The Search for the Sources of Ultrahigh-Energy Cosmic Rays

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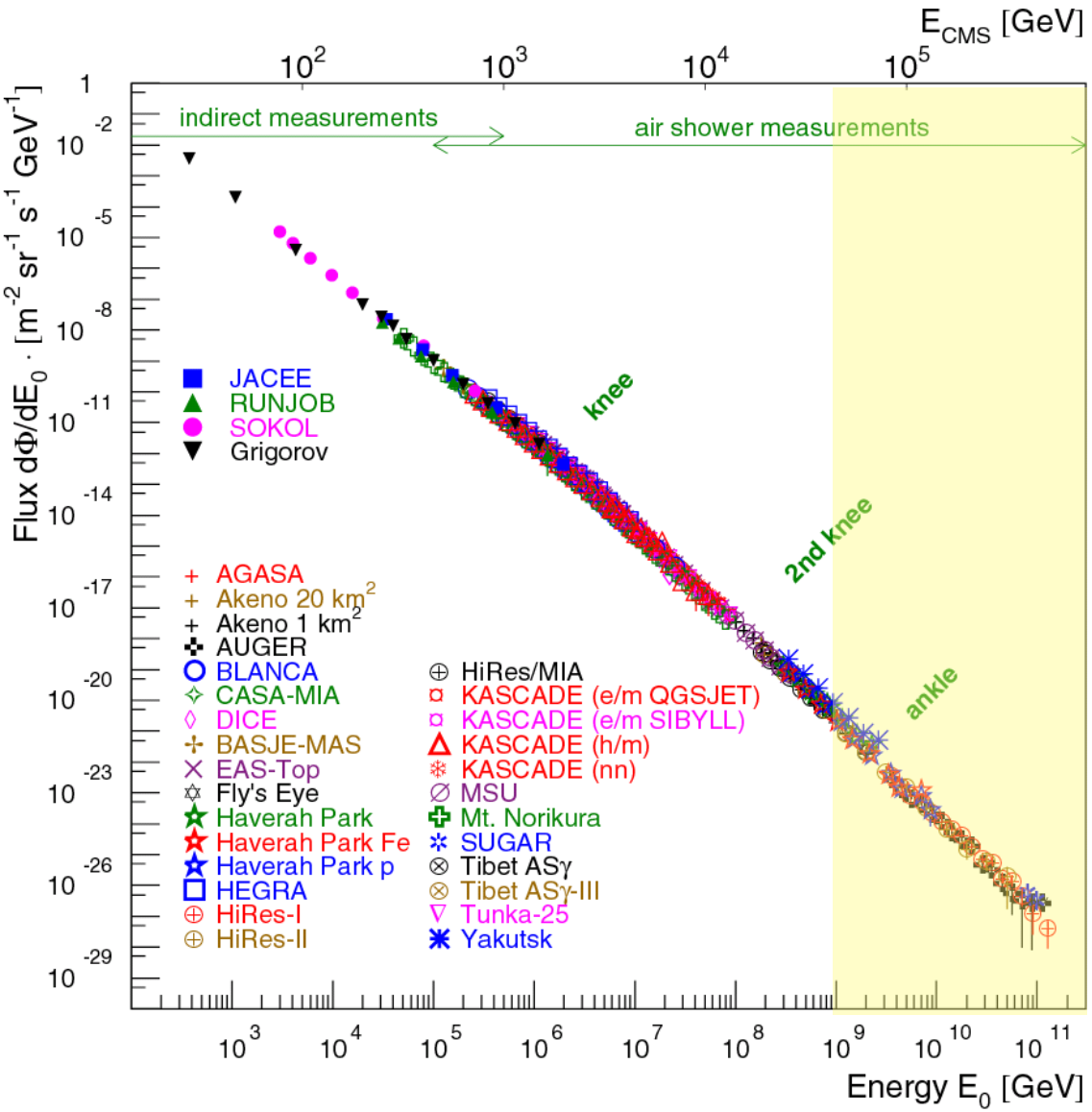
5th International Symposium on High Energy Gamma Ray Astronomy (Gamma 2012)

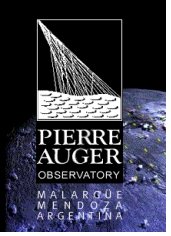
Heidelberg, July 9-13, 2012

Energy Spectrum



UHECR energies:

- GZK cutoff?
- Cosmic ray astronomy?
- Energy frontier … new physics?



Open Questions

- Energy spectrum
  - Suppression around 5×10^{19} eV (formerly known as "GZK cutoff") is firmly established after a decade of controversy (experiments agree).
  - Interpretation less obvious – depends on composition ("GZK" for protons, spallation for iron).

- Composition – protons, iron, …?
  - No agreement among experiments (within their *quoted* uncertainties). Particle physics plays a role…

- Arrival directions – the key question: where and what are the sources?
  - Proton composition
    - Above 5×10^{19} eV, particles must come from sources within ~100 Mpc .
    - Large scale structure should at some point be visible in skymap – any complete lack of anisotropy becomes hard to explain…
  - Mixed/heavy composition
    - Prospects for discovering point sources are dim…

Composition is the key…

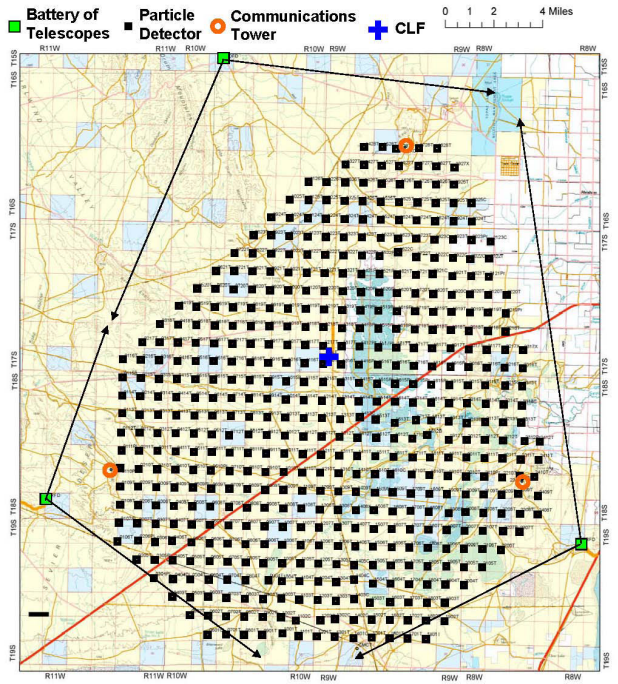
The Hybrid Generation

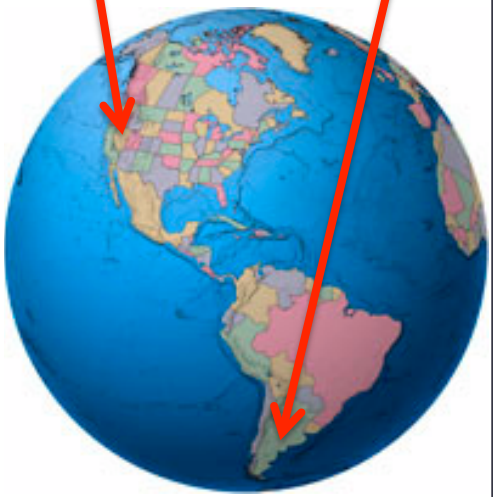
Telescope Array

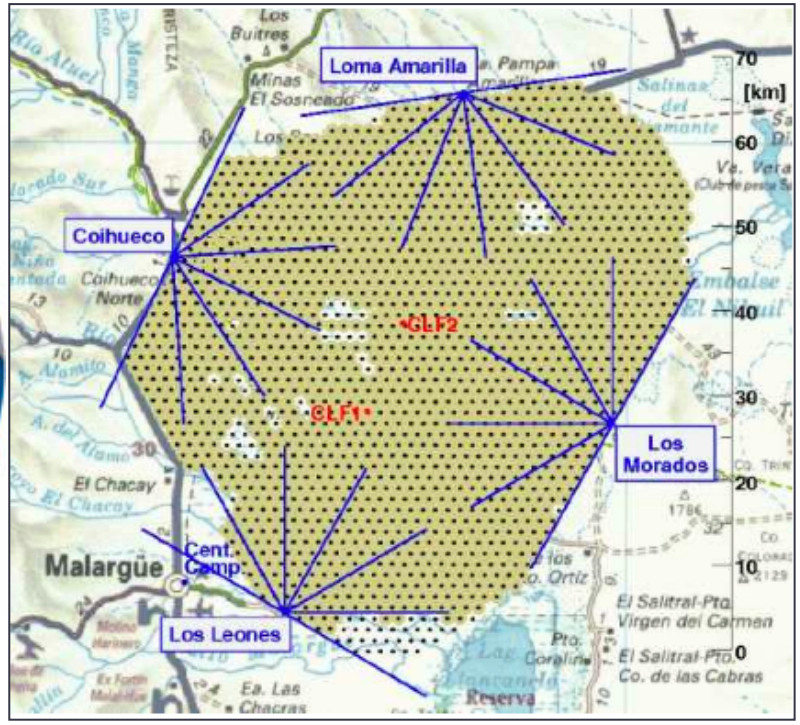
Utah, USA
~700km^2
507 two-layer 3 m^2 scintillation counters on 1.2 km grid
3 fluorescence detector sites
Data taking since 2008

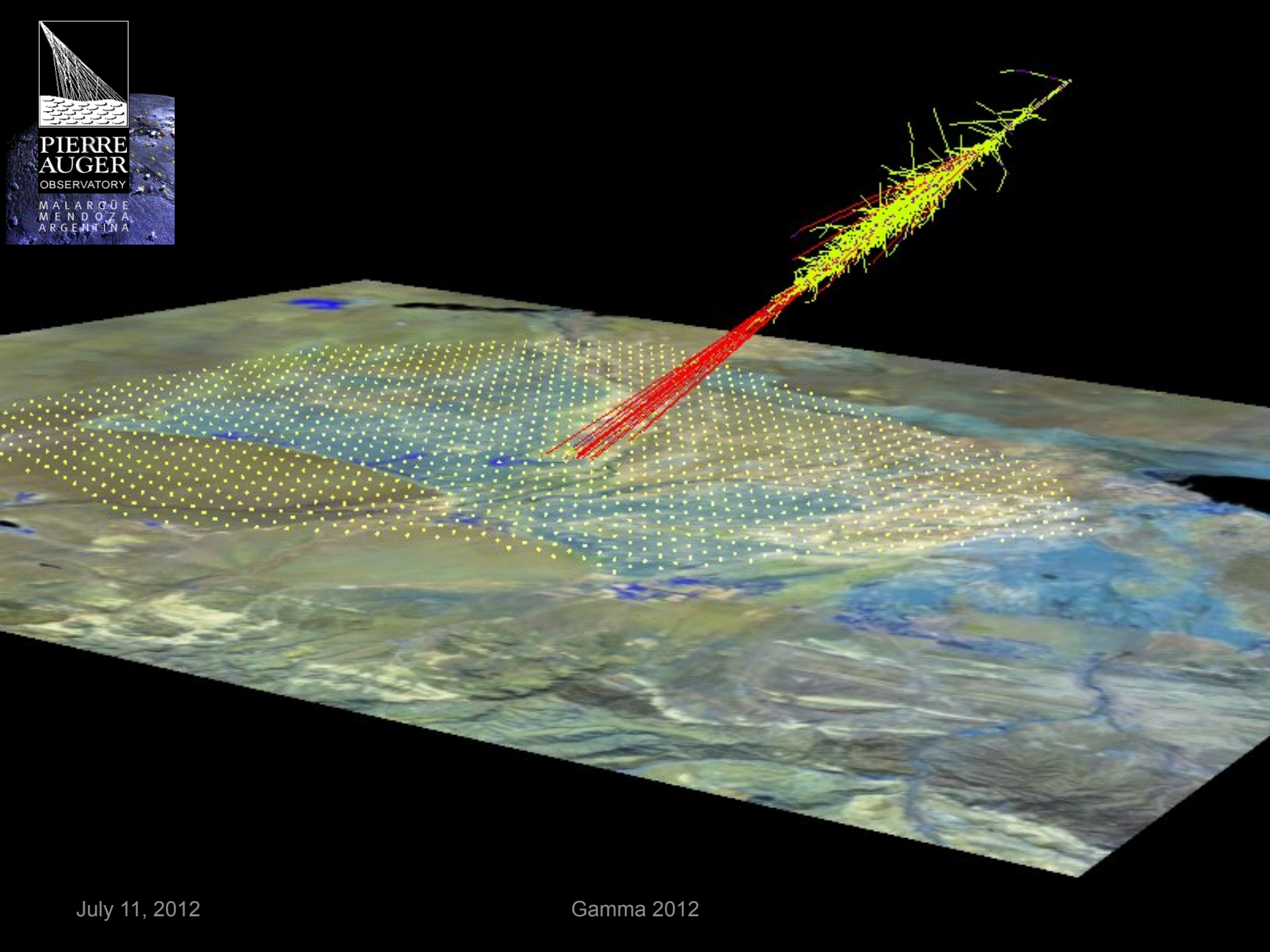
Pierre Auger Observatory

Malargüe, Argentina
~3000 km^2
1600 water Cherenkov detectors on 1.5 km grid
4 fluorescence detector sites
Data taking since 2004





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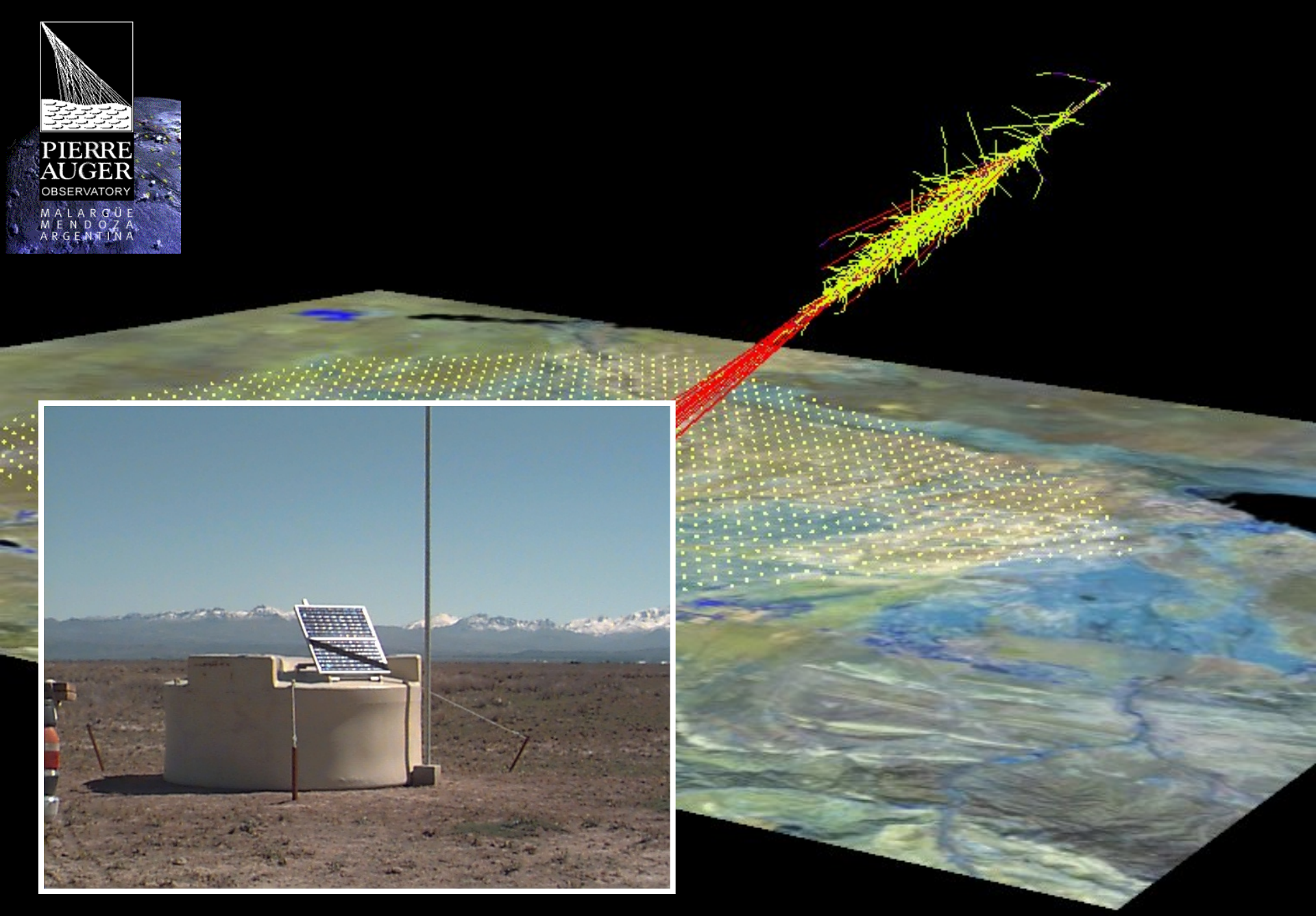
MENDOZA
ARGENTINA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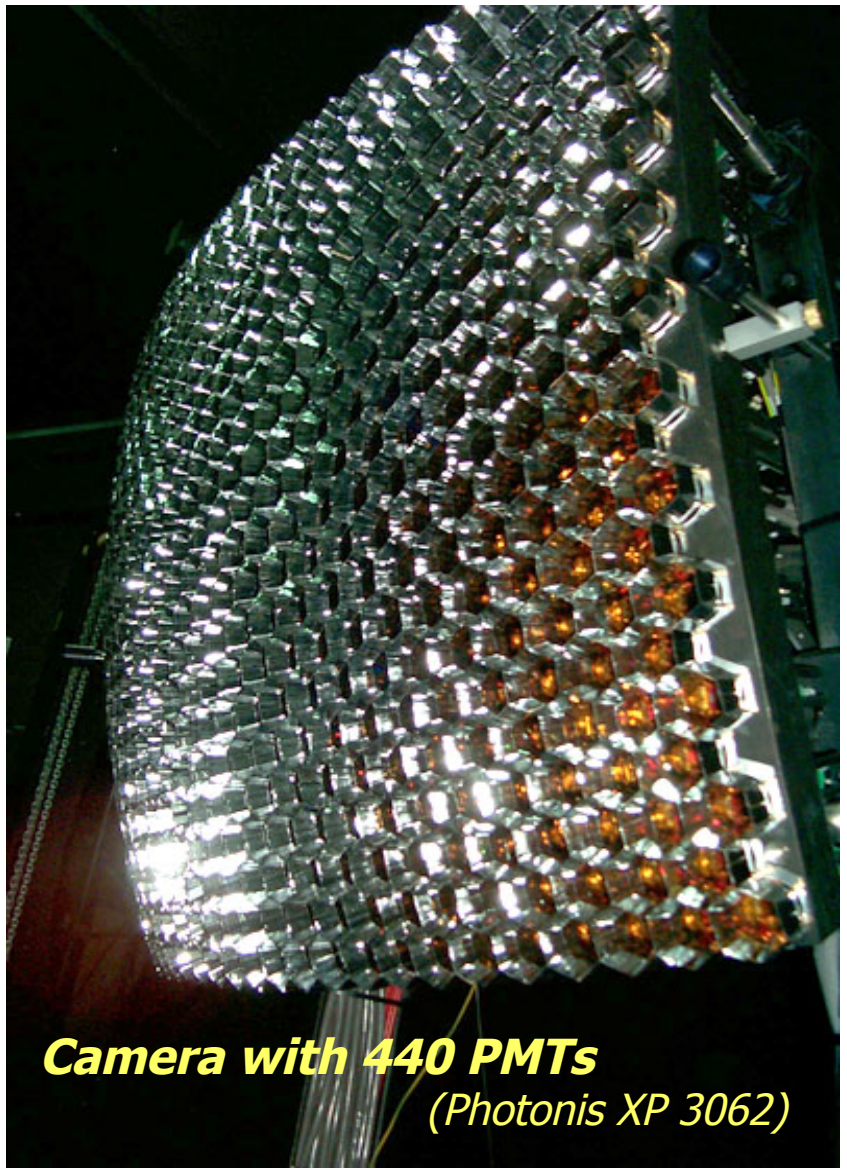
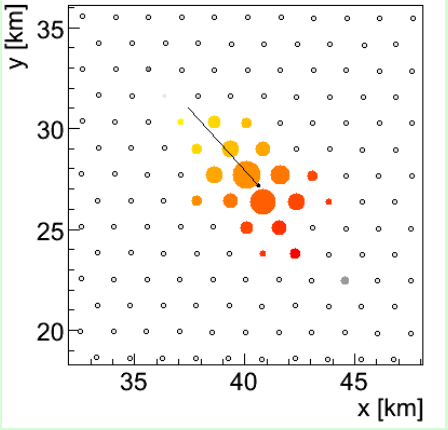
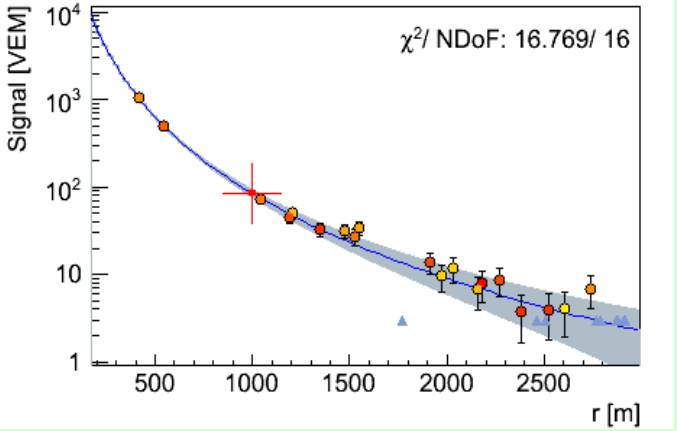


Camera with 440 PMTs
(Photonis XP 3062)

Hybrid Concept

SD





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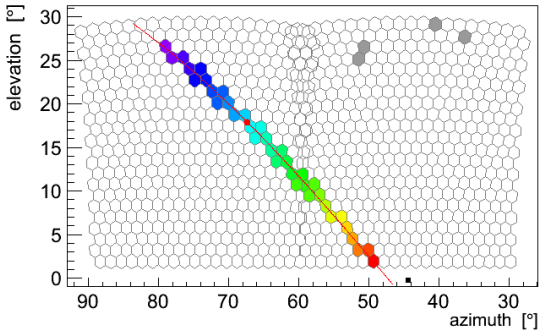
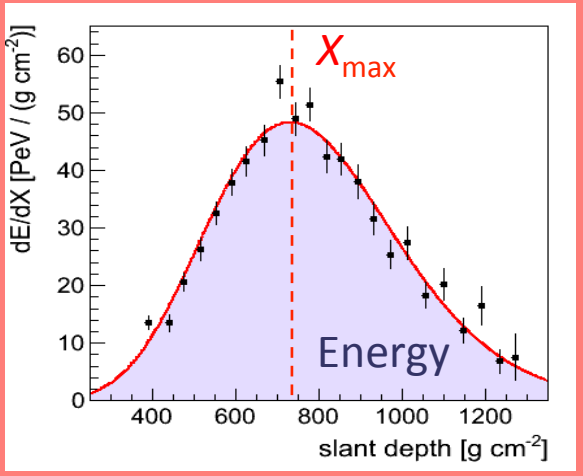
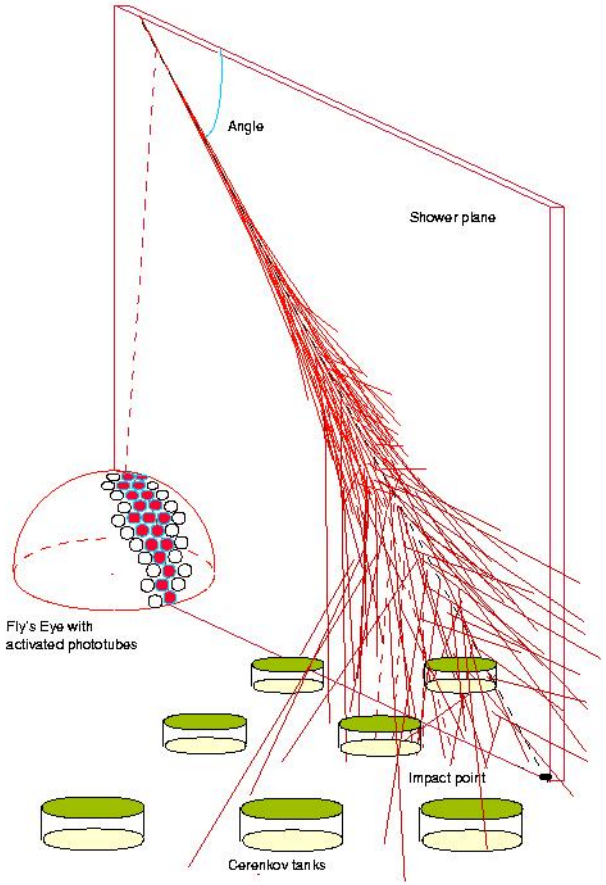
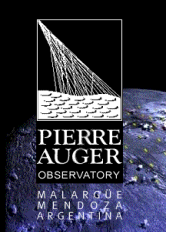








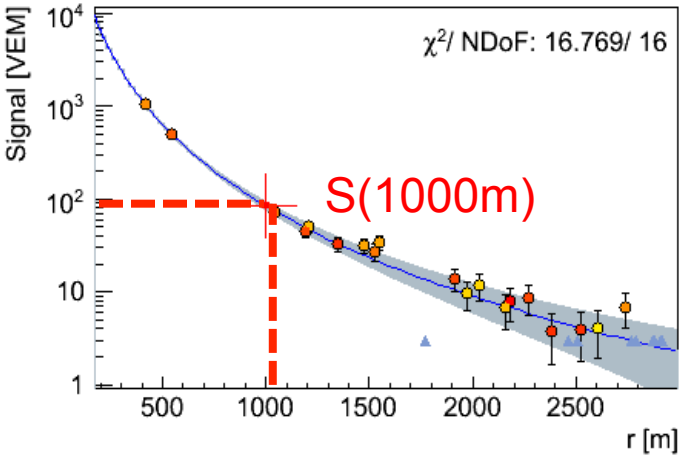
Energy Spectrum

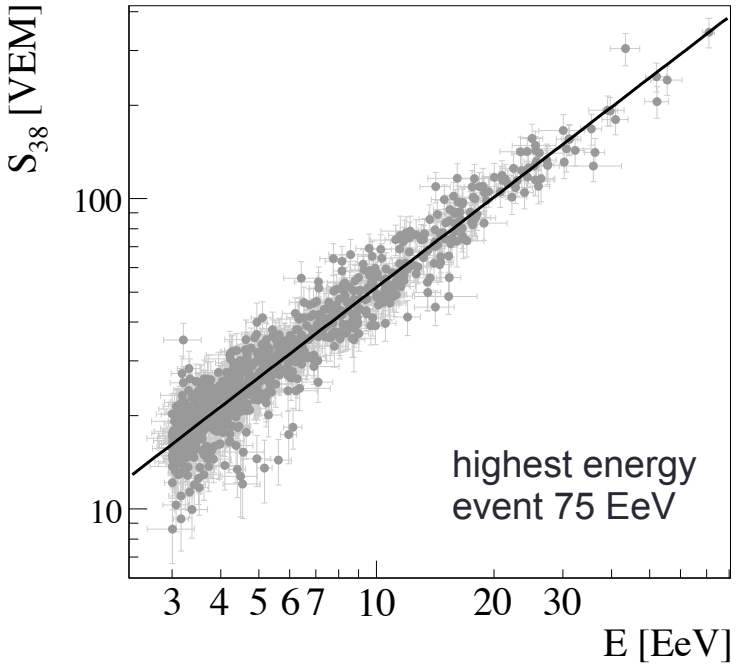
Chemical Composition

Anisotropy

Energy Calibration

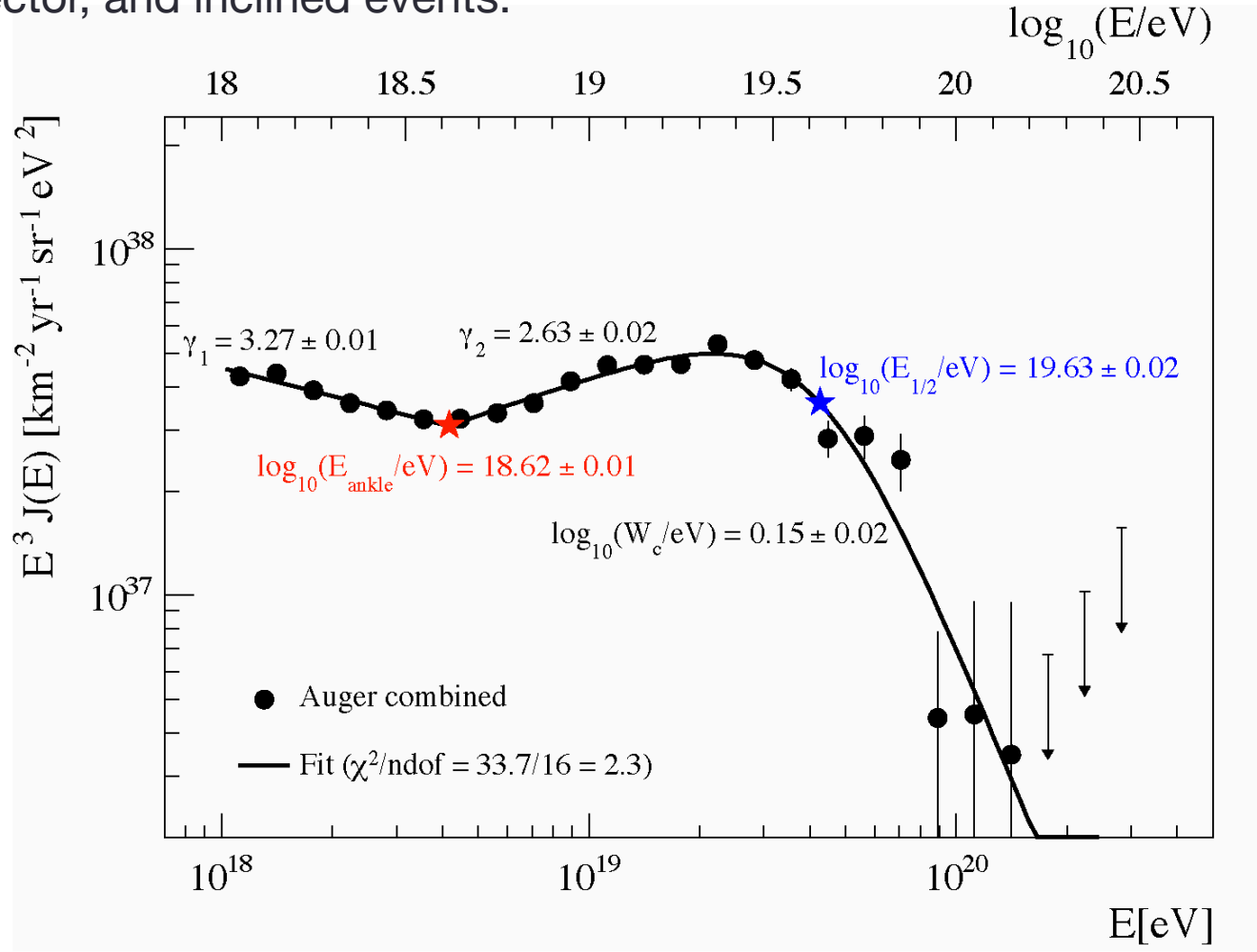
- Calibration of the surface detector is made using events with independent surface and fluorescence detector trigger and reconstruction.
- Zenith angle correction is based on data (constant intensity cut method) – assuming an isotropic flux, equal intensity at different zenith angle must correspond to the same energy.
- Overall fluorescence detector energy resolution is ~8%.
- Total systematic uncertainty of energy scale: 22% (dominated by 14% error on fluorescence yield).





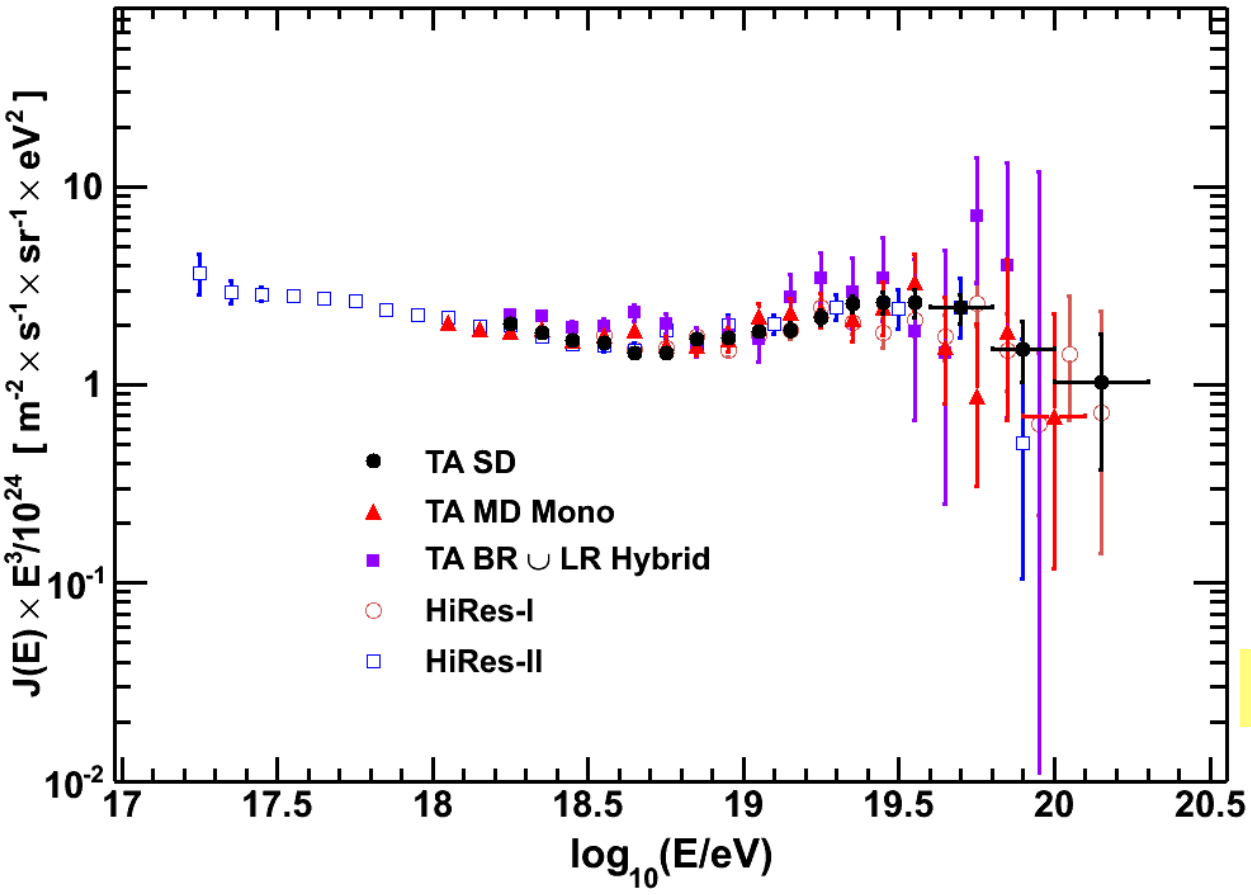
Combined Auger Energy Spectrum

- Internal agreement between spectra produced with hybrid, surface detector, and inclined events.



TA Energy Spectra

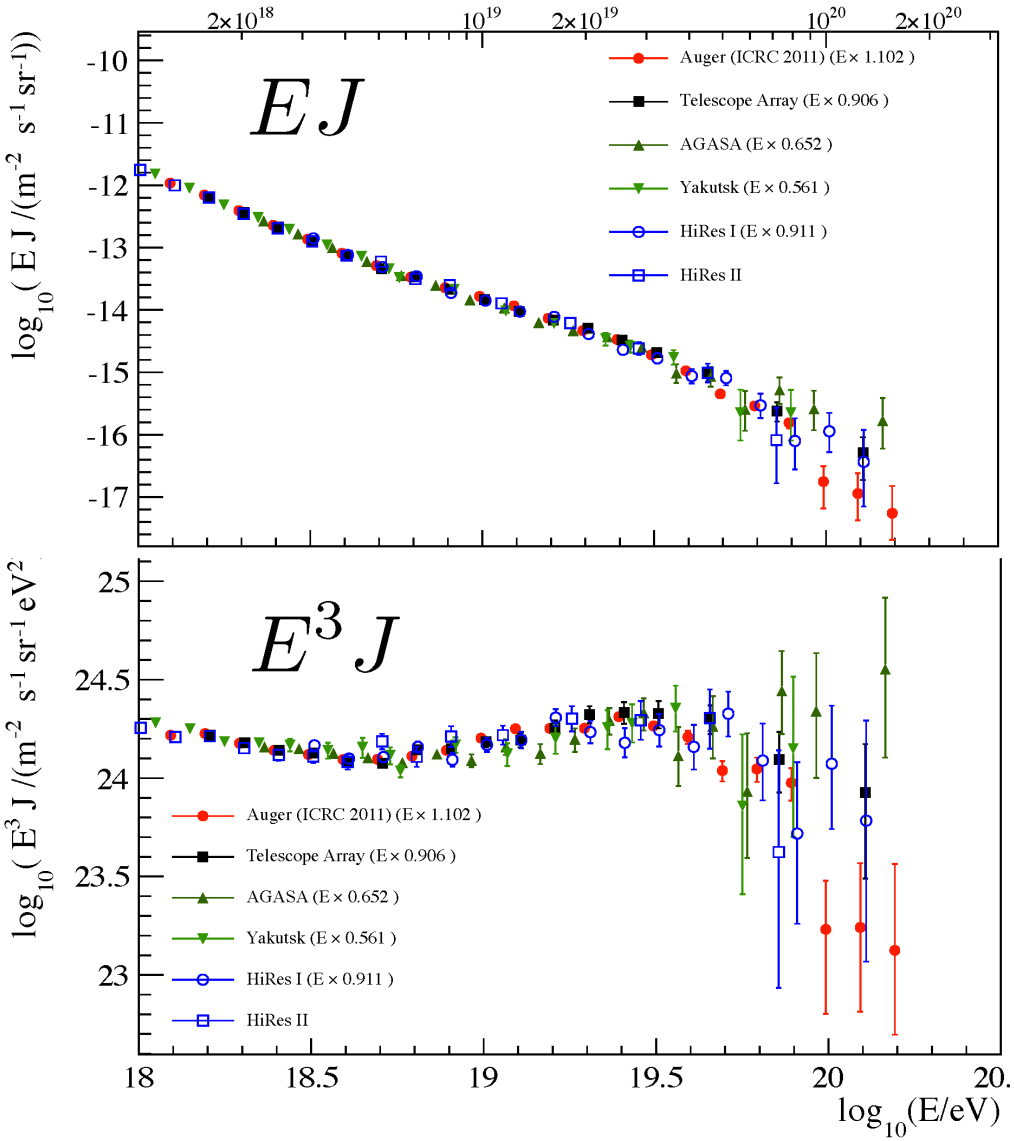
- Like in Auger, there is internal consistency - spectra from surface detector, monocular fluorescence detectors, and hybrid events agree.



Poster P5-07b

Energy Spectrum

- Consistency within each experiment (mono/hybrid/ surface detector).
- Spectra from Auger, TA and HiRes can be brought to agreement by constant energy shifts (TA $E \times 0.906$, Auger $E \times 1.102$).
- Spectra from Auger, HiRes and TA are consistent within their systematic uncertainties.
- At low energy ($E < 40$ EeV) all spectra agree.



What Does It Mean?

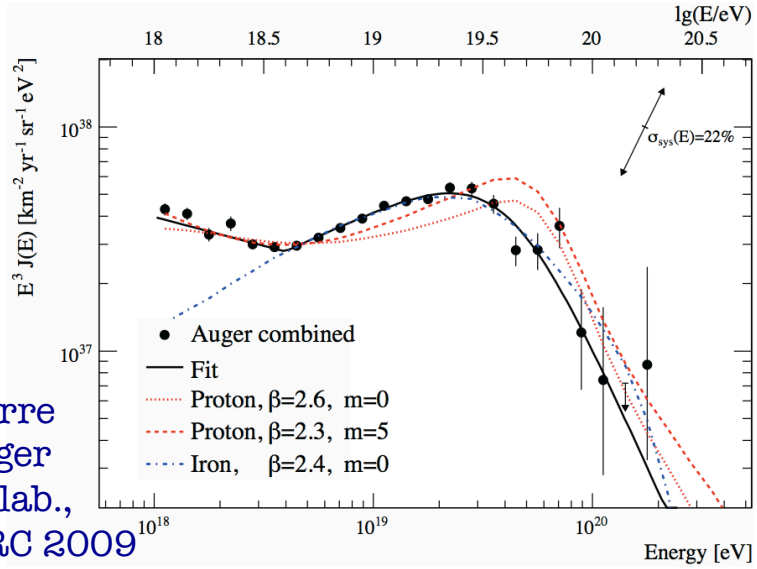
- Experimental agreement – composition is light at the ankle.
- Above the ankle…

Iron composition:

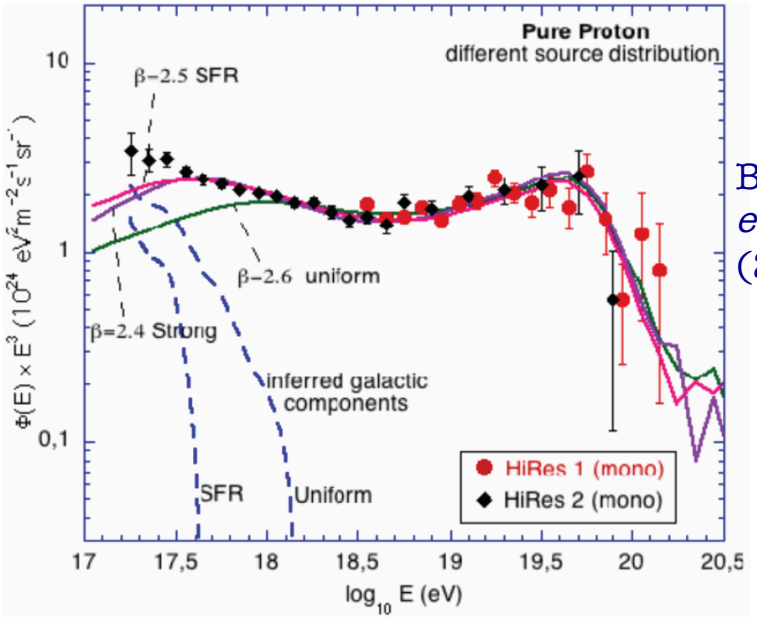
- Suppression at $E > 4\times10^{19}$ eV is due to spallation.
- Ankle is the transition from Galactic to extragalactic origin.

Proton composition:

- Suppression at 5×10^{19} eV is the GZK suppression.
- Ankle is the "e^+e^- dip" from the GZK interaction.



Pierre Auger Collab., ICRC 2009



Berezinsky *et al.* (2005)

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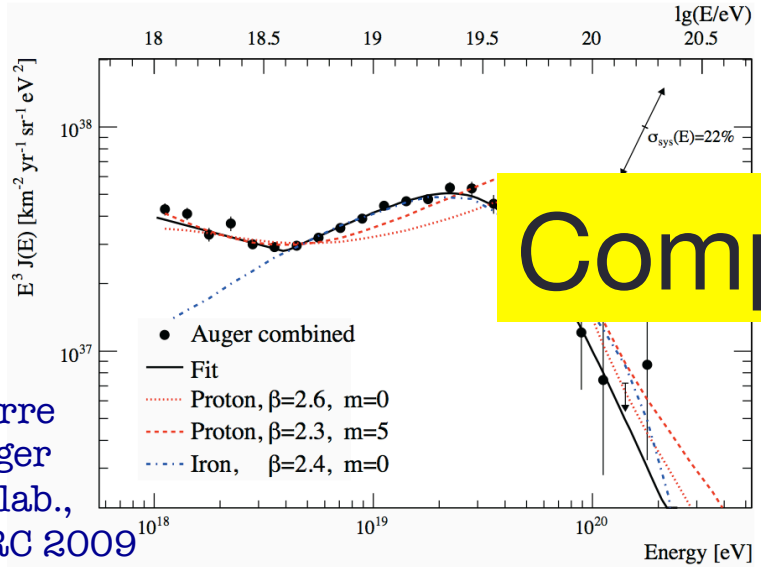

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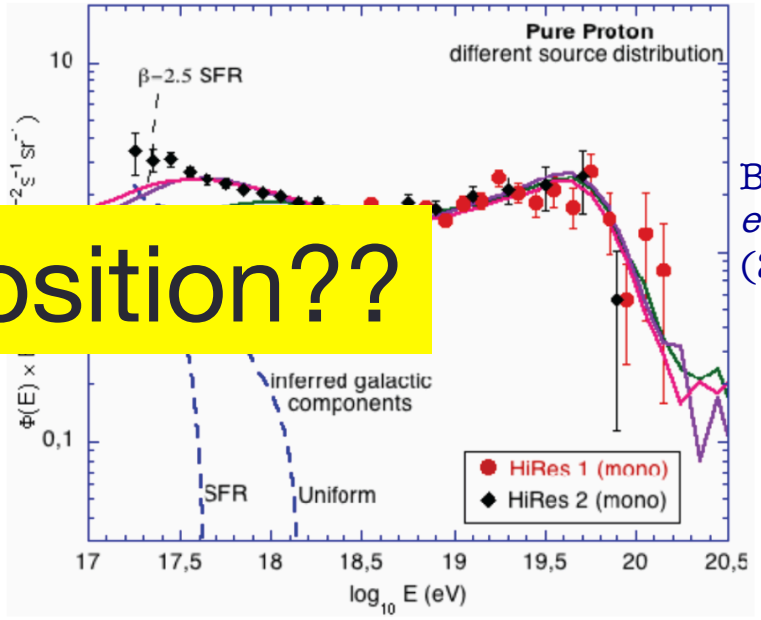

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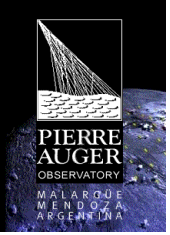

Energy Spectrum

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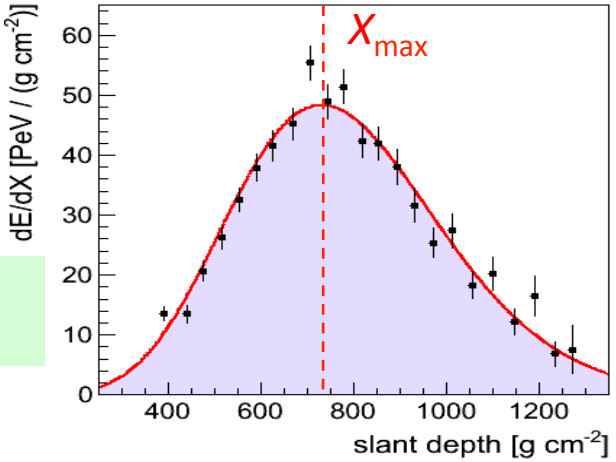
Anisotropy

Cosmic Ray Mass Composition

- Mass-dependent shower observables are:
  - $\langle X_{max} \rangle$ – atmospheric depth where shower attains maximum size.
  - RMS(X_{max}) – fluctuations on event-by-event basis.

Directly measured by fluorescence detectors.



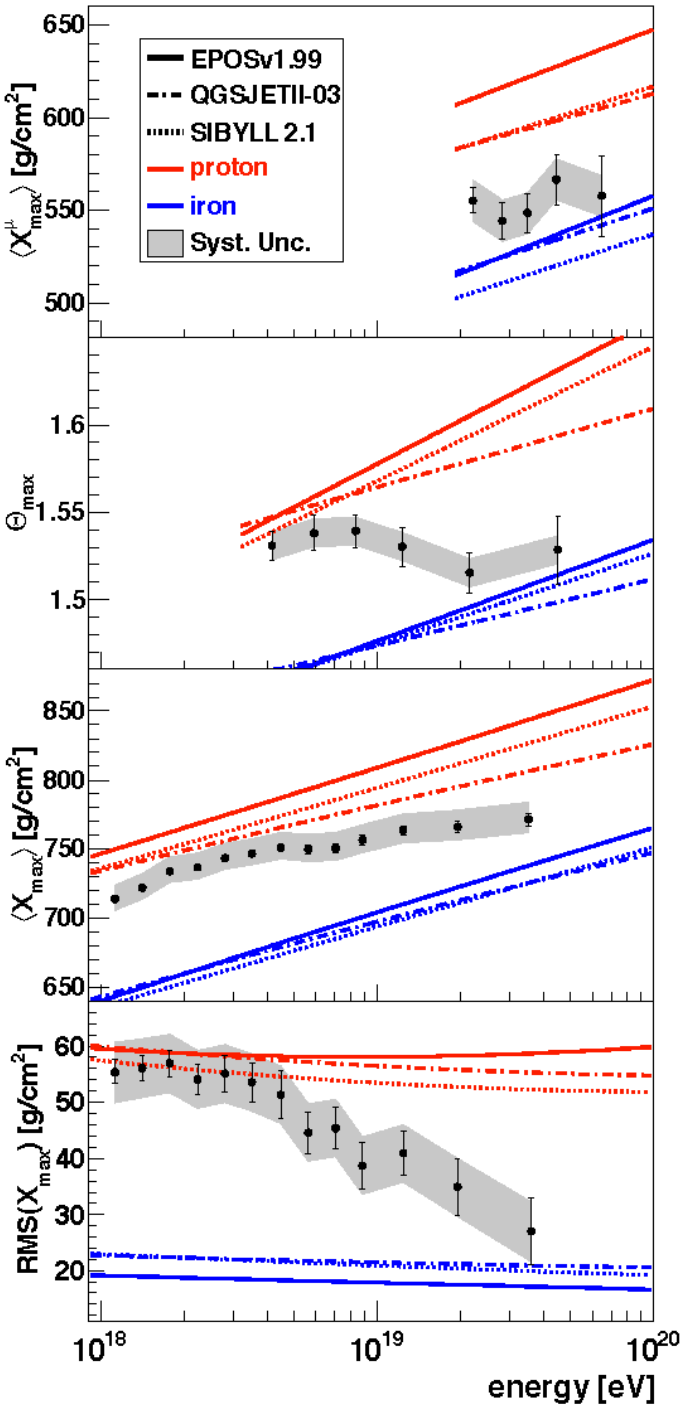
  - $\langle X^{\mu}_{max} \rangle$ – depth (along shower axis) where number of muons reaches maximum (restricted to inclined showers and detectors far from core).
  - θ_{max} – time profile of the tank signals (higher production height gives narrower time pulse).

Measured by surface detector array.

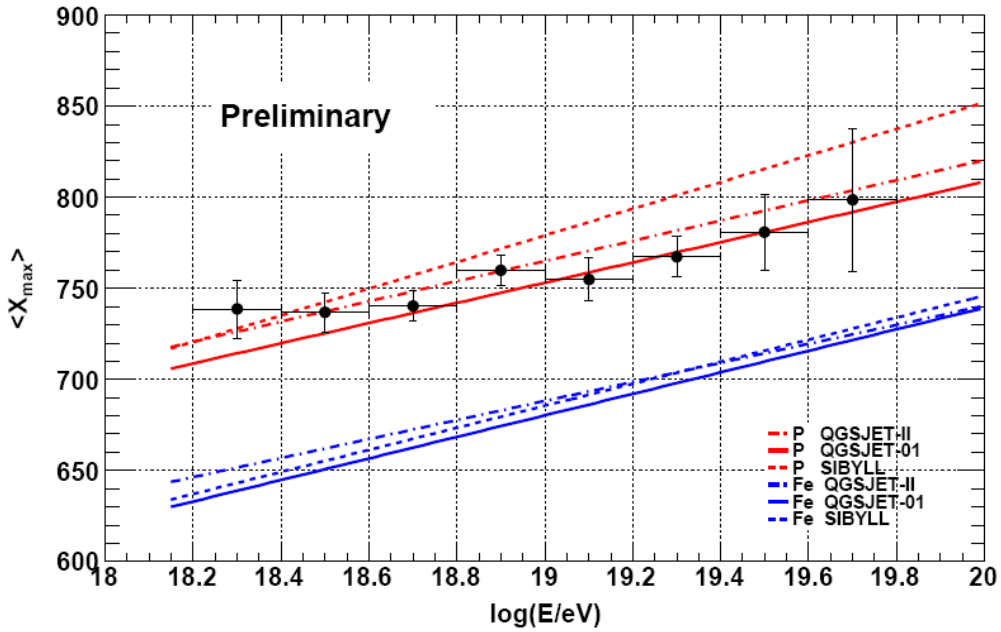
- Important caveat:
  - X_{max} depends on height of first interaction and shower development and therefore on the quality of hadronic interaction models used in air shower simulations.

Results

- Primary composition is inferred from comparison with simulations.
- Evolution of $\langle X_{max} \rangle$, θ_{max}, and $\langle X^{\mu}_{max} \rangle$ with energy is similar. RMS(X_{max}) is compatible within experimental uncertainties.
- The techniques are mostly independent and have different systematic uncertainties.
- All analyses are more compatible with simulations of heavier primaries than pure protons.

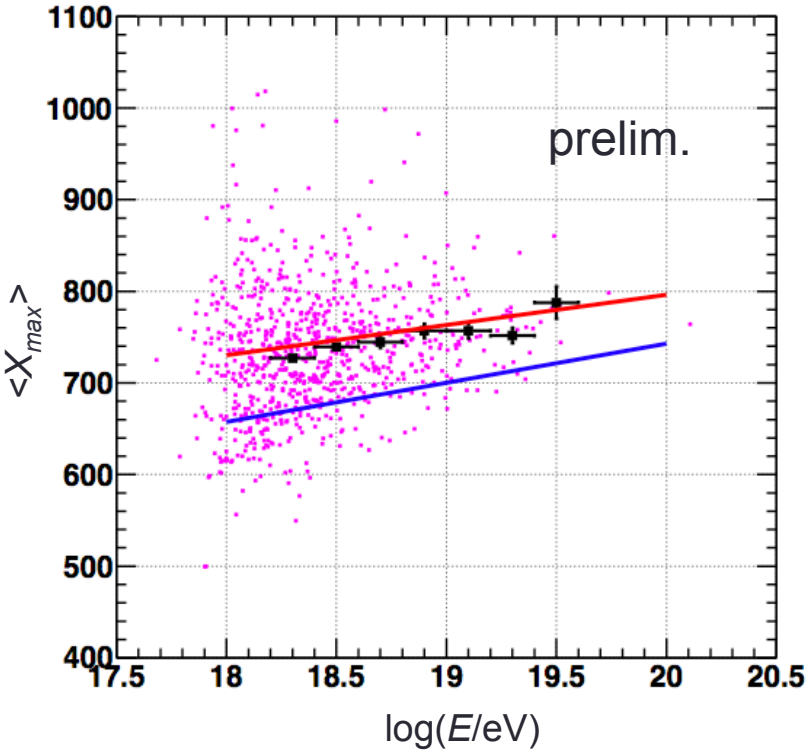


TA Results



- TA stereo fluorescence data

- $\langle X_{max} \rangle$ in both TA analyses (and HiRes) is consistent with simulations using a purely protonic composition.



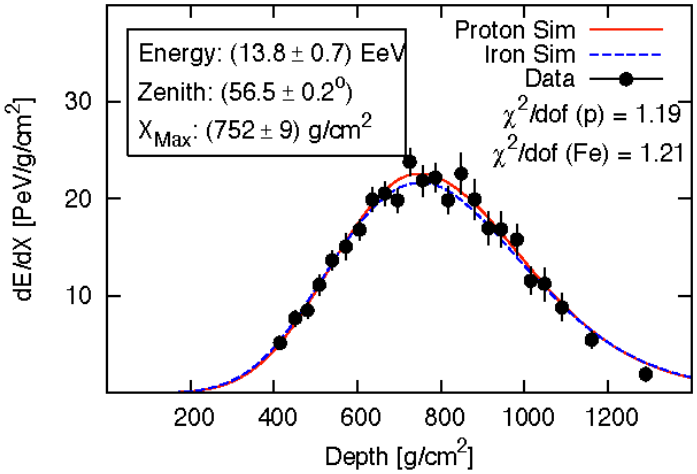
- TA hybrid data (middle drum fluorescence detector and surface array, predictions from QGSJet-II)

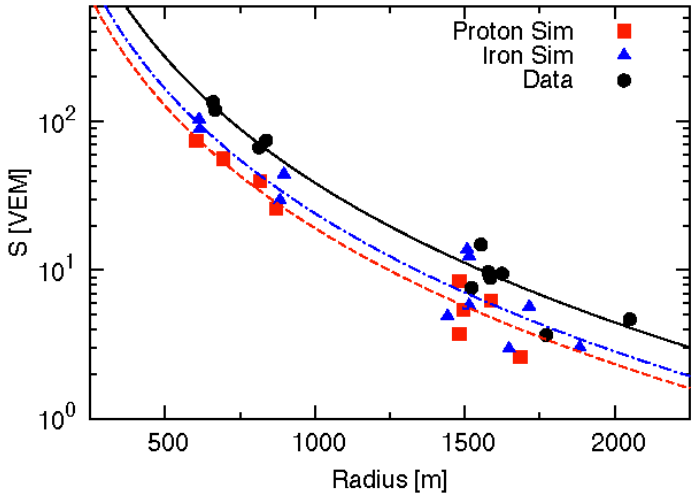
Hadronic Interactions

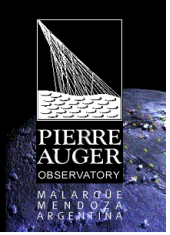
- Interpretation of composition-related observables depends on hadronic interaction models. How well do current models describe cosmic ray data?

- *Example:* hybrid event compared to proton and iron simulations in both fluorescence and surface detector.
  - Longitudinal profile fits well, lateral profile (muon-dominated) shows discrepancy.
  - Data/simulation of S(1000m) is 1.5 for vertical and 2 for inclined events.

- Hadronic interaction models currently underestimate the number of muons in proton showers by a factor 25%...100%. A similar discrepancy exists for simulations of iron primaries.







Energy Spectrum

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Anisotropy

Correlations with AGN?

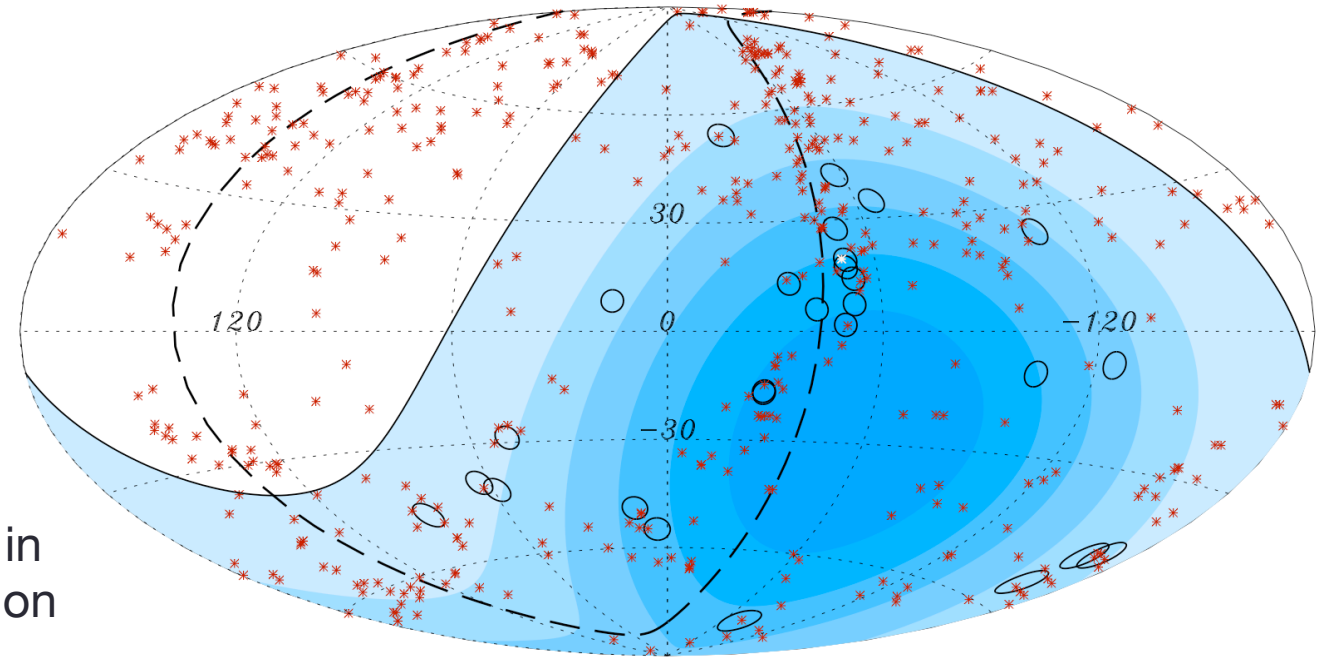
- 12th Catalog of Quasars and Active Nuclei by Veron-Cetty and Veron (Astron. & Astrophys. 455 (2006) 773).

Parameters:

- redshift $z < 0.018$
- threshold energy $E > 56$ EeV
- angular distance $\Delta\theta < 3.1°$

- Parameters were optimized in an exploratory search in early data; correlation was tested on independent data.

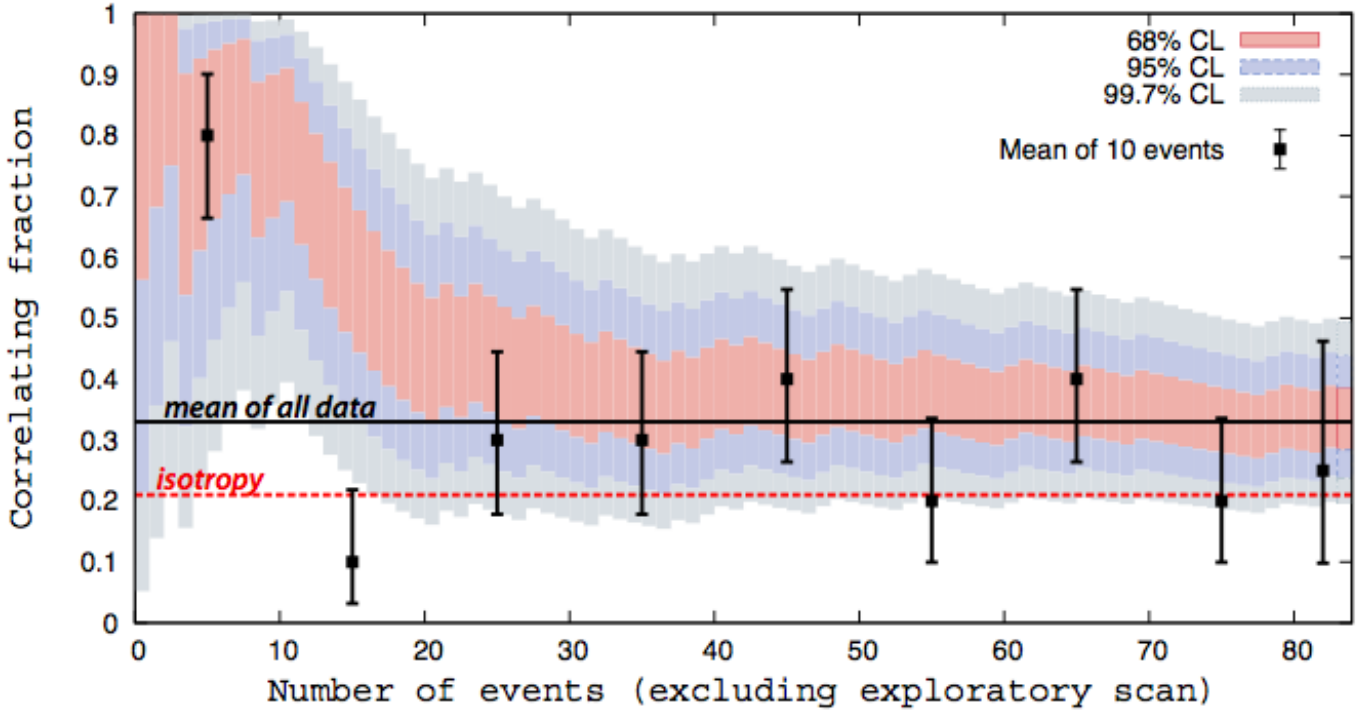
AGN (red), data (circles), exposure (blue)



Auger Collab., Science 318 (2007) 938

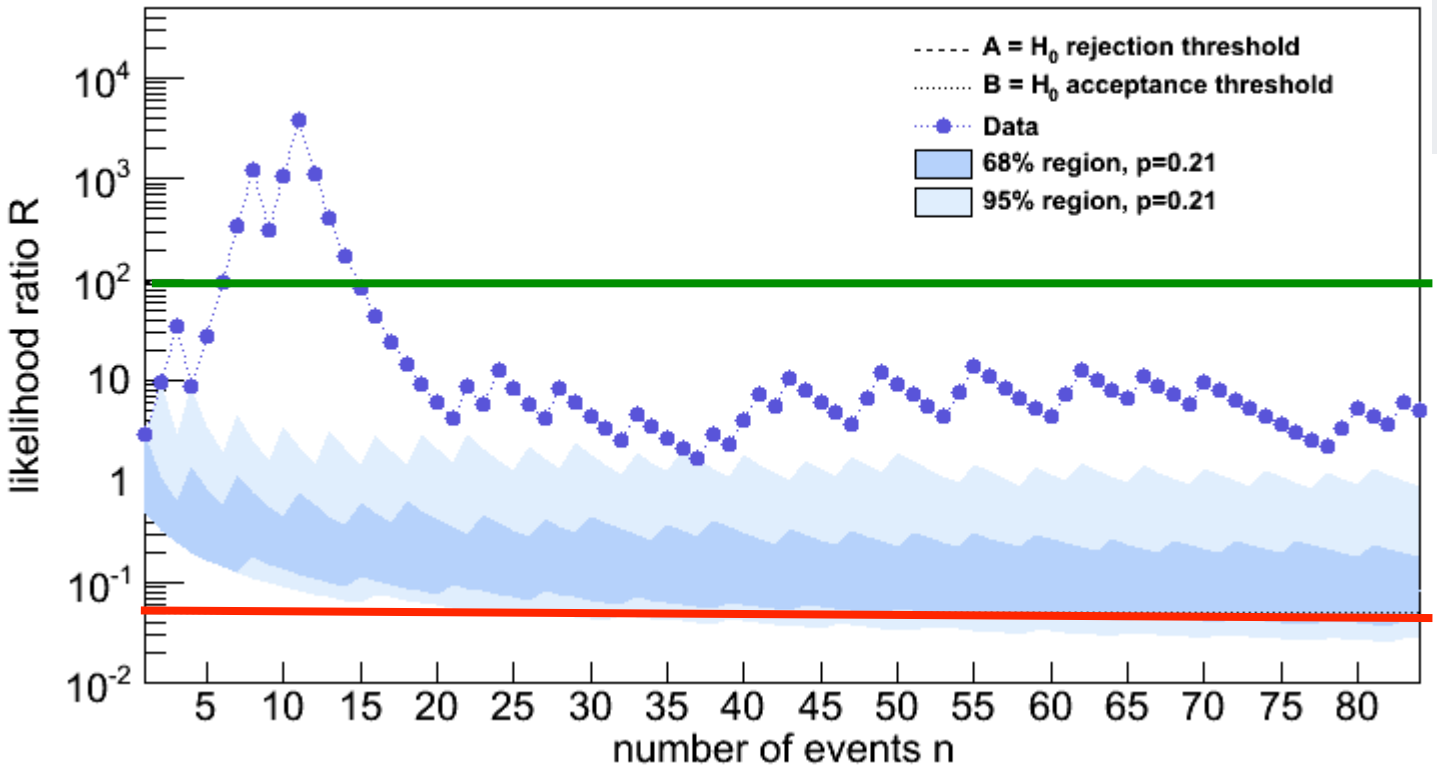
Correlations with AGN?

- Overall correlation strength has decreased with time from (62±10)% to (33±5)%, with currently (June 2011) 28 out of 84 events correlating, with isotropic expectation p_{iso} = 21%.
- p=0.006 (*note*: this number is not a measure of evidence against the null hypothesis).



Correlations with AGN?

- Sequential likelihood ratio test shows time development – ratio R is likelihood of signal hypothesis ($p > p_{iso}$) over null hypothesis ($p_{iso} = 0.21$).



type-1 error rate
$\alpha = 1\%$
type-2 error rate
$\beta = 5\%$

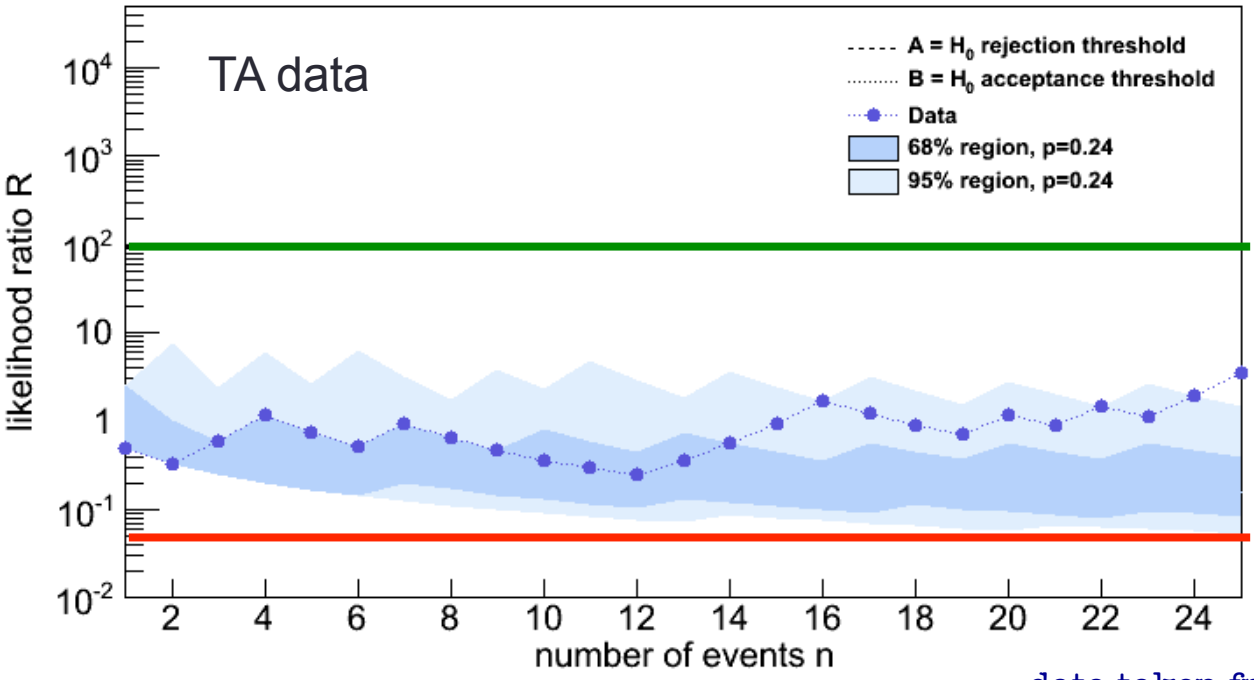
Null hypothesis rejected.

Null hypothesis accepted.

Method: ApJ 687 (2008)1035

AGN Correlations in the Northern Sky?

- No evidence for correlations in HiRes data (2 out of 13 events) – but energy scale is important! Astropart. Phys. 30 (2008) 175
- In current TA data (using the same AGN catalog and cosmic ray event selection), 11 out of 25 events correlate with AGN, for p_{iso}=0.24 (2% probability).



type-1 error rate
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type-2 error rate
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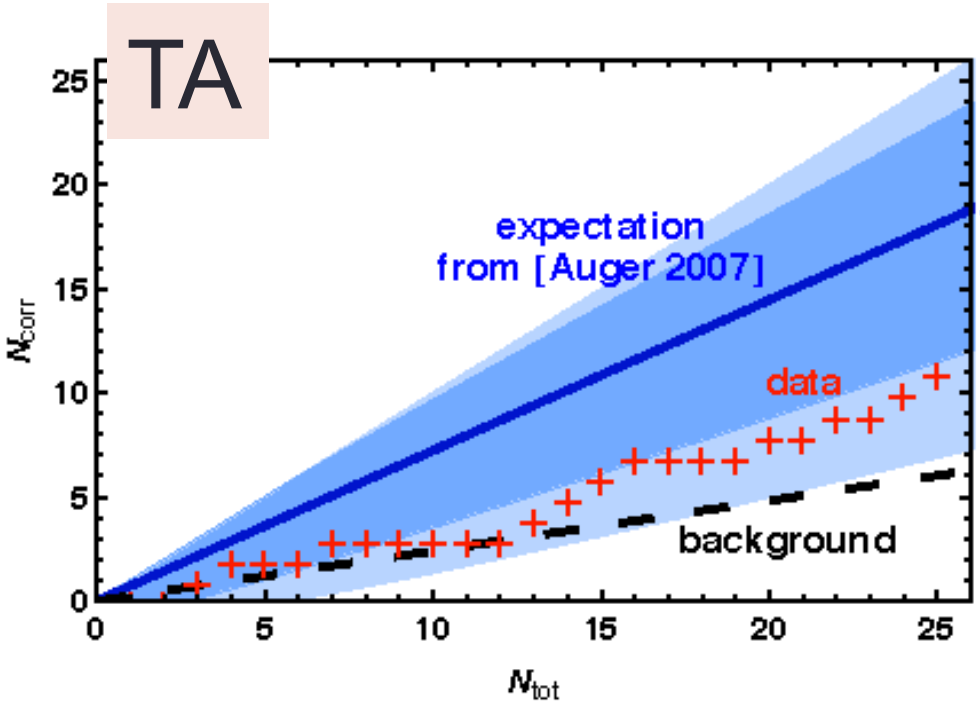
Null hypothesis rejected.

Null hypothesis accepted.

data taken from arXiv:1205.5984

AGN Correlations

- AGN correlation in Auger and TA data is not in disagreement…
- … neither experiment can, however, exclude the null hypothesis at this point. More data will tell…



original Auger result:
(62±10)% correlating fraction

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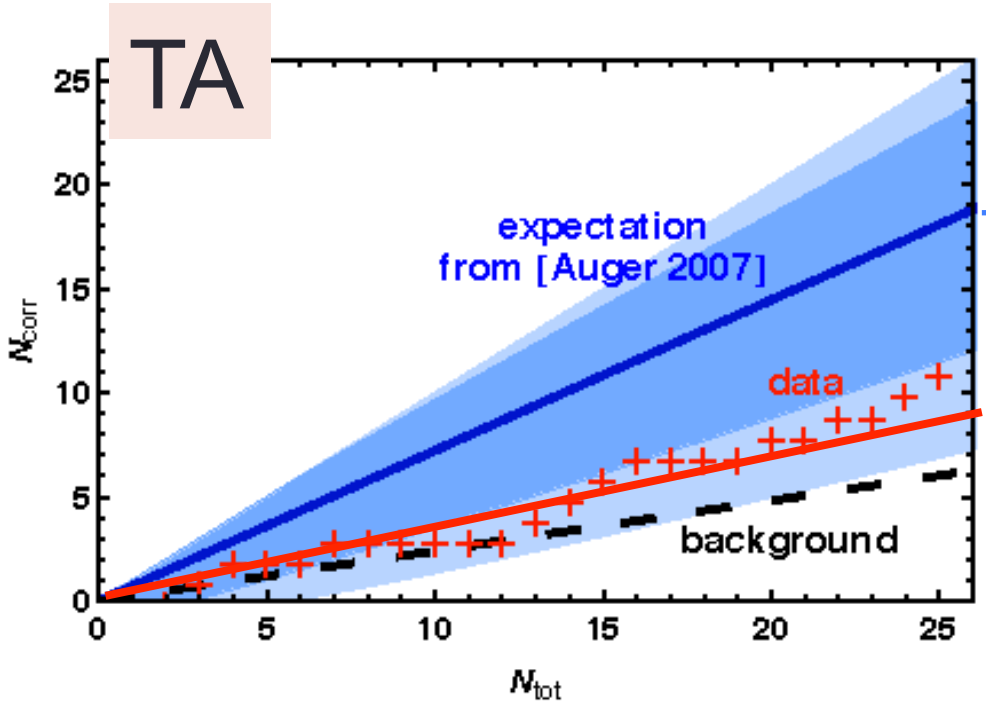
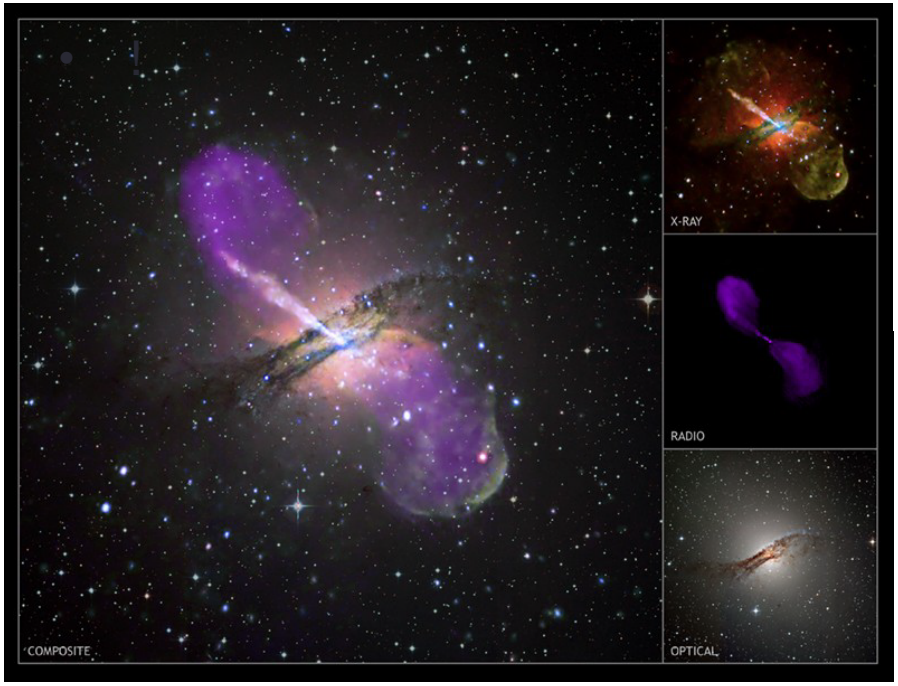


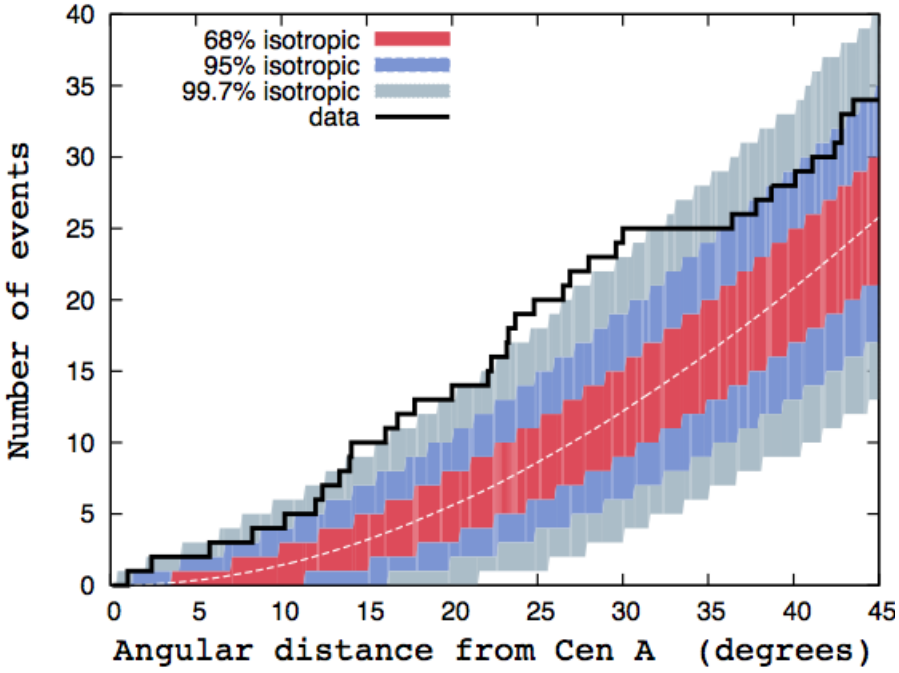
original Auger result:
(62±10)% correlating fraction

updated Auger result:
(33±5)%

CenA

- Largest overdensity of cosmic rays is currently found in the region around CenA (3.8 Mpc).
- KS test yields 4% probability.





- We need to test the CenA hypothesis, *i.e.* determine and freeze the analysis parameters, and test with new data

Other Searches for Anisotropy

- No significant clustering (multiplets) observed in Auger and TA data (long, long ago claimed by AGASA).

- AGN correlation could be indicative of an underlying anisotropy following the large-scale structure.

  – *Auger*: other, more complete object catalogs checked: 2MRS, Swift-BAT, and HIPASS; no significant signal.

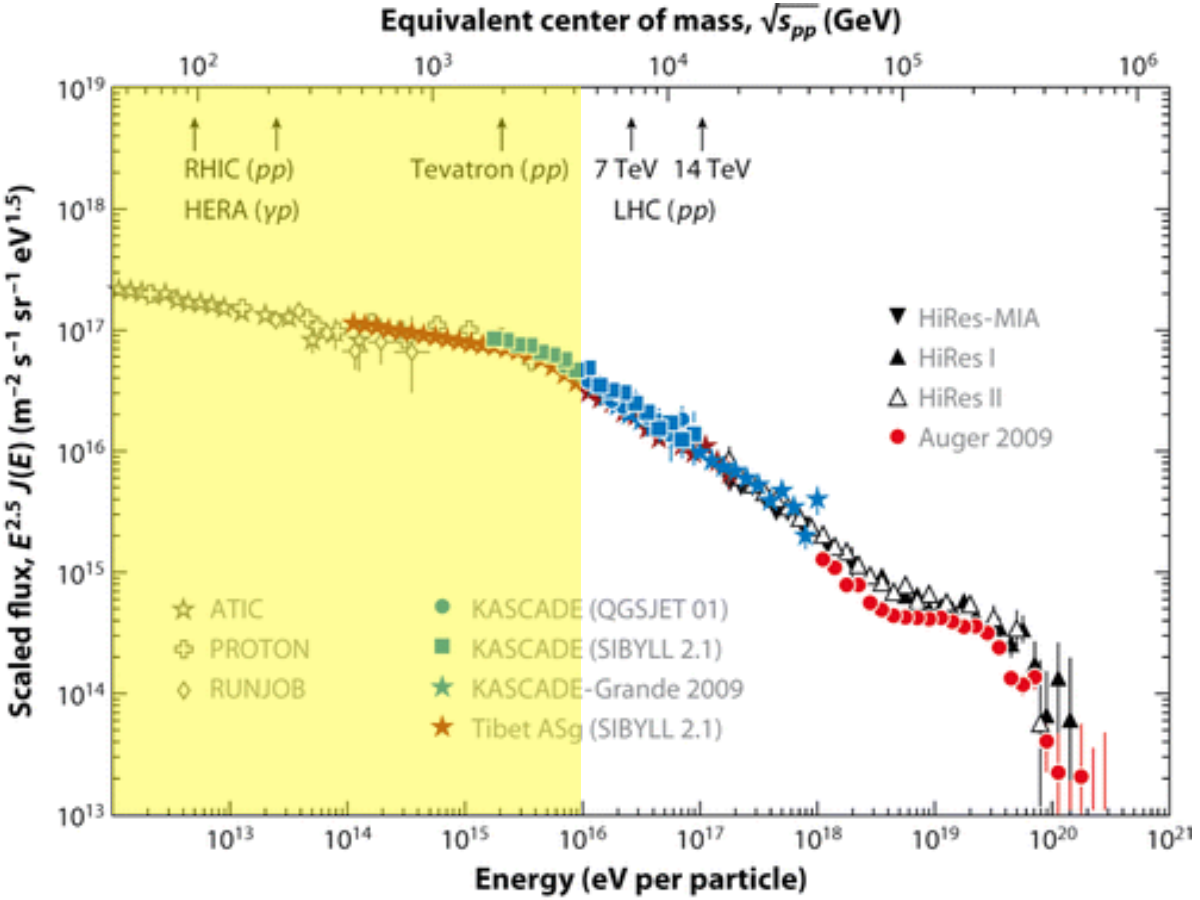
  – *TA*: data is consistent with a uniform distribution and (at 95% CL) with the large-scale structure (2MASS Galaxy Redshift Catalog XSCz) – more events are needed. If isotropy persists, the case for proton composition is weakened…

Poster P5-07b

- We need more data at the highest energies (as usual), and clean hypothesis tests with controlled trials (for example CenA).

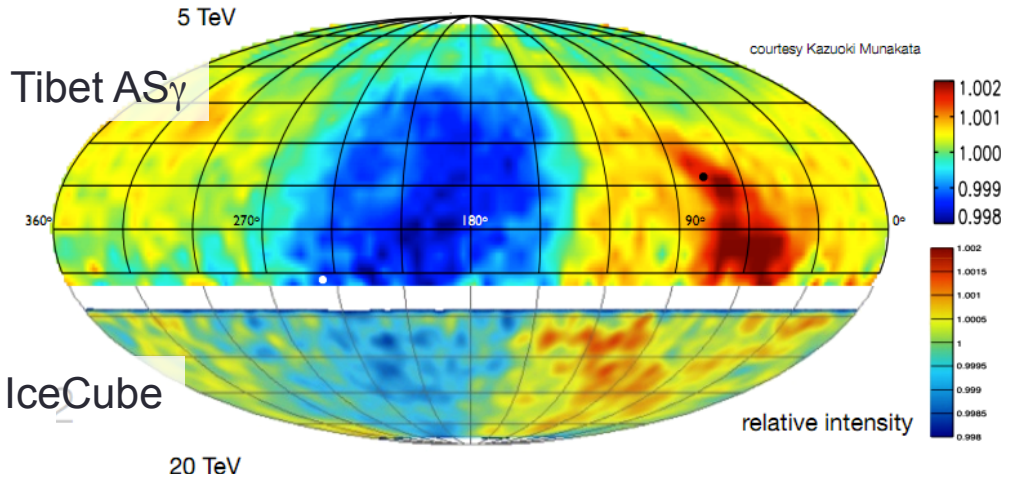
Cosmic Ray Anisotropy at TeV

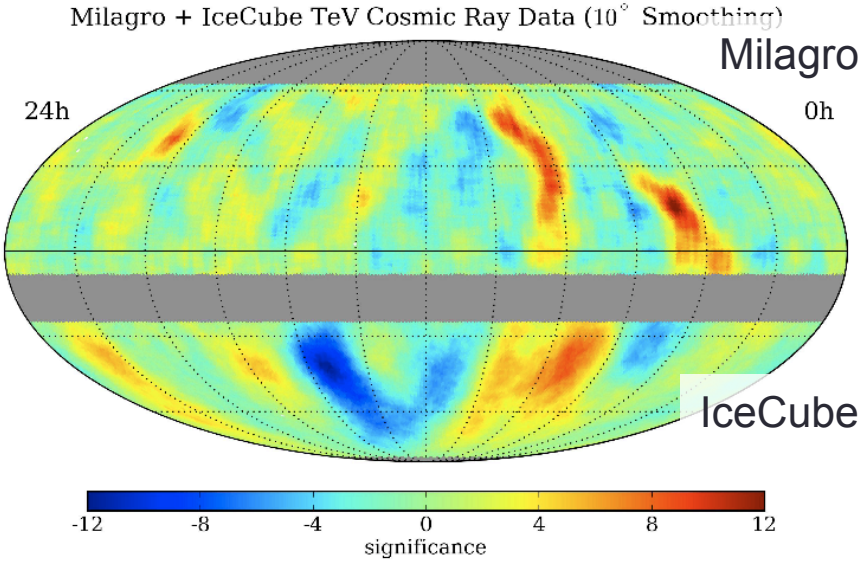
- At lower energies (TeV and PeV), Galactic cosmic ray flux is *not* isotropic…



Cosmic Ray Anisotropy at TeV

- Large-scale anisotropy (>60°) at the level of 10^{-3} observed in the northern and southern sky.
- Small-scale anisotropy (10°- 20°) at the level of 10^{-4}.





Tibet ASγ Collab., Science 314 (2006) 439
IceCube Collab., ApJ 718 (2010) L194

Milagro Collab., PRL 101 (2008) 221101
IceCube Collab., ApJ 740 (2011) 16

Nearby Supernova Remnants?

- Is the large-scale anisotropy indicative of nearby cosmic ray sources, *e.g.* shocks of supernova remnants (SNRs)?
  - Transport of cosmic rays at these energies in the Galactic magnetic field is diffusive.
  - Flux from a single nearby source would be observed on Earth as a dipole with its maximum towards the source.
  - Observed (large-scale) structure would be the sum of the contributions from a few nearby recent SNRs and the large scale distribution of SNRs in our Galaxy.

Erlykin & Wolfendale, Astropart. Phys. 25 (2006) 183
Blasi & Amato, JCAP 1201 (2012) 11

- Smaller structure could be caused by cosmic ray propagation in turbulent magnetic fields within a few tens of parsecs from Earth.

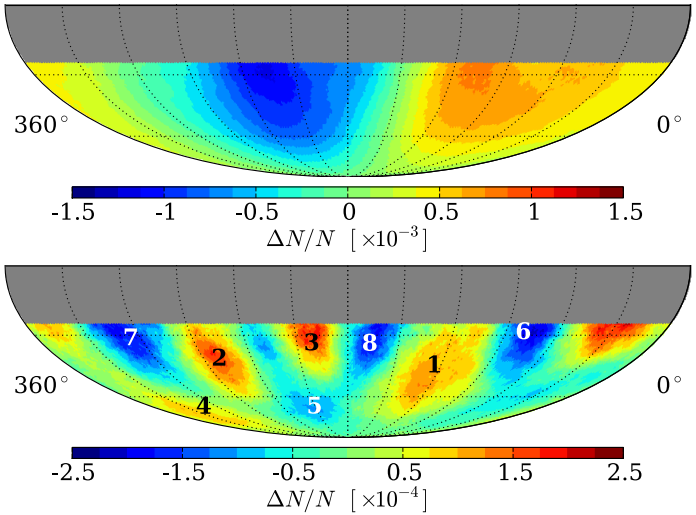
Giacinti & Sigl, arXiv:1111.2536

Poster P5-13

- Both models predict a dependence of the anisotropy on energy…

From TeV to PeV

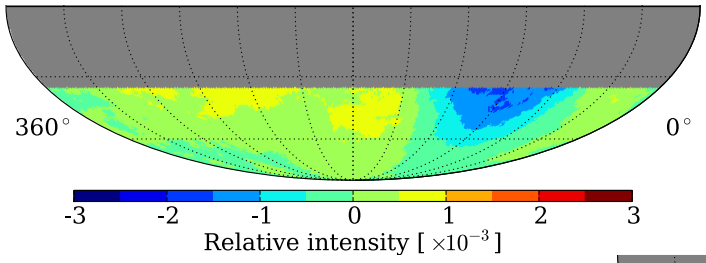
20 TeV



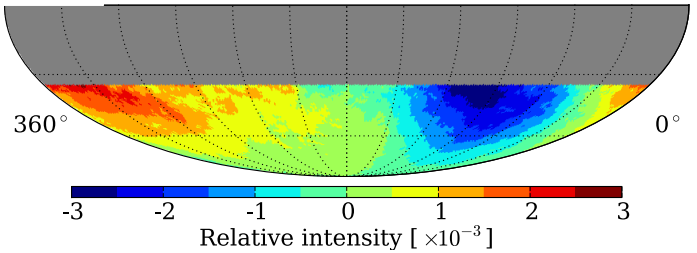
- Anisotropy changes in phase and amplitude with energy.

energy

400 TeV



2 PeV



IceCube
ApJ 718 (2010) L194
ApJ 740 (2012) 16

IceCube/IceTop
ApJ 746 (2012) 33

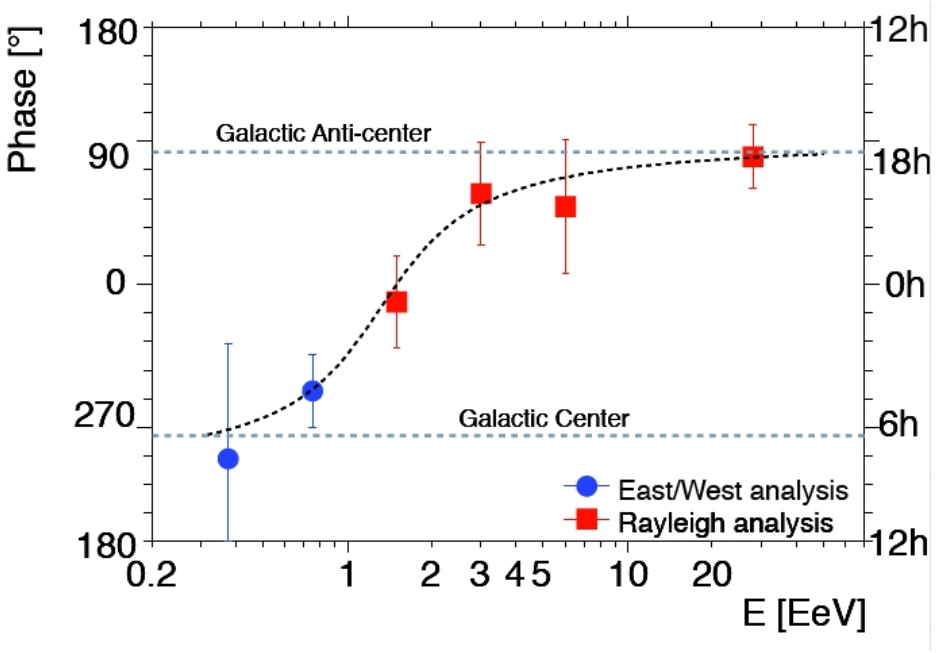
Poster P5-06

Large-Scale Anisotropy at Auger Energies?

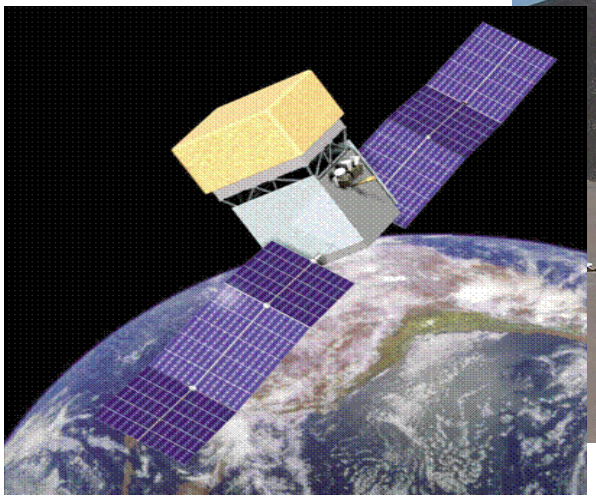
- First-harmonic analysis of possible modulations in the right ascension distribution of cosmic rays at $E > 0.25$ EeV.
- No significant amplitude, but phase shows smooth transition from right ascension 270° below 1 EeV to 100° above 5 EeV.
- Indicative of a tendency of maxima to appear around the same right ascension (similar effect seen in 1960s at northern latitudes).

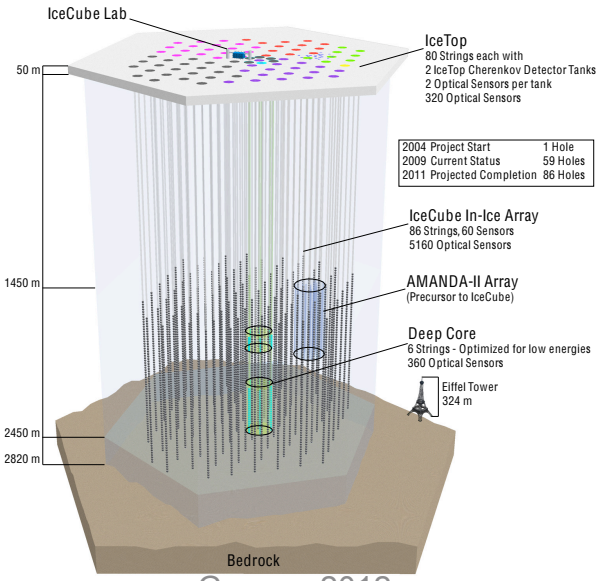
- 10^{-3} level effect, but *a posteriori*, needs confirmation with more data.
- Consistency of phase measurement in adjacent energy bins is first indication of underlying anisotropy.

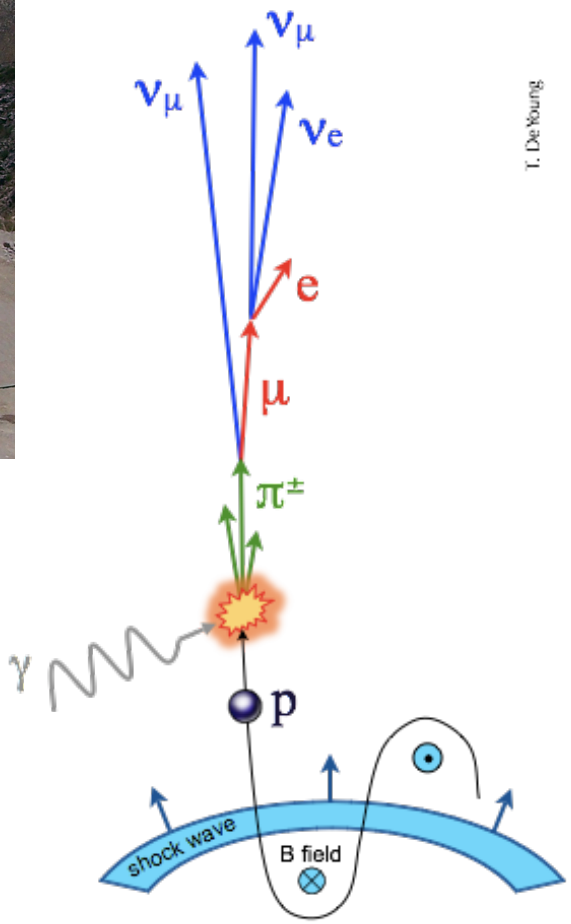
Astropart. Phys. 34 (2011) 627



Indirect Detection



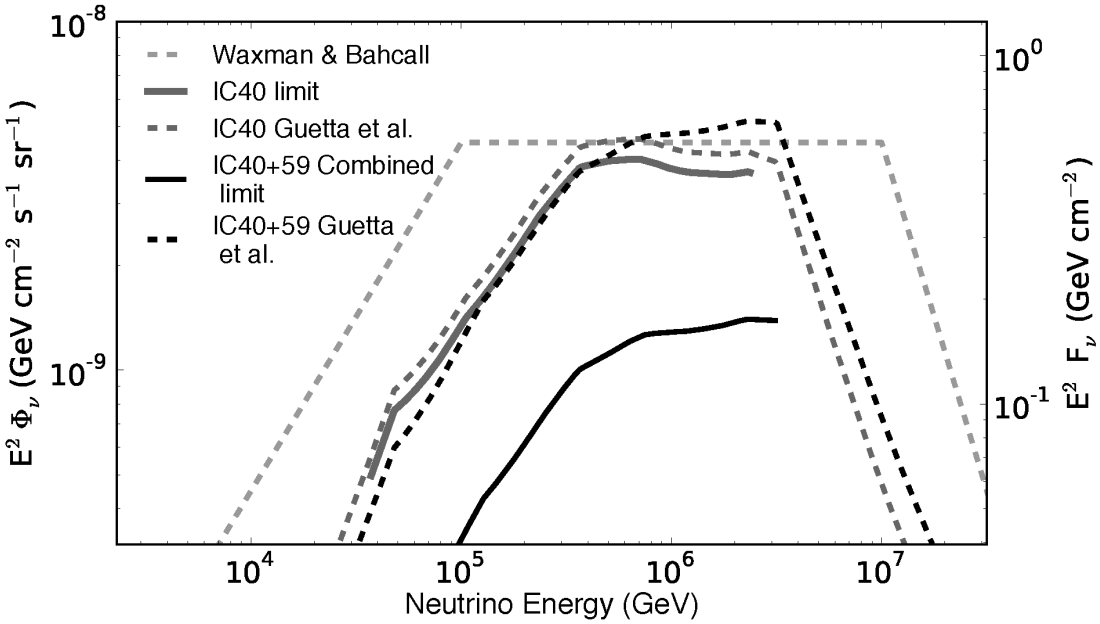




Gamma Ray Bursts

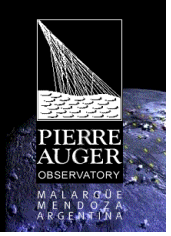
- IceCube has reached the sensitivity to test models of ultrahigh-energy cosmic ray acceleration in GRBs.
- Cosmic ray flux should be accompanied by prompt TeV neutrinos produced in proton-photon interactions in the fireball.

Nature 484 (2012) 351



- Non-observation of associated neutrino flux in two years of IceCube data starts to constrain models of neutrino and cosmic ray production.

Talk by I. Taboada (this conference)



Summary

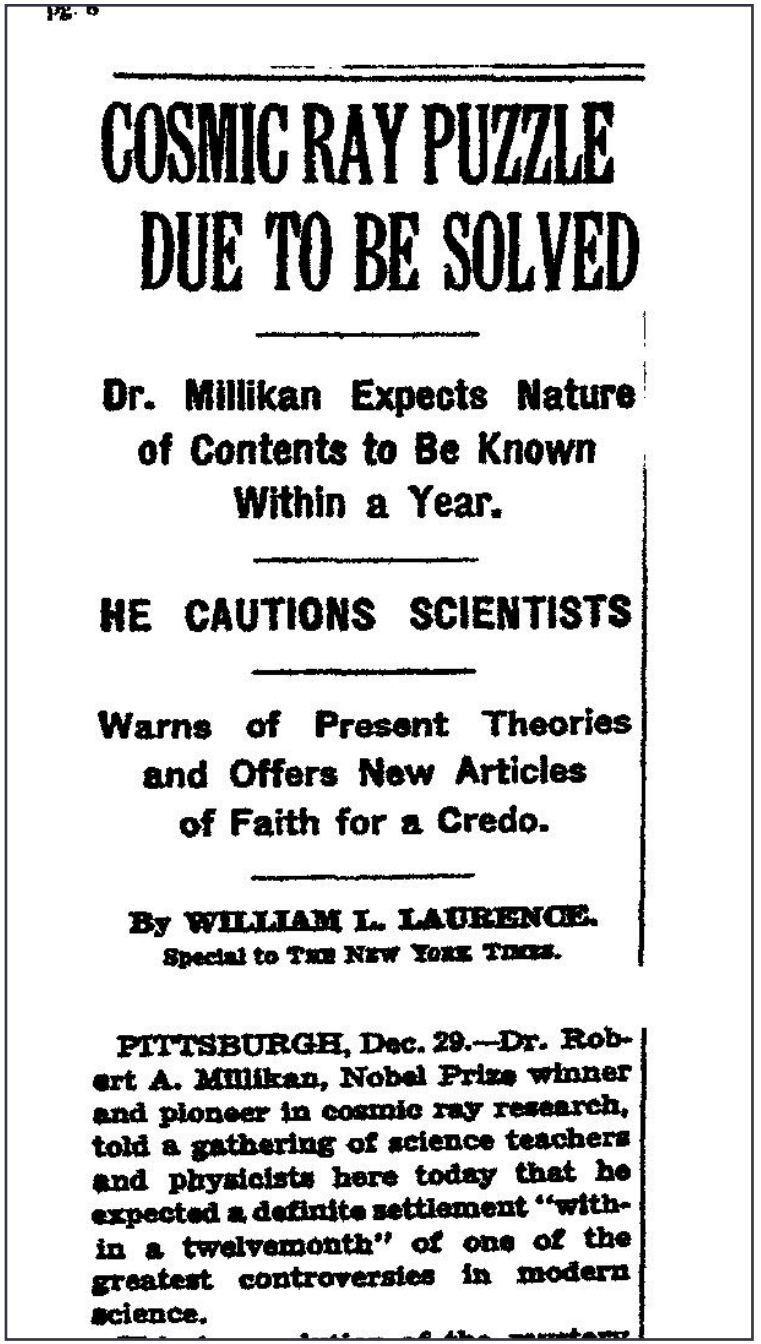
- The hybrid concept for large ultrahigh-energy cosmic ray detectors has proved successful.
- The existence of a flux suppression at 5×10^{19} eV (consistent with the GZK suppression) is firmly established.
- Exotic physics (top-down models) are not favored (photon limits).
- Sources of cosmic rays have not been positively identified. More data will help to clarify anisotropy results and extent of correlations with AGN.
- Composition-sensitive parameters in Auger data are currently better described by simulations of heavier primaries than of pure protons.
  - Heavy composition? Problems with models?
  - Simulations do not correctly reproduce the number of muons in air showers.

The Future

- *New York Times, Dec. 30, 1934*

Robert A. Millikan

…told a gathering of science teachers and physicists here today that he expected a definite settlement "within a twelvemonth" of one of the greatest controversies in modern science.



pg. 6

COSMIC RAY PUZZLE DUE TO BE SOLVED

Dr. Millikan Expects Nature of Contents to Be Known Within a Year.

HE CAUTIONS SCIENTISTS

Warns of Present Theories and Offers New Articles of Faith for a Credo.

By WILLIAM L. LAURENCE.
Special to THE NEW YORK TIMES.

PITTSBURGH, Dec. 29.—Dr. Robert A. Millikan, Nobel Prize winner and pioneer in cosmic ray research, told a gathering of science teachers and physicists here today that he expected a definite settlement "within a twelvemonth" of one of the greatest controversies in modern science.