Experimental approaches for 100 TeV γ-ray Astronomy

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Abstract: *The high energy end of gamma ray source spectra might provide important clues regarding the nature of the processes involved in gamma ray emission. The HESS collaboration has already reported several galactic sources with hard emission spectra extending up to more than 30TeV. Measurements at 100TeV and above should be an important goal for the next generation of high energy γ-ray astronomy experiment. We have identified three approaches based on the Imaging Atmospheric Cherenkov Technique (IACT) and providing the required* ***~1km²*** *effective collection area:* ***low elevation*** *observation,* ***large field of view*** *telescopes, or a* ***high density telescope array****. Here we comment of the advantages and disadvantages of these approaches and report simulation based estimates of their energy ranges and sensitivities.*

Motivation for a 100 TeV astronomy

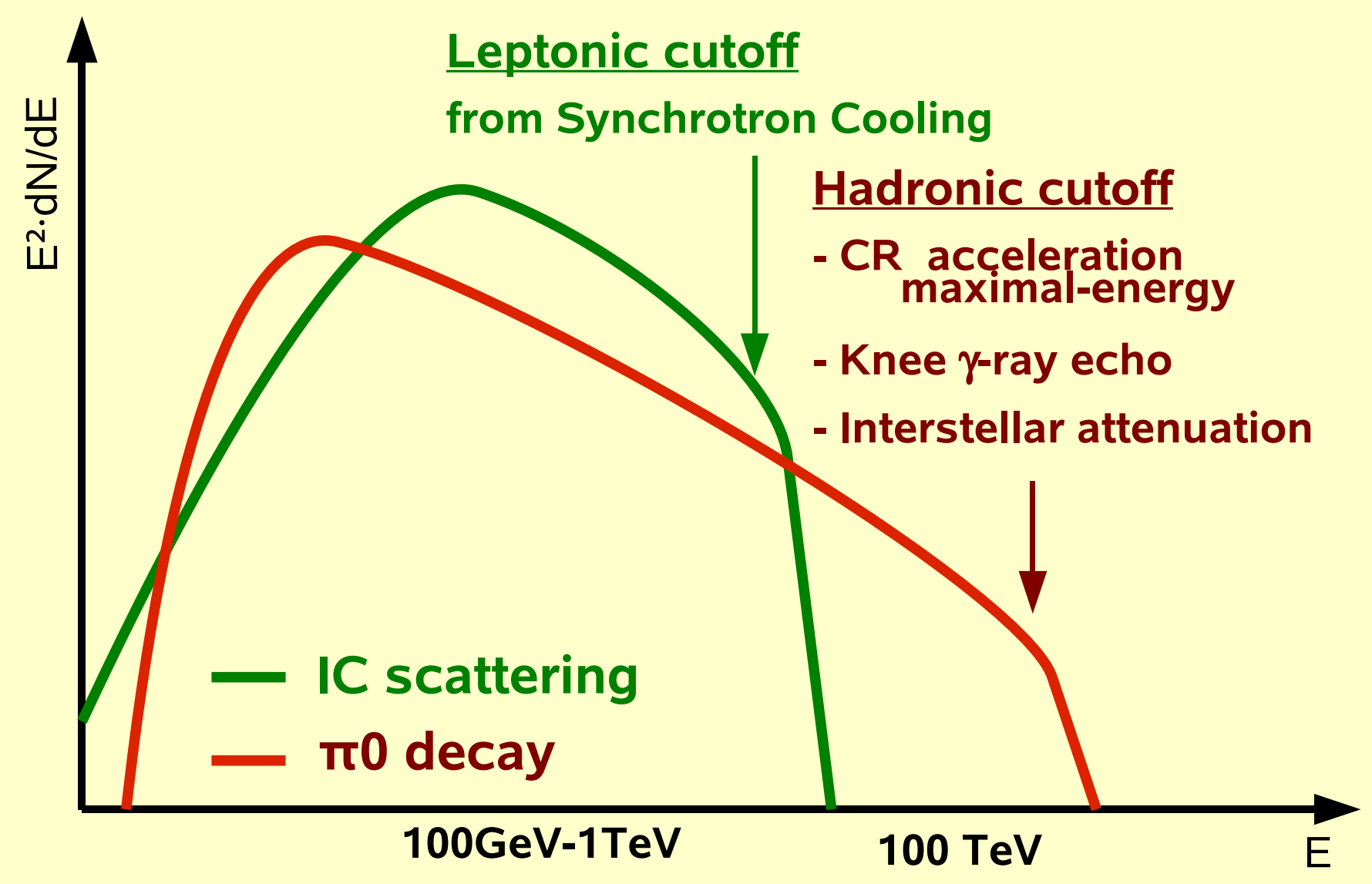


Fig 1: *Schematic spectra of two gamma ray emission process*

Questions about the origin of galactic **Cosmic Rays** (CR) have motivated the development of γ-ray astronomy over 100GeV as γ-rays from π0 decay were expected to primarily trace CR acceleration sites [1].

However, measured TeV spectra are most generally explained in terms **Inverse Compton** (IC) scattering on the high energy electrons [2] responsible for the X-ray synchrotron emission also observed in TeV sources. Observations have not allowed to unambiguously identify a hadronic component in γ-ray spectra [3] [4].

At higher energy, **synchrotron cooling** of electrons becomes more important and should cause IC component of spectra to soften. A **cutoff is expected** below 100TeV (seems to be already seen in Vela X [5]). γ-ray resulting from hadron processes may not display a similar cutoff [6]. Their contribution can extend up to several hundred TeV. A 100TeV astronomy should provide a clear discrimination between γ-rays from lepton and hadron processes.

Required exposure 100TeV astronomy

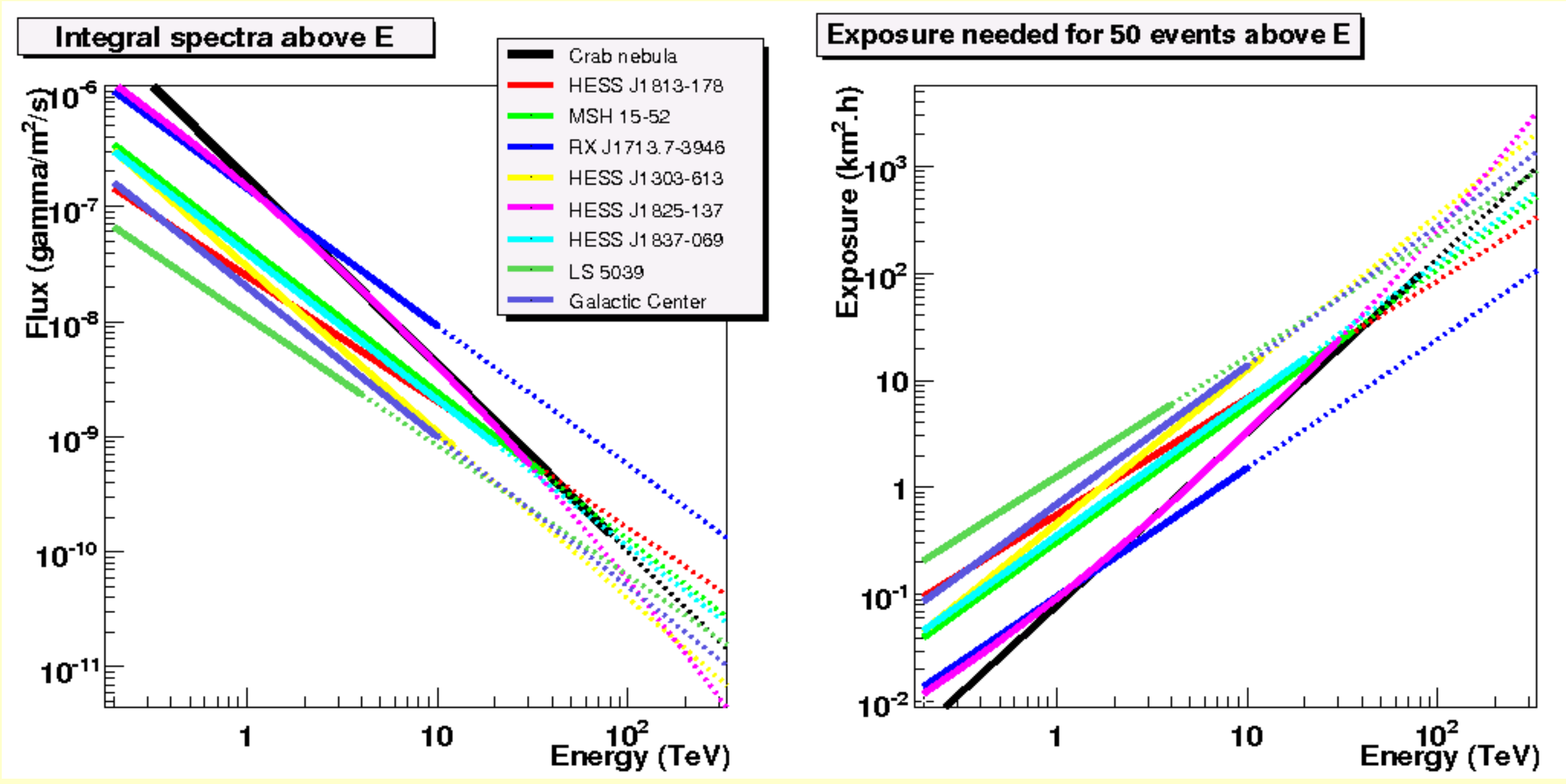


Fig 2: *Integral spectra of several sources [2] [6] and minimal exposure to measure them*

The highest energy γ-ray source ever measured is the Crab nebula. It required 5 years of observation with HEGRA [2] to measure its power low spectrum extending up to 80TeV.

On the left-hand side of figure 2, the Crab spectrum as measured by HEGRA is shown along with other galactic sources spectra recently measured with HESS [7]. The dotted lines indicate their power law extrapolation to higher energies.

Current experiments are not likely to reach hundred TeV because of their limited effective collection area. The right-hand side of figure 2 shows the exposure necessary for detecting 50 γ-rays from these sources. **For 100TeV, we need 100 km² h.**

Techniques for a 100km².h exposure

Atmospheric Cherenkov

Imaging **A**tmospheric **C**herenkov **T**echnique (IACT) can be used only during clear moonless nights. **The duty cycle is about 10%.** Figure 3 shows the maximum observation time per year for a source as a function of its declination. In order for their science program to be diversified, small field of view (FOV) IACT experiments generally are not dedicated to any given source for more than **100h** yearly. Still inexistent full-sky survey IACT experiments could typically obtain 200 hours of data yearly on any given source.

In order to achieve 100km²h, future IACT experiments need to offer effective collection areas of **at least 1km²** with a small FOV or **0.5km²** with full-sky survey capability.

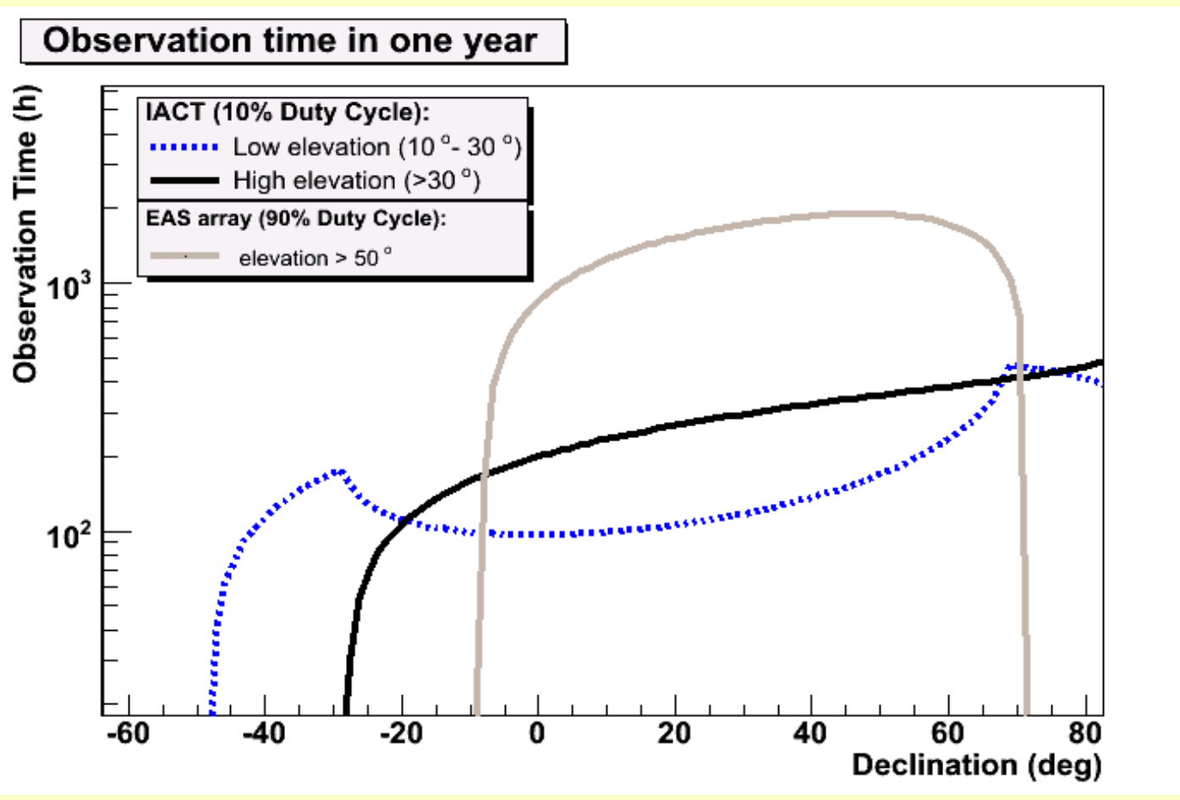


Fig 3: *Yearly observation time from 31° north of latitude*

Ground detectors

Extensive Air Shower (EAS) arrays like Milagro[8] have an almost **100% duty cycle** and could observe any source in its FOV **~1500h/year** (see figure 3).

Figure 4 shows simulations of effective area of Milagro and HAWC projects[9]. Assuming these areas remains constant at energy above 10TeV, **Mini-HAWC** could reach a 100km²·h exposure in one year.

Milagro already offers a great exposure but its sensitivity is limited by its angular resolution. **Mini-HAWC** should be a strong improvement over this.

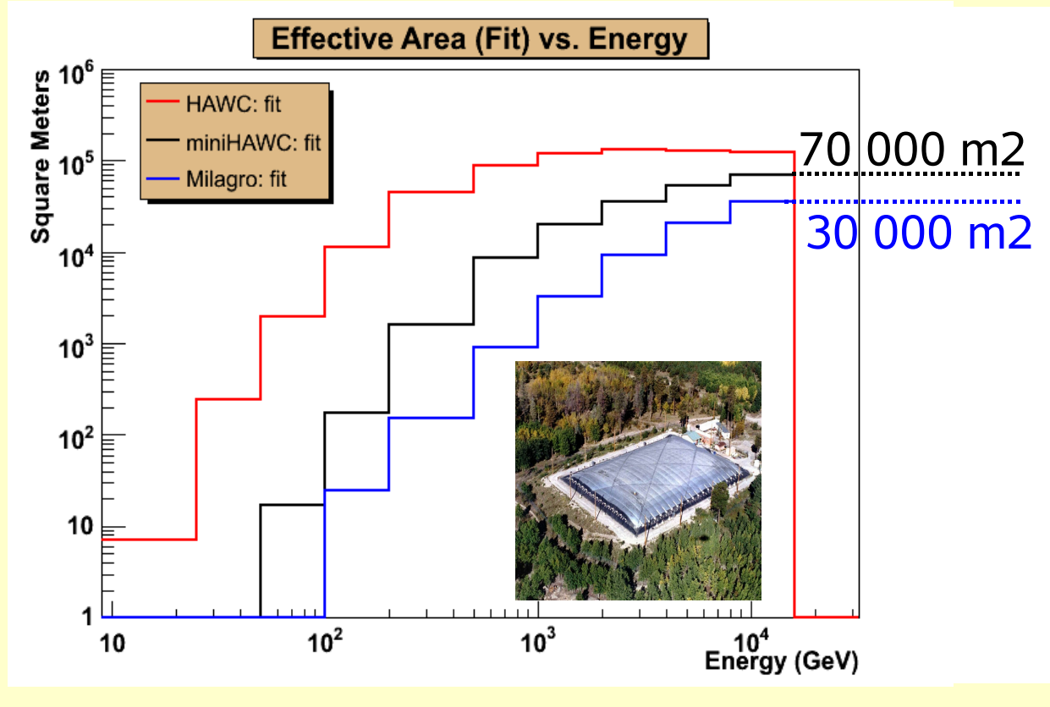


Fig 4: *Effective collection area of EAS arrays*

Air Cherenkov Approaches

Three IACT approaches

The ground level Cherenkov light pool is relatively constant within the central plateau of the light pool and decreases rapidly with the distance from the shower core outside the central plateau (see figure 5). With vertical showers, the plateau extends over a **~130m radius**. At low elevation the radius of the Cherenkov pool is much larger (>400m at 20°).

➡ **High density telescope array:** Telescopes are used in the plateau. Arrays should consist in **~40 telescopes spread in 1km².**

➡ **Low density telescope array:** Telescopes used in the tail of the light pool density profile. Telescopes need **large FOV** to observe large impact parameter showers (Figure 5).

➡ **Low Elevation observation:** images are much smaller and one telescope can reach 1km² collection area even with a small FOV (4°). The low Cherenkov light pool density is partially compensated for by the high image compactness.

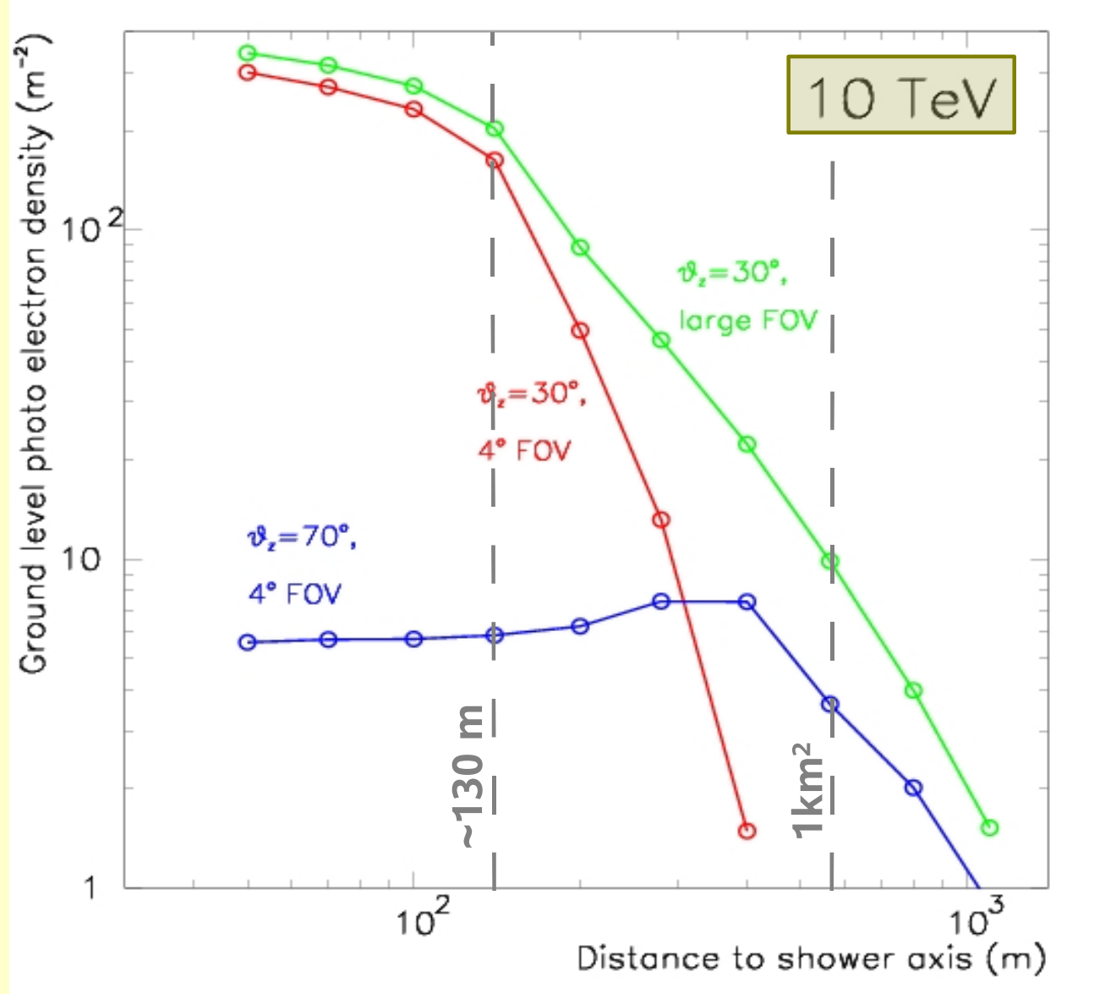


Fig 5: *Cherenkov light density at ground level*

➡ Low elevation

Observations at large zenith angle are common [10], providing large collection areas at high energies. However, several problems and difficulties appear:

- **Smaller Images**: bad discrimination and reconstruction
- **Large base line still necessary**:
  Stereoscopic views by VERITAS are not efficient (Fig 6)
- **Atmospheric monitoring becomes critical**
- **Sensitivity gradient across FOV**
- **High constraints on observing program**

For these reasons, a dedicated low elevation experiment does not seem very appealing. Figure 10 shows our estimate of VERITAS[11] 25h sensitivity at low elevation.

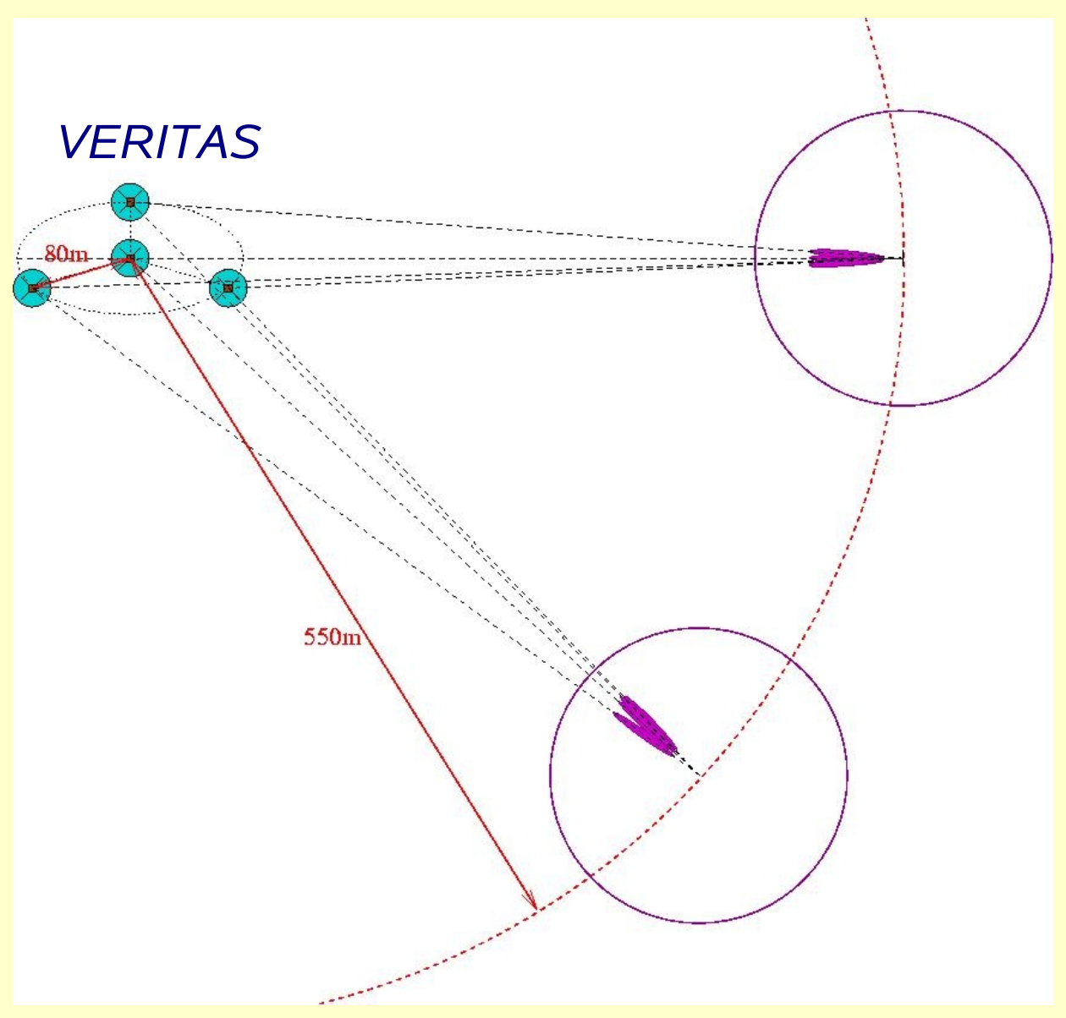
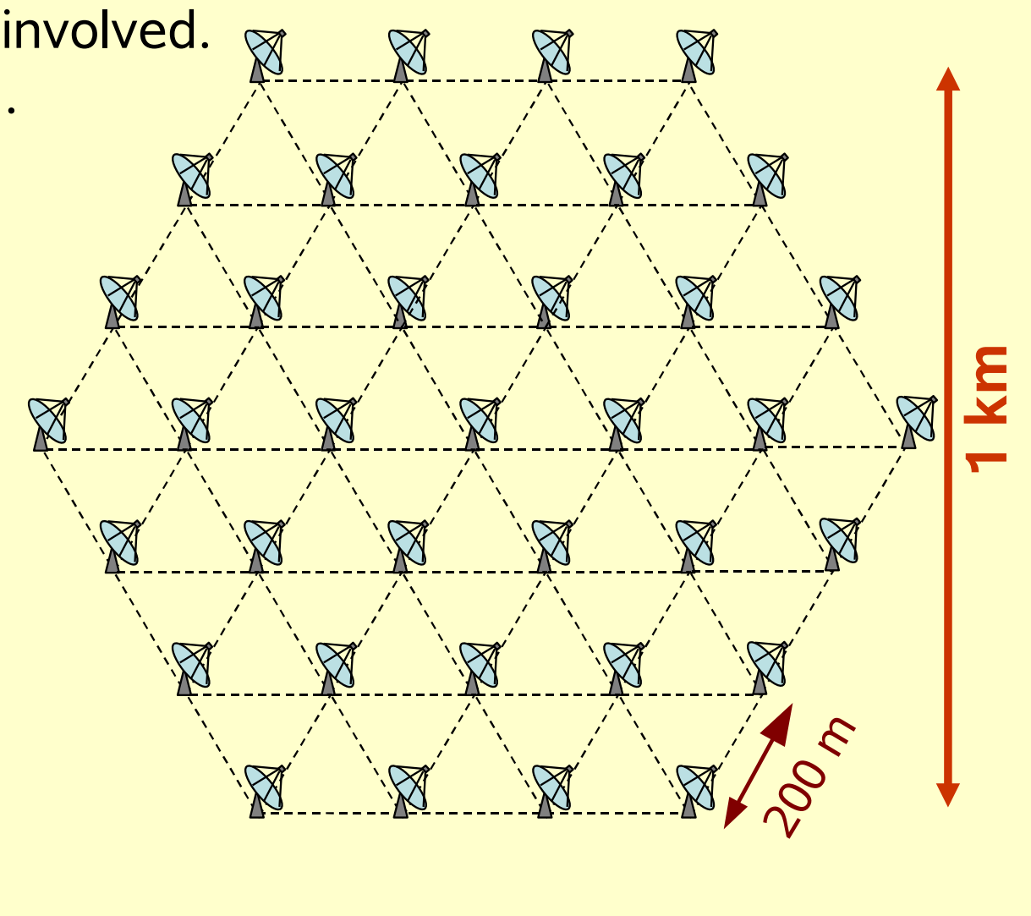


Fig 6: *Spectroscopic views at low elevation*

➡ High density telescope Array: GRATIS

A large area, high density telescope array (CTA, HE-Astro, TenTen[12], GRATIS) operating at high elevation could exploit the Cherenkov light pool plateau. Projects of this type are expensive and challenging because of the large number of units involved. They also offer the best γ-ray discrimination and reconstruction capabilities[13].

GRATIS, a minimal approach to 1TeV-100TeV large area, high density telescope array consists in 37 5.4m diameter telescopes with 4° FOV (253 0.25° pixels), covering 1km² in a 200m spaced hexagonal lattice. Any point in the array is less than 115m from a telescope (less than the Cherenkov light pool radius).



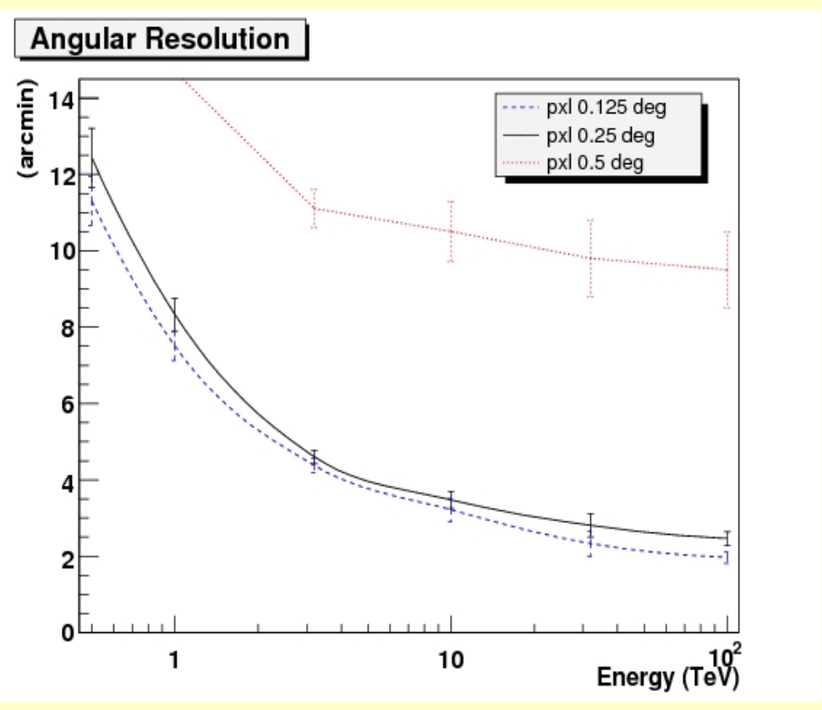


Fig 7: *Angular resolution of GRATIS*

From detailed simulations [14] we estimate the GRATIS γ-ray energy threshold (~300 GeV), angular resolution (Figure 7) and comic ray rejection for one triangular cell.

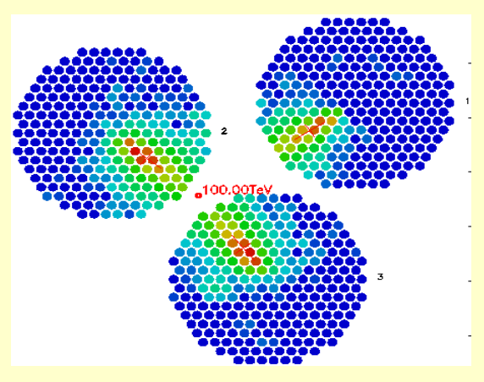


Figure 10 shows the GRATIS sensitivity of the 54 triangles in the array (red curve). This sensitivity is conservative at high energy as showers trigger more than 3 telescopes, improving rejection and angular resolution. Moreover they are also detected outside the array, increasing effective area.

➡ Large FOV telescopes: TALE

In order to exploit the tail of the Cherenkov light pool, IACT telescopes need a large FOV (~12° for 1km² effective area). We simulated an 11m² telescope with a 16°x16° camera. This design is based on the TALE project[15], which includes a “Fly's Eye” air fluorescence telescope for the study of cosmic-rays around 10^{17} eV.

Figure 8 shows the energy threshold as a function of γ-ray impact parameter. The effective collection area increases with energy. This is advantageous for sensitivity but makes spectral analysis strongly Monte-Carlo dependent. Figure 9 shows the angular resolution for 2 pixel sizes (1° and 0.5°). The degradation at high energy results from the FOV truncation in our simulation involving only one telescope unit. A “Fly's Eye” would achieve an angular resolution better than 10 arc-minutes at 100TeV.

The black curve in figure 3 shows the yearly observation time available to a TALE like “Fly's Eye” experiment in sky-survey at more that 30° elevation. Figure 10 shows the sensitivity with 0.5° pixel cameras in 200h. This curve applies for a point source and does not include the effects of γ-ray shower image shape discrimination capabilities which still have to be studied.

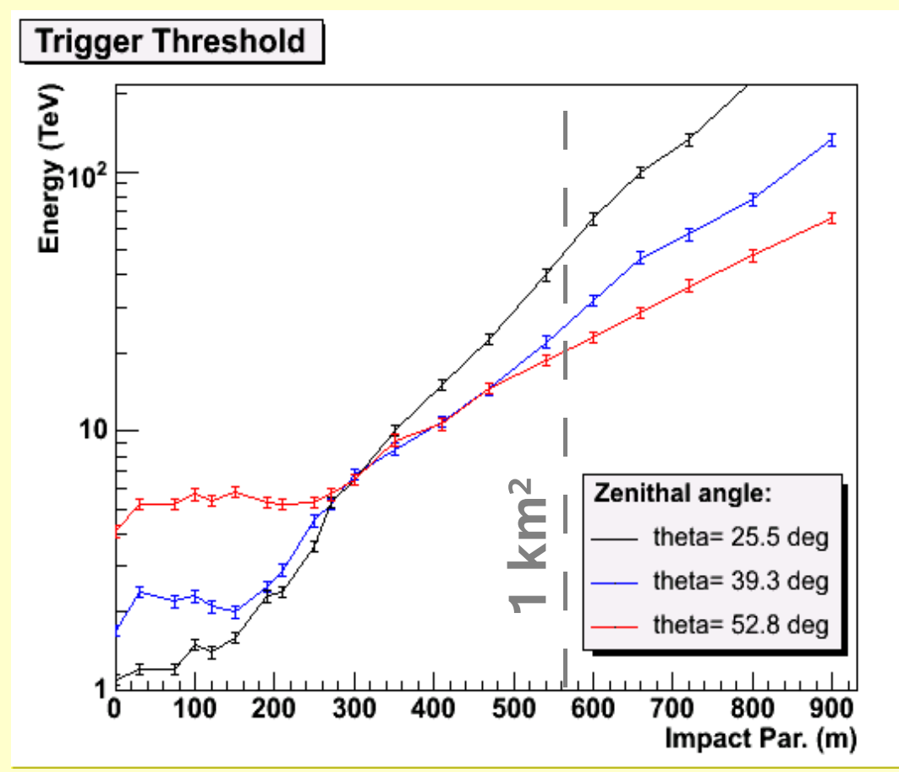


Fig 8: *TALE Energy threshold*

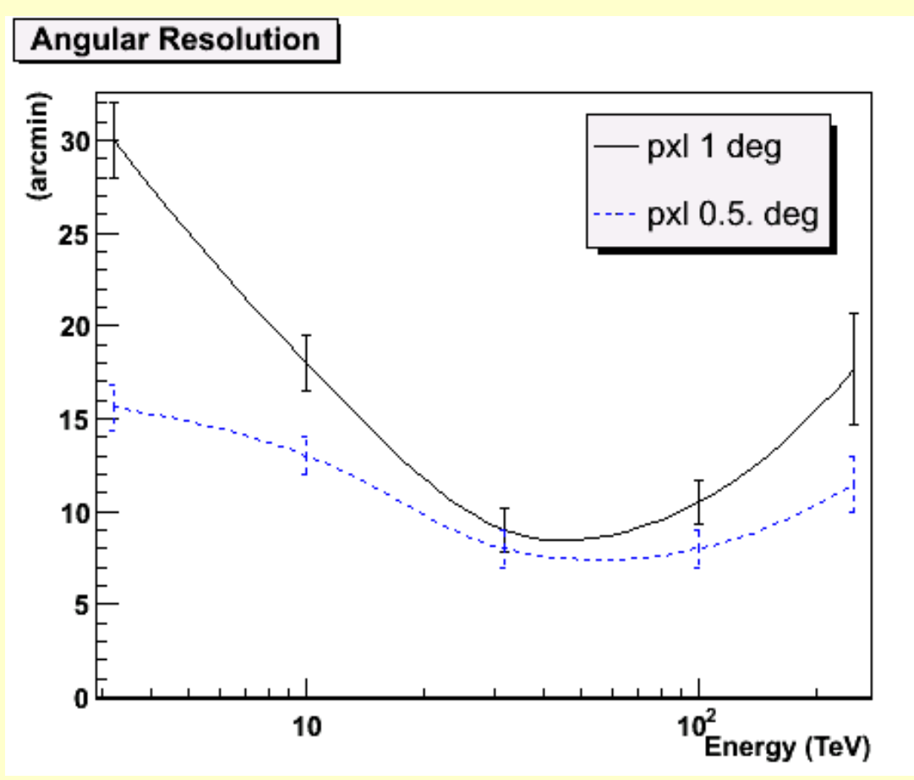


Fig 9: *TALE angular resolution*

Conclusion

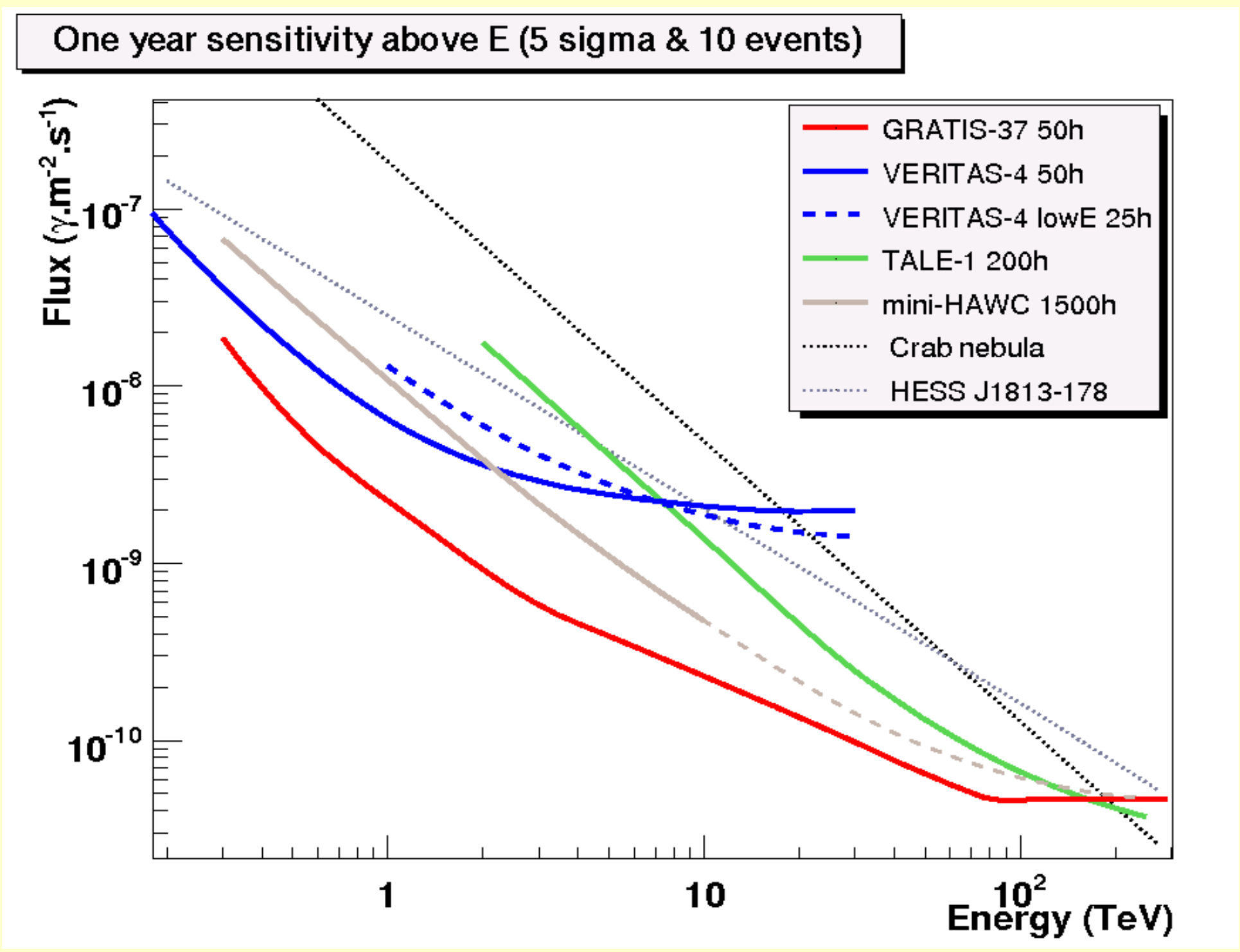


Fig 10: *Sensitivity of several experiments and project at high energy*

- Recent discoveries in the field of TeV astronomy provide motivation for extending the covered energy range to more than 100TeV where γ-ray emission models can be better discriminated. Some hard spectrum sources could even be detected in the hundred TeV range while their lower energy emission remains beyond reach.

- Simulation based preliminary capability estimates of various experimental approaches to 100TeV astronomy are compared on figure 10.

- High density IACT telescope arrays seem the most attractive from the point of view of the sensitivity they offer. Even a relatively low cost ($17M) project like GRATIS provides sufficient sensitivity to measure many galactic source spectra from 300GeV and up to more than 100TeV.

- With their all sky survey capability in an uncharted energy window, projects like TALE or mini-HAWC have a great exploratory potential.

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