Short review of ultra-high energy cosmic-rays

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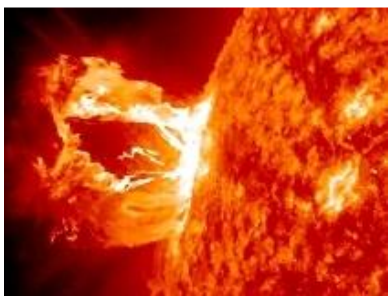
cosmic rays (CRs) - high-energy particles coming from space

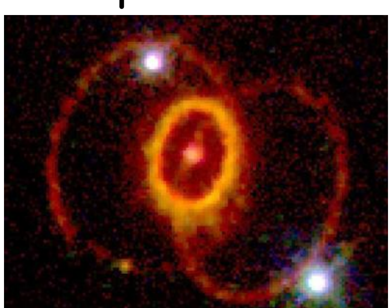
(protons, nuclei, neutrinos, photons, electrons,...)

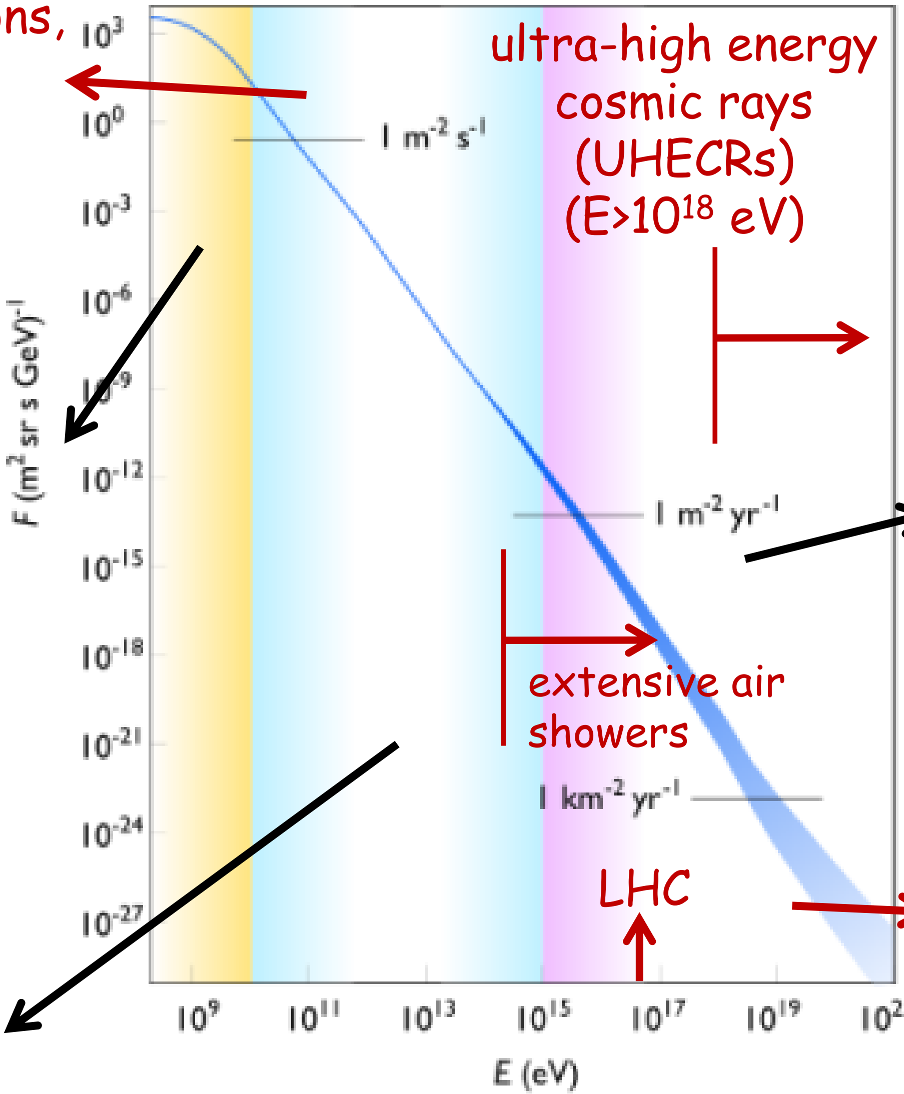
direct observations,
satellites,
balloon-borne
experiments

Sun

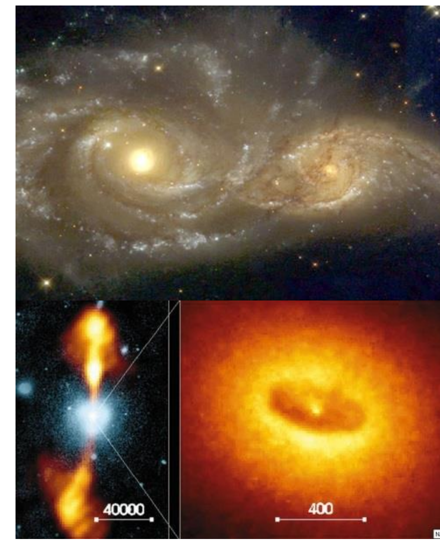


Supernovae,
pulsars

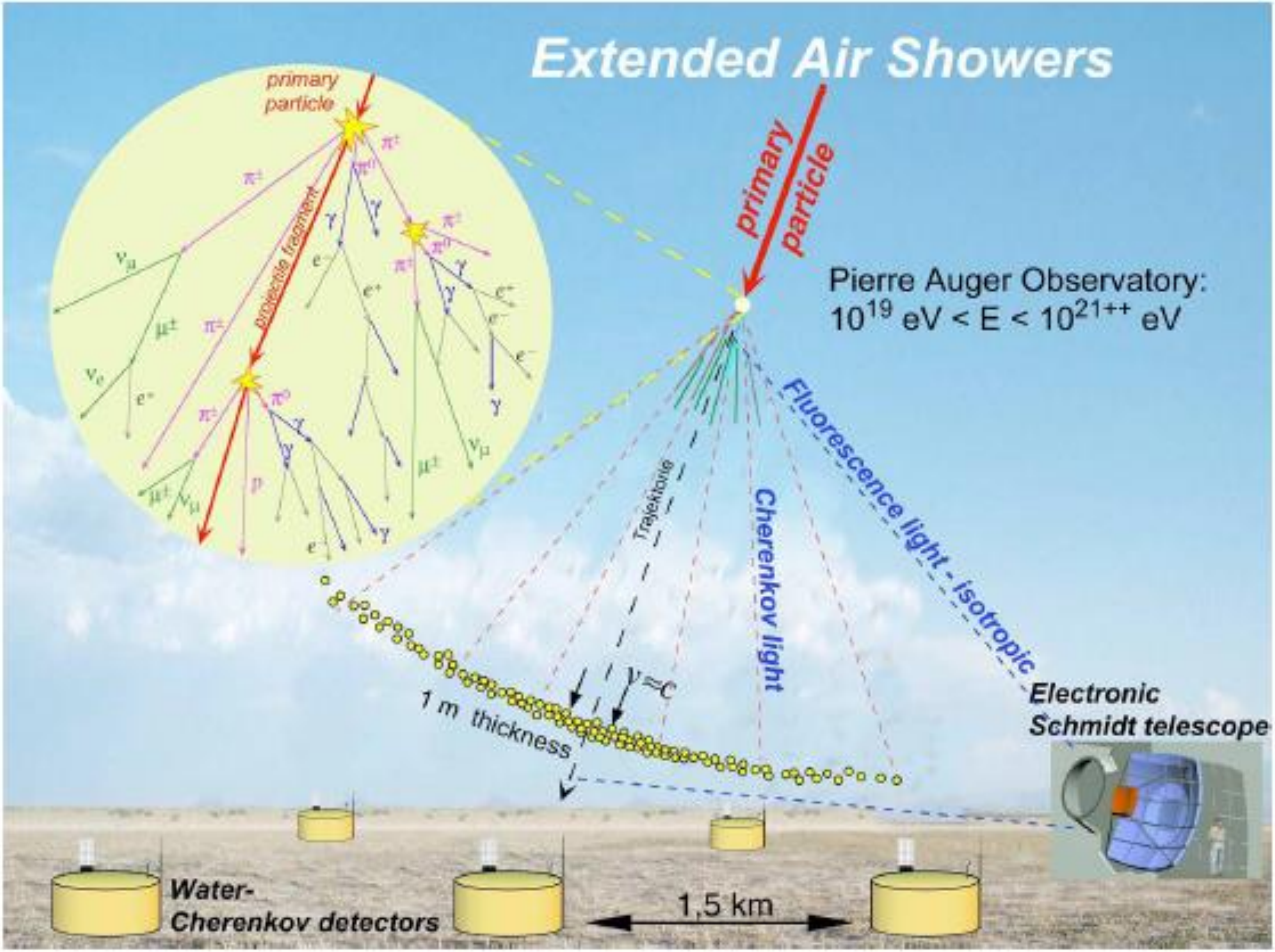




radio galaxies,
galaxy mergers,
active galactic
nuclei (AGN) ???

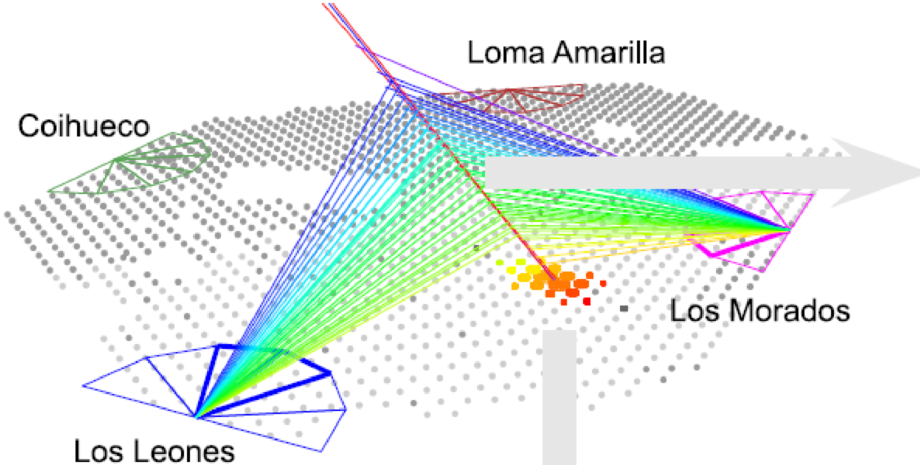


E>10^{20} eV, low flux:
1 particle/km^2/1000 yr
(indirect observations,
extensive air showers,
detector arrays
covering large area)

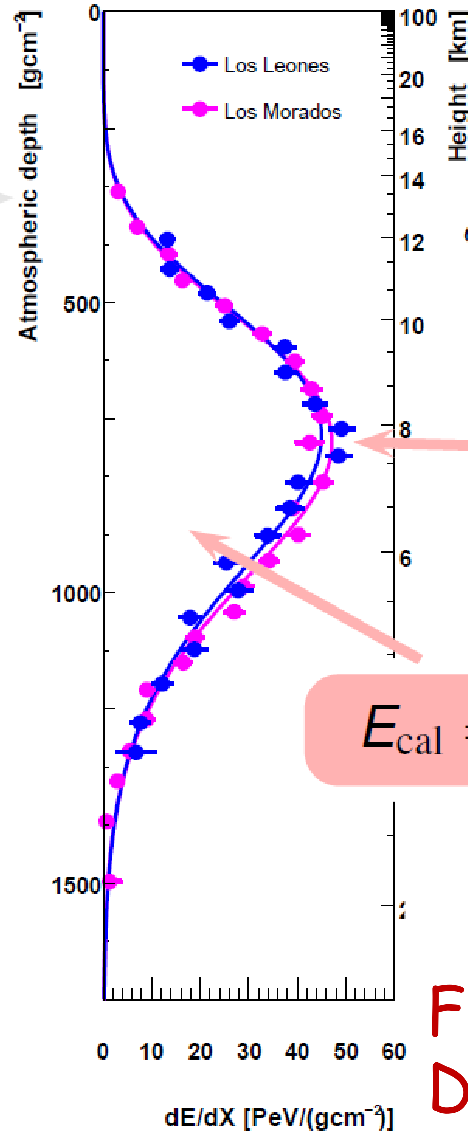


Extended Air Showers
primary particle
projectile fragment
primary particle
Pierre Auger Observatory:
10^19 eV < E < 10^21++ eV
Fluorescence light - isotropic
Cherenkov light
Trajektorie
v ≈ c
1 m thickness
Electronic Schmidt telescope
Water-Cherenkov detectors
1,5 km

Detection of air showers



top of the atmosphere



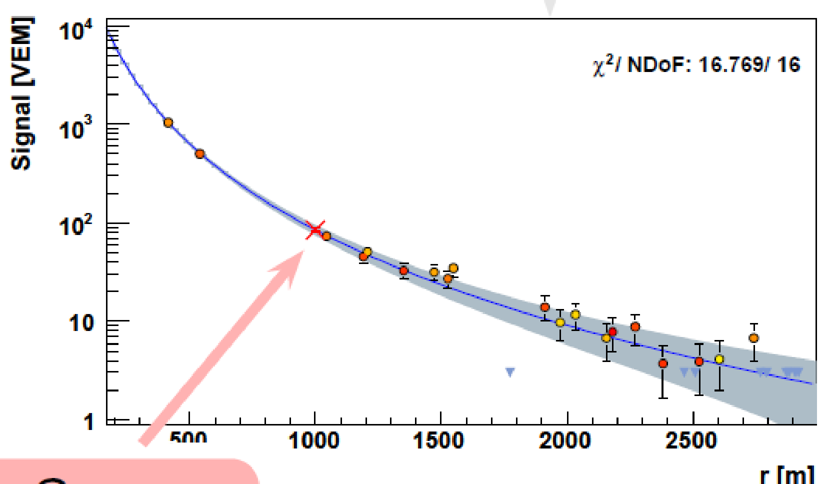
$\sigma X_{\max} \leq 20\,\mathrm{g/cm^2}$
$\Delta_{\mathrm{sys}} \leq 10\,\mathrm{g/cm^2}$

$X_{\max}$

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

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

Fluorescence Detector (FD)



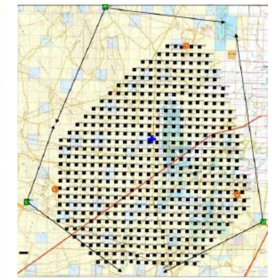
S_{1000}

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

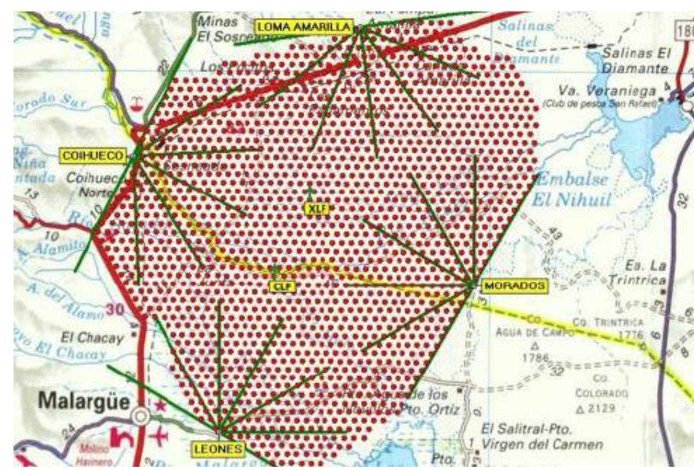
Surface Detector (SD)

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

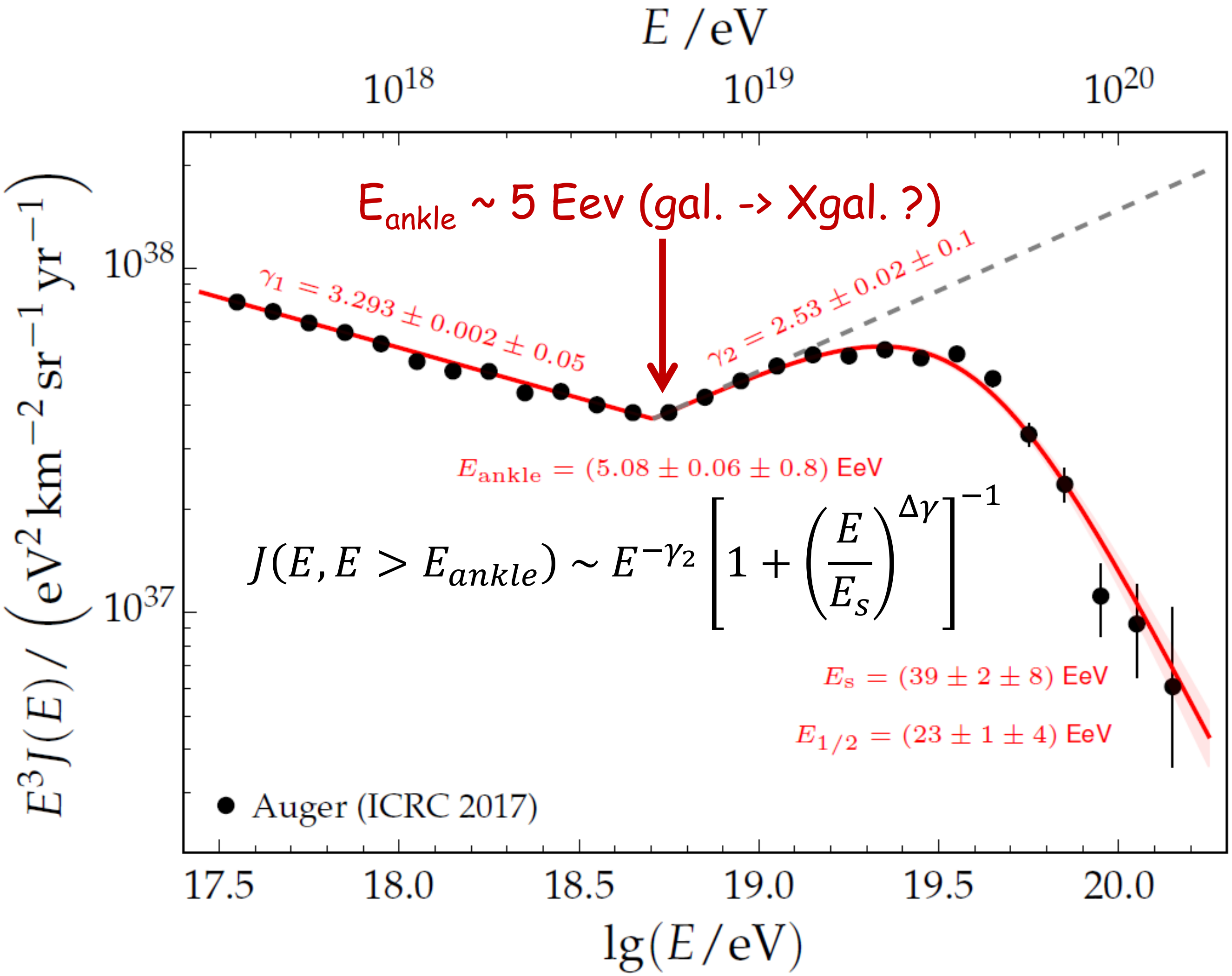
(northern hemisphere)
Telescope Array (TA)
Area: 700 km^2
Location: USA



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



UHECRs energy spectrum: combined Auger spectrum



GZK cutoff ?

or

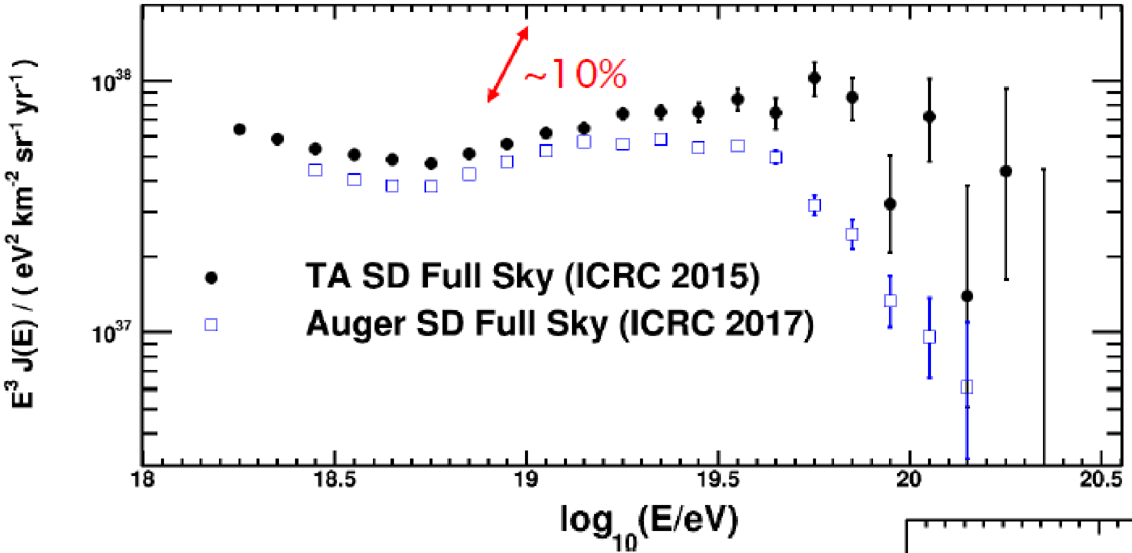
Efficiency limit of the particle acceleration by sources (cutoff in the source spectrum)? (particles accelerated to maximum energies proportional to their charges: $E_{max} = R_{cut}Z$?)

Suppression of the energy spectrum compatible with both scenarios.

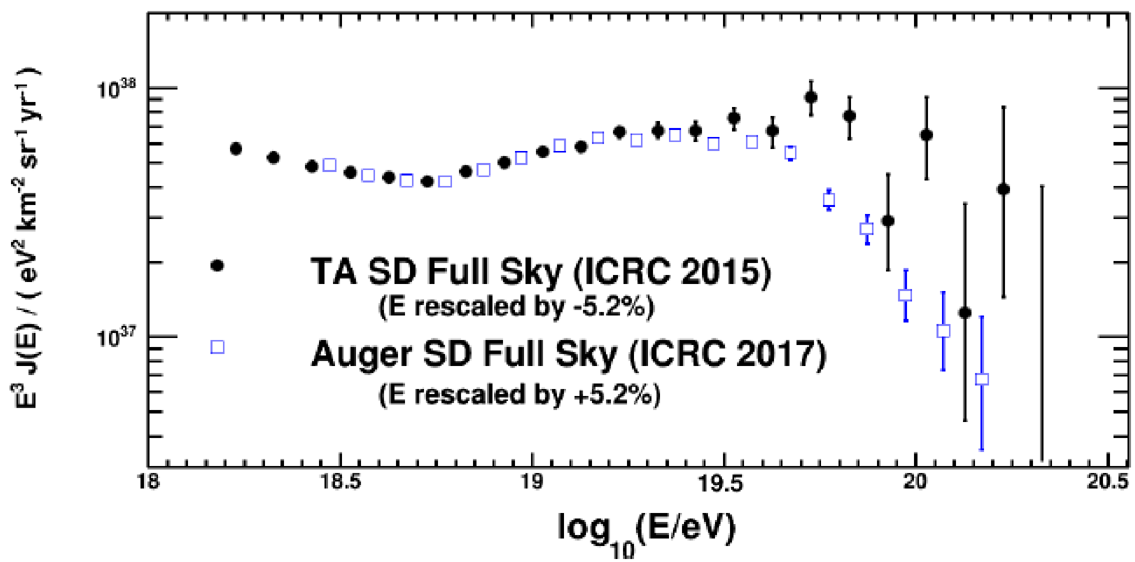
Measurements of the mass composition of UHECRs are needed.

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

UHECRs energy spectrum: are Auger and TA spectra compatible?



energy rescaling

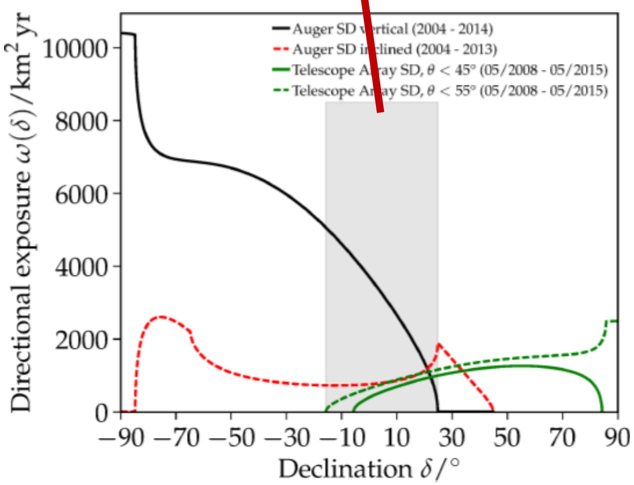


- Ankle at ~5 EeV, cutoff at ~40 to 60 EeV
- ~10% energy scale difference around ankle region well within 14% (Auger) and 21% (TA) energy scale systematic uncertainties
- Some discrepancy in shape at E > $10^{19.4}$ eV

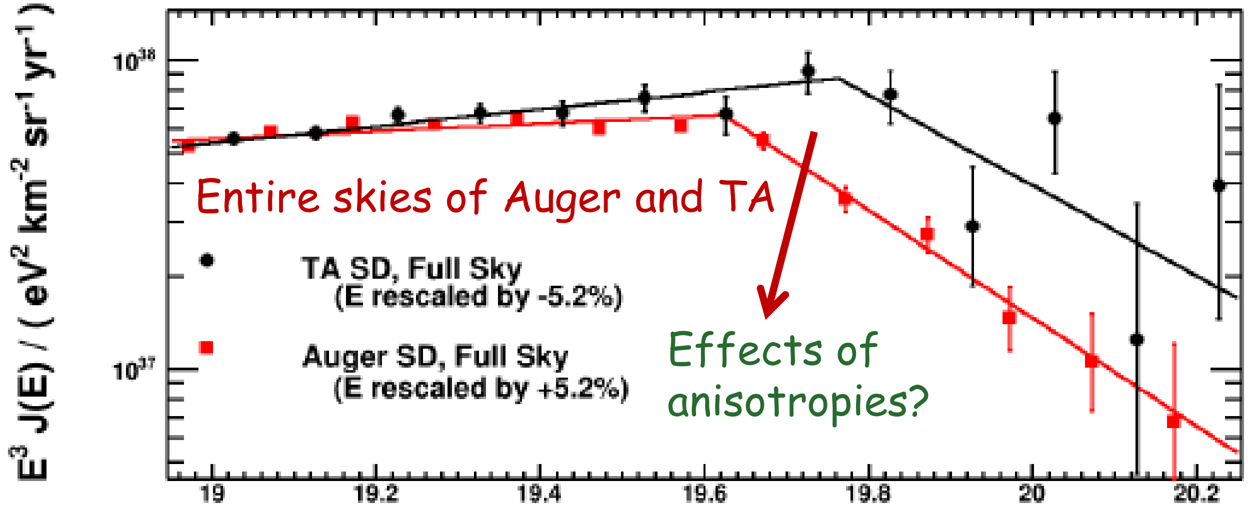
- Spectra agree in the ankle region $10^{18.4}$ eV < E < $10^{19.4}$ eV
- Difference above $10^{19.4}$ eV persists

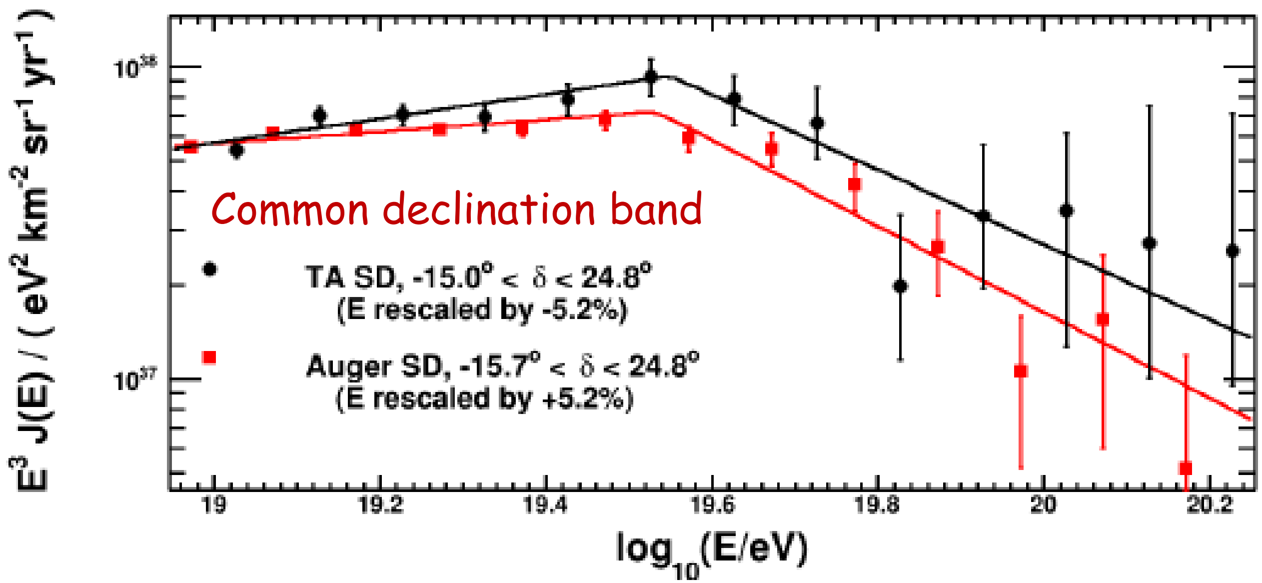
UHECRs energy spectrum: Auger and TA common declination band

the overlapping sky region seen by both detectors



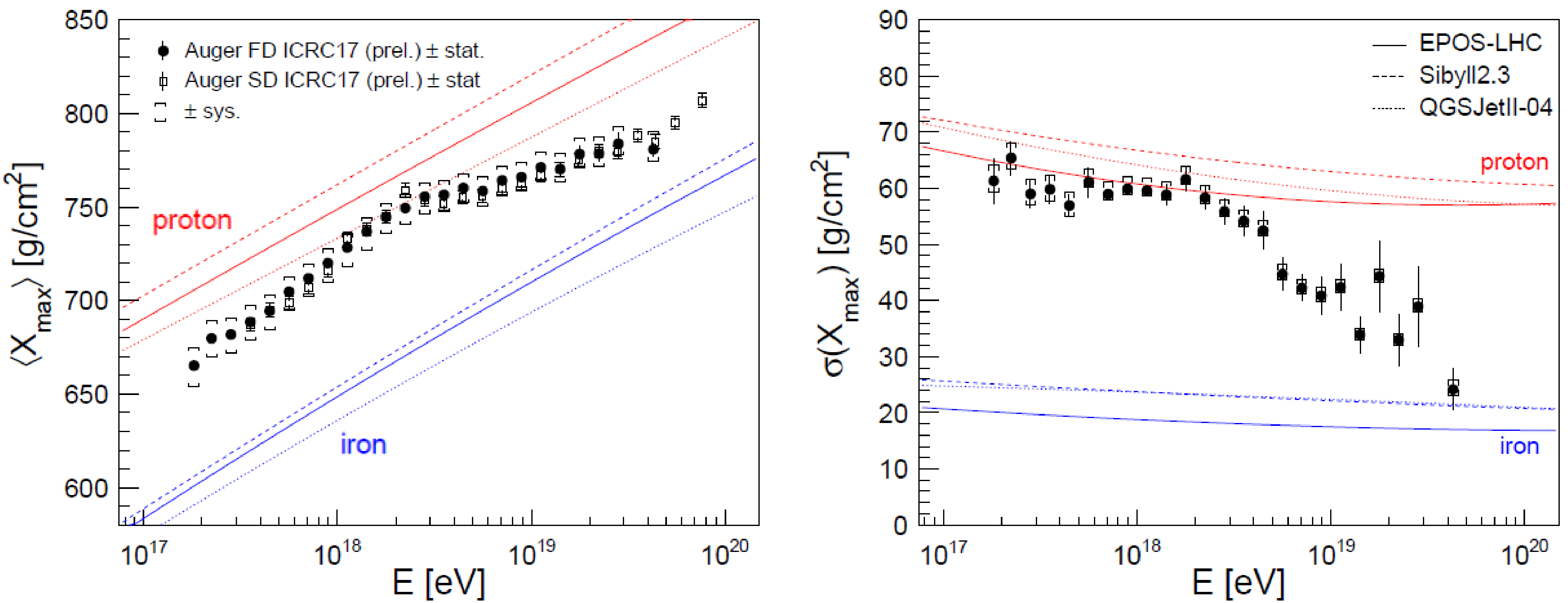
directional exposure vs declination





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

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

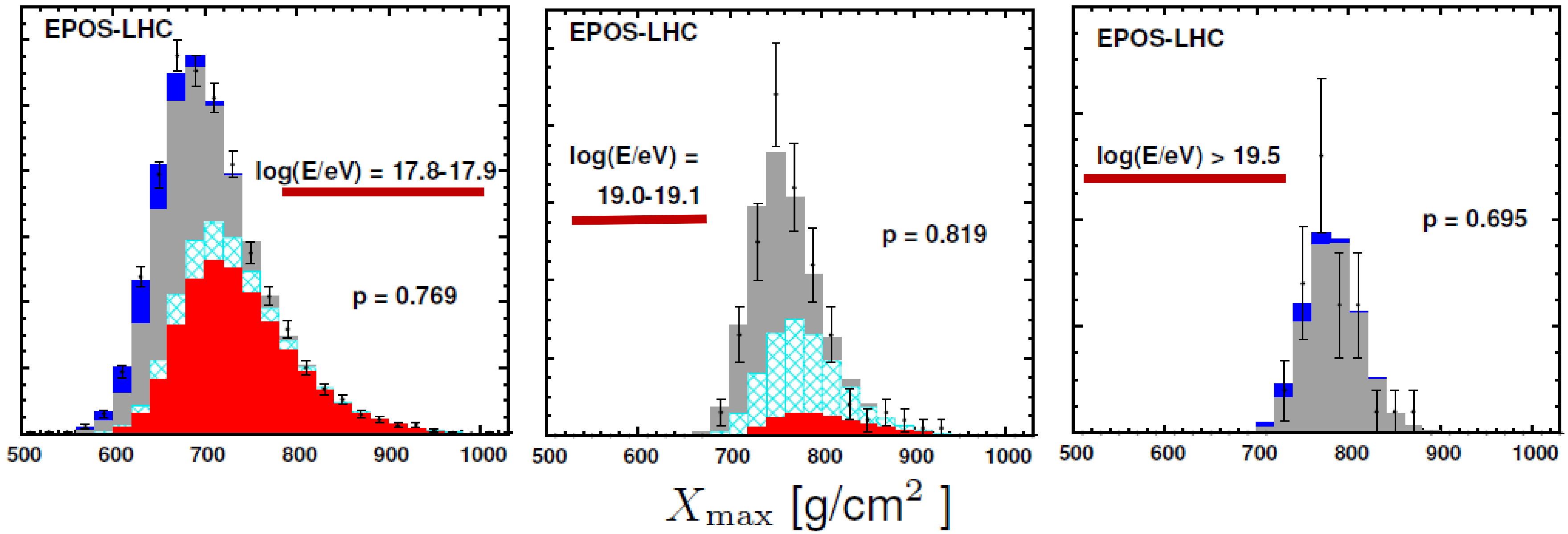


- X_{max} is an observable sensitive to the mass composition.
- The rate of change of X_{max} with Energy (elongation rate) indicates changing mass composition.
- Fluctuations of X_{max} decrease above 2 EeV, indicating a composition becoming heavier with increasing energy.
- The inferred mass composition 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

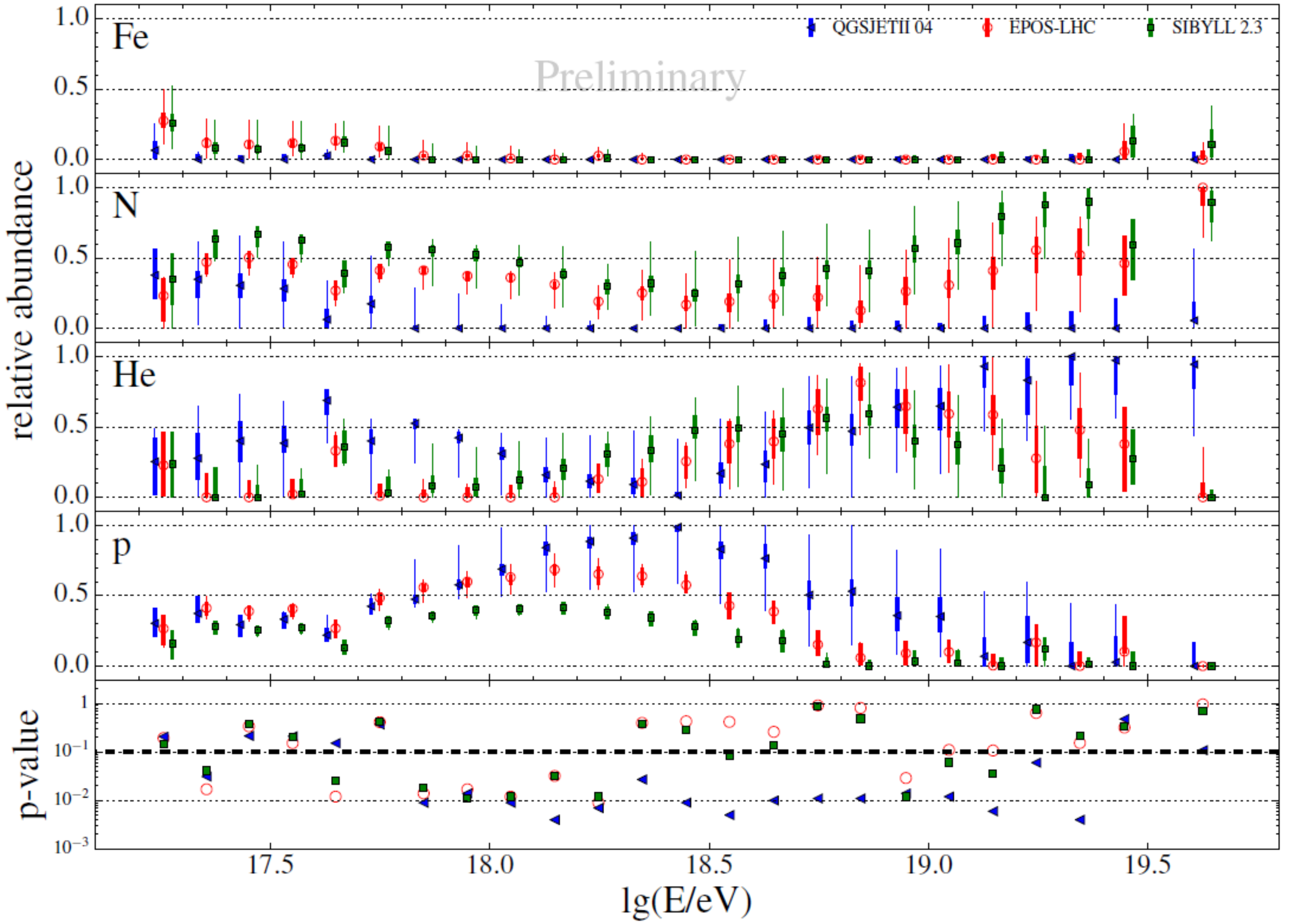
Examples of 4-component fit:

p He N Fe



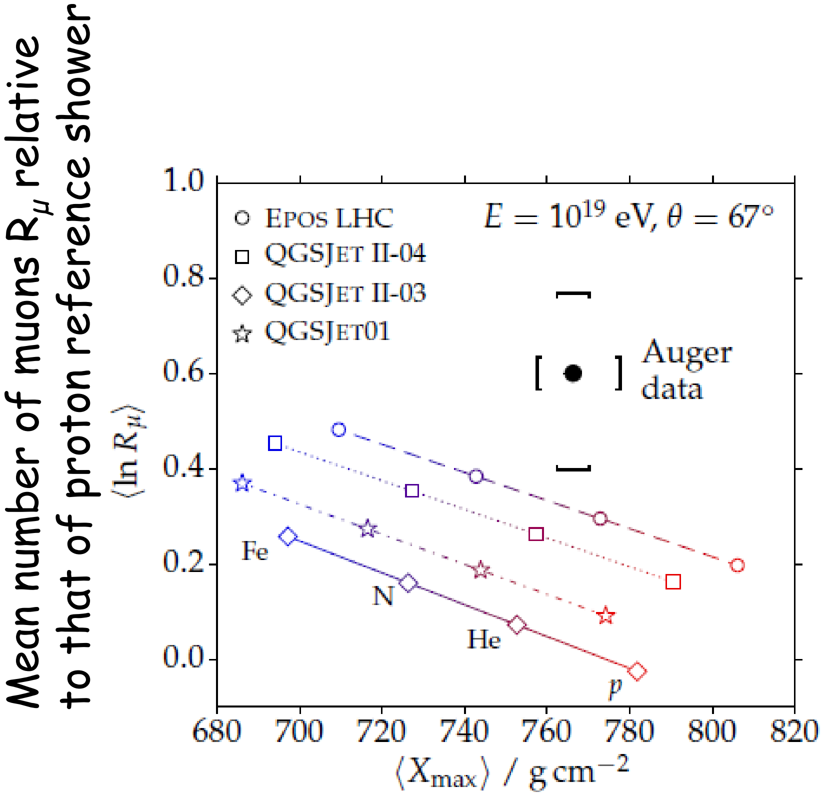
- Composition **proton-like** at 10^{18} eV and **N-like** above 10^{19} eV

AugerMix

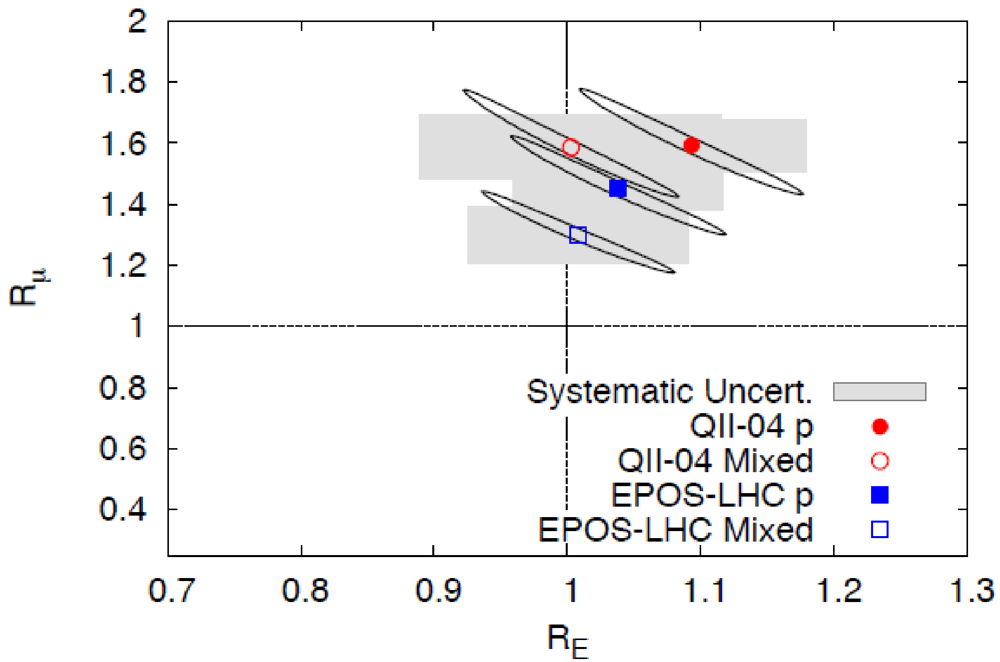


- **No model requires any significant fraction of iron at any energy.**
- For all models there is a significant reduction in the proton fraction with increasing energy above 2 EeV.
- The intermediate masses (He, N) at all energies have a strong model dependence.
- p-values indicates that **the hadronic interaction models have difficulties to reproduce the details of the observed X_{max} distribution.**

Hadronic interactions at UHE



Muon discrepancy observed in showers of 10^{19} eV



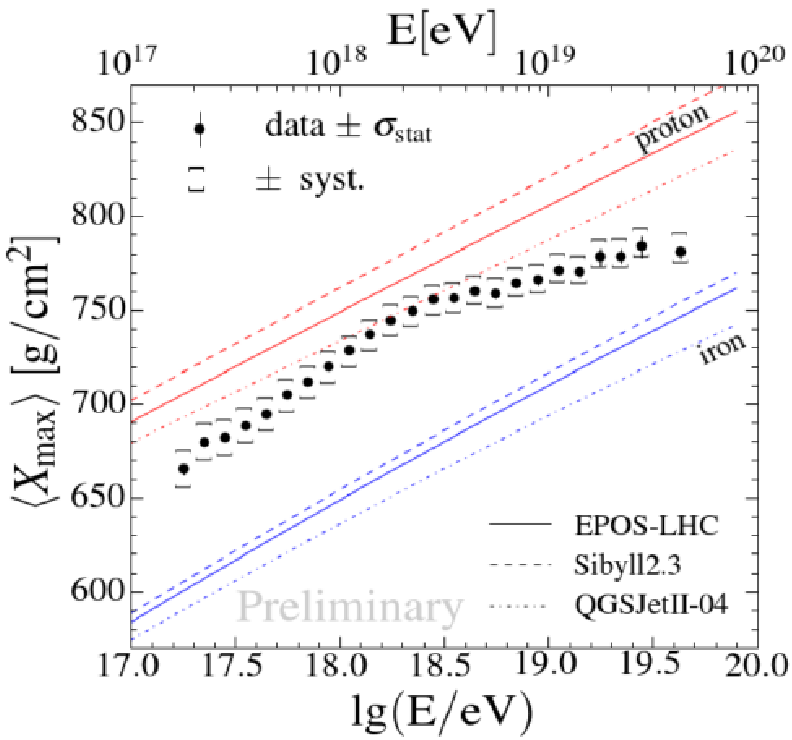
None of the hadronic interaction models can reproduce the muon number! (μ deficit in models)

Scaling factors R_μ and R_E for

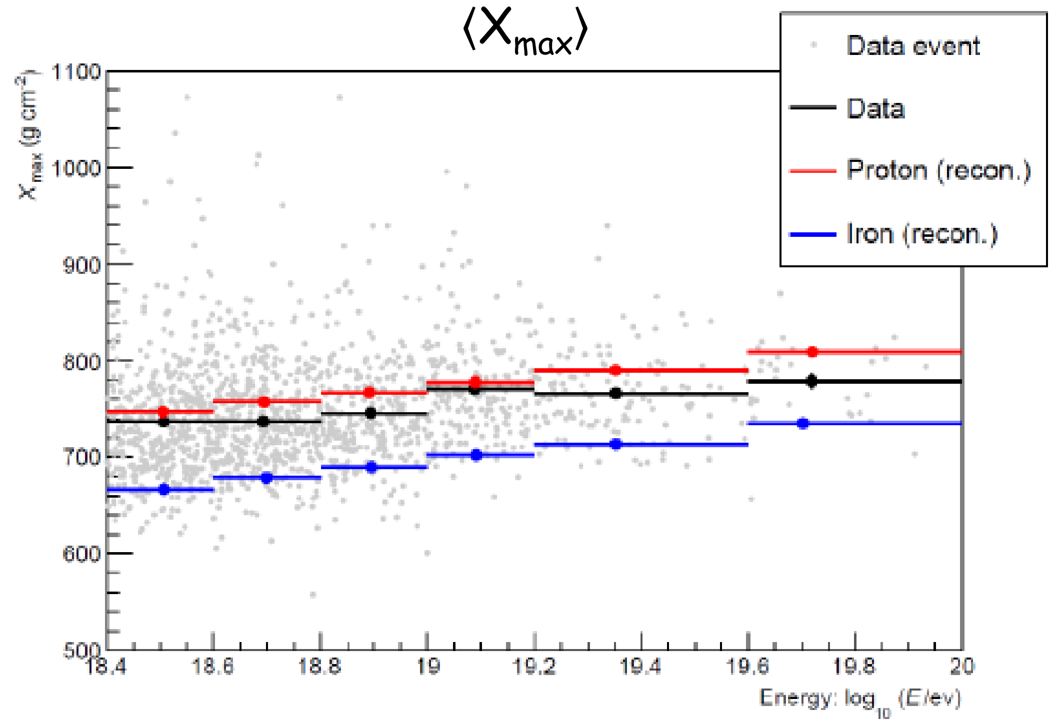
- the muon component of the shower and
- the primary energy

which bring a model calculation into agreement with data.

Mass composition: are Auger and TA compatible?



Auger Collaboration, ICRC2017

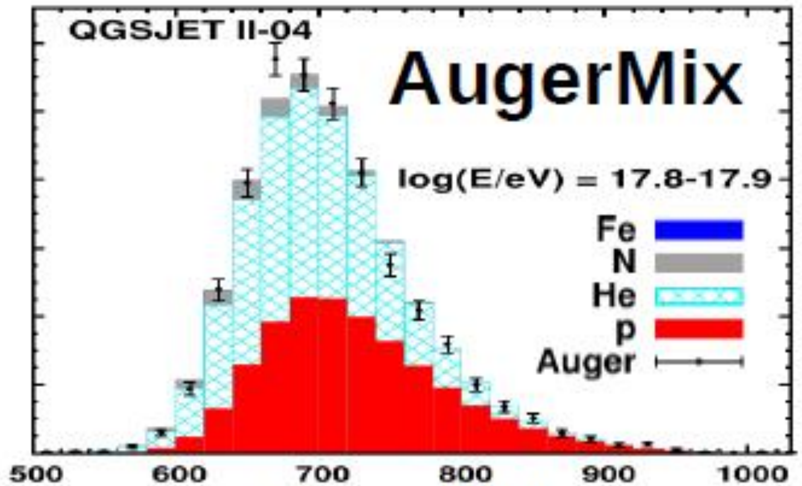


TA Collaboration, ICRC2017

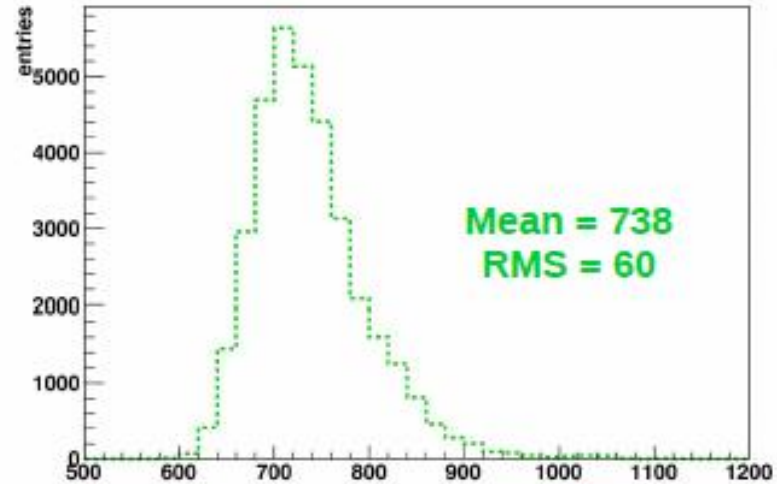
The composition which best describes Auger data in the energy range from $10^{18.2}$ to 10^{19} eV is a mix of p, He and N nuclei, i.e. AugerMix

TA data is compatible with the pure p composition

Different detectors and analysis ➔ Don't jump into conclusions



$Xmax^{Auger}$



$Xmax^{TA}$(**AugerMix**)

SAME RESULTS WITH EPOS-LHC

TA Detector Simulation

TA Analysis

Credit: V. de Souza

Repeat the same analysis

but now calculate

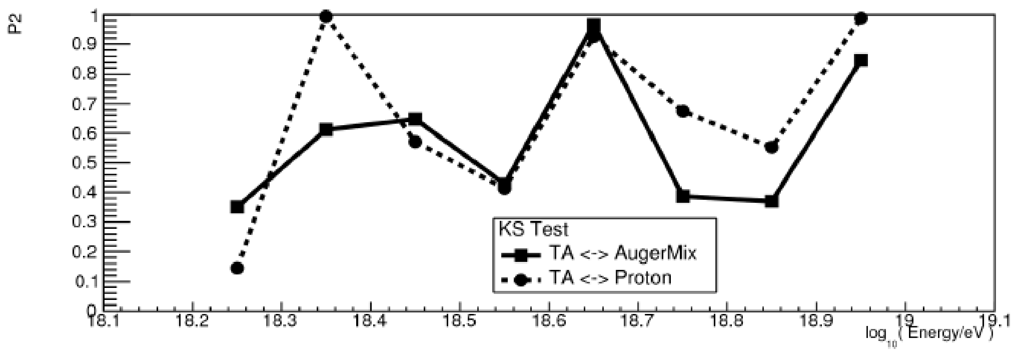
the compatibility probability

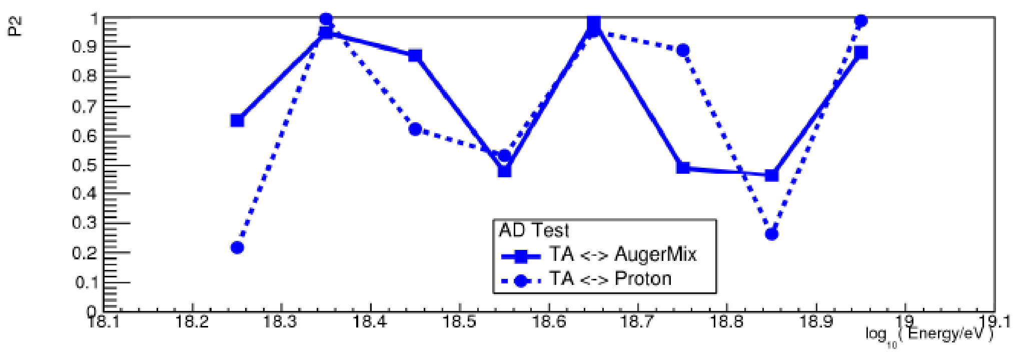
between TA data and pure p

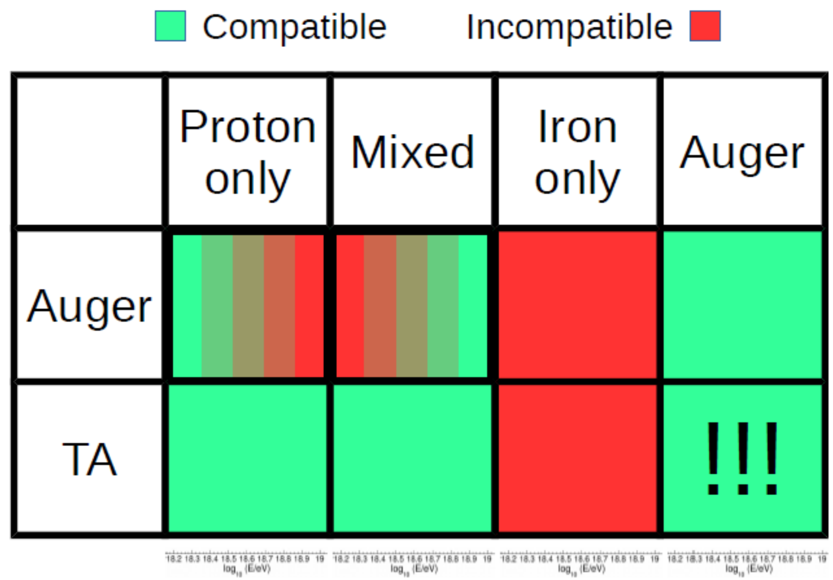
composition

Compatibility between TA data and:
- AugerMix X_{max} distribution
- pure proton X_{max} distribution

X_{max} compatibility table
$18.2 < \log_{10}(E/eV) < 19.0$







$\log_{10}(E/eV)$

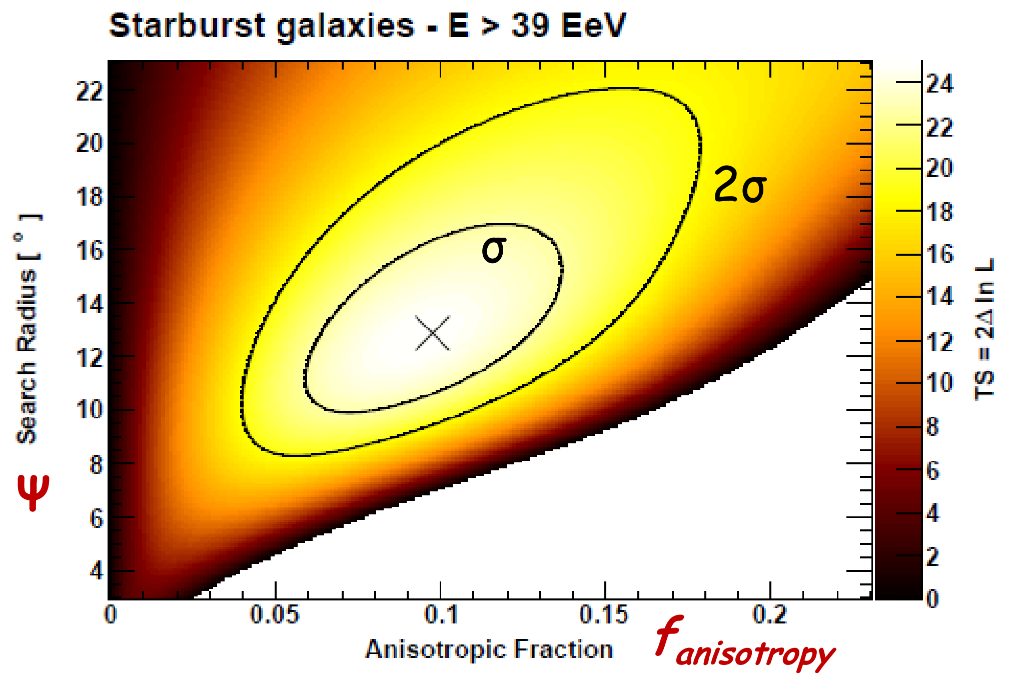
- TA X_{max} distributions **are as compatible** to pure proton composition as they are to AugerMix within the systematic uncertainties.
- **TA and Auger composition measurements agree within the systematics in the $18.2 < \log_{10}(E/eV) < 19.0$ energy range!!!**
- More TA data is needed to confirm the trend to a heavier composition seen in Auger data above 10^{19} eV.

Search for UHECR correlation with:

➢ Starburst Galaxies

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

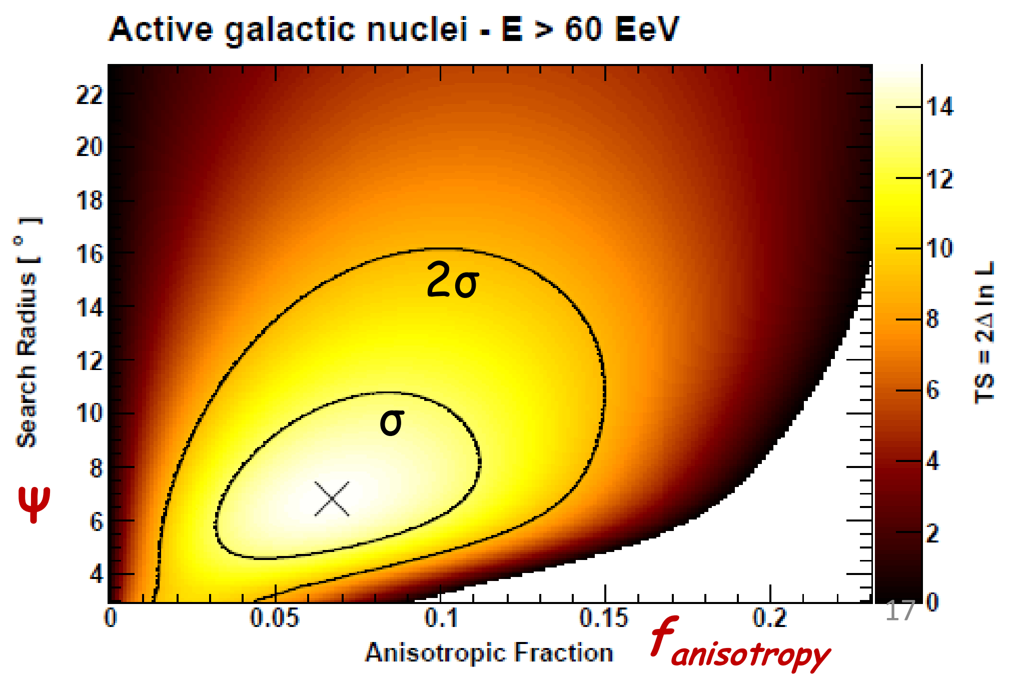
$f_{anisotropy}$ = 10%, Ψ = 13°
significance **3.9σ**



➢ γ-ray detected Active Galactic Nuclei

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

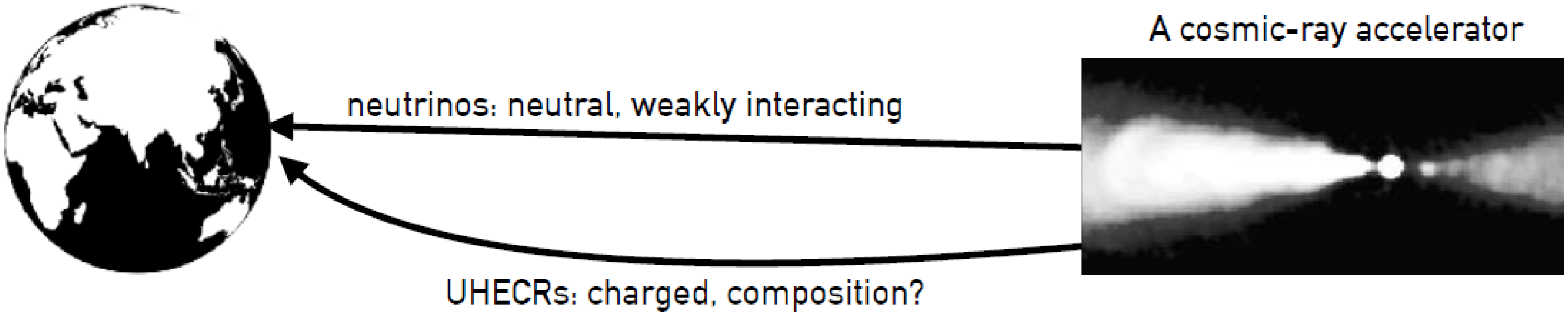
$f_{anisotropy}$ = 7%, Ψ = 7°
significance **2.7σ**



Likelihood ratio analysis

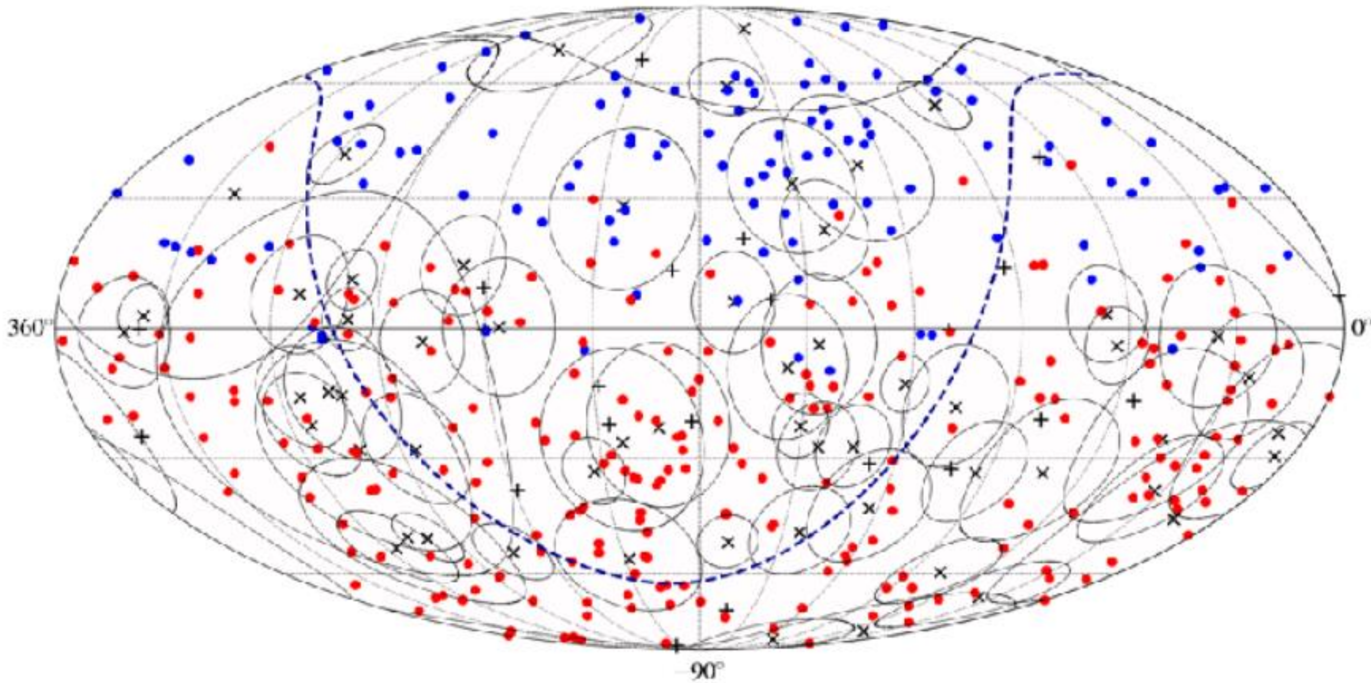
- correlation angle Ψ (takes into account the unknown deflections of the UHECRs in the magnetic field)
- H_0: isotropy
- H_1: (1-f) x isotropy + f x fluxMap(Ψ)
- Test Statistic = 2 log(H_1 / H_0)

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



The determination of the origin of CRs is a difficult task since CRs are deflected during propagation. 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.

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



● Pierre Auger Observatory
● Telescope Array
+ Track-like neutrino events
× Cascade-like neutrino events

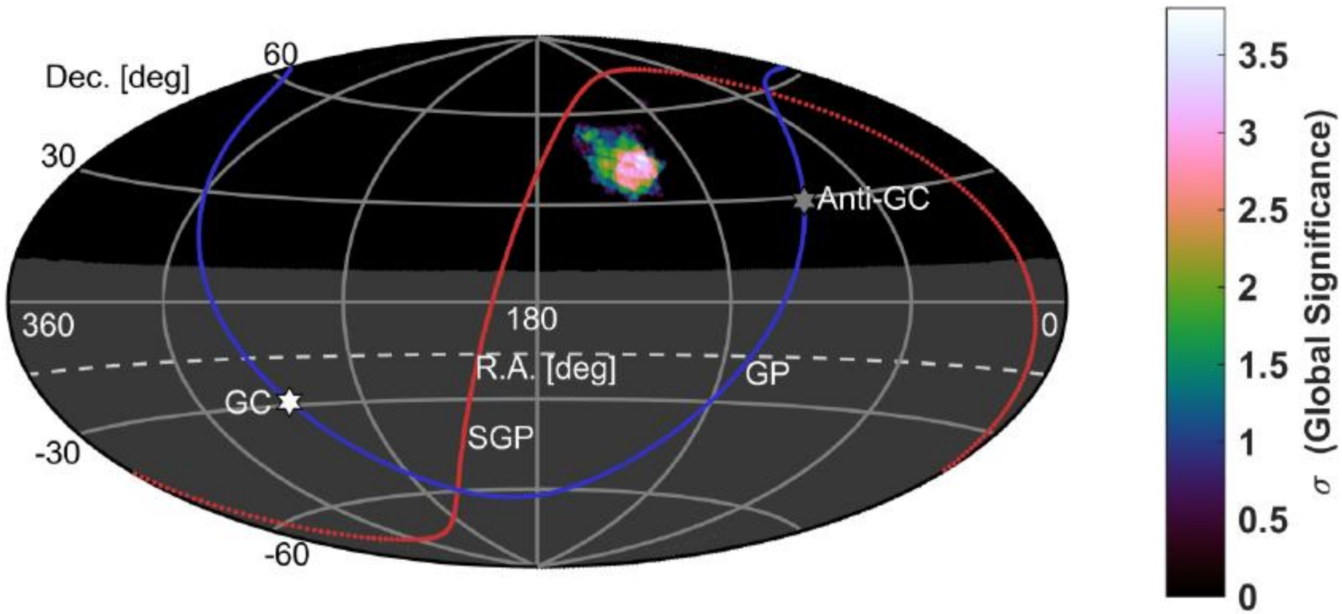
Data sample:

231 Auger events E > 52 EeV
angular resolution: 0.9°

109 TA events, E > 57 EeV, ang. res. 1.5°
58 IceCube cascade-like events, ang. res. 15°
40 IceCube track-like events, ang. res. 1°

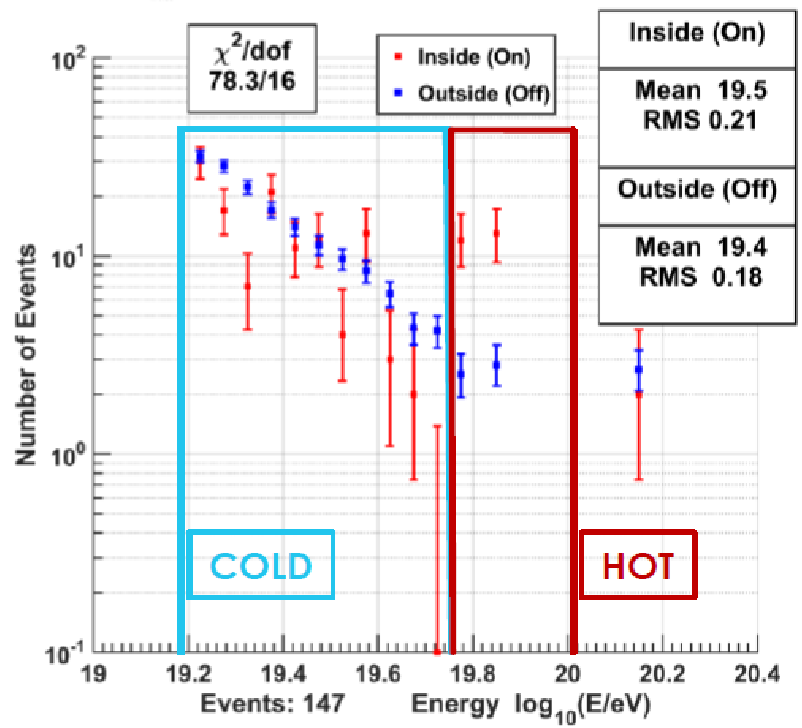
No significant correlation found

Telescope Array cold/hotspot



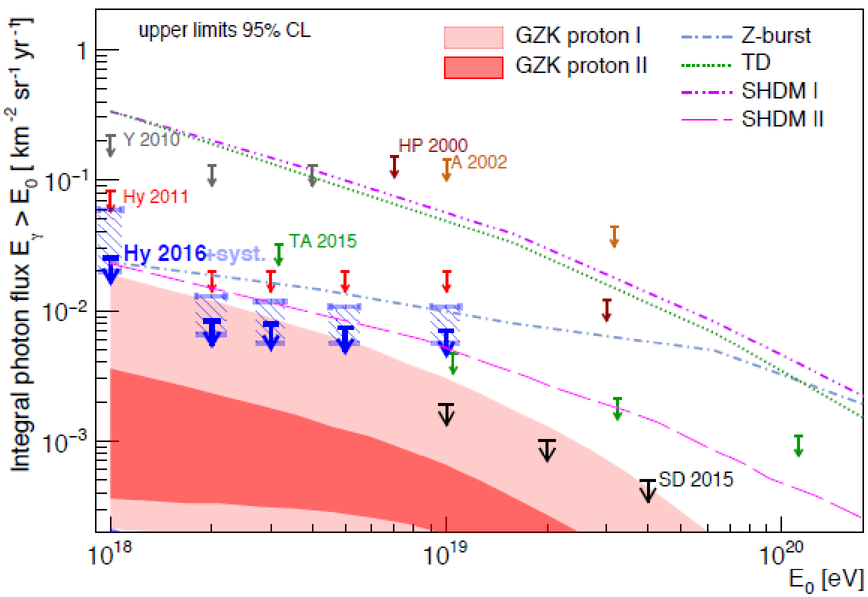
Is there a location on the sky which has a significantly different overall spectrum?

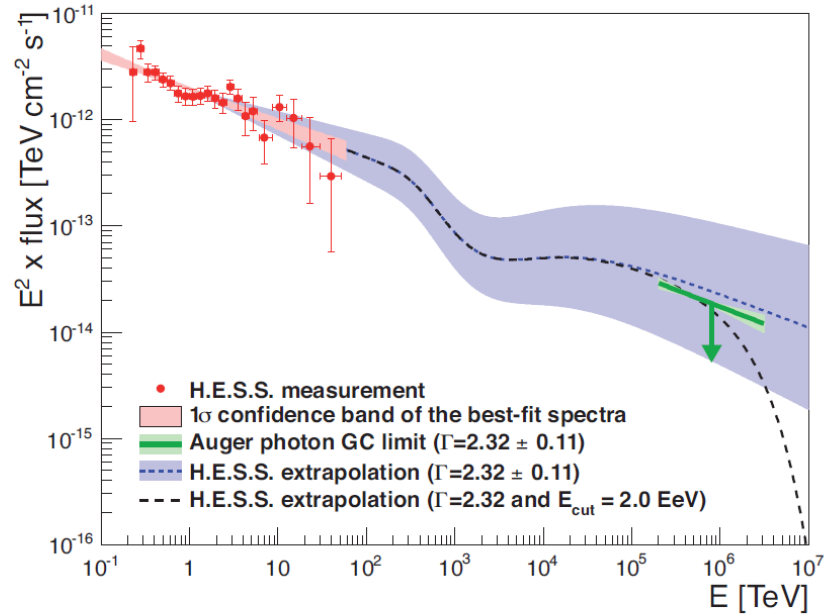
- 3.7σ deficit of low energy events and an excess of events at high energies in the same region of the sky (size of the spot of about 30°)
- Could be a signature of energy dependent magnetic deflection of cosmic rays.



Searches for cosmogenic photons

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

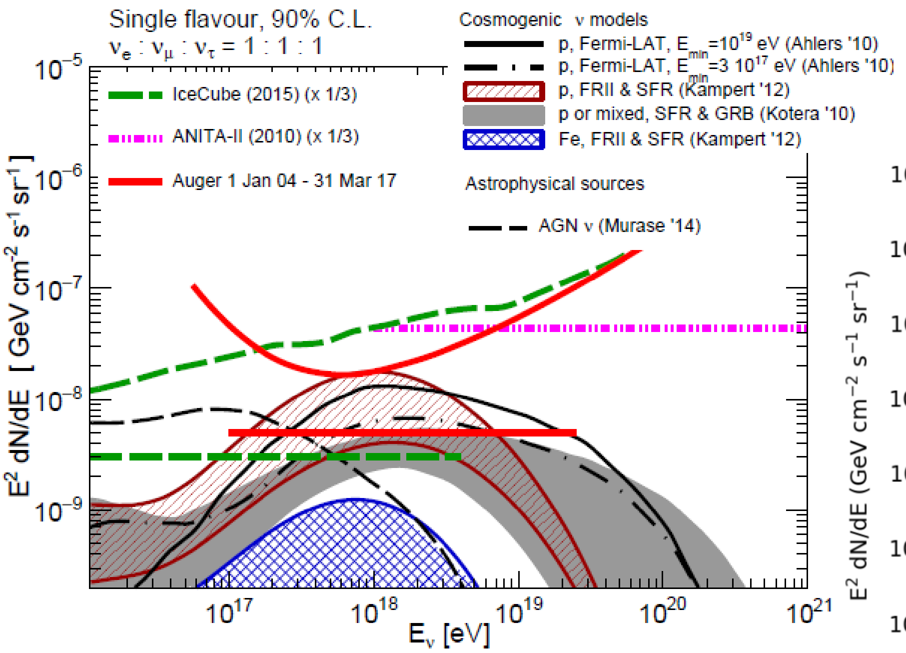


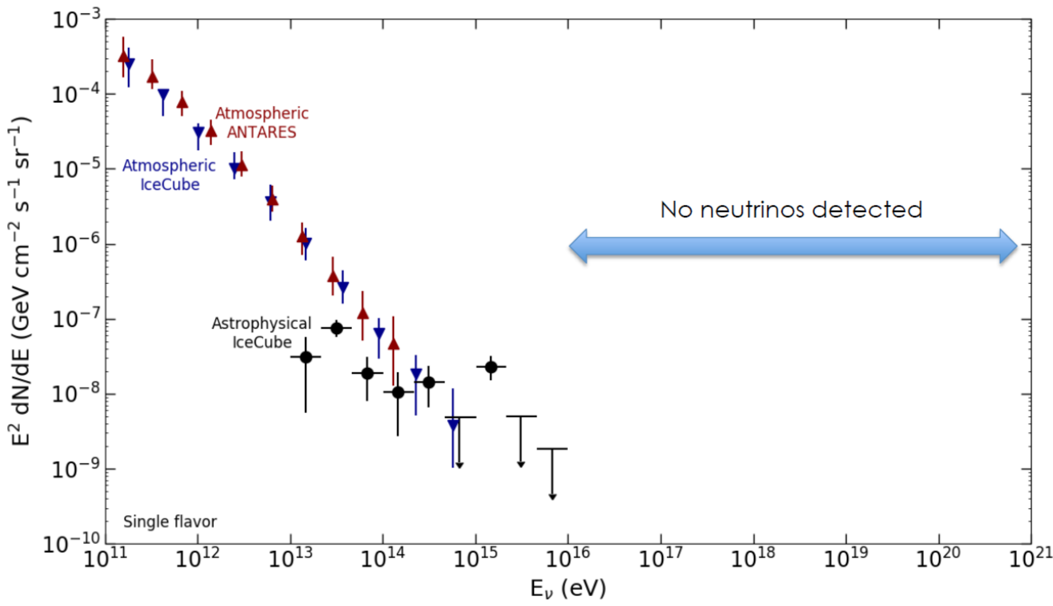


- Note that while the Auger results are stronger because of the larger exposure, the TA experiment explores a different hemisphere, relevant in the case of point sources.
- Models of top-down production of UHECR disfavoured at almost all energies.
- Models of cosmogenic photons assuming a pure proton composition can be tested.
- Constraints for photon flux spectrum from the Galactic center.

Searches for cosmogenic neutrinos

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



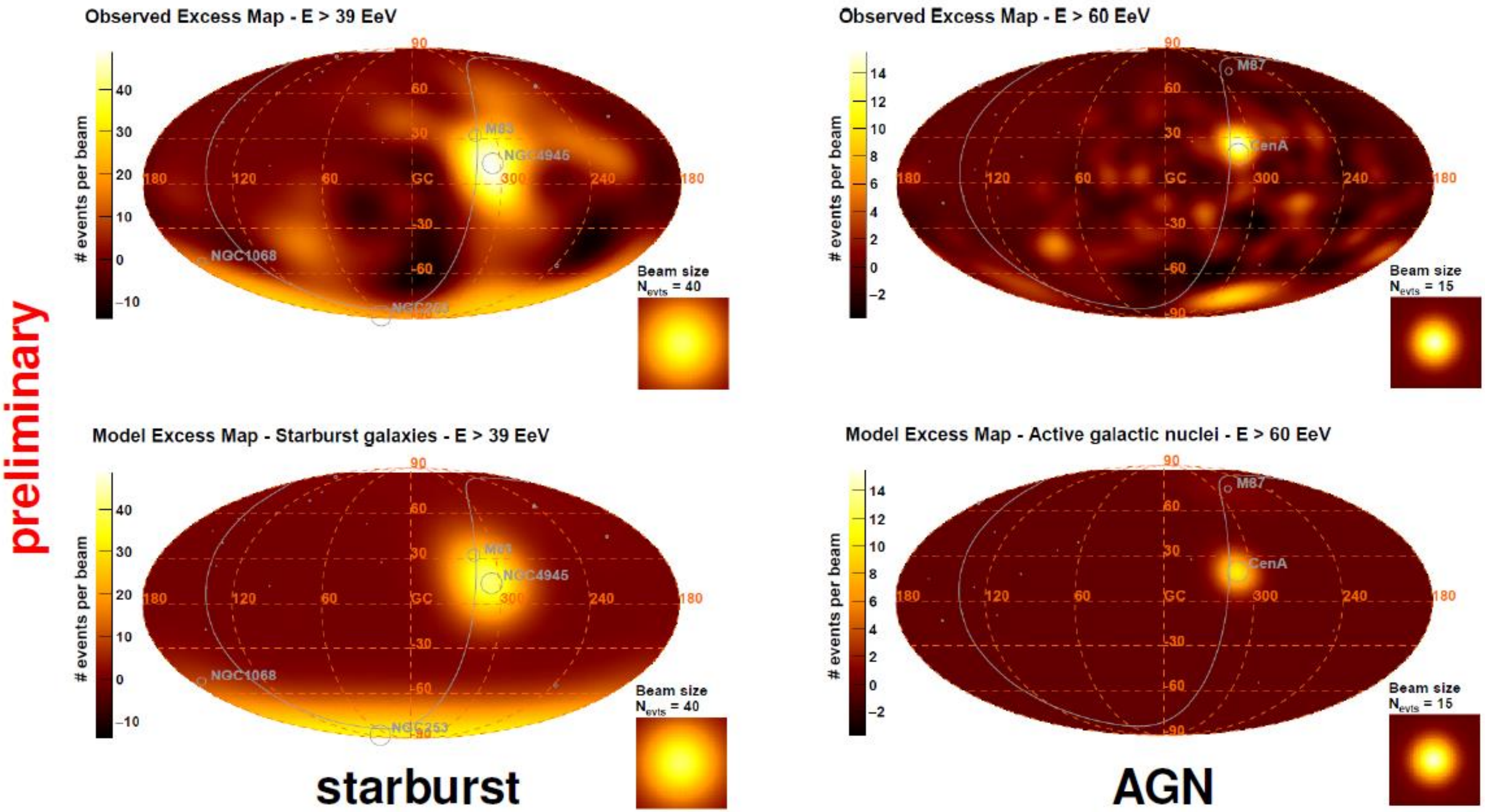


- No neutrinos observed above several PeV.
- Neutrino upper flux limits start testing the cosmogenic (GZK) ultra-high energy neutrino production models.

Summary

- Auger and TA energy spectra are consistent.
- Suppression of the UHECRs energy spectrum is compatible with GZK cutoff and with efficiency limit of particle acceleration by sources (maximum rigidity scenario).
- Auger and TA mass composition are consistent.
- UHECRs appear proton-like at 10^{18} eV and heavier up to 3×10^{19} eV (N-like).
- Current Hadronic interaction models inaccurately predict muon component in showers – implication for CR composition determination.
- TA cold/hotspot and correlation of UHECRs arrival directions with AGN/starburst galaxies (significance level $< 4\sigma$).
- No photons and neutrinos with EeV energies detected so far.

Maps for the best-fit parameters



Starburst Galaxies

- $f_{anisotropy}$ = 10%, Ψ = 13°
- Significance ~ 3.9σ

γ-ray detected AGN

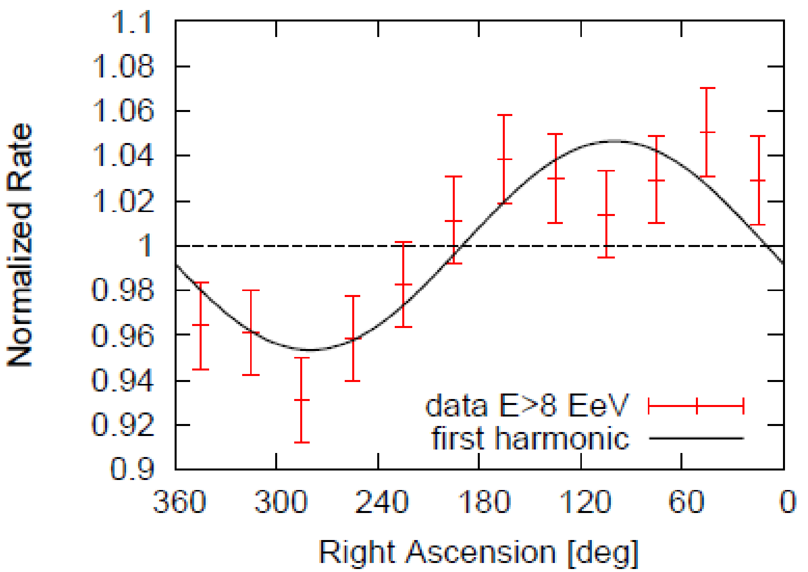
- $f_{anisotropy}$ = 7%, Ψ = 7°
- Significance ~ 2.7σ

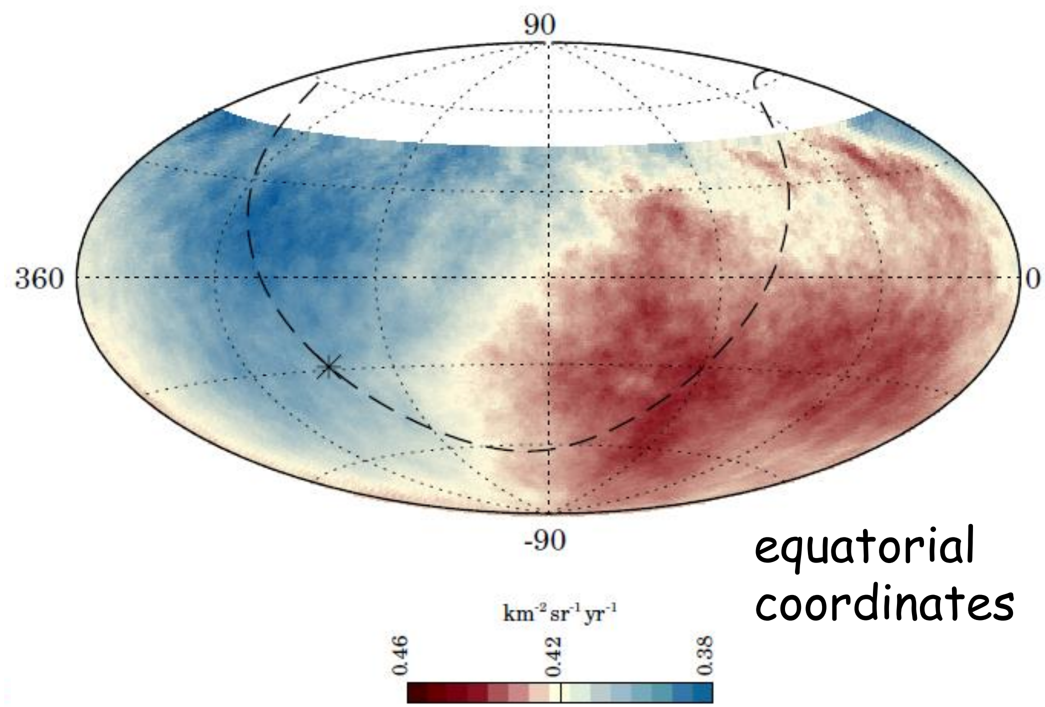
Auger observation of dipolar anisotropy above 8 EeV

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}

Significant modulation at 5.2σ (5.6σ before penalization for energy bins explored)





equatorial coordinates

3-d dipole above 8 EeV:

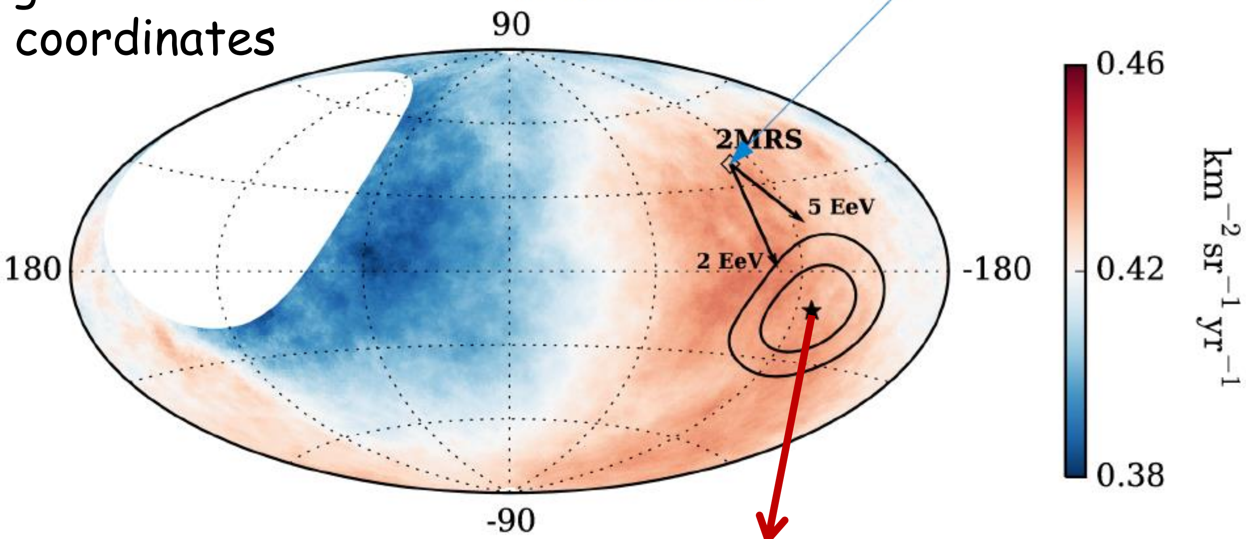
$$(6.5^{+1.3}_{-0.9})\% \text{ at } (\alpha, \delta) = (100°, -24°)$$

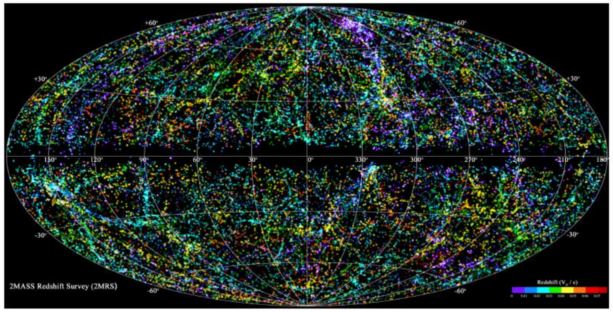
Auger observation of dipolar anisotropy above 8 EeV

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

[Erdogdu et al. 2006]

galactic coordinates





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 of sources
- diffusion in extragalactic magnetic fields from dominant nearby sources