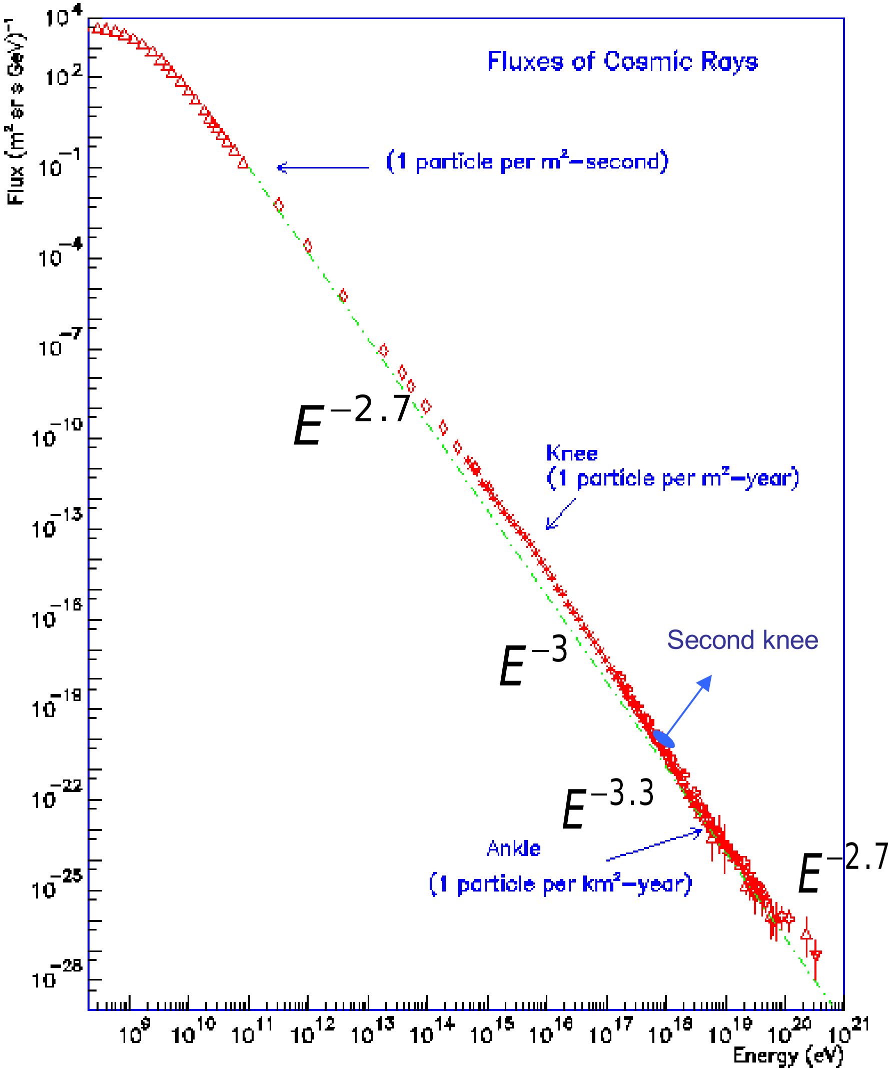
News from the Pierre Auger Observatory

M. Ave



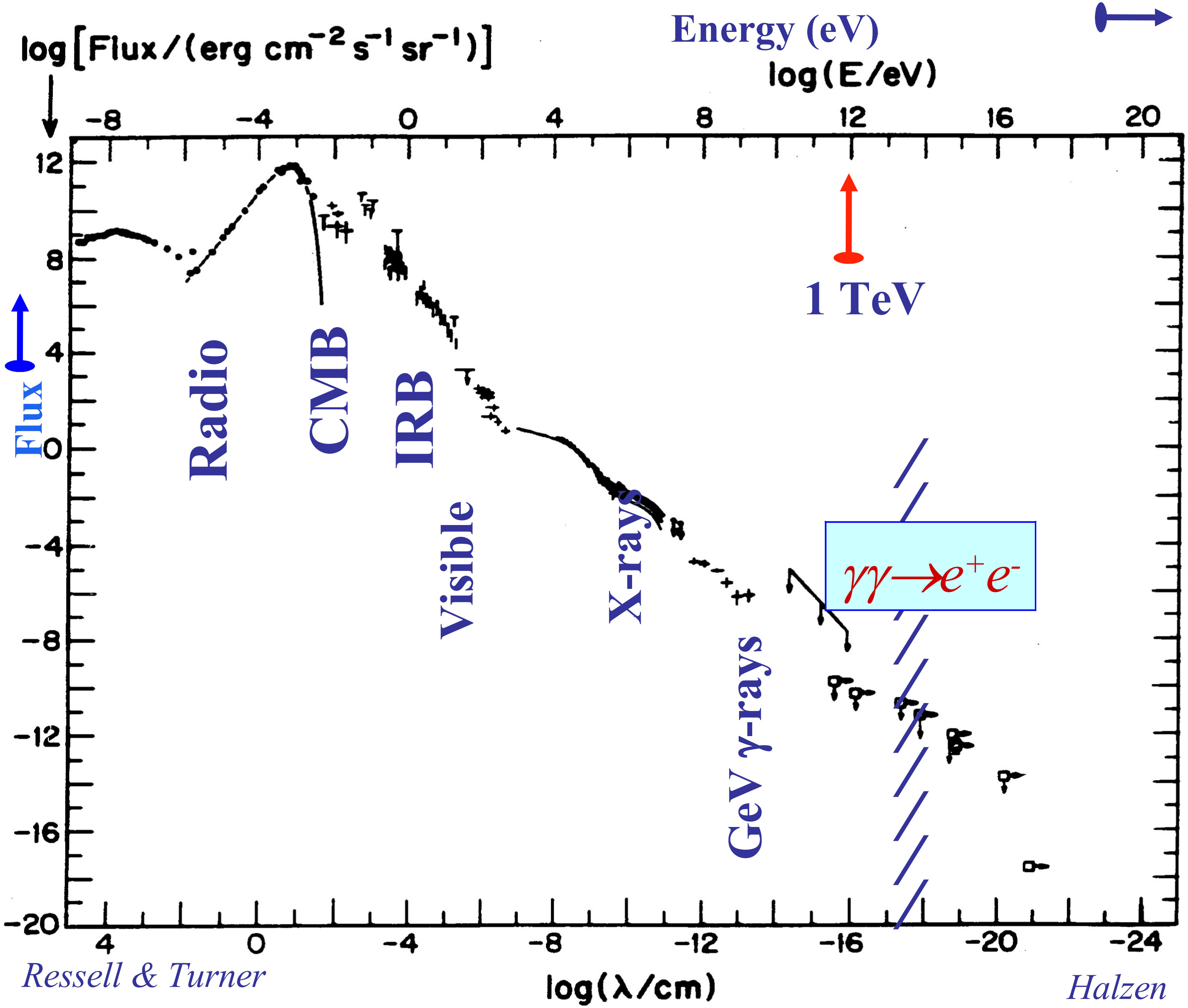
Discovered by Victor Hess in 1912

Till 50's source of high energy particles for free: positrons, muons, pions, kaons, and hyperons

Non Thermal Spectrum

Extremely isotropic

After a century!!!, Origin Unknown



Energy (eV)
log[Flux/(erg cm^{-2} s^{-1} sr^{-1})]
log(E/eV)
-8
-4
0
4
8
12
16
20
12
8
4
0
-4
-8
-12
-16
-20
Flux
Radio
CMB
IRB
Visible
X-rays
GeV γ-rays
1 TeV
$\gamma\gamma \to e^+e^-$
4
0
-4
-8
-12
-16
-20
-24
log(λ/cm)
Ressell & Turner
Halzen

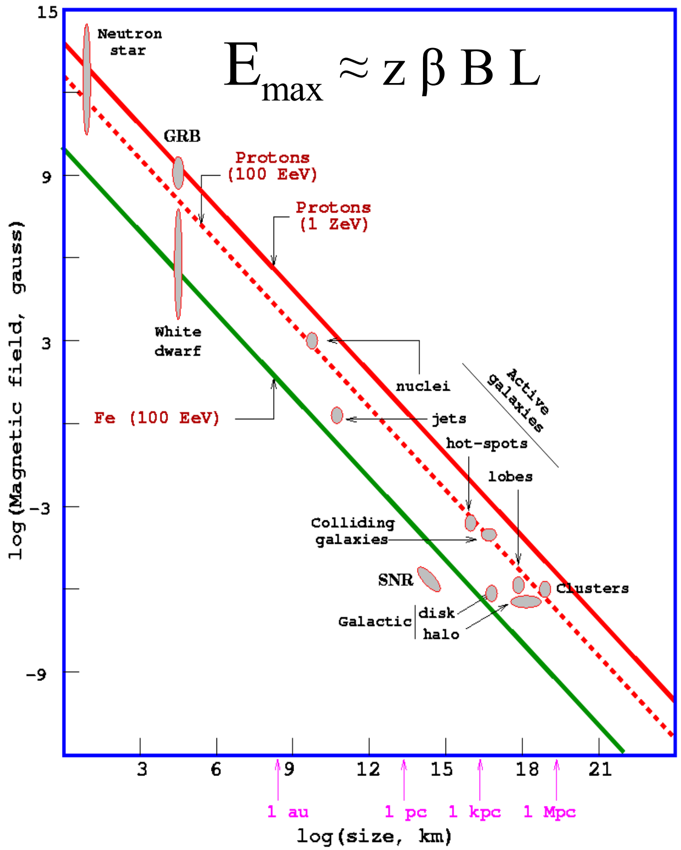
COSMIC RAYS AT THE HIGHEST ENERGIES (E> 4 x 10^{18} eV)

EXTRAGALACTIC!!!

Astrophysical sources

Hillas-plot

(candidate sites for E=100 EeV and E=1 ZeV)



Top-down scenario

- Particle physics:

Topological defects, Super Heavy Dark matter.

Difficult to produce/accelerate particles to such high energy!

Either solution (astrophysical or particle physics) will very interesting

Sources are hidden by the magnetic fields

How can we ever find the sources?

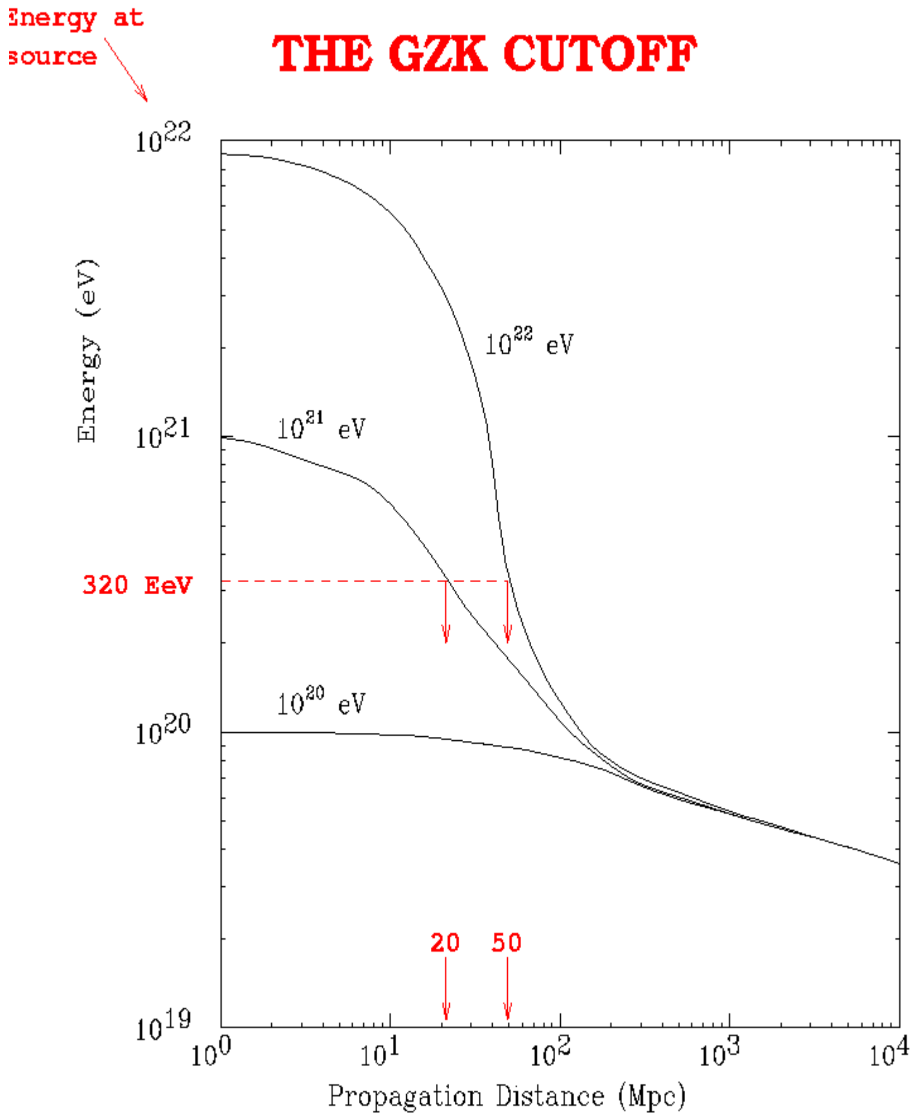
Direct

- Spectral Features
- Chemical composition dependence with energy
- Anisotropies at different energies.

Indirect

- X-Ray, Gamma Ray observations
- Neutrino Astronomy

What can we learn from the spectrum? (I)



Energy attenuation of protons

Pion photoproduction

$$p + \gamma_{2.7\,K} \rightarrow N + \pi$$

for $E_p > 5\ 10^{19}$ eV

Interaction length $\approx$ 6 Mpc

Energy loss $\approx$ 20 %/interaction

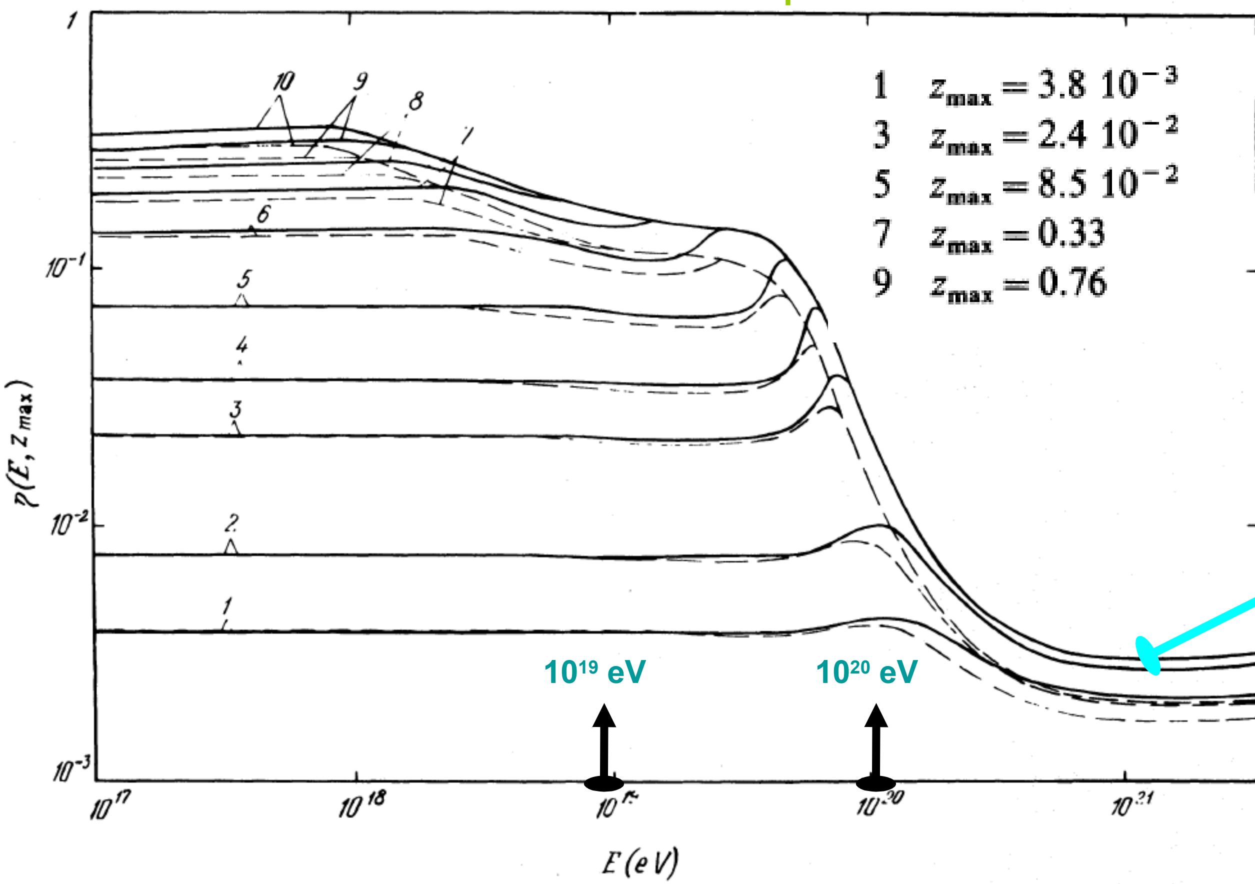
nearby sources
(<50 Mpc)

What can we learn from the spectrum? (II)

Astrophysical Sources

No magnetic field → Observed spectra same than Source spectra

BUT =3.0 Far from shock acceleration predictions =2.1



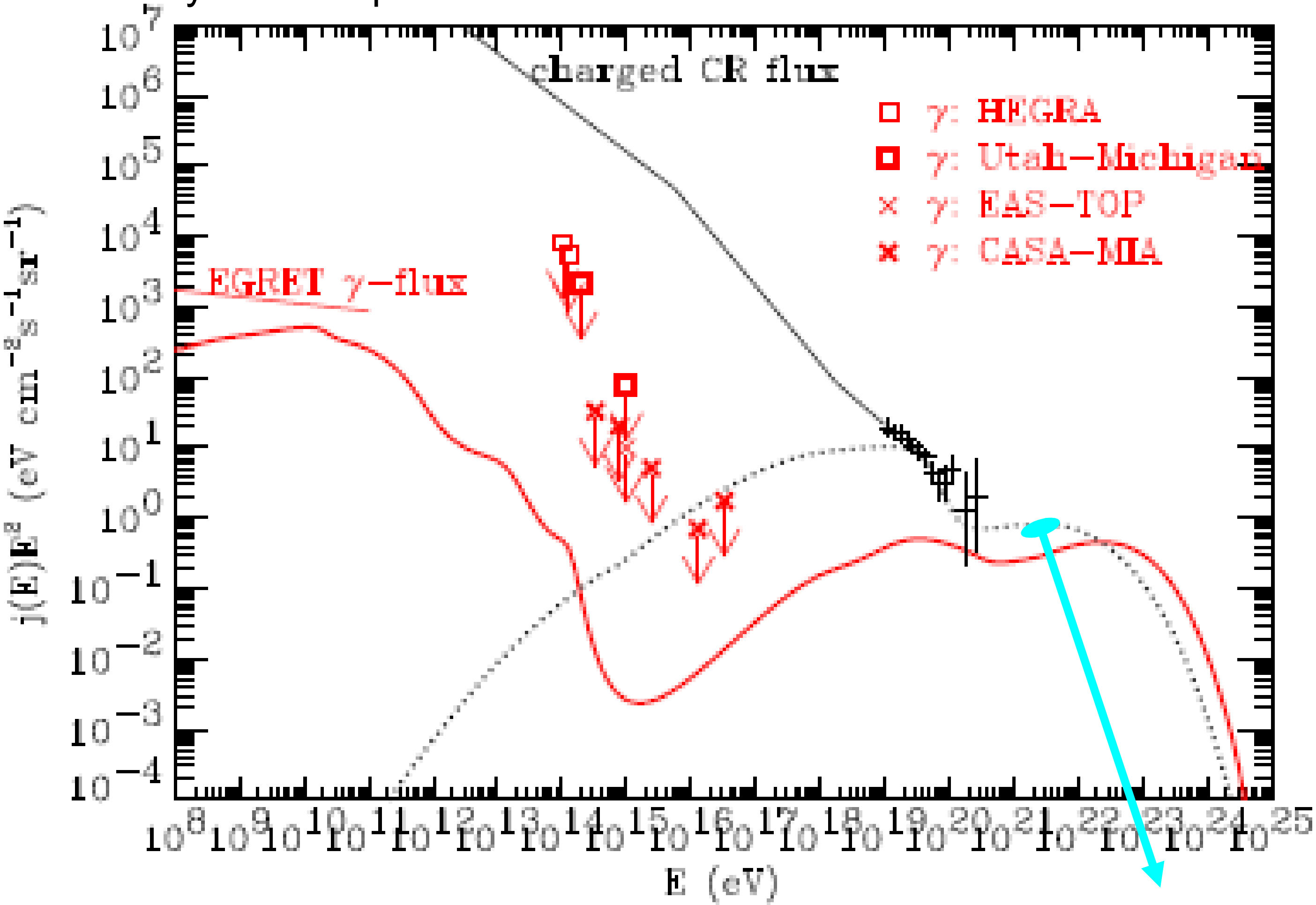
Cosmological evolution and GZK cutoff change the slope of the spectra!!!

Maximum energy > 10^{22} eV

What can we learn from the spectrum? (II)

Top Down Mechanisms

Injection spectrum: given by the hadronization of quarks resulting from the decay of this X particles



TD model

$X \rightarrow q + q$

$M_X = 10^{16} GeV$

$EGMF = 10^{-9} Gauss$

GZK feature is present but there is a recovery at very large energies!!

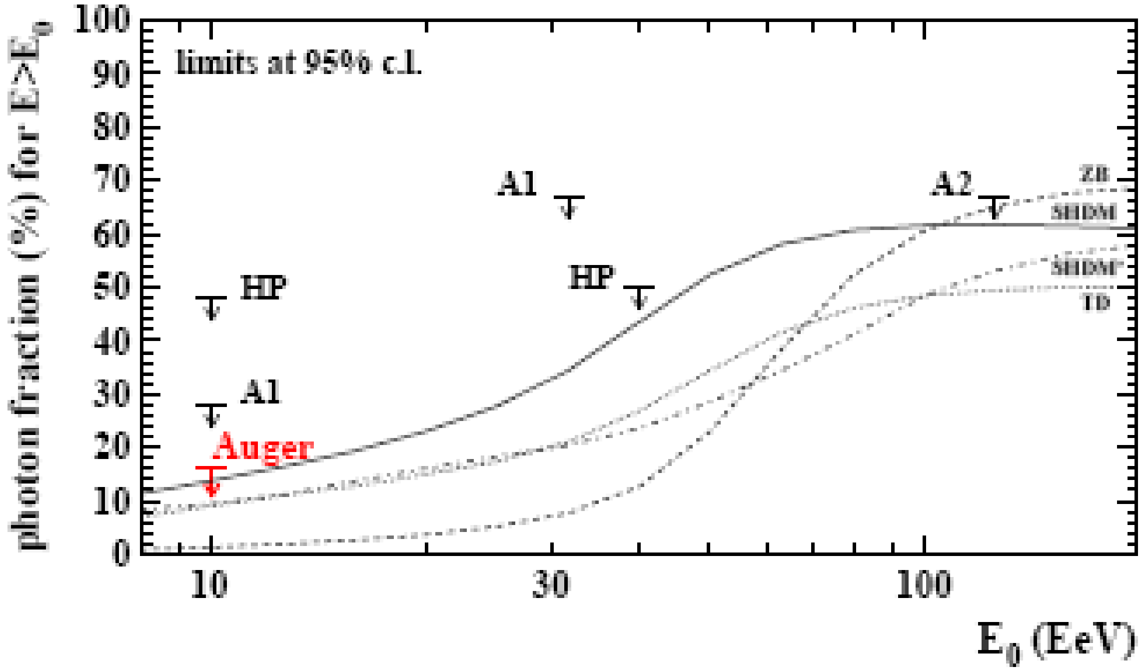
Cosmic Ray beam have a high gamma content!!!

Maximum energy 10^{25} eV

How to distinguish between Top-Down, Bottom-Up?

- **Precise measurement of the spectrum features.**
  Is there any residual flux after the GZK cutoff?

- **Gamma Ray Fraction in the Cosmic Ray beam**
- **No heavy nuclei**



Top-Down
models severely
constrained.

But what if URB
and EGMF in
LSS are larger
than we think?

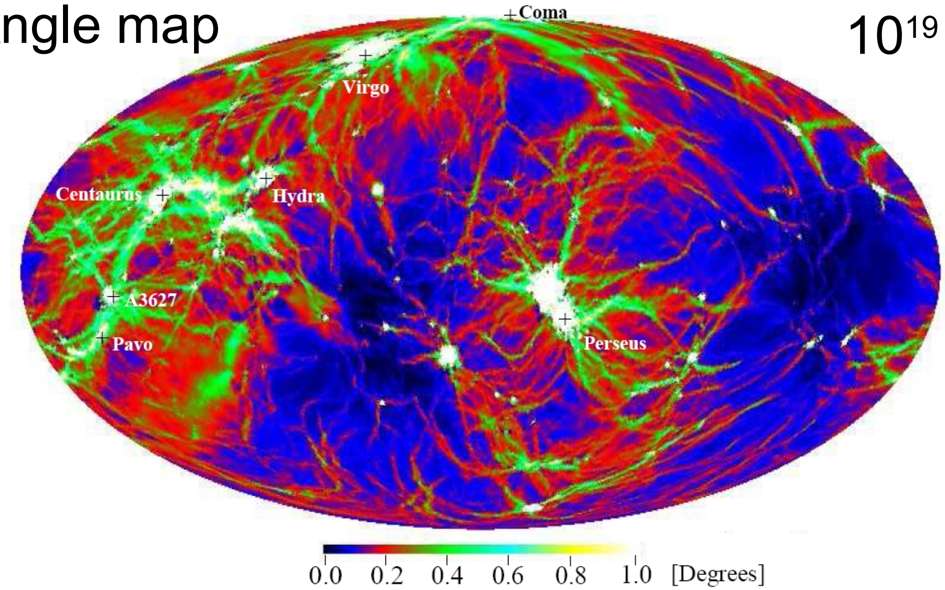
Do we expect anisotropies? (I)

First requirement: Magnetic Fields small enough

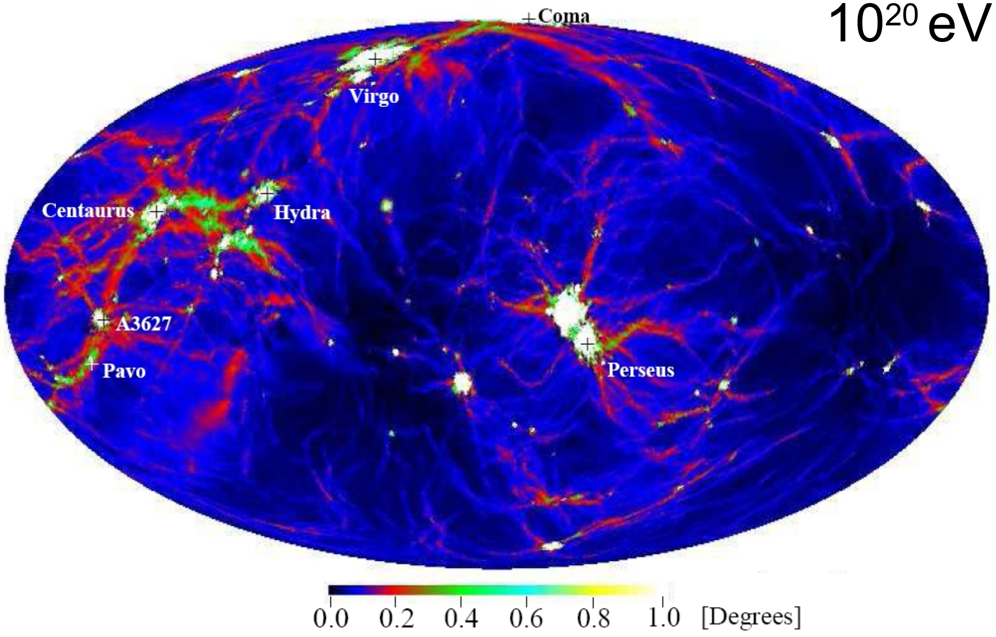
110 Mpc Deflection Angle map

Dolag et al (2003)

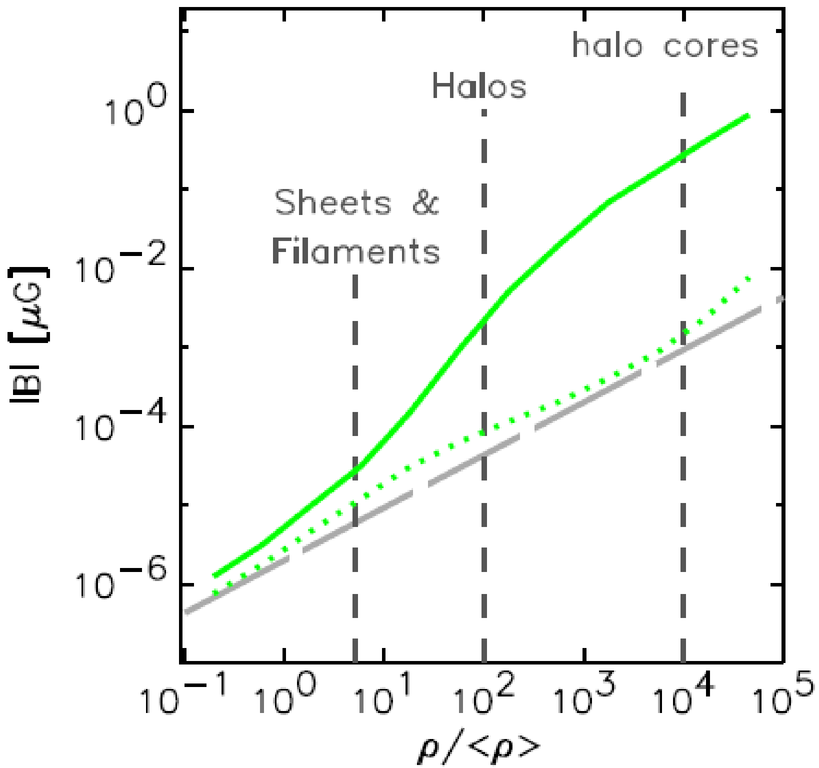
10^{19} eV



10^{20} eV



Simulations of Large scale Structure Formations to study the build up of magnetic fields through magnetohydrodynamical amplification from a seed at high redshift.



High Energy Cosmic Rays propagate mainly through voids

→ very small magnetic fields

→we are in the "ballistic" regime for almost all the energies.

The CR sky should resemble the Source distribution.

according to this calculation,

BUT other calculations claim deflections larger than 10^0 (Miniati et al)

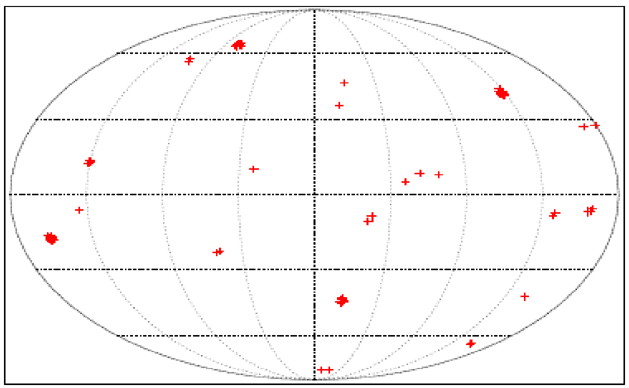
Do we expect anisotropies? (I)

Second requirement: the distribution of CRs in the sky without magnetic smearing is anisotropic

The departure from isotropy depends on:

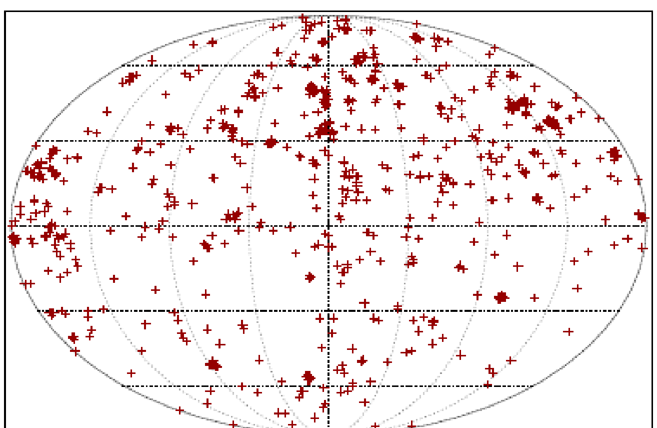
- The density of CR sources.
- The distribution of sources in the sky.
- The statistics of the experiment (all realizations of isotropy are anisotropic)

Sources distributed isotropically?



Auger N+S 2014

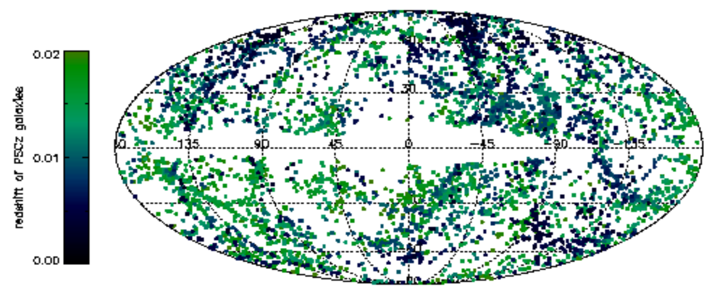
Source density 10^{-5} Mpc^{-3}



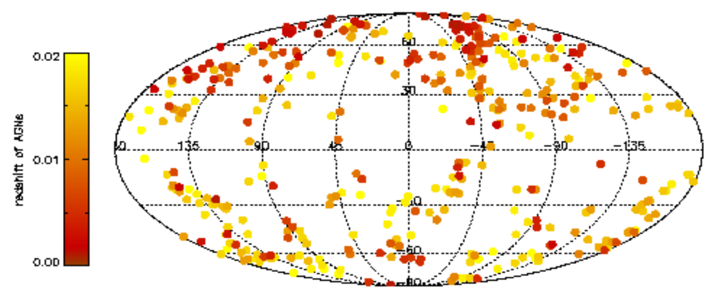
Auger N+S 2030

Source density 10^{-3} Mpc^{-3}

Sources distributed anisotropically?



IRAS galaxies ($z < 0.02$)



AGN ($z < 0.02$)

Note: we need a redshift cutoff, if not the universe is very isotropic

We expect anisotropy at some level

Particle horizons decrease with energy, above **$10^{19.7}$ eV** below **100 Mpc:**

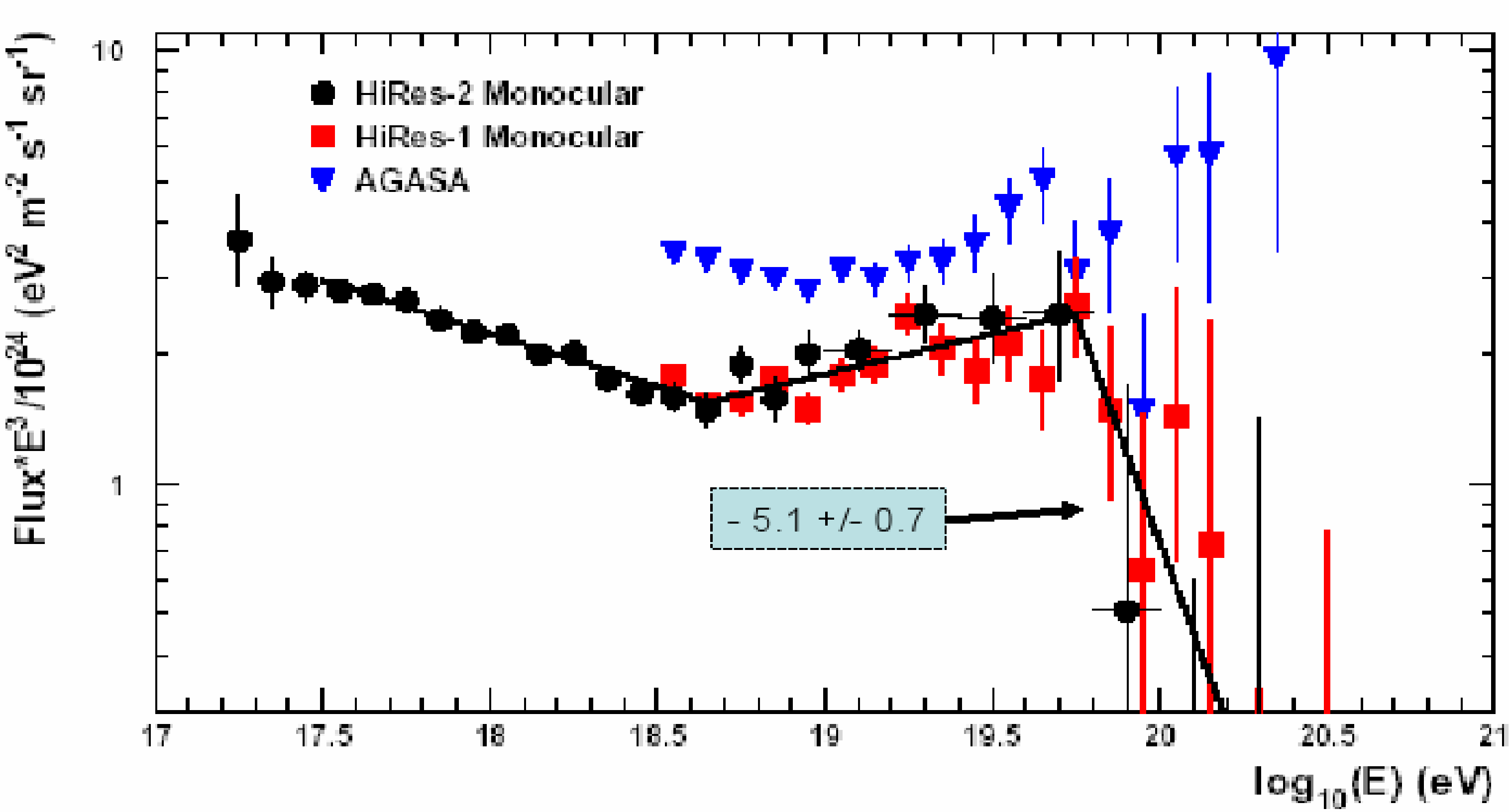
- The number of observable sources decreases.
- The distribution of matter below 100 Mpc is very anisotropic (filaments, clusters..., the cosmic web).

If the sources resemble/follow the distribution of matter, anisotropy is expected even if we have less than one event per source!

Experimental status pre-Auger

AGASA → Ground Array Technique

HiRes → FluorescenceTechnique



HiRes Group: astro-ph/0703099

The Pierre Auger Observatory: the Hybrid era

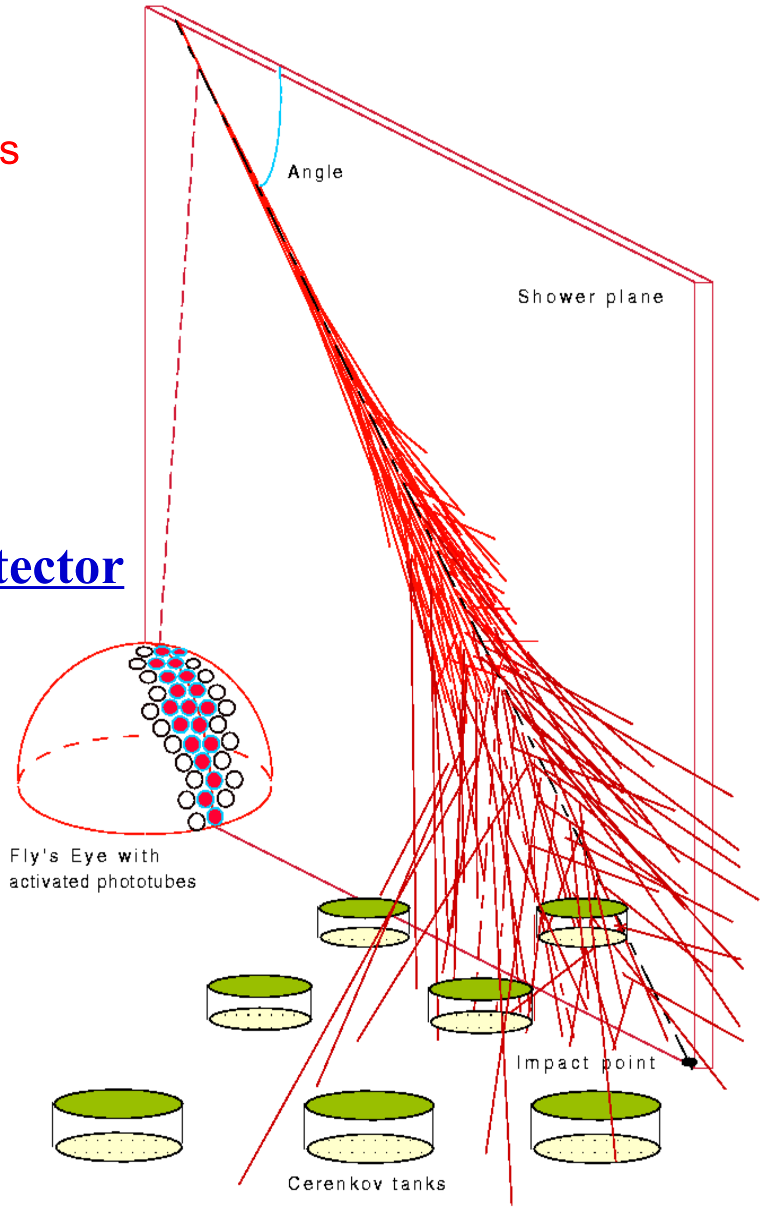
- **Energy range:** 10^{17} eV up to 10^{20} eV and beyond.
- **Exposure:** 3000 km^2 covered by a surface array and observed with Fluorescence telescopes.
- **Hybrid:** it combines the two detection techniques used by AGASA and HiRes.
- **Sensitive to the Chemical composition**: X_{max}, arrival time distributions of particles at ground...
- **Sensitive to Messengers**: large zenith angles can be used to search for neutrino fluxes.

The Auger hybrid detector concept

Cross-calibration,
improved resolution,
control of systematic errors

300-400 nm light from de-excitation of atmospheric nitrogen (fluorescence light) ≈ 4 γ's / m /electron

10^{19} eV ⟶ 10^{10} e



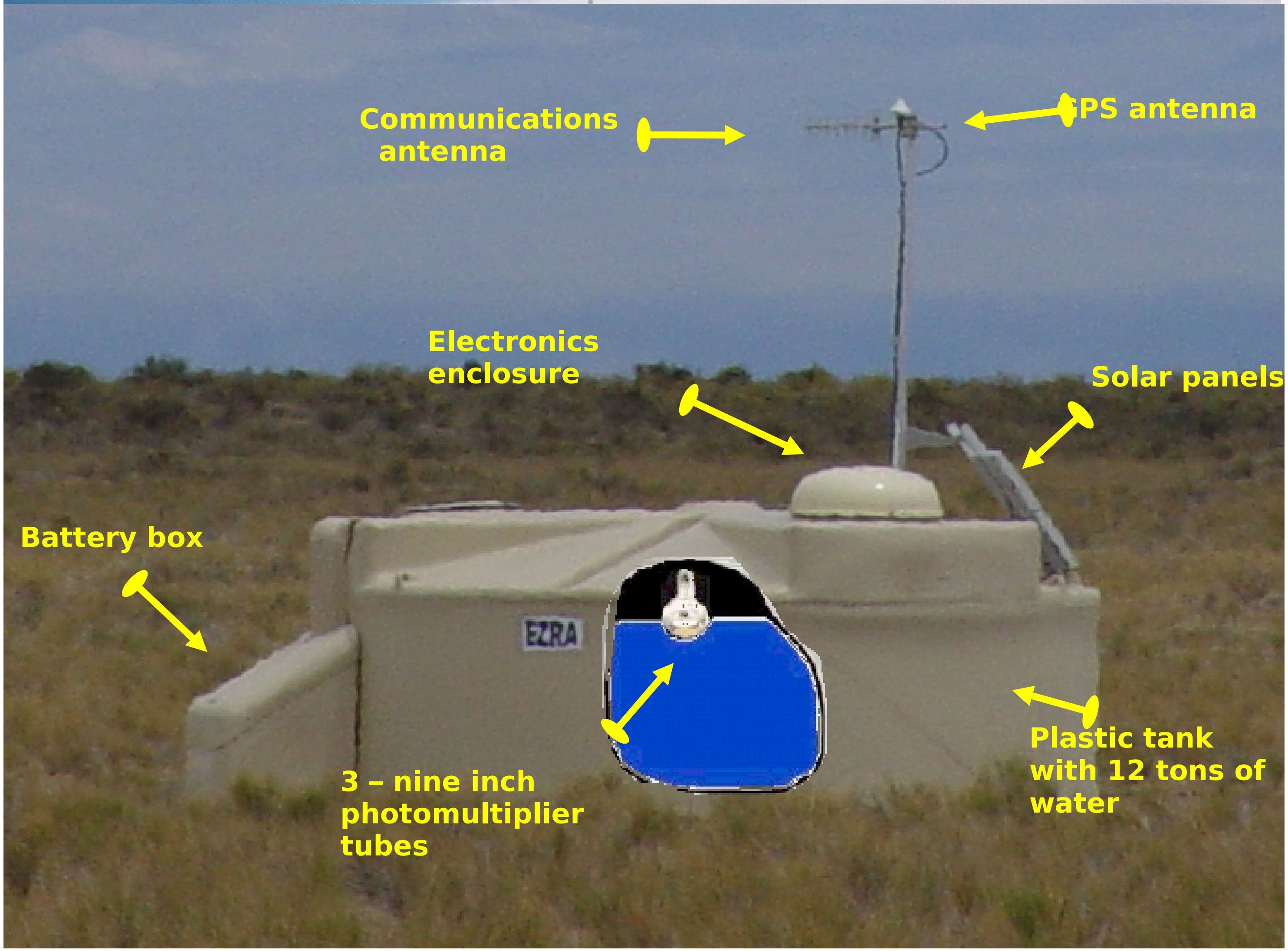
Fluorescence Detector

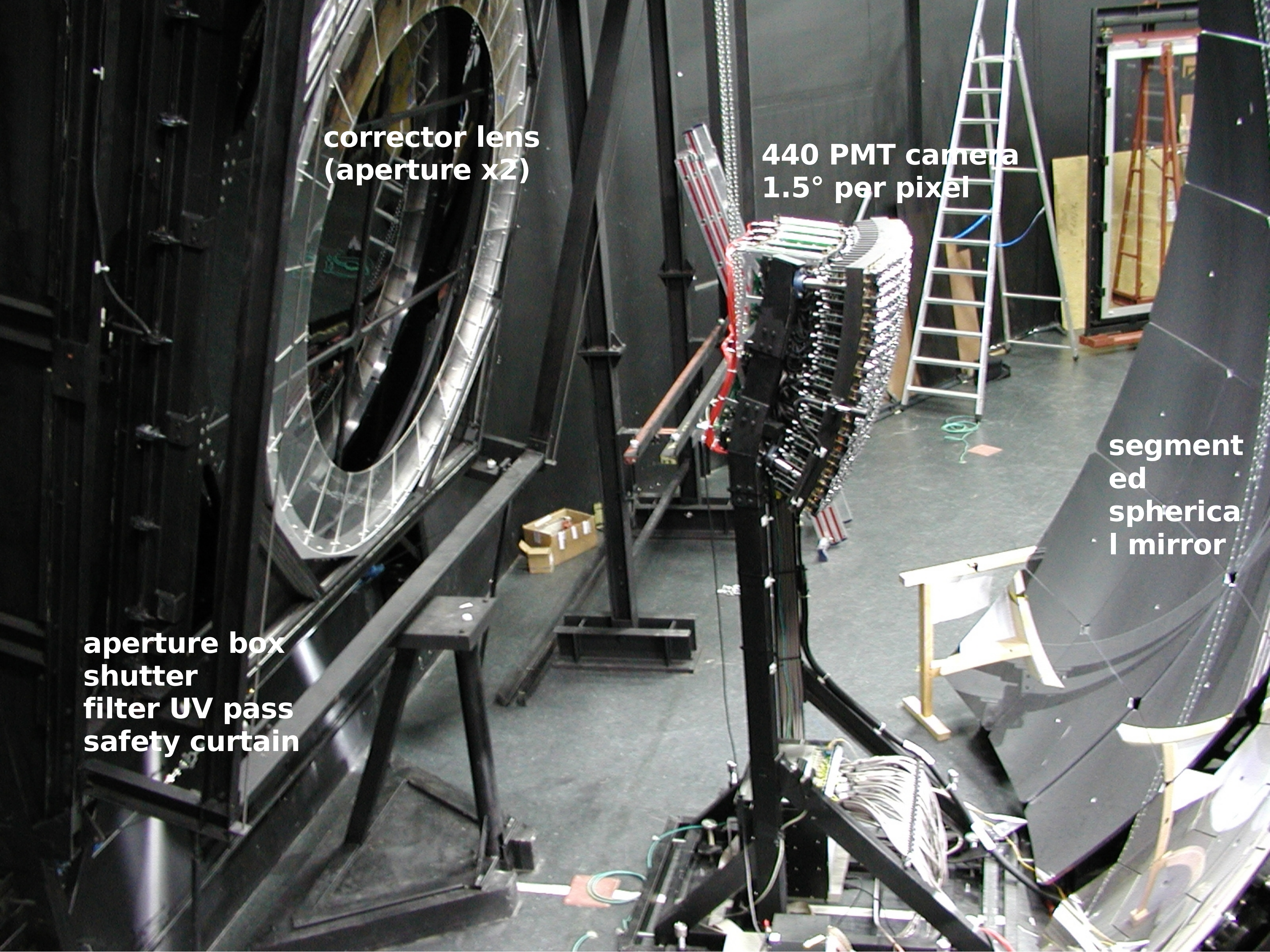
- E + longitudinal development
- Time ≈ direction
- ≈ 10% duty cycle

Surface Detector

- Shower size ≈ E
- Time ≈ direction
- 100% duty cycle

The Surface Detectors

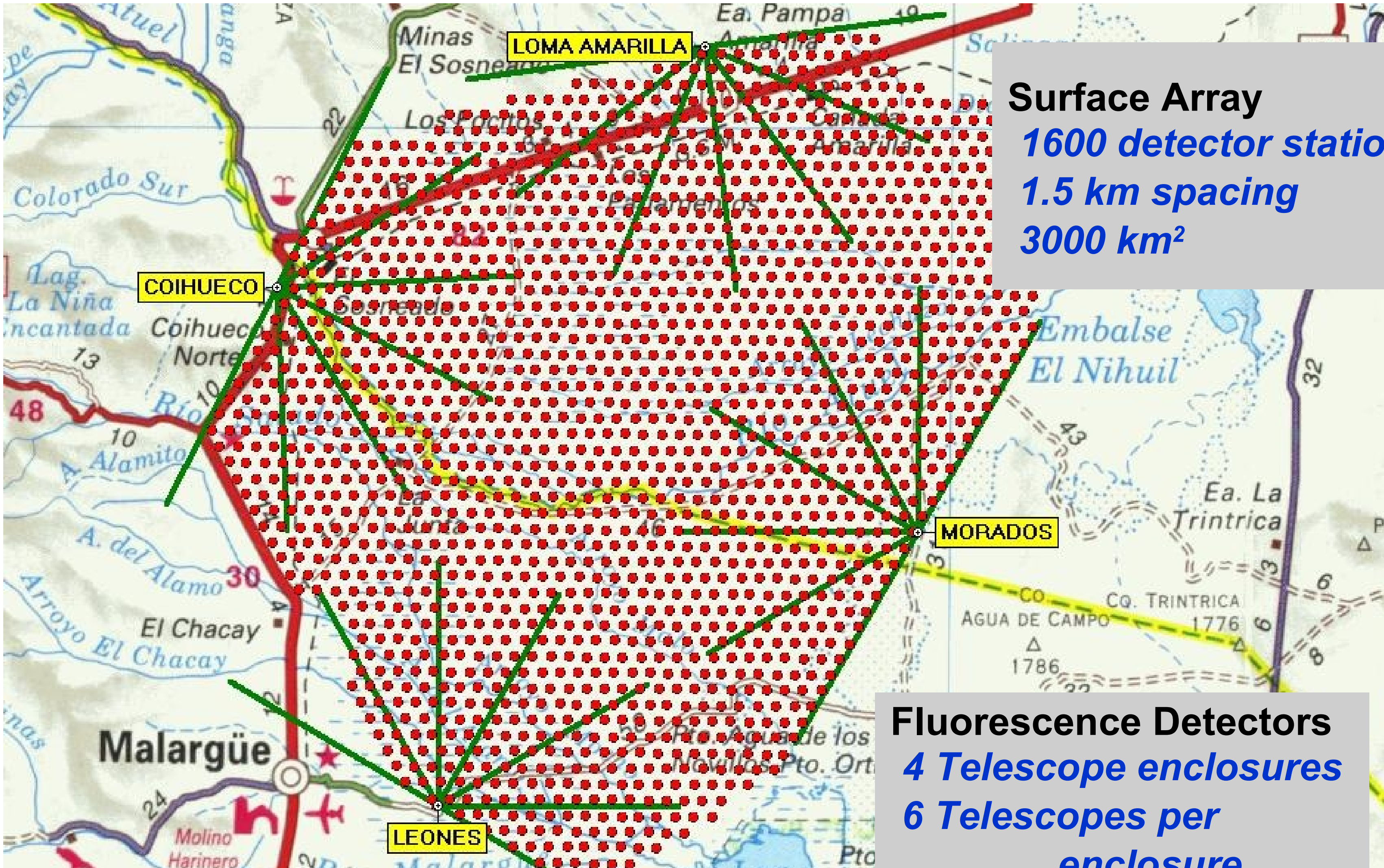



corrector lens
(aperture x2)
440 PMT camera
1.5° per pixel
segment
ed
spherica
l mirror
aperture box
shutter
filter UV pass
safety curtain

Three tanks aligned in the middle of the Pampa

Tank with antenna pointing to one of the communication towers.

The Observatory Plan



Surface Array

- *1600 detector stations*
- *1.5 km spacing*
- *3000 km²*

Fluorescence Detectors

- *4 Telescope enclosures*
- *6 Telescopes per enclosure*
- *24 Telescopes total*

Status of Construction

1438 deployed
1400 filled
1364 taking data

090707 ~ 85%

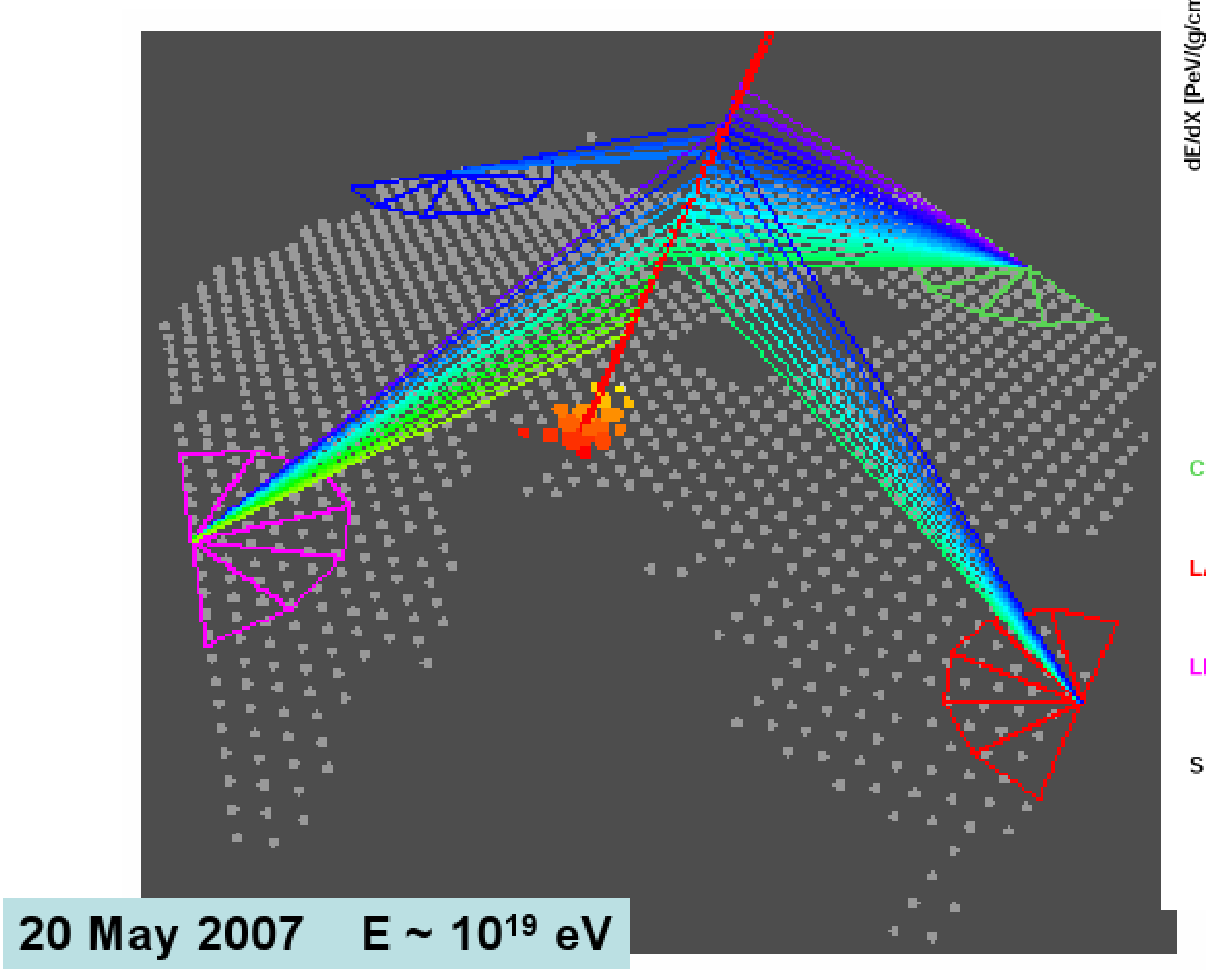
All 4 fluorescence buildings complete, each with 6 telescopes

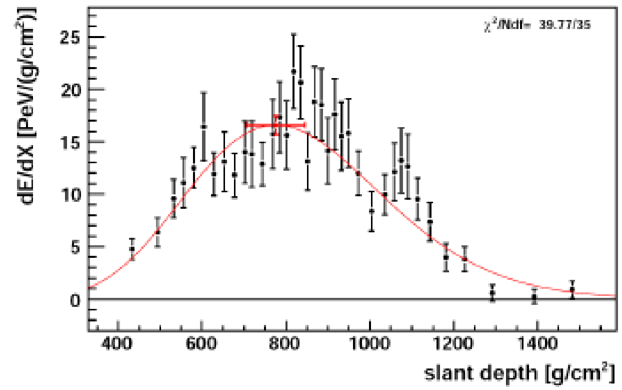
1st 4-fold on 20 May 2007

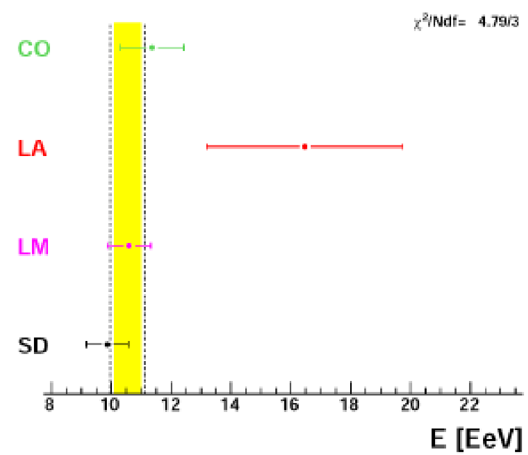
AIM: 1600 tanks

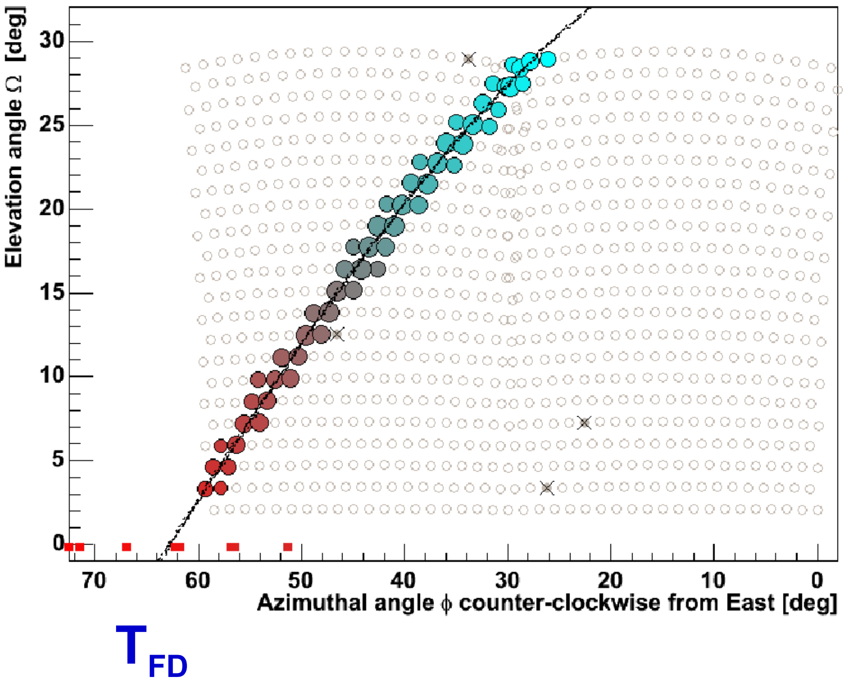
The first four-fold hybrid event

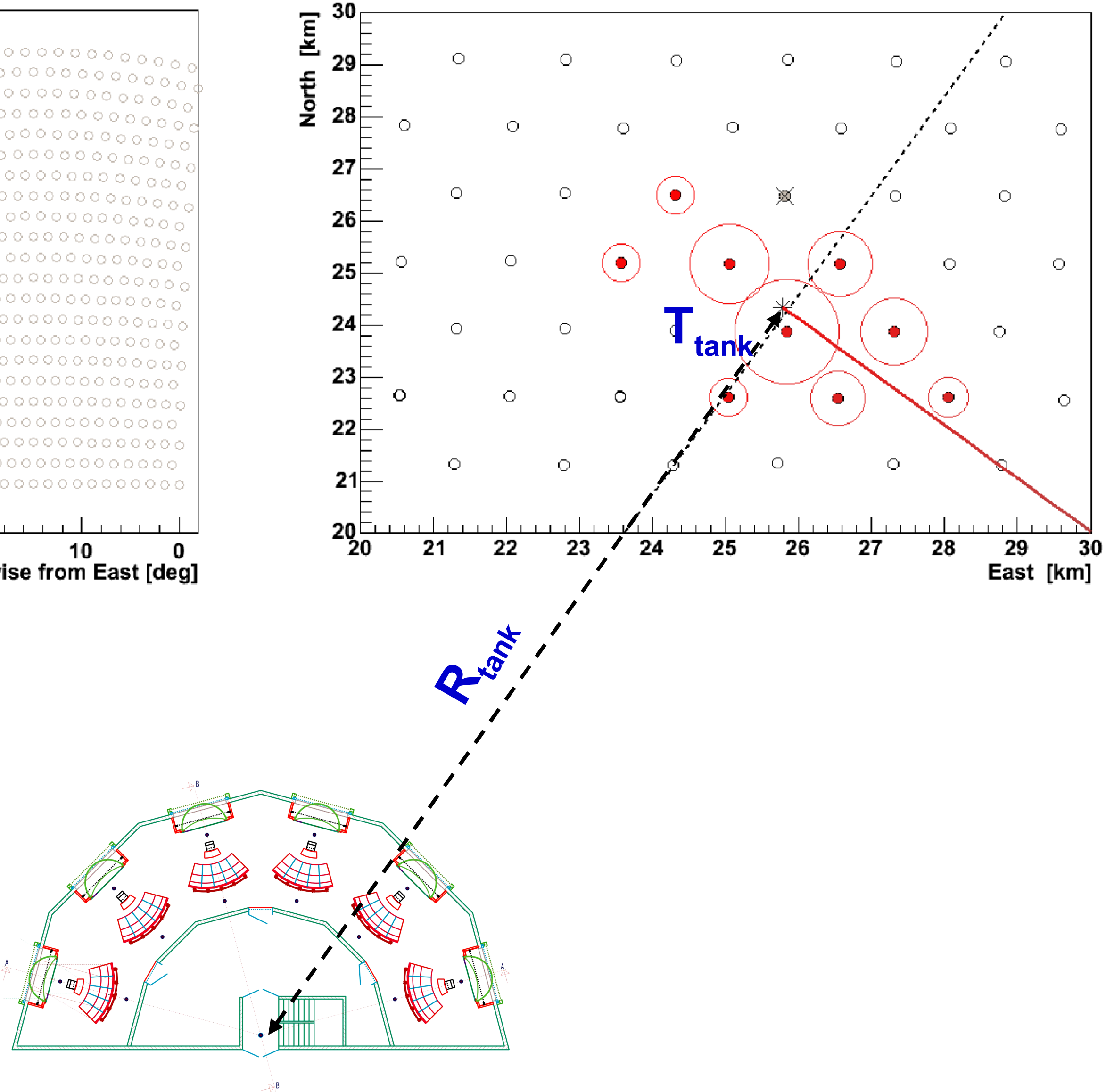
$E = 10^{19}$ eV, zenith angle 66°



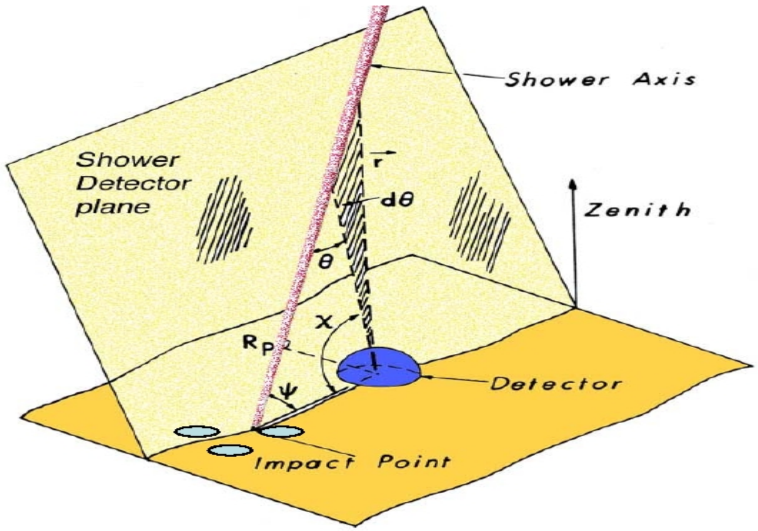




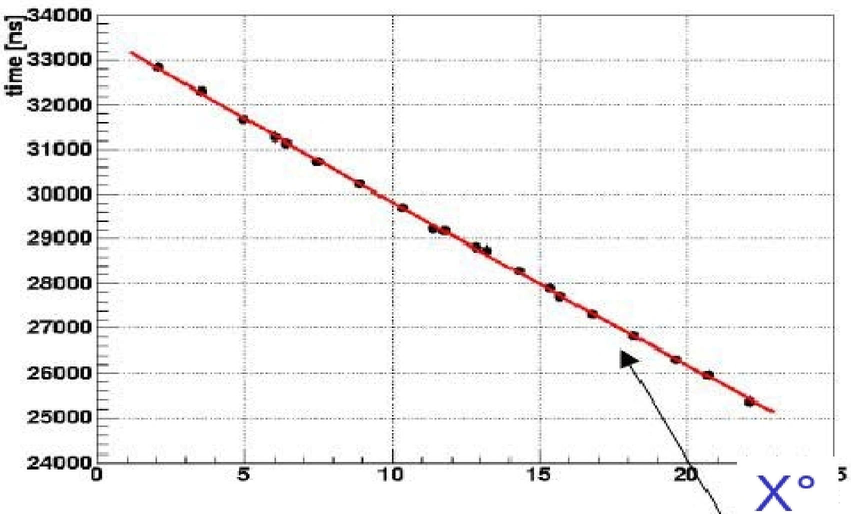


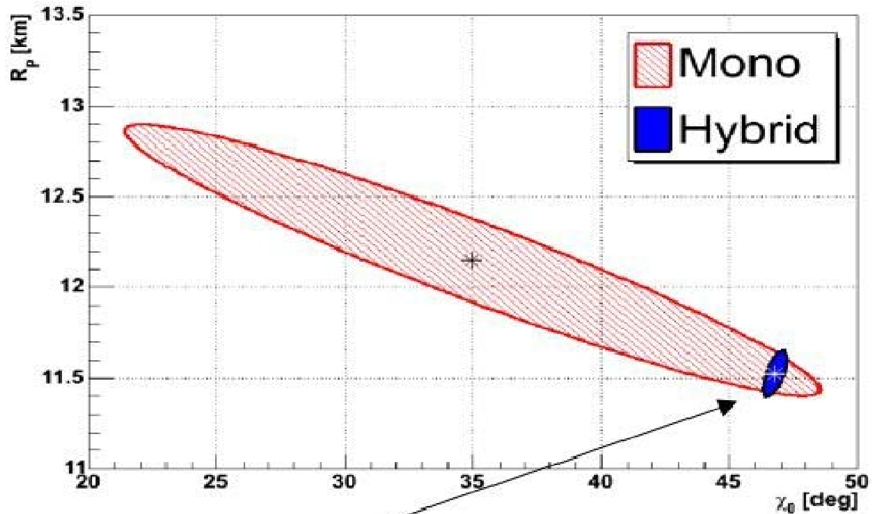


$$T_{tank} + R_{tank} / c \approx T_{FD}$$



Hybrid is necessary: a mono reconstruction is affected by large errors in axis determination!





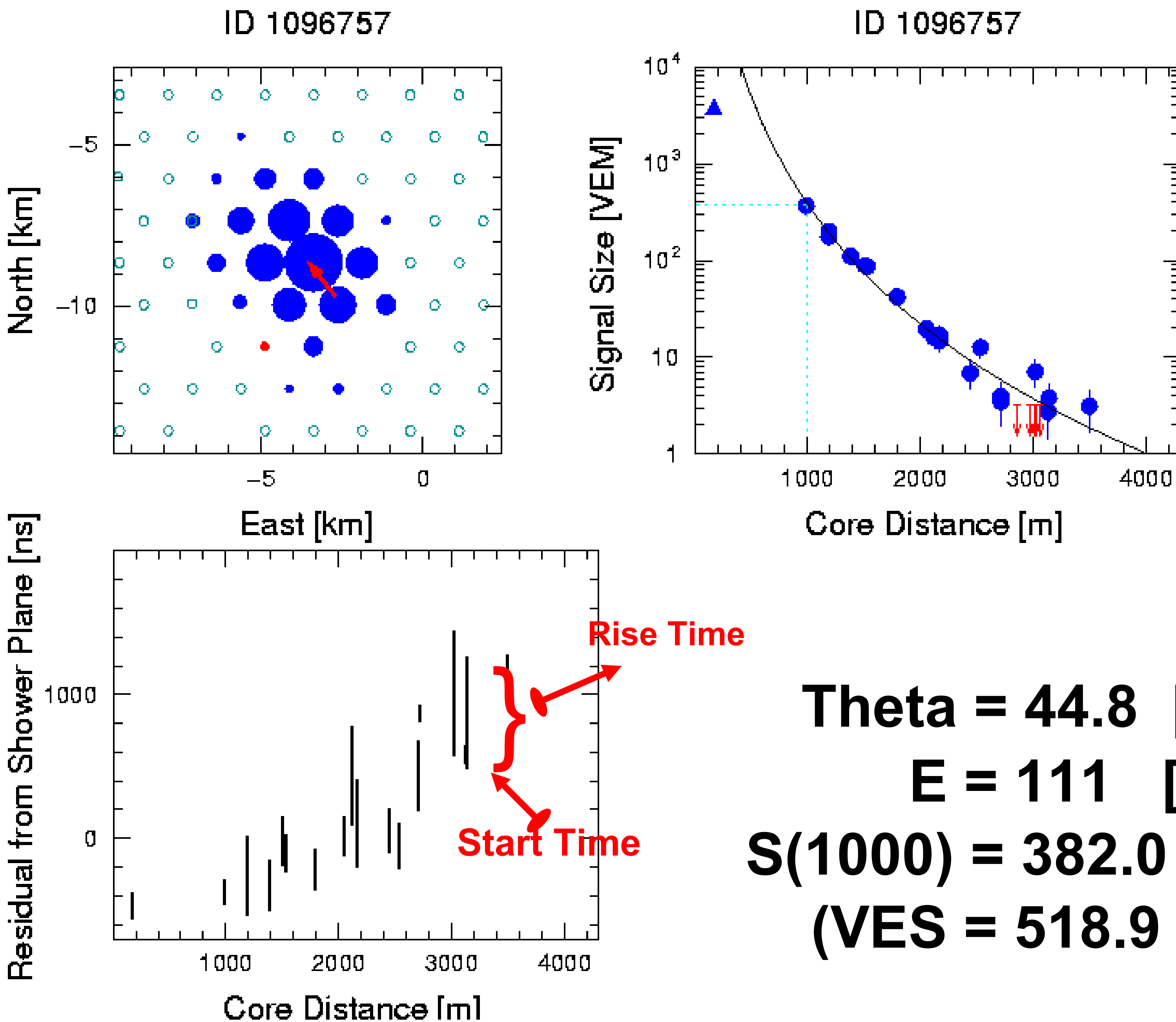
$\approx$ line but

3 free parameters

T_0 from tank!

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

SD high energy event



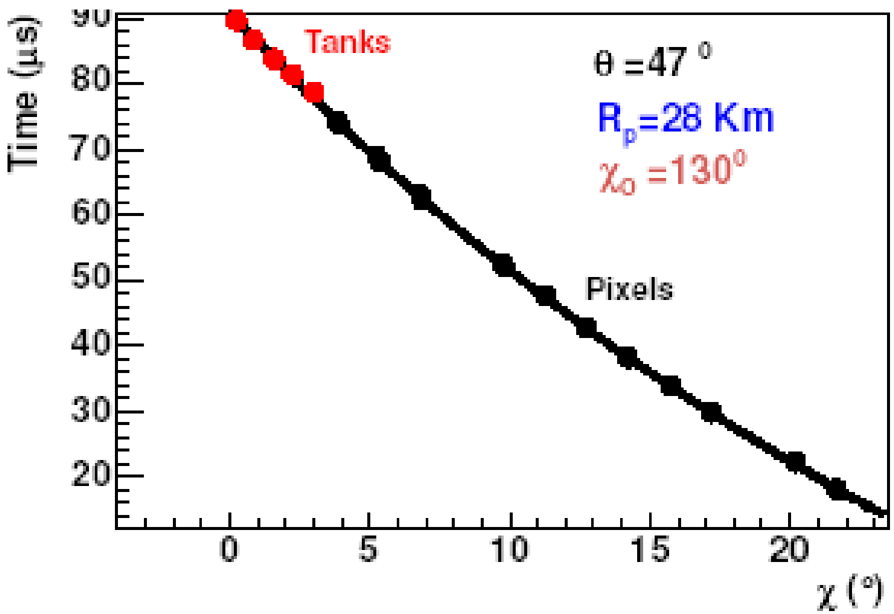
Theta = 44.8 [degree]

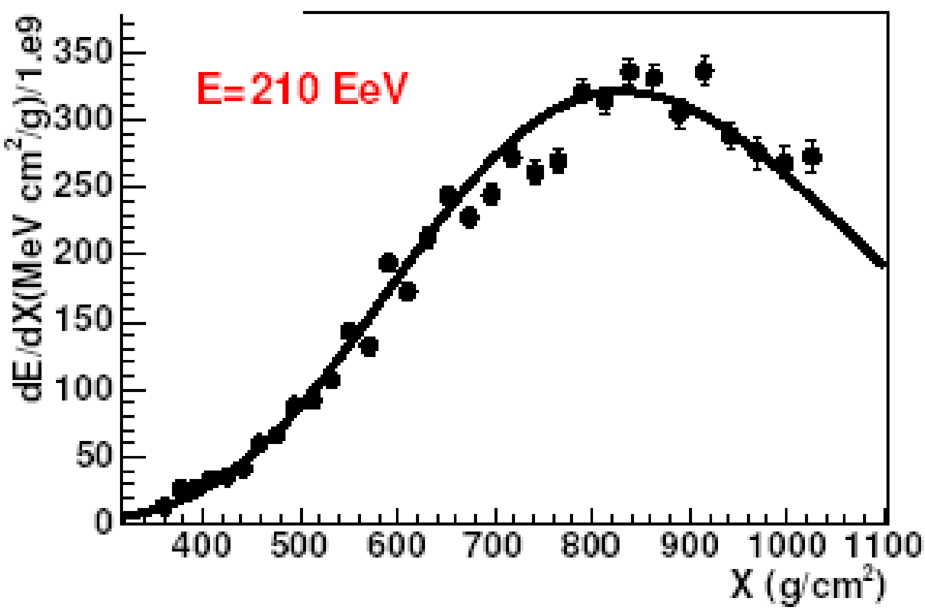
E = 111 [EeV]

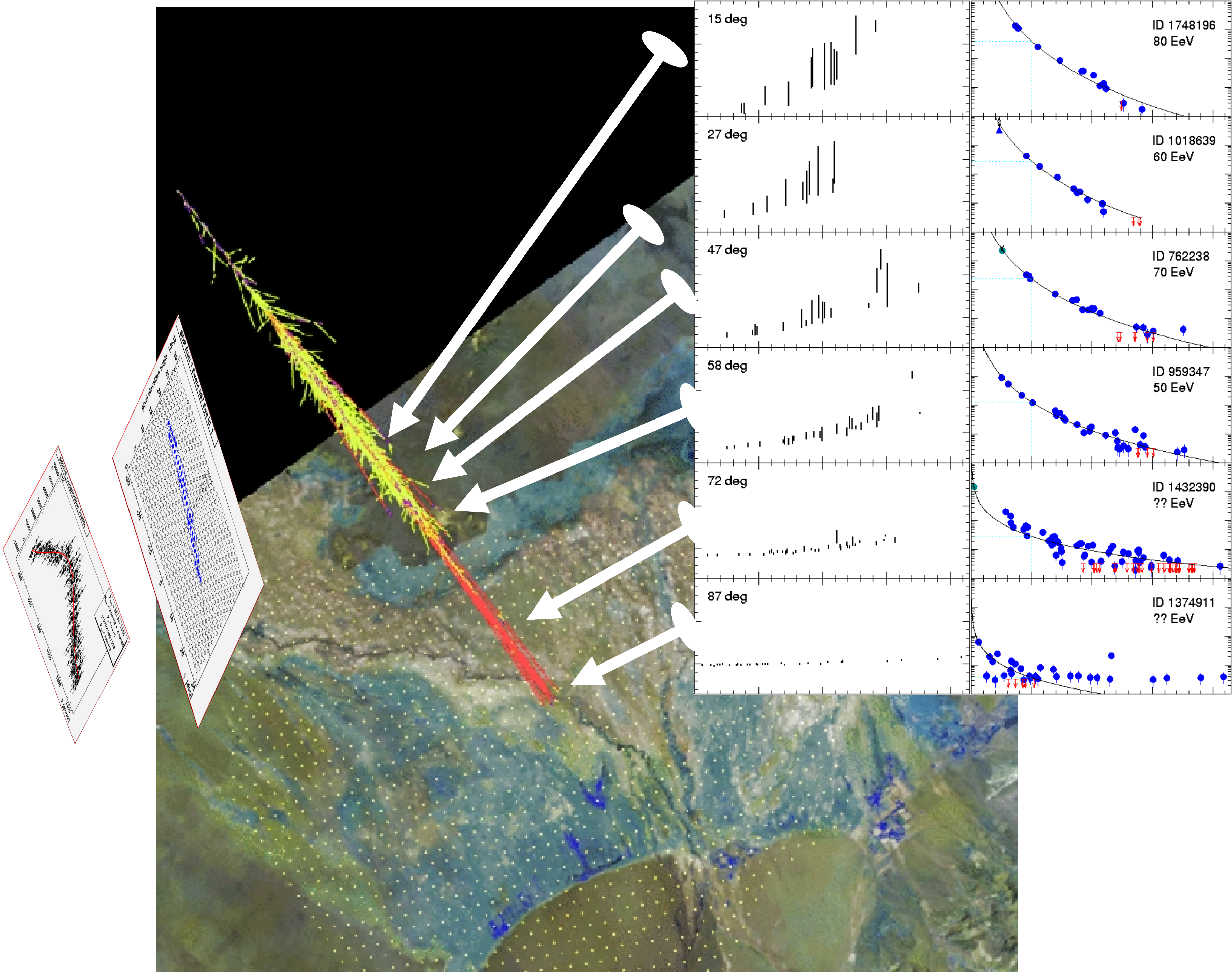
S(1000) = 382.0 [VEM]

(VES = 518.9 [VEM])

FD high energy event







15 deg
27 deg
47 deg
58 deg
72 deg
87 deg
ID 1748196
80 EeV
ID 1018639
60 EeV
ID 762238
70 EeV
ID 959347
50 EeV
ID 1432390
?? EeV
ID 1374911
?? EeV

Energy scale Pre-Hybrid

Fluorescence experiments

- Air as an electromagnetic-hadronic calorimeter medium: 25 radiation lengths, 15 interaction lengths
- UHE cosmic ray : high energy secondary hadrons interaction vs decay very good hadronic calorimeter "e/h" → 1 (only 10% of energy not in e.m. cascade)

$$N^{p.e.} = \sum_{\lambda} N_{\gamma}(\lambda)\ A'\ \varepsilon(\lambda)\ T(\lambda)$$

Fluorescence yield | Geometry | Detector | Atmosphere

FD Systematic uncertainties

Goal: go close to 10%
Currently: 22%

Ground array experiments

- S(1000) to energy converter
- EM part depend on the position of the Xmax
- Muonic part depend on the mass composition and hadronic models

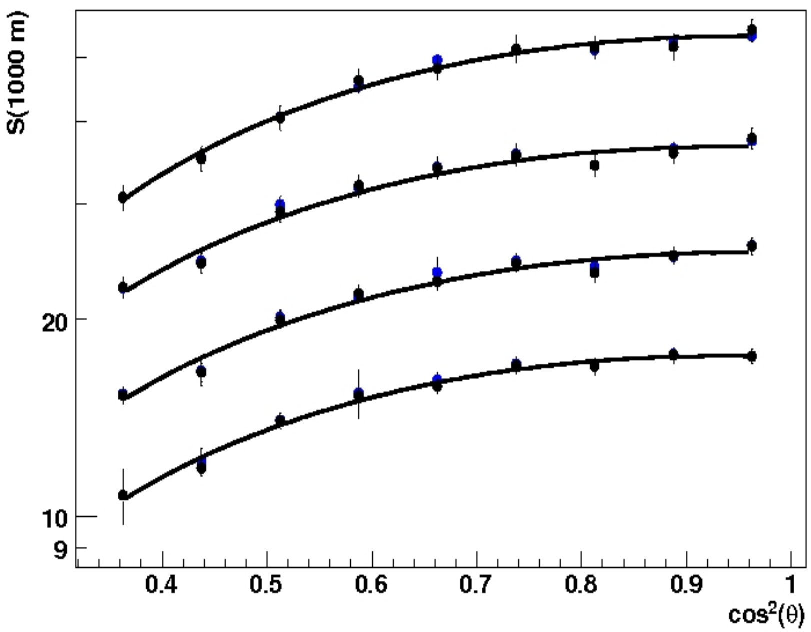
SD Systematic uncertainties

Unknown: hadronic interactions at very high energies

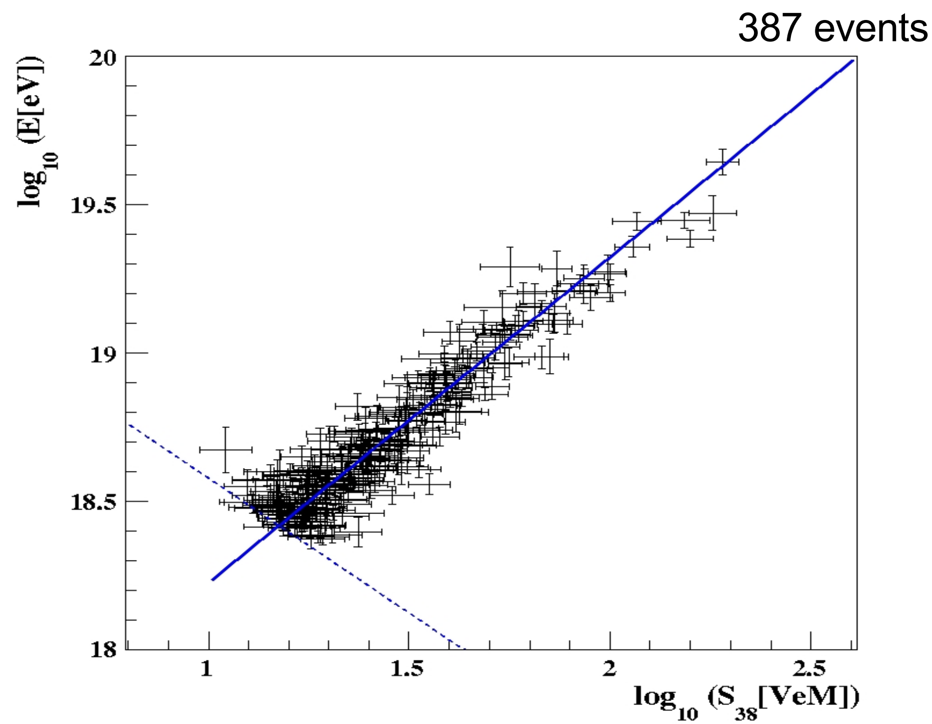
Setting the Energy Scale: Hybrid approach

Use the 10% of events with FD measurements to calibrate all the SD events.

Attenuation Curve



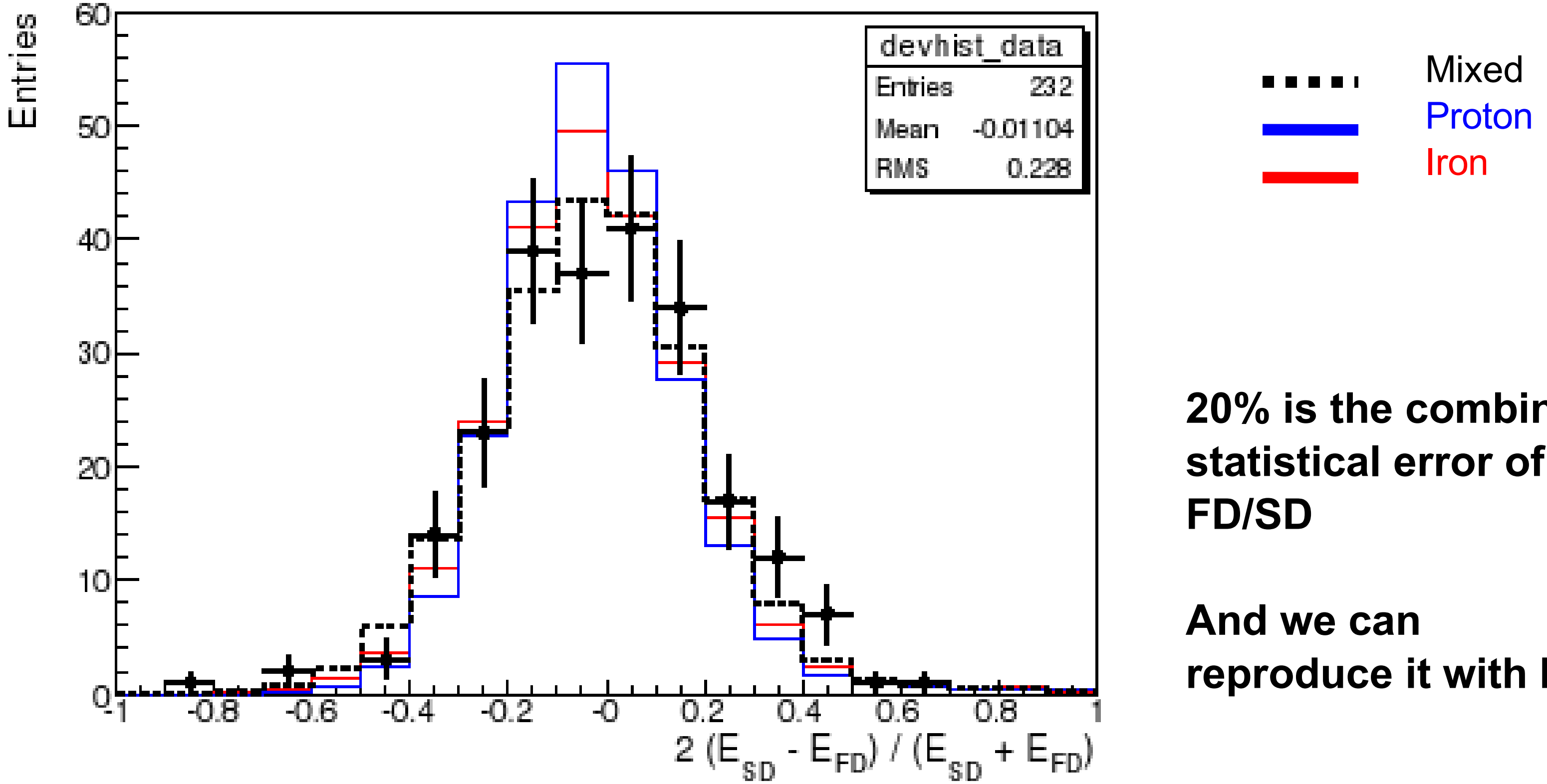
Calibration Curve



$$S(1000,\ ) \rightarrow S(1000,\ =38^0)$$

$$S(1000,\ =38^0) \rightarrow Energy$$

Statistical errors



20% is the combined statistical error of FD/SD

And we can reproduce it with MC.

Systematic errors

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%

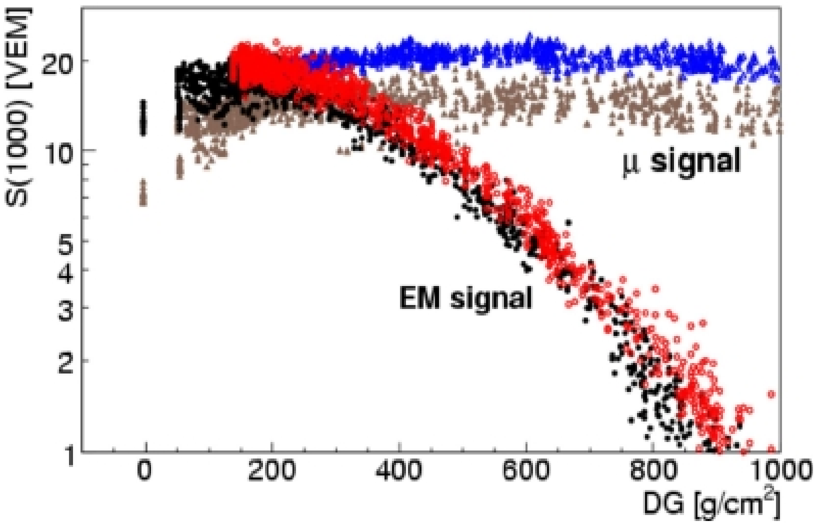
Note: Activity on several fronts to reduce these uncertainties

They are not energy dependent!

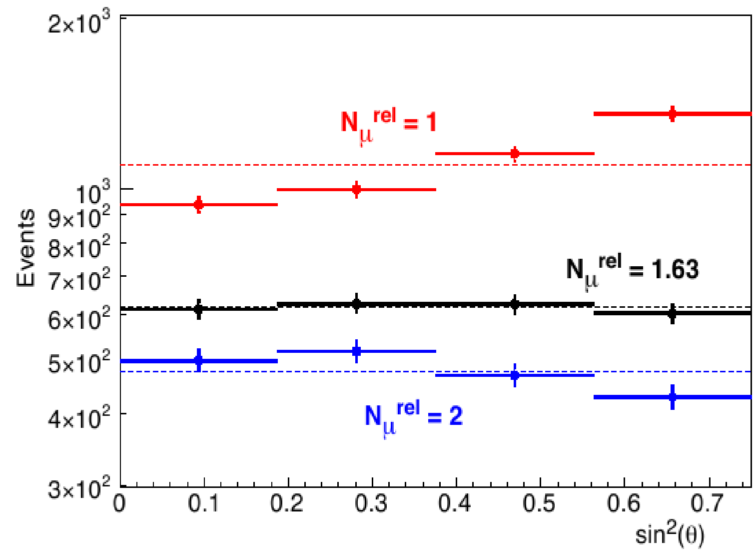
Checking the Energy Scale: SD+Shower universality

F. Schmidt research project

Model independent parameterization of Ground signals

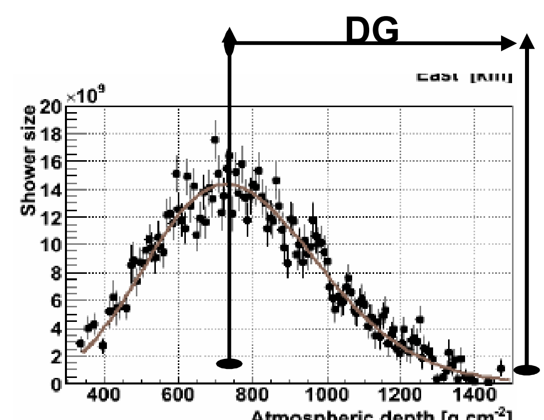


Constant Number of events for equal exposure bins



$$S(1000) = S_{EM} + N_\mu(E) S_\mu(\text{proton}, 10^{19}\,\text{eV})$$

Only possible if we know the average X_{max} as a function of energy!!



Comparison of the two methods

At a reference energy of 10^{19} eV

SD+Shower Universality

$S(1000,\Theta=38) = 37.5 \pm 1.7$ (stat) ± 2.0 (sys)

Hybrid

$S(1000,\Theta=38) = 50.0 \pm 3$ (stat) ± 11 (sys)

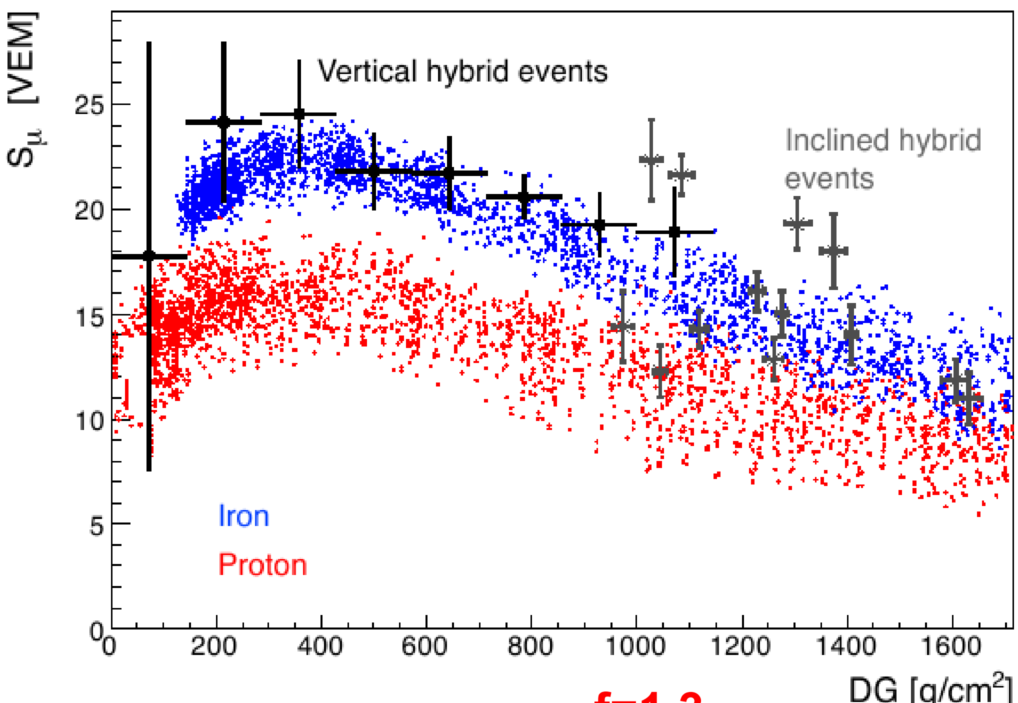
They do differ by 30%

Cross checks with Hybrid Events

$E_{event} = f \times E_{FD}$
Θ
X_{max}
S(1000)

Observables

f=1 FD scale
f=1.3 SD scale



f=1.3

S_{EM} can be predicted from the observables and substracted out to the measured S(1000) .

Summary on the checks of the energy scale

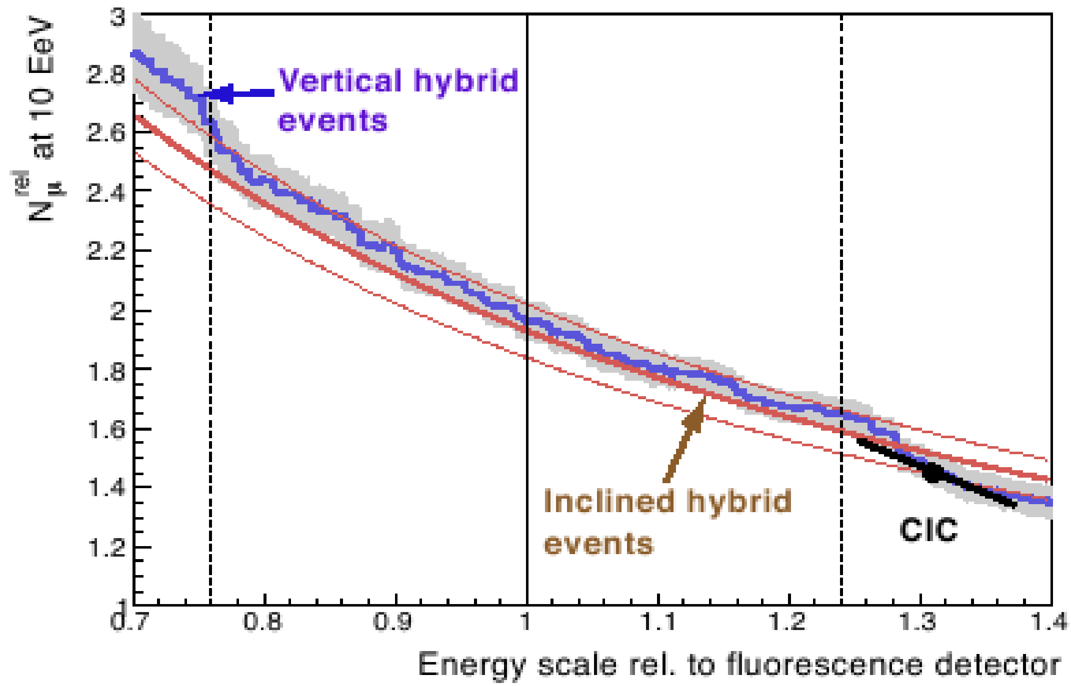
The Hybrid method has been adopted because:

•Relies on experimental values.

•Calibration over a wide enery range.

The systematics of the Hybrid method will shrink with new measurements of the Fluorecence Yield (better than 10%)

If we adopt the Hybrid energy scale we would predict a factor of two more muons.



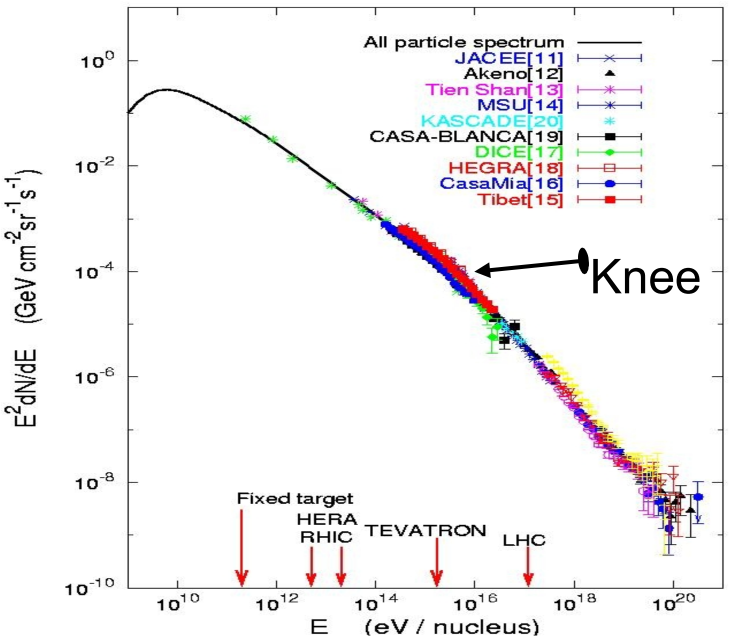
Model Prediction

And we learn something new: PAO a Particle Physics laboratory

We predict at least 40% more muons than in the models.

Very difficult to reproduce by current hadronic models, unless the (anti)baryon production in the interactions is increased by a factor of 10.

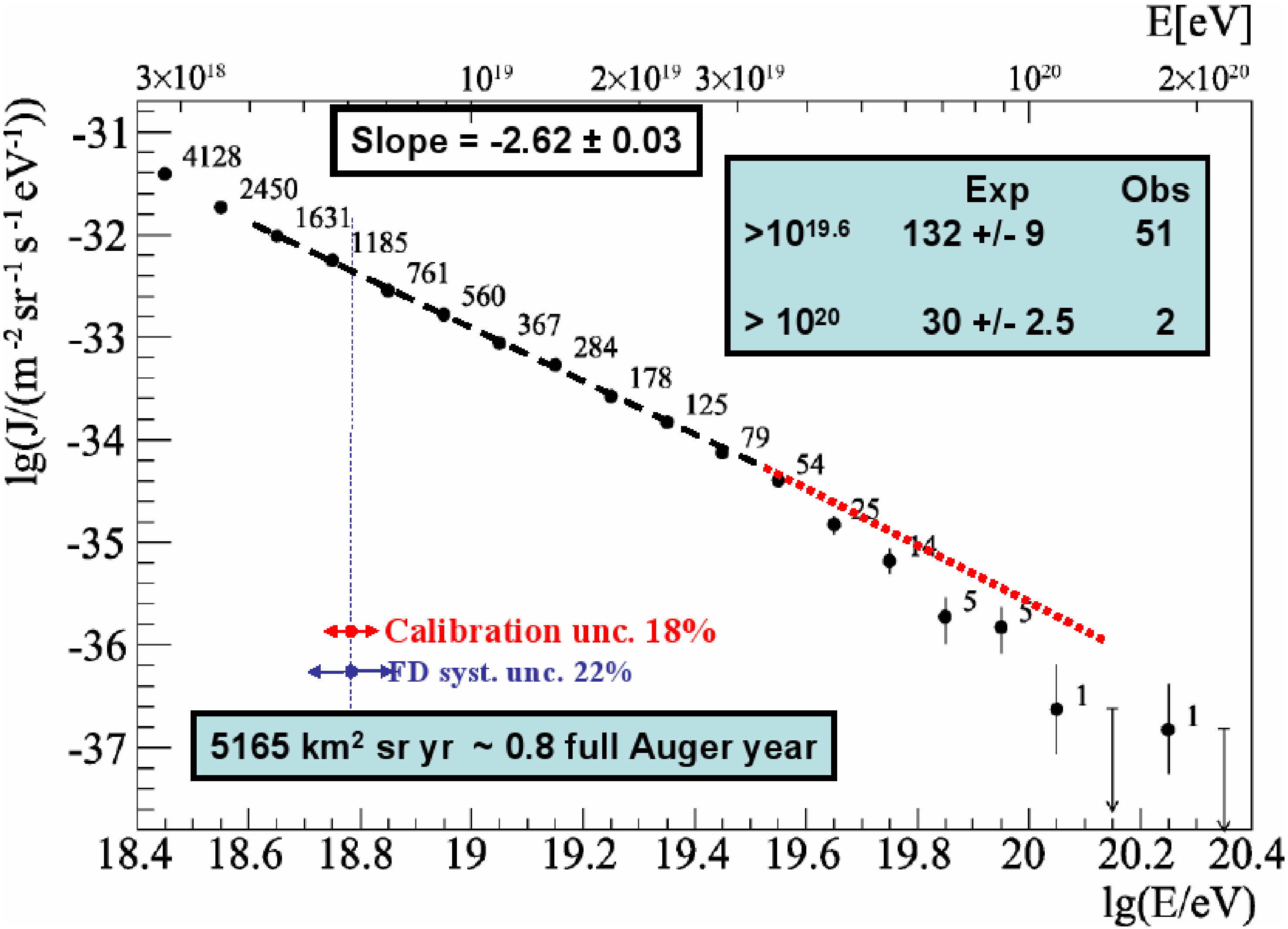
That was done and even though it is quite likely that that's not the answer.



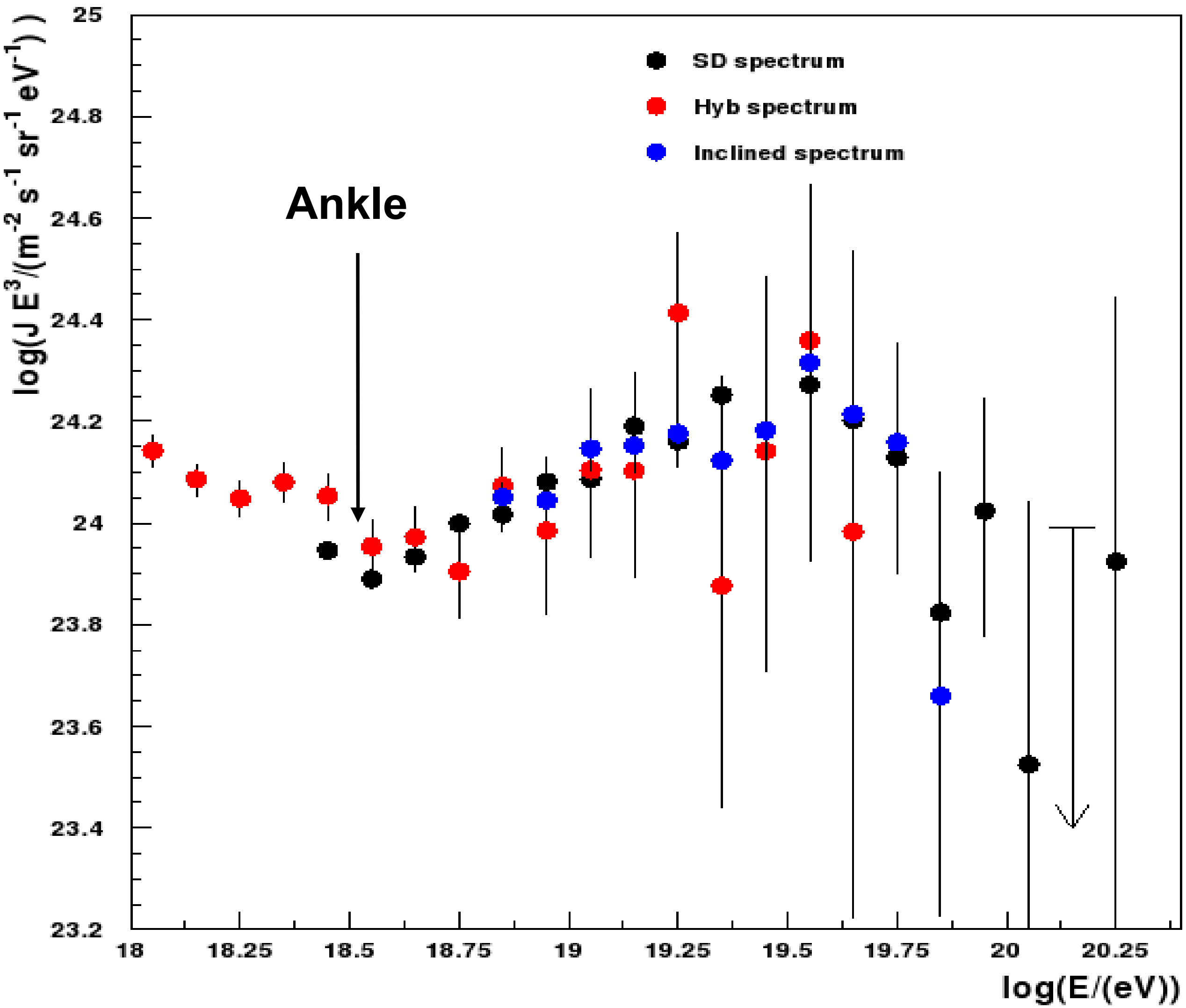
LHCf and Totem will help!

Finally the SD spectrum!

There is a clear flux suppression above $10^{19.6}$ eV



Comparison between different spectrums



$\Theta < 60^0$

$\Theta > 60^0$

Hybrid

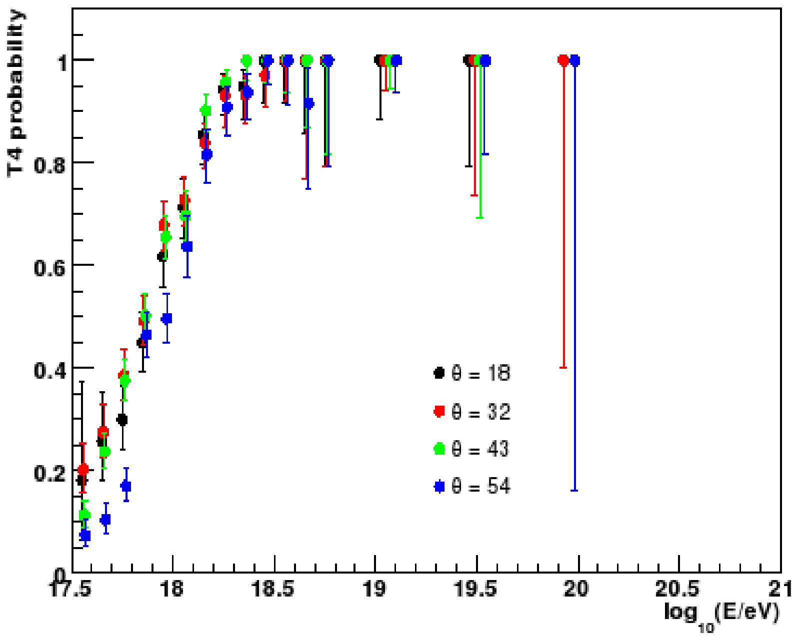
Very good agreement!

Clear change of slope at low energies, and very abrupt!

Each spectrum has different systematics

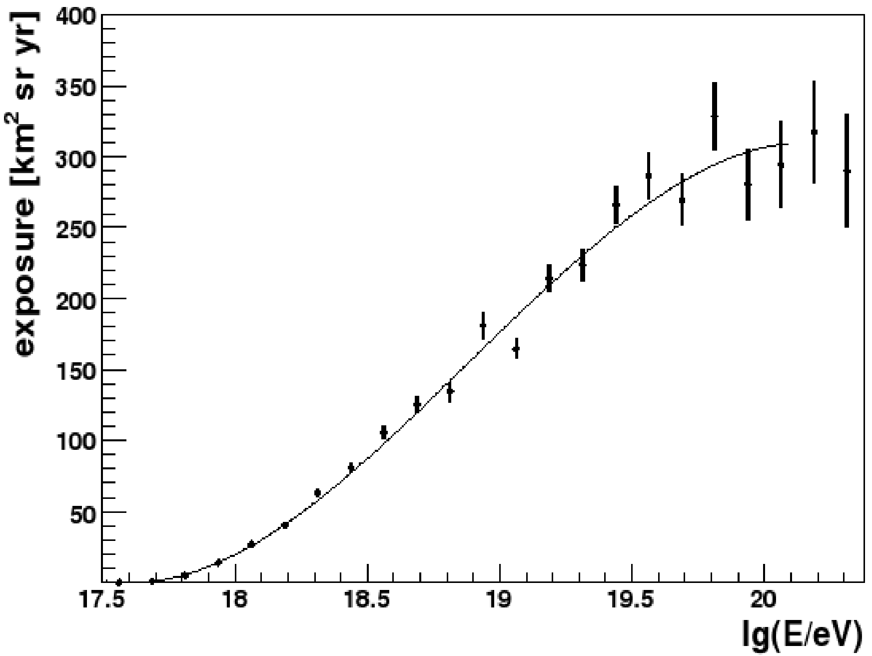
SD exposure

Simple to calculate, saturates at 4 EeV and it can be cross checked with the data.



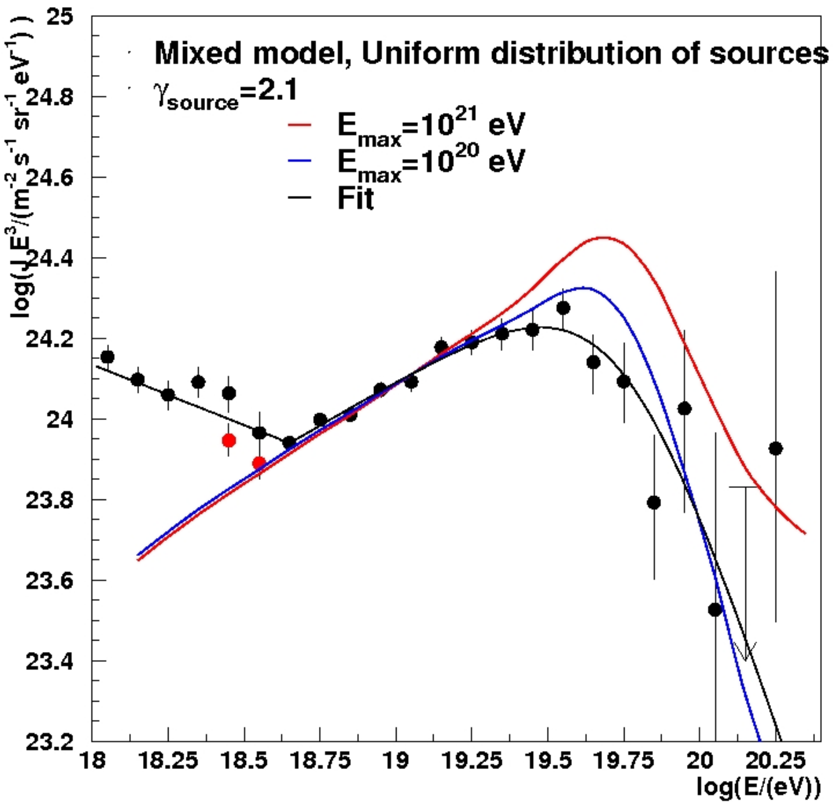
Hybrid exposure

Requires complicated MCs, depends on atmospheric conditions..



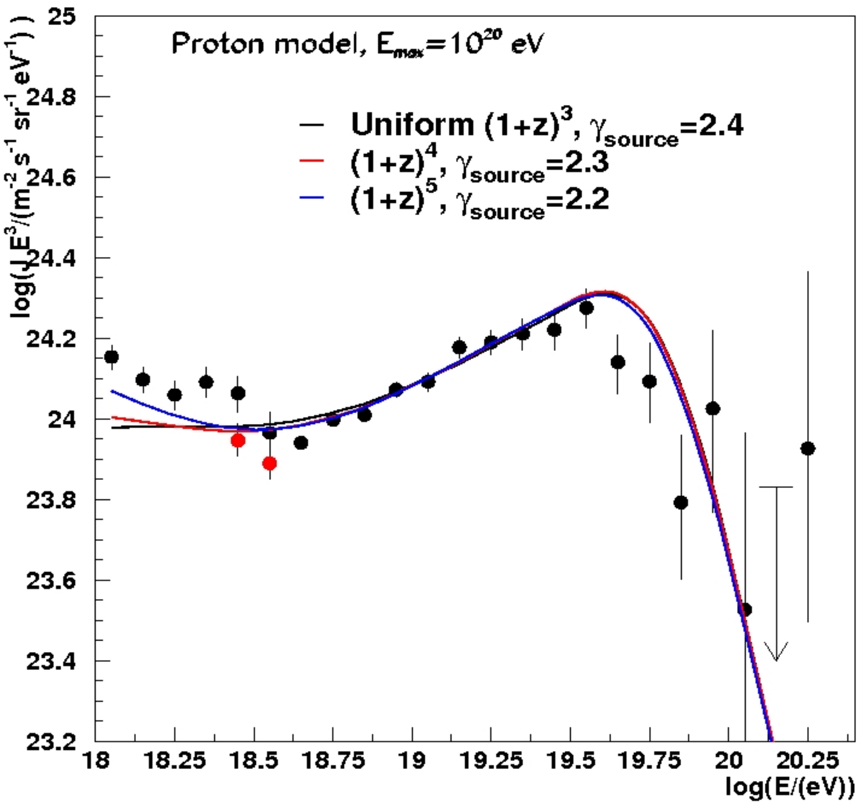
Comparison with Astrophysical Models

Mixed Models



Ankle: transition from Galactic to Extragalactic component

Proton Models

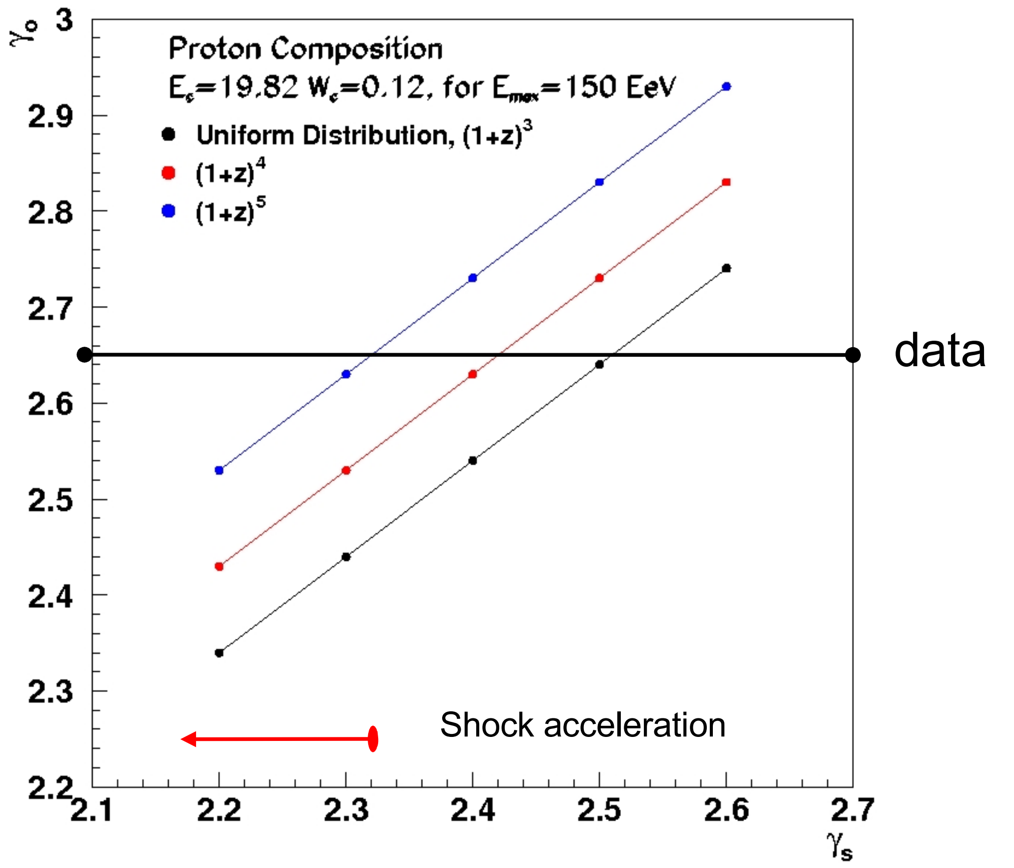


Ankle: pair production dip.

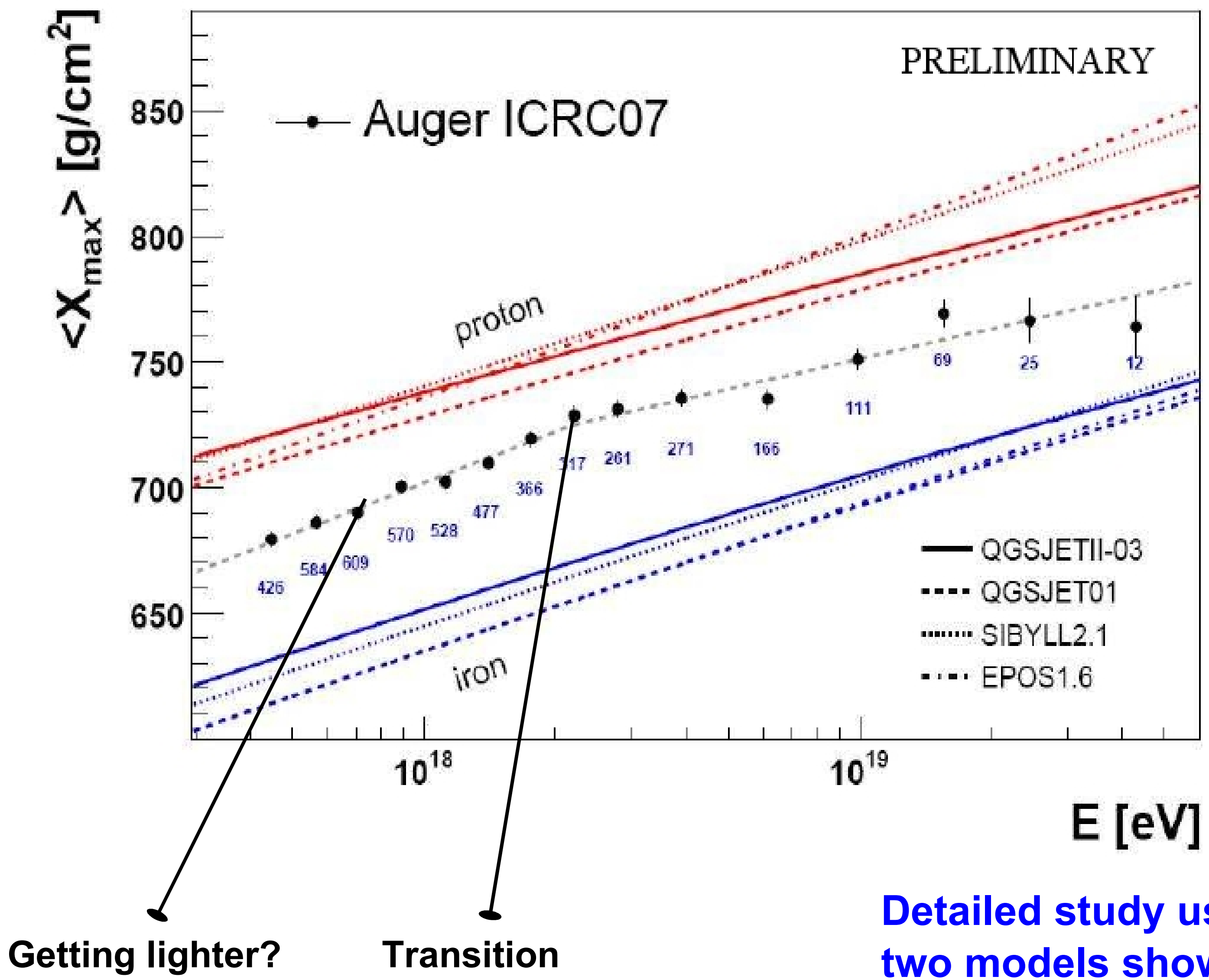
What can we learn from the spectrum?

There is a one-to-one mapping between the injection slope and the observed slope, given a source evolution $(1+z)^n$

Constrains on the cosmological source evolution?

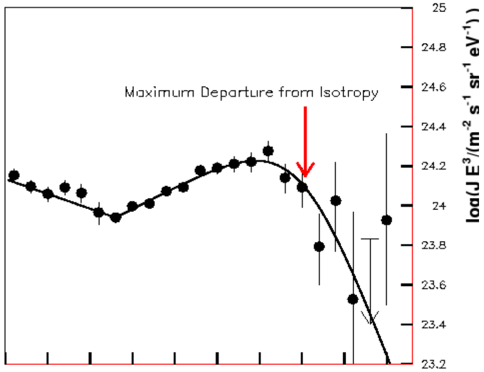


Mass Composition studies (I)



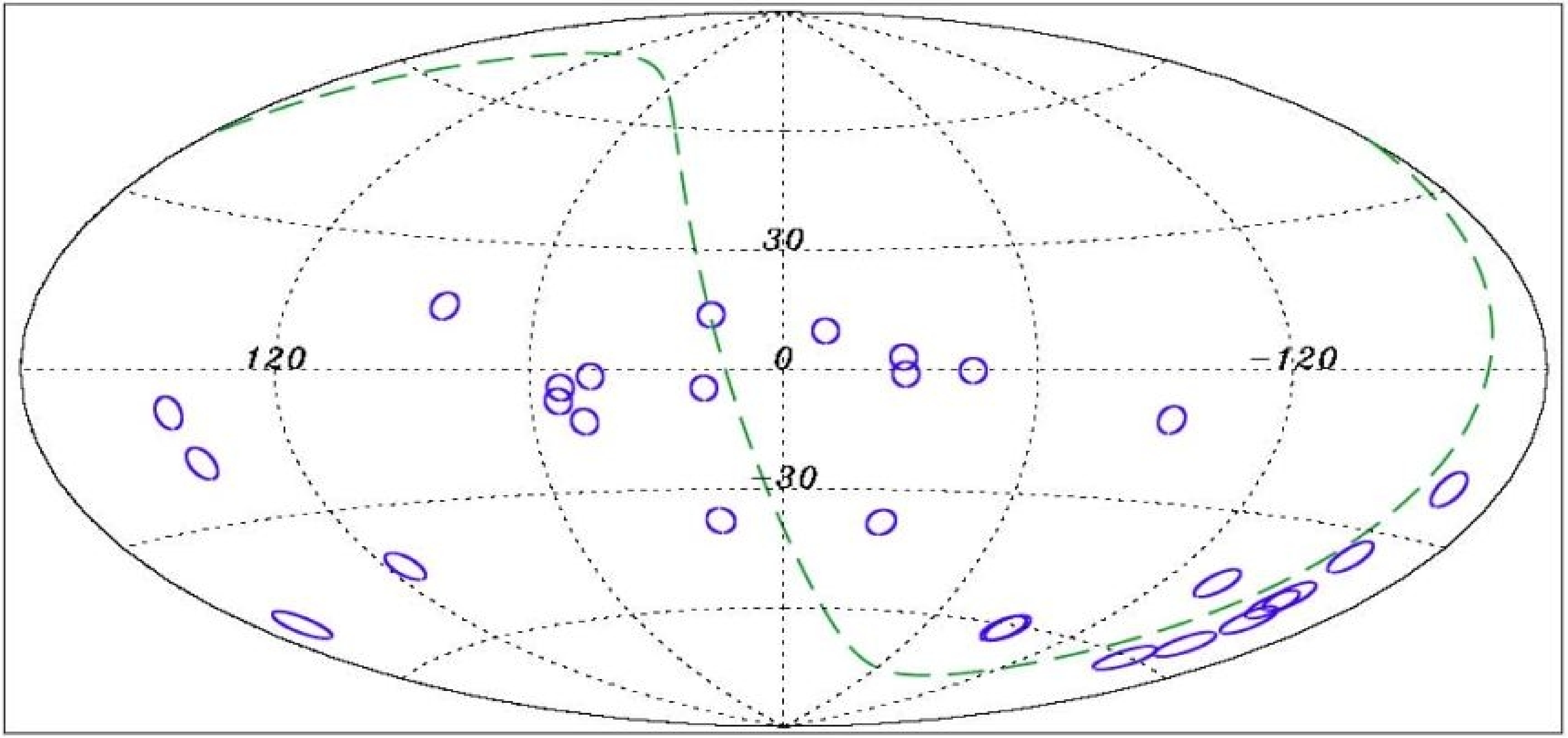
Detailed study using the two models shown before is underway.

What about our arrival directions?

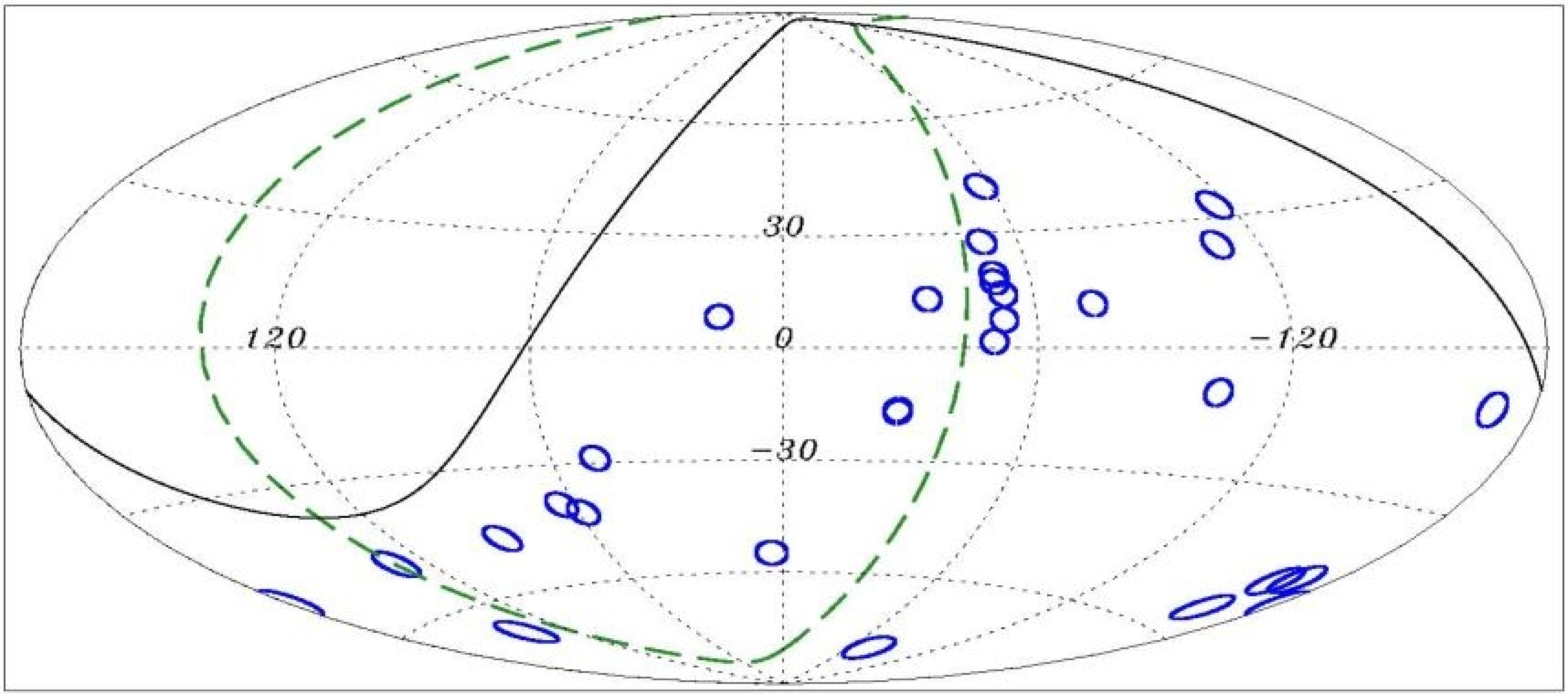


28 highest energy events

Equatorial coordinates



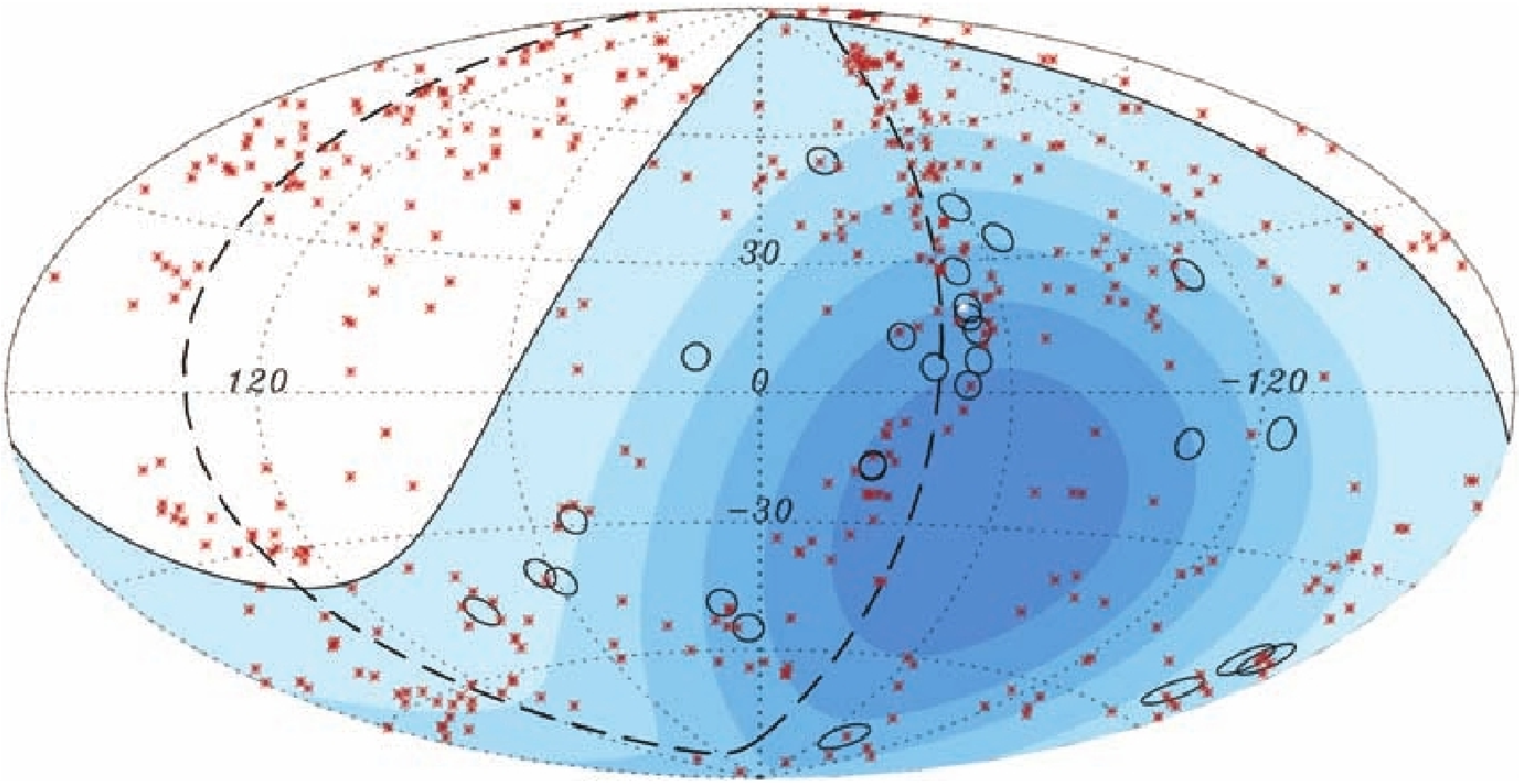
Galactic coordinates



Moreover there is a correlation with nearby matter distribution...

Correlations with AGNs in VC catalague
•Angular scale: 3 degrees
•AGN distance cut: 75 Mpc
•Energy threshold: 57 EeV
Significance after a prescription: 1.7×10^{-3}
Raw significance of a statistical test: 10^{-5} (scan over tests?)

This implies that the flux suppression is due to interactions of UHECRs with background photon fields!!



Conclusions

- It might be possible to find the sources of UHECRs, and some surprises?
- IF the anisotropy results imply proton dominated composition: Cosmic Ray Experiments as a particle physics Lab?