INFN
Istituto Nazionale di Fisica Nucleare

Wide Field of View Experiments: from Gamma-Ray Astronomy to Cosmic Ray Physics

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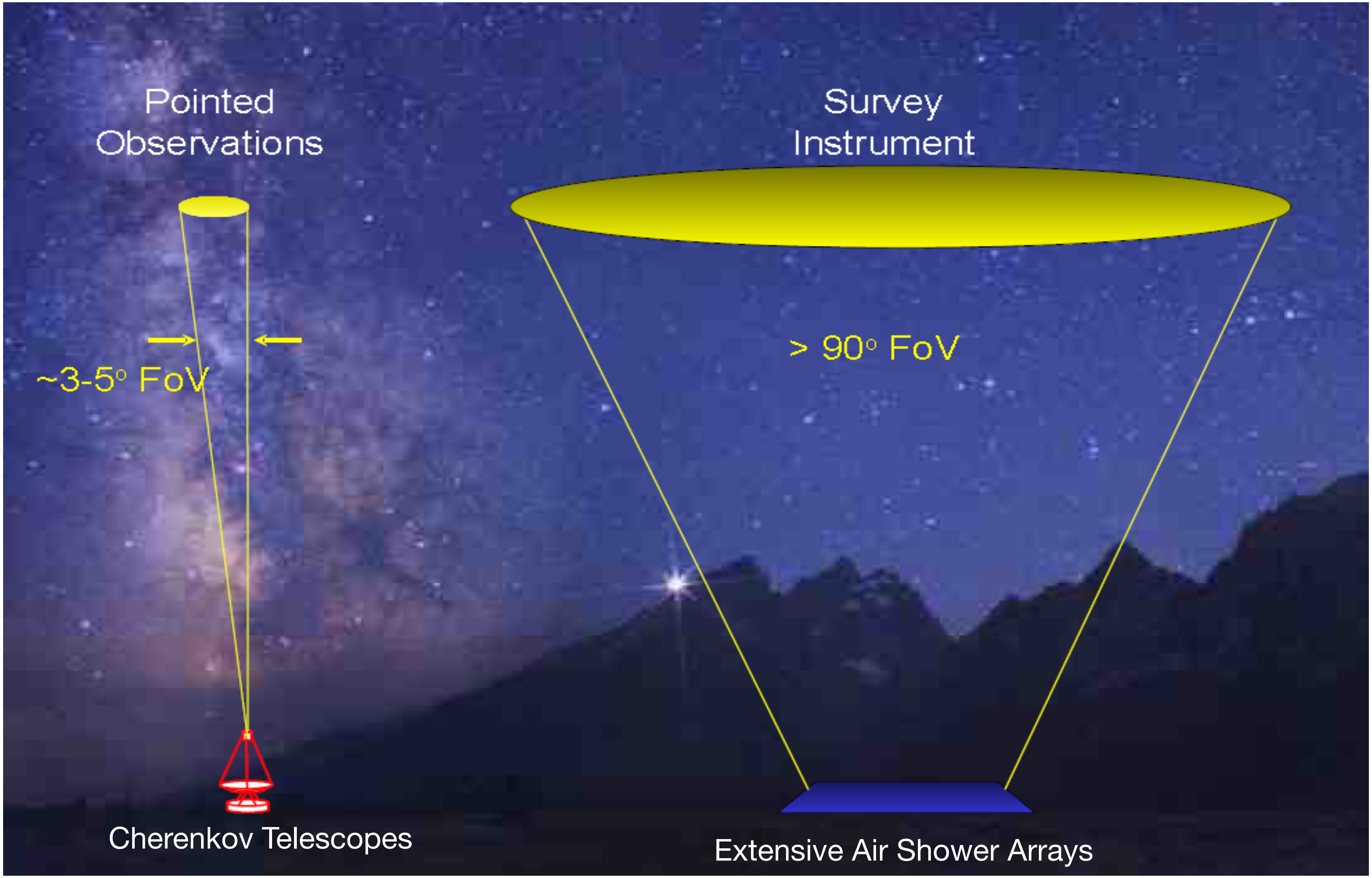
Workshop on "Perspectives in Astroparticle Physics from High Energy Neutrinos"
Sept. 25-26, 2017 - Naples, Italy

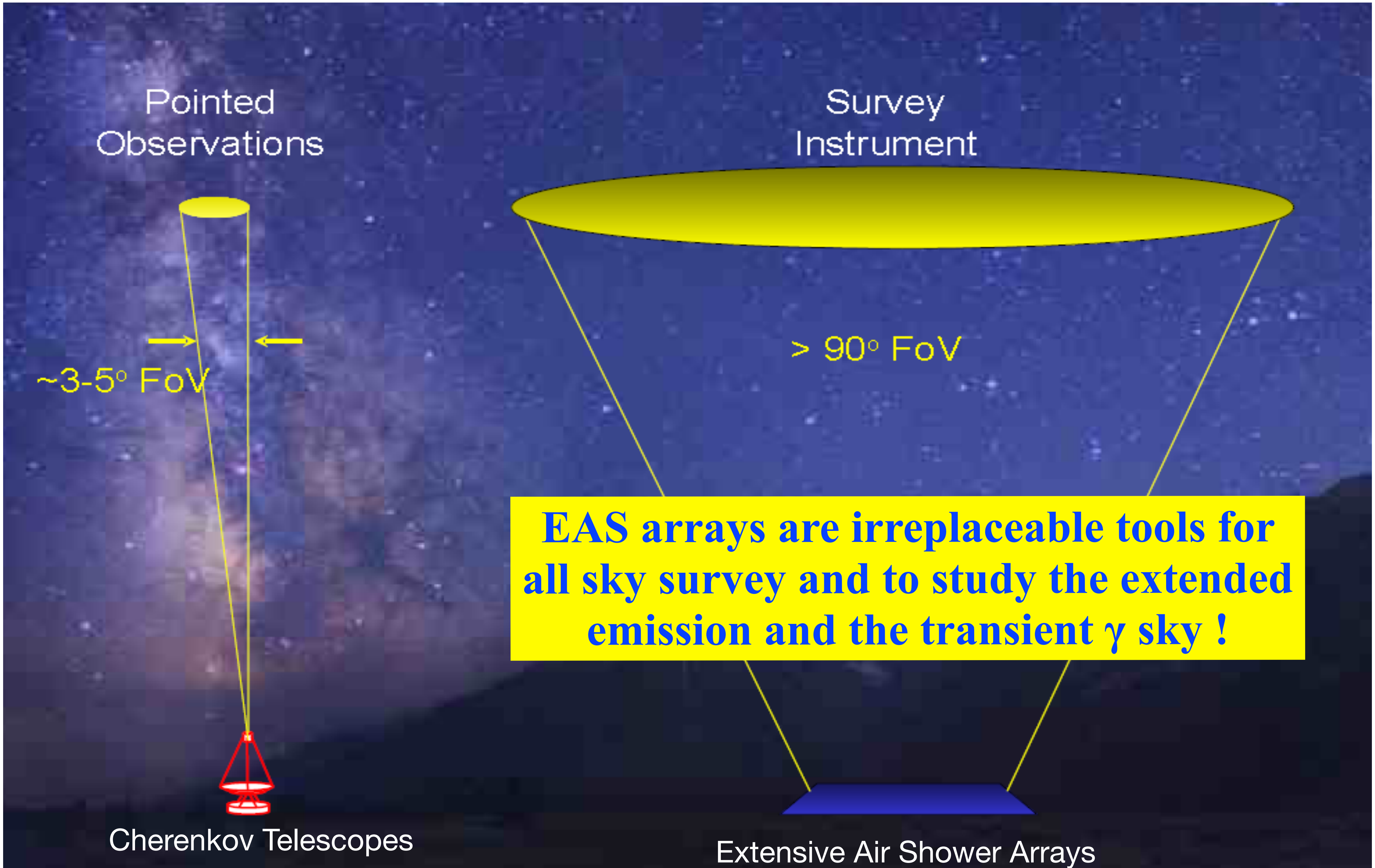
Outline

- Why a Wide Field of View detector ?
- The scientific case: open problems in Cosmic Ray Physics
- Status of current wide FoV detectors: HAWC and LHAASO
- What’s Next ? The Southern Hemisphere

Pointed and Survey Instruments



Pointed and Survey Instruments

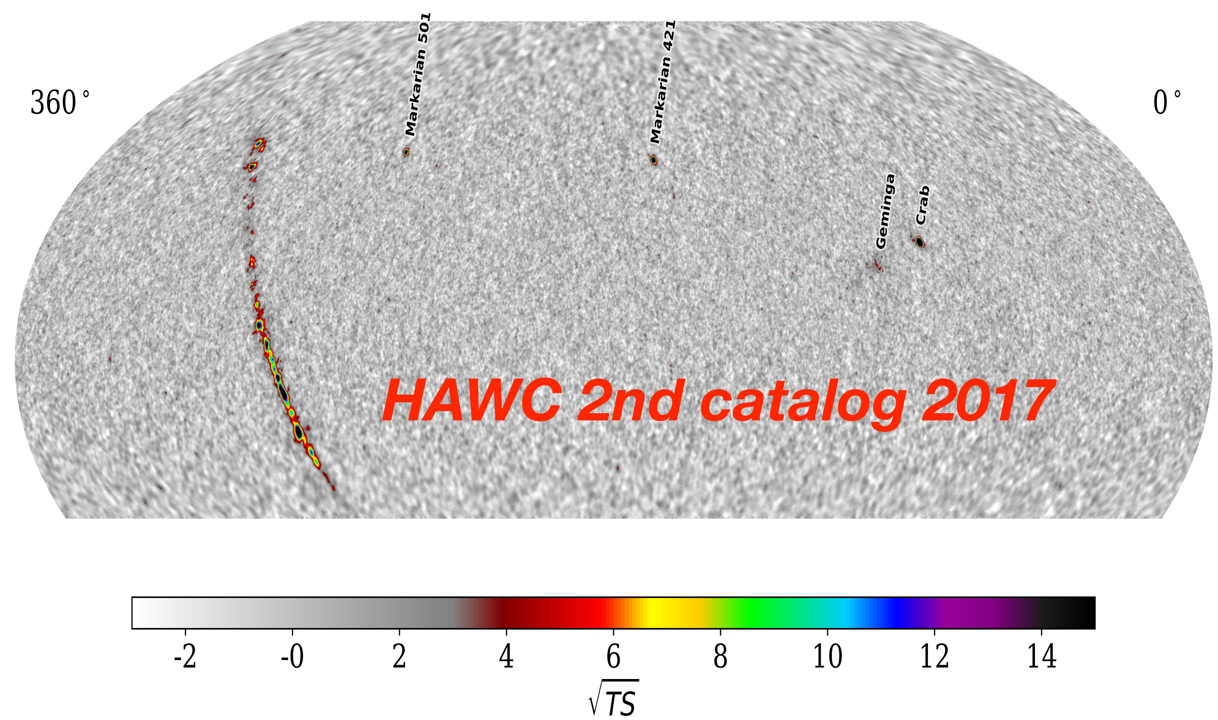


EAS arrays are irreplaceable tools for all sky survey and to study the extended emission and the transient γ sky !

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 *extended* and *diffuse emission* on scales of several degrees
- study of localized CR *anisotropies*
- search for small and nearby high latitude *molecular clouds*
- study of *CR energy spectrum* and *elemental composiiton*
- constraints on *DM* at multi-TeV scale by *'stacked analysis'*

A full exploration of the Galactic Plane requires both Northern and Southern detectors !

- 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.

The Galactic Cosmic Ray puzzle

To understand the origin of Galactic Cosmic Rays we need to

- ★ identify the main sources able to accelerate particles up to the highest energy we observe
- ★ understand how particles escape from their sources and are released into the interstellar medium (ISM)
- ★ understand how particles propagate through the Galaxy before reaching the Earth.

The three main pillars that constitute the SNR paradigm for the origin of CRs: acceleration, escape and propagation

We need to know

★ Acceleration and escape

- which acceleration mechanism ? ➜ injection spectrum
- total energy released in CRs
- maximum energy of accelerated particles: the *'proton knee'*

The description of how particles escape from a SNR shock has not been completely understood yet, the reason being the uncertainties related to *how particles reach the maximum energies.*

Morlino, 2017

★ Propagation

- magnetic field in the Galaxy
- spatial distribution of sources
- spatial distribution of CRs
- injected ➜ observed spectrum

★ Which is the chemical composition of CRs ?

Why are Wide FoV instruments so cool ?

★ Acceleration and escape → *Gamma-Ray Astronomy*

- which acceleration mechanism ? → injection spectrum
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- injected → observed spectrum

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- …d → observed spectrum

★ Which is the chemical composition of CRs ?

Wide FoV detectors = Multi-Messenger Instruments (by definition)

Cosmic Rays and γ-Ray Astronomy connection

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

$\pi^{0} \rightarrow$ **γ Gamma-Ray Astronomy**

$\pi^{+}, \pi^{-} \rightarrow$ **ν Neutrino Astronomy**

CRs, photons and neutrinos strongly correlated

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

Recent observations of PeV neutrinos by IceCube

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

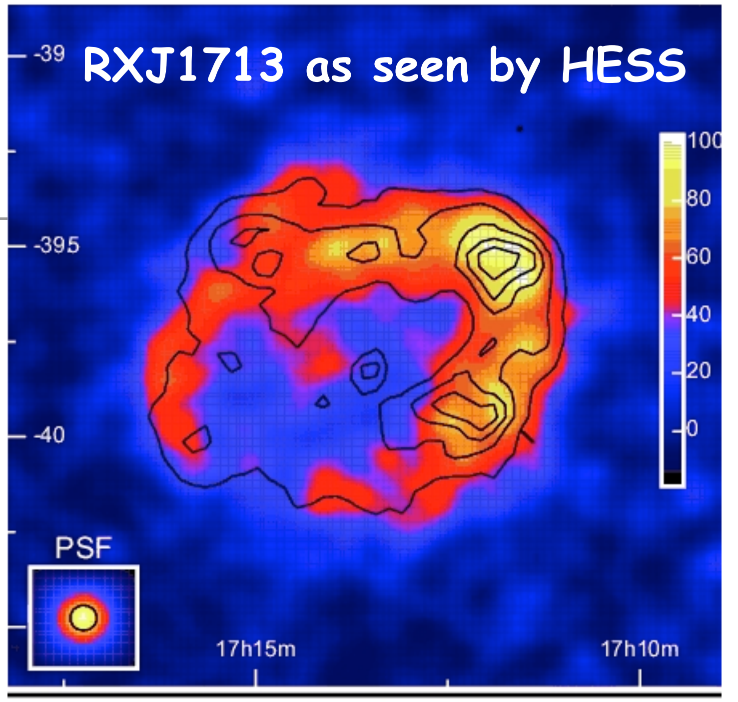
scattering of electrons on low energy photons:

- ✓ 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...)

SNR - Cosmic Rays Connection



It is beyond any doubt that bulk of the CRs are originated in SNRs where they are accelerated by diffusive shock acceleration process at supernova blast waves driven by expanding SNRs.

The question is rather *which is the total amount of energy channeled into relativistic particles and which is the final spectrum injected into the ISM.*

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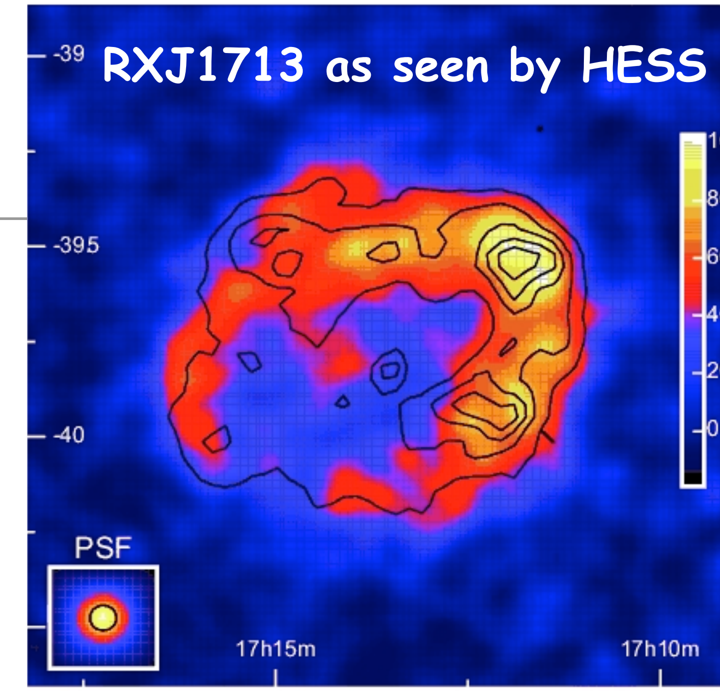

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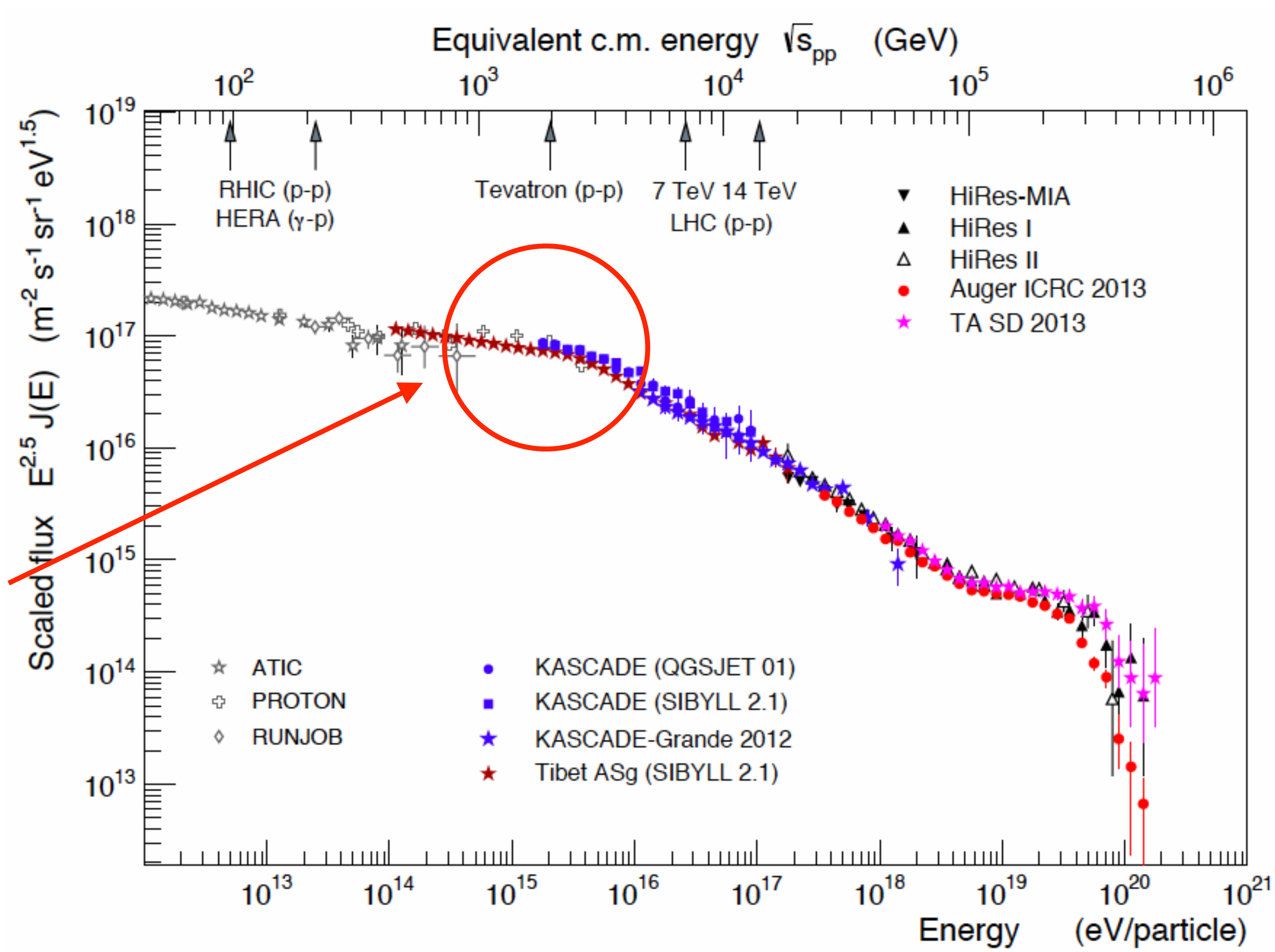

CR knee @ few PeV's
Something must happen here...

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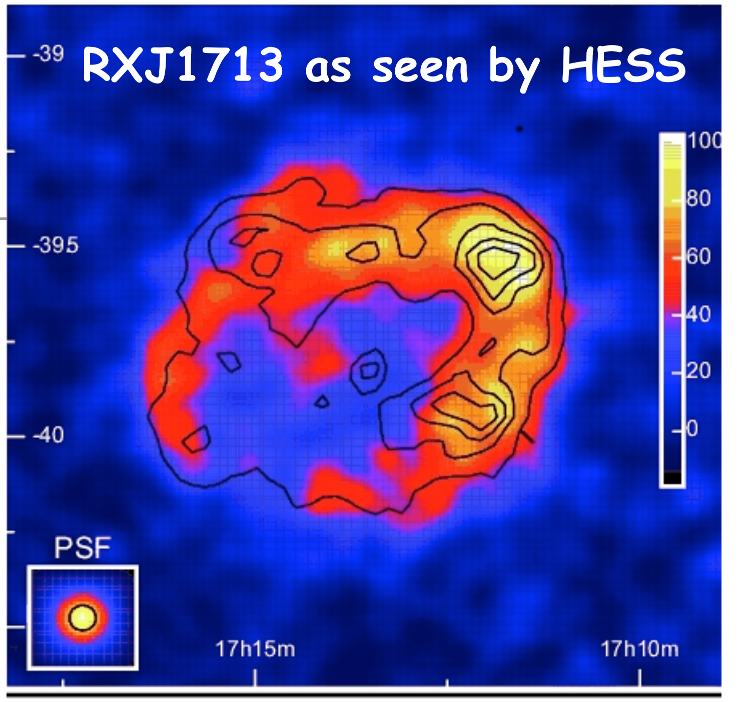

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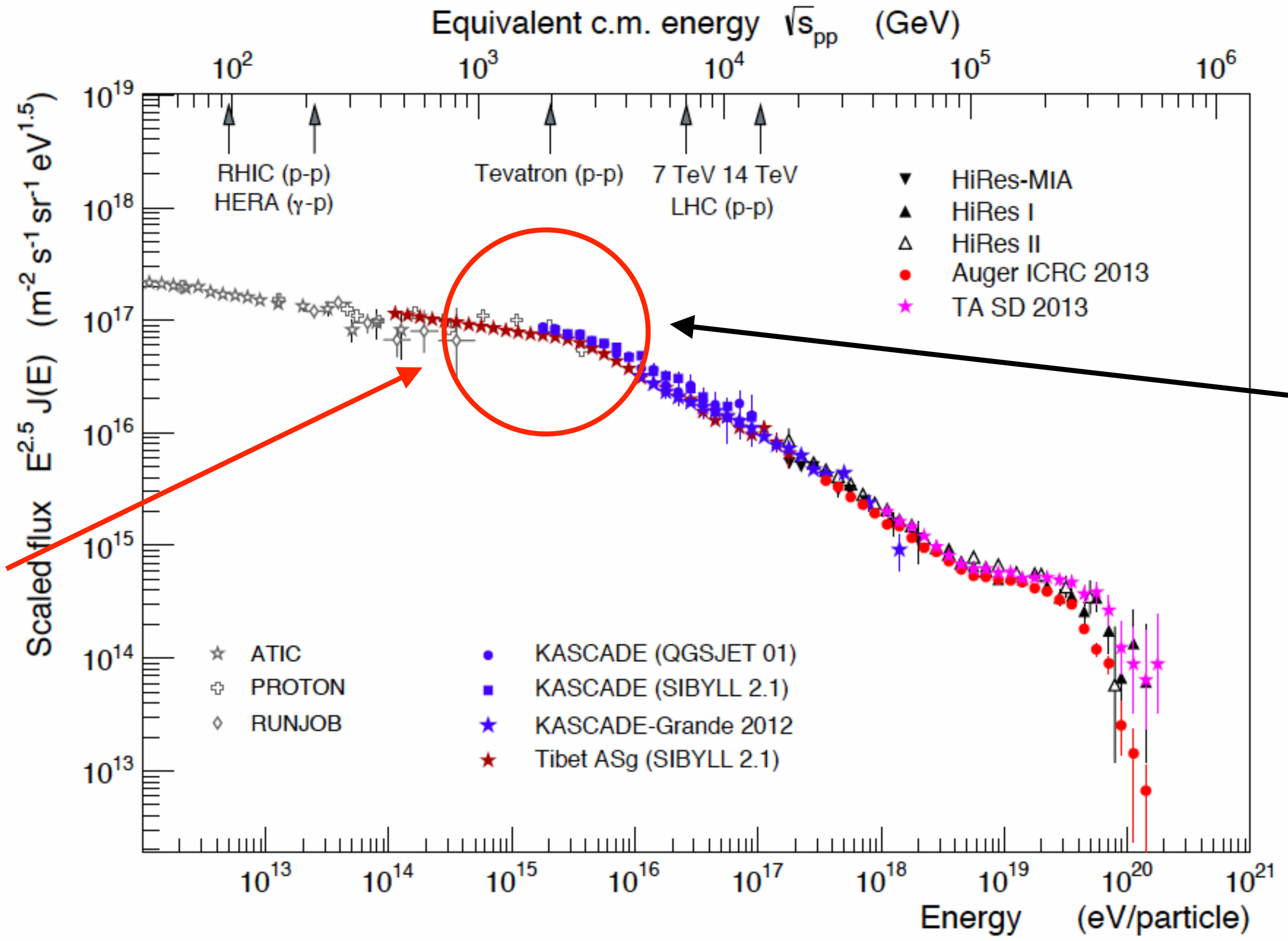
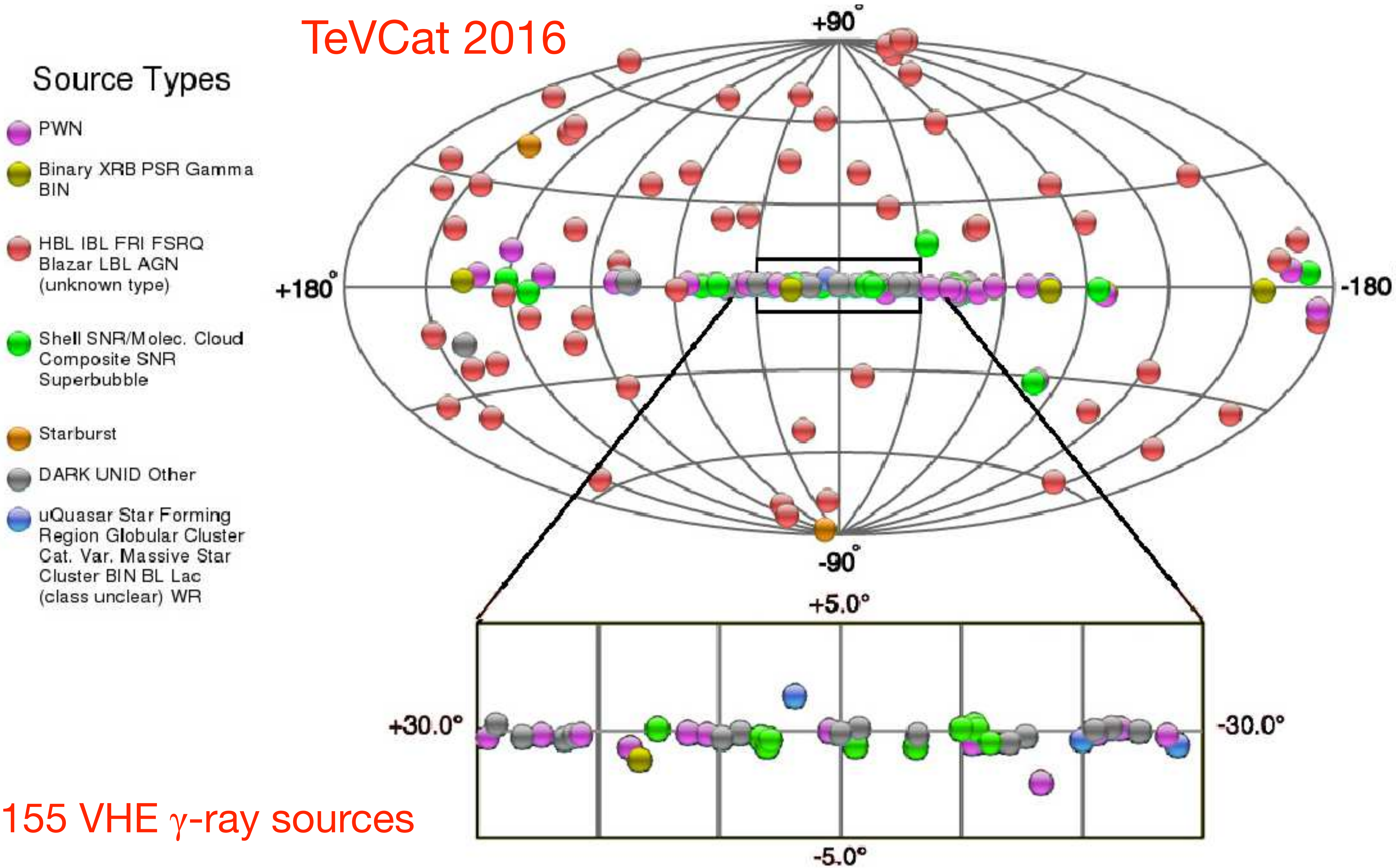


CR knee @ few PeV's
Something must happen here...

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

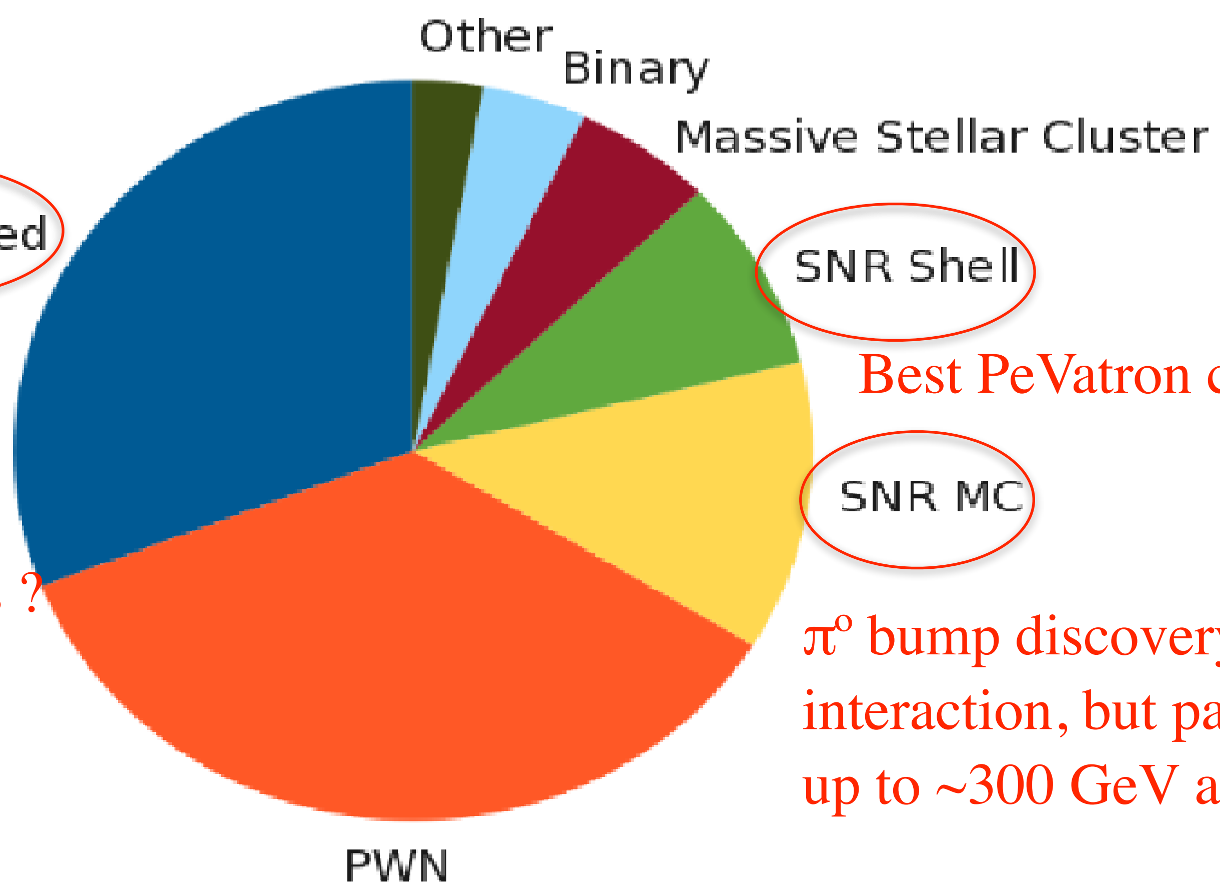
We would like SNRs to be CR PeVatrons...!

The observations: >10^{11} eV sky in photons



155 VHE γ-ray sources

Galactic TeV source populations

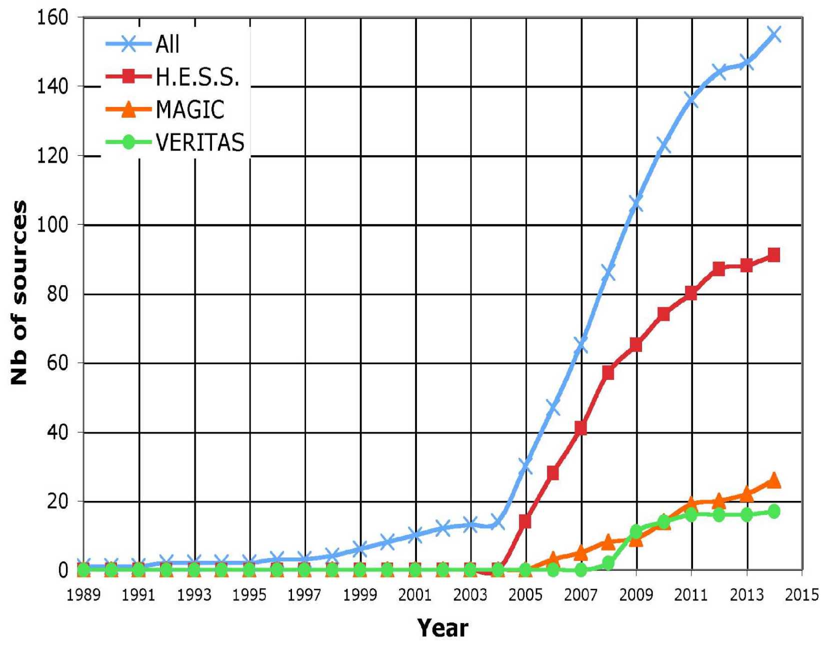


Relic PWNe

or

missing SNRs ?

Best PeVatron candidates ?



π^o bump discovery confirms hadronic interaction, but particle energies only up to ~300 GeV and steep spectra

How complete is the Survey ?

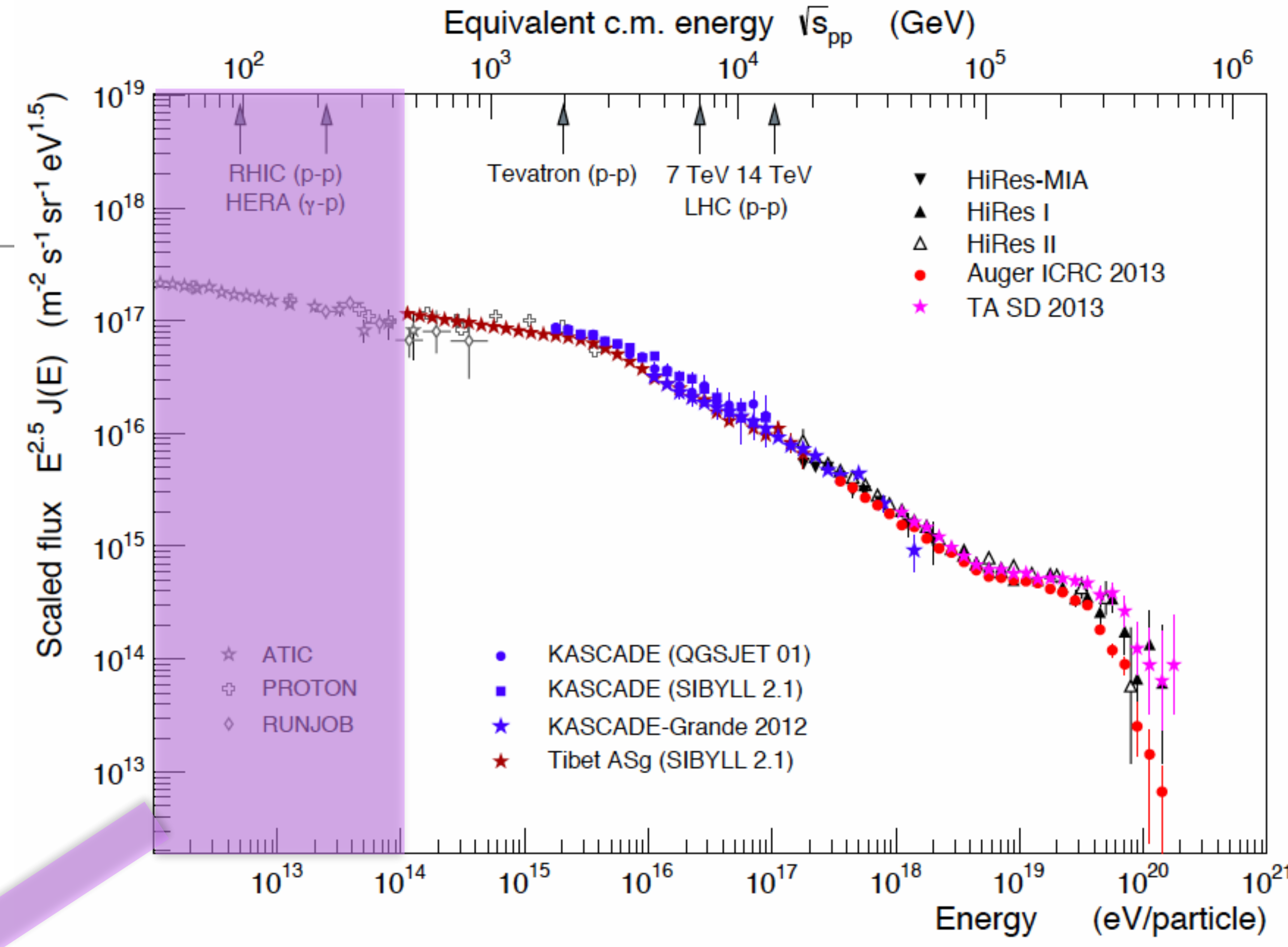
If there is a (bright) PeVatron out there, would we have detected it already ?

- Wide Field of View: all-sky survey provides un *unbiased map of the sky*
- High Energy Survey

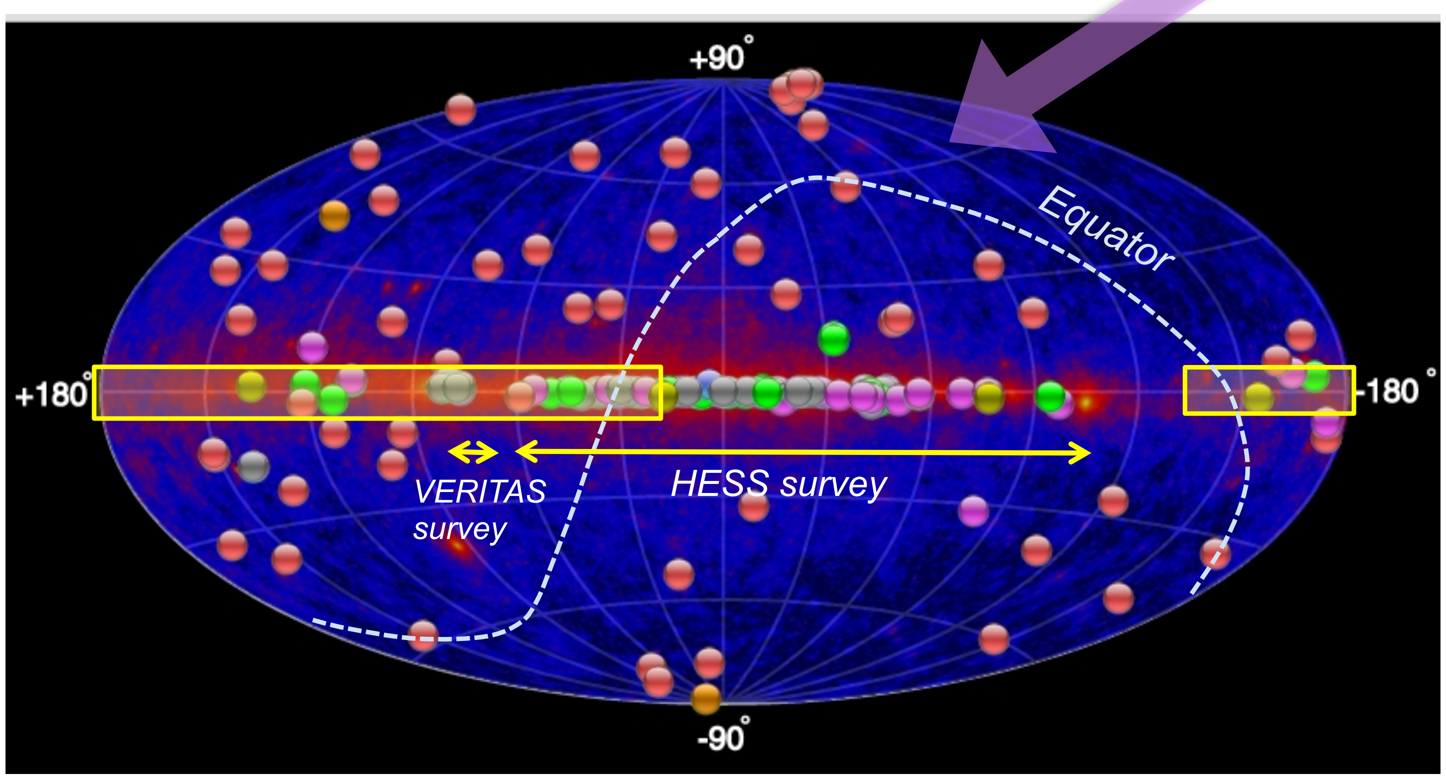
TeVatron Sky

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

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



TeV Cosmic Rays
Photons > 100 GeV !



But *'smoking gun'* still missing…
leptonic ?
hadronic (CR sources) ?

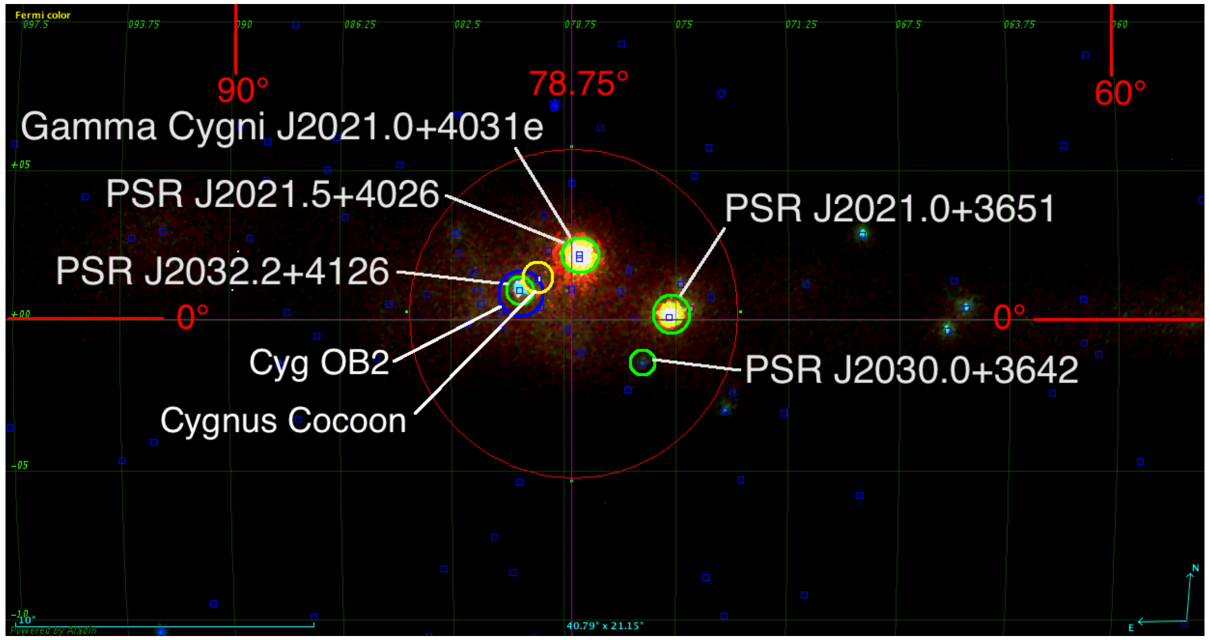
Complex scenario: each source is individual and has a unique behaviour. In general one expects a combination of leptonic and hadronic emission !

CRs diffusing away from the sources

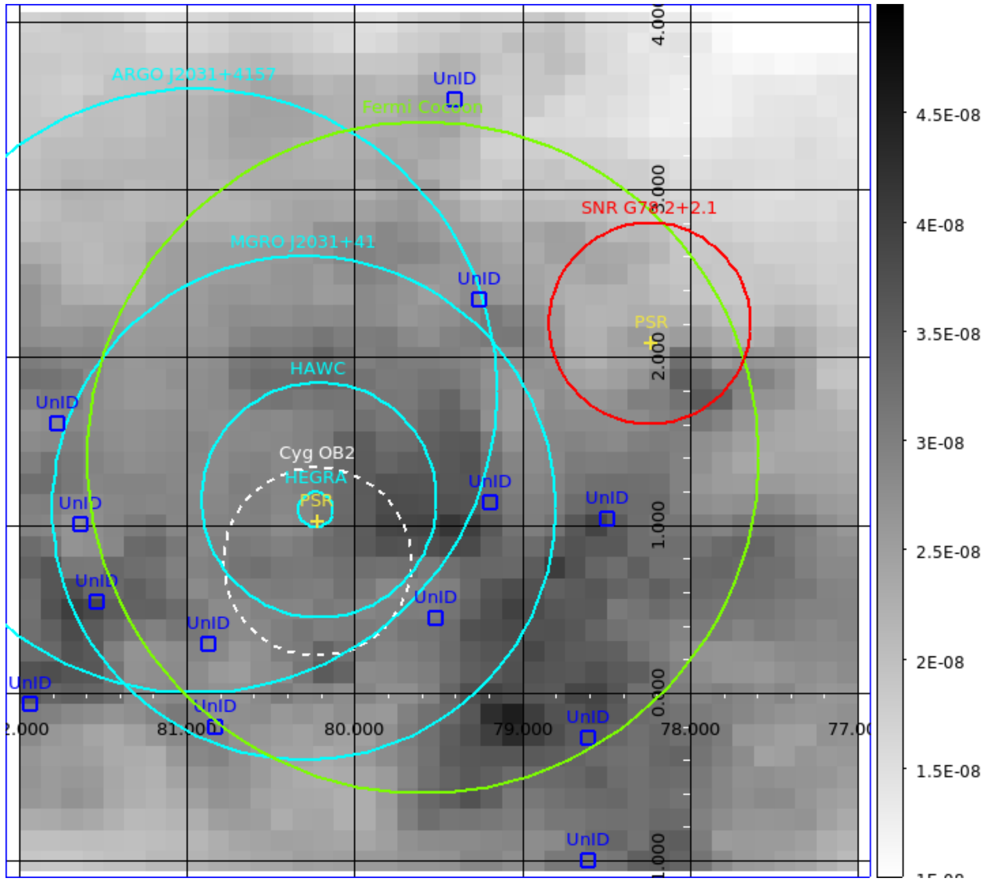
One of the most Interesting targets for the study of diffusion of CRs in our Galaxy is the *Cygnus region*.

The Cygnus region is a nearby (D = 1.3 kpc) example of a giant star-forming complex containing massive molecular gas clouds, rich populations of young stars, and luminous HII regions.

Cygnus X is the brightest diffuse γ-rays source in the northern hemisphere.



Fermi's color map of Cygnus X (red cycle)



Natural site for CR acceleration and neutrino production !

According to the third Fermi LAT source catalog (3FGL), there are 24 sources identified within a 4° radius of the center of Cygnus X.

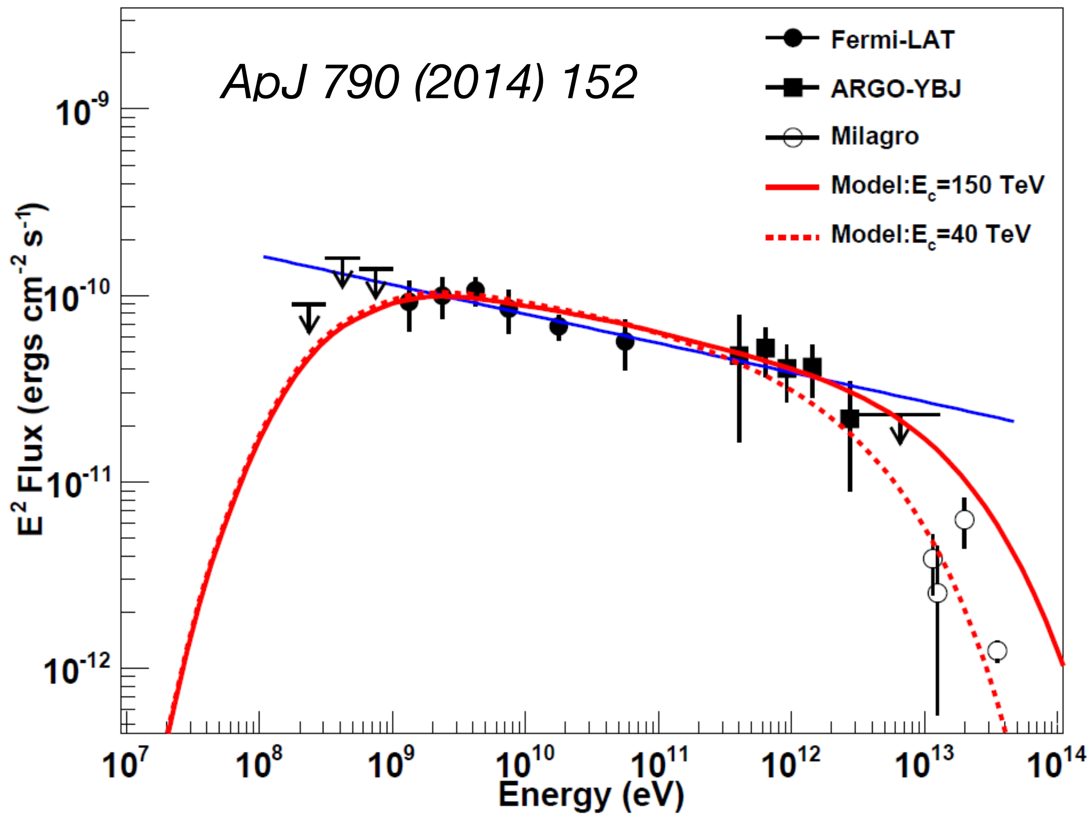
16 of them are unassociated (UnID) point sources.

ARGO J2031+4157 as the Cygnus Cocoon

The emission of ARGO J2031+4157 can be identified as the counterpart of Cygnus Cocoon at TeV energies.

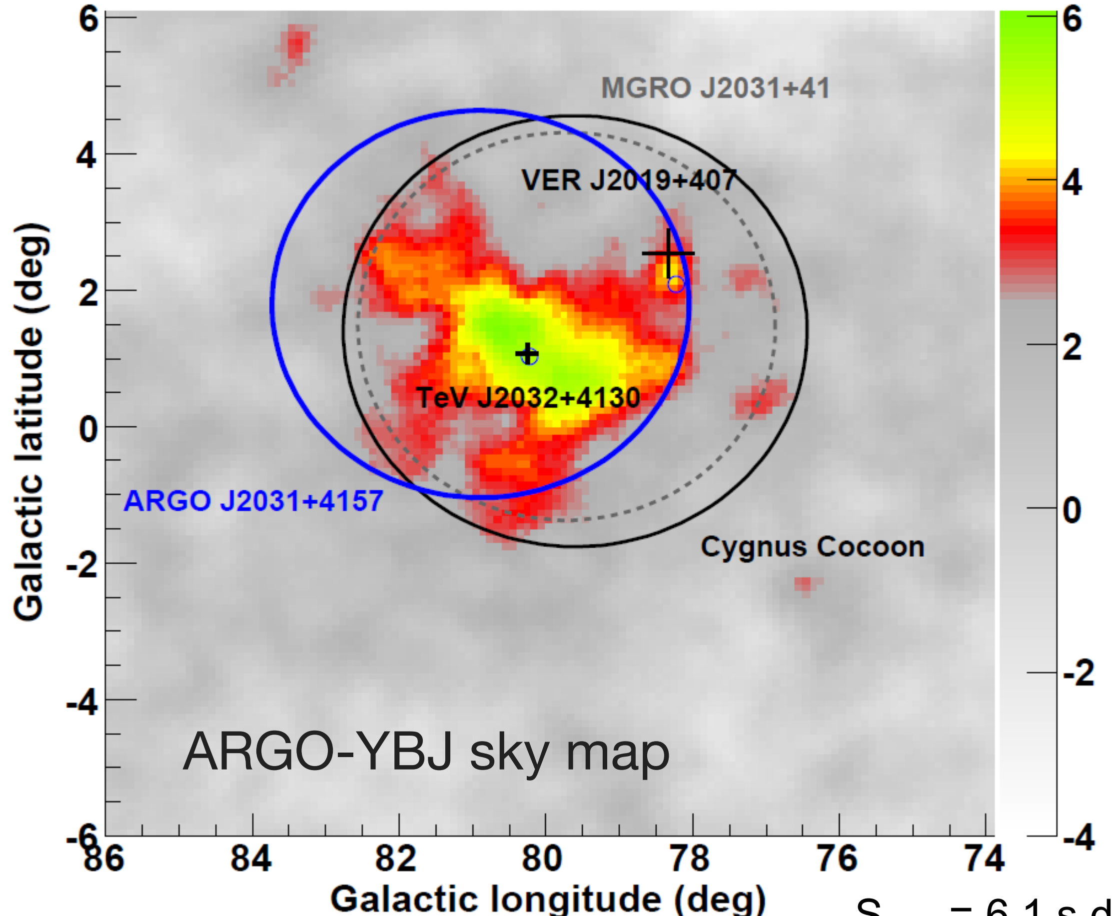
The Cocoon seems to be related to the combination of many powerful SNR and stellar-wind shocks.

A cocoon of freshly accelerated cosmic rays



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

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



S_{max} = 6.1 s.d.
σ_{ext} = 1.8°±0.5°

The scale of this region is ~ 50pc.

A *pure hadronic model* was assumed with a power law and a cutoff energy E_c =150 TeV.

Interesting implications for *neutrino production !*

Neutrinos from the Cygnus Cocoon

Assuming that the Cocoon is a single source dominated by γ-rays from neutral pion decay.

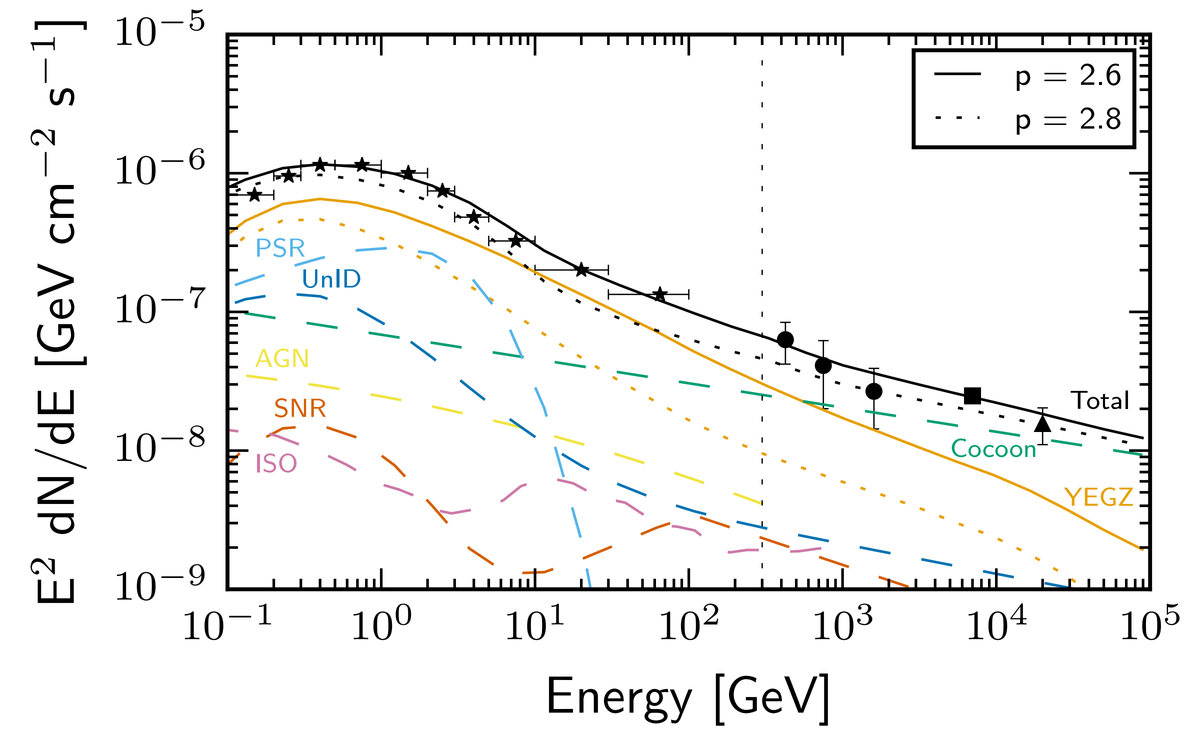
Assuming there is no steepening of the CR proton spectrum at higher energies, the authors find that *the neutrino flux (p = 2.2) at 1 PeV is a just above the differential discovery potential point sources for IceCube, based on 7 years of data.*

They also consider a smaller portion of the Cocoon coincident with a large molecular gas cloud complex which is most likely to be dominated by hadronic emission and could potentially be due to a single, hidden accelerator (a SNR or a PWN).

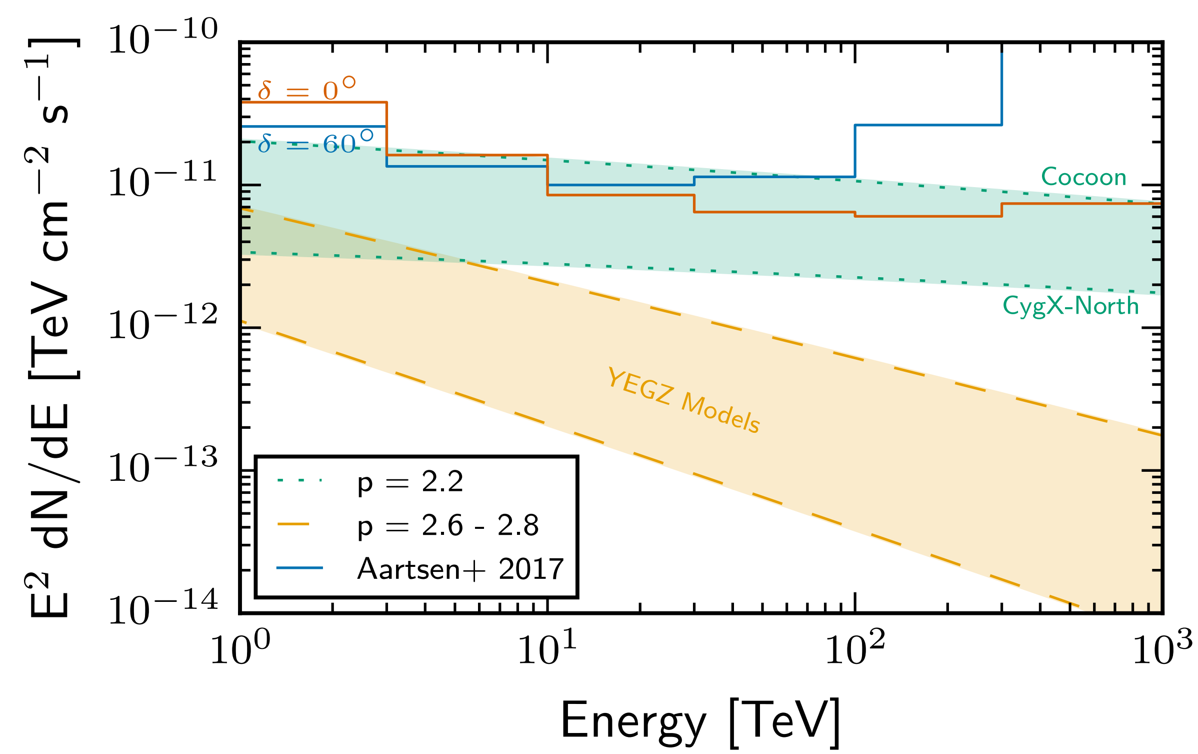
This region is in *CygX-North*.

The neutrino flux at 1 PeV is a factor of ~4 below IceCube's differential discovery potential.

This indicates that CygX-North is unlikely to be detected by IceCube as a point source.

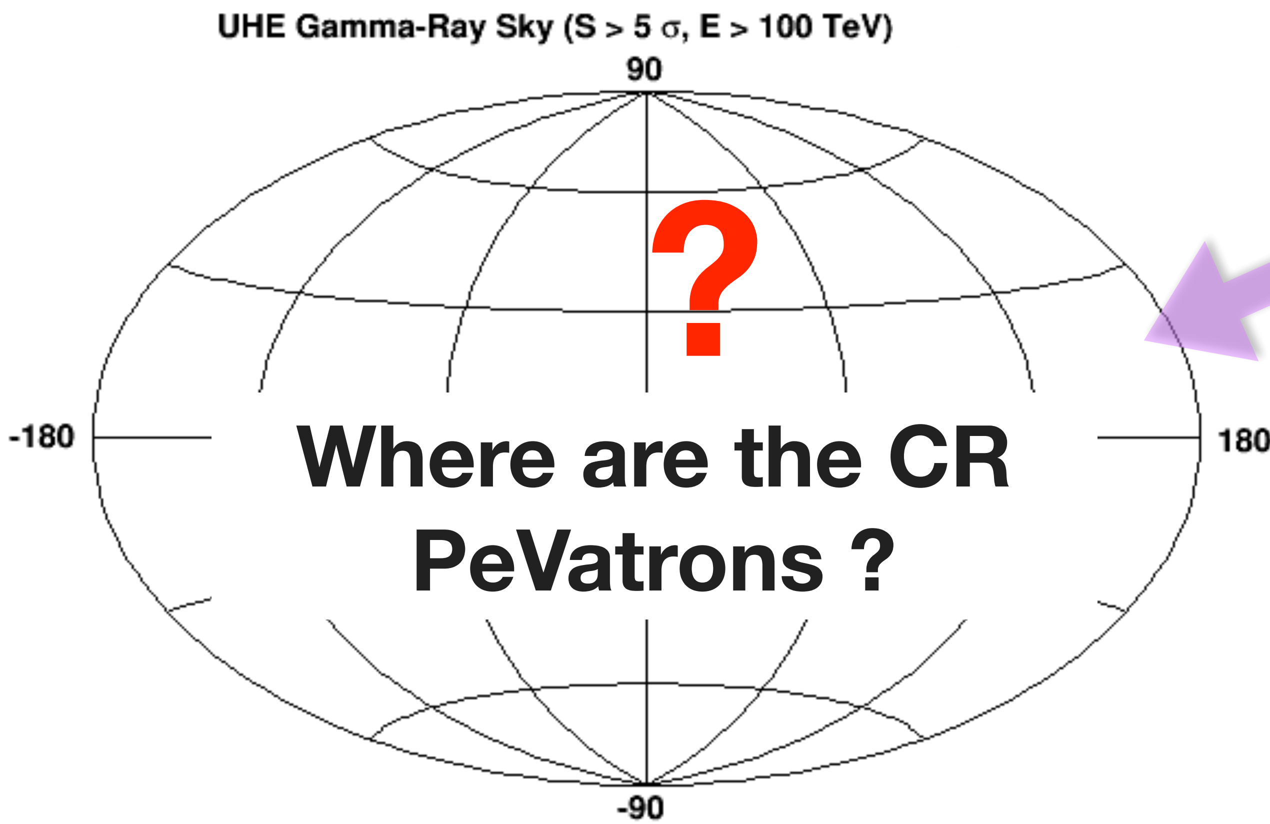


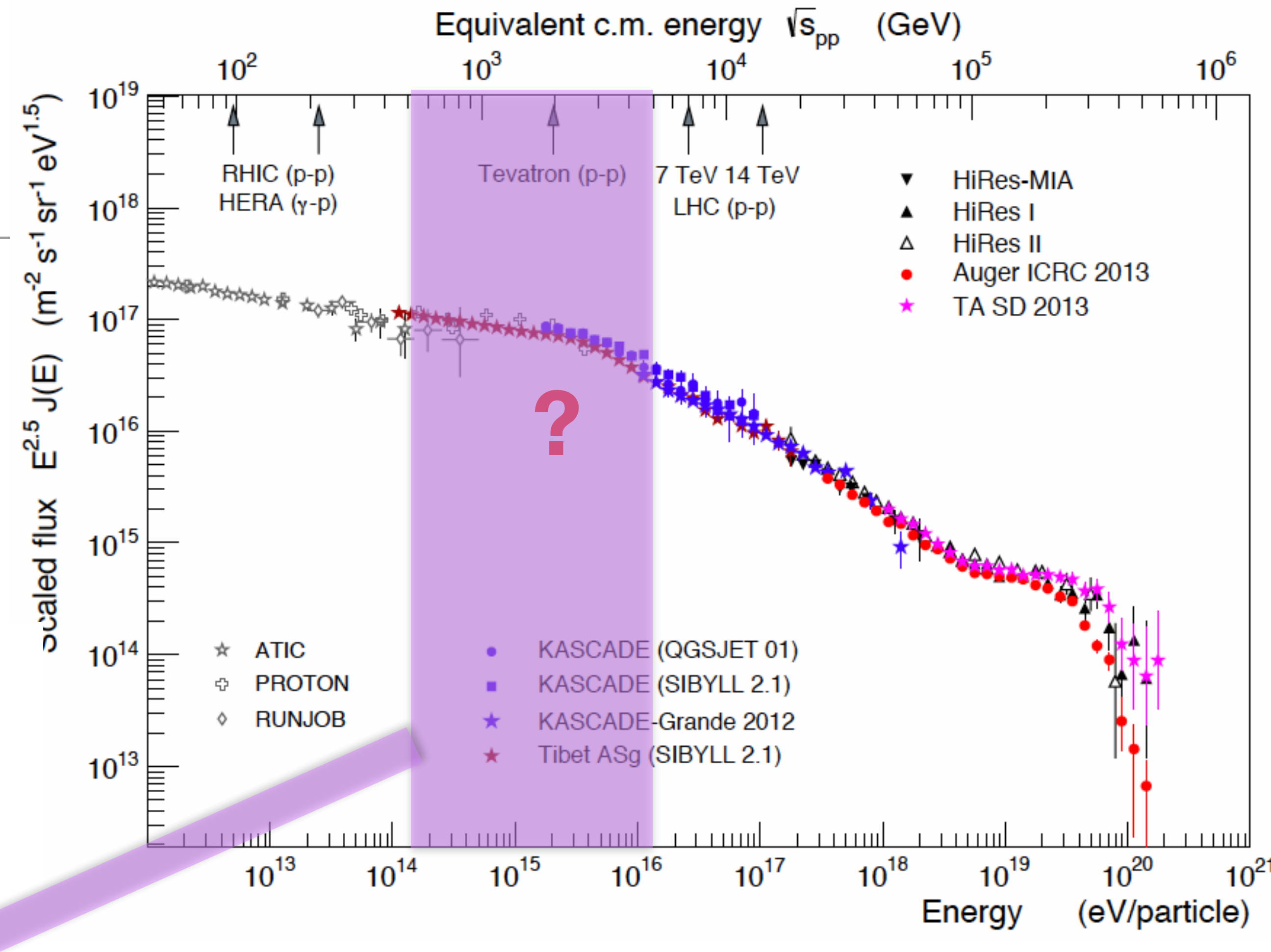
Tova M. Yoast-Hull et al. arXiv:1703.02590



PeVatron Sky

PeV Cosmic Rays
Photons > 100 TeV !





<u>Bonus @ 100 TeV:</u>

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

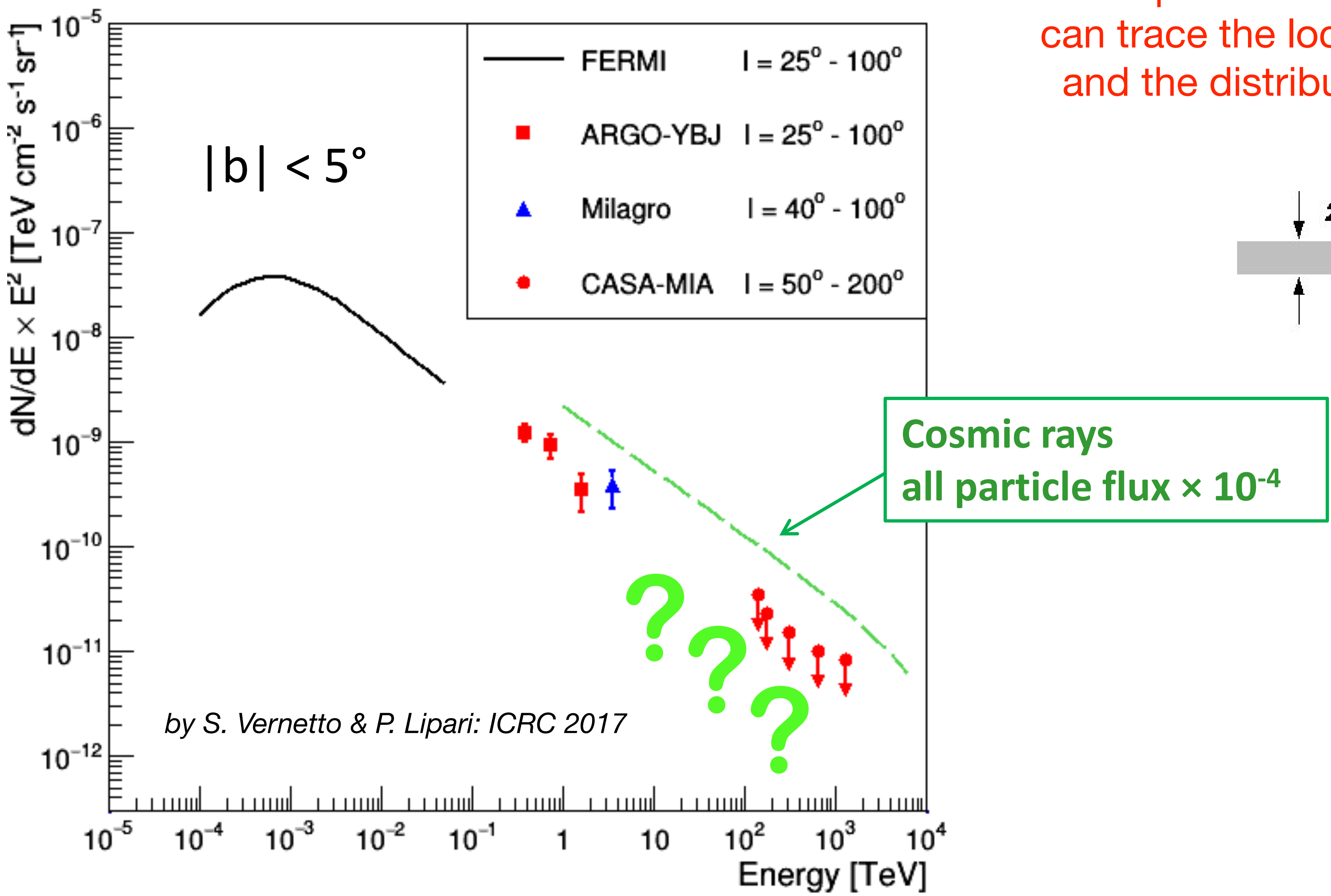
Extend energy range !
→ very large area and long observation time

→ wide-angle γ-ray detectors

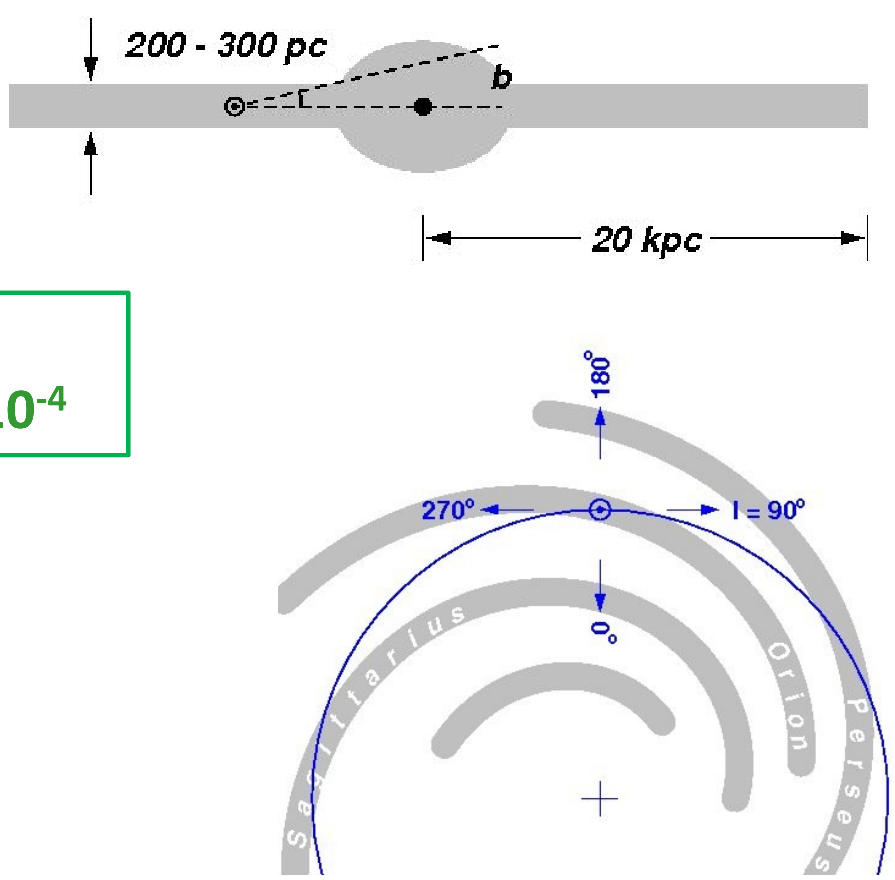
★ A power law spectrum reaching 100 TeV without a cutoff is a very strong indication of the hadronic origin of the emission

Diffuse γ-rays from the Galactic Plane

Diffuse γ-rays are produced by relativistic electrons by bremsstrahlung or inverse Compton scattering on bkg radiation fields, or by protons and nuclei via the decay of π^o produced in *hadronic interactions* with interstellar gas.

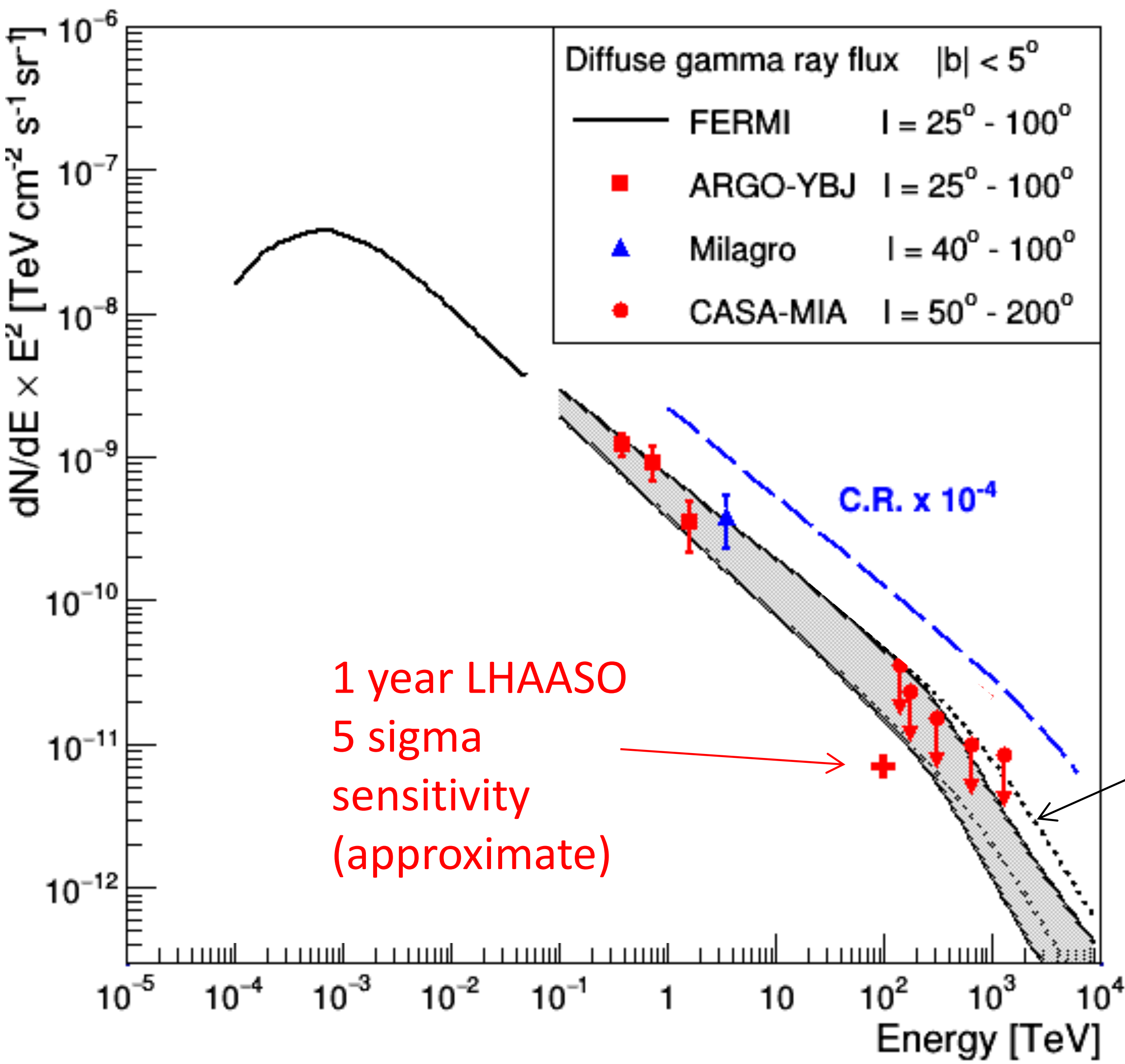


The space distribution of this emission can trace the location of the CR sources and the distribution of interstellar gas.



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 ?



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.

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

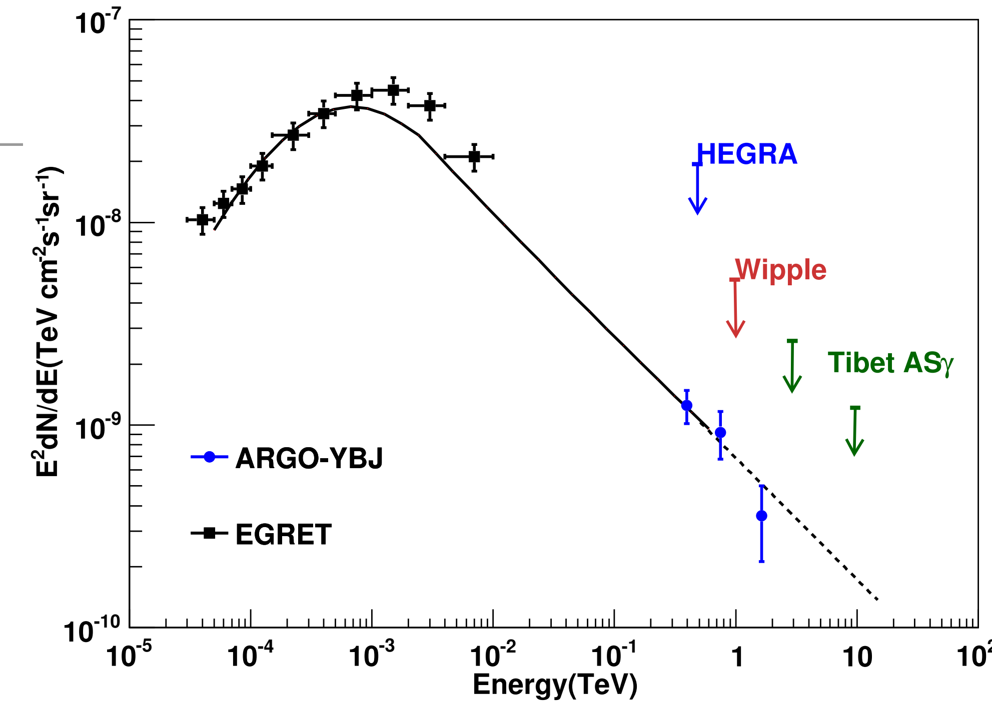
Diffuse Gamma Emission

Diffuse gamma-ray emission from the Galactic plane for $|b| < 5^\circ$

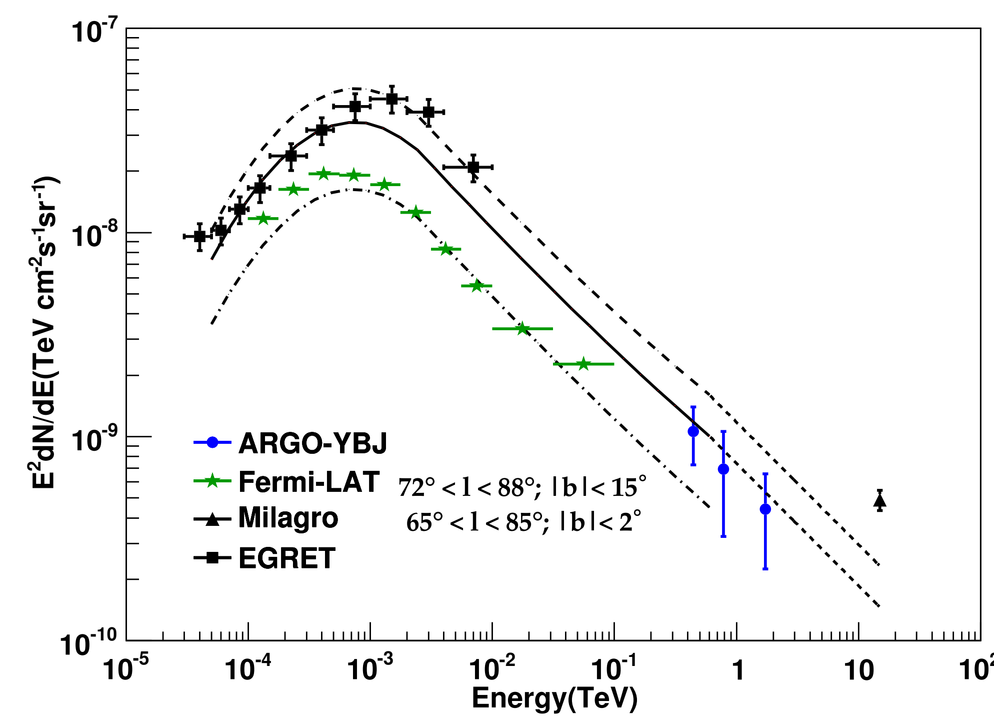
l Intervals	Significance	Spectral index	Energy(GeV)	Flux[a]
$25^\circ < l < 100^\circ$	6.9 s.d.	-2.80 ± 0.26	390	8.06 ± 1.49
			750	1.64 ± 0.43
			1640	0.13 ± 0.05
			1000[b]	0.60 ± 0.13
$40^\circ < l < 100^\circ$	6.1 s.d.	-2.90 ± 0.31	350	10.94 ± 2.23
			680	2.00 ± 0.60
			1470	0.14 ± 0.08
			1000[b]	0.52 ± 0.15
$65^\circ < l < 85^\circ$	4.1 s.d.	-2.65 ± 0.44	440	5.38 ± 1.70
			780	1.13 ± 0.60
			1730	0.15 ± 0.07
			1000[b]	0.62 ± 0.18
$25^\circ < l < 65^\circ$ & $85^\circ < l < 100^\circ$	5.6 s.d.	-2.89 ± 0.33	380	9.57 ± 2.18
			730	1.96 ± 0.59
			1600	0.12 ± 0.07
			1000[b]	0.60 ± 0.17
$130^\circ < l < 200^\circ$	-0.5 s.d.	–	–	$< 5.7^c$

[a] In units of 10^{-9} TeV^{-1} cm^{-2} s^{-1} sr^{-1}.

$25^\circ < l < 100^\circ$; $|b| < 5^\circ$



Cygnus region: $65^\circ < l < 85^\circ$; $|b| < 5^\circ$



Interestingly, *the energy spectrum of the light component (p+He) up to 700 TeV measured by ARGO-YBJ follows the same spectral shape as that found in the Cygnus region.*

A precise comparison of the spectrum of young CRs, as those supposed in the Cygnus region, with the spectrum of old CRs resident in other places of the Galactic plane, could help to determine the *distribution of the sources of CRs*.

ApJ 806 (2015) 20

Take Home Message - 1

- Maps of the gamma-ray sky not unbiased.
- PeVatrons *'smoking gun'* signature still missing.
- Measurement of diffuse γ-ray emission at 100 TeV crucial.
- Monitoring of flaring emissions (GRBs, AGNs, etc) very important.

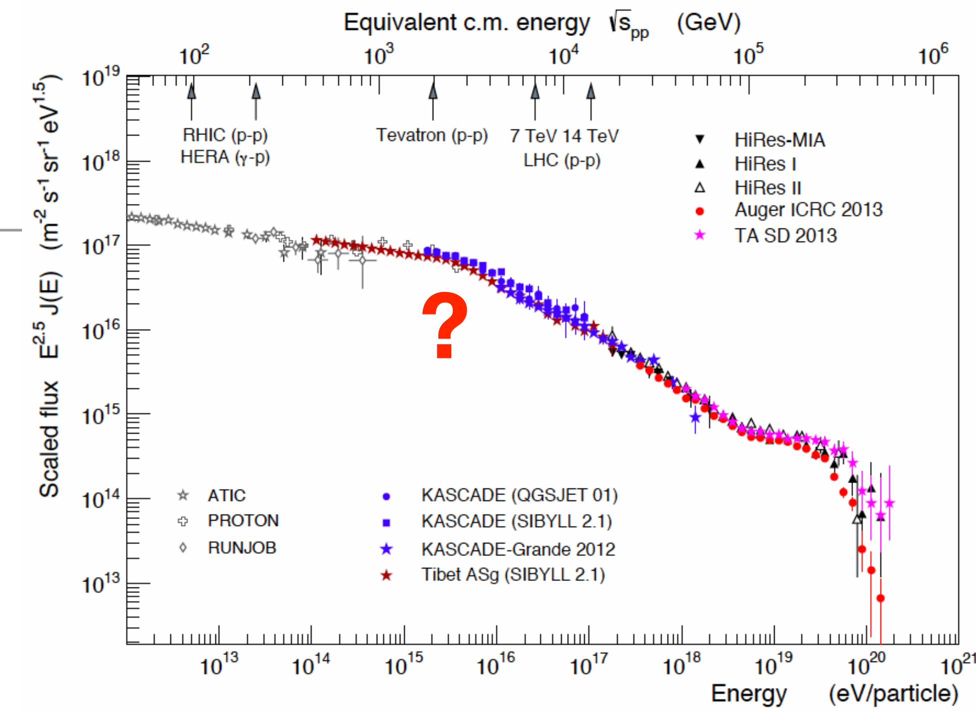
Homework

✓ All-sky survey instrument for an unbiased map of the sky at few % Crab flux level

✓ Observation of gamma-ray sky in the 100 - 1000 TeV range !

✓ Wide-angle instrument for very extended sources and diffuse emission.

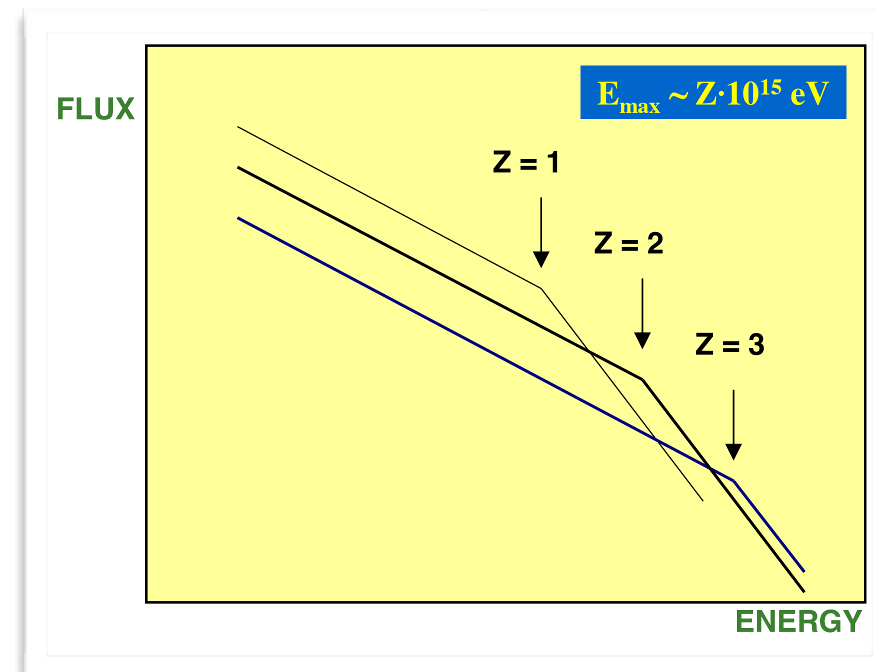
Approaching the knee



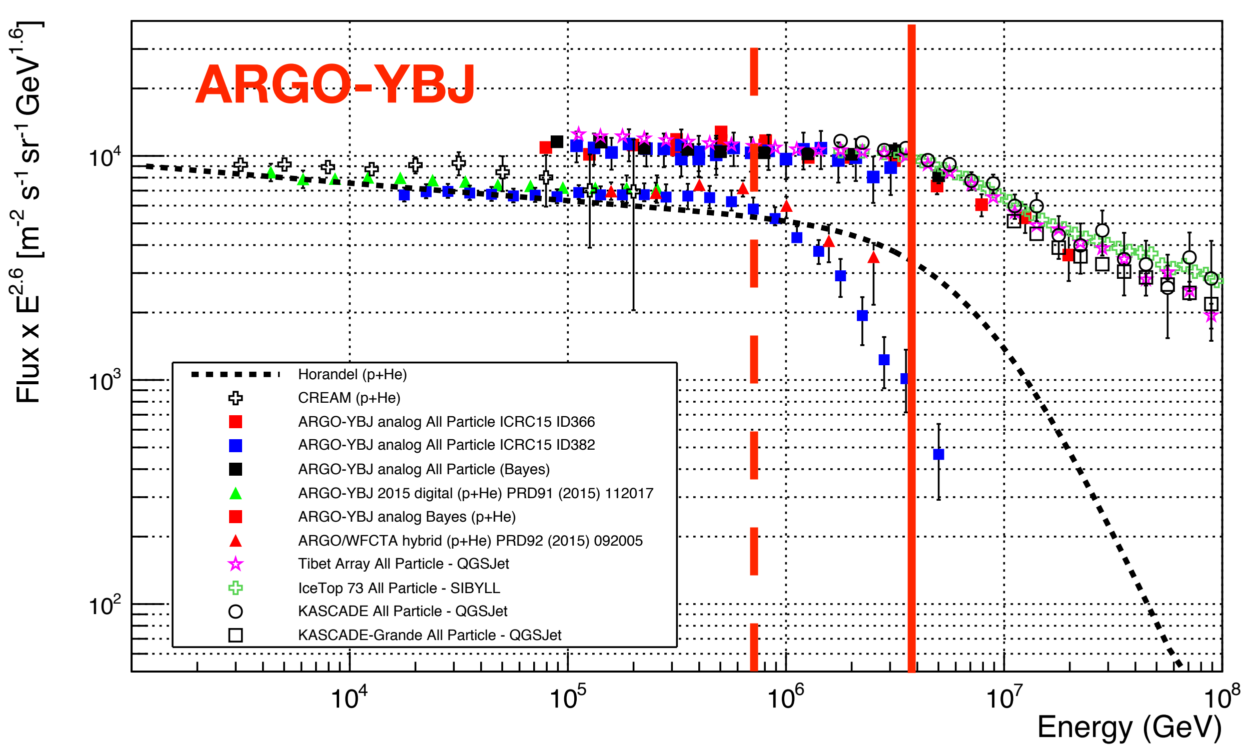
The origin of the *knee* in the all-particle spectrum of CRs is inextricably connected with the issue of the end of the Galactic CR spectrum and the transition to extragalactic CRs.

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.

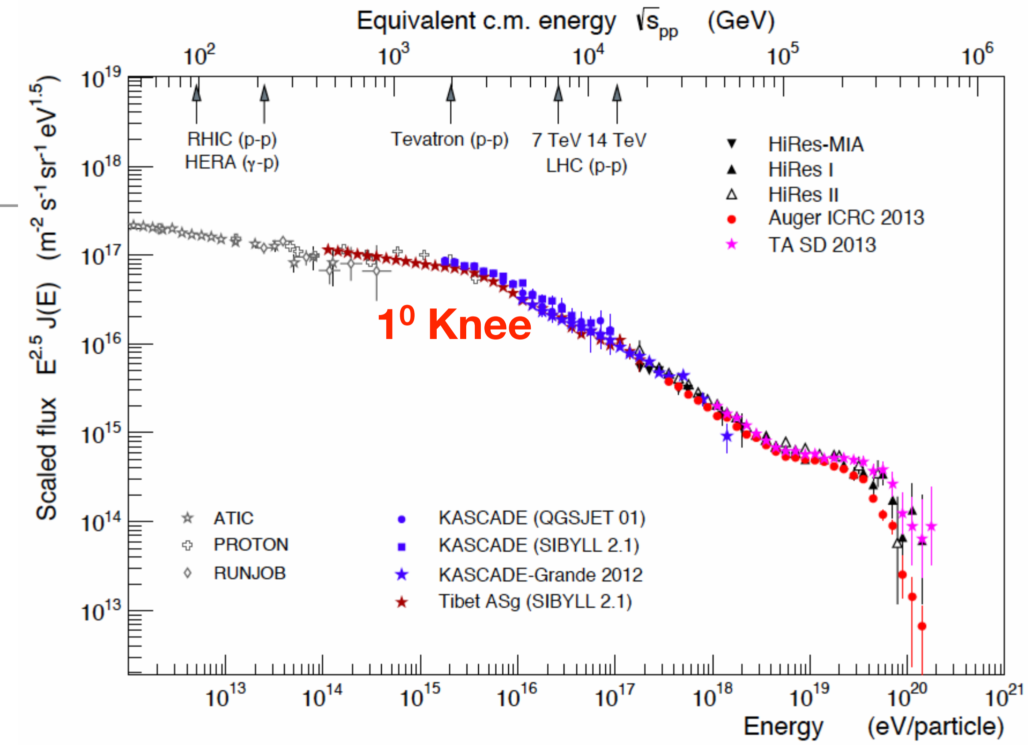


E_{max}(iron) = 26 · E_{max}(proton)



Experimental results still conflicting !

A comment on *"PeVatrons"*



The Nature of the *"KNEE"* in the Cosmic Ray Spectrum

★ Accelerator feature: maximum energy of acceleration
➜ implies that all accelerators are similar

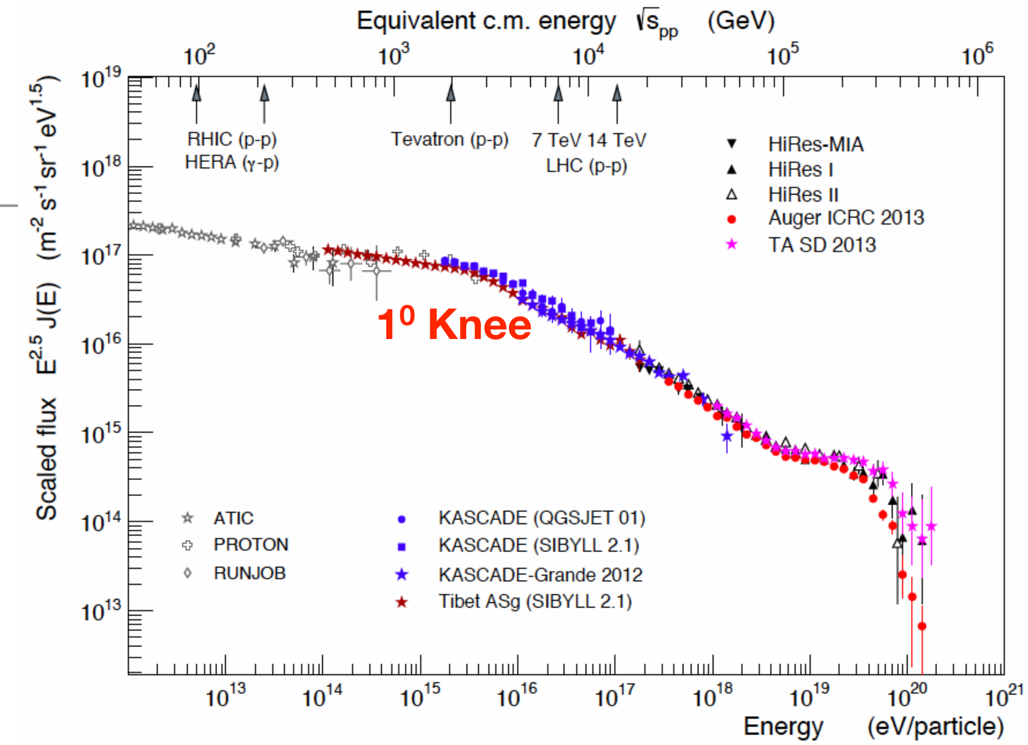
★ Structure generated by propagation: ➜ implies that the (main) Galactic CR accelerators must be capable to accelerate to much higher energy

If the "knee" is a *propagation effect*, the Galaxy contains *"super-PeVatrons"* and the study of these objects requires Gamma Astronomy at High Energy (100 - 1000 TeV).

➜ Strong interest in the PeV gamma ray (and neutrino) astronomy.

The exploration of the gamma ray sky at very high energy (E > 100 TeV) is challenging, but has great scientific interest, and is in fact crucial for a full understanding of the Galactic CR.

A comment on *“PeVatrons”*



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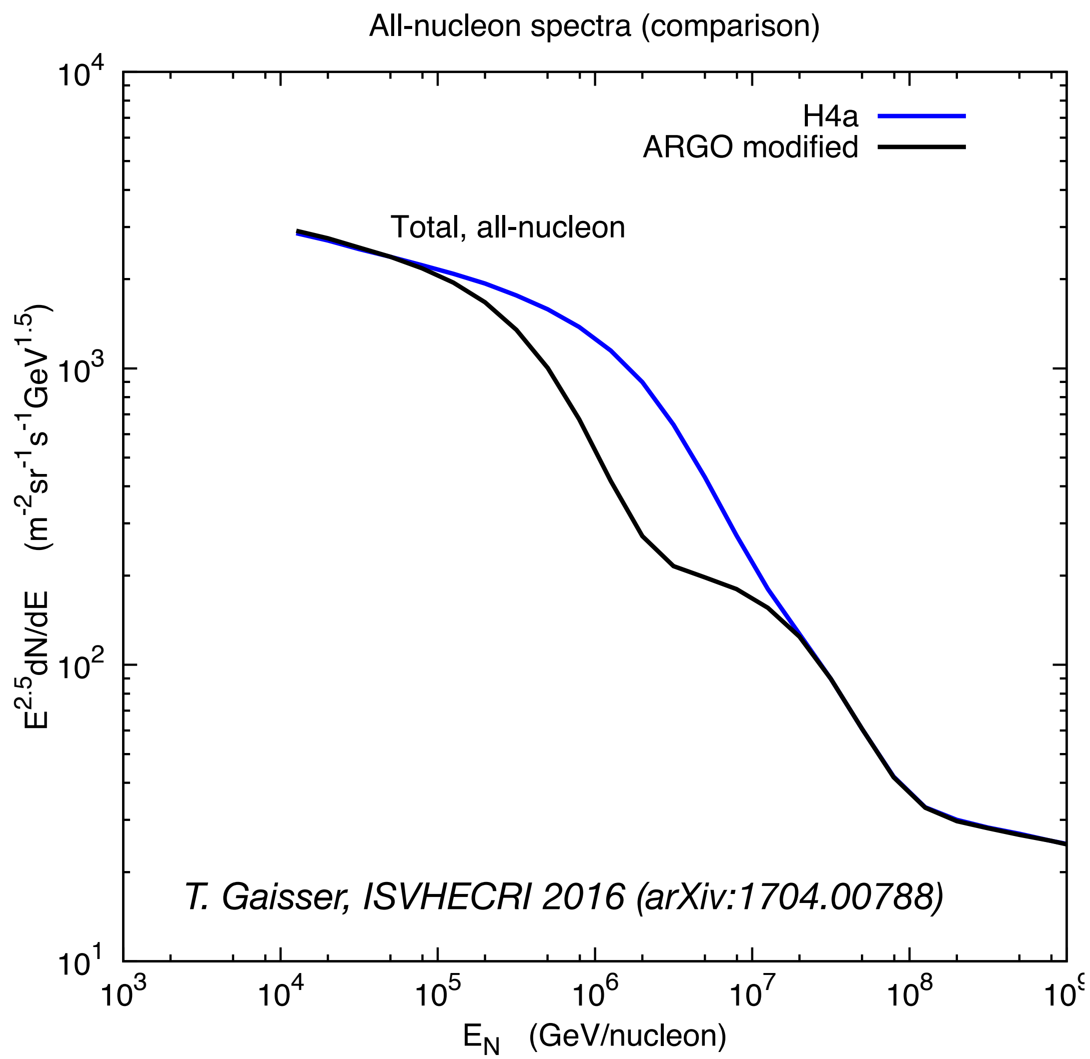
A measurement is worth 1000 theories !

CR spectrum and atmospheric neutrinos



The spectrum of nucleons for the H4a model compared with a modified version in which the cutoff rigidities for p and He are reduced to 700 GeV and the all-particle spectrum is restored by increasing the contribution of the CNO and Fe groups.

A practical aspect of the energy of the proton knee is its implication for the atmospheric neutrino flux at high energy.

Calculation of *the flux of atmospheric neutrinos depends on the spectrum of nucleons as a function of energy per nucleon,* which is dominated by protons and helium.

If the proton and helium components steepen at 700 GeV, then there should be a compensating increase in heavier nuclei to keep the all-particle spectrum constant.

The sketch illustrates the effect, which would likely be a suppression of the flux of nucleons in a range around a PeV that arises if the all-particle spectrum is dominated by heavy nuclei in this region.

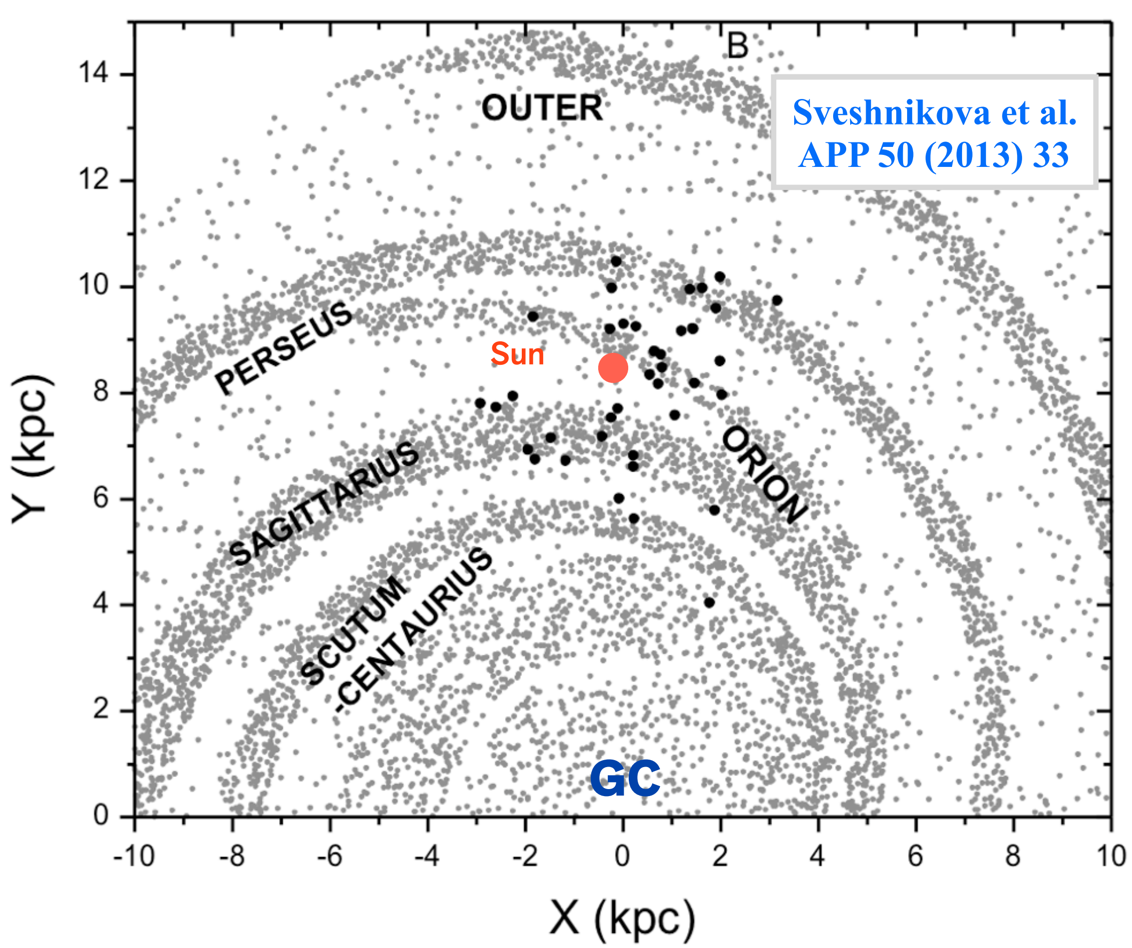
This in turn would significantly reduce the flux of muons and muon-neutrinos around 100 TeV.

The discrepancy between ARGO-YBJ and KASCADE needs to be resolved by new, more sensitive detectors

Cosmic Ray diffusive propagation and anisotropy

CR anisotropy as fingerprint for their origin and propagation

Distribution of nearby SNRs in the Galaxy



Galactic Cosmic Rays

- Accelerated in SNRs
- Propagate diffusively

Consequences for anisotropy

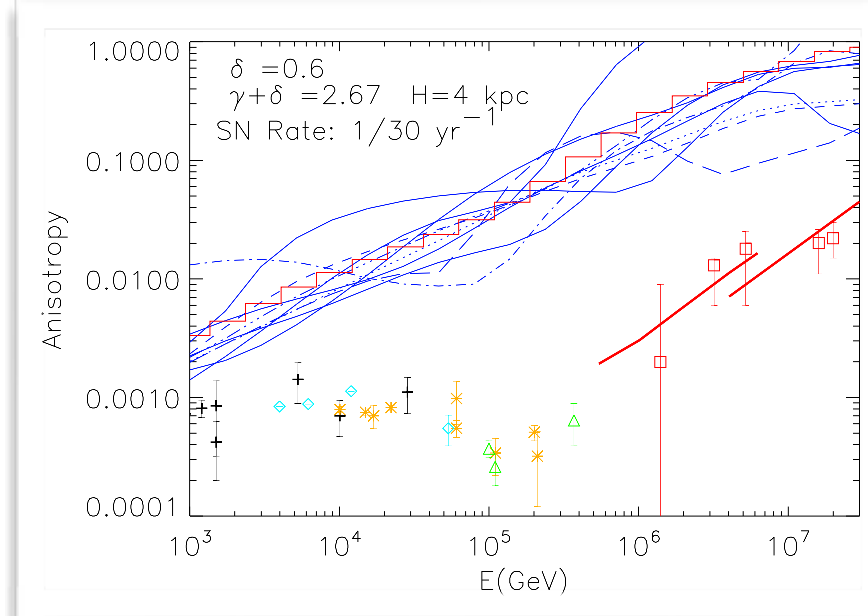
- CR density gradients are visible as anisotropy
- Anisotropy amplitude $\lesssim 10^{-2}$
- Amplitude increases with energy
- Dipole shape
- Phase pointing towards the most significant sources

A weak anisotropy is expected from the diffusion and/or drift of GCRs in GMF.

Generally speaking, the dipole component of the anisotropy is believed to be a tracer of the CR source distribution, with the largest contribution from the nearest ones.

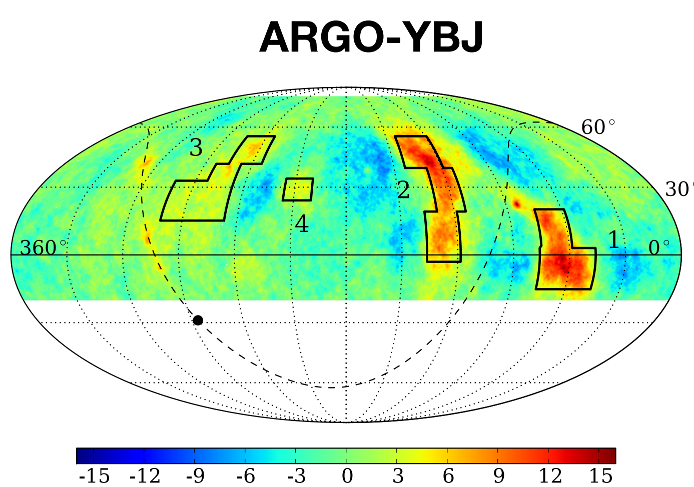
M. Ahlers & P. Mertsch, arXiv:1612.01873

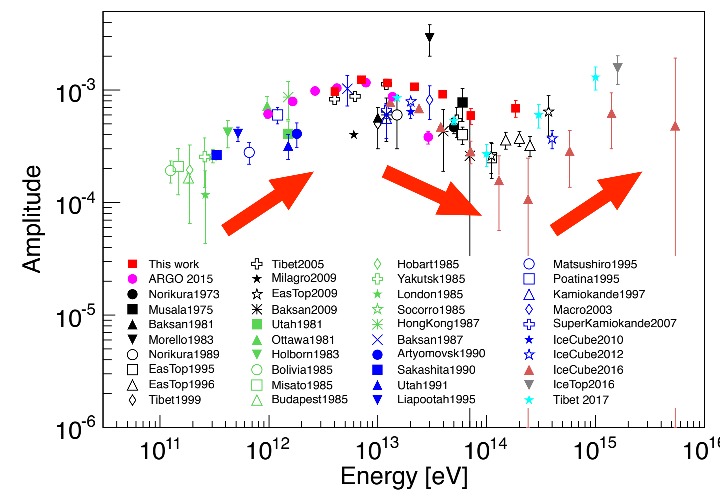
The CR anisotropy ‘problem’

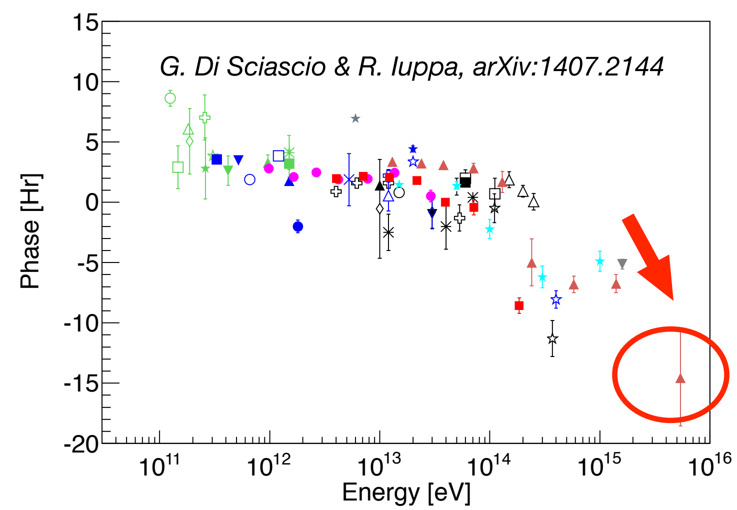


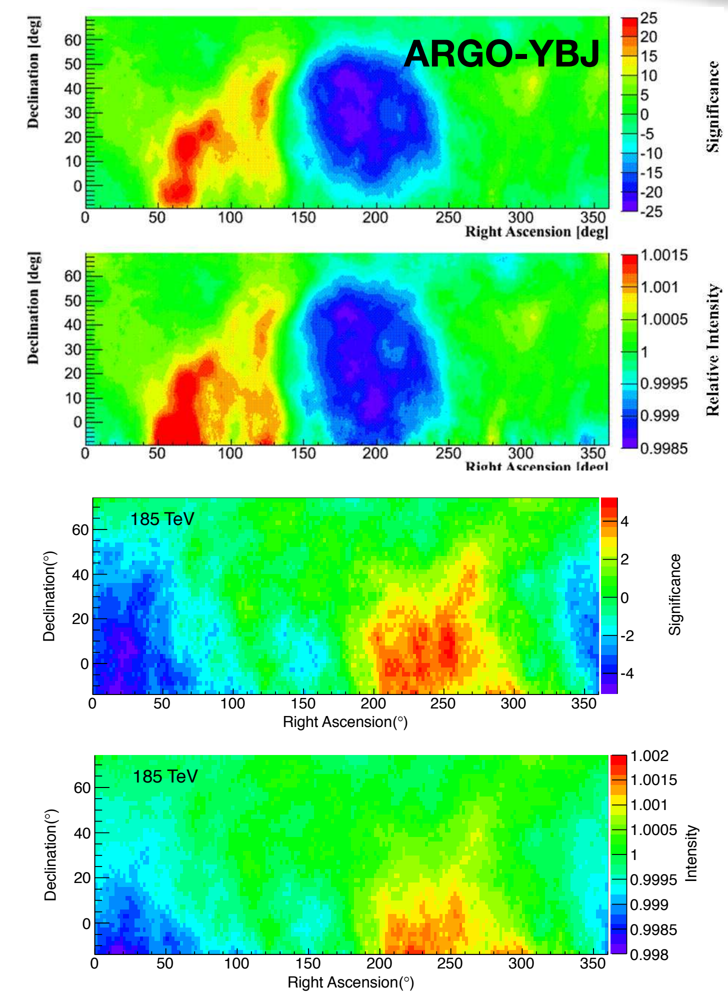
- Observed anisotropy much smaller than expectations according to diffusive models

- Unexpected evolution with energy, ‘dramatic’ above 100 TeV !









- Anisotropy not a simple dipole as foresee by diffusive models: small scale structures

The origin of high energy features cannot be explained with the conventional diffusion scenario of GCRs, and may provide us with a new hint for understanding the origin and propagation of GCRs.

Take Home Message - 2

- Energy range 10^{14} - 10^{17} eV crucial
- Experimental results conflicting !
- The origin of the observed anisotropies at different angular scales is still unknown

Homework

✓ Spectra of individual mass groups !!

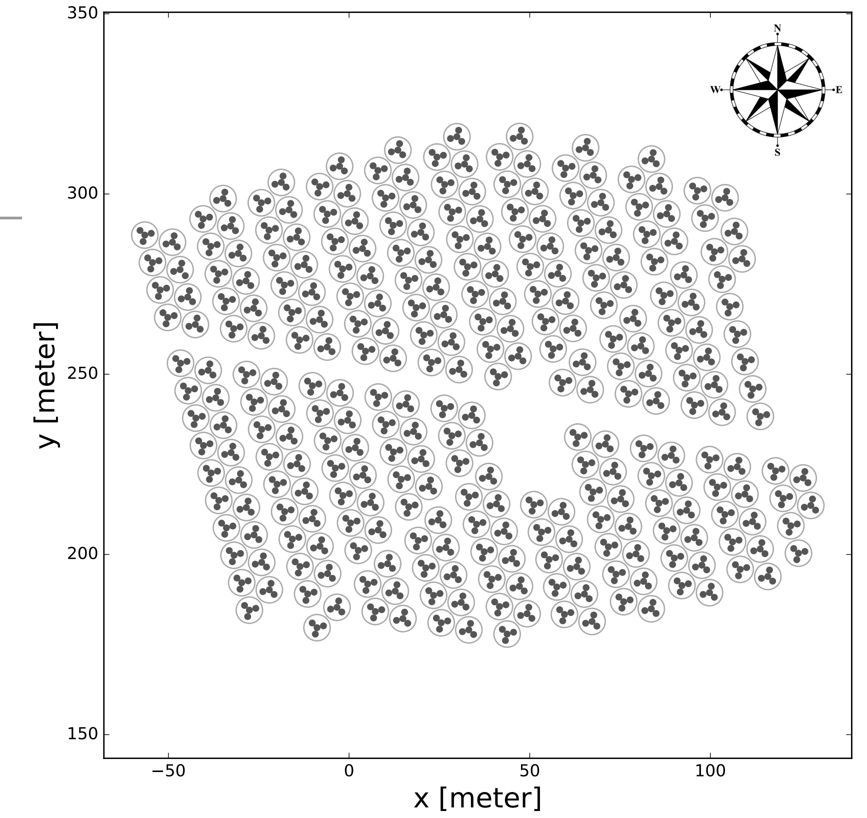
✓ Multi-parameter EAS measurements to validate hadronic interaction models

✓ Absolute energy scale calibration: low energy threshold → High altitude !

✓ Composition dependent anisotropy studies !!!

✓ High statistics in a large energy range (➜ 10^{16} — 10^{17} eV)

Northern Hemisphere: HAWC

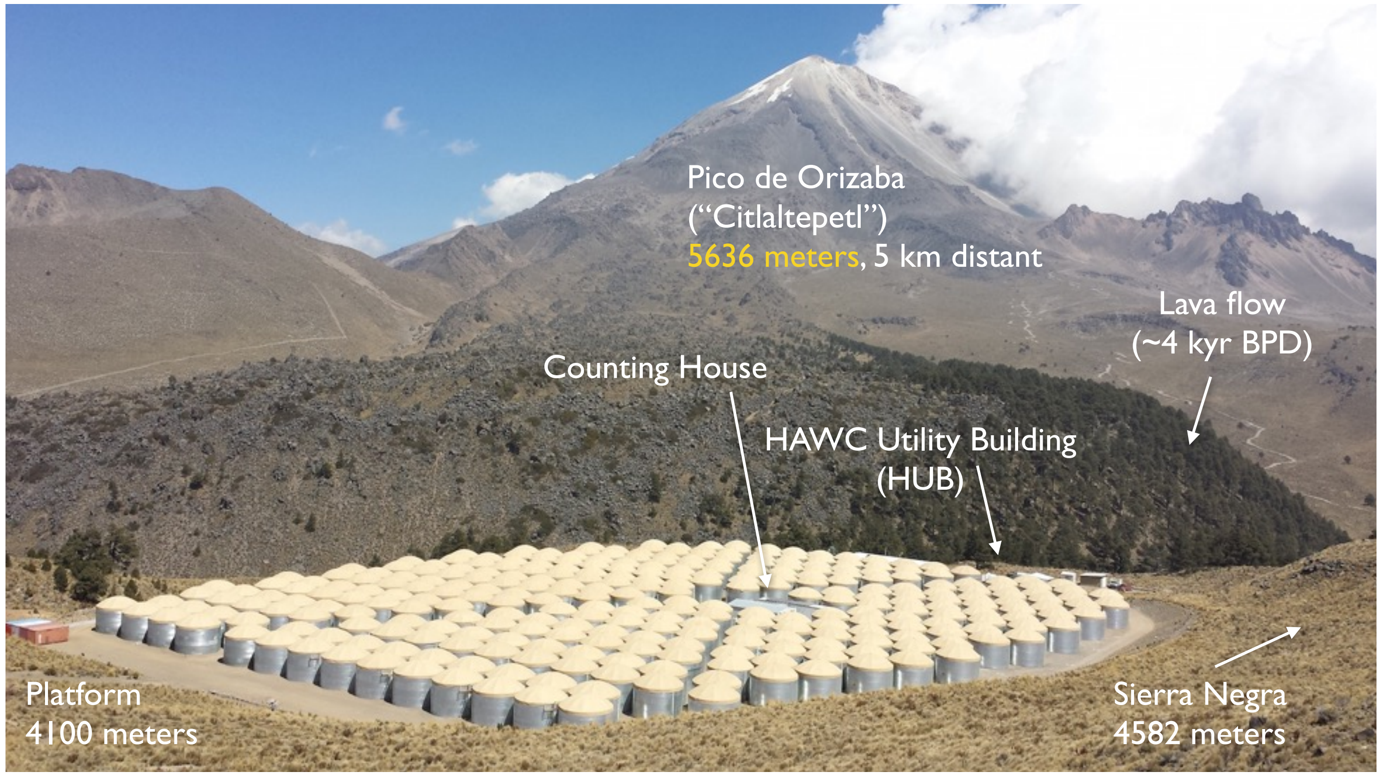


The **H**igh **A**ltitude **W**ater **C**herenkov Gamma-ray Observatory (HAWC) is up and running

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

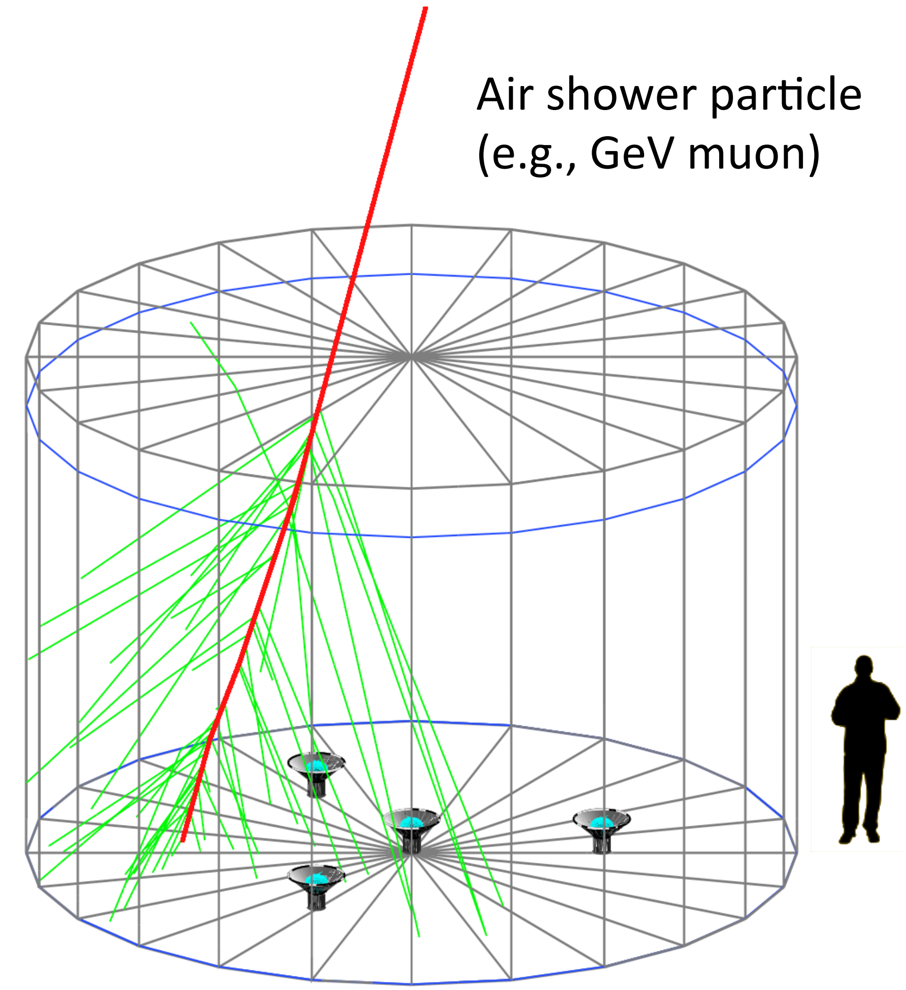
- Instrumented Area: 22,000 m^2 ≈140 X 140 m^2
- Coverage factor: ≈60 %
- 10 kHz event rate



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

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

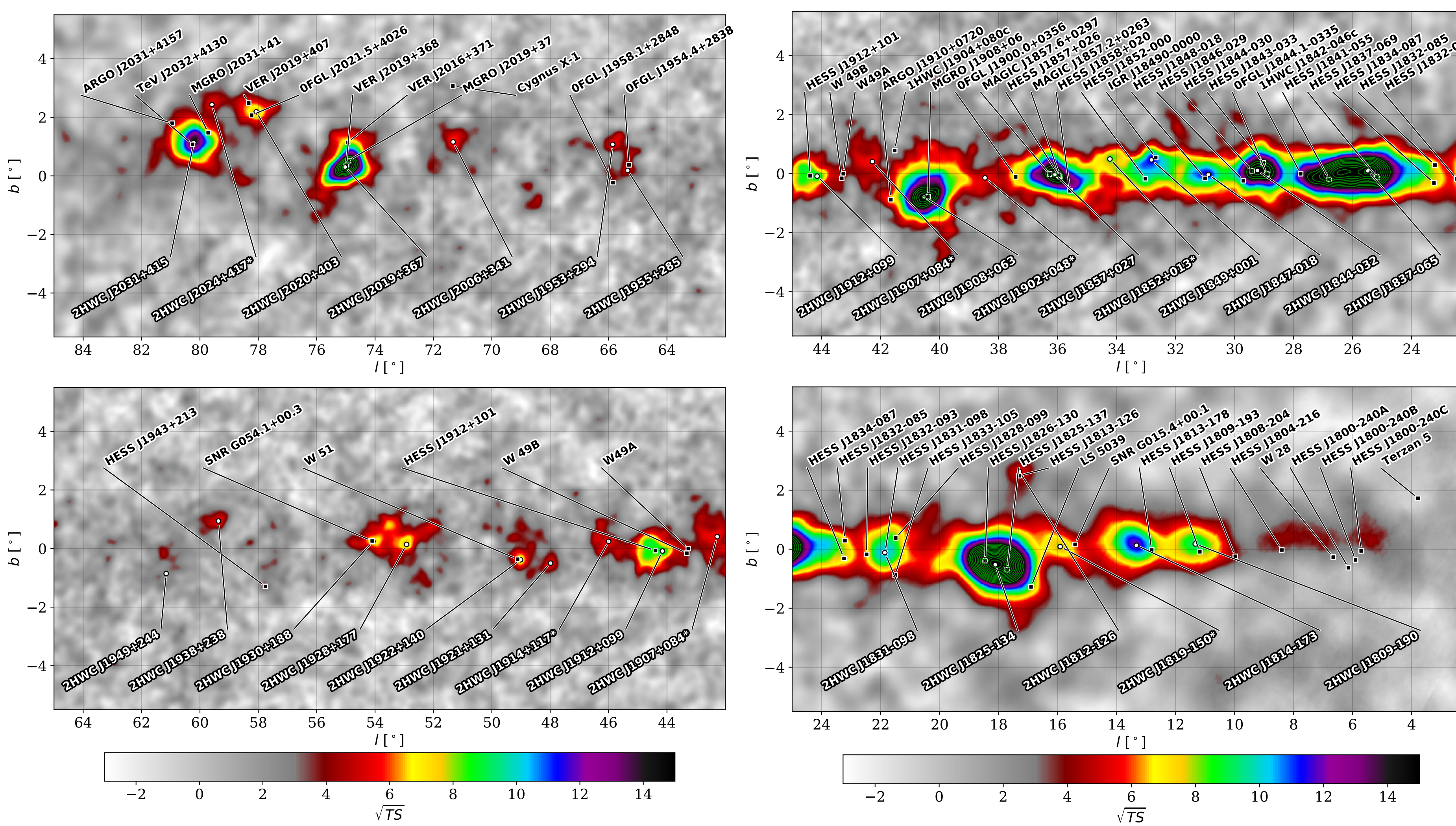
Out of these sources, 16 are more than one degree away from any previously reported TeV source

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.

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° $\tilde{E}_\gamma^{\rm MC}$.

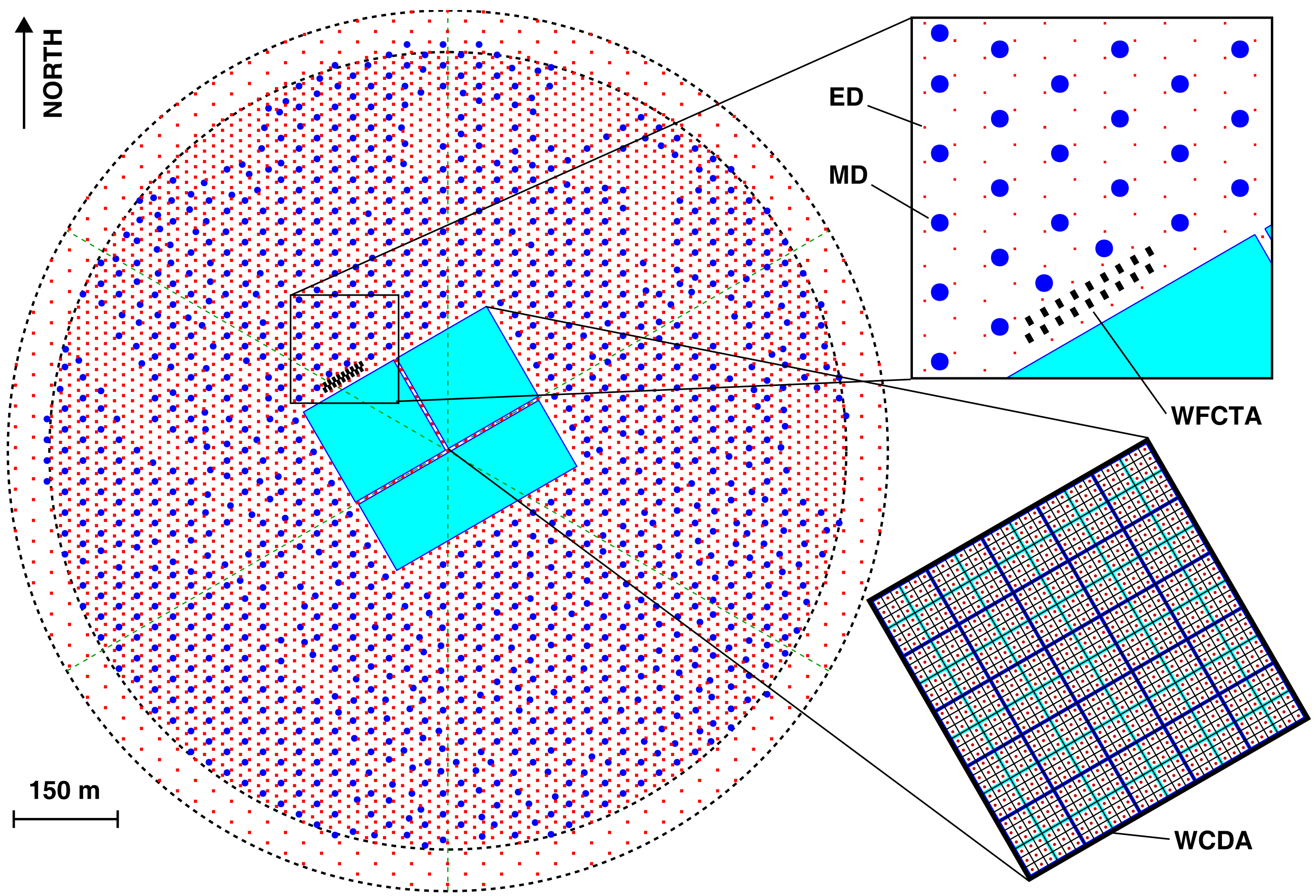
$\mathcal{B}$	$f_{\rm hit}$ (%)	ψ_{68} (°)	$\epsilon_\gamma^{\rm MC}$ (%)	$\epsilon_{\rm CR}^{\rm data}$ (%)	$\tilde{E}_\gamma^{\rm MC}$ (TeV)
1	6.7 – 10.5	1.03	70	15	0.7
2	10.5 – 16.2	0.69	75	10	1.1
3	16.2 – 24.7	0.50	74	5.3	1.8
4	24.7 – 35.6	0.39	51	1.3	3.5
5	35.6 – 48.5	0.30	50	0.55	5.6
6	48.5 – 61.8	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



Northern Hemisphere: LHAASO

- 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).



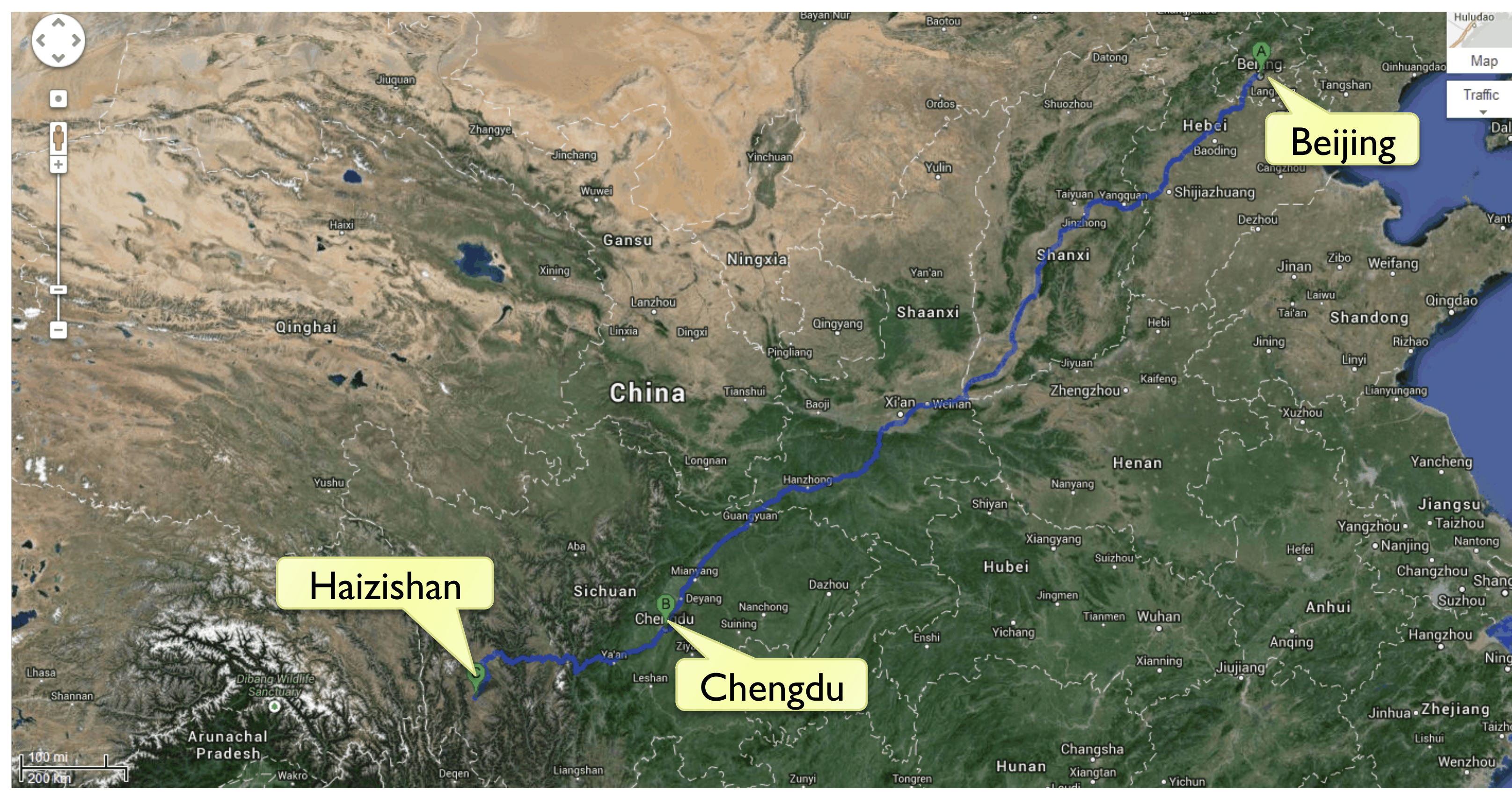
- A close-packed, surface water Cherenkov detector facility with a total area of 80,000 m^2.
- 18 wide field-of-view air Cherenkov (and fluorescence) telescopes.
- Neutron detectors

The LHAASO site

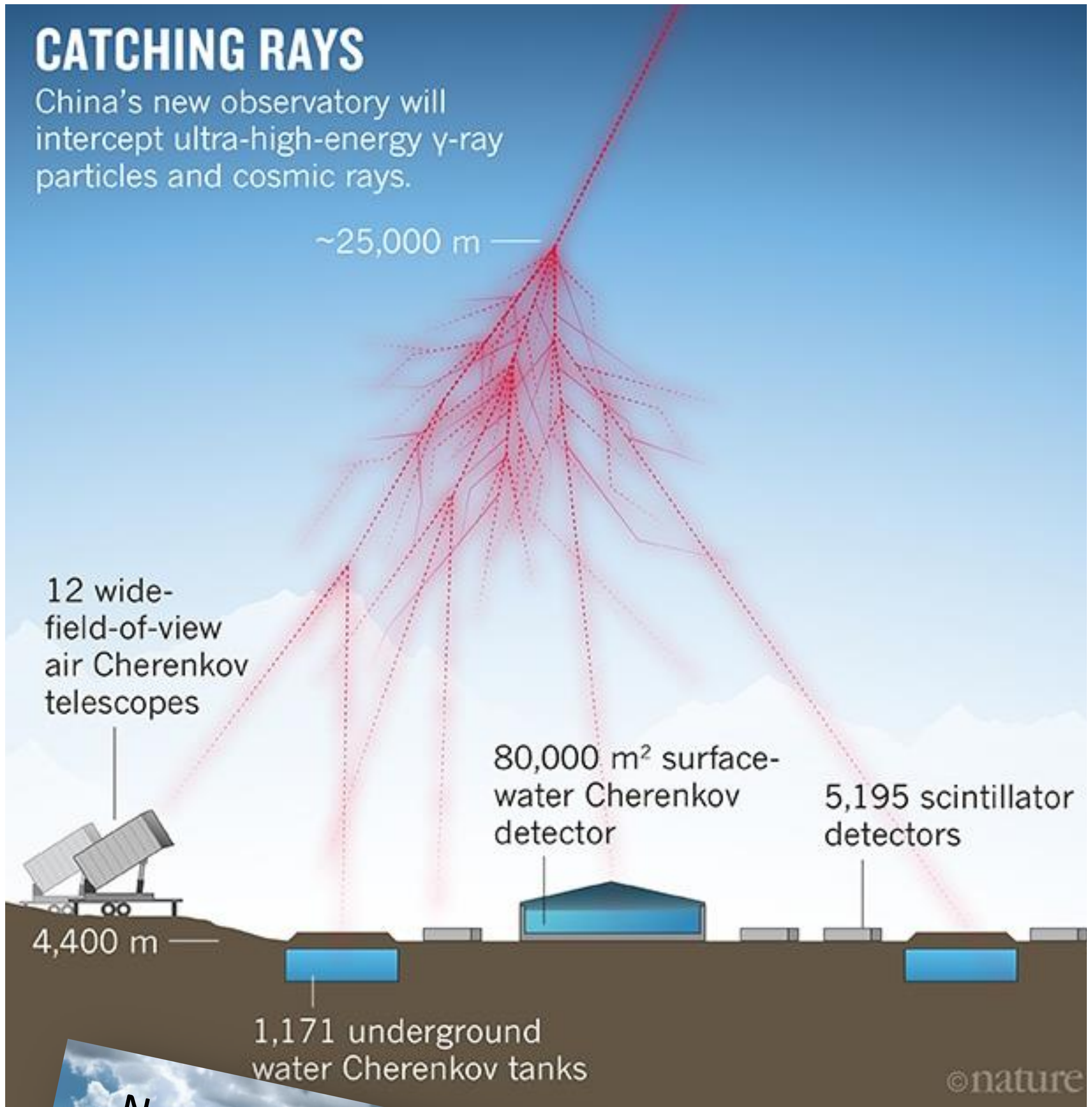
The experiment will be located at 4400 m asl (600 g/cm^2) in the Haizishan (Lakes' Mountain) site, Sichuan province

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

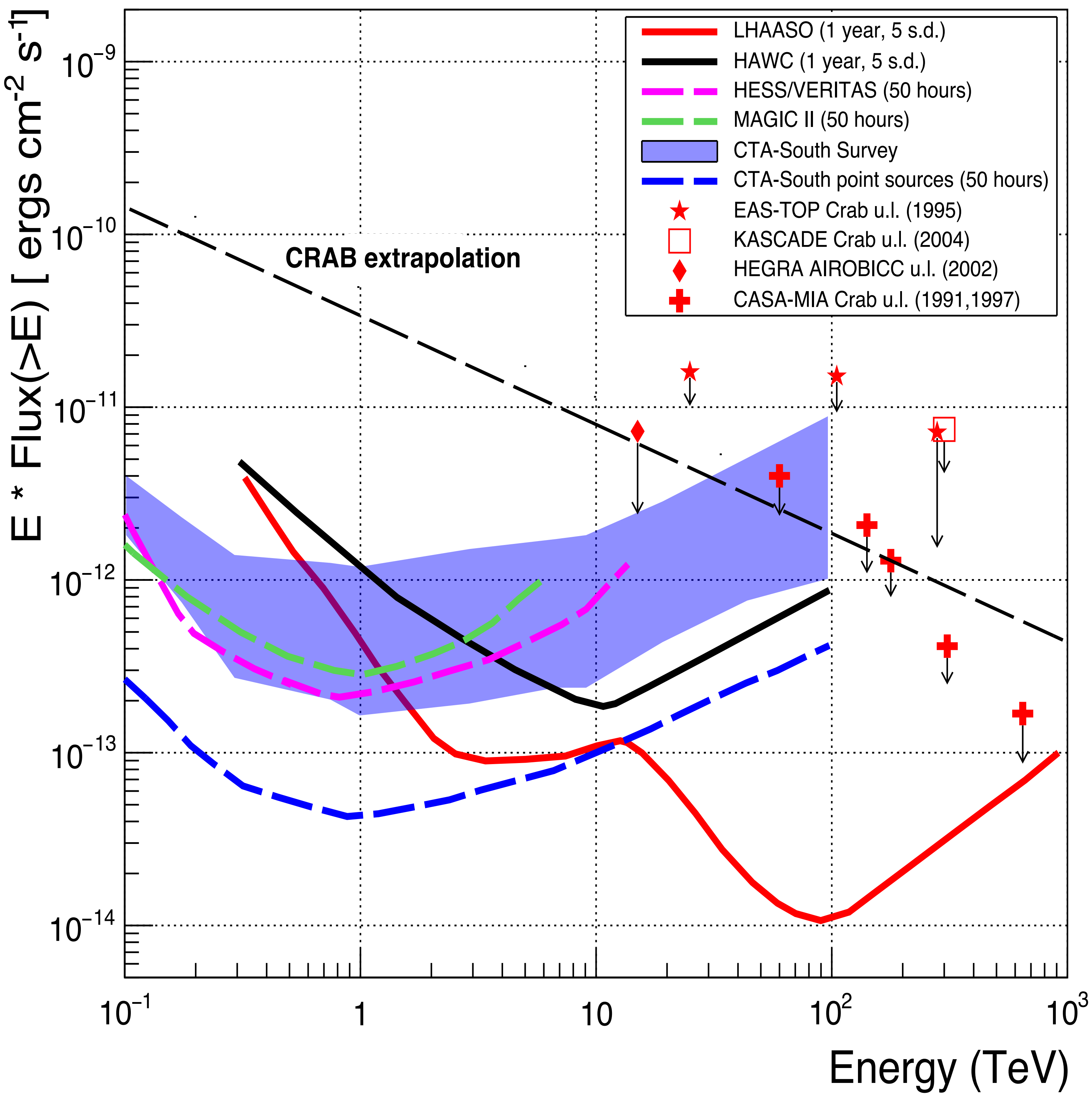


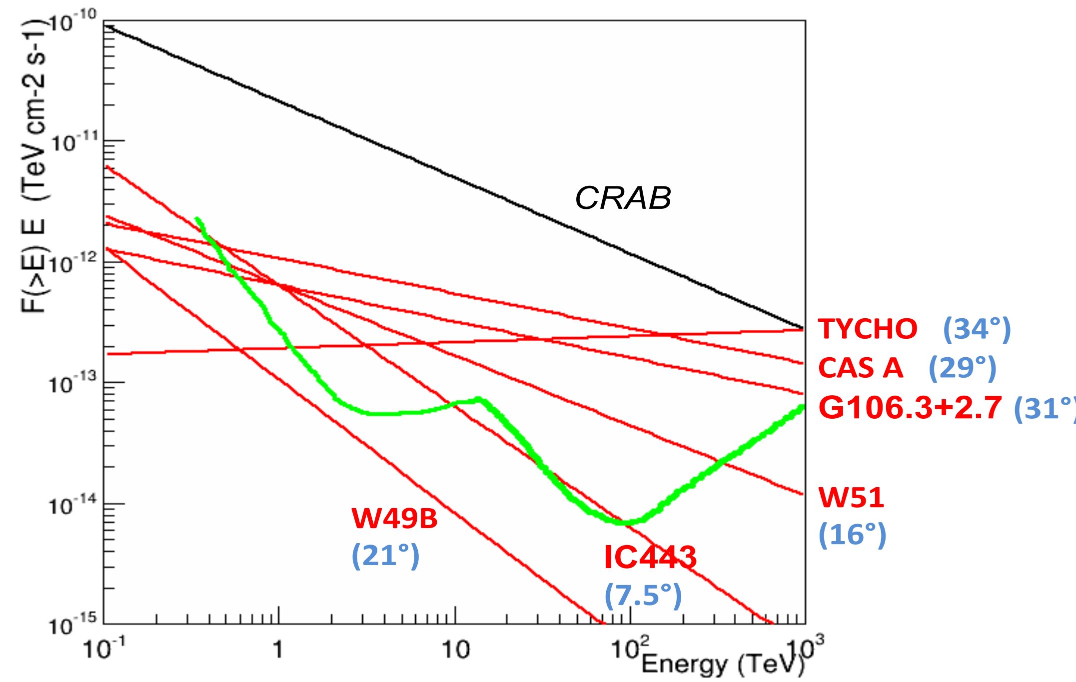
Status of the experiment



- ★ The first pond (HAWC-like) will be completed by the end of 2017 and instrumented in 2018.
- ★ 1/4 of the experiment in commissioning by the end of 2018 (sensitivity better than HAWC):
  - 6 WFCTA telescopes
  - 22,500 m^2 water Cherenkov detector
  - ≈200 muon detectors covering 250,000 m^2
- ★ Completion of the installation in 2021.

Gamma-Ray Astronomy with LHAASO





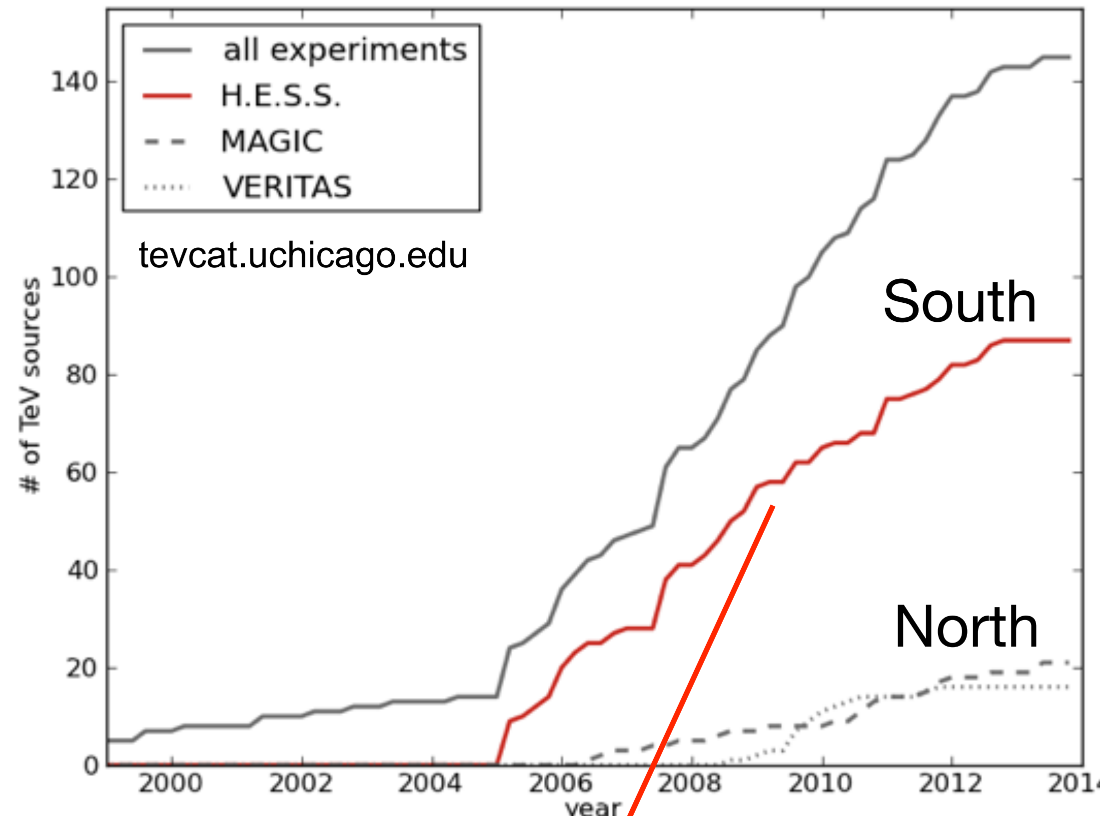
LHAASO will observe at TeVs, with high sensitivity, >40 of the sources catalogued by Fermi-LAT at lower energy, monitoring the variability of >20 AGNs.

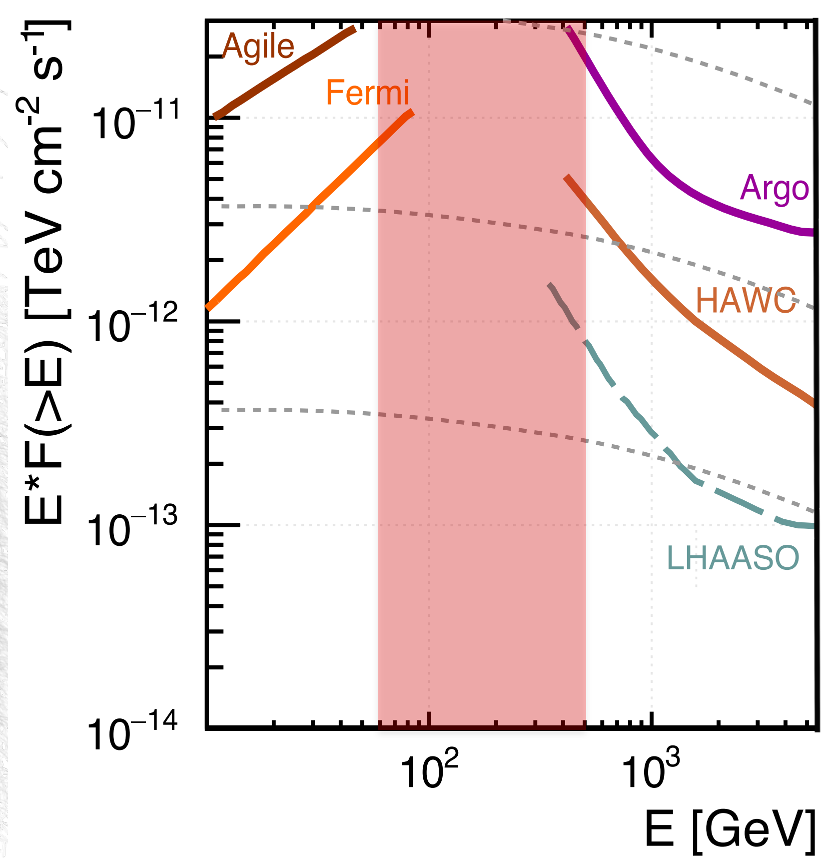
Future Wide FoV telescopes: What's Next ?

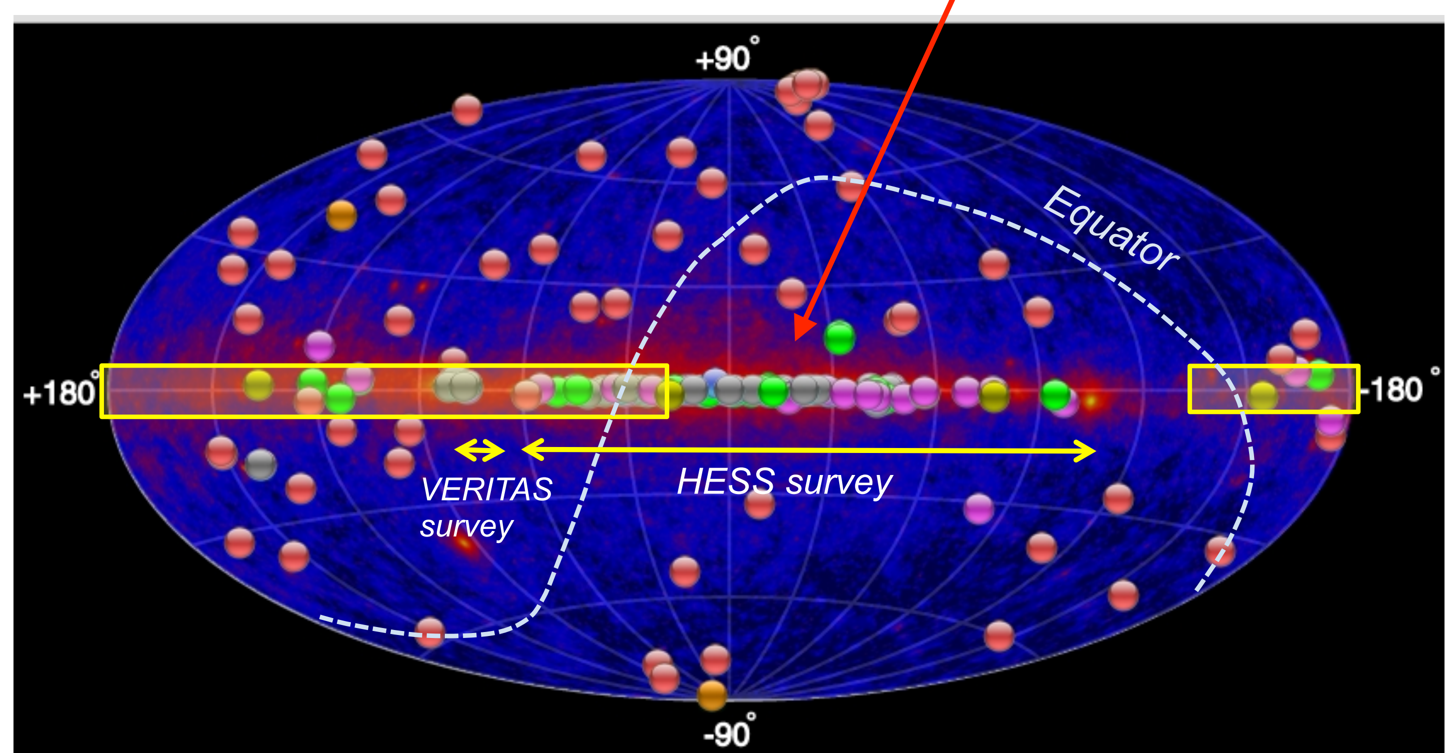
Why a new Wide FoV detector in the CTA era ?

No Wide FoV experiment to:

- Explore the 100 GeV energy region
  - ✓ Cover the gap between satellite and ground-based telescopes
  - ✓ Ability to detect extragalactic transient/flaring (AGN, GRBs)
  - ✓ Trigger observations of variable sources: "Finder for CTA"
- Survey the Inner Galaxy and the Galactic Center







Southern Hemisphere: LATTES

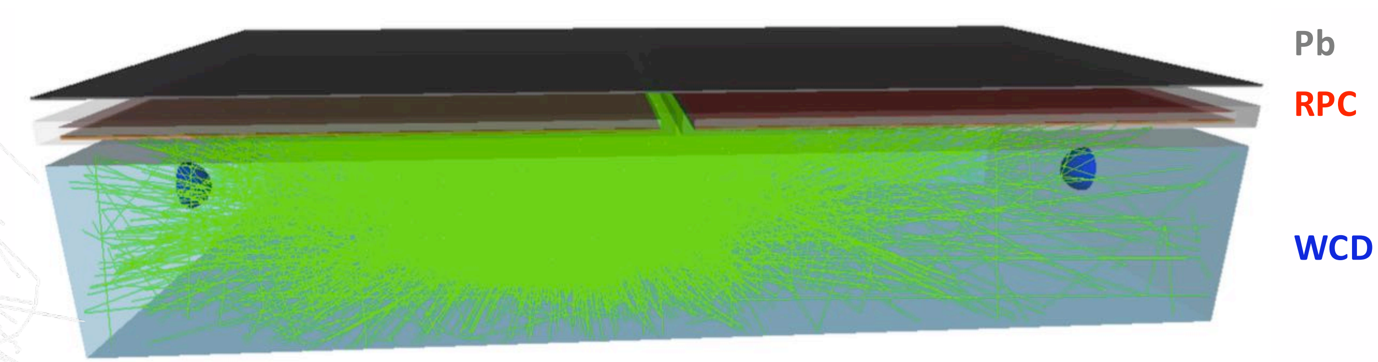
arXiv:1607.03051

P. Assis, U. Barres de Almeida, A. Blanco, R. Conceicao, B. D'Ettorre Piazzoli, A. De Angelis, M. Doro, P. Fonte, L. Lopes, G. Matthiae, M. Pimenta, R. Shellard, B. Tome'

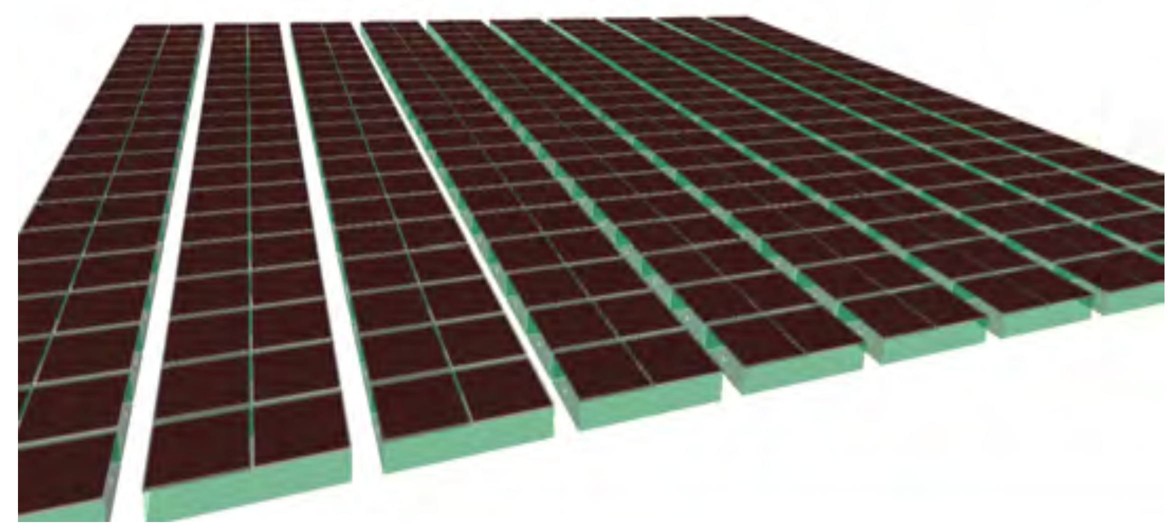
An array of hybrid detectors constituted by

1. one Water Cherenkov Detector (WCD) with a rectangular horizontal surface of 3 m × 1.5 m and a depth of 0.5 m, with signals read by PMTs at both ends of the smallest vertical face of the block.

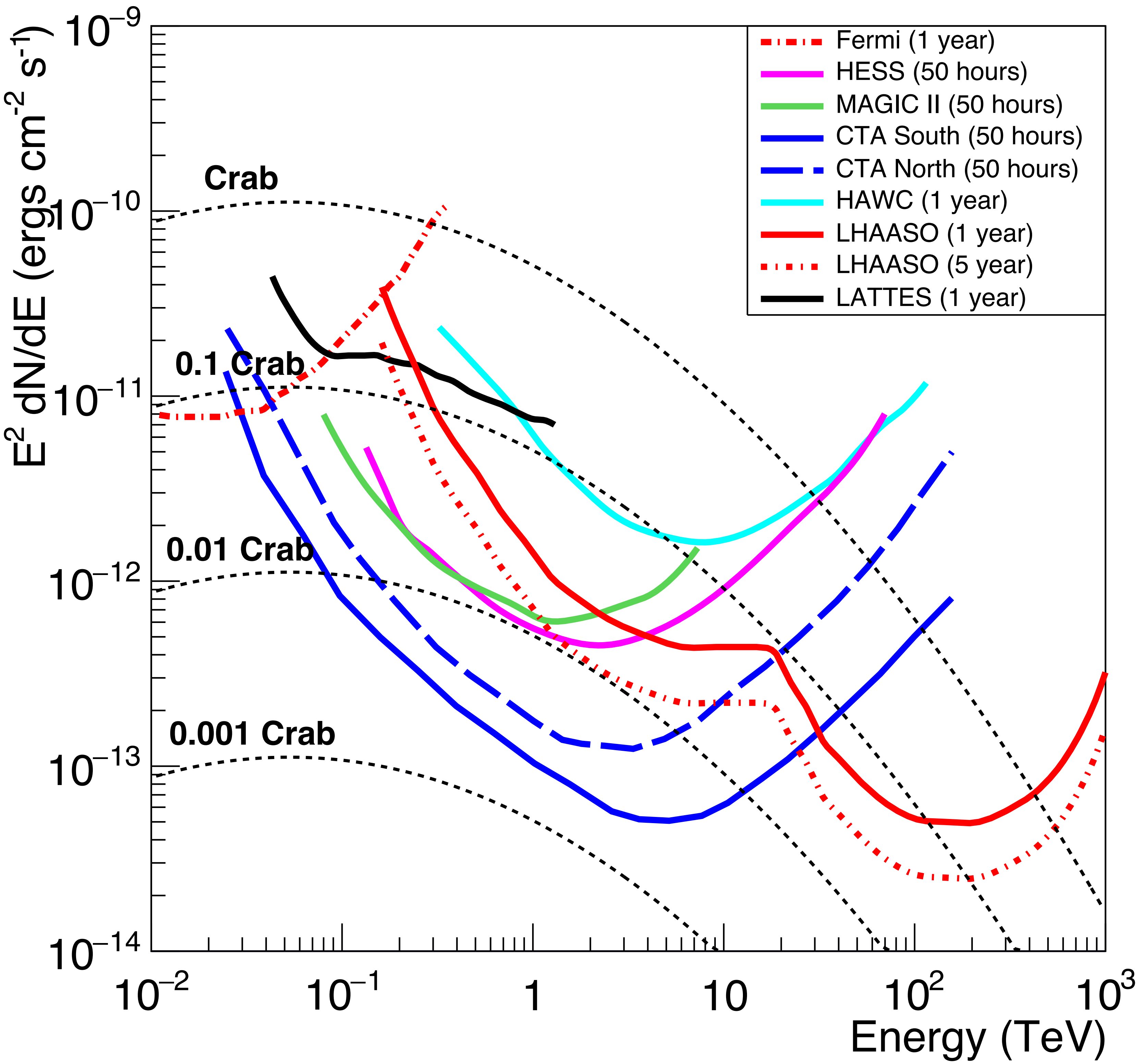
2. On top of the WCD there are two MARTA RPCs, each with a surface of (1.5 × 1.5) m^2 and with 16 charge collecting pads. Each RPC is covered with a thin (5.6 mm) layer of lead.



- Thin lead plate (Pb)
  - 5.6 mm (one radiation lenght)
- Resistive Plate Chambers (**RPC**)
  - 2 RPCs per station
  - Each RPC with 4x4 readout pads
- Water Cherenkov Detector (**WCD**)
  - 2 PMTs (diameter: 15 cm)
  - Dimensions: 1.5 m x 3 m x 0.5 m



TeV - PeV γ-ray astronomy



Conclusions

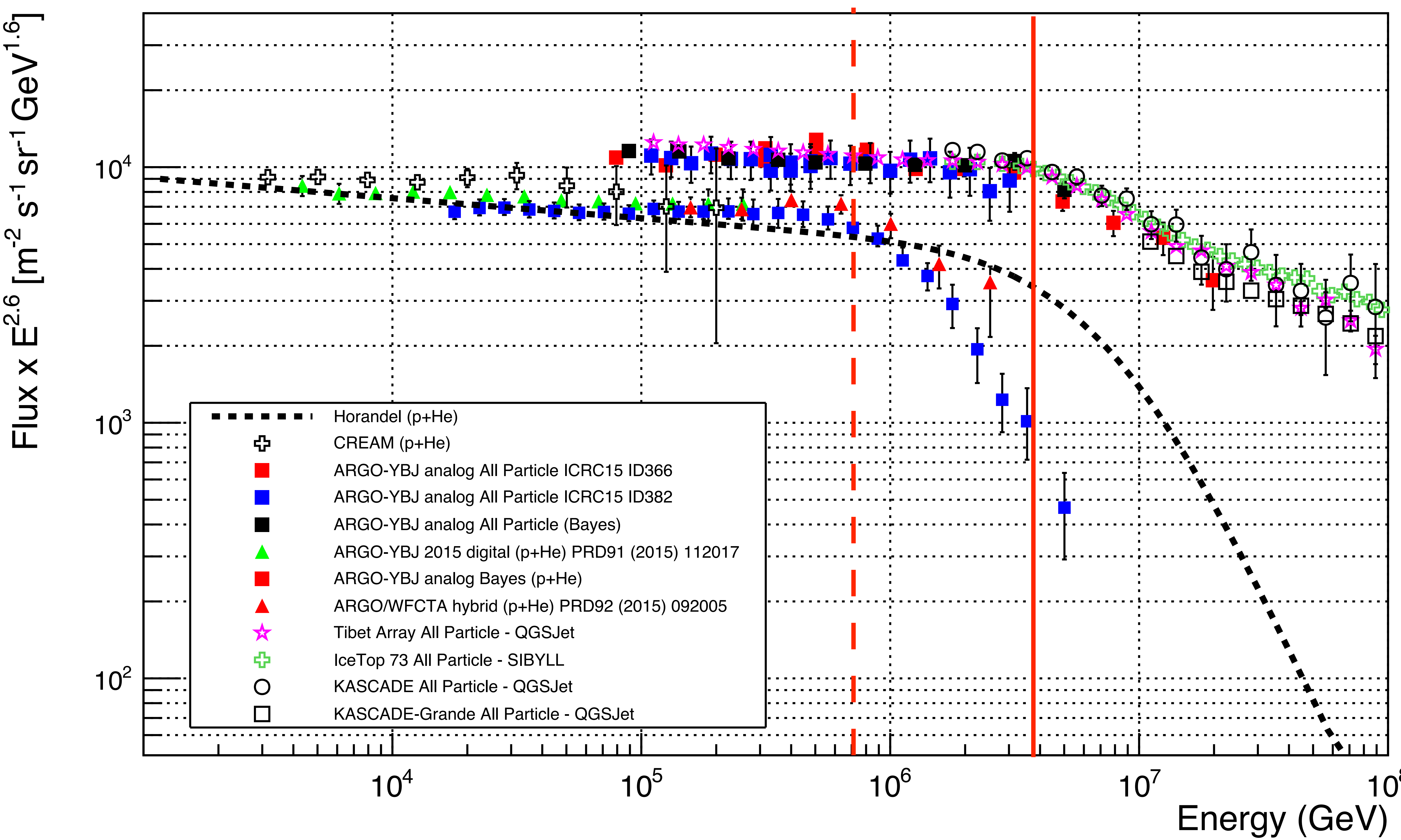
Open problems in galactic cosmic ray physics push the construction of new generation wide FoV detectors in the 10^{11} - 10^{18} eV energy range.

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

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.

- A new wide FoV detector in the Southern Hemisphere is mandatory to monitor the Inner Galaxy and the Galactic Center
- With CTA coming a future all-sky array should have ~5x increase in sensitivity over LHAASO at least.
- Extragalactic transient detection requires low threshold, $\approx$100 GeV.
- Extreme altitude (>5000 m asl) and high coverage are key.
- New ideas for background rejection below TeV for a few % Crab sensitivity !

The overall picture at the knee



LHAASO vs other EAS arrays

Experiment	Altitude (m)	e.m. Sensitive Area (m^2)	Instrumented Area (m^2)	Coverage
LHAASO	4410	5.2×10^3	1.3×10^6	4×10^{-3}
TIBET ASγ	4300	380	3.7×10^4	10^{-2}
IceTop	2835	4.2×10^2	10^6	4×10^{-4}
ARGO-YBJ	4300	6700	11,000	0.93 (central carpet)
KASCADE	110	5×10^2	4×10^4	1.2×10^{-2}
KASCADE-Grande	110	370	5×10^5	7×10^{-4}
CASA-MIA	1450	1.6×10^3	2.3×10^5	7×10^{-3}

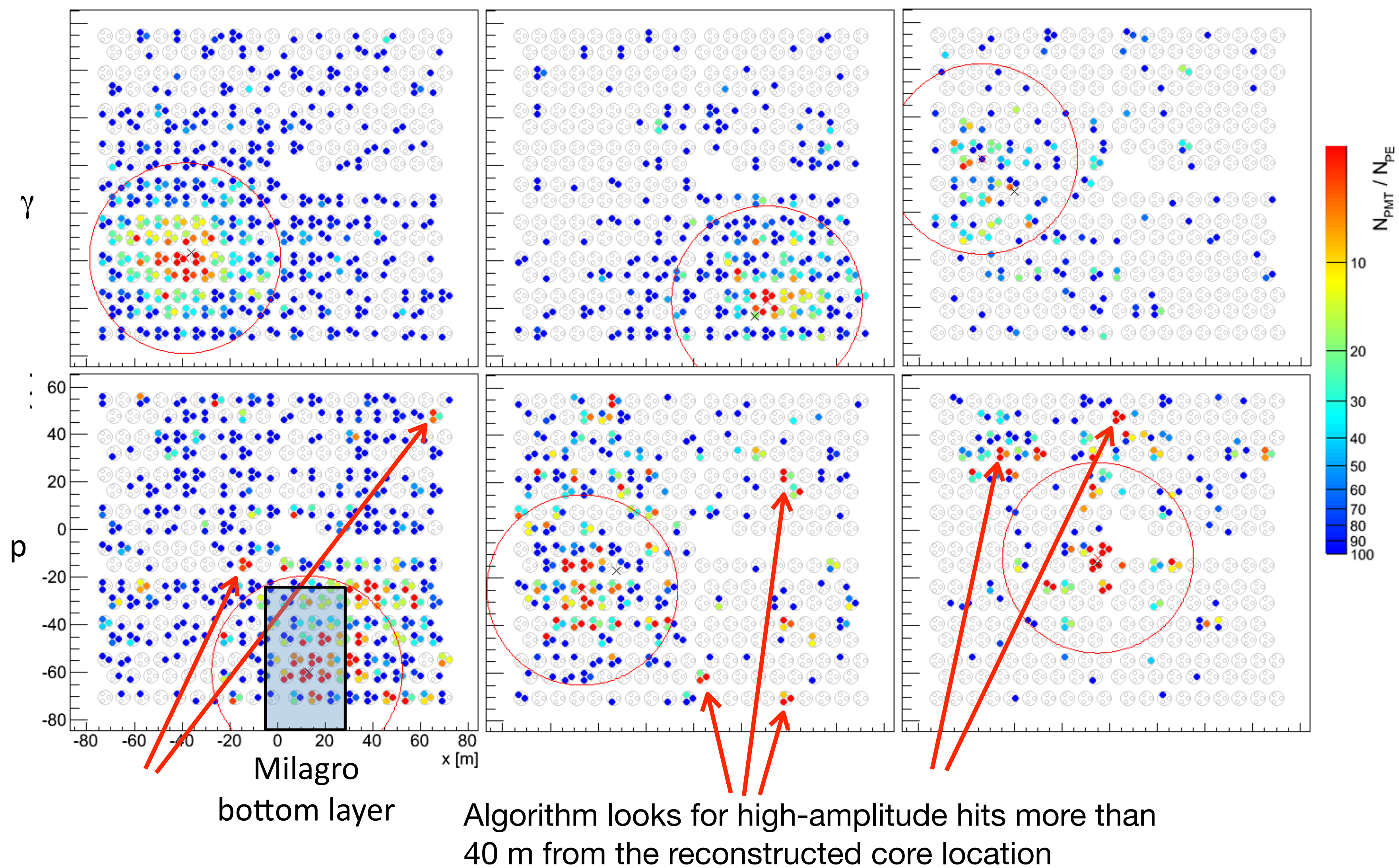
		μ Sensitive Area (m^2)	Instrumented Area (m^2)	Coverage
LHAASO (✦)	4410	4.2×10^4	10^6	4.4×10^{-2}
TIBET ASγ	4300	4.5×10^3	3.7×10^4	1.2×10^{-1}
KASCADE	110	6×10^2	4×10^4	1.5×10^{-2}
CASA-MIA	1450	2.5×10^3	2.3×10^5	1.1×10^{-2}

- ✓ LHAASO will operate with a coverage similar to KASCADE (about %) over a much larger effective area.
- ✓ The detection area of muon detectors is about 70 times larger than KASCADE (coverage 5%) !
- ✓ Redundancy: different detectors to study hadronic models dependence

(✦) Muon detector area: 4.2×10^4 m^2 + 8×10^4 m^2 (WCDA)

Background rejection

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)



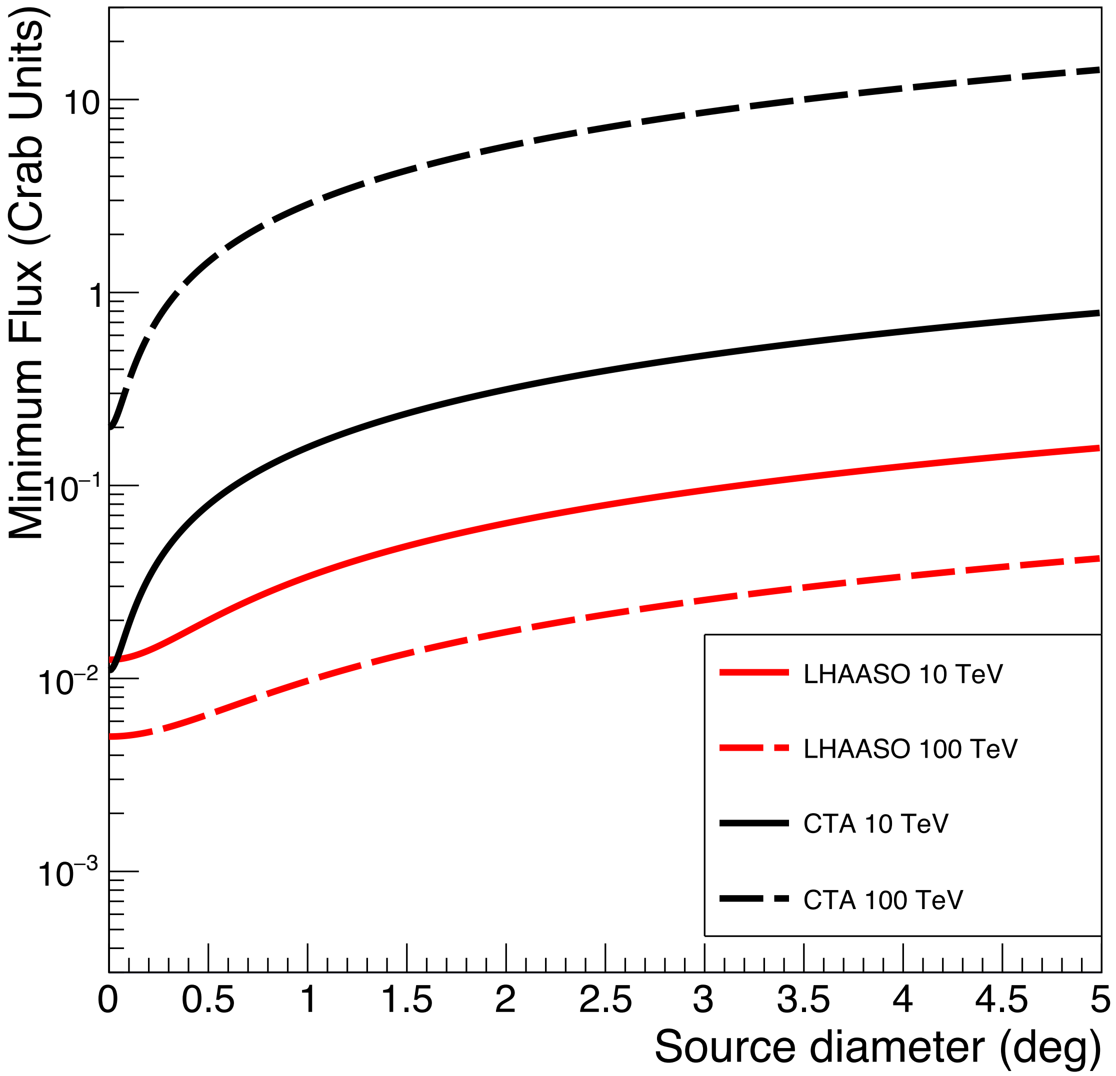
Requires sufficient number of triggered channels (>70) to work well.
Q-value max ($\varepsilon_\gamma/\sqrt{\varepsilon_{CR}}$) is estimated ~5 for point sources.

Extended sources

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

dimension of the extended source

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



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.