Physics and Astrophysics with a ground-based gamma-ray telescope of low energy threshold

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Abstract

Ground-based Cherenkov telescopes have made in recent years important contributions to high-energy gamma-ray astronomy. A lower energy threshold, considerably below 100 GeV, and improved sensitivity will be key parameters to extend their role. A lower threshold will permit these instruments to cover wavelengths with good overlap with satellite experiments, thus providing essential complementary information.

The latest generation of Imaging Air Cherenkov Telescopes was built with this criterion in mind. Preliminary studies concerning further progress in the same direction have started.

We discuss in this contribution the astrophysics and physics arguments for lowering the observable energy threshold as far as the Cherenkov technique permits, and the ensuing complementarity to results obtained with a GLAST-like satellite.

Key words: low-energy gamma-ray, Cherenkov telescope, astrophysics, cosmology

1 Introduction

Achievable sensitivity and energy threshold characterize more than other parameters the ability of Imaging Air Cherenkov Telescopes (IACTs) to operate in a wavelength domain overlapping with satellite experiments, and to complement their results. Detectors of the now operational latest generation of IACTs (CANGAROO [1], H.E.S.S. [2], MAGIC [3], VERITAS [4]) as well as STACEE [5], based on a solar array, have been designed with this objective in

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mind. In particular, MAGIC (phase 1, with conventional photomultipliers) and STACEE were proposed with the explicit goal of lowering to some 30 GeV the energy threshold at which gamma-rays can be observed. Preliminary results [6], [7], [8] indicate that this goal can be achieved.

Undoubtedly these new detectors will produce new physics in the future, and it is likely that beyond the predicted, new avenues will open. For many unanswered physics questions, an energy threshold even lower than what will be achieved in the near future could hold the key. This seems within reach if a bold increase in the light collection area is combined with innovations in technology of light-to-electron conversion. In particular, we think of large, highly reflective aspherical mirrors with improved and permanently active focusing control, and of the latest commercially available photodetectors. Eventually, an energy threshold as low as 10 GeV might be reachable. Such a telescope will be complementary to the gamma-ray satellite GLAST [9], [10], the much more powerful gamma-ray survey successor of EGRET, to be launched in 2007.

In this paper we present the science case for a low-threshold telescope (LTT), and make performance assumptions for such a device. Besides the obvious astrophysical interest in the extension to a new domain in the energy of gamma-rays, astronomical objects have been proposed as a good laboratory to study fundamental physics, not accessible to accelerator facilities. Such measurements can be performed in particular in Gamma-ray Astronomy through IACTs. By collecting large and statistically significant samples of gamma-rays in the energy range from 10 or 20 GeV upwards, overlapping with satellite observations, a whole plethora of subjects comes into reach. We discuss them in sections 3 and 4; very briefly, they are the following:
Fundamental physics: *Gamma-Ray Horizon, Dark matter, and Quantum gravity.*
Astrophysics: *Gamma-Ray Bursts, Supernova remnants,Pulsars,Active Galactic Nuclei, Diffuse photon background, Unidentified EGRET sources, and Nearby galaxies.*

In section 2 we give a brief outline of detector concepts for achieving a low energy threshold. We will discuss separately how the technical problems for one such telescope can be solved, and will give detailed estimates for its performance, based on simulations [11]. Sections 5 and 6 discuss the necessity of multi-wavelength observations and position a ground-based low energy threshold telescope with respect to GLAST.

2 Concepts for a low threshold telescope (LTT)

The window for TeV gamma-ray astronomy was opened only 15 years ago, when the Whipple collaboration reported the observation of gamma emission from the Crab Nebula [12]. In the preceding decades, many experiments with different detection techniques had searched, unsuccessfully, for gamma-ray sources in the energy range above 1 TeV. The breakthrough came by the observation of Cherenkov light produced in air showers, coupled with a technique to analyze (then with a photomultiplier camera of rather coarse pixels) the shower signals in order to filter the rare gamma-ray shower 'images' from the charged Cosmic Ray (CR) background, more frequent by many orders of magnitude. In the following years the technique of 'imaging atmospheric Cherenkov telescopes' (IACTs) was continuously refined. Along with the successes of these detectors, it was also recognized that a lower detection threshold, around a few GeV, and an increased sensitivity will be needed in order to obtain an overlap in energy between satellite-borne detectors and IACTs. As ground-based IACTs are lowering their energy threshold, the future satellite detectors are pushing up their energy limits: the future GLAST detector will reach up to 300 GeV. GLAST is well suited for detailed studies in the MeV/low GeV energy range; towards higher energies, it is limited by statistics. Event rates will be sufficient to detect many new sources, but do not permit the measurement of spectra for most of these sources, except from the strongest ones. IACTs, on the other hand, are handicapped in discovering new sources by their limited field of view, which is at most $4-5^{\circ}$.

The current generation of high performance IACTs (CANGAROO [1], H.E.S.S. [2], MAGIC [3], STACEE [5], and VERITAS [4]) have typical thresholds in the range of 30 to 100 GeV. Recently, the discussions and first design ideas for IACTs of a threshold around 10 GeV have emerged. A mix of different techniques are pursued:

- The increase of the light collection area to counteract the low photon density at ground level (typically 1 photon/m^2 between 300-600 nm from a vertically incident 20 GeV gamma-ray shower at 2000 m asl). The photon density is to first order proportional to the primary energy, provided the impact parameter of the shower is less than $\sim$120 m (at sea level, and correspondingly smaller at higher altitudes). Three different directions are followed: the construction of telescopes at high altitude, for example 5@5 [13], the construction of a large array of modest diameter IACTs where the signals are electronically superimposed, as suggested by STAR [14], and ultra-large diameter IACTs, e.g. ECO-1000 [15].
- The use of high quantum efficiency (hQE) photosensors which at least double the QE of contemporary photomultiplier cameras. This approach is intensely pushed by the MAGIC collaboration. Two different lines are pur-

sued: the development of hybrid PMTs with a hQE red-extended GaAsP photocathode and semiconductor avalanche diodes acting as electron bombarded secondary amplifier [16], and the development of SiPMs, viz. Avalanche Photodiodes operating in the Geiger mode (G-APDs) [17]. The STAR collaboration [14] also plans to use PMTs with a hQE cathode, but with a channel plate as electron multiplier.
- By the same token, Cherenkov photon transport losses in the different elements of the telescope(s) must be minimized. Such improvements will also influence the light budget, albeit less than is possible by novel photo detectors. Examples are the use of mirrors approaching the quality needed for optical telescopes, with dielectric coating to achieve a reflectivity close to 100%, and the construction of light concentrators with minimal dead area and also minimal reflectivity losses in front of the photosensors (e.g. [18])
- The background light from the night sky increases with the mirror area, potentially deteriorating small signals. In order to minimize its influence and to optimally use the information from the short Cherenkov light flashes, one can minimize any signal deterioration in the detector by using a parabolic (= isochronous) mirror profile, ultrafast PMTs, and a signal pulse shape digitized with GHz frequencies. Besides the reduction of the night sky background (NSB), a precise pulse shape analysis opens new roads in discriminating gamma-rays and hadron or muon background.
- For completeness, we mention that new telescope designs will have to put considerable effort in improving the optical quality of the telescope; this implies reducing the point spread function, reducing stray light effects, increasing the number of pixels in the camera and the camera resolution, and improving the DAQ to cope with higher data rates. Also, a higher automation of the operation and improved calibration procedures will be needed.
- Continuous real-time calibration of the atmospheric transmission is another area where much progress can still be made; this can achieve much refined corrections for data.

In the past few years, technical progress in ground-based gamma-ray astronomy was very fast, resulting in a typical mid-lifetime upgrade time for IACTs of 3-5 years and a total lifetime rarely exceeding 7-8 years. It is expected that this rapid development will continue for the next one or two decades as optoelectronics is currently a leading field of technology worldwide. Although detailed studies and tests are missing, we think it is fair to extrapolate from the past rapid improvements towards the expected performance in a few years time.

Next, we want to elaborate more on some effects of increasing the mirror diameter and of using hQE photosensors. There is a correlation between the mirror diameter and the length of the track segment from which photons can be observed. To first order, the track length scales linearly with the diameter except for tracks close to ground. Approximately, a mirror of 10 m diameter collects light from a flight path of one radiation length (0.4 hadronic absorption length). From the requirement to have images with a sufficient number of photons/photoelectrons to be analyzable, it follows for small diameter mirrors that one has to collect photons from many different tracks, i.e., multi-track showers are naturally selected. For very large mirrors, in the diameter range of 25-35 m, a single straight track can produce sufficient light to satisfy trigger requirements. Such tracks can be muons or their hadronic parent particles above the Cherenkov threshold. Using PMTs with sub-nsec time resolution and a GHz digitizing system, discrimination between light originating from single tracks (in case of a parabolic mirror one expects a spread in photon arrival times of 100-200 psec) and light from electromagnetic showers (of typically 2-3 nsec time spread [19]) will become possible. Most hadronic showers will have an even wider spread in photon arrival time, in particular a tail of photons arriving late.

There exists also a limit on the mirror diameter coming from optical imaging errors. Too large a diameter will produce blurred images. This effect becomes more critical when installing the telescopes at high altitude, as the showers will be closer to the telescope; thus there is some cancellation between the higher number of collected photons/m^2 and the smaller allowed mirror diameter.

Current photosensors are the weakest element in the chain of collecting light and its conversion into an electronic signal. Today's mean QE between 300 and 600 nm of 12-18% indicates a significant improvement potential. It is conceivable that in a few years a QE of 40-50% can be reached by hQE PMTs or G-APDs. Both types of photosensors show high sensitivity extending well beyond 600 nm; the gain in detection efficiency will thus be most pronounced for Cherenkov light from very distant showers, where the UV and most of the blue photons are lost by Rayleigh scattering. Most advanced is the development of hybrid PMTs with GaAsP photocathodes [16]. Figure 1 shows a photo of first full-scale prototypes for the MAGIC II telescope.

It is expected that in a few years a camera with such sensors can be built, provided that some life-time limitations due to the accidental exposure to bright light can be overcome. The development of the G-APDs is slower, trailing by about 3-5 years. Current devices have neither reached the QE of hQE hybrid PMTs nor the necessary area, but progress is fast. A special feature to be mentioned for G-APDs is their low operation voltage (20-100 Volts) and their operation robustness. These devices can be left switched on without damage when exposed to bright light.

When approaching a threshold in the low GeV domain, one is confronted with a new background situation. The orientation and concentration information of gamma-ray images is degraded, and can no longer be the prime factor of gamma selection. There are other handles, though: Most cosmic hadrons at

Fig. 1. *Prototypes of hybrid photomultiplier tubes*

low energy are not 'seen' any more by the new instruments because all their shower particles (other than relativistic electrons) have a momentum below their Cherenkov threshold momentum. Also, the background due to single muons should be controllable by adequate telescope geometry and suitable fast signal processing.

Cosmic electrons then become the irreducible background. Depending on the telescope location and observation direction, the earth magnetic field will result in an energy cutoff for low energy electrons [20]. Another background source, relevant at lower energies, is the increased cross-section for single high energy π^0 production in proton-nucleon interaction. The resulting electromagnetic shower is essentially indistinguishable from a shower induced by a single gamma-ray, and even stereo systems are of little help.

Two other effects will in any case limit the performance of IACTs in the low GeV domain. The influence of the earth magnetic field on the shower particles cannot be ignored any more at low energies. Again, depending on the telescope location and observation direction, the shower particles will be significantly deflected. This requires new analysis methods and simulations.

The combination of atmosphere and telescope(s) form a fully active calorimeter; hence, as in any other calorimeter, the energy and angular resolution degrade at lower energy, being dominated by statistical fluctuation. As a rule of thumb the energy resolution around 30 GeV will be around 50%, worse than what will be achieved in the GLAST detector. The same holds for the angular resolution. The resolution of IACTs rapidly improves with increasing energy. In combination with the large detection area, also the sensitivity of IACTs increases with higher energy, nearly in proportion to the drop in flux typical of many sources.

Thus spectral studies in the very important energy region between 10 and 100 GeV become feasible. It is in this region that the Universe is expected to become transparent and sources can be observed at large redshifts. In order to study the so-called gamma-ray horizon, one has to measure spectra over an extended energy range. Clearly, IACTs can do this for many AGNs while this is hardly possible with the limited statistics of GLAST data, except for the strongest sources.

As discussed above, there are at least three projects under discussion, following different solutions to reach a low energy threshold. Generically we will use the name low threshold telescope (LTT) to discuss in the next sections the physics goals of these instruments. Knowing best the ECO-1000 project [15], we will quote the basic parameters of this telescope, although no fundamental differences compared to the two competing designs are expected. Very briefly, the main parameters of ECO-1000 are:

- a mirror with 34m diameter
- overall system Quantum Efficiency increased over present numbers by a factor ≥ 2.5
- optically improved mirrors with permanent active mirror control
- data handling capability up to 15 kHz trigger rate, and pulse height digitization with a sampling rate of 2 GHz and at least 10-bit dynamic range
- repositioning time to any point on the visible sky within ≤ 15 seconds, for Gamma-Ray Burst studies
- operation up to 90° zenith angle
- field of view sufficient to cover shower images from extended sources of 0.5° to 1.0° diameter, viz. a field of view $\geq 4°$ in diameter
- operation also during periods of moonshine (albeit with higher threshold), to extend the duty cycle

3 Fundamental Physics and Exotics

3.1 Gamma-Ray Horizon (GRH)

Gamma-rays from distant sources interacting with low energy photons can produce electron pairs and thereby disappear. Low energy photons from the vast inventory of stars and dust throughout the Universe exist in large numbers and they may be considered as a diffuse, isotropic, radiation field evolving with cosmic time, the metagalactic radiation field. The present-day intensity of the metagalactic radiation field is commonly denoted as the extragalactic background light (EBL).

The pair production probability increases with distance and energy, which gives rise to a relation between the e-folding energy of the attenuation factor and the distance, measured in redshift z, to the source. This relation has been coined the gamma-ray horizon, or Fazio-Stecker relation [21].

The detection of sources beyond the gamma-ray horizon is extremely difficult due to the flux suppression. This has been a strong argument for lowering the energy threshold for the present generation of instruments (MAGIC). Sources up to redshifts $z \sim 1$ should become accessible, at least at small zenith angles, where the observable energy reaches about 50 GeV. Given the fact that the activity of active galactic nuclei was largest at redshifts $z \sim 1$, studies of this population of gamma-ray sources strongly depend on observations in the 10 GeV - 100 GeV domain.

The models of the EBL include substantial uncertainties [22]. In order to accumulate data on many sources, it will be necessary to include observations at larger zenith angles, where the energy threshold is higher. This suggests that a threshold energy (at zenith) of around 30-50 GeV is still insufficient. Only lowering the threshold further will provide enough lever arm to measure with precision the exponential energy cutoff due to cosmological absorption, which sets in at about 20-40 GeV. The spectral density of the EBL will thus be established more accurately over the wavelength range from infrared to ultraviolet, constraining more strongly the models of star and galaxy formation and evolution [23], and provide better understanding of the propagation through intergalactic space of ultra-high energy ($> 10^{19}$ GeV) cosmic rays. Also, measurements of cosmological parameters through a determination of the GRH [24] should become possible with a large sample of AGNs distributed over a range of redshifts up to $z \sim 4$.

3.2 Dark Matter Search

Cosmology provides strong arguments that about 23% of the energy in the Universe are in the form of Cold Dark Matter (CDM). Weakly interacting massive particles (WIMPs) are thought the most natural stable candidates for CDM; they decoupled in the early Universe and could now be the dark matter constituents of halos and sub-halos around galaxies. They could then be found in our galactic center (GC) and in dark matter-dominated dwarf spheroidal satellites, identifiable by having a large mass-to-light ratio [25].

The Standard Model of Particle Physics has no candidate for WIMPs, but they have been explained [26] beyond it. Supersymmetry (SUSY) provides a natural non-baryonic candidate for WIMPs, the neutralino (χ). The neutralino could be the Lightest Supersymmetric Particle, stable if R-parity (a new quantum number associated to SUSY) is conserved. Experimental data [27] provide tight constraints for the annihilation cross section and neutralino mass, in order to account for the expected relic densities. Relic neutralinos might be detected directly through their elastic scattering when they impinge on targets on Earth. In addition they might be indirectly detected by their annihilation through different channels that produce high energy gamma-rays [28]. In particular, the processes $\chi\chi \longrightarrow \gamma\gamma$ and $\chi\chi \longrightarrow Z\gamma$ would provide smoking-gun observational signatures in form of monochromatic annihilation lines.

In general, these monochromatic processes are loop-suppressed, hence of low intensity. Also, they are difficult to resolve in Cherenkov telescopes due to their limited energy resolution. Another possible signature is $\chi\chi \longrightarrow jets \longrightarrow n\gamma$, which produces a continuous energy distribution different from the power law characteristic for cosmic acceleration mechanisms.

SUSY has several free parameters, but theoretical consistencies together with constraints from the non-observation (so far) restrict their possible space. Using Minimal Supergravity (mSUGRA), one of the most explored frameworks for SUSY, one obtains (details in [29]) possible values for the thermally averaged neutralino annihilation cross section and its mass, as shown in Figure 3.2. In this scenario, neutralinos compatible with WIMPs have masses from 70 GeV/c^2 up to 1400 GeV/c^2.

The dark matter profile of our galaxy has been recently modeled according to [30] and adiabatically compressed ([29] and references therein). Due to the infall of baryons to the Galactic Center during galaxy formation, the resulting dark matter density at the center increases. This profile is fully consistent with all available observational data for the Milky Way. Figure 3.2 shows the $\langle \sigma v \rangle$ exclusion limits computed for 250 hours observation time of the GC modeled by the compressed profile for ECO-1000 and MAGIC. The probability of observing a signal is clearly much improved by access to lower energies.

In indirect dark matter searches, some Milky Way dwarf spheroidals (such as Draco, Sagittarius or the recently discovered Canis Major) are of particular interest, because strongly dominated by their dark matter content (i.e. high mass-to-light ratio). Saggitarius and Canis Major dwarfs both are obscured by the Galactic Plane, and culminate, for observers in the Northern hemisphere, at high zenith angles, two arguments playing against their observation: objects in the Galactic Plane are penalized because of additional noise due to higher NSB, and a large zenith angle translates into a higher energy threshold. For the Galactic Center, there further is still limited knowledge on the most central part of the dark matter profile, such that the exclusion limits might be uncertain by 4-5 orders of magnitude. In addition, in case of a positive detection, an interpretation in terms of non-exotic galactic sources can not be

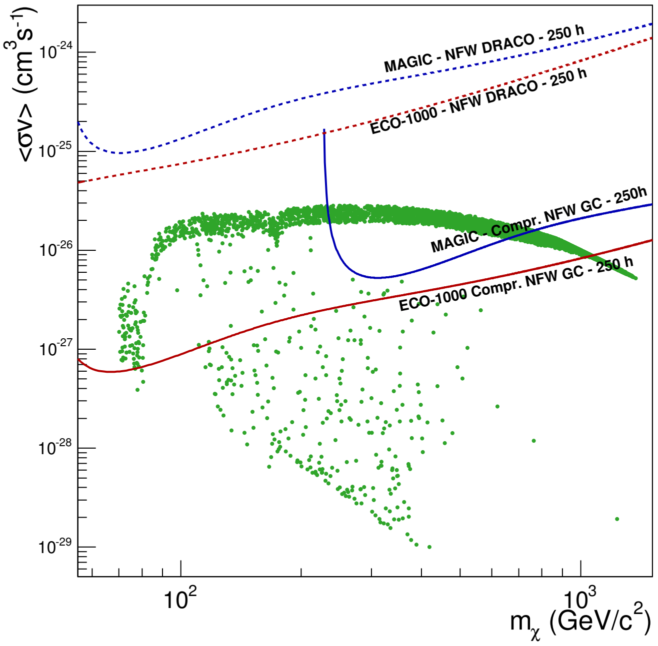

Fig. 2. *Allowed WMAP neutralino annihilation cross section* $\langle \sigma v \rangle$ *(thermally averaged) against mass* m_χ*, in the scanned mSUGRA scenario. The dashed and solid lines show expected exclusion limits for 250 hours observation time of the Draco dwarf spheroidal and the Galactic Center, respectively, assuming ECO-1000 and MAGIC. For the position of both detectors, the Galactic Center culminates at 60° zenith angle; their sensitivities and energy thresholds have been aprroximately scaled accordingly with* $\Phi_{min}(60^o) = \Phi_{min}(0^o) \cdot cos(60^o)$ *and* $E_{thr}(60^o) = E_{thr}(0^o) \cdot cos^{-2.7}(60^o)$*. For Draco, we consider a flux enhancement factor of 100, in order to account for substructure contributions within the line of sight.*

excluded.

Draco is 35° outside the Galactic Plane and has a favorable mass-to-light ratio; it could thus be a prime candidate for a Dark Matter search. A positive detection could be better interpreted within a Dark Matter scenario, and, in case of no detection, the upper limits will be tighter. Draco has more advantages: it is difficult to have contamination from a known emitter, the dark matter profiles do not suffer from the theoretical uncertainties which affect the GC, the NSB is at a minimum level, and the energy threshold of the Cherenkov Telescope is low (it culminates at 30° zenith angle for an observer in the Northern hemisphere).

We therefore have also considered Draco, adopting a dark matter profile model taken from [31]. Figure 3.2 shows the $\langle \sigma v \rangle$ exclusion limits computed for 250 hours observation of Draco with ECO-1000 or MAGIC. Under the given assumptions, a detection will require long observation times.

3.3 Quantum Gravity

Models of quantum gravity naturally contain quantum fluctuations of the gravitational vacuum, and can lead to predictions of an energy-dependent velocity for electromagnetic waves [32]. In other words, gamma-rays of different energy produced simultaneously in an astronomical object should arrive on Earth at different times, due to their propagation through the gravitational vacuum.

Even though the dispersion relation might be model-dependent, the time delay for GeV -TeV gamma-rays will be very small. All the same, it can be studied phenomenologically. In general, the delay can be expressed as an expansion of the dimensionless factor E/E_{QG}, where E_{QG} is an effective energy scale of Quantum Gravity, close to the Planck mass. Gamma-ray astronomy was proposed to probe this possible effect due to Quantum Gravity by observing energy dependences of a very rapid transient in a GRB [33]. Several measurements on an effective energy scale of Quantum Gravity have been carried out [34], [35], [36], based on this effect, with very different observational scenarios. All of them lead to lower limits for E_{QG}, down to 2 orders of magnitude below the Planck Mass.

In order to be sensitive to such an effect on the Planck Mass scale, the figure of merit for an IACT is to provide the most energetic detectable gamma-rays from the astronomical objects with the fastest emission changes and at the largest possible distances. In this category the prime candidates are GRBs or flaring AGNs. Due to their cosmological origin and the energy cut-off caused by the Gamma-ray Horizon, only detectors with a low energy threshold have a chance to detect them in the highest possible energy range. Other good candidates are pulsars. Although these objects are nearby, the period of their pulsation is well known, so they permit the measurement of time delays with high precision [36]. Also for pulsars, only detectors with a low energy threshold are suitable for the observation of the highest gamma energies due to the internal energy cutoff of their gamma-ray emission [37].

The effect of energy dependent delays due to the internal workings of the astrophysical source must be disentangled from those due to propagation effects such as Quantum Gravity. Hence a large number of sources at different redshifts and with different emission processes must be detected and measured with precision. An IACT with low energy threshold and high sensitivity will be an ideal instrument for such studies.

4 Astrophysics

4.1 Gamma-Ray Bursts

Nearly 3000 Gamma-Ray Bursts (GRBs) have been observed by BATSE, but the phenomena causing them are not fully understood. GRBs last between a fractions of a second and minutes, the X-ray emission typically runs on a scale of days, and the optical one even on a scale of weeks. Some BATSE observations (less than a percent) were complemented by EGRET, at $\sim$1 GeV of energy; however, both the field of view (FOV) and the sensitivity of EGRET were limiting factors. Encouraging is the fact that two of the EGRET-detected GRBs (GRB930131 and GRB940217) lasted longer inside the EGRET energy window than the observation in BATSE, so that an afterglow at higher energies can not be excluded, at least for some GRBs. The existence of exceptionally long GRBs, with the gamma-ray emission lasting clearly longer than emisssion in the hard X-ray range, is particularly challenging for theoretical models, that have to deal with a continuous acceleration process at a substantially higher energy than that of the prompt emission.

Multiwavelength observations of GRBs have been made possible by the fast distribution of the information coming mainly from satellites, in real time. The successful simultaneous observation of some GRBs at different wavelengths has favored, at least for longer lasting bursts, among the existing theoretical models that of a collapsing very massive star ejecting relativistic matter during a short accretion phase. While the fireball model for the initial burst is commonly accepted, theoretical models for the evolution of the emission from the burst ejecta expanding into the surrounding medium are still debated [38]. It is obvious that gamma-ray attenuation due to the metagalactic radiation field will take place, since GRBs are typically at large redshifts, rendering many of them invisible at energies above $\sim 20-40$ GeV. In turn, measurements of their high energy cutoffs will provide a new estimate of their redshifts, thus complementing optical follow-up studies which are unsuccessful in the majority of bursts.

Experimental data for higher-energy gamma-rays are not available; an LTT will thus be able to make a perhaps essential contribution, in a better position than GLAST: the limited FOV can be compensated by the fast repositioning system, assuming a trigger coming from a separate system, and the sensitivity is greatly increased by the calorimetric observation of gamma-rays typical of Cherenkov instruments. We expand on this in section 6.

Shell-type supernova remnants have long been suggested to be sites for cosmic ray acceleration below 100 TeV, mainly on the basis of general energetics arguments [39]. We know from their synchrotron, radio and X-ray emission that electrons are accelerated to TeV energies. SNRs have been detected at EGRET energies [40] and at TeV energies by IACTs, e.g. [41], [42], [43], [44].

However, there is no solid evidence for proton and ion acceleration. A possible signature of proton acceleration would be the spectrum of gamma-rays from π^0 decay arising from collisions of cosmic ray protons and nearby matter, like high density molecular clouds [45], which is symmetric (in log(E) scale) about 67.5 MeV. However, this signature could be washed out by electronic bremsstrahlung, as observed by EGRET. Another signature is provided by the high energies reached by protons and ions compared to electrons, producing a break in the spectrum when the hadronic emission begins to dominate [46]. Measuring this break requires accurate knowledge of the lower energy leptonic emission (bremsstrahlung, inverse Compton), which can be provided by an LTT. An angular resolution close to 0.1° at energies from 10 GeV up may permit discrimination of regions of enhanced matter density in direct interaction with the SNR shock, point source emission from pulsars inside the remnant, extended emission coincident with plerions, or regions of low density where the emission is most probably due to leptonic processes.

Plerions or Pulsar-Wind Nebulae are SNRs in which a pulsar wind injects energy into its surroundings. A bubble is inflated out to a radius where it is confined by the expanding shell, as already suggested by [47] for the Crab Nebula. Particle acceleration is expected in the wind termination shock. However, the flux of accelerated particles suffers adiabatic losses on leaving the expanding bubble, and therefore is believed to not contribute to the flux of cosmic rays in a major way.

Figure 3 shows the Crab plerion spectrum measured by EGRET at energies up to 10 GeV, and by Whipple and CANGAROO at TeV energies, along with the predicted spectra for different models [48]. The VHE emission is probably due to Inverse-Compton of electrons with $\Gamma > 10^8$. The observed synchrotron X-ray emission confirms the existence of these electrons of extremely high energy, while the dynamics of the particle flow only yields $\Gamma \sim 10^6$ for the postshock region.

A precise measurement of the spectrum in the 5-100 GeV energy range is crucial to constrain the model parameters and to ascertain if another source of photons is necessary, possibly bremsstrahlung from dense regions of gas.

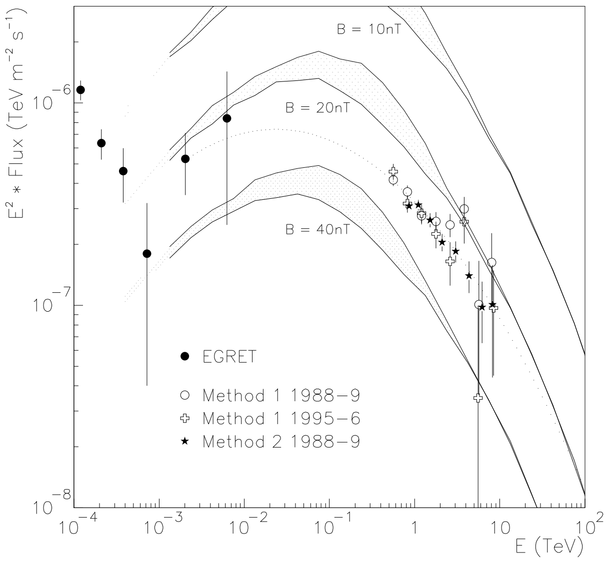

Fig. 3. *Predicted IC spectrum for the Crab Nebula according to the references in the text, compared to the EGRET, Whipple (method 1 and 2) and CANGAROO observed spectra.*

4.3 Active Galactic Nuclei

Nonthermal emission in blazars is a common phenomenon. In radio-loud blazars, a significant part of the bolometric luminosity is emitted in bipolar outflows. It is controversial whether the prime energy carrier in these jets is the Poynting flux or baryons. It is equally controversial how the energy flux of this carrier is converted into radiation in the relativistic jets, as they expand into the surrounding medium. Multiwavelength observations with high sensitivity to flux variations play a key role in solving this problem. An LTT is superior to a space-borne observatory, which has very limited sensitivity for short exposures.

Disentangling the leptonic and hadronic flux contributions to the gamma-ray emission will help uncovering the workings of the central engine in producing the jets. Since the strongly collimated gamma-rays seem to originate at the smallest scales in the jets, monitoring the gamma-ray lightcurve provides a measure of the internal dynamics of the central engine. Signatures of binary black hole systems, which are expected to be generally present in blazars, plasma instabilities and radiative limit cycles might show up in gamma-rays [49].

By lowering the IACT energy threshold significantly below 20-40 GeV where the expected gamma-ray horizon closes in, one can also expect to obtain measurements of the redshift evolution of gamma-ray emitting blazars. The co-

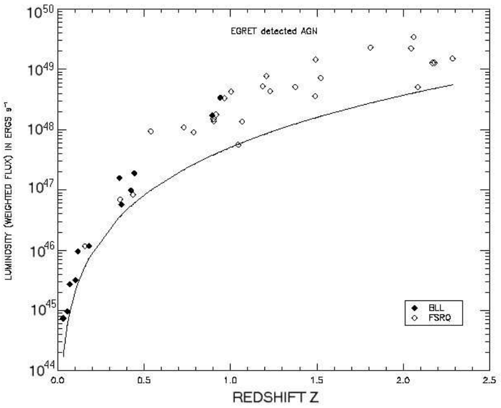

Fig. 4. *AGN luminosity at different redshifts, as measured by EGRET. The line indicates EGRET sensitivity.*

evolution of galactic bulges and central supermassive black holes is one of the crucial problems in extragalactic astronomy, amounting to the old question of what comes first, stars or black holes? Even obscured AGNs at high redshift might show up in gamma-rays owing to their penetrating nature. EGRET has, in fact, discovered a number of high redshift sources (fig.4).

4.4 Pulsars

The observation of gamma-ray pulsars in the GeV domain is of special interest: in this range, the EGRET pulsar gamma spectra cut off due to limited sensitivity, so that observations of the differential spectra of gamma-ray pulsars in this domain will give us clues about the different proposed models (*polar cap*,*outer gap*, or *slot gap*) which explain the gamma-ray emission in neutron stars. The models predict different cut-off energies, below 40 GeV for the polar cap, up to 100 GeV for the outer gap model [50], [51]. Moreover, some fraction of the unidentified sources recorded in the 3^{rd} EGRET catalogue, are believed to be radio-quiet Geminga-like pulsars [52].

Besides the EGRET sources, identified or unidentified, all radio pulsars are expected to lose part of their rotational energy through gamma-ray emission. A large collection area and a low energy threshold will allow the detection of such possibly faint emission. MAGIC and, in particular, a later LTT will also be sensitive to the weak gamma-ray flux expected from many millisecond pulsars, which are predicted to have spectra extending up to a few hundred GeV [53]; these telescopes will contribute to resolving this issue.

GLAST will extend the exploration of the gamma-ray sky up to 300 GeV, and will have, at GeV energies, a sensitivity many times higher than EGRET. However, its small detection area will restrict its performance in the high energy

Table 1

Estimates of the observation times T for MAGIC and LTT to achieve a 5σ significance. K is the monochromatic flux, E_o [37] the cutoff in the energy spectrum and Γ is the spectral index of the source. The three first sources are pulsars detected by EGRET, the next five are EGRET unidentified sources in positional coincidence with radio pulsars. The last two are millisecond pulsars. The detection times for unidentified sources have been calculated extrapolating EGRET spectra and assuming a cutoff at 30 GeV, the upper energy limit of EGRET. Observation times with MAGIC have been calculated neglecting the residual effective area below 10 GeV. The improvement in detection time is substantial.

Object (pulsar)	K $\times 10^8$ $cm^{-2}s^{-1}GeV^{-1}$	Γ	E_o GeV	T_{LTT} [min]	T_{MAGIC} [min]
Crab	24	2.08	30	0.1	60
Geminga	73	1.42	5	0.1	–
PSR B1951+32	3.8	1.74	40	0.3	180
3EG J1835+5918	9	1.69	30	4	40
3EG J1837-0604	5.5	1.82	30	35	240
3EG J1856+0114	7.4	1.93	30	35	250
3EG J2020+4017	11	2.08	30	30	290
3EG J2021+3716	11.5	1.86	30	10	70
PSR J1959+2048	5.2	2.00	770	0.1	15
PSR J1300+1240	4.7	2.00	296	0.1	20

range and for the detection of rapid flux variations. Already MAGIC should be able to observe pulsed emission close to its energy threshold, with limited imaging capabilities. The currently most optimistic estimate for the energy limit for gamma-ray detection by any LTT will be around 2 to 3 GeV, which corresponds to the threshold energy for shower electrons to radiate Cherenkov light in the upper atmosphere. In an LTT, pulsars will be measured in both imaging and non-imaging mode, using techniques currently being developed for IACTs.

The first estimations of observation times and our calculation of collection areas based on detailed Monte Carlo simulations (assuming a telescope with a mirror surface of about 1000 m^2 and an improvement in photon/photoelectron conversion by a factor of $\sim$2 show how much an LTT is superior to MAGIC in the predicted sensitivity to pulsars (see table 1).

Collection areas for an LTT will be given in [11]. Due to its low energy threshold and the energy overlap with satellites, it will be well matched to the measurements of the tail of the pulsar spectra in the GeV range, where most of the canonical pulsars are expected to have a cutoff. On top of that, the larger collection areas will allow for the first time to detect with a ground-based detector weak gamma-ray emitters such as millisecond pulsars and radio quiet pulsars.

4.5 Microquasars and X-ray Binaries

X-ray binaries provide a nearly ideal laboratory to study nearby objects of strong gravity; they are presumed to be black holes of a few solar masses, remaining from the core collapse of short-lived massive stars, and detectable through their high-energy emission. The sources are natural candidates for the production of gamma-rays up to at least GeV energies. The magnetic field frozen into the ionized, differentially rotating, accretion disk around the black hole in a binary system, can twist and reconnect to release the energy stored in the magnetic field into the kinetic energy of coronal particles. Short-lived, large-scale electric fields can accelerate charged particles up to high energies, if we extrapolate from numerical simulations of magnetic reconnection in the solar magnetosphere, the Earth's bow shock, and the geomagnetic tail [54]. Jets forming in radio-emitting X-ray binaries and the gamma-ray emission observed (for LS5039) with EGRET up to some GeV [55], are indicative of particle acceleration processes occurring at shocks in these super-Alfvenic flows.

Among the X-ray binaries, microquasars form a particularly interesting subclass, exhibiting relativistic jets as inferred from superluminal motion of radio knots. Nonthermal radio-to-X-ray emission extends through the inverse-Compton process into the GeV-TeV domain and should be observable [56]. In particular, microblazars (microquasars with their jet axes aligned roughly to the line of sight of the observer) promise to be an interesting target, for studies of short-term variability. Microblazars might even be observable from nearby galaxies, due to their Doppler-boosted flux.

One further question concerns the fraction of cosmic rays accelerated in microblazars. The detection of microquasars as powerful sources of gamma-rays above 10 GeV would have an impact on the current paradigm of the origin of cosmic rays. Currently, cosmic rays are thought to tap the energy of shock waves produced by catastrophic events, such as supernovae or Gamma-Ray Bursts, by diffusive-shock acceleration. However, relativistic particles are also produced in association with rotating magnetic fields associated with pulsars or the jets emerging from compact objects, and the particles escaping from these sources contribute to the total flux of cosmic rays [57].

4.6 Diffuse Photon Background

The diffuse photon background may be classified according to its origin: the Extragalactic Background Light (EBL) and the Diffuse Galactic Emission (DGE). The EBL is essentially isotropic, and is well established up to energies of ∼50 GeV [58,59]. In the energy range from 30 GeV to 100 GeV, a large part of the EBL may be due to the direct emission from AGNs, which have not yet been resolved [60] or due to WIMP annihilation in dark matter halos ([61]). Direct measurements of the DGE exist up to energies of ∼70 GeV [62]. The data are explained by the interaction of cosmic-ray electrons and hadrons with the interstellar radiation fields and with the interstellar matter [63]. The production mechanisms are synchrotron radiation of electrons, high-energy electron bremsstrahlung, inverse Compton scattering with low-energy photons, and π^0 production by nucleon-nucleon interactions. More recently, measurements by INTEGRAL seem to show that at MeV energies, the diffuse, galactic emission is dominated by multiple point sources [64].

New measurements of the gamma radiation (either diffuse or from point-like or extended sources) in the 10 to 300 GeV energy region will help to better understand the various sources of the diffuse gamma-ray background:

- By the detection or identification of new AGNs one will test the unresolved-blazar model for the origin of the apparent EBL. The basic assumption is an average linear relationship between gamma-ray and radio fluxes. Such a relation is suggested if the same high-energy electrons are invoked as the source of both the radio and gamma-ray emission [65].
- A deep observation of new blazars, with measurement of redshift, energy spectrum, and cutoff energy, will allow a more reliable determination of the collective luminosity of all gamma-ray blazars. A good knowledge of this contribution is a precondition for future tests of the predictions of the cascading models for the EBL.
- The detection or identification of new SNRs and pulsars will contribute to better estimates of their contribution to the DGE.

4.7 Unidentified EGRET Sources

The EGRET experiment (1991-2000) has given us the first detailed view of sources over the entire high-energy gamma-ray sky [66]. While GLAST will be the instrument of choice to improve on this view, terrestrial gamma-ray telescopes may also make their contribution. Many of the EGRET sources, including blazars, have not been detected by IACTs so far, a situation that will change with access to lower energy.

Of the 11 VHE gamma-ray sources known today, 6 are Blazars and 5 SNRs/Plerions. About half of these have been observed by EGRET. We can thus classify the VHE sources: (a) sources with a steep cut-off which are detected by EGRET, unobservable above a few 100 GeV, (b) flat spectrum sources like Mkn501, which only become observable at energies well above 100 MeV, and (c) intermediate cases like Mkn421 or the Crab Nebula.

The number of detectable sources decreases rapidly with rising energy threshold, even though the point source sensitivity of present Cherenkov telescopes is already substantially better than that of EGRET. It seems that the universe abruptly becomes much darker above a few 100 GeV. In other words, the cut-off of most high-energy source spectra seems to take place in the range 1 - 200 GeV. The first decade of energy in this range has been covered by EGRET and 57 sources have been detected [52]. The range from 10 to 200 GeV, however, has never been explored until today, and it is this “gap” that forms the major incentive behind more sensitive Cherenkov telescopes.

We have estimated observation times (5σ) for the observable EGRET sources, and found that ∼40% of them can be studied by an LTT in a few hours or less. The accessible sources touch all fields of high-energy astrophysics, and their observation will much contribute to constraining existing models in the energy domain where cut-offs set in.

4.8 Galaxy Clusters

Galaxy clusters contain a hot, intracluster medium (ICM), which probably acts as a storage volume for cosmic rays escaping from galaxies in the cluster and from AGNs [67]. The total energy and the spectrum of the stored relativistic particles is unknown, and gamma-ray observations would provide important clues about their origin. It is important to distinguish this emission component from others, possibly related with the annihilation of supersymmetric dark matter particles. Due to the expected steepness of the cosmic ray spectrum in the ICM, it is important to achieve a low gamma-ray threshold. Other suspected sources of relativistic particles are the supersonic motion of galaxies through the ICM and the accretion of material from metagalactic space onto the cluster, which induce the formation of gigantic shock waves possibly accelerating particles up to the highest observed energies [68]. The observed nonthermal radio-to-UV emission in clusters ensures the production of gamma-rays through the inverse-Compton scattering process. There is also a contribution of gamma-rays due to a calorimetric effect based on the pair production process. The gamma-rays from sources residing inside the cluster and above threshold for pair production with microwave background photons convert into pairs, which subsequently scatter microwave background photons

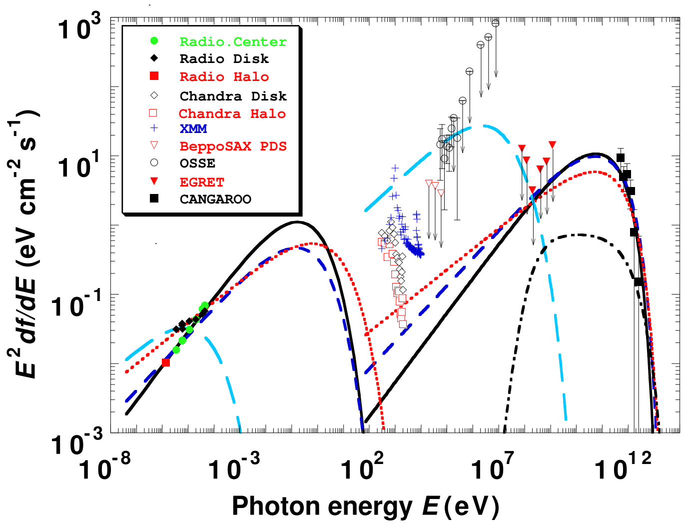

Fig. 5. *Multiwavelength spectrum of the starburst NGC 253, along with a model of the electron IC emission in the halo (for two different electron spectra, solid black and dashed blue), in the disk (red), IC localized in the galactic center (dashed cyan), and* π^0 *decay.*

to higher energies shaping a gamma-ray halo [69].

4.9 Starburst Galaxies

The Cherenkov telescope CANGAROO has recently reported the first detection (as yet unconfirmed) of a spiral galaxy at TeV energies [70]. NGC 253 is a nearby (∼2.5 Mpc) starburst galaxy, in which a high cosmic ray density and non-thermal emission are expected. The source is extended with a width of 0.3-0.6° (corresponding to 13-26 kpc), and temporally steady over two years. If true, this can be considered the first of a new class of extragalactic objects, clearly different from the other observed extragalactic TeV emitters (AGNs of the BL Lac class). The TeV gamma-rays may come from hadronic or leptonic processes originating from the cosmic ray density in a starburst (assumed high). Figure 5 shows the multiwavelength spectrum of NGC 253 and estimates of the hadronic and IC emission produced by disk and halo electrons (from [71]).

Romero et al. [72] have advanced an alternative explanation based on hadronic processes in the core of the galaxy. They suggest that proton illumination of the inner winds of massive stars could produce TeV gamma-rays without the unobserved MeV-GeV counterpart. The enhancement in cosmic ray density would be produced by collective effects of stellar winds and supernovae.

Precise spectral measurements in the range 5-100 GeV will allow the different models to be constrained; the angular resolution around 0.1° will help to localize the source of emission at low energies. Nearby starburst galaxies are ideal targets for this kind of study.

4.10 Nearby Galaxies

Nearby galaxies such as M31, M82, Arp 220, and Cen A are representative of normal spiral galaxies, starburst and merger galaxies, and active galactic nuclei. Owing to their vicinity, the morphology of these galaxies and their multifrequency properties have been studied in great detail, but lack information in the 10-300 GeV region. In normal galaxies, star formation and hence the production of collapsing massive stars with associated gamma-ray production in GRBs, supernovae and their remnants can be probed with a low-threshold IACT [70,72]. A low threshold of 10 GeV is important to observe enough flux for their detection, since the spectrum of cosmic rays (and hence gamma-rays) is expected to be very steep, falling as $E^{-2.75}$ in our Galaxy.

4.11 The Galactic Center

The Galactic Center (GC) region, besides the famous Sgr A*, contains many unusual objects which may be responsible for the high energy processes generating gamma-rays. The GC is rich in massive stellar clusters with up to 100 OB stars [73], immersed in a dense gas within the volume of 300 pc and the mass of $2.7 \times 10^7 M_\odot$, young supernova remnants e.g. G0.570-0.018 or Sgr A East, and nonthermal radio arcs.

In fact, EGRET has detected a strong source in the direction of the GC, 3EG J1746-2852 [74], which has a broken power law spectrum extending up to at least 10 GeV, with a power law index 1.3 below the break at a few GeV. If in the GC, the gamma-ray luminosity of this source is very large $\sim 2 \times 10^{37}$ erg s^{-1}, which is equivalent to $\sim$ 10 Crab pulsars. Up to now, the GC has been observed at energies above 200 GeV by the CANGAROO [75] and Whipple [76] collaborations, and more recently by H.E.S.S. [77]. High energy gamma-rays can be produced in the GC in the non-thermal radio filaments by high energy leptons which scatter background infrared photons from the nearby ionized clouds [78], or by hadrons colliding with dense matter. These high energy hadrons can be accelerated by the massive black hole associated with the Sgr A* [79], by supernovae [80], or by energetic pulsars [81]. A model based on advection-dominated accretion flow has been discussed in [82]. In order to shed new light on the high energy phenomena in the GC region, and constrain the models above, new observations with sensitivity down to 10 GeV (from a southern location) will be able to make substantial contributions.

5 LTT-s as partners in multi-wavelength observations

The study of gamma-ray sources requires a multifrequency approach. For many subjects, even simultaneous observations with instruments at different wavelengths are required, as pointed out before (e.g. [9]). An example concerning a single observation with large impact on the understanding of AGNs can demonstrate how important this can turn out to be: in the 1990s, the Compton Gamma-Ray satellite Observatory (CGRO) found that a major fraction of energy in AGNs is radiated in gamma-rays. This allowed the conclusion that all electromagnetic frequencies from radio to gamma-rays are very closely connected. Later, some blazars were found by ground-based IACTs to be extremely energetic, even at TeV-energies.

While this general framework is known, the phenomena at different energies are correlated in complicated ways, making it difficult or impossible to study details without data taken across the entire electromagnetic range. Broadly speaking, the spectral energy distribution of all radio-loud AGNs shows two maxima, one from radio to UV/X-rays, produced by synchrotron radiation, the other from X-rays to TeV caused by inverse Compton (IC) radiation. No details can be understood without studying the entire spectrum, with as much overlap between different instruments as possible.

A crucial question to study is the nature of seed photons. The accretion disk of AGNs is the most obvious source of photons, mainly in the UV domain. These photons can also be reflected/reprocessed by the broad line region clouds, producing an intense optical photon field. Farther away, dust heated to 500-1000 K is a source of infrared photons. All these are called external Compton (EC) scenarios, since the seed photons come from outside the jet. The synchrotron photons in the jet can also scatter from the electrons which produced them, in which case we have a synchrotron self-Compton scenario (SSC). In the EC models, the high frequency emission must originate within a small fraction of a parsec from the AGN core, since the photon density drops rapidly with distance. As the synchrotron-emitting shocks typically reach their maximal development much further downstream, the gamma-ray variations should precede the onset of the radio flare. Since the external photon field is independent of the electron density in the jet, the EC flux should change linearly with the synchrotron flux. In the SSC scenario the change should be quadratic, since the synchrotron photon density is also changing, not just the electron density. The SSC gamma-rays can be emitted simultaneously with, or even after, the onset of the radio flare.

Simultaneous observations in the GeV/TeV domain and at optical energies are extremely important when we expect to increase the number of detected sources dramatically as we reach a lower energy threshold (which overcomes the IR-background absorption). In TeV-blazars, the optical synchrotron flux (highly polarized) should be connected to the GeV/TeV fluxes. While contributions to the lower energy IC flux of gamma-rays may come from a wide electron energy range, and from several processes, including thermal X-rays close to the accretion disk, only the very highest energy electrons can boost the seed photons to the extreme TeV energies. The TeV variations are, therefore, a very pure IC signal, and it should in principle be easy to identify the 'parent' synchrotron component on the basis of correlations and time lags. Observations of TeV flares have provided intriguing hints, but no definite answers due to insufficient simultaneous optical and GeV/TeV data.

6 LTTs and GLAST

GLAST (Gamma-Ray Large Area Space Telescope), is the much superior successor to EGRET; it is scheduled for launch in 2007, with a likely mission duration of up to 10 years [10]. For LTTs a special synergy exists with GLAST. In particular, the energy bracket of 10 to 100 GeV will be an important overlap area open to both instruments. An LTT will be able to cover higher (>100 GeV) energies on selected sources with good statistics and resolution, whereas GLAST will be in its own at lower energies, because of its large angular acceptance and superior energy resolution.

GLAST will have an effective collection area of about 1 m^2 and will be able to detect gamma-rays with good energy and direction resolution between 30 MeV and 300 GeV, but its sensitivity above a few tens of GeV decreases rapidly. At least initially, GLAST will be run as a survey instrument; over its lifetime, it is predicted to discover thousands of new sources. However, these detections will be severely statistics-limited above a few GeV. For example from the Crab Nebula, GLAST will detect a few thousand photons above 1 GeV per year; only a few hundred of these will be above 10 GeV, and only tens will be above 100 GeV [83], [84]. For a source significantly weaker than the Crab Nebula it will not be possible to measure the spectrum above 10 GeV with an accuracy adequate for constraining source models, even though the source may be clearly detected. The low photon detection rates will also lead to a strong limitation for studies of short-term (hours or even minutes) variability, in the GeV domain.

LTTs, on the other hand, will have a high background rate and relatively small field of view, but an effective collection area four to five orders of magnitude larger than that of GLAST. Hence, given the positions of sources discovered by GLAST, LTTs can deliver spectra and light curves above 10 GeV with substantially higher accuracy and on shorter time scales, an important asset for any variability studies. Thus GLAST will typically discover the sources and measure their spectra and variability from 0.1 - 10 or 20 GeV while LTTs will complete the spectra and variability studies from 10 GeV to where the sources cut off.

GLAST and LTTs thus form an ideal pair of complementary instruments in the overlap region, from 10 to 300 GeV. The large overlap region also allows good cross-calibration such that high-accuracy spectra can be constructed, spanning an energy range of more than three orders of magnitude from 0.1 GeV to 1000 GeV or wherever the sources cut off [84].

7 Conclusion

A strong scientific case exists for the construction of gamma-ray telescopes with the lowest possible energy threshold, which should be of the order of 10 GeV. A key instrument to aim for is a telescope with a large effective mirror surface and a high quantum efficiency camera.

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