PIERRE AUGER OBSERVATORY

Vulcano Workshop 2014

Large-Scale Distribution of Arrival Directions of Cosmic Rays Detected at the Pierre Auger Observatory Above 10 PeV

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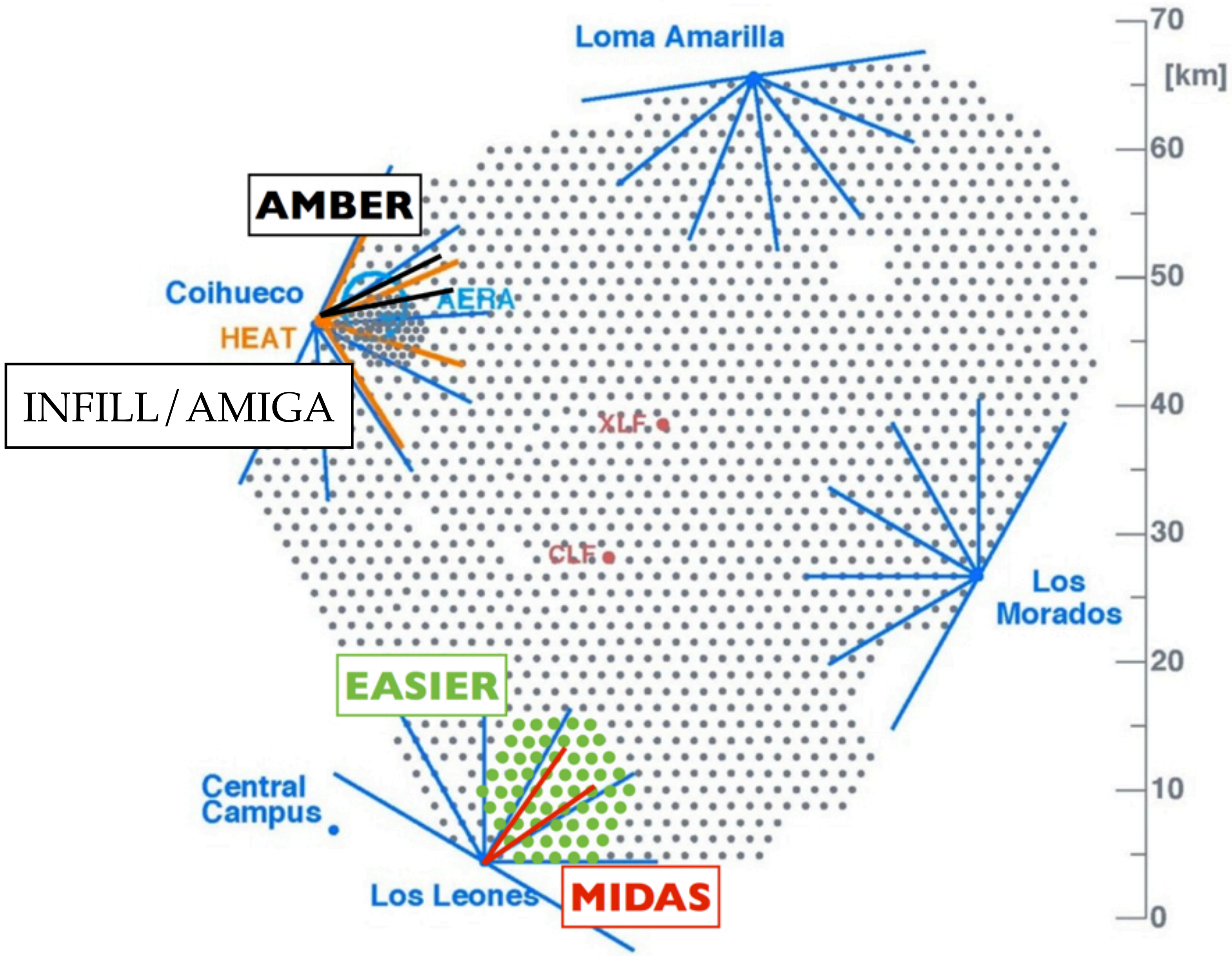
University of Torino and INFN

The world's largest cosmic ray observatory



- ***Surface Detector (SD)***: 1600 water-Cherenkov detectors covering 3000 km^2 on a triangular grid with 1500 m spacing (full efficiency @ $3 \cdot 10^{18}$ eV)

- ***Infill detector*** with 750m spacing (23.5 km^2 area) enhancing the Observatory capabilities down to 10^{16} eV (full efficiency @ $3 \cdot 10^{17}$ eV)

- ***Fluorescence Detector (FD)***: 27 fluorescence telescopes at 4 sites overlooking the SD array

Large scale anisotropy studies

- Complementary to energy spectrum & mass composition to understand CRs nature and origin
- Transition galactic/extragal. origin should induce a significant change in their LS angular distribution
  - ***if galactic at 10^{18} eV:*** %-level modulation (depending on GMF, composition, distrib. of sources, ...)
  - ***if extra-gal. at 10^{18} eV:*** no structure except for a CMB-dipole (~ 0.6 %)
  - ➡ **dipole expected:** escape from the Galaxy ***or*** extra-gal. CG
  - ➡ **quadrupole expected:** sources distributed on galactic ***or*** super galactic plane ***or*** rotation of Galaxy could produce anisotropy by virtue of moving magnetic field (i.e. GMF could transform the extra-gal CG dipole into a quadrupole)

First harmonic analysis in R.A.

[APh 34 (2011) 628]

- ***Data set:*** 1/1/2004-31/12/2012 → $3 \cdot 10^6$ events (82318 above E_{eff}, exposure ~$3.2 \cdot 10^4$ km^2 sr yr)
- ***Energy range:*** from 10^{16} eV to more than 10^{19} eV (regular SD + Infill array)
- First harmonic modulations are small:
  - Account for spurious modulations (experimental & atmospheric) → ***modified Rayleigh analysis***
  - Use methods which are not sensitive to these effects → ***East-West method***

Analysis methods

Modified Rayleigh analysis (E>1 EeV): *[Mollerach & Roulet, JCAP 0508 (2005) 004]*

- Classical Rayleigh formalism slightly modified to account for non-uniform exposure
- Fourier coeff. $a = \frac{2}{\mathcal{N}} \sum_{i=1}^{N} \omega_i cos\alpha_i$ and $b = \frac{2}{\mathcal{N}} \sum_{i=1}^{N} \omega_i sin\alpha_i$ → amplitude $r = \sqrt{a^2 + b^2}$ and phase $\phi = arctan\left(\frac{b}{a}\right)$
  - ω_i accounting for the array growth, dead time and tilt of the array
  - energy assignment corrected for weather and geomagnetic effects
  - below 1EeV weather effects also affect detection efficiency → reliably applied only above

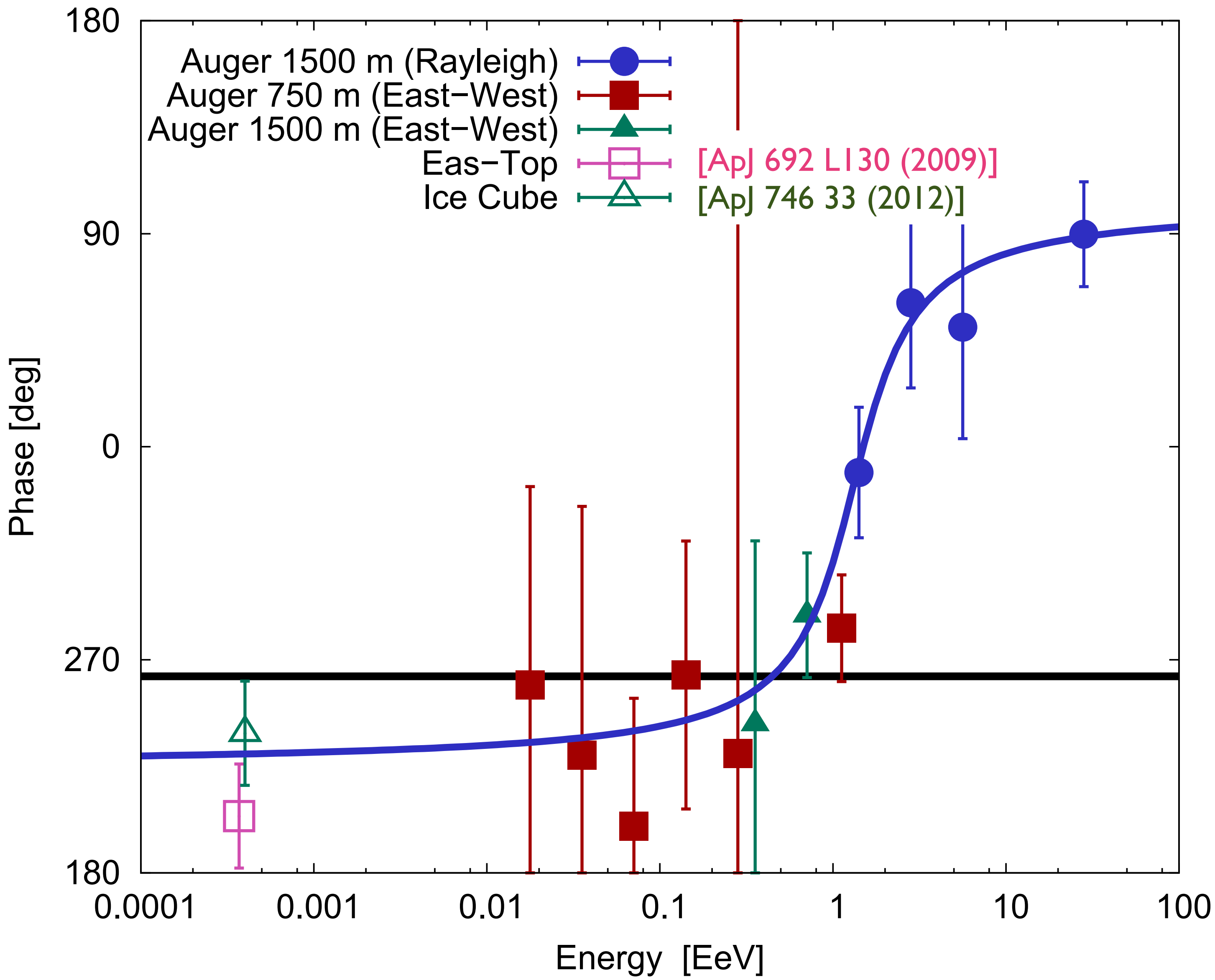
East-West method (E<1 EeV): *[R. Bonino et al., ApJ 738 (2011) 67]*

- Differential method: $\frac{dI_{tot}^{true}(t)}{dt} \simeq \frac{I_E^{obs}(t) - I_W^{obs}(t)}{< h >}$
- Instantaneous exposure for E and W events is the same, *i.e.* both sectors are equally affected by detector instabilities and weather conditions
- Standard harmonic analysis on the differences $I_E(\alpha_i)$ - $I_W(\alpha_i)$
- It allows us to remove direction-independent effects (of experimental origin):
  - no correction is needed
  - reduced sensitivity → higher sensitivity required (4 times more events)

Phase of the first harmonic

Prescription set:

data set from 1/1/2004 to 31/12/2010

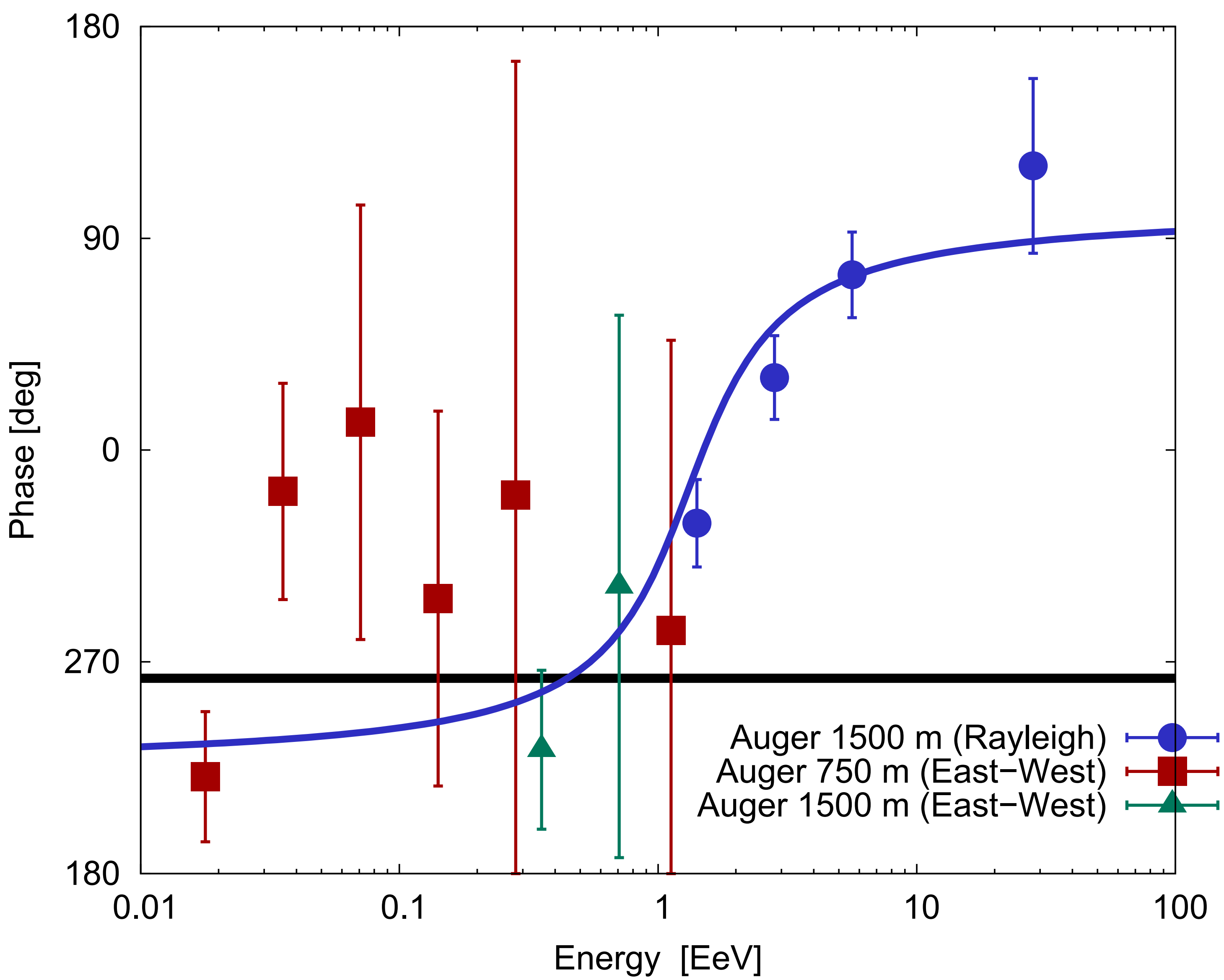


- Hint of a smooth transition from a common phase of $\alpha \simeq 270°$ ($\alpha_{GC} \simeq 268.4°$) in the bins **below 1 EeV** to $\alpha \simeq 90°$ **above 4 EeV**.
- Prescription to verify it with new data, at 99% C.L.:
  - started on 25/6/2011
  - constancy of phase at E<1 EeV with the Infill data
  - transition at E~1 EeV

Phase of the first harmonic

Prescription status:

data set from 25/6/2011 to 31/12/2012



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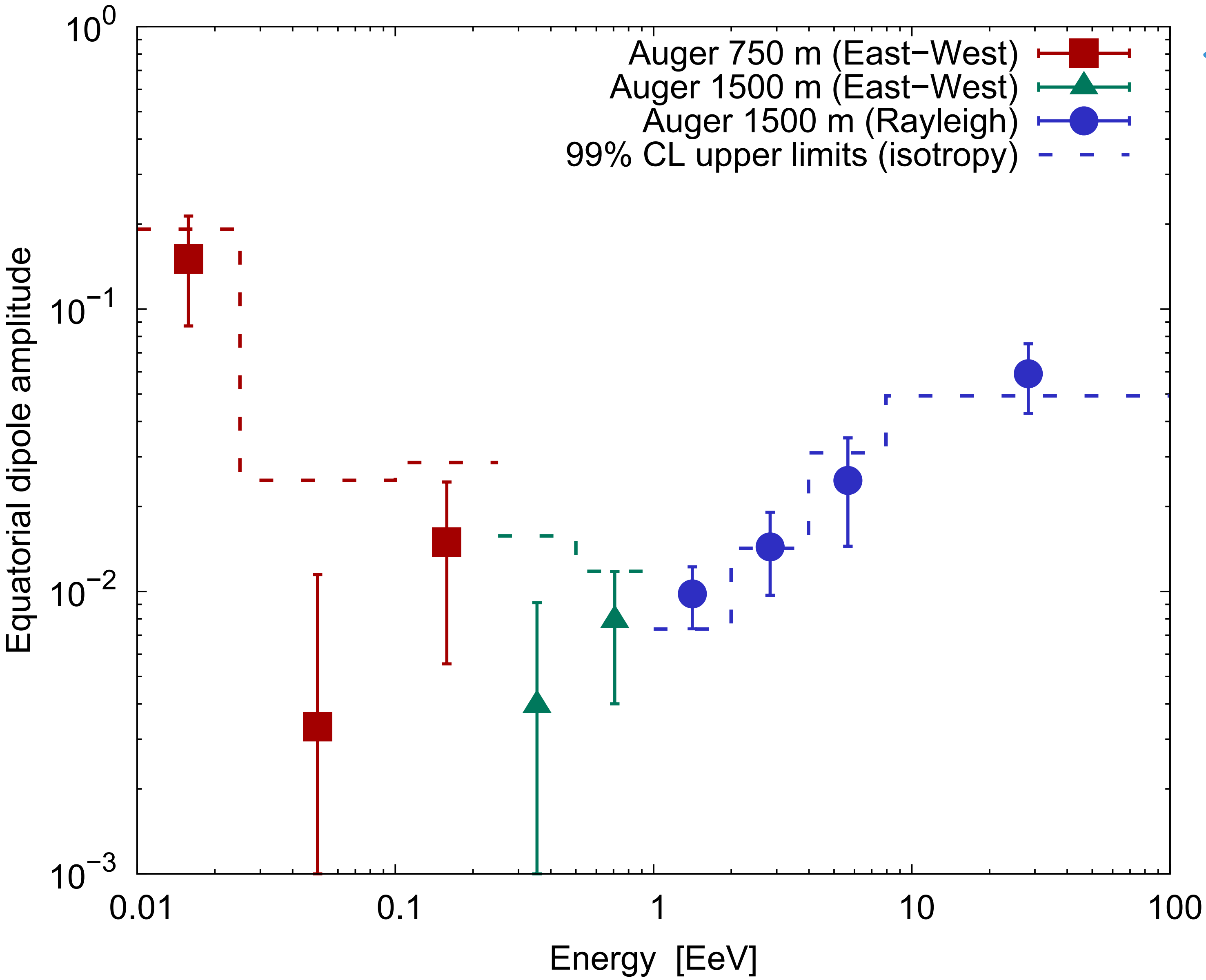
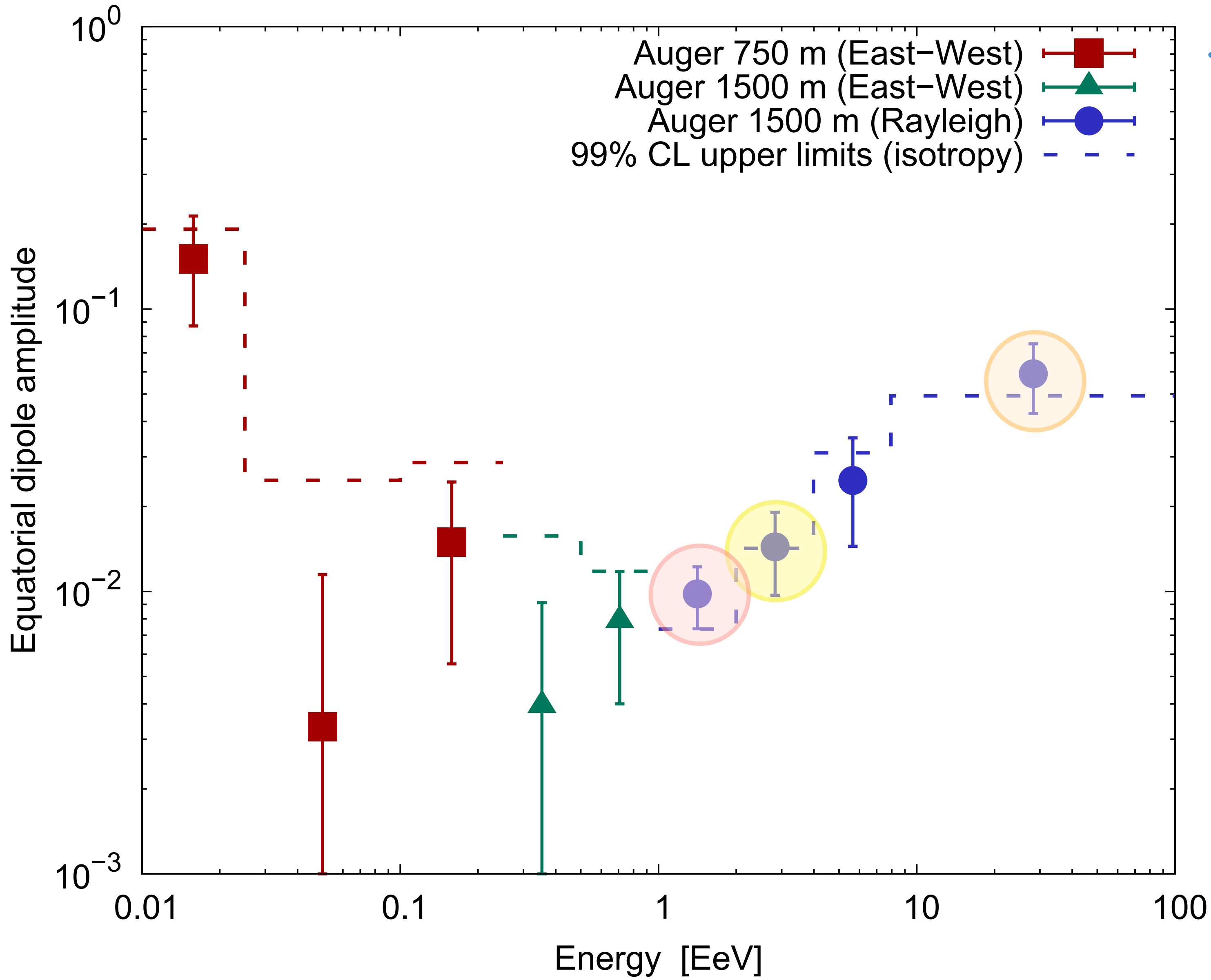
Amplitude of the first harmonic



- Equatorial dipole amplitude, $d_\perp \simeq r/\langle\cos\delta\rangle$, for a comparison with other experiments

- 3 bins above 1 EeV with chance probability < 1%:

Amplitude of the first harmonic



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ΔE [EeV]	$d_\perp \pm \sigma_{d_\perp}$[%]	$P(>d_\perp)$ [%]	$\varphi \pm \sigma_\varphi$
1-2	1.0±0.2	0.03	335±14
2-4	1.4±0.5	0.9	8±19
>8	5.9±1.6	0.1	86±16

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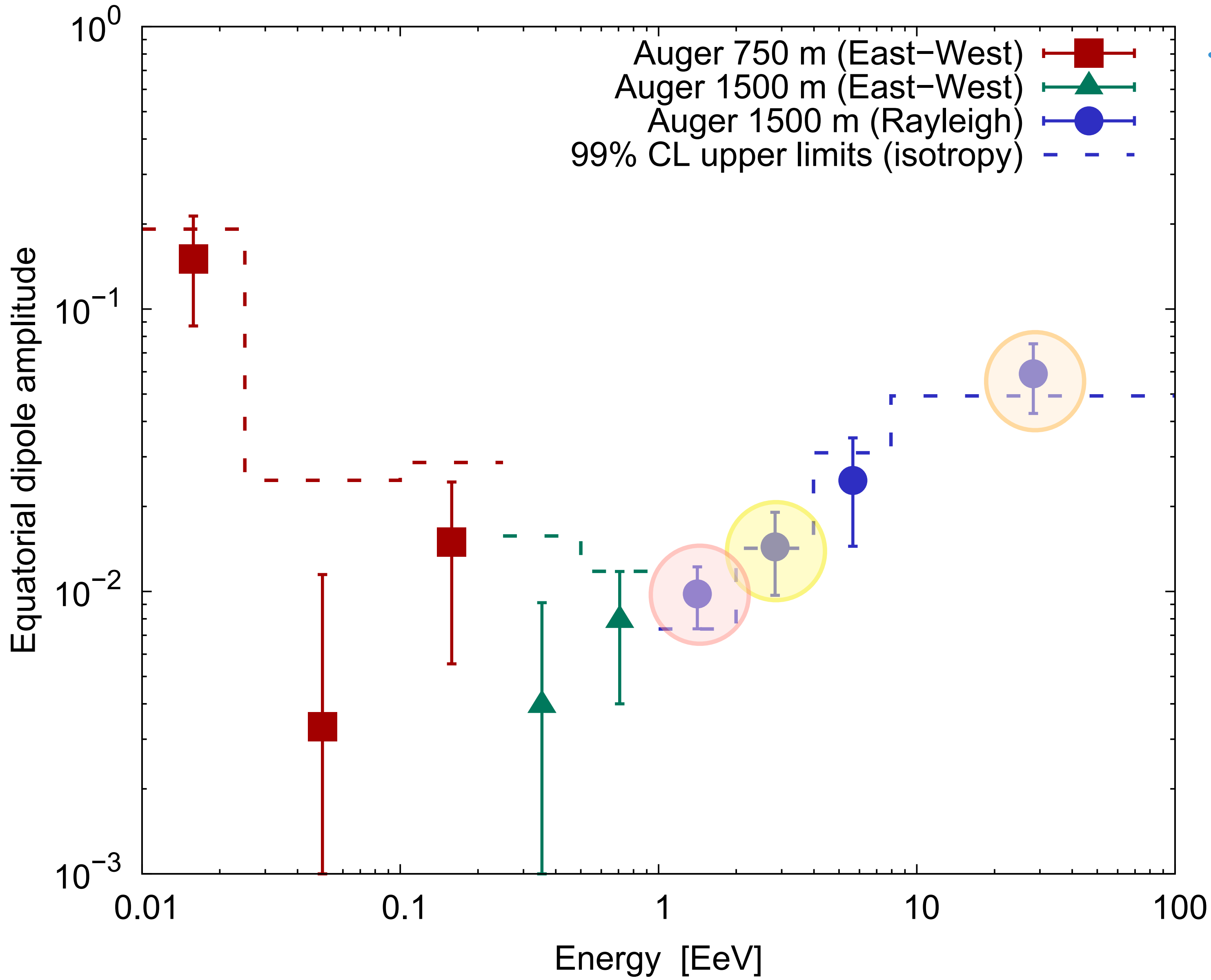

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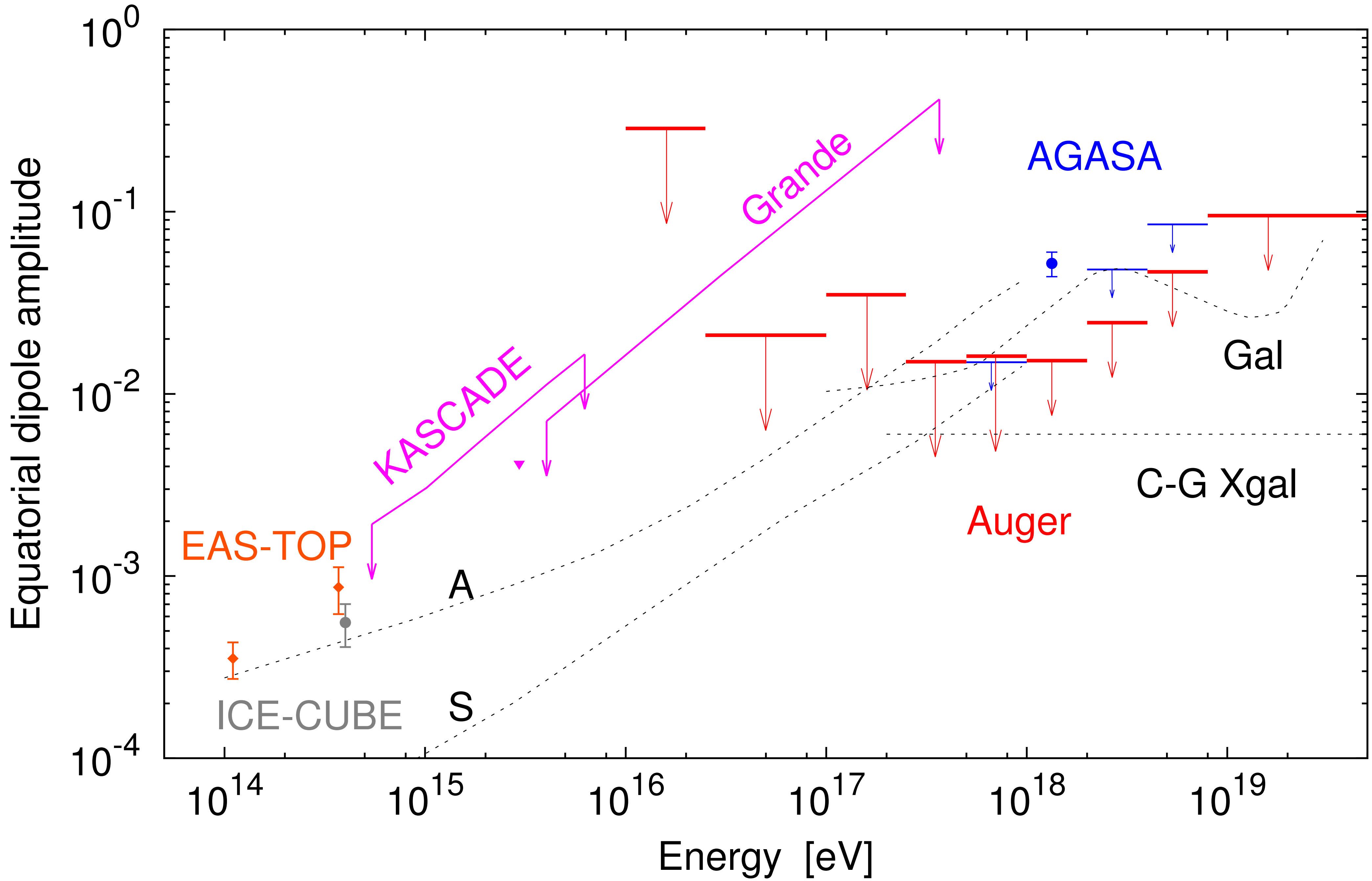
⇒ **Hint for large scale anisotropy above 1 EeV** → to be studied with future data

Upper limits on the amplitudes

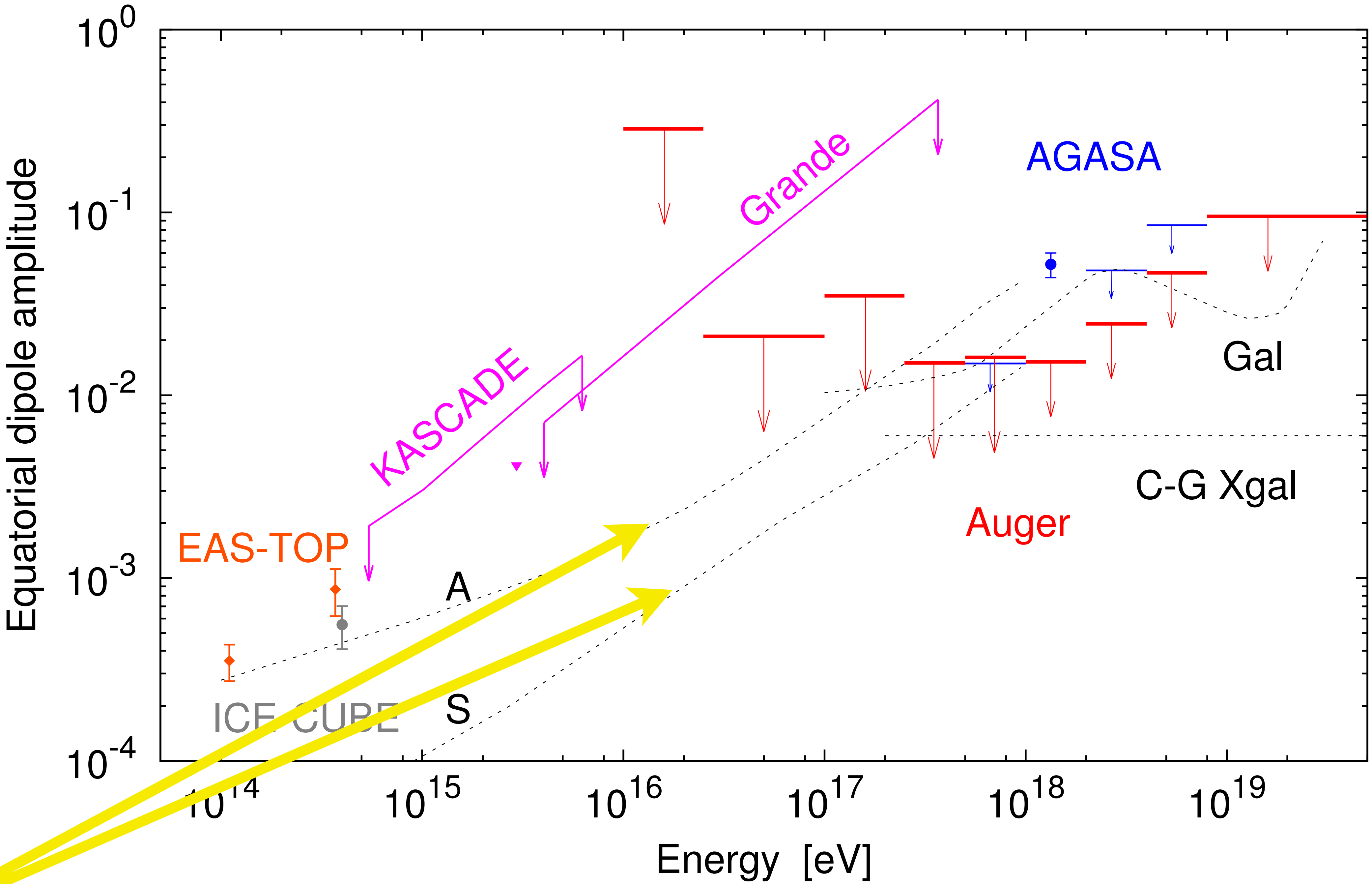


A/S: EeV CRs are galactic, their escape from the galaxy by diffusion/drift causes the anisotropies. A/S = antisymm./symm. halo field

Gal: CRs are galactic up to the highest energies, anisotropy caused by diffusive motion due to the turbulent component of the GMF

C-G Xgal: Compton-Getting effect for extragal. CRs due to the motion of our galaxy wrt the frame of extragal. isotropy (= CMB)

Upper limits on the amplitudes



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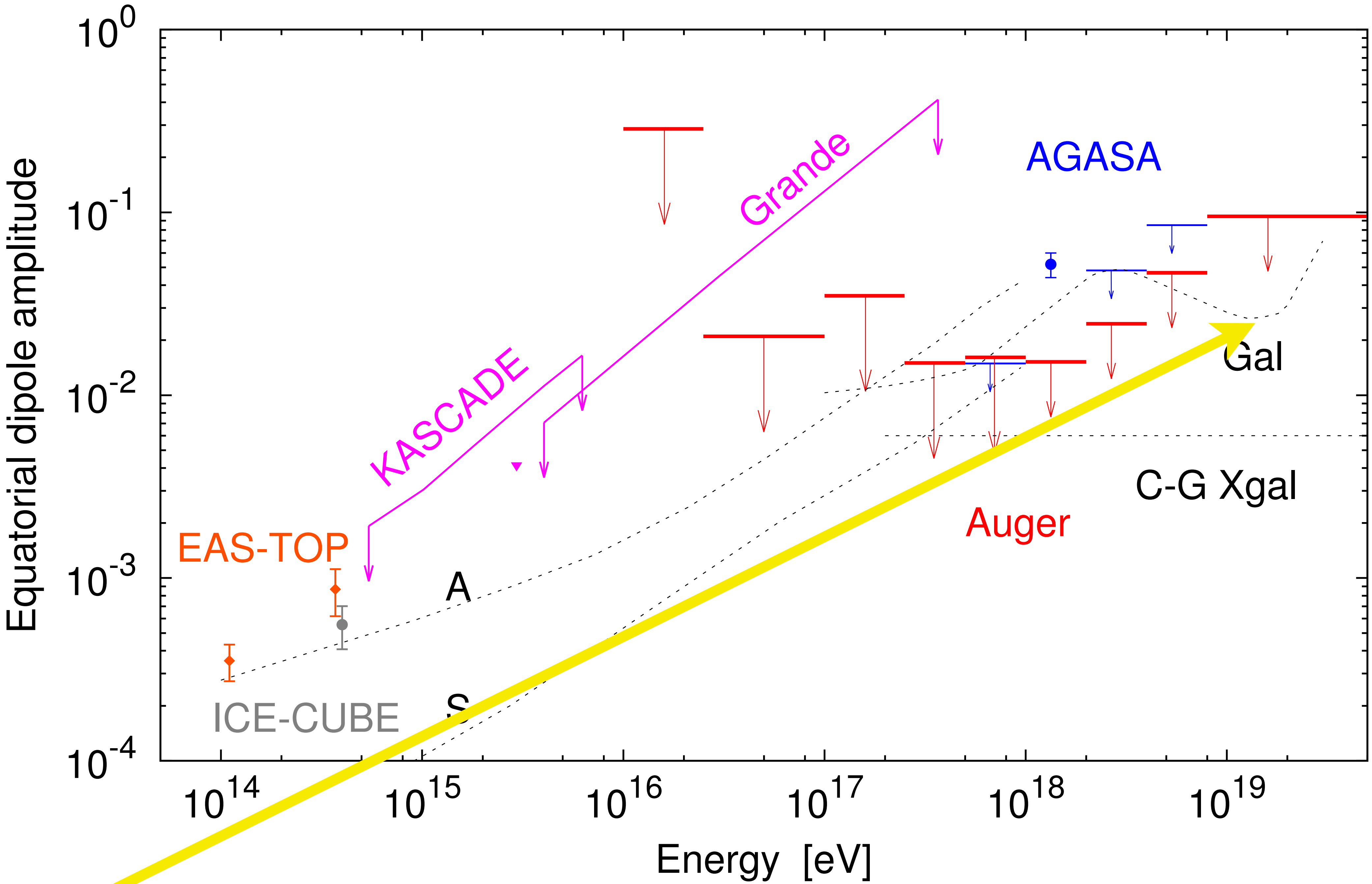

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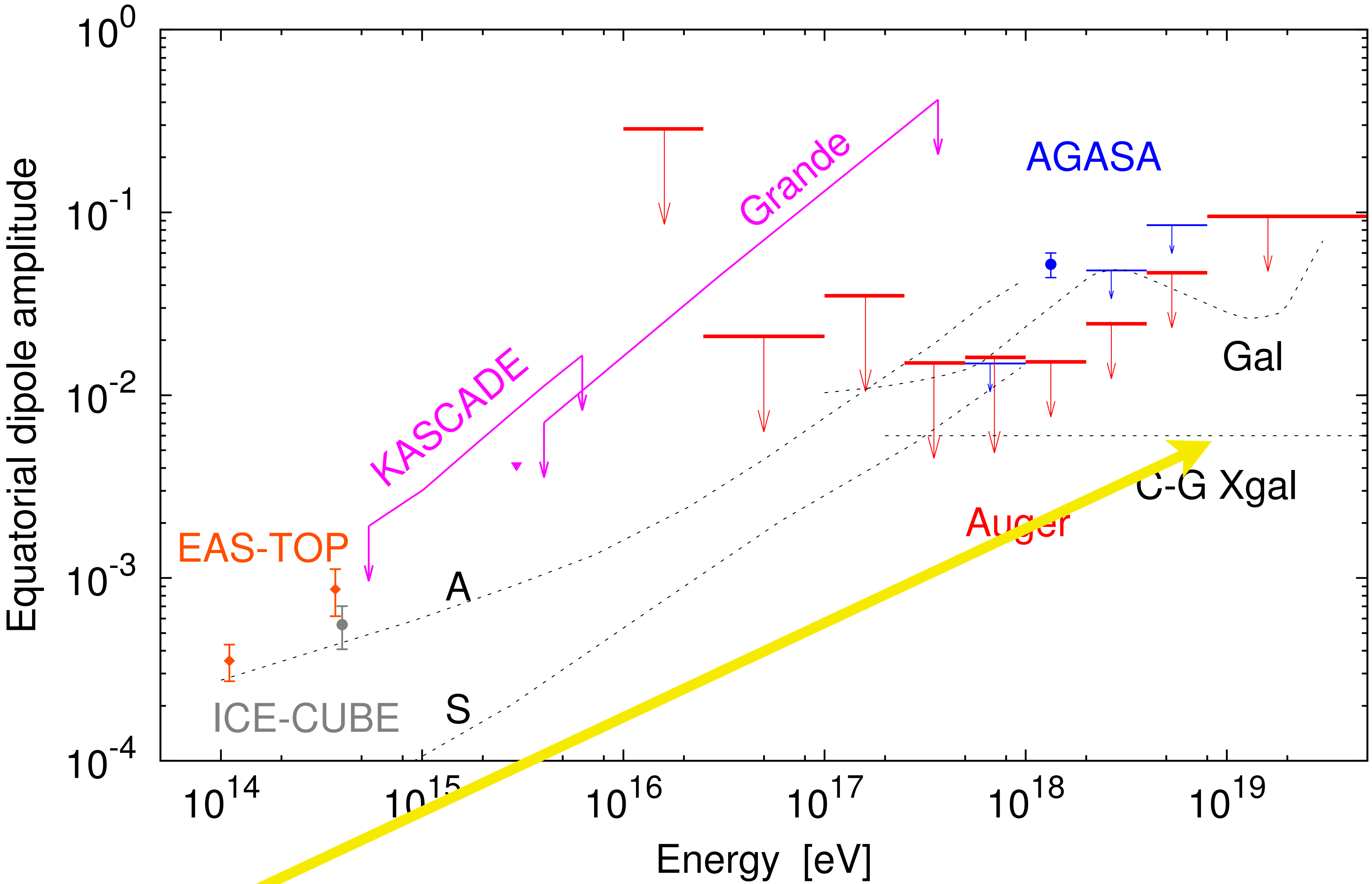

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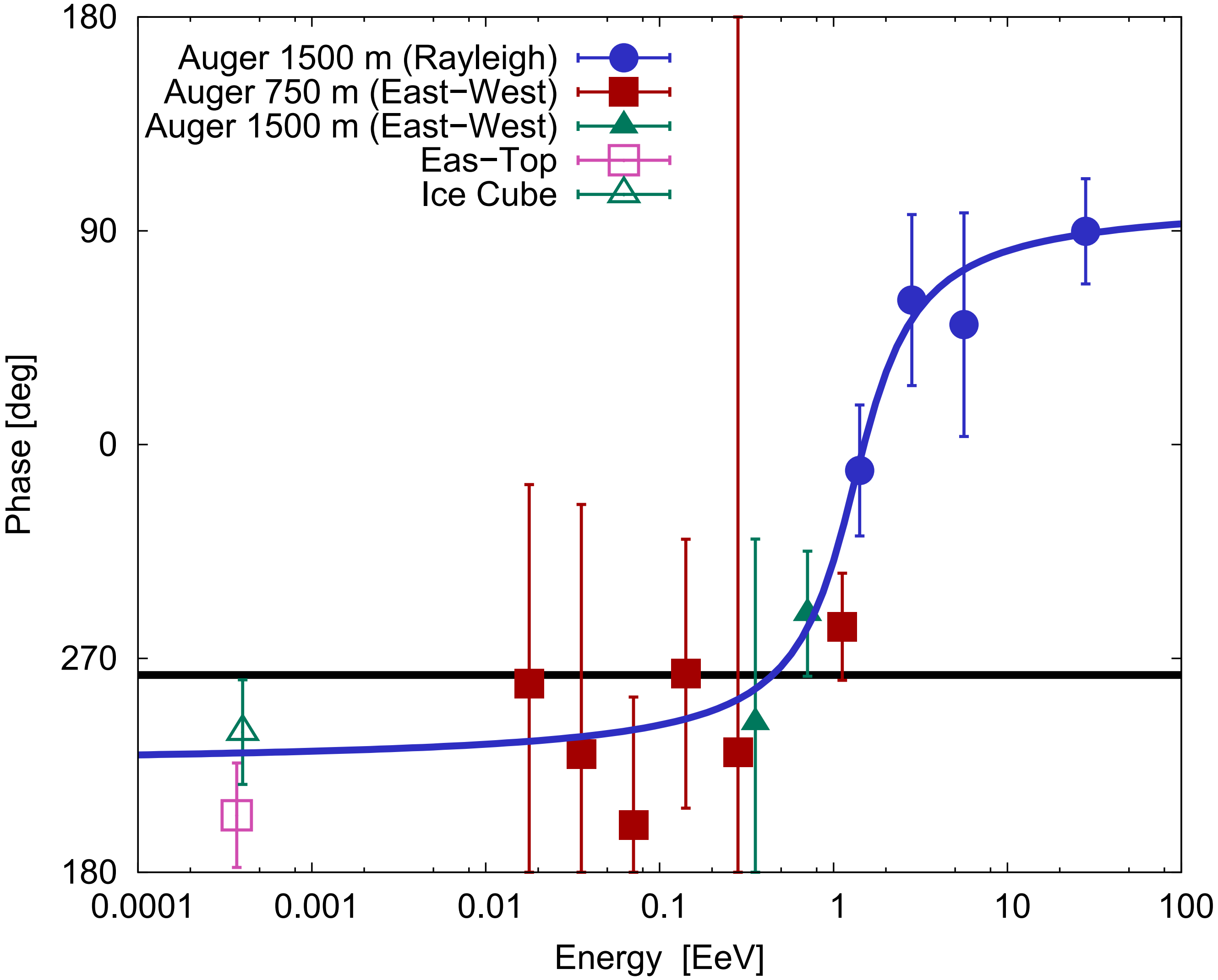
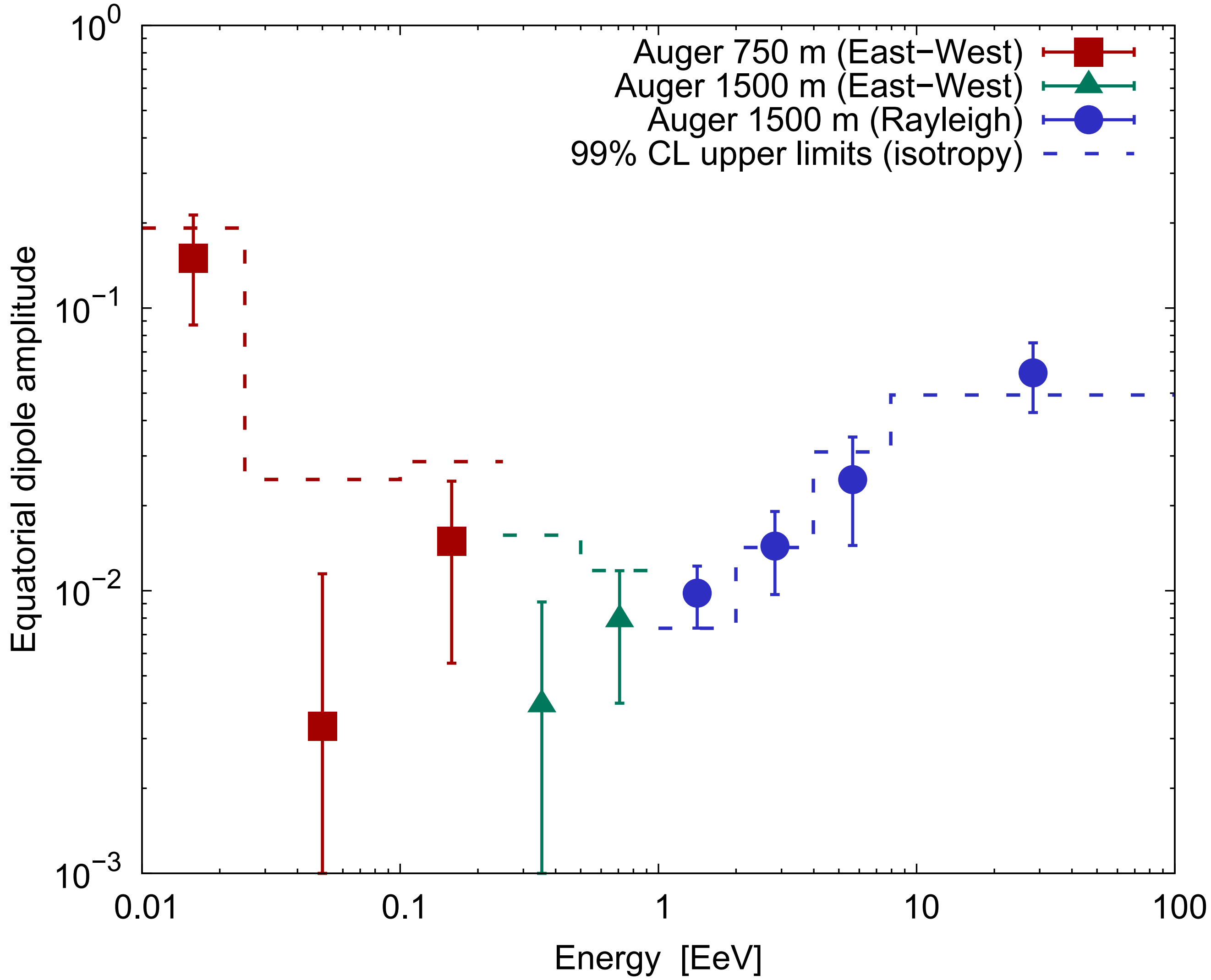
Phase Vs amplitude





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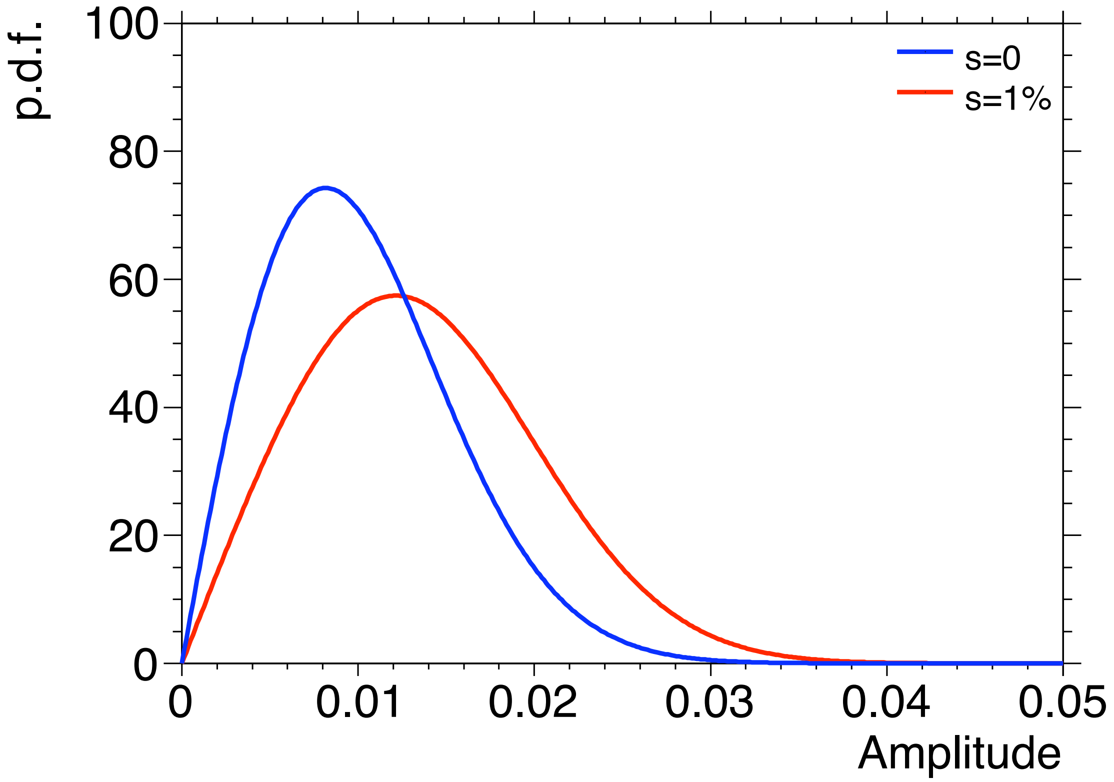
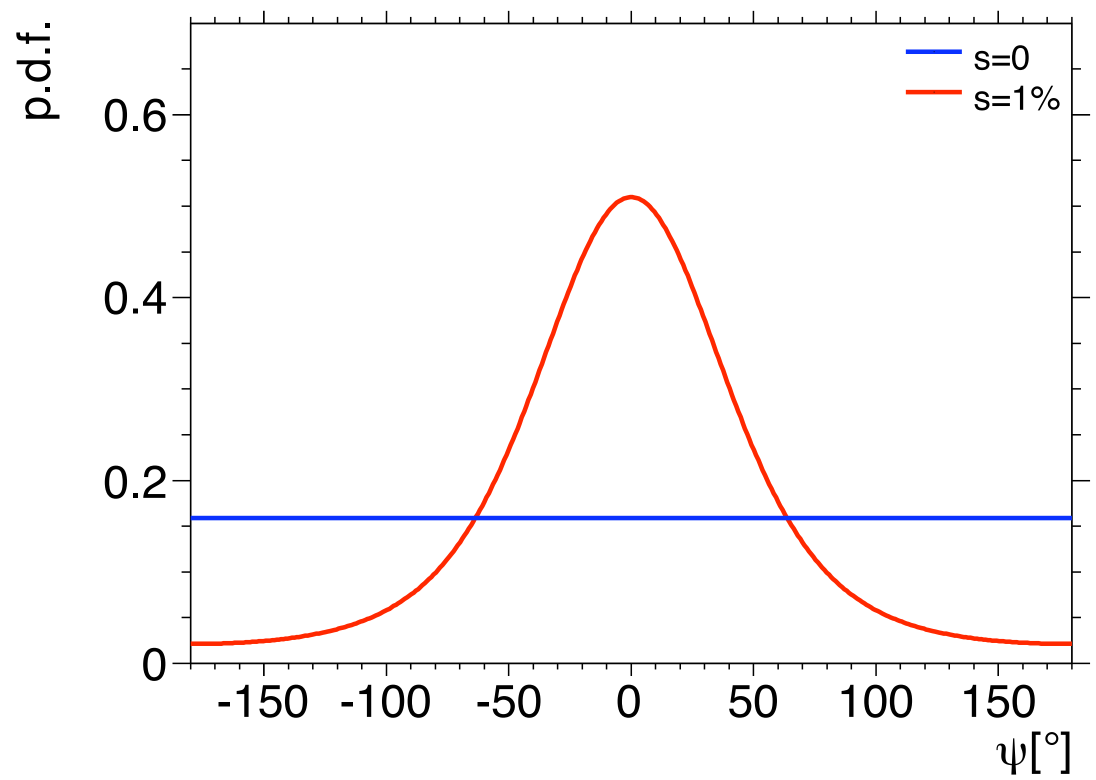
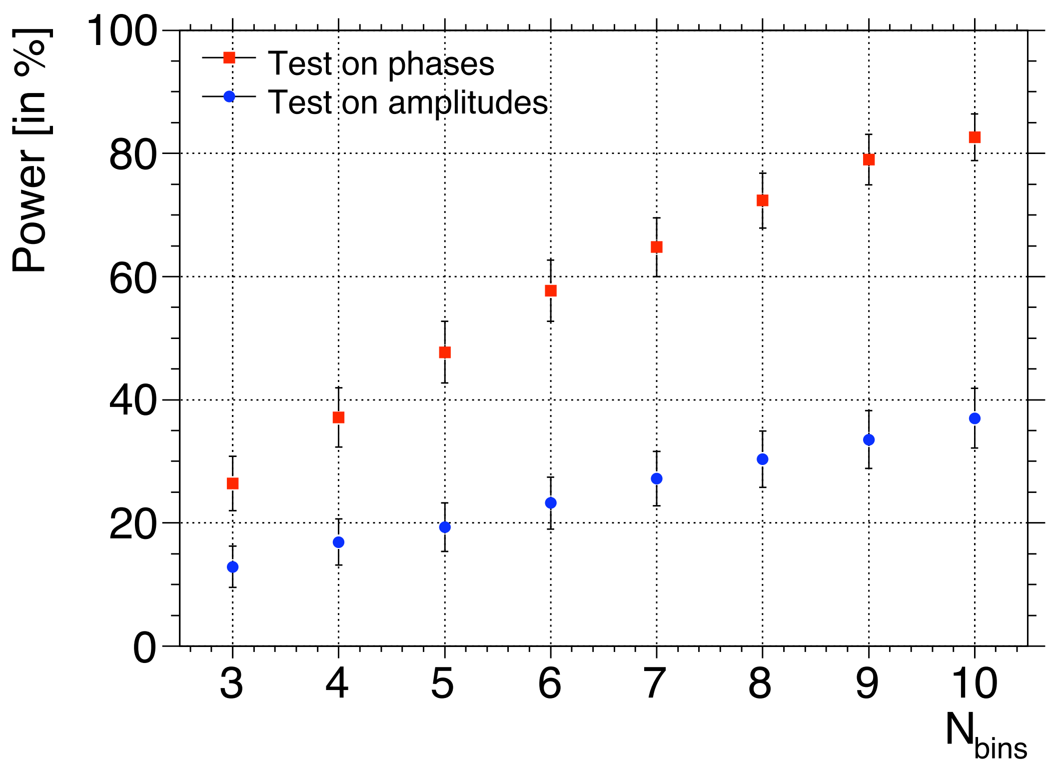






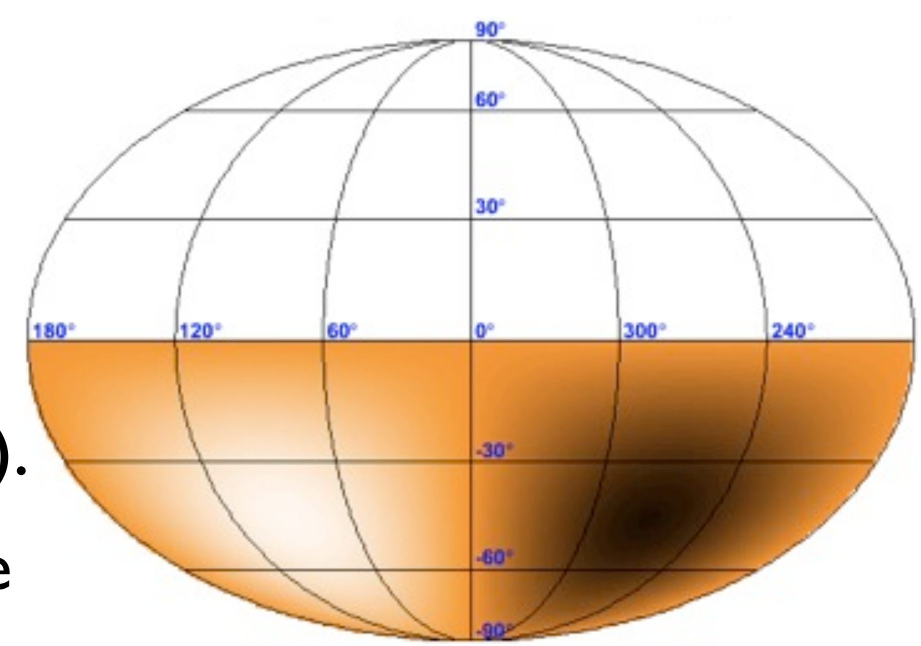
- Phase test ≈ 2.5 times more efficient
- A consistency of the phase measurement in adjacent energy intervals is thus expected with lower statistics than that required for the amplitude to significantly stand out from the background noise

Spherical harmonic analysis

[ApJS 203 (2012) 34 & ApJL 762 (2013) L13]

- Expansion in spherical harmonics: $\Phi(\mathrm{n}) = \sum_{\ell\geq 0}\sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\mathrm{n}) \rightarrow \; a_{\ell m} = \int_{4\pi} \Phi(\mathrm{n}) Y_{\ell m}(\mathrm{n})$
- Non-zero ℓ modes arise from variations of the flux on angular scales ~1/ℓ rad
- **Dipole** vector and **quadrupole** tensor of special interest, but the full set of moments is relevant
- The observed distribution is modulated not only by the CRs angular distribution Φ(E,n) but also by the **exposure function ω(E,n)**
- **Partial sky coverage:**
  - Estimation possible only by assuming a $\ell_{\max}$ to the expansion in spherical harmonics
  - Resolution degraded in proportion to exp($\ell_{\max}$).

    → with the present statistics, this prevents a reliable recovery of the coefficients as soon as $\ell_{\max} \geq 3$.



Spherical harmonic analysis
[ApJS 203 (2012) 34 & ApJL 762 (2013) L13]

Two main critical points:

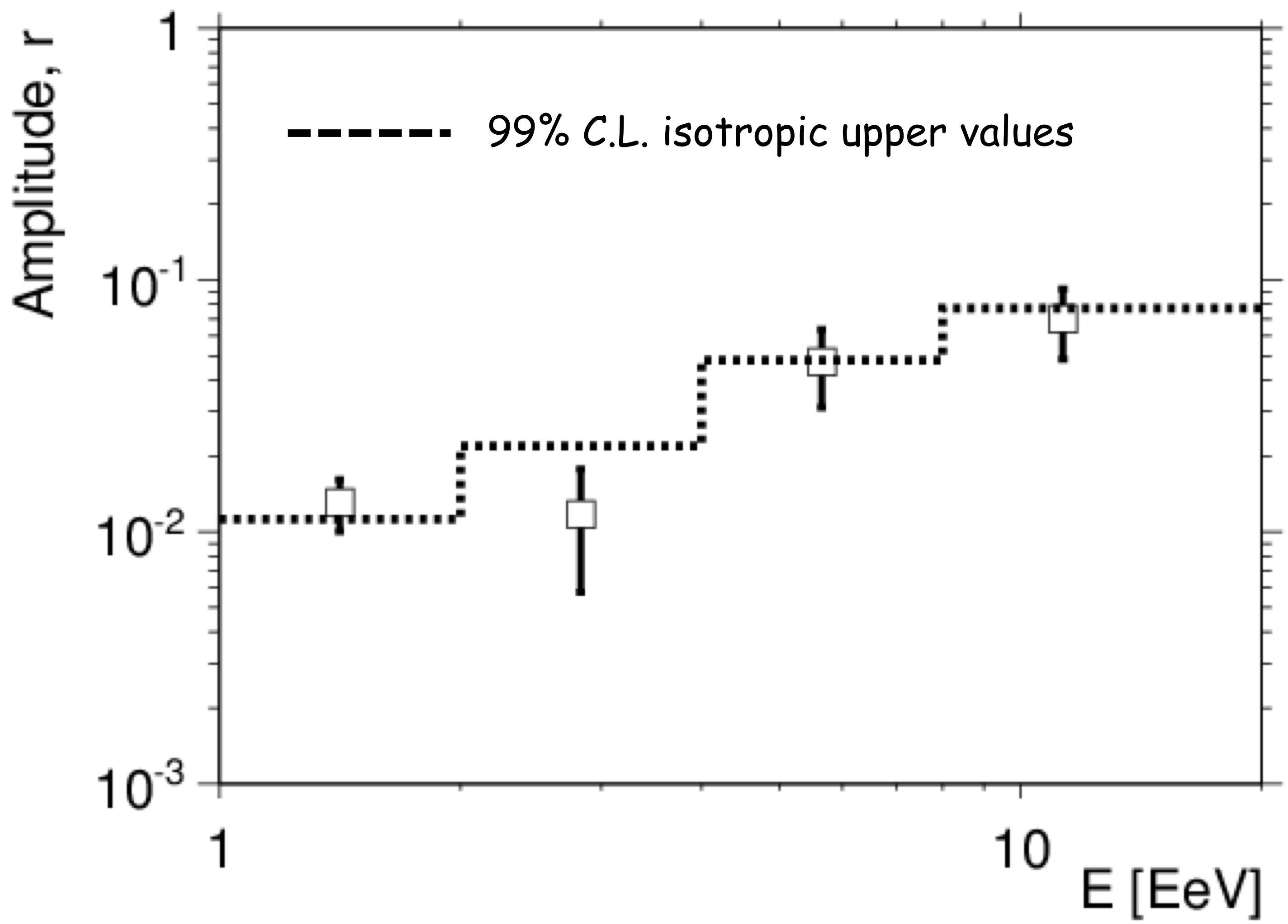
☑ **Control of the event counting rate**:
energy estimate unbiased by the known systematics → unbiased event counting rate:

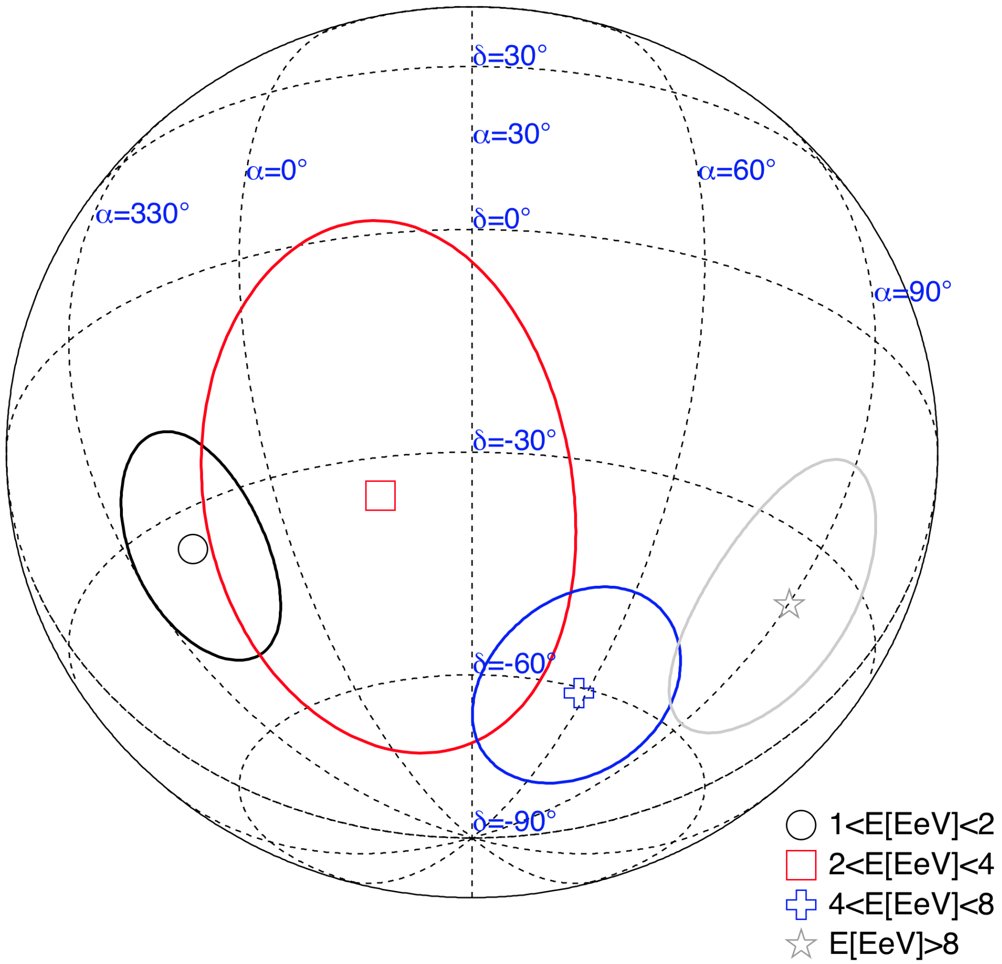
* atmospheric conditions (about 0.2%) *[APh 32 (2009) 89]*
* geomagnetic field (~ 2% for zenith angle around 55°) *[JCAP 11 (2011) 022]*

☑ Determination of the **directional exposure** $\omega(\alpha,\delta,E)$

* operational time of the detector (array growth, dead times,...)
* geometric aperture
* detection efficiency (zenithal dependence, geomagnetic effects, tilt of the array)

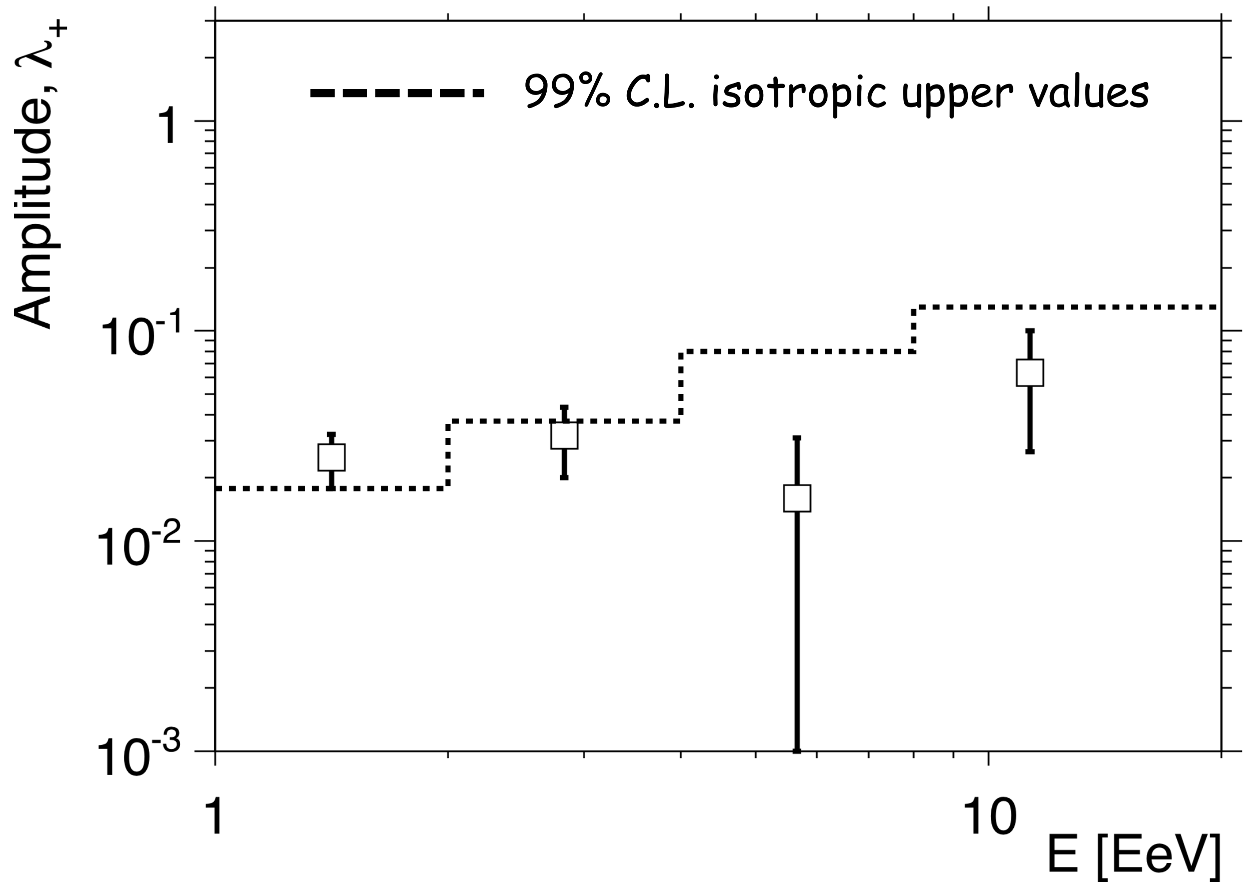
Search for dipolar patterns

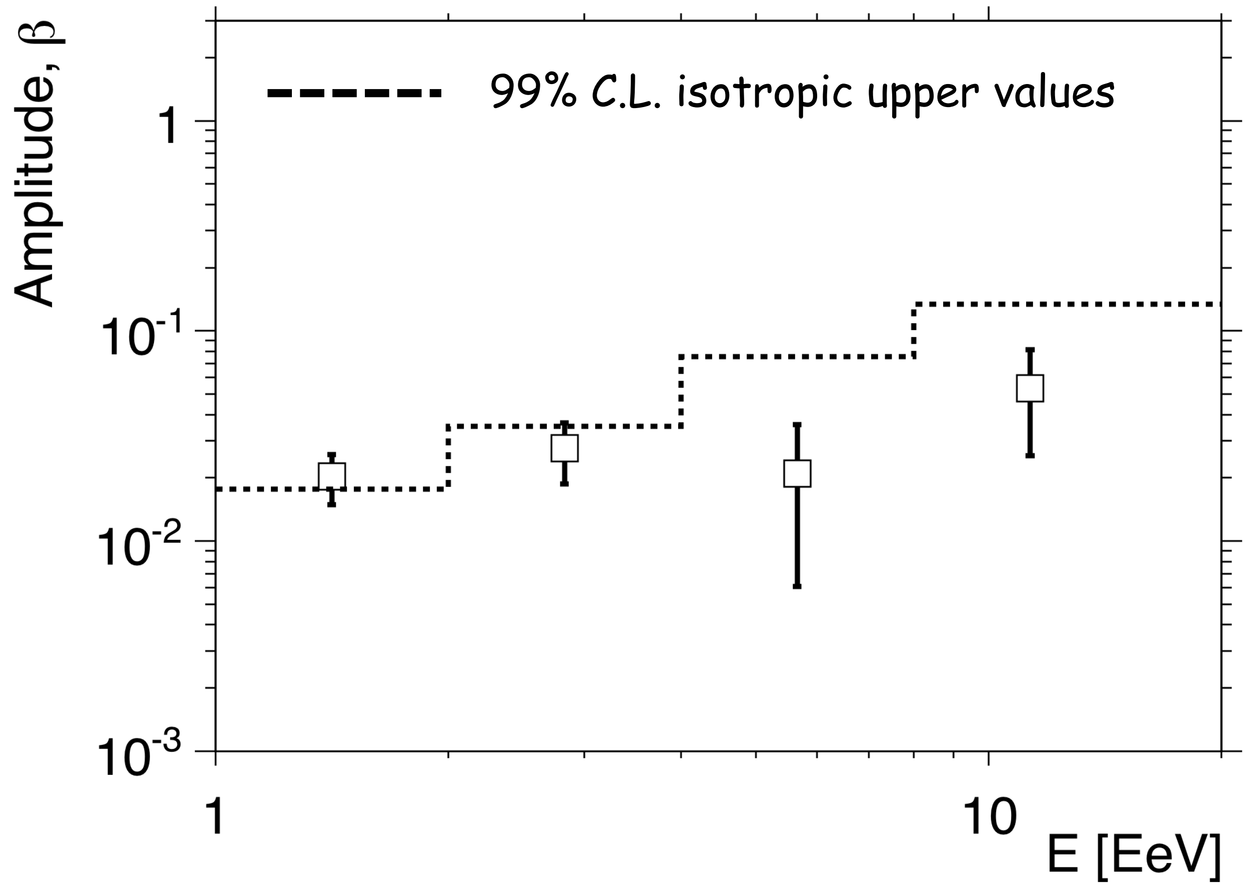




➡ **Dipole:** hints for large scale anisotropies above 1 EeV (similarly to the results obtained with the first harmonic analysis in r.a.)

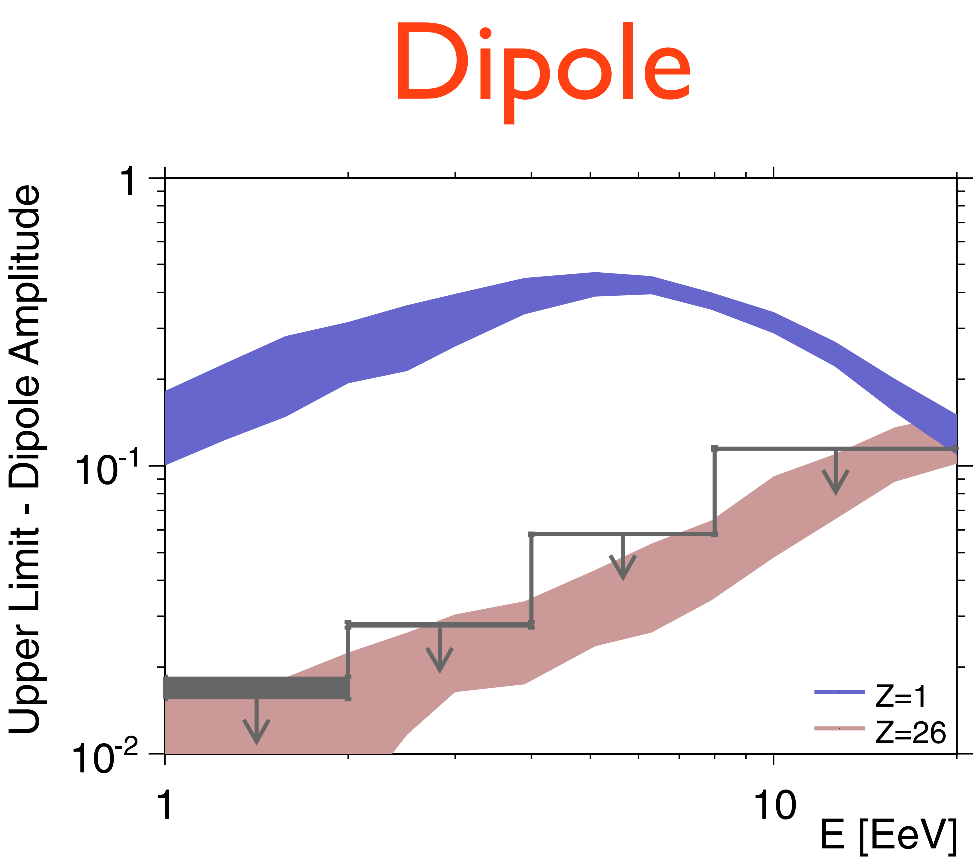
Search for quadrupolar patterns





➡ **Quadrupole:** hints of moments higher than dipole at EeV energies

Dipolar & quadrupolar patterns



- Generic estimates of the amplitudes expected from stationary galactic sources

- GMF = regular (BSS disk field and anti-symmetric halo field) + turbulent field (according to a Kolmogorov power spectrum)

➡ Unless the strength of the GMF is much higher than in the picture used here, the upper limits on dipole and quadrupole amplitudes **challenge an origin of CRs from galactic stationary sources distributed in the disk and emitting predominantly *light* particles in all directions** at EeV energy ranges

Conclusions

- Auger provides a wealth of **high quality data**, a coherent behavior of observables is observed

- **Large scale anisotropy:**
  - **Amplitudes marginally in agreement with isotropic expectations** in few energy bins
  - **Non-random phases** over a wide energy range
  - Searches in both α and δ now possible, constraining upper limits on dipole/quadrupole moments
  - Searches with full-sky coverage applied to Auger/TA data above 10 EeV soon

- **Perspectives for the future:**
  - acquire more data (next 10 years will give x3)
  - add more mass information in UHE region (**muons**)

Backup slides

Search for point-like sources

Searches for Galactic neutron sources

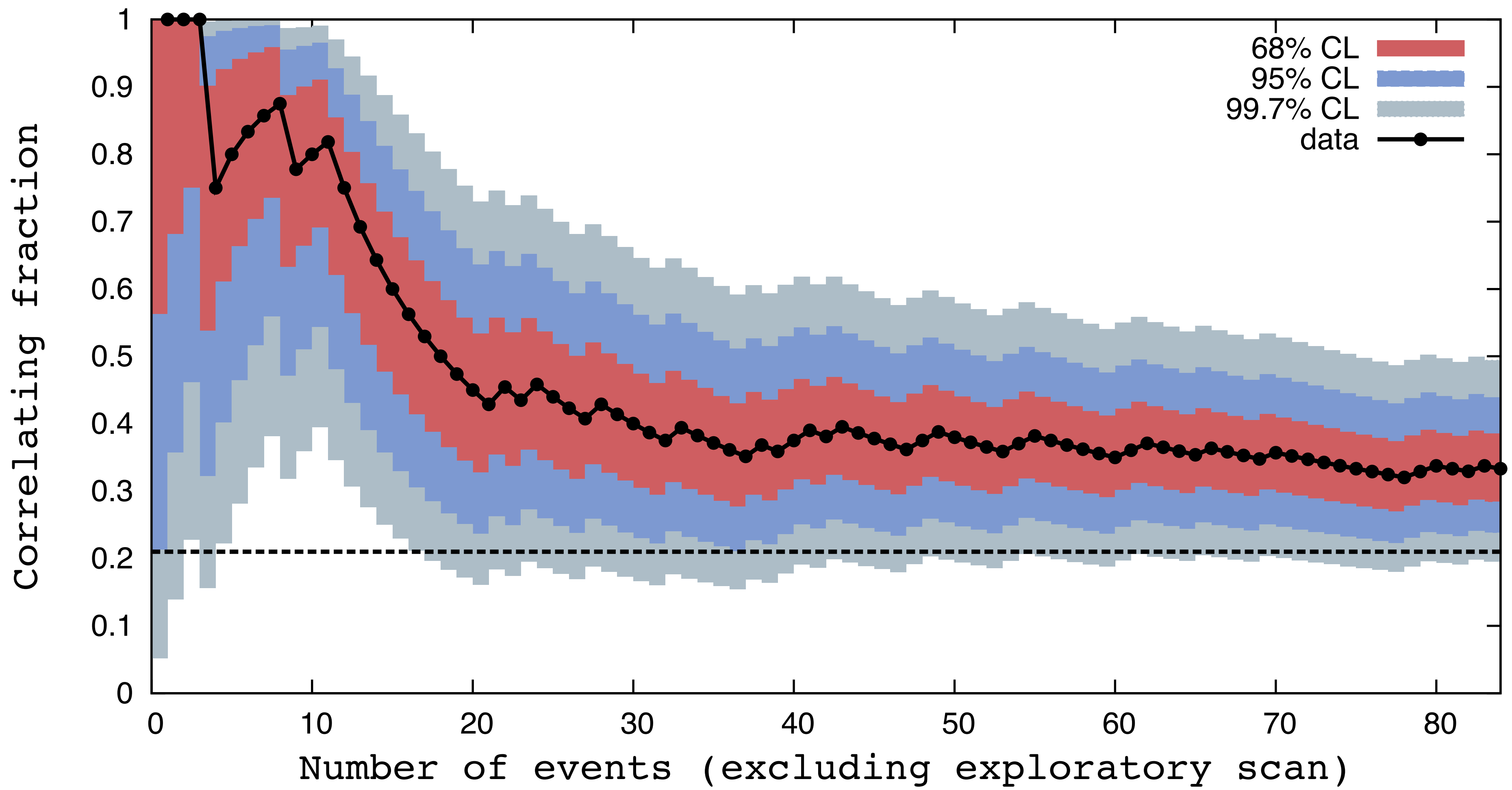
- Neutrons produce air showers that are indistinguishable from those produced by protons but they can point back to the source.
- They are unstable but at E > 1 EeV they still can reach us from Galactic sources, ie, ≃ 9.2 (E_n/EeV) kpc.
- A blind search for neutron sources in the whole exposed sky was reported in *ApJ 760 (2012) 148*, **selected candidate source lists** have been also considered:
  - **No candidate source shows a significant excess**.
  - **Null results were also derived for the *Galactic Plane* and the *Galactic Center***.

Blind searches for localized cosmic ray excesses

- **Scan the sky** over 4 energy ranges (1-2, 2-4, 4-8 EeV and > 8 EeV) and circular windows of 5° and 15°→ the largest observed significances are **compatible with isotropic expectations**.
- We explored regions within 10° of the ***Galactic*** and ***Super-Galactic planes*** and near the ***Galactic Center*** and to ***Cen A*** → **no significant departure from isotropic expectations**.

Search for point-like sources

Update on AGN correlation



- Data set up to Jun 2011: **correlating events = 28/84**, corresponding to a fraction = **33±5 %**
  ⇒ **P = 0.006**

- Clustering of correlating events in a region of 24° around **CenA**: 19 observed / 7.6 expected
  ⇒ KS test yields **4% isotropic probability**