Status of extensive air shower studies at the Pierre Auger Observatory

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The Pierre Auger Collaboration

Overview

- Cosmic ray phenomenology and observations
  - Ultra-high-energy cosmic rays
  - The tree main observables: angular distribution, energy spectrum, mass composition
- The Pierre Auger Observatory (or “Auger”)
  - Design and implementation
  - Current status and future developments
- The first results of Auger
  - Spectrum, composition, anisotropy
  - Photon limit, neutrino limit
- Perspective: astronomy, astrophysics, astroparticles and high-energy physics…

Cosmic rays and particle physics

- Long, rich and successful story
- Major discoveries
  - Antimatter, muons, pions, strange particles…

Cosmic rays and astrophysics

- Long, rich and successful story
- Major discoveries
  - Non-thermal astronomy
  - Central role of CRs in Galactic ecology
  - Existence of CRs up to 10^{20} eV!
  - CR astronomy is possible!

(ionisation, heating, magnetic fields, astrochemistry, LiBeB nucleosynthesis, star formation…)

challenge for particle acceleration!

Overcome isotropization and deflection by magnetic field

Non-thermal astronomy

- Energetic particles are ubiquitous in the universe

⬇

- Particle acceleration is a central problem
  - Physics of powerful, high-energy sources
  - Physics in “extreme conditions”
  - Multi-scale problem + conditions very different from laboratory exp. (e.g. “collisionless shocks”)

⬇

- Multi-wavelength and multi-messenger astronomy: gives access to high-energy processes

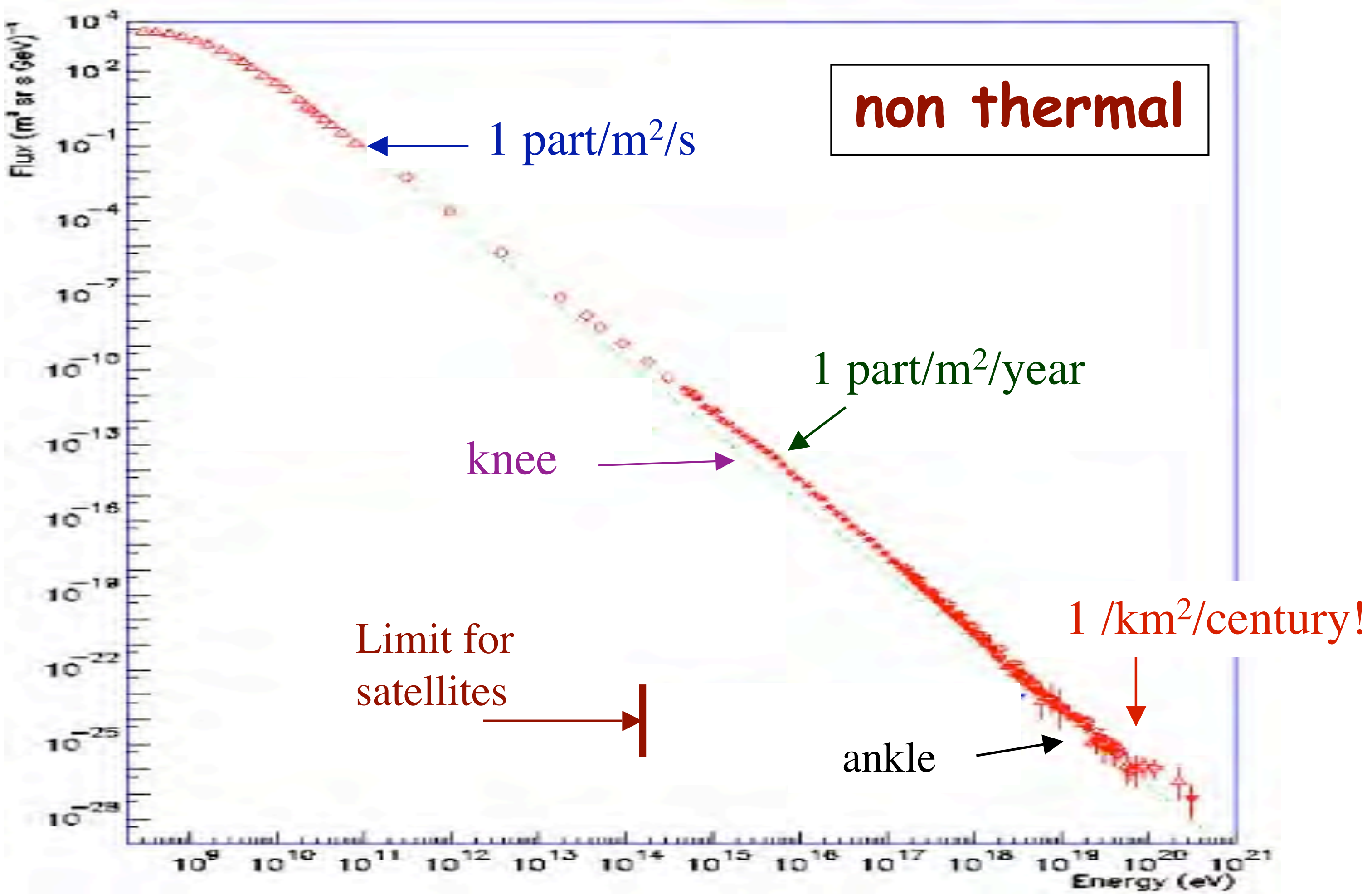
  (→ “astroparticle physics”)

- Intermediate goal: identify sources of high-energy cosmic rays!

  Neutrinos: hard to detect them, but then ~easy to find sources

  Charged CRs: ~easy to detect them, but then hard to find sources → UHE…

Price to pay for CR astronomy: very low flux!

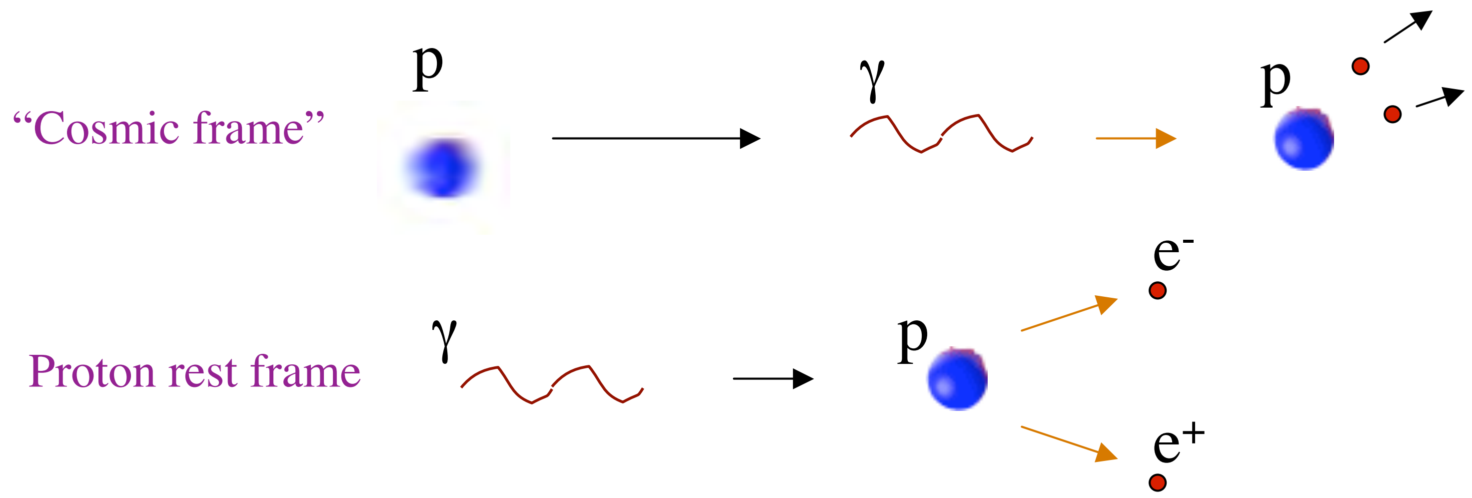


→ need for huge detectors

→ indirect measurement, hard to control

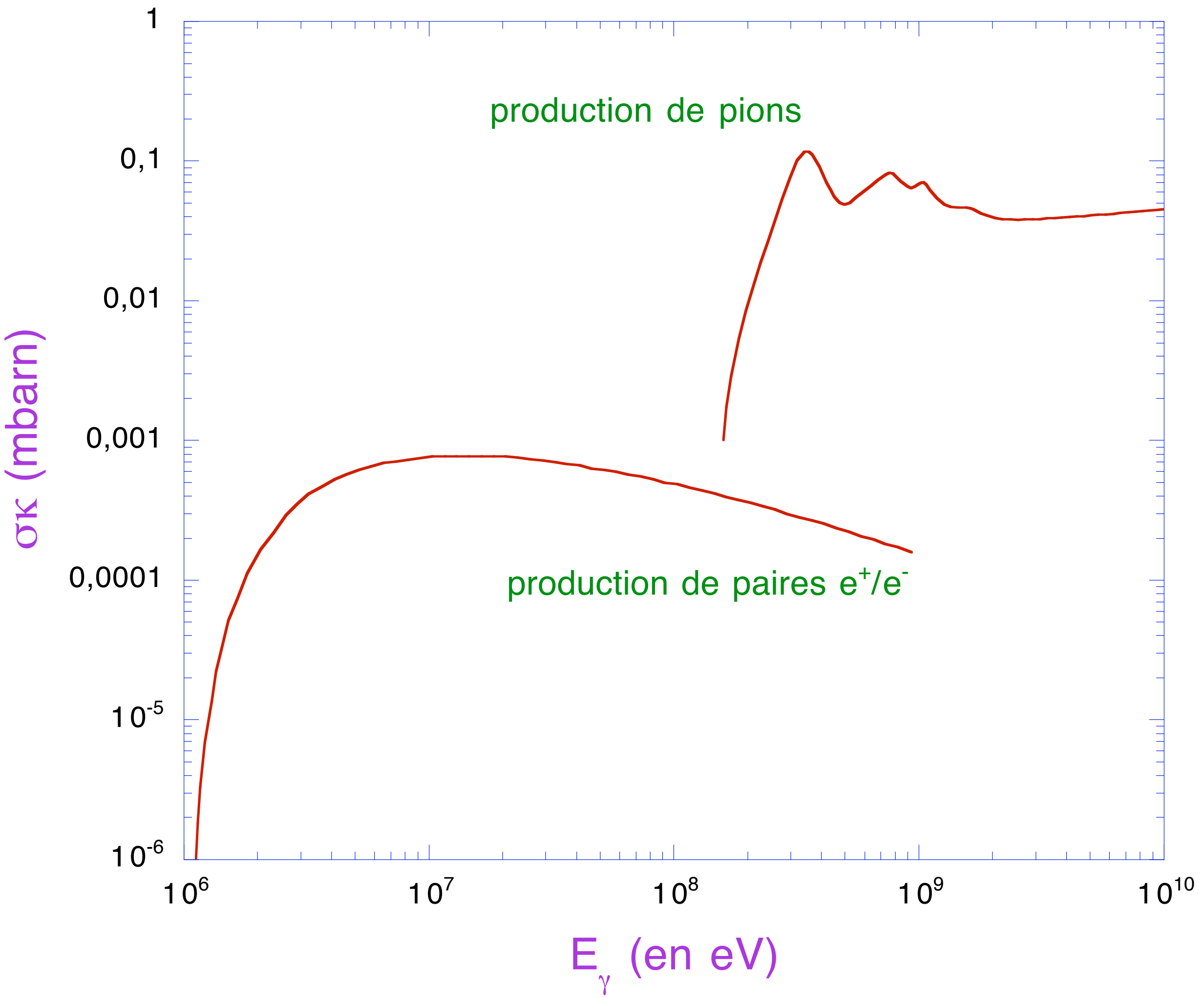
The GZK effect

- Greisen (1966) + Zatsepin & Kuz'min (1966)
- Energy losses through e^+/e^- pair and pions production!

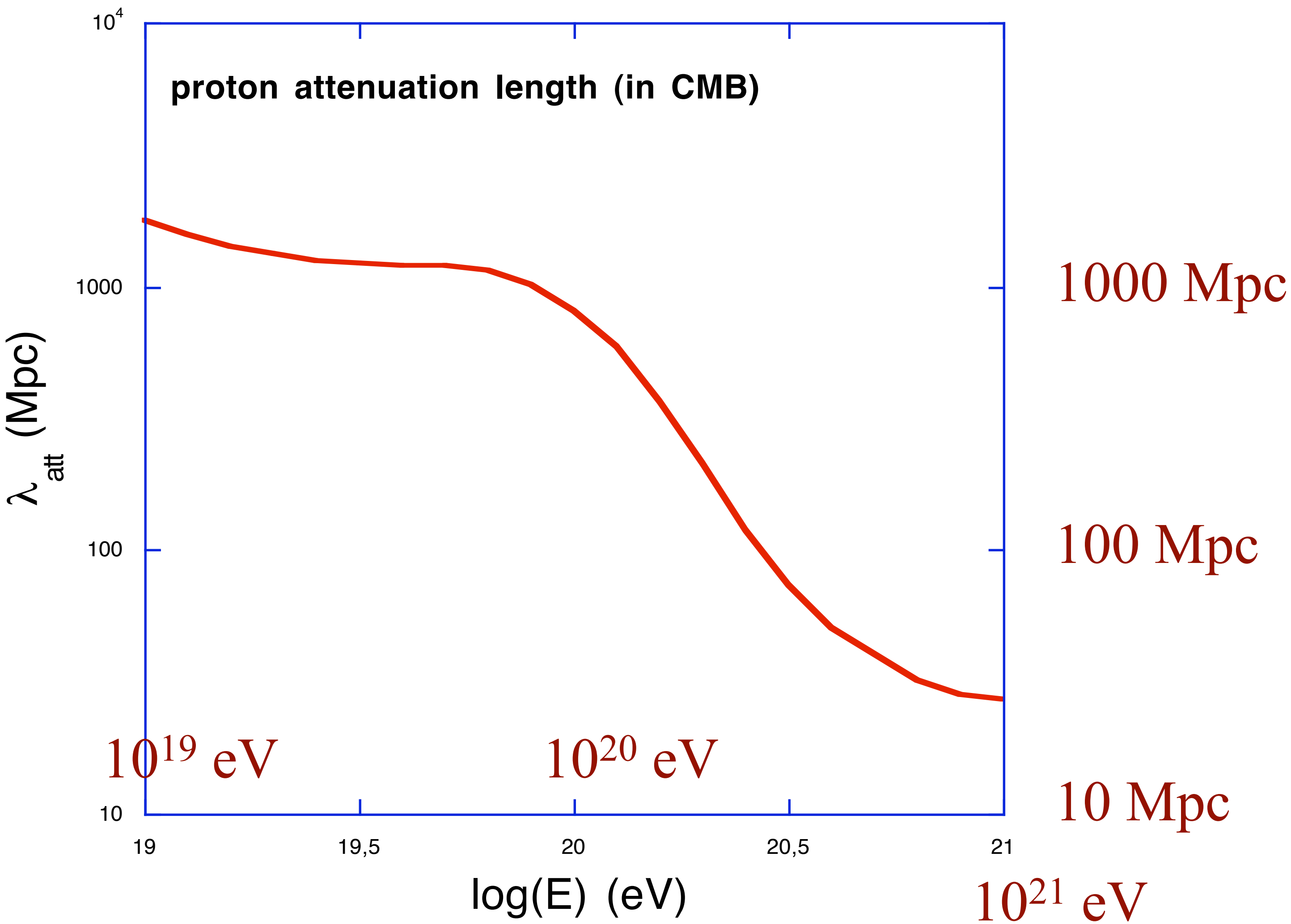


- Threshold : $E_\gamma \approx 2\, m_e c^2$ in the proton rest frame $\boxed{E_\gamma > 1 \text{ MeV}}$
- Threshold : $E_\gamma \approx m_\pi c^2$ in the proton rest frame $\boxed{E_\gamma > 160 \text{ MeV}}$

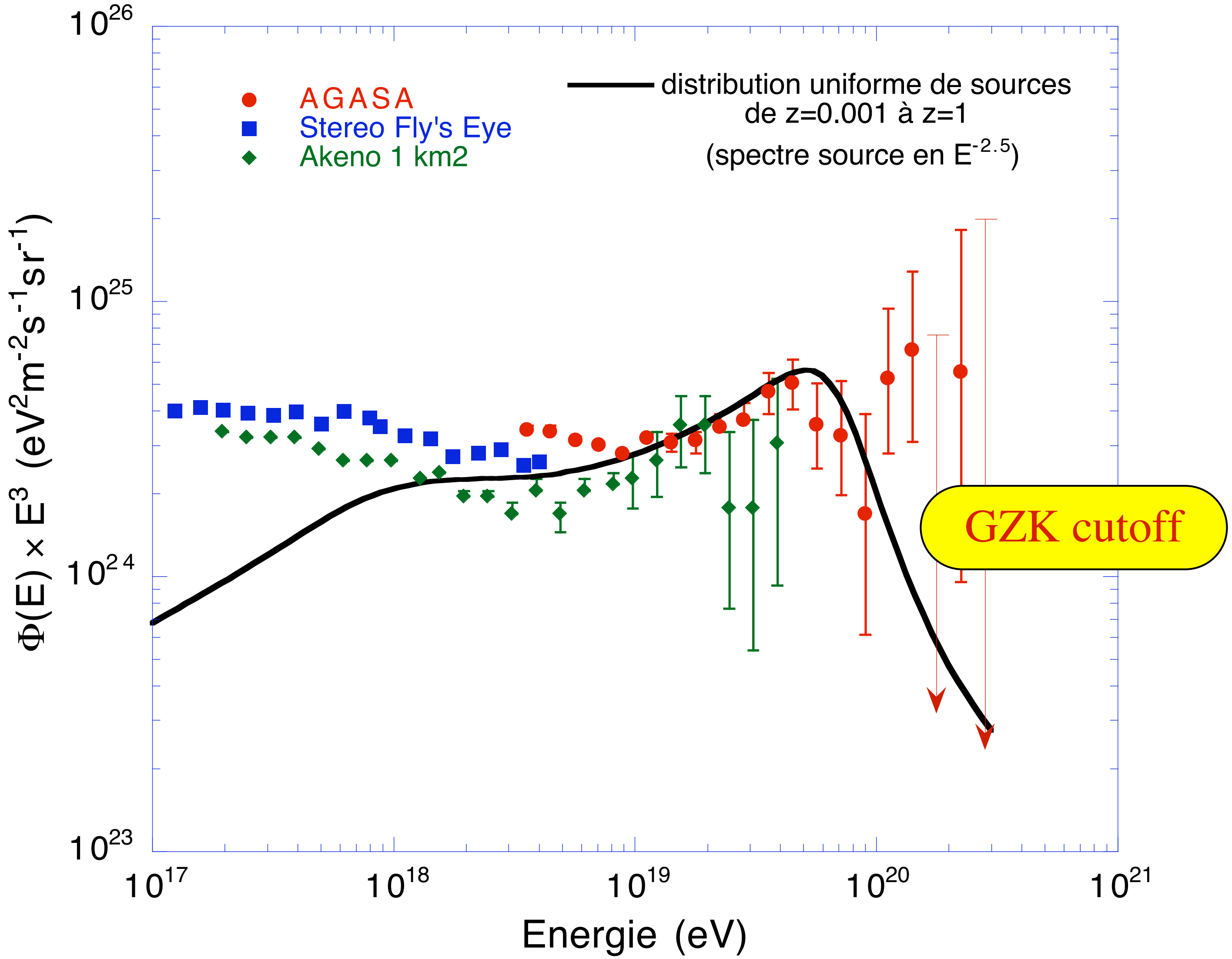
[cross section] x [inelasticity]



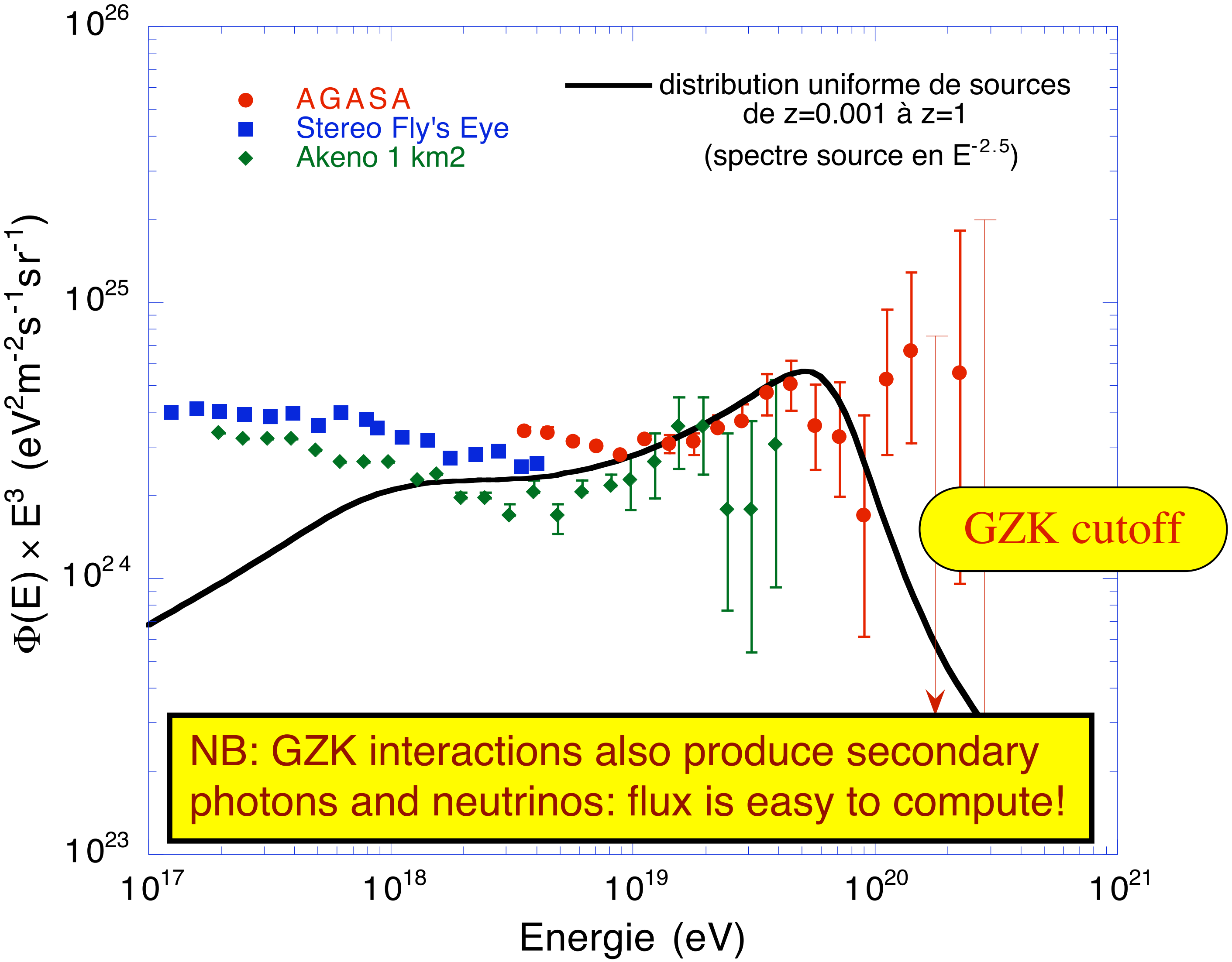
Attenuation length – horizons



Uniform source distribution



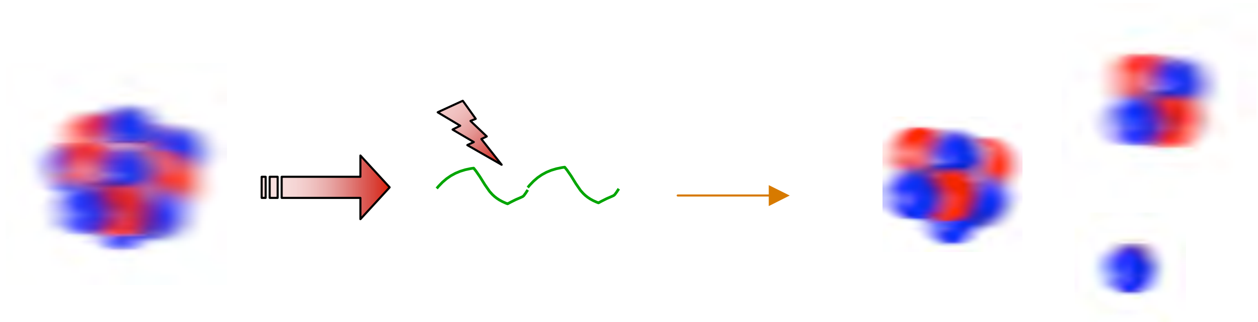
Uniform source distribution



NB: GZK interactions also produce secondary photons and neutrinos: flux is easy to compute!

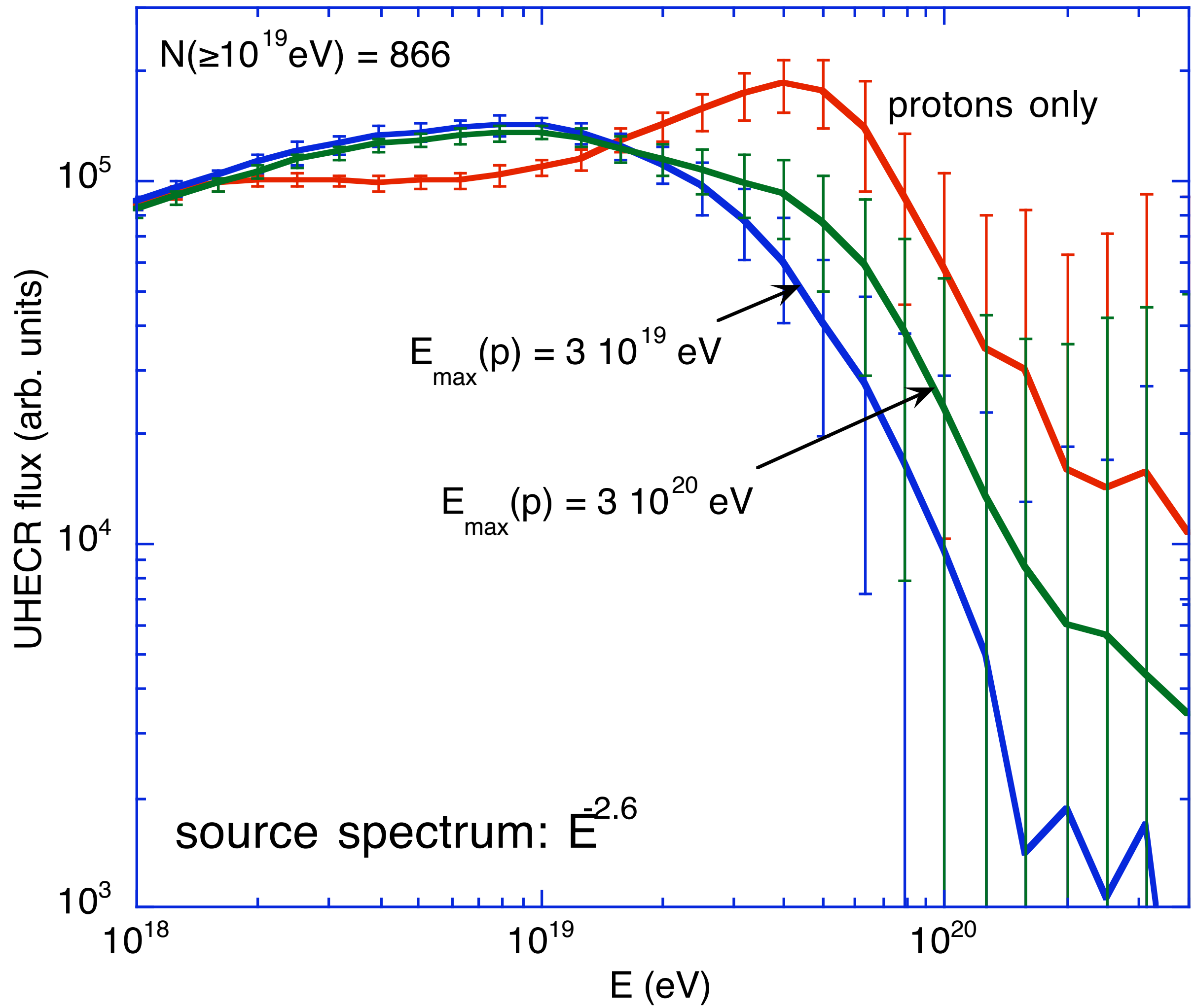
GZK effect for heavier nuclei

- Ultra-high-energy nuclei can be photo-dissociated by CMB and/or IR photons → lose nucleons, and thus energy



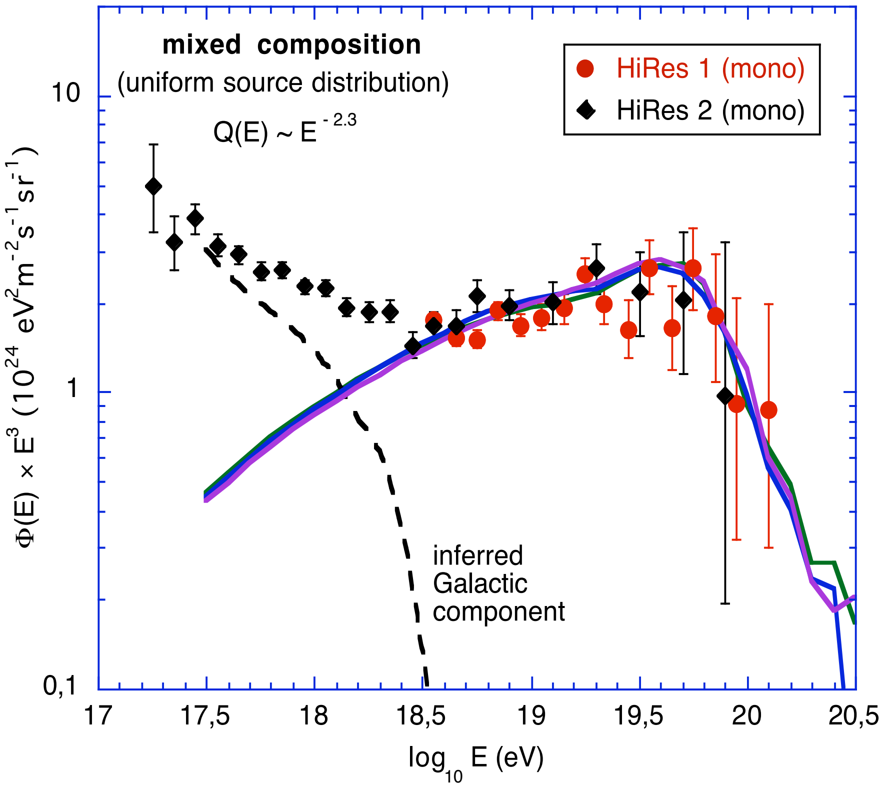
- NB: even if no UHE nuclei reach the Earth, the phenomenology of extragalactic CRs depends on the presence of nuclei at the source!

Examples of "propagated" spectra



Are there nuclei among EGCRs?

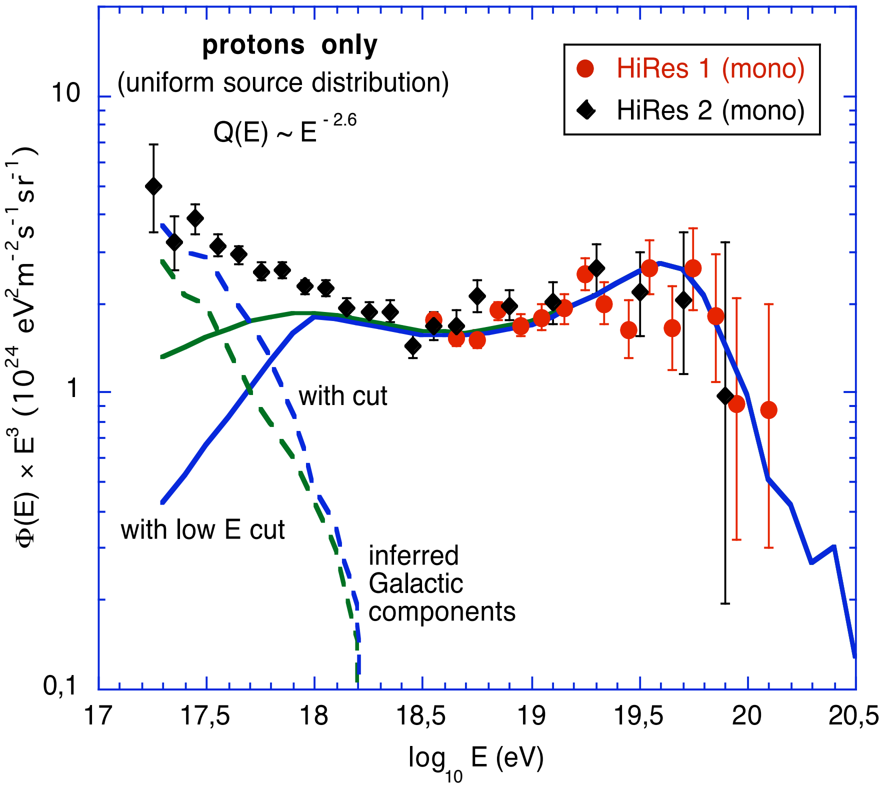
Mixed composition (Allard et al.)



Source spectrum in $E^{-2.3}$

Ankle = gal./extragal. transition

Pure protons (cf. Berezinsky et al.)

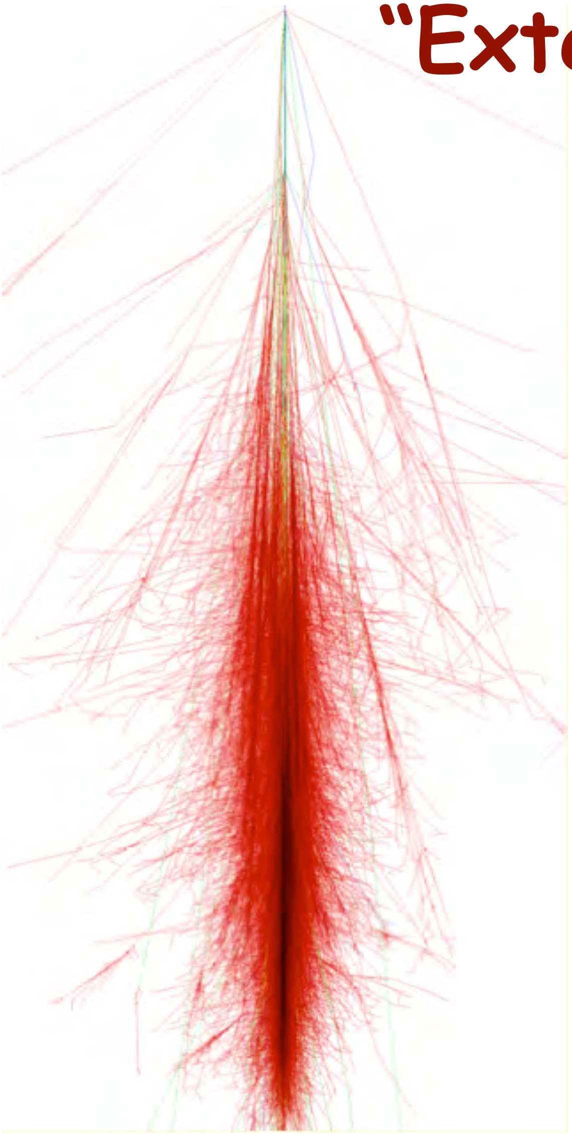


Source spectrum in $E^{-2.6}$

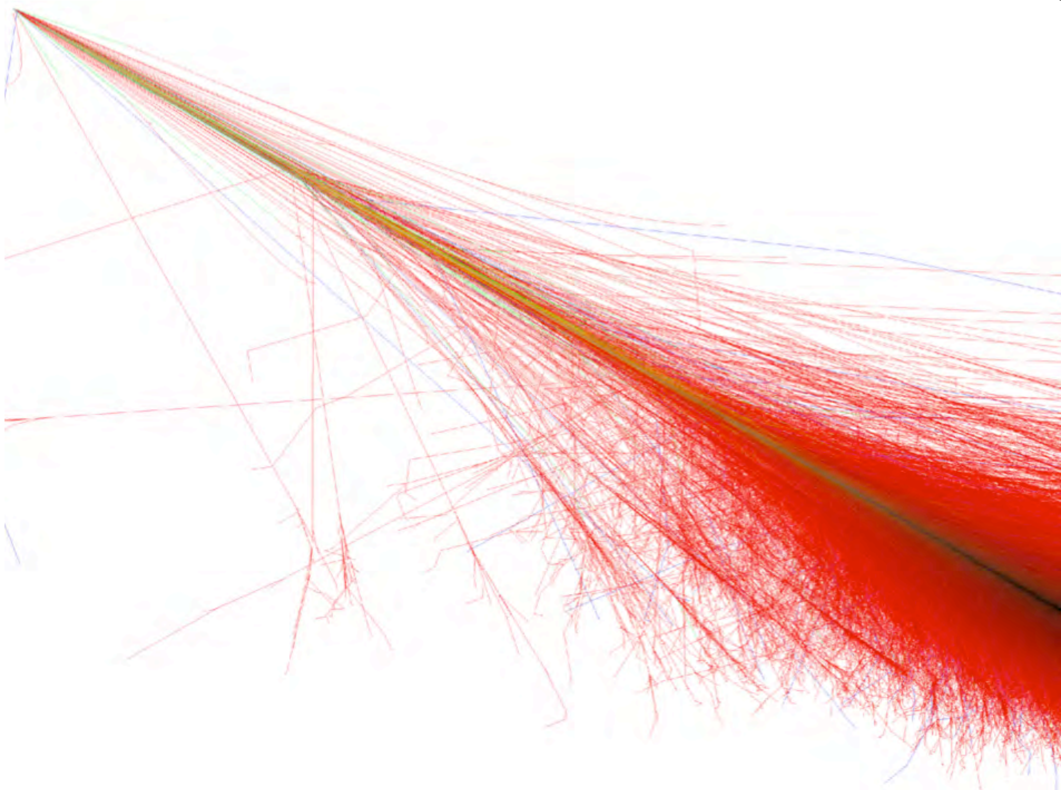
Ankle = "pair production dip"


CR detection at the
Pierre Auger Observatory
¡ Bienvenida en la tierra cósmica !

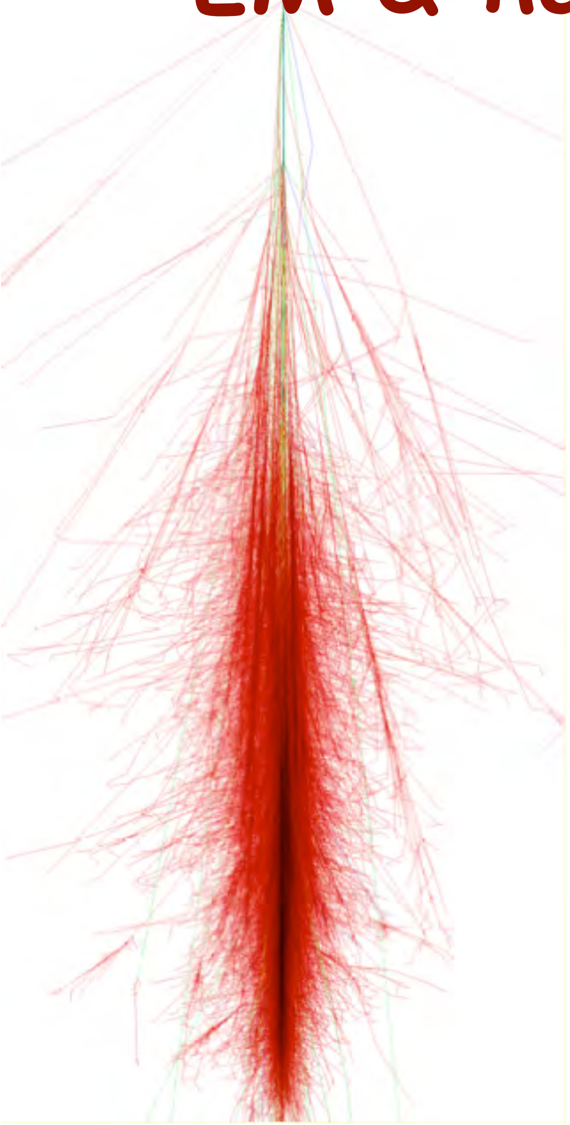
Indirect CR detection through "Extensive Air Showers"



- Induced by cosmic rays in the atmosphere



EM & hadronic “sub-showers”



- electromagnetic and hadronic subshowers

$p + p$

$\pi^{\pm}$ π^{0}

$\gamma\gamma$

$\pi^{\pm}$ π^{0}

$e^{+}e^{-}$

$\mu^{\pm}$ $\gamma\gamma$

$\pi^{\pm}$ $\gamma\ e^{+}e^{-}$

$\mu^{\pm}$

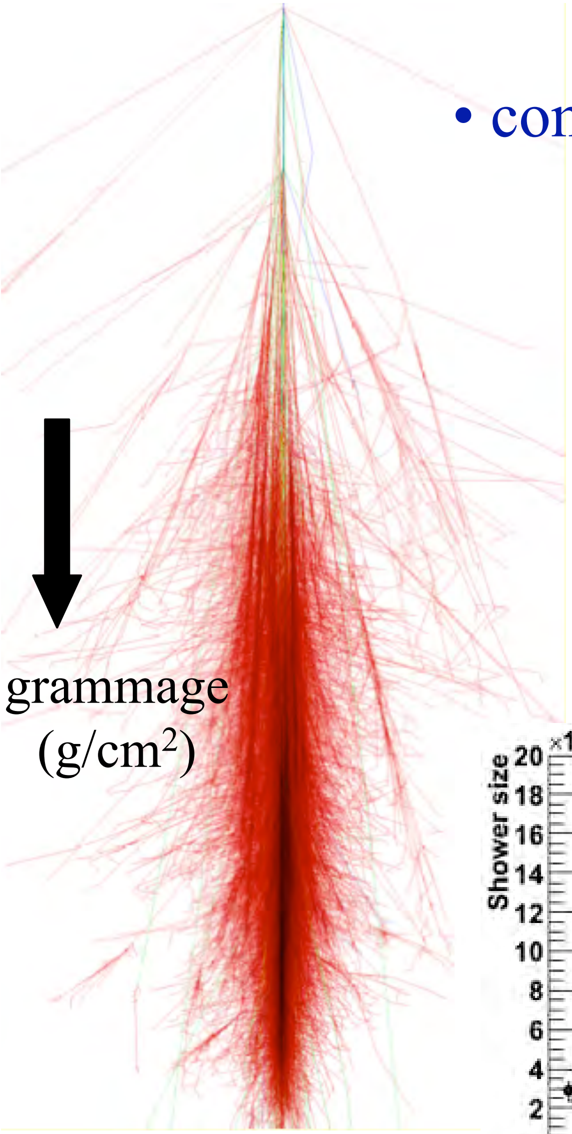
“hadronic”

uncertain at the highest energies
(hadronic-model dependent)

“EM”

subject to atmospheric
attenuation after maximum

High-energy CR detection



• comparison of observables with MC simulations

Fluorescence photons from atmosphere

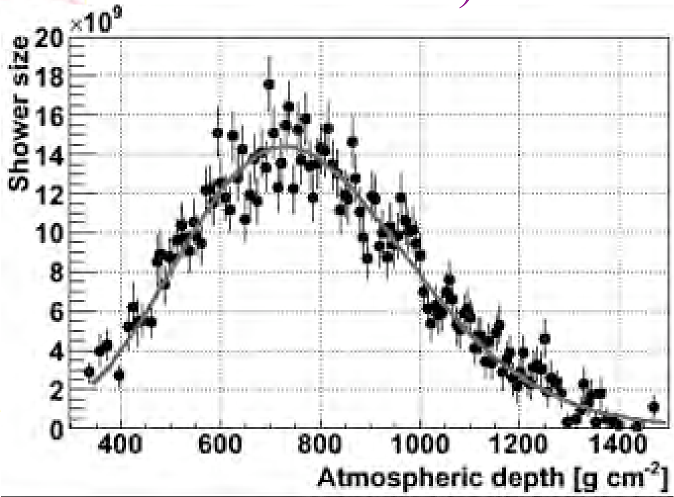
→ longitudinal shower development

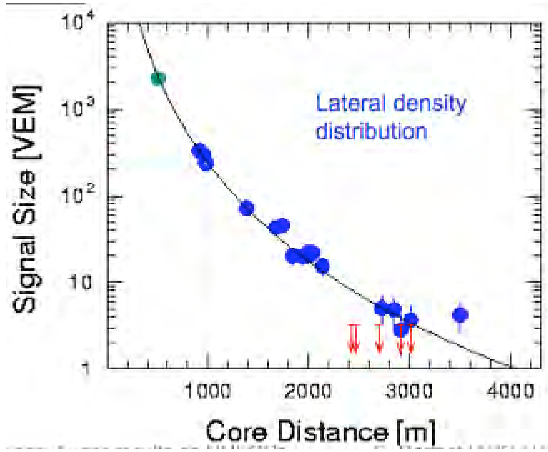
(sensible to EM sub-shower)

Density of shower particles on the ground

→ lateral distribution

(sensible to EM and hadronic sub-showers)





The Pierre Auger Observatory

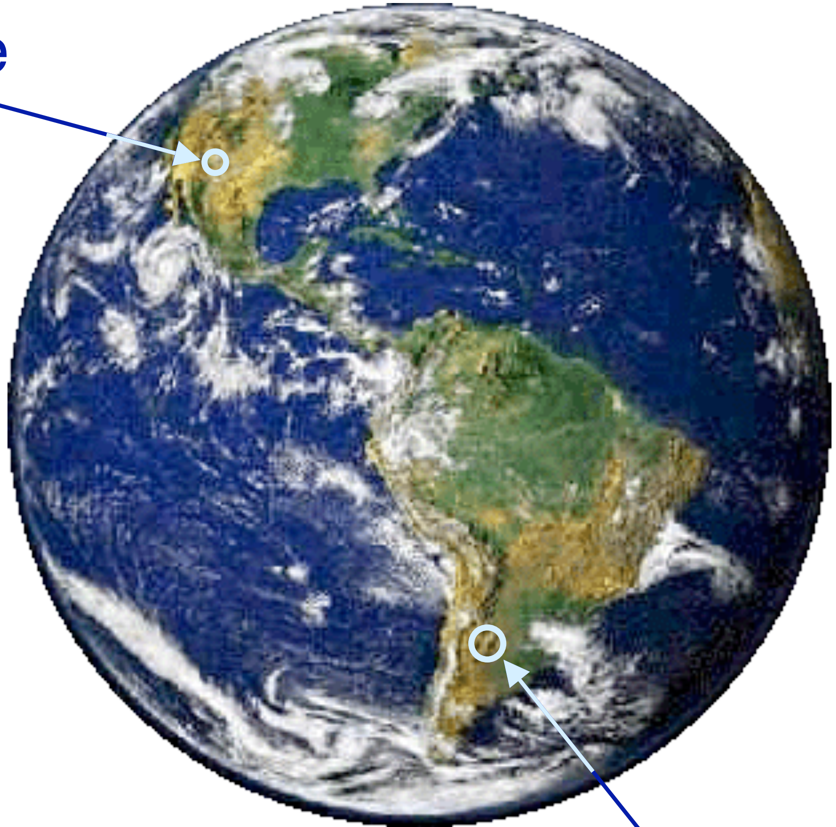
Northern site

20 000 km²

(still to be funded)

63 Institutions

369 Scientists



- *Participating Countries*

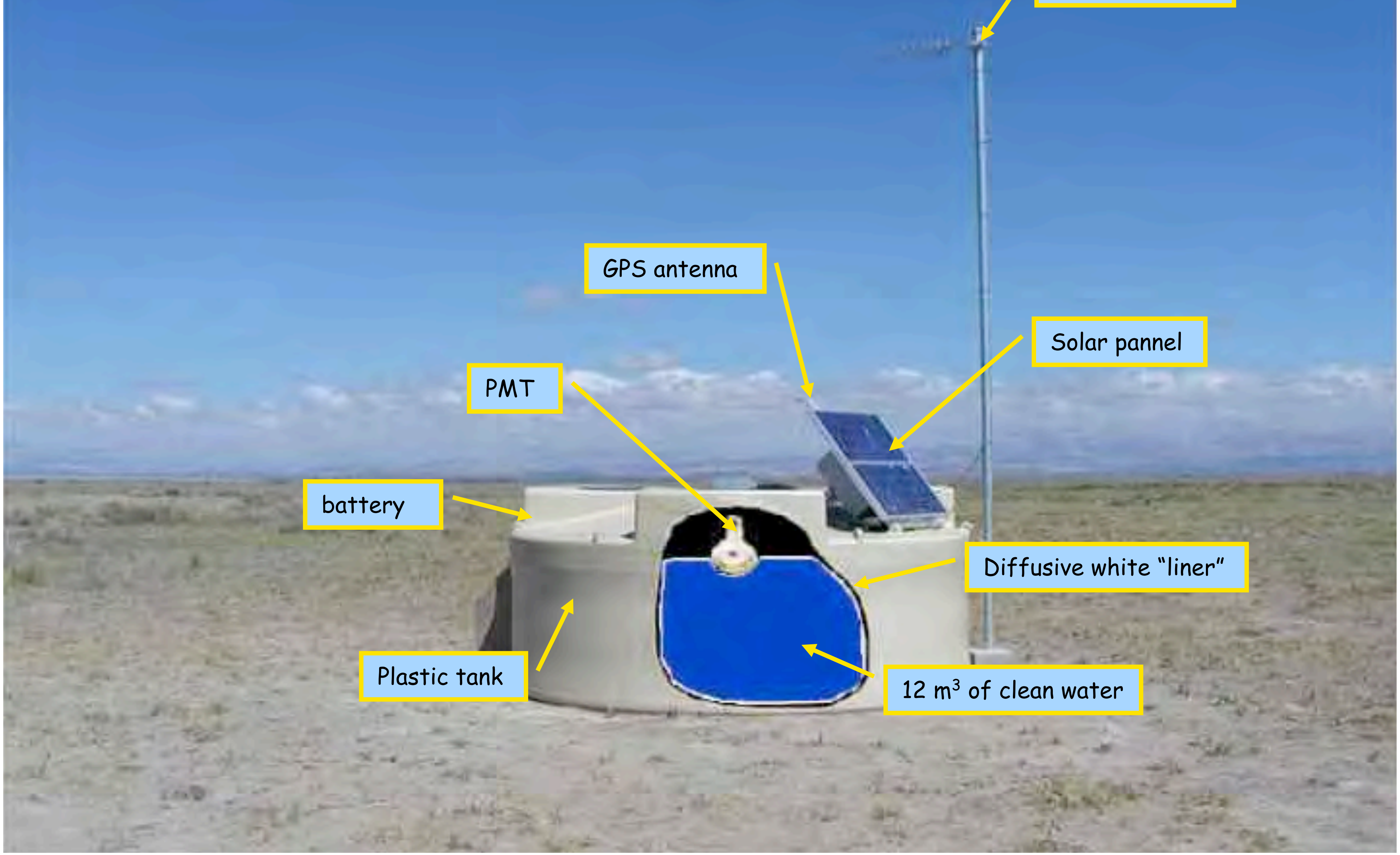
- Argentina
- Australia
- Brazil
- Czech Republic
- France (+ Vietnam)
- Germany
- Italy
- Mexico (+ Bolivia)
- Netherlands
- Poland
- Portugal
- Slovenia
- Spain
- United Kingdom
- USA

3 000 km²

Southern site

One of the Auger stations

(Cherenkov water tank)

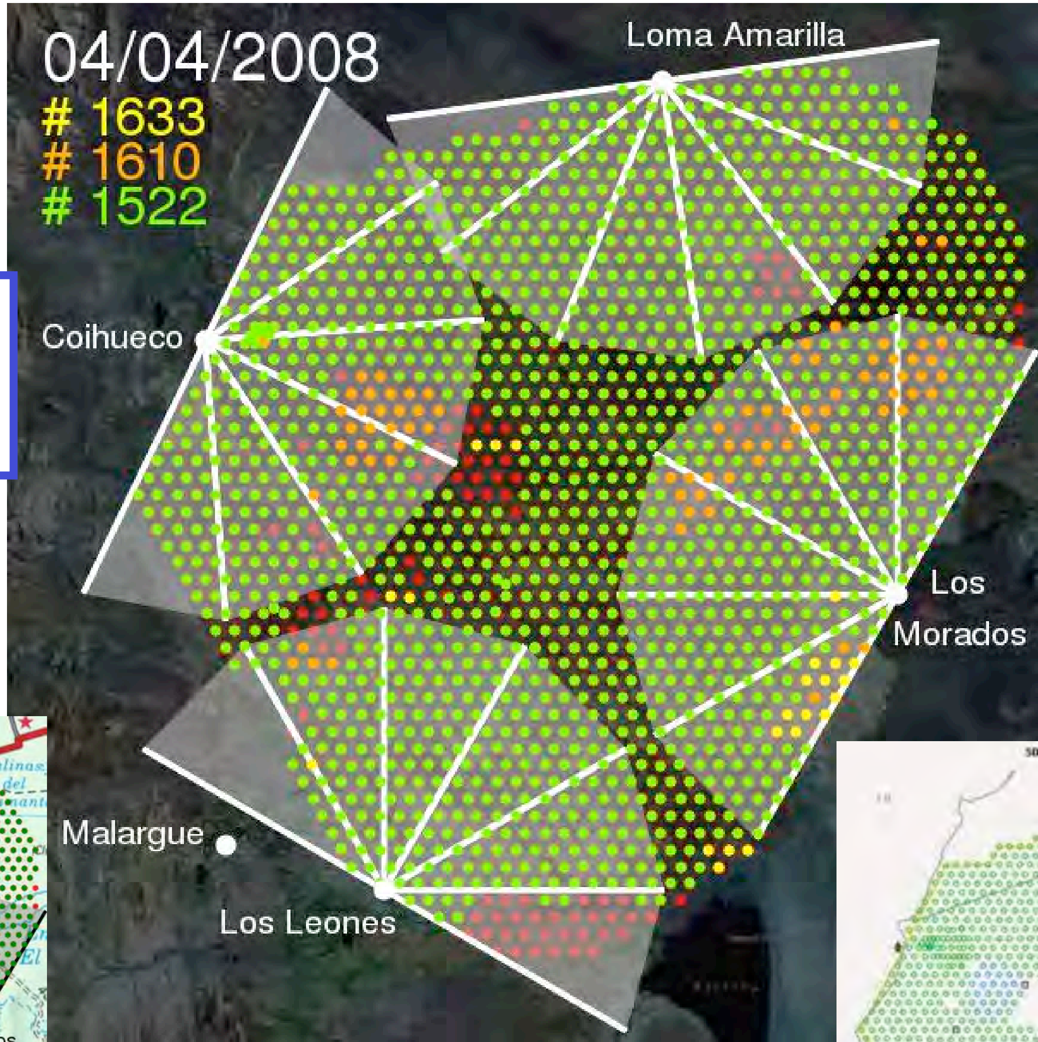


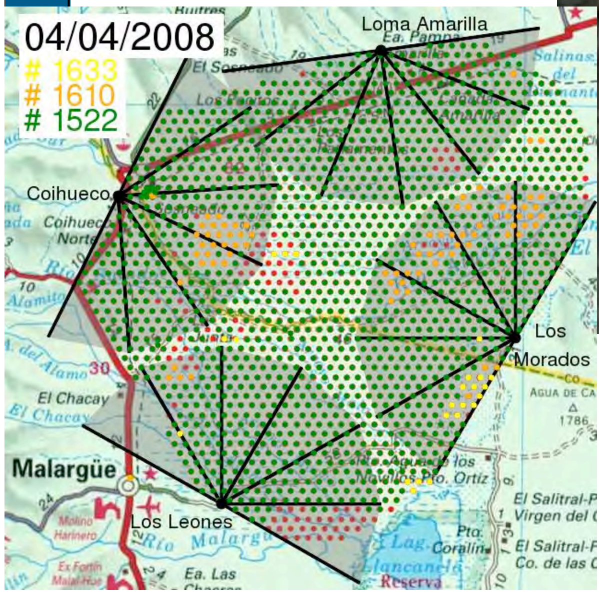
Hexagonal array (1.5 km spacing, 3000 km^2)

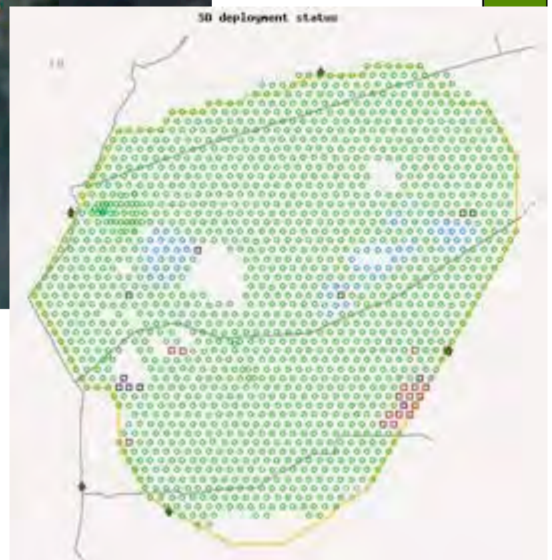
SD deployment (initial goal: 1600 tanks)

21st April 2008

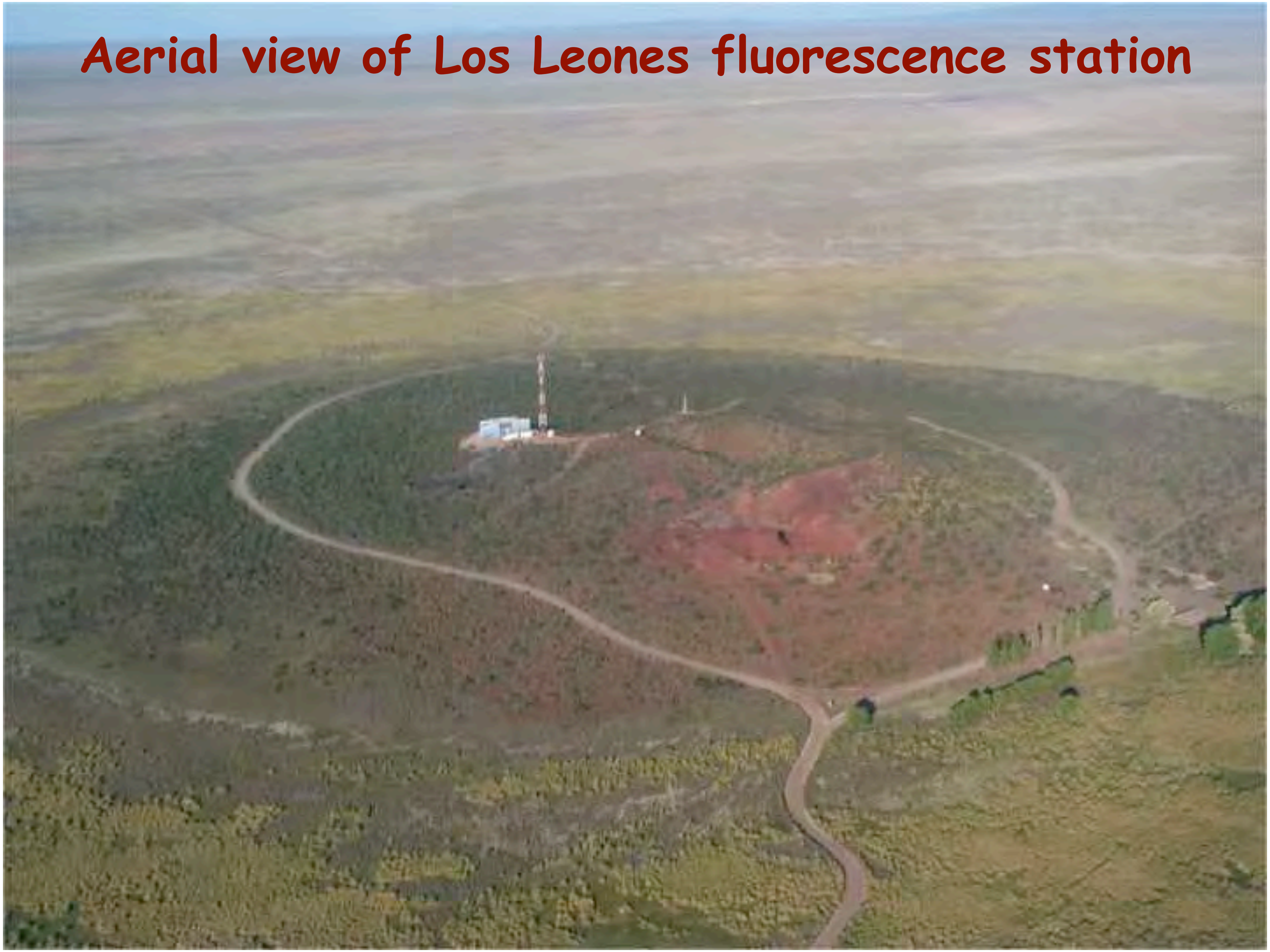
1637 deployed
1610 filled with water
1566 with electronics





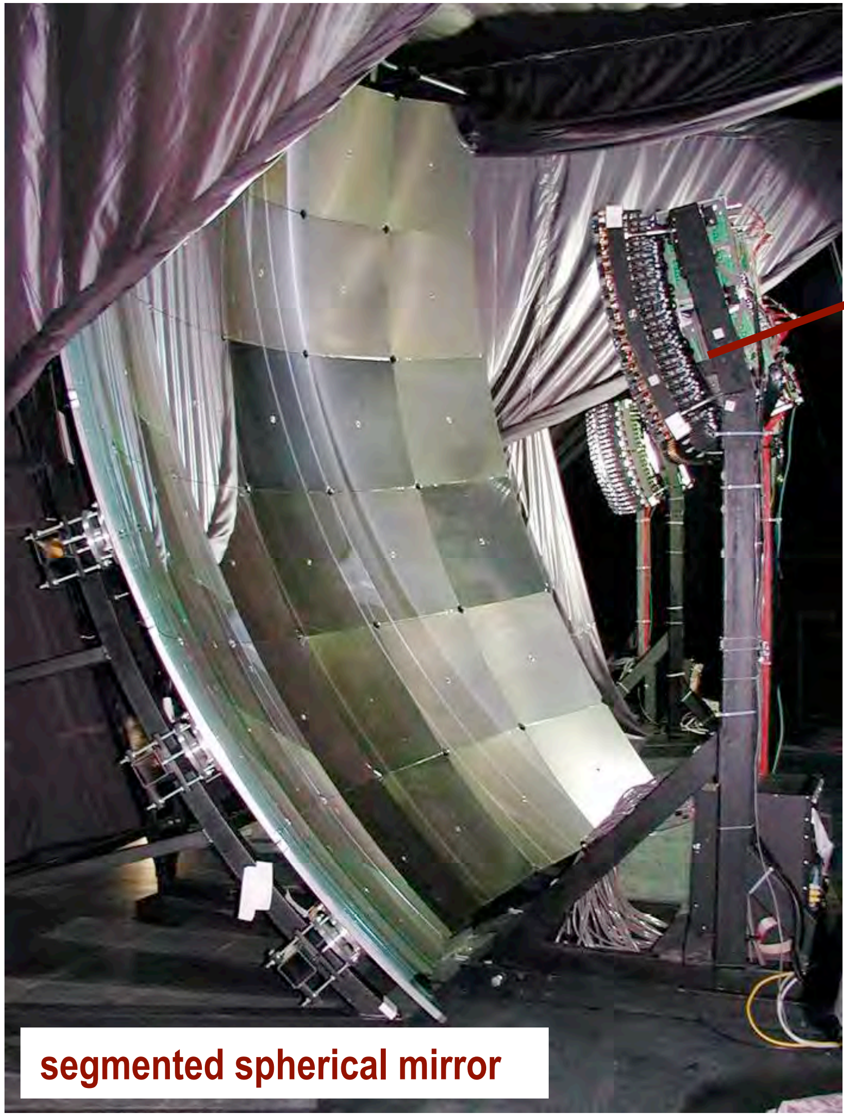


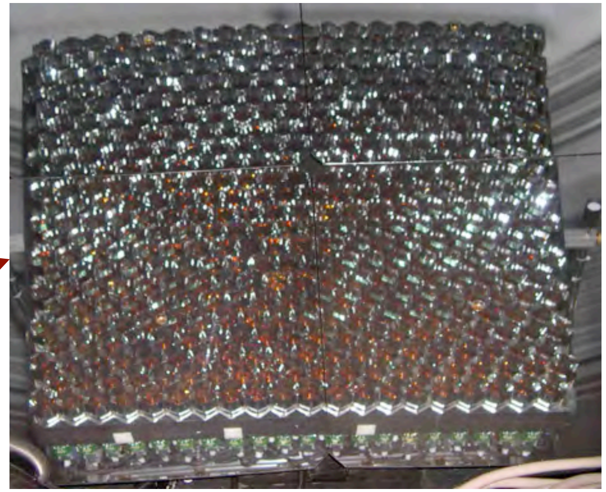
Aerial view of Los Leones fluorescence station



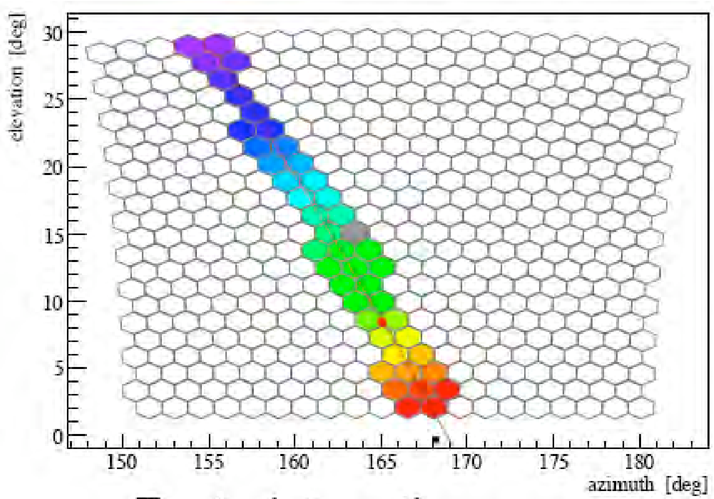
4 times 6 telescopes overlooking the site

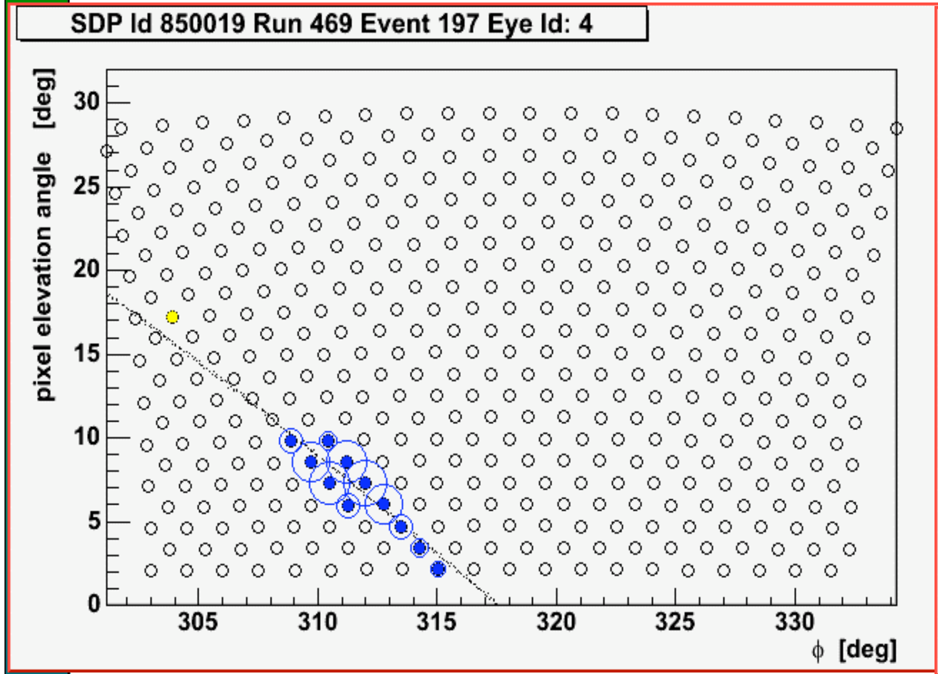
One of the fluorescence eyes

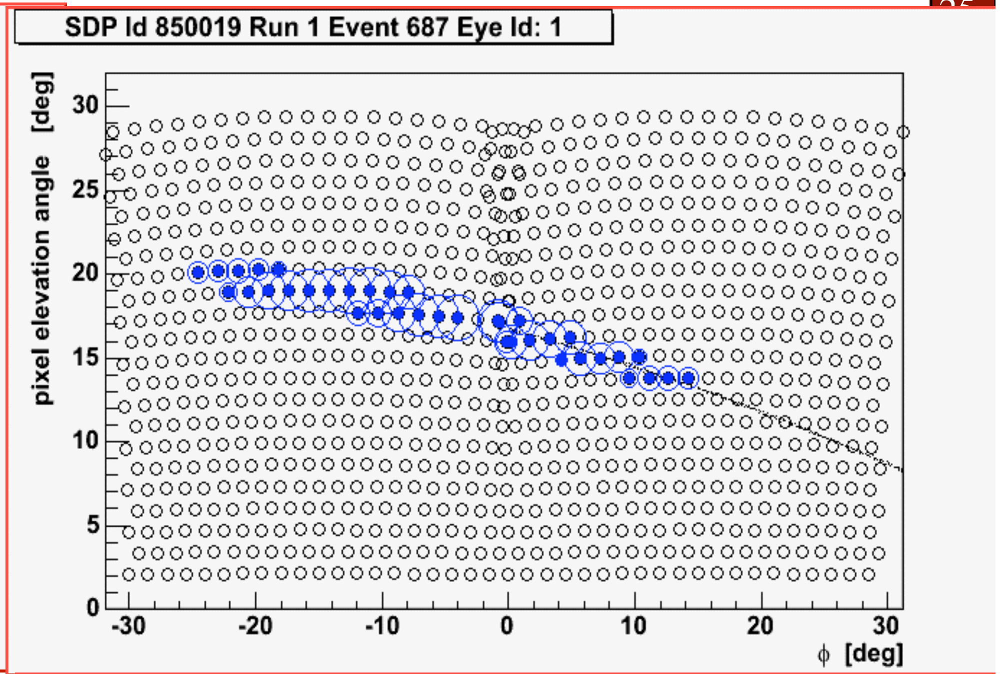


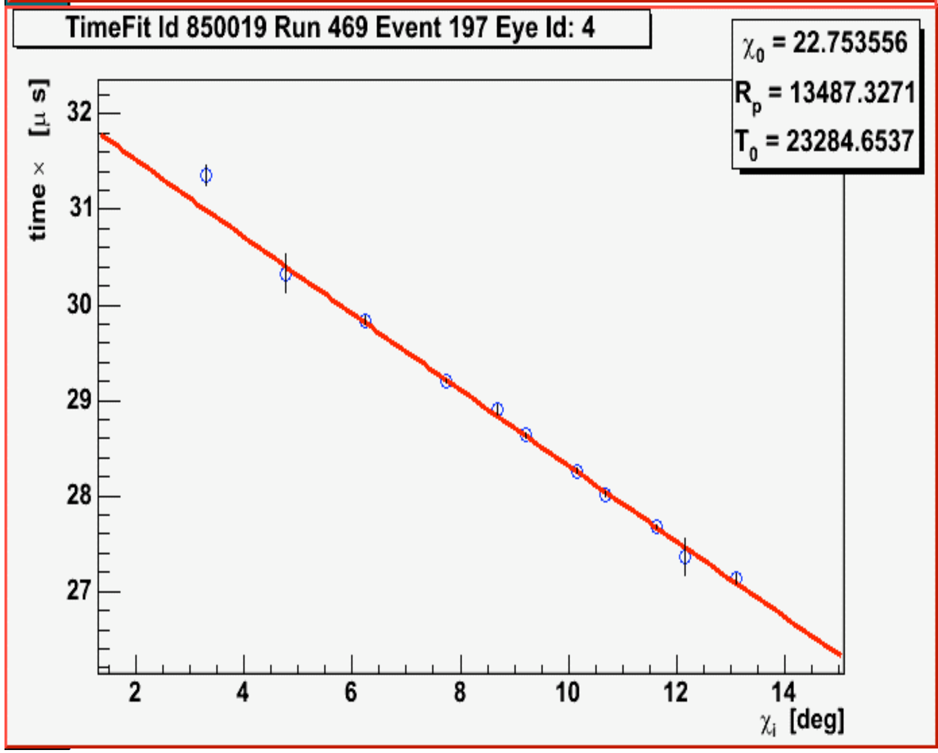


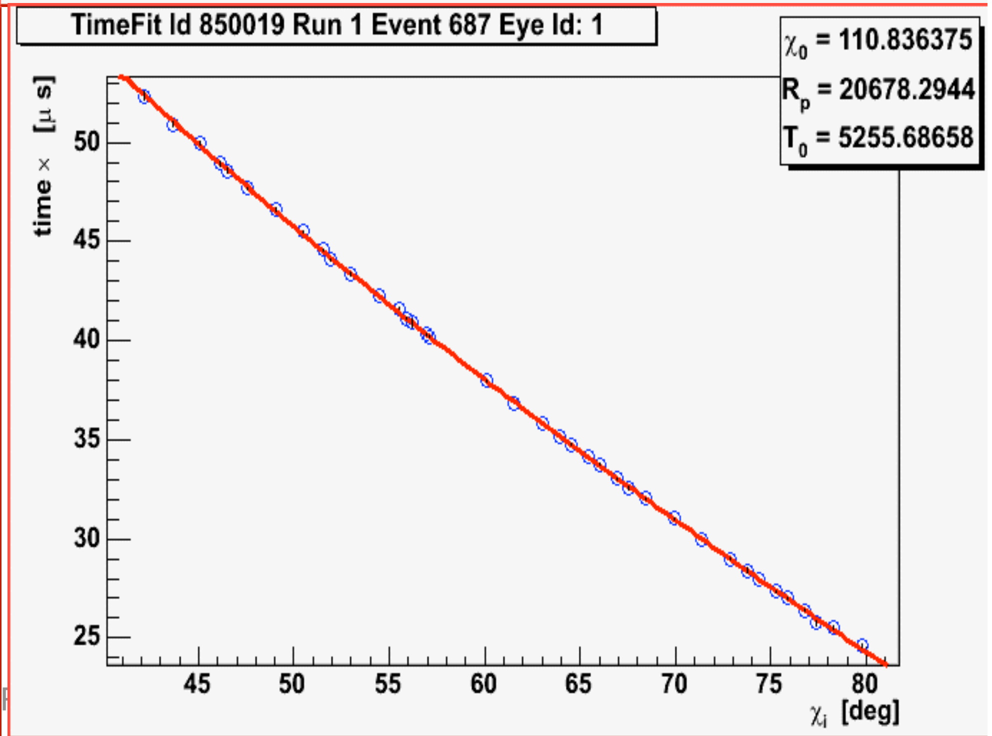
440 PMT camera 1.5° per pixel



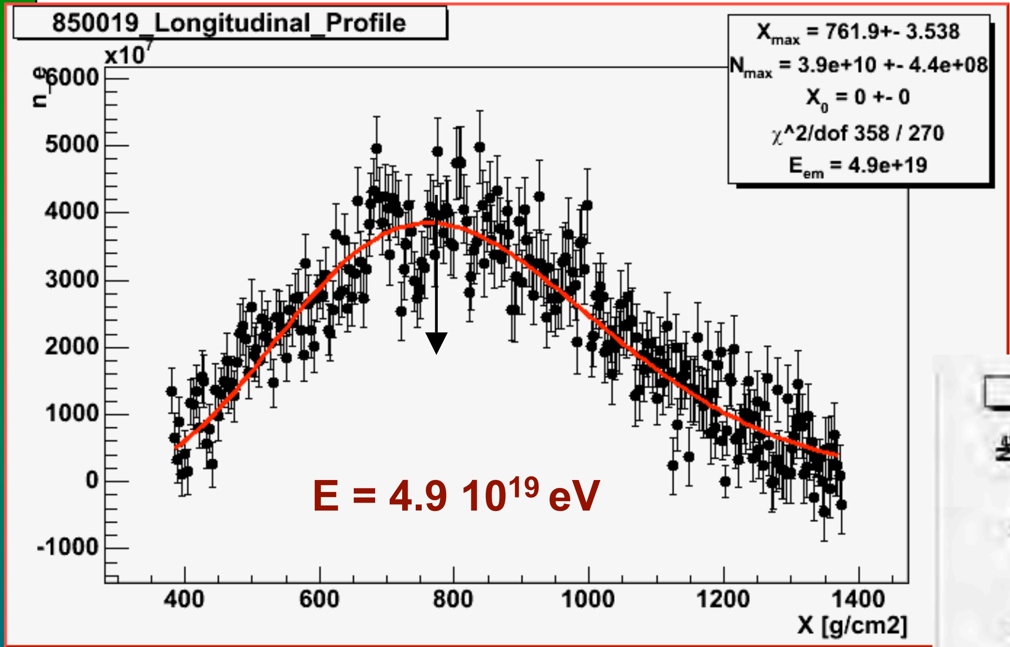

SDP Id 850019 Run 469 Event 197 Eye Id: 4
pixel elevation angle [deg]
φ [deg]


SDP Id 850019 Run 1 Event 687 Eye Id: 1
pixel elevation angle [deg]
φ [deg]

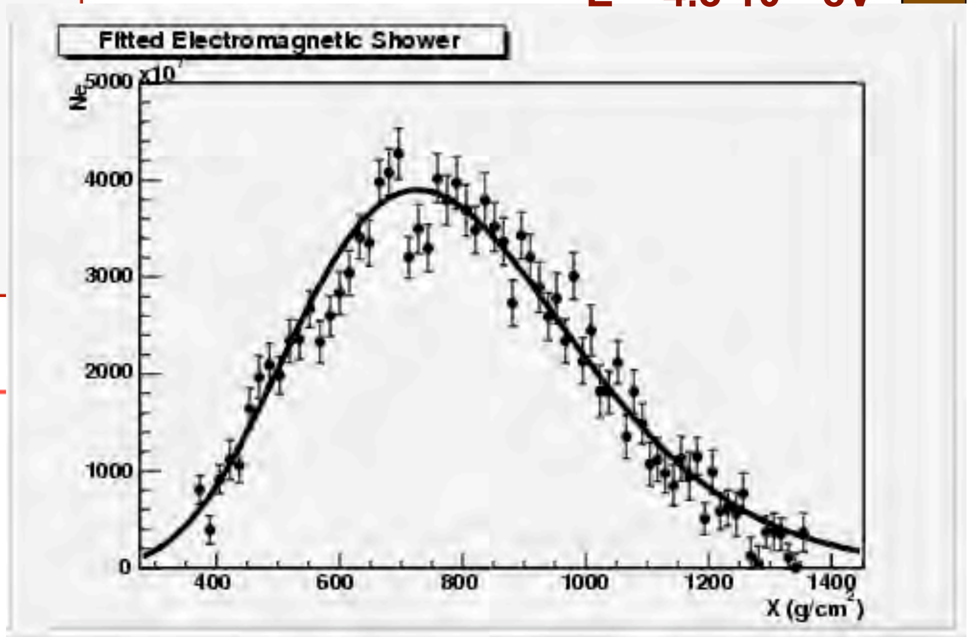

TimeFit Id 850019 Run 469 Event 197 Eye Id: 4
χ0 = 22.753556
Rp = 13487.3271
T0 = 23284.6537
time × [μ s]
χi [deg]

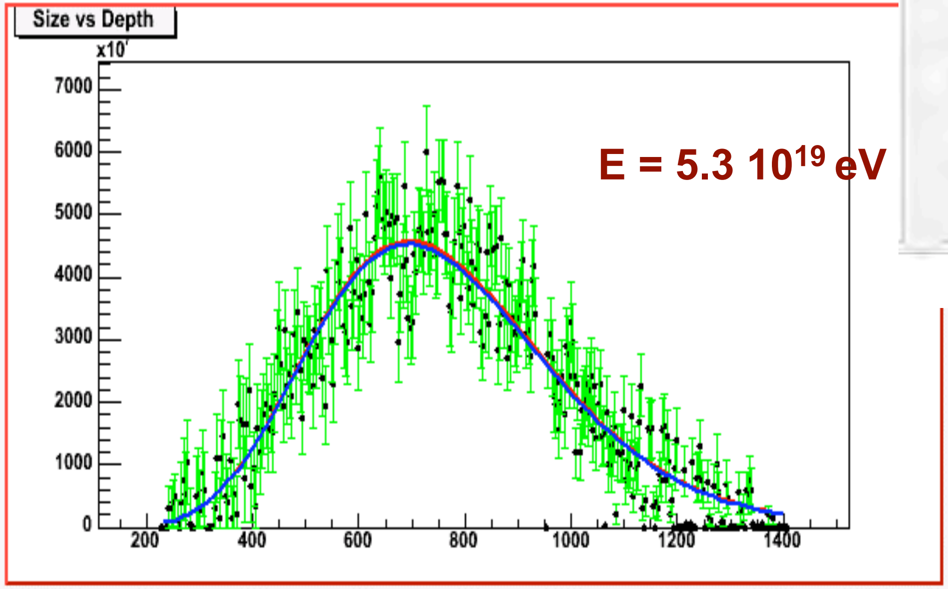

TimeFit Id 850019 Run 1 Event 687 Eye Id: 1
χ0 = 110.836375
Rp = 20678.2944
T0 = 5255.68658
time × [μ s]
χi [deg]

Independent analyses of stereo events



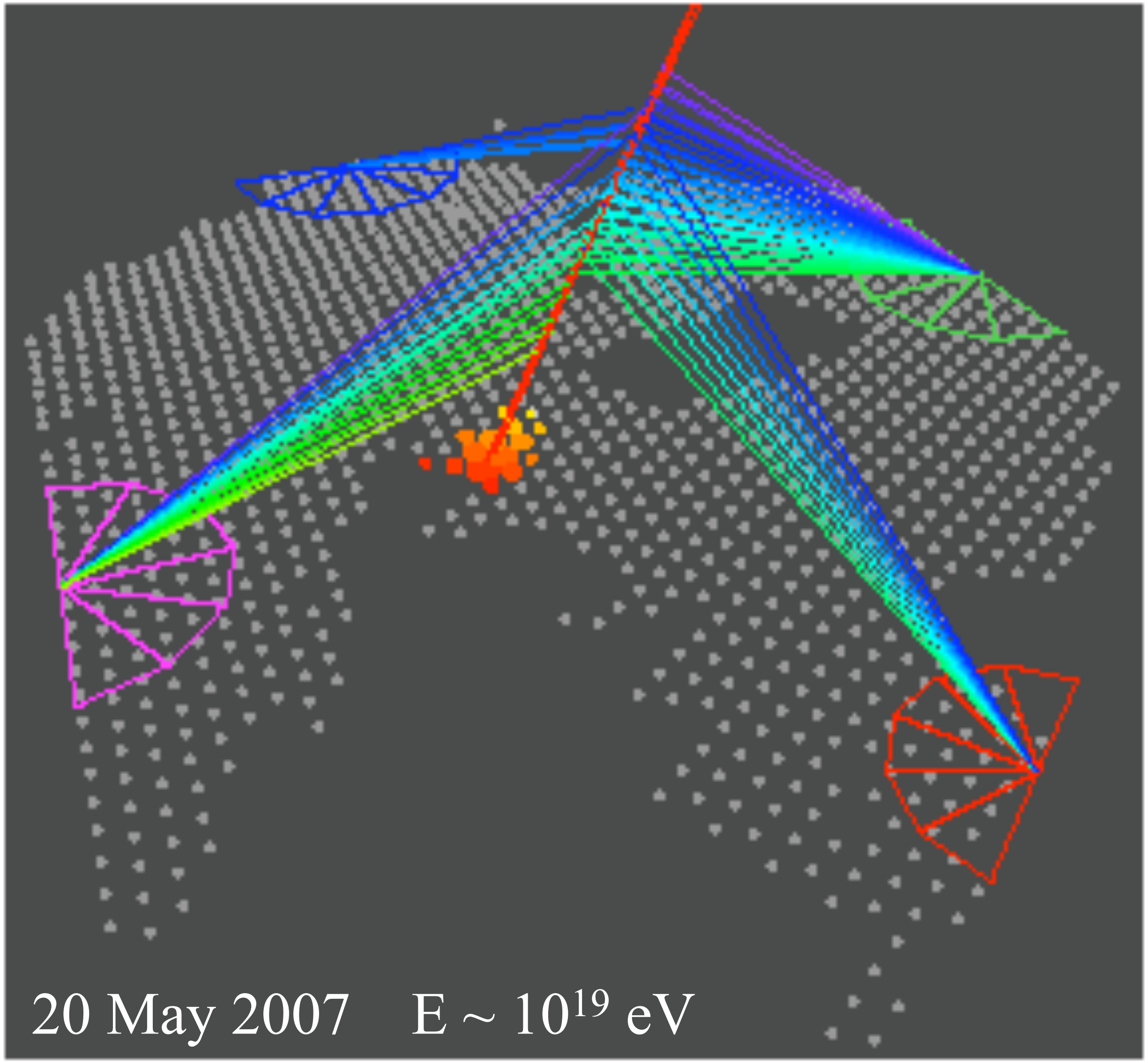
E = 4.8 10^{19} eV





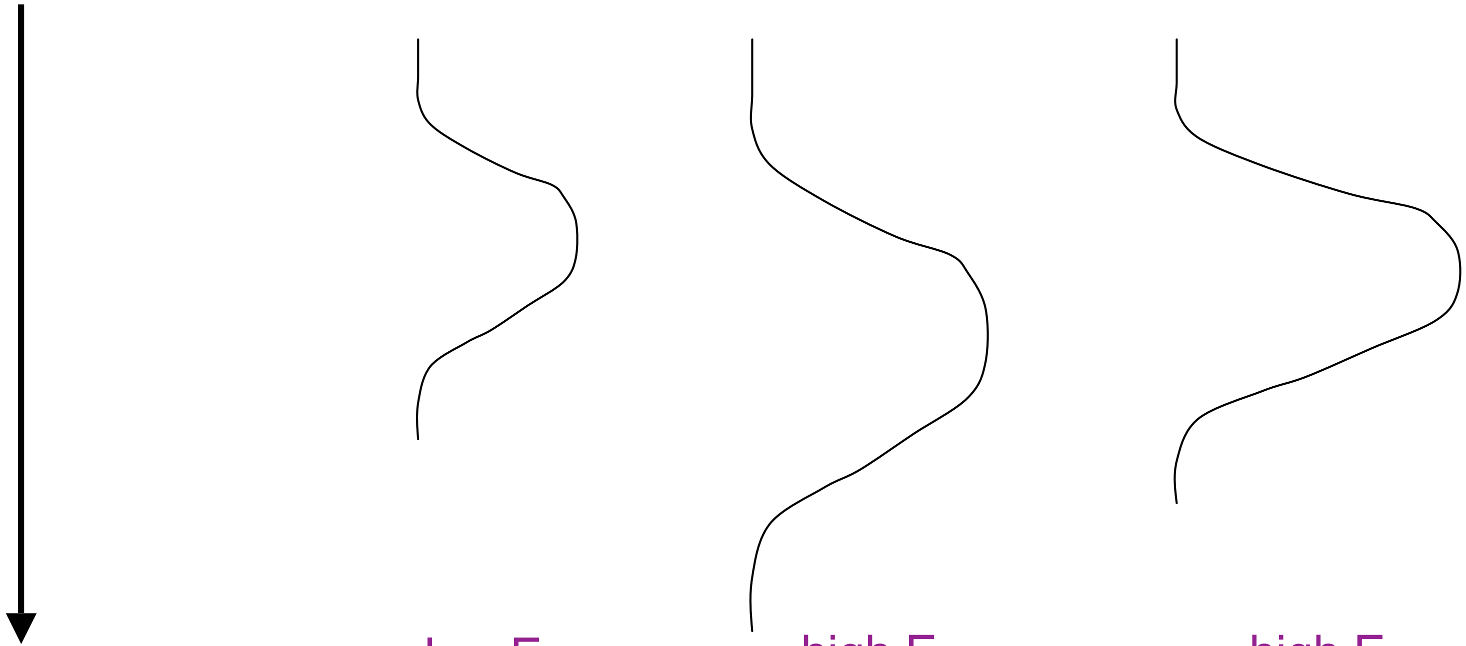
E_{em} calculated by fitting a GH profile and integrating

First 4-fold hybrid event!



Composition-sensitive observable

- Depth of shower maximum development: X_{max}



atmospheric depth (g/cm²)

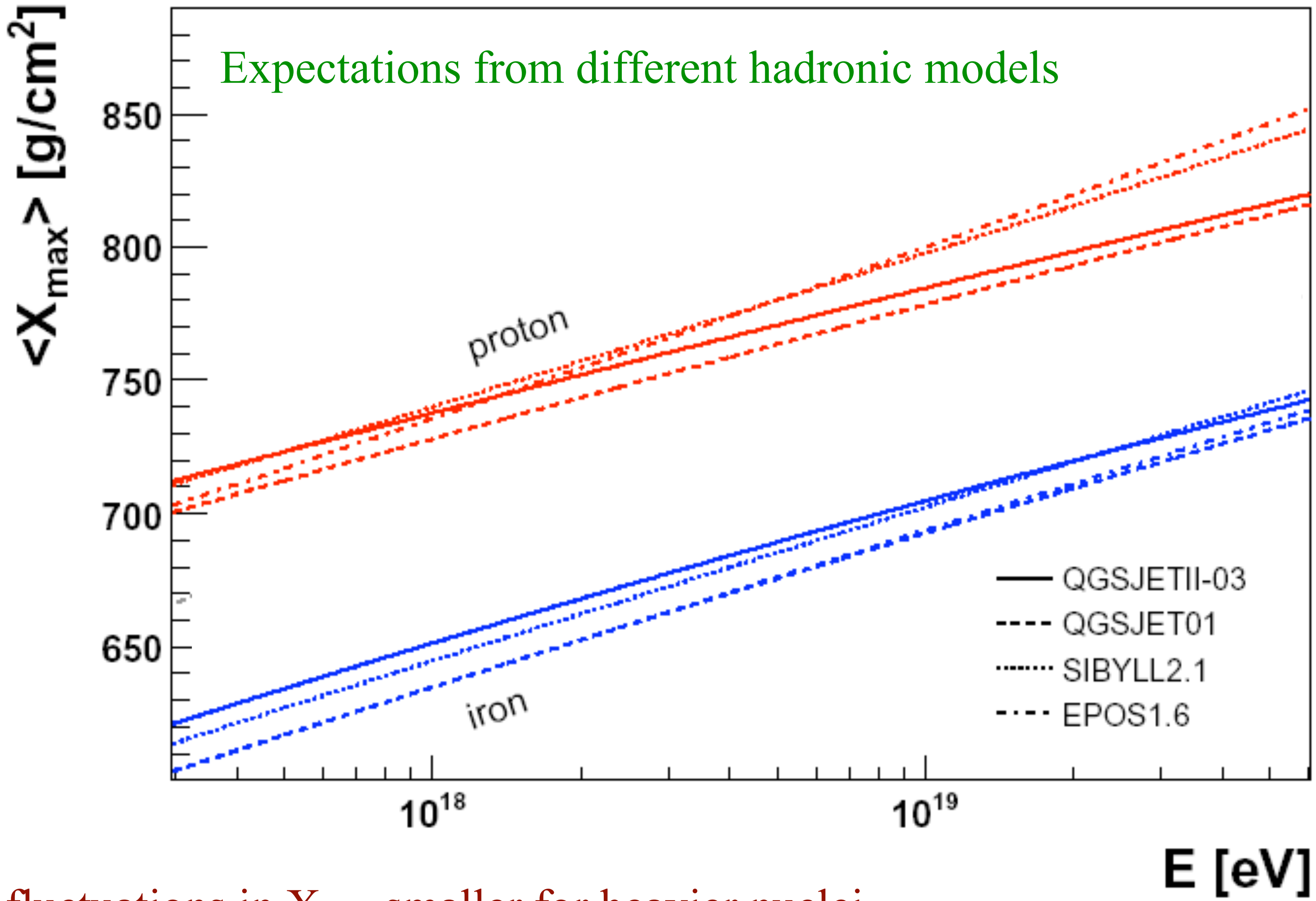
low E

high E
low A
↓
large fluctuations

high E
high A
↓
small fluctuations

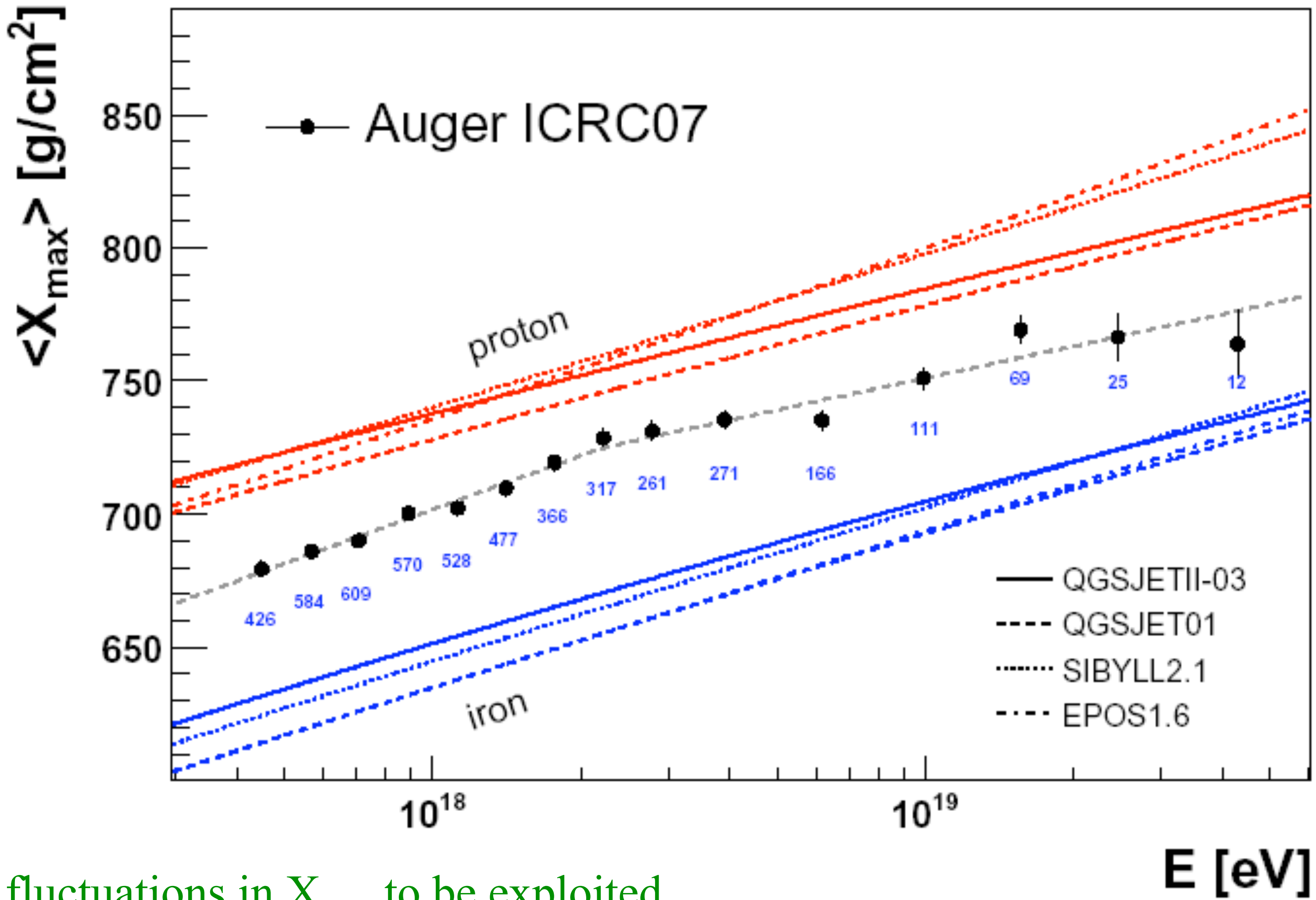
- Stochastic process

Atmospheric depth of shower maximum



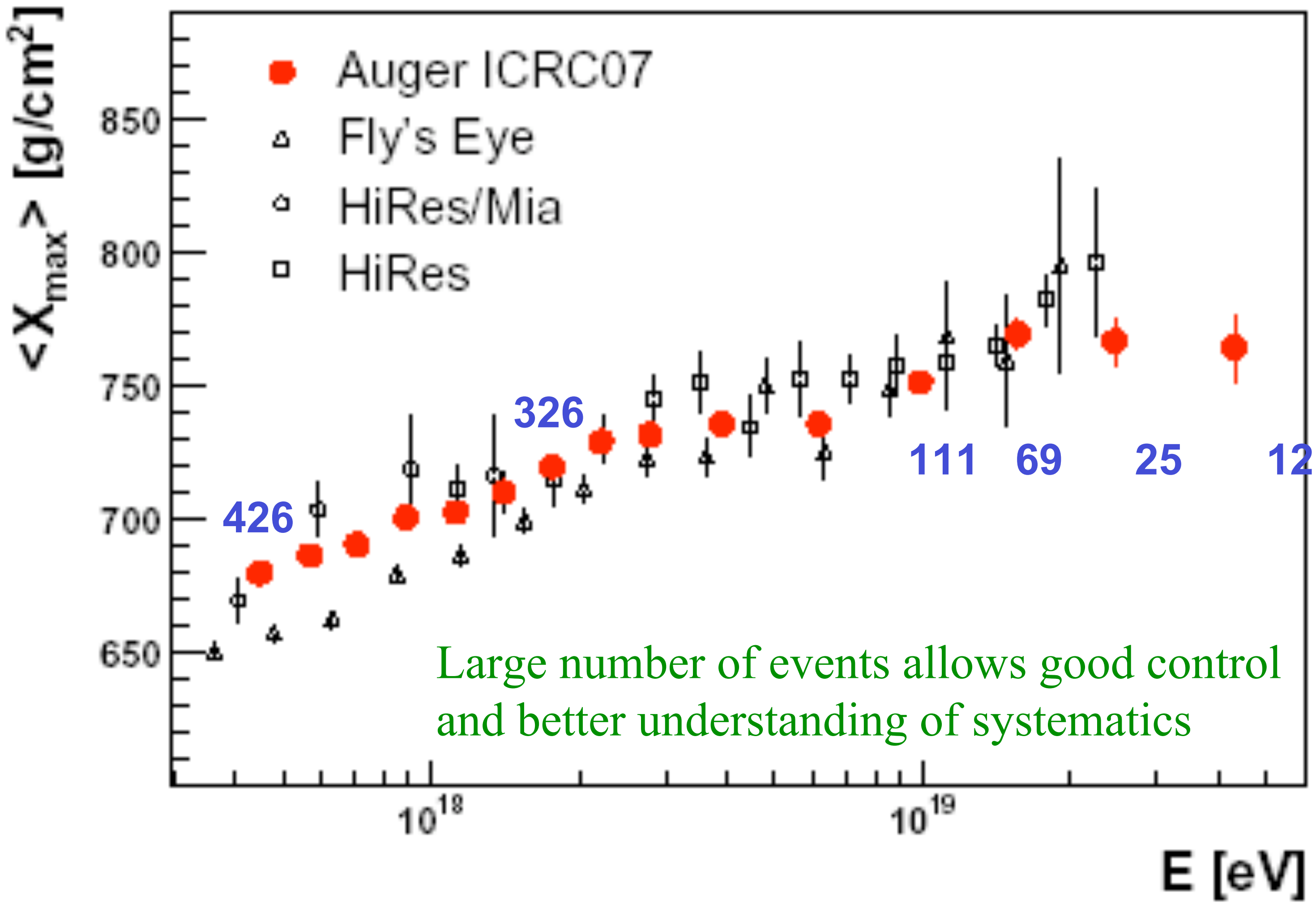
+ fluctuations in X_{max} smaller for heavier nuclei

Shower maximum measured over 2 decades in E



+ fluctuations in X_{max} to be exploited

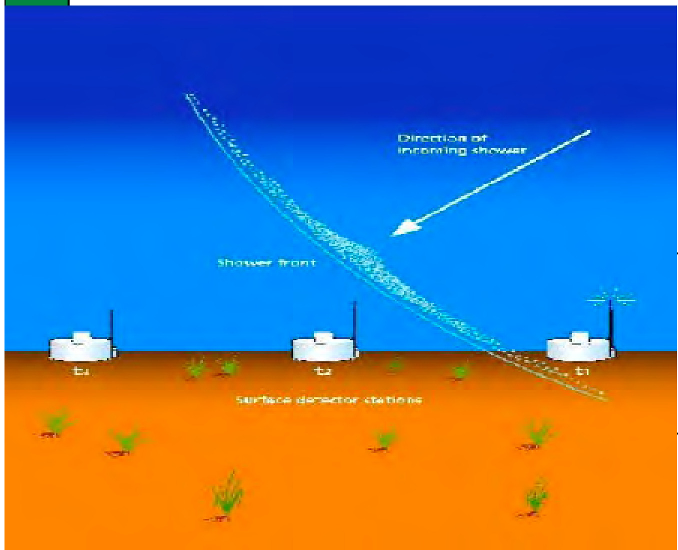
Comparison with previous studies



+ strong upper limits on UHE photons:
top-down models essentially excluded

Energy reconstruction with surface detector

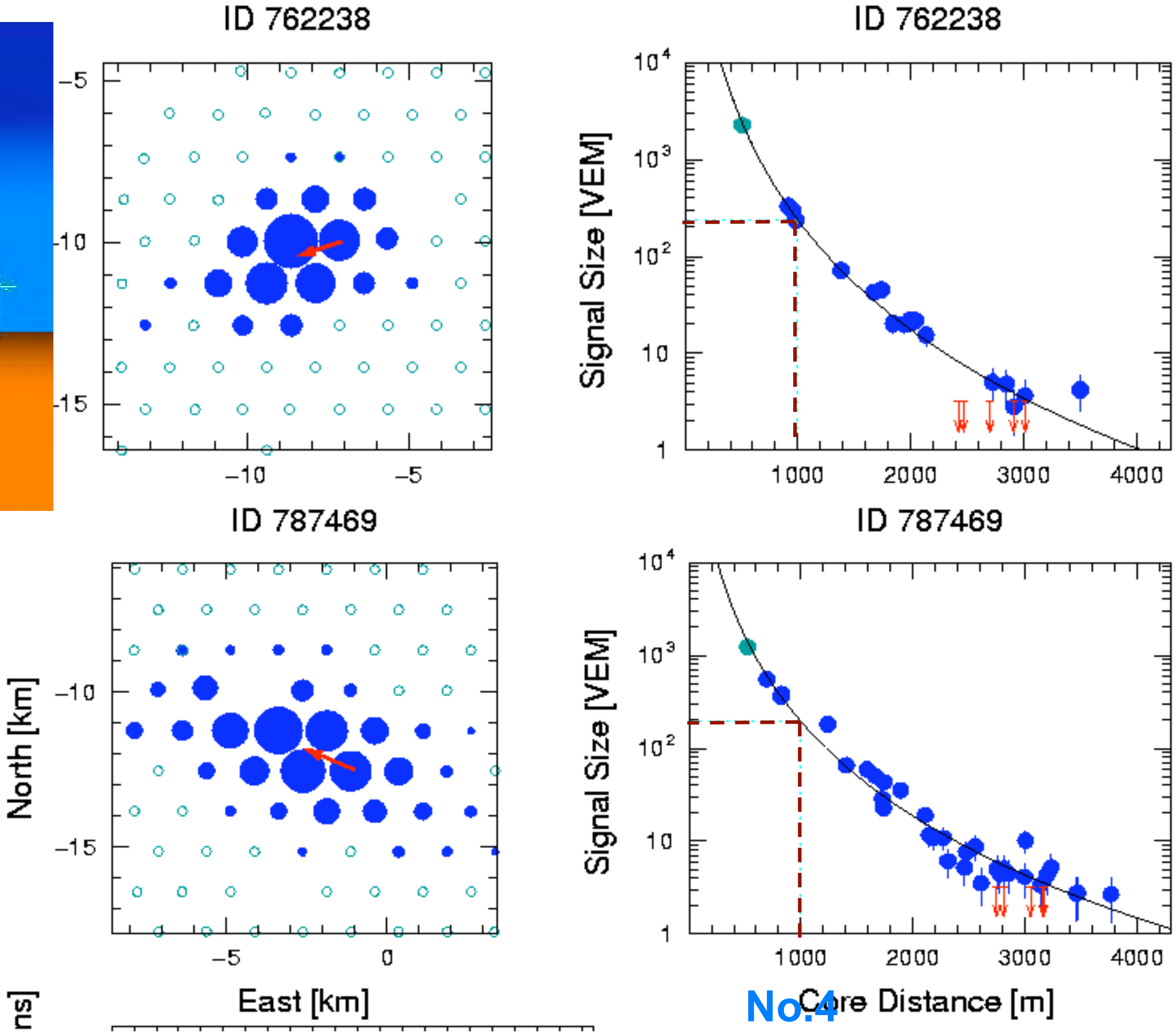
- SD energy estimator: interpolated signal in a tank at 1000 meters and 38°



timing information available for triangulation

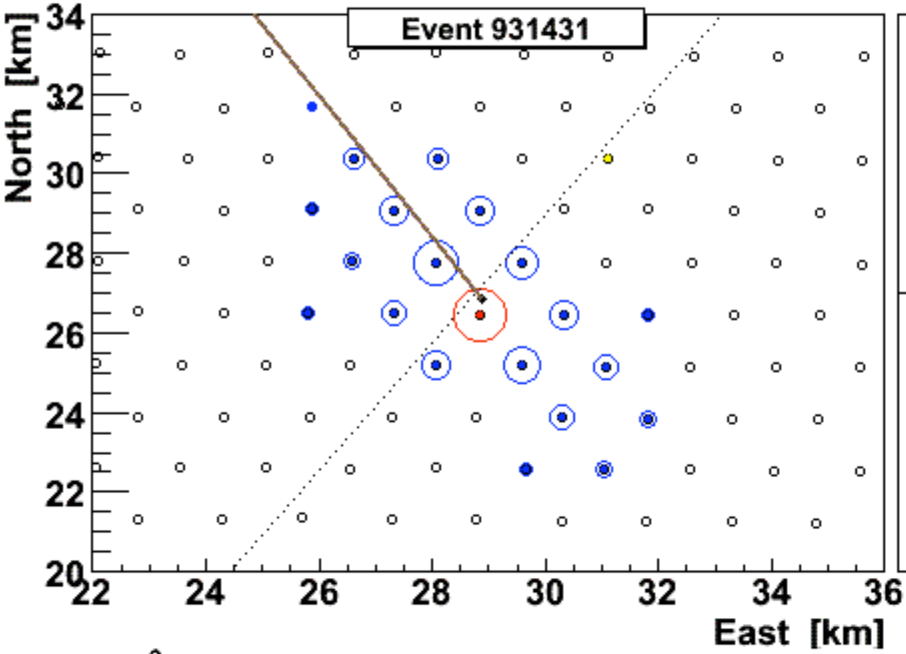
⇓

geometry reconstruction (arrival direction)



No.4

Example of a Hybrid Event



Core location

Easting 468693 $\pm$ 59

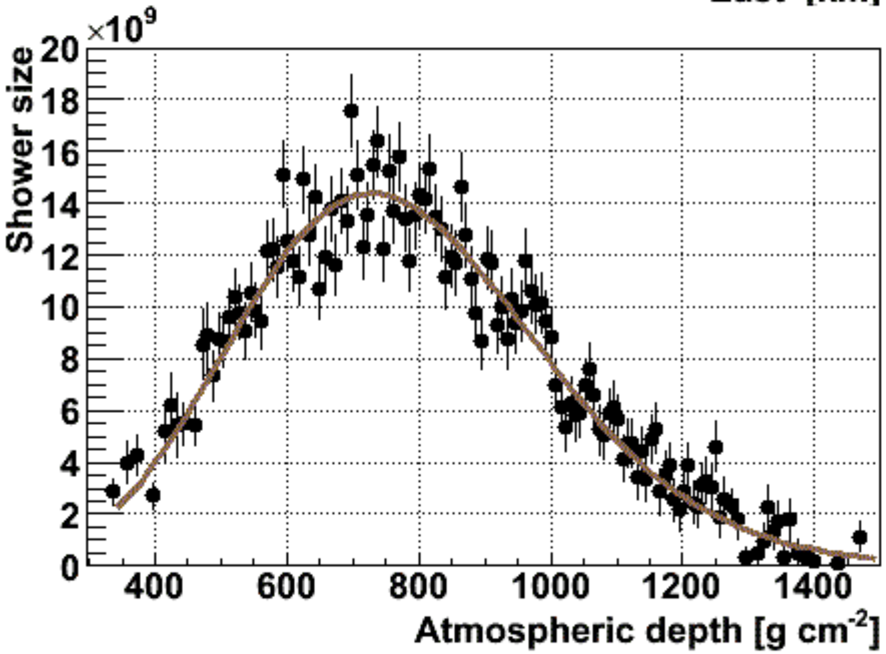
Northing 6087022 $\pm$ 80

Altitude = 1390 m a.s.l.

Shower Axis

$\theta = (62.3 \pm 0.2)^\circ$

$\phi = (119.7 \pm 0.1)^\circ$



Energy Estimate:

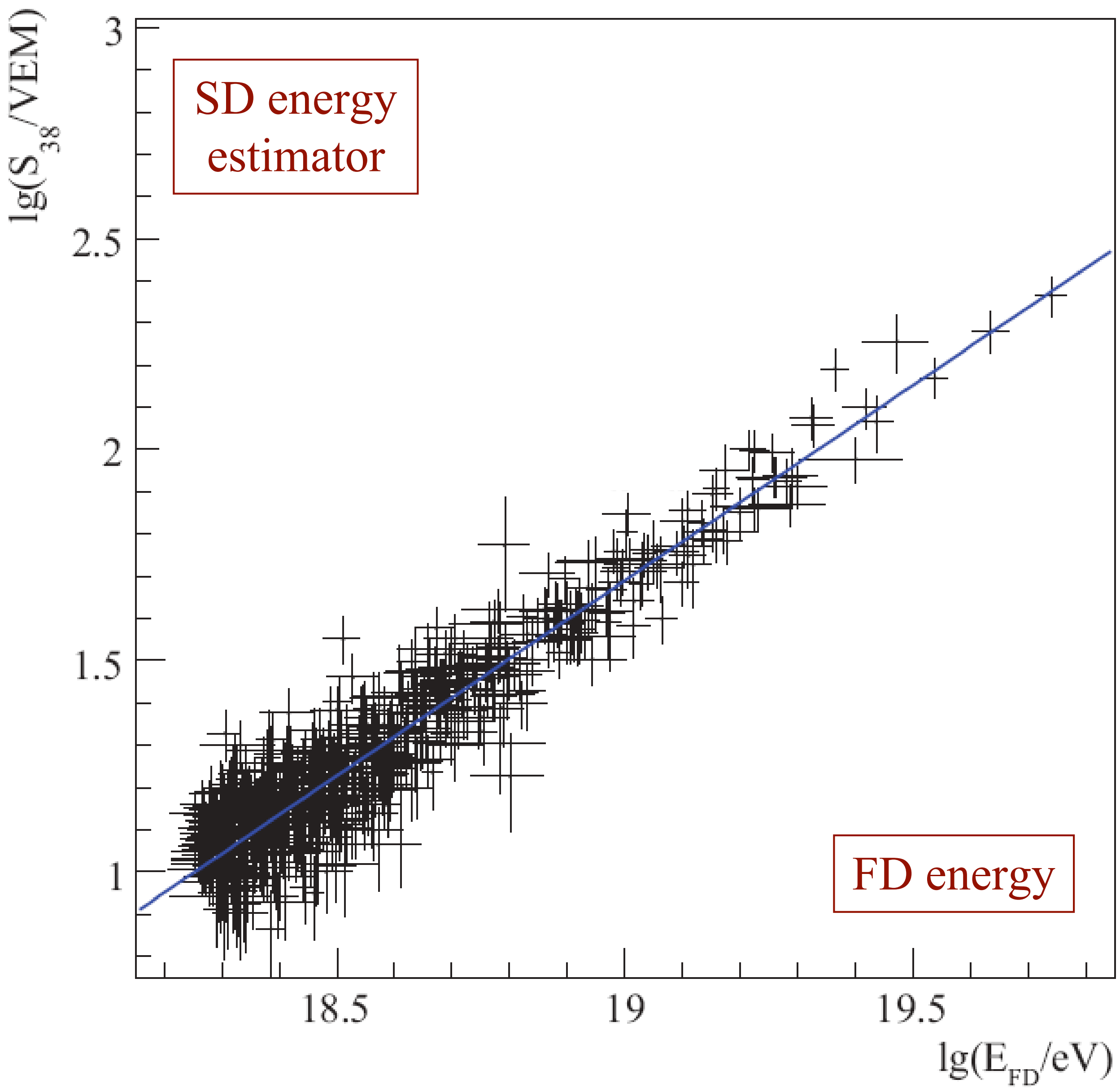
$X_{max} = (728 \pm 20)$ g cm^{-2}

χ^2/dof = 258 / 134

$E_{em} = (21 \pm 5)$ EeV

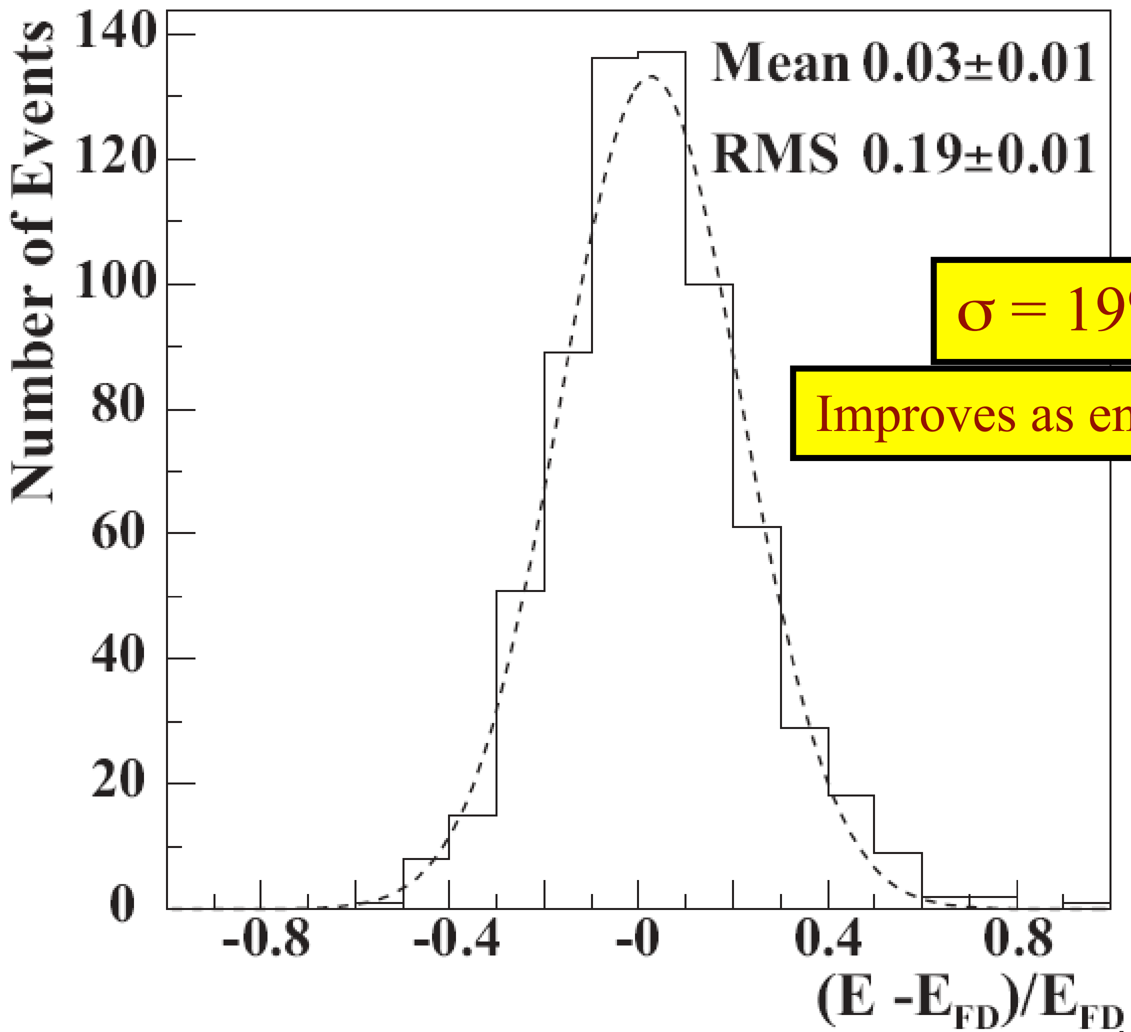
$E_{tot} = (23 \pm 6)$ EeV

Cross-calibration of the detectors



Cross-calibration of the detectors

Fractional dispersion of FD/SD energy estimates

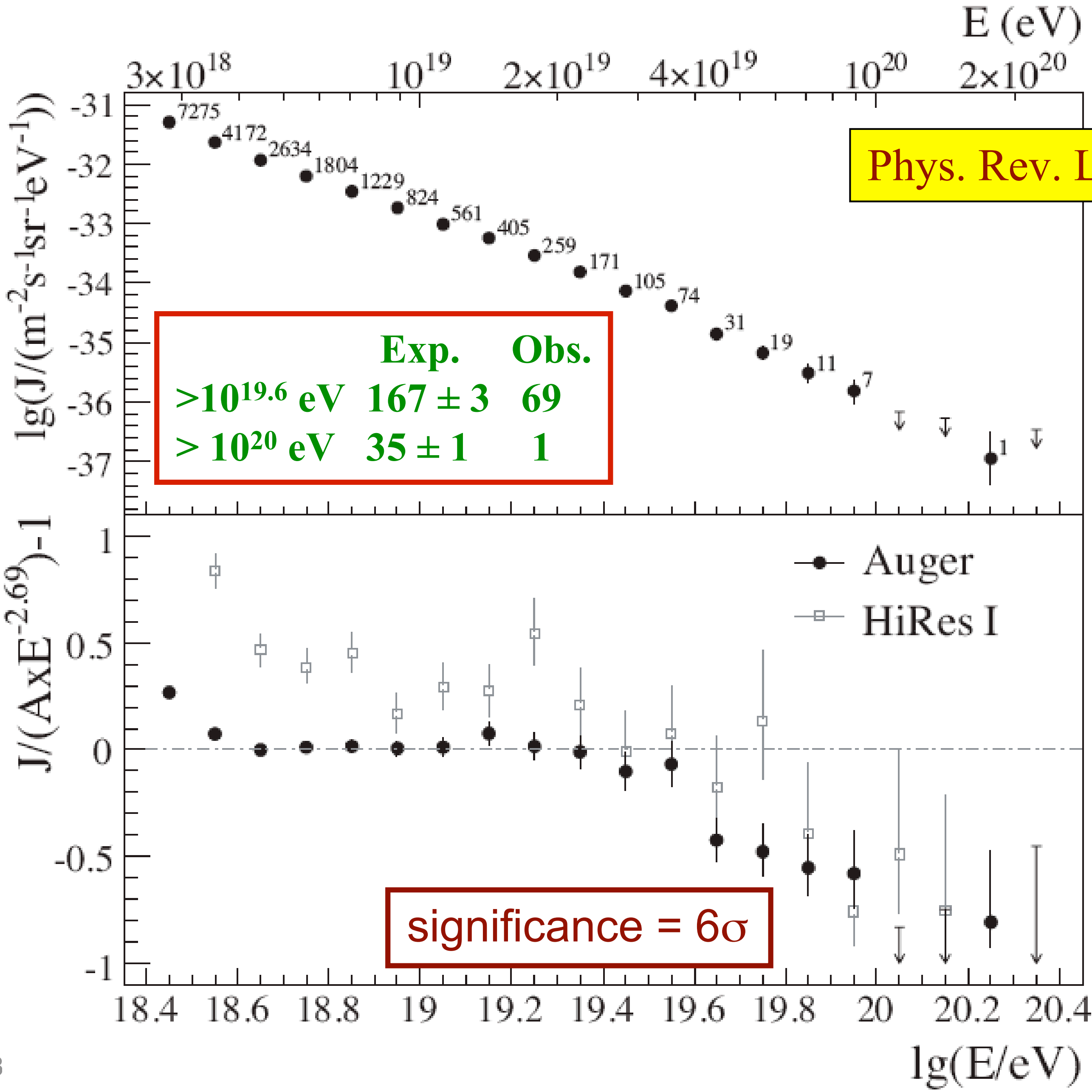


σ = 19%

Improves as energy increases!

Very good estimator !

Energy spectrum from SD showers with θ ≤ 60°

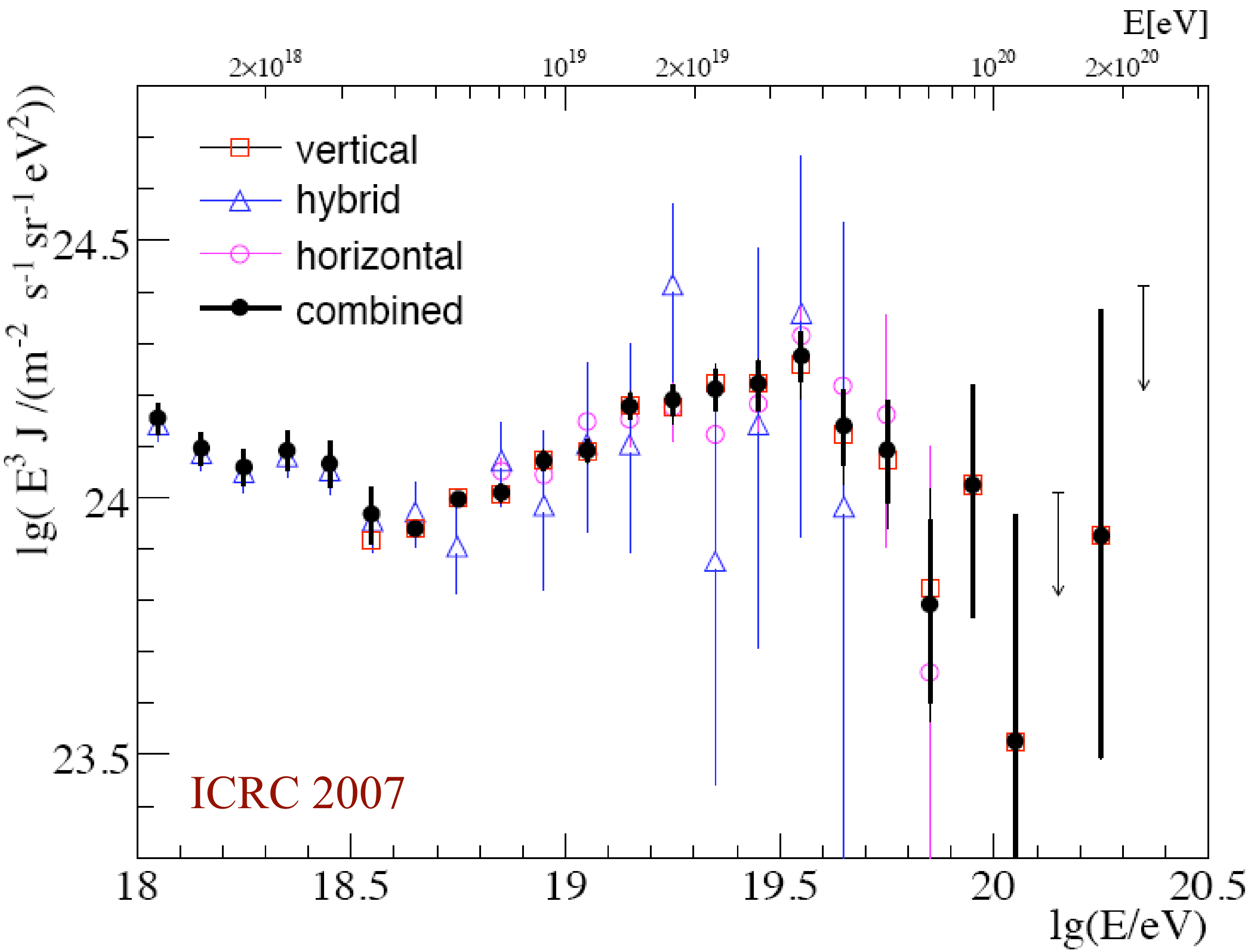


Phys. Rev. Lett. 2008

	Exp.	Obs.
$>10^{19.6}$ eV	167 ± 3	69
$> 10^{20}$ eV	35 ± 1	1

significance = 6σ

Auger energy spectrum



Auger anisotropy results

- Angular resolution of ~1°: good enough!
- No large-scale signal (dipole) at any energy above 1 EeV

  e.g. $\alpha < 0.7\%$ for $1\ \text{EeV} \leq E \leq 3\ \text{EeV}$
- No significant excess emission from Galactic center
- No signal from BL-Lacs as possibly seen by HiRes

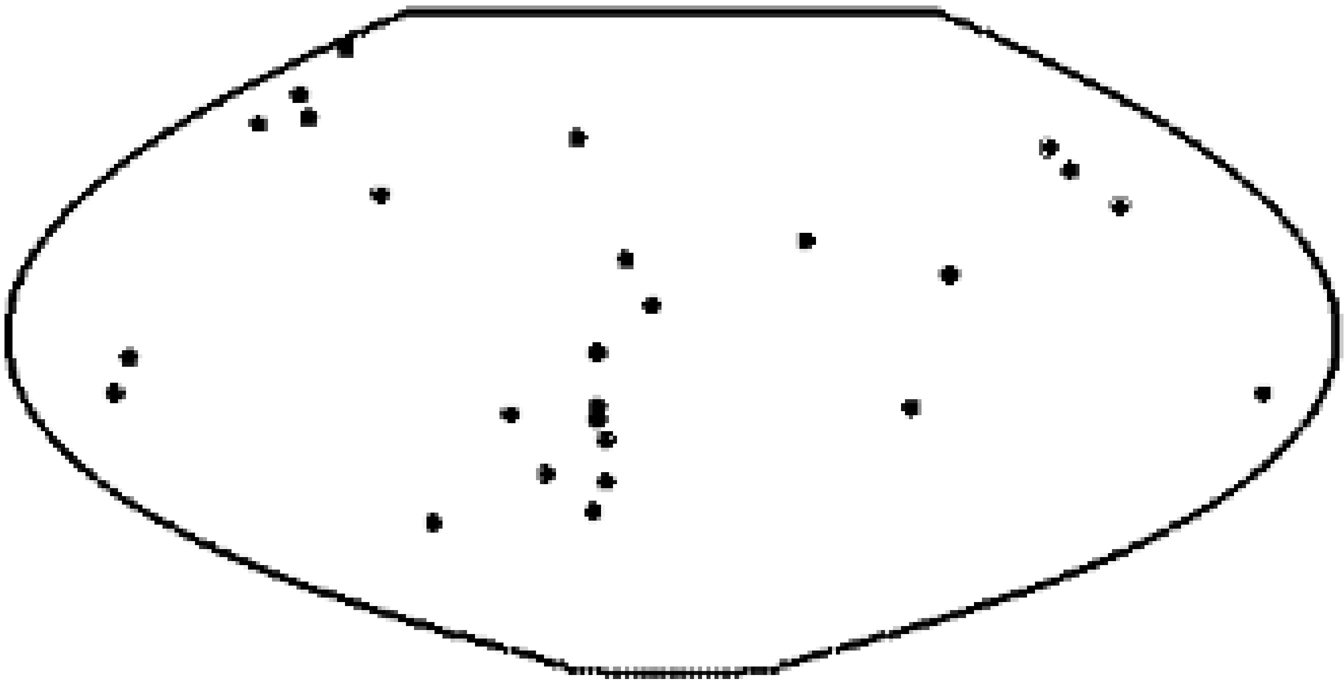
⟹ none of the previous reports have been confirmed…

Auger main anisotropy result

- Highest energy cosmic rays have an anisotropic distribution!
- First evidence that cosmic-ray astronomy is indeed possible!
- Correlation with the most nearby AGNs in the 12th Véron-Cetty/Véron catalogue
- Opening of a new era:
  - Study of particle acceleration in high-energy astrophysical sources
  - Multi-messenger study of sources
  - High-energy physics!

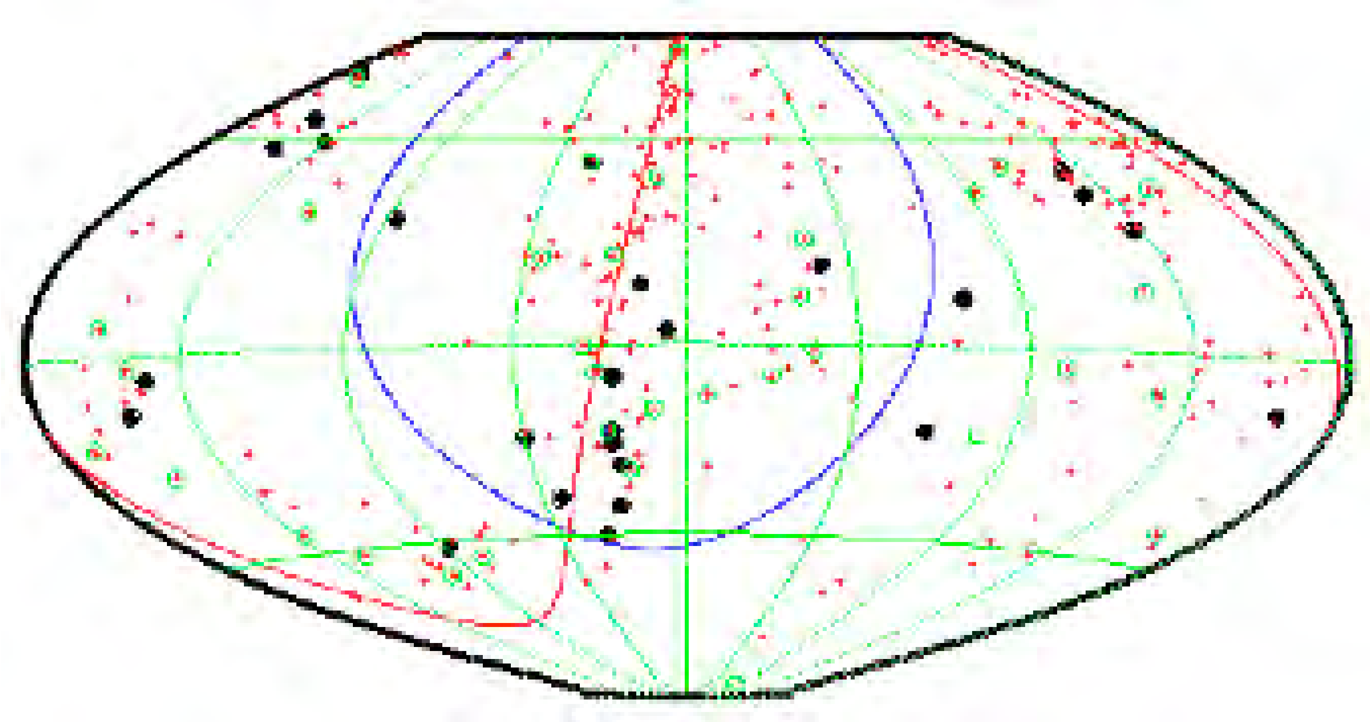
Auger main anisotropy result

Position of the 27 highest energy events on an equal exposure map



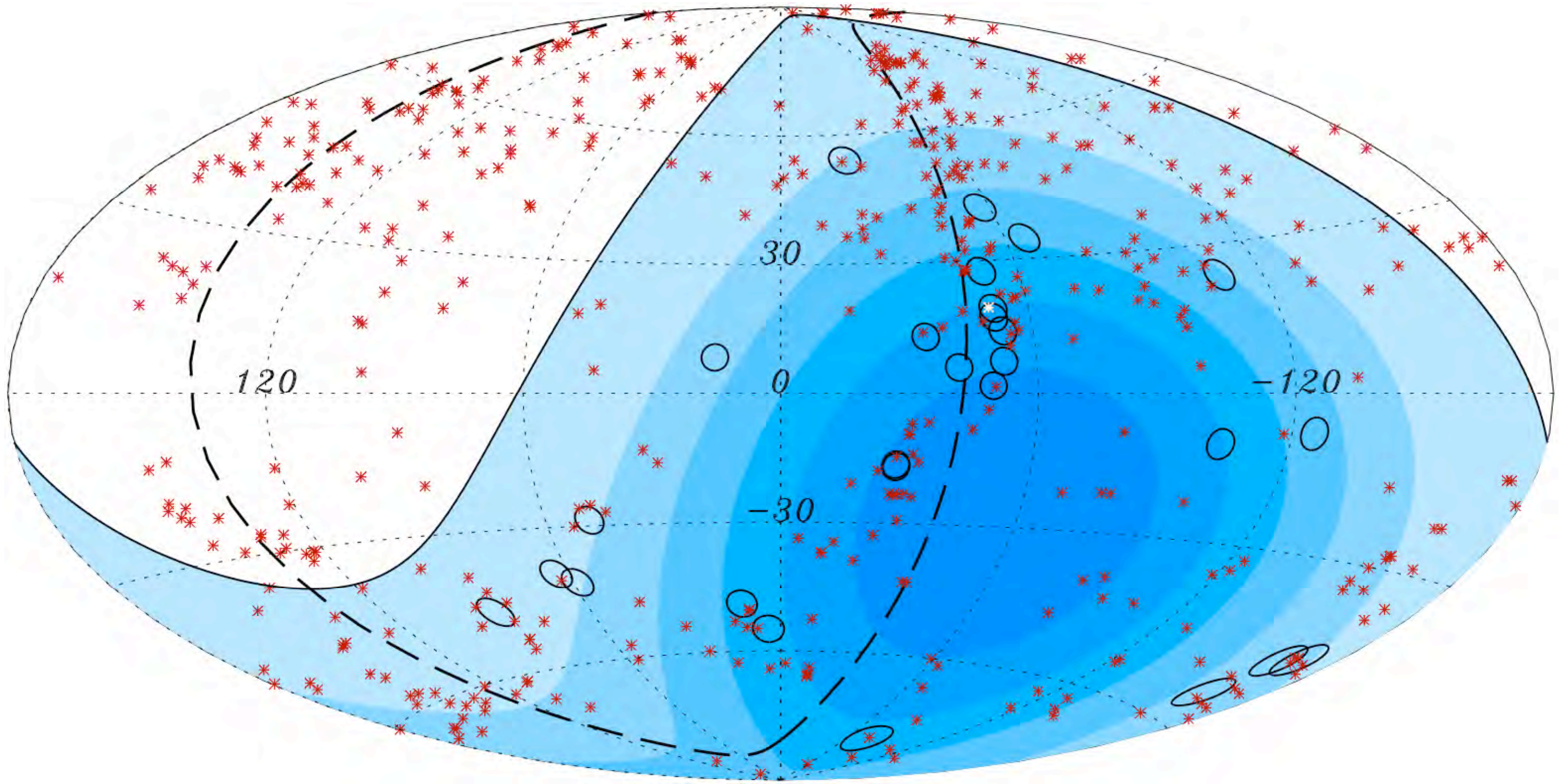
Auger main anisotropy result

Position of the 27 highest energy events on an equal exposure map



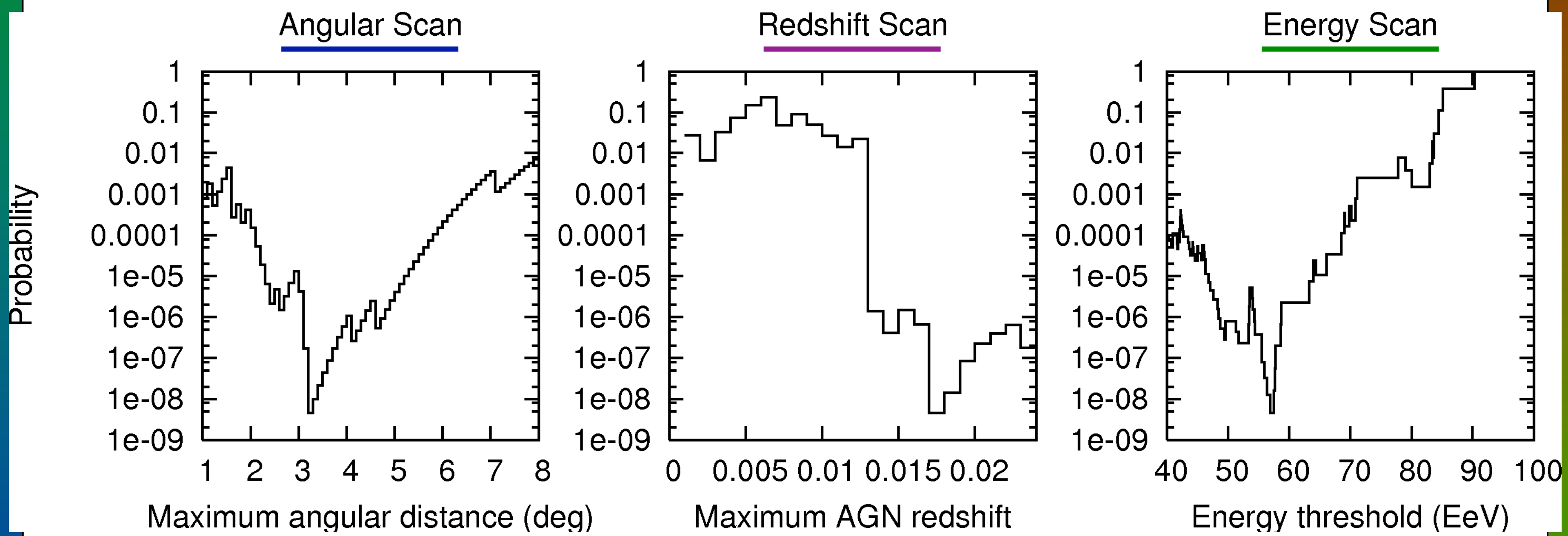
Galactic and supergalactic planes
AGNs in VCV catalogue and Swift X-ray AGN catalogue

Auger main anisotropy result



Auger main anisotropy result

3 free parameters in the definition of the correlation



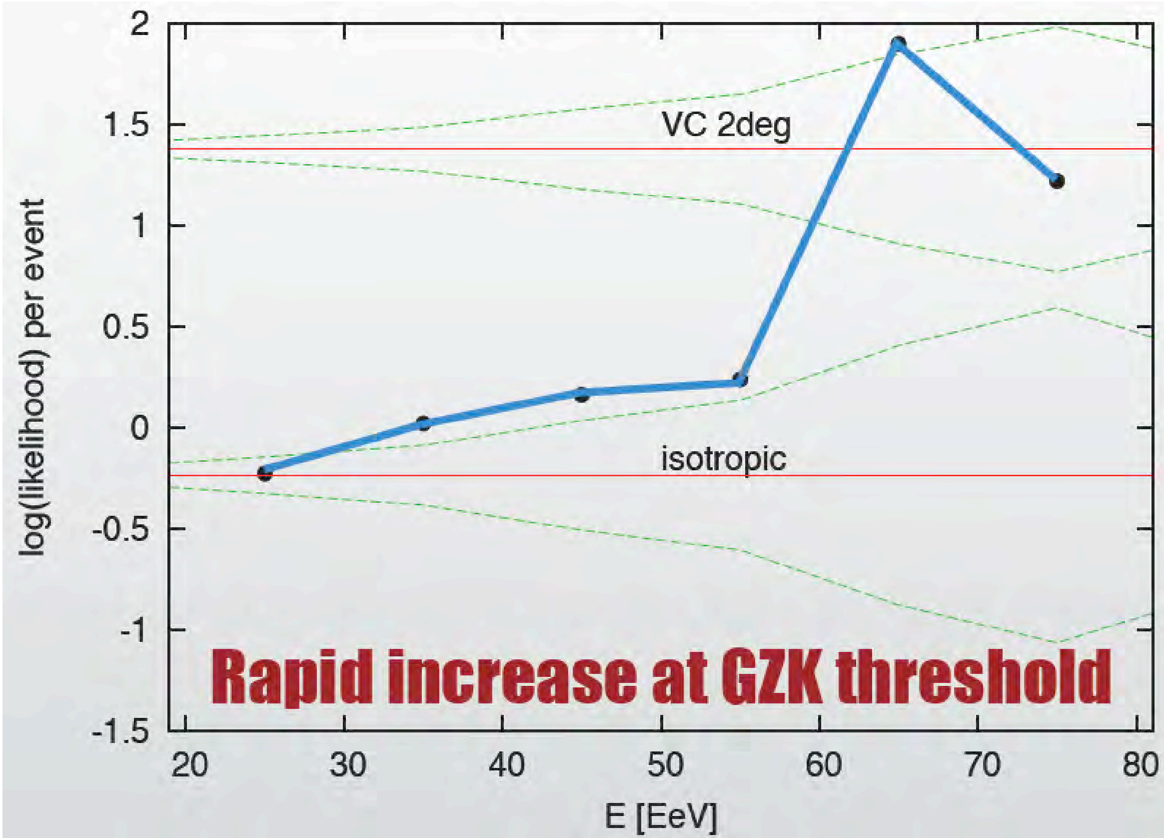
$\Delta\theta \leq 3.1°$

$z \leq 0.018$

($D \leq 75$ Mpc)

$E \geq 56$ EeV

Auger main anisotropy result



The energy above which the correlation is most significant corresponds to an energy where the CR flux drops… (supporting the GZK interpretation)

Significance of the anisotropy result

Not an "AGN correlation" result!

- Véron-Cetty / Véron, 12th Edition, 2006

  "This catalogue should not be used for any statistical analysis as it is not complete in any sense, except that it is, we hope, a complete survey of the literature."

Significance of the anisotropy result

Not an "AGN correlation" result!

- **1st step**: search between HECR arrival directions and various source catalogues (hard to estimate how many, how intensively, etc.) (data from 2004/01/01 to 2006/05/26)

- A very large "raw significance" was found with the 12th VCV catalogue of AGNs
  - Even after taking into account generous penalty factors for a posteriori searches and scanning of parameter space

⇒ Did not seem to be fluctuation

⇒ Auger collaboration set up a prescription for future data

- Most significant *a posteriori* "correlation signal":

12 out of 15 events above "56 EeV" are closer than 3.1° from an AGN in 12th VCV with $z \leq 0.018$ ($D \leq 75$ Mpc)

3.2 expected from isotropic distribution

Significance of the anisotropy result

Not an "AGN correlation" result!

- **2nd step**: predefine a region in the sky where there seems to be an excess of CR flux, and see if the next highest energy cosmic rays come from this region

21% chance from isotropic distribution

→
- Independent data set
- prescribed parameters
- unambiguous significance (Confidence Level)

- **Result**: 99% CL that the excess we had seen in the original data set was not a random fluctuation from an otherwise isotropic cosmic ray distribution

8 "correlating events" out of 13 (2.7 expected)

→ "CR distribution is anisotropic at the highest energies!"

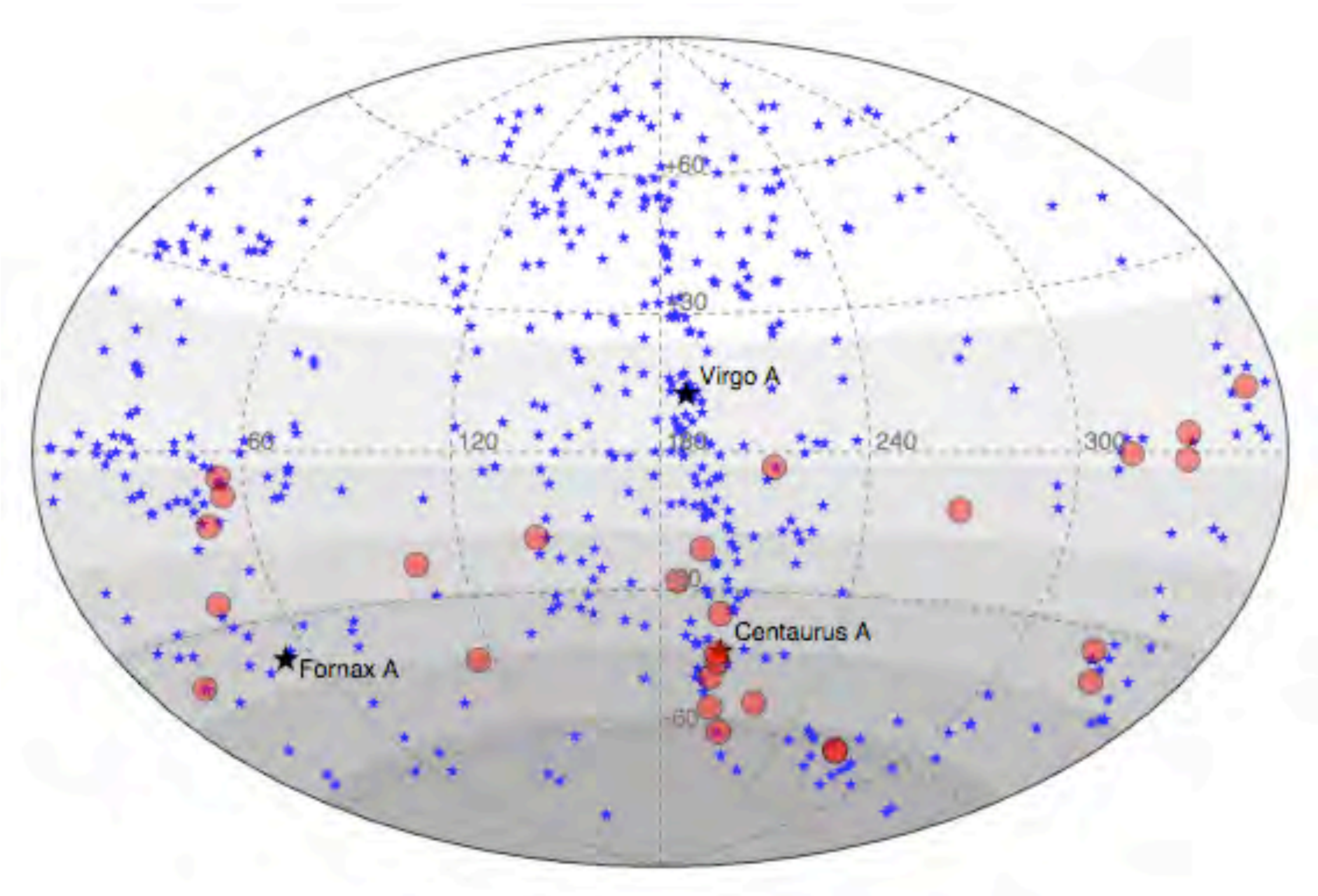
corroborated by other analyses, independent of any source catalogue

Astrophysical implications?

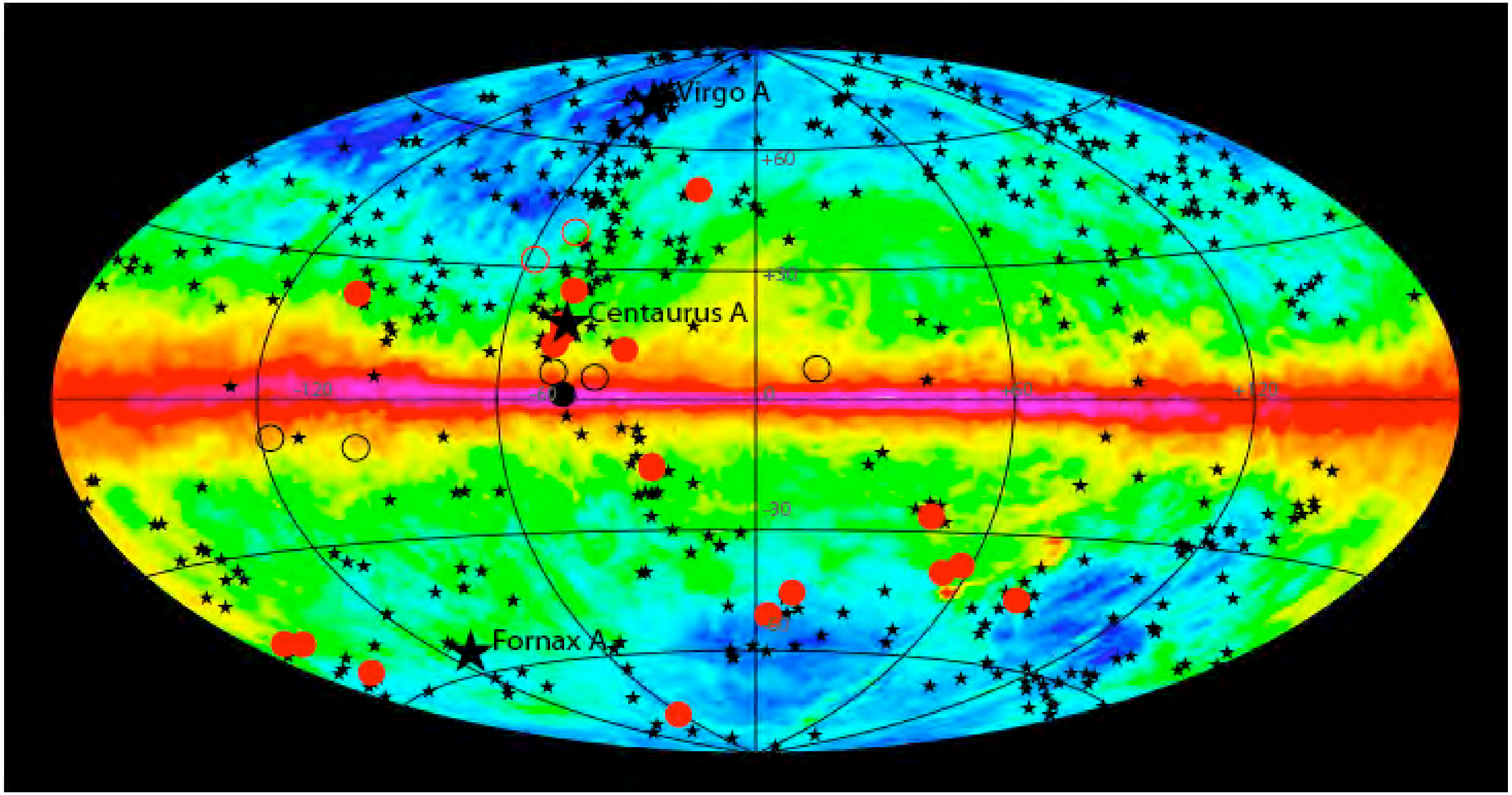
- Not clear yet! (very low statistics to check against any model, whether naive or sophisticated)
- Can UHECRs come from AGNs? ⟹ YES

  But we knew that before!
- Do UHECRs have to come from AGNs? ⟹ NO!
- NB: no claim from Auger!

Centaurus A, Virgo, Fornax, etc.



Centaurus A, Virgo, Fornax, etc.



Galactic plane: catalogue even more incomplete + larger deflections expected

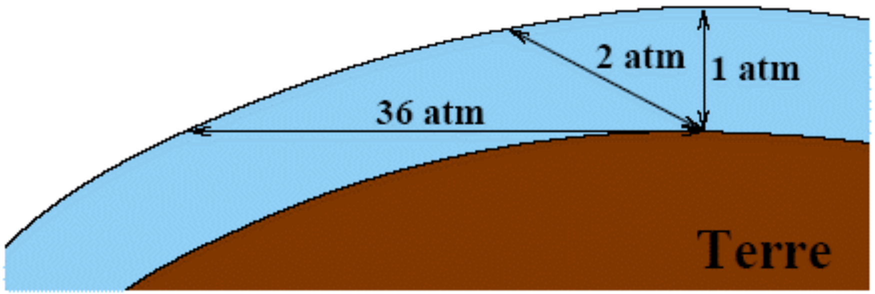
Neutrino detection with Auger

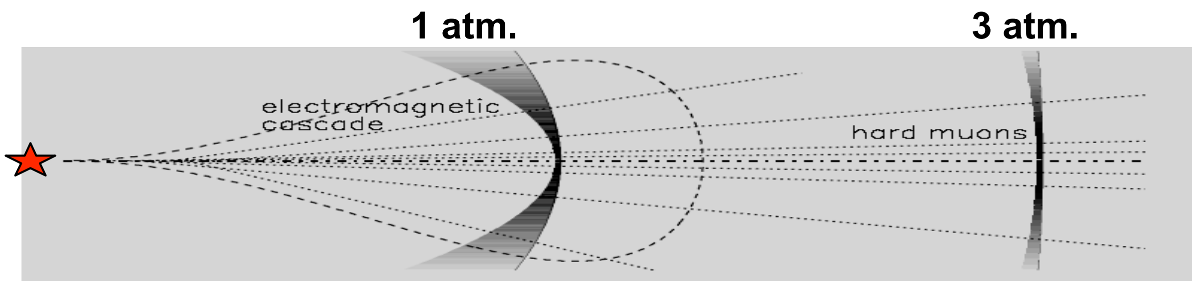
"GZK neutrinos" or from astrophysical sources

- Neutrinos can interact by chance anywhere in the atmosphere, including much deeper than would do protons, nuclei and photons

  → easy to recognize and discriminate:

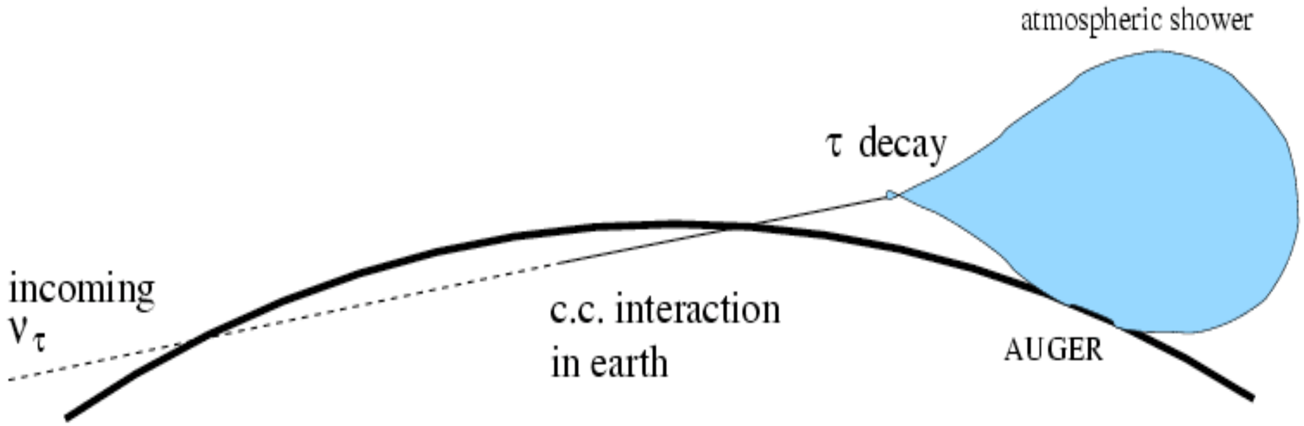
  → "young" horizontal showers





Neutrino detection with Auger

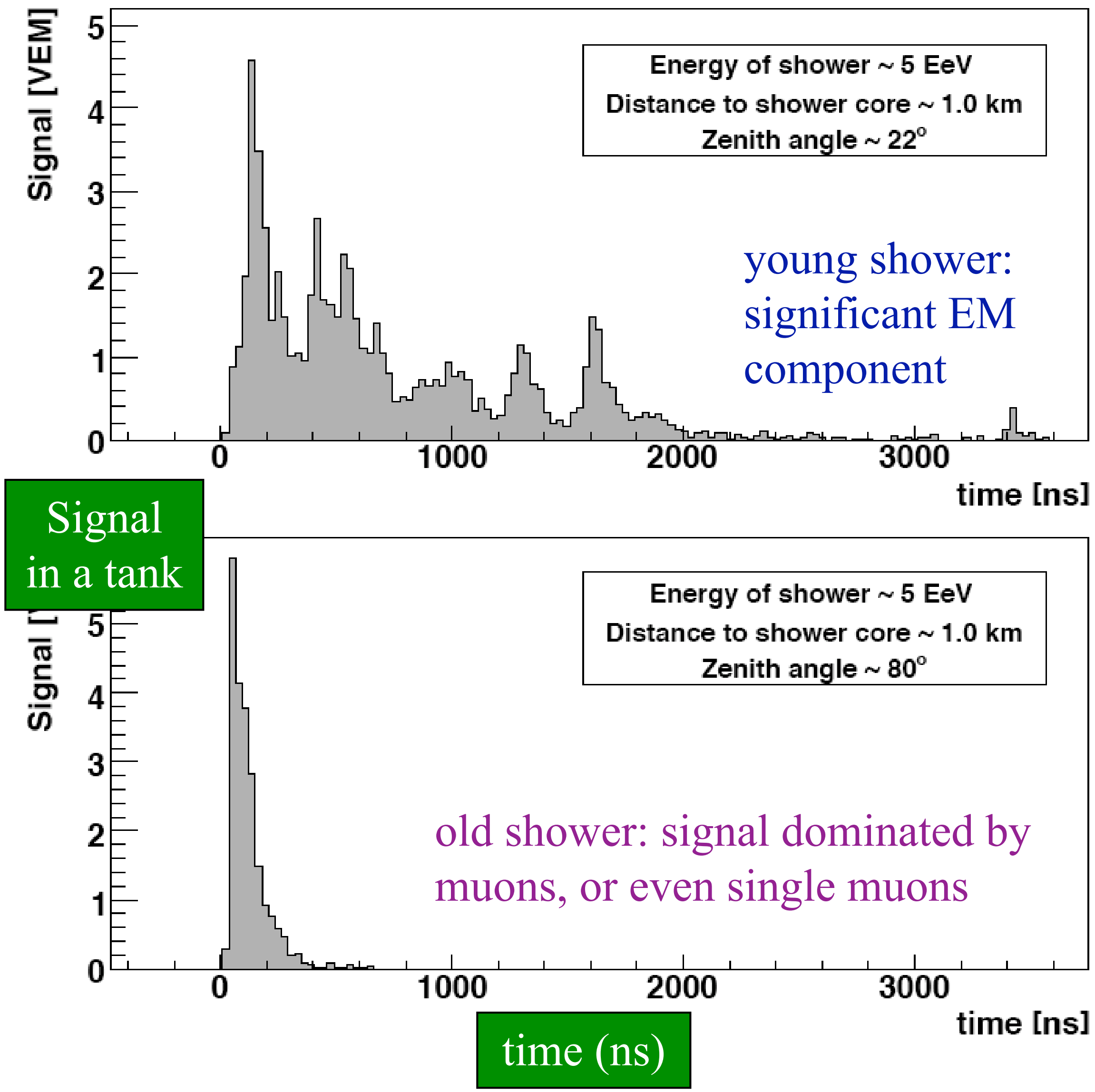
- Additional detection technique, with excellent (perfect?) discrimination:
  "Earth-skimming tau neutrinos"



➡ even more powerful (higher sensitiviy)!

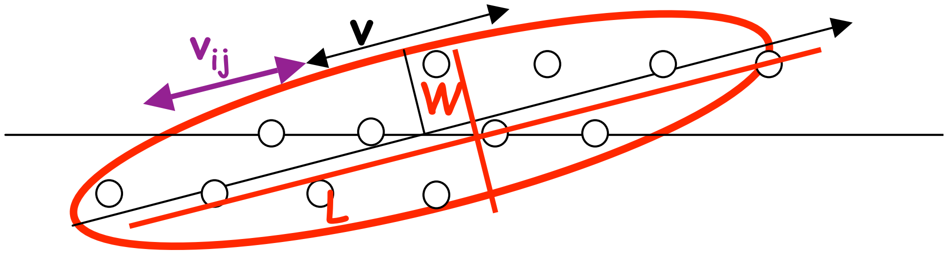
➡ most stringent upper limits in the GZK energy range
Probably a detection within a few years…

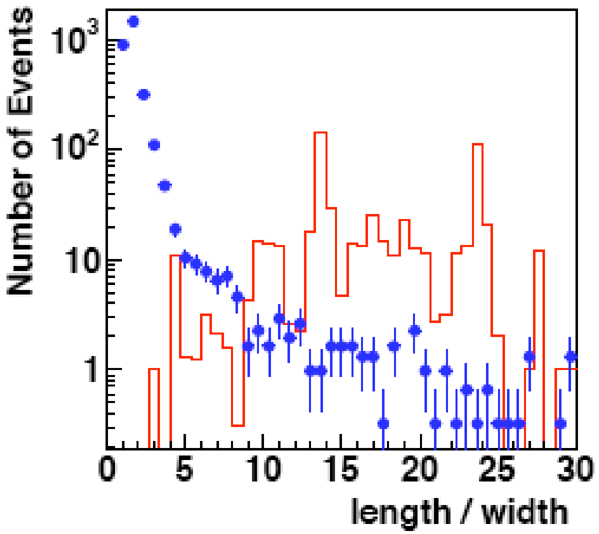
Selection criteria

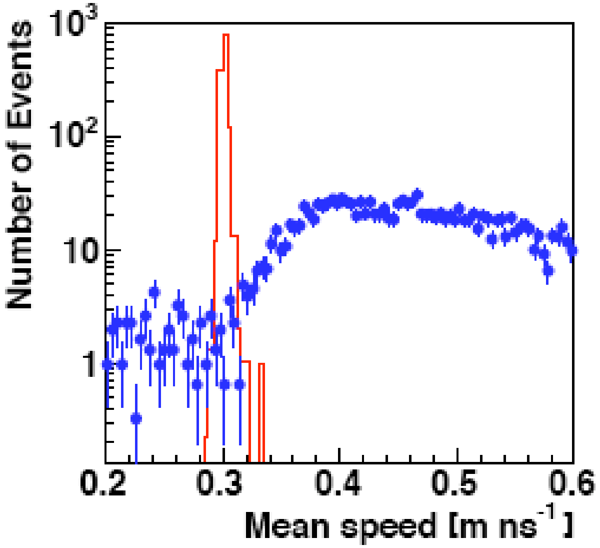


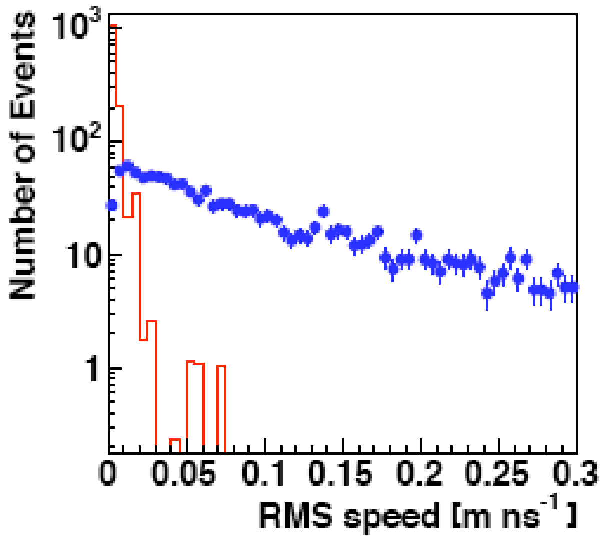
require 13 bins in a row above 0.2 VEM

Selection criteria









require elongated pattern on the ground (length/width > 5)

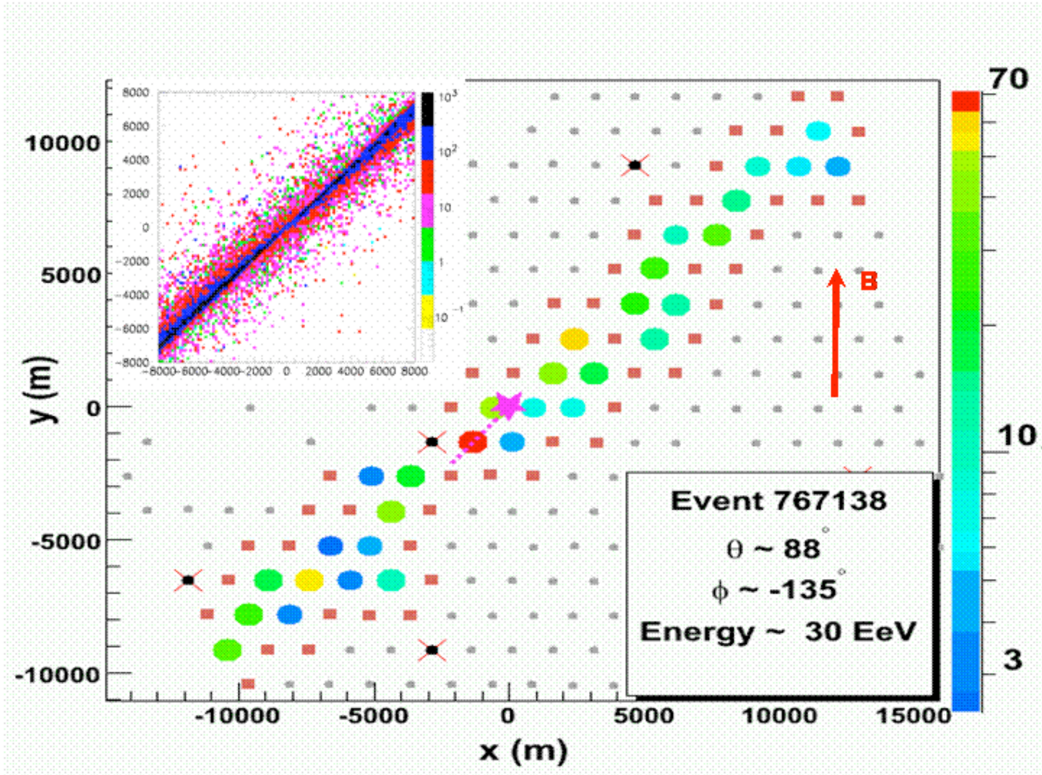
require apparent velocity on the ground in the range 0.29–0.31 m/ns

require rms velocity scatter < 0.08 m/ns

Selection efficiency: 80%

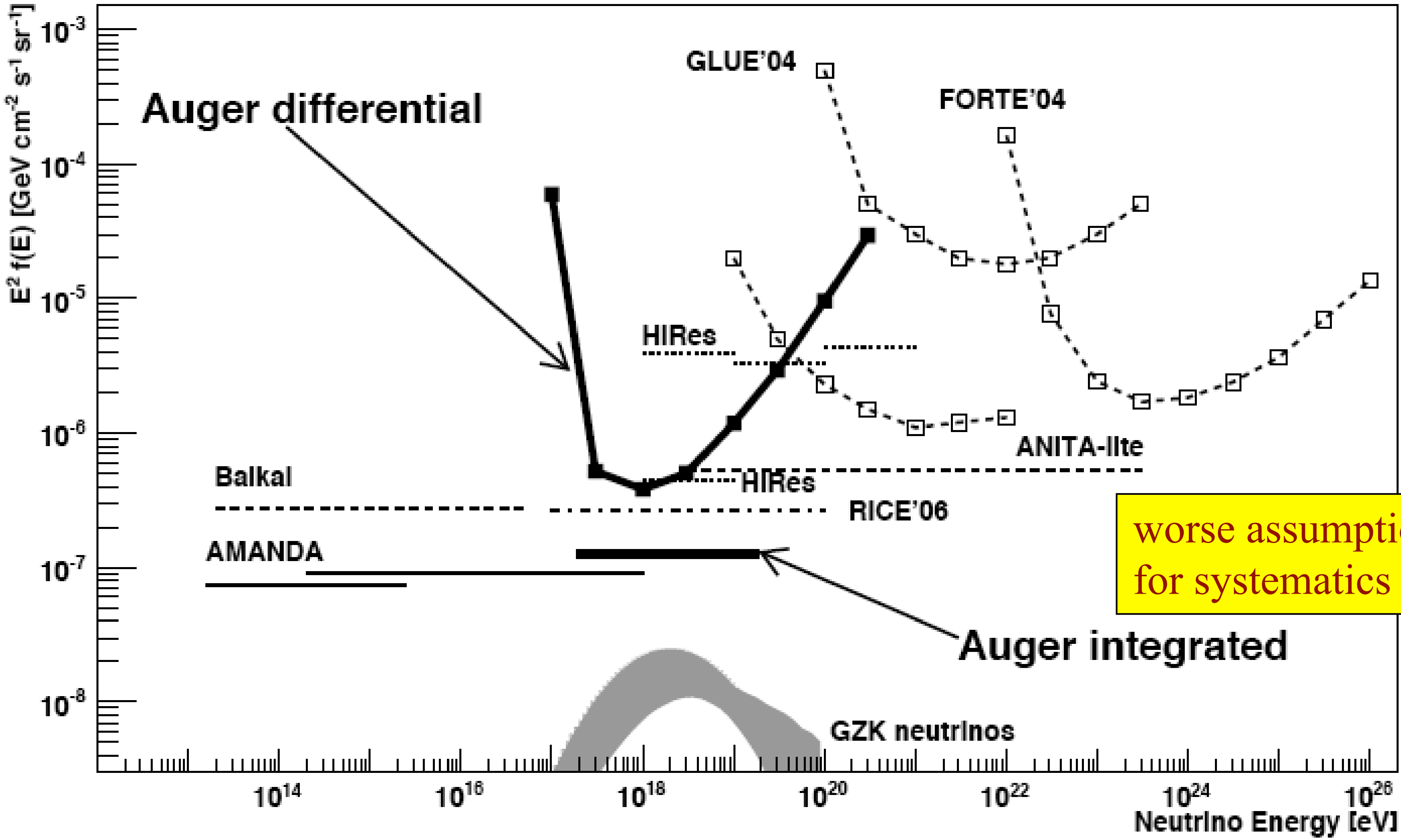
Horizontal showers

Example of a horizontal event (31 tanks)



But ZERO neutrino candidate

Auger upper limit on HE neutrinos



worse assumptions for systematics

90% confidence level (1 neutrino flavor)

Summary of Auger results

composition	E spectrum	directions
some nuclei, no photons, no neutrinos yet	ankle + GZK cutoff	anisotropic sky
matches astrophysical expactations	**Excellent news!** 40 years-old prediction!	**Most important result since 100 years!**
Implications for gal./extragal. **transition**?	⇒ nearby sources ⇒ « proton astronomy »! + isolated sources!	⇒ "cosmic-ray astronomy" is possible (it just began!)
Unity with the CR science and sources at low E?	+ high-energy physics study of showers (muons, hadronic models, energy scale)	⇒ cosmic rays integrated into the scientific *corpus* of astrophysics
Makes HECR studies even **richer**!	cf. knee + **LHC** !	

Cosmic rays, year zero!

- Historical opening of a non-photonic astronomy!
  - Eventually: identification and study of individual sources
  - Necessary to increase collecting power at the highest energies

⟹ Auger Nord (Lamar, Colorado)

(sources are there: let's go and get them!)

- Many questions
  - sources, CR origin, acceleration mechanisms, behaviour of energetic sources in the universe, link with low-energy CRs and galactic ecology
  - study of high-energy physics
- All this starts today!
- To help in this programme, neutrino astronomy is very much awaited as well, with hope and excitement!

Merci !


Pierre Auger Observatory
studying the universe's highest energy particles