Ground-based γ-ray Astronomy: an introduction

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"*Multimessenger Data Analysis in the Era of CTA*"
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Outline

- Why Gamma-Ray Astronomy ?
- The scientific case: open problems in Cosmic Ray Physics
- The “*Cosmic Ray Connection”:* cosmic rays and photons
- Detection of photons from ground
- *EAS Array technique for survey instruments*
- What’s Next ?

Questions in CR physics

- How are cosmic rays and *cosmic ray sources* distributed in the Galaxy ? Is the Earth embedded in the cosmic ray background (sea) or is it located close a source ?

- *What are* the Galactic sources of TeV and PeV cosmic rays ? How high in energy can the different Galactic sources accelerate particles ?

- How do cosmic rays *propagate* in the Galaxy ?

Astrophysics with CRs ?

- High quality information about the ***locally*** measured primary and secondary components of CRs

- CR factories can be revealed only by neutral & stable astronomical messengers: *photons and neutrinos*

- Charged CRs do not provide information about the acceleration sites

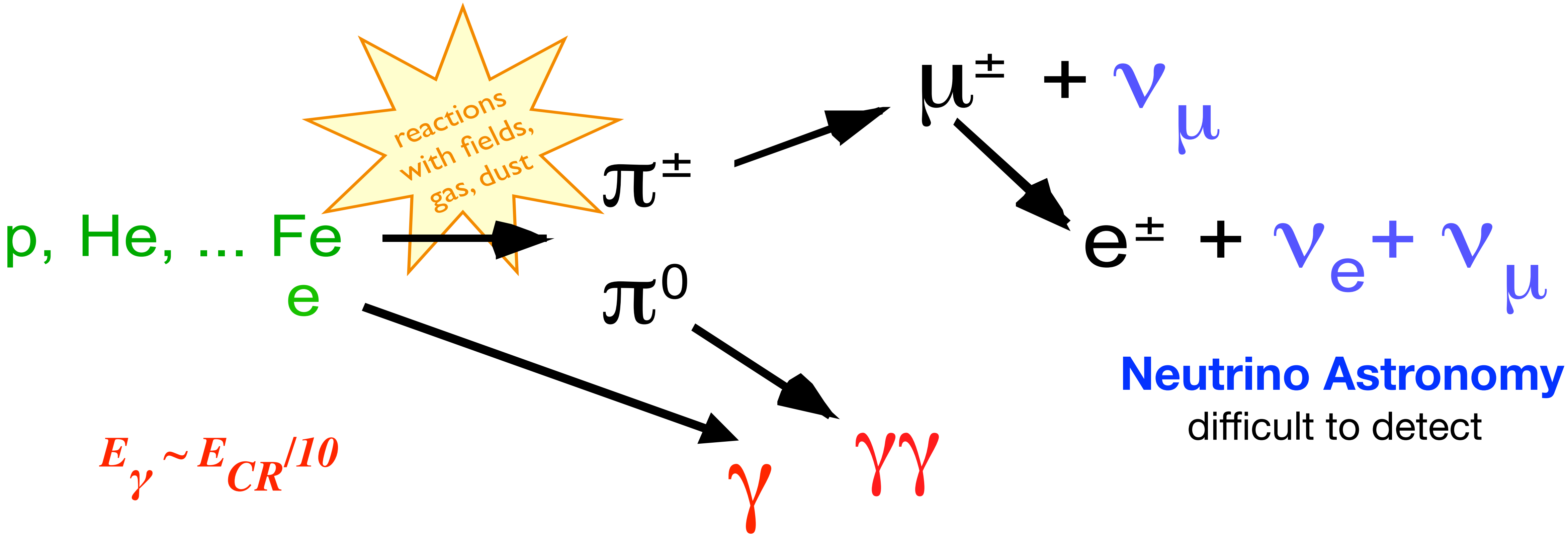
Crucial connection between charged ***cosmic rays***, ***photons*** and ***neutrinos*** in Cosmic Ray Sources

➡ ***multi-messenger astronomy***

The *"Cosmic Ray Connection"*

In CR sources *hadronic interactions* of nuclei produce ***photons*** and ***neutrinos***

➜ *CRs, photons and neutrinos are strongly correlated*: they come likely from the same sources !



reactions with fields, gas, dust

p, He, ... Fe $\rightarrow \pi^{\pm}, \pi^0$

$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}$

$\mu^{\pm} \rightarrow e^{\pm} + \nu_e + \nu_{\mu}$

$\pi^0 \rightarrow \gamma\gamma$

e $\rightarrow \gamma$

$E_{\gamma} \sim E_{CR}/10$

Neutrino Astronomy
difficult to detect

Gamma-Ray Astronomy
easy to detect

γ, ν
point back to sources
(good for astronomy)
but serious backgrounds

ONLY charged CRs observed at E > 10^{14} eV so far !

Recent observations of PeV neutrinos by IceCube

Tracers to CR accelerators

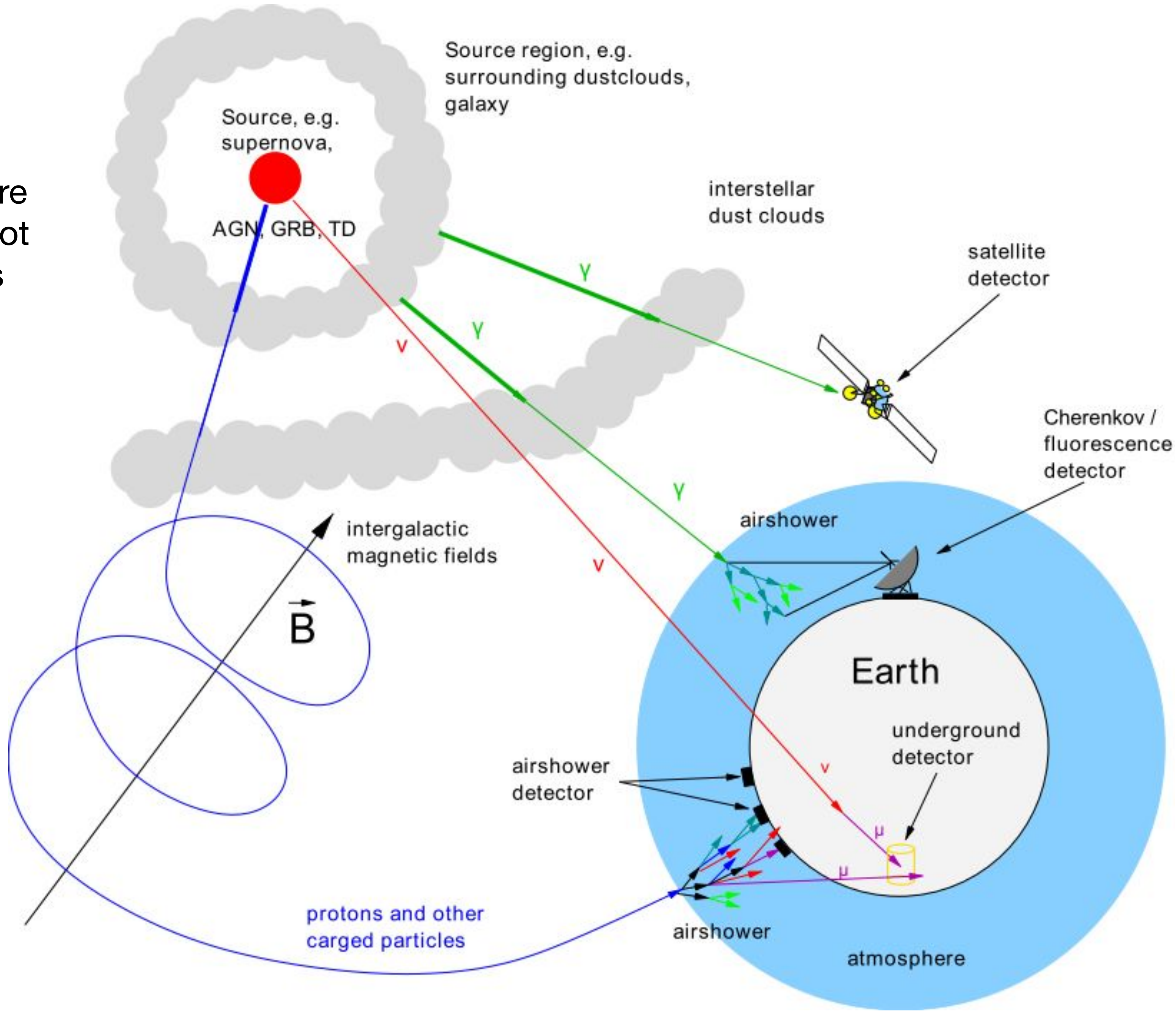
Gamma-rays and Neutrinos are the only messenger that are not deflected by magnetic fields

Interstellar magnetic field

$B \approx 3\ \mu G$

Curvature radius at 1 TeV:

$r \approx 0.3 \times 10^{-3}\ pc$



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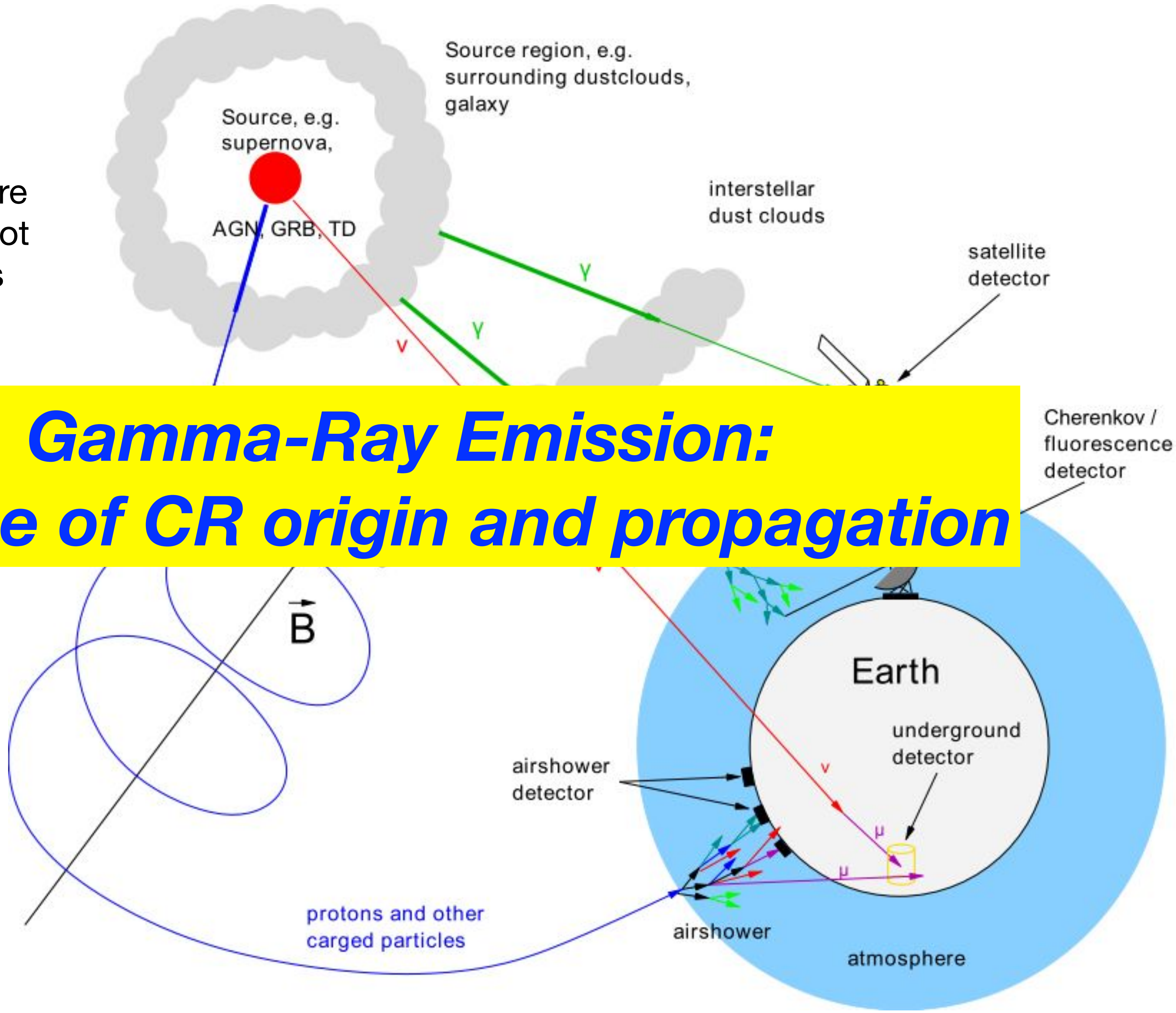
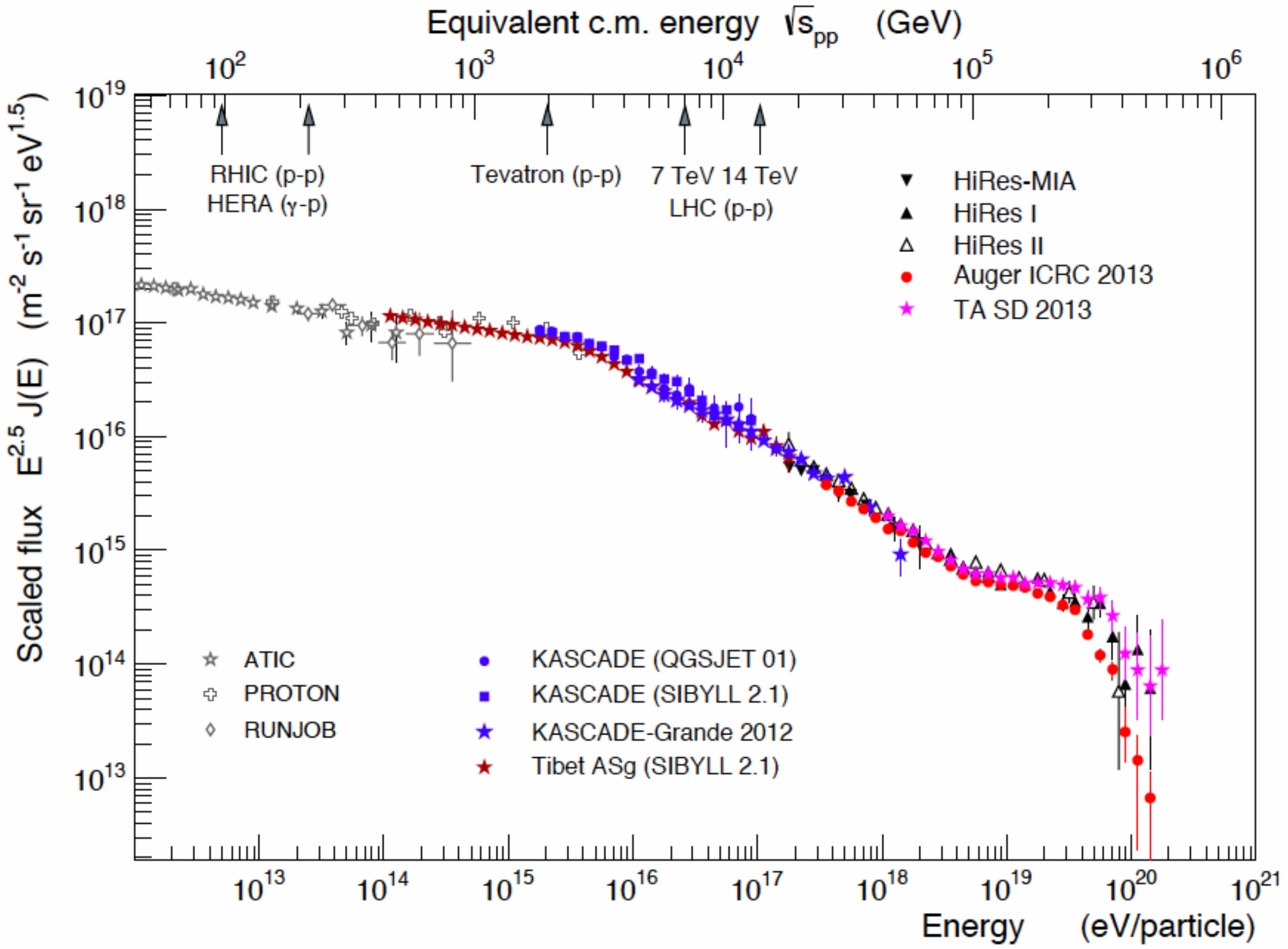


Gamma-Ray Emission:
a probe of CR origin and propagation

TeV-atron Sky

$$\boxed{\begin{array}{l} p\ \ (p,\ \gamma) \longrightarrow \pi^0 + rest \\ \qquad\qquad\qquad \hookrightarrow \gamma\gamma \end{array}}$$

Gammas from Galactic Cosmic Rays: $E_{\gamma} \sim E_{CR}/10$



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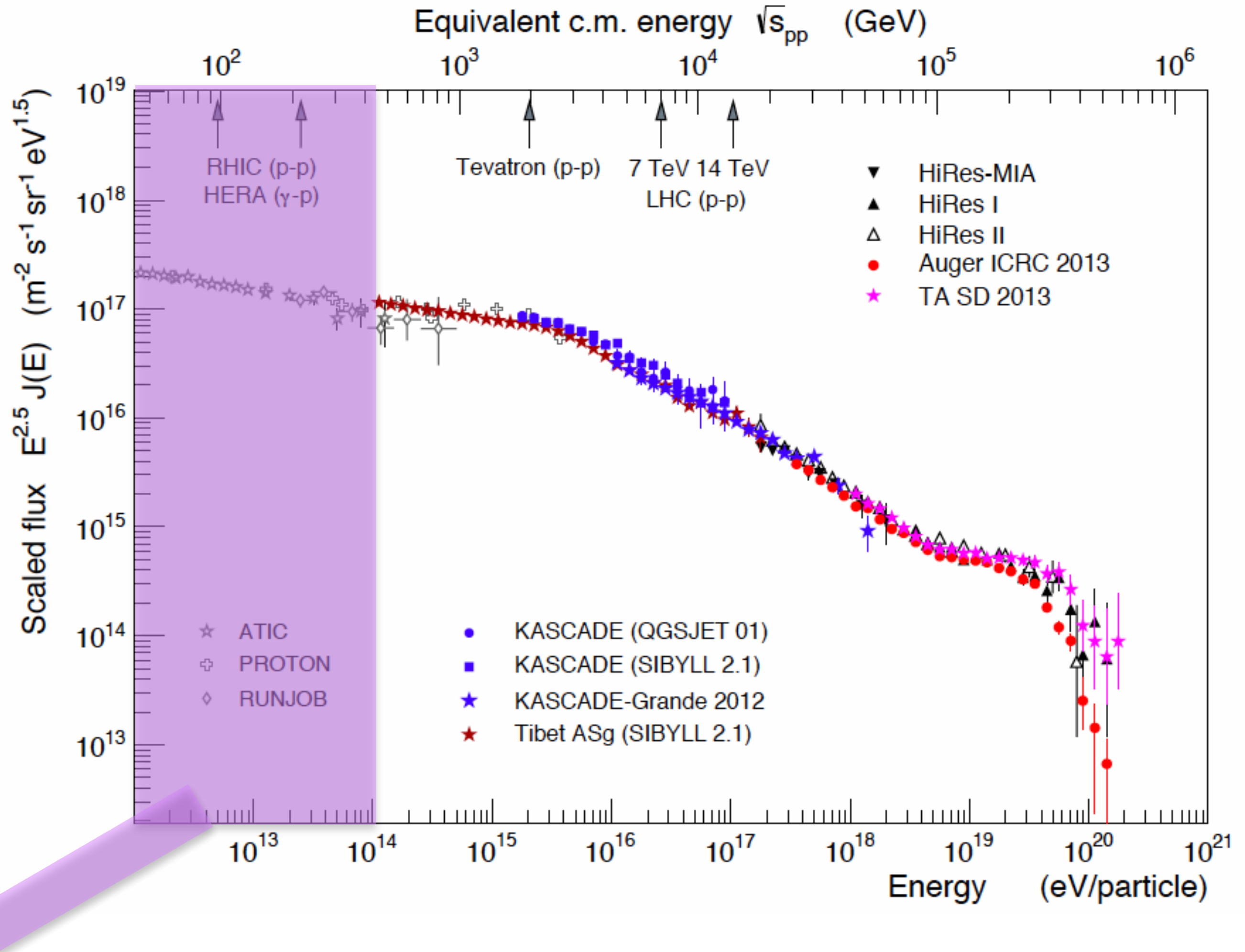
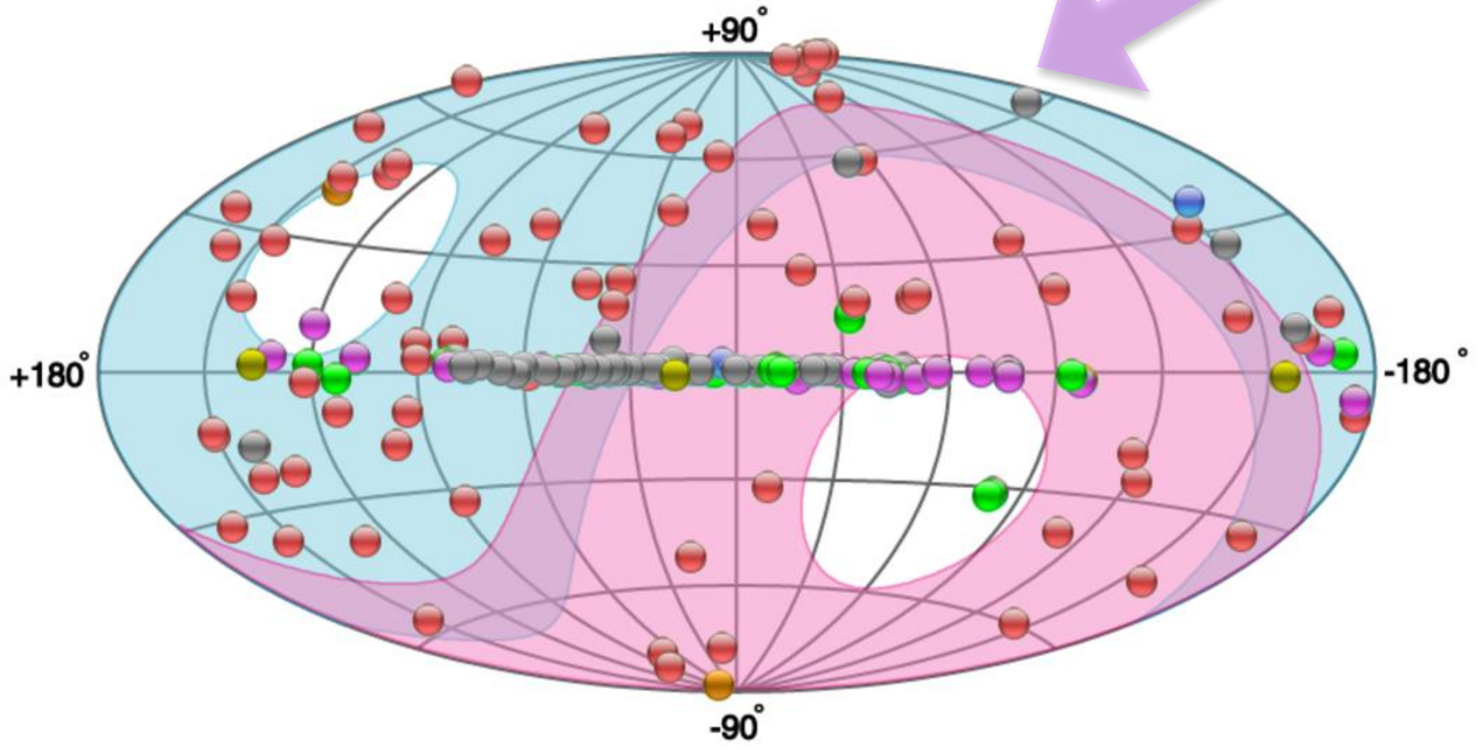


Sources of TeV Cosmic Rays

Photons > 100 GeV !



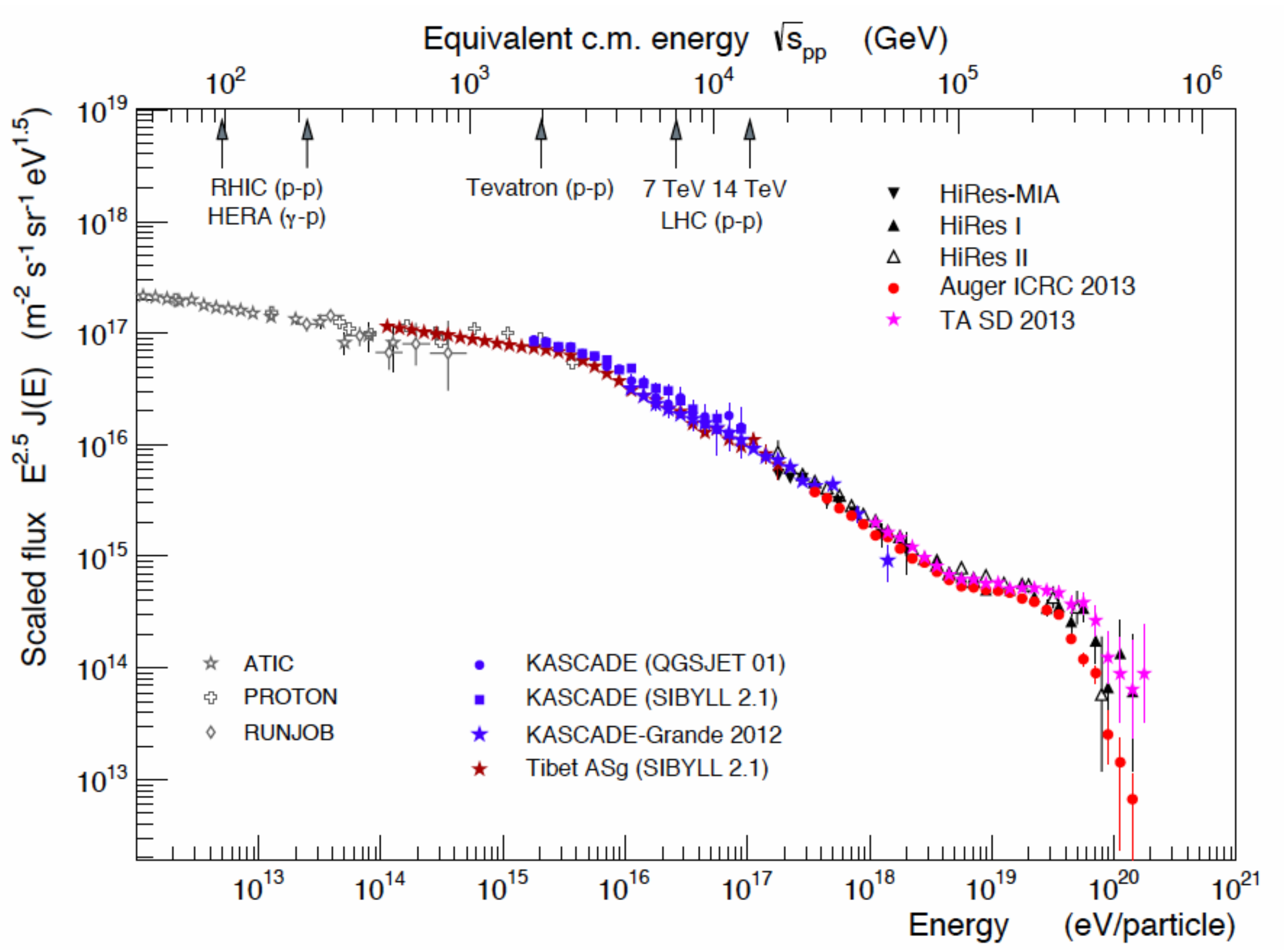
But *'smoking gun'* still missing…

leptonic ?

hadronic (CR sources) ?

Complex scenario: each source is individual and has a unique behaviour. In general one expects a combination of leptonic and hadronic emission !

The *'knee'* in the CR energy spectrum



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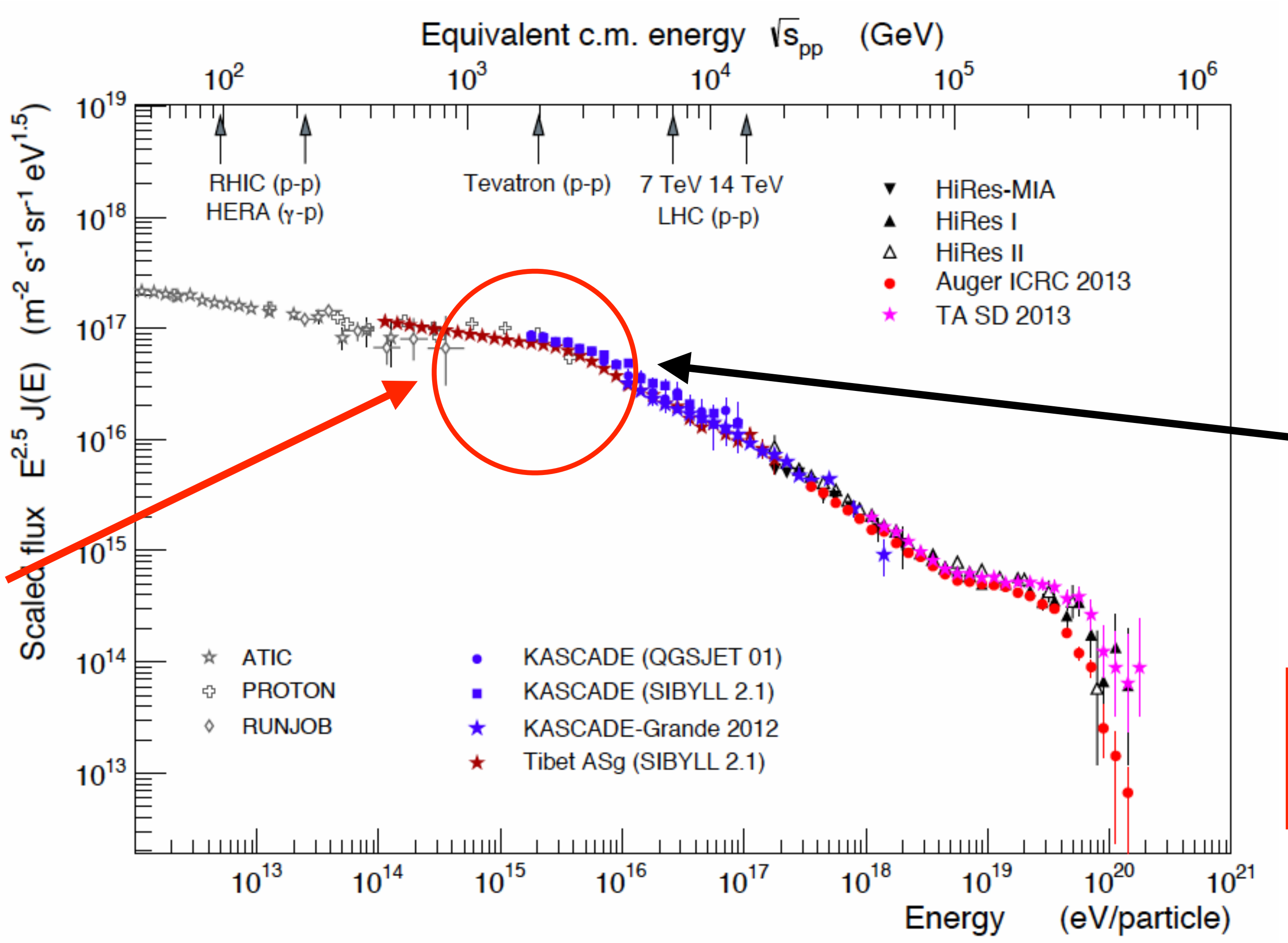

CR knee @ few PeV's
Something must
happen here...

We'd like CR sources
to accelerate (at least)
up to that energy

We would like SNRs to be CR PeVatrons…!

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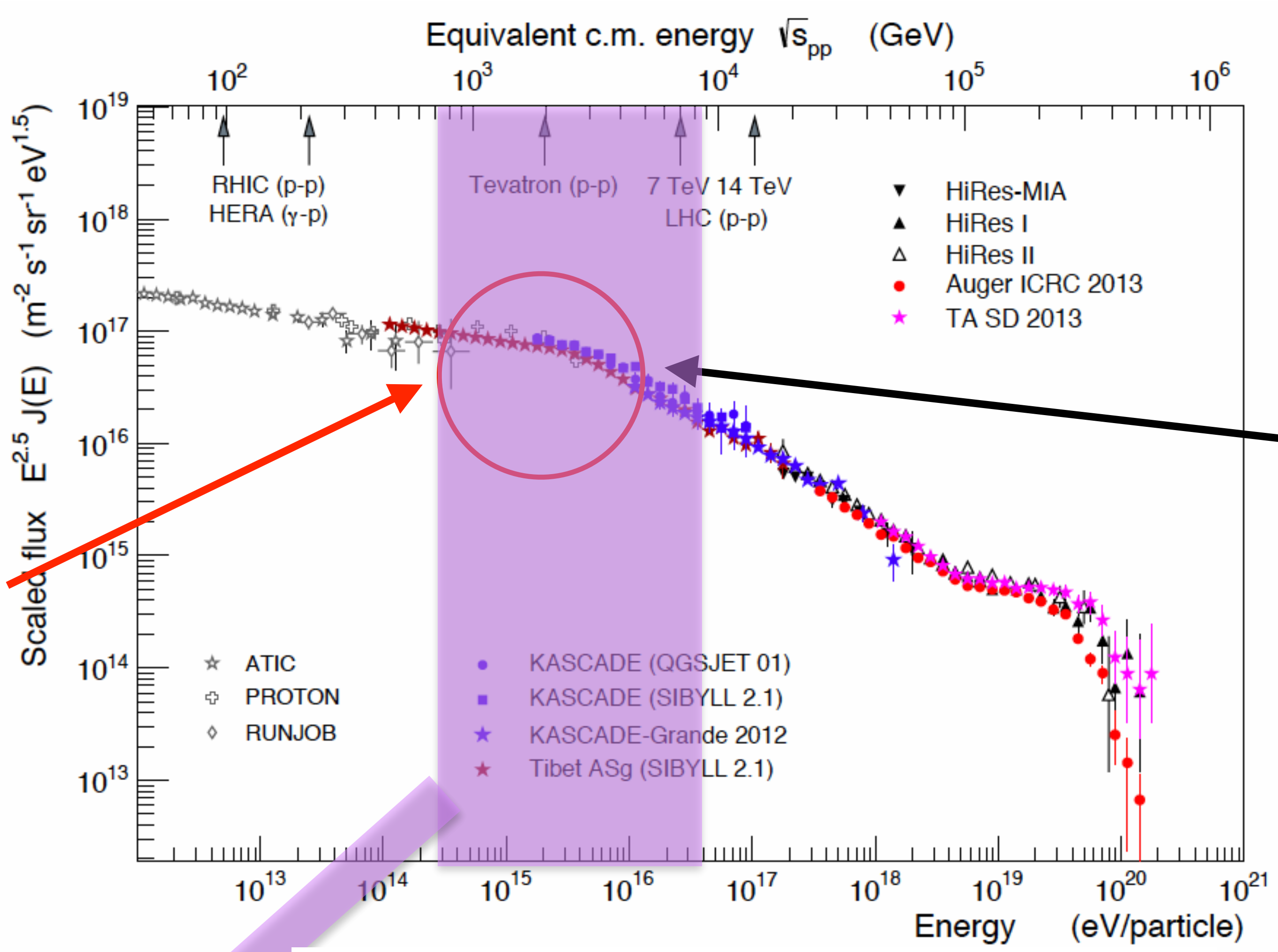

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CR knee @ few PeV's
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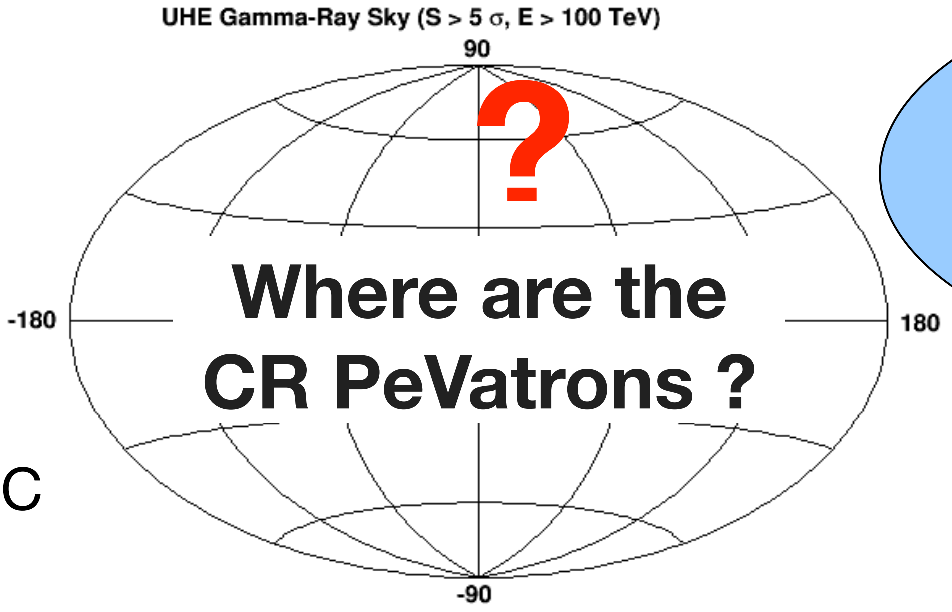
PeV Cosmic Rays
Photons > 100 TeV !

Recent hints by HESS and HAWC



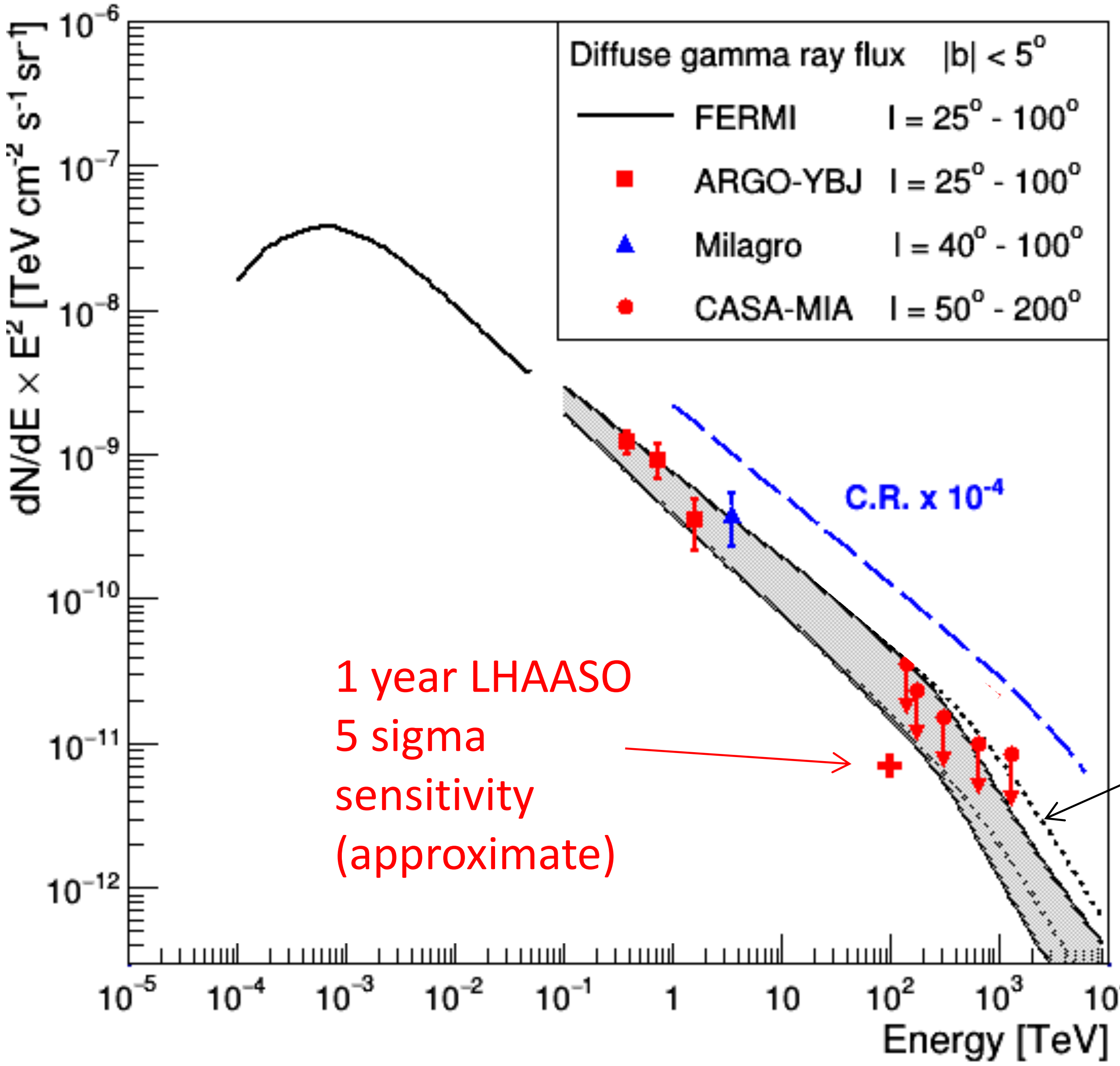
Where are the CR PeVatrons ?

Bonus @ 100 TeV:

Hadronic spectra: *hard*
Leptonic spectra: *soft*
No hard IC γ-rays >100 TeV
IC in deep Klein-Nishina

Expected Galactic diffuse γ-ray flux

Is the knee a source property, in which case we should see a corresponding spectral feature in the gamma-ray spectra of CR sources, or the result of propagation, so we should observe a *knee that is potentially dependent on location*, because the propagation properties depend on position in the Galaxy ?



1 year LHAASO
5 sigma
sensitivity
(approximate)

Unabsorbed
flux

by S. Vernetto & P. Lipari: ICRC 2017

Observing a location dependence of the knee energy (or of the spectral index !) would provide important clues on the nature of the knee.

The space distribution of this emission can trace the location of the CR sources and the distribution of interstellar gas.

Grey band: expected γ-ray flux in the region |lat|<5°, long=25°-100°

Extrapolation of the Fermi spectrum $E^{-2.65\pm0.05}$ with a steepening due to CR knee

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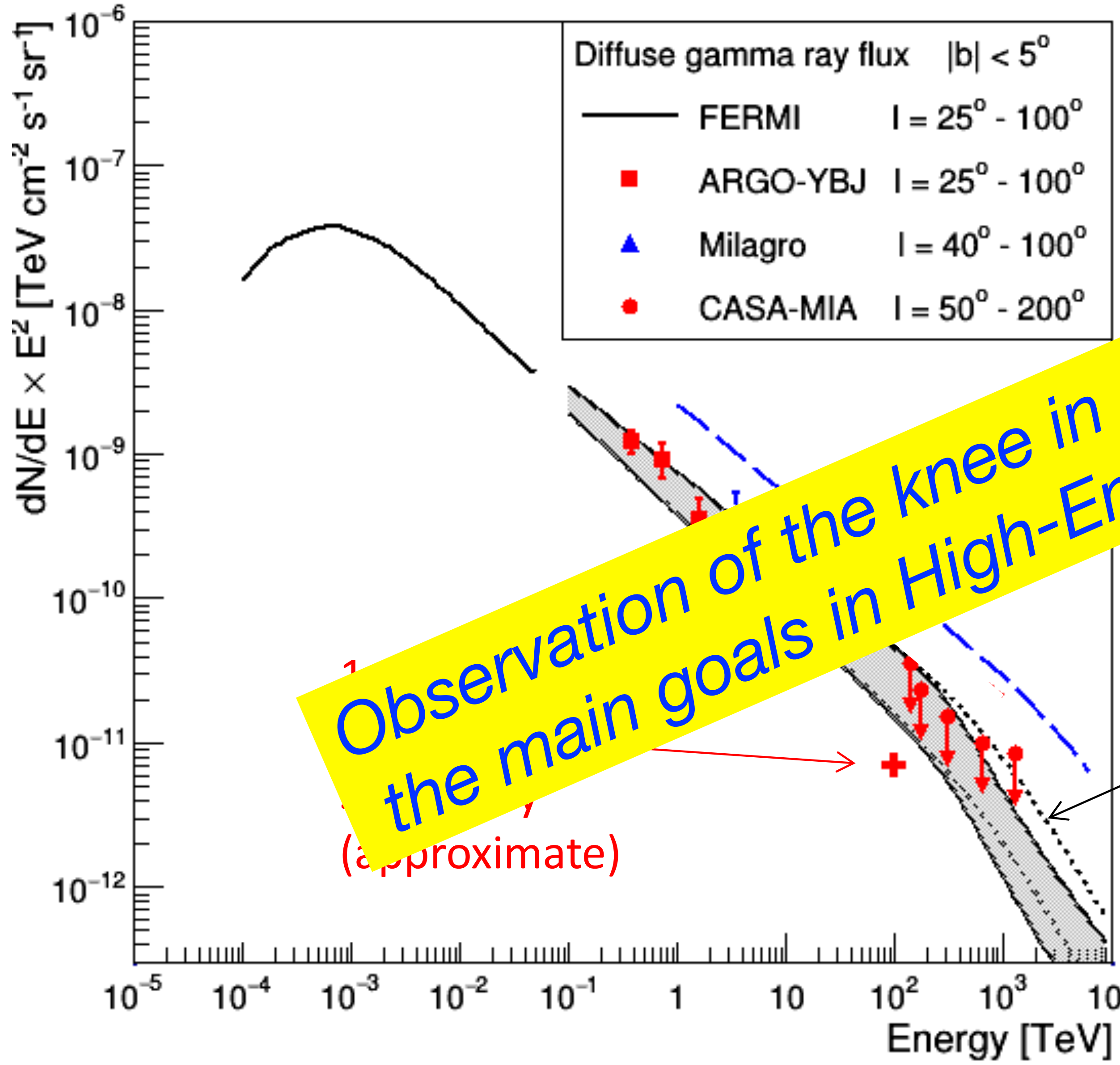

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Observation of the knee in diffuse γ-ray emission one of the main goals in High-Energy Gamma-Ray astronomy

Grey band: expected γ-ray flux in the region |lat|<5°, long=25°-100°

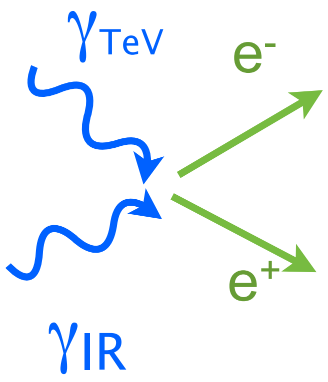
Unabsorbed flux

Extrapolation of the Fermi spectrum $E^{-2.65\pm0.05}$ with a steepening due to CR knee

Attenuation of γ-ray flux in the Galaxy

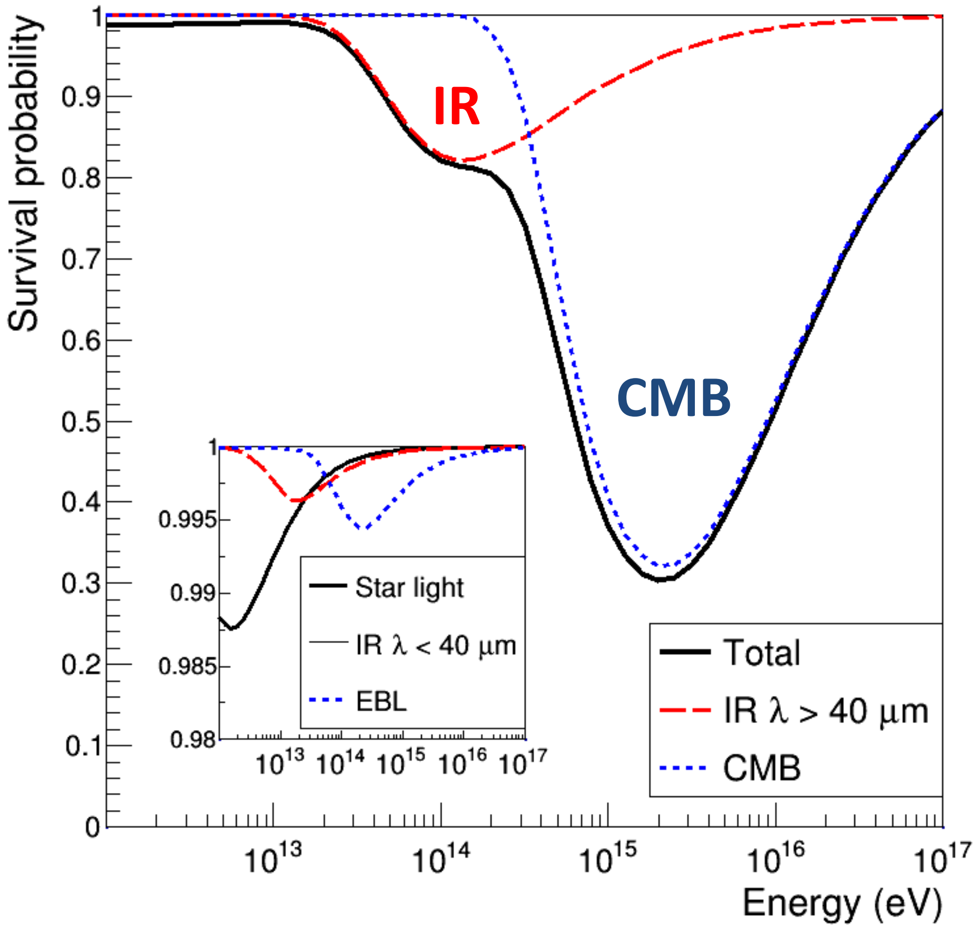
The production rate of γ-rays is not in general the emission rate observed: ***photons can be absorbed***

γ-rays meet IR-photons

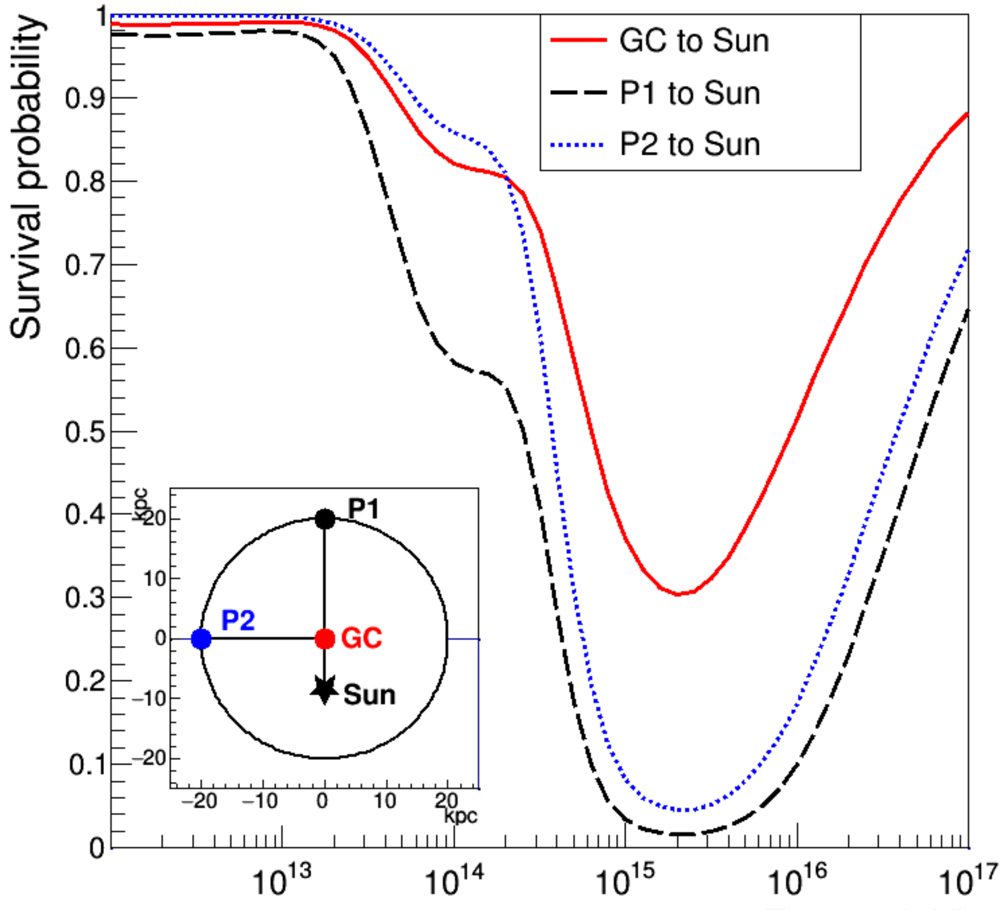


pair production in intergalactic photon fields

γ-rays from Galactic center



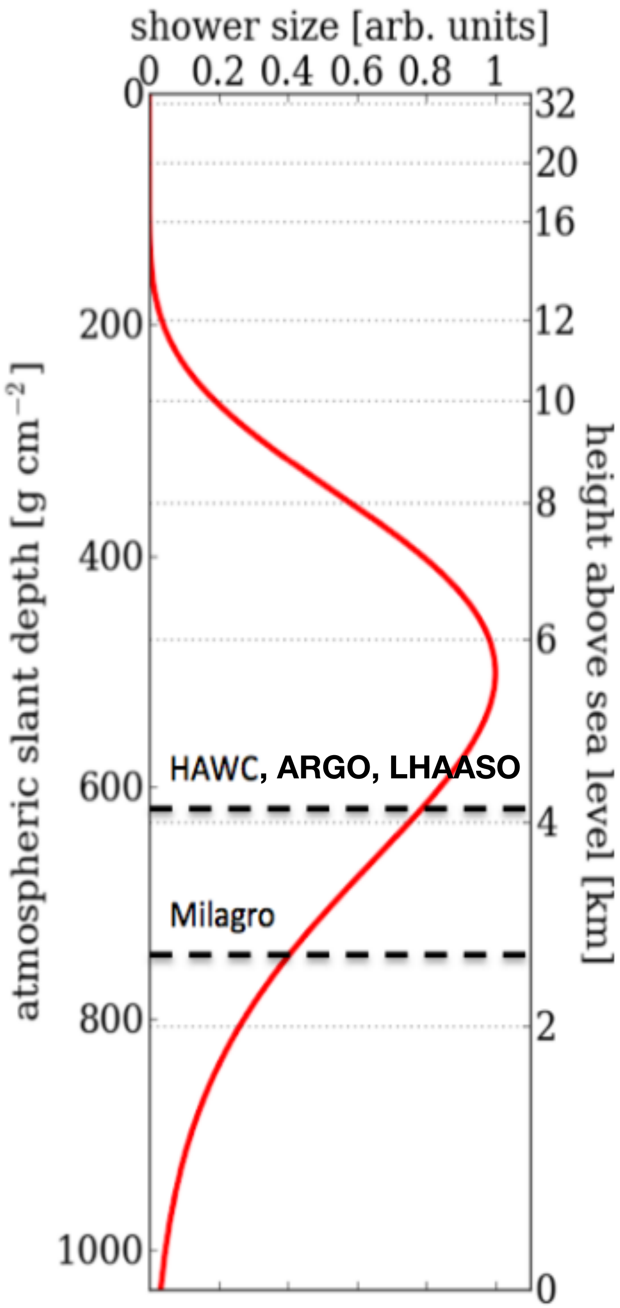
γ-rays from 3 source positions

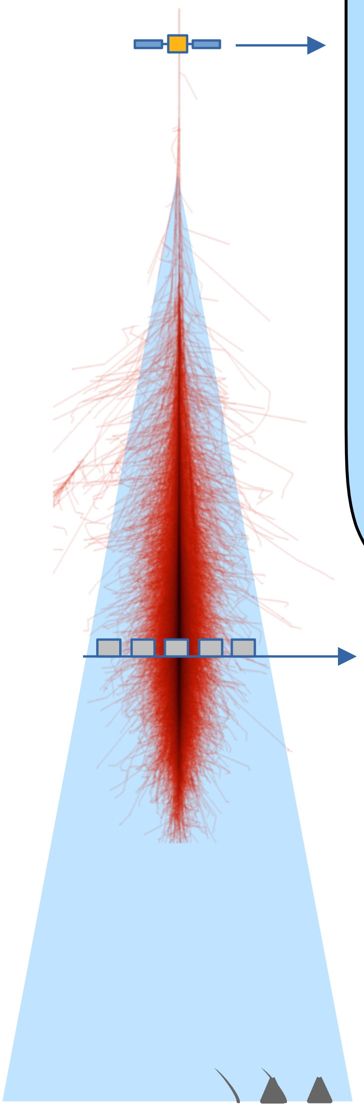


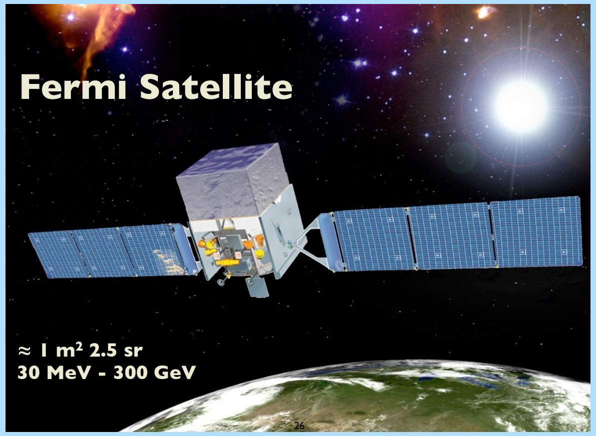
Vernetto & Lipari, PRD 94, 2016

The absorption exists but does not precludes Galactic gamma ray studies up to a few hundreds TeV. At higher energies only a fraction of the Galaxy is visible.

How do we detect γ-rays ?

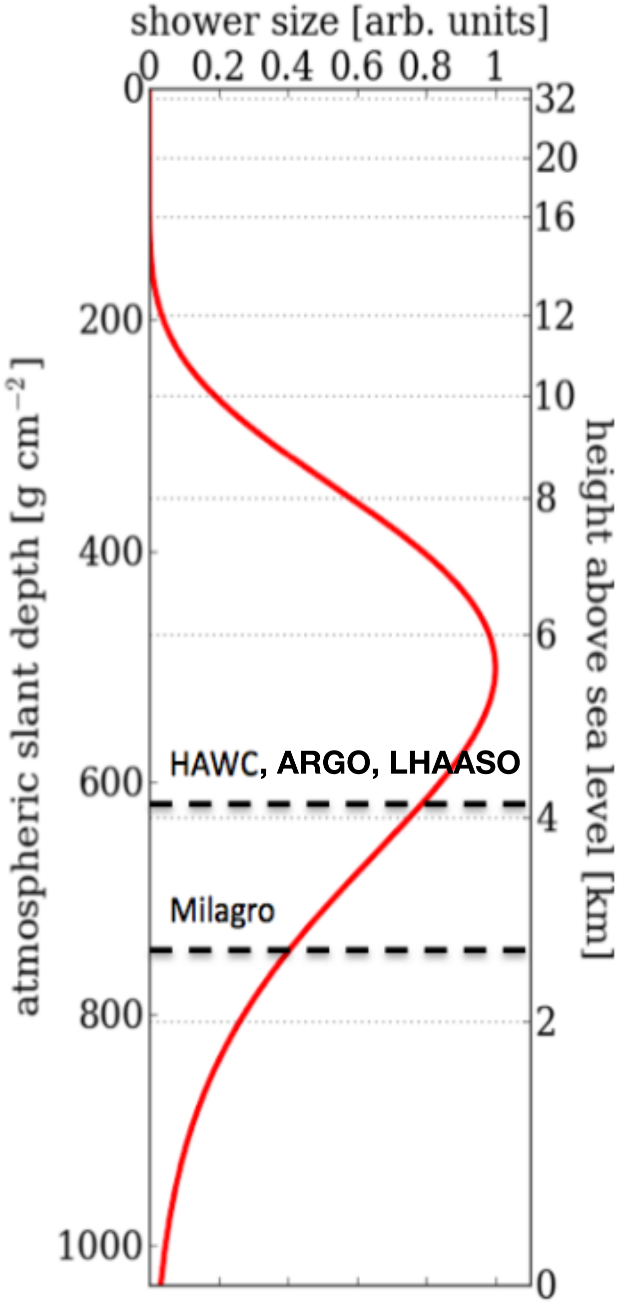


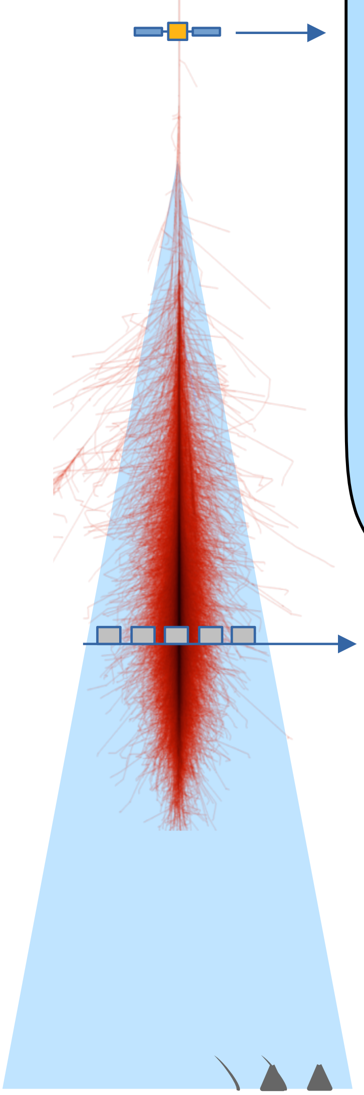


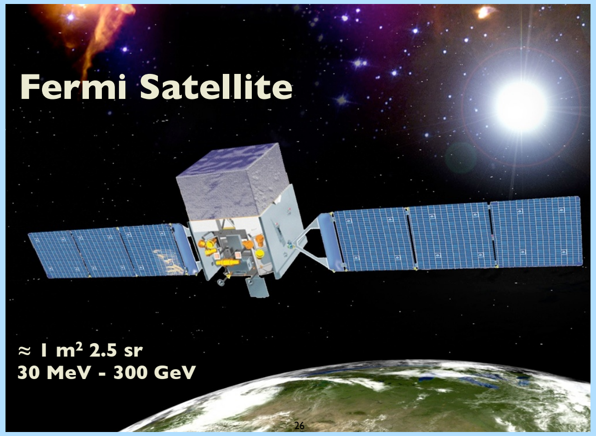


Wide Field of View
Continuous operations

How do we detect γ-rays ?







Wide Field of View
Continuous operations

TeV sensitivity

Cosmic Ray detection

In general: for all particle types

- the higher the energy ➜ the lower the flux
- the lower the flux ➜ the larger the required detector area

$$N_{evts} = Flux \times Area \times Time$$

> 100

small
given by nature

$\approx 1\ m^2$
for satellite exp

≈ 3 yrs

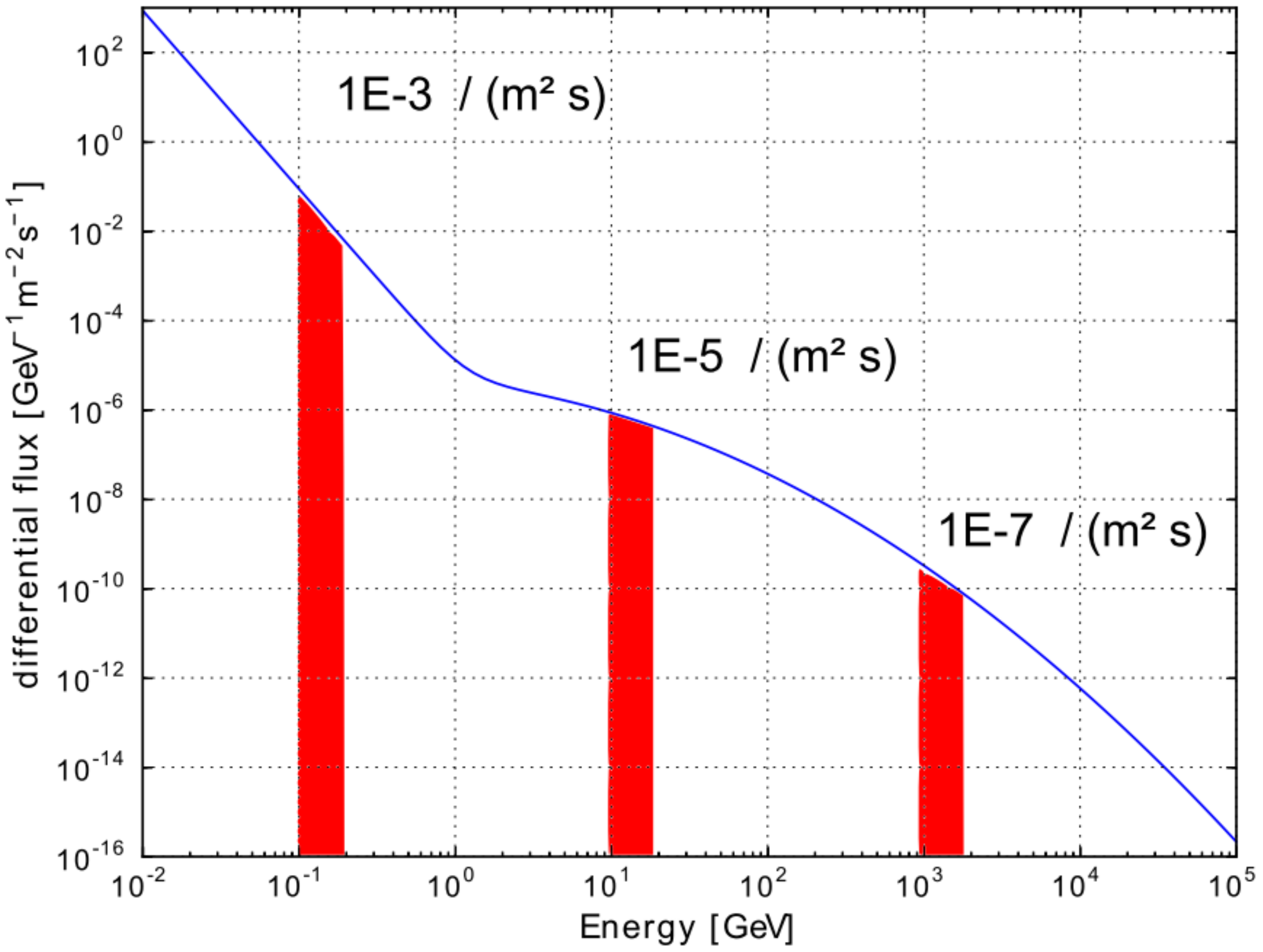
Detector size limits the smallest measurable flux !

Direct measurements of nuclei up to about 100 TeV/n

The problem of effective area

Flux of photons much lower !

Flux from Crab Nebula, the strongest TeV source



Power-law energy spectra ➜ the gamma flux decreases rapidly with increasing energy

Space instruments cannot provide enough collection area for statistical … measurement

Direct measurements of photons up to about 100 GeV

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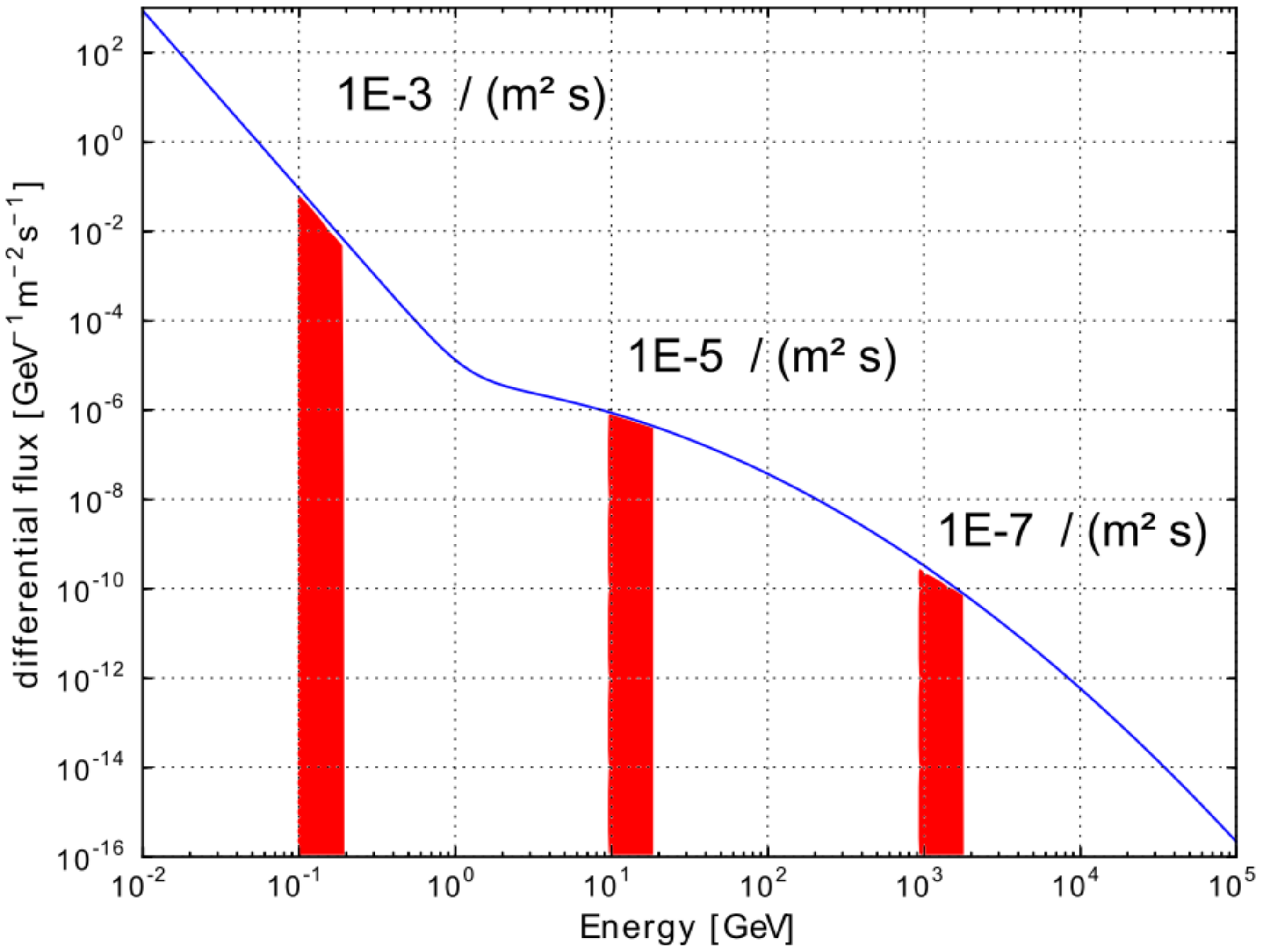

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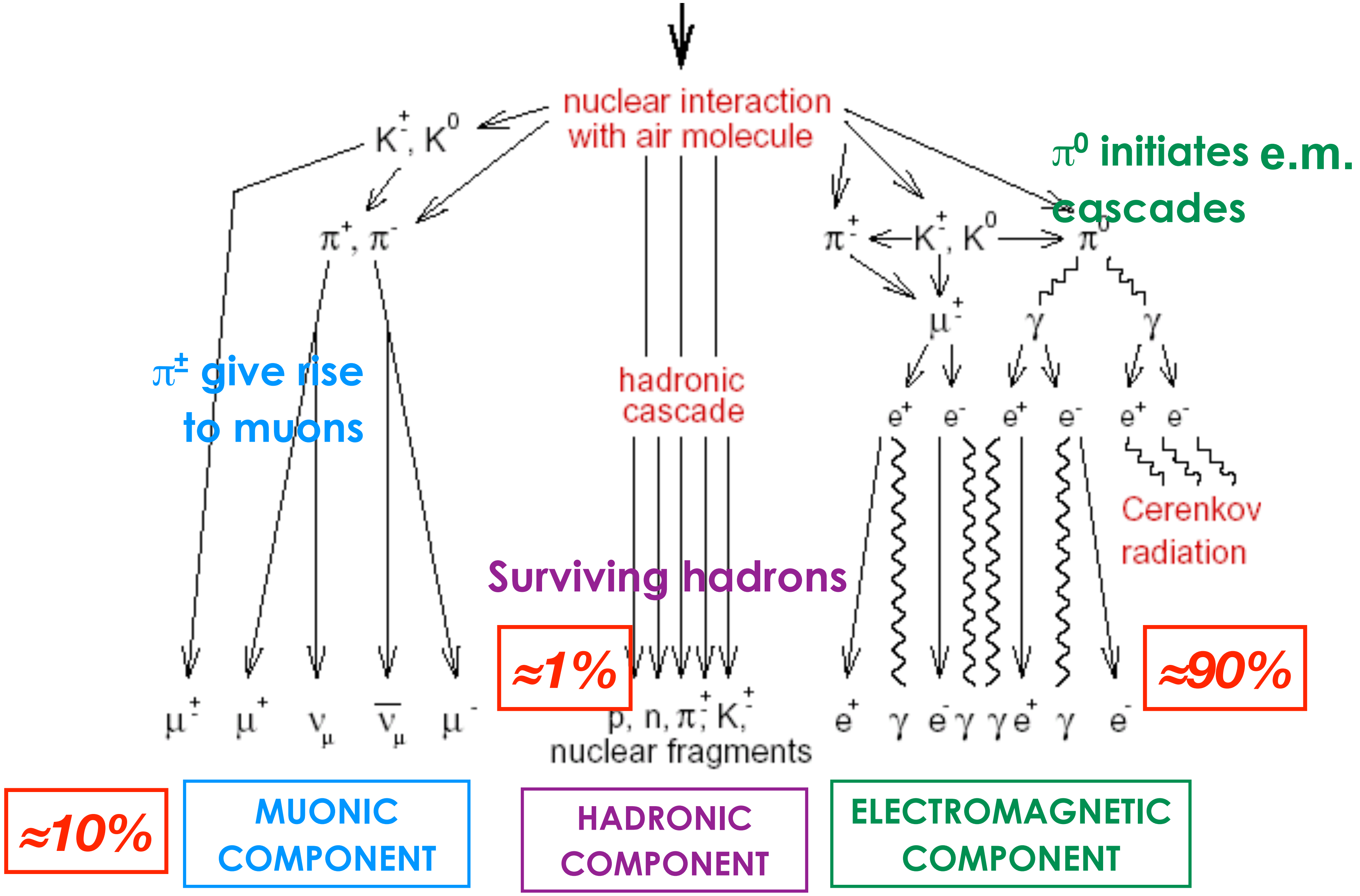
Direct measurements of photons up to about 100 GeV

To extend the energy range
➜ very large area

➜ γ-ray detectors at ground

EAS: the key to study CRs from ground

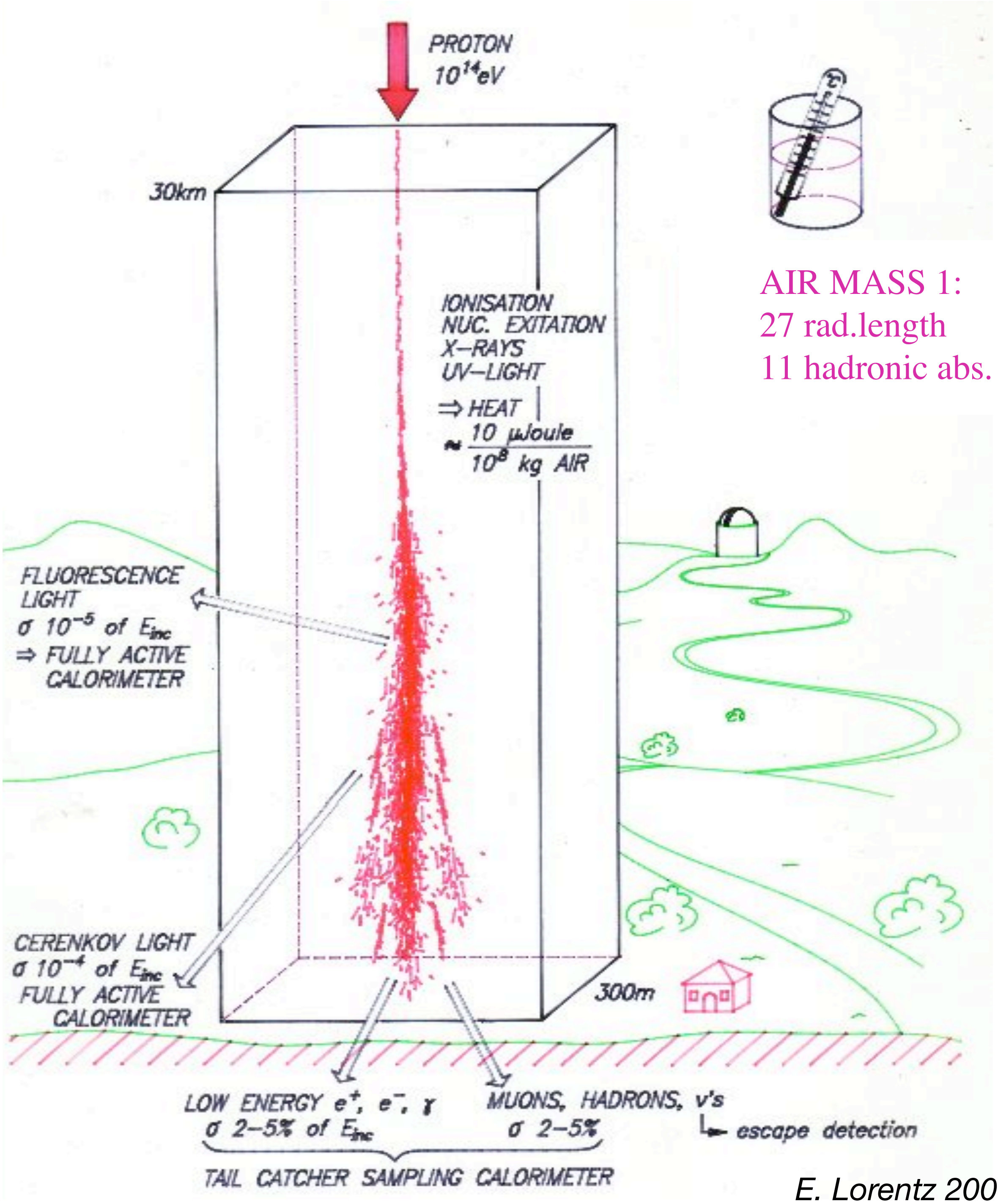
A high energy primary particle, upon entering the atmosphere, initiates a chain of nuclear interactions



The backbone of an air shower is *the hadronic component* of nucleons, pions and other particles, which feeds the electromagnetic and muonic components.

How do we detect Cosmic Rays at ground ?

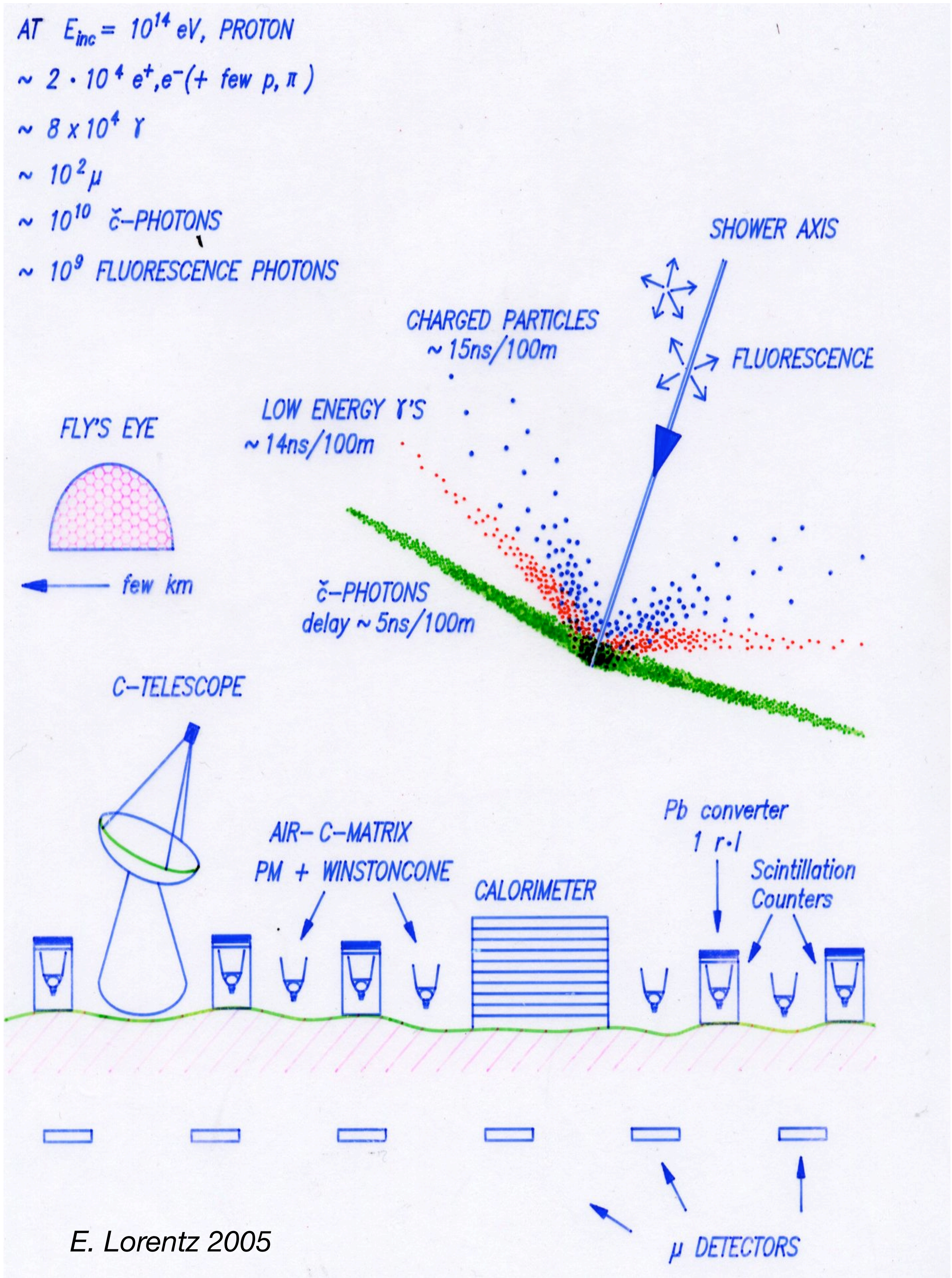
The major observables of EAS at ground are: electron-photon, muon and hadron components, Cherenkov photons, nitrogen fluorescence, radio emission ➜ *not only particles !*



AIR MASS 1:
27 rad.length
11 hadronic abs. length

E. Lorentz 2005

Different detectors for different observables



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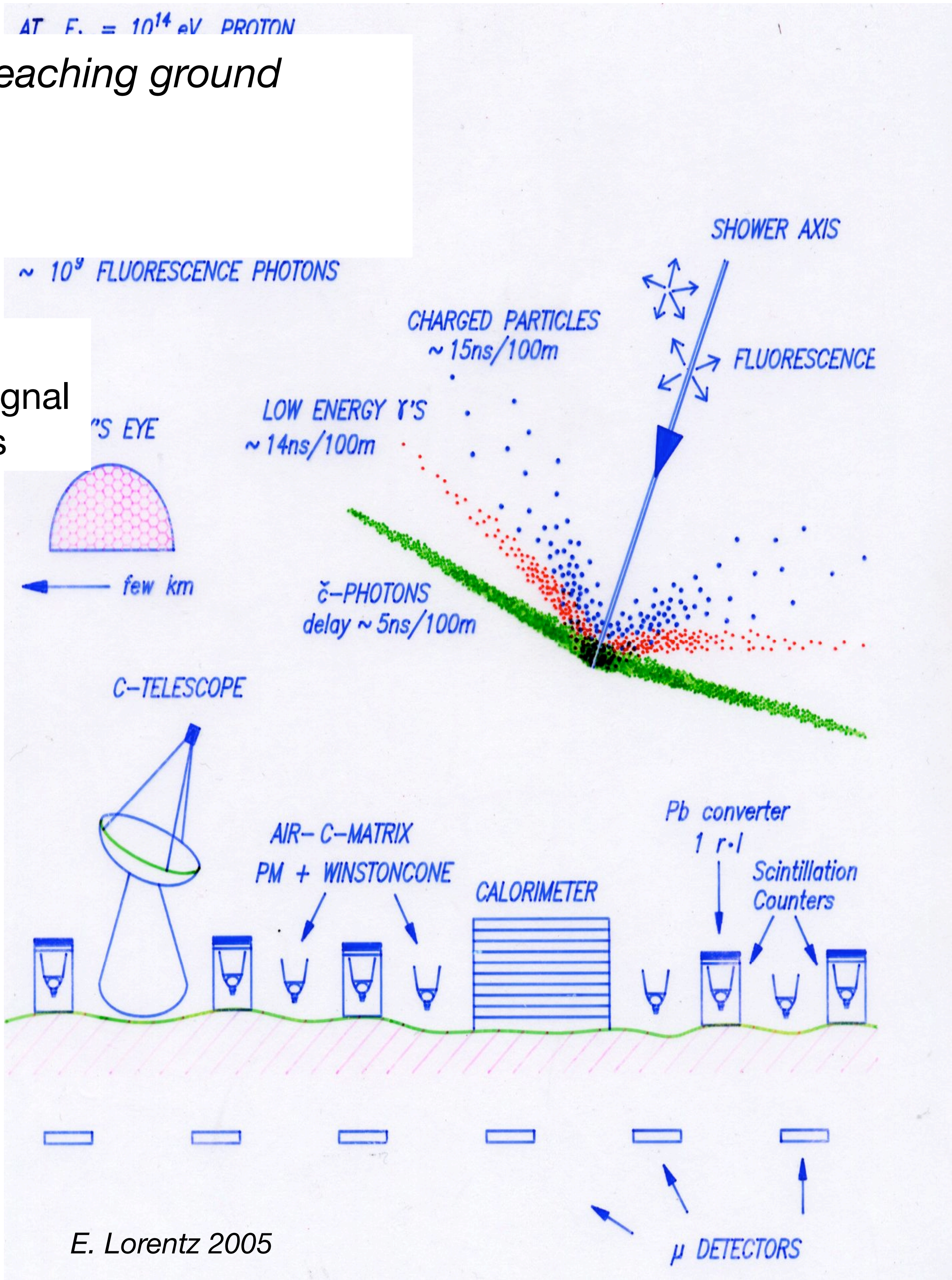

E. Lorentz 2005

1. Ground-based arrays: sample *shower tail particles reaching ground*

➜ *Tail Catcher Sampling Calorimeter*
(in HEP detector language)

Atmosphere: the absorber
Detector at ground: the device to measure a (poor) calorimetric signal
➜ signal about *direction* and *energy* from the shower tail particles

★ large shower-to-shower fluctuations

★ large geometric acceptance and high duty cycle (≈100%)

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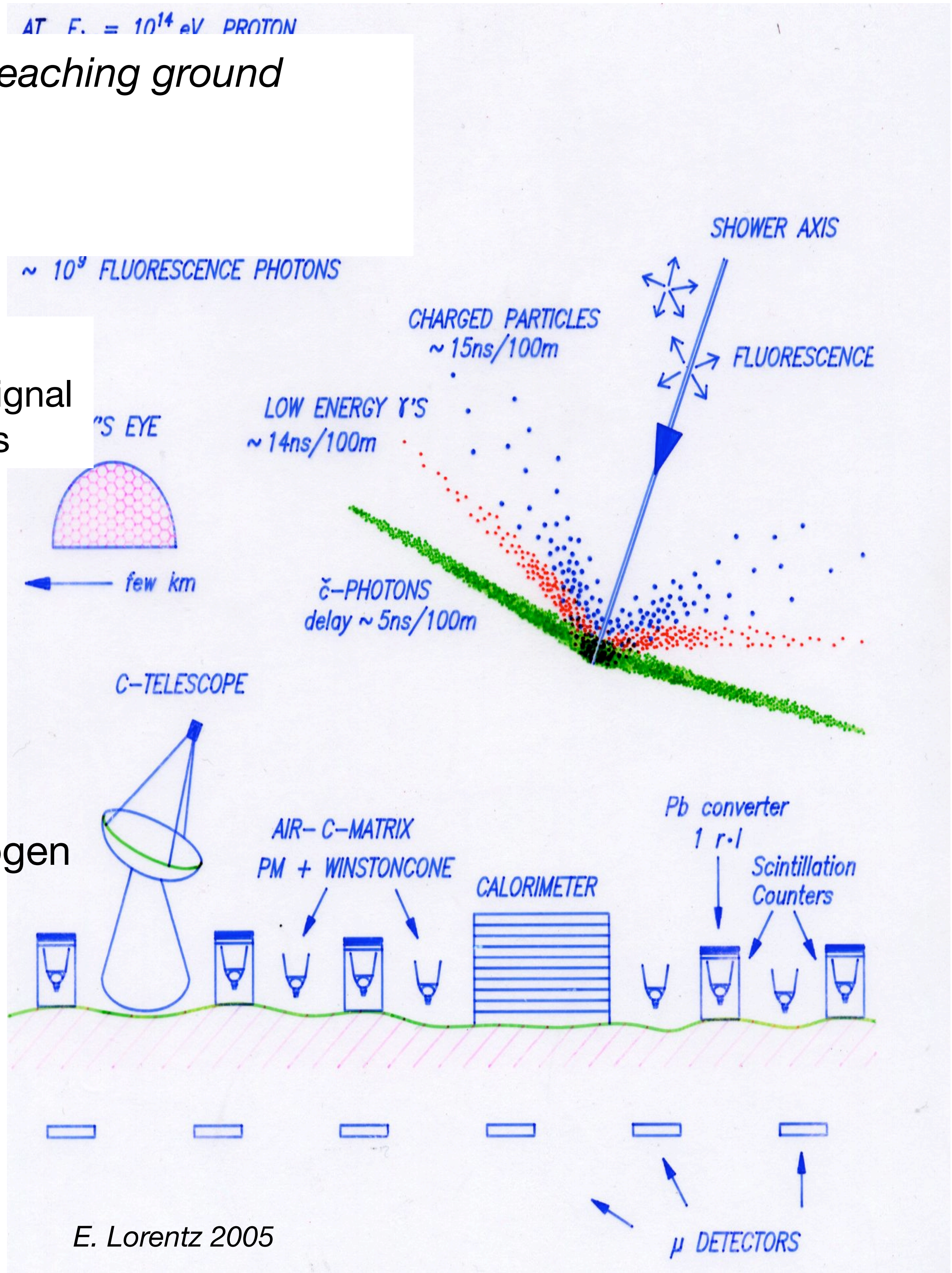
- ★ large shower-to-shower fluctuations
- ★ large geometric acceptance and high duty cycle (≈100%)

2. Telescopes: observation of Cherenkov photons/nitrogen fluorescence allows the study of EAS longitudinal profile

➜ ***Homogeneous Calorimeter***

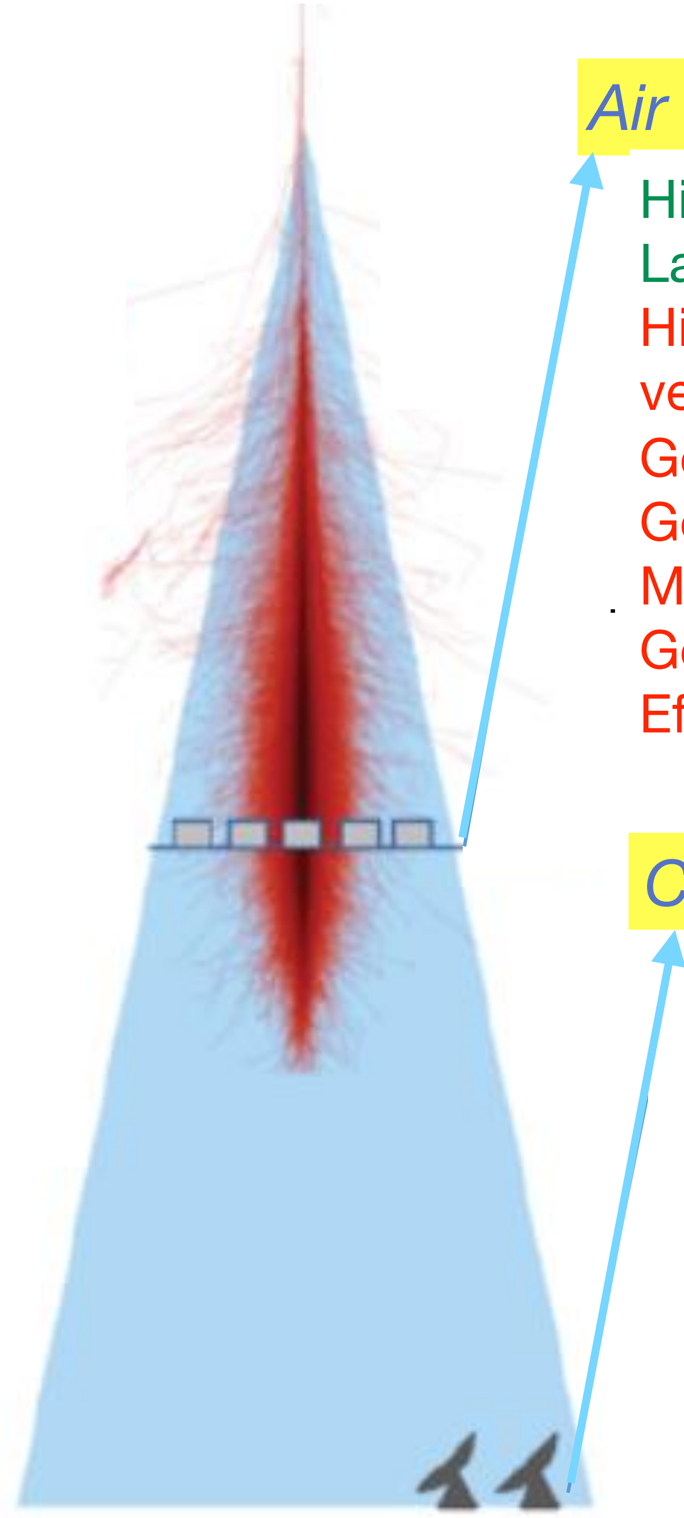
- ★ low duty cycle (≈10-15%)
- ★ good energy resolution



E. Lorentz 2005

Ground-based gamma-ray detectors

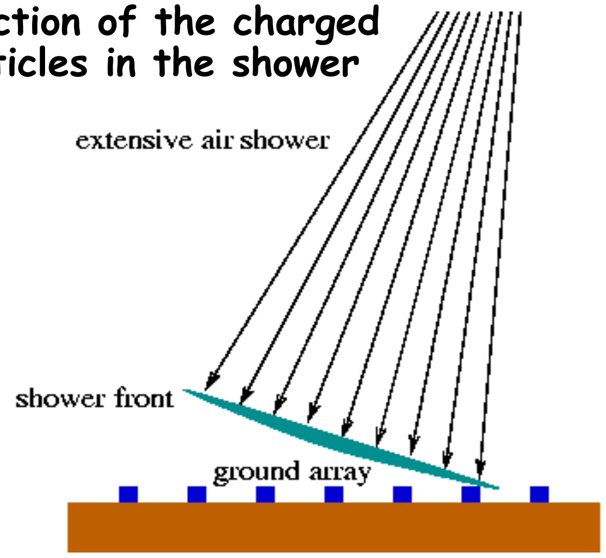
Detecting Extensive Air Showers



Air Shower Arrays (≈100 GeV → 1 PeV)

High duty-cycle (≈100%)
Large field of view (≈2 sr)
Higher energy threshold (≈300 GeV ARGO),
very strong zenith angle dependent ($\approx\cos\theta^{-(6-7)}$)
Good bkg rejection (>80%)
Good angular resolution (0.2-0.8 deg)
Modest energy resolution (≈50%)
Good Sensitivity (5-10% Crab flux)
Effective area shrinks with large zenith angle

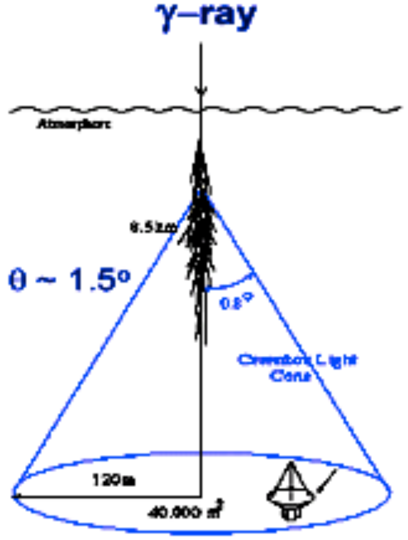
detection of the charged articles in the shower



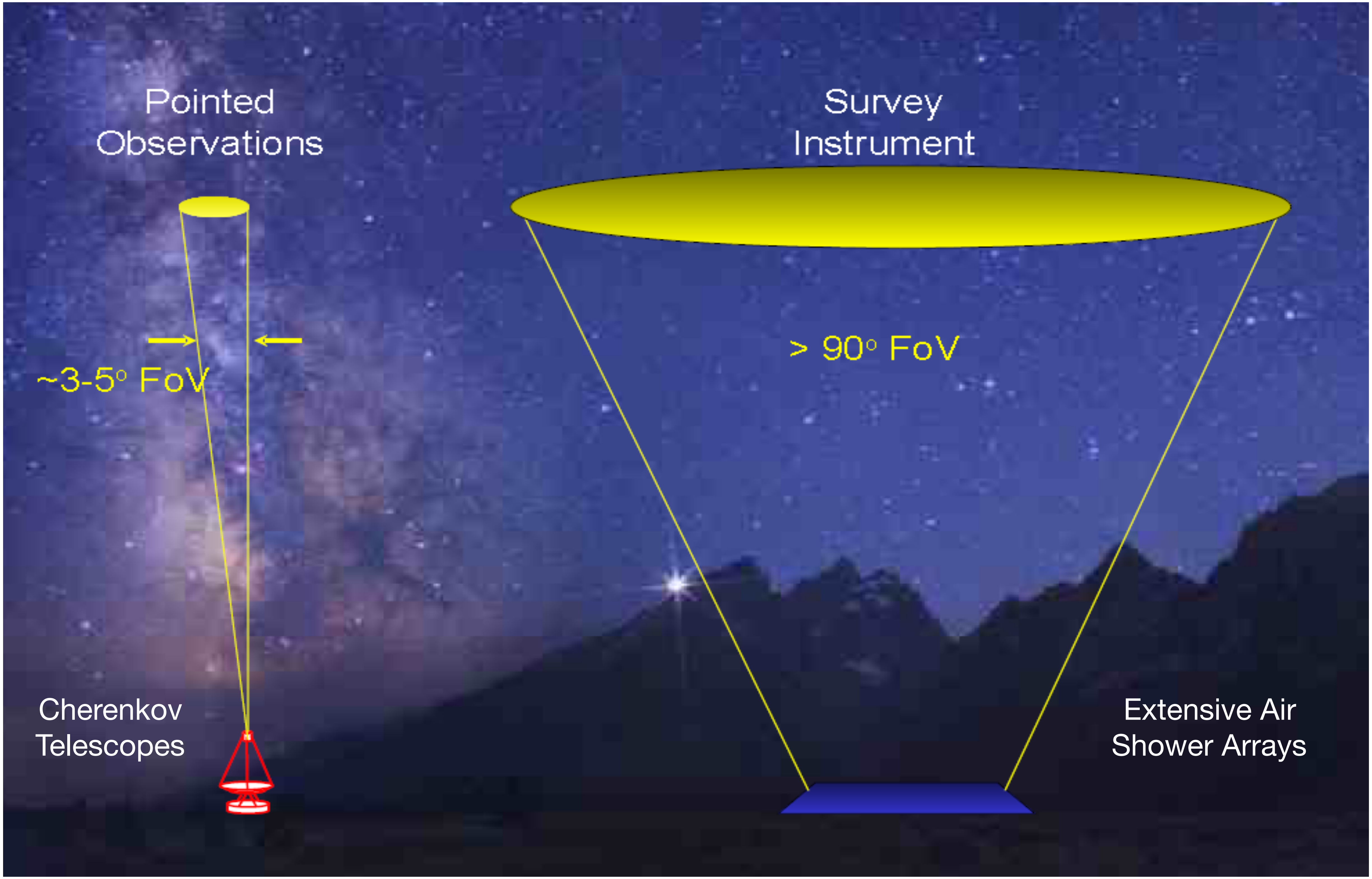
Cherenkov Telescopes (≈10 GeV → 100 TeV)

Very low energy threshold (≈10 GeV)
Excellent bkg rejection (>99%)
Excellent angular resolution (≈0.05 deg)
Good energy resolution (≈15%)
High Sensitivity (< % Crab flux)
Effective area increase with zenith angle
Small zenith angle dependent ($\approx\cos\theta^{-2.7}$)
Low duty-cycle (≈10%)
Small field of view (≈ 5 deg)

detection of the Cherenkov light from charged particles in the EAS



Wide field of view detectors



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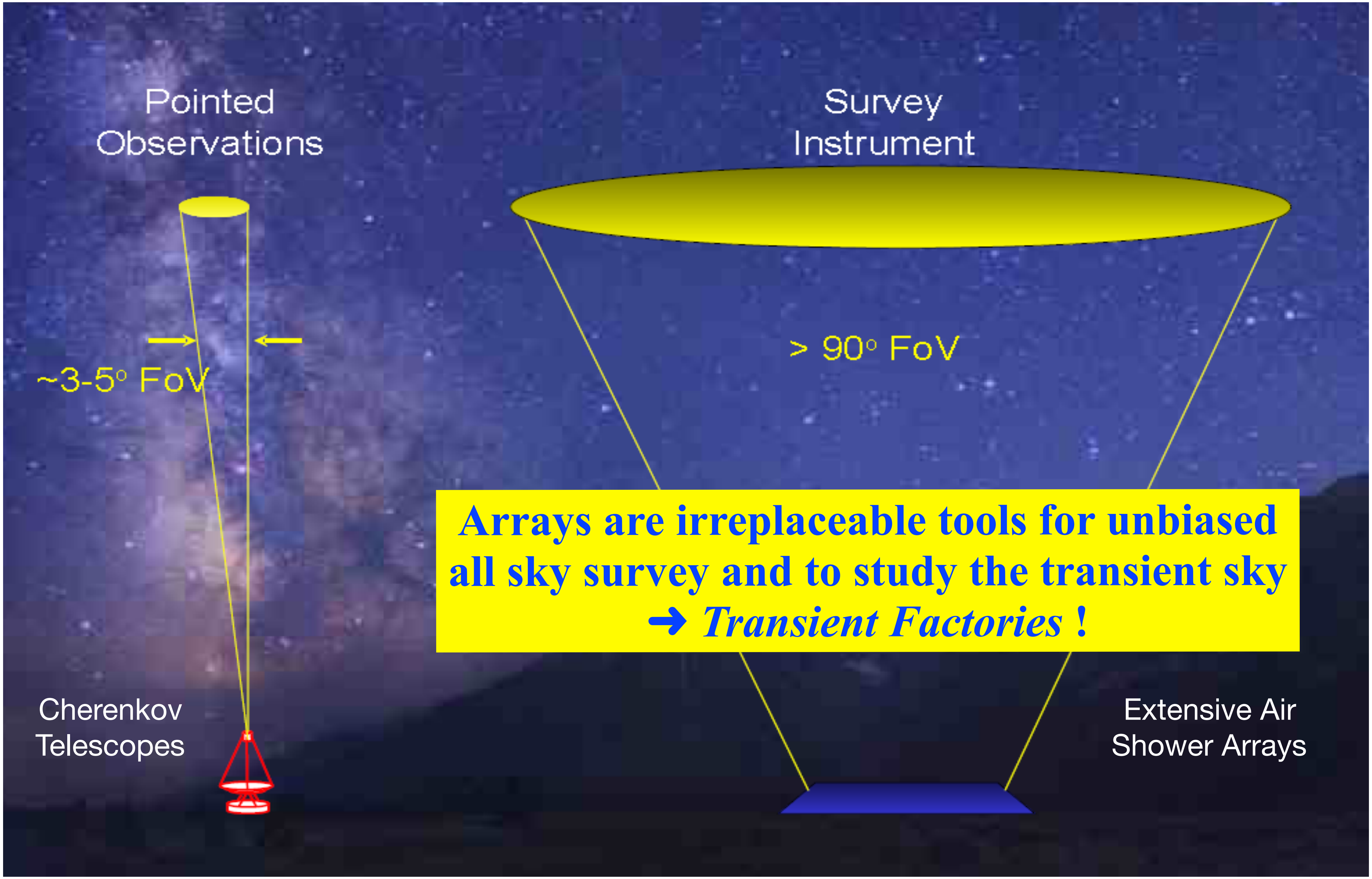
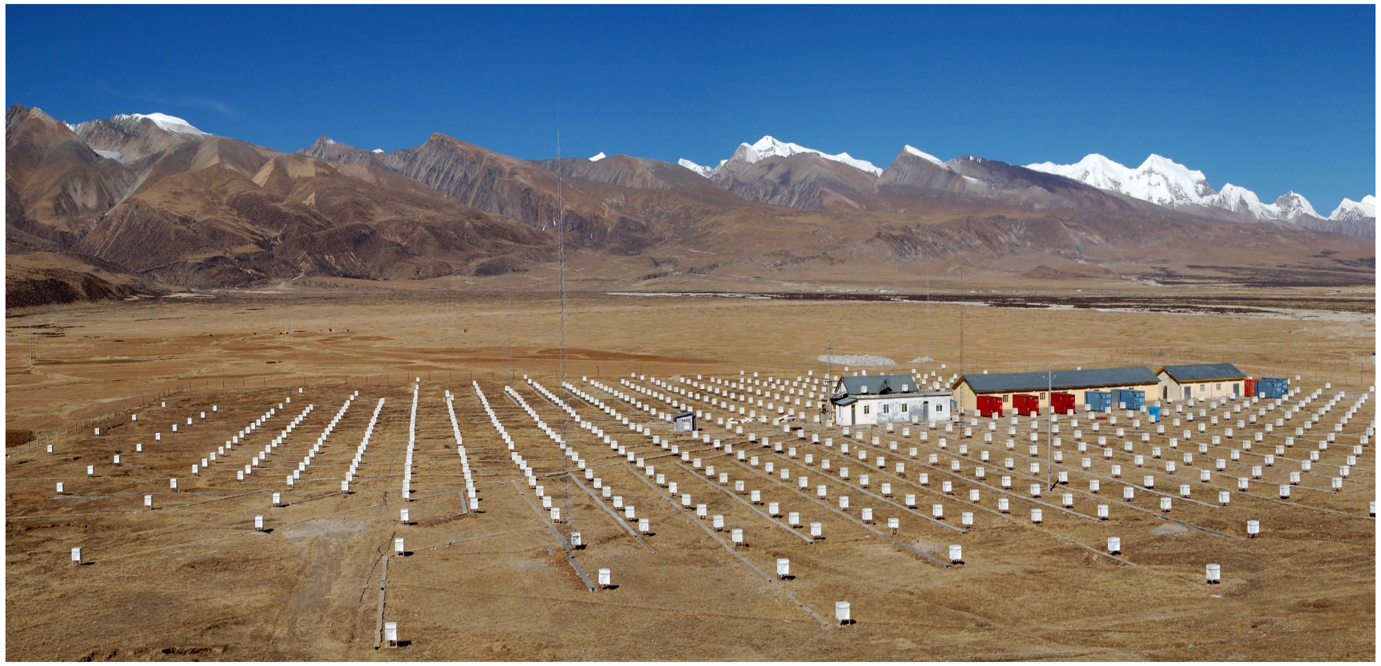


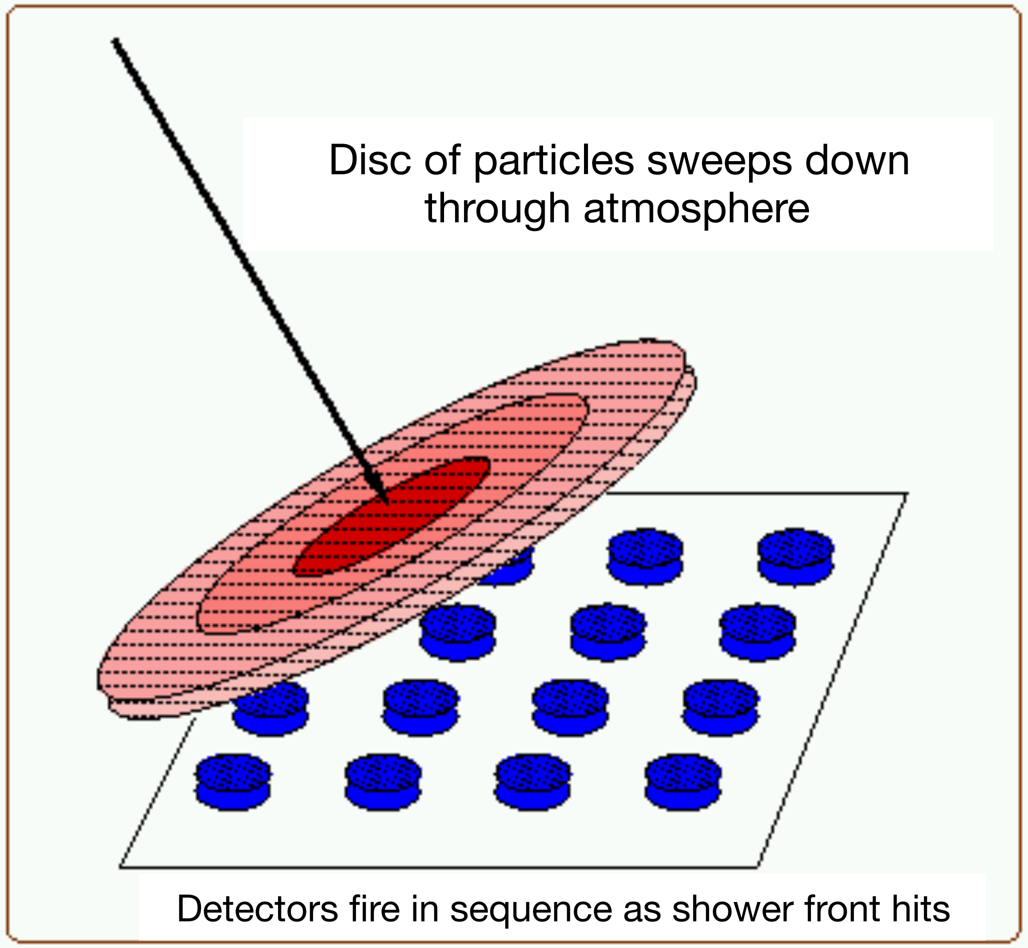
Arrays are irreplaceable tools for unbiased all sky survey and to study the transient sky ➜ *Transient Factories* !

Classical Extensive Air Shower Arrays

Large number of detectors spread over an area of order 10^5 m^2



scintillators, water tanks (Cherenkov light in water), hadron calorimeters, Cherenkov telescopes, emulsions, etc.

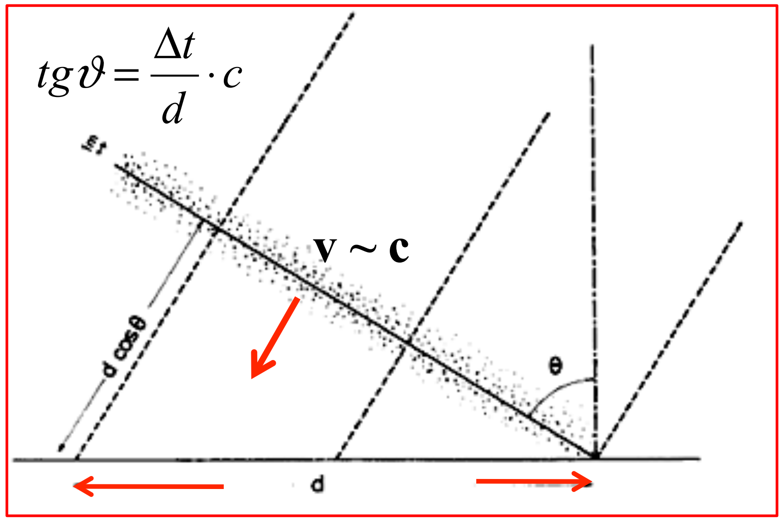


Disc of particles sweeps down through atmosphere

Detectors fire in sequence as shower front hits

coverage factor (sensitive area/instrumented area) ≈ 10^{-3} - 10^{-2}

“density sampling” + “fast timing”



$$tg\vartheta = \frac{\Delta t}{d}\cdot c$$

Sensitivity to a γ-ray point source

Sensitivity to a γ-ray point source

$$S = \frac{N_\gamma}{\sqrt{N_{bkg}}} = \frac{\int J_\gamma(E) \cdot A^\gamma_{eff}(E) \cdot \epsilon_\gamma(E) \cdot f_\gamma(\Delta\Omega) \cdot T dE}{\sqrt{\int J_{bkg}(E) \cdot A^{bkg}_{eff}(E) \cdot (1 - \epsilon_{bkg}(E)) \cdot \Delta\Omega \cdot T dE}}$$

where J_γ and J_{bkg} are the differential fluxes of photon and background, A^γ_{eff} and A^{bkg}_{eff} the effective areas, that determines the number of showers detected in a given observation time T, $\Delta\Omega = 2\pi(1 - cos\theta)$ the solid angle around the source and $f_\gamma(\Delta\Omega)$ the fraction of γ-induced showers fitted in the solid angle. The parameters ε_γ and ε_{bkg} are the efficiencies in identifying γ-induced and background-induced showers, respectively. As most of the parameters are function of the energy, the sensitivity depends on the energy spectra of the cosmic ray background and of the source.

Integral number of events

$$N_\gamma = \int_{E_{th}} J_\gamma(E) \cdot A^{\gamma}_{eff} \cdot T \cdot f_\gamma(\Delta\Omega) \cdot \epsilon_\gamma(E) \cdot dE = \Phi_\gamma(> E) \cdot A^{\gamma}_{eff}(> E) \cdot T \cdot f_\gamma(\Delta\Omega) \cdot \epsilon_\gamma(> E)$$

$$N_{bkg} = \int_{E_{th}} J_{bkg}(E) \cdot A^{bkg}_{eff} \cdot T \cdot \Delta\Omega \cdot (1 - \epsilon_{bkg}(E)) \cdot dE = \Phi_{bkg}(> E) \cdot A^{bkg}_{eff}(> E) \cdot T \cdot \Delta\Omega \cdot (1 - \epsilon_{bkg}(> E))$$

$$A^{\gamma,bkg}_{eff}(> E) = \frac{\int_{E_{th}} J_{\gamma,bkg}(E) \cdot A^{\gamma,bkg}_{eff} \cdot dE}{\int_{E_{th}} J_{\gamma,bkg}(E) \cdot dE} = \frac{\int_{E_{th}} J_{\gamma,bkg}(E) \cdot A^{\gamma,bkg}_{eff} \cdot dE}{\Phi_{\gamma,bkg}(> E)}$$

$$\Delta\Omega = 2\pi(1 - cos\Delta\theta) \simeq \pi(\Delta\theta)^2$$

$$T_{eff} = (d.c.) \cdot T \cdot f$$

fraction of time a source spend in the detector FoV

Sensitivity to a γ-ray point source

Sensitivity to a gamma-ray *point source* emitting a photon flux $\Phi_\gamma(>E)$ above the energy E

$$S = \frac{N_\gamma}{\sqrt{N_{bkg}}} = \frac{\Phi_\gamma(>E)}{\sqrt{\Phi_{bkg}(>E)}} \cdot R \cdot \sqrt{A^\gamma_{eff}(>E)} \cdot \frac{1}{\sqrt{\Delta\Omega_{PSF}}} \cdot \sqrt{T_{eff}} \cdot Q$$

$$\Delta\Omega_{PSF} \sim \pi\theta^2_{PSF}$$

$$T_{eff} = (d.c.) \cdot T \cdot f$$

$$R = \sqrt{\frac{A^\gamma_{eff}}{A^{bkg}_{eff}}}$$

$$Q = \frac{\epsilon_\gamma}{\sqrt{(1-\epsilon_{bkg})}}$$

To maximize the chances of detecting any excess from a source we look at EAS arriving from within the resolution angle θ_{psf} of a source direction. Since the significance of any excess events from within θ_{psf} would depend on the standard deviation of the number of events expected from cosmic ray EAS ($\surd$ $(\theta_{psf}{}^2)$), we must maximize the quantity

$$\frac{N_\gamma(<\theta_{psf})}{\sqrt{N_{bkg}(<\theta_{psf})}} \propto \frac{1}{\theta_{psf}} \int_0^{\theta_{psf}} \frac{dN}{d\Omega} d\Omega$$

to obtain the best value, $\theta_{psf} \approx 1.59\ \sigma$. *This resolution angle contains ≈72% of all events incident from the source direction.*

The minimum detectable flux

$\boldsymbol{\sigma_\theta}$ = angular resolution

$\boldsymbol{\Phi_{bkg}}$ = background integral flux

$\boldsymbol{\Phi_\gamma}$ = photon integral flux

Sensitivity in 1 year

$$\boxed{S \propto \frac{\Phi_\gamma}{\sqrt{\Phi_{bkg}}} \cdot R \cdot \sqrt{A^\gamma_{eff}} \cdot \frac{1}{\sigma_\theta} \cdot Q}$$

$$R = \sqrt{\frac{A^\gamma_{eff}}{A^{bkg}_{eff}}}$$

$$Q_f = \frac{\text{fraction of surviving photons}}{\sqrt{\text{fraction of surviving hadrons}}}$$

Minimum Detectable Gamma-Ray Flux (1 year):

$$\boxed{\Phi_\gamma^{MDF} \propto \sqrt{\Phi_{bkg}} \cdot \frac{1}{R \cdot \sqrt{A^\gamma_{eff}}} \cdot \sigma_\theta \cdot \frac{1}{Q}}$$

Extended sources (1)

Sensitivity to a gamma-ray *point source* emitting a photon flux $\Phi_\gamma(>E)$ above the energy E

$$S_{point} = \frac{N_\gamma}{\sqrt{N_{bkg}}} = \frac{\Phi_\gamma(>E)}{\sqrt{\Phi_{bkg}(>E)}} \cdot R \cdot \sqrt{A^\gamma_{eff}(>E)} \cdot \frac{1}{\sqrt{\Delta\Omega_{PSF}}} \cdot \sqrt{T_{eff}} \cdot Q$$

$$\Delta\Omega_{PSF} \sim \pi\theta^2_{PSF}$$

If we have an *extended source* with a photon flux equal to that of the point source we must integrate on the extension of the source to have the same number of photons.
➜ the background will increase !

$$S_{ext} = \frac{N_\gamma}{\sqrt{N_{bkg}}} = \frac{\Phi_\gamma(>E)}{\sqrt{\Phi_{bkg}(>E)}} \cdot R \cdot \sqrt{A^\gamma_{eff}(>E)} \cdot \frac{1}{\sqrt{\Delta\Omega_{ext}}} \cdot \sqrt{T} \cdot Q$$

Extended sources (2)

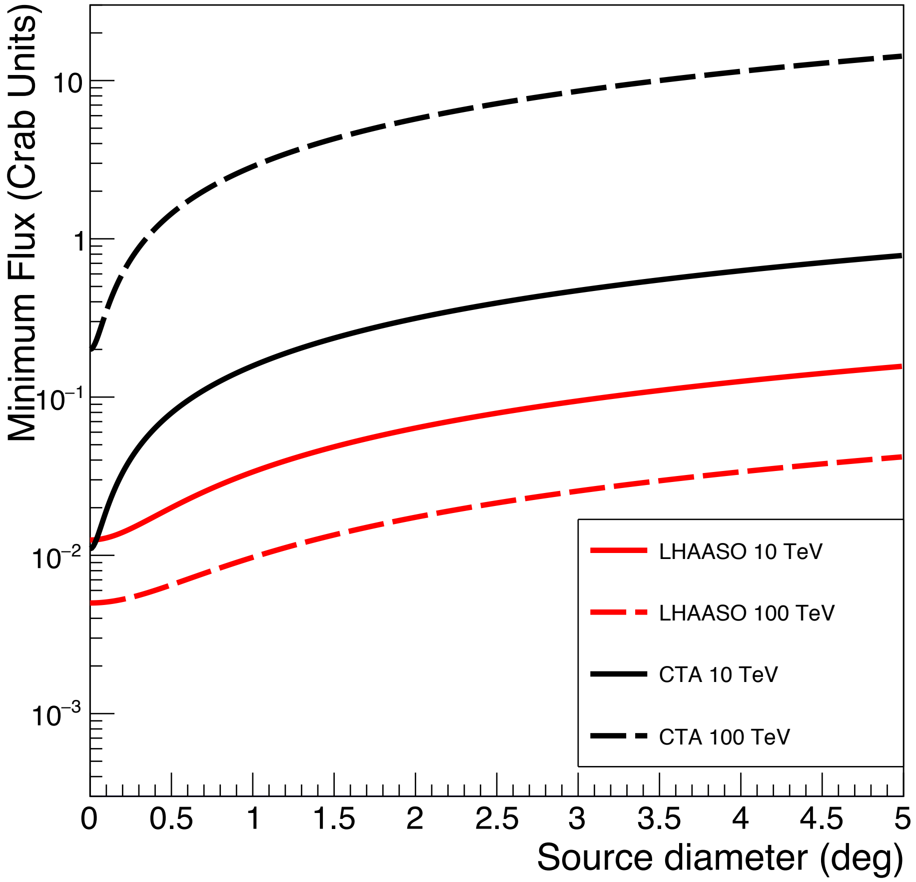
$$S_{ext} \sim \boxed{\frac{\Phi_\gamma(> E)}{\sqrt{\Phi_{bkg}(> E)}} \cdot R \cdot \sqrt{A^{\gamma}_{eff}} \cdot \sqrt{T} \cdot Q \times \frac{1}{\theta_{ext}} \cdot \frac{\theta_{ext}}{\theta_{PSF}}} \cdot \frac{\theta_{PSF}}{\theta_{ext}}$$

S point-source

$$\boxed{S_{ext} = S_{point} \cdot \frac{\theta_{PSF}}{\theta_{ext}}}$$

dimension of the extended source

Detectors with a ‘poor’ angular resolution (EAS arrays) are favoured in the extended source studies.



The minimum integral flux (in Crab units) detectable by LHAASO and CTA-South as a function of the source angular diameter, for two different photon energies.

The key parameters

$$S \propto \frac{\Phi_\gamma}{\sqrt{\Phi_{bkg}}} \cdot R \cdot \sqrt{A^\gamma_{eff}} \cdot \frac{1}{\sigma_\theta} \cdot Q$$

Because for the integral fluxes we can write

$$\Phi_\gamma \sim E_{thr}^{-\gamma}$$

$$\Phi_{bkg} \sim E_{thr}^{-\gamma_{bkg}}$$

we obtain $$\frac{\Phi_\gamma}{\sqrt{\Phi_{bkg}}} \sim E_{thr}^{-(\gamma-\gamma_{bkg}/2)} \sim E_{thr}^{-2/3}$$ being $\gamma \sim 1.5$ and $\gamma_{bkg} \sim 1.7$.

The key parameters to improve the sensitivity are

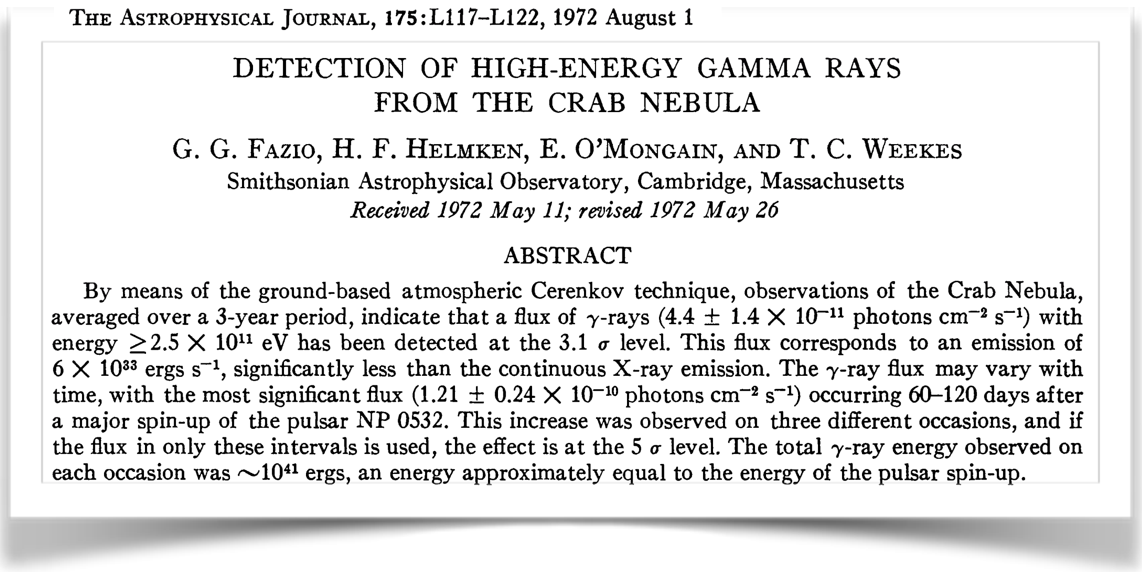
- The energy threshold
- R, the signal/background relative trigger efficiency
- The angular resolution
- Q-factor, the background rejection capability

Background of Charged Cosmic Rays

1970 - 80's: A number of groups constructed Cherenkov telescopes, but there were no outstanding results for some time. Each individual result did not exceed a 3-4 standard-deviation significance.

What were the problems that frustrated the gamma-ray search for so long ?

Any γ-ray signal were completely overwhelmed by showers produced by ordinary charged CRs (mainly protons) spread evenly over the sky.



THE ASTROPHYSICAL JOURNAL, 175:L117–L122, 1972 August 1

DETECTION OF HIGH-ENERGY GAMMA RAYS
FROM THE CRAB NEBULA

G. G. FAZIO, H. F. HELMKEN, E. O'MONGAIN, AND T. C. WEEKES
Smithsonian Astrophysical Observatory, Cambridge, Massachusetts
Received 1972 May 11; revised 1972 May 26

ABSTRACT

By means of the ground-based atmospheric Cerenkov technique, observations of the Crab Nebula, averaged over a 3-year period, indicate that a flux of γ-rays ($4.4 \pm 1.4 \times 10^{-11}$ photons cm^{-2} s^{-1}) with energy $\geq 2.5 \times 10^{11}$ eV has been detected at the 3.1 σ level. This flux corresponds to an emission of 6×10^{33} ergs s^{-1}, significantly less than the continuous X-ray emission. The γ-ray flux may vary with time, with the most significant flux ($1.21 \pm 0.24 \times 10^{-10}$ photons cm^{-2} s^{-1}) occurring 60–120 days after a major spin-up of the pulsar NP 0532. This increase was observed on three different occasions, and if the flux in only these intervals is used, the effect is at the 5 σ level. The total γ-ray energy observed on each occasion was $\sim 10^{41}$ ergs, an energy approximately equal to the energy of the pulsar spin-up.

Weekes et al. in 1972 found a marginal 3σ excess in the "on-source" counts for the Crab Nebula, recording "on-source" and "off-source" pulse counting rates.

The "off-source" counts were about 320 times as numerous as the excess counts that were attributed to gamma rays.

This was the problem !!

$$\left.\begin{array}{l} \Phi_{CRAB}(>1\ TeV)\ \sim 2\cdot 10^{-11}\ ph/cm^2\cdot s \\ \Phi_{bkg}(>1\ TeV)\cdot\Delta\Omega(=1\ msr) \sim 1.5\cdot 10^{-8}\ nuclei/cm^2\cdot s \end{array}\right\} \quad \boxed{\Phi_{signal} \approx 10^{-3}\cdot\Phi_{bkg}}$$

No possible veto with an anticoincidence shield as in satellite experiments
In addition…

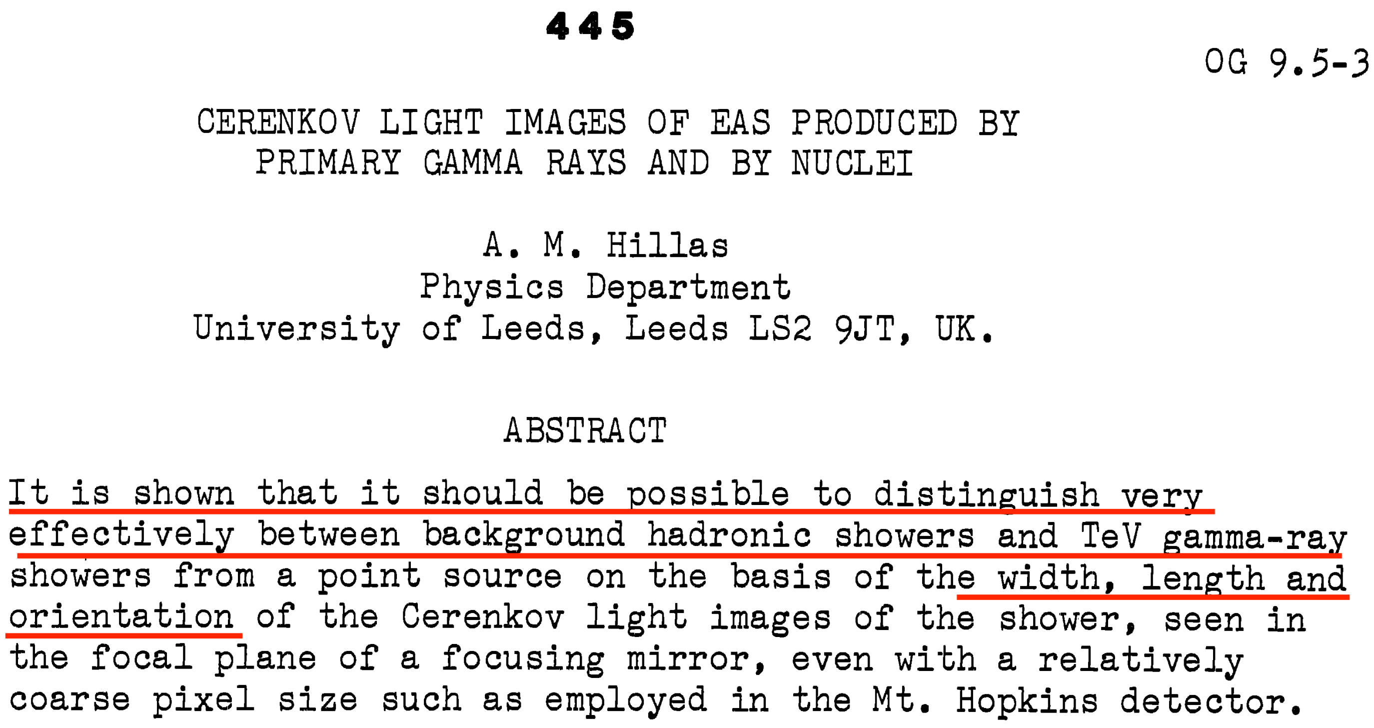
$\boxed{\textit{Cosmic Ray showers} \approx \gamma\textit{-ray showers !}}$

… fortunately, some difference does exist !!

The *“Hillas image parameters*"

In **1985** at the ICRC (La Jolla) ***Hillas*** suggested to use the ***“Hillas image parameters”*** to reduce the background

➜ *a key milestone* in the history of ground-based imaging air Cherenkov telescopes.



445

OG 9.5-3

CERENKOV LIGHT IMAGES OF EAS PRODUCED BY
PRIMARY GAMMA RAYS AND BY NUCLEI

A. M. Hillas
Physics Department
University of Leeds, Leeds LS2 9JT, UK.

ABSTRACT

It is shown that it should be possible to distinguish very effectively between background hadronic showers and TeV gamma-ray showers from a point source on the basis of the width, length and orientation of the Cerenkov light images of the shower, seen in the focal plane of a focusing mirror, even with a relatively coarse pixel size such as employed in the Mt. Hopkins detector.

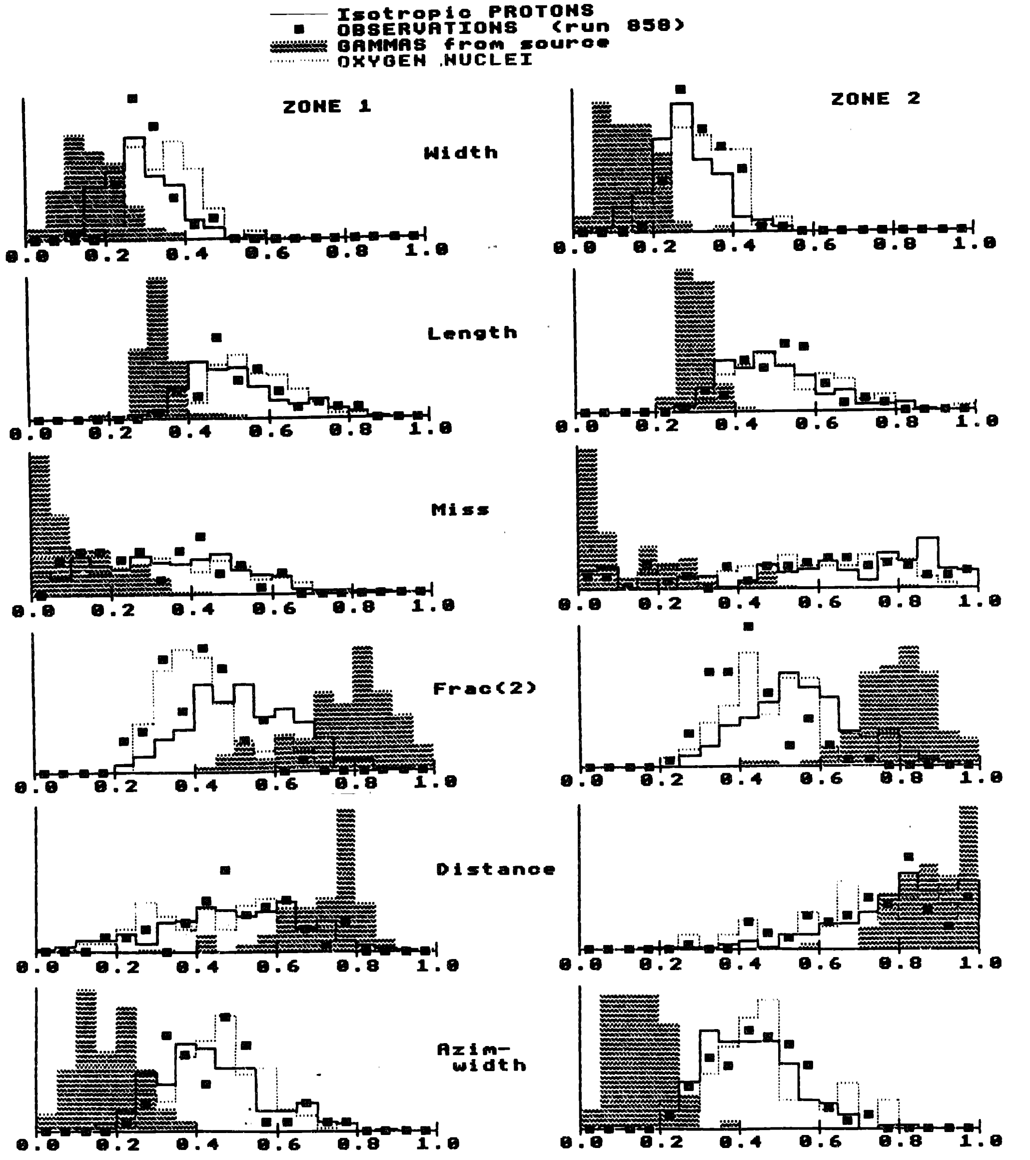


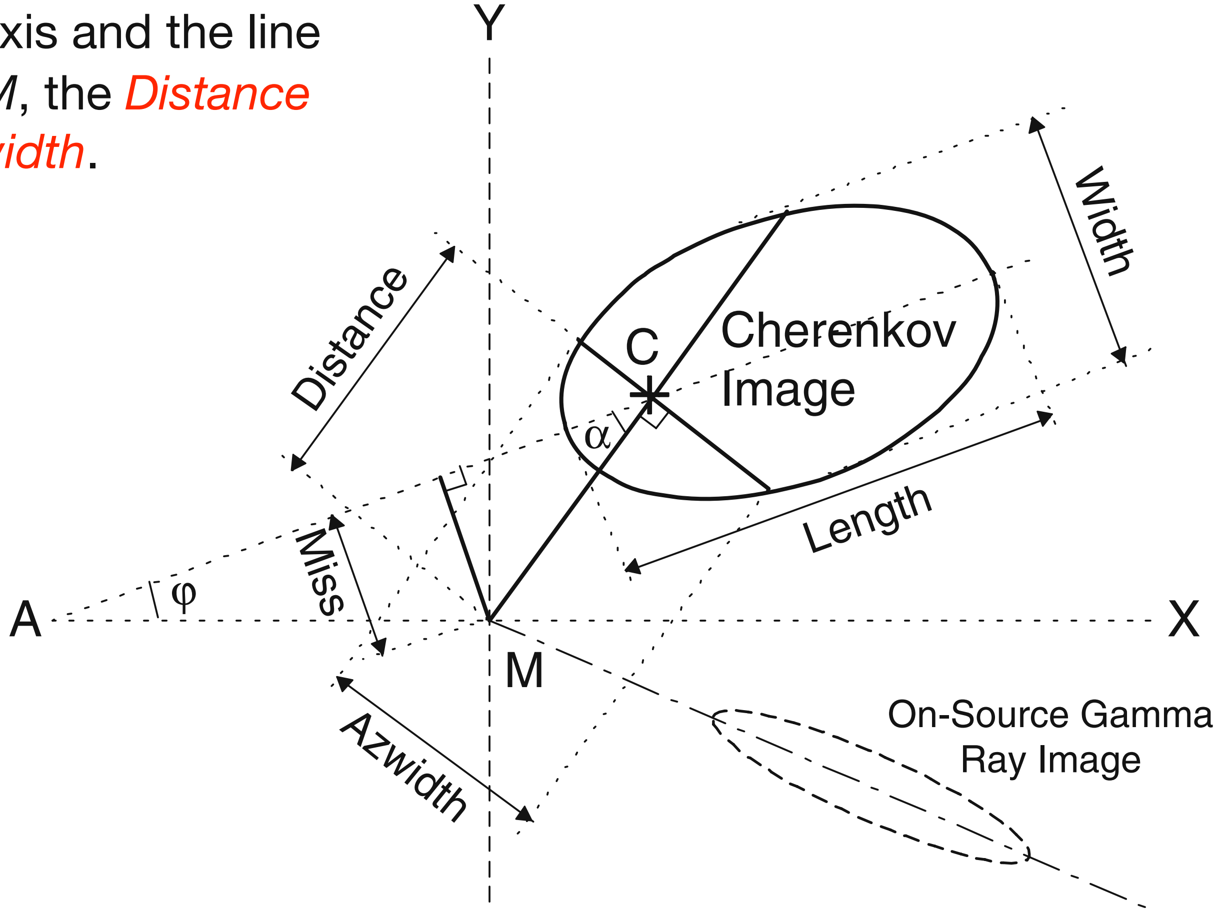
Figure 2: histograms of image characteristics. (vertical showers)

Gamma showers are slimmer, more concentrated and orientated towards the source

The basic parameters

The *solid ellipse* indicates the pixel image contour, *C* is the *centroid* of the image (location of highest brightness) and *M* the *center of the field of view*.

The relevant parameters are the *major and minor axis of the ellipse*, labeled *Length* and *Width* in the plot, the angle α between the major axis and the line connecting the centroid *C* with the center of the field of view *M*, the *Distance* between *C* and *M*, and the two quantities called *Miss* and *Azwidth*.



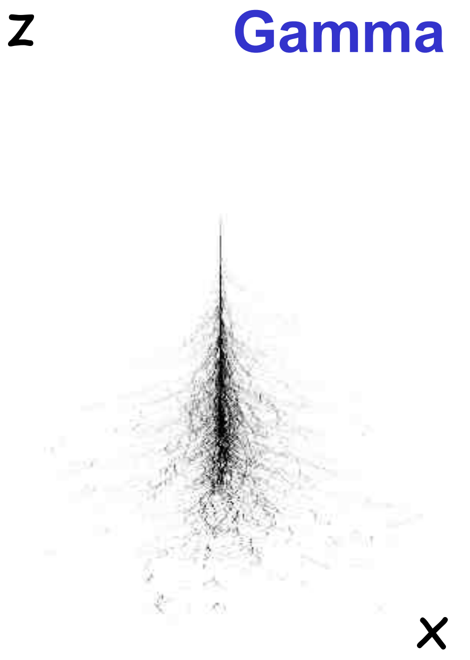
Miss is the offset or the perpendicular distance between the extension of the major axis of the ellipse and *M*, and *Azwidth* is the azimuthal width of the image as indicated; it is the r.m.s. spread of light perpendicular to the line connecting *C* with *M*.

Except for the clean regular elliptic shape this image is also representative for hadronic showers.

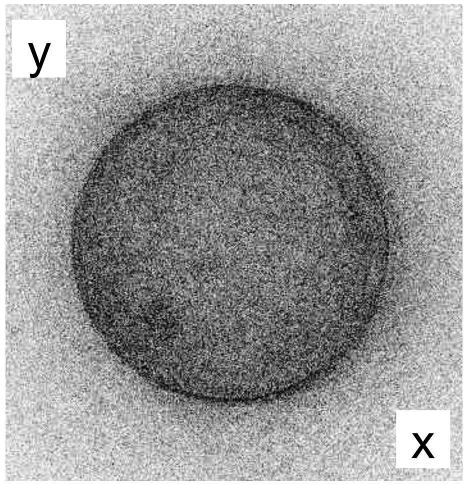
The *dashed ellipse* at the lower right with the extension of the major axis intercepting the *center M* of the mirror, labeled *On-Source Gamma Ray Image*, shows the typical narrow elliptic contour of a gamma ray shower when the mirror axis is pointing at the source and the impact parameter is non-zero.

Who is who ? Gamma-Hadron separation

Gamma



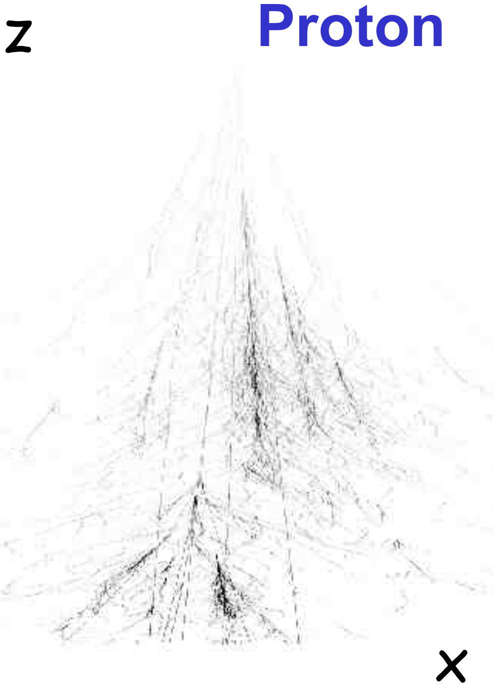
Not to scale



Particle tracks in the air

C-photon density
on ground

Proton



Not to scale

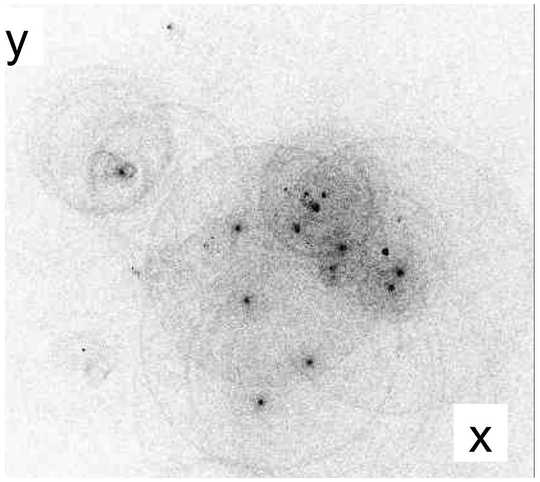
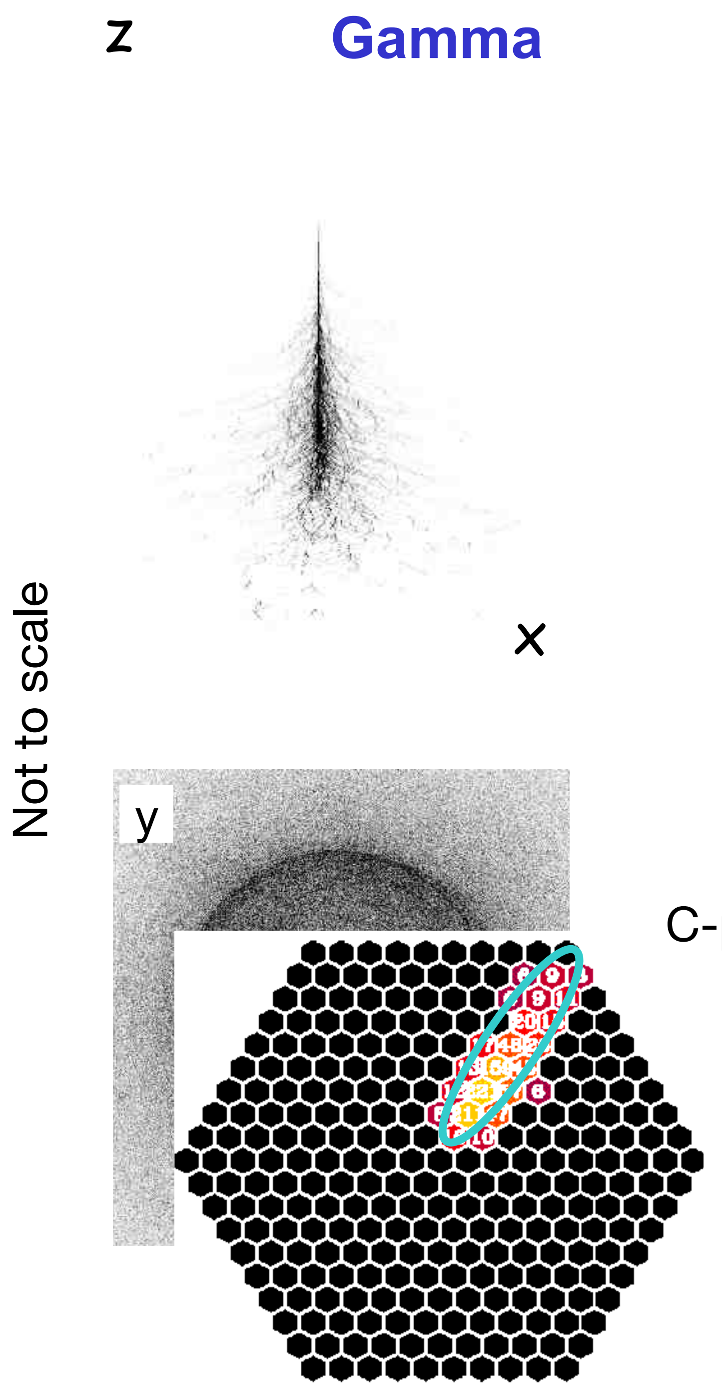


Image width

Who is who ? Gamma-Hadron separation

Gamma



Particle tracks in the air

C-photon density
on ground

Proton

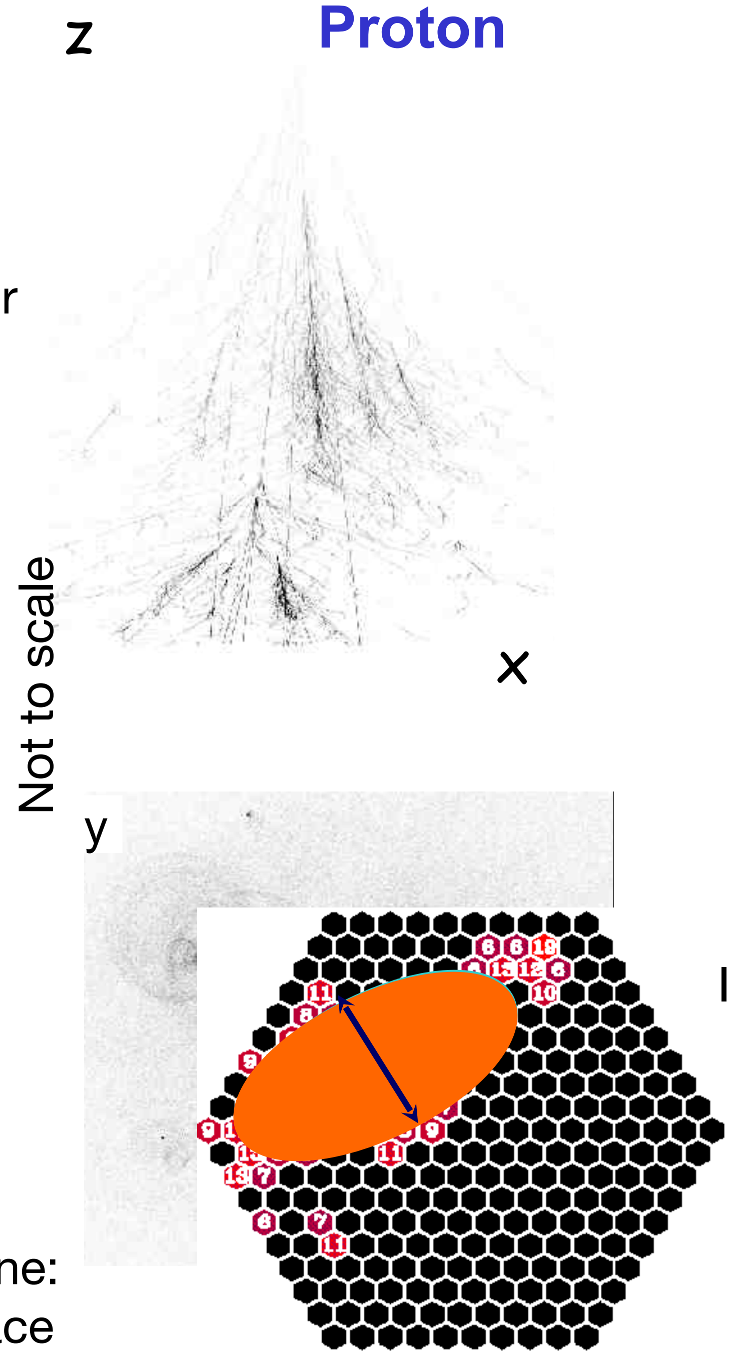


Image width

Camera plane:
angular space

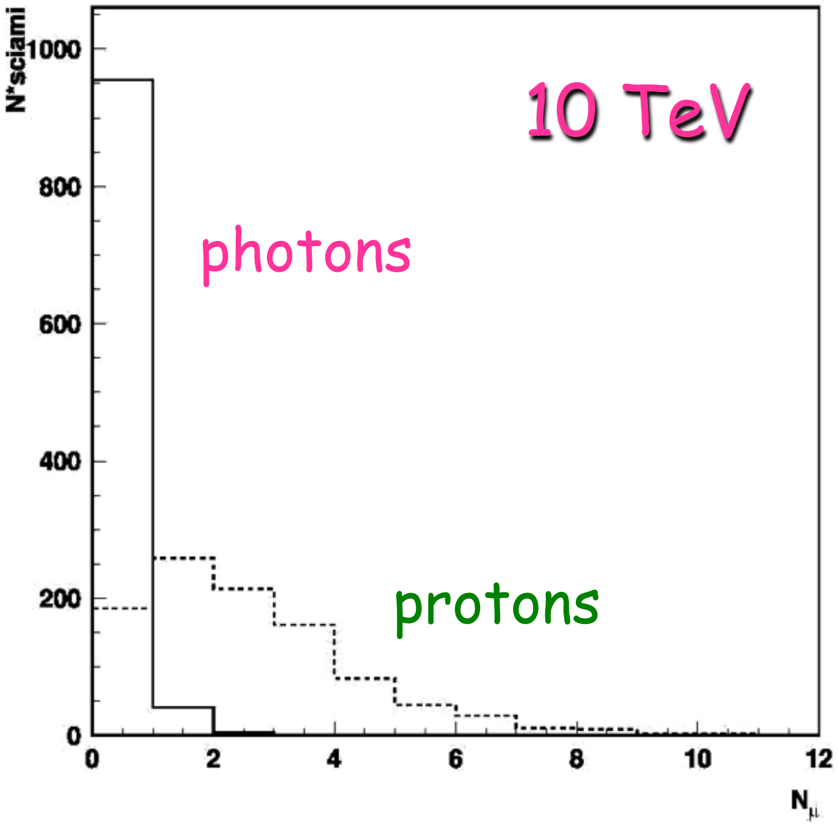
Background rejection with EAS arrays

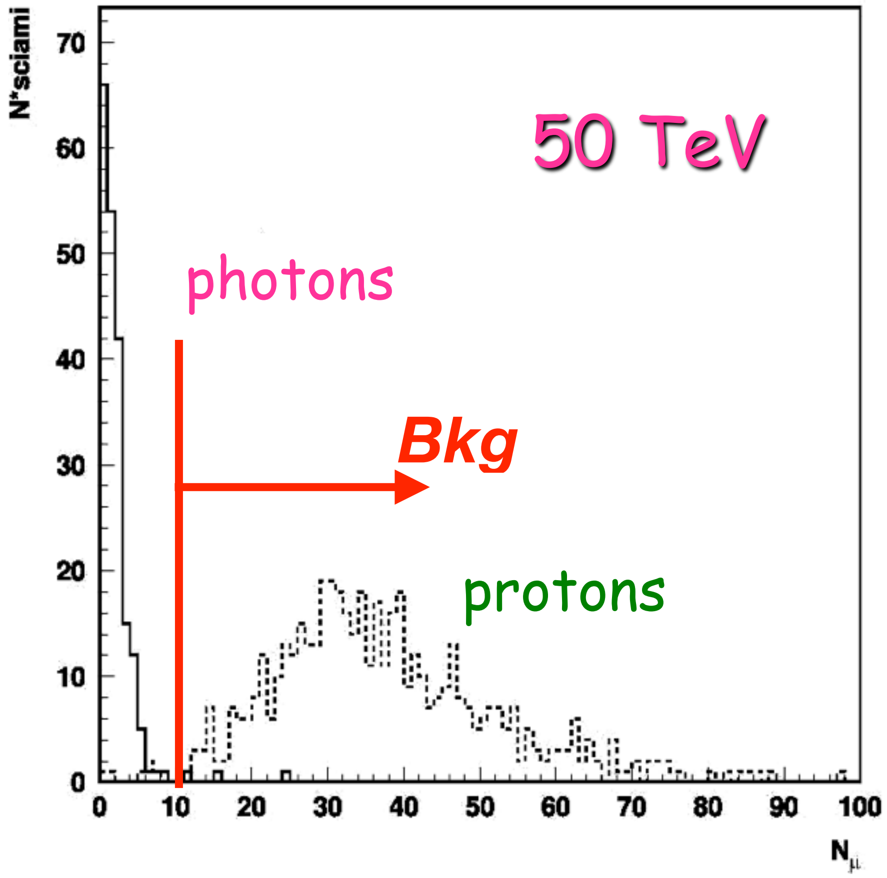
The standard technique is to look for *“muon-poor“* showers.

The ratio between the cross sections of photo-production and nucleus-nucleus interaction processes is ~10^{-3} resulting in $< N_\mu^\gamma >/< N_\mu^h > \sim 3\cdot10^{-2}$

The main limitations of this technique is due to the extent of *fluctuations* in hadron-initiated showers and to the *small number of muons*

➡ *large muon detector !*





The discrimination capability increases with the energy and the μ–detector area.

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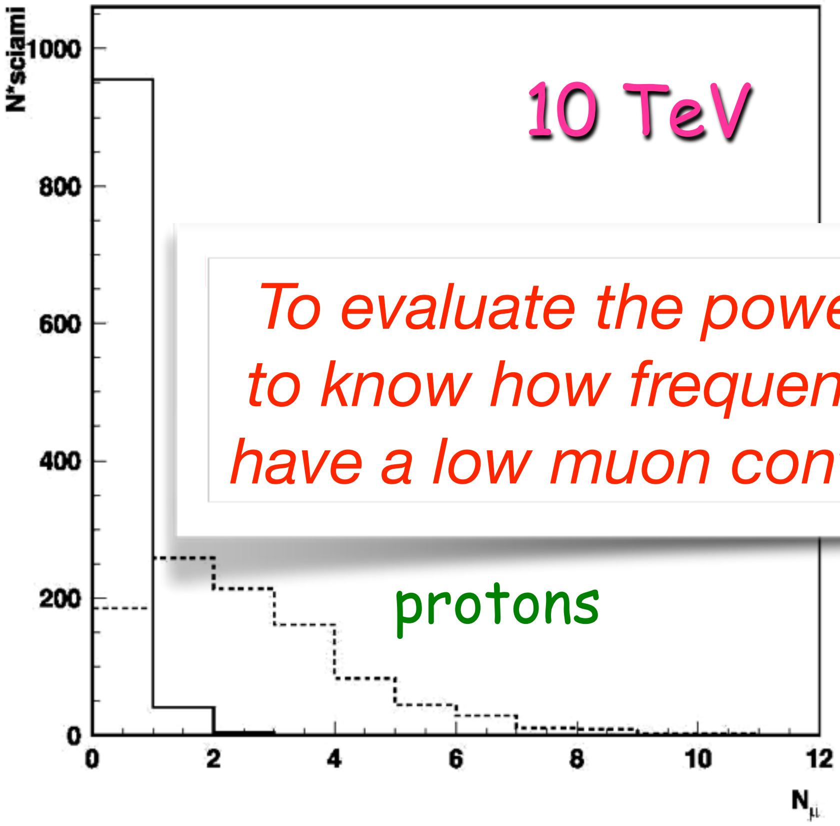
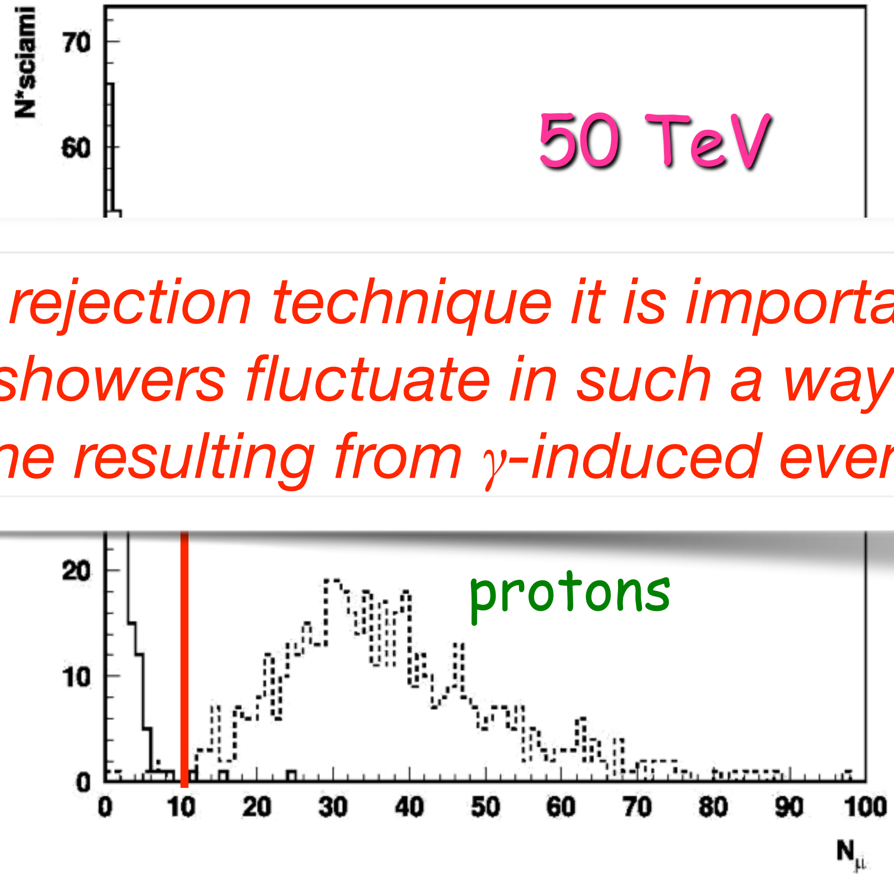


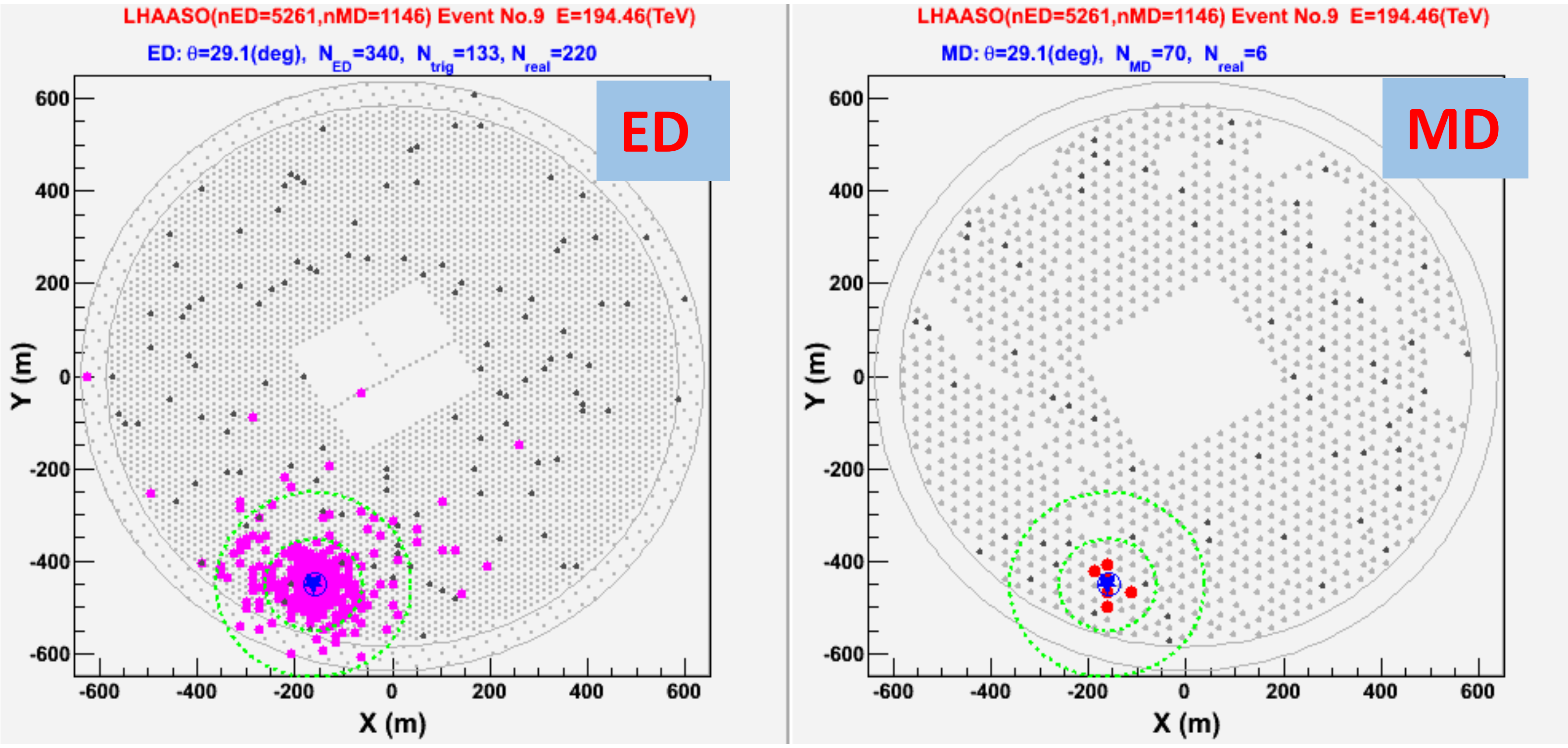


To evaluate the power of this bkg rejection technique it is important to know how frequently hadronic showers fluctuate in such a way to have a low muon content as the one resulting from γ-induced events.

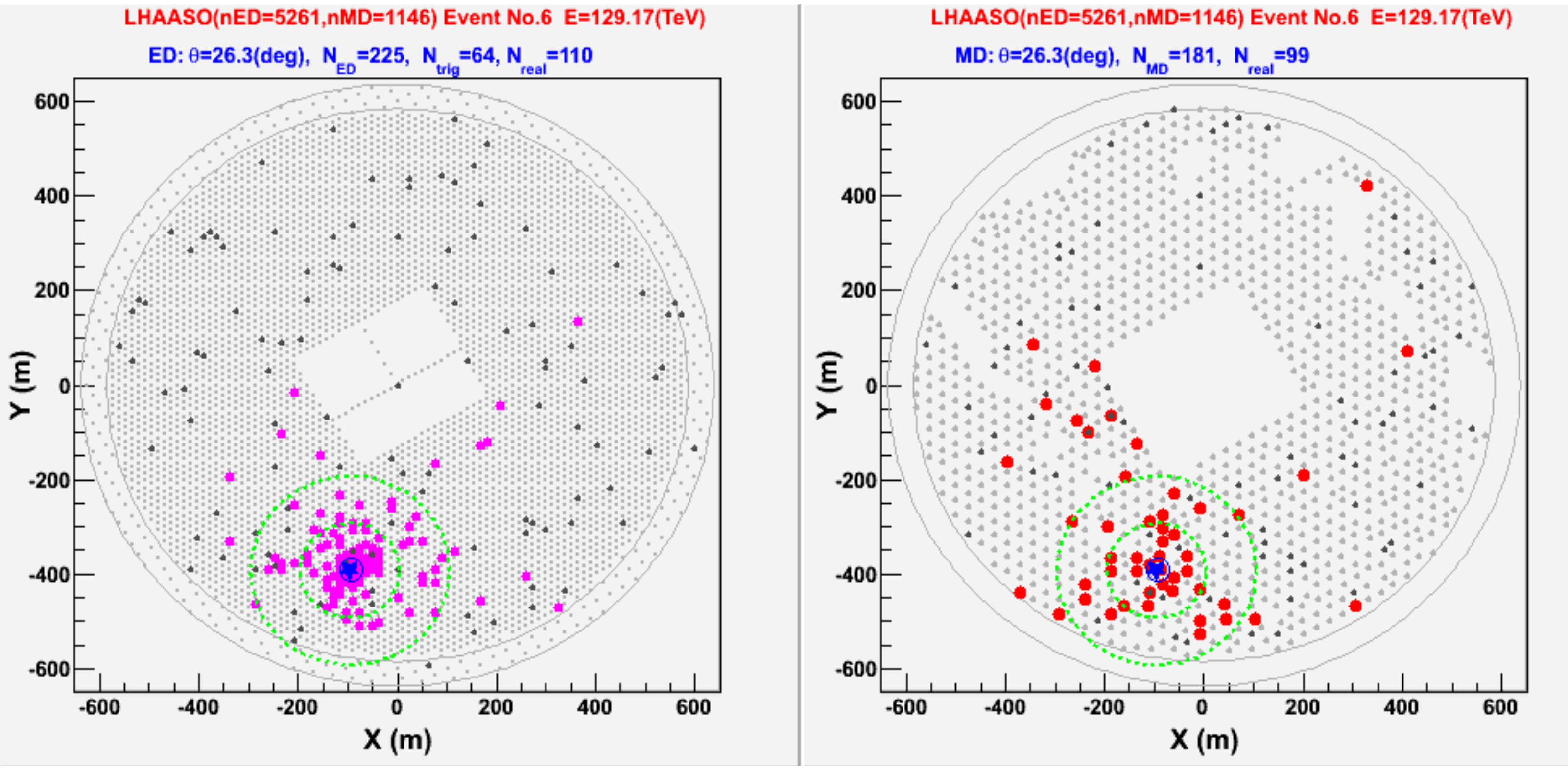
The discrimination capability increases with the energy and the μ–detector area.

Muon-poor technique with LHAASO

Gamma-ray
E=194 TeV



Proton
E=129 TeV



S.Z. Chen, WASDHA 2018

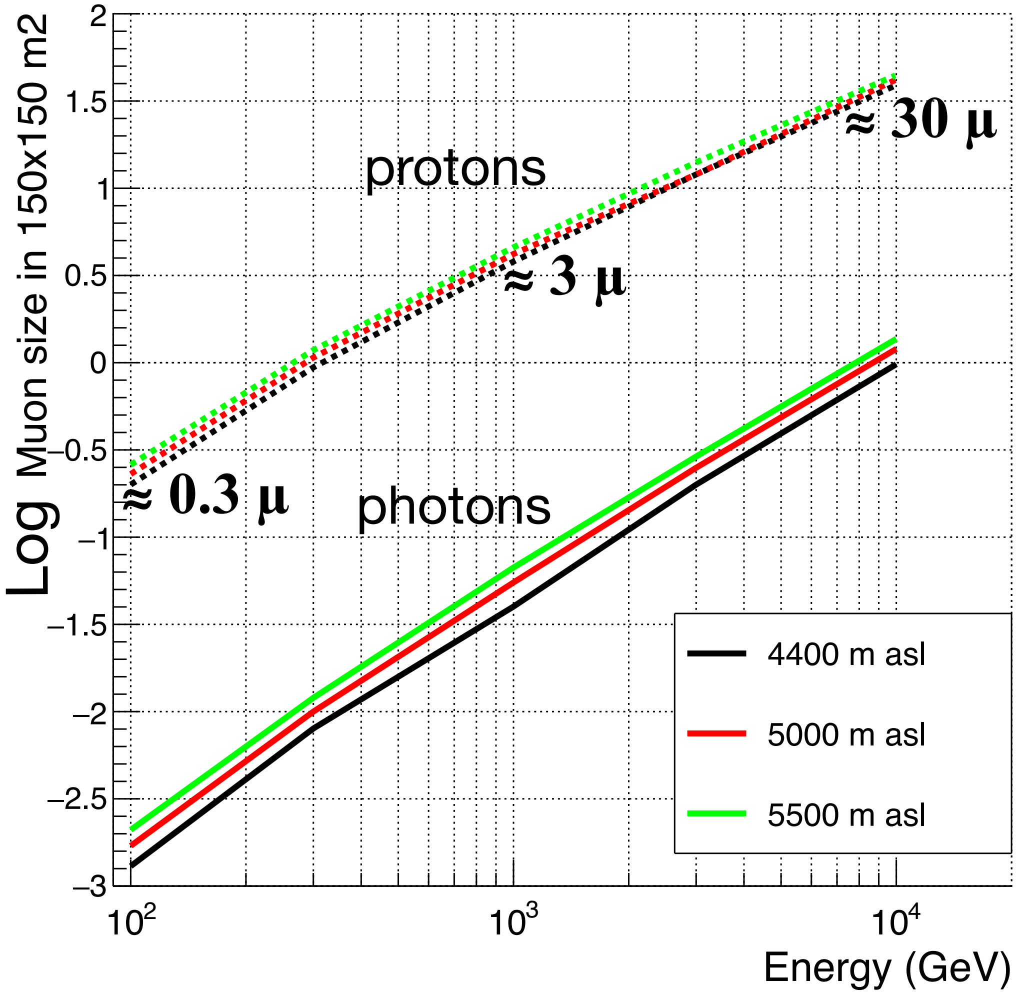
Gamma/Hadron discrimination with arrays

Classical technique:
measurement of the *muon content* event by event

But, muon size very small: ≈ 3 μ per TeV (protons)

➡ *Only high energy* (> 5 - 10 TeV) !

*Background discrimination < TeV is **OPEN PROBLEM !***



HAWC/LHAASO approach requires large area:
discrimination based on topological cut in the pattern of energy deposition far from the core (>40 m).

Requires sufficient number of triggered channels (>70 - 100)
→ minimum energy required: E > 0.7 - 1 TeV ?

New ideas ?

- *Suitable trigger logic to reject not 'symmetric' showers*
- *Calorimetry with multi-layer RPCs*
- *Calorimetry with RPCs + water Cherenkov tanks ?*

Milagro vs ARGO-YBJ

2 different approaches in the last 2 decades for ground-based survey instruments

Milagro

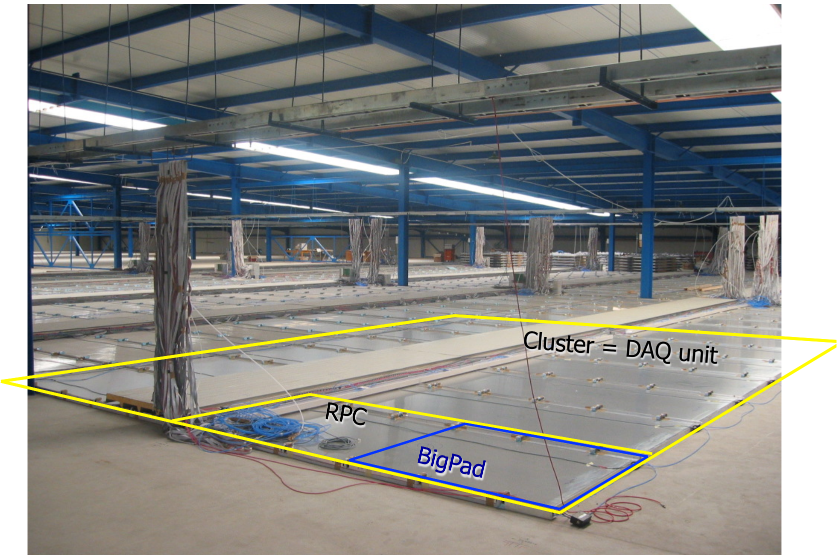
Water Cherenkov Technology

- operated from 2000 to 2008
- *2600 m* above sea level
- angular resolution ≈0.5°
- 1700 Hz trigger rate
- *Median Energy at the threshold: ≈ 2 TeV*
- *Energy range: 2 - 40 TeV*
- poor background rejection (with outrigger)
- conversion of secondary photons in water

Widely used technology in cosmic ray physics

ARGO-YBJ

Resistive Plate Chamber Technology



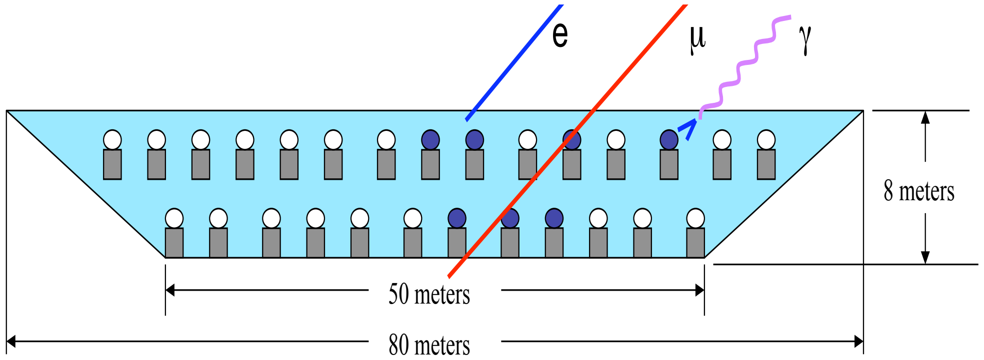
- operated from 2007 to 2012 (final configuration)
- *4300 m* above sea level
- *angular resolution ≈0.5° at 1 TeV*
- 3500 Hz trigger rate
- high granularity of the readout
- *Median Energy at the threshold: ≈300 GeV*
- *Energy Range: 340 GeV - 10 PeV*
- NO background rejection (no outrigger)
- NO conversion of secondary photons (no lead)

Widely used technology in particle physics

Milagro vs ARGO-YBJ

Milagro

Water Cherenkov Technology



Central 80 m x 60 m x 8 m water reservoir, containing two layers of PMTs

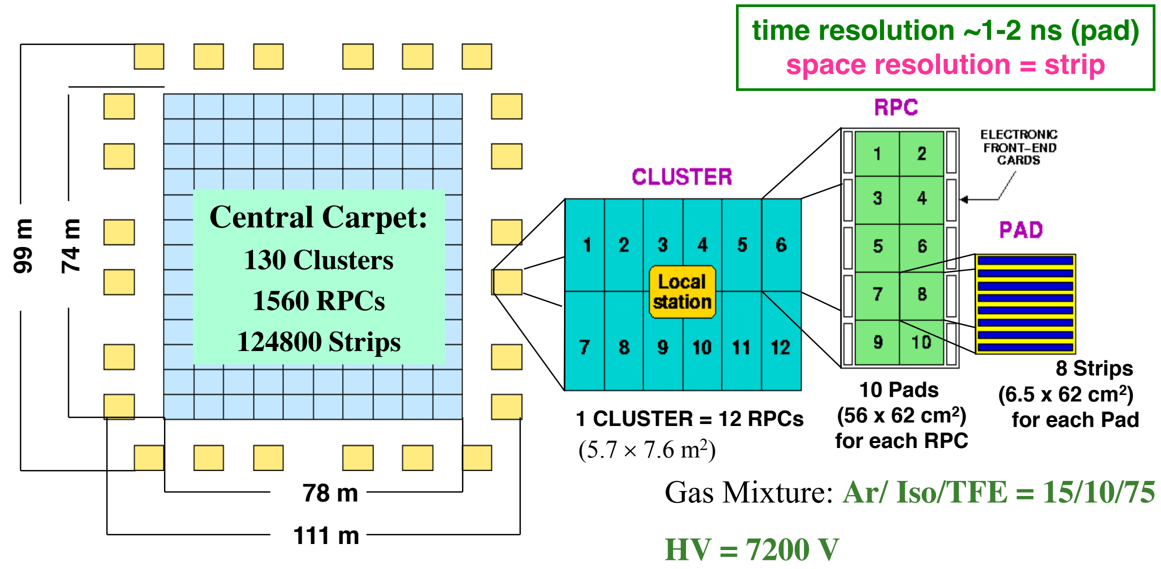
- 450 PMTs at 1.4 m below the surface (top layer)
- 273 PMTs at 6 m below the surface (bottom layer)

Outrigger Array, consisting of 175 tanks filled with water and containing one PMT, distributed on an area of 200 m x 200 m around the central water reservoir.

HAWC and ***LHAASO***

ARGO-YBJ

Resistive Plate Chamber Technology



time resolution ~1-2 ns (pad)
space resolution = strip

Gas Mixture: Ar/ Iso/TFE = 15/10/75

HV = 7200 V

Single layer of Resistive Plate Chambers (RPCs)
with a full coverage (92% active surface) of a large area (5600 m²)
+ sampling guard ring (6700 m² in total)

Space pixels: *146,880 strips* (7×62 cm²)
Time pixels: *18,360 pads* (56×62 cm²)

2 read-outs:

$\rho_{max-strip} \approx 20\ particles/m^2$

$\rho_{max-analog} \approx 10^4\ particles/m^2$

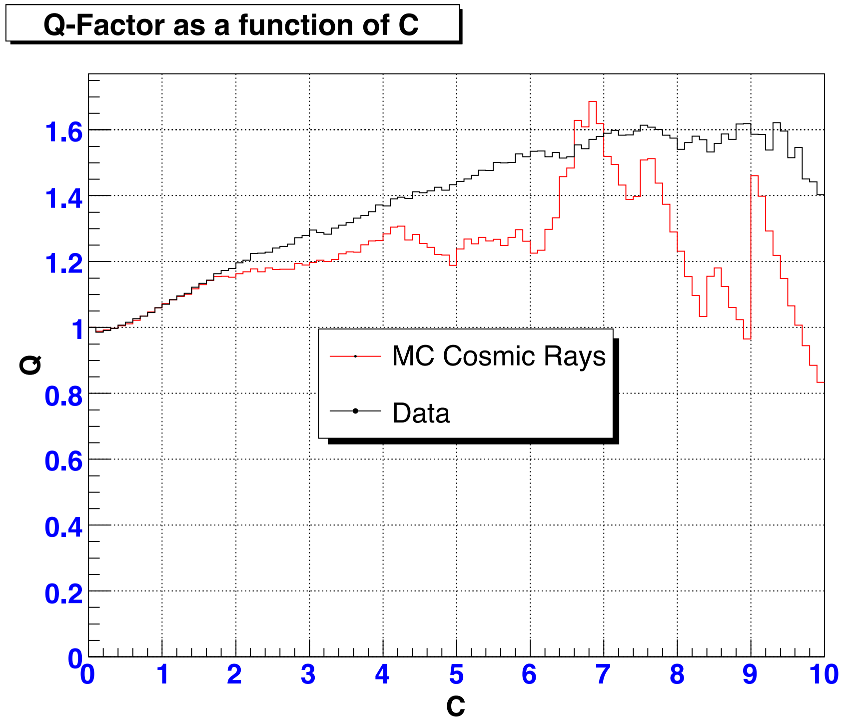
MATHUSLA proposal, CR and hadronic physics at CERN (RPC carpets above ATLAS)

Background rejection in Milagro

compactness parameter

$$C = \frac{N_{bot \geq 2PEs}}{PE_{maxB}}$$

where $N_{bot\geq 2PEs}$ is the number of PMTs in the bottom layer with more than 2 PEs, and PE_{maxB} is the number of PEs in the bottom layer tube with the maximum number of PEs.


Q-Factor as a function of C

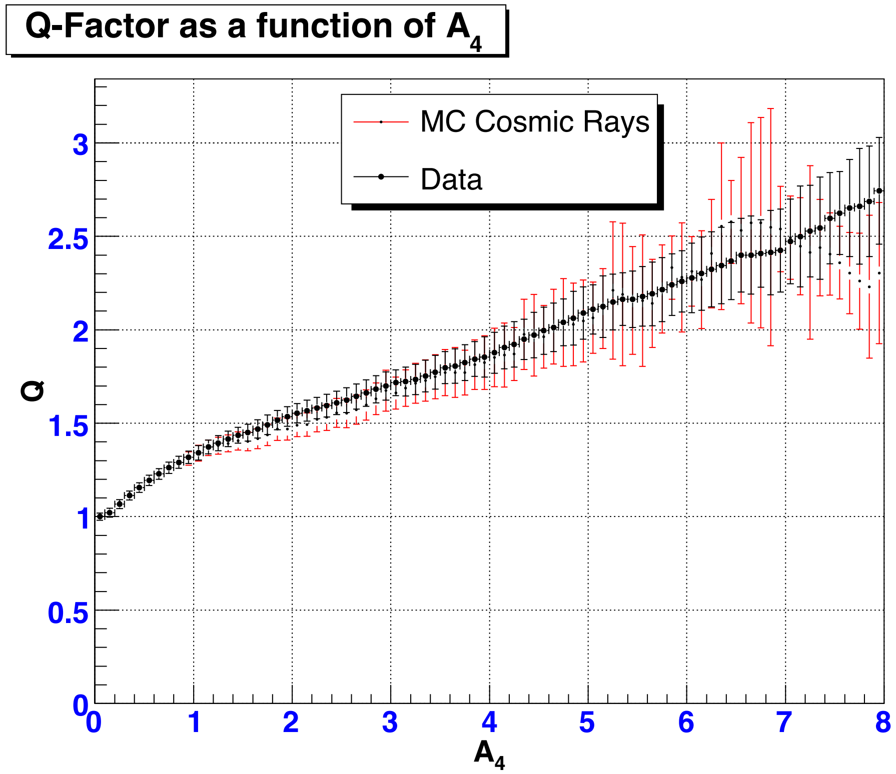
Consistent with ARGO findings after cuts on χ^2 of the temporal fit

$$A_4 = \frac{(f_{top} + f_{out}) \times N_{fit}}{PE_{maxB}}$$

- f_{top} is the fraction of the air shower layer PMTs hit in an event.
- f_{out} is the fraction of the outriggers hit in an event.
- N_{fit} is the number of PMTs that entered in the angle fit.

$(f_{top} + f_{out})$ = info on the size of the shower

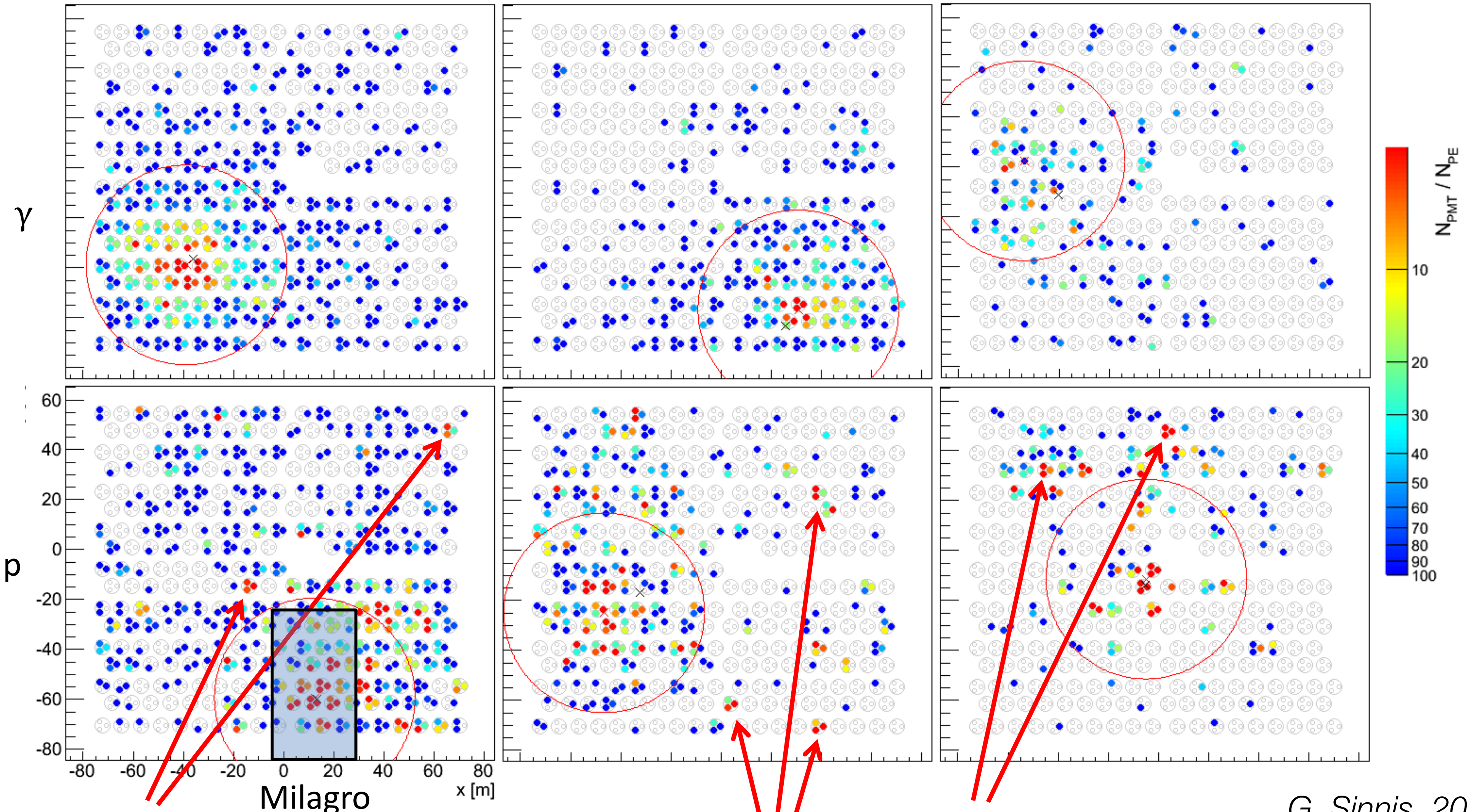
N_{fit} carries information about how well the shower was reconstructed. PE_{maxB} carries information about the ***clumpiness in the muon layer*** that is due to the penetrating muons and hadrons which are mostly presented in hadronic air showers.


Q-Factor as a function of A_4

Abdo, PhD thesis

Dimensions matter…

Hadronic showers typically deposit large amounts of energy in distinct clumps far from the shower core (>40 m) ➜ CR rejection using topological cut in hit pattern (the pattern of energy deposition in the detector)



G. Sinnis, 2010

- Algorithm looks for high-amplitude hits more than 40 m from the reconstructed core location

Requires sufficient number of triggered channels (>70) to work well.
Q-value max $(\varepsilon_\gamma/\sqrt{\varepsilon_{CR}})$ is estimated ~5 for point sources.

Scientific results

Milagro

Water Cherenkov Technology

- Gamma-ray Astronomy
- CR anisotropy
- *No results on selection of different primary masses and spectra of different elements*

HAWC

Water Cherenkov Technology

- Gamma-ray Astronomy
- CR anisotropy
- All-particle energy spectrum
- *Still NO results on the selection of different primary masses*

ARGO-YBJ

Resistive Plate Chamber Technology

- Gamma-ray Astronomy
- CR anisotropy
- All-particle energy spectrum up to the knee range
- Study of the shower core region
- Selection of light component (p+He) and *observation of the proton knee*

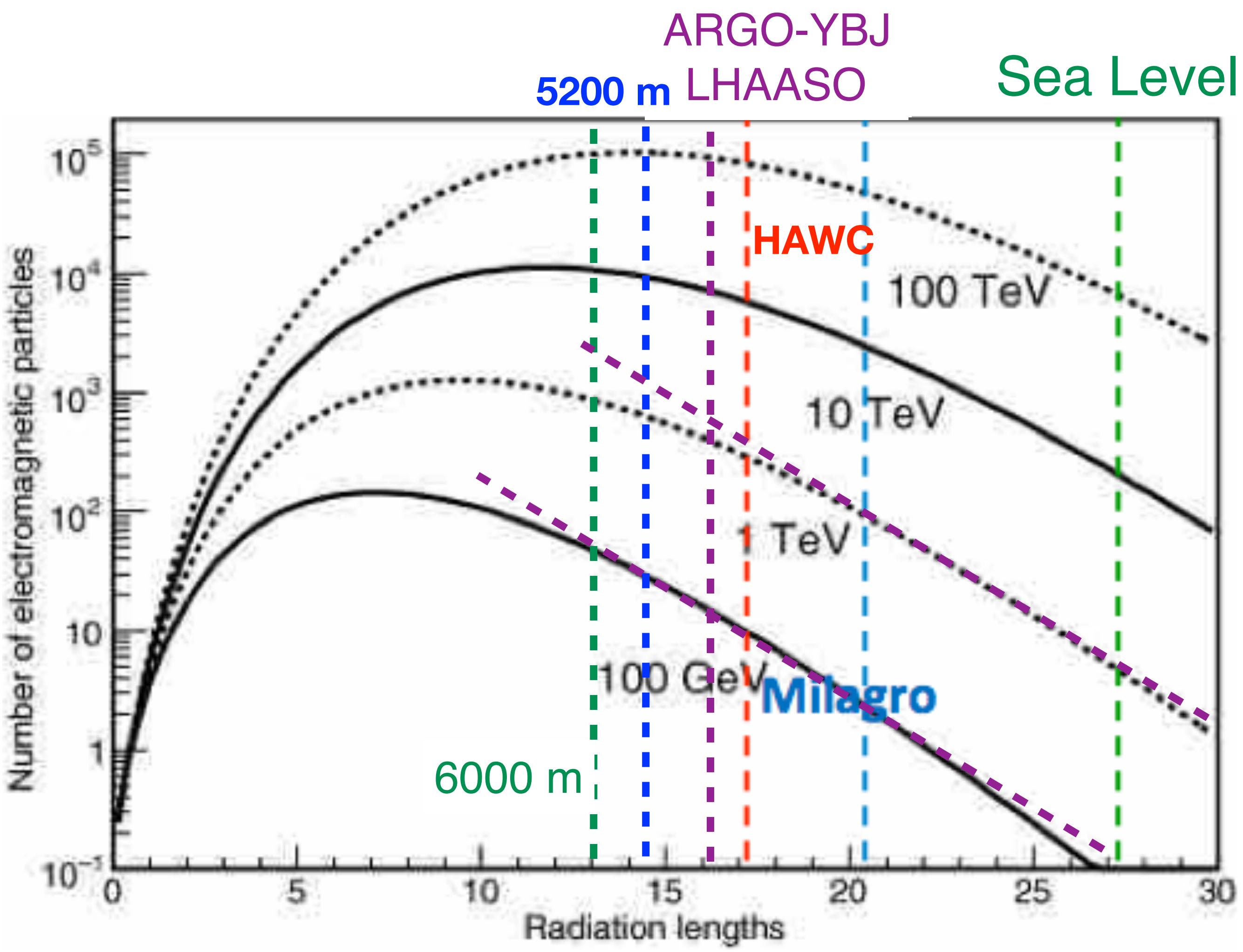
With ARGO-YBJ we demonstrated that RPCs can be safely operated at extreme altitude for many years.

Benefits of RPCs in ARGO-YBJ:

- dense sampling → low energy threshold (≈ 300 GeV)
- wide energy range: ≈300 GeV → 10 PeV
- high granularity of the read-out → good angular resolution and unprecedented details in the core region

The capability of Water Cherenkov facilities in extending the energy range to PeV and in selecting primary masses must be investigated

Lowering the energy threshold: extreme altitude



Showers of all energies have the same slope after shower maximum: ≈1.65x decrease per r.l. .
So, for all energies, if a detector is located one radiation length higher in atmosphere, the result will be a ≈1.65x decrease in the energy observable.

HAWC (4100 m asl)
ARGO-YBJ/LHAASO (4400 m asl) = 1, 1 energy thr.
Chacaltaya (5200 m asl) ≈2x, ≈3x energy thr.
6000 m asl ≈3x, ≈5x energy thr.

increase in size **decrease in en. thr.**

This imply that the effective areas of EAS detectors increases at low energies.

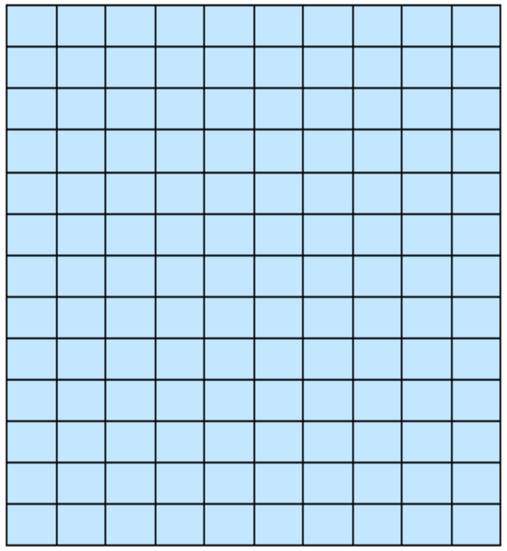
Lowering the energy threshold:

- *Extreme altitude (>4400 m asl)*
- *Detection technique and layout*
- *Coverage and granularity*
- *Trigger logic*
- *Detection of secondary photons*

ARGO-YBJ: a full coverage detector

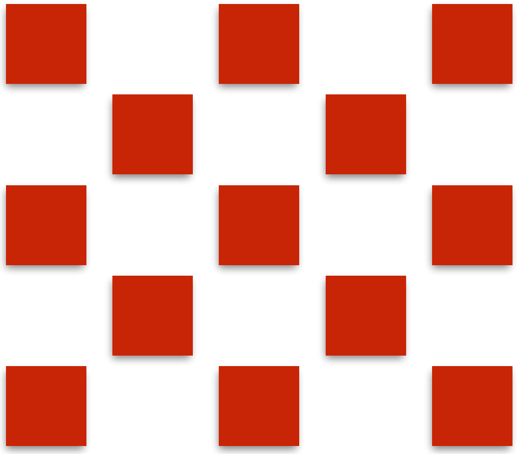
ARGO-YBJ is a high altitude full coverage EAS-array
optimized for the detection of small size air showers.

ARGO-YBJ central carpet



a continuous carpet of detectors
coverage factor ≈ 0.92

sparse array



coverage factor ≈ 10^{-3} - 10^{-2}

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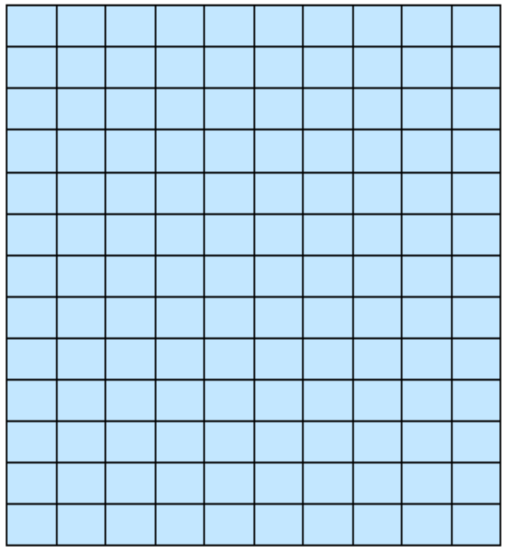

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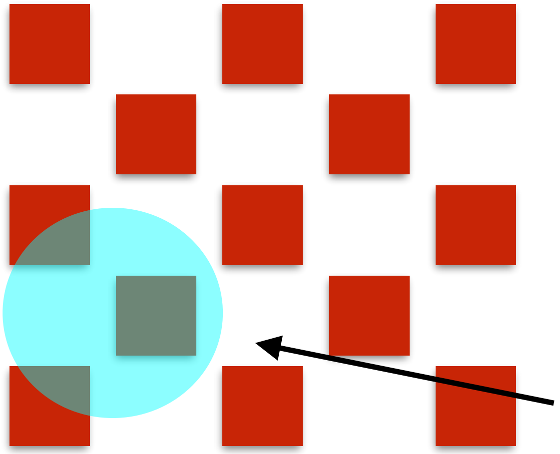

high energy shower = big shower
➔ trigger

coverage factor ≈ 10^{-3} - 10^{-2}

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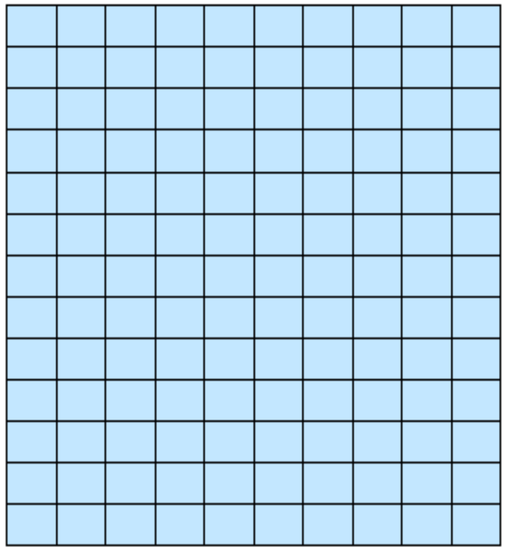

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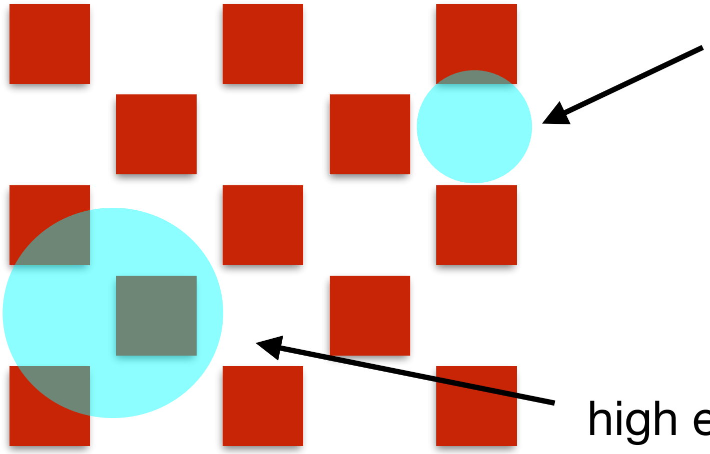

low energy shower = small shower
➔ NO trigger

high energy shower = big shower
➔ trigger

coverage factor ≈ 10^{-3} - 10^{-2}

ARGO-YBJ: a full coverage detector

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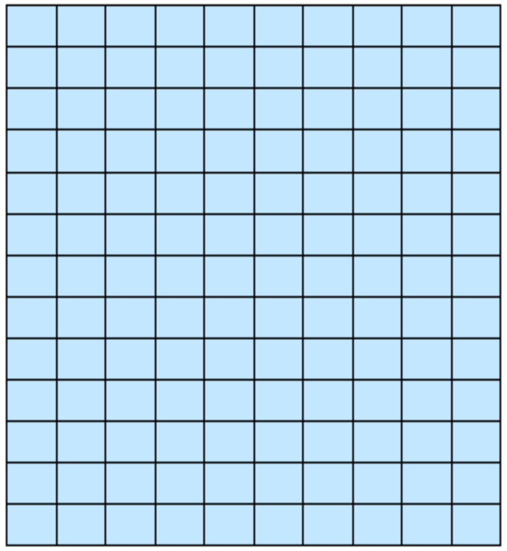
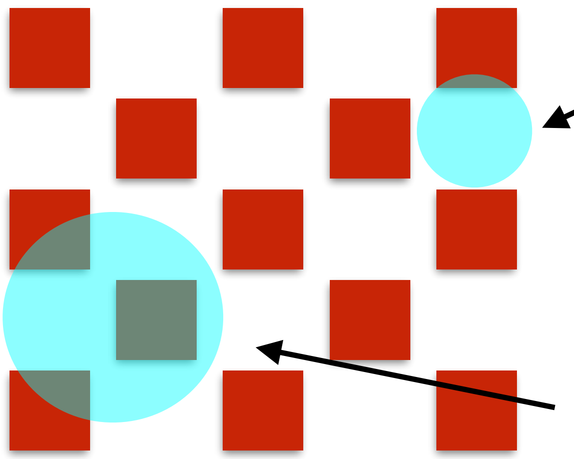
ARGO-YBJ central carpet



a continuous carpet of detectors
coverage factor ≈ 0.92

sparse array



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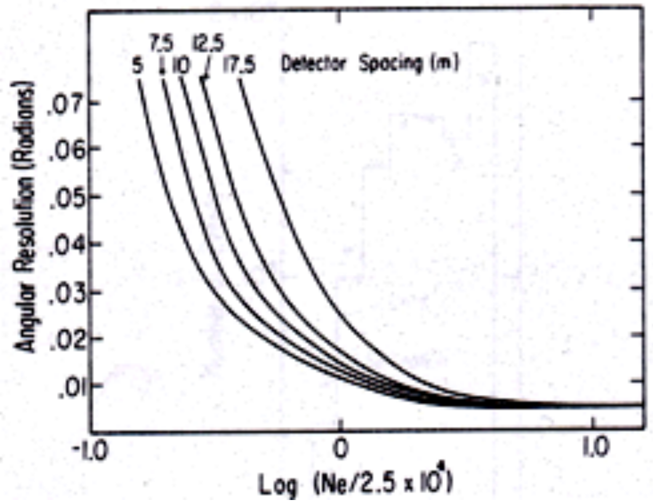
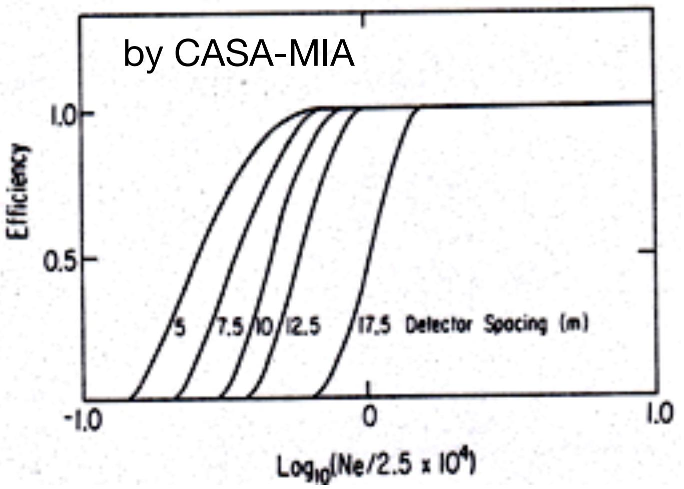
➔ trigger

coverage factor ≈ 10^{-3} - 10^{-2}



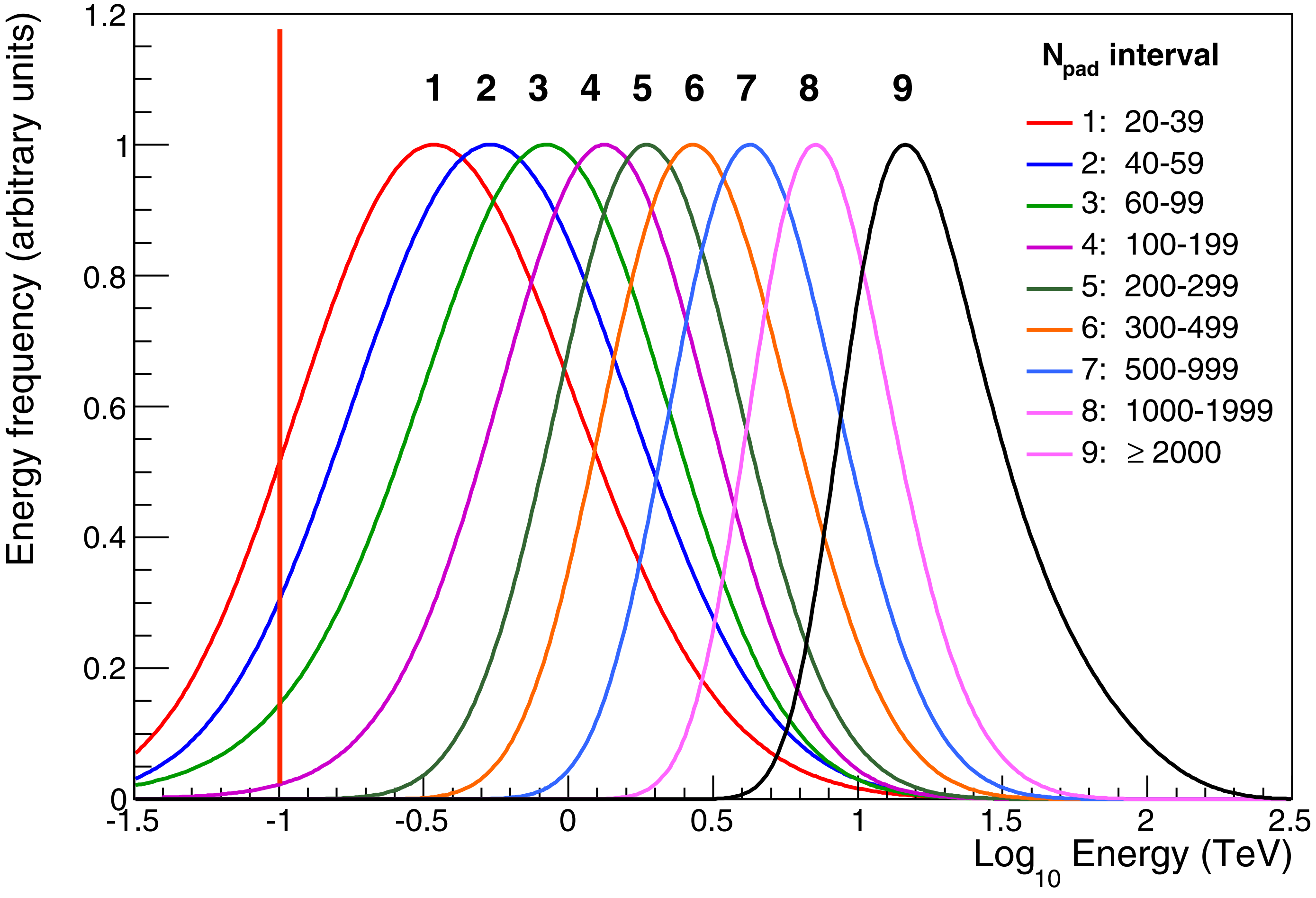


Increasing the sampling (~1% ➜100%)

- Improves angular resolution
- Lowers energy threshold

Energy threshold and resolution

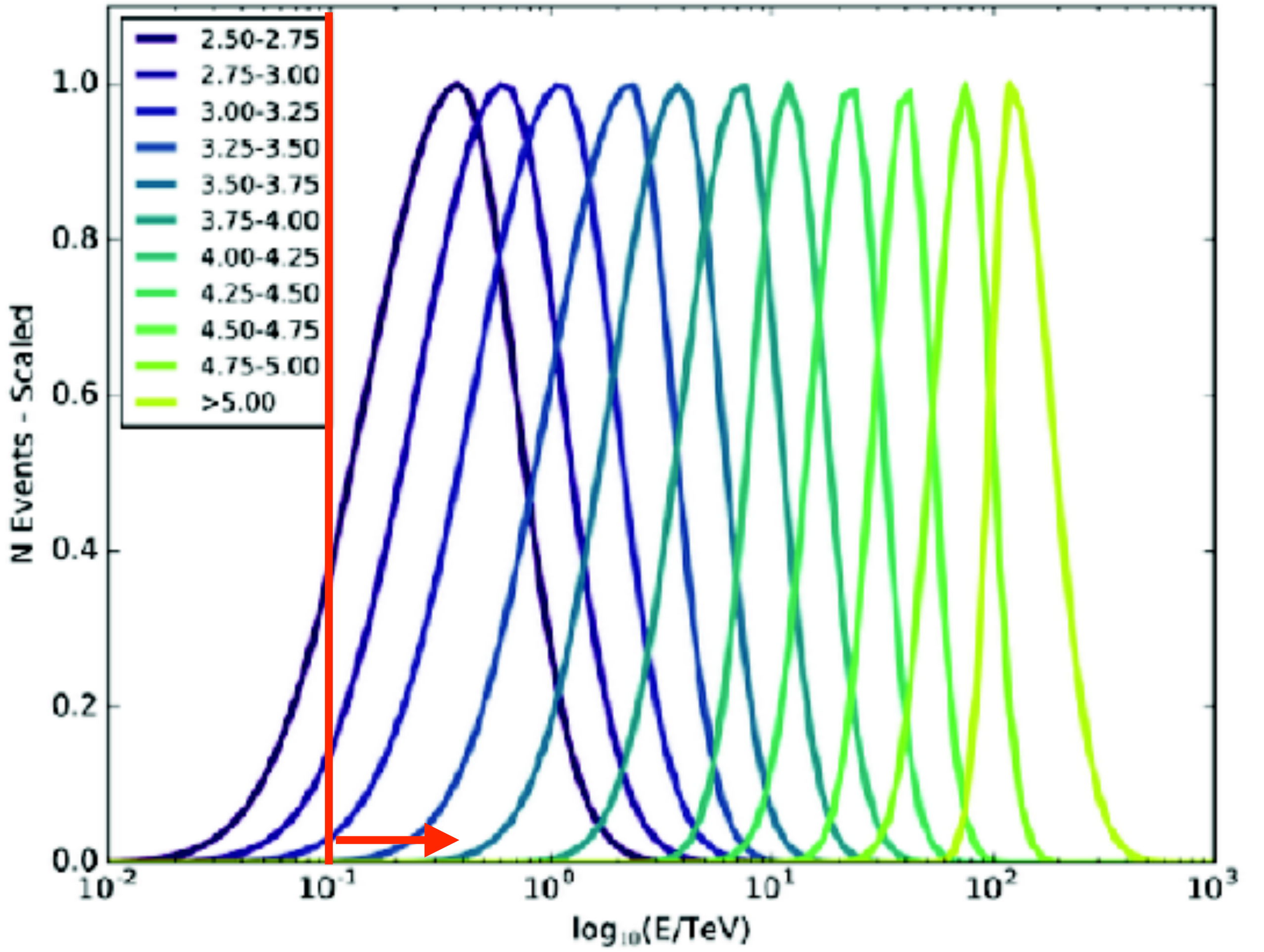
ARGO-YBJ (all triggered events)



full coverage RPC carpet operated at 4300 m asl

coverage ≈ 92%
high granularity (cm level)
Topological-based Trigger logic;
>20 pads out of 15,000 bkg free !
Noise: 380 Hz/pad

HAWC (2019) internal events only



array of water tanks operated at 4100 m asl

coverage ≈ 60%
poor granularity (m level)
Trigger rate: 24 kHz
Noise: 20-30 kHz/8” PMT (40-50 kHz/10"PMT)

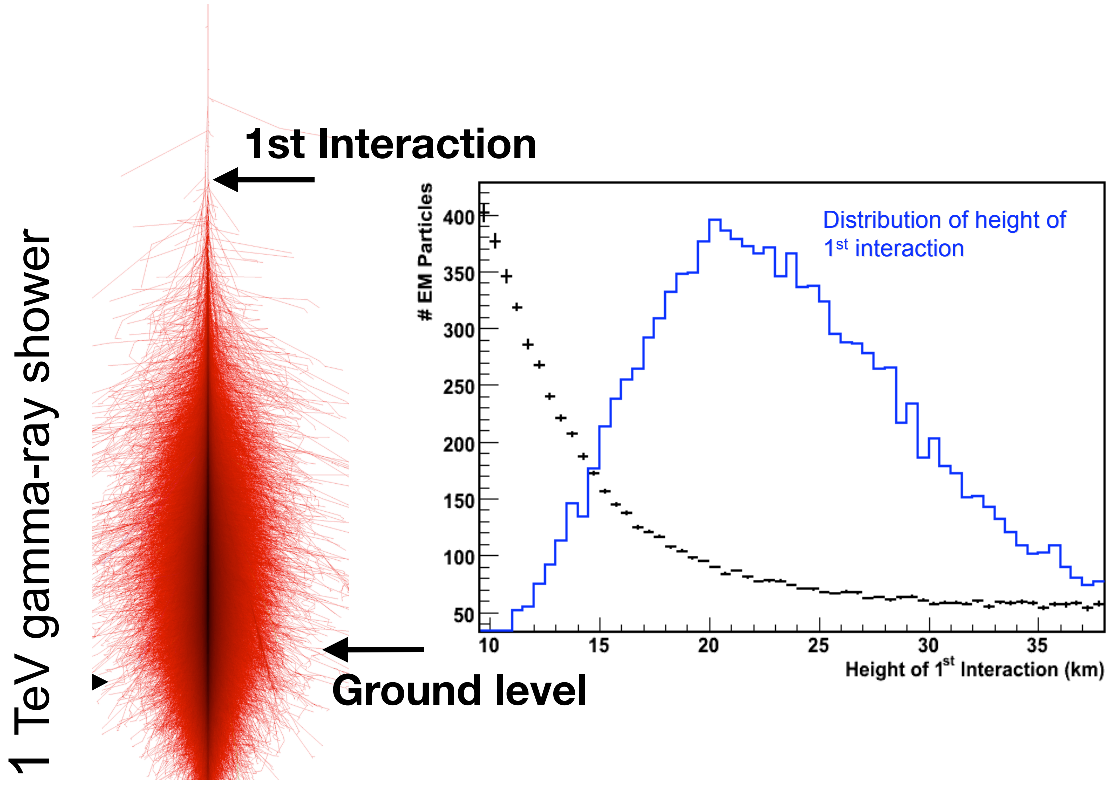
Energy resolution

The energy resolution is given by the folding of

Shower fluctuations
Fluctuations in the depth of the first interaction point

⊕

Sampling fluctuations
Fluctuations in the measured number of secondary particles



Shower fluctuations dominate energy resolution of EAS arrays.

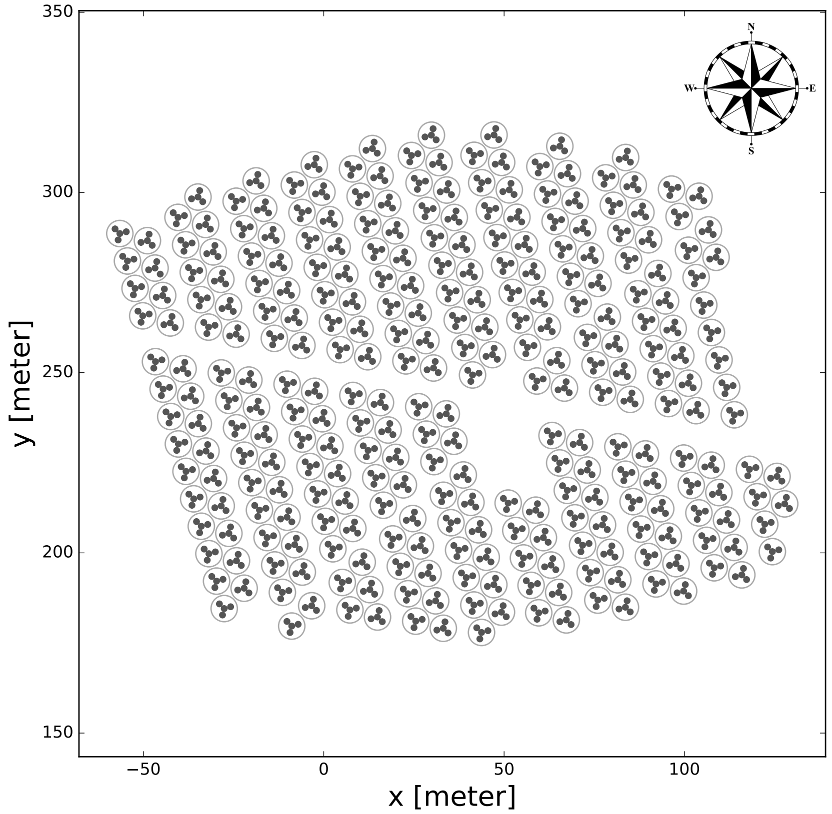
Can be reduced with high coverage and high granularity of the read-out
➜ all particles are measured !

HAWC: 40% - 55% at 1 TeV (gamma internal)
HAWC: 23% - 30% at 50 TeV (gamma internal)

ARGO: 10% at 10 TeV (protons internal)
ARGO: 5% at 100 TeV (protons internal)

IACT: 8% - 15% at 1 TeV
IACT: 15% - 35% at 50 TeV

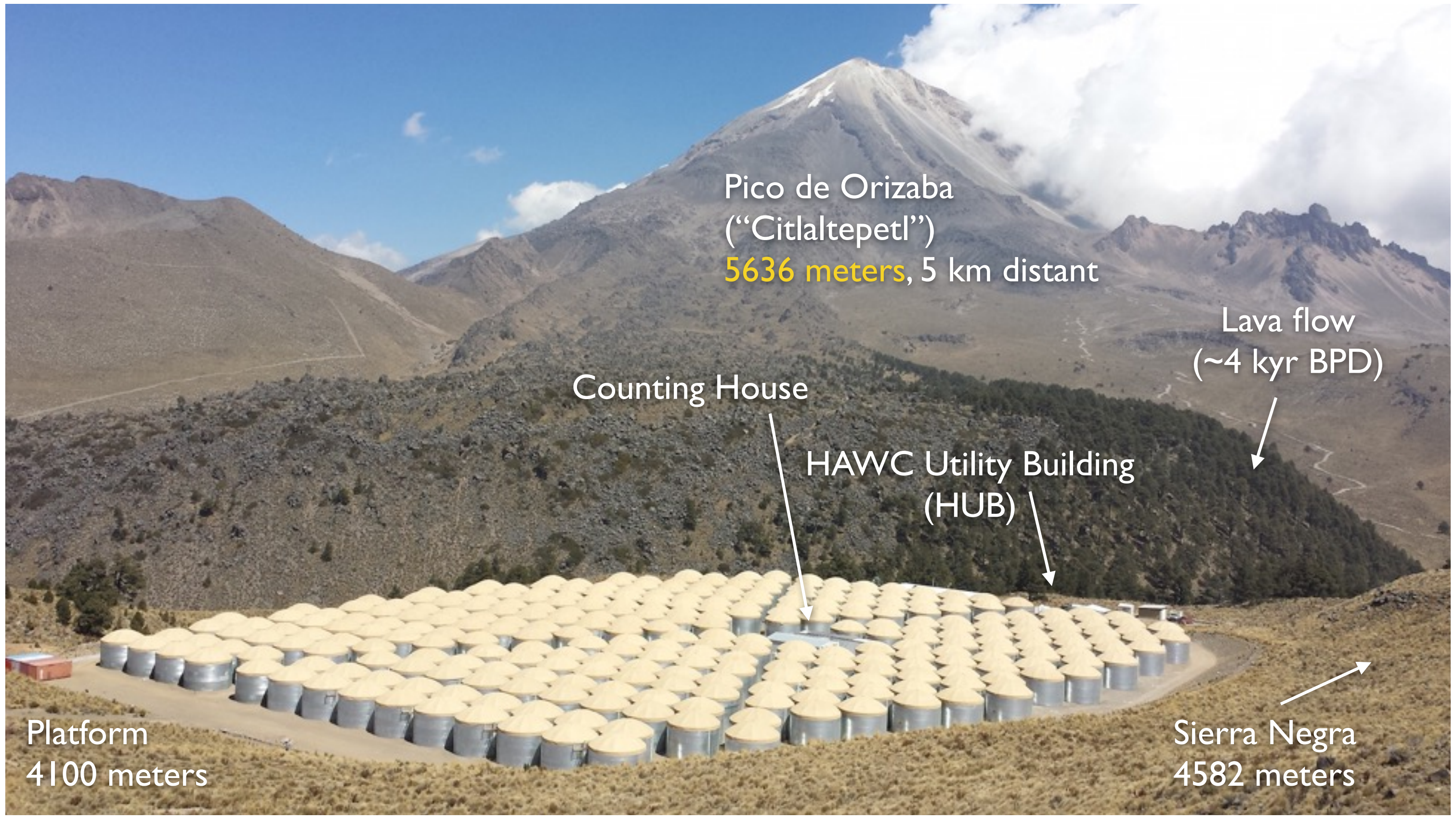
Northern Hemisphere: HAWC



The **H**igh **A**ltitude **W**ater **C**herenkov Gamma-ray Observatory (HAWC) is up and running

Goals: observe gamma rays and cosmic rays from half the sky each day between 100 GeV and 100 TeV

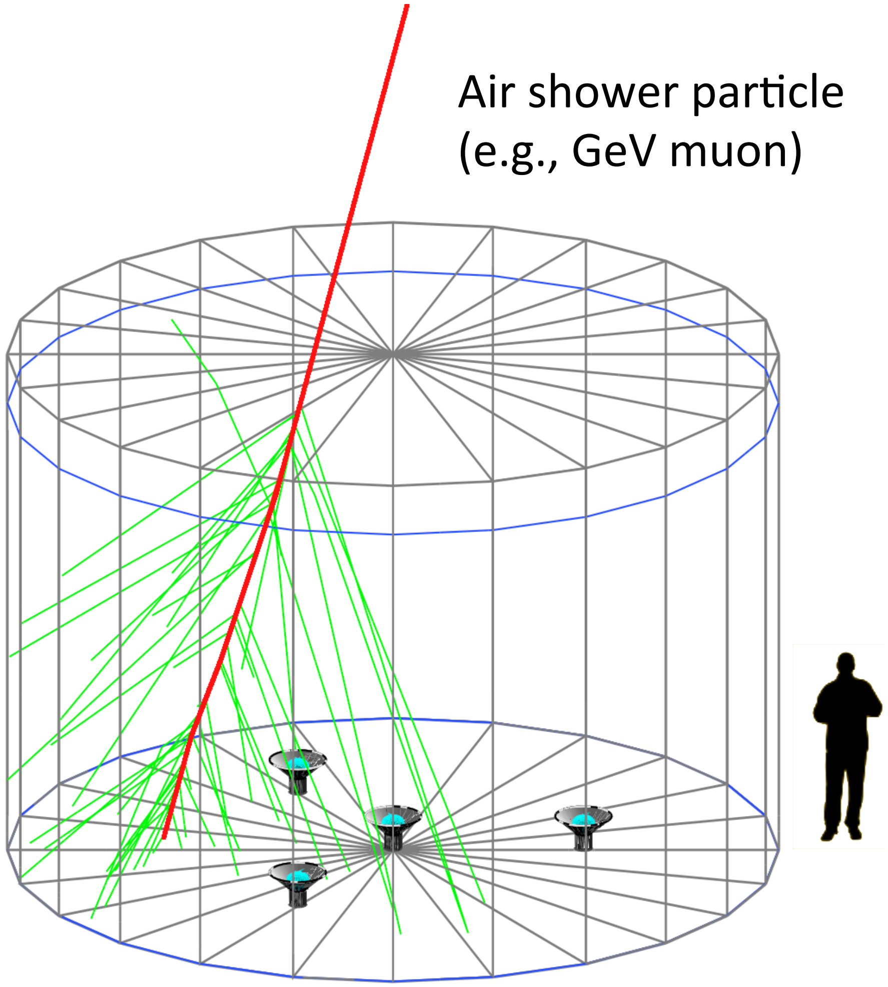
- 4100 meters above sea level
- 19°N latitude (Galactic Center at 48° zenith)
- 300 water tanks, 1200 large photocathode area PMTs 1/6th of sky in instantaneous field of view



- Instrumented Area: 22,000 m^2 ≈140 X 140 m^2
- Coverage factor: ≈60 %
- 10 kHz event rate

Water Cherenkov Method

- Robust and cost-effective surface detection technique
- Water tanks: 7.3 m radius, 5 m height, 185 kL purified water
- Tanks contain three 8” R5912 PMTs and one 10” R7081-HQE PMT looking up to capture Cherenkov light from shower front



Final tank deployed: December 15, 2014

2nd HAWC Catalog

arXiv:1702.02992

Table 1. Properties of the nine analysis bins: bin number $\mathcal{B}$, event size $f_{\rm hit}$, 68% PSF containment ψ_{68}, cut selection efficiency for gammas $\epsilon_\gamma^{\rm MC}$ and cosmic rays $\epsilon_{\rm CR}^{\rm data}$, and median energy for a reference source of spectral index −2.63 at a declination of 20° $\tilde{E}_\gamma^{\rm MC}$.

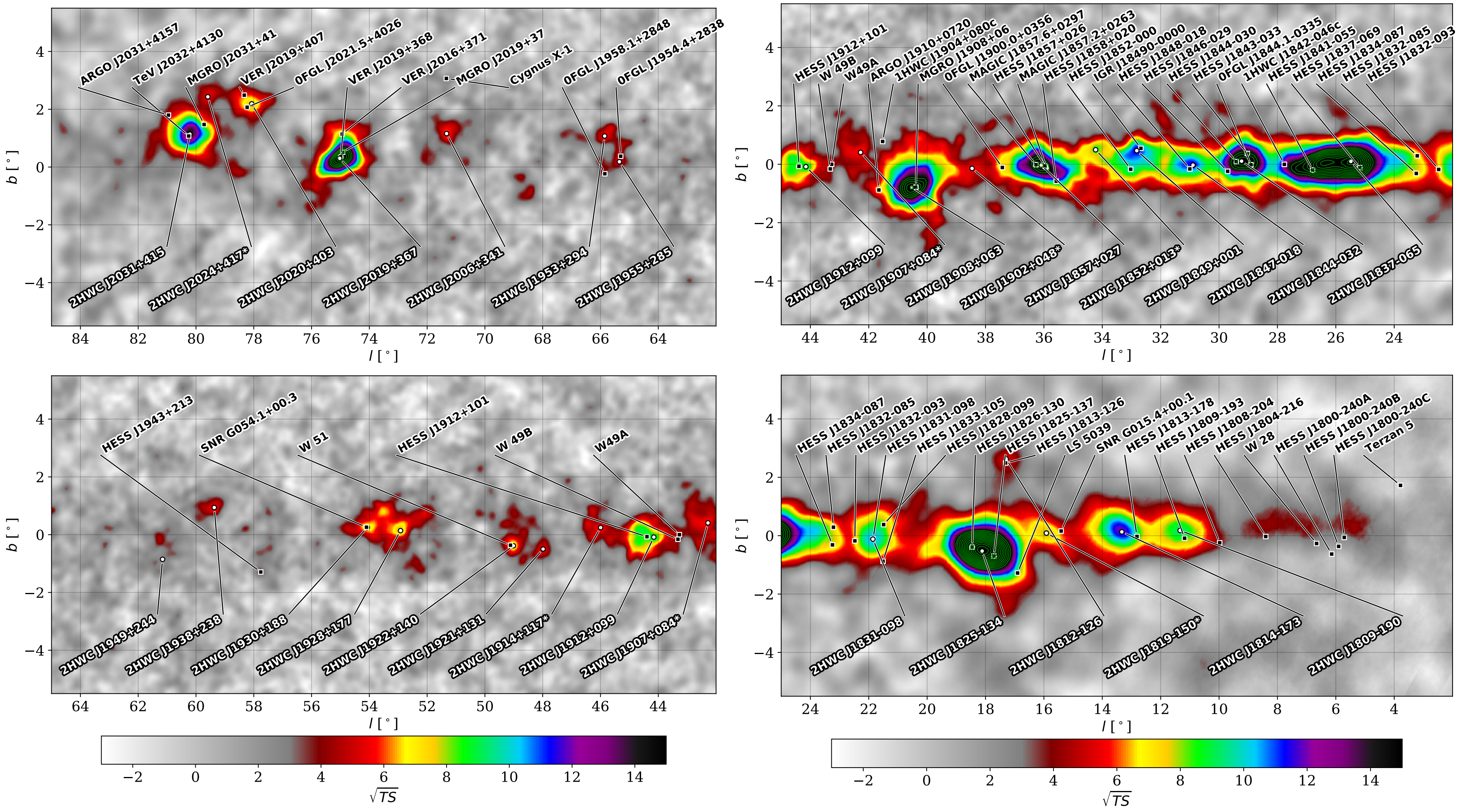
$\mathcal{B}$	$f_{\rm hit}$ (%)	ψ_{68} (°)	$\epsilon_\gamma^{\rm MC}$ (%)	$\epsilon_{\rm CR}^{\rm data}$ (%)	$\tilde{E}_\gamma^{\rm MC}$ (TeV)
1	6.7 – 10.5	1.03	70	15	0.7
2	10.5 – 16.2	0.69	75	10	1.1
3	16.2 – 24.7	0.50	74	5.3	1.8
4	24.7 – 35.6	0.39	51	1.3	3.5
5	35.6 – 48.5	0.30	50	0.55	5.6
6	48.5 – 61.8	0.28	35	0.21	12
7	61.8 – 74.0	0.22	63	0.24	15
8	74.0 – 84.0	0.20	63	0.13	21
9	84.0 – 100.0	0.17	70	0.20	51

Energy threshold ≈ 700 GeV

A total of 39 sources were detected with 507 days of data.

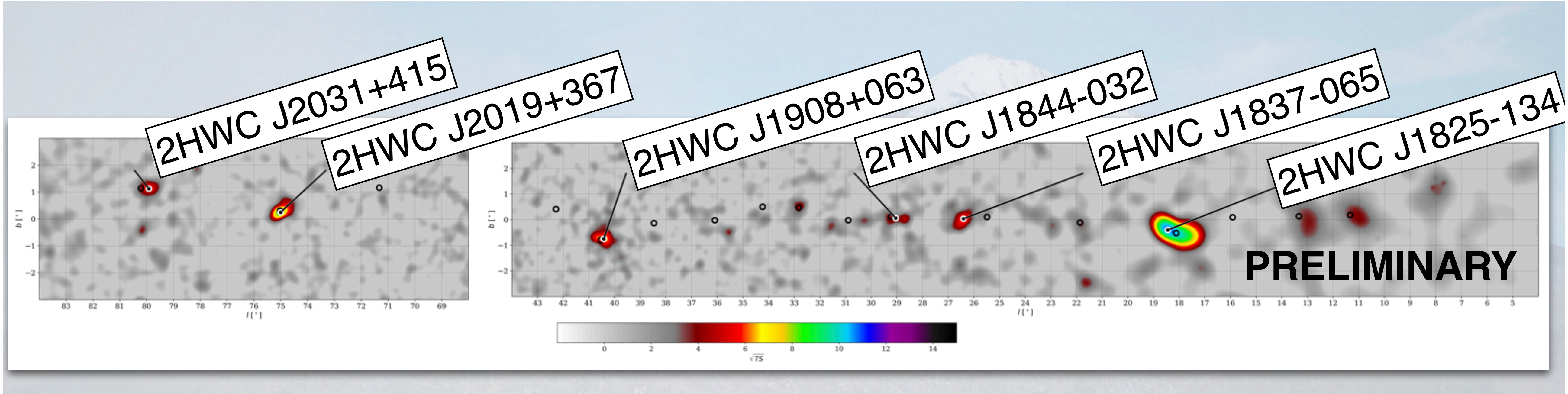
Out of these sources, 16 are more than one degree away from any previously reported TeV source

7 of the detected sources may be associated with PWN, 2 with SNRs, 2 with blazars, and the remaining 23 have no firm identification yet.



The Galaxy above 56 TeV with HAWC

Galactic Plane above 56 TeV (0.5 deg extended source assumed)

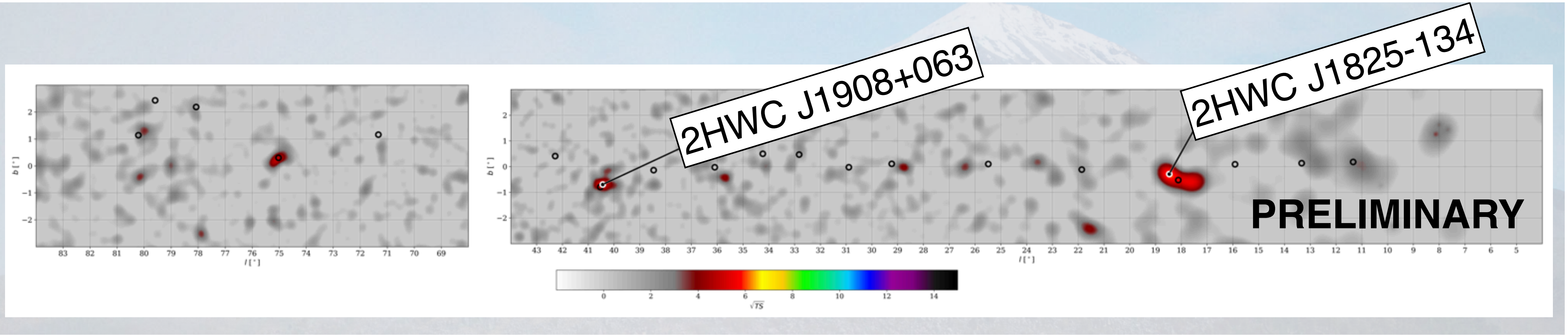


K. Malone, TeVPA 2018

6 sources in the plane > 56 TeV (plus the Crab)

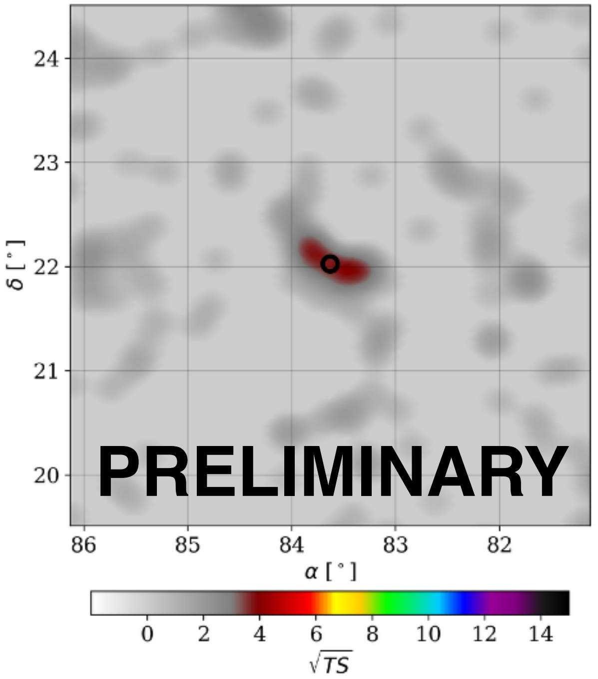
The Galaxy above 100 TeV with HAWC

Galactic Plane above 100 TeV



K. Malone, TeVPA 2018

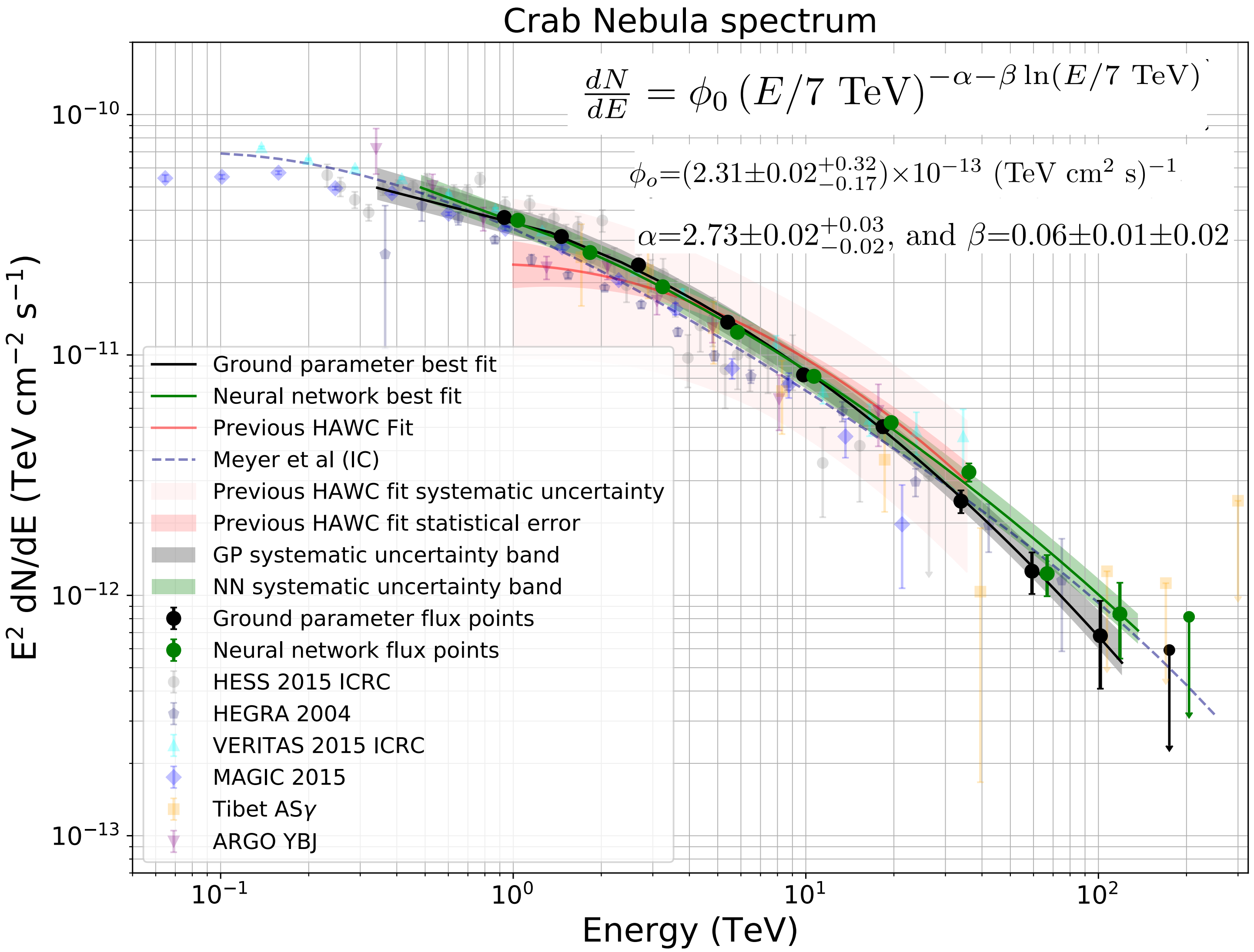
2 sources in the plane > 100 TeV (plus the Crab ?)

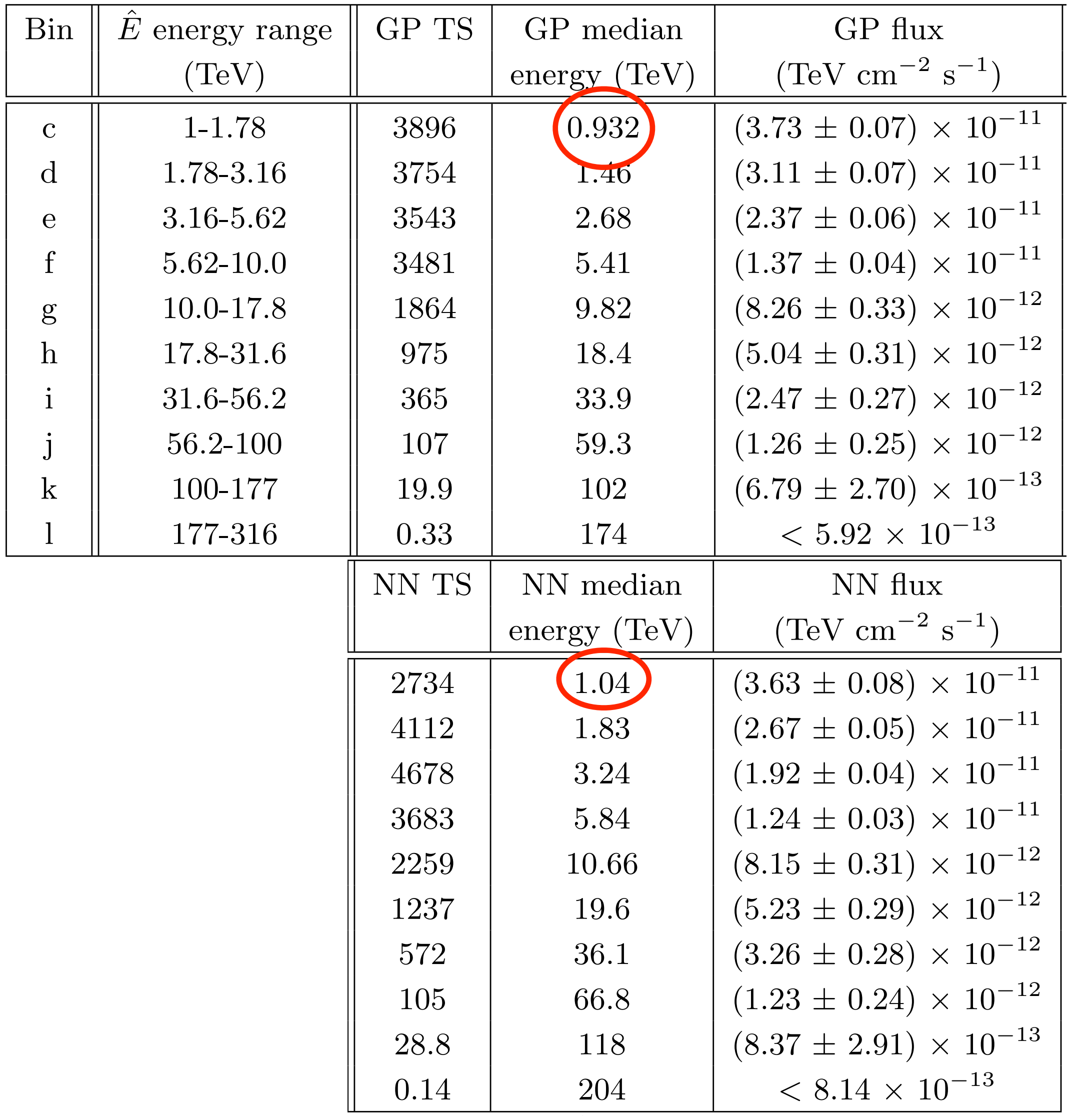


Crab Nebula with HAWC

The Crab spectrum measured between June 2015 and December 2017 with 837 days of data

arXiv:1905.12518





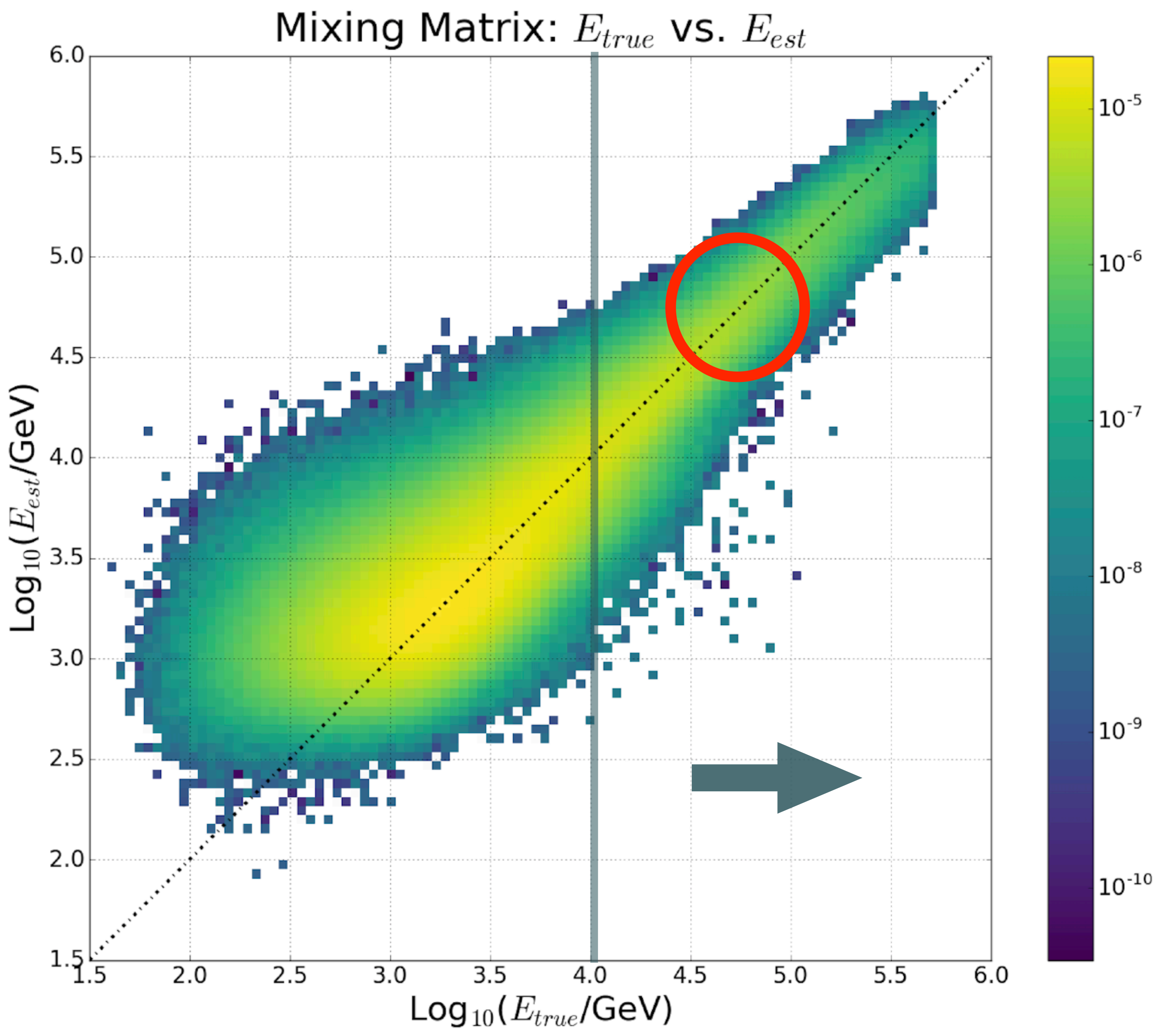
Bin	$\hat{E}$ energy range (TeV)	GP TS	GP median energy (TeV)	GP flux (TeV cm^{-2} s^{-1})	NN TS	NN median energy (TeV)	NN flux (TeV cm^{-2} s^{-1})
c	1-1.78	3896	0.932	$(3.73 \pm 0.07) \times 10^{-11}$	2734	1.04	$(3.63 \pm 0.08) \times 10^{-11}$
d	1.78-3.16	3754	1.46	$(3.11 \pm 0.07) \times 10^{-11}$	4112	1.83	$(2.67 \pm 0.05) \times 10^{-11}$
e	3.16-5.62	3543	2.68	$(2.37 \pm 0.06) \times 10^{-11}$	4678	3.24	$(1.92 \pm 0.04) \times 10^{-11}$
f	5.62-10.0	3481	5.41	$(1.37 \pm 0.04) \times 10^{-11}$	3683	5.84	$(1.24 \pm 0.03) \times 10^{-11}$
g	10.0-17.8	1864	9.82	$(8.26 \pm 0.33) \times 10^{-12}$	2259	10.66	$(8.15 \pm 0.31) \times 10^{-12}$
h	17.8-31.6	975	18.4	$(5.04 \pm 0.31) \times 10^{-12}$	1237	19.6	$(5.23 \pm 0.29) \times 10^{-12}$
i	31.6-56.2	365	33.9	$(2.47 \pm 0.27) \times 10^{-12}$	572	36.1	$(3.26 \pm 0.28) \times 10^{-12}$
j	56.2-100	107	59.3	$(1.26 \pm 0.25) \times 10^{-12}$	105	66.8	$(1.23 \pm 0.24) \times 10^{-12}$
k	100-177	19.9	102	$(6.79 \pm 2.70) \times 10^{-13}$	28.8	118	$(8.37 \pm 2.91) \times 10^{-13}$
l	177-316	0.33	174	$< 5.92 \times 10^{-13}$	0.14	204	$< 8.14 \times 10^{-13}$

These measurements are the highest-energy observation of a gamma-ray source to date.

The Ideal Observatory for PeVatrons

- Search for sources of cosmic rays close to PeV energies ➡ *High sensitivity at about 30-40 TeV*
- Test spectral break and cutoffs at several TeV ➡ *Good energy resolution at several TeVs*
- Search for different and possibly unexpected classes of sources ➡ *Unbiased survey*
- Resolve sources which might be hidden in the tails of bright sources and compare and correlate with gas surveys ➡ *Good angular resolution at several TeV*.

HAWC Mixing Matrix



S. Casanova, Roma 2019
K. Malone, TeVPA 2018

Gamma cut-off at 30 TeV imply proton cut-off at about 1 PeV.

Of course the higher energy the better but most sources become too faint.

Performance best above 10 TeV, where showers are largest

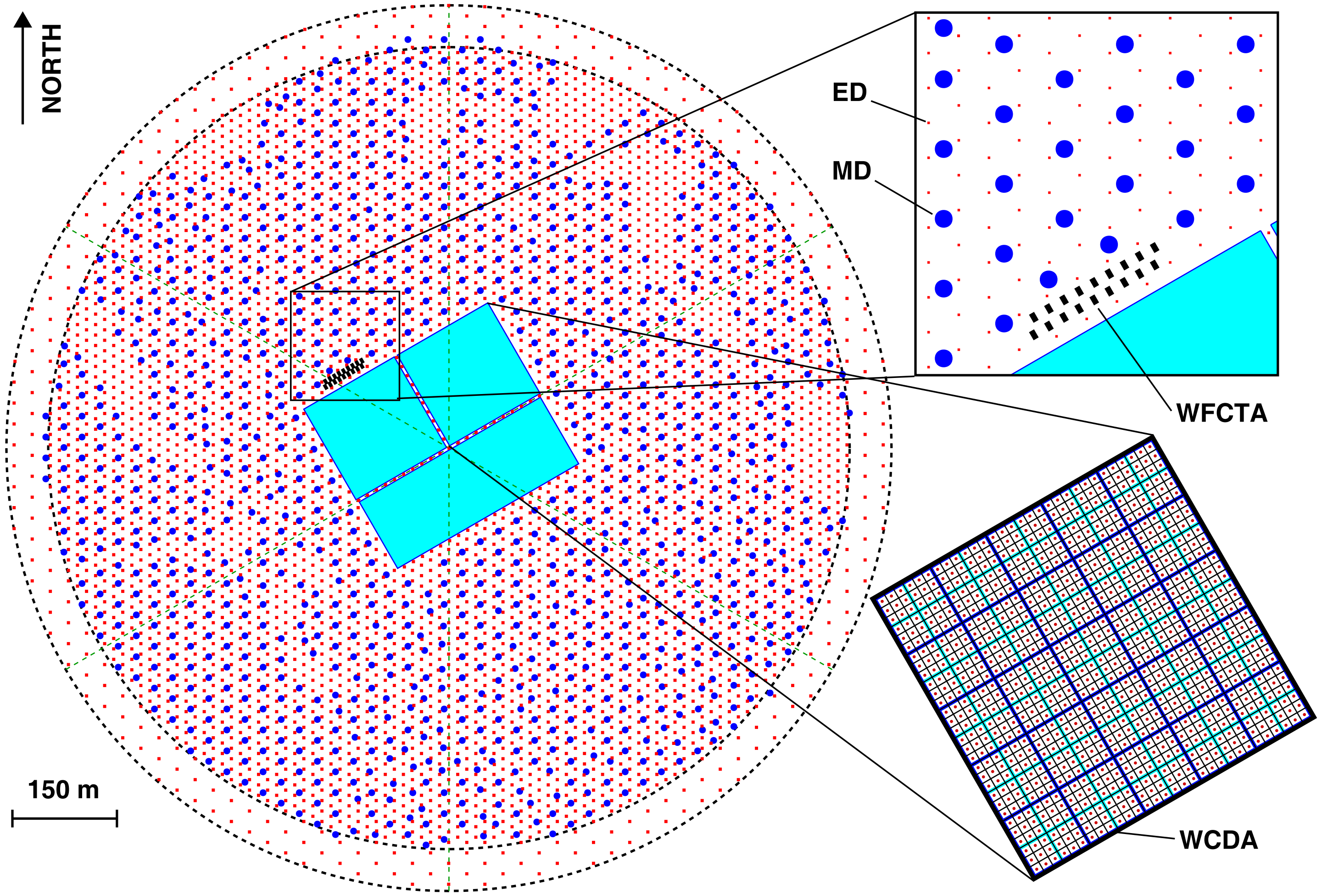
40% - 55% at 1 TeV (8%-15% IACT)
23% - 30% at 50 TeV (15%-35% IACT)

Not ideal spectroscopy, *extremely important to detect spectral break and cut-offs !!!*

Physical limits due to the *detection technique*, although there one might strive for improvements

LHAASO: from γ-ray astronomy to CR physics

- 1.3 km^2 array, including 5195 scintillator detectors 1 m^2 each, with 15 m spacing.
- An overlapping 1 km^2 array of 1171, underground water Cherenkov tanks 36 m^2 each, with 30 m spacing, for muon detection (total sensitive area ≈ 42,000 m^2).



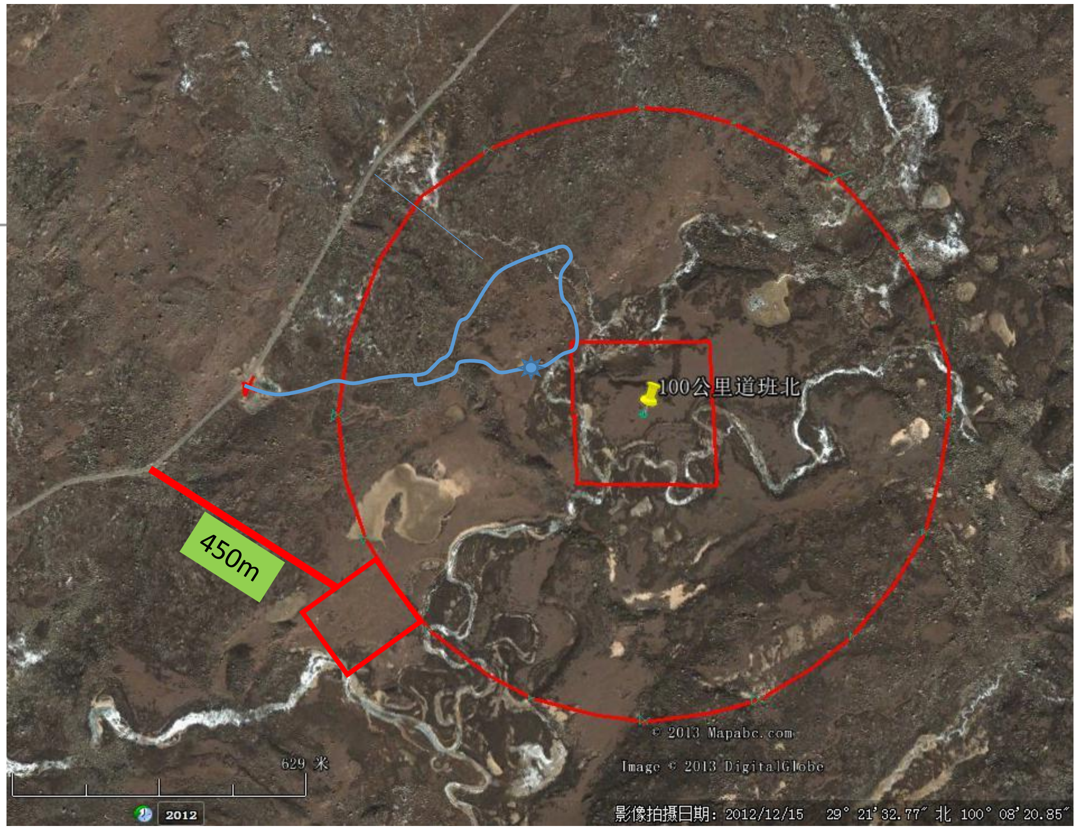
- A close-packed, surface water Cherenkov detector facility with a total area of 80,000 m^2.
- 18 wide field-of-view air Cherenkov (and fluorescence) telescopes.
- Neutron detectors

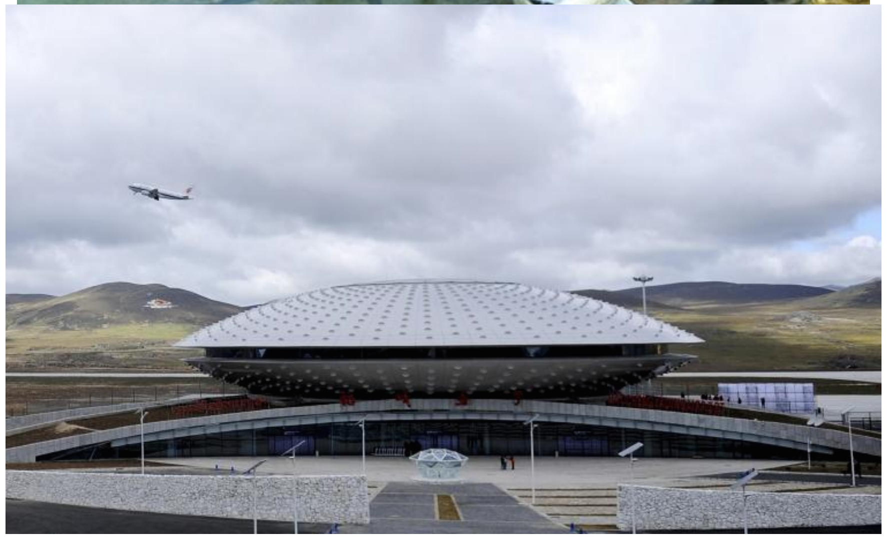
The LHAASO site

The experiment is located at 4400 m asl (600 g/cm^2) in the Haizishan (Lakes' Mountain) site, Sichuan province

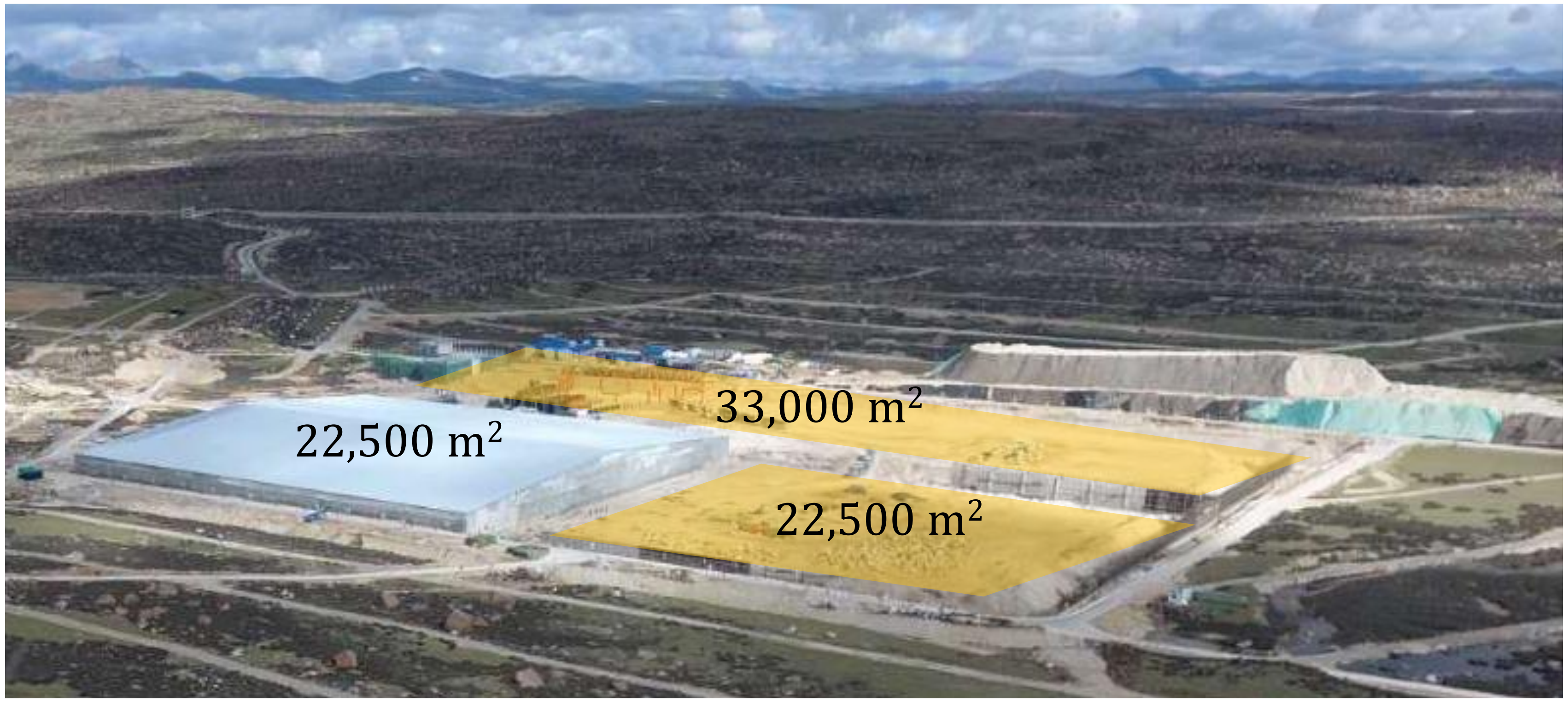
Coordinates: 29° 21' 31'' N, 100° 08' 15'' E

700 km to Chengdu
50 km to Daocheng City (3700 m asl, guest house)
10 km to the highest airport in the world

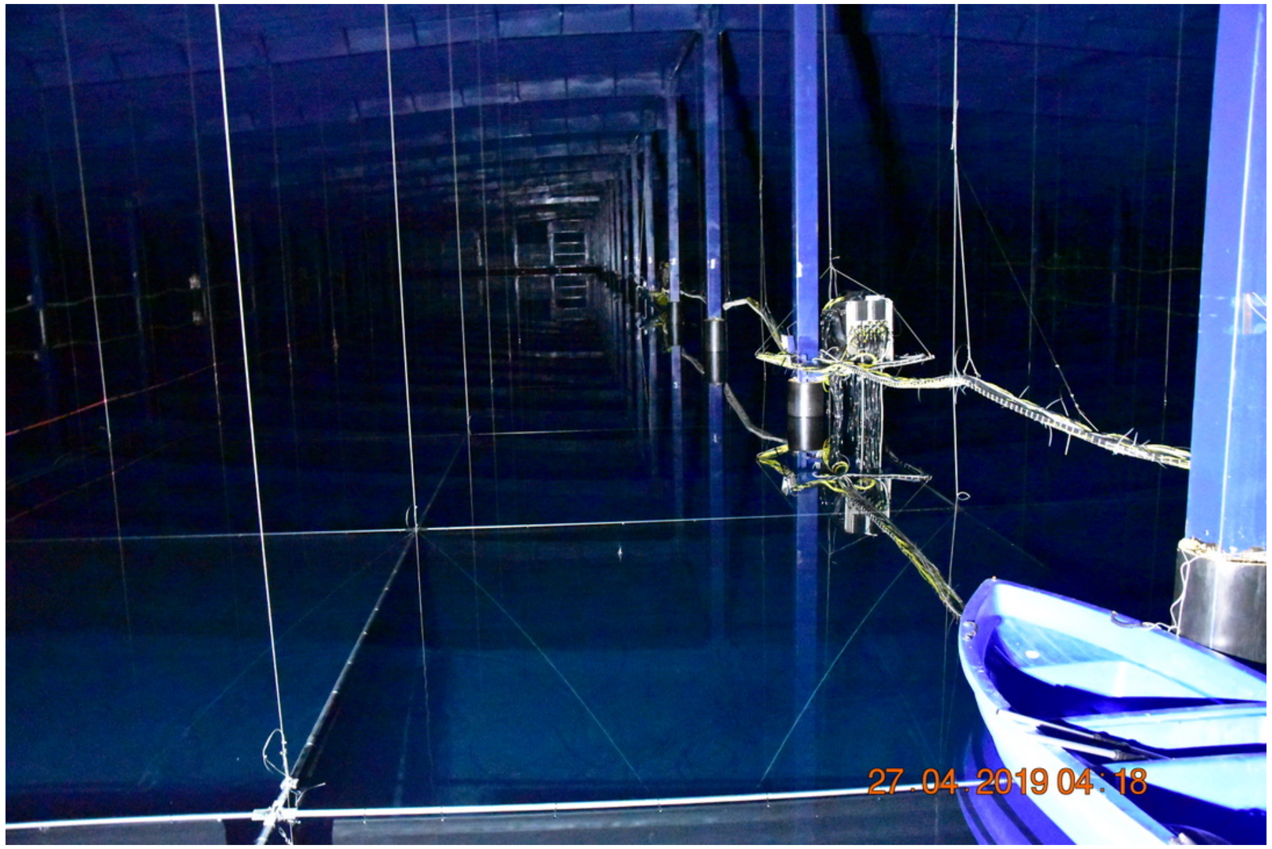




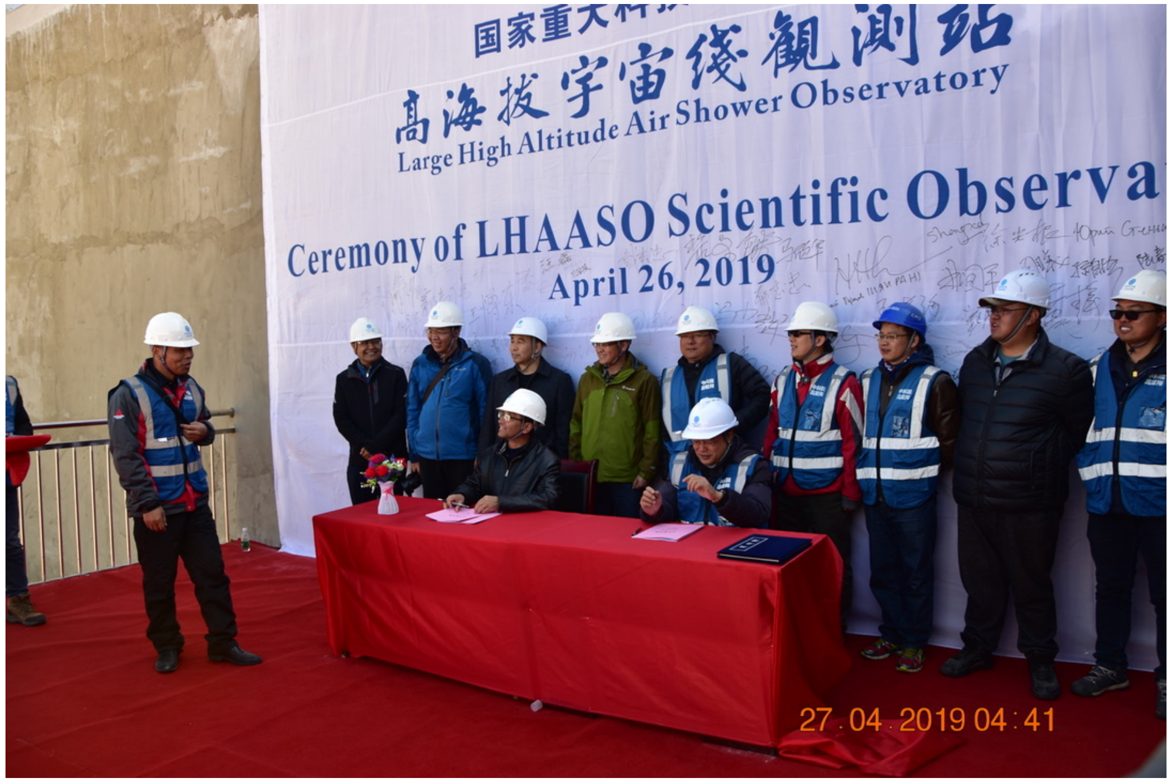
LHAASO installation: WCDA

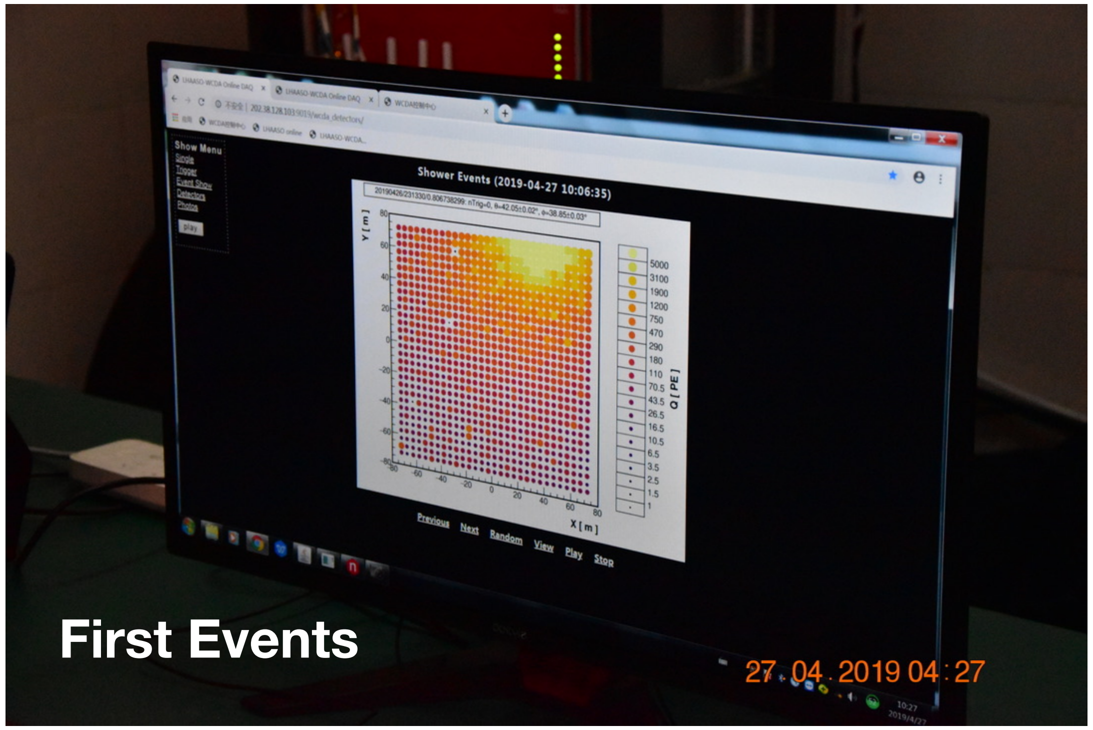


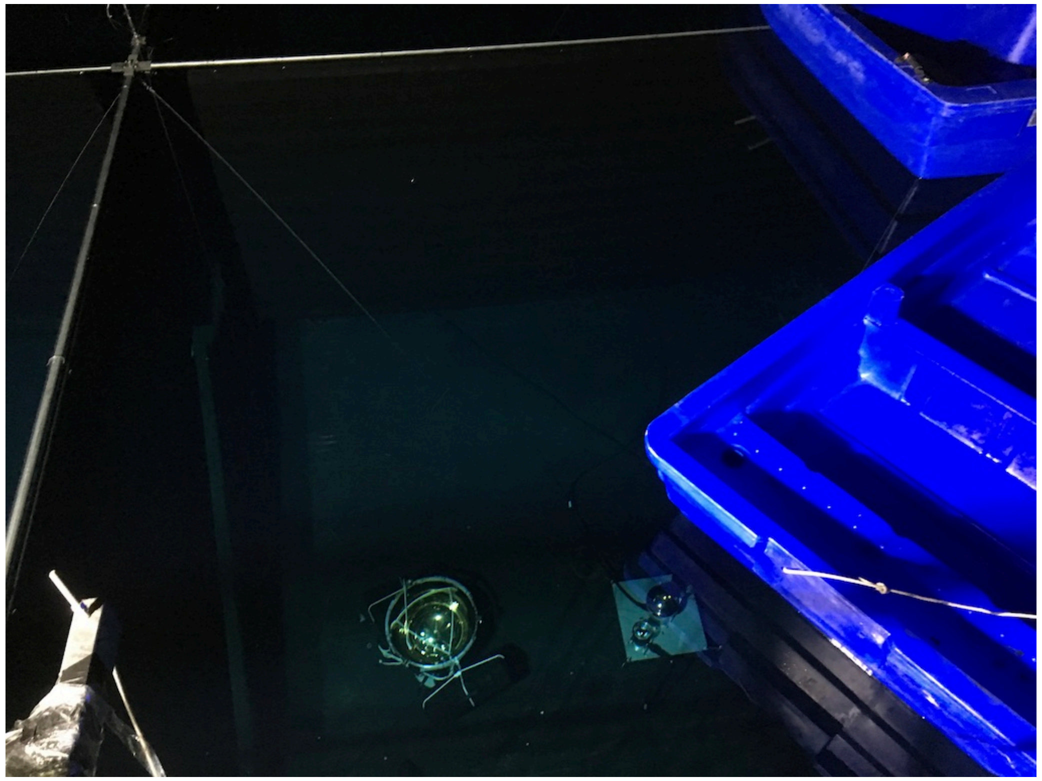
20” PMTs with special PE collecting design in #2 and #3 ponds of WCDA



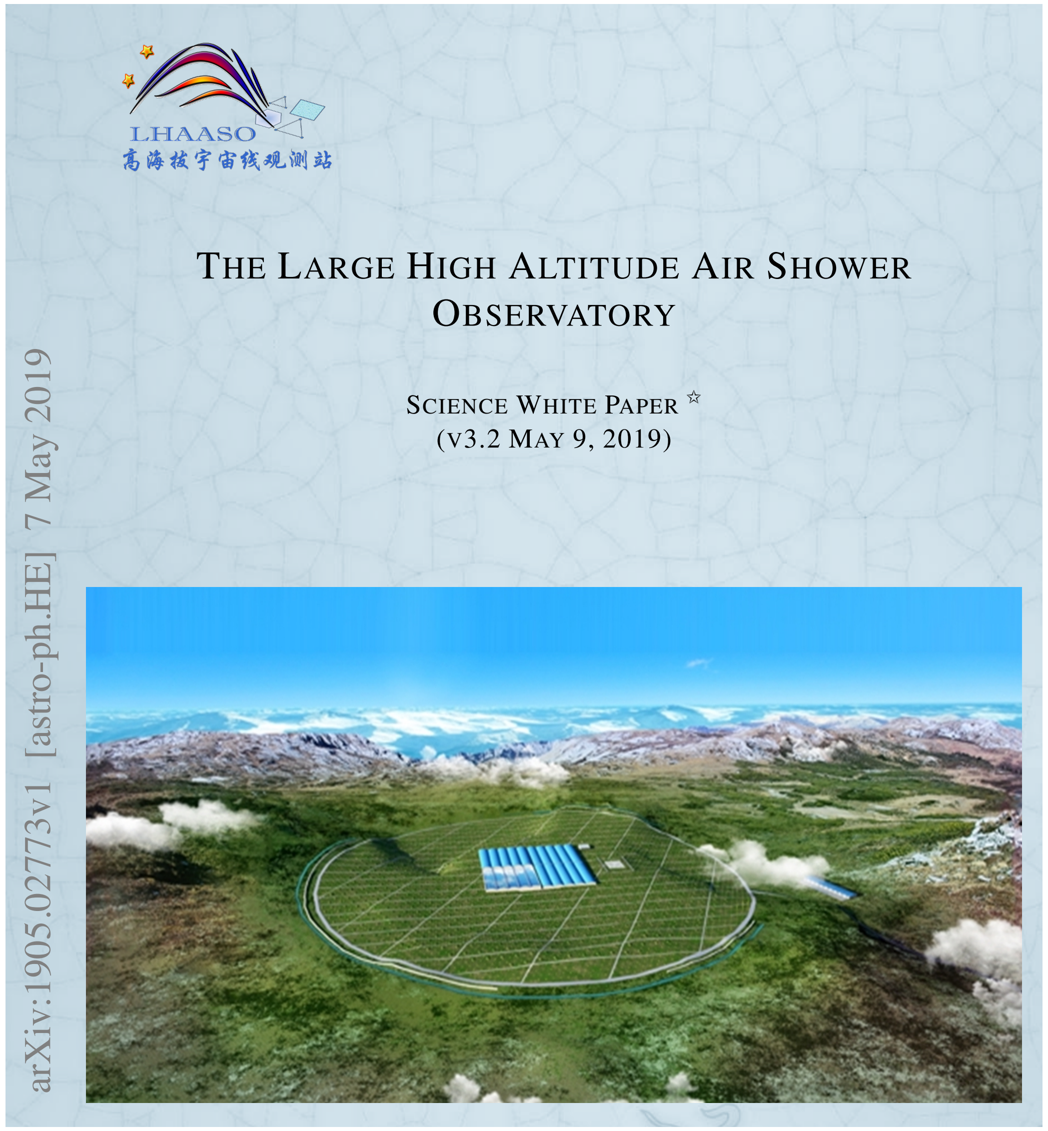
The Starting of the Data Taking




First Events



LHAASO Science White Paper



LHAASO
高海拔宇宙线观测站

THE LARGE HIGH ALTITUDE AIR SHOWER
OBSERVATORY

SCIENCE WHITE PAPER ☆
(V3.2 MAY 9, 2019)

arXiv:1905.02773v1 [astro-ph.HE] 7 May 2019

X. Bai[a,c], B. Y. Bi[a], X. J. Bi[a], Z. Cao[a,*], S. Z. Chen[a], Y. Chen[r], A. Chiavassa[e], X. H. Cui[f], Z. G. Dai[g], D. della Volpe[b,*], T. Di Girolamo[j,k], Giuseppe Di Sciascio[u], Y. Z. Fan[h], J. Giacalone[i], Y. Q. Guo[a], H. H. He[a], T. L. He[f], M. Heller[b], D.Huang[l], Y. F.Huang[g], H. Jia[l], L.T. Ksenofontov[n], D. Leahy[o], F. Li[h], Z. Li[am,ag], E. W. Liang[p], P. Lipari[q], R. Y. Liu[r], Y. Liu[s], S. Liu[h], X. Ma[a], O. Martineau-Huynh[m], D. Martraire[a], T. Montaruli[b], D. Ruffolo[t], Y. V. Stenkin[v,w], H. Q. Su[f], T. Tam[x], Q. W. Tang[y], W. W. Tian[f], P. Vallania[z,aa], S. Vernetto[d], C. Vigorito[aa,ab], J. .C. Wang[ak], L. Z. Wang[f], X. Wang[ac], X. Y. Wang[r,g], X. J. Wang[l], Z. X. Wang[ai], D. M. Wei[h], J. J. Wei[h], D. Wu[f], H. R. Wu[a], X. F. Wu[h], D. H. Yan[ak], A. Y. Yang[f], R. Z. Yang[aj], Z. G. Yao[a], L. Q. Yin[a], Q. Yuan[h], Bing Zhang[ae,af,ag], B. Zhang[f], L. Zhang[al], M. F. Zhang[f], S. S. Zhang[a], X. Zhang[r], Yi Zhao[a,ah], X. X. Zhou[l], F. R. Zhu[ah], H. Zhu[f]

★ ***Commissioning of first quarter of the experiment started April 2019*** (sensitivity ≈HAWC):

- 22,500 m^2 water Cherenkov detector
- 1/4 scintillator array
- 6 WFCTA telescopes
- ≈ 300 muon detectors

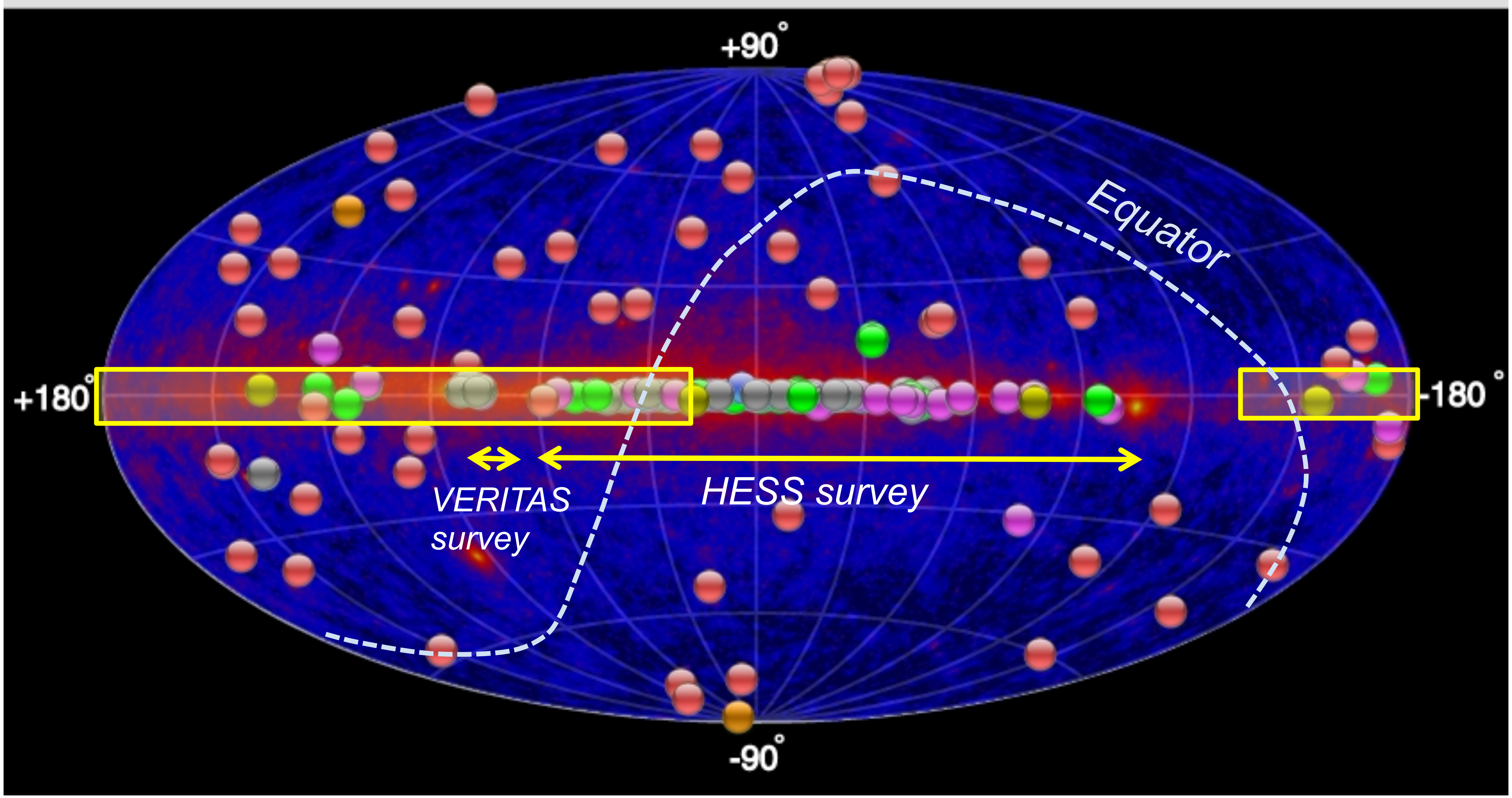
★ ***Completion of the installation by the end of 2021*.**

★ ***First Sky Map with sensitivity better than HAWC expected next year.***

Galactic Plane in the LHAASO field of view

Zenith angle < 40°

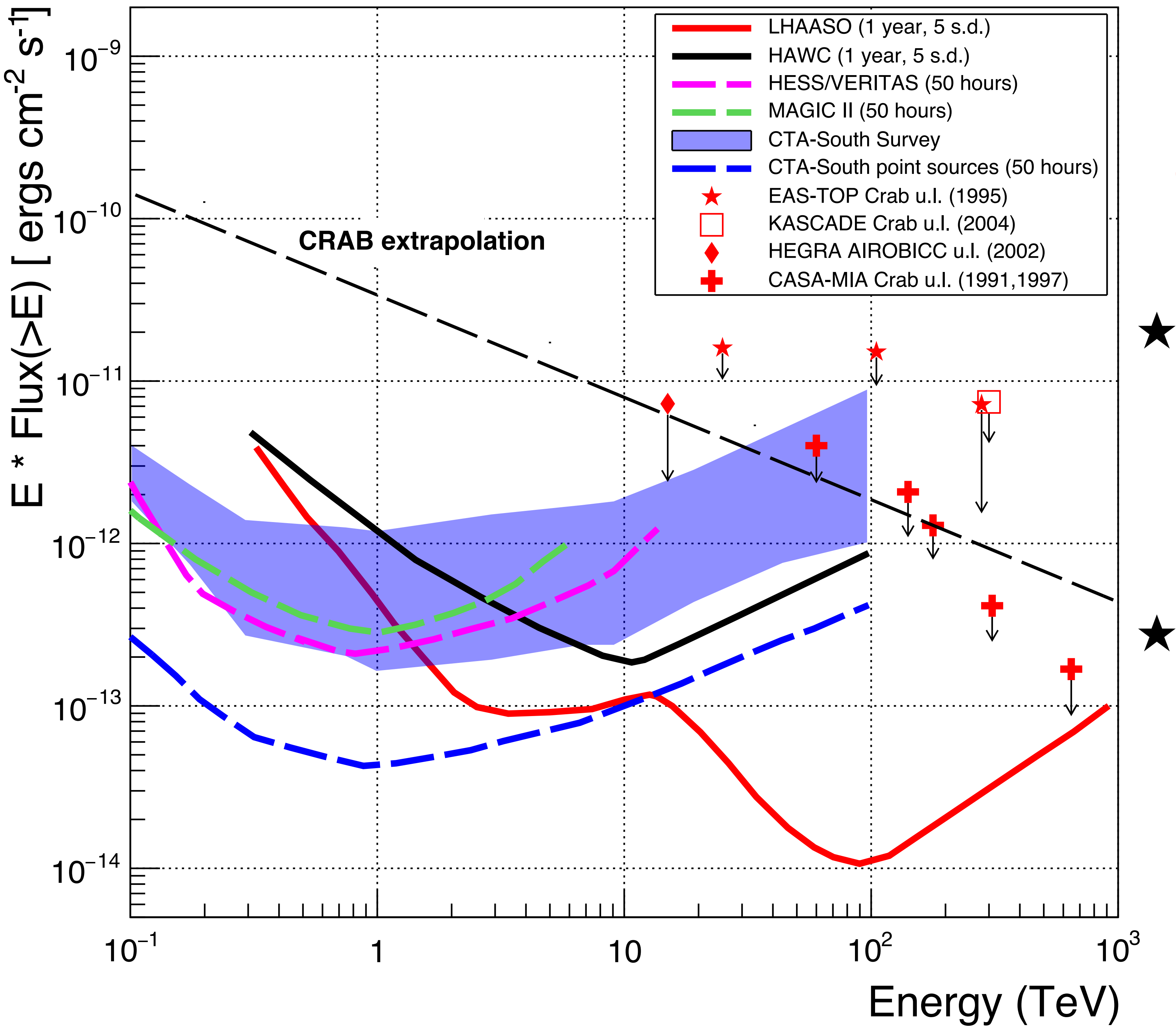
Visible Galactic Plane: l = 20° – 225°



TeV sources from TeVCat

HESS survey:	*l = 250°– 60°*	*|b| < 3.5°*
VERITAS survey:	*l = 67°– 82°*	*-1° < b < 4*

LHAASO integral sensitivity



EAS-array: 5 s.d. in 1 year

Cherenkov: 5 s.d. in 50 h *on source*

- ★ 1 year for EAS arrays means:

  (5 h × 365 d) ~1500 - 2200 of observation hours for each source (about 4-6 hours per day).

- ★ For Cherenkov:

  (5 h × 365 d) × d.c. (≈ 15%) ≈ 270 h/y for each source.

TeV sources in the LHAASO field of view

From TeVCat:

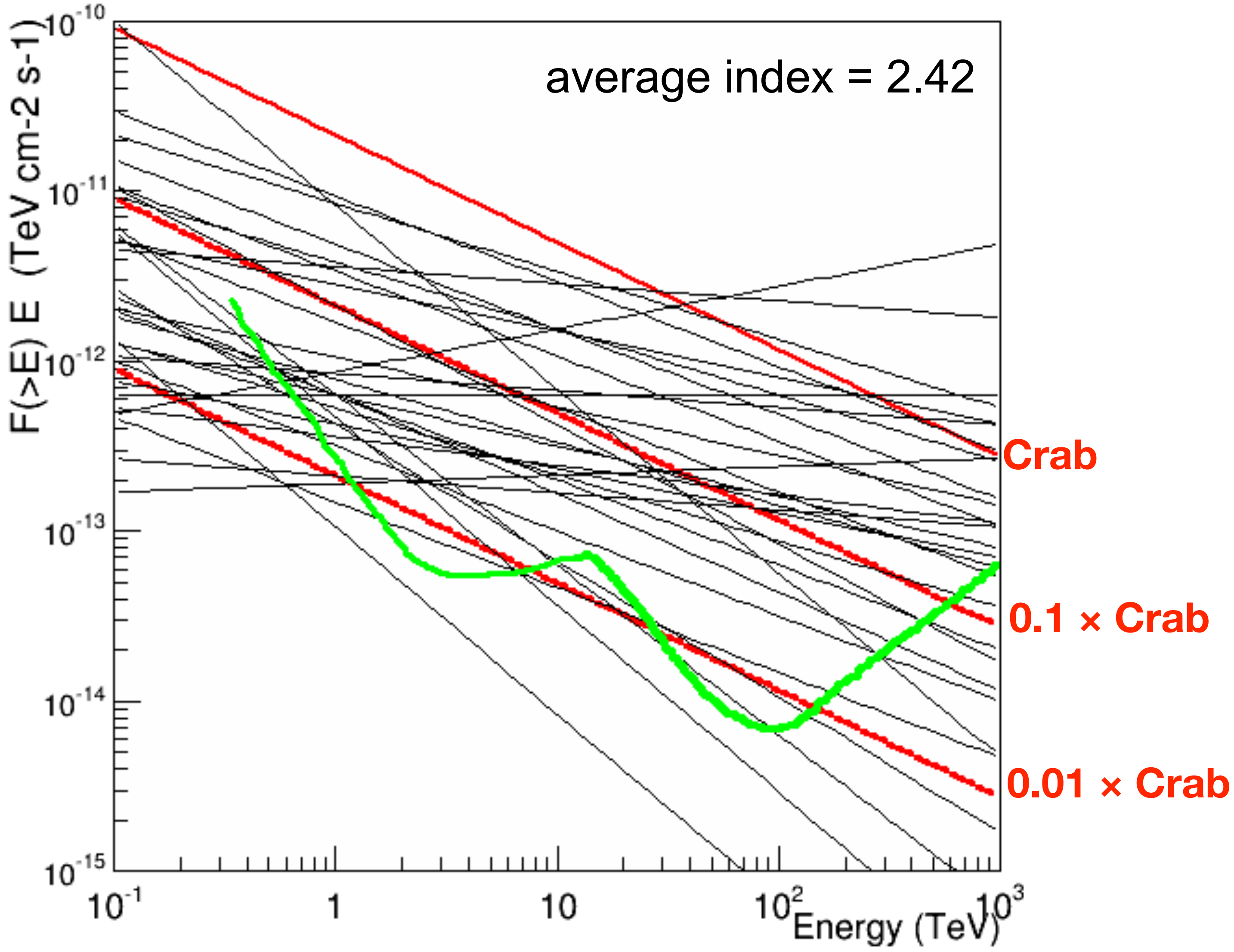
71 sources culminating at zenith angle < 40°

LHAASO latitude = *30° N*
-10° < decl < 70°

- 40 extragalactic
- 31 galactic

13 Unidentified
9 Pulsar Wind Nebulae
6 Shell Supernova Remnant
2 Binary System
1 Massive Star Cluster

Extrapolation of TeV spectra assuming no cutoff



70% of Galactic sources are extended

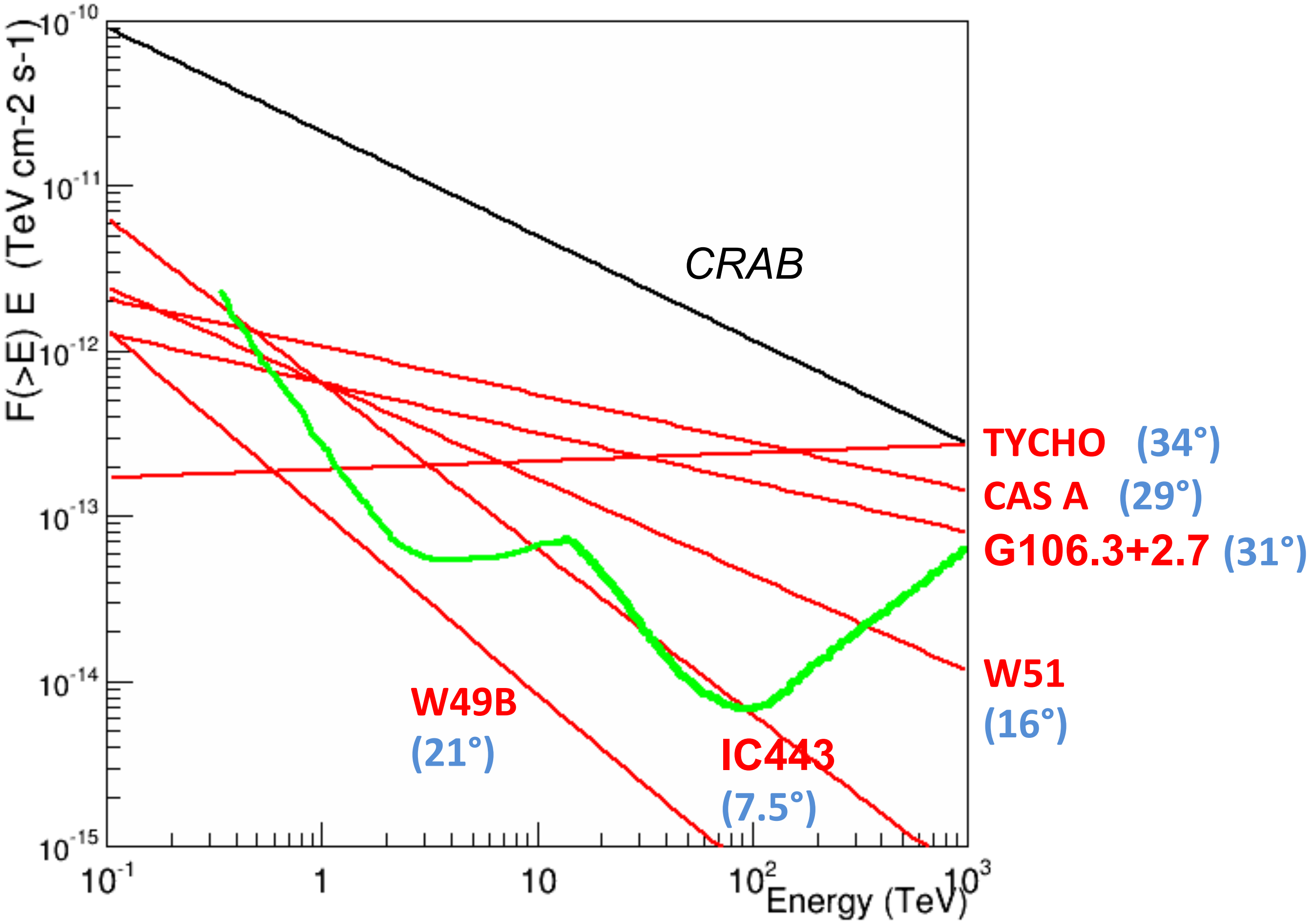
Probably the fluxes are higher then what measured by IACT

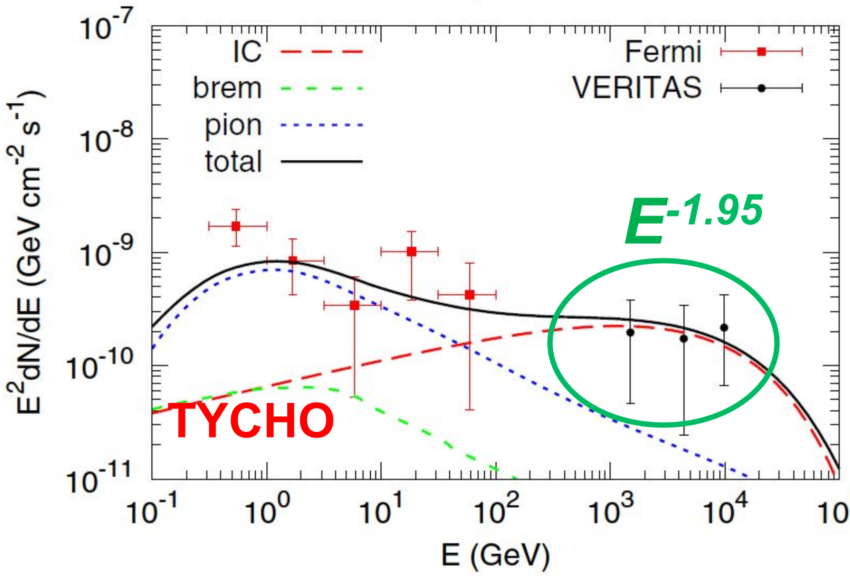
The real sensitivity depends on spectral slope, culmination angle and angular extension of the source

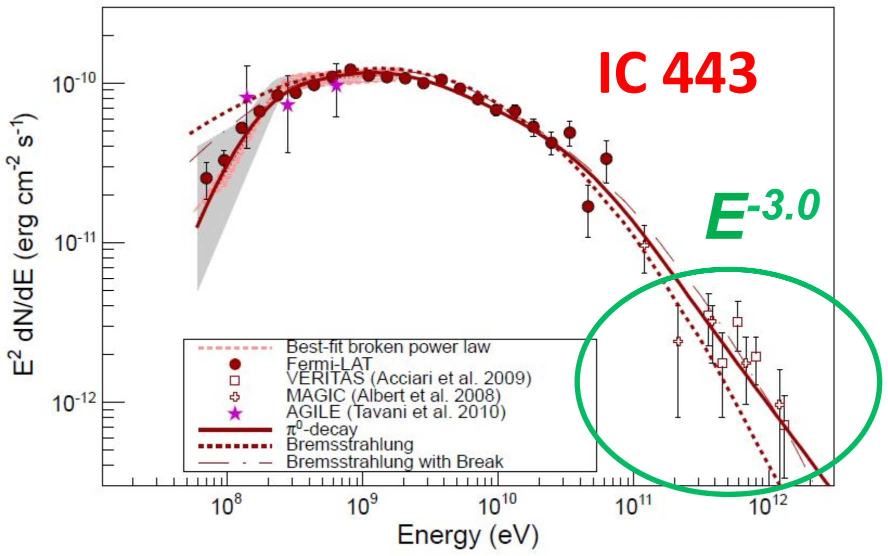
6 Shell SuperNova Remnants

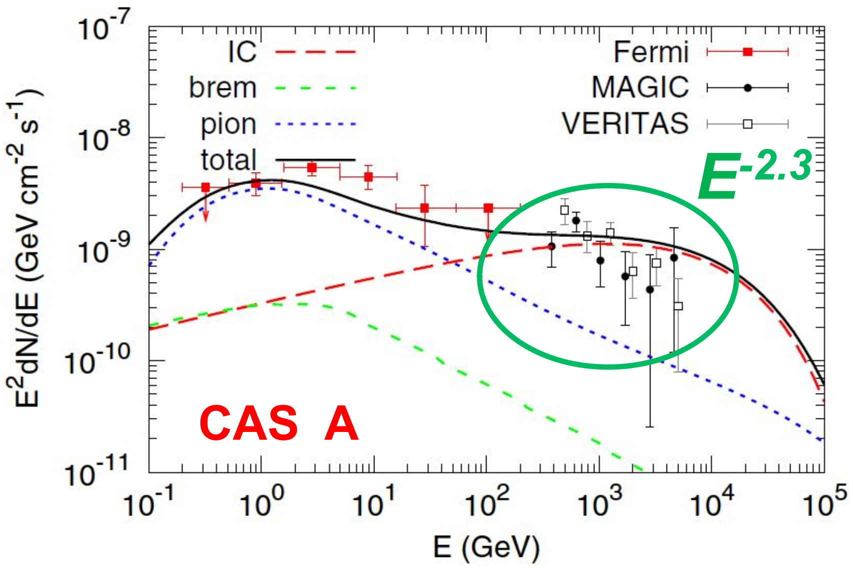
Source	Zenith angle culm.	F > 1 TeV (c.u.)	Energy range	Spectral index	Angular Extension (σ)
Thyco	34°	0.009	1-10	1.95	
G106.3+2.7	31°	0.03	1-20	2.29	0.3° x 0.2°
Cas A	29°	0.05	0.5-10	2.3	
W51	16°	0.03	0.1-5	2.58	0.12°
IC443	7.5°	0.03	0.1-2	3.0	0.16°
W49B	21°	0.005	0.3-10	3.1	

No cutoff observed in the 6 TeV spectra

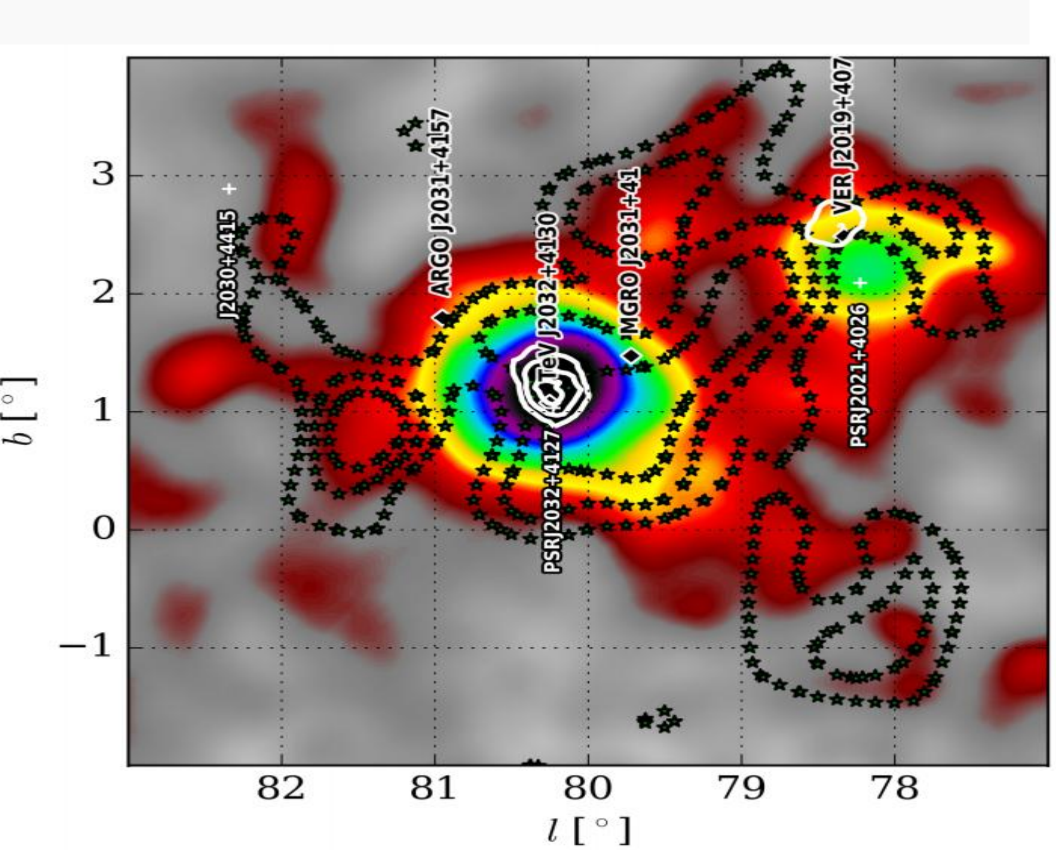




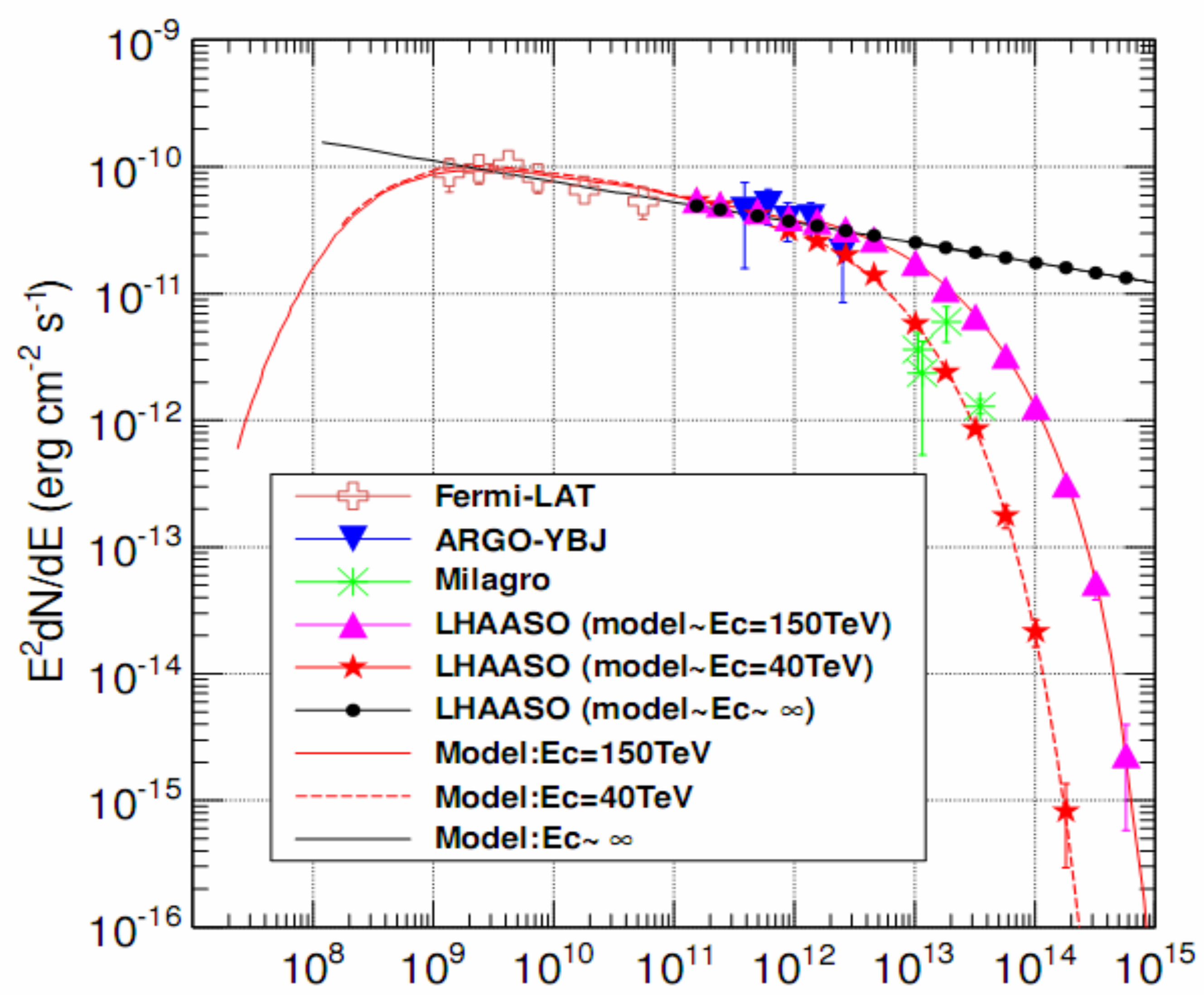




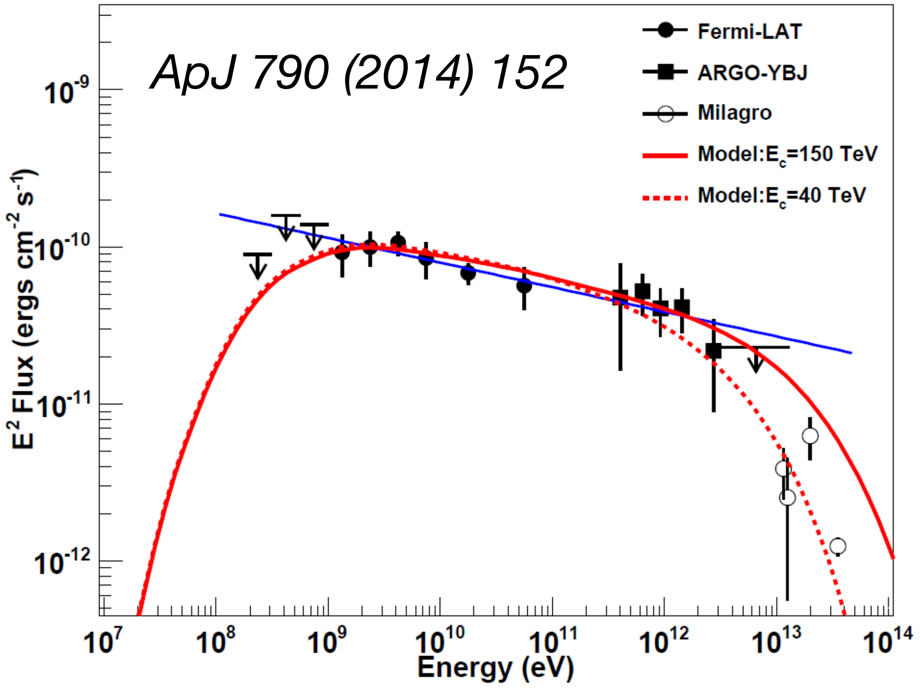
Cygnus Cocoon



Counterpart of Cygnus Cocoon at TeV energies discovered by ARGO-YBJ (ARGO J2031+4157)



Z. Cao, WASDHA 2018



ApJ 790 (2014) 152

Spectrum of ARGO J2031+4157: $dN/dE \propto E^{-2.62\pm0.27}$

Combined Fermi-LAT&ARGO spectrum: $dN/dE \propto E^{-2.16\pm0.04}$

What's Next ? Beyond HAWC/LHAASO

In the next decade CTA-North and LHAASO are expected to be the most sensitive instruments to study γ-ray astronomy in the *Northern Hemisphere from ≈20 GeV up to PeV.*

Southern Hemisphere

- *An all-sky detector in the Southern Hemisphere should be a high priority* to face a broad range of topics.

- Discovering rare transient events requires full sky coverage and very low energy threshold (100 GeV range): *transient factory*
- GRB finder for Advanced LIGO, which will detect all neutron binary coalescence with $z < 0.5$
- AGN flares & GRBs as distant probes of high energy physics (e.g. Lorentz invariance and axions)
- Survey of the *Inner Galaxy* and *Galactic Center*
- TeV Source finder for CTA south

Scientific requirements

A future Wide FoV Observatory *to be useful (to CTA)* needs:

- *Low energy threshold* (≈ 100 GeV) to detect extragalactic transient (AGN, GRBs).
- *Angular resolution ≈ 1°* at the threshold for survey of Inner Galaxy (source confusion).
- *<10% Crab sensitivity below TeV* to have *high exposure for flaring activity.*
- Good energy resolution above 10 TeV to detect spectral cut-offs
- Background discrimination capability at level of *10^{-5} (!!!) in the 100 TeV range* to observe *the knee in the energy spectrum of the gamma diffuse emission* in different regions of the GP.

★ *Is this possible ?*

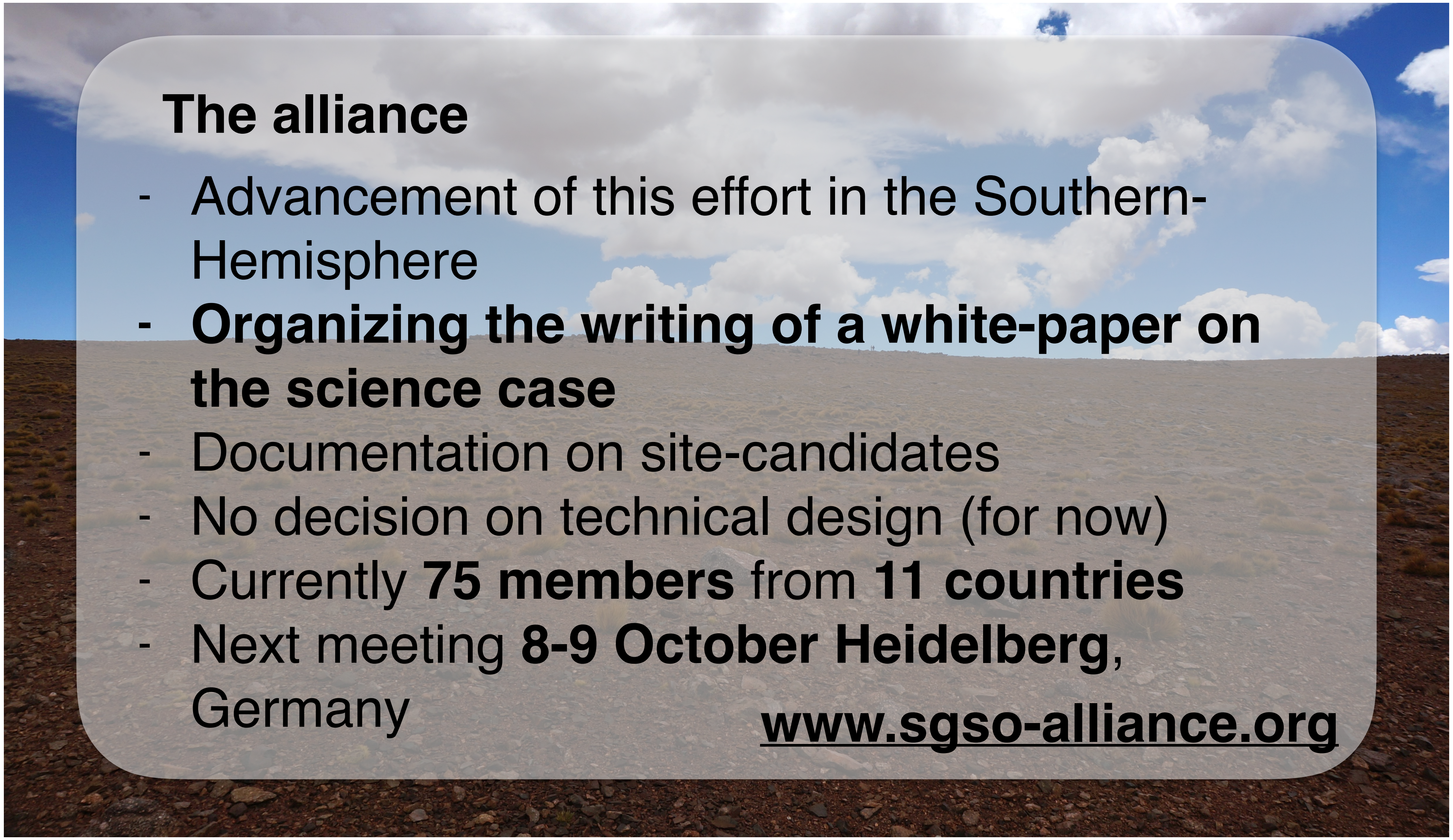
Physical limits mainly due to the detection technique !

Southern Gamma-Ray Survey Observatory

SOUTHERN
GAMMA-RAY
SURVEY
OBSERVATORY

Who are we?…

H. Schoorlemmer
Recontres du Vietnam 2018

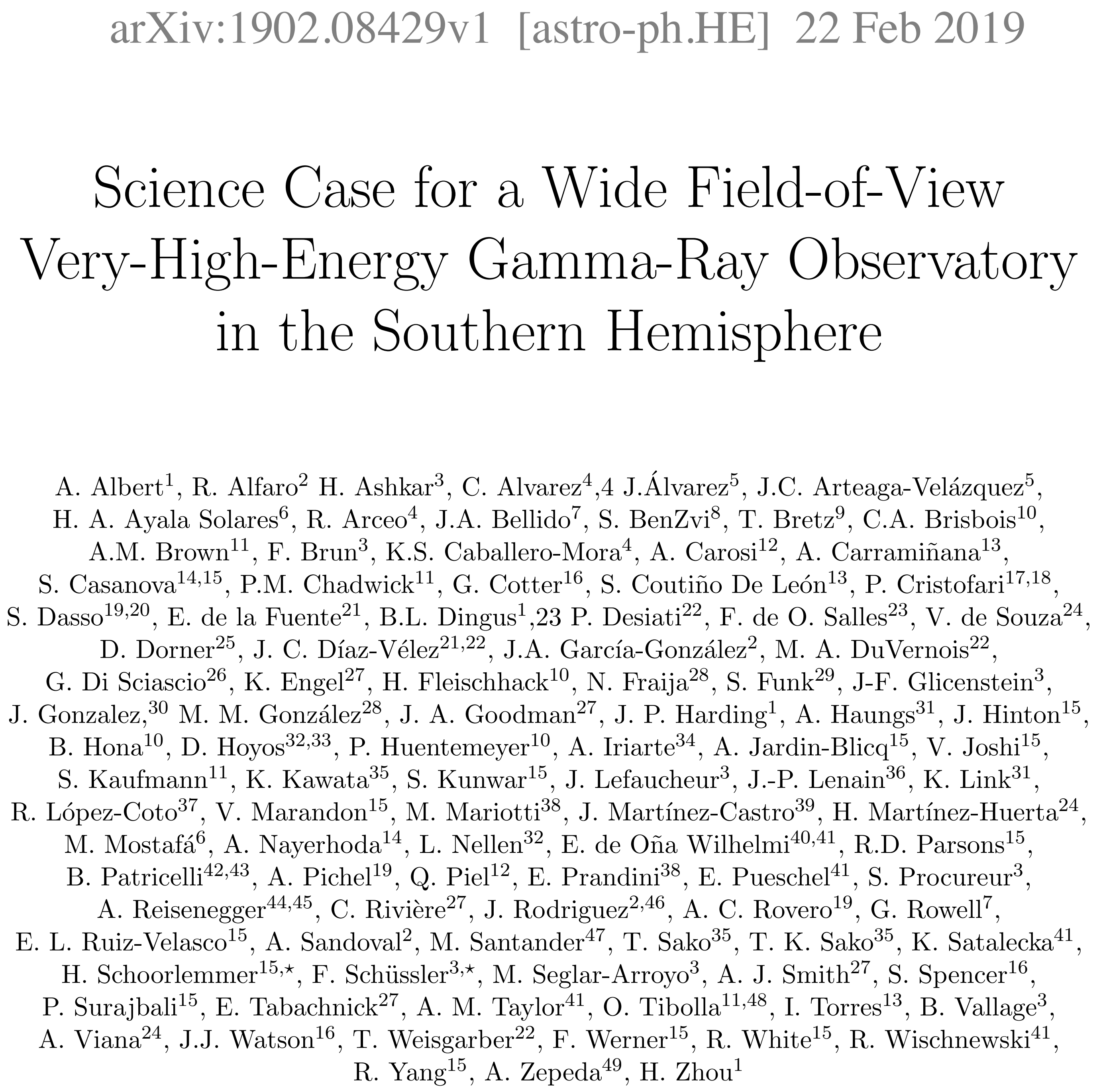


The alliance

- Advancement of this effort in the Southern-Hemisphere
- **Organizing the writing of a white-paper on the science case**
- Documentation on site-candidates
- No decision on technical design (for now)
- Currently **75 members** from **11 countries**
- Next meeting **8-9 October Heidelberg**, Germany

www.sgso-alliance.org

Science Case White Paper by SGSO



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Science Case for a Wide Field-of-View Very-High-Energy Gamma-Ray Observatory in the Southern Hemisphere

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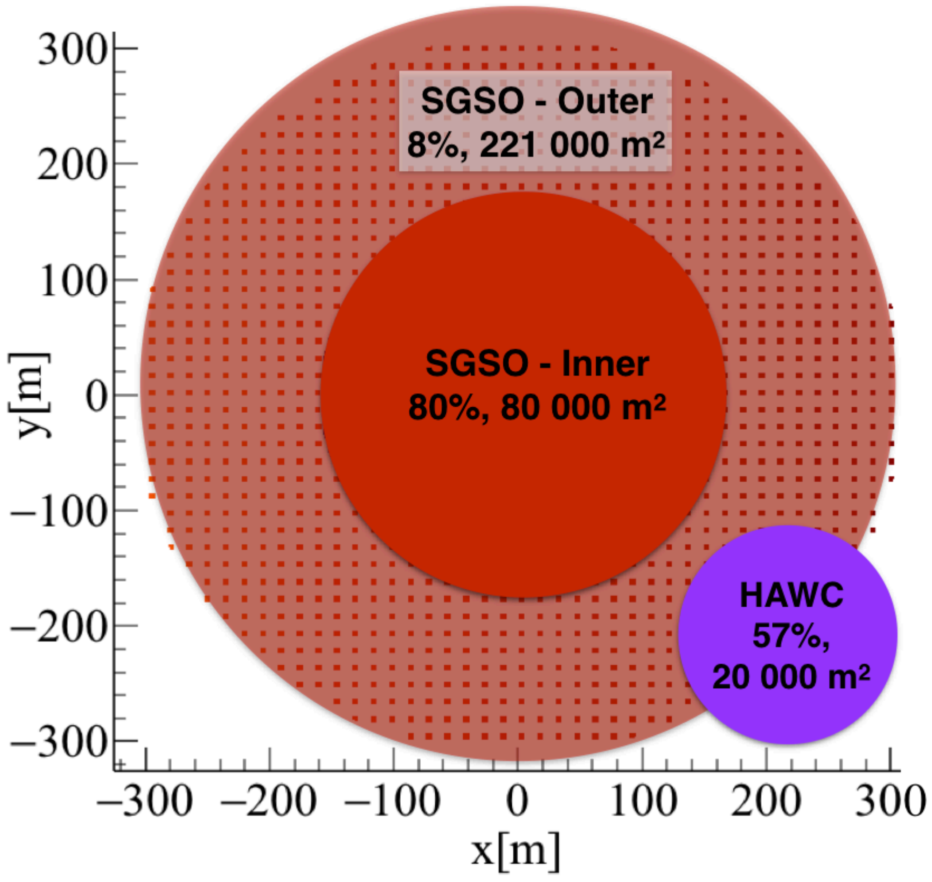
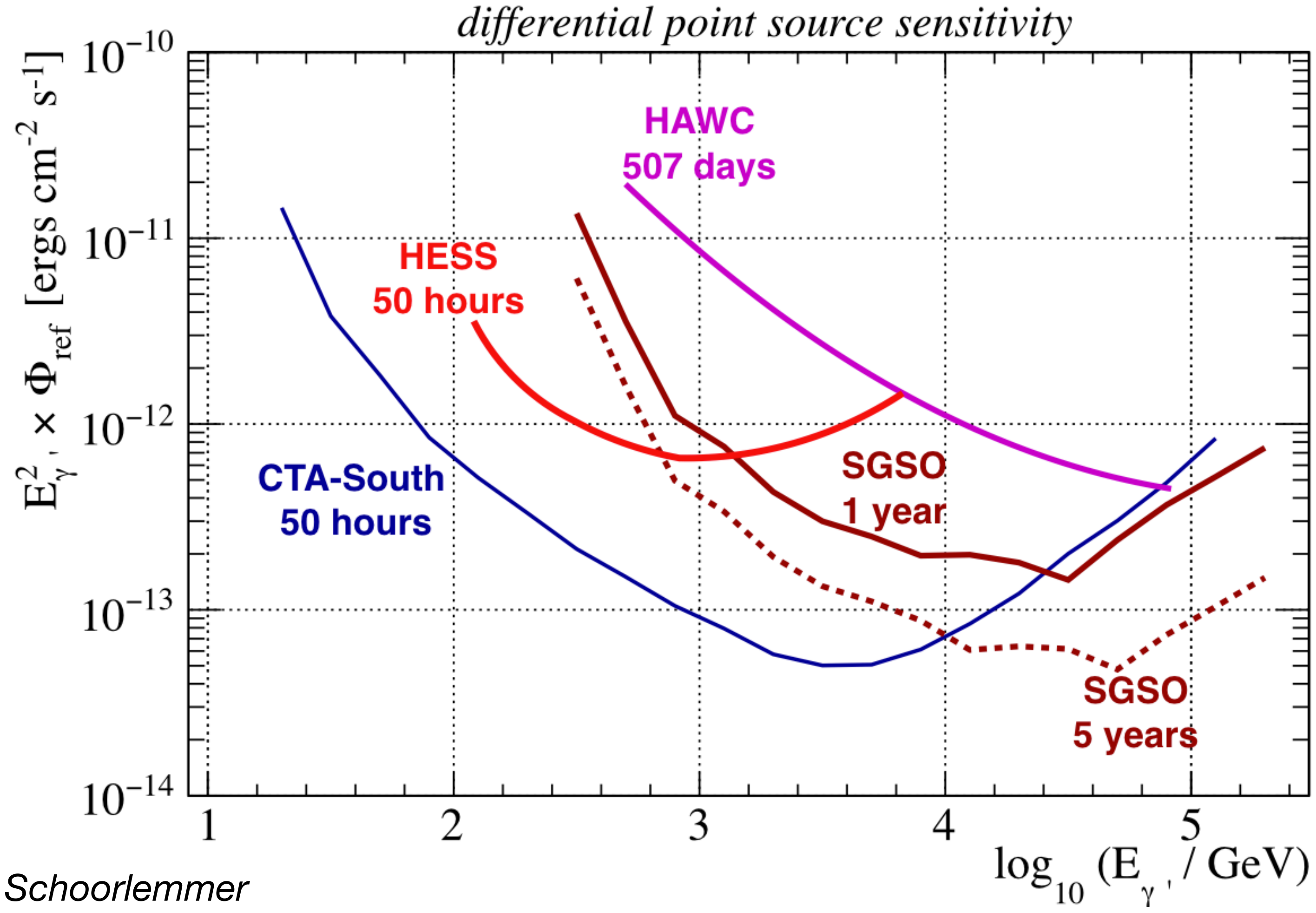
A straw mans design: point source sensitivity

Final layout in next 3 years

Size & Fill factor





H. Schoorlemmer
Recontres du Vietnam 2018

5 km above sea level

HAWC-based layout

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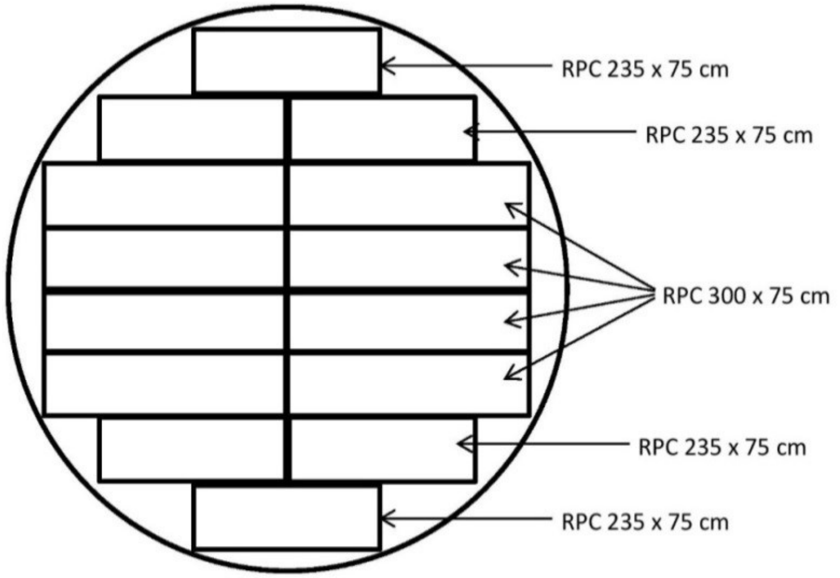
STACEX: γ-ray astronomy in the South

Southern TeV Astrophysics and Cosmic rays Experiment



STACEX proposal combines in a hybrid detector both approaches so far used in survey instruments

- Water Cherenkov technique HAWC/LHAASO - like
- RPC technique ARGO-like

Two experimental techniques operated for many years at high altitude

Benefit of Water Cherenkov:

✦ Gamma/Hadron discrimination above TeV at distances > 40 m from the core

Benefit of RPCs:

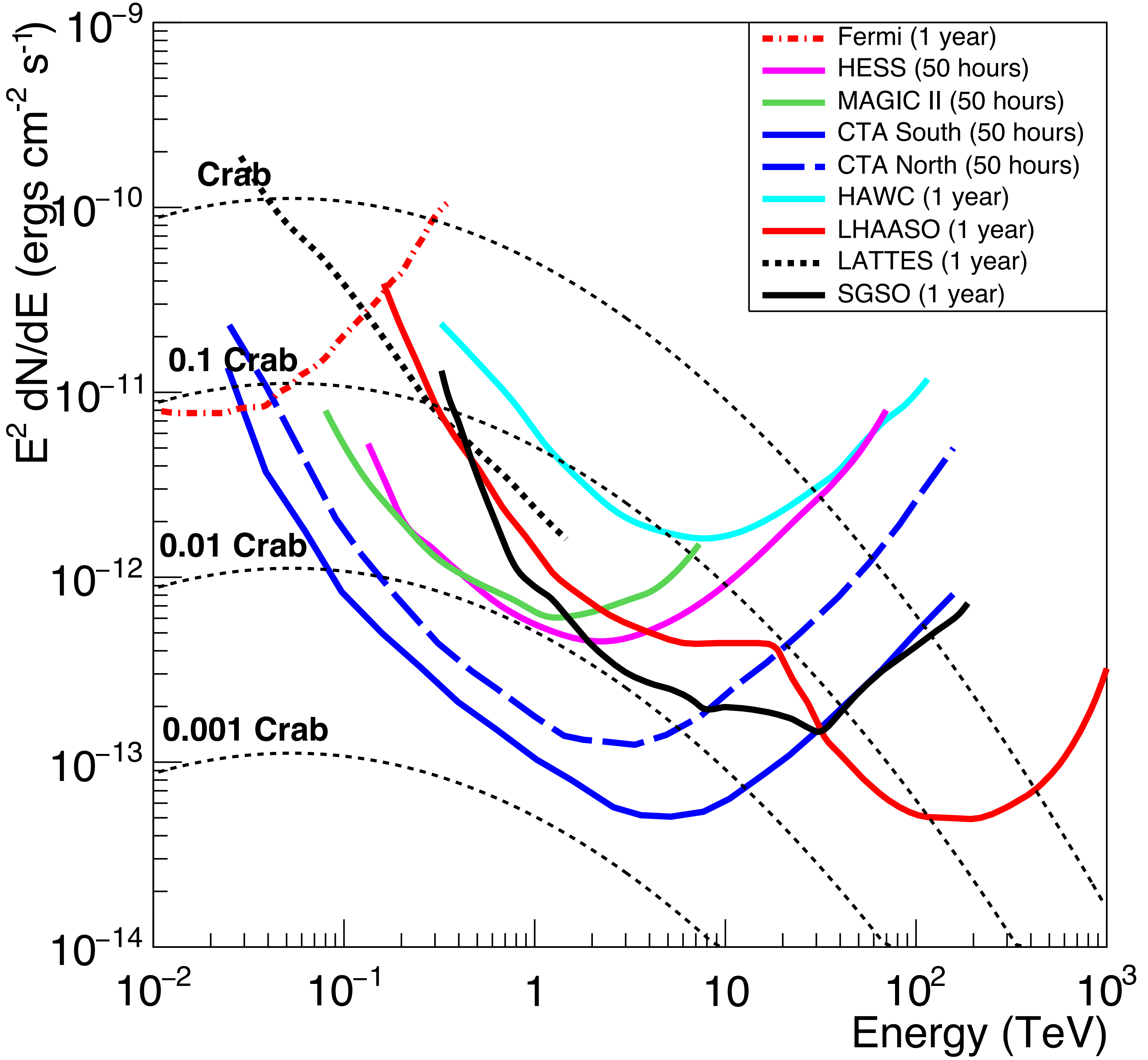
✦ Full coverage and high granularity of the read-out (*very low energy threshold*)

✦ *Better energy resolution*, in particular above 10 TeV (10% at 50 TeV)

✦ *Wide energy range* (100 GeV → 300 TeV, with only digital readout)

✦ *Elemental composition* up to ≈10 PeV (with charge readout)

Point source sensitivity



Conclusions

Open problems in cosmic ray physics push the construction of new generation Wide FoV experiments.

In the next decade CTA-North and LHAASO are expected to be the most sensitive instruments to study γ-ray astronomy in the Northern hemisphere from ≈20 GeV up to PeV.

- *An all-sky detector in the Southern Hemisphere should be a high priority* to face a broad range of topics.
- Extragalactic transient detection requires *low threshold, ≈100 GeV*.
- *Extreme altitude* (≈5000 m asl), *high coverage* and *high granularity of the read-out* are key.
- *Background rejection below TeV challenging* ➜ *RPCs + Water Cherenkov ?*
- *Selection of primary masses* crucial ➜ *RPCs + Water Cherenkov ?*
- Capability of Water Cherenkov Facilities in selecting primary masses at the knee must be investigated.
- Different groups are studying different experimental solutions (ALPACA, ALTO, LATTES, STACEX)