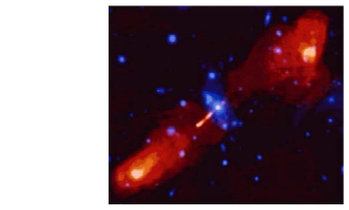
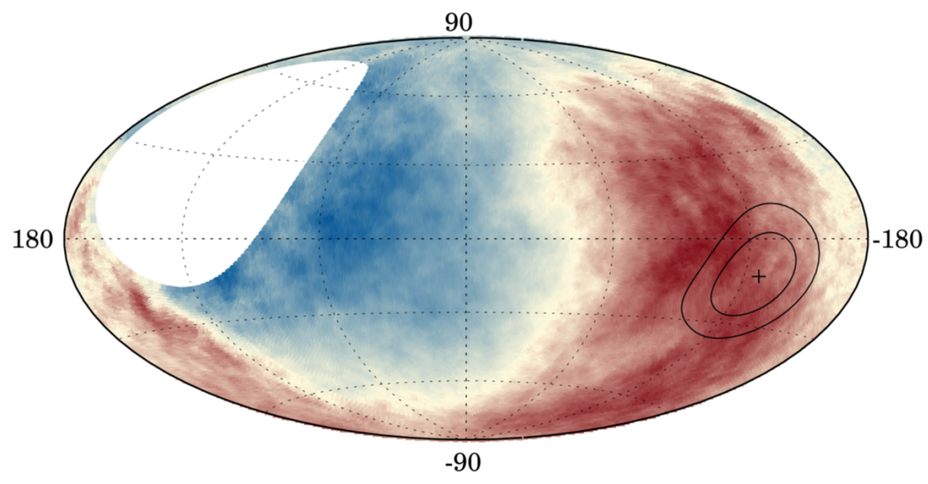
Large-scale Anisotropy in the Arrival Directions of Ultra-High Energy Cosmic Rays with the Pierre Auger Observatory

Observation of a large-scale anisotropy in the arrival directions of cosmic rays above 8EeV, **Science 22-Sep-2017**

Large-scale cosmic-ray anisotropies above 4 EeV measured by the Pierre Auger Observatory, **arXiv:1808.03579**



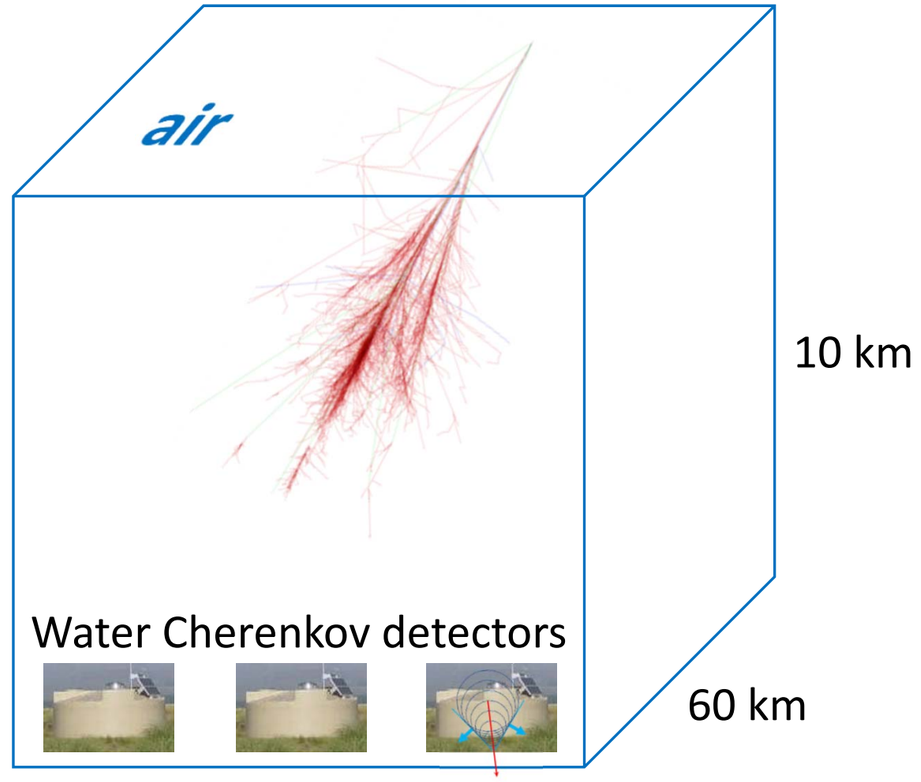


GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

Martin Erdmann for the Pierre Auger Collaboration, Berlin 28-Aug-2018

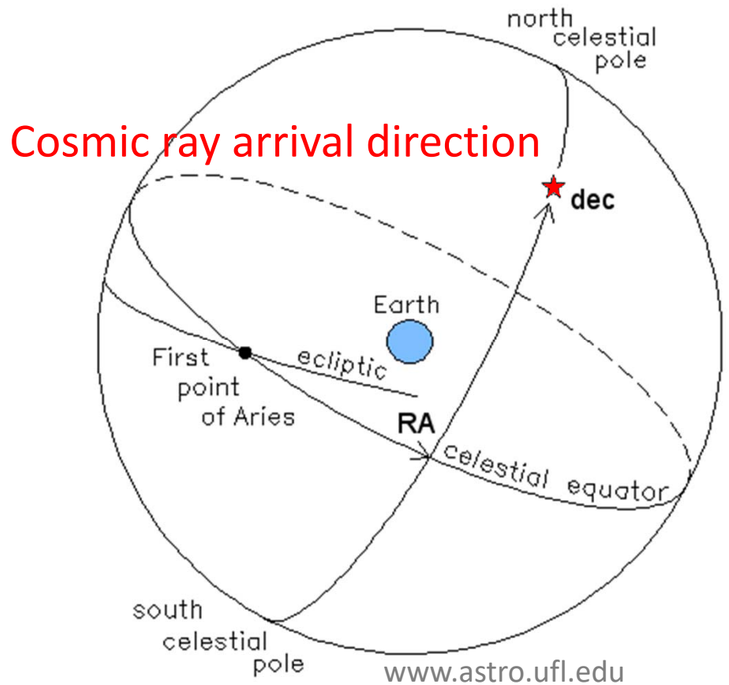
World‘s largest Calorimeter

Pierre Auger Observatory



Observation of a large-scale anisotropy in the arrival directions of cosmic rays above 8EeV, **Science 22-Sep-2017**, Vol. 357, Iss. 6357, p. 1266

Dipolar anisotropy in arrival directions

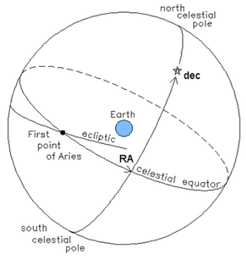


www.astro.ufl.edu

dec = declination

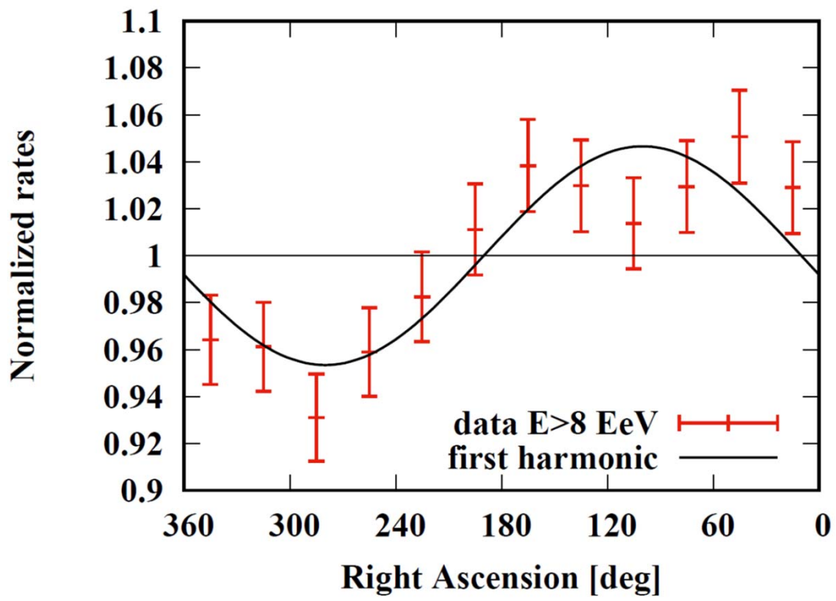
RA = right ascension

Departure from isotropic arrival [E>8EeV]

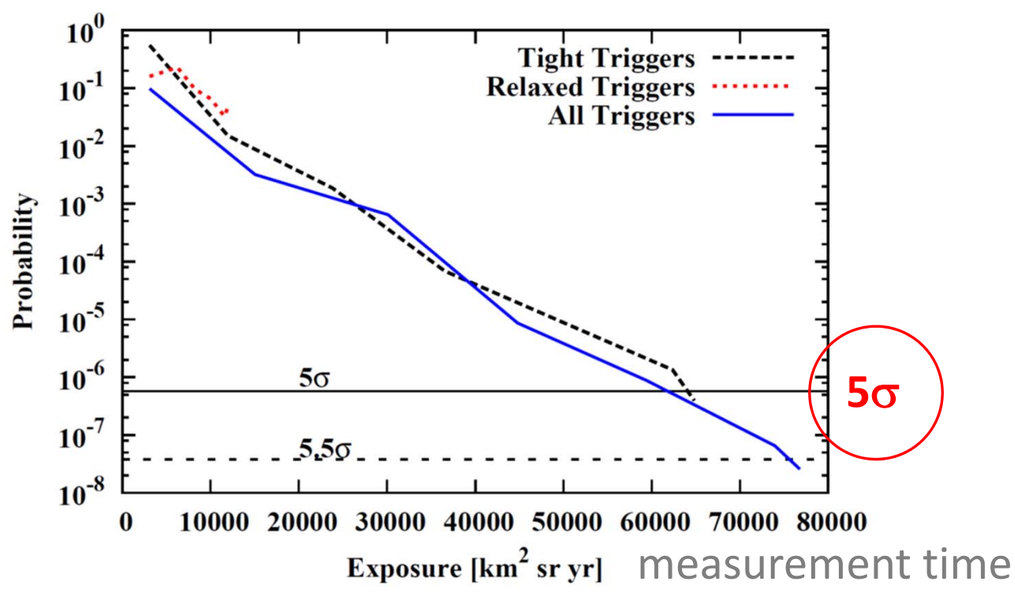


First-harmonic Fourier components

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



Number of events	Fourier coefficient a_α	Fourier coefficient b_α	Amplitude r_α	Phase φ_α [°]
32,187	-0.008 ± 0.008	0.046 ± 0.008	$0.047^{+0.008}_{-0.007}$	100 ± 10



measurement time

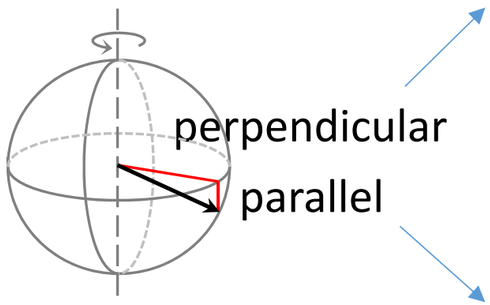
First clear anisotropy signal

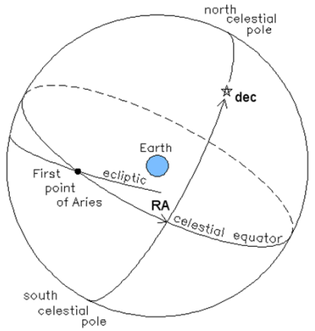
Reconstructing the 3dim. Dipole

Combine 2 first-harmonic Fourier analyses

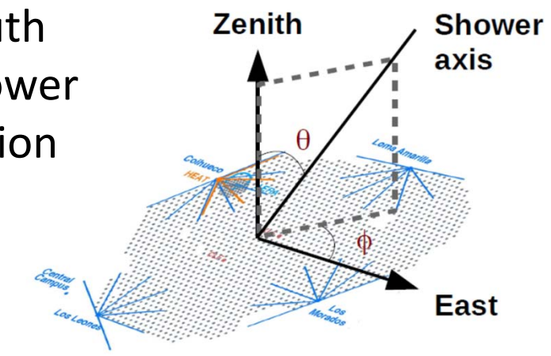
Dipole components

Right ascension

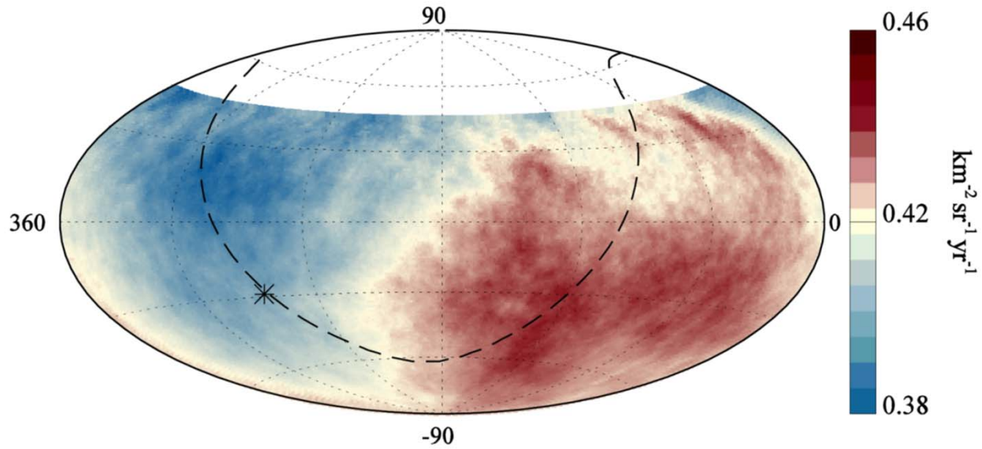




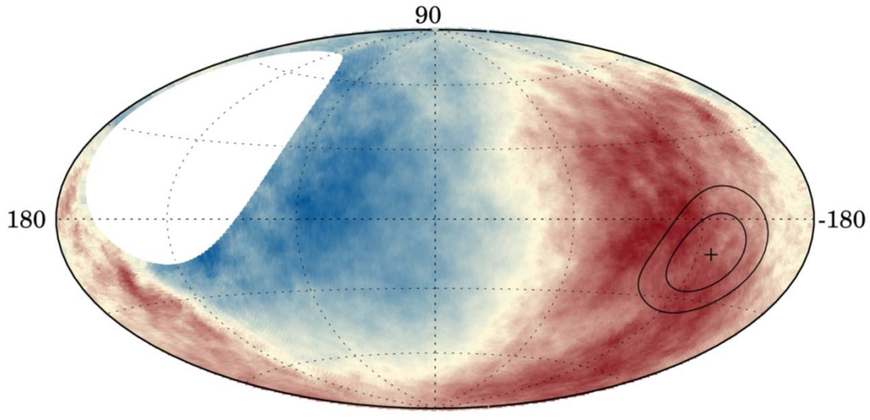
Azimuth of shower direction



Equatorial coordinates

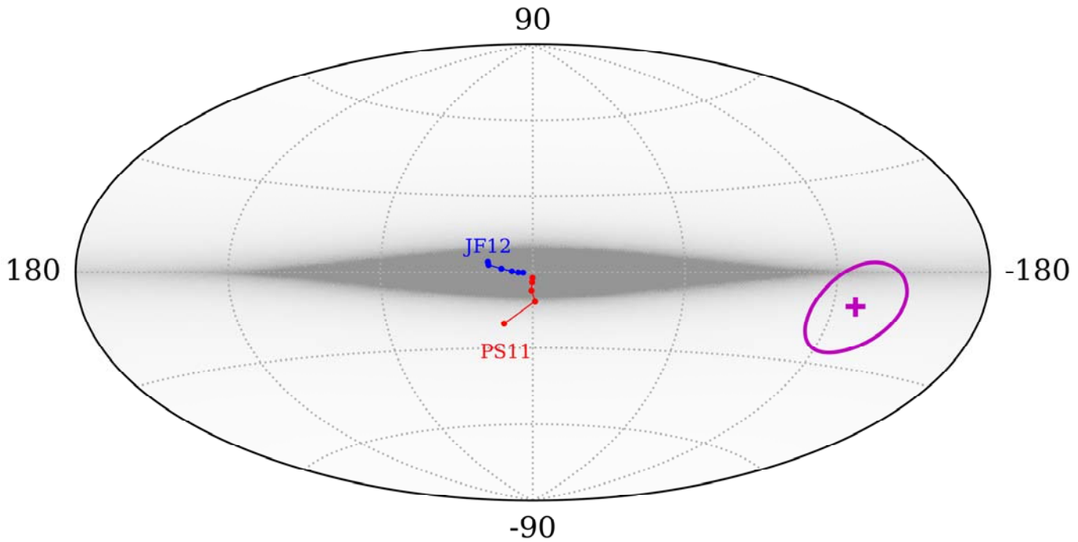


Galactic coordinates



Amplitude 6.5 (+1.3/-0.9) %

Galactic origin?



Model

- Sources continuous in Galaxy, density as luminous matter (gray)
- Cosmic rays: various rigidities ***R=E/Z*** propagated through Galactic magnetic field (JF12, PT11)
- Flux weight by integrating matter density along path through Galaxy

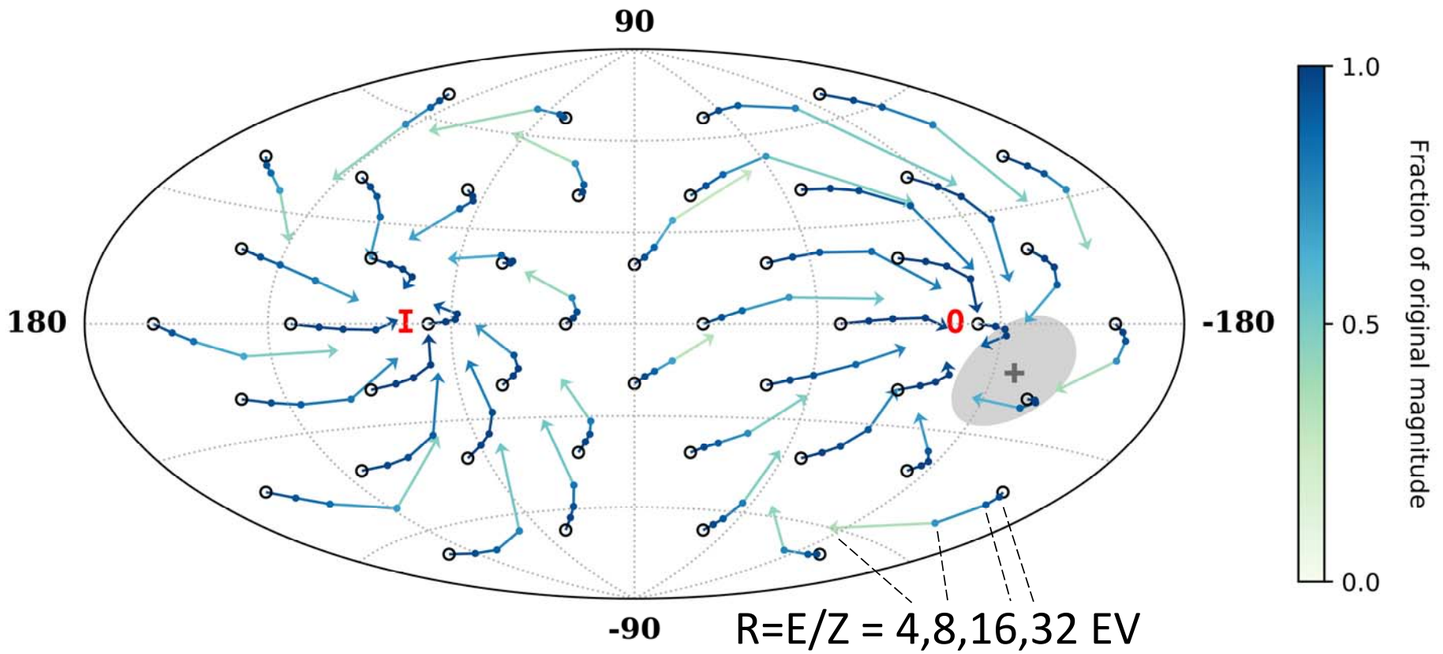
Messages

- Dipole *directions* close to Galactic center
- Dipole *amplitudes* too large for Galactic cosmic-ray origins (>0.8)

Unlikely to arise from Galactic component

arXiv:1808.03579

Extragalactic origin: Galactic Magnetic Field



Model effect of Galactic Magnetic Field

- Directional change of extragalactic dipole
- Line color: suppression of dipole amplitude
- Arrows start at extragalactic directions → reconstruct on Earth for different CR rigidities

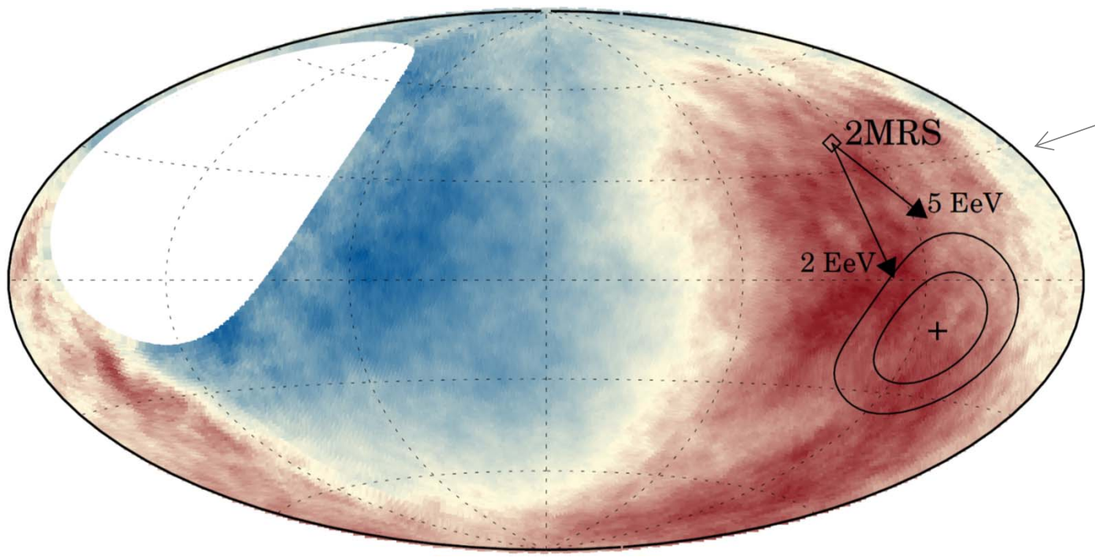
Messages

- mild changes: dipole direction & amplitude
- extragalactic dipoles at positive Galactic longitudes align closer to inner spiral arm, opposite half to outer spiral arm

Dipole most likely of extragalactic origin

Examples extragalactic origins

arXiv:1808.03579



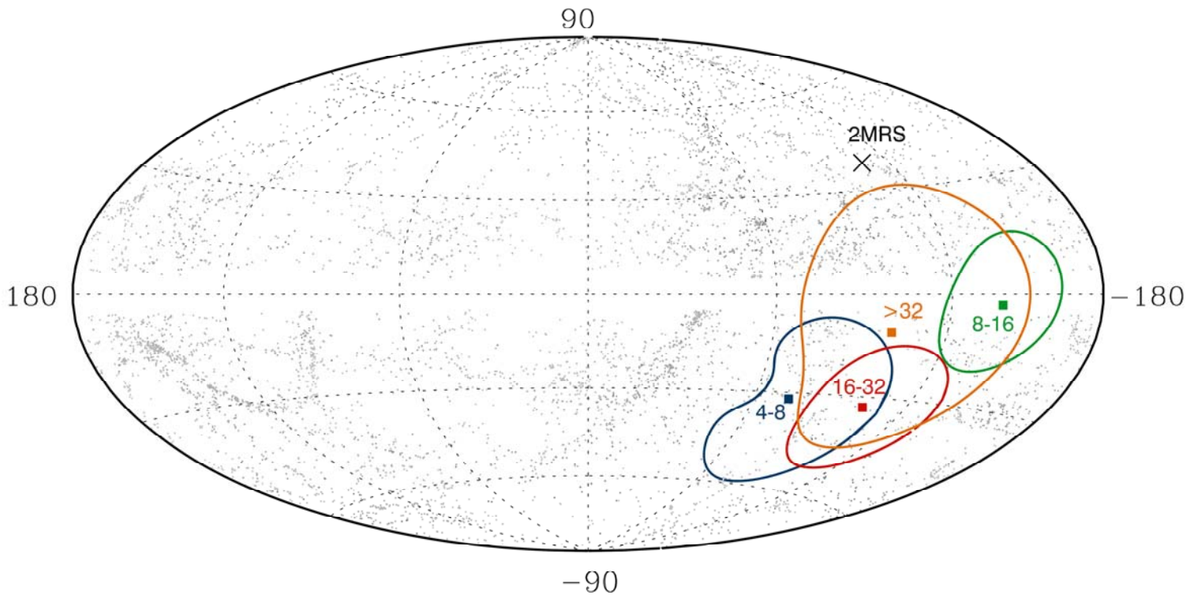
example: 2MRS (<100 Mpc) flux weighted

dipole plus galactic magnetic field deflections

Also possible: diffusive propagation from powerful sources in a few nearby galaxies

arXiv:1808.03579

Energy dependence of dipole direction



Measurements

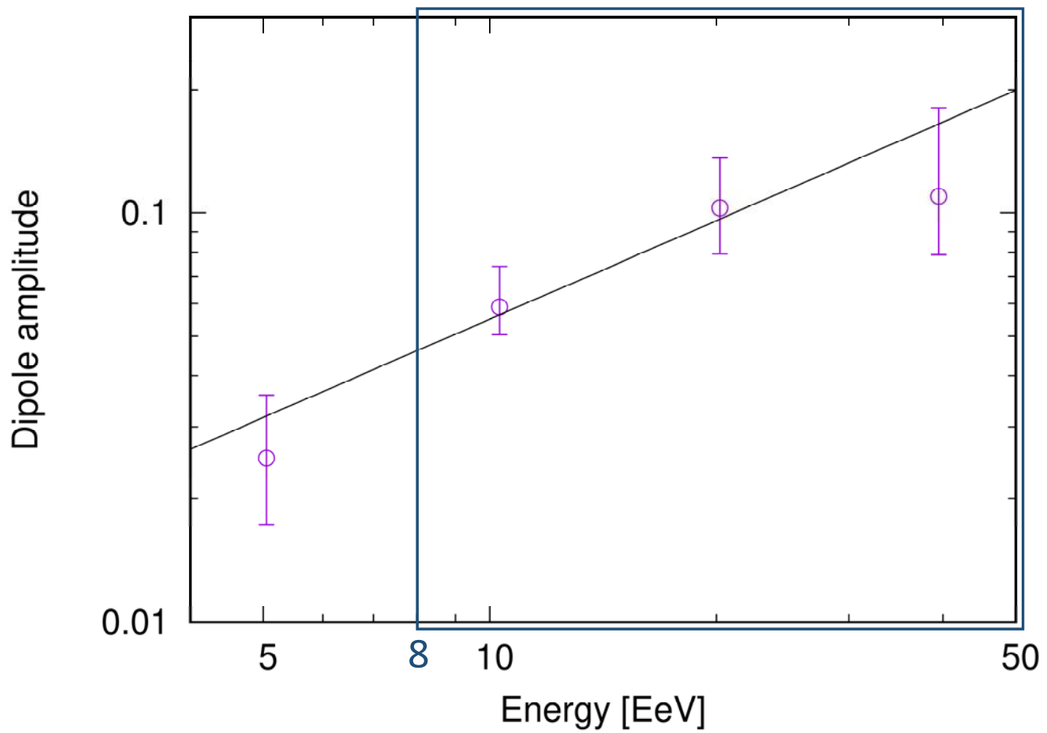
- Direction of dipole for different energy bins
- Gray symbols: 2MRS galaxy catalog (<100 Mpc)
- Cross symbol: direction of flux-weighted 2MRS dipole

Interpretation

- no clear trend in change of dipole direction as function of energy

arXiv:1808.03579

Energy dependence of dipole amplitude



Measurement

- Growing amplitude of dipole with increasing energy

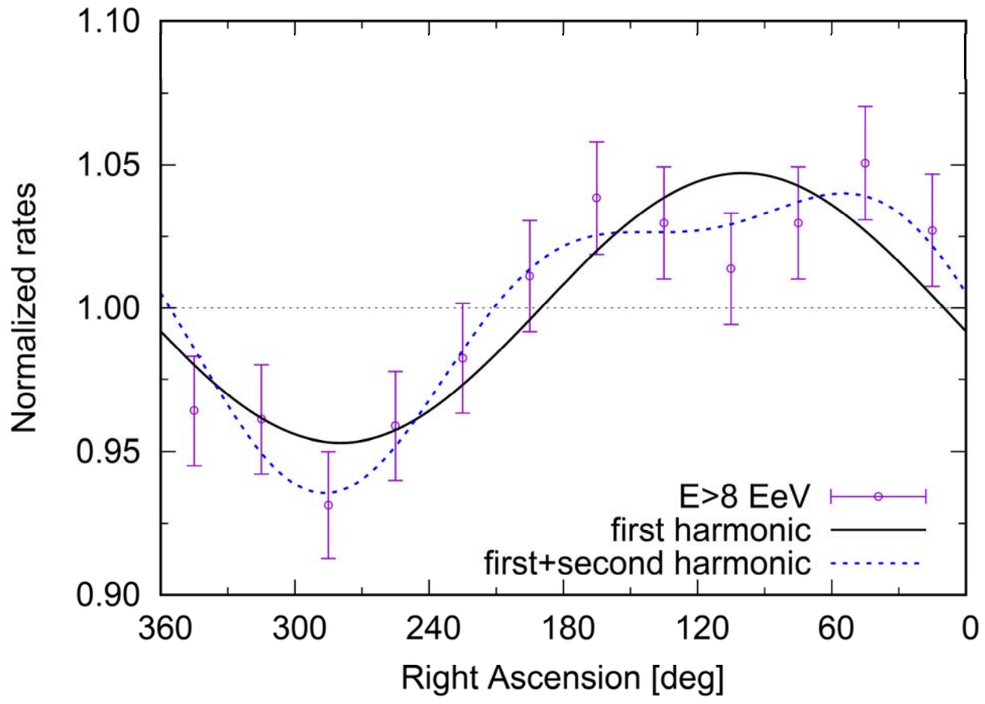
Interpretation

- Smaller deflections of cosmic rays at higher rigidities
- Increased attenuation for cosmic rays from distant sources, increased relative flux from nearby sources

→ more anisotropic

arXiv:1808.03579

Combine Dipolar & Quadrupol contributions?



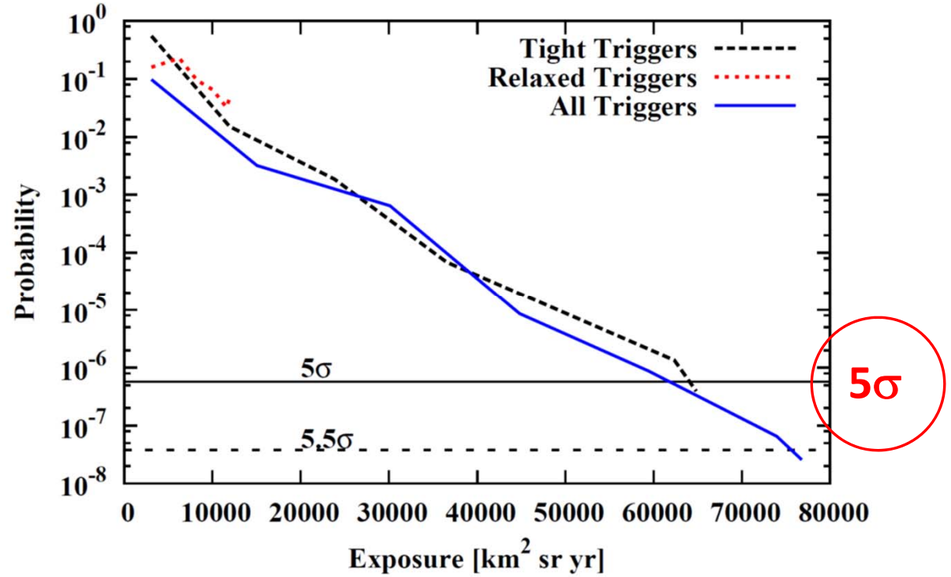
Observations

- Quadrupolar components not statistically significant
- Dipolar components consistent with dipole-only results

Conclusion

Observation

- Dipolar anisotropy with > 5 σ significance !
- Dipole amplitude increases with cosmic-ray energy



Interpretation

- Unlikely of Galactic origin
- Easily explained by extragalactic origin
- Not yet clear: dipolar anisotropy may
  - arise from diffusive propagation from powerful sources in few nearby galaxies
  - reflect known anisotropy in distribution of galaxies within few hundred Mpc

Amplitude & Phase

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

$$r_\alpha = \sqrt{a_\alpha^2 + b_\alpha^2}$$

$$\tan\varphi_\alpha = \frac{b_\alpha}{a_\alpha}$$