Future TeV Wide Field of View Experiments

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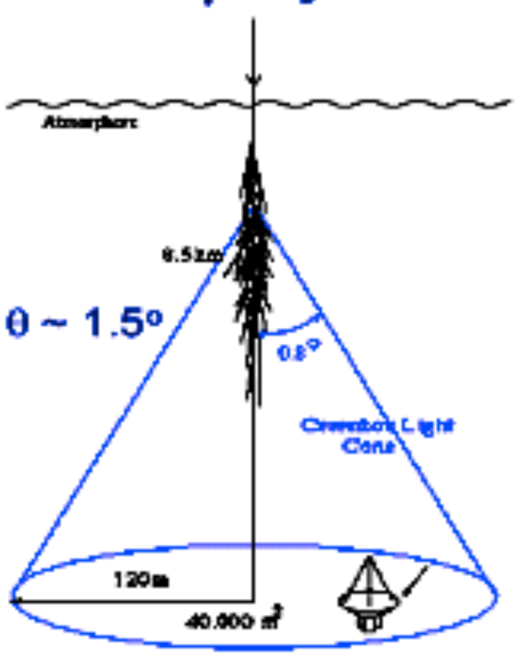
13th AGILE Science Workshop "AGILE: 8 and counting"
May 25 and 26, 2015 - ASI Headquarters, Rome

Ground-based Gamma-Ray Astronomy

Detecting Extensive Air Showers

Air Cherenkov Telescopes

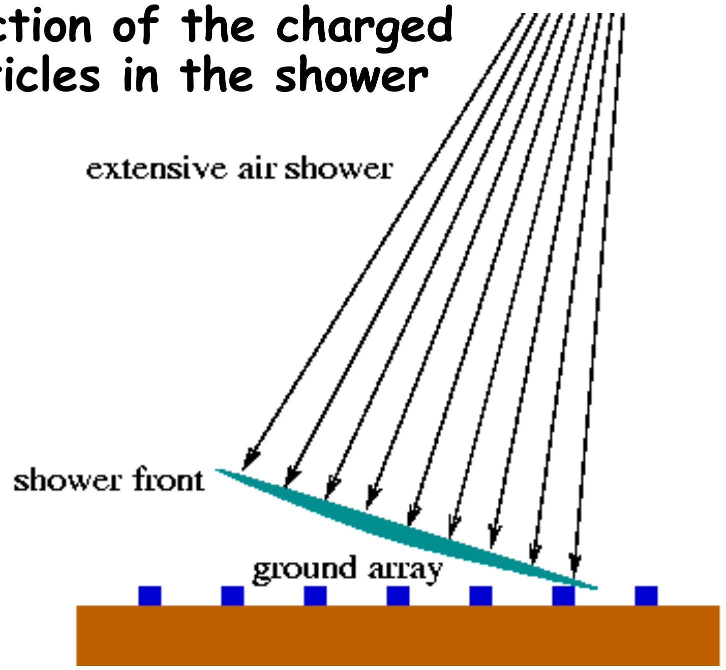
detection of the Cherenkov light
from charged particles in the EAS



Very low energy threshold (≈ 60 GeV)
Excellent bkg rejection (99.7 %)
High sensitivity (< 10^{-2} Φ_{crab})
Good energy resolution
Low duty-cycle (~ 5-10 %)
Small field of view $\Delta\theta$ < 4°

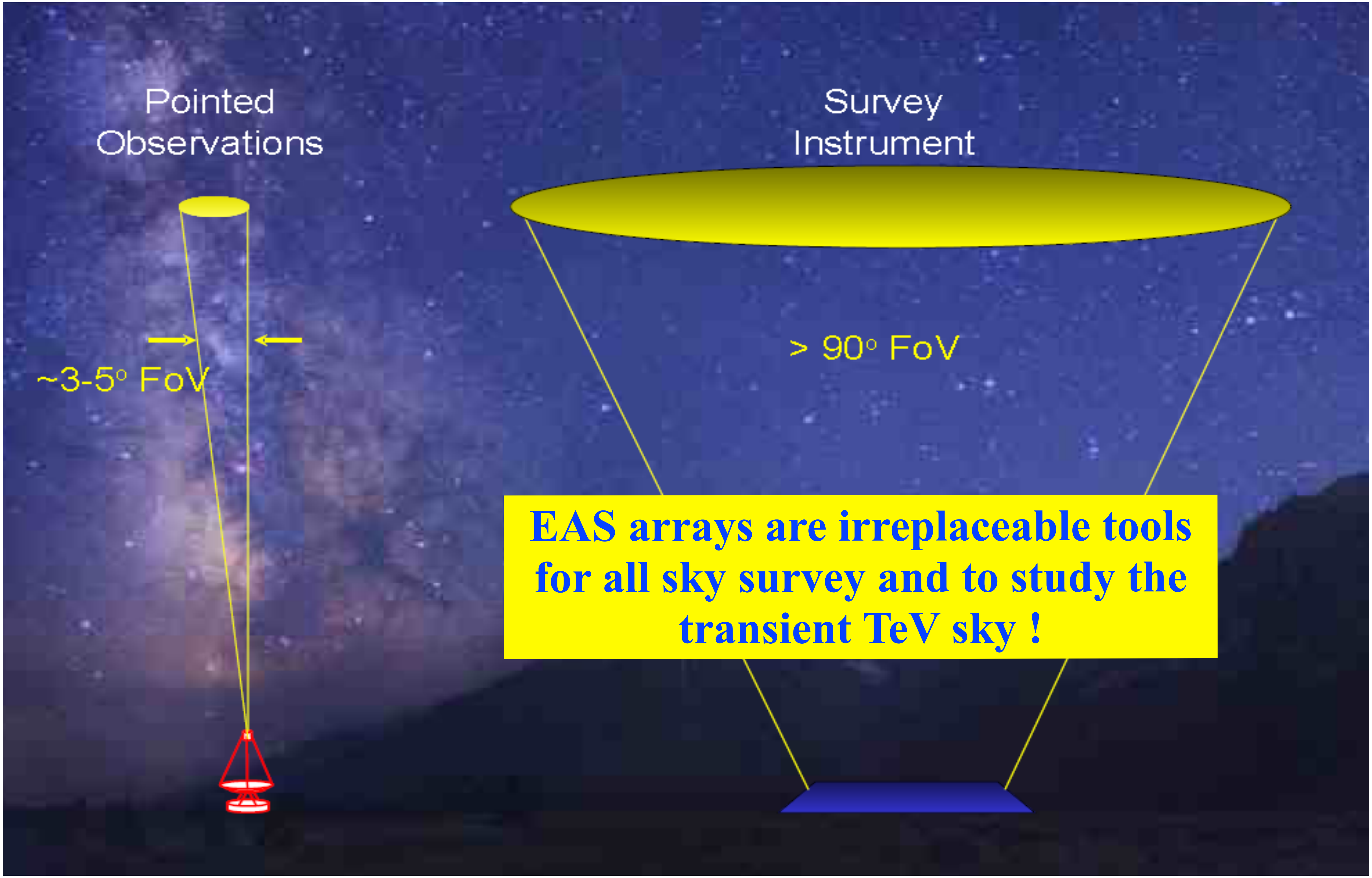
EAS arrays

detection of the charged
particles in the shower



Higher energy threshold (≈ 0.3 TeV)
Moderate bkg rejection (≈ 50 %)
Good sensitivity (≈ 0.25 Φ_{crab})
Modest energy resolution
High duty-cycle (> 90 %)
Large field of view (~2 sr)

Pointed and Survey Instruments



Cosmic Ray Experiments & Cosmic Ray Physics

CR Experiments $10^{12} \rightarrow 10^{18}$ eV:

- ARGO-YBJ
- TIBET ASγ
- GRAPES
- KASCADE
- KASCADE-Grande
- Tunka-133
- IceTop

Future:

- HAWC
- LHAASO
- HiSCORE
- TIBET ASγ enhancements

Not discussing: Highest Energy Cosmic Rays
(Auger, TA/TALE, Yakutsk, JEM-EUSO)

- The *'Scientific Case'* for new generation Extensive Air Shower (EAS) arrays in the 10^{12} - 10^{18} eV energy range

➜ open problems in Galactic Cosmic Ray Physics

Galactic CRs: main open problems

✦ Cosmic Ray Sources: *"PeVatrons"*

accelerators

"astronomy" (gamma, neutrino) but also *anisotropy* !

old nearby sources: no more photons but CRs → anisotropy !

✦ Proton energy spectrum: *"proton knee"*

acceleration mechanisms, propagation, neutrinos, background

Multi-parameter, Multi-wavelenght, Multi-messanger

electrons
muons
hadrons
cherenkov
…

X → PeV

photons
charged
neutrinos

Fermi, Agile, Pamela, AMS, MAGIC, CTA, ARGO-YBJ, Km3Net, …
same scientific program/goals: different/complementary approaches !

USA: VERITAS + HAWC

GERMANY: HESS + MAGIC + CTA + HiSCORE

The ‘*Cosmic Ray connection*'

★ Hadronic emission (CR sources): $p + p/\gamma \Rightarrow n\ (\pi^+ + \pi^- + \pi^0) + h$

γ **Gamma-Ray Astronomy**

ν **Neutrino Astronomy**

CRs, photons and neutrinos strongly correlated: the ‘*cosmic ray connection*'

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

Recent observations of PeV neutrinos by Icecube

★ Leptonic emission (Inverse Compton): $e + \gamma \Rightarrow e' + \gamma'$

scattering of electrons on low energy photons:

- ✓ Cosmic Microwave Background (CMB)
- ✓ Infrared, optical photons
- ✓ Synchrotron photons

SSC model: photons radiated by high energy (10^{15} eV) electrons boosted by the same electrons

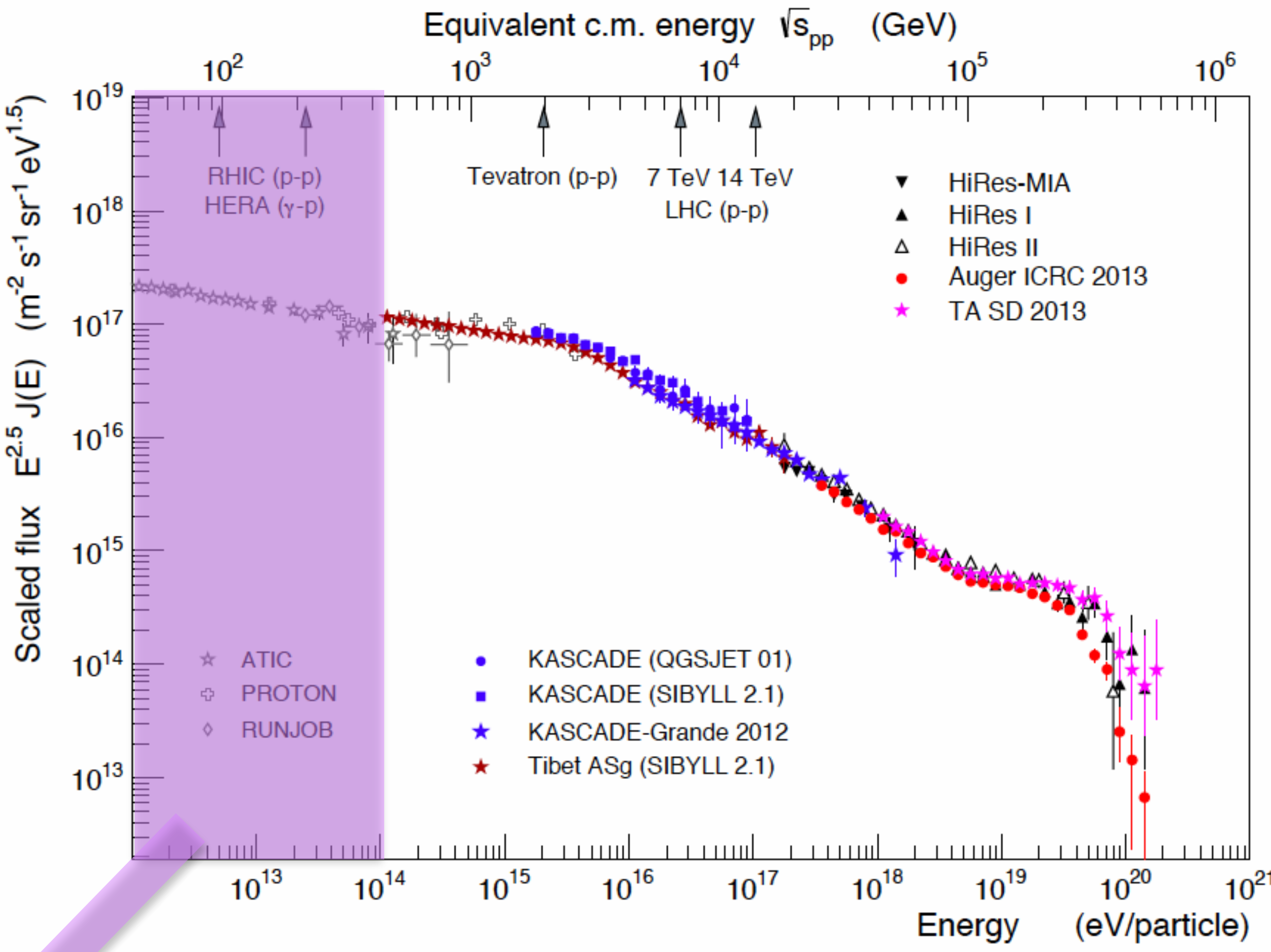
Gammas (and neutrinos) point back to their sources (SNR, PWN, BS, AGN ..)

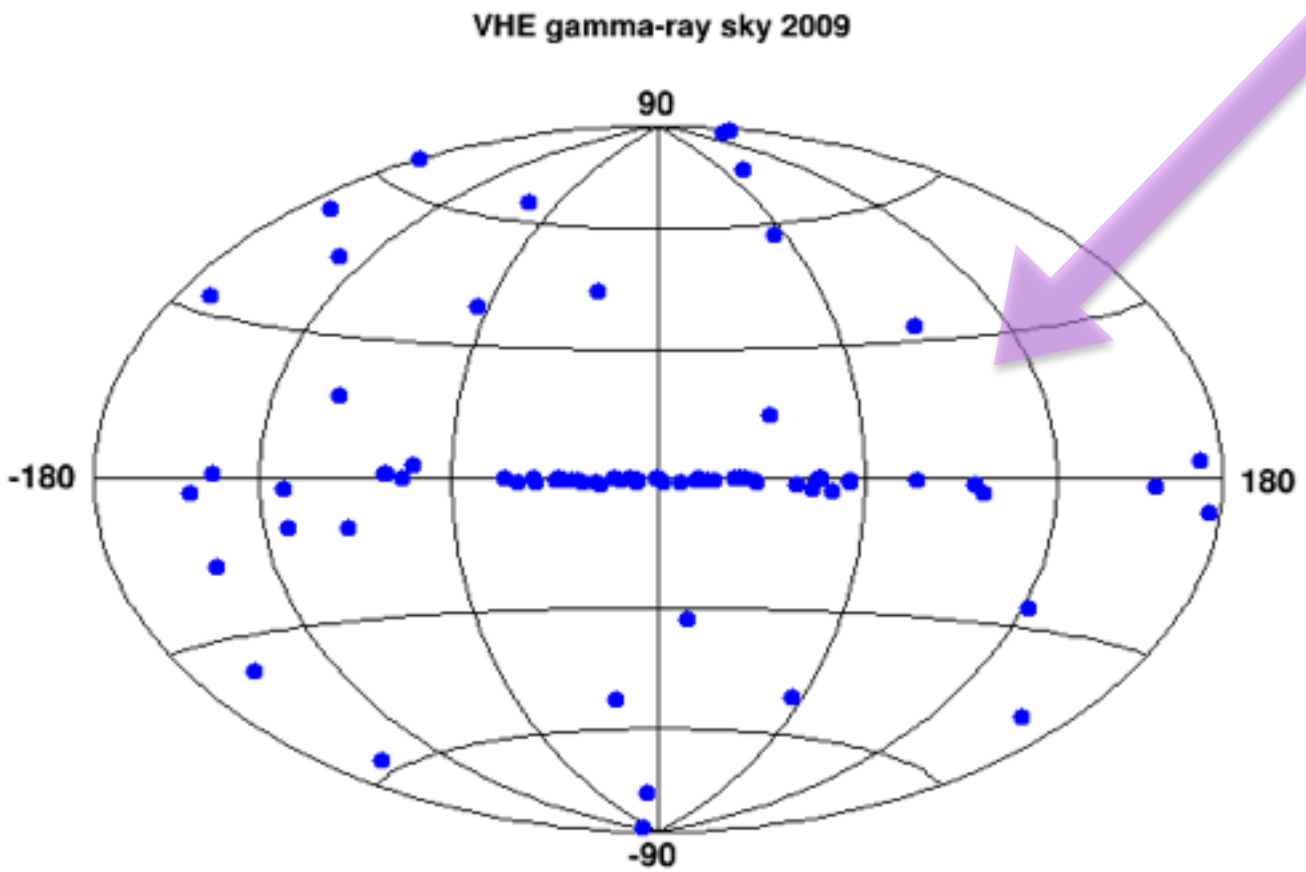
TeVatron Sky

$$p\ (p,\ \gamma) \longrightarrow \pi^0 + rest$$
$$\hookrightarrow \gamma\gamma$$

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

TeV Cosmic Rays
Photons > 100 GeV !



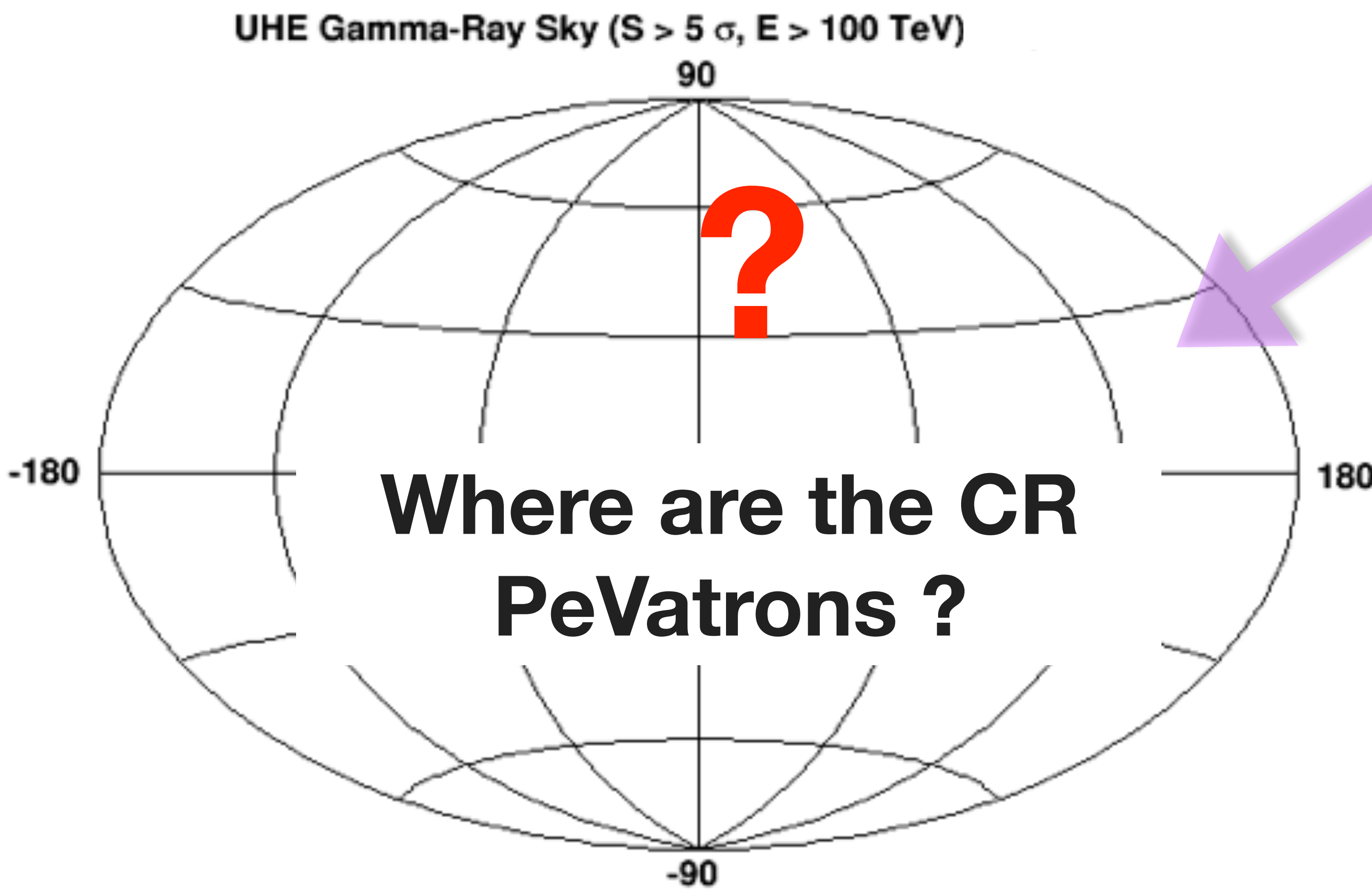


But smoking gun still missing…
leptonic ?
hadronic ?

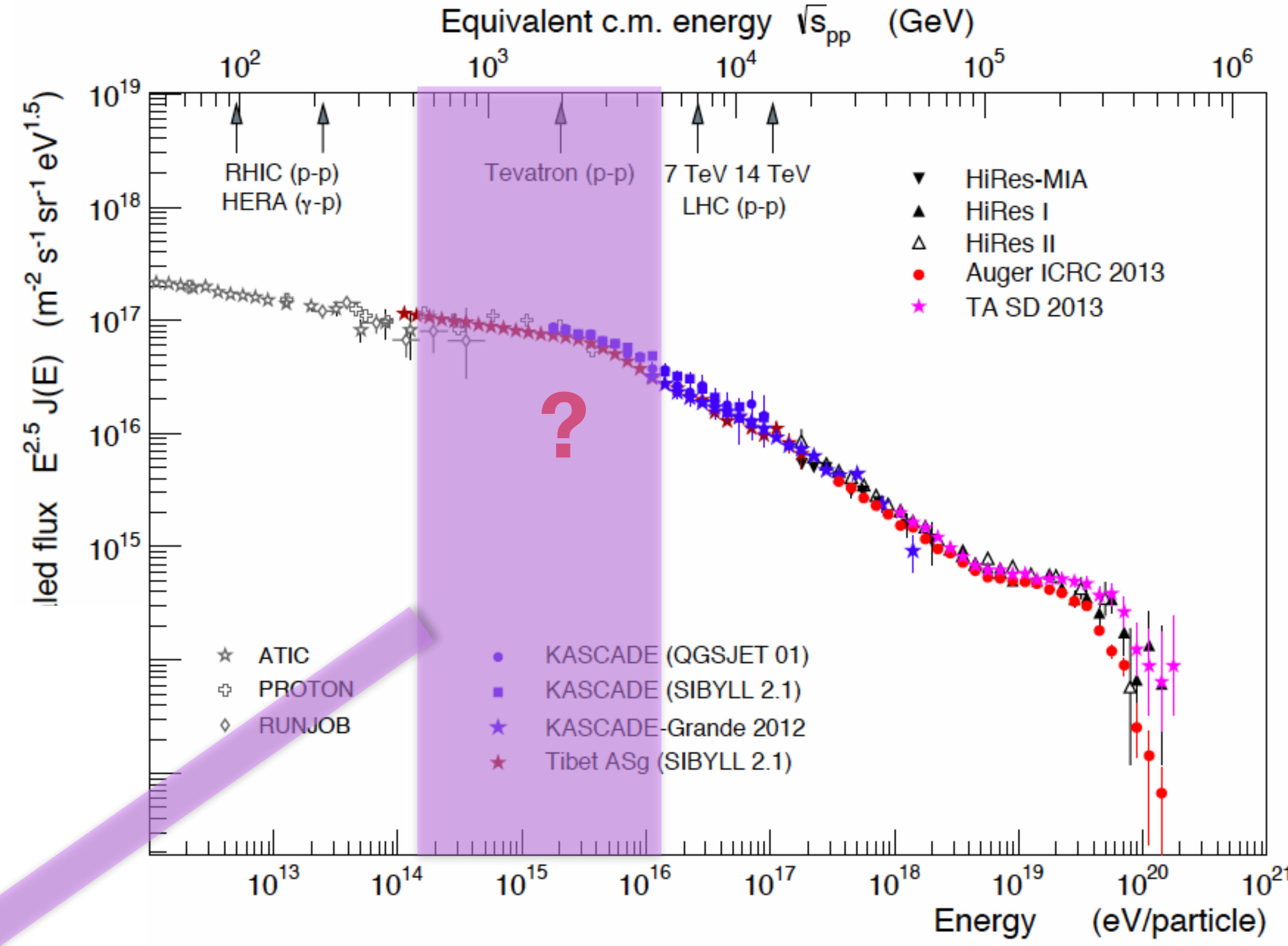
Complex scenario: each source is individual and has a unique behaviour. In general one expects a combination of leptonic and hadronic emission !

PeVatron Sky

PeV Cosmic Rays
Photons > 100 TeV !



Where are the CR PeVatrons ?

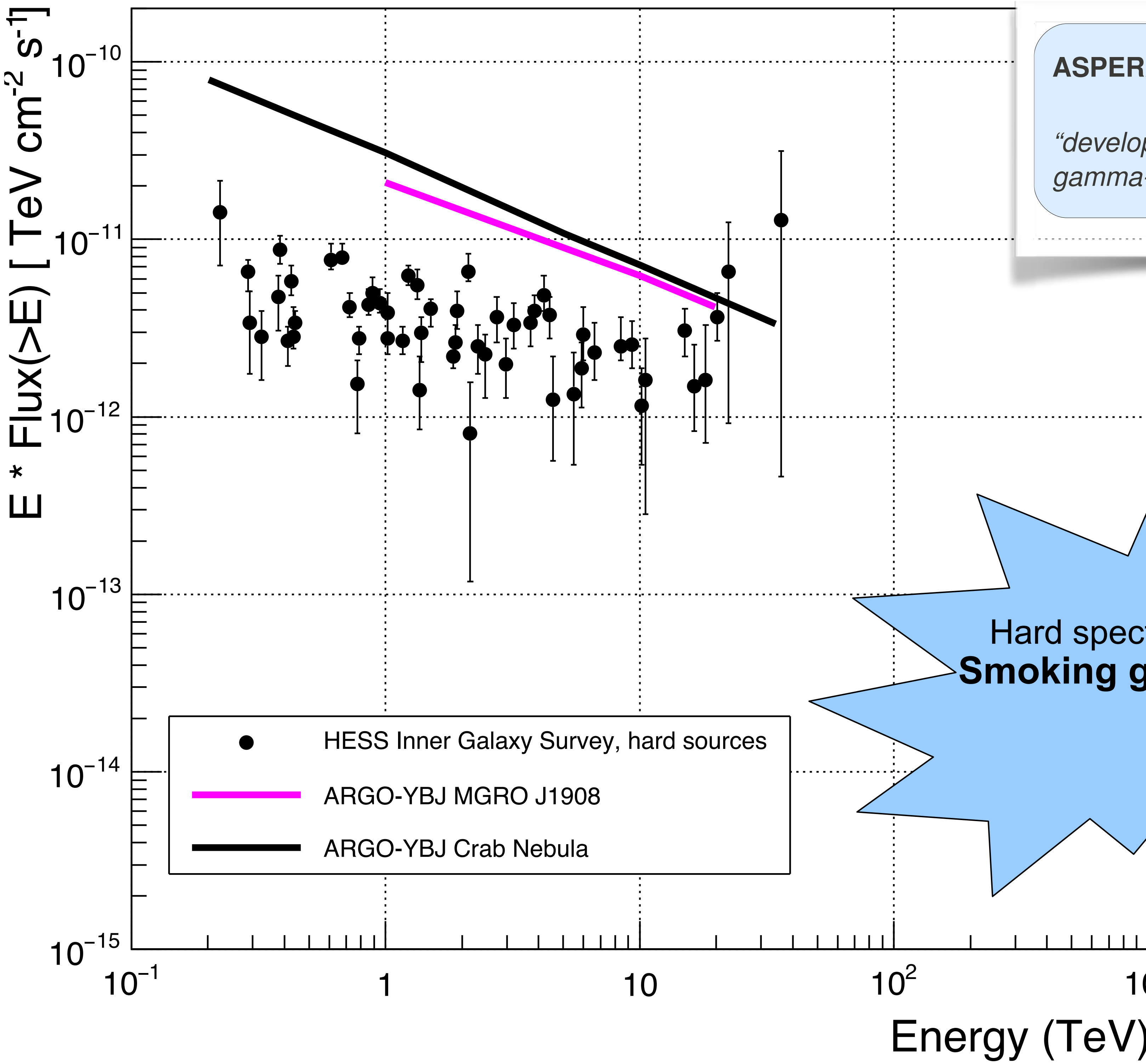


Bonus @ 100 TeV:

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

★ A power law spectrum reaching 100 TeV without a cutoff is a very strong indication of the hadronic origin of the emission

Opening the PeVatron range



ASPERA recognizes the importance of

"development of ground-based wide-angle gamma-ray detectors"

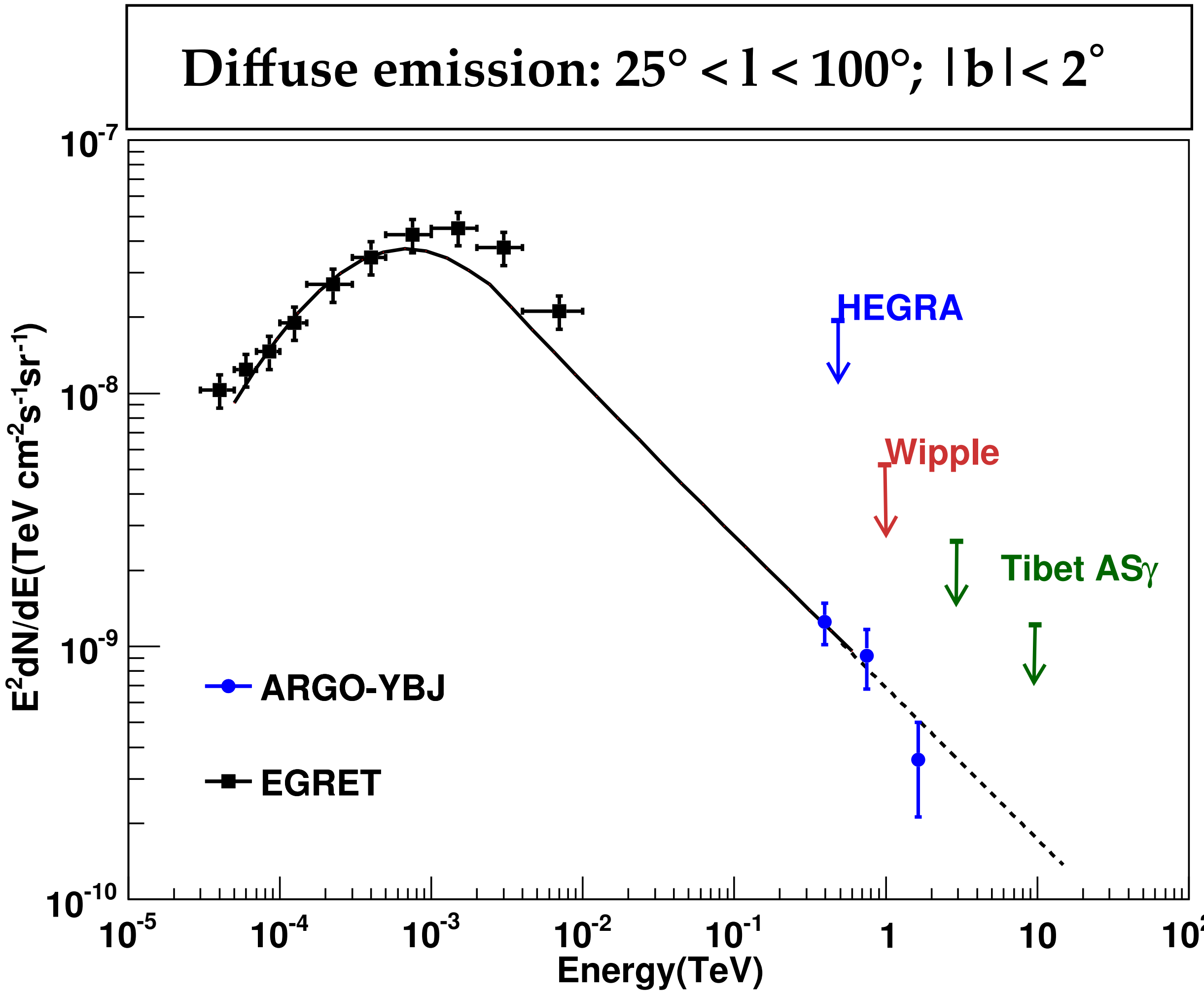
ASPERA

Hard spectra @ 100 TeV:
Smoking gun signature !

The strong case for all sky survey instruments

The all-sky survey provides un *unbiased map of the sky* useful to

- enable the detection of unexpected sources
- provides testing ground for new theoretical ideas
- provides targets for in-depth observations

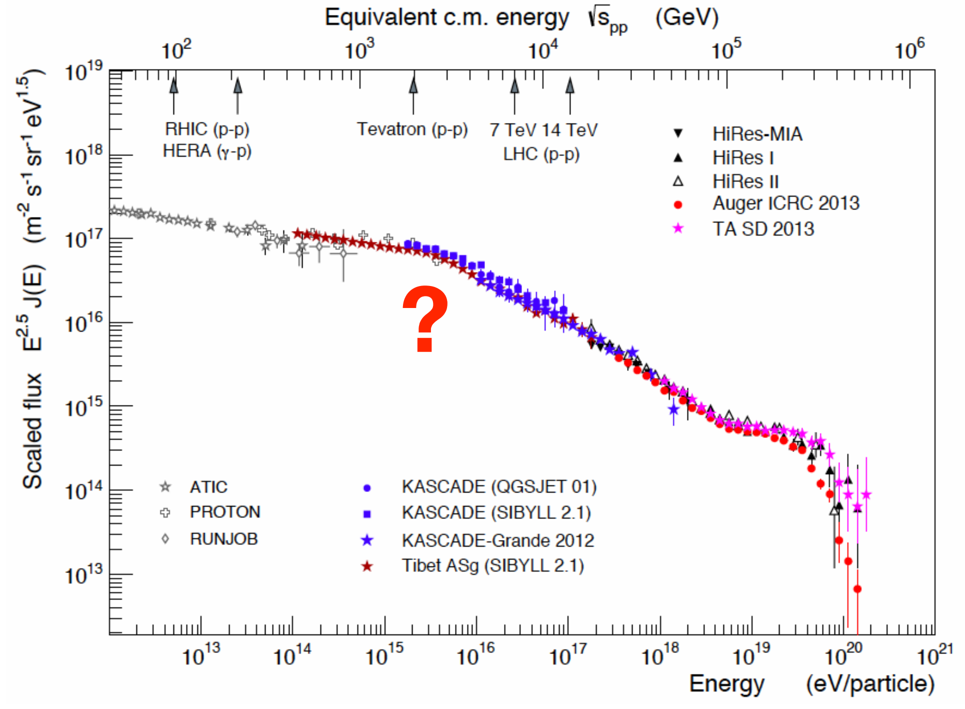


- study of flaring phenomena (GRBs, solar flares, AGNs)
- probe of diffuse emission on scales of several degrees
- study of localized CR anisotropies
- search for small and nearby high latitude molecular clouds
- constraints on Dark Matter at multi-TeV scale by *'stacked analysis'*
- blind search for annihilation in Dark Matter subhalos of the Galaxy, without any *a priori* association with an astrophysical object (dwarf galaxy, Galactic Center, etc)
- search for new, unexpected classes of VHE sources ('*dark accelerator*') useful to constrain the density in the Galactic halo of *cloudlets:* cold and dense clumps of material that may constitute a sizeble fraction of *baryonic matter* mostly invisible but not for their gamma-ray emission for CR interaction

Approaching the knee

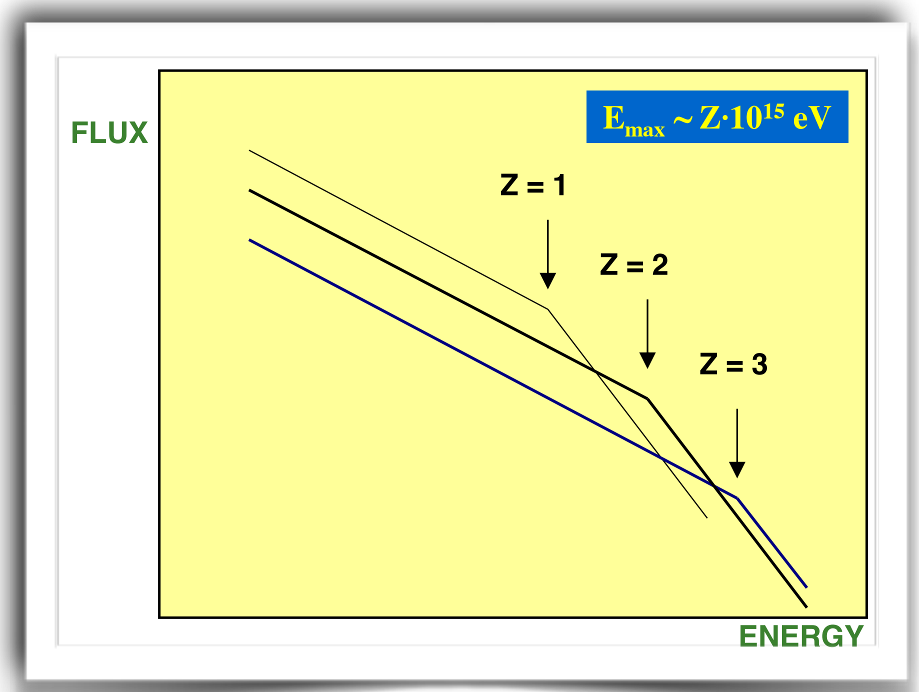
Energy spectrum, elemental composition, anisotropy:

3 fragments of a *"Rosetta stone"* crucial for understanding origin, acceleration and propagation of the radiation



The standard model:

- Knee attributed to light (proton, helium) component
- Rigidity-dependent structure (Peters cycle): cut-offs at energies proportional to the nuclear charge $E_Z = Z \times 4.5$ PeV
- The sum of the flux of all elements with their individual cut-offs makes up the all-particle spectrum.
- Not only does the spectrum become steeper due to such a cutoff but also heavier.



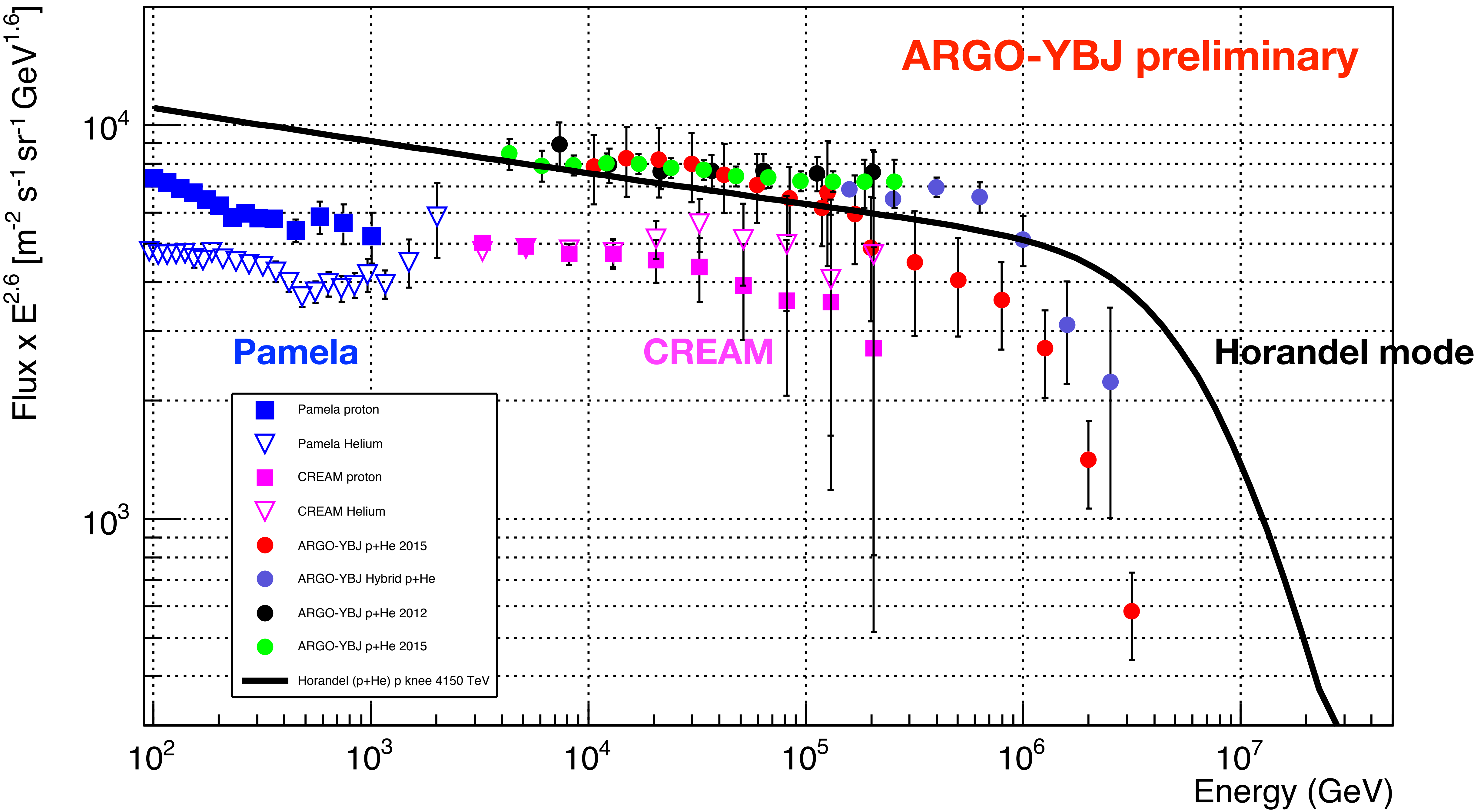
E_{max}(iron) = 26 · E_{max}(proton)

But

The latest results by ARGO-YBJ are deeply challenging the standard model of galactic CRs !

Light component spectrum (3 TeV - 5 PeV) by ARGO-YBJ

ARGO-YBJ reported evidence for a proton knee starting at about 650 TeV and not at 4 PeV (“standard model”)



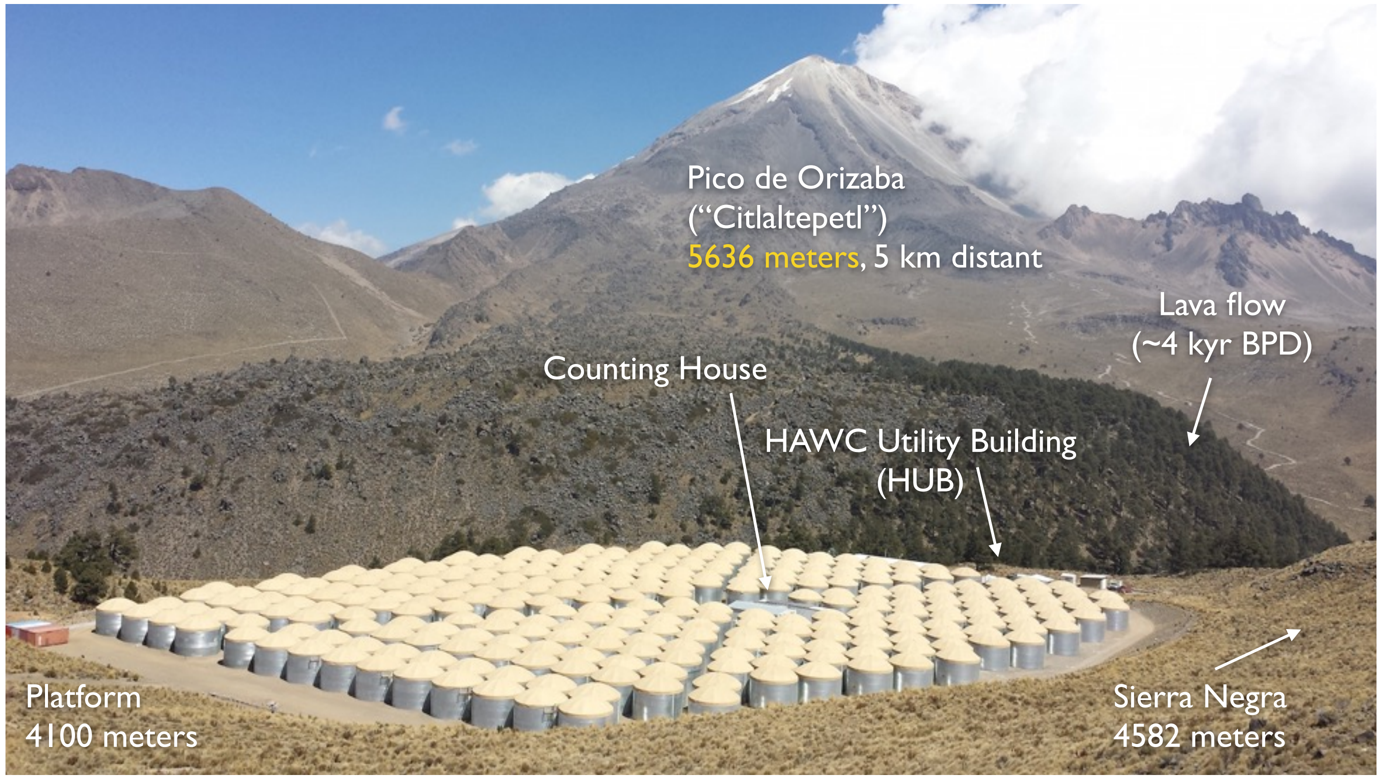
HAWC

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

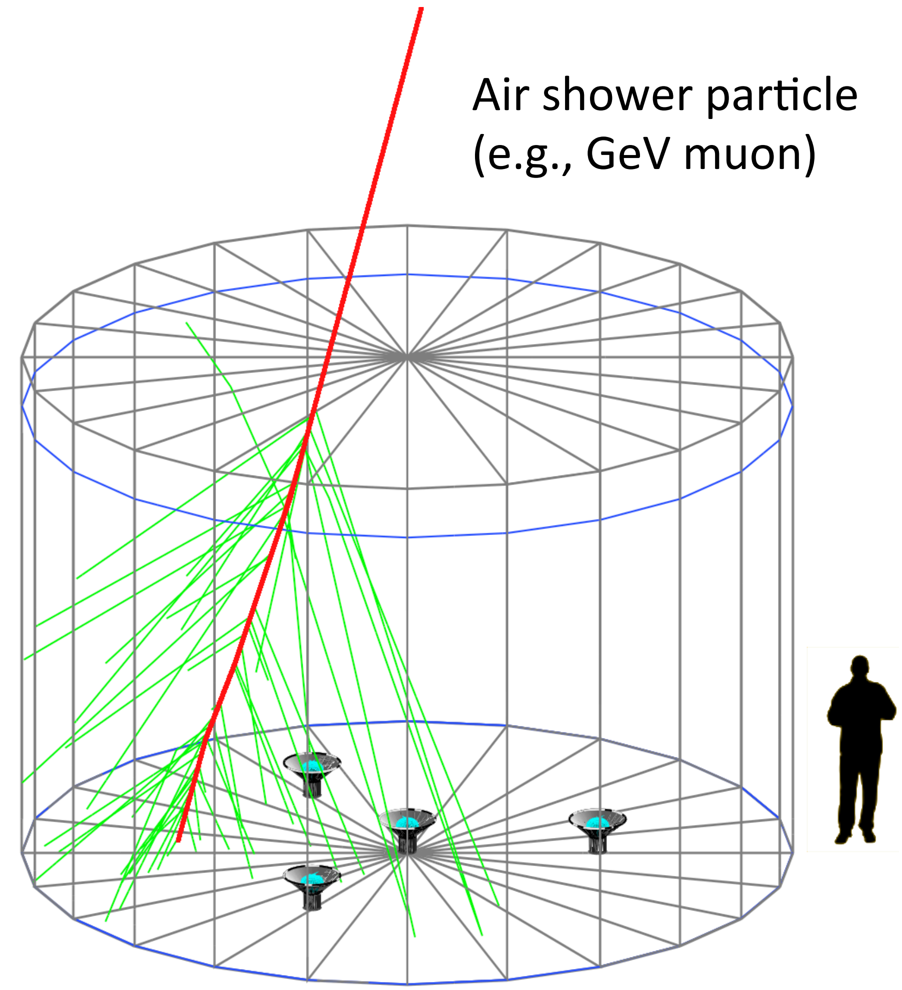
- 4100 meters above sea level
- 19°N latitude (Galactic Center at 48° zenith)
- 300 water tanks, 1200 large photocathode area PMTs 1/6th of sky in instantaneous field of view
- Current status: tank construction and water filtration completed, final PMTs deployed. 270 tanks in DAQ

- Instrumented Area: 140 X 140 m^2
- Coverage factor: 57 %
- 10 kHz event rate



Water Cherenkov Method

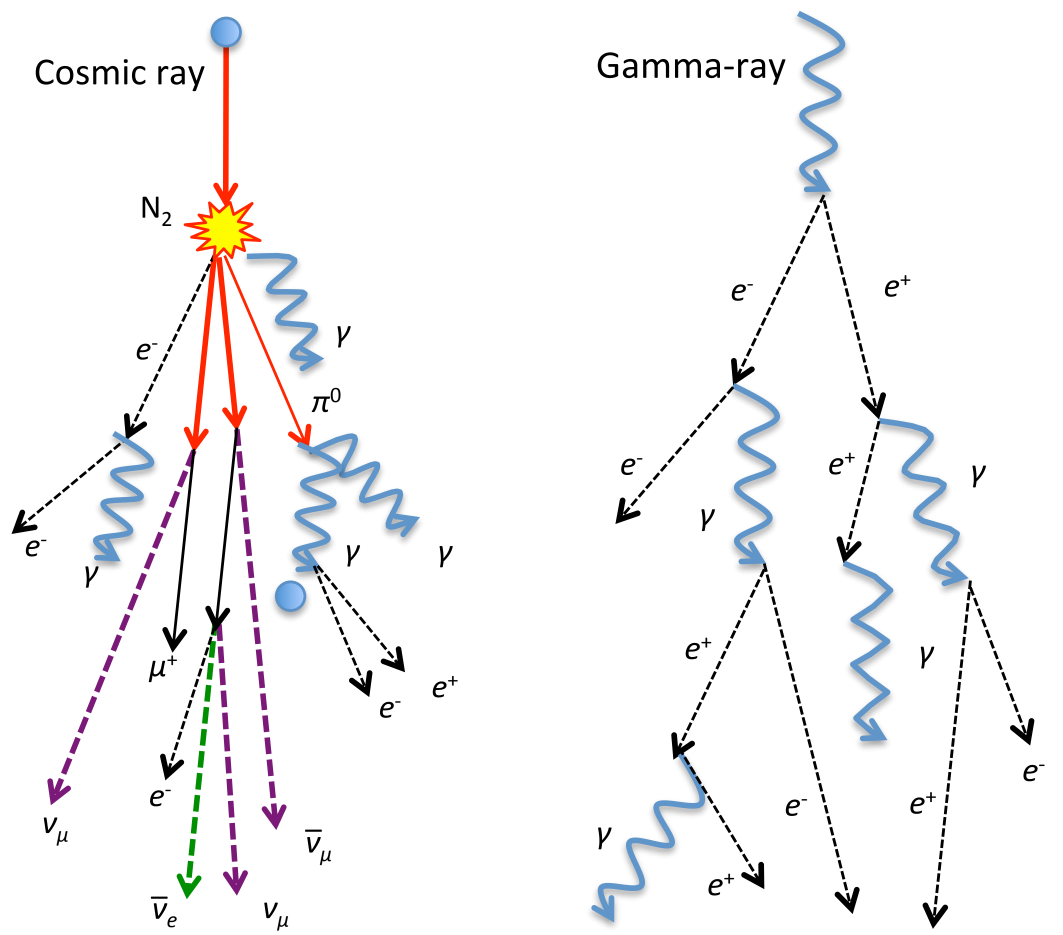
- Robust and cost-effective surface detection technique
- Water tanks: 7.3 m radius, 5 m height, 185 kL purified water
- Tanks contain three 8” R5912 PMTs and one 10” R7081-HQE PMT looking up to capture Cherenkov light from shower front

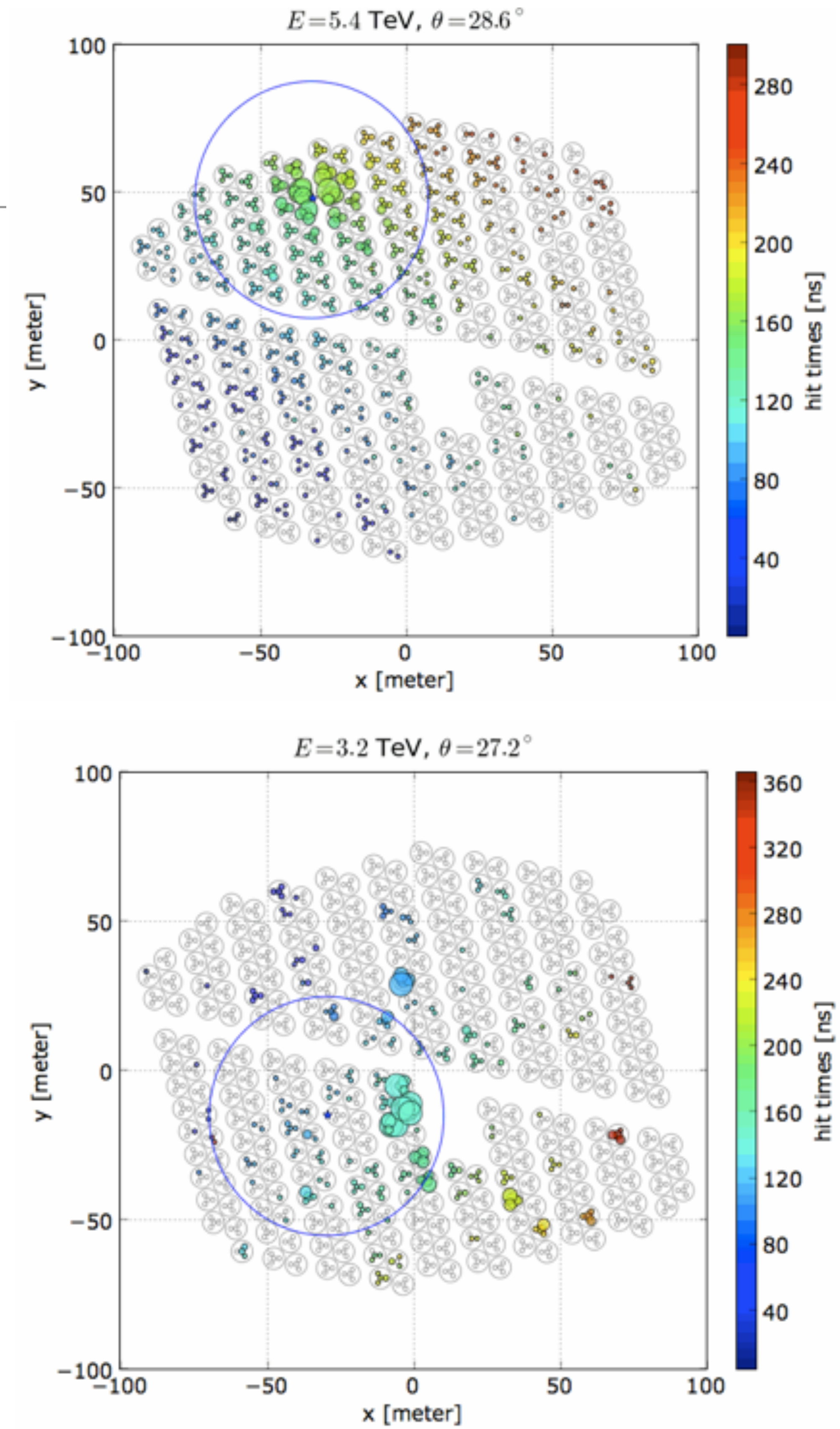


Final tank deployed: December 15, 2014

Background rejection

CR rejection using topological cut in hit pattern away from the shower core





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

Effective Area

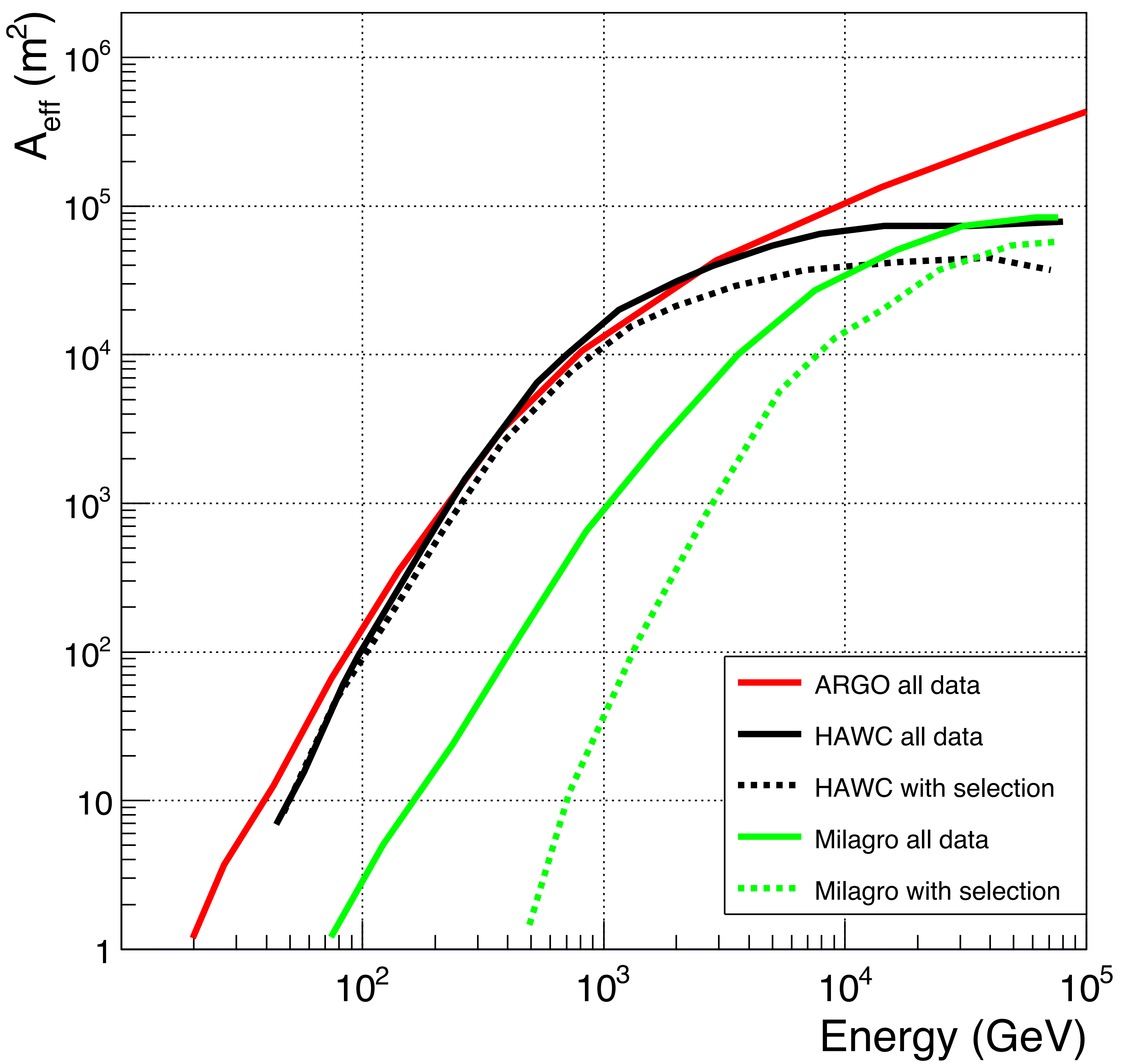
HAWC is a factor of 4.5 larger than ARGO-YBJ but effective areas similar below few TeV.

HAWC

- Instrumented Area: 120 X 140 m^2
- Coverage factor: 57 %
- Segmentation of the Read-out: >15 m

ARGO-YBJ

- Central Carpet: 76 X 75 m^2
- Coverage factor: 92 %
- Segmentation of the Read-out: 6 X 62 cm



The combination of

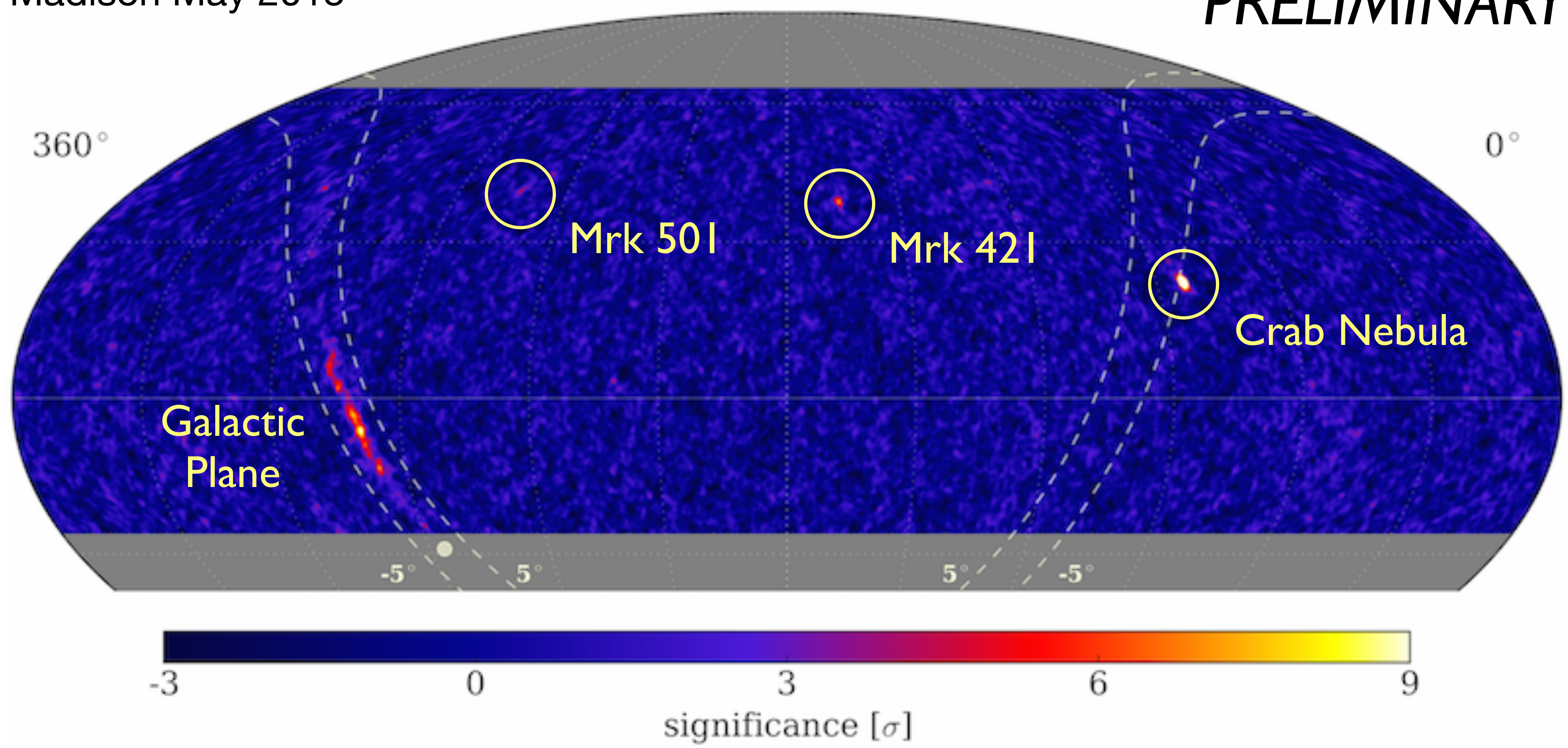
- full coverage
- high segmentaion of the read-out

makes the ARGO-YBJ experimental approach well suitable for high efficiency detection of sub-TeV showers.

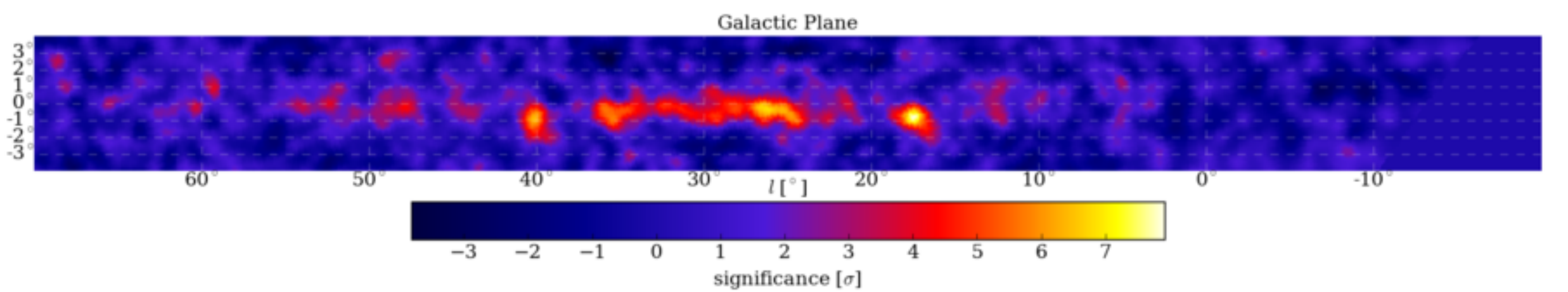
HAWC-250 Sky Map

S. BenZvi, IPA 2015, Madison May 2015

PRELIMINARY

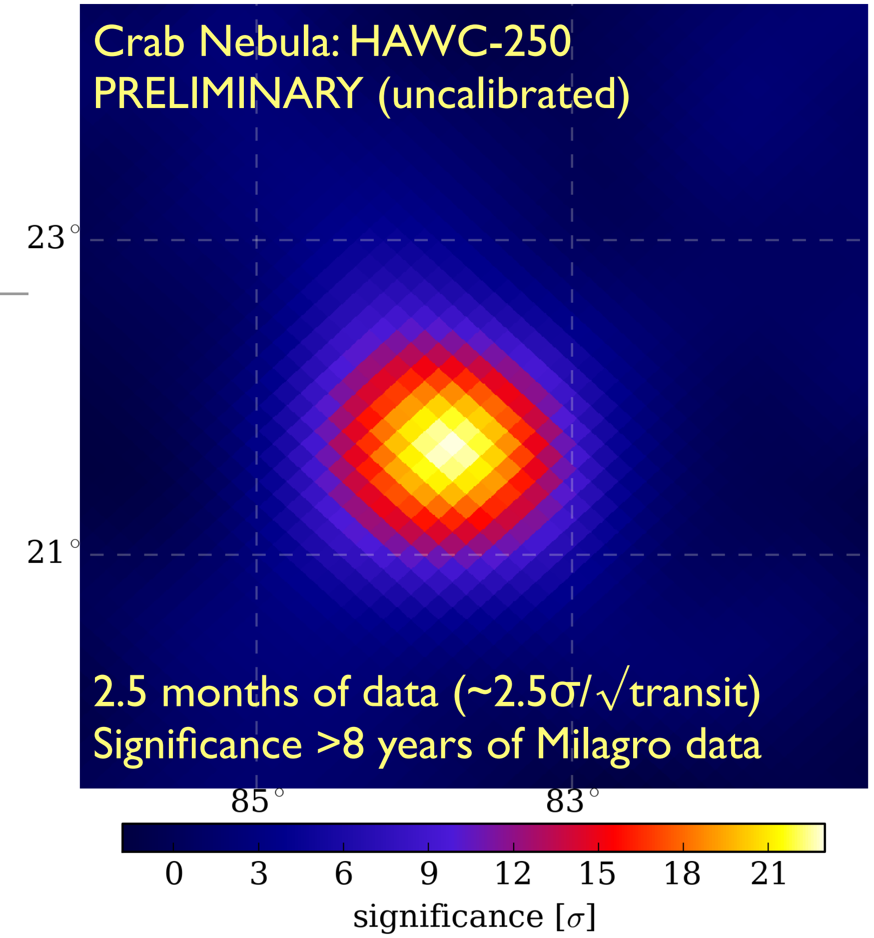


HAWC view of the Galactic Plane (PRELIMINARY)

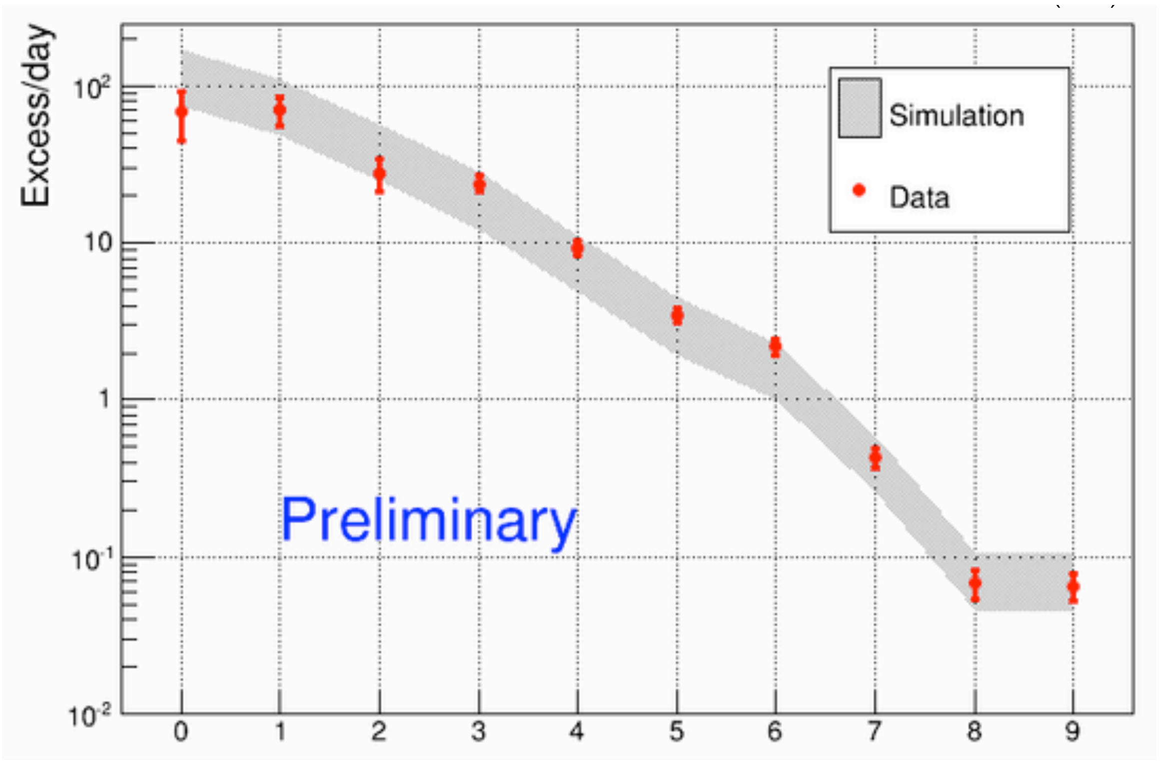


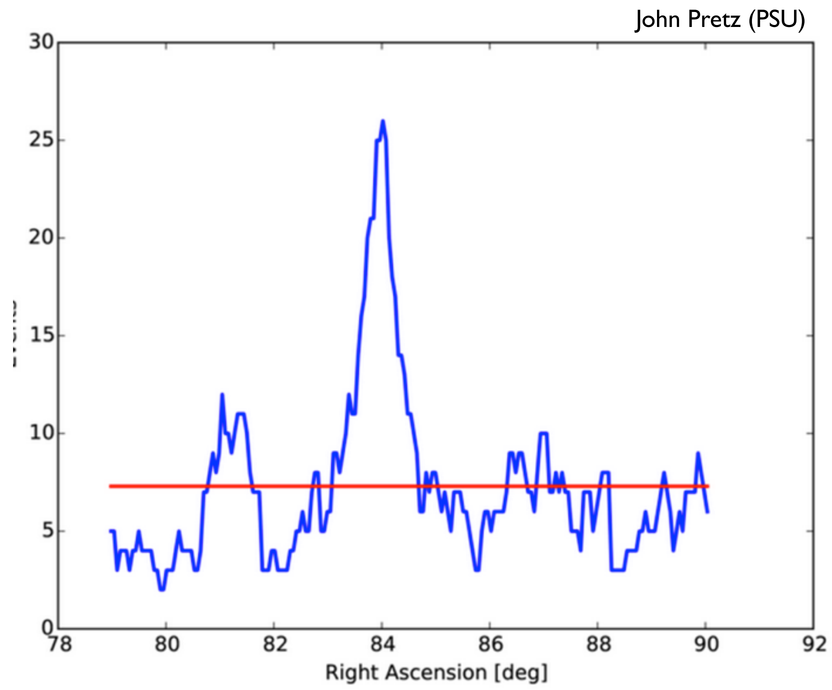
Crab Nebula: HAWC - 111

- Trigger rate: 10 kHz, >99.9% cosmic rays
- Roughly 400 gammas/day from the Crab Nebula
- Tight cuts on high-energy sample: signal/background ~ 3



Excess counts from Crab Nebula: data vs. simulation





- 9 analysis bins in N_{hit}
- Bin 0: ~300 GeV median
- Bin 9: ~10 TeV median

S. BenZvi, IPA 2015, Madison May 2015

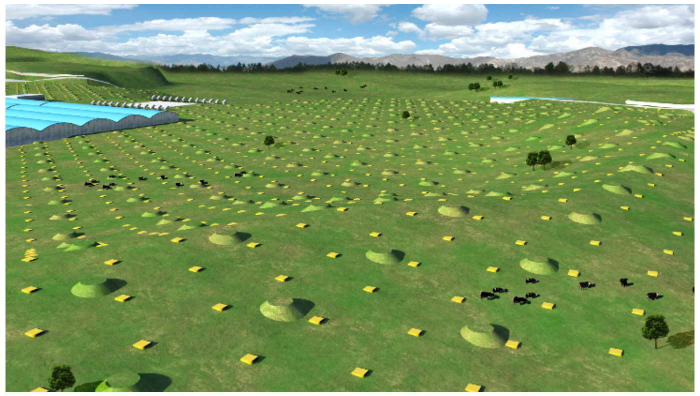
What is LHAASO ?

The Large High Altitude Air Shower Observatory (LHAASO) project is a new generation all-sky instrument to investigate the '*cosmic ray connection*' through a combined study of cosmic rays and gamma-rays in the wide energy range 10^{11} -- 10^{17} eV.

The first phase of LHAASO will consist of the following major components:

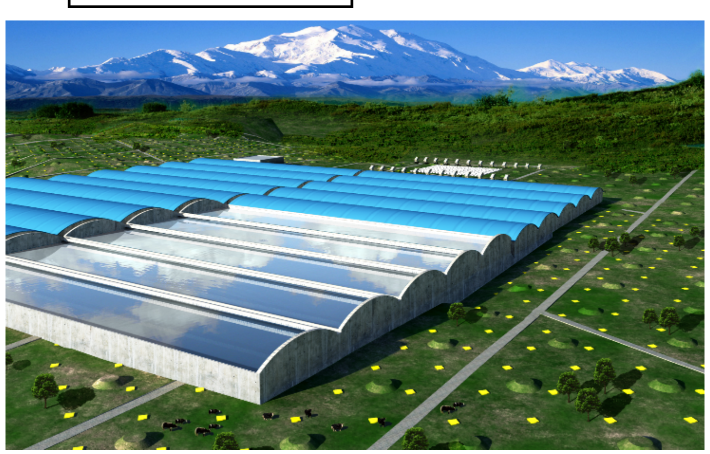
- 1 km^2 array (LHAASO-KM2A), including 5635 scintillator detectors, with 15 m spacing, for electromagnetic particle detection.
- An overlapping 1 km^2 array of 1221, 36 m^2 underground water Cherenkov tanks, with 30 m spacing, for muon detection (total sensitive area 40,000 m^2).
- A close-packed, surface water Cherenkov detector facility with a total area of 90,000 m^2 (LHAASO-WCDA), four times that of HAWC.
- 24 wide field-of-view air Cherenkov (and fluorescence) telescopes (LHAASO-WFCTA).
- 452 close-packed burst detectors, located near the centre of the array, for detection of high energy secondary particles in the shower core region (LHAASO-SCDA).

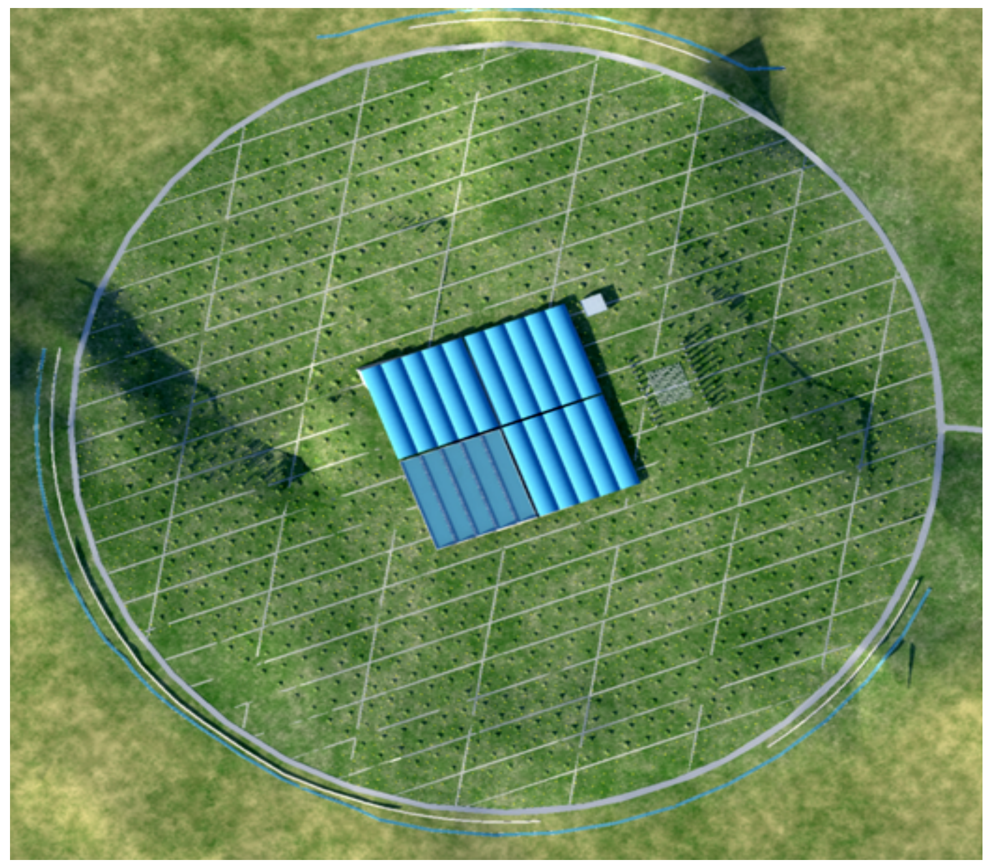
LHAASO main components

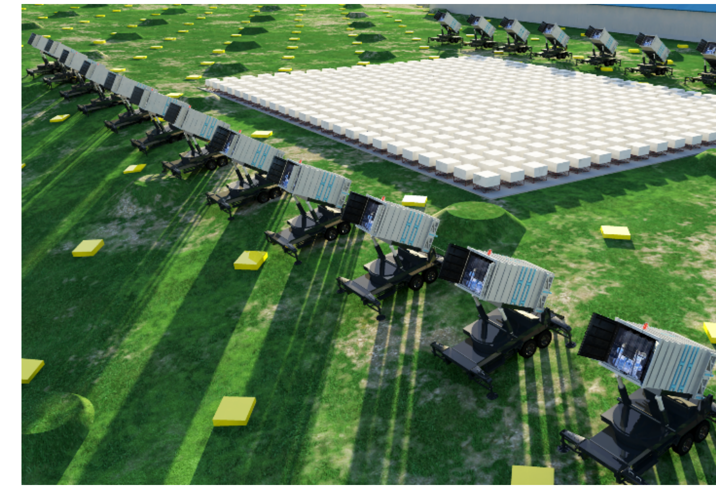


1 KM2A:
5635 EDs
1221 MDs

WCDA:
3600 cells
90,000 m^2

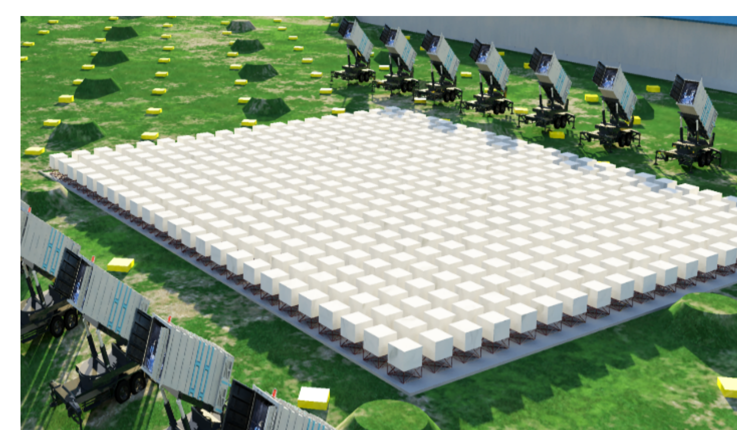






WFCTA:
24 telescopes
1024 pixels each

SCDA:
452 detectors



The LHAASO site

The experiment will be located at 4300 m asl (606 g/cm^2) in the Daocheng site, Sichuan province, China.

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

Status of LHAASO

- LHAASO is one of the '*Five top priorities*' projects of the Strategic Plan of IHEP approved by the Chinese Academy of Sciences (CAS).

- The National Reform and Development Commission (NRDC) and the Finance Ministry (FM) allocated for LHAASO 1 Billion CNY (about 160 M US$) ➜ *“Flagship Project”.*

- The government of Sichuan province will cover the total cost of the infrastructure construction: 300 M CNY.

Tentative Schedule (May 2015)

★ July 2015: start of construction of first quarter of WCDA, KM2A.
★ May 2016: installation of PMTs in the first pond.

★ Spring, 2017: start scientific operation of the first quarter of LHAASO.

★ 2019: conclusion of installations.

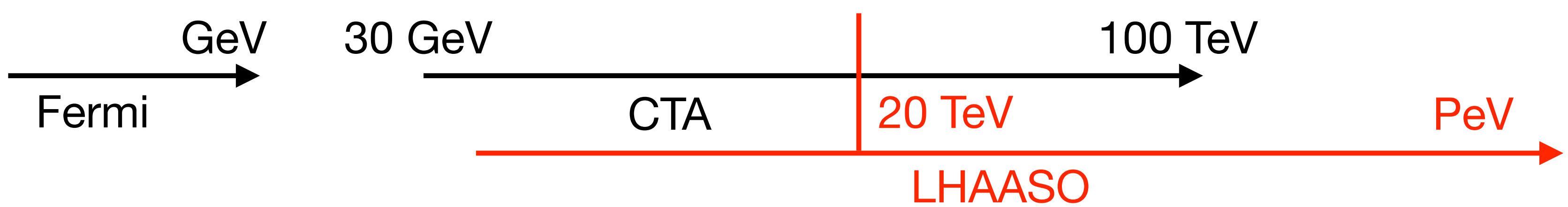
Why LHAASO ?

The LHAASO experiment will be the next generation ground-based experiment, capable of acting simultaneously as a Gamma Ray Telescope and a Cosmic Ray Detector.

✤ Gamma-Ray Astronomy ($10^2 \rightarrow 10^6$ GeV): full sky continuous monitoring

- *Below 20 TeV*: continuous monitoring of the Northern sky at < 0.01 of the Crab flux → Sky survey: complementarity with CTA (Cherenkov Telescope Array)

- *Above 20 TeV*: continuous monitoring of the Northern sky up to PeV with a sensitivity 2000x CTA for sky survey > 70 TeV → search for PeV cosmic ray sources (*Pevatrons)*



✤ Cosmic Ray Physics ($10^{12} \rightarrow 10^{17}$ eV): precluded to Cherenkov Telescopes

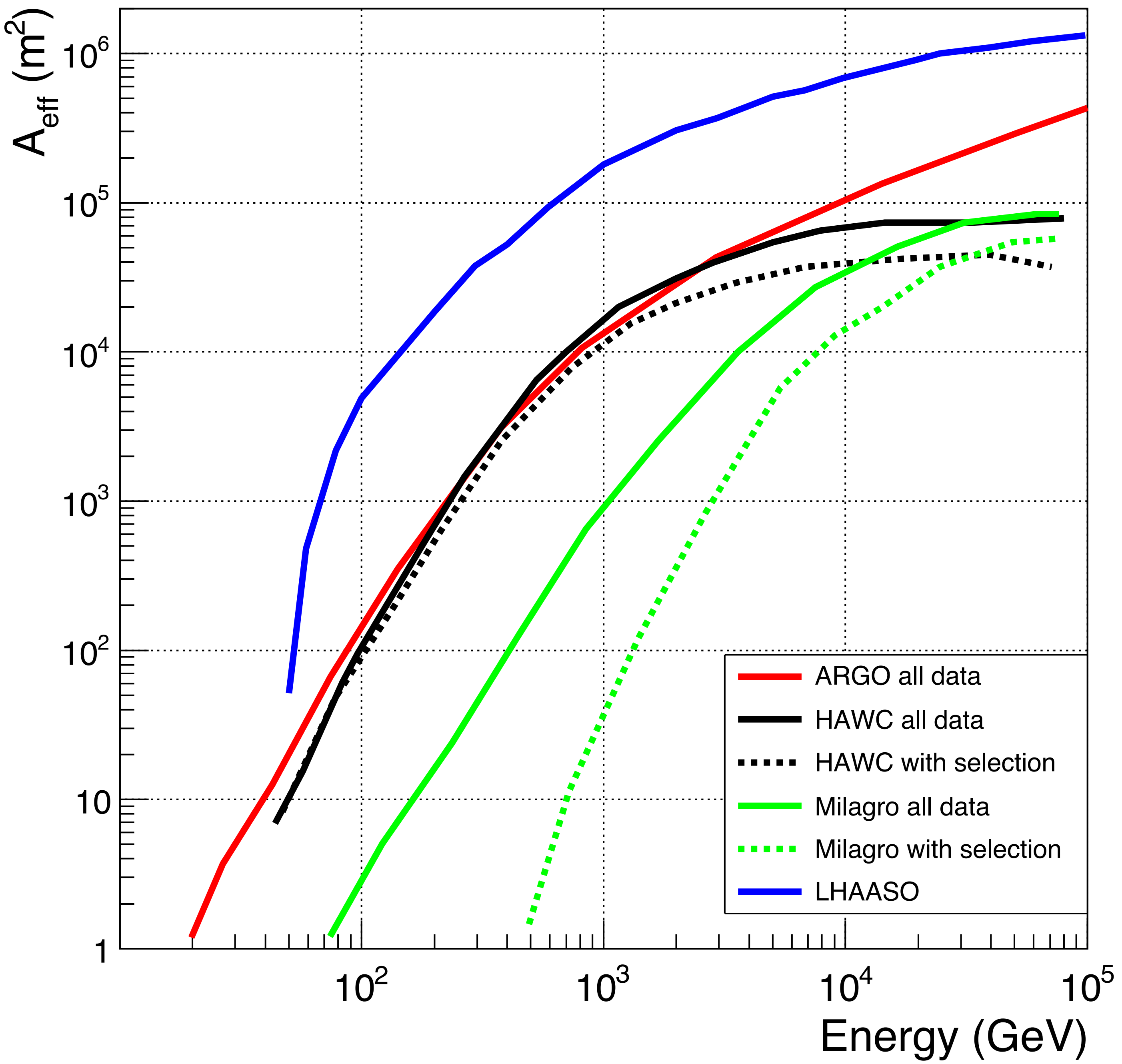
- CR energy spectrum
- Elemental composition
- Anisotropy

Effective Area

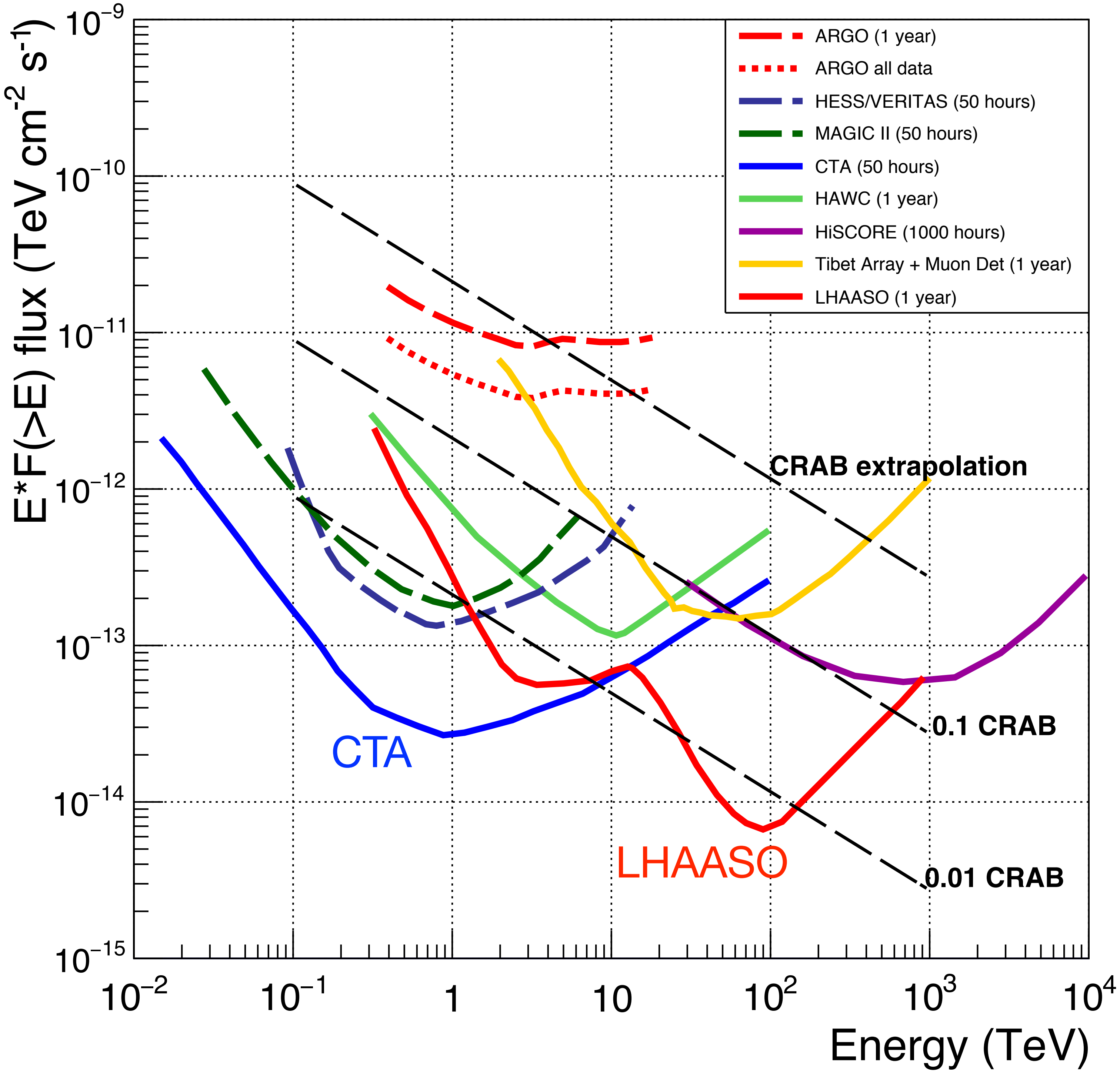
LHAASO

- Instrumented Area: 300 X 300 m^2
- Coverage factor: 90 %
- Segmentation of the Read-out: 5 m

100 GeV ≈ 5,000 m^2
1 TeV ≈ 180,000 m^2
100 TeV ≈ 1.4 10^6 m^2



Sensitivity to gamma point sources



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.

The big advantage of LHAASO

- High Energy (>10 TeV)
- Sky Survey

LHAASO Physics Potential

From TeVCat:

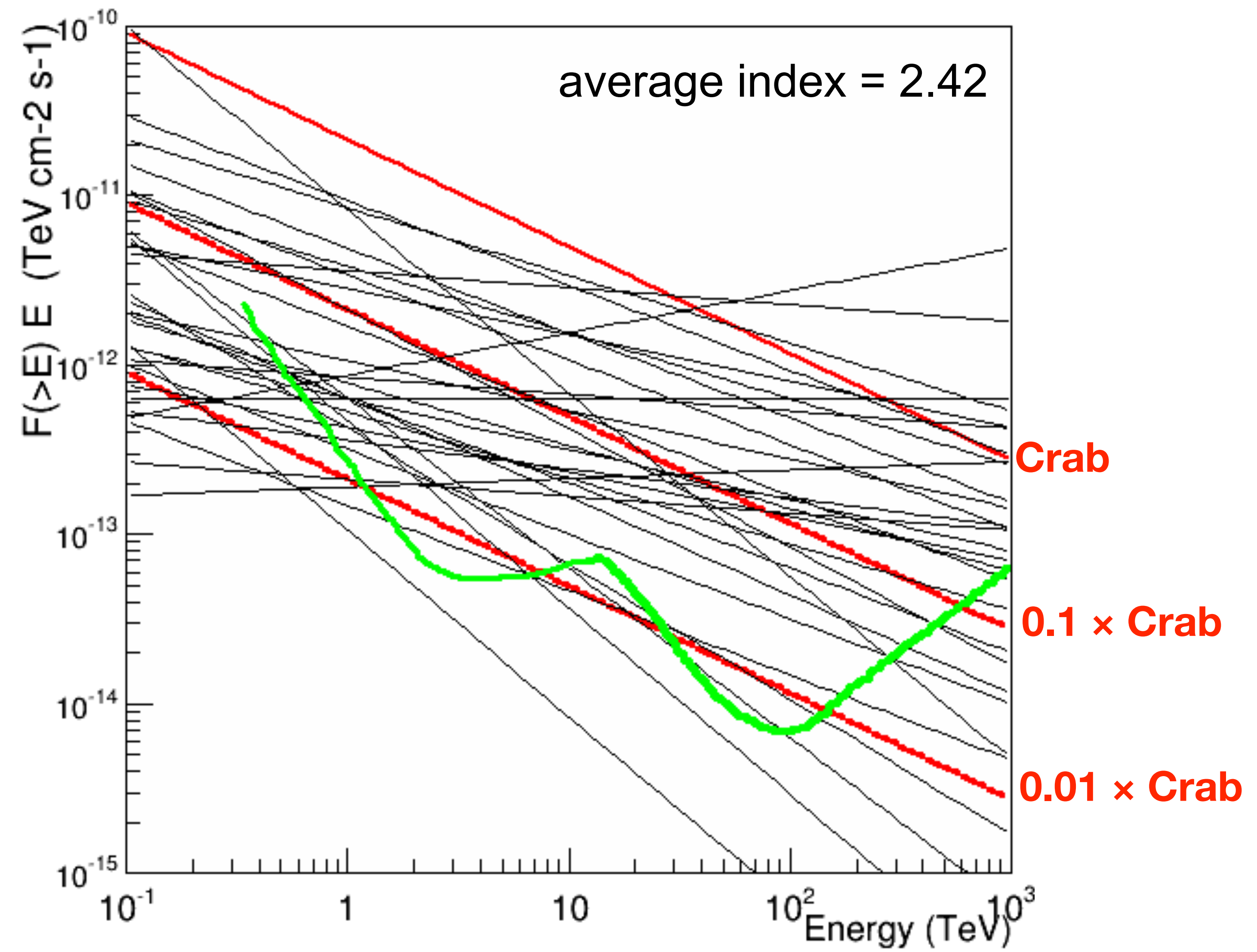
71 sources culminating at zenith angle < 40°

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



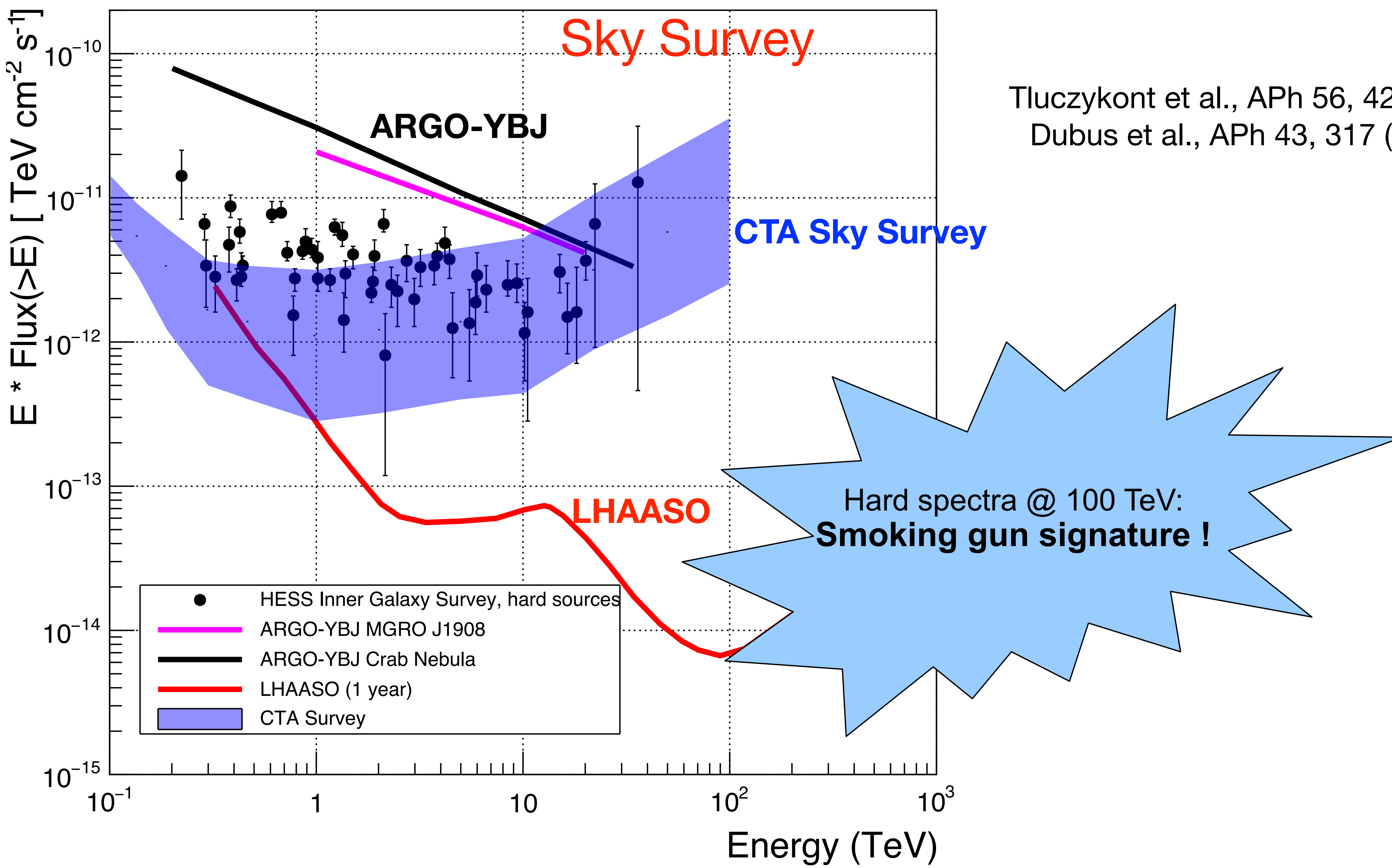
70% of Galactic sources are extended

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

Opening the PeVatron range

Lhaaso has no competitors for sky survey: in one year it can survey the Northen sky at 100 TeV at a level < 0.01 Crab !



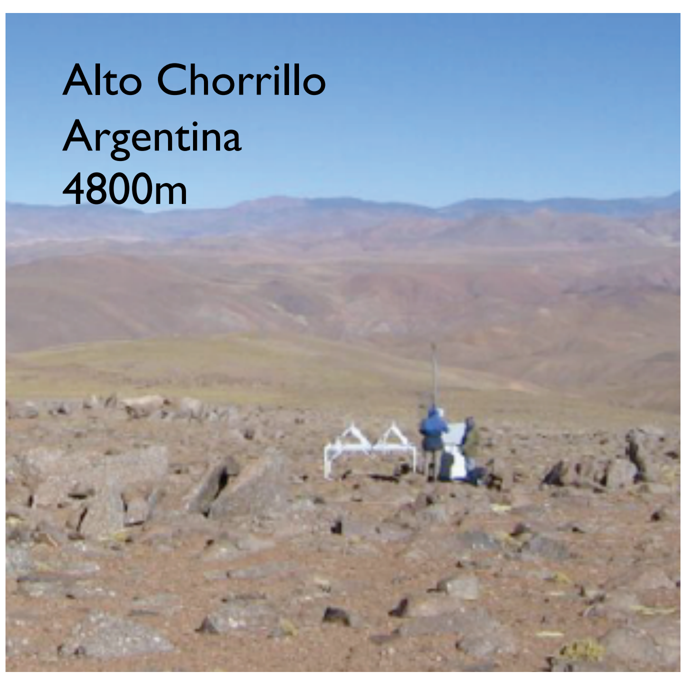
Tluczykont et al., APh 56, 42 (2014)
Dubus et al., APh 43, 317 (2013)

Outlook: Southern Hemisphere

All the future Wide Field of View detector located in the Northern Hemisphere

To maximize the scientific return for Galactic sources, a future instrument should be located at sufficiently Southern latitude to continuously monitor the Galactic Center and the Inner Galaxy.

In the near future such an instrument will be paired with the coming km^3 Mediterranean neutrino detector



36 **CF6 Working Group Summary**

LHAASO The LHAASO (Large High Altitude Air Shower Observatory) is an ambitious project based upon a combination of water Cherenkov technology, scintillation detectors, and air Cherenkov technology. LHAASO will consist of a $\sim$90,000m^2 water Cherenkov detector surrounded by 5100 scintillation detectors distributed over an area of $\sim$1km^s with 43,000 m^2 of buried muon detectors. In addition 24 air fluorescence/Cherenkov telescopes will be located onsite. At an altitude of $\sim$4300m, it is expected that LHAASO will have somewhat better sensitivity than HAWC at low energies (<10 TeV), with significantly improved sensitivity at higher energies. This project recently received approval from the Chinese government and the completion of construction is expected in 2018.

A Future Wide-Field High-Duty Cycle Gamma-Ray Experiment HAWC was designed and built based on the results from the Milagro experiment. Similarly, the design of a future wide-field high duty-cycle experiment will be based upon the results from HAWC (or LHAASO). There are two distinct paths for a future instrument: significantly higher sensitivity to higher energy gamma rays, in excess of 100 TeV or significantly reducing the useful energy threshold. If the HAWC data shows that exciting physics is to be found at the highest energies (cosmic-ray origins, Galactic gamma-ray sources), then a plan to increase the collecting area at the highest energies would be recommended. Such an upgrade could be performed at the existing HAWC site or at a new location, perhaps in the Southern hemisphere to provide an alert system for the CTA South. On the other hand, if extragalactic phenomena, especially transient events such as flares from active galaxies to gamma-ray bursts, yield a rich source of information on particle acceleration, ultra-high-energy cosmic rays, and tests of fundamental physics, a detector with a significantly lower energy threshold would be recommended. Such an instrument would require the highest altitude site attainable, and thus would naturally be placed in the Southern hemisphere. Within the Chajnantor plateau in Chili it seems feasible to site such an instrument at $\sim$6km above sea level.

Conclusions

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

First HAWC results are round the corner.

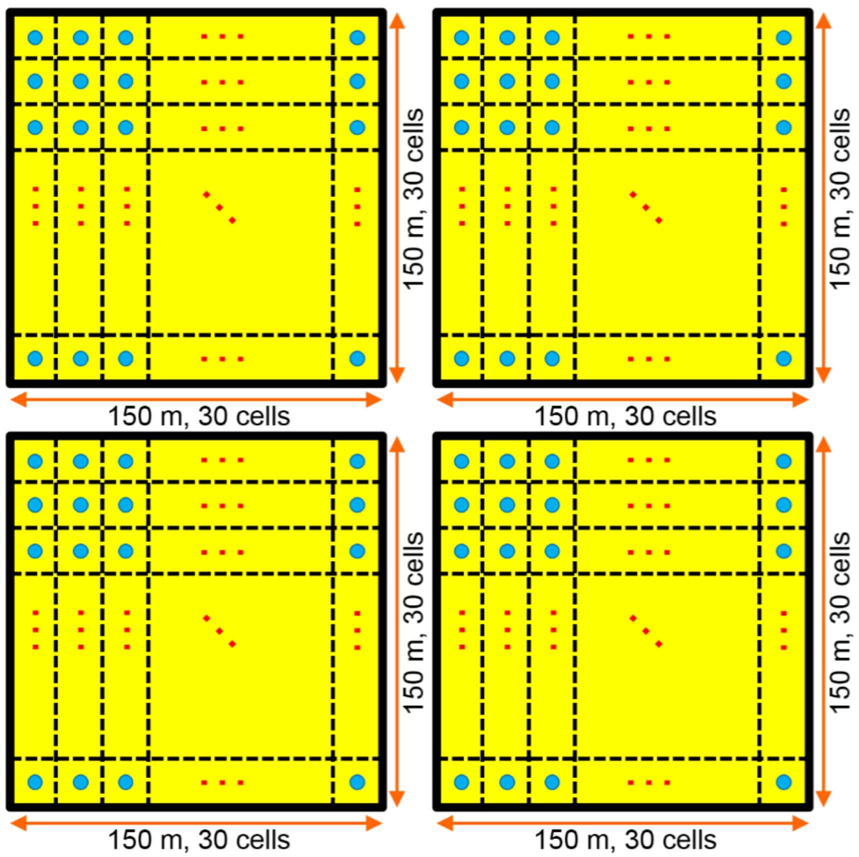
LHAASO is the most ambitious project with very interesting prospects, being able to deal with all the main open problems of cosmic ray physics at the same time.

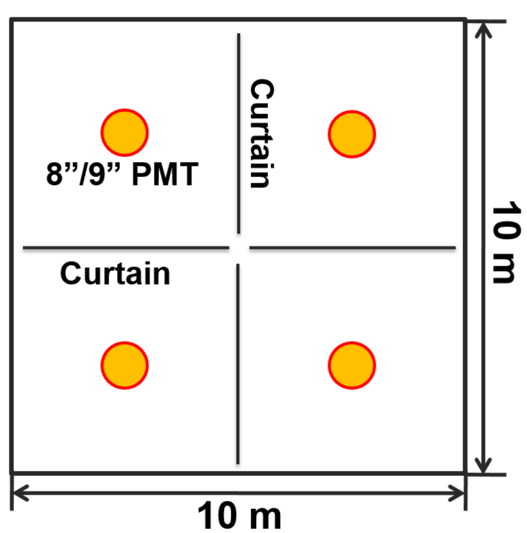
It is proposed to study CRs in a *unprecedented wide energy range 10^{11} - 10^{18} eV*, from those observable in space with AMS and approaching those investigated by AUGER, thus including, in addition to the 'knee', the whole region between 'knee' and 'ankle' where the galactic/extra-galactic CR transition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

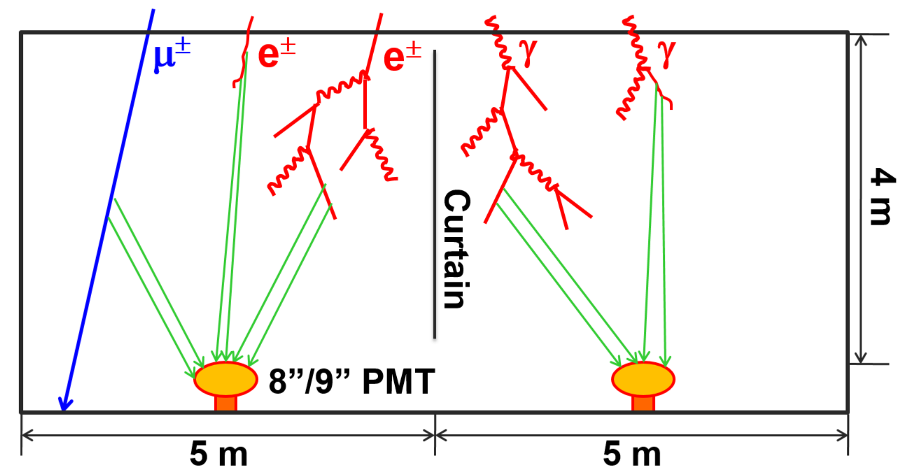
At the same time it is proposed as a tool of great sensitivity - unprecedented above 20 TeV - to monitor '*all the sky all the time*' a gamma-ray domain extremely rich of sources variable at all wavelengths.

Due to the modular structure of the experiment, first physics results are expected after only 2-3 years from the start of installation. Final installation in 5-6 years.

Water Cherenkov Detector Array

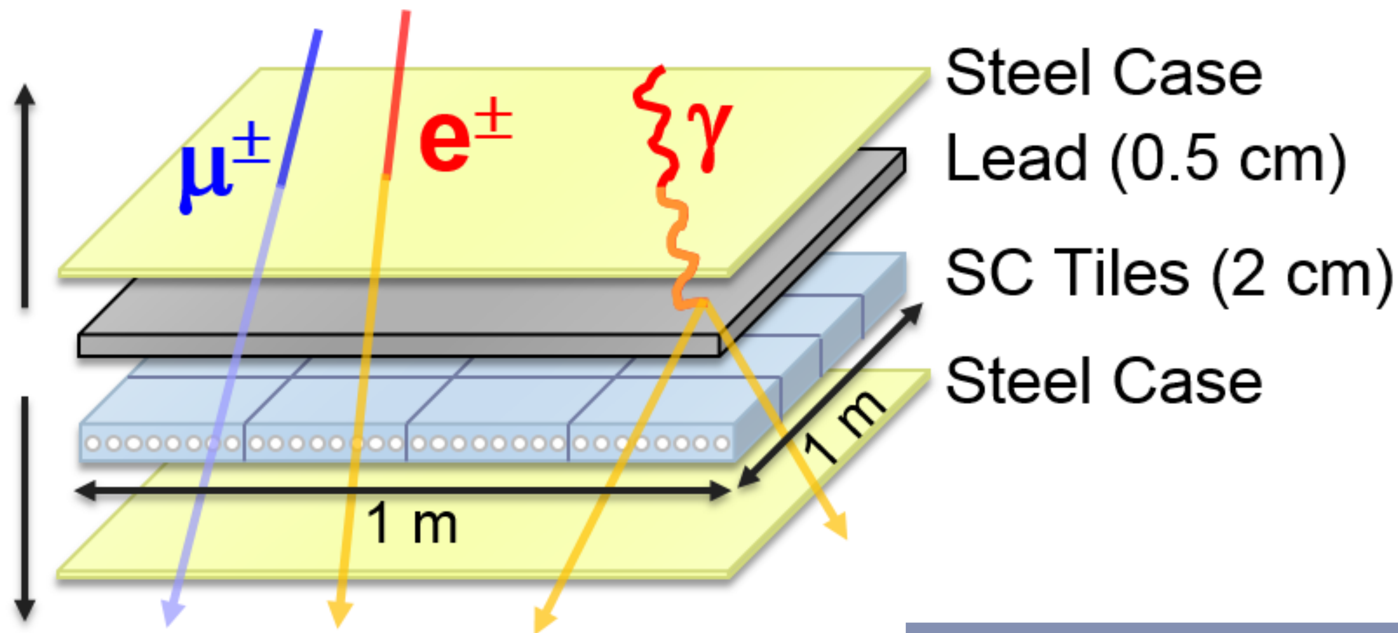


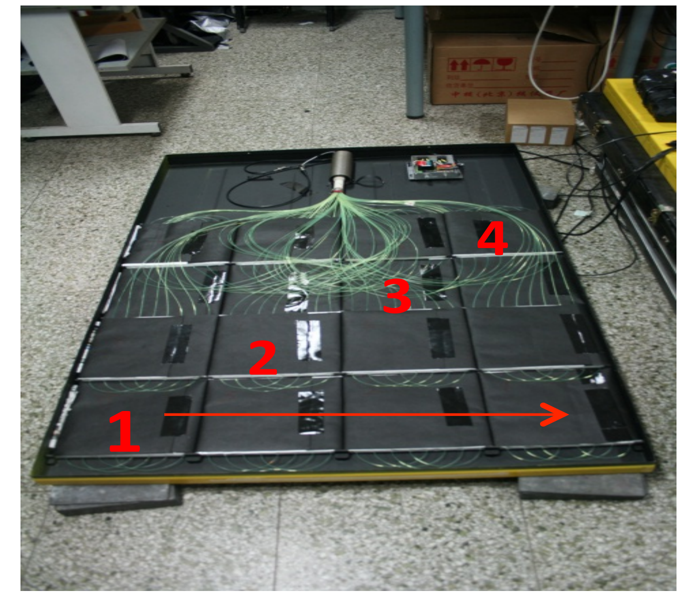


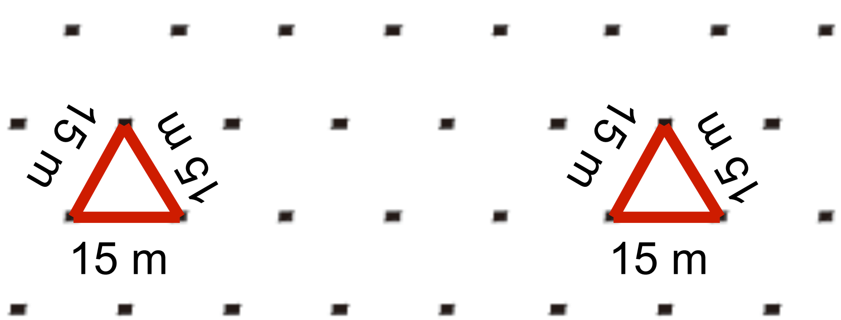


Item	Value
Cell area	25 m^2
Effective water depth	4 m
Water transparency	> 15 m (400 nm)
Precision of time measurement	0.5 ns
Dynamic range	1-4000 PEs
Time resolution	<2 ns
Charge resolution	40% @ 1 PE 5% @ 4000 PEs
Accuracy of charge calibration	<2%
Accuracy of time calibration	<0.2 ns
Total area	90,000 m^2
Total cells	3600

Electromagnetic particle Detector

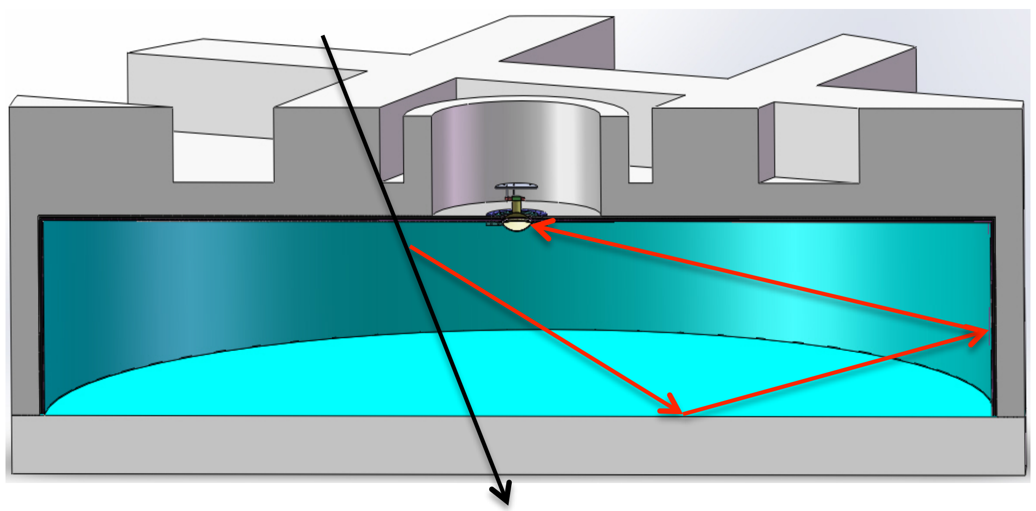


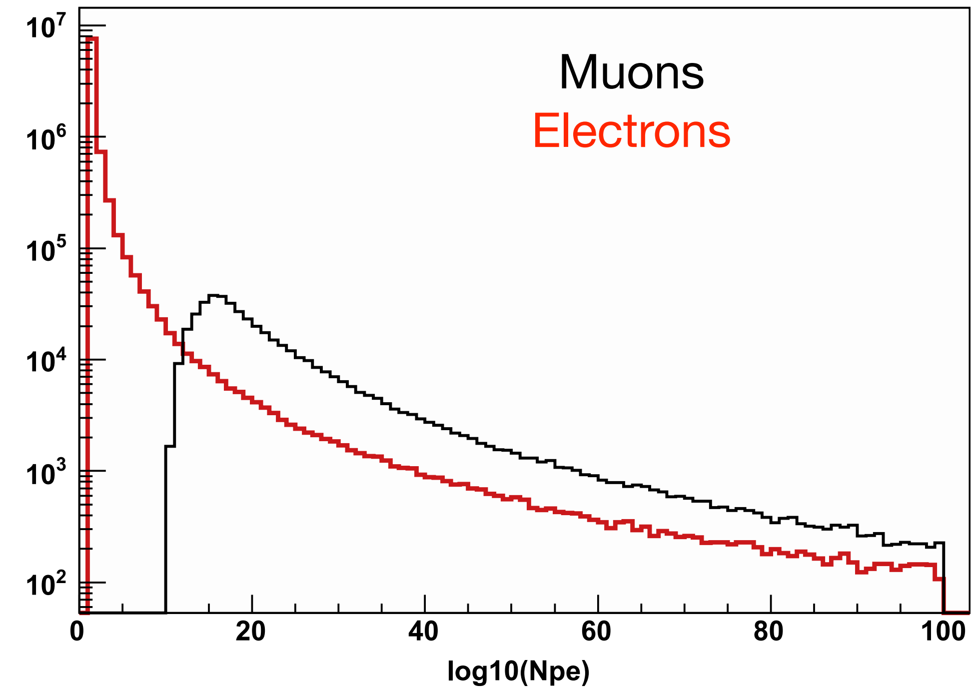




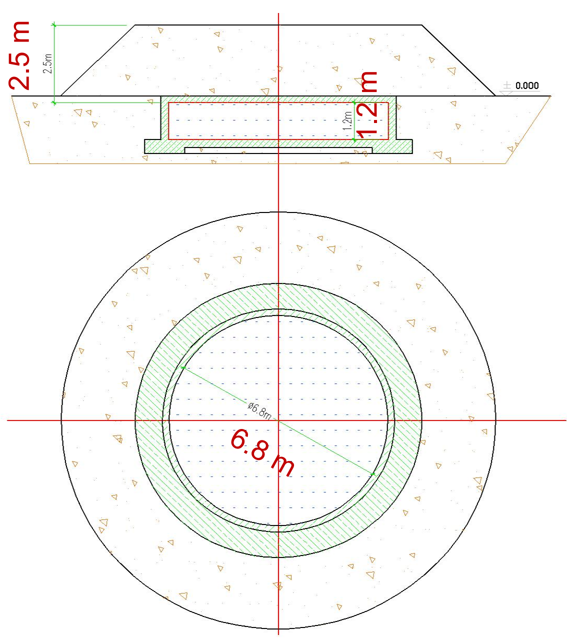
Item	Value
Effective area	1 m^2
Thickness of tiles	2 cm
Number of WLS fibers	8/tile×16 tile
Detection efficiency (> 5 MeV)	>95%
Dynamic range	1-10,000 particles
Time resolution	<2 ns
Particle counting resolution	25% @ 1 particle 5% @ 10,000 particles
Aging	>10 years
Spacing	15 m
Total number of detectors	5635

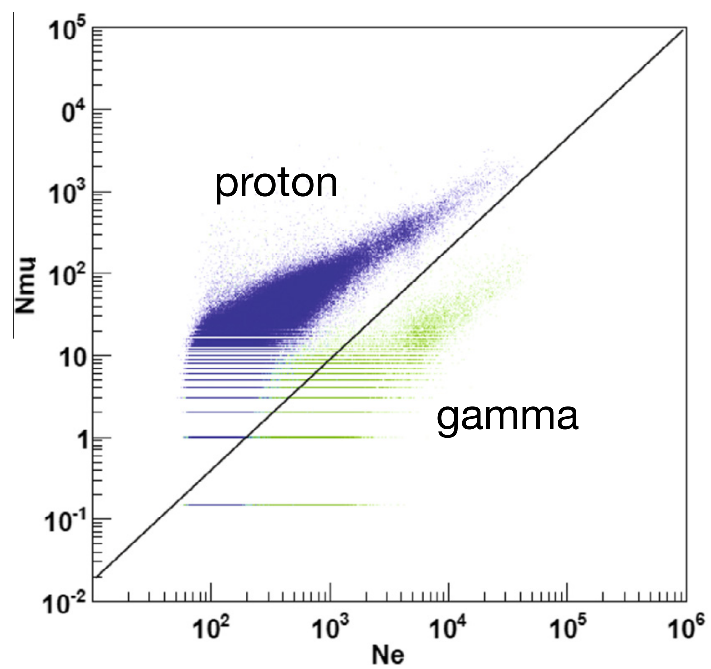
Muon Detector





Photoelectrons distribution at R > 100 m from the shower core position



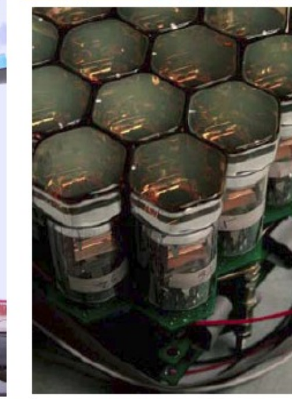


Item	Value
Area	36 m^2
Depth	1.2 m
Molasses overburden	2.5 m
Water transparency (att. len.)	> 30 m (400 nm)
Reflection coefficient	>95%
Time resolution	<10 ns
Particle counting resolution	25% @ 1 particle 5% @ 10,000 particles
Aging	>10 years
Spacing	30 m
Total number of detectors	1221

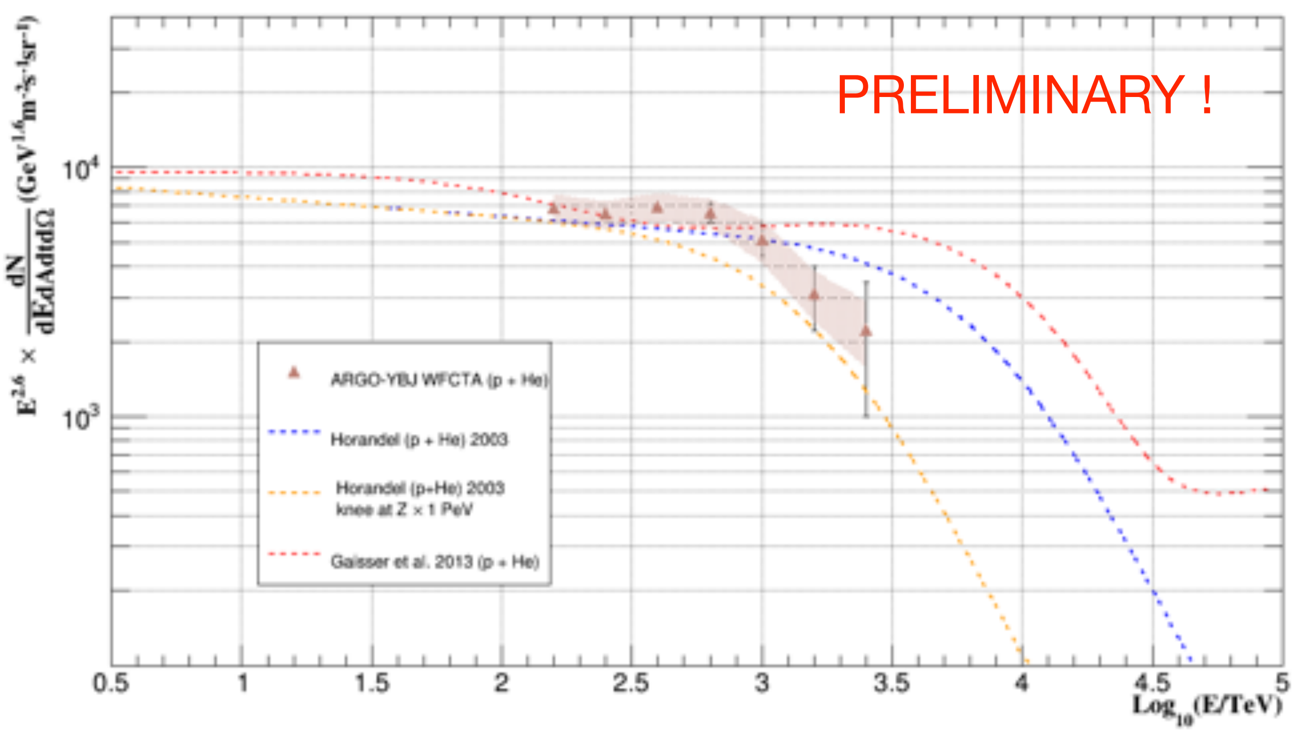
Wide field of view Cherenkov Telescope Array

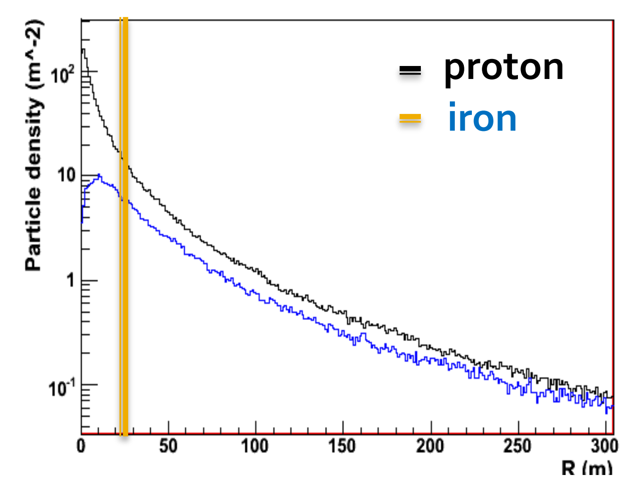
24 telescopes (Cherenkov/Fluorescence)

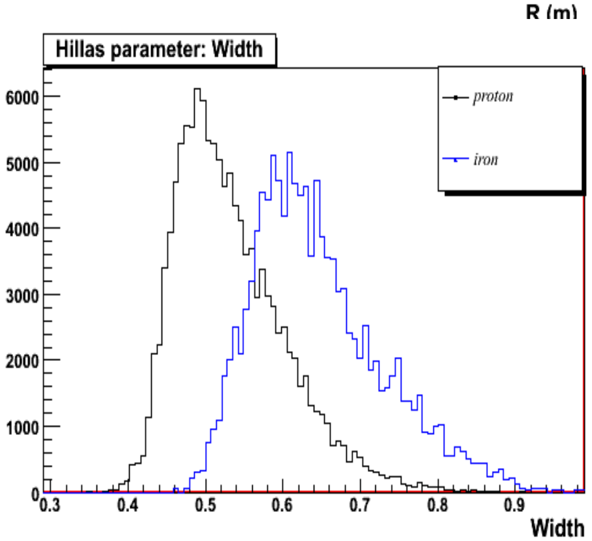
- 5 m^2 spherical mirror
- 16×16 PMT array
- pixel size 1°
- FOV: $14° \times 14°$
- Elevation angle: 60°

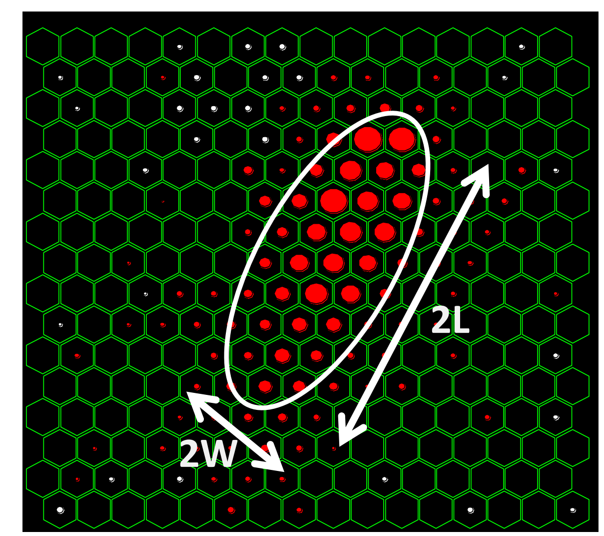


ARGO-YBJ / WFCTA



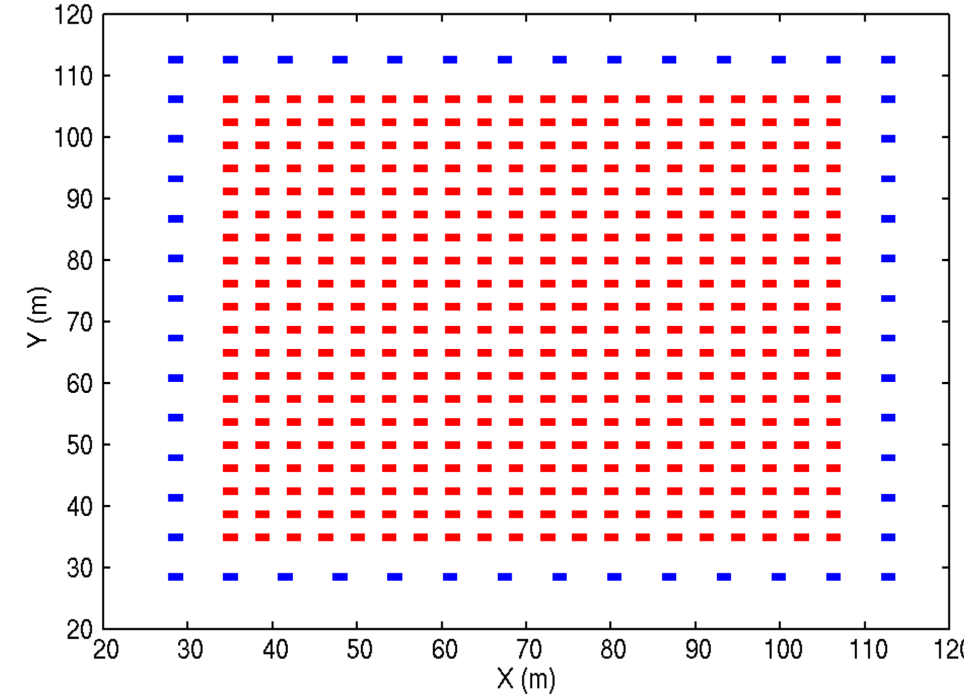




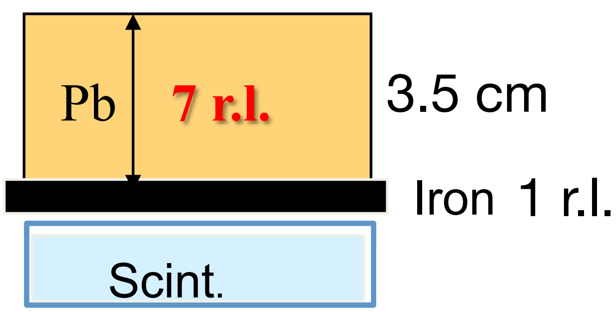


Shower Core Detector Array

- 425 close-packed burst detectors, located near the centre of the array, for the detection of high energy secondary particles in the shower core region.



Burst Detector



The burst detectors observe the electron size (burst size) under the lead plate induced by high energy e.m. particle in the shower core region

- Number of SCD: 0.5 m^2 x 452
- Cover Area: 5170 m^2
- Energy region: 30 TeV - 10 PeV
- Core position resolution: 1.5 m @50 TeV

Each burst detector is constituted by 20 optically separated scintillator strips of 1.5 cm × 4 cm × 50 cm read out by two PMTs operated with different gains to achieve a wide dynamic range (1- 10^6 MIPs).

- **Lead plate (80 cm X 50 cm X 7 rl)**
- **Iron plate (1 m X 1 m X 1 rl)**