Study of the High Energy Cosmic Rays with the Auger experiment

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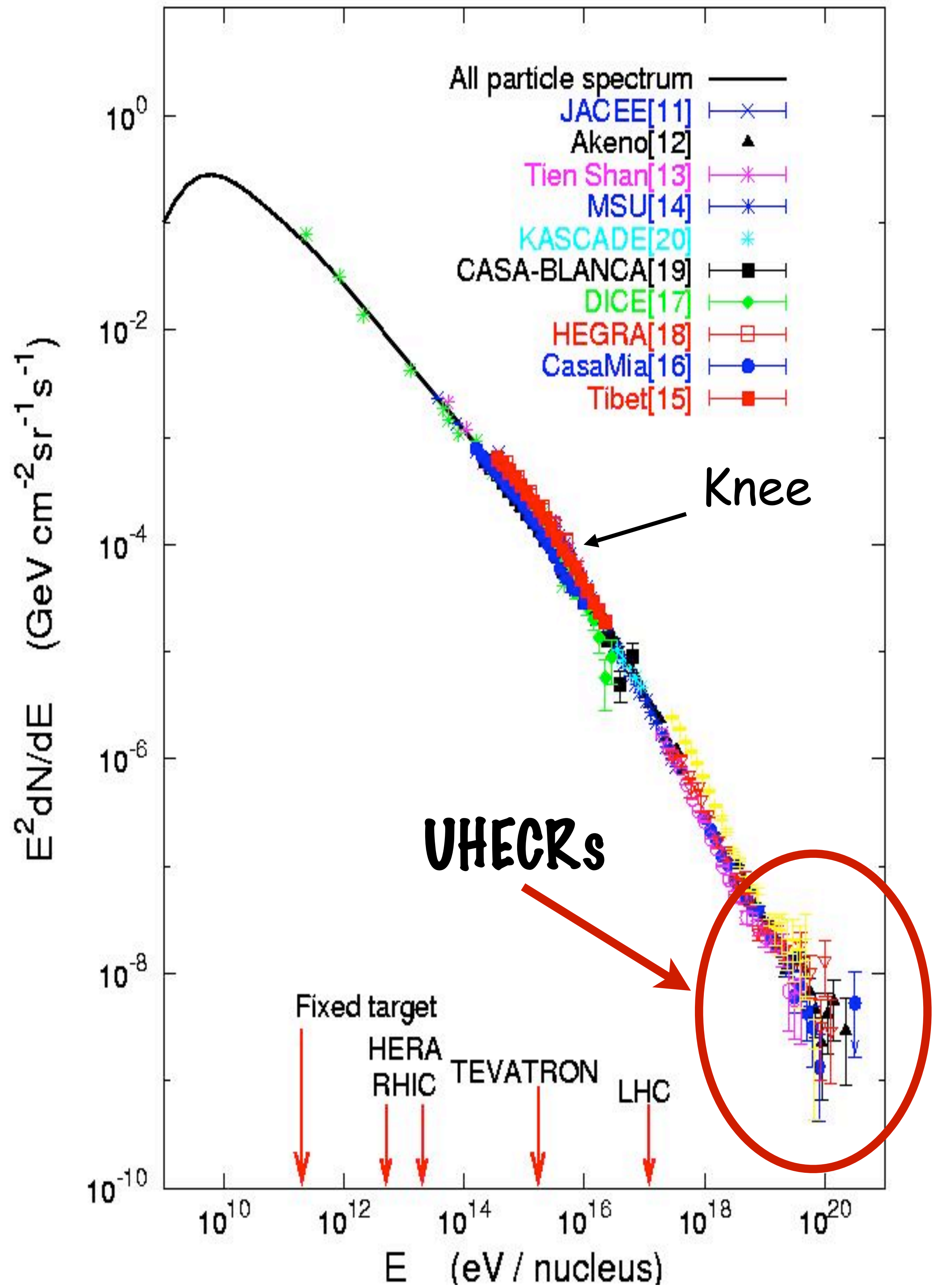
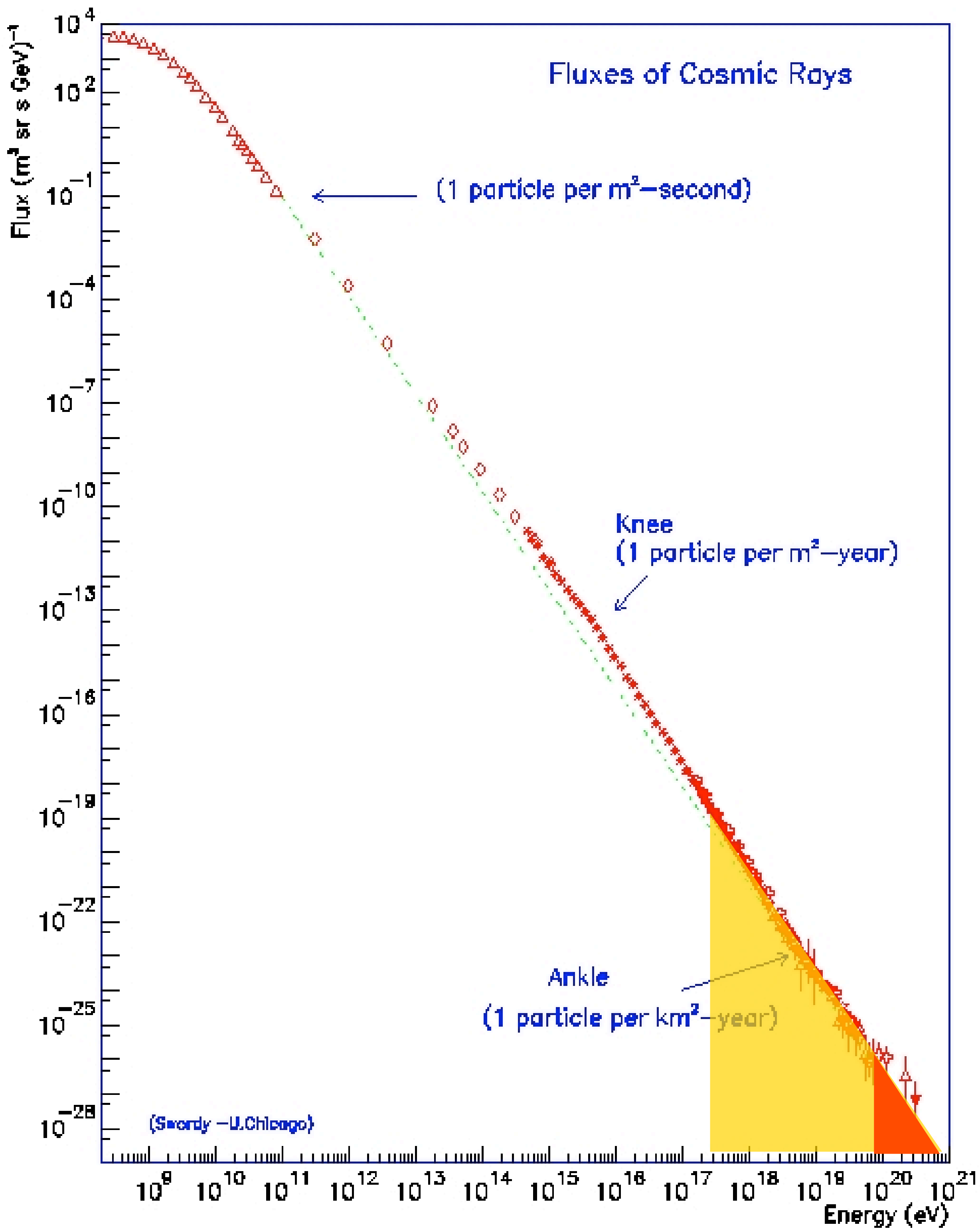
- The Pierre Auger Observatory for UHE Cosmic Rays
- Selection of Science results
- Future plans

Why do we study UHE Cosmic Rays?

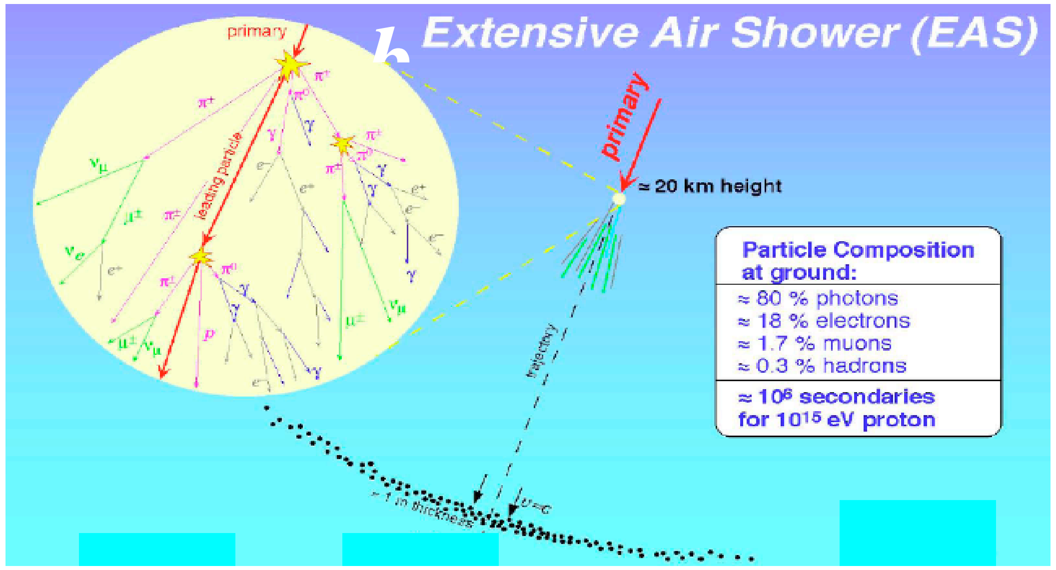


- UHECRs: $E>10^{18}$ eV
- Center of mass energy larger than that of LHC
- Galactic Magnetic Field can contain CRs up to 10^{17}-10^{18} eV: **UHECRs are expected to be extra-galactic**
- At the "end" of the spectrum: **flux cutoff expected** due to CR interaction on CMB photons (GZK effect, pion photo-production)
- UHECRs are expected to come from "close" sources (GZK effect, < 100 Mpc) and to be marginally deflected by GMF: **CR astronomy possible**

How do we study UHE Cosmic Rays?



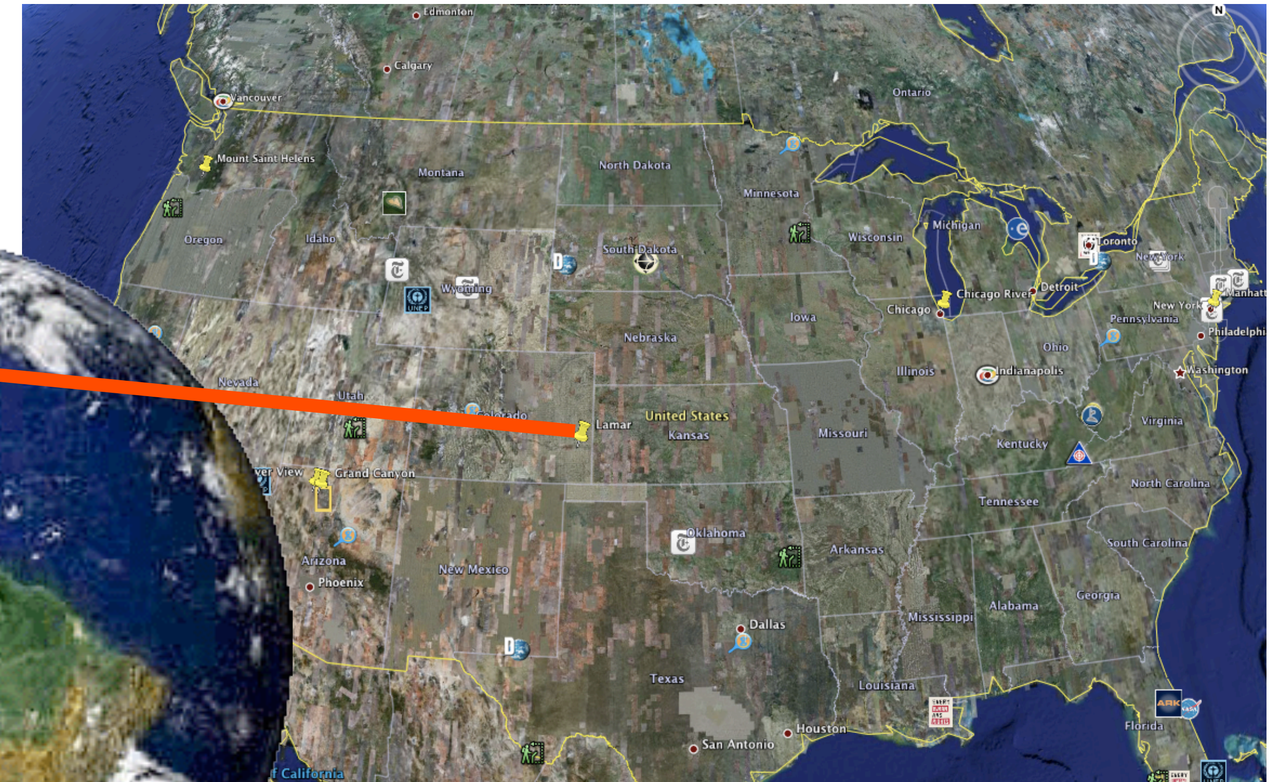
- CR flux very low at UHE:
  - E>5 10^{17} eV: 1/km^2/day
  - E>10^{20}: 1/km^2/100 y
- Extensive air shower technique needed

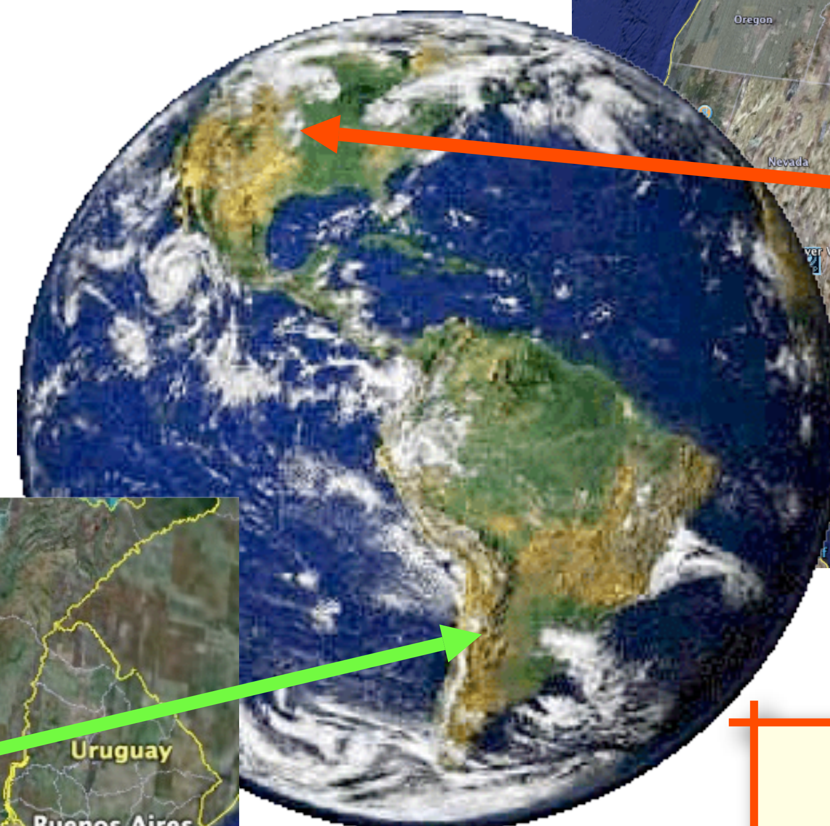


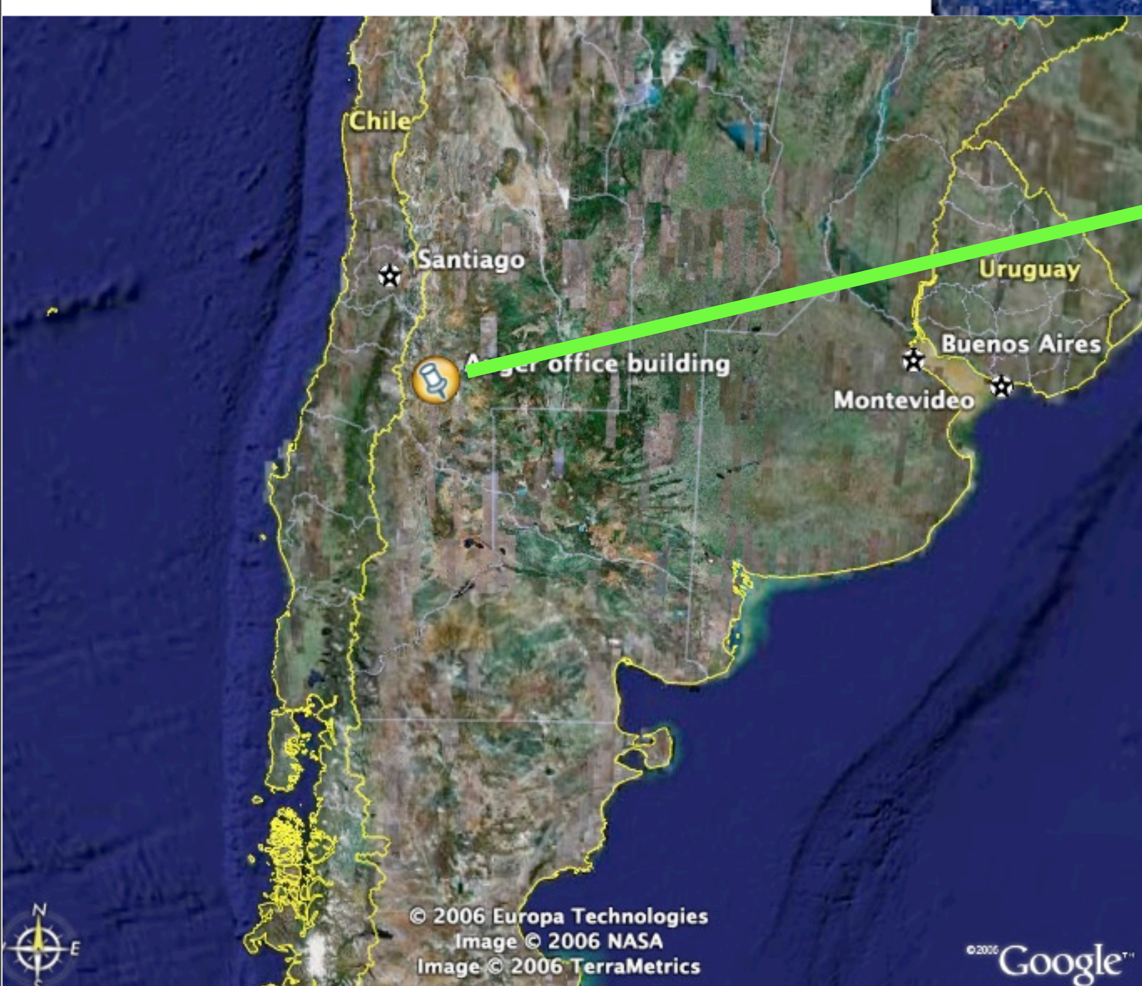
- Measure lateral distribution by sampling of particles on the ground OR longitudinal profile with fluorescence telescopes
- Huge areas and very long term measurements required

The Pierre Auger Observatory

Malargüe, Mendoza,
Argentina
(Built)





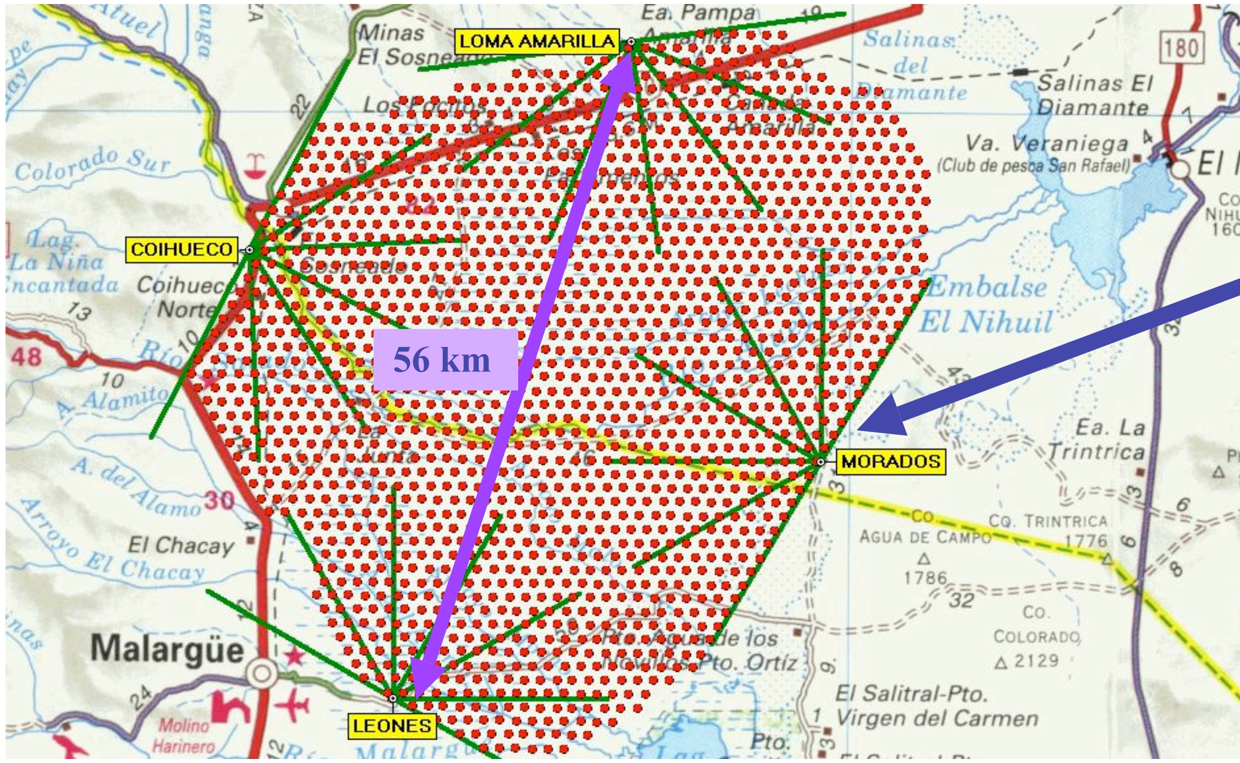


Lamar, South-East Colorado,
USA
(Planned)

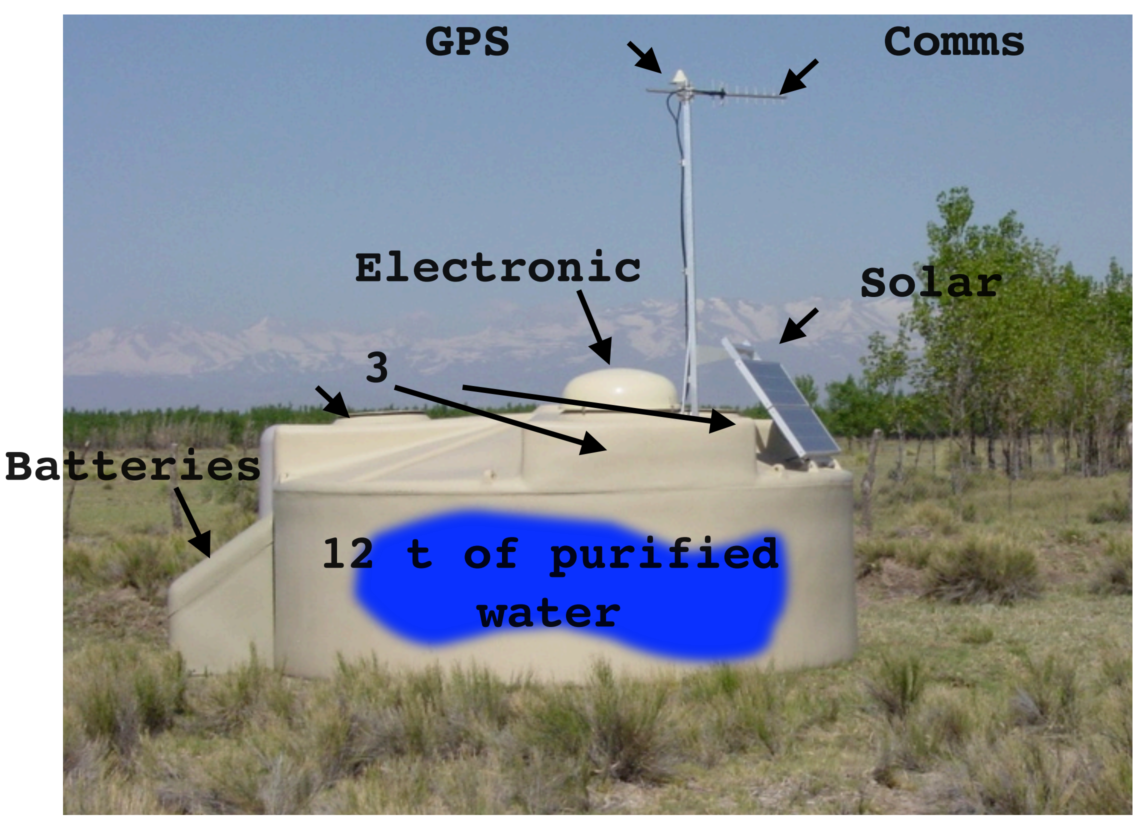
15+2 countries,
>85 institutions
>400 authors

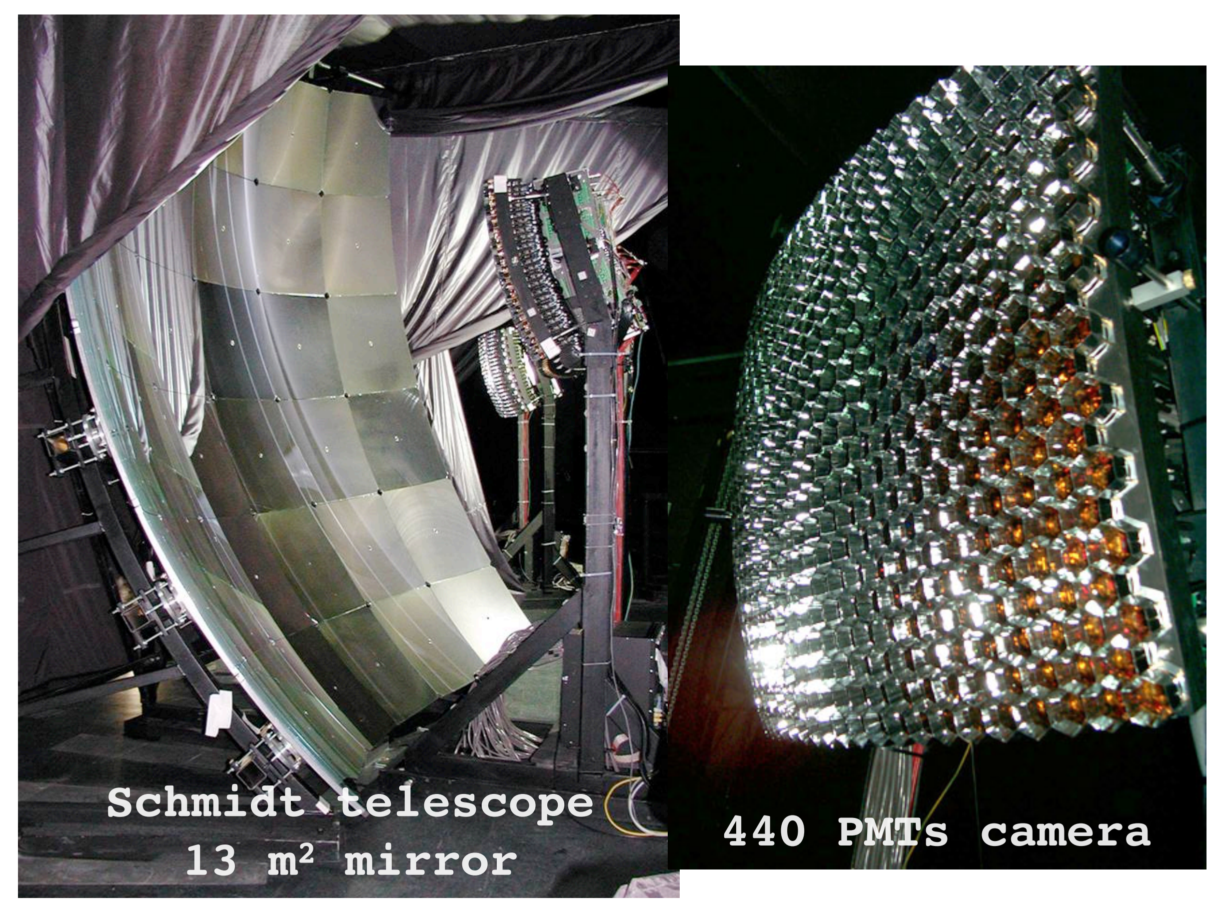
The Southern Pierre Auger Observatory: A giant and hybrid detector (3000 km^2)

Surface Detector (SD): 1600 water Cherenkov tanks, 100% duty cycle



Fluorescence Detector (FD): 4 x 6 telescopes 13% duty cycle

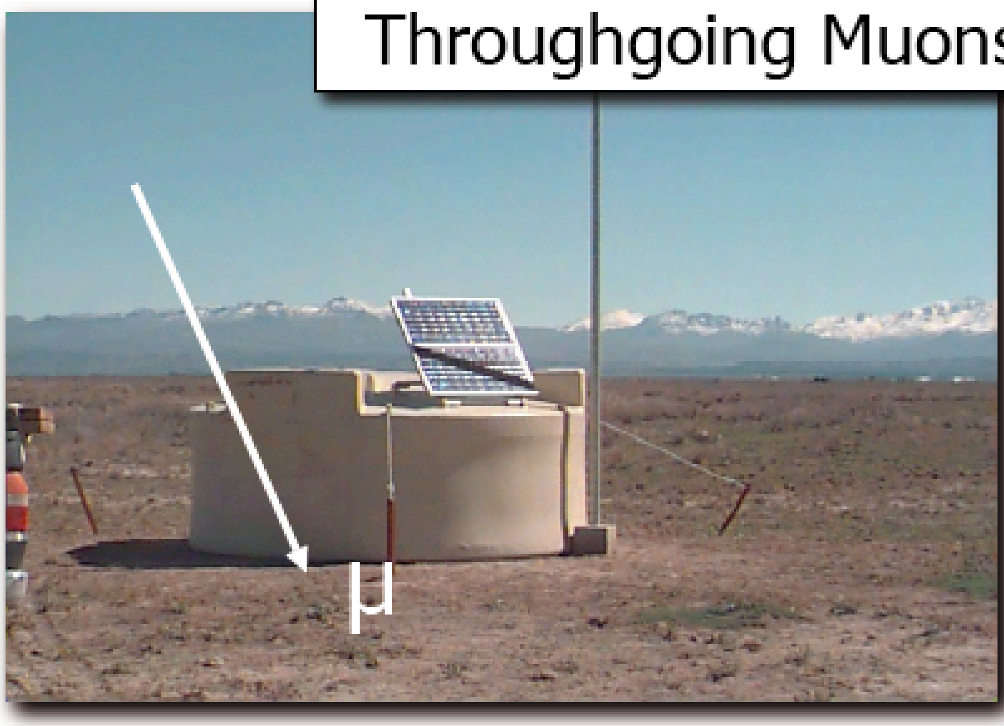


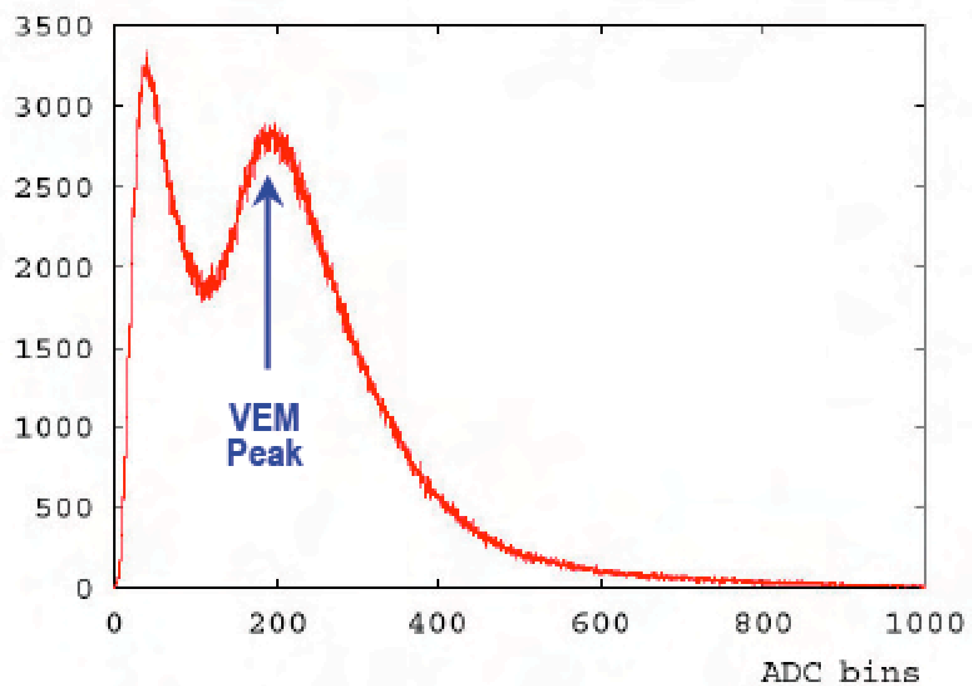


Detector Calibration

Ground-Array

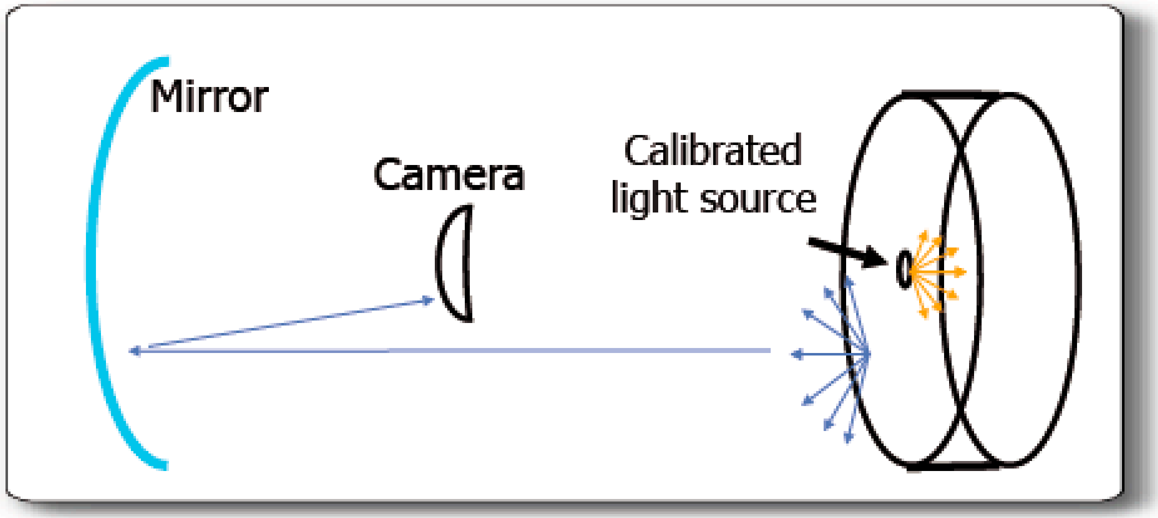
Throughgoing Muons





Fluorescence Telescopes

Diffuse Lightsource



Goals of the Observatory

Detection with high statistics of cosmic rays with energies $>10^{19}$eV.

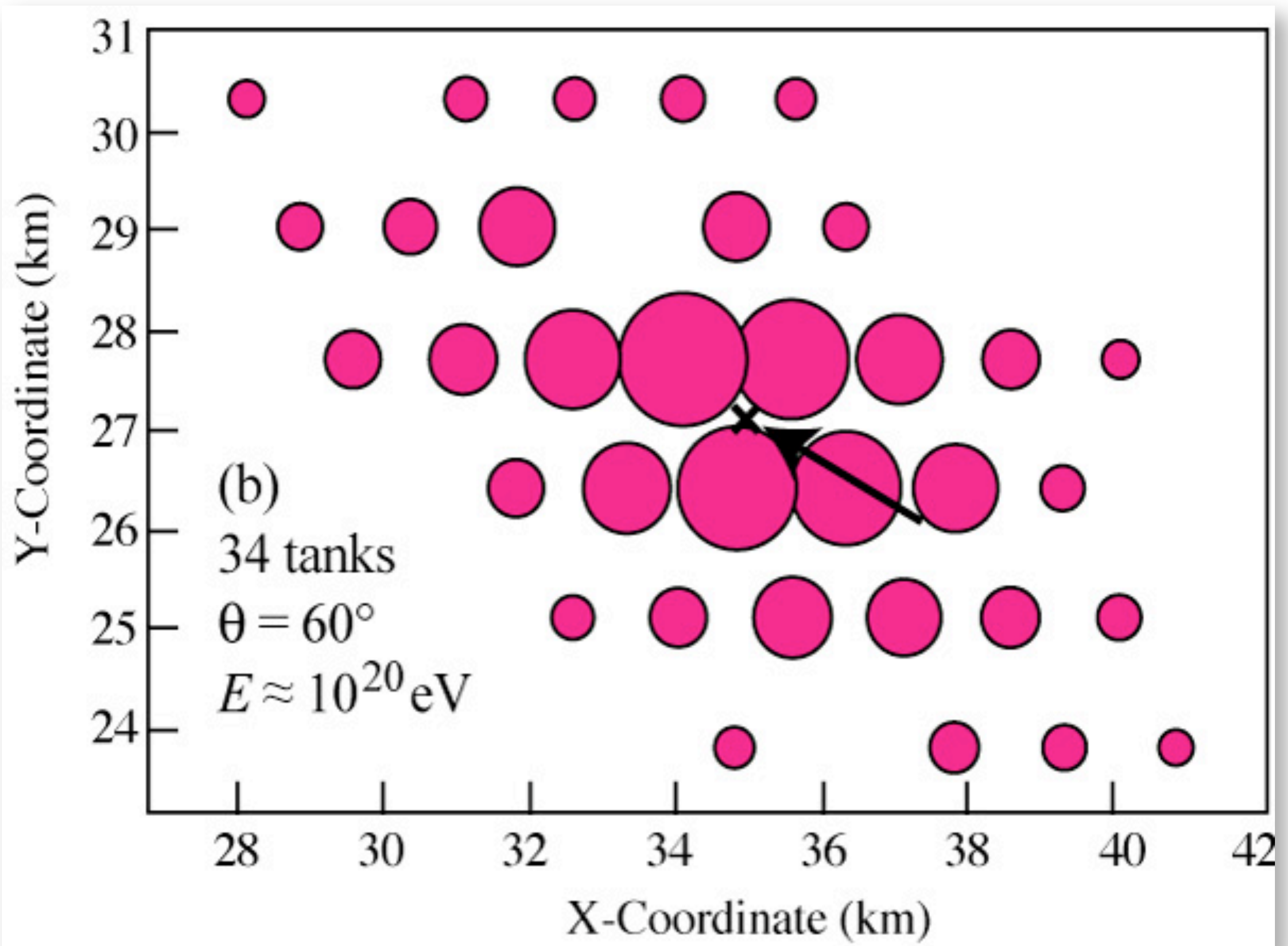
- Spectrum
  - ➡ Requiers a good energy determination ≈ 20 - 30 %
- Arrival directions
  - ➡ Angular resolution ≈1°
- Composition
  - ➡ Fast electronics to measure details of the shower front (SD)
  - ➡ Field of view to observe shower development (FD)

➡ Science results

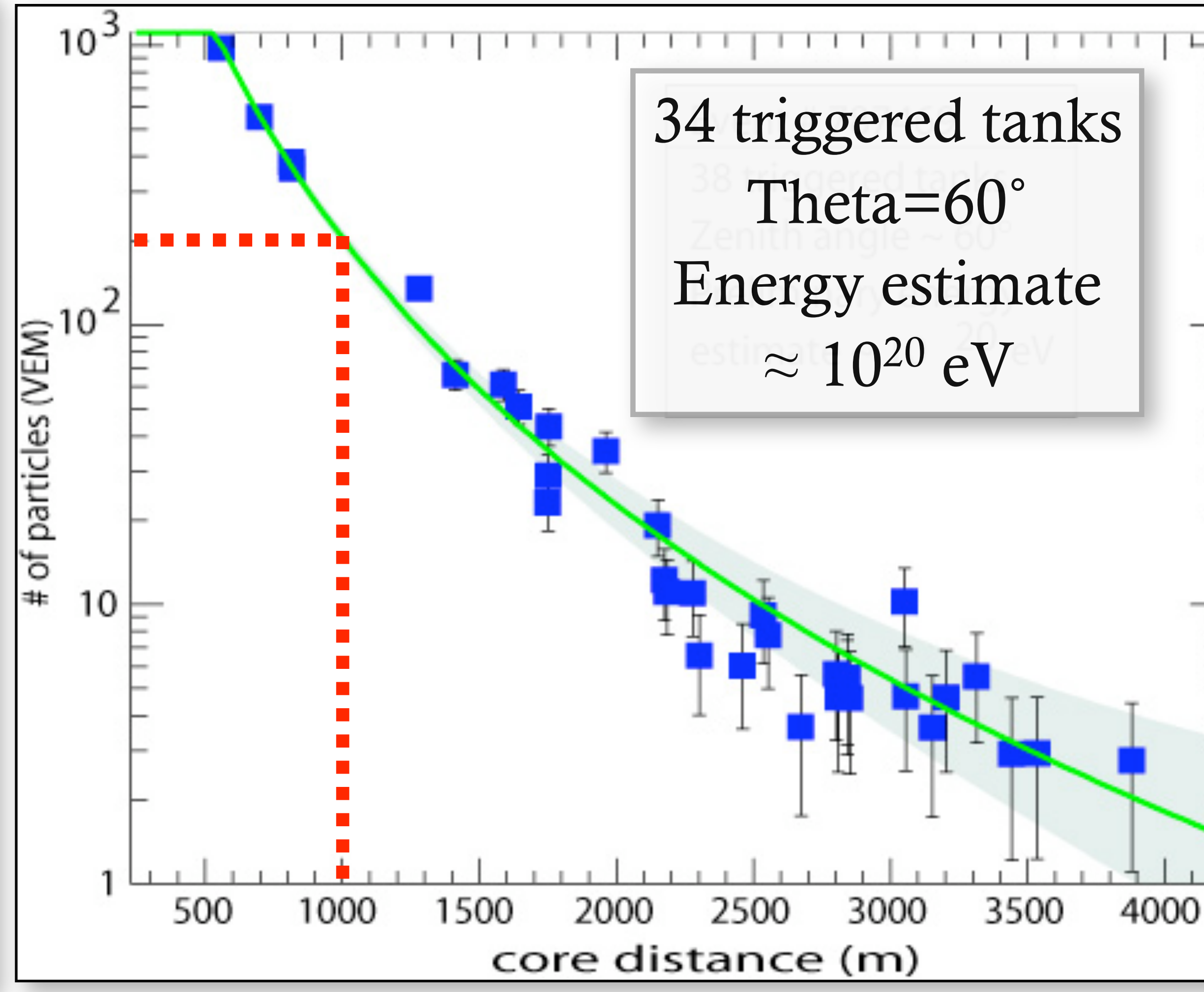
Energy spectrum

Primary energy determination: SD

SD measures the lateral structure of the shower at ground



One event seen by SD



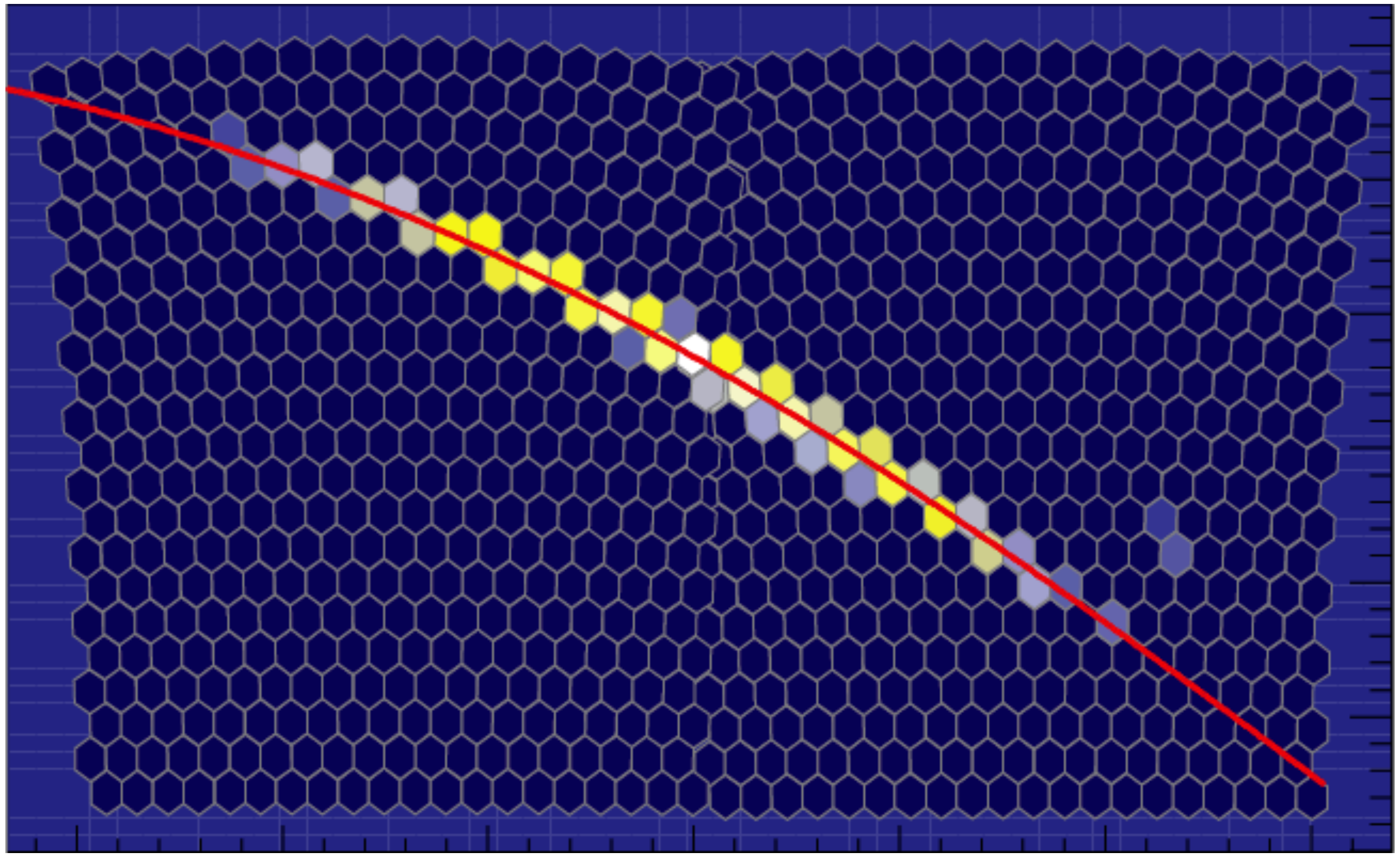
Particle lateral distribution

- Reconstruct geometry (arrival direction & impact point)
- Fit particle lateral distribution (LDF)
- S(1000) [signal at 1000 m] is the Auger energy estimator

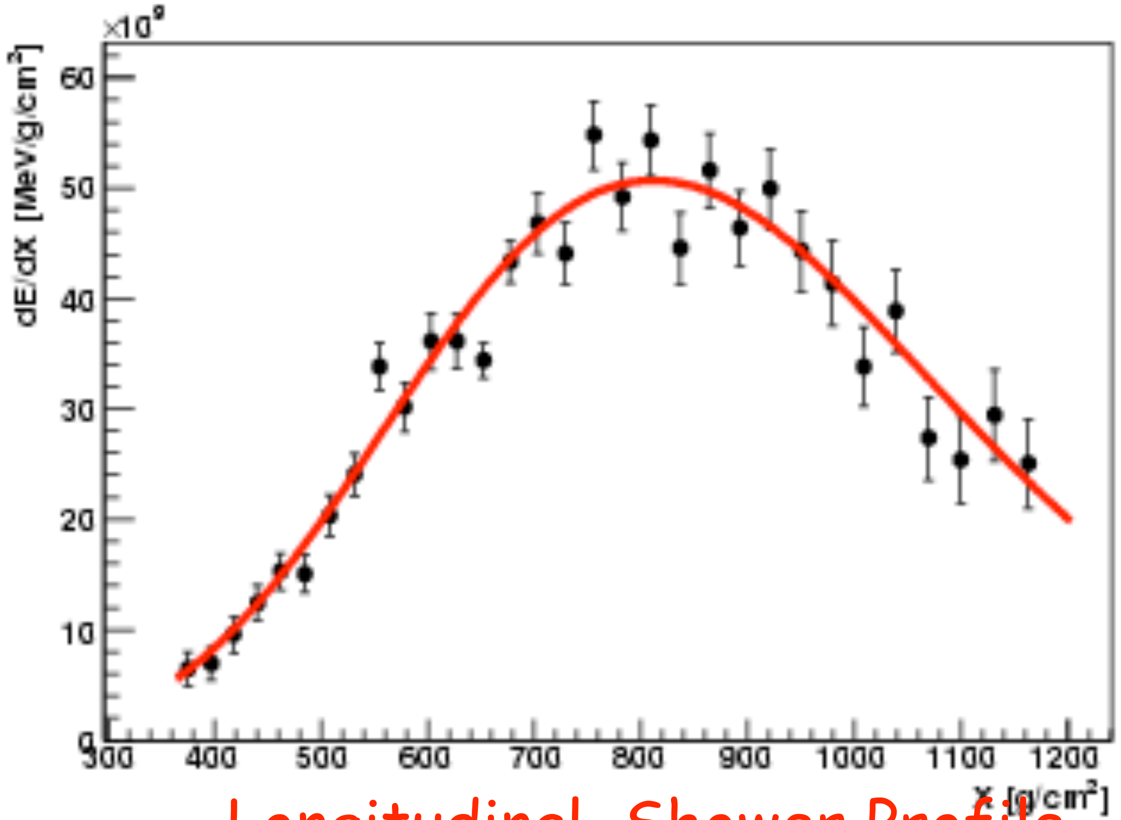
  ("ideal" distance depends on detectors spacing)

Primary energy determination: FD

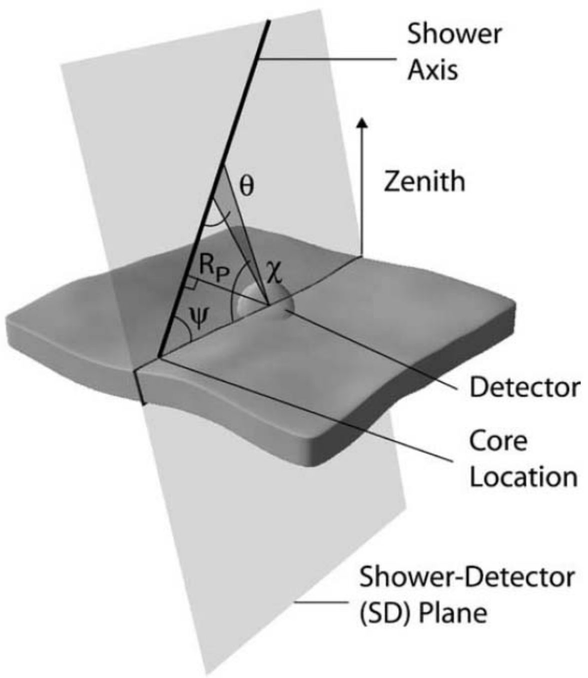
FD records the longitudinal profile of the shower during its development in atmosphere



One event seen by FD



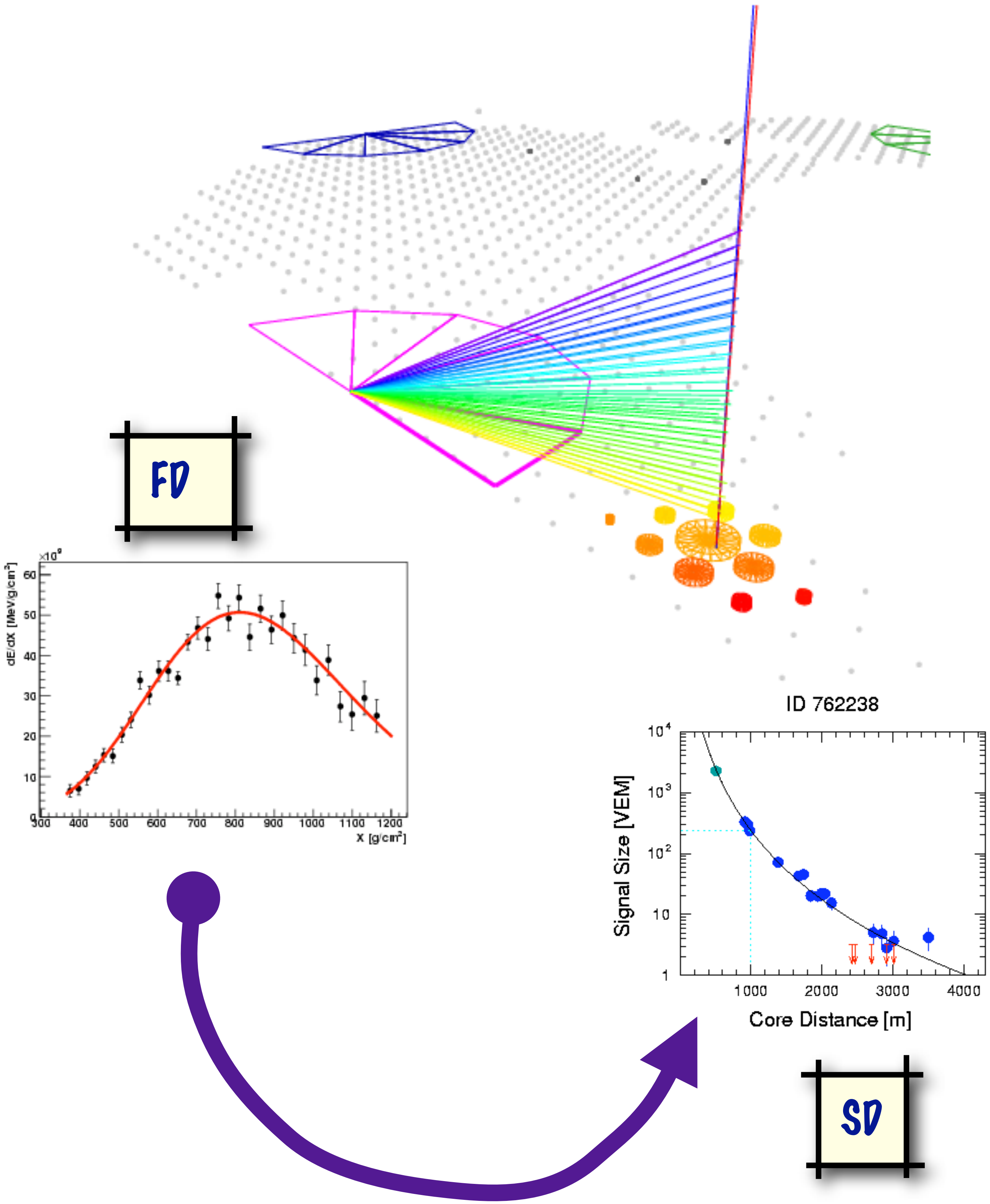
Longitudinal Shower Profile



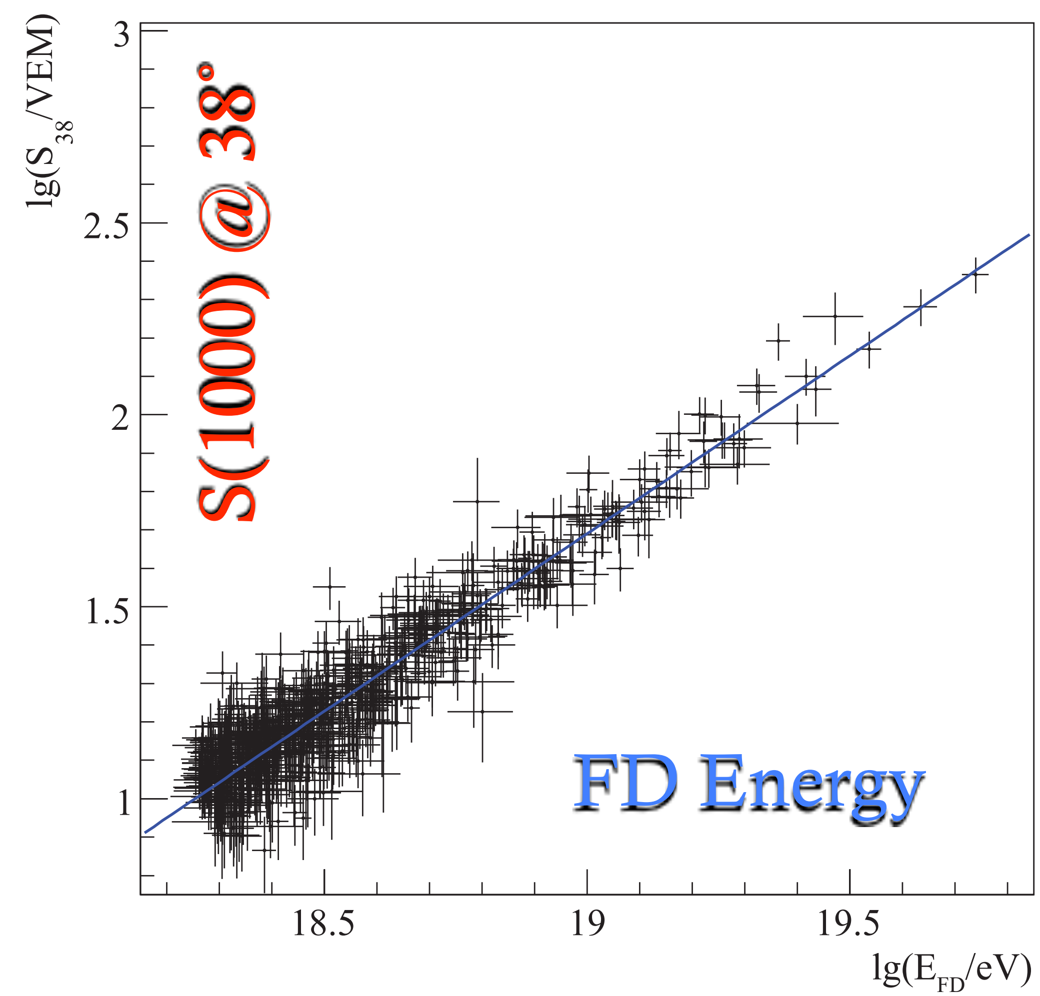
- Reconstruct geometry (shower detector plane, SDP, and shower axis in SDP)
- Fit longitudinal shower profile
- E ∝ area under the curve
- Calorimetric measurement

$$\int \frac{dE}{dX} dX \sim E$$

Primary energy determination: SD+FD



Hybrid Events are used to calibrate the SD energy estimator, S(1000) (converted to the median zenith angle, S38) from the FD calorimetric energy



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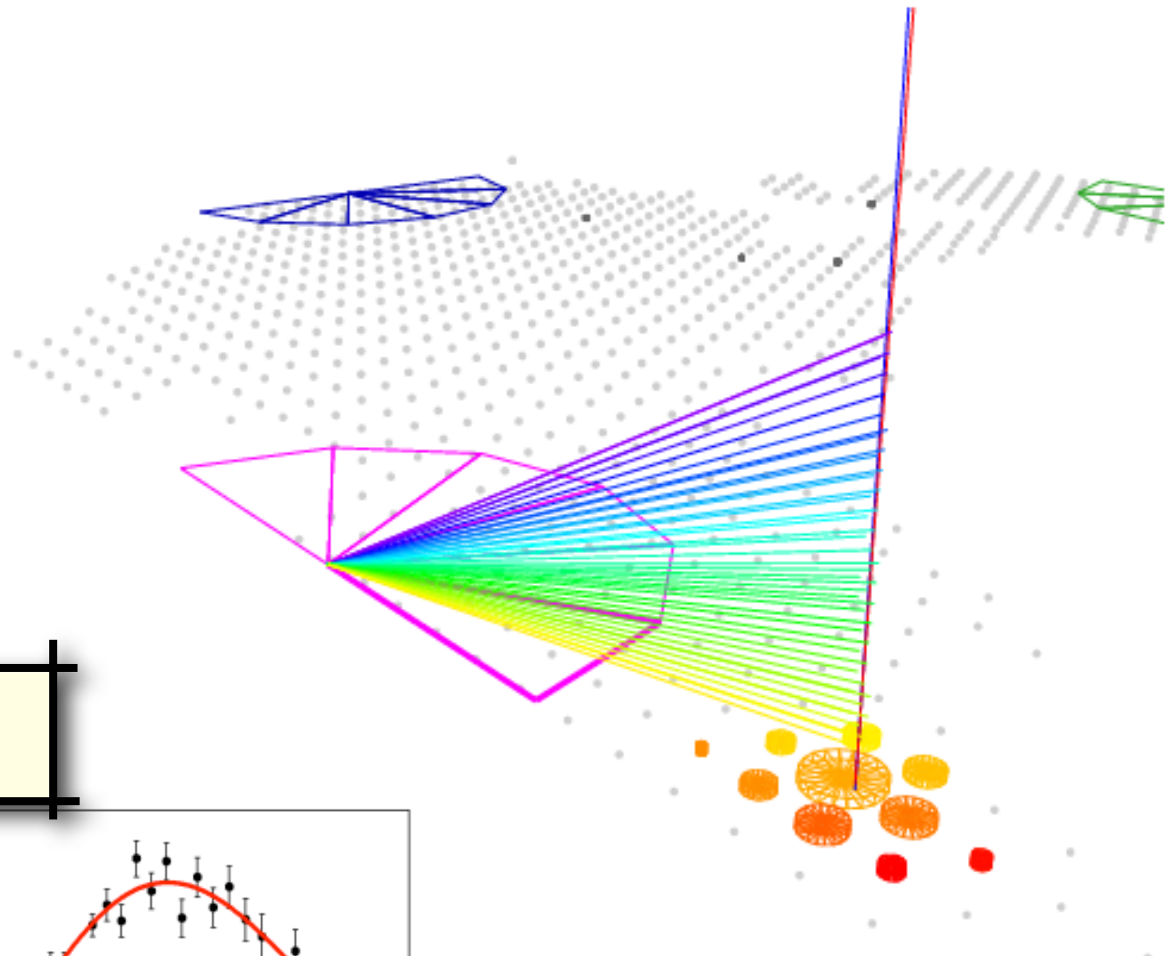

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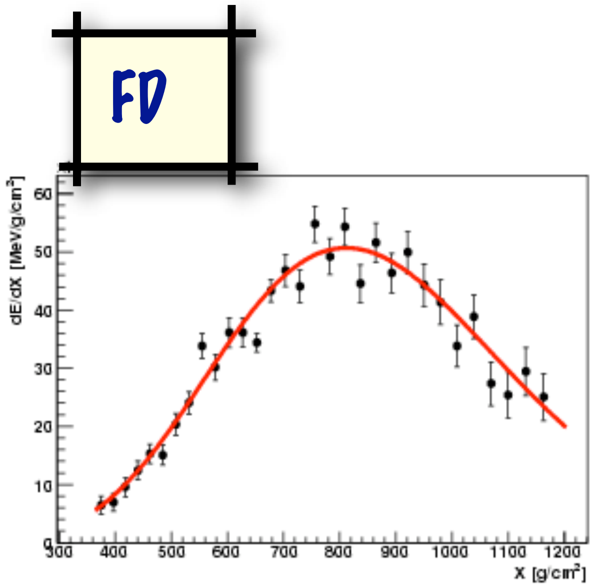
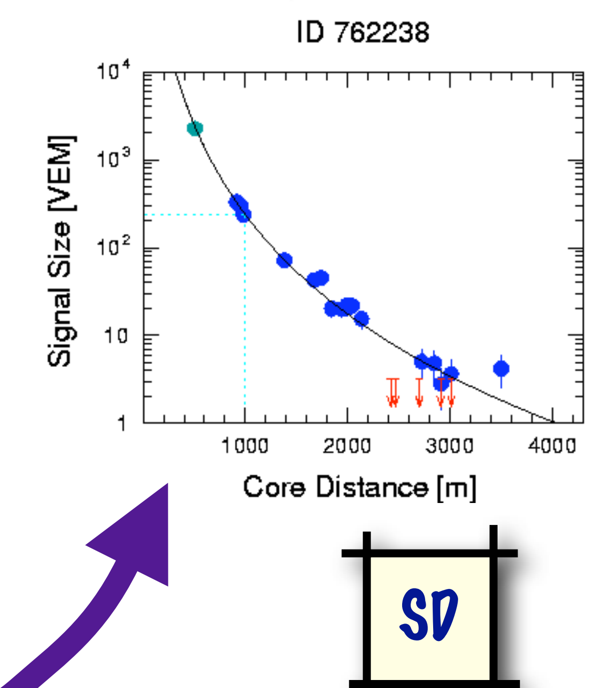
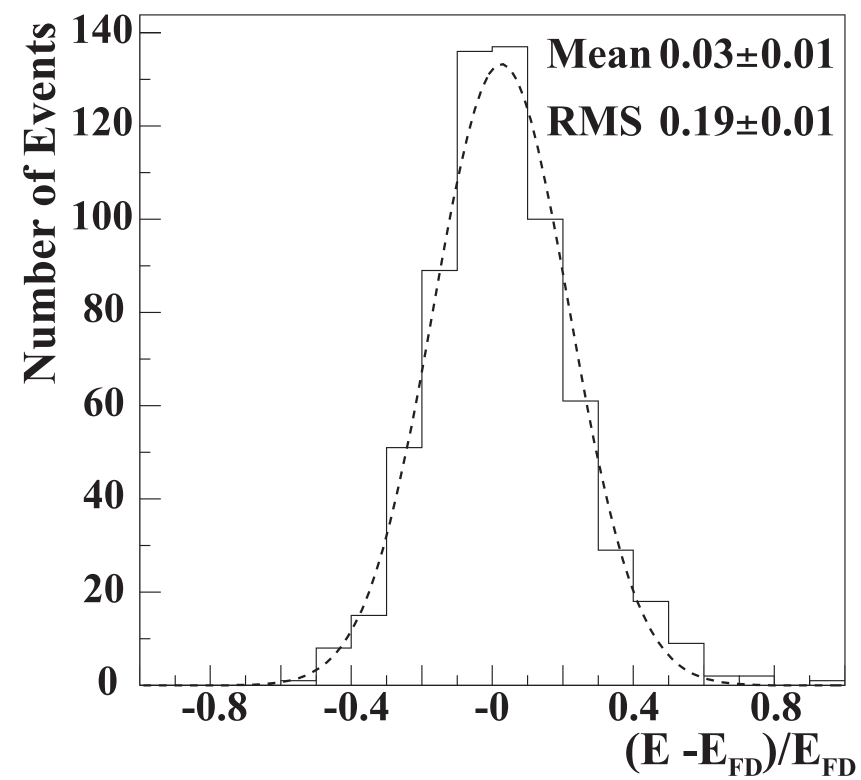
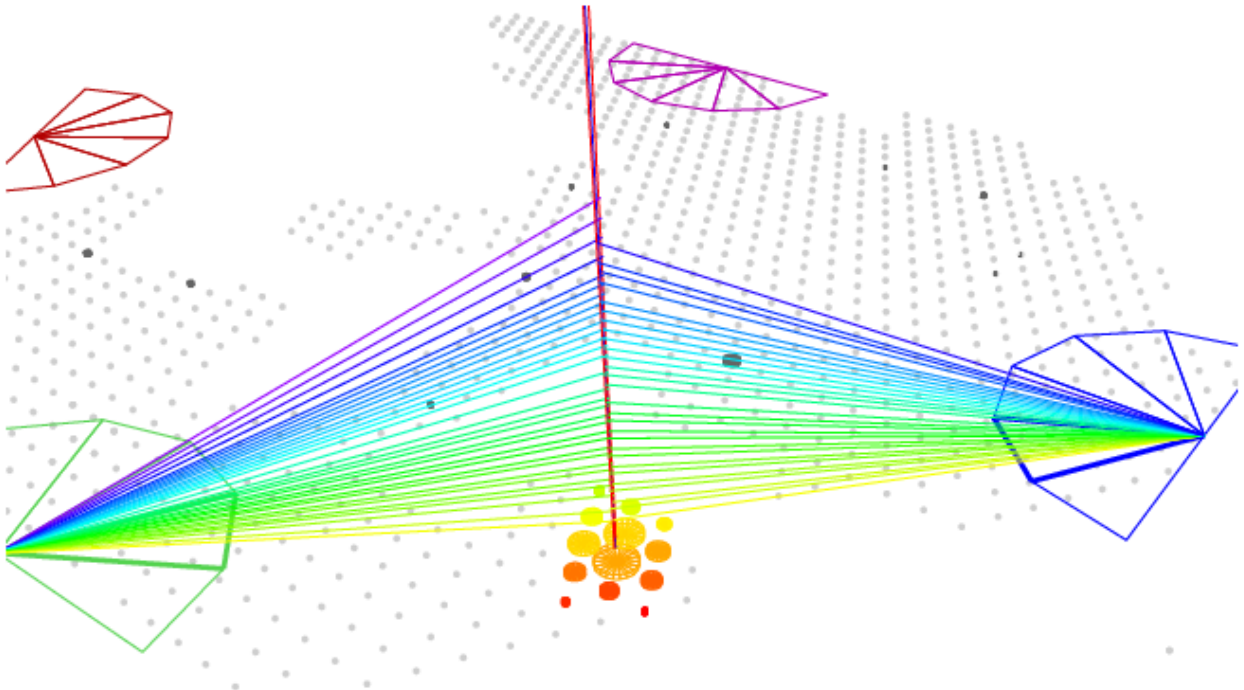






Energy resolution: statistical ≈ 19%

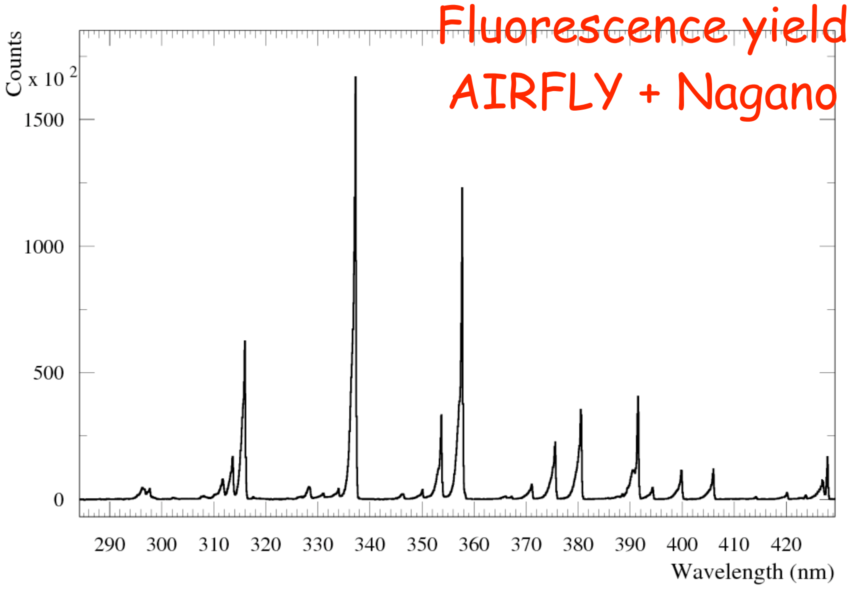
FD Energy systematic uncertainty



Stereo events

⇒ reconstruction uncertainty

- 10%, consistent with MC



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%

Total FD E uncertainty: 22%

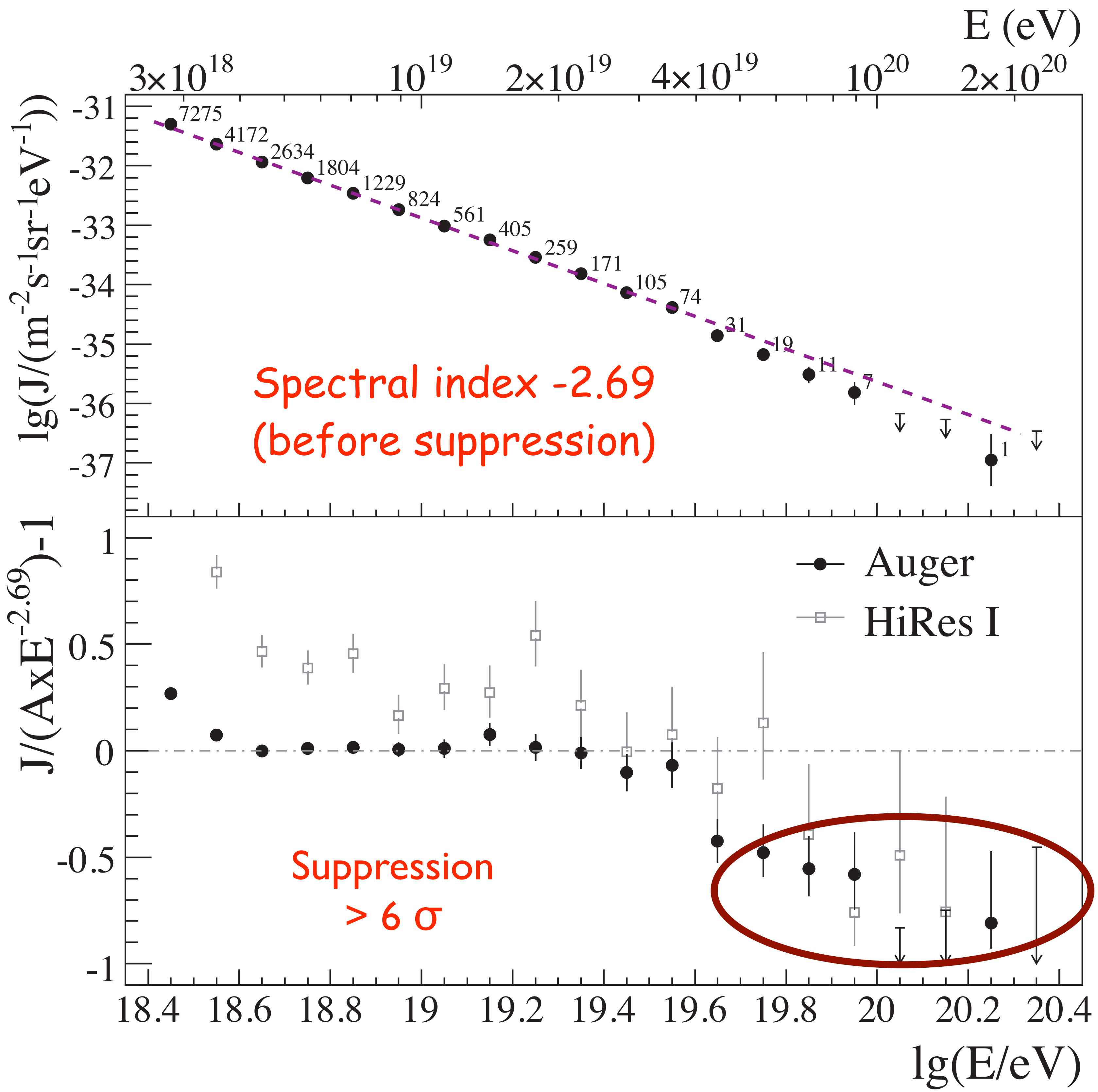
Spectrum: Flux suppression

- Flux suppression at the highest energy

  Significance does not depend on energy scale

- Auger and HiRes compatible within 15%

  Consistent with the uncertainties of the experiments

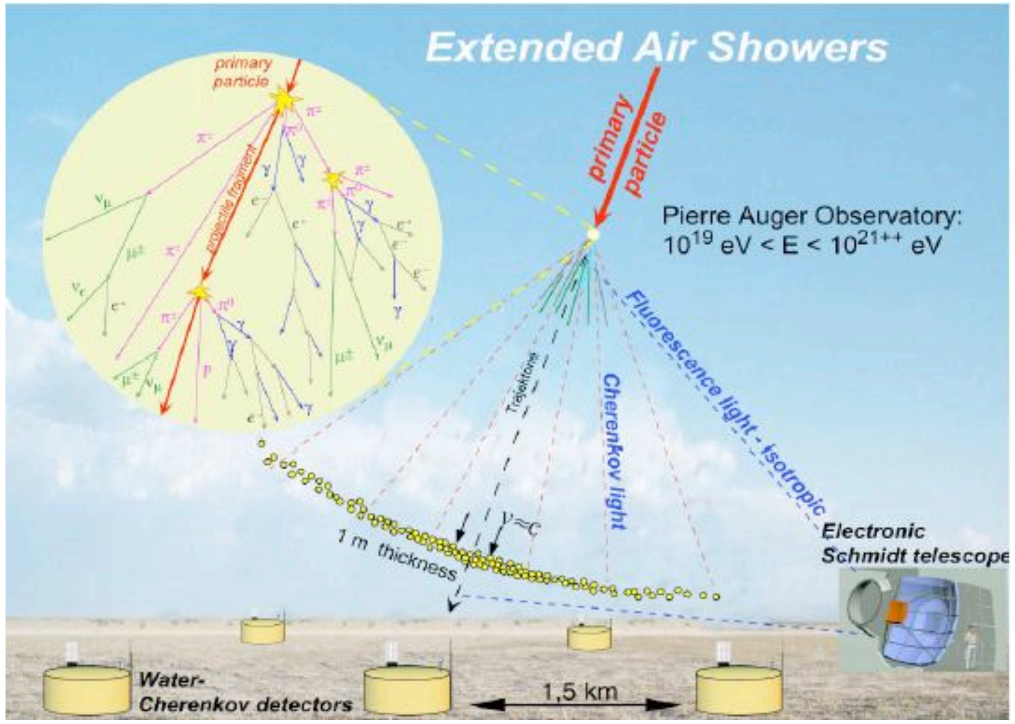


Anisotropies of the highest energy cosmic rays

Arrival direction determination

Time of flight technique:

Dt among the arrival times of particles in different detectors give the arrival direction. Accuracy depends on timing precision and arrival time fluctuations

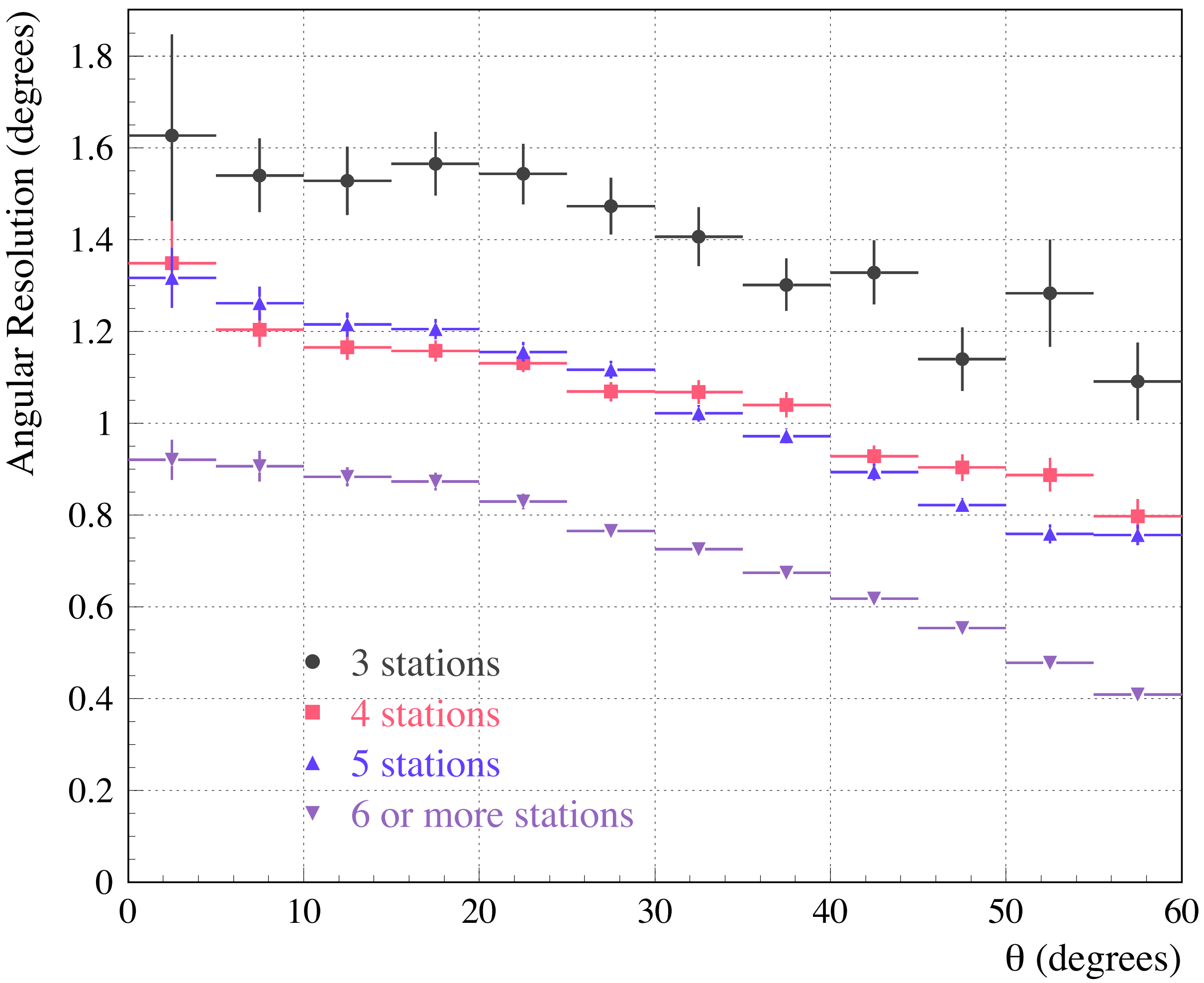


Angular resolution: angular radius that contains 68% of the showers coming from a point source.

Estimated on event-by-event basis

Verified with hybrid events (2 independent geometrical reconstructions)

E>10^{19} eV: > 6 tanks: < 1°



Search for anisotropy of UHECRs

- Define a data set (adjusting minimum energy E)
- Define a tentative source catalogue (adjusting depth z)
- Count number of events k at less than angular distance ψ from a source (we call this a correlation)
- Calculate probability for such a number of correlations to occur by chance :

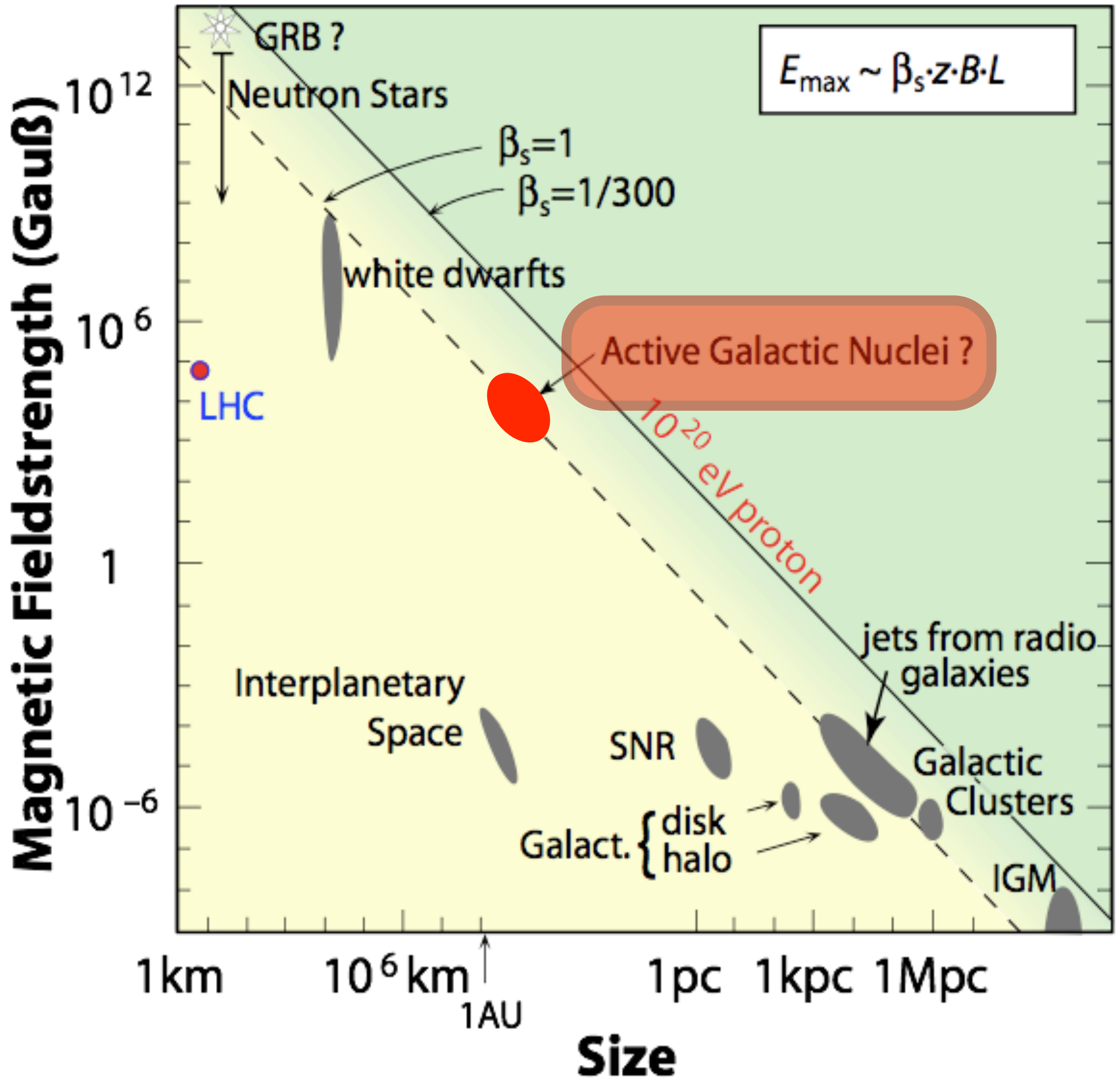
$$P(E,z,\psi) = \sum_{j=k}^{N(E)} \binom{N(E)}{j} p(z,\psi)^j (1-p(z,\psi))^{N(E)-j}$$

where P(E,z,ψ) is the cumulative binomial probability and p(z, ψ) is the chance probability for a CR seen by Auger (exposure weighted) to fall within ψ° of one of the sources in the catalogue

- Look for the minimum of P(E,z,ψ) as a function of E, z and ψ.

Use Veron-Cetty & Veron 12th AGN Catalogue

AGNs are potential sources



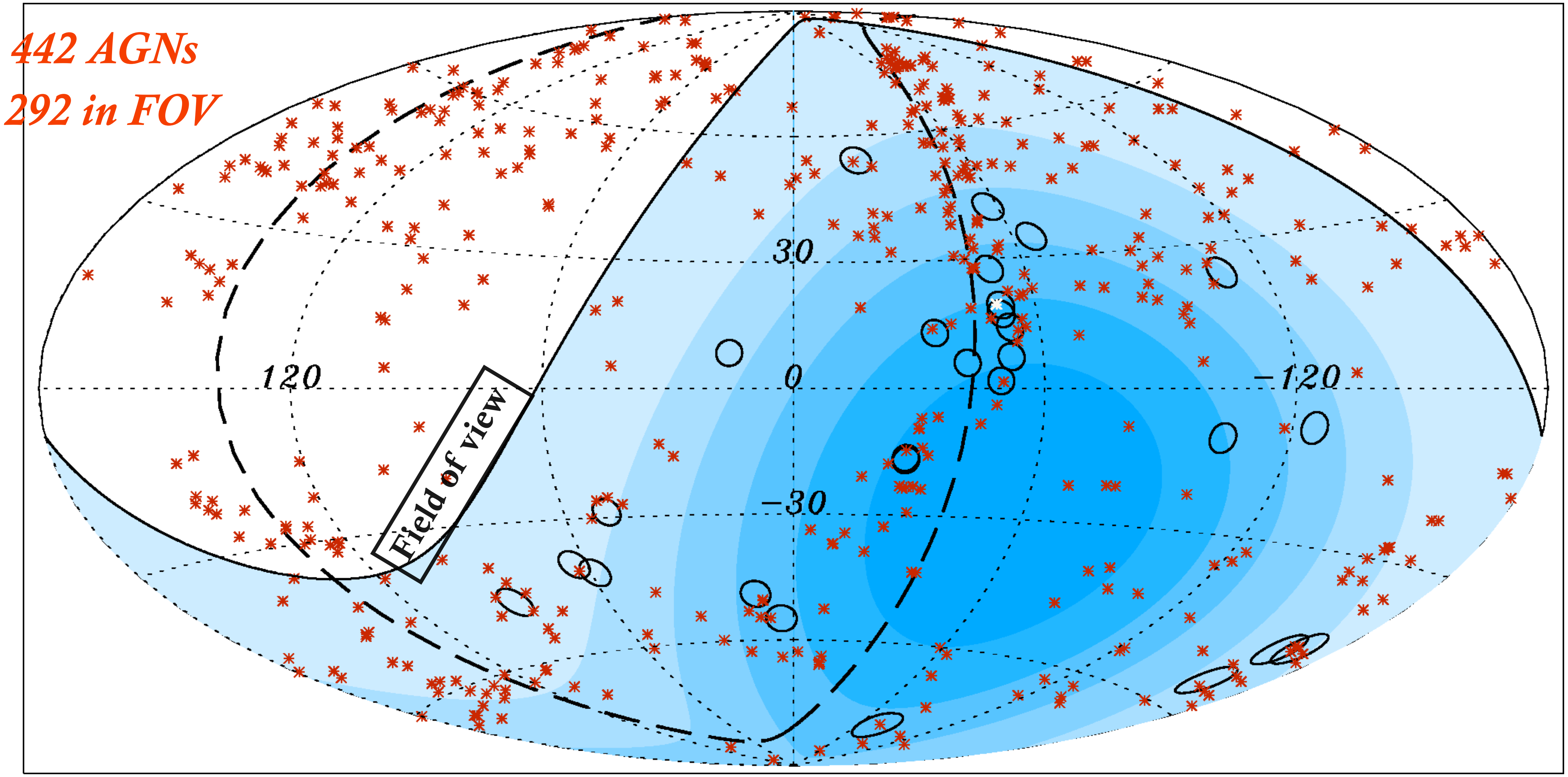
A correlation was observed, then a prescription was set :

E_{th} = 57 EeV z_{max} = 0.017 ψ = 3.2°

Test built to have 1% probability to incorrectly reject isotropy.

Test passed: 99% c.l. anisotropy

Whole data-set: 1 Jan 2004 - 31 Aug 2007



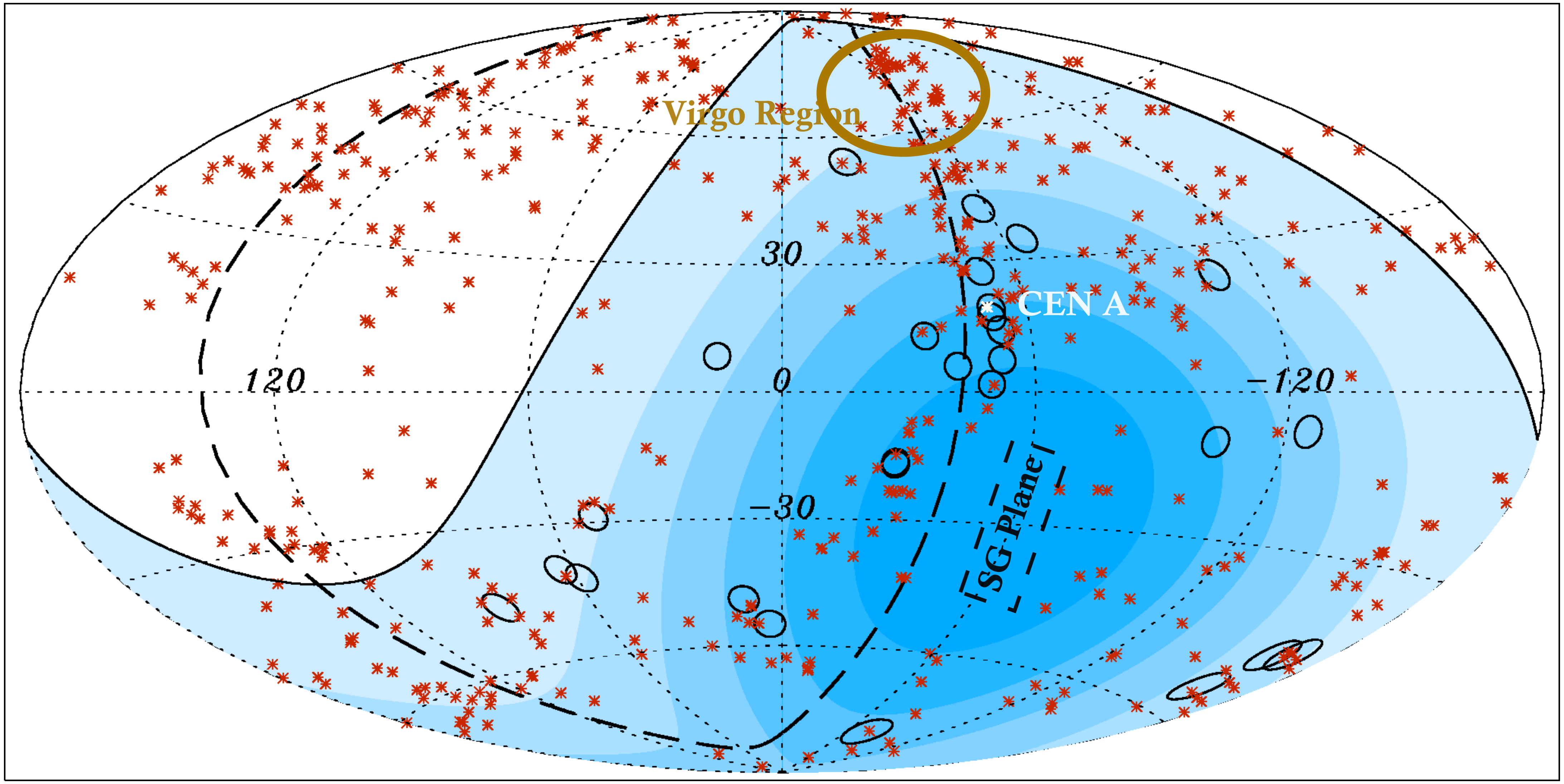
E_{th} = 57 EeV z_{max} = 0.017 ψ = 3.2°

20/27 events correlated (6 expected by chance)

10^{-5} isotropic simulations have comparable departures under similar scan

Observed correlation shows that UHECR above ≈ 60 EeV are extra-galactic

Anisotropy properties and implications



The correlation with VCV does not prove that AGNs are the sources.

AGN distribution is as non-uniform as local matter distribution.

AGNs may be the tracers of the real sources (galaxies, starbust galaxies/GRBs, clusters...)

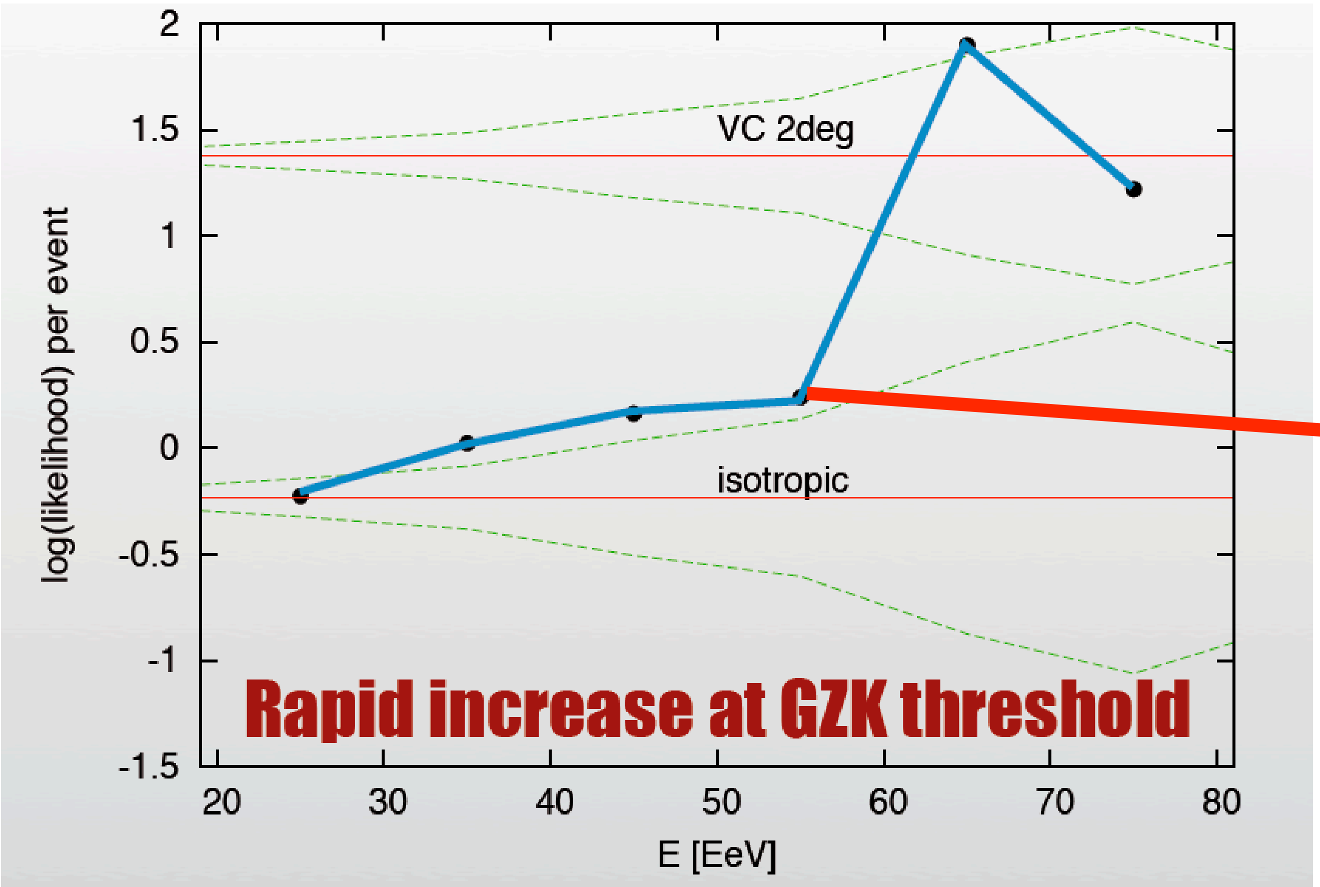
Or a subset of AGNs could be the sources

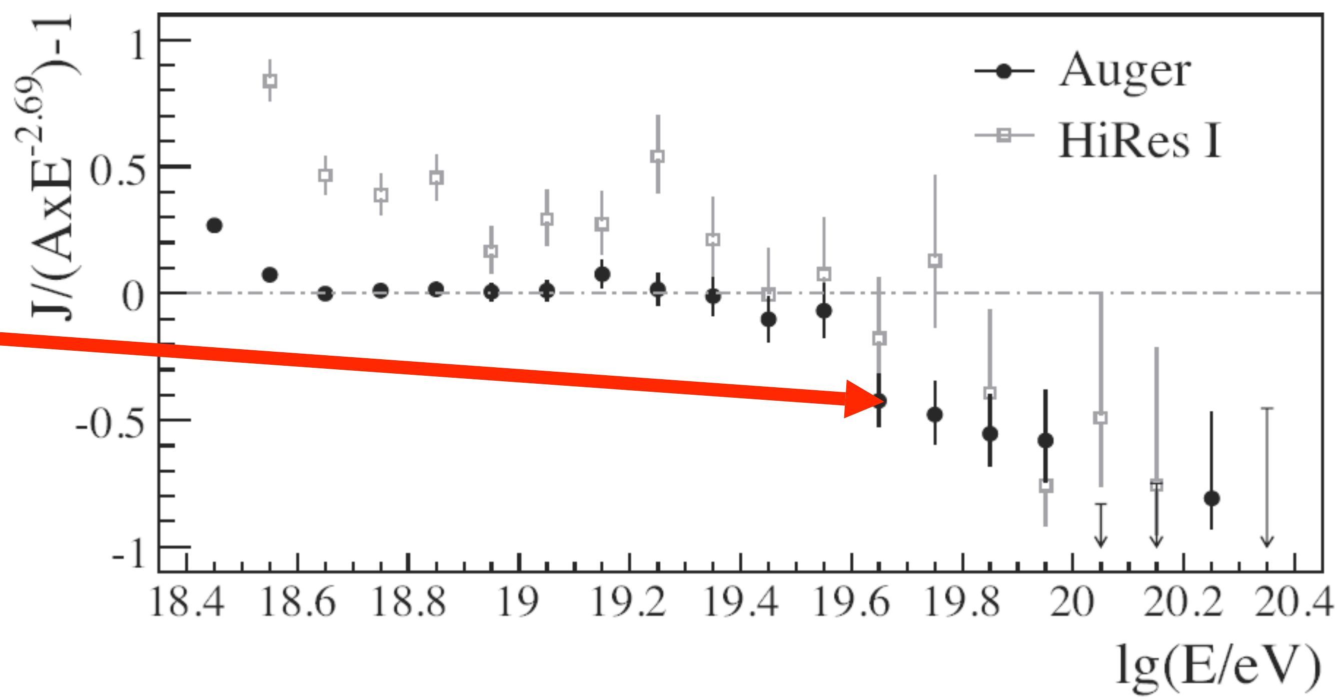
2 events within 3° from CEN A - Several events close to the SG plane

Paucity of events from Virgo region

MORE DATA NEEDED

Correlation strength as a function of Energy





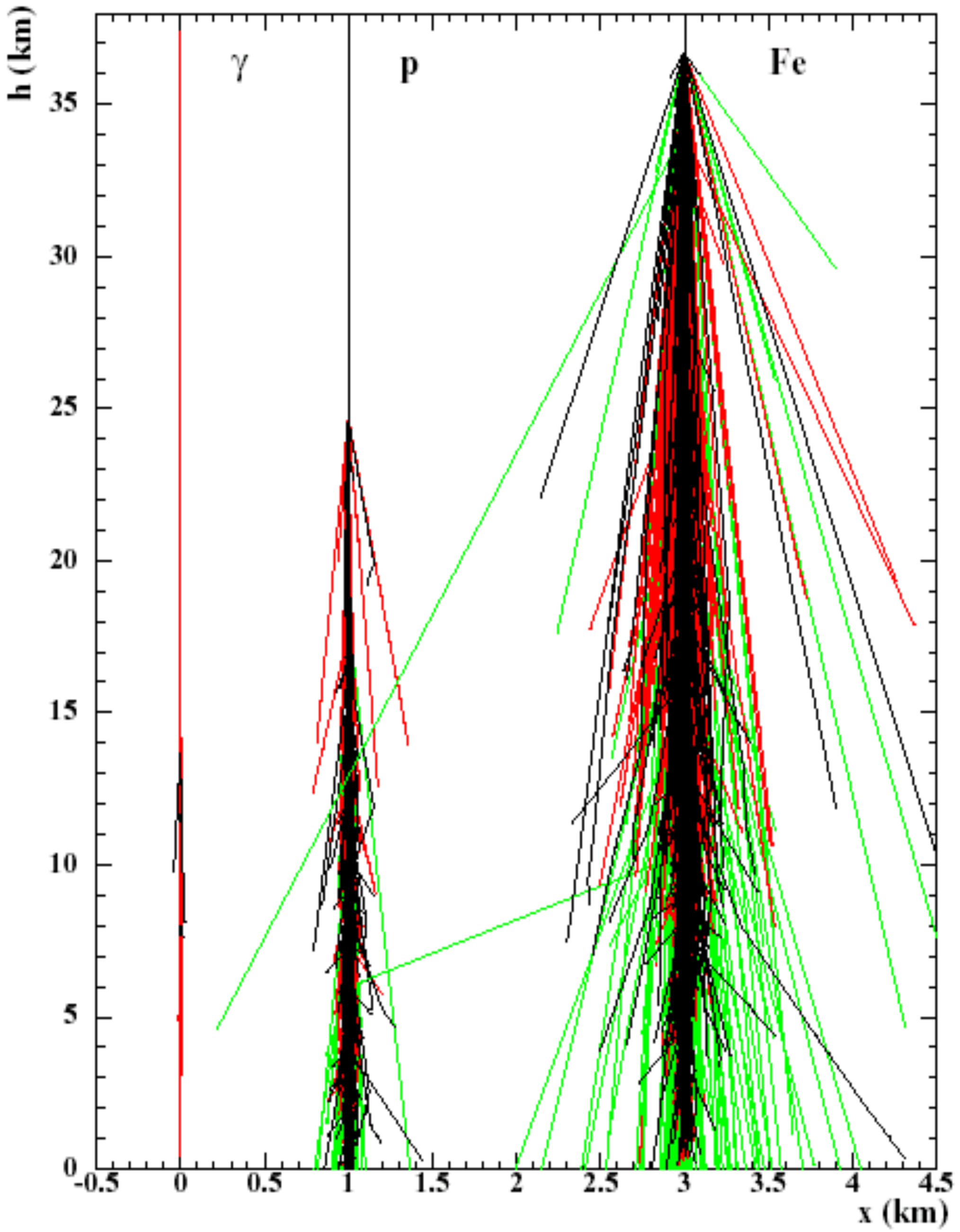
Maximum signal occurs @ same energy where the flux is reduced by 50% with respect to an extrapolated power law

Supports evidence that the steepening in the CR spectrum is due to the GZK cutoff and not to acceleration limits at the sources

Primary particle

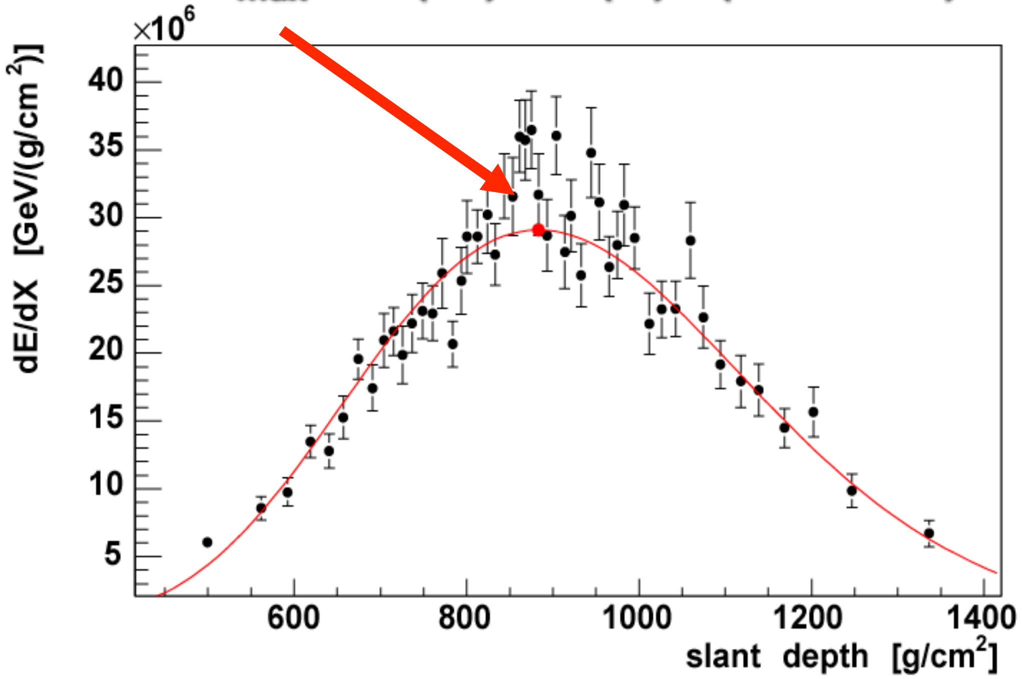
Primary mass determination

Lighter the primary, deeper the maximum



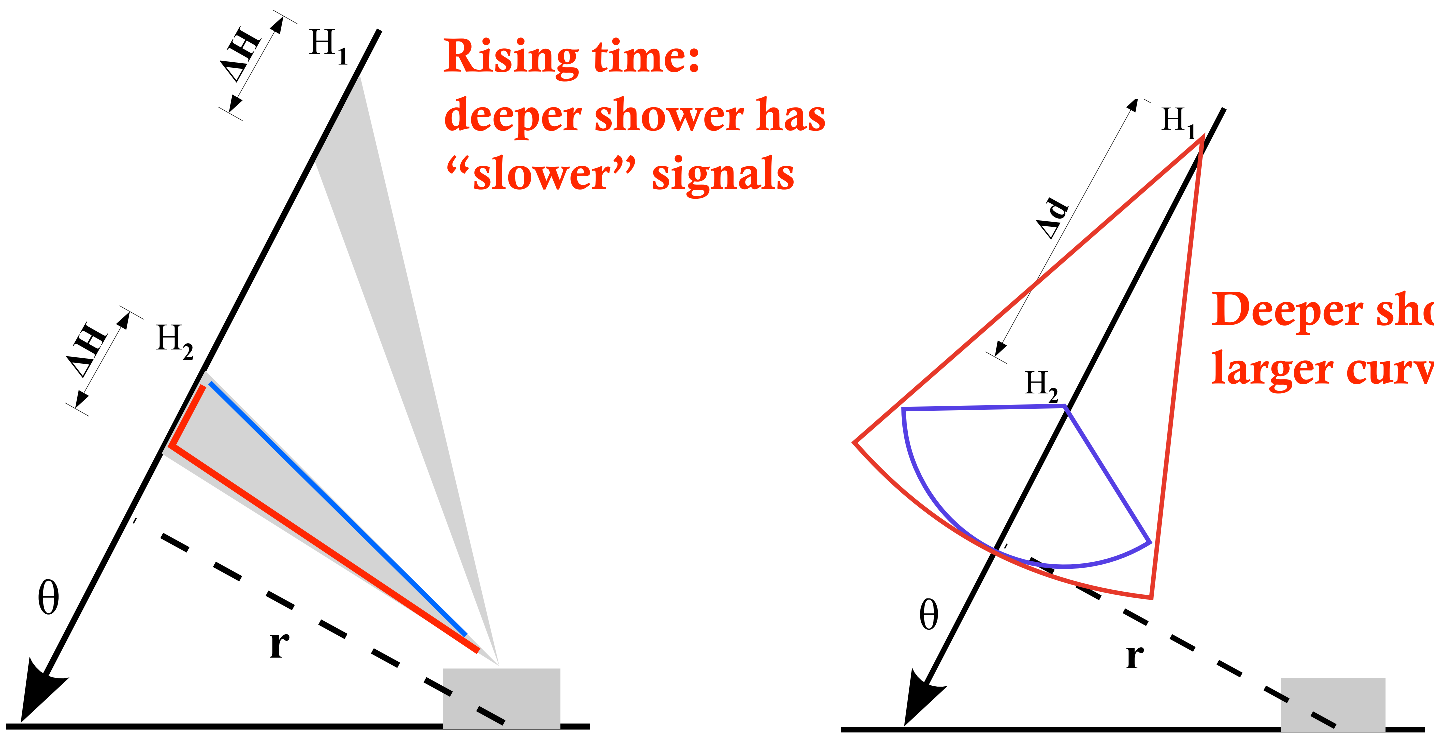
FD observable

$X_{max} \sim \ln(E_0) - \ln(A)$ (MC Sim.)



Most sensitive observable to composition: X_{max}
Accuracy: 20 g cm^{-2}

SD observables

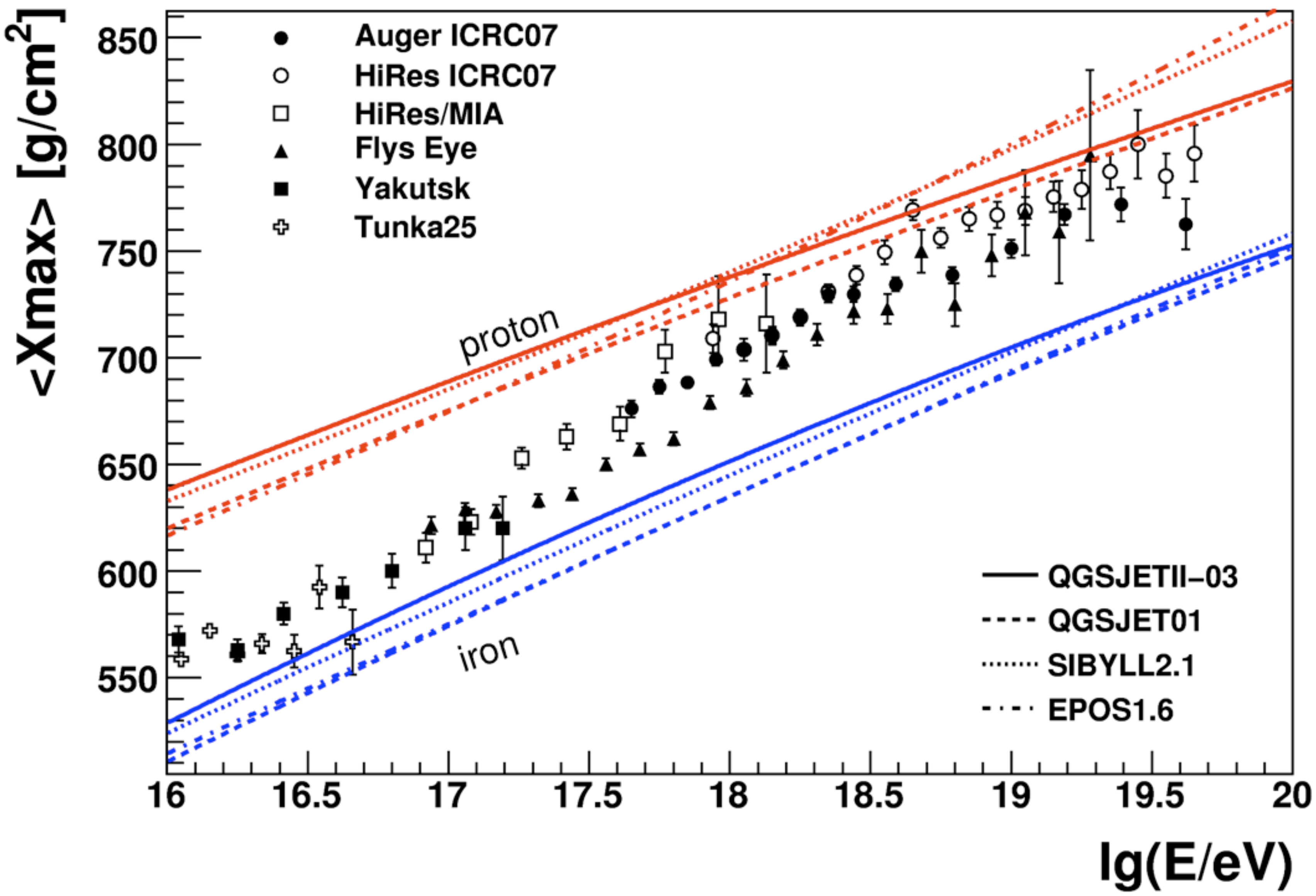


Rising time: deeper shower has “slower” signals

Deeper shower: larger curvature

Composition from Xmax measurement

M.Unger, **arXiv:0812.2763** [astroph]

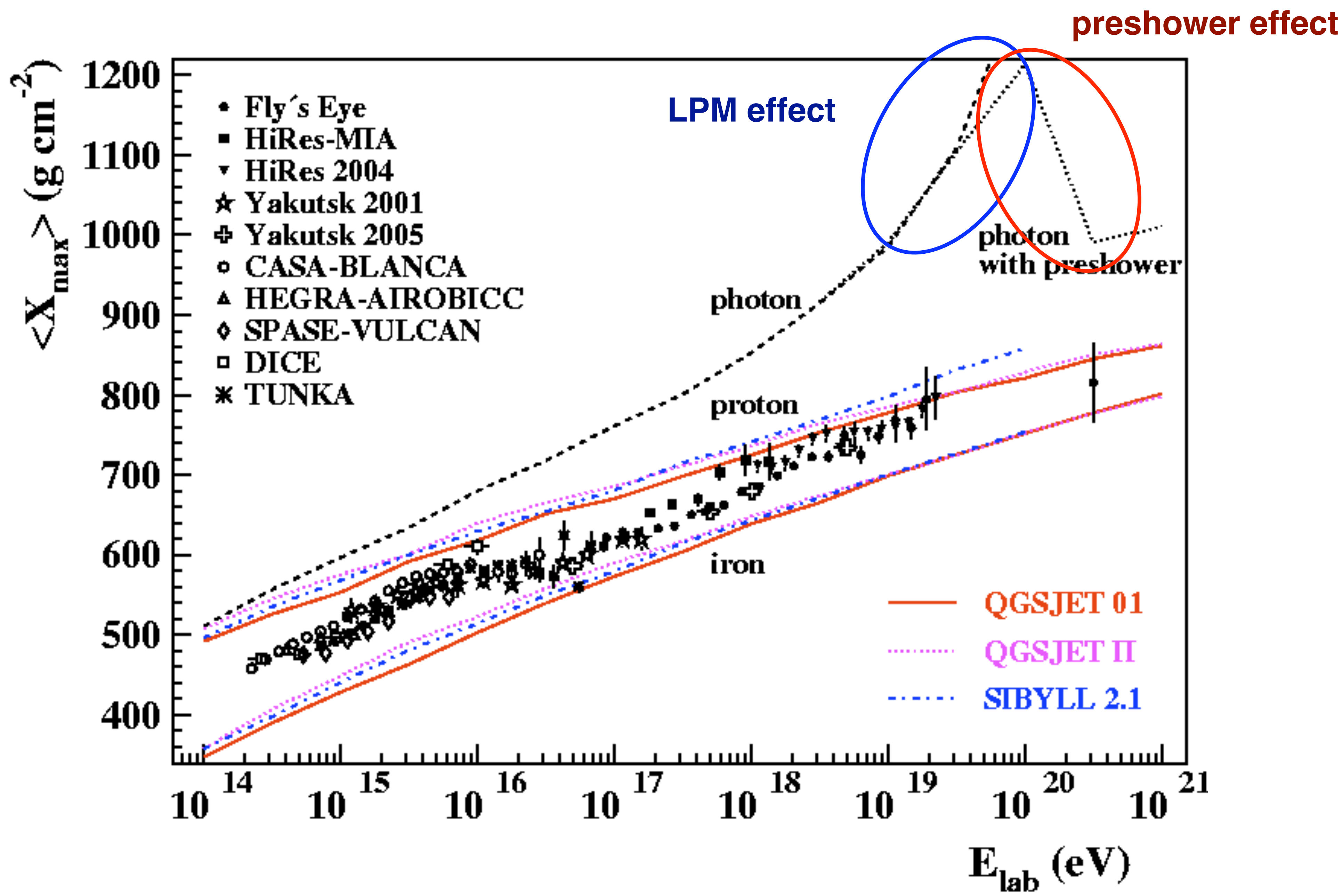


P. Auger Observatory data suggest mixed composition at all energies

→ interpretation depends on hadronic interaction models

→ measurements are compatible within experimental uncertainties

Photon-hadron separation

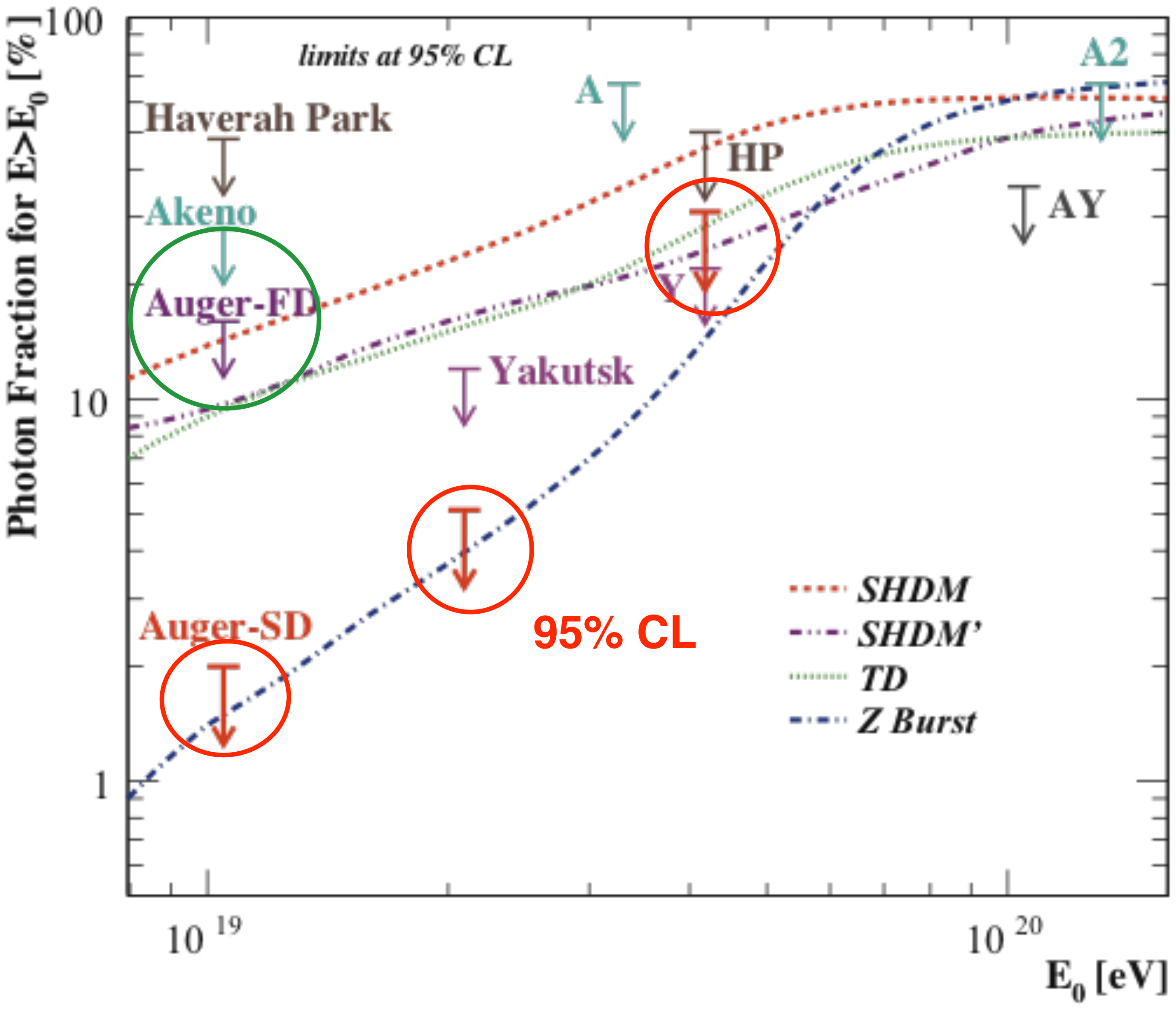


Photon showers develop deeper and contain less muon

→ average separation in Xmax ~200 g cm2 is detectable!

Experimental limits and predictions

E >10^{19}eV:



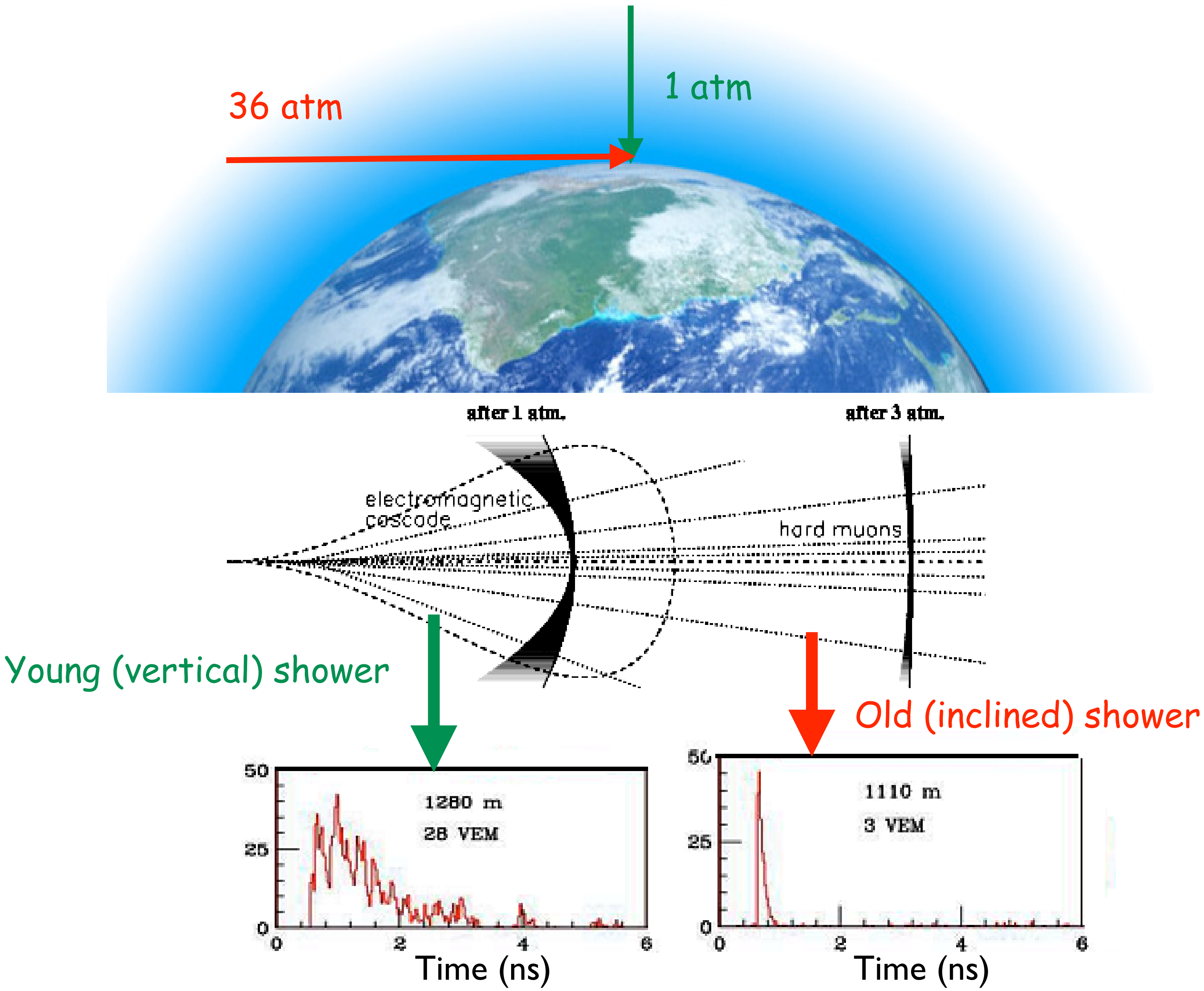
SD:
Astropart. Phys. 29 (2008) 234
Based on SD signal rise time and shower curvature

FD:
Astropart. Phys 27 (2007), 155
Based on Xmax

Topdown models severely constrained!

for reference to models & exp. data see
→ M. Risse, P. Homola, Mod. Phys. Lett. A **22** (2007) 749

Auger as a neutrino detector



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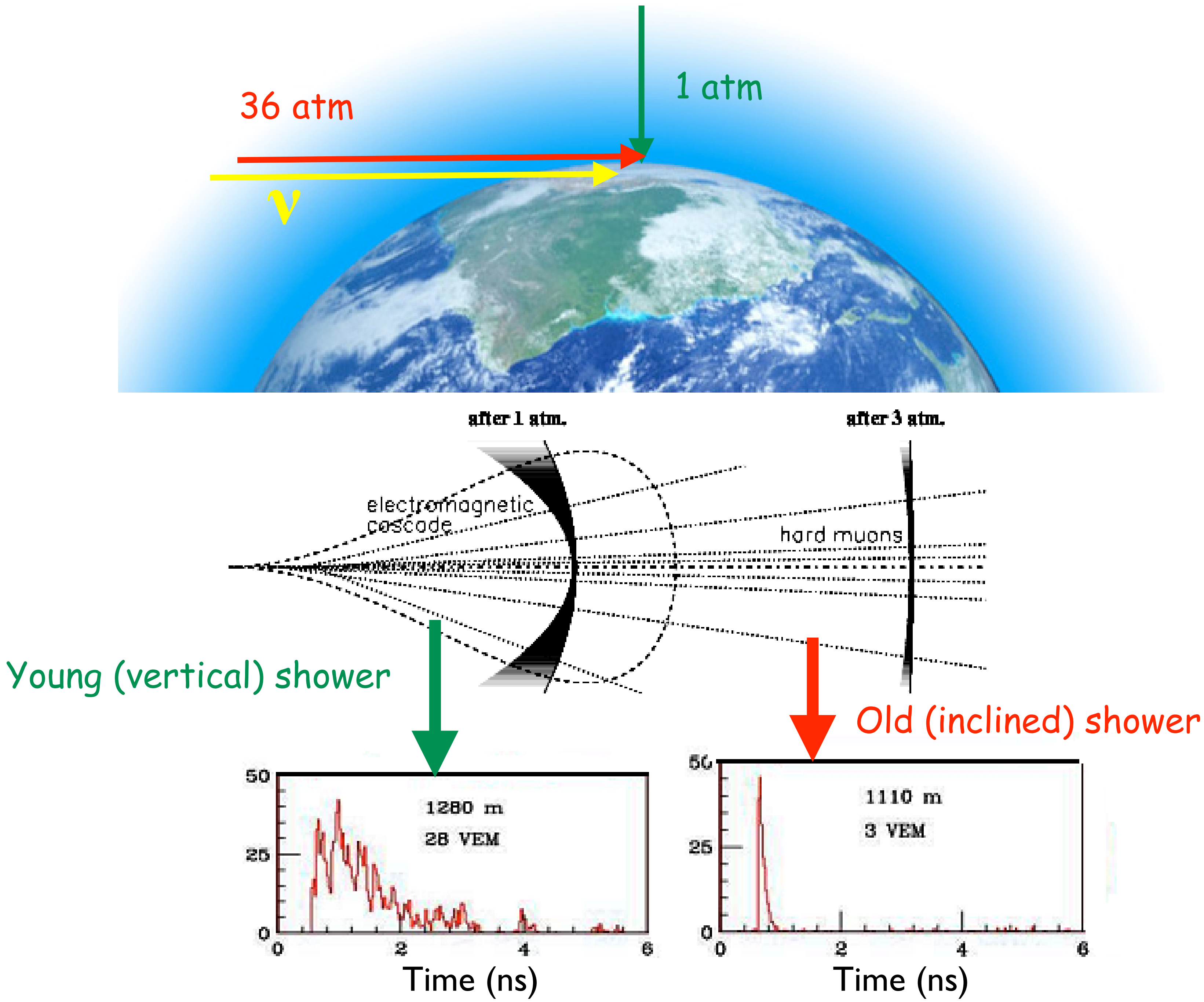
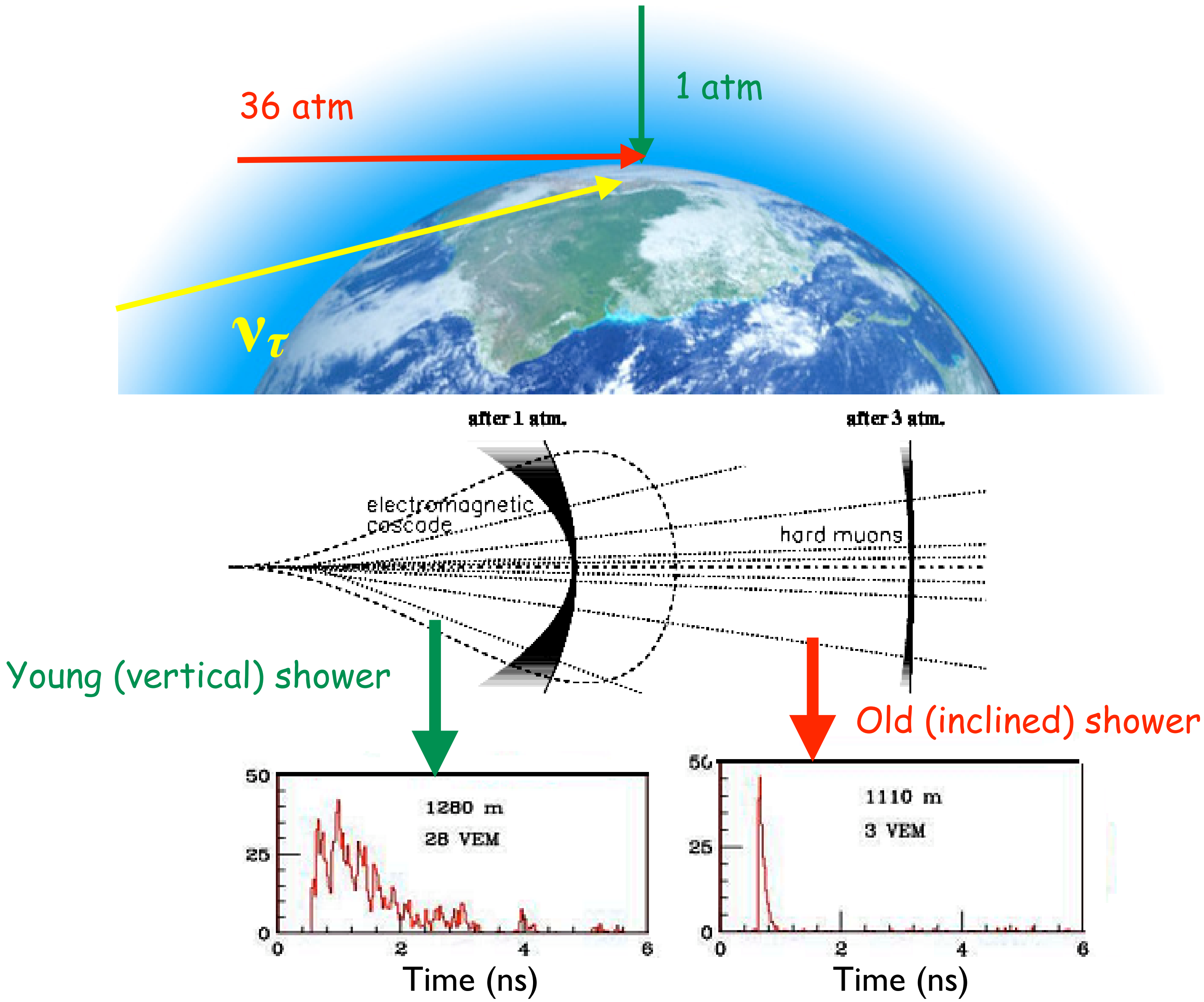


If an inclined neutrino produces a shower close to the detector :

it will induce inclined but young shower

Auger as a neutrino detector

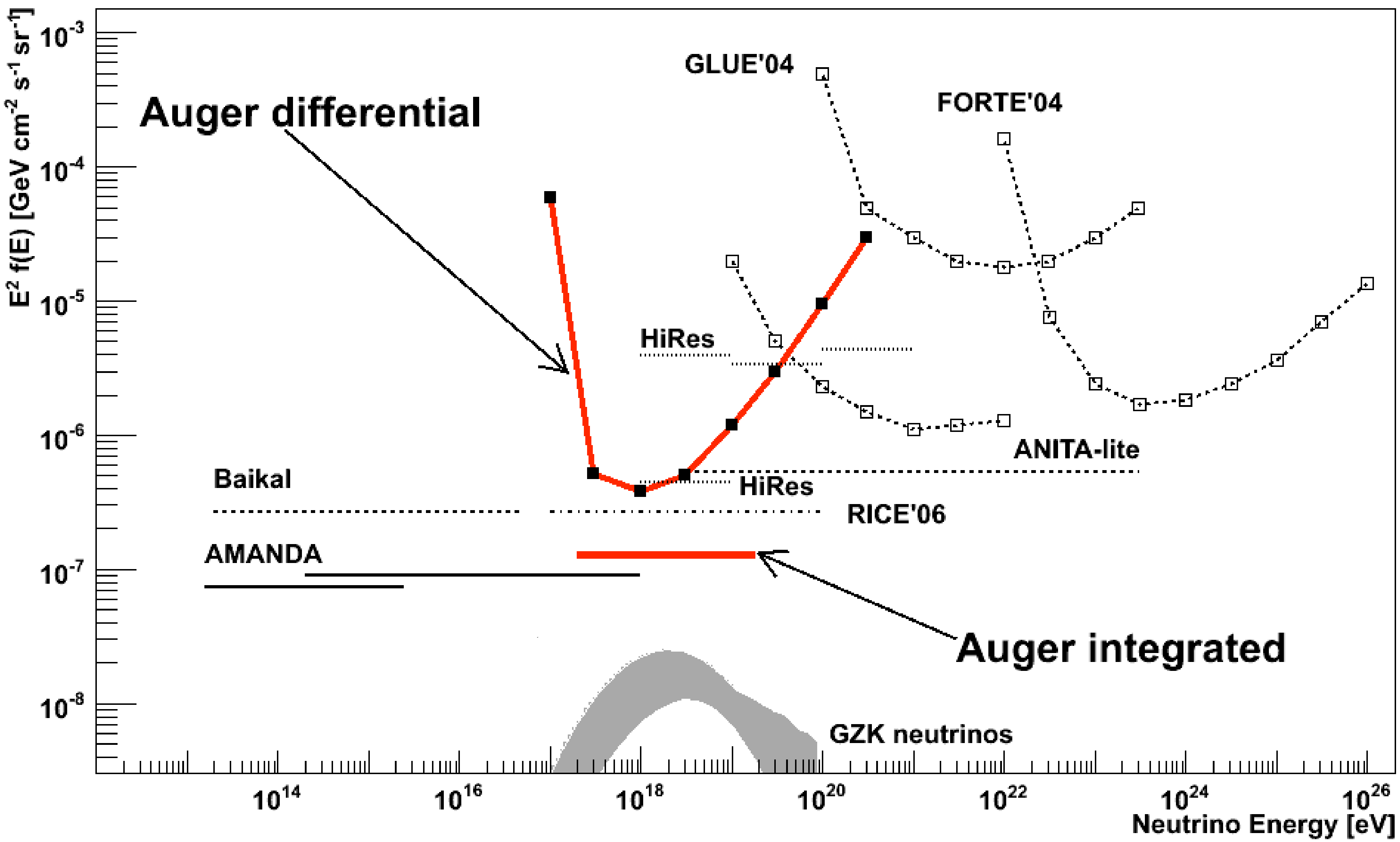


An earth skimming ν_τ (entering earth below horizon) can produce a τ crossing the earth that can decay in a horizontal shower above the array

Tau neutrino diffuse flux: Auger limits

Existence of UHECRs implies existence of UHE neutrinos
(either from interactions at the source or during propagation)

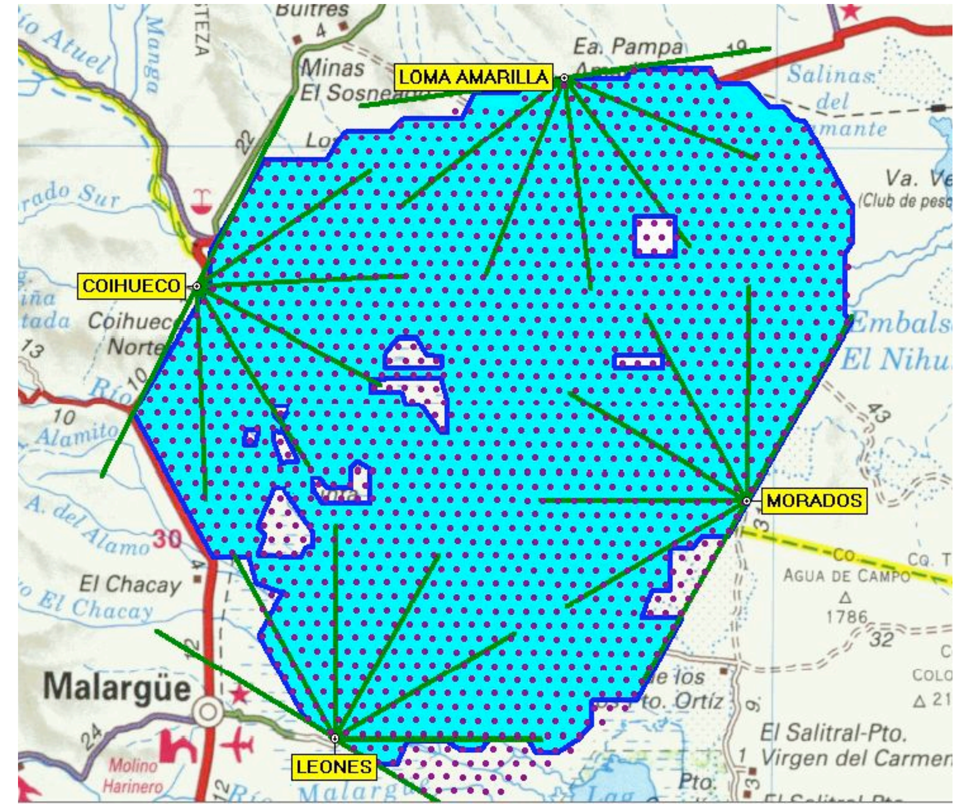
Suppression of UHECR flux + correlation with "nearby" X-galactic objects -> interaction of UHECR on CMB



Future plans

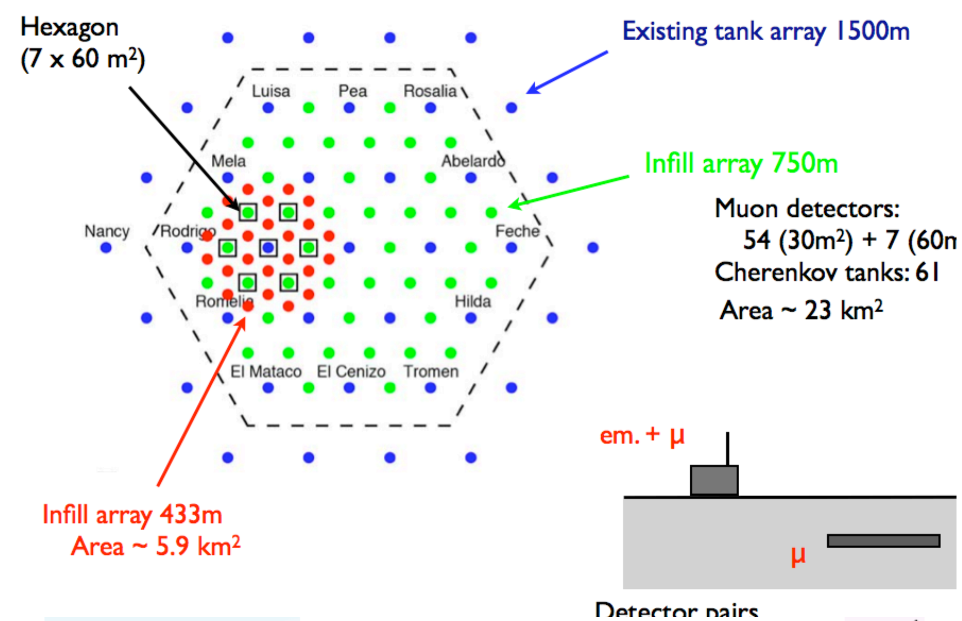
@ Auger South

"Normal" array completed (filling the holes...)
Long term operation started
New data to be released @ next ICRC

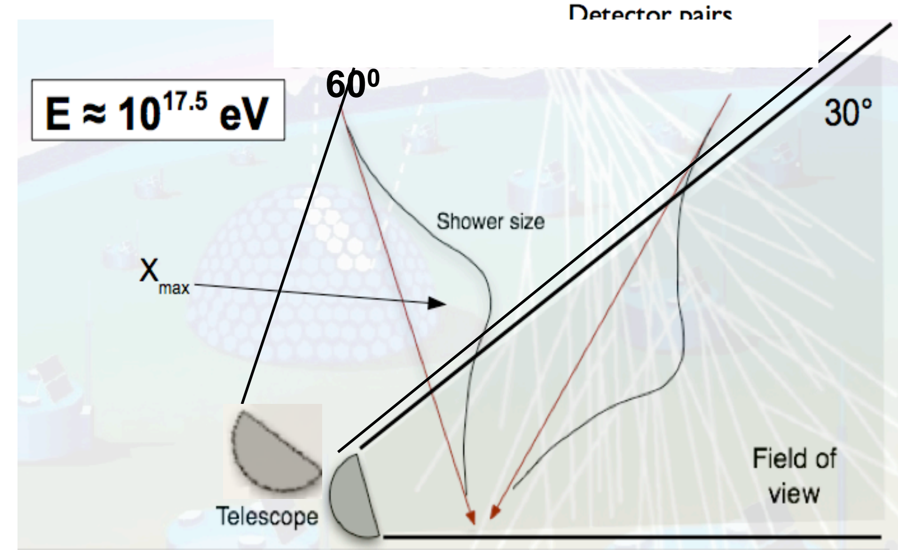


Completing the "enhancements" to decrease the threshold down to 0.1 EeV

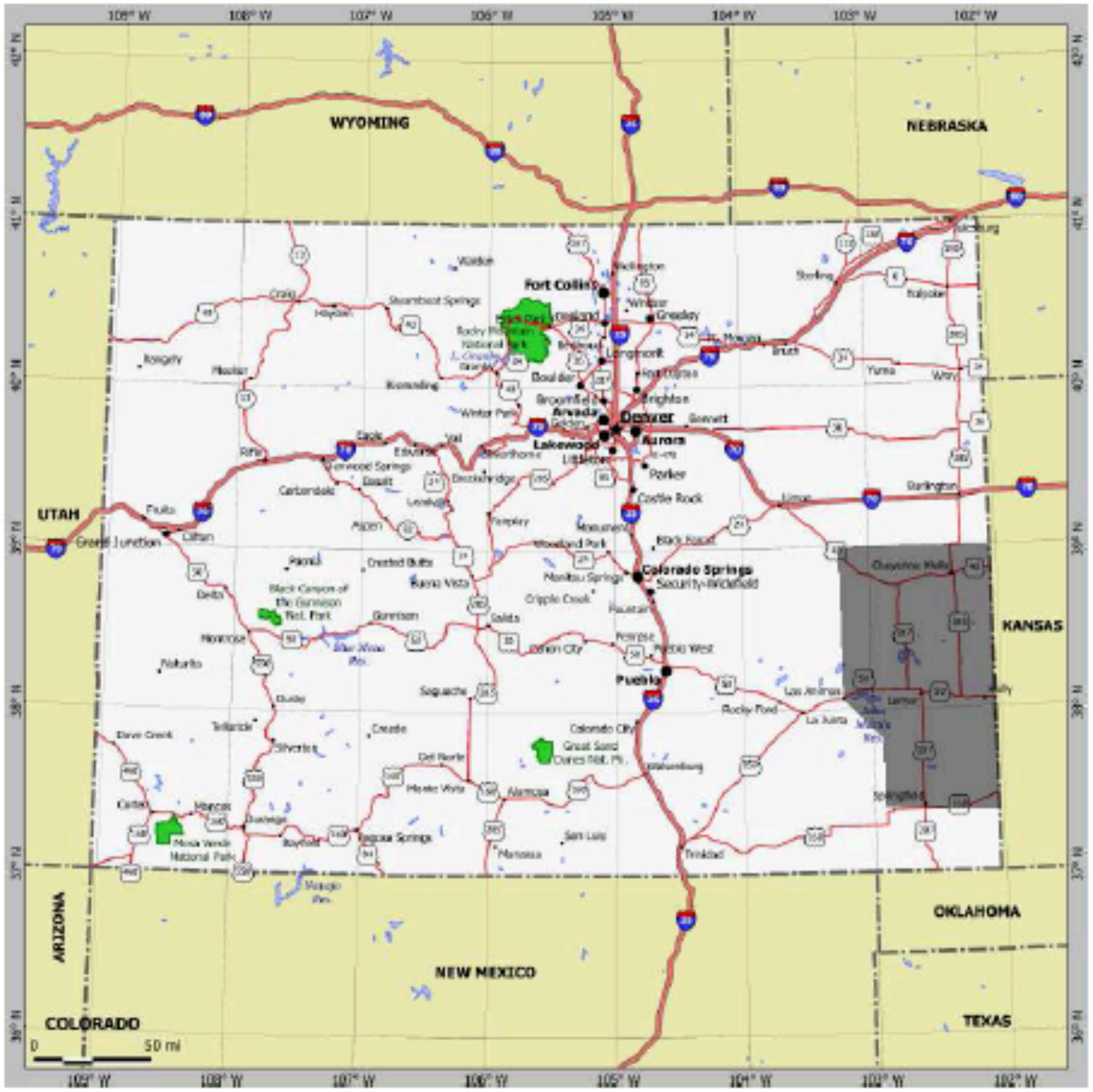
AMIGA
85 detectors with spacing 430-750 m
WCD + 30 m^2 buried μ counters

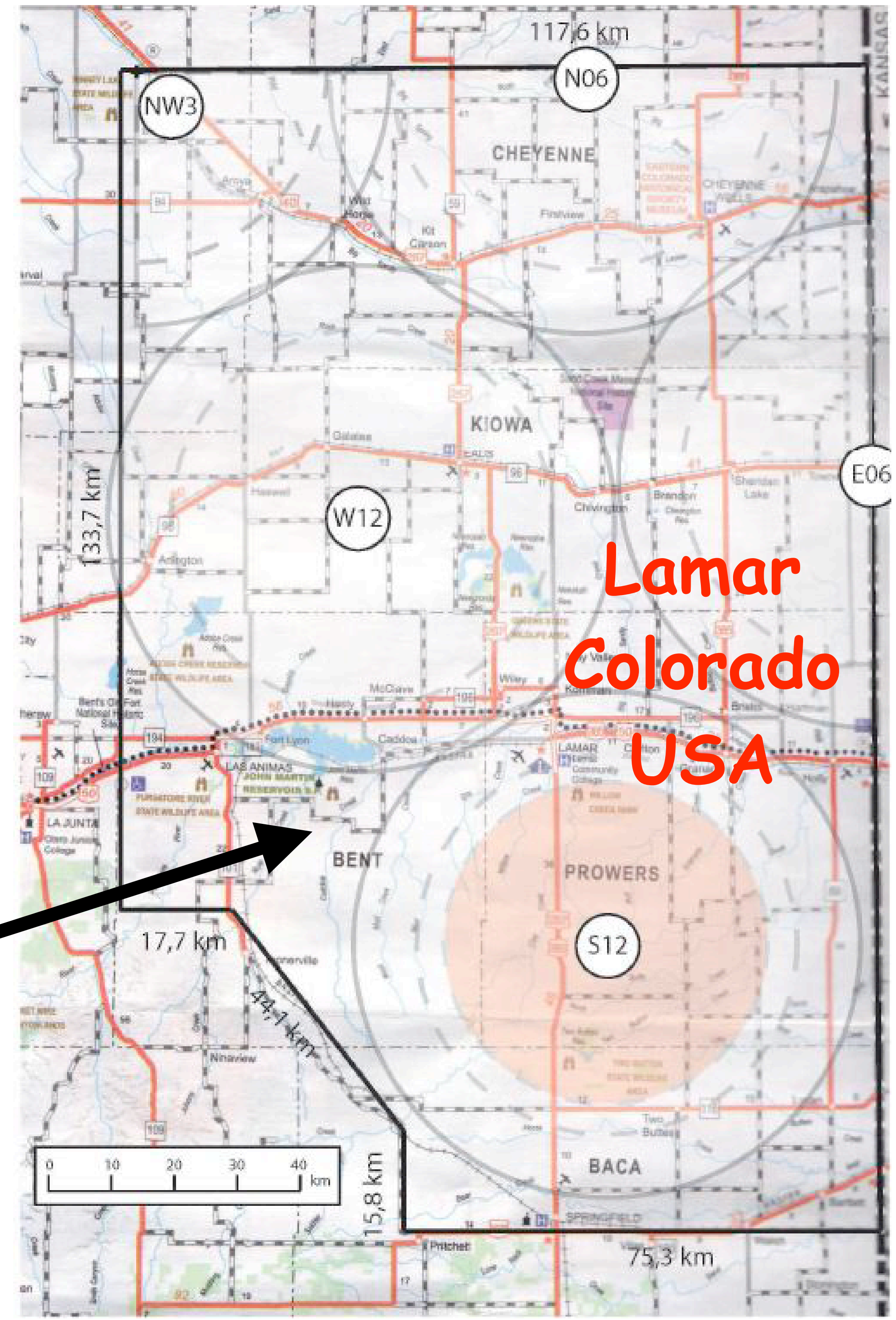


HEAT
3 additional FD with FOV 30-60 at Coihueco
Overlooking AMIGA



Auger is going North





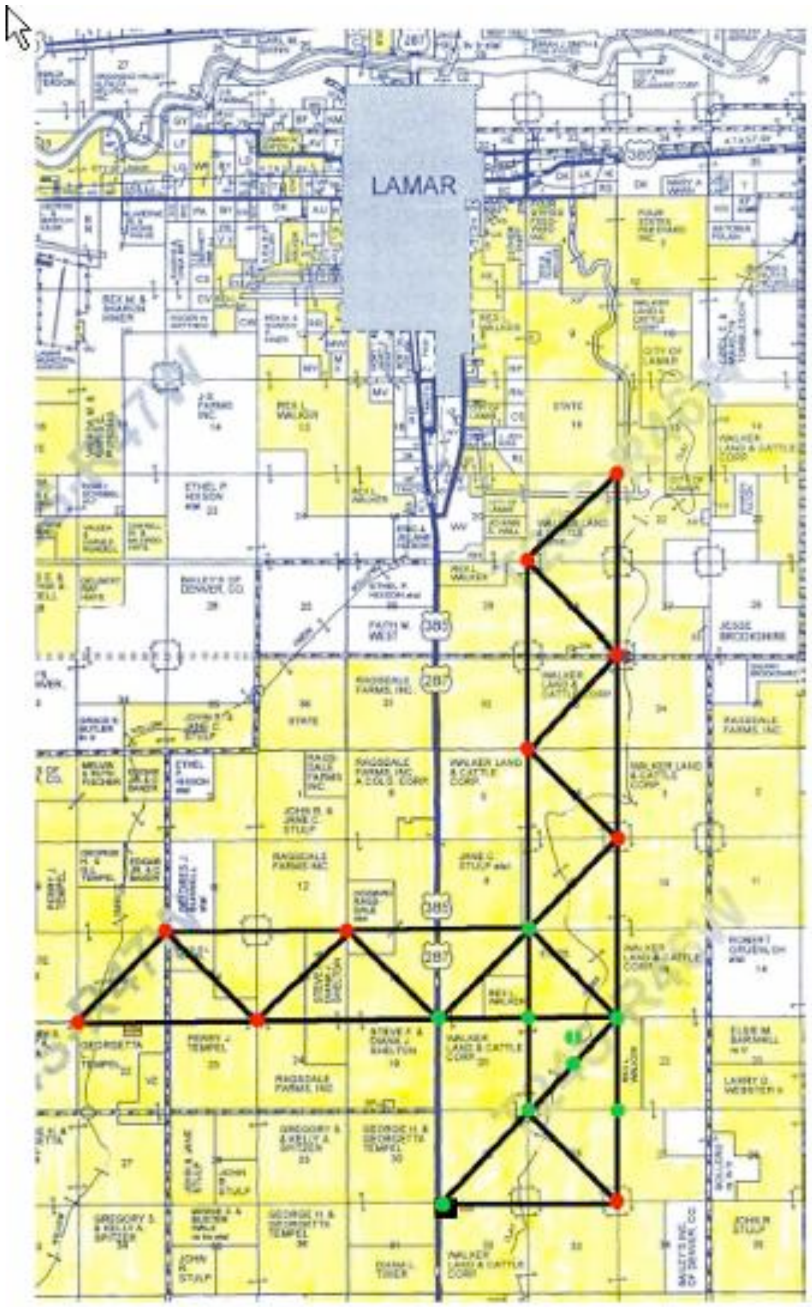
20000 km^2

4000 stations, 2.2 km grid

+ 200 stations, 1.5 km grid (2000 km^2)

7 FD sites (42 telescopes)

R&D Array fully funded
20 water Cherenkov tanks
Deployment end of 2009




Thank you

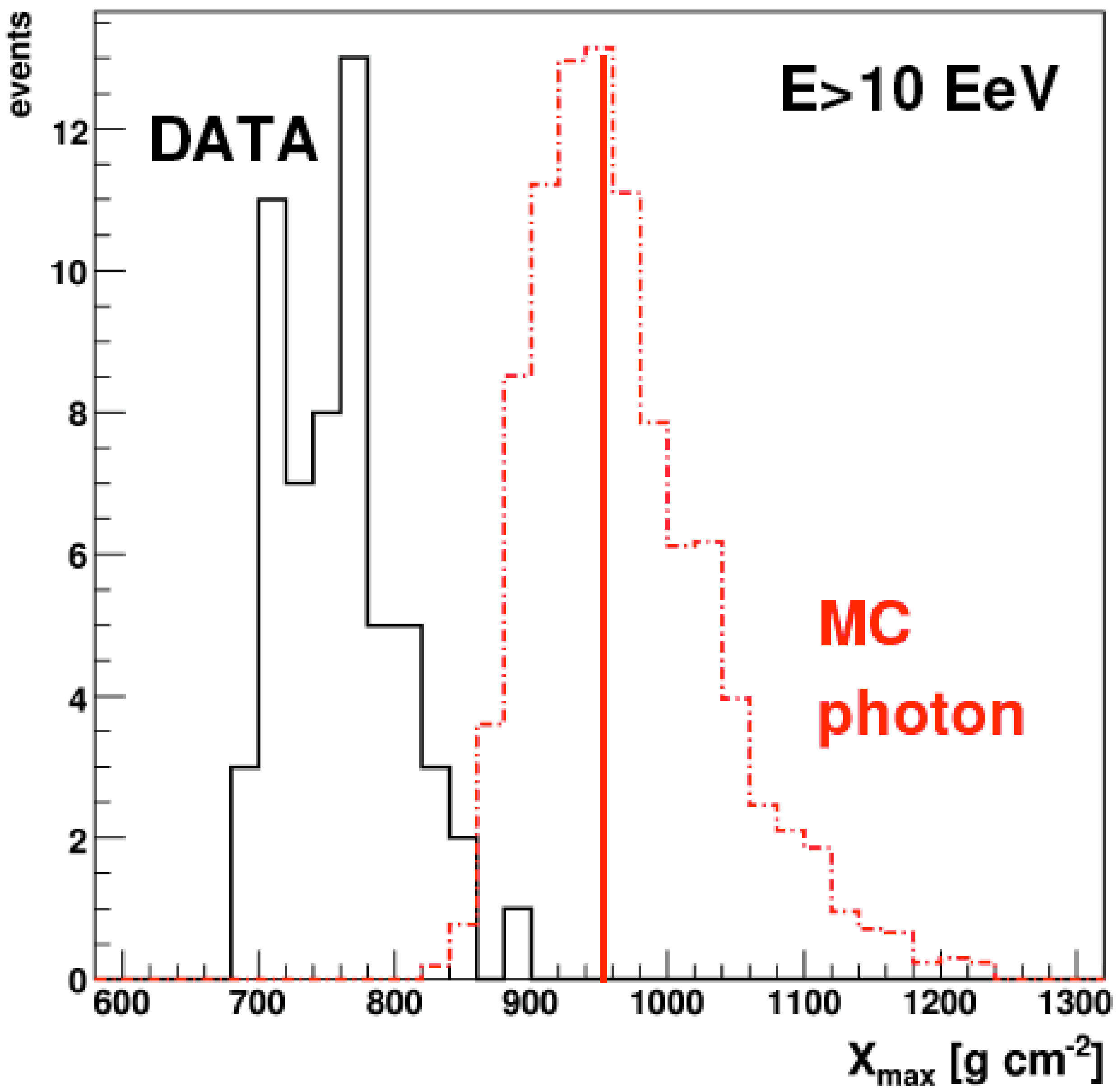
FD limits in the EeV range

▹ larger hybrid events sample

reconstruction quality cuts
fiducial volume cuts
cloud coverage correction

▹ powerful statistical method

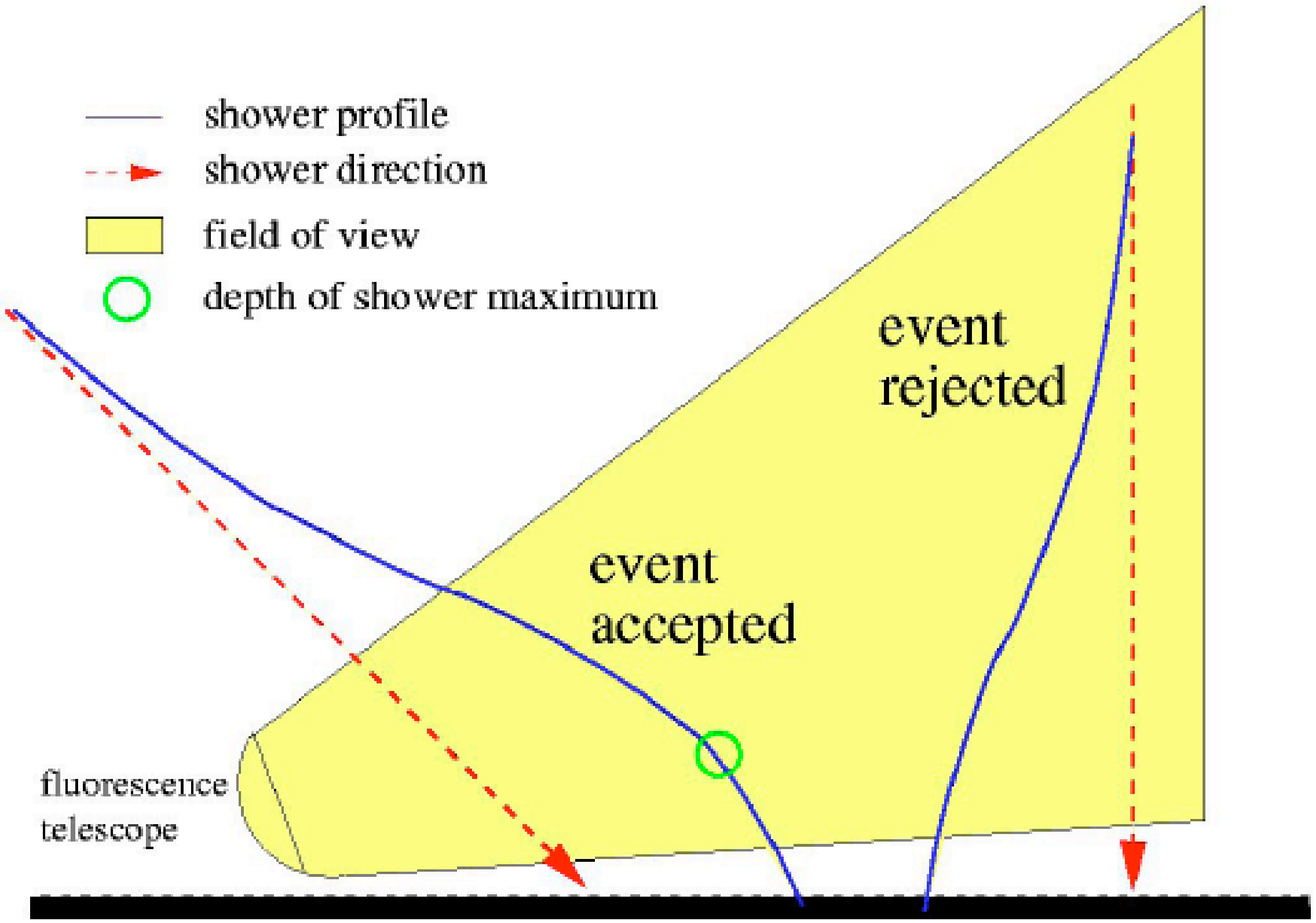
X_{max} as discrimination variable
and cut at median of
MC photon distribution
(eff $\equiv$ 0.5)



FD limits in the EeV range

▹ **larger hybrid events sample**

reconstruction quality cuts
fiducial volume cuts
cloud coverage correction

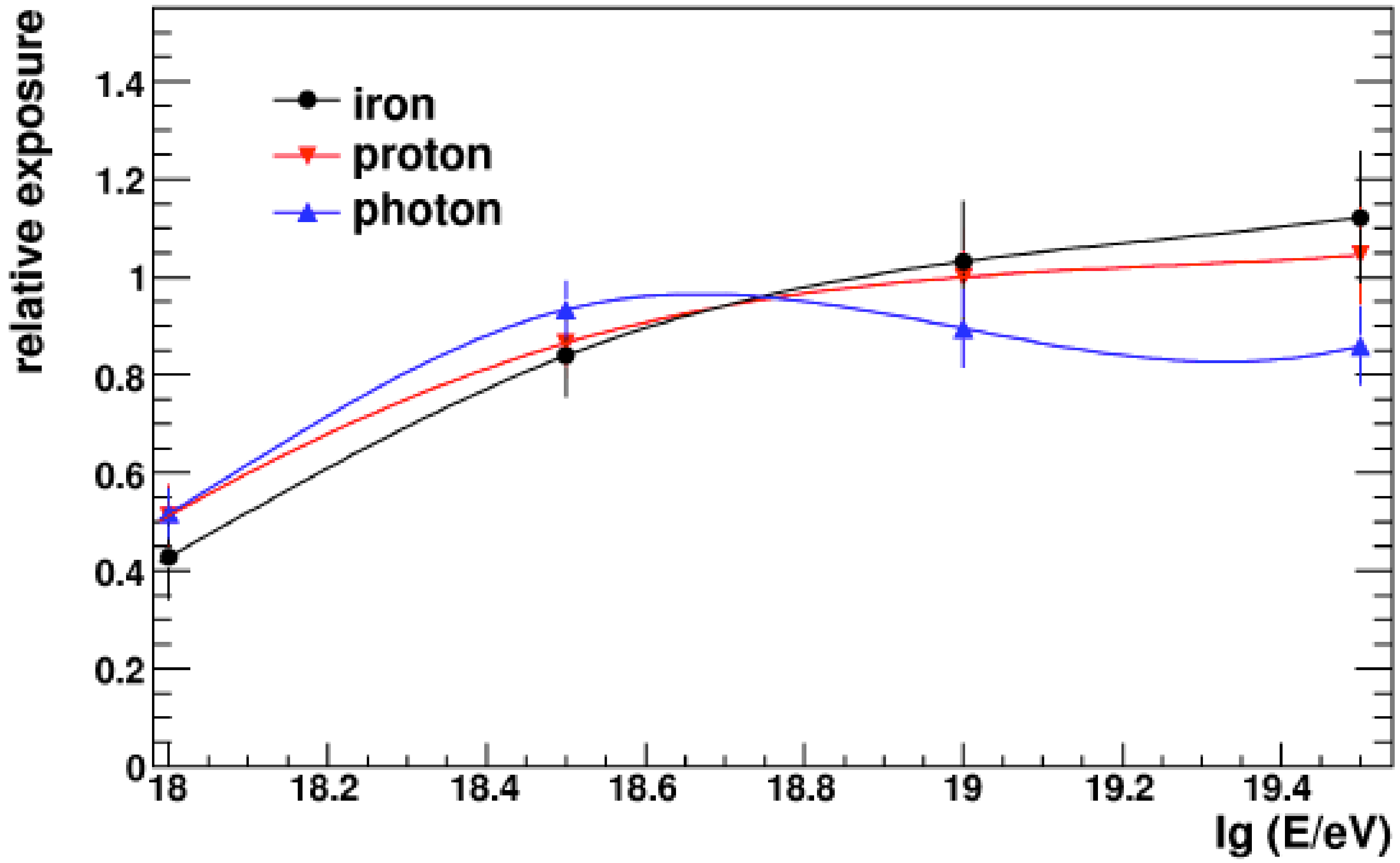


FD limits in the EeV range

▹ **detector efficiency study**

- detailed detector simulation (CORSIKA, FLUKA, QGSJET01)

- different inducing primaries (iron proton photon)



▹ **relative acceptance correction**
conservative approach

N_γ observed candidates above cut (95% cl)
ε min relative detector acceptance
f photon candidate cut efficiency = 0.5
ε_{cl} pass the cloud check

$$F^{ul} = \frac{N_{\gamma\ c.l.} \cdot 1/\varepsilon_{min} \cdot 1/f}{N_{total} \cdot \varepsilon_{cl}}$$

Constant Intensity Cut

- Isotropy of Cosmic Rays
  ⇨ Integrated constant Intensity

- Constant Intensity
  ⇨ Constant Energy

- Relate S(1000) to S_{38}
  (signal at 38°)

  38° is the average zenith angle of events