Large-scale anisotropies above 0.03 EeV measured by the Pierre Auger Observatory

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PIERRE AUGER OBSERVATORY

THE PIERRE AUGER OBSERVATORY

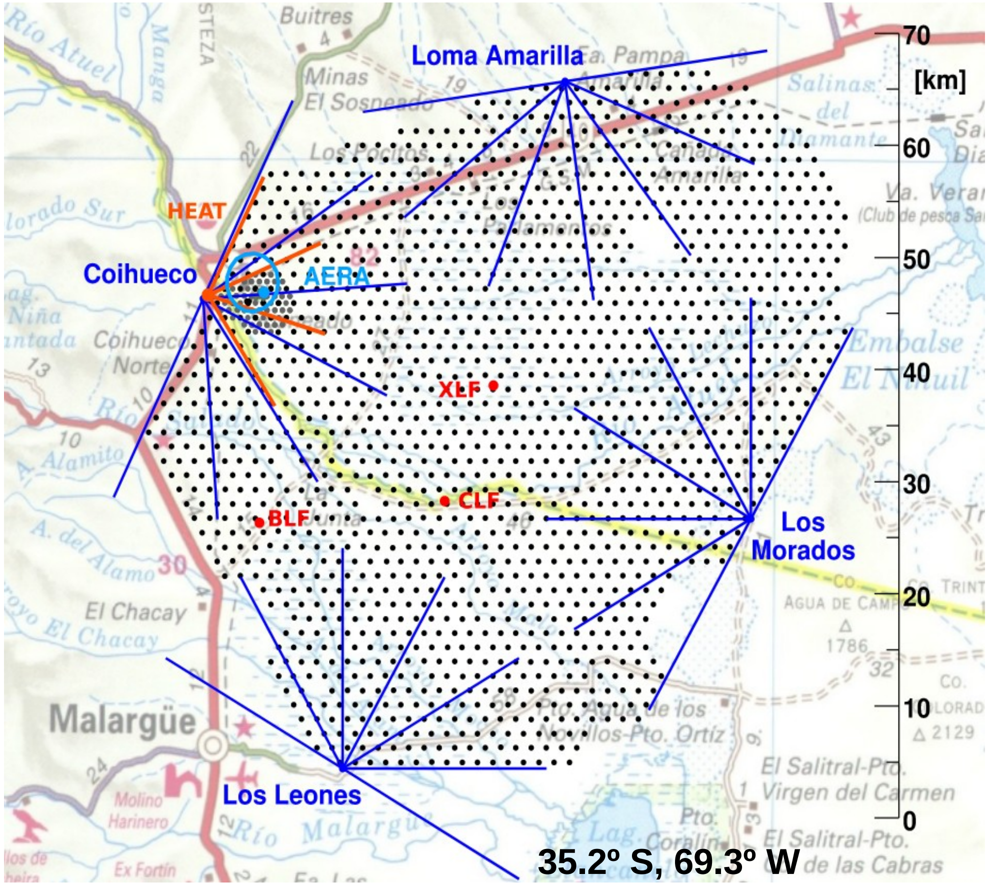
WATER-CHERENKOV SURFACE DETECTORS
(lateral shower profile, ~100% duty cycle)

SD1500: array with 1.5 km separation → 3000 km²
fully efficient for E > 2.5 EeV ($\theta < 60^o$), > 4 EeV ($\theta < 80^o$)

SD750: array with 750 m separation → 23 km²
fully efficient for E > 0.3 EeV ($\theta < 55^o$)

FLUORESCENCE DETECTORS
(longitudinal shower profile, ~13% duty cycle)

27 telescopes in 4 buildings



For the present analyses we use surface detector data: much larger statistics, simpler exposure

LARGE SCALE ANISOTROPIES CAN HELP TO UNDERSTAND THE ORIGIN OF UHECR

They could originate from:

- **anisotropies in the distribution of extragalactic CR sources**
- **diffusive propagation from individual sources**
- **diffusive escape from the Galaxy**

They can be present at all energies **(while more localized anisotropies eventually at highest energies)**

We here update and extend analyses including data up to 31 August 2018

anisotropies above full efficiency (E > 4 EeV): (Science 357 (2017) 1266; ApJ 868 (2018) 4)
reconstruct full 3D dipole (and quadrupole)

anisotropies in right ascension at energies E > 0.03 EeV:
reconstruct equatorial dipole component

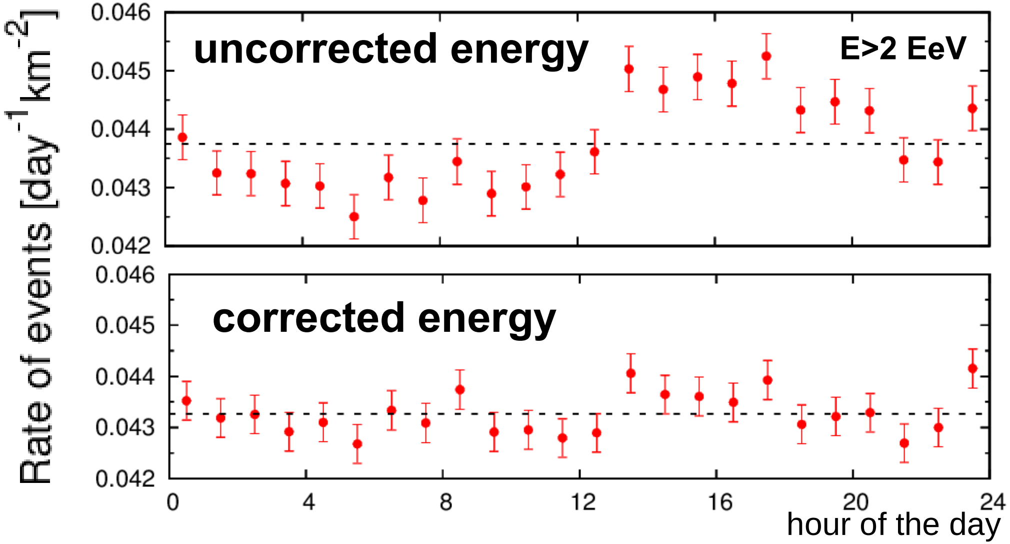
Some of the challenges to measure dipole anisotropies:

Some detectors may not always be working → need to know how many detectors are operational at any time and account for that

The atmosphere changes:

when it is hot the air is less dense
→ increased lateral spread of air showers
→ CR energy is overestimated
→ larger rates above a threshold
→ need to account for this in energy assignment to avoid day/night or summer/winter modulations

JINST 12 P02006 (2017)



Earth magnetic field: larger lateral spread of showers perpendicular to B
→ affects energy reconstruction → need to correct energy assignment

JCAP 11 (2011) 022

Slight slope of the terrain (~0.2°) → more exposure towards South → need correction

WEIGHTED FOURIER ANALYSIS

to obtain modulation in right ascension and azimuth: $x = \alpha \text{ or } \phi$

Fourier coefficients of order k

$$a_k^x = \frac{2}{\mathcal{N}} \sum_{i=1}^{N} w_i \cos(kx_i), \quad b_k^x = \frac{2}{\mathcal{N}} \sum_{i=1}^{N} w_i \sin(kx_i)$$

amplitude

$$r_k^x = \sqrt{(a_k^x)^2 + (b_k^x)^2},$$

phase

$$\varphi_k^x = \frac{1}{k} \arctan \frac{b_k^x}{a_k^x}$$

Weights:

$$w_i = [\Delta N_{\text{cell}}(\alpha_i^0)(1 + 0.003 \tan\theta_i \cos(\phi_i - \phi_0))]^{-1}$$

- ΔN_{cell}: number of active detector ‘hexagons’
- α_i^0: right ascension of the zenith of the observatory
- θ_i, ϕ_i: event coordinates
- ϕ_0: Average tilt of the array ϕ_0 = -30^o (~South-East)

For dipolar modulation, $d_\perp \simeq \dfrac{r_1^\alpha}{\langle \cos\delta \rangle}$ **and** $d_z \simeq \dfrac{b_1^\phi}{\langle \sin\theta \rangle \cos l_{obs}}$

$l_{obs} = -32.5^o$

above 4 EeV, SD1500 fully efficient up to 80° → cover 85% of the sky (dec < 45°)

3D dipole: equatorial dipole ($d_\perp$) , NS component (d_z) , total amplitude (d) and direction

Energy [EeV] interval	median	N	$d_\perp$	d_z	d	α_d [°]	δ_d [°]
4 - 8	5.0	88,325	$0.010^{+0.007}_{-0.004}$	-0.016 ± 0.009	$0.019^{+0.009}_{-0.006}$	69 ± 46	-57^{+24}_{-20}
≥ 8	11.5	36,928	$0.060^{+0.010}_{-0.009}$	-0.028 ± 0.014	$0.066^{+0.012}_{-0.008}$	98 ± 9	-25 ± 11
8 - 16	10.3	27,271	$0.056^{+0.012}_{-0.010}$	-0.011 ± 0.016	$0.057^{+0.014}_{-0.008}$	97 ± 12	-11 ± 16
16 - 32	20.2	7,664	$0.075^{+0.023}_{-0.018}$	-0.07 ± 0.03	$0.10^{+0.03}_{-0.02}$	80 ± 17	-44 ± 14
≥ 32	39.5	1,993	$0.13^{+0.05}_{-0.03}$	-0.09 ± 0.06	$0.16^{+0.06}_{-0.03}$	152 ± 19	-34^{+19}_{-20}

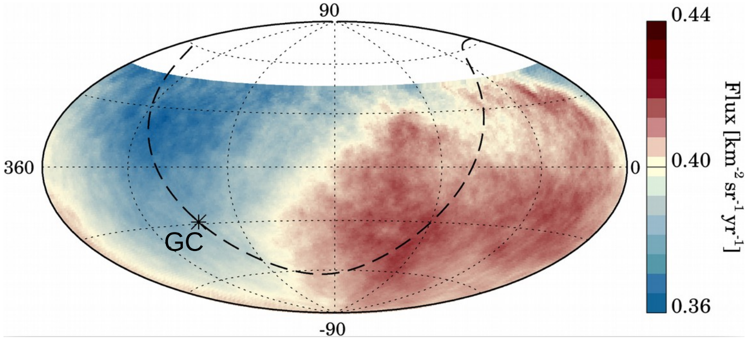
has $P = 1.4 \times 10^{-9}\ (6\sigma)$

was 2.6×10^{-8} in Science 357 (2017) 1266

(consistent with 15% increase in statistics)

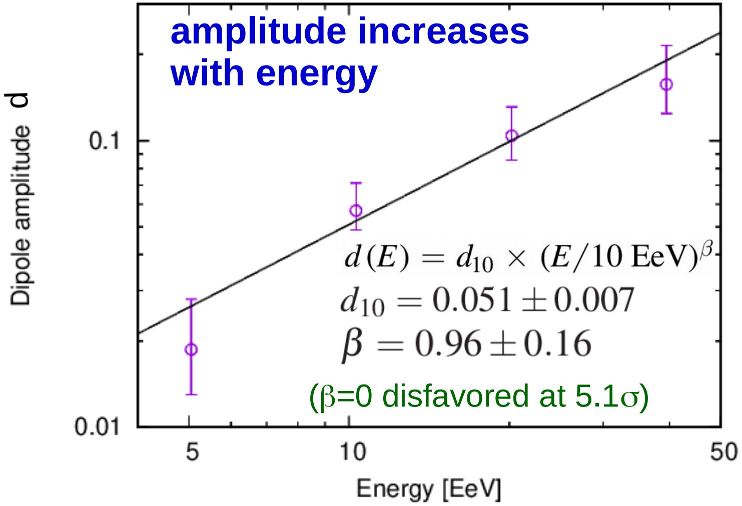
was $0.065^{+0.013}_{-0.009}$

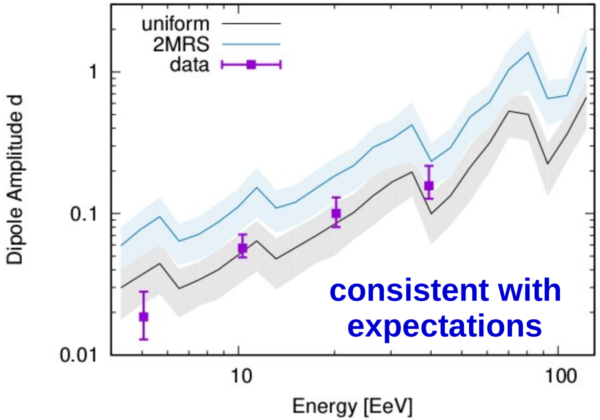
FLUX MAP FOR E > 8 EeV



equatorial coordinates, smoothed on 45° radius windows

Energy dependence of dipolar modulation

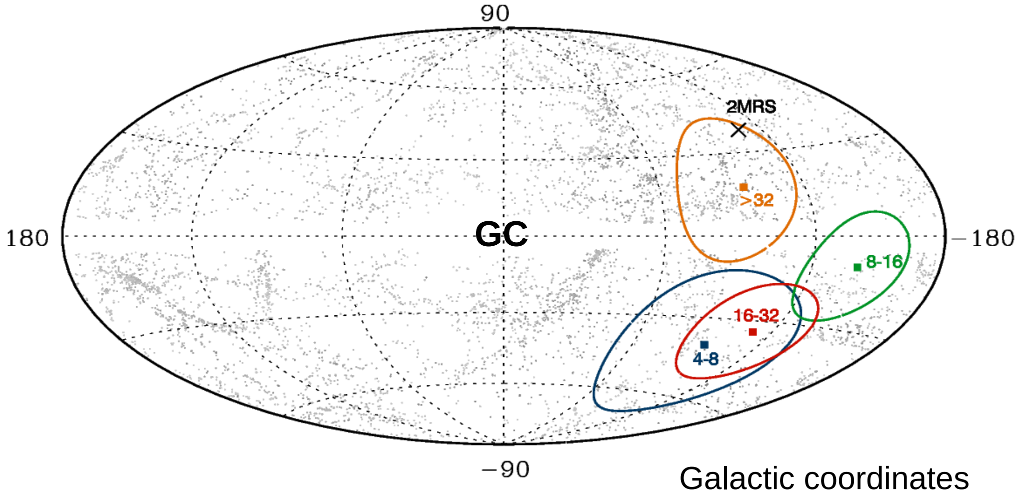




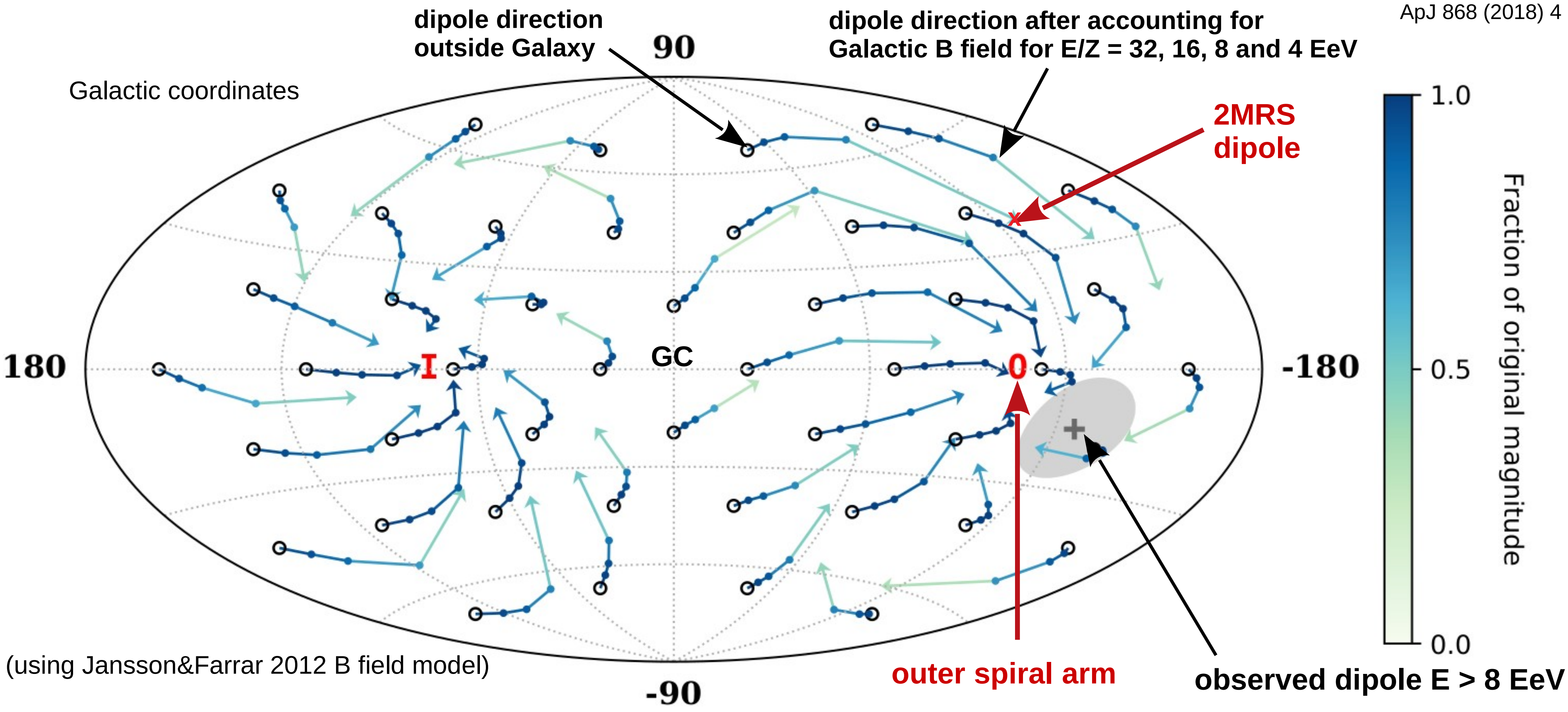
[models with source density 10^{-4} Mpc^{-3} from PRD92 (2015) 063014]

dipole direction away from Galactic Center

close to outer spiral arm in all E bins above 4 EeV



Effect of Galactic B field on extragalactic dipole direction (and amplitude)



extragalactic dipole direction gets shifted towards spiral arms by Galactic B field

Allowing also for the presence of quadrupolar components

Dipole and quadrupole components in the two energy bins. The x axis is in the direction $\alpha = 0°$

Energy [EeV]	d_i	Q_{ij}
4 - 8	$d_x = -0.001 \pm 0.008$	$Q_{zz} = -0.003 \pm 0.039$
	$d_y = 0.008 \pm 0.008$	$Q_{xx} - Q_{yy} = -0.004 \pm 0.028$
	$d_z = -0.014 \pm 0.022$	$Q_{xy} = 0.006 \pm 0.014$
		$Q_{xz} = -0.008 \pm 0.018$
		$Q_{yz} = -0.005 \pm 0.018$
≥ 8	$d_x = -0.004 \pm 0.012$	$Q_{zz} = 0.032 \pm 0.061$
	$d_y = 0.054 \pm 0.012$	$Q_{xx} - Q_{yy} = 0.077 \pm 0.048$
	$d_z = -0.011 \pm 0.035$	$Q_{xy} = 0.038 \pm 0.024$
		$Q_{xz} = 0.015 \pm 0.029$
		$Q_{yz} = -0.016 \pm 0.029$

no significant quadrupolar components
→ dipolar amplitudes consistent with dipole only results

Modulation in right ascension from 0.03 EeV up to > 32 EeV

Use Fourier analysis in RA for E > 2 EeV

below 2 EeV, non-negligible amplitudes at anti-sidereal frequency suggest possible leftover systematics could be present at sidereal frequency

Use East-West method below 2 EeV (uncertainties larger but always safe)

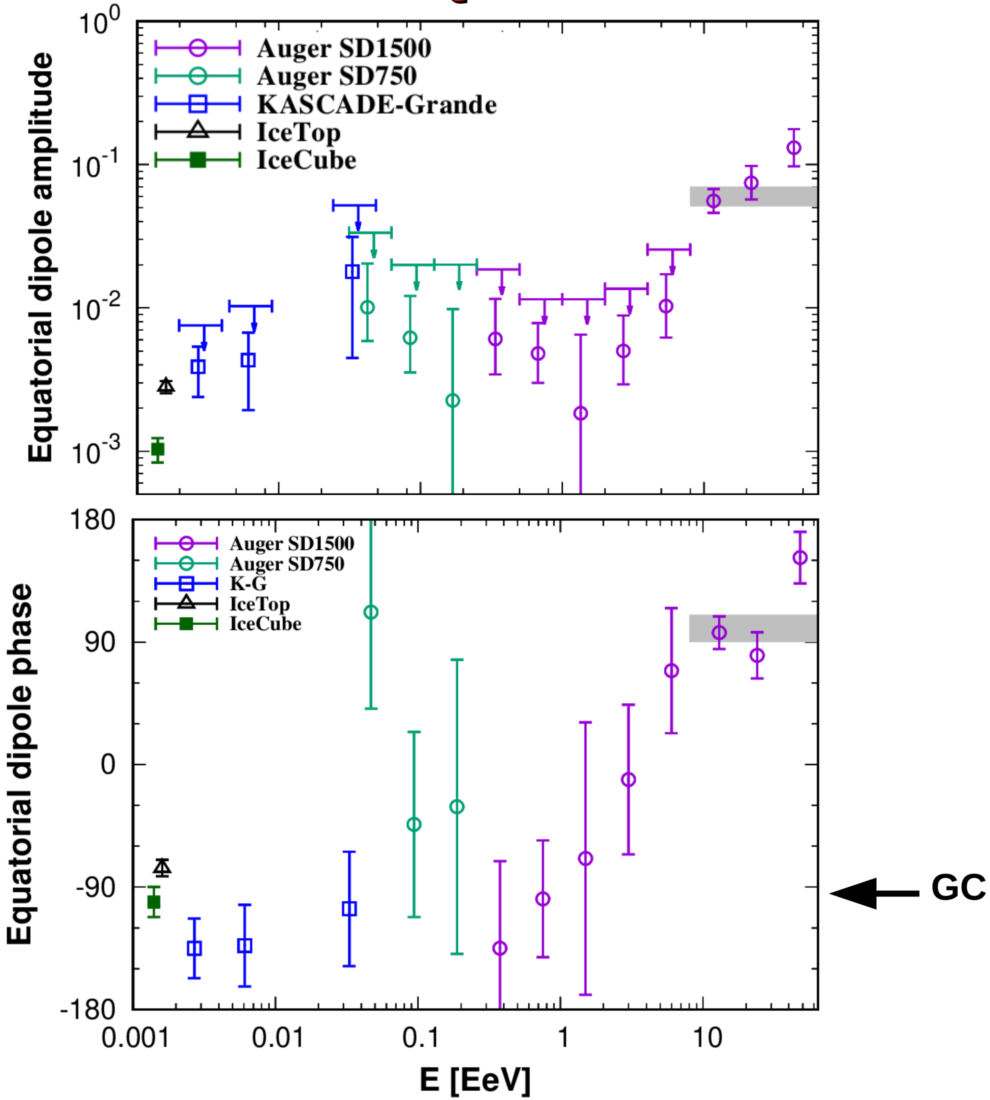
systematic effects are the same in East & West sectors
→ difference between both rates gives clean measurement of derivative of modulation from which the actual modulation can be recovered

use SD1500 array and E-W for 0.25 EeV < E < 2 EeV ($\theta < 60°$)

For E < 0.25 EeV, smaller SD750 array has actually better sensitivity

use SD750 array and E-W for 0.03 EeV < E < 0.25 EeV ($\theta < 55°$)

EQUATORIAL DIPOLE RESULTS



amplitudes grow, from below 1%
to above 10%

phases shift, from ~GC
to ~ opposite direction

Suggests transition from anisotropies of Galactic origin below ~1 EeV to extragalactic origin above few EeV

Extragalactic component could be sizeable below 1 EeV, as long as it is sufficiently isotropic

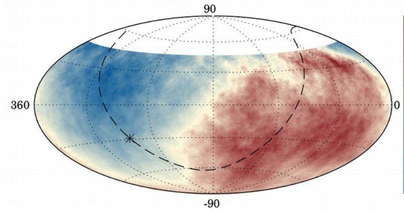
EQUATORIAL DIPOLE RESULTS

	E [EeV]	N	$d_\perp$	α_d [°]	$P(\geq d_\perp)$	$d_\perp^{99}$	$d_\perp^{UL}$
East-West	0.03125 - 0.0625	432,155	$0.010^{+0.010}_{-0.004}$	112 ± 71	0.54	0.028	0.033
(SD750)	0.0625 - 0.125	924,856	$0.006^{+0.006}_{-0.003}$	-44 ± 68	0.50	0.016	0.020
	0.125 - 0.25	488,752	$0.002^{+0.008}_{-0.002}$	-31 ± 108	0.94	0.019	0.020
East-West	0.25 - 0.5	770,316	$0.006^{+0.005}_{-0.003}$	-135 ± 64	0.45	0.015	0.018
(SD1500)	0.5 - 1.0	2,388,467	$0.005^{+0.003}_{-0.002}$	-99 ± 43	0.20	0.008	0.011
	1 - 2	1,243,103	$0.0018^{+0.0047}_{-0.0002}$	-69 ± 100	0.87	0.011	0.011
Fourier	2 - 4	283,074	$0.005^{+0.004}_{-0.002}$	-11 ± 55	0.34	0.010	0.014
(SD1500)	4 - 8	88,325	$0.010^{+0.007}_{-0.004}$	69 ± 46	0.23	0.018	0.026
	8 - 16	27,271	$0.056^{+0.012}_{-0.010}$	97 ± 12	2.3×10^{-6}	0.033	–
	16 - 32	7,664	$0.075^{+0.023}_{-0.018}$	80 ± 17	1.5×10^{-3}	0.063	–
	≥ 32	1,993	$0.13^{+0.05}_{-0.03}$	152 ± 19	5.3×10^{-3}	0.12	–
	≥ 8	36,928	$0.060^{+0.010}_{-0.009}$	98 ± 9	1.4×10^{-9}	0.028	–

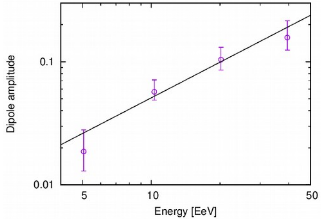
99 %CL upper-bounds

SUMMARY

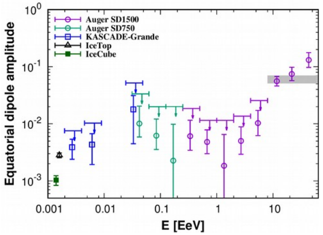
- the bin above 8 EeV has the most significant departure from isotropy, with $d = 0.066^{+0.012}_{-0.008}$ and 125º away from GC, indicative of an extragalactic origin



- above 4 EeV the dipole amplitude grows with energy



- below 8 EeV the amplitudes are not significant
  99% CL upper bounds on $d_\perp$ are at the level of 1 to 3%



- results on the right ascension phases suggest that the anisotropy has a predominantly Galactic origin below 1 EeV and a predominantly extragalactic origin above few EeV