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**Investigating Extended Gamma-Ray Sources
with ASTRI and CTAO:
Observation, Analysis and Modelling**

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Abstract

This thesis investigates the gamma-ray emission from Galactic sources with next-generation IACTs (Imaging Atmospheric Cherenkov Telescopes) like the telescopes of the ASTRI (Astrofisica con Specchi a Tecnologia Replicante Italiana) Mini-Array and CTAO (Cherenkov Telescope Array Observatory), with the dual aim of addressing the role of young massive star clusters (YMSCs) in the acceleration of Galactic cosmic rays and improving their characterization capabilities of Galactic sources in the multi-TeV energy regime.

The first part focuses on the characterization of ASTRI, using Monte Carlo simulations to test the analysis chain and to benchmark sensitivity. The point-spread function (PSF) was derived from both simulations and real data from the first ASTRI telescopes, i.e. ASTRI-Horn and ASTRI-1, leading to an energy-dependent description suitable for morphological analyses. In addition, the residual background across the field of view was studied, and a two-dimensional model was implemented in the instrument response functions, improving the reliability of extended source reconstructions.

The second part addresses the scientific potential of the first stereoscopic phase of the ASTRI Mini-Array. A survey strategy was proposed to target ultra-high-energy sources discovered by LHAASO (Large High Altitude Air Shower Observatory). Dedicated simulations of the Cygnus region, the Boomerang Nebula, and SS 433 demonstrated that the Mini-Array can resolve complex morphologies, constrain emission mechanisms, and identify candidate PeVatrons in the multi-TeV energy range.

The final part examines YMSCs as possible gamma-ray emitters. Source models were constructed and compared to TeV halo templates. Simulations with ASTRI and CTAO response functions were used to test a morphological classification scheme based on excess count profiles. The results show that the mechanical efficiency of stellar winds influences the gamma-ray morphology, and that some of the extended sources observed by LHAASO may be consistent with a YMSC origin.

In summary, the thesis has: validated the ASTRI analysis pipeline with simulations; introduced refined PSF and background modelling methods; developed survey and analysis strategies for the ASTRI Mini-Array; and it also proposed a morphological framework to identify YMSCs as potential Galactic cosmic-ray accelerators. These contributions strengthen the technical and scientific preparation of ASTRI and provide concrete improvements and methodologies for the study of gamma-ray sources.

Contents

Abstract	i
1 An Introduction to the High Energy Sky	1
1.1 CR Origins and Detection Techniques	1
1.2 Energy Spectrum of Cosmic Rays	2
1.2.1 Spectrum Interpretations and Open Problems	2
1.3 Implications for High-Energy Astrophysics	4
1.4 The Gamma-Ray Approach to Cosmic-Ray Sources	6
1.5 The LHAASO Revolution	7
1.5.1 Supernova Remnants	9
1.5.2 Pulsar Wind Nebulae	10
1.5.3 Microquasars	11
1.5.4 TeV Halos	12
1.5.5 YMSC	13
1.6 Prospects for High Energy Astrophysics and CR Origins	16
2 IACTs and Their Characteristics	19
2.1 Current-Generation IACTS	20
2.1.1 The VERITAS Array	20
2.1.2 The H.E.S.S. Array	21
2.1.3 The MAGIC Telescopes	21
2.2 The Cherenkov Telescope Array Observatory	22
2.3 The ASTRI Project	25
2.3.1 The ASTRI - Horn Case	25
2.3.2 The ASTRI Mini-Array	27
2.4 The Commissioning of ASTRI-1	27
2.4.1 Operational Site and Environment Conditions	29
2.4.2 Camera and Subsystems	30
2.4.3 Scientific Validation and Observations	31
2.4.4 Calibration and Data Analysis	33
2.4.5 Next Steps and Future Developments	35

3	ASTRI Performance Characterisation	37
3.1	Crab Nebula Simulations	37
3.2	Measuring the PSF	40
3.2.1	PSF of Monte Carlo Data	41
3.2.2	PSF Computation from ASTRI - Horn Data	49
3.2.3	PSF from ASTRI - 1 Data	52
3.3	Background Characterisation Across the FoV	57
3.3.1	Background Dataset	58
3.3.2	Background Modelling	61
3.3.3	Incorporation of the 2D Background into the IRF	63
3.4	An Accurate Computation of the PSF	64
3.4.1	Data Analysis Strategy and Implementation	66
3.4.2	Analysis Results and PSF Values	68
4	The First Stereoscopic Phase of the ASTRI Mini-Array	73
4.1	A Systematic Survey	74
4.1.1	Detection of LHAASO Sources	75
4.2	Relevant Scientific Case Studies	77
4.2.1	The Cygnus Region	79
4.2.2	The Boomerang Nebula Region	80
4.2.3	SS 433 and Its Region	81
5	YMSCs as Galactic CR Sources	85
5.1	γ -Ray Emission from YMSCs:	87
5.2	A Morphological Approach to Source Classification	88
5.2.1	Motivation and Analysis Strategy	89
5.3	The Sample	90
5.4	Modelling the Sources	92
5.4.1	YMSCs Model Production	92
5.4.2	TeV Halos Modelling	95
5.5	CTAO and ASTRI Mini-Array Simulations	96
5.5.1	Excess Counts Profiles Analysis	96
5.6	Classification Methodologies	99
5.7	Morphology Dependence on Mechanical Efficiency	100
5.8	Classification of LHAASO Sources	102
5.9	The Gas Distribution around YMSCs	108
5.9.1	Distance Computation of MCs	108
5.9.2	Gas Density around the YMSCs	112
5.9.3	Morphology Analyses with MCs Modellization	115
	Conclusions	121
	Bibliography	123

Chapter 1

An Introduction to the High Energy Sky

Cosmic Rays (CRs) represent one of the most interesting manifestations of high-energy phenomena in the Universe. CRs consist of charged particles coming from astrophysical objects scattered across both Galactic and extragalactic environments. The population of particles is mostly dominated by protons and helium nuclei, which represent more than 99% of the population, while those of electrons, positrons, neutrons, and heavier nuclei give a small but non-negligible contribution. In any astrophysical system, the role of CRs cannot be neglected due to their extraordinarily wide energy coverage, extending across more than thirteen orders of magnitude, from approximately 10^8 eV to beyond 10^{21} eV.

1.1 CR Origins and Detection Techniques

The variety of CR particles and their energetics implies that their origins and production mechanisms are equally diverse. The bulk of cosmic rays observed from roughly $\sim 10^9$ eV up to $\sim 10^{15}$ eV are generally attributed to Galactic accelerators, with supernova remnants and associated shock-acceleration mechanisms considered the primary contributors. For the highest energies ($\geq 10^{18}$ eV), extragalactic sources such as active galactic nuclei (AGNs), radio galaxies, and powerful transients are the leading candidates needed to explain the observed ultra-high-energy fluxes. The large span of energies has a direct consequence on what the best observational strategies are. For particles with energies less than the order of 10^{14} eV, direct detection with detectors on balloons or satellites is practical; for particles of higher energies, indirect detection with ground-based experiments constitute the only viable way. These latter methods rely on the extended air showers resulting from primary CRs interactions with the Earth's atmosphere (see Chapter 2).

Through these different observation methodologies, CR physics has a long history of fundamental discoveries. For instance, the first detection of antiparticles in the form of the positron (e^+) was made through CR observations, followed later by the identifi-

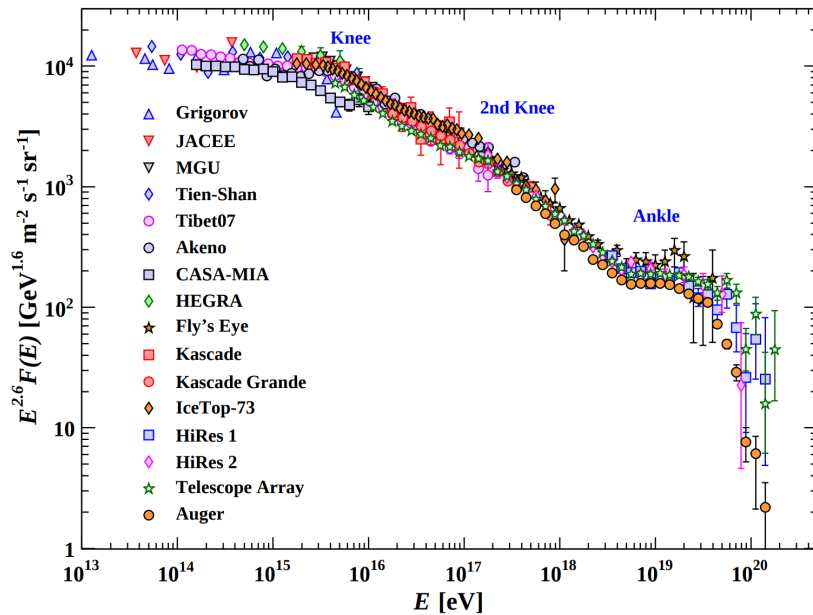


Figure 1.1: All-particle spectrum of CRs with data from different experiments, from [2], with the shape of a broken power law.

cation of pions. However, key questions remain unsolved. In particular, the nature of the acceleration mechanisms, the detailed transition between Galactic and extragalactic origins, and the role of particle propagation effects all remain topics of debate.

1.2 Energy Spectrum of Cosmic Rays

One of the defining characteristics of CRs is the shape of the energy spectrum, which is found to be consistent across different measurements [1]. The CR flux is well described by a non-thermal distribution spanning more than ten decades in energy. This behaviour, summarized in Figure 1.1, can be parameterized by a broken power law: N denotes the number of particles, E their kinetic energy, and γ_i are the spectral indexes.

The spectrum exhibits three principal regimes. In the interval between approximately 1 GeV and 5 PeV, the spectral slope is $\gamma \approx 2.7$. At around $\sim 3 - 5$ PeV, the slope steepens, giving rise to the so-called *knee* of the spectrum, where the index is $\gamma \approx 3.0$. Beyond this point, up to $\sim 3 \times 10^3$ PeV, the spectrum maintains this steeper slope before undergoing another change in index, known as the *ankle*, where it hardens again to $\gamma \approx 2.6$. The interplay between these features underpins the complex morphology of the all-particle CR distribution, clearly shown in Figure 1.2.

1.2.1 Spectrum Interpretations and Open Problems

Despite the lack of generally accepted reasons for the spectrum's distinct features, there are some general conclusions which can be made, which have been accepted by the scientific community. Below the knee, Galactic accelerators are believed to dominate the particle flux, with supernova remnants (SNRs) as the leading candidates (see Section

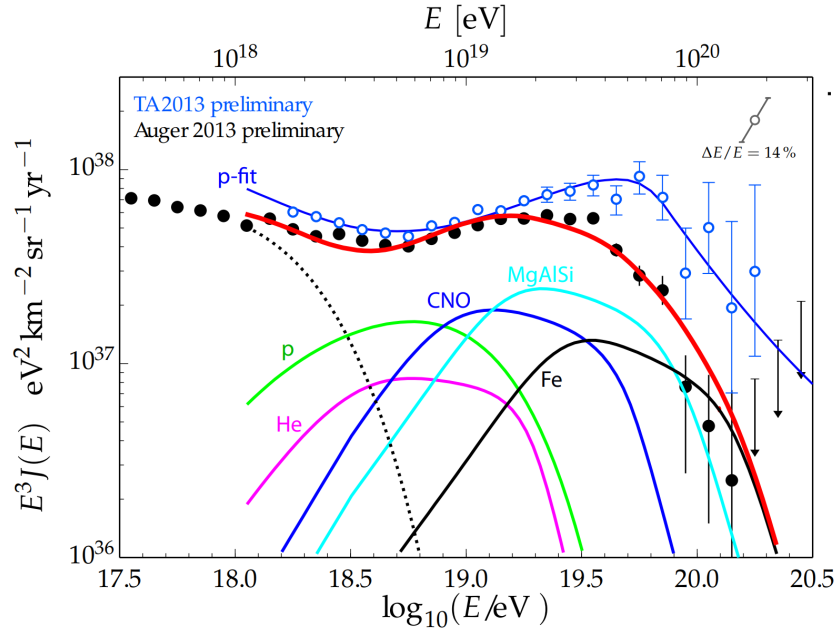


Figure 1.2: CRs spectrum, with a clear cutoff at energies 10^{21} eV, evident from the plot by Auger and Telescope Array Collaboration [3].

1.5.1). Conversely, at energies above the ankle, extragalactic accelerators must be invoked. The range between these two limits remains disputed with related uncertainties regarding the overall composition and acceleration processes.

The knee, in particular, has been linked to changes in the chemical composition of CRs. Evidence suggests that the feature may be generated either by a cutoff in the flux of lighter elements [4], or alternatively by the disappearance of intermediate-mass nuclei [5]. Other proposals highlight propagation effects or complex multi-step acceleration models within SNRs (e.g. [6]). Such hypotheses remain difficult to validate, as direct composition measurements become increasingly challenging at high energies.

At the opposite ends of the spectrum, additional peculiarities appear. Below approximately 1 GeV, the influence of the solar wind suppresses the arrival of Galactic CRs, leaving only locally produced solar particles detectable in this region. At the extreme high-energy end, near 10^{20} eV, the flux exhibits a suppression that is widely attributed to the Greisen-Zatsepin-Kuzmin (GZK) effect [7, 8]. At these energies, protons are expected to lose energy through interactions with cosmic microwave background (CMB) photons, producing pions via the resonant channel:

$$p + \gamma_{\text{CMB}} \rightarrow \Delta^+ \rightarrow p + \pi^0, \quad (1.1)$$

$$p + \gamma_{\text{CMB}} \rightarrow \Delta^+ \rightarrow n + \pi^+, \quad (1.2)$$

where Δ^+ denotes the baryonic resonance state. This process effectively sets a horizon of about 50 Mpc for protons above 10^{20} eV, as their mean free path is severely constrained. Nevertheless, occasional detections of particles exceeding the GZK cutoff —

most famously the so-called *Oh-My-God Particle* [9] — continue to stimulate theoretical speculation. Possible explanations include the existence of nearby, extremely powerful accelerators within the local universe, or even the necessity of revisiting certain aspects of fundamental physics under extreme conditions.

Historically, the CR spectrum was described as a simple power law with index $\alpha = 2.7$ up to the knee ($\sim 3 \times 10^{15}$ eV). However, recent high-precision measurements by experiments such as CALET and DAMPE suggest that the structure of the spectrum below 1 PeV is more complex. In particular, the data reveal both hardenings and steepenings between 100 GeV and 100 TeV [10, 11]. These features challenge the long-standing assumption that the sub-PeV spectrum is featureless, instead pointing toward a rich variety of processes at play within Galactic accelerators. Beyond the knee, a further steepening to $\alpha = 3.1$ persists until the ankle ($\sim 3 \times 10^{18}$ eV). At this point, the hardening of the spectrum is often interpreted as the onset of the extragalactic component. Some analyses also highlight the presence of a *second knee* at approximately 10^{17} eV, potentially associated with the contribution of heavy nuclei. Recent experimental results suggest that the Galactic-to-extragalactic transition likely occurs in the energy range between this second knee and the ankle [12, 13].

1.3 Implications for High-Energy Astrophysics

The emerging picture of the CR spectrum, with its combination of universal features (knee, ankle and cutoff) and subtle fine structure (spectral hardenings and softenings), exemplifies the challenges of modern high-energy astrophysics. The complexity of the observed flux distribution requires both sophisticated theoretical models and increasingly precise observational campaigns. In this regard, recent advances in detection technology, such as LHAASO, have provided unprecedented sensitivity at the highest energies, reinforcing the idea that CR research stands at the intersection of particle physics, astrophysics, and cosmology.

In summary, CRs serve not only as tracers of astrophysical processes across the Galaxy and beyond, but also as unique probes of fundamental physics under conditions unattainable in terrestrial laboratories. Their spectrum encapsulates an extraordinary story of acceleration, propagation, and interaction, which continues to motivate one of the most active fields of inquiry in modern physics.

The efficiency of particle acceleration places strict requirements on the astrophysical environments capable of producing CRs. For charged particles to gain significant energy, they must remain confined within magnetized regions of a source. The actual trajectory of each particle is dictated by the strength and orientation of the local magnetic field, and if the motion drives it outside the acceleration zone prematurely, further energy gain becomes impossible. This simple physical consideration already excludes many candidate sources. The confinement condition can be quantified by introducing the particle's Larmor radius R_L , which describes the circular motion of a charge Ze with

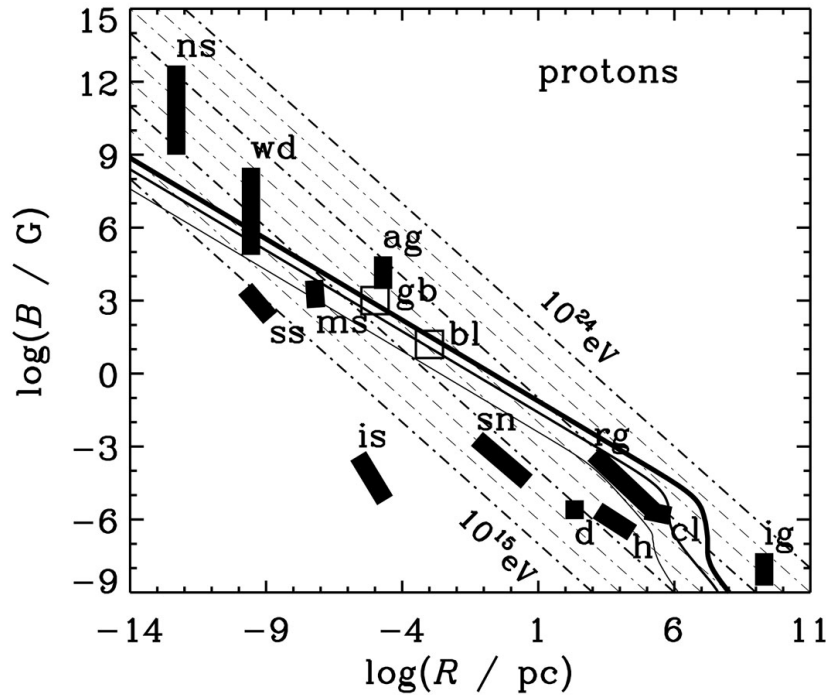


Figure 1.3: The Hillas diagram from [14], showing magnetic field versus gyroradius for proton momenta. Solid curves correspond to different shock-waves velocities: the upper solid curve indicates the maximum attainable energy $\beta = 1$, the middle and lower solid curves indicate plausible less effective acceleration processes. Typical size and magnetic field of possible acceleration sites are shown for neutron stars (ns), white dwarfs (wd), sunspots (ss), magnetic stars (ms), active galactic nuclei (ag), interstellar space (is), SNRs (sn), radio galaxy lobes (rg), galactic disk (d) and halo (h), clusters of galaxies (cl), intergalactic medium (ig), blazar (bl) and gamma ray burst (gb).

energy E in a magnetic field of strength B_S :

$$R_L = \frac{E}{ZeB_S}. \quad (1.3)$$

If R_L surpasses the characteristic size R_S of the acceleration region, the particle will escape. The requirement $R_L \leq R_S$ therefore provides an estimate for the largest attainable energy in such an environment:

$$E_{\max} = ZeB_S R_S. \quad (1.4)$$

This relationship, widely known as the Hillas criterion [14], offers a geometrical framework for identifying plausible CR accelerators. Figure 1.3 presents different classes of astrophysical objects mapped according to their sizes and magnetic field strengths, including neutron stars (NS), white dwarfs (WD), gamma-ray bursts (GRBs), AGN with jets and cores, SNRs, and large-scale intergalactic shocks. Also considered are Galactic structures such as the disk and halo, galaxy clusters, and interacting galaxies. An additional implication arises when applying Equation 1.3 to typical interstellar magnetic fields: protons with energies below 10^{18} eV remain magnetically confined within the

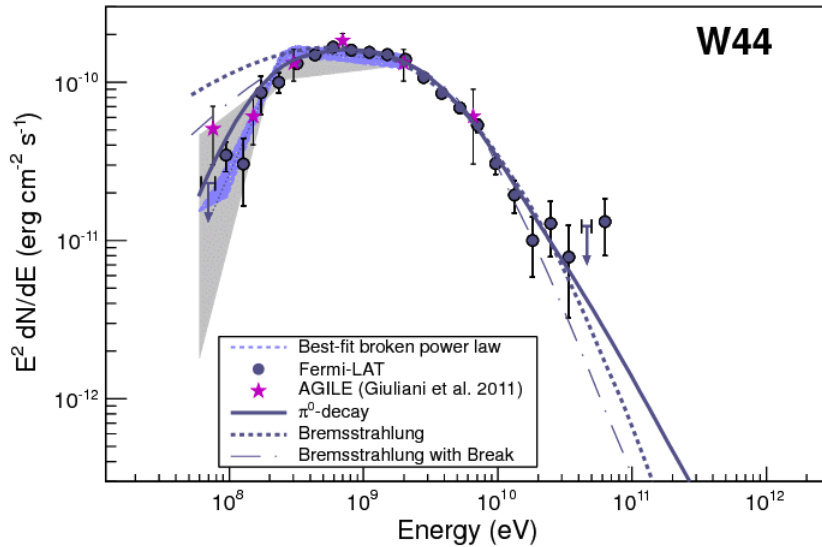


Figure 1.4: Gamma-ray spectrum of SNR W44 as measured with the Fermi LAT, in blue, and AGILE, in magenta. Taken from [18].

Galactic disk, reinforcing the interpretation that the sub-knee spectrum originates from Galactic sources. At higher energies, however, magnetic trapping becomes inefficient, enabling particles to escape and traverse intergalactic distances [15].

1.4 The Gamma-Ray Approach to Cosmic-Ray Sources

CRs are charged particles, and their trajectories are scrambled by Galactic magnetic fields. This deflection erases any memory of their birthplace, making it impossible to directly associate them with specific astrophysical objects. To circumvent this limitation, one must instead rely on neutral messengers, such as γ rays, which preserve directional information and thus provide a powerful tracer of CR accelerators.

The production of high-energy photons is intimately linked to the presence of relativistic particles. Depending on the environment, different mechanisms dominate: (i) relativistic electrons may generate γ rays via Bremsstrahlung in matter or by inverse Compton (IC) scattering on ambient photon fields; (ii) accelerated hadrons collide with surrounding gas, producing neutral pions whose subsequent decay yields energetic photons. Identifying whether leptonic or hadronic channels dominate in a given source is fundamental to determining the underlying acceleration processes [16, 17]. A distinctive hadronic signature is the ‘pion bump,’ a spectral excess around ~ 100 MeV like the one visible in Figure 1.4, corresponding to the rest mass of the π^0 , which constitutes direct evidence of CR nuclei being accelerated in situ.

The observed γ -ray spectrum is therefore a sensitive diagnostic tool, as it reflects both the acceleration mechanism and the conditions of the surrounding medium. The photon energy range extends from ~ 1 MeV—the scale associated with electron–positron annihilation ($2m_e \approx 1.022$ MeV)—up to the most extreme energies accessible in nature.

Table 1.1: Conventional sections of the γ -ray energy spectrum.

Domain	Energy range
Low-energy γ rays	$\sim 1\text{--}30$ MeV
High-energy γ rays	30 MeV–100 GeV
Very-high-energy (VHE) γ rays	100 GeV–100 TeV
Ultra-high-energy (UHE) γ rays	> 100 TeV

Conventionally, this broad band is subdivided into several domains (see Table 1.1), each historically associated with distinct detection techniques and astrophysical targets.

1.5 The LHAASO Revolution

The identification of the pion bump at ~ 100 MeV provided one of the first direct signatures of hadronic acceleration in astrophysical sources [19, 20]. At the opposite end of the spectrum, the detection of ultra-high-energy (UHE, $E > 100$ TeV) γ -rays was long regarded as unambiguous evidence for freshly accelerated cosmic rays, since leptonic IC emission is expected to be strongly suppressed in the Klein–Nishina regime at these energies [16]. This reasoning led to the definition of *PeVatrons* as Galactic accelerators capable of boosting protons to PeV energies and producing γ -rays above 100 TeV [17]. γ -ray signatures near the pion bump detected by AGILE and Fermi-LAT support the role of SNRs in accelerating protons at GeV energies [19, 20]. However, no SNR has yet been firmly associated with photons above 100 TeV. The lack of clear SNR detections at UHE motivated the exploration of other candidate accelerators. One important clue came from the Fermi-LAT detection of the Cygnus Cocoon, an extended γ -ray emitting region powered by the Cygnus OB2 stellar association [21]. This, together with subsequent VHE observations of other massive star clusters, suggested that superbubbles and star-forming regions might also play a role in CR acceleration.

A pivotal breakthrough came with the LHAASO results. In 2021, the collaboration reported the discovery of twelve Galactic sources emitting γ -rays up to 1.4 PeV [22]. This unprecedented achievement demonstrated that UHE emission is not limited to a single class of objects. Many of the detected sources appear spatially coincided with pulsars and their wind nebulae (PWNe), which are traditionally considered leptonic accelerators [23, 24]. This finding challenges the long-standing assumption that UHE γ -rays automatically imply hadronic acceleration, and motivates a refined terminology in which we distinguish between generic PeVatrons (i.e. accelerators of either leptons or hadrons) and hadronic PeVatrons (i.e. accelerators of CR protons and nuclei). The LHAASO detections thus opened the possibility that several classes of sources contribute to the observed PeV CR population [25]. In PWNe, the dominant mechanism might not be the standard diffusive shock acceleration but instead magnetic reconnection, potentially responsible for impulsive events rather than steady UHE emission [25]. At the same time, some of the LHAASO regions remain consistent with an SNR origin, keeping open the possibility that remnants may produce PeV γ -rays even beyond their

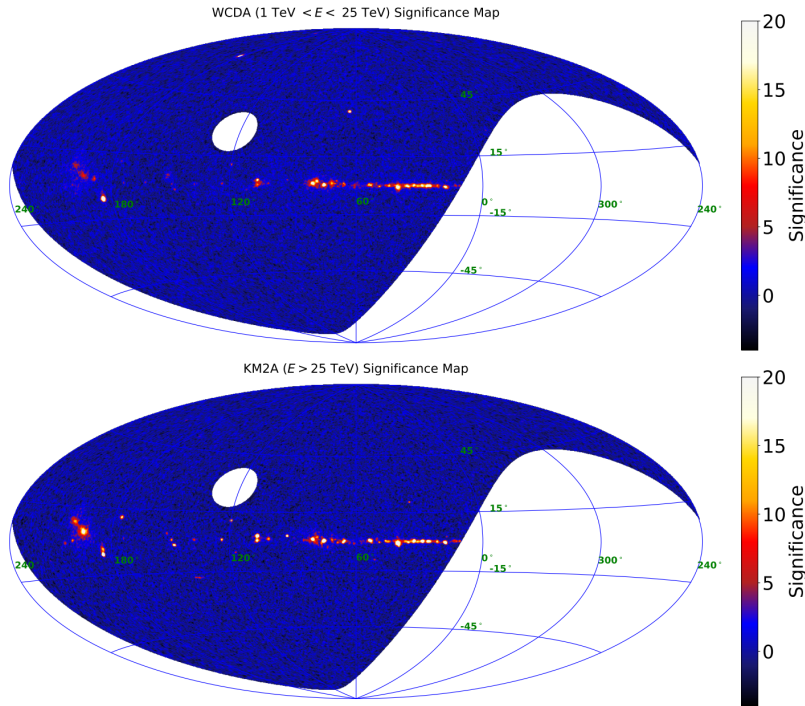


Figure 1.5: Distribution of the sources in the first LHAASO catalog in the form of a significance map, from [26].

earliest evolutionary stages [13].

A further complication arises from the limited angular resolution of air shower arrays such as LHAASO, which makes source identification challenging. Future instruments like the ASTRI Mini-Array and CTAO, with superior angular resolution in the 10–100 TeV range, will be crucial to disentangle the nature and morphology of these accelerators [22]. LHAASO has revolutionized our understanding of Galactic CR accelerators. By establishing the existence of multiple sources emitting photons well above 100 TeV, it has blurred the distinction between hadronic and leptonic PeVatrons and opened a new era of multimessenger studies combining γ -rays and neutrinos to constrain the physics of the most extreme Galactic accelerators.

Since then, the LHAASO Collaboration have released the *First Catalog of Very-/Ultra-High-Energy Gamma-Ray Sources* [26]. Based on data from the Water Cherenkov Detector Array (WCDA) and the Kilometer Sq. Array (KM2A) collected over thousands of hours, the catalog includes 90 sources in the Northern hemisphere, visible in Figure 1.5. Of these, 32 are previously unknown in the TeV range, and 43 sources exhibit UHE emission (i.e. above 100 TeV) at $\geq 4\sigma$ significance. Furthermore, the catalog confirms that multiple Galactic sources emit gammas up to or above 1 PeV, expanding the sample beyond the first 12 so-called PeVatrons originally reported. The catalog also provides spectral parameters of several sources characterised by a hard power-law spectra extending without detected cut-offs, at least up to 100 TeV. The most likely PeVatron candidate objects include many classes of astrophysical objects, which are briefly described below.

1.5.1 Supernova Remnants

SNRs arise from the explosion of massive stars, where the stellar ejecta expand at supersonic velocities into the surrounding interstellar medium (ISM). This process drives a powerful shock front that sweeps up ambient material and compresses magnetic fields, creating a natural environment for particle acceleration [27]. Within this framework, the diffusive shock acceleration (DSA) mechanism offers an efficient means of energizing charged particles, and the interaction of these accelerated CRs with the ISM naturally gives rise to high-energy (HE) and very-high-energy (VHE) γ -ray emission.

From an energetic perspective, SNRs can comfortably sustain the Galactic CR population. Each supernova explosion releases $E_{\text{SN}} \approx 10^{51}$ erg in kinetic energy, and diverting $\sim 10\%$ of this budget into non-thermal particles is sufficient to reproduce the observed CR luminosity [17, 13]. The power-law particle spectra expected from DSA further support the paradigm that SNRs are the dominant sources of Galactic CRs [16]. Observational evidence strengthens this view: non-thermal X-ray emission correlated with TeV γ rays points to amplified magnetic fields capable of sustaining multi-TeV particle populations [28, 29], while CR-induced modifications in Balmer line profiles provide additional confirmation of shock acceleration [17]. Spatial associations between γ -ray emission and dense molecular clouds (MCs) further suggest hadronic interactions are at work.

A decisive breakthrough came with the detection of the π^0 -decay feature in the middle-aged remnant W44 by *AGILE* [19], later confirmed by *Fermi*-LAT in W44, IC 443, W51C, and W49B [20]. These results directly demonstrated proton acceleration, though the observed emission did not extend beyond ~ 100 GeV. However, unambiguous evidence for PeV acceleration in individual SNRs remains elusive. Models predict that protons may only reach PeV energies during the earliest ($\lesssim 100$ yr) evolutionary stages, particularly in highly energetic explosions ($E_{\text{SN}} \sim 5\text{--}10 \times 10^{51}$ erg) at the start of the Sedov phase [29]. Even if the SNR itself no longer confines PeV particles, escaped CRs can still illuminate their surroundings. In particular, giant MCs can act as calorimeters if local diffusion is suppressed, leading to delayed γ -ray emission at UHEs [30]. Intriguingly, LHAASO has reported that nearly half of its current PeVatron candidates may be linked to middle-aged SNRs [31]. Determining whether the γ rays originate inside the remnant shocks or from illuminated clouds remains one of the most pressing questions in CR astrophysics.

Despite their many successes, the SNR paradigm is not without shortcomings. The predicted spectra from standard DSA models differ from the CR spectra measured at Earth, suggesting that modifications to the acceleration and escape physics are required [16]. Furthermore, isotopic anomalies—such as the enhanced $^{22}\text{Ne}/^{20}\text{Ne}$ ratio in Galactic CRs—pose difficulties for a model relying exclusively on isolated SNRs. These challenges motivate consideration of additional contributors, such as superbubbles, PWNe, or γ -ray binaries, to fully account for the observed CR population.



Figure 1.6: Multi-wavelength image of Cassiopeia A, one of the most studied Galactic SNRs. Shock-accelerated particles and their interaction with the ISM give rise to non-thermal X-ray and γ -ray emission (in blue). Optical radiation is in white, while infrared is in red and green.

1.5.2 Pulsar Wind Nebulae

PWNe are expected to represent the most abundant class of Galactic high-energy sources [32]. Their γ -ray activity can persist for $\sim 10^5$ years [24], which may explain why more than one third of the PeVatron candidates identified by LHAASO are linked to these objects [24]. PWNe are also the only environments where PeV electron acceleration has been directly confirmed through synchrotron emission. Particle acceleration is thought to occur at the termination shock, formed by the interaction of the pulsar wind with the parent SNR.

Observationally, PWNe satisfy the basic criteria for PeVatrons: they show extended TeV–PeV emission, multi-wavelength non-thermal counterparts, and curved γ -ray spectra [24, 32]. Their UHE component is usually interpreted as IC scattering of electrons on the Cosmic Microwave Background (CMB) radiation. However, theoretical modelling encounters difficulties, mainly due to Klein–Nishina suppression, which requires extremely efficient acceleration mechanisms [33].

The maximum achievable particle energy is constrained by two main conditions. First, the polar-cap potential drop limits the energy to

$$E_{\max} = q \left(\frac{\dot{E}}{c} \right)^{1/2}, \quad (1.5)$$

where q is the particle charge [24]. Reformulating this in terms of observable parameters

gives

$$E_{\gamma,\max} \approx 0.9 \eta_e^{1/3} \eta_B^{0.65} \dot{E}_{36}^{0.65} \text{ PeV}, \quad (1.6)$$

where η_B and η_e denote the magnetic and electric field fractions, respectively, and $\dot{E}_{36}$ is the pulsar spin-down luminosity in units of $10^{36} \text{ erg s}^{-1}$. Only extremely energetic pulsars ($\dot{E} \gtrsim 10^{36} \text{ erg s}^{-1}$) meet this requirement. A second limit arises from balancing acceleration and radiative losses at the termination shock radius $R_{0.1}$ (in 0.1 pc units):

$$E_{\gamma,\max} \approx 2.7 \eta_e^{0.65} \eta_B^{-0.33} R_{0.1}^{0.65} \dot{E}_{36}^{-0.33} \text{ PeV}. \quad (1.7)$$

This is particularly stringent for young, bright pulsars such as the Crab.

While hadronic acceleration inside PWNe cannot be ruled out, their global contribution to the Galactic CR flux is negligible [11]. Producing CR energetics comparable to SNRs would require unrealistically short initial spin periods. Consequently, PWNe may supplement but cannot dominate Galactic CR composition or anisotropy. A comprehensive overview of LHAASO PWNe candidates is provided in [24], where most detected sources are compatible with a PWN origin, with the notable exception of LHAASO J2032+4127 (see Figure 1.3).

1.5.3 Microquasars

Interest in γ -ray binaries (microquasars) as candidate Galactic CR accelerators originates from their similarities with AGNs, which are believed to dominate the extra-galactic CR contribution [11]. Microquasars are known to accelerate electrons up VHE [34]. Their radiation-dominated environments make Klein–Nishina losses inefficient, and $\gamma\gamma$ absorption is negligible for photons up to $\sim 100 \text{ TeV}$. Despite these features, their rarity compared to SNRs or PWNe makes them unlikely to explain the observed Galactic CR energy density, anisotropy, or composition. Nonetheless, several γ -ray binaries have been detected at multi-TeV energies without evidence of cutoffs above 10 TeV (e.g. [34] for the case of SS 433). In particular, SS 433 shows emission above 10 TeV, with a jet kinetic luminosity of

$$L_{\text{kin}} \sim 10^{39} \text{ erg s}^{-1}, \quad (1.8)$$

which exceeds by more than an order of magnitude the power required for particle injection [31, 34]. The microquasar V4641 Sgr, a black hole binary with ultra-relativistic jets, represents a new class of γ -ray source of significant interest for future observatories.

Observations further indicate that γ -ray flux often correlates with orbital phase, suggesting that the acceleration mechanism operates at binary scales. A key open question is whether this acceleration resembles the processes identified in the Crab Nebula (e.g. reconnection-driven events; [35, 36]) or requires a binary-specific mechanism, as implied by recent X-ray studies of SS 433 [23]. Although no microquasar was among the 12 LHAASO PeVatron candidates [22], they were present in the first LHAASO catalog [26], and this class remains a promising target for next-generation extensive air-shower arrays and Cherenkov telescopes [37, 38].

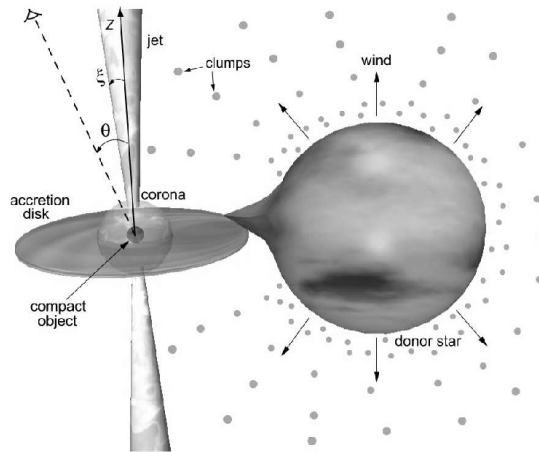


Figure 1.7: Schematic representation of a microquasar system, highlighting jet-driven γ -ray emission, from [39].

1.5.4 TeV Halos

The identification of TeV halos originates from the extended emission surrounding Geminga and Monogem pulsars, first revealed by MILAGRO [40] and subsequently confirmed by HAWC [34]. These halos extend over nearly $\sim 10^\circ$, suggesting that CR transport in their vicinity is significantly inhibited compared with the ISM. The γ -ray signal is attributed to IC scattering of electrons injected by the pulsar onto background radiation fields, with diffusion coefficients several hundred times smaller than the Galactic average [41]. The underlying cause of this slow diffusion remains uncertain, though the phenomenon enables probing of 'invisible' pulsars lacking strong radio or GeV beams. Importantly, the γ -ray spectra of halos can directly constrain the injection cut-off of PWN) electrons.

Evidence from LHAASO reveals several extended TeV emitters, many spatially associated with pulsars [26]. The only secure halo reported so far is LHAASO J0621+3755 [41], alongside the established Geminga, Monogem, and HESS J1831-098 halos [42]. A viable halo candidate must coincide with a pulsar of sufficient spin-down power, be old enough for electrons to propagate into the ISM (avoiding bow-shock confinement [43]), and display an extension exceeding possible X-ray PWN emission. Otherwise, γ -ray emission could be of hadronic or compact PWN origin [42].

Experimental constraints further complicate halo detection. Air shower arrays lack angular resolution to probe morphology, while IACTs struggle due to their limited field of view (FoV). This explains the absence of Geminga and Monogem in current IACT observations, despite their brightness. Future instruments, such as the ASTRI Mini-Array (FoV $\sim 10^\circ$ above 10 TeV) and CTAO small-size telescopes in the south (FoV $> 8^\circ$), will enable morphological studies and high-resolution spectra. Simulations with ASTRI already suggest that a single pointing could recover Geminga's spectrum up to 50 TeV with strong significance [44]. Repeated exposures will allow detailed radial profiling and firm discrimination between halo and PWN scenarios.

1.5.5 YMSC

Young massive star clusters (YMSCs) are widespread in the Milky Way and have been extensively catalogued thanks to surveys such as [45]. In addition to the thousands of clusters that have already been identified, many are still embedded in their natal H II regions, making them observationally challenging. These systems drive powerful stellar winds, whose combined kinetic power across the Galaxy is of the order of $10^{41} \text{ erg s}^{-1}$, comparable to that released by supernovae. If even a modest fraction of this energy is converted into relativistic particles, YMSCs could represent an important contributor to the Galactic CR population. The possibility that superbubbles (SBs)—large shells produced by the combined activity of OB associations—play a role in CR acceleration was first discussed in the early 1980s [21]. YMSCs ($M \gtrsim 10^4 M_{\odot}$) provide ideal conditions: they host numerous massive stars with energetic winds [46], exhibit a turbulent plasma environment [21], and contain multiple SNRs evolving within the same cavity [47]. Typical SB radii can exceed 100 pc, suggesting extended γ -ray emission regions, now confirmed by VHE detections in sources such as the Cygnus Cocoon [48], Westerlund 2 [25], 30 Dor in the LMC [49], the Central Molecular Zone [31], and Westerlund 1 [25].

Several mechanisms have been proposed for particle acceleration in such environments, including colliding stellar winds [50], stochastic (second-order Fermi) acceleration in turbulent superbubbles [51, 11], and shocks at the termination of collective cluster winds [52]. Regardless of the process, efficient acceleration would naturally produce gamma-ray emission. Observationally, only a limited number of clusters have been firmly detected in the GeV domain, with fewer cases confirmed at TeV energies, likely due to their extended and faint nature. As suggested by [53], some YMSCs may already be hidden among the population of unassociated Fermi-LAT sources. Indeed, statistical studies reveal significant correlations between Fermi detections and WISE H II regions, whereas no strong correlation is found with Gaia clusters [54, 55]. Nevertheless, some of the brightest Gaia clusters—such as NGC 3603, NGC 6611, NGC 6618, and Berkeley 59—show positional overlap with gamma-ray sources, motivating targeted analyses [53]. A handful of particularly powerful clusters (e.g., Westerlund 1, Westerlund 2, and Cygnus OB2) are already established as VHE gamma-ray emitters. However, the small sample size and severe source confusion still hinder a robust estimate of the global CR contribution of YMSCs. Current ground-based gamma-ray observatories face additional difficulties due to the large angular extent of these systems. Future instruments such as ASTRI and CTAO, with improved sensitivity to extended sources and better angular resolution, are expected to provide decisive constraints on the VHE emission from massive clusters and on their role as Galactic accelerators [55].

Collective shocks from stellar winds and SNe may also explain the anomalous $^{22}\text{Ne}/^{20}\text{Ne}$ abundance ratio [47, 16], long considered problematic for the isolated-SNR scenario [28]. While a single wind provides only ~ 10 –50% of the kinetic power of an SNR [46, 11], the combined outflows of tightly packed stars, including Wolf-Rayet systems, can drive

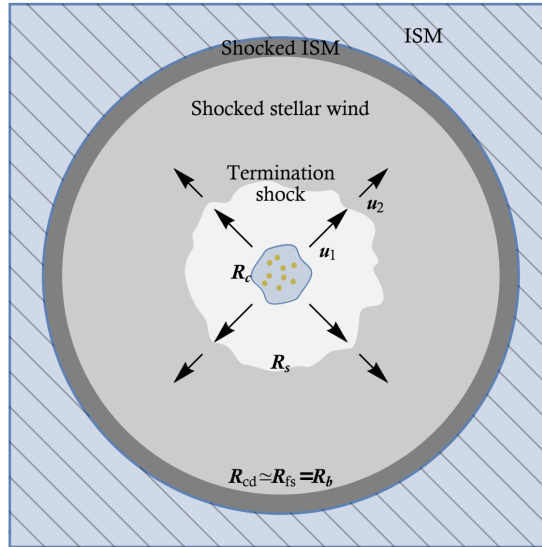


Figure 1.8: Schematization of the YMSC wind-blown bubble, from [52].

a global outflow capable of accelerating CRs [11]. The dominant mechanism is likely second-order Fermi acceleration [21], less efficient than SNR shocks but active for $\sim \text{Myr}$, far longer than the brief acceleration window of SNRs. Observations of extended γ -ray halos around Cygnus OB2, Westerlund 1, and Westerlund 2 reveal CR densities declining as $n_{\text{CR}}(r) \propto 1/r$, supporting continuous injection [48]. Magnetic turbulence up to $B \sim 100 \mu\text{G}$ may develop in cluster cores [46], allowing acceleration beyond the PeV domain with spectra consistent with the Galactic CR knee [11, 47]. The transition from isolated SNRs to clustered environments may thus naturally explain the spectral break.

The OB-type stars in the YMSCs, particularly those that are more massive, are known to play important roles as providers of stellar winds that carry significant mechanical energies [56]. When a significant number (i.e. several 10s to 1000s) of such stars coexist within a few pc^3 , those region becomes highly favorable to accelerate particles to relativistic velocities. Many mechanisms have been explored over decades to identify the acceleration processes of CRs within these scenarios, with earlier postulates indicated acceleration could take place at the termination shock of individual stellar winds [57]. On young and highly concentrated stellar structures, like YMSCs, such collisions are rendered ever more complex—and possibly significantly enhanced—through the development of a phenomenon known as a collective wind. This refers to a collective outflow formed by combining individual stellar winds, which ends up being a unified and ordered wind structure and generates a large-scale bubble within the surrounding ISM. In this scenario, high-energy particles can be accelerated at termination shocks that form around collective-cluster-generated winds [52]. Furthermore, collisions between such winds—individual or collective—coupled with density fluctuations that can be seen at various spatial scales, can lead to various modes of magnetohydrodynamic turbulence that causes second-order Fermi acceleration processes resulting in an overall growth by orders of magnitude of the total number of energetic particles within the system [51].

[52] emphasize the importance of spatially-resolved particle transport, adopting a steady-state, spherically symmetric treatment of CR diffusion and advection within and around the bubble. The structure of such a bubble, originally described by [58] and further developed in subsequent works (e.g. [59]) are characterised by key elements, visible in Figure 1.8, which include:

- A central **wind-driving region** where the stellar winds are expanding freely at velocity $v_w \approx 10^3 \text{ km/s}^{-1}$, enclosed by a termination shock (TS). Its density profile follows

$$\rho(r) = \frac{\dot{M}}{4\pi r^2 v_w}, \quad r > R_c, \quad (1.9)$$

where R_c is the cluster core radius. It carries the kinetic energy that powers the bubble. This region is characterised by high mechanical luminosity ($L_w \sim 10^{39} \text{ erg s}^{-1}$), representative of a typical YMSC.

- A **termination shock** at a radius R_{ts} , beyond which the wind becomes subsonic and CRs are accelerated. It is formed where the ram pressure of the free stellar wind balances the pressure of the shocked wind:

$$\frac{\dot{M} v_w}{4\pi R_{ts}^2} = \frac{7}{25} A^2 \rho_0 t^{-4/5}. \quad (1.10)$$

At the termination shock of this bubble, cosmic rays can be efficiently accelerated via diffusive shock acceleration (DSA).

- A **dense shell** located at $R_{sh} > R_{ts}$ where hadronic interactions between CR protons and ambient gas nuclei produce neutral pions, which decay into gamma rays.
- A **contact discontinuity** which constitutes the interface between the shocked stellar wind and the shocked ISM. It separates the hot plasma from the cold, dense shell outside of it.
- A layer of swept-up **shocked ISM**, compressed and cooled behind the forward shock. Because its cooling timescale is very short ($\sim 10^4 \text{ yr}$), this component collapses into a thin, dense shell bounding the bubble and $R_{cd} \simeq R_{fs} \equiv R_b$ [60].
- The outermost **forward shock** shock, driven into the ISM by the expanding bubble. It sweeps up and compresses ambient gas into the thin shell surrounding the bubble.

The gamma-ray emissivity is calculated from the CR energy density and the target gas density using standard hadronic interaction cross-sections.

According to recent studies [25] on the spectromorphological analysis of Westerlund 1, the investigation of the radial brightness profiles reveals an interesting displacement of the peak emission with respect to the geometrical centre of the source, visible in

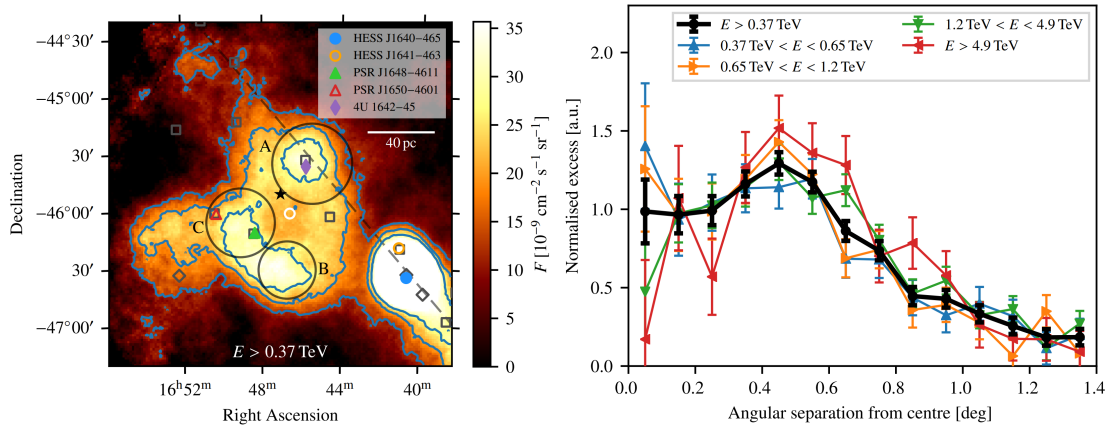


Figure 1.9: Flux map of the HESS J1646–458 region (left) and corresponding radial excess profiles (right), from [25]. The flux map shows the position of Westerlund 1 (black star), the Galactic plane (grey dashed line), and reference regions used in the analysis. The radial profiles, computed with respect to the indicated reference point, illustrate the displacement of the emission peak from the cluster centre.

Figure 1.9. Instead of a simple centrally peaked distribution, the analysis shows that the profile exhibits a maximum at a finite distance from the core, producing a structure that resembles a ring-like morphology. This feature indicates that the intensity does not monotonically decrease with radius, but rather reaches its highest value at a characteristic distance. Remarkably, this distance is found to be close to the expected termination shock radius, where the outflow of energetic particles from the central cluster is balanced by the surrounding medium. Such a configuration suggests a strong connection between the observed gamma-ray morphology and the physical processes governing particle acceleration and confinement in the vicinity of Westerlund 1. The Morlino et al. model [52] therefore reproduces observed GeV–TeV gamma-ray spectra and spatial profiles around several known YMSCs, including Westerlund 1 and NGC 3603. An important conclusion from Morlino et al.’s work is that YMSCs can act as extended, long-lived sources of Galactic cosmic rays and contribute to the diffuse gamma-ray background. Their model provides a physically motivated framework for interpreting gamma-ray halos around clusters, which can complement or, in some cases, rival traditional SNR scenarios for cosmic-ray origin.

1.6 Prospects for High Energy Astrophysics and CR Origins

The large effort carried out with both ground-based and space-borne facilities has led to major progress in our understanding of CRs and their potential sources. Yet, despite these advances, the long-standing question of their origin remains unresolved. The connection between γ -ray astronomy and CR studies has been dramatically highlighted in recent years. The LHAASO experiment reported, in 2021, the detection of VHE energies photons from the Crab Nebula, long regarded as the ‘standard candle’ of γ -ray

astronomy [22]. This discovery not only challenges long-standing emission models for the Crab but also provides direct evidence that nature hosts genuine PeVatrons. The fact that CRs are observed up to $\gtrsim 10^{20}$ eV strongly suggests that the current absence of photon detections beyond a few PeV is more a consequence of instrumental limitations than of astrophysical impossibility. The recent LHAASO results highlight the key elements needed for further progress: improved angular resolution in the very-high and UHE γ -ray domain, increased sensitivity of future neutrino detectors, multi-wavelength and multi-messenger analyses of individual sources, and a deeper theoretical understanding of the microphysics at work in different environments [61]. Among these aspects, angular resolution appears to be of primary importance, since it will allow for more reliable source associations, the study of energy-dependent morphologies, and stronger links with observations at other wavelengths. High sensitivity at the highest energies is also crucial, although LHAASO has already shown that PeVatrons can be detected in our Galaxy. What is missing, however, is an unambiguous identification of the parent accelerators and a clear separation between hadronic and leptonic emission. Morphological information will also help to probe the physical conditions of candidate PeVatrons: for example, compact emission regions in PWNe indicate strong magnetic fields and severe synchrotron losses, while the detection of extended X-ray structures would imply that the γ -ray signal is produced through IC scattering of the cosmic microwave background [61]. Such detections, currently challenging for instruments like *XMM-Newton* or *Chandra*, may become possible with the larger field of view of *eROSITA*.

Imaging Atmospheric Cherenkov Telescopes (IACTs) offer some advantages with respect to air shower arrays, in particular their excellent angular resolution ($< 0.1^\circ$ at 1 TeV) and low-energy threshold. Although their duty cycle and field of view are limited, these features make them well suited for detailed morphological studies. The ASTRI Mini-Array and CTA are expected to be decisive in this respect, enabling both deeper investigations of known sources and the discovery of hundreds of new ones in the TeV domain (see Section 2). The first telescopes of the ASTRI Mini-Array are already scheduled to become operational in 2025-2026, preceding the full operation of next-generation neutrino observatories such as IceCube-Gen2, KM3NeT-ARCA, and P-ONE. This temporal overlap will open the way to combined γ -ray-neutrino studies. Predictions show that a coordinated system such as the Planetary Neutrino Monitoring System could detect neutrino emission from several LHAASO sources within the next two decades [61]. The technological progress of the next decade will need to be matched by increasingly sophisticated theoretical frameworks, enabling us to distinguish between different classes of sources and acceleration mechanisms. We are at an exciting turning point in VHE/UHE astrophysics: more than a century after the discovery of CRs, we now know that SNRs dominate the lower-energy component, but additional accelerators are required to explain PeV energies and the observed composition. Superbubbles and massive star clusters are among the strongest candidates, while PWNe—though typically associated with leptonic processes—may also play a role, at least statistically, given their prevalence among the brightest γ -ray sources. At present, only the Crab Nebula has a

firm association, while most other LHAASO detections remain ambiguous, potentially linked to PWNe, SNRs, massive clusters, or TeV halos.

Ultimately, multi-wavelength and multi-messenger observations with higher resolution and sensitivity will be essential to disentangle these associations. The LHAASO results already mark the beginning of a new era in the study of Galactic PeVatrons, and the performance of upcoming facilities will be decisive in piecing together the puzzle of cosmic-ray origins.

Chapter 2

IACTs and Their Characteristics

In 1989, the Whipple Observatory found that the Crab Nebula emits very high-energy gamma-ray radiation at TeV energies [62]. This was a key event, as it was the initial step in gamma-ray astronomy, achieved using Imaging Atmospheric Cherenkov Telescopes (IACTs). Since that time, ground-based observatories have allowed for more progress in the field. By using several IACTs in an array configuration, i.e. with distances of roughly 100 m between them, it is possible to point the same objects simultaneously using multiple instruments as one single telescope.

VHE gamma rays cannot reach the ground directly, as the Earth's atmosphere is opaque to them. Nevertheless, their interaction with air nuclei initiates a cascade of secondary particles, the so-called *Extensive Air Shower* (EAS) [63]. These showers are not exclusive to gamma rays: CRs also produce them, although with different physical characteristics. In both cases, a large number of ultra-relativistic charged particles are generated, which, while propagating through the atmosphere, emit Cherenkov radiation whenever their velocity exceeds the speed of light in air. The resulting optical and near-UV photons form a nanosecond-scale bluish flash that can be recorded by IACTs [64, 65]. The detection principle relies on exploiting the atmosphere as a gigantic calorimeter. The Cherenkov photons, produced within a narrow cone around the shower axis, illuminate an area on the ground of several 10^4 m^2 , much larger than the physical collecting surface of the telescope. An IACT positioned inside this 'light pool' can focus part of the signal onto a fast camera, where the shower image is formed. By analysing the morphology and time structure of these images, it is possible to reconstruct both the energy and the arrival direction of the primary particle [62, 66]. Gamma-induced showers are purely electromagnetic: pair production and subsequent bremsstrahlung processes dominate their development. In contrast, hadronic interactions produce a more irregular structure. Both types of showers generate Cherenkov light, but their spatial and temporal profiles are different. Cosmic rays constitute an isotropic background that outnumbers gamma events by roughly three orders of magnitude, even in the direction of bright sources such as the Crab Nebula [66]. Efficient gamma-hadron separation thus represents a key challenge in ground-based gamma-ray astronomy.

The Cherenkov effect arises because a charged particle moving faster than c/n (where

Table 2.1: Key parameters of major IACT facilities currently in operation. Energy ranges are indicative and depend on the specific analysis methods.

Name	Number of Telescopes	Energy Range	FoV	Angular Resolution
H.E.S.S.	4 + 1 (28 m)	30 GeV – 100 TeV	3.2° – 5.0°	0.08° – 0.14°
VERITAS	4 (12 m)	50 GeV – 50 TeV	3.5°	0.10° – 0.14°
MAGIC	2 (17 m)	25 GeV – 30 TeV	3.5°	0.08° – 0.17°

n is the refractive index of the medium) polarizes the surrounding molecules, creating a coherent shockwave in the electromagnetic field. The emitted radiation is confined to a cone with aperture angle θ , defined by the relation

$$\cos \theta = \frac{1}{\beta n}, \quad (2.1)$$

where $\beta = v/c$ is the normalized particle velocity. For typical atmospheric conditions at sea level ($n \approx 1.0003$), the Cherenkov angle is about one degree, and the energy threshold for electrons is around 20 MeV [67]. This radiation, discovered by Cherenkov in 1934 and theoretically described by Frank and Tamm shortly after Cherenkov in 1934, laid the foundation for the development of IACTs several decades later. Cherenkov flashes are extremely short, with durations of a few nanoseconds, depending on the primary energy. This imposes stringent requirements on both the optical design of the telescopes and the performance of their readout systems. Historically, cameras have been based on photomultiplier tubes (PMTs), with timing resolutions of a few nanoseconds [68], but more recently silicon photomultipliers (SiPMs) have emerged as an alternative, thanks to their compactness and robustness. SiPMs also allow innovative dual-mirror designs such as the Schwarzschild–Couder (SC) optical configuration implemented in the ASTRI prototype.

2.1 Current-Generation IACTS

In this section an overview of the most relevant IACT arrays currently in operation is provided. These include **H.E.S.S.**, **VERITAS**, and **MAGIC**. Their main technical features are summarized in Table 2.1. These have substituted earlier third-generation instruments such as CANGAROO and HEGRA. The next major step in the field will be represented by the Cherenkov Telescope Array Observatory and the ASTRI Mini-Array, which is currently under advanced development and will constitute the fourth generation of ground-based γ -ray observatories.

2.1.1 The VERITAS Array

The **Very Energetic Radiation Imaging Telescope Array System** (VERITAS) is located at the Fred Lawrence Whipple Observatory (Arizona, USA). Operational since

2007, it consists of four 12 m Davies–Cotton telescopes with $f/D = 1$ optics, each reflector being composed of 350 identical hexagonal facets [69]. This design provides a total collecting area of 110 m² and improves optical performance compared to earlier instruments such as the 10 m Whipple telescope. Each camera includes 499 photomultipliers (PMTs) with 0.15° angular spacing, complemented by hybrid Winston-type light concentrators to enhance collection efficiency. VERITAS is optimized for the 100 GeV – 10 TeV range, but remains sensitive up to 50 TeV. An auxiliary telescope provides precise pointing calibration.

2.1.2 The H.E.S.S. Array

The **High Energy Stereoscopic System** (H.E.S.S.), located in Namibia, consists of four 13 m Davies–Cotton telescopes operational since 2003, and a fifth instrument, H.E.S.S. II, inaugurated in 2012 [70]. The latter is a 28 m parabolic telescope, with a focal length of 36 m, a reflective surface made of 850 mirror facets, and a mass approaching 600 tonnes. The addition of H.E.S.S. II extended the array’s sensitivity down to ~30 GeV, bridging the gap with space-based detectors. The smaller telescopes, with focal ratio $f/D \approx 1.15$, each host a 960-pixel PMT camera with 0.15° pixel size and 5° FoV. Non-imaging Winston cones [71] increase photon collection efficiency and reduce stray light, while auxiliary guide telescopes ensure arcsecond-level pointing accuracy.

2.1.3 The MAGIC Telescopes

The **MAGIC Florian Goebel¹ Telescopes** (with MAGIC standing for Major Atmospheric Gamma-ray Imaging Cherenkov) are located at the Observatorio del Roque de los Muchachos on La Palma (Canary Islands, Spain), at 2200 m above sea level. The first telescope (MAGIC-I) became operational in 2004, followed by MAGIC-II in 2009, placed 83 m apart to enable stereoscopic reconstruction. With their 17 m parabolic dishes ($f/D = 1$), the MAGIC telescopes provide the lowest energy threshold among IACTs, down to 25 GeV, thus filling the observational gap between satellite missions and ground-based detectors [72]. Their reflective areas total 236 m², composed of 964 spherical mirrors in MAGIC-I and 247 one-square-metre facets in MAGIC-II. Both telescopes employ an active mirror control system [73] to maintain focus at ~10 km, the typical altitude of EAS development [74].

The MAGIC cameras, 1.5 m in diameter and 450 kg in weight, have a FoV of 3.5°. The inner region hosts 397 PMTs with 0.1° FoV, surrounded by 180 larger 0.2° FoV PMTs [68]. The on-axis point spread function corresponds to ~0.5 pixels, ensuring high angular resolution. Winston cones are again adopted to maximize photon collection efficiency [75]. Owing to its large mirror area and fast readout electronics, MAGIC remains the benchmark instrument for low-energy ground-based gamma-ray astronomy.

¹https://en.wikipedia.org/wiki/Florian_Goebel

Class	Mirror diameter	Energy range	FoV	Telescopes
LST	23 m	20–500 GeV	4.5°	8 (4 North, 4 South)
MST	12 m	0.1–10 TeV	~7°	23 (9 North, 14 South)
SST	4 m	1–300 TeV	~9°	37 (South only)

Table 2.2: Specifications of the three classes of CTAO telescopes, each optimized for a specific energy range.

2.2 The Cherenkov Telescope Array Observatory

The CTAO (Cherenkov Telescope Array Observatory, [76]) will be the next step in VHE gamma-ray astronomy and is expected to have better flux sensitivity, angular resolution, and energy resolution than currently operating facilities.

Its setups, telescope positions, and telescope diameters were optimized through Monte Carlo simulations [77]. The intent was to determine which setup would be the most sensitive over the energy range, which goes from 20 GeV up to 300 TeV. To maintain consistently high sensitivity across this range, the CTAO will use three kinds of telescopes: Large-Sized Telescopes (LSTs), Medium-Sized Telescopes (MSTs), and Small-Sized Telescopes (SSTs). The SSTs are especially suited for detecting the most energetic gamma rays.

The CTAO will be composed of two arrays: the Northern site, located at the Observatorio del Roque de los Muchachos (La Palma, Canary Islands, Spain), and the Southern site, at the ESO Paranal Observatory in Chile. This dual-site configuration ensures full sky coverage, with the Northern array optimized for extragalactic science and the Southern one for Galactic studies. In total, the CTAO will consist of more than 100 Imaging Atmospheric Cherenkov Telescopes (IACTs), distributed across three different classes, each optimized for a specific energy regime (see Table 2.2).

The scientific performance of the CTAO will surpass the current generation of IACTs by more than an order of magnitude in sensitivity, while also providing improved angular and energy resolution [78]. Figures 2.1–2.3 summarize the main performance indicators of the Observatory.

Large-Sized Telescopes The LSTs are designed to extend the energy coverage of the CTAO down to 20 GeV, bridging the gap between space-based gamma-ray instruments (e.g., Fermi-LAT) and ground-based facilities. Each LST is a lightweight, alt-azimuth mounted telescope with a 23 m mirror diameter (effective area $\sim 370 \text{ m}^2$), based on a parabolic optical configuration to preserve the isochronicity of Cherenkov pulses. The focal length is 28 m, and the reflector is composed of 198 hexagonal mirrors [79]. Despite their large size (45 m height, 100 tons weight), LSTs are able to reposition within 20 s, allowing efficient follow-up of transient phenomena such as gamma-ray bursts. The camera hosts 1855 PMTs with a pixel size of 0.1° , for a total FoV of 4.5° [80]. The first prototype, LST-1, was inaugurated in 2018 in La Palma and is currently under commissioning by the CTAO.

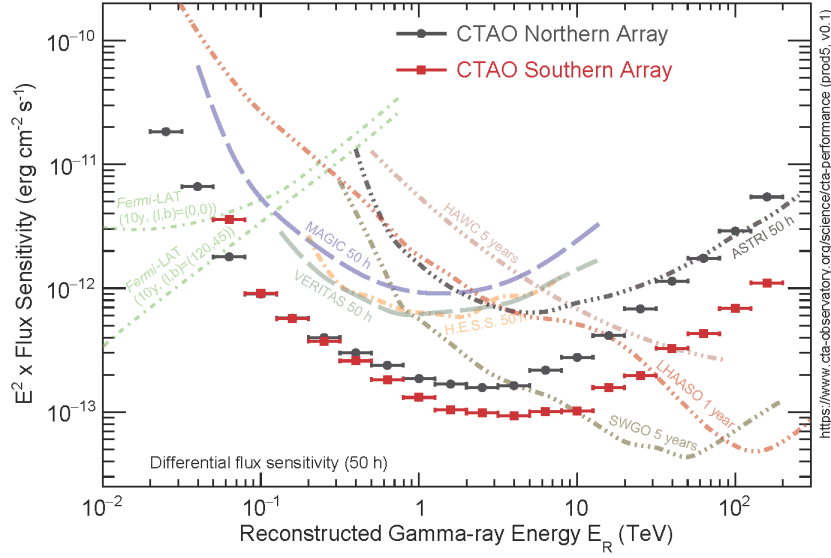


Figure 2.1: Differential sensitivity of the CTAO arrays compared with current IACTs. CTAO will improve sensitivity by more than one order of magnitude in most of the accessible energy range [78].

Medium-Sized Telescopes The MSTs are the workhorses of the CTAO, designed to cover the core energy range between 100 GeV and 10 TeV. Two designs are considered: a single-mirror Davies–Cotton telescope (MST, 12 m aperture, 16 m focal length), equipped with PMT cameras (NectarCAM or FlashCAM) [81]; and the Schwarzschild–Couder Telescope (SCT), a dual-mirror system with a 9.7 m primary and 5.4 m secondary reflector, optimized for wide FoV and equipped with SiPM-based cameras with over 11,000 pixels [82]. A prototype SCT (pSCT) has been installed at the Fred Lawrence Whipple Observatory and successfully detected the Crab Nebula with high significance.

Small-Sized Telescopes SSTs are dedicated to the exploration at multi-TeV energies, where Cherenkov light is abundant and widely distributed on the ground. For this regime, a large number of compact telescopes spread over several km^2 is more efficient. CTAO will host 70 SSTs in the Southern site only, to probe energies up to 300 TeV. The final design, based on the ASTRI dual-mirror SC configuration (see Section 2.3), features a 4.3 m segmented primary and a 1.8 m monolithic secondary mirror [83]. The camera (CHEC-S) adopts SiPM technology, with 2048 pixels covering a FoV of $\sim 9^\circ$ [84].

The CTAO will improve the current sensitivity by about one order of magnitude compared to H.E.S.S., MAGIC and VERITAS, and will extend the accessible energy domain from a few tens of GeV up to 300 TeV. Figure 2.1 shows the differential sensitivity of CTAO, benchmarked against existing facilities. The angular resolution will reach arcminute scale at TeV energies (see Fig. 2.3), while the energy resolution will be better than 10% over most of the core energy range.

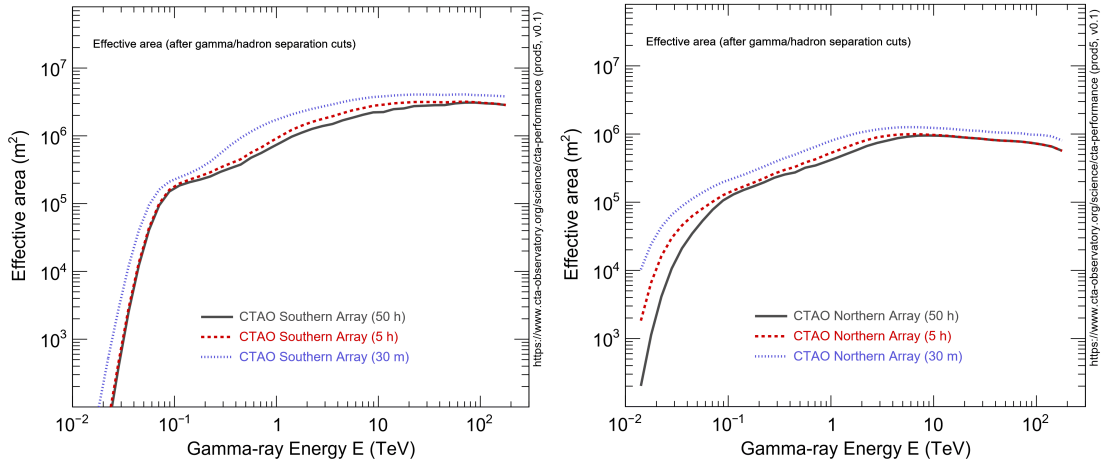


Figure 2.2: Effective collection area of the CTAO telescopes for different energy bands. The three telescope classes contribute differently across the energy spectrum, ensuring wide-band coverage [78].

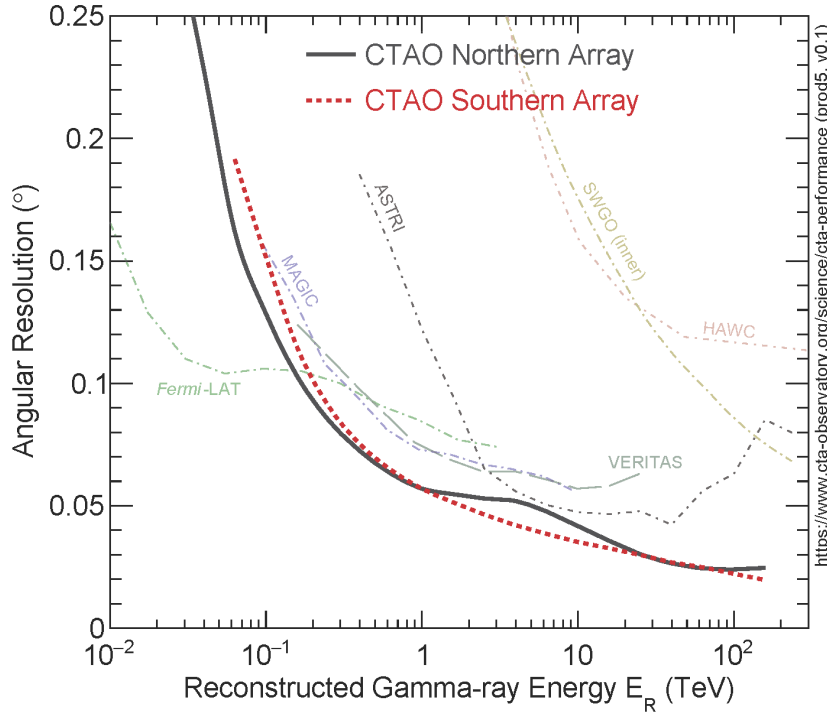


Figure 2.3: Angular resolution of the CTAO arrays as a function of energy, compared to current IACTs. At TeV energies, CTAO will achieve arcminute-level resolution [78].

2.3 The ASTRI Project

ASTRI, an Italian National Institute for Astrophysics (INAF)-launched project, marks the beginning of a new era in the field of VHE gamma-ray astronomy. Its basic aim includes the installment of a new class of IACTs that is based with a unified design, conceptualizations, hardware production, as well as raw data acquisition methodology and data analysis. This will be possible thanks to the multiple breakthroughs in the fields of optical design concepts as well as signal acquisition technologies [85]. The ASTRI (*Astrofisica con Specchi a Tecnologia Replicante Italiana*, or Italian Replicated Mirror Astrophysics Technology) project encompasses the replicated mirror production technology created at the INAF. ASTRI has been provided with particular funding from the Italian Ministry of Education, University and Research (MIUR), which has been channeled through INAF for the coordination of a consortium of several overseas collaborators. This is made of the Universidade de Sao Paulo (Brazil), the North-West University (South Africa), the Italian National Institute for Nuclear Physics (INFN), as well as the Instituto de Astrofisica de Canarias (Spain). The ASTRI project has, in the course of time, considerably enlarged the scope of its mission. After the successful erection and commissioning of the prototype, the ASTRI-Horn telescope, the next step was the creation of a mini-array of nine ASTRI modules. This array is currently being deployed at the Observatorio del Teide in Tenerife (Canary Islands, Spain).

An integral part of this advancement is the adoption of the variant SC optical setup, becoming the first IACT to employ a double-mirror system [85]. While this innovative setup was bound to face manufacturing as well as alignment challenges due to the asphericity of the optical surfaces, it has several distinct advantages:

- it is possible to install smaller, more compact detectors at the focal plane.
- the effective focal length can be reduced, allowing for a large plate scale. This minimizes the true size of the focal surface, improving prospects for creating compact SiPM arrays. Such devices boast fast timing, excellent photon-number resolution, and offer superior performance in the conditions relevant for Cherenkov imaging [86].
- a broad field of view (FoV) without the need for a physically large camera. This is of particular importance in the case of VHE gamma-ray observations, as high-energy showers cover larger spatial regions and require careful imaging, even at large off-axis positions.
- individual deployments and closely packed telescope arrays, thanks to the design's spatial efficiency and compact size.

2.3.1 The ASTRI - Horn Case

ASTRI-Horn is an end-to-end, fully integrated telescope system SST prototypes. Funded since 2011 and installed at the INAF M. G. Fracastoro Observatory in Serra La Nave,

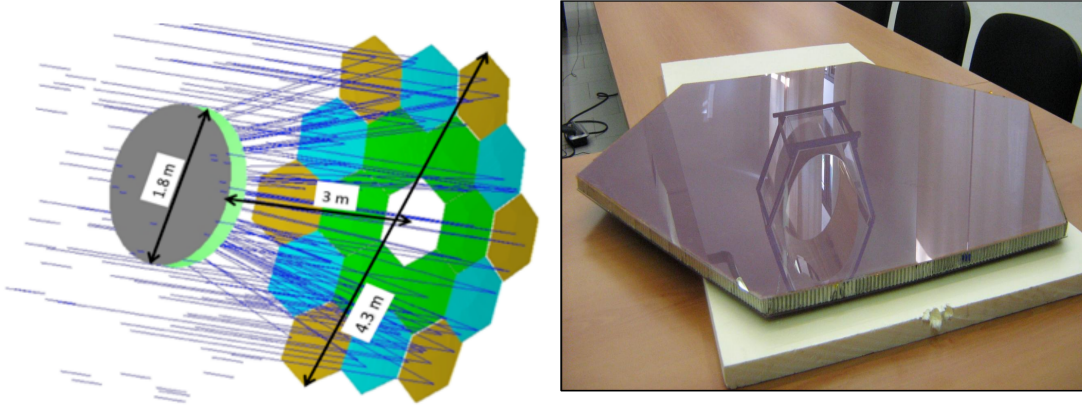


Figure 2.4: *Left*: Optical layout for the ASTRI SST-2M telescope from [89]. The panels belonging to the three different rings are displayed in different colours. *Right*: an hexagonal segment of the ASTRI primary mirror, from [90].

Mount Etna, Sicily, at 1725 m above sea level, the ASTRI-Horn telescope began operating in May 2017. The nature of the project was the following:

- Development, implementation, as well as certification of the first ASTRI prototype telescope, comprising of tuning activities for the next nine ASTRI telescopes in the small-scale array setting.
- Emphasize scientific quality of a two-mirror SC optics specifically designed for Cherenkov imaging, end-to-end system validation of the entire system comprised of optics as well as the related camera;
- Subject the engineering and maintenance provisions to true observation conditions, for the specific purposes of Reliability, Availability, and Maintainability (RAM);
- Be a long-term training lab for hardware and software component developments, as well as operators training.

Opto-mechanically, the ASTRI-Horn telescope utilizes the double-mirror design variant of the SC, in particular for the realization of a large, aplanatic FoV of the size of 9.6 degrees [87]. First proposed in gamma-ray astronomy by [88], the design of the SC is one of the best for optimal imaging performance for large FoVs. This ASTRI-Horn design is specifically tailored in that it achieves the same performance (e.g. point spread function) in large part of the entire FoV. Furthermore, the composite focal ratio of $f/0.5$ significantly enhances the photon collecting efficiency and optical quality compared with the standard Davies-Cotton or parabolic designs. Two different fabrication processes were employed for the primary and the secondary mirrors. The 18 hexagonal, aspheric segments of the primary mirror are 849 mm in diameter each, for a total of 4.3 m (see Fig. 2.4). The primary mirror segments were made using the cold-slumping replication technique [91]. Different from the above, the secondary mirror is a single monolithic,

aspheric mirror of 1.8 m diameter and 19 mm thickness, made using hot-slumping [91]. With a mirror separation of 3 mm, the telescope design is made compact, except for accommodation of the Cherenkov camera in correspondence of the focus plane. This new design provides one extremely compact, efficient, as well as technologically scalable telescope well-optimized for mass production in large-scale arrays for high-energy detection of the universe’s most powerful phenomena. Its focal plane is populated with a modular array of SiPMs read out by specially designed front-end electronics optimized for detecting nanosecond-time-scale Cherenkov light flashes from gamma-ray-initiated air showers [84]. The sensor arrangement provides high photon detection efficiency, low dead time, and excellent timing properties necessary for event reconstruction and background rejection.

Thus far, two different structural variants of the telescope have been created for the ASTRI scientific instruments. Originally, the earlier setup implemented in the ASTRI-Horn prototype was lighter, while the more robust version was developed for the ASTRI Mini-Array as well as future SST deployments. With the exception of the structure design, the setup as a whole was kept the same, but for several smaller adaptations in order to obtain increased steadiness, reduced mass, as well as increased manageability.

2.3.2 The ASTRI Mini-Array

The Mini-Array constitutes the core of the ASTRI scientific project and objectives. The group of nine ASTRI telescopes is currently being installed at the Observatorio del Teide, in Tenerife, according to the layout shown in Figure 2.5. The first telescope, i.e. ASTRI-1, already completed and undergoing its commissioning phase. Currently, ASTRI-2 through 7 have already been installed, as it is visible in Figure 2.6. ASTRI-2, 3 and 4 will soon undergo extensive calibrations and will be ready to collect data in stereo mode within months.

The Mini-Array will take advantage of the stereoscopic system, exploiting the large FoV to provide a better angular resolution despite the modest raw aperture of the optics in comparison to other IACTs. Once completed and fully integrated, the telescopes of the Mini-Array will be sensitive at energies between 1 and 300 TeV, with an angular resolution of 3 arcsec at 10 TeV, and energy resolution of 10% at 10 TeV. The preliminary plot of the differential flux sensitivity of the Mini-Array is reported in Figure 2.7.

2.4 The Commissioning of ASTRI-1

One of a telescope’s most significant milestones in its life cycle is the stage of commissioning. The subsystems, which were already validated individually by laboratory testing, demonstrate their capability to function as a complete scientific instrument and thus bridge the gap between design and scientific use. Distinct from previous periods of validation in engineering, a stage of commissioning entails the testing of the telescope, camera, and software to make them ready for use in real observation environments.



Figure 2.5: Final layout for the ASTRI Mini-Array at the Teide Observatory, from [38]. The Figure shows the final positions for the 9 telescopes, the position of the two meteorological towers, the position of the LIDAR, the position of the transformer station and that of the local control room and of the data centre.

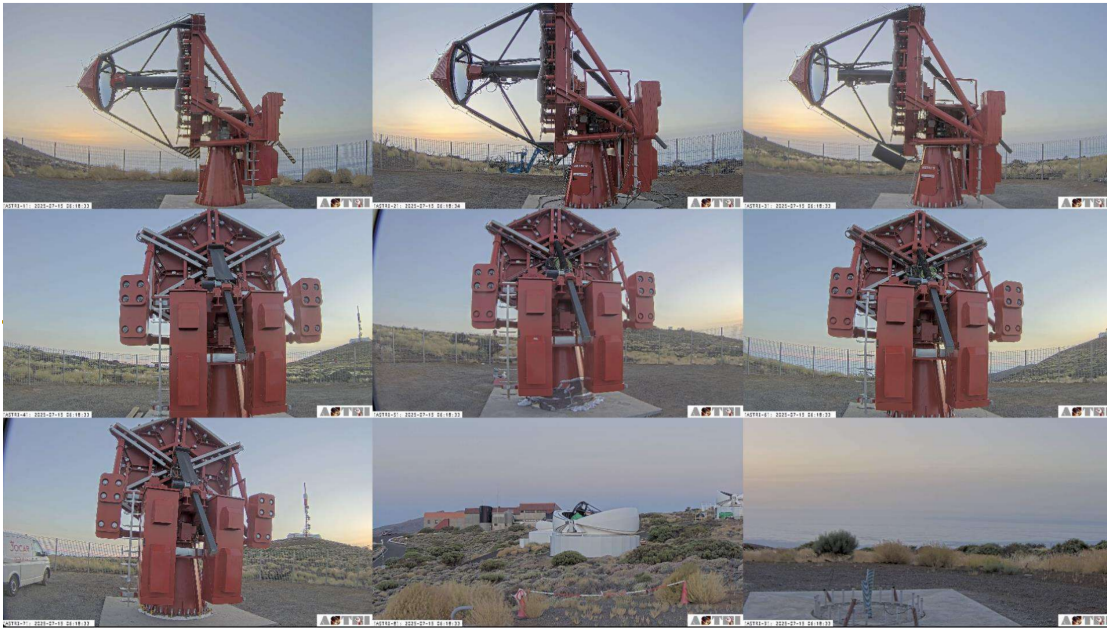


Figure 2.6: Current deployment status of the ASTRI Mini-Array in Tenerife.

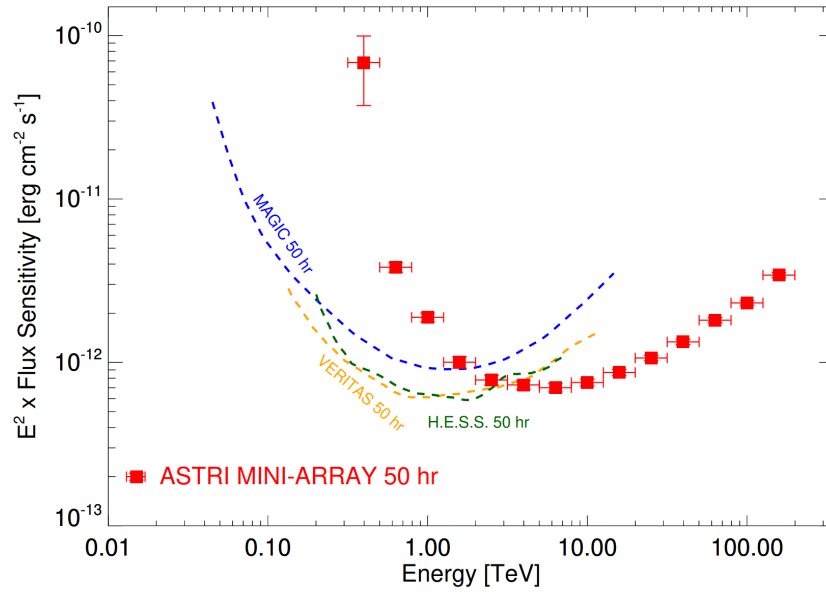


Figure 2.7: ASTRI MiniArray on-axis differential sensitivity for 50 h integration time, compared with those of current IACTs (preliminary plot taken from [38])

In the context of a ground-based gamma-ray instrument like the telescopes of the ASTRI Mini-Array, commissioning plays a dual role. On one hand, it validates that the instrument meets its design requirements in terms of sensitivity, stability, and operational conditions against environmental conditions. On the other, it initiates the scientific characterisation of the system, through reference observations of well-known sources that serve as calibration benchmarks. This phase is therefore both technical and scientific: it requires the scheduling of tests, careful calibration strategies, and the progressive development of data analysis pipelines, while simultaneously producing the first datasets that establish the instrument’s capability to contribute to the broader goals of the collaboration. From an operational standpoint, commissioning is inherently iterative. Observations are planned not with the sole aim of acquiring science, but also of probing the response of the system under different regimes: varying observational strategies, calibration procedures, and environmental constraints. For the purposes of this thesis, the commissioning of ASTRI-1 is particularly relevant, as it provides the methodological and organisational foundation for the scientific results discussed in the following chapters. The lessons learned in terms of calibration, data handling, and performance validation directly impact the reliability of the subsequent analyses, ensuring that the reported findings rest on a solid, tested, and operationally developed observational framework.

2.4.1 Operational Site and Environment Conditions

The commissioning of ASTRI-1 was strongly influenced by the environmental conditions of the Teide Observatory, which both granted opportunities and imposed constraints on the operational strategy. Site characterisation and environmental monitoring became central elements of the campaign, as they directly influenced data quality, system safety,

and the long-term sustainability of operations.

From the earliest phases, strict thresholds had to be defined for the operational safety of the telescope. Wind speed limits were set at 50 km h^{-1} for standard observations, with an automatic parking procedure triggered in the range $50\text{--}60 \text{ km h}^{-1}$. The mechanical structure was designed to withstand gusts exceeding 150 km h^{-1} while parked, yet the adopted operational thresholds reflected a conservative approach to ensure pointing reliability and the safety of optical elements. Through systematic behaviour monitoring in this range, a new upper limit was therefore established, and procedures were adapted to safeguard the camera electronics. Rapid increases in humidity led to the interruption of observing runs, with operators returning the telescope to parking position to avoid issues due to internal condensation. *Calima* events (i.e. dust intrusions from the Sahara) did not correspond to a formally defined threshold, but were nonetheless considered as a risk factor, particularly for the sky quality and the cleanliness of mirrors and filters.

Environmental conditions also included the photometric quality of the sky. Measurements of the night sky background (NSB) in the V band consistently yielded values around $21.0 \text{ mag arcsec}^{-2}$, confirming the excellence of the Teide site. However, localised conditions could degrade the background, most notably due to bright stars within the field of view. Stars such as Zeta Tauri and Beta Tauri produced significant increases in trigger rates during the Crab campaign, introducing non-negligible dead time and distorting variance measurements. Various mitigation strategies were tested, including adjustments to global trigger thresholds, development of algorithms to dynamically reconfigure trigger masks for affected photodetector modules (PDMs), and exploratory efforts to disable the trigger of specific pixels in the camera GUI. Although the latter was not fully automated during the commissioning phase, its implementation was recognised as a priority for routine operations.

The presence of the Moon was initially considered as a background illumination source. Despite the increased NSB and elevated trigger rates, commissioning observations demonstrated that scientific data could still be obtained in the presence of moderate moonlight. ASTRI-1 was able to detect the Crab Nebula with high significance under lunar conditions, highlighting the robustness of the system but also emphasising the need for careful calibration of energy thresholds in bright-sky scenarios.

2.4.2 Camera and Subsystems

One of the key tasks of the commissioning campaign was to test and confirm the telescope's focal plane instruments and ancillary systems. The Cherenkov camera, the relevant front-end and back-end electronics, lid system, power and cooling system, and Pointing Monitoring Camera (PMC) were tested in great detail to make sure that they would operate reliably under real observation conditions.

Furthermore, calibration campaigns were carried out in several phases. Pixel calibrations were first obtained using collimated lasers, though strong vignetting in some optical setups made this approach less effective, while more robust calibration products were

later obtained directly using telescope observations. Additional calibrations included essential trigger scans, and gain matching of the high-gain (HG) and low-gain (LG) channels to provide a consistently calibrated instrument. The trigger system, tightly coupled to the background conditions, underwent dedicated commissioning tests. Trigger scans showed a strong influence of bright stars on the trigger rates, necessitating a re-evaluation of thresholds. The nominal dead time per event, measured at 200–300 μ s, implied an effective maximum rate of about 3 kHz for periodic triggers, but safe operation during science runs was limited to 300–600 Hz. As stated in Section 2.4.1, although not fully automated during commissioning, this approach proved promising for routine operations.

The lid mechanism, designed to protect the focal plane from dust and sunlight damage, was a recurring source of operational difficulty. Failures occasionally forced multiple attempts in opening or closing the lids, and their proximity to the secondary mirror led to a redesign of the components due to possible interference with focusing. Software updates to the lid controller progressively improved reliability.

The Cherenkov camera demonstrated remarkable overall stability, but it still required iterative minor adjustments during the first months of commissioning. Early runs highlighted sporadic issues with individual PDMs, including faulty High Voltage channels, and unstable behaviour of specific modules. Many of these were resolved through hardware interventions, such as the replacement of VDB boards or firmware updates.

The PMC provided an independent astrometric reference for telescope pointing and autoguiding. Its intrinsic precision was excellent, with sub-arcsecond stability, but a measurable and variable offset relative to the telescope optical axis was identified during the commissioning tests. This offset, reaching up to a few arcminutes, was strongly dependent on azimuth and elevation, and therefore required the development of an updated pointing model. When used in closed-loop autoguiding, the PMC reduced tracking dispersion to a few arcseconds, greatly improving pointing accuracy. The commissioning of the PMC therefore provided not only an auxiliary tool for pointing but also a calibration baseline for validating telescope alignment.

2.4.3 Scientific Validation and Observations

Beyond the technical validation of subsystems, the commissioning of ASTRI-1 was designed to demonstrate that the telescope was capable of delivering scientifically relevant data. This required a structured programme of observations, progressively moving from technical calibration targets to benchmark astrophysical sources, and culminating in the first detections that validated the instrument’s scientific readiness.

The Crab Nebula was adopted as the primary calibration and verification source throughout the commissioning. Its well-known spectrum and flux in the very-high-energy regime made it the natural choice to establish the sensitivity, energy threshold, and response functions of the instrument. Observations were conducted in wobble mode with offsets of 0.5° , and later extended to larger offsets (1.5° , 2.5° , and 3.5°) to probe

off-axis performance. Many runs were also acquired under different conditions: low and high zenith angles, with and without moonlight, and against various background fields. The campaign produced more than 100 hours of cumulative exposure, distributed across multiple months, which built a statistically significant dataset. Early runs already demonstrated the stability of the data acquisition chain, while subsequent ones focused on refining data quality checks and background estimation strategies. Using the acquired data, science verification activities were explicitly designed to validate the instrument response functions (IRFs) and to confirm that the telescope could reproduce expected astrophysical signals. The tests included:

- evaluation of the NSB variance and its impact on trigger thresholds;
- measurement of the point spread function from stellar fields and comparison with simulated optics;
- determination of the energy dispersion and effective area through simulations matched to Crab observations;
- end-to-end validation, tracing the entire chain from observation to analysis, ensuring that calibration, cleaning, and event reconstruction worked correctly.

Commissioning also required the establishment of tools for data quality monitoring. Software pipelines for quick-look analysis were progressively developed to provide feedback on detection significance, θ^2 distributions, and background estimates on an observational run-by-run basis. Issues were systematically logged and addressed, ensuring that scientific results rested on validated datasets.

Monte Carlo simulations played a central role in the scientific validation. The configurations in `simtelarray` were refined over a period of time to include realistic optics, electronic cross-talk, and atmosphere models. Photon, proton, and helium nuclei simulations were needed to show both signal and background scenarios. Particular effort was put in providing datasets at a range of wobble offsets and at energies up to 300 TeV and beyond, to be commensal with the Crab campaign. Comparisons between data and simulations showed typical concordance in essential parameters (size distributions, Hillas parameters, detection significance), but some fine-tuning was needed in background handling and range of low-gain chain response. The simulation-observation-analysis cycle was repeated many times to develop reliable IRF.

Detection of the Crab Nebula A key milestone in the commissioning of ASTRI-1 was the first scientific detection of the Crab Nebula. Despite the novelty of the operations and the still ongoing refinement of the camera and data pipeline, a preliminary detection was already achieved during the first observational shift, in November 2024. With only 3.1 hours of effective exposure, a detection corresponding to a statistical significance of 5.6σ was obtained using the Li & Ma method [92]. This represented the first unambiguous proof that the telescope was able to deliver scientifically relevant results, marking the transition from purely technical commissioning to genuine scientific

validation.

Following this initial success, the Crab campaign continued under different observational regimes to probe the robustness of the detection. In particular, several runs were performed under moderate moonlight conditions, which had the effect of significantly increasing the night-sky background and raising trigger rates. Nevertheless, the telescope achieved a 5.2σ detection in 2.6 hours under these conditions, demonstrating that ASTRI-1 remained scientifically effective even in the presence of elevated background light. This result not only validated the robustness of the instrument, but also confirmed the possibility of extending the scientific duty cycle by exploiting also bright-sky periods. By the end of 2024, a cumulative dataset of nearly 60 hours of Crab observations had been acquired. When analysed collectively, these data yielded a detection significance of 18.3σ , firmly establishing the capability of ASTRI-1 to detect reference sources at the expected confidence levels. The excess maps and θ^2 distributions produced from these observations showed a clear, spatially consistent excess at the Crab position, providing both statistical and morphological confirmation of the detection.

Observational Strategies and Validation

The observational strategy adopted during commissioning deliberately included variations in wobble offset, zenith angle, and background fields. Runs were taken at the nominal 0.5° wobble offset, but also at larger offsets (1.5° , 2.5° , 3.5°) to characterise IRFs across the field of view. Observations at low zenith angles were complemented by runs at higher elevations to probe the energy threshold and effective area under different atmospheric depths. Tests were also conducted with the Moon at large angular separations from the pointing direction to evaluate scattered light contamination. Together, these configurations provided a rich dataset that went beyond a simple detection, enabling a comprehensive validation of the telescope’s scientific performance.

2.4.4 Calibration and Data Analysis

One of the key successes of ASTRI-1 in providing dependable scientific data was its subsystem calibration, as well as the creation of a strong data processing chain. The work done during the commissioning phase was basically an extensive application of the procedures for calibration, their testing and integration with the automated tools for the analysis.

Calibration Strategies Several complementary approaches were adopted to calibrate the focal plane camera and its electronics.

- **Pedestal and Gain Calibration:** Regular measurements of pedestals and electronic gain were performed to monitor the stability of individual PDMs. Particular attention was paid to modules exhibiting anomalous behaviour, which required hardware replacement or recalibration.

- **HG/LG Ratio:** Dedicated runs at high zenith angles were scheduled in order to verify the consistency and relative calibration of the HG and LG acquisition chains. These tests ensured a consistent dynamic range across the camera.
- **Trigger Scans:** Crucially, systematic scans of the trigger thresholds were carried out repeatedly, to characterise the response of the camera to the NSB. The threshold scans were performed both in dark-sky conditions, in presence of the Moon, and with bright stars entering the field of view and allowed for the identification of optimal thresholds that minimized the dead time while maintaining a good sensitivity.
- **Pixel Equalisation Matrices:** Pixel-to-pixel response was calibrated using collimated light sources. Early attempts suffered from vignetting and optical artefacts, but improved matrices were later derived from telescope observations with dithering strategies, which averaged over sky gradients.
- **Illuminator Tests:** The external illuminator was employed to measure the overall optical throughput and to validate calibration constants in controlled conditions. Tests with continuous and pulsed light provided cross-checks of both variance-based and event-based acquisition.

Commissioning revealed several recurrent calibration anomalies. A small subset of pixels produced invalid calibration coefficients (i.e. NaN values) or reported negative photo-electron counts. These were flagged by the pipeline and excluded from analyses. Timing errors in the nanosecond counters, due to the absence of a White Rabbit timing system, introduced periodic resets of ~ 3.3 ns; although irrelevant for most science runs, this required correction in post-processing. Sporadic instabilities in variance measurements were also noted at high trigger rates, often correlated with environmental conditions such as high humidity.

Data Analysis Parallel to calibration, the data analysis chain was also subject of commissioning activities. The analysis is composed of:

- **Raw Data Conversion:** The binary data were converted to FITS files, i.e. the standard format used for subsequent processing.
- **Level-0 Products, Technical Data and Variance:** An automated generation of sets of technical data (SCITECH0) and variance computation (SCITECH0_VAR) files for scientific data reduction files provided the first scientifically usable outputs. Variance products were particularly important for monitoring NSB conditions and calibration stability.
- **Higher-Level Reductions:** Quick-look pipelines then produced level 1 and 2 data files, which included the calibrated charge distributions, cleaned images, and all the reconstructed Hillas parameters of the particle showers. These allowed near real-time checks of data quality and the first scientific detections.

- **Archiving and Databases:** All processed files were stored at the Rome HPC and mirrored in the ASTRI & Miniarray Archive System (AMAS) archive for long-term storage.

To support nightly operations, a semi-automated quick-look analysis was implemented. This system generated significance maps and preliminary θ^2 distributions within hours of data acquisition. The results were used to validate both calibration outputs and the scientific validity of the runs. Data quality checks systematically flagged anomalous runs (e.g. unusual variance values, unstable pedestal levels, etc.), allowing observers to correct procedures the following shift day.

2.4.5 Next Steps and Future Developments

The commissioning of ASTRI-1 not only confirmed the current performance of the telescope but also outlined the priorities for the future, both in terms of technical and organisational matters.

One of the most important aspects is the integration of the supervisory control and data acquisition (SCADA) system, which will provide a unified control of the telescopes, the camera, and the data acquisition chain, thus allowing a decrease of the operator workload and of the risk of human error. Moreover, the plan for further improvements of calibration and analysis pipelines include a special focus on the automation of the treatment of anomalous pixels, and the implementation of dynamic trigger masking. At the same time, the same efforts will concentrate on pushing further the Monte Carlo simulations in terms of higher energies and larger off-axis angles to allow a more precise validation of the instrument response functions. The environmental monitoring will also change, for example, an automated alarm system for humidity and wind is envisaged to ensure better oversight of the operational safety. Moreover, these technical developments will be accompanied by the scheduling of the observing shifts. In the commissioning phase, the control of the telescope was mainly given to on-site observers, while remote participation was limited. The operations in the future will rely on a more structured shift system characterised by predefined rosters and training for new operators, but more remote observations will also be possible. Such measures, tightly connected with the experience gained during the commissioning phase, will establish a firm operational model for the coordinated management of the ASTRI Mini-Array.

Chapter 3

ASTRI Performance Characterisation

3.1 Crab Nebula Simulations

As detailed in the previous chapters, in order to assess the telescope effectiveness as an astrophysical observation tool, a standard analysis begins with simulations of a point source like the Crab Nebula. This is an ideal tool used in mapping out instrument response as well as any analytical processing chain. A crucial step in this process is comparing simulations from Monte Carlo (MC) codes to results obtained from empirical analysis of observational data. This is needed for several reasons. First, it is possible to assess whether such simulation data realistically represents the detector response, including energy reconstruction, angular resolution, and effective area. Secondly, comparing simulations against real observations ensures that the MC data may confidently be used for performance validation as well as for interpreting future scientific observation.

An important aspect of the performance characterisation of ASTRI telescopes is the determination of the observation time required to achieve a significant detection (5σ). To address this, dedicated simulations using the **Gammapy** software package [93, 94] were carried out, which assumed the Crab Nebula spectrum measured by HEGRA [95]:

$$\frac{dJ_\gamma}{dE} = (2.79 \pm 0.02_{\text{stat}} \pm 0.5_{\text{sys}}) \times 10^{-7} E^{-(2.59 \pm 0.03_{\text{stat}} \pm 0.05_{\text{sys}})} \text{ ph m}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}, \quad (3.1)$$

and used the ASTRI instrument response functions [96] to generate event lists corresponding to different observation times. Exposures up to 100 hours were tested, considering both the case of a single ASTRI telescope (ASTRI-1, mono mode) and that of an array of three ASTRI telescopes (ASTRI-3T, stereo mode). The mono configuration corresponds to the operational setup of ASTRI-1 during its commissioning phase, while the stereo configuration anticipates the performance of the partial ASTRI Mini-Array, which will be available for use in 2026. By progressively increasing the simulated exposure, the growth of the detection significance as a function of time can be evaluated, thereby estimating the minimal exposure required for a 5σ detection in each configura-

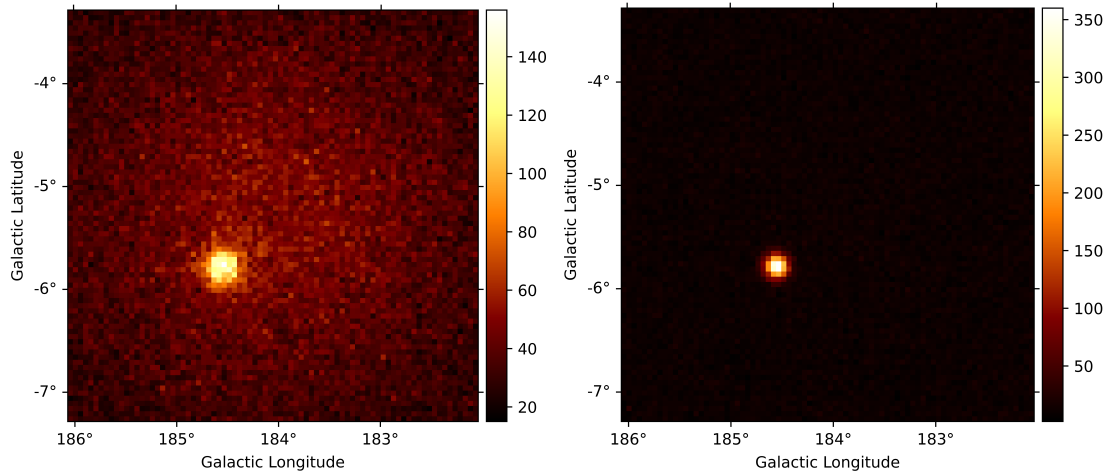


Figure 3.1: Simulated counts map of the Crab Nebula with a wobble angle of 0.7° , for 100 h of exposure in mono (*left*, ASTRI-1) and stereo mode (*right*, ASTRI-3T). The stereoscopic configuration enhances sensitivity and improves background suppression.

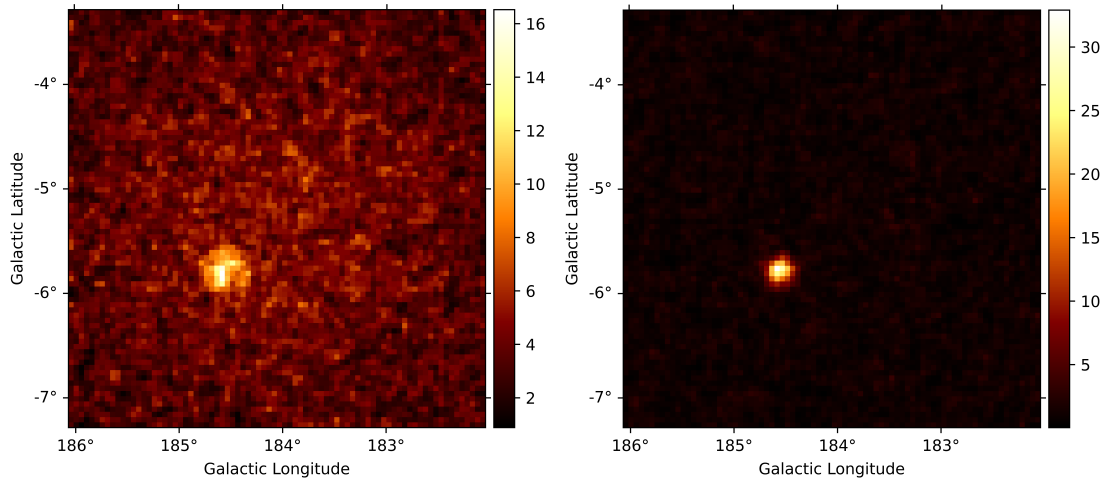


Figure 3.2: Same as Figure 3.1, but with only 10 hours of simulated observations.

tion. The results show that in mono mode the detection significance increases steadily, with the Crab becoming significantly detectable within 2.56 hours, in agreement with the observations obtained during commissioning. In stereo mode, the improved background rejection and stereoscopic reconstruction lead to a much faster growth of the significance, with a clear detection achievable after 1.26 hours of exposure. Figures 3.1 display the simulated counts maps for the Crab Nebula in the mono and stereo modes, respectively, for 100 hours of exposure. In both cases the Crab is clearly visible within the field of view, with a significantly enhanced contrast in the stereoscopic configuration.

The results of the Crab simulations are summarized in Figure 3.3. The plot shows the detection significance in terms of σ as a function of the observation time, providing a clear comparison between the two telescope configurations.

Considering a more realistic initial livetime of 10 hours, similar simulations were also used to test the reconstruction capabilities of the ASTRI data analyses (see Figure

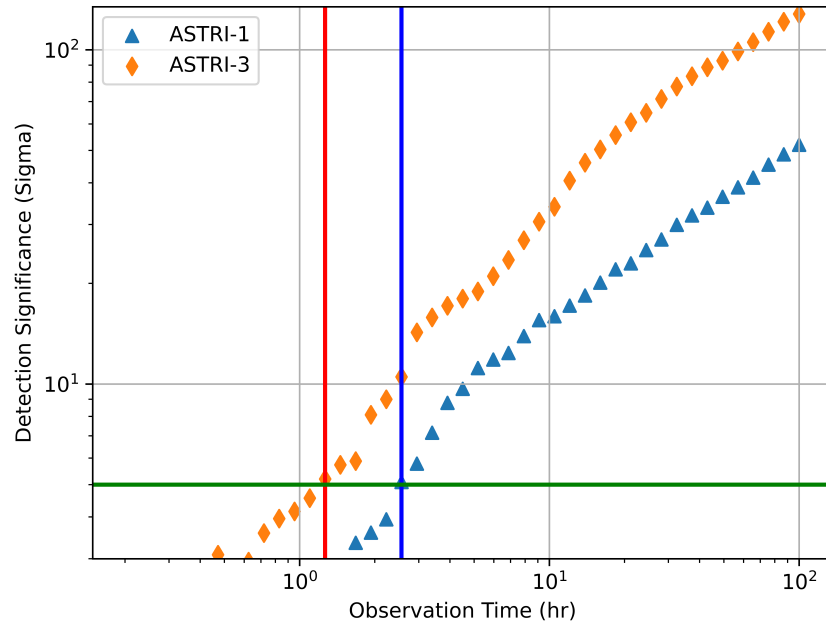


Figure 3.3: Detection significance in σ as a function of the observation time. Orange diamonds and blue triangles represent ASTRI-3T and ASTRI-1 simulations, respectively. The horizontal green line indicates the 5σ threshold, and the vertical lines show the time at which the threshold is reached with each configuration.

3.2). Figures 3.4 and 3.5 show the best fits of a power law spectrum to the simulated data in the case of ASTRI-1 and ASTRI-3T. The parameters for both best fits are compatible with the ones from [95] and were reported in Table 3.1. These simulations provided a quantitative benchmark for the expected performance of ASTRI telescopes in detecting standard sources, and they guided the planning of observational campaigns during commissioning and beyond.

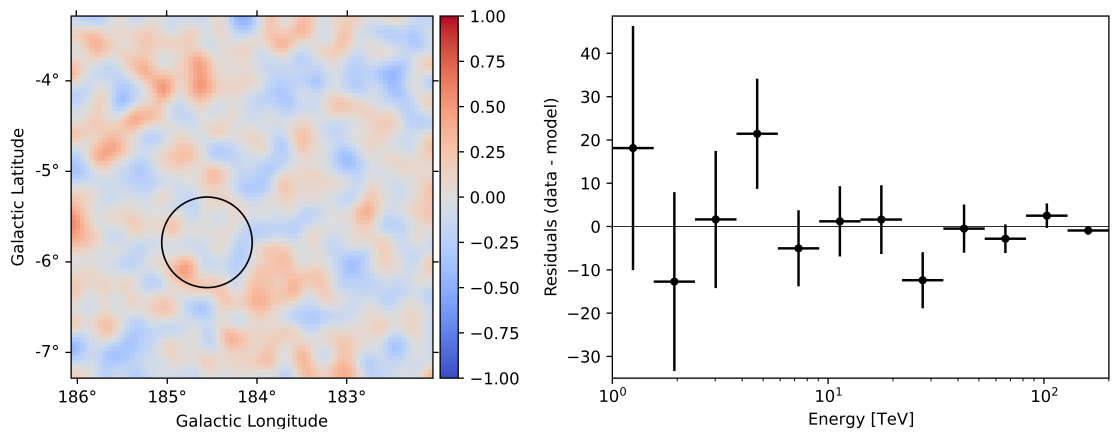


Figure 3.4: Spatial (*left*) and spectral (*right*) fit residuals for the ASTRI-1 10 hours simulations of the Crab Nebula, with the fit parameters in Table 3.1.

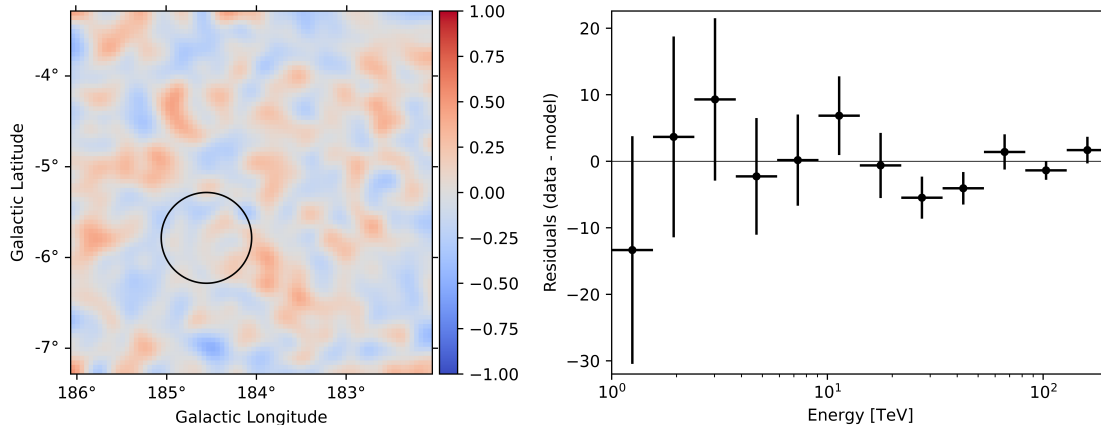


Figure 3.5: Same as Figure 3.4, but for ASTRI-3T simulations.

Parameter	ASTRI-1	ASTRI-3T
Amplitude [$\text{TeV}^{-1} \text{s}^{-1} \text{cm}^{-2}$]	$(3.2 \pm 0.3) \times 10^{-11}$	$(2.7 \pm 0.2) \times 10^{-11}$
Spectral Index	2.77 ± 0.11	2.58 ± 0.14

Table 3.1: Summary of the power-law parameters obtained by performing a fit on the ASTRI-1 and ASTRI-3T simulated data. The reference energy was fixed at 1 TeV.

3.2 Measuring the PSF

The Point-spread Function (PSF) of the system is the spatial intensity distribution in the image plane that results from an ideal point source of light (an infinitesimally small object) in the object plane. The PSF therefore characterise the difference between real and reconstructed gamma-ray photon arrival directions, effectively describing the spatial distribution of light on the focal plane. For Cherenkov telescope arrays, the optical design generally aims for a PSF that is about half the pixel size of the detectors. At larger off-axis angles, however, the optical aberrations become more dominant in determining image quality, producing in most cases a wider PSF as well as worse off-center capabilities in the optics. Because of the particularly optimized SC optics, the ASTRI telescopes are the first IACT telescopes whose PSF is contained in one Cherenkov pixel over the whole field of view, up to the maximum of $\sim 5^\circ$ off-axis [38].

In segmented mirror telescopes, the PSF is the additive result of the effect of the segments of the mirror individually. Therefore, the PSF of the ASTRI telescopes is the sum of contributions of its 18 mirrors, and segment alignment is critical to the achievement of the desired optical resolution. A good knowledge of the PSF is essential both for gamma-ray background sky modelling and for analysing data in the field of gamma-ray science. The 68% containment radii, as measurements of the extent of the PSF, are essential in evaluating the precision of gamma-ray point source localizations. Comparing and modelling the ASTRI-Horn MC data and observational campaign real data is a fundamental prerequisite for subsequent ASTRI-Mini Array and CTAO data analyses.

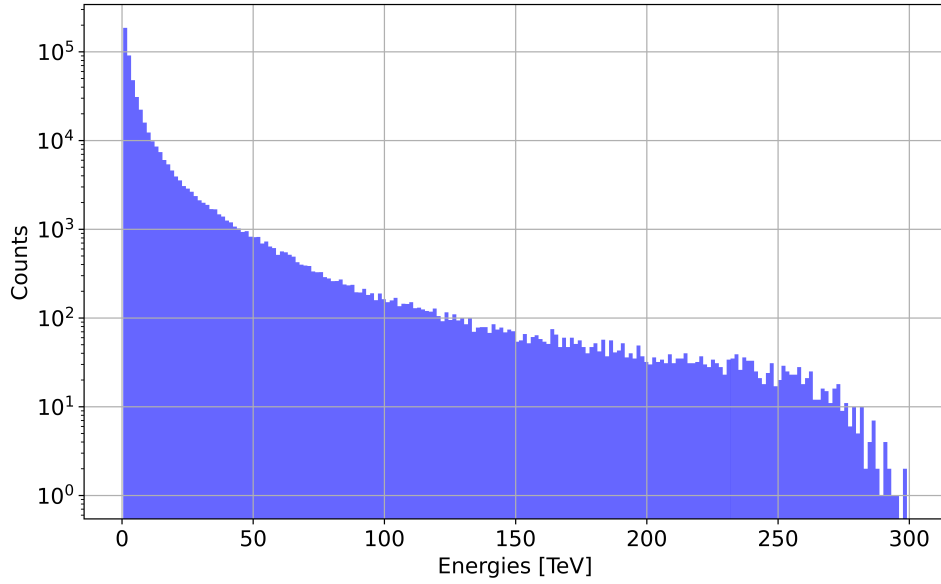


Figure 3.6: Energy distribution of simulated gamma-rays in the MC dataset.

3.2.1 PSF of Monte Carlo Data

The following part of this thesis uses a dataset resulting from Crab Nebula MC simulations¹ of the ASTRI-Horn telescope. This dataset covers a wide range of gamma-ray- and proton-induced air showers, which themselves were modelled using the CORSIKA [97] simulation software. The detector response was simulated by using the `Simtelarray` tool. The simulations range over energy from 500 GeV up to 300 TeV. Our work aims to model the PSF of the MC data as a function of the energy by characterising the width of the event spatial distribution. Figure 3.6 shows the energy distribution of the simulated gamma-ray data, while the spatial distribution of event detections around the camera's focal plane is represented in Figure 3.7. The data have been simulated in wobble pointing condition, therefore the emission peak position is expected at about 0.5° from the

¹Version: pass.v0.0.2

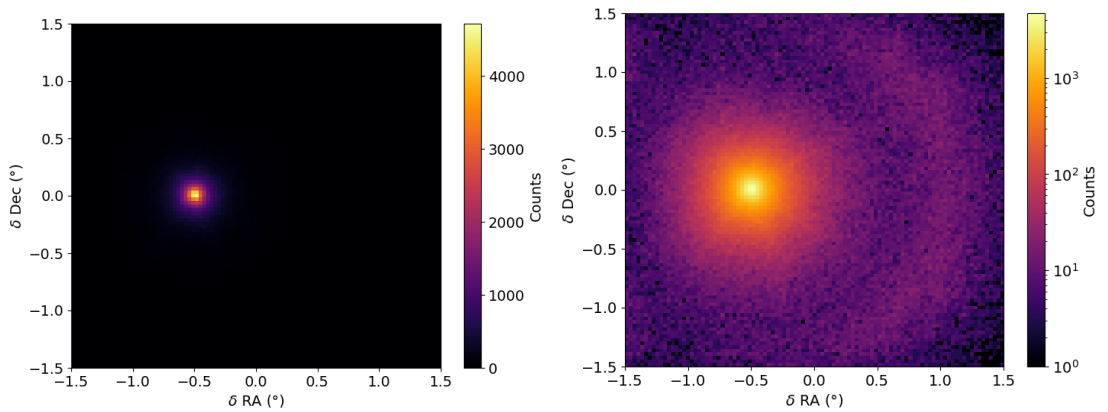


Figure 3.7: Counts maps of MC events projected onto the focal plane of the ASTRI-Horn camera in linear (*left*) and logarithmic (*right*) scale.

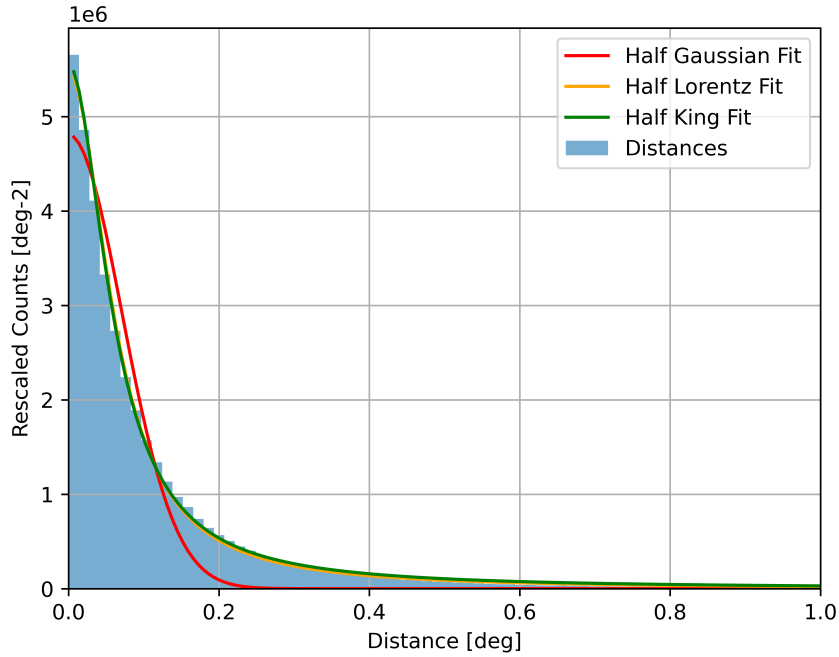


Figure 3.8: Distance distribution of MC events with respect to the reconstructed source position.

centre of the focal plane. While the theoretical source position is defined at $(-0.5, 0)$ relative to the simulated pointing direction, independent estimate can be obtained by performing a 2D Gaussian fit to the pixel map. The peak of the fitted Gaussian leads to a source location estimation of $(-0.51, 0.01)$, confirming compatibility with the source theoretical position.

To determine the PSF of the telescope, a modelling of the spatial distribution of detected events was carried out, using several analytical form. Since the modelling was carried out using simulated gamma-ray data only, the resulting PSF is free from instrumental and background noise. In order to determine such PSF estimate, various analytical models apart from simple Gaussian behaviour were explored:

- A 2d Gaussian, commonly utilized because of its mathematical convenience:

$$f_{\text{Gauss}}(\theta) = A \cdot \exp\left(-\frac{\theta^2}{2\sigma^2}\right), \quad (3.2)$$

with A the amplitude of the function and σ the standard deviation.

- A Lorentzian function profile, better suited to explain wider angular distributions in reconstructed gamma-ray events at low energies:

$$f_{\text{Lor}}(\theta) = \frac{A}{1 + \left(\frac{\theta}{\gamma}\right)^2}, \quad (3.3)$$

where γ now controls the width of the distribution.

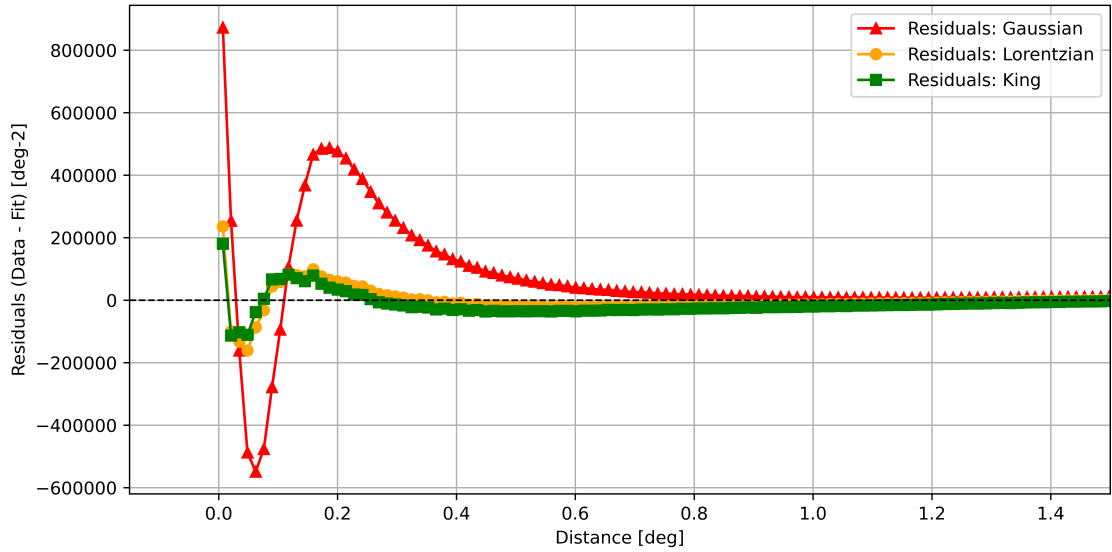


Figure 3.9: Distance residuals from the fit of all three functions used on MC events.

- A King profile, which is frequently used in high-energy astrophysics for PSF modelling with wide wings, is of the form:

$$f_{\text{King}}(\theta) = A \cdot \left(1 - \frac{1}{\gamma}\right) \cdot \left(1 + \frac{\theta^2}{2\sigma^2\gamma}\right)^{-\gamma}, \quad (3.4)$$

where σ is the core width and γ controls the weight of the tails.

Each of these models was fit to the radial distribution of reconstructed event positions (Figure 3.8), which is defined as the angular distance between the source expected position and the event position on the camera field:

$$\theta = \sqrt{(\Delta\alpha)^2 + (\Delta\delta)^2}. \quad (3.5)$$

Here, $\Delta\alpha$ and $\Delta\delta$ represent the differences in right ascension and declination, respectively, in the camera projected coordinates. These distance was also rescaled over the area on the 2D ring corresponding to each distance bin. The goodness of the fits can be evaluated also using the residuals shown in Figure 3.9. Among the tested functions, the Gaussian provides the poorest fit. In contrast, the Lorentzian and King functions exhibit similar performance, with a slight advantage observed for the King function, especially at low angular distances, and for the Lorentzian at $\theta > 0.4^\circ$.

To assess the capability of the King function to model the angular resolution of the instrument, a fit of MC data in discrete energy intervals is necessary. This is because a more rigorous evaluation of the goodness of fit of the Lorentzian or King functions to the MC data requires verifying whether or not the chosen function is capable of reproducing the signal distribution across all energy intervals considered in the analysis. This test is essential because the validity of a functional model in this context is not limited to its agreement with the data general behaviour; rather, it must demonstrate consistency

across the full range of the energies simulated even if the parameters of the PSF can vary with energy due to instrumental effects, reconstruction biases, and the intrinsic physics of the interaction processes. Therefore, a function that matches the data well in one interval but fails in others would indicate that it lacks the correct underlying physics to represent the full dataset. The MC dataset was divided into 8 logarithmically spaced bins, covering the reconstructed energy range from 1 TeV to 40 TeV. For each of these energy bins, the distribution of reconstructed angular distances between the simulated event directions and the nominal source position was computed. The resulting angular distributions were then fitted using the King function previously defined in Equation 3.4. The fits were carried out independently for each energy bin, using a least-squares minimization procedure applied to the histogrammed distance distributions. In all energy intervals shown in Figures 3.10 - left panels, where the King function provided an excellent description of the MC data, with no systematic deviations visible between the function and the data distributions. This consistency across the full energy range indicates that the King function is a robust model for the angular distribution of reconstructed gamma rays in our instrument response simulations.

Once the fits were performed, a quantitative measure of the angular resolution was extracted. In this work, the PSF is characterised using the $R_{39\%}$ quantity, defined as the containment radius within which 39% of the reconstructed events from a point-like source are enclosed. The motivation for adopting this containment fraction is based in the statistical properties of a two-dimensional Gaussian distribution: for a one-dimensional Gaussian, the standard deviation σ corresponds to the interval containing 68.27% of the total probability, while in two dimensions the cumulative distribution of a circularly symmetric Gaussian is given by

$$F(r) = 1 - e^{-r^2/(2\sigma^2)}. \quad (3.6)$$

Here, r is the radial coordinate from the distribution's peak and σ is the Gaussian width parameter. When the radius is set equal to σ , the cumulative fraction becomes

$$F(\sigma) = 1 - e^{-1/2} \approx 0.3935, \quad (3.7)$$

meaning that only $\sim 39\%$ of events are contained within one Gaussian standard deviation in two dimensions. Thus, $R_{39\%}$ is the direct two-dimensional analogue of σ , providing a containment-based measurement that can be directly compared to the σ parameter obtained from a parametric fit to the angular distribution.

This equivalence is particularly advantageous when testing the validity of PSF model functions, since it allows for a one-to-one correspondence between a model parameter and a non-parametric, data-driven measurement of angular resolution. Moreover, choosing $R_{39\%}$ minimizes the influence of non-Gaussian tails on the PSF estimate: higher containment radii such as $R_{68\%}$ probe farther into the distribution tails, making them more sensitive to deviations caused by reconstruction biases or background contamination.

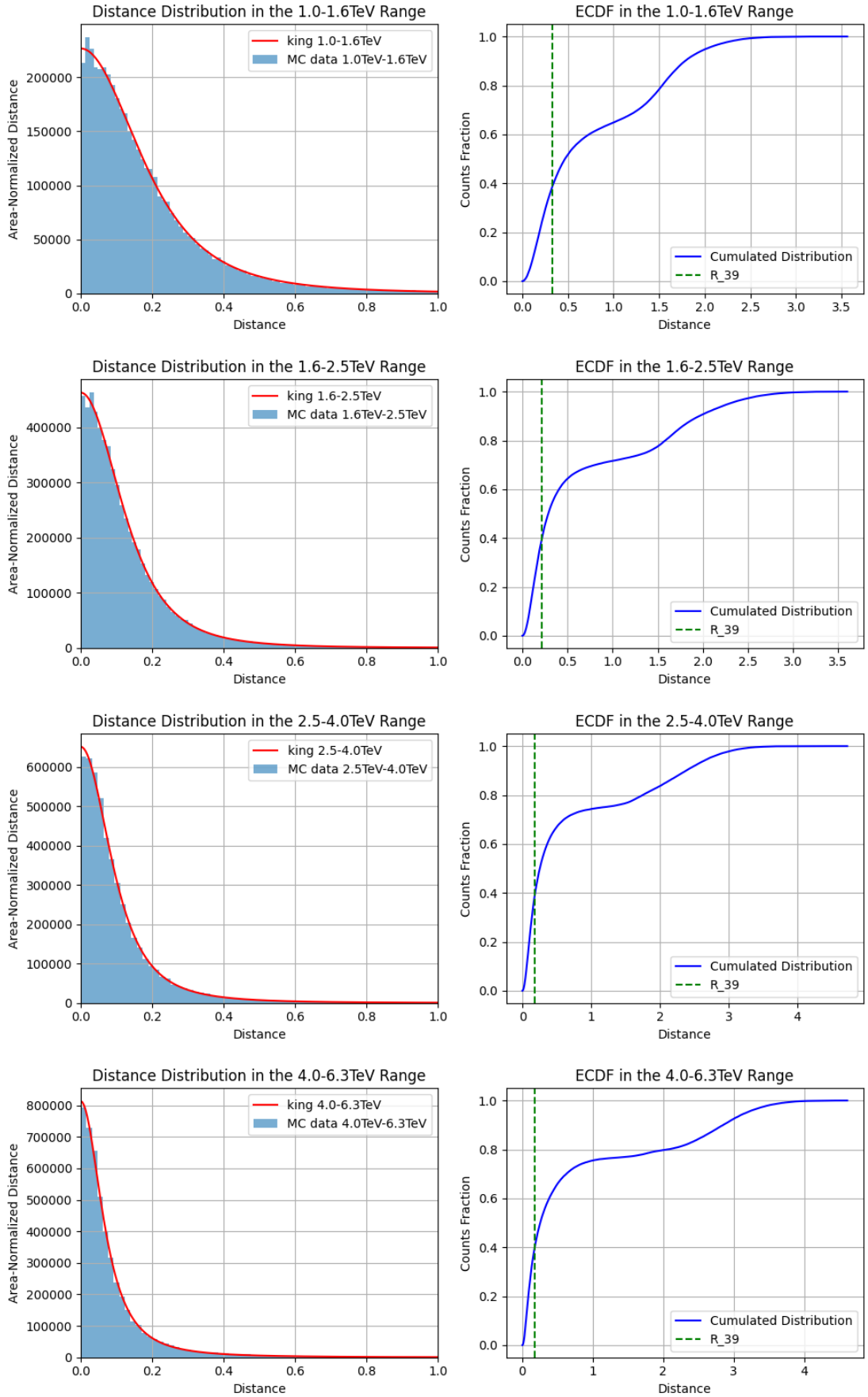


Figure 3.10: Angular distance distributions (*left* panels) and corresponding ECDF (*right* panels) in different energy bins. The vertical dashed lines indicate the non-parametric estimate of $R_{39\%}$ obtained directly from the ECDF, providing a data-driven measurement of the angular resolution that can be compared with the parametric PSF fit.

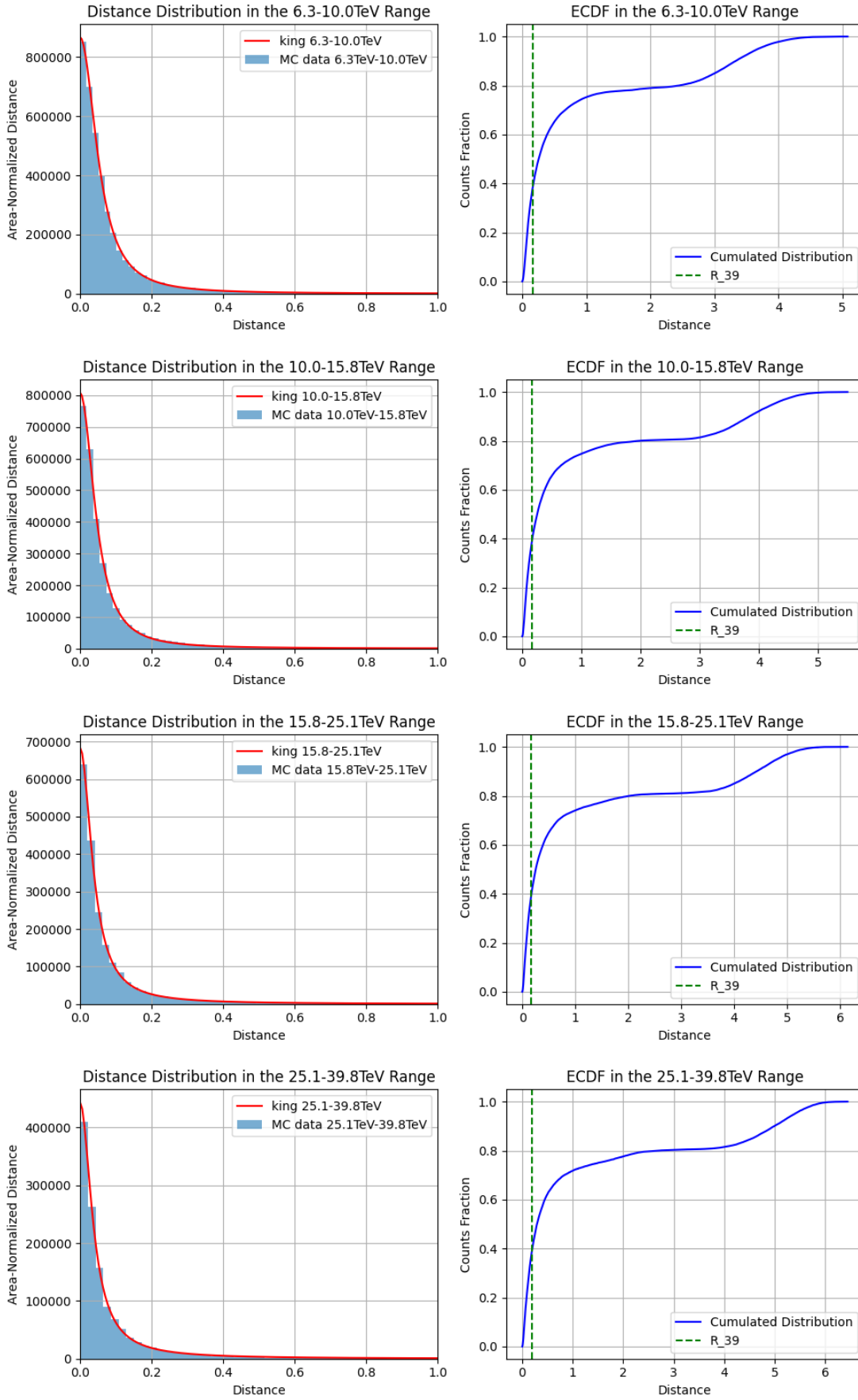


Figure 3.10: Continuation.

To obtain $R_{39\%}$ in a non-parametric way, it is possible to employ the *Empirical Cumulative Distribution Function* (ECDF) of the measured angular distances in each energy bin (see Figures 3.10, right panels). The ECDF for a dataset $\{x_1, x_2, \dots, x_n\}$ is formally defined as:

$$\hat{F}_n(t) = \frac{1}{n} \sum_{i=1}^n \mathbf{1}(x_i \leq t), \quad (3.8)$$

where $\mathbf{1}(\cdot)$ is the indicator function, equal to 1 if its argument is true and 0 otherwise, and n is the total number of events in the sample. In our case, x_i corresponds to the angular distance θ_i of the i -th event from the nominal source position. The ECDF therefore returns, for any given angular radius t , the fraction of events whose reconstructed directions lie within that radius. From the ECDF, $R_{39\%}$ can be determined directly by identifying the angular distance t for which $\hat{F}_n(t) = 0.39$. This approach is model-independent, relying purely on the empirical distribution of the MC data without any assumption about the functional form of the PSF. In practice, for each energy bin, the angular distances were sorted in ascending order and computed the cumulative fraction of events as a function of radius. The $R_{39\%}$ value was obtained by interpolation between the two nearest radii surrounding the 0.39% containment fraction. The results from the ECDF-based method and the King function fits can be seen in Figure 3.12. Up to several tens of TeV, there is agreement between the results within 1σ in each of the energy bins, further reinforcing the conclusion that the King function provides an accurate description of the PSF.

An interesting and recurring feature, easily observed in the ECDFs, of the simulated angular distances is the presence of a secondary rise, or bump, at higher angular distances from the nominal source position. This feature is visible across all energy bins, and its position in the ECDF corresponds to a non-negligible fraction of events reconstructed at offsets much larger than the instrument's core PSF width. Such behaviour is not expected in an idealized, purely Lorentzian or King-function-like PSF, where the cumulative fraction should rise steeply near the core radius and then asymptotically approach unity without significant inflections. The systematic presence of this high-distance bump therefore points to an underlying effect in the simulation or reconstruction process rather than to a statistical fluctuation. The origin of this behaviour can be traced to the observational mode of the simulated data. In fact, the MC production was performed in *mono* mode. In this case, the reconstruction of the primary gamma-ray direction relies on the parametrization of the Cherenkov light image through the Hillas parameters, which describe the intensity distribution of the image as an ellipse in the camera plane. The visual, geometrical definitions of the key parameters are visible in Figure 3.11, and they include the ellipse length, width, orientation, and centroid position, all of which are derived from the light distribution. The main directional reconstruction method in *mono* mode uses the major axis of the ellipse and additional image-shape parameters to estimate the angular displacement between the image centroid and the source position in the camera coordinates. While effective in many cases, this method suffers from an

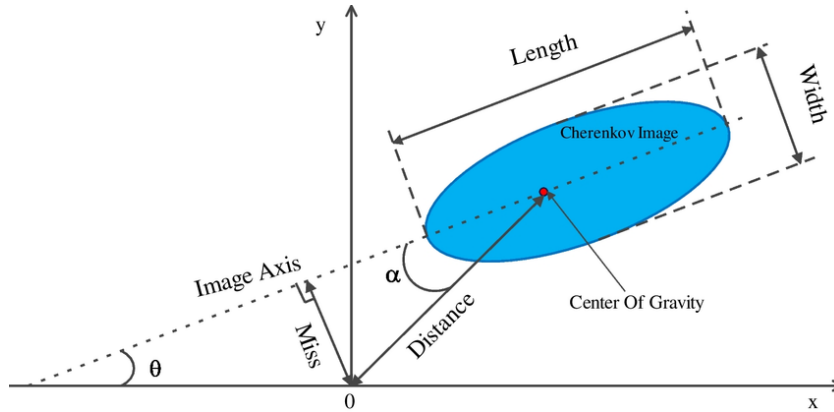


Figure 3.11: Geometrical definition of the Hillas parameters used to characterise the Cherenkov image from [98].

intrinsic degeneracy: given a single elliptical image, there is an ambiguity as to whether the primary particle arrived from one end of the major axis or from the opposite end. In stereoscopic observations, this degeneracy is broken by intersecting the major axes from multiple telescope images, allowing for an unambiguous reconstruction of the true source position. In mono mode, however, the absence of this cross-check means that in some fraction of events, the reconstruction algorithm places the source position in the 'mirror' location—i.e., the position symmetric to the true source with respect to the centre of the camera. This effect is essentially a misreconstruction arising from the head–tail ambiguity of the Hillas-ellipse method.

When projected into angular distance space, these mirror reconstructions produce a population of events at a characteristic large offset from the true source location. In the ECDF, this manifests as a distinct change in slope at high angular distances: the cumulative fraction rises more quickly than expected in the tails, producing the observed bump. Since this effect is geometric and intrinsic to the mono-mode reconstruction, it appears consistently in all energy bins, although its relative intensity can vary with energy due to differences in image brightness, shape resolution, and reconstruction quality. Furthermore, it is also worth noting that the angular position of the high-distance bump in the ECDF is not fixed, but exhibits a clear dependence on the event energy, shifting to larger angular offsets as the energy increases. This behaviour can be understood in terms of the image morphology in the camera: higher-energy gamma-ray showers produce brighter and longer Cherenkov images, which correspond to larger Hillas length parameters. Because the displacement between the image centroid and the true source position grows with the Hillas length, and because the Hillas length scales with the shower energy due to the larger number of Cherenkov photons and greater image extension, the mirror position is located at a correspondingly larger angular distance from the true source at higher energies. This trend is entirely consistent with the geometrical origin of the effect and serves as further evidence that the bump is a reconstruction artefact rather than a feature of the instrument's intrinsic PSF. Understanding and identifying this feature is important for two reasons. First, it highlights a limitation of mono-mode

data, especially when used for PSF characterisation, as the misreconstructed component inflates the apparent tail of the distribution and can bias containment-radius estimates if not accounted for. Second, its consistent presence across all energies provides a diagnostic signature that can be used to separate genuine instrumental broadening from reconstruction artefacts.

3.2.2 PSF Computation from ASTRI - Horn Data

Once the shape of the expected angular distribution of gamma-ray radiation from a point-source has been firmly established through the analysis of Monte Carlo simulations, and the expected values of the PSF parameters have been quantified over the relevant energy range, the next natural step is verifying the PSF using real observational data. The reason for this is that, although MC simulations incorporate detailed models of the detector geometry, electronics, trigger conditions, and reconstruction algorithms, they inevitably rely on assumptions and simplifications that may not fully capture all aspects of the instrument’s performance under operational conditions. Discrepancies can arise from poor knowledge of the atmospheric profile, optical response, or calibration constants, as well as from environmental effects that are difficult to model precisely.

By computing the PSF directly from real data with the expectations obtained from MC simulations, one can directly assess the validity of the simulation-based modelling and identify any deviations that may point to unknown effects. This comparison must be performed across the same energy interval and using identical analysis procedures to ensure that any differences are intrinsic and not the result of methodological biases. In this context, the PSF derived from MC simulations serves as a benchmark, while the measurement from real data provides the empirical truth under actual observing conditions. The degree of agreement between the two is a powerful diagnostic of both the accuracy of the simulations and the stability of the instrument over time, making this validation step an indispensable component of any HE astrophysics analysis pipeline.

Real Data Background Modelling A fundamental added difficulty in modelling the PSF from real observational data, as opposed to Monte Carlo simulations, is the presence of background events. In Monte Carlo productions dedicated to point-like gamma-ray sources, the simulated event sample can be studied free of background contamination, selecting solely gamma-ray showers generated according to the source spectrum and reconstructed with the instrument model. This idealized environment allows for a clean extraction of the PSF without the need to disentangle the signal from unrelated events. In real data, however, the situation is significantly more complex: the recorded event sample contains not only gamma rays from the target source but also a dominant hadronic component arising from hadronic cosmic rays, misidentified electromagnetic showers, and, depending on the observation mode, possible contributions from diffuse gamma-ray emission. This background component is typically several orders of magnitude more numerous than the signal and, even if most of it is rejected by signal

reconstruction algorithms, can bias the derived PSF by artificially broadening the measured angular distribution if not properly accounted for.

The impact of the background on the PSF measurement depends strongly on the angular distance from the nominal source position. For a point-like source in the centre of the FoV, the gamma-ray signal is concentrated in the central region of the camera, with the majority of events contained within a small angular radius defined by the instrument’s resolution. Beyond this core region, the event distribution becomes increasingly dominated by background, which is broadly isotropic in camera coordinates over the small section of field of view relevant to the analysis. For this reason, background modelling is most reliable at small angular scales, where the signal-to-background ratio is highest and the isotropy assumption for the background holds locally. In practice, one can fit the background level in the angular distribution using regions close to the source position but outside the PSF core, ensuring that the fit is not significantly affected by large-scale spatial gradients in the background. By restricting the background modelling to this small-angle regime, one can construct a robust empirical description of the background contribution and subtract it from the total angular distribution. The resulting background-subtracted profile can then be used to fit the PSF shape of the point-like source with minimal contamination.

However, even when restricting the background estimation to relatively small angular regions, typically on the scale of a few degrees or less, in order to minimise the influence of large-scale gradients, the assumption of a homogeneous background level may not hold. Several factors can contribute to residual spatial variations in the background, even at these smaller scales. For instance, the instrument acceptance is not perfectly uniform across the field of view: optical vignetting, camera pixel response variations, and the geometry of the trigger and reconstruction algorithms can introduce smooth but non-negligible acceptance gradients. As a result, even within degree-scale regions, the background distribution may still exhibit small but systematic deviations from uniformity. Neglecting these variations can bias the derived PSF, particularly in analyses where high precision in the tail region of the angular distribution is required.

ASTRI - Horn Real Dataset A total of 29 hours of observational data from the 2022-2023 Crab Nebula observational campaigns with the ASTRI-Horn telescope have been employed for this study. The data were processed with the standard reconstruction pipeline, yielding for each event a set of image parameters and a gamma/hadron separation variable, referred to here as *gammaness*. The gammaness parameter quantifies the probability that a reconstructed event is a gamma-ray, based on a multivariate classification algorithm trained on Monte Carlo simulations of gamma-ray and hadron showers. Events were selected by requiring a gammaness parameter greater than 0.8 in order to enhance the purity of the gamma-ray sample.

The same analysis procedure previously applied to the MC data was repeated on these observational data. Given that the functional form of the signal distribution in the MC

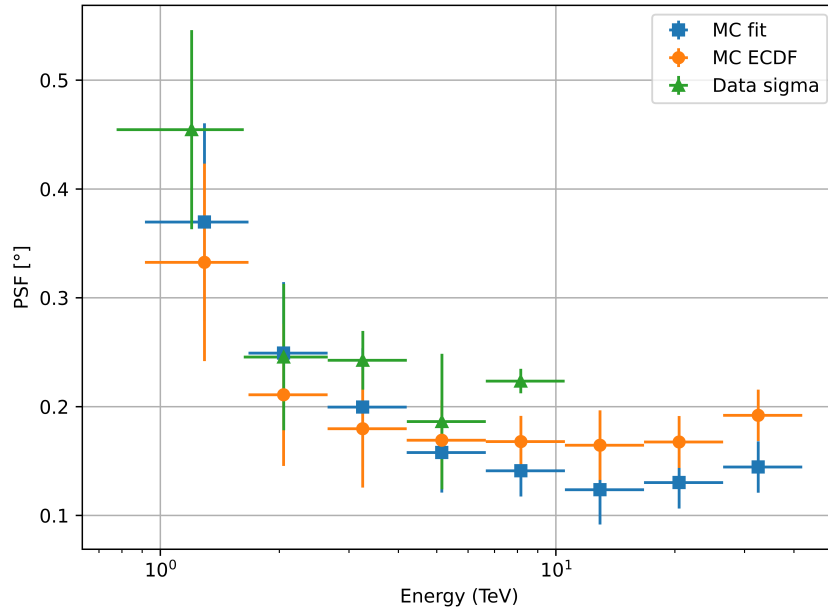


Figure 3.12: Comparison between the PSF obtained from MC simulations, both with the ECDF and the King function fit methods, and the Crab Nebula observations.

case was previously well described by both the King and Lorentzian functions, and that the real data distributions appeared qualitatively similar, the same parametric models were adopted for the signal component in the real data fit. However, the King/Lorentzian model function requires an extra background term to describe the isotropic component, due to other events surviving the gammaness cut or diffuse gamma-ray emission. The spatial distribution of the excess signal has been modelled by fitting a King function combined with a constant term:

$$f_{\text{King}}(\theta) = A \cdot \left(1 - \frac{1}{\gamma}\right) \cdot \left(1 + \frac{\theta^2}{2\sigma^2\gamma}\right)^{-\gamma} + K_{bkg}, \quad (3.9)$$

which allows a description of both the point-like source component and the residual background level.

For the analysis of the Crab Nebula observations, the binned energy range was chosen to overlap the one used for the MC analysis, ensuring consistent comparisons between the simulated and observed PSF parameters. A clear signal is observed up to energies of approximately 10 TeV, above which the statistical uncertainties begin to dominate, and no signal clearly emerges from the background. Figure 3.12 shows the comparison between the PSF derived from the observational dataset and that obtained from the MC simulations. The two distributions display overall compatibility within the statistical uncertainties, both in terms of the core width and in the behaviour of the tails.

E_{min} (TeV)	E_{max} (TeV)	Gammaness
0	0.7943	1.00
0.7943	1.2589	0.41
1.2589	1.9953	0.59
1.9953	3.1623	0.78
3.1623	5.0119	0.90
5.0119	7.9433	0.92
7.9433	12.5893	0.94
12.5893	19.9526	0.90
19.9526	31.6228	0.87
31.6228	50.1187	0.91
50.1187	79.4328	0.93
79.4328	125.8925	0.91
125.8925	300.0000	0.95

Table 3.2: Energy bin ranges and the corresponding gammaness values chosen.

3.2.3 PSF from ASTRI - 1 Data

The measurement of the PSF width of the first telescope of the ASTRI Mini-Array that has been fully deployed in at the Teide Observatory in Tenerife, was based on a dedicated dataset of 59 hours of Crab Nebula observations, acquired with ASTRI-1. All the data used was taken under relatively homogeneous observational parameters: all observations were taken in the first observational campaign (i.e. from November 2024 to February 2025) at favourable zenith angles $Z_{\max} = 30^\circ$, ensuring comparable atmospheric path lengths and minimizing variations in image morphology due to changing shower projection effects. The pointing strategy employed a wobble offset of 0.5° from the Crab position, alternating between symmetric directions around the source (0, 90, 180 and 270 degrees). This offset-wobble observation mode is also advantageous for background estimation, as it provides control regions at the same angular distance from the camera centre as the source position, thereby preserving acceptance symmetry. For the present analysis, a selection cut of $\gamma_{\text{ness}} > G_{\text{cut}}$ displayed in Table 3.2 was imposed, to optimise the trade-off between gamma-ray purity and statistics. This cut efficiently suppresses the hadronic background while retaining the majority of the gamma-ray signal from the Crab Nebula. After applying the gammaness cut and basic quality selection criteria (i.e. good weather, stable trigger rates, and successful image parameterization), the surviving event sample is shown in Figure 3.13 and it was used to construct the spatial distribution of the signal. Figure 3.14 shows the spatial distribution of the excess events in camera coordinates, clearly centred on the nominal Crab position.

Following the procedure applied to the MC simulations (see Section 3.2.1), the angular distribution of events was derived for the real Crab Nebula dataset described in the previous section. The fitting was performed over angular distances up to 1.25° from the nominal source position. This scale was chosen to be sufficiently large to capture all of the PSF signal and its tail region, while still remaining small enough to minimise the influ-

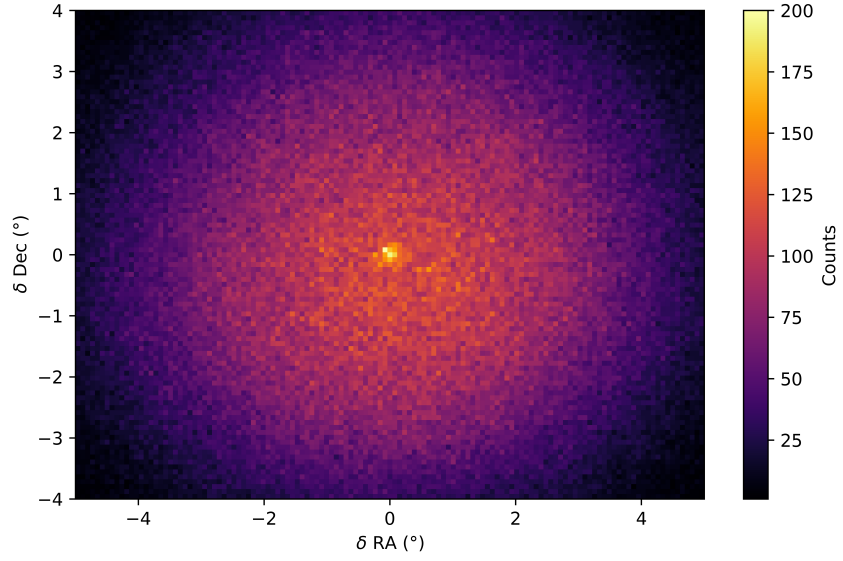


Figure 3.13: Counts maps of real ASTRI - 1 data selected as described in section 3.2.2, projected onto the camera focal plane. Both coordinates are in degrees and centred on the Crab Nebula nominal position (Gal. coord.: $l = 184.5547$, $b = -05.7833$)

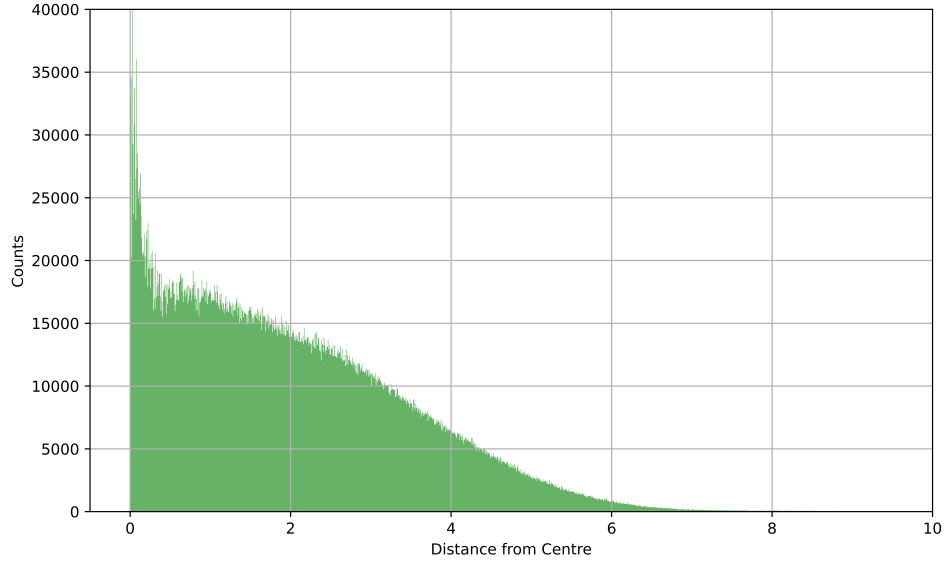


Figure 3.14: Spatial distribution of excess events in camera coordinates after gammaness selection. The origin corresponds to the nominal source position in the reconstructed field of view.

ence of large-scale acceptance variations and astrophysical gradients in the background. Despite this restriction to degree-scale regions, the fitted background term showed small but statistically significant residuals. Such deviations, although small, were taken into account with a model including a linear gradient in the angular distance from the source position. A linear model provides a minimal yet effective way to capture such small-scale variations without introducing unnecessary complexity into the fit, though a more complete and effective analysis of the signal across the whole FoV would require better and more complex parametrization of the background. The full model used for the angular distribution of events, $N(\theta)$, combines the King or Lorentzian profile for the signal component with a linear background term:

$$N(\theta) = N_{\text{sig}} \cdot S(\theta; \mathbf{p}) + (B_0 + B_1 \theta), \quad (3.10)$$

where θ is the angular distance from the nominal source position, $S(\theta; \mathbf{p})$ represents the chosen PSF shape (either King or Lorentzian function) with parameter set $\mathbf{p}$, N_{sig} is the signal normalization, B_0 is the constant background level, and B_1 quantifies the background gradient. Figure 3.15 illustrates the quality of this modelling. The dataset used here corresponds to the entire available Crab Nebula observation set, spanning reconstructed energies from 0.8 TeV to 300 TeV. The angular distribution has been fitted using the Lorentzian PSF shape plus the linear background term. Here, the total fit to the data, corresponding to the full model of Equation 3.10, yields a $\sigma_{\text{PSF}} = 0.17^\circ$ and is shown as a solid red curve. For clarity, the individual components of the fit are also displayed: the Lorentzian-shaped signal term is plotted in orange, while the background contribution, including the linear gradient, is shown in blue. This decomposition illustrates the relative importance of the signal and background across the full angular range. The inclusion of the gradient significantly reduces the residuals compared to a constant background model, confirming that this approach captures the small but non-negligible spatial variations in the background.

The PSF extraction procedure was repeated in several independent energy bins. The results confirm that the presence of a non-uniform background is a constant feature across the entire energy range: in every energy bin considered, the fitted background term exhibited a gradient with respect to a purely constant value, with the higher energy bins having the most statistically significant. The linear parametrisation of the background was found to provide a satisfactory description in all energy bins, with no evidence that a higher-order polynomial or more complex functional form was required. This validates the choice of a linear gradient as the minimal model capable of capturing the observed behaviour. At intermediate energies, where the gamma-ray signal from the Crab Nebula is still relatively strong, the PSF core and tail are clearly resolved above the background level, and the separation between the signal and background components is unambiguous. However, at and beyond a reconstructed energy threshold of ~ 25 TeV, the statistical significance of the signal drops rapidly, and the fitted signal profile becomes increasingly dominated by statistical fluctuations in the background. This is a natural consequence

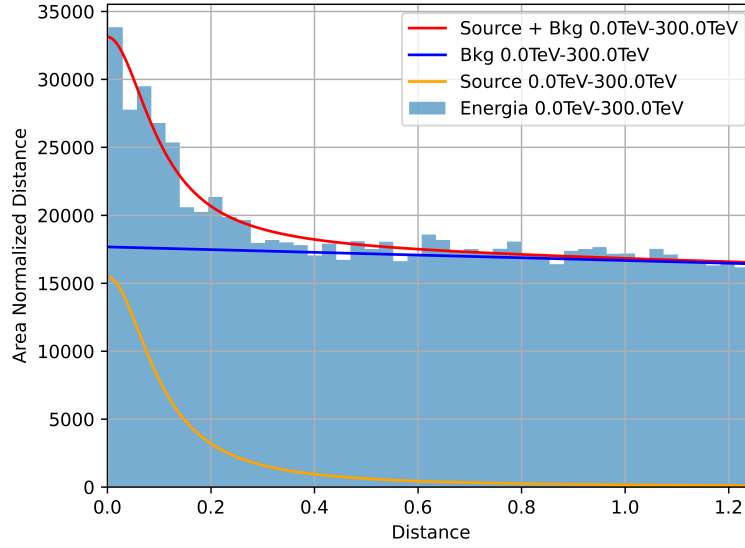


Figure 3.15: Fit of the real Crab Nebula data (0.8–300 TeV) using a Lorentzian PSF shape plus a linear background term as defined in Eq. 3.10. The solid red curve represents the total fit, while the orange curve shows the signal component and the blue curve corresponds to the background contribution, including the linear gradient. The clear separation of these components illustrates the contribution of the gradient term at larger angular distances.

of the shape of the Crab Nebula spectrum, combined with the finite exposure time of the dataset. In this HE regime, the PSF cannot be reliably determined, as the fit parameters become strongly degenerate between the signal and background terms.

Figure 3.16 shows representative fits for low-, intermediate-, and high-energy bins, illustrating the persistence of the background gradient across energies. Further energetic bins display the eventual dominance of the background. Before the ~ 25 TeV, the signal-to-background ratio remains sufficient in all cases, and the extracted PSF can be seen in Figure 3.17. The values found are consistent within 2σ with those contained in the IRF for the ASTRI - 1 telescope [96]. It should be specified that, while the adoption of a linear gradient model for the background has proven sufficient to capture the dominant non-uniformities within the 1.25° fitting radius, it represents only a first-order approximation to the true background structure in real data. For a more accurate determination of the PSF, particularly in the tail region where the signal-to-background ratio is intrinsically low, a more detailed background model is required. Such a model would need to account for spatial variations on multiple angular scales, possible azimuthal asymmetries in the camera acceptance, and time-dependent effects related to changing observational conditions.

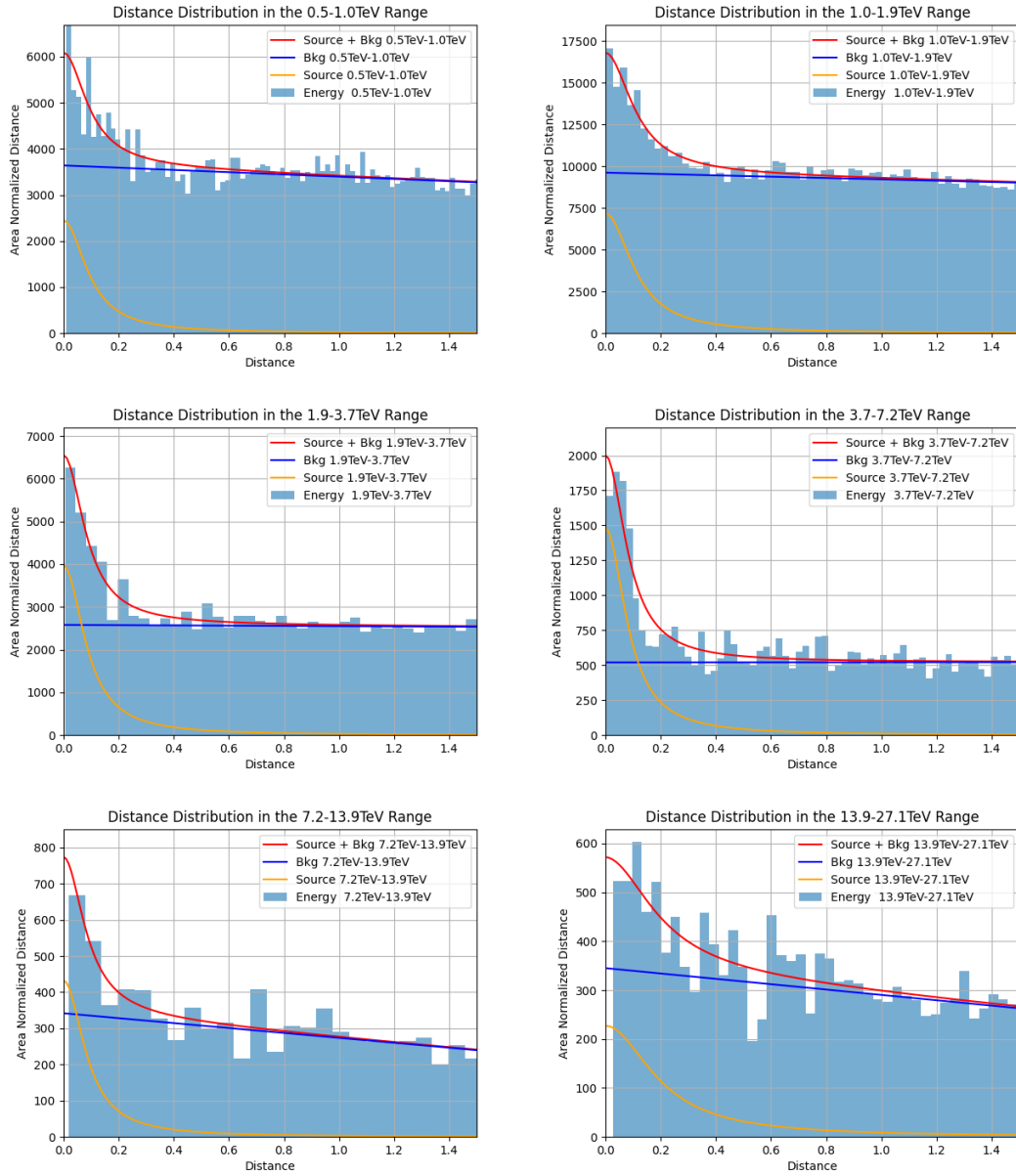


Figure 3.16: Fits to the angular distributions of the Crab Nebula data in independent energy bins, ranging from 0.5 TeV to 27.1 TeV. Each panel shows the measured distribution together with the Lorentzian PSF component and the linear background contribution, illustrating the fit quality and PSF parameters across energy.

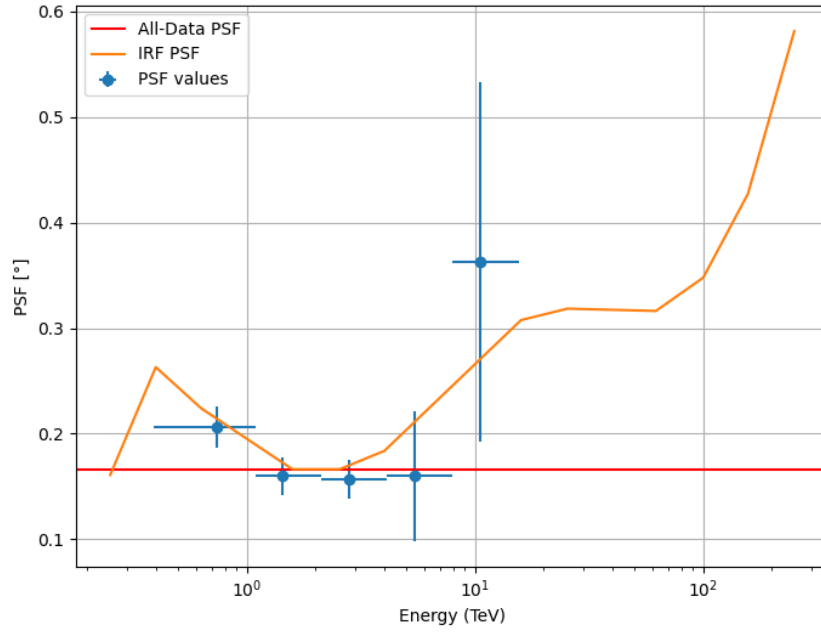


Figure 3.17: PSF width according to ASTRI-1 observations in different reconstructed energy bins (blue points) compared to the one estimated from the MC data (orange line). The red line identifies the PSF given by the fit shown in Figure 3.15. At higher energies ($\gtrsim 27$ TeV, green triangles) the reduced signal statistics lead to degeneracies between signal and background, preventing a reliable PSF determination.

3.3 Background Characterisation Across the FoV

As mentioned in the previous section, the precision of the PSF determination depends critically on the accuracy with which the background contribution is modelled. This is especially true at large angular distances from the source position, where the background dominates the measured distribution and any inaccuracies in the background model can be directly propagated into the PSF fit, biasing the extracted parameters and potentially leading to incorrect conclusions about the signal reconstruction. While a constant or linear gradient background model may provide a satisfactory first-order description for degree-scale regions around a bright point source, at angular scales beyond $\sim 1.5^\circ$ the residual background often exhibits more complex spatial structures. These complications can arise from multiple sources: the inhomogeneous acceptance of the camera, imperfections in the flat-fielding of photomultiplier responses, localised regions of reduced sensitivity due to inactive pixels, optical aberrations in the mirror system, or incorrect signal direction reconstruction. An additional and important factor to consider is the presence of intrinsic azimuthal asymmetries in the background. Unlike radial gradients, which can be partially accounted for by a one-dimensional dependence on the angular distance θ , azimuthal asymmetries require a two-dimensional treatment in camera coordinates. Such asymmetries can be caused by the MC-based IRF used in the reconstruction pipeline or the arrival direction misreconstruction of the showers.

These effects must be incorporated into the background modelling, ideally one that

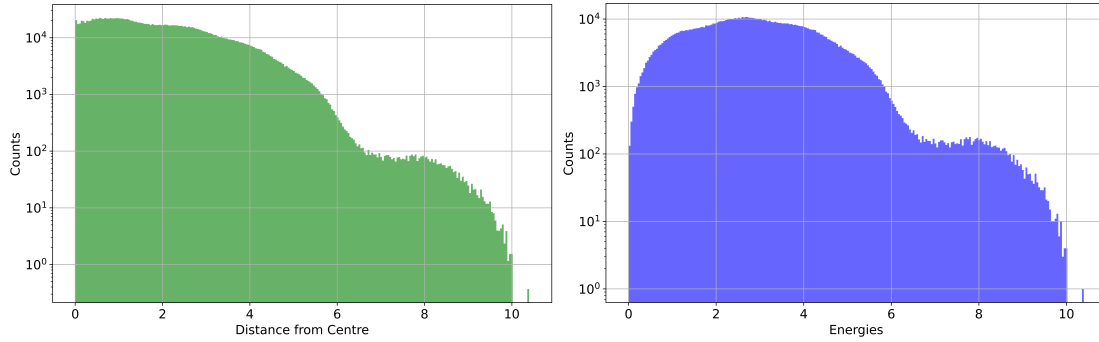


Figure 3.18: Spatial and energetic distributions of events in camera coordinates after gammaness selection. The position (0,0) corresponds to the centre of the field of view.

is energy-dependent, which can be built from high-statistics off-source observations. Ultimately, such refinements are essential for studies that rely on precise knowledge of the instrument response over extended regions, such as morphological analyses of extended sources or searches for diffuse emission.

3.3.1 Background Dataset

In order to investigate the spatial behaviour of the background across the entire FoV of the instrument, a dedicated study was performed using a dataset of observations taken in fixed-pointing mode. In this observation mode, the telescope keeps a fixed azimuth and elevation (or zenith), allowing the sky to drift across the field of view as the Earth rotates and providing a stable instrumental setup that is particularly suitable for studying spatial variations of the background across the camera. The fixed-pointing dataset was carefully selected to include only observations taken at low zenith angles, specifically $\text{zenith} < 25^\circ$ (with an average zenith angle of $\sim 20^\circ$), in order to minimise acceptance variations due to atmospheric effects. The total exposure time for this fixed-pointing dataset amounts to approximately 15 hours.

To increase the available statistics and improve the robustness of the background modelling, an additional 71 hours of Crab Nebula observations taken at zenith angles $\text{zenith} < 30^\circ$ were added to the fixed-pointing dataset. However, in this case the source itself was not the object of interest, and using the sky coordinates directly was avoided. Instead, only the reconstructed directions of the events were considered, expressed in camera coordinates. This is justified because, over the course of the observations, the apparent position of the Crab Nebula changes in camera coordinates due to the Earth's rotation, and the four wobble pointings used during the observations further displace the source location within the FoV. As a result, the gamma-ray excess from the Crab is effectively spread out over a wide area of the camera, diluting the source contribution to the point where the dataset is statistically equivalent to a pure background observation. This method allows to leverage the high-statistics Crab dataset as an effective background tracer without introducing significant contamination from the source itself.

The same gammaness cuts as in Table 3.2 were applied to the complete dataset. To

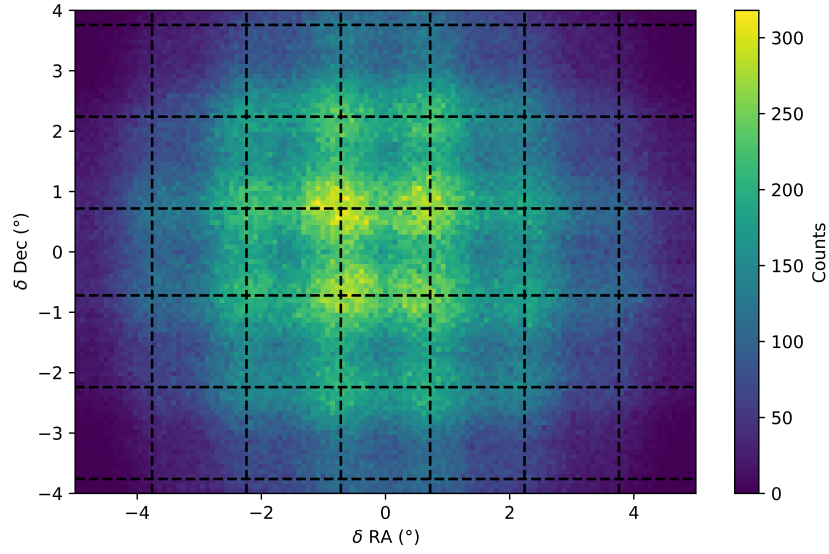


Figure 3.19: Background counts map in camera coordinates, illustrating the spatial structures as a function of reconstructed energy. The grid-like, uniform, X-shaped, and rounded filamentary patterns discussed in the text are visible across different energy ranges.

provide a visual overview of the data used in this study, Figure 3.18 shows, respectively, the reconstructed energy distribution and the spatial distribution of events across the camera coordinates for the combined dataset.

Figure 3.19 shows the resulting total counts map of all events in the background dataset, expressed in camera coordinates. It is immediately apparent from the counts map that the background distribution is still neither spatially constant nor purely radially symmetric. Instead, the map exhibits both large-scale gradients and localised variations in event density. The large-scale deviations from uniformity are likely related to variations in the camera acceptance and optical throughput. Such non-uniformities must be carefully accounted for in any PSF determination that extends over the full field of view, since a purely radial background model would fail to capture these azimuthally dependent features. The clear grid-like pattern coincides precisely with the boundaries of the PDMs of the camera. To guide the eye, the dashed black lines in Figure 3.19 indicate the positions of the PDM edges, and the correspondence between these boundaries and the grid pattern in the event density is unambiguous. This feature possibly originates from systematic effects in the reconstruction pipeline of the event arrival direction. A closer inspection of the background data spatial structure as a function of reconstructed energy reveals four distinct morphological behaviours, clearly visible in Figure 3.20. The signal with energies below approximately 2.5 TeV, which dominates the total photon flux, exhibits a pronounced grid-like pattern, visible also in the overall morphology. In the intermediate range (2.5–25 TeV), no significant large-scale structure is visible, and the background appears relatively uniform. Between 25 and 250 TeV, a different feature emerges: an X-shaped pattern with filamentary structures extending toward the edges of the FoV. At the highest energies, i.e. above 250 TeV, these filaments

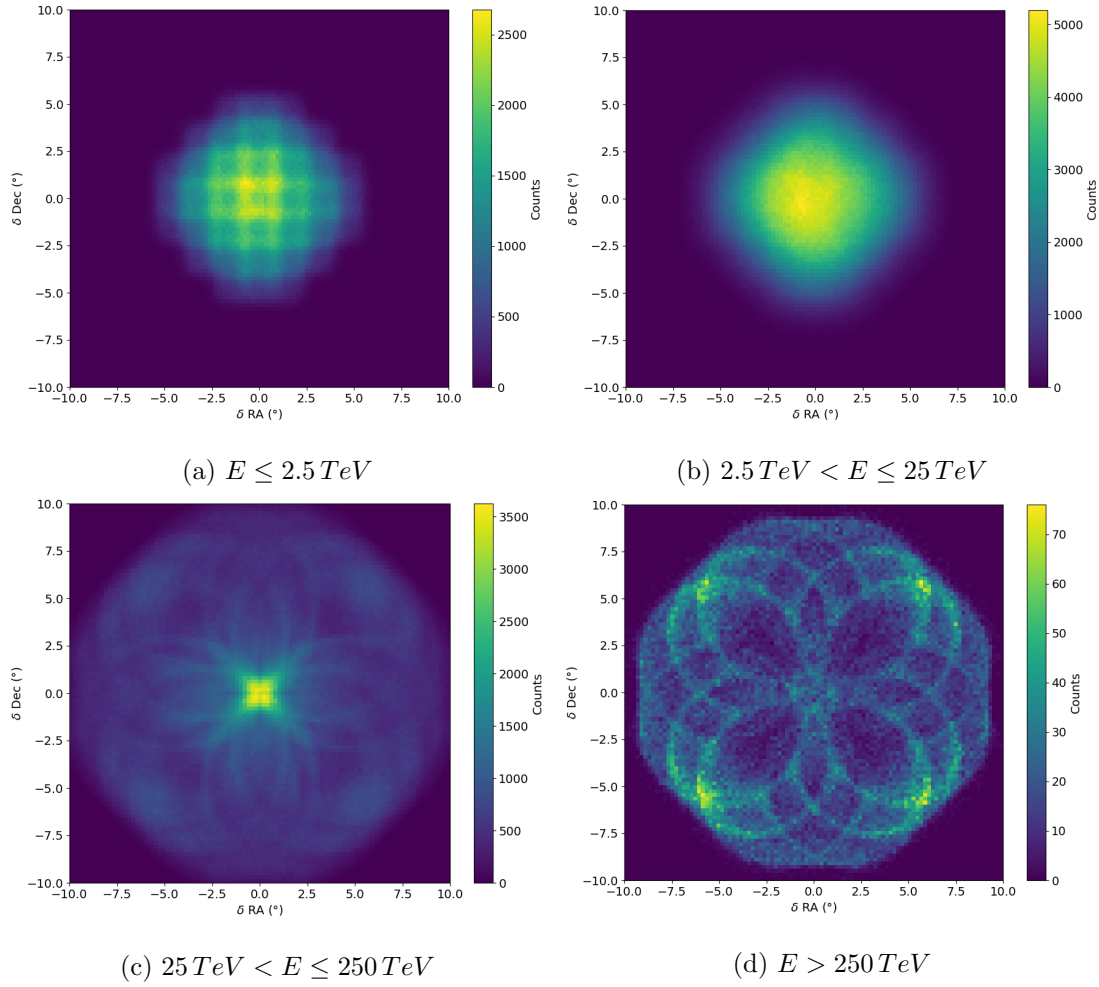


Figure 3.20: Spatial and energetic distributions of events in camera coordinates after gammaness selection. The position (0,0) corresponds to the centre of the field of view.

appear more rounded and localised, forming rounded structures. These variations introduce high-frequency spatial structure that cannot be captured by a smooth analytical background model and must therefore be accounted for.

The presence of both large-scale gradients and PDM-scale features underscores the need for a multi-scale background modelling approach if the goal is to achieve reliable scientific analyses and astrophysical objects across the entire camera. However, it remains highly valuable to characterise and model the general radial behaviour of the background. This is because, to first order, the acceptance of the instrument — and hence the average background rate — tends to decrease with increasing angular distance from the camera centre due to optical and geometrical effects. By quantifying this radial trend, one can capture the dominant large-scale component of the background, which serves as a baseline for more refined models incorporating azimuthal and high-frequency corrections. Furthermore, a well-constrained radial profile can be directly compared between datasets taken under different observational conditions to assess stability and identifying systematic changes in the instrument response. Even when the two-dimensional modelling is required, the radial component plays an important role in constraining the parameter space and reducing degeneracies in the fit, improving the robustness of the PSF estimation.

3.3.2 Background Modelling

To quantitatively describe the background signal distribution as a function of the angular distance from the centre of the field of view, a series of fits to the azimuthally averaged event density profile were performed. The goal was to identify a parametric form capable of reproducing both the core and the outer regions of the distribution with sufficient accuracy for PSF modelling. To this end, three candidate models were tested:

1. Double Gaussian:

$$f_{\text{DG}}(x) = A_1 \exp\left(-\frac{(x - \mu_1)^2}{2\sigma_1^2}\right) + A_2 \exp\left(-\frac{(x - \mu_2)^2}{2\sigma_2^2}\right), \quad (3.11)$$

representing the sum of two Gaussian profiles with potentially different centres and widths.

2. Double Lorentzian:

$$f_{\text{DL}}(x) = \frac{A_1}{1 + \left(\frac{x - \mu_1}{\gamma_1}\right)^2} + \frac{A_2}{1 + \left(\frac{x - \mu_2}{\gamma_2}\right)^2}, \quad (3.12)$$

which is the same as the previous case, but with Lorentzian functions.

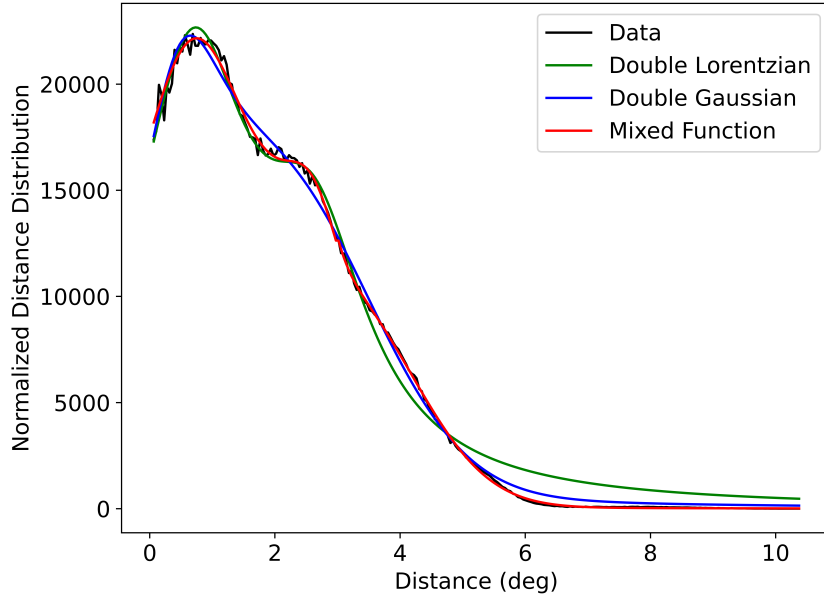


Figure 3.21: Radial background profile and corresponding fits with the three tested models (double Gaussian, double Lorentzian, and piecewise Lorentzian–Gaussian).

3. Piecewise Lorentzian–Gaussian:

$$f_{LG}(x) = \begin{cases} \frac{A_{1l}}{1 + \left(\frac{x - \mu_{1l}}{\gamma_{1l}}\right)^2} + \frac{A_{2l}}{1 + \left(\frac{x - \mu_{2l}}{\gamma_{2l}}\right)^2}, & x \leq 3^\circ \\ \frac{A_{1g}}{1 + \left(\frac{x - \mu_{1g}}{\gamma_{1g}}\right)^2} + A_{2g} \exp\left(-\frac{(x - \mu_{2g})^2}{2\sigma_{2g}^2}\right), & x > 3^\circ \end{cases} \quad (3.13)$$

where the inner region ($x \leq 3^\circ$) is described by a double Lorentzian, while the outer region ($x > 3^\circ$) transitions to a double Gaussian form.

The performance of these models was assessed by fitting them to the full radial background profile, as shown in Figure 3.21, and by examining the residuals in Figure 3.22. The results indicate that:

- The double Lorentzian provides a reasonable description of the core region ($x \lesssim 3^\circ$) but fails to reproduce the faster fall-off observed at larger distances.
- The double Gaussian behaves conversely: it models the outer region well but underestimates the extended tails in the inner FoV.
- The piecewise Lorentzian–Gaussian model achieves the best overall performance, combining the strengths of the Lorentzian in the core with the Gaussian’s accuracy in the outer region. This yields residuals that are consistently smaller than those from the other models across the entire FoV.

Based on this comparison, the piecewise Lorentzian–Gaussian function was selected as the baseline radial background model for all subsequent performance analyses, unless stated otherwise.

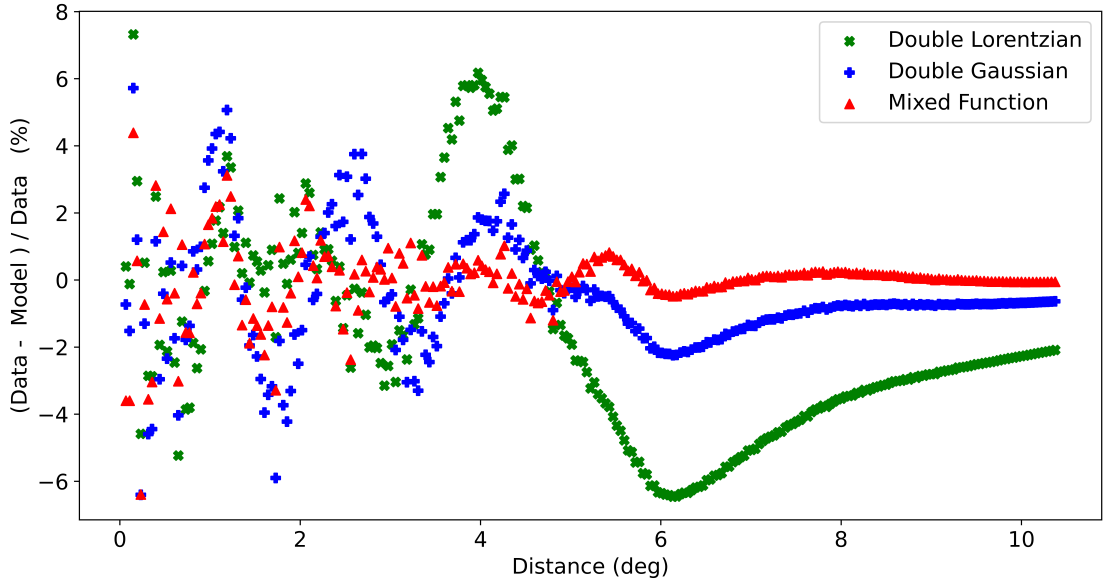


Figure 3.22: Residuals of the three fitted models with respect to the measured background profile, illustrating the superior performance of the piecewise Lorentzian–Gaussian function.

3.3.3 Incorporation of the 2D Background into the IRF

In order to properly account for the two-dimensional nature of the grid-like background structure observed at low energies, a new version of the ASTRI IRF with the data available was produced, in which the background component was replaced by a spatial model incorporating the grid pattern described in Section 3.3.1. The resulting background relevant plots are shown in Figure 3.23. This modified IRF preserves the original instrument energy dispersion, effective area and PSF components, ensuring that the adaptation does not introduce biases into other IRF quantities.

To validate the suitability of this new IRF, `gammapy` simulations were used to generate simulated event lists for background observations. By comparing the simulated spatial distributions with the real background data, it was possible to assess the ability of the modified IRF to reproduce the observed morphology. During these tests, it emerged that the choice of energy binning in the `gammapy` simulation pipeline significantly impacts the quality of the reproduction. In particular, a finer energetic sampling of 10 bins per decade yielded noticeably better agreement with the data, as can be seen from the comparison of spatial distribution histograms in Figure 3.24. Consequently, the use of 10 bins per decade in the background component of the IRF is adopted as a necessary condition for accurate two-dimensional background modelling in the subsequent analyses. The agreement between the simulated and measured background maps shown in Figures 3.24 and 3.25, where it can be seen that the discrepancies between the real and simulated data are within $\sim 5\%$. The fact that in Figure 3.24 the Lorentzian–Gaussian accurately follows the background behaviour in both binning cases corroborates the suitability of the function in modelling the background and the grid structure can be considered correctly

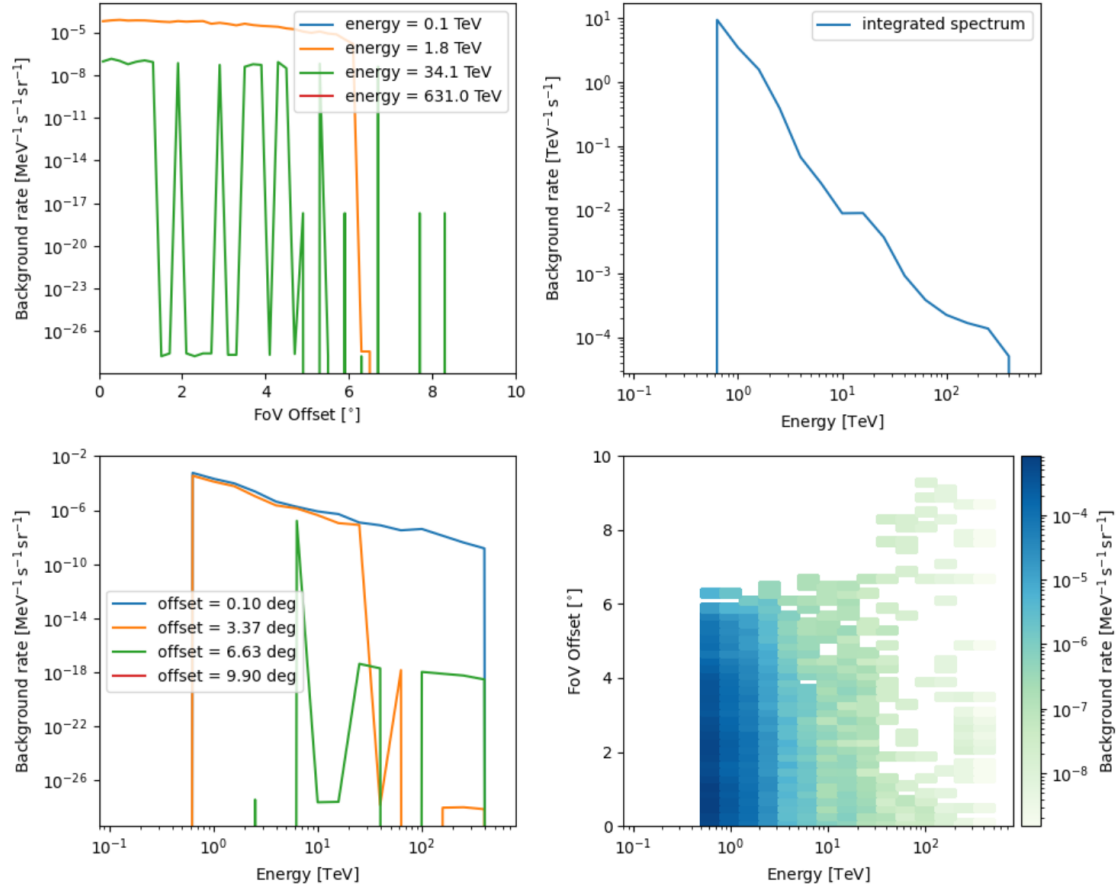


Figure 3.23: Modified ASTRI IRF with the background component replaced by the two-dimensional grid-like spatial model. Shown are the new background spectrum and the rate as a function of the FoV offset and energy.

implemented in the new version of the IRF.

3.4 An Accurate Computation of the PSF

Having validated the modified ASTRI IRF with the two-dimensional background component through simulations and data comparison, it was then applied to the analysis of real ASTRI-1 Crab Nebula observation data. The primary objective of this step was to disentangle the astrophysical signal from the instrumental and atmospheric backgrounds employing the improved background model. In practice, this approach allows to subtract the structured background directly using the IRF, leaving a residual distribution that is the Crab signal. Furthermore, by relying on the IRF simulations, the method ensures that the subtraction remains consistent both across the full energy range and within the field of view for any livetime of the observations, facilitating data analyses with different datasets.

A dataset consisting of 142 hours of Crab Nebula data collected between November 2024 and March 2025 was used to estimate the PSF again. The events were selected according to the gammaness cuts in Table 3.2, ensuring consistency with the previous

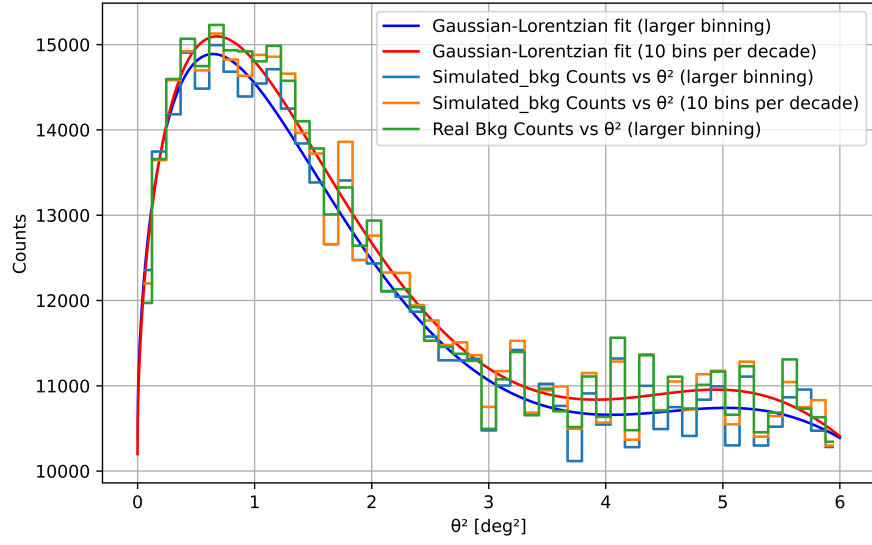


Figure 3.24: Comparison between the spatial distribution of real background events (green) and simulated data, both with a larger (blue) and smaller binning (orange).

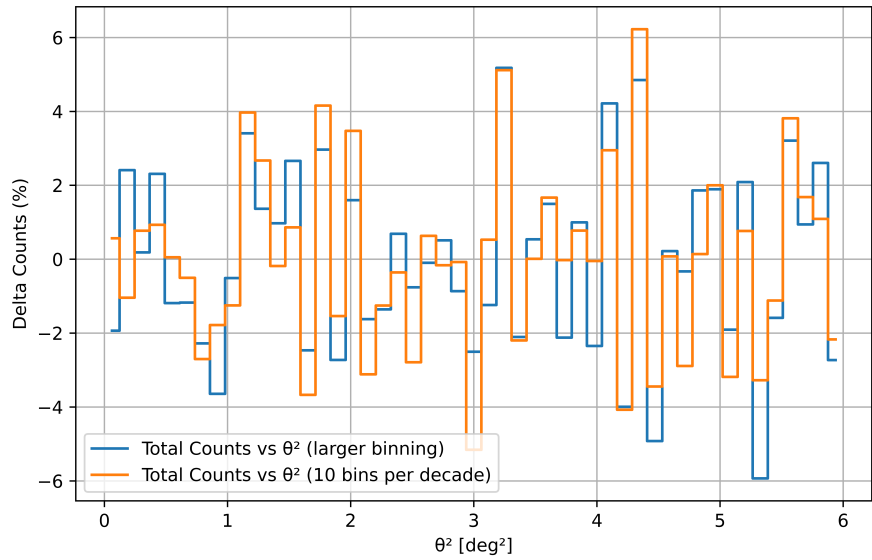


Figure 3.25: Residual map showing the difference between real and simulated background data. Deviations remain within $\sim 6\%$, consistent with statistical fluctuations.

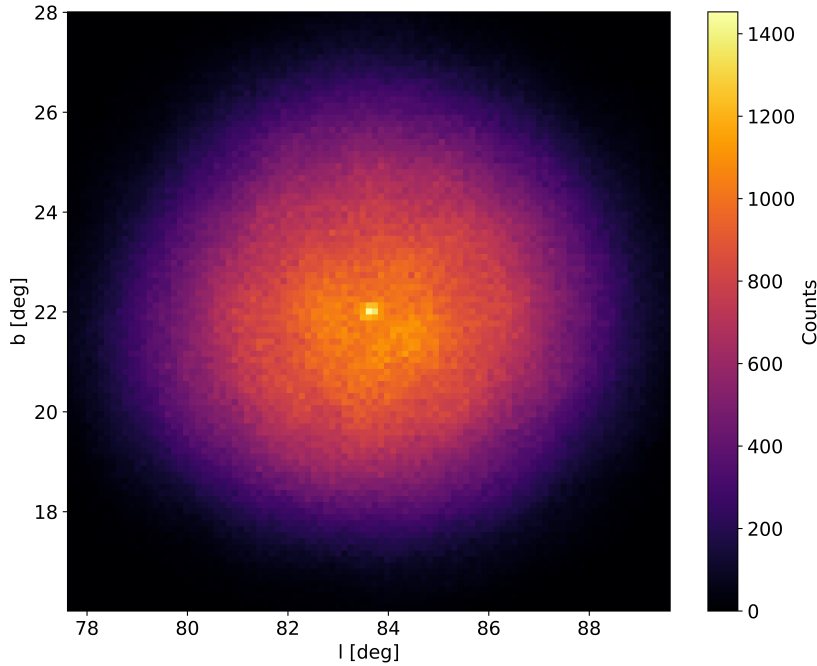


Figure 3.26: Crab Nebula counts map from ASTRI-1 observations (142 hours), centred on the nominal source position. The structured background has been subtracted using the modified IRF, leaving the residual astrophysical signal.

background studies (i.e. Sections 3.2.3 and 3.3). After the event selection, the counts map shown in Figure 3.26 was constructed, centred on the nominal position of the Crab Nebula. As expected, the central source dominates the field of view, producing a very strong and concentrated signal. Therefore, in this representation, the grid-like background structure that was clearly observed in the background-only dataset is no longer immediately visible, though still present in the data as an underlying component.

3.4.1 Data Analysis Strategy and Implementation

The procedure adopted for the analysis of the Crab Nebula data can be summarised in three main steps. The workflow is as follows:

- **Map dataset construction:** The real Crab data were inserted into a `gammapy MapDataset` using the reconstructed right ascension (RA), declination (Dec), and energy of each event. This provides a structured, multidimensional representation of the data, compatible with the analysis framework.
- **Background simulation:** The background contribution was simulated for a total exposure time equal to the sum of the observational runs, relying on the modified IRF background component. This ensures that the simulated background has both the correct morphology (i.e. a grid structure) and the proper normalisation.
- **Excess computation and analysis:** The background dataset is subtracted from the real data map to obtain the excess dataset corresponding to the Crab signal.

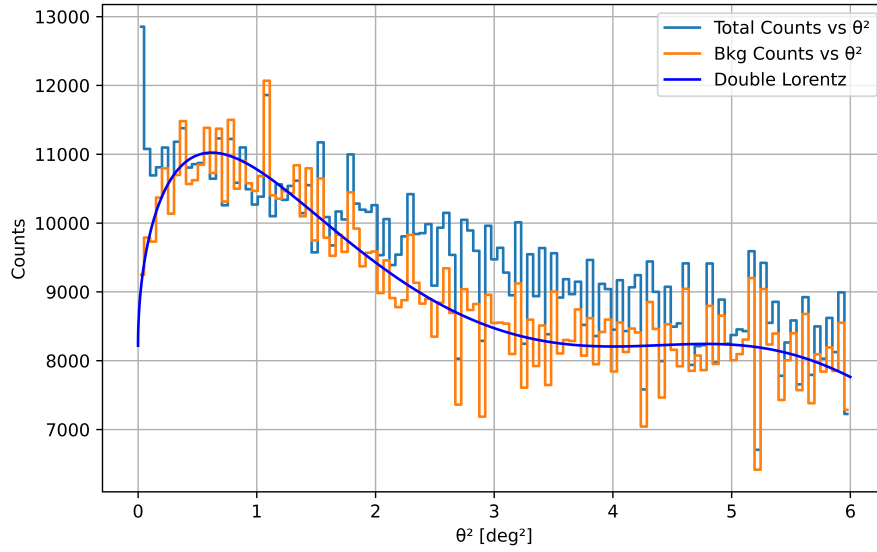


Figure 3.27: θ^2 distributions of events with respect to the centre of the field of view (nominal Crab Nebula position). The comparison between real Crab data and the simulated background dataset highlights the excess at small angular distances, consistent with the expected signal from a point-like source. The blue line is the best fit of the simulated background data with Equation 3.14.

This excess dataset, cleaned of background contributions, is then analysed in order to extract the PSF and its energy dependence.

The θ^2 distributions of events as a function of the distance from the centre of the FoV, which again coincides with the nominal position of the Crab Nebula, are shown in Figure 3.27. Real data and simulated background dataset are compared and, as expected, the two distributions exhibit very similar behaviour across most of the FoV. This confirms the accuracy of the background model in reproducing the overall structure of the data. However, the real Crab dataset shows a clear excess at small angular distances from the centre, consistent with the expected morphology of a point-like source, given by the Crab Nebula signal. It is also worth noting that the background distribution increases quite rapidly as the centre of the FoV is approached. This implies that the observed excess of counts in the real data near the origin is even more significant than it appears. In other words, since the background expectation is low in this region, the contribution of the Crab is amplified, which leads to a reduced PSF as the signal peak is higher.

In the present analysis, events within $\theta^2 \leq 6$ were considered, corresponding to $\theta \leq 2.5^\circ$. Within this range, the background was modelled with the double Lorentzian function, defined as in Equation 3.12 and expressed here as a function of θ^2 :

$$f(x) = \frac{A_1 \gamma_1^2}{\gamma_1^2 + x + \mu_1^2 - 2\mu_1\sqrt{x}} + \frac{A_2 \gamma_2^2}{\gamma_2^2 + x + \mu_2^2 - 2\mu_2\sqrt{x}}. \quad (3.14)$$

Here, $x = \theta^2$ is the new θ^2 coordinate and it has been substituted for clarity, while $A_{1,2}$ are still the amplitudes, $\mu_{1,2}$ the centroids, and $\gamma_{1,2}$ the widths. The curve fit

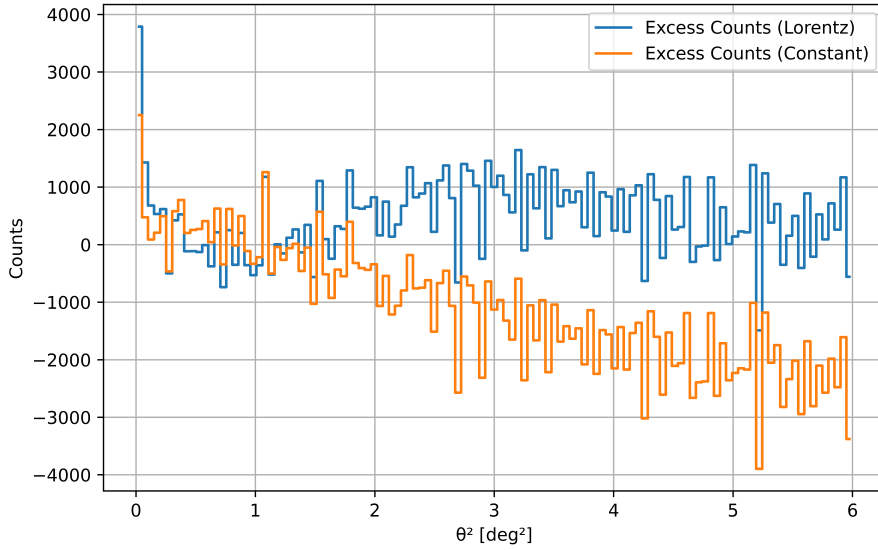


Figure 3.28: Residuals of the background fits obtained with a constant model (orange) and with the double Lorentzian model (blue). The double Lorentzian provides a significantly better representation of the data, especially at small θ^2 values, where the constant background assumption underestimates the true distribution.

corresponding to this model is shown in blue in Figure 3.27. This function provides a significantly better description of the background distribution than a constant model, both at higher θ^2 values and, most importantly, in the crucial region of small θ^2 . A constant or linear background assumption systematically underestimates the signal close to the origin, thereby diluting the excess attributed to the source. The difference between linear and double Lorentzian background models is made explicit in Figure 3.28, where the residuals of the two fits are displayed: the double Lorentzian captures the background structure better, reducing deviations across the full angular range. The adoption of this ad-hoc background model has a direct impact on the estimated Crab Nebula signal. In particular, by properly accounting for the rapid fall of the background counts near the source position, the excess counts at $\theta^2 \approx 0$ are enhanced by a factor ~ 1.6 with respect to the constant background model.

3.4.2 Analysis Results and PSF Values

The PSF could then be derived by fitting the excess distribution with a King function, able to capture both the Gaussian-like core of the distribution and the non-negligible tails that are often present in real data. The fit of the King function to the excess distribution, together with the corresponding excess data, is shown in Figure 3.29. From the best-fit King function parameters, the total width of the PSF was computed. The value obtained is $\sigma_{\text{PSF}} = 0.14^\circ$ across the entire energy range considered. This value was derived through the calculation of the containment radius r_{68} of the 2d data distribution, defined as the angular radius within which 68% of the total signal events are enclosed. The computation of r_{68} from the King function from the radial profile of the King

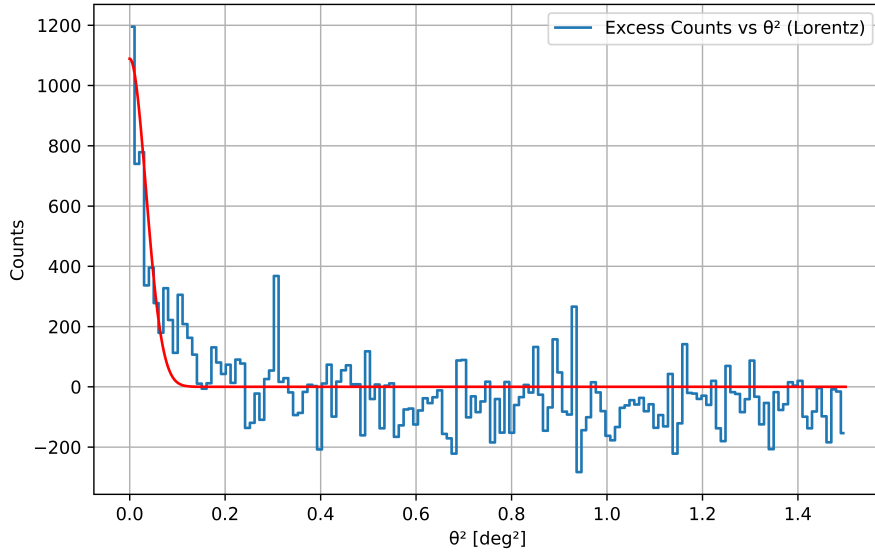


Figure 3.29: θ^2 distribution of the excess data for the Crab Nebula dataset, together with the best-fit King function.

function was obtained by integrating it to obtain the cumulative distribution of events as a function of angular distance θ . Explicitly, the cumulative fraction of enclosed counts at a given radius r is given by

$$F(r) = \frac{\int_0^r 2\pi \theta K(\theta; \sigma, \gamma) d\theta}{\int_0^\infty 2\pi \theta K(\theta; \sigma, \gamma) d\theta}, \quad (3.15)$$

where $K(\theta; \sigma, \gamma)$ denotes the King function in two dimensions with scale parameter σ and tail parameter γ . The containment radius r_{68} is then obtained by solving the equation:

$$F(r_{68}) = 0.68. \quad (3.16)$$

The procedure previously described was subsequently applied independently to each of the energy bins used in the analysis described in Section 3.2.2, with the aim of investigating whether the PSF estimation exhibits any improvement with the new IRF for the data in each bin. The steps of this procedure are displayed in Figures 3.30. The results are shown in Figure 3.31, which illustrates the energy-dependent PSF estimates. The comparison of the PSF estimates obtained with the two background modellizations shows that the values are compatible within uncertainties in the lowest energy bin. However, in the subsequent bins the use of the double-Lorentzian background model systematically leads to slightly smaller PSF values, with the difference being $> 1\sigma$ and therefore statistically significant. This indicates that the refined description of the background distribution prevents an artificial broadening of the excess signal that a linear background approximation causes. Furthermore, the improved modellization makes it possible to extend the analysis to an additional energy bin, thereby allowing the PSF to be measured up to energies of approximately 30 TeV.

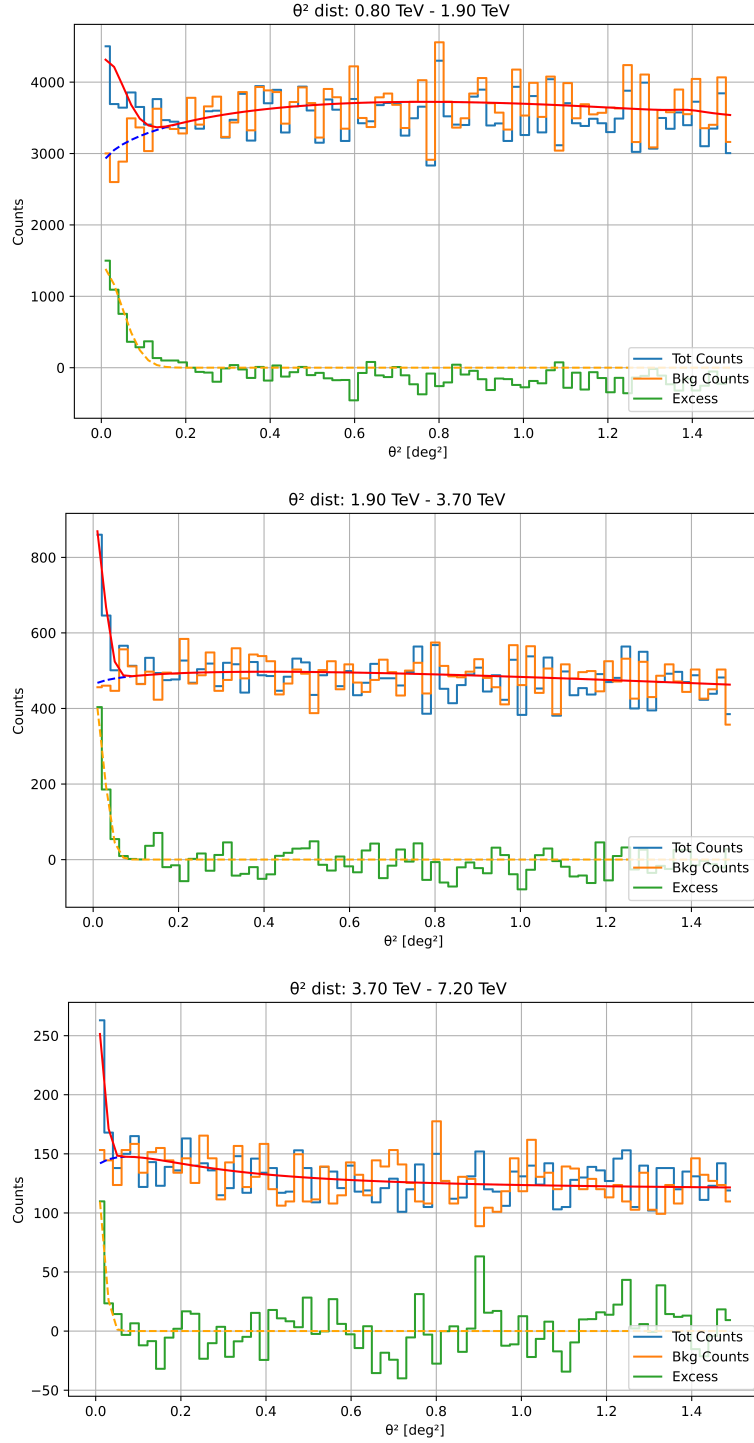


Figure 3.30: Distributions of θ^2 for different energy bins. The blue line corresponds to the real data distribution, the orange line to the background model, and the green line to the excess distribution. The blue dashed line is the best fit of the background according to Eq. 3.14, the yellow dashed line is the King function best fit of the excess, and the red line is the total fit obtained as the sum of the two components.

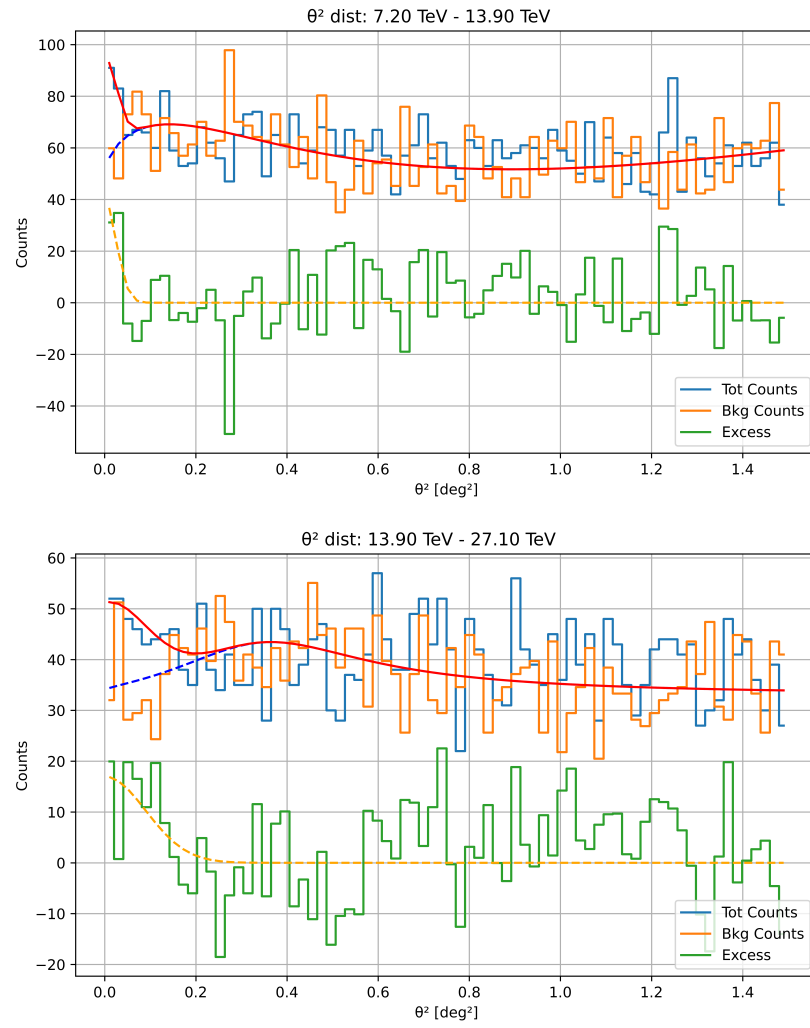


Figure 3.30: Continuation.

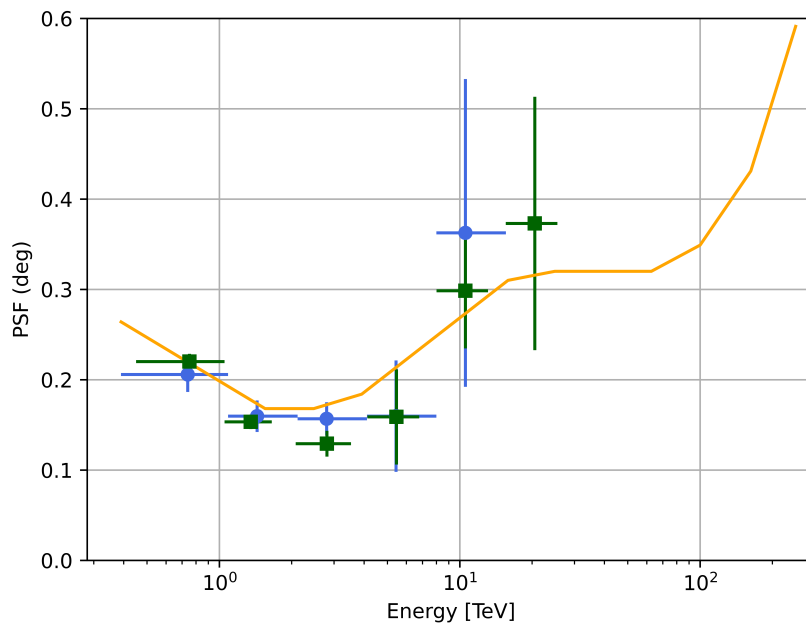


Figure 3.31: Energy-dependent PSF estimates obtained with the two background models: linear (blue) and double-Lorentzian (green). The MC data PSF is also shown in orange for reference. While the results are consistent within uncertainties in the lowest energy bin, the double-Lorentzian model systematically yields slightly smaller PSF values at higher energies. This refined background description also allows the analysis to be extended up to ~ 30 TeV.

Chapter 4

The First Stereoscopic Phase of the ASTRI Mini-Array

Operating with multiple telescopes confers immediate and substantial advantages. Chief among them is the possibility to exploit stereoscopic observations to improve reconstruction of the arrival direction and energy of the primary event. This results in a marked enhancement of the instrument’s angular resolution, energy resolution, and background discrimination capabilities compared to the monoscopic mode. The aim of this work is to provide an effective study on the performances of the ASTRI-Mini Array in the first stages of its operative life. The focus is therefore to characterise its capabilities not only when the full array becomes operational, but also during its earlier stages, when only a subset of telescopes—specifically, the first three—will be active. Understanding the performance of this partial array is fundamental for maximizing the scientific output during the early science period.

When only a single telescope is available, the observational program is necessarily restricted to point sources. However, the simultaneous use of multiple telescopes significantly broadens the scientific potential. With stereoscopy, it becomes feasible to detect and analyse fainter and more complex sources that would otherwise remain out of reach. Particularly, extended sources and complex regions of the Galactic plane—which present the most interesting applications for fine morphological studies—can be investigated thanks to the improved capabilities of the stereoscopy mode. Moreover, the relatively large and nearly uniform PSF across the ASTRI Mini-Array’s wide FoV facilitates systematic surveys of complex regions without substantial degradation in image quality toward the edges of the FoV. The approaching of the operational phase with only three telescopes opens up critical questions: Which sources will be detectable? In what observation time frames? The answers to these questions are crucial to efficiently plan the observation schedule and prioritize targets that promise significant scientific returns within a limited number of observation hours.

4.1 A Systematic Survey

An effective strategy to address the aforementioned questions is to consider existing source catalogs compiled by current-generation experiments that observe the Northern Hemisphere sky. In particular, LHAASO represents an invaluable reference. LHAASO is located at a latitude comparable to that of the ASTRI Mini-Array and has recently provided detailed catalogs of VHE gamma-ray sources, many of which have been detected with high significance. LHAASO’s sensitivity to a wide range of source classes—from PWNe and SNRs to unidentified sources and complex regions—makes it a particularly suitable dataset for informed early ASTRI observations. By examining the distribution and characteristics of sources detected by LHAASO, one can derive a list of promising candidate targets for the ASTRI Mini-Array during its partial-array phase. Criteria for selection would include:

- Source visibility based on the ASTRI Mini-Array’s geographical location (i.e. declination and zenith angle constraints during the observational year).
- Source flux and expected integrated observational time needed for a detection (a few hours to tens of hours).
- Angular extension of the source, relevant in morphological studies.
- Scientific relevance, focusing on sources that could significantly benefit from improved morphological studies, energy spectra measurements, or time variability analysis.

A systematic approach to the selection and prioritization of these early targets is essential. Not only would this allow for efficient use of limited telescope time during its early phases, but also enable early science verification and foster synergies with other observatories operating in complementary energy ranges or modalities.

Simulation work is also critical within such a framework. Through simulation of observations and responses to telescopes for different types of sources, one can predict performances even for the partial array mode. Such a study will inform the observation strategy as well as aid in setting priority among targets with respect to numerical performance prediction. Ultimately, the commissioning and early observing periods for the ASTRI Mini-Array, though involving only three telescopes (ASTRI-3T), is promising to making important scientific contributions. Through planning guided by proven source lists (such as the ones observed by LHAASO), extensive simulation, and deployment of advanced observing strategies, it is possible to achieve scientifically relevant results. Apart from verifying operational ability for the ASTRI Mini-Array, such initial results will also give a clearer idea about ASTRI synergies with the CTAO, as well as within the broader scope of multi-wavelength and multi-messenger astrophysics.

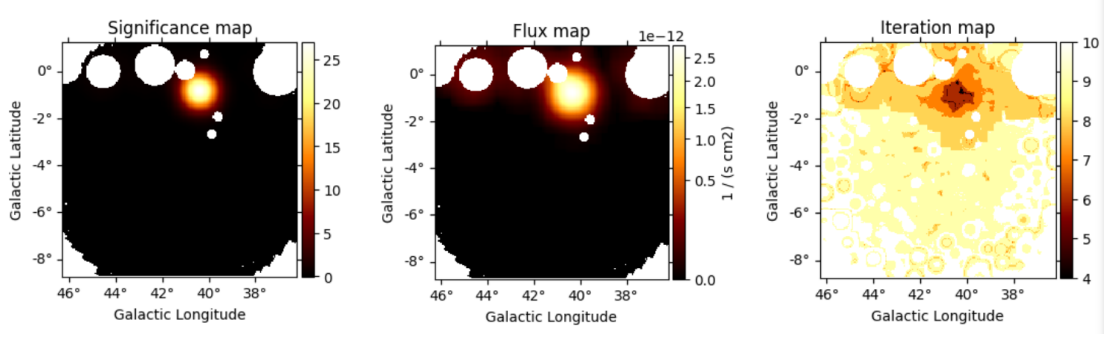


Figure 4.1: Maps generated to perform the TS map estimation of 1LHAASO J1908+0615u, chosen as an example. The white circles indicate the masks applied over other sources present around the one currently being analysed.

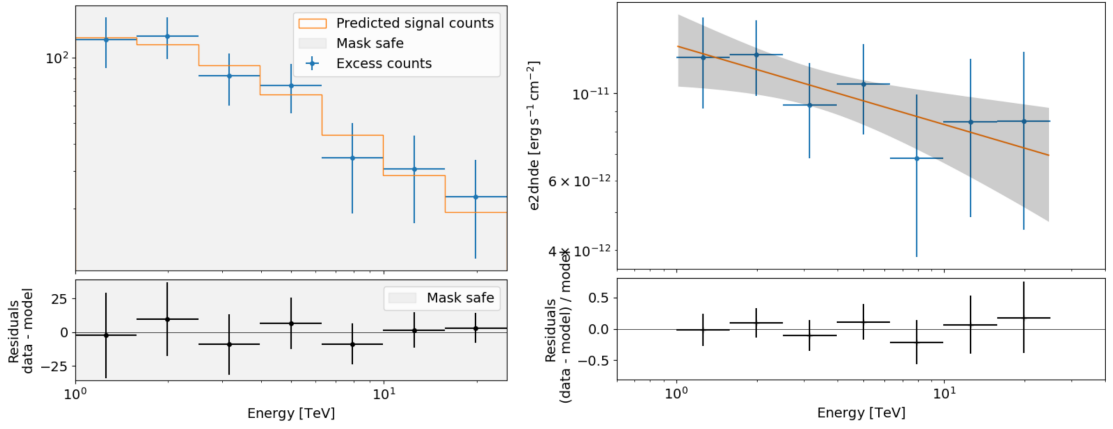


Figure 4.2: *Left:* Fitting of the spectral model to the simulated observation data of 1LHAASO J1908+0615u, chosen as an example. *Right:* Relative final plot with the best fit model, flux points, and relative residuals.

4.1.1 Detection of LHAASO Sources

The first LHAASO source catalog was selected as the primary reference for this study, since it provides a collection of bright and well-characterised gamma-ray emitters particularly suitable for observations with the ASTRI telescope. This catalog represents the most complete sample of UHE sources currently available in the northern hemisphere, including several objects whose nature demands detailed morphological studies to be thoroughly understood. A dedicated analysis pipeline has been developed to systematically process all the sources included in the catalog according to their Galactic coordinates. This framework enables an automated selection of each target within the field of view of the ASTRI telescope and ensures that the analysis is consistently adapted to the specific position of the source on the sky. The main goal of the pipeline is to quantify the minimum observation time required for ASTRI-3T to achieve a significant detection of each source, using the LHAASO-given spectral and morphological parameters as input.

The simulation procedure follows several steps:

- **A FoV is defined** to perform a simulation of an observation. The whole $10^\circ \times 10^\circ$

FoV of ASTRI is simulated.

- The **sources are selected** from the catalog according to their position with respect to the relevant region. Only the central $7.5^\circ \times 7.5^\circ$ section is actually considered for the selection, in order to account for extended sources.
- A **3d Gammapy simulation** of all the selected sources within the FoV with the measured spectrum and angular dimension. A power law spectrum was assumed as a spectral model, and a 2d gaussian profile was used as the respective spatial model, as described in the LHAASO catalog. The IRF of ASTRI-3T is applied to generate a realistic simulated dataset, including both gamma-ray signal and background events.
- Each of the sources is then **analysed singularly** in turn by masking all the other sources simultaneously. A detection performing a TS map estimation. An example of significance map, a flux map, and an iteration map are shown in Figure 4.1, and were generated for each iteration (i.e. each of the sources in the FoV).
- The **peaks of the significance** then are found. The detection can be considered successful when the peak is found within 1 standard deviation of the gaussian model from the nominal position of the source given by the LHAASO catalog with more than 5σ significance.
- A **preliminary spectral analysis** is conducted by fitting a spectral model to the simulated observation data with the likelihood method. The results are visible in Figure 4.2.
- The **flux points** can be also computed by fitting the norm of the global model in energy bands, to obtain a final plot with the best fit model, flux points and residuals like the one in Figure 4.2.
- The procedure is then iterated over all sources and multiple observation livetimes to estimate the minimum time required for a 5σ detection and the one needed to measure a spectrum in a minimum number of energy bins. These results provide a direct estimate of the feasibility and performance of ASTRI-3T observations, and serve as a benchmark for future observation planning.
- Finally, the whole process is repeated with a new FoV, shifted by 7.5° with respect to the previous one, to ensure full coverage of the sky. By limiting the shift to this value, all sources are analysed with a maximum offset of 3.75° from the centre of the camera, i.e. within safety area in which the performance of ASTRI camera are stable.

Pointings covering the whole sky were used to estimate which sources could be detected within a 200 hours limit, and what the minimum livetime to achieve a 5σ detection would be. Out of the 90 sources in the WCDA catalog, 46 were found to be visible

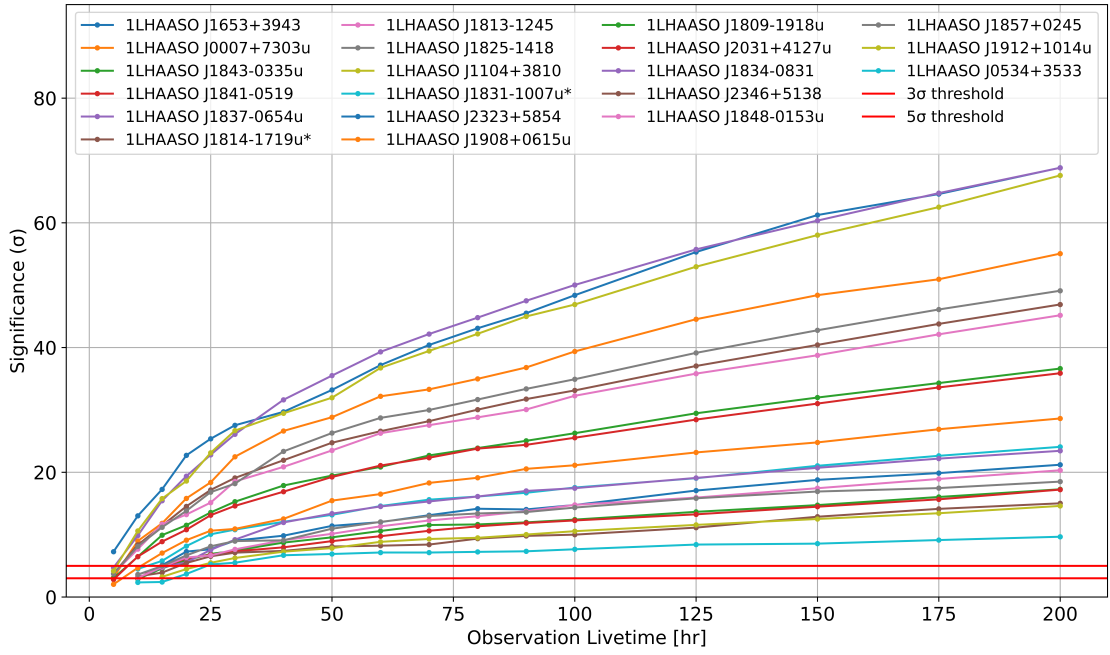


Figure 4.3: Simulated detection plot of the 20 LHAASO sources in the WCDA catalog with the fastest possible detection with ASTRI-3T.

by ASTRI-3T with the systematic survey described above. The 20 sources detectable with the smaller amount of observation hours are also shown in Figure 4.3, which attest to the capabilities of ASTRI-3T, and its ample choice of targets in the first phase of stereoscopic observations.

Among all the simulations that were systematically analysed, particular attention was devoted to identifying the regions of the sky where the most promising sources from the LHAASO catalog are concentrated. The evaluation was based on three main criteria: the speed of detection, expressed in terms of the minimum observation time required to reach a statistically significant signal, the brightness of the spectrum in the 1–25 TeV energy band, which is of primary relevance for the performance of ASTRI, and crucially the number of visible sources within a single FoV. The sources fulfilling these conditions define the regions of highest scientific interest, which are discussed in detail in the following section.

4.2 Relevant Scientific Case Studies

The analysis mentioned above highlighted three regions of particular interest that were selected as potential observational targets for ASTRI-3T. These regions present a combination of favorable observational characteristics and astrophysical relevance. As shown in Figure 4.4, their visibility from the ASTRI site is maximized during the summer months, approximately from May to October, when extended observing campaigns can be effectively scheduled. Therefore, the capability of ASTRI-3T to access these regions when LHAASO observations are hindered provides a unique opportunity to enhance

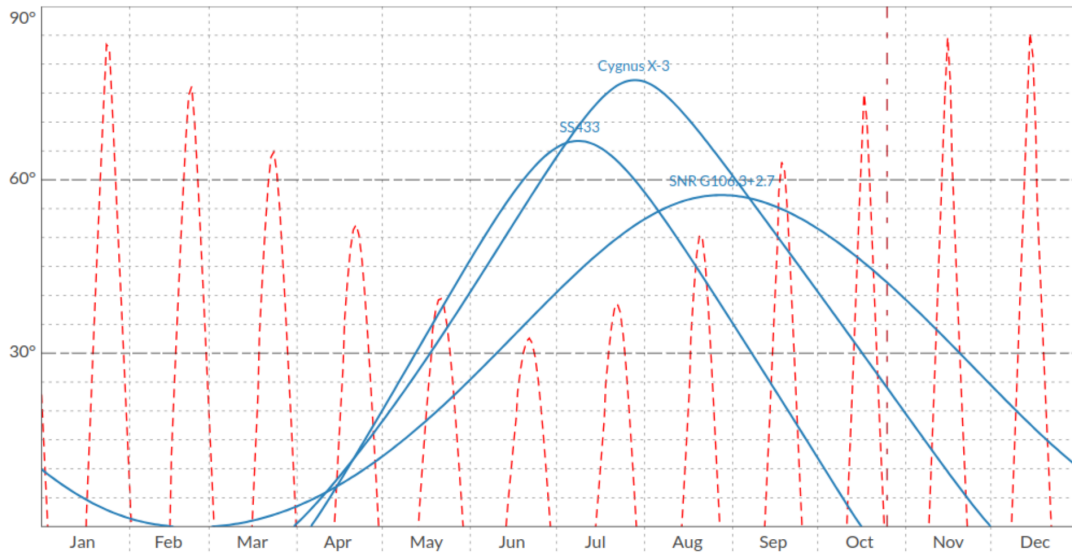


Figure 4.4: Visibility plot of the three regions identified as promising science cases with ASTRI-3T.

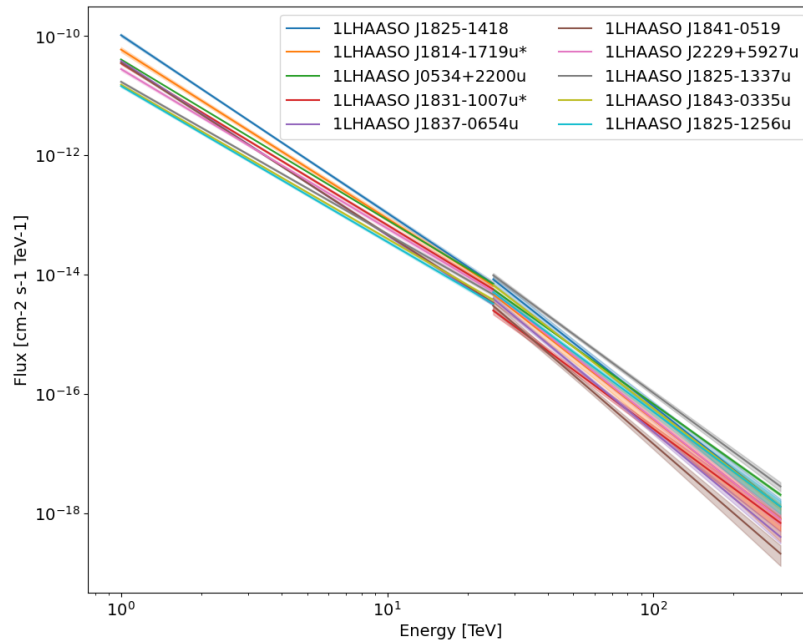


Figure 4.5: Spectra of the most luminous sources seen by the two main instruments of LHAASO: WCDA (range 1-25 TeV) and KM2A (>25 TeV).

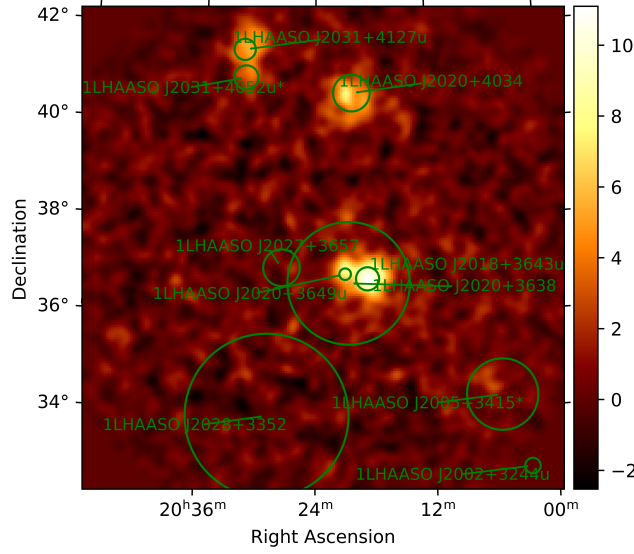


Figure 4.6: Excess map of the Cygnus region simulation. The circles indicate the position of all the sources from the LHAASO catalog simulated.

source coverage. Figure 4.5 shows the spectra of the brightest sources as measured by the two main LHAASO instruments, WCDA (1-25 TeV) and KM2A (> 25 TeV), and included in their respective catalogs. This combined view provides an overview of the spectral properties of the most prominent TeV emitters detected so far across the wide energy range covered by LHAASO. Among the first 10 most luminous of the sources, two are located within the three regions that have been identified as optimal observational targets for ASTRI-3T, namely 1LHAASO J2229+5927 in the region around the Boomerang Nebula and 1LHAASO J1908+0615u near the SS433 microquasar, thus reinforcing the scientific relevance of these regions.

4.2.1 The Cygnus Region

The Cygnus region is the first promising observation target, and it represents one of the most complex and intriguing areas of the very-high-energy sky, as visible in Figure 4.6. It hosts a large number of overlapping sources and extended structures, making it both scientifically compelling for morphological studies and observationally challenging. This area contains hot spots and molecular clouds associated with star-forming regions, as well as a variety of SNRs and PWNe. In particular, it has been suggested as a candidate site for a super PeVatron, capable of accelerating particles to energies of at least 10 PeV.

Among the most prominent sources in this region are the YMSC Cygnus OB2 (associated with 1LHAASO J2031+4052u*), which represents one of the largest stellar associations in the Galaxy. The SNR Gamma Cygni (1LHAASO J2020+4034) is another key object, providing evidence of hadronic acceleration in an environment rich in interstellar material. The pulsar PSR 1LHAASO J2032+4127 and its nebula (1LHAASO

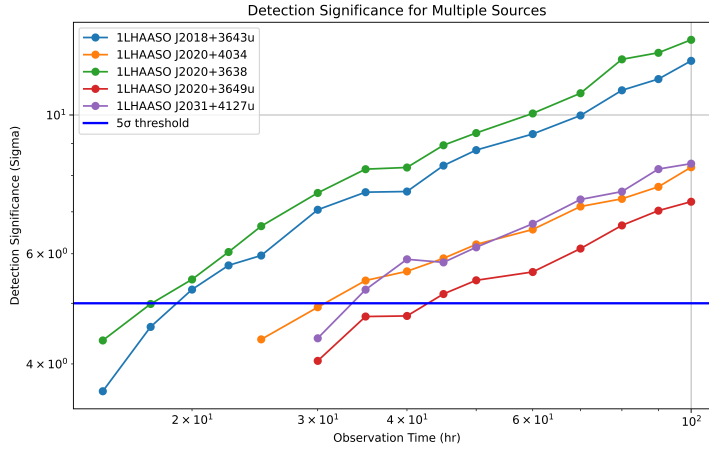


Figure 4.7: Simulated detection significance curves for all the LHAASO sources within a $10^\circ \times 10^\circ$ region centred on (75.89, 0.0616).

J2031+4127u) add to the complexity of the field, together with the nearby unidentified source 1LHAASO J2020+3649u, which coincides with VER J2019+368 and may be associated with extended particle acceleration phenomena. Other notable sources include 1LHAASO J2018+3643u (MGRO J2019+37), 1LHAASO J2020+3638, and the candidate PWN 1LHAASO J2005+3415*. The overall morphology of the region suggests the presence of a large-scale bubble structure encompassing multiple accelerators and interacting environments, but the better angular resolutions of next-generation IACTs is necessary to resolve the complex structure that characterise the region.

A major observational limitation for LHAASO is that the Cygnus region culminates in July, the most heavily affected period by monsoon conditions at the LHAASO site in Sichuan. This seasonal constraint highlights the potential for complementary observations, aided by the fact that most of the region can be observed with a single pointing thanks to the large FoV of the ASTRI telescopes, thus reducing the observation livetime needed. It should be noted that, with this preliminary analysis and according to the results displayed in Figure 4.7, five of the sources are already detectable with ~ 40 hours of observation. With a more dedicated source modellization and a background subtraction that better represents a complex region such as this, more could also be detected within a few tens of hours, and their morphology studied.

4.2.2 The Boomerang Nebula Region

The Boomerang region offers a different but equally interesting case for the study of Galactic particle accelerators. The primary source of interest is the Boomerang Nebula (G106.3+02.7, or 1LHAASO J2228+6100u), a peculiar SNR with a compact emission region ($\sigma \simeq 0.2^\circ$) that makes it one of the most fitting targets for extended morphological studies. Its morphology, shaped by interaction with dense interstellar material, has led to its characterisation as a cometary nebula, and it has long been considered a strong

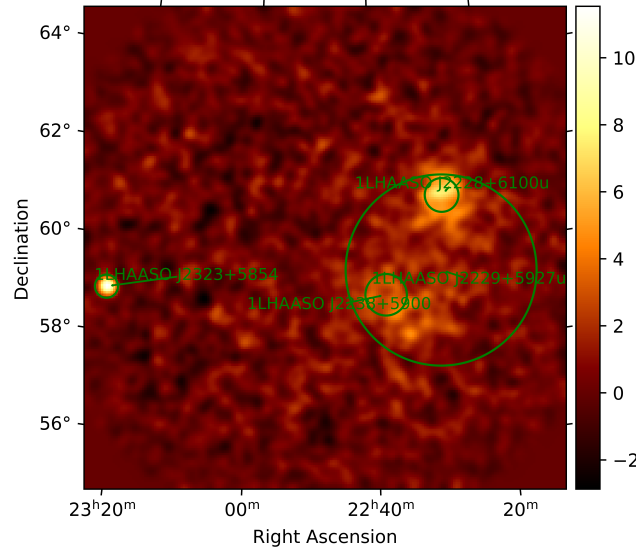


Figure 4.8: Excess map of the Boomerang region simulation. The circles indicate the position of all the sources from the LHAASO catalog simulated.

candidate for efficient hadronic acceleration. Unlike the more chaotic Cygnus field, the Boomerang region, shown in Figure 4.8, is dominated by a handful of distinct sources that can be observed simultaneously with the large FoV. Among these, the extended emission identified with 1LHAASO J2229+5927 ($\sigma \simeq 1.8^\circ$) stands out: its large angular size poses a challenge for both background subtraction and source modelling, yet its detection would provide key insights into the spatial distribution of particle acceleration beyond compact SNR shells. The pulsar wind nebula 1LHAASO J2238+5900 adds another interesting object in the field, exemplifying leptonic acceleration scenarios. Finally, the Cassiopeia A SNR (1LHAASO J2323+5854), although well studied, provides a valuable reference source.

The simulations show that, according to Figure 4.9, most of these objects can be firmly detected with tens of hours of exposure, with 1LHAASO J2228+6100u and Cassiopeia A reaching high detection significance relatively quickly, while the more diffuse J2229+5927 requires longer integration times. This diversity of source characteristics within a single pointing makes the region particularly appealing for testing the performance of the array under different observational conditions. In this sense, the Boomerang region can be seen as a natural bridge between targeted studies of individual remnants and the more complex, source-rich environments such as Cygnus.

4.2.3 SS 433 and Its Region

The field around SS 433 can be seen in Figure 4.10 and it represents the third and last environment that has emerged as possible for ASTRI-3T observations. SS433 itself is a well-known microquasar with prominent east and west jet lobes, which make it a benchmark system for the study of relativistic outflows interacting with the in-

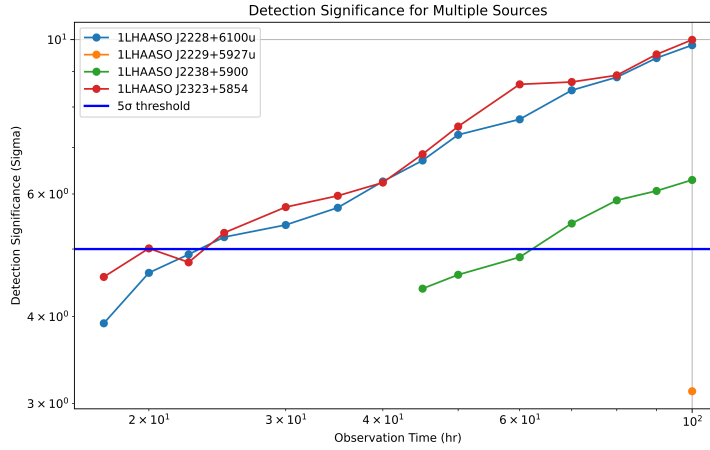


Figure 4.9: Simulated detection significance curves for all the LHAASO sources within a $10^\circ \times 10^\circ$ region centred on (108.07, 0.739).

terstellar medium. The lobes have luminosities individually detectable by ASTRI-3T with 20 hours of dedicated observations, and the system is angularly extended enough that can be resolved. These two factors make SS433 a particularly interesting microquasar to be observed at multi-TeV energies. This area is also home to 1LHAASO J1908+0615u, a leptonic source believed to be powered by PSR J1907+0602 and standing out as one of the brightest emitters detected by LHAASO in the multi-TeV band, as visible in Fig. 4.5. Its brightness, combined with the presence of multiple nearby sources, makes the region an ideal test for morphological disentangling and spectral modelling at very-high energies. Beyond these two prominent objects, the field is crowded with additional candidates: some are likely associated with pulsars such as 1LHAASO J1857+0245, 1LHAASO J1906+0712, and 1LHAASO J1913+1011, while many others remain uncertain or unidentified (e.g., 1LHAASO J1857+0203u, 1LHAASO J1858+0330, 1LHAASO J1902+0648, 1LHAASO J1907+0826). This mixture of established and unidentified emitters creates a complex observational scenario reminiscent of the Cygnus region, but with its own distinctive interplay of jets, pulsars, and extended structures.

The simulated detection significance curves (see Figure 4.11) show that several of these sources, and 1LHAASO J1908+0615u and both lobes of SS433 in particular, can surpass the 5σ threshold within tens of hours of exposure. This rapid rise in significance highlights the potential for efficient monitoring and follow-up campaigns. Conversely, fainter or more diffuse sources will require longer integrations, offering a natural gradient of observational challenges within a single pointing. Thanks to the wide field of view of the ASTRI Mini-Array, the entire SS433–J1908 region can be covered in a single observation as well, reducing the total time needed to achieve meaningful constraints on multiple objects simultaneously.

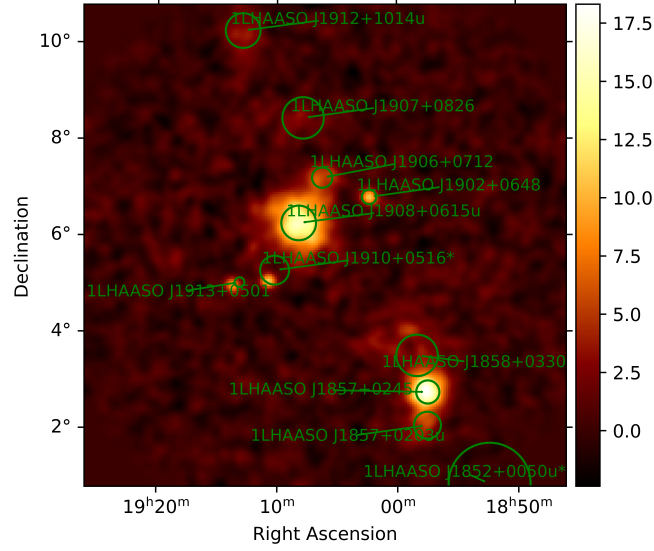


Figure 4.10: Excess map of the SS 433 region simulation. The circles indicate the position of all the sources from the LHAASO catalog simulated.

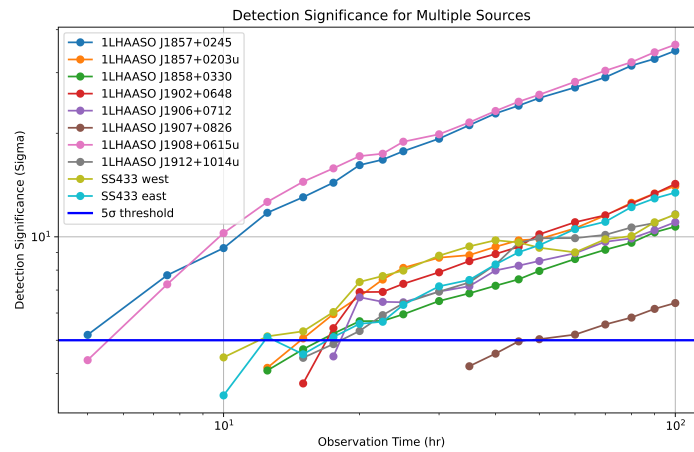


Figure 4.11: Simulated detection significance curves for all the LHAASO sources within a $10^\circ \times 10^\circ$ region centred on (39.752, -0.581).

Chapter 5

YMSCs as Galactic CR Sources

Both observational and theoretical evidence support the idea that the transition between galactic and extragalactic CRs occurs gradually across the energy range spanning from PeV to EeV. The results obtained based on the analysis of cosmic ray composition and shown in Figure 5.1 are that the mass of the primary particles increases beyond about 1 PeV, peaks in several hundred PeV, then falls, only to rise again, at the ankle energy [99]. This resultant picture matches that of a charge-dependent cut-off case, where galactically-accelerated particles reach their respective energy cut-offs, thus enriching the spectrum with more massive nuclei until a relatively lighter extragalactic component starts to dominate. The spectral structure of CRs also offers clues. The spectrum *knee* at ~ 3 PeV has long been a hallmark feature of the spectrum, and its concave shape necessitates fine-tuning if it is to be interpreted as the intersection of two unrelated components—galactic and extragalactic. As highlighted by [100], this tuning problem is particularly relevant well below the ankle. By contrast, the second knee around 0.5 EeV—being less pronounced and extending over a limited energy range—can more plausibly be attributed to the decline of heavy galactic CRs, as the extragalactic light component begins to emerge [101, 102]. Detection of a transition at several hundred PeV requires severe selection criteria for galactic CR accelerators. A large fraction, possibly up to 10-20%, should have the potential of accelerating heavy nuclei to such remarkable energy levels, which are equivalent to proton accelerations of more than 10 PeV [100]. Their exact properties are yet uncertain. Ordinary SNRs that are expanding through their ISM face essential difficulties in attaining PeV energy scales, even considering their potential for magnetic-field amplification via CR-driven instabilities [103, 28]. Such energy milestones are attained, if they are, only under extraordinarily rare conditions—i.e., in very young, fast-expanding remnants or cases of prolonged Bohm-like diffusion [104, 105, 106]. Only in such rare cases the uppermost attainable energy is believed to be able to reach PeV energies and therefore contribute to the CR spectrum at those energies.

In order to answer the question of what astrophysical objects can contribute to sustaining the CR flux at and around the *knee*, various alternative environments for galactic acceleration have recently been put forward. Among them are PWNe, microquasars, the

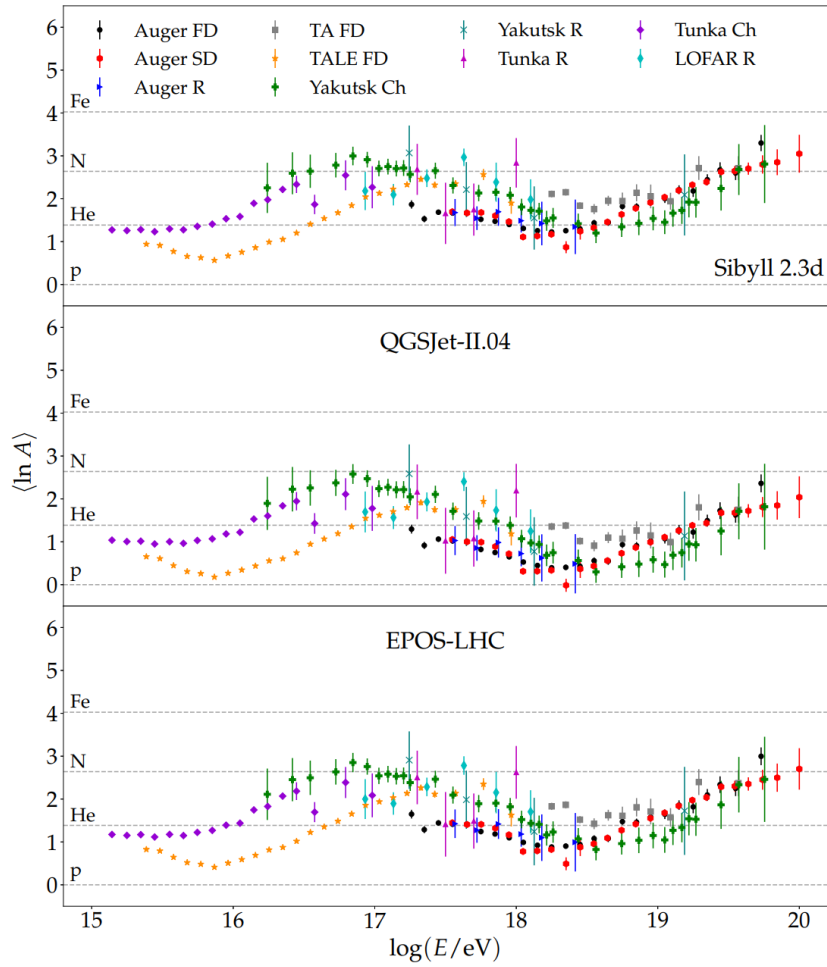


Figure 5.1: Mean logarithmic mass of CRs as a function of the energy according to various experiments and interaction models, from [99].

Galactic Centre, and acceleration processes connected to superbubbles associated with collective stellar feedback [107]. Specifically, young stellar populations that are strong winds emitters have attracted much interest in recent years, showing their potential to reach gamma-ray outputs in several hundred TeV [108, 22, 25]. Most frequently, star formation takes place in clustered environments, where powerful stellar winds excavate superbubbles in the MCs they are embedded in [109]. Here, CR acceleration can occur via several processes, including wind termination shocks [110, 57], turbulences [21, 111], and subsequent SN explosive events [112, 113, 114]. One of the most compelling reasons for a superbubble origin of CRs comes from the observed $^{22}\text{Ne}/^{20}\text{Ne}$ ratio in galactic CRs, which can easily be explained by enrichment due to Wolf-Rayet stellar winds [115].

5.1 γ -Ray Emission from YMCSs:

Highly energetic hadronic CRs, upon interacting with interstellar gas and radiation field backgrounds, produce secondary γ -ray photons with comparably high energy. For a while now, this γ -ray emission production process has been a strong motivator for looking for γ -ray activity around YMCSs (e.g. [57]). A previous detection in the direction of the Cygnus X star-forming region was made with an hypothesis-confirming result using the Fermi-LAT, wherein a spatially extended γ -ray structure (informally referred to as the *Cygnus cocoon*) was identified within the energy interval spanned between ≈ 1 GeV and several hundred GeV [48]. In following observations using Fermi-LAT thereafter, similar diffuse γ -ray emission has been observed around other YMCSs within the Milky Way and similar works with ground-based Cherenkov telescopes, still more sensitive at even higher energies (above 1 TeV), have also been reported with some significant detections. A few examples of systems emitting at TeV energies are:

- **The Cygnus region**, which is rich in TeV-scale γ -ray sources [116, 117] and notably hosts the Cygnus OB2 star association, characterised by high mass and luminosity. Cygnus OB2 is an important scientific case study for various reasons. Firstly, the detection by the LHAASO experiment [22] of a gamma-ray photon with energy over 1.4 PeV in spatial coincidence with the position of Cygnus OB2. This is an important hint on the existence of cosmic rays with energies over 10 PeV, hence qualifying Cygnus OB2 as a unique Galactic PeVatron candidate; furthermore, the diffuse gamma-ray emission has been investigated in depth, covering spectral analyses as well as morphological characterisations within an extremely broad energy spectrum, reaching the high energy domain ($1 \text{ GeV} < E_\gamma < 100 \text{ GeV}$) and up to the lower parts of the very-high-energies ($0.1 \text{ TeV} < E_\gamma < 100 \text{ TeV}$) [108, 22].
- **Westerlund 1**, a YMCS hosting numerous Wolf-Rayet stars and high-mass binaries, long considered a potential Galactic accelerator. Westerlund 1 has been associated with extended γ -ray emission first detected by the H.E.S.S. telescope array in the TeV domain [118], with a source morphology suggesting particle acceleration on parsec scales [25]. More recently, observations with Fermi-LAT have revealed

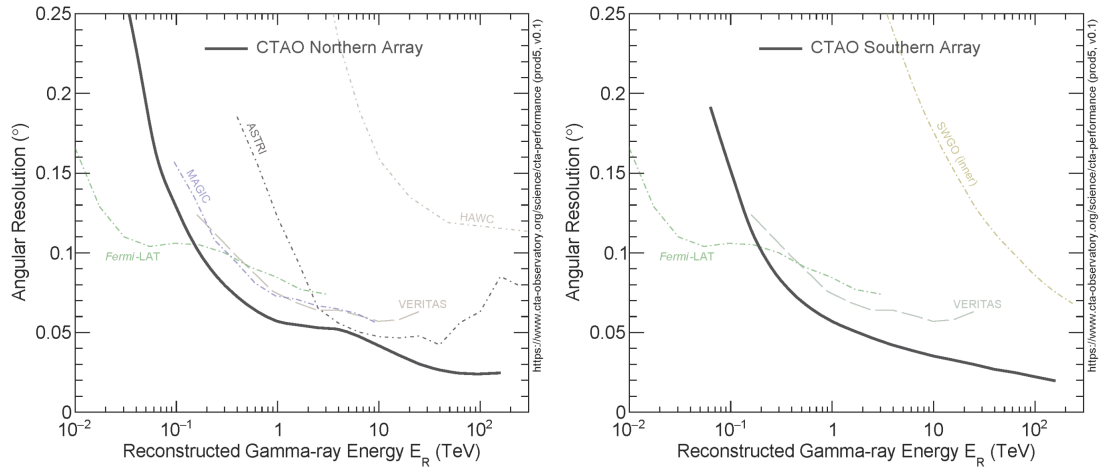
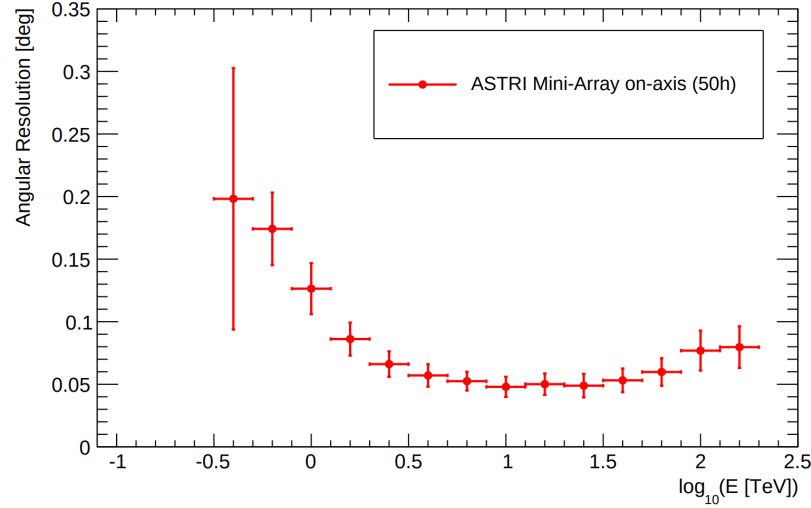
GeV-scale emission spatially coincident with the cluster region [119], strengthening the evidence for multi-TeV particle acceleration.

- **Westerlund 2**, another YMSC situated within the RCW 49 complex of star forming region, home to numerous O-type stars and binaries. High-energy γ -ray emission was first reported by the H.E.S.S. telescope array [120], revealing a spatially extended TeV source (HESS J1023–575) coincident with the cluster. Subsequent observations with Fermi-LAT confirmed GeV-scale emission [121], pointing to ongoing particle acceleration across a broad energy range.
- **30 Dor C** and its surrounding superbubble, located in the Large Magellanic Cloud, whose discovery is specifically interesting because of its large distance. It represents the first extragalactic superbubble detected in very-high-energy γ rays, observed by both H.E.S.S. and Fermi-LAT [122, 123].

Despite these findings, though, it remains uncertain whether the origin of the γ -ray emissions thus observed could be positively identified with the YMSCs themselves. Although the exact sites of cosmic-ray acceleration remain poorly constrained due to the limited angular resolution at high energies, and several YMSCs show strong evidence of hadronic cosmic-ray production, but a relevant leptonic contribution or hybrid models cannot be excluded. Another issue is the mixed nature of the production processes for the high-energy γ rays. In an hadronic scenario, the γ -rays result from the decay of the neutral pions (plus other short-lived objects) produced upon the collision between the surrounding matter and hadronic CRs. On the other hand, in a leptonic scenario, the accelerated high-energy electron and positrons could also produce γ -rays through IC scattering, namely boosting low-energy environmental photons to TeV energies. Crucially, differencing between these two scenarios requires both spectral and morphological analyses of the observed γ -ray emission. The morphological studies, in particular, will be possible with the next-generation of Cherenkov telescopes and spectral analyses must be complemented with multi-wavelength observations so that the origin of emission and involved physical processes could be constrained. With the progressive deployment and commissioning of new-generation IACT observatories such as the ASTRI Mini-Array and CTAO, it is anticipated that a growing fraction of the presently unidentified γ -ray sources may be classified as YMSCs, thereby shedding light on their role as potential cosmic-ray accelerators.

5.2 A Morphological Approach to Source Classification

The potential of these IACTs to characterise the morphology of YMSCs and resolve their gamma-ray emission can be examined in order to identify the main features with respect to other extended TeV sources with similar angular sizes, such as TeV halos. Clearly, classifying sources between different classes of astrophysical objects requires a very good angular resolution δl at TeV and multi-TeV energies, such as the one of the CTAO or

(a) CTAO angular resolution for both the Northern (*left*) and the Southern (*right*) sites.

(b) ASTRI-Mini Array angular resolution.

Figure 5.2: Angular resolutions of next-generation IACT facilities from [78] and [44].

ASTRI-Mini Array. While the single telescopes of the two facilities are expected to have $\delta l \sim 10^{-1} \text{deg}$, as shown in Figure 5.2 both the CTAO and ASTRI-Mini Array will reach $\sim 3 \text{ arcmin}$ once the complete arrays will be fully operational.

5.2.1 Motivation and Analysis Strategy

The first objective of the present study is to simulate the spatially extended emission of the YMSCs in the TeV gamma-ray energy range. The analysis presented here relies on the assumption that YMSCs are powerful cosmic-ray accelerators in conjunction with their powerful stellar winds, as well as with supernova feedback, to show how spectromorphological studies in the TeV energy scale can provide an integral role in revealing high energy acceleration mechanisms for these complex systems.

Initial analyses of a restricted sample of bright and extended regions around known YMSCs revealed recurring morphological features in their TeV morphology. When com-

pared to TeV halos, these features proved to be defining characteristics of YMSCs and are useful to separate between these two classes of sources. Such results prompted the development of a methodological approach to consistently classify unidentified sources in order to uncover the astrophysical nature of galactic extended sources. The methodologies described were then tested on the sources of the first LHAASO catalog [26] to estimate the performances of the CTAO and the ASTRI-Mini Array in associating unclassified emission with YMSCs.

5.3 The Sample

The aim being probing emission up to 100 TeV, simulations assuming observations with SSTs located in the most suitable hemisphere for each source were performed. Specifically, the YMSCs situated in the northern sky are modelled using the IRFs of the ASTRI Mini-Array, while sources located in the southern hemisphere the IRFs of the CTAO Southern Array are employed. The physical characteristics of the following sample of YMSCs are summarised in Table 5.1:

- Cygnus OB2:** it is one of the most massive and compact OB associations in the Milky Way that harbors hundreds of massive stars [124]. It is located towards the centre of the Cygnus-X star forming complex ($l \approx 80.22^\circ, b \approx 0.79^\circ$), an extended radio structure hosting numerous MCs [125], HII regions and OB stars [126]. Several studies have assessed Cygnus OB2's age (e.g. [127], [128] and [129]), leading to estimates based on the stellar population. O-type dwarfs' and blue supergiants' presence entail a young age of about 2 ± 1 Myr [129]. X-ray surveys aimed at low-mass stars propose an in-between age of 3–5 Myr [130]. More recent modelling based on both rotating and non-rotating stellar tracks of evolution identified common ages in the range from 2 to 4 Myr, consequently supporting the star formation hypothesis persisting over the last ~ 7 Myr, with a maximum about 4 Myr ago [131, 132, 131].
 The exact distance in Cygnus OB2 continues to be considerably uncertain. Previous estimates have ranged between 1300 and 2100 pc. Traditionally, a commonly adopted value of 1400 ± 80 pc, based on spectroscopy, has been adopted by [129] and agrees with maser parallax observations for neighboring MCs [133]. In this work, the distance was based on Gaia DR2 data, which suggest a complicated setup with two main subgroups and an average distance of 1600 pc [134, 135].
- Westerlund 1:** it is the most massive young stellar cluster currently known in the Milky Way (the estimated mass is $\sim 10^5 M_\odot$ [136, 137]) and it has already been studied with HESS data [138]. Discovered by [139], it is located at ($l \approx 339.54^\circ, b \approx -0.40^\circ$) [137], and has a compact structure with a half-mass radius of about 1 pc. Westerlund 1 harbours a rich and evolved stellar population, including a notable fraction of known Galactic Yellow Hypergiants [136] and Wolf-Rayet stars [140].

The cluster age is uncertain, due to the complicated history of star formation. Various studies point towards an age interval of 3–5 Myr [136, 140, 137]; yet, fresh data suggest the presence of earlier constituents with an age near 10 Myr [141]. For this research, mid value of 4 Myr was chosen, consistent with [142].

The distance of Westerlund 1 has been a source of significant debate. Early estimates placed this distance at roughly 4 kpc [136, 143] and later studies based on Gaia data have come up with similar results [144, 145]. However, some estimates placing the distance near 2.7 kpc have also been put forward [146, 147], though the suitability of the Gaia DR2 data in an area so densely populated has come under question [148]. In this work, a distance of 3.9 kpc was adopted, consistent with [25].

- **Danks 1 and Danks 2:** these two YMSCs lie near the centre of the G305 H II complex ($l \approx 305.34^\circ$, $b \approx 0.07^\circ$ and $l \approx 305.39^\circ$, $b \approx 0.09^\circ$ for the two clusters, respectively), one of the most important star-formation sites in the Milky Way. A mean distance of about 3.8 ± 0.6 kpc was estimated for them with both spectrophotometric techniques and with kinematic estimates. Both belong to a heterogeneous environment with stellar populations that represent many different aspects of evolutionary development from deeply embedded protostars to late Wolf-Rayet stars [149].

Spectroscopic analysis of the stellar populations reveals that Danks 2 is the older of the two clusters with an age estimate of 3_{-1}^{+3} Myr, compared to Danks 1, a considerably younger cluster with an age of $1.5_{-0.5}^{+1.5}$ Myr [149]. The comparatively younger cluster, Danks 1, is more compact and more massive ($8000 \pm 1500 M_\odot$), and is one of most compactly formed clusters discovered in the Galaxy with a density of roughly $\log(\rho/M_\odot \text{ pc}^{-3}) \approx 5.5$ [149]. In contrast, Danks 2, with its larger age, is less massive ($3000 \pm 800 M_\odot$)

The chronological order of star formation evolution for the G305 region begins with Danks 2, followed by Danks 1, with the stellar feedback from the previous cluster most likely determining a pivotal role. A significant complement of detached multi-massive stars, mostly of Wolf-Rayets, also fill out the entire region, thus introducing further sophistication to the formation scenario.

- **Markarian 50:** This quite young star cluster lies in the H II region Sh 2-157. It is situated along our Galaxy's Perseus arm, with Galactic coordinates of ($l = 111.36^\circ$, $b = -0.20^\circ$). It was identified as a main source of excitation for nearby nebulae [150]. Its distance was estimated as being 3460 ± 350 pc.

The cluster harbors a Wolf-Rayet star (HD 219460), a member of a closely tied binary. Isochrone fitting analysis gives an age estimate of 7.5 ± 2 Myr. The value of its initial mass function from that diagram translates approximately to $x \approx 1.0$, slightly below that (Salpeter value) usually taken for a standard initial mass function, hence agreeing with other relatively young open cluster observations [150]. Observational nucleus/corona structure most likely reflects star formation

Table 5.1: Main parameters of the YMSCs studied in this work. For each YMSC the columns contain the name, the distance of the object from the Sun (Cyg: [152, 134], Wd1: [138], Dk1 & 2: [149], Mrk50: [150]), its age (Cyg: [127, 128, 129], Wd1: [141, 153], Dk1 & 2: [149], Mrk50: [150]), and its luminosity ([55]), respectively.

Cluster Name	Distance (kpc)	Age (Myr)	L_{kin} (erg s ⁻¹)
Cygnus OB2	1.6	1–6	2×10^{38}
Westerlund 1	3.9	3–10	1×10^{39}
Danks 1	3.8	1.5	8×10^{37}
Danks 2	3.8	3	7×10^{37}
Markarian 50	3.4	7.5	9×10^{36}

history more than dynamical evolution. In addition, its proximity with NGC 7510 and Cas OB2 raises a possibility that a sequential star formation event has taken place along this portion of the Perseus arm [151].

5.4 Modelling the Sources

This section briefly describes the models adopted for the simulations of all sources considered, both YMSCs and TeV halos.

5.4.1 YMSCs Model Production

The following work was based on the Morlino et al. model [52] as described in Section 1.5.5, in order to model the $\sim 10 - 100$ pc region around the centre of each source,. According to the model, the fast collective cluster wind impacting on the surrounding large-scale wind-blown bubble of material produces a strong termination shock at which particle acceleration may occur. Their work addresses the mechanisms by which relativistic particles—primarily protons—are accelerated and subsequently produce the high-energy gamma-ray emission detected around YMSCs through interactions with ambient matter. Given the growing speed of the wind-powered bubble, one can reasonably treat the system as being stable. The size of the bubble R_b that is excavated by the collective winds around each YMSC and the termination shock radius are therefore constant in time and they can be computed as [25, 60]:

$$\begin{aligned}
 R_b(t) &= 112 \left(\frac{\eta_m L_{w,c}}{10^{37} \text{ erg s}^{-1}} \right)^{1/5} \left(\frac{n_0}{10 \text{ cm}^{-3}} \right)^{-1/5} \left(\frac{t}{10 \text{ Myr}} \right)^{3/5} \text{ pc} \\
 R_{ts}(t) &= 26 \eta_m^{-1/5} \left(\frac{\dot{M}_c}{10^{-4} M_\odot \text{ yr}^{-1}} \right)^{3/10} \left(\frac{v_w}{2000 \text{ km s}^{-1}} \right)^{1/10} \\
 &\quad \left(\frac{n_0}{10 \text{ cm}^{-3}} \right)^{-3/10} \left(\frac{t}{10 \text{ Myr}} \right)^{2/5} \text{ pc.}
 \end{aligned} \tag{5.1}$$

Here, L_w and v_w are the YMSC wind luminosity and velocity in erg s⁻¹ and km s⁻¹, respectively, $\rho_H = n_H m_p$ is the gas density around it (n_H is the particle density in cm⁻³

and m_p is the proton mass) and t_{age} is the age of the YMSC in Myr. η_m is the mechanical efficiency and it represents the fraction of wind energy converted into effective mechanical energy which can inflate the bubble. In the case of an adiabatic scenario, $\eta_m = 1$ and the values of R_b and R_{ts} reduce to:

$$\begin{aligned} R_b &= 0.88 L_w^{0.2} \rho_H^{-0.2} t_{\text{age}}^{0.6} \text{ pc} \\ R_{ts} &= 0.92 L_w^{0.3} v_w^{-0.5} \rho_H^{-0.3} t_{\text{age}}^{0.4} \text{ pc}. \end{aligned} \quad (5.2)$$

Under the stationary R_b and R_{TS} hypothesis, where spherical geometry is assumed and stochastic (second-order Fermi) acceleration as well as dissipation of energy are disregarded, the CR distribution function $f_{\text{CR}}(r, E)$, a function of the distance from the centre of the cluster and the particle energy, will be governed by a steady-state transport equation. This equation will include equilibrium within transport process schemes such as diffusion, advection, momentum alterations as a result of compression, as well as those connected to source injection:

$$\frac{\partial}{\partial r} \left[r^2 D(r, p) \frac{\partial f}{\partial r} \right] - r^2 u(r) + \frac{d}{dr} [r^2 u(r)] \cdot \frac{p}{3} \frac{\partial f}{\partial p} + r^2 Q(r, p) = 0. \quad (5.3)$$

Here, $u(r)$ refers to the velocity of radial outflow, while $D(r, p)$ represents a coefficient of diffusion that can change with spatial parameters as well as with the momentum of the particles. The final term, $Q(r, p)$, is a source function that represents the influx of recently accelerated particles. In the specific case of injection at the termination shock, along with supersonic outflow from the YMSC, most source terms are expressed by a delta function valid for spatial positions as well as momentum and $Q(r, p)$ becomes:

$$Q(r, p) = \frac{\eta_{\text{inj}} n_1 u_1}{4\pi p_{\text{inj}}^2} \delta(p - p_{\text{inj}}) \delta(r - R_{\text{TS}}), \quad (5.4)$$

where n_1 stands for particle number density upstream of the termination shock formation site, u_1 is the radial velocity corresponding to the colder stellar wind, the injection efficiency parameter η_{inj} represents the ratio of accelerated to total particles and thus is the injection efficiency, and R_{TS} is the termination shock radius. Solving Equation 5.3 with appropriate boundary conditions allows for the determination of the CR distribution throughout the system. In the main zones (i.e. in the wind-driven region for $r < R_{TS}$ and in the DSA zone for $r < R_b$), the CR distribution is:

$$f_1(r, p) \simeq f_{\text{TS}}(p) \cdot \exp \left[- \int_r^{R_{\text{TS}}} \frac{u_1}{D_1(r', p)} dr' \right], \quad (5.5a)$$

$$f_2(r, p) = f_{\text{TS}}(p) e^\alpha \left(\frac{1 + \beta(e^{\alpha_B - \alpha} - 1)}{1 + \beta(e^{\alpha_B} - 1)} \right) + f_{\text{gal}}(p) \left(\frac{\beta(e^\alpha - 1)}{1 + \beta(e^{\alpha_B} - 1)} \right), \quad (5.5b)$$

where the following definitions apply:

$$\alpha(r, p) = \frac{u_2 R_{\text{TS}}}{D_2(p)} \left(1 - \frac{R_{\text{TS}}}{r} \right), \quad \alpha_B = \alpha(r = R_b, p), \quad \beta(p) = \frac{D_{\text{ism}}(p) R_b}{u_2 R_{\text{TS}}^2}. \quad (5.6a)$$

Table 5.2: Wind velocities assumed for each YMSC and their computed bubble sizes R_b and termination shock radii R_{ts} in pc and degrees around YMSCs.

Cluster Name	Wind Speed (km s ⁻¹)	R_b (pc)	R_{ts} (pc)	R_b (°)	R_{ts} (°)
Cygnus OB2	2500	97.1	15.2	3.47	0.55
Westerlund 1	3000	159.3	25.2	2.36	0.38
Danks 1	3000	53.4	8.0	0.81	0.12
Danks 2	3000	78.8	10.1	1.19	0.15
Markarian 50	3000	90.5	7.9	1.53	0.13

f_{TS} is the distribution of injected particles at the termination shock and can be expressed as:

$$f_{TS}(p) \approx \frac{3n_1 u_1^2 \epsilon_{CR}}{4\pi \Lambda_p (m_p c)^3 c^2} \left(\frac{p}{m_p c} \right)^{-s} \left[1 + a_1 \left(\frac{p}{p_{max}} \right)^{a_2} \right] e^{-a_3 (p/p_{max})^{a_4}} \quad (5.7)$$

where:

$$\Lambda_p = \int_{x_{inj}}^{\infty} x^2 f_{TS}(x) \left(\sqrt{1+x^2} - 1 \right) dx, \quad x = p/m_p c. \quad (5.8)$$

The maximum momentum p_{max} is related to the maximum achievable momentum (or energy) in the system through

$$\frac{D_1(E_{max})}{u_1} = R_{TS}. \quad (5.9)$$

When computing the CR flux across the systems described in 5.3, a wind velocity of 3000 km s⁻¹ was assumed, following the assumptions of the [52] model. Mass losses and gas density around the YMSCs of $10^{-4} M_{\odot} \text{ yr}^{-1}$ and 10 cm^{-3} respectively were assumed. Wind luminosities were taken from [55]. The YMSCs in the sample exhibit a compact structure, which is likely to enhance the formation of powerful collective winds resulting from the interaction and merging of individual stellar winds [154]. Cygnus OB2 was treated as the only exception, because the its massive OB stars are likely more widely separated compared to the ones in the other, more compact systems. This causes their stellar winds merging to occur after a significant deceleration [155]. Following the parameter values adopted in [25], a wind velocity of 2500 km s⁻¹ was therefore assumed. The physical parameters of Table 5.1 were used to calculate the size of the region of interest around each YMSC R_b , and the size of the termination shock radius R_{TS} . The resulting radii (both in pc and in °) are shown in Table 5.2.

When radiative cooling losses are taken into account, the mechanical efficiency of the cluster wind tends to decline, as demonstrated by numerical simulations (e.g., [156]). This reduction is influenced by both the YMSC age and the ambient gas density. According to Equation 5.1, lower mechanical efficiency values correspond to smaller bubble radii and larger termination shock sizes. In scenarios where efficiency becomes very low, the termination shock can expand to the edge of the bubble and collapse. For this reason, the analysis was restricted to cases where $\eta \geq 0.1$. Taking Westerlund 1 as an example, the way the bubble and termination shock radii vary with different mechanical

η_m	R_b (pc)	R_{ts} (pc)	R_b ($^\circ$)	R_{ts} ($^\circ$)
0.10	102.4	27.4	1.54	0.41
0.25	123.0	22.8	1.85	0.34
0.50	141.3	19.9	2.13	0.30
0.75	153.3	18.3	2.31	0.28
1.00	162.4	17.3	2.45	0.26

Table 5.3: Computed sizes of R_b and R_{ts} around Westerlund 1 for different η_m values.

efficiency values of η_m was further examined. These results are reported in Table 5.3.

The gamma-ray emission from the bubble region was then calculated using the **Naima** library [157]. The proton spectrum, derived throughout the region using Equations 5.5a and 5.5b, was converted into the corresponding secondary gamma-ray emission spectrum. This process relied on modelling gamma-ray production primarily through *proton-proton* (p-p) interactions, which result in the creation and subsequent decay of neutral pions, producing photons with energies above 100 MeV. **Naima** computes this pion-decay radiation using the **PionDecay** class, which implements the analytical parametrizations developed by [158]. These parametrizations are based on a combination of Monte Carlo simulations and experimental accelerator data, providing a consistent and accurate description of the gamma-ray energy spectra and production rates across a broad energy range. The **hiEmodel** parameter allows users to select among different high-energy models, including direct fits and Monte Carlo results. A four-dimensional model was constructed to describe the gamma-ray emission within a three-dimensional spherical volume as a function of photon energy. The spatial distribution of the flux was calculated on an angular grid finer than the resolution of the observing instruments (approximately $2.5'$), to ensure accurate simulation of observational data. Along the energy axis, the gamma-ray flux was computed in 100 logarithmically spaced bins spanning the $0.1\text{--}10^4$ TeV range.

5.4.2 TeV Halos Modelling

The TeV halos around Geminga and Monogem were selected as comparable sources to YMSCs in angular extension and energetics, though the origin of the emission is believed to be leptonic in origin. Thanks to prolonged observations performed by multiple Cherenkov facilities, these halos can be modelled using observational gamma-ray radiation profiles. In the present work, the following profile from [40] was used:

$$\frac{d^2N}{dEd\Omega} = N_0 \left(\frac{E}{20 \text{ TeV}} \right)^{-\alpha} \frac{1.22}{\pi^{3/2}\theta_d(E)(\theta + 0.06\theta_d(E))} e^{-\theta^2/\theta_d(E)^2}, \quad (5.10)$$

where N_0 is the flux normalization at 20 TeV, Ω denotes a solid angle and θ_d is a diffusion angle proportional to the square root of the diffusion coefficient and is of the order of a

few degrees:

$$\theta_d \equiv \frac{180^\circ}{\pi} \cdot \frac{r_d}{d_{\text{src}}}. \quad (5.11)$$

Here, d_{src} is the distance of the source from Earth, while the diffusion radius r_d and the diffusion coefficient $D(E)$ are:

$$r_d = 2\sqrt{D(E_e)t_E} \quad D(E_e) = D_0 \left(\frac{E_e}{10 \text{ GeV}} \right)^{1/3}, \quad (5.12)$$

where t_E is the smaller of two timescales: the injection time (in this case the age of the pulsar), or the cooling time (i.e. the lifetime of the electrons in the interstellar medium after synchrotron and inverse Compton losses). The function in Equation 5.10 represents the best spatial and spectral morphology fit to the emission profiles of the halos around both pulsars obtained using a maximum likelihood technique. The underlying model was developed using data that ranged over the 8–40 TeV range, and its validity was extended to cover the full energy range used in the simulations. The same function was used to compute a 3d model with the same spatial and spectral requirements as the ones used for the 4d YMSCs models.

5.5 CTAO and ASTRI Mini-Array Simulations

The 4d YMSC models and the 3D TeV halo models described above were adapted to be compatible with the **Gammapy** software package, and then used to carry out simulations of gamma-ray observations. The simulations were run in the 1 to 200 TeV range of energies for both classes of astrophysical objects. Observations of the YMSCs were performed using the full ASTRI Mini-Array (9 telescopes) IRF [96], along with the IRFs for the CTAO southern site at a 20° zenith angle [78]. All results reported in this work were obtained assuming a total live-time of 200 hours, with sources positioned on-axis. Each YMSC was simulated separately, with the exception of Danks 1 and Danks 2, which were also modelled together due to their close angular separation (0.05°).

For every simulation, non-astrophysical background components were also included, comprising cosmic-ray and atmospheric diffuse backgrounds and field-specific and instrumental sky backgrounds. The components were modelled with appropriate functions available from the **Gammapy** package. All the simulations have been performed for an $8 \times 8 \text{ deg}^2$ field of view in order to ensure that the entire angular coverage of each YMSC fell inside the simulation region and have been stored in **MapDatasets**.

5.5.1 Excess Counts Profiles Analysis

To investigate how the sources would appear in gamma-ray observations, an analysis of their radial emission profiles was conducted. These profiles represent the gamma-ray signal intensity as a function of angular distance from the source centre. The goal was to parameterise and compare the spatial behaviour of the YMSCs and the TeV halos. To

this end, the excess emission maps, which correspond to background-subtracted gamma-ray count distributions, were particularly relevant. The excess counts per square degree were calculated by correcting the raw counts in each annular bin of the radial profile for the area of the corresponding ring centred on the emission peak. Additionally, a correction was applied for the variation in effective area across the simulated field of view by taking into account the instrument response function in each pixel of the simulated count map.

The source position used as the profile centre was estimated differently depending on the morphological characteristics of the simulated object. For TeV halos, the peak of the gamma-ray emission distribution was used, reflecting their typical spatial structure. In contrast, for YMSCs, which are assumed to exhibit spherical symmetry given the adopted model, the barycentre of the emission was chosen as the central reference point. The characteristic angular extent of each source was quantified by computing the 90% containment radius (r_{90}), defined as the radius of a circular region enclosing 90% of the total excess counts. This metric serves as an effective measure of the observed source size. To facilitate a direct comparison between different source types, the amplitude of each radial profile was normalized by dividing by its maximum value, allowing the profiles to be plotted on the same scale. The full radial profiles were derived by summing the simulated gamma-ray emission over the entire 1–200 TeV energy range. These are presented in Figure 5.3. For further comparative analysis, the radial coordinate was rescaled by r_{90} , such that all profiles fall within the normalized interval $0 < r/r_{90} < 1$. Two functional forms were considered as candidate fits for describing the radial behaviour of the emission:

$$f_g(r; r_p, N, a, w) = N \exp \left\{ - \left[\frac{(1 + e^{a(r-r_p)})}{w} (r - r_p) \right]^2 \right\}, \quad (5.13)$$

$$f_l(r; r_p, N, a, w) = \frac{N}{1 + \left(\frac{r-r_p}{w} \right)^2} [1 + a(r - r_p)^2]. \quad (5.14)$$

Two functional forms were adopted to fit the normalized radial profiles. The first consists of a Gaussian distribution modified to incorporate peak asymmetry, while the second is based on a Lorentzian profile and is designed to better capture extended tails in the emission—features that are often prominent in the morphology of spatially extended gamma-ray sources. Both functions are expressed in terms of a normalization factor (N), a width parameter (w), and a peak position (r_p), all defined in units of the 90% containment radius. An additional parameter, a , was introduced to quantify the asymmetry of the curve relative to its peak.

The complete results of the fits can be found in Table 5.4. Both functions are fitted to the simulated data, as shown by the reduced χ^2 values. Though the use of the modified Lorentzian leads to better χ^2 values for the radial profiles of both YMSCs and TeV halos, the modified Gaussian function results in a better fit in the case of the Markarian

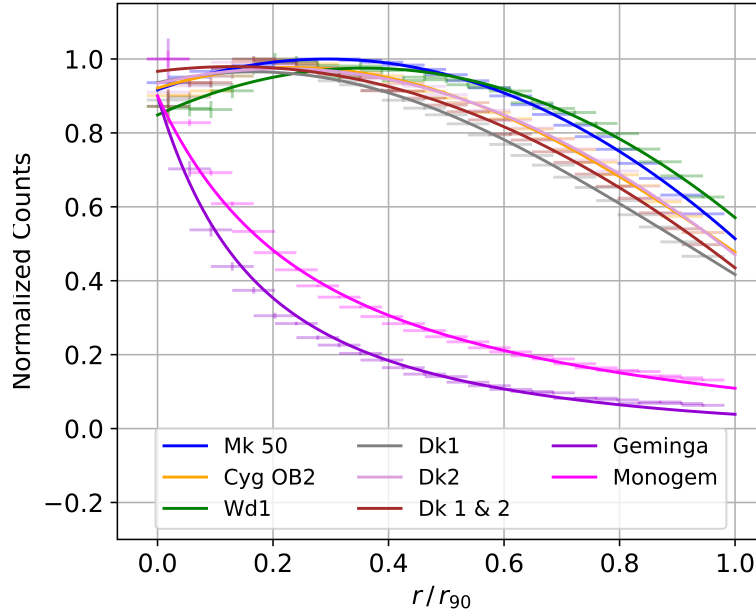


Figure 5.3: Gamma-ray emission radial profiles as a function of the distance from the centre for all YMSCs and TeV halos in the sample. The profiles have been rescaled by dividing by the maximum of their radial emission for clarity of comparison. Here the data are fitted with the better fitting function (i.e. the modified Gaussian or the modified Lorentzian) for each object, according to the relative χ^2 values in Table 5.4.

Table 5.4: Fit parameters for the simulated data using both fitting functions. The data have been binned into 50 intervals between the centre of each source and its 90% containment radius so that the bin width roughly corresponds to the angular resolution of the ASTRI Mini-Array and the CTAO. The reduced χ^2 have been calculated over the number of degrees of freedom $n_{\text{dof}} = 46$.

Source	χ_g^2	$r_{p,g}$	a_g	χ_l^2	$r_{p,l}$	a_l
Cygnus OB2	1.84	0.11 ± 0.07	1.0 ± 0.1	1.16	0.25 ± 0.02	-0.98 ± 0.03
Westerlund 1	0.28	0.2 ± 0.1	1.9 ± 0.2	0.82	0.37 ± 0.01	-1.28 ± 0.09
Danks 1	1.22	0.10 ± 0.06	0.7 ± 0.1	0.81	0.20 ± 0.03	-0.81 ± 0.03
Danks 2	0.81	0.10 ± 0.07	1.1 ± 0.1	0.99	0.23 ± 0.01	-0.95 ± 0.03
Danks 1 & 2	1.37	0.10 ± 0.06	1.0 ± 0.1	1.13	0.19 ± 0.02	-0.93 ± 0.02
Markarian 50	7.25	0.282 ± 0.005	0.80 ± 0.05	11.42	0.312 ± 0.004	-0.99 ± 0.04
Geminga	5.96	0.00 ± 0.08	-3.1 ± 3.1	0.90	0.00 ± 0.05	1.7 ± 0.6
Monogem	54.93	0.01 ± 0.04	-2.4 ± 2.5	2.63	0.00 ± 0.04	2.6 ± 0.5

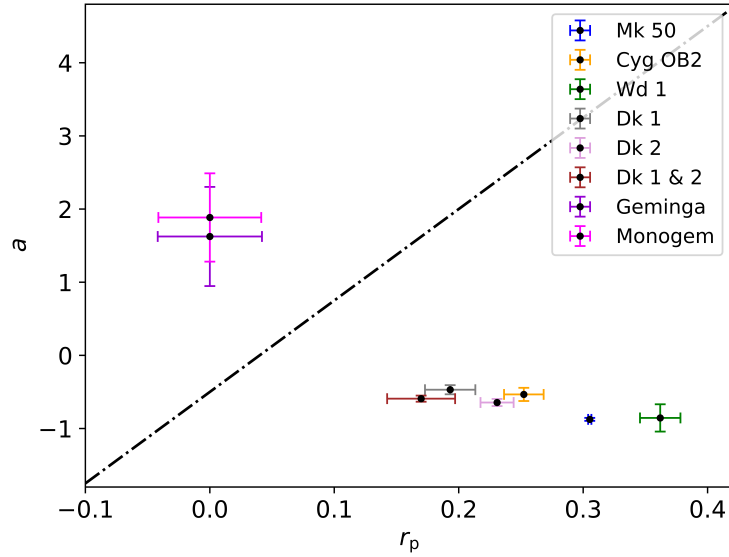


Figure 5.4: Values of the curve anisotropy and emission peak position in units of r_{90} obtained with the modified Lorentzian fit to the data. In all the cases studied, YMSCs display lower a values and higher r_p values, positioning themselves in the lower-right corner. On the other hand, TeV halos are on the opposite corner of the plot, in a region ideally above the dot-dashed line.

50 YMSC. All the profiles of the YMSCs show a similar behaviour, characterised by an emission peak at larger distances from the centre of the systems with respect to TeV halos.

5.6 Classification Methodologies

Among the parameters obtained from the profile fitting procedure, the anisotropy parameter (a) and the peak position (r_p) emerge as particularly effective in distinguishing between the two classes of sources considered in this study. As illustrated in Figure 5.4, in the case of the modified Lorentzian function, the combined use of these two parameters provides a potentially robust diagnostic for classifying unidentified sources as either YMSCs or TeV halos based solely on their morphological characteristics. While the emission peak position may exhibit some variation depending on the specific physical conditions of the YMSCs, the anisotropy parameter consistently offers a reliable means of characterising source morphology and assessing its likely origin. A similar trend is observed when employing the modified Gaussian function for profile fitting, although in this case the anisotropy parameter a is generally less well constrained. Nonetheless, YMSCs tend to exhibit lower values of a and higher values of r_p , reinforcing their distinct morphological signature.

Radial integrated excess profiles show yet another way of obtaining morphological data and are potentially exploitable as a follow-up tool of classification of undetected

Table 5.5: Areas between the reference curve and the integrated profiles for the considered sources. Positive areas indicate that the profile curve is below the reference function $f_r(r)$, while negative areas indicate it is above.

Object	Area
Mk 50	0.045
Cyg OB2	0.040
Wd 1	0.054
Dk 1	0.034
Dk 2	0.040
Dk 1 & 2	0.039
Geminga	-0.062
Monogem	-0.027

YMSCs. Figure 5.6 shows the cumulative excess counts of each YMSC and TeV halo. The same normalization technique used on the differential profiles has been employed here for the sake of comparison consistency. The Geminga and Monogem integrated profiles vary significantly from those of YMSCs, whose cumulative numbers have more rapid increase at smaller radii. The fact is indicated by the presence of the two groups of sources co-existing in separate areas of the cumulative profile parameter space. A reference curve, indicated by a dot-dashed curve in Figure 5.6, was chosen to characterise these areas. The function that produces two plane sectors is as follows:

$$f_r(r) = -0.8 r^3 + 1.5 r^2 + 0.2 r. \quad (5.15)$$

The area differences between the reference curve and the integrated profile of each source:

$$A_i = \int_0^1 f_r(r) dr - \int_0^1 f_i(r) dr \quad (5.16)$$

are listed in Table 5.5 and serve as an indication of the confidence in source classification. In the present case, all sources are correctly classified, with positive values for all YMSCs and negative values for the Geminga and Monogem TeV halos.

5.7 Morphology Dependence on Mechanical Efficiency

The previous observation simulations assume a $\eta_m = 1$. As stated in Section 5.4.1, this is only valid if the adiabatic losses are negligible. According to recent studies, this is not likely to be the case for at least some of the observed YMSCs, whose bubbles appear smaller than what would be predicted if all the wind energy were converted to mechanical energy and contributed to inflate the bubble. Figure 5.5 shows how radiative losses, which are proportional to the medium density, cause the mechanical efficiency to decrease with an increasing density. The black solid line shows the $n_{g0}^{-2/3}$ scaling of η_{mech} , which describes well the variation of mechanical efficiency with the ambient density at almost all times. While higher N_{OB} values give slightly larger mechanical

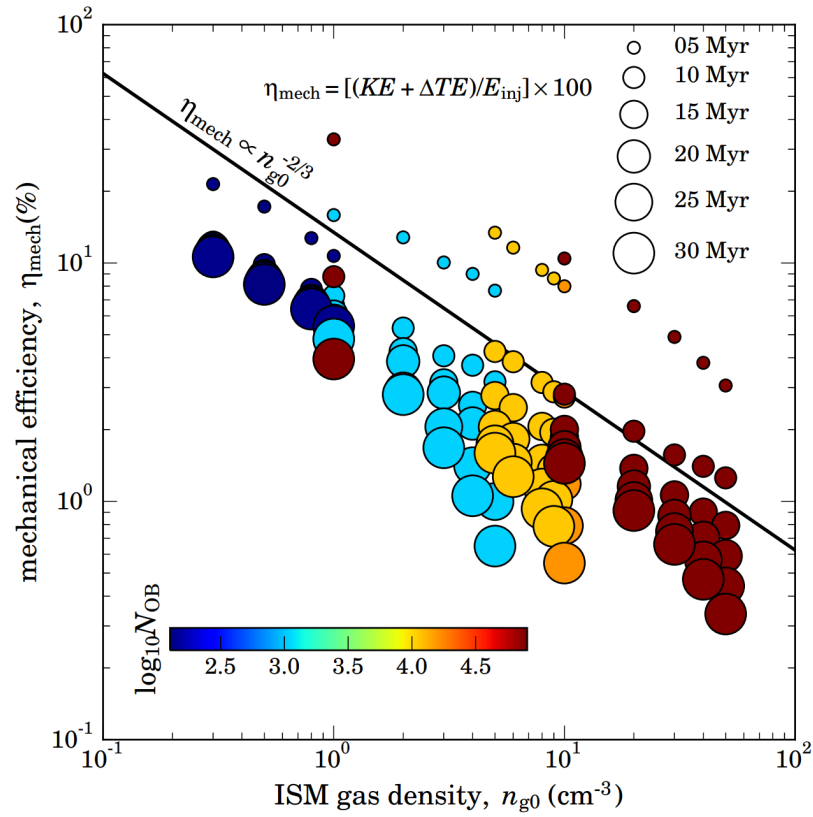


Figure 5.5: Efficiency of mechanical energy retention in superbubbles as a function of ISM density for different simulations from [156]. Colours represent N_{OB} and the sizes of circles stand for different times.

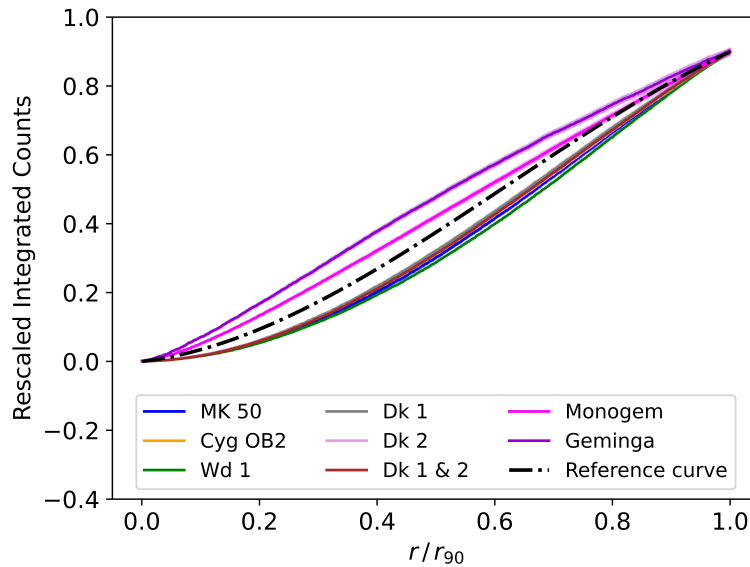


Figure 5.6: Integrated counts profile curves of the emission from the centres of each source. The curves have been re-scaled over the total emission for clarity of comparison. Both YMSCs and TeV halos are shown, with the reference function (black dot-dashed curve) dividing the two classes of objects: TeV halos are above the reference curve and YMSCs are below.

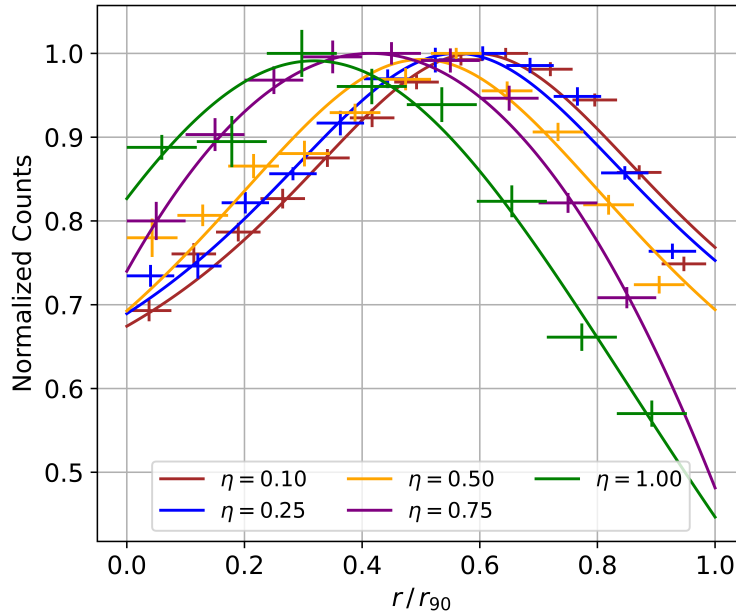


Figure 5.7: Westerlund 1 gamma-ray emission radial profiles as a function of the distance from the centre for varying values of η_m . The profiles have been rescaled as before and the data are fitted with the modified Lorentzian function.

efficiencies, different medium density and age estimates clearly lead to more relevant variations in η_m . A factor 10 uncertainties in either of these two variables can change the efficiency by a factor between 5 and 10. What is crucial in the main classification methodology aforementioned, however, is the relative position of the emission peak and the shape of the emission profile around it. The absolute size of the bubble is therefore less relevant than the R_{TS}/R_b ratio, which gets higher for lower mechanical efficiency values.

5.8 Classification of LHAASO Sources

To calibrate the classification ability of the ASTRI Mini-Array and CTAO, the data science protocols presented in Section 5.6 were also applied to an expanded source sample from the first LHAASO catalog [26]. The sample comprised all those sources being covered by at least one or both of the main LHAASO instruments as being non-point-like and with an angular extent $3\sigma < 4^\circ$ and, accordingly, being fully contained in one pointing observation. There were 29 and 26 sources observable to WCDA and KM2A, respectively, of which 22 were common for both. For sources observable to both WCDA and KM2A, there are two separate source models contained within the LHAASO catalog, each comprising a spatial characterisation (typically a two-dimensional Gaussian distribution) and spectral component, also being modelled as a power-law distribution with an normalizing factor N_0 and spectral index γ . The energy intervals for which the spectral parameters are given also differ with the detector instrument: for WCDA detections,

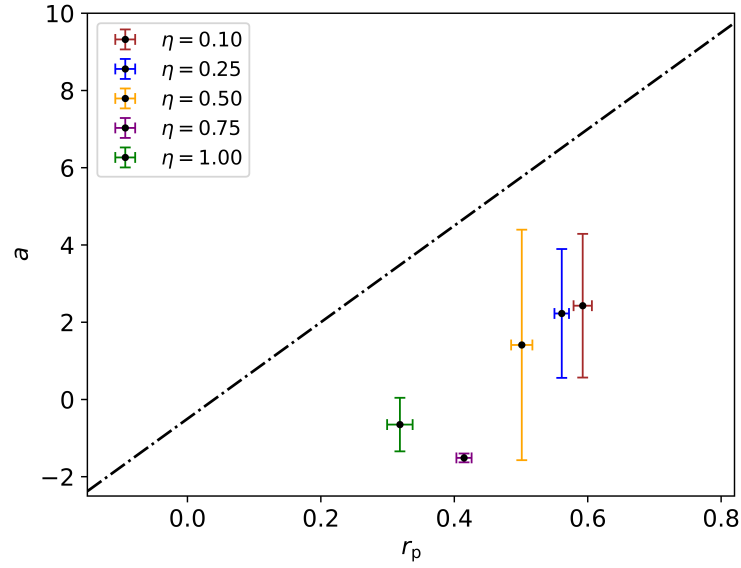
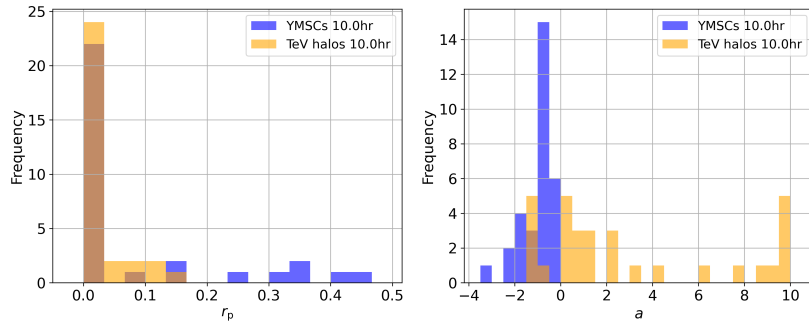
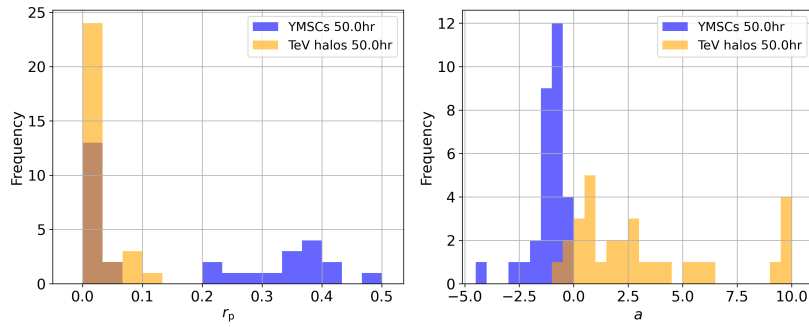


Figure 5.8: Values of the curve anisotropy and emission peak position in units of r_{90} obtained with the modified Lorentzian fit to the data. For all η_m values, Westerlund 1 displays a and r_p values in a region below the dot-dashed line.

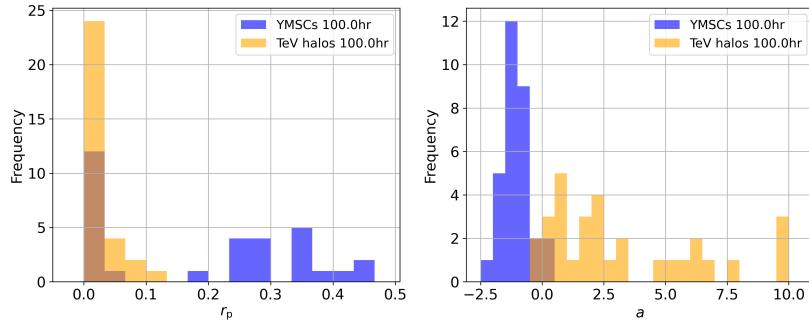
the spectrum at an energy range of 1–25 TeV is given, whereas for KM2A detections, spectral parameters are given at energies greater than 25 TeV. Three-dimensional models appropriate for **Gammapy** simulations were made for the sources passing selection cuts on the spatial model, i.e., those defined by an angular width $0 < \sigma < 1.33^\circ$ of an anisotropic 2D Gaussian distribution. Since no information apart from the extension of the best-fitting Gaussian is given in the LHAASO catalog, a morphology constant with energy was assumed. For each of the sources, two models were created with the same spectral and spatial properties as those inferred by LHAASO, i.e. radial extensions of 3σ , but with an emission profile following the modified Lorentzian function in Equation 5.14 with typical YMSCs and TeV halo parameters alternatively. For all models of those sources visible to both LHAASO instruments, a broken power-law spectrum was assumed with the spectral break at 25 TeV. The spectral indices, normalizations, and reference energies derived were from the LHAASO catalog. For those sources where detection was achieved using only one of the instruments (WCDA or KM2A), an individual power-law spectrum was assumed according to the LHAASO-reported quantities. A total of 66 models were obtained, simulated and modelled from IRFs of both the ASTRI Mini-Array and the CTAO. For double detections of sources by WCDA and KM2A, the respective spectral models were also jointed by filling the 1–25 TeV and 25–300 TeV energy ranges with the WCDA and KM2A models, respectively. Simulations were produced autonomously and detections occurred at the mean LHAASO-reported positions, i.e. weighted on the WCDA and KM2A reported positions with the weights being the expected excess photon counts. This method automatically brought the observation centre and the WCDA centre of emission into agreement because of the higher energy photon counts.



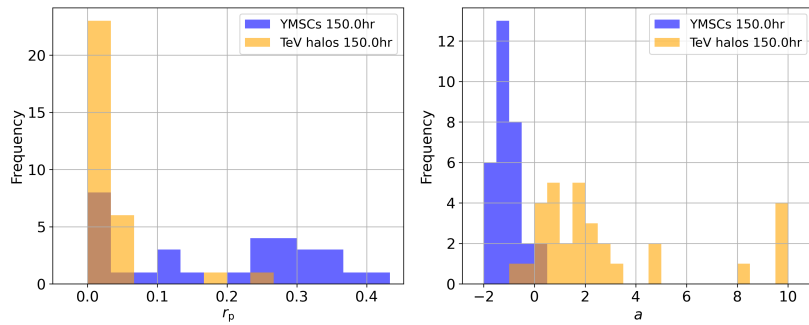
(a) 10 hours simulations distributions.



(b) 50 hours simulations distributions.

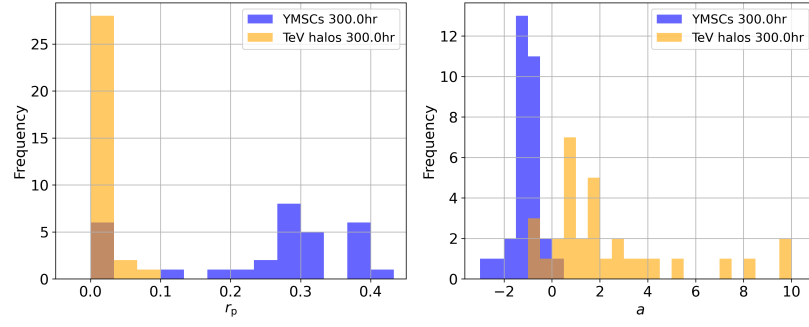


(c) 100 hours simulations distributions.



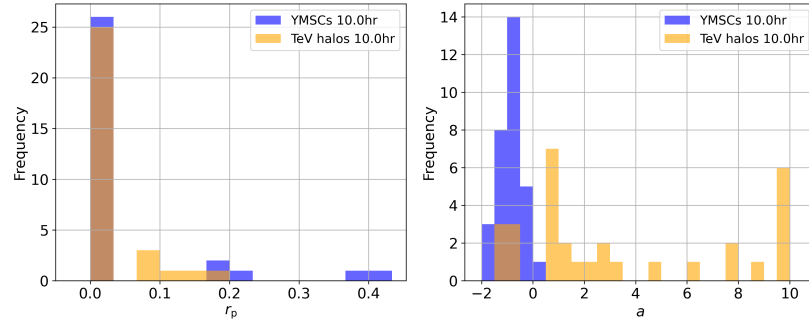
(d) 150 hours simulations distributions.

Figure 5.9: Peak position (*left*) and anisotropy (*right*) parameters distributions for the listed livetimes. Blue distributions are the results of YMSc simulations with the CTAO IRF, orange ones are derived from TeV halos simulations. Brown counts indicate that the estimated peak position of the YMSc and TeV halo simulations coincide.

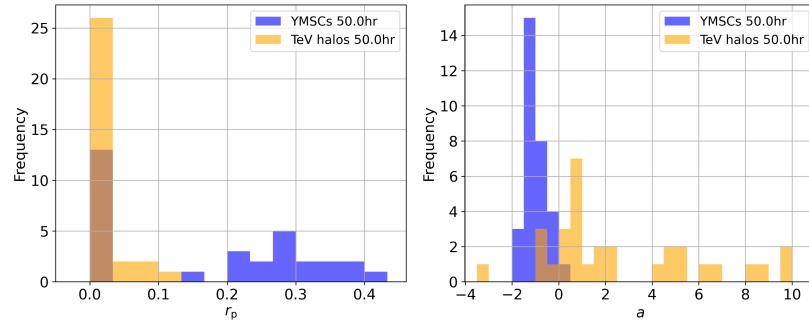


(e) 300 hours simulations distributions.

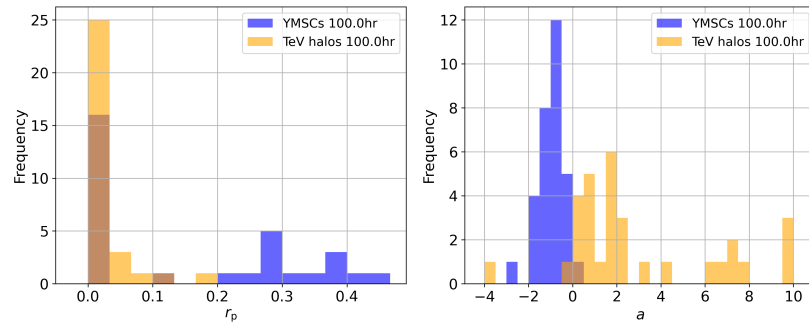
Figure 5.9: Continuation.



(a) 10 hours simulations distributions.

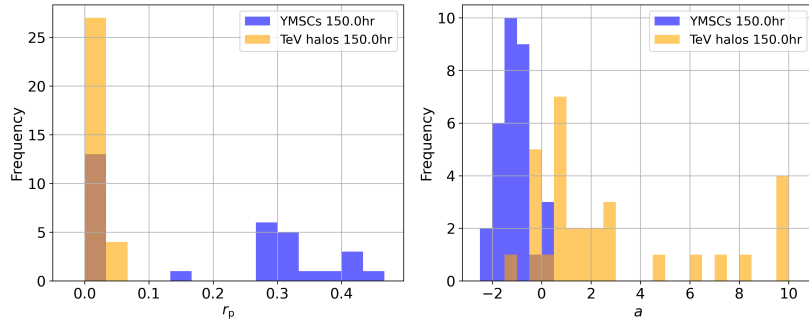


(b) 50 hours simulations distributions.

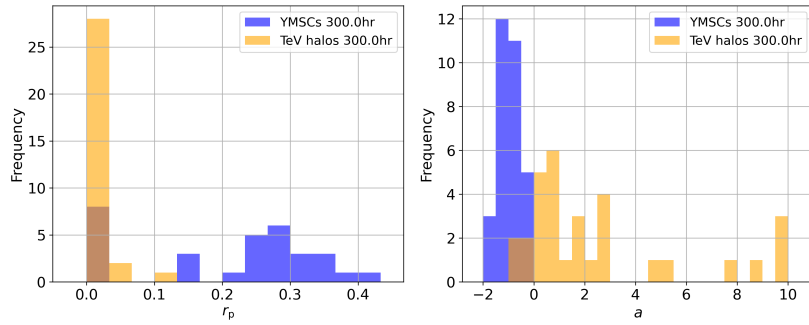


(c) 100 hours simulations distributions.

Figure 5.10: Same as Figure 5.9, but for simulations with the ASTRI Mini-Array IRF.



(d) 150 hours simulations distributions.



(e) 300 hours simulations distributions.

Figure 5.10: Continuation.

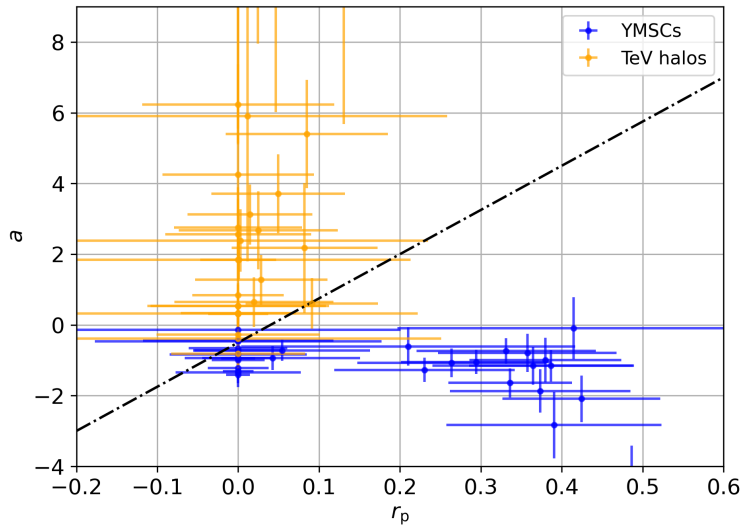


Figure 5.11: Values of the curve anisotropy and emission peak position in units of r_{90} of all the LHAASO sources simulated with the CTAO IRF. Orange crosses are used for TeV halos and blue crosses are used for YMSCs. The dot-dashed, black line is the same from Figure 5.4.

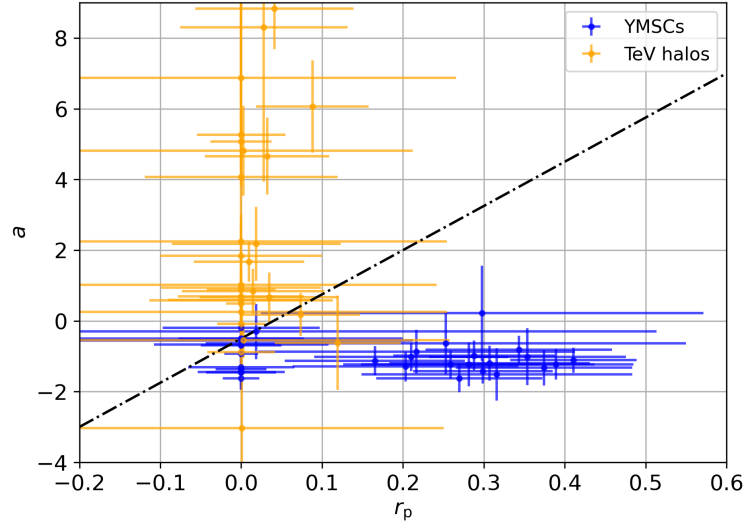


Figure 5.12: Same as Figure 5.11, but for the case of simulations with the ASTRI Mini-Array IRF.

Radial excess profiles with instrumental effects were calculated for all the simulations. The procedure was then repeated for various observation livetimes (300 hours, 150 hours, 100 hours, 50 hours, and 10 hours) to determine the lowest observational time to yield an accurate classification between the unidentified extended sources. The radial profiles were then fitted using routines based on the modified Lorentzian function from Equation 5.14, enabling an extraction of the peak location of the emission (r_p) and anisotropy parameter (a). The respective distributions of the parameters are reported in Figure 5.9 and Figure 5.10, obtained from simulations using IRFs of the CTAO and ASTRI Mini-Array, respectively. In all the tested livetimes, the location of the maximum of the emission distinguishes obviously YMSC and TeV halo models with six sources using the IRF of the CTAO and three using the IRF of the ASTRI at least at $\Delta r_p \geq 0.15r_{90}$ separation. The results show that for those sources the classification can be achieved reliably basing on 10 hours observation. The percentage of sources being properly classified significantly increases with exposure time. As summarised in Table 5.6, for an exposure time of 50 hours and 100 hours, correct classification according to only r_p corresponds to 45.5% and 51.5% of cases using the CTAO IRF and to 40.9% and 48.5% using the ASTRI Mini-Array IRF. For an observation time of 300 hours, correct classification corresponds to 74.2% and 69.7% sources using the CTAO IRF and the ASTRI IRF, respectively, according only to the peak position. Better classification results are obtained taking into account both morphological parameters (a and r_p). This better performance can be seen from figures 5.11 and 5.12, where simulated results distributions for the a - r_p parameter spaces are presented for observations of 50 hours duration. For an ASTRI Mini-Array example, only 8 of 66 best fits give incorrect classification (i.e., being at the incorrect semi-plane), and 5 of them are flagged as uncertain because they possess error bars over the classification boundary (dot-dashed line). For the case of the CTAO IRF,

only 6 best fits give incorrect classification, all being flagged as uncertain too. In both examples, correct classification remains for 68.2% and 65.2% of sources, respectively, taking into account both parameters for an observation program of 50 hours duration.

5.9 The Gas Distribution around YMSCs

In the simulations described in Section 5.5, the model proposed by Morlino et al. [52] was used, in which the gas density surrounding the YMSCs is normally treated as a constant parameter. While this simplifying assumption allows for a tractable and computationally less expensive description of particle transport and emission processes, it inevitably limits the accuracy of morphological predictions. A more realistic description of the gas distribution is crucial, especially in the prospect of comparing theoretical expectations with high-resolution observational data provided by the next-generation IACTs. The morphology of the non-thermal emission is, in fact, strongly dependent on the spatial structure of the ambient medium with which CRs interact to produce gamma-ray radiation.

The density of hydrogen within the stellar bubble carved by the YMSCs is particularly difficult to constrain. The interstellar medium can only be indirectly inferred, and its distribution is far from uniform. Direct mapping of neutral hydrogen is hindered by absorption and line-of-sight confusion effects, which complicate the reconstruction of the three-dimensional density profile. As a consequence, one often has to rely on radio observations, which provide the most reliable large-scale maps of the neutral hydrogen component. A significant contribution to the total gas density is provided by molecular hydrogen. Despite being the dominant phase in the dense regions around YMSCs, molecular hydrogen is essentially invisible in direct emission. Its distribution must therefore be traced indirectly through surrogate molecules, such as carbon monoxide (CO), whose rotational transitions are observable at millimeter wavelengths. These molecular tracers, combined with neutral hydrogen radio surveys, offer the best available means to reconstruct a realistic density profile around YMSCs.

5.9.1 Distance Computation of MCs

In order to obtain a realistic description of the gas distribution surrounding the YMSCs in the initial sample 5.3, it is essential to use reliable CO surveys as tracers of molecular hydrogen within the bubble excavated around each YMSC. However, the use of existing surveys is not always straightforward. A first difficulty arises from the angular size of the bubbles: in some cases the angular extension of these systems is comparable to, or even larger than, the fields typically covered by available datasets. As a result, finding a survey that is both sufficiently extended in sky coverage and complete in sensitivity is not trivial. The problem is exacerbated by the location of many YMSCs with respect to the Galactic plane. Most molecular surveys have been designed to probe the dense molecular disk, and therefore focus on narrow latitude strips, usually within $\pm 1^\circ$ around

Table 5.6: Percentage of correct classifications, misclassifications, and inconclusive classifications according to the fit r_p and a parameters from simulations performed using the CTAO South and the ASTRI Mini-Array IRFs for different livetimes. The parameters are grouped by source type: YMSCs and TeV halos.

CTAO South						
Livetime	YMSC Sources			TeV Halo Sources		
	Classified (%)	Misclassified (%)	Inconclusive (%)	Classified (%)	Misclassified (%)	Inconclusive (%)
10 h	12.9	3.2	83.9	6.5	6.5	87.0
25 h	19.4	3.2	77.4	22.6	3.2	74.2
50 h	48.4	0.0	51.6	35.5	0.0	64.5
75 h	51.6	6.5	41.9	32.3	0.0	67.7
100 h	54.8	0.0	45.2	48.4	0.0	51.6
150 h	58.1	3.2	38.7	64.5	3.2	32.3
300 h	74.2	0.0	25.8	77.4	0.0	22.6

ASTRI Mini-Array						
Livetime	YMSC Sources			TeV Halo Sources		
	Classified (%)	Misclassified (%)	Inconclusive (%)	Classified (%)	Misclassified (%)	Inconclusive (%)
10 h	6.5	3.2	90.3	3.2	0.0	96.8
25 h	16.1	0.0	83.9	19.4	3.2	77.4
50 h	38.7	0.0	61.3	38.7	0.0	61.3
75 h	45.2	3.2	51.6	32.3	3.2	64.5
100 h	51.6	0.0	48.4	41.9	0.0	58.1
150 h	54.8	0.0	45.2	58.1	0.0	41.9
300 h	64.5	0.0	35.5	71.0	0.0	29.0

$b = 0^\circ$. While such coverage is sufficient for studying the bulk of star-forming activity, a non-negligible fraction of YMSCs may be found at non-zero Galactic latitude ($b \neq 0$), due either to their intrinsic location above the plane or to projection effects. In such cases, the $\pm 1^\circ$ strip of coverage excludes potentially relevant molecular material associated with the stellar bubble. For a comprehensive morphological study, one requires surveys spanning several degrees in latitude, a condition met only by a limited subset of existing datasets.

A further complication is that the information provided by CO surveys must inherently be three-dimensional. A simple two-dimensional projection of the CO intensity on the plane of the sky is insufficient, since it does not allow one to distinguish between foreground and background structures along the line of sight. In order to properly identify the MCs physically interacting with the YMSC, in the bubble, it is necessary to combine the spatial coordinates (l, b) with the radial velocity information provided by the Doppler shift of the CO lines. This allows us to assign each cloud a position in phase space, and to determine whether it falls within a radius R_b from the centre of the YMSC.

Distance Estimation Uncertainties Since direct parallax measurements are only available for relatively nearby objects, the standard approach for the estimation of the distance of a MC relies on converting the observed radial velocity into its distance through the Milky Way rotation curve [159, 160]. While this method provides an indispensable tool for Galactic studies, its application is not free of complications and systematic uncertainties. The basic assumption underlying the velocity–distance relation is that gas clouds participate in circular Galactic rotation. Any given observed radial velocity v_r along a given line of sight should correspond to a unique Galactocentric radius R , and therefore, to a heliocentric distance d . However, in practice several effects introduce significant deviations from this idealized case:

- **Particular motions:** Gas clouds may have velocities several km s^{-1} more or less with respect to the mean Galactic rotation. These can arise from spiral-arm shocks, gravitational perturbations by the Galactic bar, or local stellar feedback. Such peculiar velocities translate directly into errors in the inferred distance.
- **Near–far ambiguity:** In the inner Galaxy (i.e. $|l| < 90^\circ$), the same radial velocity can correspond to two different heliocentric distances along the line of sight. Resolving this degeneracy often requires additional information, such as HI absorption studies or associations with objects of known distance.
- **Deviations from the rotation curve:** The Galactic rotation curve is derived under simplifying assumptions. Local inhomogeneities in the mass distribution, as well as uncertainties in the fundamental constants (e.g. the solar Galactocentric distance $R_0 = 8.05 \text{ kpc}$ and the local standard of rest velocity $V_0 = 238 \text{ km s}^{-1}$), propagate into the distance estimation.

Estimating the Distance Despite the limitations above, the method remains the best available for large-scale mapping of molecular and atomic gas. The key relation connecting the observed radial velocity v_r to the Galactic rotation is obtained by projecting the circular velocities of the Sun and of the cloud onto the line of sight:

$$v_r = \left(\frac{V(R)R_0}{R} - V_0 \right) \sin l, \quad (5.17)$$

where $V(R)$ is the circular velocity of the cloud at Galactocentric radius R , V_0 is the circular velocity of the Sun around the Galactic centre, R_0 is the Galactocentric distance of the Sun, and l is the Galactic longitude of the line of sight. Equation 5.17 can be inverted to obtain the Galactocentric radius R of the cloud, and with some simple trigonometry it becomes:

$$d = R_0 \cos l \pm \sqrt{R^2 - R_0^2 \sin^2 l}, \quad (5.18)$$

where the $\pm$ sign reflects the near-far ambiguity. For inner-Galaxy lines of sight, both solutions are geometrically possible; for the outer Galaxy ($|l| > 90^\circ$), only one solution exists.

An important simplification arises for the so-called tangent point, where the line of sight is tangent to the circular orbit around the Galactic centre. In this case, the Galactocentric radius reduces to

$$R = R_0 \sin l, \quad (5.19)$$

and the radial velocity reaches its maximum absolute value along the line of sight. The tangent-point method allows one to directly measure the rotation curve in the inner Galaxy without ambiguity:

$$V(R) = v_r + V_0 \sin l. \quad (5.20)$$

Selection of the CO Survey data For the purpose of tracing the molecular hydrogen distribution around the sample of YMCSs, the large-scale CO survey by Dame et al. [161] was employed, which remains one of the most complete and widely used CO surveys of the Galactic plane. This dataset combines several previous surveys into a uniform product, providing near full-sky coverage at millimeter wavelengths (115 GHz). For each of the systems described in Section 5.3, the corresponding velocity intervals expected for their associated bubbles were computed, based on their positions and radial velocities. These intervals are summarized in Table 5.7.

Using these computed velocity intervals, it is possible to extract the relevant portions of the three-dimensional CO data cube for each YMCS. Specifically, the corresponding velocity bins were selected and combined with the spatial information in Galactic longitude and latitude, thereby obtaining 3D maps of the molecular gas distribution associated with each bubble. The resulting maps are shown in Figure 5.13, where the CO emission has been integrated along the line of sight within the selected velocity ranges. The panels display the morphology of the molecular material in the vicinity

Table 5.7: Velocity intervals adopted for the YMSC systems in our sample. The Δl and Δv columns show the angular and velocity resolutions of the relative section of the Milky Way. The *Survey* column references the relative sub-survey of Dame et al..

Source	$v_{\min}$ (km s $^{-1}$)	$v_{\max}$ (km s $^{-1}$)	δl ($^{\circ}$)	Δv (km s $^{-1}$)	Survey
Cygnus OB2	-13.51	-8.51	0.125	0.65	[162]
Westerlund 1	-45.49	-37.78	0.125	1.25	[163]
Danks 1	-18.49	-15.17	0.125	1.25	[163]
Danks 2	-19.29	-14.35	0.125	1.25	[163]
Markarian 50	-61.25	-58.25	0.125	0.65	[164]

of the YMSC, providing a direct observational counterpart to the theoretical modelling presented above.

5.9.2 Gas Density around the YMSCs

The Dame et al. CO survey provides the emission data in terms of brightness temperature, T_B , rather than directly in flux density or column density. This choice is natural for radio and millimeter-wave observations, where the antenna temperature serves as a proxy for the intensity received by the telescope. However, for physical interpretation of the molecular environment around young massive star clusters, the relevant quantity is the molecular hydrogen density, which requires a conversion from brightness temperature into mass density. The methodology used to perform this conversion follows the formalism described in [165], which provides a systematic procedure to convert CO brightness temperature maps into flux densities, column densities, and ultimately volume densities.

The brightness temperature is first related to the specific intensity by the Rayleigh–Jeans approximation:

$$I_{\nu} = \frac{2k_B T_B}{\lambda^2}, \quad (5.21)$$

where k_B is Boltzmann’s constant and λ is the wavelength of the observed transition ($\lambda \simeq 2.6$ mm for CO $J = 1 \rightarrow 0$). The flux density per telescope beam, where the beam represents the effective angular response of the telescope, is then obtained by integrating the intensity over the beam solid angle Ω_{beam} :

$$S_{\nu} = I_{\nu} \Omega_{\text{beam}}. \quad (5.22)$$

For a Gaussian beam, the solid angle is expressed as

$$\Omega_{\text{beam}} = 1.133 \theta_{\text{FWHM}}^2, \quad (5.23)$$

where θ_{FWHM} is the full width at half maximum of the beam in radians. Following the calibration procedure recommended in the Dame survey and applied in [165], the conversion of the observed brightness temperatures to Jy/beam also requires includes a correction factor of 1.22 to account for beam efficiency. The resulting flux density per

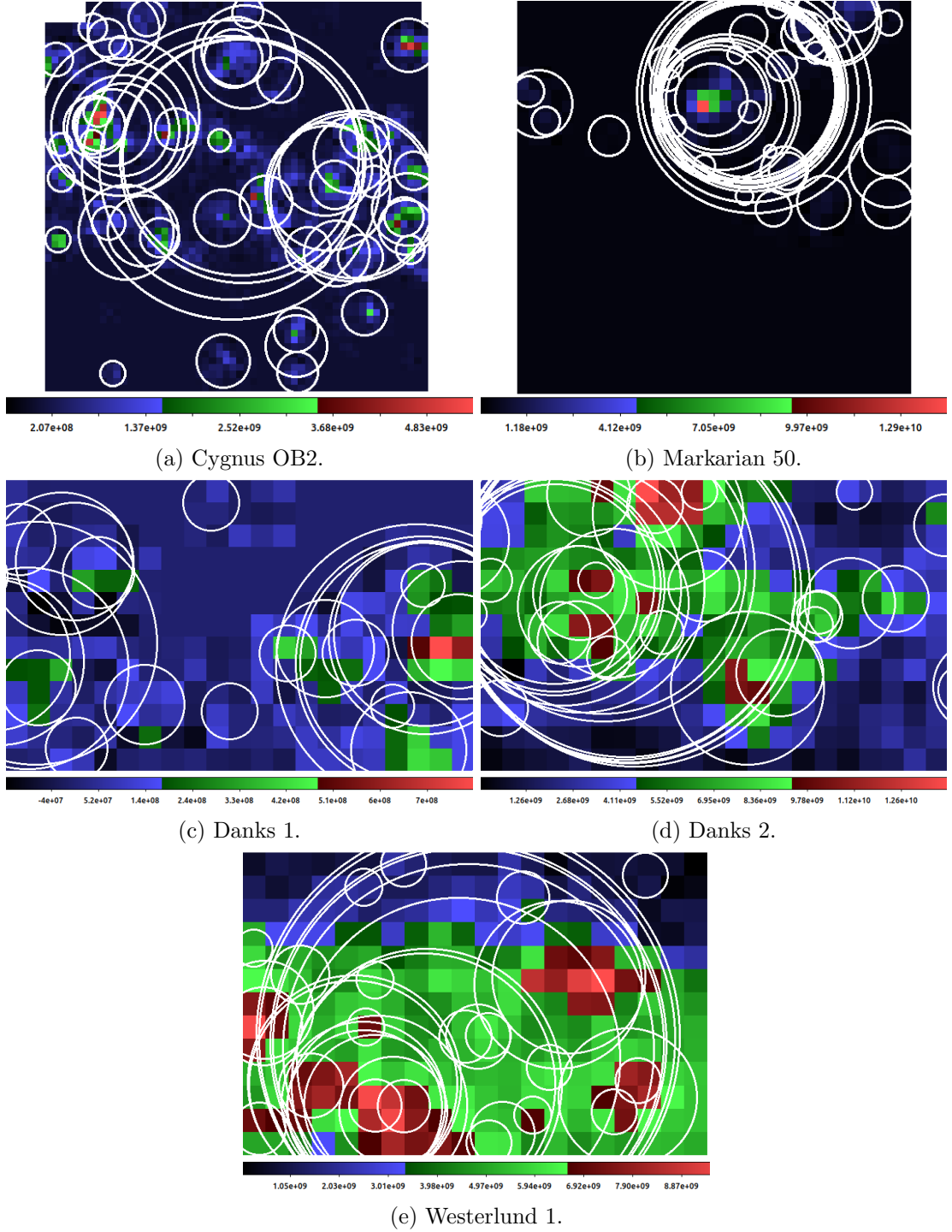


Figure 5.13: Integrated CO emission maps for the YMSC regions, respectively. Each map is obtained by selecting the appropriate velocity intervals from the Dame et al. survey and integrating along the line of sight. The white circles outlining the clouds identified by the dendrogram technique described in Section 5.9.2.

beam, expressed in Jy beam^{-1} , is therefore given by:

$$S_\nu [\text{Jy beam}^{-1}] = \frac{2k_B T_B}{\lambda^2} \Omega_{\text{beam}} \times \frac{1}{1.22} \times 10^{26}. \quad (5.24)$$

Here, the multiplicative factor 10^{26} converts SI units into Janskys. The integrated CO intensity W_{CO} can then be obtained by summing over the velocity channels,

$$W_{\text{CO}} = \int T_B(v) dv \quad [\text{K km s}^{-1}]. \quad (5.25)$$

To convert this intensity into molecular hydrogen column density, the standard CO-to-H₂ conversion factor, X_{CO} can be used:

$$N(\text{H}_2) = X_{\text{CO}} W_{\text{CO}}. \quad (5.26)$$

Typical values of this conversion factor have been discussed extensively in the literature. A canonical value is $X_{\text{CO}} = 2 \times 10^{20} \text{ cm}^{-2} (\text{K km s}^{-1})^{-1}$, consistent with [166] and adopted by [165]. This factor may vary depending on metallicity and local conditions, but provides a standard reference.

The integrated column density obtained above represents the number of molecular hydrogen atoms per unit area along the line of sight. To reconstruct the three-dimensional density distribution, knowledge of the path length is required. Two approaches are typically employed:

1. For spherical systems of radius R , the average density is approximated as

$$n(\text{H}_2) \approx \frac{N(\text{H}_2)}{2R}. \quad (5.27)$$

2. For pixel-based maps, the angular size $\Delta\theta$ of each pixel at distance d corresponds to a physical size $\Delta x = d \Delta\theta$. The cell volume is then $\Delta V = \Delta x^2 \Delta z$, where Δz is the depth associated with the velocity channel, determined via the Galactic rotation curve. The resulting density is therefore

$$n(\text{H}_2) = \frac{N(\text{H}_2)}{\Delta z}. \quad (5.28)$$

Cloud Identification and Spherical Modelling In order to reduce the computational cost of constructing full three-dimensional gas density maps, the MCs associated with each system were approximated as overlapping spheres of homogeneous density. This simplification preserves the essential spatial and density distribution of the gas, while enabling a tractable treatment of the large-scale structures surrounding the sources. The radius and integrated intensity of each sphere were derived using the dendrogram technique, implemented through the **Astrodendro** Python package¹ [167]. The principle of the dendrogram technique is to decompose emission maps hierarchically, representing

¹<https://dendrograms.readthedocs.io>

Table 5.8: Number of MCs found with the relative minimum size of each cloud (in number of pixels).

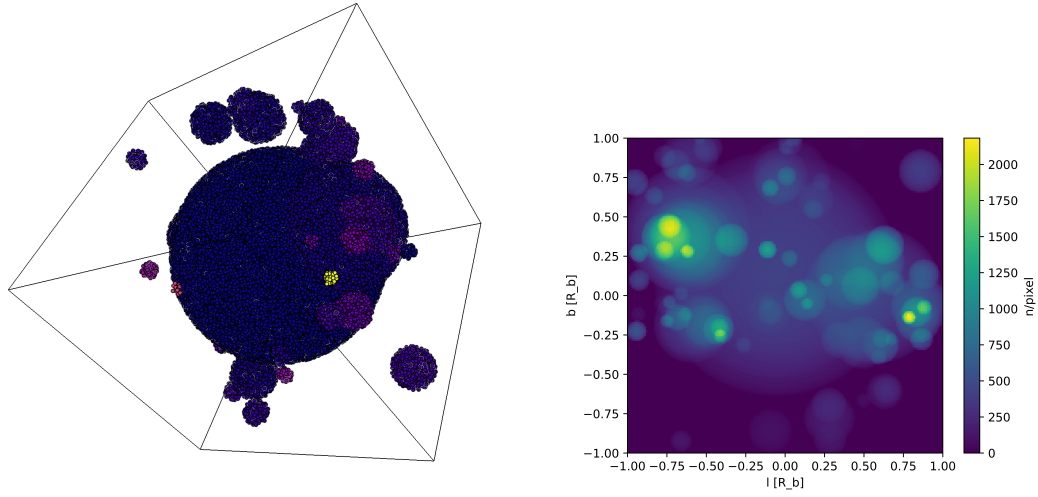
Source	$N_{pxl,min}$	N_{MC}
Cygnus OB2	25	102
Westerlund 1	4	41
Danks 1	4	39
Danks 2	4	39
Markarian 50	4	47

the data distribution as a ‘tree’ structure composed of leaves, branches, and a trunk. Leaves correspond to local maxima in the data, the trunk represents the lowest-level data, and the branches connect the two categories. By applying thresholds in both the minimum number of pixels that a leaf can be made of and minimum flux between the leaves (δ), the algorithm isolates significant cloud-like structures in the dataset, avoiding irrelevant detections due to noise fluctuations. The adopted pixel thresholds are shown in Table 5.8, which lists the number of structures found given a $\delta = 3$. These values ensure that only coherent and physically meaningful structures are identified. The result of the **Astrodendro** algorithm is a catalog of MCs characterised by position, radius, and integrated intensity. The resulting set of identified clouds is displayed in Figure 5.13. In this figure, the white circles indicate the position and extent of the spherical cloud models. Their distribution follows closely the morphology of the emission visible in the underlying pixel maps, demonstrating that the dendrogram-based selection reproduces the overall structure of the molecular material. The combination of the hierarchical decomposition with the spherical approximation thus provides an efficient and physically motivated representation of the gas distribution suitable for further modelling.

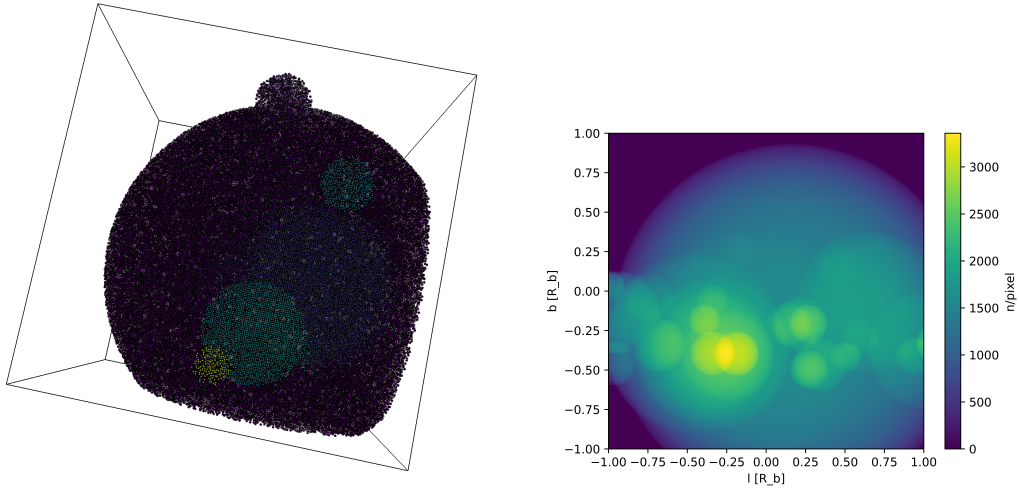
Through this procedure, the three-dimensional CO data cubes can be transformed into the molecular gas density maps visible in Figure 5.15, enabling a direct comparison between the observed structure of the bubbles around YMCSs and the predictions of theoretical models.

5.9.3 Morphology Analyses with MCs Modellization

Simulations analogous to those described in Section 5.5 were performed for the YMCSs included in the sample. These simulations do not assume a uniform density any longer, but they account for the distribution of MCs derived from the dendrogram analysis. Figure 5.17 illustrates the appearance of the simulated systems as they would be observed with the respective IACTs (ASTRI Mini-Array or CTAO). In these excess maps, the MCs within the cluster wind bubbles are illuminated by gamma-ray radiation, which originates from the interactions of accelerated particles with the dense gas. The resulting morphology reflects the spatial distribution of the clouds, producing a structured gamma-ray excess that follows closely the underlying gas density. The figure demonstrates how the combination of gas maps and particle acceleration models leads to distinct observational signatures in the very-high-energy band.

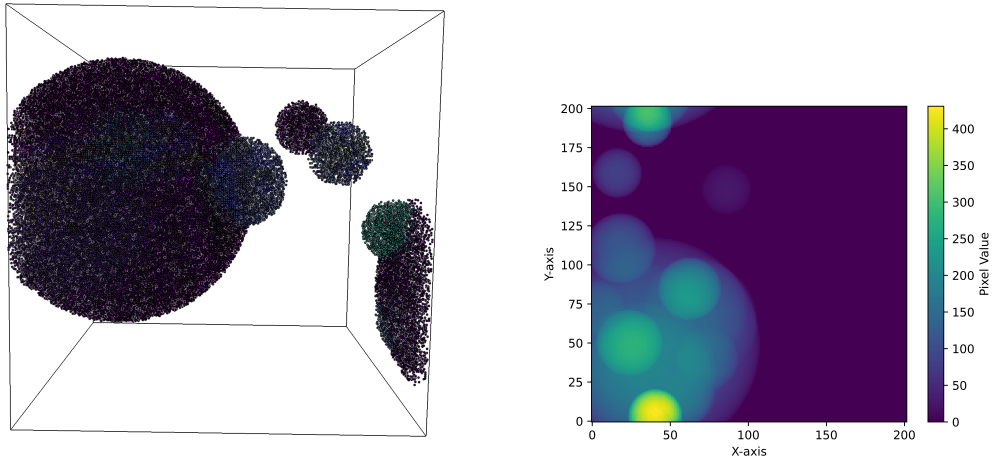


(a) Cygnus OB2

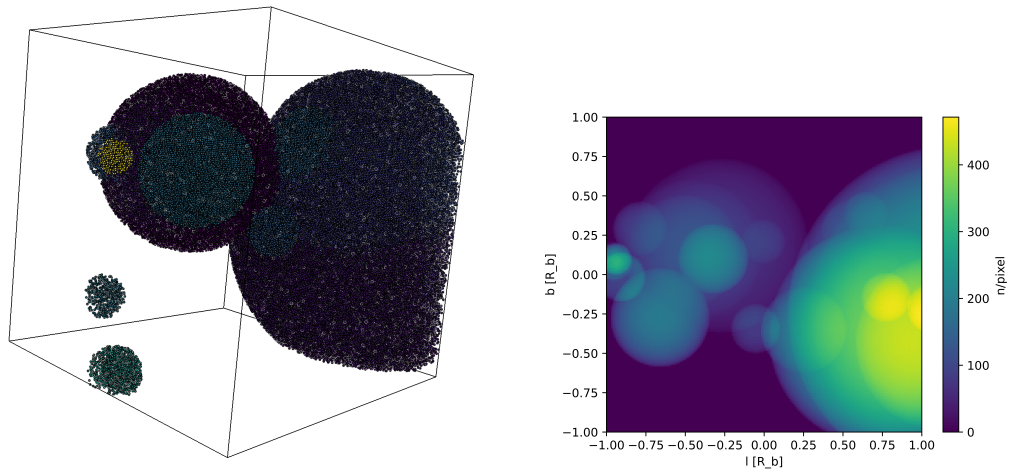


(b) Westerlund 1

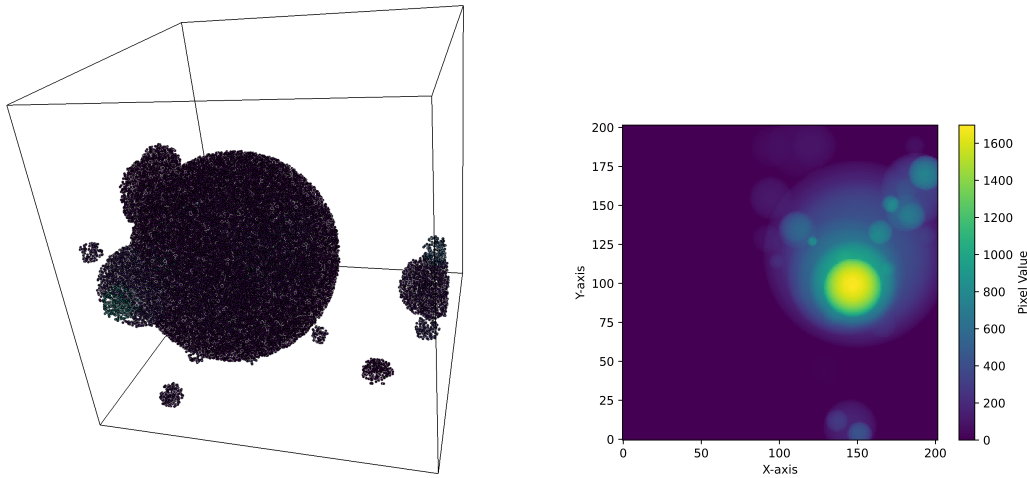
Figure 5.14: Three-dimensional molecular gas density maps (*left*) constructed from the spherical cloud models derived with the dendrogram technique, and their pixel maps integrated along the line of sight (*right*). The maps show how the hierarchical decomposition and spherical approximation reproduce the overall structure of the molecular material.



(c) Danks 1



(d) Danks 2



(e) Markarian 50

Figure 5.15: Continuation.

Clearly, the presence of MCs inside and around the bubbles breaks the spherical symmetry that is often assumed in simplified models. As a result, the study of the morphology cannot be restricted to radial profiles alone, but must also consider azimuthal profiles, which provide complementary information on the angular distribution of the emission.

Analysis of Azimuthal Profiles An azimuthal profile describes how the emission varies as a function of the angle around the cluster, at a fixed distance from its centre. The azimuthal coordinate ϕ is defined in the plane of the sky, with $\phi = 0^\circ$ corresponding to the north in the adopted reference system. The angle increases counter-clockwise from this axis. Figure 5.16 illustrates the definition of the azimuthal coordinate system. To construct the azimuthal profiles, the cluster bubble is divided into concentric annuli, each of which is further subdivided into angular slices. The resulting regions are annular sectors, corresponding to the intersections between the annuli and the angular divisions. Each annular sector provides a measurement of the average intensity within a well-defined radial and angular interval.

As an illustrative example, the radius of the bubble was divided into four annuli of $\sim 0.5^\circ$ width each, while the full 360° was divided into eight angular sectors. Due to the larger Cygnus OB2 bubble size, this system was divided in six annuli instead. This sectioning results in $6 \times 8 = 48$ annular sectors for Cygnus OB2, and $4 \times 8 = 32$ annular sectors for all the others systems. For each annular sector $A(\phi, r)$, defined by its radial range $[r_{\text{in}}, r_{\text{out}}]$ and angular interval $[\phi_{\text{min}}, \phi_{\text{max}}]$, the azimuthal intensity is computed as

$$I(\phi, r) = \frac{1}{A(\phi, r)} \int_{A(\phi, r)} I(x, y) dA, \quad (5.29)$$

where $I(x, y)$ is the surface brightness at pixel position (x, y) and $A(\phi, r)$ is the area of the annular sector. In practice, the integral reduces to an average over the set of pixels contained in the annular sector:

$$I(\phi, r) = \frac{1}{N_{\text{pix}}} \sum_{i=1}^{N_{\text{pix}}} I_i, \quad (5.30)$$

where N_{pix} is the number of pixels in the region and I_i the brightness value of each pixel.

Figure 5.17 presents the resulting azimuthal profiles of each YMCS, which have been rescaled over the respective maximum value for clarity of comparison. Multiple local luminosity increases, shown as frequent peaks in the profiles, indicate the presence of a clumpy medium (e.g. for Cygnus OB2 and Danks 2), while flat (e.g. those of Westerlund 1) or single-peaked profiles (e.g. Danks 1 or Markarian 50) reflect a more homogeneous or shifted gas distribution. By comparing profiles for different radii, the the gamma-ray morphology across the whole bubble can be evaluated.

Beyond morphological information, azimuthal profiles can in principle partially address the uncertainties in the distance assignment of MCs mentioned in Section 5.9.1. If

certain dense and brightly illuminated clouds dominate the azimuthal emission in specific angular directions, their association with the cluster can be inferred with higher confidence. In this way, the method offers the possibility of providing independent constraints on the distances of selected molecular structures within the bubble, complementing velocity-based estimates from the Galactic rotation curve.

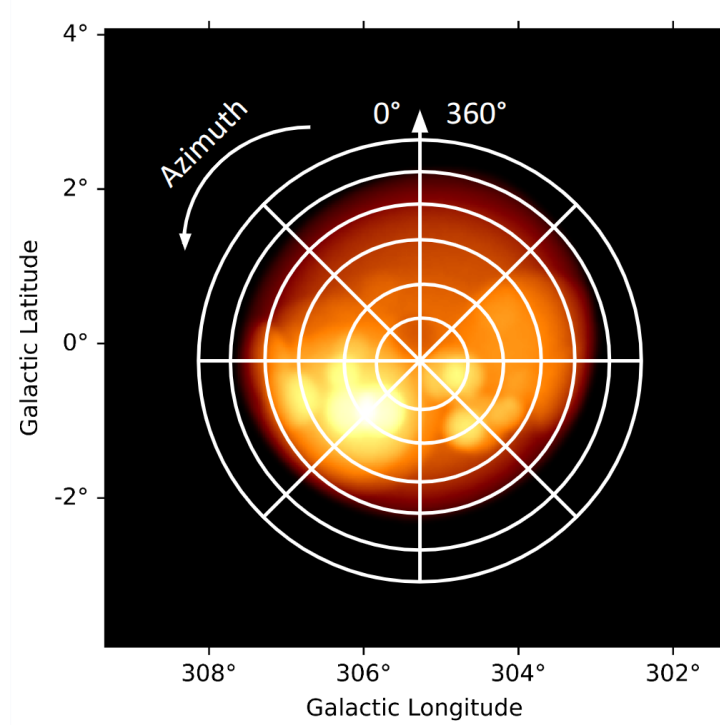
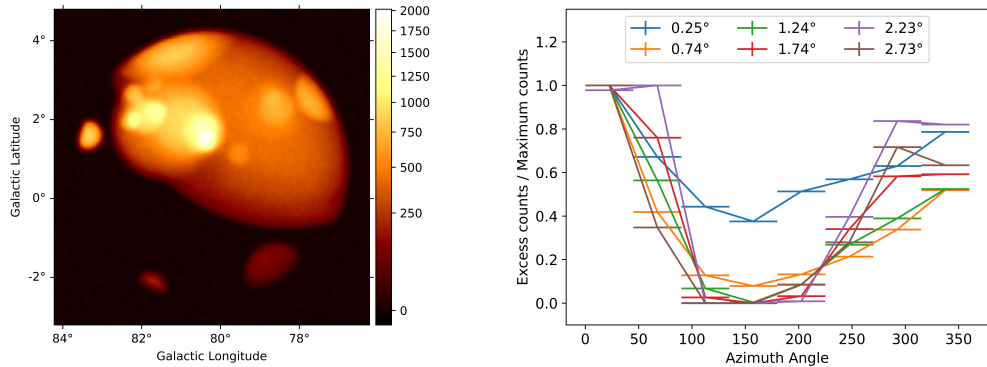
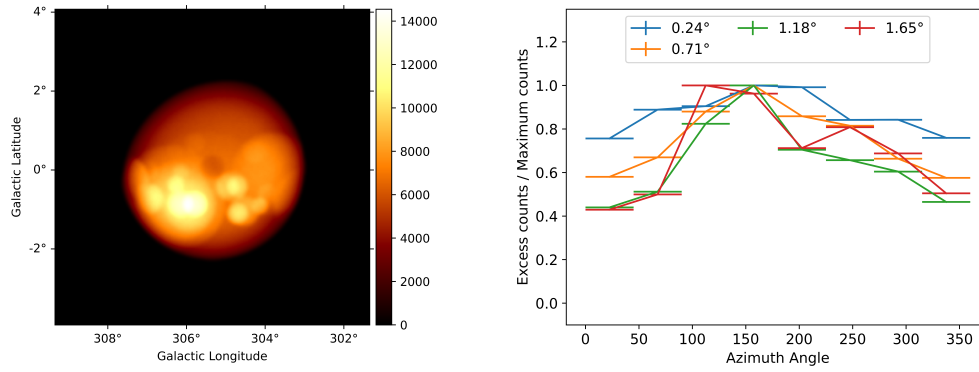


Figure 5.16: Schematic representation of the azimuthal coordinate system. The angle $\phi = 0^\circ$ is oriented vertically upward, and increases counter-clockwise. The circle representing the cluster bubble is divided into annuli and angular sectors, producing annular sectors used to compute the azimuthal profiles.

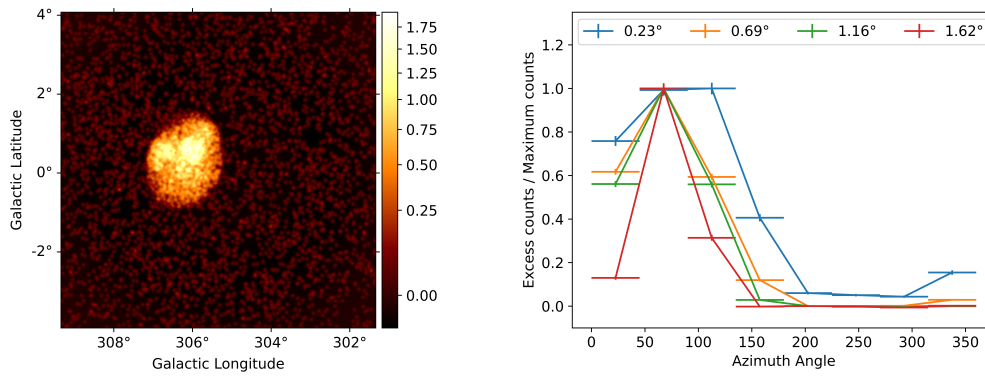


(a) Cygnus region: excess map (left) and azimuthal profile (right).

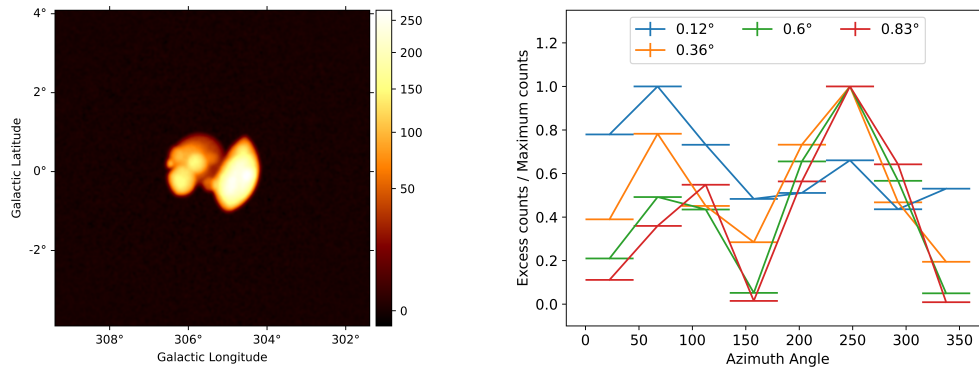
Figure 5.17: Excess maps (left) and azimuthal profiles (right) of the gamma-ray emission for different annular regions around the bubbles of the YMSCs.



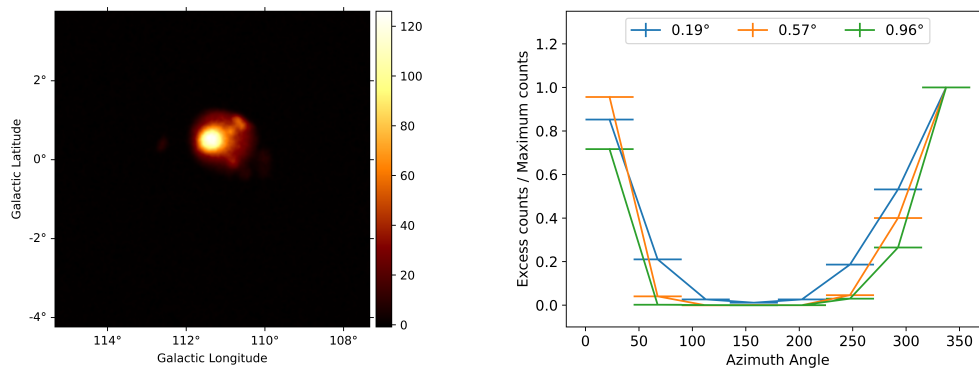
(b) Wd1 region: excess map (left) and azimuthal profile (right).



(c) Dk1 region: excess map (left) and azimuthal profile (right).



(d) Dk2 region: excess map (left) and azimuthal profile (right).



(e) Mk50 region: excess map (left) and azimuthal profile (right).

Figure 5.17: Continuation.

Conclusions

This work has demonstrated the capabilities of future gamma-ray telescopes- namely the ASTRI Mini-Array and CTAO -in the study of extended sources, by combining telescope commissioning studies, instrumental characterization, simulation studies, and source morphology characterization. The work can be divided into three main strands.

First, the performance of the ASTRI system was studied in detail. Observation simulations of the Crab Nebula were used in order to validate the detection analysis chain and to establish a benchmark for sensitivity and morphological reconstruction. A systematic analysis of the point-spread function PSF was carried out, both on simulated datasets and on real observations with the ASTRI-Horn and ASTRI-1 telescopes. This work led to the development of strategies for an energy-dependent PSF estimation, improving the accuracy of morphological studies. In parallel, the background across the field of view was characterised using dedicated datasets, and a two-dimensional background model was devised, implemented and tested. The incorporation of this model into the instrument response functions represents a concrete step forward in providing realistic tools for the analysis of both point- and extended sources.

Second, the first stereoscopic phase of the ASTRI Mini-Array was investigated. A survey strategy was defined to maximise its scientific output, particularly in relation to ultra-high-energy sources detected by LHAASO. Simulations and case studies demonstrated the capability of the Mini-Array to provide morphological and spectral information in the 1–100 TeV domain. Specific analyses focused on the Cygnus, the Boomerang Nebula, and SS 433 regions, show that, even incomplete, the Mini-Array can resolve overlapping sources, constrain emission mechanisms, and identify candidate PeVatrons. This part of the work highlighted how the ASTRI Mini-Array will bridge the gap between wide-field detectors such as LHAASO and the future CTAO arrays.

Third, the thesis investigated young massive star clusters (YMSCs) as possible cosmic-ray accelerators. A morphological framework was developed to compare the expected gamma-ray emission of YMSCs with that of TeV halos. Source models were produced and tested through simulations with ASTRI and CTAO response, with the goal of identifying classification criteria based on excess counts profiles and morphological features. The analysis showed that the mechanical efficiency of stellar winds affects the resulting gamma-ray morphology, and that these differences are potentially observable with future facilities. The proposed classification methodology was applied to a subset of LHAASO sources, suggesting that at least some of them may be explained by

YMSCs. Systematic uncertainties remain in the modelling of gas distributions around YMSCs, in the distances of molecular clouds, and in the calibration of background levels. These limitations constrain the precision of the current results, but the methods developed are designed to be directly applicable to future dedicated datasets.

The contributions of this work can help strengthen both the technical and scientific preparation of ASTRI and CTAO, providing tools and methodologies that will be directly exploitable when the next generation of Cherenkov telescopes enters operation.

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