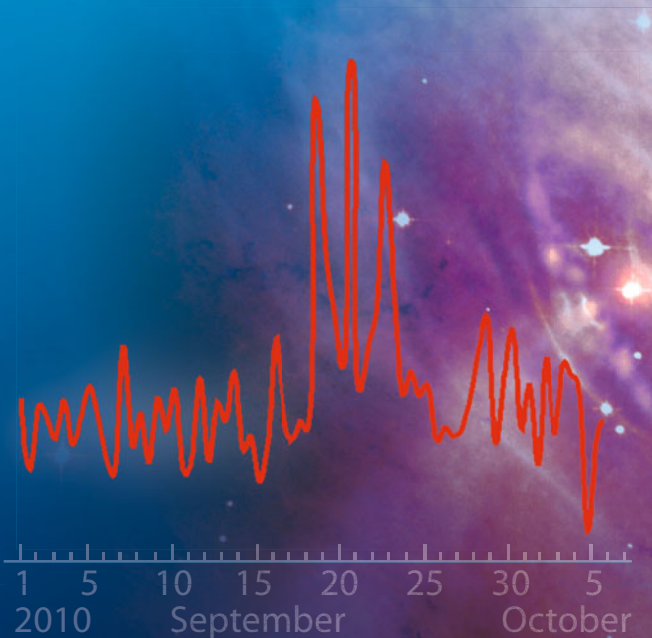


Saas-Fee Advanced Course 40  
Swiss Society for Astrophysics and Astronomy

Felix Aharonian  
Lars Bergström  
Charles Dermer

# Astrophysics at Very High Energies



 Springer

# SaaS-Fee Advanced Course 40

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Felix Aharonian · Lars Bergström  
Charles Dermer

# Astrophysics at Very High Energies

Saas-Fee Advanced Course 40

Swiss Society for Astrophysics and Astronomy  
Edited by R. Walter and M. Türler

 Springer

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This Series is edited on behalf of the Swiss Society for Astrophysics and Astronomy:  
Société Suisse d'Astrophysique et d'Astronomie Observatoire de Genève, ch. des Maillettes 51,  
CH-1290 Sauverny, Switzerland

*Cover Illustration:* A composite image of the Crab Nebula showing the X-ray (blue), and optical (red) images superimposed. The X-ray emitting region is smaller because the higher energy X-ray emitting electrons radiate away their energy more quickly than the lower energy optically emitting electrons. The inner ring is about one light year across (Credit: X-ray: NASA/CXC/ASU/J. Hester et al.; Optical: NASA/HST/ASU/J. Hester et al.). The inset features the gamma-ray variability of the central part of the pulsar wind nebula, as observed by the Fermi/LAT, indicating that electrons are accelerated up to PeV energies, the highest energy electrons ever measured (Credit: ISDC/M. Balbo).

ISSN 1861-7980 ISSN 1861-8227 (electronic)  
ISBN 978-3-642-36133-3 ISBN 978-3-642-36134-0 (eBook)  
DOI 10.1007/978-3-642-36134-0  
Springer Heidelberg New York Dordrecht London

Library of Congress Control Number: 2013932553

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# Preface

The 40th “Saas-Fee Advanced Course” of the Swiss Society for Astrophysics and Astronomy devoted to Astrophysics at Very-High Energies was held from March 14 to 20, 2010 in Les Diablerets, in the Swiss Alps. It gathered 105 participants and included a Fermi hands-on tutorial and an INTEGRAL data analysis tutorial.

The course was organized as 28 lectures reviewing the state of knowledge, open questions, and forecasts in the field of high and very-high energy gamma-ray astrophysics, a field that has encountered a revolution in the last years with the success of Cherenkov astronomy and the launch of the Fermi mission. Impact of gamma-ray observations on our knowledge of particle acceleration in galactic and extragalactic sources were reviewed as well as the prospects for dark matter detection and advances from the multi-messenger approaches.

The lectures were given by three world experts in the field:

Prof. Felix A. Aharonian is Professor of Astrophysics at the Dublin Institute for Advanced Studies (Ireland) and the Head of the High Energy Astrophysics Theory Group at the Max-Planck-Institut für Kernphysik in Heidelberg (Germany). His main scientific interests are the processes in thermal and non-thermal relativistic plasmas, physics and astrophysics of relativistic winds and jets, non-thermal processes in large-scale AGN Jets and in clusters of galaxies, the origin of galactic and extragalactic cosmic rays, the diffuse extragalactic background radiation, observational gamma-ray cosmology, and the imaging atmospheric Cherenkov array technique. Prof. Aharonian is involved in a number of major high energy experiments, in particular as a member of the Science Working Group of ASTRO-H, of the Collaboration Board of H.E.S.S. and of the Consortium Board of KM3NeT.

Prof. Lars Bergström is Professor at the University of Stockholm (Sweden) and the Head of the Cosmology, Particle Astrophysics and String Theory Group. He is also Director of the Oskar Klein Centre for Cosmoparticle Physics. One of his main lines of research is the investigation of the nature of dark matter, in particular supersymmetric and Kaluza-Klein particles and the prediction of indirect detection rates of various dark matter particle candidates. His group is active in many aspects of observational and theoretical supernova cosmology, gravitational lensing, determination of cosmological parameters, models for dark matter, and

string cosmology. He is collaborating in various experiments to search for evidences for dark matter, in particular Fermi, IceCube and PAMELA.

Dr. Charles D. Dermer is the Head of the Space Radiations Section in the Space Science Division of the Naval Research Laboratory in Washington, DC. His interests cover many areas of astrophysics, including cosmic rays, the multi-wavelength astronomy of blazars, the physics of neutron stars and black holes, gamma-ray bursts, merging clusters of galaxies, and solar flares. He uses theoretical modeling, supported by numerical simulations of the basic physical processes involving high-energy interactions between particles and photons in magnetized plasma, to identify the nature of high-energy astronomical sources and the physical mechanisms responsible for the observed gamma ray and particle emissions. Dr. Dermer was one of four GLAST Interdisciplinary scientists, and is currently a full Fermi Collaboration Member. He has served on numerous review and study panels, including the Advanced Compton Telescope Working Group and the VERITAS External Oversight Committee.

This volume of the Saas-Fee lecture notes provides a broad overview of astrophysics at high and very-energy energies, as well as an introduction to multi-messenger astronomy and the possible nature of dark matter. Prof. Felix Aharonian presents the breakthrough in very-high energy gamma-rays achieved by the current generation of Cherenkov telescopes. He describes the main results and their implications for theoretical models of the TeV gamma-ray emission with a focus on Galactic sources. Dr. Charles Dermer follows a similar approach for the other breakthrough in high-energy observations achieved by the Fermi gamma-ray space telescope in the spectral window of GeV gamma-rays. In this second part, emphasis is given on the physics at play in blazars—the most extremely luminous and variable active galactic nuclei—as constrained by the unprecedented gamma-ray observations by Fermi. The third contribution to this book is of a quite different nature. Prof. Lars Bergström gives us a broad overview of multi-messenger astronomy and the quest of identifying the nature of dark matter both theoretically and experimentally. He perfectly succeeded in making the challenges of current astroparticle physics and theoretical cosmology understandable to astronomers.

We are very grateful to the lecturers for their enthusiasm in communicating their deep knowledge, their brilliant lectures, as well as for writing the rich manuscripts composing this book. We extend our warmest thanks to the course secretary, Martine Logossou, for her effective administration of registrations, of the budget, and her organizational help during the course. We acknowledge the design of the course poster by Jean-Christophe Leyder. We also would like to thank all speakers of the INTEGRAL tutorial session held on Thursday afternoon. In particular, Peter Kretschmar from ESA and our colleagues from the ISDC Data Centre for Astrophysics: Enrico Bozzo, Carlo Ferrigno, Lucia Pavan, Nicolas Produit, Claudio Ricci, and Reiner Rohlfs. Last but not least, we thank Elizabeth Hays and Elizabeth Ferrara from the NASA Fermi Science Support Center and

Andrea Tramacere from the ISDC to offer the course participants the opportunity of a hands-on session on Fermi data analysis.

One of the highlights of the course was the concert “Il Viaggio d’Amore”, a love journey from the Renaissance to nowadays, offered by Arianna Savall Figueras and Petter Udland Johansen. Many participants made a memorable walk with torches from Les Diablerets to the little church of Vers l’Eglise where the concert took place. It was a magical evening and we would like to thank again the two outstanding performers for their delighting music.

The Eurotel-Victoria provided—as so often in the past—a pleasant environment for the Saas-Fee Course and a generous banquet dinner. The organization of this course would not have been possible without the financial support of the Swiss Society for Astrophysics and Astronomy (SSAA), the Swiss Institute of Particle Physics (CHIPP), and the Swiss Academy of Sciences (SCNAT). We are very grateful to these organizations for their contribution, which allowed the participants to attend a very diverse, interesting, and successful 40th Saas-Fee Course.

Versoix, October 2012

Roland Walter  
Marc Türler





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# Gamma Rays at Very High Energies

Felix Aharonian

## 1 Introduction

Cosmic gamma rays carry key information about high energy phenomena in a large variety of astrophysical environments. Being a part of *modern astrophysics* and *astroparticle physics*, gamma-ray astronomy is a discipline in its own right [52]. It addresses an impressively broad range of topics related to the non thermal processes in the Universe, including acceleration, propagation, and radiation of relativistic particles on all astronomical scales: from compact objects like pulsars (neutron-stars) and microquasars (accreting stellar mass black holes) to giant jets and lobes of radio-galaxies and galaxy clusters.

The gamma-ray phenomena generally proceed under extreme physical conditions in environments characterized with huge gravitational, magnetic and electric fields, relativistic bulk motions and shock waves, highly excited (turbulent) plasma, etc. Consequently, any coherent description and interpretation of phenomena related to gamma-rays requires deep knowledge of many disciplines of physics like nuclear and particle physics, quantum and classical electrodynamics, special and general relativity, plasma physics, magnetohydrodynamics, etc.

The energy range covered by gamma ray astronomy spans from 0.1 MeV to 100 EeV (throughout these lectures I will use the energy units which are common in high energy physics and astrophysics:  $1 \text{ keV} = 10^3 \text{ eV}$ ,  $1 \text{ MeV} = 10^6 \text{ eV}$ ,  $1 \text{ GeV} = 10^9 \text{ eV}$ ,  $1 \text{ TeV} = 10^{12} \text{ eV}$ ,  $1 \text{ PeV} = 10^{15} \text{ eV}$ ,  $1 \text{ EeV} = 10^{18} \text{ eV}$ ). While the lower bound associates with the region of nuclear gamma-ray lines, the upper bound is determined by the highest energy particles observed in cosmic rays. Because of the

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essentially different detection methods and approaches applicable to different energy bands, currently this enormous energy domain of cosmic electromagnetic radiation is covered inhomogeneously. In particular, so far cosmic gamma-rays are detected in ‘low’ (LE or MeV), ‘high’ (HE or GeV) and very high (VHE or TeV) energy bands.

## 1.1 Status of Observational Gamma Ray Astronomy

### (i) Low Energy Band: 0.1–100 MeV

This energy interval is uniquely linked to several astrophysical phenomena, in particular to the nucleosynthesis of heavy elements related to the type Ia supernovae (SNIa), Gamma Ray Bursts, Solar flares, interactions of sub-relativistic cosmic rays with the interstellar gas and dust, production and annihilation of positrons, etc. While many aspects of these phenomena can be best probed with low energy gamma-rays, the MeV gamma-ray sky remains an almost unexplored frontier. The main challenge of low energy gamma-ray astronomy is the design and construction of detectors with a sensitivity compatible to the conservative flux predictions. Unfortunately, the combination of several principal factors—the low detection efficiency, the modest angular resolution and the high level of backgrounds of different origin—severely limit the potential of detectors operating in this energy region.

The minimum detectable energy fluxes, even after significant improvements as foreseen for the next generation of low-energy gamma-ray detectors, will still remain modest, hardly better than  $10^{-12}$  erg/cm<sup>2</sup> s. Even so, low-energy gamma-rays are messengers of crucial astronomical information that cannot be obtained by other means. This concerns, for example the probes of the flux of sub-relativistic ( $E \leq 100$  MeV) cosmic rays in the Interstellar Medium (ISM) through the prompt *de-excitation* gamma-ray lines (see e.g. Ref. [178]). On the other hand, gamma-ray continuum at MeV energies produced via *bremsstrahlung* of electrons (positrons), as well as at the *positron annihilation in flight* (in sources with high positrons-to-electron ratio) contains unique information about relativistic electrons below 100 MeV [58]. In the environments with low magnetic field, in particular in the ISM ( $B \leq 10$   $\mu$ G), such an information is not accessible via synchrotron radio emission because it appears at non-visible frequencies below 1 MHz. The information about low-energy electrons and protons (nuclei) is important for the understanding of the energy balance between different forms of matter, magnetic fields and cosmic rays. In the galactic disk, such measurements have some other astrophysical implications, for example they provide direct estimates of the ionization and heating rates of the interstellar gas by low-energy cosmic-ray protons and electrons.

Another important implication of MeV gamma-ray emission is related to studies of mildly relativistic *thermal* plasmas formed in the vicinity of compact relativistic objects like neutron stars and black holes. The detection of characteristic MeV radiation dominated by the Comptonized free-free (*bremsstrahlung*) emission and electron–positron annihilation, gives direct information on electrons in such extreme thermal plasmas (see e.g. [223]). However, in most cases the fast radiative

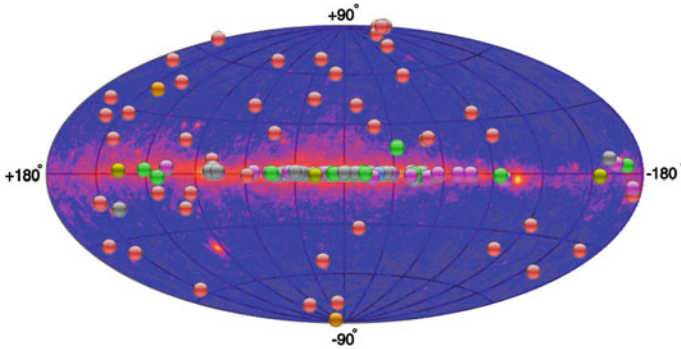
cooling of electrons prevents their heating to temperatures beyond  $10^9$  K, thus the electron cooling proceeds through radiation in hard X-rays. Consequently, the proton temperature can significantly exceed the electron temperature. The formation of hot two-temperature plasmas,  $T_i \gg T_e$ , in strong shock waves or in accretion flows close to black holes, can be studied by detection of characteristic gamma-ray line emission produced through the chain of spallation and excitation reactions. A clear signature of radiation at the final stage of such hot plasmas when all nuclei are destroyed and the nucleonic component of plasma basically consists of protons and neutrons (with a small fraction of deuterium in equilibrium), is the continuum due to the proton-neutron bremsstrahlung and the broadened and “blue-shifted” deuterium line [69]. In accreting solar-mass black holes, this radiation is released, depending on  $T_i$ , typically between 1 and 30 MeV.

Finally, one of the major objectives of MeV gamma-ray astronomy remains the exploration of 0.511 MeV line emission due to annihilation of the positrons which are copiously produced in various astrophysical environments (see e.g. the recent review [210] on the annihilation line from the Galactic Center).

(ii) *High Energy Band: 0.1–100 GeV*

Before the launch of the *Fermi Gamma-ray Space Telescope* (formerly GLAST) in May 2008, the high energy space-based gamma-ray astronomy has been dominated by the results obtained with the EGRET telescope aboard Compton Gamma Ray Observatory. Because of the rather modest angular resolution of EGRET (of order of a few degrees), only two source populations—the active galactic nuclei and pulsars—have been clearly identified as high energy gamma-ray emitters. With the *Fermi* LAT (Large Area Telescope) the HE gamma-ray astronomy entered a new era. This instrument with significantly improved (compared to EGRET) angular resolution ( $0.6^\circ$  at 1 GeV and better than  $0.15^\circ$  at energies above 10 GeV) and flux sensitivity (better than  $10^{-12}$  erg/cm<sup>2</sup> s) [86], is a perfectly designed tool for deep gamma-ray surveys with an effective field of view of order of 2 steradian. Over the last three years, *Fermi* LAT has been releasing vast amount of important astronomical information. The high energy gamma-ray sky revealed by *Fermi* (see Fig. 1) is really very impressive! These results confirm, to a large extent, the optimistic pre-launch expectations concerning, in particular, the dramatic increase of the number of gamma-ray emitting pulsars and AGN, discovery of new classes of *compact/variable* and *extended* galactic and extragalactic gamma-ray sources, the detection of multi-GeV components of GRBs, etc. The second *Fermi* LAT gamma-ray source catalogue [200], based on the first two years of observations, consists of almost 2000 galactic and extragalactic gamma-ray emitters. While more than half of these objects are associated with counterparts representing known source populations (more than one hundred sources being firmly identified), the origin of approximately 1/3 of these objects remains an open issue. This concerns, first of all, the extended sources located in the galactic plane, e.g. SNRs and PWNe, for which the chance of confusion with the diffuse emission of the galactic disk is especially high. Because of the limited angular resolution, the most reliable approach for identification of GeV gamma-ray sources is the analysis based on temporal studies. In this regard it is quite natural that the best “astronomical





**Fig. 1** The overall MeV/GeV gamma-ray sky (the *blue to red color* background) as seen by *Fermi* [200] and the positions of discrete TeV gamma-ray sources detected with ground-based instruments; the regularly updated version of this figure can be found on the “TeVcat” webpage: <http://tevcap.uchicago.edu>. The SNRs (in association with GMCs or without) are shown with a *green* symbol, the pulsar wind nebulae are shown in *violet*, the binary systems—in *yellow*, starburst galaxies—in *brown*, AGN (all types)—in *red*. The so-called “dark” sources without any reliable association with the well known objects are shown with a *grey* symbol

clocks”—the Pulsars—constitute the largest population of identified galactic GeV gamma-ray sources. The periodic character of gamma-ray emission of the galactic binary systems or the sporadic flares of AGN provide another tool for identification of variable gamma-ray sources based on simultaneous observations in different energy bands. In general, the multi-wavelength observations is a key component for identification of gamma-ray emitters, as well as for deeper understanding of the nature of these objects.

The *Fermi* observations significantly enhance our knowledge about the diffuse gamma-ray backgrounds of different origin. In particular, *Fermi* has extended the range of observations of the diffuse emission of the Galactic Disk and the isotropic (extragalactic) gamma-ray background to several hundreds of GeV and helped to clarify some controversial issues related to the contributions of different source populations and the relevant radiation mechanism.

A number of important results, especially at energies below 1 GeV, have been recently reported also by the Italian gamma-ray satellite *AGILE* [207]. In general, the observations by *Fermi* and *AGILE* support many phenomenological concepts and theoretical models in different areas of astrophysics. At the same time, these observations resulted in a number of “unplanned” discoveries and revealed some puzzling phenomena like flares of the Crab Nebula or existence of multi-kpc scale non-thermal structures—giant reservoirs of relativistic particles centered on the core of the Galaxy (“Fermi bubbles”).

Concerning the next generation space-based gamma-ray detectors, it is likely that in the foreseeable future one cannot expect significant developments beyond the level achieved by *Fermi* LAT, except perhaps for the energy band below 1 GeV down to several tens of MeV. The design and construction of a space-based instrument in

this energy interval with an affordable effective detection area of order of  $1 \text{ m}^2$  and angular resolution of about  $1^\circ$ , would increase significantly the detection rate (photon statistics) and improve the flux sensitivity of *Fermi* LAT below 1 GeV potentially by an order of magnitude. The optimization of the pair-conversion tracking detection technique with a focus on energies around 100 MeV would be an attractive and promising strategy given the number of outstanding astrophysical questions (relevant to nearly all source populations) not fully addressed by *Fermi* LAT.

(iii) *Very High Energy Band: 0.1–100 TeV*

One of the most remarkable achievements of recent years in astrophysics was the sudden emergence of very-high-energy gamma-ray astronomy as a truly astronomical discipline. The observations conducted by HESS, MAGIC, VERITAS (see Figs. 4, 5, 6) and MILAGRO groups resulted in the discovery of many sources with a number in excess of 130 (see Fig. 1). These sources represent almost all major *non-thermal* astrophysical source populations, including shell type Supernova Remnants, Pulsar Wind Nebulae, Star Forming Regions, Giant Molecular Clouds, X-ray Binary Systems, Blazars, Radio-galaxies, Starburst Galaxies (for a review see e.g. [27, 154]). In general, this success was a big surprise, especially given the rather difficult past and the controversial history of the field over the last four decades (see e.g. [52, 248]). In this regard, a question naturally arises concerning the reasons which made possible this success. A likely answer to this question perhaps can be formulated as a fortunate combination of two independent factors:

- (a) the practical realization of the great potential of stereoscopic arrays of Imaging Atmospheric Cherenkov Telescopes (IACTs) as effective multifunctional tools for spectral, temporal, and morphological studies of VHE gamma-ray sources;
- (b) the existence of a large variety of perfectly designed machines—*TeVatrons*, *PeVatrons*, and *EeVatrons*—“factories” of relativistic matter where the effective particle acceleration is accompanied by effective radiation processes.

The discussion of the nature of VHE gamma-ray source populations constitutes a major purpose of this chapter.

## 1.2 Links to Other Disciplines

Gamma-ray astronomy has deep intrinsic links to other astronomical disciplines and cosmology. For example, relativistic electrons responsible for radio emission of the Galactic Disk, produce, at interactions with ambient gas and radiation fields, diffuse gamma-ray emission in the MeV and GeV energy bands. At higher (TeV) energies of electrons, the synchrotron radiation appears in the X-ray energy band, while the inverse Compton (IC) scattering of same electrons results in high energy gamma-rays in the TeV energy domain. The link between synchrotron X-rays and very high energy IC gamma-rays is common for source population of quite different origin, in particular for Supernova Remnants, Pulsar Wind Nebulae, X-ray binaries, Blazars,

etc. Another example is the interactions of cosmic ray (CR) protons with matter and radiation that produce  $\pi^0$  mesons, the decay of which results in the so-called hadronic component of gamma-rays. Neutrinos from decays of  $\pi^\pm$  mesons produced in same interactions, constitute the basis of high energy neutrino astronomy. The common origin of high energy neutrinos and hadronic gamma-rays as secondary products of interactions of cosmic rays is an indication of the important role of gamma-ray astronomy for realization of the so-called *multi-messenger* approach in the solution of the problem of origin of galactic and extragalactic cosmic rays—one of the key objectives of the new interdisciplinary research area called Astroparticle Physics.

The topics related to gamma-ray astronomy cannot be reduced to merely non-thermal phenomena. For example diffuse galactic and extragalactic infrared/optical radiation components have thermal origin and formally do not associate with high energy processes. On the other hand, they play an important role in production and absorption of high energy gamma-rays through the inverse Compton scattering and photon–photon pair production processes. This determines the deep links of gamma-ray astronomy to infrared and optical astronomies, as well as to cosmology. For example, the characteristic absorption features in the spectra of high energy gamma-rays arriving from distant extragalactic objects caused by interactions with the Extragalactic Background Light (EBL) contain unique cosmological information about the epochs of formation of galaxies and their evolution in the past. The indirect search for non-baryonic Dark Matter through high energy gamma-ray, as well as detection of gamma-radiation related to large scale cosmological structures (clusters of galaxies) are two other important (not yet realized) issues at the interface of gamma-ray astronomy and cosmology.

The above examples demonstrate the distinct feature of high energy gamma-ray astronomy as a *multi-disciplinary* research area and a key component of astroparticle physics in the context of *multi-wavelength* and *multi-messenger* approach in the studies of the most energetic processes in the Universe.

The links of the TeV domain to its closest neighbour—the GeV domain—are expected to be especially tight. It is generally believed that the TeV and GeV gamma-ray fluxes should strongly correlate, therefore the TeV gamma-ray sources should be also prominent GeV sources. However the GeV–TeV links are not so straightforward as it may look at first glance.

### **On the GeV–TeV Links**

Over the last several years the number of VHE sources have been dramatically increased; presently (first half of 2012) it exceeds 130. At first glance, it looks a modest achievement compared to the almost 2000 sources detected by *Fermi* LAT. However, when one takes into account the limited observation time (the duty factor of observations with Cherenkov telescopes does not exceed 10%) and the small field of view (less than 0.01 steradian) of IACT arrays, one may conclude that there should be a plenty of VHE gamma-ray emitters to be discovered by next-generation instruments.

It is expected that the next generation major ground based detector, the Cherenkov Telescope Array (CTA), with an order-of-magnitude improved sensitivity (see Sect. 2), will increase dramatically, by one or perhaps even two orders of magnitude, the number of VHE gamma-ray sources. However, the predictions on the number of VHE sources based on extrapolations from observations at other wavelengths, should be taken with a caution. Indeed, as long as we deal with poorly understood phenomena in a new energy band, often seemingly reasonable extrapolations could appear wrong. Moreover, since in sources of different power the acceleration, radiation and absorption processes can proceed with different efficiencies, the predictions based on the so-called ‘LogN–LogS’ relations, could lead to misleading conclusions even in the case of well established source populations. This rather general statement concerns all wavelengths of non thermal electromagnetic radiation, including the two closest neighbours—the GeV and TeV bands. For example, the increase of the overall luminosity of a compact object could reduce the maximum achievable energy of electrons (because of the enhanced inverse Compton cooling), and, at the same time, increase the probability for absorption of VHE gamma-rays inside the source. This kind of non-linear effects should have a strong impact on gamma-ray fluxes, but act in different energy bands quite differently. Consequently one should expect essentially different ‘LogN–LogS’ relations applied to GeV and TeV energies.

For copious gamma-ray production two conditions are required—an effective particle *accelerator* and a surrounding dense *target* in the form of gas, radiation or magnetic field. In the case of energy-dependent escape of particles (protons or electrons) from the accelerator, the resulting spectrum of particles inside the ‘old’ accelerator can be significantly *softer* than the spectrum of escaped particles outside the accelerator. Correspondingly, the gamma-ray spectrum from the accelerator will be softer compared to the energy spectrum of gamma-ray produced outside the accelerator. Since the diffusion of low energy protons is significantly slower, the impact of the escape is less critical for GeV gamma-rays. Thus an observer detecting GeV, but not TeV gamma-ray, from an accelerator at late epochs of its evolution, might conclude that we see an *active* source which however does not accelerate particles beyond TeV energies. But in reality, the accelerator could be a *dead* TeVatron or PeVatron. The ambiguity can be resolved through comparison of gamma-ray spectra detected from inside and outside the accelerator.

Because of propagation effects, the hadronic gamma-ray sources are expected to be more extended at TeV than at GeV energies. For example, the gamma-ray sources can be due to protons which left the accelerator and interact with nearby dense molecular clouds. In such cases gamma-rays can be produced predominantly from the clouds but not from the accelerator itself; the latter could be not active anymore, or the gas density inside the source cannot be sufficient for production of detectable gamma-ray fluxes. This might be a quite natural explanation of the so-called ‘dark accelerators’—VHE gamma-ray sources from regions without counterparts observed at other wavelengths. For electrons, which suffer significant radiative (synchrotron and inverse Compton) losses on time-scales shorter than the escape time, just an opposite picture is expected—strong VHE gamma-ray emission of IC origin from a

compact region which coincides with the accelerator, and more extended emission at lower energies from run-away electrons.

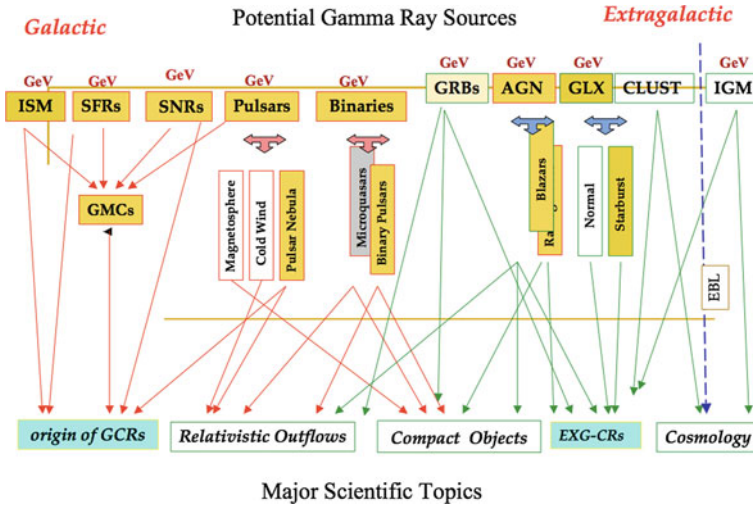
Finally, the energy dependent absorption of gamma-rays due to photon–photon collisions inside the compact objects can significantly change the original (production) spectrum of gamma-rays. The impact of absorption can be different for different energy intervals of gamma-rays depending on the spectral energy distribution (SED) of the surrounding target photon gas. For example, in compact X-ray regions, e.g. in accretion flows close to black holes, the absorption effect is strongest at GeV energies, while in binary systems containing luminous optical stars, TeV gamma-rays suffer most severe absorption.

In summary, depending on specifics of acceleration and propagation of charged particles (protons and electrons), as well as depending on the combination of gamma-ray production/absorption mechanisms, one can expect quite different relations between the GeV and TeV fluxes. They can correlate, anti-correlate, or behave in a random fashion. Thus, the energy spectra of GeV gamma-ray sources should not necessarily extend to TeV energies, while the TeV gamma-ray sources could appear without a GeV counterpart. Therefore the GeV and TeV gamma-ray sources can be represented quite differently in the given source population. For example, while the *Fermi* observations have proved that a large fraction of pulsars are prolific MeV/GeV gamma-ray emitters, the ground-based observations show that Pulsar Wind Nebulae radiate most effectively in the TeV gamma-ray band. On the other hand it is remarkable that both GeV and TeV gamma-rays are detected from sources representing almost all ‘suspected’ non thermal source populations of galactic and extragalactic origin, in particular from Supernova Remnants (SNRs), Pulsar Wind Nebulae (PWNe), Giant Molecular Clouds (GMCs), Compact Binaries (CBs), Starburst Galaxies, Radio Galaxies and Blazars. High energy gamma-rays are detected also from the Sun and Moon, as well as from Gamma Ray Bursts.

Figure 2 shows the populations of sources established as GeV and TeV gamma-ray emitters, and demonstrates the complex links related to several major research areas of astrophysics and astroparticle physics: Origin of Galactic and Extragalactic Cosmic Rays, Physics and Astrophysics of Compact Objects (Black Holes and Neutron stars), Relativistic Outflows (AGN jets and Pulsar Winds), Cosmology (Dark Matter, Extragalactic radiation and magnetic fields), etc.

## 2 Astrophysical Potential of Ground-Based Detectors

Earth’s atmosphere is not transparent to gamma-rays of any energy. Therefore, their registration requires detectors installed on space platforms. However, the satellites cannot offer, at least in the foreseeable future, detection areas significantly exceeding  $1 \text{ m}^2$ ; this constrains the *effective* studies of tiny fluxes of cosmic gamma-rays to energies  $\leq 100 \text{ GeV}$ . Fortunately, at higher energies an alternative method can be used for detection of gamma-rays. The method is based on the registration of atmospheric



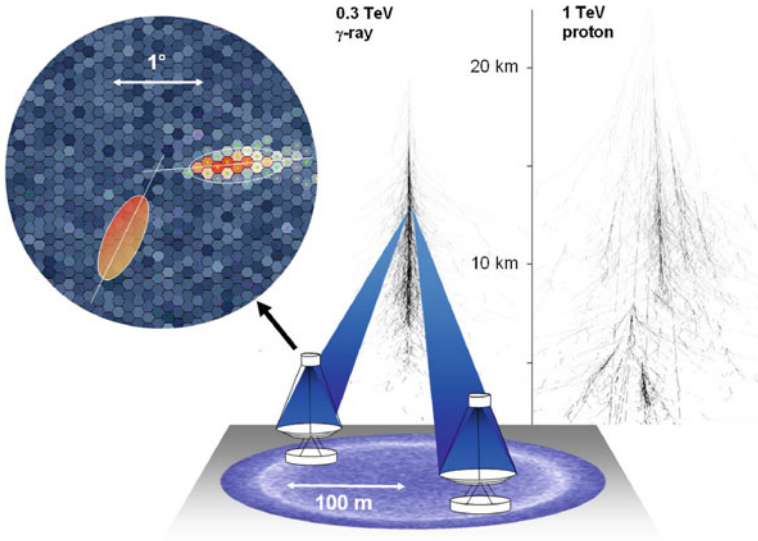
**Fig. 2** GeV and TeV source populations and the links between the major scientific topics

showers (initiated by interactions of gamma-ray) either directly or through their Cherenkov radiation.

The faint and brief Cherenkov signal which lasts only several nanoseconds can be detected by large optical reflectors equipped with fast multi pixel cameras. With a telescope consisting of an optical reflector of diameter  $D \approx 10$  m, and a multichannel camera with pixel size  $0.1^\circ\text{--}0.2^\circ$  and field-of-view  $\theta \geq 3^\circ$ , primary gamma-rays of energy  $\geq 100$  GeV can be collected from distances as large as 100 m. This provides huge detection areas,  $A \geq 3 \times 10^4$  m<sup>2</sup>, which largely compensate the weak gamma-ray fluxes at these energies. The total number of photons in the registered Cherenkov light image is a measure of energy, the orientation of the image correlates with the arrival direction of the gamma-ray, and the shape of the image contains information about the origin of the primary particle (a proton or photon). The basic principles of operation of the IACT technique is illustrated in Fig. 3.

The stereoscopic observations of air showers with two or more 10m diameter telescopes located at distances of about 100 m from each other provide a quite low energy threshold around 100 GeV, effective (by a factor of 100) rejection of hadronic showers, and good angular ( $\approx 0.1^\circ$ ) and energy ( $\approx 15\%$ ) resolutions (see e.g. [53]). At energies around 1 TeV, this results in a minimum detectable energy flux of  $10^{-13}$  erg/cm<sup>2</sup> (see Fig. 7), a quite impressive sensitivity even in the standards of advanced branches of astrophysics. In particular, it is much better than in any other gamma-ray domain, including the GeV energy band, where the sensitivity of *Fermi* LAT, even after dramatic improvement compared to the performance of the previous gamma-ray space-borne instruments, still cannot compete with the performance already achieved in the TeV energy band. Thanks to very large collection area, the IACT technique provides large gamma-ray photon statistics even from





**Fig. 3** The operation of the imaging atmospheric Cherenkov telescope technique (from Ref. [154])



**Fig. 4** The HESS system of four 13 m diameter Cherenkov telescopes. While this system has been operating in Namibia since 2003, the new 28 m diameter telescope is under construction (the picture in the center of the original HESS array is a photo montage)

relatively modest TeV gamma-ray emitters. Coupled with good energy and angular resolutions, the rich photon statistics allows deep morphological, spectral, and temporal studies. This makes the IACT arrays perfect multifunctional and multi-purpose astronomical tools for exploration of a broad range of non-thermal objects and phenomena, both of galactic and extragalactic origin. Currently, three major IACT arrays (see Figs. 4, 5, 6) HESS (High Energy Stereoscopic System), MAGIC (Major Atmospheric Imaging Cherenkov) and VERITAS (Very Energetic Radiation Imaging Telescope Array System)—located both in the northern (MAGIC, VERITAS) and southern (HESS) hemispheres, determine the status of VHE gamma-ray



**Fig. 5** The system of two 17 m diameter MAGIC gamma-ray telescopes at the Roque de los Muchachos observatory (La Palma, Canary Islands)

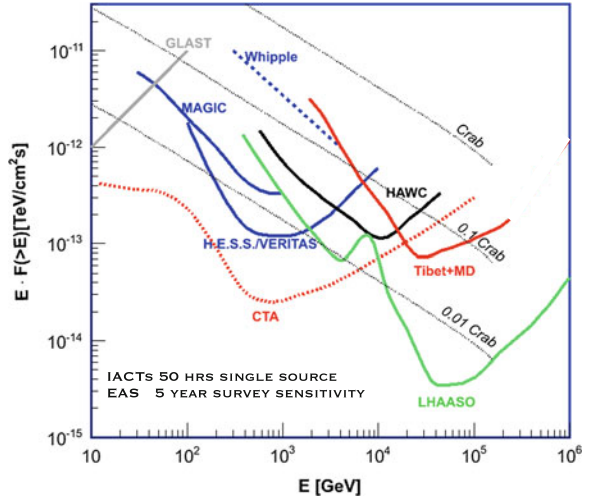


**Fig. 6** The VERITAS system of four 12 m diameter Cherenkov telescopes located in southern Arizona

astronomy. What concerns the previous generation instruments, one should mention, amongst others, the 10 m diameter single dish of the Whipple Observatory (south Arizona) and the HEGRA array of five relatively modest (4 m diameter) Cherenkov telescopes (La Palma, Canary Islands). These instruments, which can be considered as prototypes of the current IACT arrays, played a crucial role in the development of ground-based gamma-ray astronomy. While the Whipple collaboration pioneered the implementation and successful realization of the *imaging* atmospheric Cherenkov technique, the HEGRA collaboration convincingly demonstrated the power of the *stereoscope* approach. In this regard, it is not a big surprise that the performance of the current (and the next) generation IACT arrays are not far from the early predictions based on the extrapolation of the performance of the single Whipple dish and the HEGRA telescope array (see e.g. [52]).



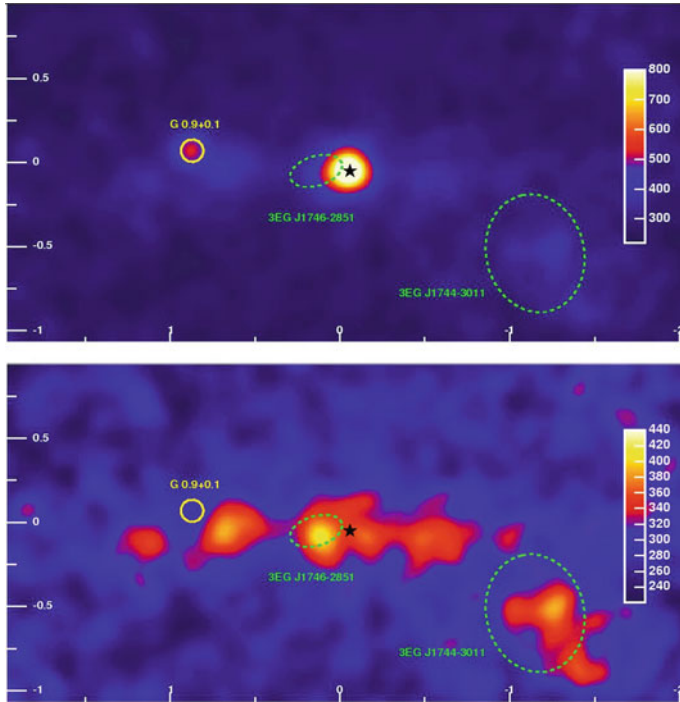
**Fig. 7** The energy-flux sensitivities of the current and future ground-based detectors—the IACT and EAS arrays in the energy range  $10^{10}$  to  $10^{16}$  eV (courtesy of Gus Sinnis)



## 2.1 IACT Arrays

Figures 7, 8, 9, and 10 represent three characteristic examples demonstrating the great performance of the stereoscopic IACT technique for morphological, spectral and temporal studies, respectively.

- (i) Figure 8 shows the VHE gamma-ray map of an extraordinary site—the central several hundred parsec region of our Galaxy which harbours a variety of potential gamma-ray emitters. This region has been predicted as a possible gamma-ray source also because of predicted sharp concentration of Dark Matter. Deep observations of HESS did reveal that this compact region (angular size less than  $2^\circ$ ) is packed with several gamma-ray sources, including a point like source in the very center of the Galactic Center, diffuse emission contributed by giant molecular clouds, a composite supernova remnant, as well as an interesting but not yet identified extended source.
- (ii) Figure 9 demonstrates the power of the IACT technique for spectroscopic studies. The energy spectra of two active galactic nuclei, Mkn 421 and Mkn 501, have been measured by the HEGRA IACT array. The spectra based on very large gamma-ray statistics (60,000 and 40,000 from Mkn 421 and Mkn 501, respectively), detected during high states of these objects, can be fitted with the canonical “power-law with exponential cut-off” function. Note that the measured spectral points extend beyond  $3E_0$ ; this is a remarkable result even for the standards of laboratory experiments.
- (iii) High detection rates of gamma-rays by IACT arrays are possible even for relatively modest energy gamma-ray flux of about  $10^{-11}$  erg/cm<sup>2</sup> s. This makes these instruments powerful tools for temporal studies of highly variable VHE sources. This is demonstrated in Fig. 10 for a major flare of the blazer

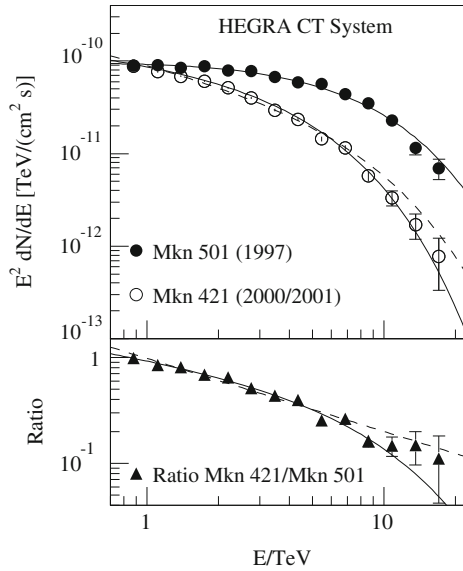


**Fig. 8** The image of the several-hundred parsec region of the Galactic Center in TeV gamma-rays. It contains a point like source (angular radius less than a few arcminutes) the gravity center of which coincides with an accuracy of 13 arcseconds with the compact radio source Sgr A\*—a super massive *black hole* at the dynamical center of the Milky Way [21, 32]. The second point like source located about one degree away positionally coincides with the composite supernova remnants G09+0.1 [37]. A prominent feature of this region is the ridge of diffuse emission tracing several well identified giant molecular clouds [39]. This complex region contains some other, not yet firmly identified, “hot spots”

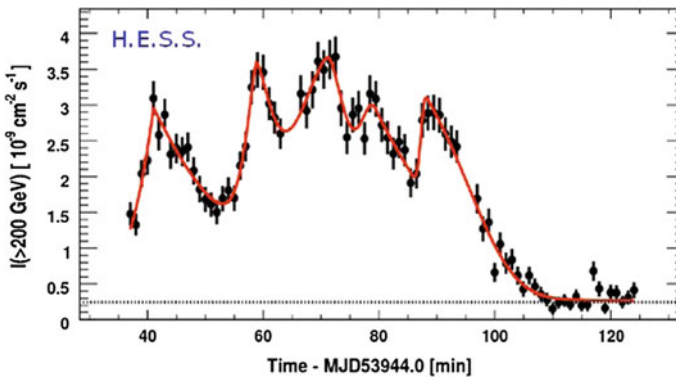
PKS 2155-304 on the night of July 29–30, 2006. The outburst was so powerful that the detection rate of VHE gamma-rays by the HESS telescopes “jumped” a level of several (background-free) events per second leading to the discovery of variability of the source on an exceptionally short time-scale of about 2–3 arcmin.

## 2.2 Potential of EAS Arrays

The IACT arrays are designed for observations of point-like or moderately extended (with angular size  $1^\circ$  or less) objects with known celestial coordinates. However, the high sensitivity and relatively large ( $\geq 4^\circ$ ) field of view of IACT arrays allow effective all-sky surveys as demonstrated by the HESS collaboration. On the other hand, the potential of IACT arrays is limited for the search of very extended structures (like



**Fig. 9** The energy spectra of active galactic nuclei Mkn 501 and Mkn 421 measured by the HEGRA stereoscopic system of Cherenkov telescopes in the high states (from Ref. [30]). The spectra are well described by “power-law with exponential cut-off”,  $E^{-\Gamma} \exp(-E/E_0)$ , with  $\Gamma = 1.92$  and  $E_0 = 6.2 \text{ TeV}$  for Mkn 501, and  $\Gamma = 2.19$  and  $E_0 = 3.6 \text{ TeV}$  for Mkn 421. To demonstrate the difference in two energy spectra and to reduce the impact of possible systematic effects, the ratio of the Mkn 421 and Mkn 501 spectra is shown in the *lower panel*



**Fig. 10** The *light curve* of the exceptional outburst of the blazar PKS 2155-304 on the night of July 29–30 2006. More than 10,000 gamma-rays have been detected during 90 min leading to extraction of sharp flares on minute time-scales

diffuse emission of the galactic disk), as well as for the solitary events like GRBs. In this regard, the detection technique based on direct registration of particles that comprise the extensive air showers (EAS), is a complementary approach to the IACT technique.

The traditional EAS technique, based on scintillators or water Cherenkov detectors spread over large areas, works quite effectively for detection of cosmic rays at ultra-high energies,  $E \geq 100$  TeV. In order to make this technique more adequate to purposes of gamma-ray astronomy, the detection energy threshold should be reduced by two orders of magnitude. This can be achieved using dense particle arrays located on very high altitudes. The feasibility of both approaches recently have been successfully demonstrated by the ARGO and Milagro groups. The significance map of the galactic plane region  $l \in [30^\circ, 220^\circ]$  and  $b \in [-10^\circ, 10^\circ]$  obtained with the Milagro detector [13] is shown in Fig. 11. Eight candidate sources at a median energy of  $\sim 20$  TeV have been found with pre-trial significance  $\geq 4.5\sigma$ . After accounting for the trials over  $\approx 400$  square degree region, four of these candidates survived as reliable detections with an after-trial statistical significance exceeding  $4\sigma$ .

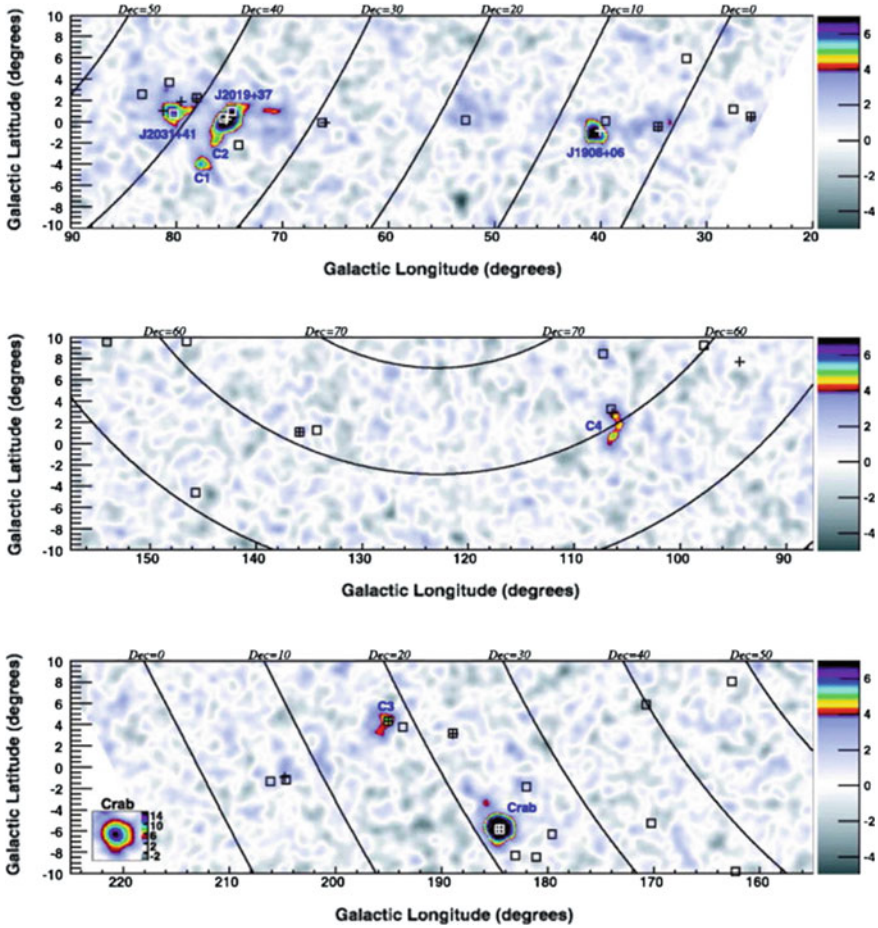
These results, as well as the prospects of continuous monitoring of a significant part of the sky, which might lead to exciting discoveries of yet unknown VHE transient phenomena in the Universe, justifies the new proposals of high altitude EAS detectors (see for a review [27]) like HAWK, a High Altitude Water Cherenkov Experiment under construction on a site close to Sierra Negra, Mexico. The 5 year survey sensitivity of HAWK at energies between 1 and 10 TeV is expected to be comparable to the sensitivity of *Fermi* around 1 GeV. In this regard *HAWK* will be complementary to *Fermi* for continuous monitoring of more than 1 steradian fraction of the sky at TeV energies. At higher energies, one should mention the ambitious LHAASO (Large High Altitude Air Shower Observatory) detector facility at Yangbajing, Tibet. This array consisting of several types of detectors of electromagnetic and muon components of air showers will cover huge area and achieve an impressive sensitivity at energies of several tens of TeV.

### 2.3 Future IACT Arrays

Planning of the next generation of Imaging Atmospheric Cherenkov Telescope (IACT) arrays has two major objectives: (i) an order of magnitude improvement of the flux sensitivity in the standard 0.1–10 TeV energy interval (TeV regime), and (ii) an aggressive expansion of the energy domain of IACT arrays in both directions—down to 10 GeV (multi-GeV regime) and well beyond 10 TeV (sub-PeV regime).

#### TeV Regime

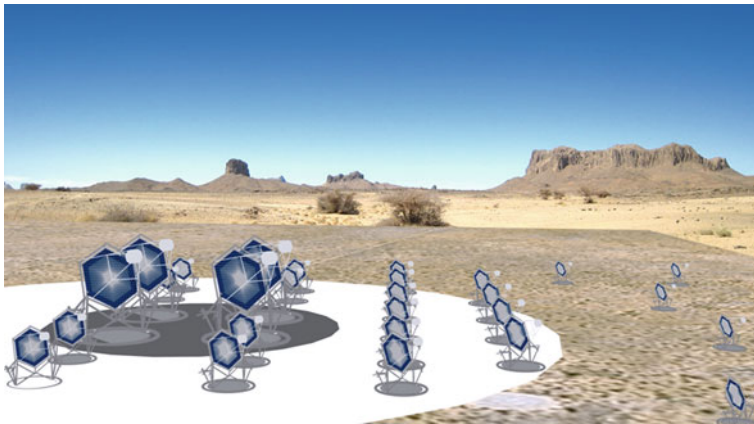
The best performance the IACT technique is achieved in this energy regime, and still the potential is not saturated. The combination of three basic factors, (i) high



**Fig. 11** Significance map of the Galactic plane at energies above 20 TeV produced on the basis of MILAGRO data [13]. The *color code* shows the pre-trials significance in this PSF-smoothed map. The maximum positive value of the color code saturates at  $7\sigma$ , although three of the gamma-ray sources are detected with higher statistical significance

efficiency of detection/identification of electromagnetic showers, (ii) good accuracy of reconstruction of the direction and energy of primary gamma-ray, and (iii) large gamma-ray photon statistics, allows reduction of the minimum detectable energy flux to the level of  $10^{-14}$  erg/cm<sup>2</sup> s, and improvement of the angular resolution to  $\delta\theta \approx 2-3$  arcmin.

Such an impressive performance can be achieved by stereoscopic arrays consisting of tens of 10 m diameter class (HESS-type) telescopes. The flux sensitivity  $10^{-14}$  erg/cm<sup>2</sup> s at TeV energies would be a great achievement even in the standards of the most advanced branches of observational astronomy. This should allow



**Fig. 12** Layout of the future Cherenkov telescope array

us to probe the gamma-ray luminosities of potential TeV emitters at the levels of  $10^{32}(d/10 \text{ kpc})^2 \text{ erg/s}$  for galactic sources and  $10^{40}(d/100 \text{ Mpc})^2 \text{ erg/s}$  for extragalactic objects. Although for moderately extended sources, e.g. of angular size  $\Psi \sim 1^\circ$ , the minimum detectable energy flux will be by a factor of  $\Psi/\delta\theta \sim 10\text{--}30$  higher, yet it would be better than the energy flux sensitivities of the best current X-ray satellites, *Chandra*, *XMM-Newton*, *INTEGRAL* and *Suzaku*, i.e. should allow the deepest probes of non thermal high energy phenomena in extended sources, in particular in shell type Supernova Remnants (SNRs), Giant Molecular Clouds (GMCs), Pulsar Driven Nebulae (Plerions), Clusters of Galaxies, hypothetical Giant Pair Halos around AGN, etc. Such a system of 10–12 m diameter class IACTs with a field of view (FoV) of  $6\text{--}8^\circ$ , most likely will constitute the core of the Cherenkov Telescope Array (CTA)—an initiative towards the major ground-based gamma-ray detector (see Fig. 12). The huge area covered by tens of telescope should provide dramatic increase of the gamma-ray photon statistics. On the other hand, the detection of the cascades in many projections will improve the angular resolution, and the efficiency of suppression of hadronic showers. All these factors should allow an improvement of the sensitivity of CTA in the TeV region, compared to the current instruments, by a factor of five (see Fig. 7). Correspondingly, the required observation time of the objects would be reduced by a factor of 25.

### Sub-PeV Regime

The general tendency of decreasing gamma-ray fluxes with energy becomes especially dramatic above 30 TeV. The reasons could be different, e.g. external and internal absorption of gamma-ray, limited efficiency of particle acceleration processes, escape of highest energy particles from the production region, etc. Any meaningful study of cosmic gamma-rays beyond 30 TeV requires detection areas