LHAASO: a new generation EAS array

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"Multimessenger high energy astrophysics in the era of LHAASO"
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LHAASO: from γ-Ray Astronomy to Cosmic Rays

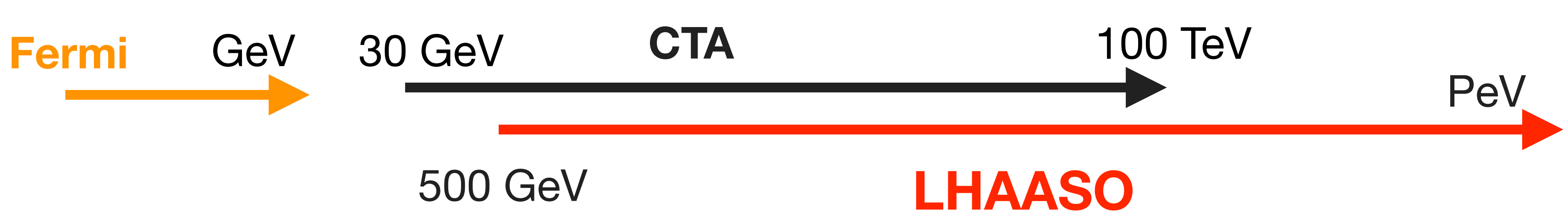
LHAASO (Large High Altitude Air Shower Observatory) is an experiment able of acting simultaneously as a Cosmic Ray Detector and a Gamma Ray Telescope

✤ Cosmic Ray Physics ($10^{12} \rightarrow 10^{18}$ eV): precluded to Cherenkov Telescopes

- CR energy spectrum
- Elemental composition
- Anisotropy

✤ Gamma-Ray Astronomy ($10^{11} \rightarrow 10^{15}$ eV): full sky continuous monitoring

- Complementary with CTA below 20 TeV, with better sensitivity at higher energies and for flaring emission (GRBs), unbiased all-sky survey, extended and diffuse emission.
- Searching for *PeVatrons* (→ neutrino sources)



The LHAASO experiment

LHAASO will exploit

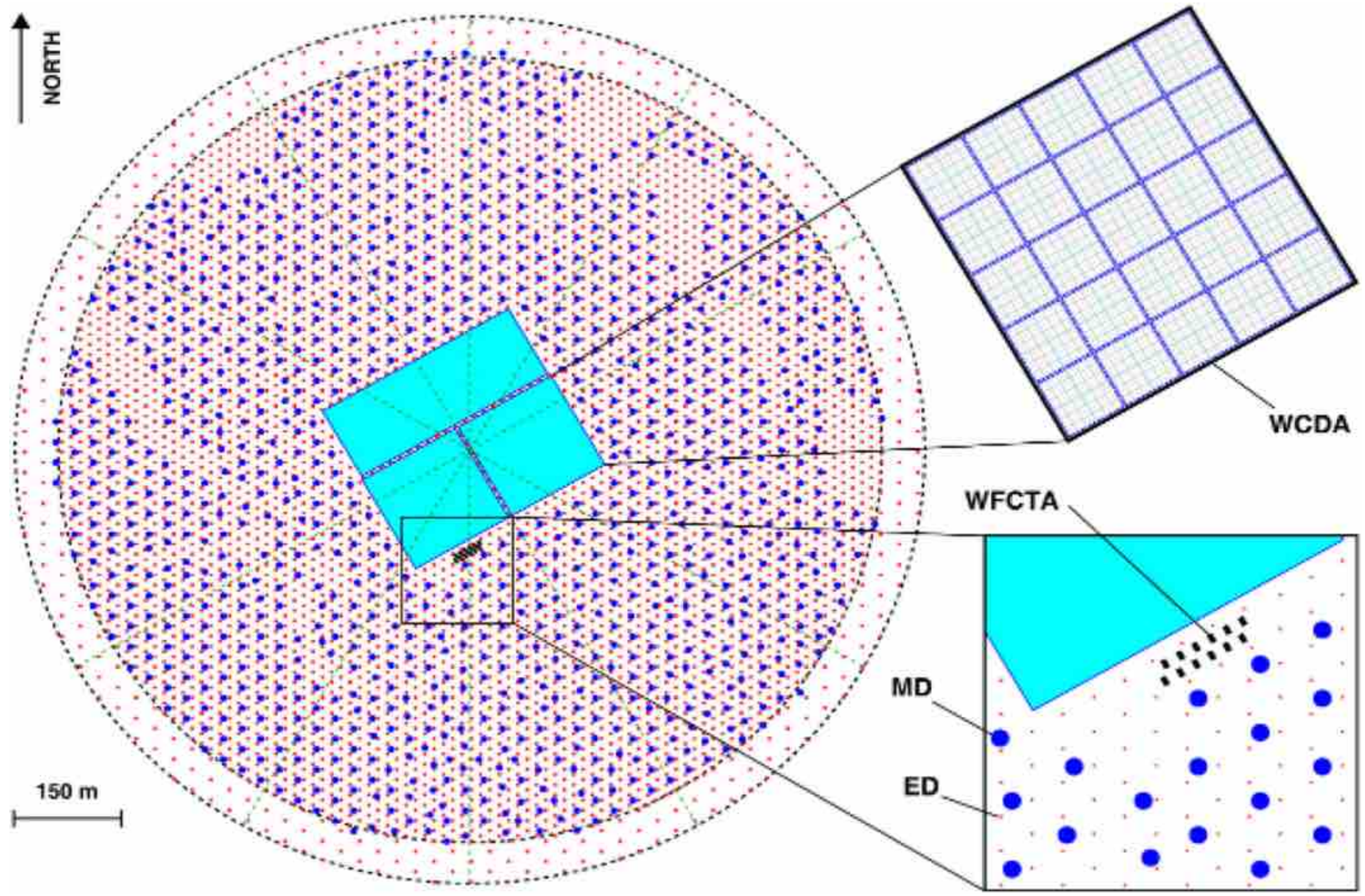
1. *Traditional scheme and detectors*: dense scintillator array overimposed to an array of underground water tanks for muon detection. Water Cherenkov ponds, Cherenkov/Fluorescence Telescopes

2. *Large implementation*: 1.3 km^2 array, about 40,000 m^2 muon detector sensitive area, about 80,000 m^2 water Cherenkov detector facility

3. *Modern and sophisticated technology*: SiPM, White Rabbit, …

LHAASO layout

- *1.3 km² array*, including *5195 scintillator* detectors 1 m² each, with 15 m spacing.
- An overlapping *1 km² array* of *1171*, underground water Cherenkov tanks 36 m² each, with 30 m spacing, for *muon detection* (total sensitive area ≈ *42,000 m²*).



- A close-packed, surface *water Cherenkov detector* facility with a total area of *80,000 m²*.
- 12 wide field-of-view air Cherenkov (and fluorescence) telescopes.
- Neutron detectors

LHAASO vs other EAS arrays

Experiment	g/cm^2	Detector	ΔE (eV)	e.m. Sensitive Area (m^2)	Instrumented Area (m^2)	Coverage
ARGO-YBJ	606	RPC/hybrid	$3 \cdot 10^{11} - 10^{16}$	6700	11,000	0.93 (central carpet)
BASJE-MAS	550	scint./muon	$6 \cdot 10^{12} - 3.5 \cdot 10^{16}$		10^4	
TIBET ASγ	606	scint./burst det.	$5 \cdot 10^{13} - 10^{17}$	380	3.7×10^4	10^{-2}
CASA-MIA	860	scint./muon	$10^{14} - 3.5 \cdot 10^{16}$	1.6×10^3	2.3×10^5	7×10^{-3}
KASCADE	1020	scint./mu/had	$2 - 90 \cdot 10^{15}$	5×10^2	4×10^4	1.2×10^{-2}
KASCADE-Grande	1020	scint./mu/had	$10^{16} - 10^{18}$	370	5×10^5	7×10^{-4}
Tunka	900	open Cher. det.	$3\cdot10^{15} - 3 \cdot 10^{18}$	-	10^6	-
IceTop	680	ice Cher. det.	$10^{16} - 10^{18}$	4.2×10^2	10^6	4×10^{-4}
LHAASO	600	Water C scintill/muon/hadron Wide FoV Cher. Tel.	$10^{12} - 10^{17}$	5.2×10^3	1.3×10^6	4×10^{-3}

Muon detectors

Experiment	m asl	μ Sensitive Area (m^2)	Instrumented Area (m^2)	Coverage
LHAASO (✦)	4410	4.2×10^4	10^6	4.4×10^{-2}
TIBET ASγ	4300	4.5×10^3	3.7×10^4	1.2×10^{-1}
KASCADE	110	6×10^2	4×10^4	1.5×10^{-2}
CASA-MIA	1450	2.5×10^3	2.3×10^5	1.1×10^{-2}

(✦) *Total Muon detector area:* 4.2 x 10^4 m^2 + 8 x 10^4 m^2 (WCDA) ≈ 10^5 m^2 !!!

Caveat

1. The informations contained in this talk refer to official and published calculations that the LHAASO collaboration used to evaluate the well-known sensitivity curve.

2. New calculations are under way with the actual experimental configuration and new reconstruction algorithms. *Important improvements will be published soon.*

3. In this talk I will focus on the performance in *gamma-ray astronomy*, therefore I will introduce the performance of WCDA and KM2A apparata.

Sensitivity to a γ-ray point source

Sensitivity in 1 year

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

σ_θ = angular resolution

Φ_{bkg} = background integral flux

Φ_γ = photon integral flux

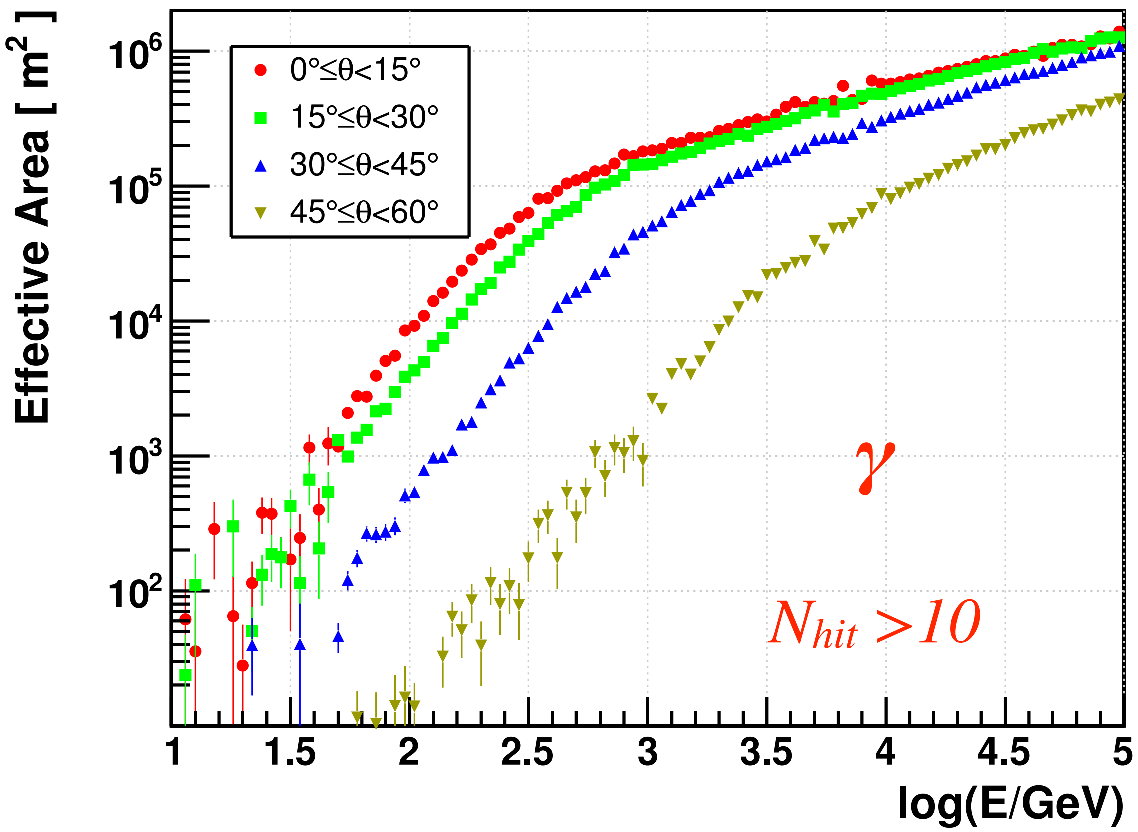
$$R = \sqrt{\frac{A_{eff}^{\gamma}}{A_{eff}^{bkg}}}$$

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

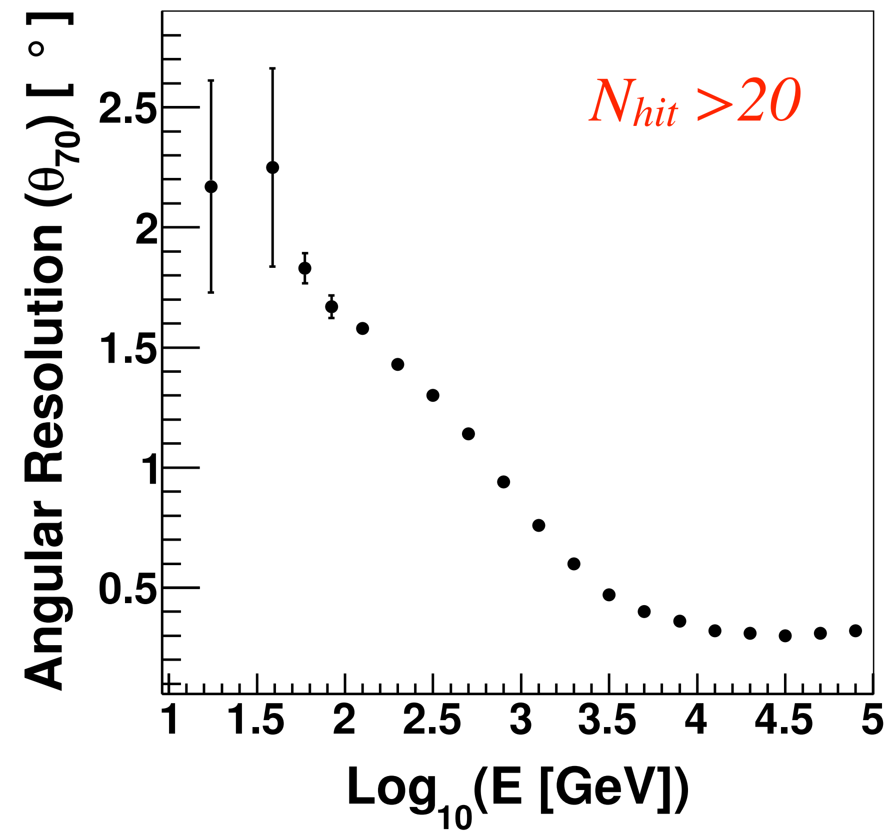
Minimum Detectable Gamma-Ray Flux (1 year):

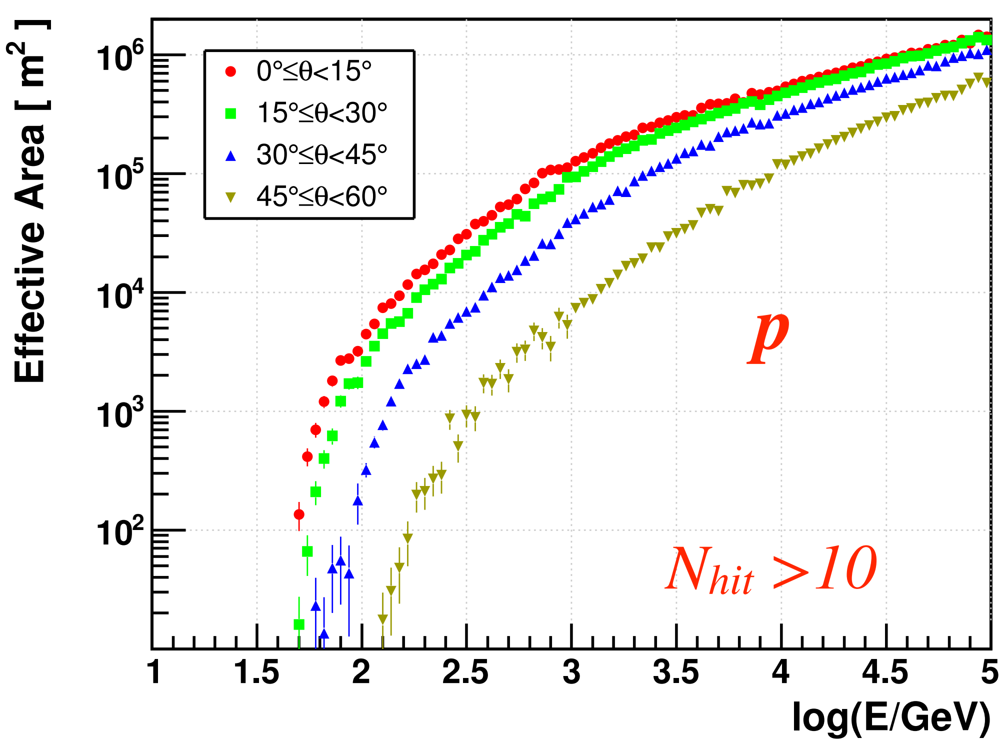
$$\Phi_\gamma^{MDF} \propto \sqrt{\Phi_{bkg}} \cdot \frac{1}{R \cdot \sqrt{A_{eff}^{\gamma}}} \cdot \sigma_\theta \cdot \frac{1}{Q}$$

WCDA performance - 1



X. Bai et al., arXiv:1905.02773





The angular resolution is *≈ 0.3° above 10 TeV*

The core resolution *≈ 4 m above 1000 hits*

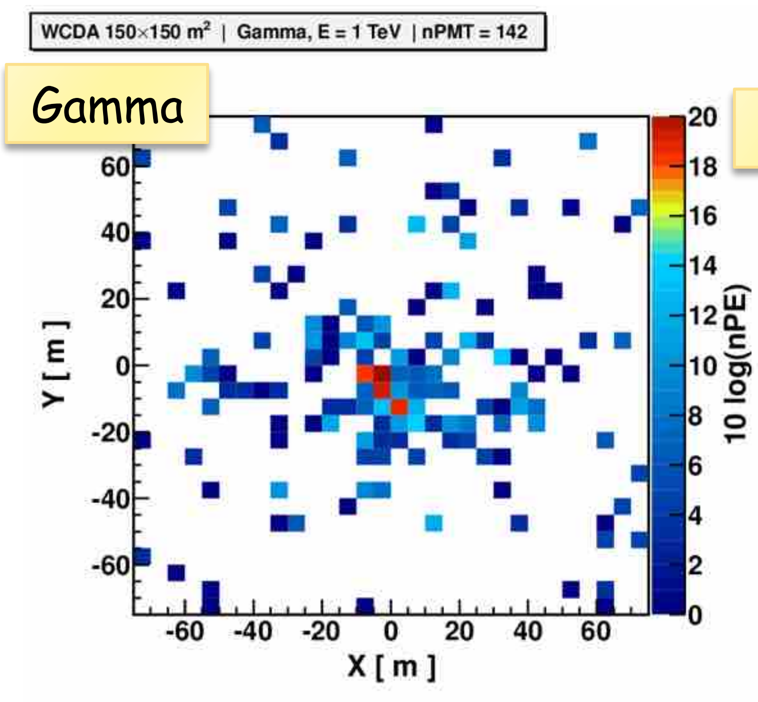
Effective Area (vertical events):

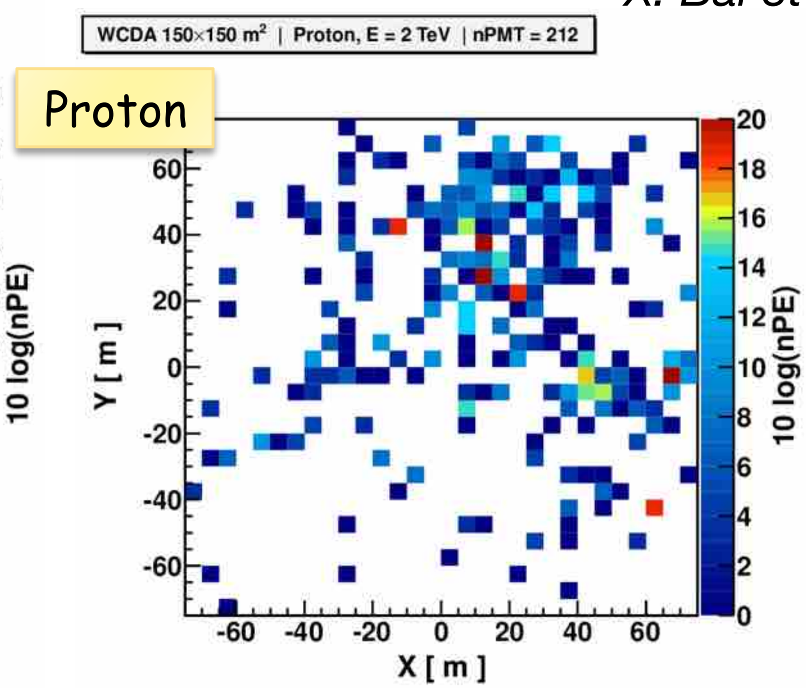
≈ 10^4 m^2 at 100 GeV

≈10^5 m^2 at 1 TeV

≈10^6 m^2 at 1 PeV

WCDA performance - 2





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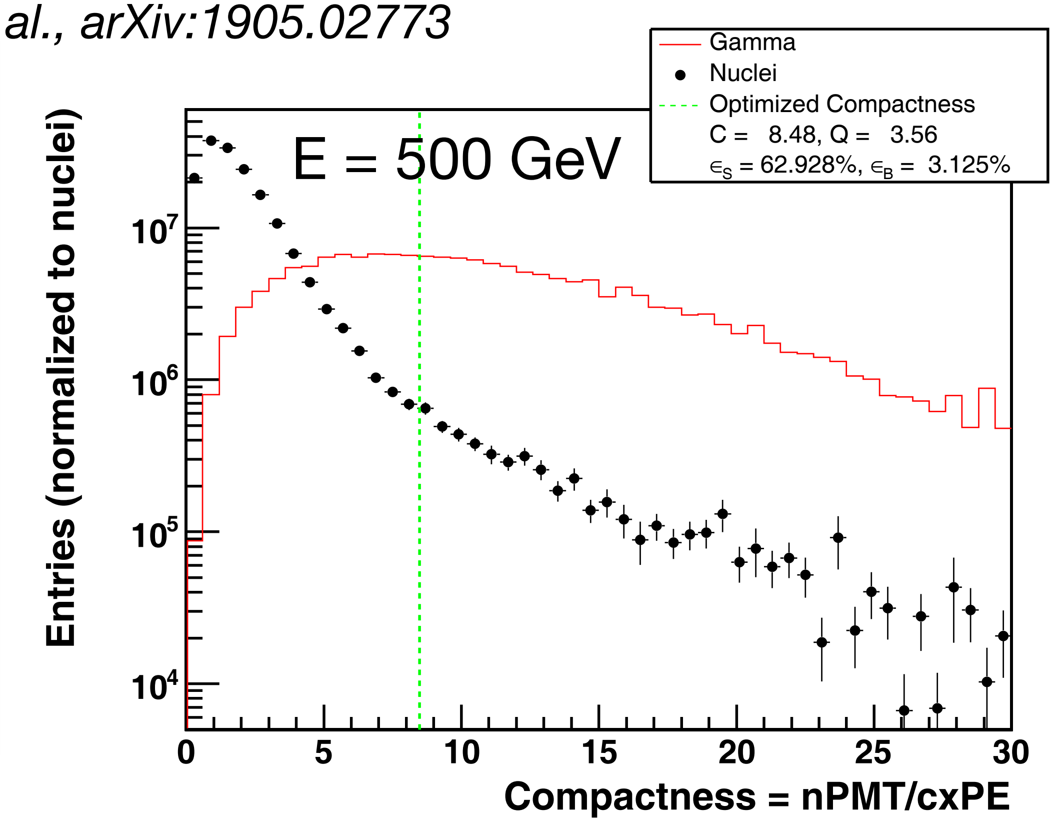
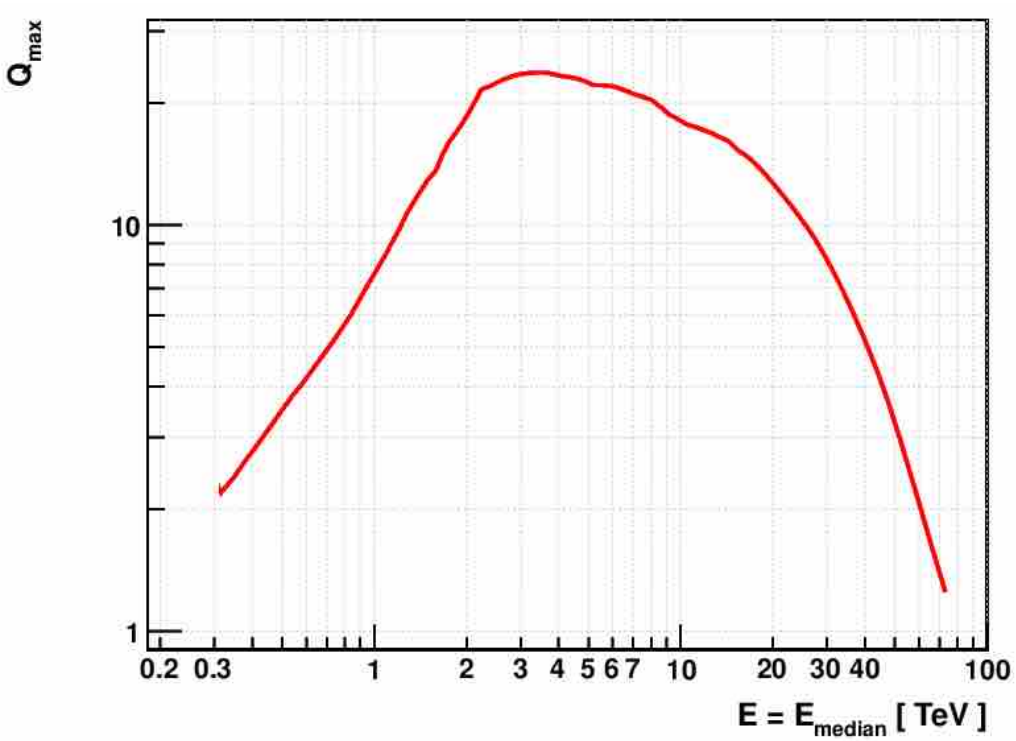


Q-factor: 3 at 500 GeV, 7 at 1 TeV, 22 at 5 TeV.



Hadronic showers are identified through the pattern of energy deposition in the detector

Brightest "sub-core":

- Signal of the brightest PMT *outside the shower core region* (e.g., 40 m).

Shower "Compactness" to reject cosmic ray background:

C = Nhit/PE40, where Nhit is the number of PMTs fired in an event and PE40 is the total number of photo-electrons in the PMT with the largest signal that is located outside a radius of 40 m from the reconstructed shower core.

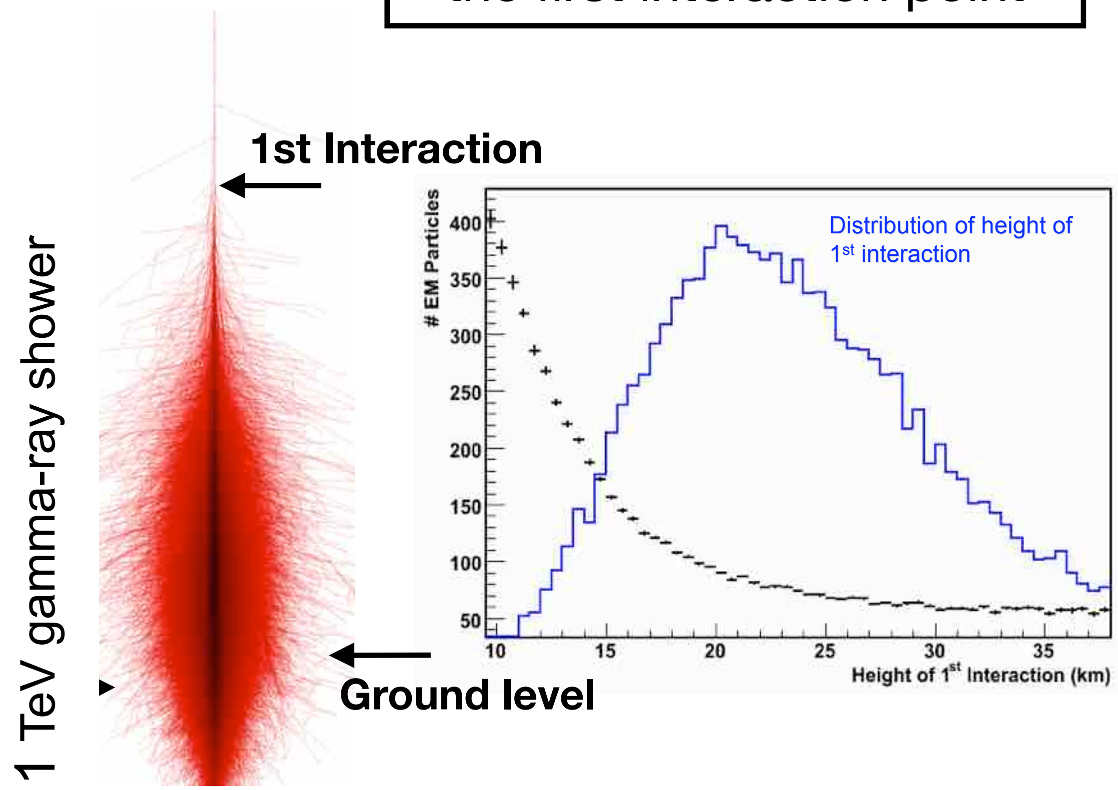
WCDA - Energy resolution

The energy resolution is given by the folding of

Shower fluctuations
Fluctuations in the depth of the first interaction point

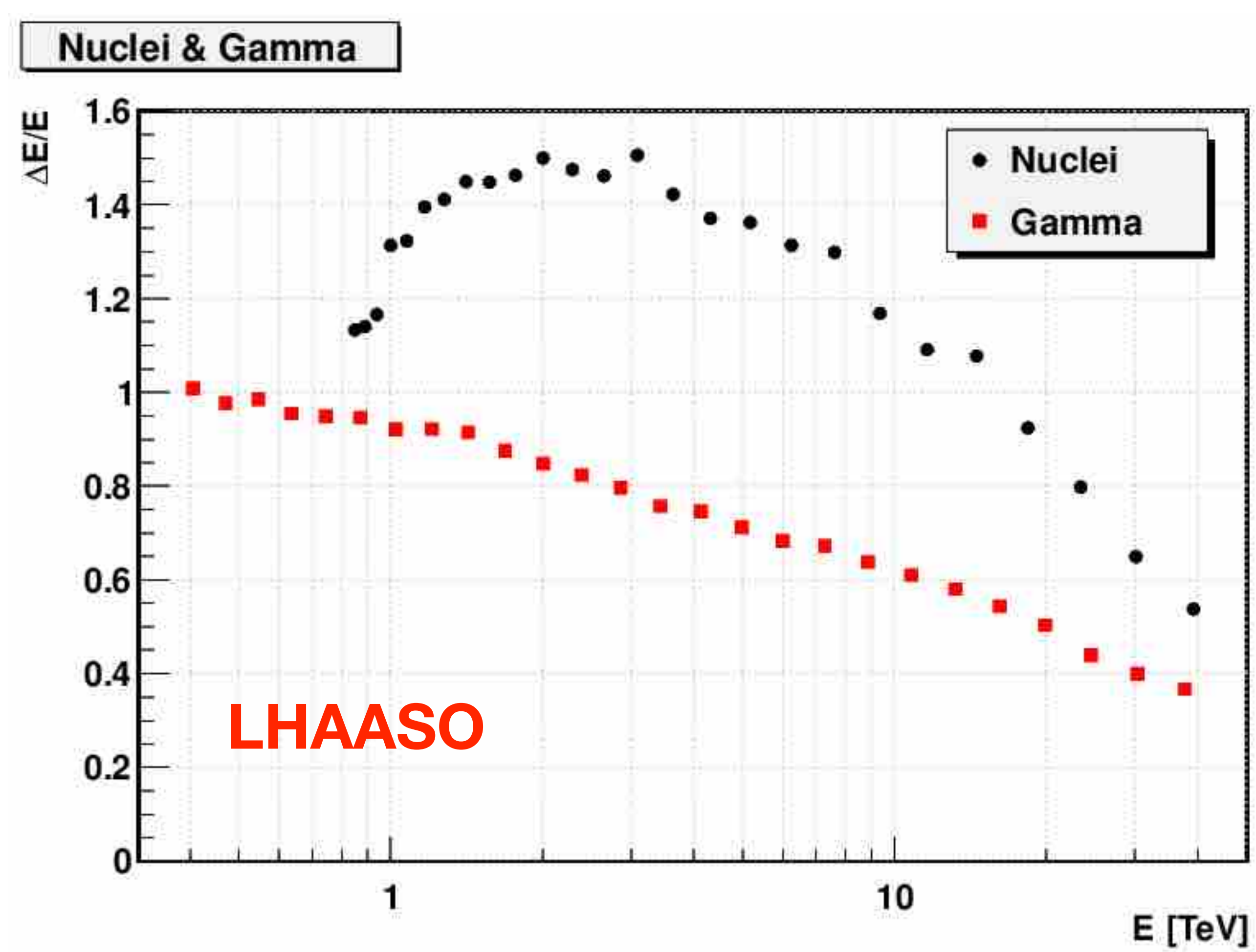
⊕

Sampling fluctuations
Fluctuations in the measured number of secondary particles



Shower fluctuations dominate energy resolution of EAS arrays.

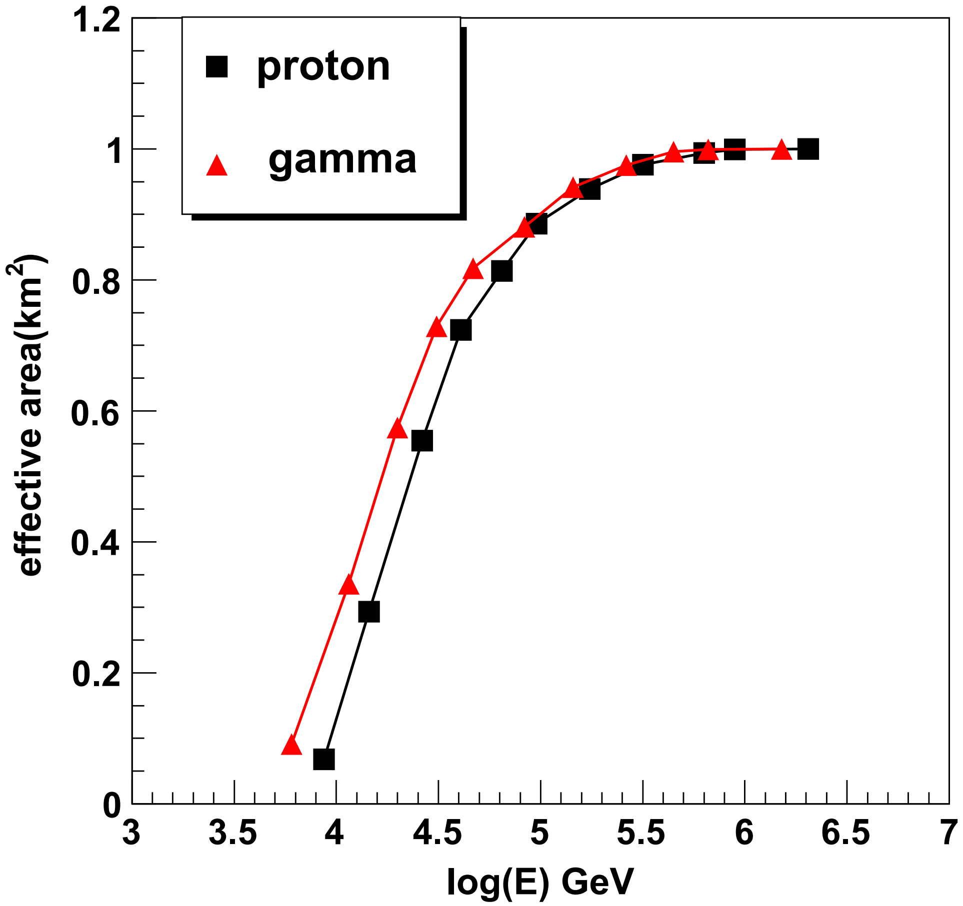
IACT: 8% - 15% at 1 TeV
IACT: 15% - 35% at 50 TeV



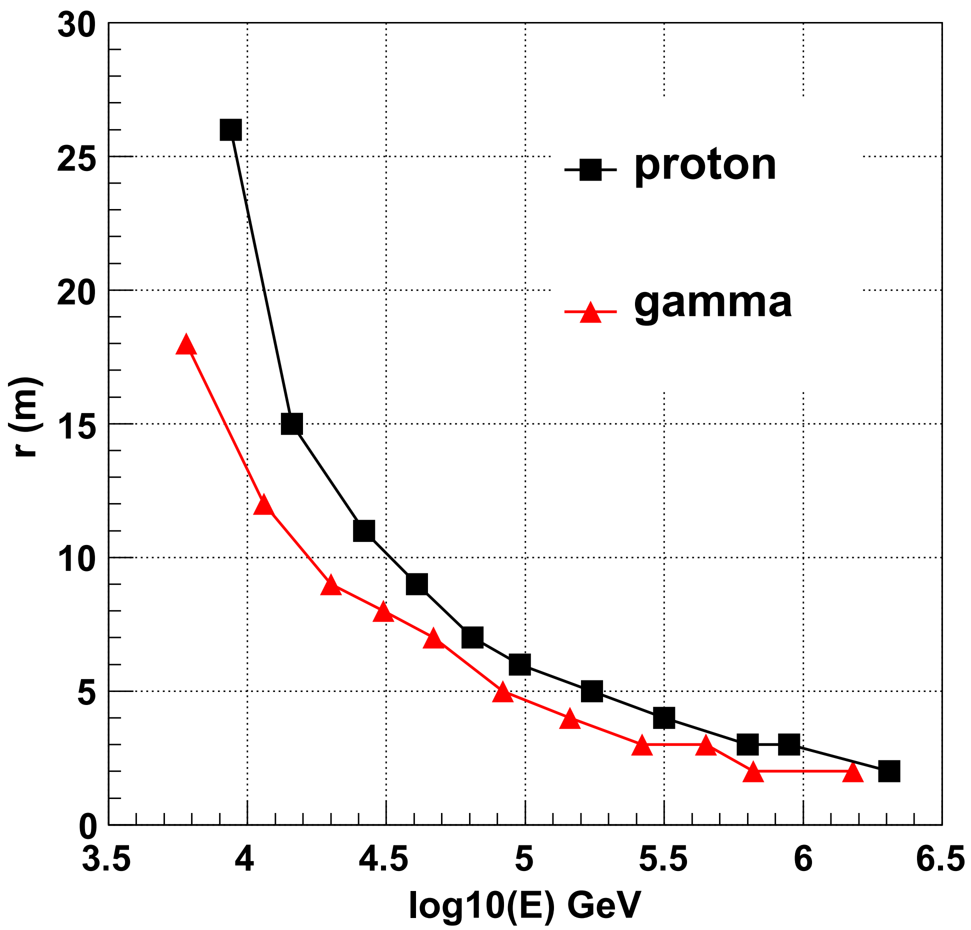
KM2A performance - 1

S. Cui et al. / Astroparticle Physics 54 (2014) 86–92

'*Standard Reconstruction'*: shower core position, size and age are reconstructed with a iterative fit by using a NKG function. Arrival direction reconstructed with a conical correction and an iterative procedure. The number of muons in the MDs is selected in a time window 30 ns around the trigger time measured in the EDs. *Internal events* with the reconstructed shower core position within 560 m from the center of the array are considered.

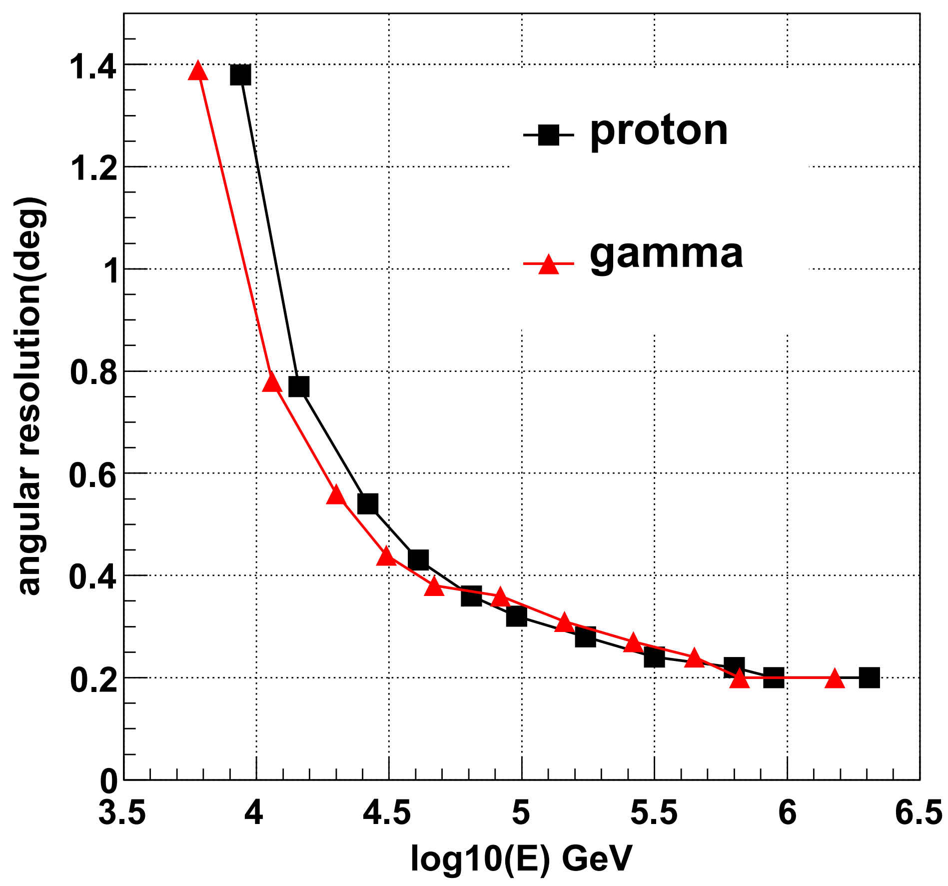


For gamma rays the effective area is *0.8 km^2 at 30 TeV*



The core position resolution is 7 m at 30 GeV and *2 m at 1 PeV*

KM2A performance - 2



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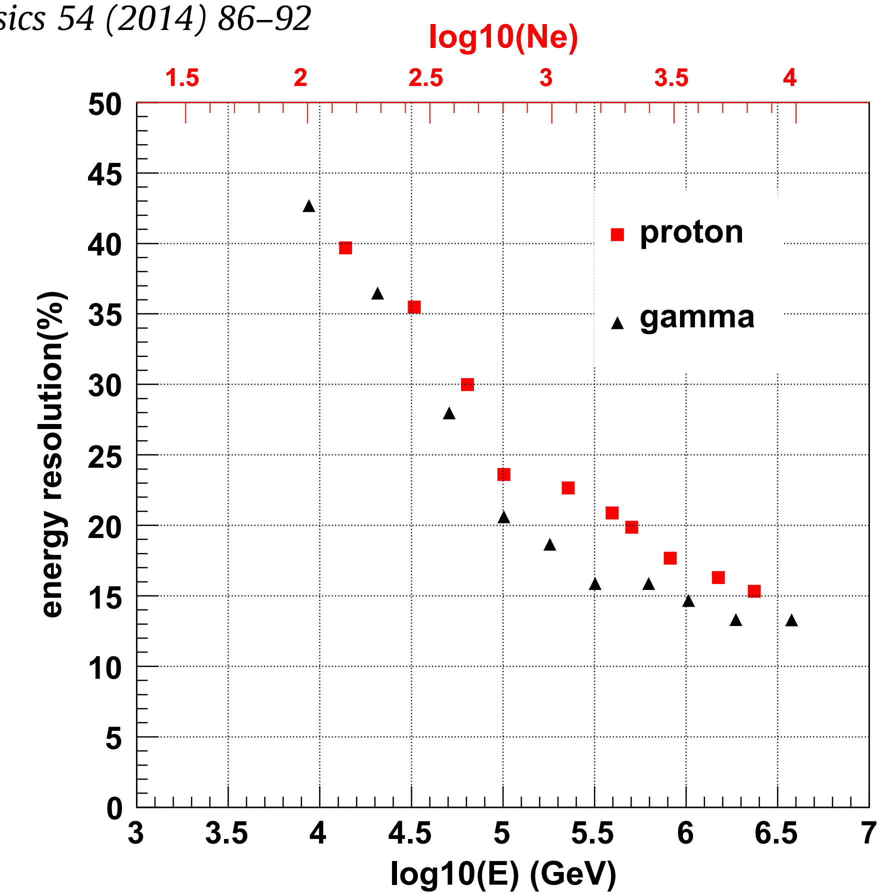
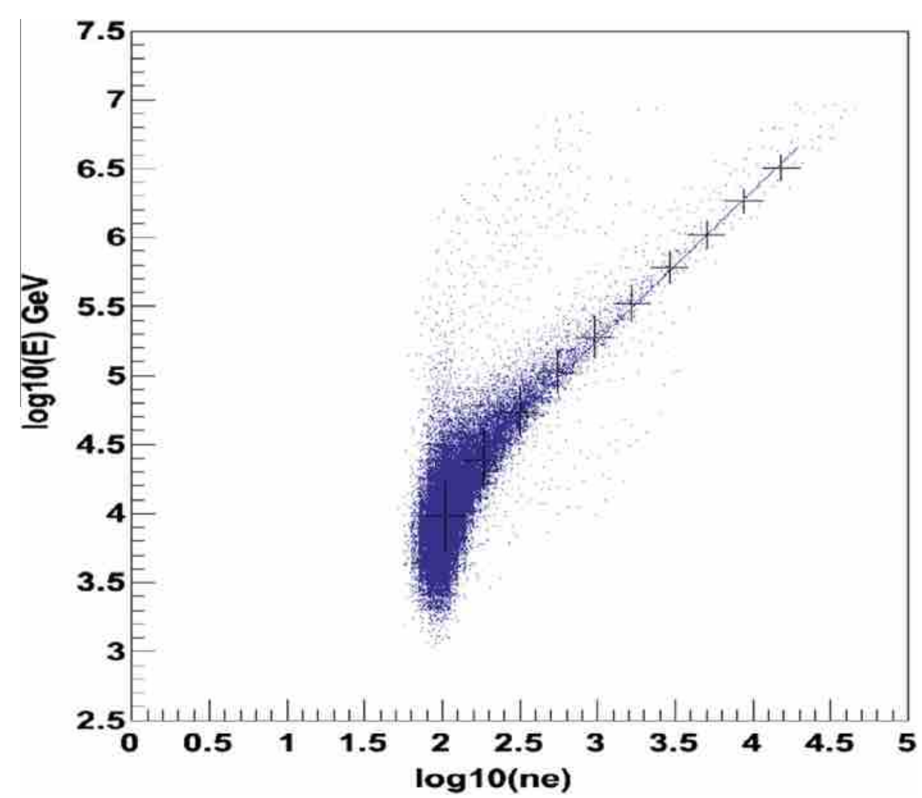


The energy resolution is 28% at 30 TeV and *15% at 1 PeV*

The angular resolution is *0.4° at 30 TeV* and *0.2° at 1 PeV*

what is the angular resolution limits of an array?

➜ *Hofmann talk*



KM2A performance - 3

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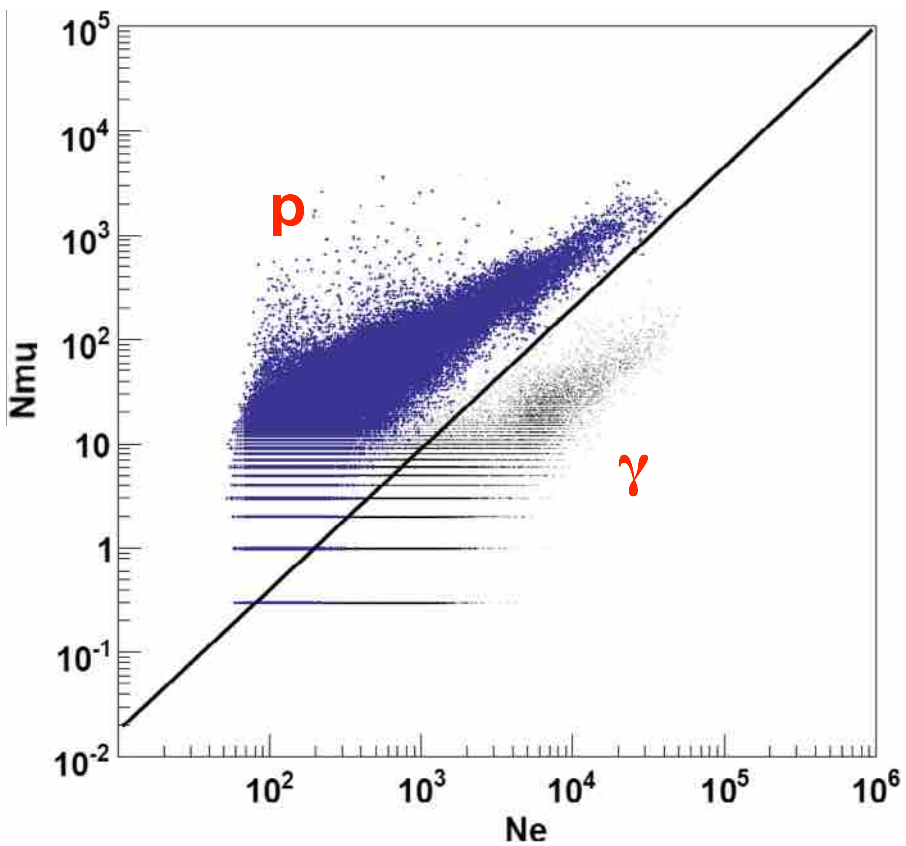
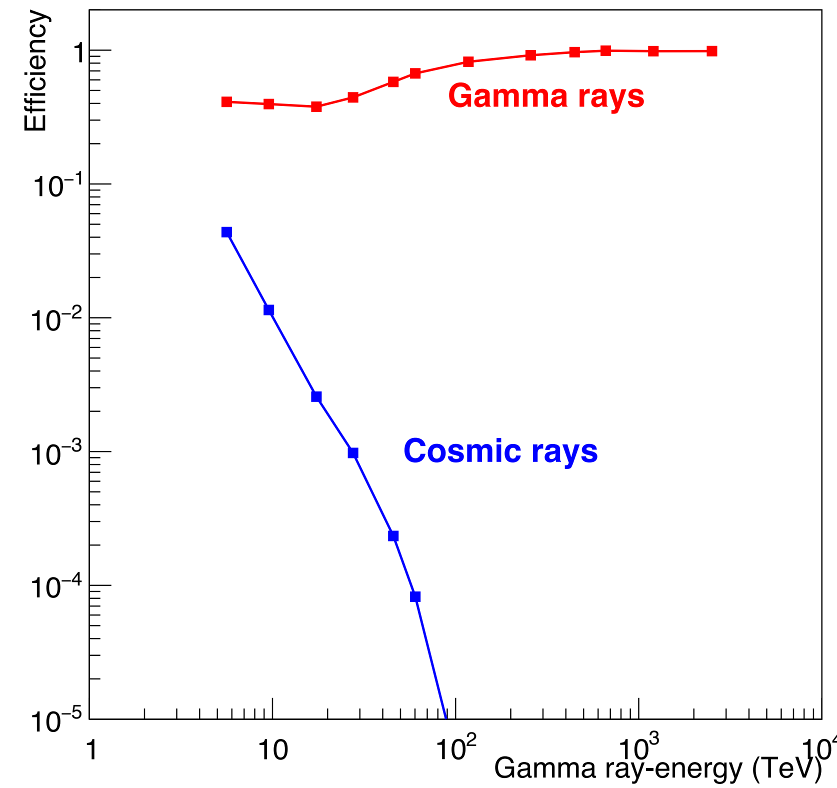
Number of detected muons



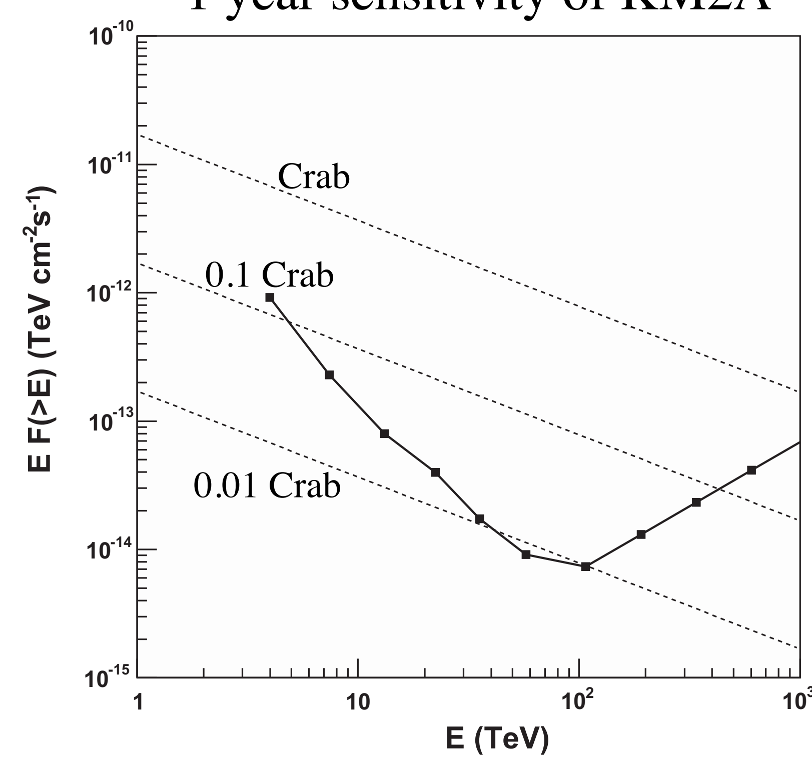


Fraction of surviving gamma and p-induced events after the selection cut.

The large area of the MD array of KM2A allow *rejection of cosmic ray background at a level of 10^{-5} at about 100 TeV*.

Above 100 TeV, in the *'back-ground free'* regime, 10 signal events are taken to measure the sensitivity of array.

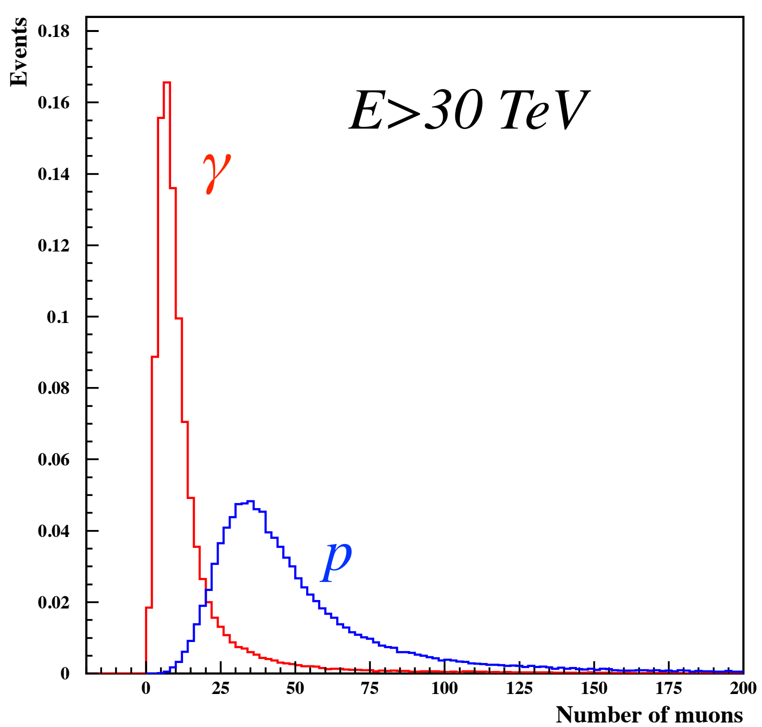
1 year sensitivity of KM2A



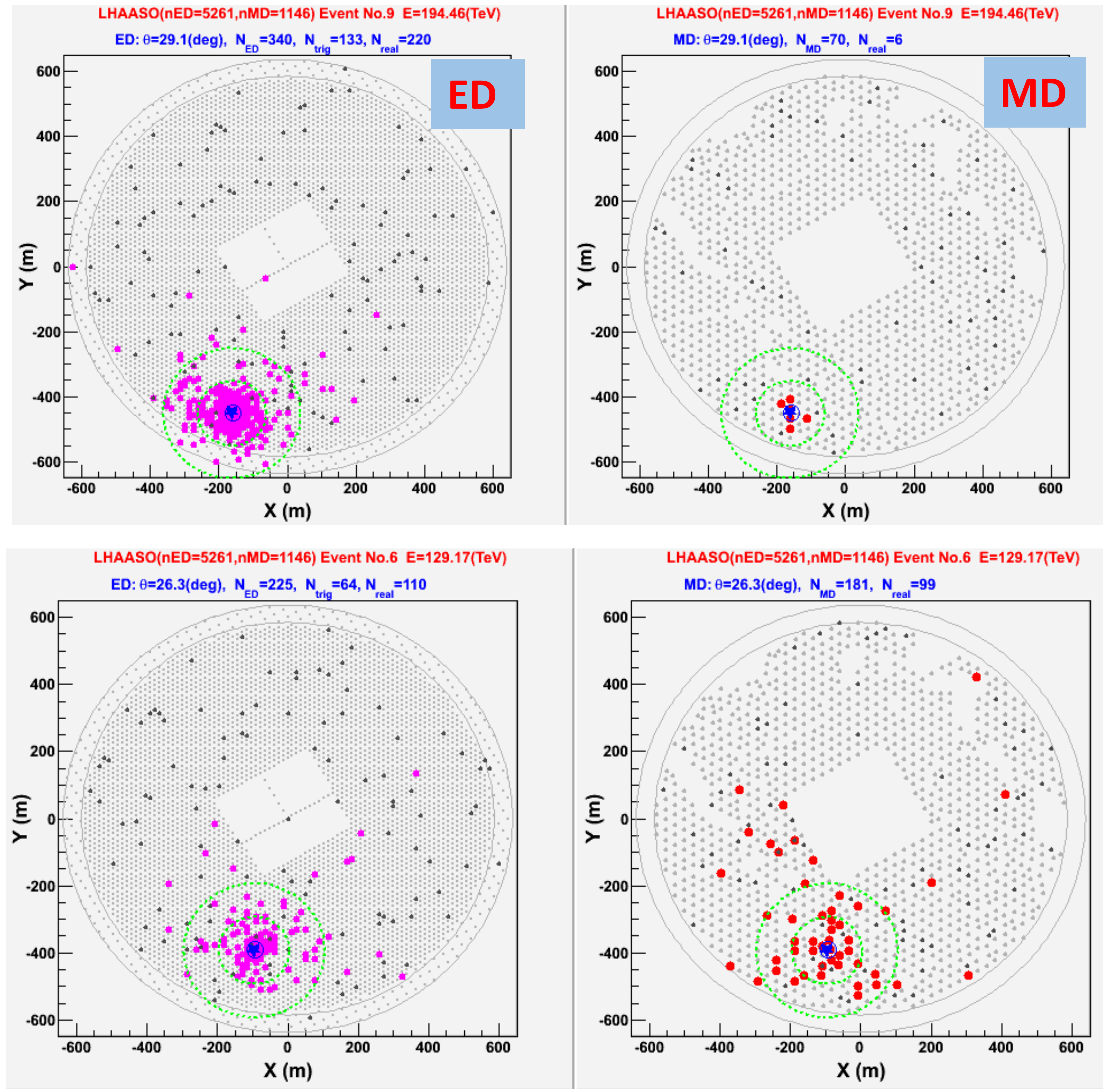
At 50 TeV 1,700 events from Crab, expected sensitivity at level of 0.008 Crab flux

Muon-poor technique

Gamma-ray
E=194 TeV

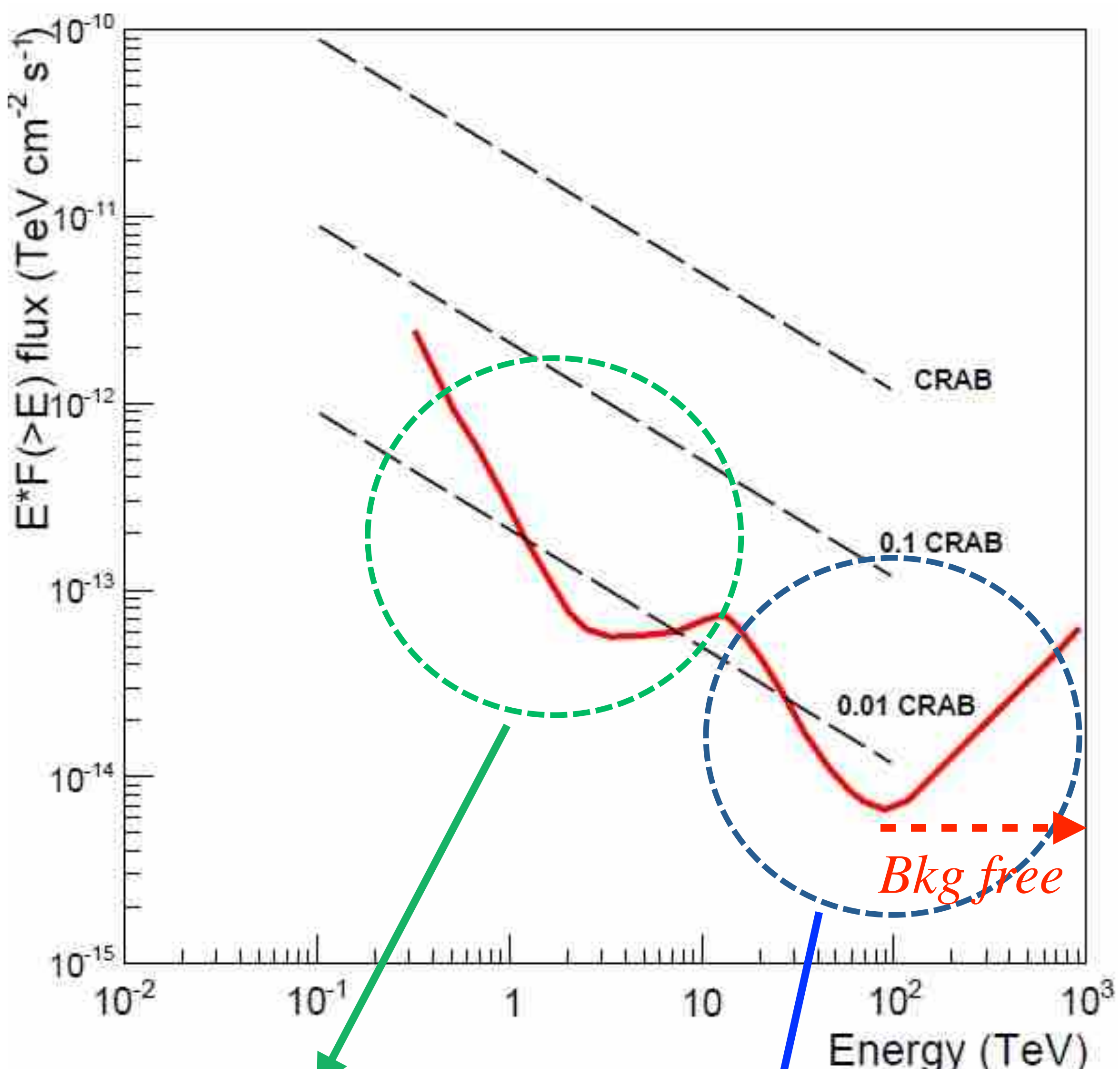


Proton
E=129 TeV



S.Z. Chen, WASDHA 2018

LHAASO integral sensitivity for Crab-like sources



WCDA

1 KM2A (EDs + MDs)

5 σ detection

$N_\gamma / N_p^{1/2} > 5$

The sensitivity increases with T $^{1/2}$

Background free

$N_p = 0$

Detection requirement:

$N_\gamma \geq 10$

The sensitivity increases with T

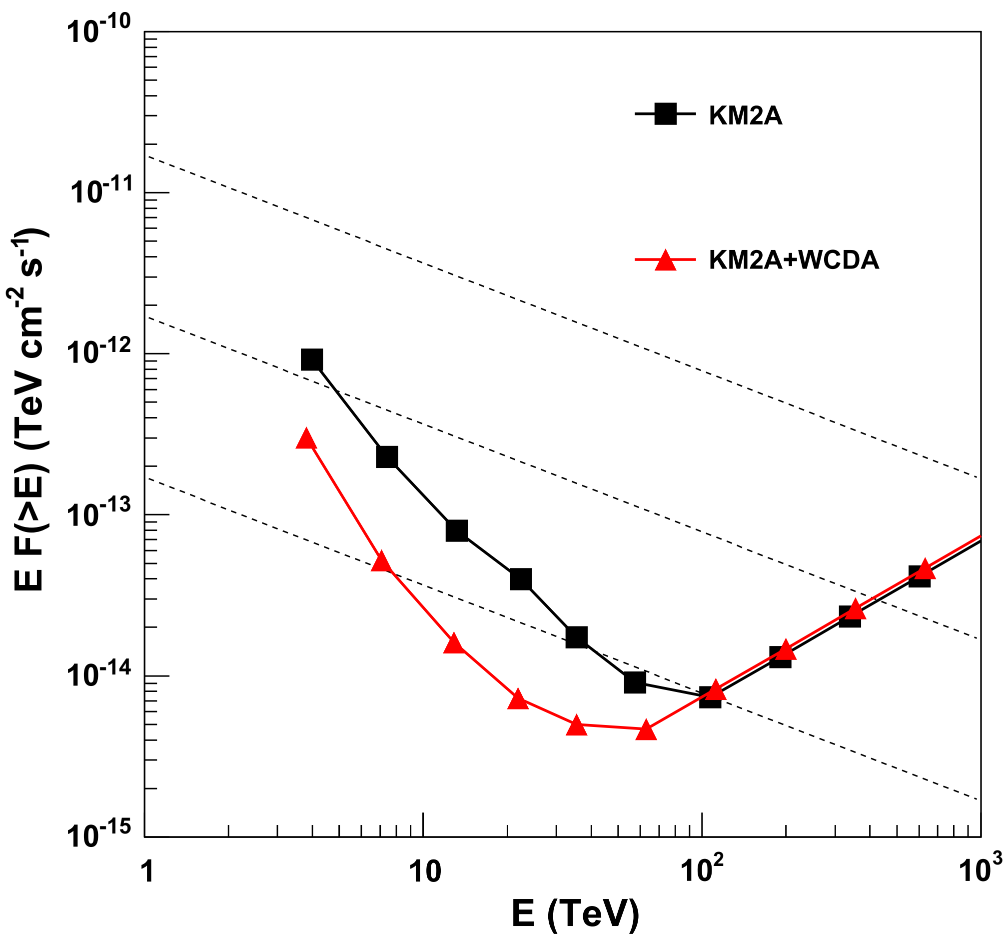
MC show that at 10 (30) TeV the fraction of CRs surviving the discrimination is only 0.01 % (0.004 %).

At larger energy (*E ≥ 100 TeV*) the rate of CRs left after the rejection procedure is less than one event per year (*a surving fraction smaller than 10^{-5}*).

The observations of gamma rays can therefore be considered as *background free* in exposures of one year or less.

WCDA as a muon detector

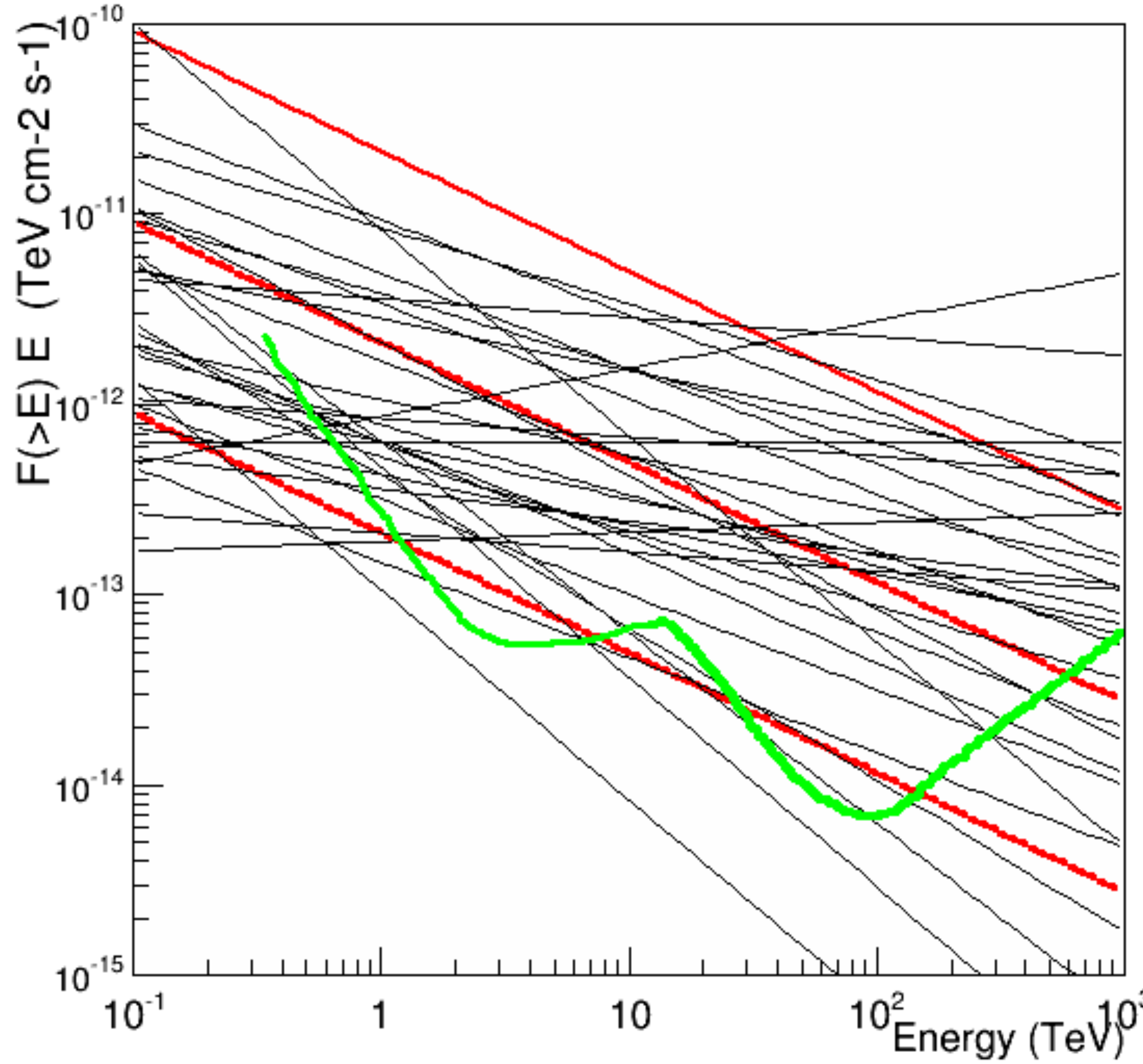
S. Cui et al. / Astroparticle Physics 54 (2014) 86–92



Expected improvement by using muons detected by WCDA

Final calculations with the final layout underway

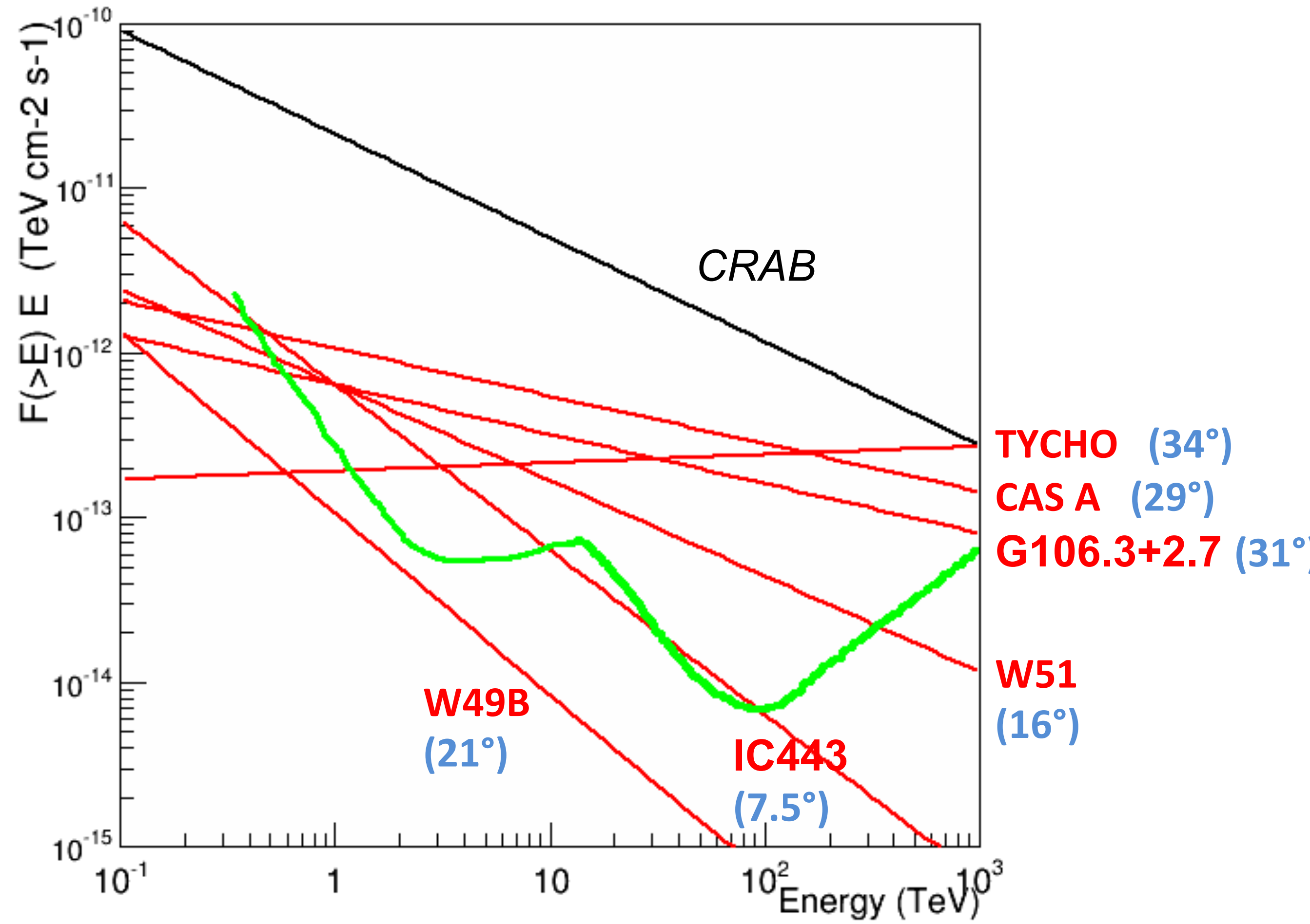
Extrapolation of TeV spectra assuming no cutoff



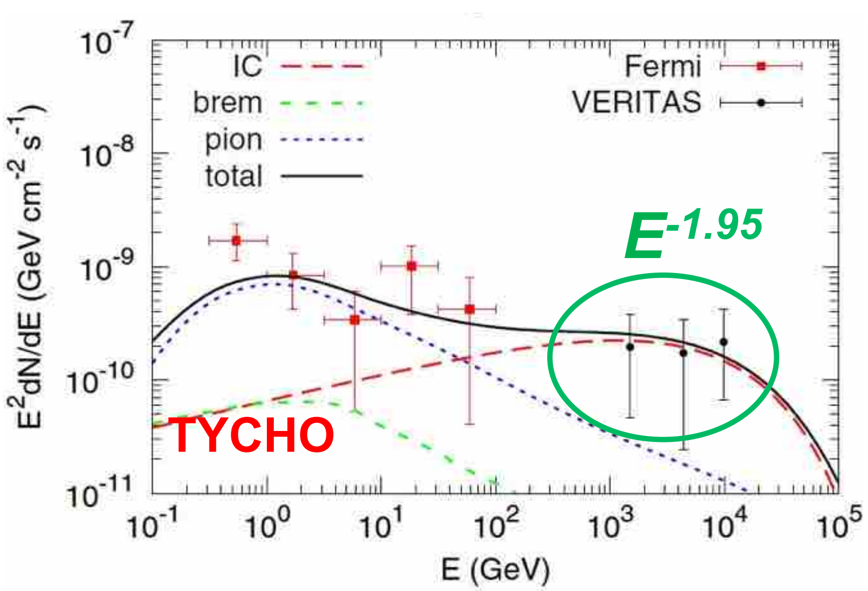
X. Bai et al., arXiv:1905.02773

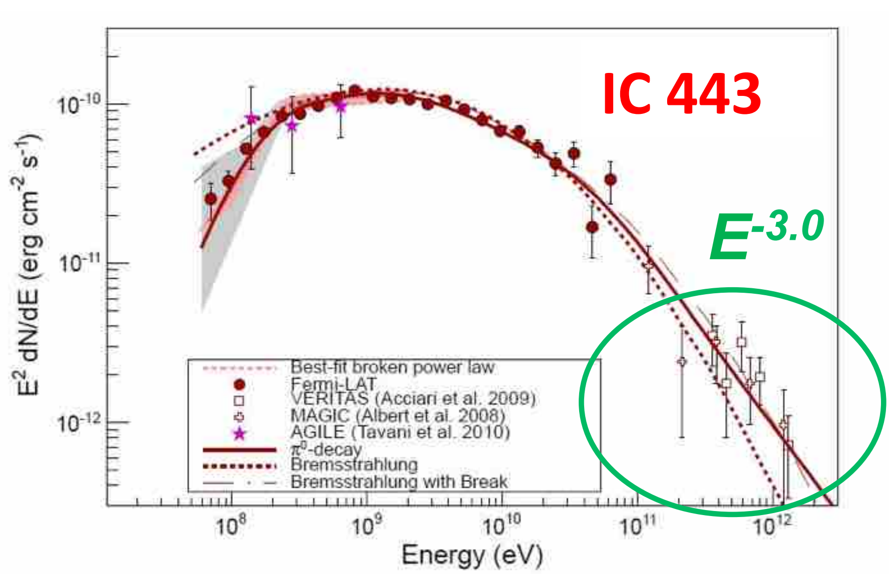
6 Shell SuperNova Remnants

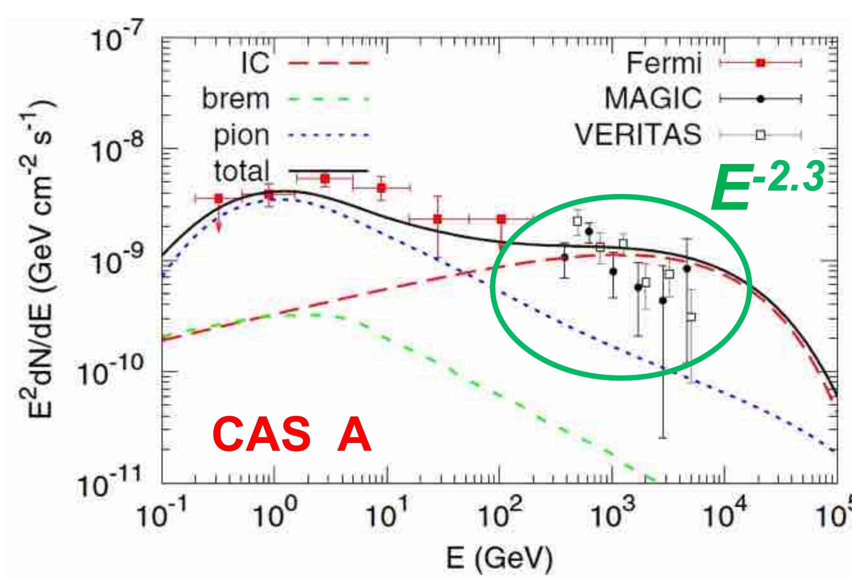
Source	Zenith angle culm.	F > 1 TeV (c.u.)	Energy range	Spectral index	Angular Extension (σ)
Thyco	34°	0.009	1-10	1.95	
G106.3+2.7	31°	0.03	1-20	2.29	0.3° x 0.2°
Cas A	29°	0.05	0.5-10	2.3	
W51	16°	0.03	0.1-5	2.58	0.12°
IC443	7.5°	0.03	0.1-2	3.0	0.16°
W49B	21°	0.005	0.3-10	3.1	



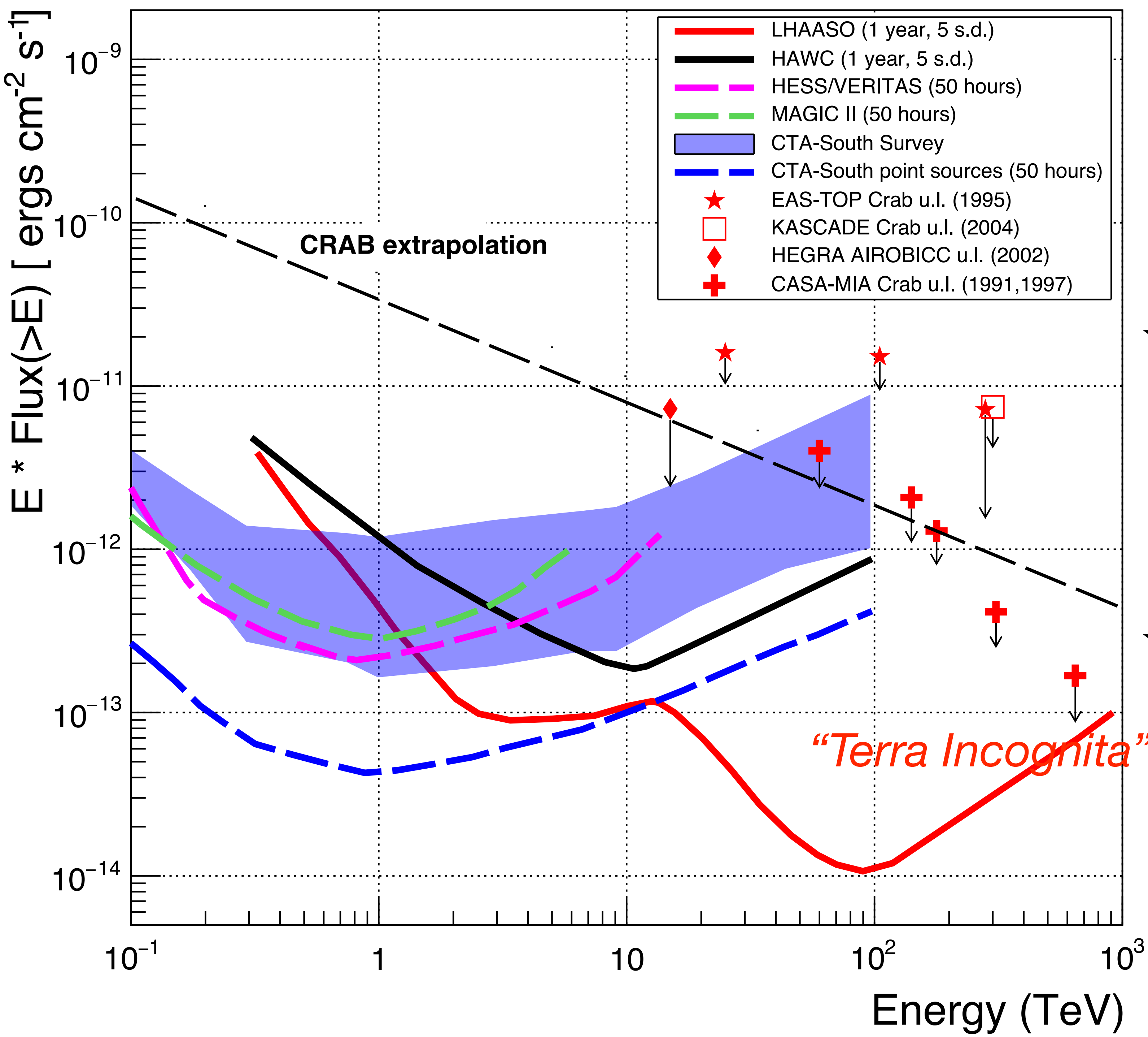
No cutoff observed in the 6 TeV spectra







Opening the PeV range



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.

LHAASO sensitivity at 100 TeV

Experiment	Angular resolution	μ detector sensitive area (m^2)	EAS array instrumented area (m^2)	μ detector coverage	Background hadron surviving efficiency
LHAASO-KM2A	0.3° (100 TeV) 0.2° (1 PeV)	42,000	1.3×10^6	4.4×10^{-2}	$\sim10^{-5}$ ($\geq$100 TeV)
CASA-MIA	2° (100 TeV) $\sim0.5^\circ$ (646 TeV)	2500	230,000	1.1×10^{-2}	10^{-2} (178 TeV) 2×10^{-4} (646 TeV)

At 100 TeV, the angular resolution of the LHAASO-KM2A array for gamma rays is ≈ 7 times better than that of CASA-MIA, and the area is ≈ 4 times larger.

The efficiency in background rejection is about $2x10^3$ times better in LHAASO, due to the larger muon detector area. According to

$$F_{min} \propto \frac{\sigma}{Q \times \sqrt{A \times T}}$$

The LHAASO sensitivity is ≈ 500 times better than that of CASA-MIA at 100 TeV.

Extended Source Sensitivity

≈ 70 % of TeV Galactic Sources are extended !

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.

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

→ dimension of the extended source

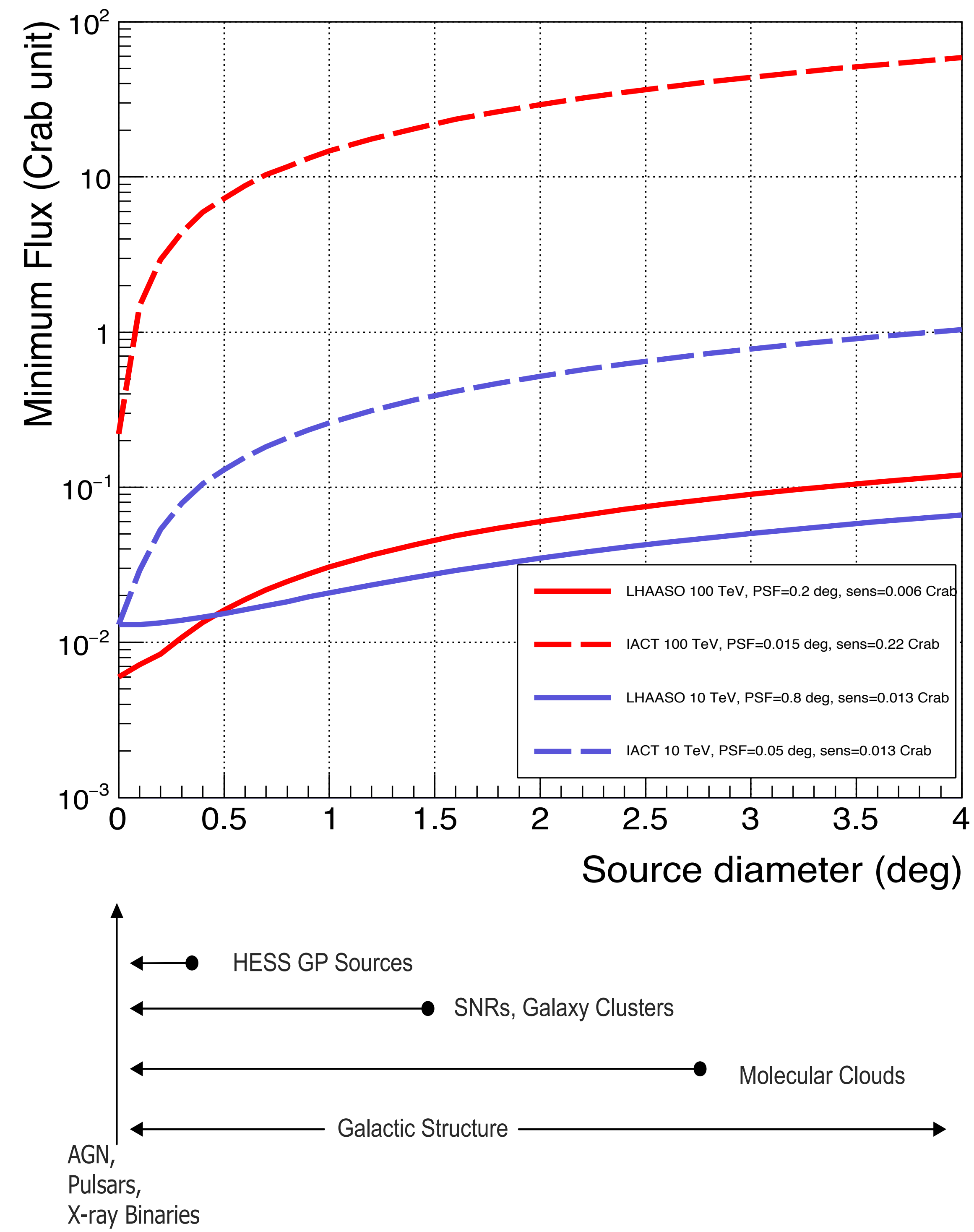
Detectors with a 'poor' angular resolution are favoured in the extended source studies.

- When the *source size is large compared to PSF*, sensitivity is reduced by a factor of

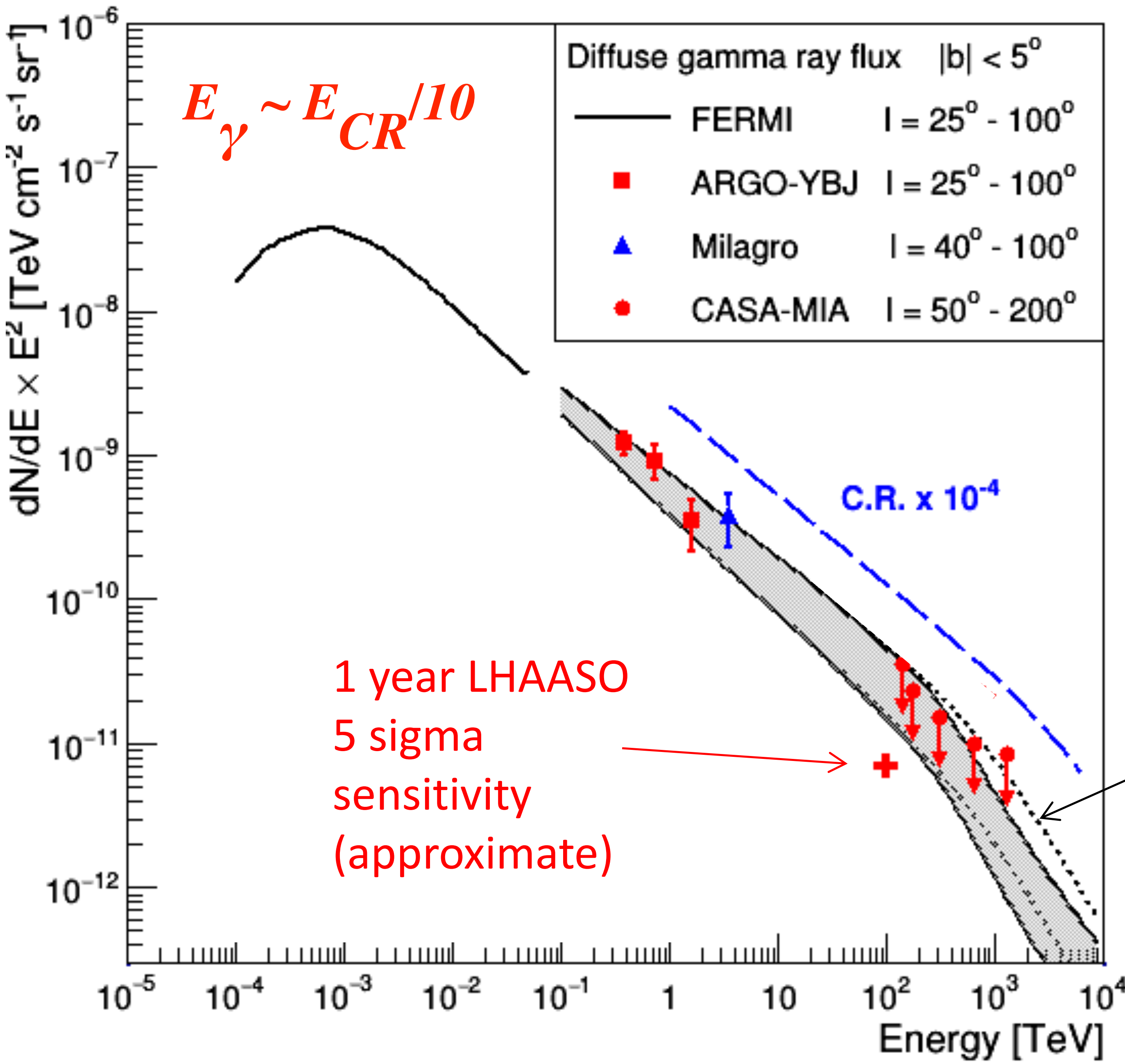
  $\sim \sigma_{detector} / \sigma_{source}$

- When the *source size is large compared to the FOV*, sensitivity is reduced by a factor of

  $\sim \sigma_{detector} / \sigma_{source}$



Expected Galactic diffuse γ-ray flux



by S. Vernetto & P. Lipari: ICRC 2017

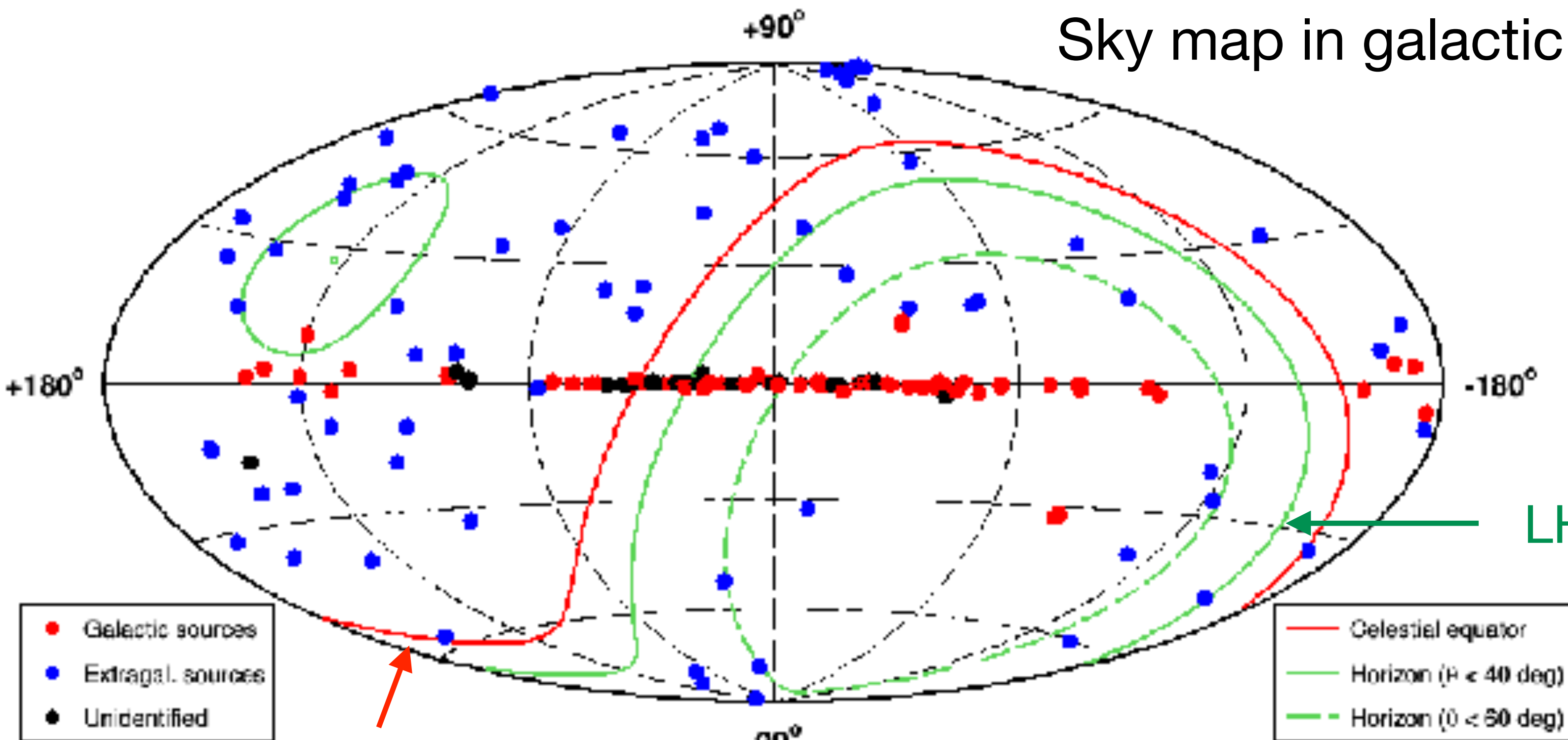
Grey band: expected γ-ray flux in the region |lat|<5°, long=25°-100°

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

Unabsorbed flux

➜ *Dmitri Semikoz talk*

LHAASO field of view

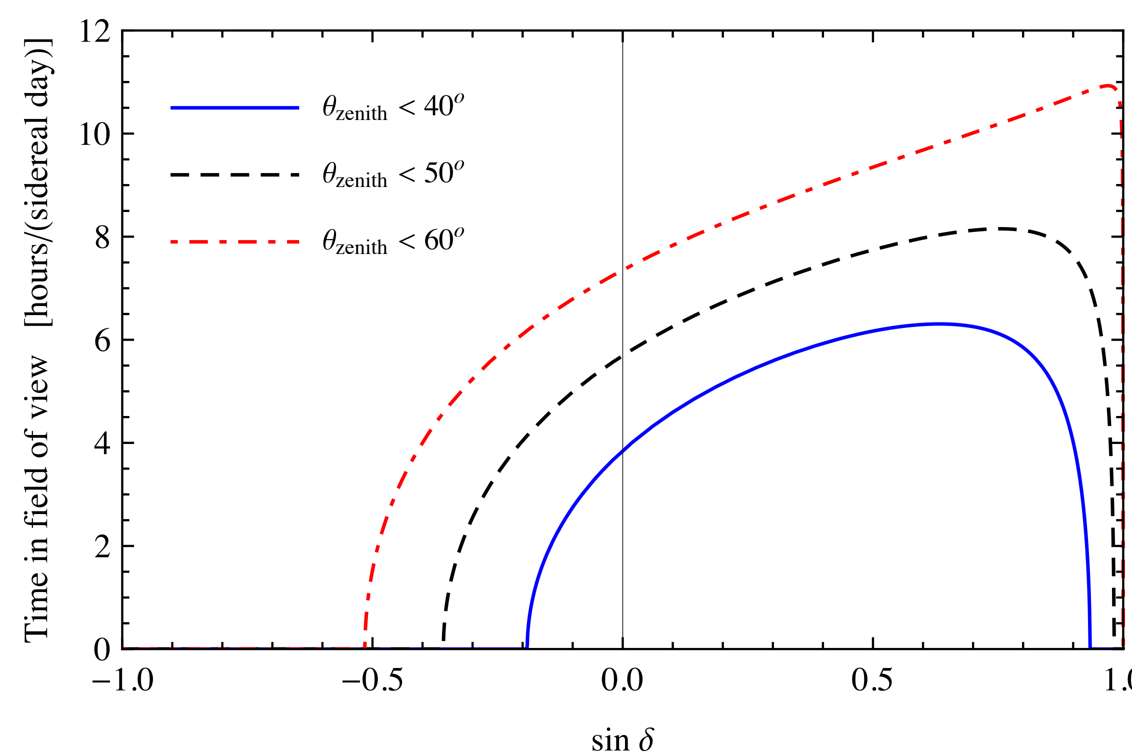


Sky map in galactic coordinates

X. Bai et al., arXiv:1905.02773

LHAASO field of view (θ < 40º, 60º)

Celestial equator



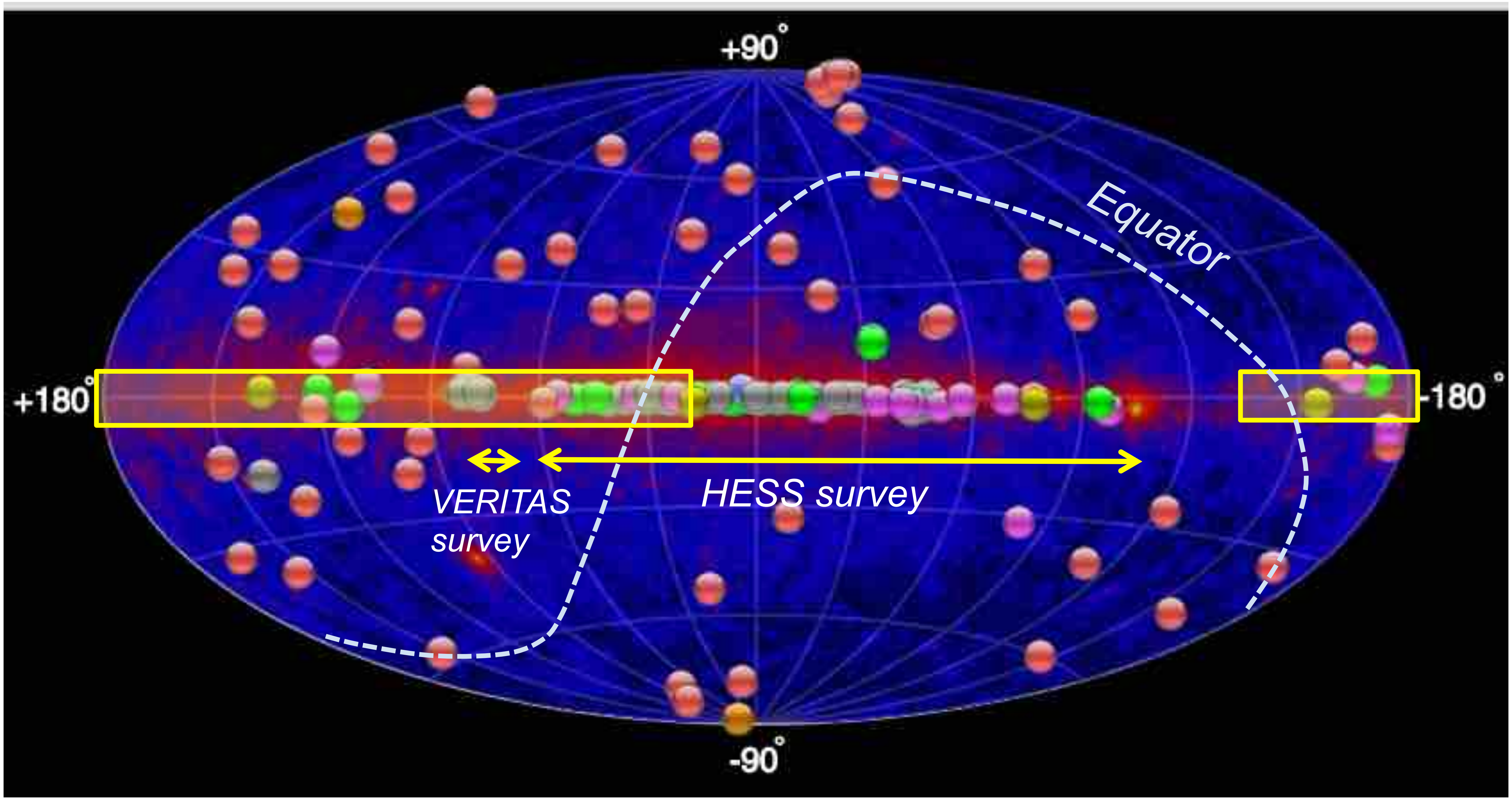
Observation time (hours) per day as a function of the source declination, for 3 values of the maximum zenith angle.

The area under the curves is proportional to the total exposure (observation time × solid angle).

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

Conclusions

Open problems in galactic cosmic ray physics push the construction of new generation wide FoV detectors in the 10^{11} - 10^{18} eV energy range.

LHAASO is the most ambitious experiment with very interesting prospects, being able to deal with all the main open problems of cosmic ray physics at the same time.

It is proposed to study CRs in a *unprecedented wide energy range 10^{11} - 10^{18} eV*, from those observable in space and approaching those investigated by AUGER/TA, thus including, in addition to the 'knee', the whole region between 'knee' and 'ankle' where the galactic/extra-galactic CR transition is expected.

At the same time it is proposed as a tool of great sensitivity - unprecedented above 30 TeV - to monitor *'all the sky all the time'* a gamma-ray domain extremely rich of sources variable at all wavelengths.

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.

LHAASO is expected to open the PeV window to observations!

Point source sensitivity