Large-scale cosmic -ray anisotropies measured by the Pierre Auger Observatory

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ApJ in press

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PIERRE AUGER OBSERVATORY

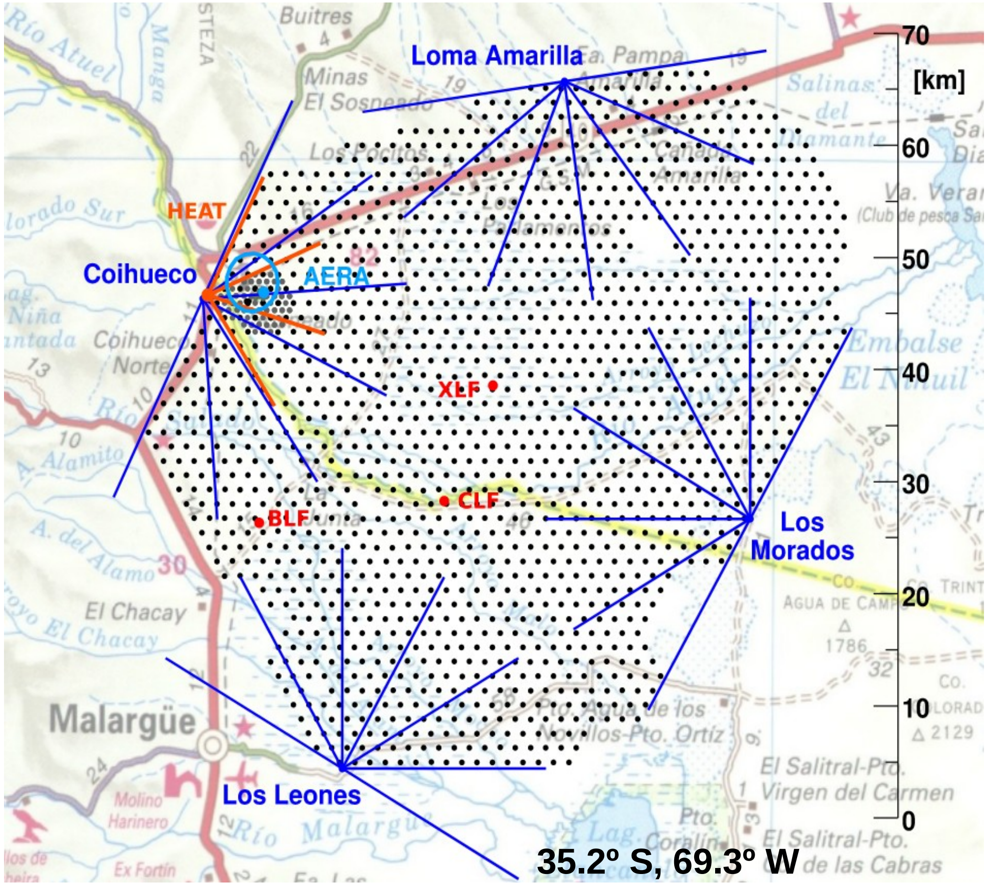
THE PIERRE AUGER OBSERVATORY

WATER-CHERENKOV SURFACE DETECTORS
(~100% duty cycle)

SD1500: array with 1.5 km separation → 3000 km²
fully efficient for E > 2.5 EeV (θ < 60º), > 4 EeV (θ < 80º)
Exposure above 4 EeV: 123,000 km^2 sr yr (Jan04-Dec22)

SD750: array with 750 m separation → 23 km²
fully efficient for E > 0.2 EeV (θ < 55º)
Exposure above 0.03 EeV: 269 km^2 sr yr (Jan14-Dec21)

FLUORESCENCE DETECTORS (~13% duty cycle)



use surface detector data for present analyses : much larger statistics, simpler exposure

We here update previous large-scale anisotopy analyses, including full Phase I data (19 years)

Science 357 (2017) 1266
ApJ 868 (2018) 4
ApJ 891 (2020) 142

Large angular-scale anisotropies can be present at all energies. They can originate from:

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

Due to deflections, small or intermediate angular-scale anisotropies eventually only appear at highest energies
At present just hints at ~20 degree scales around direction of CenA (see di Matteo's talk)

we reconstruct 3D dipole (and quadrupole) above full efficiency (E > 4 EeV)

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

to avoid spurious signals need to account for: active detectors vs. time,
atmospheric effects in E reconstruction (spurious diurnal and annual modulations) ,
geomagnetic effects and slope of the array (spurious azimuthal modulation affecting d_z)

JINST 12 P02006 (2017)
JCAP 11 (2011) 022

above full efficiency we use weighted Fourier analysis to obtain modulation in right ascension and azimuth: $x = \alpha \text{ or } \phi$

Fourier coefficients of order k

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

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:

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

$$\mathcal{N} = \sum_{i=1}^{N} w_i$$

- 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** $d_z \simeq \dfrac{b_1^\phi}{\langle \sin\theta \rangle \cos l_{obs}}$

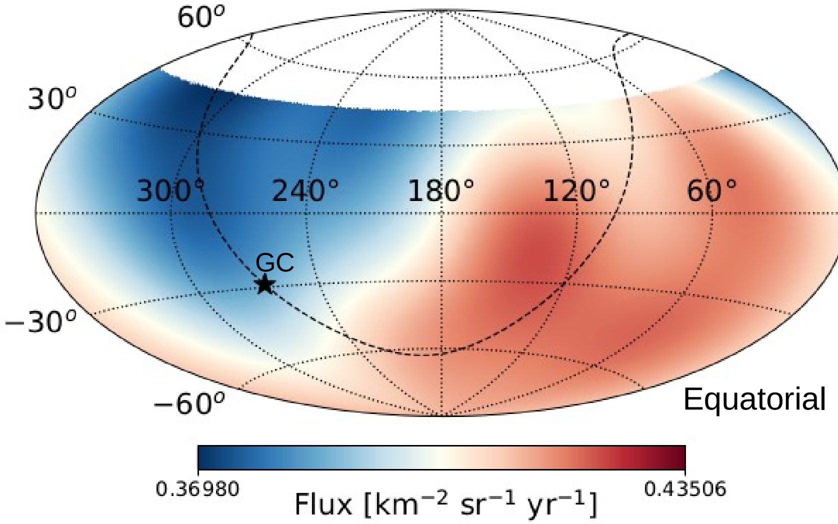
$l_{obs} = -35.2^o$

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

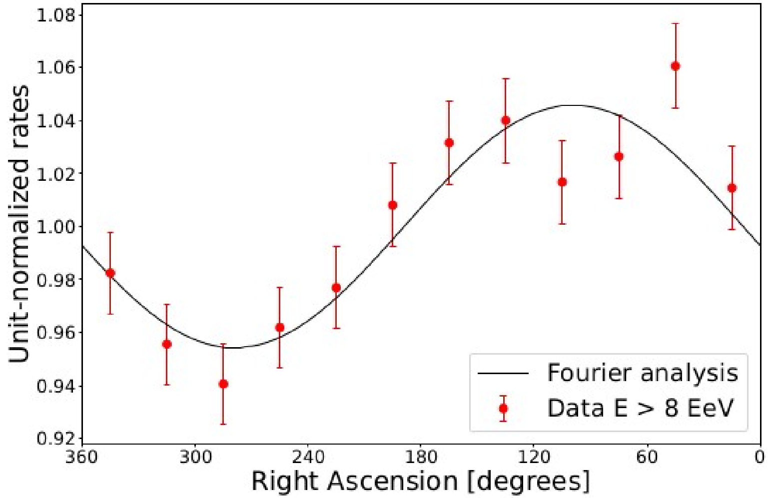
E [EeV]	N	$d_\perp$ [%]	d_z [%]	d [%]	α_d [°]	δ_d [°]	$P(\geq r_1^\alpha)$
4-8	118,722	$1.0^{+0.6}_{-0.4}$	-1.3 ± 0.8	$1.7^{+0.8}_{-0.5}$	92 ± 28	-52^{+21}_{-19}	0.14
$\geq$8	49,678	$5.8^{+0.9}_{-0.8}$	-4.5 ± 1.2	$7.4^{+1.0}_{-0.8}$	97 ± 8	-38^{+9}_{-9}	8.7×10^{-12}
8-16	36,658	$5.7^{+1.0}_{-0.9}$	-3.1 ± 1.4	$6.5^{+1.2}_{-0.9}$	93 ± 9	-29^{+11}_{-12}	1.4×10^{-8}
16-32	10,282	$5.9^{+2.0}_{-1.8}$	-7 ± 3	$9.4^{+2.6}_{-1.9}$	93 ± 16	-51^{+13}_{-13}	4.3×10^{-3}
$\geq$32	2,738	11^{+4}_{-3}	-13 ± 5	17^{+5}_{-4}	144 ± 18	-51^{+14}_{-14}	9.8×10^{-3}

6.8σ

→ **5.7σ**

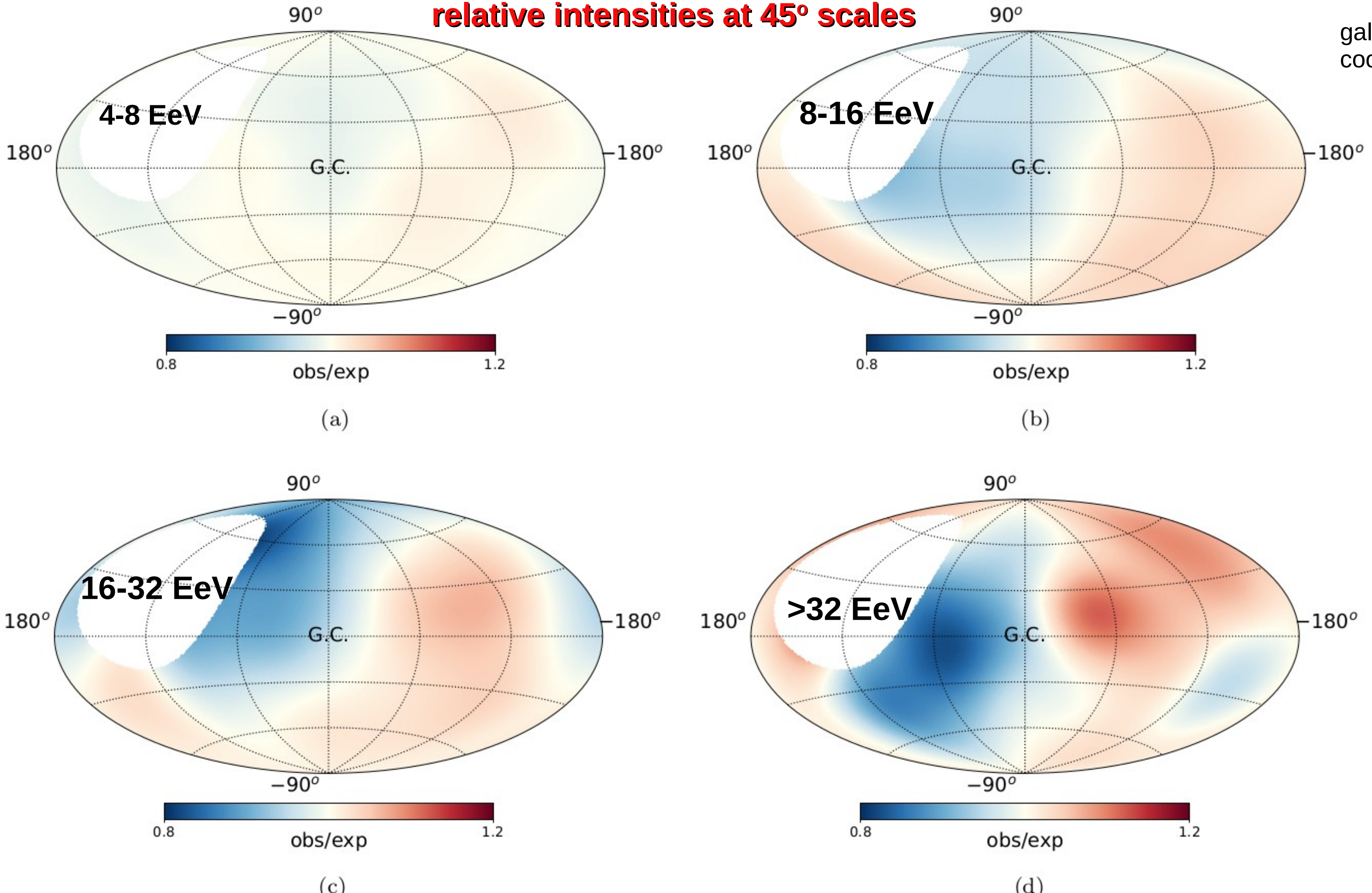


E>8 EeV



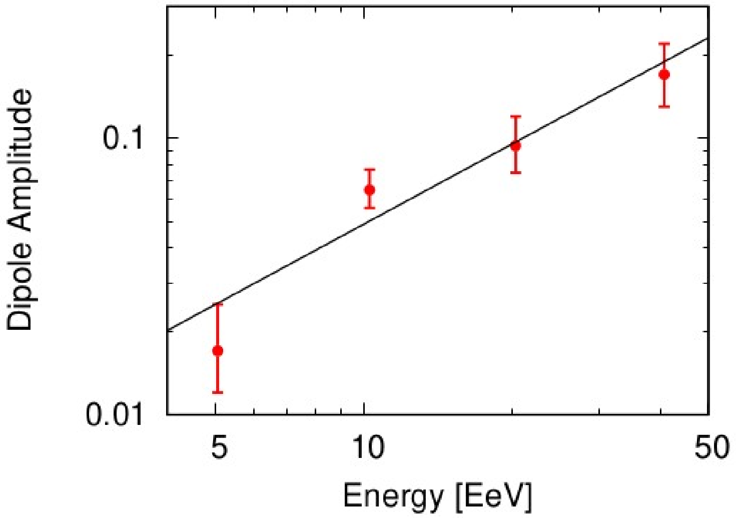
relative intensities at 45º scales

galactic
coordinates



(a) (b) (c) (d)

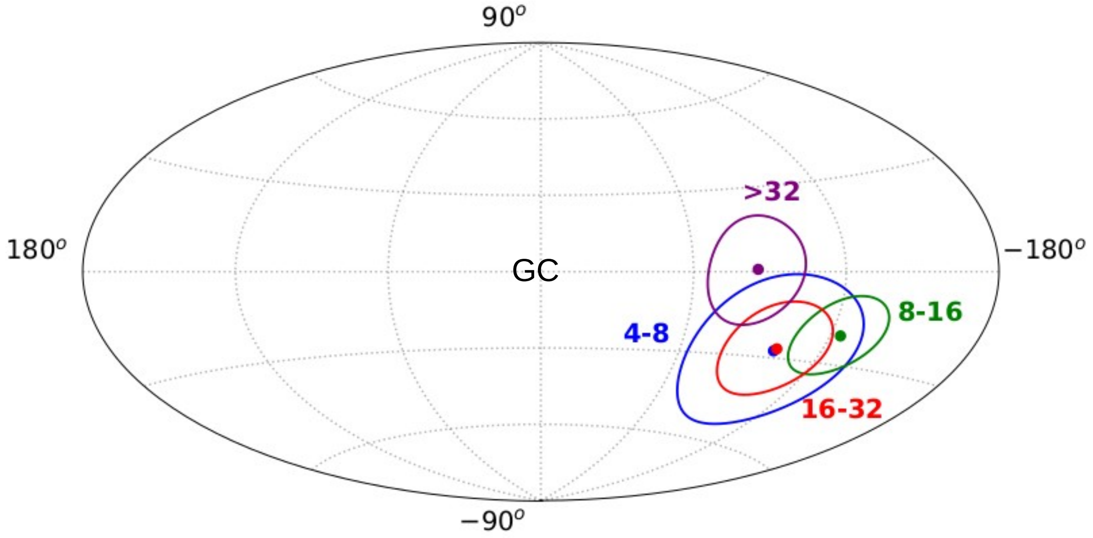
evolution with energy



$$d(E) = d_{10} \times (E/10\,\mathrm{EeV})^{\beta}$$

$$d_{10} = 0.049 \pm 0.009$$

$$\beta = 0.97 \pm 0.21$$



results including also quadrupole components

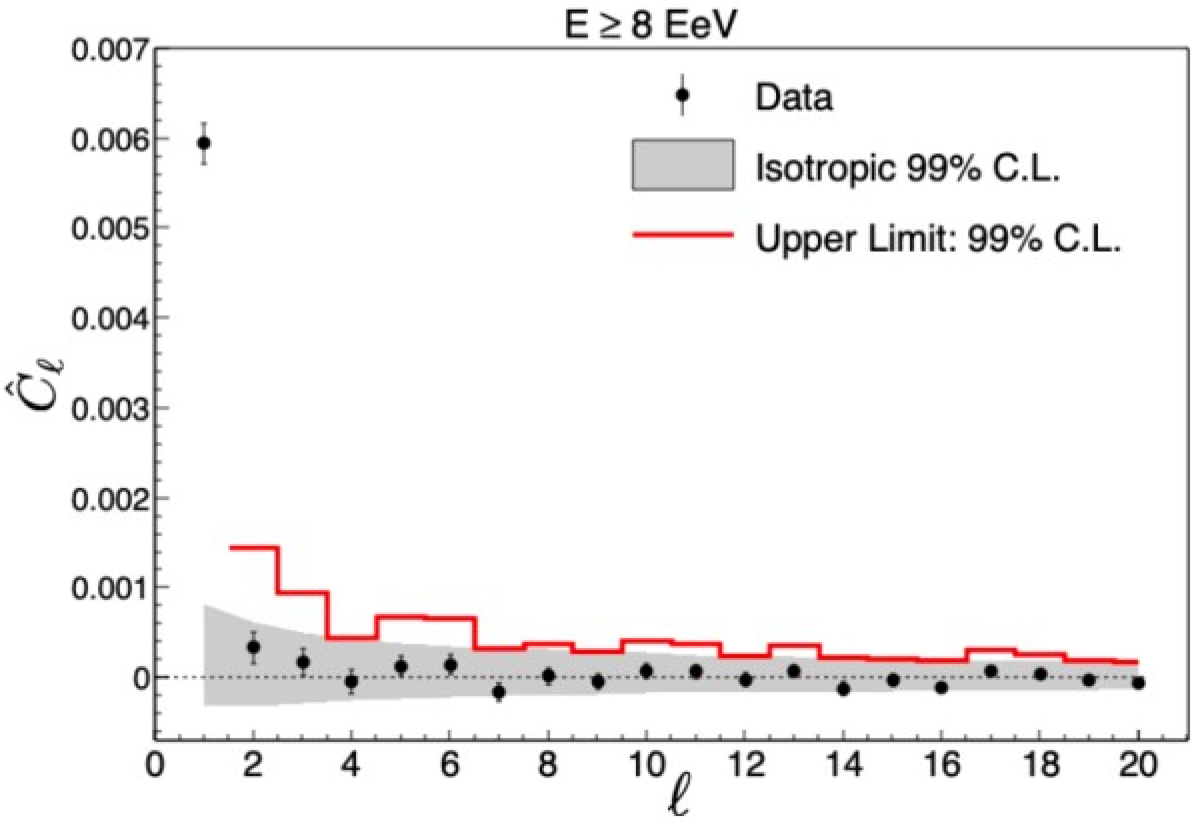
	4–8 EeV	≥ 8 EeV	8–16 EeV	16–32 EeV	≥ 32 EeV
d_x	0.003 ± 0.007	-0.002 ± 0.011	-0.002 ± 0.012	0.029 ± 0.024	-0.1 ± 0.5
d_y	0.005 ± 0.007	0.059 ± 0.011	0.048 ± 0.012	0.088 ± 0.024	0.1 ± 0.5
d_z	0.002 ± 0.019	-0.02 ± 0.03	0.02 ± 0.04	-0.15 ± 0.07	-0.23 ± 0.13
Q_{zz}	0.03 ± 0.03	0.04 ± 0.05	0.10 ± 0.06	-0.13 ± 0.13	-0.16 ± 0.25
$Q_{xx} - Q_{yy}$	0.018 ± 0.025	0.07 ± 0.04	0.03 ± 0.04	0.18 ± 0.08	0.30 ± 0.17
Q_{xy}	-0.016 ± 0.012	0.026 ± 0.019	0.041 ± 0.022	-0.05 ± 0.04	0.11 ± 0.08
Q_{xz}	-0.010 ± 0.016	0.017 ± 0.025	0.003 ± 0.029	0.10 ± 0.06	-0.10 ± 0.10
Q_{yz}	-0.019 ± 0.016	0.005 ± 0.025	-0.029 ± 0.029	0.09 ± 0.06	0.13 ± 0.10
Q	0.018 ± 0.010	0.028 ± 0.015	0.05 ± 0.02	0.10 ± 0.03	0.13 ± 0.06
Q^{UL}	0.04	0.05	0.08	0.15	0.26

→ none significant, except dipole

check that no spurious modulations are present in solar and antisidereal frequencies

E [EeV]	r_1^{solar} [%]	$P(\geq r_1^{\text{solar}})$	r_1^{antis} [%]	$P(\geq r_1^{\text{antis}})$
2-4	$0.4^{+0.3}_{-0.2}$	0.18	$0.3^{+0.3}_{-0.1}$	0.48
4-8	$0.7^{+0.5}_{-0.3}$	0.28	$0.4^{+0.5}_{-0.2}$	0.65
≥ 8	$0.3^{+0.9}_{-0.04}$	0.91	$1.4^{+0.7}_{-0.5}$	0.10
8-16	$0.6^{+0.9}_{-0.2}$	0.71	$1.1^{+0.8}_{-0.5}$	0.36
16-32	$2.2^{+1.6}_{-0.9}$	0.29	$2.7^{+1.6}_{-1.0}$	0.15
≥ 32	$1.6^{+3.5}_{-0.4}$	0.83	$1.0^{+4}_{-0.01}$	0.93

angular power spectrum above 8 EeV: the only relevant multipole is the dipole



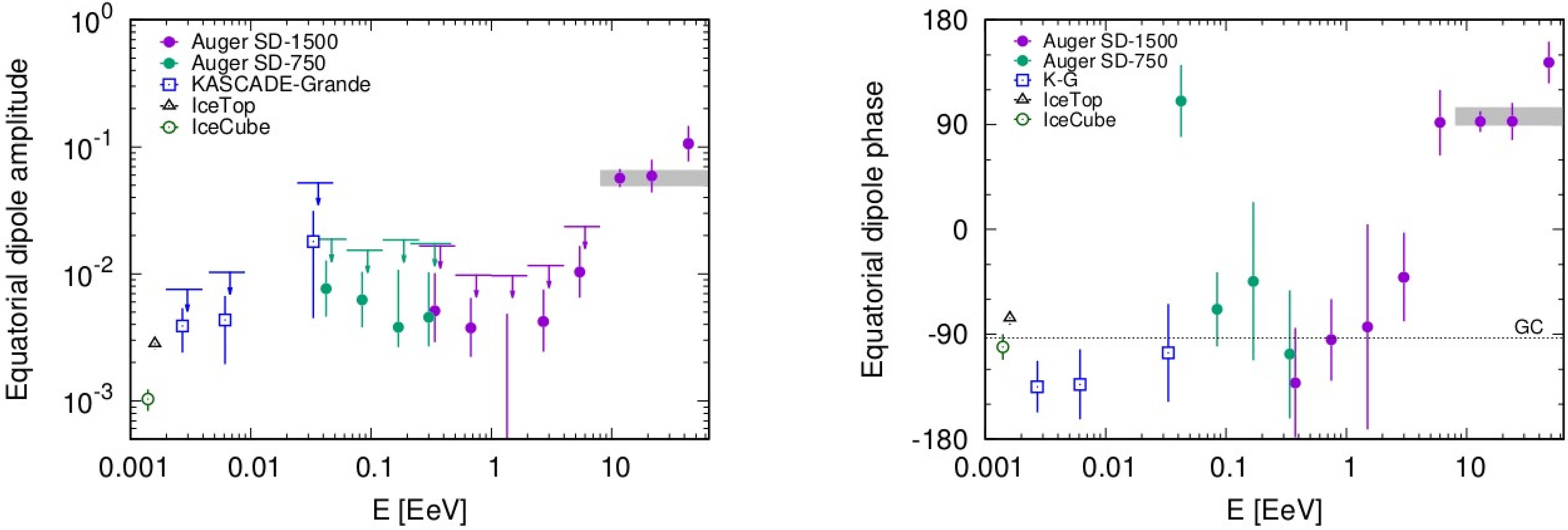
see also
JCAP06(2017)026

extending the search to lower energies

		E [EeV]	N	$d_\perp (\%)$	α_d [°]	$P(\geq r_1^\alpha)$	$d_\perp^{\rm UL} (\%)$
SD750	East – West	1/32-1/16	1,811,897	$0.8^{+0.5}_{-0.3}$	110 ± 31	0.22	1.9
		1/16-1/8	1,843,507	$0.6^{+0.4}_{-0.2}$	-69 ± 32	0.23	1.5
		1/8-1/4	607,690	$0.4^{+0.7}_{-0.1}$	-44 ± 68	0.79	1.8
	Fourier	0.25-0.5	135,182	$0.5^{+0.6}_{-0.2}$	-107 ± 55	0.65	1.7
SD1500	East – West	0.25-0.5	930,942	$0.5^{+0.5}_{-0.2}$	-132 ± 47	0.51	1.7
		0.5 - 1	3,049,342	$0.4^{+0.3}_{-0.2}$	-95 ± 35	0.28	1.0
		1-2	1,639,139	$0.1^{+0.4}_{-0.1}$	-84 ± 88	0.93	1.0
	Fourier	2-4	380,491	$0.4^{+0.3}_{-0.2}$	-41 ± 38	0.36	1.2

below full efficiency use East-West method to obtain equatorial dipole:
systematic effects are the same for rates from E or W
their difference is free from systematics and allows to infer modulation,
although with reduced sensitivity (by factor 2)

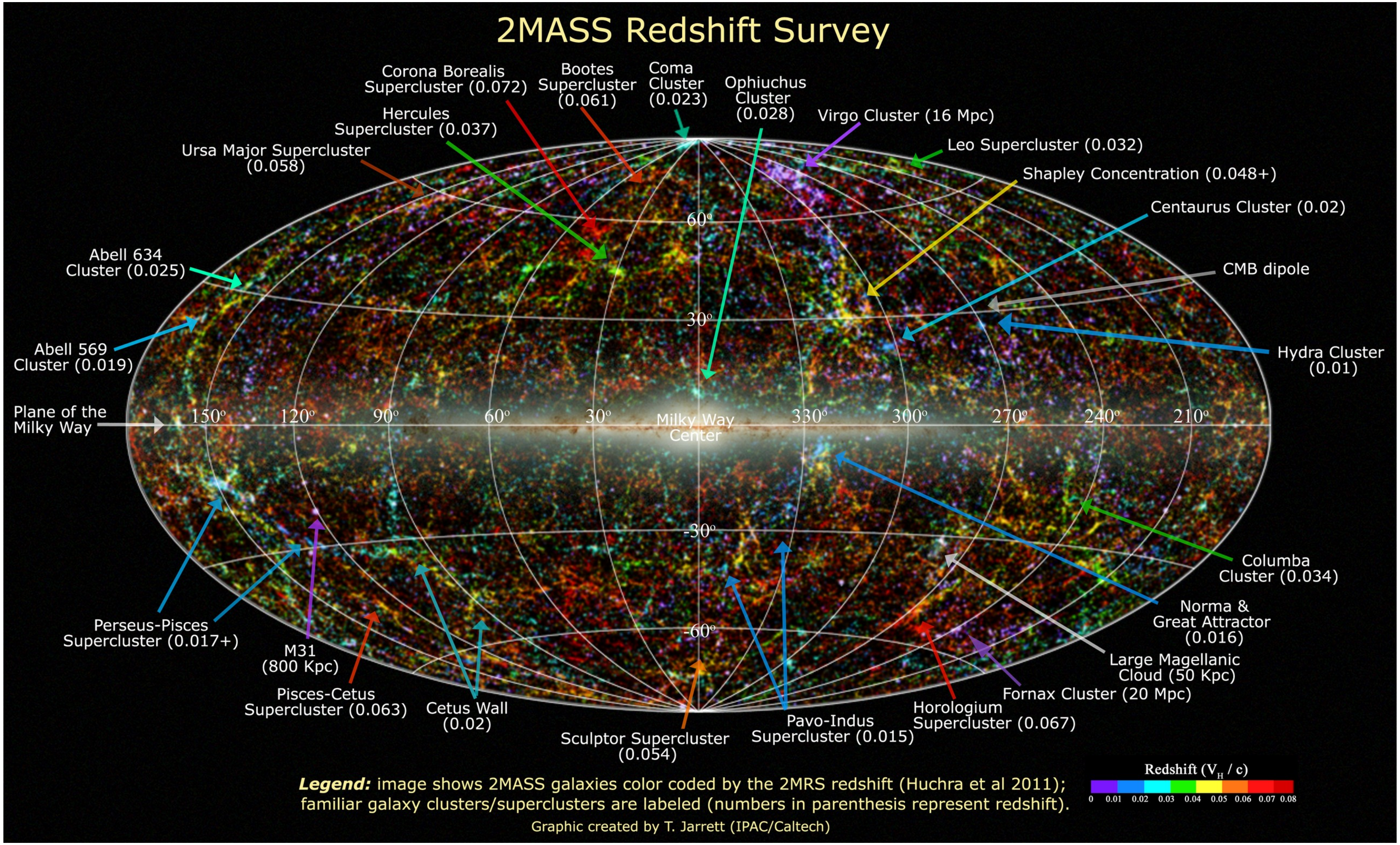
Equatorial dipole results



below 4 EeV, equatorial dipole below 1-2%, but no significant determination
phases consistently close to the Galactic Center direction

anisotropies dominated by a Galactic origin below few EeV?
note that Compton Getting effect due to Solar System motion d_{CG}~0.6% PLB 640 (2006) 225
this would be affected by deflections in Gal B field
also E fields induced by Galaxy rotation may have an impact JCAP 12 (2022) 021

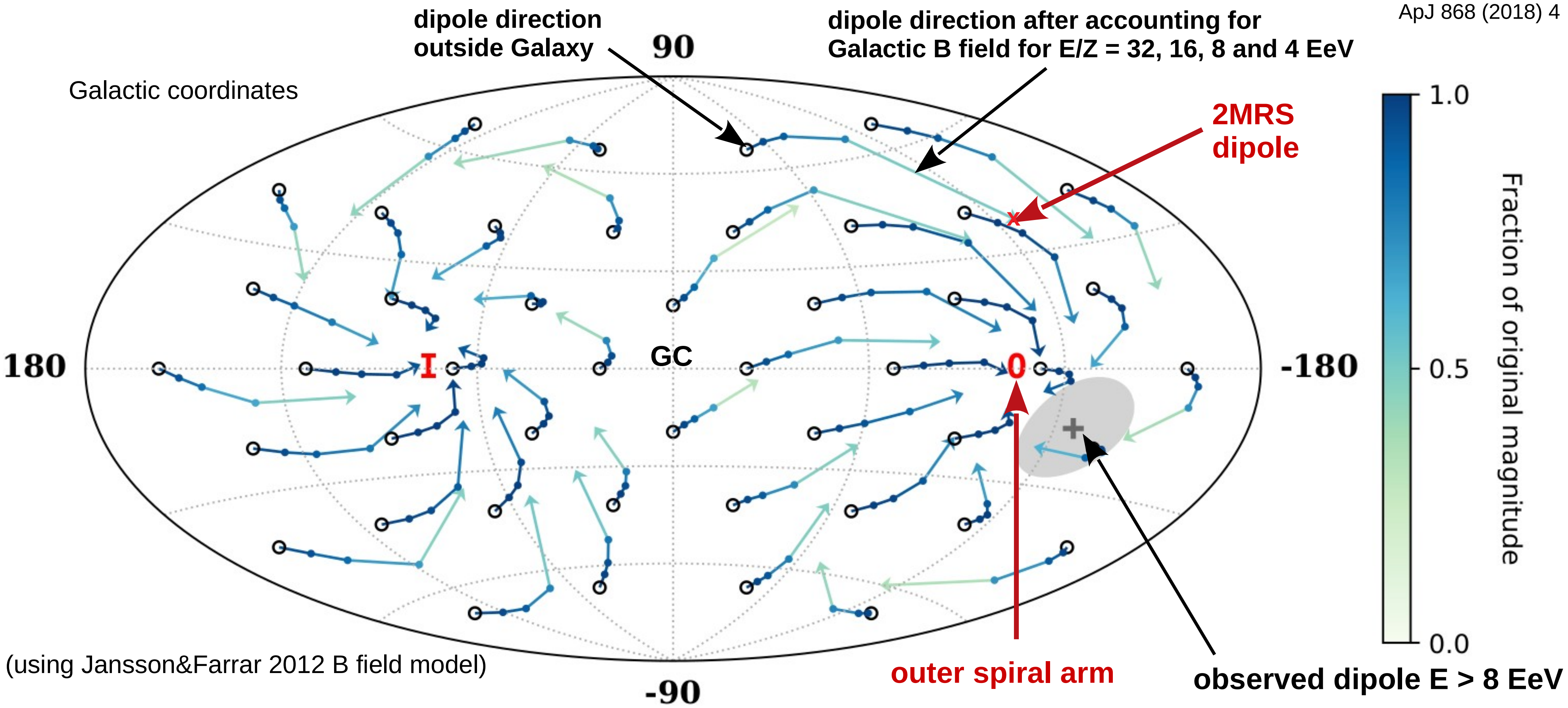
nearby (< 100 Mpc) galaxy distribution is not uniform



if galaxies trace UHECR sources → UHECR arrival directions not uniform

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

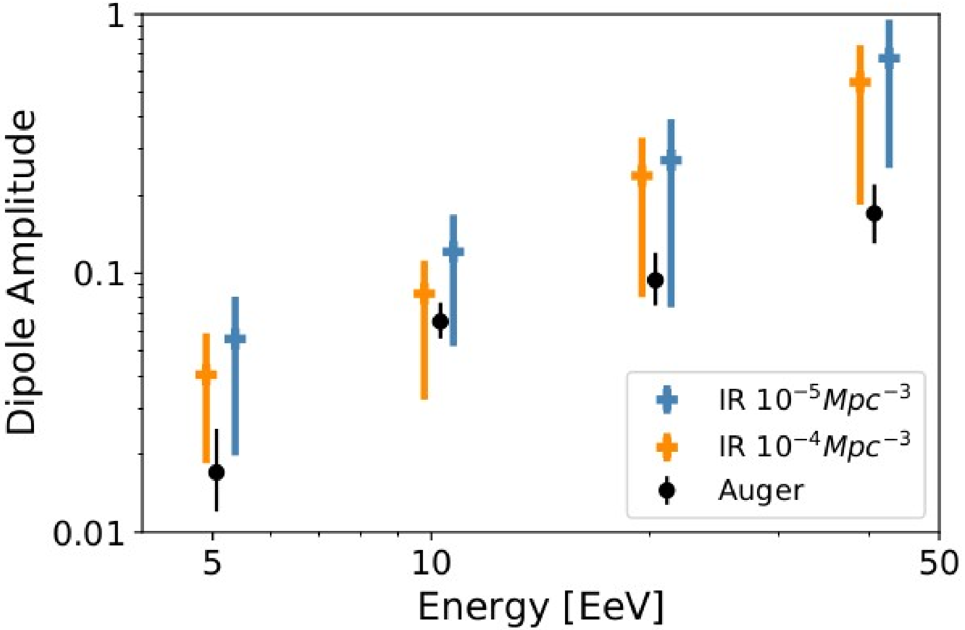
ApJ 868 (2018) 4

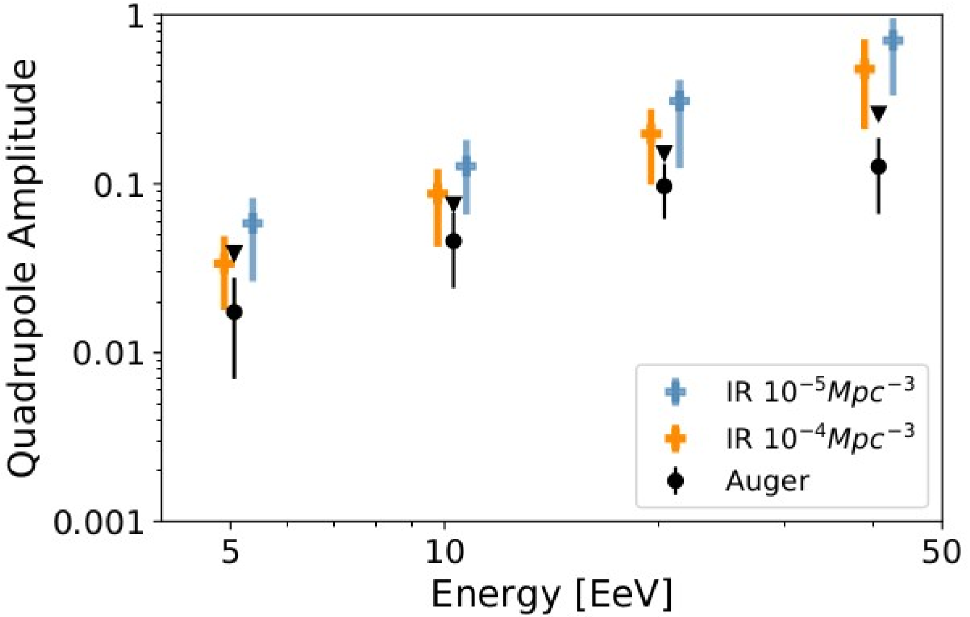


extragalactic dipole direction gets shifted towards spiral arms by Galactic B field

deflections also generate higher multipoles, which may also result from source distribution (eg SGP)

expected dipole and quadrupole from sources taken from 2MRS catalog (volume limited) with densities 10^{-4} and 10^{-5} Mpc^{-3} and after deflections in JF12 galactic magnetic field model using composition and spectrum inferred from combined fit JCAP05 (2023) 024





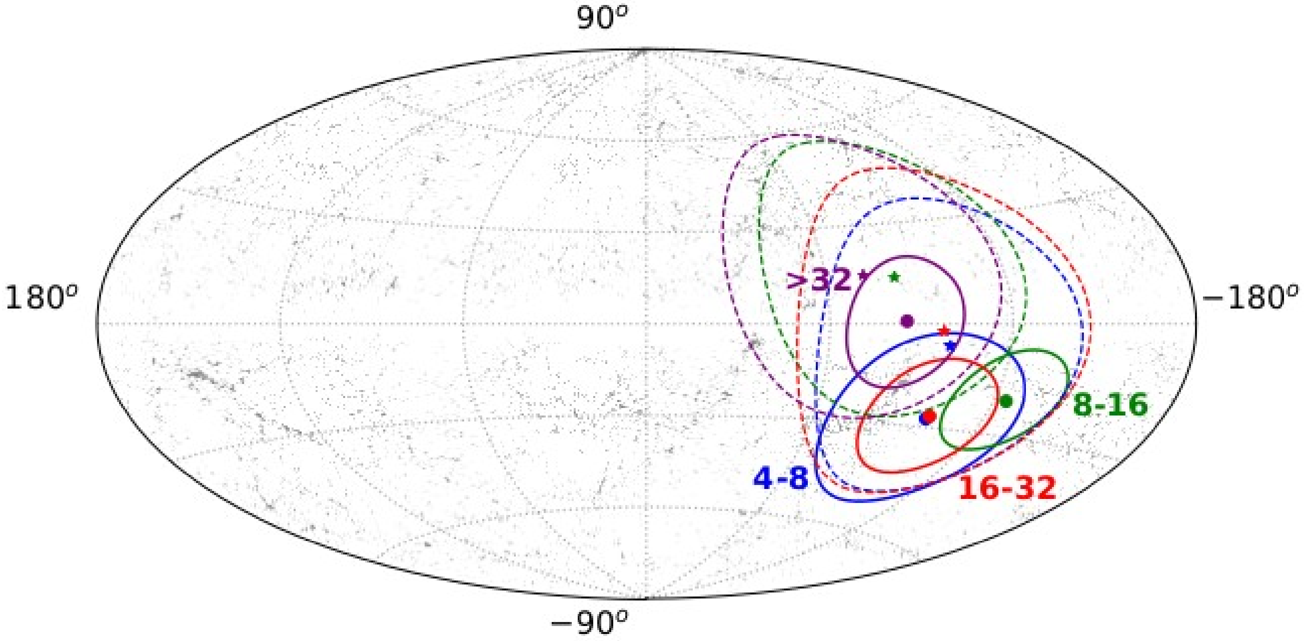
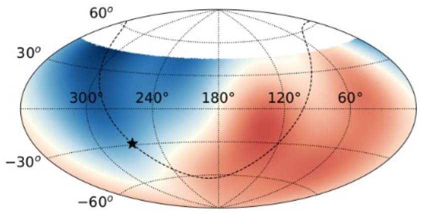


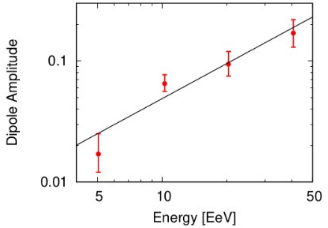
Figure 6. Map in Galactic coordinates showing the predictions for the direction of the mean dipole (star symbols) and the 68% CL contour regions (dashed lines) obtained for 10^3 realizations of the source distribution for a density of $10^{-4}\,\mathrm{Mpc}^{-3}$ and for each energy bin above 4 EeV. This is compared to what obtained in data (continuous lines). The gray dots represent the location of the galaxies in the IR catalog within 120 Mpc.

CONCLUSIONS

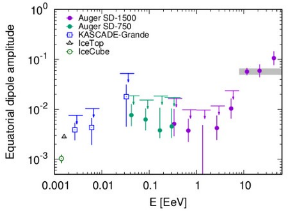
- **for E > 8 EeV: $d = 0.074^{+0.010}_{-0.008}$ and points 115º away from GC**
  It is indicative of an extragalactic origin



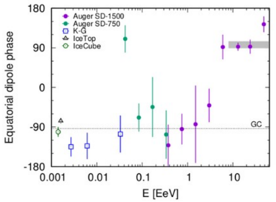
- **above 4 EeV the dipole amplitude grows with energy**



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



- **the right ascension phases lie close to Galactic Center one:**
  Galactic origin below 1 EeV and/or effects of Gal B field
  on an extragalactic component?



- **Results consistent with expectations from some astrophysical models**