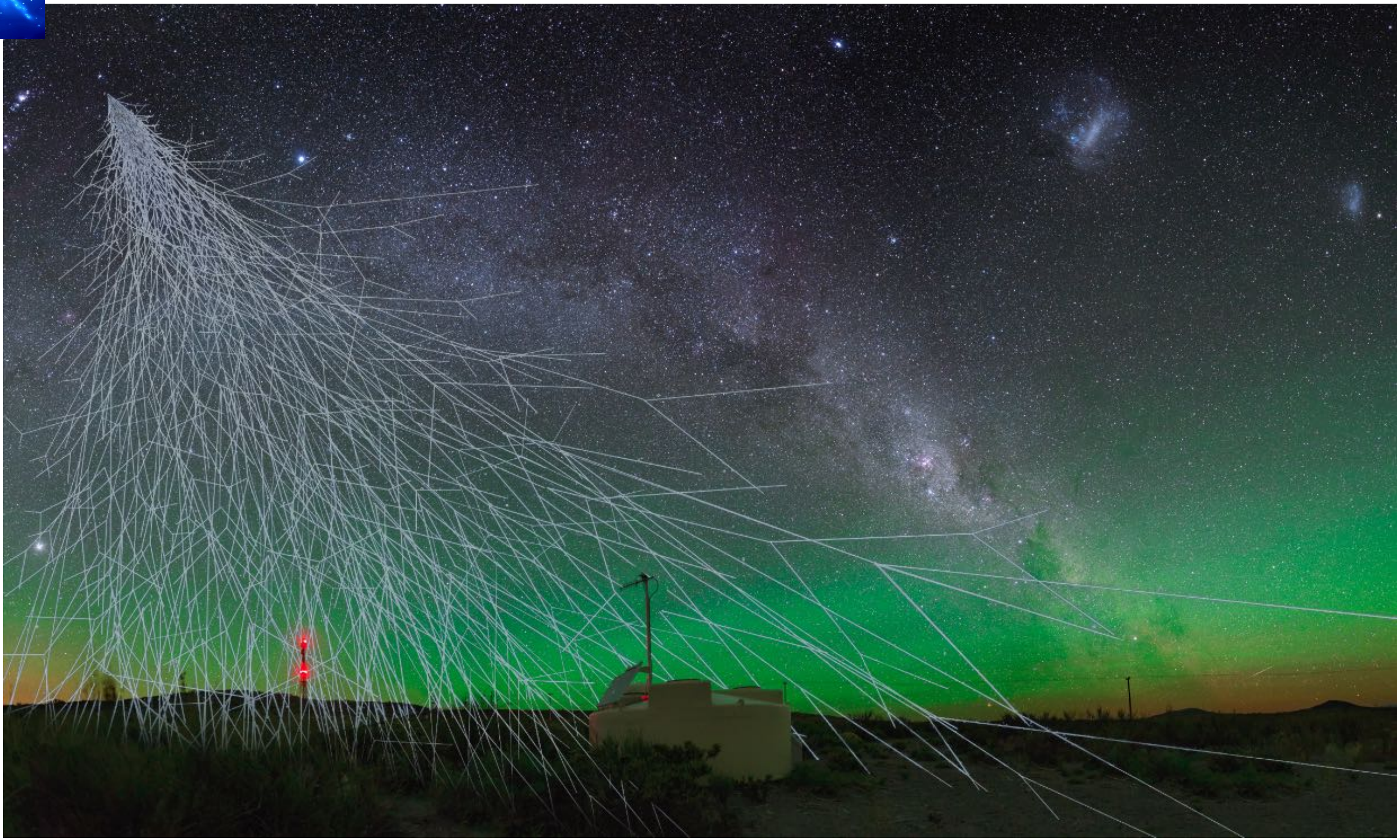
# RESULTS FROM THE PIERRE AUGER OBSERVATORY



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**See also talks by:**

- **Daniela Mockler (spectrum)**
- **Juan Miguel Carceller (composition)**
- **Francisco Pedreira  (Multimessengers)**
- **Dhital Niraj  (Auger upgrade)**
- **Joerg Hoerandel (radio detection)**

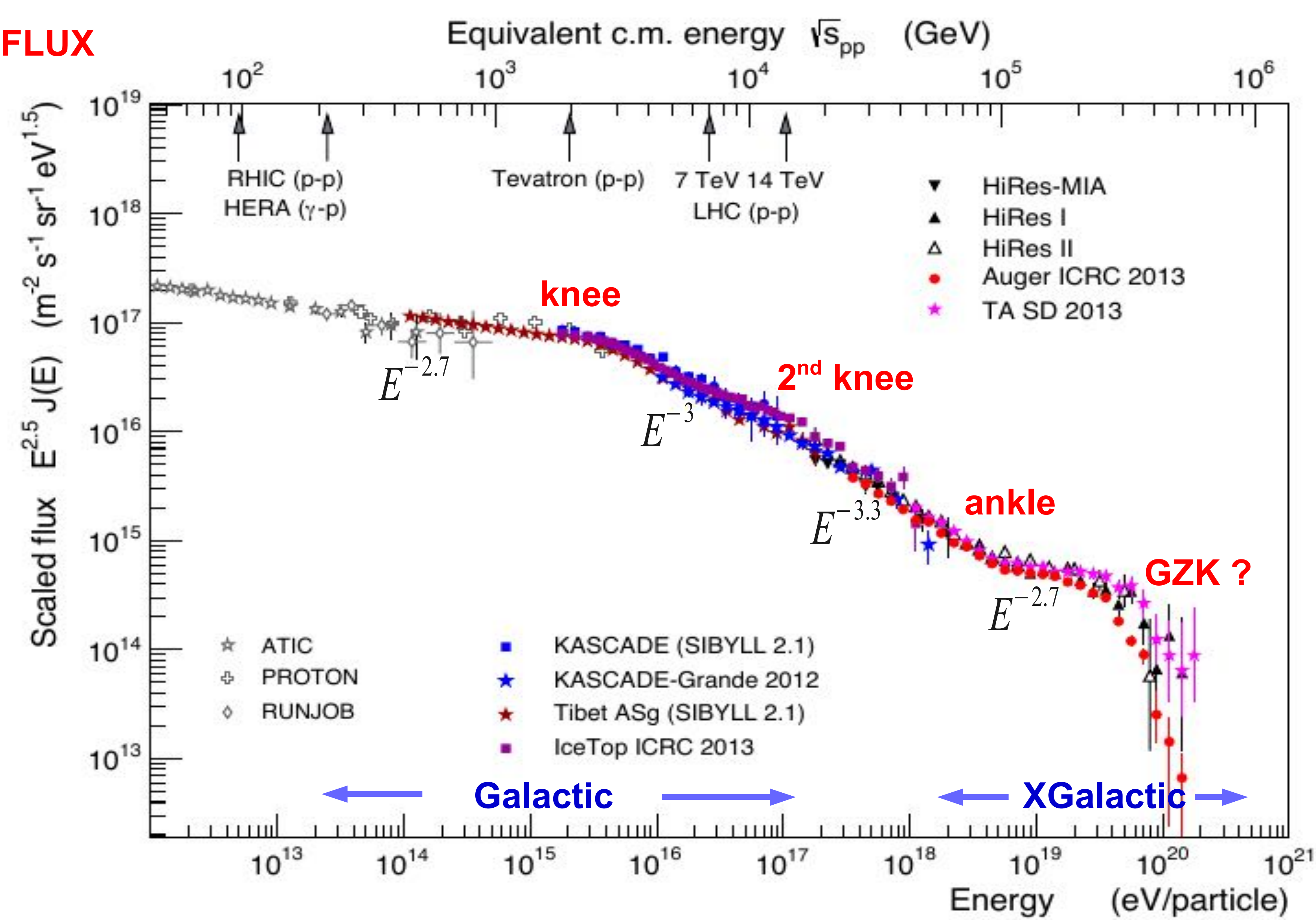
**STUDY:**
- SPECTRUM
- COMPOSITION
- ANISOTROPIES

**TO UNDERSTAND:**
- NATURE OF COSMIC RAYS (CRs)
- WHAT SHAPES THEIR SPECTRUM
- WHICH ARE THE SOURCES

**AND ALSO LEARN ABOUT:**
- HOW THEY GET ACCELERATED
- MAGNETIC FIELDS
- COSMOLOGICAL SOURCE EVOLUTION, ...

AIR SHOWER PROPERTIES DEPEND ON HADRONIC INTERACTIONS AT ENERGIES BEYOND THOSE REACHABLE AT COLLIDERS

$E^{2.5}$ x FLUX

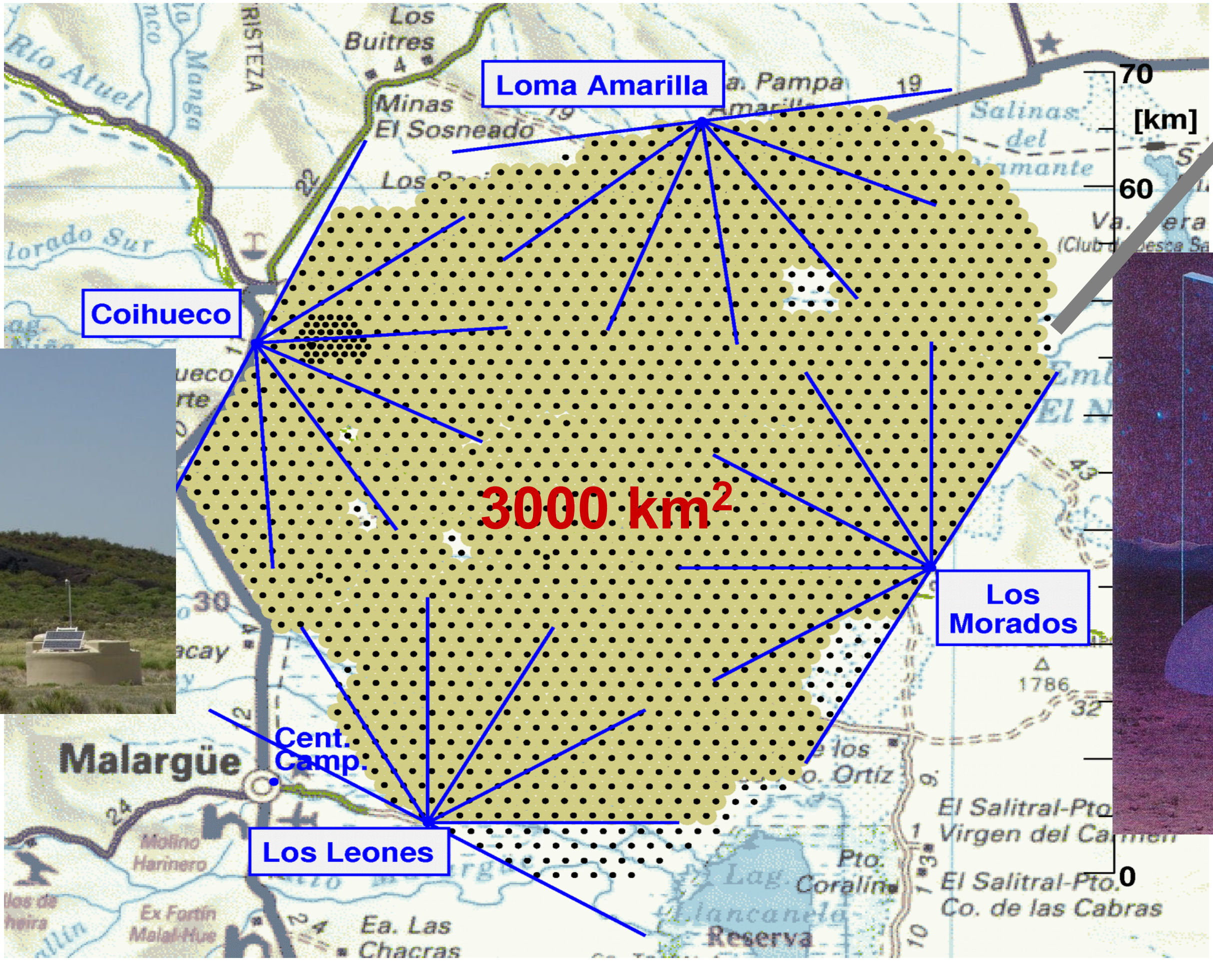


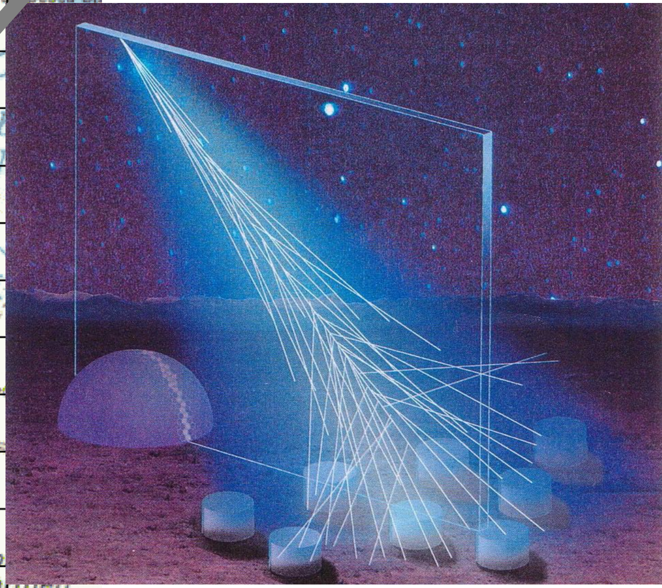
Equivalent c.m. energy $\sqrt{s}_{pp}$ (GeV)
$10^2$
$10^3$
$10^4$
$10^5$
$10^6$
RHIC (p-p)
HERA (γ-p)
Tevatron (p-p)
7 TeV 14 TeV
LHC (p-p)
HiRes-MIA
HiRes I
HiRes II
Auger ICRC 2013
TA SD 2013
knee
$2^{nd}$ knee
ankle
GZK ?
$E^{-2.7}$
$E^{-3}$
$E^{-3.3}$
$E^{-2.7}$
Scaled flux $E^{2.5}$ J(E) ($m^{-2}$ $s^{-1}$ $sr^{-1}$ $eV^{1.5}$)
$10^{19}$
$10^{18}$
$10^{17}$
$10^{16}$
$10^{15}$
$10^{14}$
$10^{13}$
ATIC
PROTON
RUNJOB
KASCADE (SIBYLL 2.1)
KASCADE-Grande 2012
Tibet ASg (SIBYLL 2.1)
IceTop ICRC 2013
Galactic
XGalactic
$10^{13}$
$10^{14}$
$10^{15}$
$10^{16}$
$10^{17}$
$10^{18}$
$10^{19}$
$10^{20}$
$10^{21}$
Energy (eV/particle)


**DETECTING UHECRs:** at the highest energies, only few cosmic rays arrive per km$^2$ per century !
to see some, huge detectors are required:

Malargüe, Argentina

## THE PIERRE AUGER OBSERVATORY



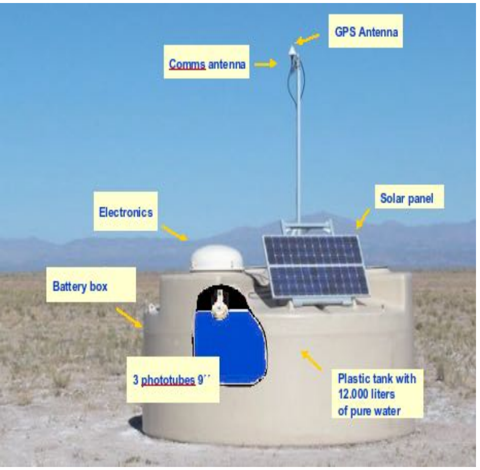



**the Auger Collaboration: ~ 400 scientists, 17 countries, taking data since 2004**

Argentina Australia Belgium Brazil Czech-Republic France Germany Italy Mexico Netherlands Poland Portugal Slovenia Spain USA Colombia* Romania*(* associate)

# HYBRID CONCEPT

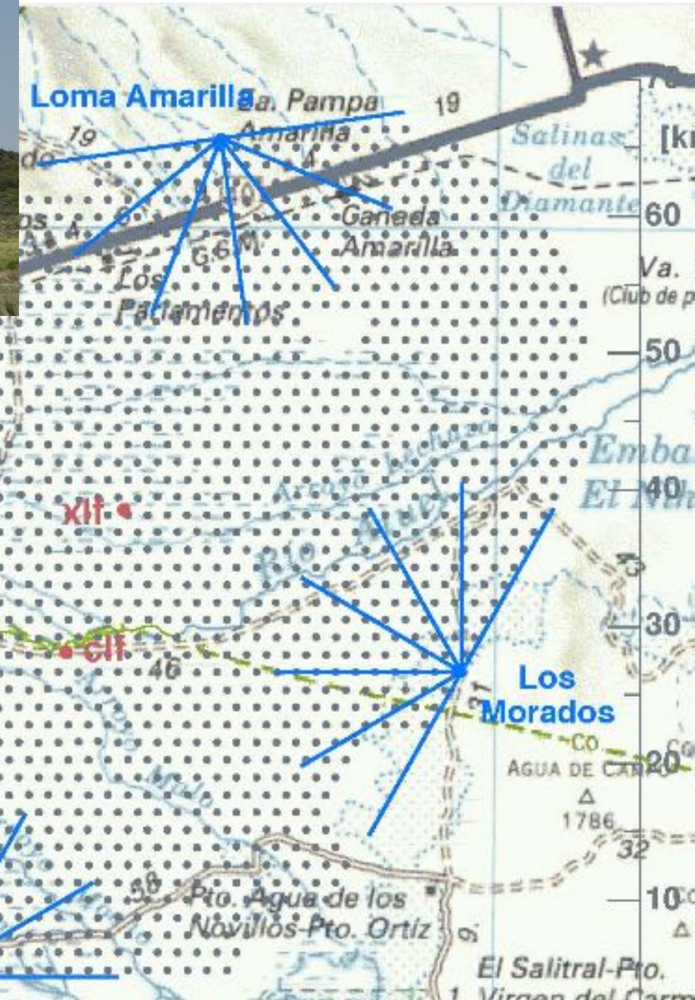
## Surface Detector
**1660 water-Cherenkov stations**




35.15◦ S 69.2◦ W ~ 1400 m a.s.l.

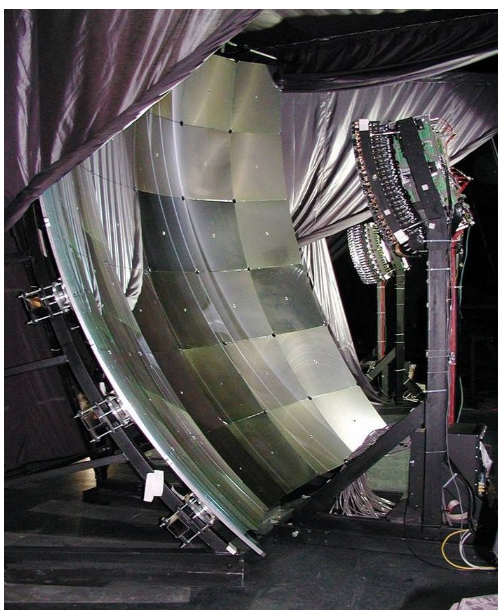
3,000 km²
1,5 km grid

Infill: 23 km²
750 m grid




AMIGA:
muon detectors

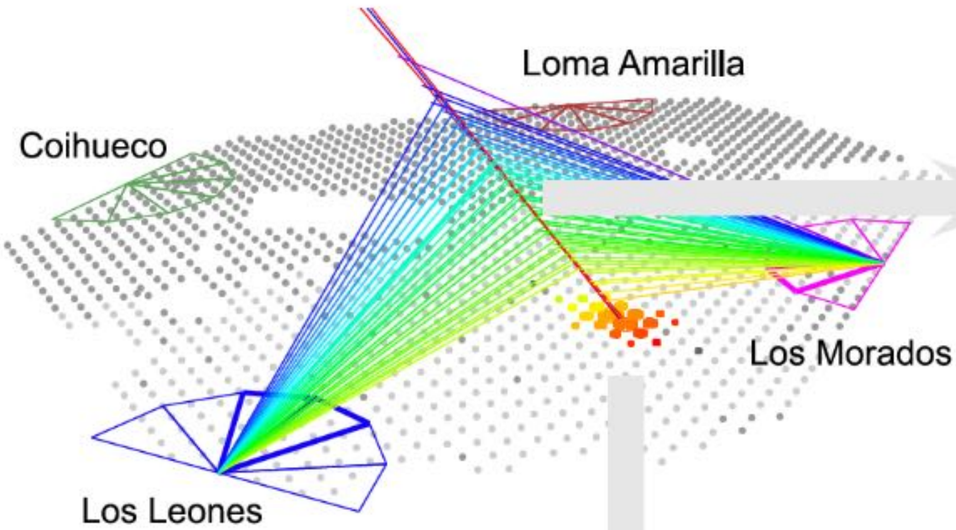
## Fluorescence Detector
**27 telescopes in 4 locations**

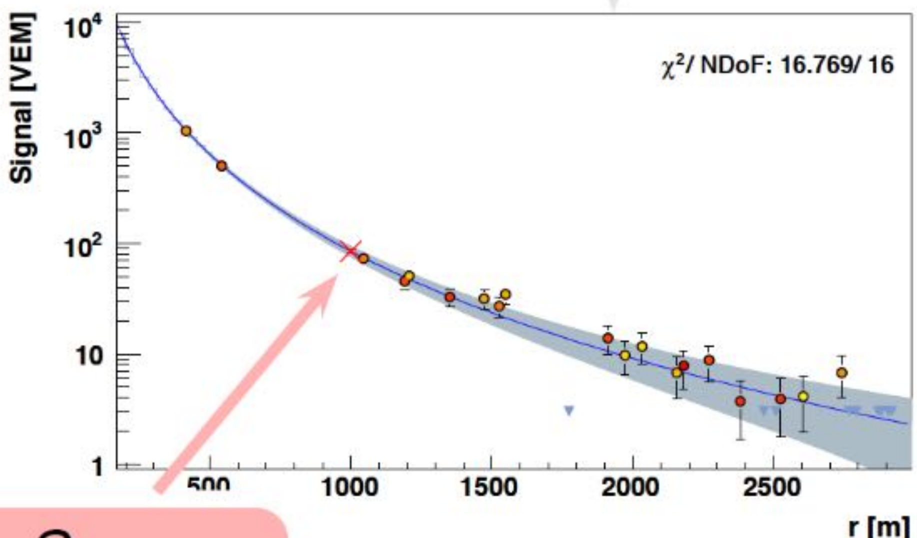


HEAT:
3 higher elevation telescopes

AERA: radio detection ~50 MHz
17 km$^2$

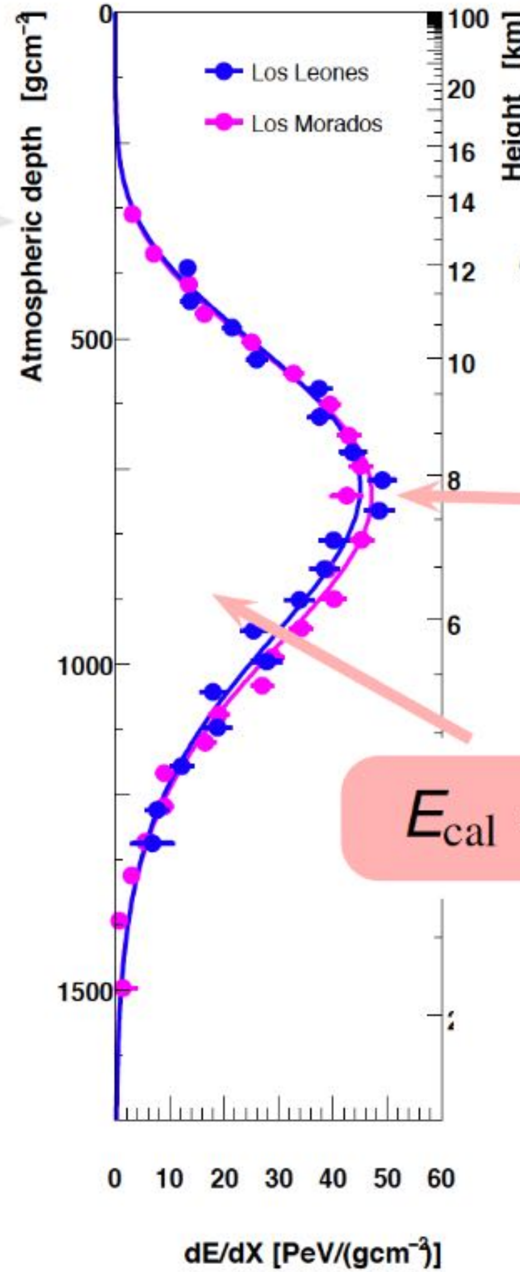
# HYBRID CR AIR SHOWER DETECTION




$S_{1000}$

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




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

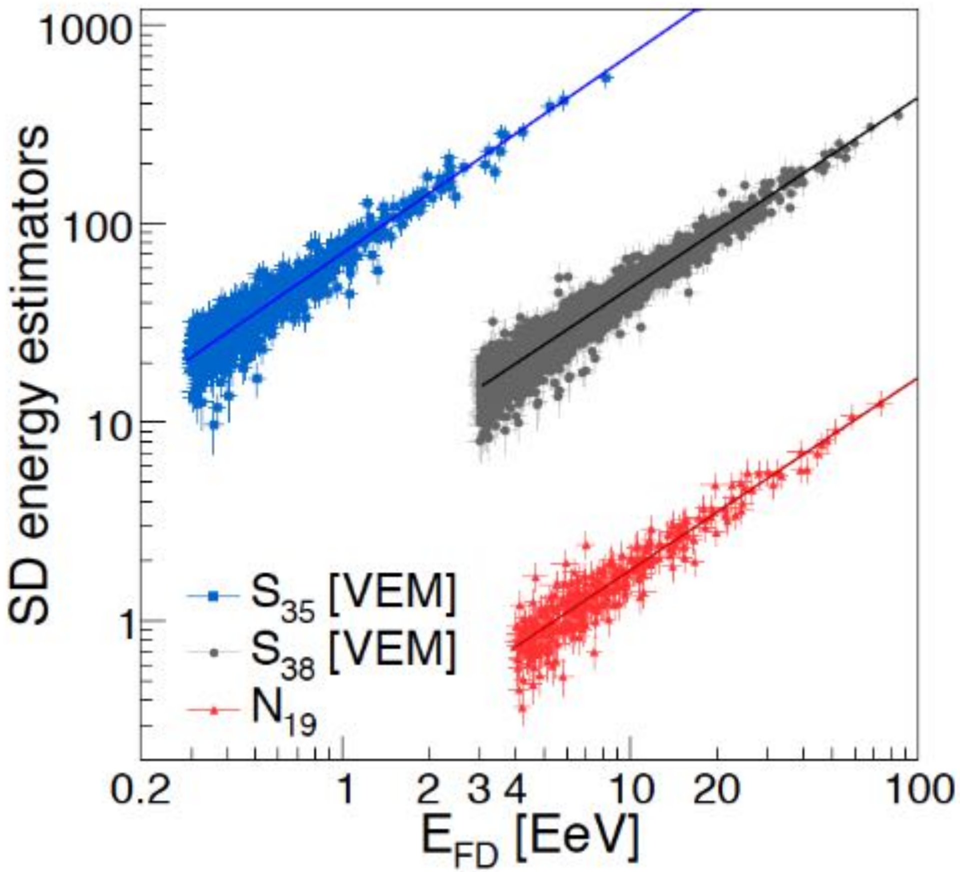
$X_{\mathrm{max}}$

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

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

**(FD duty cycle ~15%)**

# Energy calibration
(vertical, inclined, Infill)

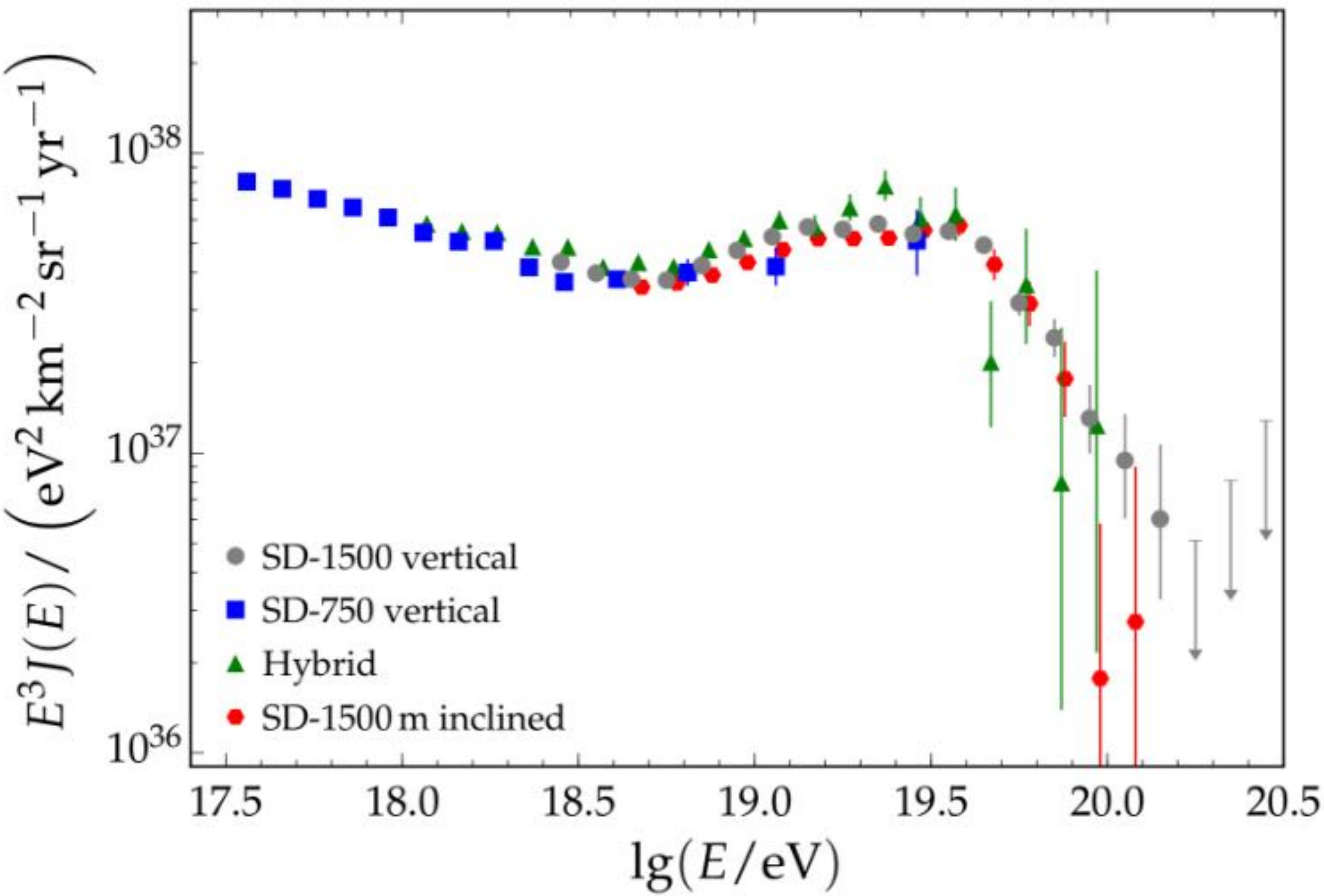



**For 1500 m array, zenith<60: S(1000m) → $S_{38}$ (accounting for atmospheric attenuation)**

**For zenith>60 : $N_{19}$ (muonic signal normalization compared to that from protons at 10 EeV)**

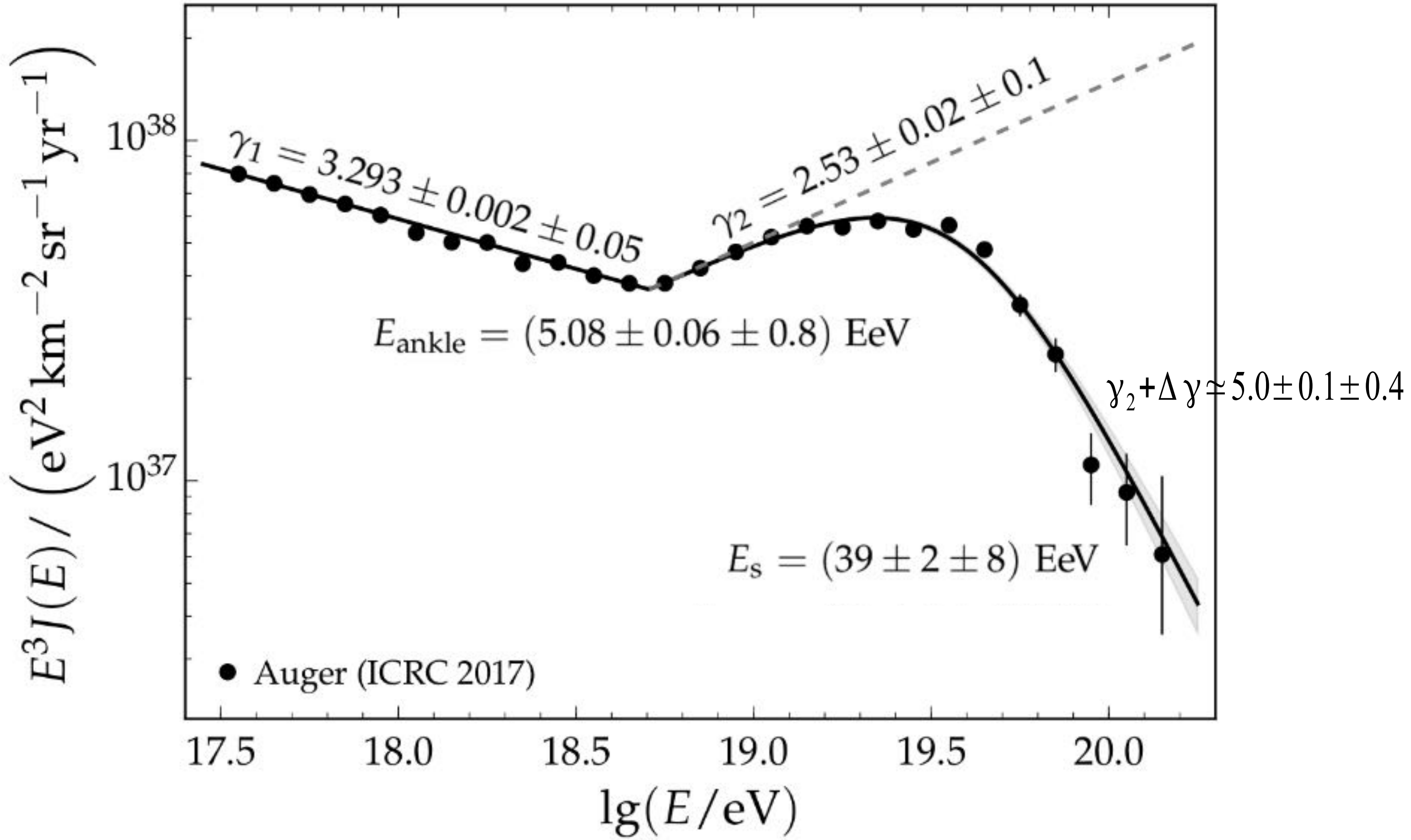
**For 750 m array, zenith<55: S(450m) → $S_{35}$**

# SPECTRUM FROM VERTICAL (INFILL AND 1500m ARRAYS) AND INCLINED EVENTS



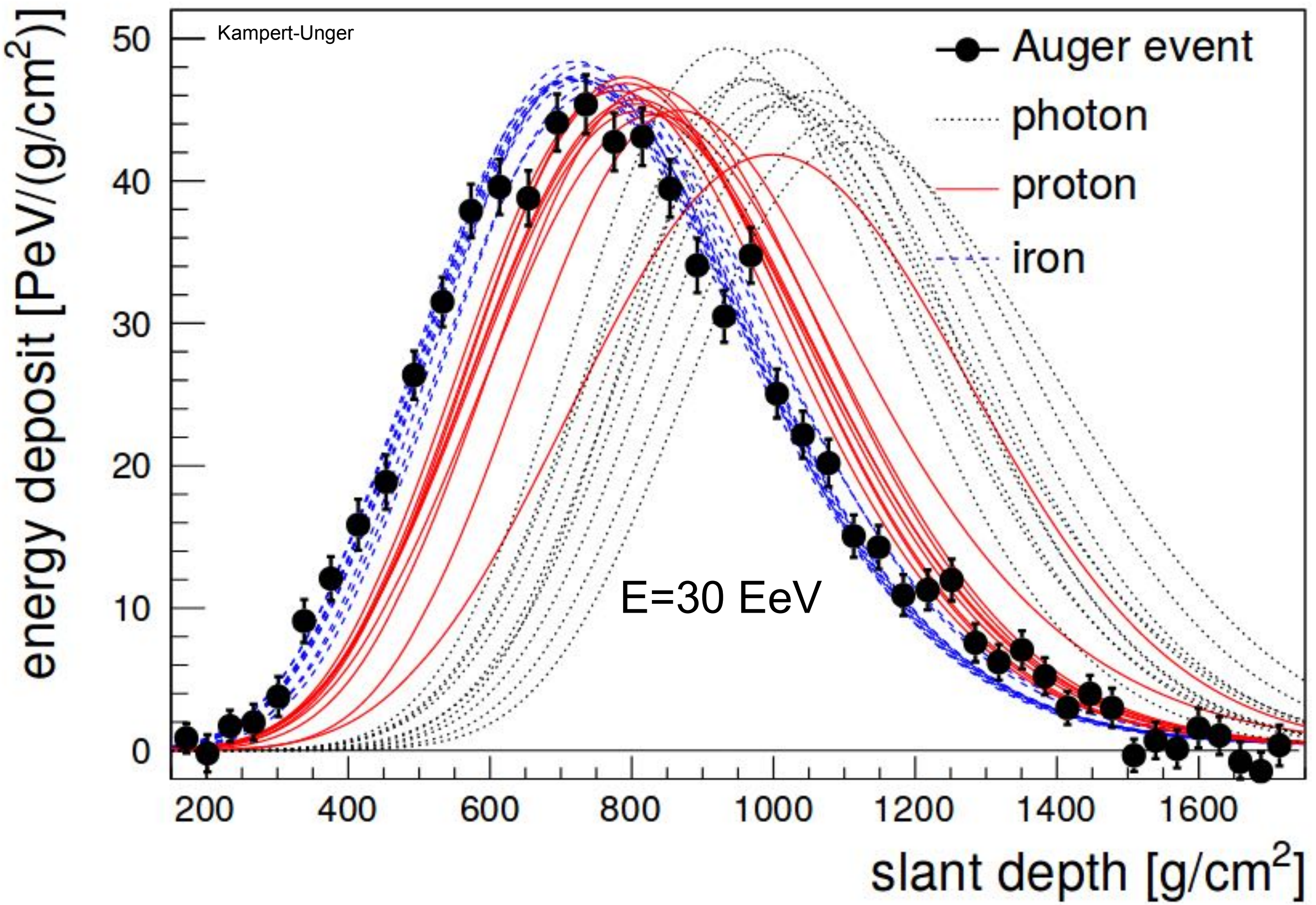
# Broken power law fit + suppression

$$J_{unf}(E) = \begin{cases} J_0\left(\frac{E}{E_{ankle}}\right)^{-\gamma_1} & E < E_{ankle} \\ J_0\left(\frac{E}{E_{ankle}}\right)^{-\gamma_2}\left[1+\left(\frac{E_{ankle}}{E_s}\right)^{\Delta\gamma}\right]\left[1+\left(\frac{E}{E_s}\right)^{\Delta\gamma}\right]^{-1} & E > E_{ankle} \end{cases}$$




**Ankle at 5 EeV (but is it due to Galactic-Extragalactic transition? pair production dip?…?)**
**Suppression above 40 EeV (due to GZK of protons or Fe? Acceleration limit at sources?…?**

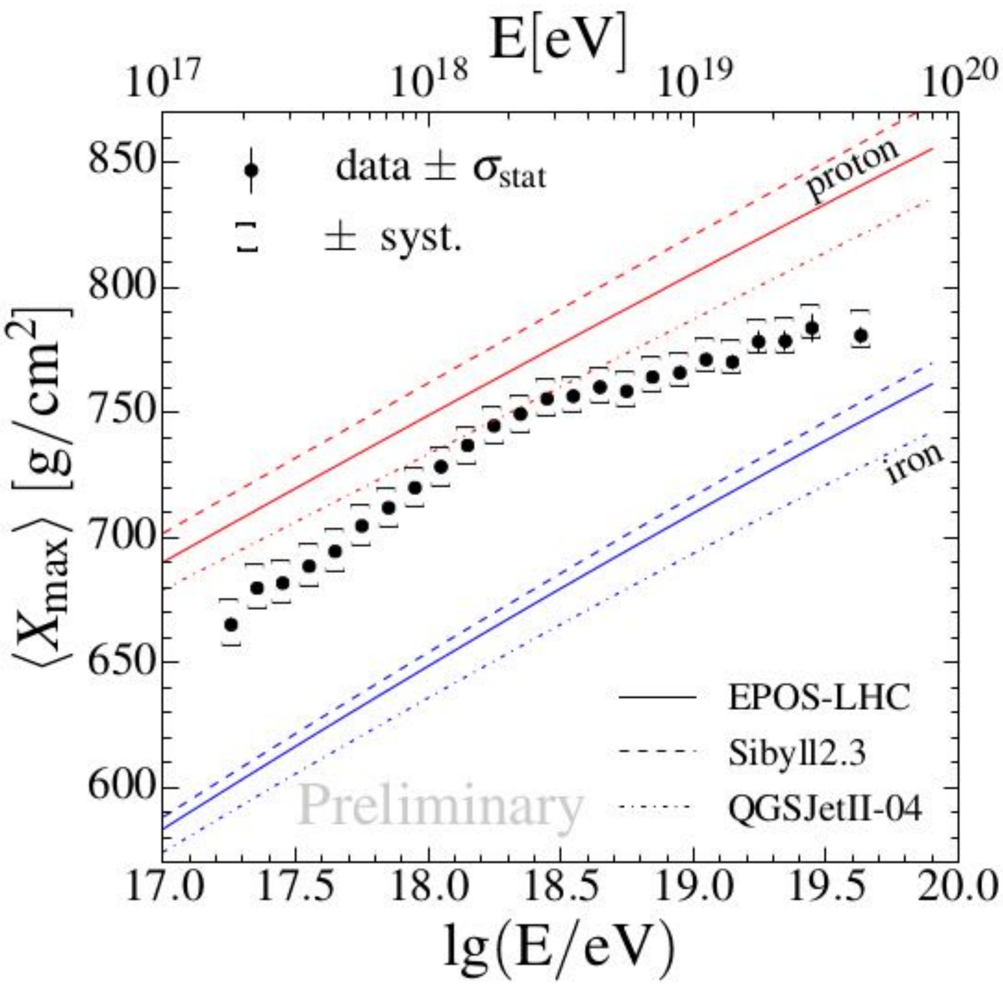
# Xmax vs. composition

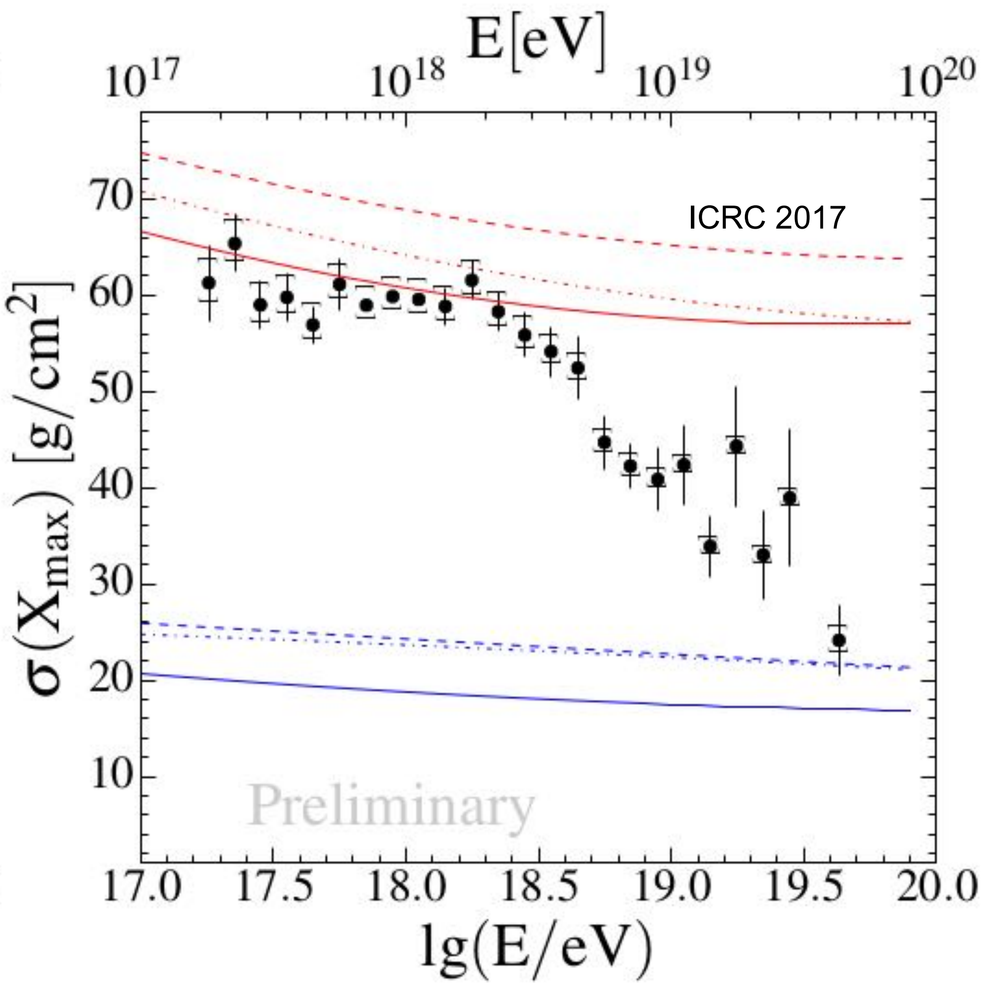



**Nuclei behave as $A$ nucleons with** $E_n = E_0 / A$

→ less penetrating, smaller fluctuations

# COMPOSITION FROM $X_{max}$ at Auger



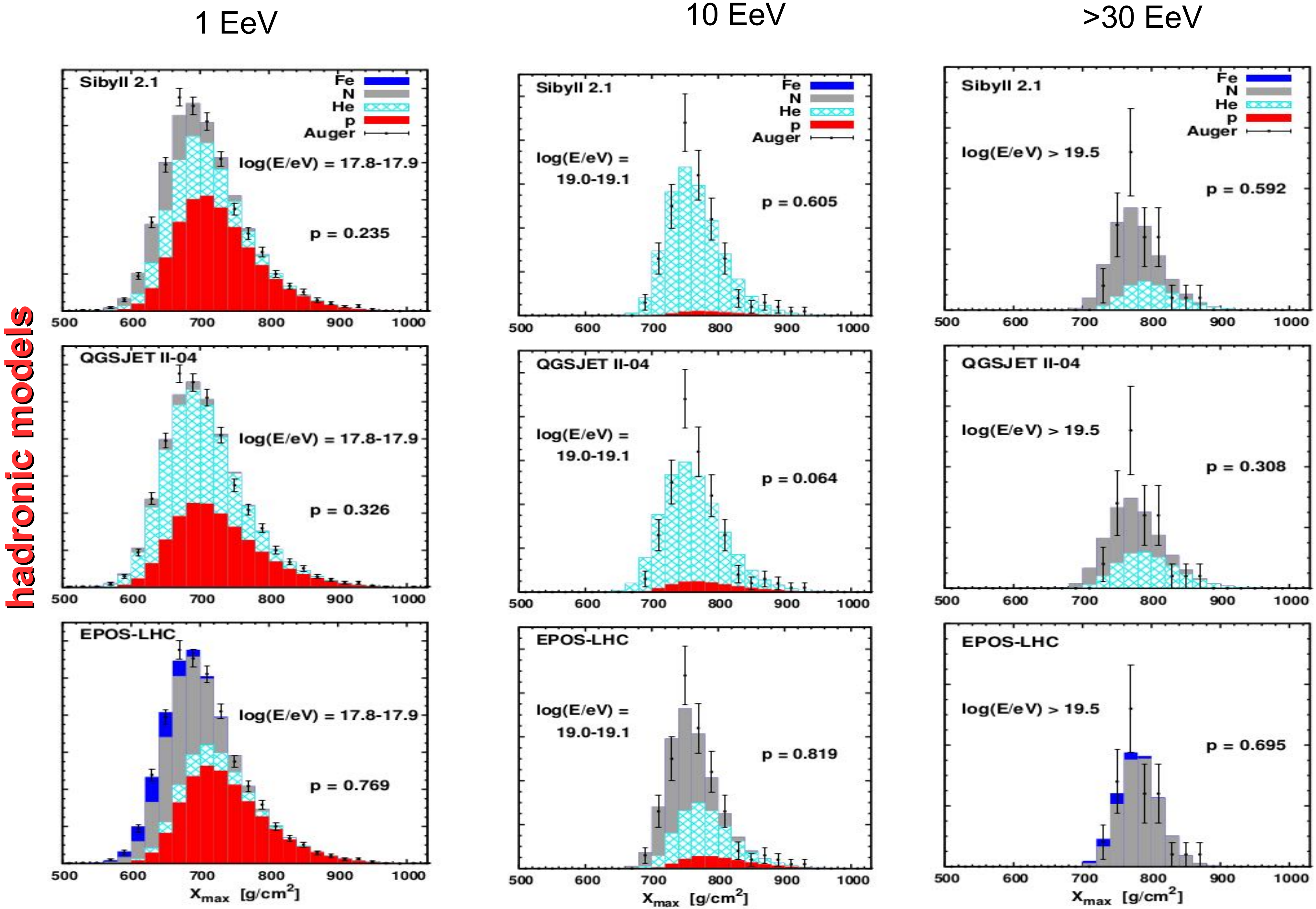

**Break in the elongation rate at ~ 2 EeV (80 g/cm$^2$/decade → 26 g/cm$^2$/decade)**

**[ while constant composition → 60 g/cm$^2$/decade ]**

**$X_{max}$ dispersion becomes narrower**

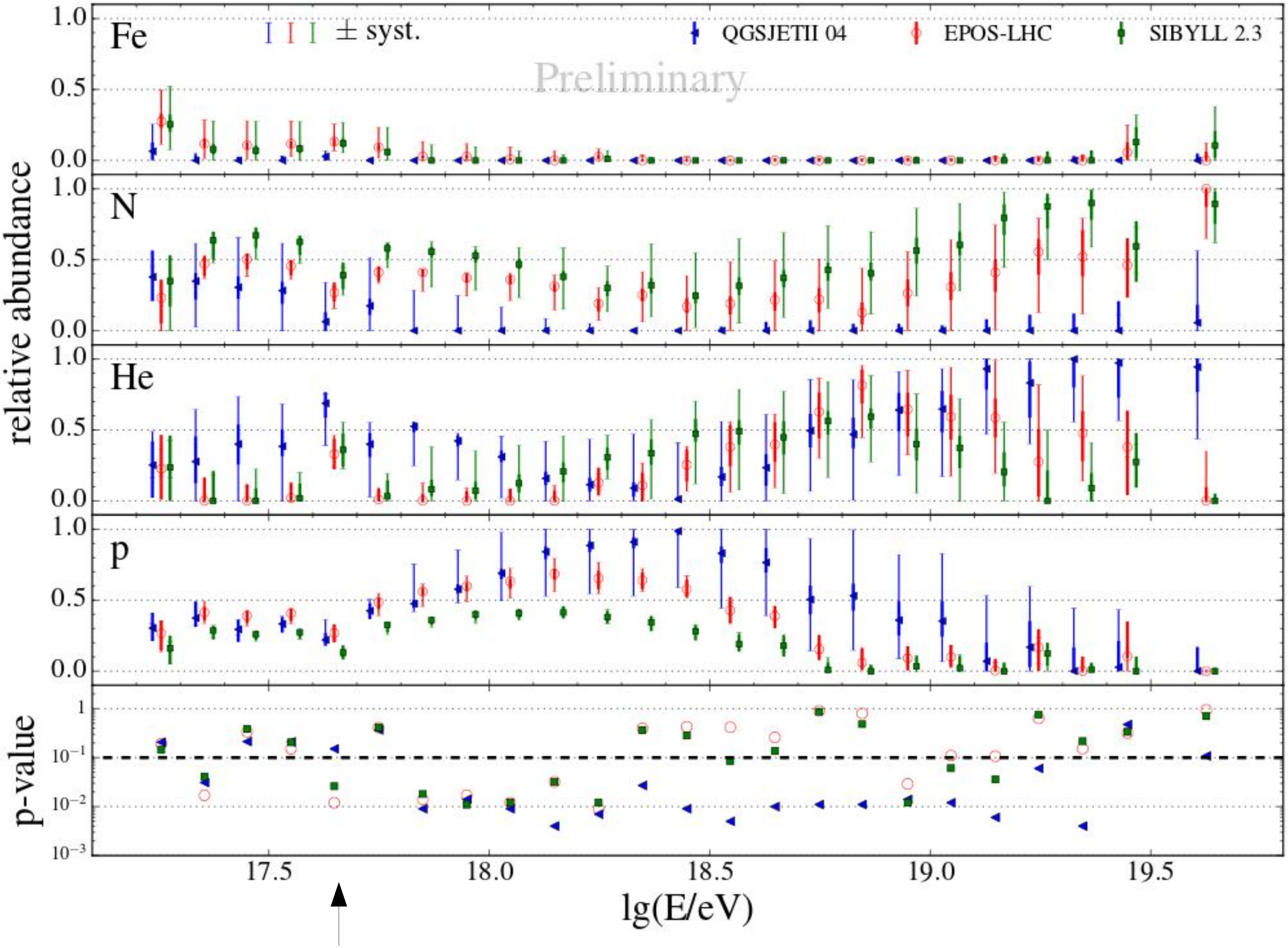
**→ CRs become increasingly heavier above 2 EeV**

# For increasing energies transition from light to heavy




PRD 2014

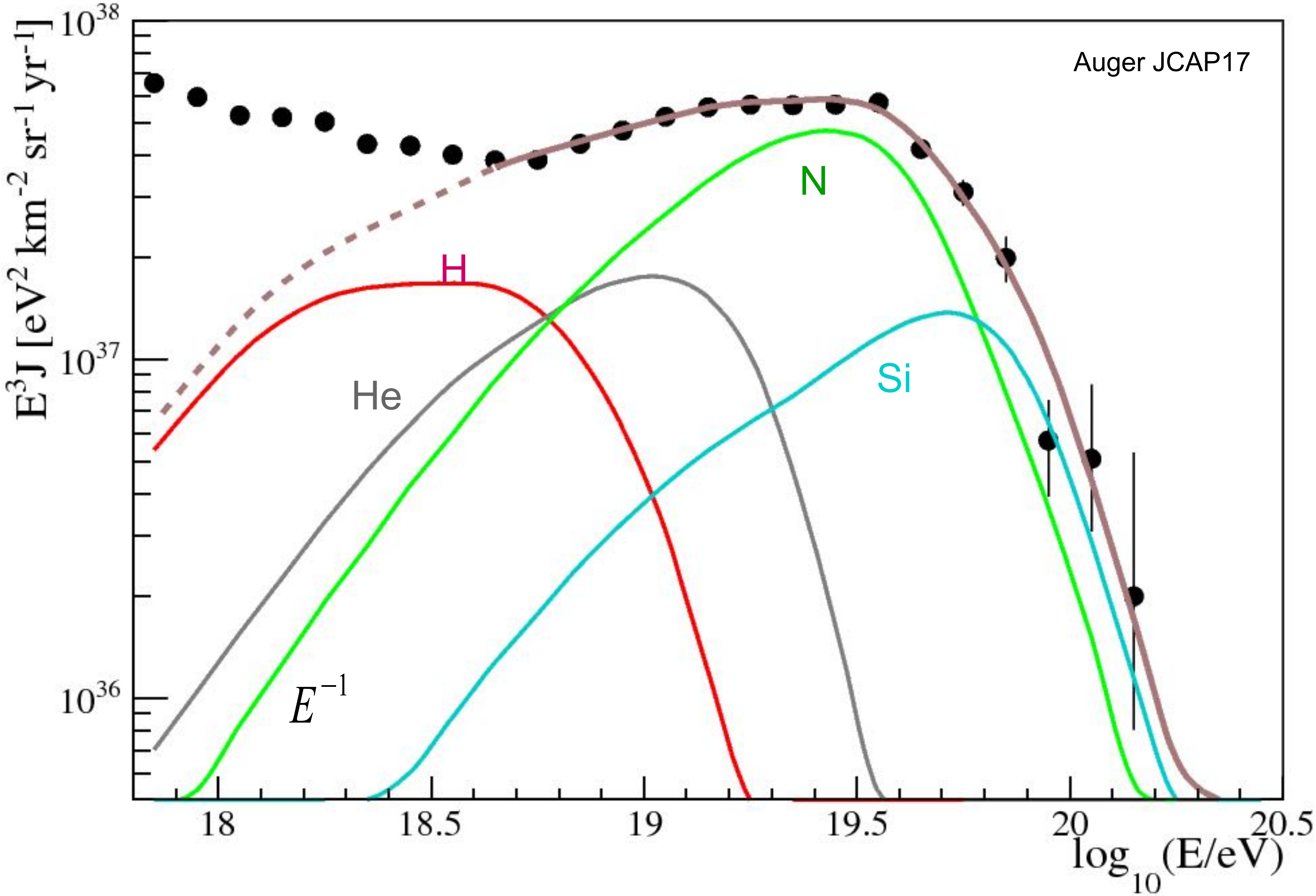
Light composition between 1 and 5 EeV,
becoming heavier (He and N) at higher (and lower) energies, little or no Fe




HEAT allows to extend composition measurements to lower energies

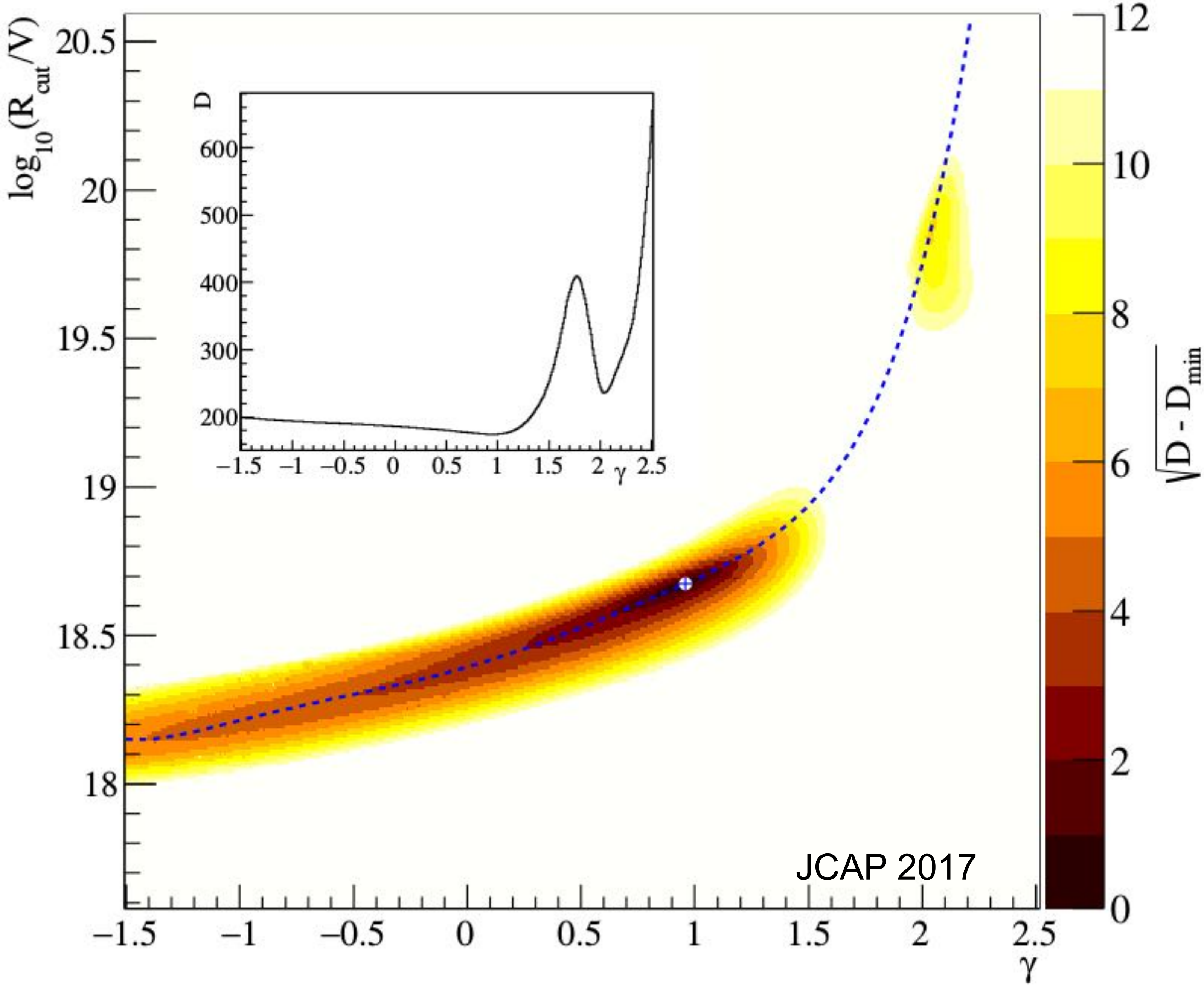
## Trying to explain both spectrum and composition:

**favor mixed composition scenarios with low rigidity cutoff (~5 EV)**

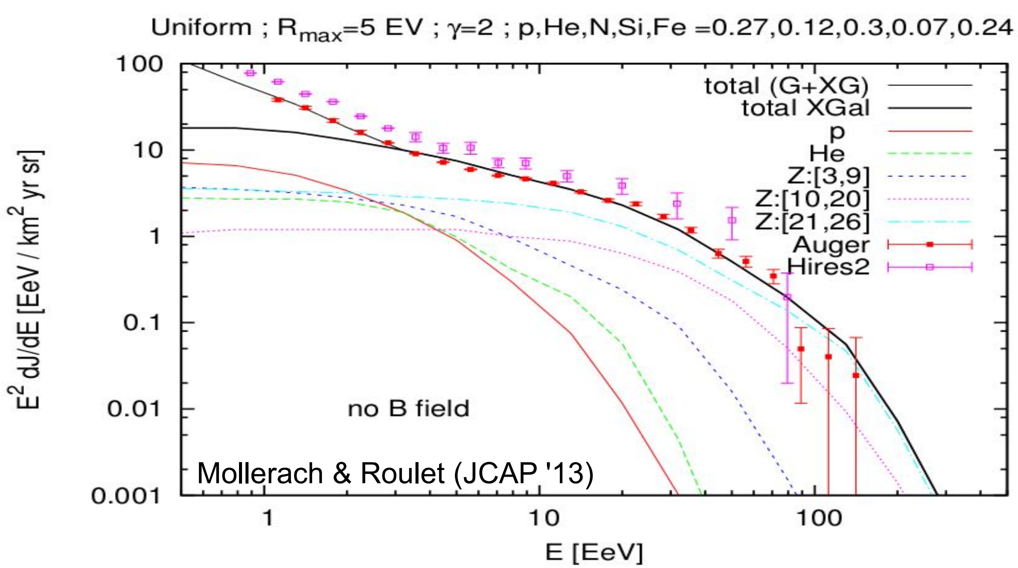


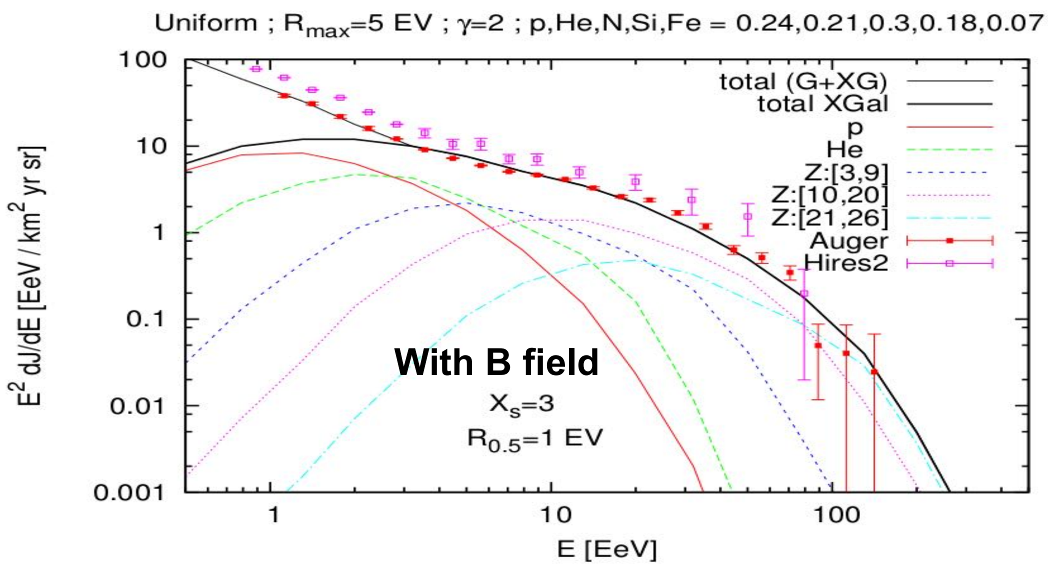

**note that hard spectra, dN/dE ~ $E^{-1}$, seem to be required in mixed models to avoid too much mixture at given E, i.e. to reduce RMS(Xmax)**

# FITTING SOURCE SPECTRAL INDEX AND CUTOFF



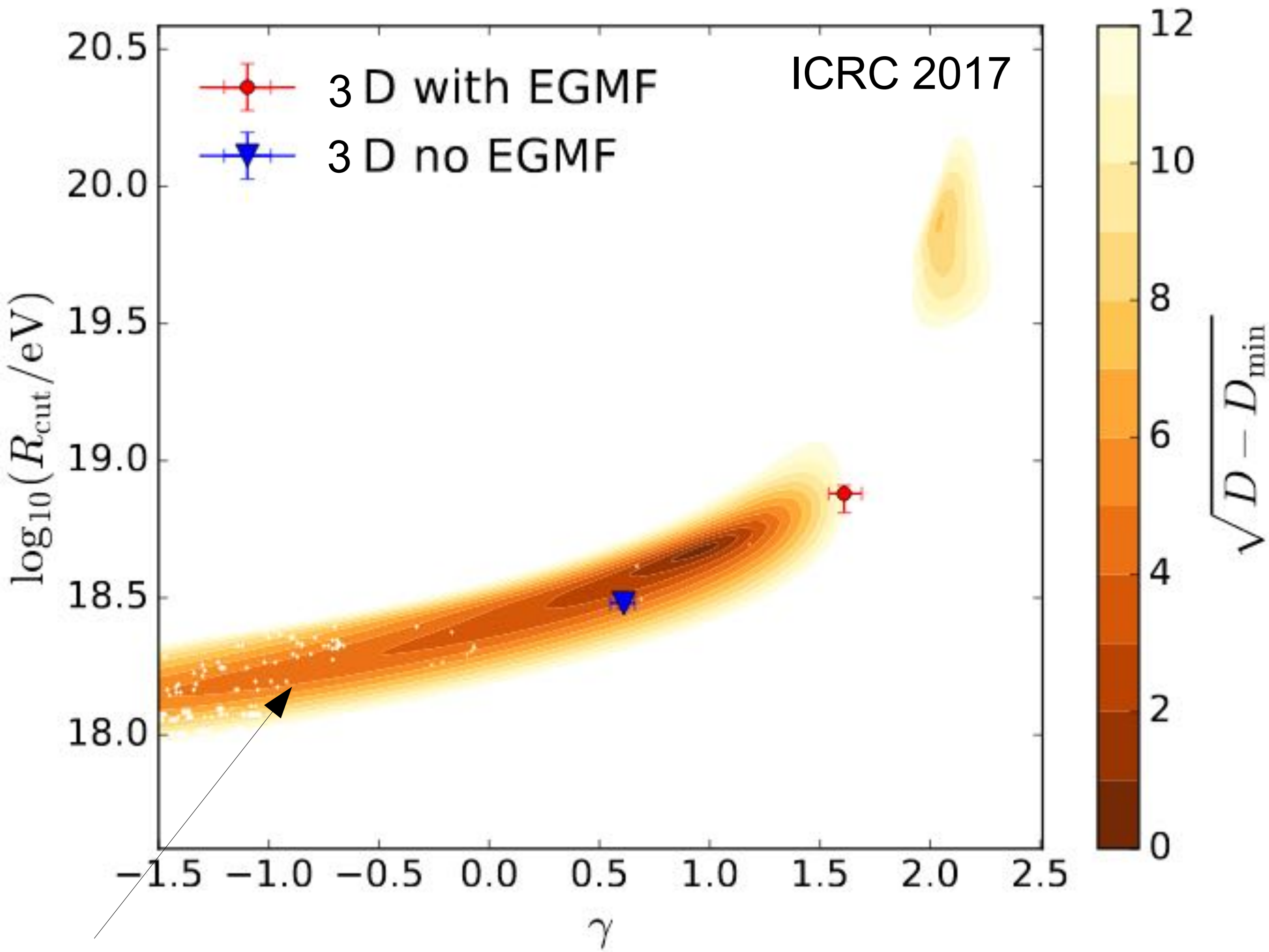
# Diffusion in X-gal turbulent B fields can modify spectra and composition at UHE




**Hard spectra at E < Z EeV may be due to diffusion (magnetic horizon)**
**source spectra may be softer**

## FITTING SOURCE SPECTRA ADOPTING POWER LAW WITH RIGIDITY CUTOFF INCLUDING EXTRAGALACTIC MAGNETIC FIELDS




JCAP 2017 fit

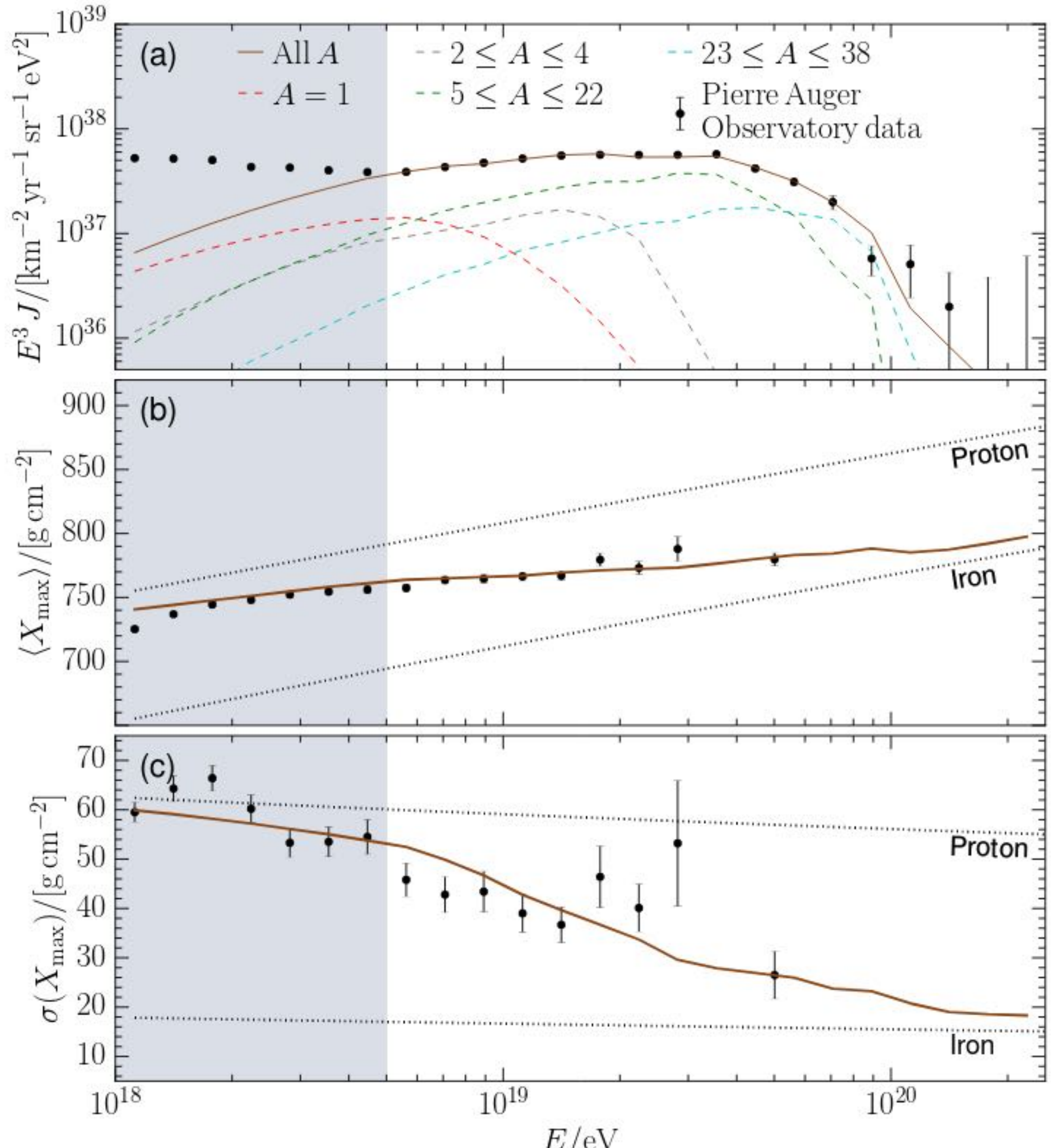
$\gamma$ =0.6, $R_{cut}$=3 EV

No B field

$\gamma$ =1.6, $R_{cut}$=7.5 EV

With B field

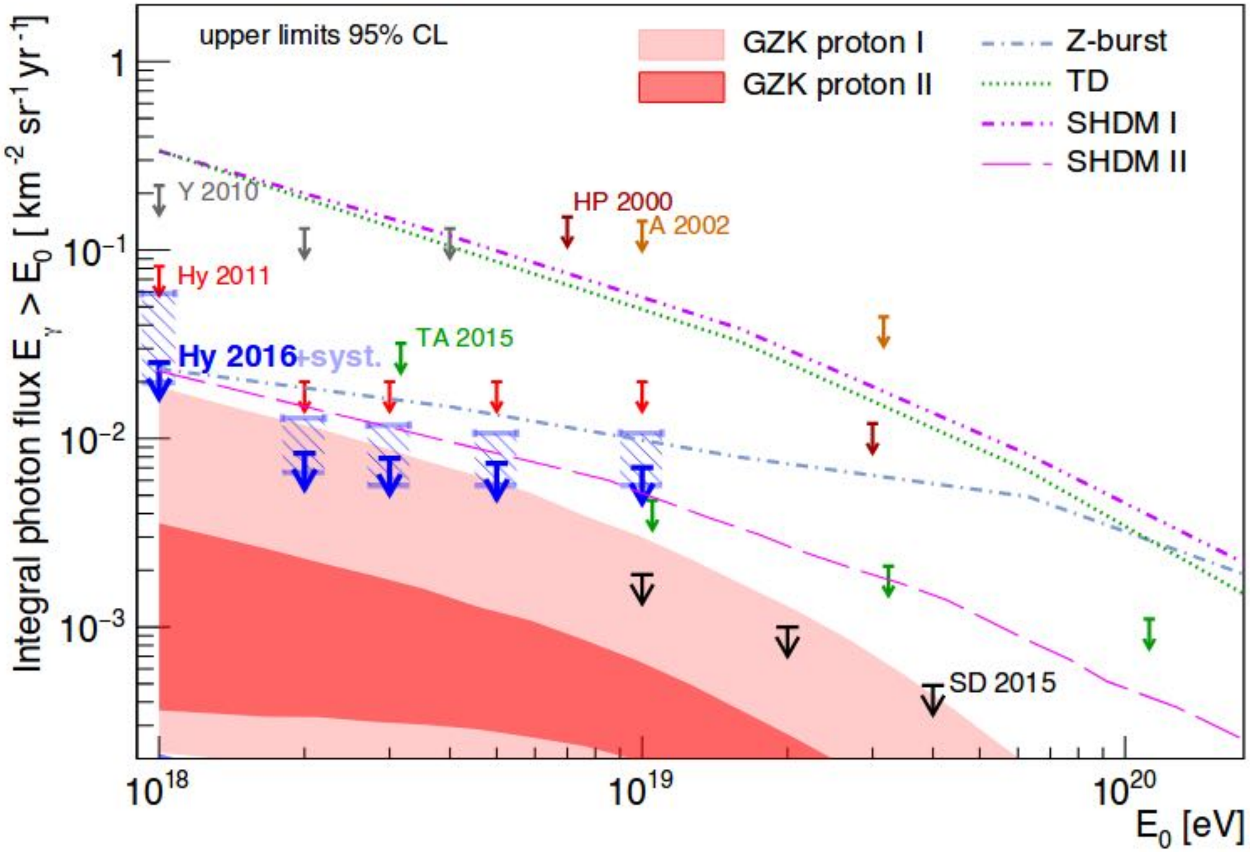
# FIT INCLUDING EXTRAGALACTIC B FIELD EFFECTS




| Model | $\gamma$ | $\log_{10}(\frac{R_{\mathrm{cut}}}{\mathrm{eV}})$ | $f_{\mathrm{H}}/\%$ | $f_{\mathrm{He}}/\%$ | $f_{\mathrm{N}}/\%$ | $f_{\mathrm{Si}}/\%$ | $f_{\mathrm{Fe}}/\%$ |
|---|---|---|---|---|---|---|---|
| I | $1.61^{+0.08}_{-0.07}$ | $18.88^{+0.03}_{-0.07}$ | 3.0 | 2.1 | 73.5 | 21.0 | 0.4 |

# BOUND ON DIFFUSE PHOTON FLUXES

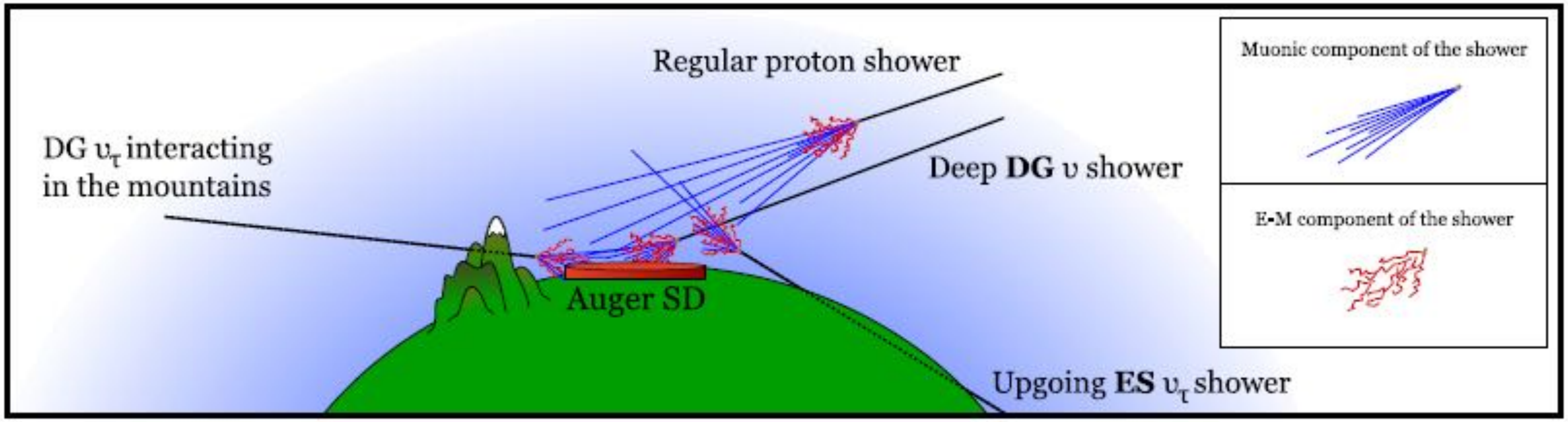
**photon showers are more penetrating (small curvature radius) and lack muons (electromagnetic signal in detectors have long rise times) → essentially no UHE photon candidates observed**



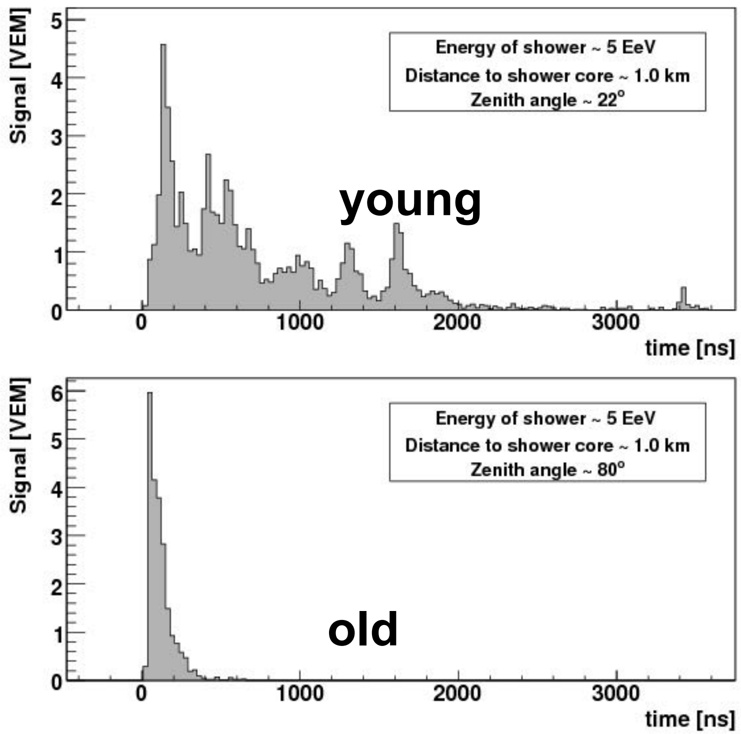

ICRC 2017

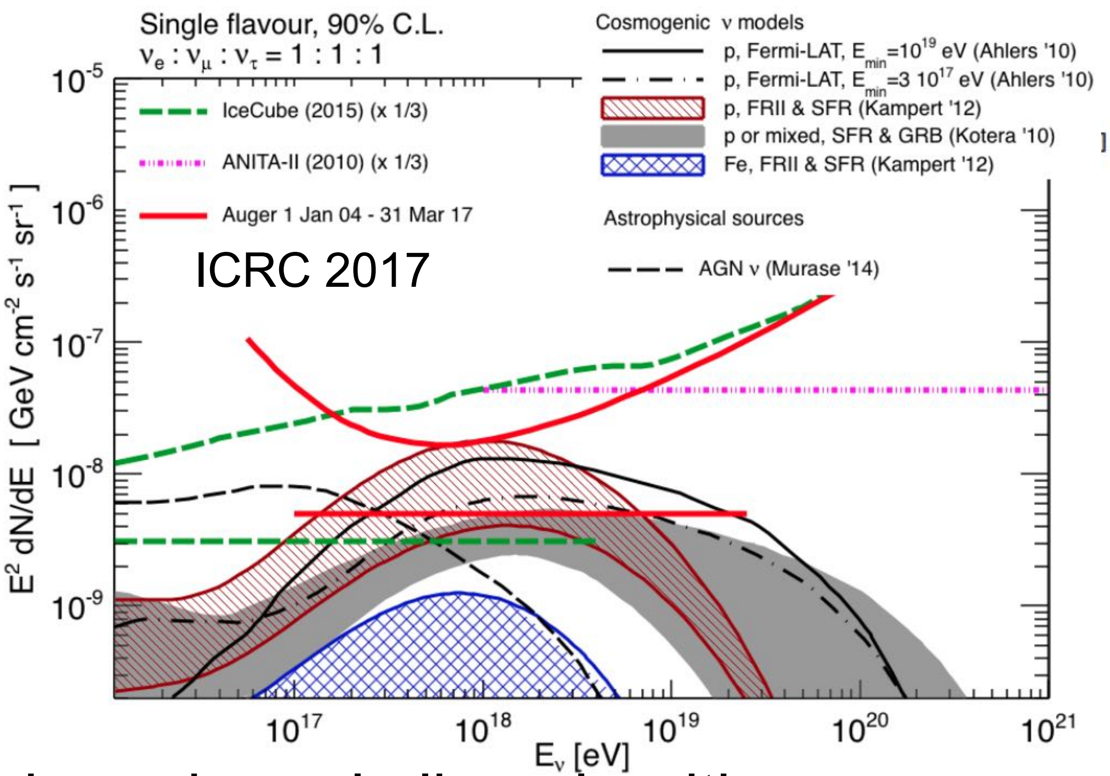
**excludes most top-down models, but still above cosmogenic photon flux**

# NEUTRINO DETECTION IN AUGER



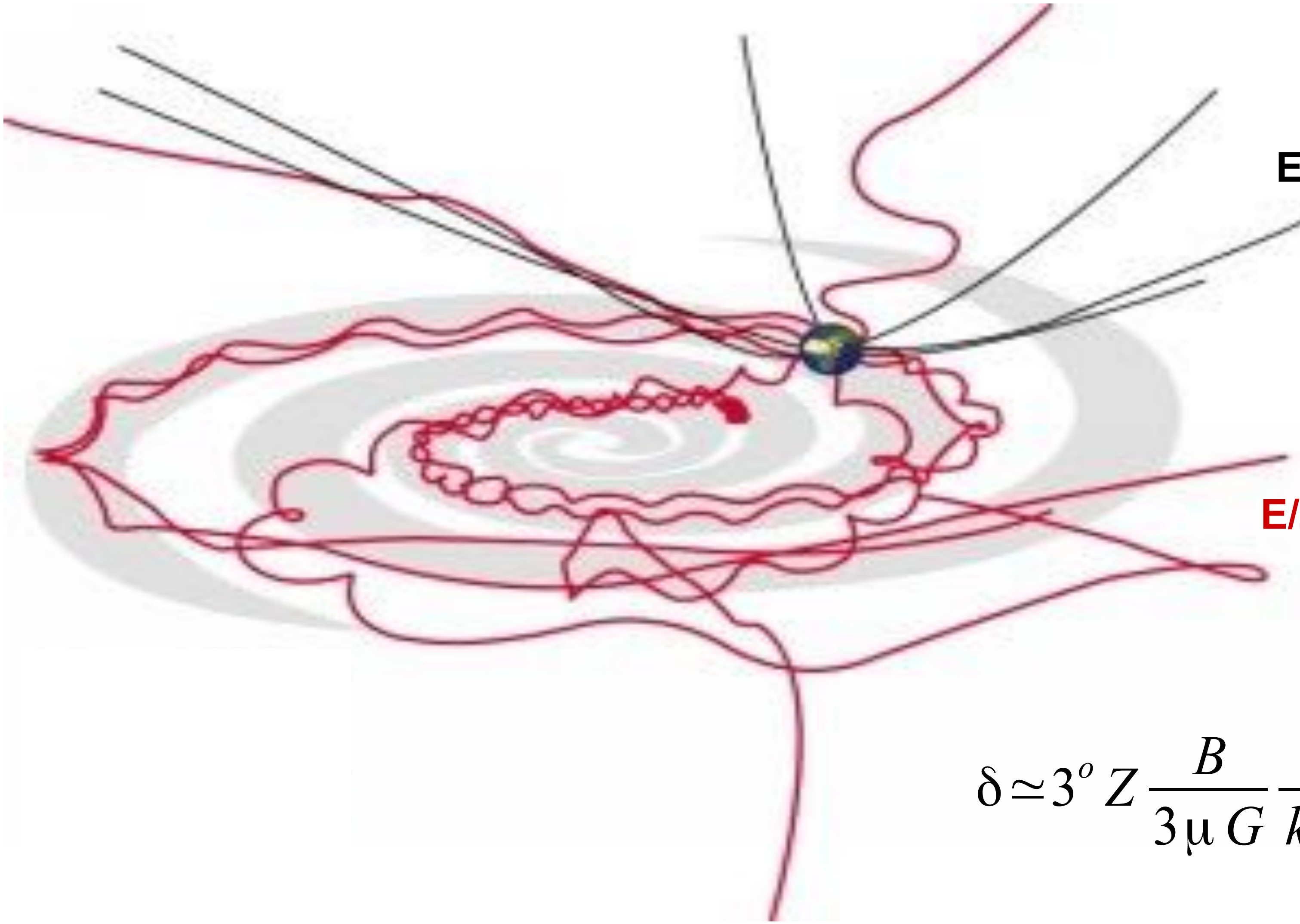

## Only neutrinos can produce young horizontal showers




**0 events observed** → bounds scale linearly with exposure

# Being charged, cosmic rays get deflected by Galactic (and extra-galactic) magnetic fields




$$\delta \simeq 3^o Z \frac{B}{3\mu G} \frac{L}{kpc} \frac{6\times 10^{19} eV}{E}$$

**at the highest energies, astronomy with CRs may become possible**
**at lower energies, anisotropies on large angular scales could be present (dipole)**

# Some of the difficulties to measure dipole anisotropies:

**If the detectors don't work some hours of the day (e.g. cold winter mornings after several cloudy days → no battery) this would lead to a dipolar modulation of the rates → need to know exactly how many detectors are operational every minute and account for that**

**The Observatory 'breathes':**

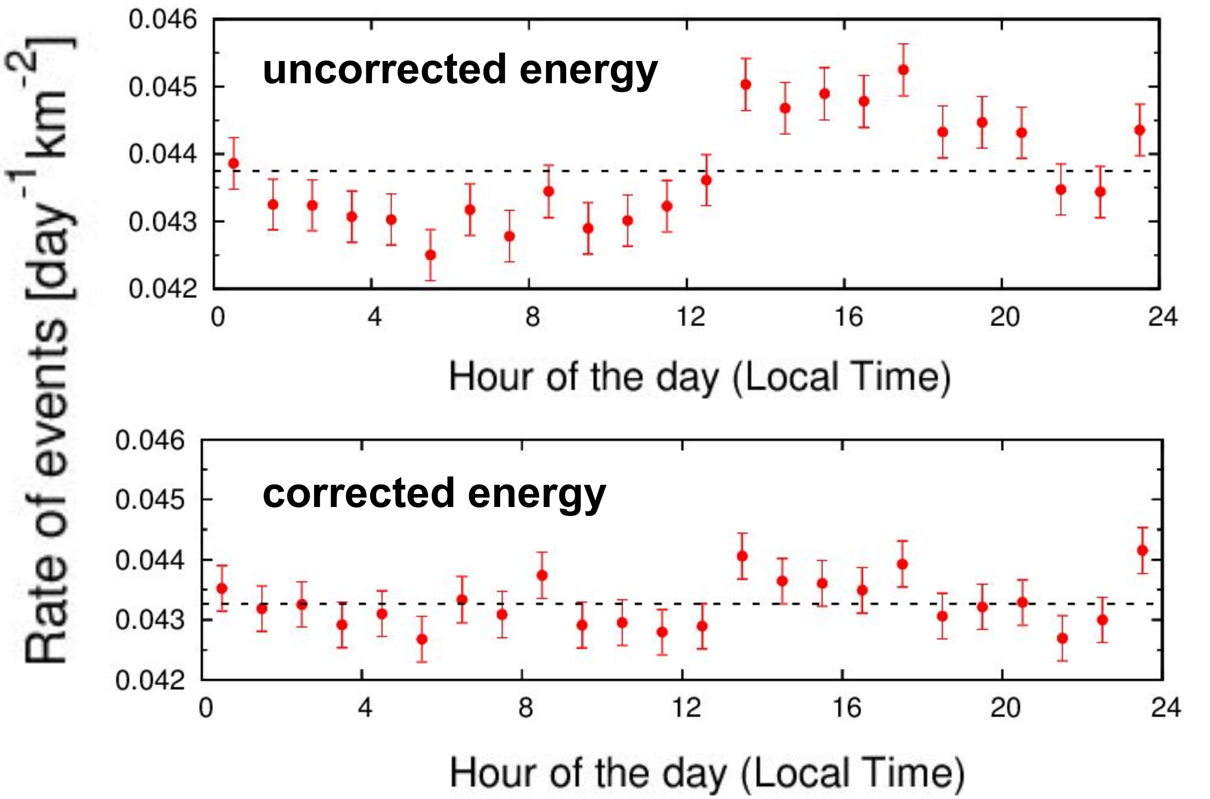
**when it is hot the air is less dense**

**→ air showers more spread laterally**

**→ CR energy is overestimated**

**→ larger rates above $E_{th}$**

**→ need to account for this to avoid day/night or summer/winter modulations**



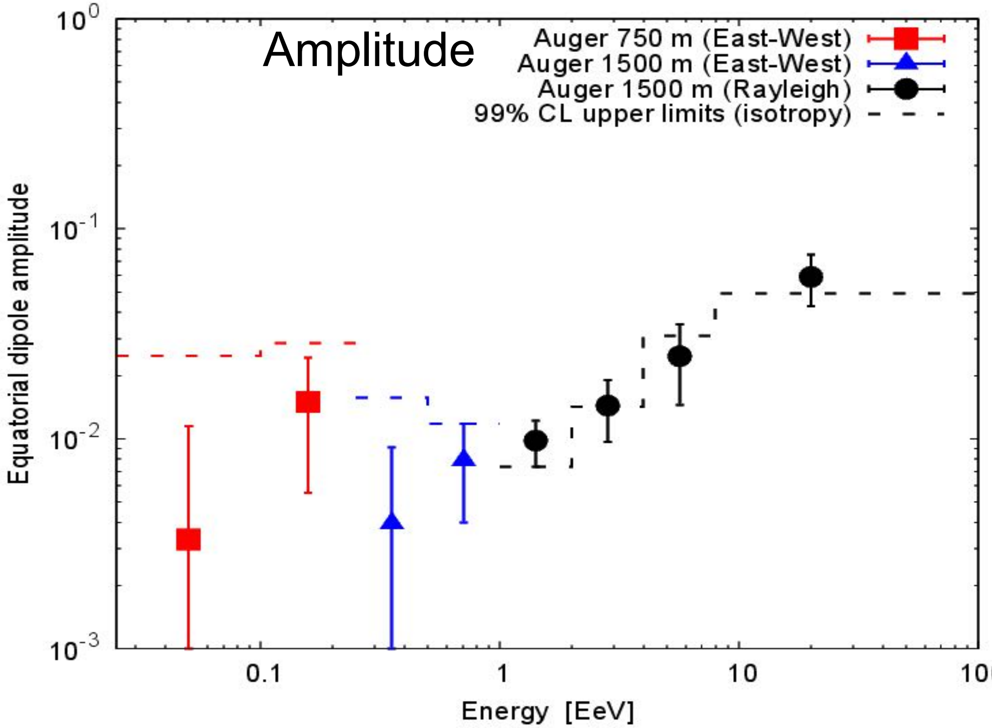

**Slight slope of the terrain → more events from South → need correction**

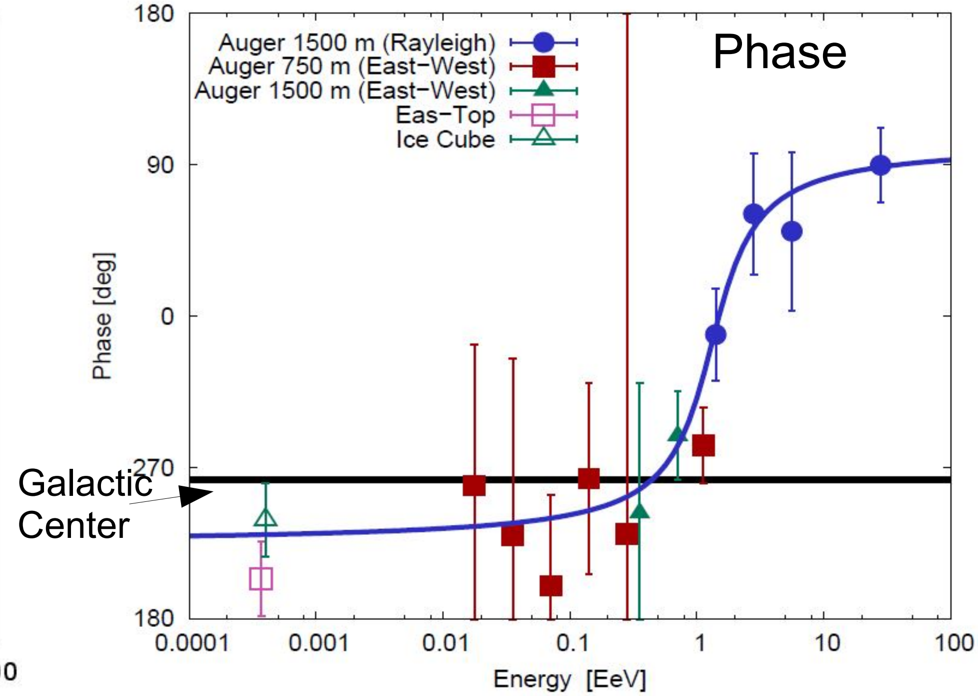
**Earth magnetic field → affects energy reconstruction → need correction**

# Amplitude and Phase of equatorial dipole component

**(from Fourier analysis in Right Ascension)**

back in ICRC 2013, ApJL2013




(data up to 2012 and events with $\theta < 60^{o}$ )

**3 bins above EeV had amplitude with < 1% chance to arise from isotropy**

**Transition in phase between 'GC' below EeV and extragalactic flux above few EeV?**

**ApJ 2015**

# Large scale distribution of ultra high energy cosmic rays detected at the Pierre Auger Observatory with zenith angles up to 80°

The Pierre Auger Collaboration

## ABSTRACT

We present the results of an analysis of the large angular scale distribution of the arrival directions of cosmic rays with energy above 4 EeV detected at the Pierre Auger Observatory including for the first time events with zenith angle between 60° and 80°. We perform two Rayleigh analyses, one in the right ascension and one in the azimuth angle distributions, that are sensitive to modulations in right ascension and declination respectively. The largest departure from isotropy appears in the $E > 8$ EeV energy bin, with an amplitude for the first harmonic in right ascension $r_1^\alpha = (4.4 \pm 1.0) \times 10^{-2}$, that has a chance probability $P(\geq r_1^\alpha) = 6.4 \times 10^{-5}$, reinforcing the hint previously reported with vertical events alone.

**Data up to end of 2013, including events with E>4 EeV up to zenith 80°**

**Also obtain NS dipole component $d_z$ from Fourier analysis in azimuth**

COSMIC RAYS

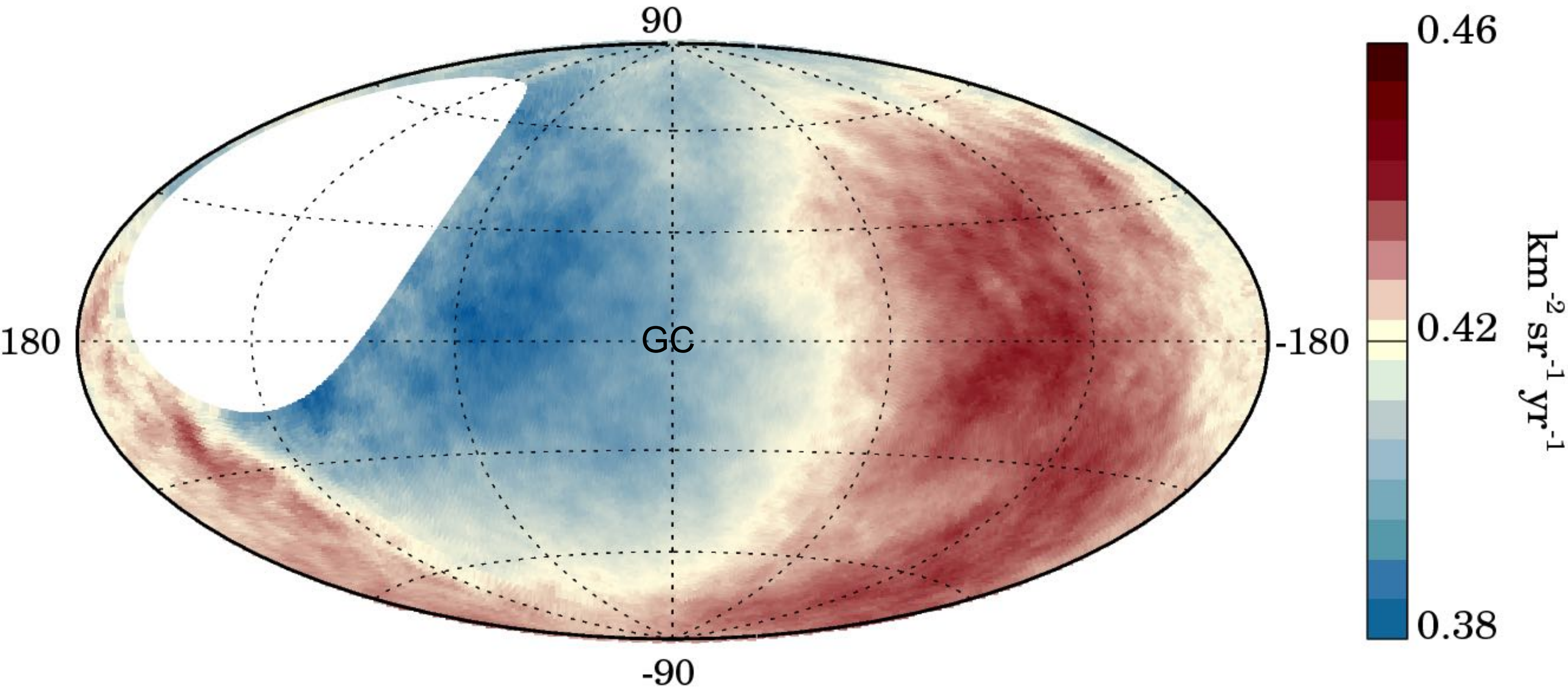
# Observation of a large-scale anisotropy in the arrival directions of cosmic rays above $8 \times 10^{18}$ eV

**The Pierre Auger Collaboration***†

Cosmic rays are atomic nuclei arriving from outer space that reach the highest energies observed in nature. Clues to their origin come from studying the distribution of their arrival directions. Using $3 \times 10^4$ cosmic rays with energies above $8 \times 10^{18}$ electron volts, recorded with the Pierre Auger Observatory from a total exposure of 76,800 $km^2$ sr year, we determined the existence of anisotropy in arrival directions. The anisotropy, detected at more than a $5.2\sigma$ level of significance, can be described by a dipole with an amplitude of $6.5^{+1.3}_{-0.9}$ percent toward right ascension $\alpha_d = 100 \pm 10$ degrees and declination $\delta_d = -24^{+12}_{-13}$ degrees. That direction indicates an extragalactic origin for these ultrahigh-energy particles.

Science DOI:10.126/science.aan4338

# Observed cosmic ray flux with E > 8 EeV




**Dipolar modulation, ~ 6.5% excess 125° away from Galactic center**

# MODULATION vs. RIGHT ASCENSION

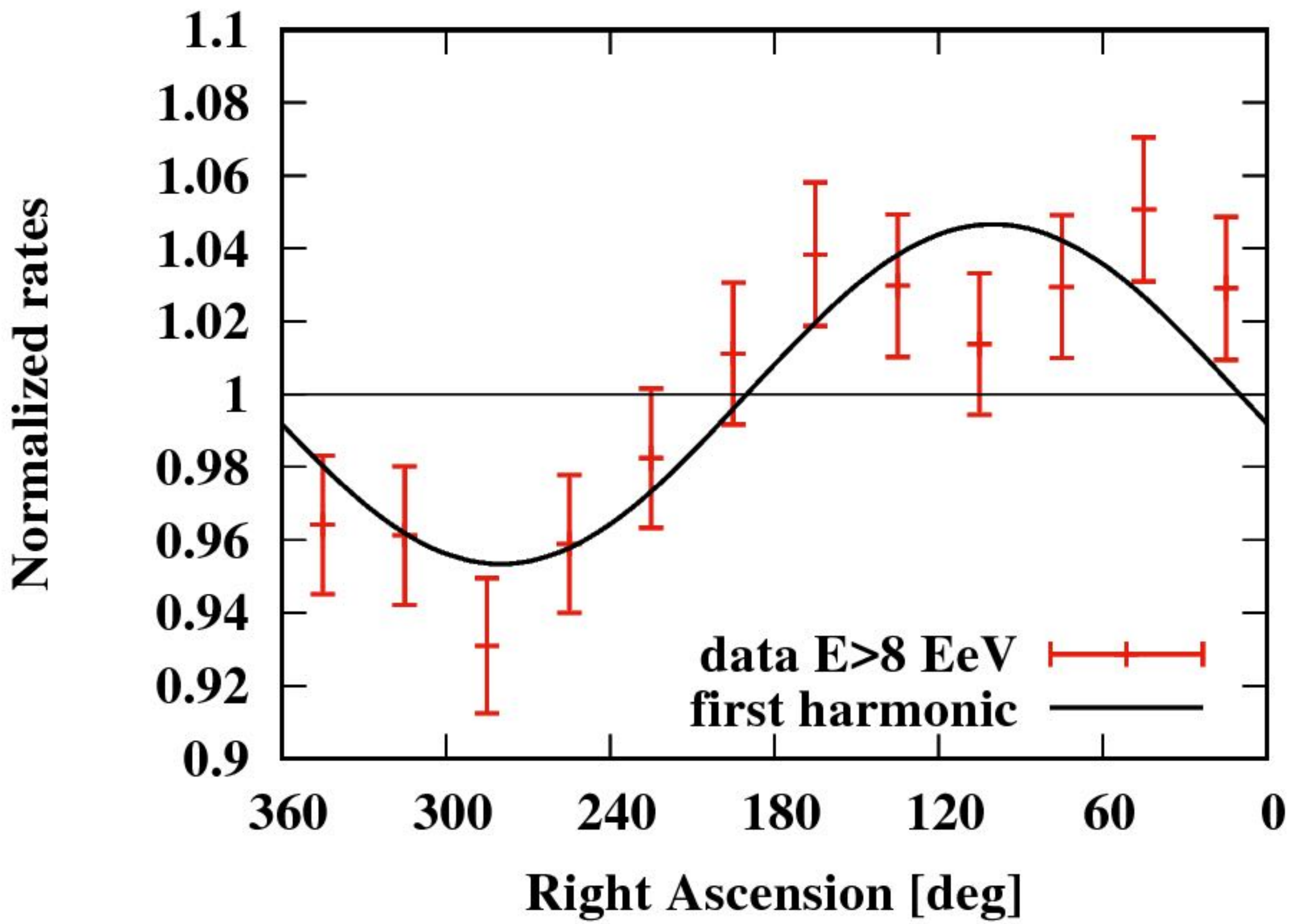


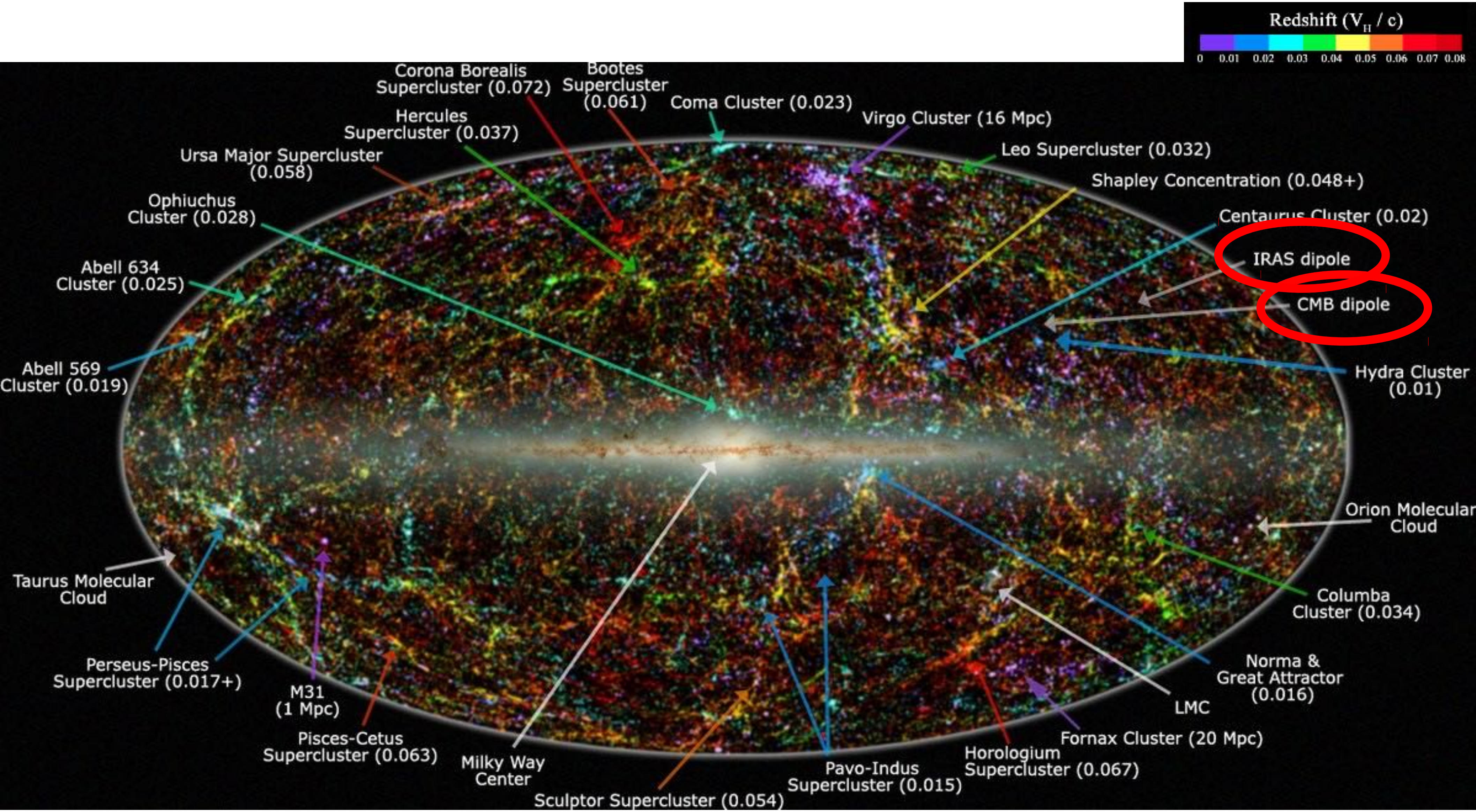

**Table 1. First harmonic in right ascension.** Data are from the Rayleigh analysis of the first harmonic in right ascension for the two energy bins.

| Energy (EeV) | Number of events | Fourier coefficient $a_\alpha$ | Fourier coefficient $b_\alpha$ | Amplitude $r_\alpha$ | Phase $\varphi_\alpha$ (°) | Probability $P(\geq r_\alpha)$ |
|---|---|---|---|---|---|---|
| 4 to 8 | 81,701 | 0.001 ± 0.005 | 0.005 ± 0.005 | $0.005^{+0.006}_{-0.002}$ | 80 ± 60 | 0.60 |
| ≥8 | 32,187 | −0.008 ± 0.008 | 0.046 ± 0.008 | $0.047^{+0.008}_{-0.007}$ | 100 ± 10 | $2.6 \times 10^{-8}$ |

**5.6 σ**

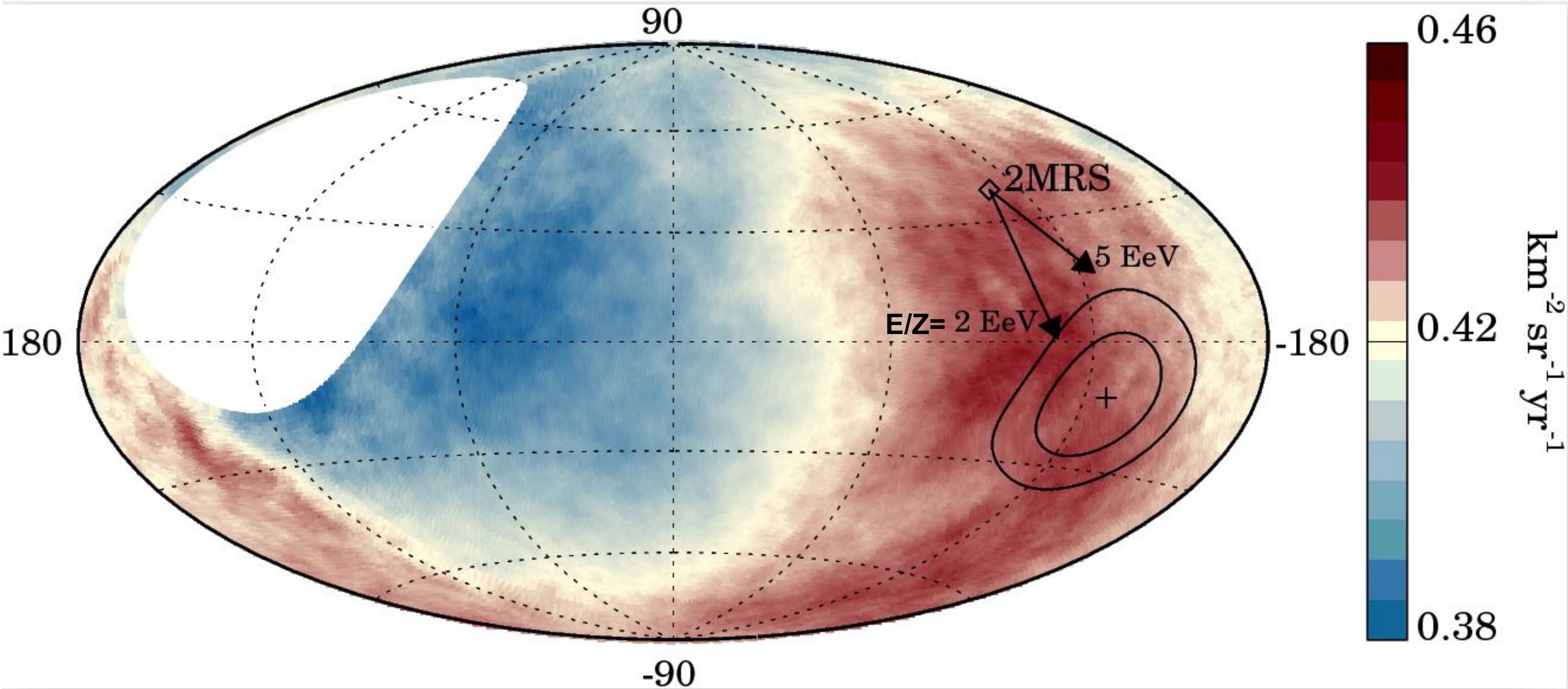
**(penalized → 5.2 σ)**

# Galaxy distribution at different distances




**We are falling towards a region with more galaxies → dipole of the CMB**
**In this direction there should be also more CR sources**

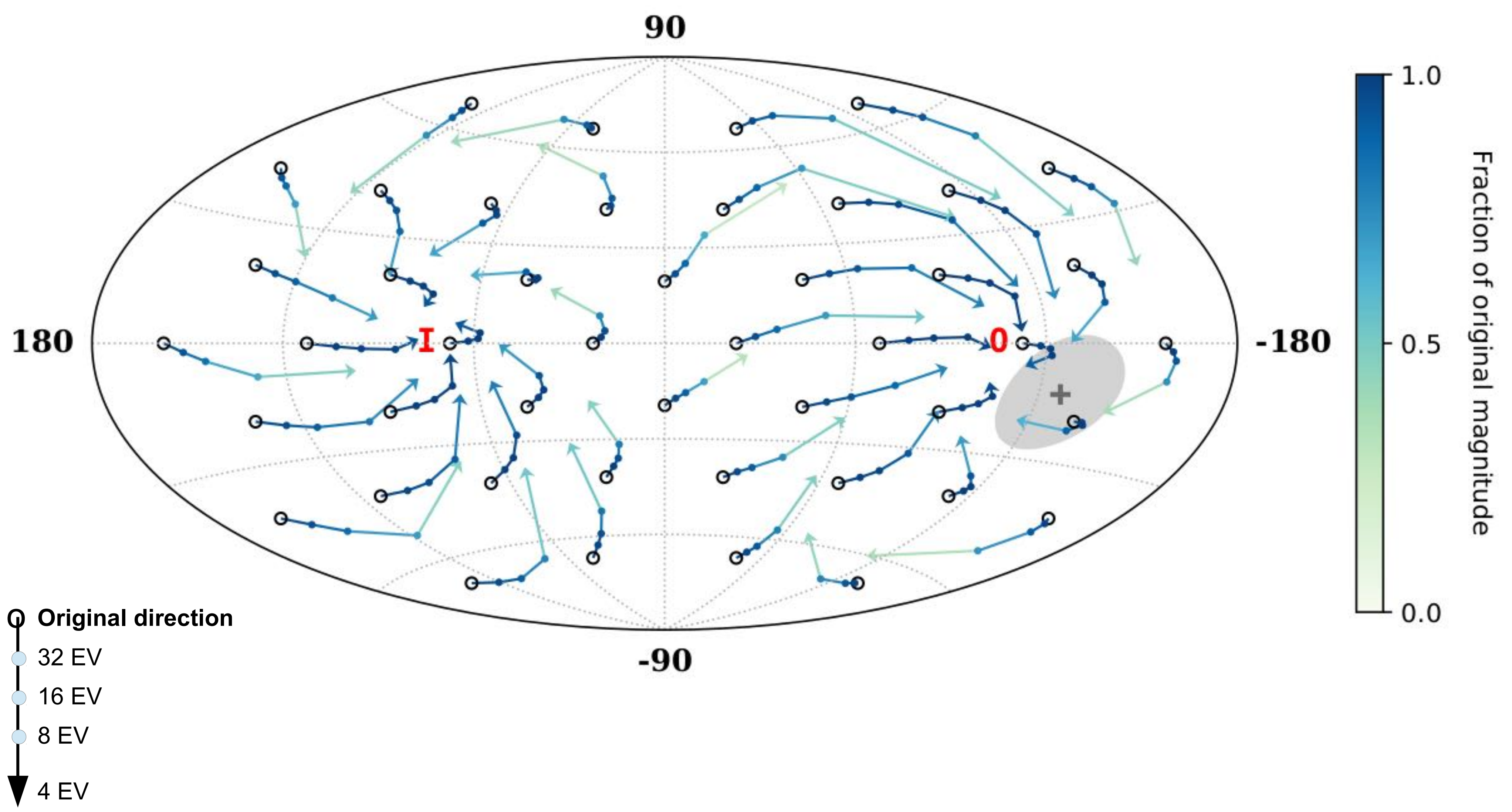
The galactic magnetic field tends to shift the dipole resulting from the galaxy distribution towards a direction closer to the observed one




This suggests that at these energies CRs are extragalactic and are considerably deflected by magnetic fields

Due to many sources distributed as galaxies or diffusion from nearby galaxies?

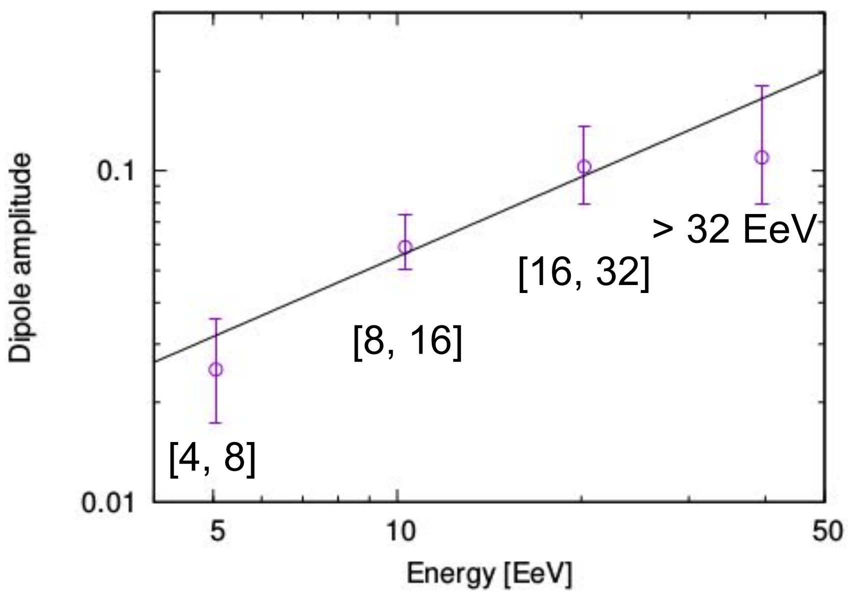
# DEFLECTION (AND DEMAGNIFICATION) OF EXTRAGALACTIC DIPOLE AFTER CROSSING THE GALACTIC MAGNETIC FIELD

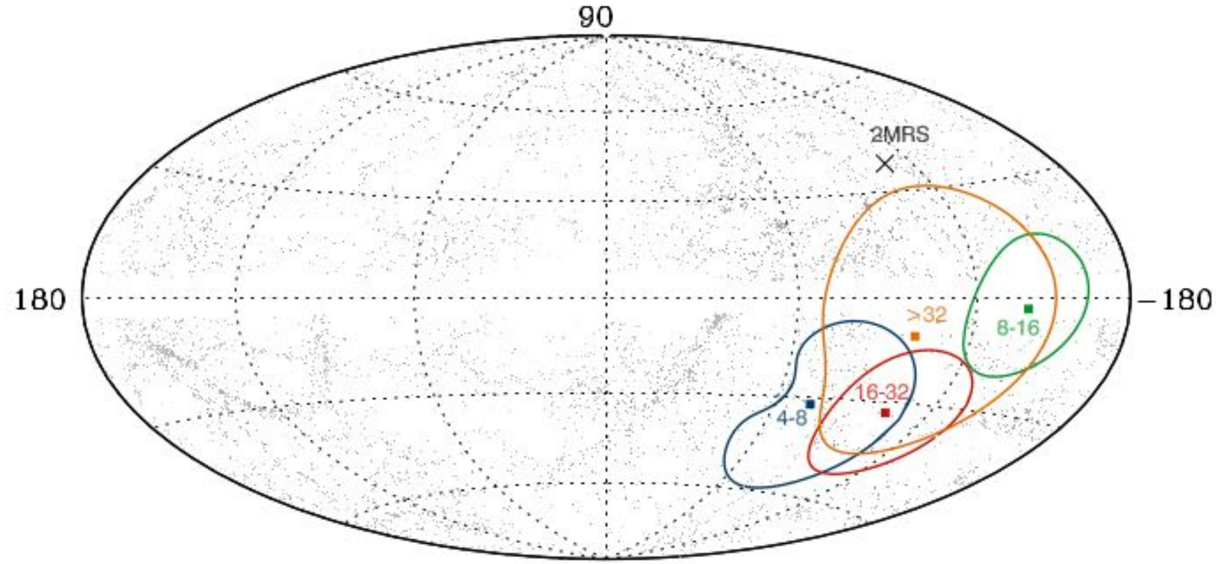



**Observed dipole not far from Outer spiral arm attractor**

# ENERGY DEPENDENCE OF DIPOLE

arXiv:1808.03579



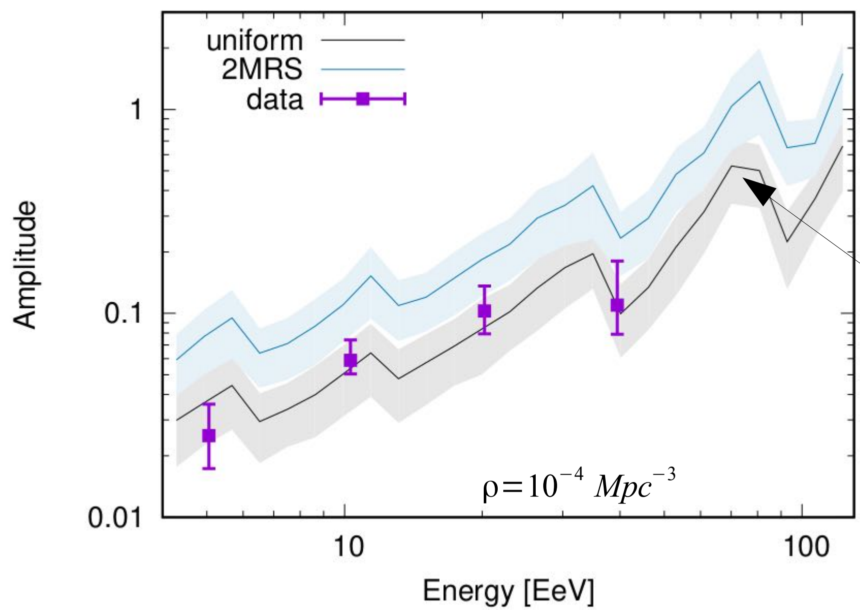




points away from GC
for all E bins above 4 EeV

$$d \simeq d_{10}\left(\frac{E}{10\,EeV}\right)^{\beta}$$

$$d_{10} = 0.055 + 0.008$$

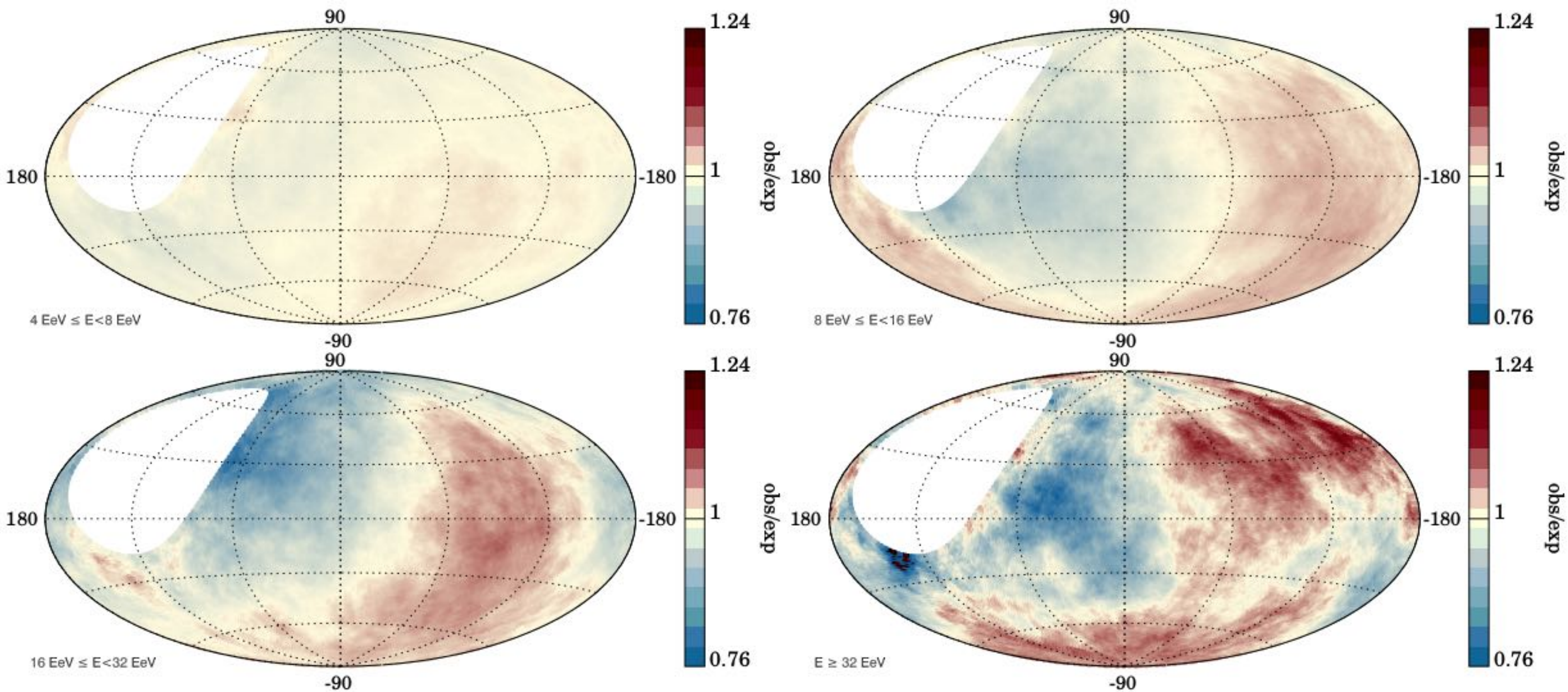
$$\beta = 0.79 \pm 0.19$$




values obtained consistent with expectations

Mixed composition scenarios with rigidity cutoff

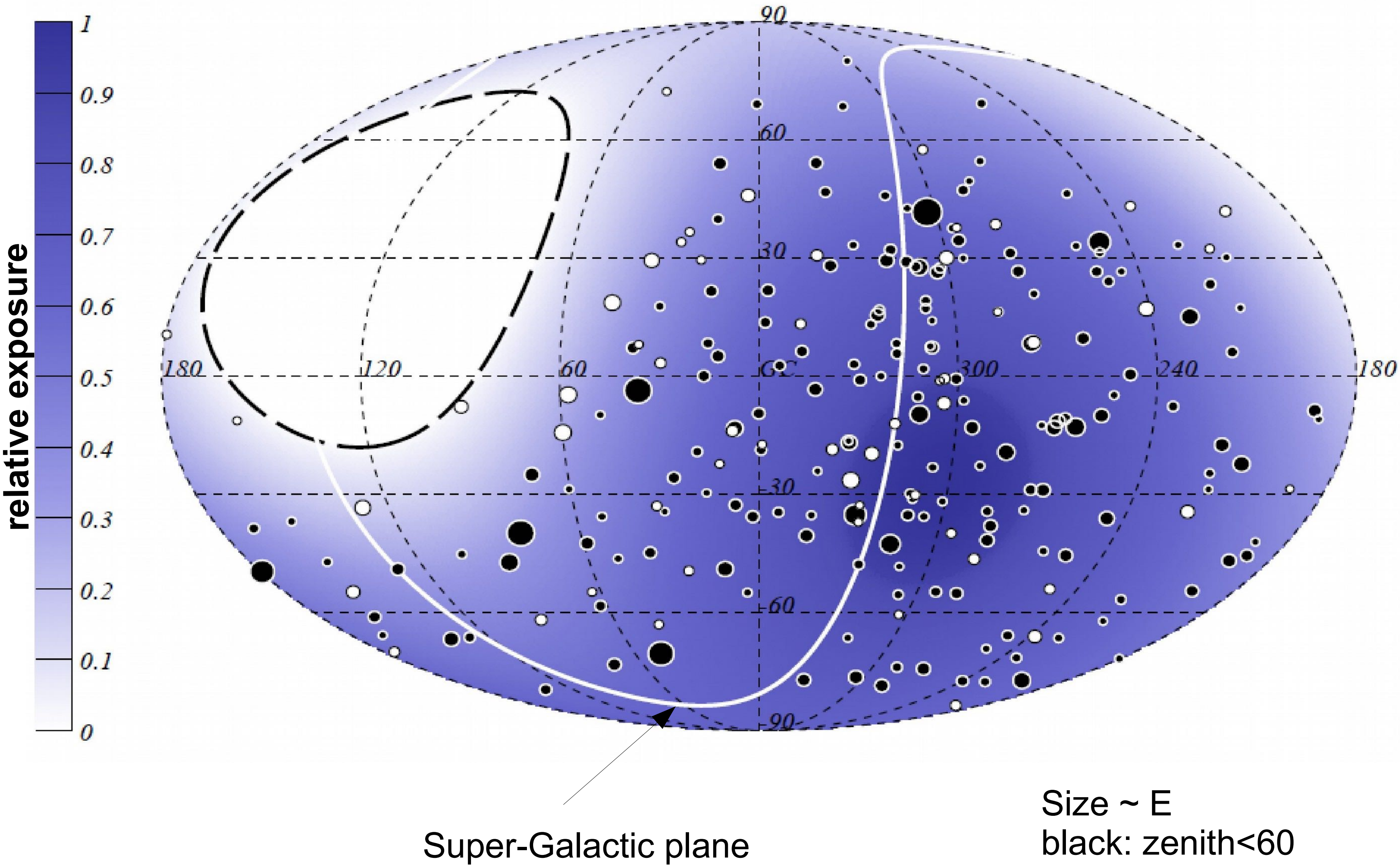
# MAPS OF EXCESS FLUX IN DIFFERENT ENERGY BINS



# HIGHEST ENERGY EVENTS

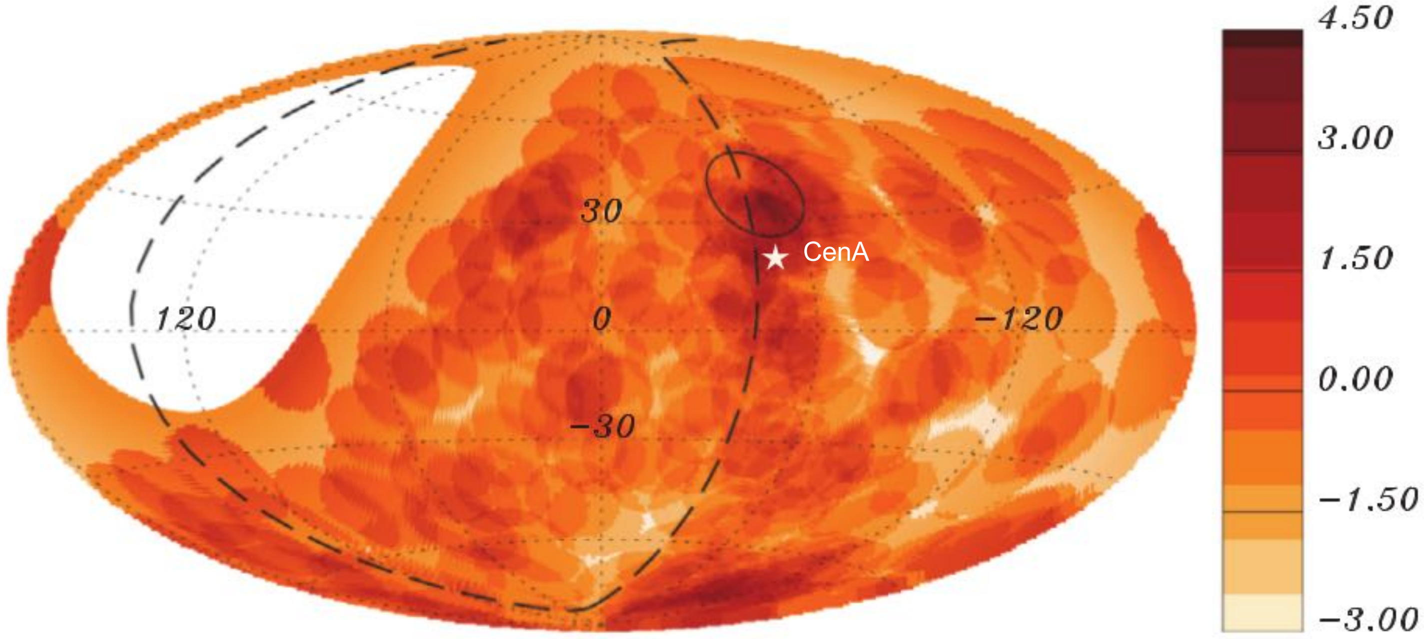
ApJ 2015

**DATA UP TO March 2014, Exposure = 66450 km$^2$ sr yr, 231 events with E > 52 EeV**




Size ~ E
black: zenith<60

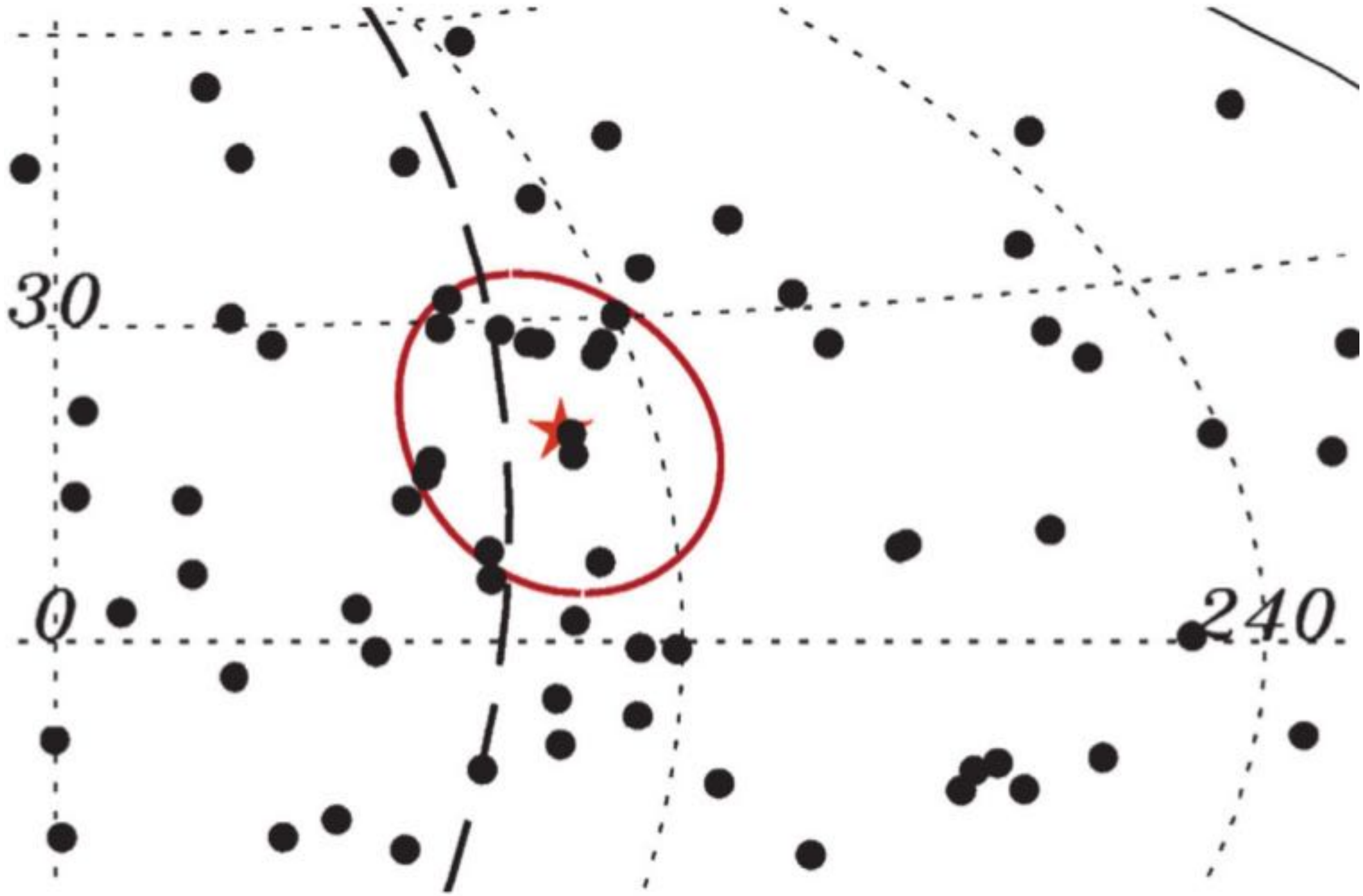
# At energies above 40 EeV some hints of more localized excesses are seen (10° to 20°)




[most significant excess near CenA, for E>54 EeV, 12 deg, obs/exp=14/3.2]
(but not unlikely given the scan performed)

# Centaurus A region,  E > 58 EeV  (15° centered on CenA)

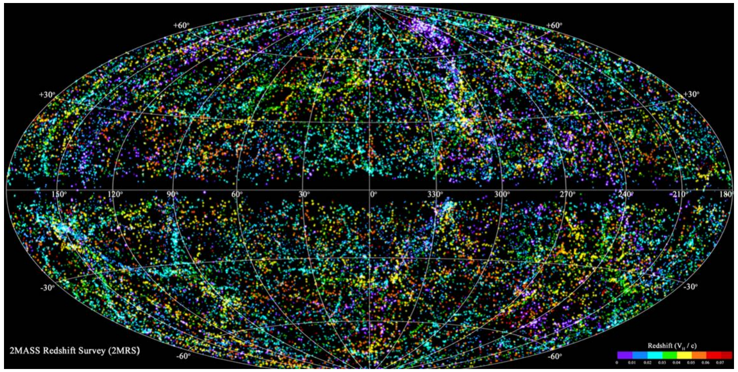
obs/exp = 14/4.5



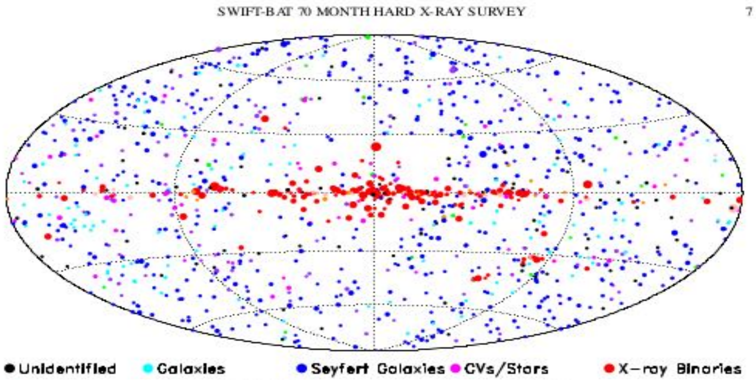

**Cen A is the closest active radio galaxy, a quite promising UHECR source**

# Cross-correlation with catalogs: count pairs between events and objects

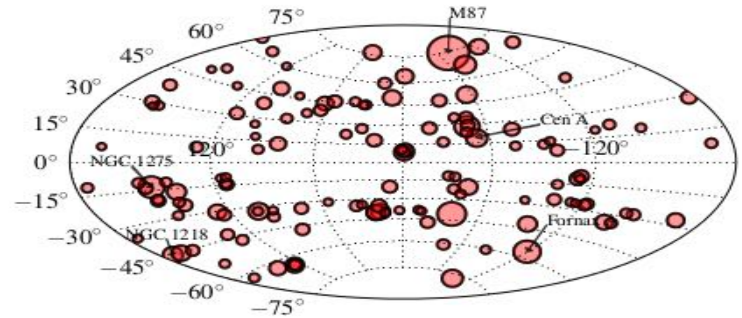
**We considered three catalogs:**




**2MRS IR galaxies (Huchra et al. 2012)**
**in nearby Universe: 37209 gal within 200 Mpc**
(may trace GRBs or young pulsars)



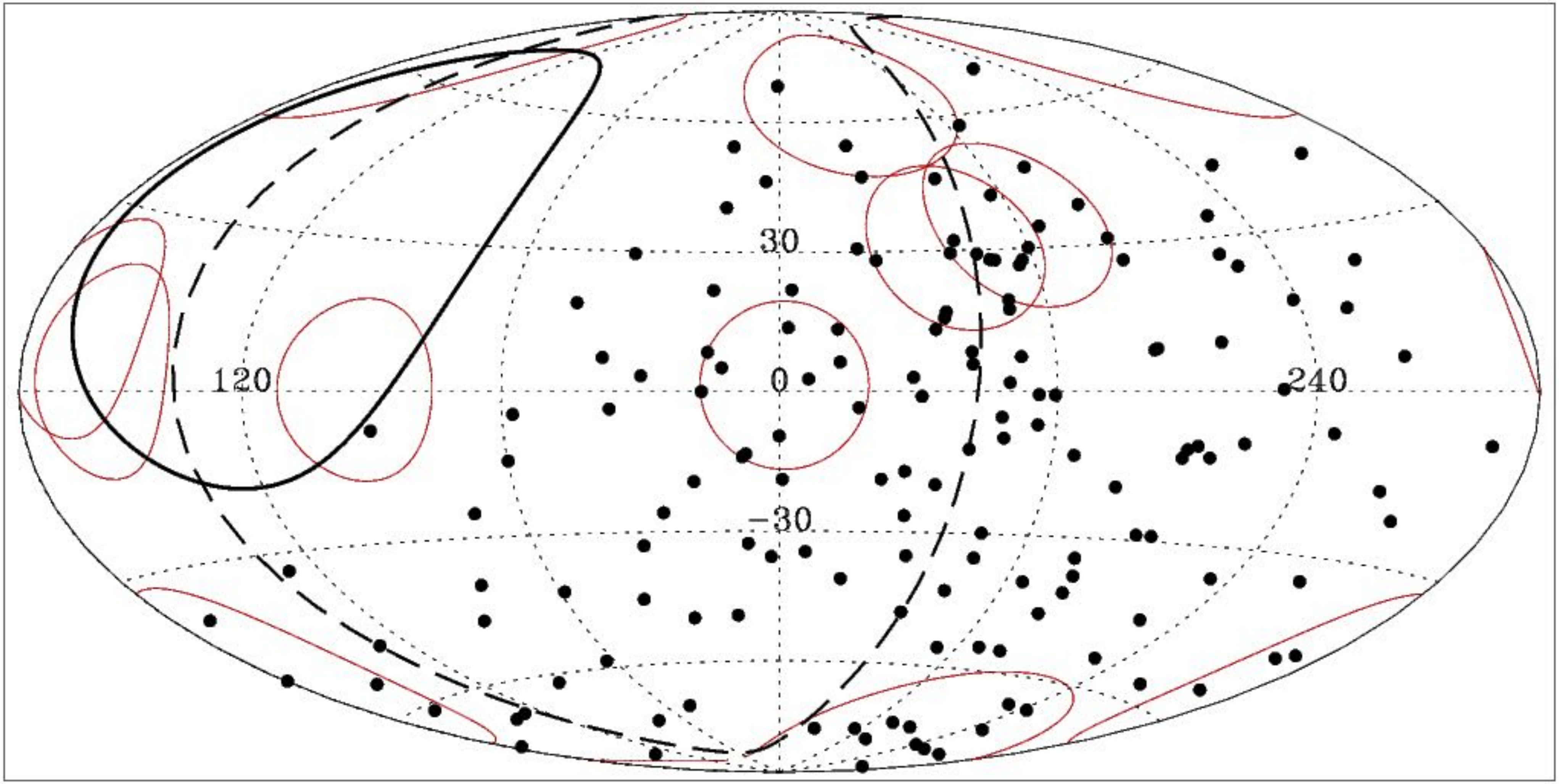

**Active Galactic Nuclei (AGN) from Swift BAT**
**70 month X-ray catalog (Baumgartner et al)**
**296 AGN within 200 Mpc with flux>13.4E-12 erg/cm$^2$ s**
(mostly Seyfert in spirals)
Also restrict catalog to intrinsically brightest ones




**Radio-Galaxies with jets (Van Velzen et al 2012):**
**205 objects within 200 Mpc**
(mostly Fanaroff-Riley in ellipticals)

**We scan over the maximum distance to the objects from 10 Mpc up to 200 Mpc to account for possible attenuation of faraway sources**

**Most significant correlation for bright Swift AGN** ($L>10^{44}$ erg/s, dist < 130 Mpc)




**E > 58 EeV & 18°** obs/exp=62/32.8

# UPDATE AT ICRC2017

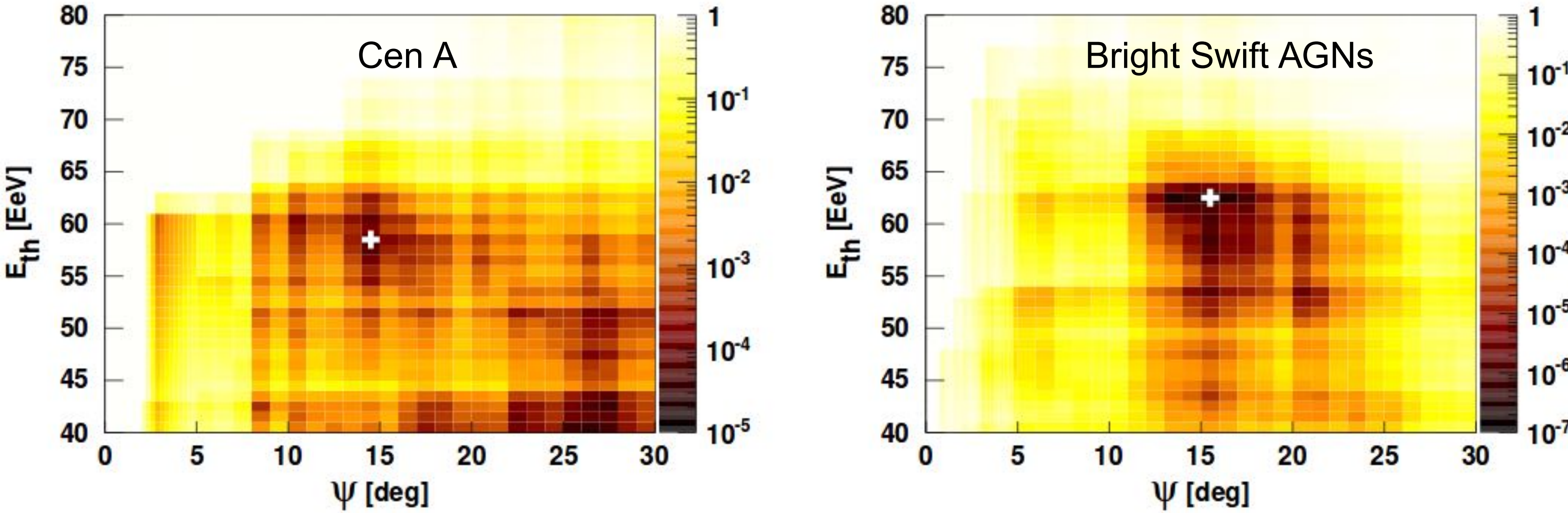



**Figure 1:** *Left*: Correlation of events with Cen A as a function of the angular distance $\psi$ and the energy threshold $E_{th}$. *Right*: Scan in ($E_{th}$, $\psi$) for the cross-correlation of events with the most luminous AGNs of the *Swift*-BAT catalog within 130 Mpc and brighter than $10^{44}$ erg/s.

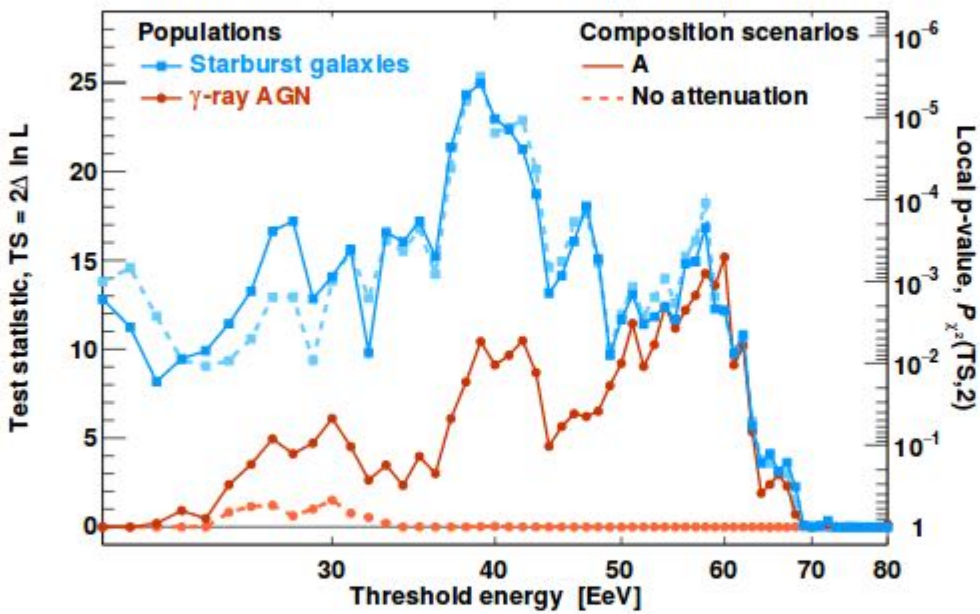
## Penalized probabilities

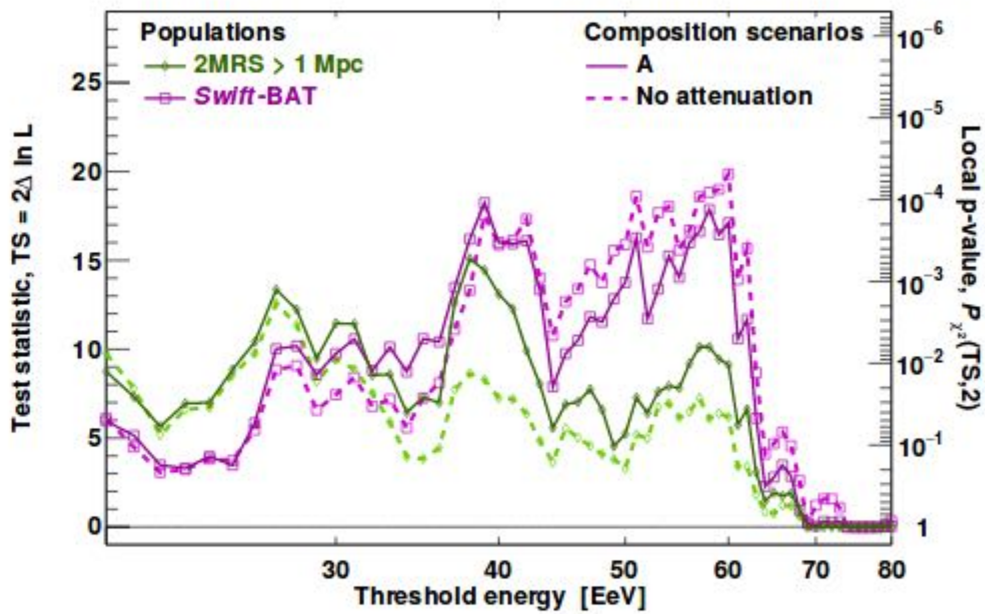
| | ApJ 2015 | ICRC 2017 |
|---|---|---|
| **Cen A** | 1.4E-2 | 1.1E-3 |
| **Bright Swift AGNs** | 1.3E-2 | 6.5E-4 |

# Search for correlations using Likelihood method

(using EM flux as proxy for CR flux, and CR attenuation, ...)

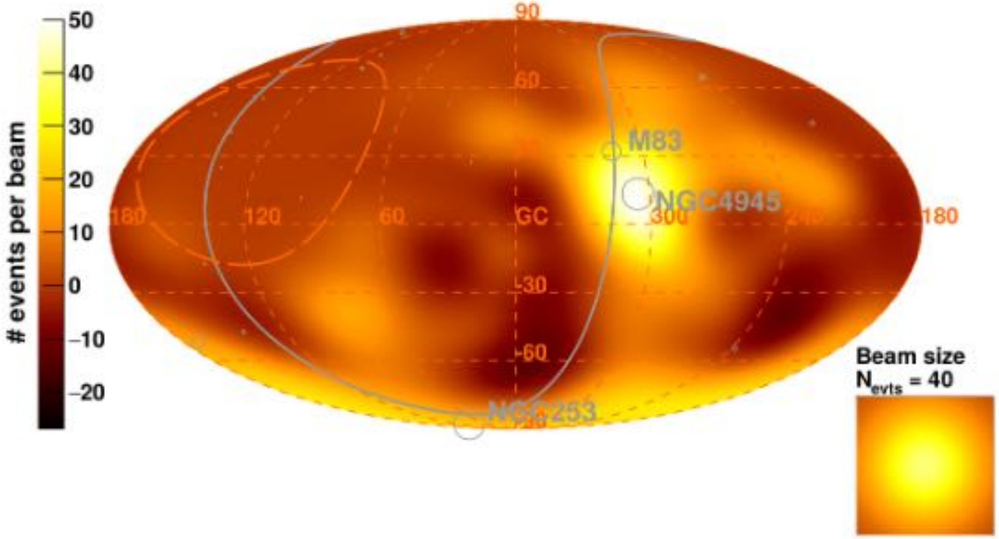
ApJL 2018



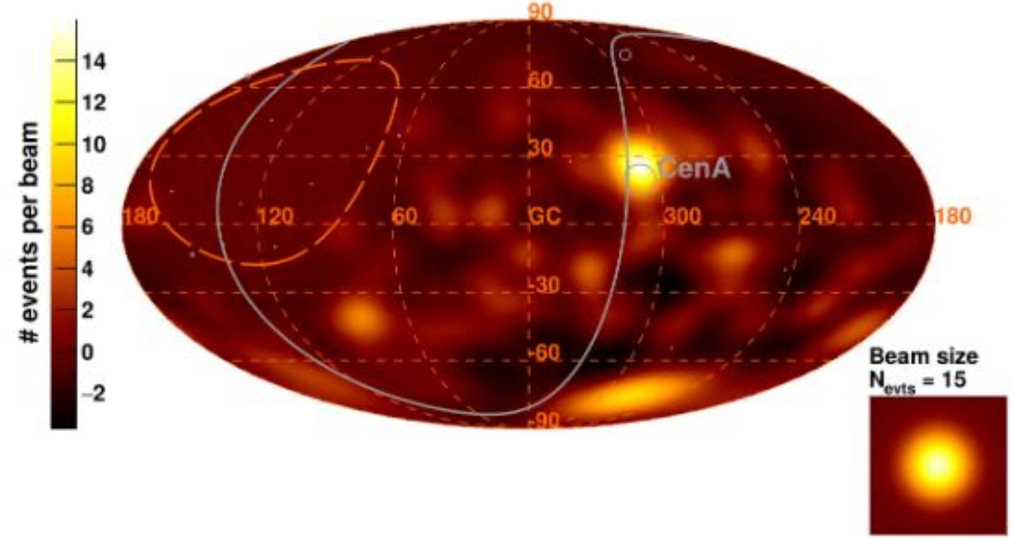




**Starburst Galaxy catalog compiled by Fermi team (weighted by radio-flux)**
**AGNs observed by Fermi: mostly Cen A + M87 + Blazars (weighted by gamma flux)**
**2MRS Galaxies (weighted by IR flux)**
**Swift-BAT AGNs (weighted by X-ray flux)**

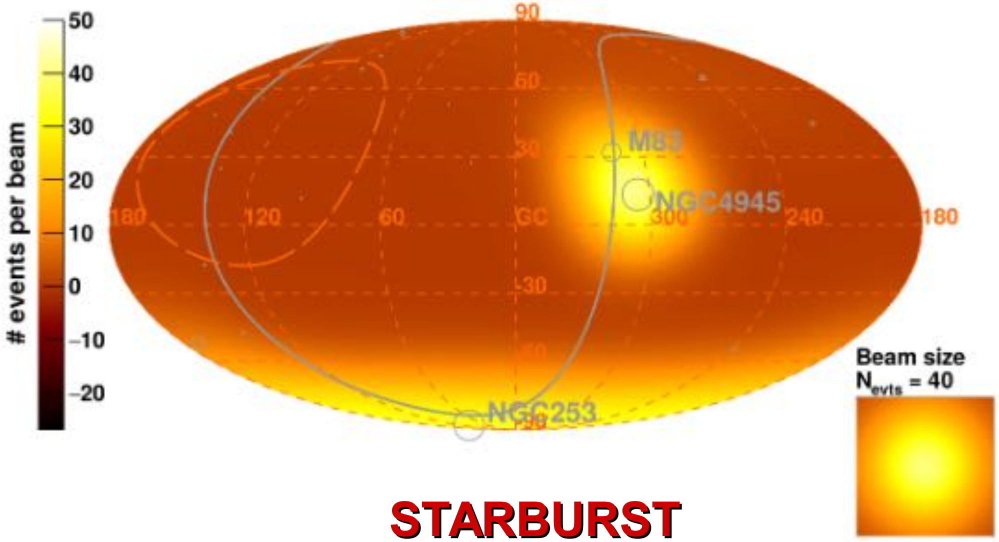
Observed Excess Map - E > 39 EeV



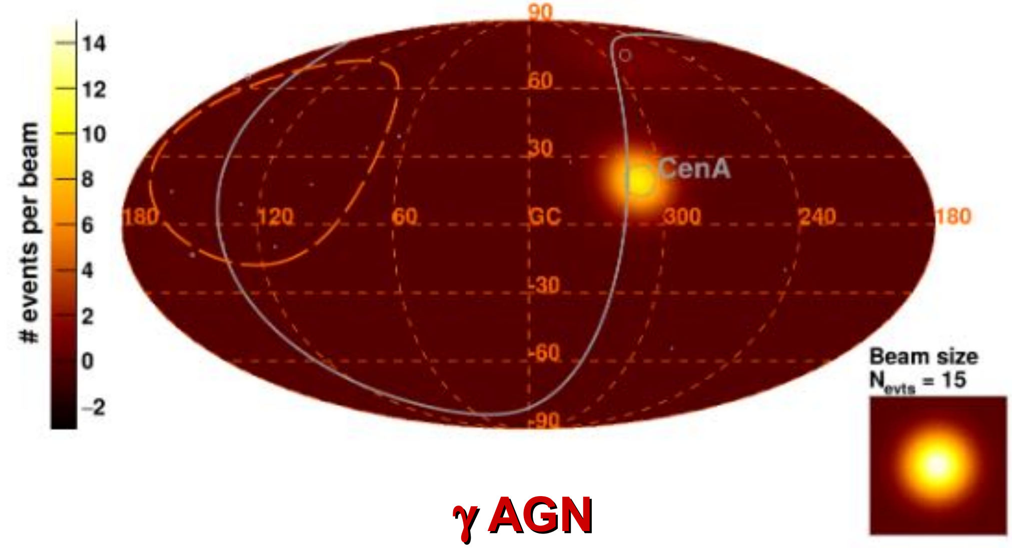

Observed Excess Map - E > 60 EeV




Model Excess Map - Starburst galaxies - E > 39 EeV




Model Excess Map - Active galactic nuclei - E > 60 EeV




**STARBURST**

Fraction from SBG=10% , angle=13°
Significance: 3.9 σ

**γ AGN**

Fraction from AGN = 7% , angle=7°
Significance: 2.7 σ

**Since deflections are proportional to the CR charge**
**→ it would be important to separate light from heavy CRs**

# THE FUTURE: ONGOING UPGRADE

SSD: Scintillators over the Surface Detectors
(2018-2019)

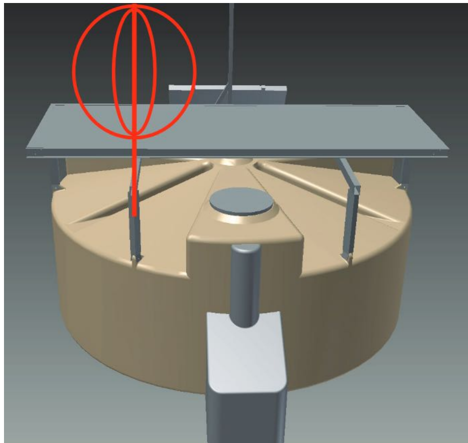
adding additional scintillator detectors
and refurbished electronics
(and small PMT to increase dynamic range)

This will make it possible to separate muonic and electromagnetic signals
→ allow for composition measurements event by event
- do astronomy with light nuclear component
  and help to understand:
- origin of the flux suppression at highest energies
- proton contribution at the highest energies
- EAS physics and hadronic multiparticle production


AMIGA:
Scintillators underground in Infill

RADIO UPGRADE:

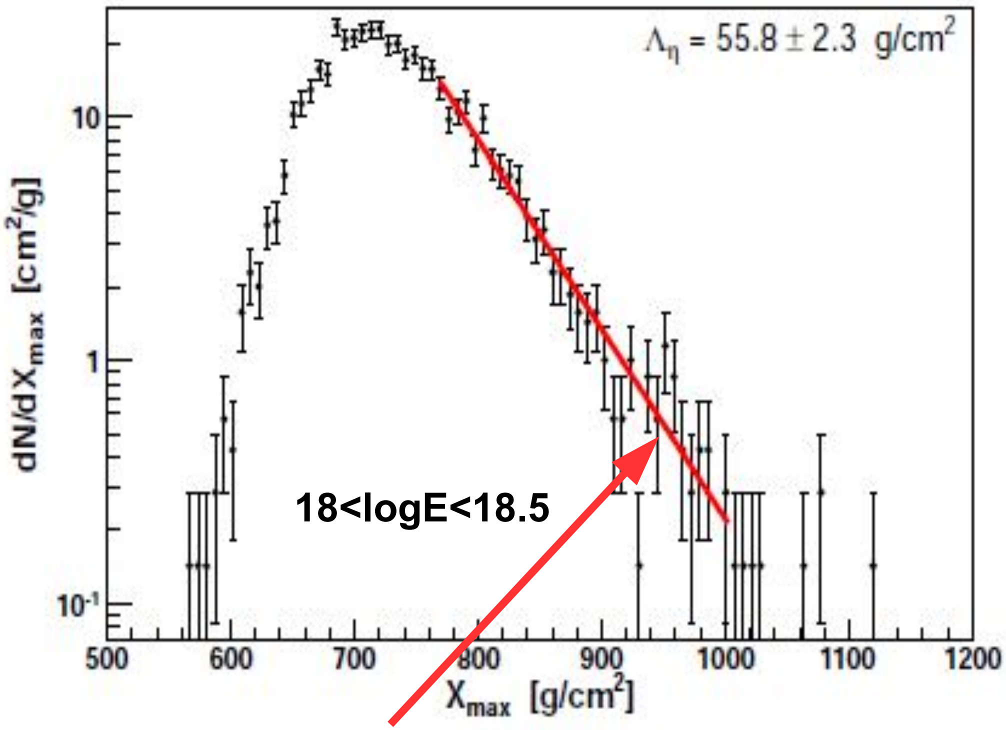
AERA: 17 km$^2$
→ 3000 km$^2$ ?

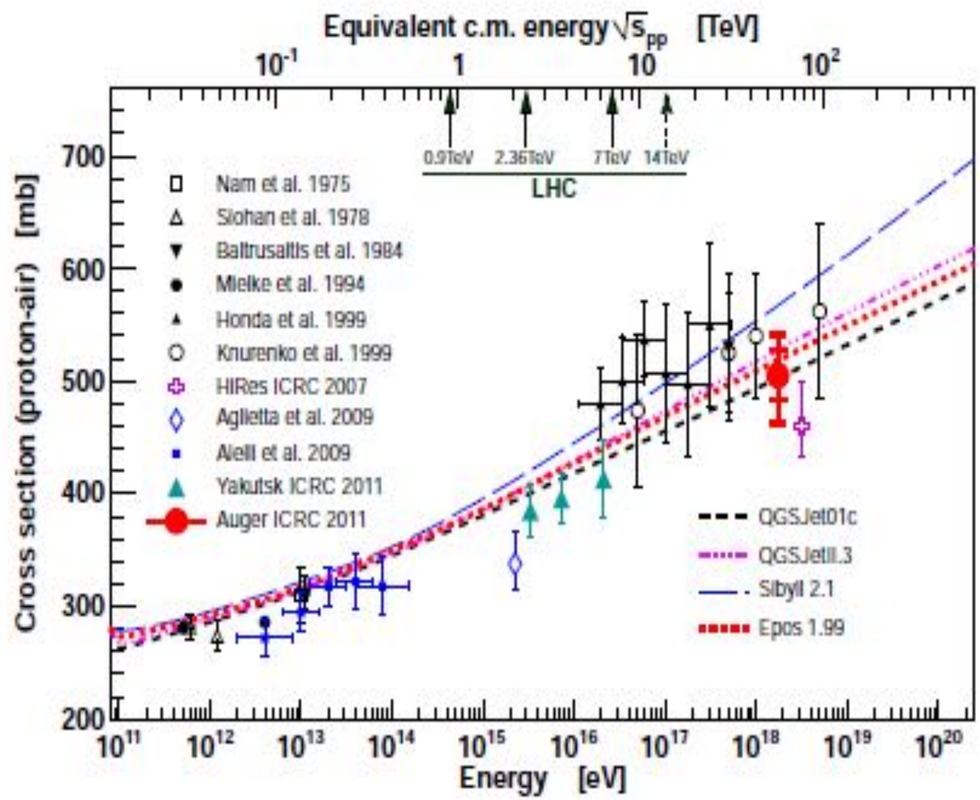


# BACKUP

# p-air CROSS SECTION FROM AIR SHOWERS

**Xmax distribution sensitive to depth of first interaction → to p-air cross-section**



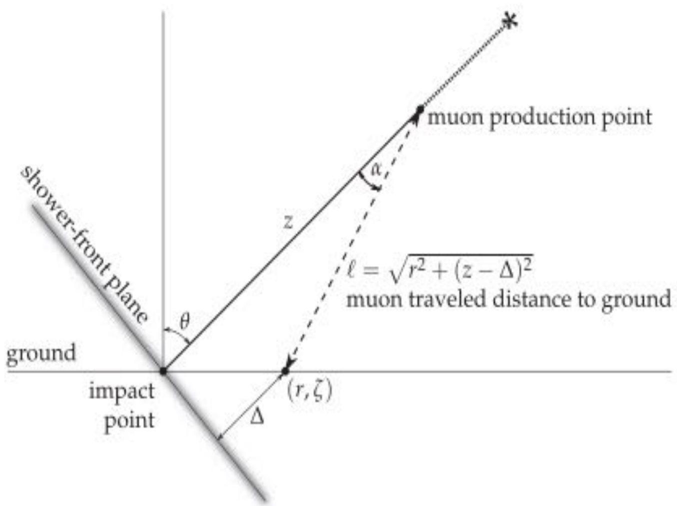

PRL 2012

**would be steeper for larger cross section**

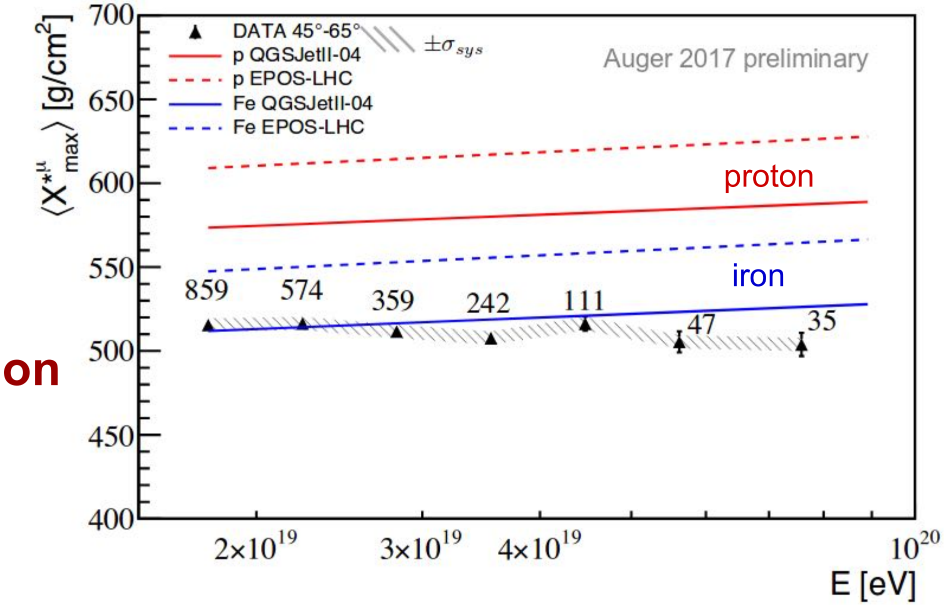
## p-air cross section looks 'normal'

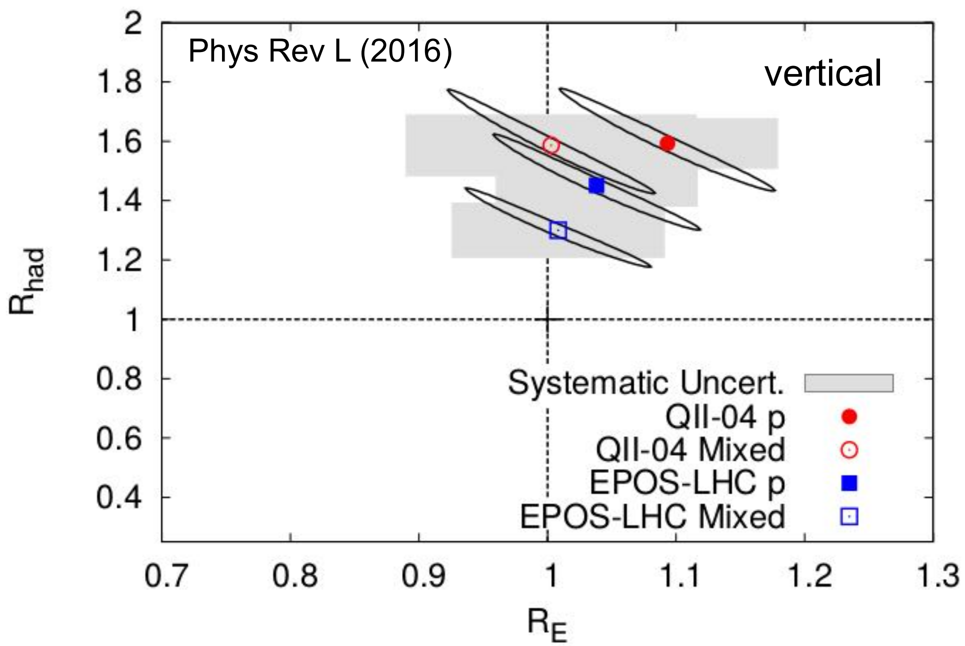
**also pp cross section can be inferred**

# DEPTH OF MUON PRODUCTION from timing in SD

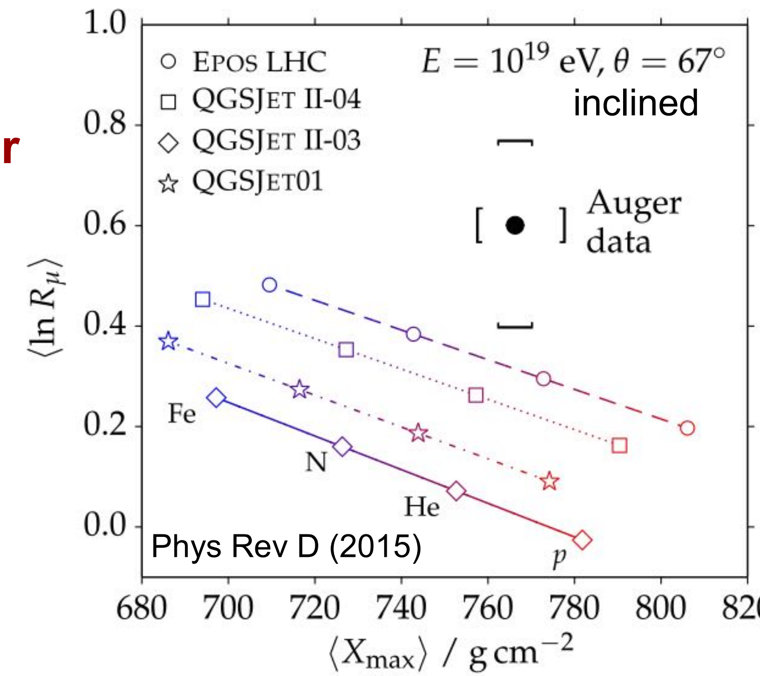



**Muon production depth**




**Muon number**




**Muons are produced too early and too much (as compared to expectations)**

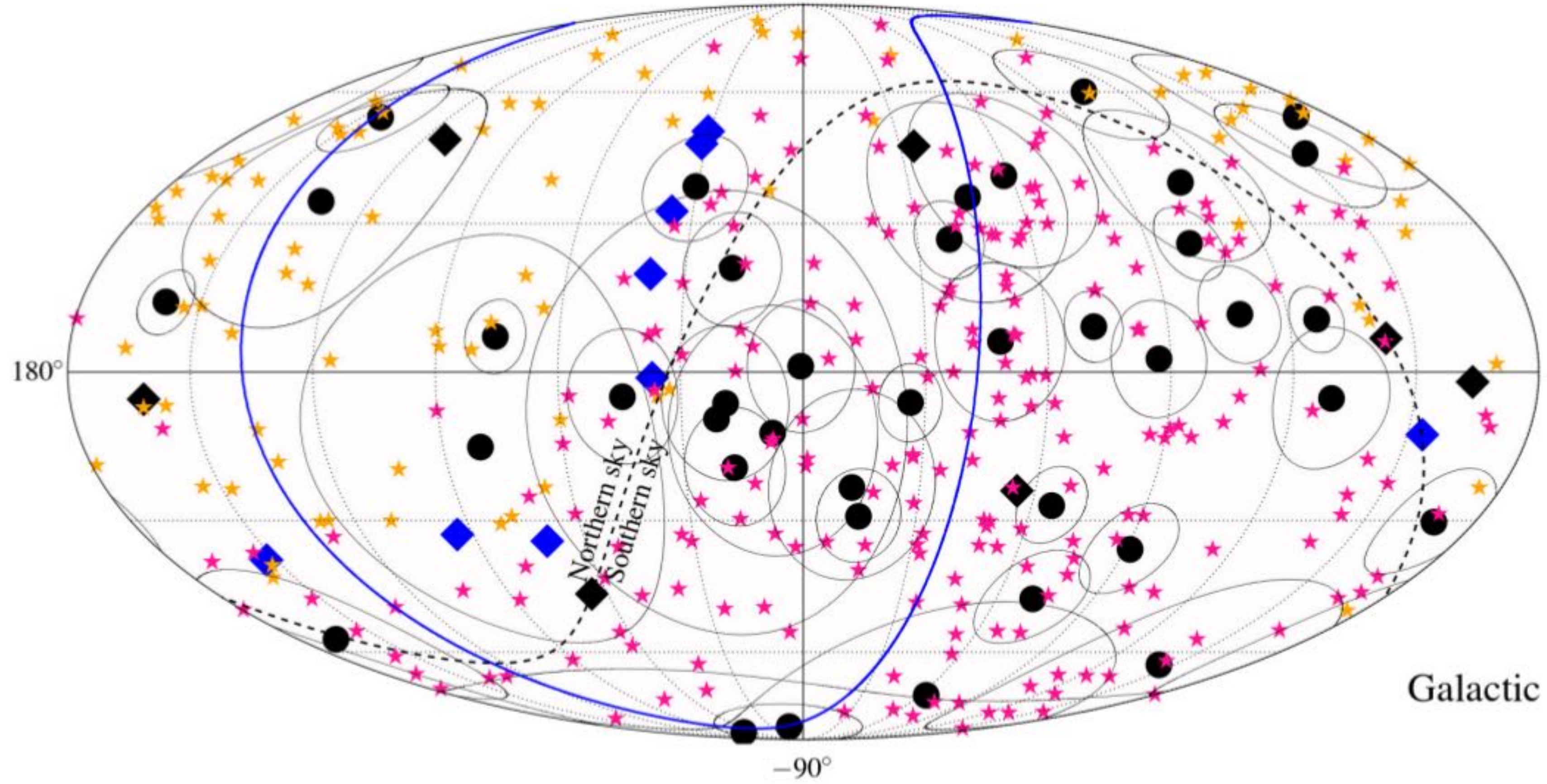
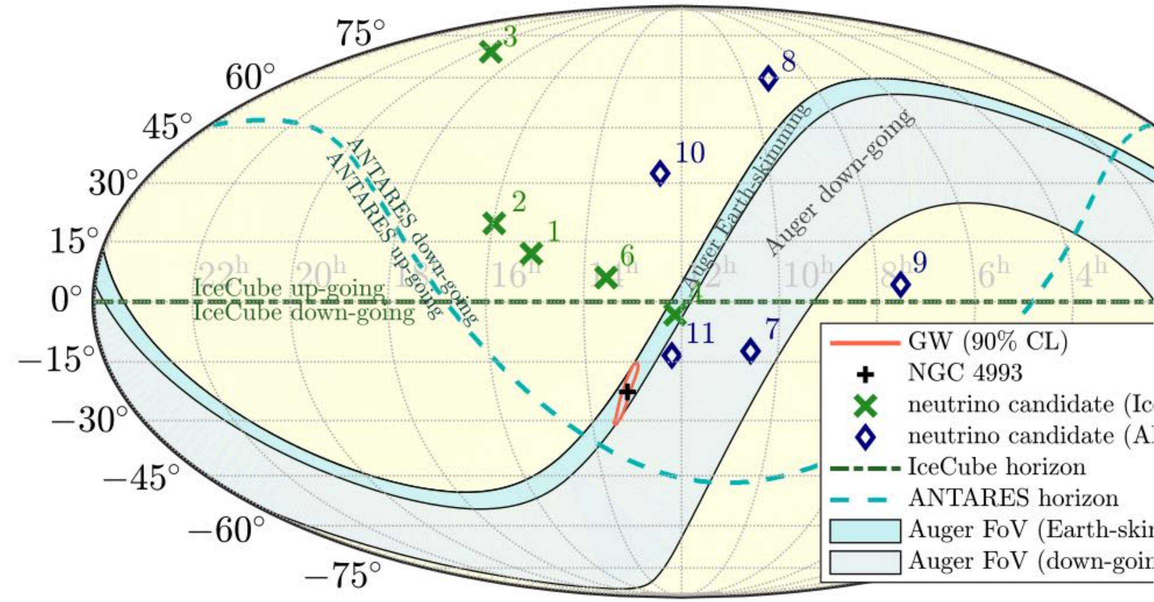



**Figure 7**. Maps in Equatorial and Galactic coordinates showing the arrival directions of the IceCube cascades (black dots) and tracks (diamonds), as well as those of the UHECRs detected by the Pierre Auger Observatory (magenta stars) and Telescope Array (orange stars). The circles around the showers indicate angular errors. The black diamonds are the HESE tracks while the blue diamonds stand for the tracks from the through-going muon sample. The blue curve indicates the Super-Galactic plane.



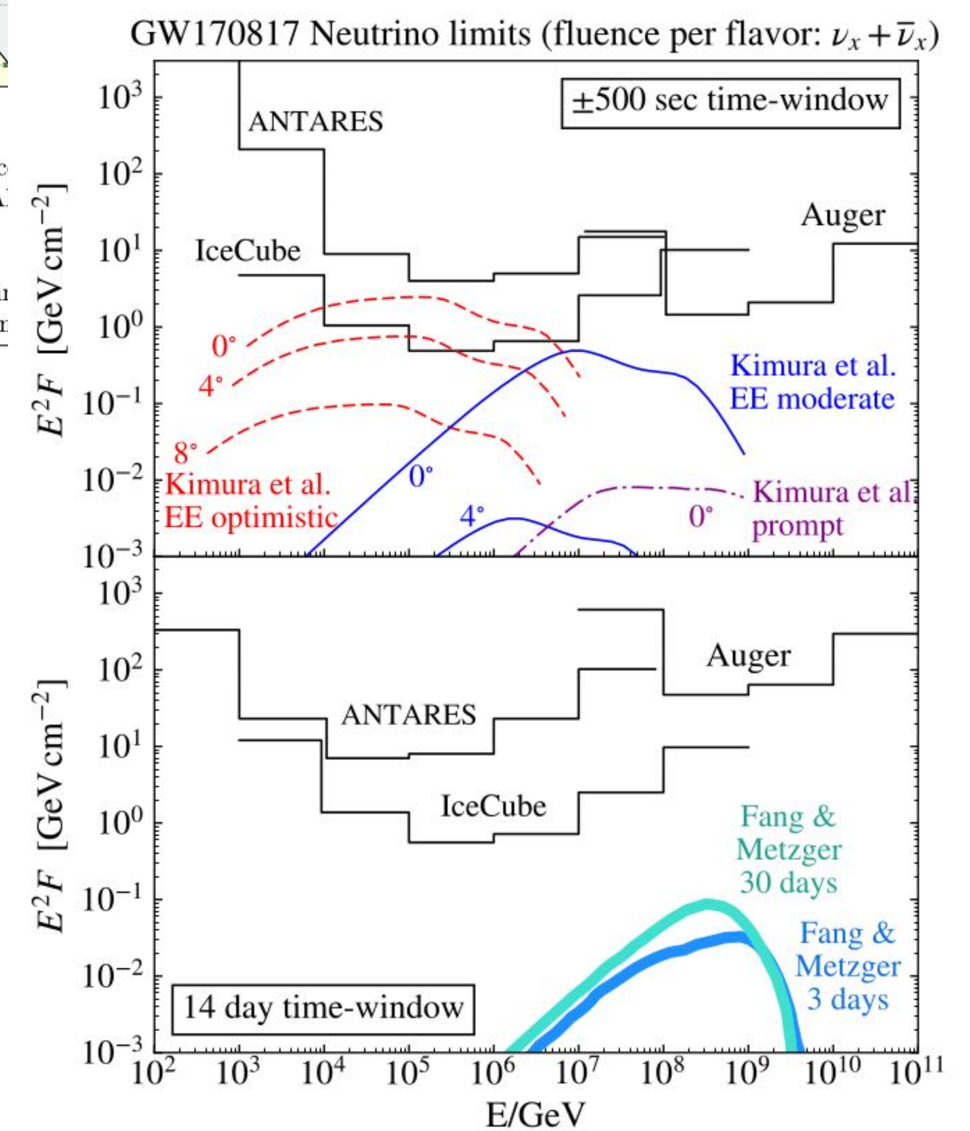




**Figure 2.** Upper limits (at 90% confidence level) on the neutrino spectral fluence from GW170817 during a ±500 s window centered on the GW trigger time (top panel), and a 14 day window following the GW trigger (bottom