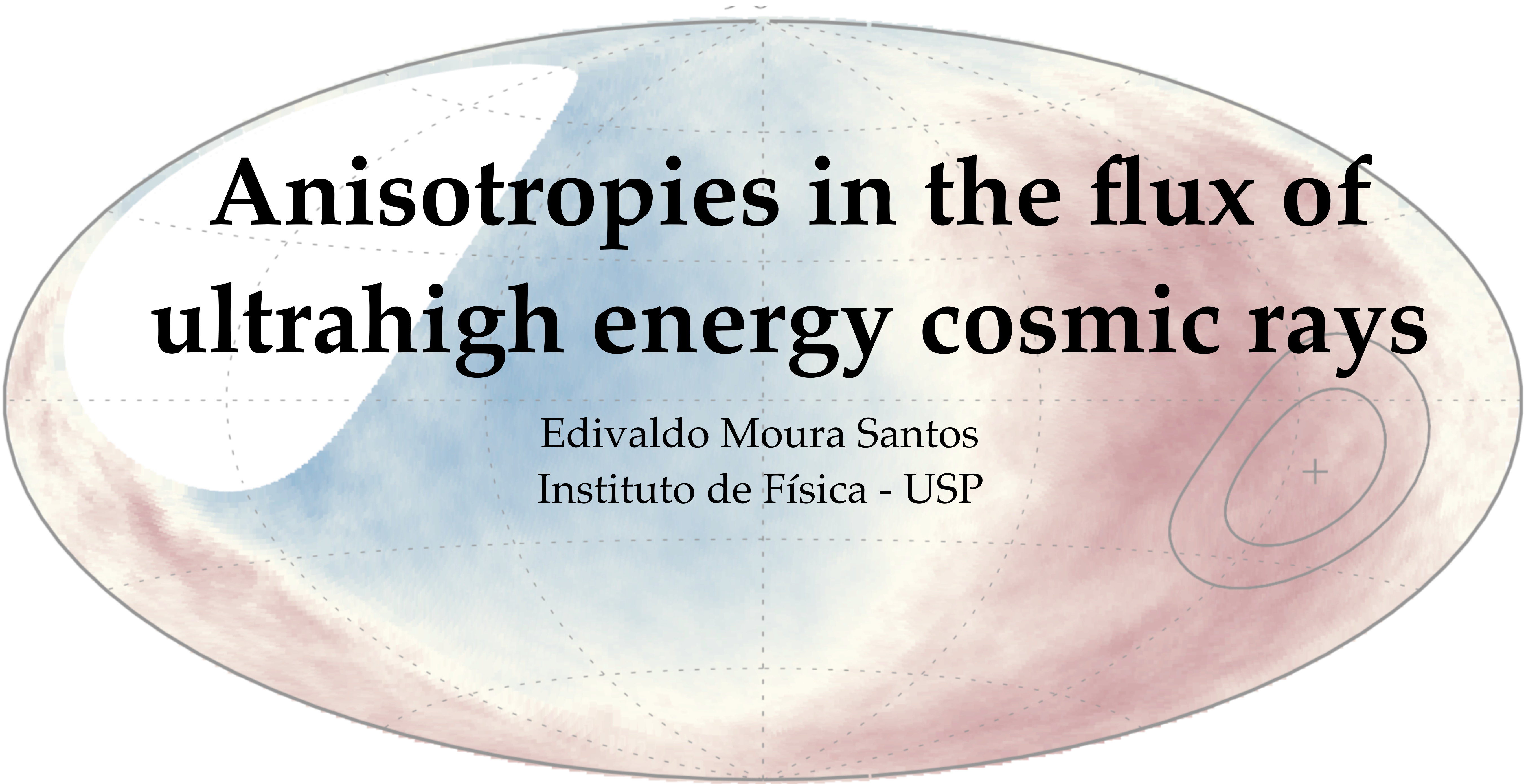


Anisotropies in the flux of ultrahigh energy cosmic rays

Edivaldo Moura Santos
Instituto de Física - USP

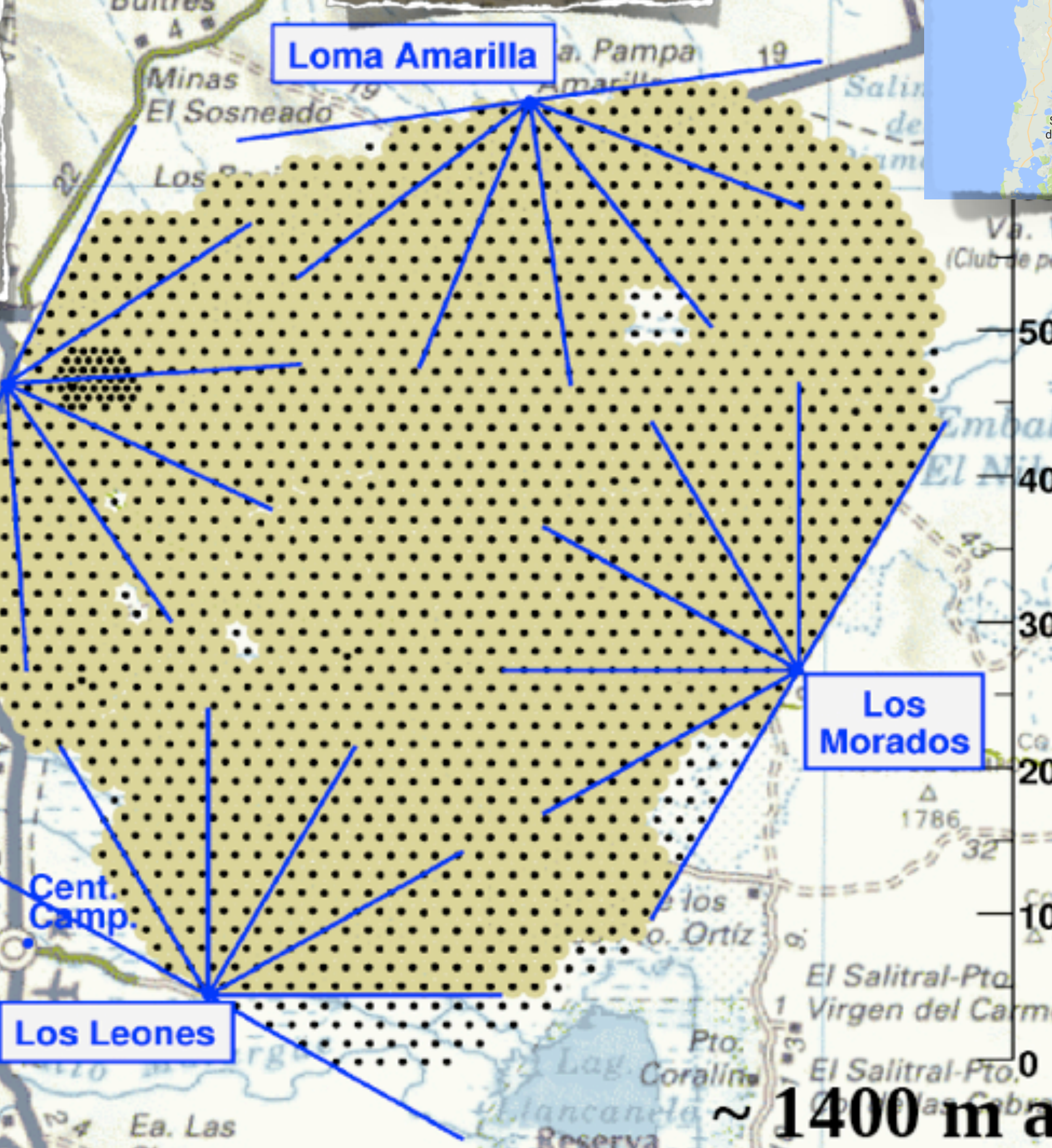
FAPESP-JSPS Workshop Feb 18-20, 2019, IF-USP

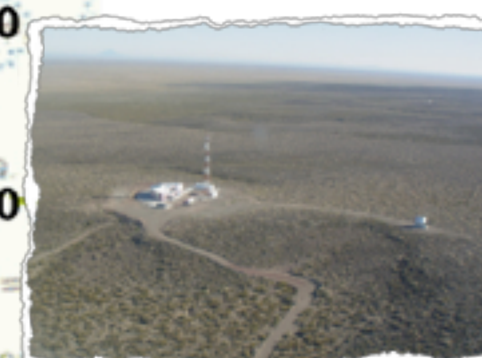
The Pierre Auger Observatory

3000 km² surface array (1660 detectors)

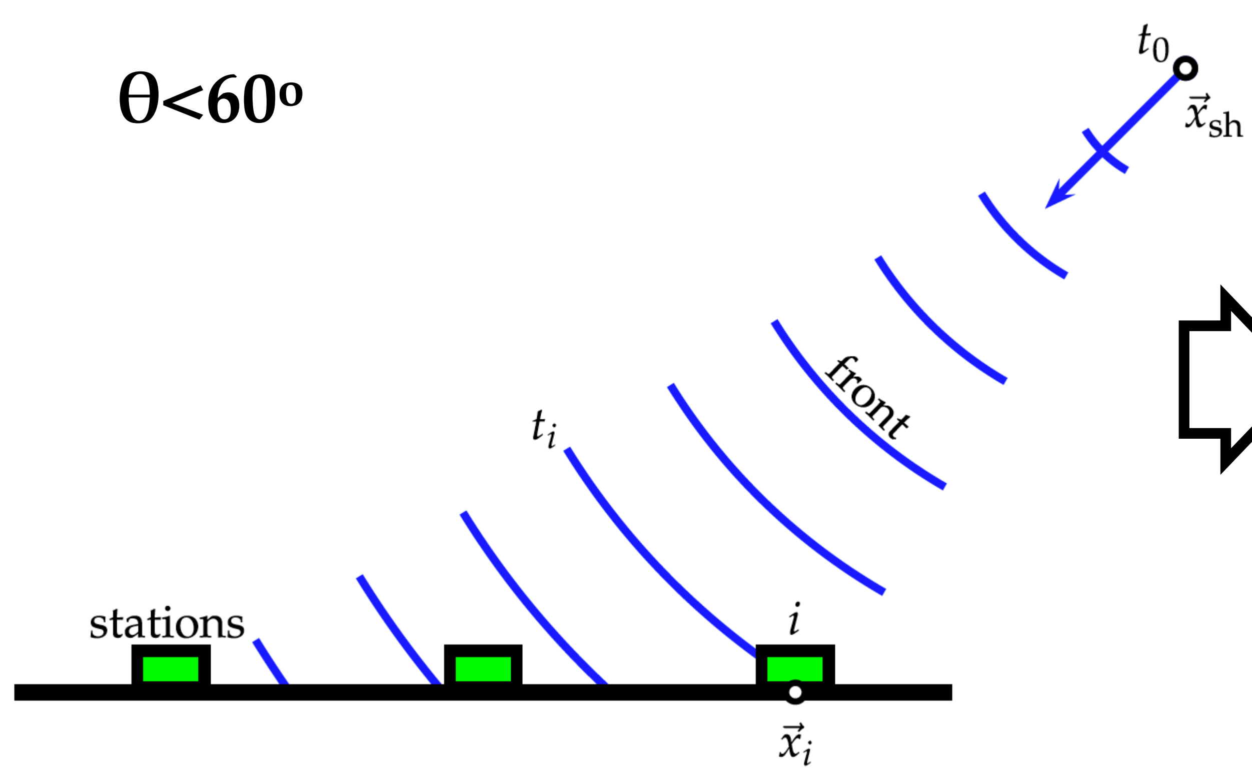
1.5 km triangular grid

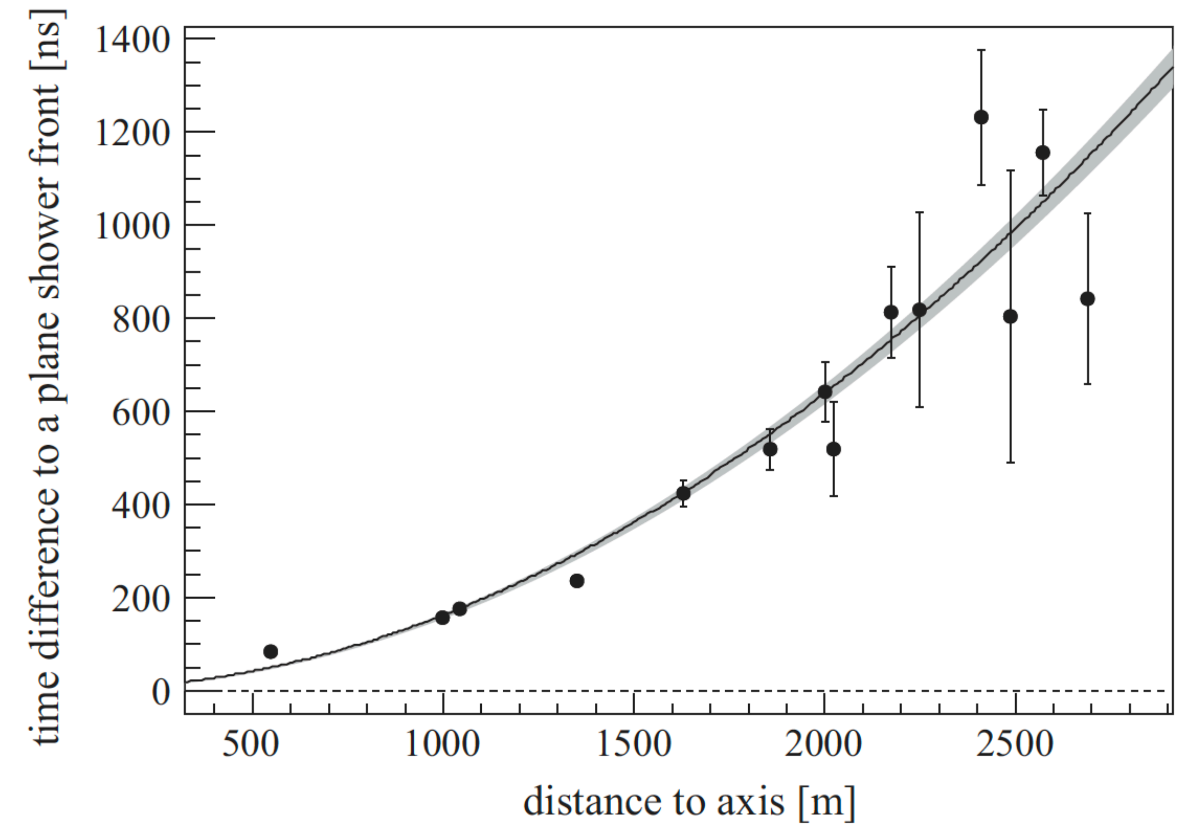
27 fluorescence telescopes

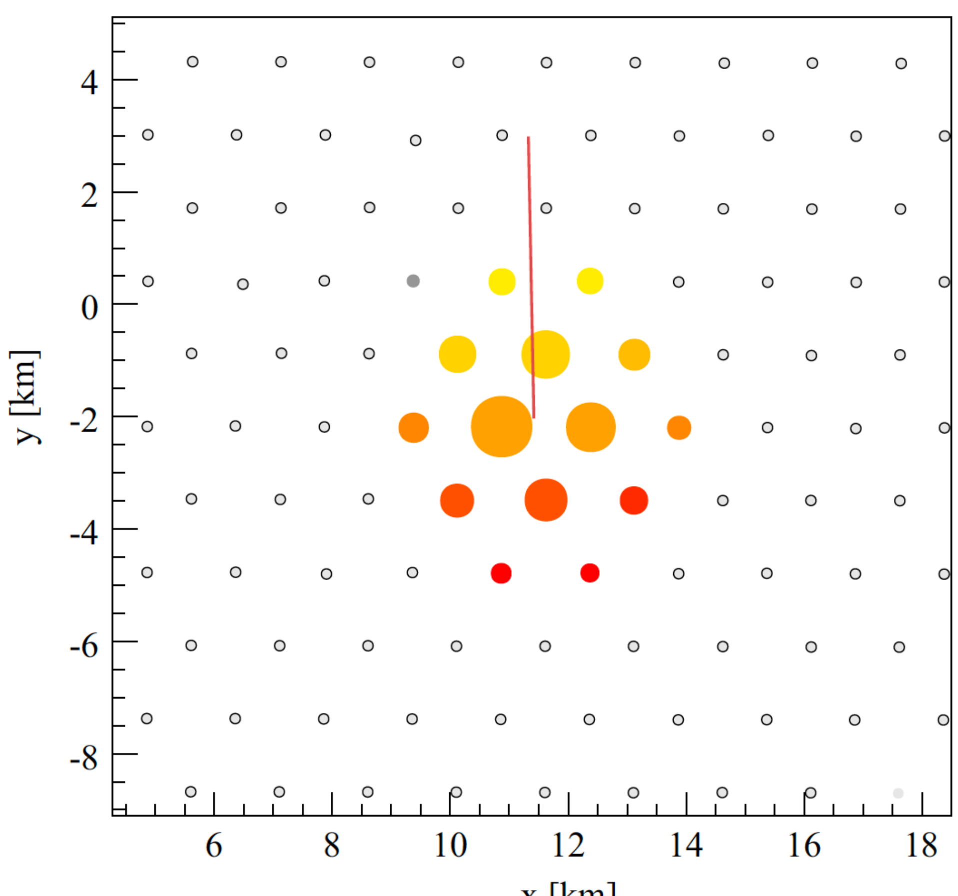


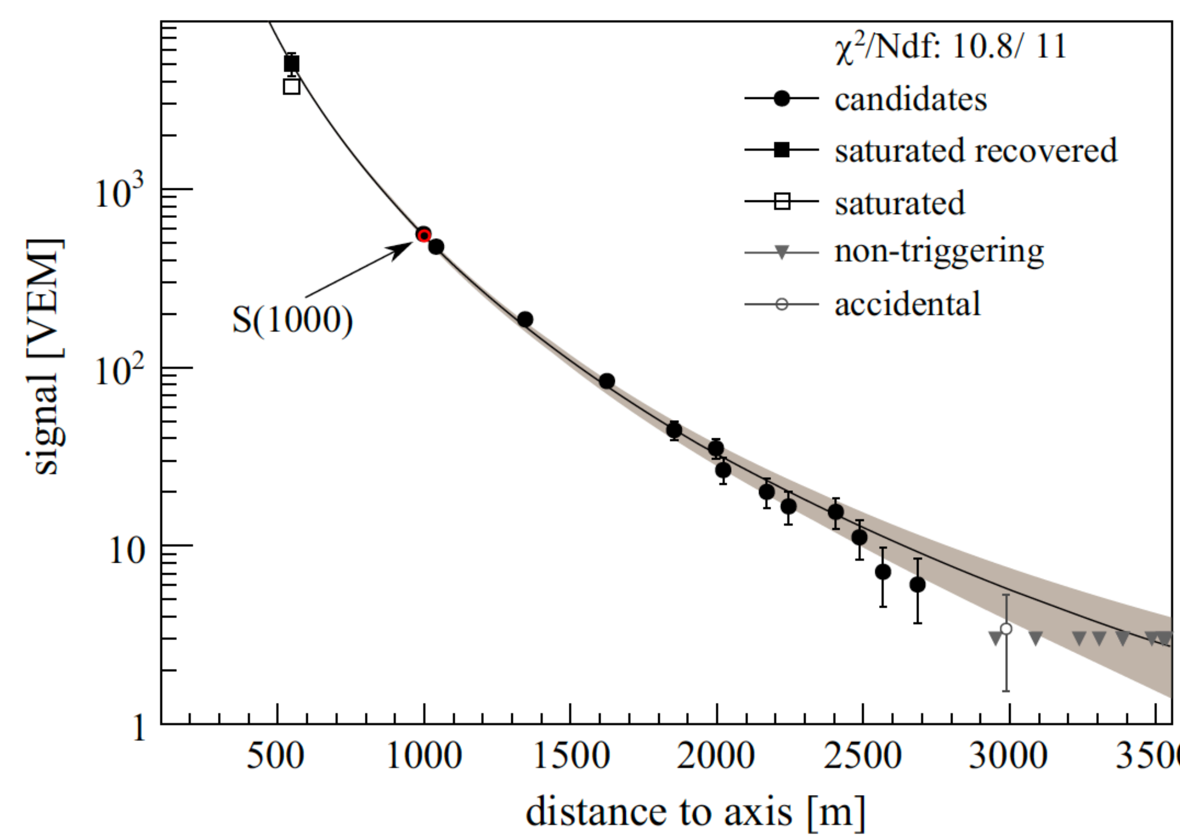


Surface detector vertical event reconstruction



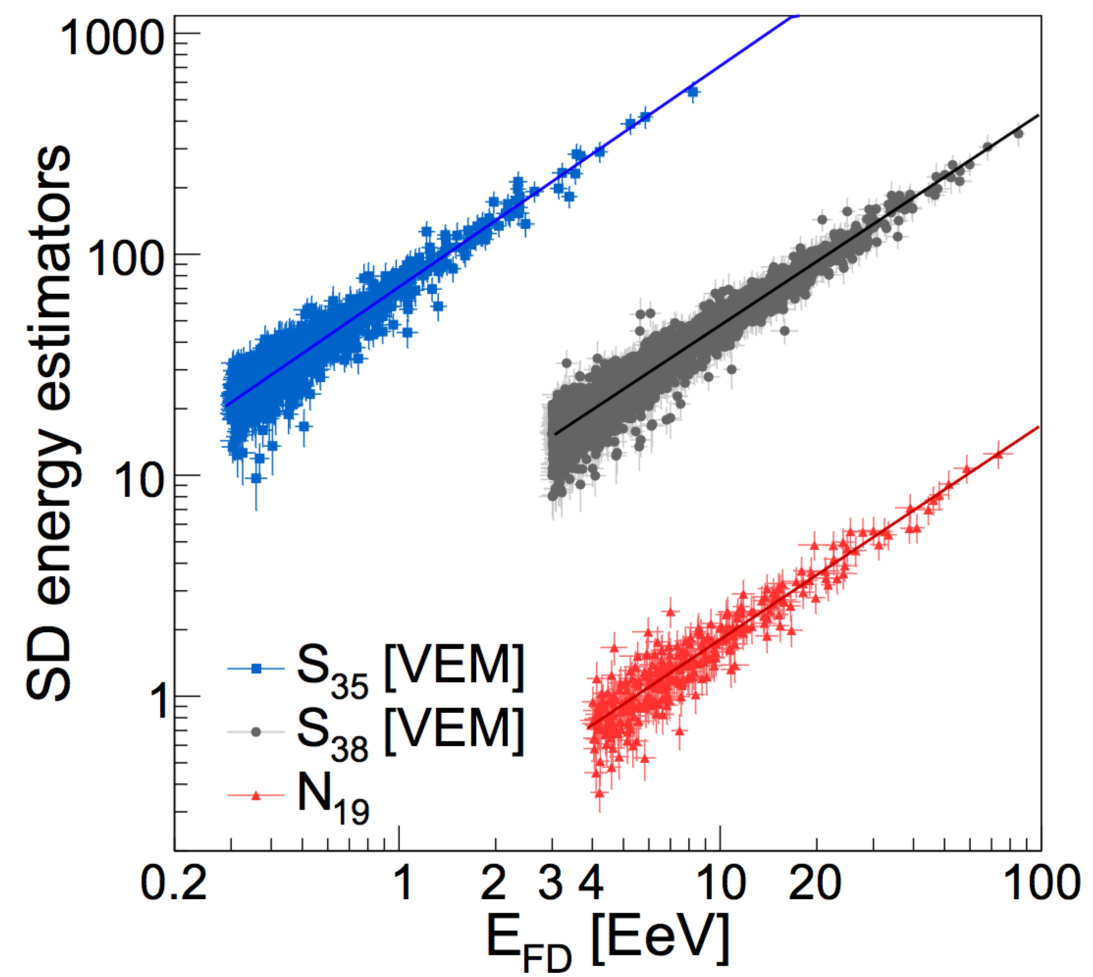


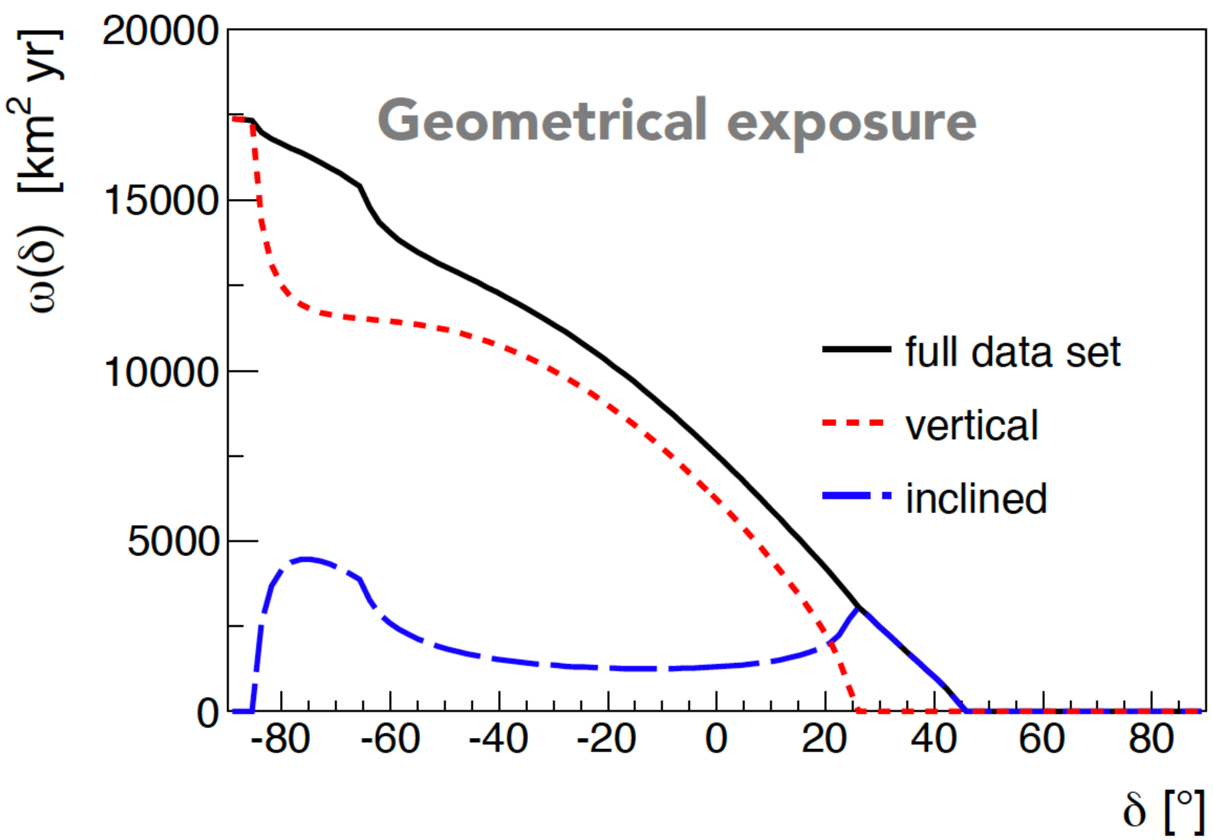




General note on Auger SD data samples - I

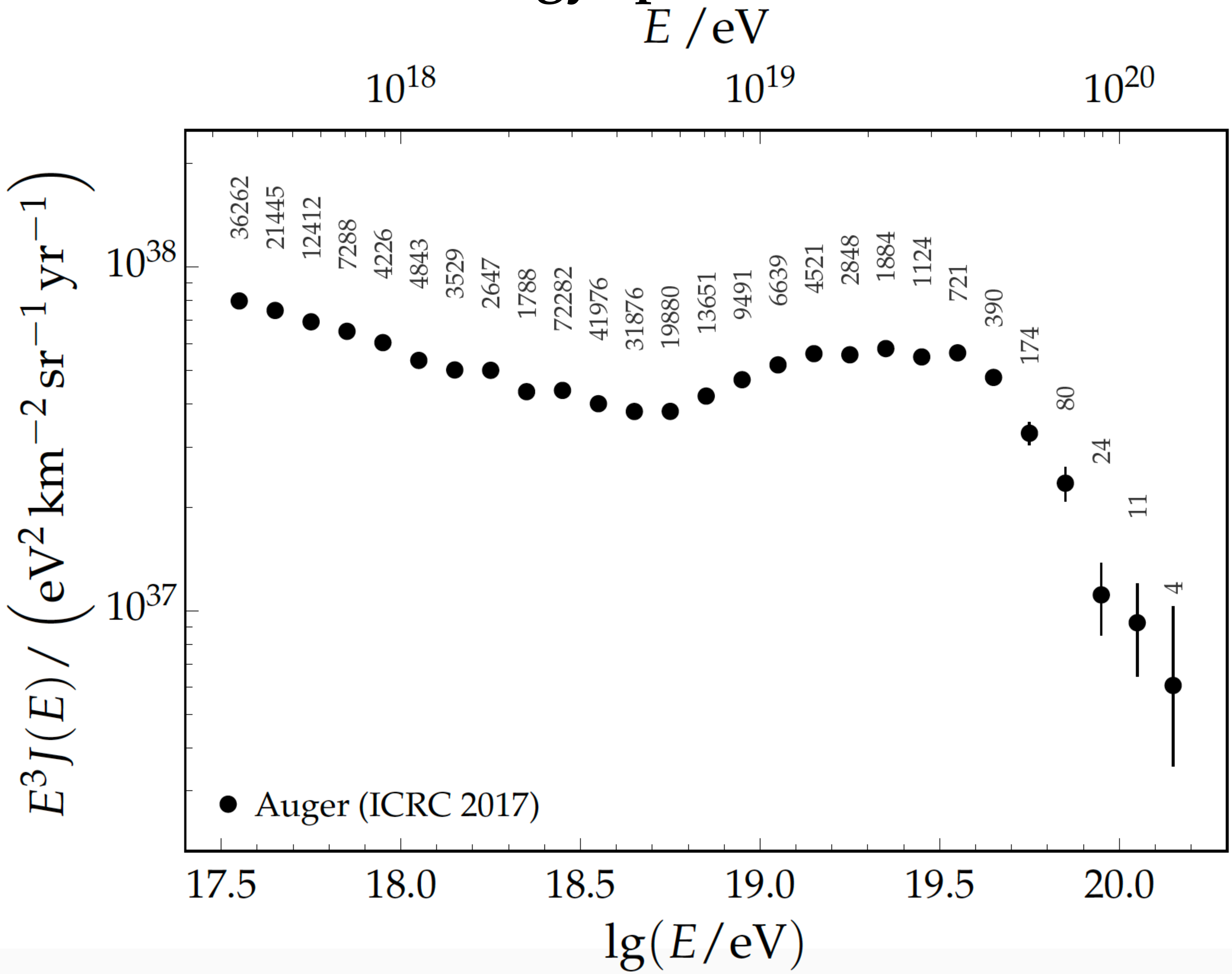
- Data-driven energy calib. using hybrid events
- Different SD estimators are correlated to the quasi-calorimetric energy measured by the FD
- Here, we should use two samples, depending on the zenith angle of the events:
  - Vertical: 0º<θ<60º (S_{38} x E_{FD})
  - Inclined: 60º<θ<80º (N_{19} x E_{FD})





- Inclined sample provides about ~30% of extra sky coverage
- This extra coverage is very important to many of the analyses to be discussed here

Energy spectrum

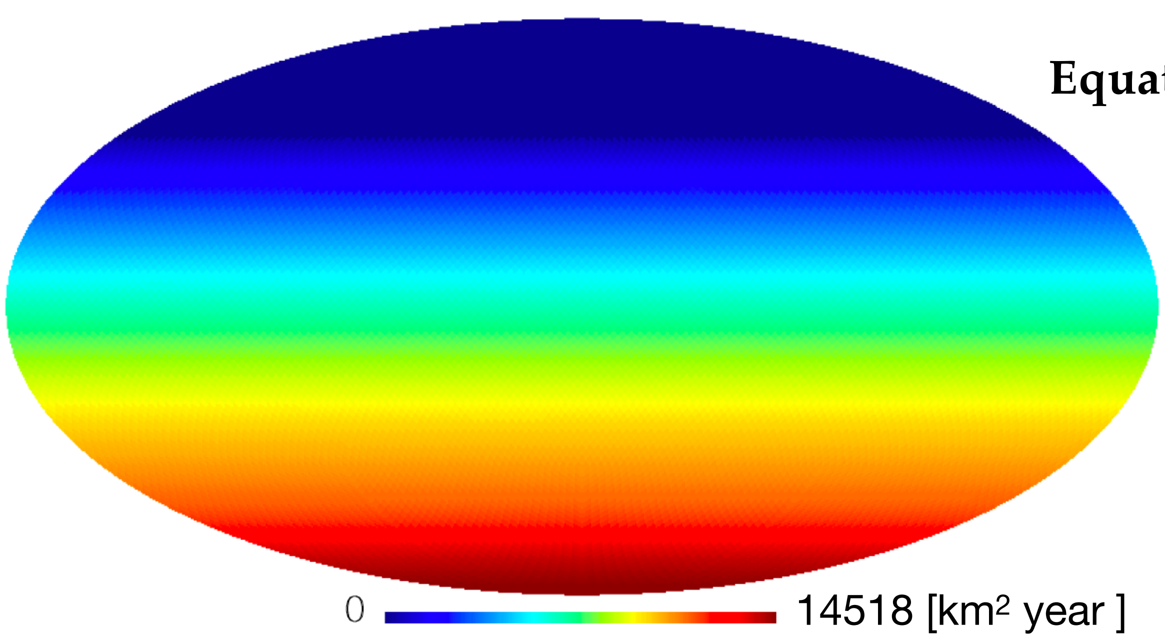


Dipole above 8 EeV (8×10^{18} eV) - dataset

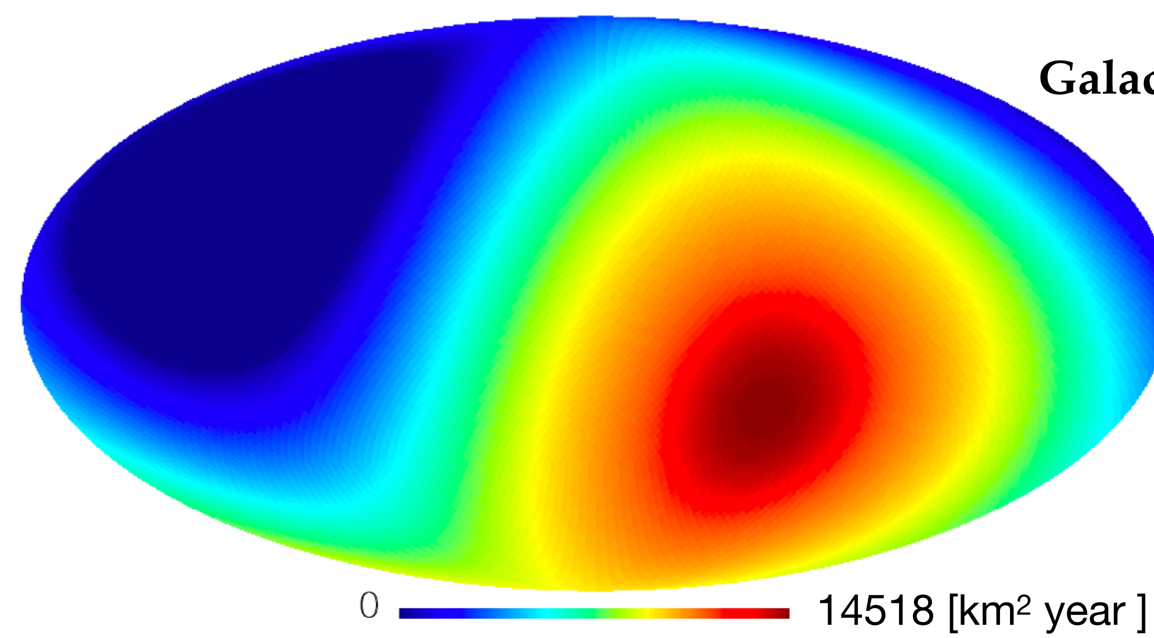
- **Period: 01-01-2004 to 08-31-2016**
- **Additional sky coverage (~30%) provided by inclined events ($60^o<\theta<80^o$)**
- **Enhanced statistics (~19%) with the use of relaxed (but high quality) triggers**
- **Total integrated exposure of 76,800 km² sr year**

Directional exposure

Equatorial



Galactic



Dipole detection

Science 57 (2017) 1266

Analysis of first harmonic modulation in RA and azimuth

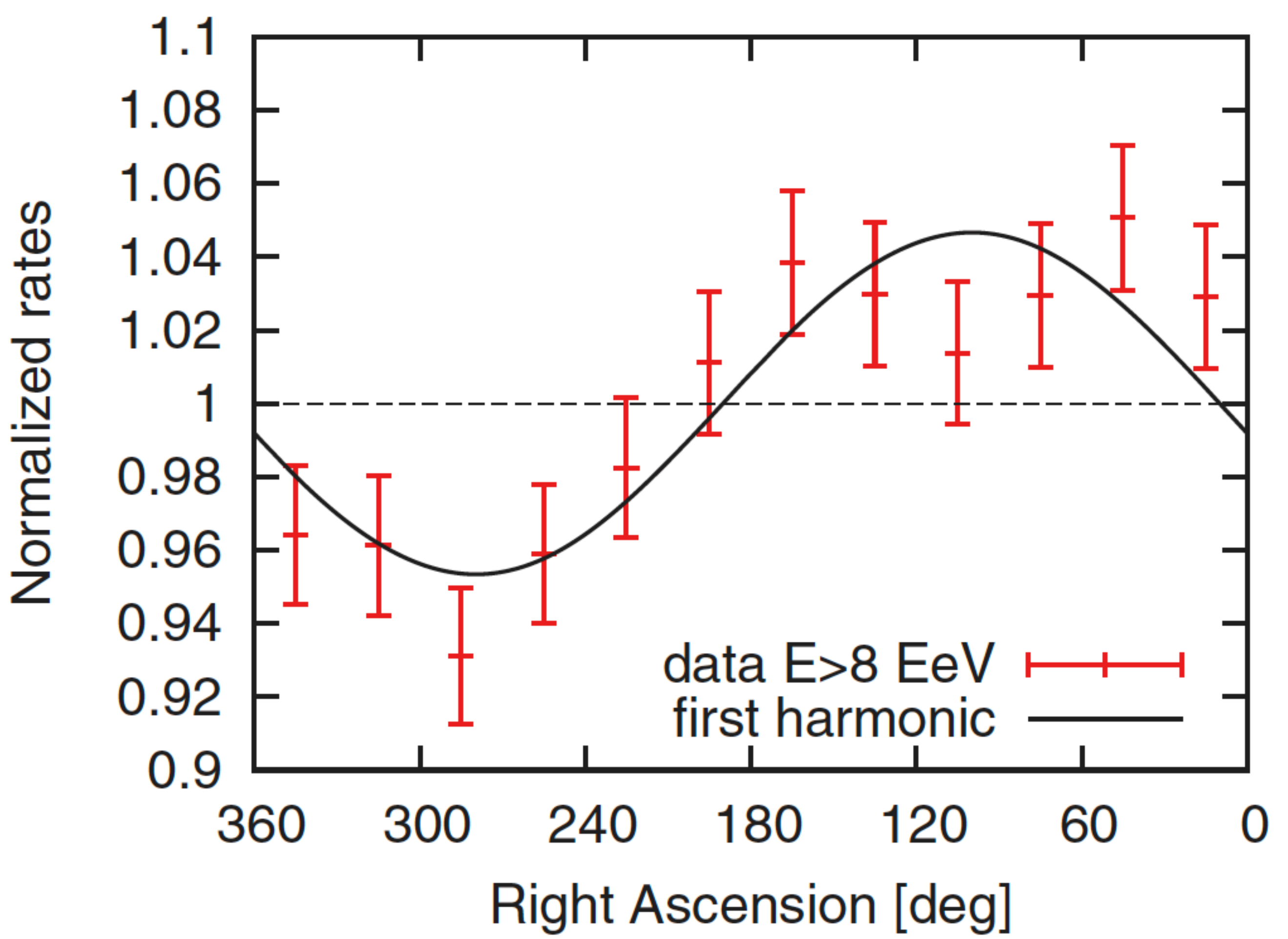
$$a_\alpha = \frac{2}{\mathcal{N}} \sum_{i=1}^{N} w_i \cos \alpha_i$$

Account for non-uniformities of the exposure in RA and a slight tilt of the array

$$b_\alpha = \frac{2}{\mathcal{N}} \sum_{i=1}^{N} w_i \sin \alpha_i$$

Amplitude and phase of modulation

$$r_\alpha = \sqrt{a_\alpha^2 + b_\alpha^2} \qquad \tan \varphi_\alpha = \frac{b_\alpha}{a_\alpha}$$



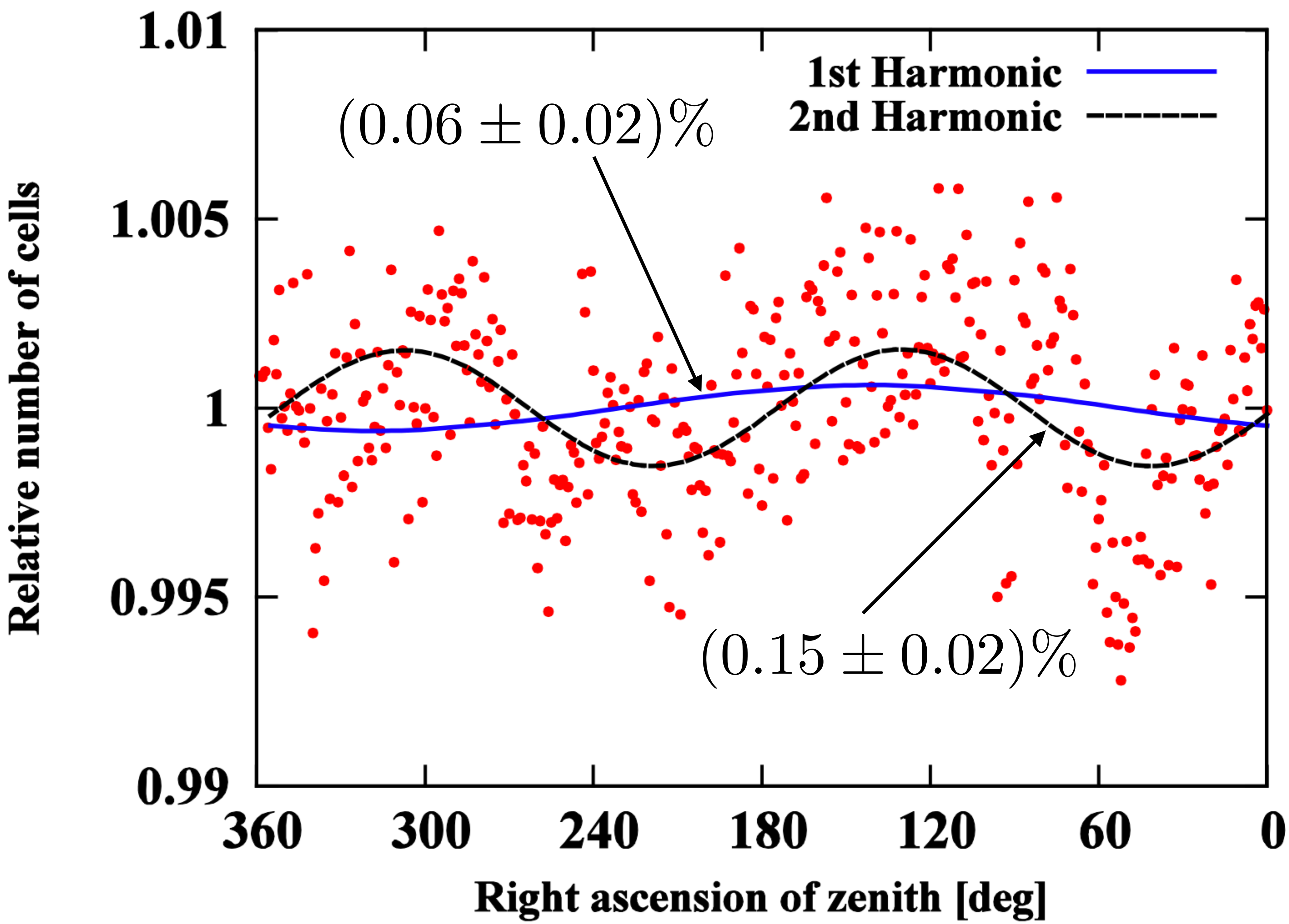
Energy (EeV)	Number of events	Fourier coefficient a_α	Fourier coefficient b_α	Amplitude r_α	Phase φ_α (°)	Probability $P(\geq r_\alpha)$
4 to 8	81,701	0.001 ± 0.005	0.005 ± 0.005	$0.005\,^{+0.006}_{-0.002}$	80 ± 60	0.60
≥8	32,187	−0.008 ± 0.008	0.046 ± 0.008	$0.047\,^{+0.008}_{-0.007}$	100 ± 10	2.6×10^{-8}

pre-trial probability:

$$P(\geq r_\alpha) = \exp\left(-\frac{N r_\alpha^2}{4}\right)$$

- 5.6 σ pre-trial signal
- 5.2 σ post-trial (penalized for scan in 2 energy bins)

Sidereal time modulation of the exposure



Reconstruction of the 3D dipole

Science 57 (2017) 1266

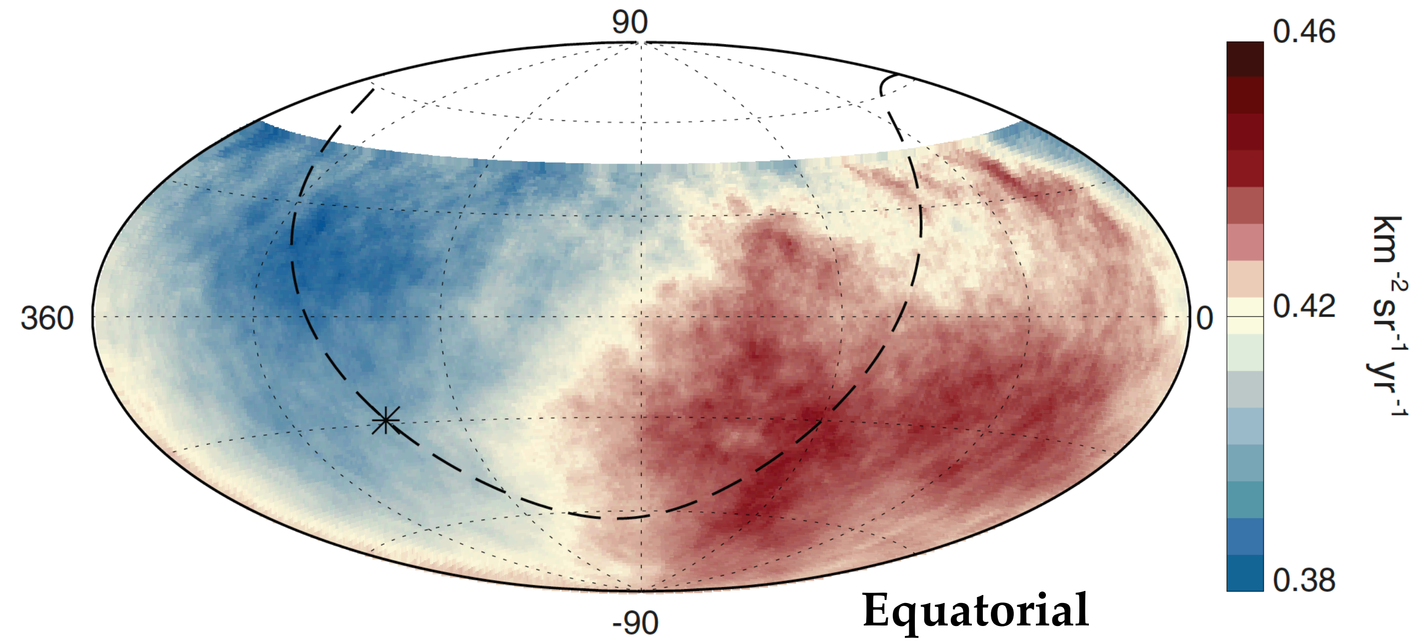
Components parallel and perpendicular to the Earth rotation axis:

$$d_z \approx \frac{b_\varphi}{\cos\,\ell_{\text{obs}}\langle\sin\theta\rangle} \qquad d_\perp \approx \frac{r_\alpha}{\langle\cos\delta\rangle}$$

Right ascension and declination:

$$\alpha_{\text{d}} = \varphi_\alpha \qquad \tan\delta_{\text{d}} = \frac{d_z}{d_\perp}$$

E>8 EeV



Equatorial

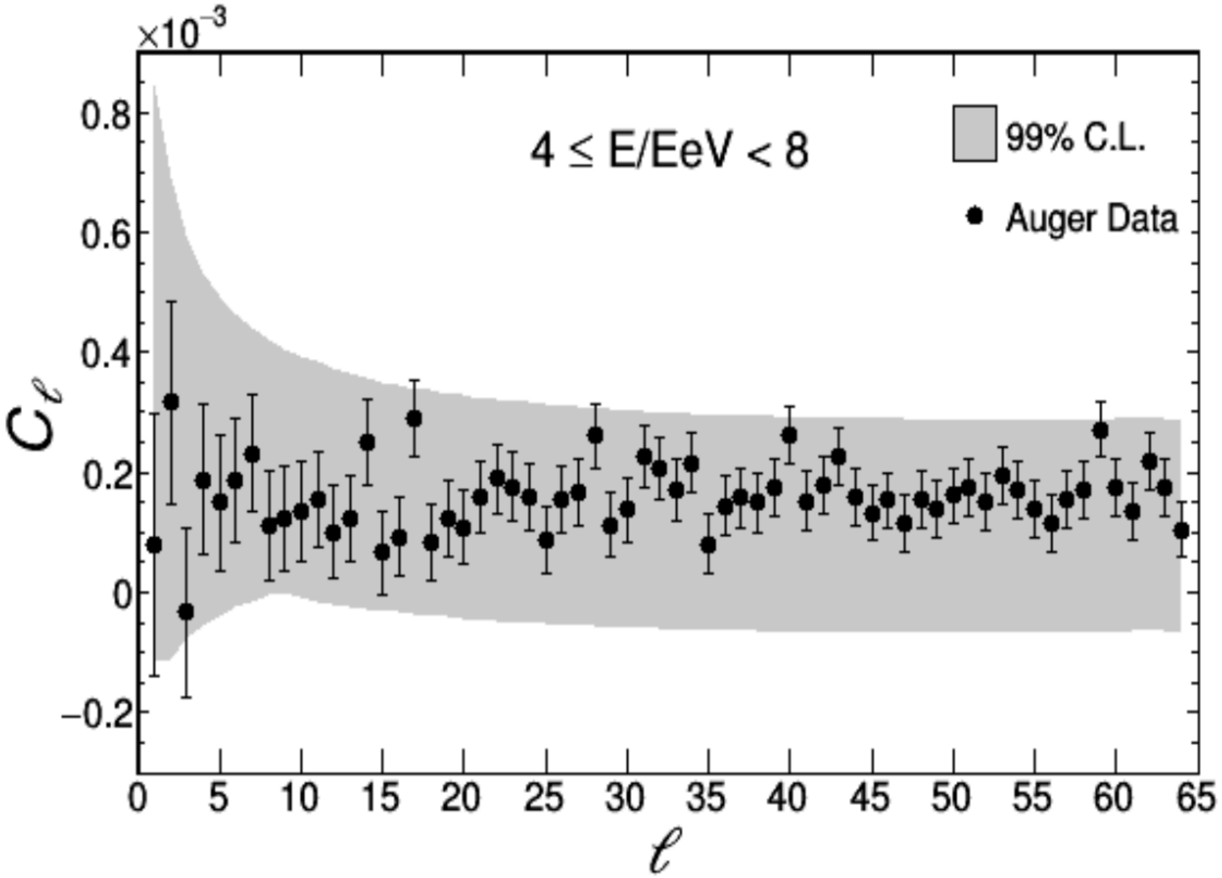
Energy (EeV)	Dipole component d_z	Dipole component $d_\perp$	Dipole amplitude d	Dipole declination δ_d (°)	Dipole right ascension α_d (°)
4 to 8	-0.024 ± 0.009	$0.006^{+0.007}_{-0.003}$	$0.025^{+0.010}_{-0.007}$	-75^{+17}_{-8}	80 ± 60
≥8	-0.026 ± 0.015	$0.060^{+0.011}_{-0.010}$	$0.065^{+0.013}_{-0.009}$	-24^{+12}_{-13}	100 ± 10

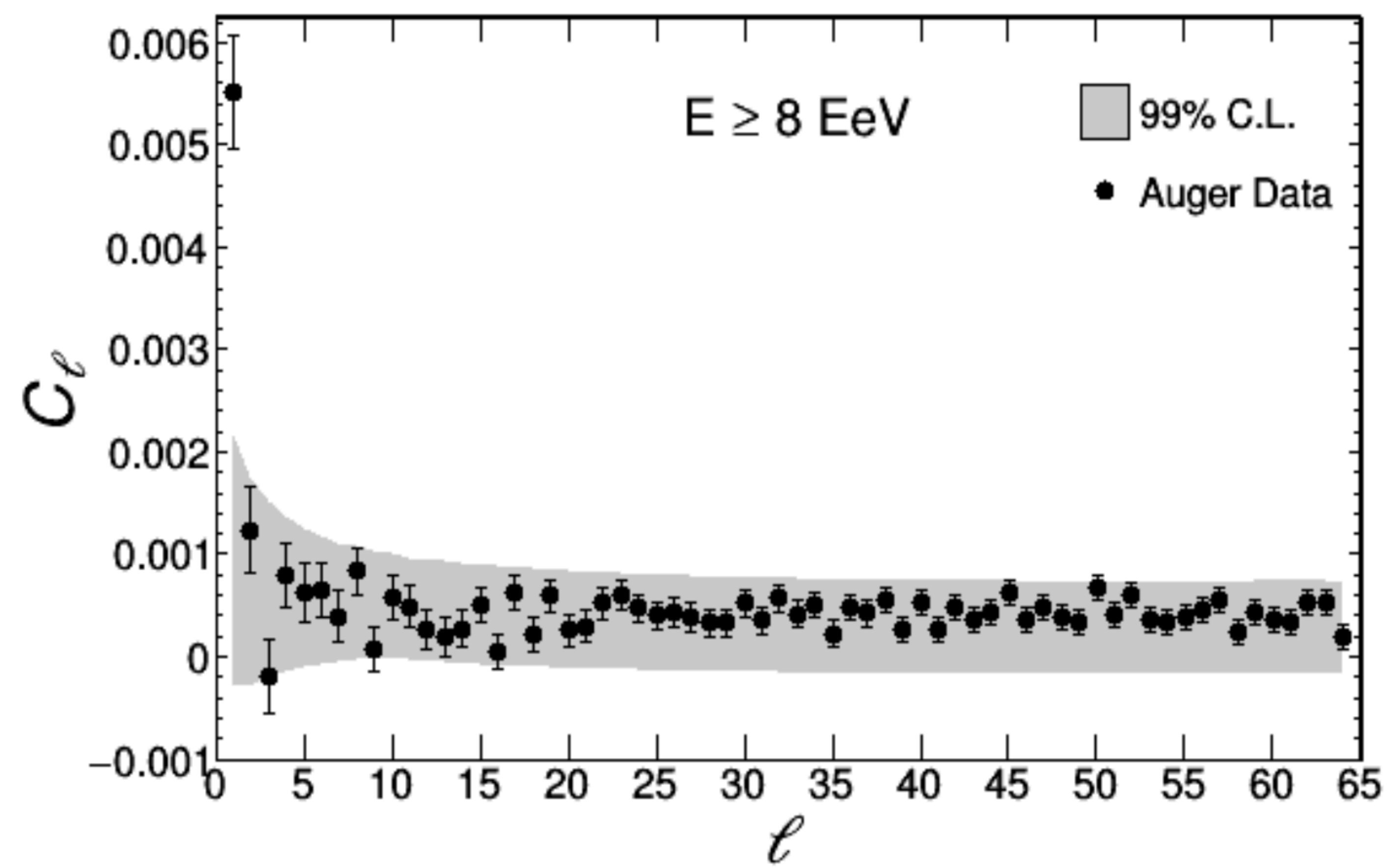
- **Reconstruction assumes the dipole is the dominant component of the anisotropy**
- **Analysis of the power spectrum gives support to this hypothesis**

Power spectrum

JCAP 06 (2017) 026

- **Further evidence of the dominance of the dipole coming from the power spectrum**

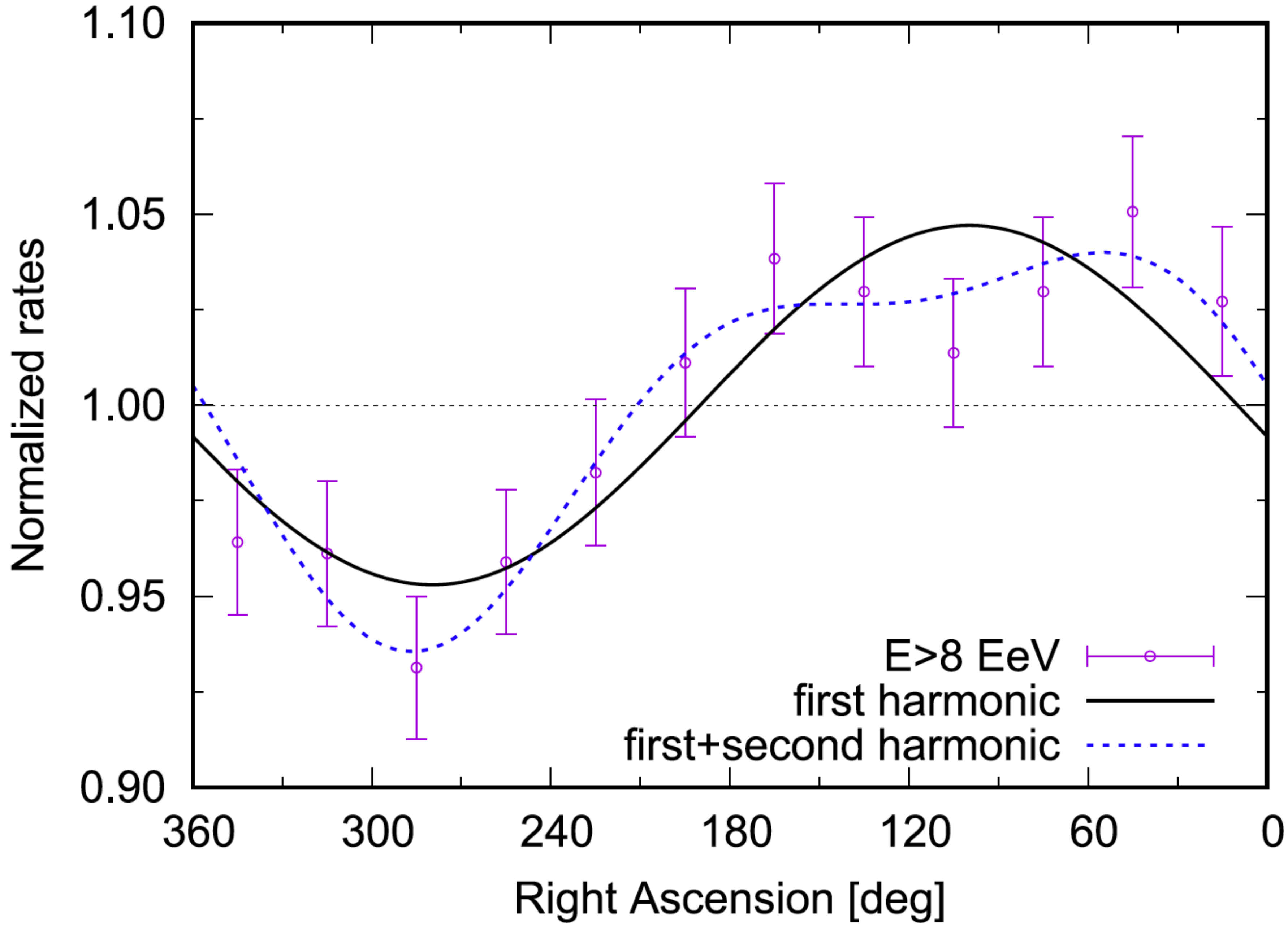




- **Slightly different data sample:**
  - **01-01-2004 to 12-31-2013**
  - **Tight fiducial quality trigger**

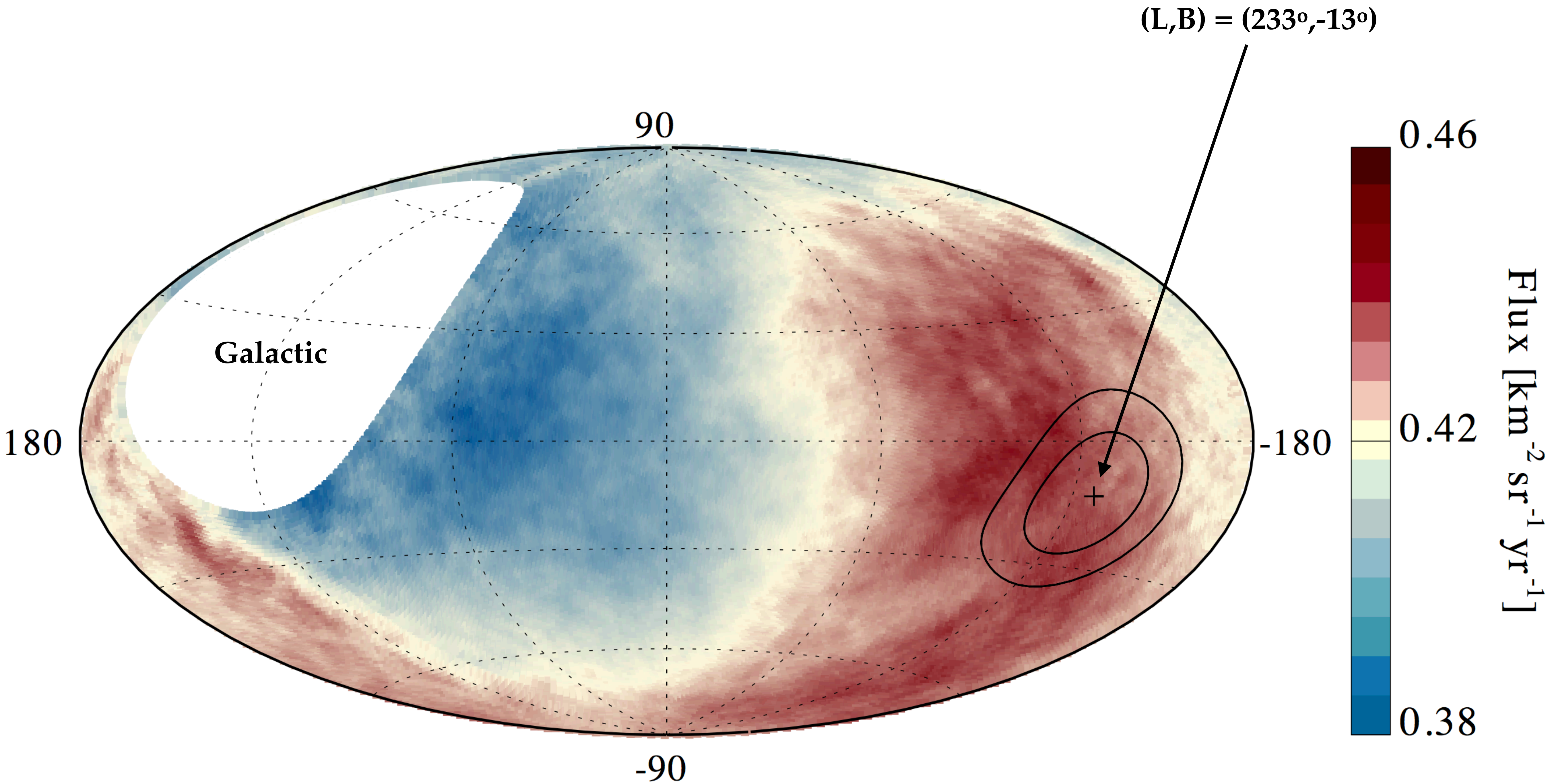
$$C_\ell = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2$$

Sub-dominance of quadrupolar anisotropy



Energy (EeV)	Events	k	a_k^α	b_k^α	r_k^α	$\varphi_k^\alpha(^\circ)$	$P(\geqslant r_k^\alpha)$
4–8	81,701	1	0.001 ± 0.005	0.005 ± 0.005	0.005	80 ± 60	0.60
		2	-0.001 ± 0.005	0.001 ± 0.005	0.002	70 ± 80	0.94
$\geqslant 8$	32,187	1	-0.008 ± 0.008	0.046 ± 0.008	0.047	100 ± 10	2.6×10^{-8}
		2	0.013 ± 0.008	0.012 ± 0.008	0.018	21 ± 12	0.065

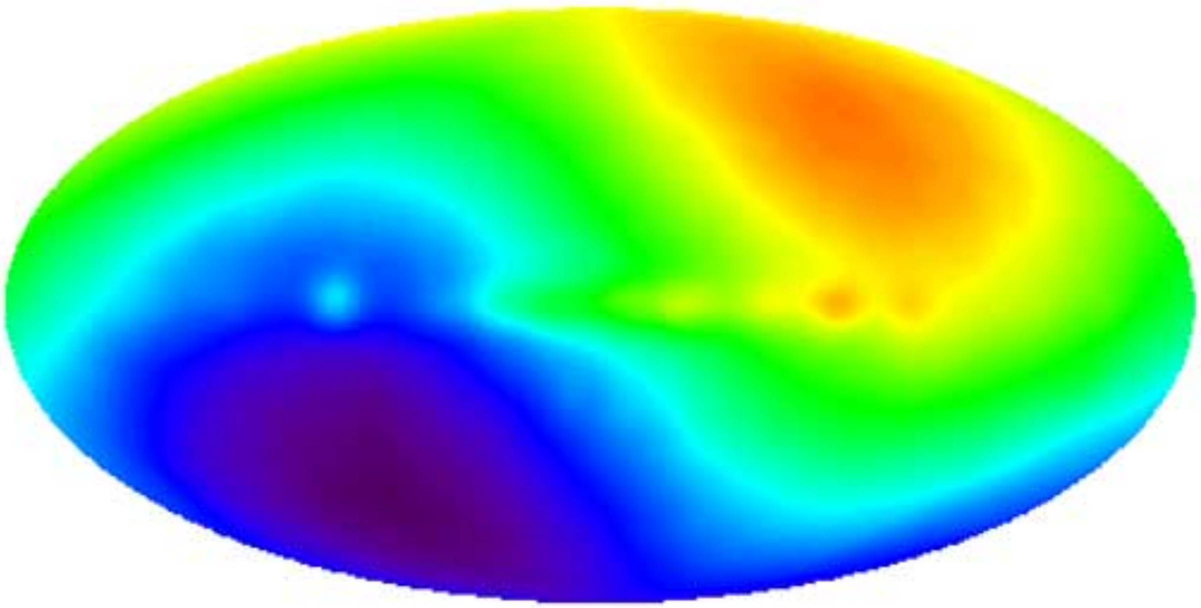
Final sky map: galactic coordinates



- Broad 45º top-hat beam applied
- Dipole maximum is about 125º away from the galactic center

Cosmological Compton-Getting effect

COBE CMB dipole: $(\ell, b) = (264^\circ, 48^\circ)$



$$v_\odot = 369.0 \pm 2.5 \text{ km s}^{-1}$$

order 10^{-3} effect

- **Assumption: sources of UHECRs are distributed at cosmological distances**
- **Movement of the solar system barycenter in the CMB rest frame should also induce a dipolar anisotropy in the flux of UHECR aligned with the CMB dipole**

$$J'(E') \simeq J(E) \left[1 - \frac{\mathbf{u} \cdot \mathbf{p}}{p} \left(2 - \frac{\mathrm{d} \ln J}{\mathrm{d} \ln E'}\right)\right]$$

Spectra in the CMB (unprimed) and observer (primed) frames

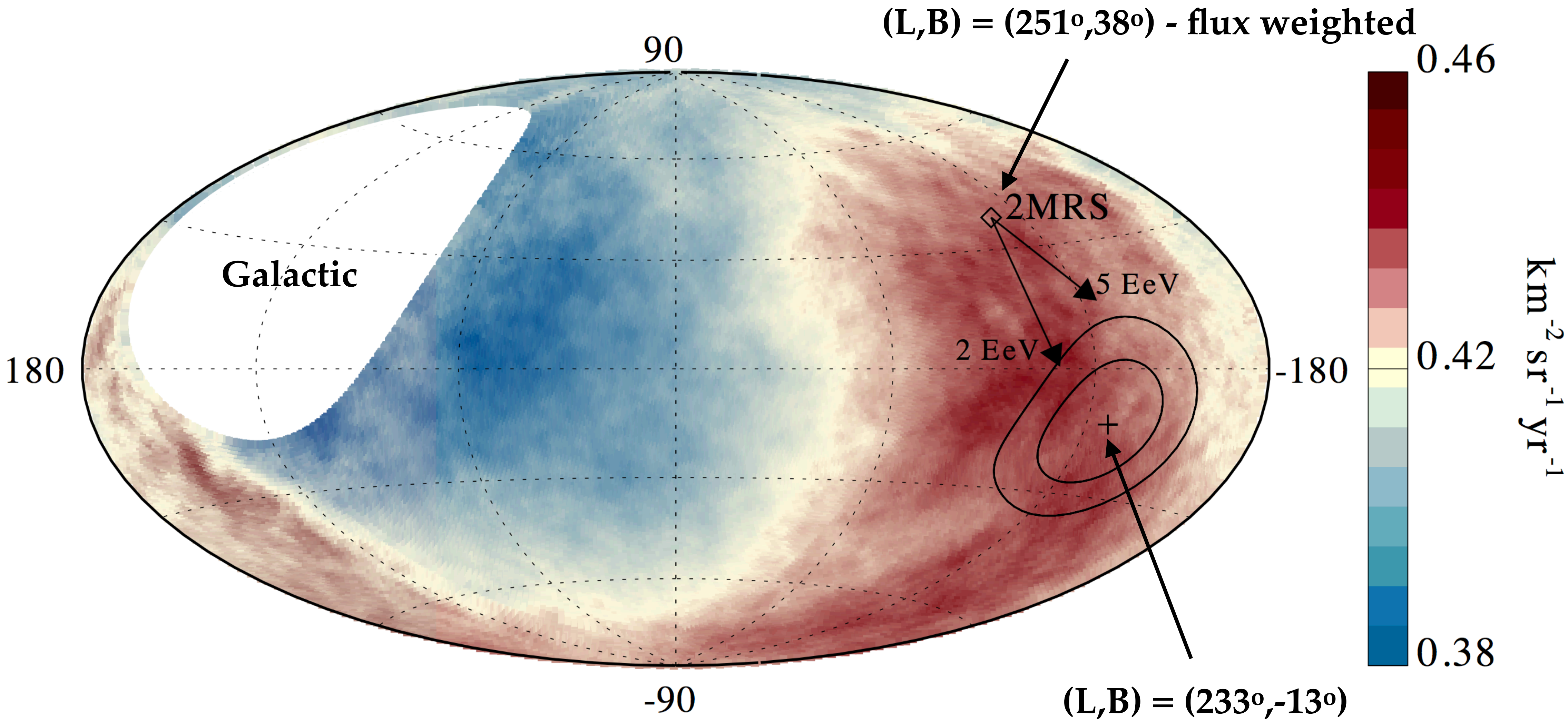
- **Amplitude is below 1% for a spectrum $E^{-2.7}$ above the ankle:**

$$A_{CCG} = \frac{J_{max} - J_{min}}{J_{max} + J_{min}} = \left(2 - \frac{\mathrm{d} \ln J}{\mathrm{d} \ln E'}\right) \simeq 0.6\%$$

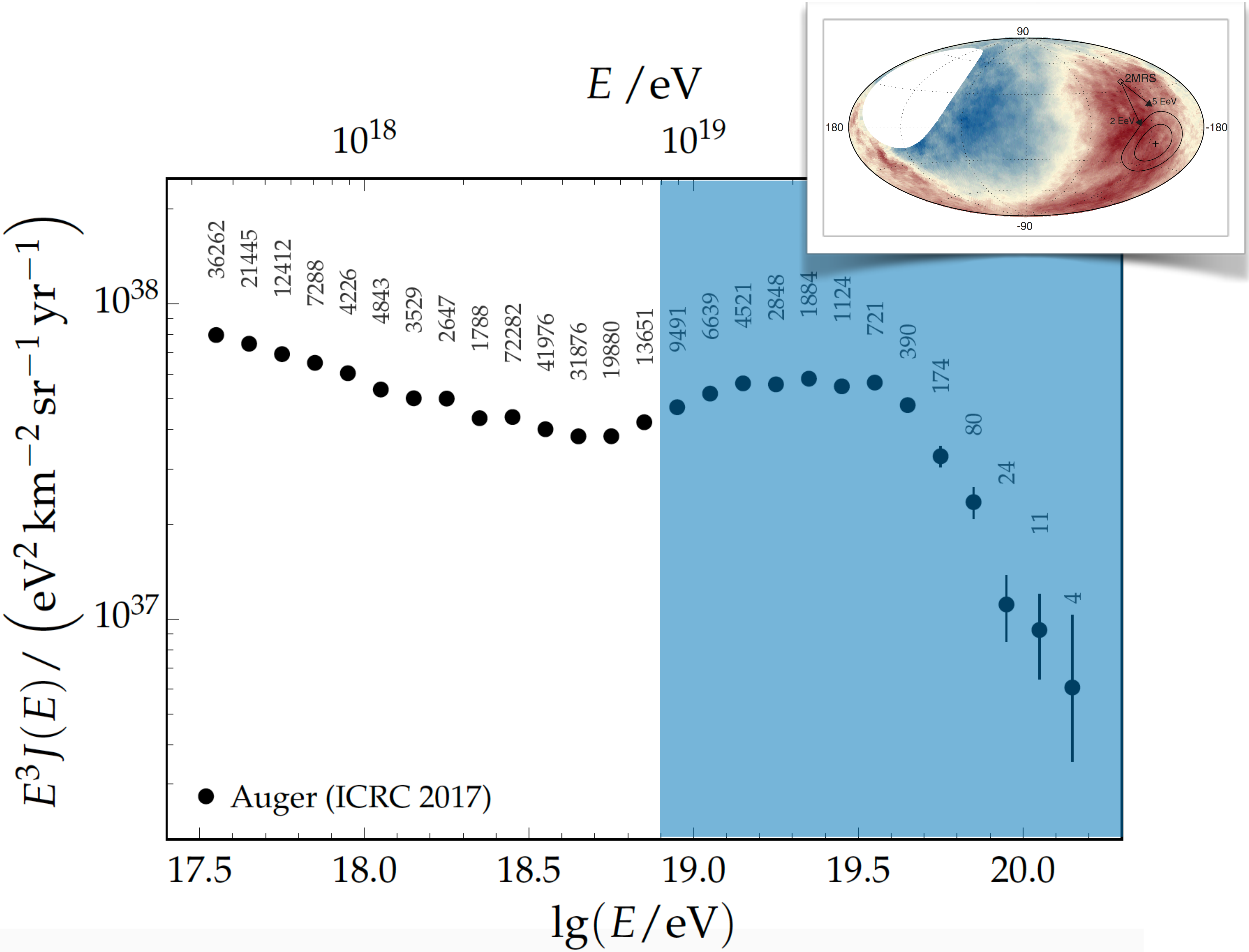
- **3-sigma detection would need ~10^6 events**

Compton & Getting, Phys. Rev. 47 (1935) 817
Phys. Lett. B 640 (2006) 225–229

Is it consistent with local matter distribution and mag. fields?

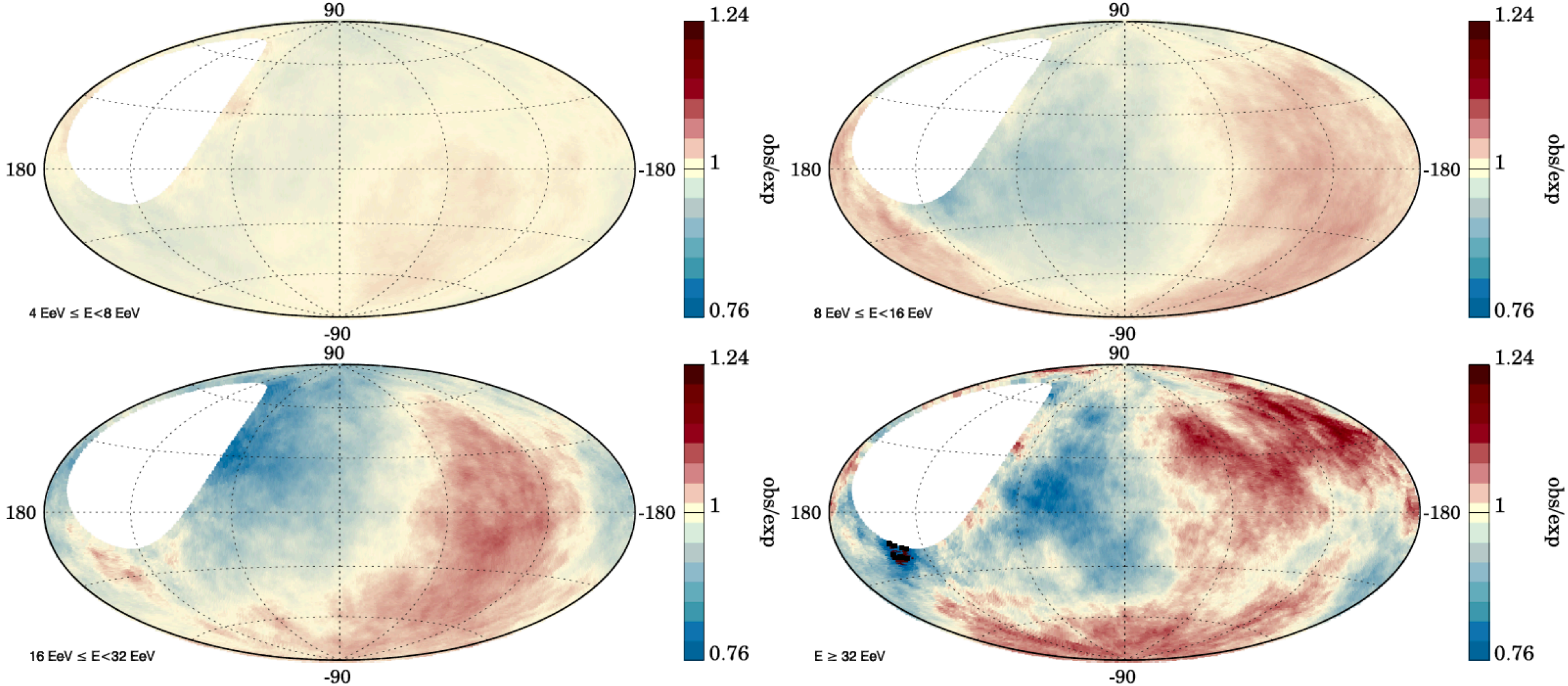


- **Two rigidities shown: E/Z = 2, 5 EeV representing the typical Z values (1.7-5) inferred from X_{max} at 10 EeV**
- **Typically, up to 5-20% (around 10 EeV) dipole amplitudes can be obtained from local inhomogeneities and deflection in magnetic fields depending on CR composition**


E / eV
10^{18}
10^{19}
10^{38}
10^{37}
$E^3 J(E) / (\mathrm{eV^2\,km^{-2}\,sr^{-1}\,yr^{-1}})$
36262
21445
12412
7288
4226
4843
3529
2647
1788
72282
41976
31876
19880
13651
9491
6639
4521
2848
1884
1124
721
390
174
80
24
11
4
Auger (ICRC 2017)
17.5
18.0
18.5
19.0
19.5
20.0
lg(E/eV)
90
-90
180
-180
2MRS
5 EeV
2 EeV

Energy evolution

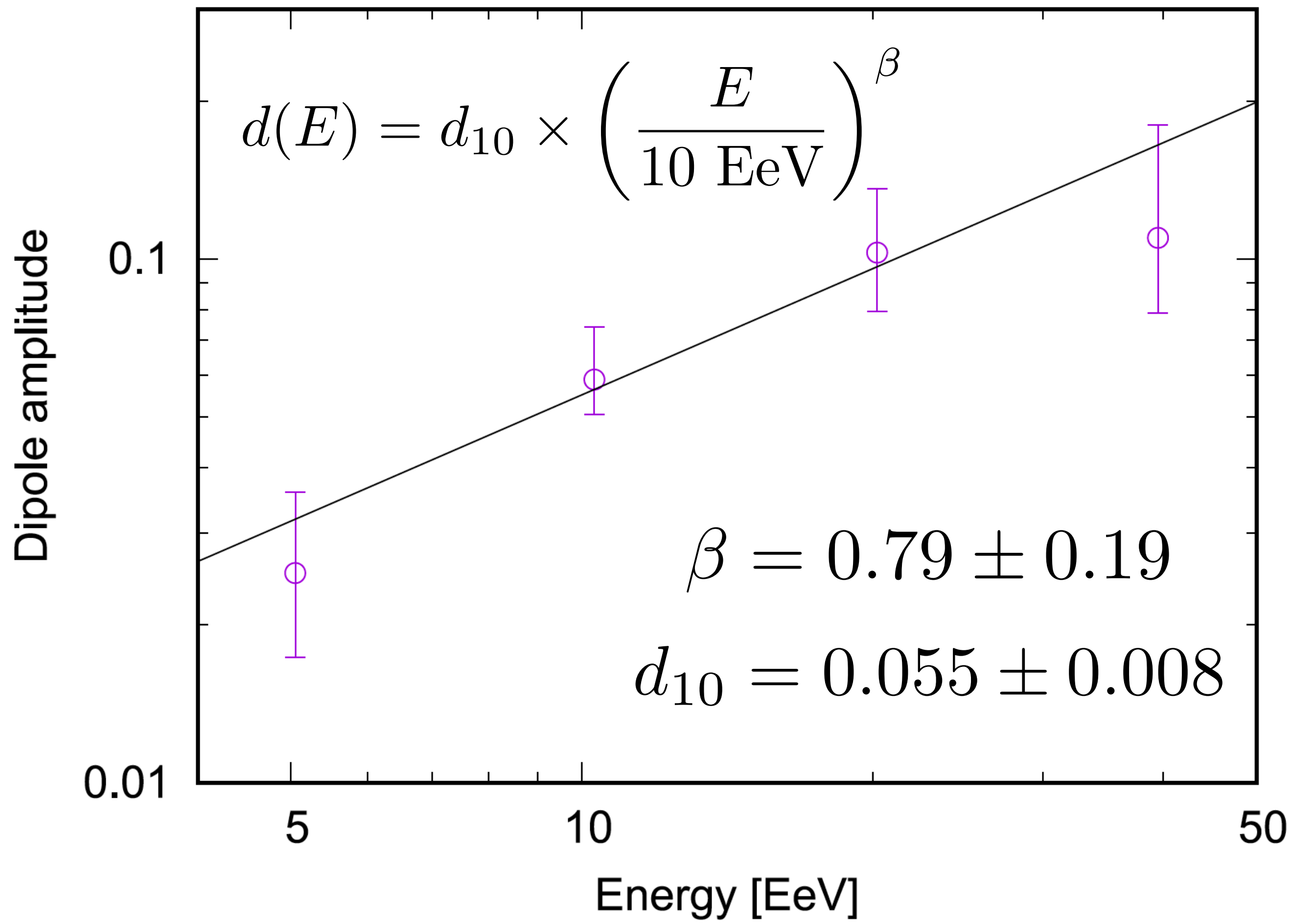
ApJ 868 (2018) 4



Energy (EeV)	Events	a_1^α	b_1^α	r_1^α	φ_1^α (deg)	$P(\geqslant r_1^\alpha)$
8–16	24,070	-0.011 ± 0.009	0.044 ± 0.009	0.046	104 ± 11	3.7×10^{-6}
16–32	6604	0.007 ± 0.017	0.050 ± 0.017	0.051	82 ± 20	0.014
$\geqslant$32	1513	-0.03 ± 0.04	0.05 ± 0.04	0.06	115 ± 35	0.26

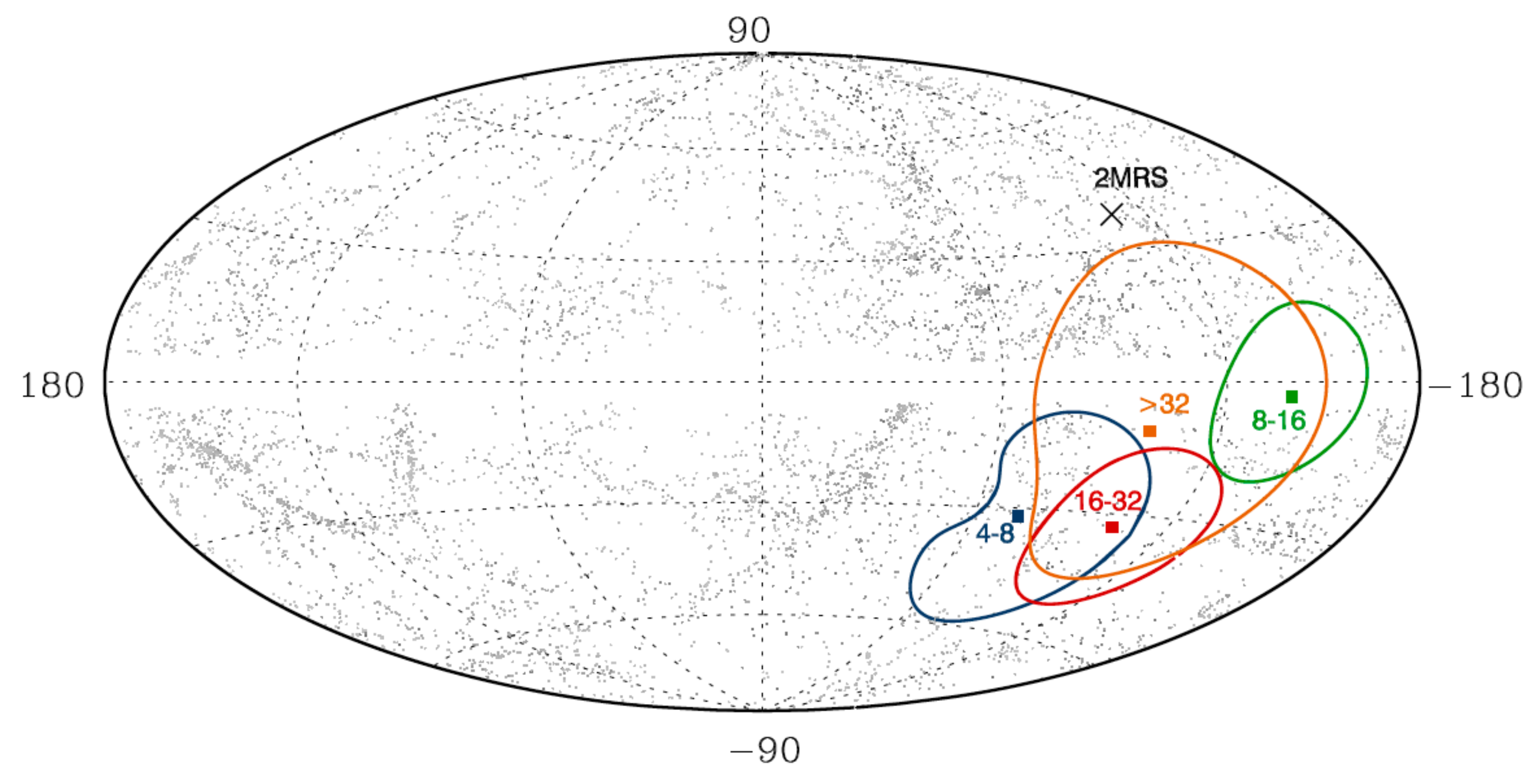
Energy evolution

ApJ 868 (2018) 4



Energy independent amplitude disfavored at 3.7σ level

No trend with energy seem for the dipole direction with current uncertainties



Summary

- **Anisotropy searches performed at all angular scales: small, intermediate and large**
- **Observation of a dipolar large scale pattern at more than 5σ level above 8 EeV**
- **Direction of the dipole (~125^o away from GC) is better explained if the bulk of these UHECRs are extragalactic in origin**
- **No statistically significant sign of anisotropy seen so far at lower energies (around and below the ankle)**
- **Above 8 EeV, amplitude increases with energy, while direction seems to be fairly stable.**
- **Quadrupole is sub-dominant and not statistically significant with current statistics**