The Pierre Auger Observatory: review of latest results and perspectives

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Outline:

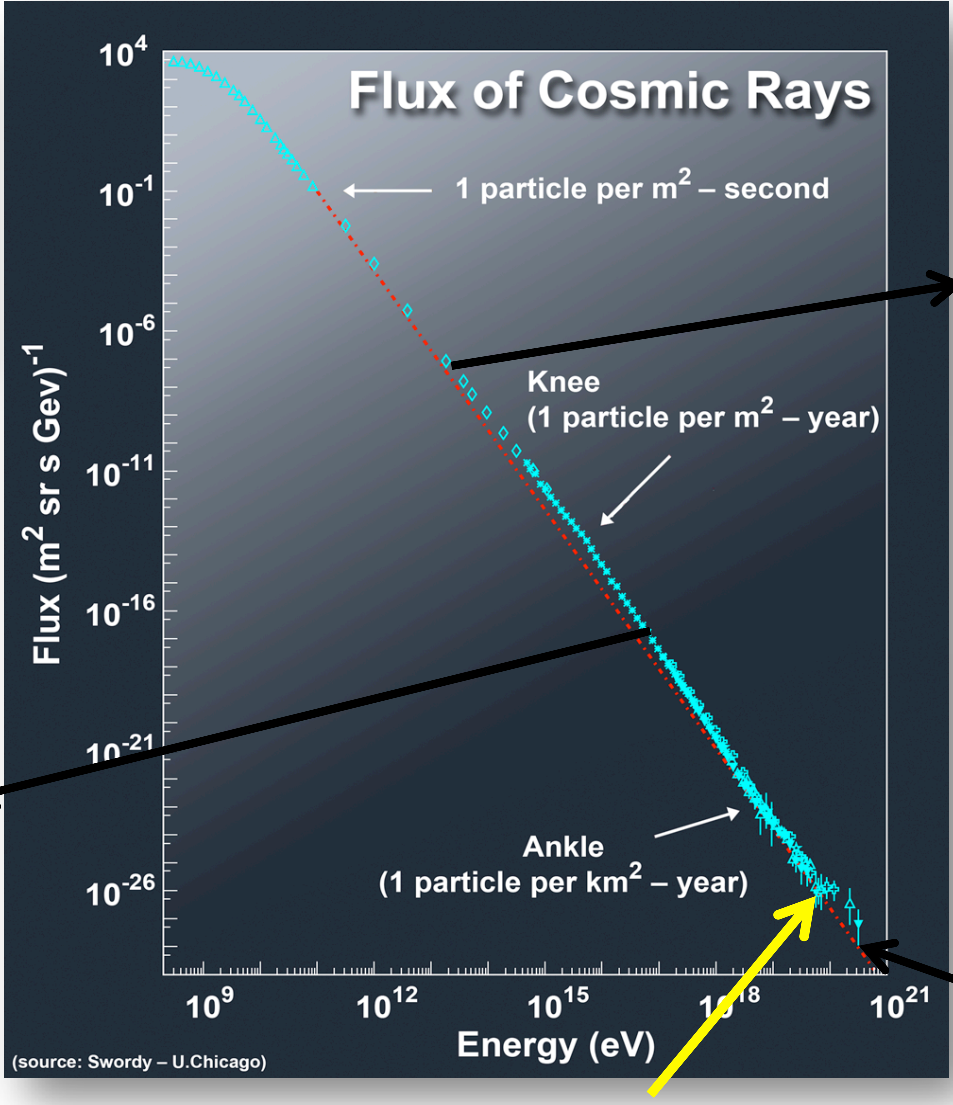
- short CRs introductions
- spectrum, mass composition
- search for sources of CRs
- photon and neutrino limits
- upgrade of the detector: Auger prime
- summary

7th ICNFP2018, 4 - 12 Jul 2018, **2018, Kolymbari-Chania**

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

Sun

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

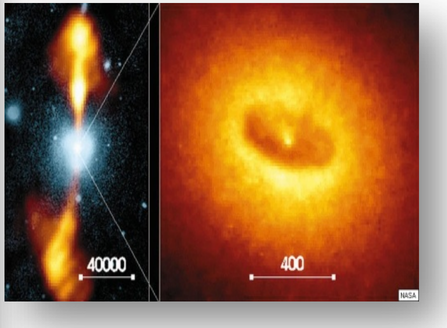


(source: Swordy – U.Chicago)

Supernovae, pulsars

Radio galaxies, galaxy mergers,

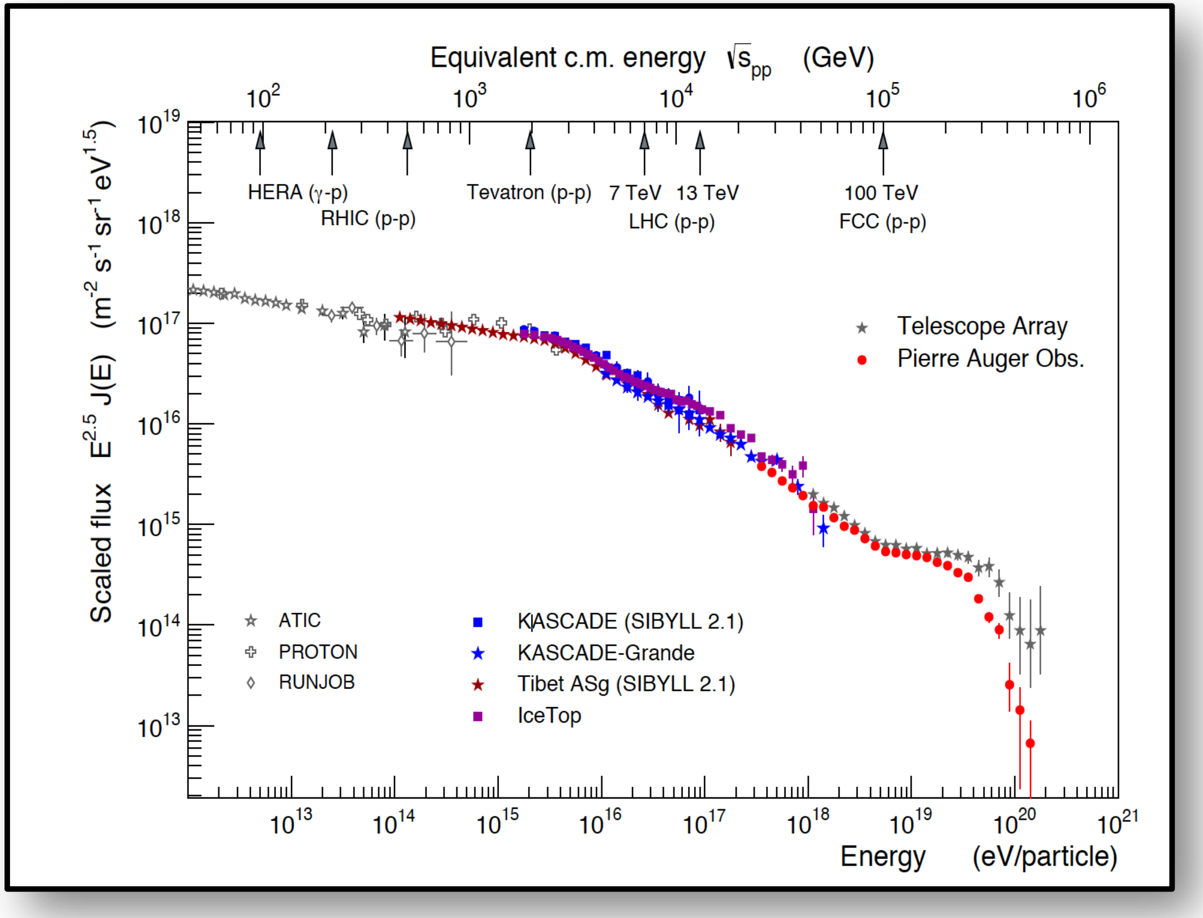
Active galactic nuclei (AGN) ???



?

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?

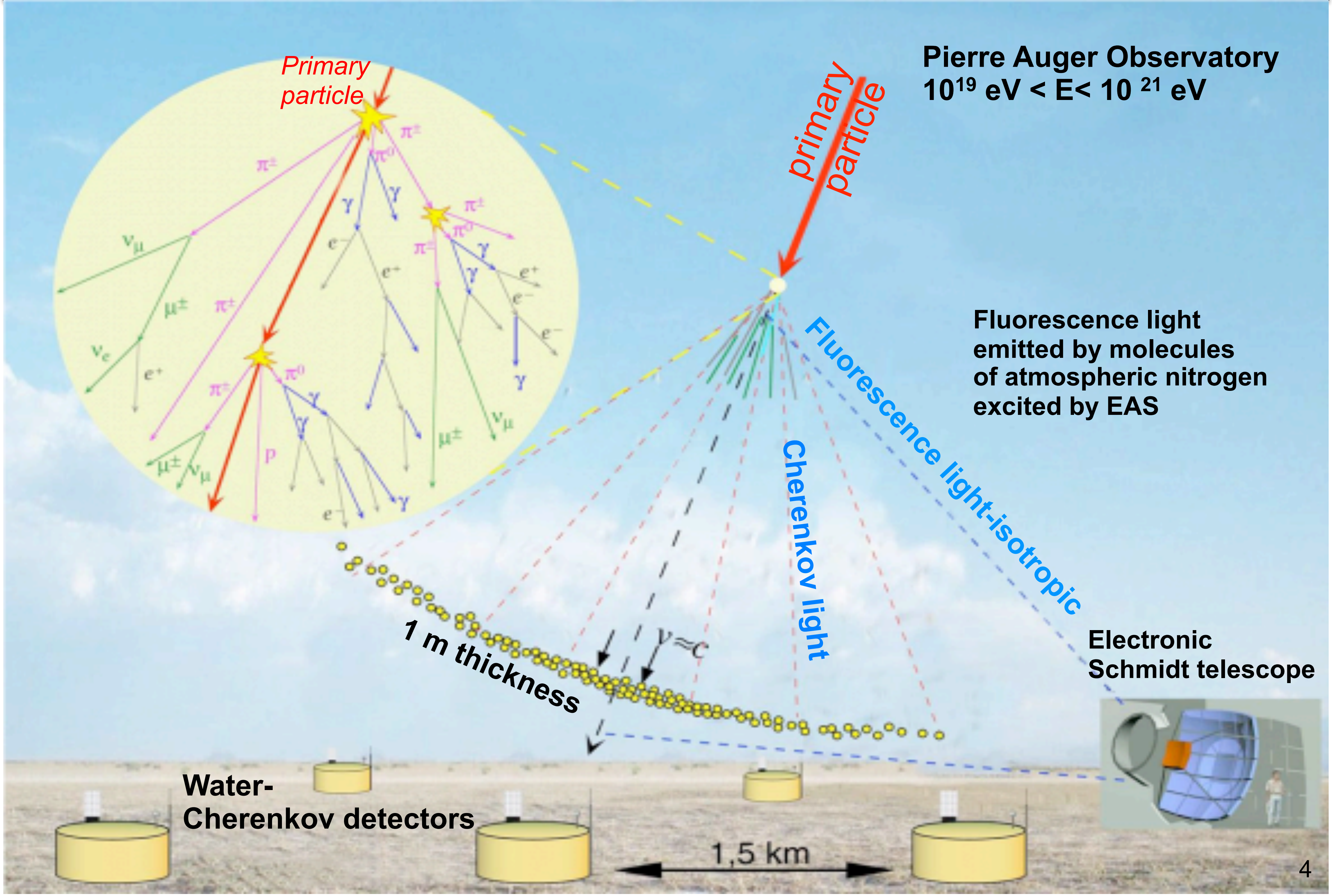
(past the GZK cut-off ! or efficiency limit of the particle acceleration by sources)

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



Pierre Auger Observatory
10^{19} eV < E< 10^{21} eV

Fluorescence light emitted by molecules of atmospheric nitrogen excited by EAS

Electronic Schmidt telescope

Water-Cherenkov detectors

Pierre Auger Observatory - the largest UHECRs observatory

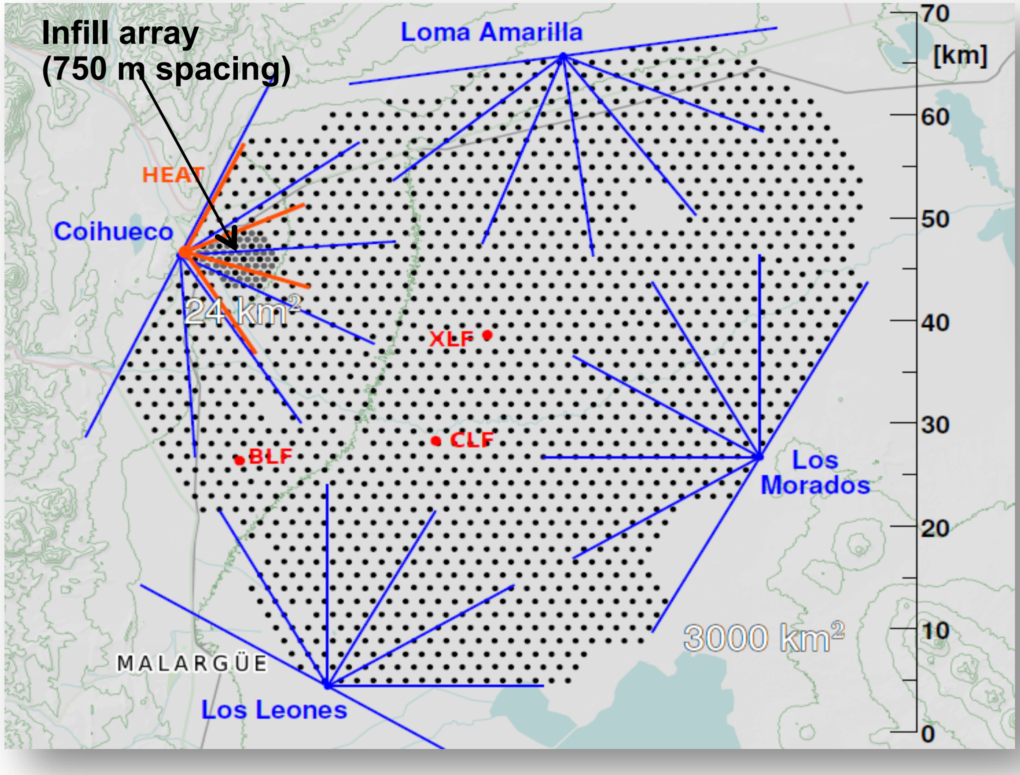
What is/are: spectrum mass composition sources

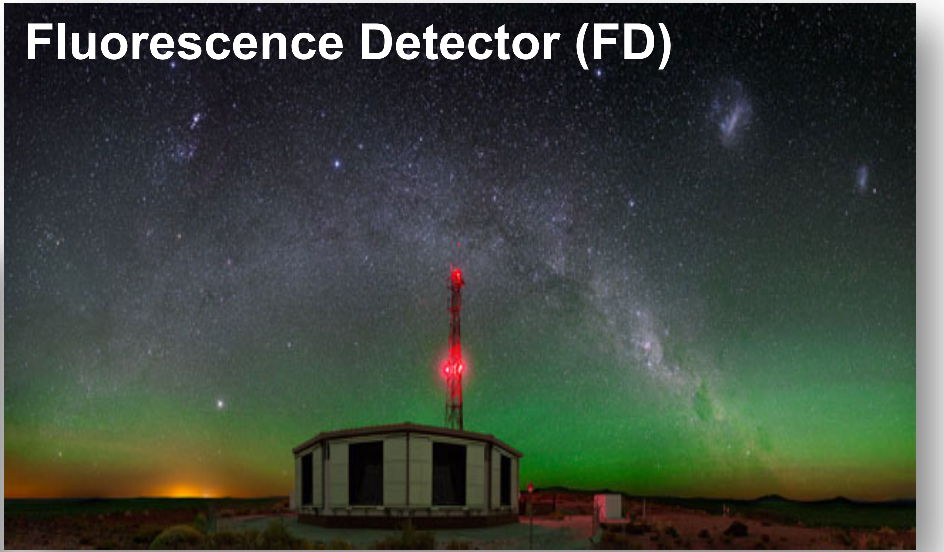
Southern hemisphere

Pierre Auger Observatory (Auger)

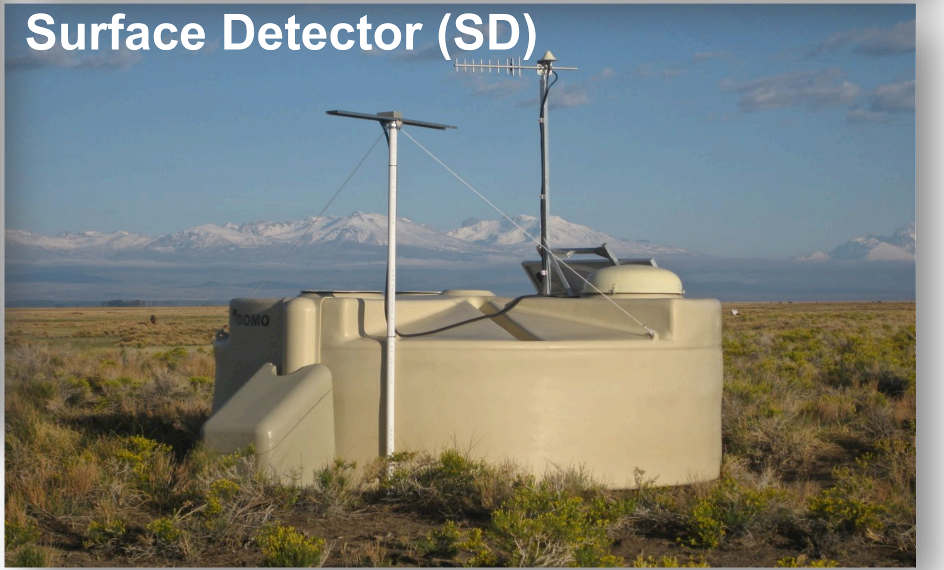
Area: 3000 km^2

Location: Argentina





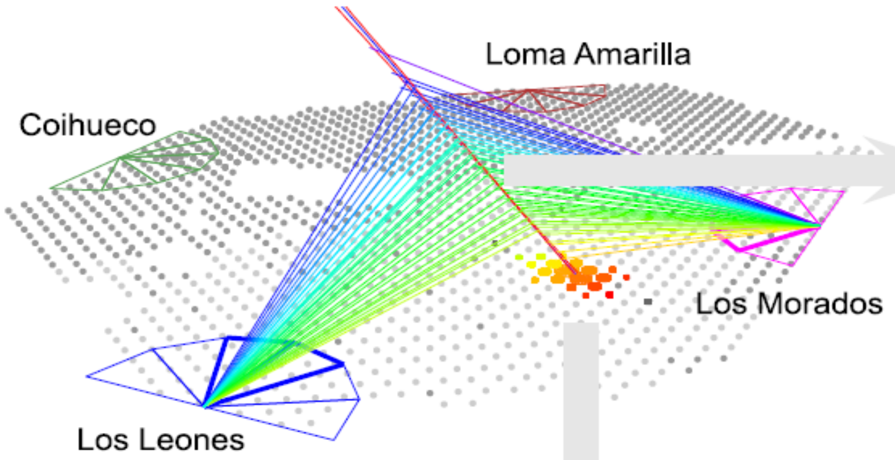
Fluorescence Detector (FD)

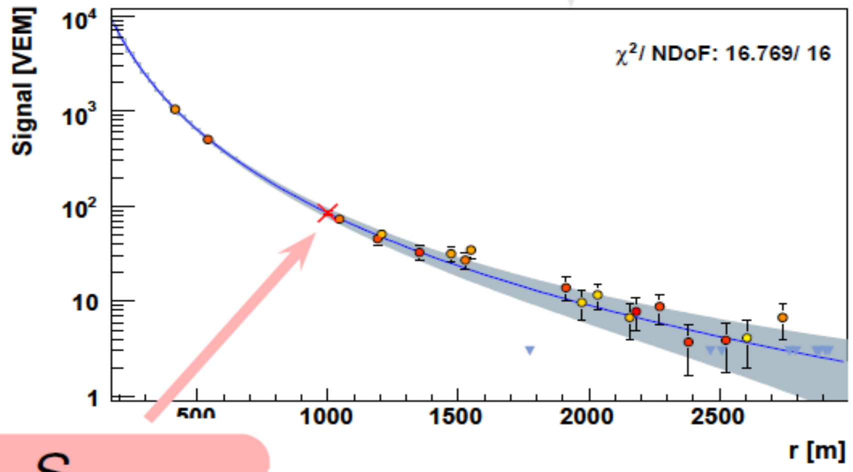


Surface Detector (SD)

> 1600 SD stations over 3000 km^2
  (1500 m spacing) and 5 FD stations
  (4 with telescopes with FoV$_{FD}$ = 2 - 30 deg, and 1 FoV$_{HEAT}$ = 2 – 60 deg in elevation)

Detection of air showers



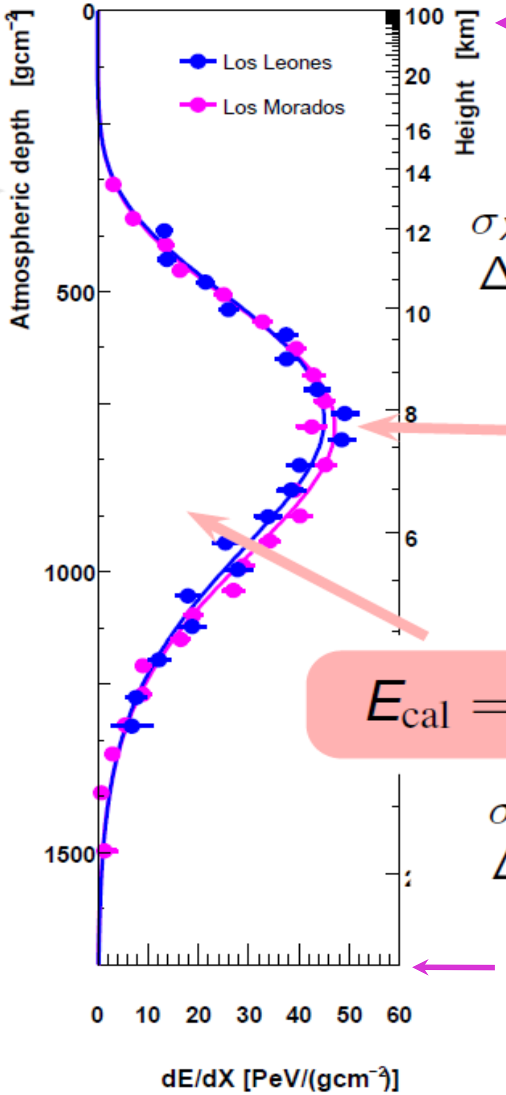


S_{1000}

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

Surface Detector (SD)
100 % duty cycle

top of
the atmosphere



detector level

Energy deposited by EAS

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

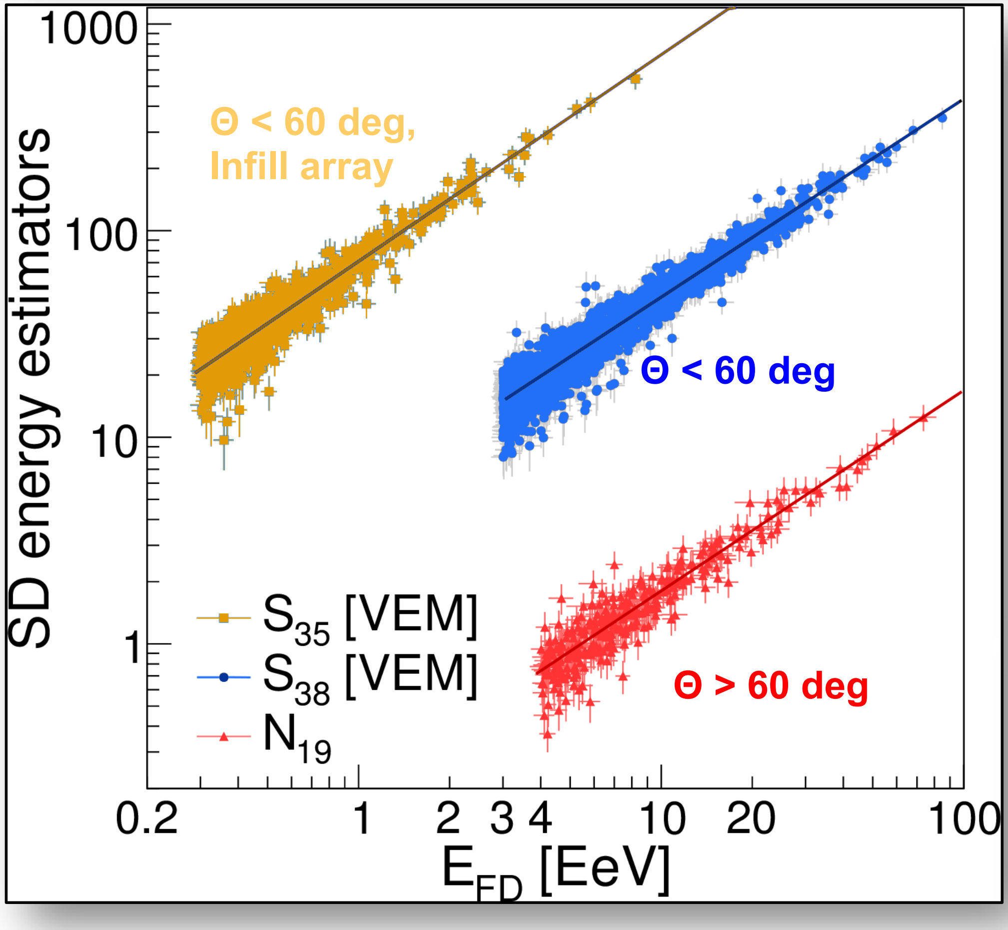
$X_{\max}$

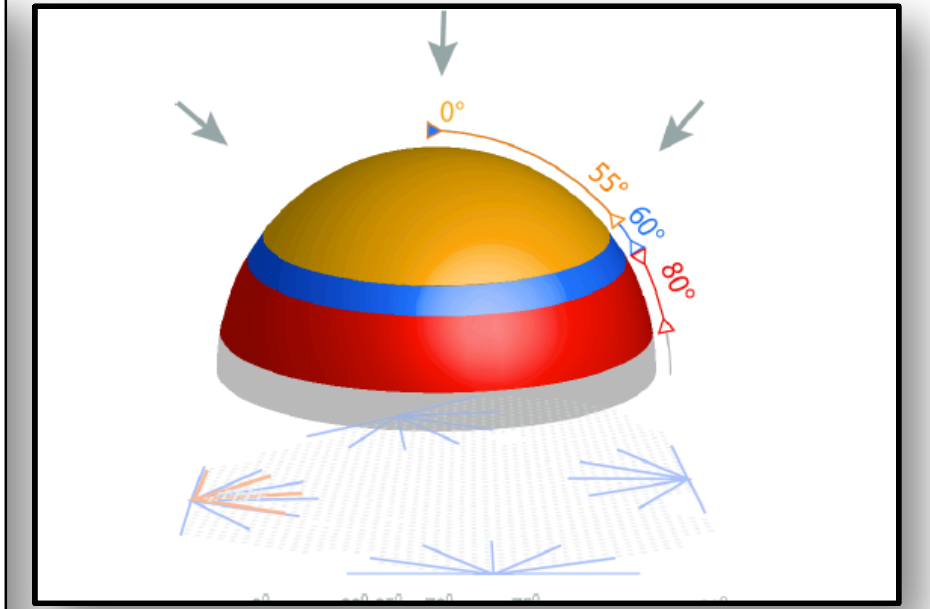
$E_{\text{cal}} = \int \frac{\mathrm{d}E}{\mathrm{d}X}\,\mathrm{d}X$

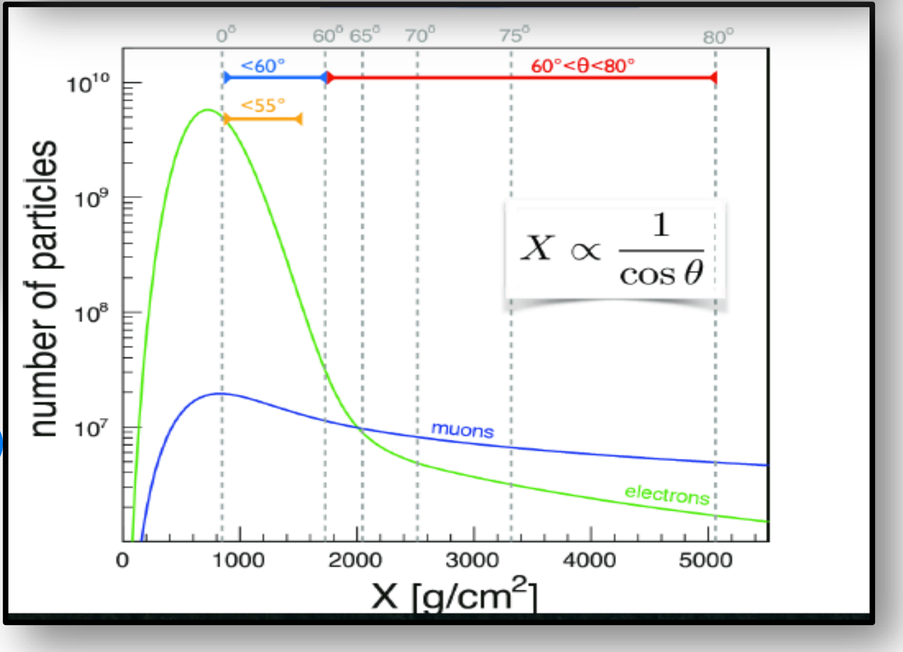
$\sigma_E / E \sim 8\,\%$
$\Delta_{\text{sys}} \approx 15\,\%$

Fluorescence Detector (FD)
15 % duty cycle

Hybrid Energy Calibration







Auger "design concept". Twofold benefit:

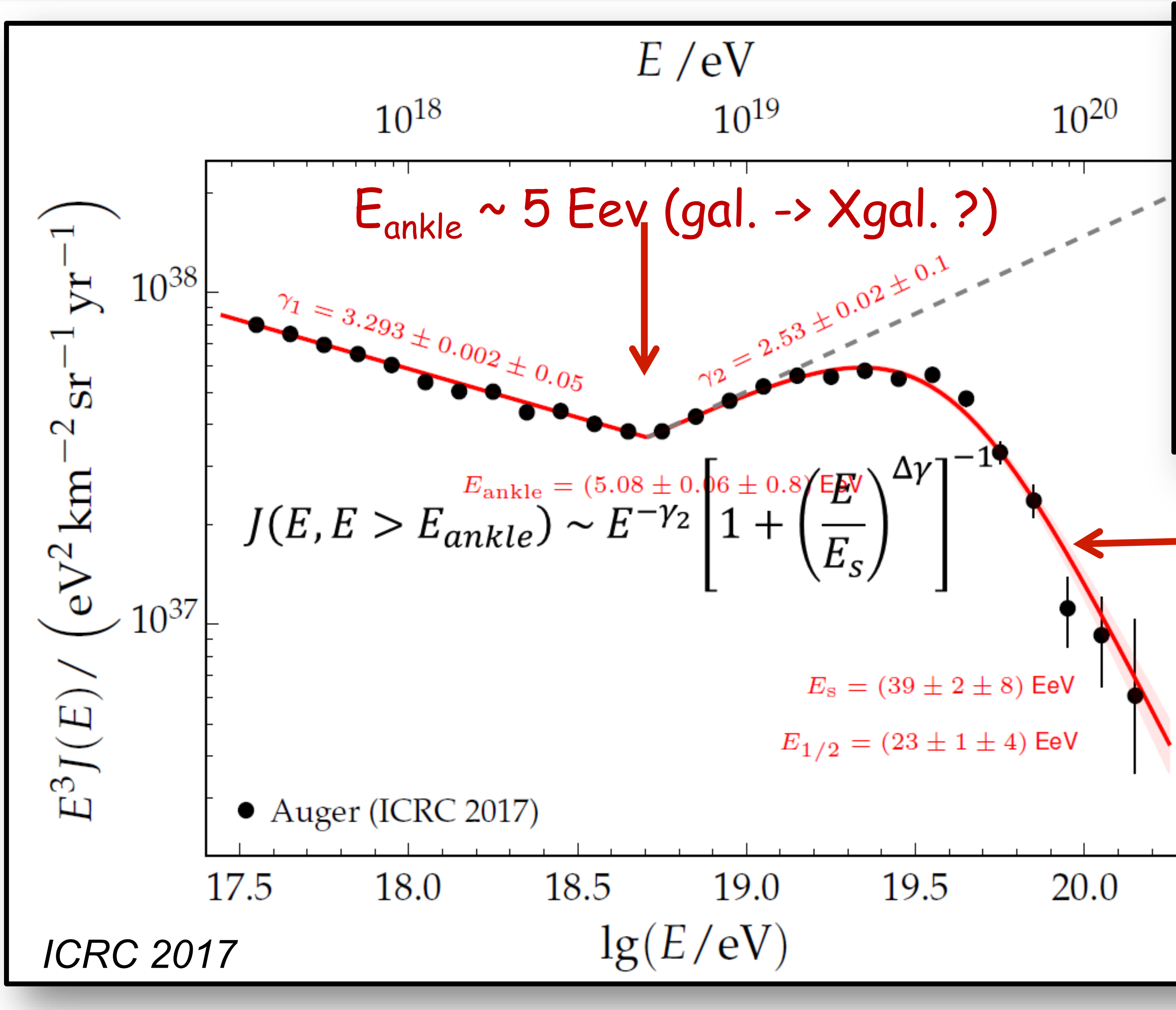
> Hybrid events fewer (DC ≈ 15%) but superior (better geometry, energy and mass determination)

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

$$E_{\mathrm{SD}} = A\big(\underbrace{S(1000)/f_{\mathrm{CIC}}(\theta)}_{S_{38}}/\mathrm{VEM}\big)^{B}$$

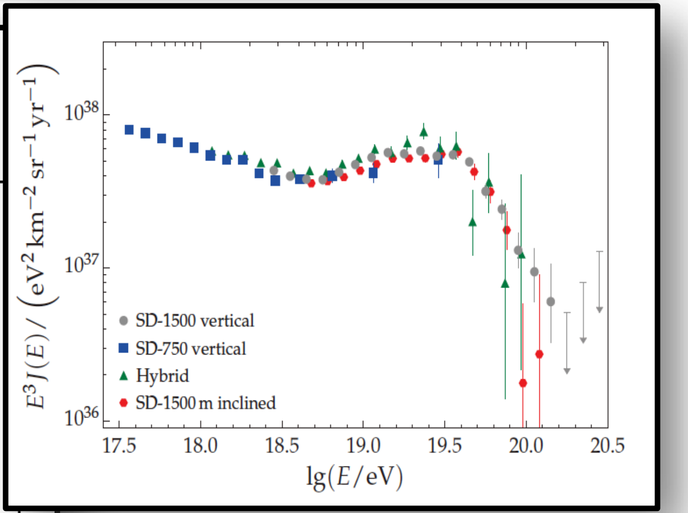
Spectrum of UHCR

UHECRs energy spectrum: combined Auger spectrum



E_{ankle} ~ 5 Eev (gal. -> Xgal. ?)

ICRC 2017



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

Auger $\Delta E / E = 14\%$

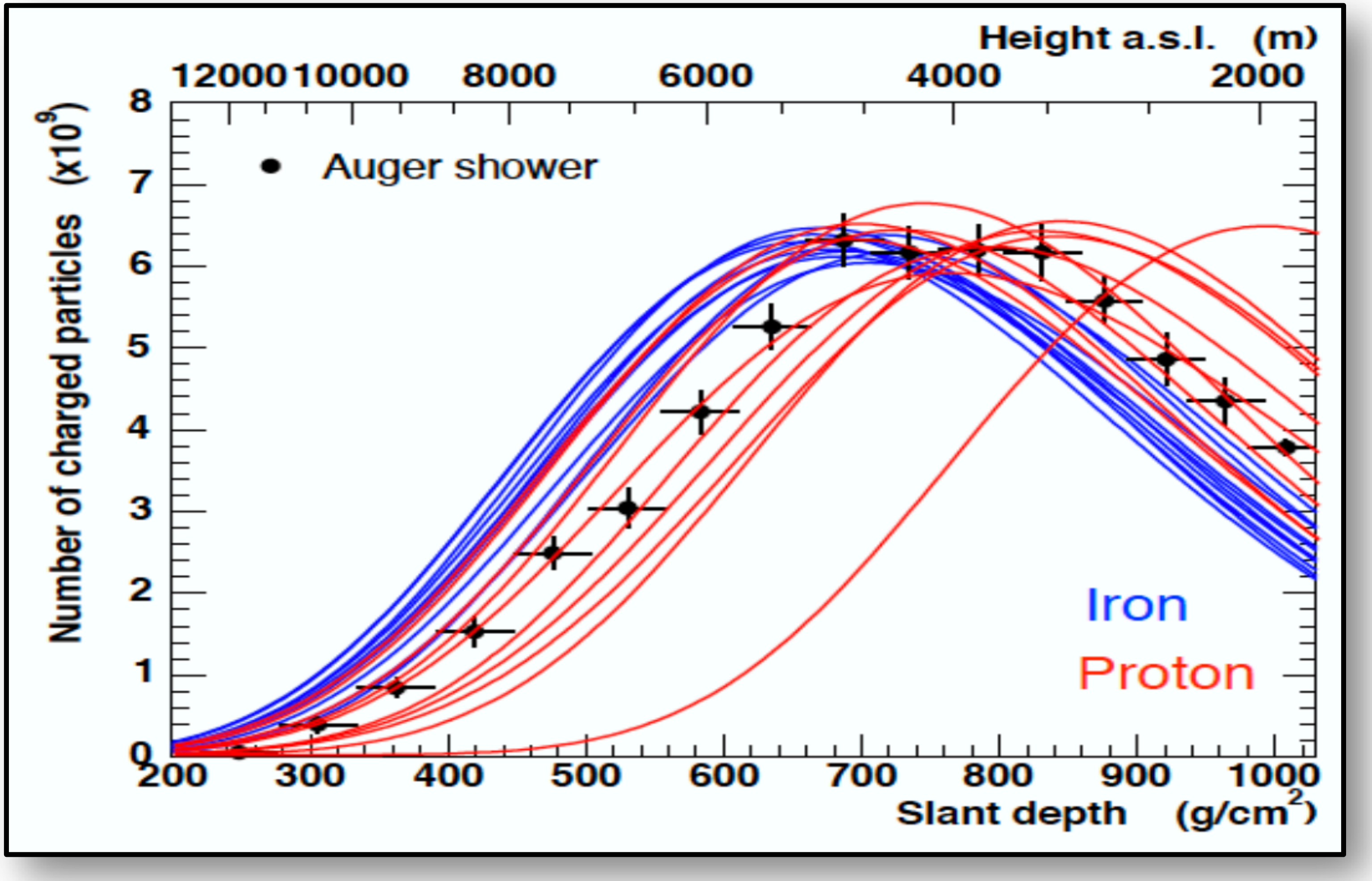
Data: Jan 2004 – Dec. 2016
~ 200 000 events
67 000 km^2 sr yr exposure

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

Mass compositiom of UHCR

Depth of shower maximum

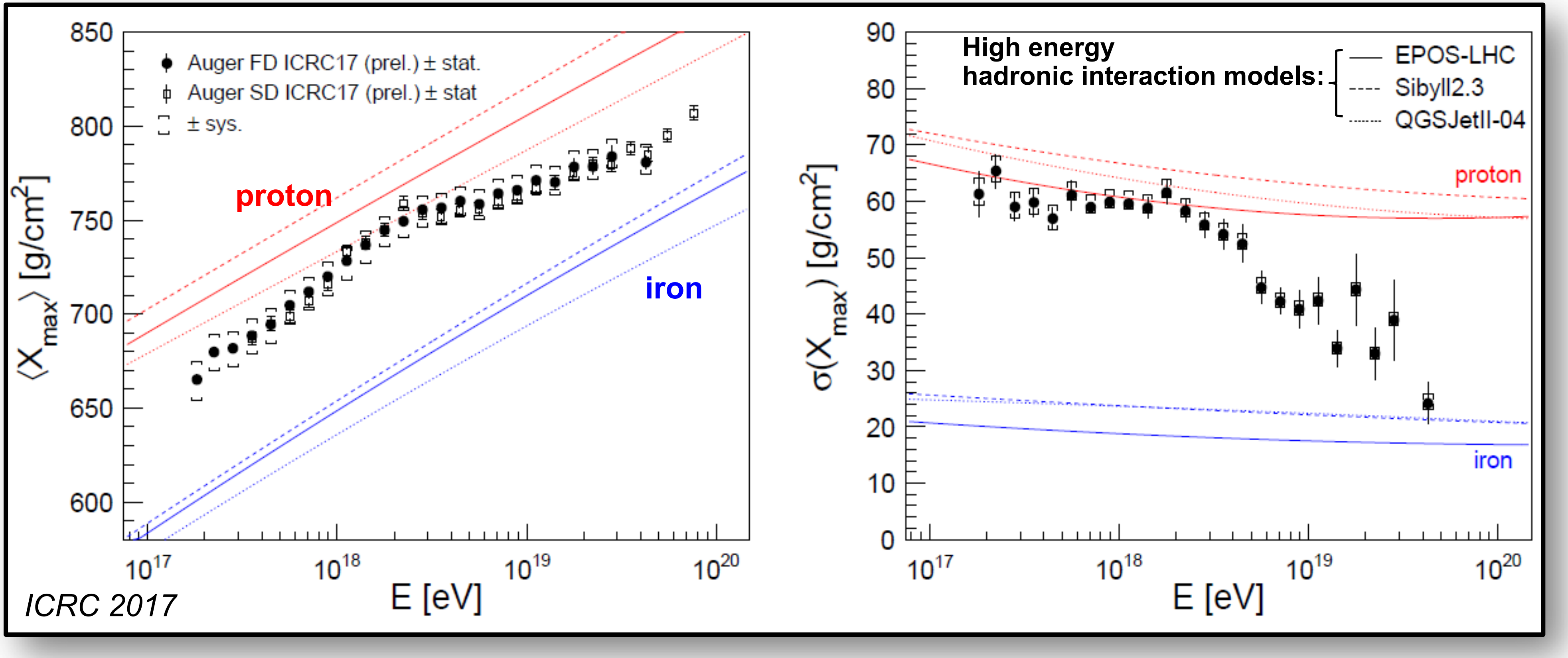
- X_{max} is the atmospheric depth at which the energy deposited by EAS reach the maximum, an observable sensitive to the mass composition.



p-induced showers develop deeper than
Fe-induced ones and have larger fluctuations

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

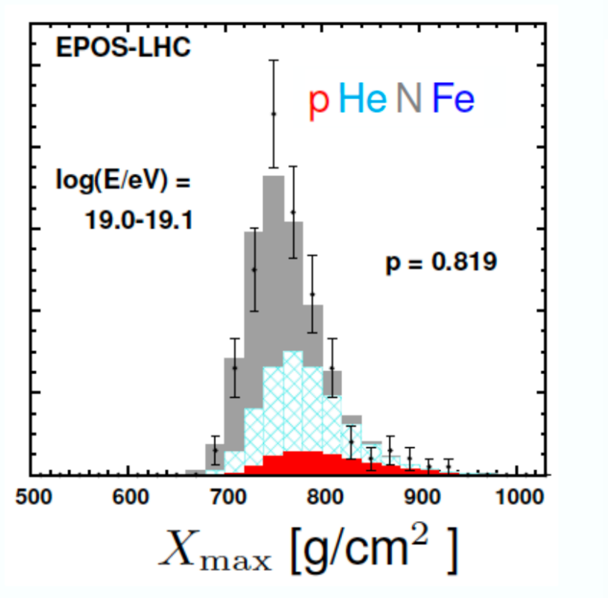
- > *The rate of change of X_{max} with energy (elongation rate) indicates changing mass composition*



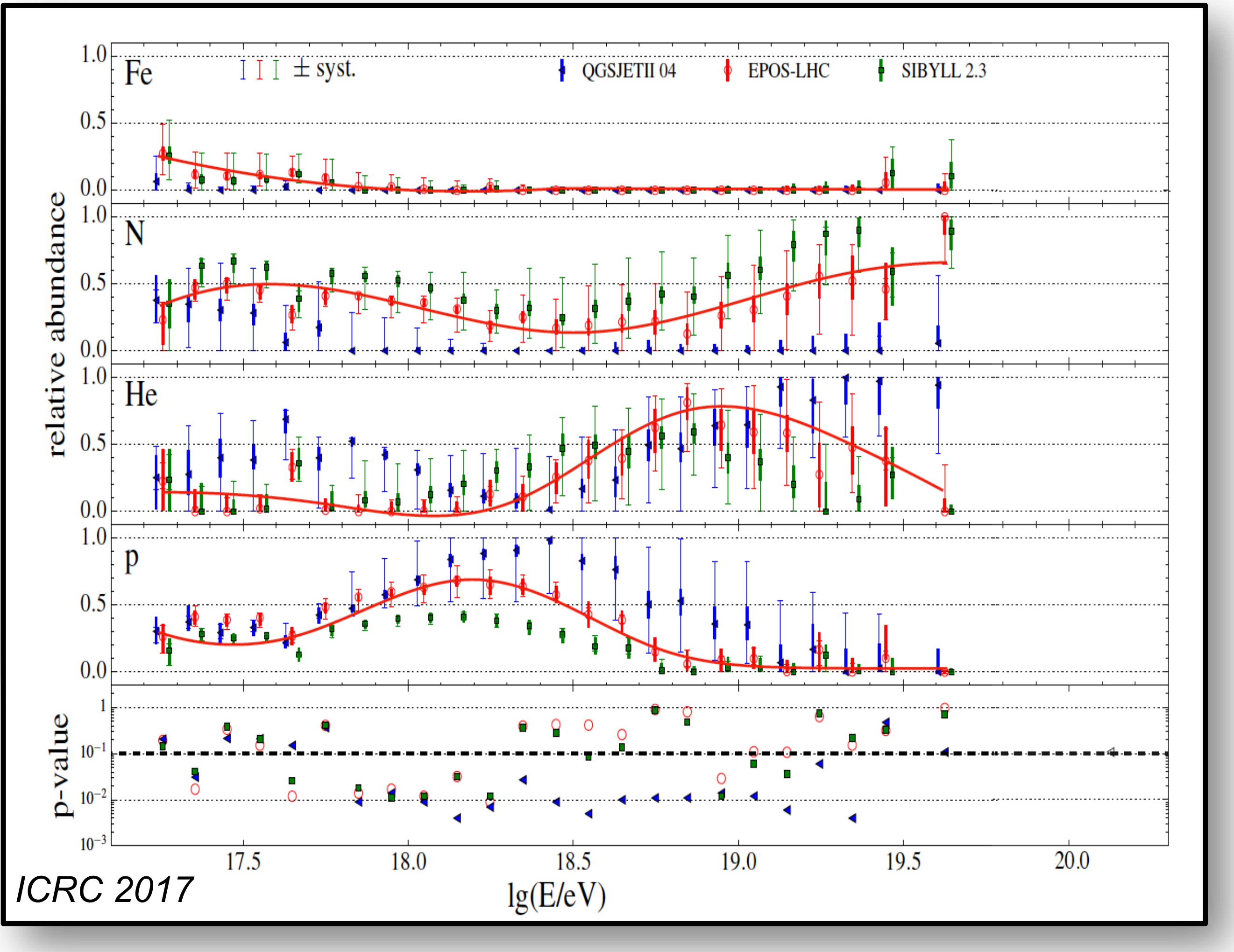
- > Fluctuations of X_{max} decrease above $2*10^{18}$ eV, indicating a composition becoming heavier with increasing energy.
- > The inferred mass composition relies heavily on validity of the hadronic interaction models (extrapolations of the experimental data to high energy is associated with high uncertainty).

AugerMix

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



P-value is the goodness of the fit



ICRC 2017

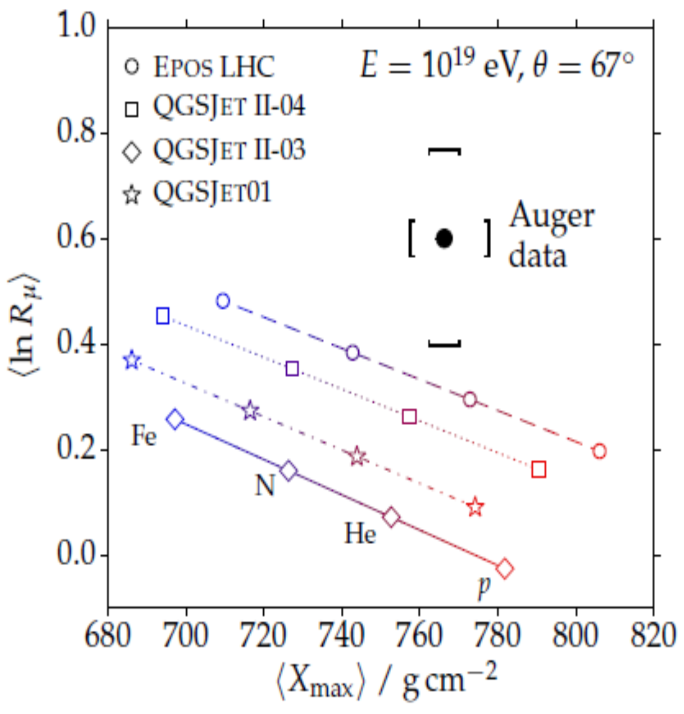
> *No model requires any significant fraction of iron at any energy.*

> *A significant reduction in the proton fraction above 2 EeV.*

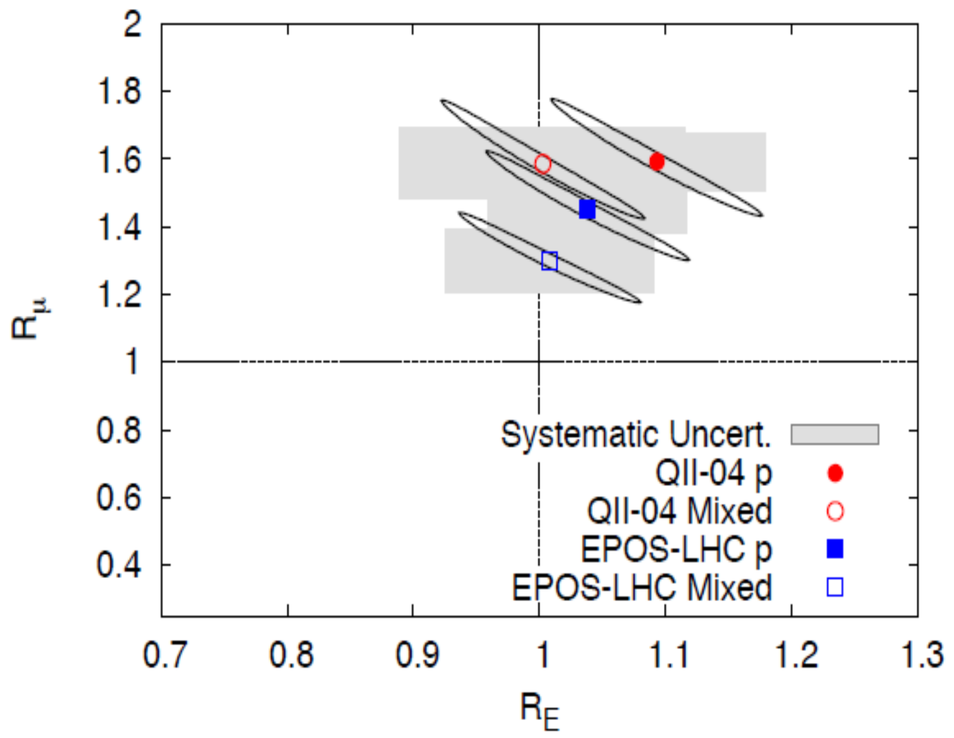
> the large fraction of small p-values(<0.1) indicates that the hadronic interaction models have difficulties to reproduce the details of the observed X_{max} distribution.

Hadronic interactions at UHE

Mean number of muons R_μ relative to that of proton reference shower



Phys. Rev. D 91, 032003 (2015)



Phys. Rev. Lett. 117, 192001 (2016)

> None of the hadronic interaction models can reproduce the muon number! (μ deficit in models)

Scaling factors R_μ and R_E for

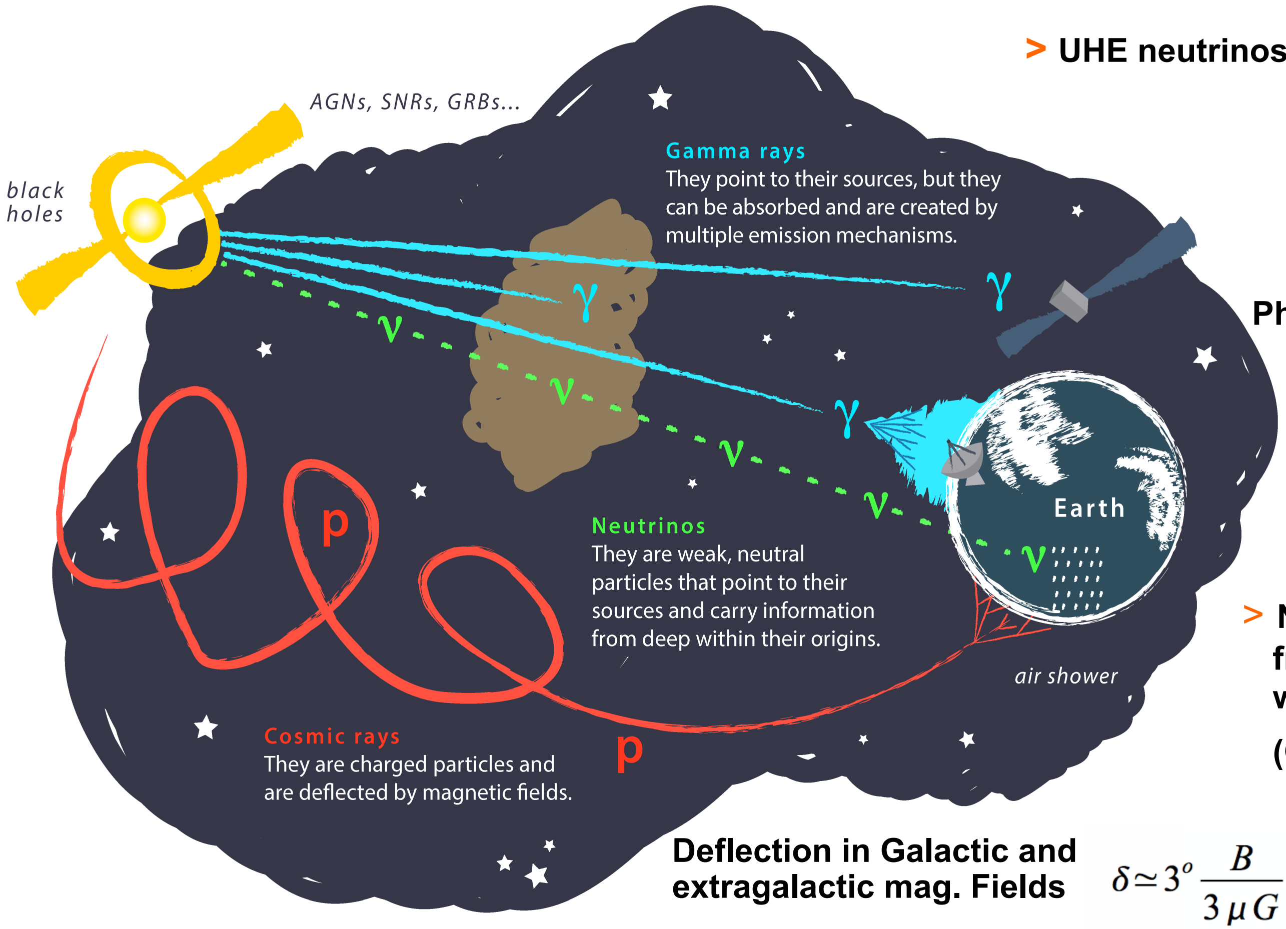
- the muon component of the shower and
- the primary energy

which bring a model calculation into agreement with data.

Sources of UHCR

Neutrino/photon production: hadronic model

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



Gamma rays
They point to their sources, but they can be absorbed and are created by multiple emission mechanisms.

Neutrinos
They are weak, neutral particles that point to their sources and carry information from deep within their origins.

Cosmic rays
They are charged particles and are deflected by magnetic fields.

Hadronic model:

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

$$\boxed{\begin{aligned} &p + p(\gamma) \to \pi^{\pm} + X \\ &\qquad \hookrightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu}) \\ &\qquad\qquad \hookrightarrow e^{\pm} + \bar{\nu}_{\mu}(\nu_{\mu}) + \nu_{e}(\bar{\nu}_{e}) \end{aligned}}$$

Photons arise from decays of neutral pions:

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

> **Neutrinos/photons are also produced from interaction of Cosmic-rays with Microwave Background**

(GZK or cosmogenic neutrinos/photons)

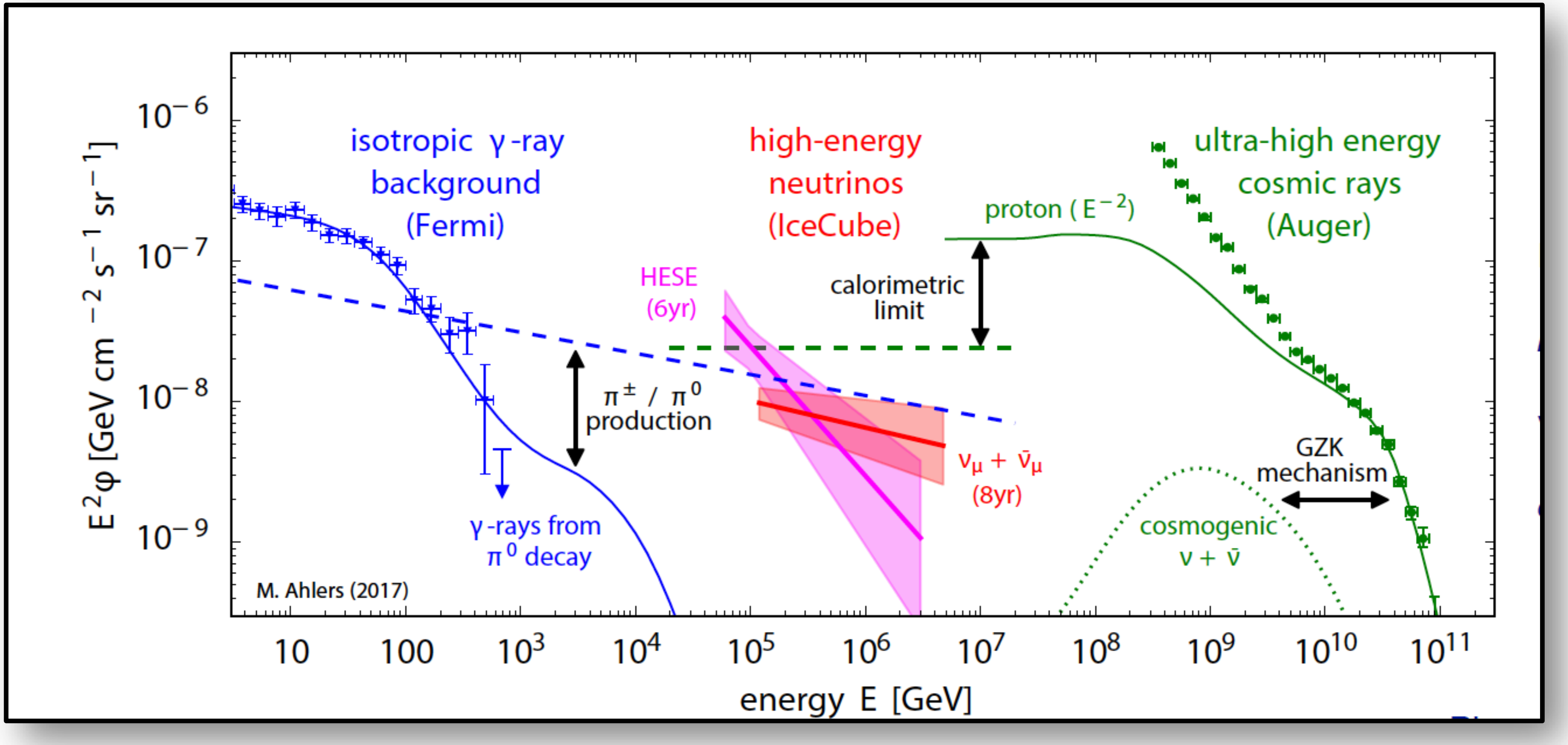
Deflection in Galactic and extragalactic mag. Fields

$$\delta \simeq 3^{o} \frac{B}{3\,\mu G} \frac{L}{kpc} \frac{6\times10^{19} eV}{E/Z}$$

> 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.

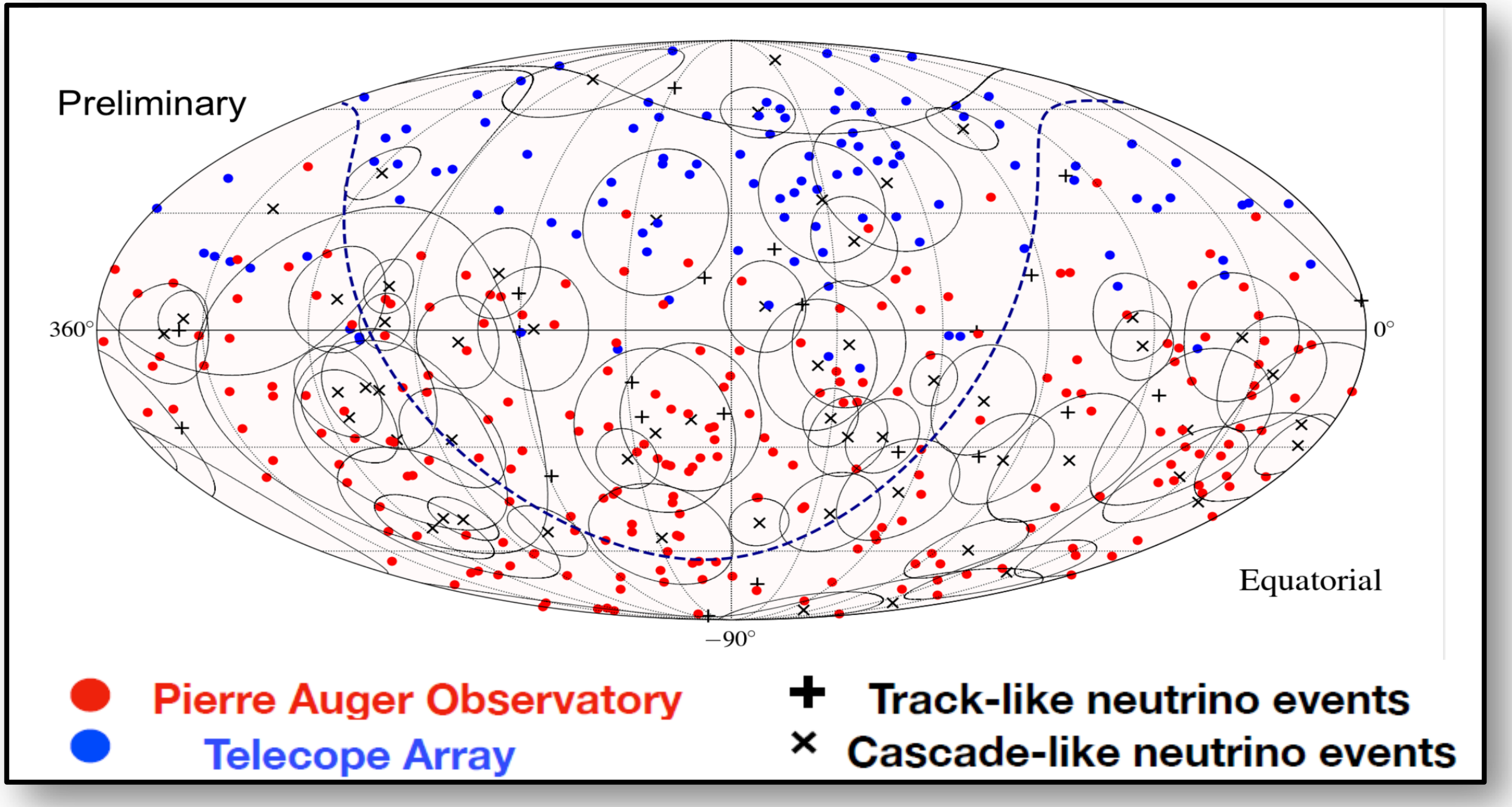
Global picture – energy density and multi-messenger physics



$$\rho_{\text{decade}} = \int_{\text{decade}} E \frac{\mathrm{d}N}{\mathrm{d}\ln E}\, \mathrm{d}\ln E$$

Energy density per decade similar in all three messenger particles

All-sky search for correlations in the arrival directions of astrophysical neutrino candidates and UHECRs (TA, Auger, IceCube)



IceCube, Auger and Telescope Array
JCAP01(2016)037

Data sample:
231 **Auger** events E > 52 EeV
angular resolution: 0.9^o

109 **TA** events, E > 57 EeV, ang. res. 1.5^o
58 **IceCube** cascade-like events (n_e), ang. res. 15^o
40 **IceCube** track-like events (n_m), ang. res. 1^o

No significant correlation found

Search for UHECR correlation with:

> Starburst Galaxies

- *Fermi*-LAT search list for star-formation objects
- 23 objects within 250 Mpc

$f_{anisotropy}$ = 10%, Ψ = 13°
significance 3.9σ

> γ-ray detected Active Galactic Nuclei

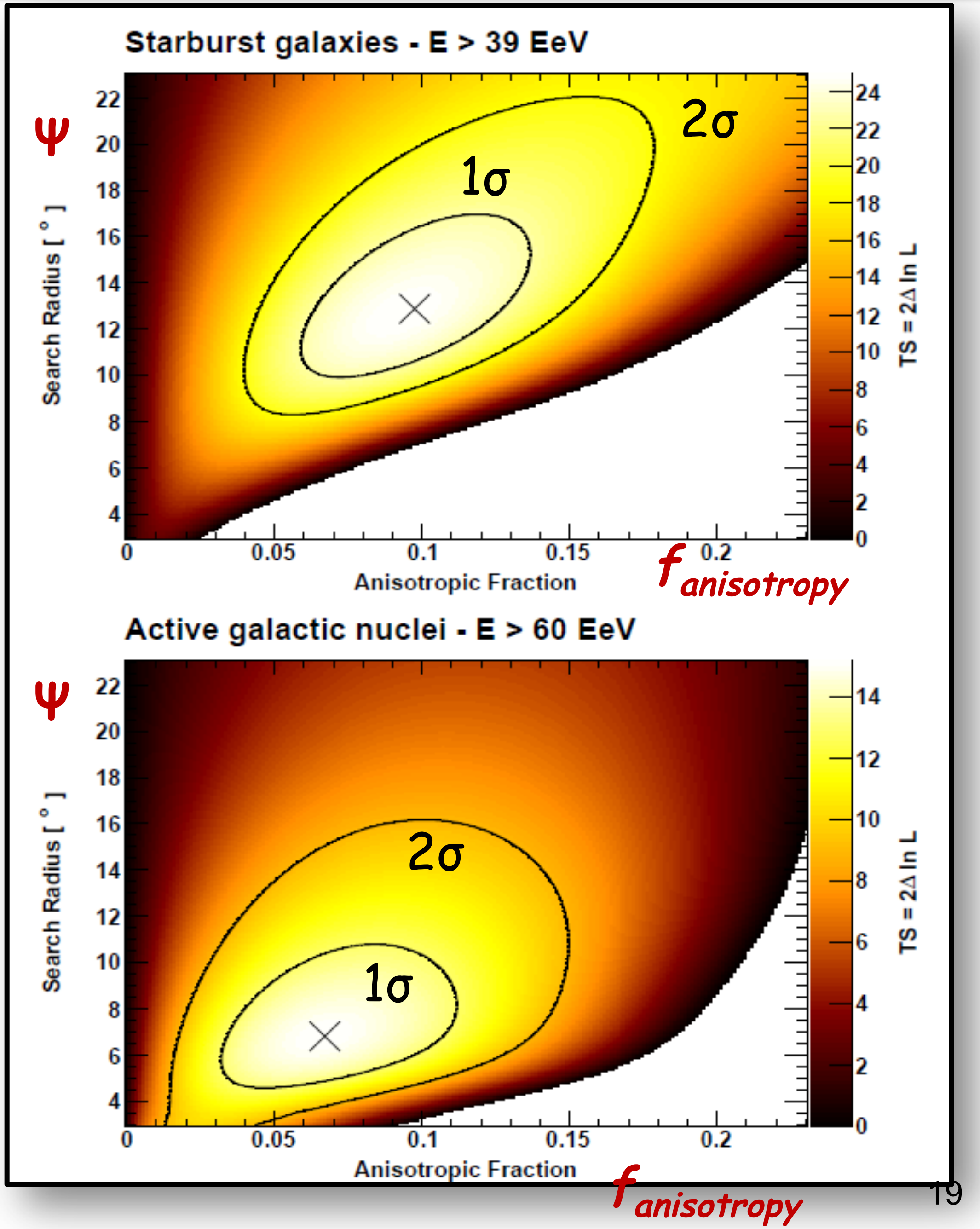
- 2FHL AGNs (*Fermi*-LAT)
- 17 objects within 250 Mpc

$f_{anisotropy}$ = 7%, Ψ = 7°
significance 2.7σ

Likelihood ratio analysis

- correlation angle Ψ (takes into account the unknown deflections of the UHECRs in the magnetic field)
- H_0: isotropy
- H_1: (1-f) x isotropy + f x fluxMap(Ψ)
- Test Statistic = 2 log(H_1 / H_0)

Astrophysical Journal Letters, 853:L29 (2018)

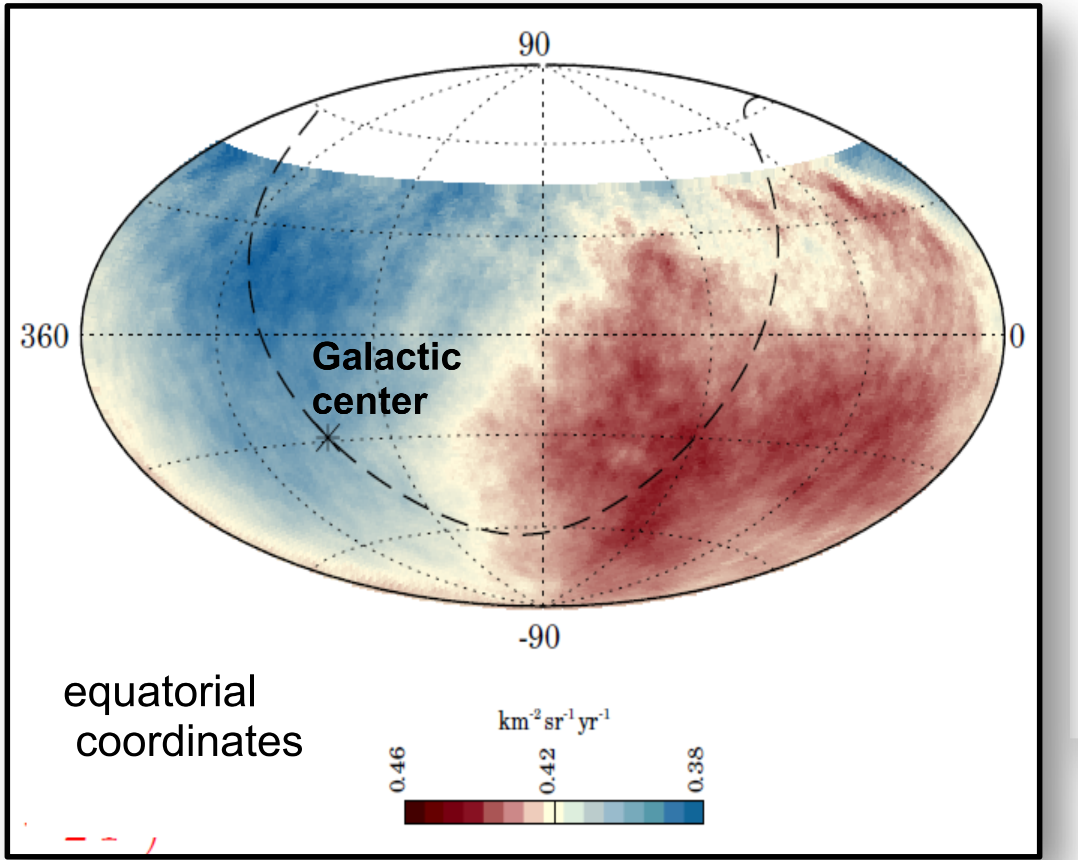


Auger observation of dipolar anisotropy above 8 EeV

Harmonic analysis in right ascension α

E [EeV]	events	amplitude r	phase [deg.]	$P(\geq r)$
4-8	81701	$0.005^{+0.006}_{-0.002}$	80 ± 60	0.60
> 8	32187	$0.047^{+0.008}_{-0.007}$	100 ± 10	2.6×10^{-8}

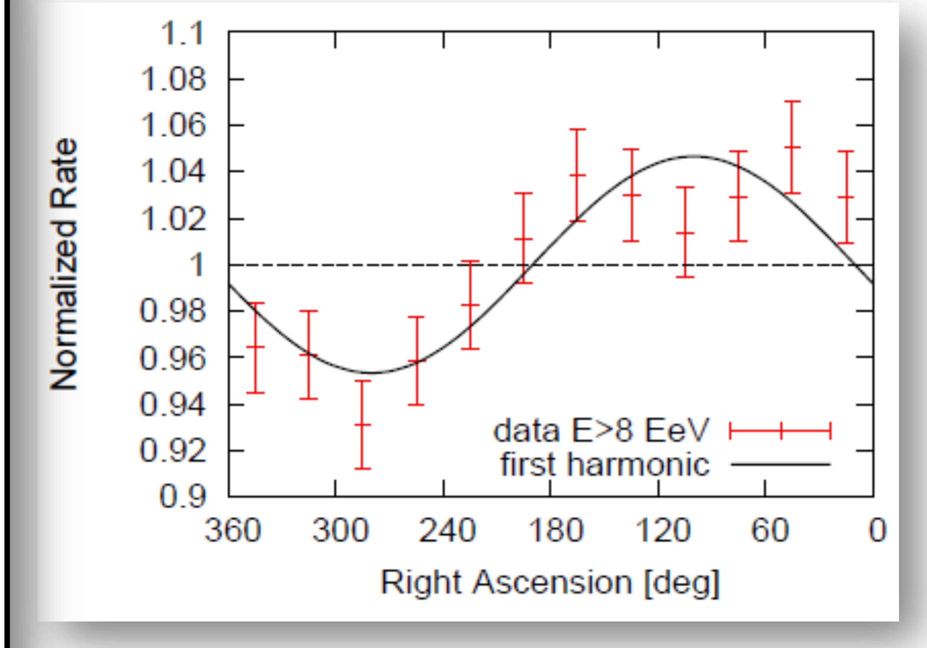
Top 10 breakthroughs of 2017" : Physics World



The Pierre Auger Collaboration, Science 357 (2017)

Significant modulation at 5.2σ

(5.6σ before penalization for energy bins explored)



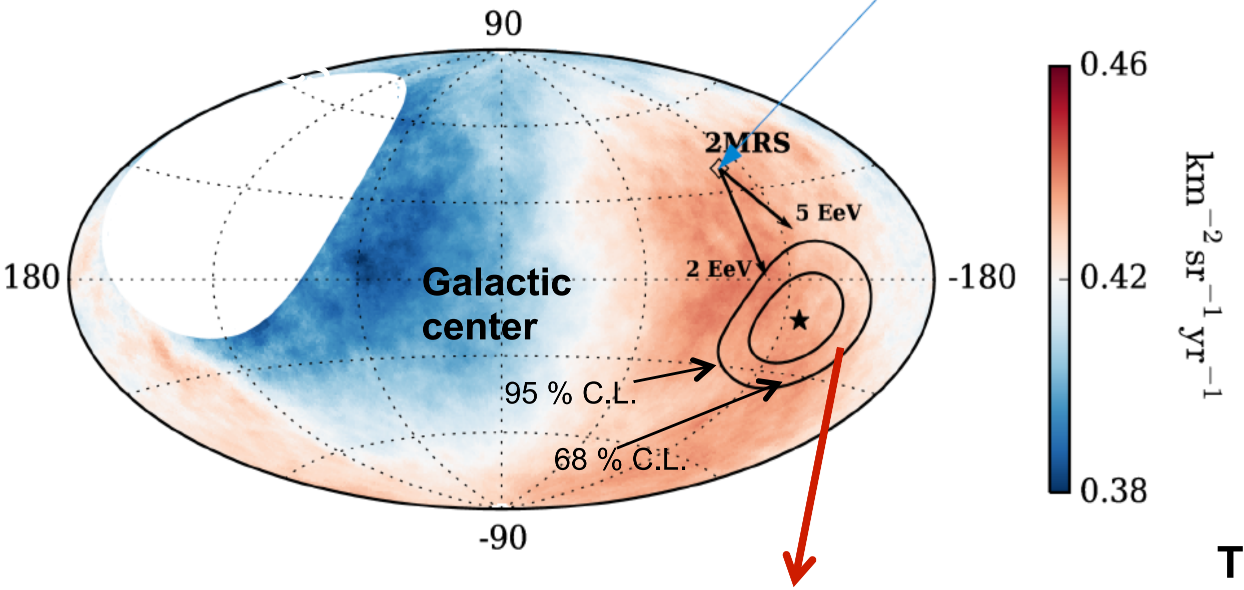
3-d dipole above 8 EeV:

$(6.5^{+1.3}_{-0.9})\%$ at $(\alpha, \delta) = (100°, -24°)$

Auger observation of dipolar anisotropy above 8 EeV

The flux-weighted dipole from IR galaxy distribution in 2MRS points to (l,b)=(251°,38°) → ~55° from observed

[Erdogdu et al. 2006]

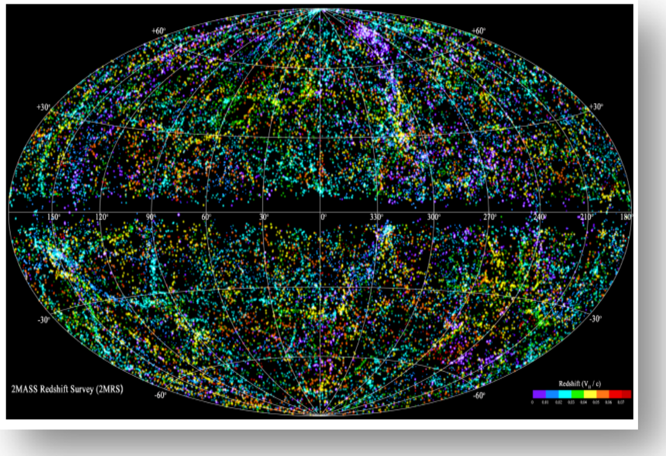


Observed dipole, Gal. coord. (l, b) = (233°, −13°), ~120° away from GC -> disfavours galactic origin

Large-scale anisotropy can arise from:

> inhomogeneous large-scale distribution on sources
> diffusion in extragalactic magnetic fields from dominant nearby sources

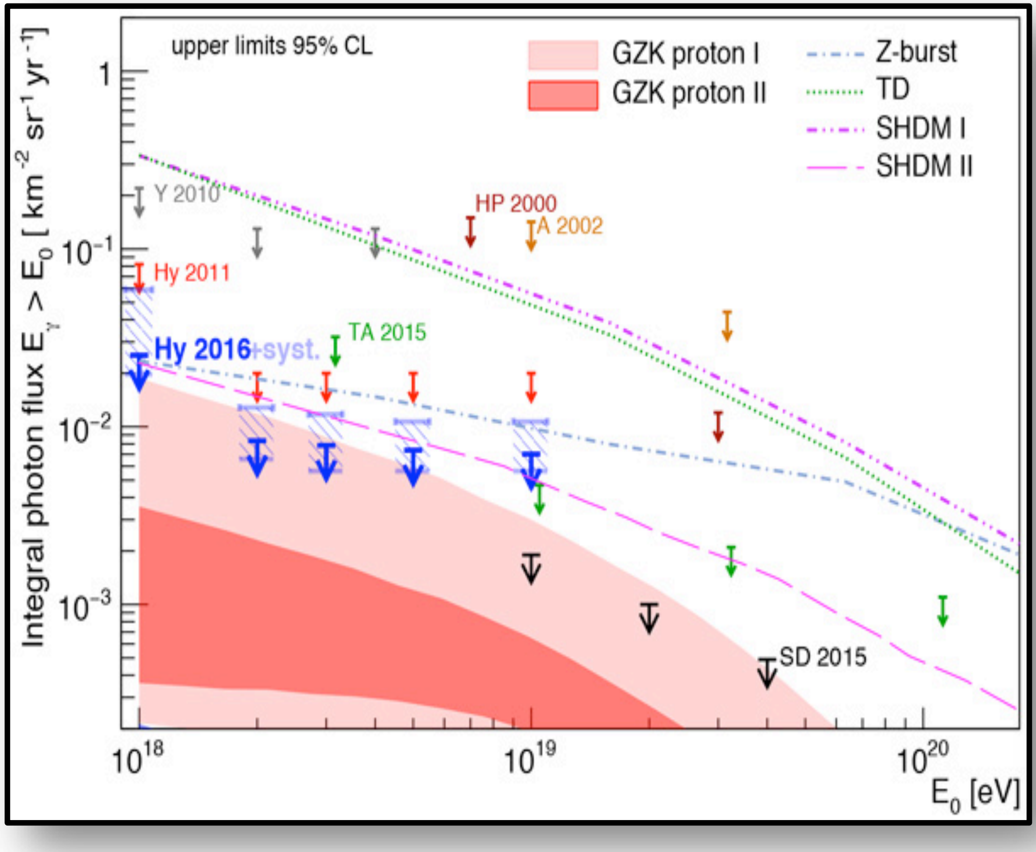
Distribution of distribution of galaxies in the nearby Universe : 2MRS catalog



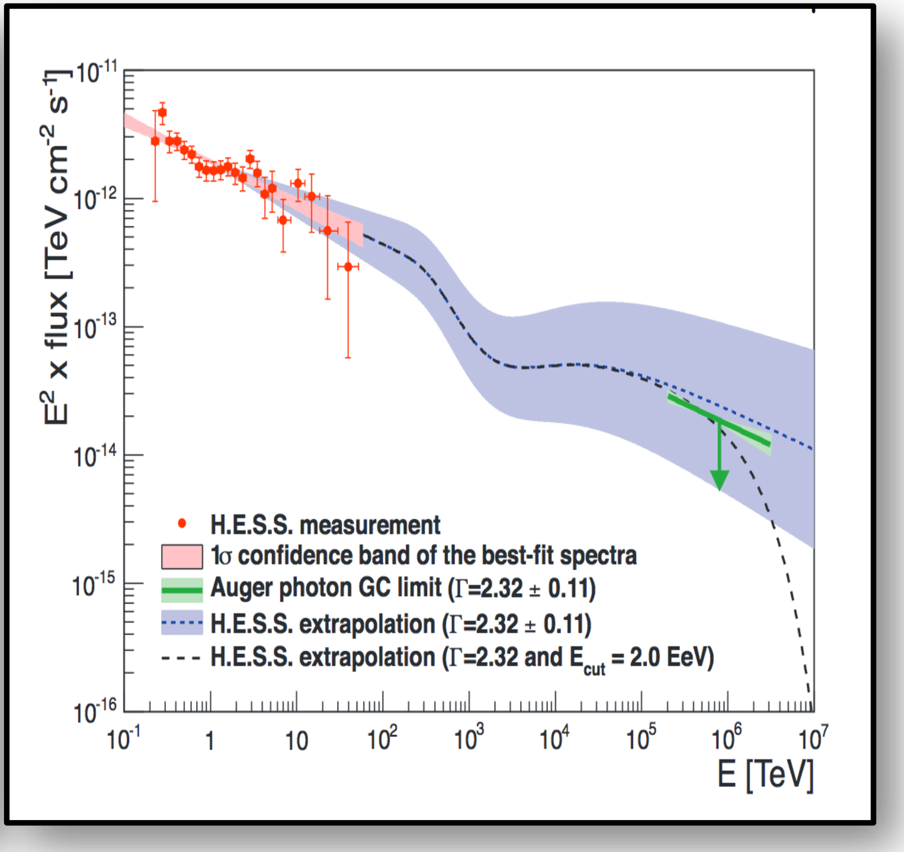
Traces of CRs in the galactic magnetic field

Searches for cosmogenic photons

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



JCAP 1704 (2017) no.04, 009

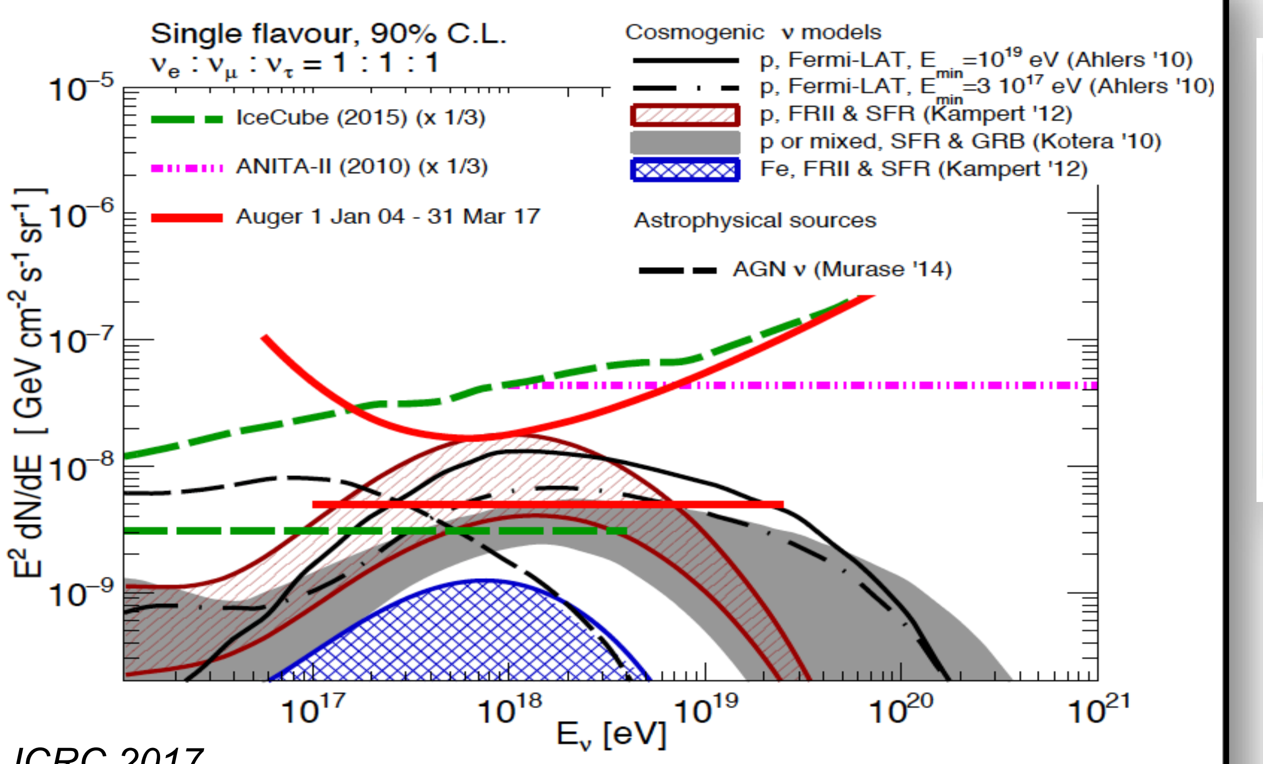


ApJL 837 L25 (2017)

> 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.

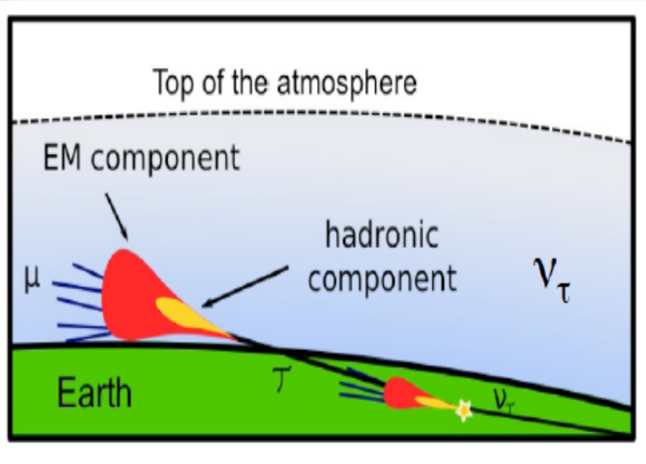
Searches for cosmogenic neutrinos

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



ICRC 2017

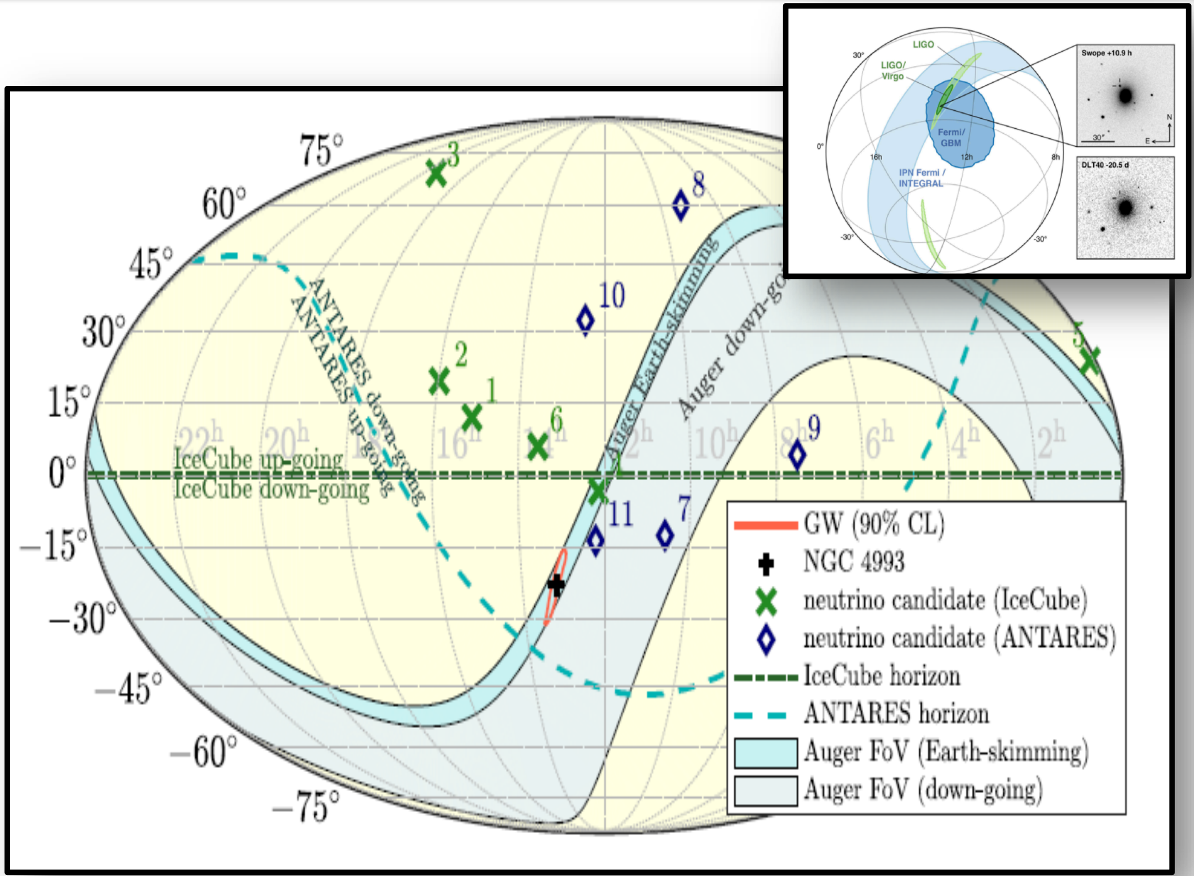
Earth-skimming channel

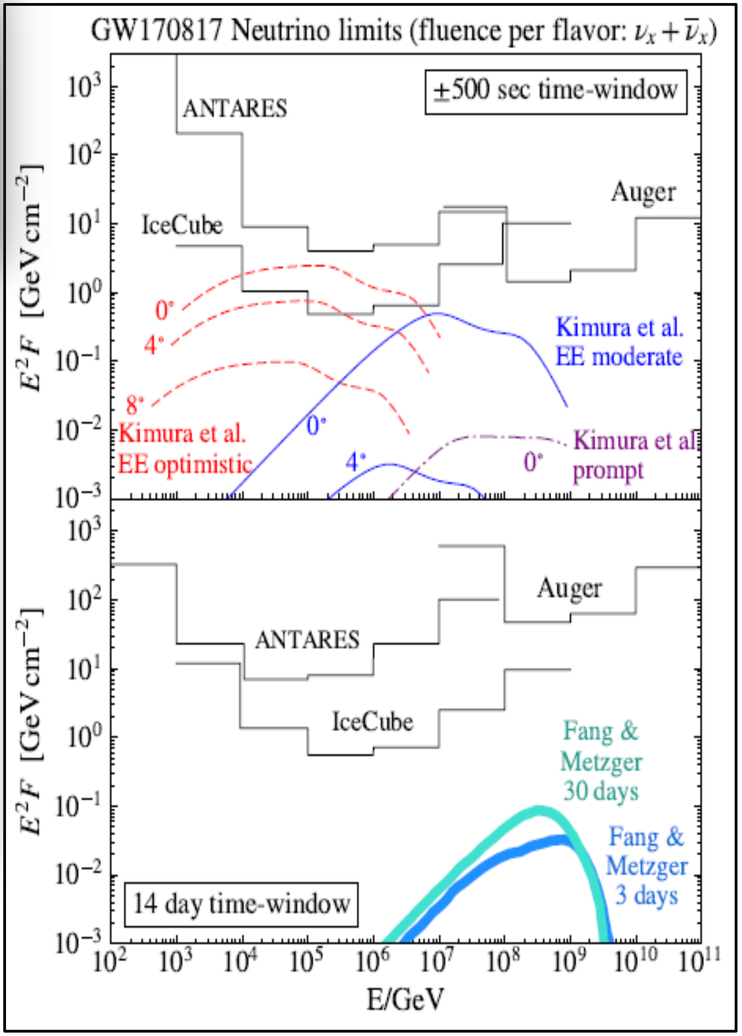


> No neutrinos observed.

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

Search for high-energy neutrinos from binary neutron star merger (GW170817) with ANTARES, IceCube, and Auger





Astrophysical Journal Letters, 850:L35 (2018) (5 collab.)

> The 3 detectors complement each other in the energy bands in which they are most sensitive

> No significant neutrino counterpart within a ±500 s window, nor in the subsequent 14 days

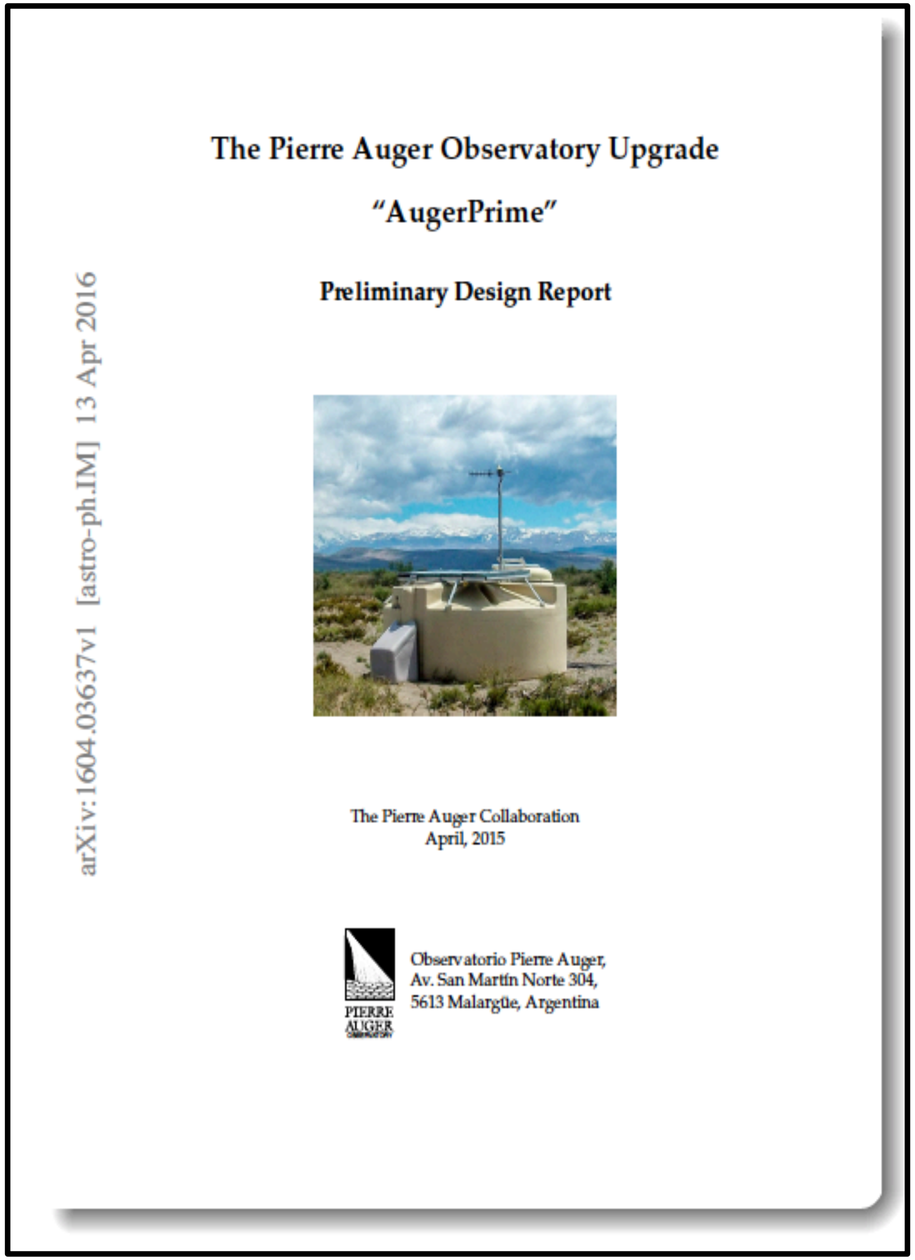
> Optimistic scenarios for on-axis emission (the angle between the jet and the line of sight) are constrained by the present non-detection.

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



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

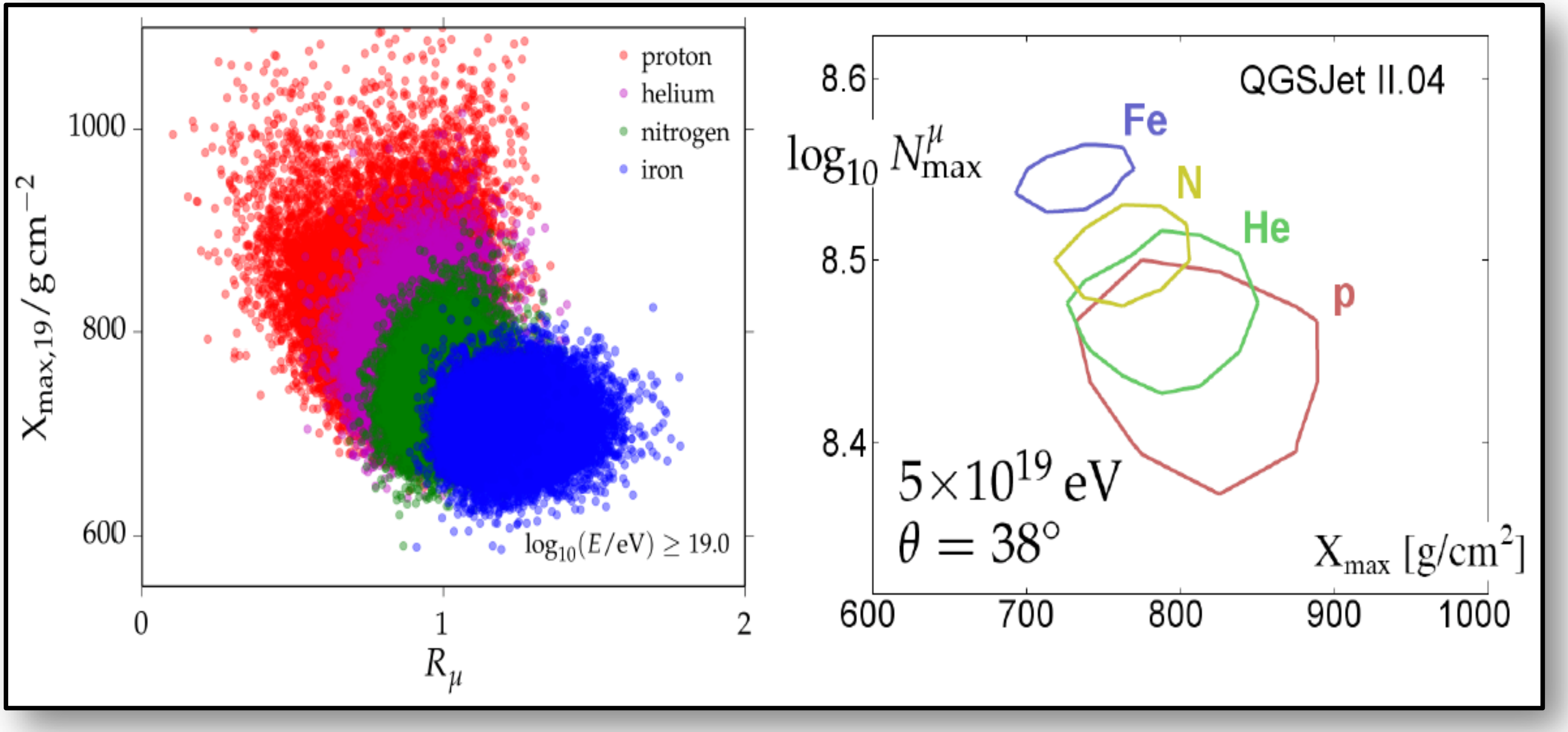
arXiv:1604.03637v1 [astro-ph.IM] 13 Apr 2016

Auger Prime: Increased Composition Sensitivity

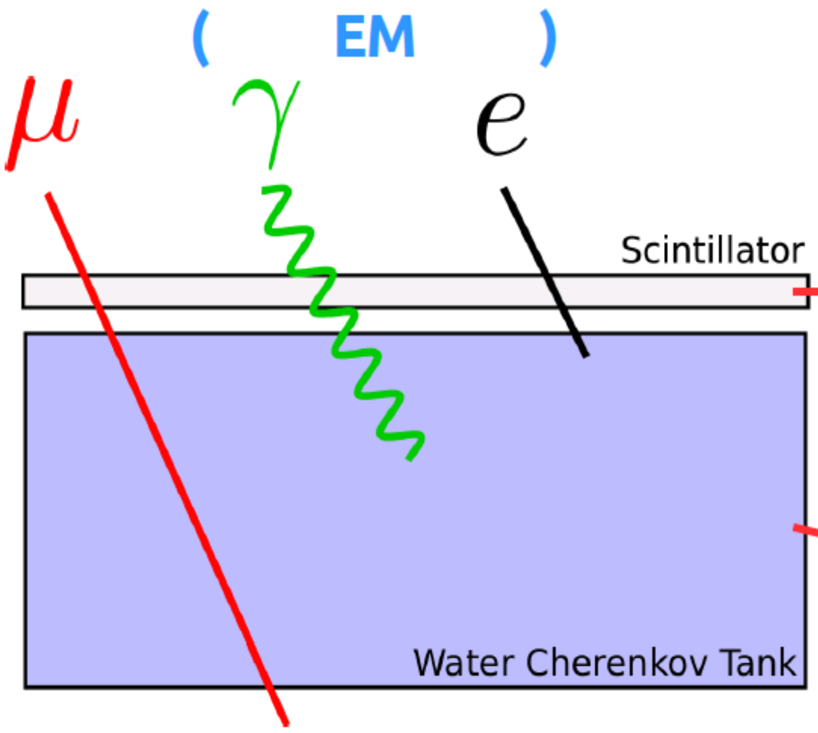
with SSD

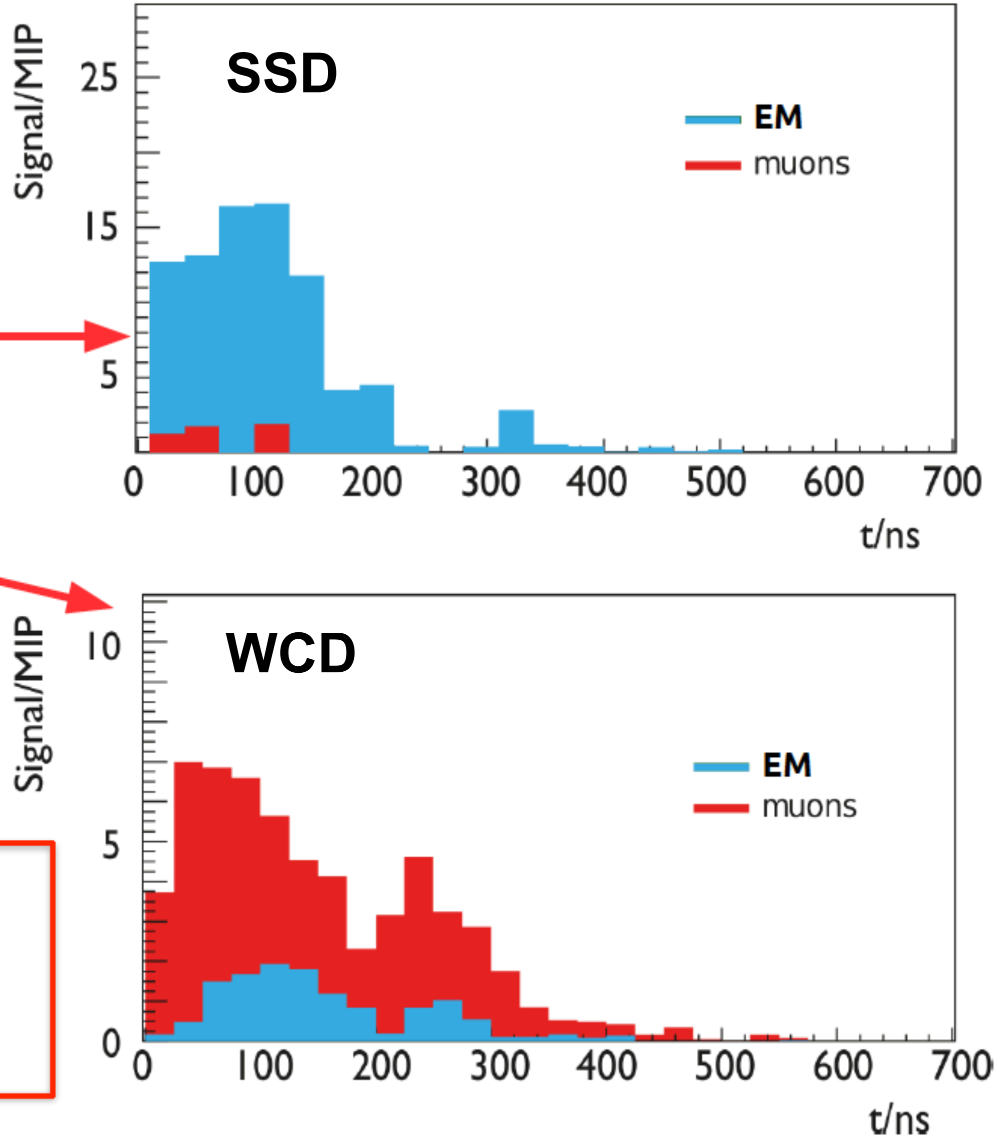
main goal !

X_{max} and muons



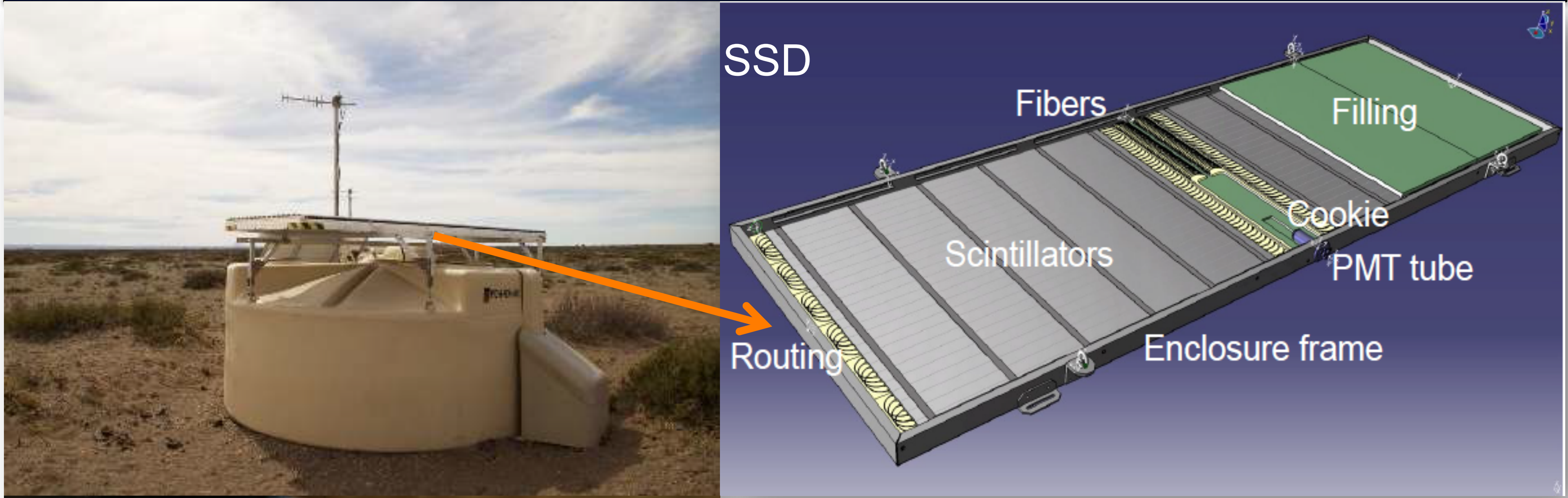
Complementary response

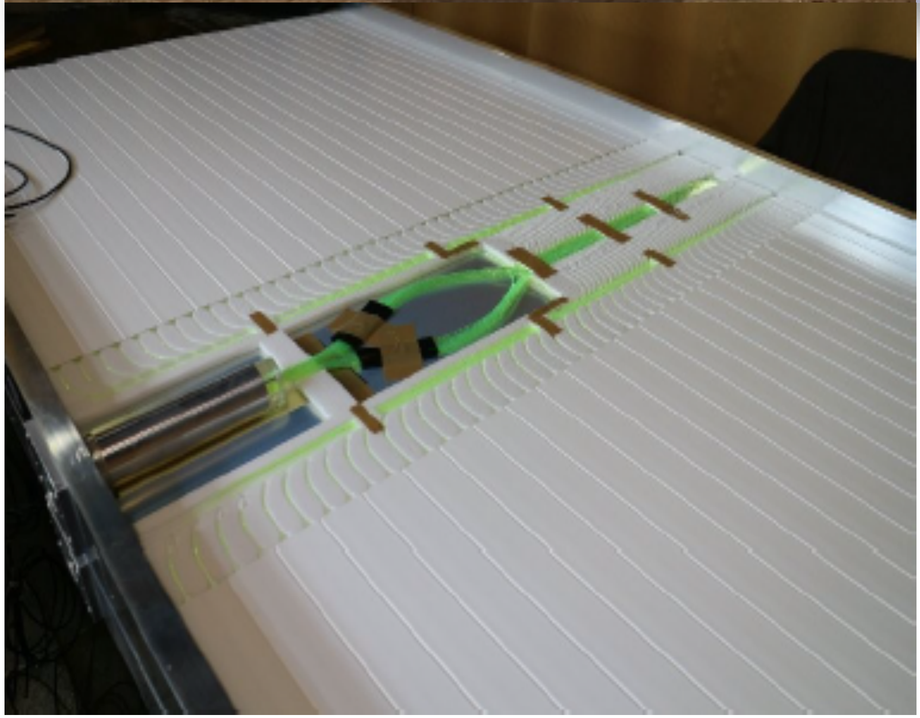




$$S_{\mu,\mathrm{WCD}} = a\,S_{\mathrm{WCD}} + b\,S_{\mathrm{SSD}}$$
$$S_{\mathrm{em},\mathrm{WCD}} = c\,S_{\mathrm{WCD}} + d\,S_{\mathrm{SSD}}$$

Detector Upgrades for AugerPrime

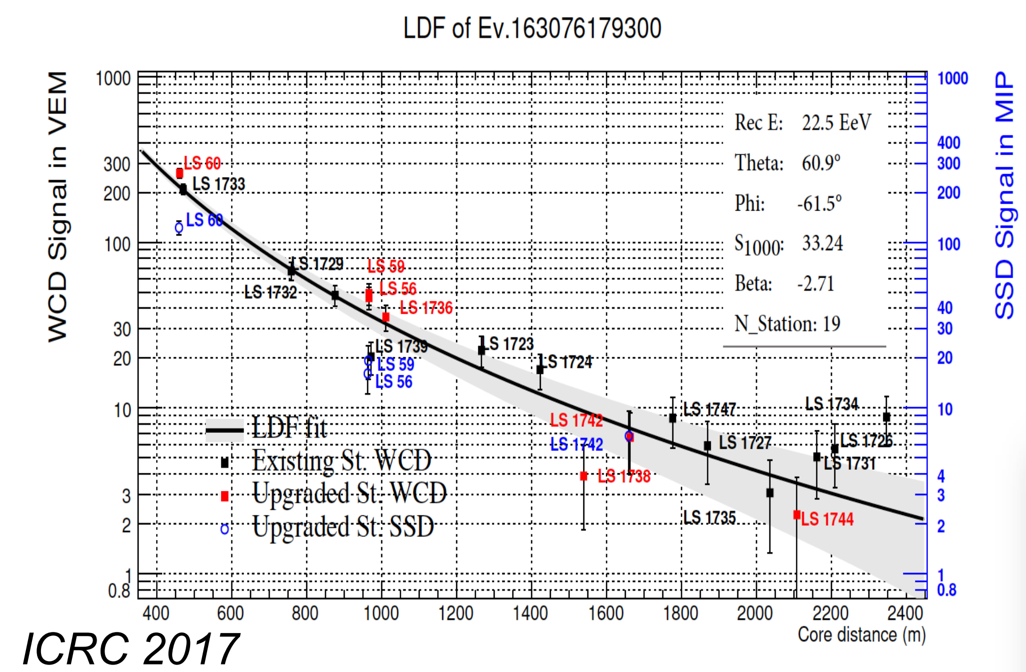




- 3.8 m^2 scintilators (SSD) on each 1500-m array station
- Upgrade of station electronics
- Additional small PMT to increse dynamic range
- Buried muon counters in 750-m array (AMIGA)
- Increasded FD uptime

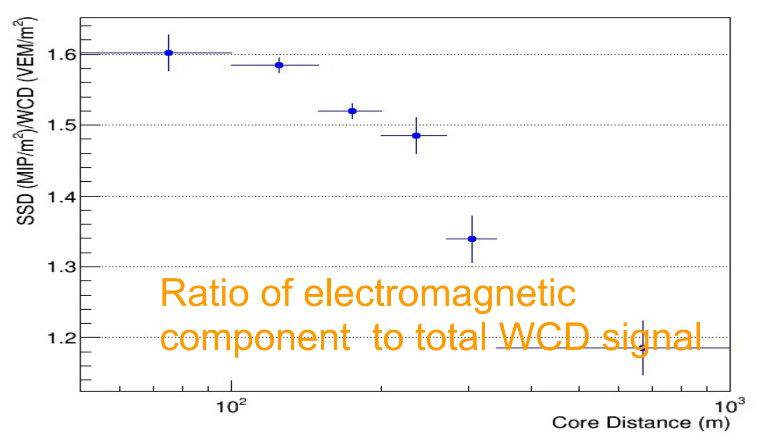
Status and Plans

2016: Engineering Array: 12 stations



ICRC 2017

2016-09-15: first station in field



Ratio of electromagnetic component to total WCD signal

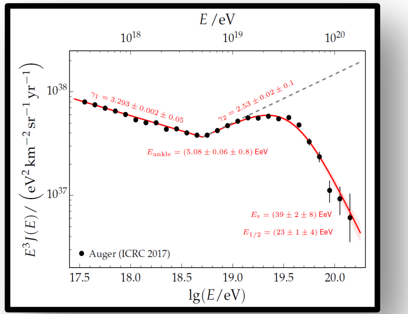
2018-2019: deployment of 1200 SSD

2019-2025: data taking
(almost double exposure)

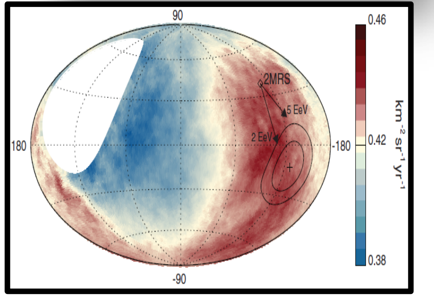
Goal: composition measurement at 10^{20} eV
- composition-enhanced anisotropy studies
- particle physics with air showers

Summary

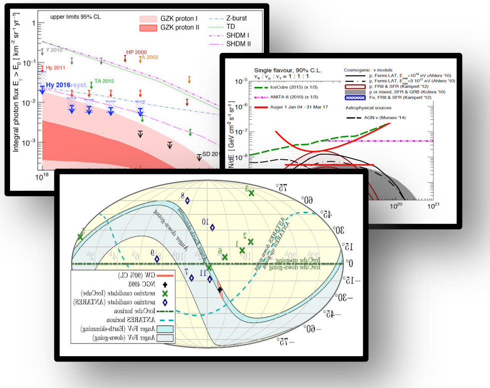
- Suppression of the UHECRs energy spectrum is compatible with GZK cutoff but also with efficiency limit of particle acceleration by sources (maximum rigidity scenario).



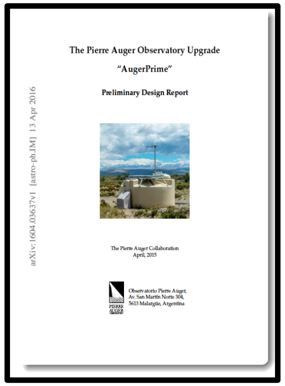
- UHECRs appear proton-like at 10^{18} eV and heavier up to 10^{19} eV (N-like).
- Current Hadronic interaction models inaccurately predict muon component in showers – implication for CR composition determination.



- No significant correlation found between UHECRs arrival directions and different families of the point sources.
- Orientation of the observed dipole anisotropy in the arrival directions of UHECRs indicates their extragalactic origin.



- 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

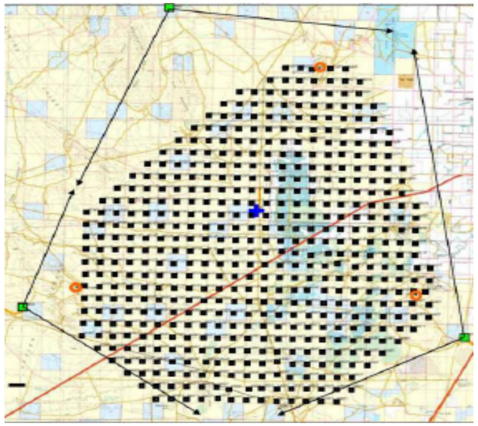
arXiv:1604.03637v1 [astro-ph.IM] 13 Apr 2016

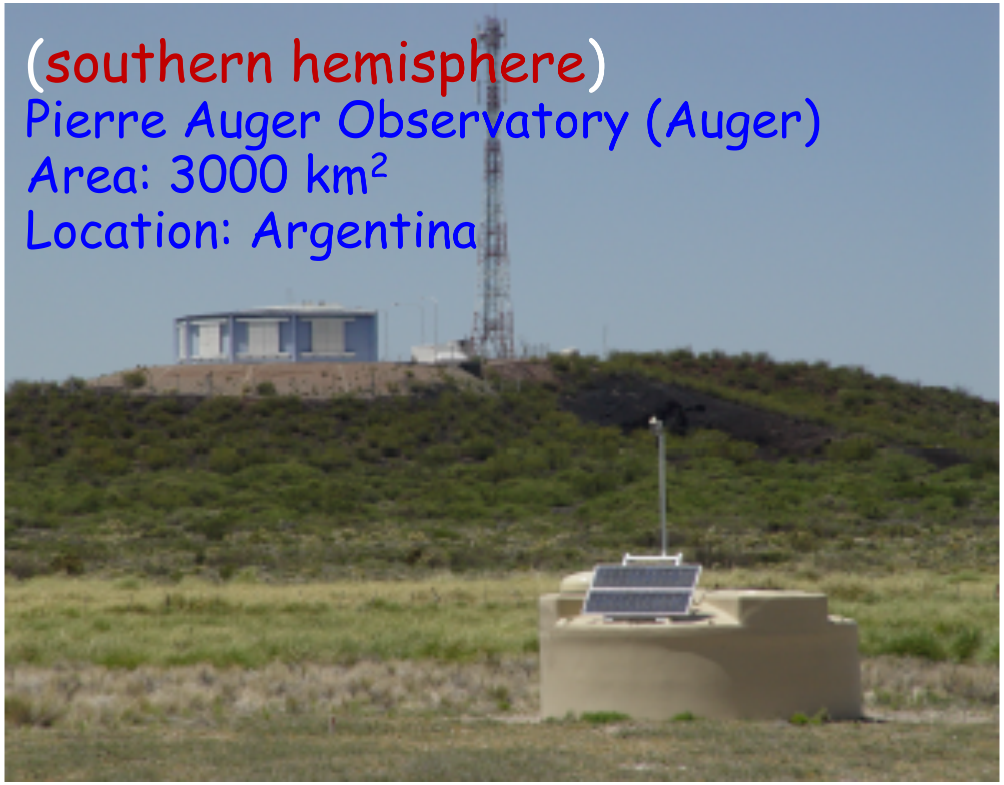
The Pierre Auger Collaboration
April, 2015

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

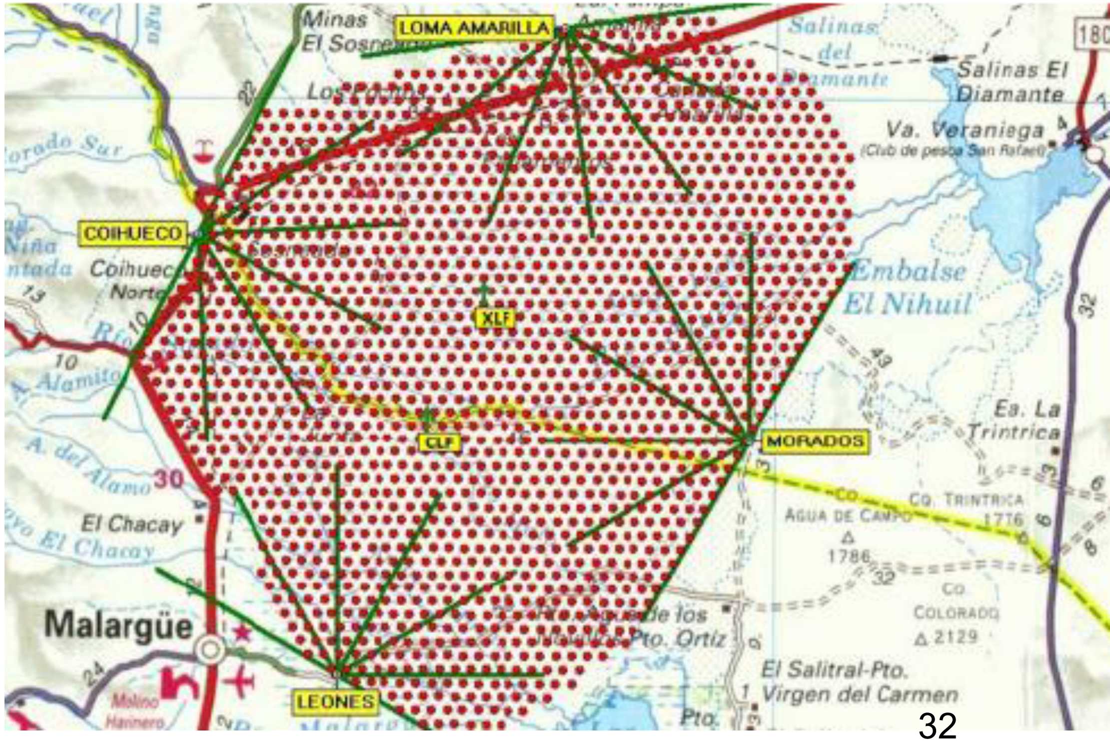
The largest detectors of ultra-high Energy cosmic rays (UHECRs)

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

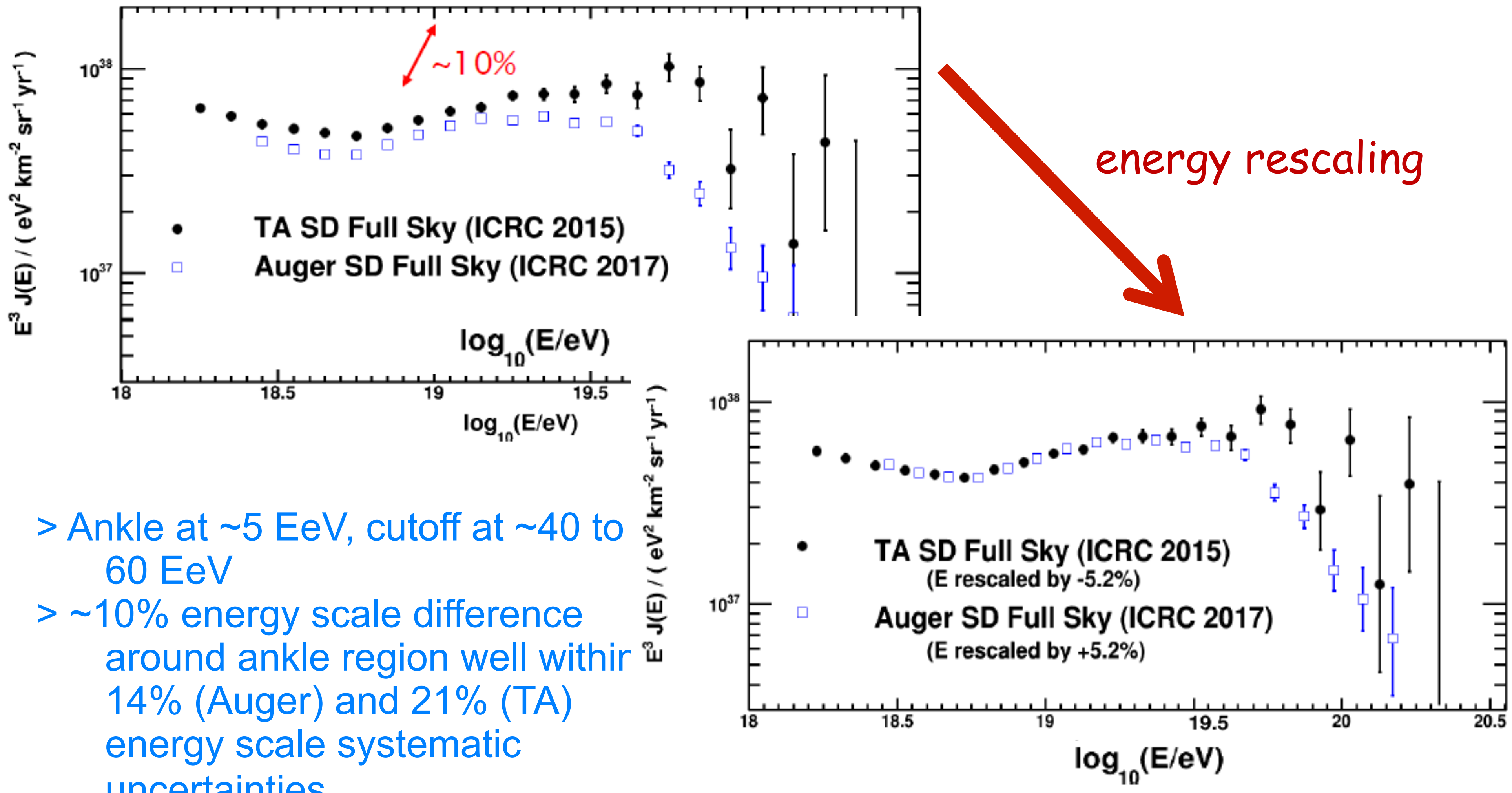




(southern hemisphere)
Pierre Auger Observatory (Auger)
Area: 3000 km^2
Location: Argentina



UHECRs energy spectrum: are Auger and TA spectra compatible?



> 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

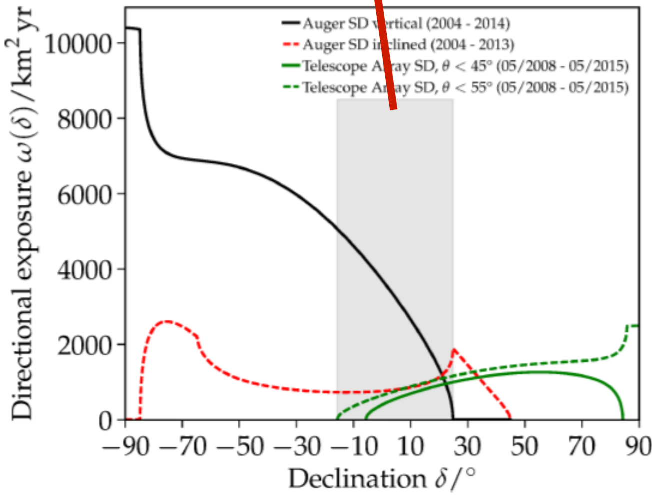
> Some discrepancy in shape at E > $10^{19.4}$ eV

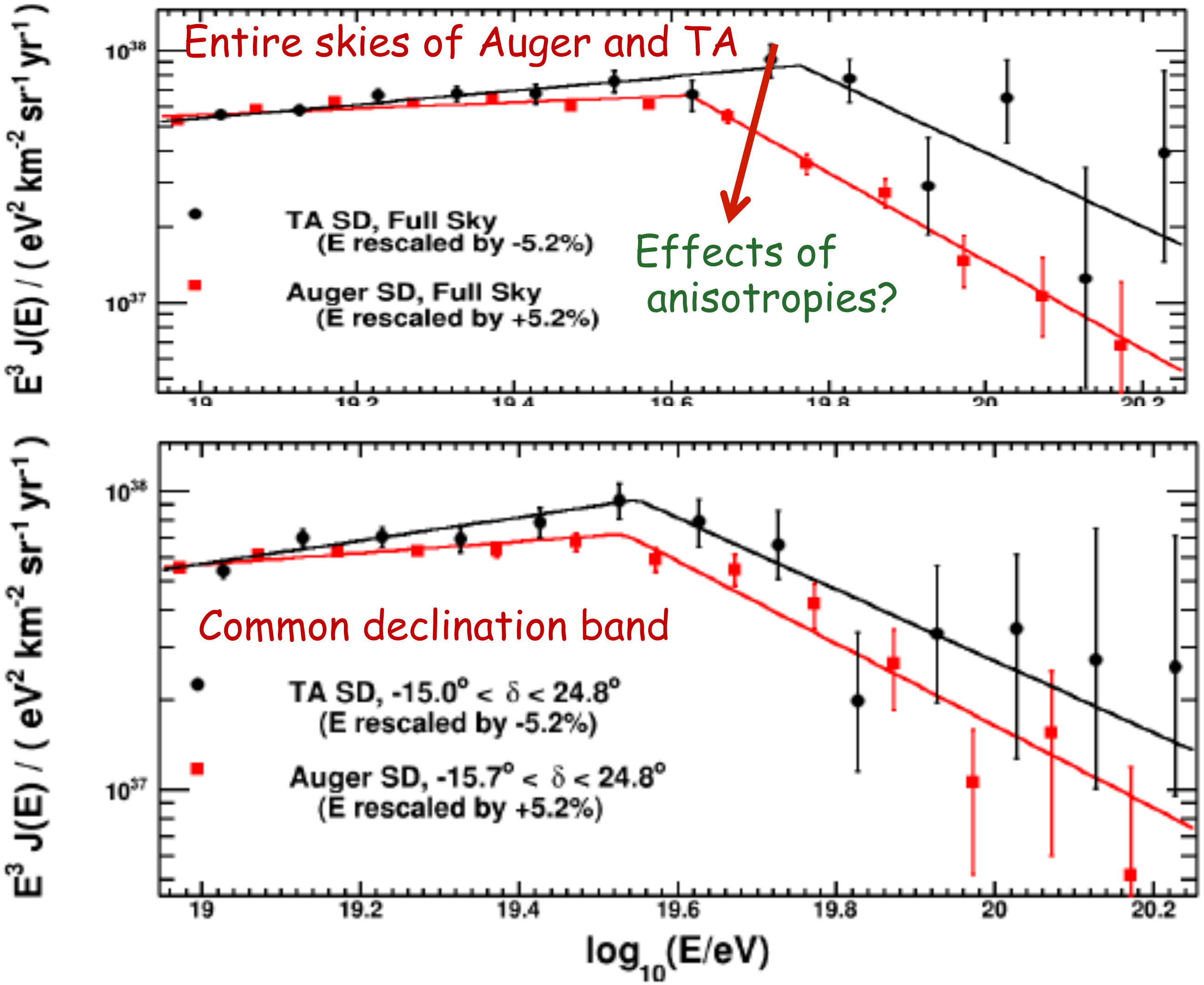
› Spectra agree in the ankle region $10^{18.4}$ eV < E < $10^{19.4}$ eV

› Difference above $10^{19.4}$ eV persists

UHECRs energy spectrum: Auger and TA common declination band

the overlapping sky region seen by both detectors




Entire skies of Auger and TA

Effects of anisotropies?

Common declination band

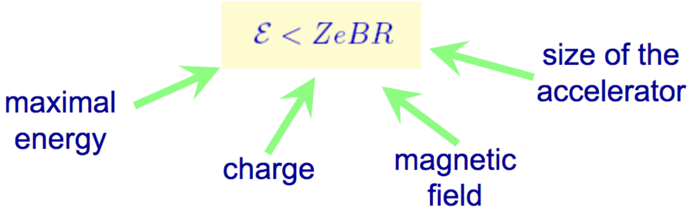
> Better agreement between TA and Auger in the common declination band

- spectrum cutoff roughly in agreement
- smaller differences remain but within systematics

> Auger and TA energy spectra consistent within systematic uncertainties

Rigidity scenario

geometry: the Hillas criterion:
Larmor radius < size of accelerator
(otherwise lefts the accelerator)



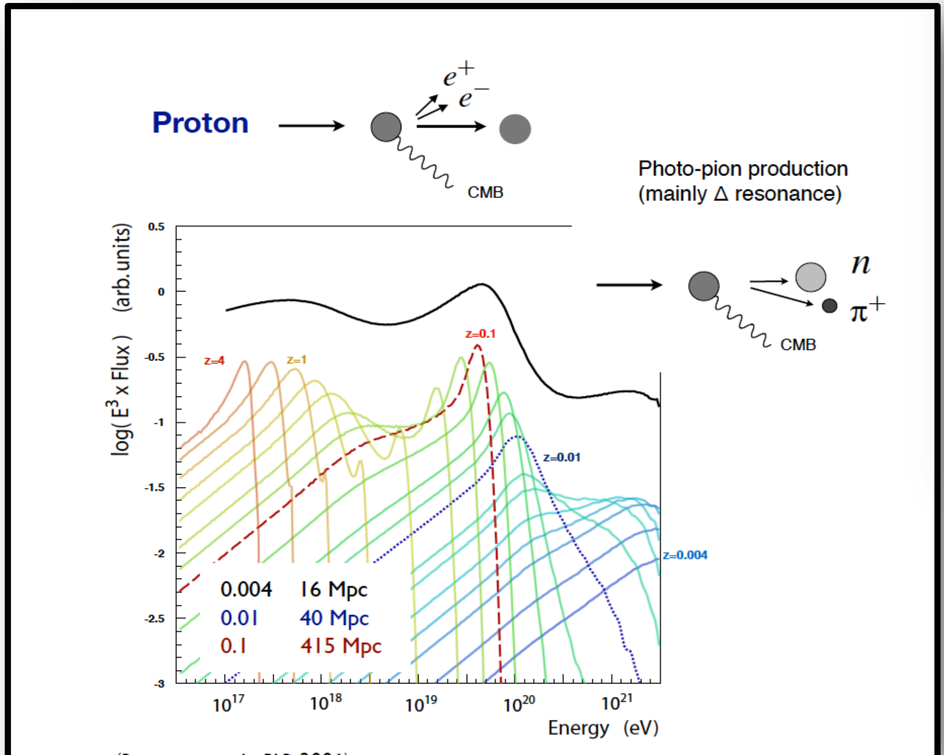
$\mathcal{E} < ZeBR$

maximal energy

charge

magnetic field

size of the accelerator



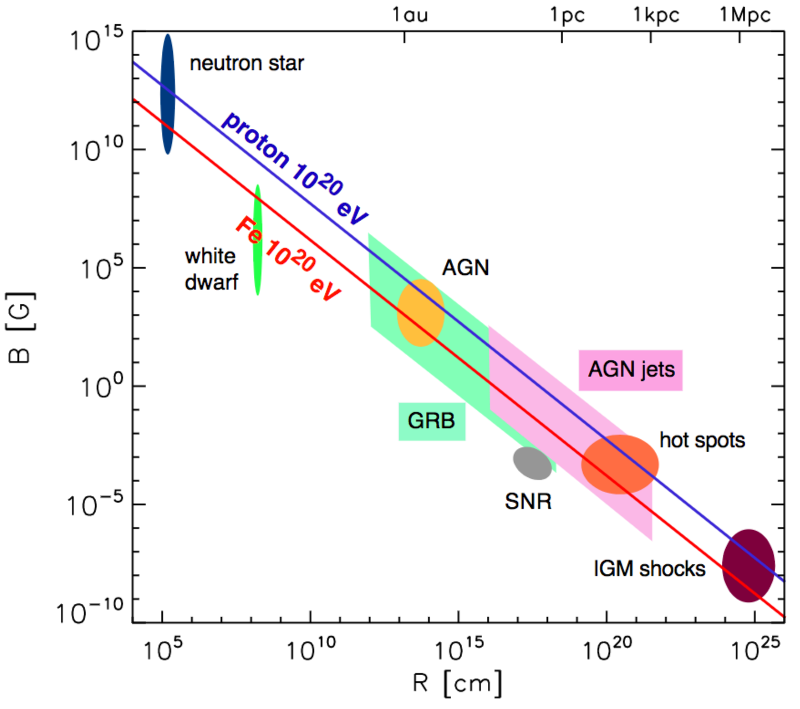


Figure 11:

Updated Hillas (1984) diagram. Above the blue (red) line protons (iron nuclei) can be confined to a maximum energy of $E_{\max} = 10^{20}$ eV. The most powerful candidate sources are shown with the uncertainties in their parameters.

(Kotera & Olinto, ARAA 2011)

Photo-dissociation scenario