Anisotropy Studies

with

The Pierre Auger Observatory

Miguel @ Penn State

for the Pierre Auger Collaboration

August 27, 2013

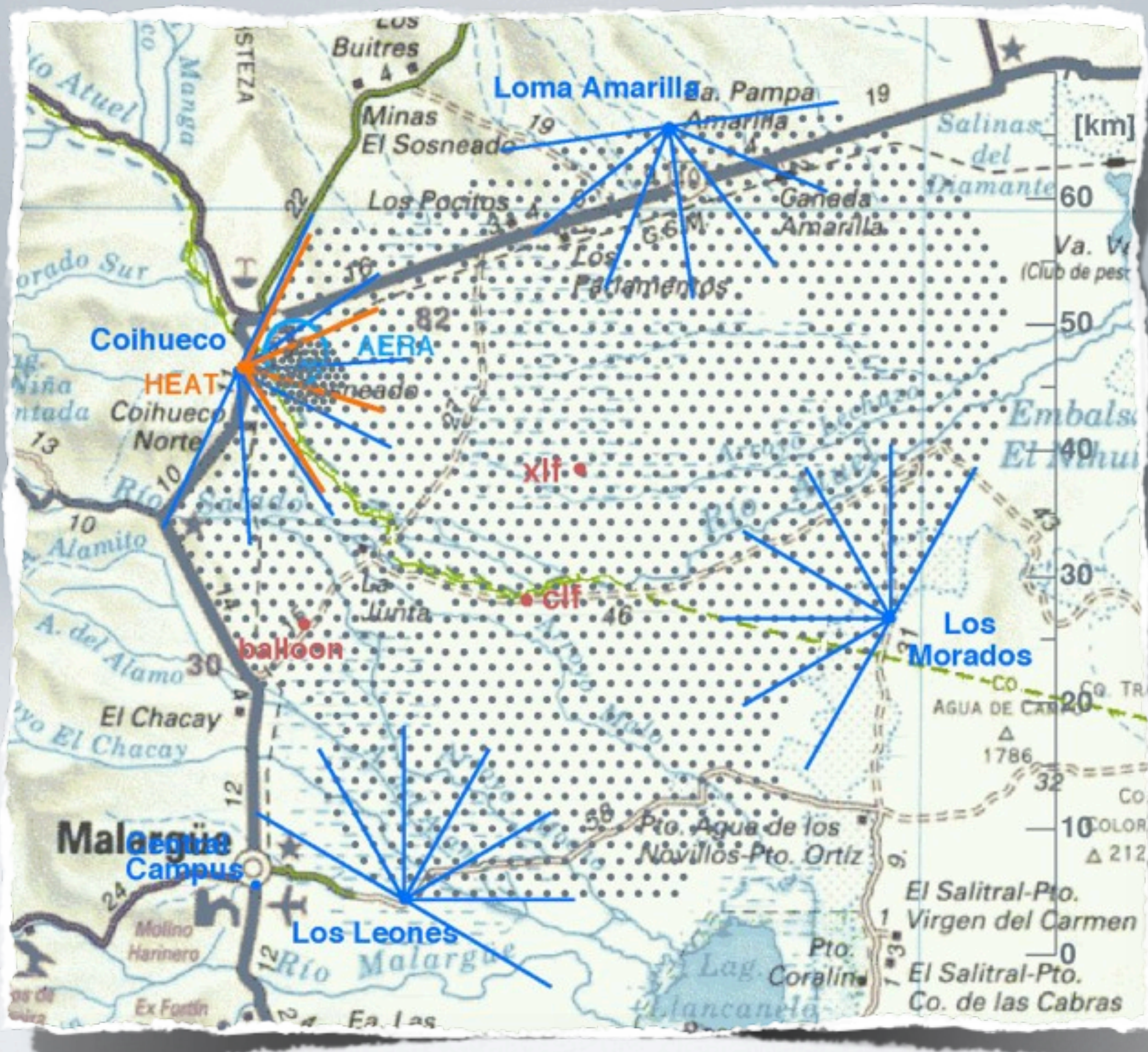
PIERRE AUGER OBSERVATORY

TeV Particle Astrophysics 2013 - UC Irvine - August 26-29, 2013

LAUNDRY LIST

- Large scale *first harmonic* (amplitude & phase)
- Upper limits on *dipole* & *quadrupole* amplitudes
- *Blind searches* for localized cosmic rays excesses
- Directional *neutron searches*
- *Full sky* searches

AUGER


Loma Amarilla
Coihueco
HEAT
AERA
xlf
clf
balloon
Los Morados
Los Leones
Malargüe
Campus
[km]
60
50
40
30
20
10
0

LARGE SCALE FIRST HARMONIC

MOTIVATION

- Understand the nature and the *origin of cosmic rays*.

- *Transition* from a galactic to an extragalactic origin should induce a significant change in the *large scale angular distribution* of cosmic rays.

ANALYSIS METHODS

- Study of the large scale distribution of arrival directions of cosmic rays based on the first harmonic analysis in right ascension.

- Auger data from 01 Jan 2004 to 31 Dec 2012

- All energies above 10^{16} eV

ANALYSIS METHODS

- Small modulations ⇒ account for spurious modulations
  - evolution of the array size
  - dead period of each detector
  - weather variations (daily and seasonal modulations)
  - etc. etc.

ANALYSIS METHODS

Modified Rayleigh for E > 1 EeV

- Fourier coefficients a and b

$$a = \frac{2}{N}\sum_{i=1}^{N} w_i \cos\alpha_i \qquad b = \frac{2}{N}\sum_{i=1}^{N} w_i \sin\alpha_i$$

$\Rightarrow$ Amplitude r and phase ϕ

$$r = \sqrt{a^2 + b^2} \qquad \phi = \arctan(b/a)$$

- Weights w_i account for array growth, dead time, tilt, etc.

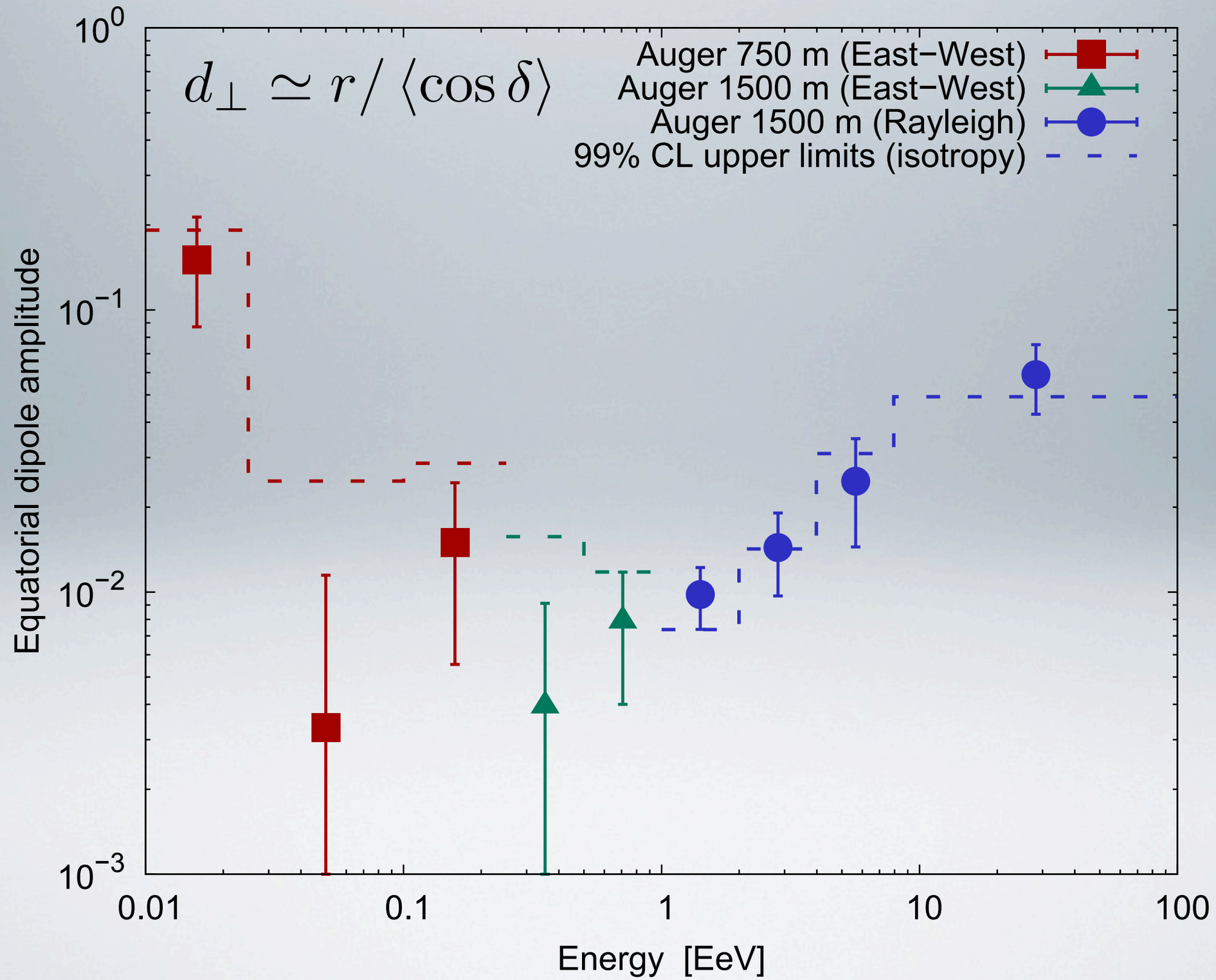
- Energy assignment corrected for weather and geomagnetic effects.

ANALYSIS METHODS

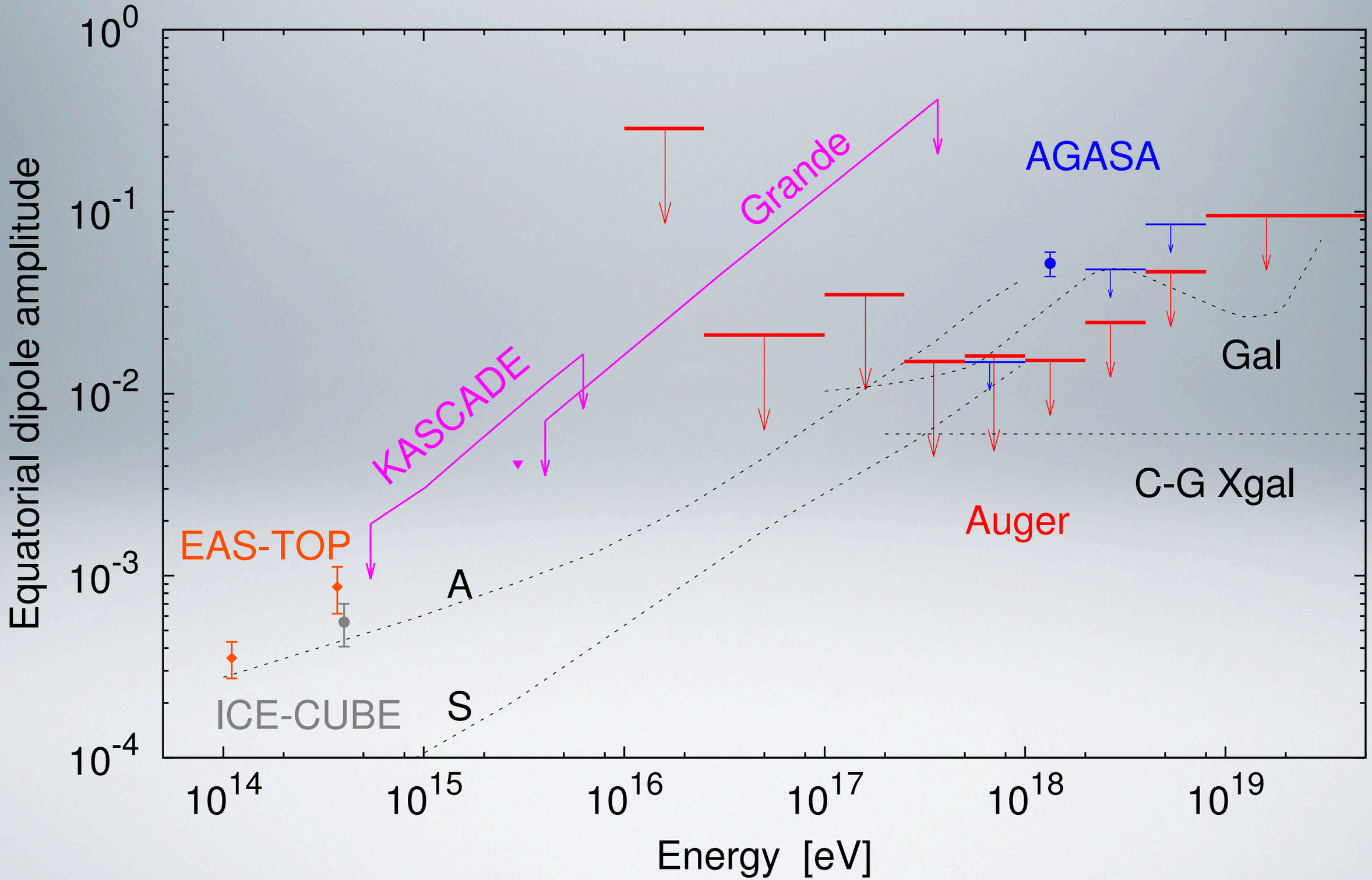
East-West method for E < 1 EeV

- Difference between counting rates: $I_E(\alpha^0)$ - $I_W(\alpha^0)$
- Removes systematic effects.
- Reduced sensitivity.

AMPLITUDE

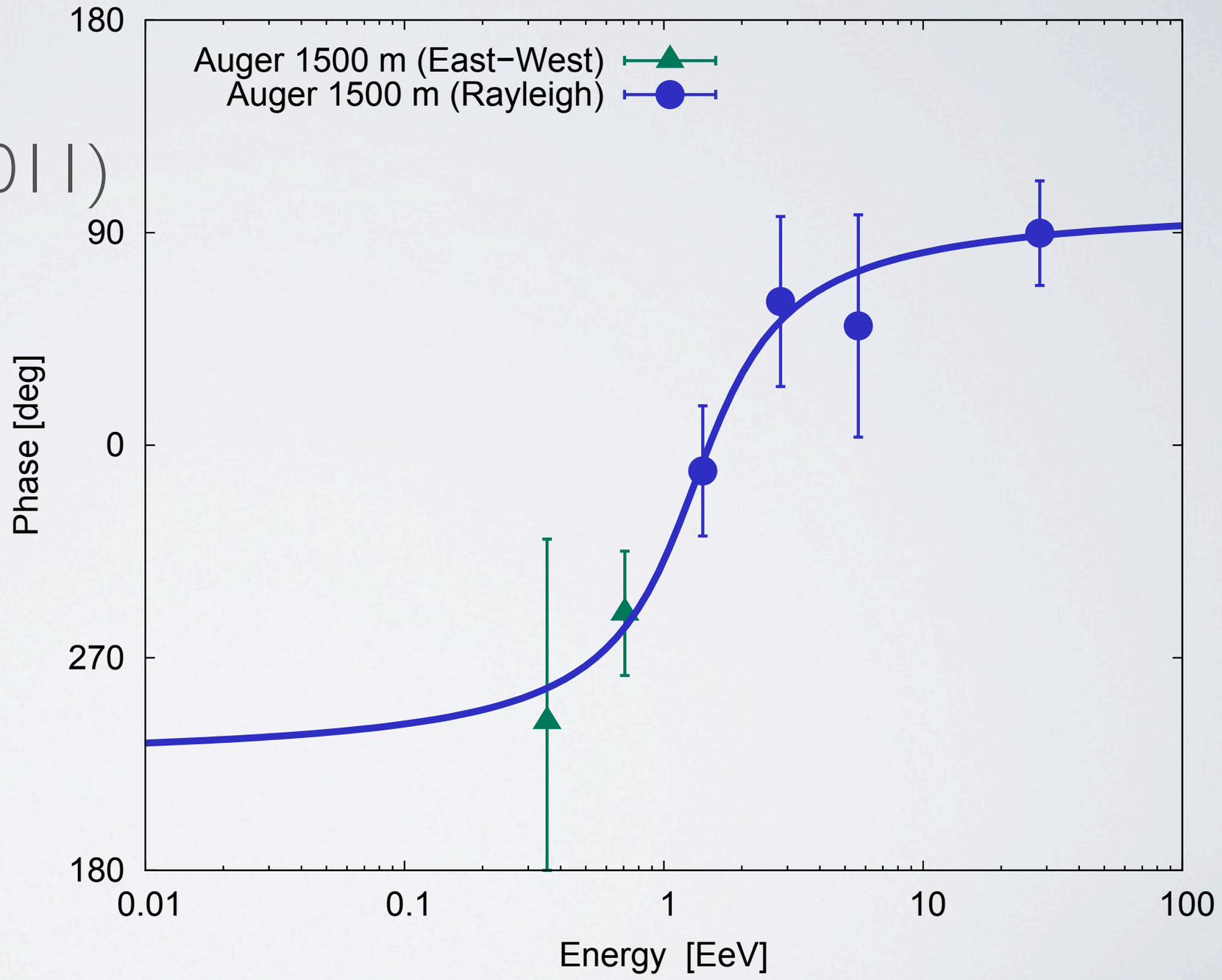

$d_\perp \simeq r / \langle \cos\delta \rangle$
Auger 750 m (East−West)
Auger 1500 m (East−West)
Auger 1500 m (Rayleigh)
99% CL upper limits (isotropy)
Equatorial dipole amplitude
10^0
10^{-1}
10^{-2}
10^{-3}
0.01
0.1
1
10
100
Energy [EeV]

UPPER LIMITS



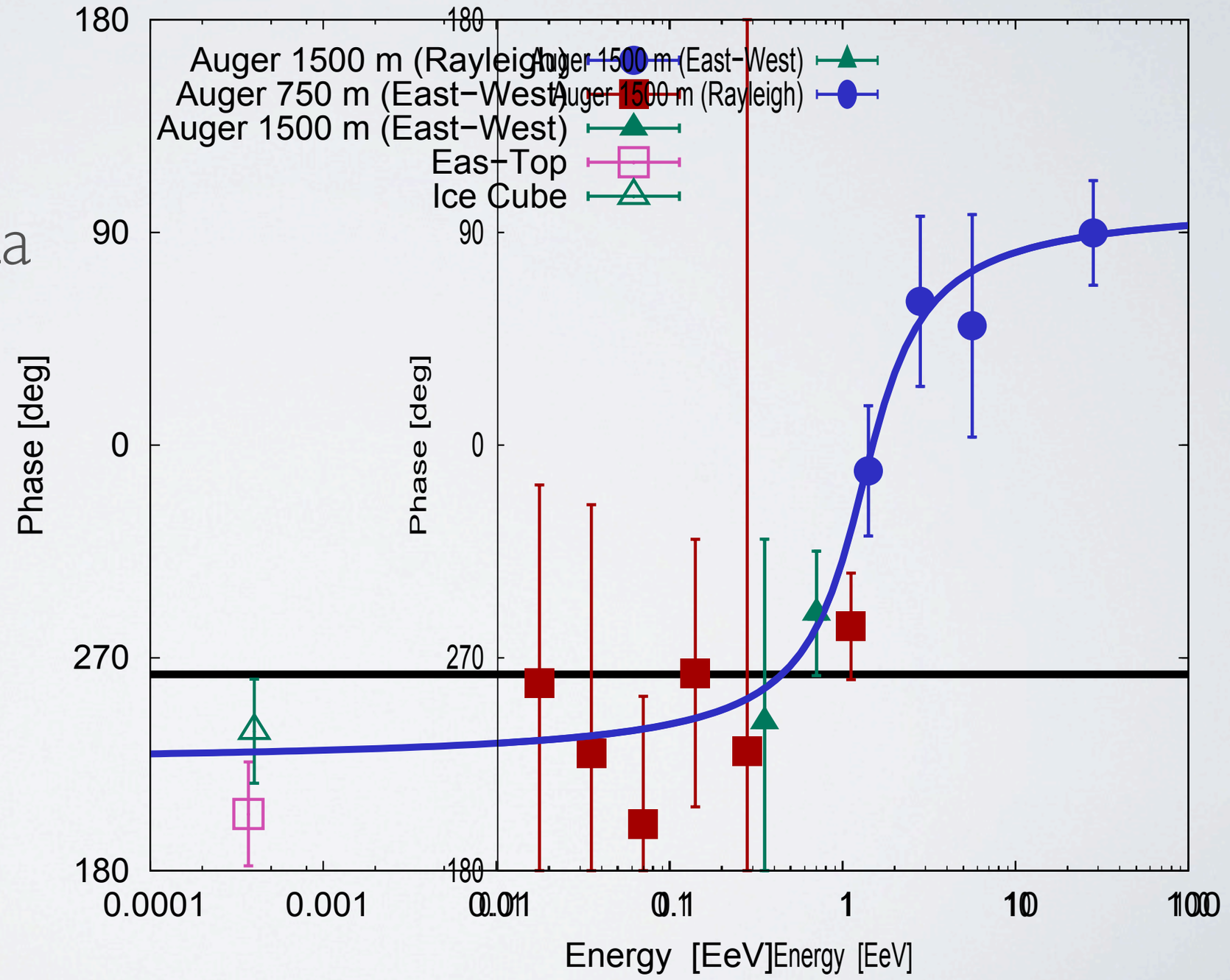
PHASE

- P. Abreu et al., APP (2011)
- Data up to 2009
- Hint of a *transition* from a phase of 270° below 1 EeV to 90° above 4 EeV.
- $\alpha_{GC} = 268.4^{\circ}$



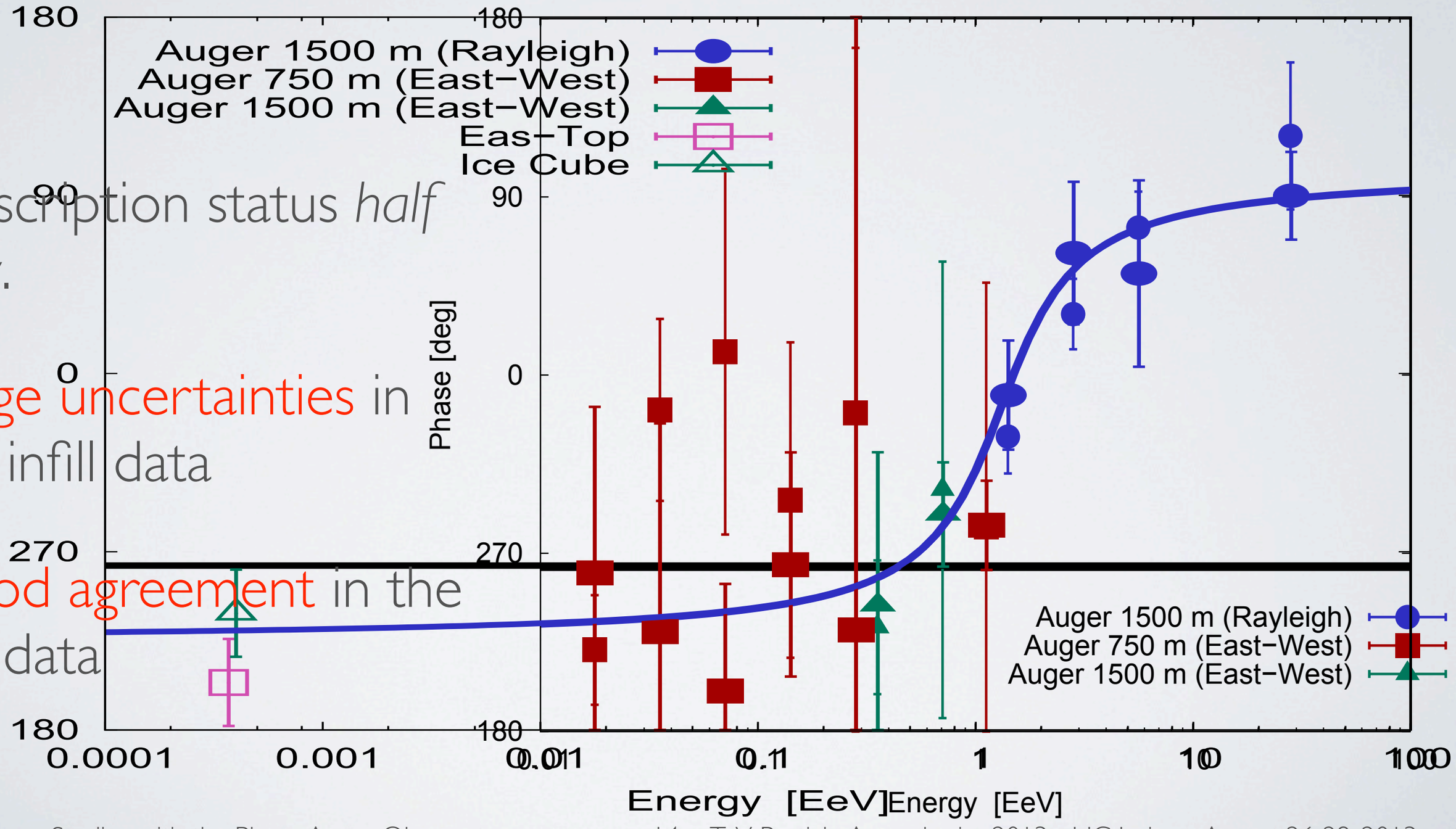
PHASE

- *Prescription* with data until Apr 2011.
- Constant phase below 1 EeV
- Phase transition at higher energies



PHASE

- Prescription status *half way*.
- Large uncertainties in the infill data
- Good agreement in the SD data



CONCLUSIONS

- Updated results for amplitude and phase of first harmonic analysis in right ascension, dipole upper limits.

- Hint for large scale anisotropy from amplitudes above 1 EeV.

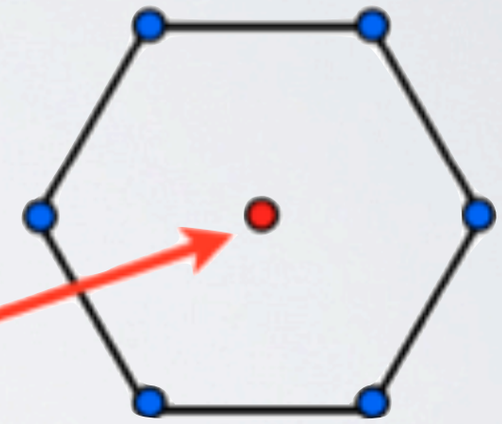
- Hint for large scale anisotropies given by the phase analysis over a wide energy range.

- Prescription to establish (99% CL) whether the phase consistency in adjacent energy intervals is real.

Upper Limits on Dipole & Quadrupole Amplitudes

METHOD

- SD data between 01 Jan 2004 and 31 Dec 2012 (~680,000)
- above 1 EeV
- below 55 degrees
- Operational *elemental cell*
- Remove periods of unstable DAQ.
- Correct S(1000) for weather and geomagnetic effects.



METHOD

- Determine detector efficiency and *directional exposure*.

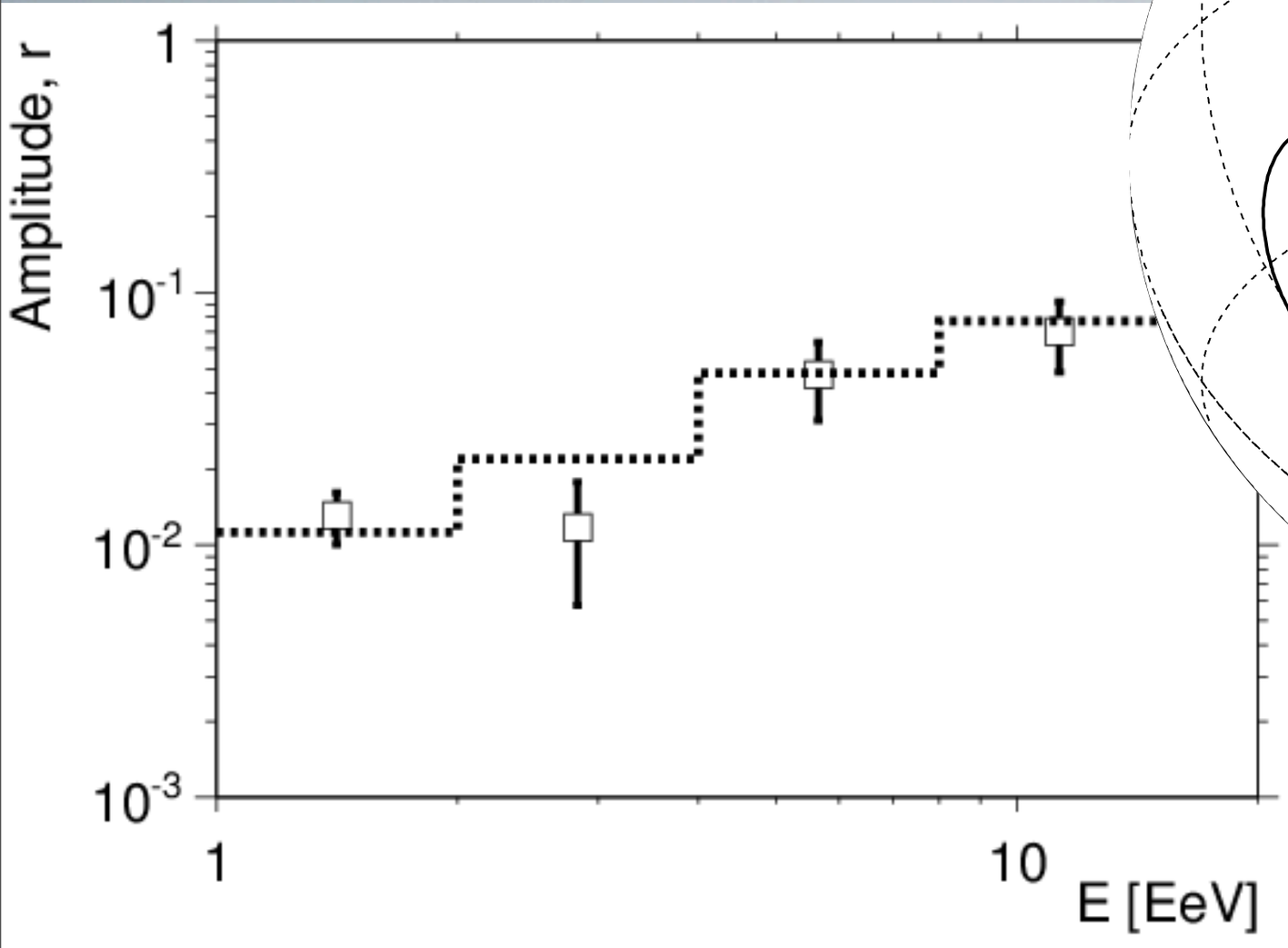
- Correct for geomagnetic effects and the tilt of the array.

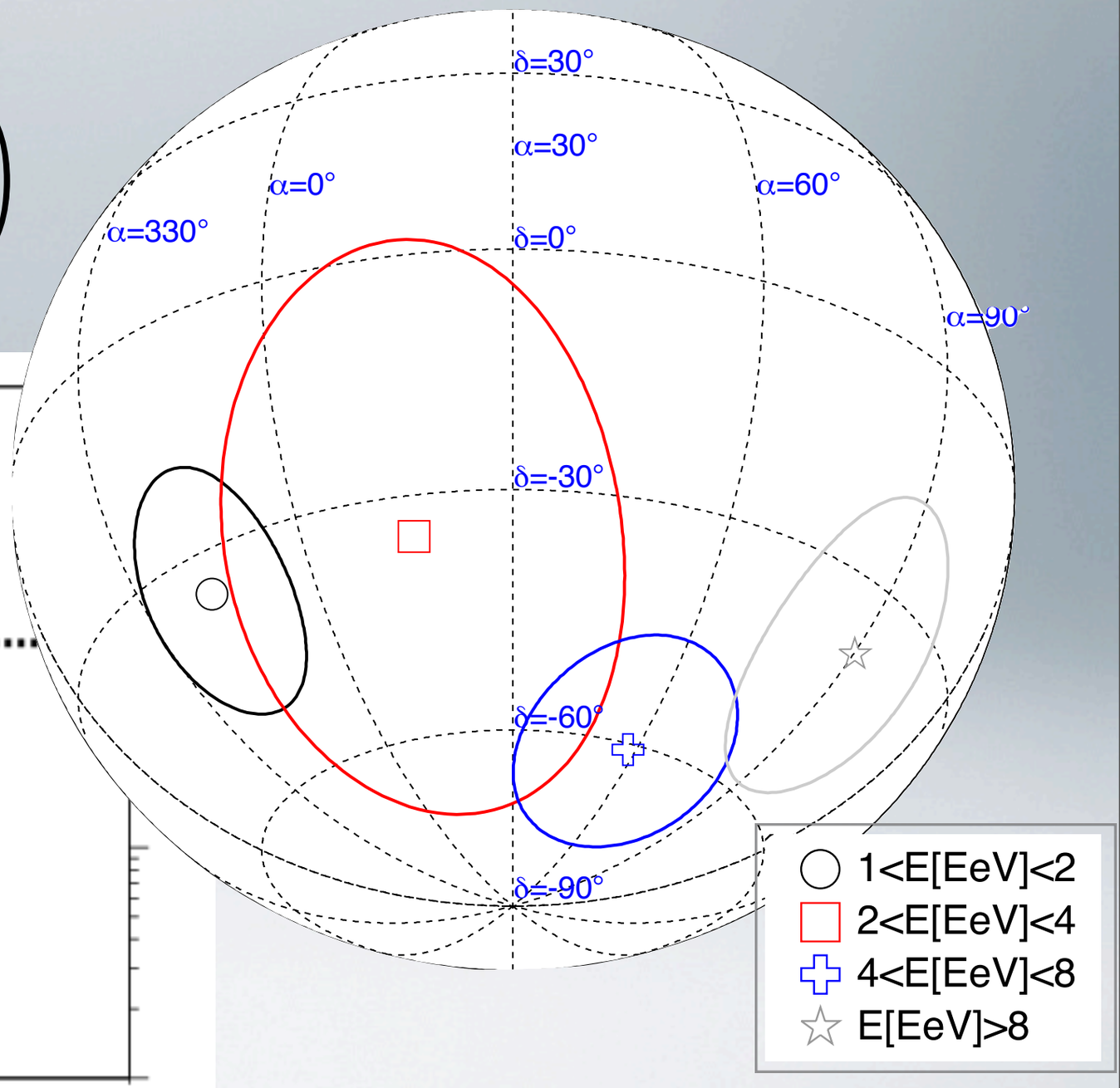
- Account for the spatial extension of the array.

- Search for large scale anisotropies assuming the multipolar expansion is *bounded*.

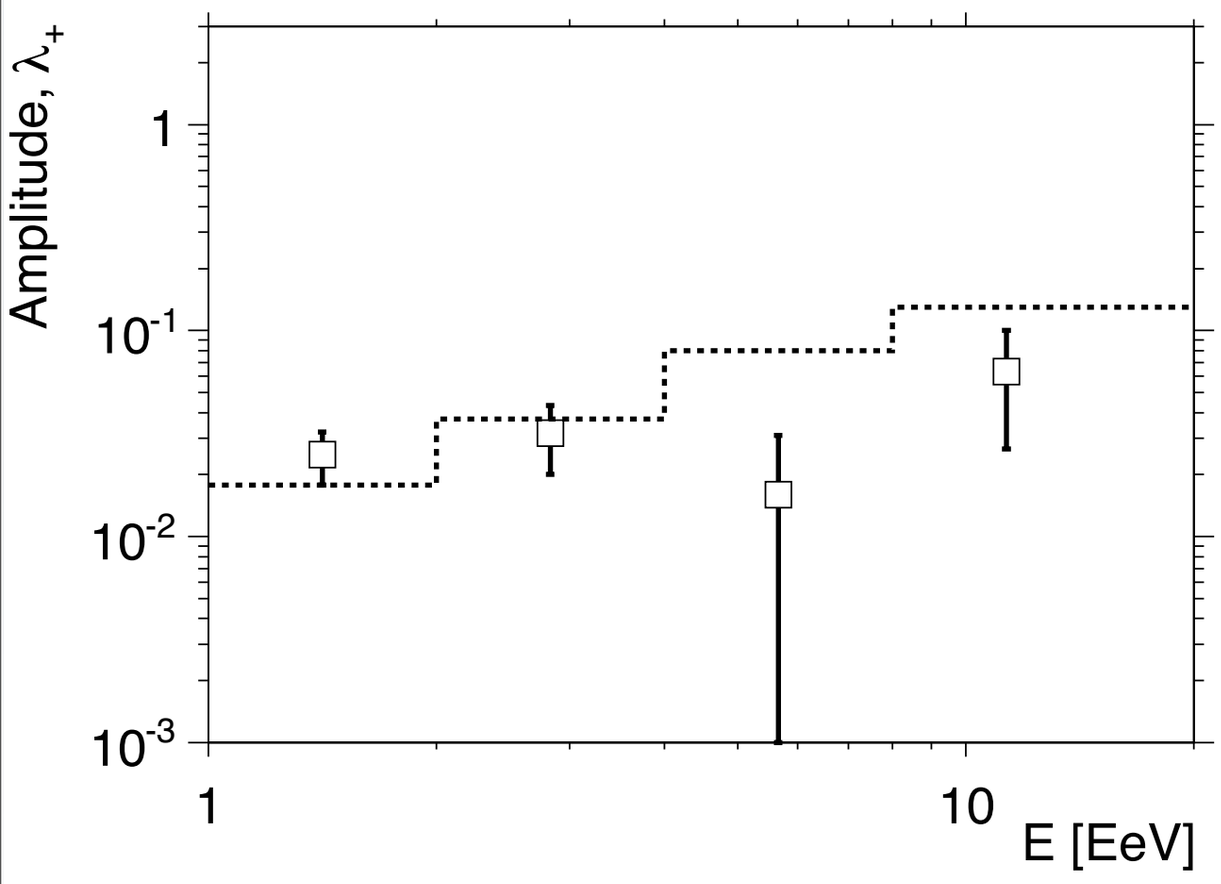
DIPOLAR PATTERNS

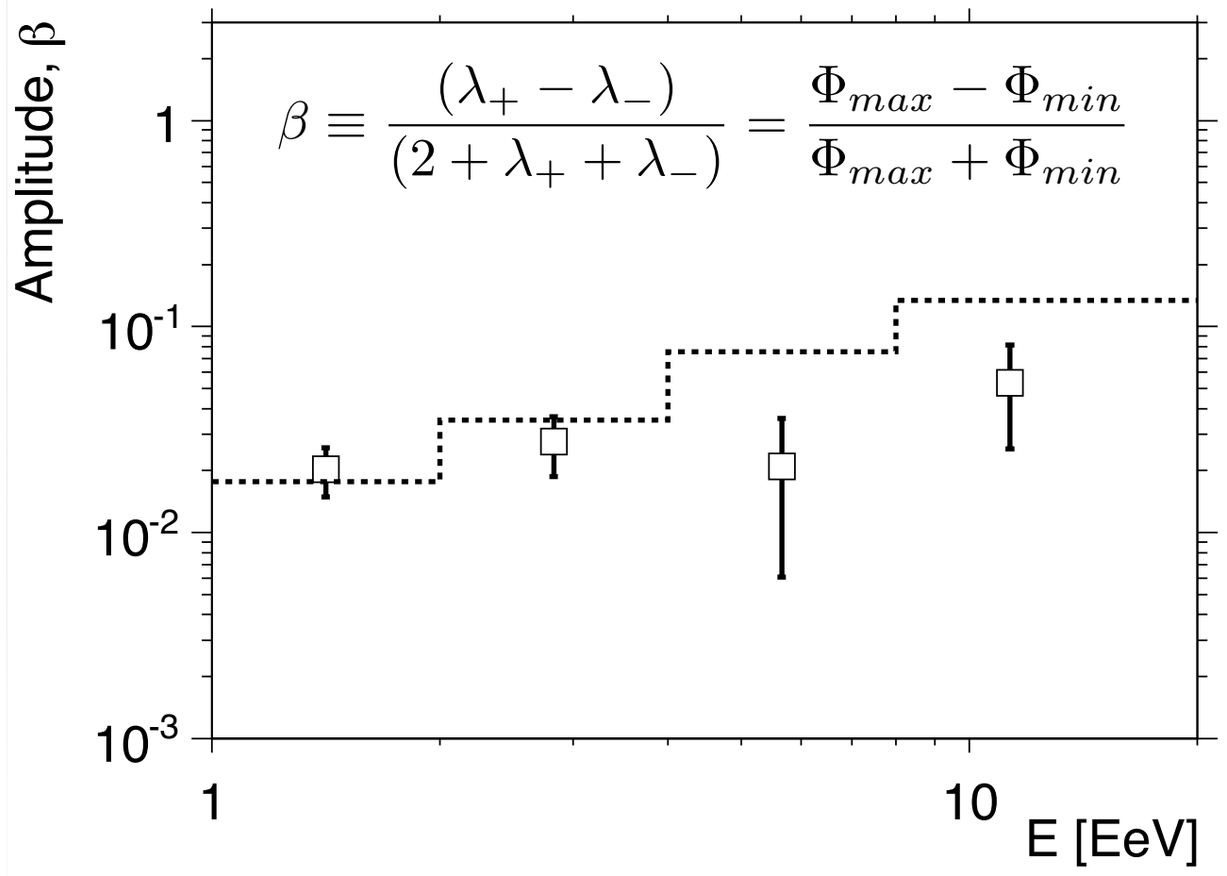
$$\Phi(\mathbf{n}) = \frac{\Phi_0}{4\pi}\left(1 + r\ \mathbf{d}\cdot\mathbf{n}\right)$$





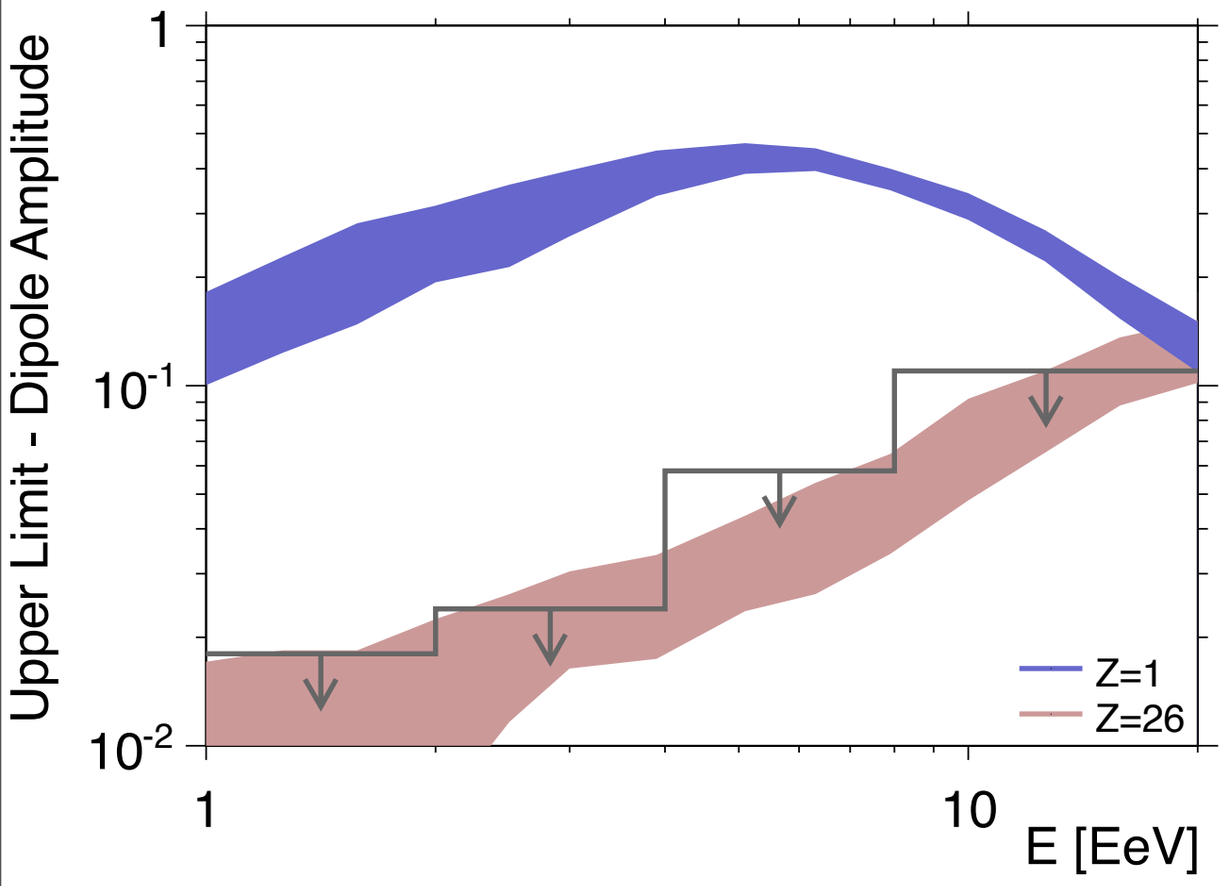
QUADRUPOLAR PATTERNS

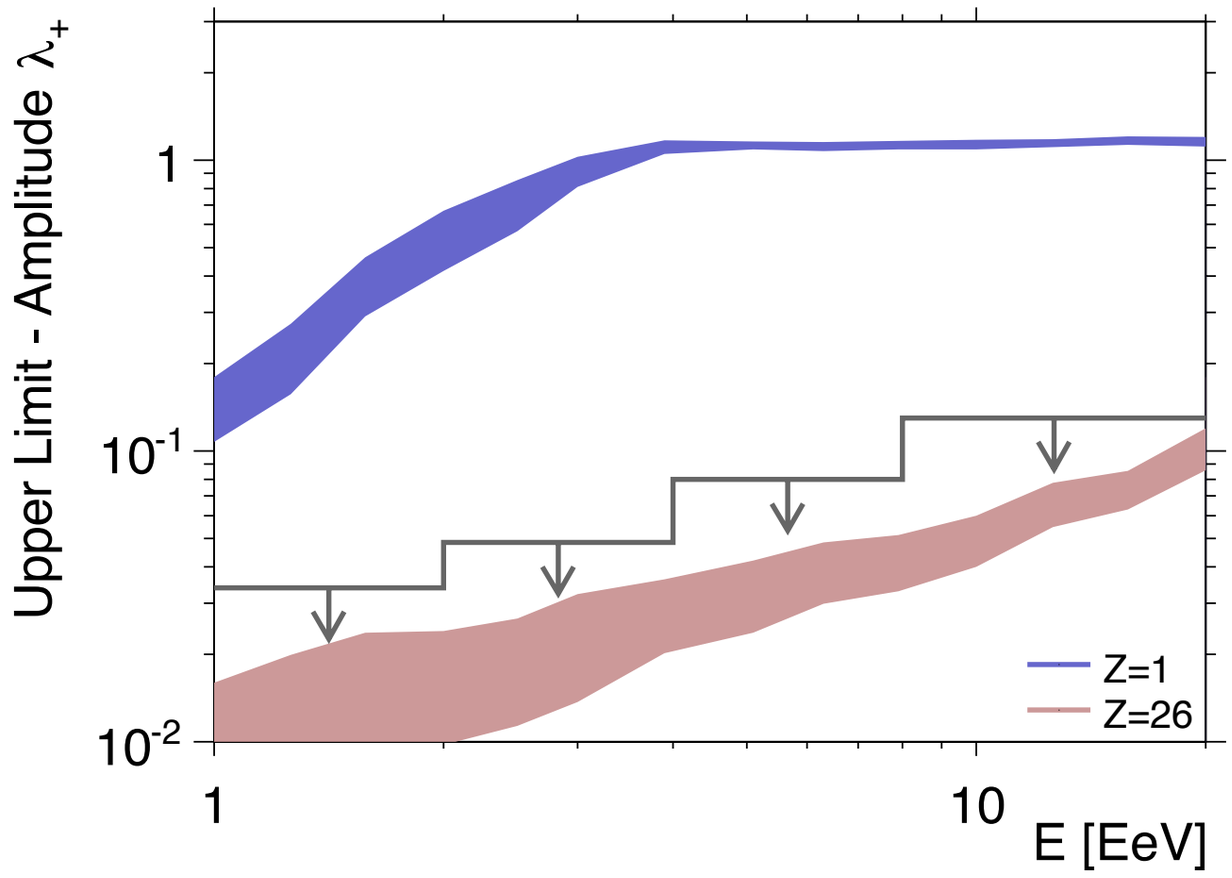




$$\Phi(\mathbf{n}) = \frac{\Phi_0}{4\pi}\left(1 + r\ \mathbf{d}\cdot\mathbf{n} + \lambda_+(\mathbf{q}_+\cdot\mathbf{n})^2 + \lambda_0(\mathbf{q_0}\cdot\mathbf{n})^2 + \lambda_-(\mathbf{q}_-\cdot\mathbf{n})^2\right)$$

UPPER LIMITS





Bisymmetric Spiral Structure model with anti-symmetric halo with respect to the galactic plane, and a turbulent field generated according to a Kolmogorov power spectrum.

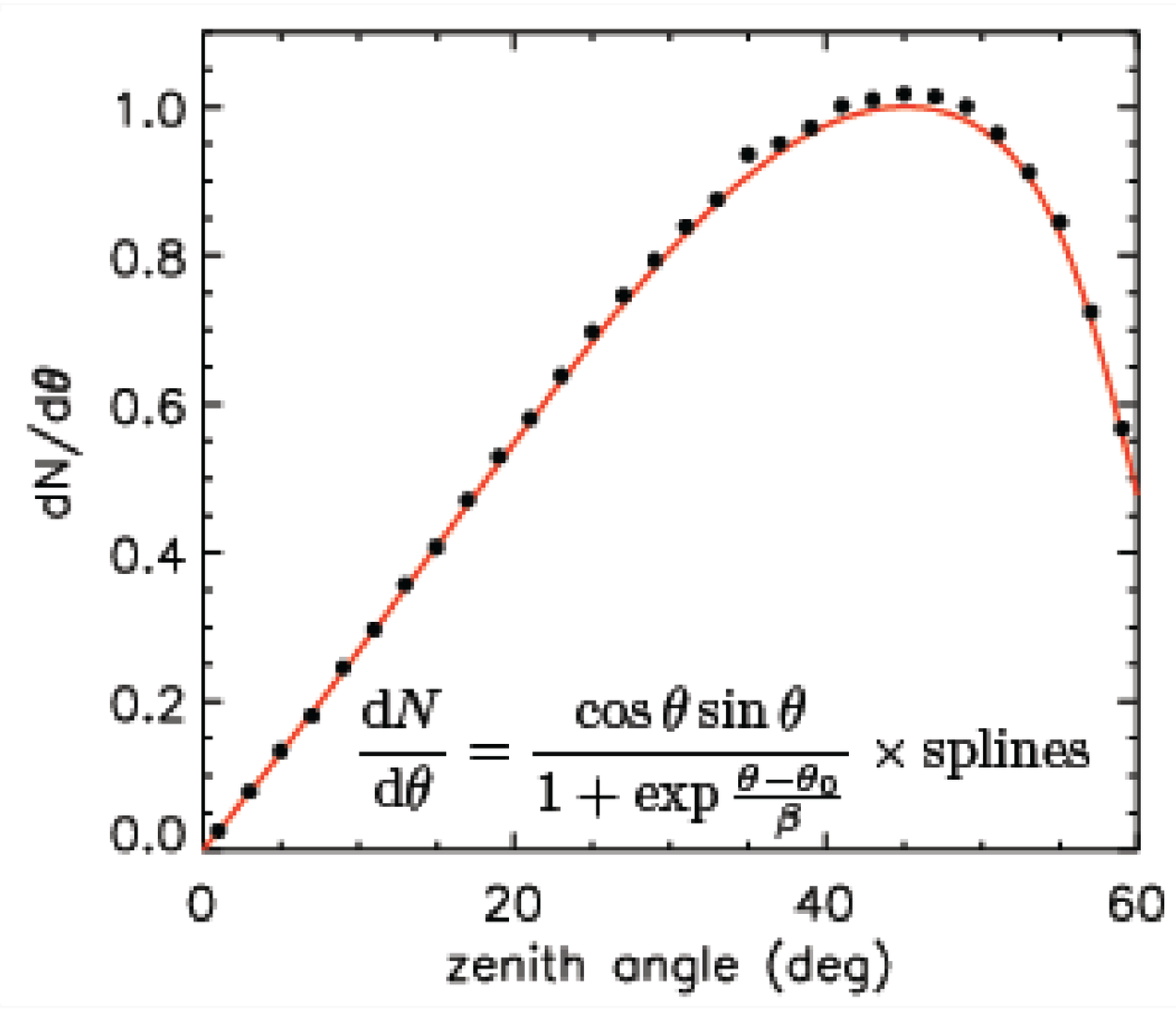
CONCLUSIONS

- Updated 3D search for large scale patterns
- Hints in the dipolar patterns to be tested with an independent data set.
- Hints of higher moments at EeV energies.
- Potential of the observational limits to test the hypothesis of a light component from stationary sources densely distributed in the Galactic disk and emitting in all directions.

BLIND SEARCHES FOR LOCALIZED COSMIC RAYS EXCESSES

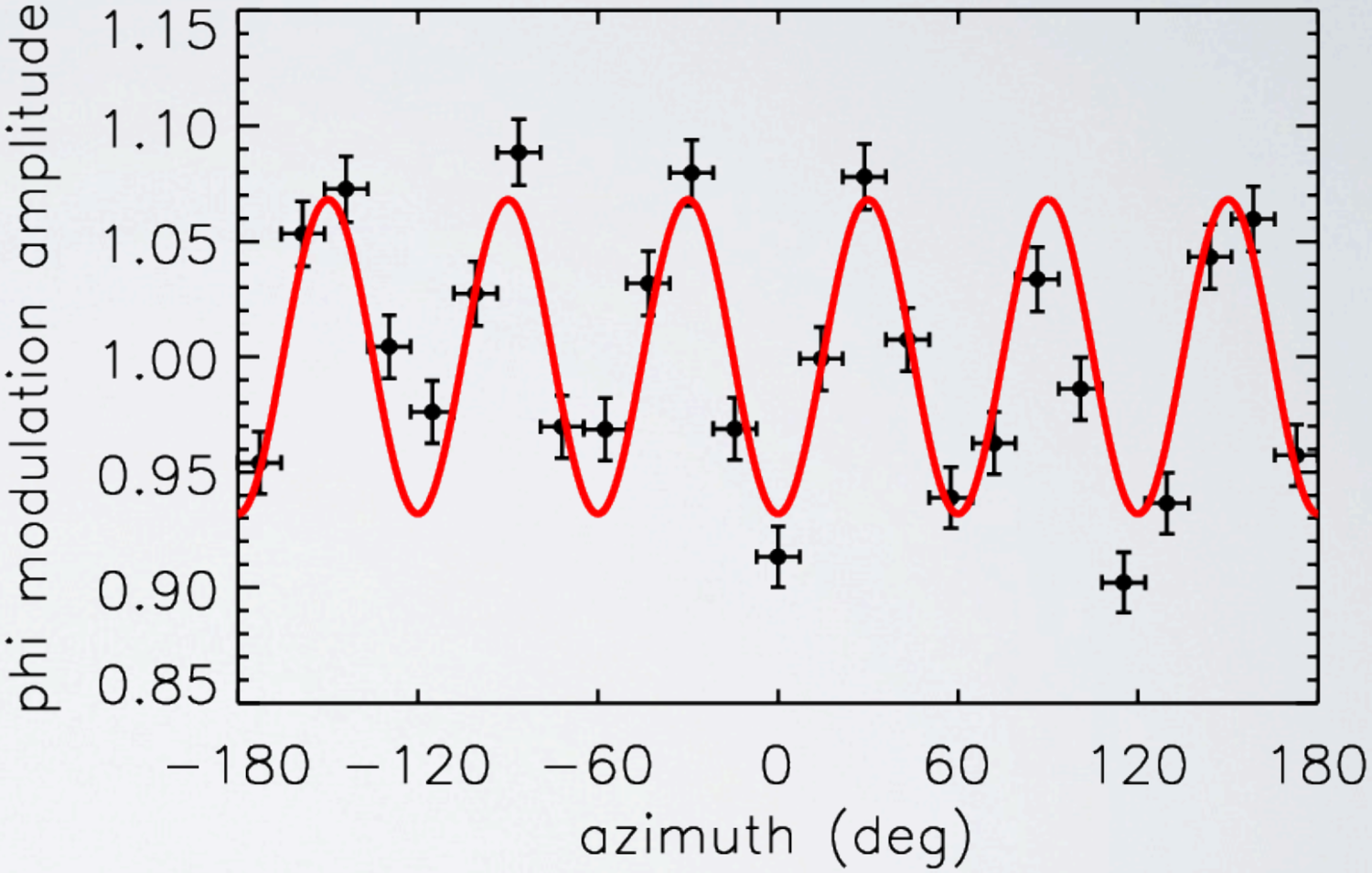
METHOD

- Calculate efficiency and acceptance.
- Account for dependence on arrival direction below full efficiency.



METHOD

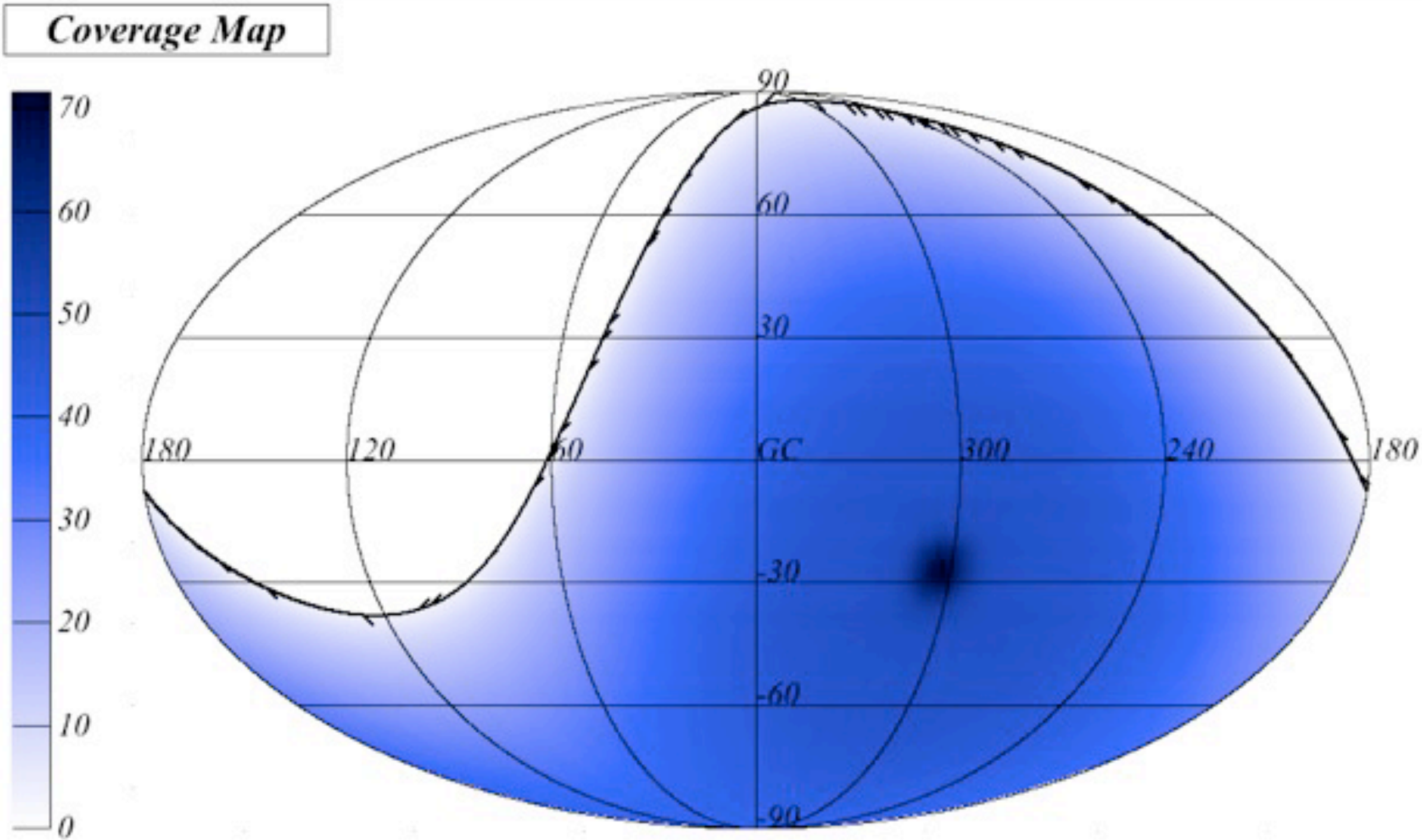
- Account for an azimuthal modulation at low energy and large zenith angles



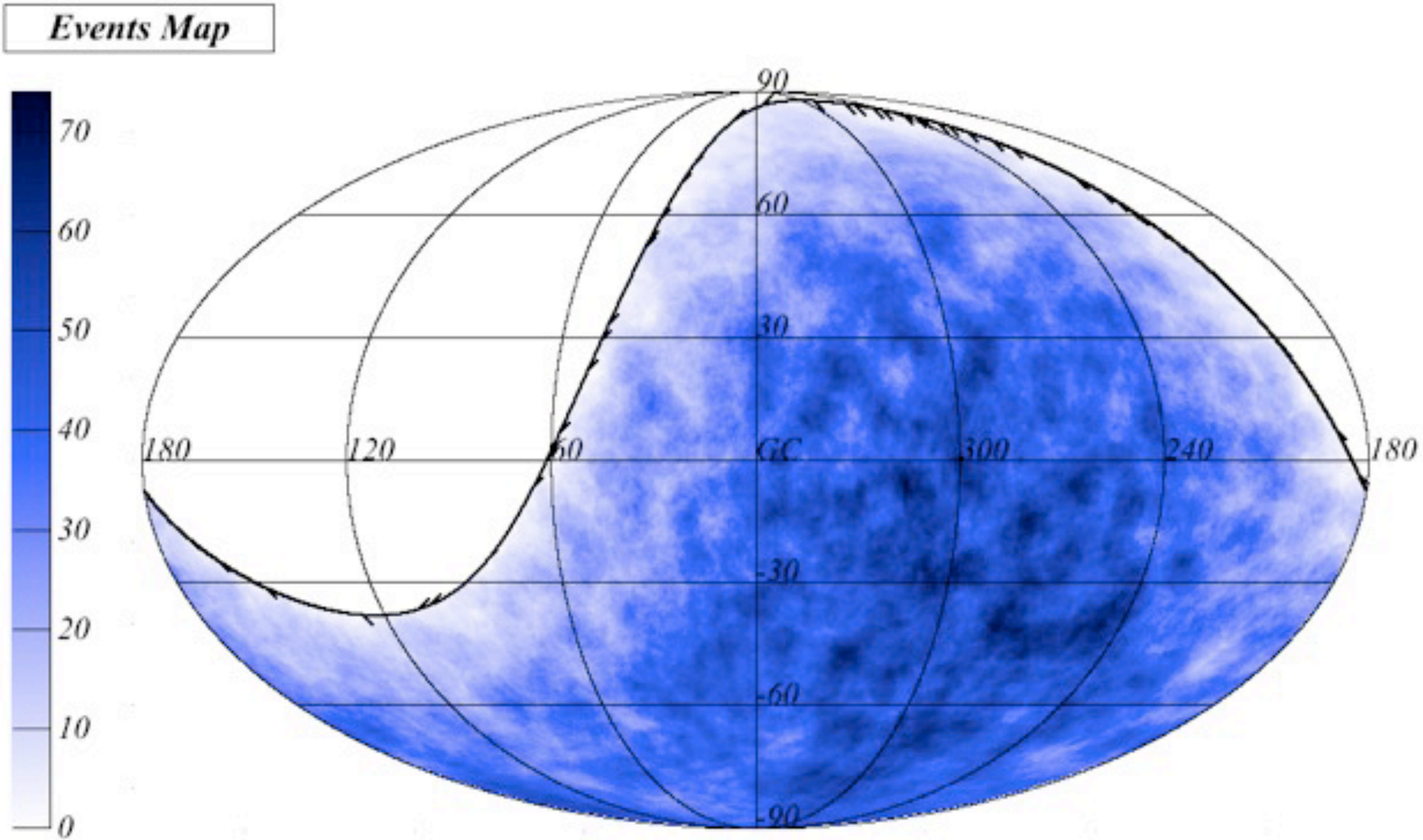
$$1 \text{ EeV} \leq E \leq 2 \text{ EeV}$$

$$54^\circ \leq \theta \leq 60^\circ$$

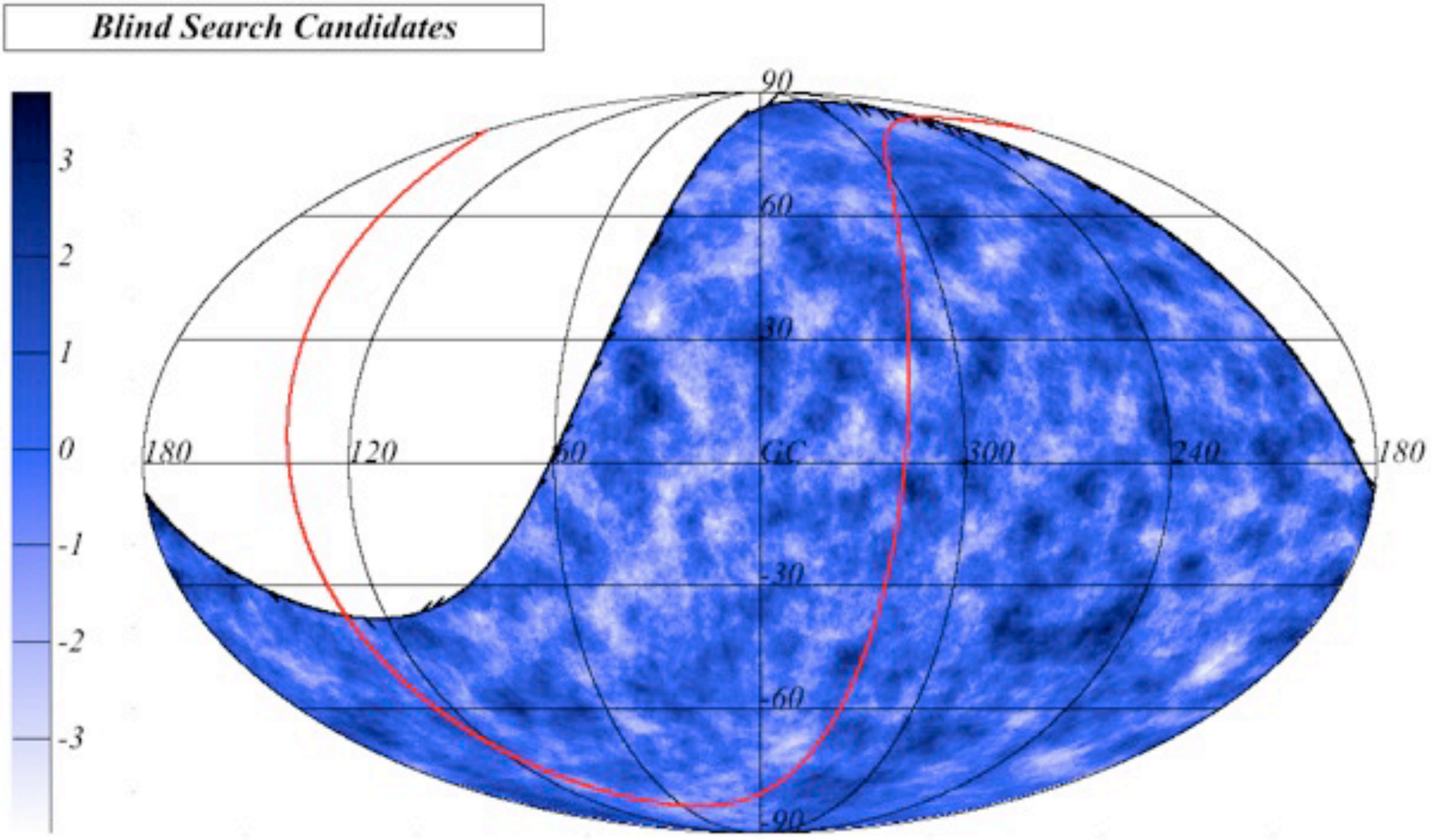
EXPOSURE


Coverage Map
70
60
50
40
30
20
10
0
90
60
30
180
120
GC
300
240
180
-30
-60
-90

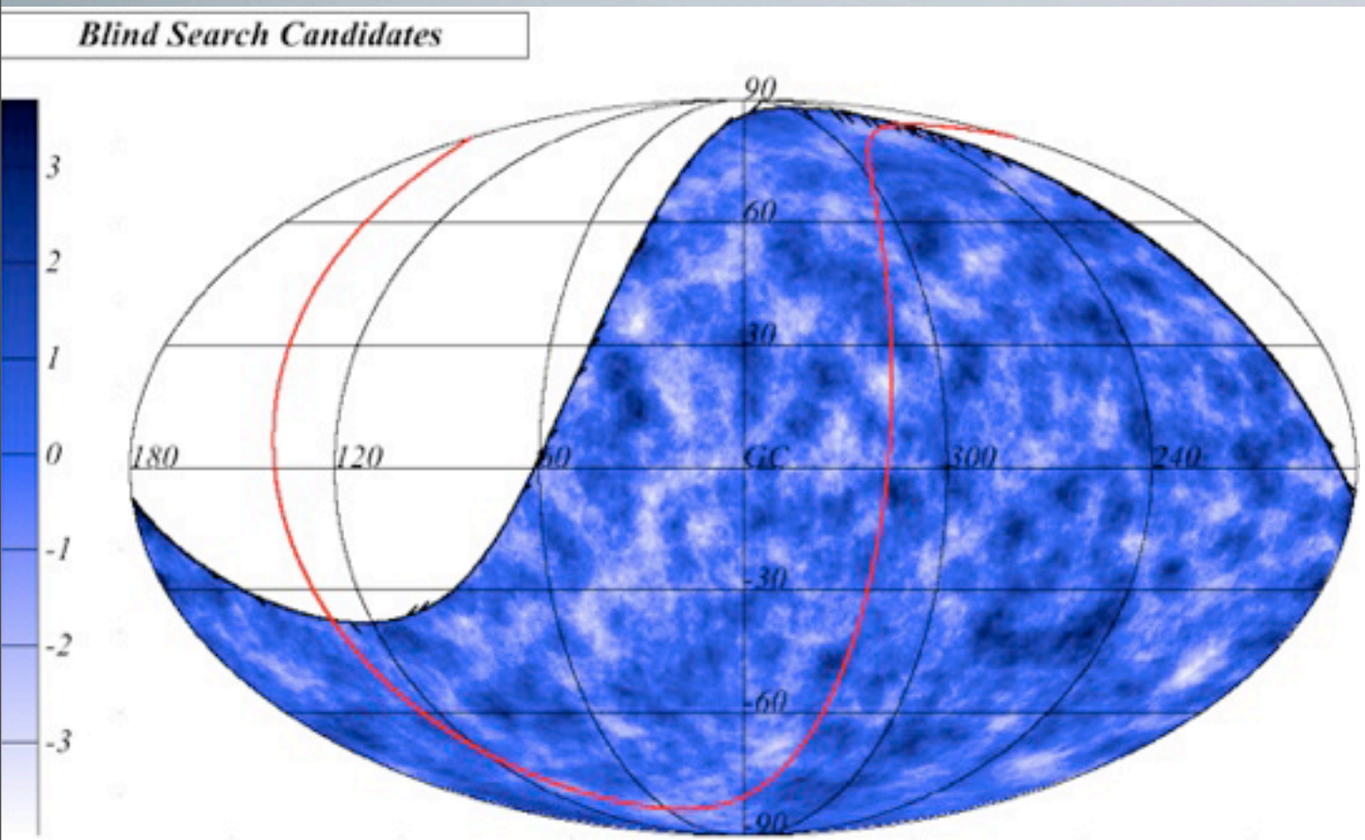
DATA

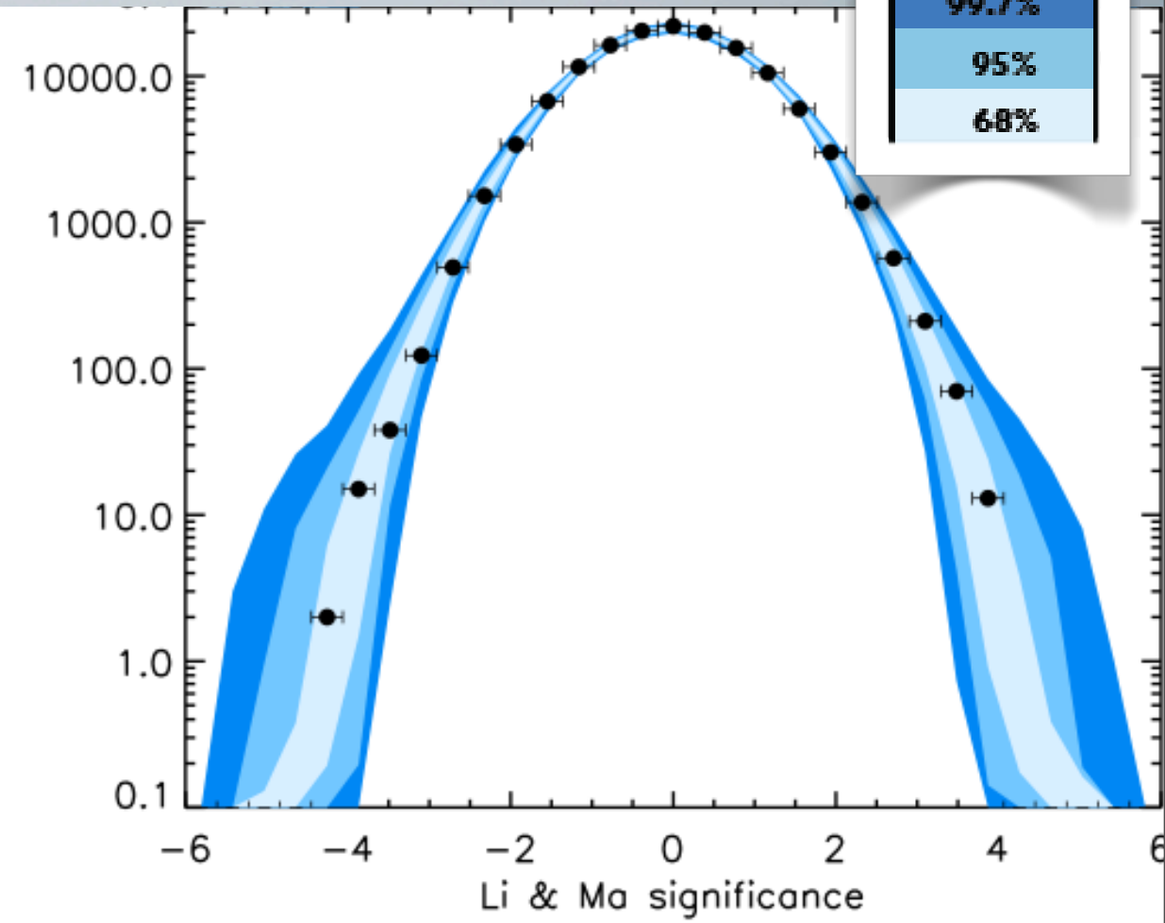

Events Map
70
60
50
40
30
20
10
0
90
60
30
180
120
60
GC
300
240
180
-30
-60
-90

COMPUTE SIGNIFICANCES



COMPUTE SIGNIFICANCES

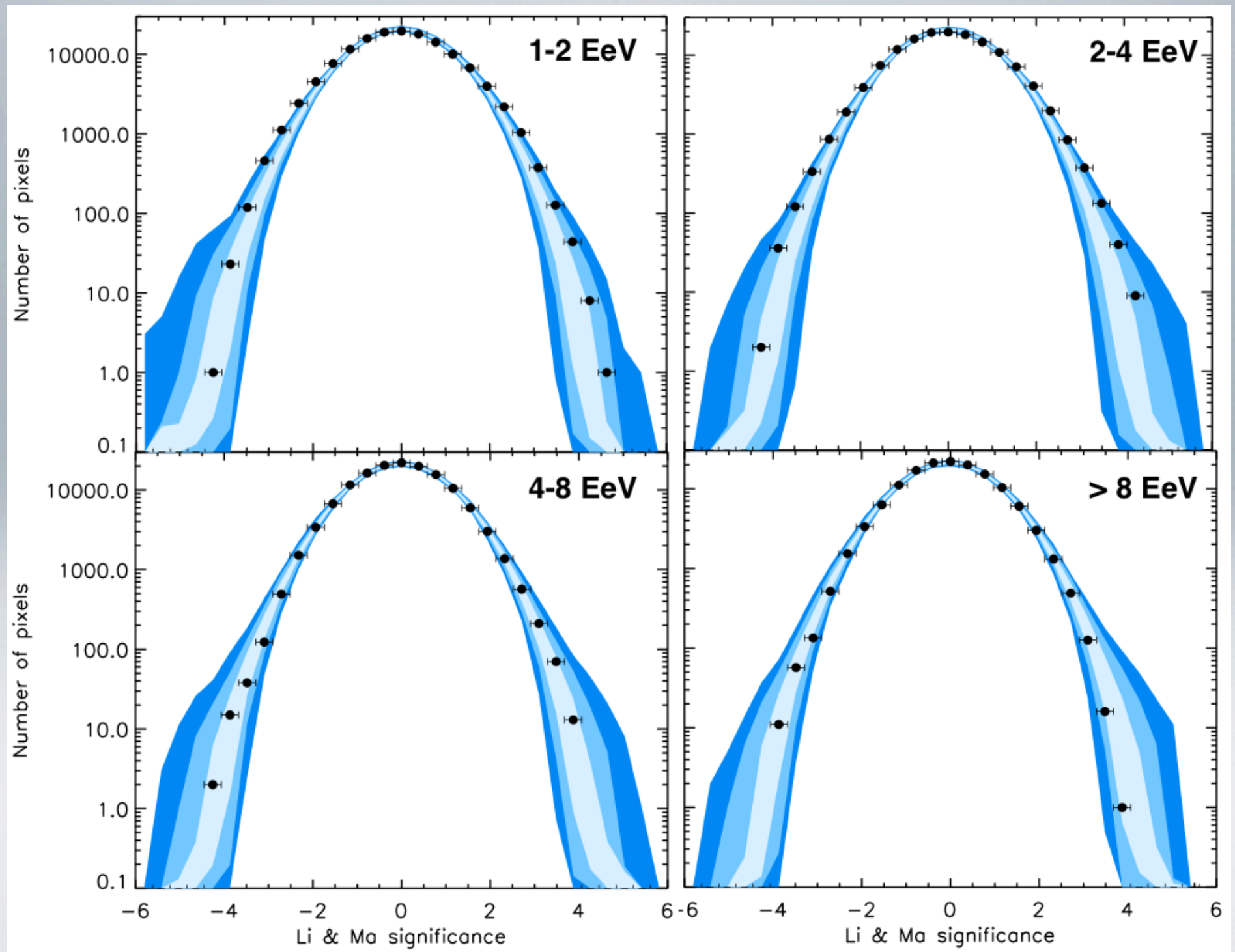




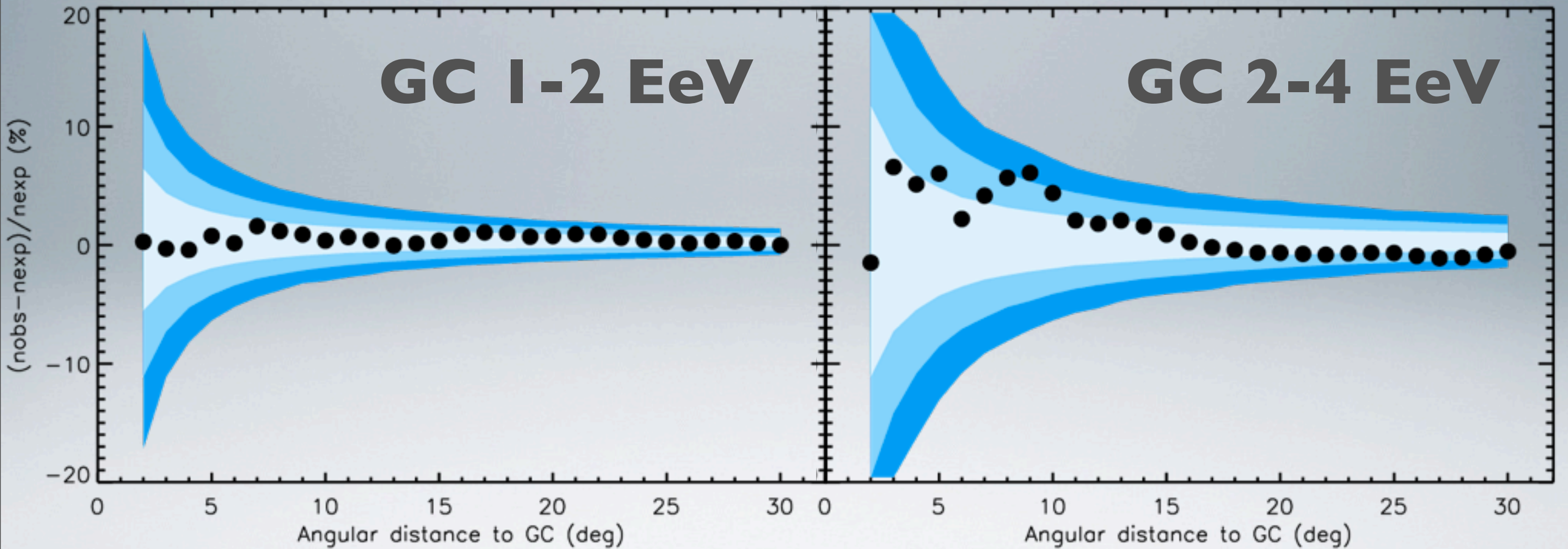
Sky map of significances

Distribution of significances

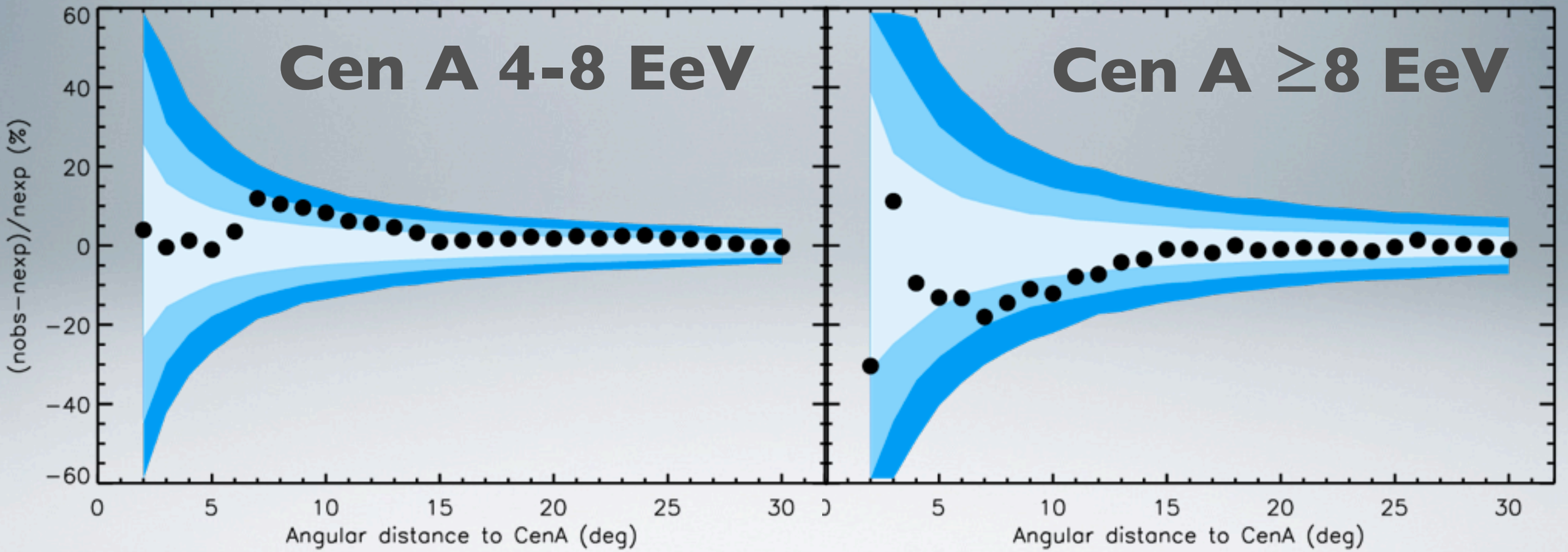
FULL SKY SIGNIFICANCES



SEARCHES ON THE GC



SEARCHES ON CEN A



CONCLUSIONS

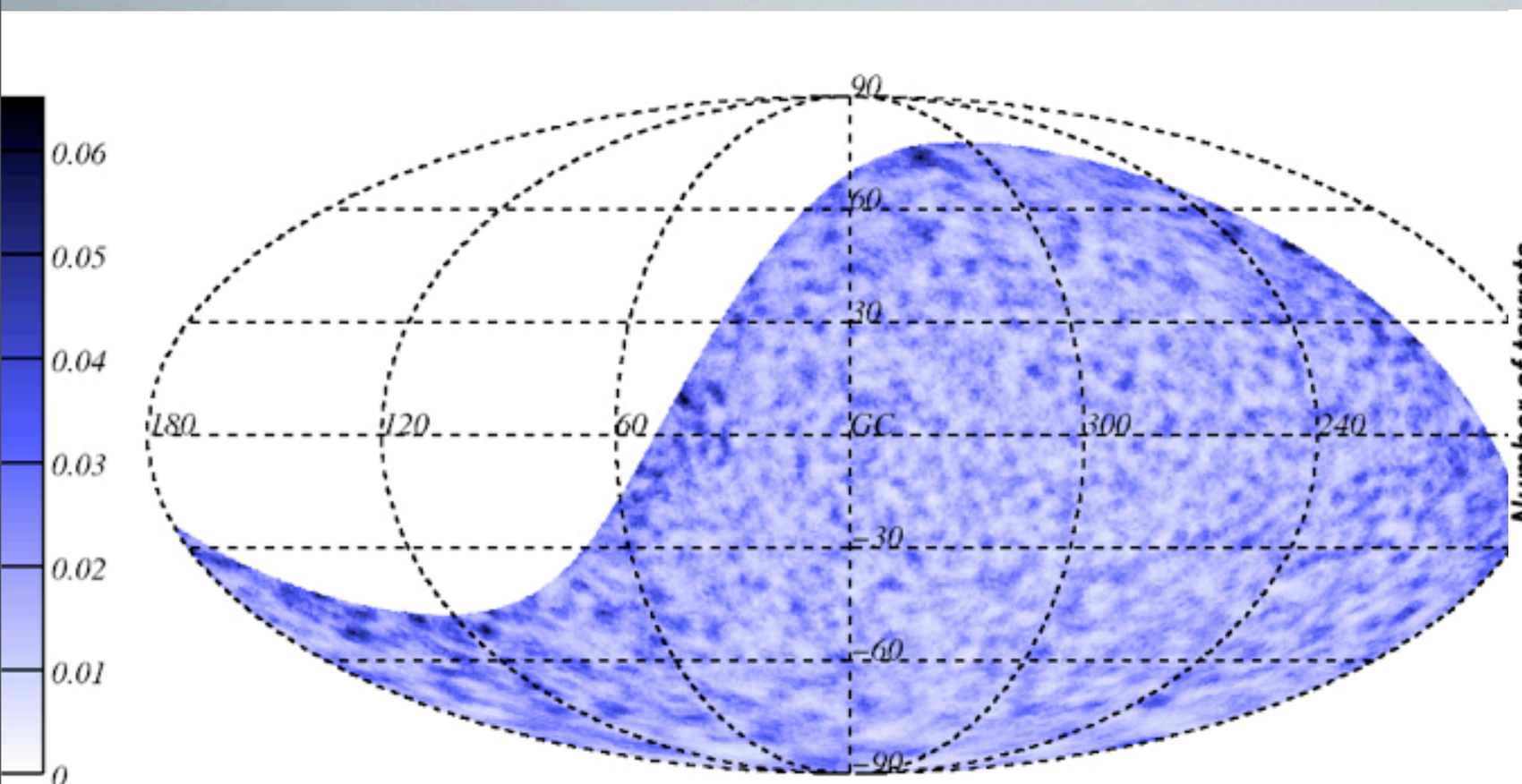
- Searches for excesses flux with respect to isotropic expectations at energies above 1 EeV at intermediate angular scales.

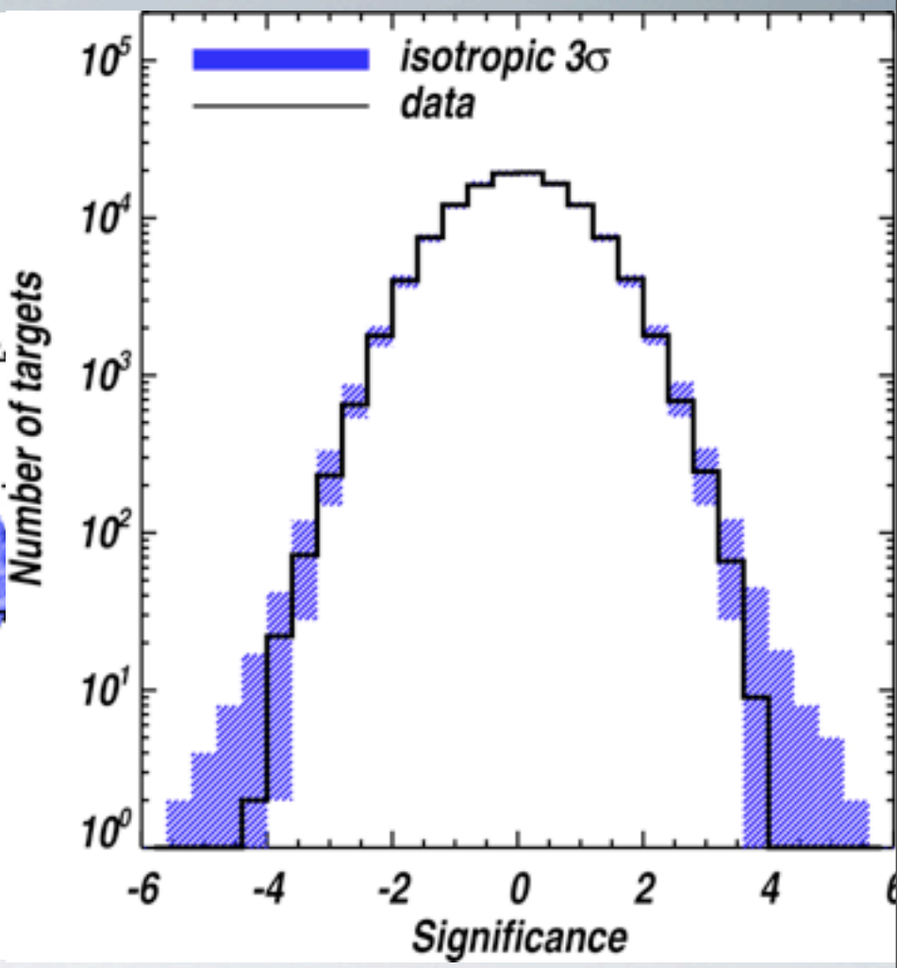
- The largest observed significances are compatible with isotropic expectations.

- No significant departures from isotropic expectations for the Galactic Center, Cen A, the Galactic and Super-Galactic planes.

Directional Neutron Searches

PREVIOUS RESULTS



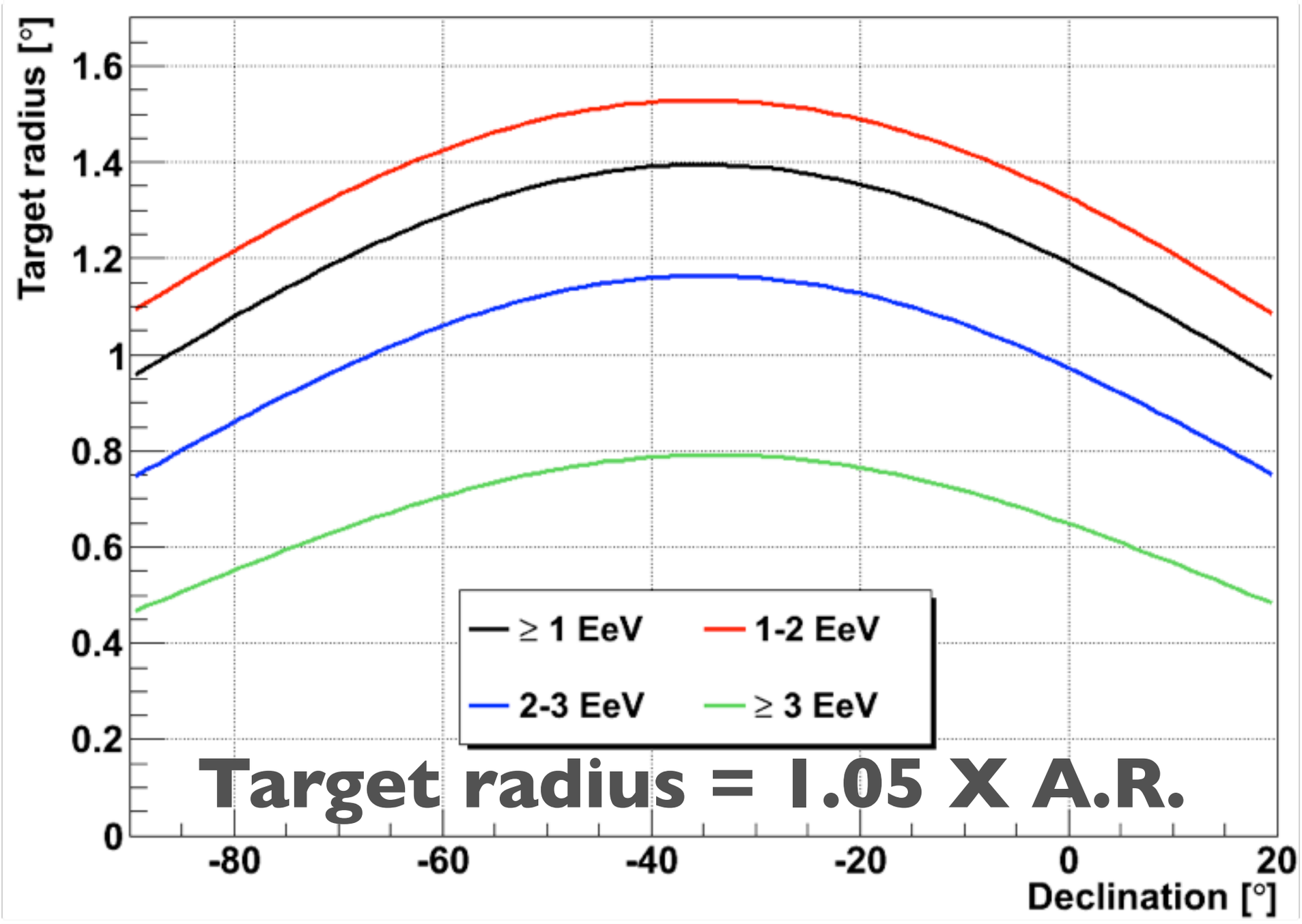


A blind search for neutron sources in the whole exposed sky was reported in Astrophys. J. 760, (2012) 148.

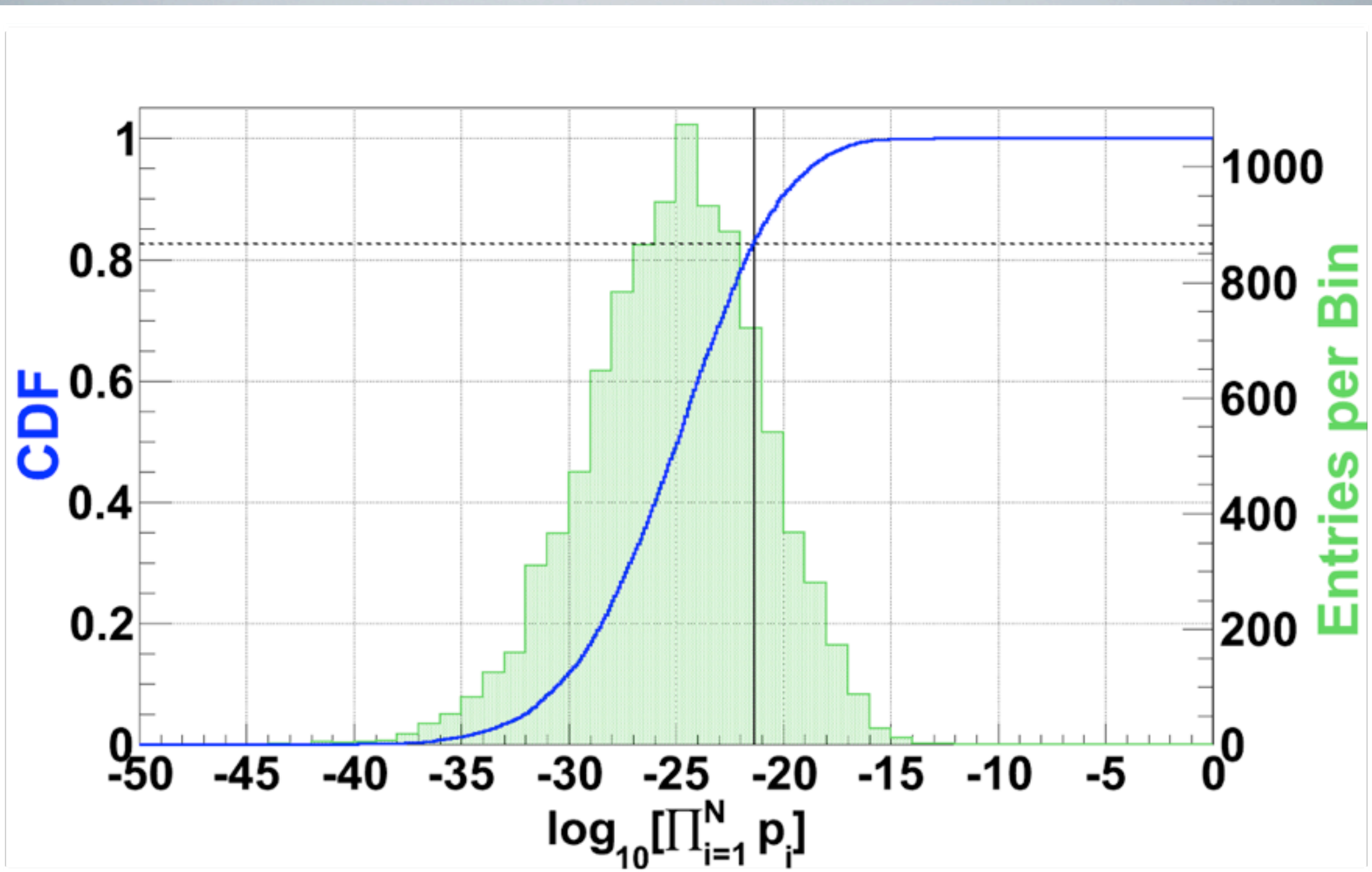
STACKED SOURCES

- 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.
- No repeated candidate sources.

METHOD


Target radius [°]
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-80
-60
-40
-20
0
20
Declination [°]
≥ 1 EeV
1-2 EeV
2-3 EeV
≥ 3 EeV
Target radius = 1.05 X A.R.

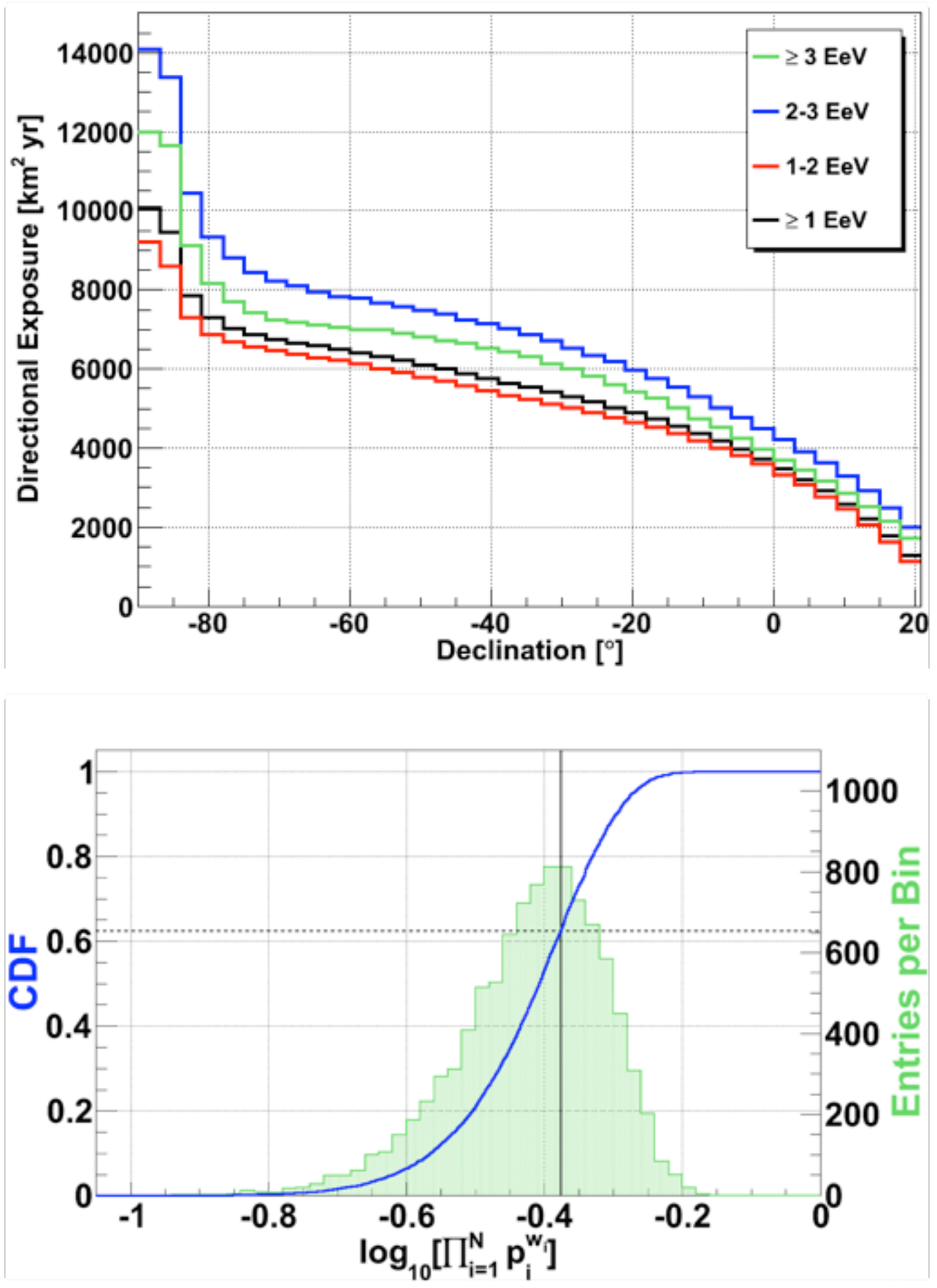
METHOD


CDF
1
0.8
0.6
0.4
0.2
0
1000
800
600
400
200
0
Entries per Bin
-50
-45
-40
-35
-30
-25
-20
-15
-10
-5
0
$\log_{10}[\prod_{i=1}^{N} p_i]$

METHOD

- Weights are included to account for **fluxes** and **exposure**.

- Weighted combined P-value uses the weights w_i as powers for the p_i values.



RESULTS

		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
LMXB	142	0.17	0.38	0.31	0.13	0.70	0.37	0.33	0.04
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.

RESULTS

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

No significantly small *individual* p-value.

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	-

CONCLUSIONS

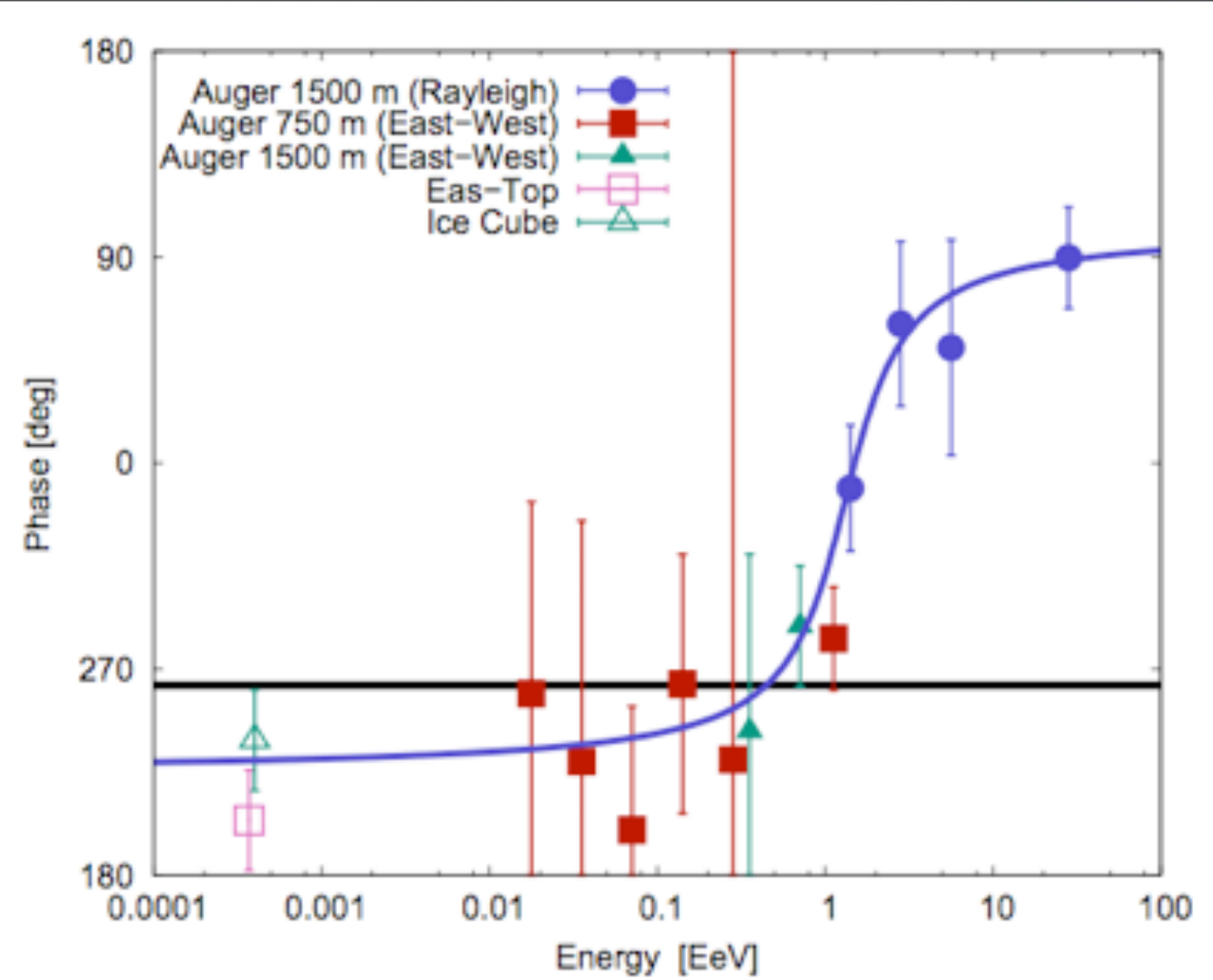
- A *search for astrophysical neutron sources* has been performed using the SD data of the Auger Observatory.
- No significantly small P-value was found for any of the classes of potential Galactic sources considered.
- After penalizing for multiple trials within each stack, *no candidate source* shows a significant excess.
- Upper limits on neutron fluxes are reported (assuming an E^{-2} spectra above $1\ EeV$).
- Null results were also derived for the Galactic Plane and the Galactic Center.

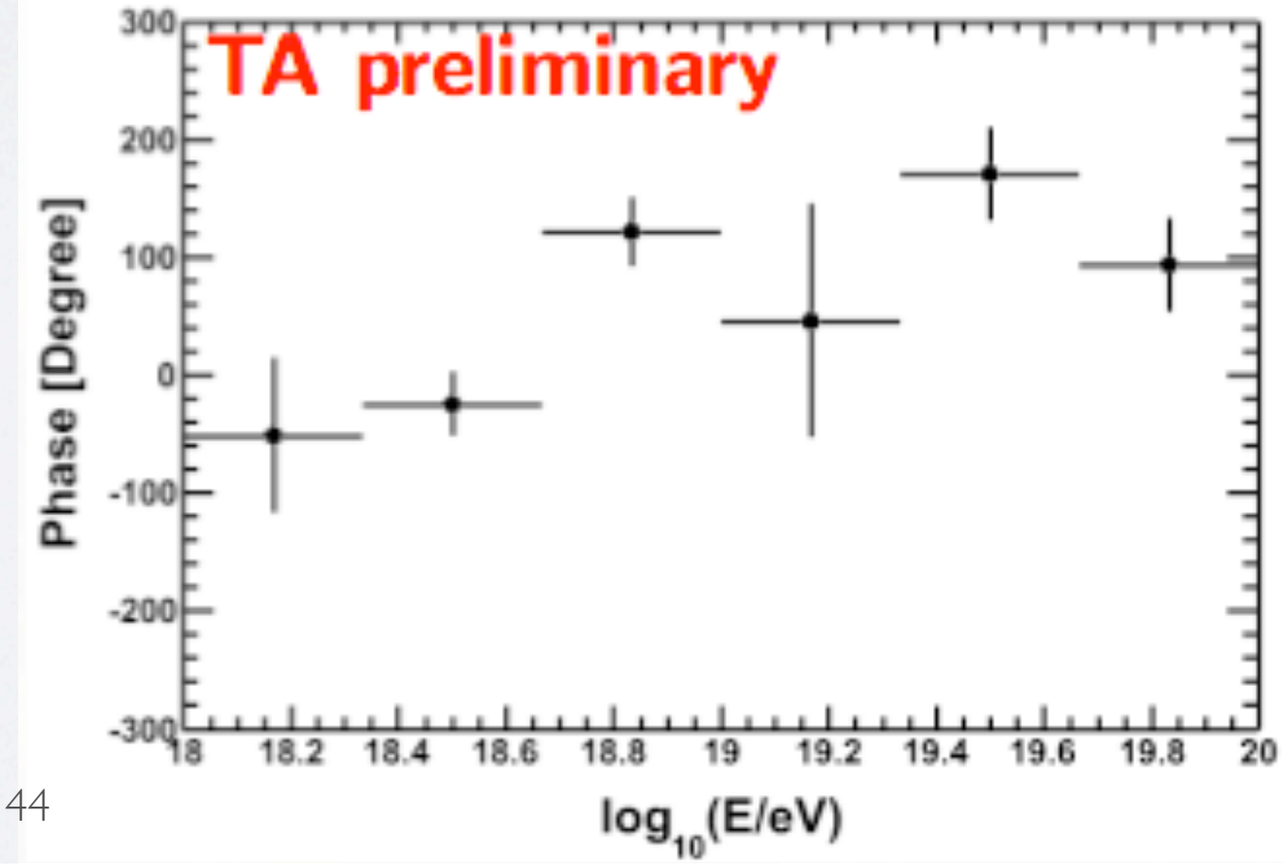
FULL SKY SEARCHES

MOTIVATION

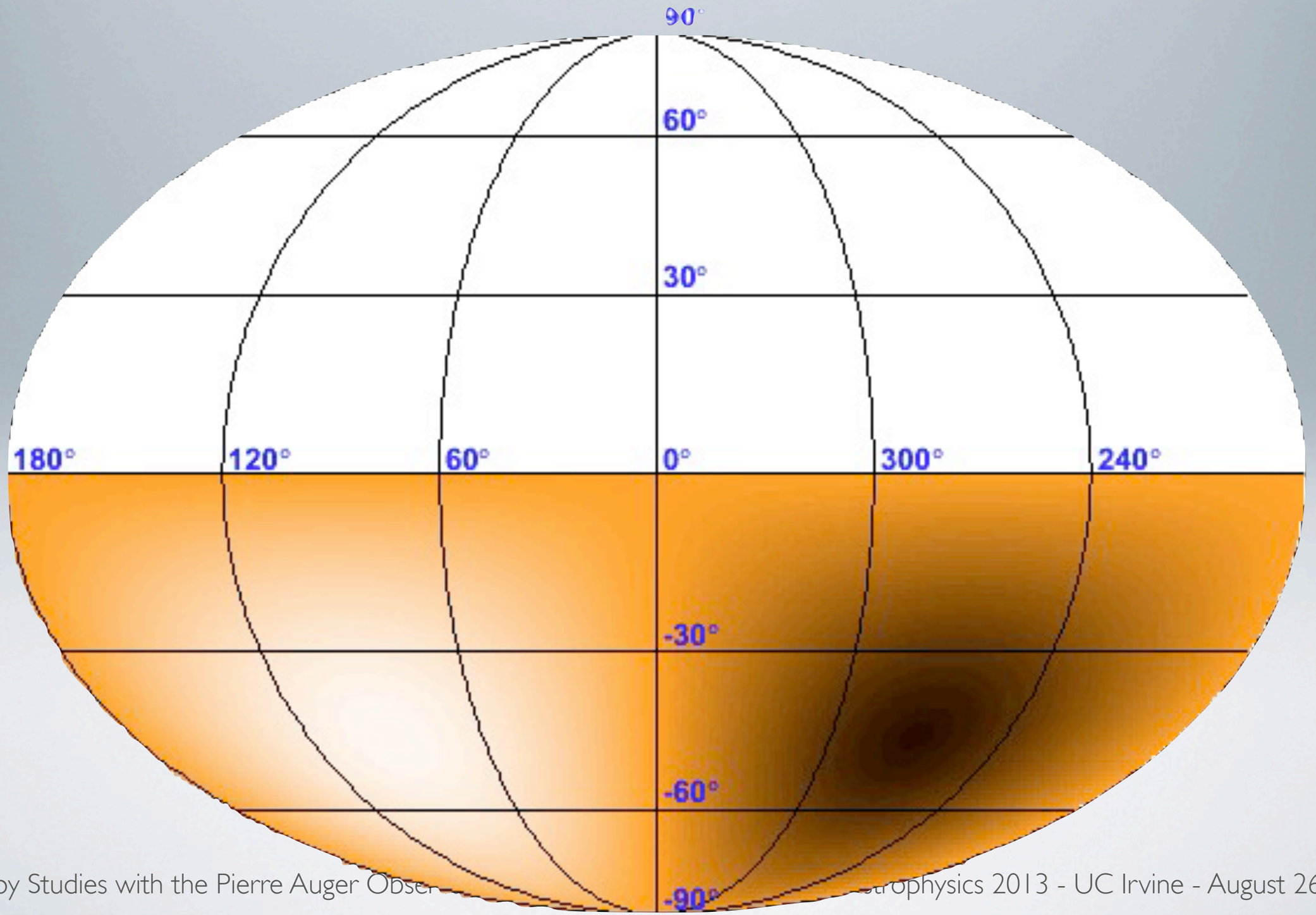
- *Hints in RA in both hemispheres*
- Anisotropy studies with Auger +TA data:

⇒ *Increased statistics + full-sky coverage!*

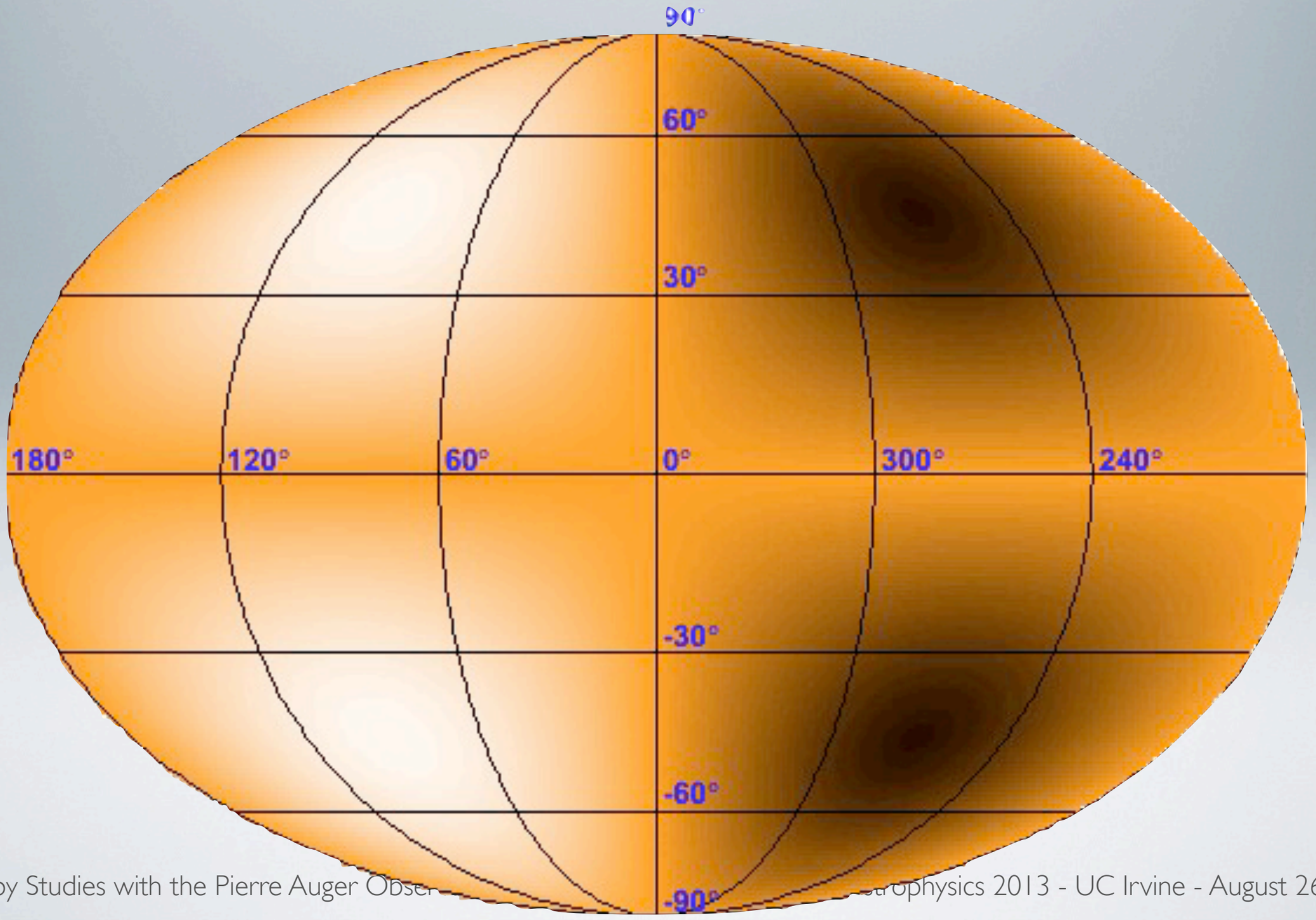




EXPANSION IN SPHERICAL HARMONICS



EXPANSION IN SPHERICAL HARMONICS

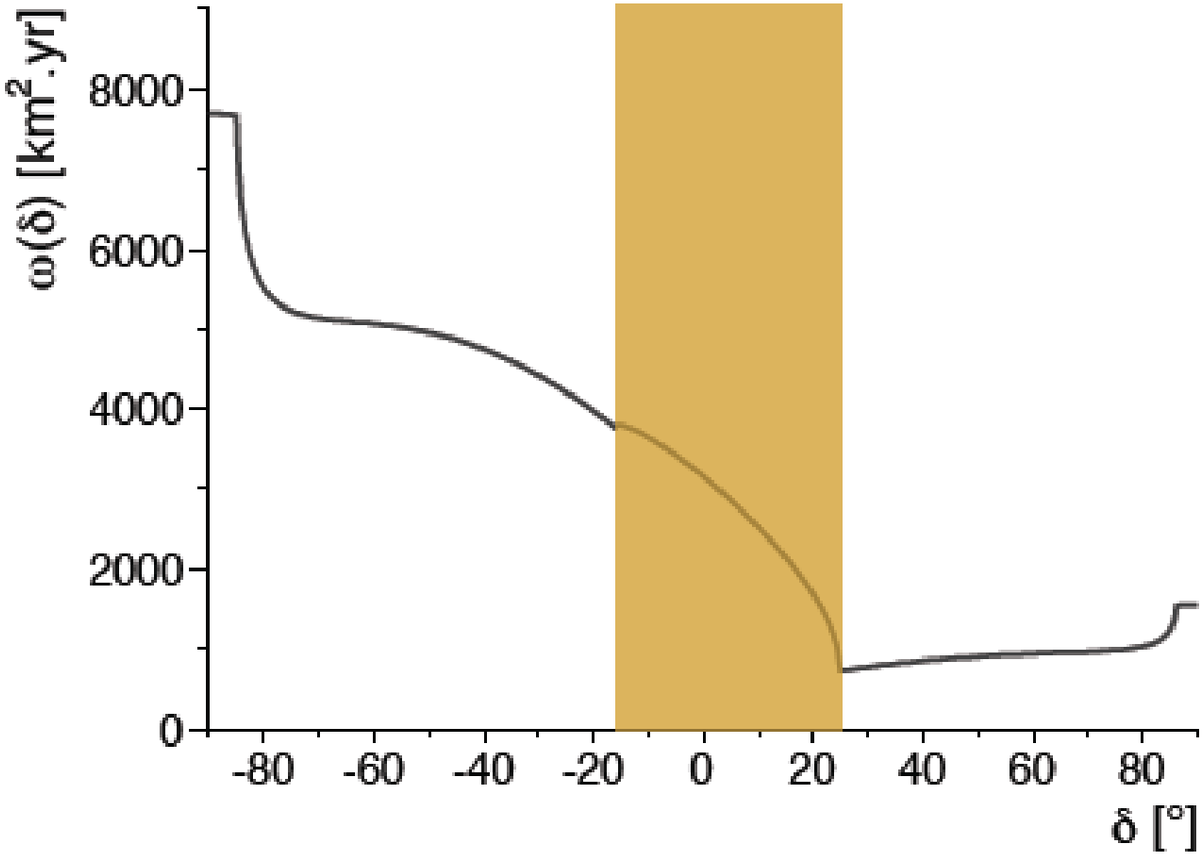


FULL SKY COVERAGE

- Account for different zenith ranges

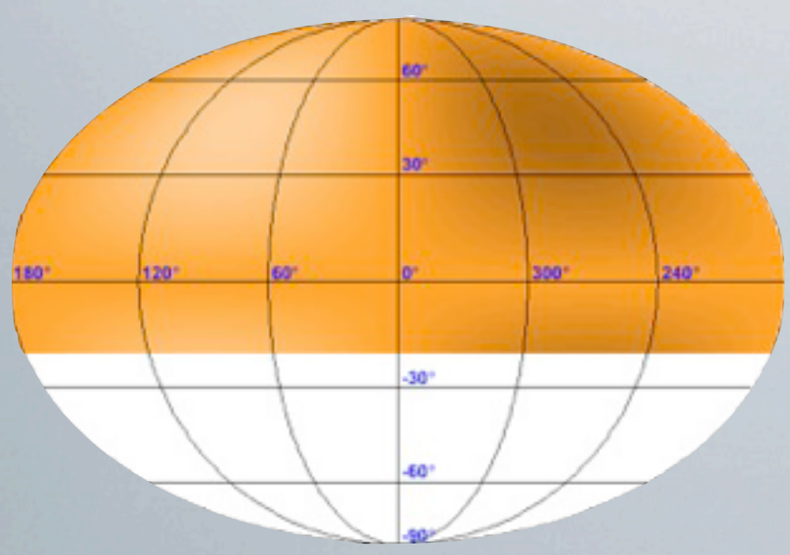
- Calculate geometrical directional exposure
  ⇒ different *energy thresholds*

- Uncertainty in the **relative exposures**



$$\omega(\vec{n}; b) = \omega_{\mathrm{TA}}(\vec{n}) + b \cdot \omega_{\mathrm{Auger}}(\vec{n})$$

ESTIMATING COEFFICIENTS



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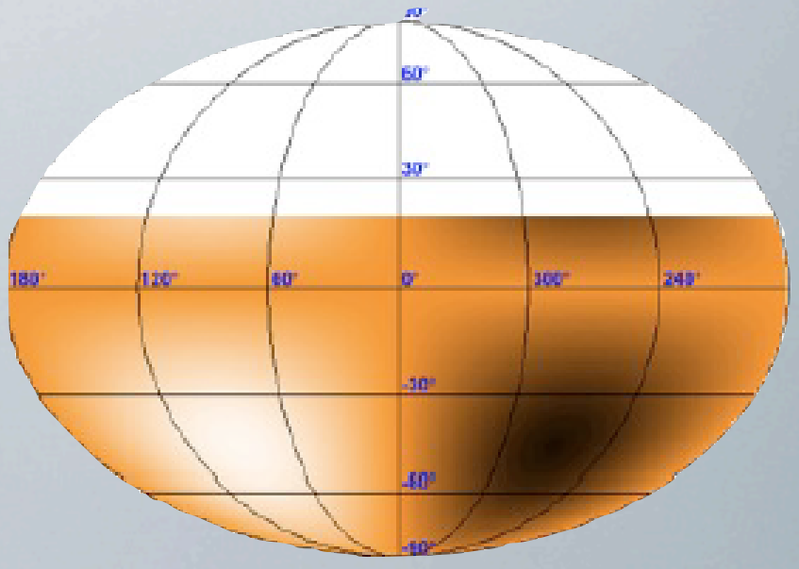

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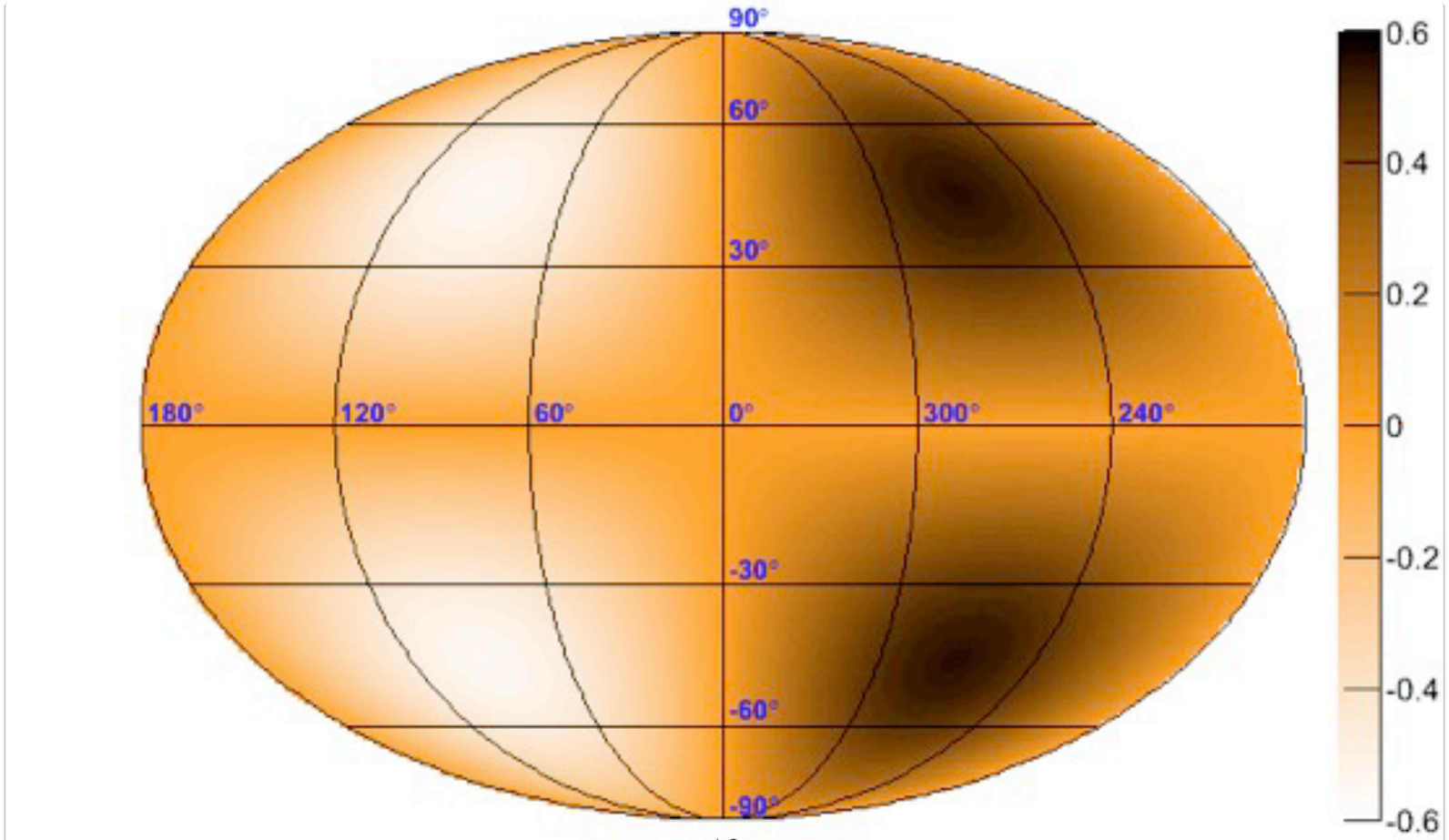
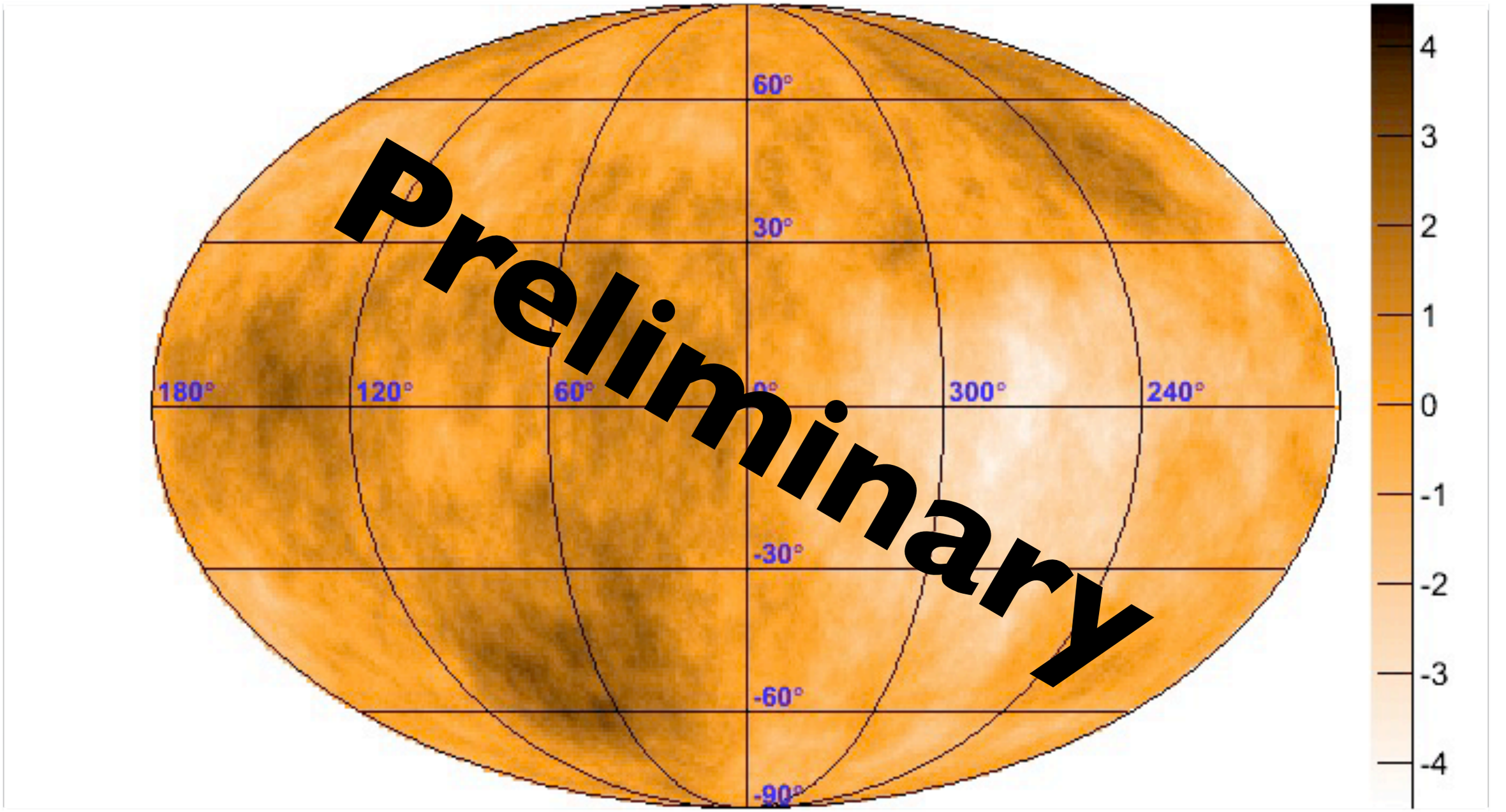


FULL SKY MAP

E > 10 EeV; 30° smoothing



OUTLOOK

- Measuring unambiguously spherical harmonic coefficients requires *full-sky coverage*.

- Design of a method that accounts empirically for any source of systematics in the relative exposures of combined experiments.

- The method pertains to any full-sky coverage achieved by combining data sets from different observatories.

- This opens a rich field of *anisotropy studies*.

- *Application to Auger+TA data above* $\boldsymbol{10^{19}}$ **eV** *in progress!*

CONCLUSIONS

- Hints of large scale anisotropy.
- Updated upper limits on dipole, quadrupole, and neutron fluxes.
- Galactic origin above ankle is starting to be challenged.
- Full sky analyses are *in progress*.

Thank you very much!