Studies of the arrival direction distribution of cosmic rays at the Pierre Auger Observatory

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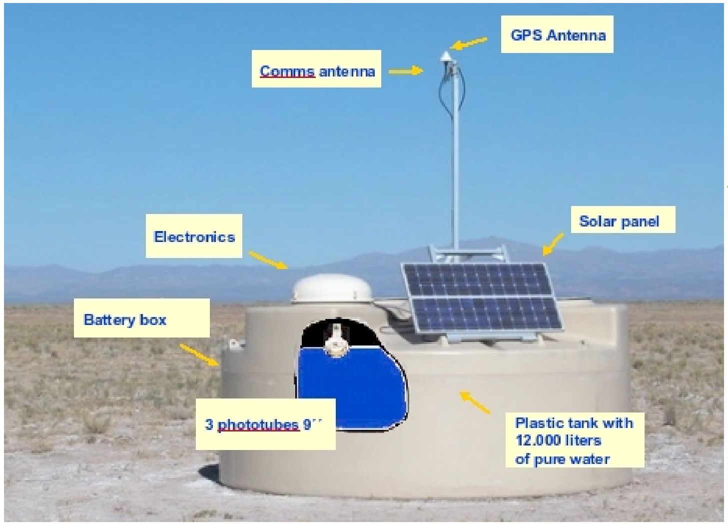
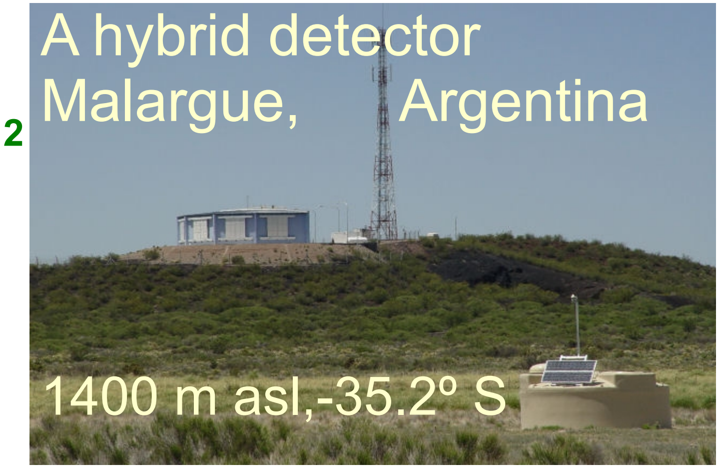
for The Pierre Auger Collaboration

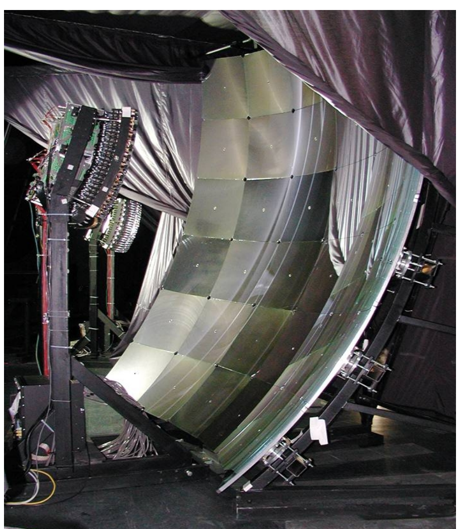
THE PIERRE AUGER OBSERVATORY

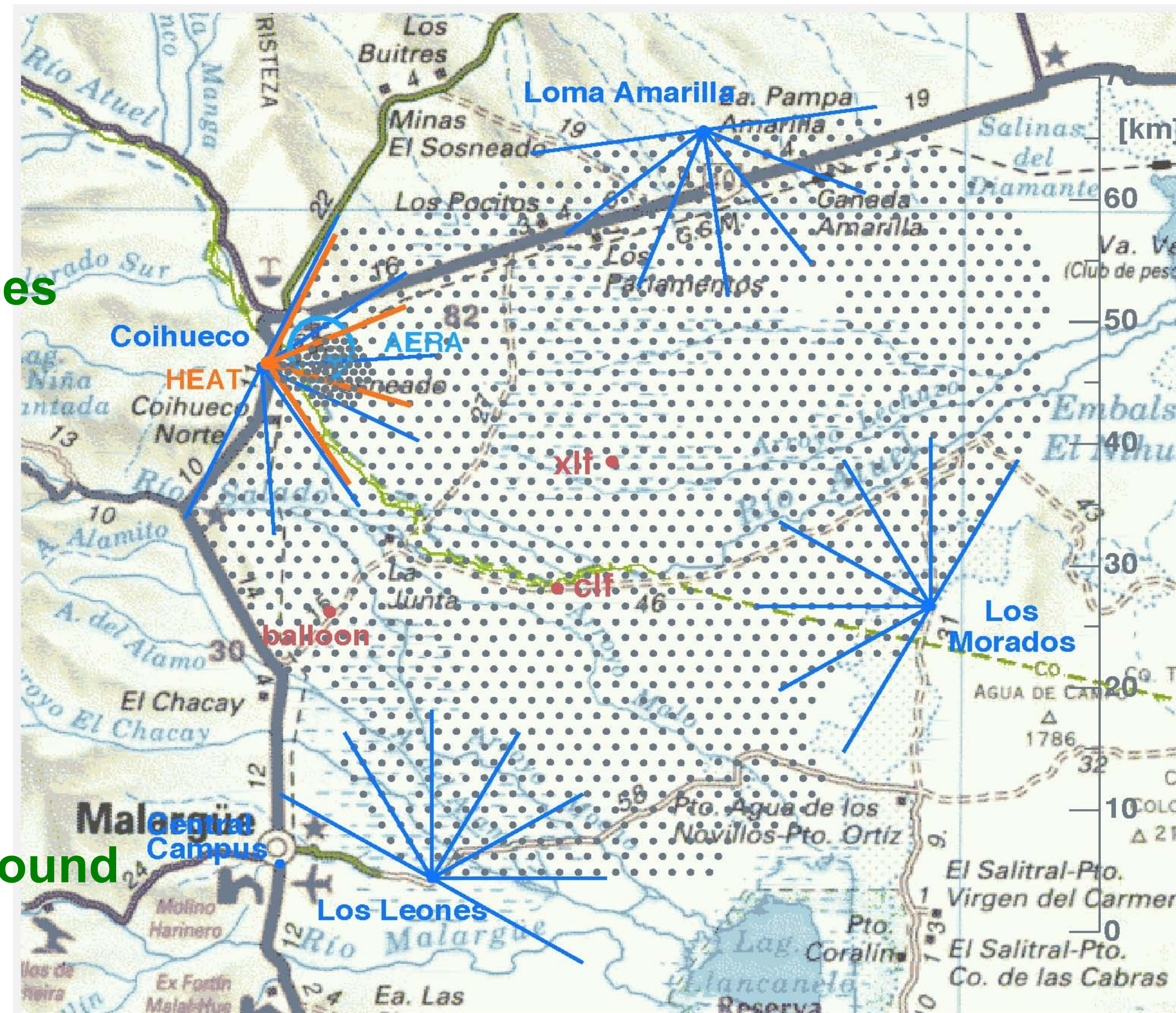


Surface detector: 3000 km^2
1660 water Cherenkov stations in 1.5 km grid
Infill: 25 km^2 → 750 m grid



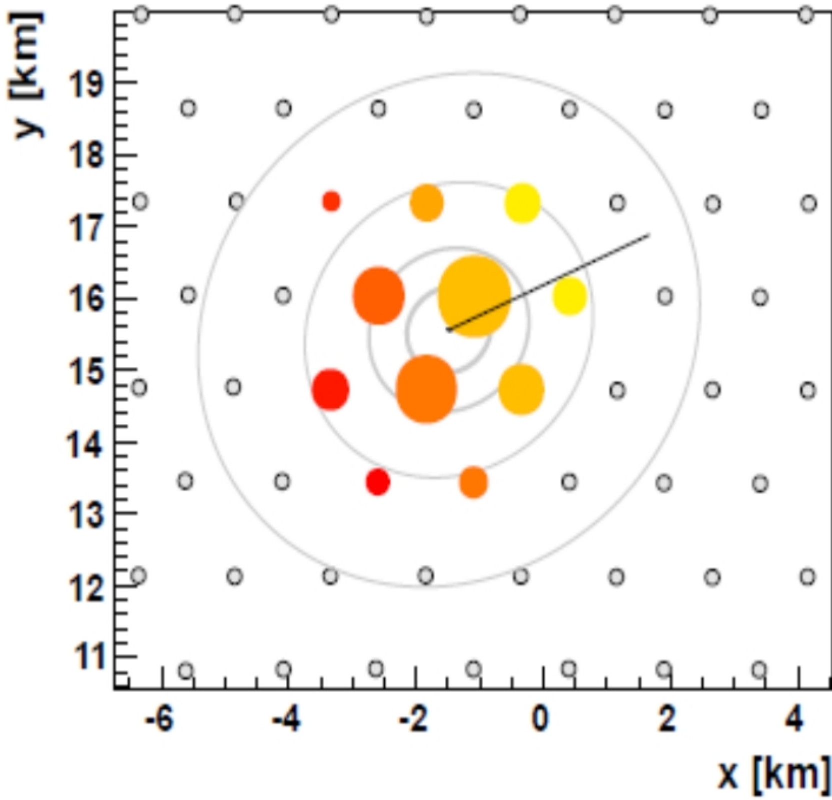
Fluorescence detector:
24 telescopes at 4 locations
Heat: 3 higher elevation telescopes

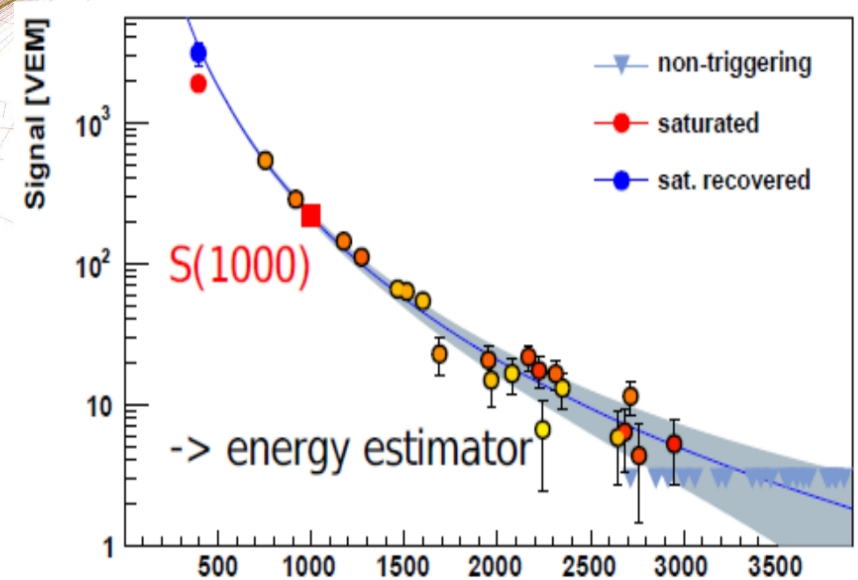




AMIGA: muon detectors underground
AERA: 124 radio antennas in the infill region

SD air shower reconstruction

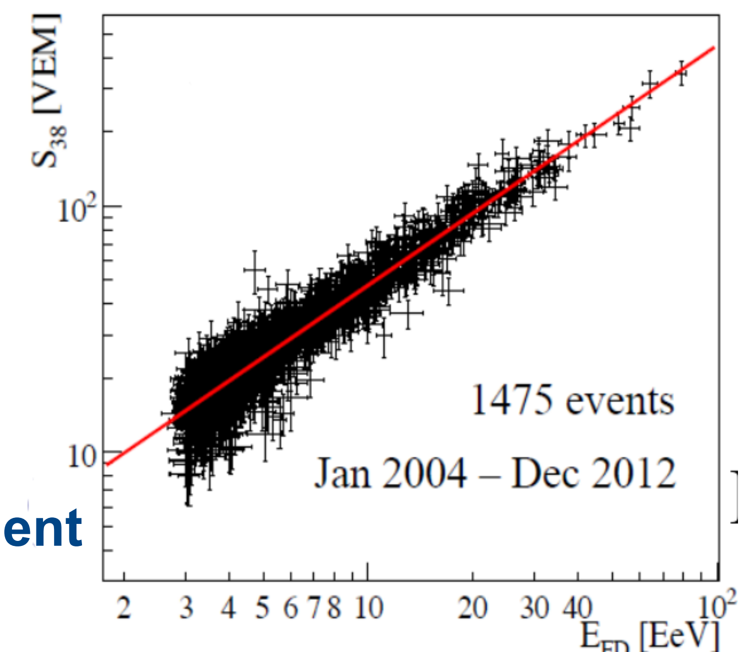




Atmospheric attenuation derived from data (constant intensity cut method)

S38=S(1000)/CIC(θ)

Arrival directions:
from fit to arrival times of shower front
Angular resolution:
< 1º if E > 3 EeV
< 2.2º for events with low SD-mutiplicity



Energy calibration: SD calibrated with FD
FD (calorimetric) energy largely independent on composition and hadronic models

Anisotropy searches

Motivations: structure in the distribution of arrival directions may help to understand nature and origin of UHECRs

Large scale anisotropies:

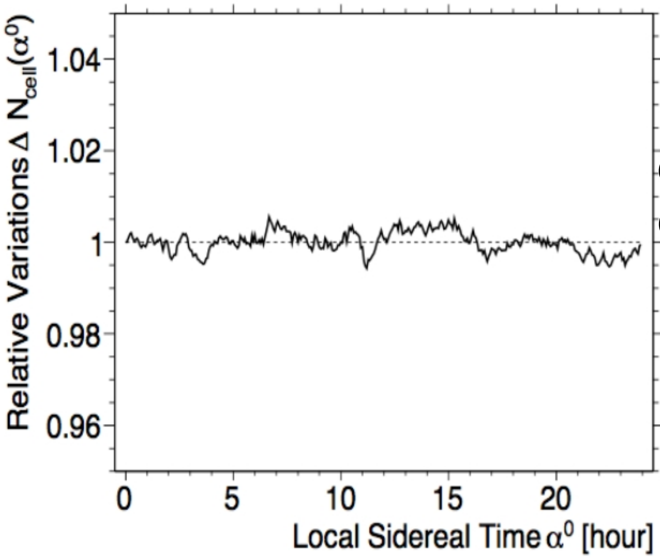
- Could signal galactic-extragalactic transition
- Galactic: diffusion & escape of galactic CRs below EeV energies might generate dipole pattern → Amplitude model-dependent, below few %.
- Extragalactic: diffusion in XG magnetic field and dipolar inhomogeneity of the nearby sources distribution. Small dipole due to our motion (Compton-Getting effect, expected below 1%).

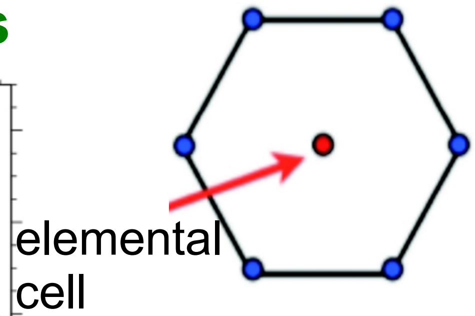
Small scale anisotropies:

- Largest energies: above GZK a light composition component would arrive with small deflection from the source → trace source population
- Lower energies: EeV neutrons travel ~ 10 kpc before decaying → point like excess could identify galactic CRs sources

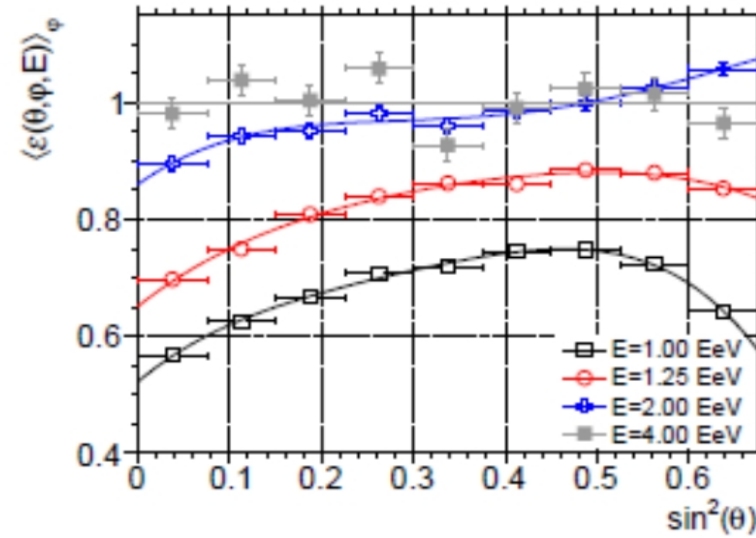
LARGE SCALES: detector effects carefully taken into account

Array size modulations

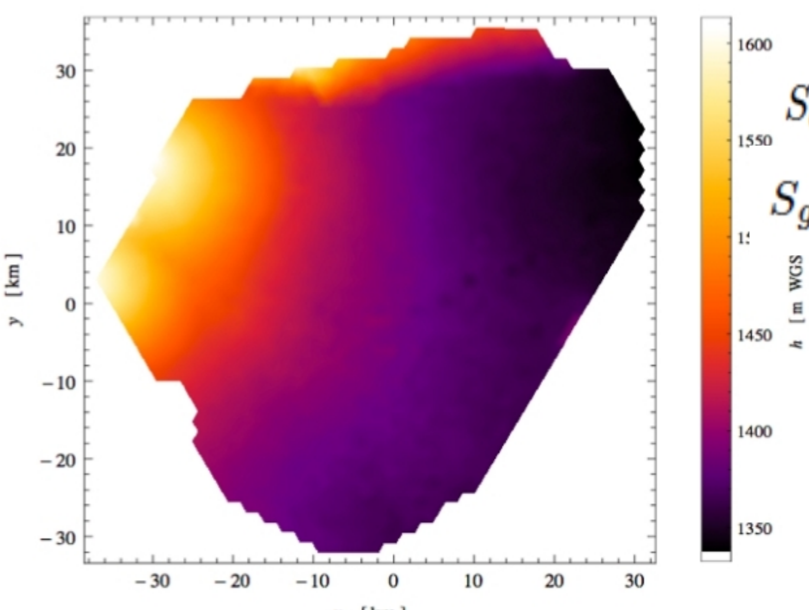




Detection efficiency



Tilt of the array

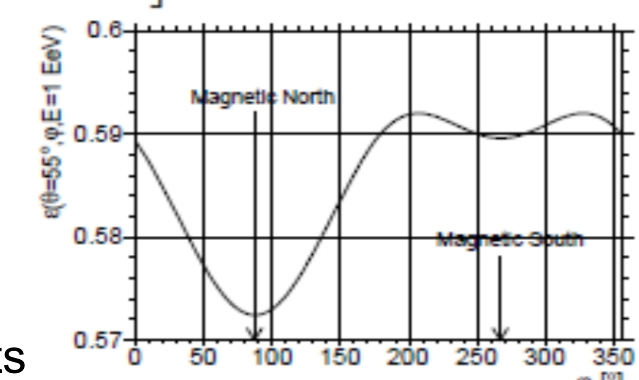


Atmospheric and geomagnetic effects on energy assignment

$$S_{atm}(1000) = [1 - \alpha_P(\theta)(P - P_0) - \alpha_\rho(\theta)(\rho_d - \rho_0) - \beta_\rho(\theta)(\rho - \rho_d)]\, S(1000)$$

$$S_{geom}(1000) = \left[1 - g_1 \cos^{-g_2}(\theta) \sin^2\left(\widehat{\mathbf{u},\mathbf{b}}\right)\right] S(1000)$$

g_1=4.2 10^{-3}
g_2=2.8



Geomagnetic effects

Two analysis:

- **2D: Harmonic analysis in right ascension** $I(\alpha) = I_0(1 + r\cos(\alpha - \varphi))$

E > 1 EeV: Rayleigh weighted for exposure

$$a = \frac{2}{\mathcal{N}} \sum_{i=1}^{N} w_i \cos(\alpha_i), \quad b = \frac{2}{\mathcal{N}} \sum_{i=1}^{N} w_i \sin(\alpha_i) \qquad w_i \equiv [\Delta N_{\mathrm{cell}}(\alpha_i^0)]^{-1}$$

$$r = \sqrt{a^2 + b^2}, \quad \varphi = \arctan\frac{b}{a}$$

E < 1 EeV: East – West: independent of detector and atmospheric effects, but with reduced sensitivity

$$I_E(\alpha^0) - I_W(\alpha^0) = -\frac{N}{2\pi} \frac{2\langle\sin\theta\rangle}{\pi\langle\cos\delta\rangle} r \sin(\alpha^0 - \varphi)$$

amplitude r → equatorial dipole component

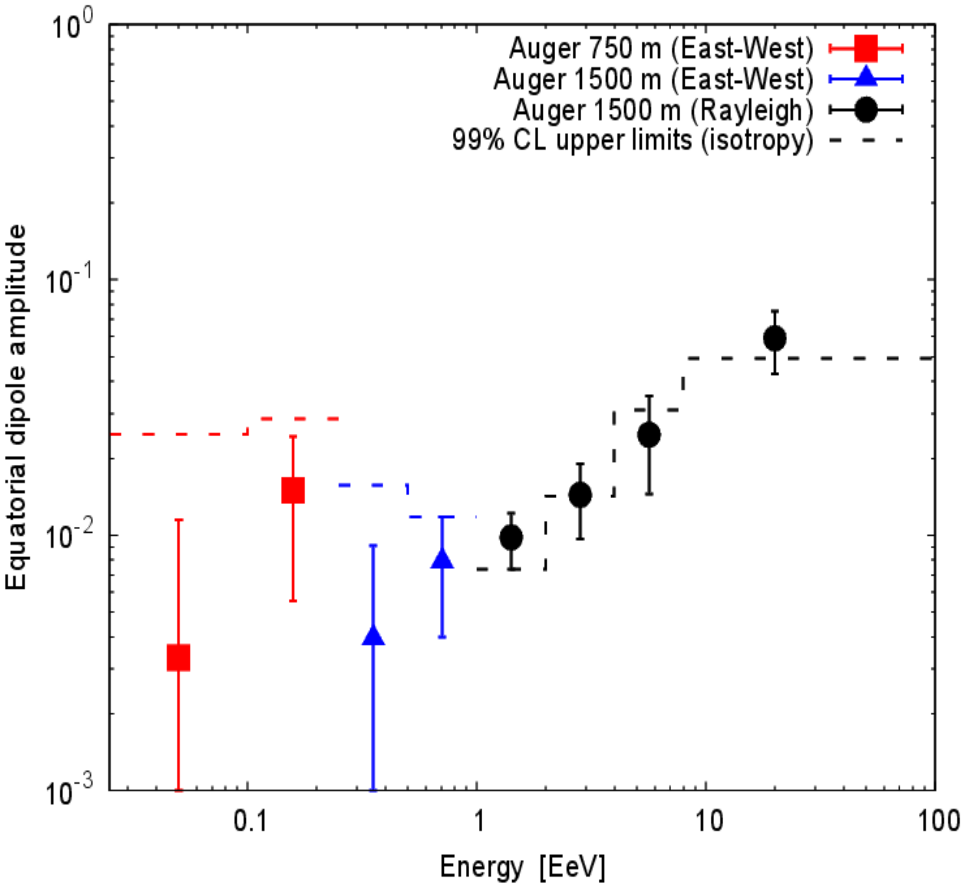
$$\boxed{r = \left| \frac{\langle\cos\delta\rangle d_\perp}{1 + \langle\sin\delta\rangle d_\parallel} \right|}$$

- **3D: Spherical harmonic in (ra,dec)**

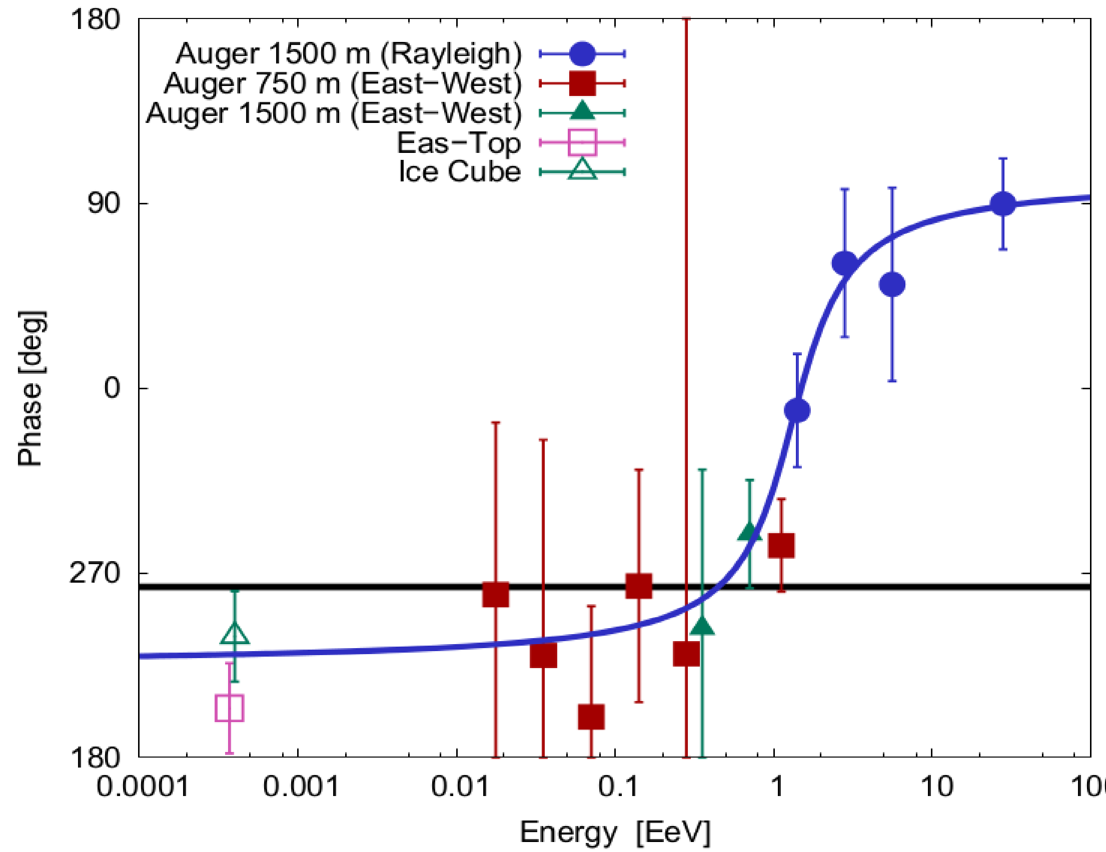
First-Harmonic analysis in Right Ascension

SD Data: 1 January 2004 – 31 December 2012 E > 0.025 EeV

AMPLITUDE



PHASE

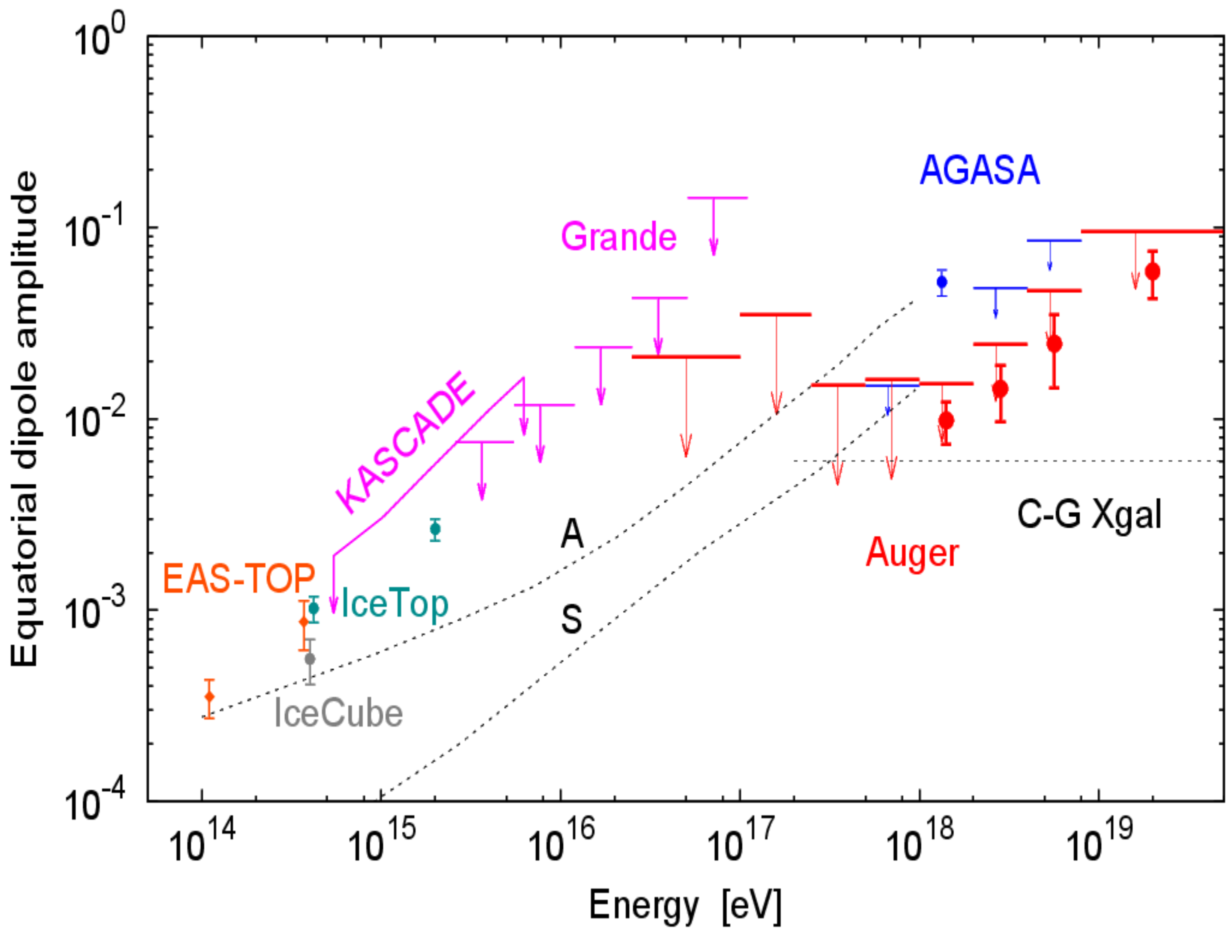


$d_{\perp} \approx r/\langle\cos\delta\rangle$
3 bins above 1 EeV have isotropic probability < 1%

Hint to a constant value, RA ~ 270° (GC) below 1 EeV and a transition to a constant value (RA ~ 90°) above 4 EeV

Ongoing test with independent data

Auger ICRC 2013



Equatorial dipole upper limits

Interesting hint of LS anisotropy: dipole rising from ~1% @ 1 EeV to few % @ 10 EeV

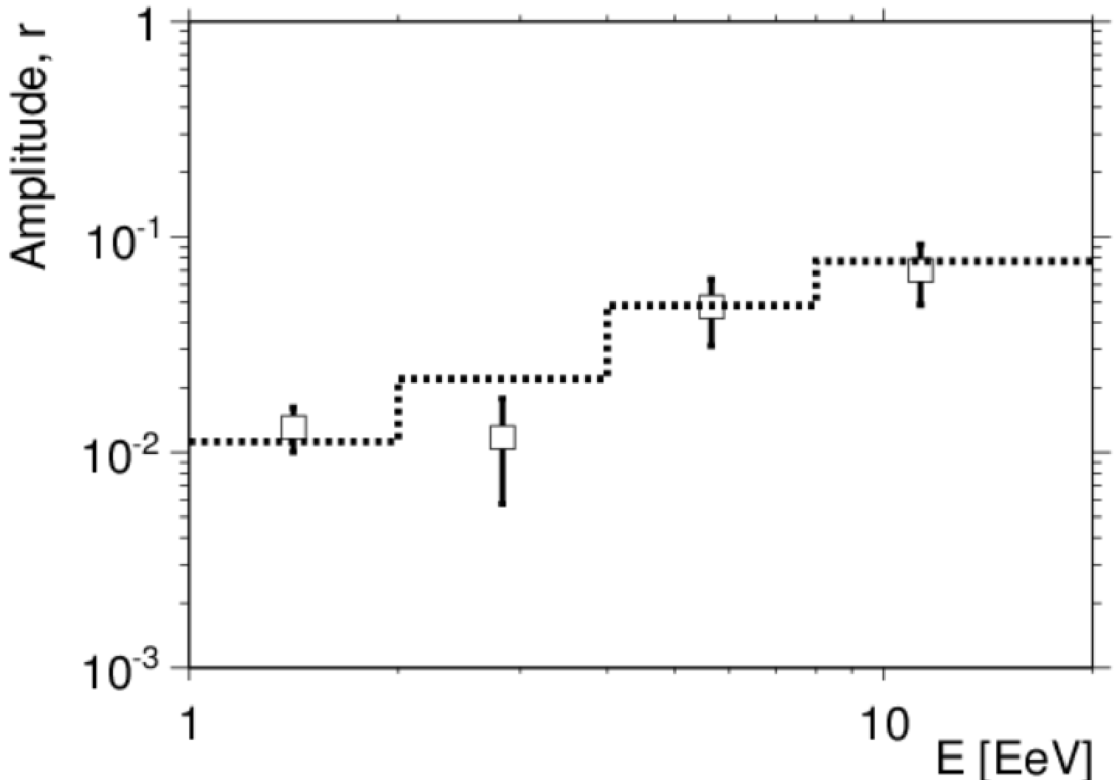
E[EeV]	N	$d_\perp$[%]	φ [°]	P($>d_\perp$)[%]	$d_\perp^{ul}$[%]
1 - 2	557829	1.0±0.2	335±14	**0.03**	1.5
2 - 4	148790	1.4±0.5	8±19	**0.9**	2.5
4 - 8	31270	2.5±1.0	63±25	5.5	4.8
> 8	12292	5.9±1.6	86±16	**0.1**	9.4

3D dipole reconstruction

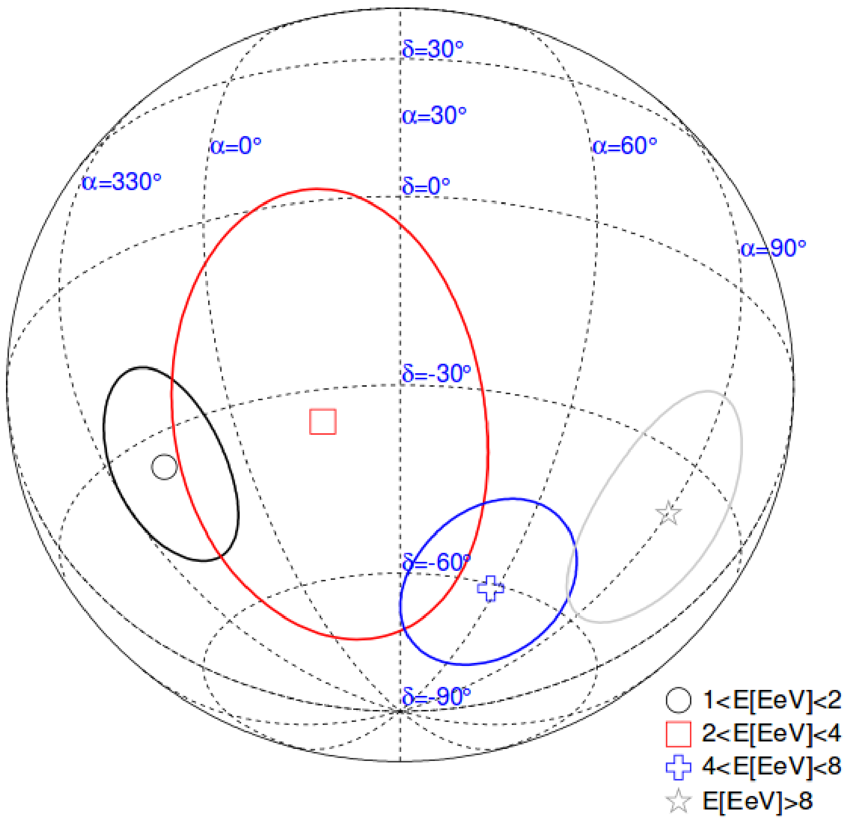
Full multipole analysis: $$\Phi(\mathbf{n}) = \sum_{\ell \geq 0} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\mathbf{n}) \longrightarrow a_{\ell m} = \int_{4\pi} \mathrm{d}\Omega\ \Phi(\mathbf{n}) Y_{\ell m}(\mathbf{n})$$

Incomplete sky-coverage and non-uniform exposure:

$$b_{\ell m} = \int_{\Delta\Omega} \mathrm{d}\Omega\ \omega(\mathbf{n}) \Phi(\mathbf{n}) Y_{\ell m}(\mathbf{n}) = \sum_{\ell' \geq 0} \sum_{m'=-\ell'}^{\ell'} a_{\ell' m'} \int_{\Delta\Omega} \mathrm{d}\Omega\ \omega(\mathbf{n}) Y_{\ell' m'}(\mathbf{n}) Y_{\ell m}(\mathbf{n})$$



Total dipole amplitude



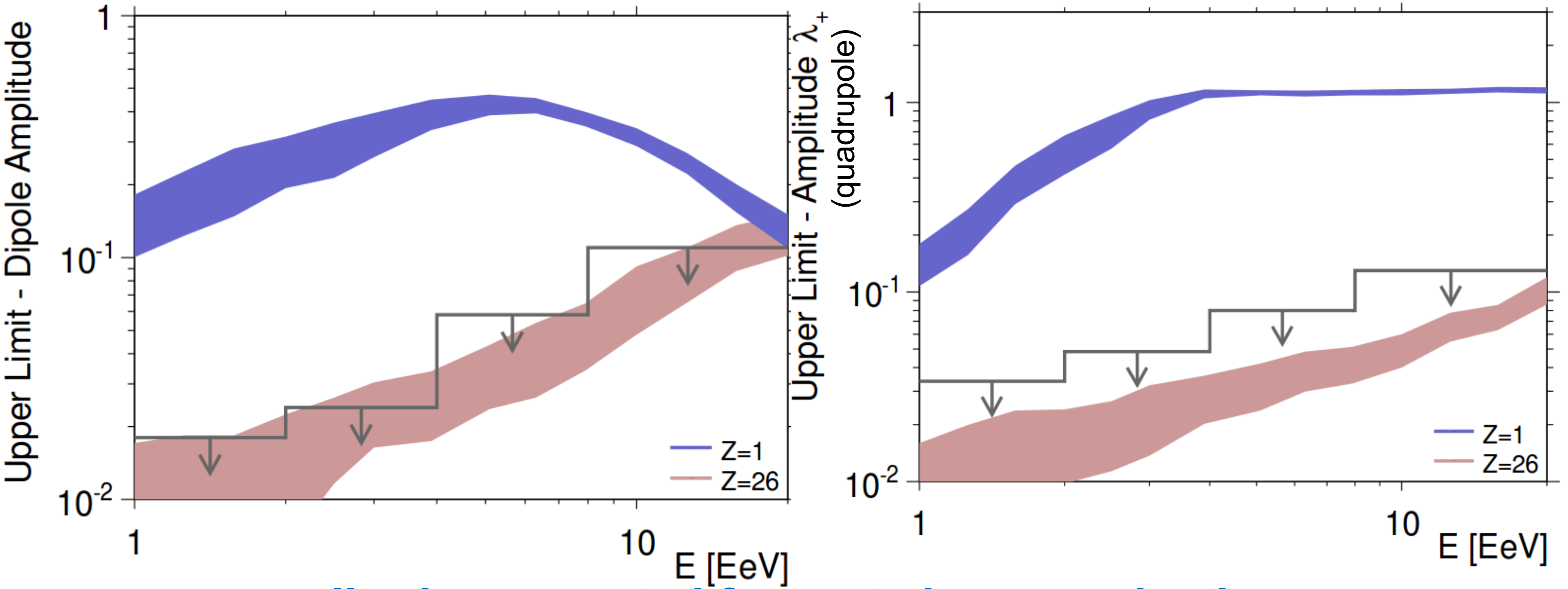
dec → pointing to the southern hemisphere

RA → evolving with energy

Auger ICRC 2013

Galactic or extragalactic?

Auger ApJL 2013



amplitudes expected from stationary galactic sources

Galactic magnetic field: Regular: disk field and halo field + Turbulent field

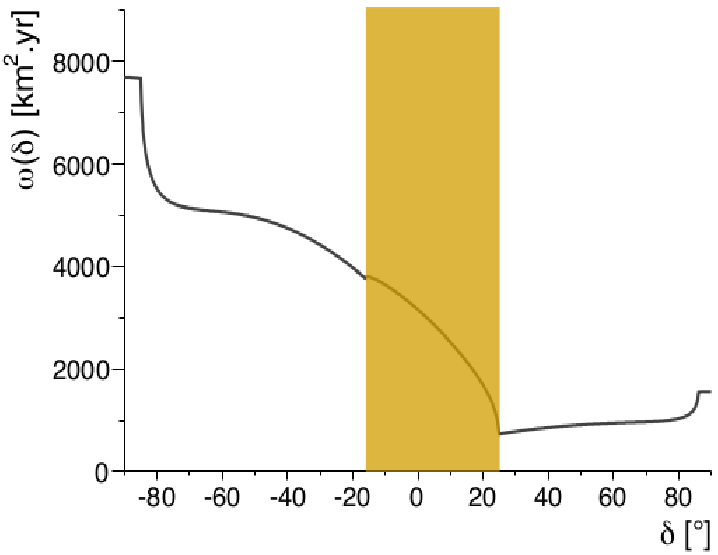
BSS model: Symmetric with respect to the galactic plane (logarithmic spiral model with reversal direction in two arms)

Anti-symmetric with respect to the galactic plane and purely toroidal

Kolmogorov power spectrum

Protons @ EeV energies from galactic origin disfavored

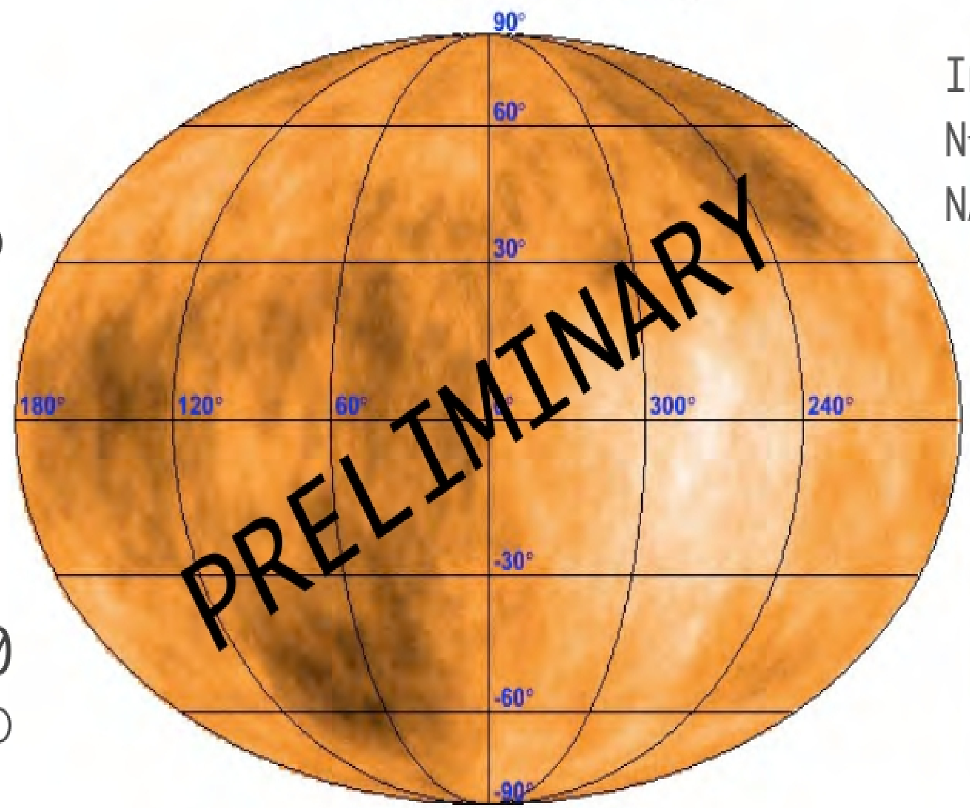
Ongoing joint Auger-TA project to combine data from two hemispheres → measure dipole above 10 EeV with full-sky coverage



N_{TA}~1800
(~5200 km^2 sr yr)

N_{Auger}~10900
(~32000 km^2 sr yr)

E > 10^{19} eV ; 30° smoothing



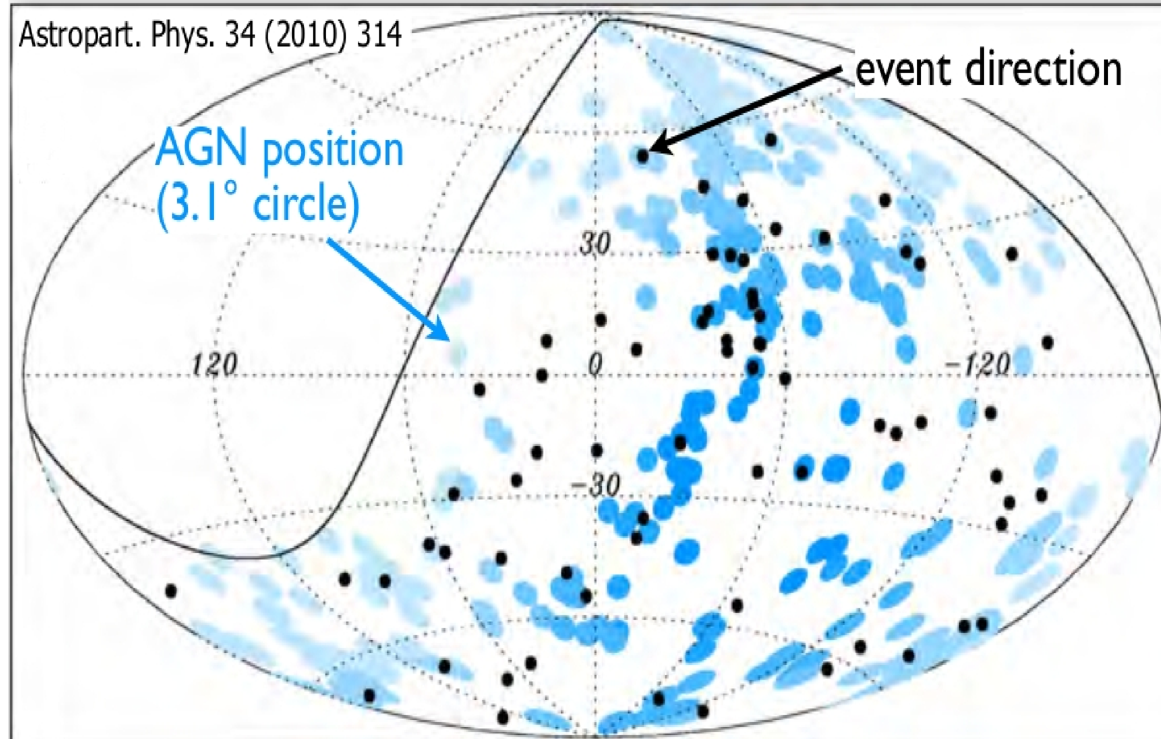
In the overlap :
N_{TA}~650
N_{Auger}~3400

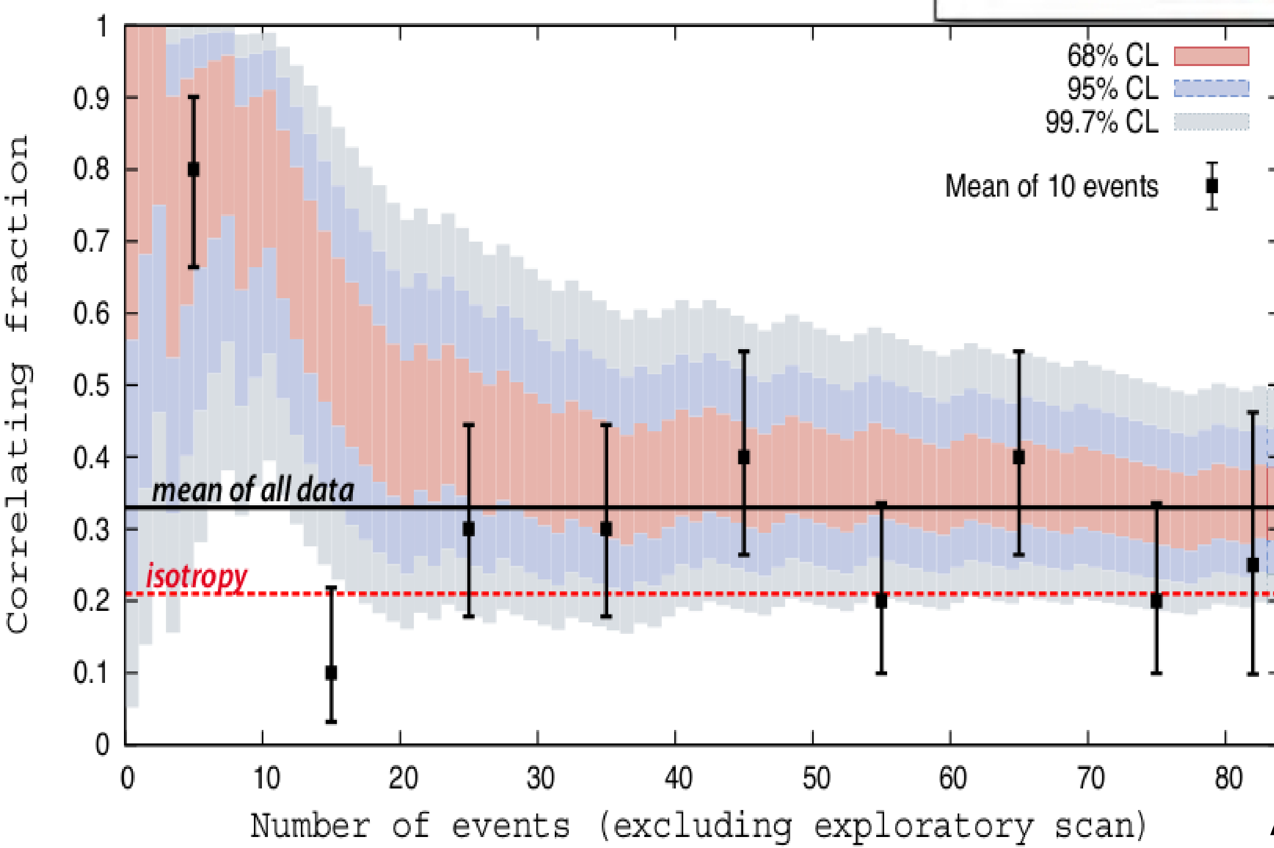
First Combined Auger and TA Analysis

Auger-TA ICRC 2013

SMALL SCALES
Correlation with AGNs: VCV catalog

E > 55 EeV
$\Delta\Psi \leq 3.1\,°$
$z \leq 0.018$



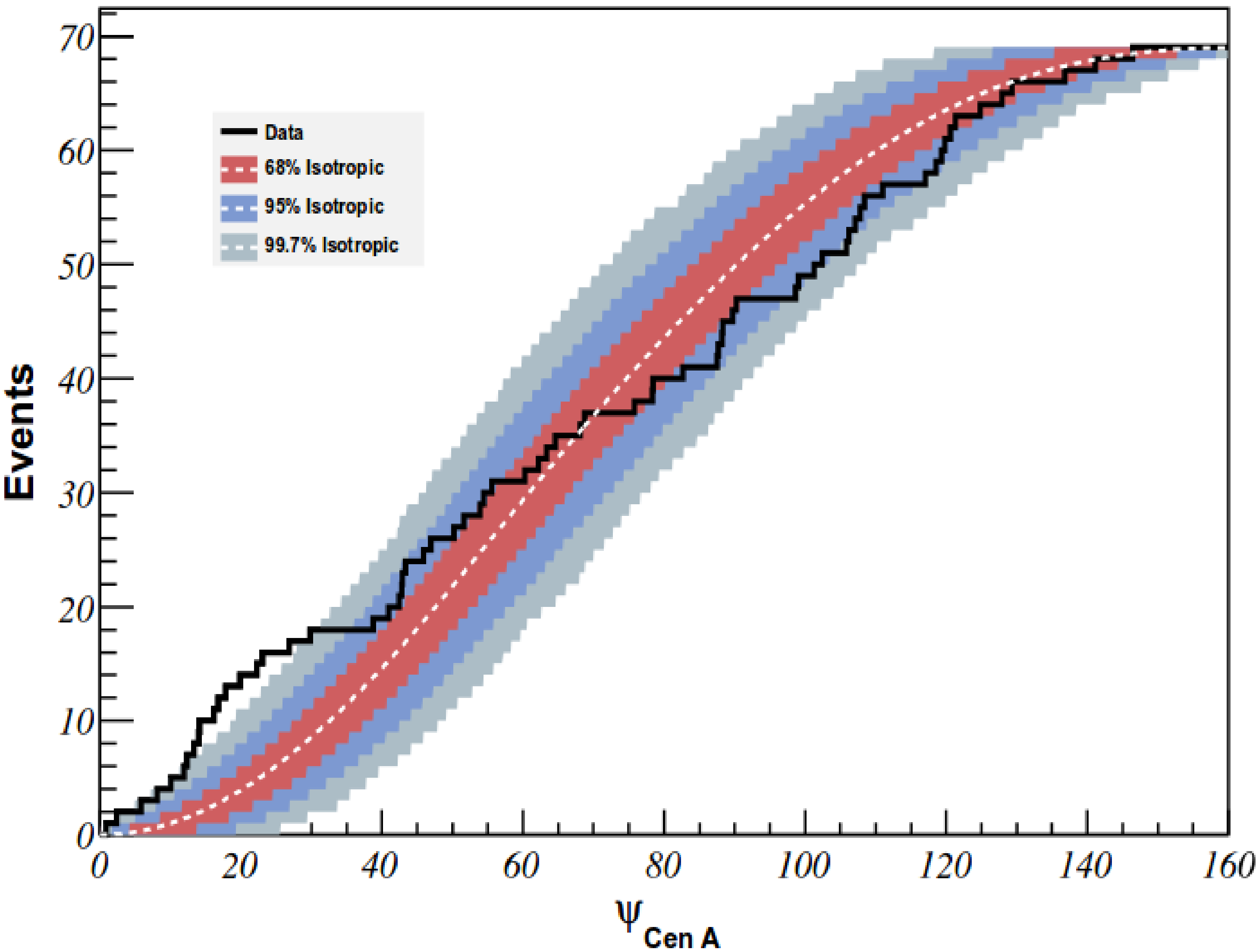


correlation
28/84 = (33 ± 5)%
with iso-bkg = 21%

Small fraction of light (correlating) UHECRs?
Mostly heavy composition?

Auger ICRC 2011

Excess near Cen A



Closest AGN
at 3.8 Mpc

at 18 deg
13/69 events
isotropic → 3.2

Interesting region being monitored, not significant → KS prob 4%

Galactic neutron searches

- Neutrons of 1 EeV can reach us from ~ 9 kpc ($\langle d \rangle$ = 9.2 E[EeV] kpc)

- Produced by protons in pion-producing interactions with ambient photons, protons or nuclei, also producing gamma rays

- Travel without deflections

- Air showers indistinguishable from protons

Blind search: no significant point-like (at the angular resolution) overdensity found → sources are extragalactic, or transient, or optically thin to escaping protons, or weak & densely distributed

ApJ 760 (2012)

Search for point-like excess of EeV CRs around different stacked sets of sources (HESS, Fermi sources, X-ray binaries, pulsars, Galactic Plane and Galactic center, magnetars, microquasars, etc.): no candidate found with significant excess → Flux(>1EeV) < 0.01 km^{-2} yr^{-1}

ApJL (2014)

Summary

Arrival directions quite isotropically distributed

Large scales anisotropy hints:

- Dipole amplitudes with isotropic probability < 1% in three energy ranges equatorial dipole rising from ~1% @ 1 EeV to few % @ 10 EeV

- Constant phase of first-harmonic in right ascension in independent energy ranges points to ~ 270^o (GC direction) below 1 EeV and ~ 90^o at higher energies → Ongoing test with independent data

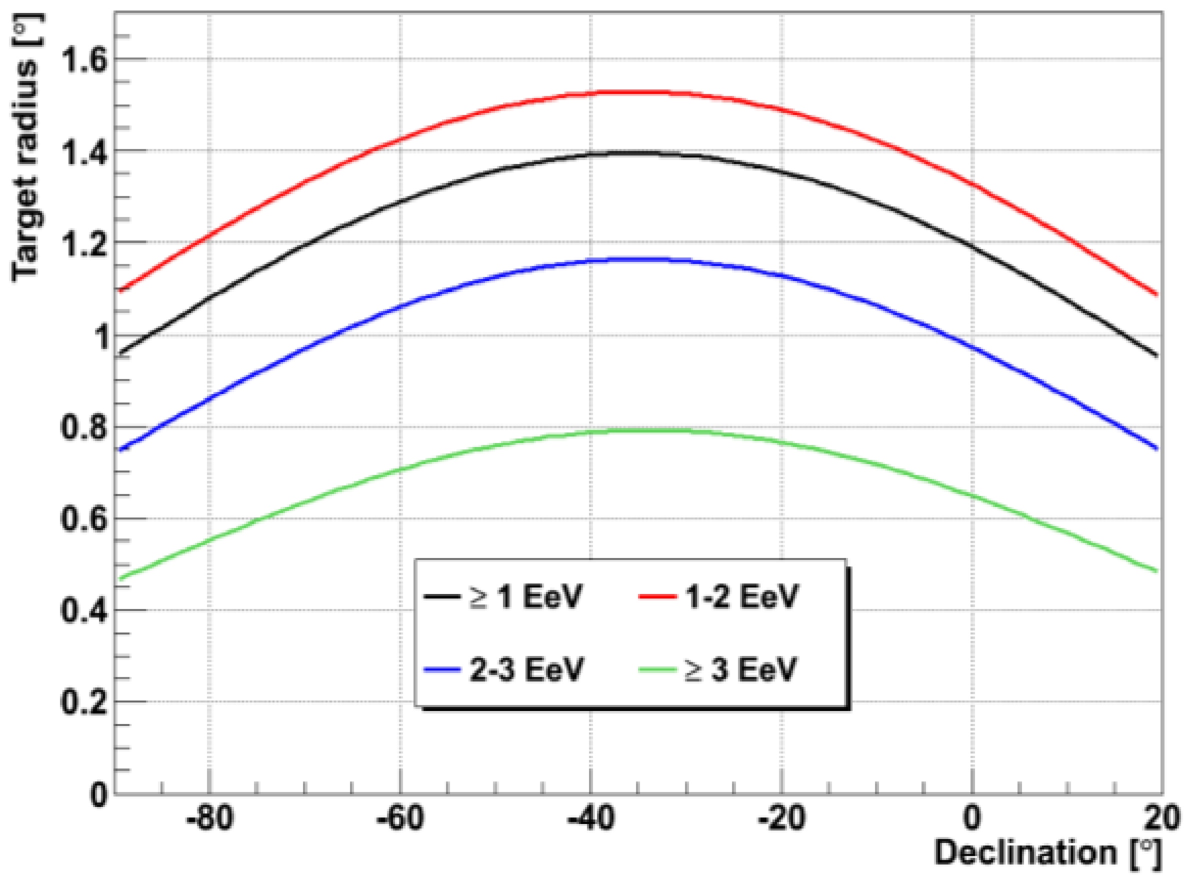
- Upper limits on dipole and quadrupole patterns challenge models with a galactic light component at EeV energies (measurements suggest light composition around 1 EeV)

Small angular scales:

- Correlation with AGNs above 57 EeV decreased to 33%
- Excess near Cen A?
- No point-like (neutron) excess at 1 EeV

BACK UP

- The target radius is 1.05 x AR. AR ≡ angular resolution ≡ 68% containment radius



Neutron searches

- Ten stacks of sources:
  - HESS source catalog (http://www.mpi-hd.mpg.de/hfm/HESS/pages/home/sources/).
  - Gamma-ray pulsars (Fermi 2nd Catalog, Astrophys. J. Suppl. S.**199**, (2012) 31).
  - Low-mass x-ray binaries (Astron. Astrophys. **469**, (2007) 807).
  - High-mass x-ray binaries (Astron. Astrophys. **455**, (2006) 1165).
  - Millisecond radio pulsars (Astron. J. **129**, (2005) 1993-2006).
  - Standard radio pulsars (Astron. J. **129**, (2005) 1993-2006).
  - Microquasars (http://www.aim.univ-paris7.fr/CHATY/Microquasars/microquasars.html).
  - Magnetars (http://www.physics.mcgill.ca/~pulsar/magnetar/main.html).
  - Galactic Plane.
  - Galactic Center.

Neutron searches

- Weighted and unweighted stacked analysis for each target set and each energy range.

		Weighted p-value P_w				Unweighted p-value P			
Stack	No.	1-2 EeV	2-3 EeV	$\geq$ 3 EeV	$\geq$ 1 EeV	1-2 EeV	2-3 EeV	$\geq$ 3 EeV	$\geq$ 1 EeV
Reg. PSRs	1326	0.95	0.06	0.49	0.67	0.80	0.43	0.48	0.89
msec PSRs	83	0.68	0.61	0.74	0.85	0.23	0.80	0.88	0.42
γ-ray PSRs	75	0.02	0.90	0.14	0.089	0.59	0.49	0.71	0.60
LMXB	142	0.17	0.38	0.31	0.13	0.76	0.37	0.33	0.64
HMXB	77	0.82	0.76	0.49	0.84	0.68	0.82	0.43	0.61
HESS	60	0.48	0.28	0.41	0.62	0.86	0.30	0.59	0.83
Microquasars	13	0.95	0.52	0.65	0.94	0.70	0.13	0.51	0.23
Magnetars	13	0.79	0.94	0.40	0.96	0.98	0.90	0.59	0.98
G. Center	1	-	-	-	-	0.77	0.41	0.45	0.73
G. Plane	1	-	-	-	-	0.68	0.85	0.31	0.81

- **No significantly small combined p-value.**

- List of targets with smallest p-value in each stack, for the energy range E ≥ 1EeV.
- The ULs are Zech 95% CL (NIM A **277**, (1989) 608).
- The penalized p-value is $p^{*}=1-(1-p)^{N}$.

Stack	RA [°]	DEC [°]	Obs	Exp	Flux U.L. [$km^{-2}yr^{-1}$]	E-Flux U.L. [$eV\ cm^{-2}\ s^{-1}$]	p-value	p^{*}
Reg. PSRs	267.44	-56.09	249	204	0.0161	0.117	0.0012	0.78
msec PSRs	270.46	-14.29	174	146	0.0156	0.114	0.014	0.70
γ-ray PSRs	195.60	-32.95	222	191	0.0146	0.107	0.017	0.72
LMXB	129.35	-42.90	238	208	0.0135	0.0983	0.023	0.96
HMXB	249.77	-46.70	237	208	0.0129	0.0945	0.028	0.88
HESS	284.58	2.09	101	80.6	0.0155	0.113	0.016	0.61
Microquasars	288.75	10.08	68	53.4	0.0161	0.118	0.030	0.33
Magnetars	248.97	-47.59	224	209	0.00992	0.0724	0.15	0.88
G. Center	266.40	-28.94	178	186	0.0062	0.045	0.73	-
G. Plane	Galactic lat. = 0°		15488	15600	-	-	0.81	-