Recent Results of the Observatory Pierre Auger

João R. T. de Mello Neto
Instituto de Física
Universidade Federal do Rio de Janeiro

S. Tomé e Príncipe, September 2009

Outline

- Cosmic ray detection and the Pierre Auger Observatory;
- The P. Auger recent results (concentrate on physics)
  - Measurement of the spectrum
  - Correlation of CR with celestial objects
  - Mass Composition
  - Neutrino limits
  - Photon limits

  (Lorentz Invariance violation)
- The future

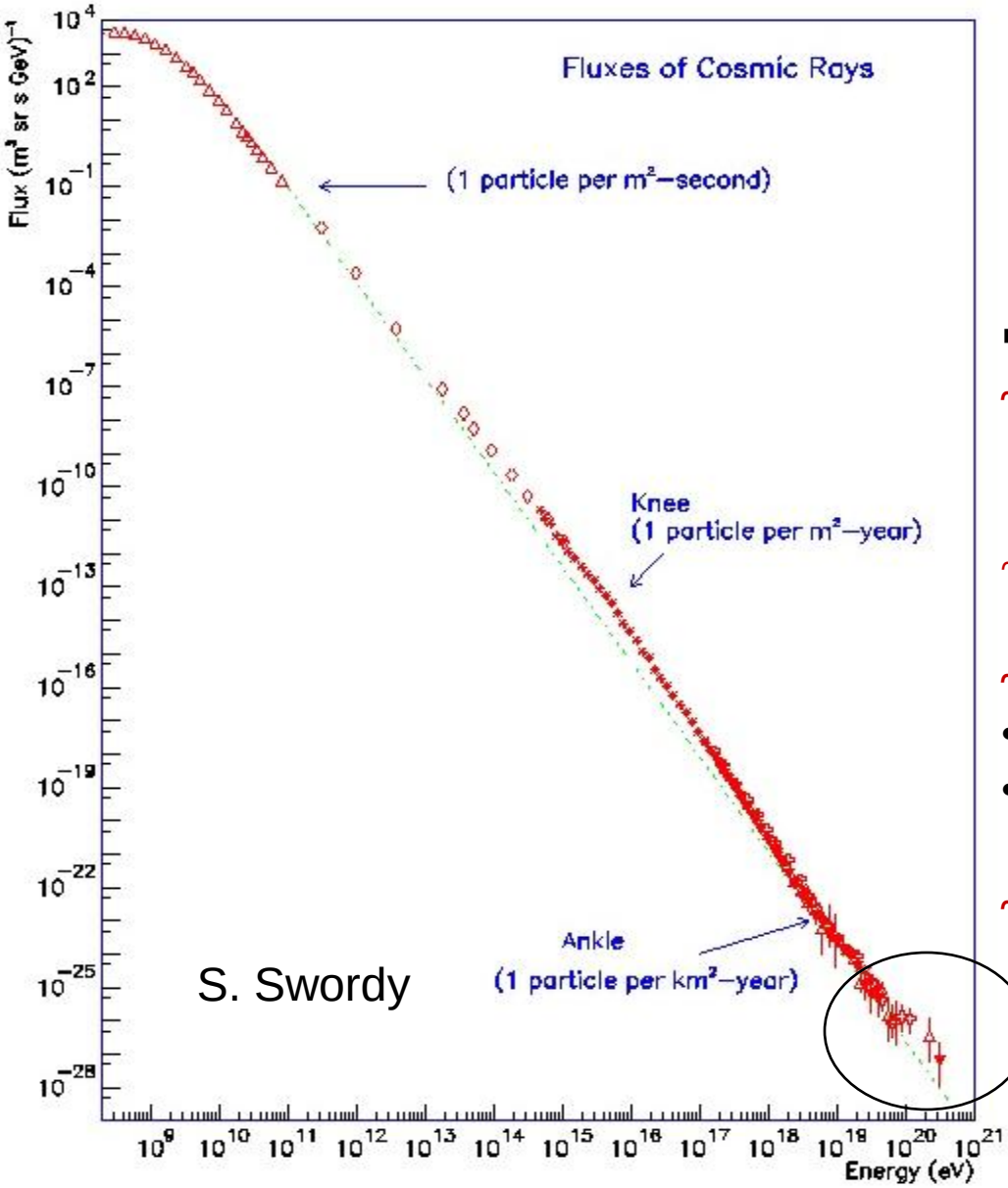
Astroparticle needs ultimessenger approach with complementary experiments.

Auger: charged particles, photons and neutrinos!

Open questions

- How cosmic rays are **accelerated** at $E > 10^{19}$ eV ?
- What are the **sources**?
- How can they **propagate** along astronomical distances at such high energies?
- What can we learn about **cosmic objects**, **large-scale structure** and magnetic fields?
- **Particle astronomy**?
- What can we learn about **particle interactions** at these otherwise inaccessible energies, which reach 450 TeV in the center-of-mass system?
- What is the **mass composition** of cosmic rays?

Cosmic rays flux vs. Energy



(nearly) uniform power-law spectrum spanning **10** orders of magnitude in E and **32** in flux!

- structures :

~ 3 – 5 10^{15} eV: knee

limiting energy galactic CR accelerators
onset of diffusion losses from the galaxy

~ 10^{17} eV : second knee

fading of heavy galactic CR component

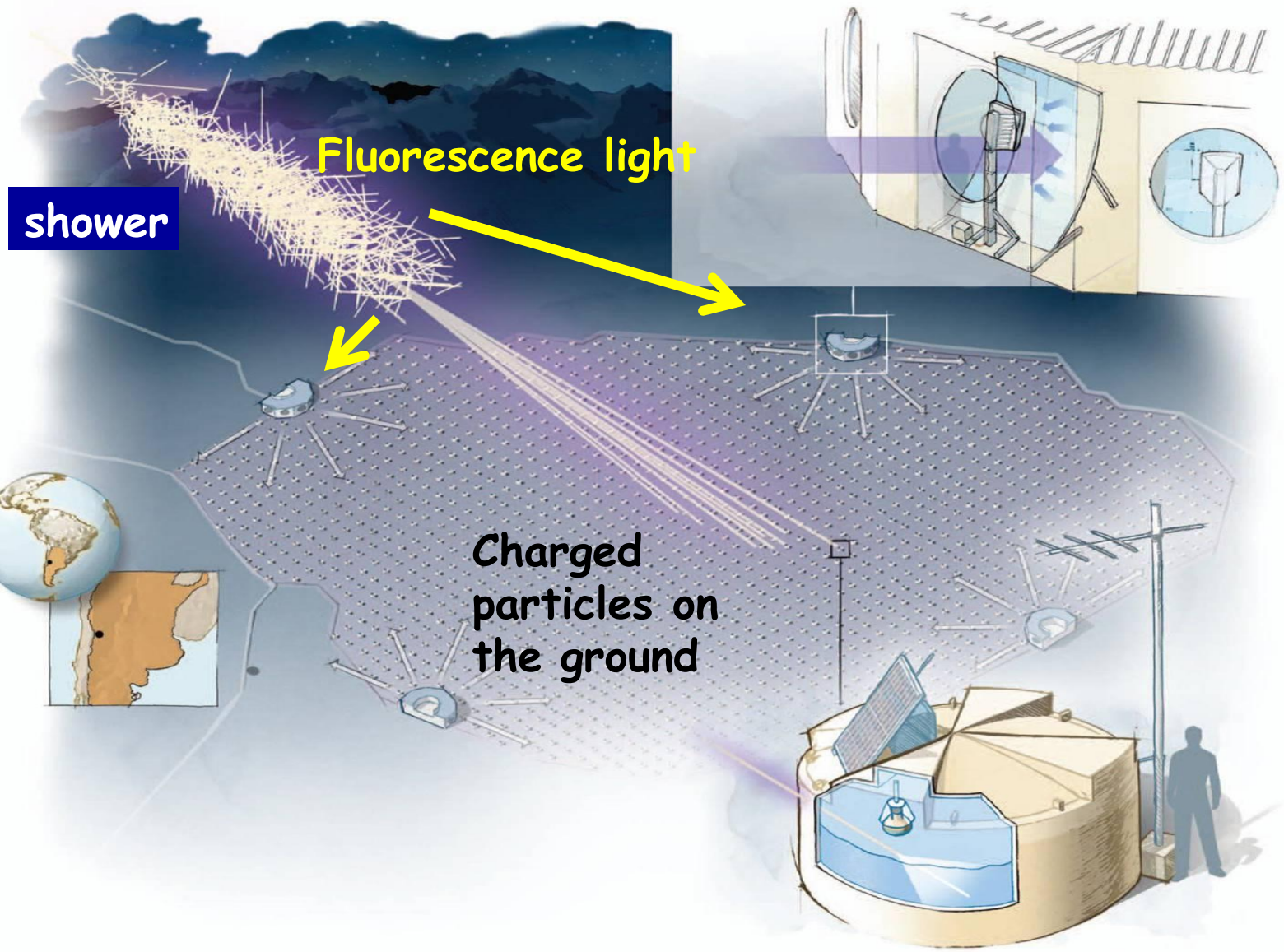
~ 3 10^{18} eV: ankle

- onset of the extragalactic CR component
- energy losses of extragalactic protons by pair production

~ GZK cuttof

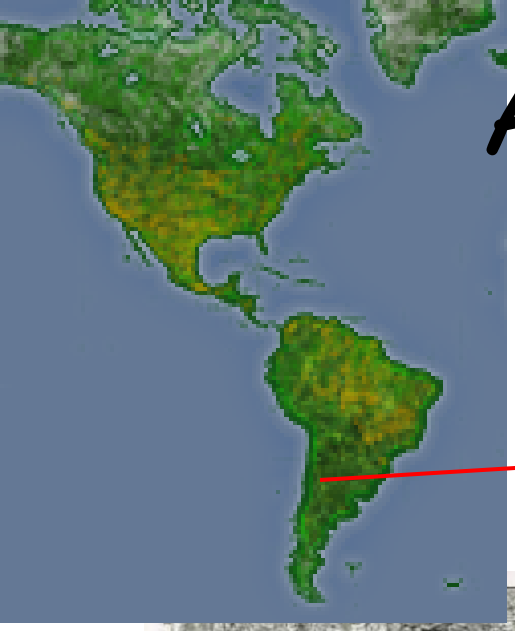
UHECR
- one particle per century per km^2
- many interesting questions

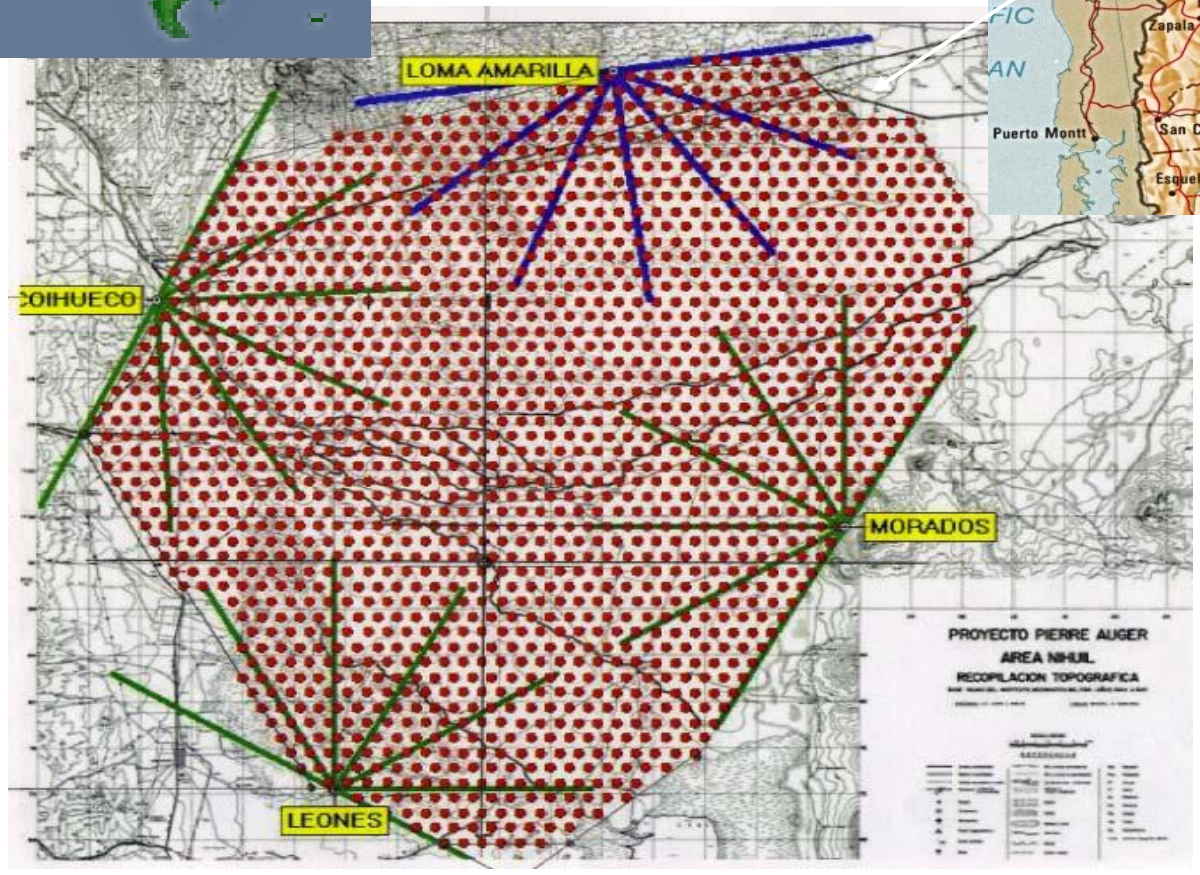
Pierre Auger Observatory layout



Auger South

Completed by
August 2008





1600 water detector tanks in 3,000 km^2 surface detector array, 1.5 km triangular grid

4 Fluorescence Detector Sites
24 telescopes in total

The Auger Collaboration

A True International Partnership

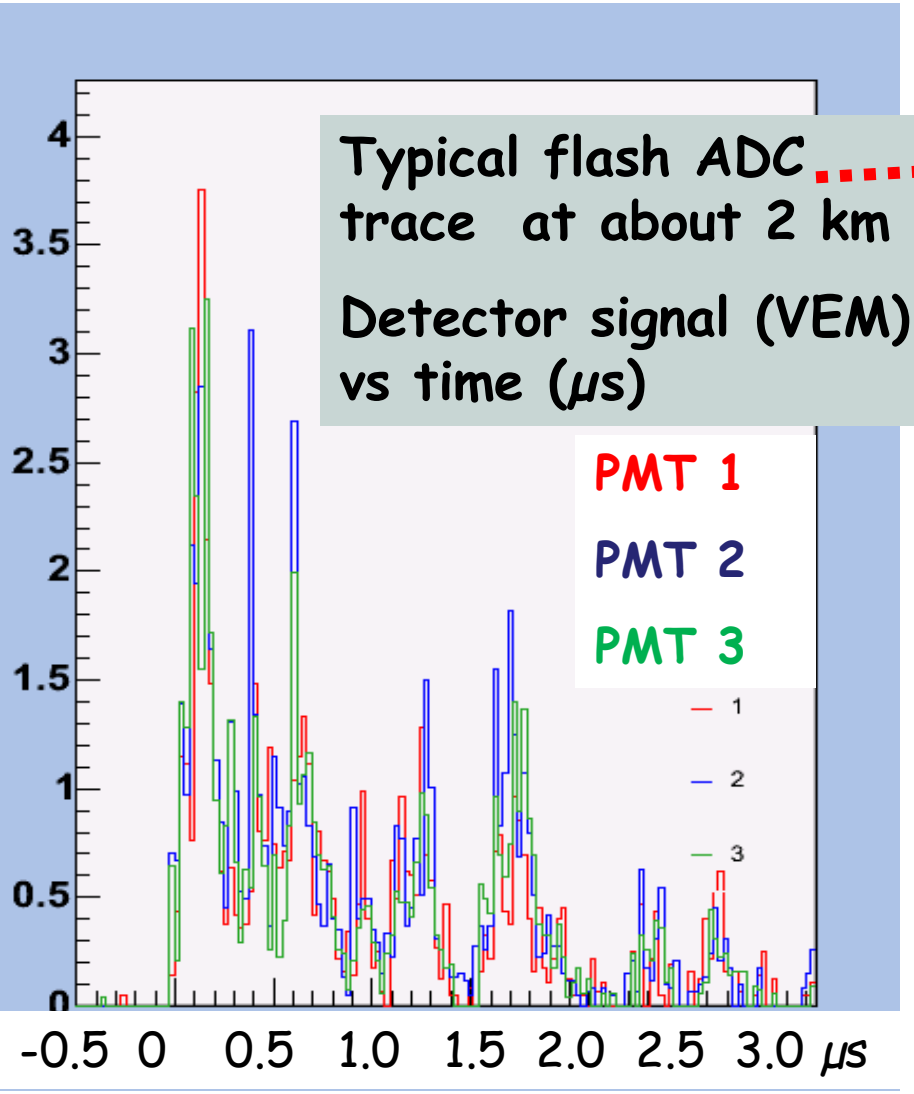
No country, region or institution dominates

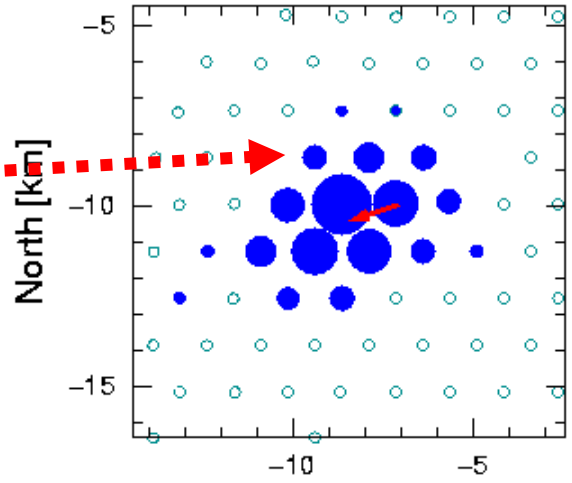
Argentina
Australia
Bolivia*
Brazil
Czech Republic
France
Germany
Italy
Mexico
Netherlands
Poland
Portugal
Slovenia
Spain
United Kingdom
USA
Vietnam*

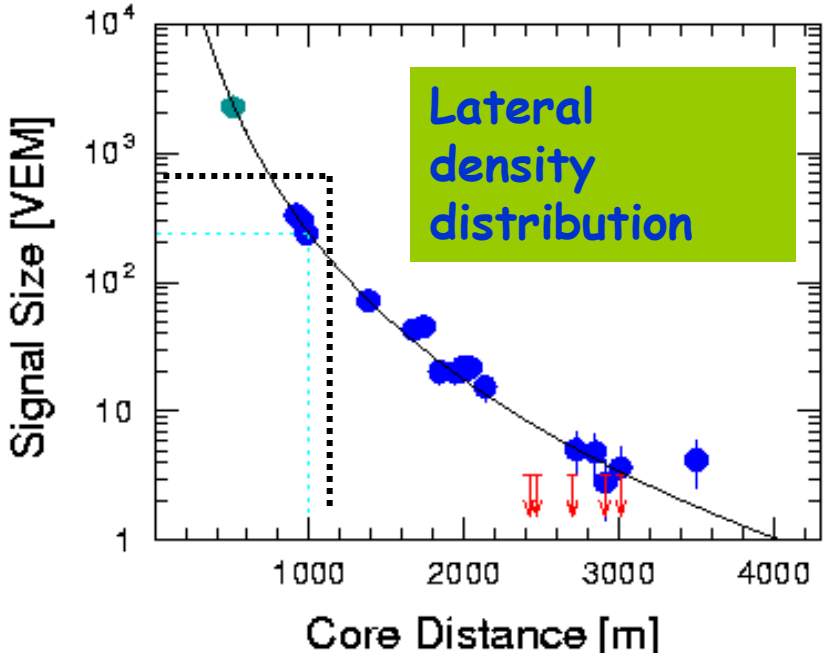
*** associate**

A surface detector event

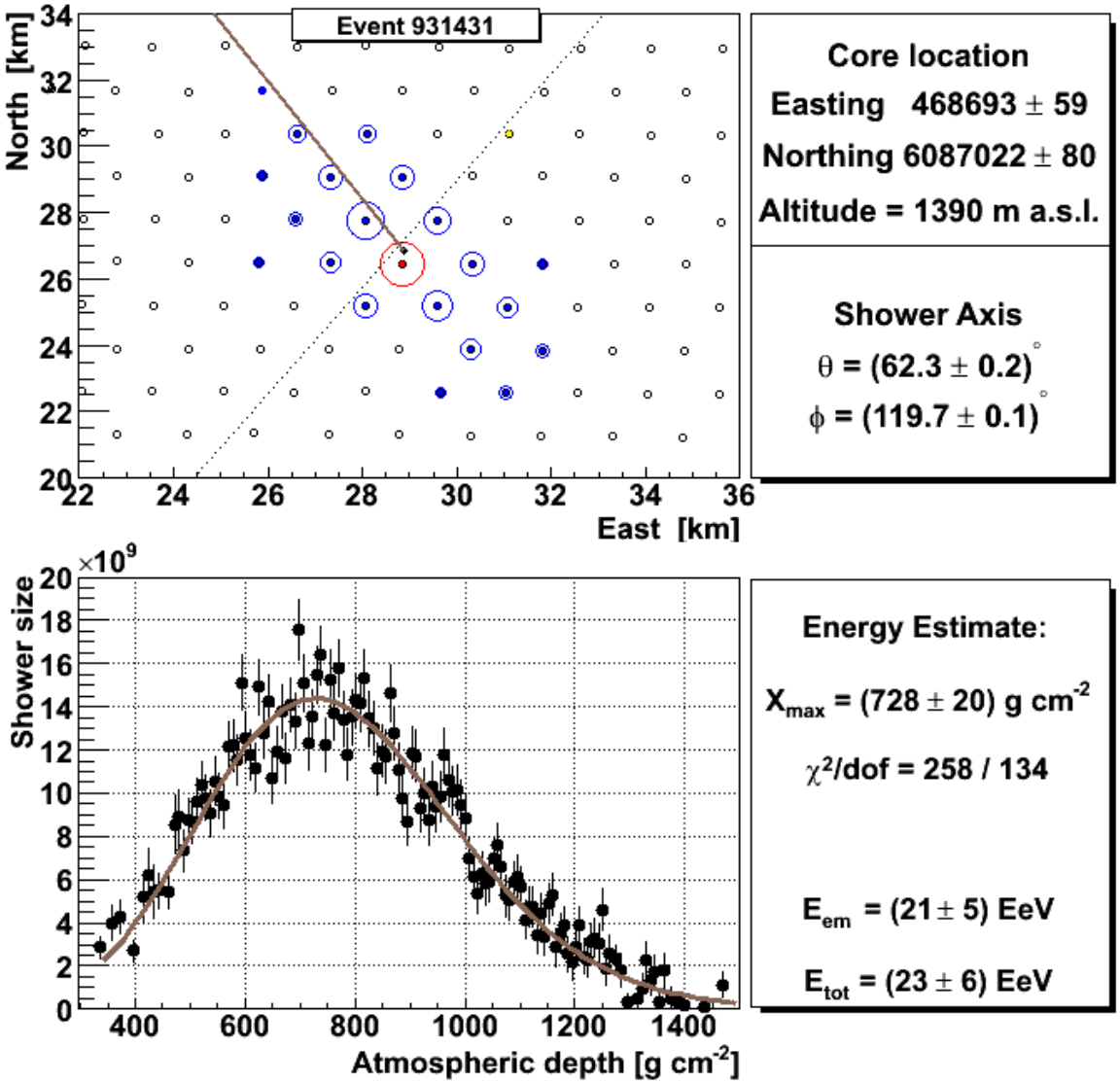
18 detectors triggered, θ~ 48°, ~ 70 EeV





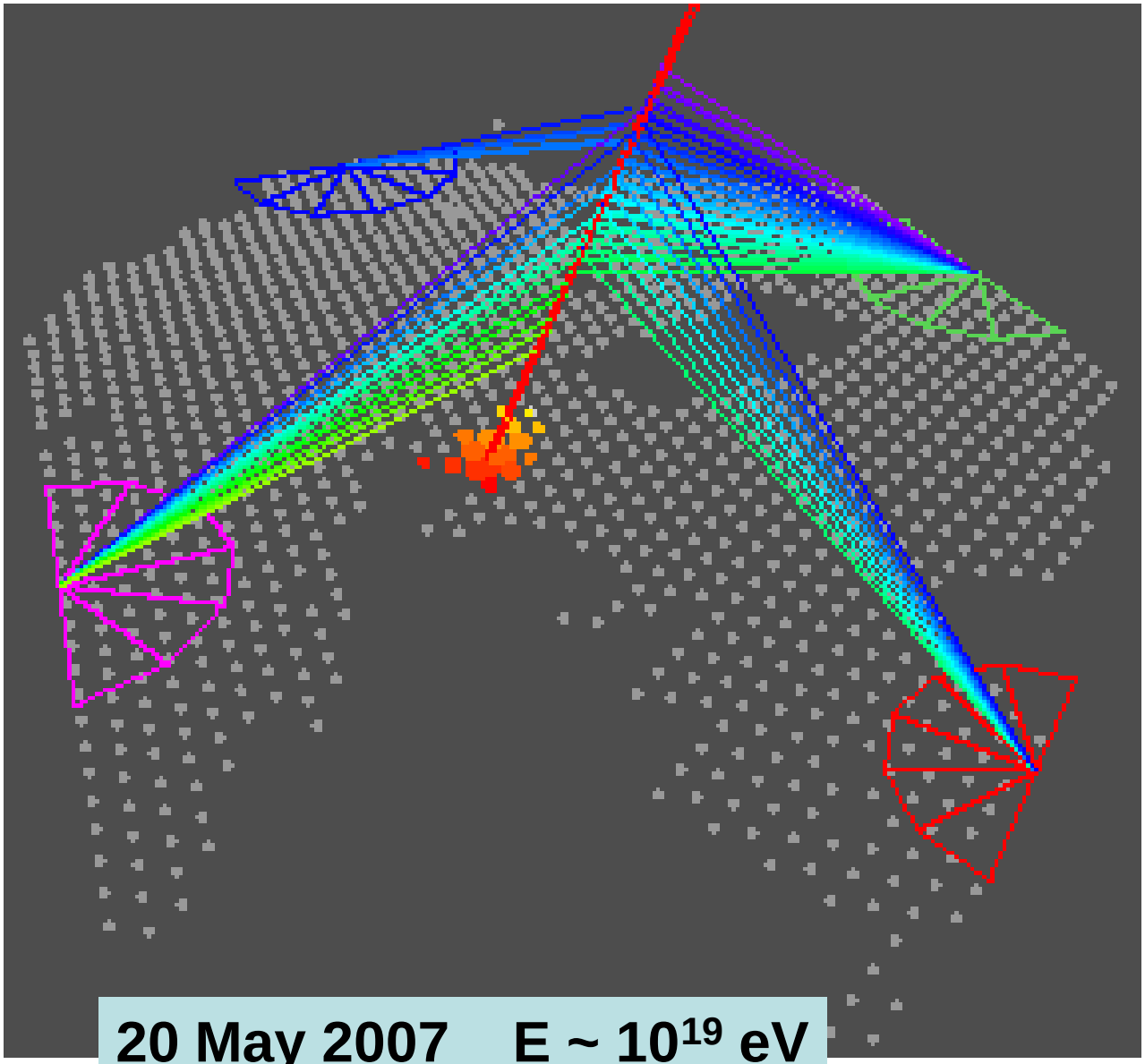


An hybrid event



longitudinal profile

First 4-fold hybrid on 20 May 2007



20 May 2007 E ~ 10^{19} eV

First **hybrid quadriple** event!

Signal in **all four FD** detectors and **15 SD** stations!

GKZ suppression

- Cosmic rays $E = 10^{20}$ eV interact with 2.7 K photons
- In the proton frame $E_\gamma = 300 MeV$

$$p + \gamma_{3k} \rightarrow \Delta^+ \rightarrow p + \pi^0$$
$$\rightarrow n + \pi^+$$

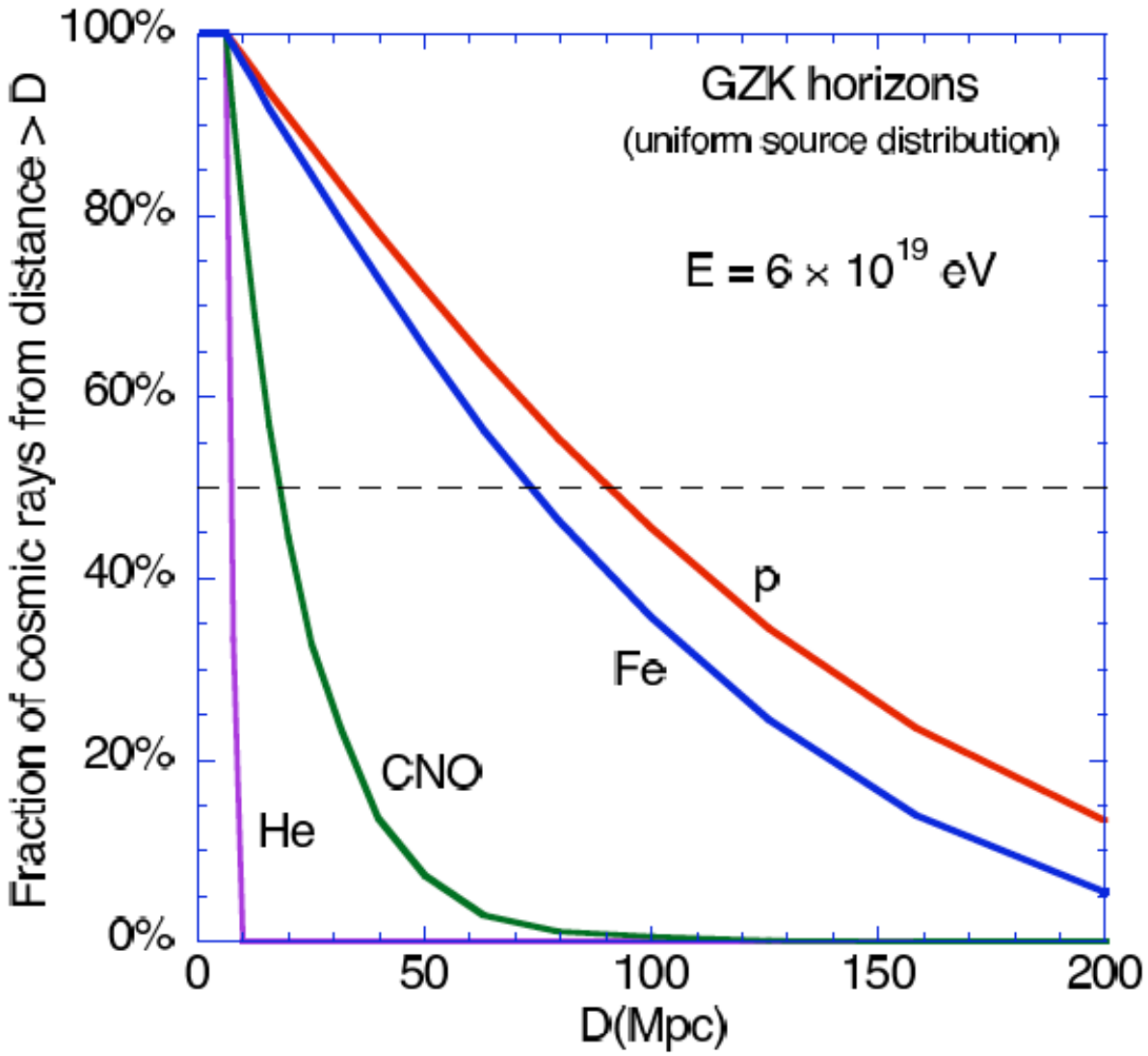
Photon-pion production

$$p + \gamma_{3k} \rightarrow p + e^+ + e^-$$

- Proton with less energy, eventually below the cutoff energy
  E_{GZK}= 5x 10^{19} eV

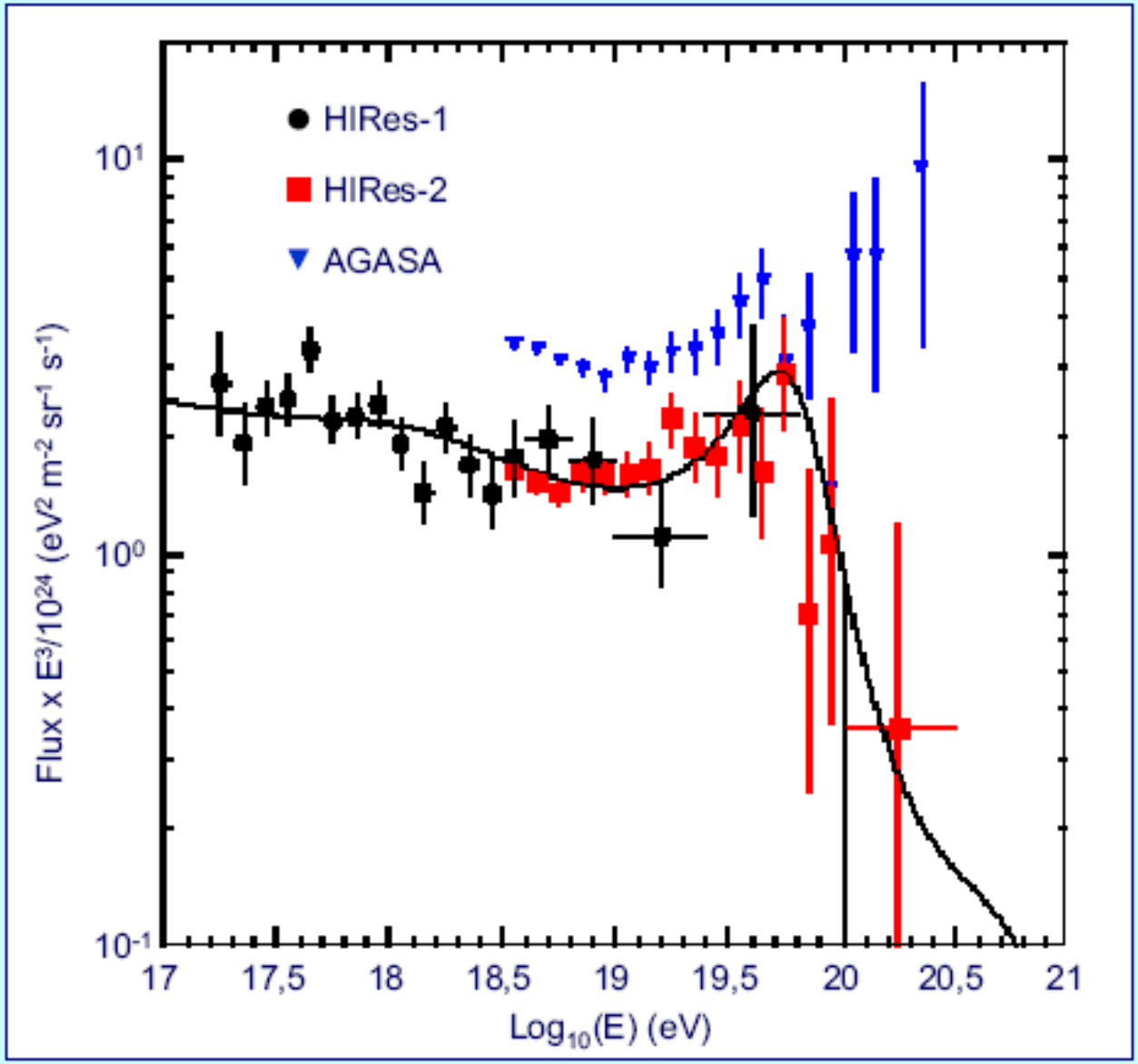
Universe is opaque for E > E_{GZK} !

GZK horizons



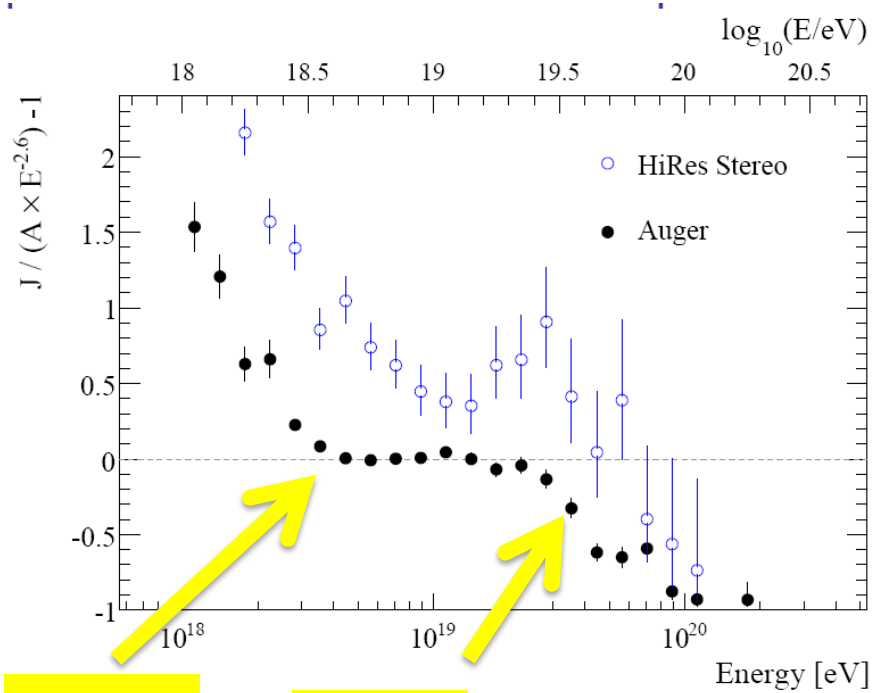
Allard et al,2008

The UHECR spectrum before Auger



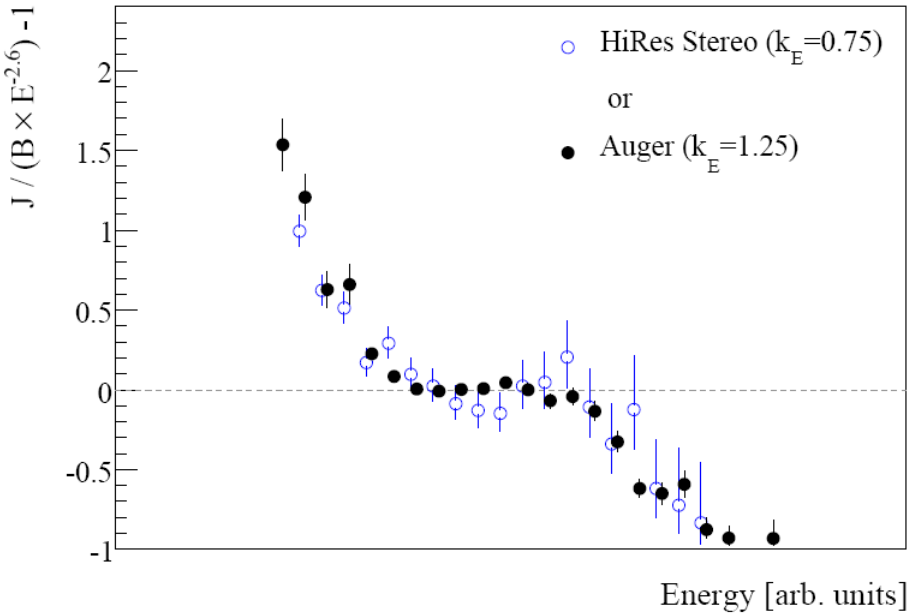
Many exotic models invented to take into account the AGASA data

Auger and Hi-Res energy spectra



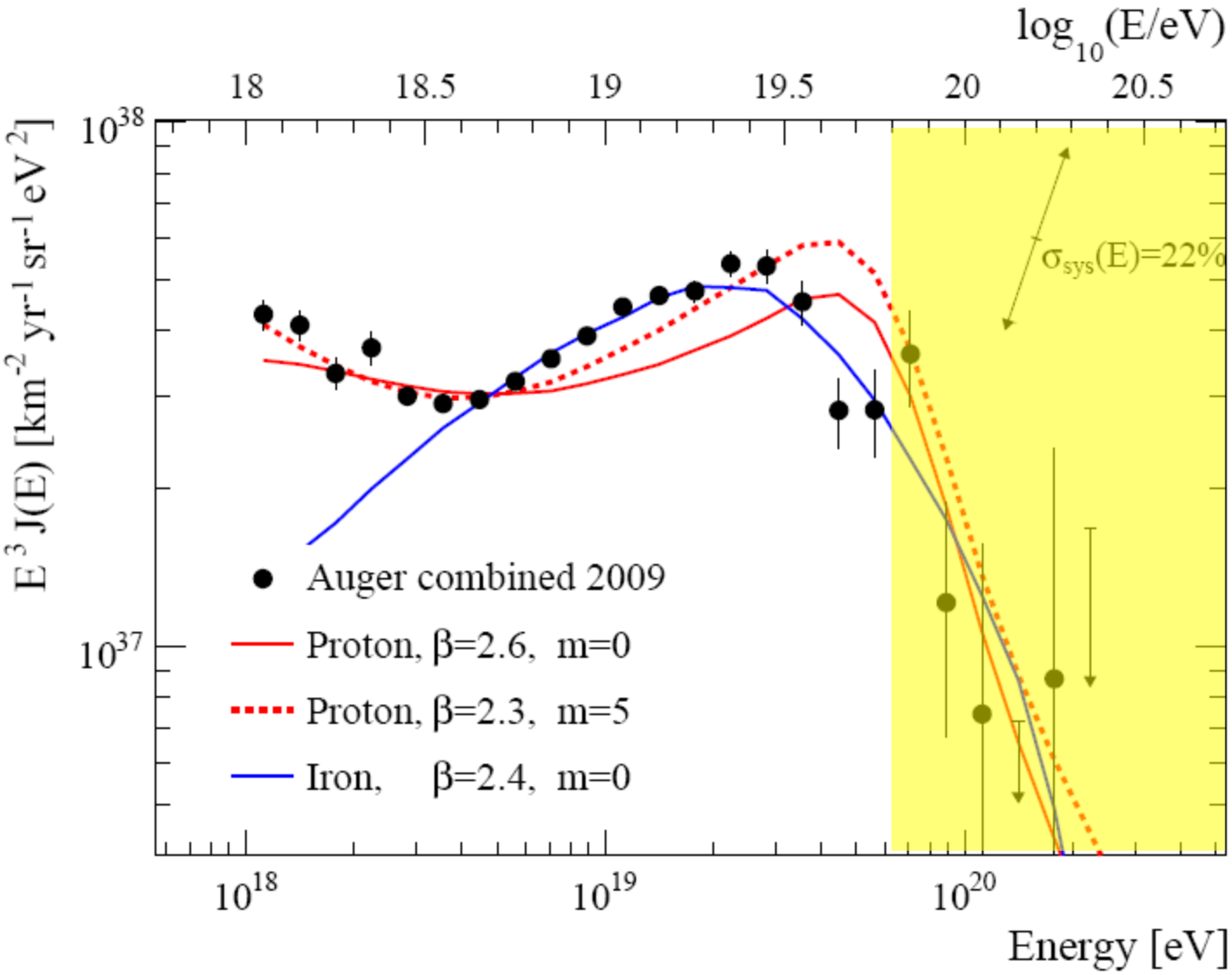
Ankle

GZK



Differences compatible within 25% of energy scale

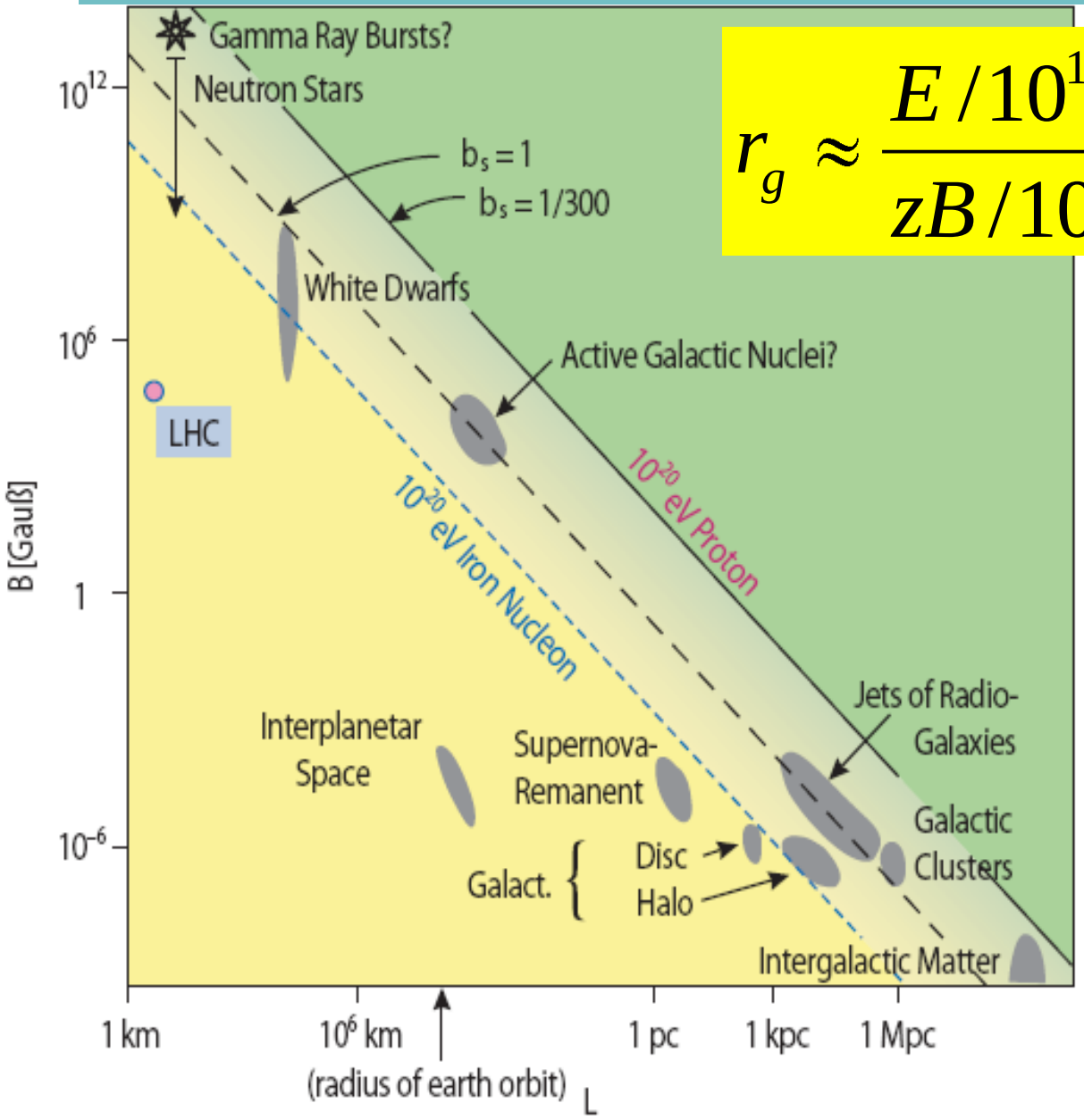
The combined Auger energy spectrum



Simple models:
$\Phi_{source} \sim E^{-\beta}$
$\sim (1+z)^m$
fit the data surprisingly well.

Constraining models need composition measurement.

Hillas plot



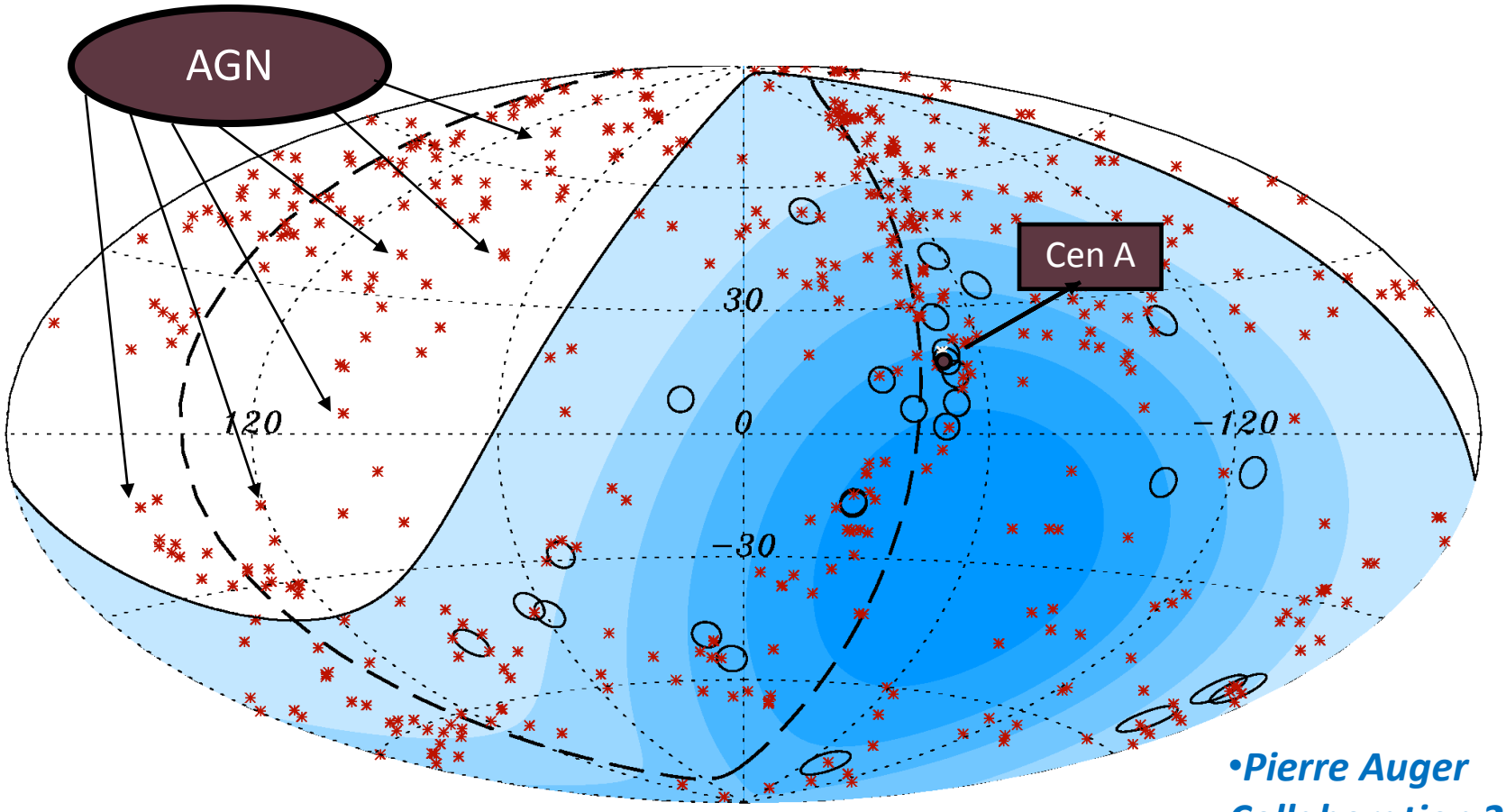
$$r_g \approx \frac{E/10^{18}eV}{zB/10^{-9}G} Mpc$$

Minimum requirement for an acceleration site: containment of the accelerated cosmic ray

b_s accounts for the bulk Lorenz factor of the medium where the acceleration proceeds

Energy losses in sources neglected

Auger Highest-energy sky map



At energies above 60 EeV the arrival directions of cosmic rays become anisotropic. a correlation between the arrival directions and Active Galactic Nuclei (AGN) listed in the Veron-Cetty and Veron catalogue has been found

- ***Pierre Auger Collaboration 2007, Science, 318, 939***
- ***Pierre Auger Collaboration 2008, APh, 29, 188***

Is The Map Anisotropic?

- The search: using data between 01Jan 2004 and 26 May 2006
  - Correlation of $E>E_{min}$ events with VC catalog AGN of $z<z_{max}$ within γ degrees.
    Optimize (E_{min}, z_{max}, γ) to maximize deviation from isotropy

- The prescription:
  - FIX test parameters:
    E_{min} = 56EeV, z_{max}=0.018, γ=3.1degrees
  - accumulate *new* data. Terminate test when probability of isotropy to have yielded *new* data < 1%
  - Period I (9/14)

Is the map anisotropic?

- The confirmation:
  - Data collected between 27 May 2006 and 31 August 2007
  - it only required 8 new events to fulfill prescription
  - From 8 new events 6 correlate, probability to get from isotropy <1%
  - Period II (9/13)

- Combining old + new data, accounting for “trials” over the 3 parameters:
  - False positives occur only **once every 10^5** isotropic realizations

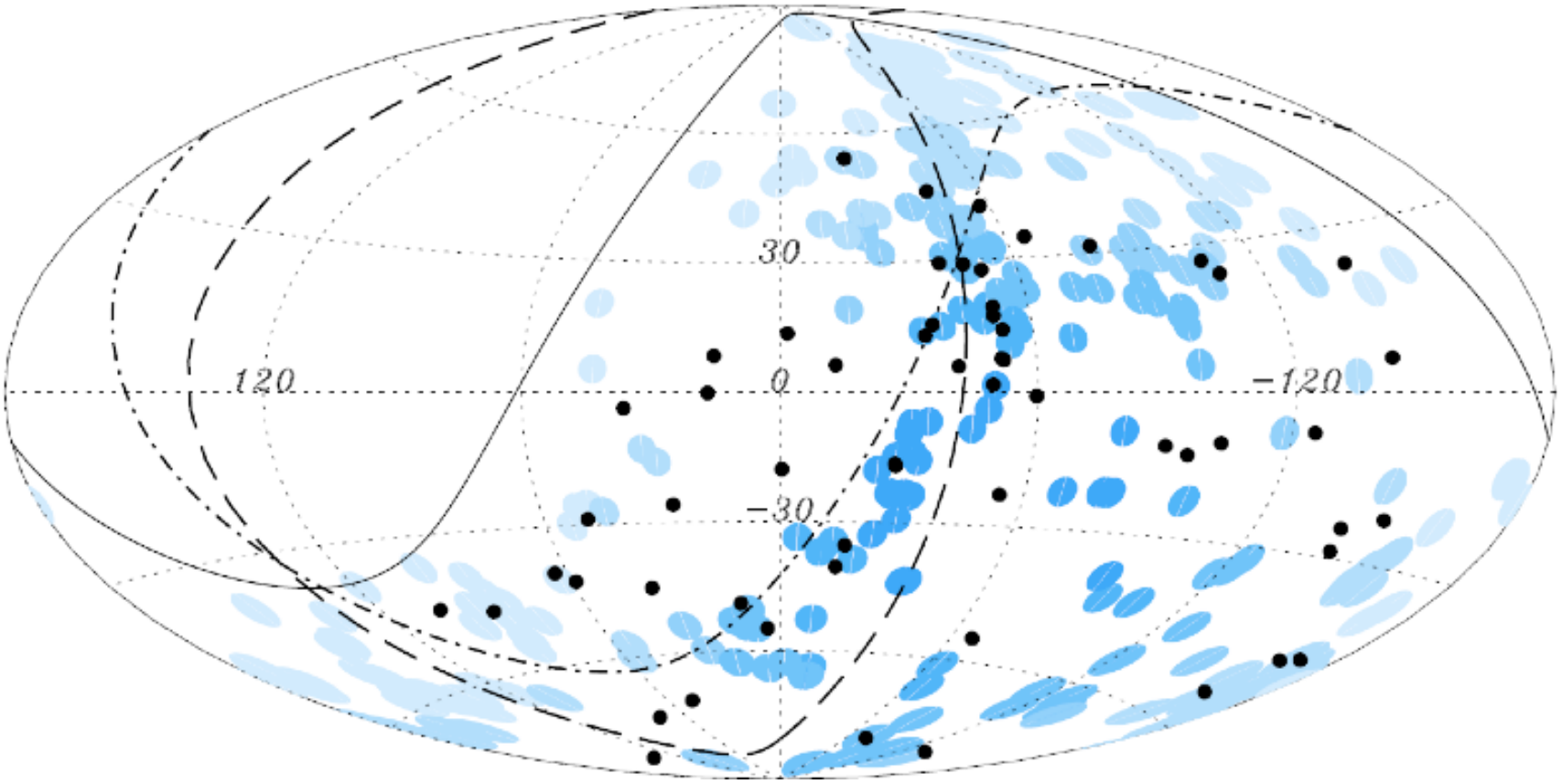
What does it mean?

- VC Catalog **not an unbiased** statistical sample (nor homogenous neither statistically complete);
- Not an obstacle to demonstrating the **existence of anisotropy** (CR preferentially close to objects in sample);
- The observed correlation identifies neither **individual sources** nor a **specific class** of astrophysical sites of origin;
- Clues to the **extragalactic origin** of UHECRs and suggests that the **suppression of the flux** is due to interaction with the **CMB;**
- **Charged particle astronomy is possible!**

The (recent) data for anisotropy analysis

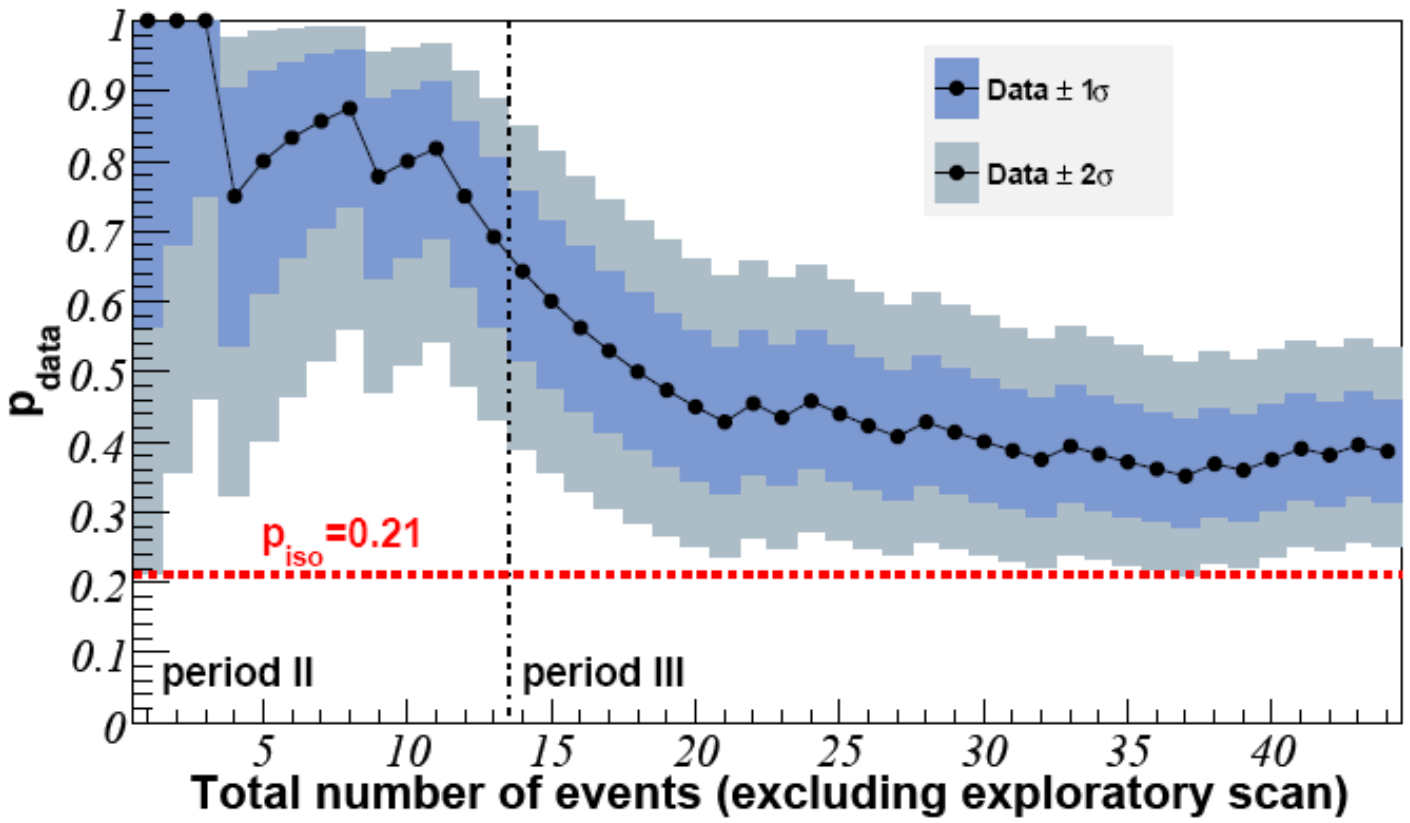
- Total of 58 events with E > 55 EeV (= 55 x 10^{18} eV):
- From 1 January, 2004 through 31 March, 2009.
- Surface detector data with at least 5 active neighboring tanks.
- Zenith angle < 60 degrees.
- Angular uncertainty < 0.9 degrees.
- Energy resolution is 17% .
- Energy systematic uncertainty is 22 %.

The Auger UHECR sky



Auger ICRC09

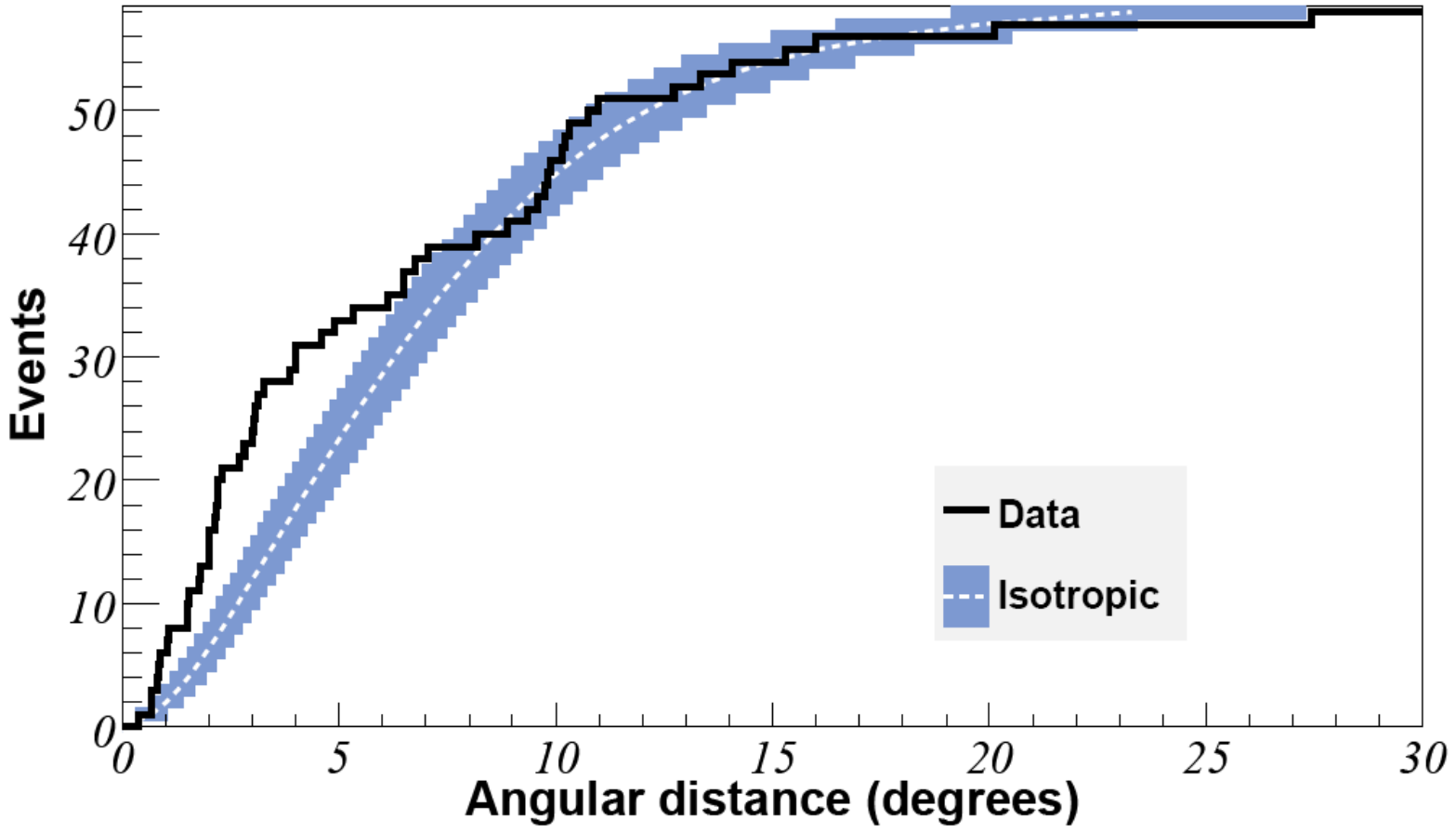
Monitoring the signal



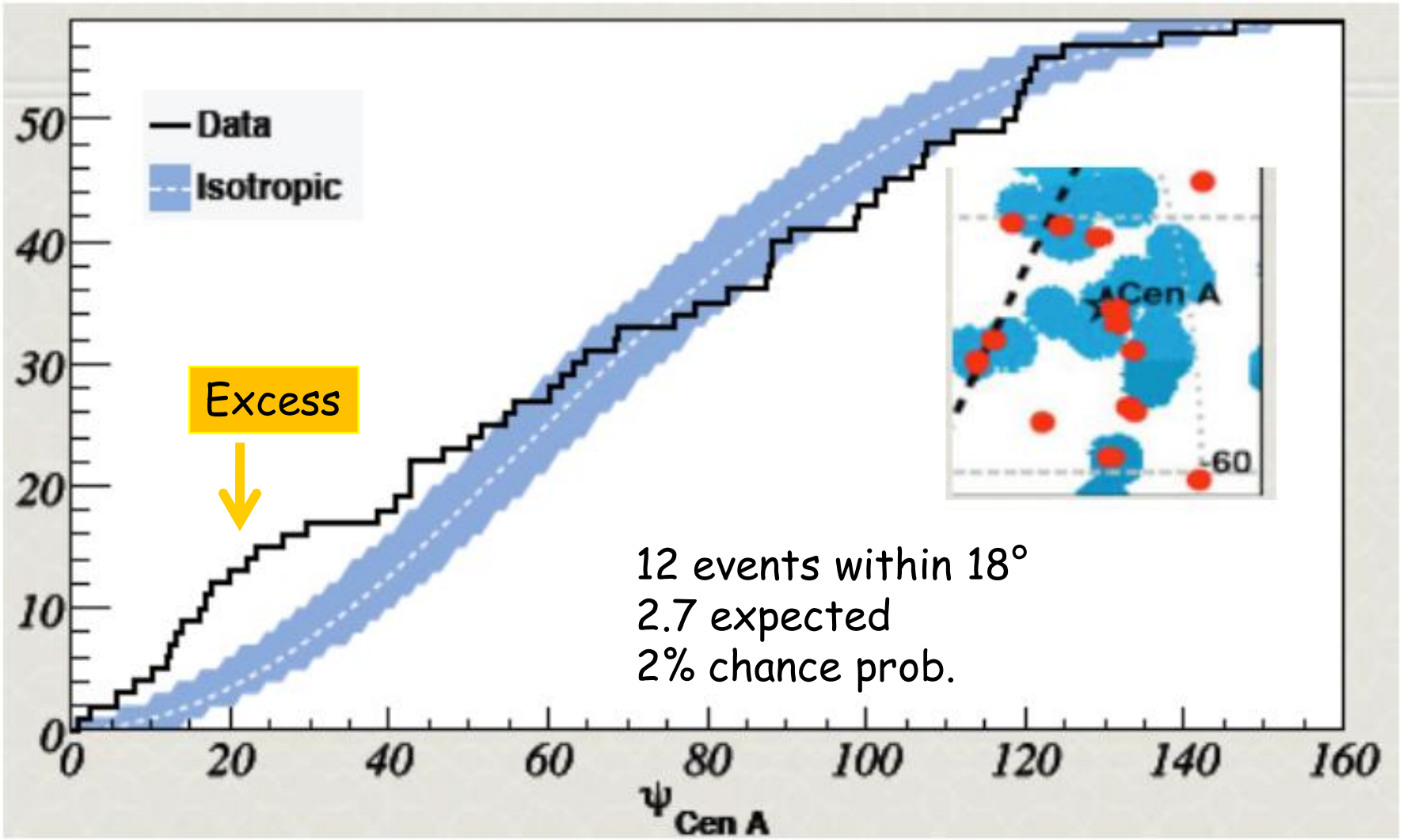
$p_{data} = 0.38 \pm 0.07$

Compatible with ANIsotropy

Cumulative angular distribution



Integral angular distribution



A posteriori analysis : other catalogues

Procedure working with any type of astrophysical catalogue : building *smooth density maps to be compared to the data*

- The flux of expected CR is described by a normalized function such that it gives the *probability to detect a CR in any direction (weight each source by its* measured flux and by the GZK attenuation factor)
- Two free parameters:

  σ = smoothing angle (gaussian lobe)

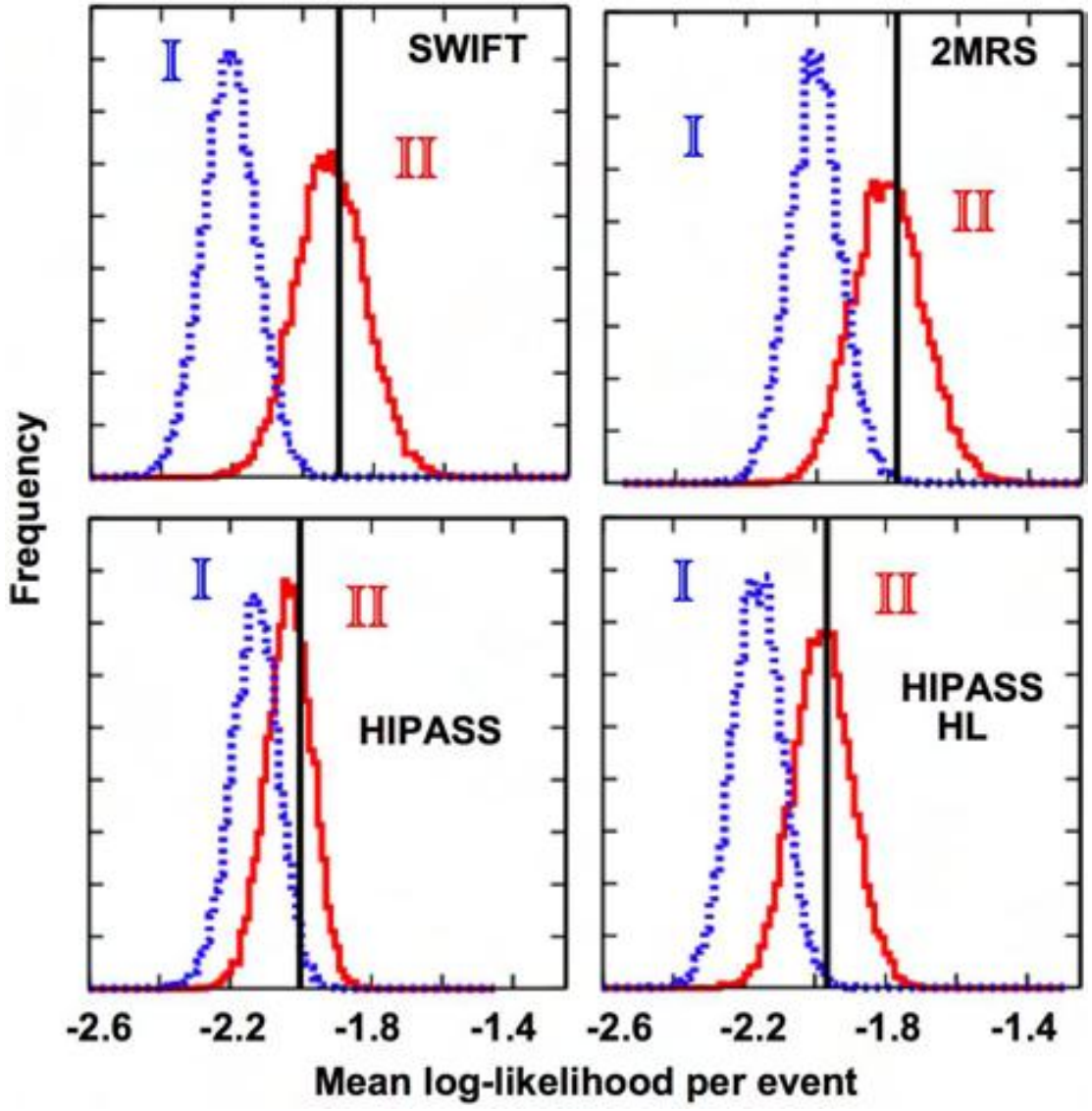
  f_{iso} = fraction of isotropic background (incompleteness)
- Comparison to the data through a log-likelihood maximization to find **σ** and f_{iso}

$$LL = \sum_{k=1}^{N_{data}} \ln F_c(n_k)$$

A posteriori analysis : other catalogues

- **SWIFT-BAT**: most uniform all-sky hard X-ray survey, containing 261 Seyfert galaxies and AGN
- **2MRS**: ~20,000 galaxies, excellent image of the distribution of local matter
- **HIPASS**: 3000 galaxies detected in radio, favoring gas-rich galaxies (GRBs and magnetars)
- **HIPASS-HL**: 750 most luminous galaxies from HIPASS favoring gas-rich galaxies (GRBs and magnestars)

A posteriori analysis : other catalogues



Using these parameters, generate by MC the distributions of the log-likelihood, and calculate the fraction of isotropic data sets giving a higher value than in the data

Significances ~ 10^{-4}

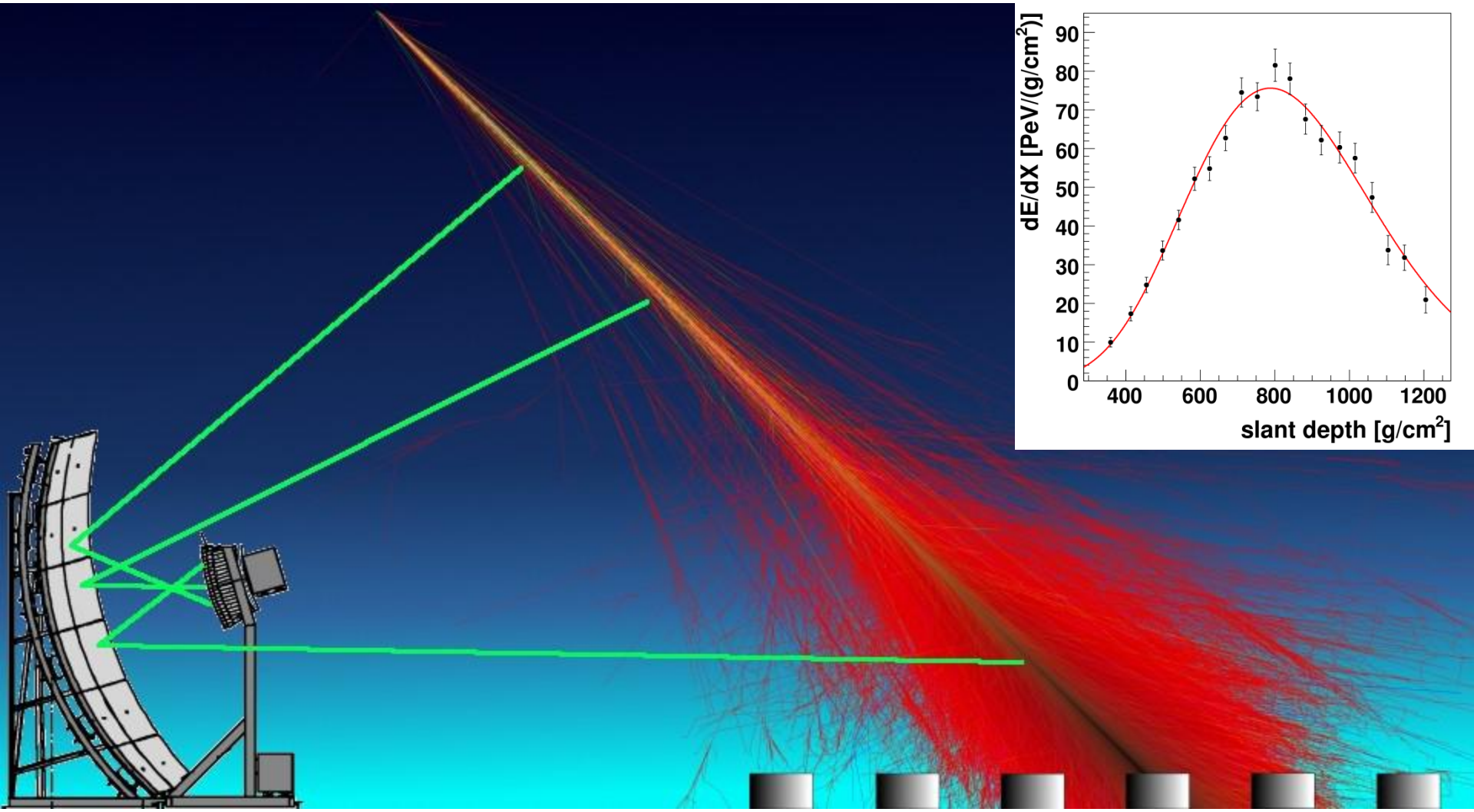
Other anisotropy results

- There is **no evidence** for significant excess of cosmic ray arrival directions
  - from the galactic center,
  - for clustering on different angular scales at the highest energies and
  - for correlations with BL Lac objects

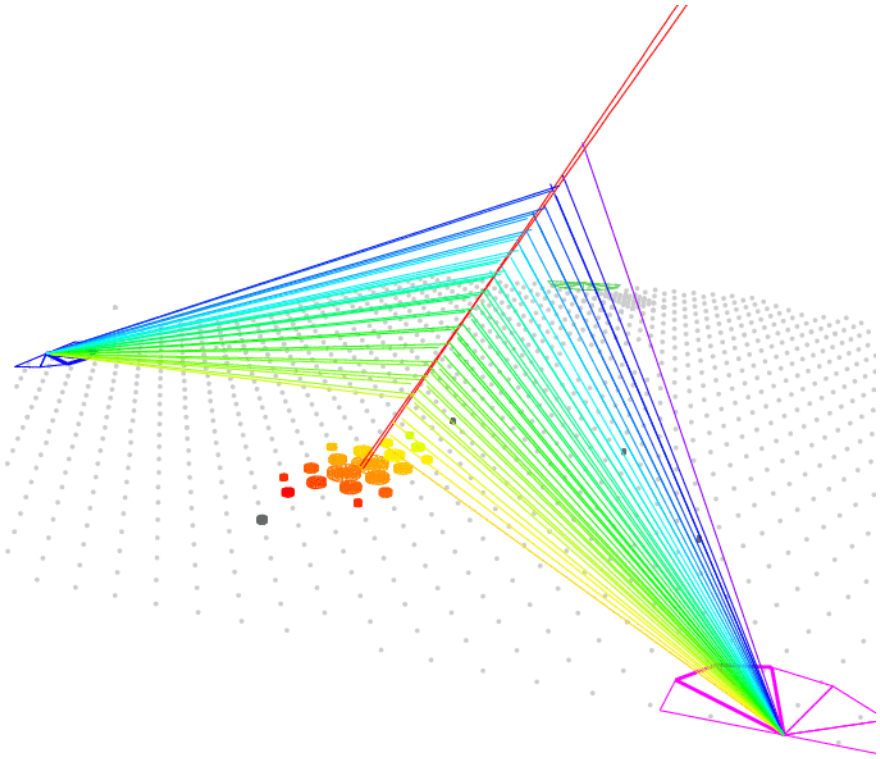
Composition from hybrid data

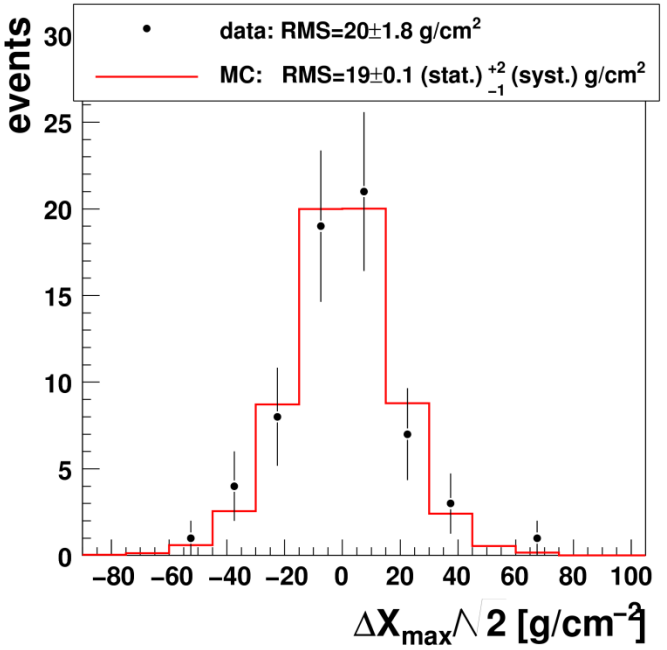
- UHECR: observatories detect induced showers in the atmosphere
- Nature of primary: look for diferences in the shower development
- Showers from **heavier** nuclei develop **earlier** in the atm with **smaller** fluctuations
  - They reach their maximum development higher in the atmosphere (lower cumulated grammage, X_{max})
- X_{max} is increasing with energy (more energetic showers can develop longer before being quenched by atmospheric losses)

The fluorescence detector measures the longitudinal shower profile

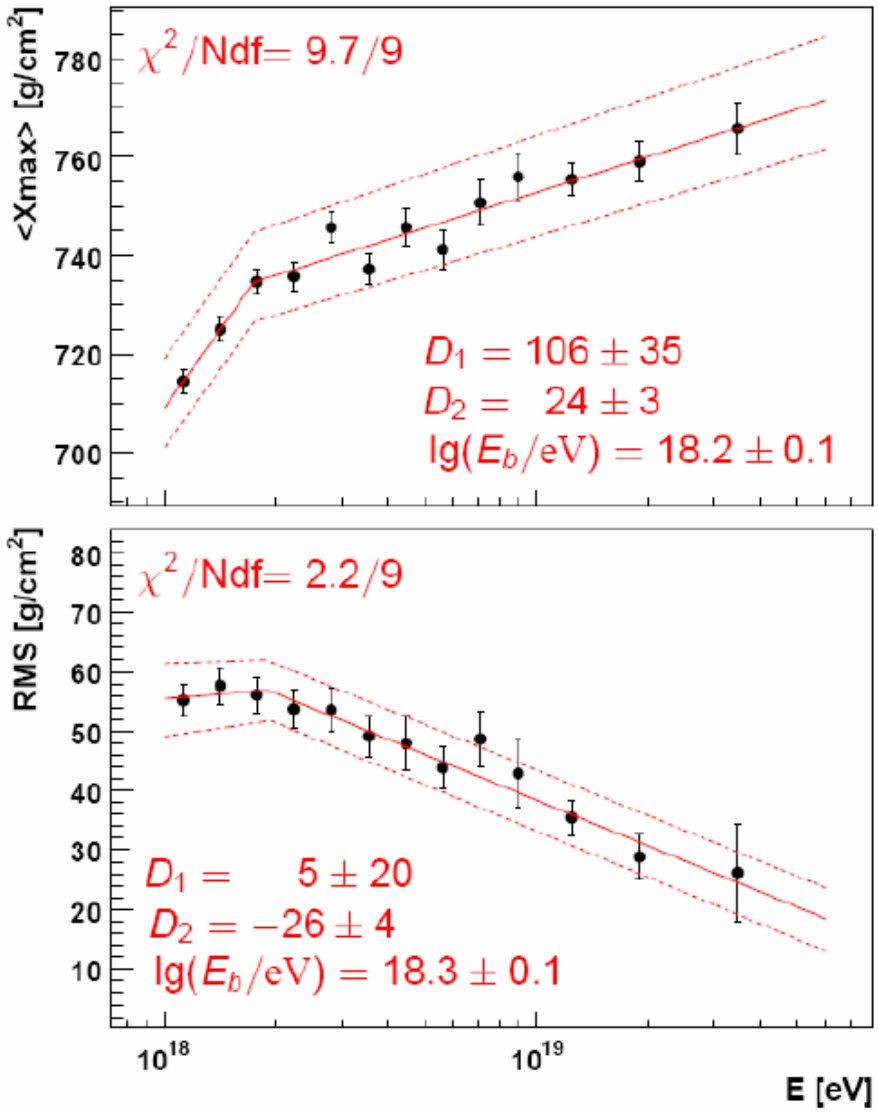


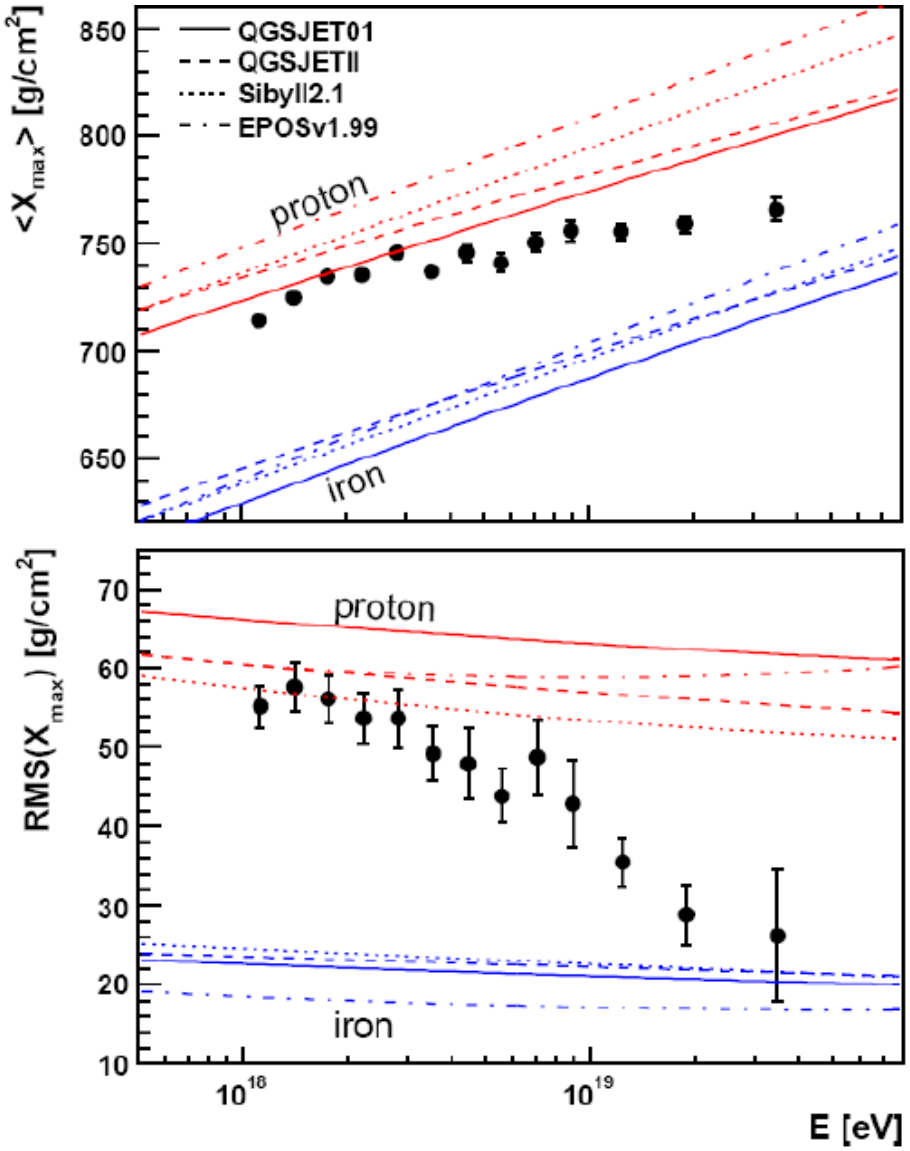
Resolution of the reconstructed Xmax



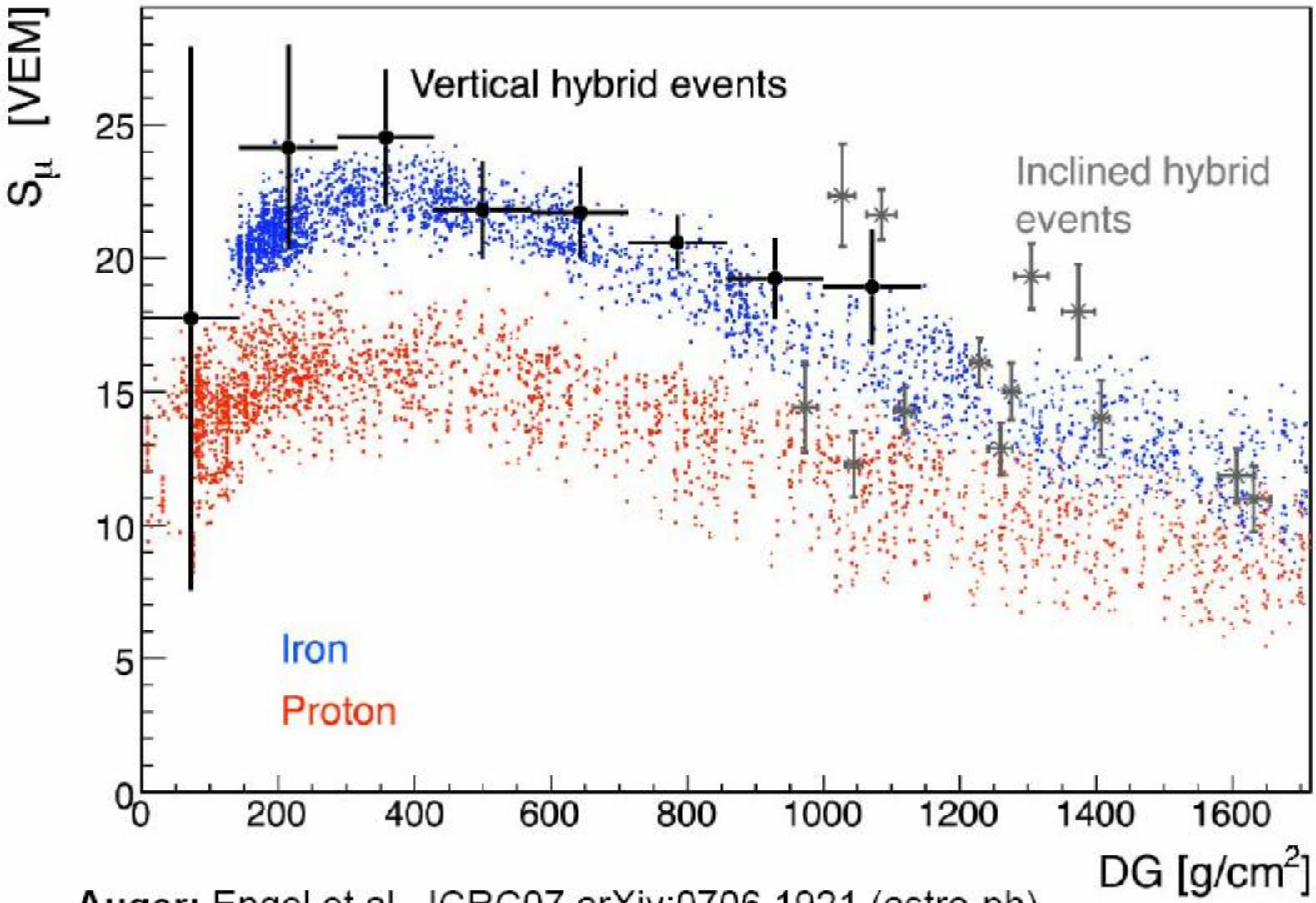


Xmax average and rms





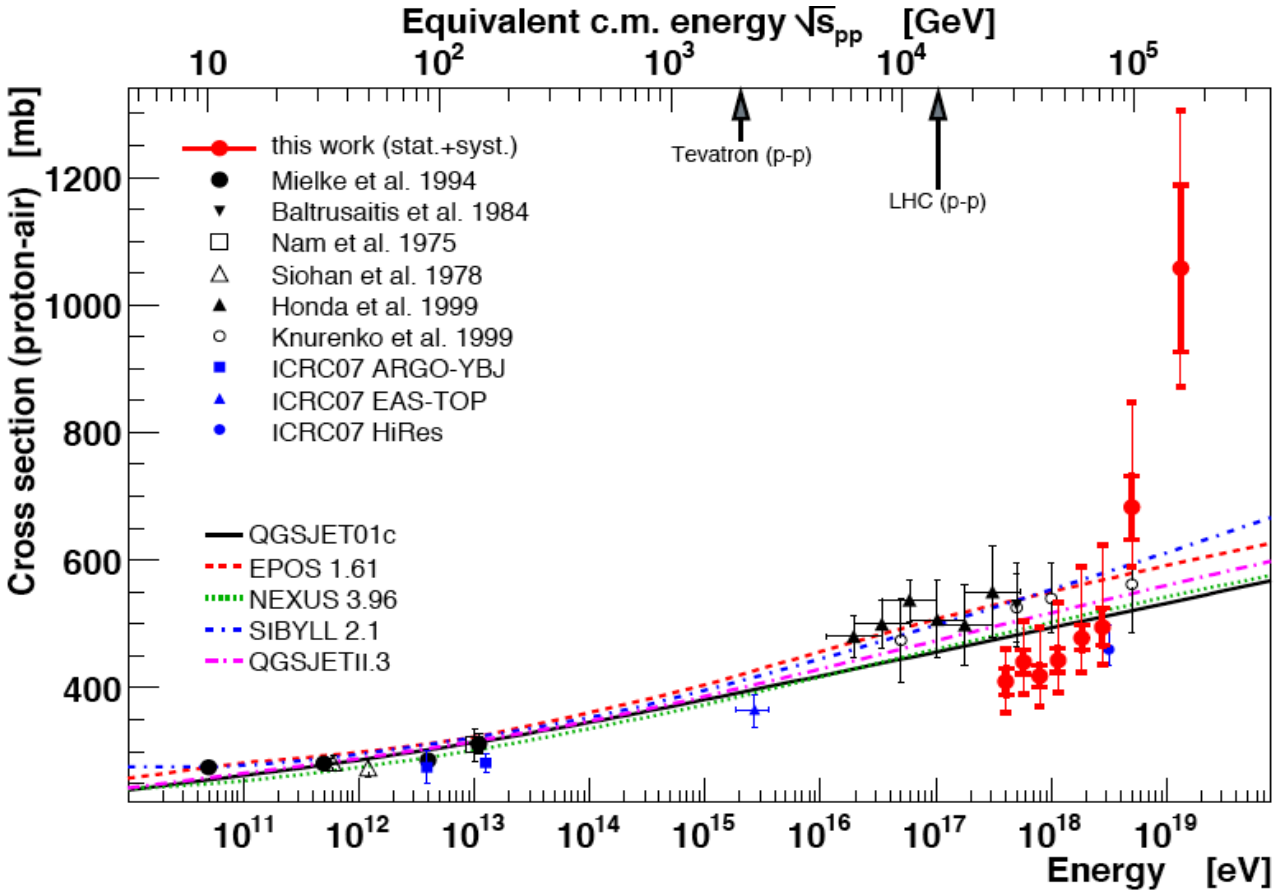
Muon content of events > EeV



Auger: Engel et al., ICRC07 arXiv:0706.1921 (astro-ph)

Hadronic physics

- Either primaries are heavy at the highest energies or new hadronic interactions above ~100 TeV c.m.s.



R. Ulrich's thesis

A puzzle

- Observed **Xmax** average value and fluctuations suggest **Fe-dominance** at $E > 3 \times 10^{19}$ eV.
- **Dilema**:
  - If composition is **heavy**, **the AGN correlations** are difficult to understand;
  - If composition is **light**, we do not understand the **hadronic interactions**;
- Based on Xmax up to 40 EeV, puzzling composition:
  - **Unexpected Astrophysics**: sources are very Iron rich and have low Emax;
  - **Interesting Particle Physics**: Hadronic models do not represent the UHE interactions;

Expected UHE neutrino flux

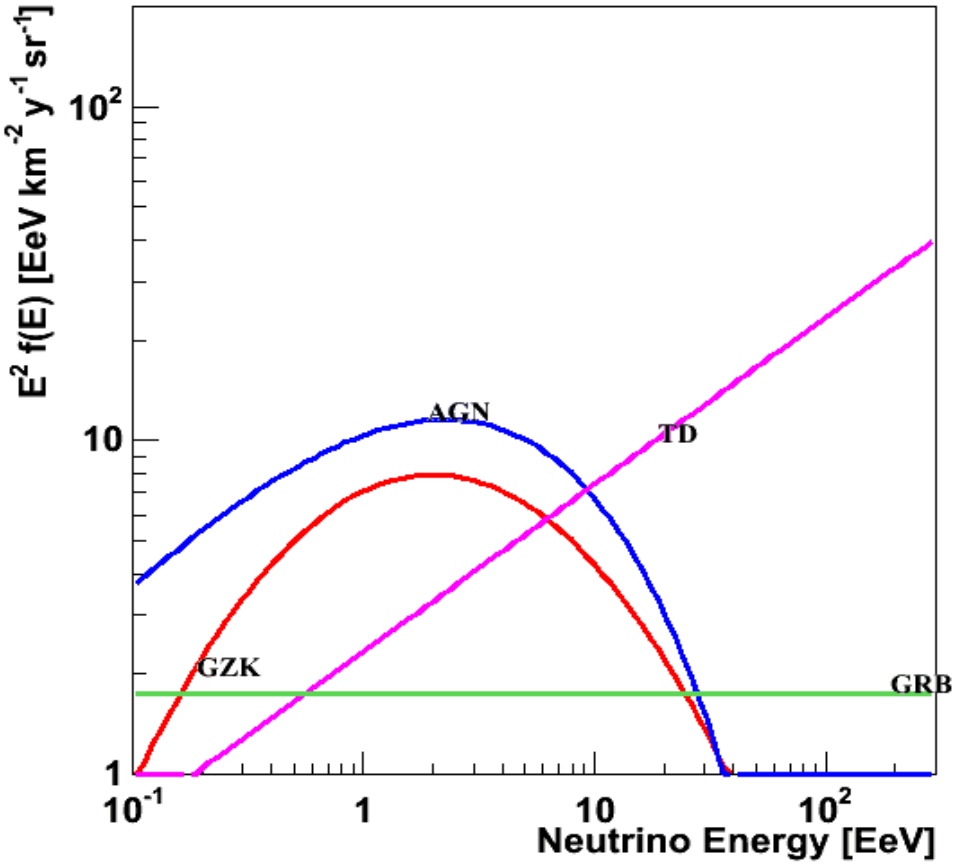
- $\Phi(\nu_{UHE})$ predicted in most models astrophysics

("bottom-up": AGN, GRBs…)
or exotic physics
("top-down")

- no GZK cut for the ν_{UHE}
- garanteed flux : ν cosmogenic

(produced by interaction GZK of hadronic cosmic rays)

$$p^+\gamma_{CMB} \rightarrow \Delta^+ \begin{cases} \rightarrow p^+\pi^0 \rightarrow p^+\gamma\gamma \\ \rightarrow n\pi^+ \rightarrow n\nu_\mu\mu^+ \rightarrow n\nu_\mu\bar{\nu}_\mu\nu_e e^+ \end{cases}$$



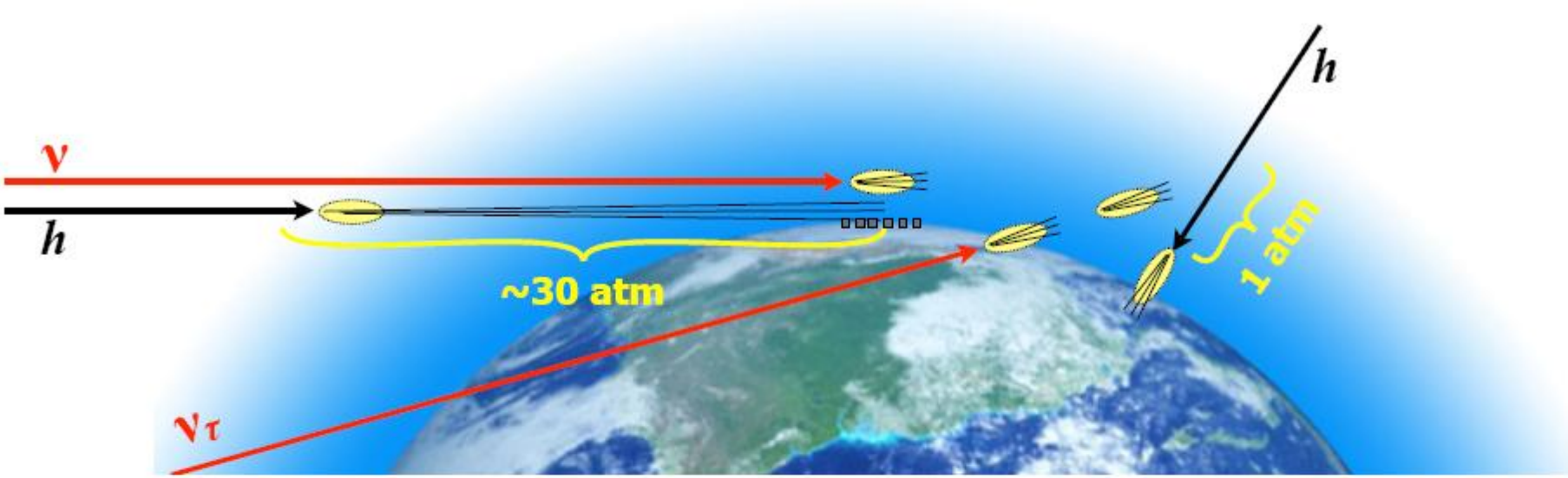
- $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$ in the source

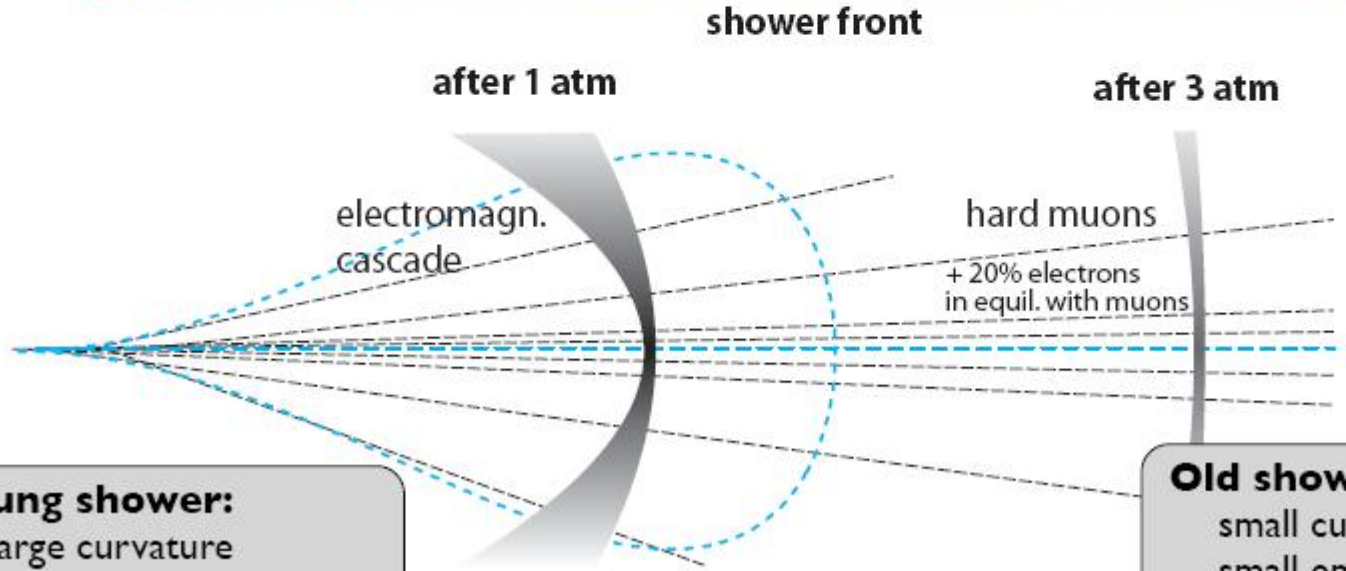
+ oscillations on the way:

$\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$ at Earth

…but very small number of expected events: weak flux and cross sections

Neutrino induced showers

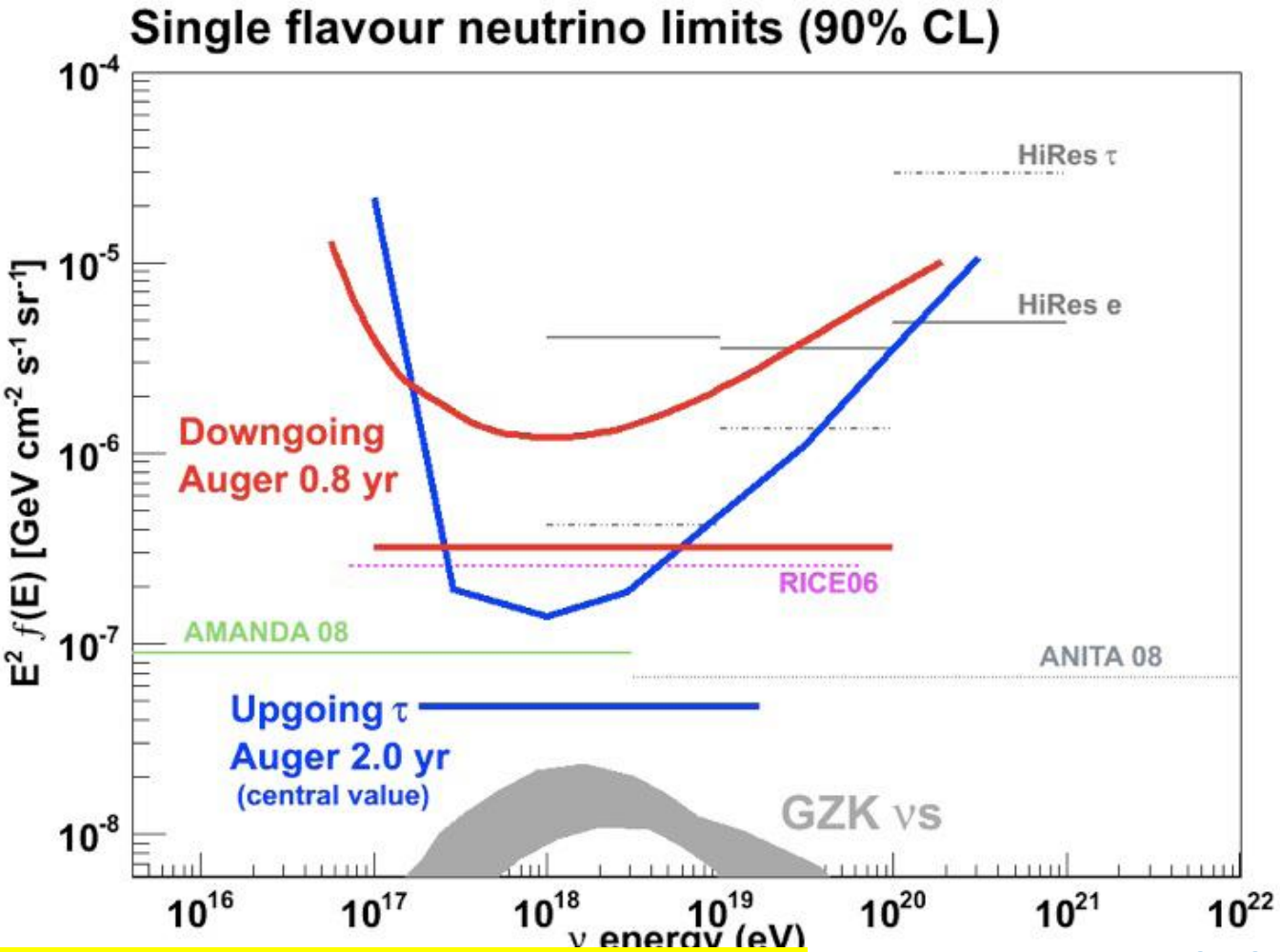




Young shower:
large curvature
large em. component
extended time structure

Old shower:
small curvature
small em. component
compressed time structure

Auger neutrino limits



Several astrophys. models excluded; cosmogenic neutrinos in reach

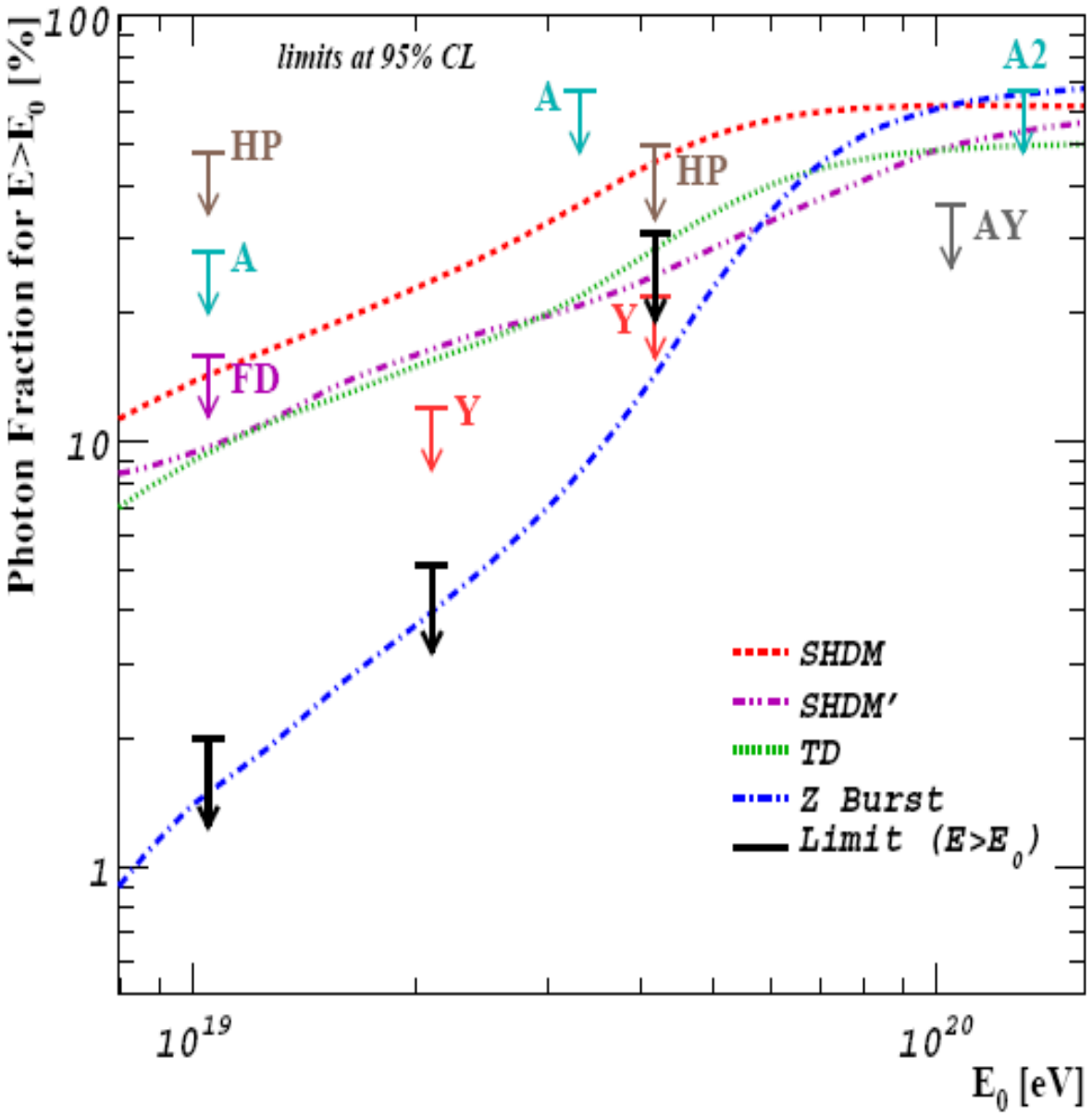
ICRC 2009, update from Auger Collaboration, Phys. Rev. Lett, 2008

Top down models

- **acceleration models (astrophysics):**
  - active galactic nuclei, gamma-ray bursts...
  - not easy to reach > 100 EeV;
  - photon fractions typically < ~ 1%

- **non-acceleration models (particle physics)**
  - UHECR: decay products of high-mass particles (> 10^{21}eV)
  - super-heavy dark matter (SHDM): from early universe and concentraded on the halo of galaxies and clusters of galaxies
  - topological defects (TD) produced throughout the universe
  - UHECR produced as secondary particles (hadronization process) and are most photons and neutrinos, with minority of nucleus
  - photon fraction typically > ~ 10%
  - SHDM: CR from our galaxy, photons with a hard energy spectrum
  - TD: sources distributed in the universe, photons interact with CMB (expect smaller photon fraction)

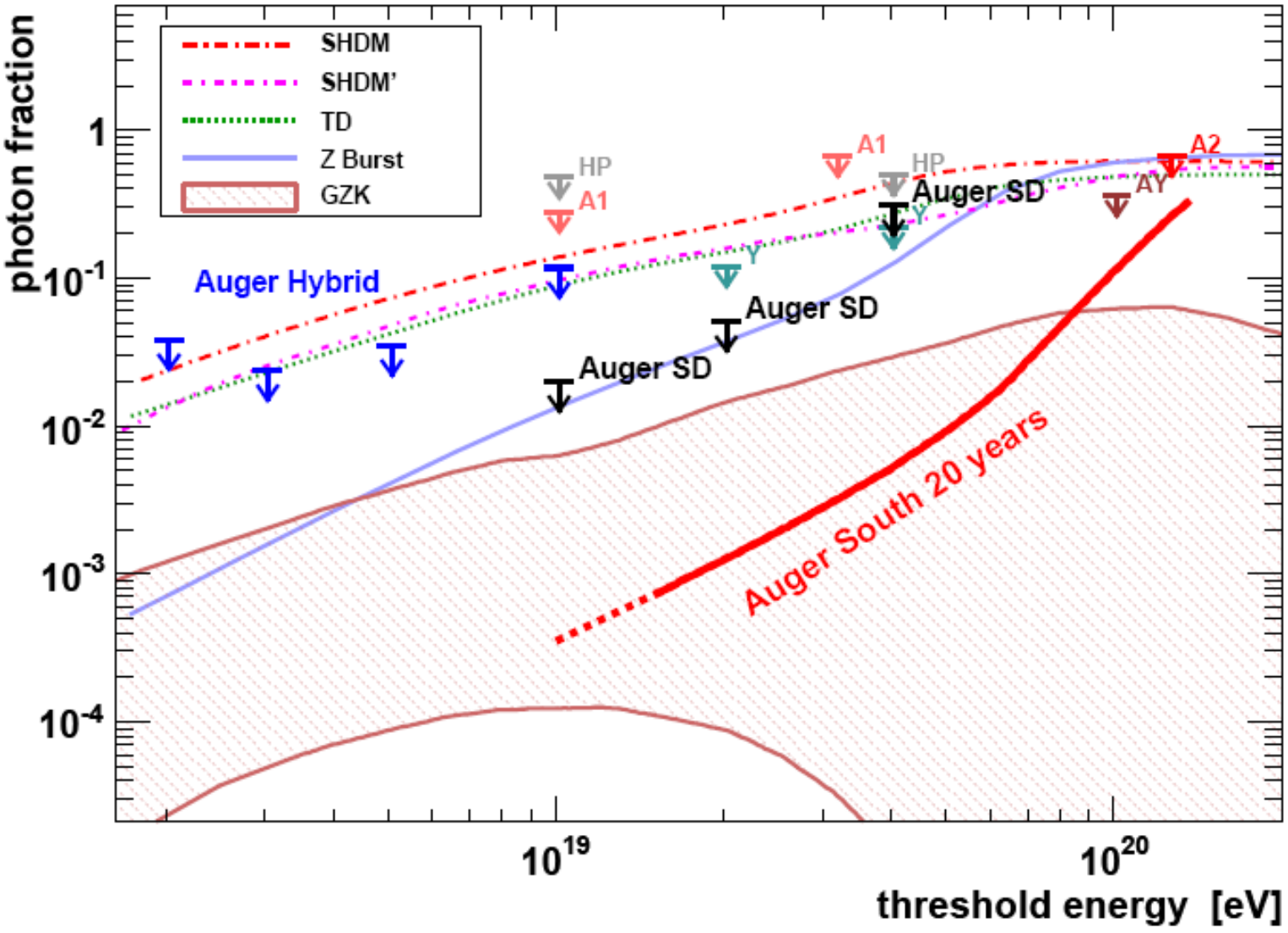
photon limits



A = Agasa
HP = Haverah Park
Y = Yakutsk

Pierre Auger Collaboration, Astrop. Phys. 2008

photon limits



Need lots of new data above 60 EeV

to determine if we are observing:

New Physics

Proton primaries determined by patterns in sky distribution

➔ new interactions to explain composition measurements

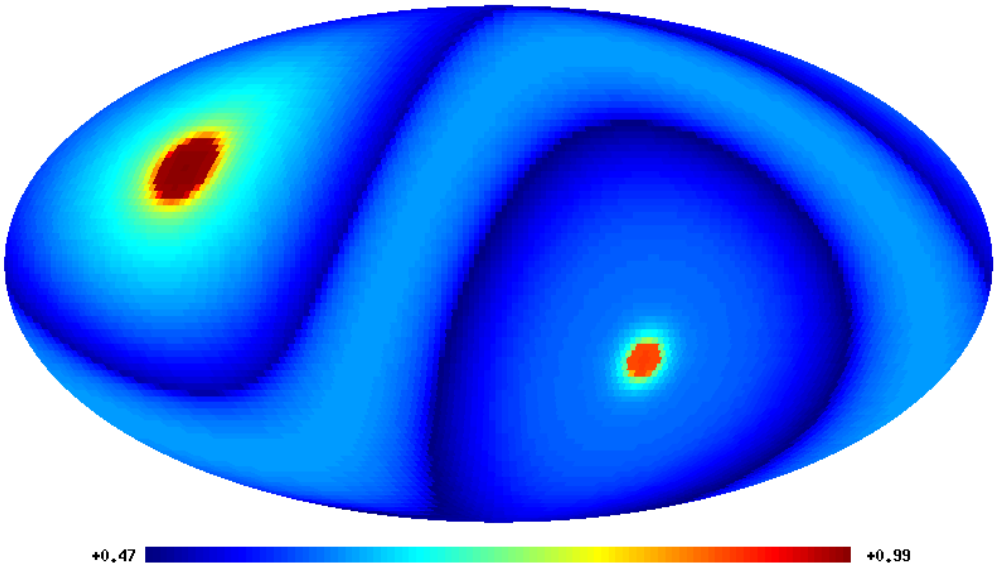
New Astrophysics

Heavy primaries confirmed by patterns in sky distribution

➔ new source models to explain heavy dominance

Auger North

- Planned location in Colorado, US
- Full-sky coverage
- Optimized for operation in energies where arrival directions are anisotropic
- Sufficient exposure to:
  - Detect individual sources
  - Calculate fluxes, spectra
  - Answer fundamental questions about nature's most powerful accelerators, their physics, and their energy sources
  - Map the Galactic/intergalactic magnetic field!



B. Siffert

Auger South Enhancements

- Infill array: denser arrray, 750 m
- Threshold for infill array: 10^{17} eV
- AMIGA: Auger Muons and Infill for the Ground Array
  - denser array, 433 m tank distance, underground muon counter (buried 3 m)
- HEAT: High Elevation Auger Telescopes
  - 3 ``standard´´ Auger telescopes tilted to cover 30 - 60° elevation
  - Custom-made metal enclosures
  - Also prototype study for northern Auger Observatory
- CR composition and the structure of the galactic/extragalactic transition

Conclusion

- A strong suppression in the cosmic ray flux was observed;
- The P. Auger observatory has established the anisotropy of UHECR for E>57 EeV;
- New data has weakened the signal strength, but the anisotropy distribution is confirmed at 99% CL.
- A correlation between the CR directions and the VC AGN catalogue was established;
- The sources of UHECR are not yet determined;
- Recent limits on tau neutrino showers and down neutrinos
- Stringent limits on photon showers
- We need Auger North !