The Extreme Universe

Ultra-High Energy Cosmic Ray & Neutrino Observations

Karl-Heinz Kampert
University of Wuppertal

e-mail: kampert@uni-wuppertal.de

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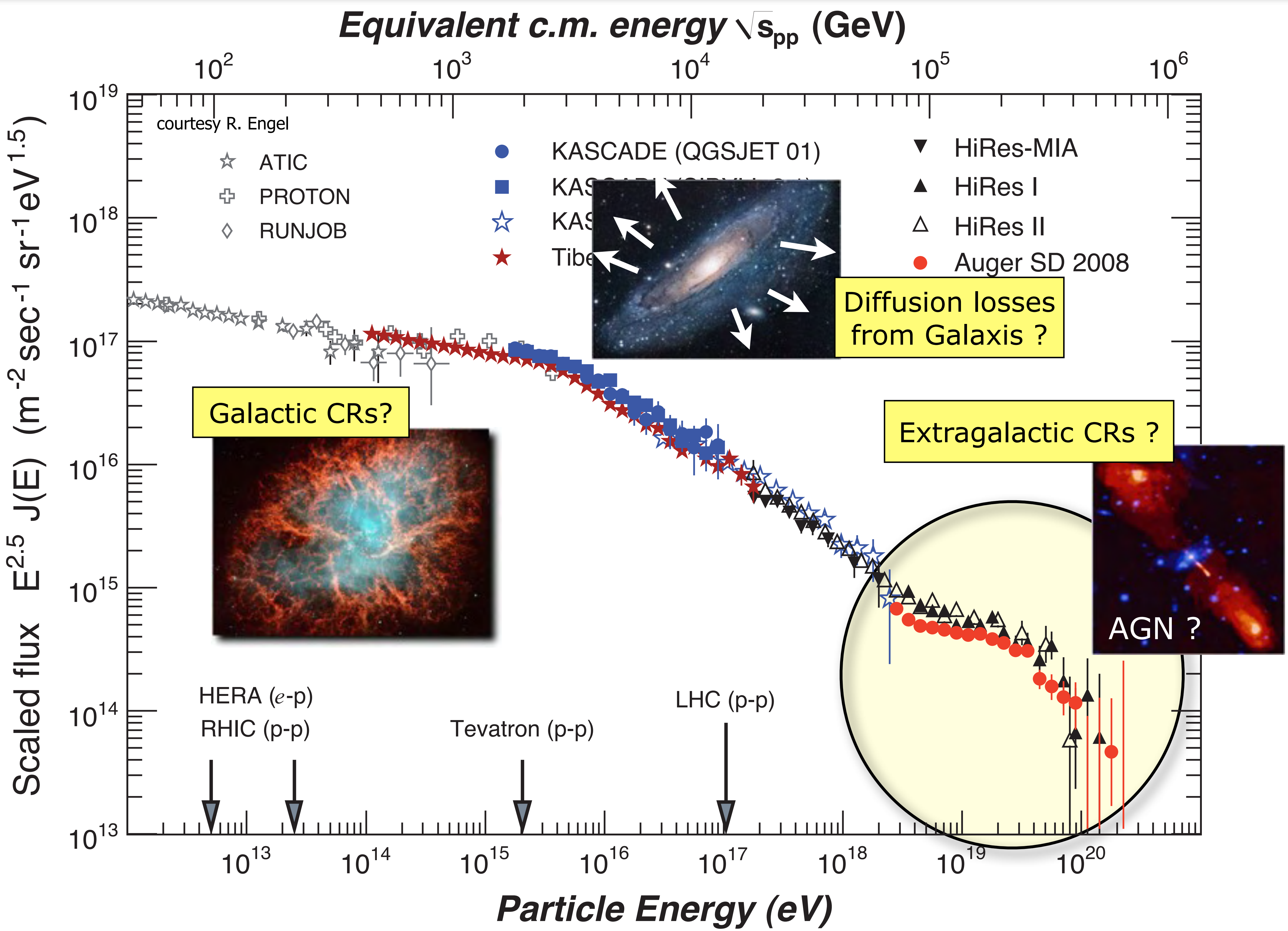
Outline

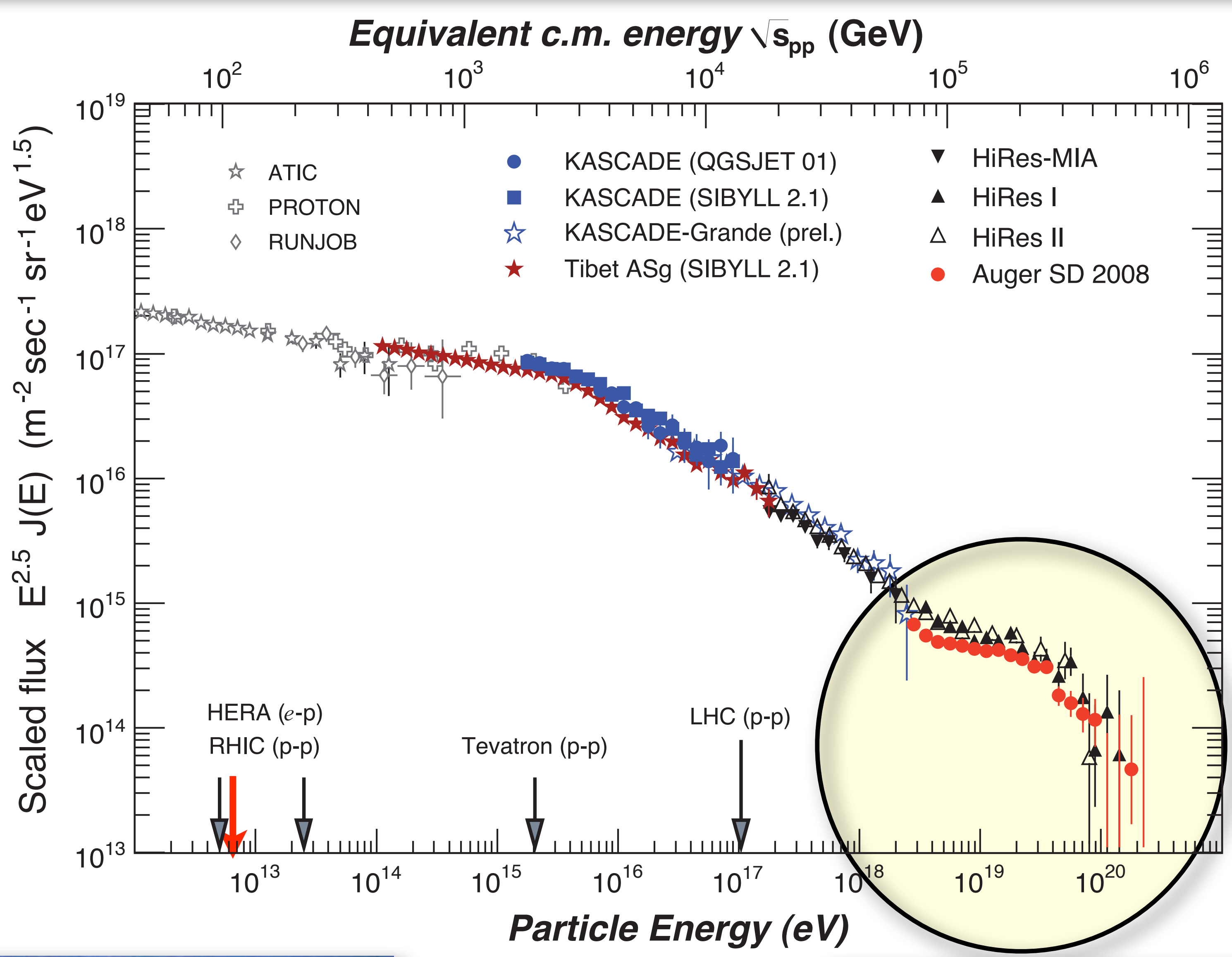
- **The Extreme Universe: Science Case**
- **UHECRs**
  - Latest News from Auger, HiRes and TA
    - *Energy Spectra: GZK-Effect*
    - *Anisotropies: Search for Sources*
    - *Mass-Compos.: Puzzling Results*
    - *Photon Limits: Propagation and TopDown Tests*
- **Tests of Fundamental Physics**
- **Neutrino Astronomy**
  - Latest Results from IceCube, ANTARES, Auger, ...
- **Future Directions**

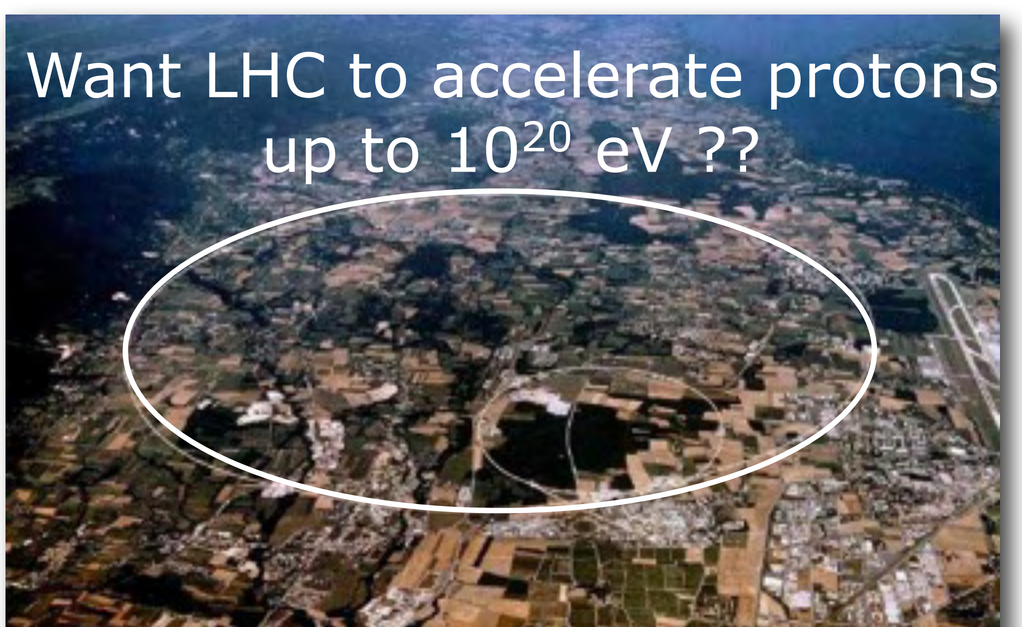
Largely based on results presented at ICRC in Łódź, last week

All Particle Cosmic Ray Spectrum

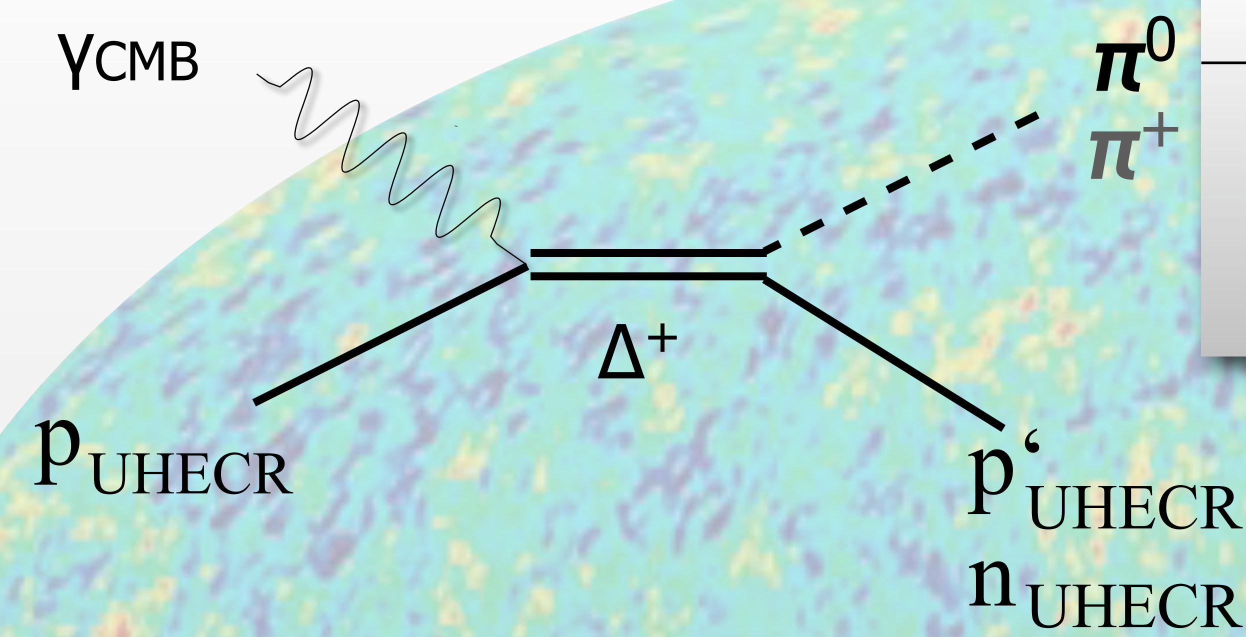


All Particle Cosmic Ray Spectrum





CR Absorption in CMB (GZK-Effect)



Greisen-Zatsepin-Kuz'min (1966)

$$p + \gamma_{CMB} \rightarrow \Delta \quad \rightarrow \quad p + \pi^0$$
$$\rightarrow \quad n + \pi^+$$

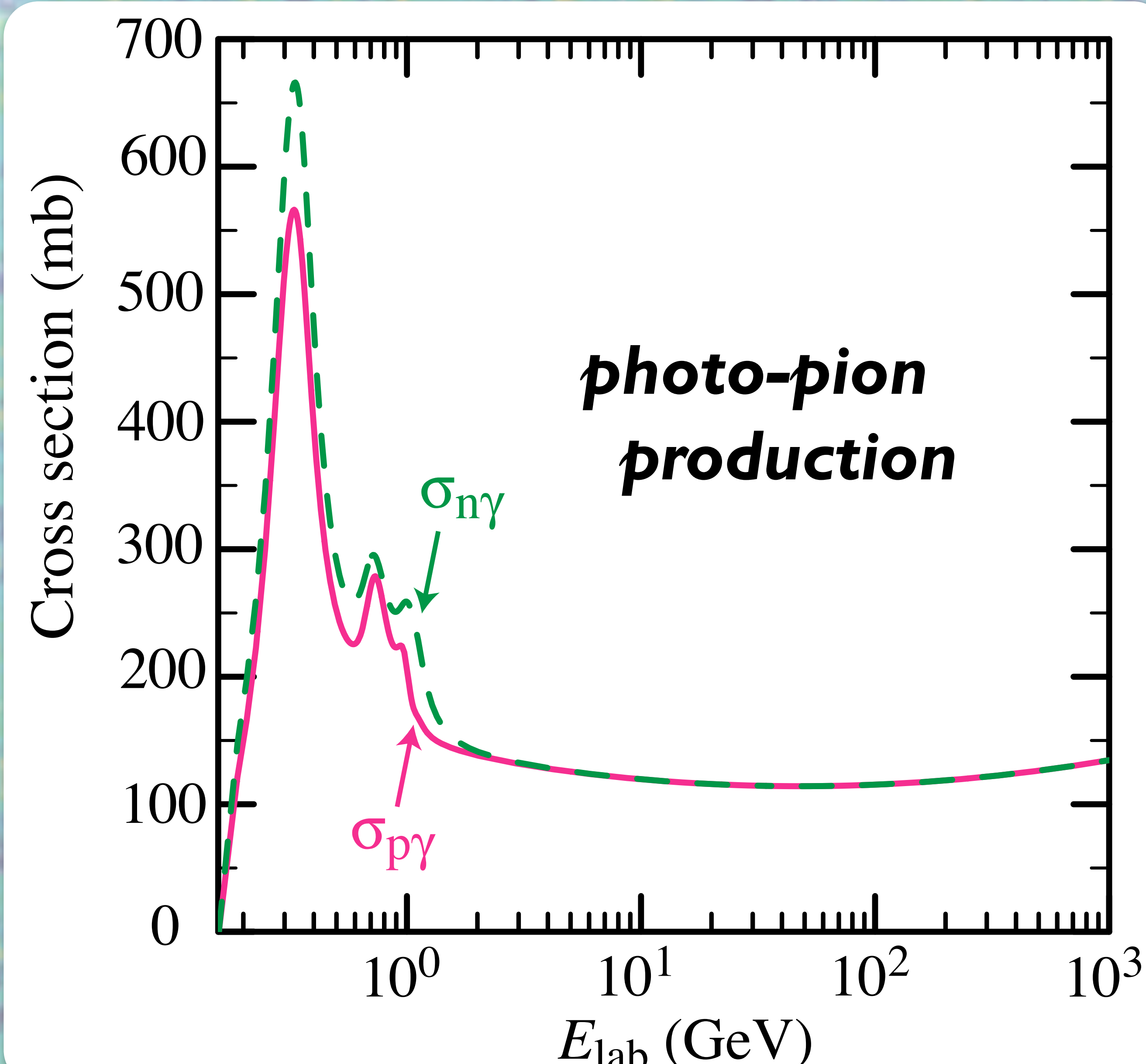
threshold: $E_p E_\gamma > (m_\Delta{}^2 - m_p{}^2)$

$\Rightarrow E_{GZK} \approx 6 \cdot 10^{19}$ eV

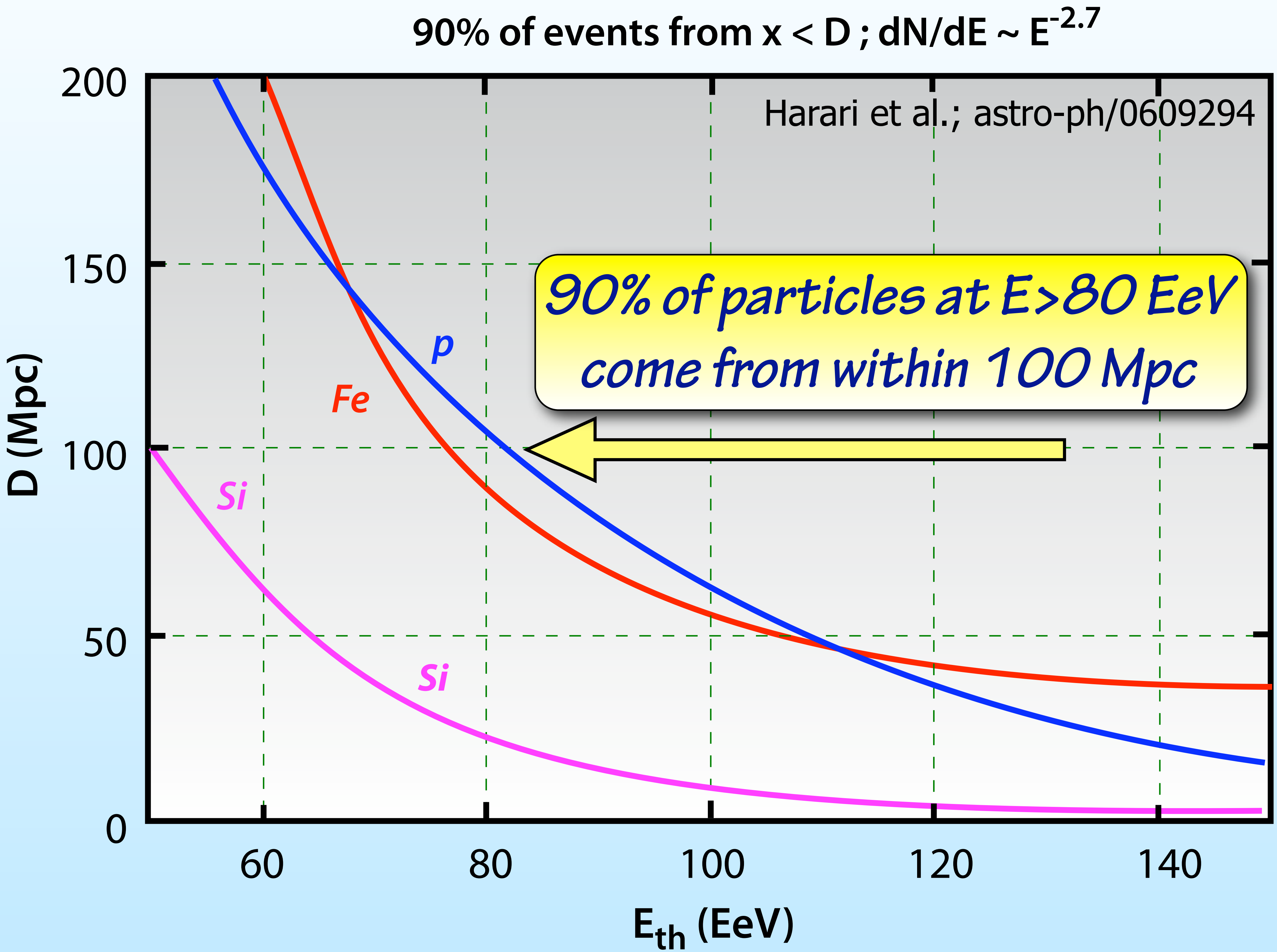
X-section is known,

$n_\gamma = 412/\text{cm}^3$ is known

$$\lambda_{free} = \frac{1}{n_\gamma \cdot \sigma_{p\gamma}} \approx 8 \text{ Mpc}$$



The GZK Horizon



UHECR Science Case

- Sources of most energetic CRs need to be nearby
- Deflections in magnetic fields are moderately weak

➠ Opportunity to identify sources by CR-Astronomy !

➠ need to measure: direction, energy, particle-type

By-Products:

- Do Particle Physics at the Highest Energies,

  e.g. pA and ν- cross-sections
- Probe Fundamental Physics, e.g. Tests of LIV
- Learn about Cosmic Environments, e.g. B-Fields

HiRes Experiment (Dugway, Utah)

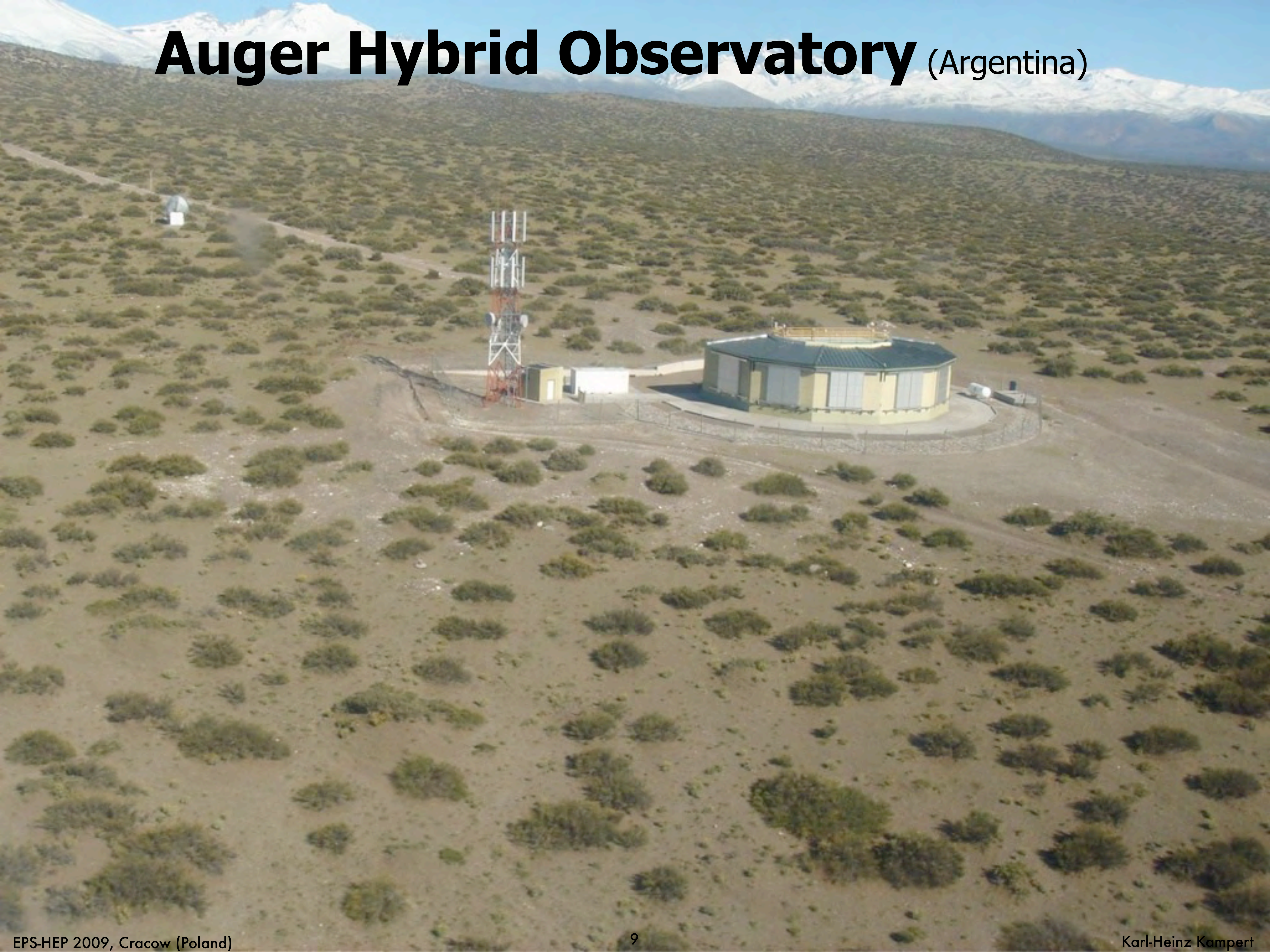
HiRes-I
21 mirrors
1 ring, full azimuth, 3°-17° elevation
Sample & Hold DAQ System

HiRes-II
42 mirrors
2 rings, full azimuth, 3°-31° elevation
FADC DAQ System
Took data: Dec. 1999-April 2006

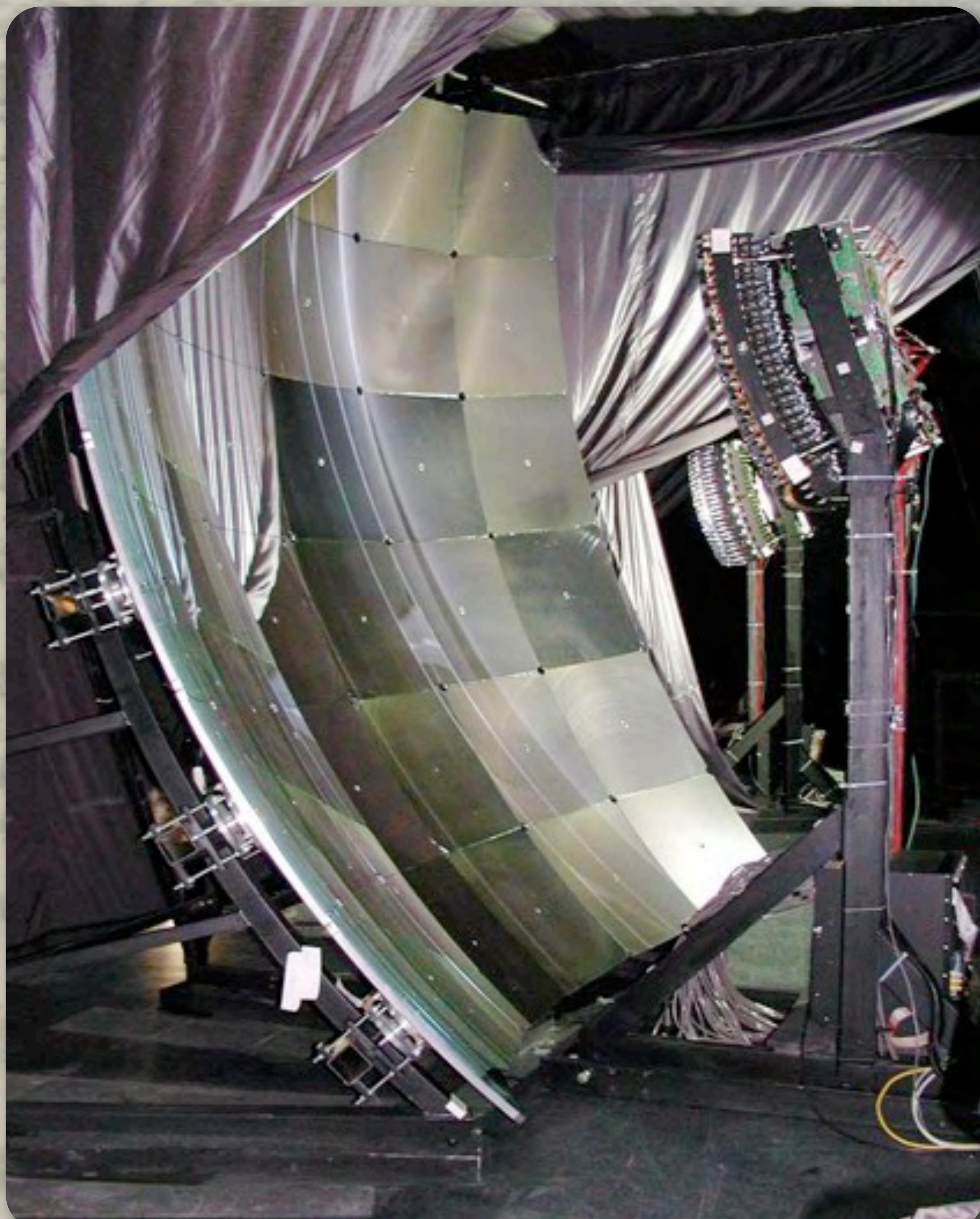
Both:
5.1 m^2 mirrors, 16x16 PMTs

HR I+II data taking:
June 1997-April 2006

Auger Hybrid Observatory (Argentina)

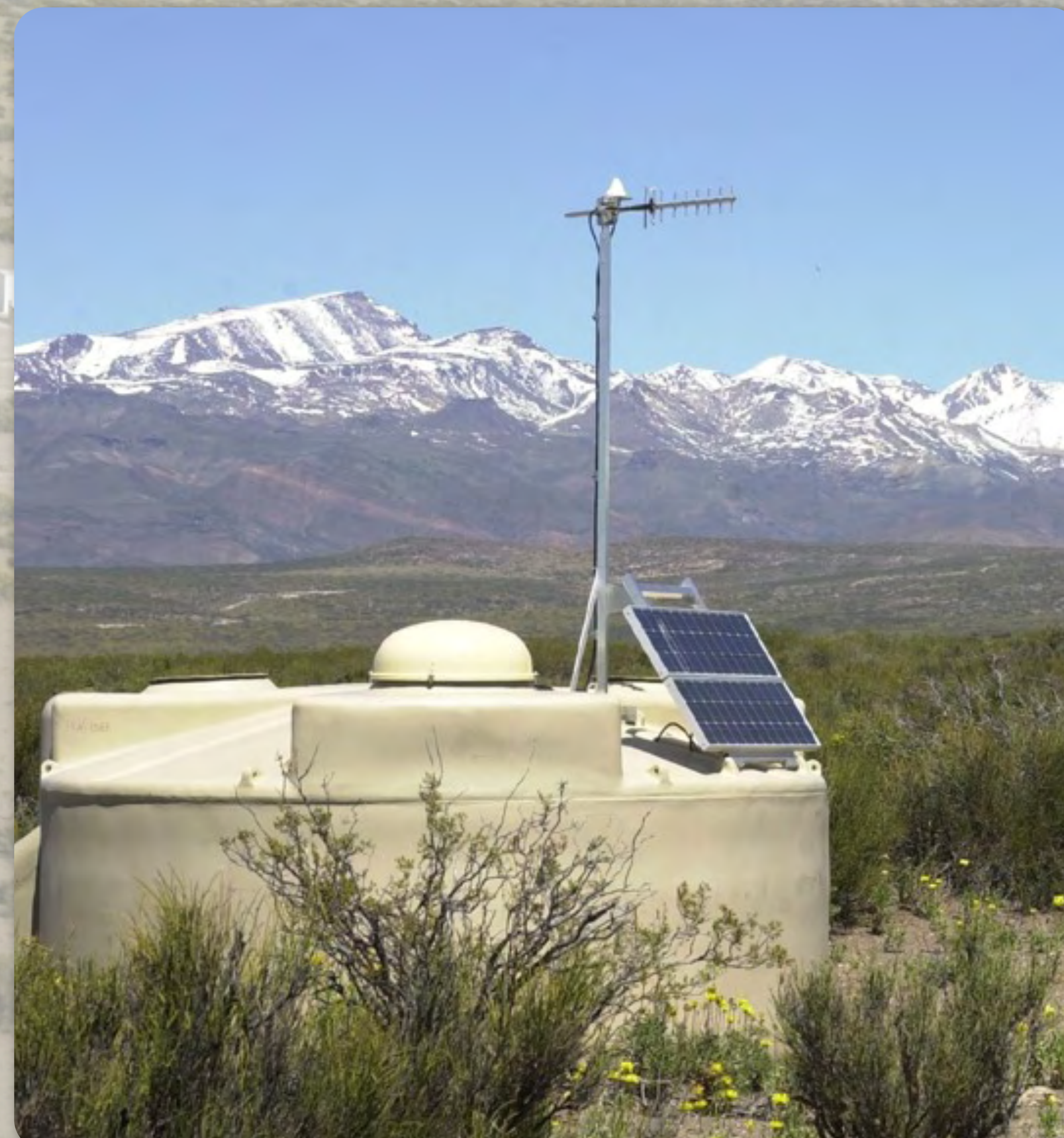


Auger Hybrid Observatory (Argentina)



24 fluorescence telescopes...

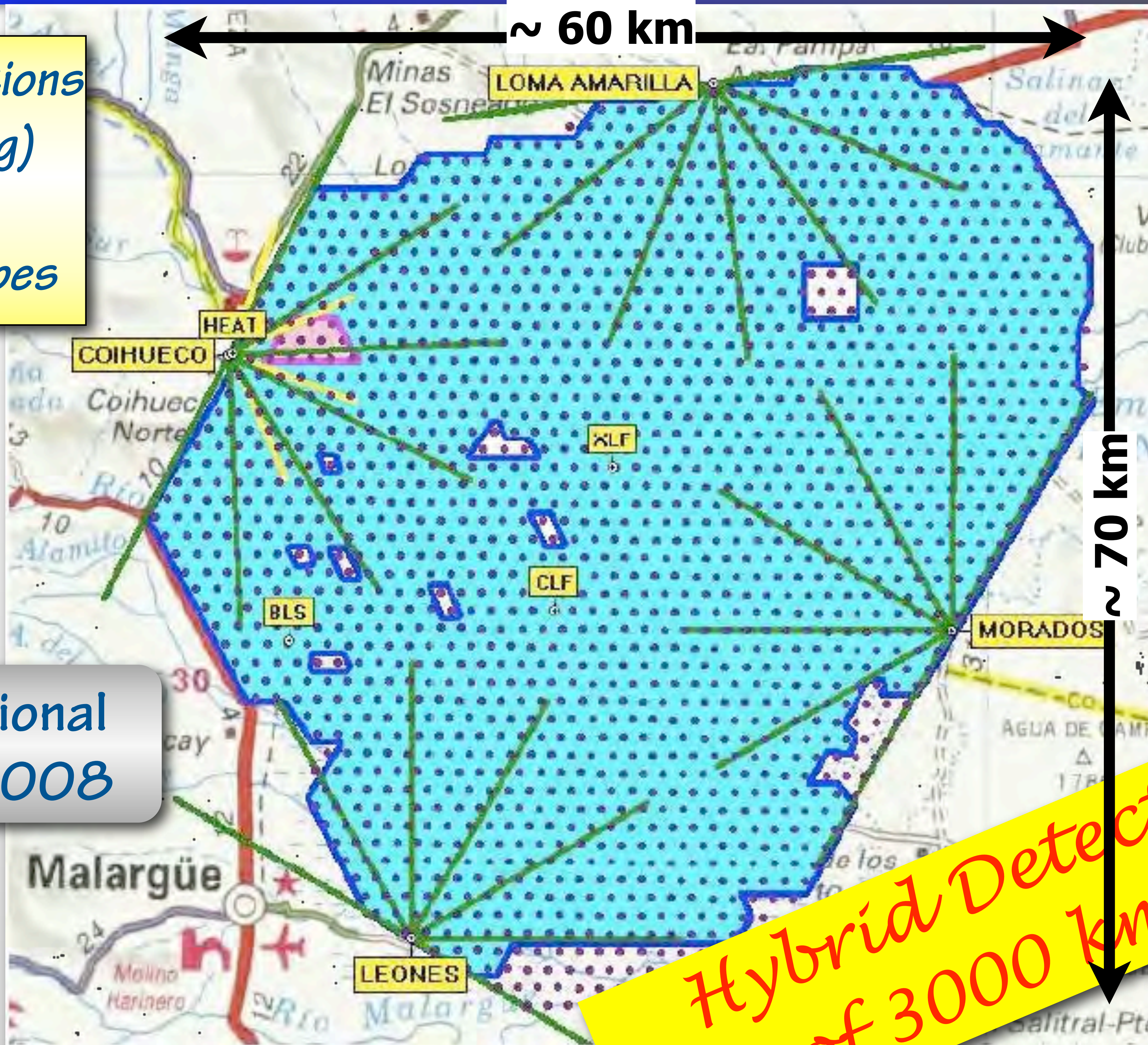
...1600 Water Cherenkov tanks



Pierre Auger Observatory

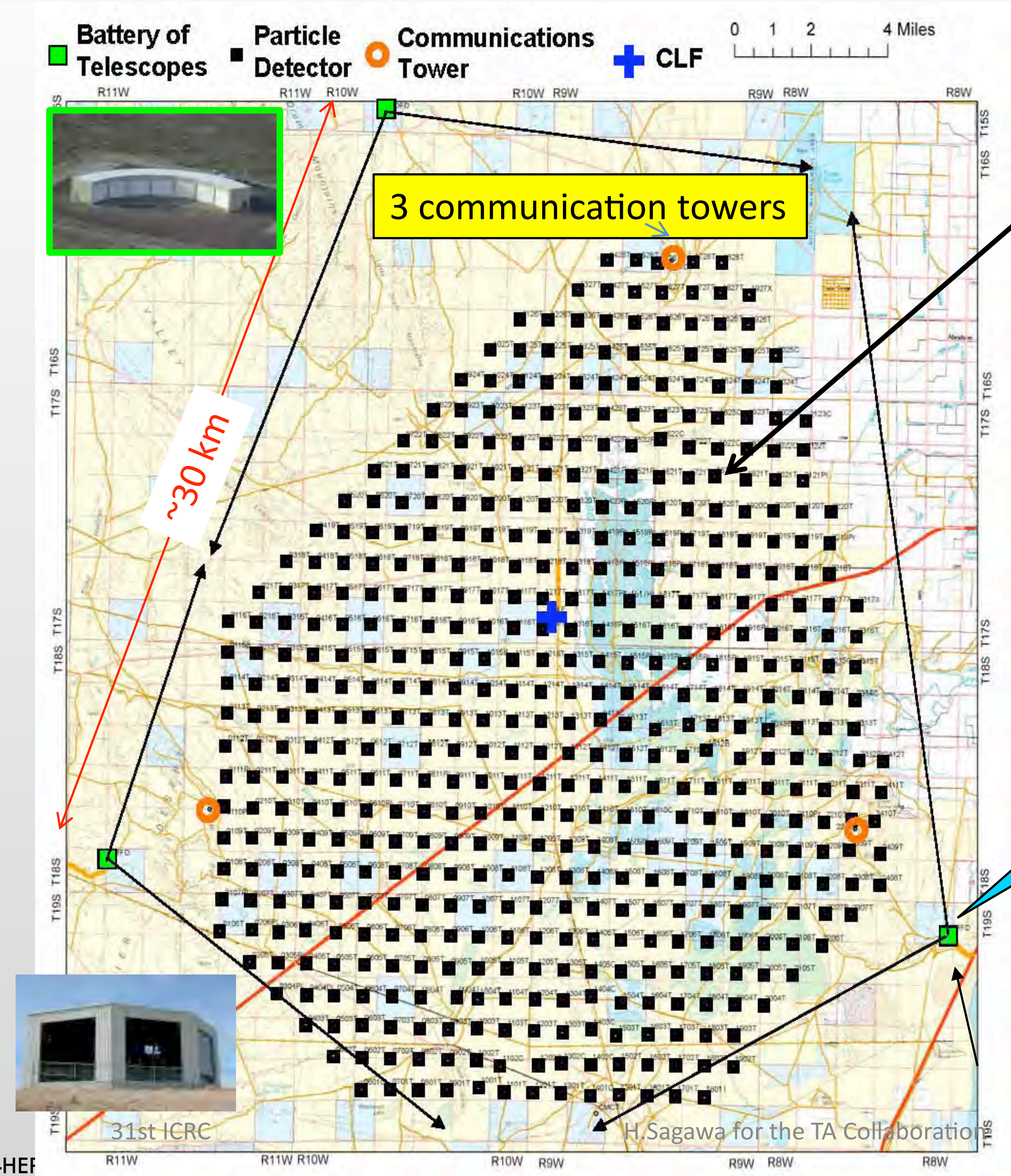
1600 SD stations
(1.6 km spacing)
= 3000 km²
24 FD telescopes

Fully Operational
since June 2008



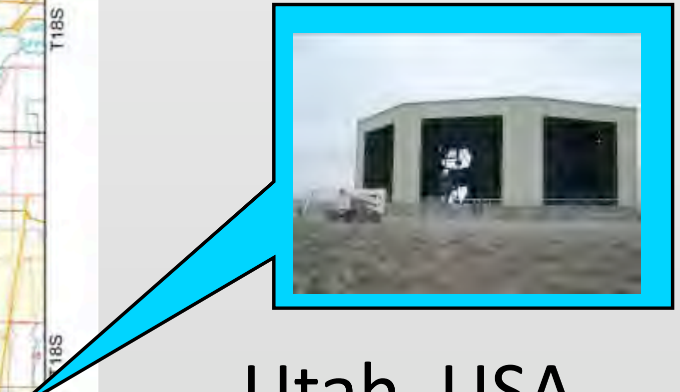
Telescope Array (Utah)

Fully Operational since March 2008



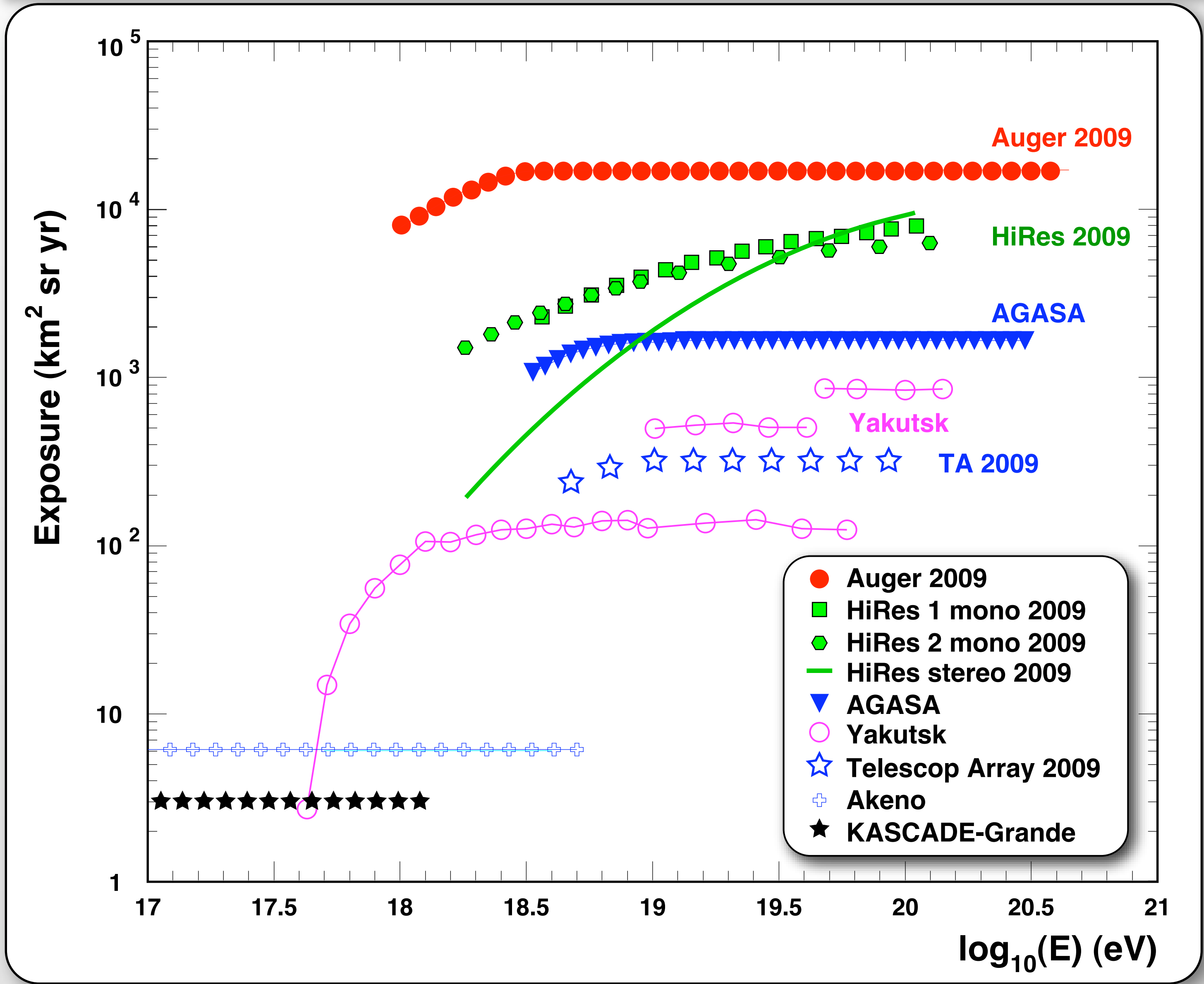
507 Plastic Scintillator Detectors cover ~700 km^2 (1.2km spacing)

3 Fluorescence Telescope Stations overlook the array.



Utah, USA
39.3 $^\circ$N, 112.9 $^\circ$W
alt. 1400 m

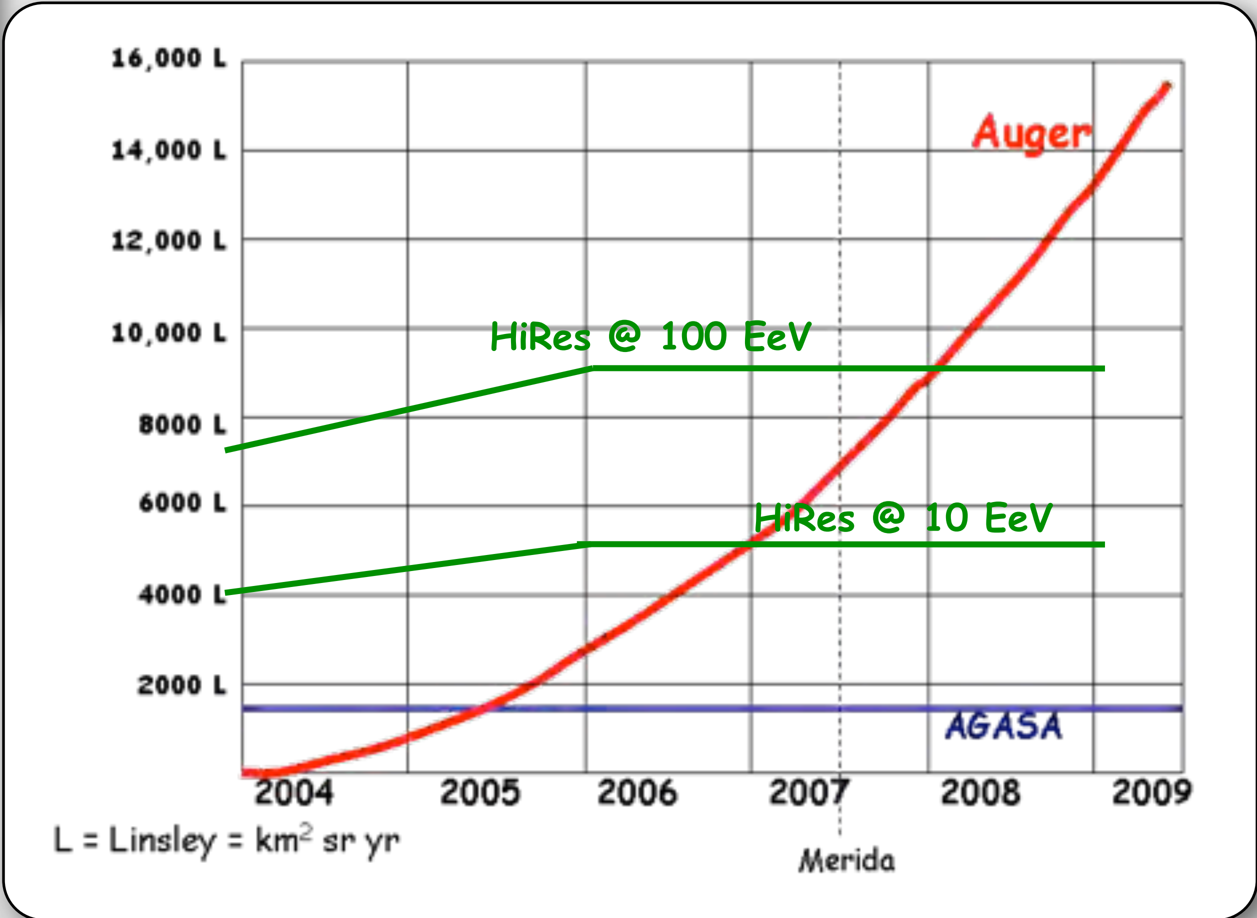
Exposures @ ICRC 2009



As a fct of energy...

AGASA : HiRes : Auger
1 : 5 : 10

... and time



L = Linsley = km² sr yr

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UHECR Energy Spectrum

Hybrid: More than Sum of the Two

Surface Detecor Based:

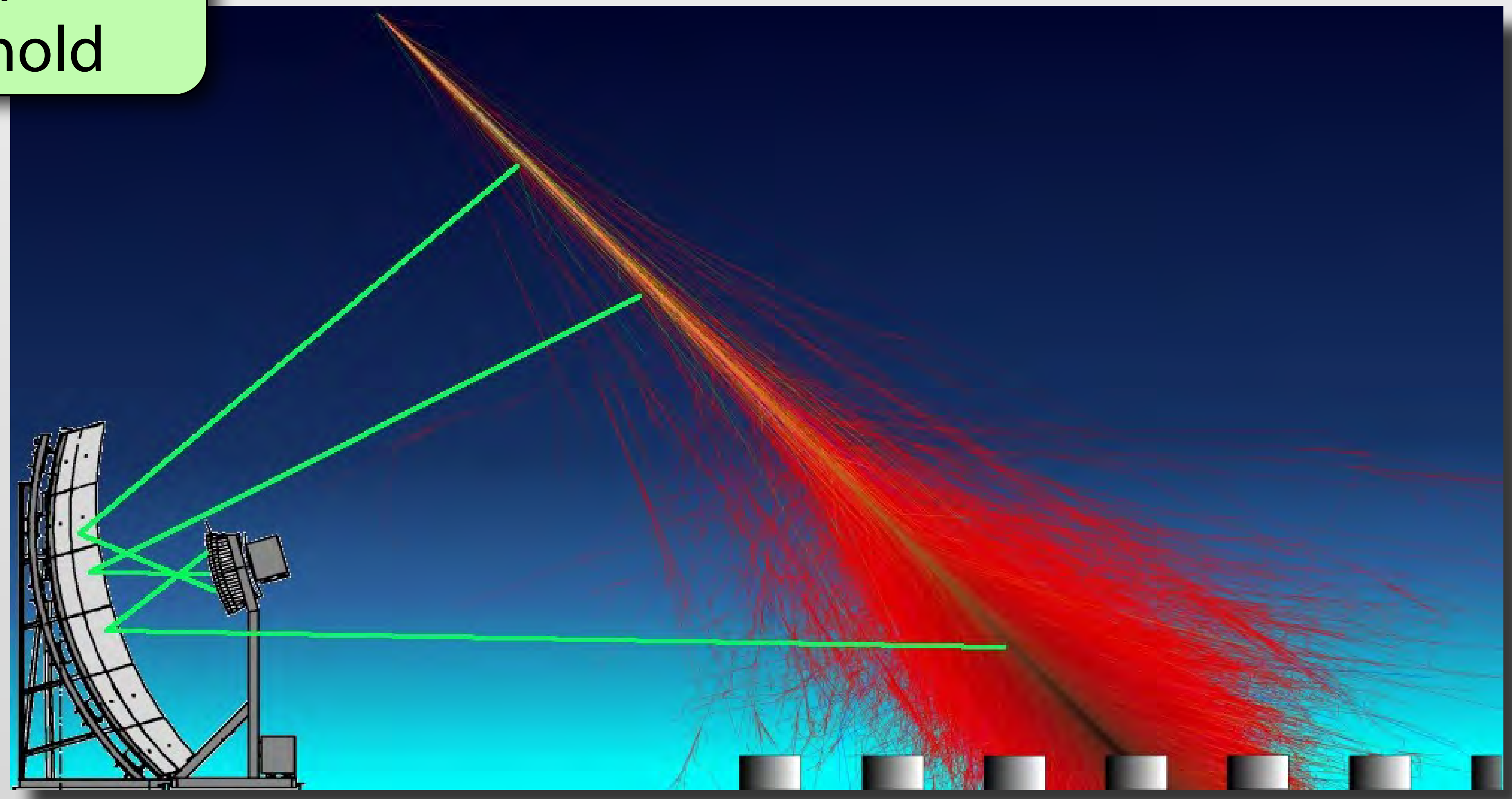
+ High Statistics (24 hrs a day)
+ Simple geometrical exposure
– Calibration of Energy from EAS-simul.

Fluorescence Detecor Based:

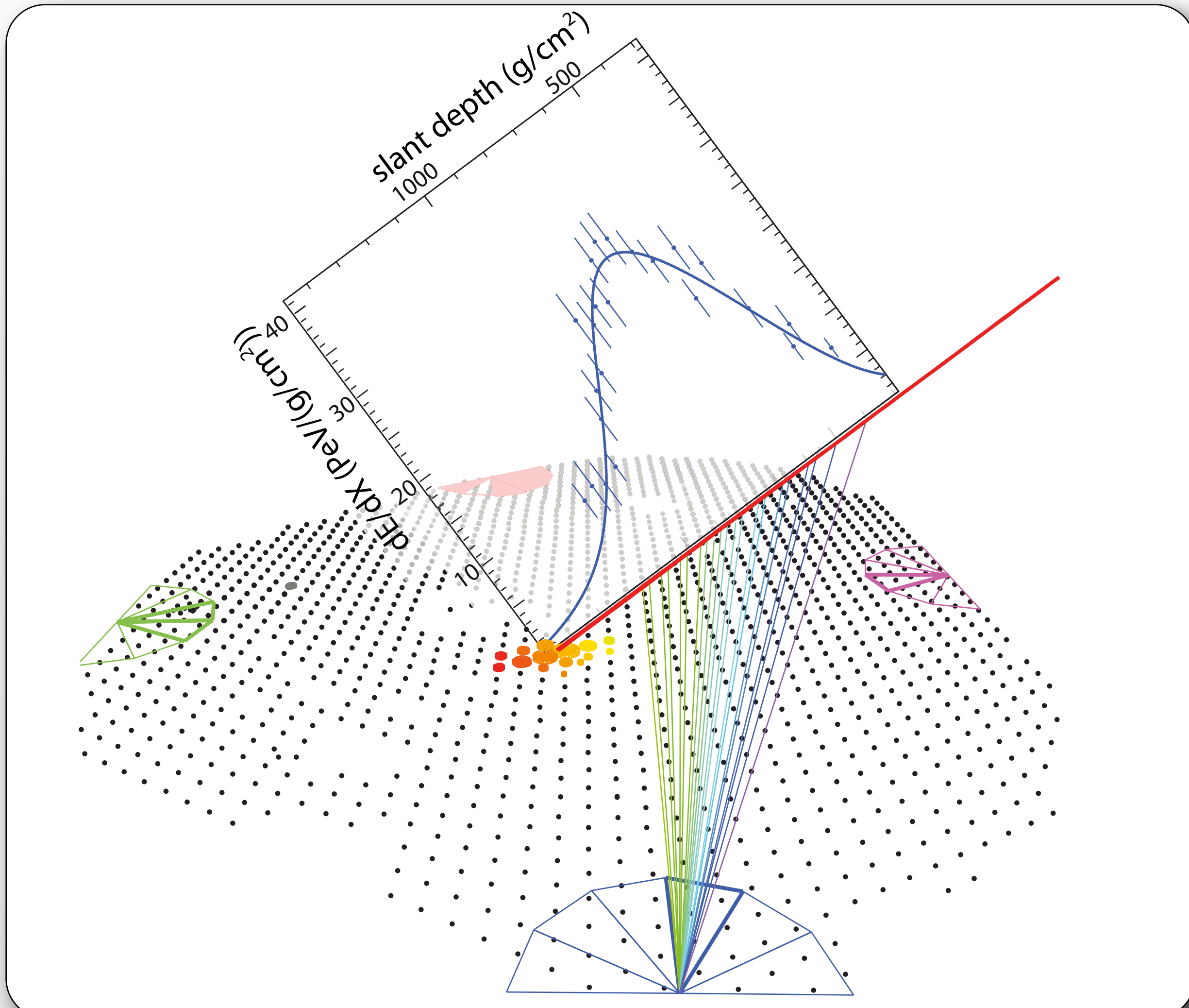
+ High Resolution
+ Low energy threshold
+ Calibration by laboratory expt's
– about 15 % duty cycle
– complicated apertur

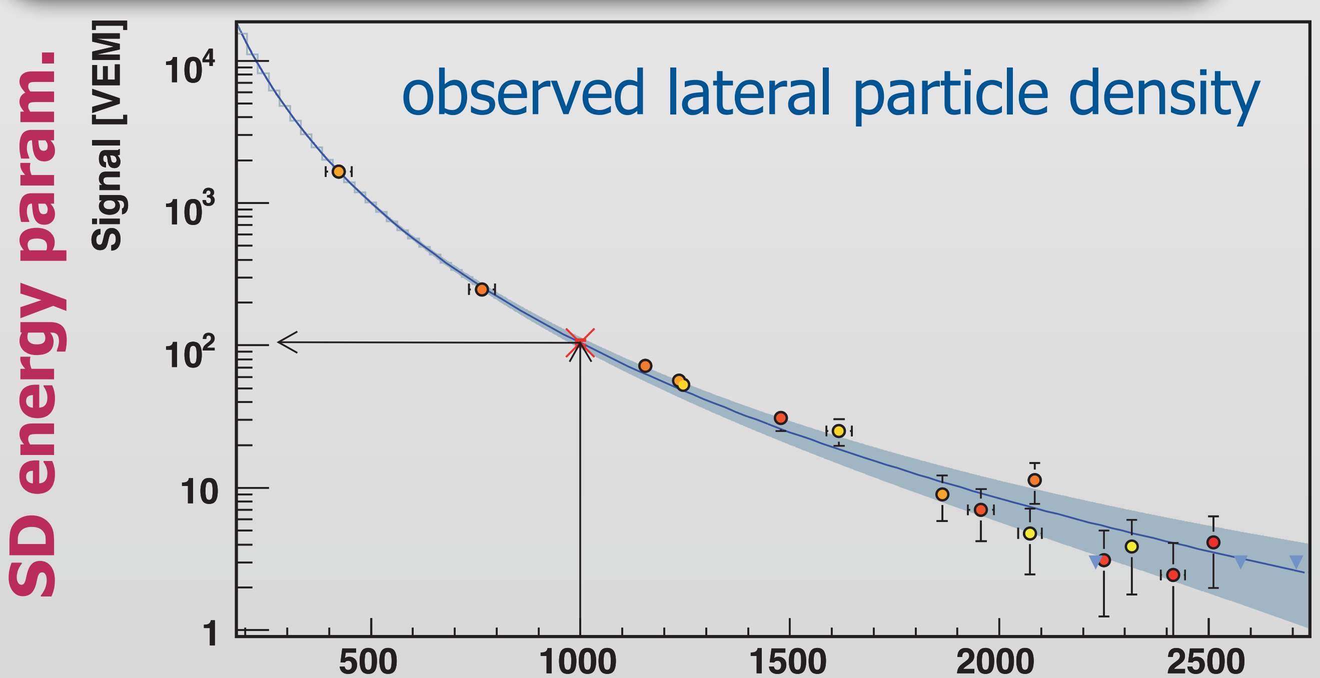
Hybrid Based:

+ Well known calibration
+ Flat, well known aperture
+ Low energy threshold

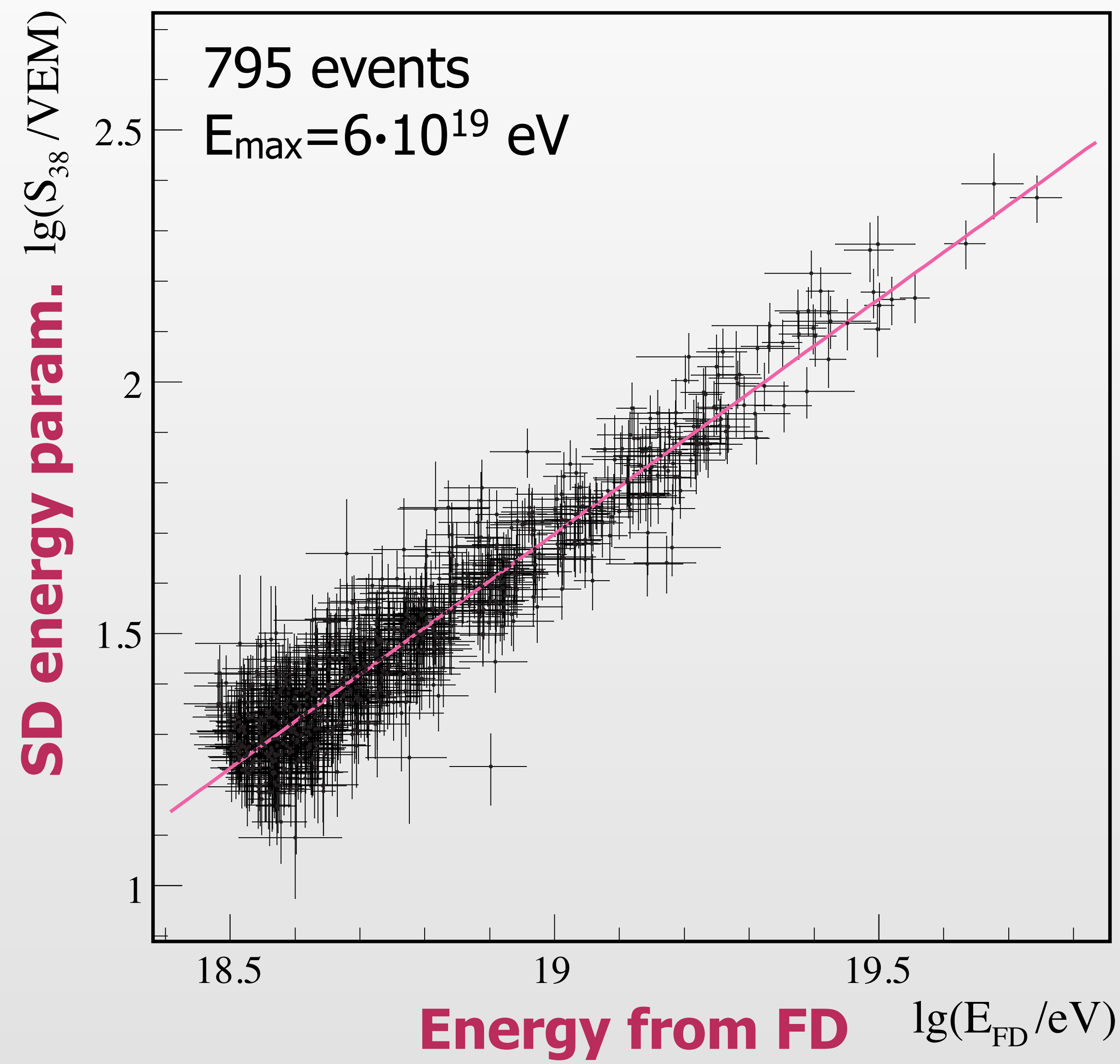


Ground Array calibrated by Fluorescence Obs.



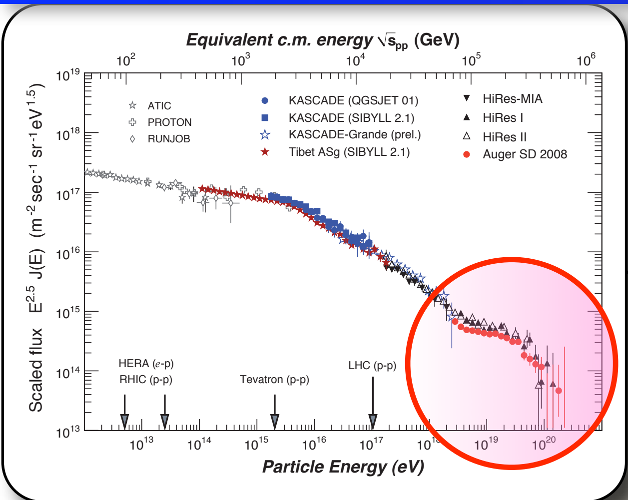


Auger @ ICRC09

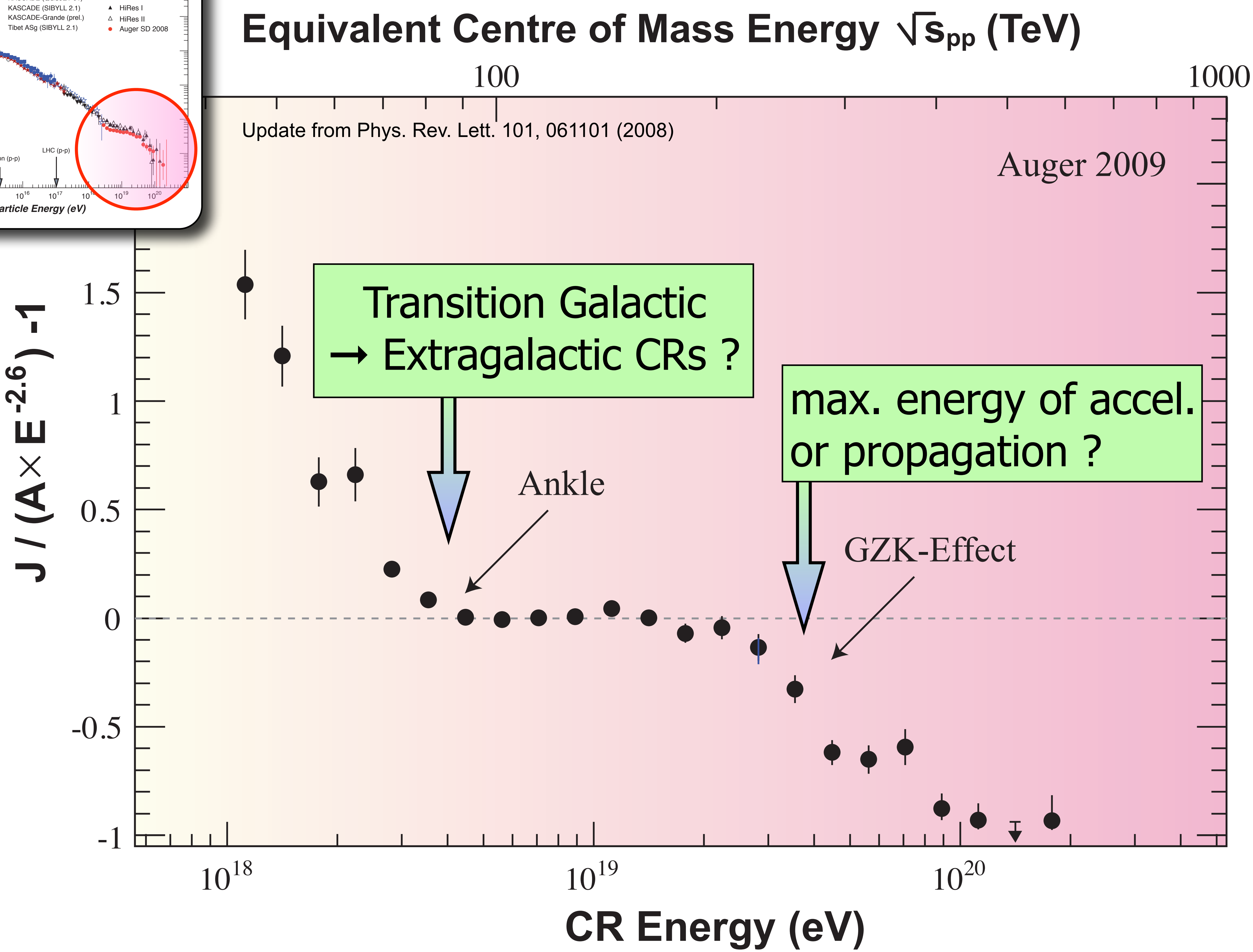


Applied by Auger and Telescope Array

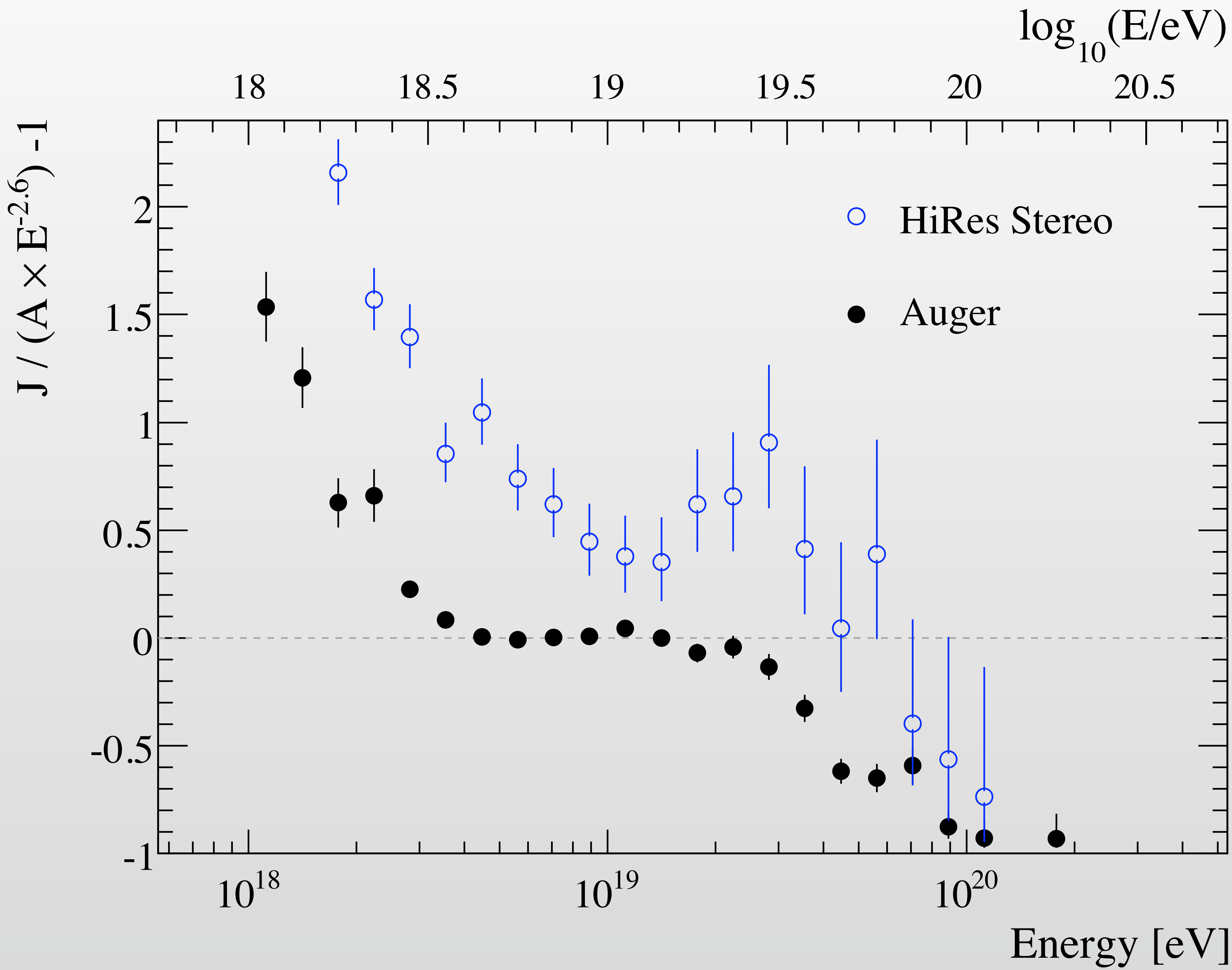
Hybrid Energy Spectrum



Auger @ ICRC09

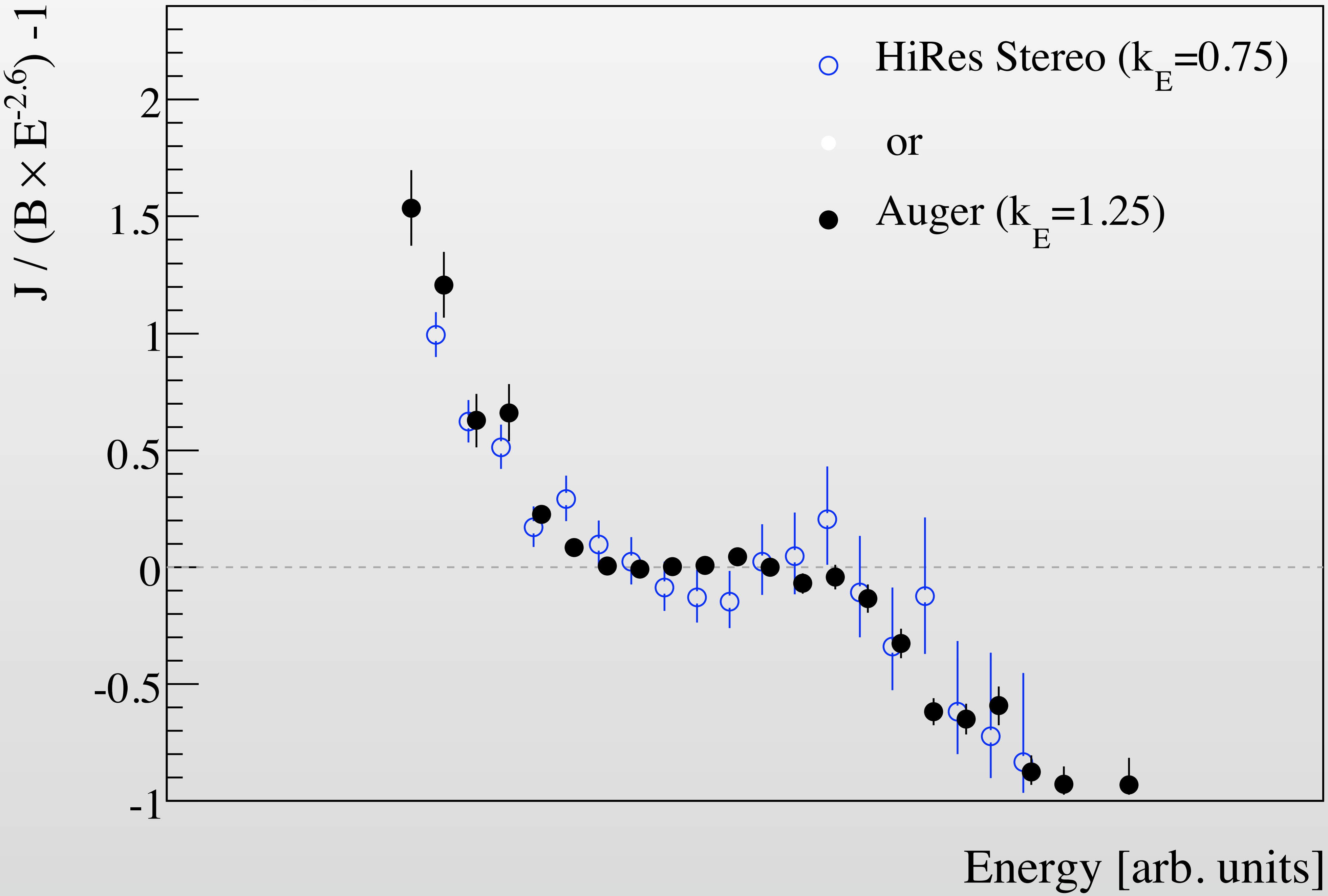


Comparison HiRes - Auger



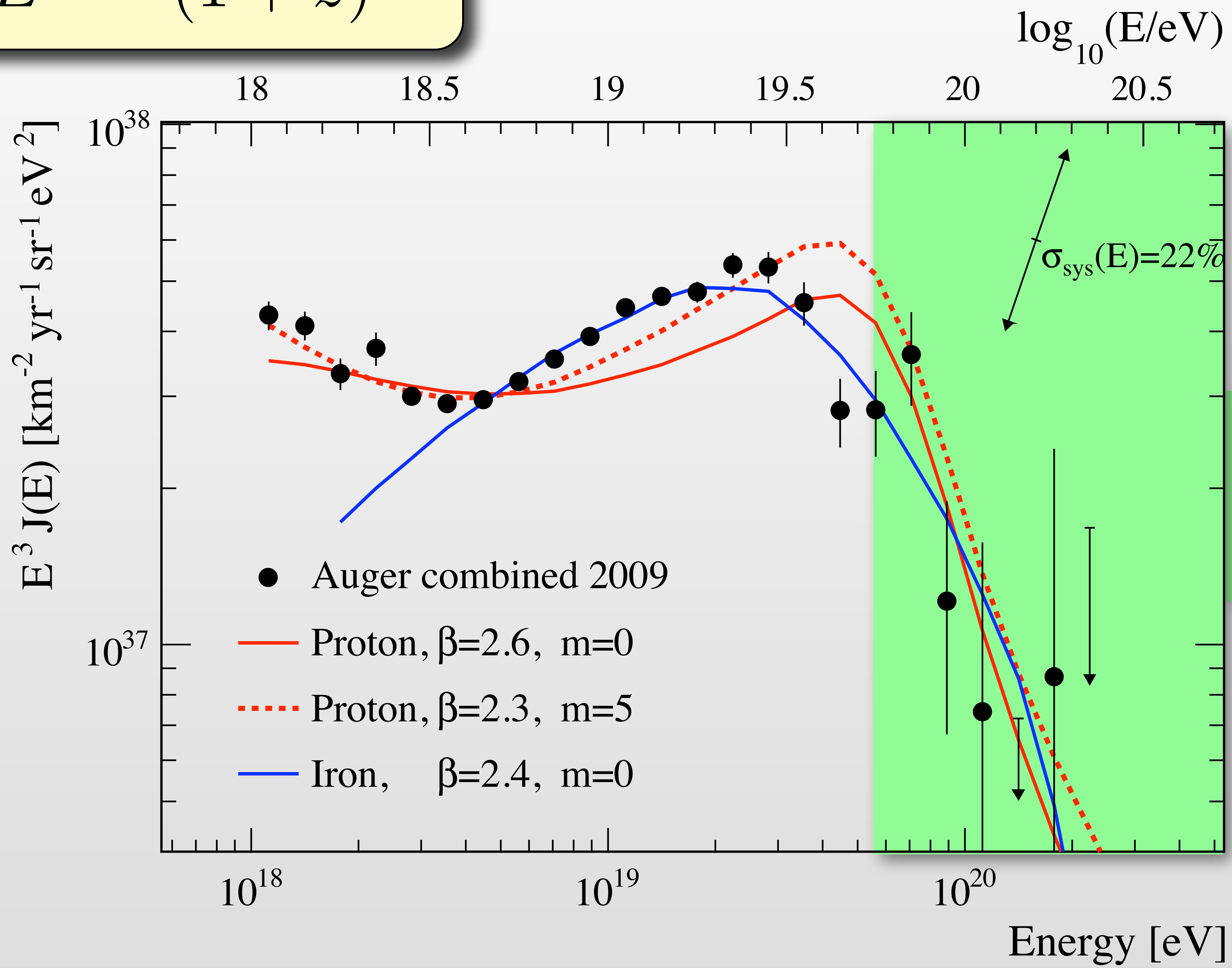
Comparison HiRes - Auger

differences compatible with 25 % uncertainty of energy scale



Comparison with Astrophys. Models

$$\phi(E) \propto E^{-\beta} \cdot (1+z)^{m}$$



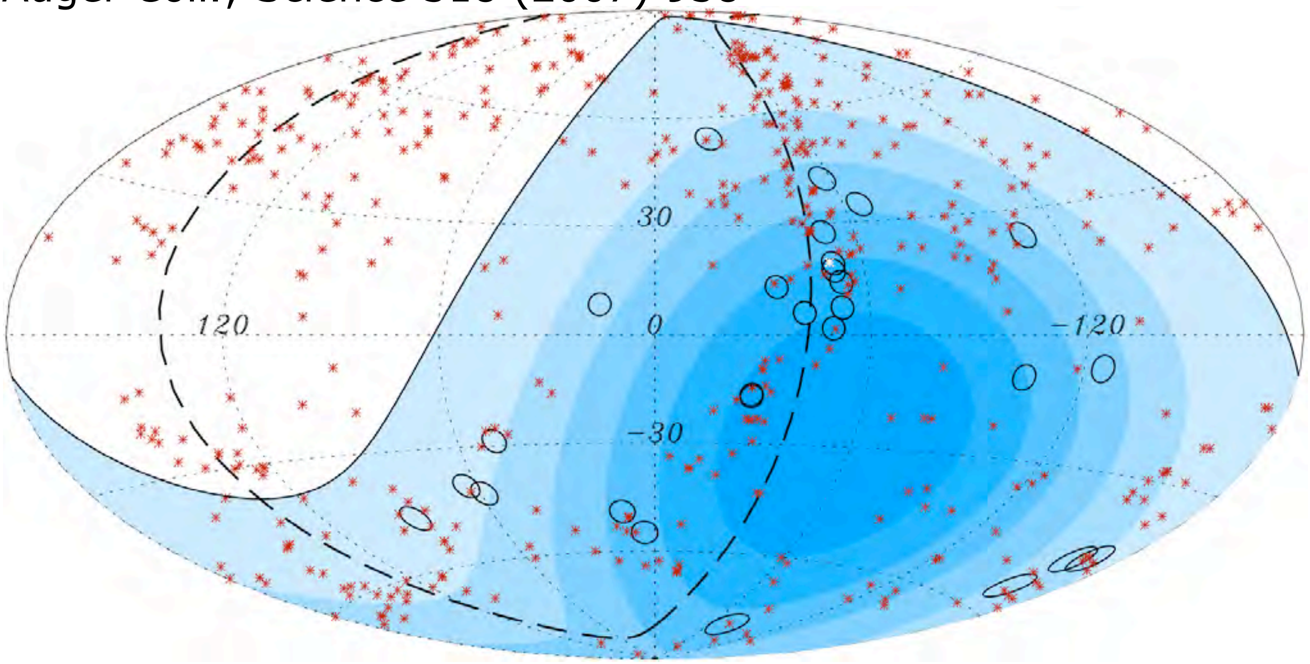
Anisotropic distribution

- Simple models fit data surprisingly well
- Constraining models needs composition measurement

UHECR Anisotropies

Auger Sky above 60 EeV

Auger Coll.; Science 318 (2007) 938



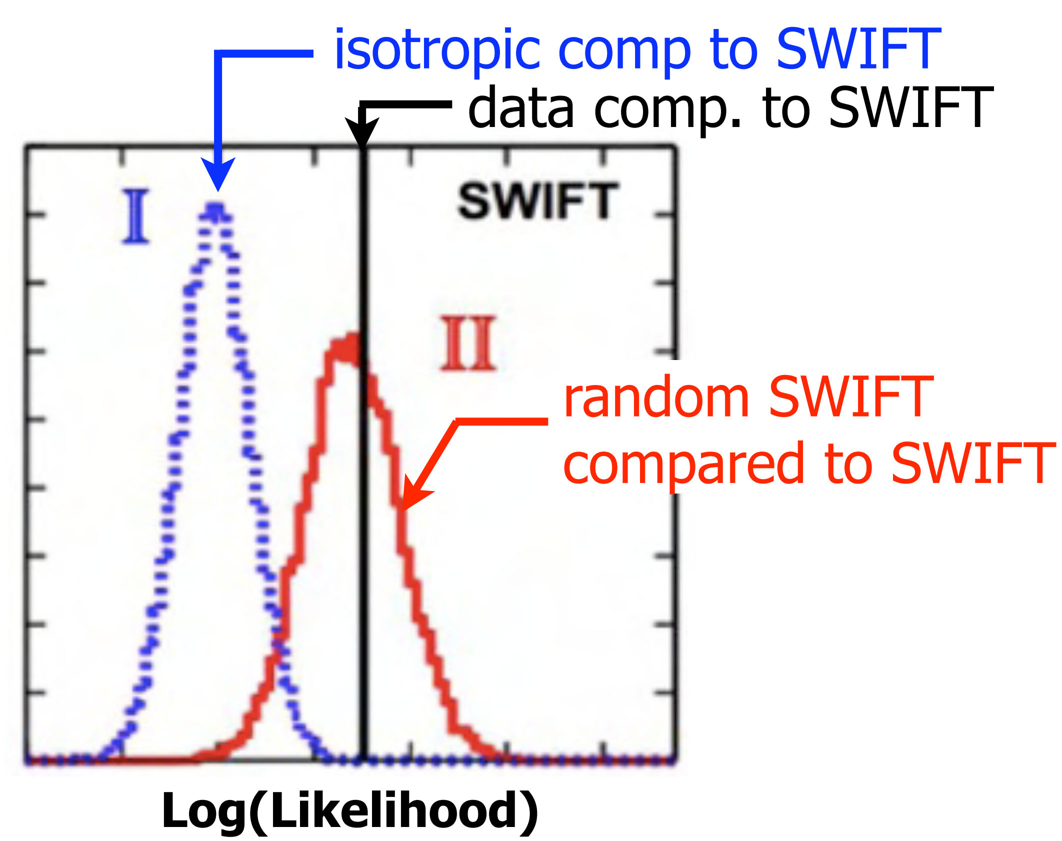
Auger Coll.; ICRC (2009)

27 events as of November 2007
(with Verón-Cetty-Verón catalogue)

58 events now
(with Swift-BAT AGN density map)

Simulated data sets based on isotropy (I) and Swift-BAT model (II) compared to data (black line/point).

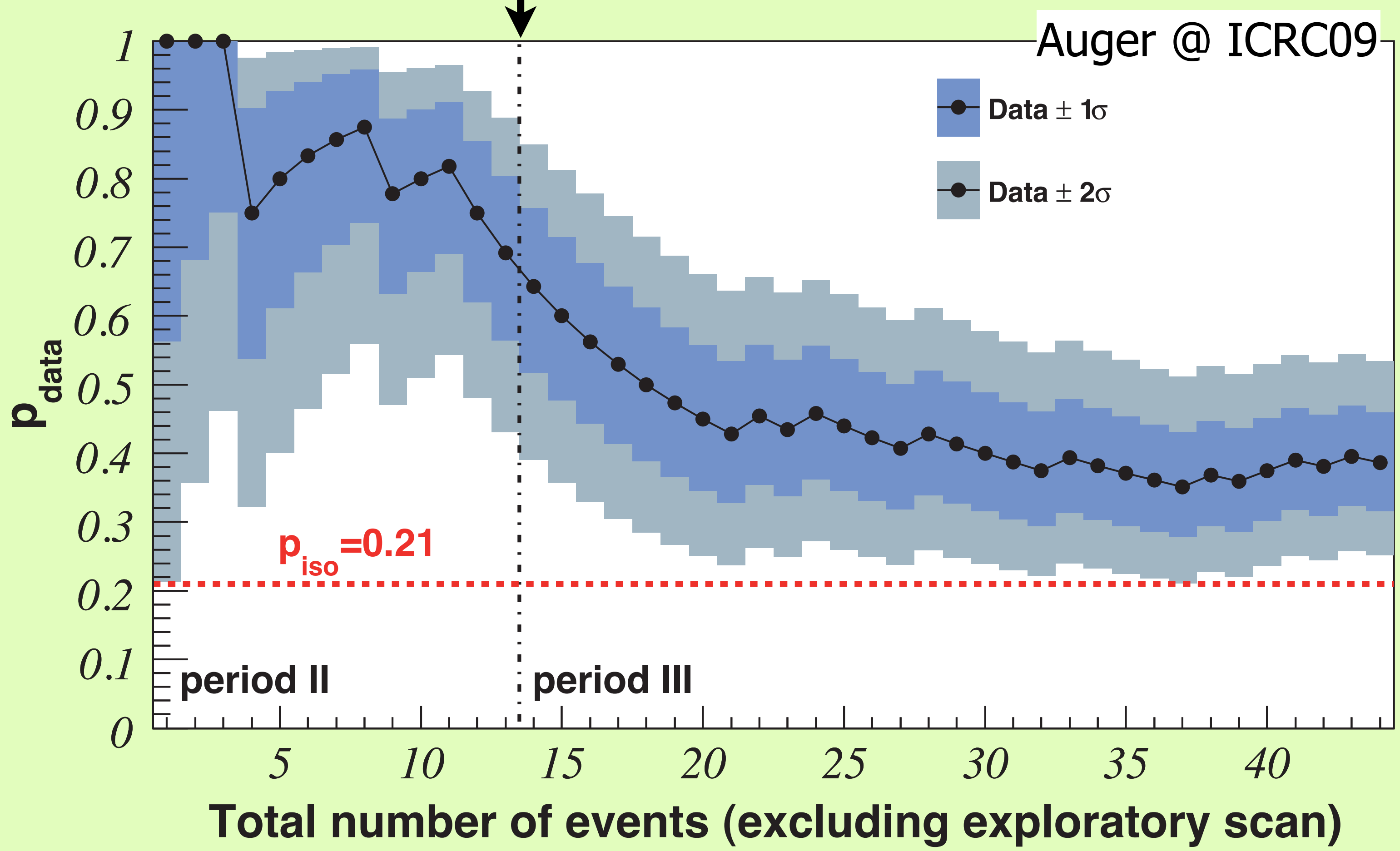
<10^{-5} samples of isotropic distr's give higher LL than data



However ...

date of Auger publication in Science

Auger Coll.; ICRC (2009)

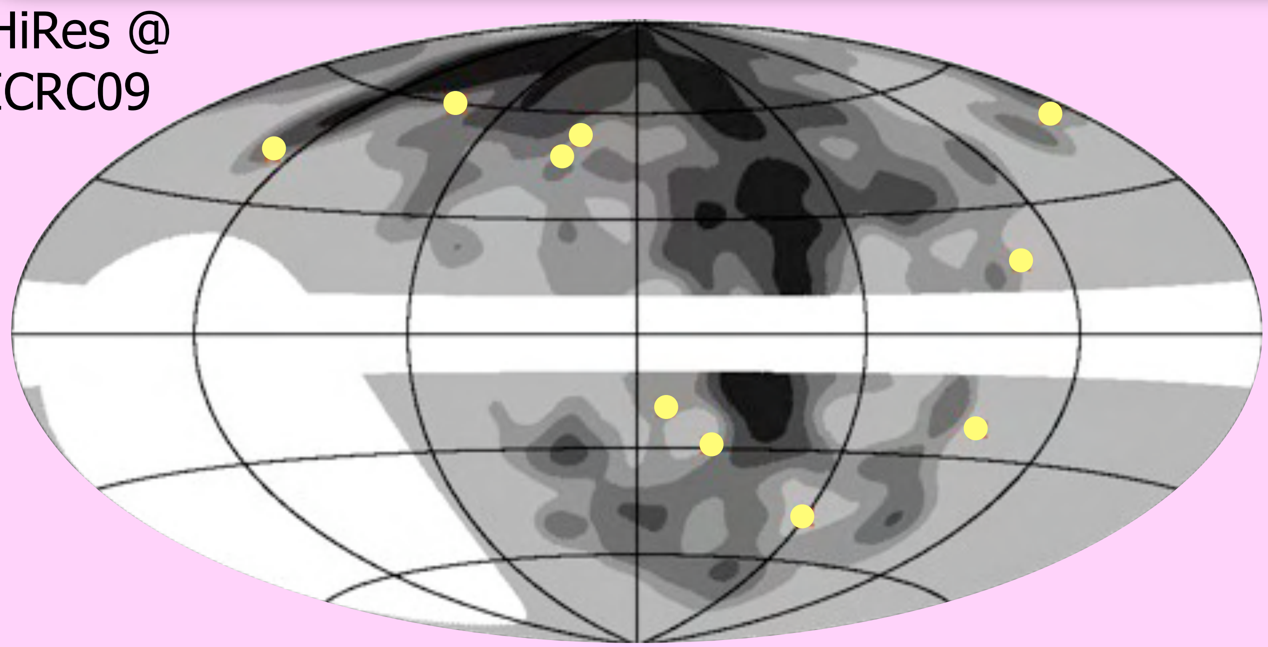


period I: exploratory; prescription
period II: up to publication
period III: since publication

Auger correlation strength with VCV dropped from ~70% to ~40%
(still, isotropy excluded at >99%)

latest:26 of 58 correlate

HiRes @ ICRC09



HiRes Sky plot of Northern Sky
10 evts above 57 EeV
(42 EeV on Auger scale)
compatible with isotropy

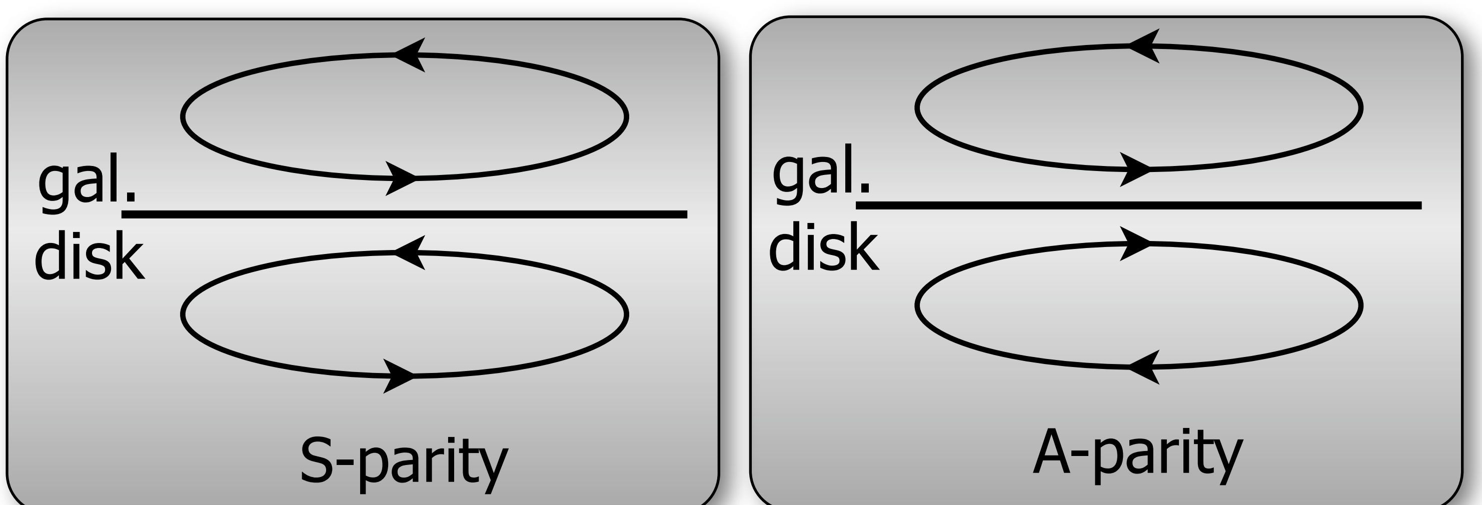
TA sees 3 correlated events out of 4 measured ones

TA @ ICRC09

Galactic Magnetic Fields are important

- Does GMF disturb the expected correlation of the highest energy cosmic rays (HECRs) with their sources (even if HECRs are mainly protons) ?
- Can there be differences between Southern and Northern sky?
- Can HECRs obtain information on GMF ?
- 0.2-0.3 μG near solar system; but mG parallel to galactic disk found

four basic models for GMF



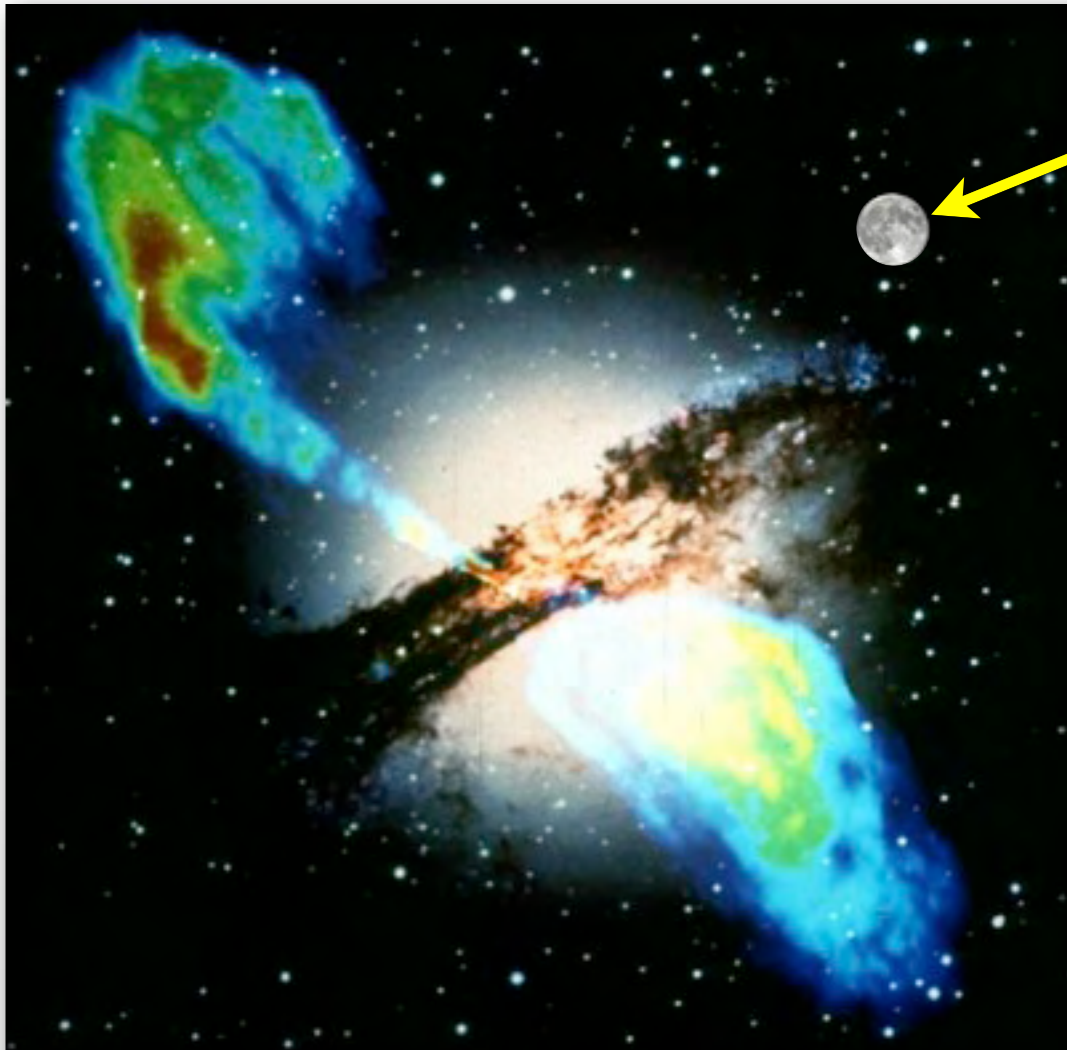
$\otimes$

- AS: no reversals between spiral arms
- BS: reverals between sprial arms

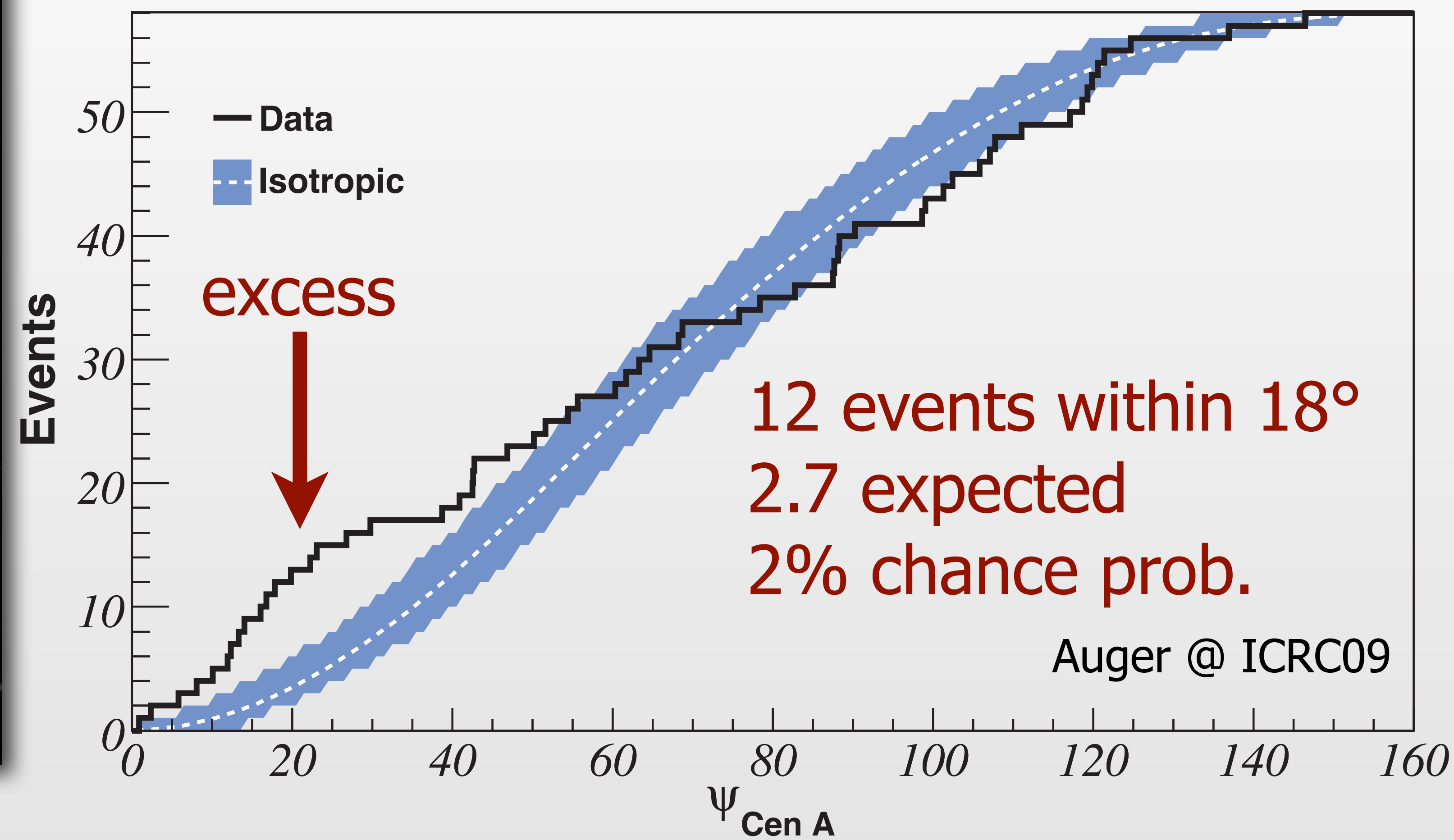
Correlations at 3-5° scale possible except for AS-structure models in northern sky

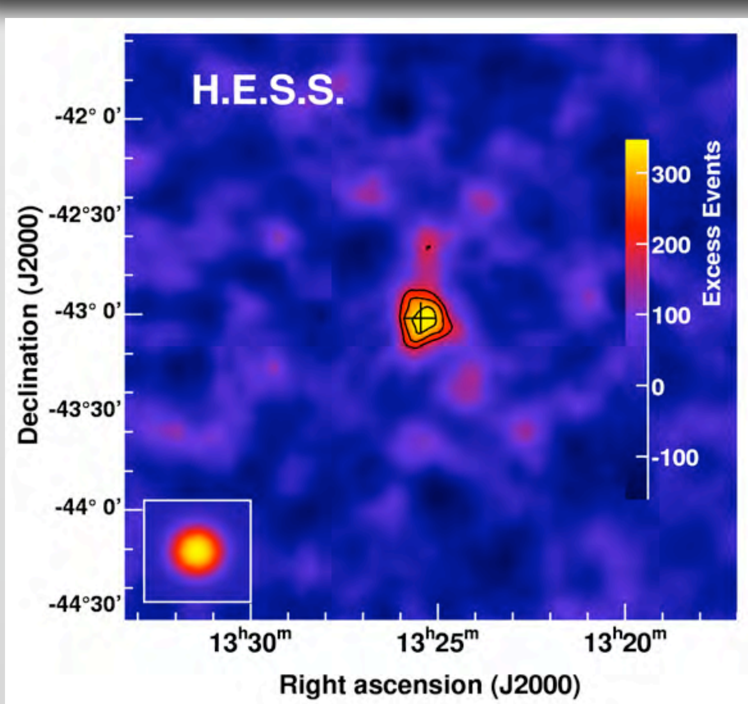
Takami @ ICRC09

Centaurus A appears interesting



moon for comparison of scale





central AGN core
now also seen by HESS and FERMI-LAT

HESS @ ICRC09

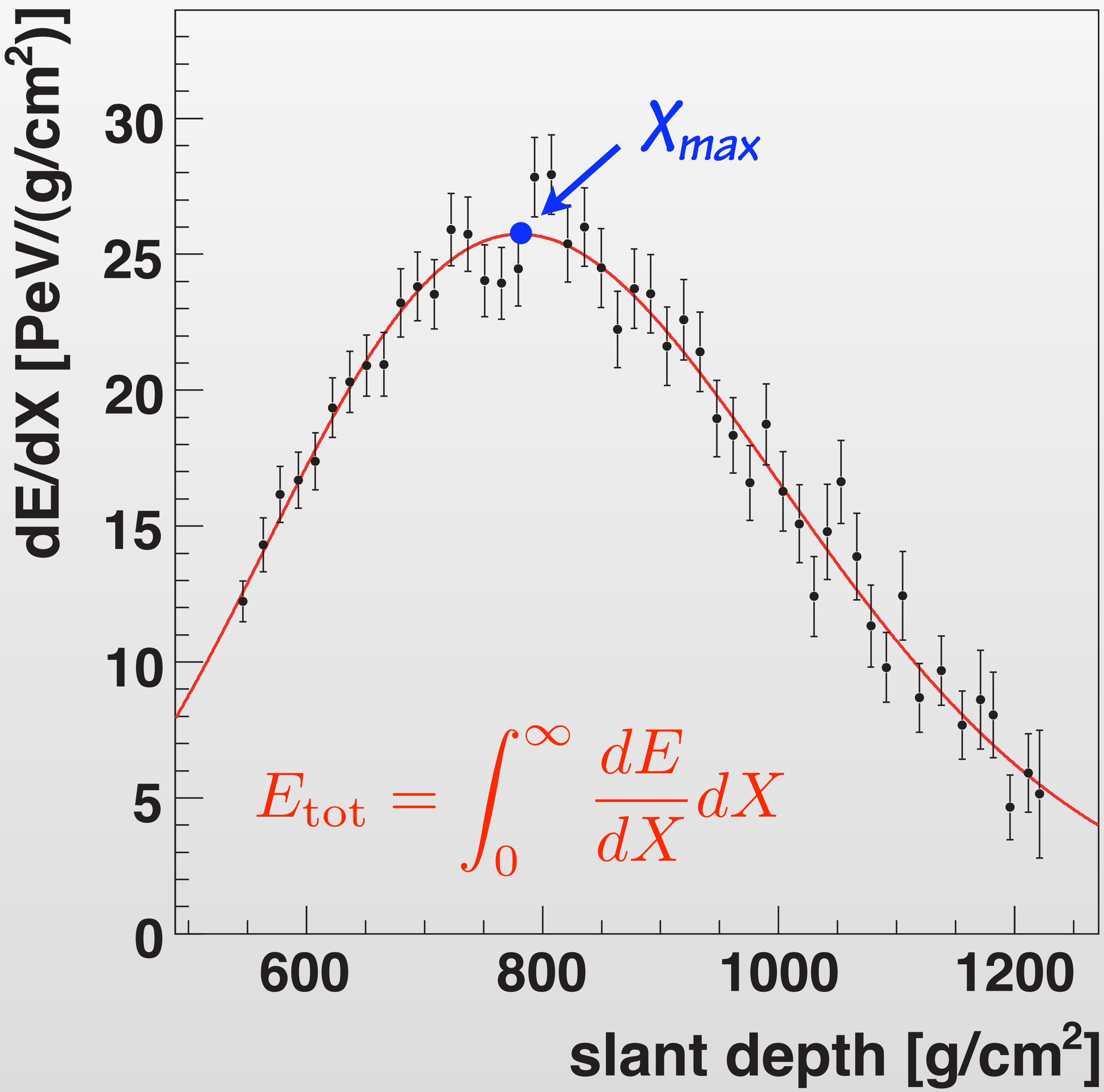
Cen A brightest radio source; d~ 3.5 Mpc

UHECR Composition

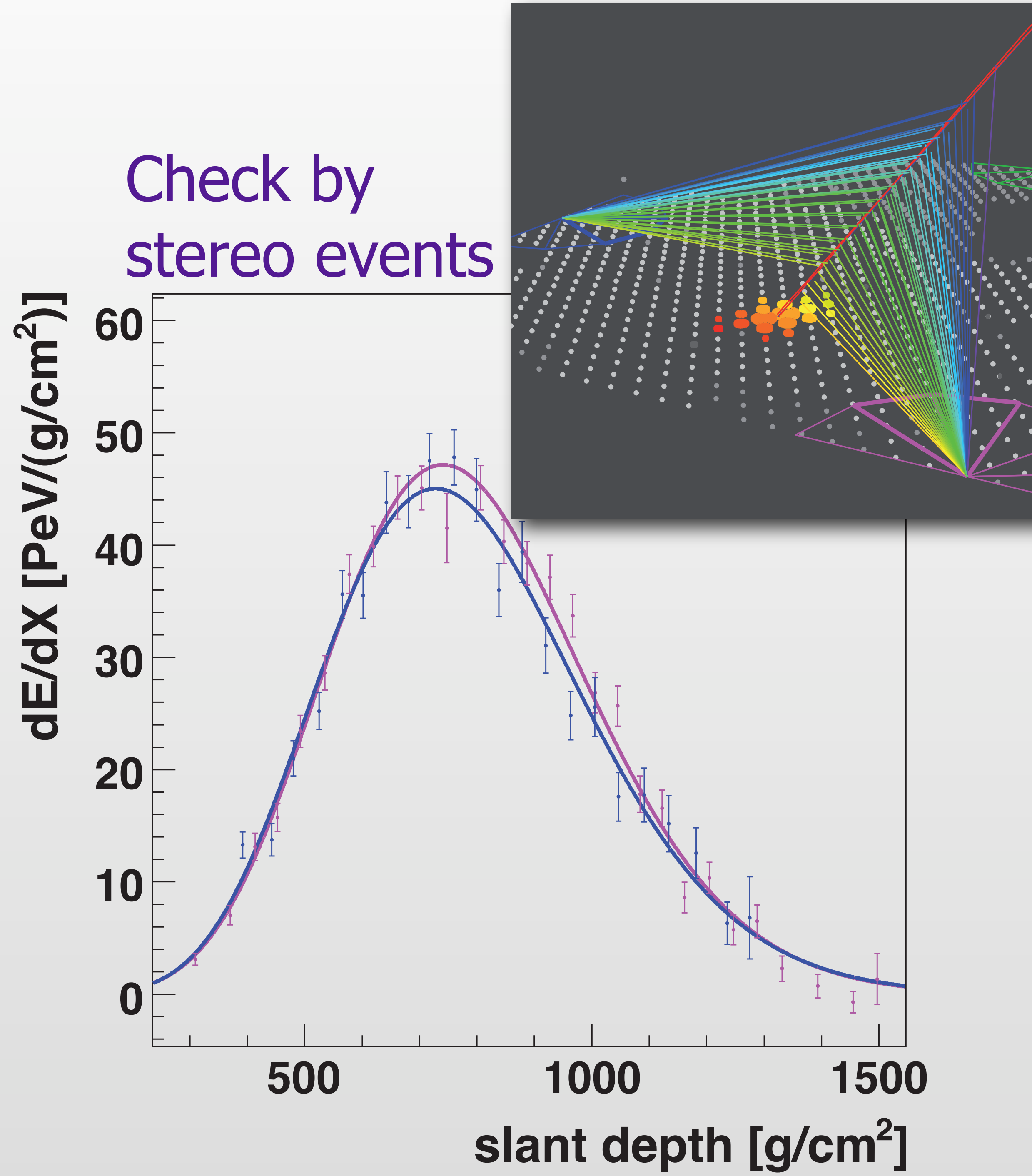
Composition from X_{max} observations

Performed by HiRes, Auger and TA

Example: Auger Hybrid

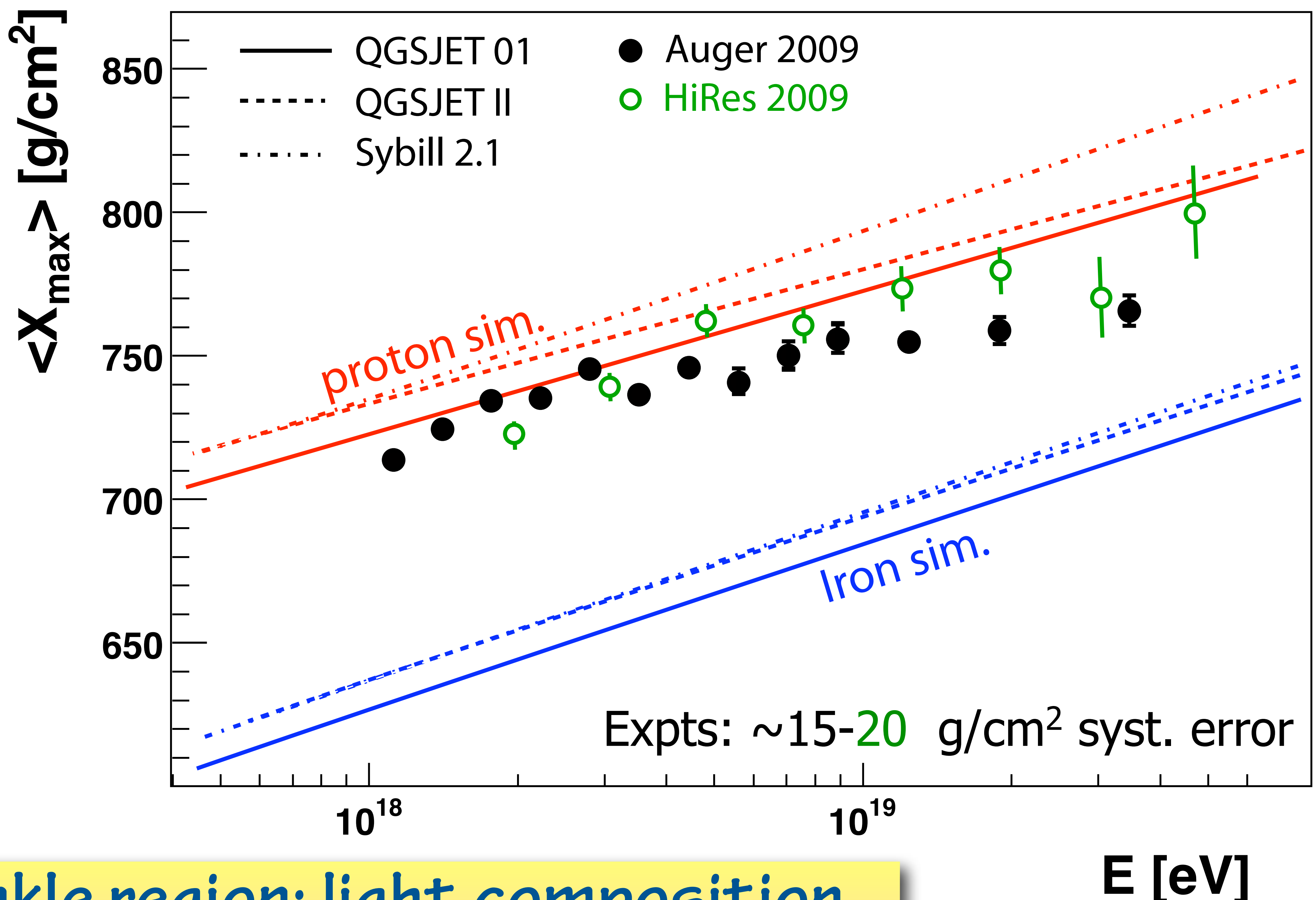


Check by stereo events



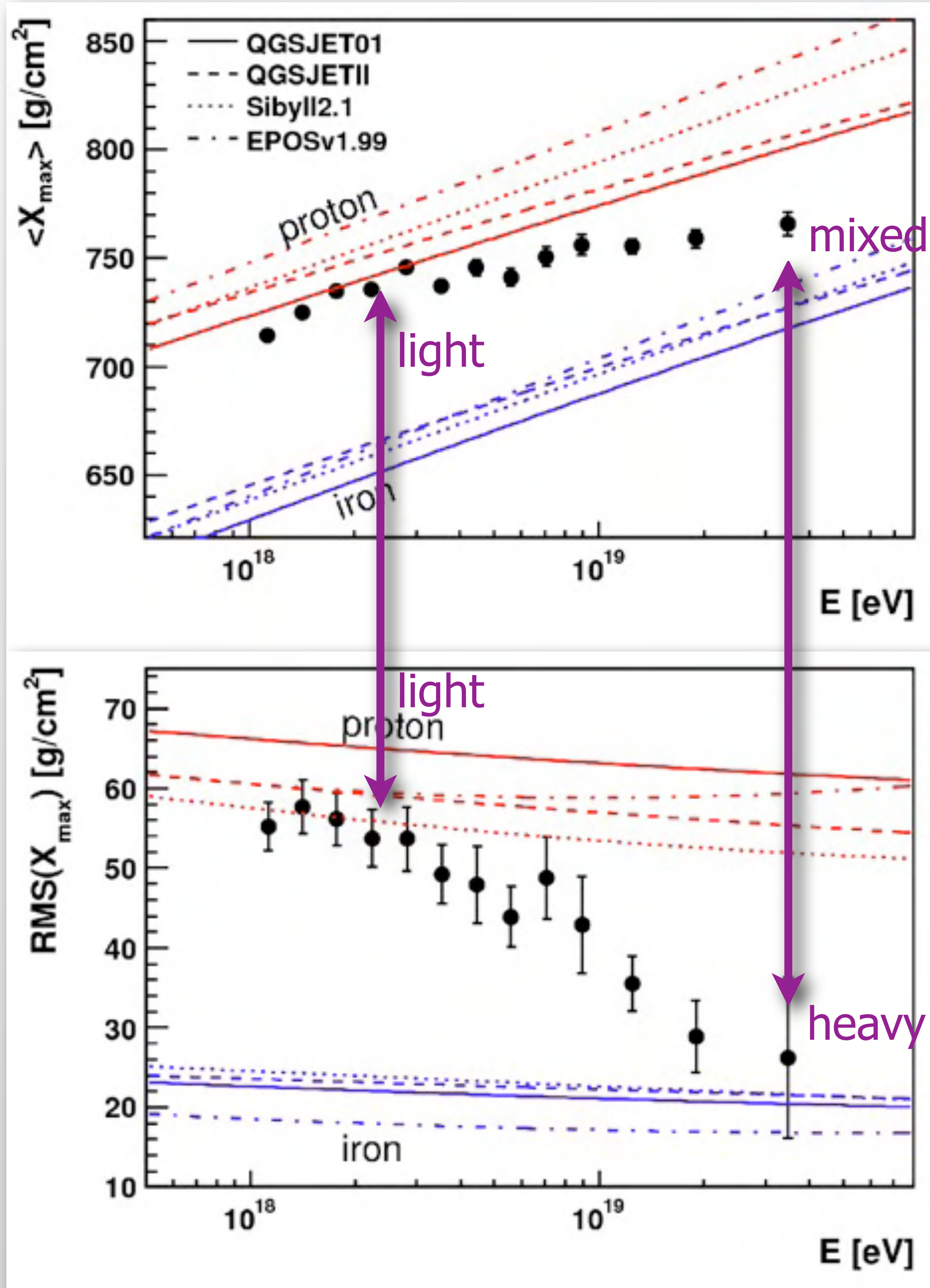
Analysis of stereo data: $\sigma(X_{max})$ = 20-25 g/cm^2

Composition from Xmax



- Ankle region: light composition
- Higher Energies: Auger - mixed ; HiRes - light
  (but within systematic uncertainties)

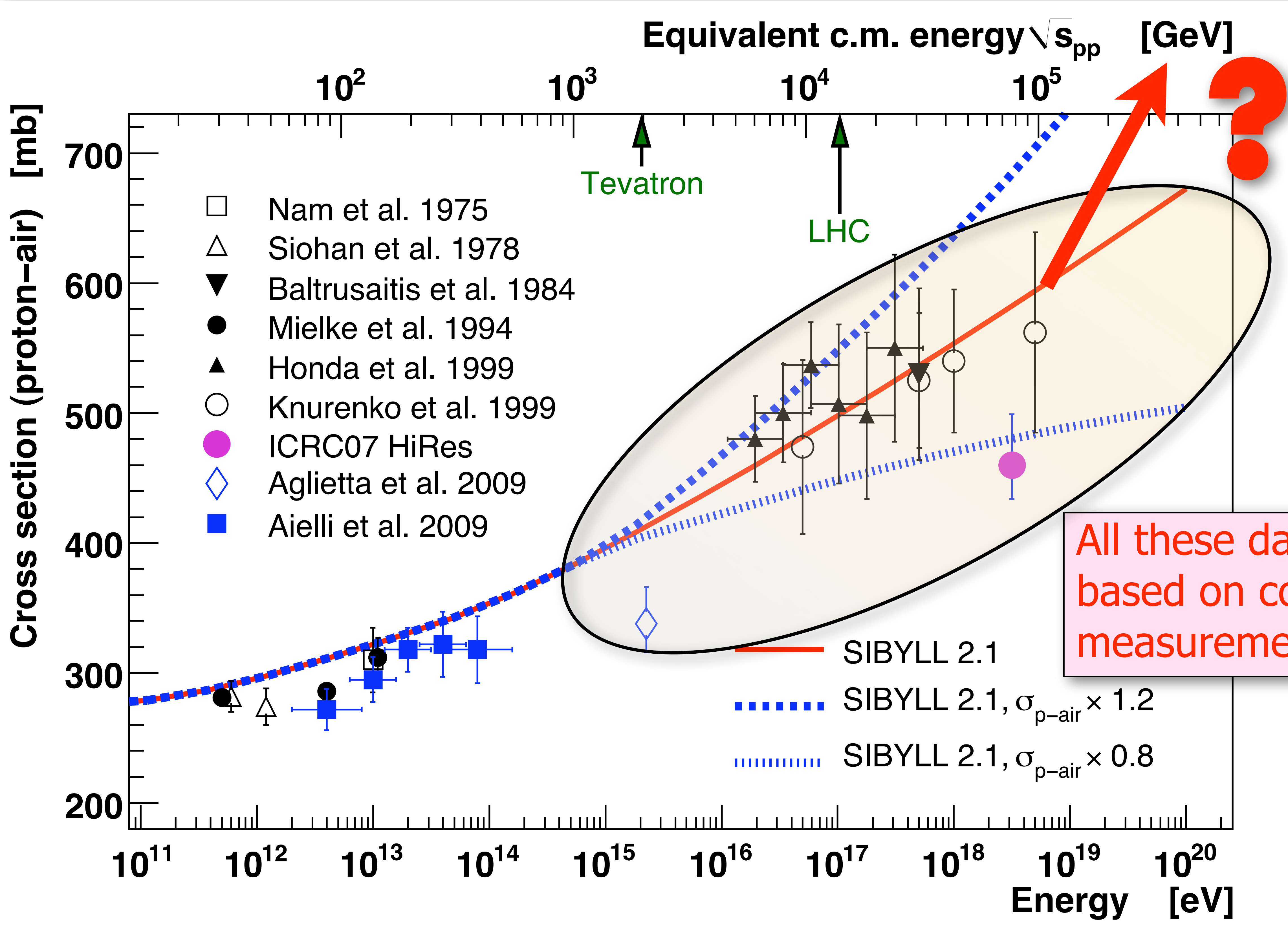
Surprise: Very Small Fluctuations of X_{max} !



Auger @ ICRC 2009

Observed Fluctuations suggest Fe-dominance at $E > 3 \cdot 10^{19}$ eV !

Hints for increasing X-Section ?



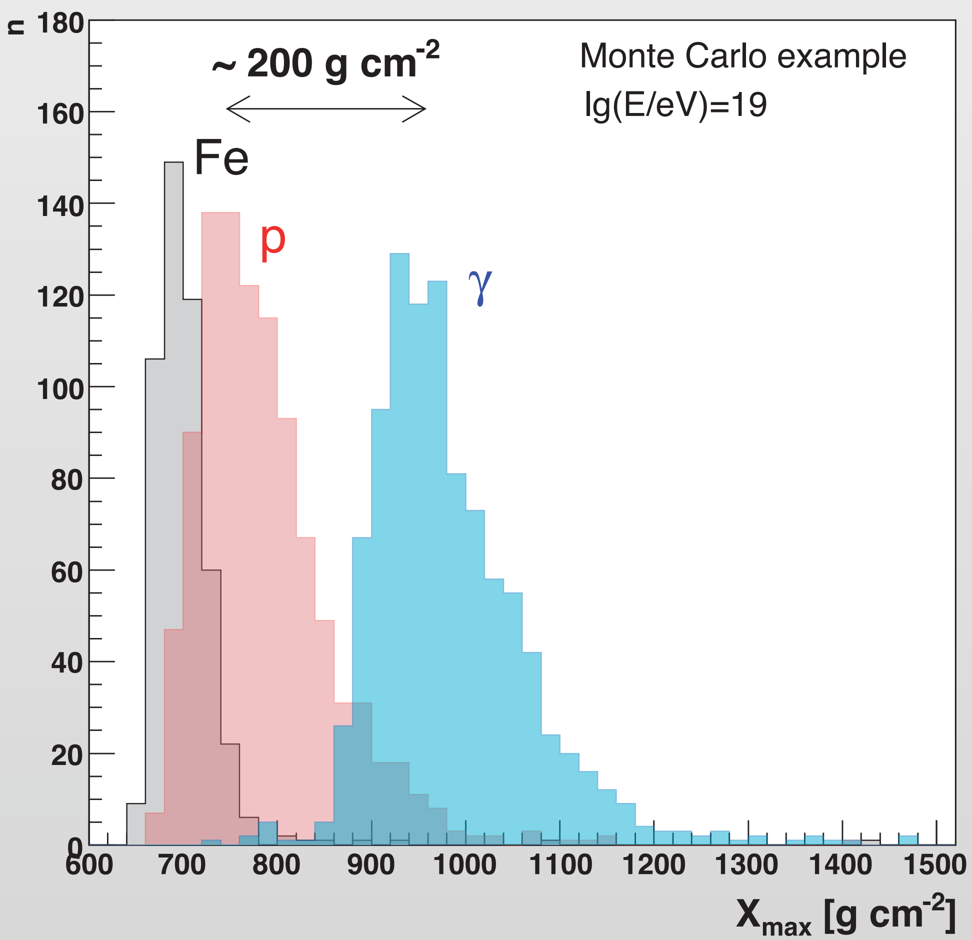
All these data are based on cosmic ray measurements!

Search for Photons

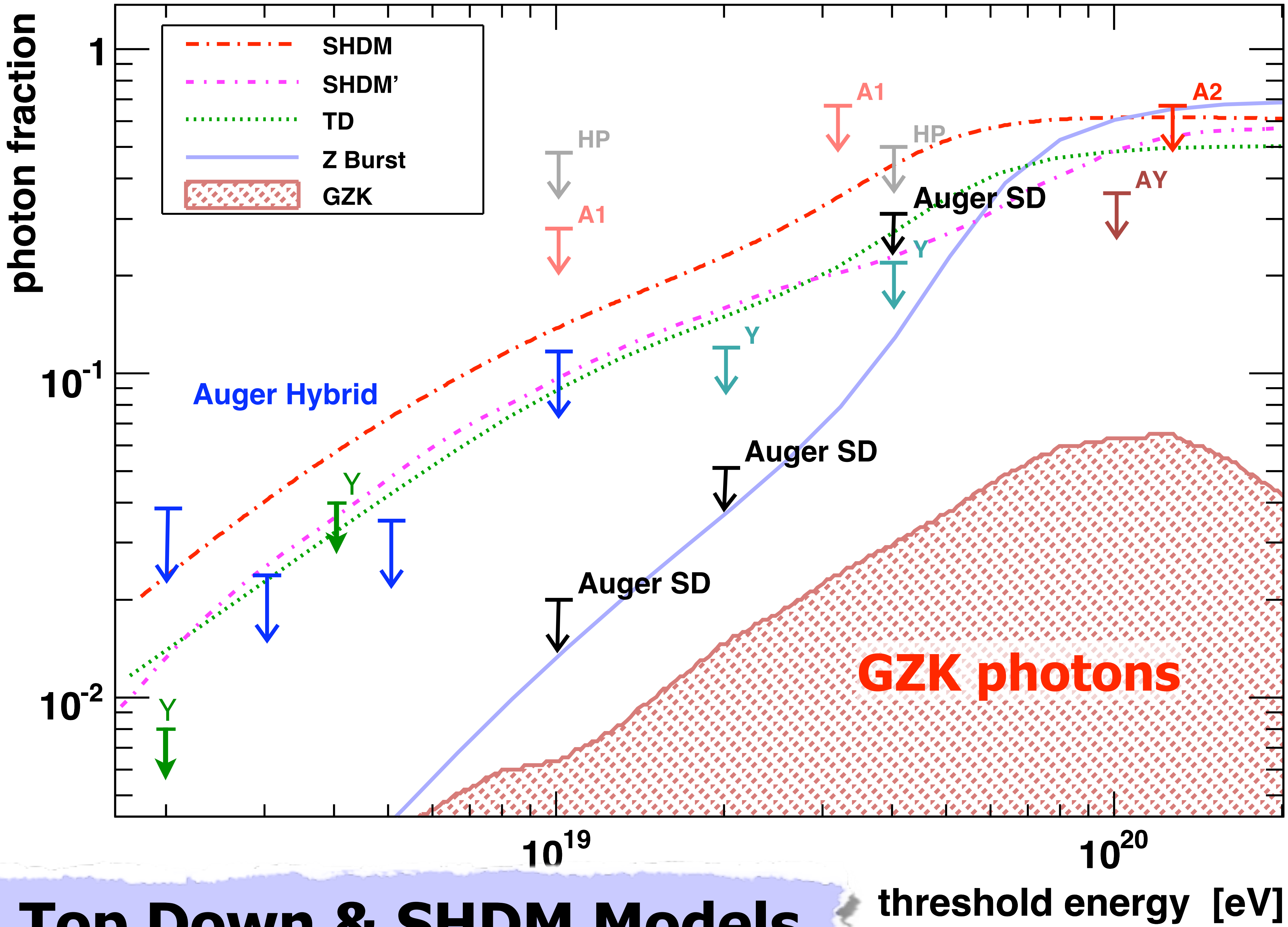
Motivation for Photon Search

- **acceleration of nuclear primaries + photo-disintegration in CMB during propagation**
  ➙ expect small fraction of photons
- **non-acceleration models (decay/annihilation of primordial relicts; Super-Heavy Dark Matter)**
  ➙ expect large fraction of photons
- **Z-Burst Models: interaction of EHE-ν's with cosmogenic ν's**
  ➙ sensitive to ν-mass and detection of cosmogenic ν's
- **tests of fundamental physics**
  ➙ Lorentz-invariance Violation (LIV)
  ➙ smoothness of space-time

Very good γ-Hadron Discrimination by X_{max} Measurements



Photon Upper Limits vs Predictions



HP: Ave et al. '00 & '02
A1: Shinozaki et al. '02
A2: Risse et al. '05
AY: Rubtsov et al. '06
Y: Glushkov et al. '07

SHDM, TD, Z Burst: Gelmini et al. '05

SHDM': Ellis et al. '06

GZK: Gelmini et al. '07

Auger 09
Yakutsk 09

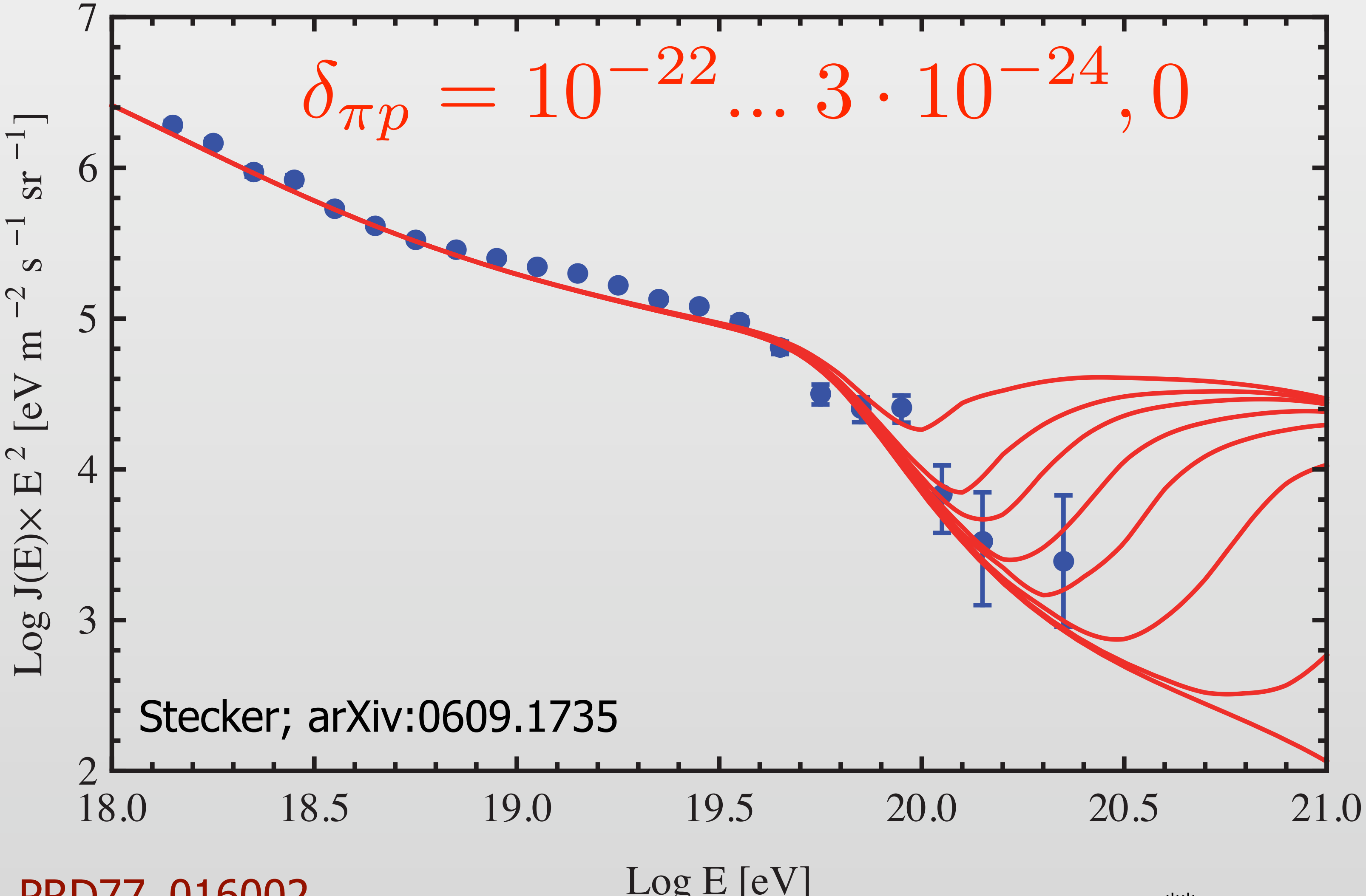
Top Down & SHDM Models largely ruled out

Tests of Fundamental Physics

Lorentz Invariance Violation (I)

- **LIV related to structure of space time near Planck scale**
- Vacuum Cherenkov Radiation ➙ expect strong E-losses
  absence ➙ best presently existing SEM-Parameters *
- Particle dependent maximum c_j ➙ GZK-effect altered** $p + \gamma \to p + \pi$

$$c_i - c_j = \frac{\epsilon_i - \epsilon_j}{2} \equiv \delta_{ij}.$$



* Klinkhamer, Risse; PRD77, 016002

** Coleman, Glashow; PRD59, 116008

Lorentz Invariance Violation (II)

Galaverni & Sigl
PRL 100 (2008)

LIV ➙ may modify photon dispersion relation

$$\omega^2 = k^2 + m^2 + \xi_n k^2 (k/M_{Pl})^n$$

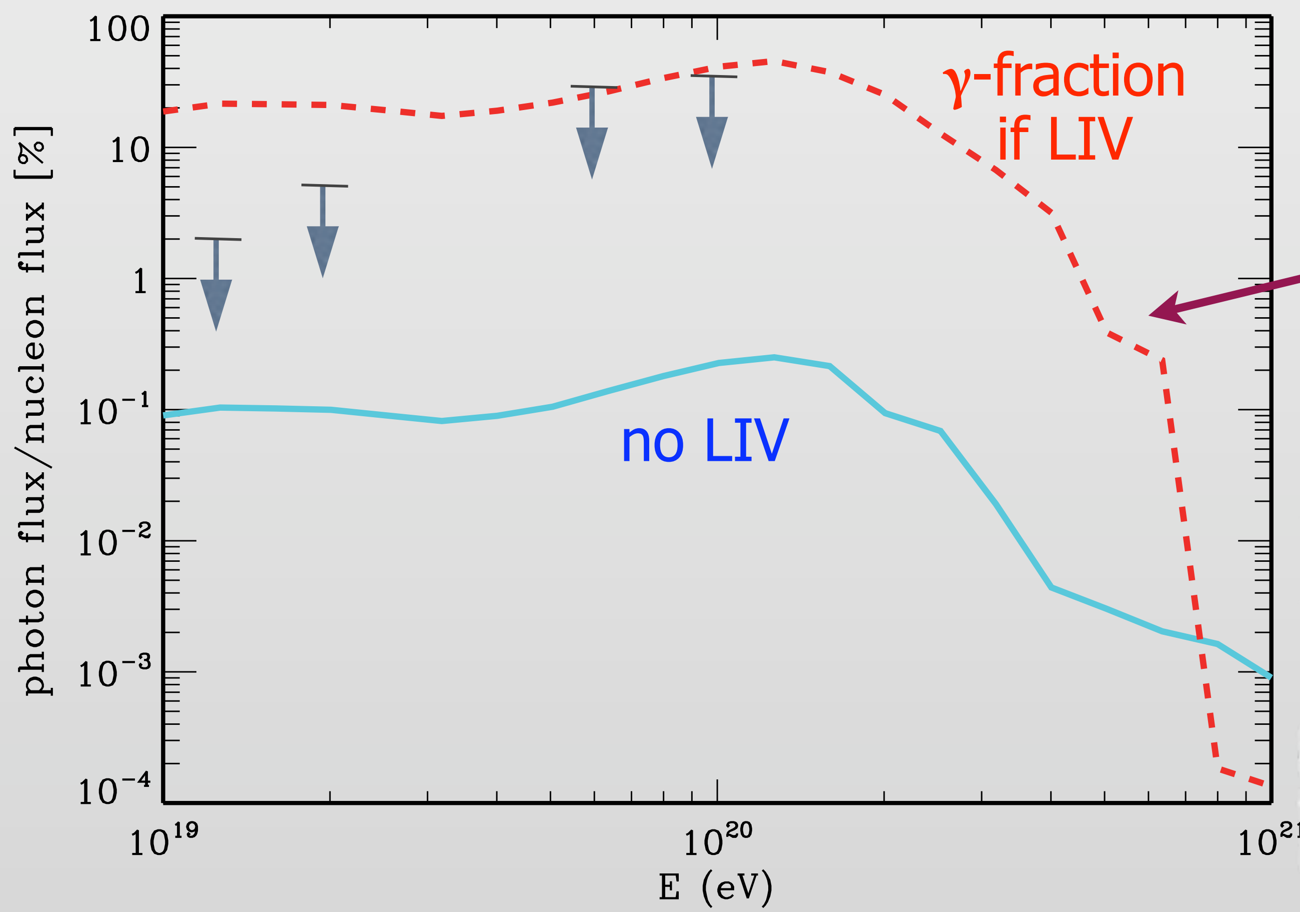
➙ affect the threshold for e^+e^- pair production

➙ $p + \gamma_{CMB} \rightarrow \Delta \rightarrow n + \pi^0$

$\hookrightarrow \gamma\gamma \not\rightarrow e^+e^-$

cascading of UHE photons suppressed

expect significant photon fraction above ~ 10^{19} eV



$$\xi_1 \leq 2.4 \times 10^{-15}$$
$$\xi_2 \geq -2.4 \times 10^{-7}$$

7 orders of magnitudes better than previous limits!

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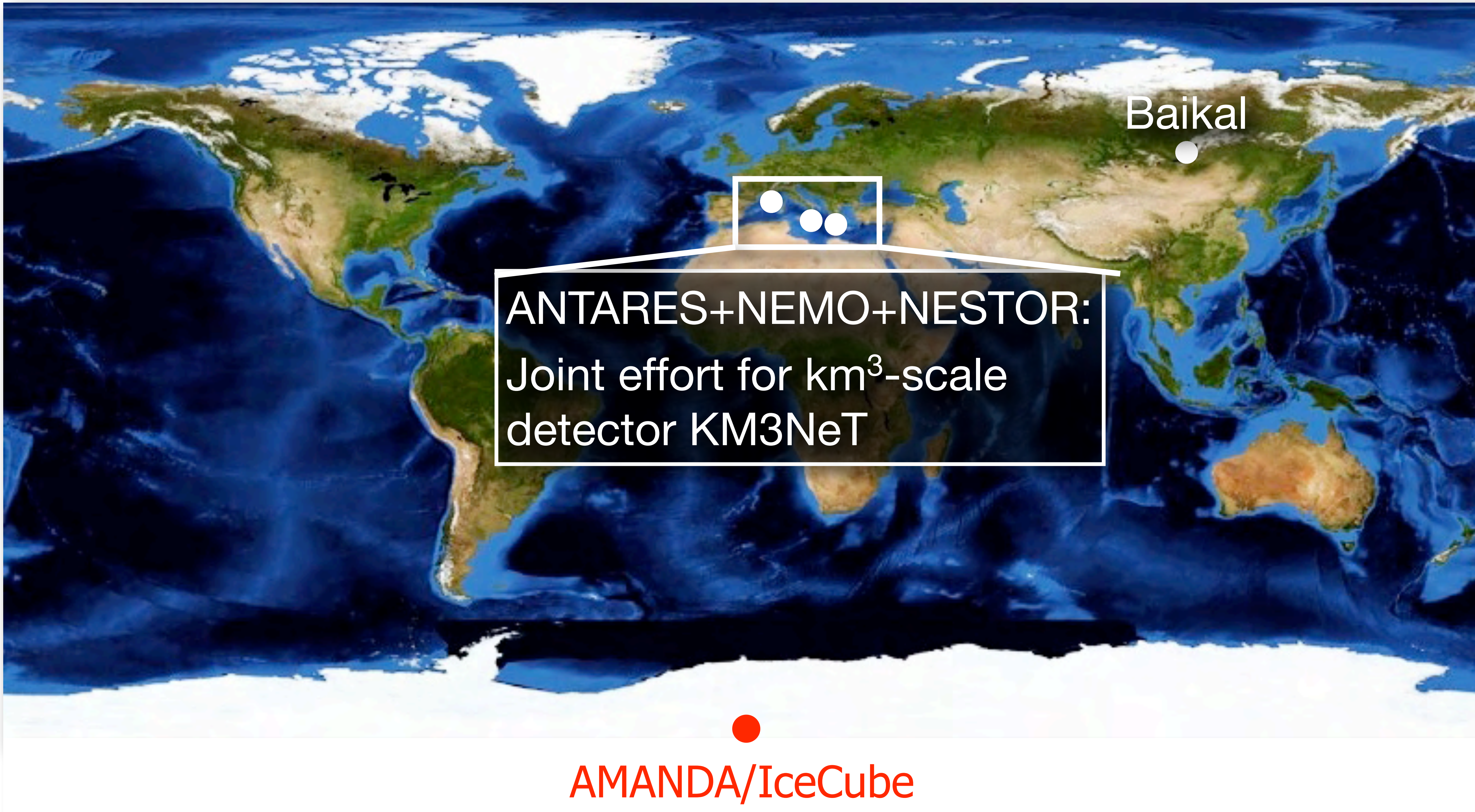
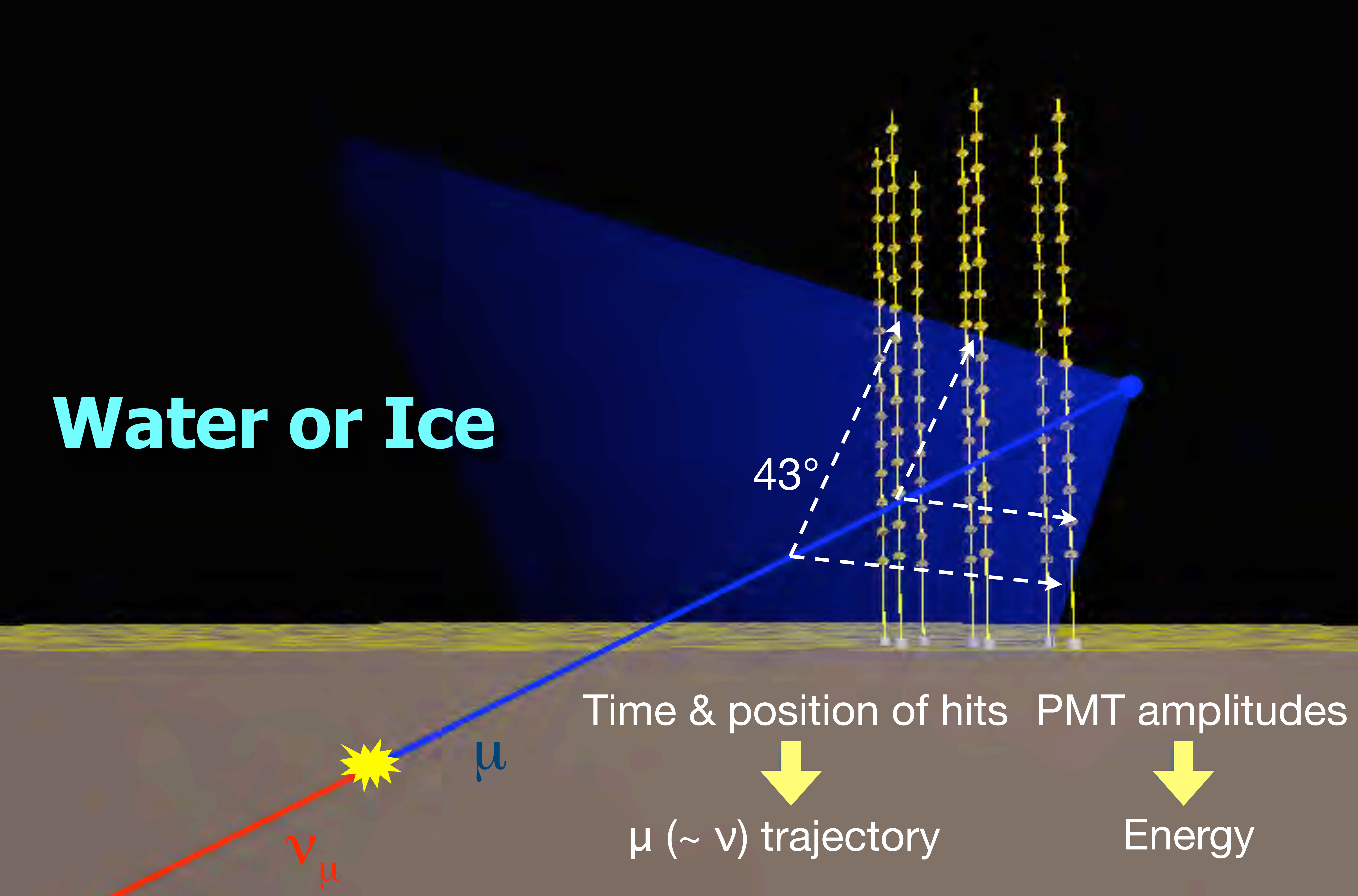
Neutrino Astronomy

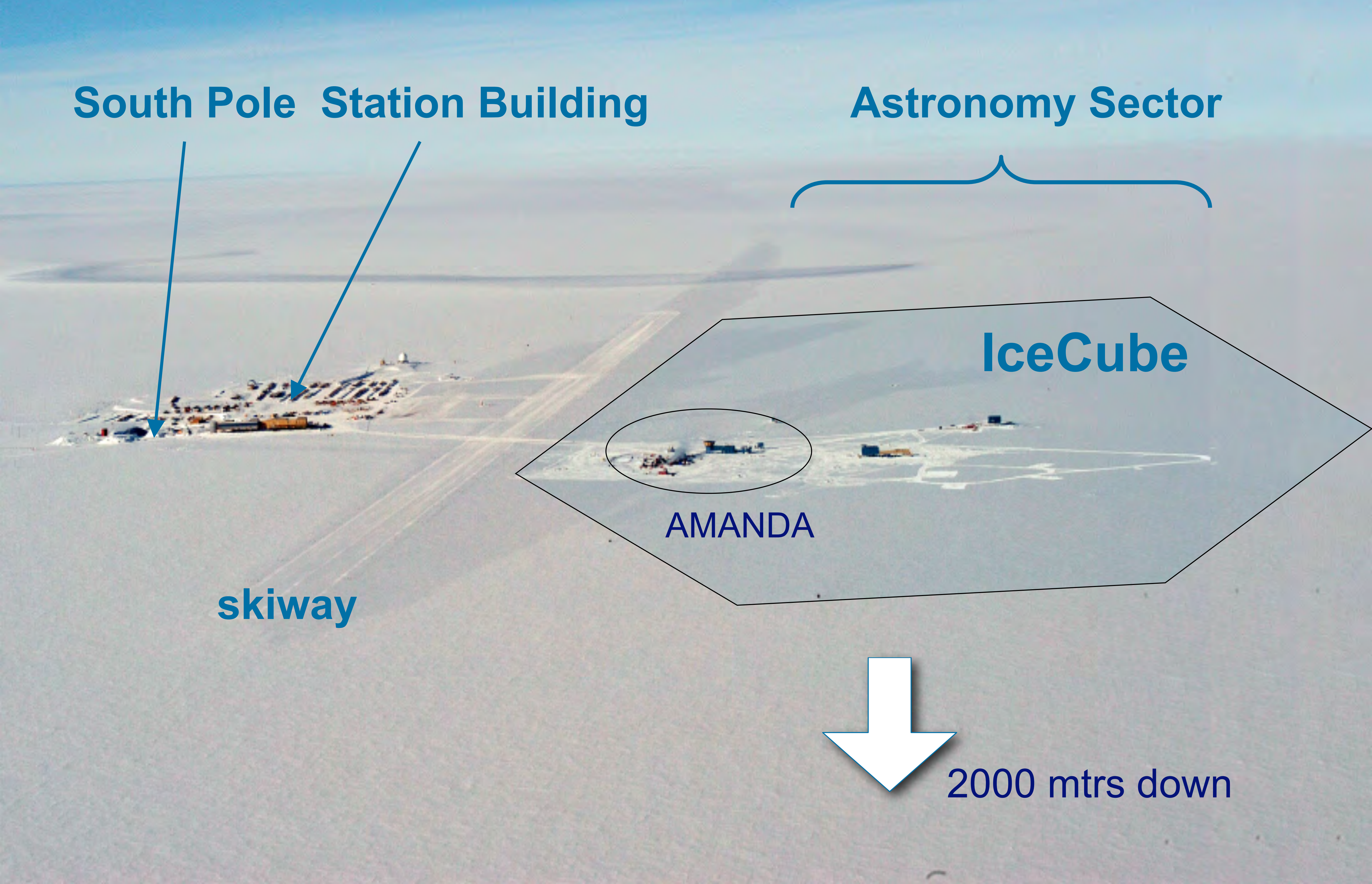
ν-Telescope Projects



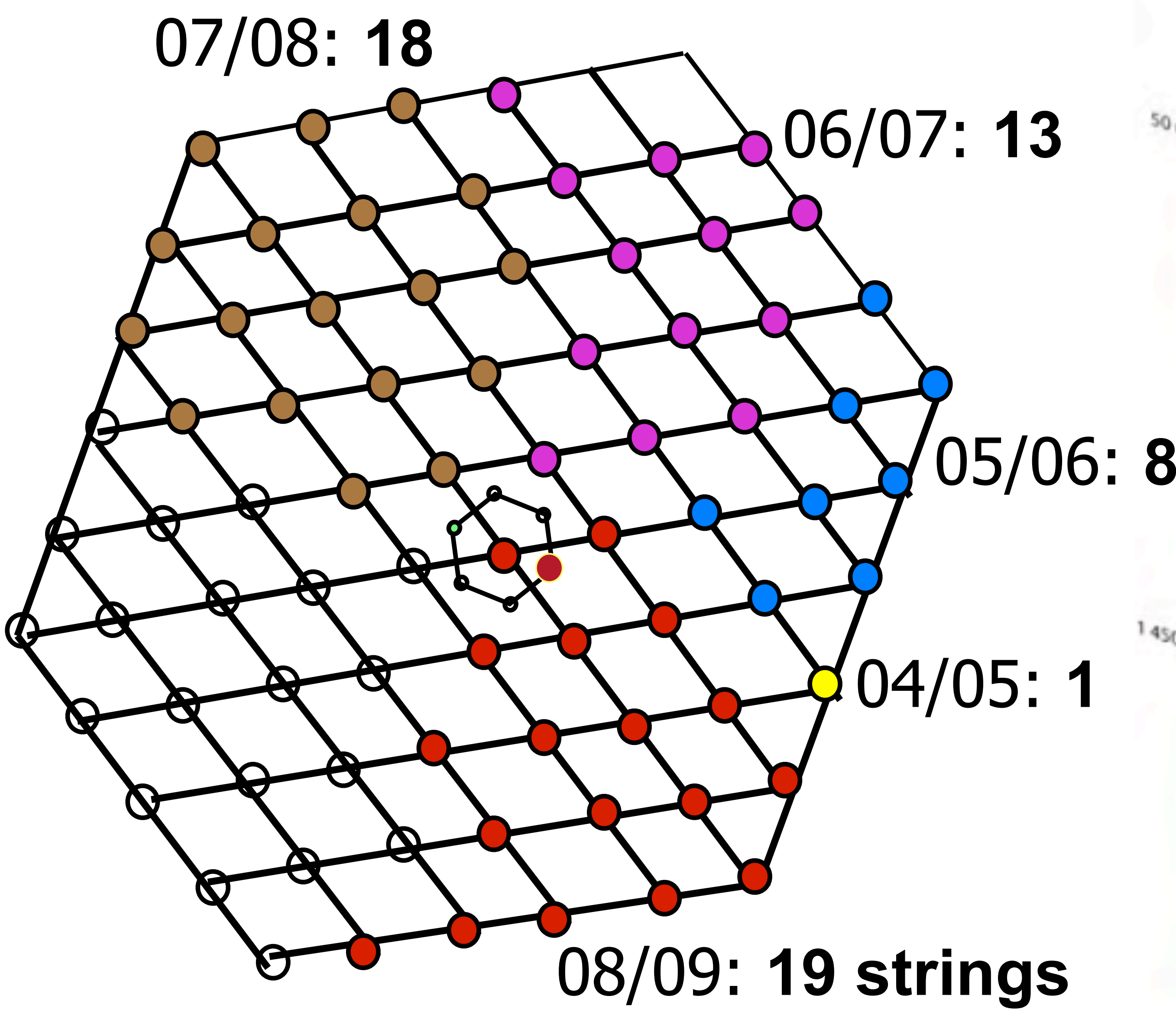
Principle of Neutrino Detection

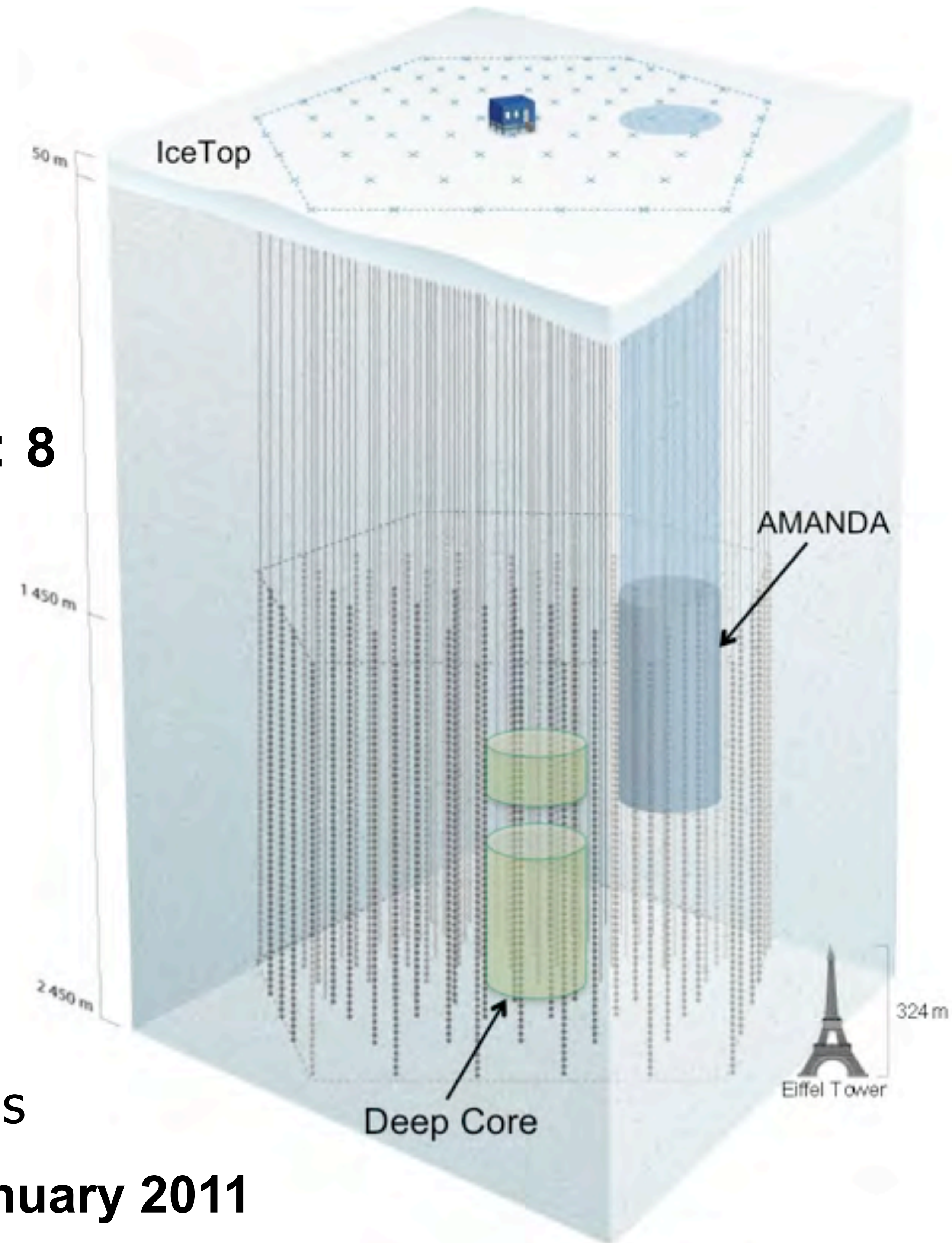


IceCube at South-Pole



IceCube Observatory





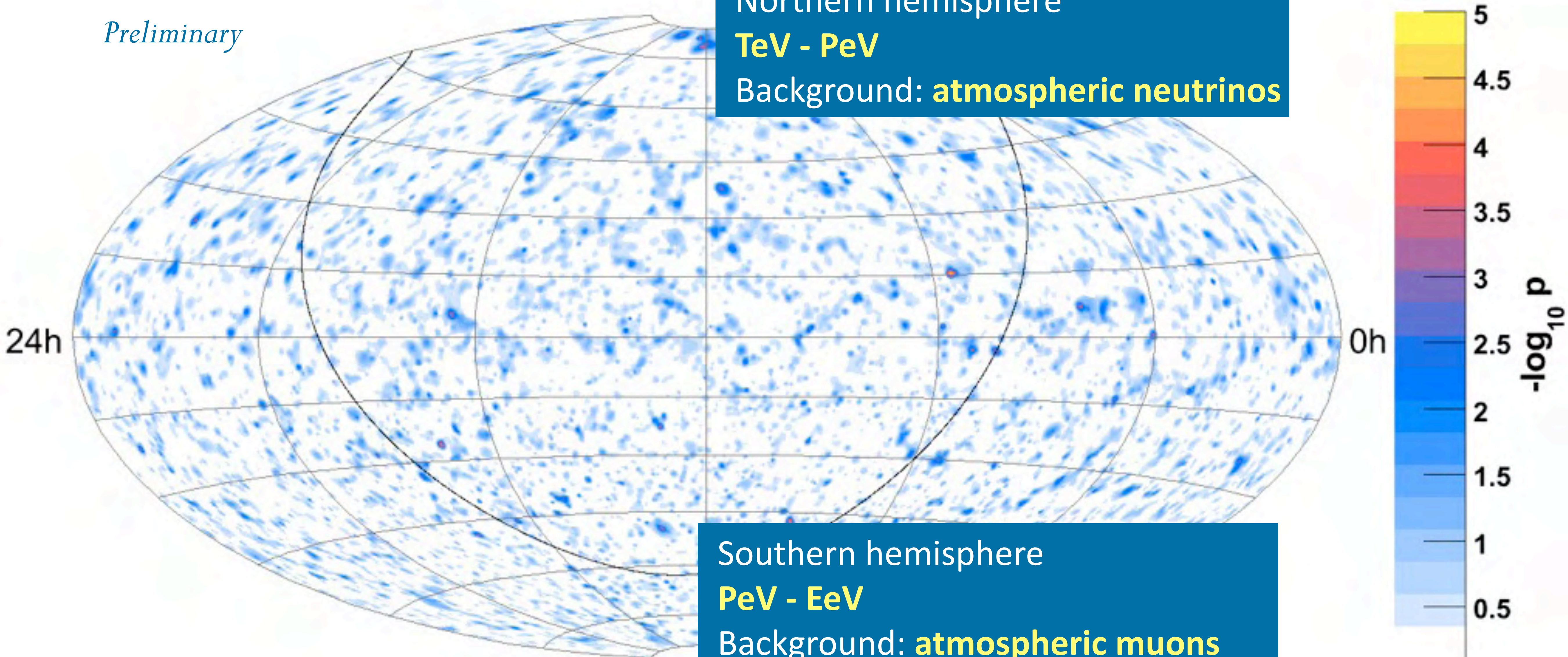
Remaining: 22 IceCube Strings
5 DeepCore Strings

→ **complete in January 2011**

Antares

- Detector at 2500 m depth
- Site 40 km SSE of Toulon
- 40 km data cable
- Counting room La Seyne-sur-Mer

All-sky map (6 months IceCube 2008, 40 strings)



Northern hemisphere
TeV - PeV
Background: **atmospheric neutrinos**

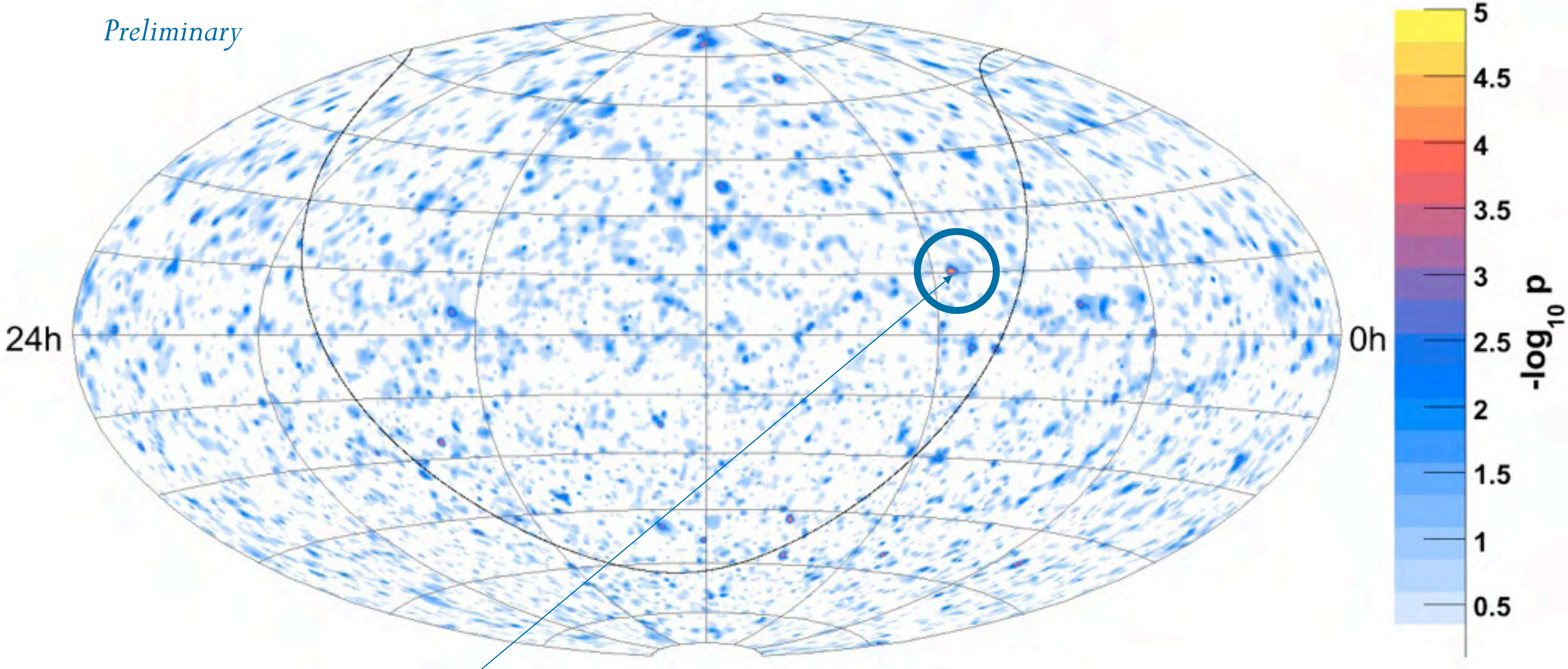
Southern hemisphere
PeV - EeV
Background: **atmospheric muons**
Reduced by 10^{-5} using energy cut

175.5 days livetime,

6796 up-going events,
10981 down-going events

C. Spiering

All-sky map (6 months IceCube 2008, 40 strings)

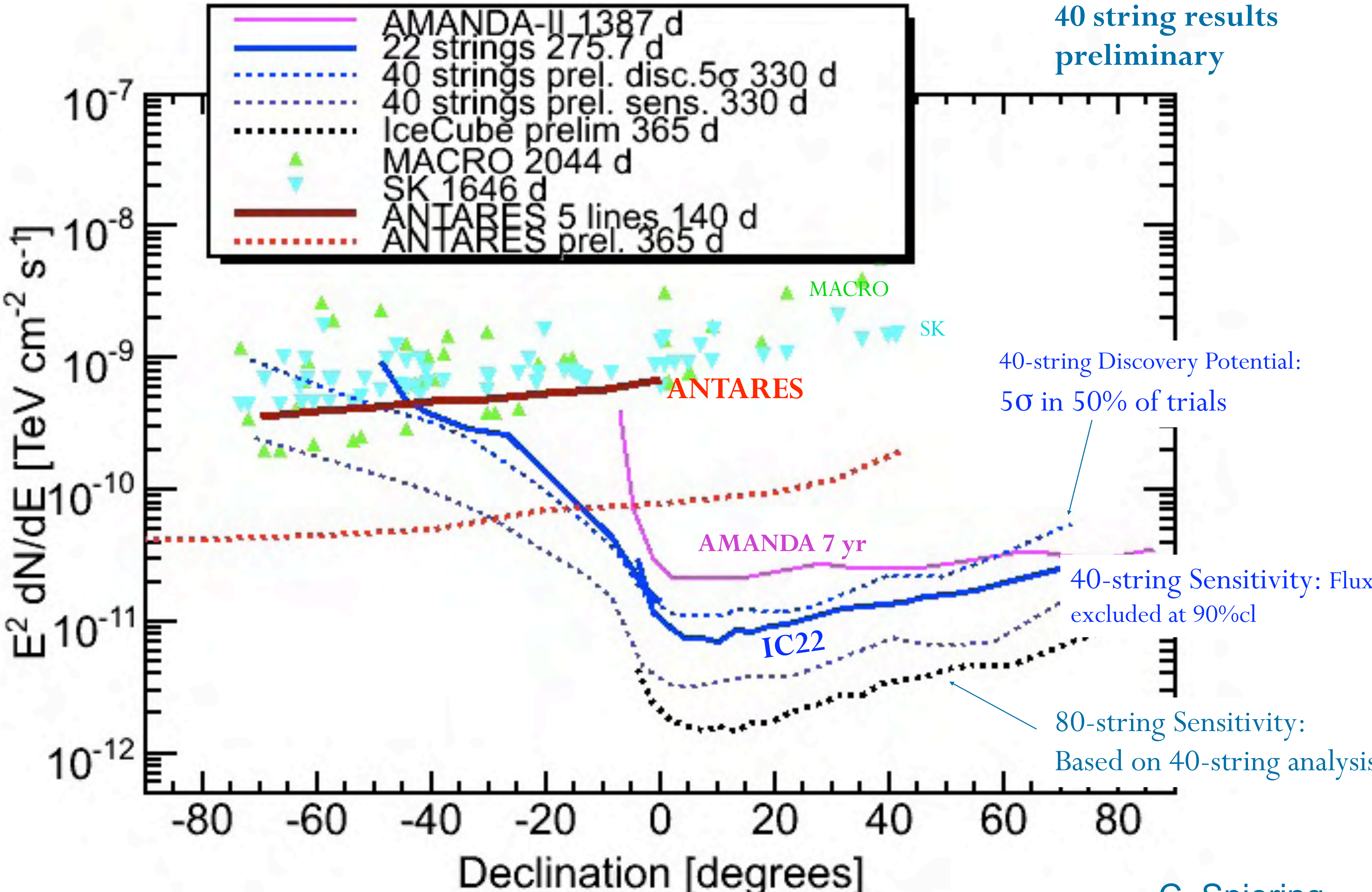


Hottest location at r.a.=114.95°, dec.=15.35°
Pre-trial $-\log_{10}$(p-value) = 4.43

all-sky p-value is 61% → not significant

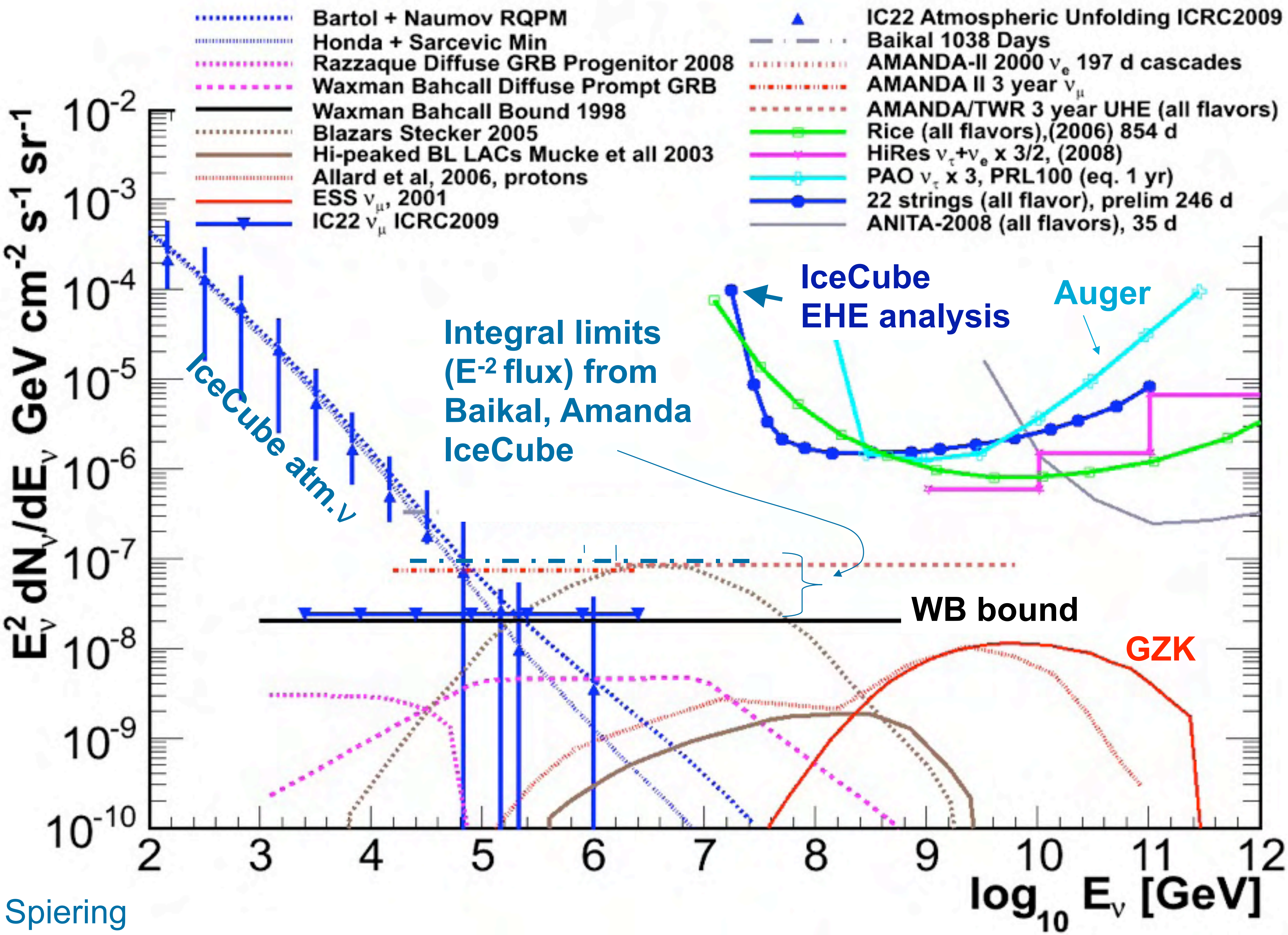
C. Spiering

Point Sources limits/sensitivities



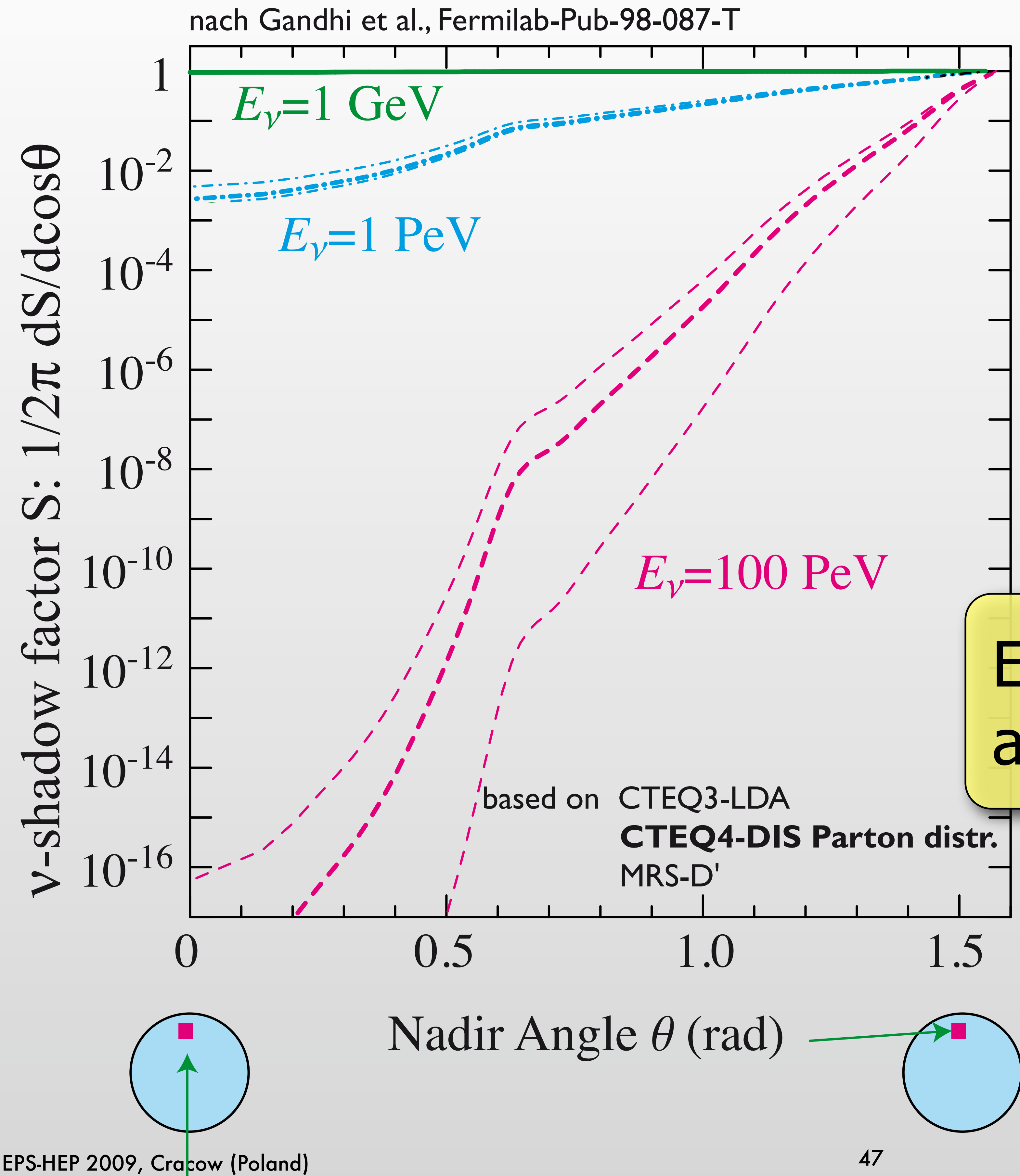
C. Spiering

Diffuse Neutrino Fluxes



C. Spiering

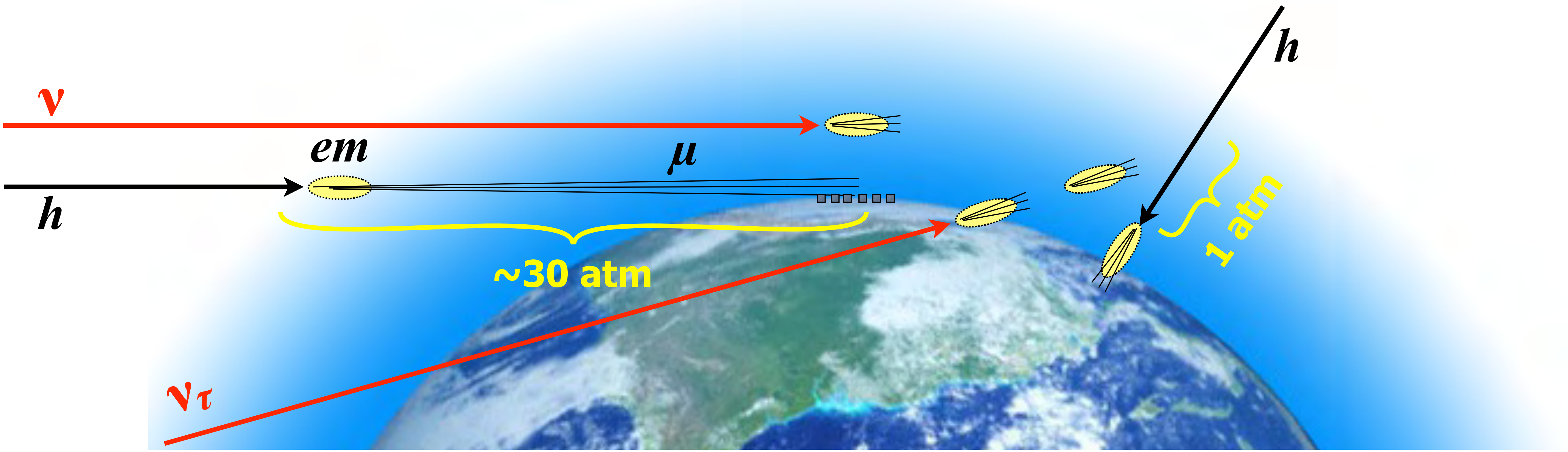
Neutrino Absorption in Earth

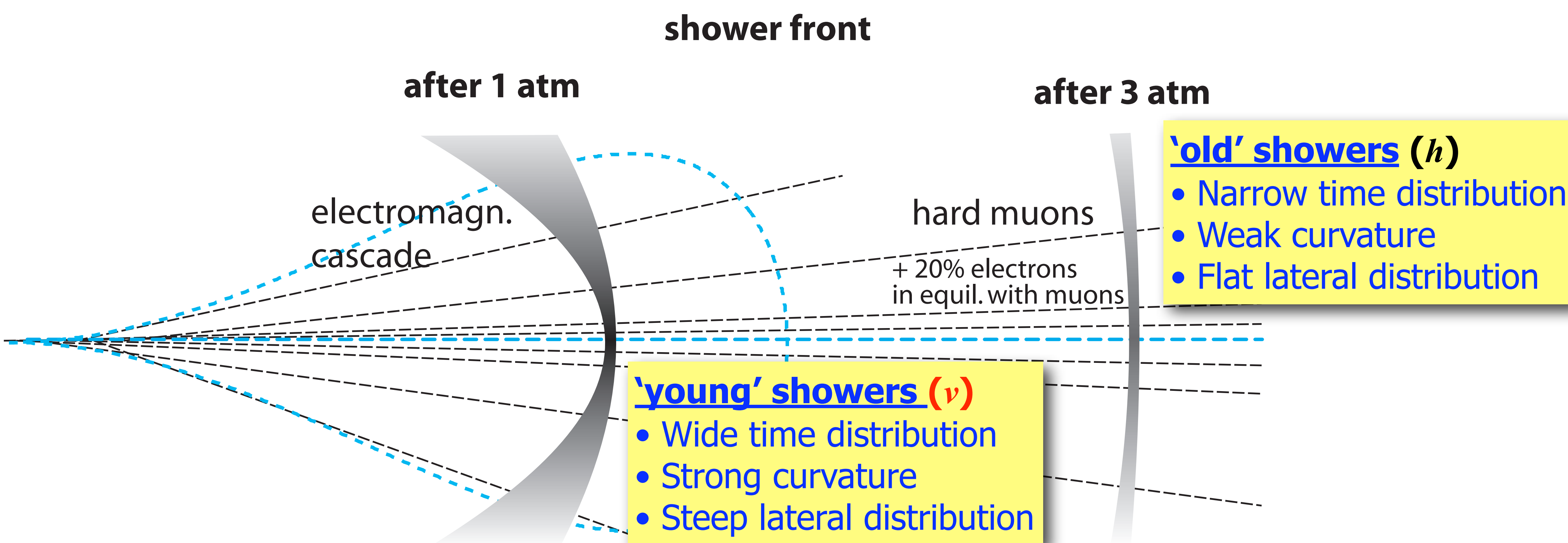


Earth becomes ‚opaque‛ above $E_\nu \gtrsim 100$ TeV

EeV Neutrinos by Horizontal EAS

Only a neutrino can induce a young horizontal shower !

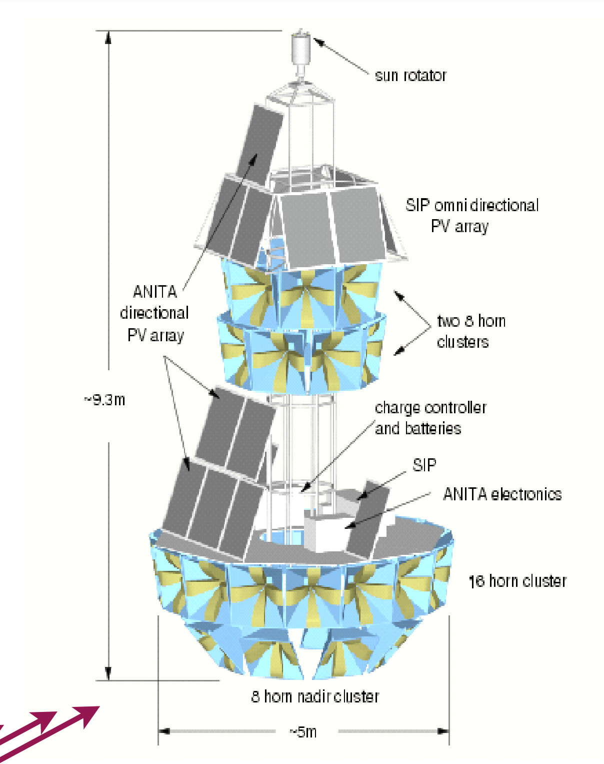




EeV Neutrinos by Radio-Signals

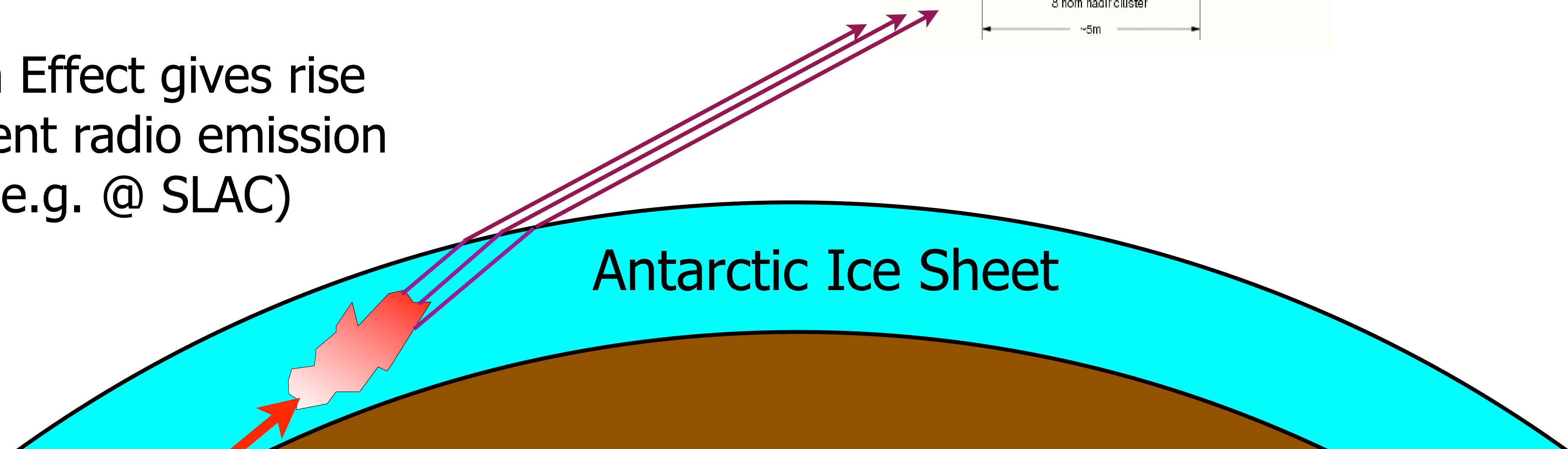
Concept of ANITA

Results: PRL (2009)



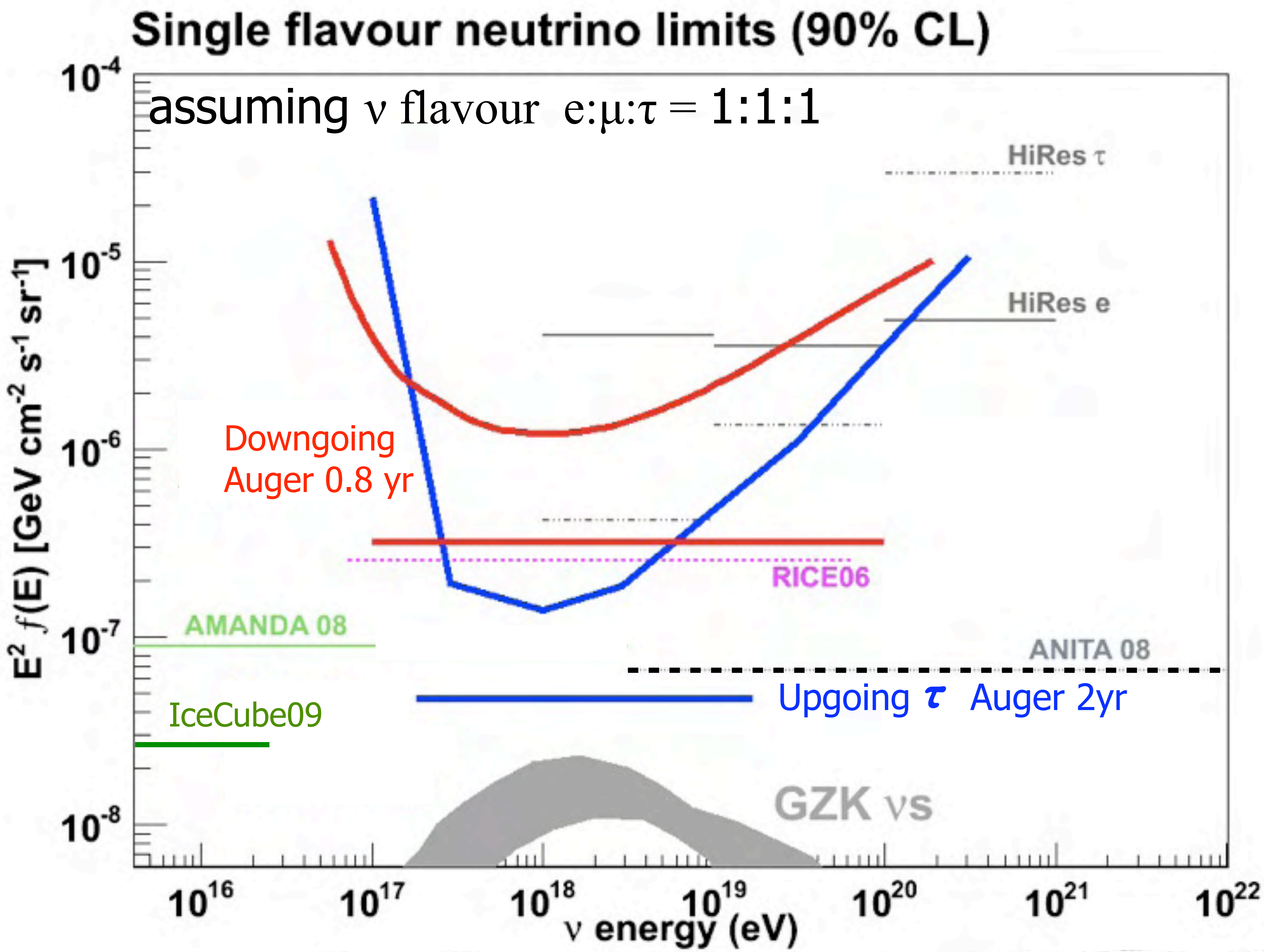
230-1200 MHz
Horn-Antennas

Askaryan Effect gives rise to coherent radio emission (verified e.g. @ SLAC)



Huge volumes can be observed

UHE Diffuse Neutrino Flux Limits



Several astrophys. models excluded; cosmogenic neutrinos in reach !

European Physical Society HEP 2009
16-22 July 2009 Krakow, Poland

Future Directions

UHECRs

GZK-effect established

➙ Filter to nearby sources

But: steep spectrum above 60 EeV requires huge apertures

UHECR-Astronomy around the corner

➙ CR sources will be identified,

better knowledge of magn. fields required ➙ projects with astronomers

Want to to measure spectra/composition of individual sources

Study **fundamental physics**, particle physics, exotics

Auger-North + JEM-EUSO

New techniques

Radio observation of EAS may reduce costs

UHE-ν's

Present results from **UHECR suggests a few ν's year/km^3**

➙ If sources are seen, another undisputable proof for CR-accelerators

First 2 years of IceCube should tell...

SN-explosion in Galaxy or LMC ➙ hundreds of ν's would be seen

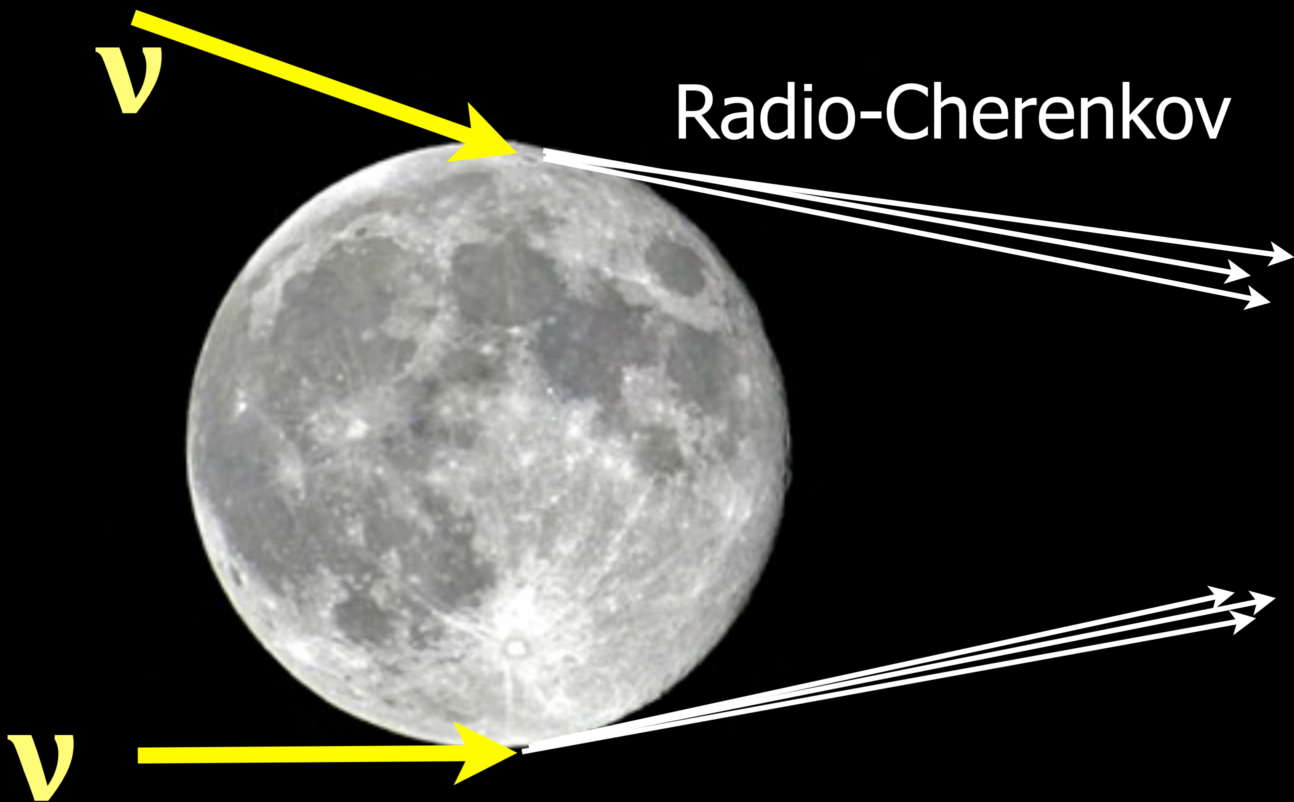
Competative Dark-Matter limits come for free

km3net + New Techniques

km3net large enough?

Acoustic a/o Radio techniques very attractive for huge volume instrumentation; but applicability to be proven...

Moon Regolith serves as ν -Target



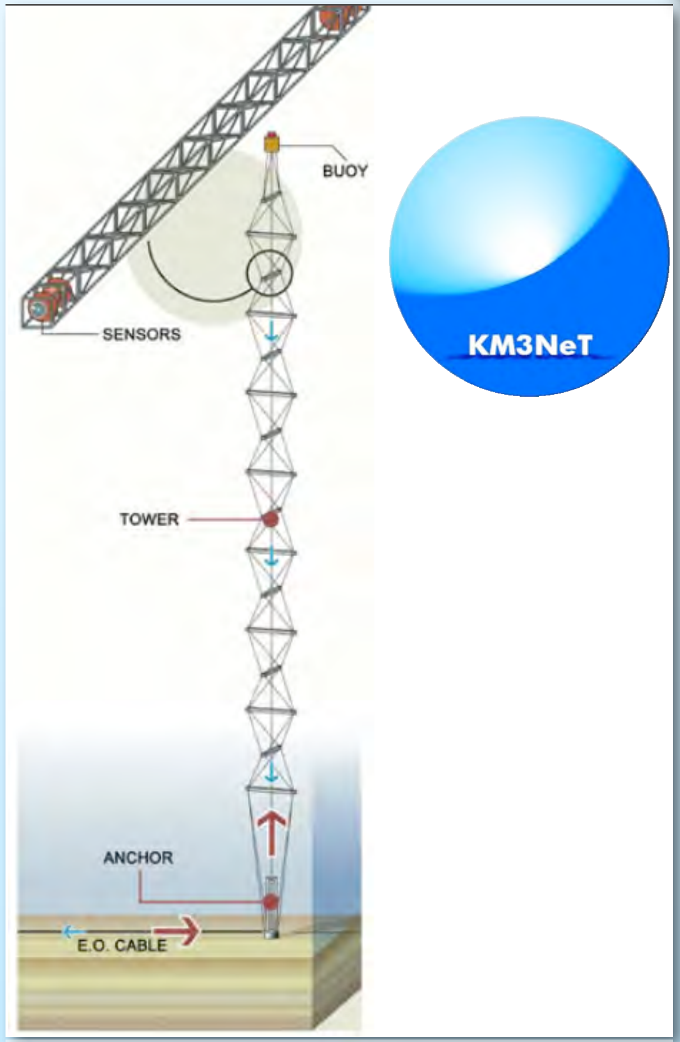
First observations performed already

Will be fully exploited by LOFAR

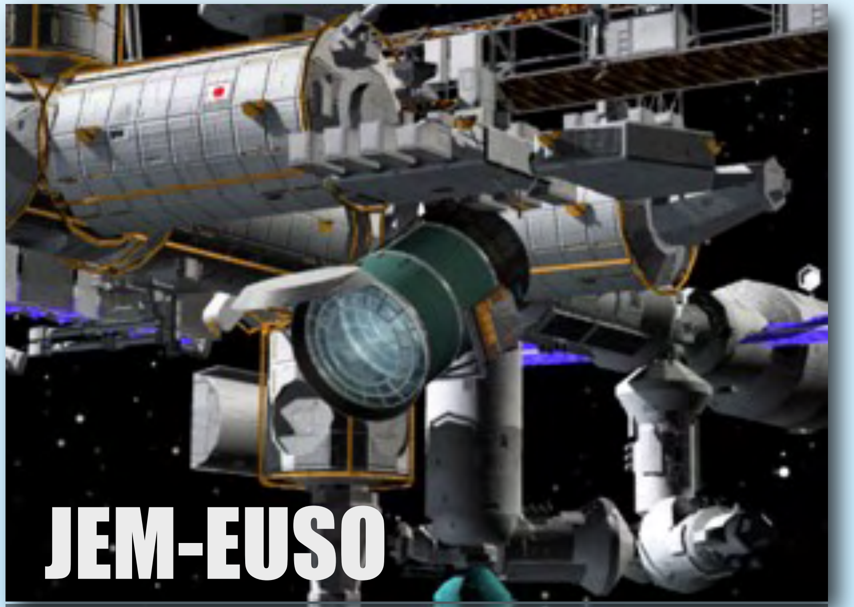
Very exciting time also for Astroparticle Physics

Radio

Auger-North



KM3Net++



JEM-EUSO