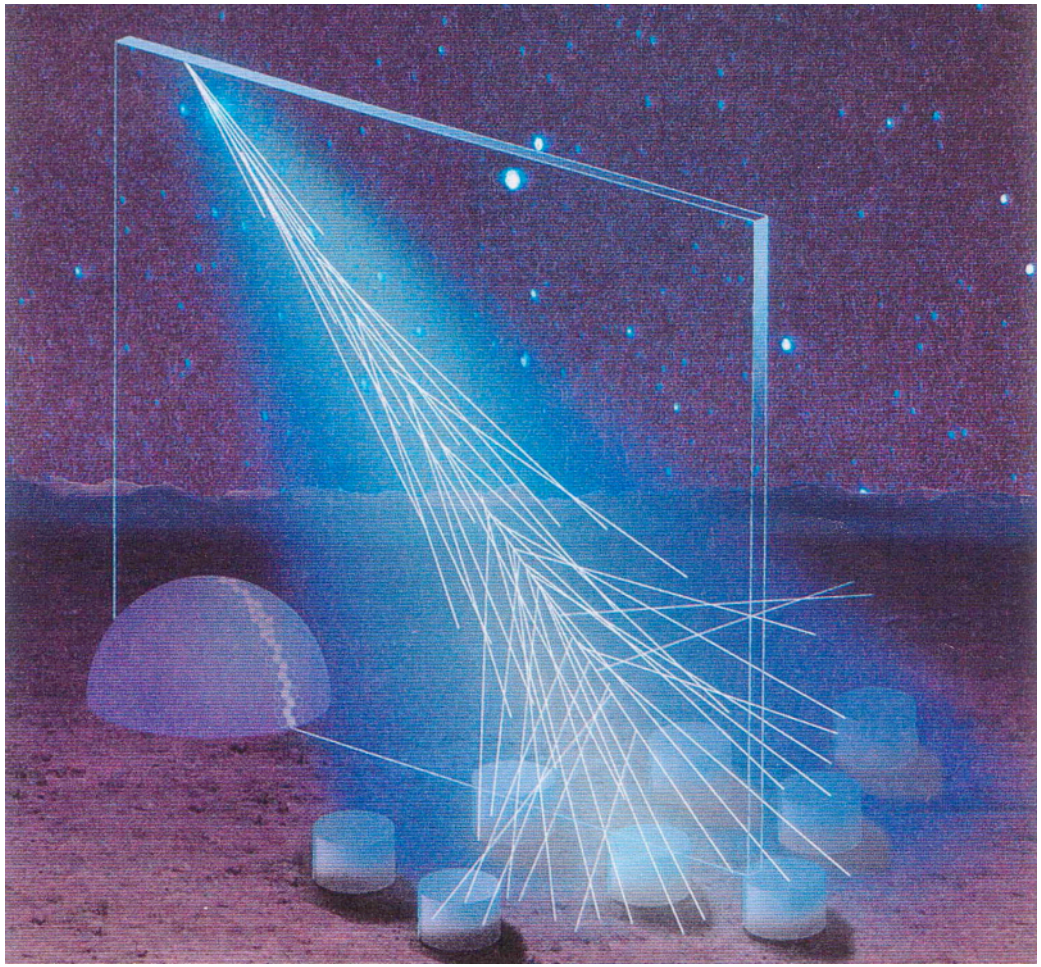
Pierre Auger Observatory

- a new stage in the study of the ultra-high energy cosmic rays



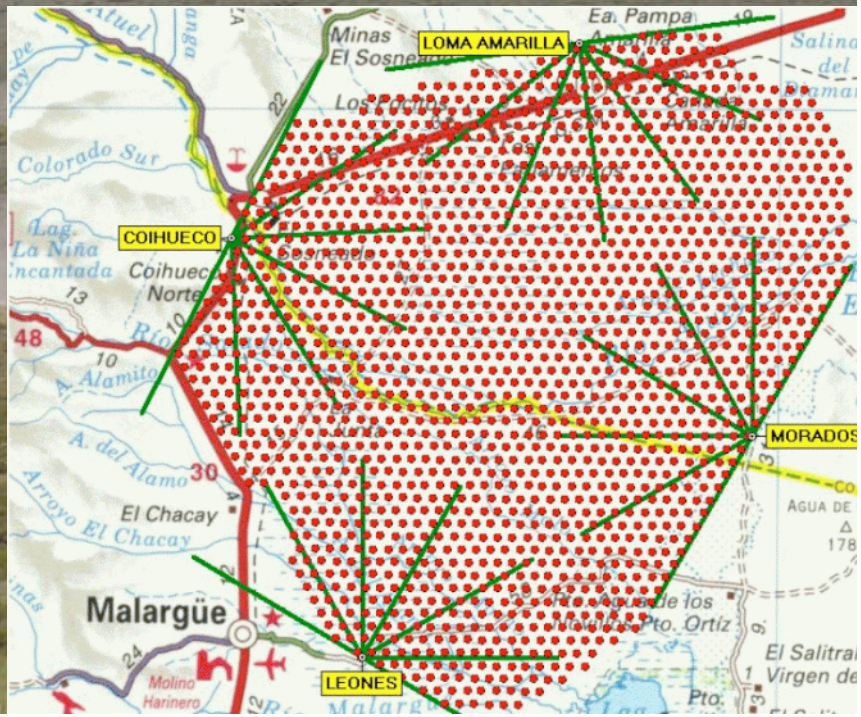
- Large aperture
(~ 3000 km^2, $E > 10^{18}$ eV)
- Hybrid cosmic ray detection
- Full sky exposure (2 sites)

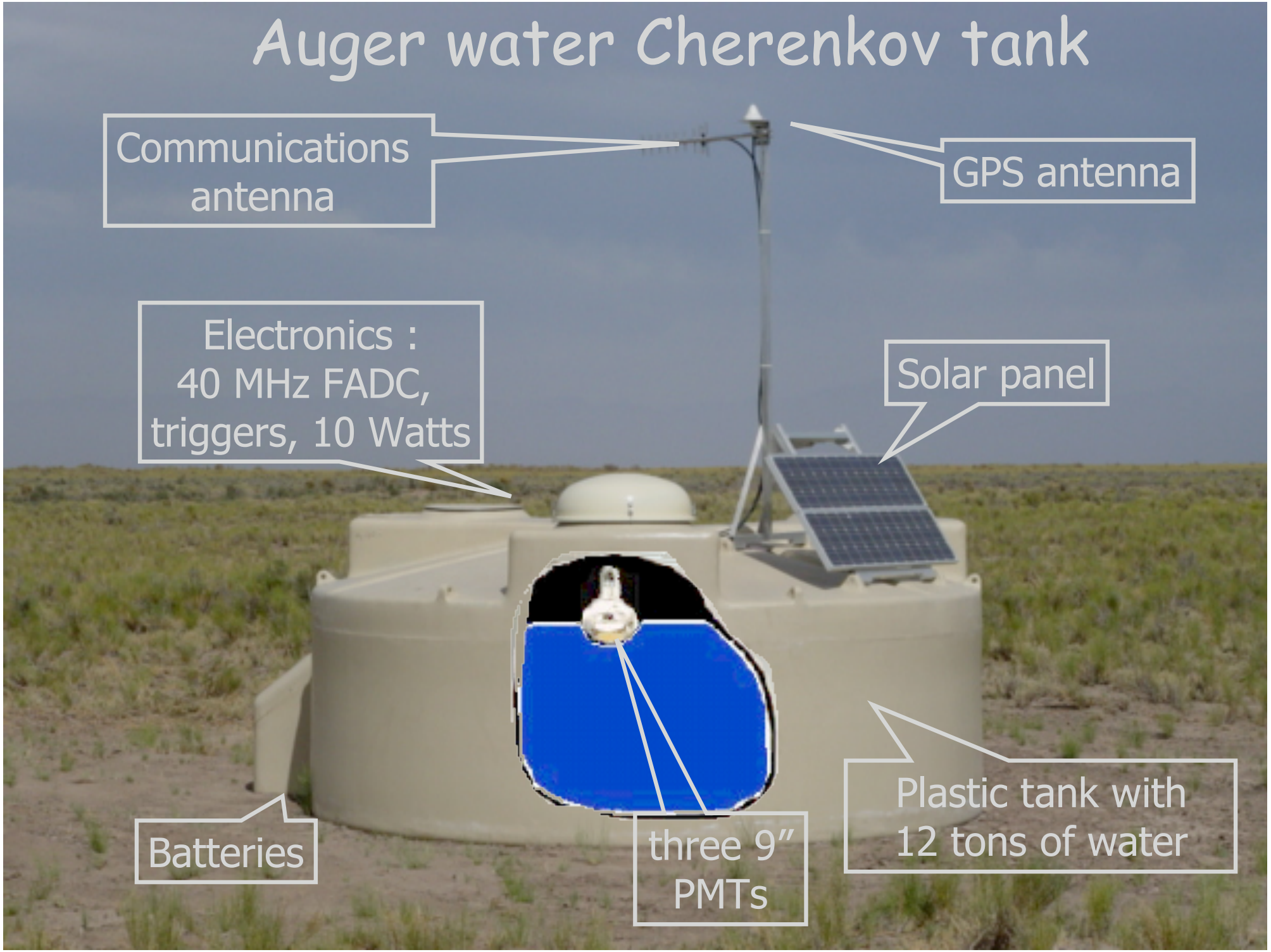
- Cosmic rays energy spectrum
- Composition studies
- Anisotropies search

Southern Auger Observatory
Malargüe (Mendoza), Argentina

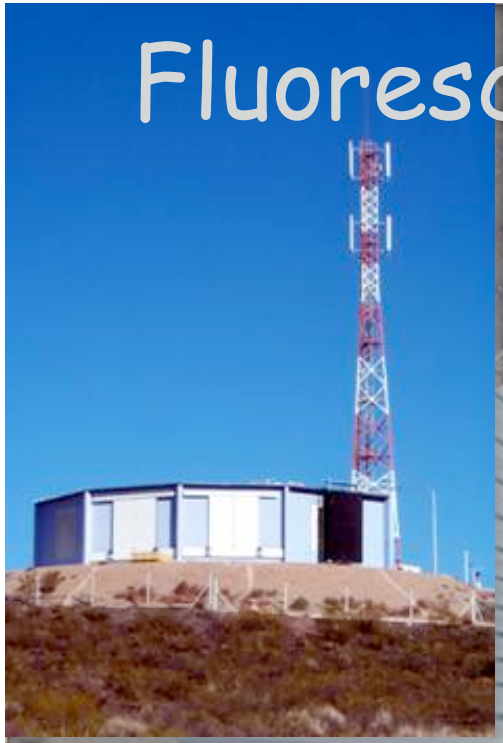
- ✓ 17 countries
- ✓ > 70 institutions / labs
- ✓ ~ 300 physicists

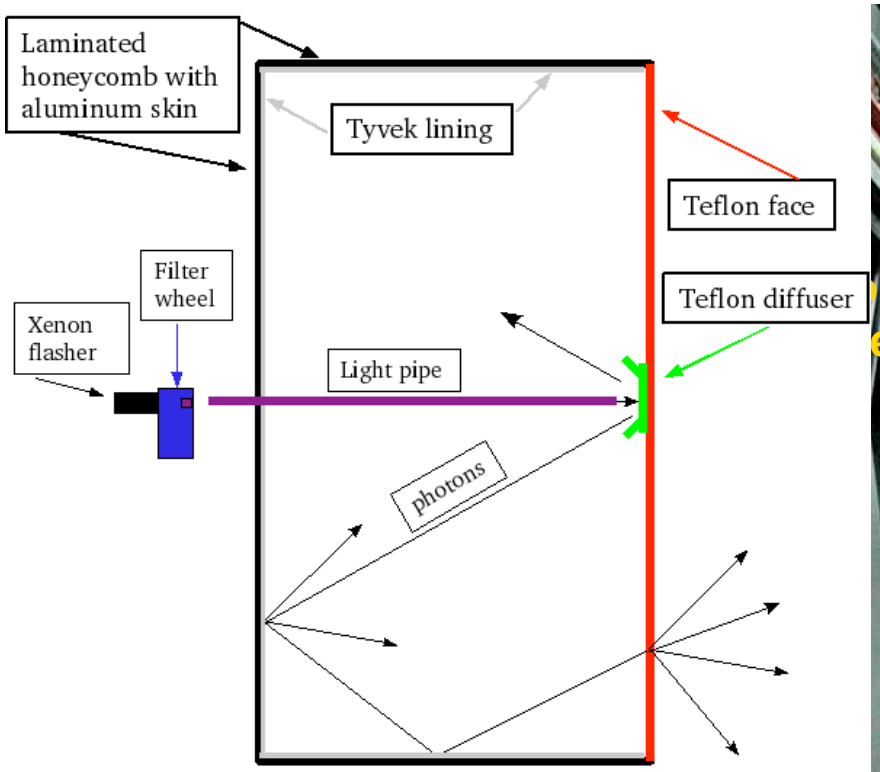
- ✓ 1600 Water Cherenkov tanks (Surface Detector)
- ✓ 4 Fluorescence Sites (Fluorescence Detector)




Auger water Cherenkov tank
Communications antenna
GPS antenna
Electronics : 40 MHz FADC, triggers, 10 Watts
Solar panel
Batteries
three 9” PMTs
Plastic tank with 12 tons of water

Fluorescence Detector site (an "eye")





r lens
e x2)

440 PMT camera
1.5° per pixel

segmented spherical mirror

aperture box
shutter
filter UV pass
safety curtain

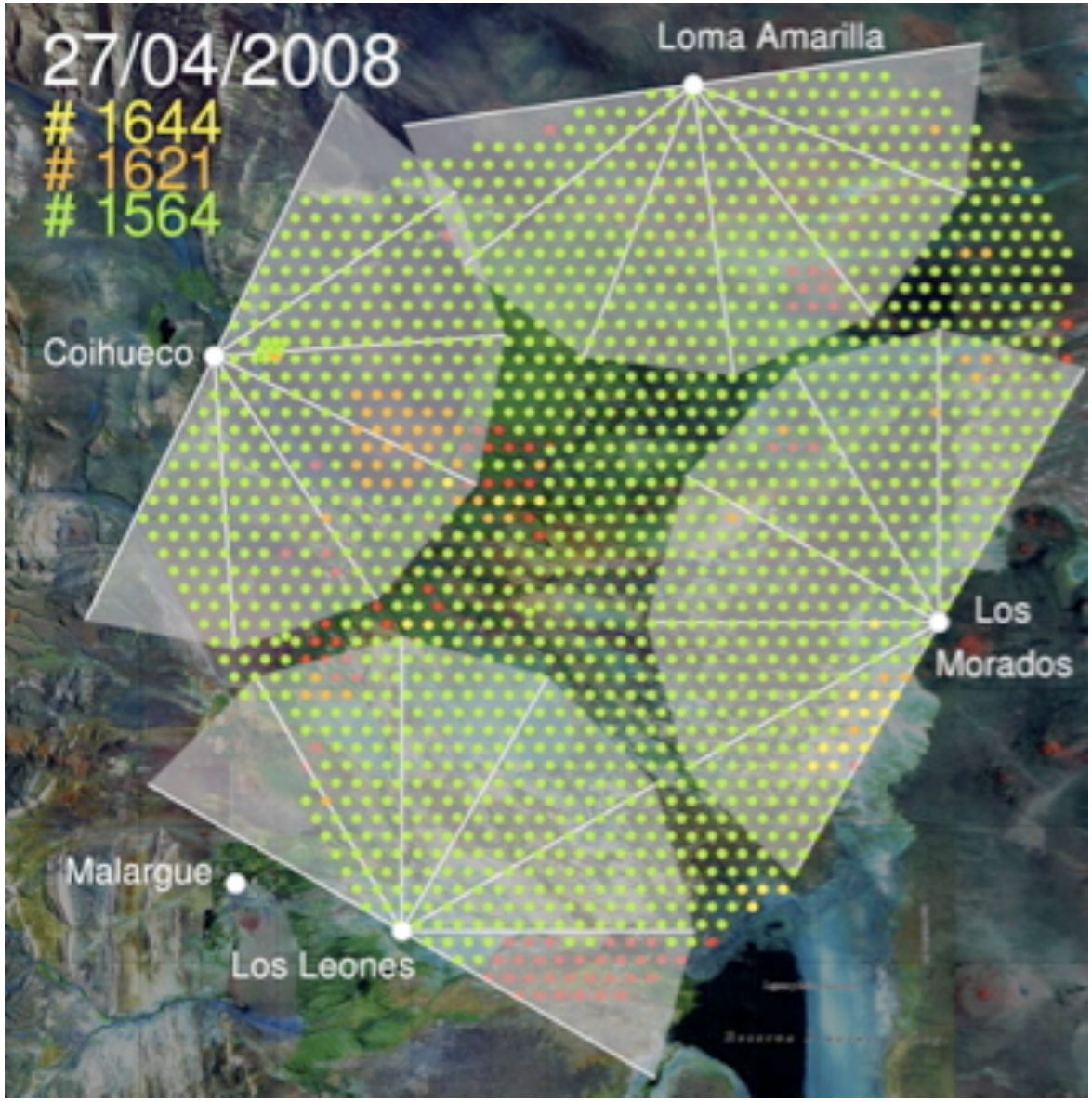
Atmospheric monitoring

- LIDAR per FD site
- + meteo station per FD site
- Central Laser Facility
- regular balloon flights

↳ **Attenuation length**
↳ **Aerosols concentration**

Balloons ↳ (*T, p*) profiles

http://www.auger.org/technical_info/

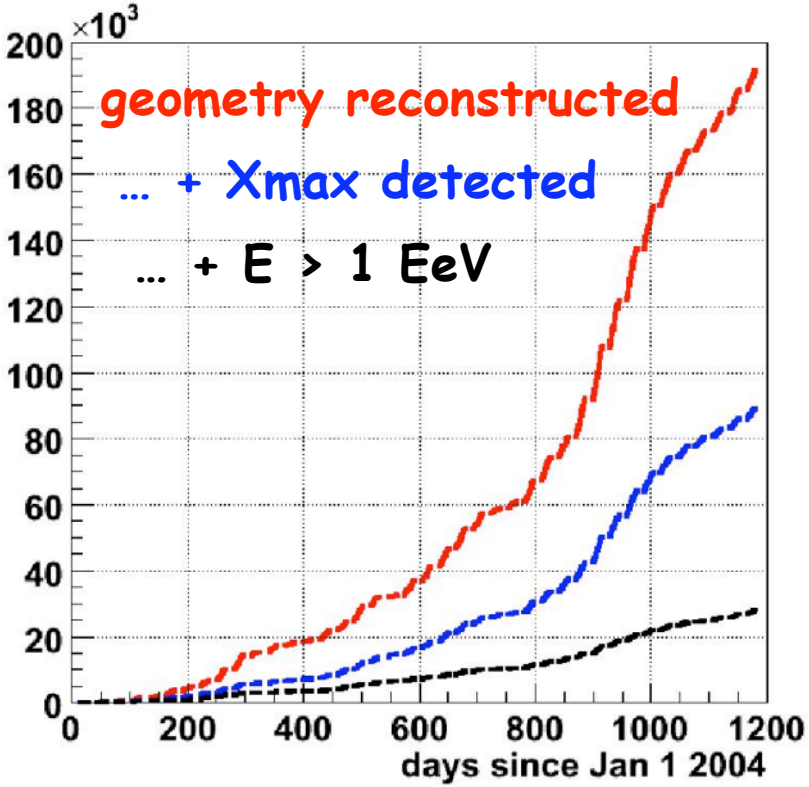


Actual status

- **Surface detector (SD):**
  1644 tanks (> 1600) deployed
  1621 tanks filled with water
  1564 tanks operational
  > 95% achieved

- **Fluorescence Detector (FD):**
  All 4 telescopes operational

Nb of detected hybrid events :

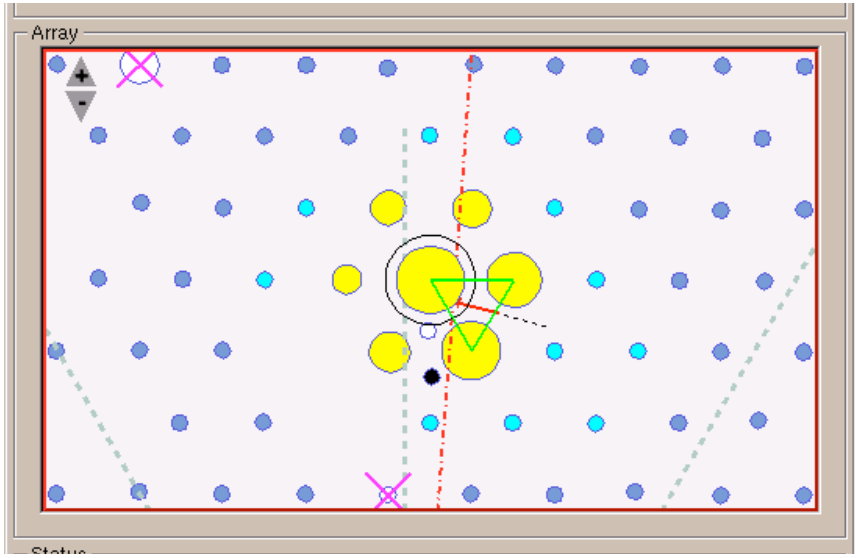


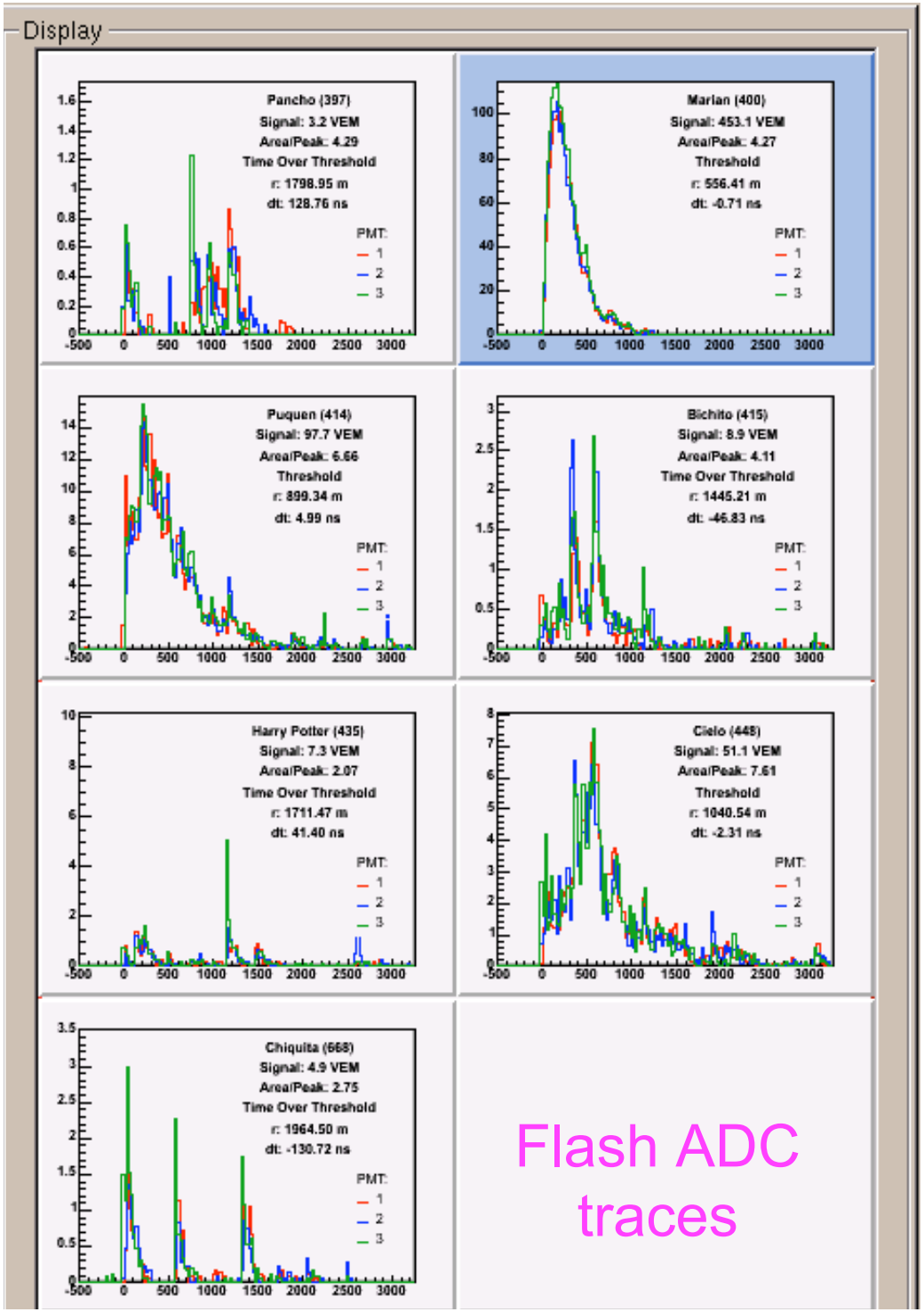
- Data by the growing array since Jan 1, 2004
- Integrated exposure ~$1.1 \cdot 10^4$ km^2 sr yr

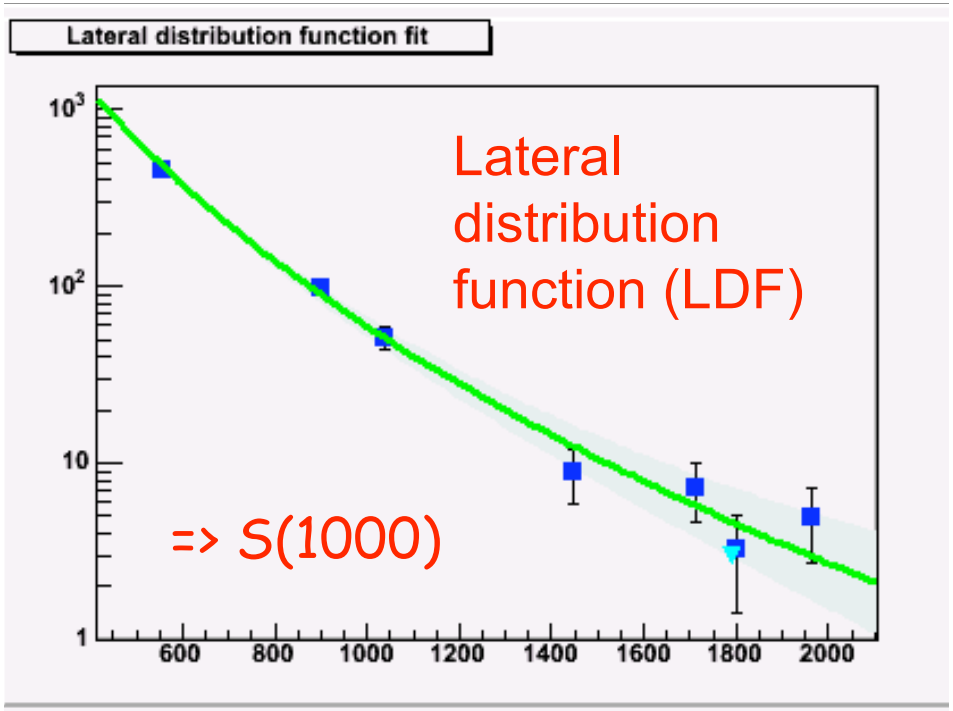
(~1.5 years of the complete array)

SD event observables

Hybrid event θ ~ 30°, ~ 8 EeV

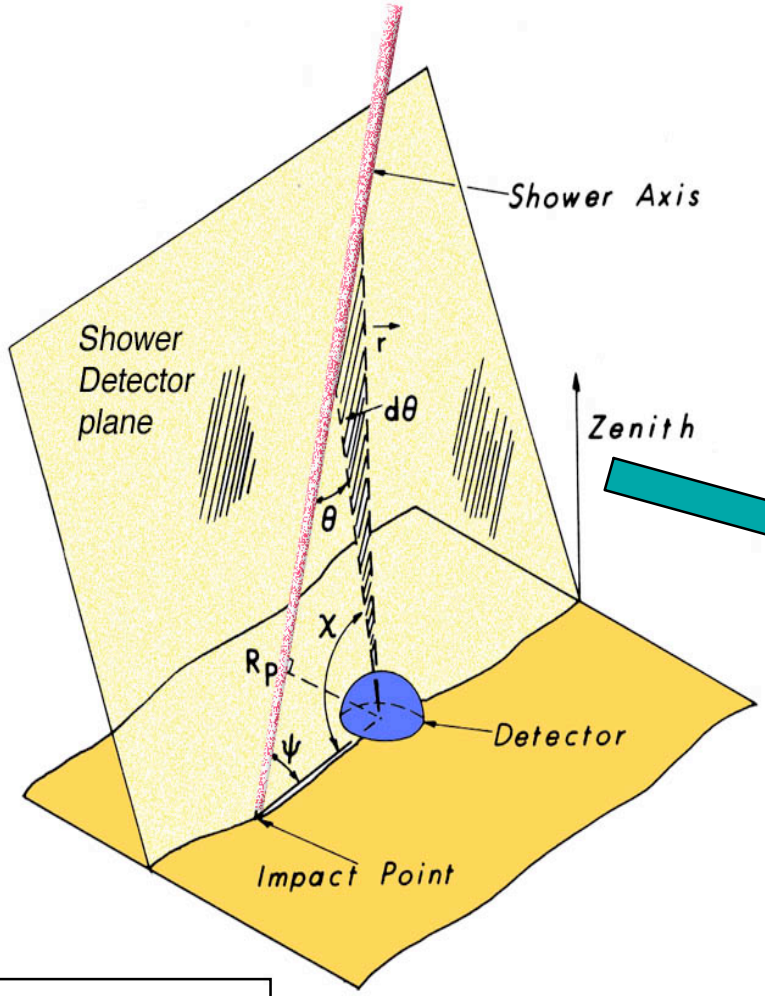




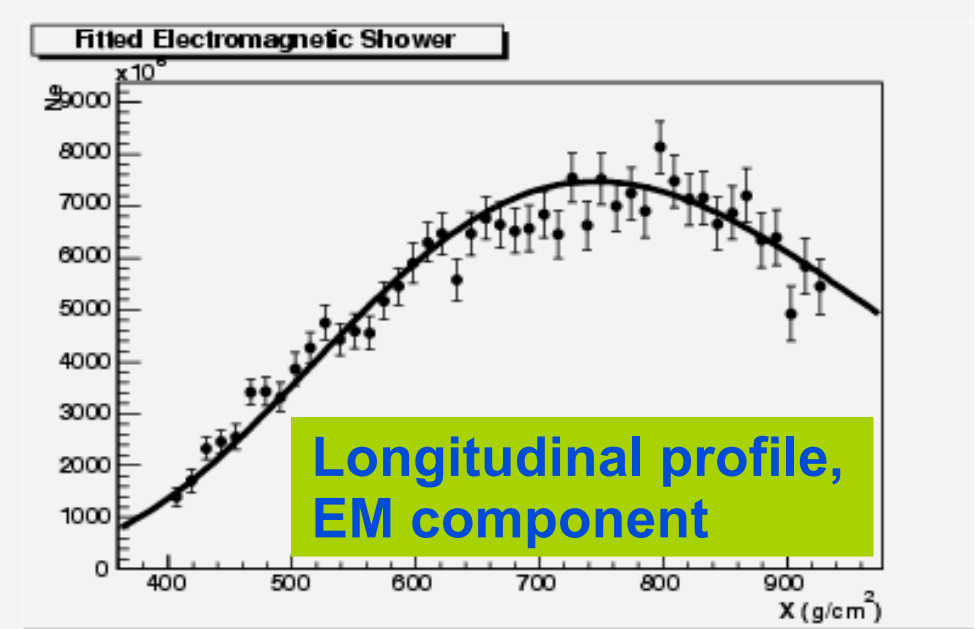


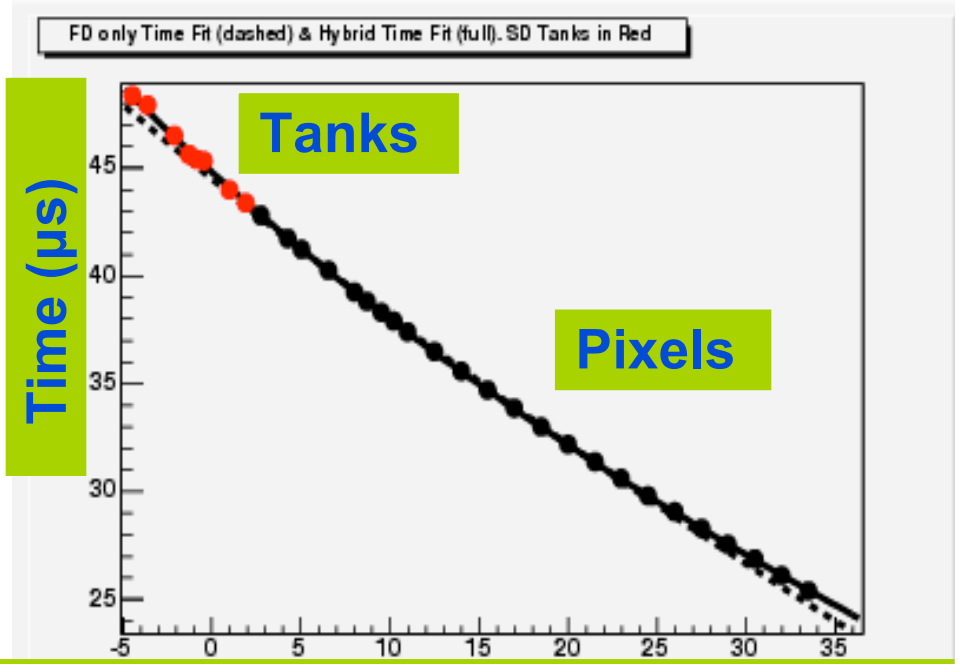
FD event observables

The same hybrid event
θ ~ 30°, ~ 8 EeV



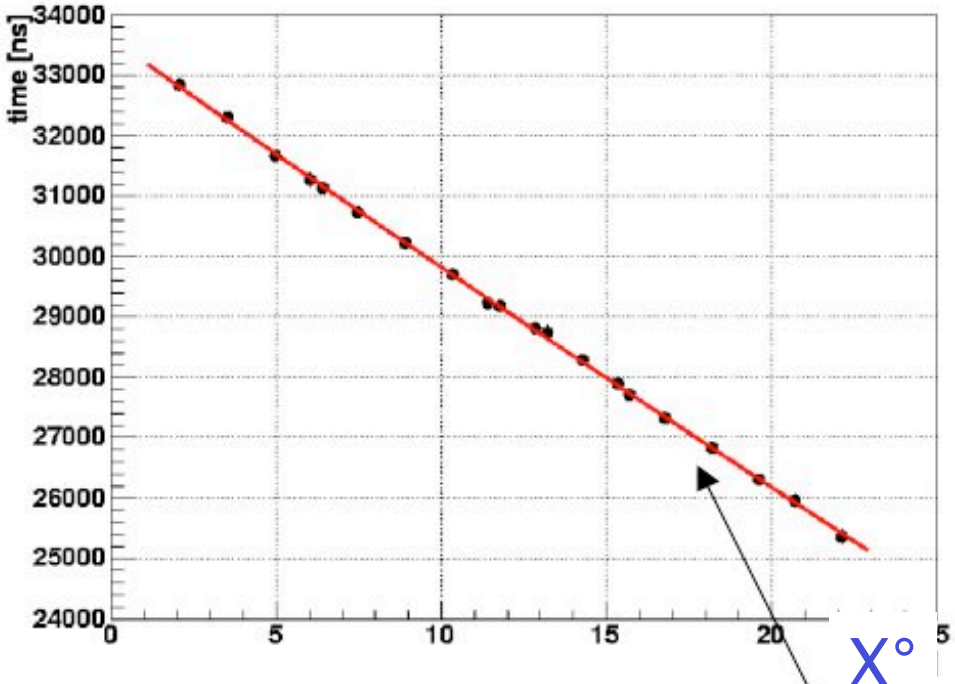
$T_i (\chi_i) \Rightarrow R_p$



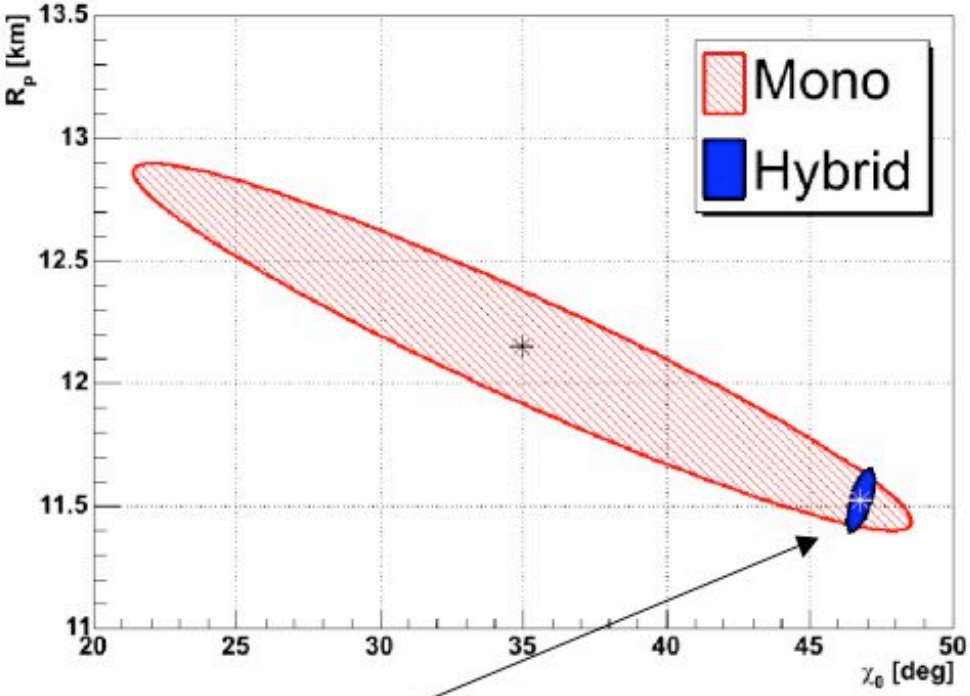


Precise geometry - the key of the hybrid reconstruction
1 tank is enough !

Time, t **R_p, km**



X°



≈ line but
3 free parameters

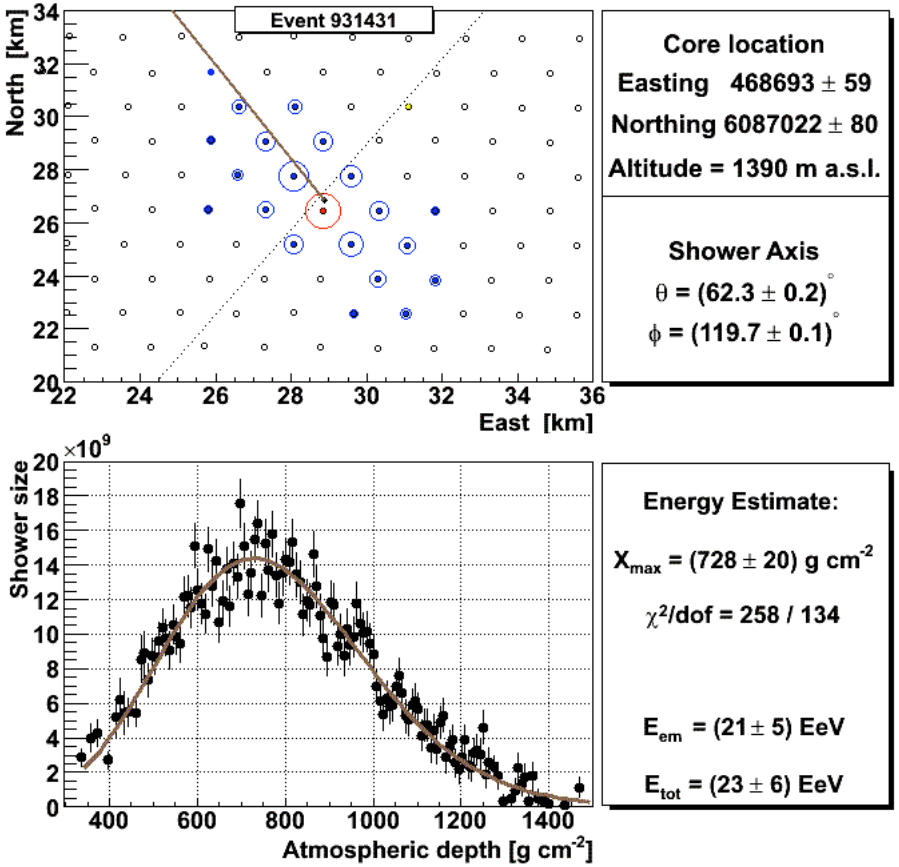
T_0 from tank!

$$t(\chi) = T_0 + \frac{R_p}{c} \tan\left[\frac{(\chi_0 - \chi)}{2}\right]$$

⇒ Good resolution in E and X_{max}

astro-ph/0608670

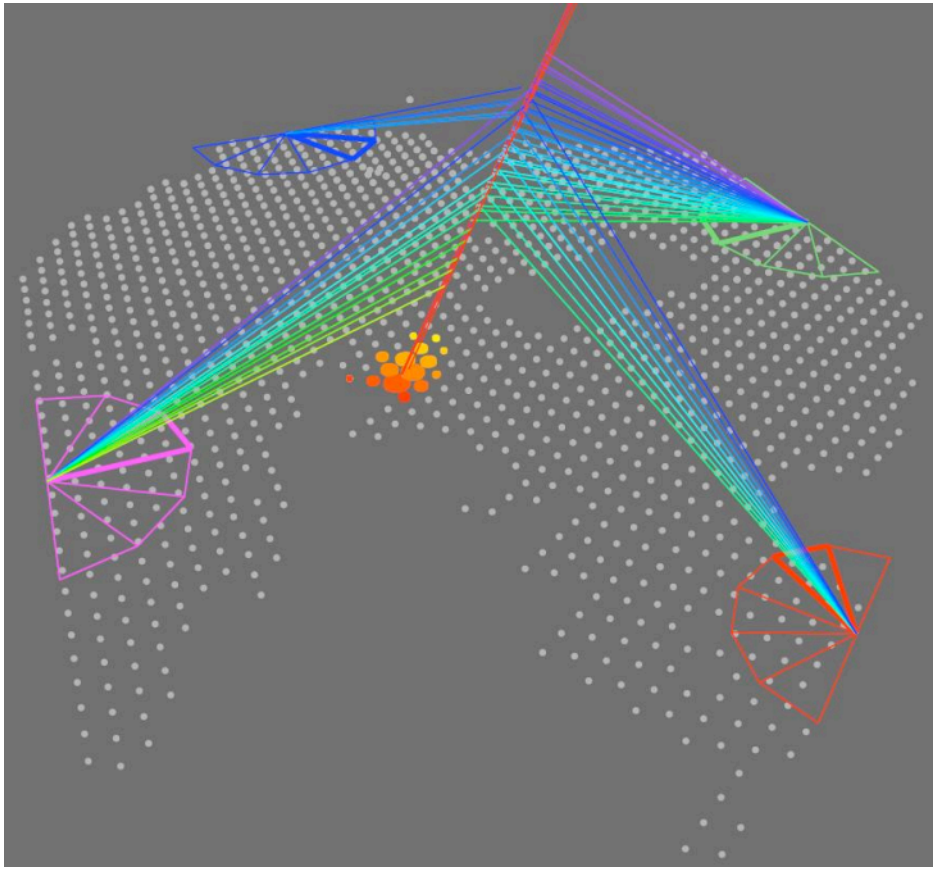
Examples of Auger hybrid events



One of the first high quality "Golden" hybrids

FD: calorimetric energy measurement

The first « quadruple » hybrid event



20 May 2007 E ~ 10^{19} eV

Pierre Auger Observatory

- a new stage in the ultra-high energy cosmic ray studies

Energy spectrum

Serguei Vorobiov, Nova Gorica U., Slovenia Quarks-2008, Sergiev Posad, May 27

Auger energy assignment

Energy scale is determined from the data
The dependence on interaction models or primary composition is a few %

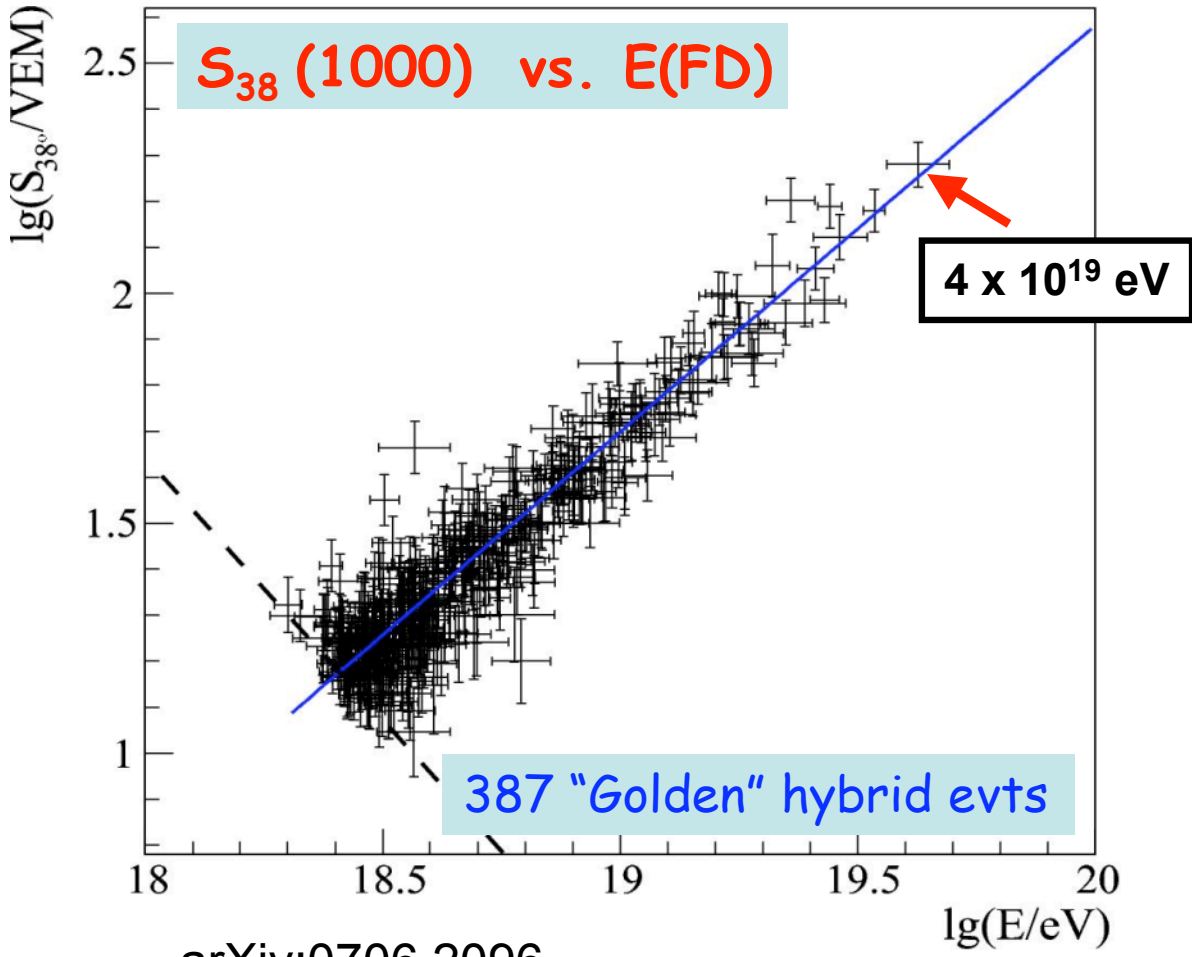
Surface detector signal at 1000 m of the shower axis, S(1000) - E estimator

– S(1000) at zenith angle of 38° (constant intensity)

- determined for each SD event

S(1000) : proportional to the primary energy (MC)

Calibrated on the FD Energy



arXiv:0706.2096

Systematic errors in the energy determination by the hybrid method

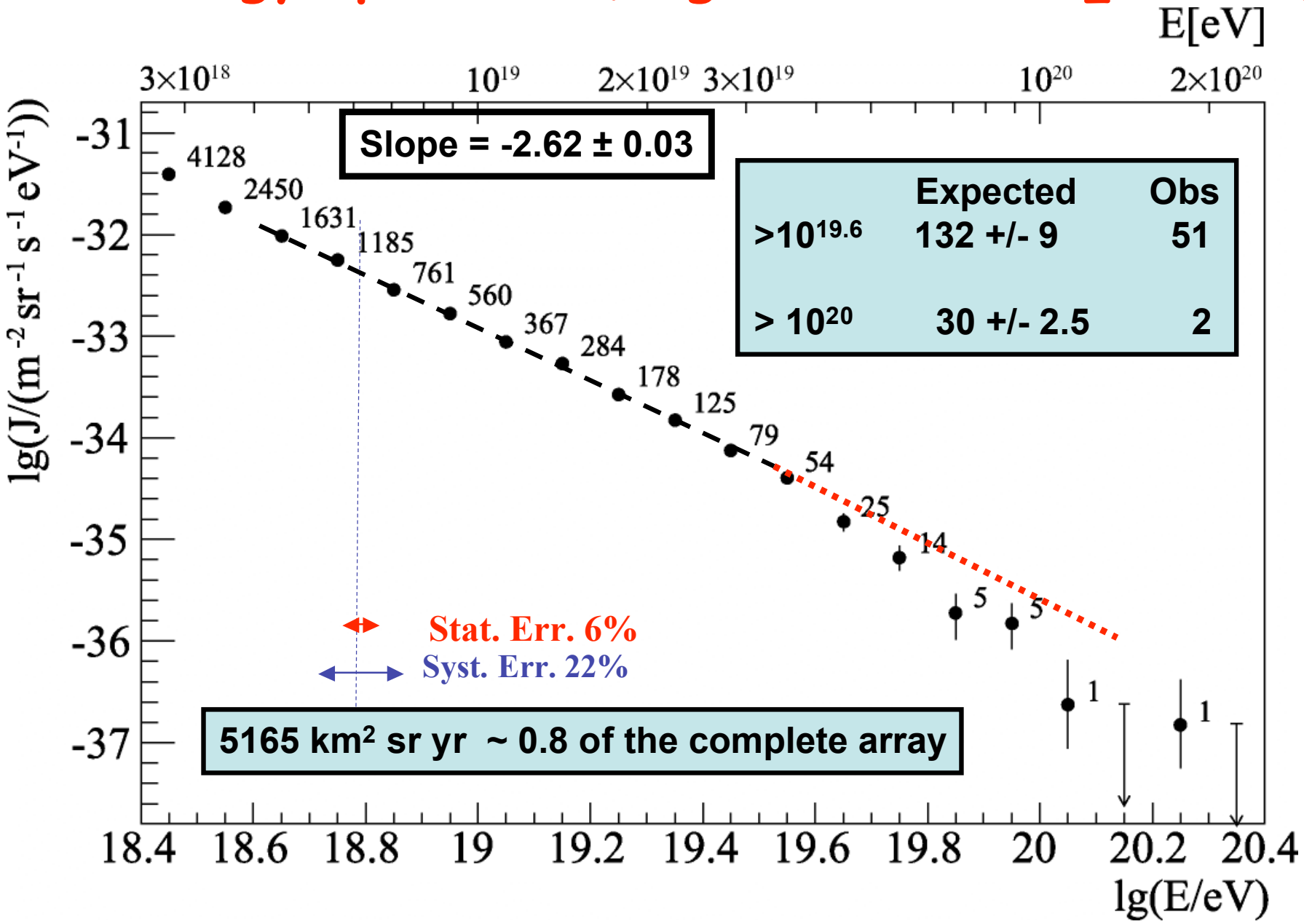
Source	Systematic uncertainty
Fluorescence yield	14%
P,T and humidity effects on yield	7%
Calibration	9.5%
Atmosphere	4%
Reconstruction	10%
Invisible energy	4%
TOTAL	22%

Fluorescence Detector uncertainties dominate

(SD energy estimator uncertainty is ~6% at 10^{19} eV & improves with E)

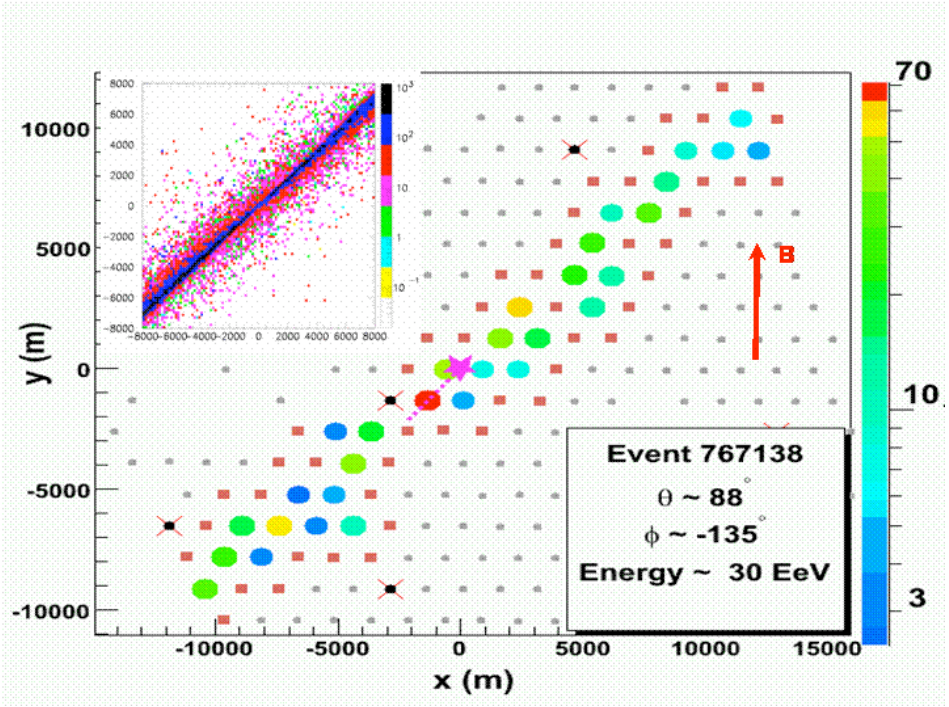
arXiv: 0706.1105, 0709.2125

Energy spectrum (Auger SD data $\theta_z < 60°$)



arXiv:0706.2096

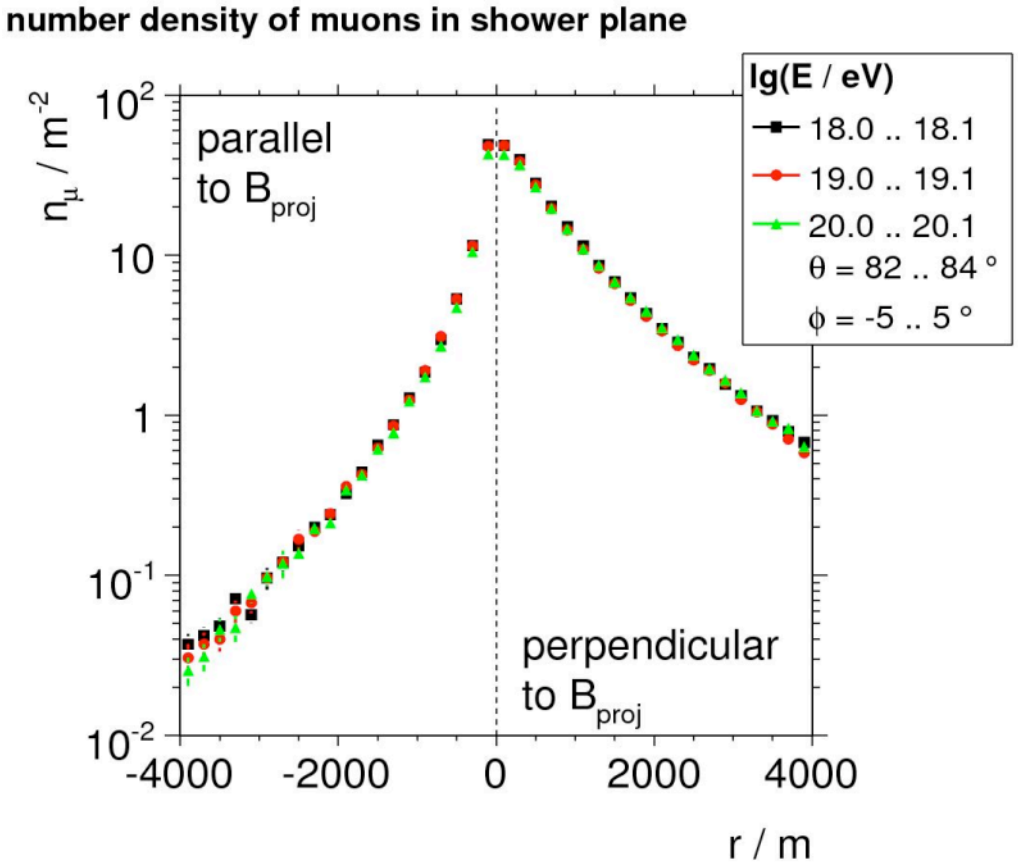
Cross-check with the inclined events (θ_Z > 60°)



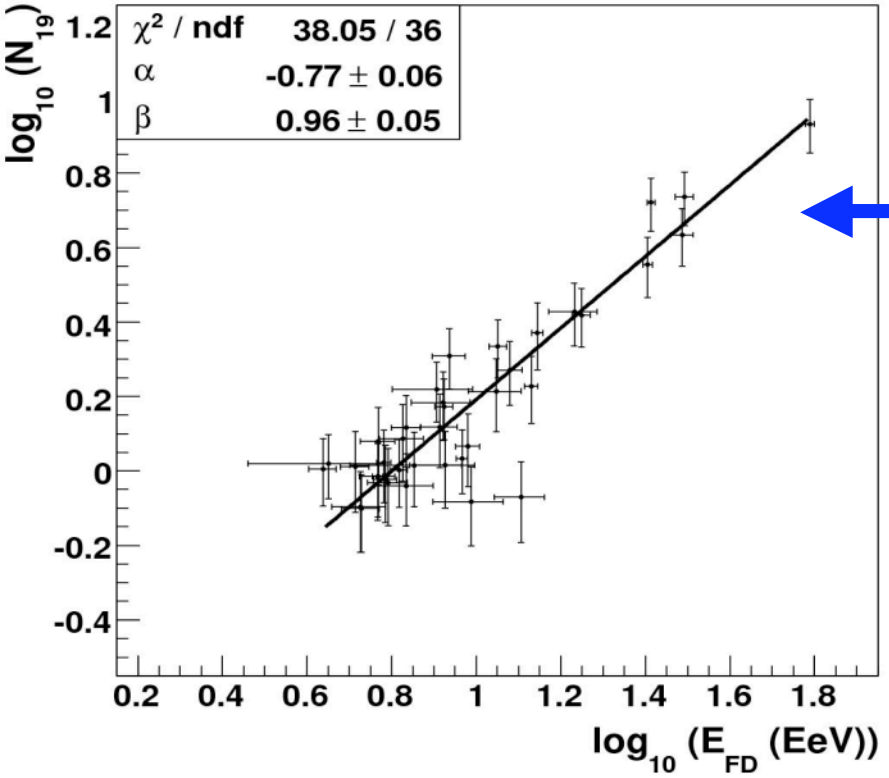
- Additional exposure & sky coverage
- Contain essentially muons

- Muon distribution depends mostly on arrival zenith and azimuth
- Its shape is mass and model independent

arXiv:0706.3796



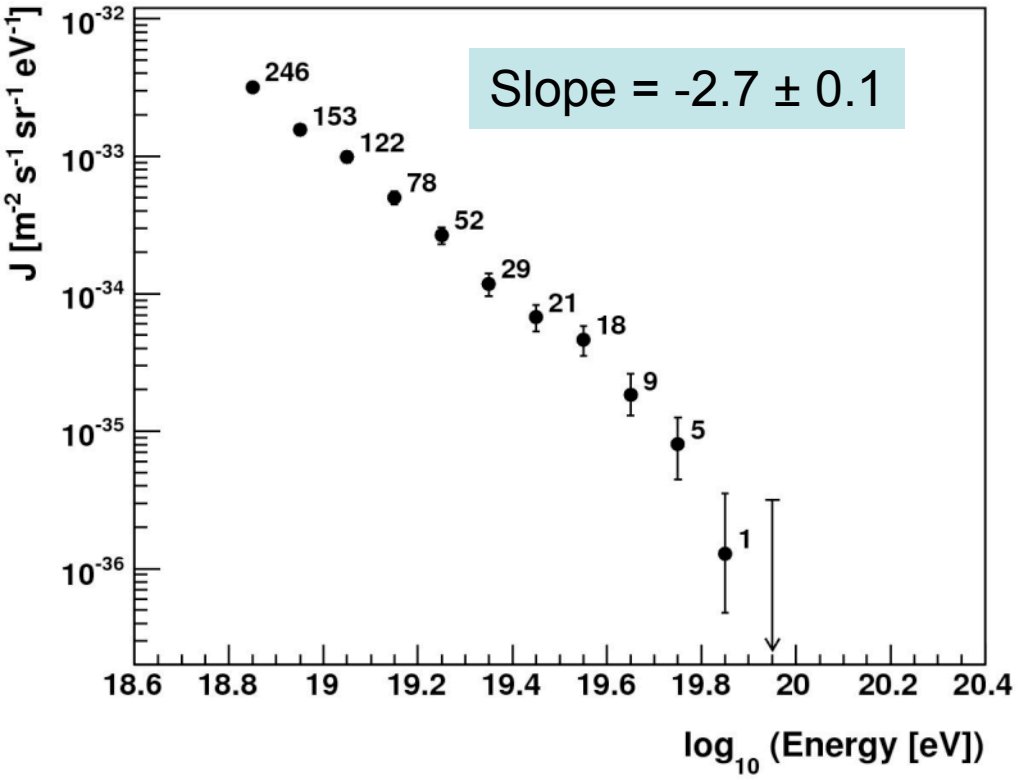
Auger energy spectrum of the inclined events



Calibration of the muon map normalization on the FD energy

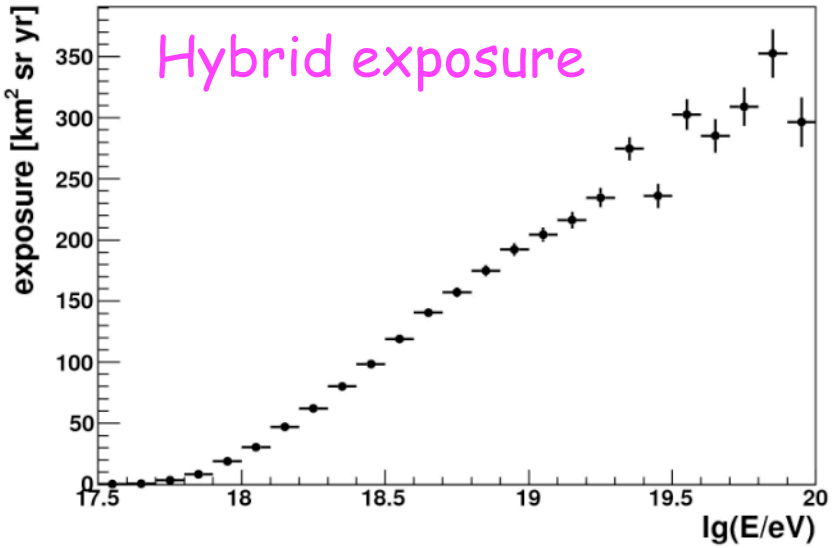
734 events (60° < θ < 80°)
Jan 2004 - Feb 2007

Integrated exposure
1510 km2 sr yr
(29% w.r.t. θ < 60°)

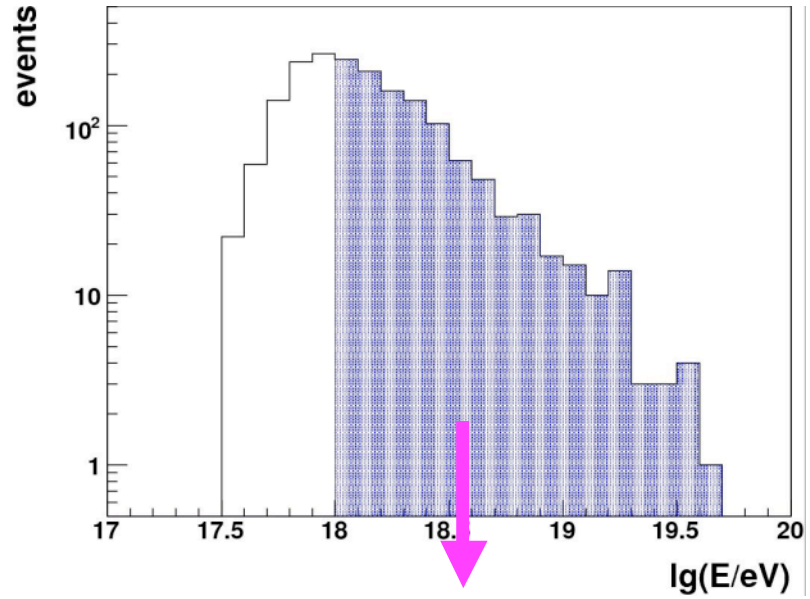


arXiv:0706.4322

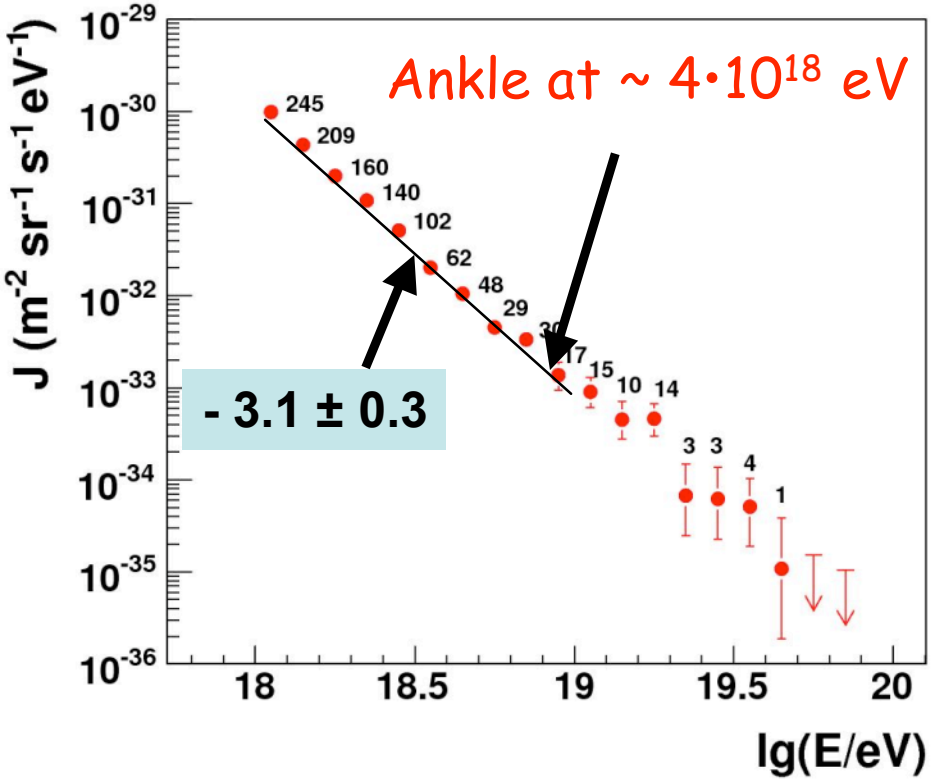
Auger energy spectrum with the hybrids



- ✓ Dist. tank - shower < 750 m
- ✓ θ_Z < 60°
- ✓ Development in the F.O.V of FD (« fiducial volume cuts » (E))
- ✓ χ^2/Ndof (GH fit) < 2.5
- ✓ Xmax bracketed
- ✓ Cherenkov contrib. < 50%
- ✓ atmospheric measurements available
- ✓ σ_E/E < 20 %

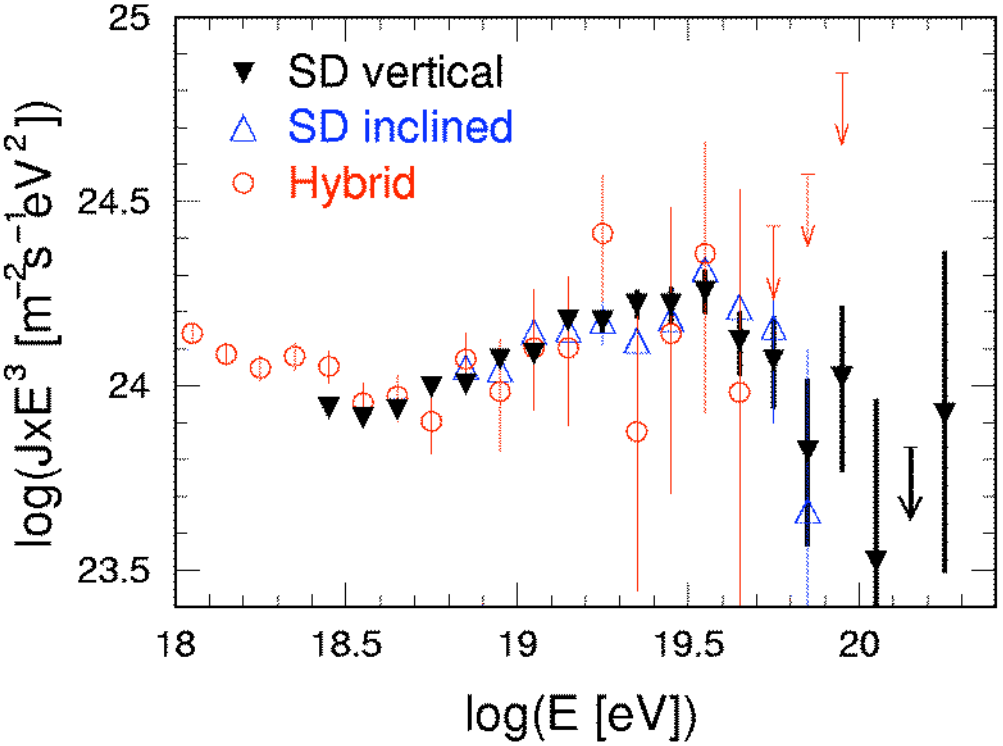


1092 events E > 10^{18} eV selected

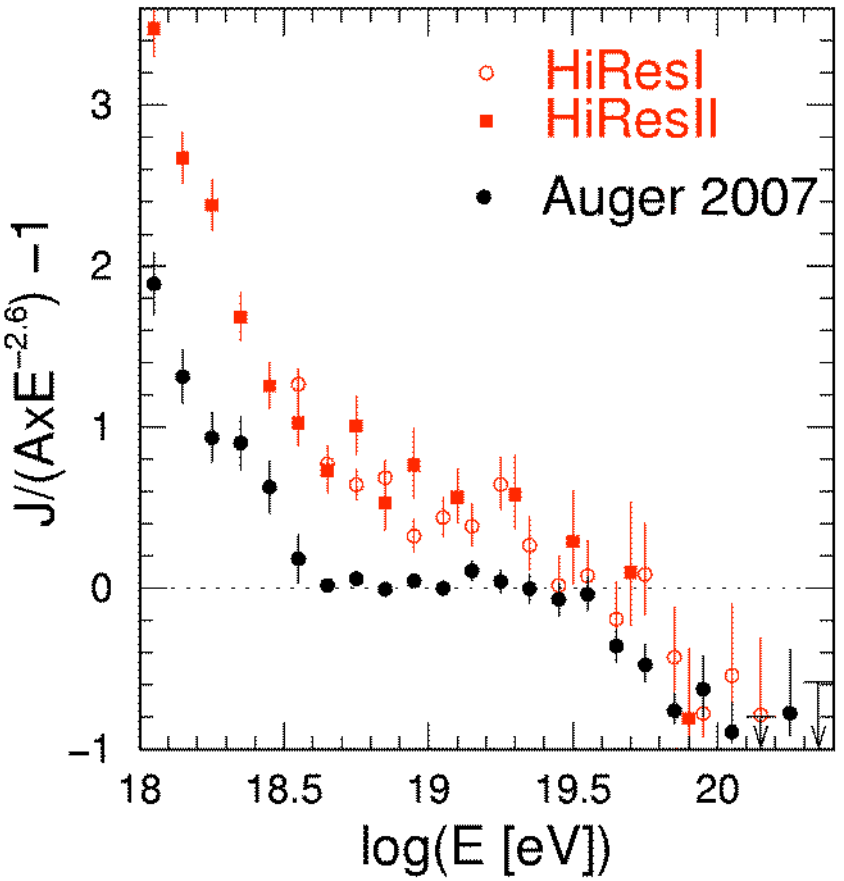


arXiv:0706.2643

Combined Auger spectrum



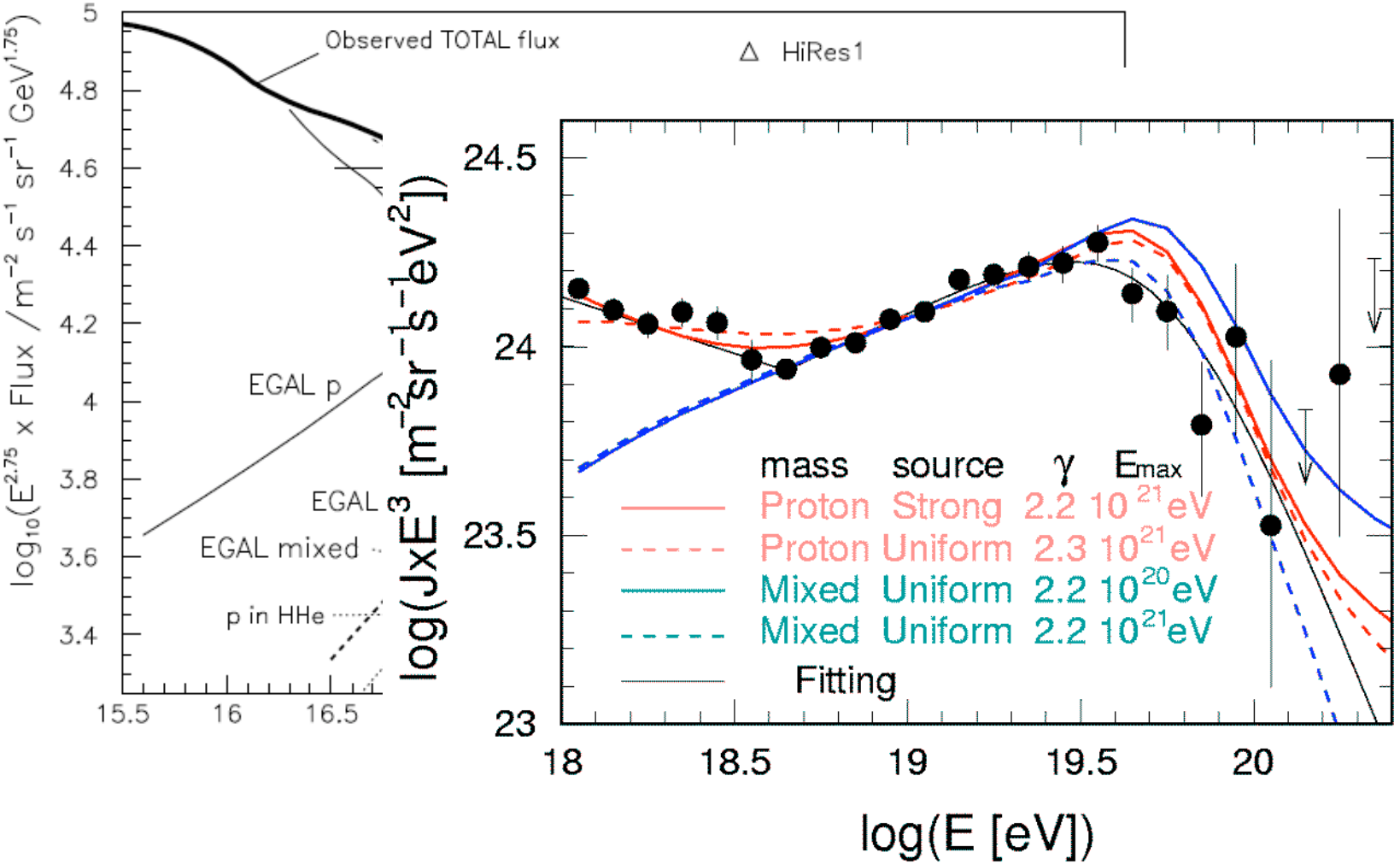
Residuals w.r.t. « standard» spectrum



- ankle at ~ 4.5 x 10^{18} eV
- steepening at ~ 3.55 x 10^{19} eV

arXiv: 0707.2638, 0801.2321

Interpretations and astrophysical implications



Ankle: galactic/extra-galactic transition ?

Suppression : GZK effect? **=> propagation models**

Knowledge of MASS is crucial

astro-ph/0607109, arXiv: 0707.2638

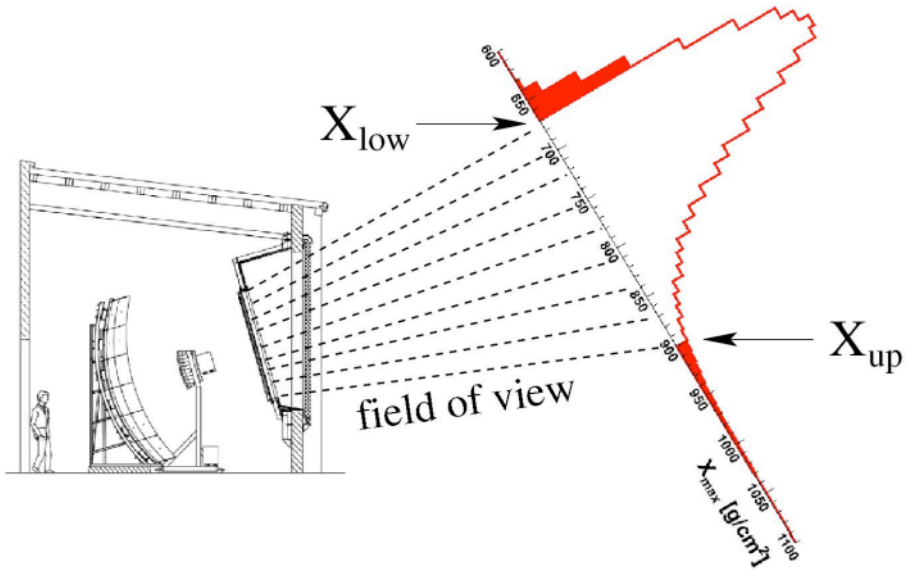
Pierre Auger Observatory

- a new stage in the ultra-high energy cosmic ray studies

Composition studies

Serguei Vorobiov, Nova Gorica U., Slovenia Quarks-2008, Sergiev Posad, May 27

Studies of the composition variation with energy



4329 high quality hybrid events

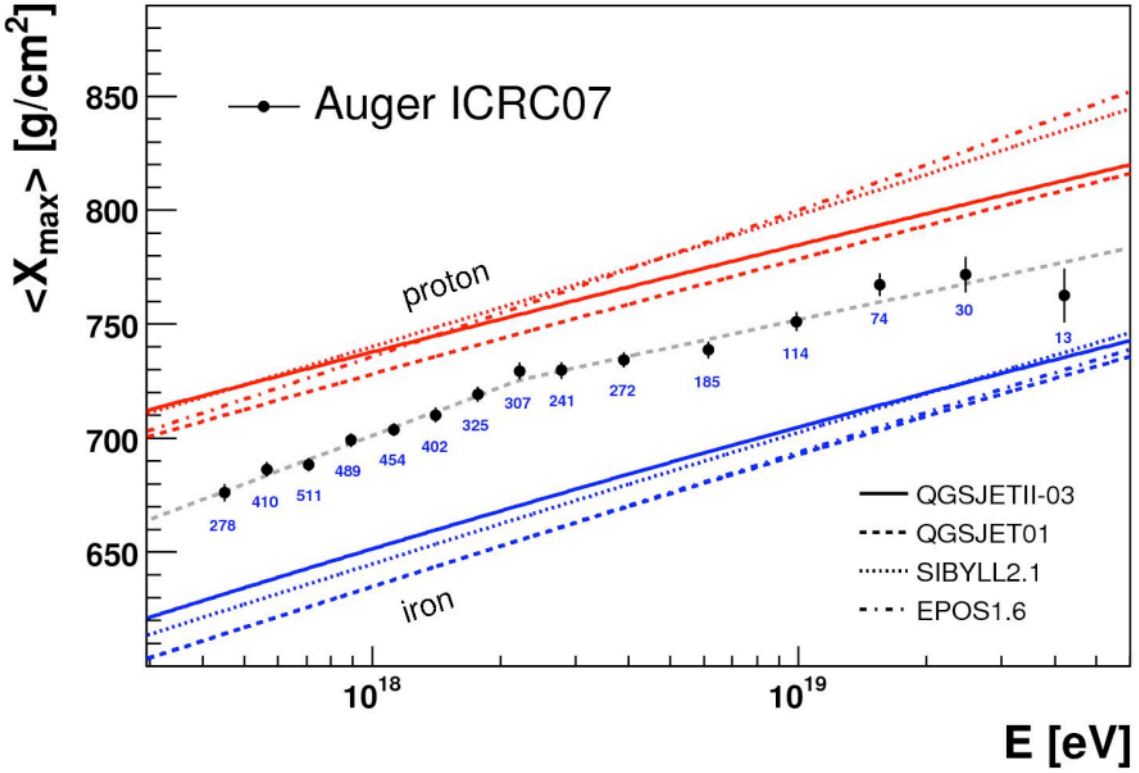
$$\langle X_{\rm max}\rangle = D_{\rm p}\left[\ln\left(E/E_0\right) - \langle \ln A\rangle\right] + {\rm c}_p$$

D_p, c_p : elongation rate & mean depth (at E_0) for protons

"Elongation rate" measured on 2 decades in E

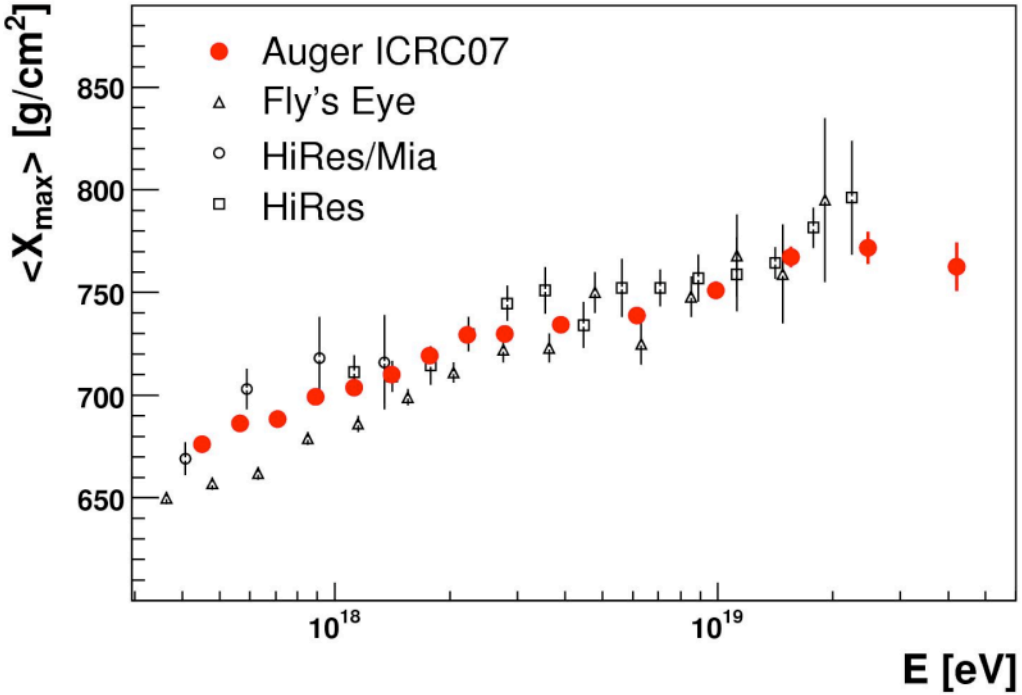
Interpretation depends on hadronic interaction models

Fluctuations of Xmax have to be exploited



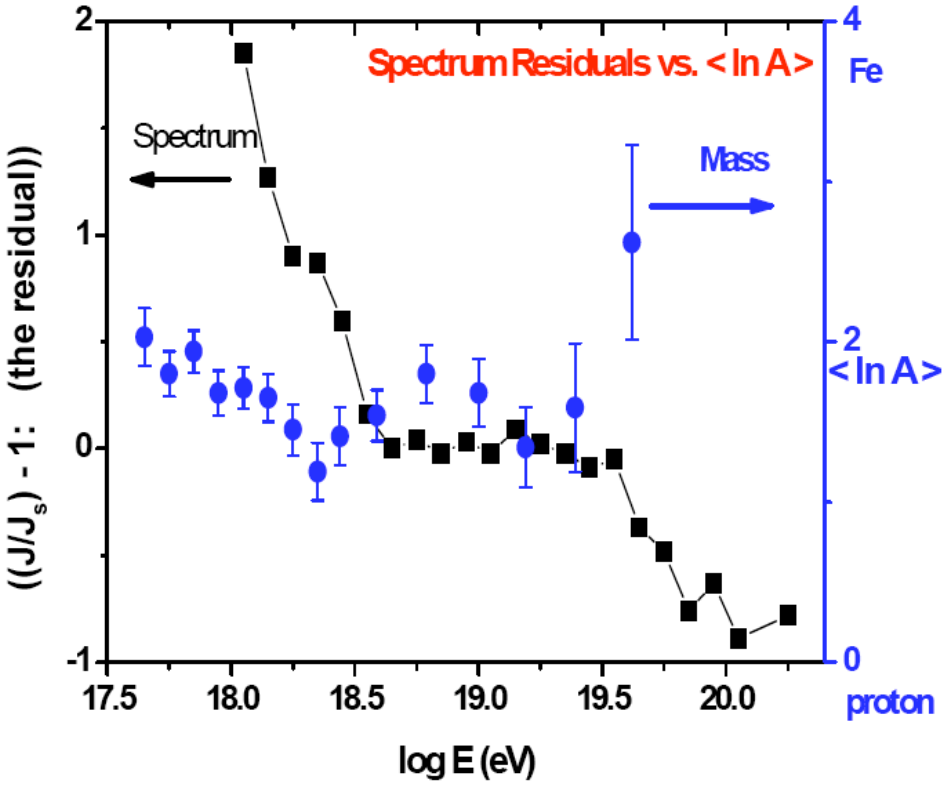
arXiv:0706.1495

Comparison with the previous Xmax measurements and with the Auger energy spectrum



Auger : gain in precision, covered energy range, better control of systematic errors

QGSJETII-03 assumption :



Composition is not proton-dominated at the highest energies ?

Need to modify hadronic models (larger cross-section and/or more muons) ?

arXiv:0706.1495, 0801.2321

Studying photon contents in the UHECR

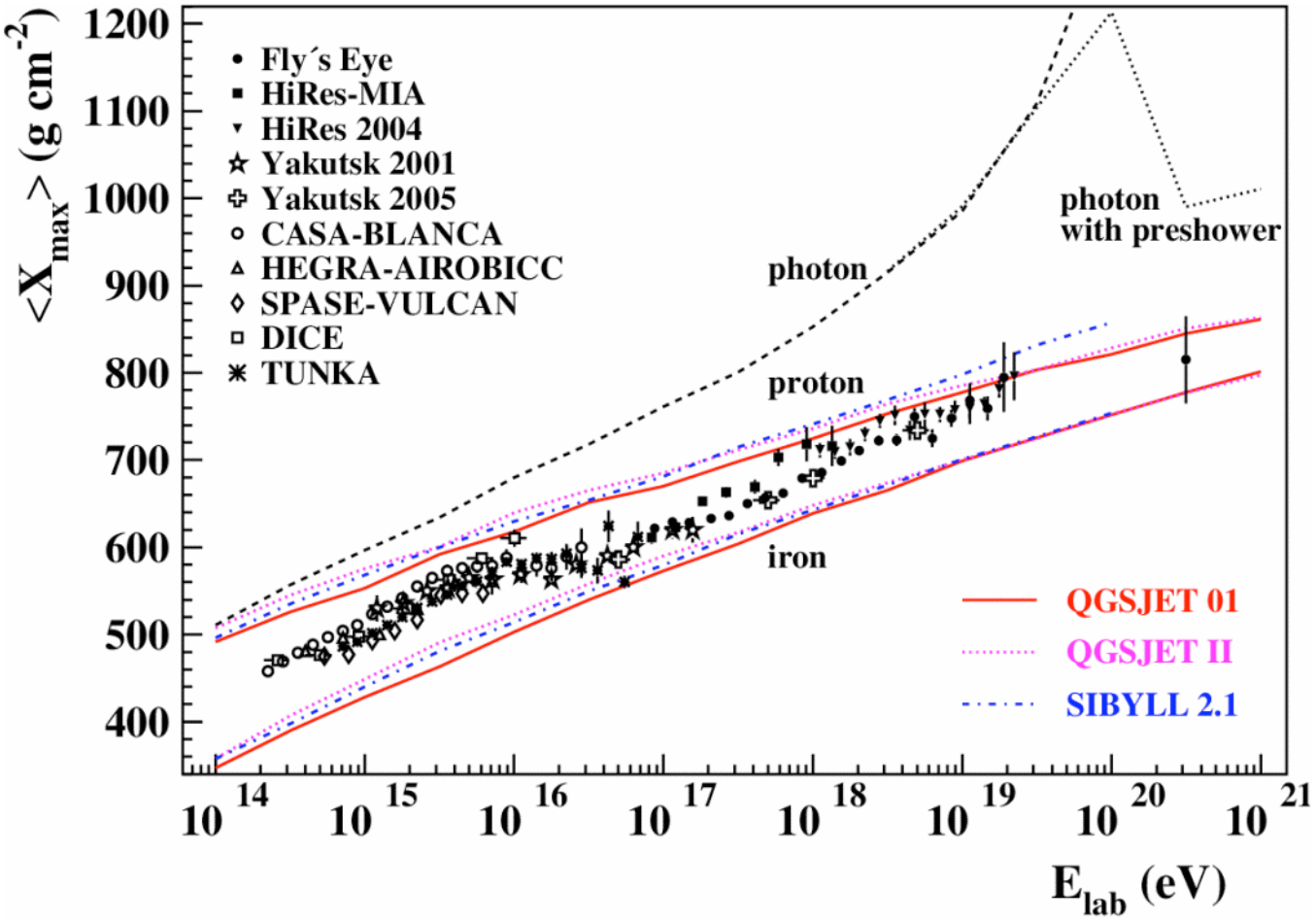
- Discrimination between models of UHECR origin

Photon elongation rate:
- LPM effect,
- magnetic conversion in the terrestrial field (« preshower », > 50 EeV for the Southern Auger site)

- Photon showers *vs* hadron ones:
  - less developed (deeper maximum)
  - with poorer muon contents
  - modelled with greater confidence

- Previous limits by ground arrays only

- Auger: direct X_{max} measurement with the hybrid events => upper limit of 16% at 95%CL above 10 EeV



(astro-ph/0606619) Lower hybrid statistics => extract upper limit from SD data

Resulting upper limits on UHE photons

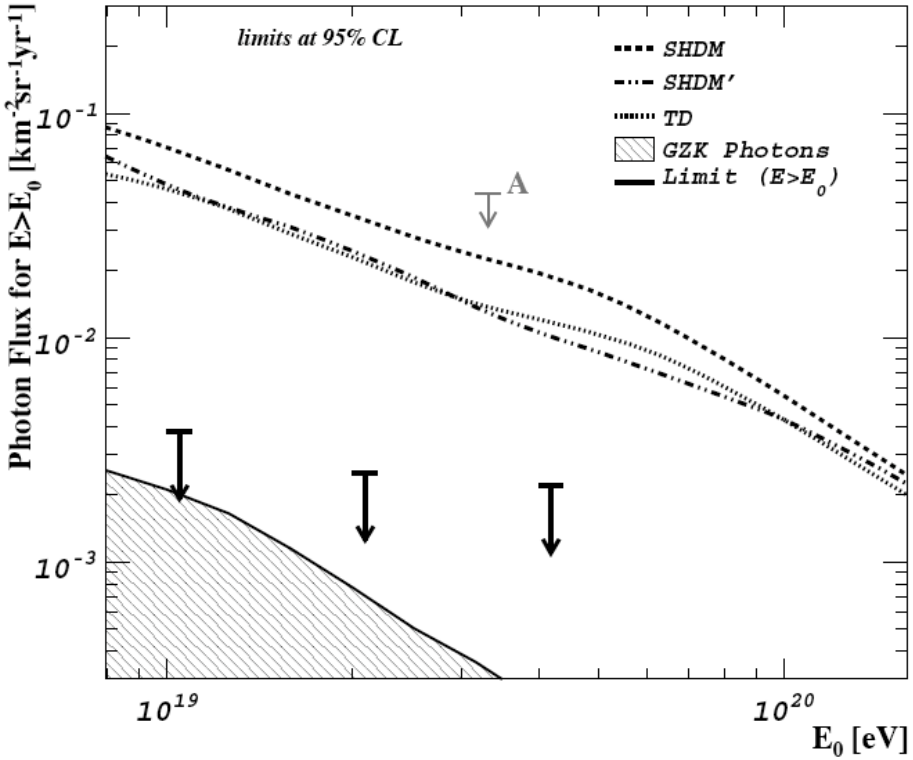
Upper limits on photon flux and fraction above 10, 20, and 40 EeV at 95% CL

Significant improvement upon the results from the previous experiments

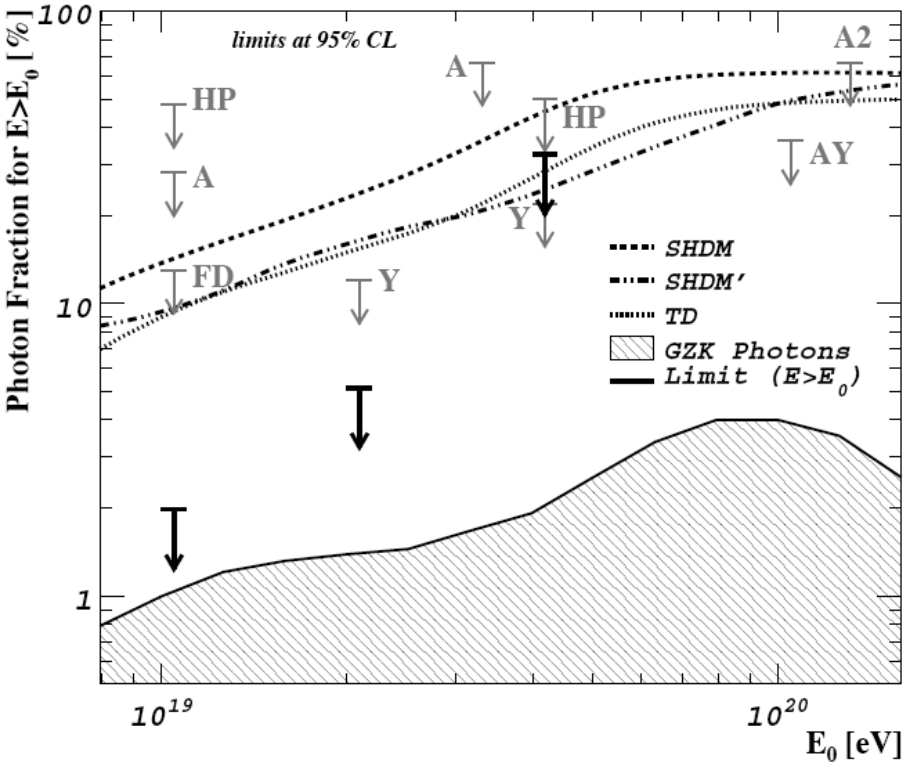
Exotic models of UHECR production are strongly constrained

With the future data, GZK photons level may be reached

Flux limit



Fraction limit



arXiv:0712.1147

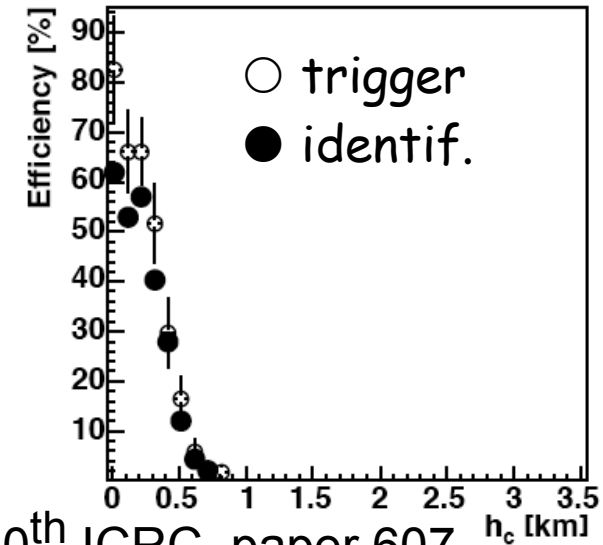
Auger sensitivity to the up-going tau-neutrinos

$L_{int}(\nu) \sim 500$ km $L_{decay}(\tau) \sim 50$ km $L_{Eloss} \sim 10$ km (at 1 EeV)

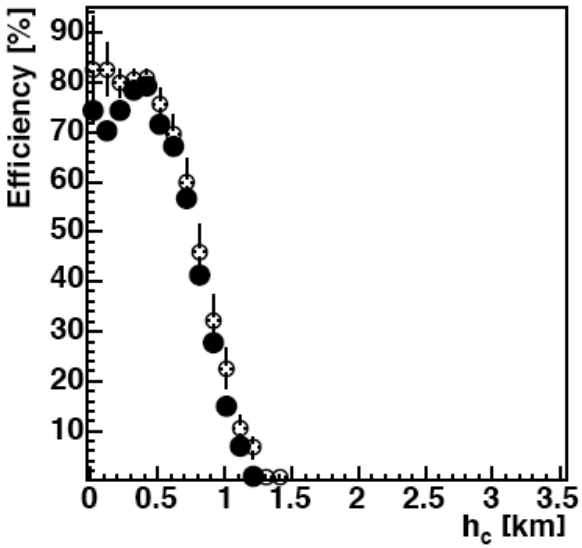
θ>95, Earth opaque (μ), much larger (e), much smaller

h_c - height reached by the shower along the axis at 10 km from the τ decay

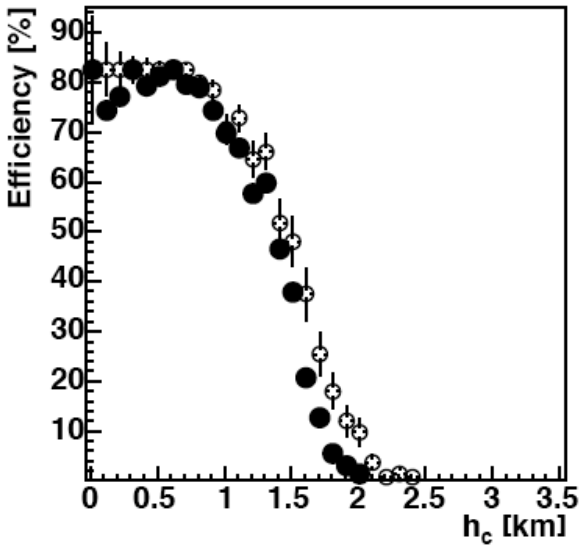
$\log_{10}(E_\tau/eV) = 17.5$



$\log_{10}(E_\tau/eV) = 18.5$



$\log_{10}(E_\tau/eV) = 19.5$

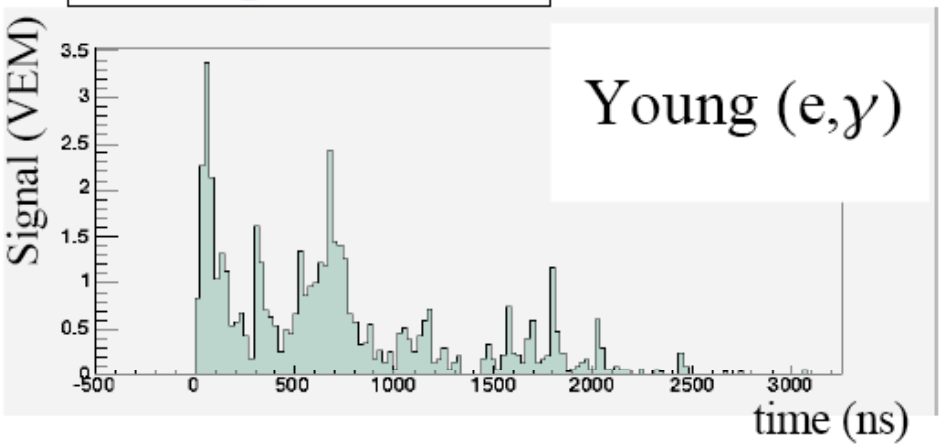


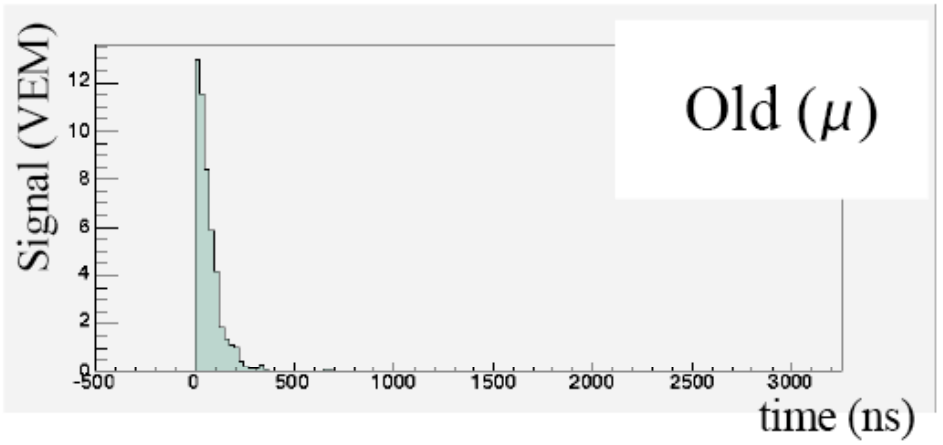
30th ICRC, paper 607

Search for Earth-skimming tau-neutrinos

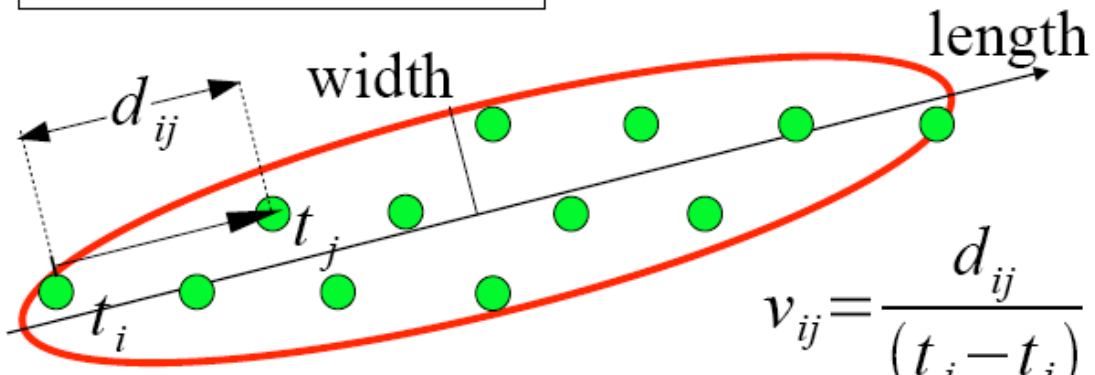
Shower induced by emerging τ : start close to the detector (young) and is very inclined (90°< ϑ <95°)

Young Showers





Inclined Showers

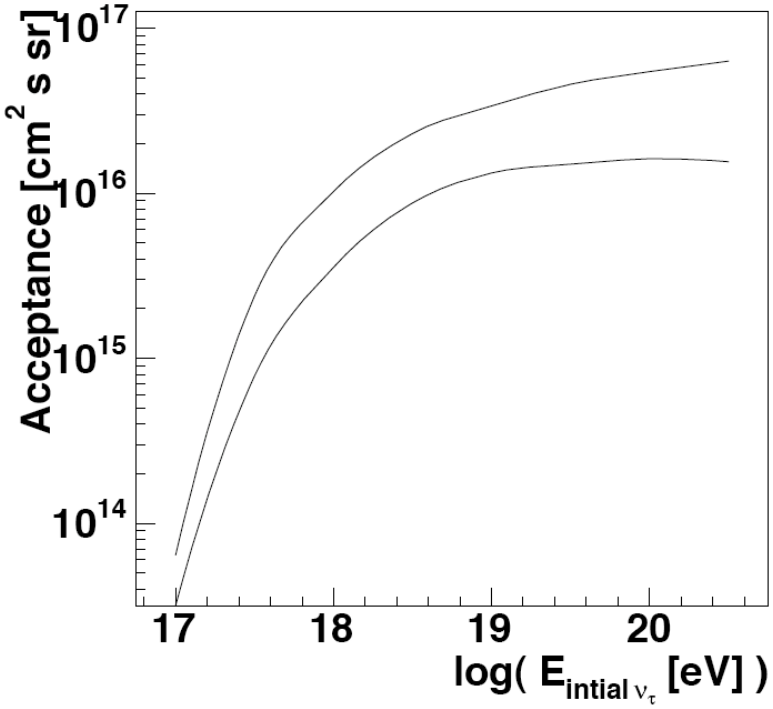


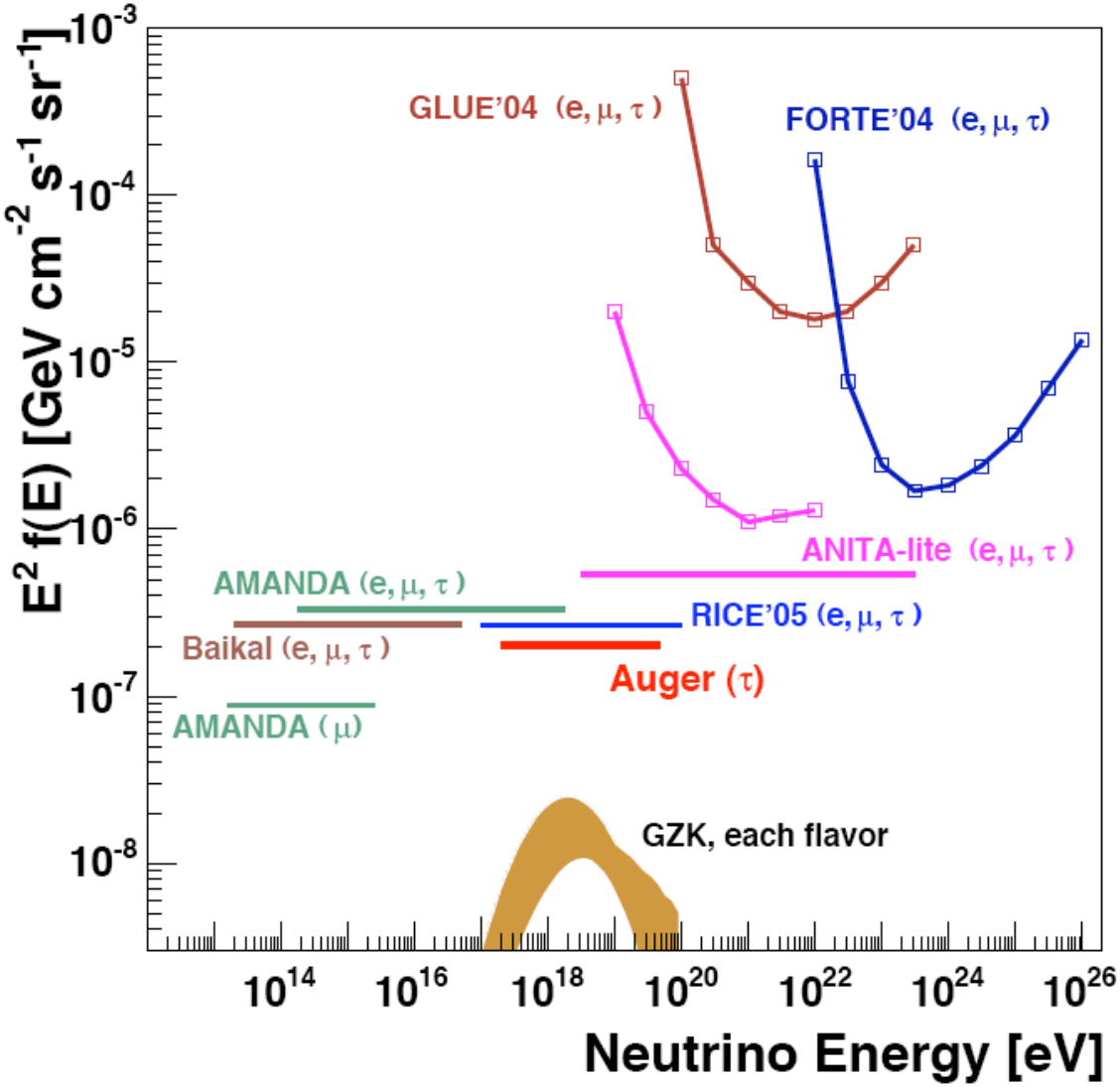
$$v_{ij} = \frac{d_{ij}}{(t_j - t_i)}$$

length/width > 5
<v> ∈ (0.29,0.31) m/ns
RMS(v) < 0.08 m/ns

arXiv:0706.1658

Auger Limit at 90% CL to an E^{-2} diffuse ν_τ flux





Uncertainties:

ν cross-section	15%
τ energy losses	40%
τ polarization	30%
Site topography	18%
Interactions in the Earth	5%
EAS & detector sim	25%

arXiv:0706.1658, journal paper soon

Pierre Auger Observatory

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Anisotropies search

Serguei Vorobiov, Nova Gorica U., Slovenia Quarks-2008, Sergiev Posad, May 27

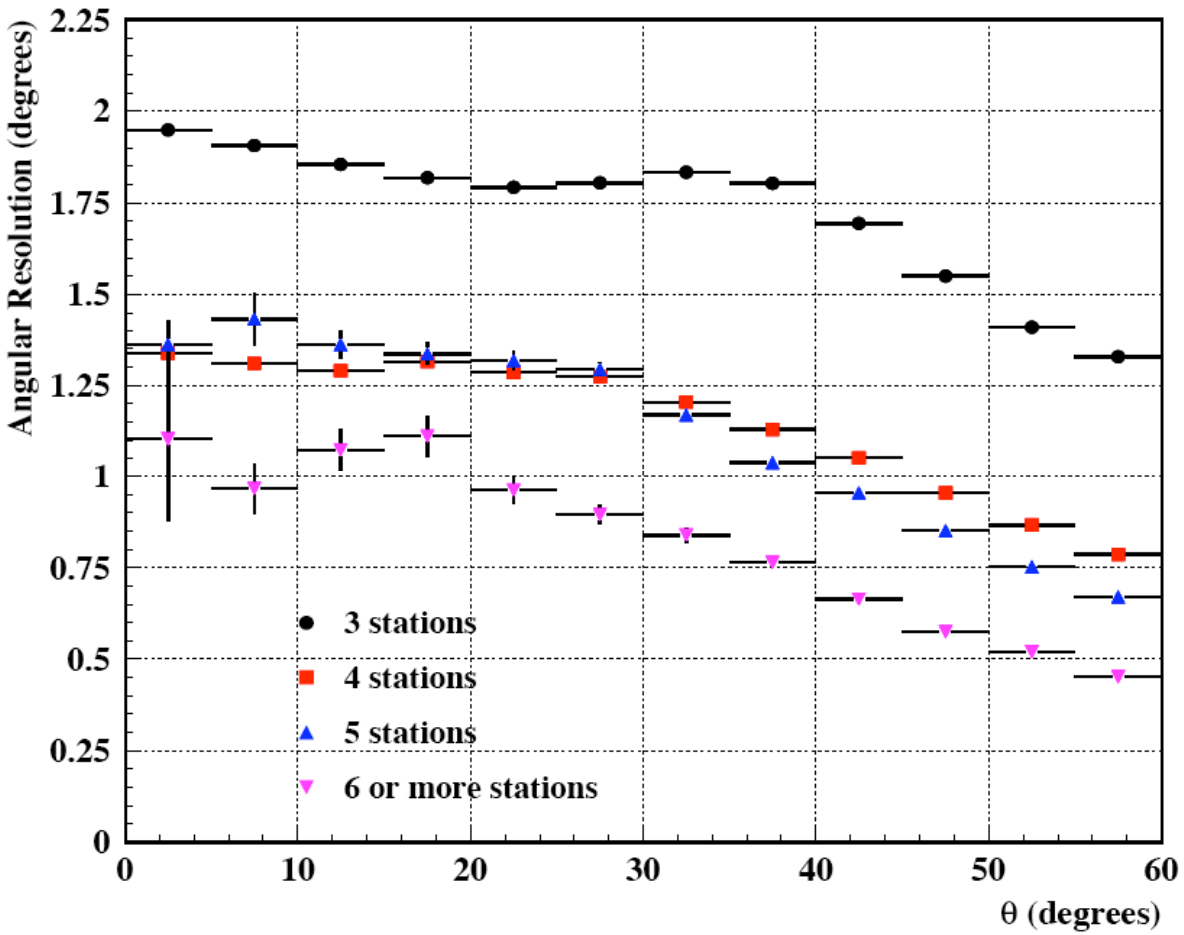
Detector angular resolution

- Surface detector : event reconstruction from the shower front arrival times, on an event by event basis

$$F(\eta) = \frac{1}{2}(V[\theta] + \sin^2(\theta)V[\phi])$$

$$e^{-\eta^2/2\sigma^2}\ d(\cos(\eta))d\phi$$

The angular resolution (AR) is defined as the angular radius that contains 68% of showers coming from a point source



$$AR = 1.5\sqrt{F(\eta)}$$

3 tanks:

E < 4 EeV

4 tanks:

3 EeV < E < 10 EeV

5+ tanks:

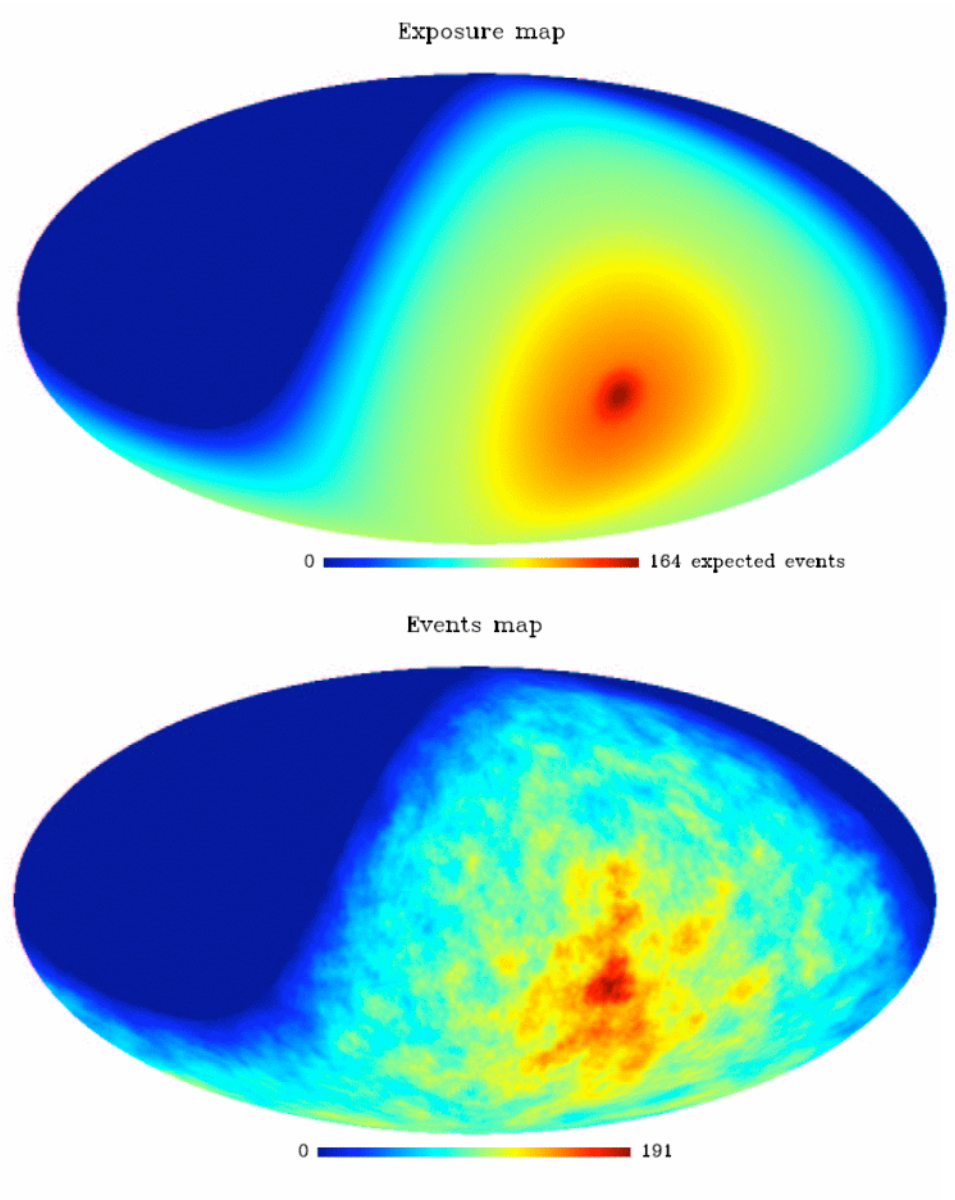
E > 8 EeV

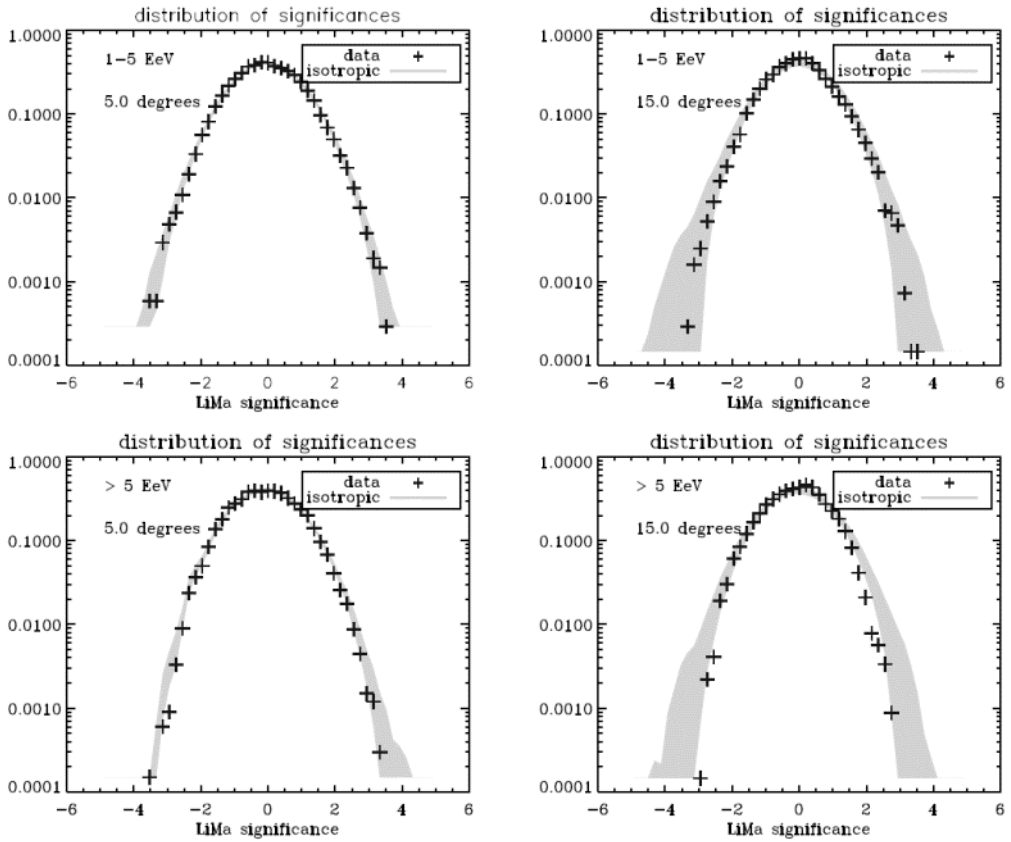
Cross-checks using:

- the station pairs (twin tanks) located ~ 11 m apart
- the hybrid events (AR ~ 0.6º)

arXiv:0709.2125

Coverage map, event map



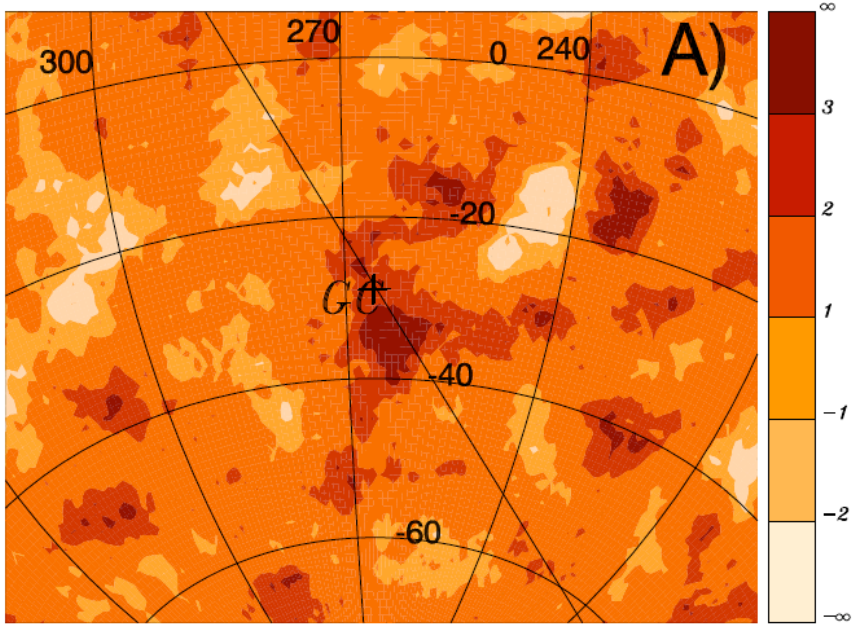


Growing array
Weather effects

At large angular scales the Auger sky is compatible with isotropy

Auger Galactic Center studies

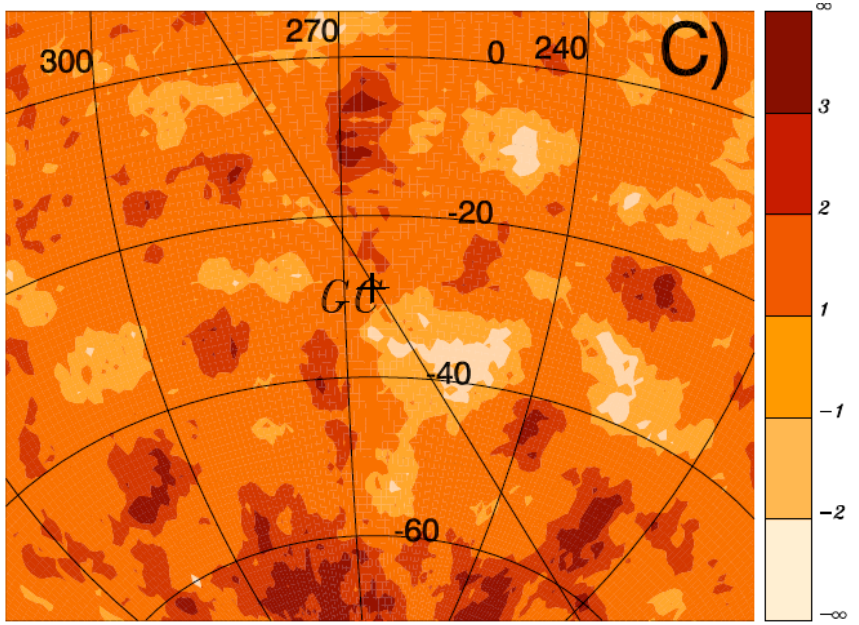
1 < E < 10 EeV



Search for extended (in top-hat windows of 10 and 20 degrees) and point-like source (Gaussian beam matching angular resolution)

No excess is found, overdensity distributions compatible with the isotropic sky

0.1 < E < 1 EeV



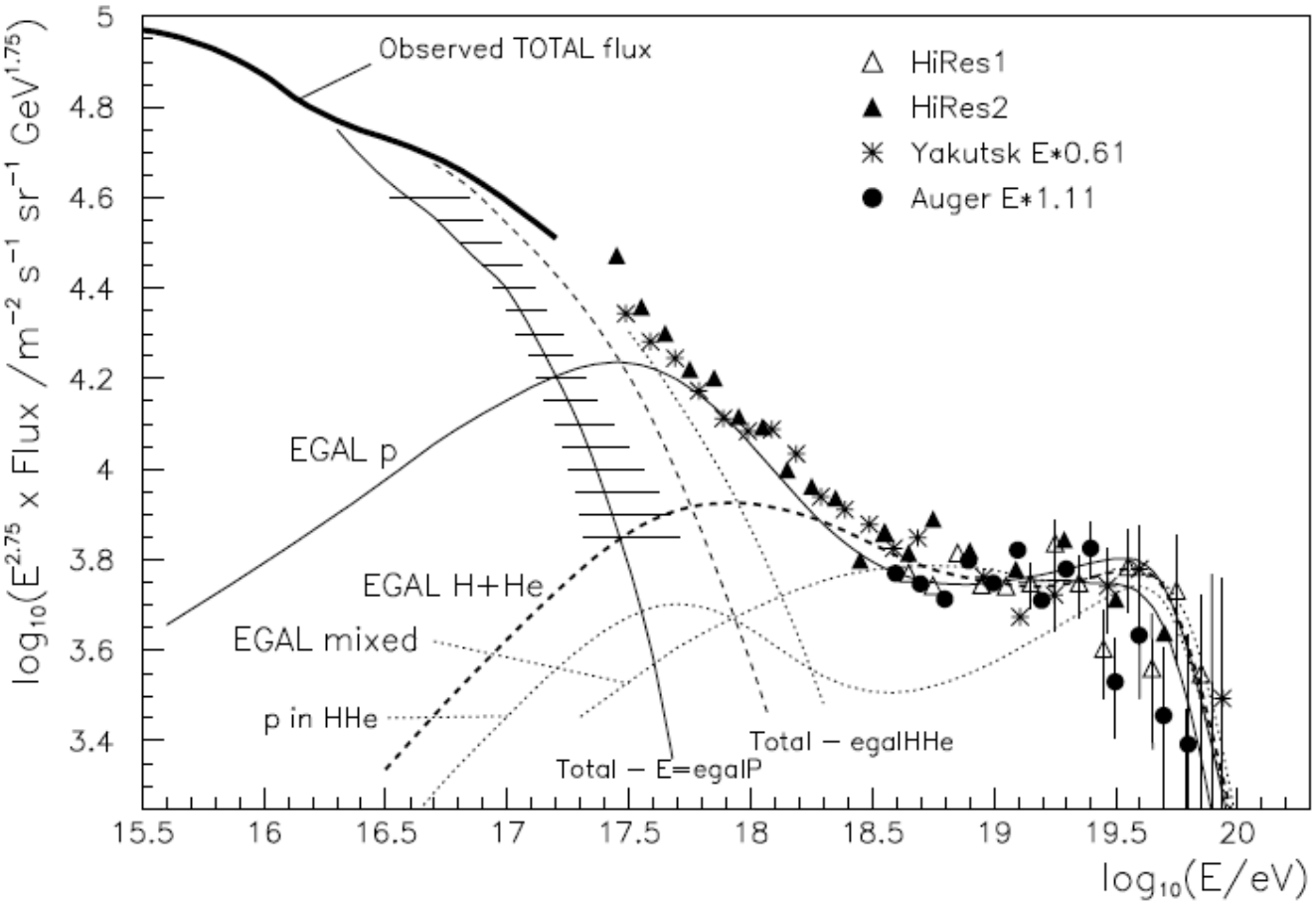
Upper limit on the point-like source allows to exclude most of the neutron production models at the Galactic Center

No confirmation of previous indications for excess from GC region

arXiv:0706.2669

Large-scale anisotropies search : motivations

- If transition galactic - extragalactic at the ankle: at EeV energies CR diffusive escape from the Galaxy is efficient enough => %-level modulation (model-dependent)
- If transition galactic - extragalactic at $5 \cdot 10^{17}$ eV: at EeV energies the CR sources cosmologically distributed => no large-scale pattern except for CMB-like dipole (~ 0.6%)



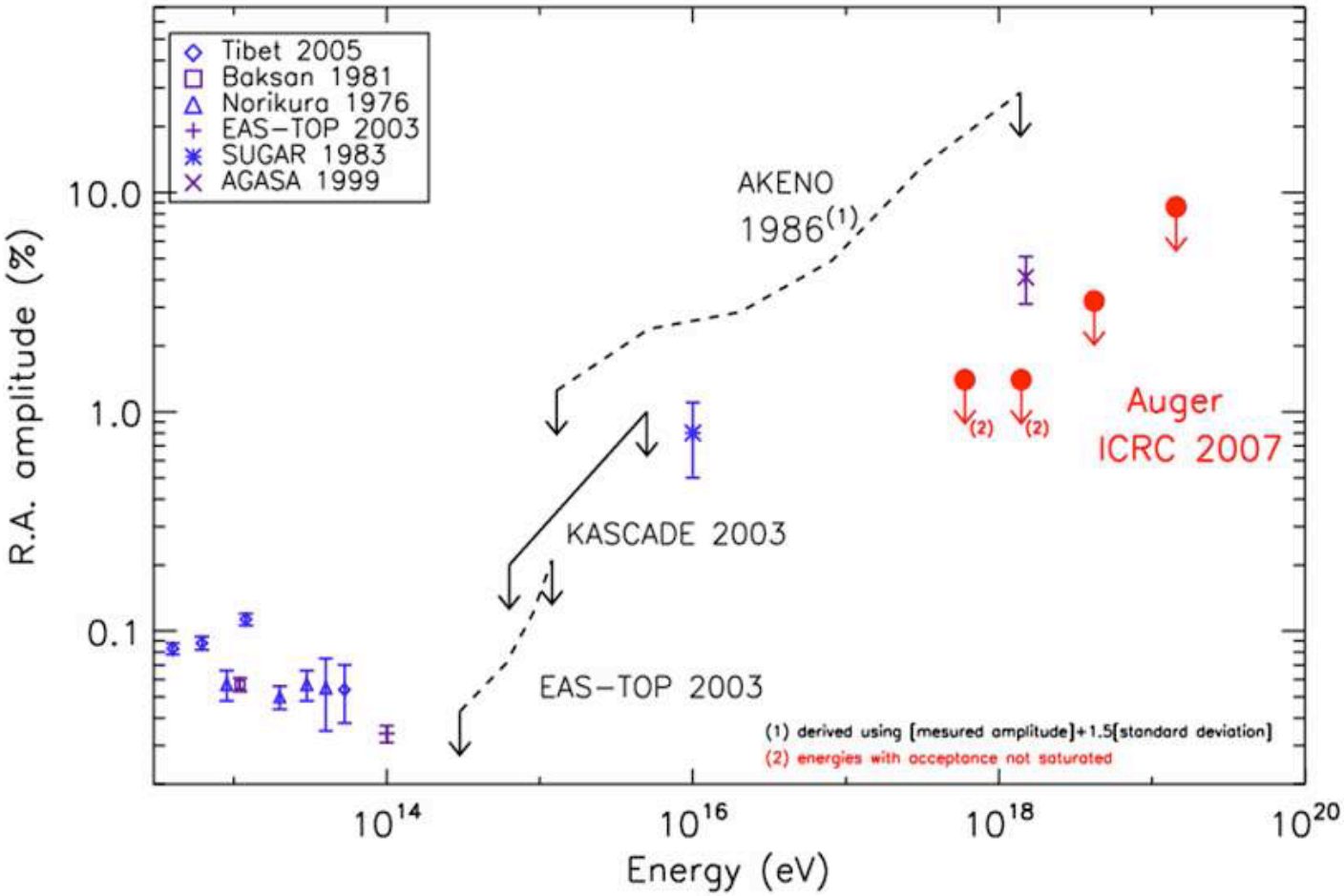
=> studies of the large-scale anisotropy and its evolution with primary energy is a tool to learn about origin and the mechanisms of the propagation of the UHECR

Large-scale anisotropies search : results

Three complementary analyses of the Right Ascension distribution at EeV energies

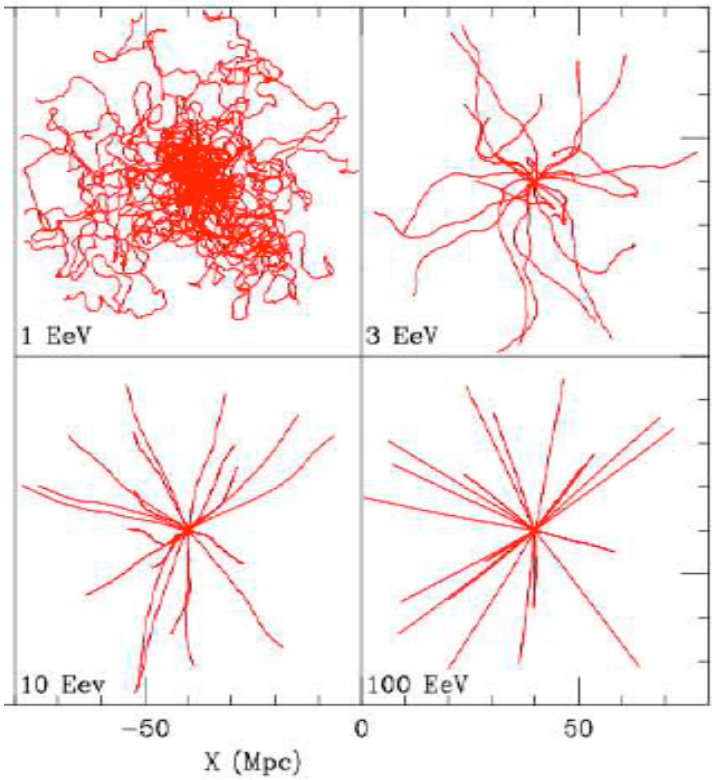
No anisotropy found

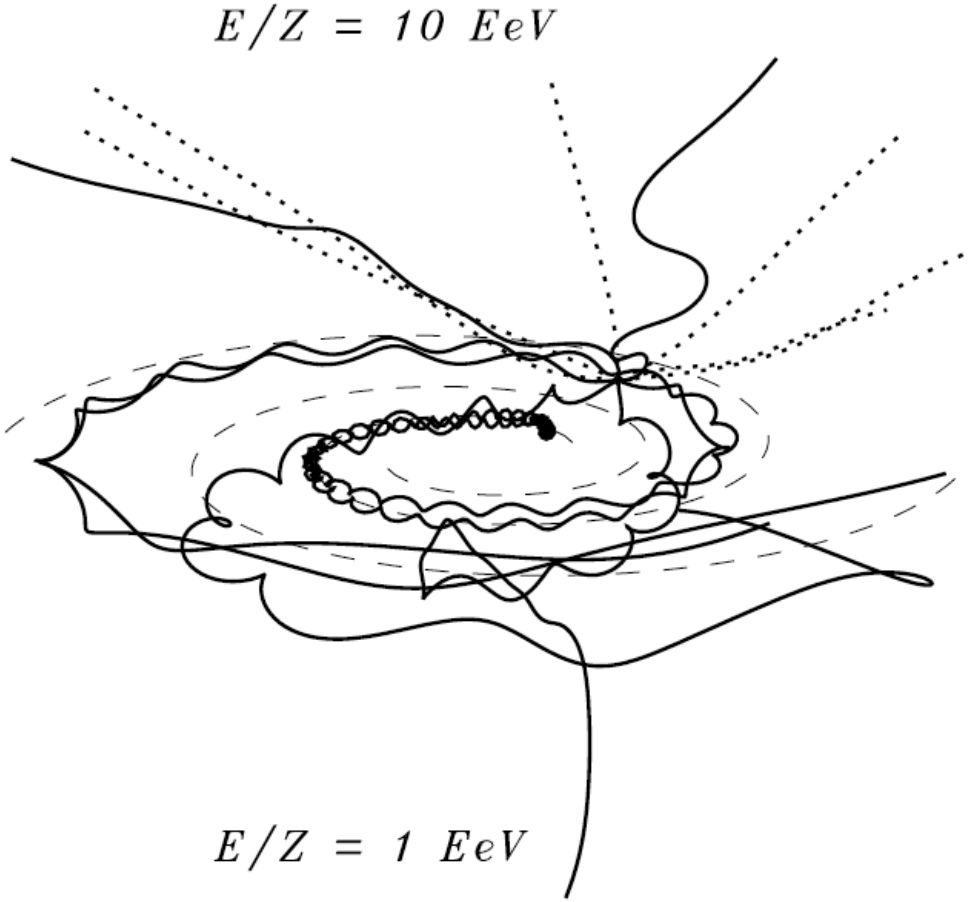
Upper Limit on the first harmonic modulation of 1.4 % at (1 EeV < E < 3 EeV)



arXiv:0706.2640

At the highest energies : smaller magnetic deflections !

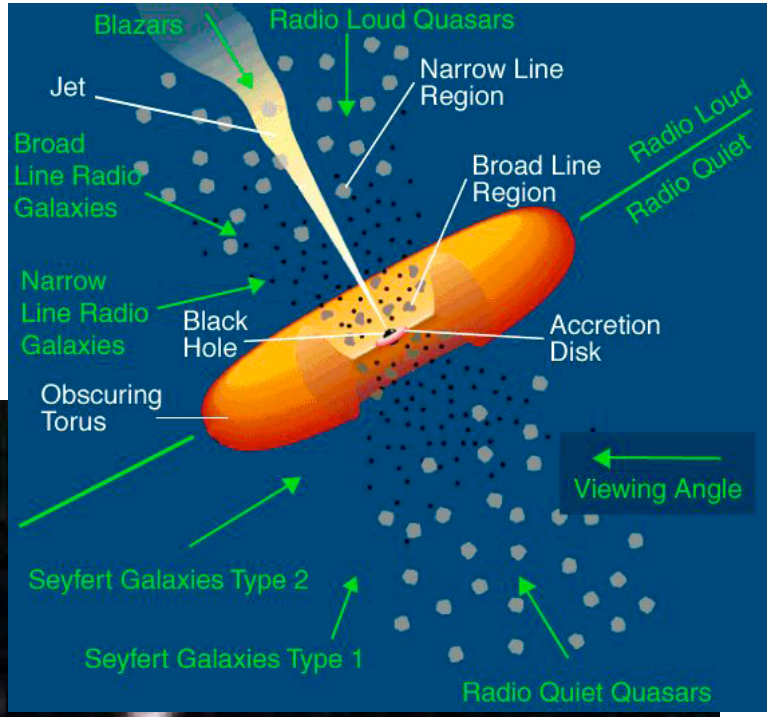


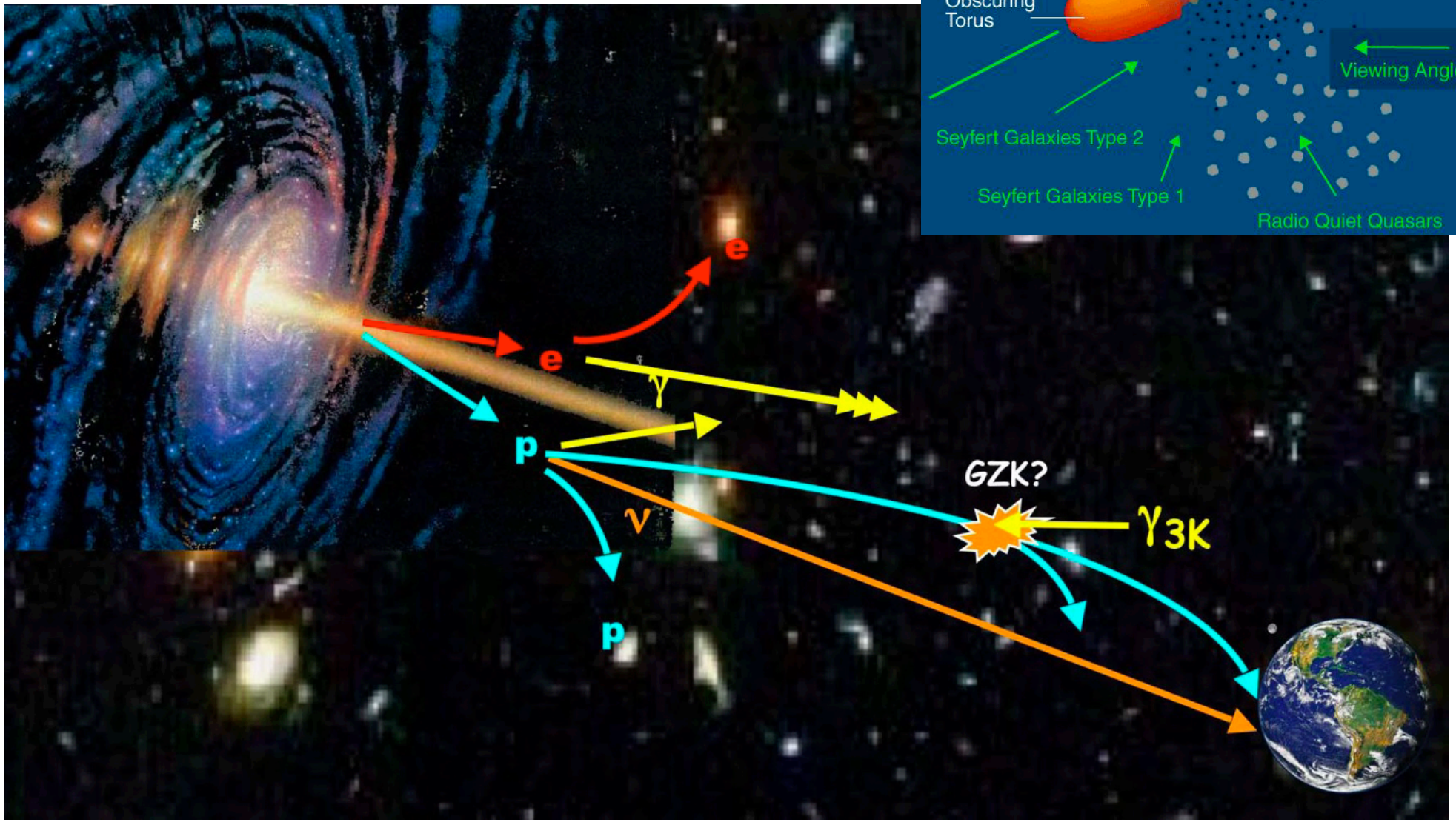


Redshift	Lum.Distance
0.004	16 Mpc
0.01	40 Mpc
0.05	200 Mpc
0.1	415 Mpc

Anisotropy studies : look for small-scale clustering and the correlations with the candidate astrophysical objects

Active galactic nuclei as candidates for the UHECR sources





Analysis method for the correlation search

- Under cosmic ray event isotropy hypothesis

Probability *P* that ≥ *k* out of *N* events (with energy > E_{min}) correlate by chance with the selected objects (at redshift < z_{max})

$$P = \sum_{j=k}^{N} \binom{N}{j} p^j (1-p)^{N-j}$$

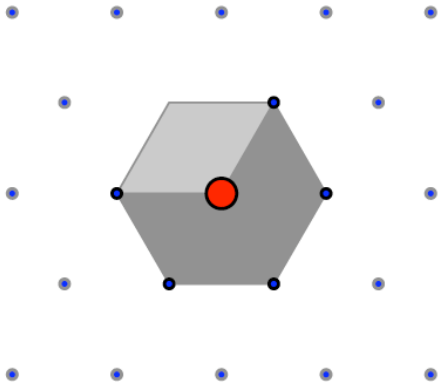
p is the fraction of the sky (exposure-weighted) defined by the regions at angular separation less than ψ from these objects

- Scan over parameter space (E_{min}, z_{max}, ψ) for the minimum of P (P_{min})
- Scan over simulated isotropic sets of events : fraction of sets with $P < P_{min}$ gives the « penalized » probability $\mathcal{P}$
- If $\mathcal{P}$ small enough (~ 10^{-3}) : confirmation with an independent data set (Auger anisotropy search protocol)

Exploratory scan

data selection

- 01/2004 - 05/2006 ($\approx$ 480.000 events)
- quality criteria *"ICRC05-T5"* $\longrightarrow$ angular resolution $\sigma_\Psi < 1^\circ$
- zenith angle $< 60^\circ$



strong correlation signal

- sharp energy threshold $E \geq 56$ EeV
- nearby sources $z \leq 0.018$
  ($D \leq 75$ Mpc for $H \approx 70$ km/sec/Mpc)
- resonable angular spread $\Delta_\Omega(\mathrm{CR} : \mathrm{AGN}) \leq 3.1^\circ$

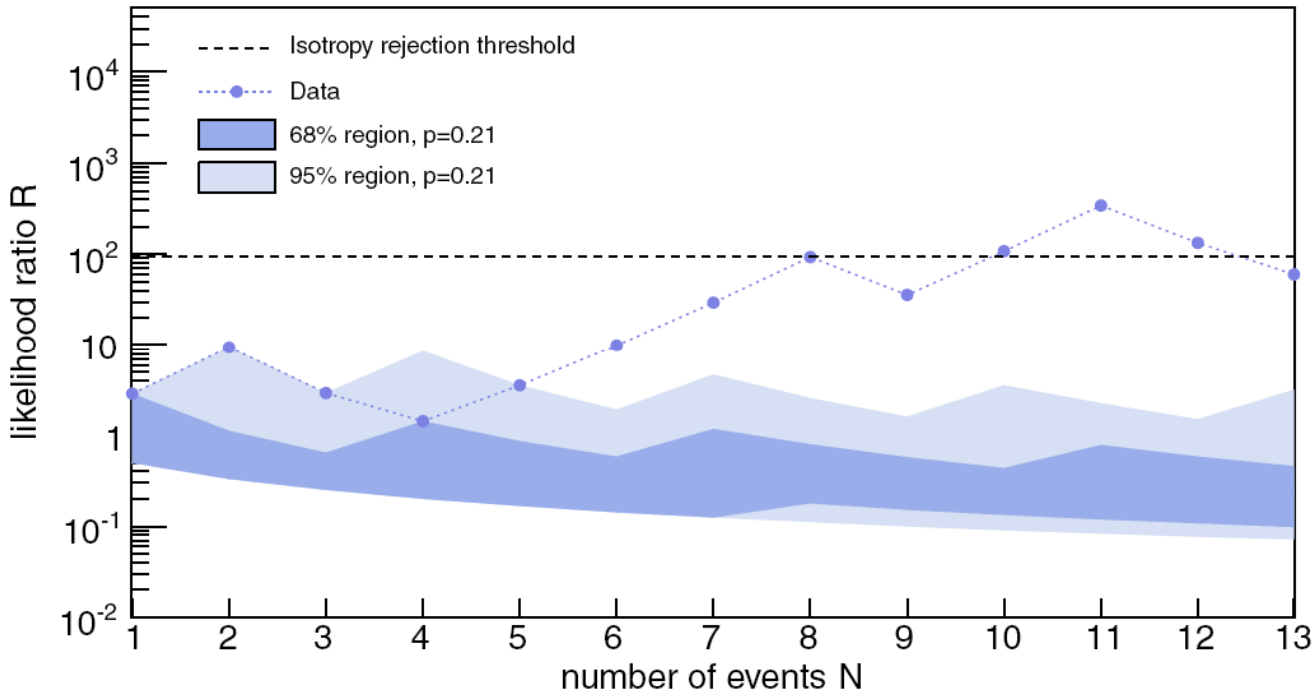
- 12 out of 15 events correlate
- expected 3.2 chance correlations ($P_{\mathrm{iso}} \approx 21\%$)

- Pierre Auger anisotropy search protocol
- fixing parameters *a priori* $\longrightarrow$ PRESCRIPTION
- signal testing with NEW dataset

Signal confirmation

new dataset

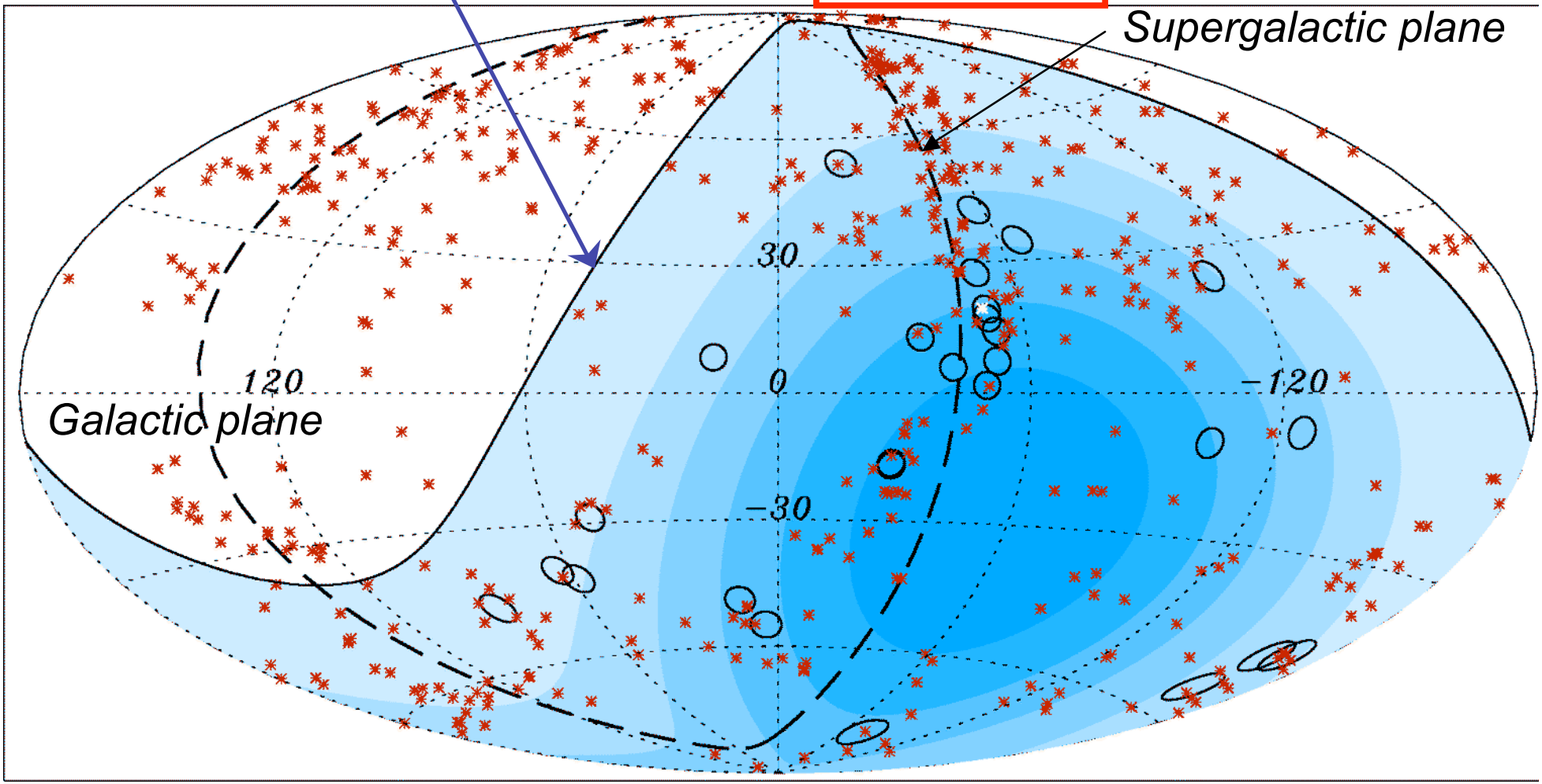
- 06/2006 - 08/2007 (additional $\approx$ 500.000 events)
- prescribed confidence level 99%
- 8 out of 13 events correlate (2.7 expected)



The most energetic Auger events *vs* the closest AGNs

Auger field of view ($\theta_z < 60°$)

$\mathcal{P} \sim 10^{-5}$



20 *(exp. 5.6)* out of

27 Auger events with E > 57 EeV

(ψ < 3.2° radius circles)

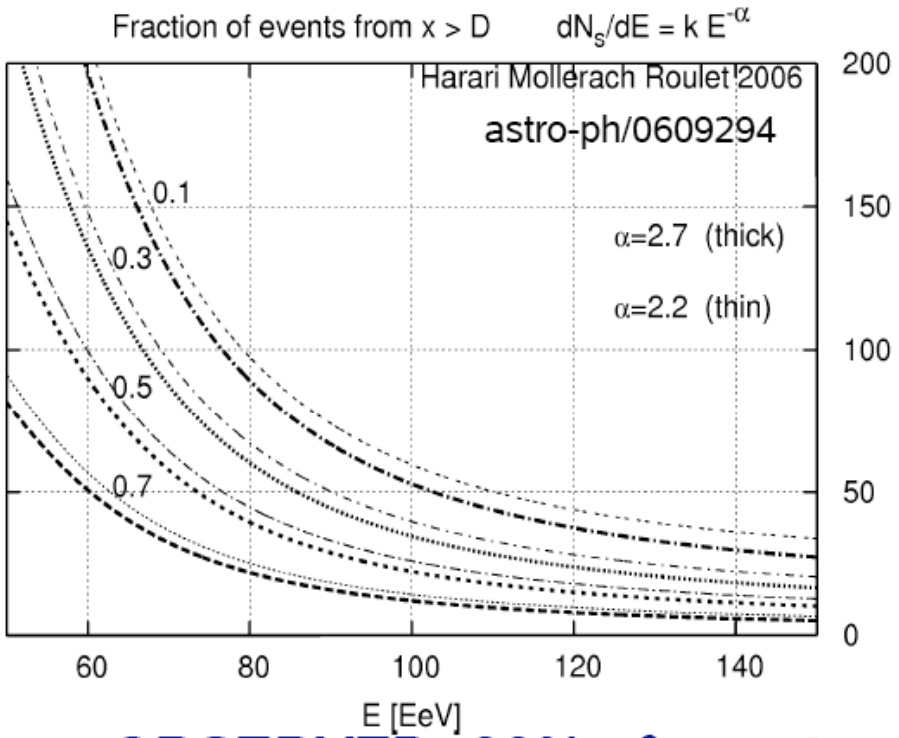
* 442 AGN (292 in the f.o.v.)

at z ≤ 0.017 (D ≤ 71 Mpc)

arXiv:0712.2843

THEORETICAL INTERPRETATION: GZK HORIZON

Fraction of the protons with energy > E that arrive from sources at distances > D



Uniform distribution of sources

π and e+e- production off CMB

PREDICTION:
≈ 70% of the events arrive from sources at distances less than 100 Mpc if E > 70 EeV

OBSERVED: 80% of events correlated with AGNs if E > 56 EeV (± 30% ?)

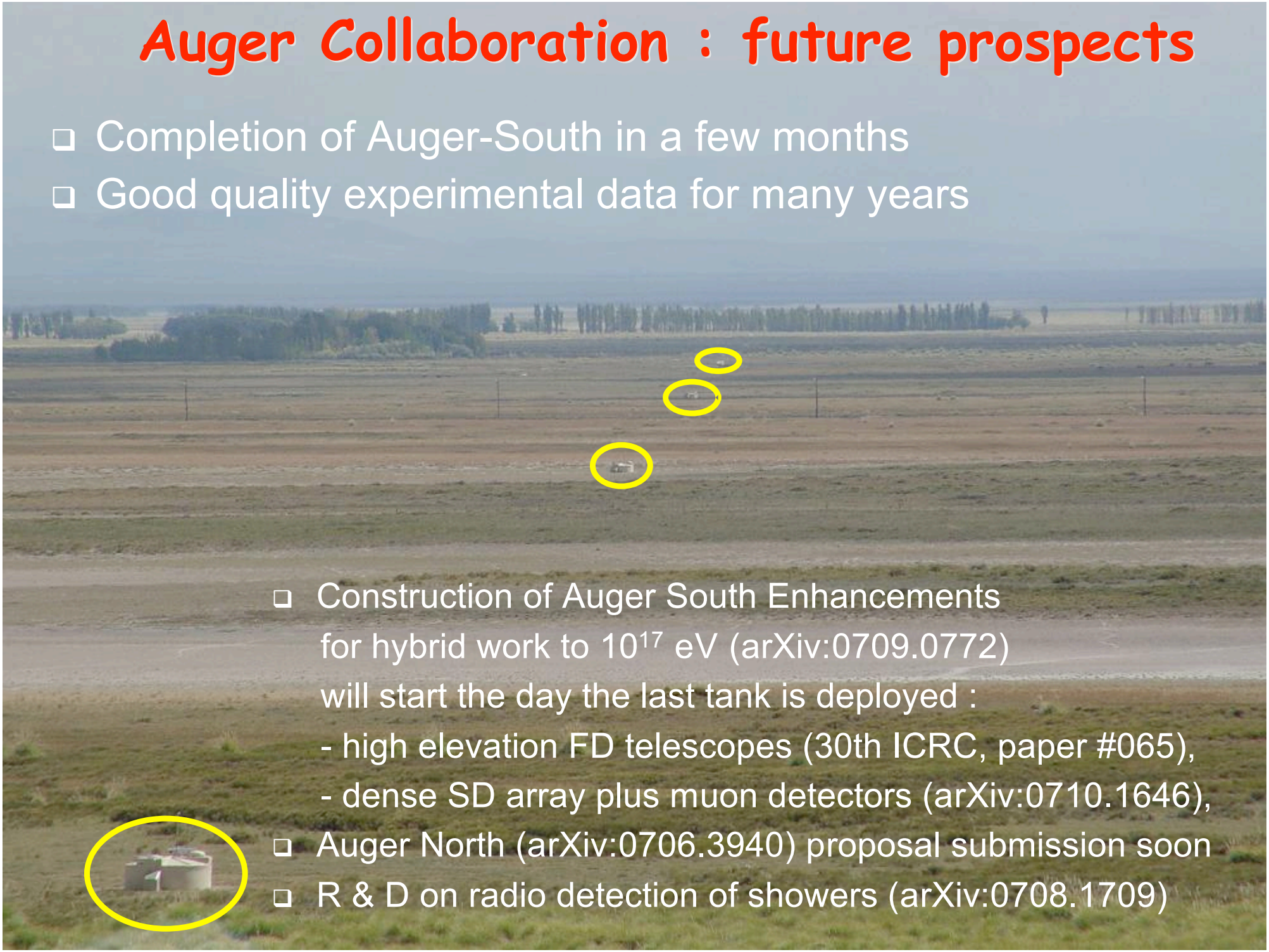
E underestimated / Local inhomogeneities / Heavy nuclei ?

Need to reconcile composition hints with the small angular separation from the AGNs, compatible with the expected Galactic Magnetic Field deflections for protons

Are the AGN sources, or just tracers ?

Auger Collaboration : future prospects

- Completion of Auger-South in a few months
- Good quality experimental data for many years



- Construction of Auger South Enhancements
  for hybrid work to 10^{17} eV (arXiv:0709.0772)
  will start the day the last tank is deployed :
  - high elevation FD telescopes (30th ICRC, paper #065),
  - dense SD array plus muon detectors (arXiv:0710.1646),
- Auger North (arXiv:0706.3940) proposal submission soon
- R & D on radio detection of showers (arXiv:0708.1709)