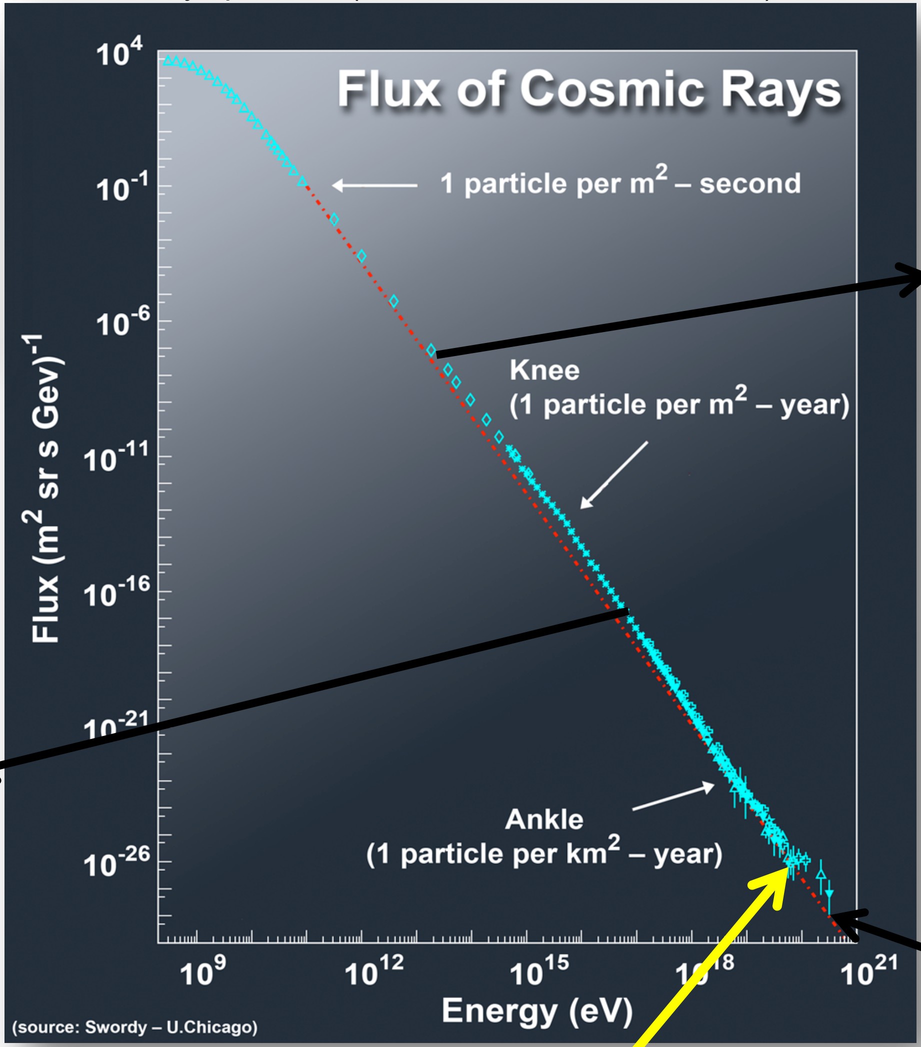
The Pierre Auger Observatory: review of latest results and perspectives

Dariusz Gora
IFJ PAN, Kraków, Poland

Cosmic rays (CRs) – high-energy particles coming from space (protons, nuclei, neutrinos, photons, electrons,…)

Sun

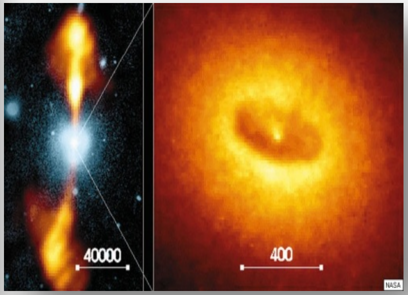
Cosmic ray spectrum (credit: HAP / A. Chantelauze)



Supernovae, pulsars

Radio galaxies, galaxy mergers,

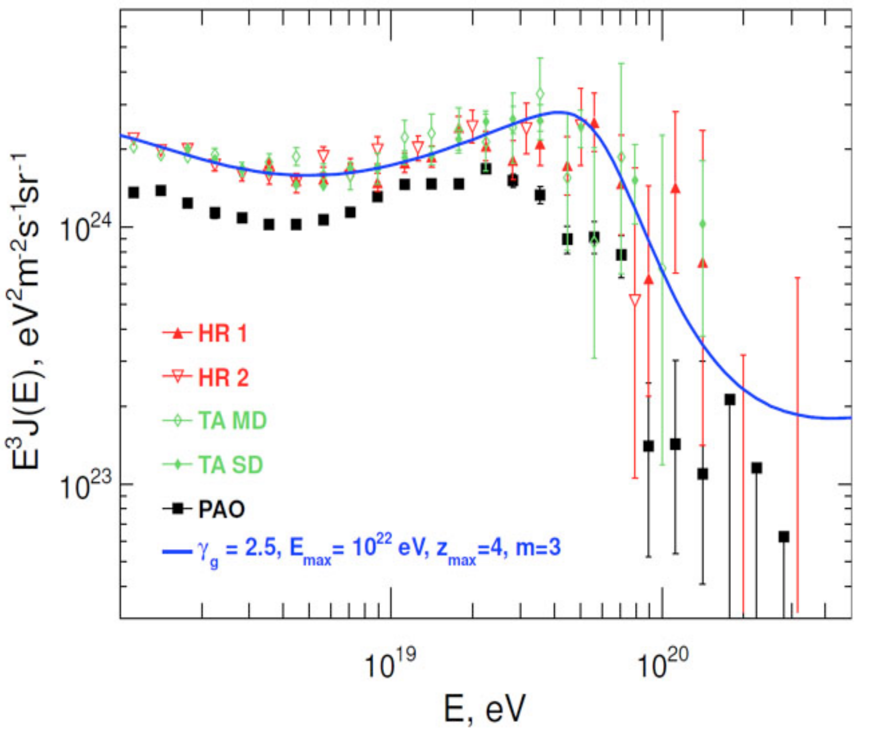
Active galactic nuclei (AGN) ???



?

Ultra High Energy Cosmic Rays (UHCRs), E > 10^{17} eV

Cosmic-Ray mystery



Still open questions:

> What's their composition?

> Where do they come from?

→ *anisotropies weakly correlated to known possible sources: active galactic nuclei, gamma-ray burst,…*

> How do they reach such tremendous energies?

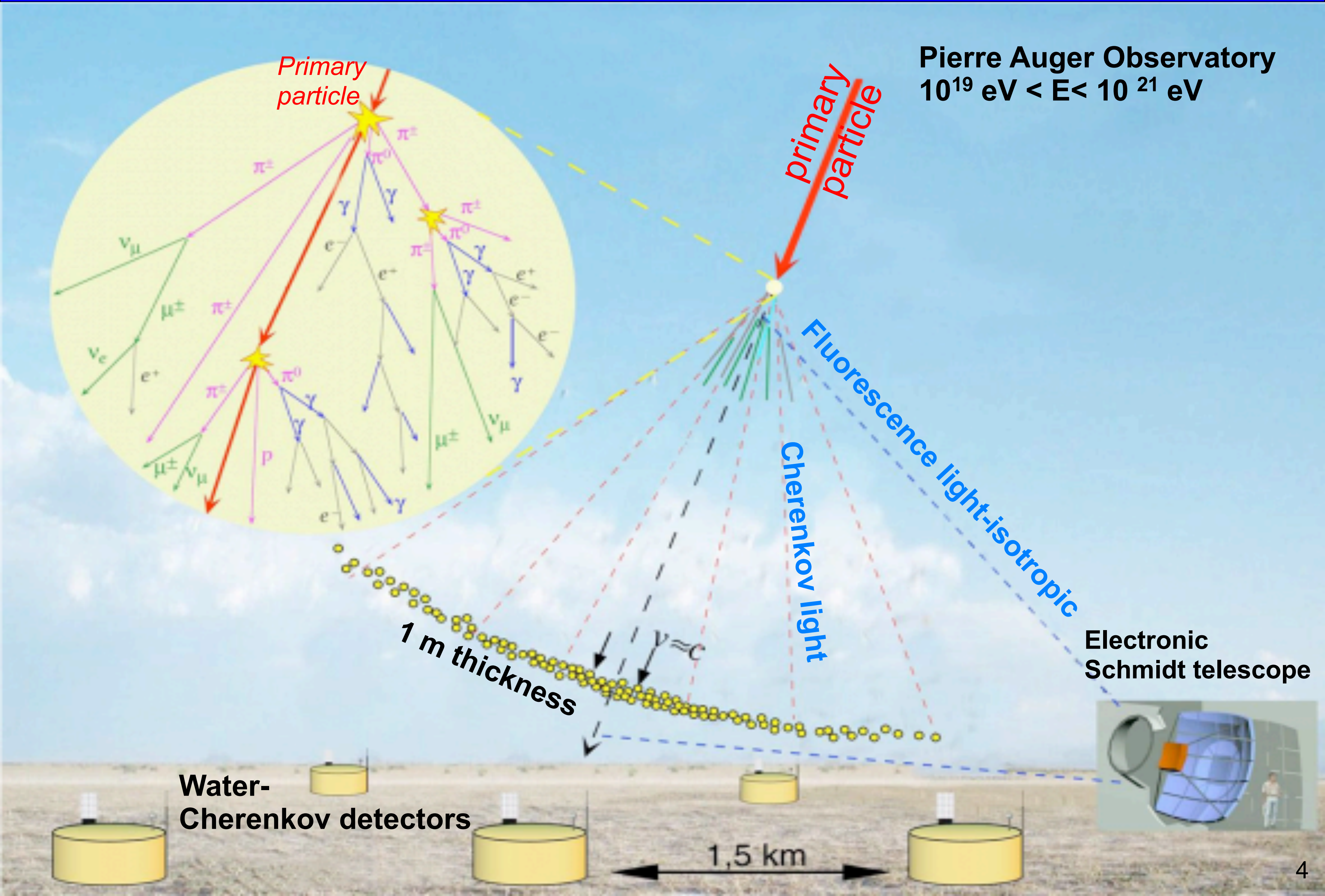
(past the GZK cut-off !)

Greisen-Zatsepin-Kuzmin (1966) – *cosmic ray absorption in Cosmic Mirowave Background CMB (1965):*

$$p + \gamma_{cmb} \longrightarrow \Delta(1232) \longrightarrow p + \pi^0 \quad \text{or} \quad n + \pi^+$$

suppression of cosmic ray flux above energy of 4 x10^{19} eV (GZK-cut-off), maximum source distance of 50-100 Mpc

Extended air showers



Ground arrays

Oldest technique in the field: **Rossi group at MIT** in late 1940

Array at Harvard consisting of 12 0.9m2scintillators up to 1 EeV, 1959:

Vulcano Ranch in New Mexico 19 3.26 m^2 scintillators almost 1 km apart covering about 10 km up to 10 EeV, 1962-87:

Haverah Park (England) with water tanks that absorb the em component and produce Cherenkov light (a vertical muon on average produces 220 MeV (10 km2)

Yakutsk: scintillators, Cherenkov light detectors and muon detectors (20 km^2) with smaller spacing

Akeno: 1979 20 km^2 -> Agasa 100 km^2

Sidney: 100 km2 array of muon counters of 6 m^2 of liquid scintillator viewed by1 PMT on a 1600 m square grid buried to have a muon threshold of 1 GeV

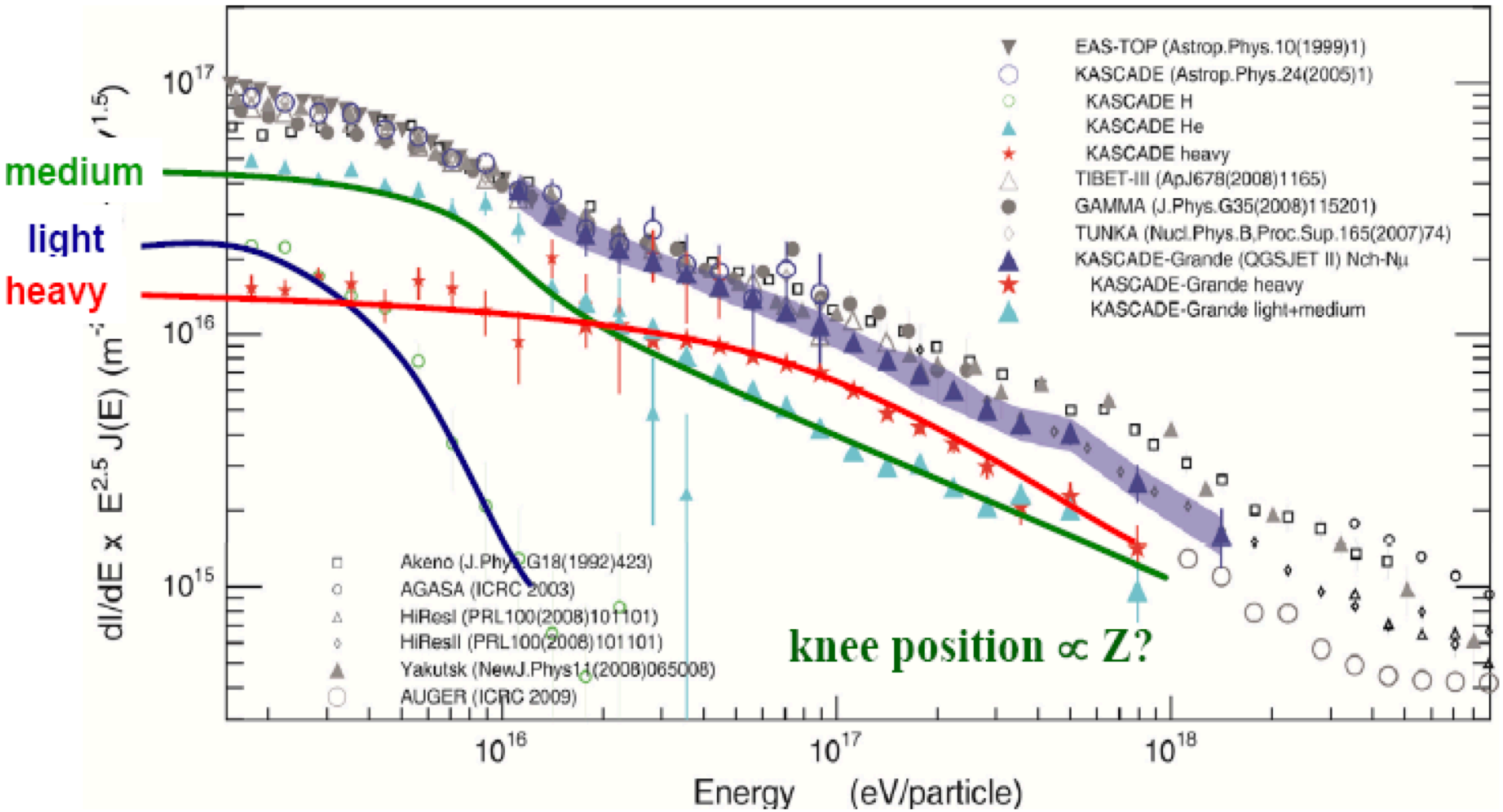
KASKADE: experiment

KASCADE

Measurements of air showers in the energy range E_0 = 100 TeV - 80 PeV

= **KArlsruhe Shower Core and Array Detector**

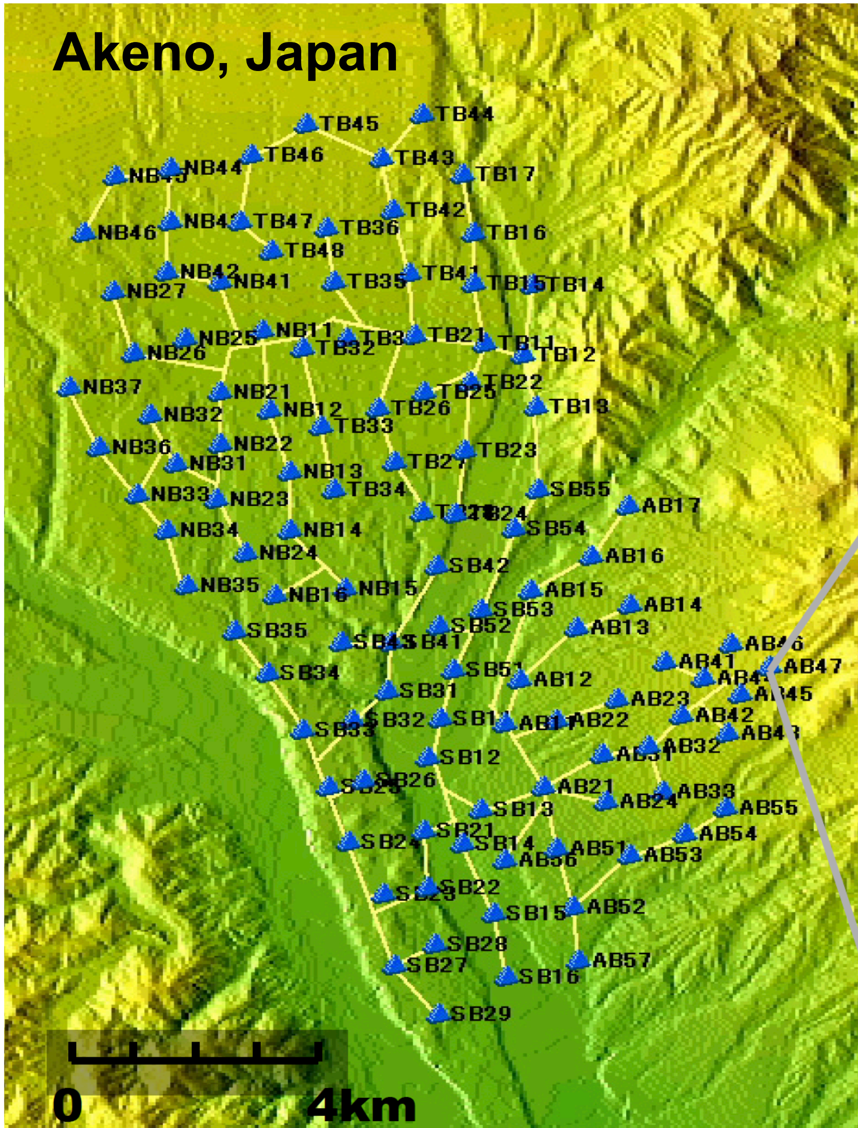
KASKADE: results



$E_{max} \propto Z$?

Knee as effect of accelartion of CR in sources like for example supernova

AGASA: Akeno Giant Air Shower Array



AGASA: Akeno Giant Air Shower Array

111 detektorów elektronów
27 detektorów mionów

AGASA: Akeno Giant Air Shower Array

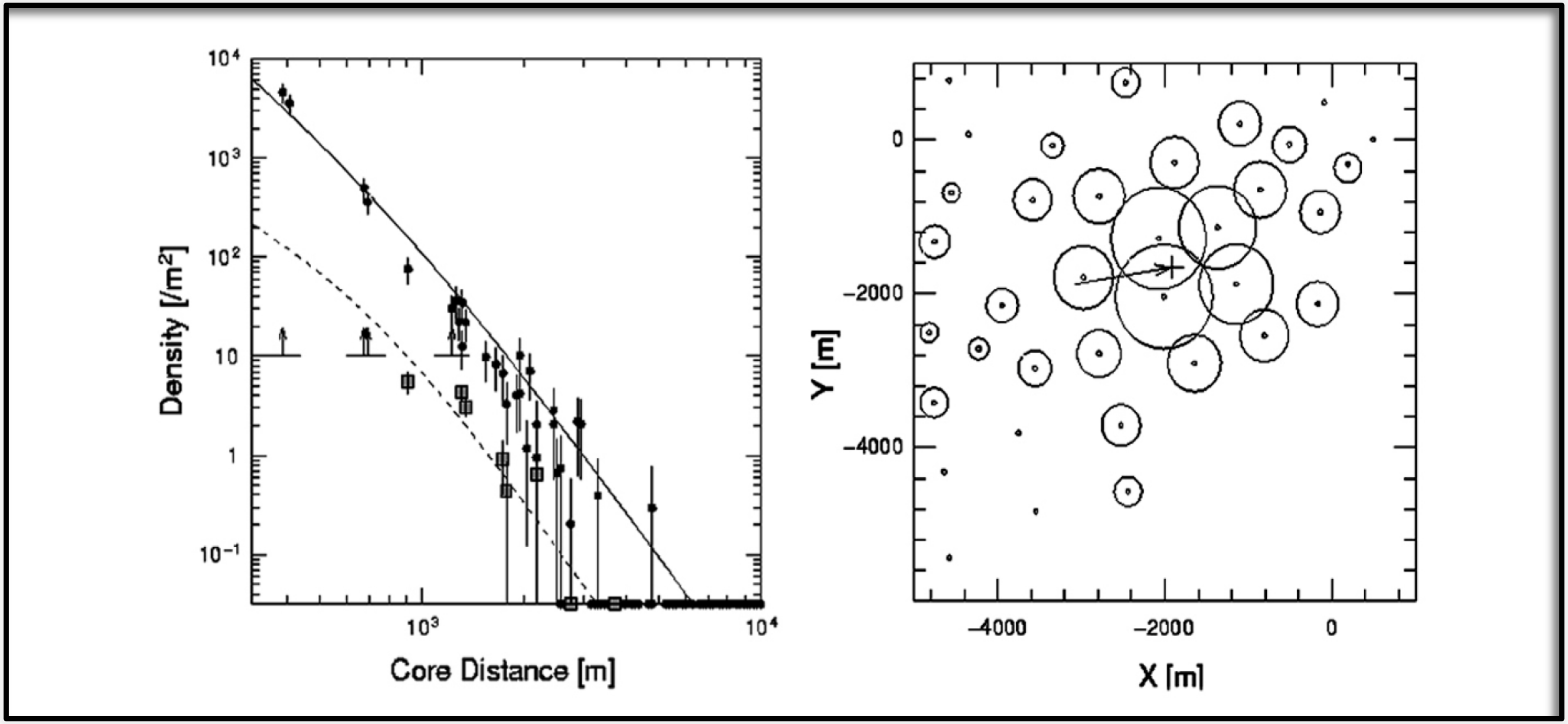
Reconstruction of the EAS in the ground grid

The highest energy event from the AGASA detector **(E~2.0 × 10^{20} eV)**
on December 3, 1993

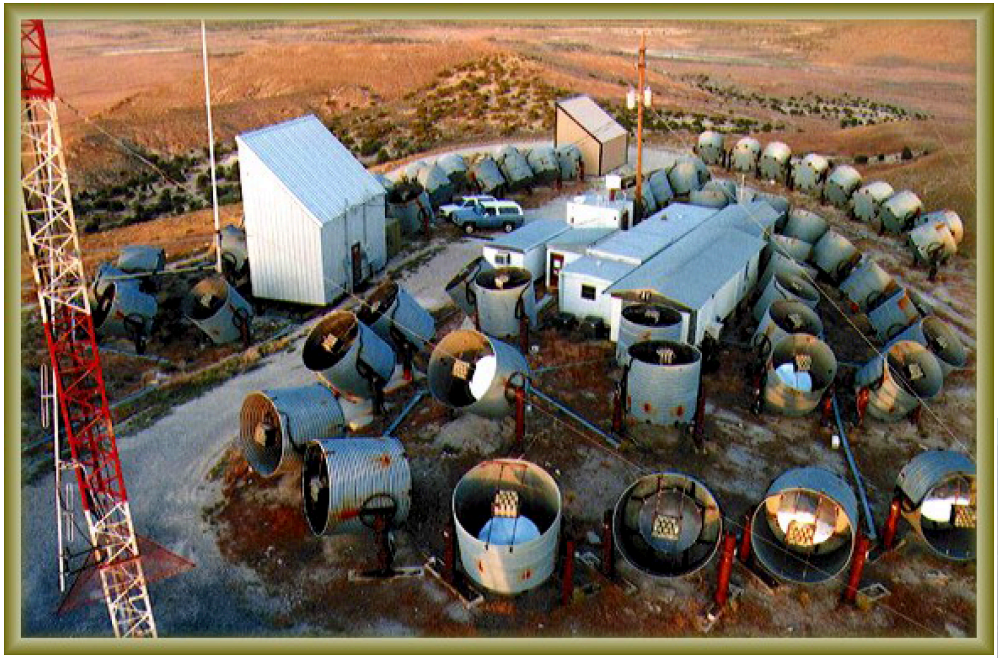
$\rho(r) \propto k\, r^{-(\eta+f(r))}$

$E_0 = a\, \rho_{600}{}^{b}$

Caviat: a,b from MC simulations

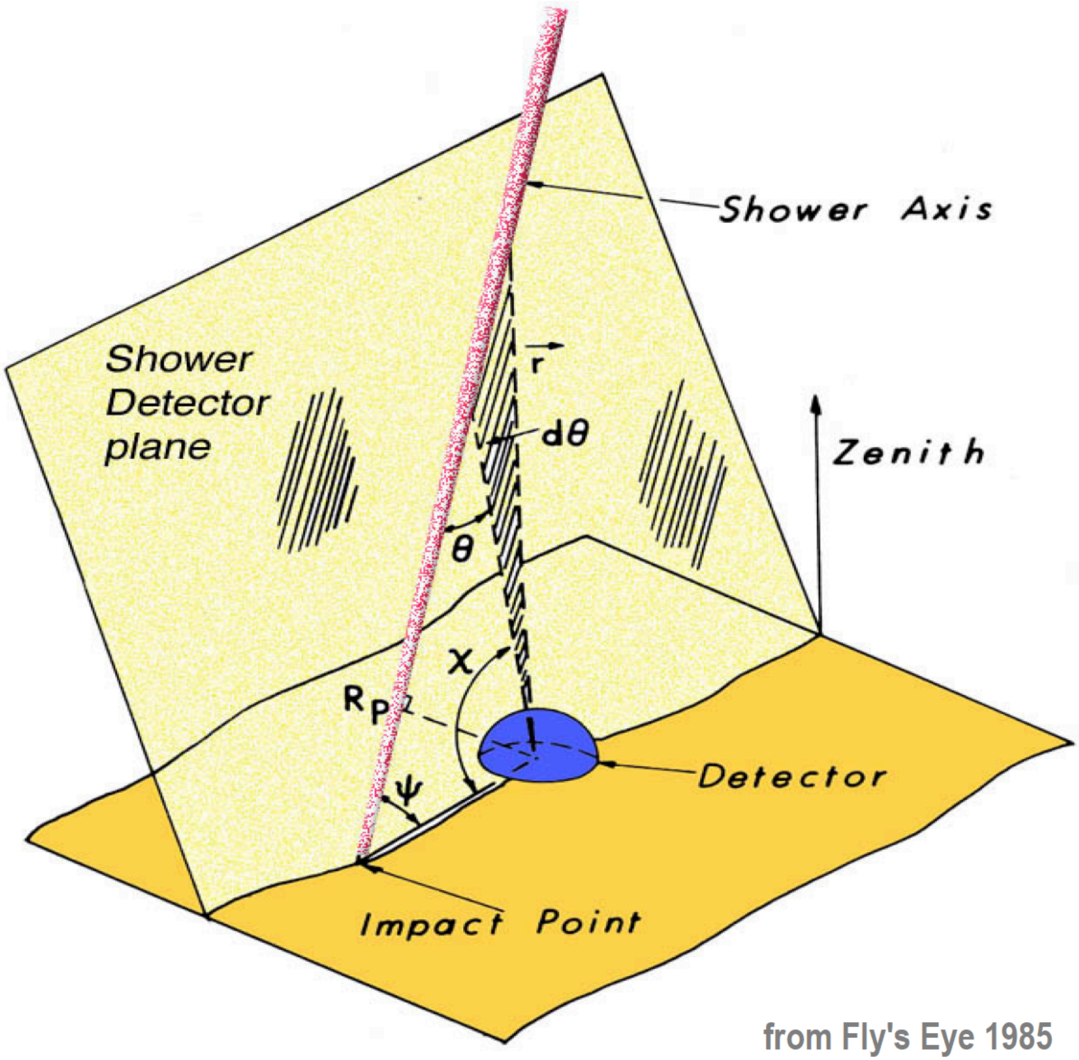


The fluorescence detector: HiRes (1985 year)



HiRes

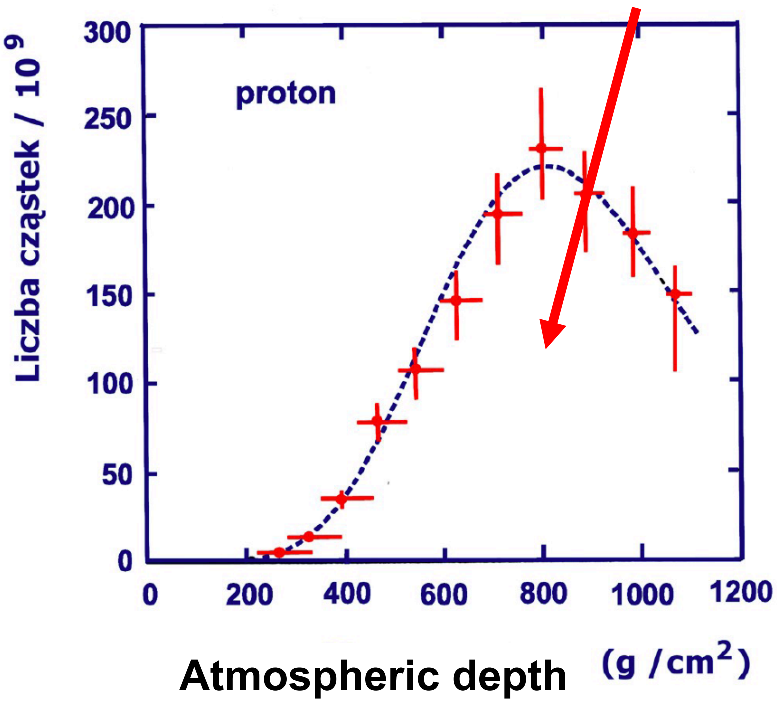
The fluorescence detector: HiRes (1985 year)



from Fly's Eye 1985

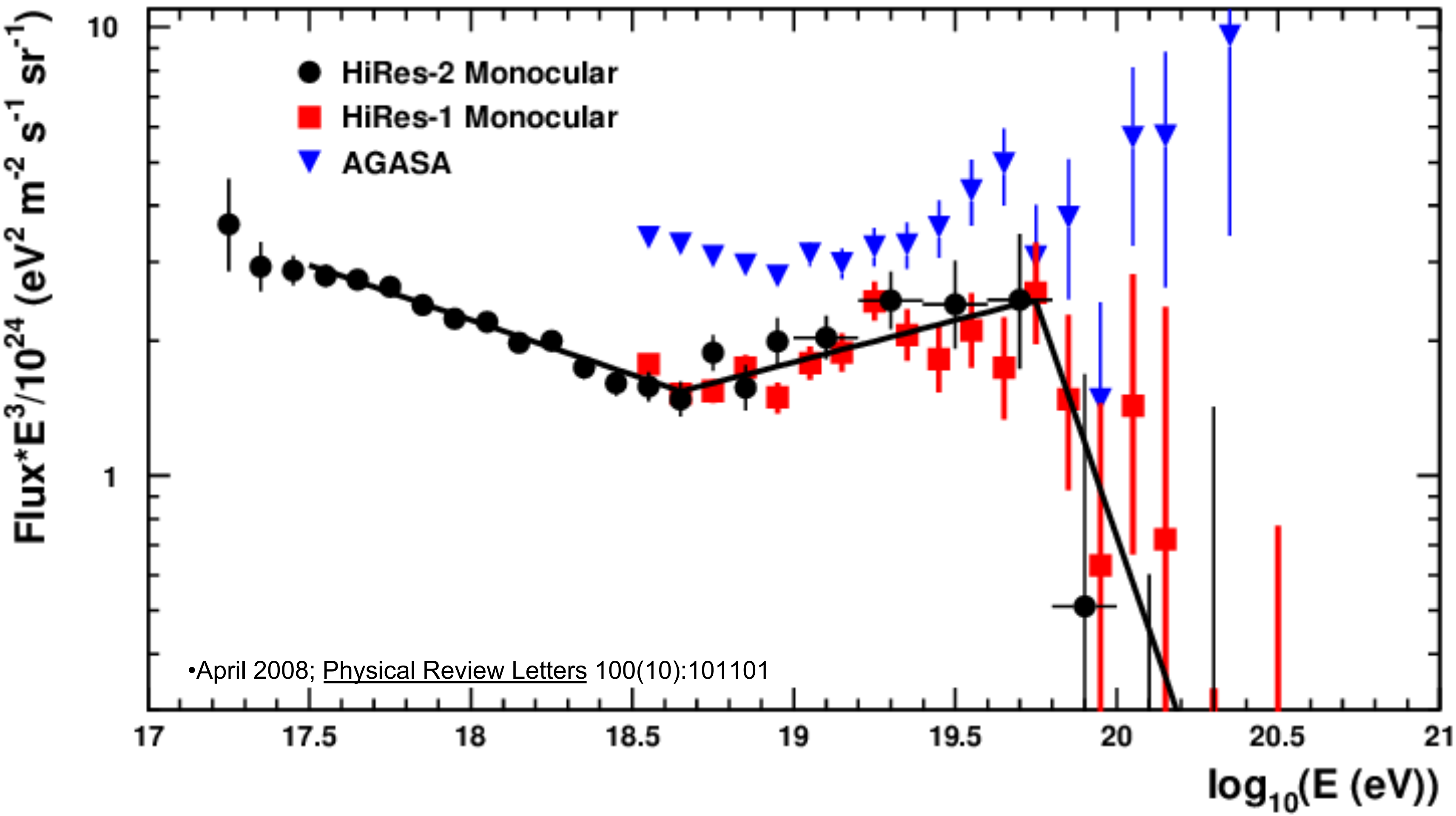
Xmax, calorimetric energy

$$E_{\mathrm{cal}} = \int \frac{\mathrm{d}E}{\mathrm{d}X}\,\mathrm{d}X$$



Energy spectrum measured by AGASA and HiRes

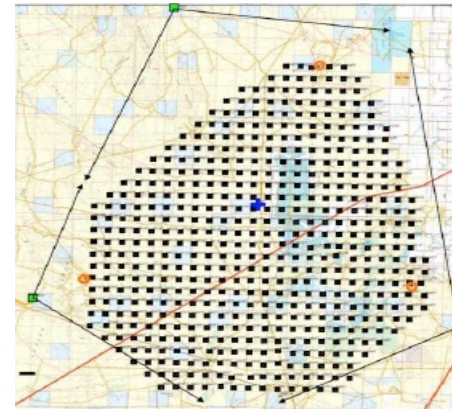
Astropart.Phys. 19 (2003) 447-462



inconsistency of spectra due to the use of different detection techniques ?

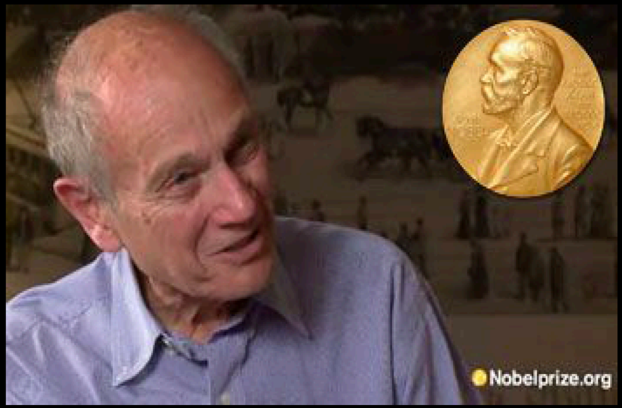
The largest detectors of ultra-high energy cosmic rays

(northern hemisphere)
Telescope Array (TA)
Area: 700 km^2
Lcation: USA o



(southern hemisphere)
Pierre Auger Observatory (Auger)
Area: 3000 km^2
Location: Argentina

Pierre Auger Collaboration



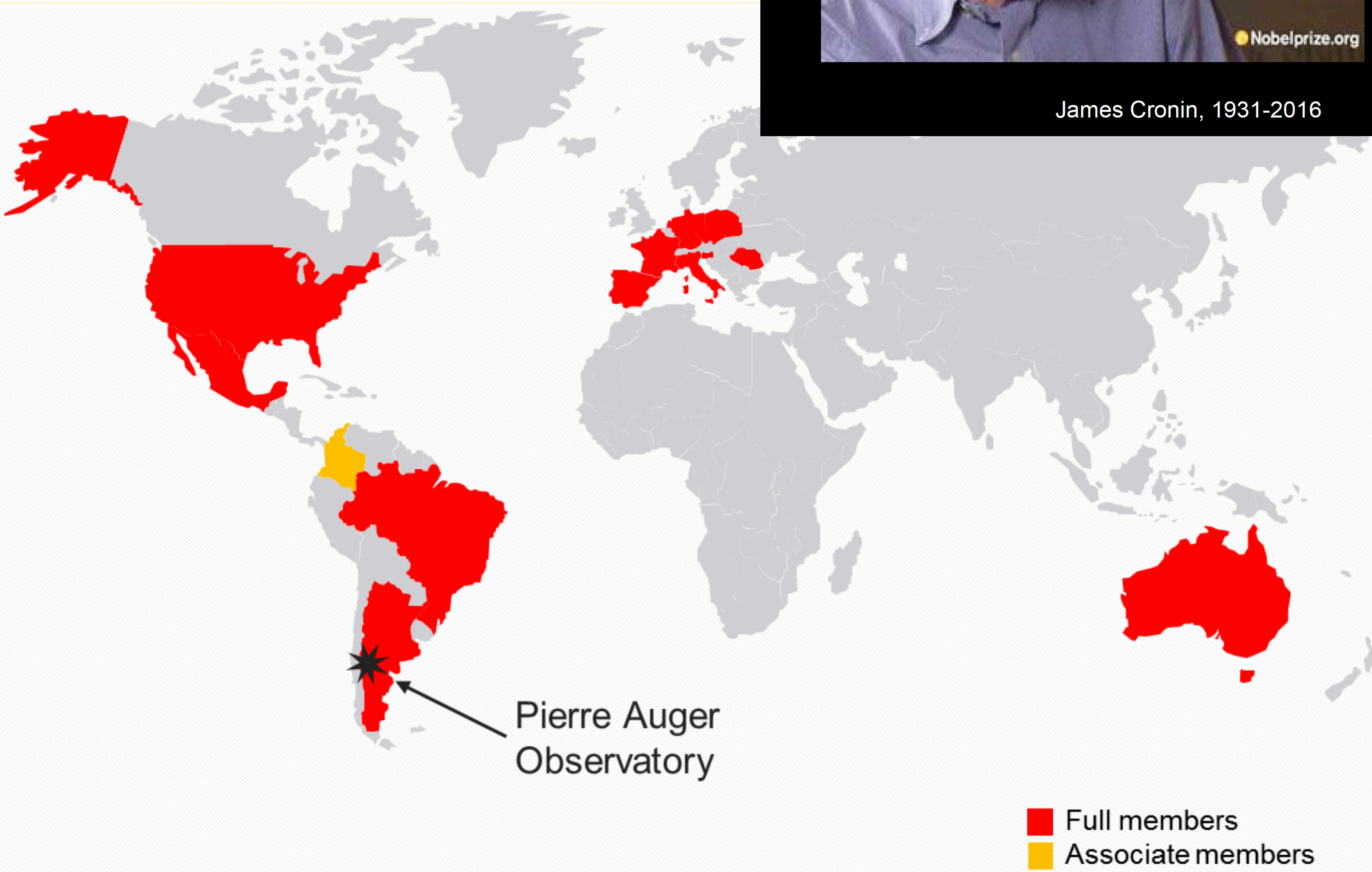
James Cronin, 1931-2016

1995: proposal to construct the Pierre AugerObservatory,

International Collaboration:
Now: 16 countries, 98 institutions, 500+ collaborators

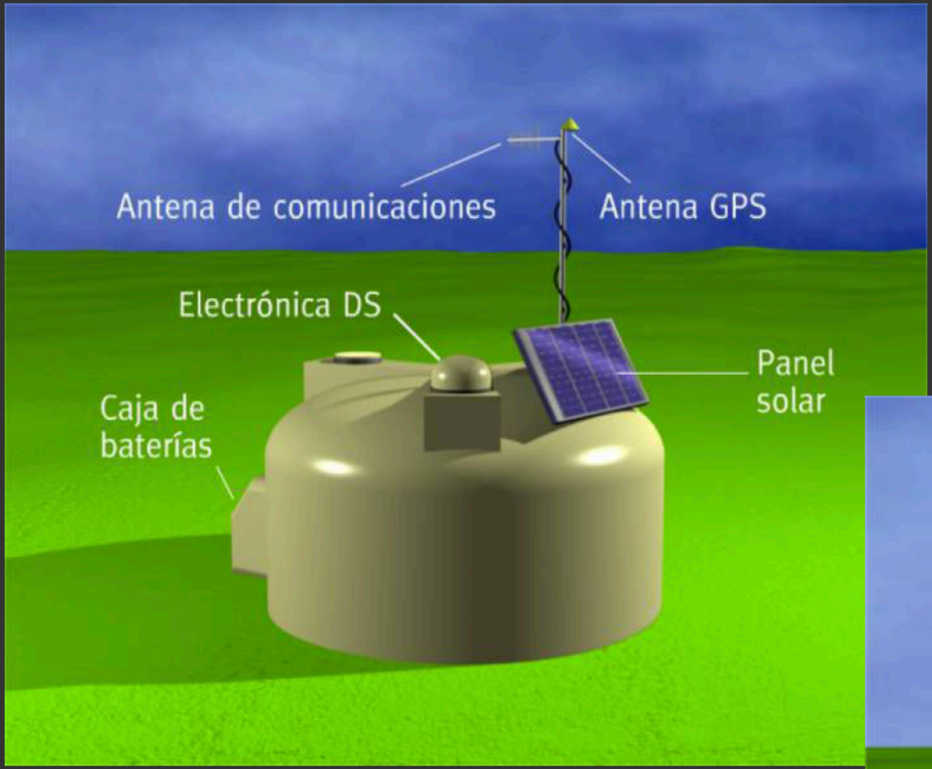
Argentina
Australia
Brasil
Colombia*
Czech Republic
France
Germany
Italy
Mexico
Netherlands
Poland
Portugal
Romania
Slovenia
Spain
USA

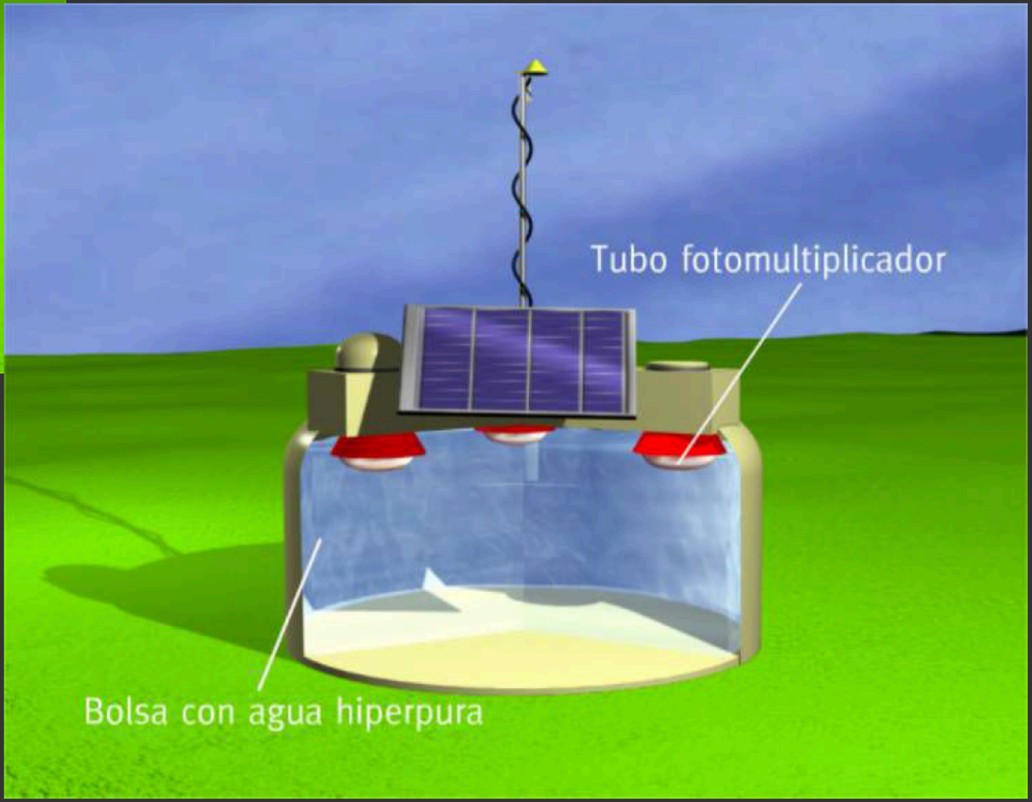
**associated*



Surface Water Cherenkov Detectors (SD's)

Surface Water Cherenkov Detectors (SD's)



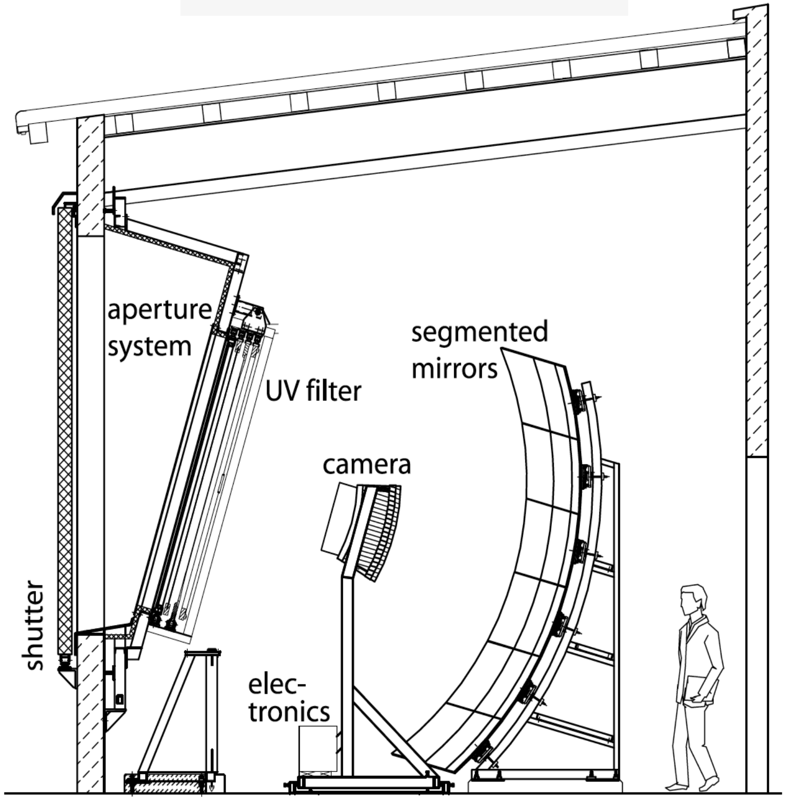


12 Tn of pure water in liner
3 PMT's per detector
SD's sensitive to:
- e^+, e^- (signal proportional to E)
- γ (signal proportional to E)
- μ (signal proportional to trace length)

Fluorescence Telescopes (FD's)

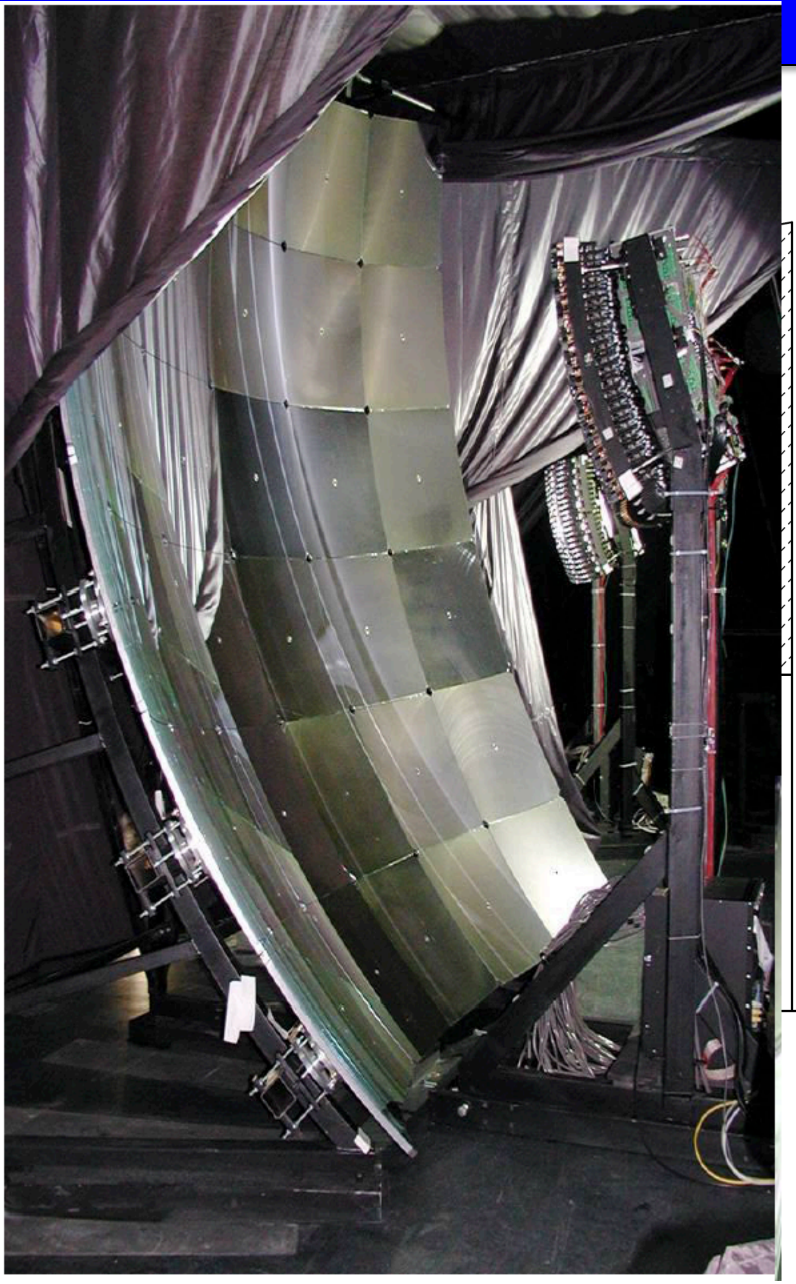
FD telescopes at Los Morados

elevation 1.5° – 30°



Fluorescence Telescopes (FD's)

FD telescopes at Los Morados

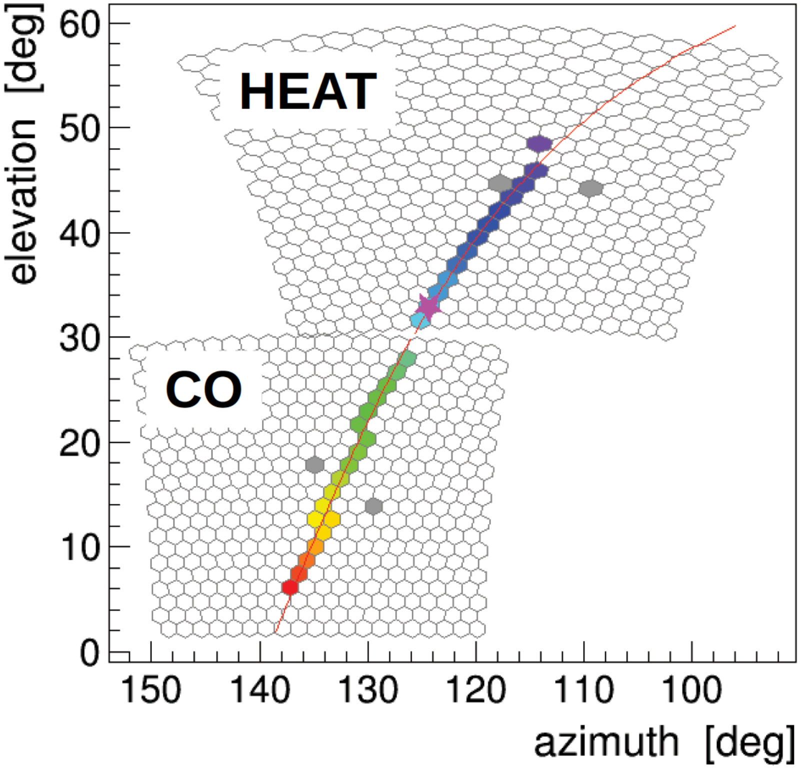


Fluorescence Telescopes (FD's)

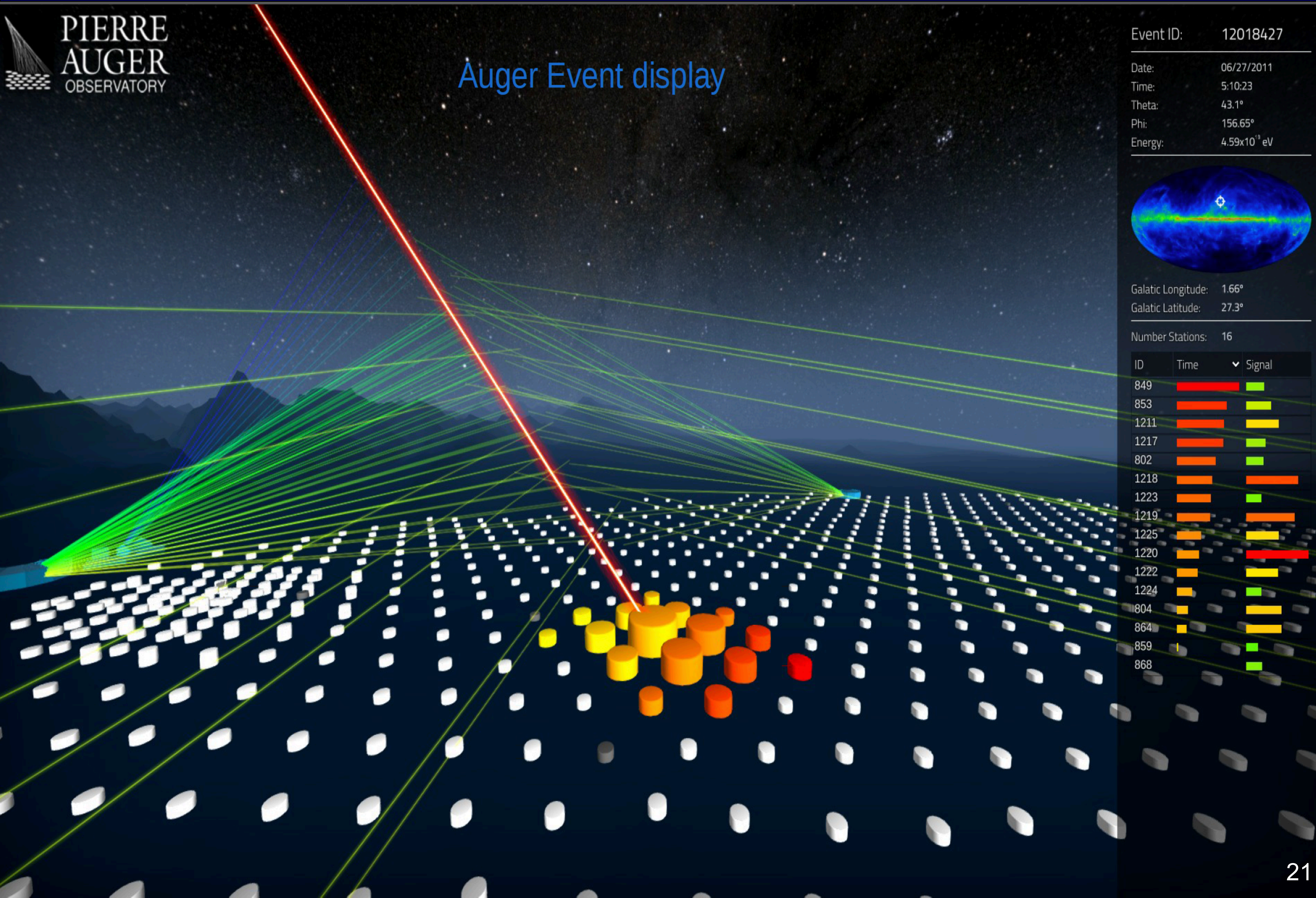
High Elevation Auger Telescopes (HEAT)

Detection of showers with $E < 10^{18}$ eV

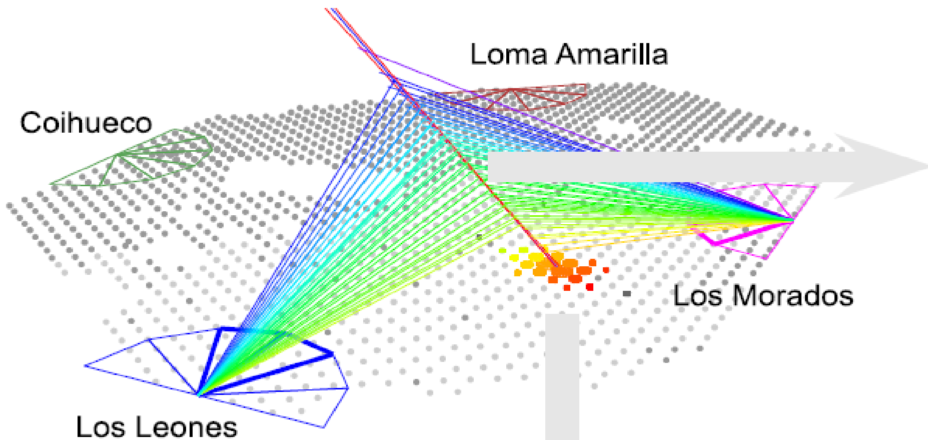
Combined FOV $1.5^\circ - 58^\circ$

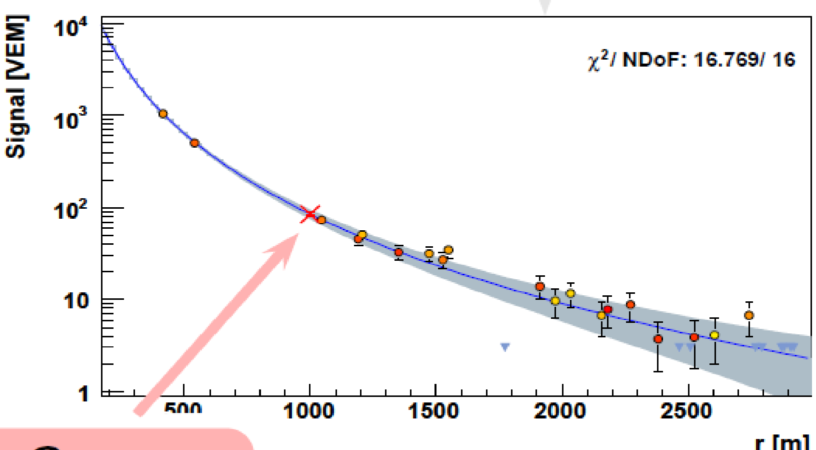


Example of hybrid : event seen by SDs and FDs



Detection of air showers



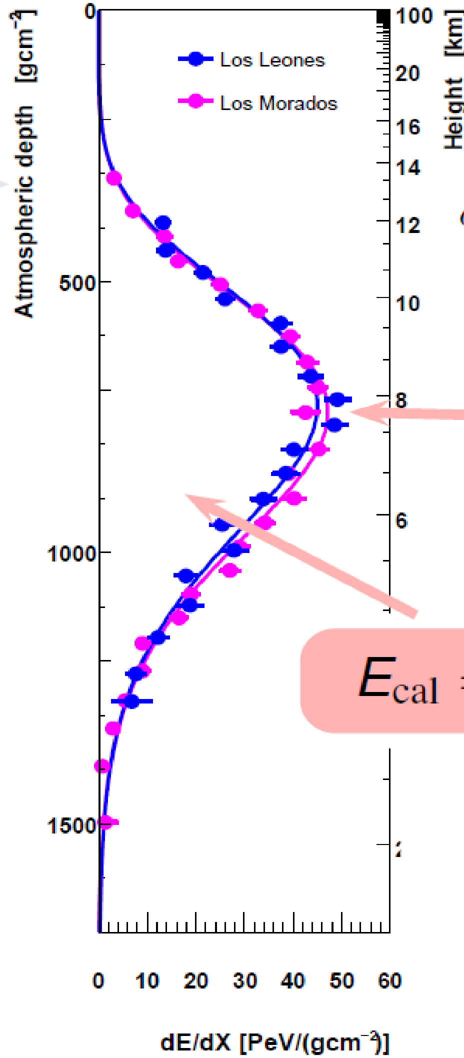


S_{1000}

$E_{\rm surface} = f(S_{1000},\ \theta)$

Surface Detector (SD)

top of the atmosphere



$\sigma X_{\rm max} \lesssim 20\ {\rm g/cm^2}$
$\Delta_{\rm sys} \lesssim 10\ {\rm g/cm^2}$

$X_{\rm max}$

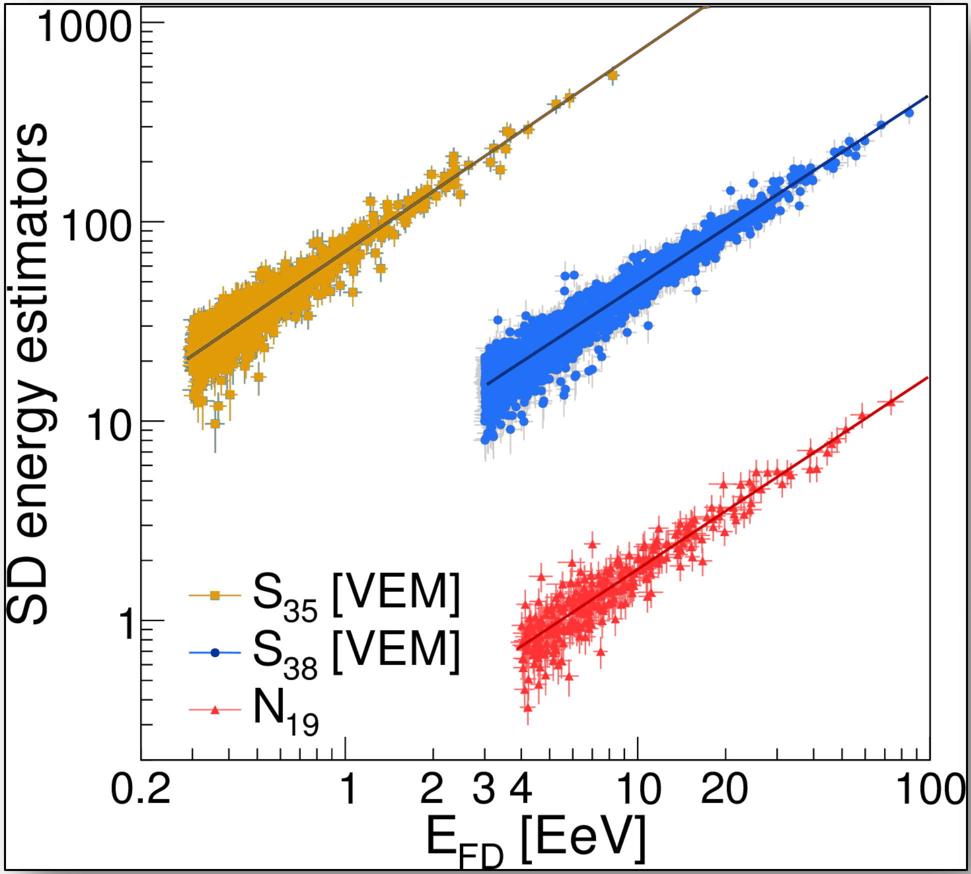
$E_{\rm cal} = \int \frac{{\rm d}E}{{\rm d}X}\,{\rm d}X$

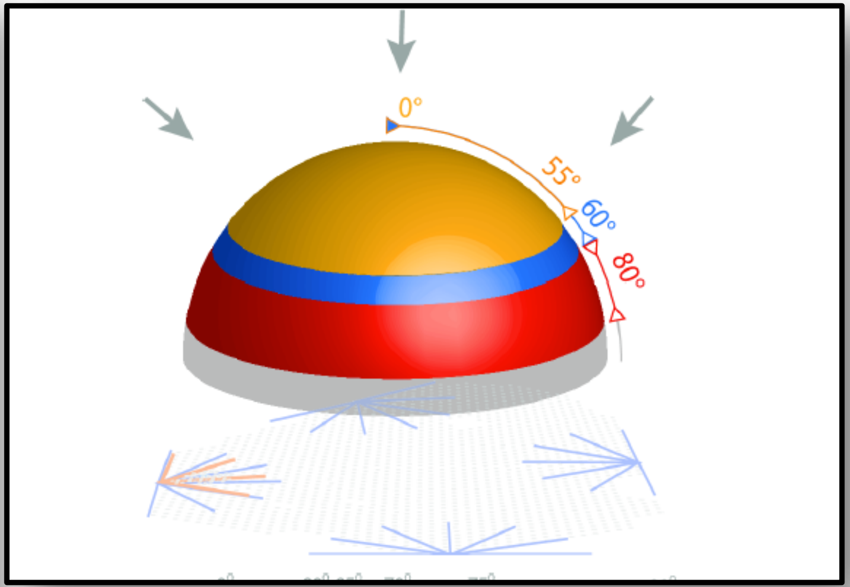
$\sigma_E/E \sim 8\,\%$
$\Delta_{\rm sys} \approx 15\,\%$

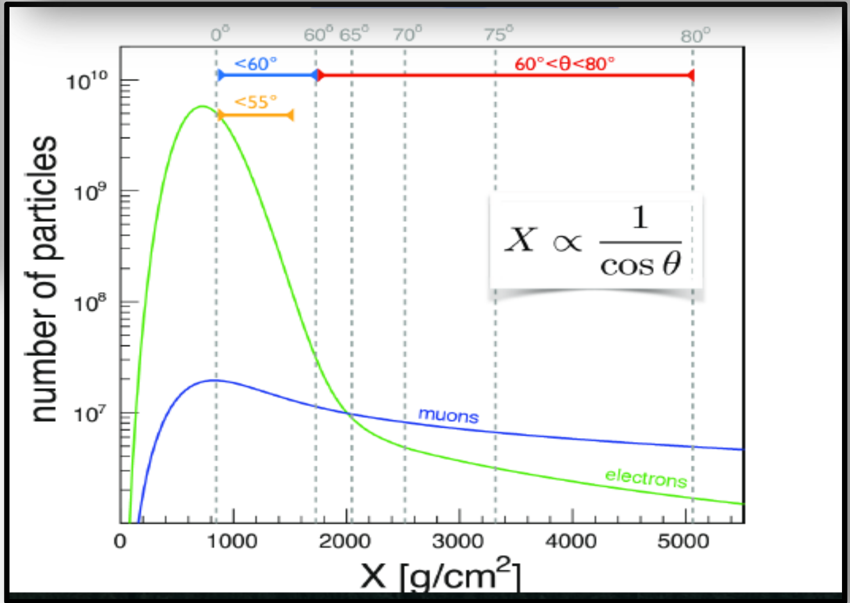
detector level

Fluorescence Detector (FD)

Hybrid Energy Calibration







Auger "design concept". Twofold benefit:

> Hybrid events fewer (DC ≈ 15%) but superior (better geometry, energy and mass determination)

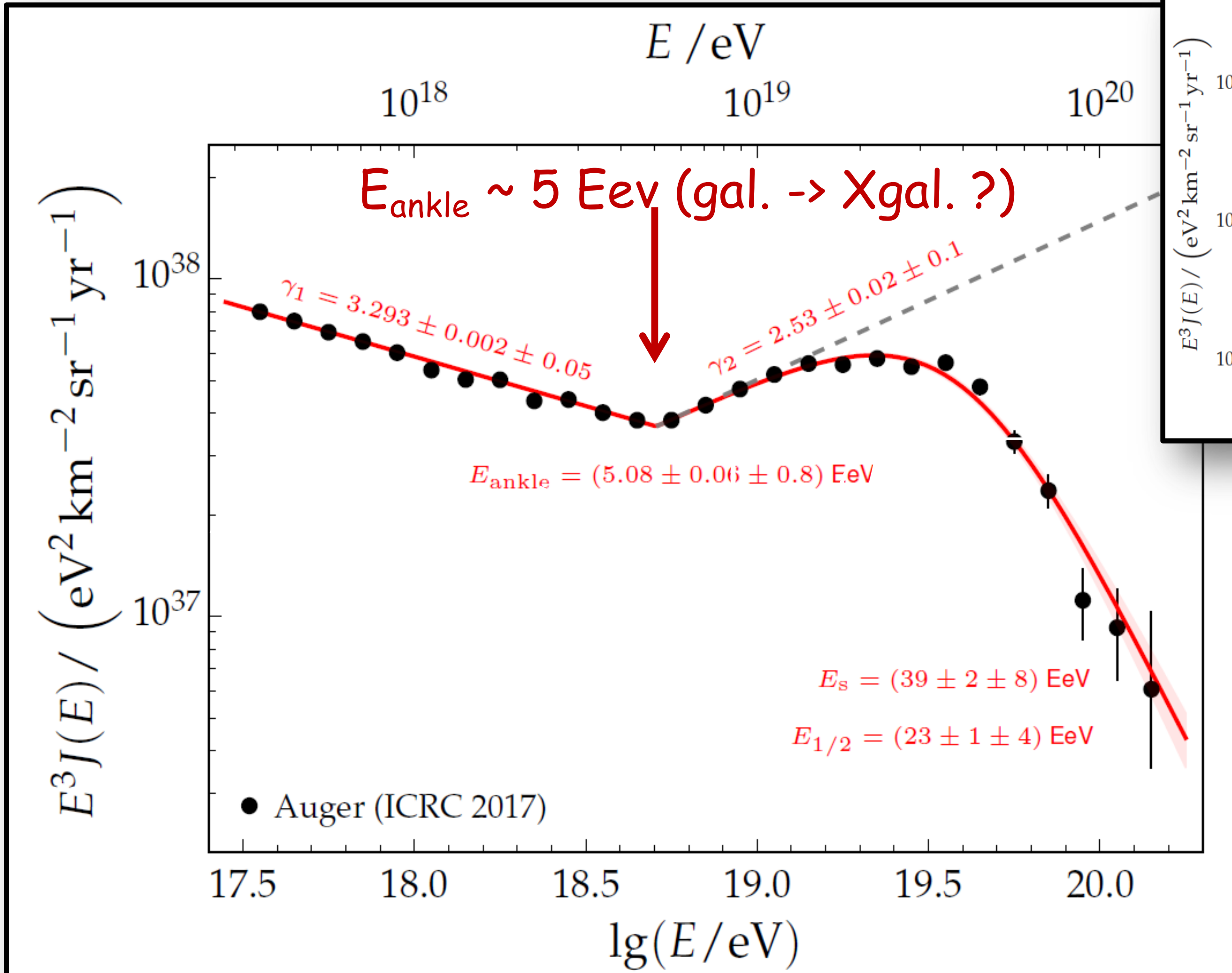
> Hybrid events calibrate SD events (DC ≈100%)

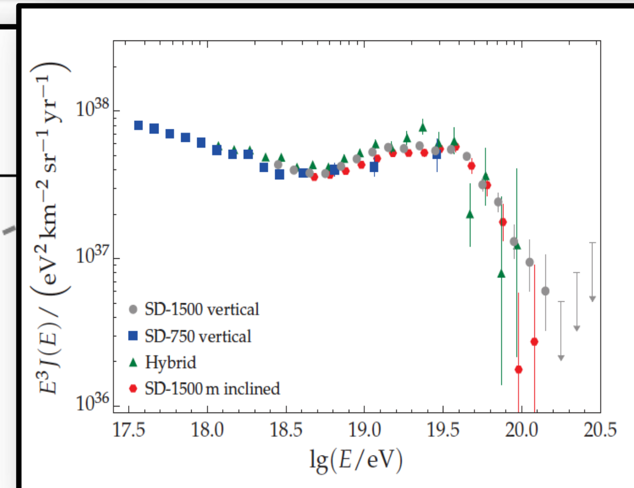
FD: σE = 8%, σsyst = 14%

SD: σE = 10% (at 10^{19} eV)

Spectrum of UHCR

UHECRs energy spectrum: combined Auger spectrum





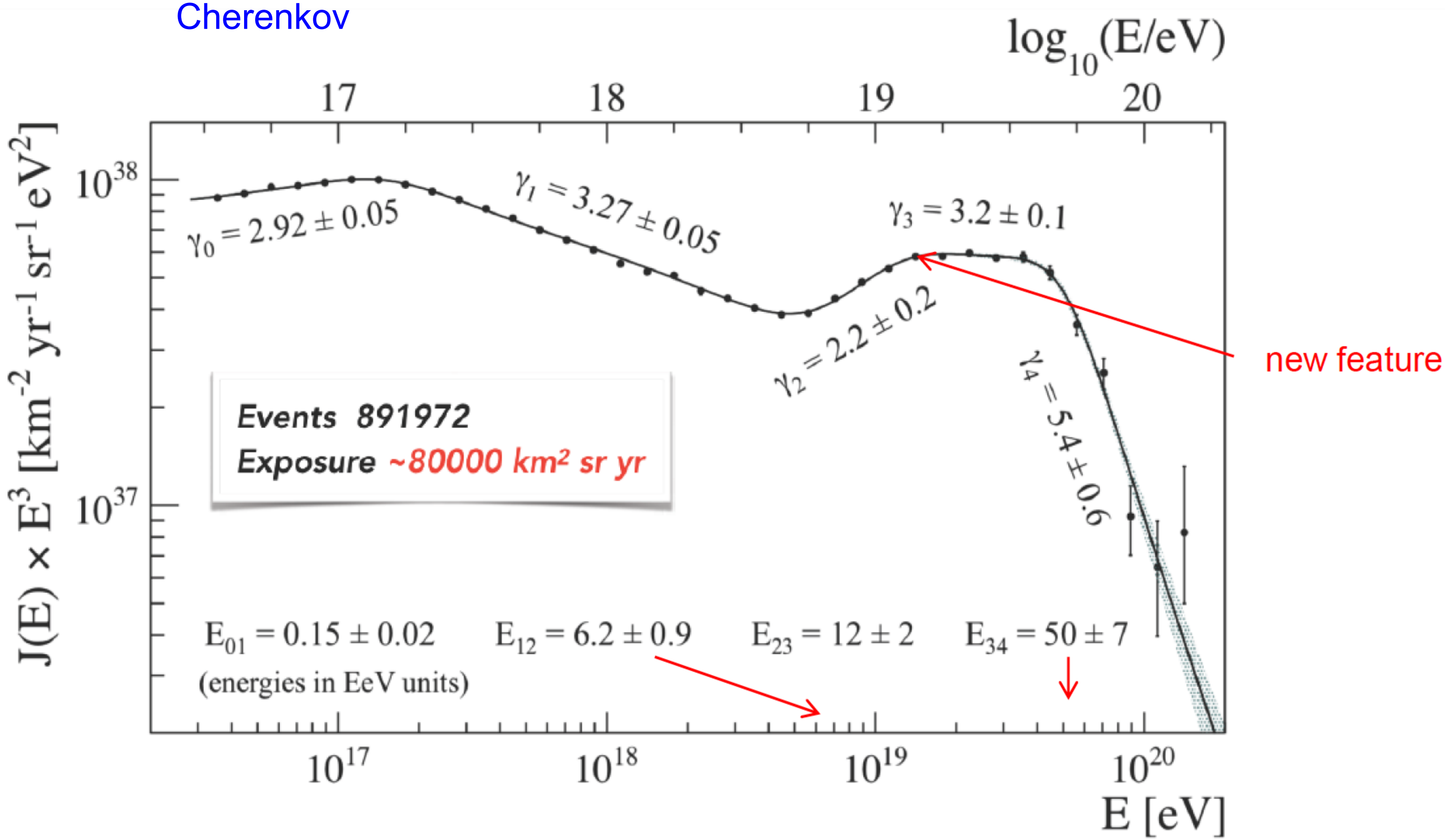
GZK cutoff ?
or
Efficiency limit of the particle acceleration by sources (cutoff in the source spectrum) ?

› The cosmic ray flux is well described by a broken power law plus smooth suppression at the highest energies.

UHECRs energy spectrum: combined Auger spectrum

Hybrid FD+SD
SD 1500 m Θ< 60 deg
SD 1500 m Θ> 60 deg
SD 750 m
Cherenkov

combined



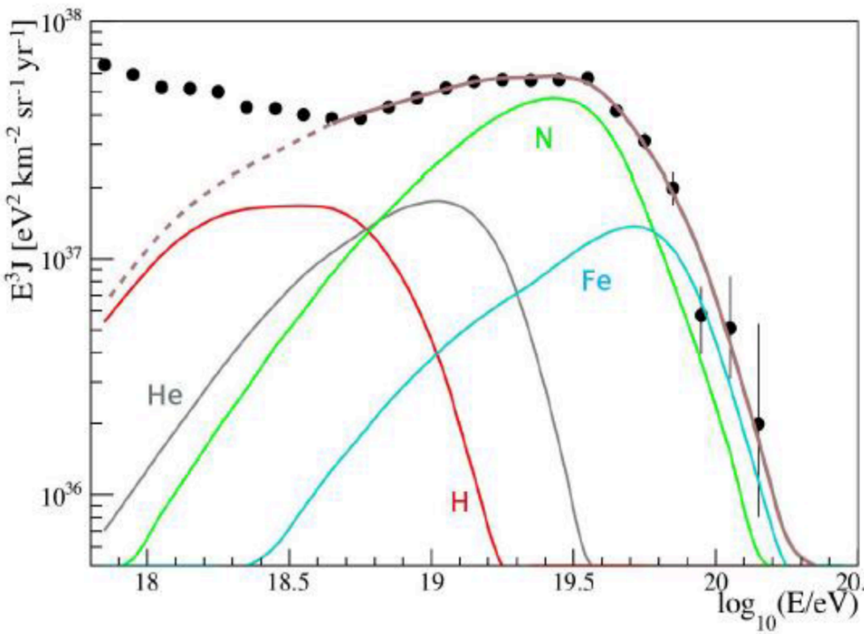
[Phys. Rev. Lett 125, (2020) 121106, Phys. Rev. D 102, 062005 (2020)]

UHECRs energy spectrum: astrophysical interpretation

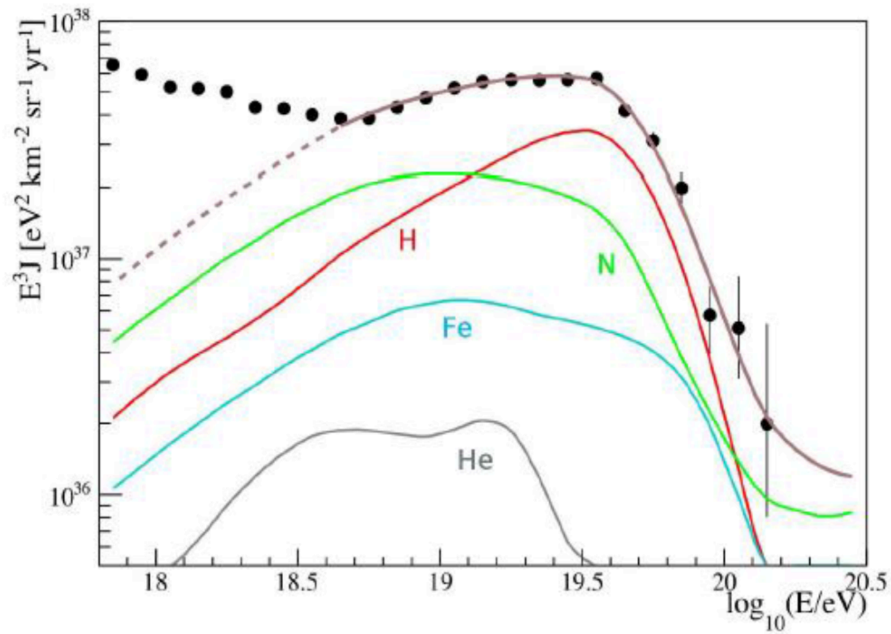
The flux suppression may be due to the GZK effect, or to a limit of acceleration efficiency at the sources

Examples of spectrum scenarios:

Maximum acceleration efficiency
Emax(A) = Z Emax(p)

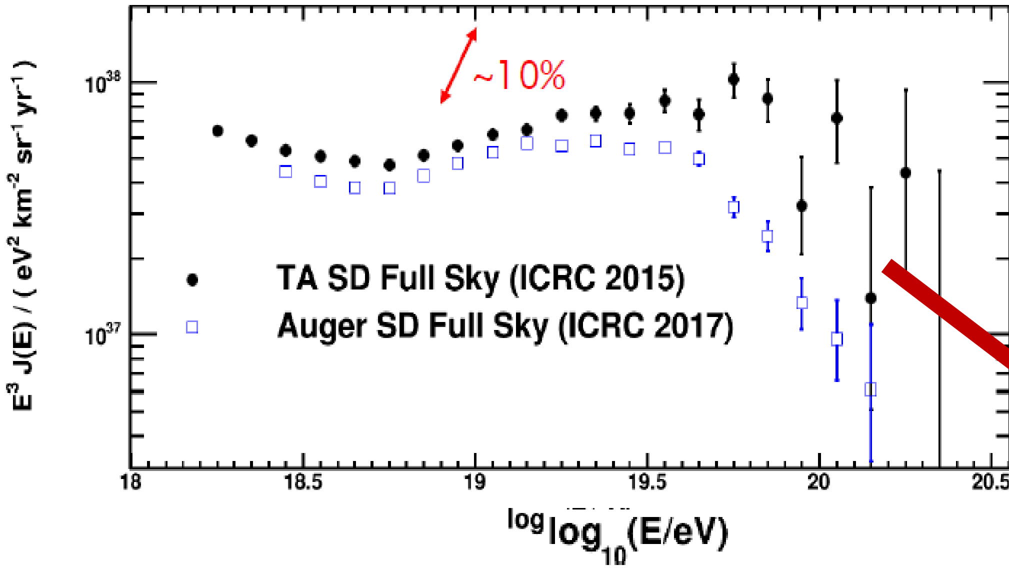


propagation effect
GZK/disintegration

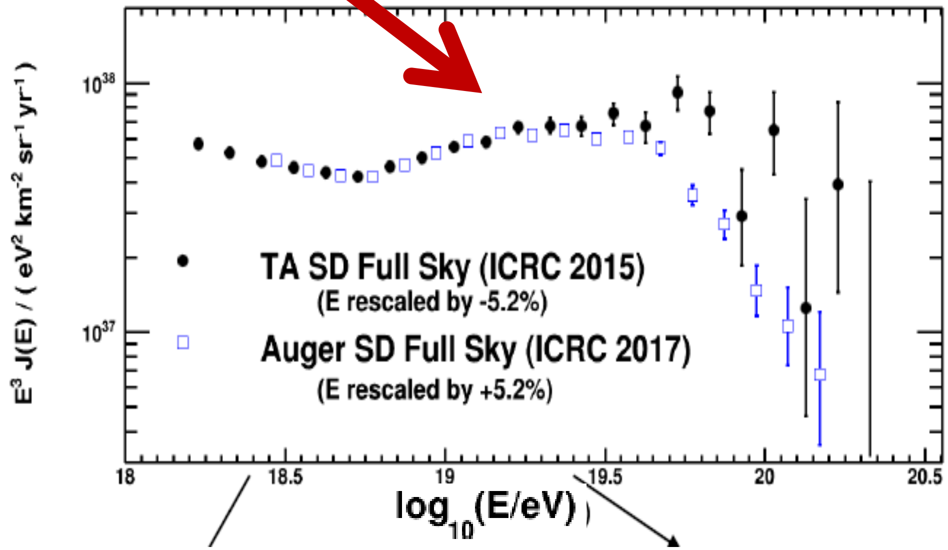


Need precise composition measurements

Are Auger and TA spectra compatible?



energy rescaling



Ankle at ~5 EeV, cutoff at ~40 to 60 EeV

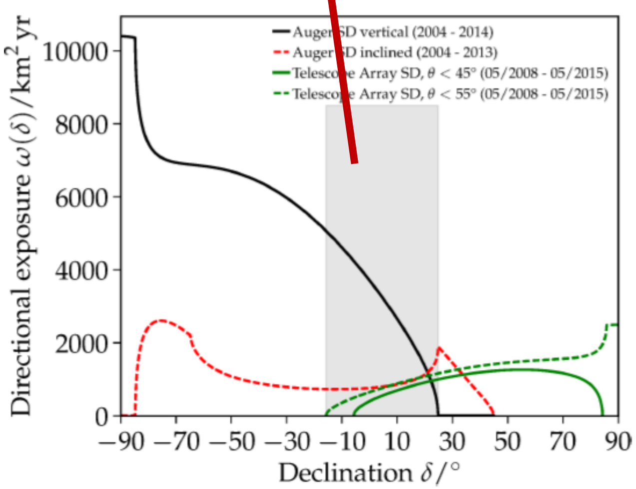
- ~10% energy scale difference around ankle region well within 14% (Auger) and 21% (TA) energy scale systematic uncertainties
- Some discrepancy in shape at E > $10^{19.4}$ eV

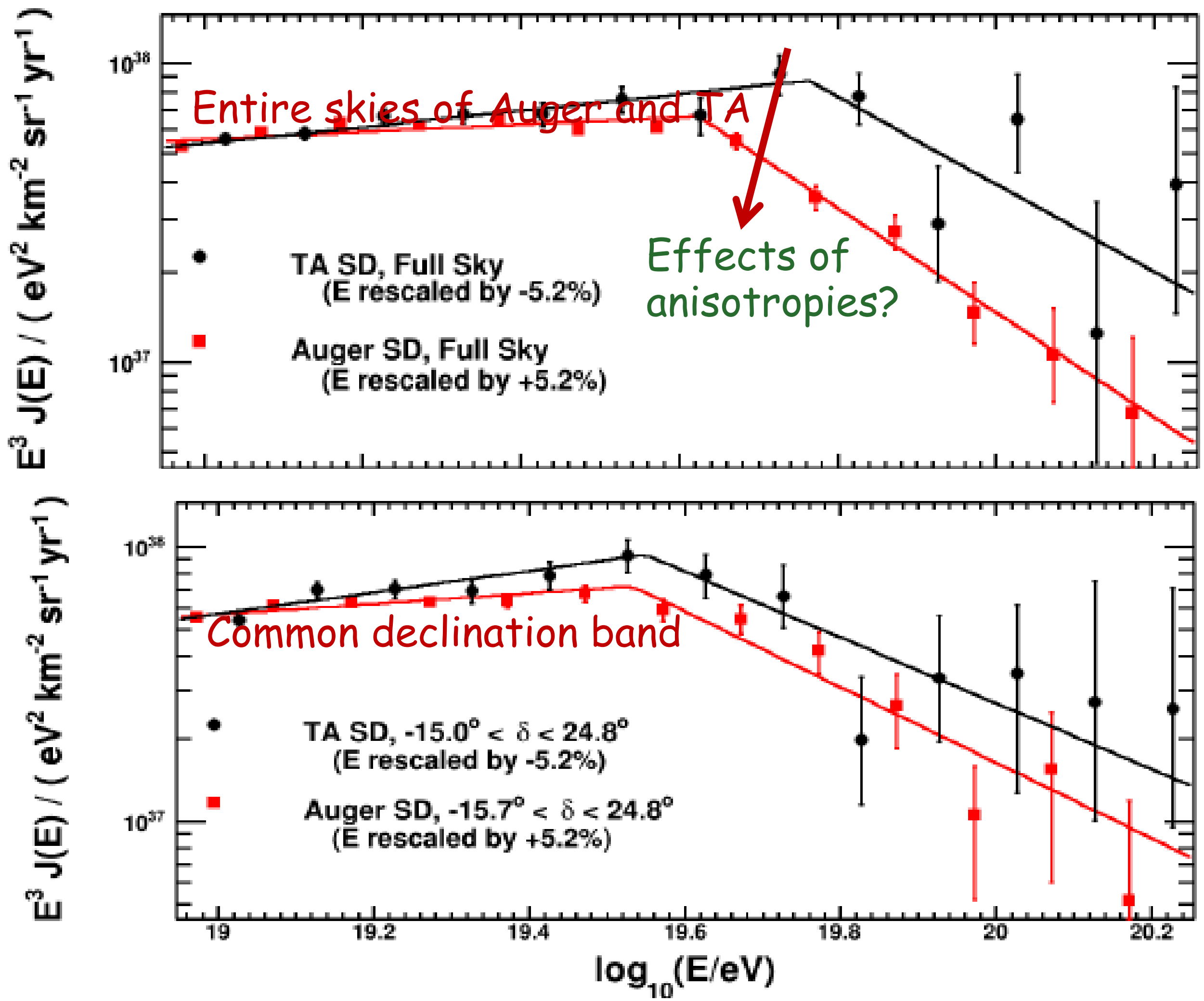
> Spectra agree in the ankle region $10^{18.4}$ eV < E < $10^{19.4}$ eV
> Difference above $10^{19.4}$ eV

Energy spectrum: Auger and TA common declination band

directional exposure vs declination

the overlapping sky region seen by both detectors

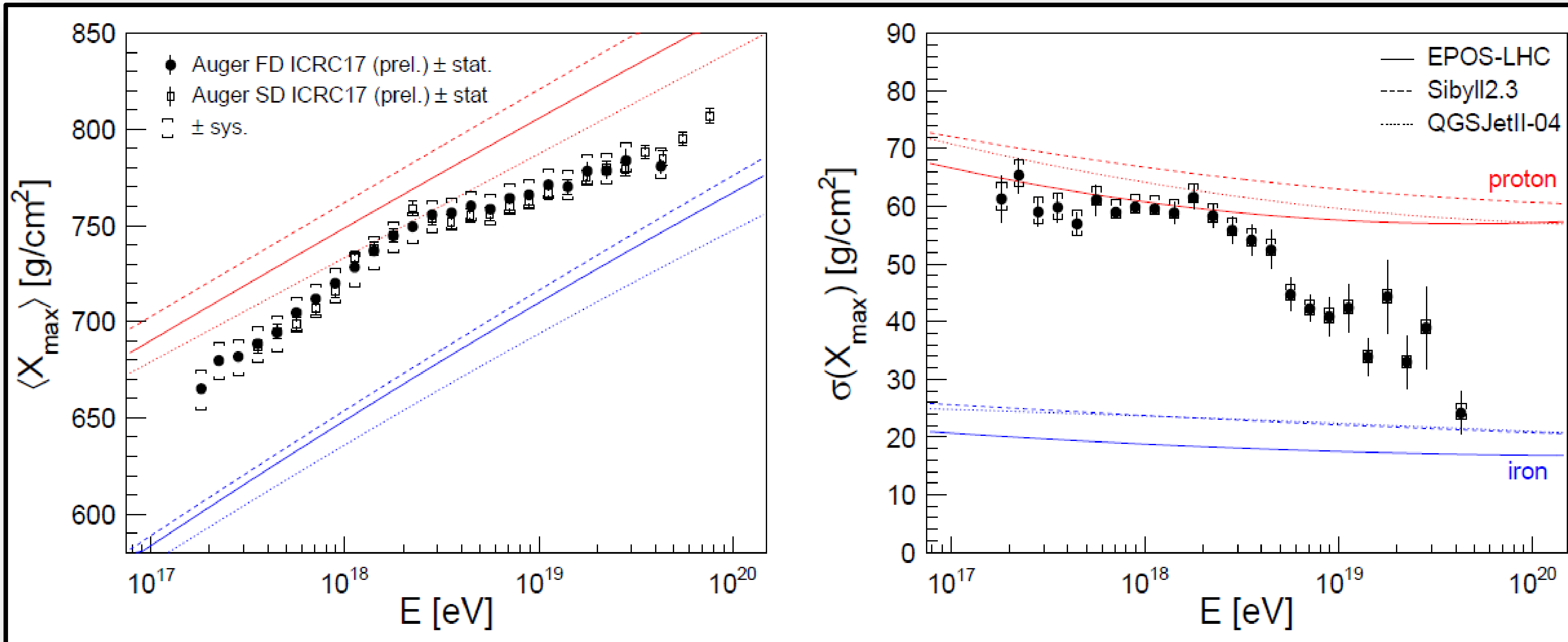




- Better agreement between TA and Auger in the common declination band
  - spectrum cutoff roughly in agreement
  - smaller differences remain but within systematics
- Auger and TA energy spectra consistent within systematic uncertainties

Mass compositiom of UHCR

Mass composition: average X_{max} and X_{max}-fluctuations



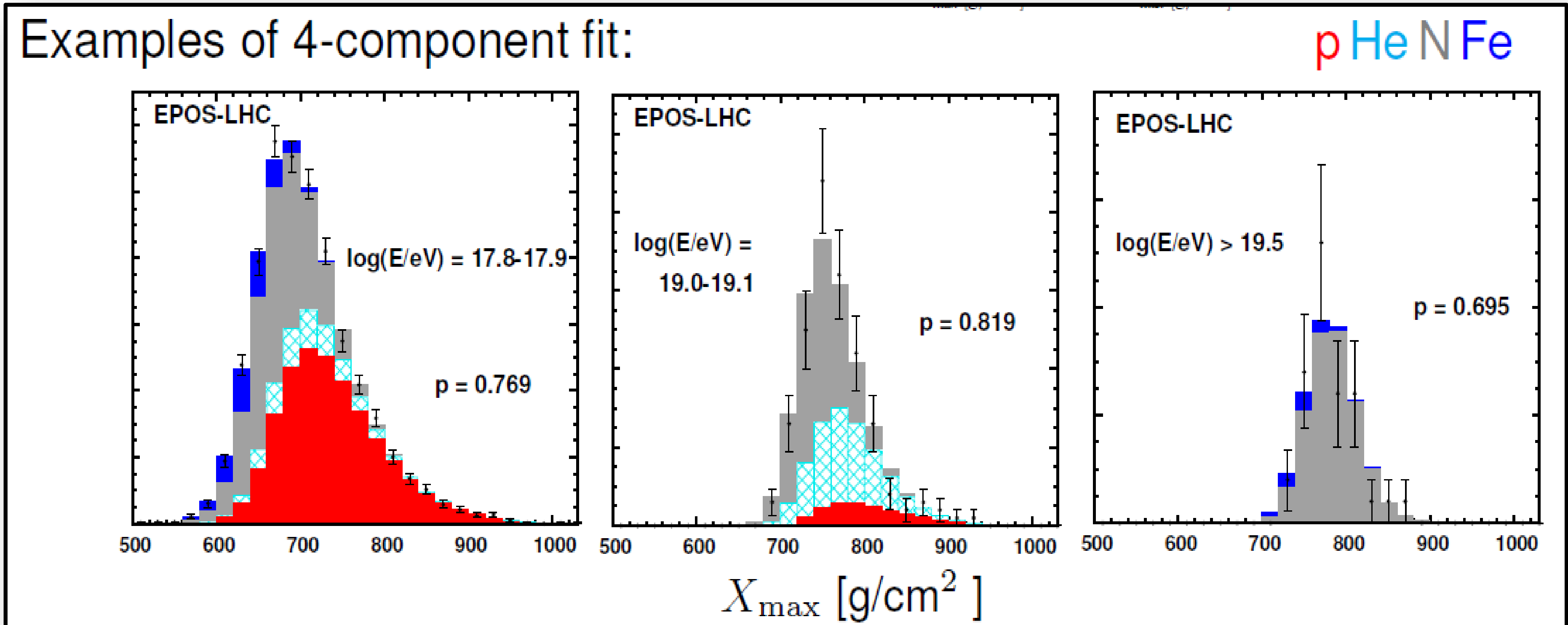
> X_{max} *is an observable sensitive to the mass composition.*
> *The rate of change of X_{max} with Energy (elongation rate) indicates changing mass composition.*

> Fluctuations of X_{max} decrease above $2{*}10^{18}$ eV, indicating a composition becoming heavier with increasing energy.

> The inferred mass composition relies heavily on validity of the hadronic interaction models (extrapolations of the experimental data to high energy is associated with high uncertainty).

Mass composition: (p-He-N-Fe)-fit of X_{max} distributions to Auger data

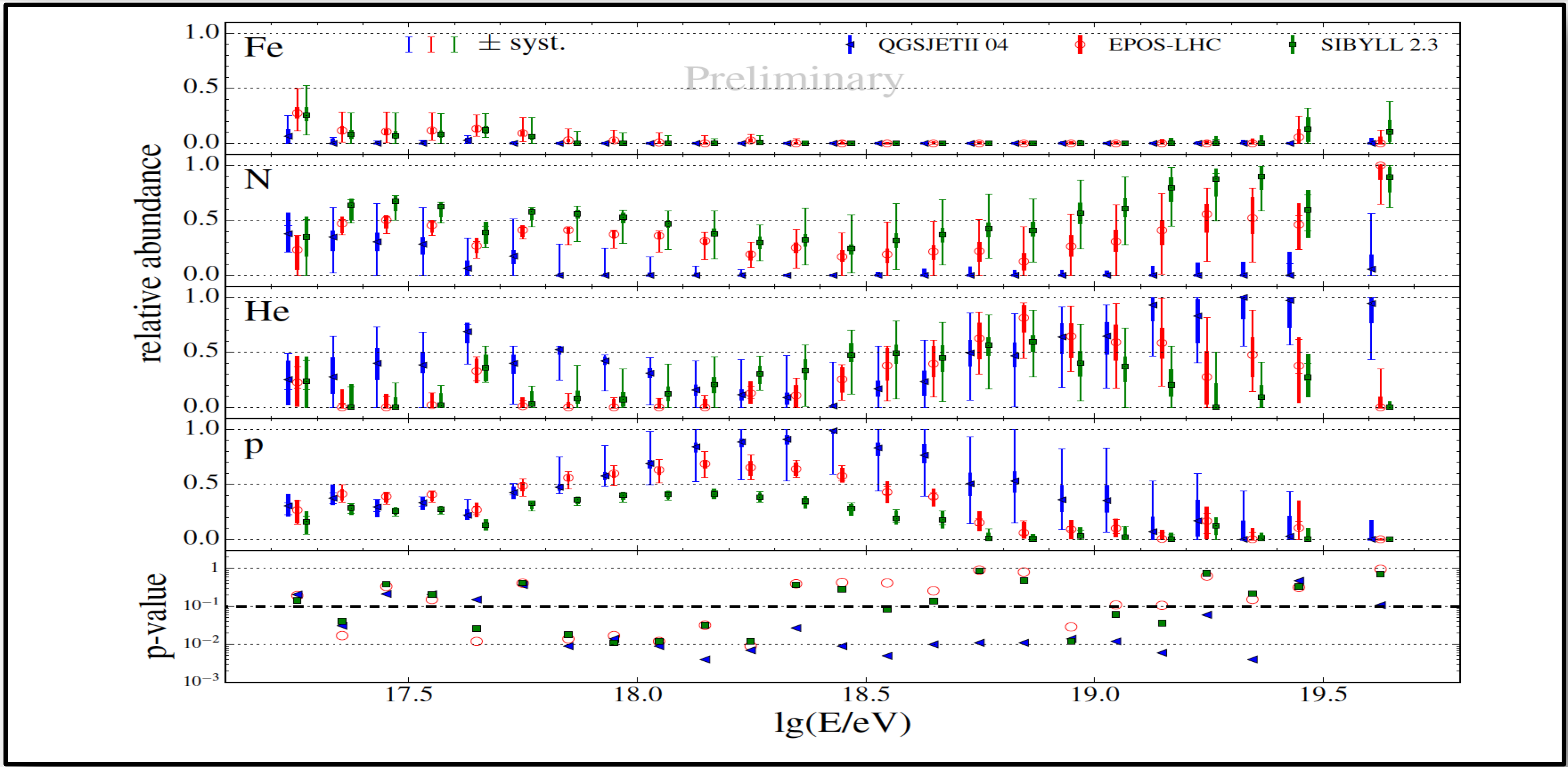
Examples of 4-component fit:



> Composition **proton-like** at 10^{18} eV and **N-like** above 10^{19} eV

> The composition which best describes Auger data is a mix of **p** He and **N** nuclei, i.e. **AugerMix**

AugerMix

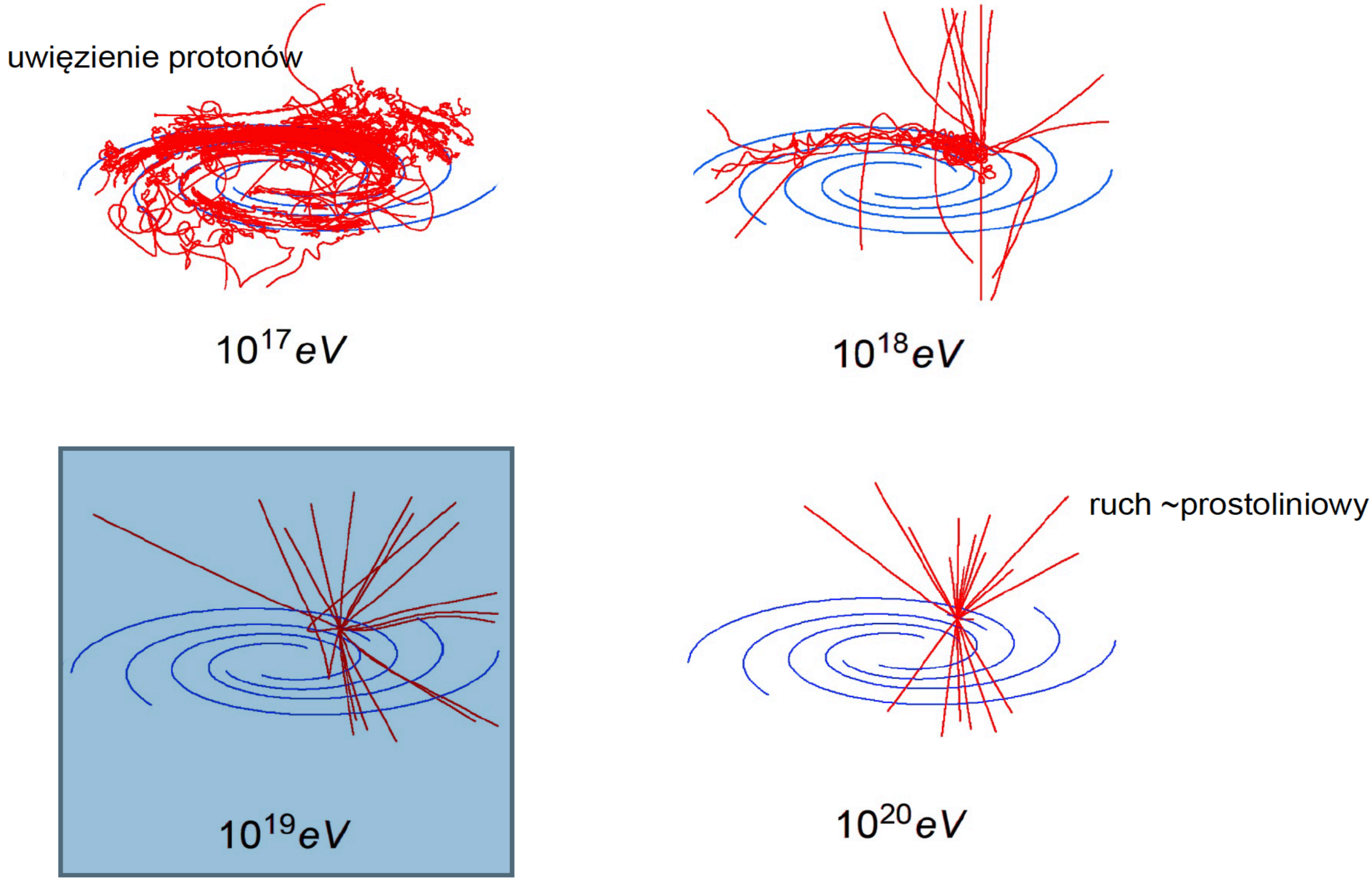


> *No model requires any significant fraction of iron at any energy.*
> *A significant reduction in the proton fraction above 2 EeV*

> The intermediate masses (He, N) at all energies have a strong model dependence.
> p-values indicates that the hadronic interaction models have difficulties to reproduce the details of the observed X_{max} distribution.

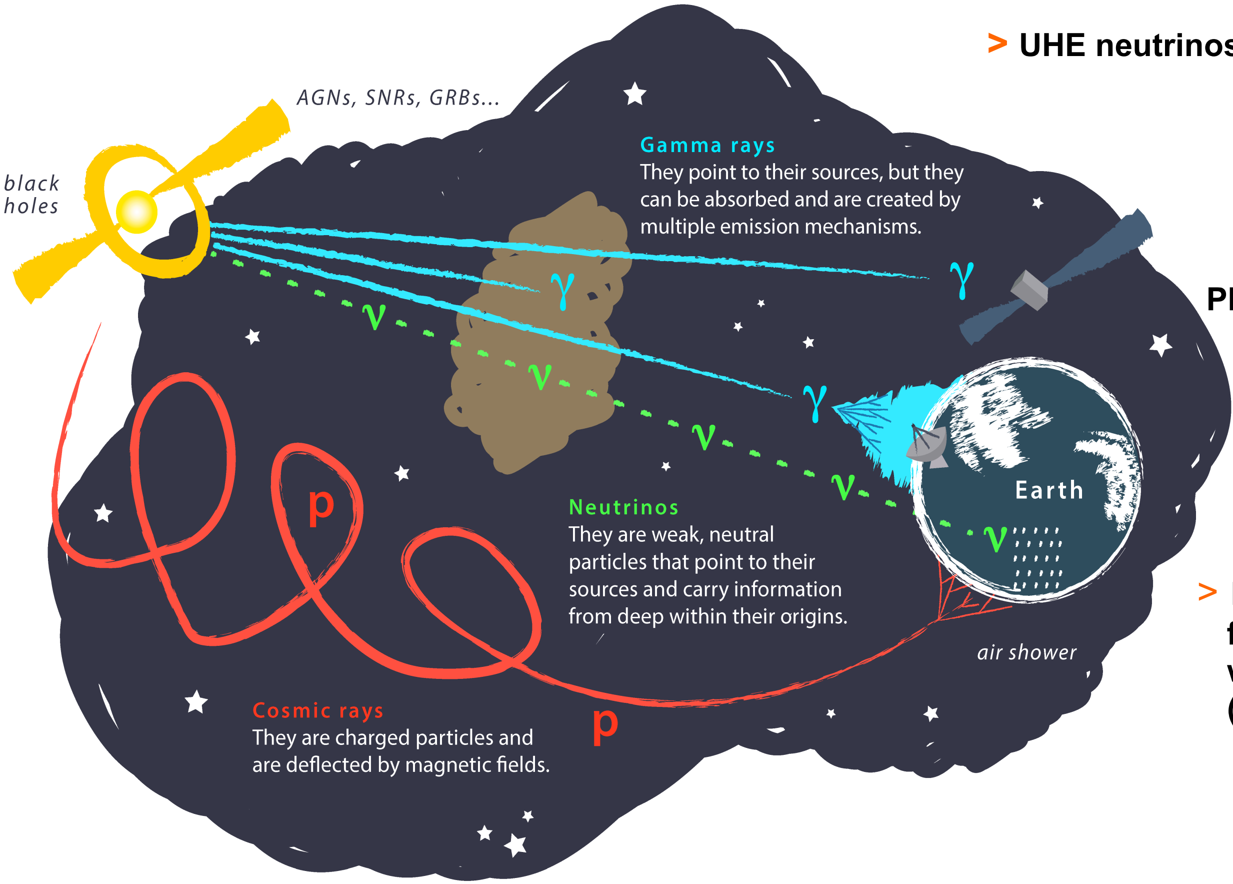
Sources of UHCR
(next talk)

Propagation of cosmic rays in the Galaxy



Neutrino/photon production: hadronic model

Image: Juan Antonio Aguilar and Jamie Yang. IceCube/WIPAC



Hadronic model:

> **UHE neutrinos arise from decays of charged pions:**

$$\begin{aligned} p + p(\gamma) &\rightarrow \pi^{\pm} + X \\ &\hookrightarrow \mu^{\pm} + \nu_\mu(\bar{\nu}_\mu) \\ &\quad \hookrightarrow e^{\pm} + \bar{\nu}_\mu(\nu_\mu) + \nu_e(\bar{\nu}_e) \end{aligned}$$

Photons arise from decays of neutral pions:

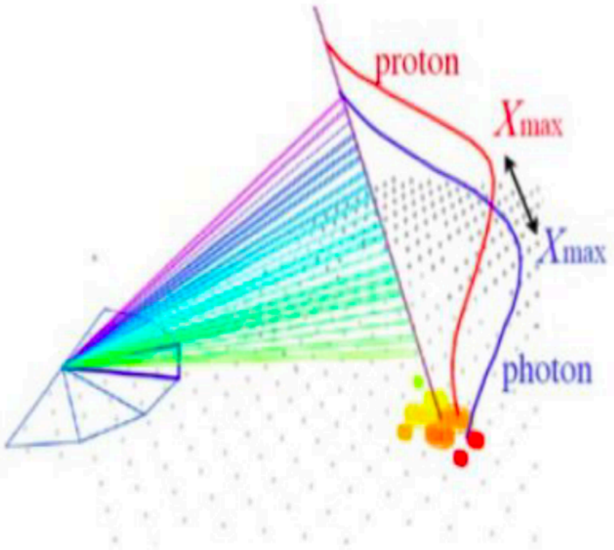
$$\begin{aligned} p + p(\gamma) &\rightarrow \pi^{0} + X \\ &\hookrightarrow 2\gamma \end{aligned}$$

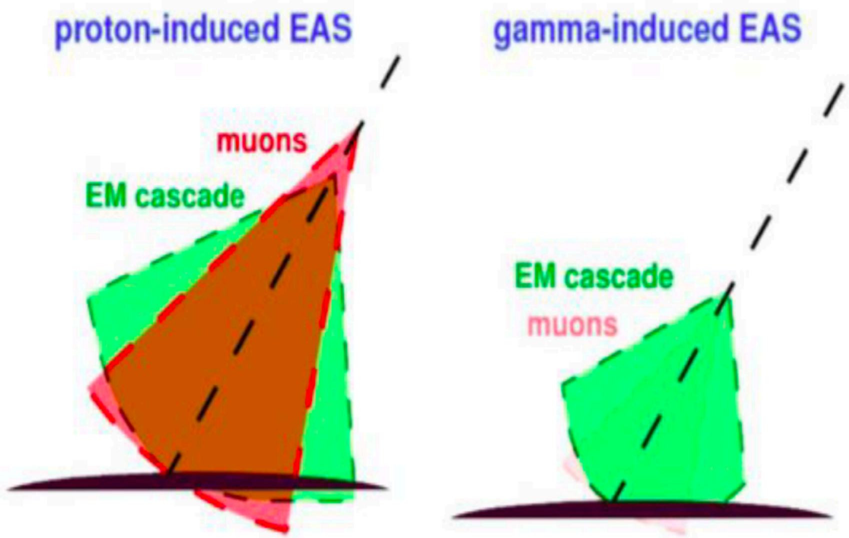
> **Neutrinos/photons are also produced from interaction of Cosmic-rays with Microwave Background (GZK or cosmogenic neutrinos/photons)**

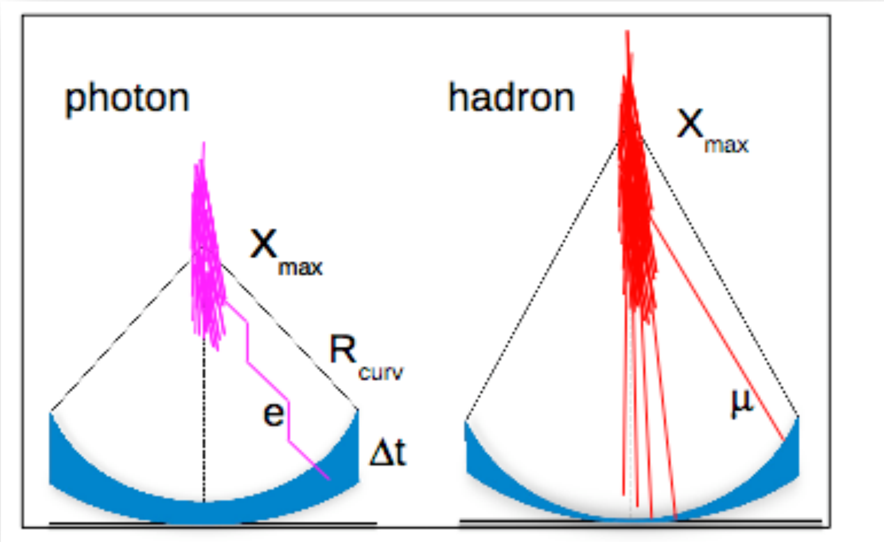
> The determination of the origin of CRs is a difficult task since CRs are deflected during propagation and the extent of this angular deflection is still poorly constrained.

> On the other hand, neutrinos propagate unaffected from their sources to us. They can deliver potentially valuable information on the sources of the most energetic CRs.

Gamma-induced shower: deeper, less muons







Gamma-induced showers:

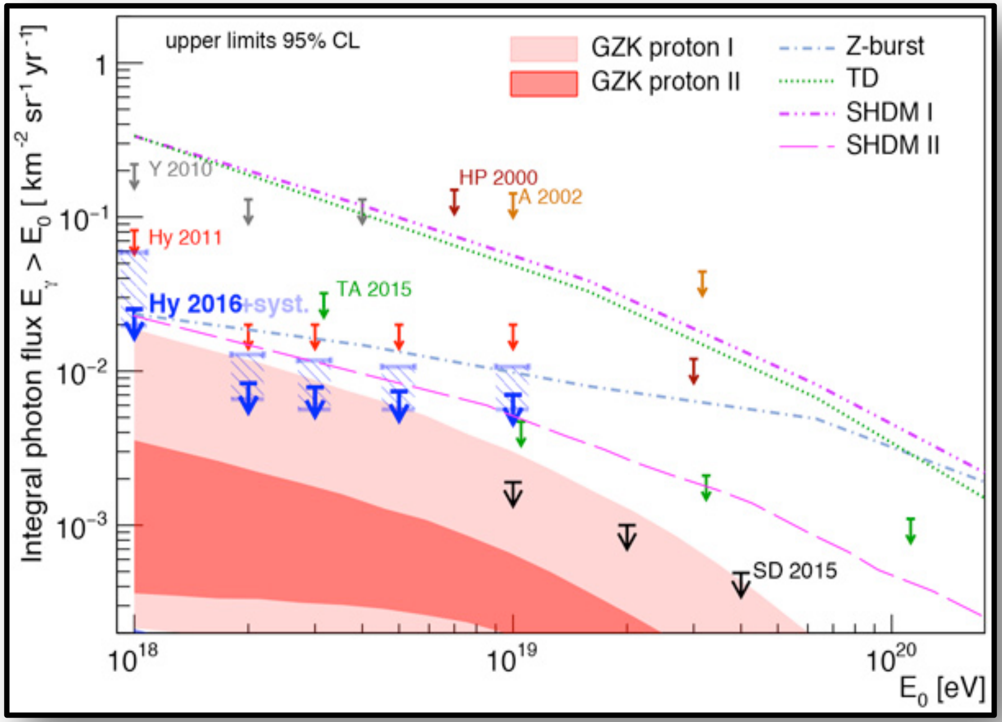
- Larger X_{max} (deepest 1st interaction)
- Larger R_{curv}
- Less muons
- Larger spread in the signal risetime

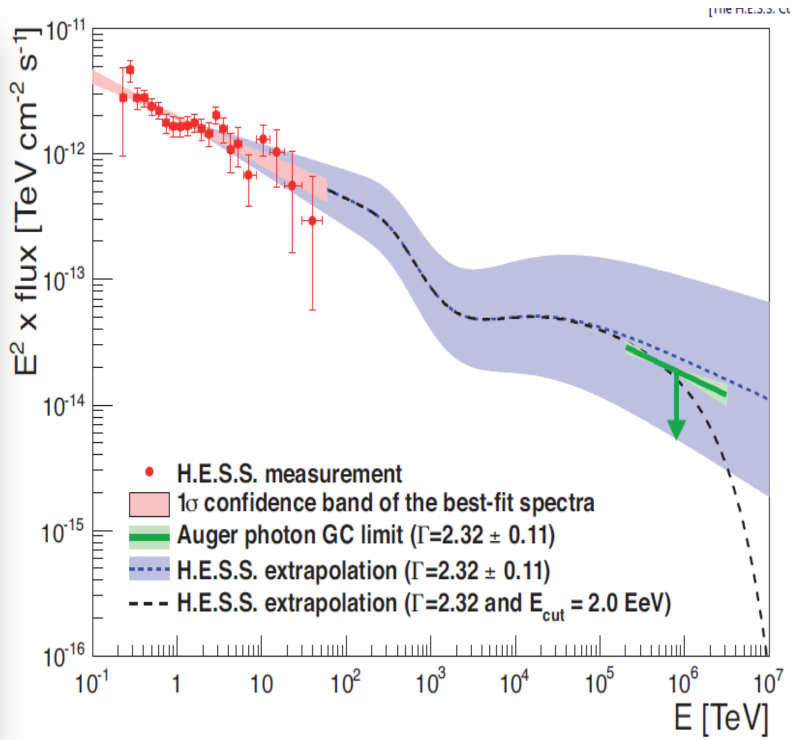
Nuclear showers:

- Smaller X_{max}
- Smaller R_{curv}
- More muons
- Smaller spread in the signal risetime

Searches for cosmogenic photons

$p + \gamma_{CMB} \rightarrow p + \pi^0$ $\pi^0 \rightarrow \gamma + \gamma$

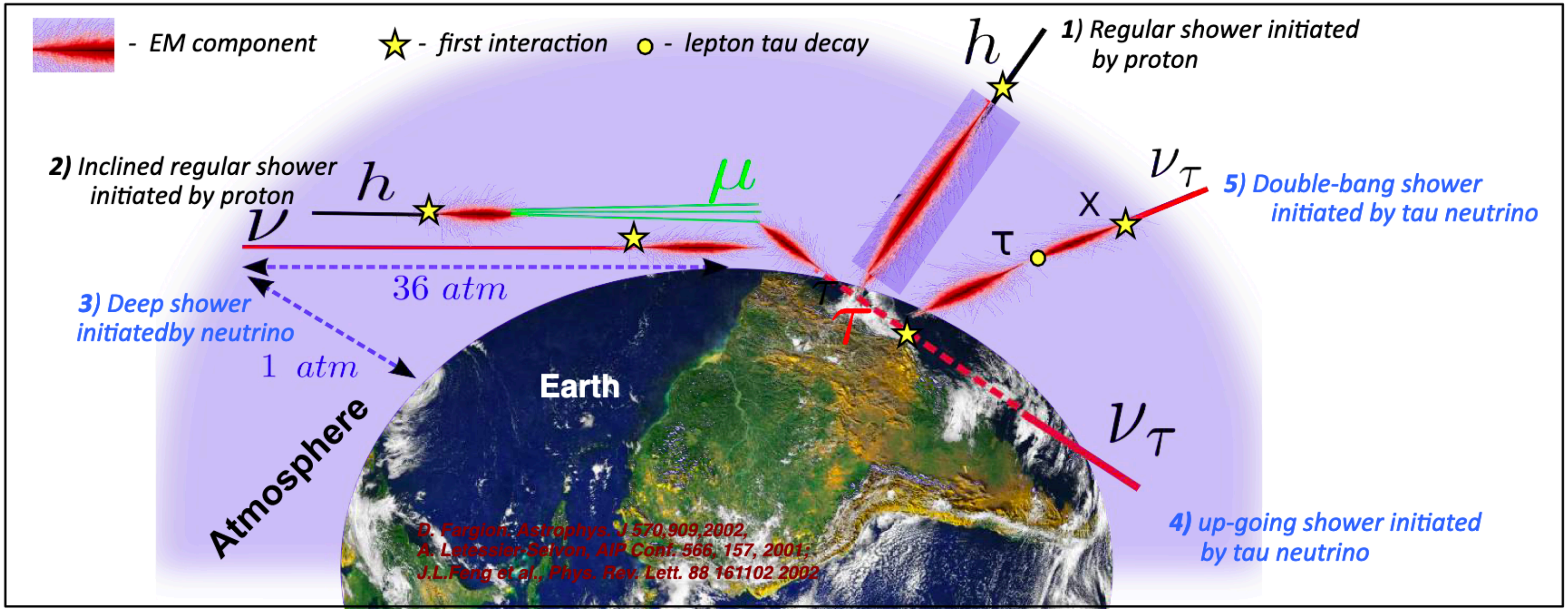




> Models of top-down production of UHECR disfavoured at almost all energies.
> Models of cosmogenic photons assuming a pure proton composition can be tested.
> Constraints for photon flux spectrum from the Galactic center.

Searches for cosmogenic neutrinos

Challenge: identify neutrino showers in dominant background of nucleonic showers

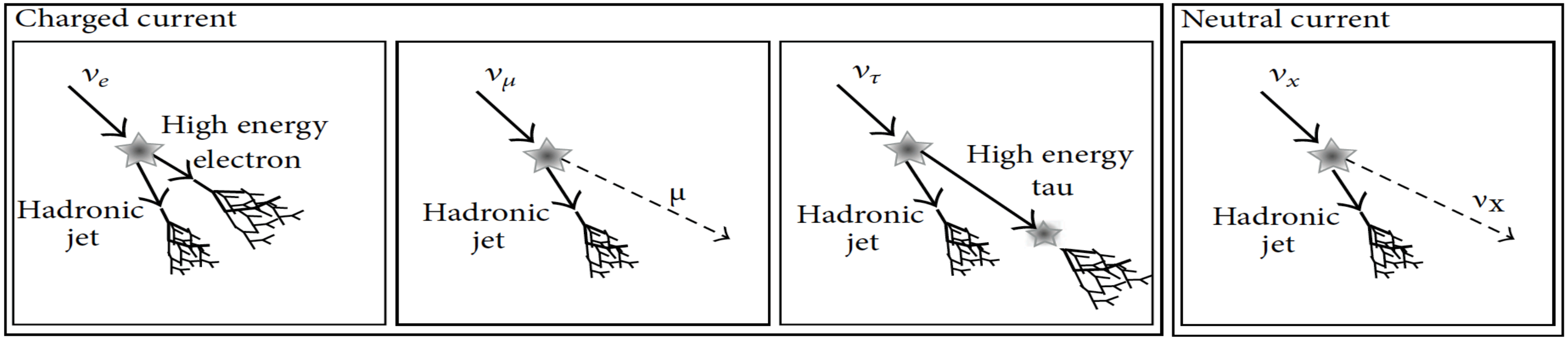


The discrimination power is enhanced when looking at inclined showers ➔ large slant depth

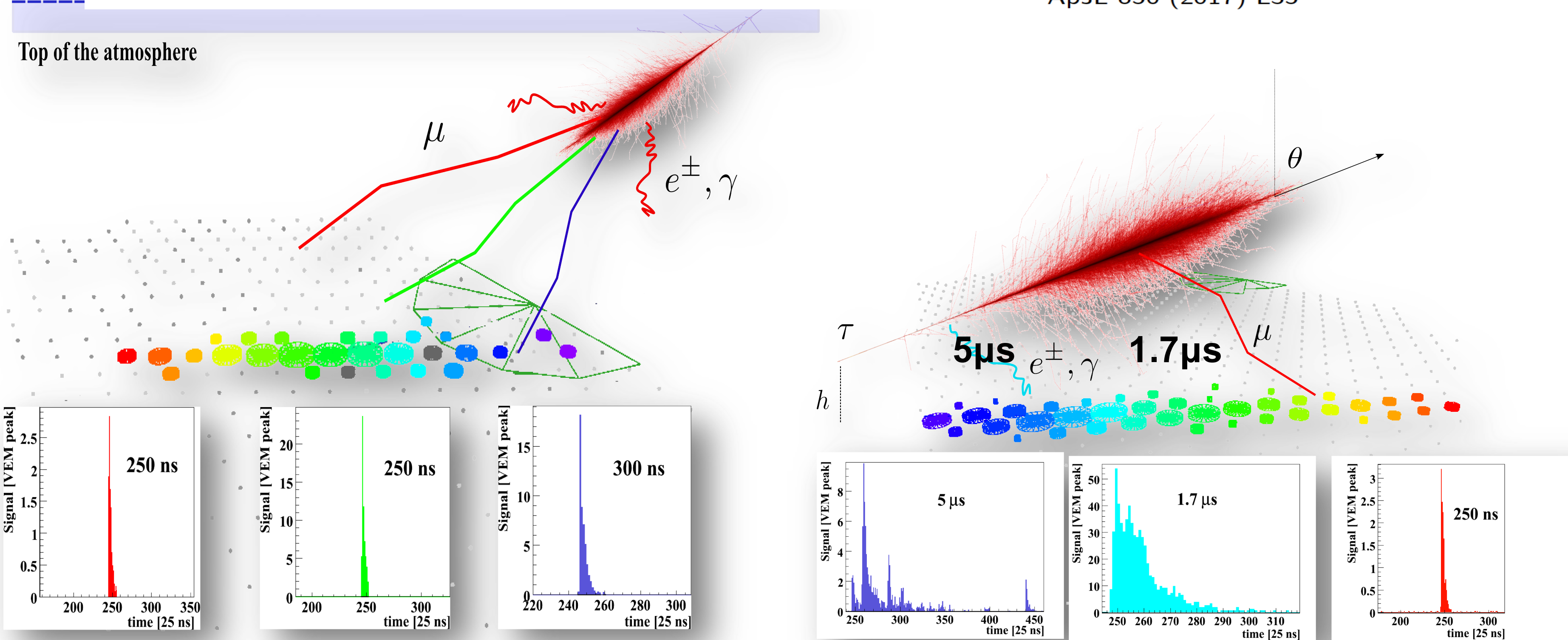
(1-2) Nucleonic cosmic rays initiate showers high in the atmosphere.
Shower at ground: narrow front mainly composed of muons (electromagnetic component absorbed in atmosphere)

(3-4-5) Neutrinos can initiate deep showers
Shower at ground: broad front with electromagnetic + muonic components.

Searches for cosmogenic neutrinos



ApJL 850 (2017) L35

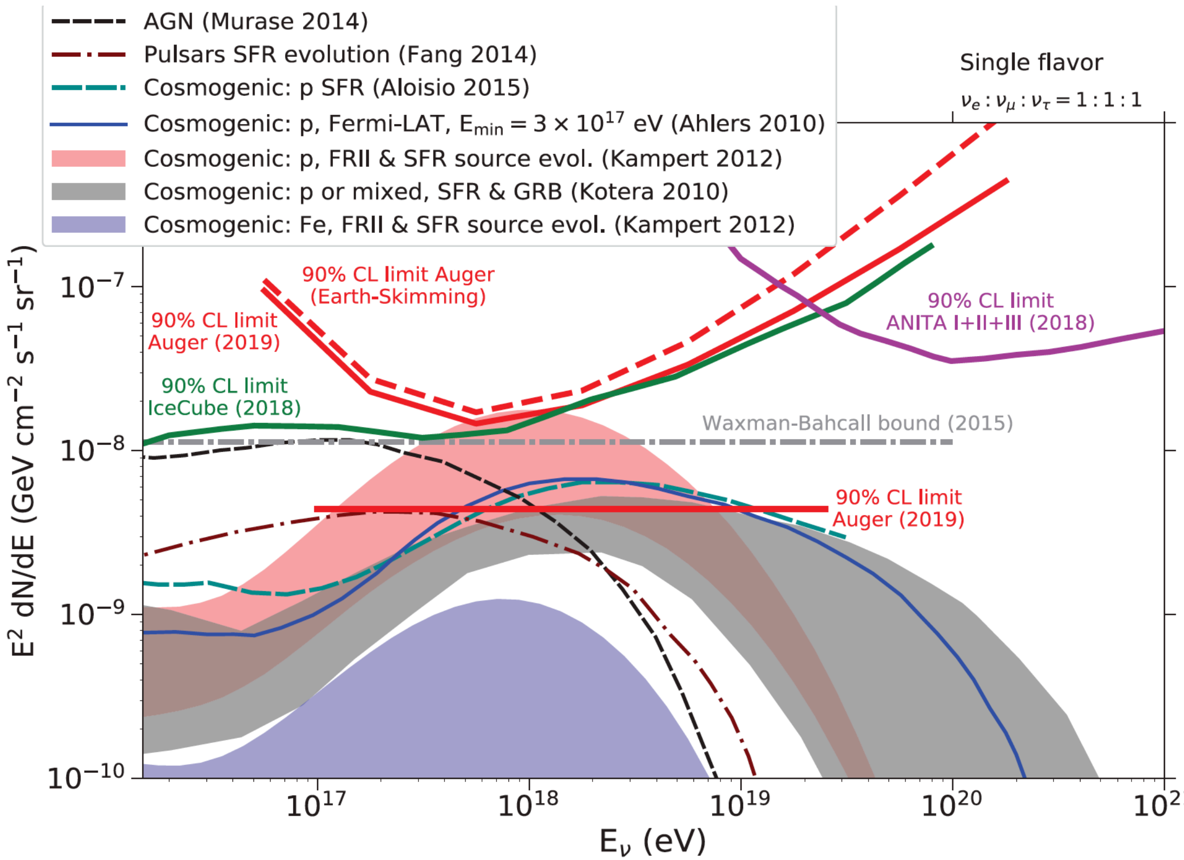


Signature: inclined shower with significant electromagnetic content

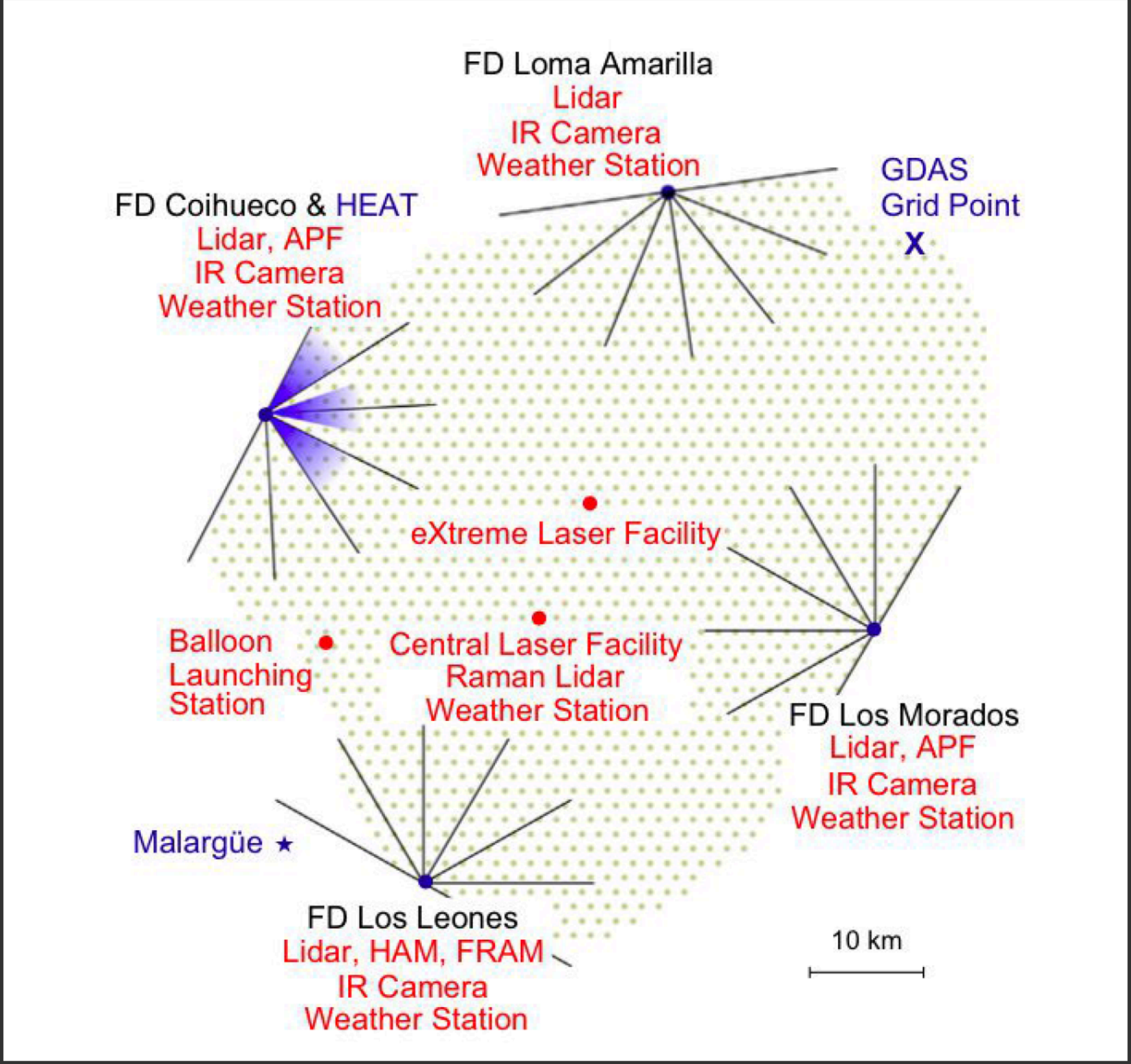
Searches for cosmogenic neutrinos

$p + \gamma_{CMB} \rightarrow n + \pi^+ \qquad \pi^+ \rightarrow e^+ + 3\nu$

No candidates: constraints on proton-dominated astrophysical models and source evolution



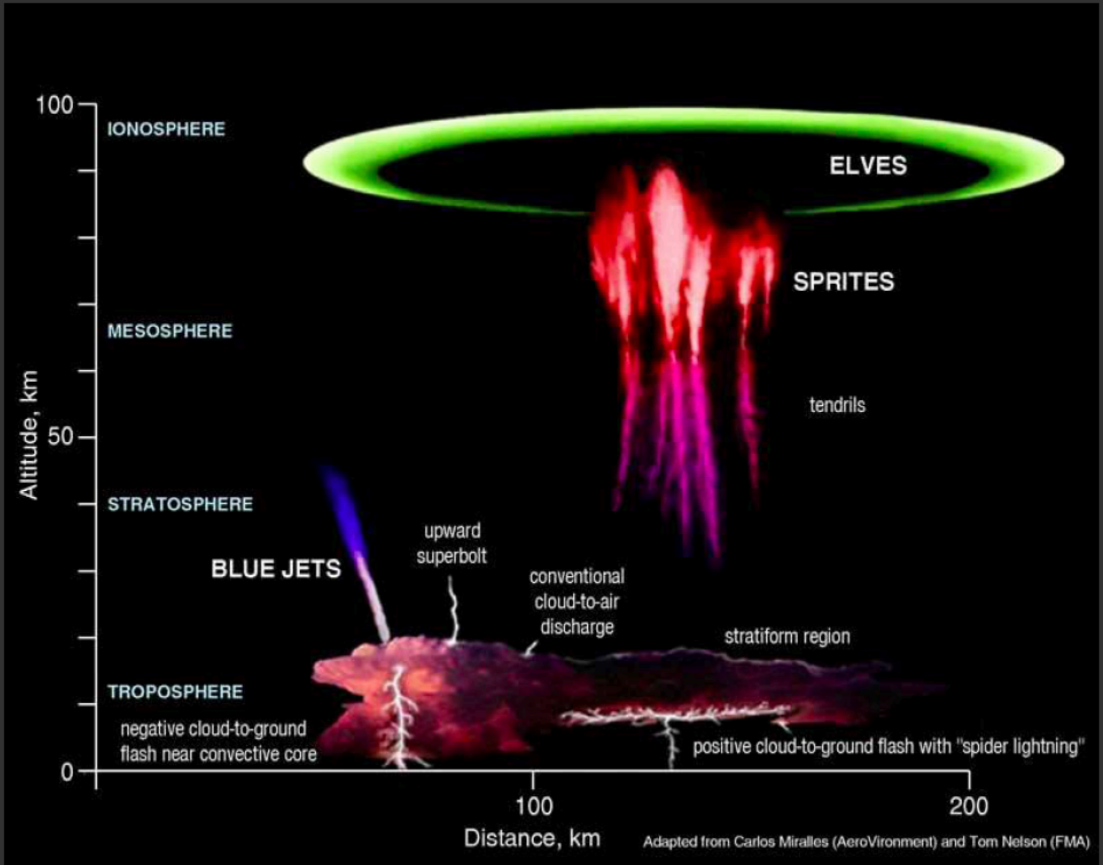
> Neutrino upper flux limits start testing the cosmogenic (GZK) ultra-high energy neutrino production models.

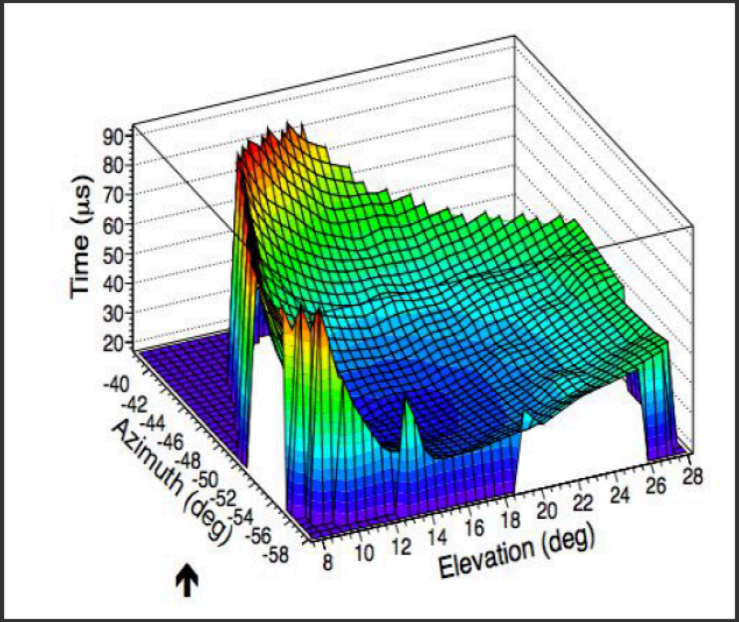

FD Loma Amarilla
Lidar
IR Camera
Weather Station
GDAS
Grid Point
X
FD Coihueco & HEAT
Lidar, APF
IR Camera
Weather Station
eXtreme Laser Facility
Balloon
Launching
Station
Central Laser Facility
Raman Lidar
Weather Station
FD Los Morados
Lidar, APF
IR Camera
Weather Station
Malargüe
FD Los Leones
Lidar, HAM, FRAM
IR Camera
Weather Station
10 km





Transient atmospheric events - Elves
Solar Physics - Space Weather (see LAGO presentation by I. Torres)
Atmospheric Physics



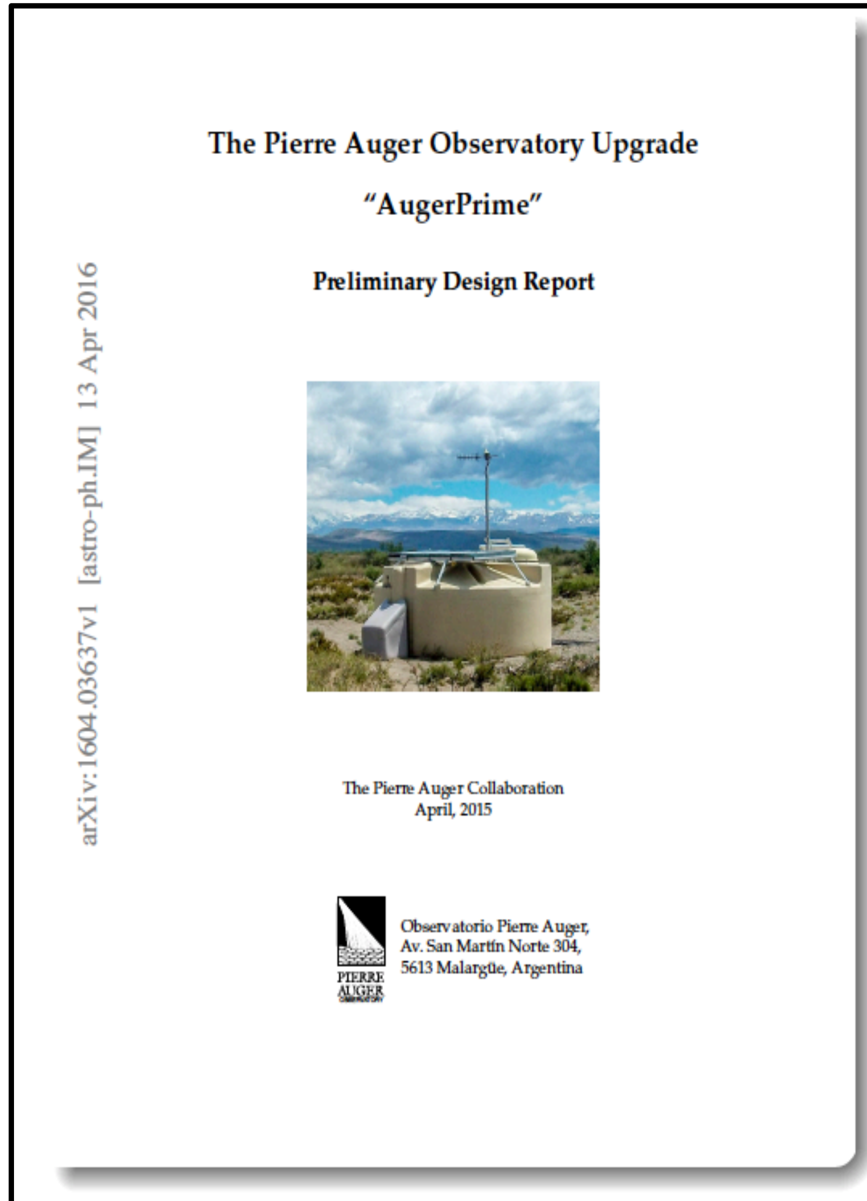


Auger prime

Open questions

> Origin of the flux suppression
> Proton fraction at UHE
> Rigidity-dependence of anisotropies
> Hadronic physics above sqrt(S)=140 TeV

Need large-exposure detector with composition sensitivity



arXiv:1604.03637v1 [astro-ph.IM] 13 Apr 2016

The Pierre Auger Observatory Upgrade

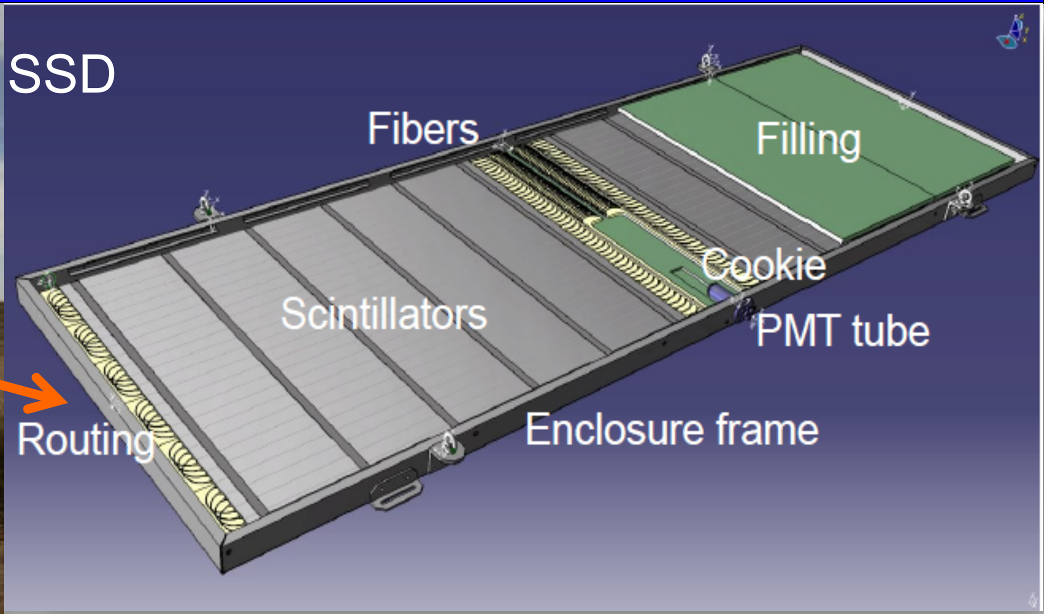
"AugerPrime"

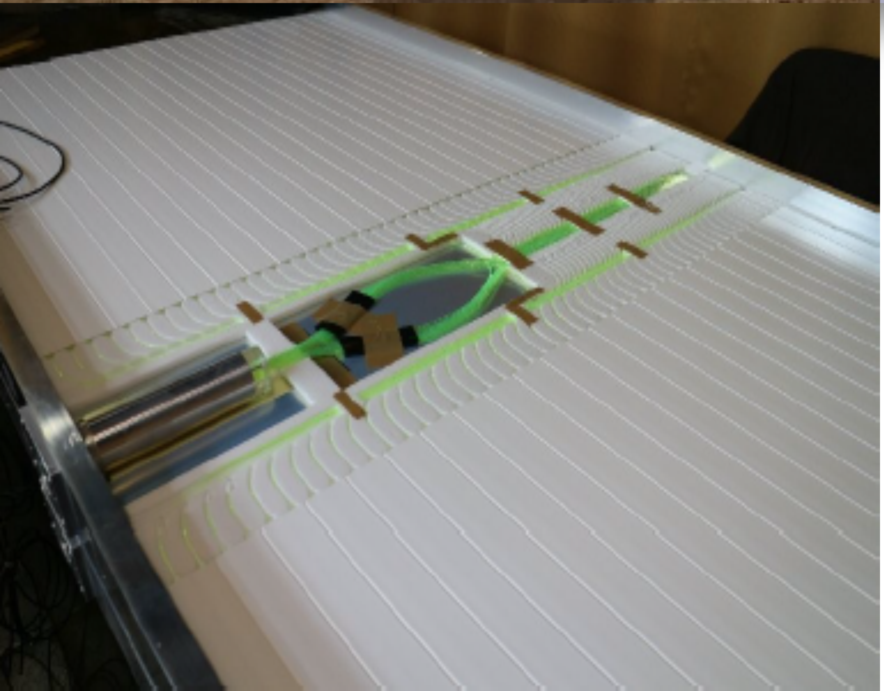
Preliminary Design Report

The Pierre Auger Collaboration
April, 2015

Observatorio Pierre Auger,
Av. San Martín Norte 304,
5613 Malargüe, Argentina

Detector Upgrades for AugerPrime





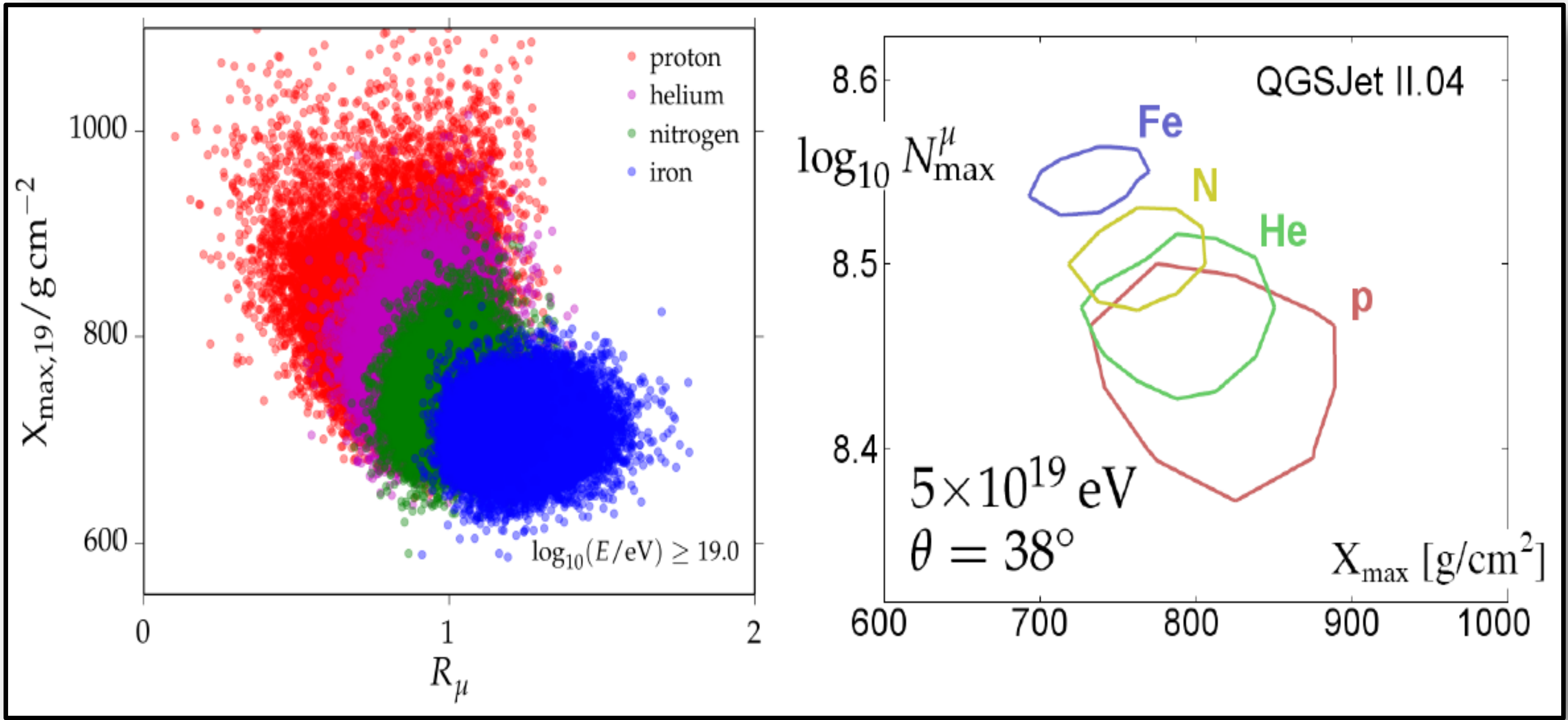
- 3.8 m^2 scintilators (SSD) on each 1500-m array station
- Upgrade of station electronics
- Additional small PMT to increse dynamic range
- Buried muon counters in 750-m array (AMIGA)
- Increasded FD uptime

Auger Prime: Increased Composition Sensitivity

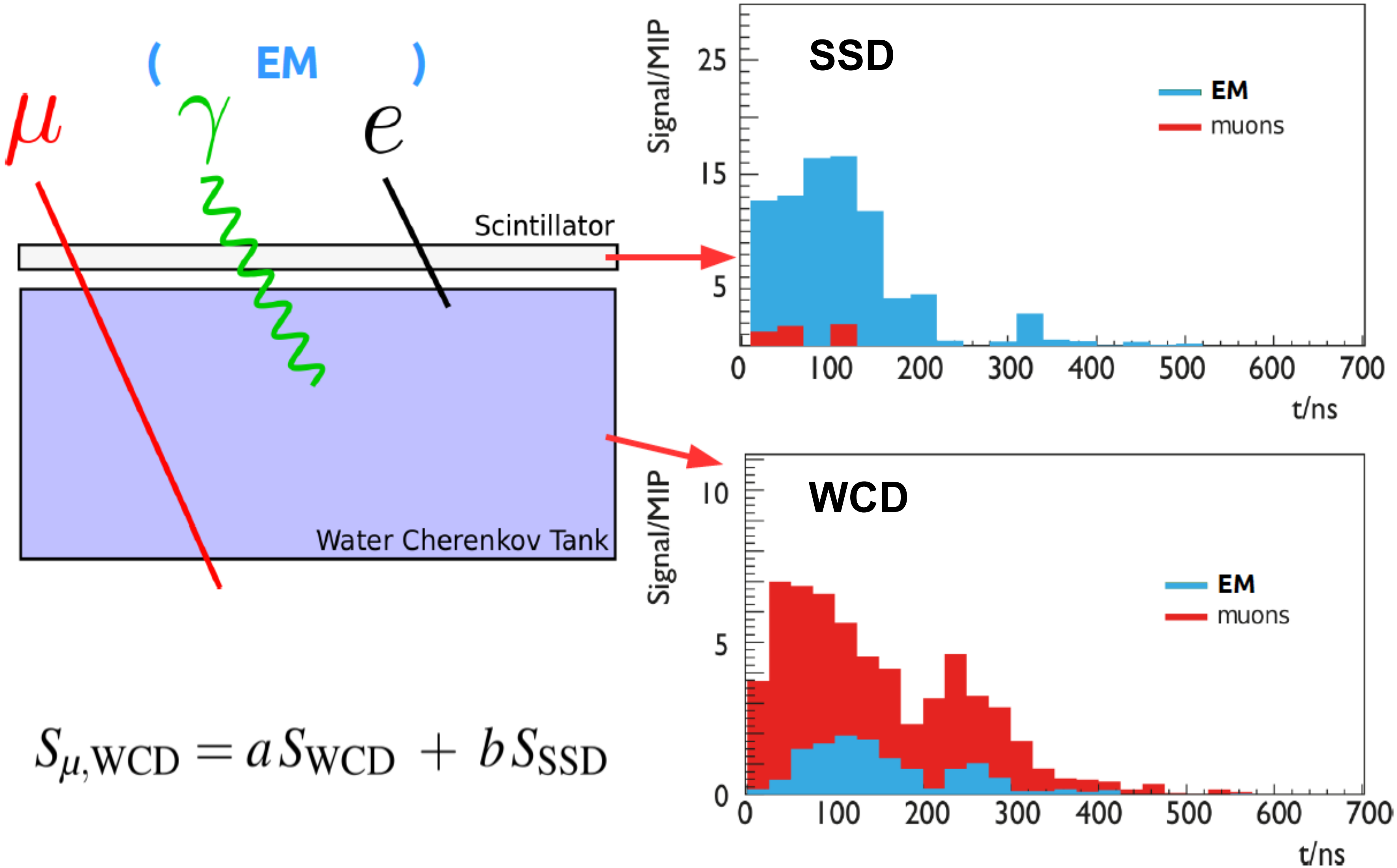
with SSD

main goal !

X_{max} and muons



Complementary response



$$S_{\mu,\mathrm{WCD}} = a\, S_{\mathrm{WCD}} + b\, S_{\mathrm{SSD}}$$

Plans

2016: Engineering Array

2018-2019: deployment of 1200 SSD

2019-2025: data taking
(almost double exposure)

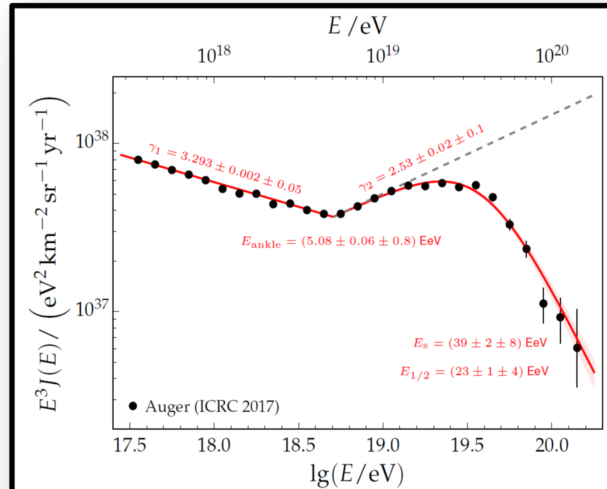
Goal: composition measurement at 10^{20} eV
- composition-enhanced anisotropy studies
- particle physics with air showers

Summary

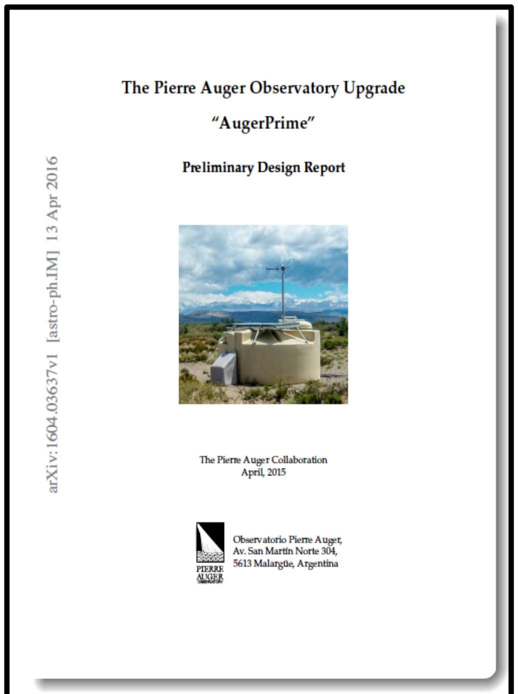
> Suppression of the UHECRs energy spectrum is compatible with GZKcutoff but also with efficiency limit of particle acceleration by sources (maximum rigidity scenario).

> UHECRs appear proton-like at 10^{18} eV and heavier up to 10^{19} eV (N-like).

> No photons and neutrinos with EeV energies detected so far - exotic scenarios of the UHECRs origin disfavored.



> Auger Prime: Increased Composition Sensitivity


The Pierre Auger Observatory Upgrade

"AugerPrime"

Preliminary Design Report

The Pierre Auger Collaboration
April, 2015

Observatorio Pierre Auger,
Av. San Martín Norte 304,
5613 Malargüe, Argentina

arXiv:1604.03637v1 [astro-ph.IM] 13 Apr 2016