



## TenTen: A New Array of Multi-TeV Imaging Cherenkov Telescopes

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**Abstract:** The exciting results from H.E.S.S. point to a new population of  $\gamma$ -ray sources at energies  $E > 10$  TeV, paving the way for future studies and new discoveries in the multi-TeV energy range. Connected with these energies is the search for sources of PeV cosmic-rays (CRs) and the study of multi-TeV  $\gamma$ -ray production in a growing number of astrophysical environments. *TenTen* is a proposed stereoscopic array (with a suggested site in Australia) of modest-sized (10 to 30m<sup>2</sup>) Cherenkov imaging telescopes with a wide field of view (8° to 10° diameter) optimised for the  $E \sim 10$  to 100 TeV range. *TenTen* will achieve an effective area of  $\sim 10$  km<sup>2</sup> at energies above 10 TeV. We outline here the motivation for *TenTen* and summarise key performance parameters.

### Motivation for Multi-TeV Studies

Ground-based  $\gamma$ -ray astronomy operating in the  $\sim 0.1$  to  $\sim 10$  TeV range has become a mainstream astronomical discipline due to the exciting results from H.E.S.S. [29] in the Southern Hemisphere over recent years. In the Northern Hemisphere the MAGIC [35] and MILAGRO [37] telescopes are now producing results and similar high impact can soon be expected from VERITAS [36]. The TeV source catalogue extends to over 30 individual sources, and we are now able to perform detailed studies of extreme environments capable of CR particle acceleration. Several key points can be extracted from the results of H.E.S.S. and others which motivate development of a new dedicated instrument for studies at multi-TeV ( $E > \text{few TeV}$ ) energies (see also [16, 28]):

**Increasing variety of TeV Sources:** The number of environments established as sources of gamma radiation (to energies exceeding  $\sim 10$  TeV in many cases) is growing and include, in the case of Galactic sources — shell-type supernova remnants (SNRs), pulsar-wind-nebulae (PWN), compact binaries and/or X-ray binaries, young stellar systems/clusters and molecular clouds acting as targets for CRs in their vicinity. There are also

several Galactic sources (all extended) that to-date have no known counterpart at lower energies, and so remain unidentified. Extragalactic sources comprise active galaxies with jets aligned along our line of sight, the so-called Blazars, and at least one misaligned Blazar.

**Hard Photon Spectra:** The majority of new Galactic sources generally exhibit hard power law photon spectra  $dN/dE \sim E^{-\Gamma}$  where  $\Gamma < 2.5$  without indication of cutoffs, suggesting that their emission extends beyond 10 TeV.

**Extended Sources & Large Field of View:** The majority of Galactic sources are extended (up to several degrees in scale) in morphology, providing insight into  $\gamma$ -ray production and transport processes, especially when coupled with multiwavelength results. Effective studies of these sources therefore require large instantaneous fields of view, not only to encompass sources of interest but to also allow adequate selection of regions for CR background estimation. The 5° FoV cameras in H.E.S.S. for example have been designed with these aspects in mind. This large FoV has permitted highly successful surveys of the inner Southern Galactic Plane within just a few years [20, 22], and also the establishment of degree-scale morphology in several strong sources.

**Limited Multi-TeV Sensitivity of Present In-**

**struments:** Current instruments operate with a  $\sim 0.1$  TeV threshold energy and effective collection area ( $E > 10$  TeV) of less than  $1 \text{ km}^2$ . The majority of source studies are therefore made in the  $0.1$  to  $\sim 10$  TeV band. The fluxes of these new sources are in the few to  $\sim 15\%$  Crab flux range, reflecting the instrumental sensitivities. With the limited observational opportunities due to the ever growing source catalogues, the accumulation of high statistics in the multi-TeV band is difficult. Fig. 1 illustrates this point where a new weak TeV source is revealed to the north of HESS J1825–137 after only deep ( $> 50$  hr) observations. Further, detailed studies of this weak source, motivated perhaps by its relatively rare coincidence with a MeV/GeV EGRET source, would not be practical with H.E.S.S. Such studies would require  $> 100$  hr of observations and face stiff competition from other source programmes.

**$E > 10$  TeV Sources Already Exist:** For those Galactic sources (two shell-type SNRs and several PWN [21, 23, 25, 24, 26]) with strong fluxes ( $> 15\%$  Crab) and/or deep observation times ( $\geq 50$  hr), photon spectra have been established to energies  $\sim 50$  TeV or greater, demonstrating that particle acceleration to energies exceeding  $100$  TeV is occurring in these types of objects. MILAGRO has also recently revealed degree-scale emission (with total flux exceeding  $1$  Crab) at energies above  $10$  TeV in the Cygnus and other regions of the Northern Galactic Plane [6, 7], highlighting the potential of future all-sky-monitors in the multi-TeV range. These points provide clear observational evidence that rich astrophysics potential awaits in the  $E > 10$  TeV range.

In addition there are strong theoretical grounds for pushing deep into the multi-TeV domain:

**Particle Acceleration to the knee and beyond:** The desire to understand particle acceleration to the CR *knee* ( $E \sim 1$  PeV) energy and beyond remains a key motivation for multi-TeV studies. While it is generally accepted that CRs can be accelerated in shell-type SNRs [41] to energies  $E_{\text{max}} \sim \text{few} \times 10^{14}$  eV [33] (via the diffusive shock acceleration process), there is considerable uncertainty as to how particles can reach the *knee* energy and beyond (eg. [30, 32]) in so-called *Pevatrons*. Several ideas have been put forward, for example: strong amplification of pre-shock mag-

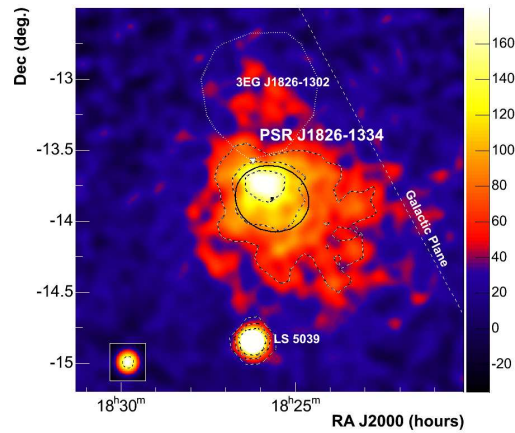


Figure 1: H.E.S.S. image of the PWN HESS J1825–137 [24] resulting from 52 hr observations. A considerably weaker source is revealed to the north of HESS J1825–137, and is possibly a counterpart to the EGRET source 3EG J1826–1302. This weaker source is unlikely to be studied further in depth by H.E.S.S. This image nicely illustrates a variety of Galactic source types in the same FoV — a strong extended PWN; weak extended source with MeV/GeV counterpart and a pointlike compact binary (LS 5039).

netic fields [3]; local Gamma-Ray-Bursts (GRBs) [5, 4]; and superbubbles which combine the effects of many SNRs and maybe Wolf-Rayet/OB stellar winds [9, 1, 13, 8]. Extragalactic sources with large-scale kpc shocks such as galaxy clusters (eg. [19]) and AGN jets and giant lobes (eg. [2]) could also be sources. Only observations around  $100$  TeV and greater can begin to solve the mystery of PeV CR acceleration.

**$E > 10$  TeV — Easier Separation of Hadronic & Electronic Components:** A major complication in interpreting present results in the  $0.1$  to  $\sim 10$  TeV range concerns the separation of  $\gamma$ -ray components from accelerated hadrons (from secondary  $\pi^0$ -decay) and those from accelerated electrons (most commonly from inverse-Compton scattering). Multiwavelength information, in particular at radio and X-ray energies, can provide constraints on these components but often one requires model-dependent assumptions to decide the nature of the parent particles. At energies  $E > 10$  TeV the electronic component can be sup-

pressed due to strong radiative synchrotron energy losses suffered by electrons in magnetised post-shock environments, such as that in shell-type SNRs. In addition, the Klein-Nishina effect on the inverse-Compton cross-section can significantly reduce the efficiency of this process. Except in those cases where a strong source of electrons exists, such as in PWN, interpretation of  $E > 10$  TeV spectra may therefore be much more confidently interpreted as arising from accelerated hadrons.

**Probing Local Intergalactic/Interstellar Photon Fields:**  $E > 10$  TeV photons can indirectly probe ambient soft photon fields. In the  $\sim 10$  to  $\sim 100$  TeV energy range, absorption on the cosmic infra-red background (CIB) in the 10 to 100  $\mu\text{m}$  range dominates with mean free paths extending beyond 1 Mpc. Constraints on the (nearby) intergalactic CIB via  $\gamma$ -ray spectral studies of nearby extragalactic sources, such as M 87 (an established TeV source) can yield important information concerning star and galaxy formation in our local intergalactic neighbourhood [27]. Constraints on the interstellar CIB may also be possible via  $E > 10$  TeV spectral studies of Galactic source populations [12].

## TenTen: Initial Simulation Study & Performance

Given source fluxes which rapidly decrease with energy (typically a power law), any dedicated instrument operating in the multi-TeV energy domain would need to achieve a very large effective collection area  $A_{\text{eff}} \sim 10 \text{ km}^2$ . While there are several promising ways to achieve  $10 \text{ km}^2$  using ground-based techniques, earlier simulations [14] have shown that a proven, technically straightforward, and yet highly sensitive method would employ stereoscopy in an array of 30 to 50 modest-sized imaging atmospheric Cherenkov telescopes (IACTs) in a cell-based approach. Each telescope would have mirror area 10 to 30  $\text{m}^2$ , field of view (FoV)  $5^\circ$  to  $10^\circ$ , and inter-telescope spacing within a single cell  $\geq 200$  metres (in contrast to  $\sim 100$  m employed by arrays such as H.E.S.S.). The large FoV, limited practically by optical aberrations, allows events to trigger out to core distances  $\geq 200$  m, thereby increasing the effective

collection area of a cell. We propose here such an array, known as *TenTen*, which stands for  $10 \text{ km}^2$  above 10 TeV. Similar and other ideas for 100 TeV studies have also been suggested [39, 40, 34].

Our initial simulation study [17] examined the performance of a single cell of 5 telescopes, each with mirror area  $23.8 \text{ m}^2$  (84x60 cm spherical mirror facets) and 1024 pixel camera spanning  $8.2^\circ$  diameter (with pixel diameter  $0.25^\circ$ ). The layout of the cell has the outer four telescopes arranged in a square of side length  $L$  with a single telescope at the centre (similar to the HEGRA IACT-System layout[15]). Gamma-ray and proton extensive air shower simulations ( $30^\circ$  zenith — with CORSIKA v6.204 [11] and SIBYLL [10]) coupled with telescope responses (based on [31]) were used to investigate basic performance parameters of the cell. An observation altitude 200 m a.s.l. was chosen since we are investigating sites in Australia. For  $E > 10$  TeV, low-altitude sites may be beneficial compared to mid/high altitudes due to the larger distances between telescopes and shower maxima. Details concerning this study including ongoing work are summarised in our companion paper/poster [18]. Briefly, we found that for a cell with side length  $L = 300$  m, an on-axis  $\gamma$ -ray effective collection area  $A_{\text{eff}}$  exceeding  $1 \text{ km}^2$  for  $E > 30$  TeV can be achieved in a single cell, and that somewhat similar cosmic-ray background rejection power and arc-minute angular resolution is achieved in the  $E > 10$  TeV range as H.E.S.S. and the HEGRA IACT-System achieve(d) in their respective energy ranges. An energy threshold in the 1 to few TeV range is also indicated. This encouraging result suggests that expanding the array to (for example)  $\sim 10$  sufficiently spaced cells (so that there are no common events between cells) could yield collection areas  $\sim 10 \text{ km}^2$ , exceeding that of H.E.S.S. by factors approaching 50 at 100 TeV. The approximate flux sensitivity (based on the improvement in collection area over H.E.S.S.) and energy coverage of *TenTen* is depicted in Fig. 2. Flux sensitivities for large extended sources such as the  $2^\circ$  diameter shell type SNR RX J0852.0–4622 would be  $\sim 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$  at 10 TeV. For point-like sources, the accessible fluxes would be a factor of 10 to 20 lower again (less than  $\sim 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$  above 10 TeV). Importantly, a 1 to a few TeV

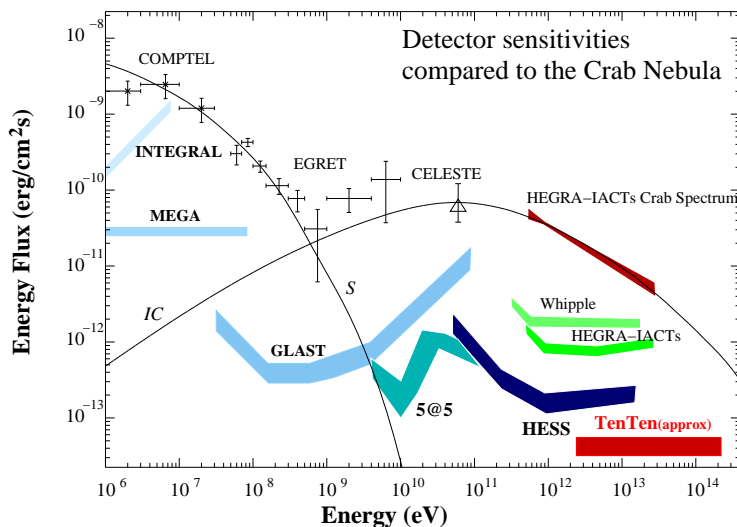


Figure 2: Approximate point source energy flux sensitivity for *TenTen* (assuming 10 cells of 5 telescopes discussed in text) in comparison with other instruments in the  $\gamma$ -ray regime and the flux from the Crab Nebula. An observation time of 50 hr and signal significance of  $5\sigma$  is demanded. The *TenTen* sensitivity is estimated from its collection area improvement over H.E.S.S. from our initial simulation study.

energy threshold would also allow detailed studies of existing  $\gamma$ -ray sources that are at the threshold of detection for H.E.S.S. Despite our simulations being limited to  $E \leq 100$  TeV, we also expect high collection area above this energy. Note that in the 200 TeV to 100 PeV range,  $\gamma$ -ray absorption on the cosmic microwave background (CMB) becomes important, with mean free path  $\leq 100$  kpc [38], limiting the focus of  $\gamma$ -ray astronomy in this energy range to Galactic sources.

## Conclusions

We have outlined the motivation for a new array of IACTs achieving  $10 \text{ km}^2$  at  $E > 10$  TeV and described some important performance parameters. This array, known as *TenTen*, could also be considered complementary to future MeV to TeV  $\gamma$ -ray instruments such as GLAST, HESS-II and MAGIC-II. Studies are currently underway to further optimise individual telescopes (optics, electronics, camera design), overall layout parameters, and site potential in Australia.

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