Anisotropies in the flux of ultra-high energy cosmic rays

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Overview

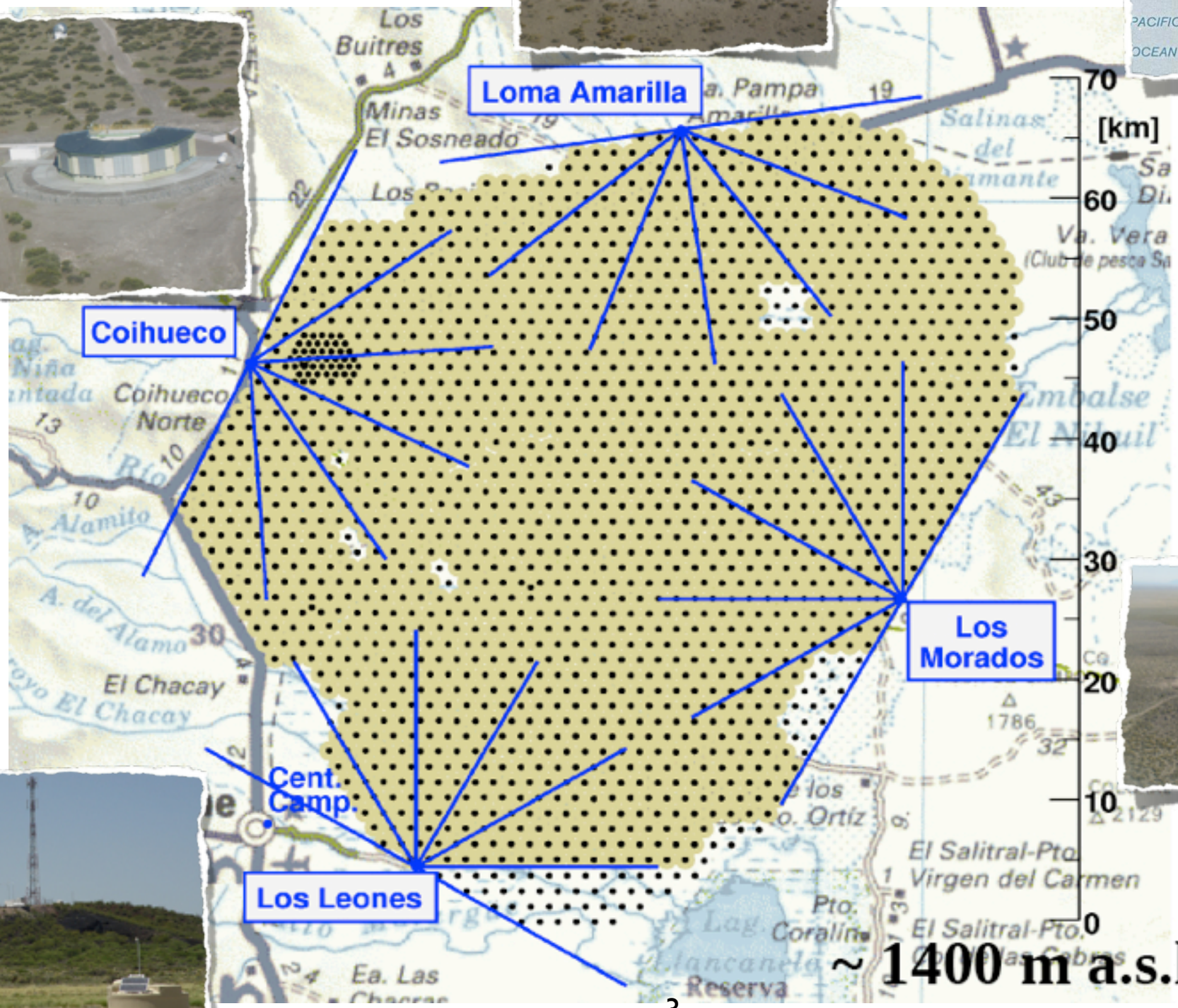
- **Some notes on datasets**
- **Searches for small to intermediate scale anisotropies**
- **Searches for large scale anisotropies**
- **Combined full sky analyses**
- **Summary**

The Pierre Auger Observatory

3000 km² surface array (1660 detectors)

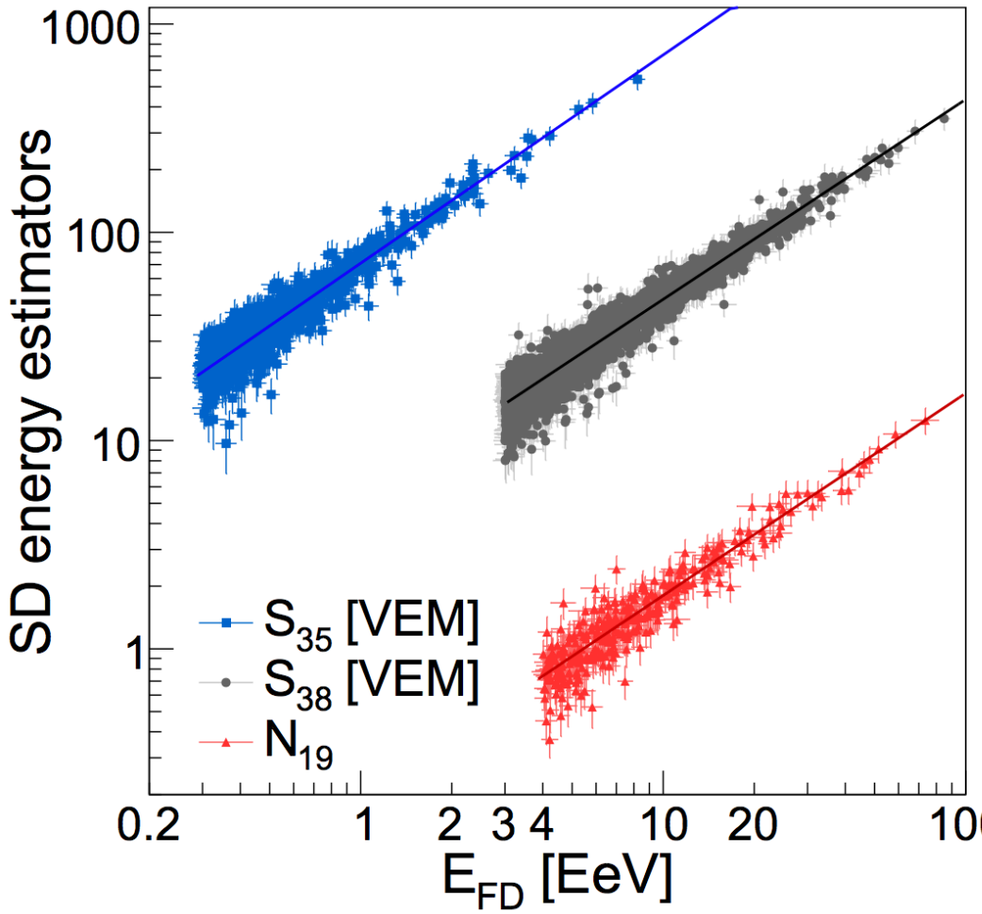
1.5 km triangular grid

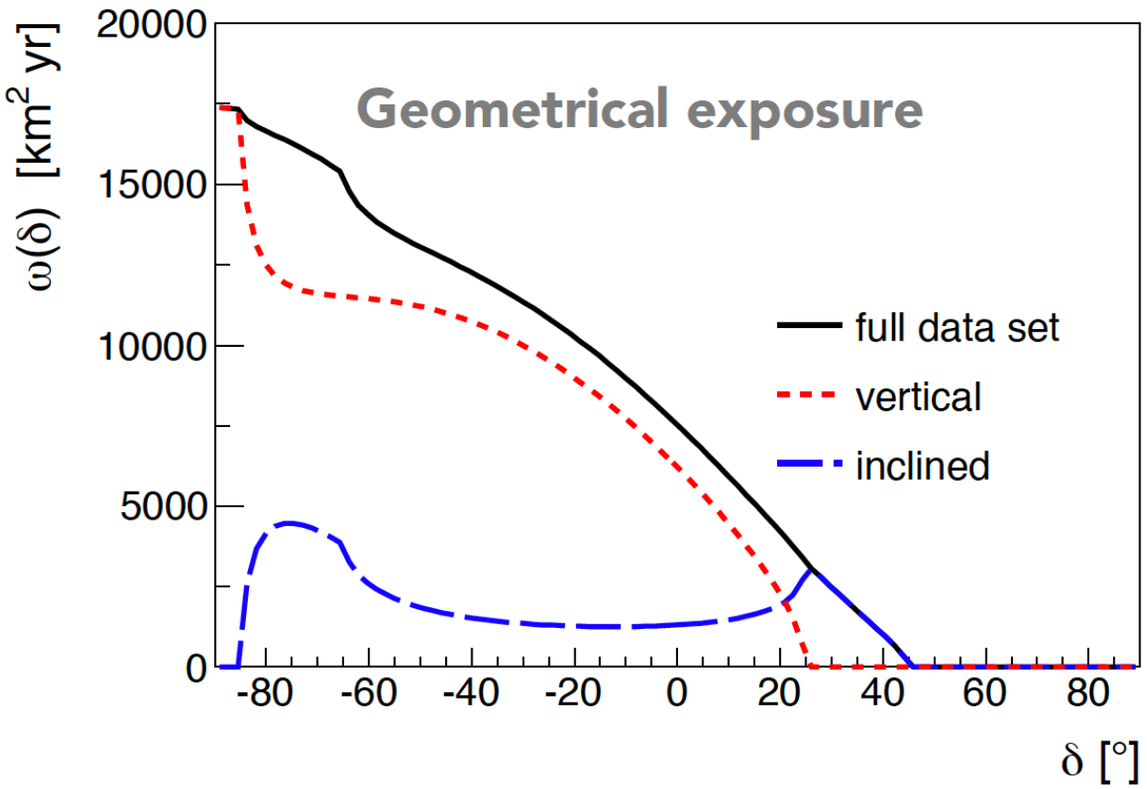
27 fluorescence telescopes



General note on Auger SD data samples - I

- Data-driven energy calib. using hybrid events
- Different SD estimators are correlated to the quasi-calorimetric energy measured by the FD
- Here, we should use two samples, depending on the zenith angle of the events:
  - Vertical: $0^o<\theta<60^o$ (S_{38} x E_{FD})
  - Inclined: $60^o<\theta<80^o$ (N_{19} x E_{FD})





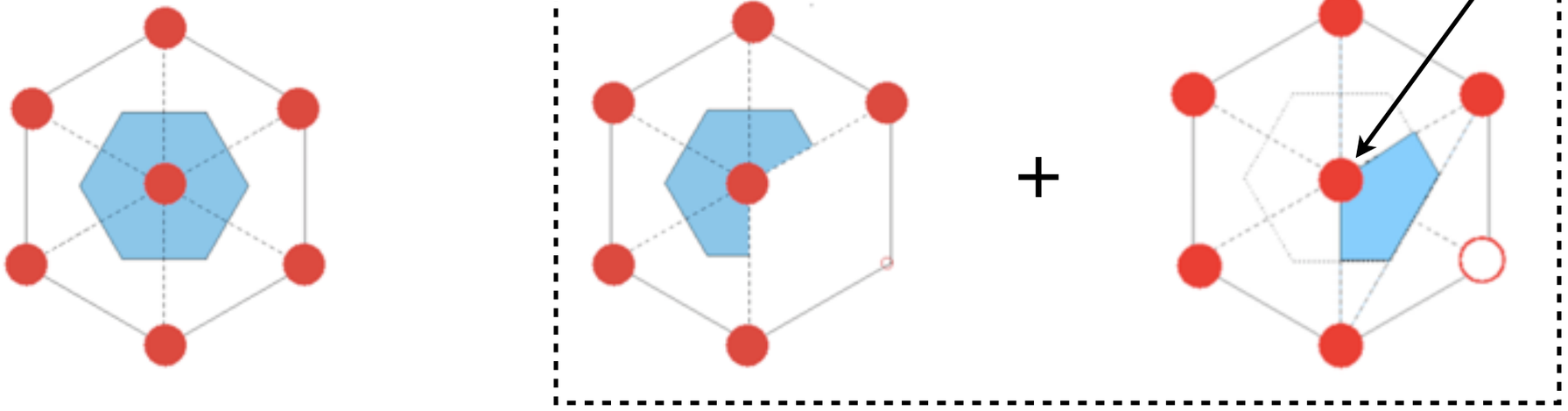
- Inclined sample provides about ~30% of extra sky coverage
- This extra coverage is very important to many of the analyses to be discussed here

General note on Auger SD data samples - II

6T5 (tight trigger)

5T5-pos+ (relaxed trigger)

Hottest and/or closest to the core station

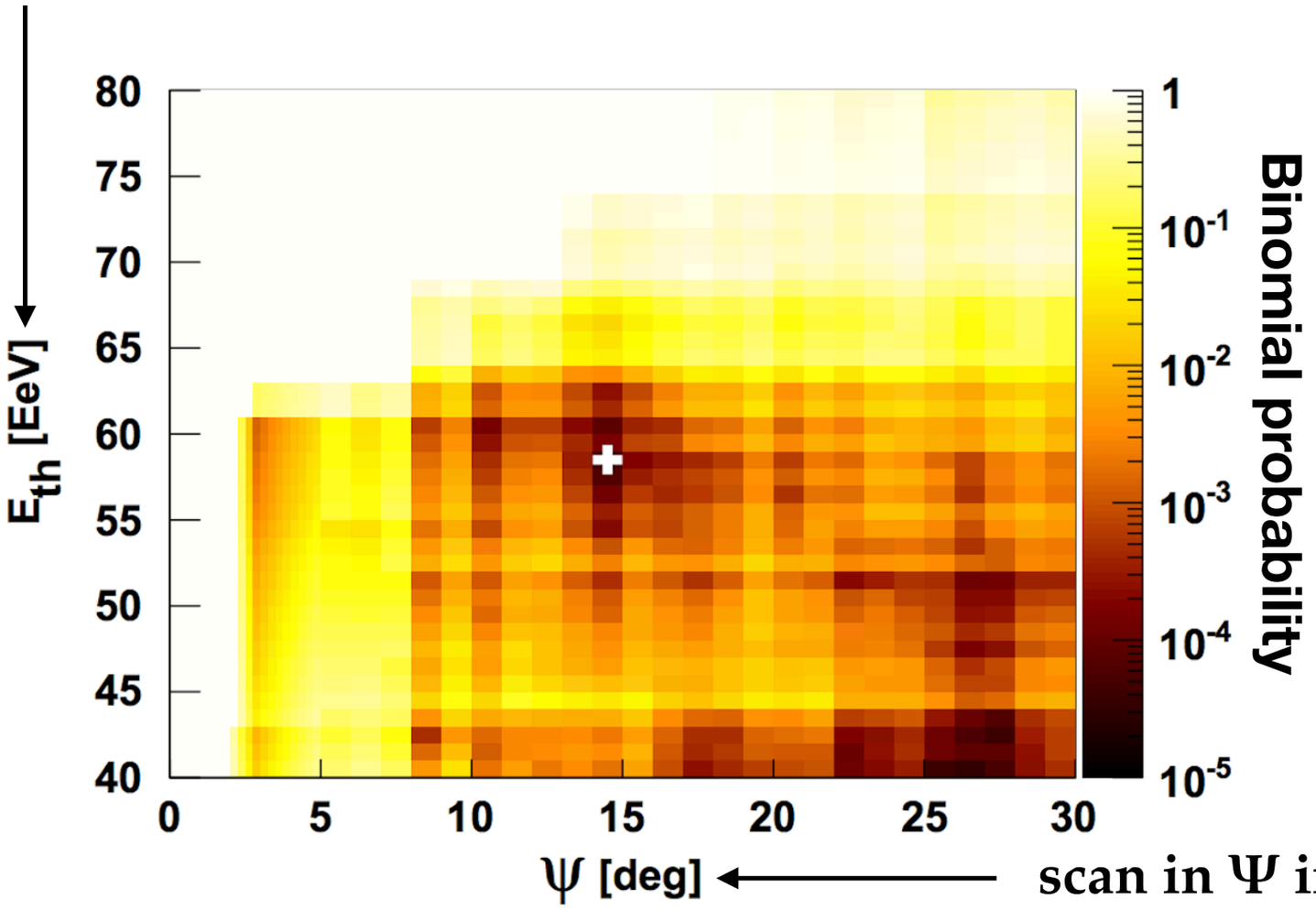


Core inside equilateral **Core inside isosceles**

- **6T5**: all 6 stations in the first crown active at the moment the event is detected
- **5T5-pos+**: 5 stations in the first crown active at the moment the event is detected, and core falls either inside an equilateral or an isosceles triangle
- Checked that reconstruction is not biased by including this events
- Important extra statistics! : 5T5-pos+ / 6T5 ~ 18%

Small to intermediate scale anisotropies

Centaurus A



Minimum probability found at:

E_{th} = 58 EeV, Ψ = 15°

n_{obs} = 19, n_{exp} = 6.0

$P \sim 1.1 \times 10^{-5}$

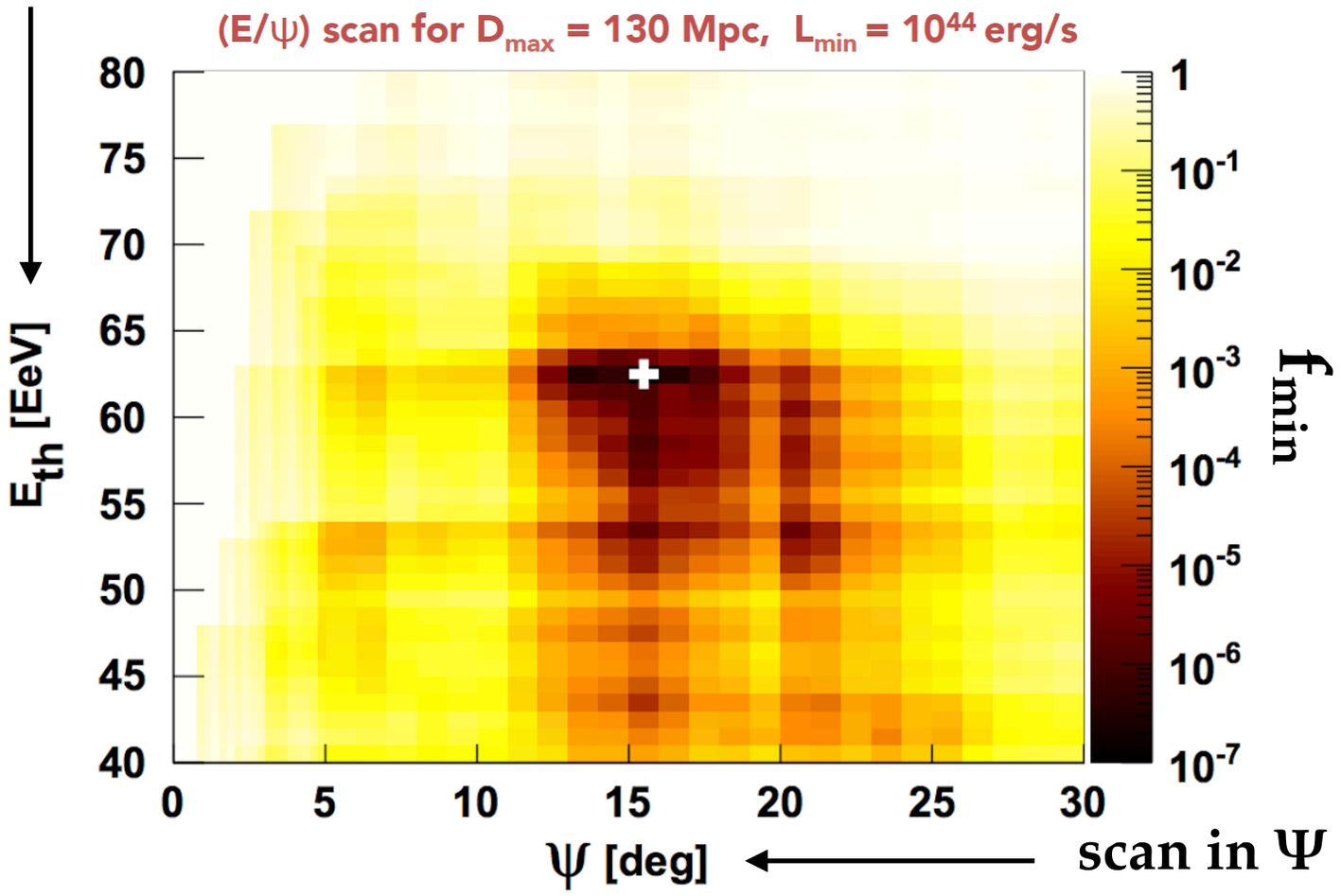
Post-trial (E_{th}, Ψ):

$\sim 1.1 \times 10^{-3}$

- Get the cumulative number of events for a given energy threshold (Eth) and angular window (Ψ) around CenA for data (n_{obs})
- Estimate the average number of events inside the same angular window form simulations (n_{exp})
- Compute binomial probability P of measuring n_{obs} given n_{exp}
- Penalize for scan in energy threshold and angular window (post-trial prob.)

Bright AGNs from Swift-BAT catalog

scan in E_{th} in 1 EeV steps



Minimum probability found at:

E_{th} = 62 EeV, Ψ = 16°

$n_{obs} = 57$, $n_{exp} = 26.4$

$f_{min} = 1 \times 10^{-7}$

Post-trial (E_{th},Ψ,L_{min}, D_{max}):

$\sim 6.5 \times 10^{-4}$

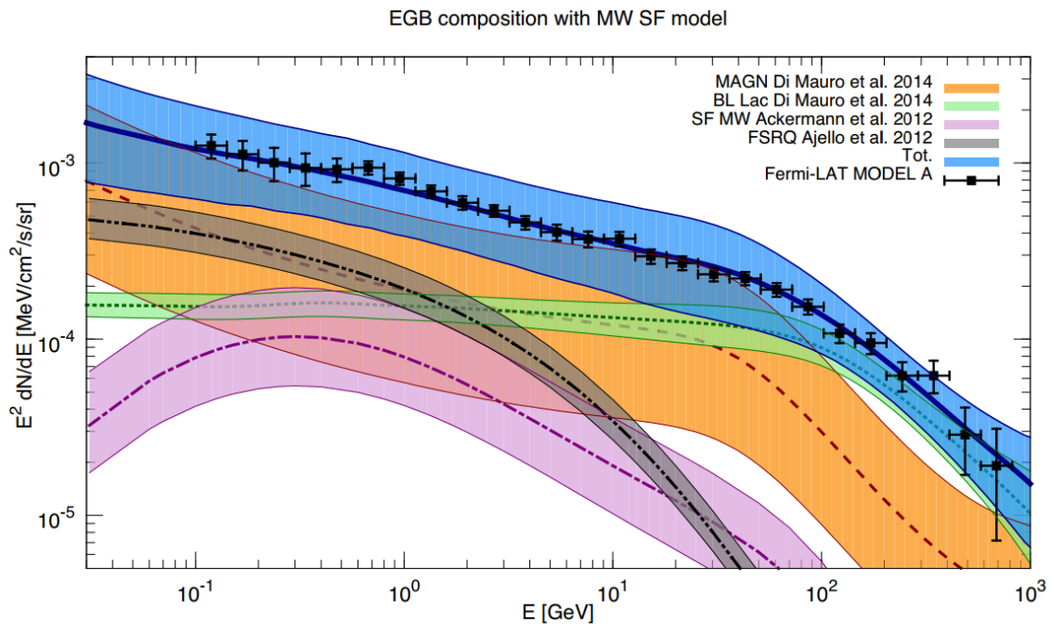
scan in Ψ in 0.25° up to 5° and 1° above

- Get the cumulative number of pairs for a given energy threshold (E_{th}) and angular distance (Ψ) wrt to catalog objects (n_{obs})
- Estimate the fraction of isotropic simulations (f_{min}) with number of pairs as large as in the data
- Penalize for scan in energy threshold, angular window, minimum luminosity of source and maximum distance (post-trial prob.)

Selection of extragalactic gamma-ray sources

AGNs and starburst galaxies dominate the x-gal γ-ray background

Di Mauro & Donato, PRD 91 (2015) 123001



Active Galactic Nuclei:

- **Fermi 2FHL catalog**
- **Φ(>50 GeV) as proxy for UHECR flux**
- **17 objects up to 250 Mpc**
- **Most blazars and BL-Lac type**

Starburst galaxies:

- **Fermi-LAT list of star-formation objects (Ackermann+12)**
- **Φ(>1.54 GHz) as proxy for UHECR flux**
- **Brightest objects selected: Φ(>1.54 GHz) > 0.3 Jy**
- **23 objects in final sample**

Assumption: UHECR flux is correlated to the non-thermal photon flux

Construction of the likelihood

Unbinned likelihood:

exposure

$$\mathbf{L} = \Pi_{i=1}^{N} \left[\omega(\hat{\mathbf{n}}_i) \times \mathrm{model}(\hat{\mathbf{n}}_i)\right]$$

$$\left[\alpha \times \mathrm{sources} + (1-\alpha) \times \mathrm{isotropy}\right] \otimes \mathrm{Gaussian}(\theta)$$

Include weights to account for flux attenuation (especially important for AGNs)

2D parameter space (α,θ):
- **α: Anisotropic fraction**
- **θ: RMS deflection**

Scan in energy threshold [20:80] EeV in steps of 1 EeV

Test statistics (TS) is a log-likelihood ratio of two hypotheses:

$$\mathrm{TS} = 2 \ln \left(\frac{H_1}{H_0} \right)$$

H_1: AGN or starburst as sources

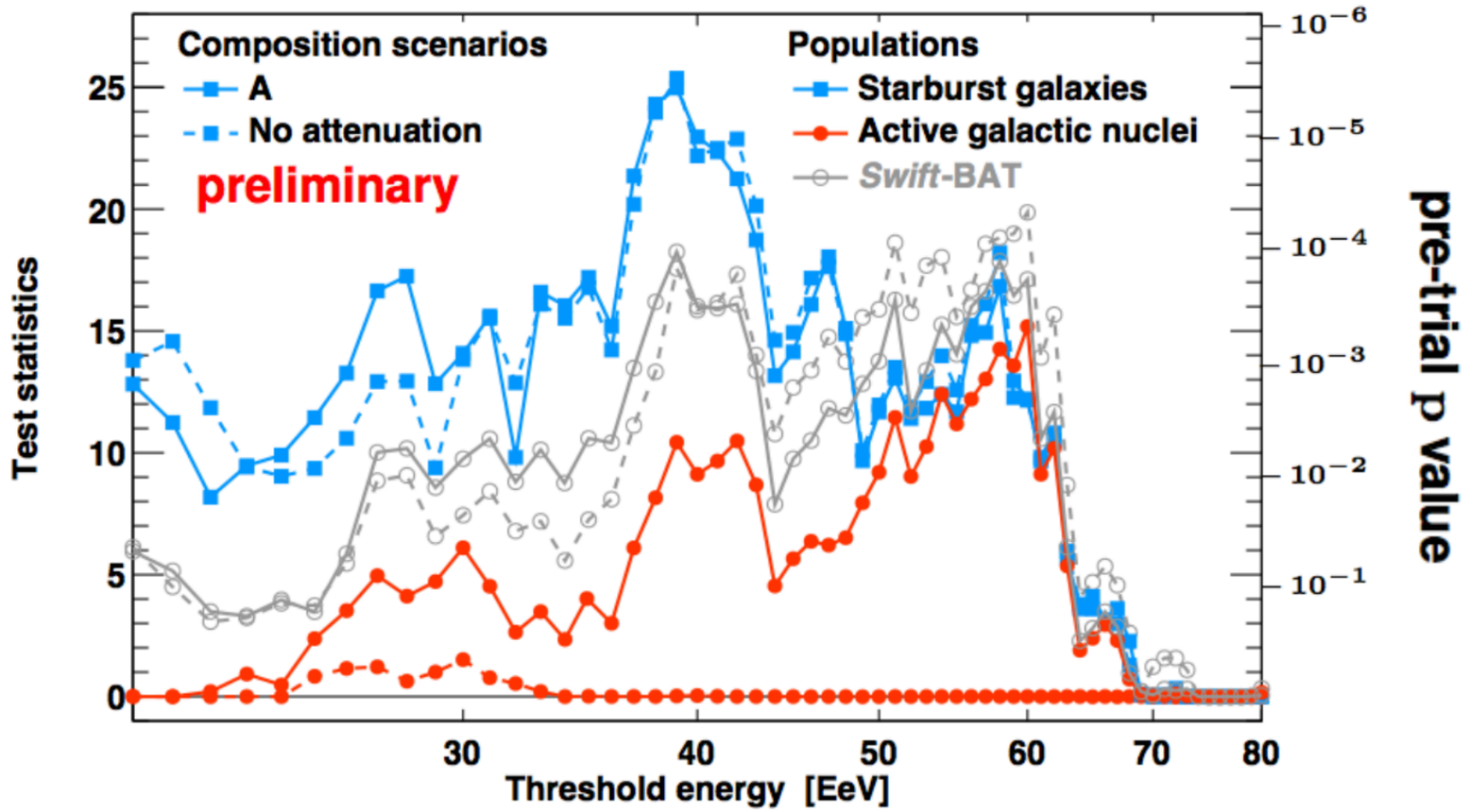
H_0: Isotropy

TS vs threshold energy

Starburst Galaxies
TS = 24.9, E_{th} = 39 EeV

γ-ray detected AGNs
TS = 15.2, E_{th} = 60 EeV

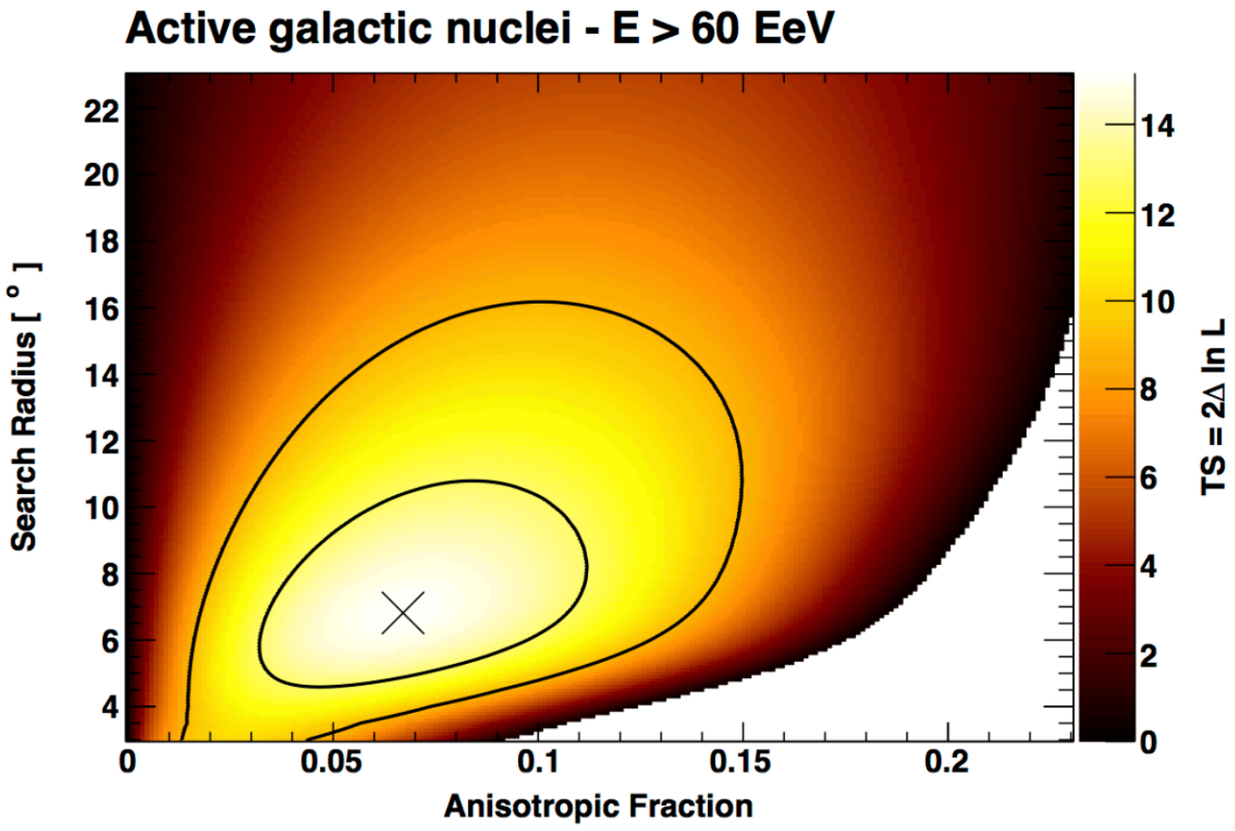
***Swift*-BAT AGNs**
TS = 19.9, E_{th} = 60 EeV

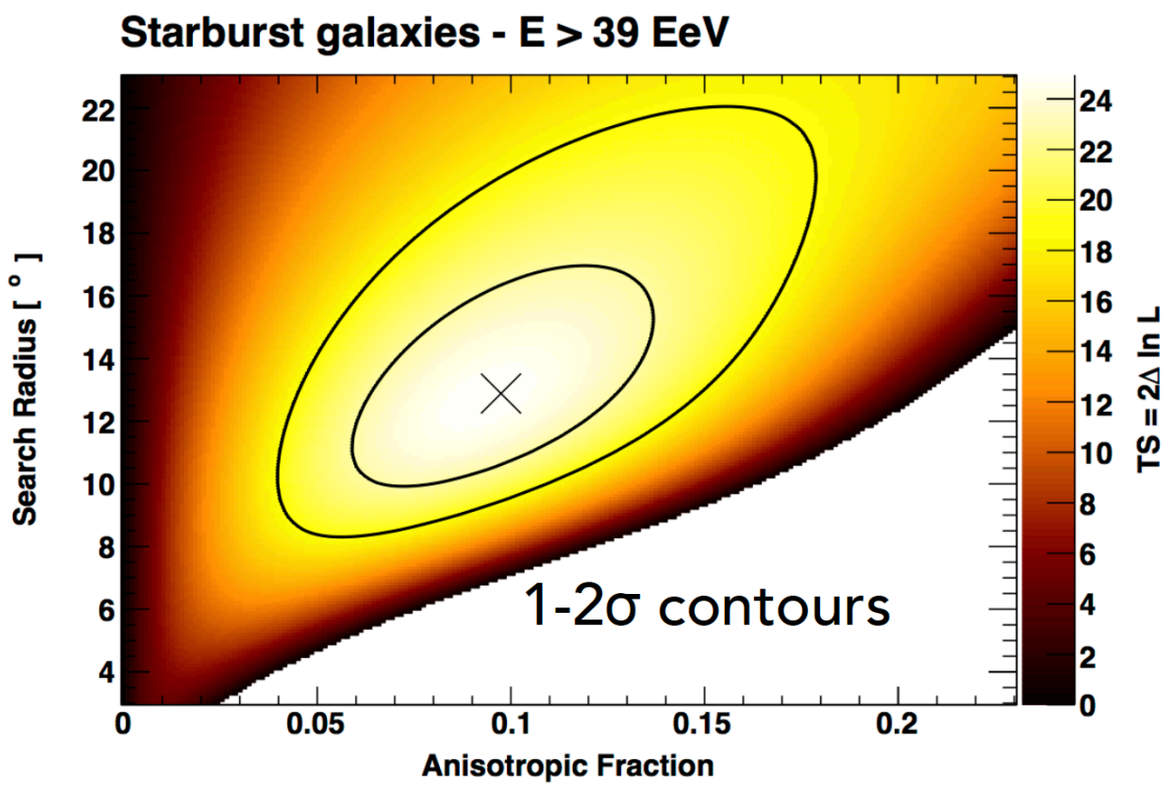


- **Flux attenuation weights very important for AGNs, but negligible for starburst (nearby)**
- **Weights, however, depend strongly on the mass composition scenario**

Mass composition scenario:
- **Combined spectrum+Xmax fit**
- **EPOS-LHC as hadronic model**
- **Uniform source distribution**

Element	Fraction
H	0%
He	67.3%
N	28.1%
Si	4.6%
Fe	0%





$\alpha = 7\%,\ \theta = 7^\circ$

TS = 15.2

Eth = 60 EeV

Pre-trial: 5 x 10^{-4}

Post-trial: 3 x 10^{-3} (2.7σ)

$\alpha = 10\%,\ \theta = 13^\circ$

TS = 24.9

Eth = 39 EeV

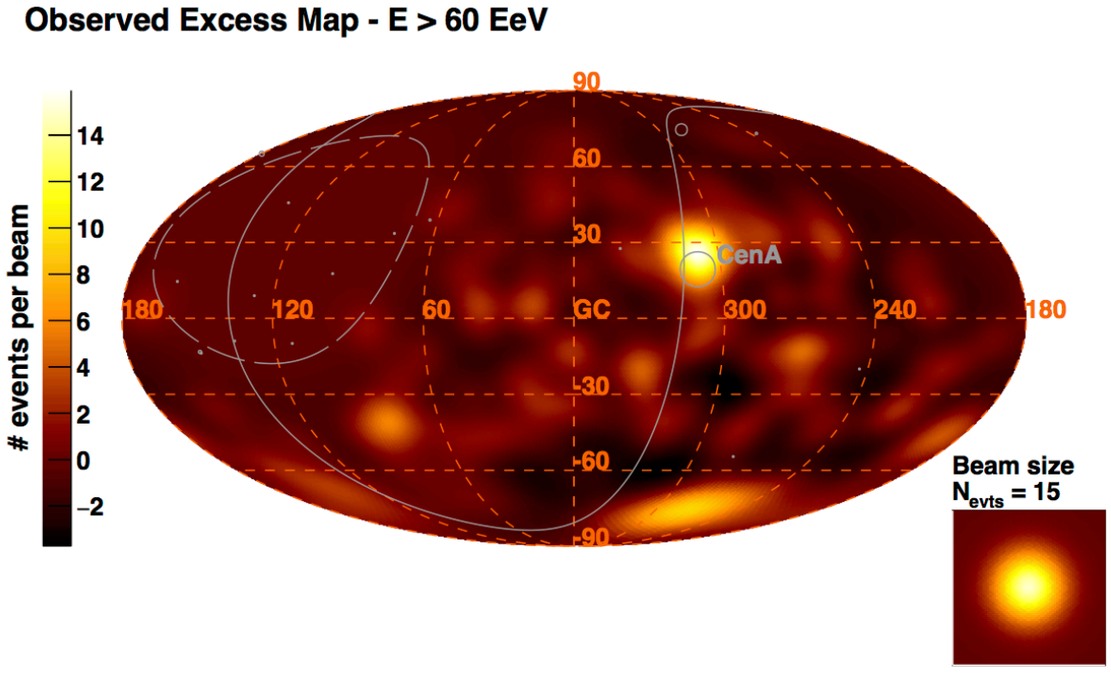
Pre-trial: 4 x 10^{-6}

Post-trial: 4 x 10^{-5} (3.9σ)

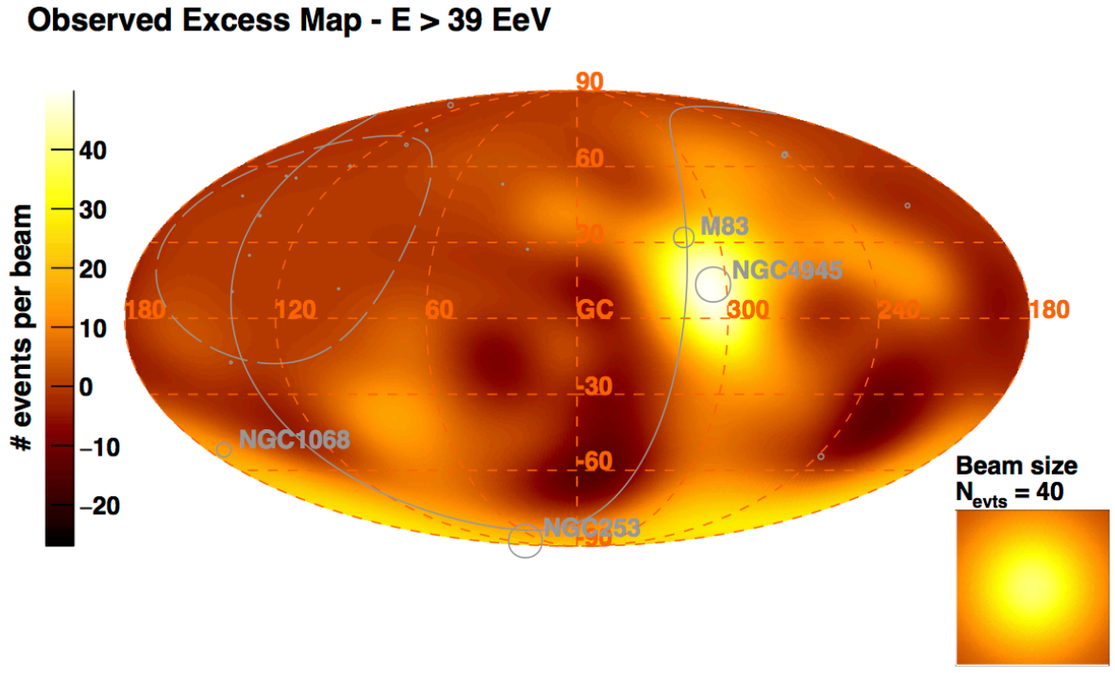
- **Post-trial prob. = fraction of isotropic simulations with TS greater than in data while scanning across the same energy bins**
- **Previous searches and hidden trials not account for**

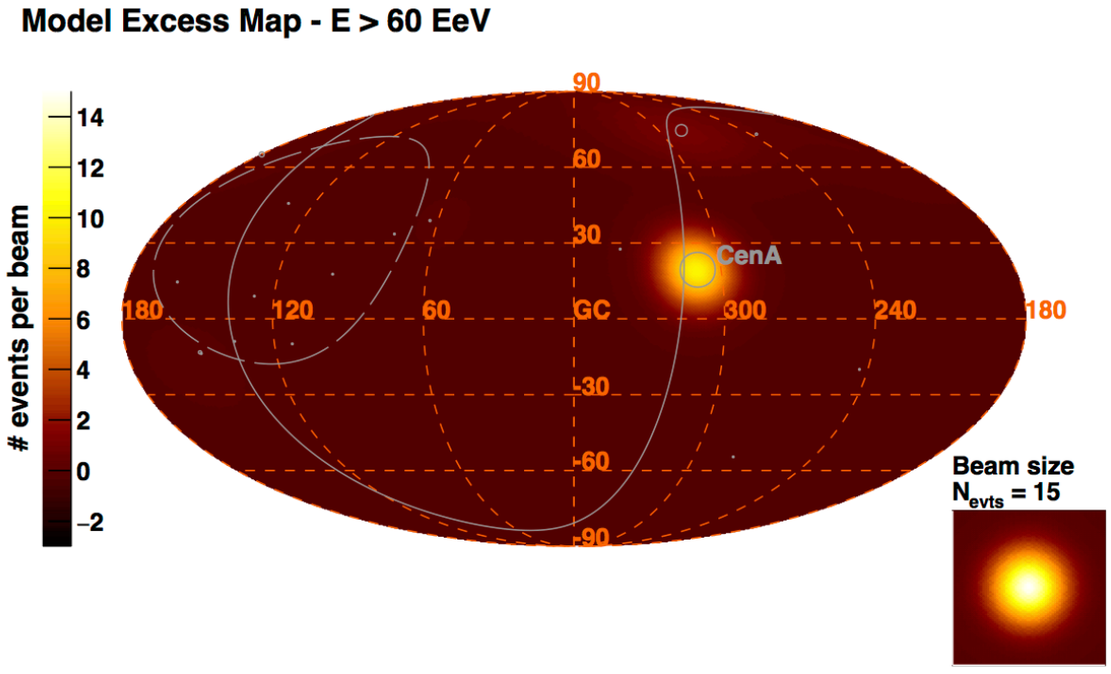
Best-fit maps (galactic coord.)

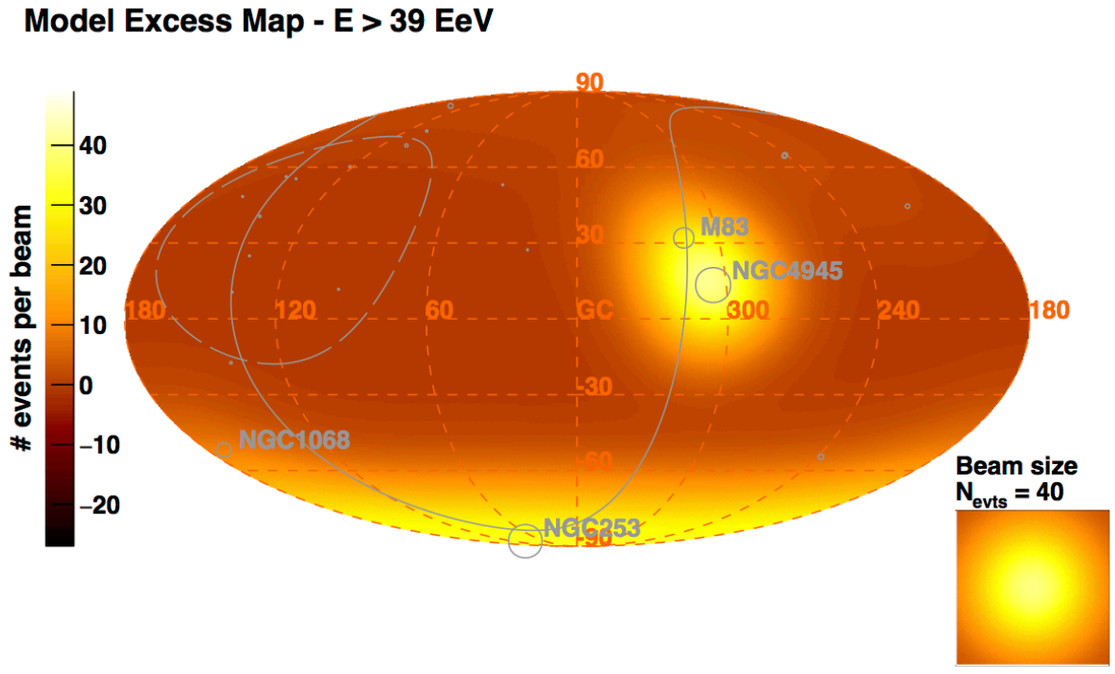
γ-ray AGNs



Starburst galaxies





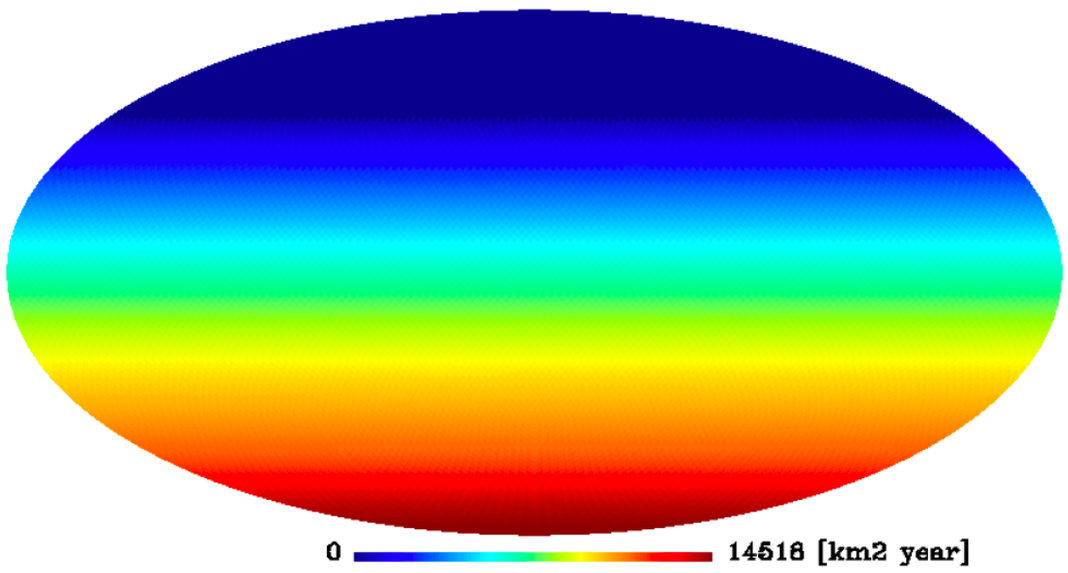


Large scale anisotropies

Dipole above 8 EeV - dataset

- **Period: 01-01-2004 to 08-31-2016**
- **Additional sky coverage (~30%) provided by inclined events ($60^o<\theta<80^o$)**
- **Enhanced statistics with the use of relaxed (but high quality) triggers**
- **Two major systematic effects understood and corrected:**
  - **Weather (temperature and pressure) induced modulations**
  - **Distortions on ground level muon density by the geomagnetic field**
- **Total integrated exposure of 76,800 km² sr year**

Directional exposure



Dipole detection

Science 57 (2017) 1266

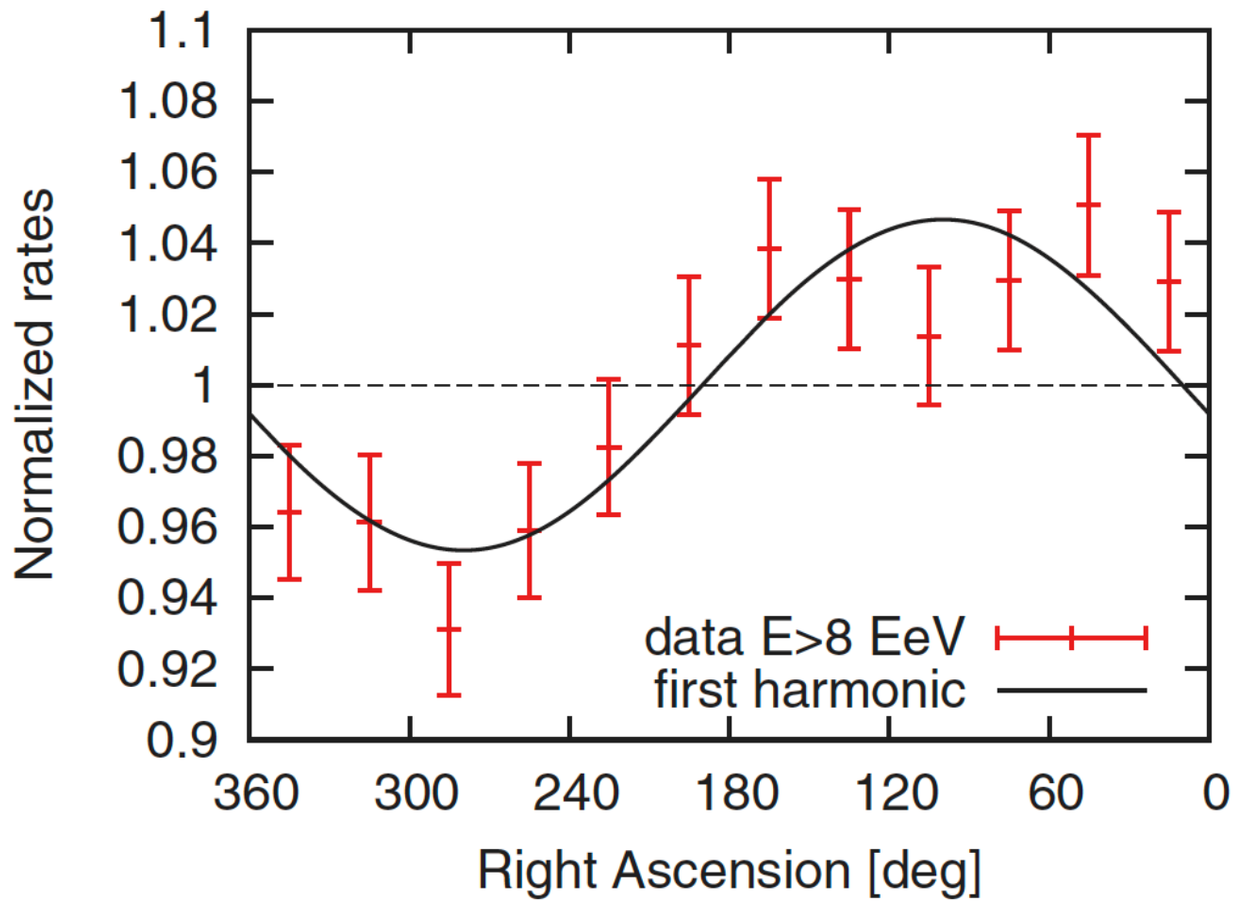
Analysis of first harmonic modulation in RA and azimuth

$$a_\alpha = \frac{2}{N}\sum_{i=1}^{N} w_i \cos\alpha_i \qquad b_\alpha = \frac{2}{N}\sum_{i=1}^{N} w_i \sin\alpha_i$$

Account for non-uniformities of the exposure in RA and a slight tilt of the array

Amplitude and phase of modulation

$$r_\alpha = \sqrt{a_\alpha^2 + b_\alpha^2} \qquad \tan\varphi_\alpha = \frac{b_\alpha}{a_\alpha}$$



Energy (EeV)	Number of events	Fourier coefficient a_α	Fourier coefficient b_α	Amplitude r_α	Phase φ_α (°)	Probability $P(\geq r_\alpha)$
4 to 8	81,701	0.001 ± 0.005	0.005 ± 0.005	$0.005\ ^{+0.006}_{-0.002}$	80 ± 60	0.60
≥8	32,187	−0.008 ± 0.008	0.046 ± 0.008	$0.047\ ^{+0.008}_{-0.007}$	100 ± 10	2.6×10^{-8}

pre-trial probability:

$$P(\geq r_\alpha) = \exp\left(-\frac{N r_\alpha^2}{4}\right)$$

- 5.6 σ pre-trial signal
- 5.2 σ post-trial (penalized for scan in 2 energy bin)

Dipole reconstruction

Science 57 (2017) 1266

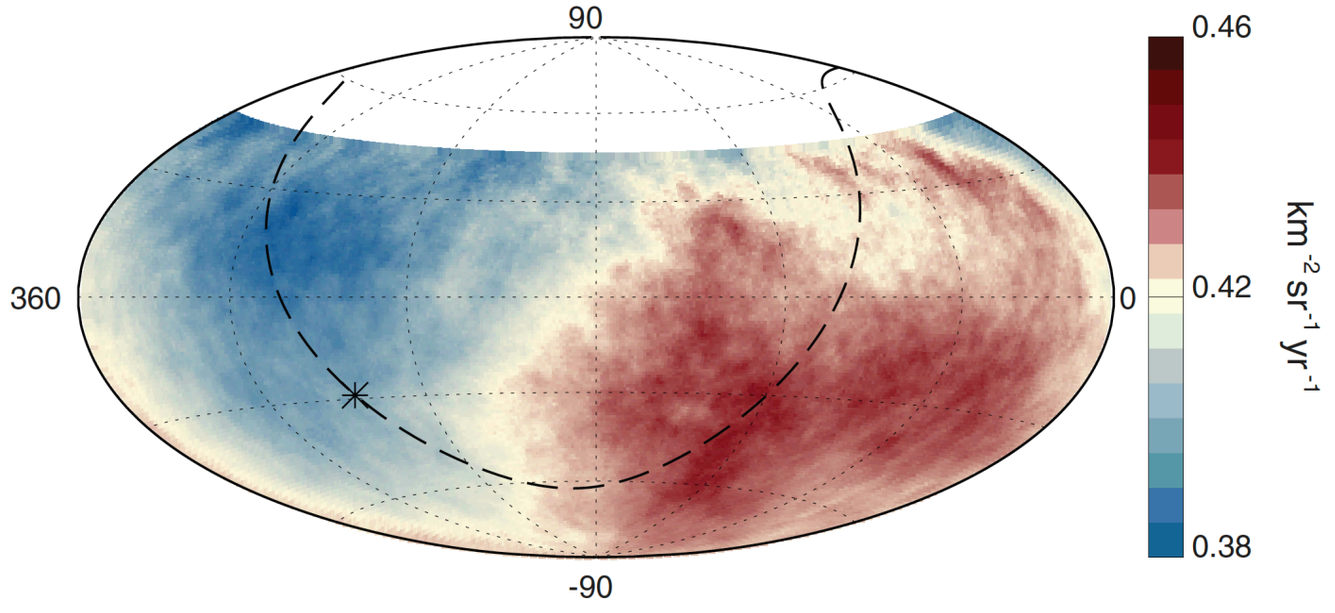
Components parallel and perpendicular to the Earth rotation axis:

$$d_z \approx \frac{b_\varphi}{\cos \ell_{\rm obs} \langle \sin \theta \rangle} \qquad d_\perp \approx \frac{r_\alpha}{\langle \cos \delta \rangle}$$

Right ascension and declination:

$$\alpha_{\rm d} = \varphi_\alpha \qquad \tan \delta_{\rm d} = \frac{d_z}{d_\perp}$$

E>8 EeV

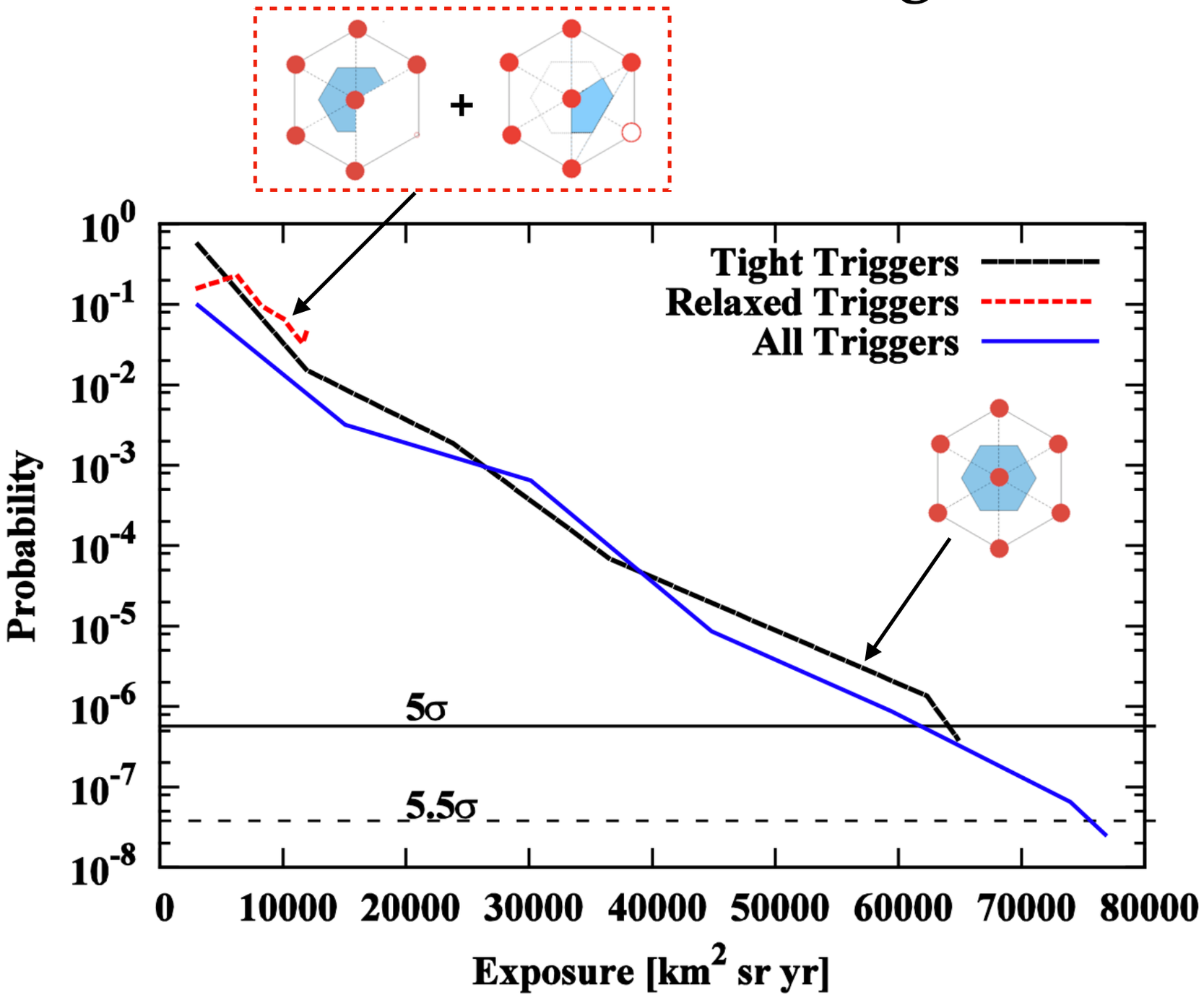


Energy (EeV)	Dipole component d_z	Dipole component $d_\perp$	Dipole amplitude d	Dipole declination $\delta_{\rm d}$ (°)	Dipole right ascension $\alpha_{\rm d}$ (°)
4 to 8	−0.024 ± 0.009	$0.006^{+0.007}_{-0.003}$	$0.025^{+0.010}_{-0.007}$	-75^{+17}_{-8}	80 ± 60
≥8	−0.026 ± 0.015	$0.060^{+0.011}_{-0.010}$	$0.065^{+0.013}_{-0.009}$	-24^{+12}_{-13}	100 ± 10

- **Reconstruction assumes the dipole is the dominant component of the anisotropy**
- **Analysis of the power spectrum gives support to this hypothesis**

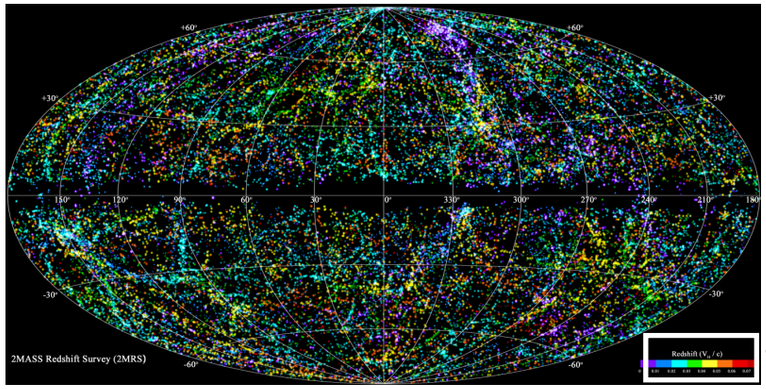
Time evolution of the signal

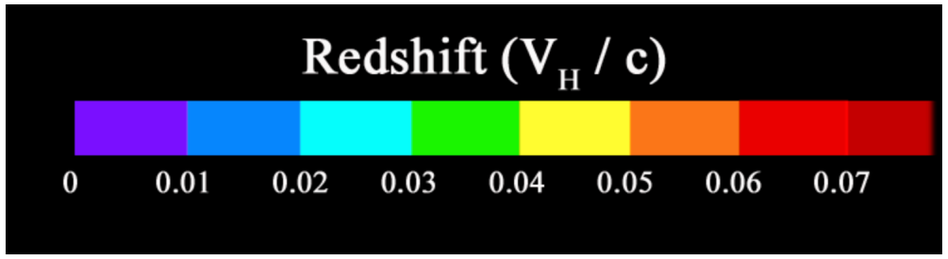
Science 57 (2017) 1266

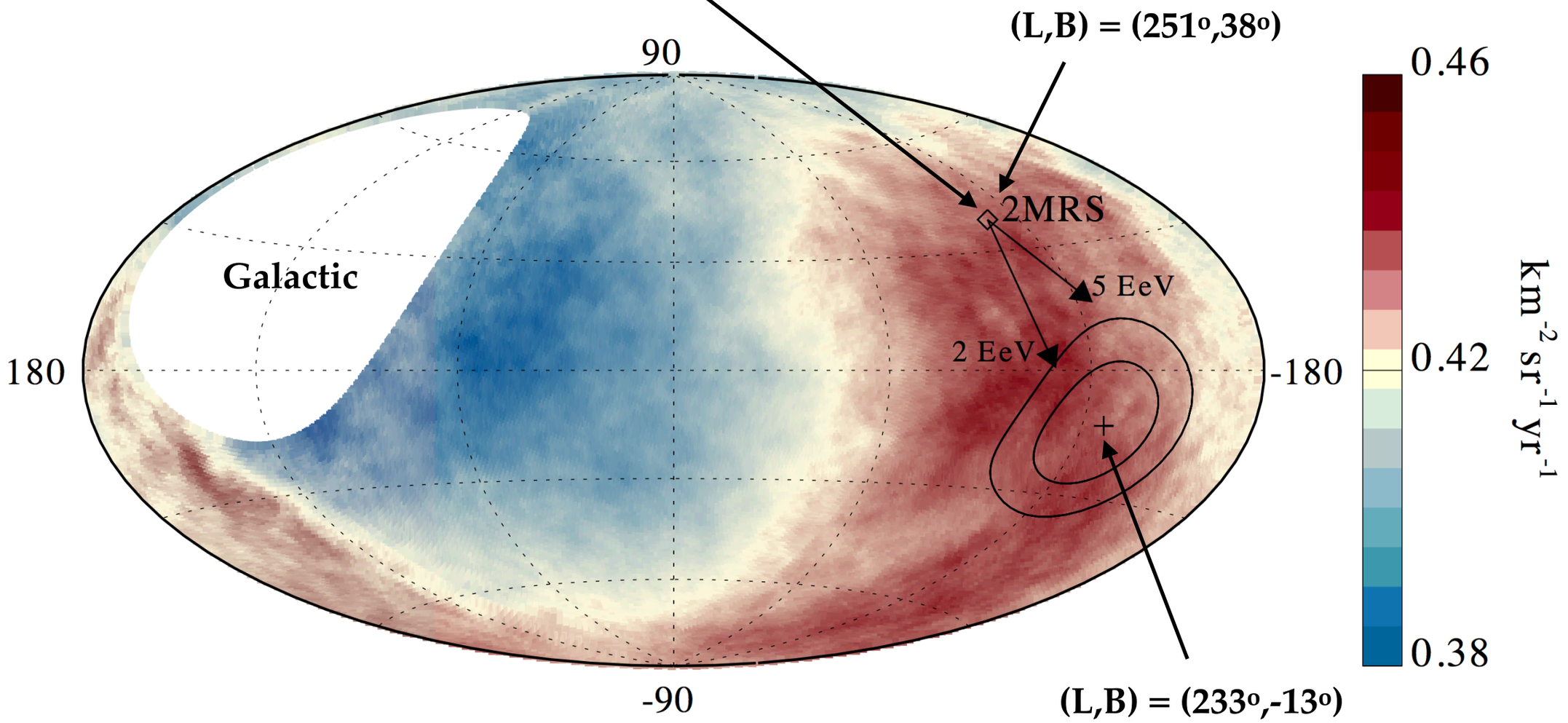


- **Steady drop of the chance probability as data is accumulated**

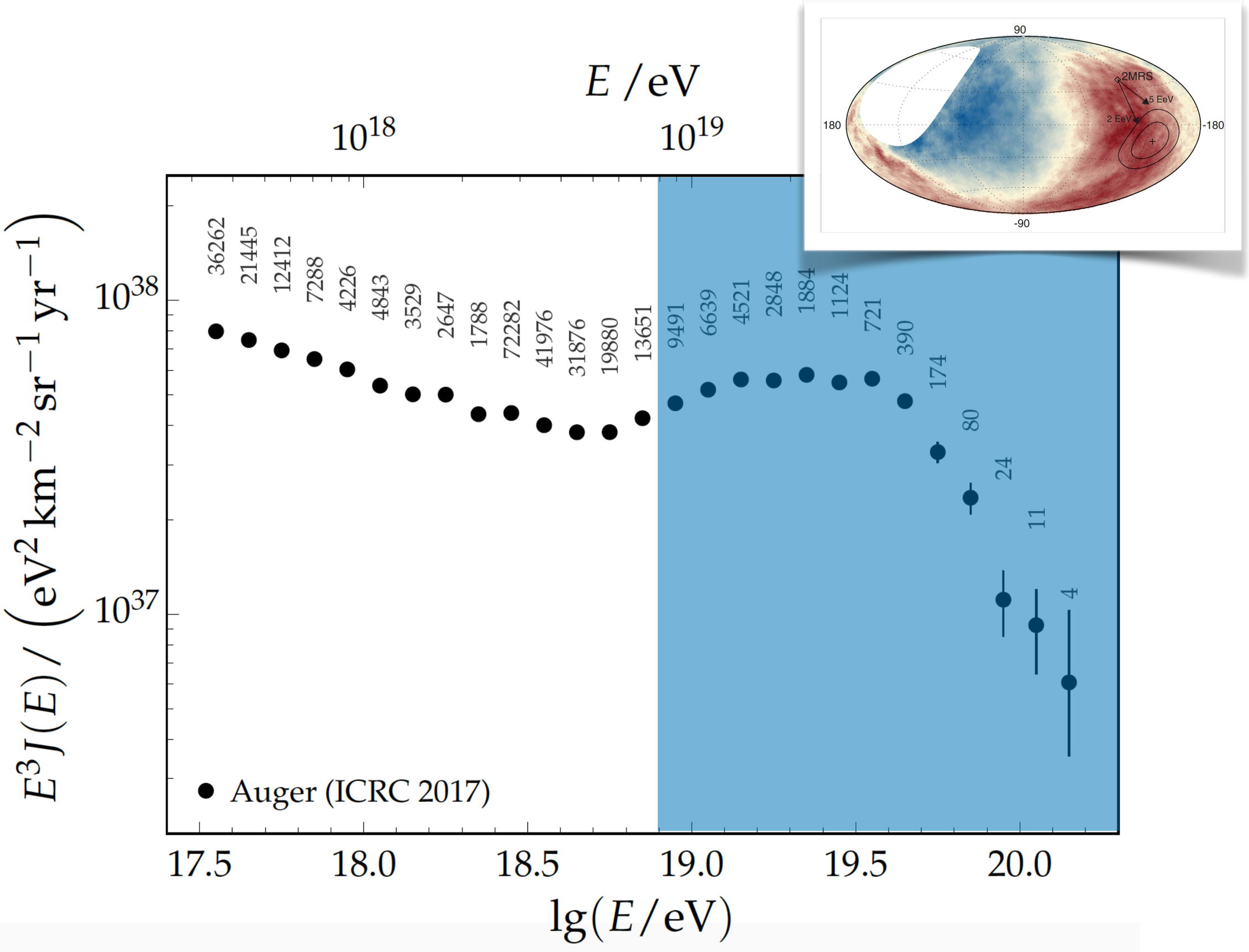
2MASS Redshift Survey (2MRS)







Typically, 5-20% dipole amplitudes can be obtained from local inhomogeneities and diffusion through magnetic fields depending on CR composition

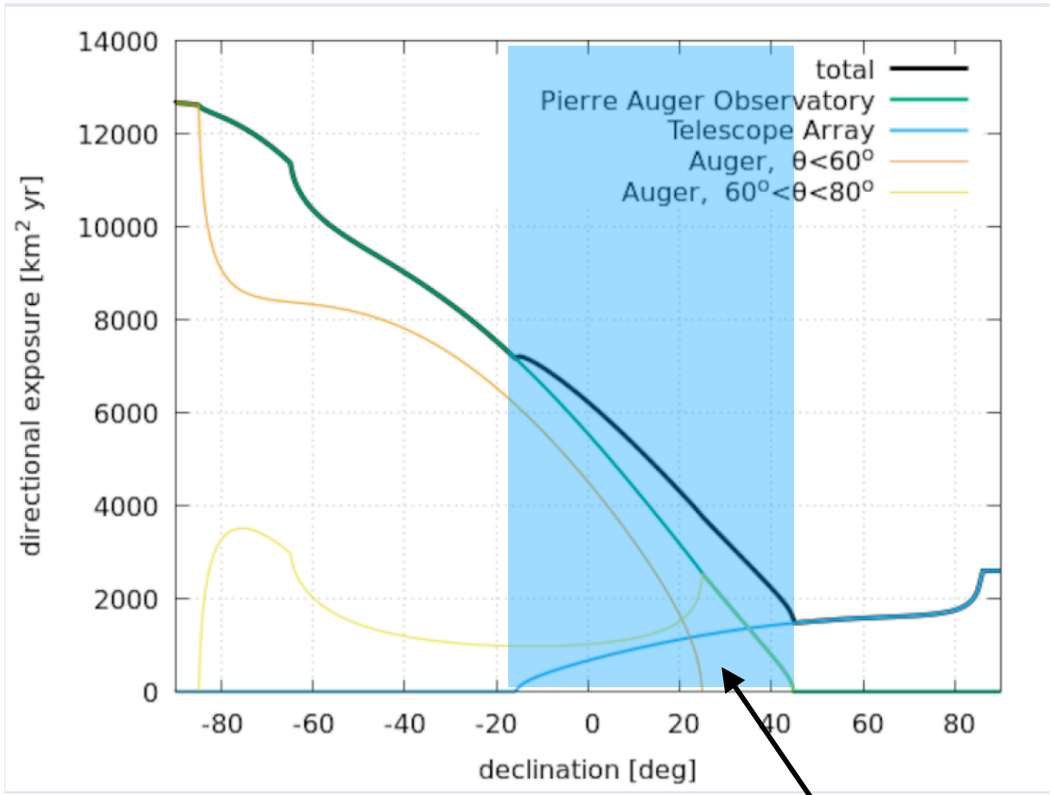

$E^3 J(E) / \left(\mathrm{eV}^2\,\mathrm{km}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{yr}^{-1}\right)$
10^{38}
10^{37}
E / eV
10^{18}
10^{19}
36262
21445
12412
7288
4226
4843
3529
2647
1788
72282
41976
31876
19880
13651
9491
6639
4521
2848
1884
1124
721
390
174
80
24
11
4
Auger (ICRC 2017)
17.5
18.0
18.5
19.0
19.5
20.0
$\lg(E/\mathrm{eV})$
90
180
-180
-90
2MRS
5 EeV
2 EeV

Combined full sky analyses

Combined analysis at higher energies

UHECR2016

TA	Auger
θ < 55 deg.	θ < 80 deg.
8700 km² sr yr	66452 km² sr yr
E > 57 EeV	E > 40 EeV
83 events	602 events



- Twice as many events as in ApJ 794 (172) 2014

- Found E_{Auger} and E_{TA} for which the integrated fluxes match:

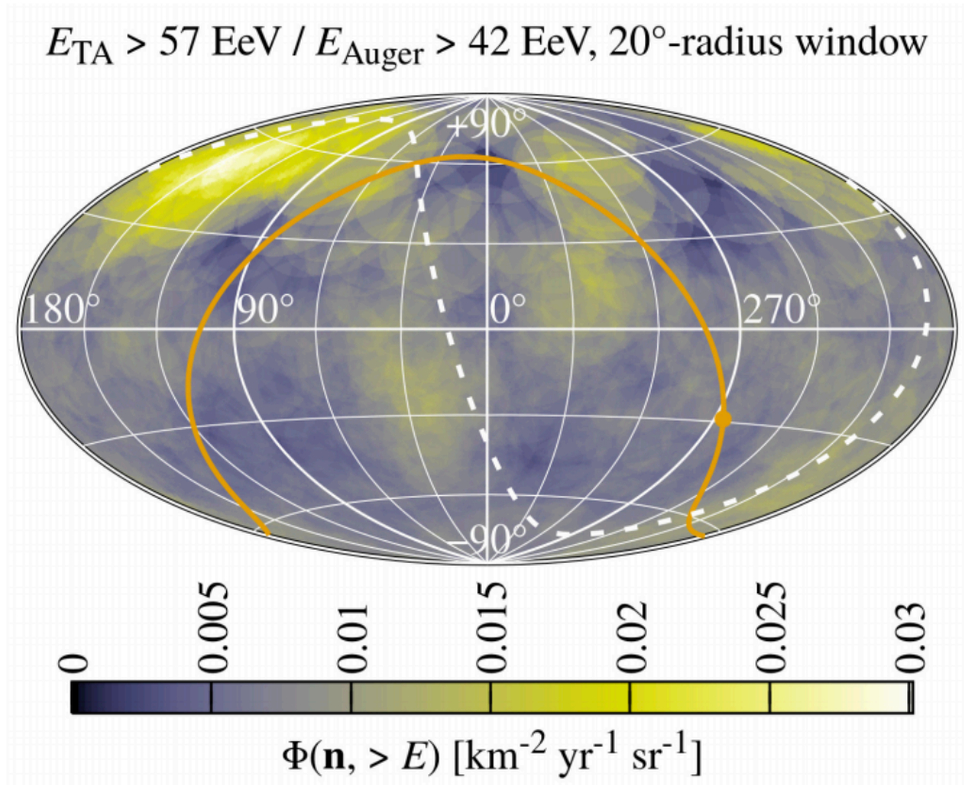
$$\sum_{\text{events in band}} \frac{1}{\omega(\mathbf{n}_i)}$$

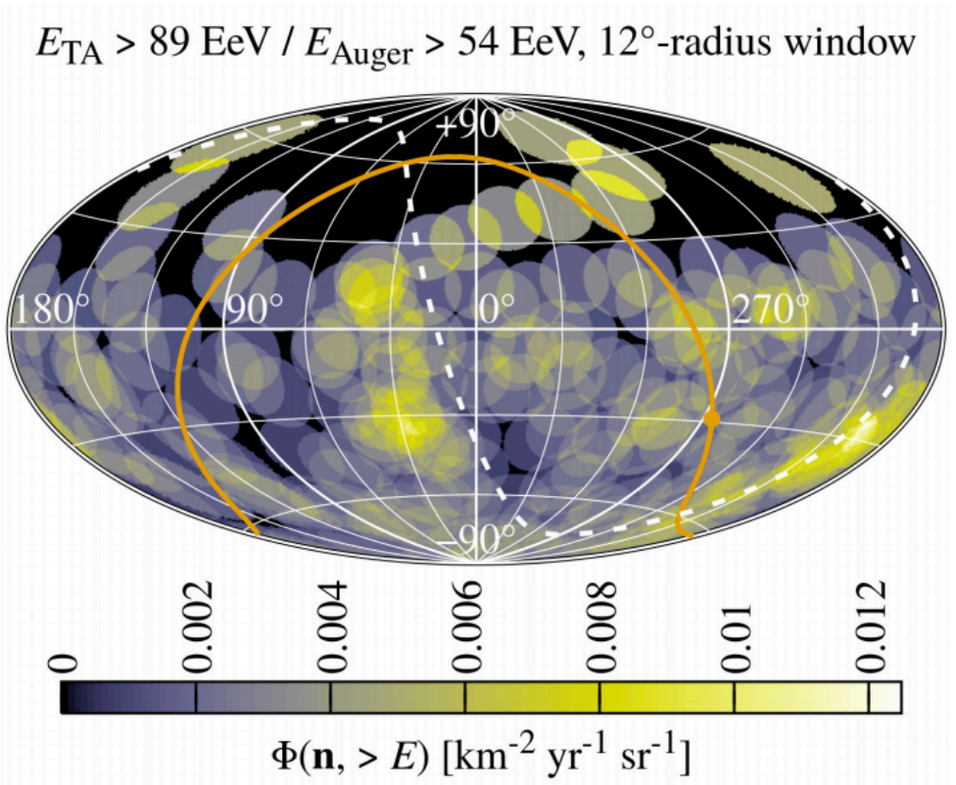
⇦ Unbiased flux estimator

Common band: [-16,+45]
Fiducial band: [-12,+42]

reference flux $km^{-2}\ yr^{-1}$	E_{Auger} EeV	E_{TA} EeV	flux stat. uncertainty Auger	TA	motivation
0.042	42 ± 1	57 ± 4	9%	16%	TA 2014 [4]
0.013	54 ± 1	89^{+4}_{-17}	14%	29%	Auger 2015 [5]

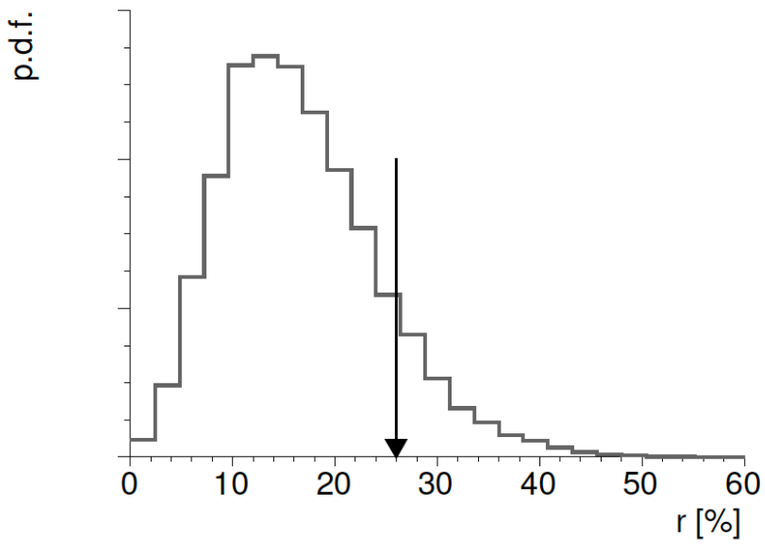
Combined flux sky map (equatorial)

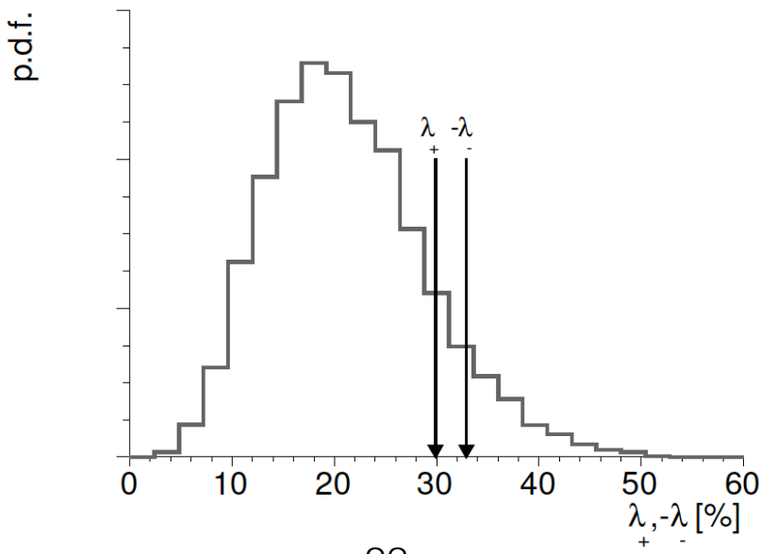


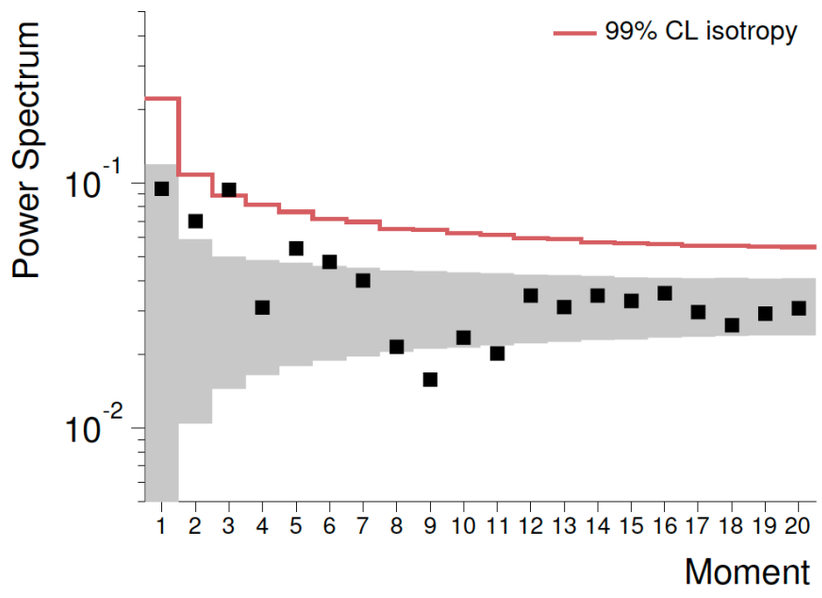


$$\Phi(\mathbf{n}) = \frac{\Phi_0}{4\pi}\left(1 + r\mathbf{d}\cdot\mathbf{n} + \lambda_+(\mathbf{q}_+\cdot\mathbf{n})^2 + \lambda_0(\mathbf{q}_0\cdot\mathbf{n})^2 + \lambda_-(\mathbf{q}_-\cdot\mathbf{n})^2 + ...\right)$$

Compatibility with isotropy







Summary

- **Anisotropy searches performed at all angular scales: small, intermediate and large**
- **Indications of anisotropy at the 4σ level from a maximum log-likelihood analysis based on starburst galaxy model**
- **Observation of a dipolar large scale pattern at more than 5σ level above 8 EeV**
- **Direction of the dipole (~120^{o} away from GC) is inconsistent with a galactic origin for the bulk of this UHECRs**
- **Full sky coverage achieved with combined Auger-TA flux sky maps at high energy thresholds (no significant anisotropy seen so far)**