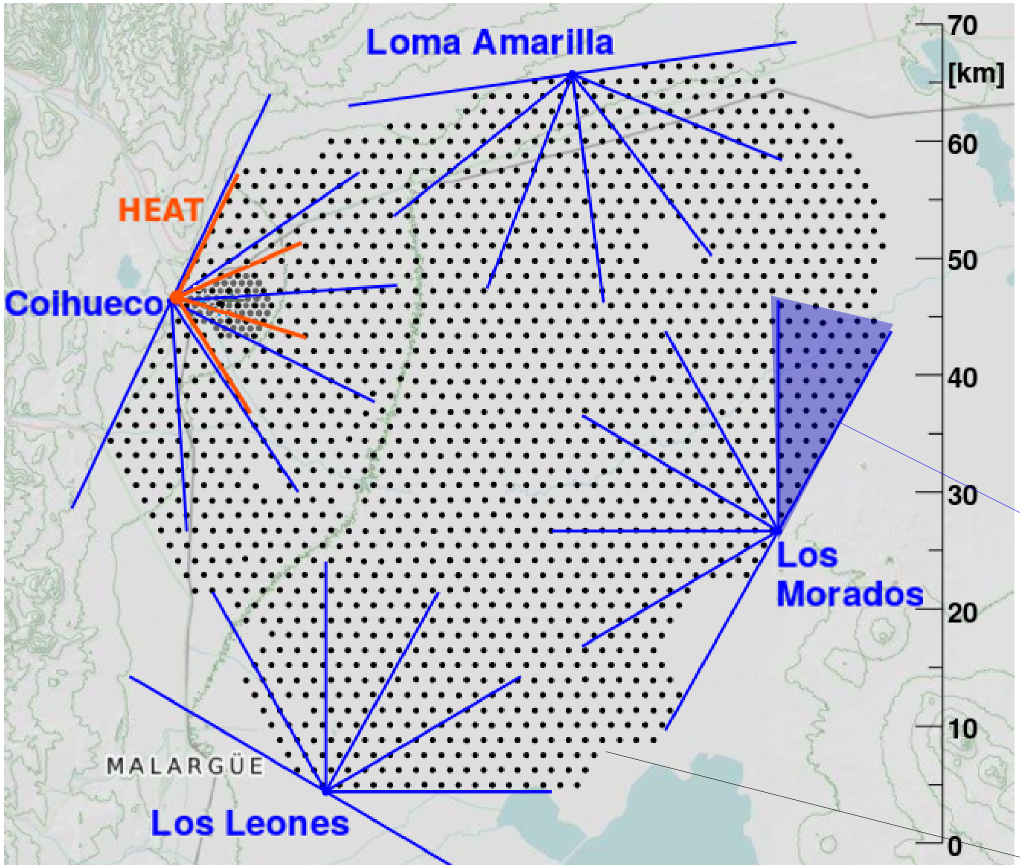
Study of the origins of ultra-high energy cosmic rays with the Pierre Auger Observatory

Quentin Luce, CRIS 2018, 19th June 2018

PIERRE AUGER OBSERVATORY

IPN INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

Introduction



Pierre Auger Observatory:

Detection surface of **3,000 km²** located in the argentinian Pampa, at an altitude of 1,400 m above sea level with a total exposure in 2017 of **76,800 km² sr^{-1} yr^{-1}**

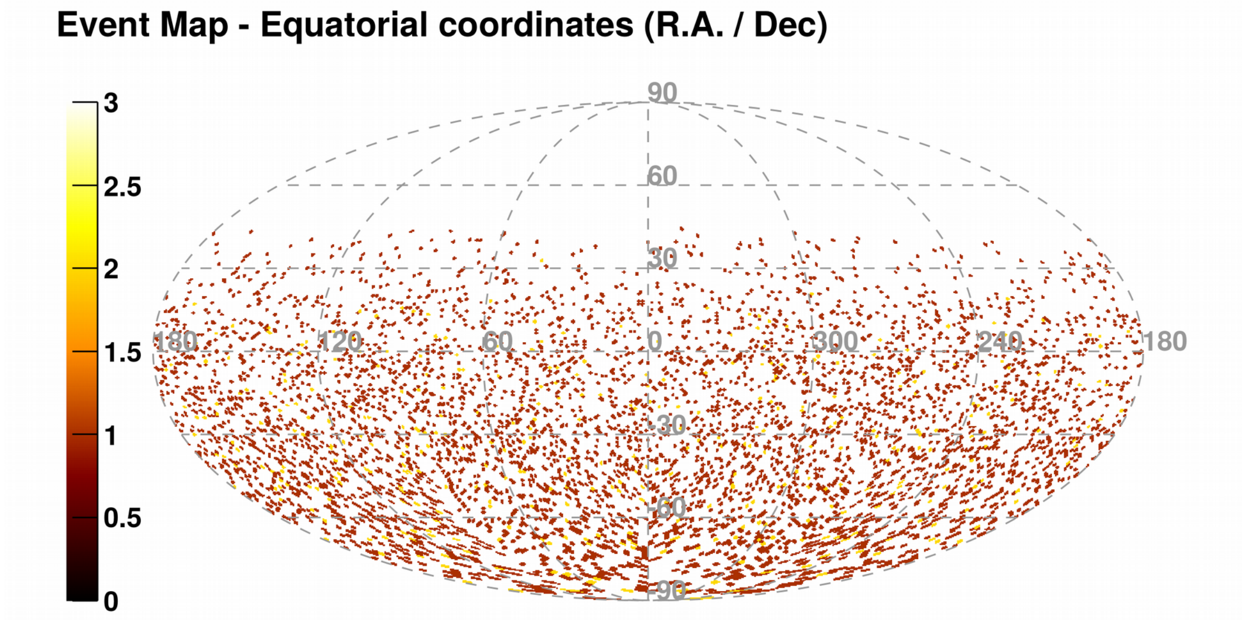
Detection of atmospheric air shower

Objective:
Determination of the origin of the Ultra-High Energy Cosmic Rays

Fluorescence detector (FD):
- 24+3 telescopes in 4 sites
- FoV of 1 telescope: 30° in elevation and 30° in azimtuh
- ~10% duty cycle
- Full efficiency above 0.6 EeV

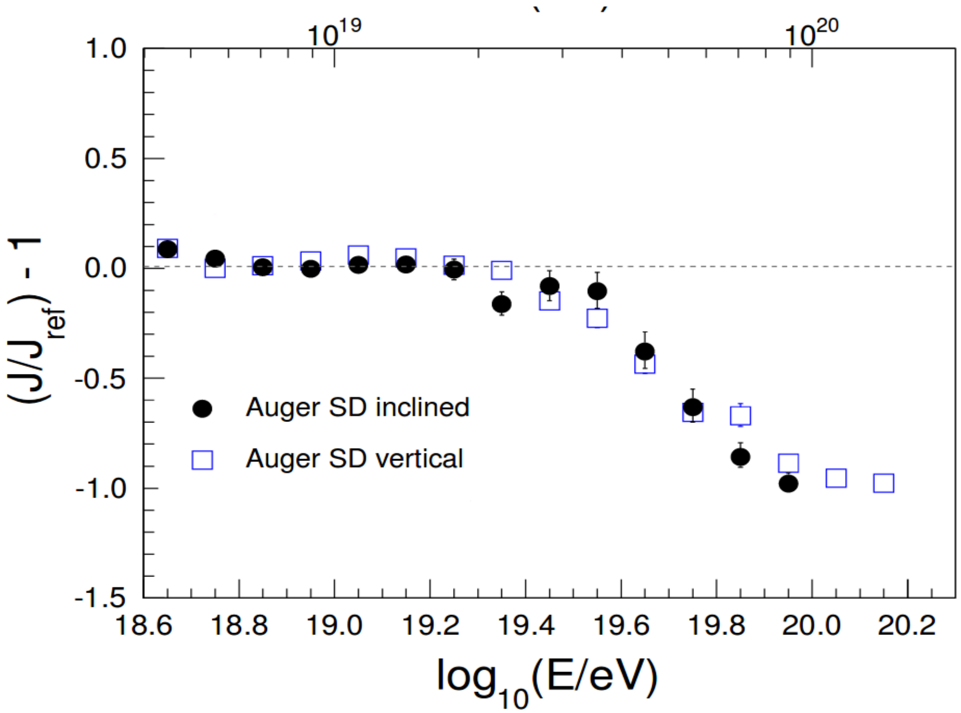
Surface detector (SD):
- 1,600 water Čerenkov station
- Spaced by 1,500 meters (or 750 meters)
- **100% duty cycle**
- Full efficiency **above 4 EeV**

Two different data sets



Combination of **vertical** events ($\theta<60°$) and **inclined** events ($60°<\theta<80°$) for a total sky coverage around **85%** ($-90°<\delta<45°$)

Angular resolution: < 1°



Systematics uncertainties on energy scale: ~14%

Consistency of all the different reconstructions

A discovery at large scale

Obersvation of a Large-scale Anisotropy in the Arrival Directions of Cosmic Rays above 8×10^{18} eV

Science 357 (2017) no.6537, 1266-1270

Rayleigh analysis in right ascension

Study in two energy ranges, **4 EeV < E < 8 EeV** and **E > 8 EeV**

First-harmonic Fourier components:

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

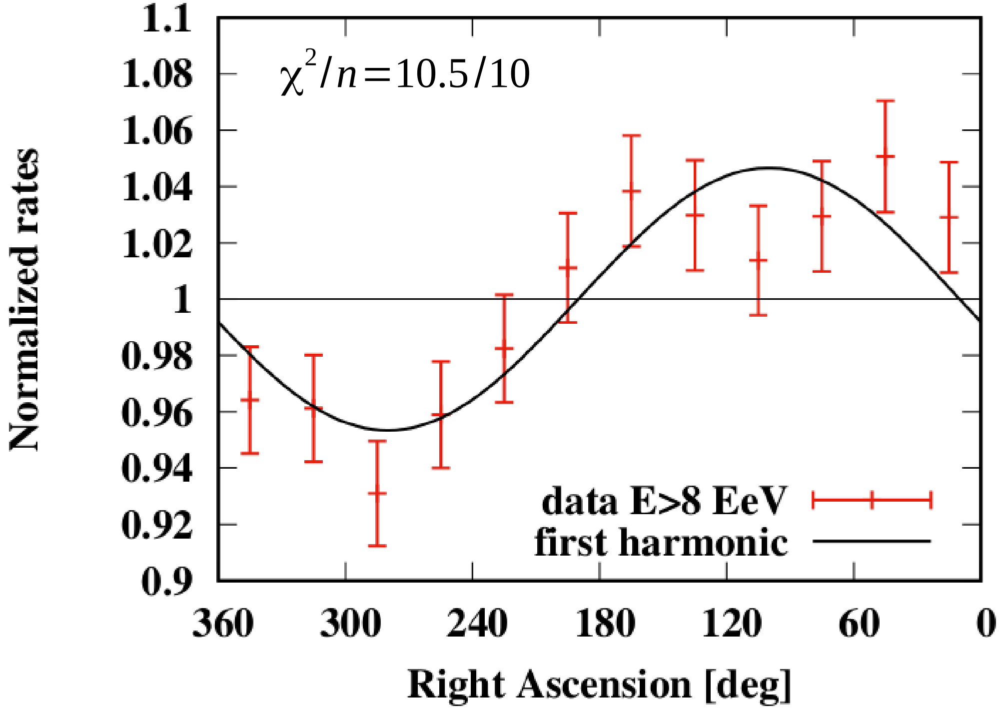
w_i take into account nonuniformities in **exposure** (±0.6%) and **tilt** (~0.2°) of the surface array

Amplitude and phase of the first-harmonic:

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

Deviation from isotropy: (Linsley, 1975)

$$P(r_\alpha) = \exp(-\mathcal{N} r_\alpha^2/4)$$



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}

First harmonic significant at the **5.4σ level after penalization**

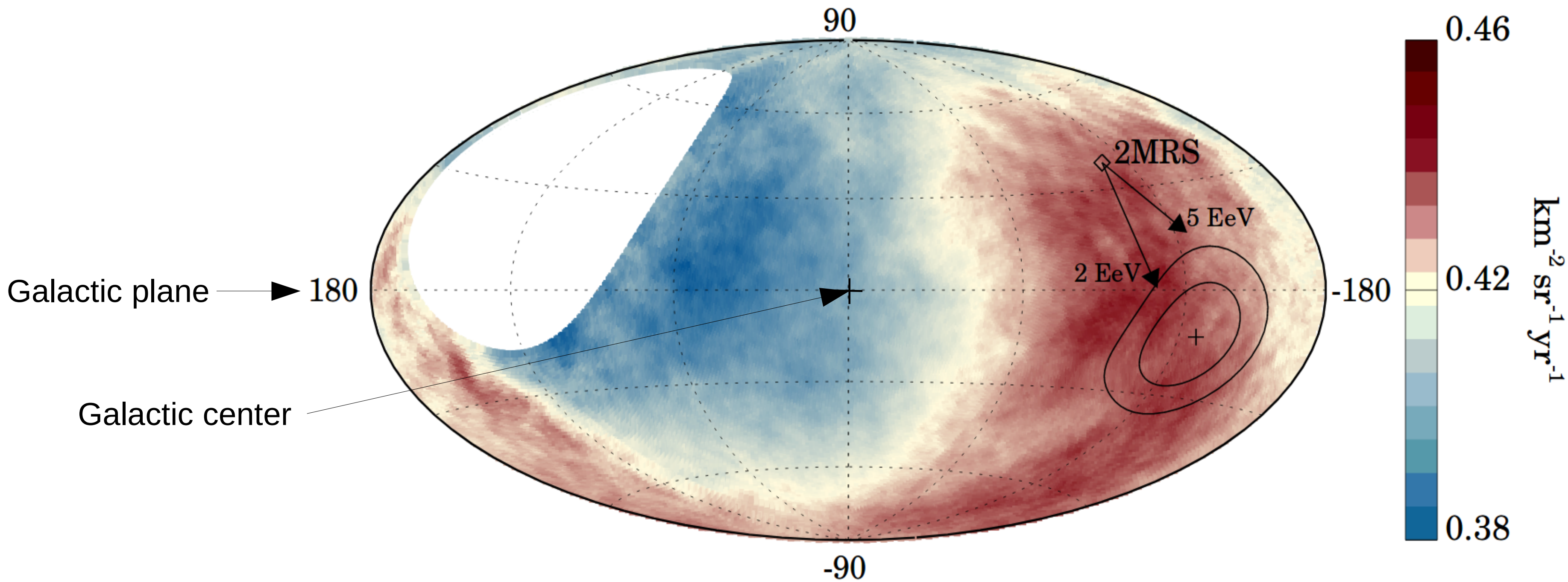
Reconstruction of the dipole above 8 EeV

Combination of the Rayleigh analyzes to extract the dipole amplitude:

in right ascension → sensitive only to the orthogonal component to the Earth's axis
in azimuth angle → projection along the Earth's axis

Amplitude $d = 6.5^{+1.3}_{-0.9}$ %

Longitude $\mathfrak{l}$ = 233°, Latitude $\mathfrak{b}$ = -13°



Implication on the origin of the UHECR:

Dipole direction **far away from the Galactic center** (~125°). Above 40 EeV, no anisotropies associated with Galactic plane or Galactic center

2MRS dipole x GMF deflection → observed dipole?

Extragalactic origin of the highest energy cosmic rays

Indication at intermediate scale

Indication of Anisotropy in Arrival Directions of Ultra-High Energy Cosmic Rays through comparison to the flux Pattern of Extragalactic Gamma-ray Sources

Astrophys.J. 853 (2018) no.2, L29

Extragalactic tested population

Starburst galaxies

M82

Intense star formation + winds

23 objects from *Fermi-LAT* observations within **250 Mpc** with a radio flux at **1.4GHz > 0.3 Jy**

Nearby galaxies

e.g.: NGC253, M82, NGC4945, NGC1068

Active Galactic Nuclei

Centaurus A

Jets and radiolobes

17 objects from 2FHL catalog within **250 Mpc**
(*Fermi*-LAT, > 50 GeV)

More distant galaxies

e.g.: Centaurus A, Mkn421, Mkn501

Maximum likelihood analysis

~ 5,500 events recorded by the Pierre Auger Observatory above 20 EeV
Source of the anisotropic component modeled as a **Fischer distribution** centered on its coordinates

Sky *model* $= [(1-\alpha)\, isotropic + \alpha\,(population\ density)] \otimes Fischer(\theta)$

α: anisotropy fraction
θ: search radius

4.0σ post-trial
Fraction: 10%
Angle: 13°

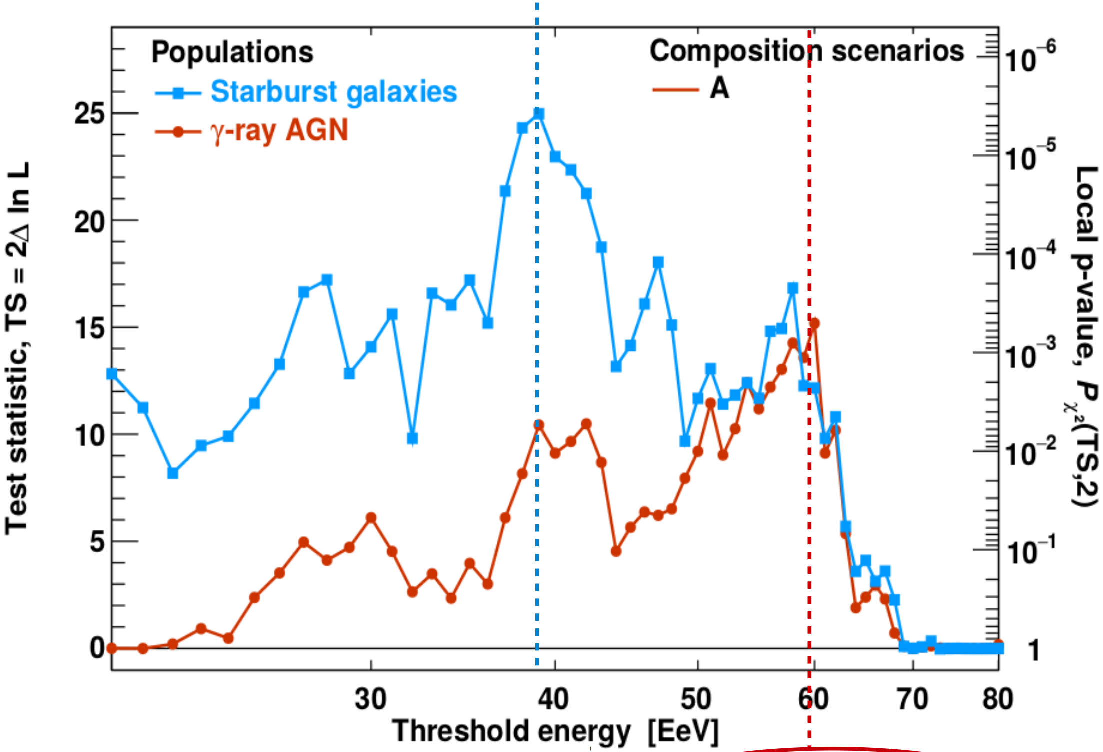
Null hypothesis = isotropy (α = 0)

Likelihood:

$$L(\alpha,\theta) = \prod_{N}^{i=1} model(\alpha,\theta) \times exposure$$

Test statistics:

$$TS = 2\log\frac{L(\alpha,\theta)}{L(\alpha=0,\theta)}$$

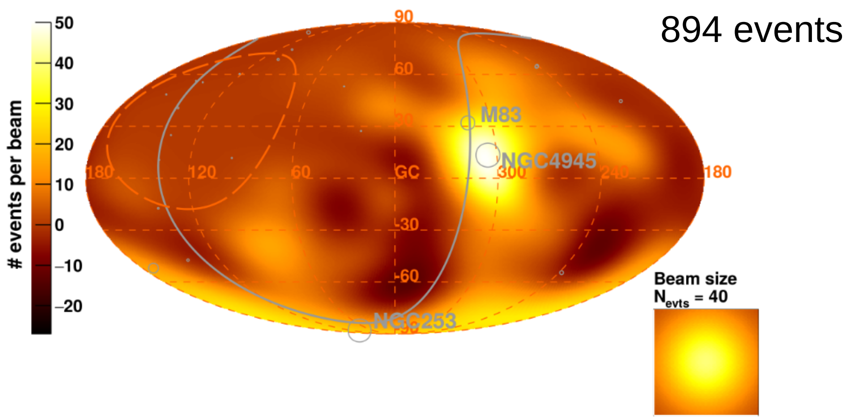


2.7σ post-trial
Fraction: 7%
Angle: 7°

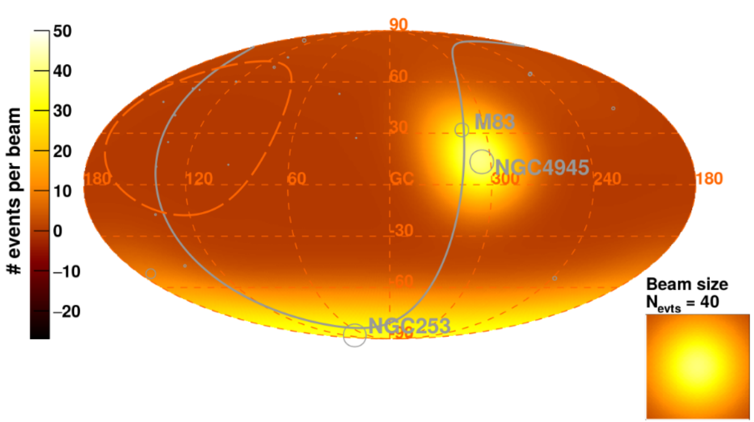
Resulting maps

STARBURST

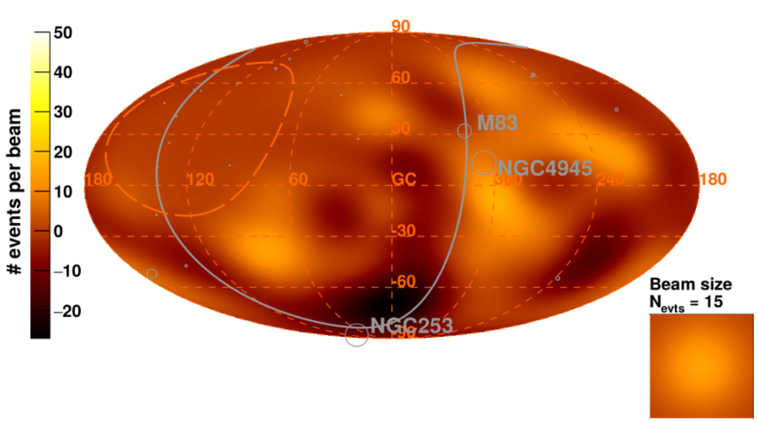
Observed Excess Map - E > 39 EeV



Model Excess Map - Starburst galaxies - E > 39 EeV

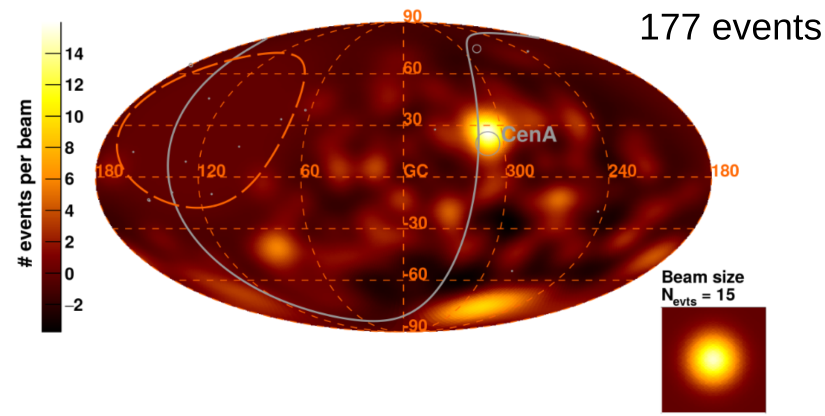


Residual Excess Map - Starburst galaxies - E > 39 EeV

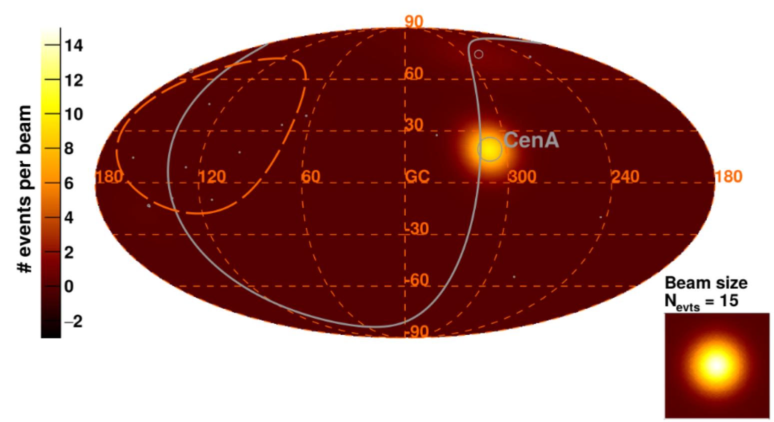


AGN

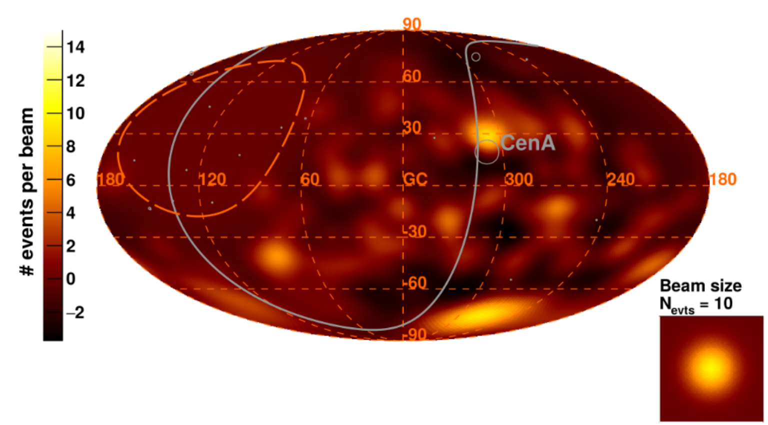
Observed Excess Map - E > 60 EeV



Model Excess Map - Active galactic nuclei - E > 60 EeV

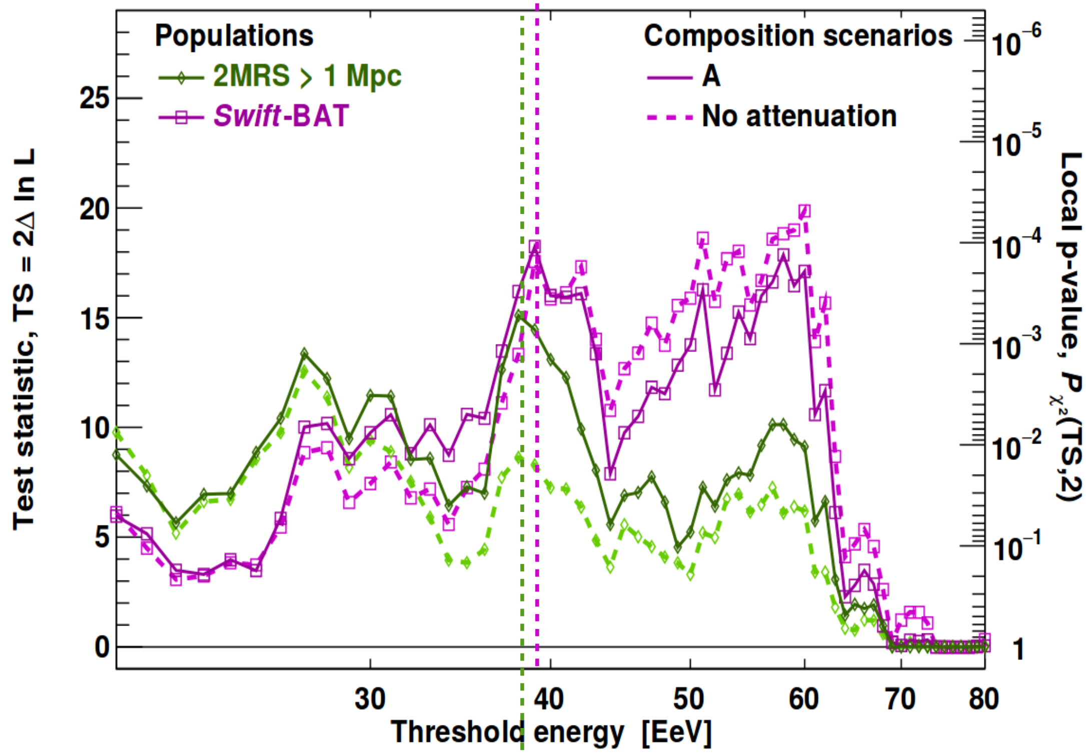


Residual Excess Map - Active galactic nuclei - E > 60 EeV



Other sky models

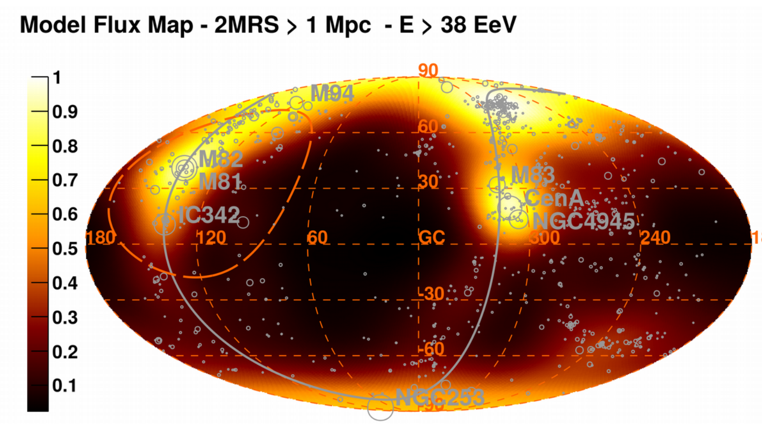
3.2σ post-trial
Fraction: 7%
Angle: 13°



2.7σ post-trial
Fraction: 7%
Angle: 7°

2MRS sample

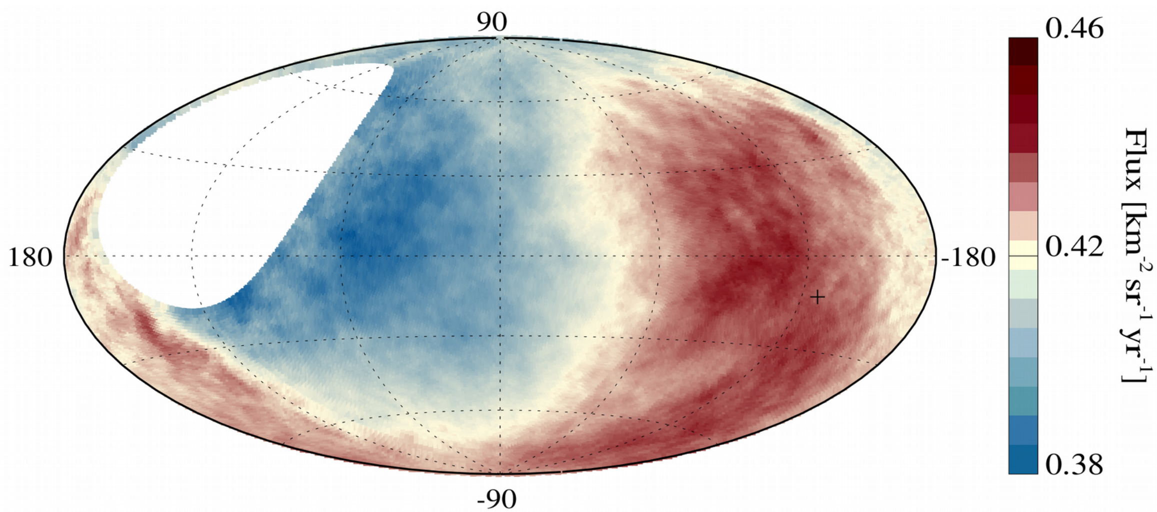
Sources beyond **1 Mpc** and within **250 Mpc**
Use of infrared K-band flux corrected for Galactic extinction
Trace distribution of extragalactic matter
Include SBs and AGNs



***Swift*-BAT**

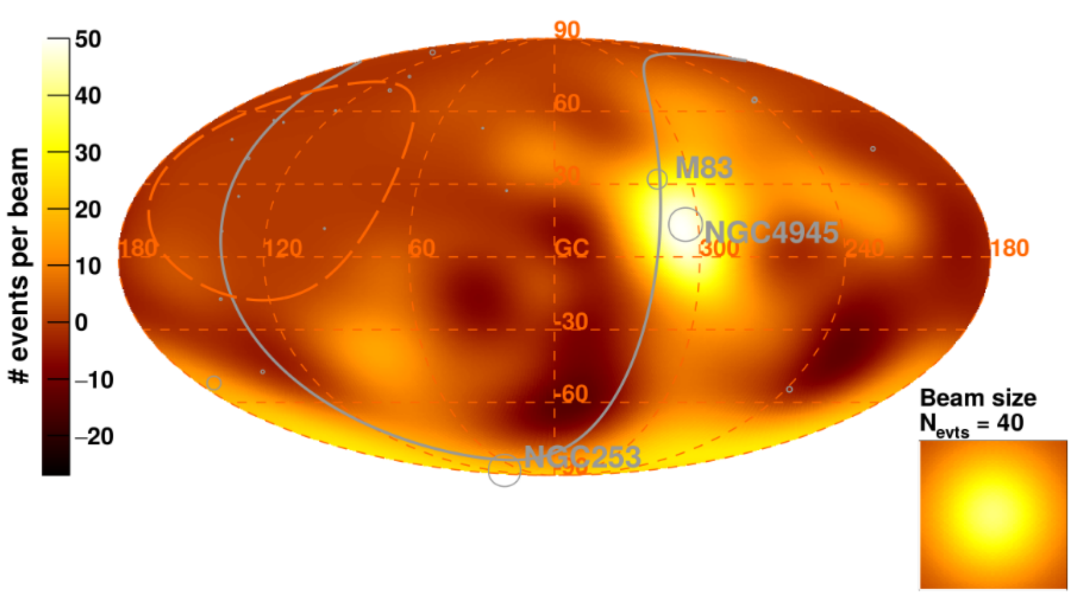
Sources within **250 Mpc**
X-ray sky → selection of radio-loud and radio-quiet AGNs
Dominated by Centaurus A

To conclude



Science 357 (2017) no.6537, 1266-1270

Observed Excess Map - E > 39 EeV



Astrophys.J. 853 (2018) no.2, L29

Discovery:
Above 8 EeV → 27,000 events have shown presence of a dipole with a **significance at 5.4σ**

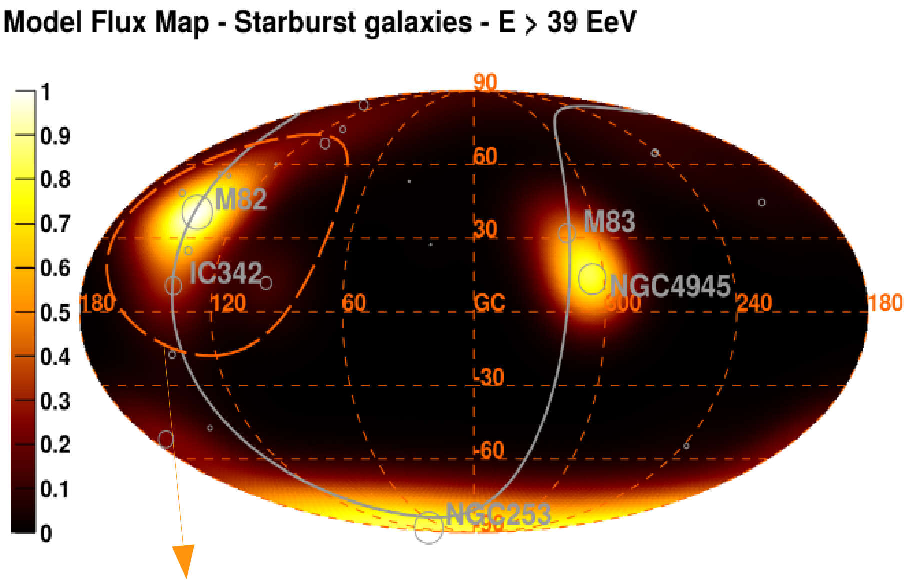
Extragalactic origin

Longitude l = 233°
Latitude b = -13°
Amplitude $d = 6.5^{+1.3}_{-0.9}$ **%**

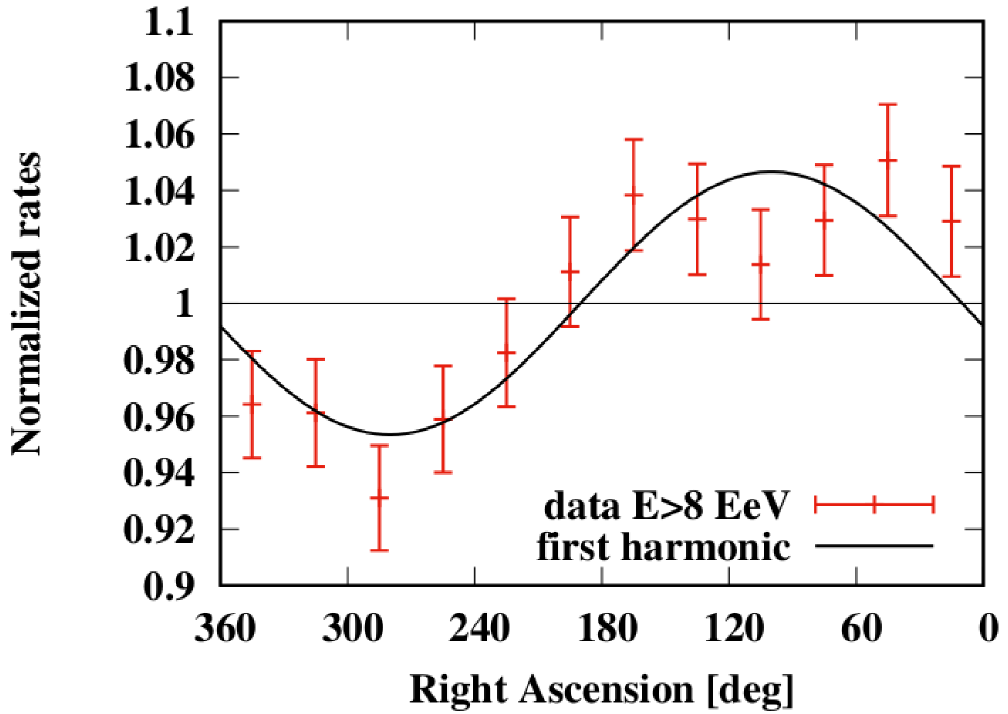
Indication:
Above 39 EeV → from ~900 events, indication of anisotropy with a significance of
4.0σ for starburst catalog
(fraction α = 10 %)

<u>Other catalogs:</u>
3.2σ for Swift-BAT catalog
2.7σ for AGN catalog
2.7σ for 2MRS catalog

In the future...



Coverage limit of the Pierre Auger Observatory



Sources are still unknown !

Full sky-coverage by combining Auger data and **Telescope Array data?**

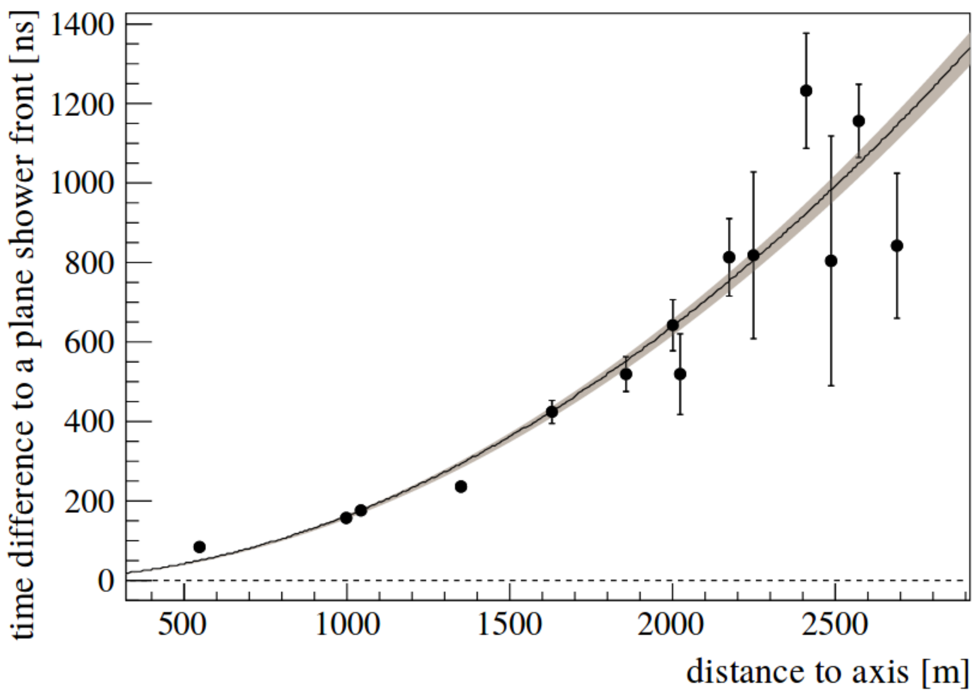
Evolution with energy of the dipole amplitude and direction?

How to connect intermediate and large angular-scale anisotropy?

Back-Up

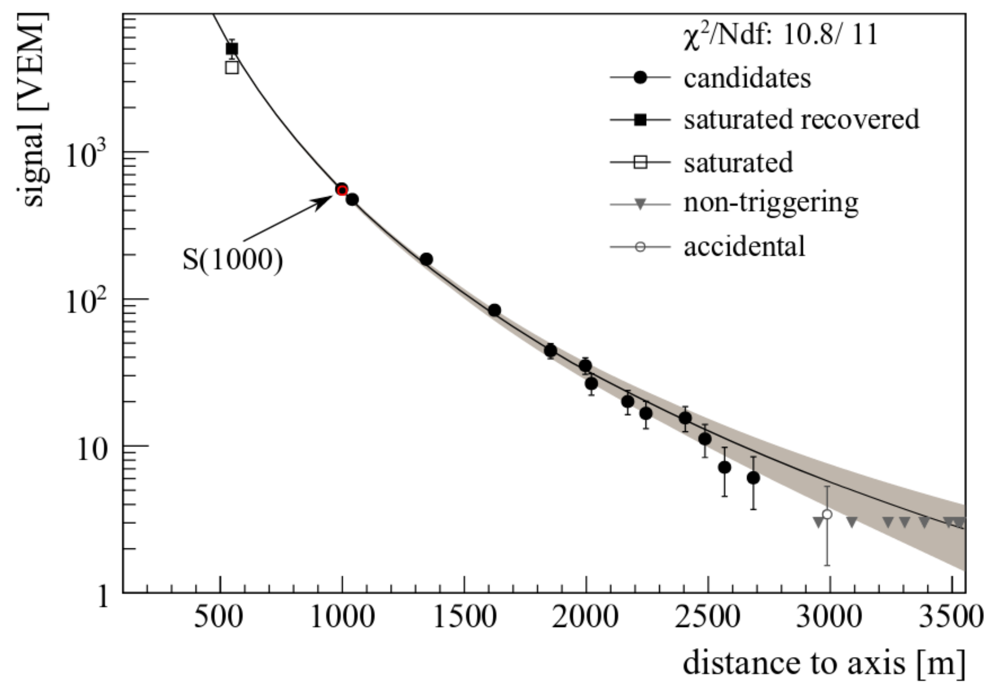
Reconstruction of SD event

SD event = at least 3 triggered stations
From each station, extraction of its **start-time** (time of the first particles in the station) and of its **signal**



Geometry reconstruction:
Time = f(distance) : reconstruction of the arrival direction (θ, φ)

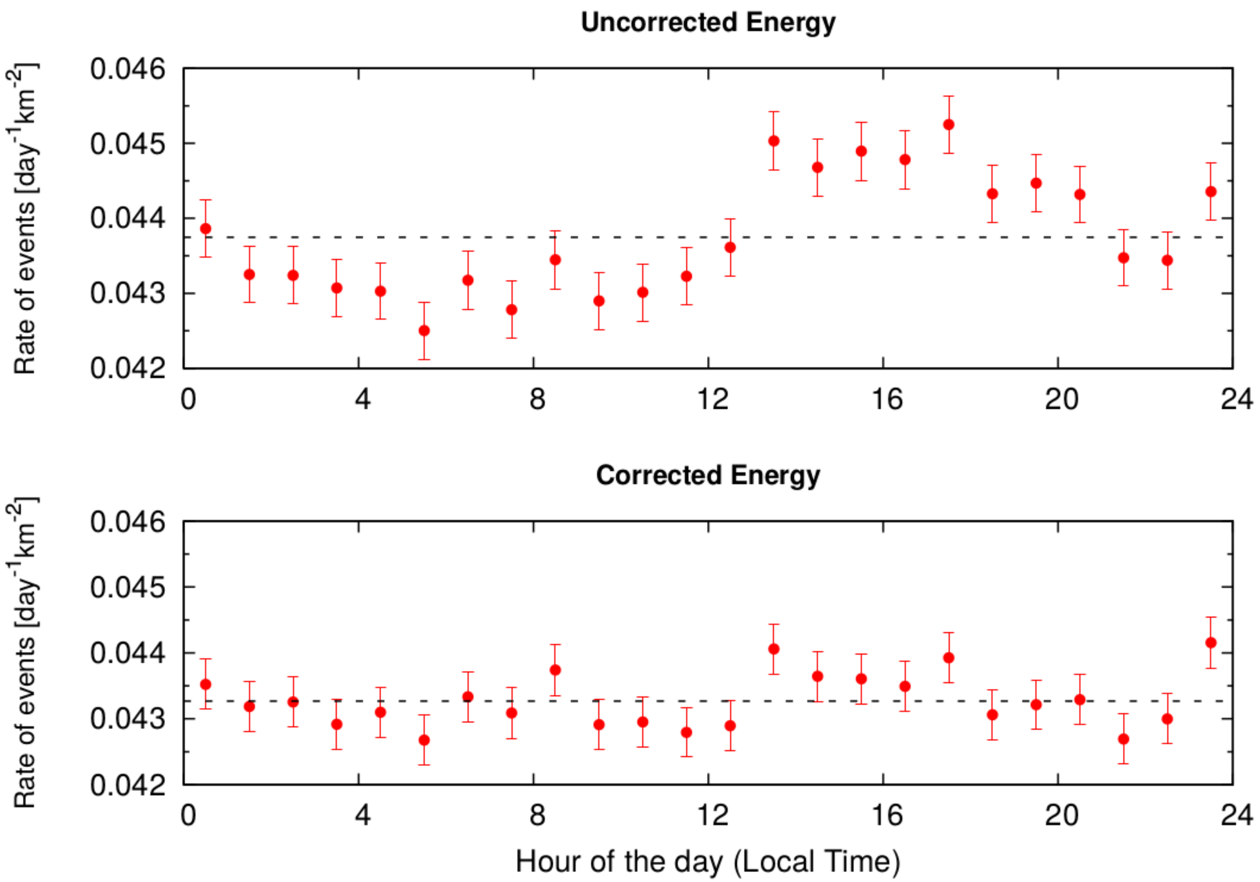
Angular resolution: < 1°



« Energy » reconstruction:
Signal = f(distance) : reconstruction of the lateral profile of the shower

Energy resolution: ~14%

Correction of the SD energy



Results

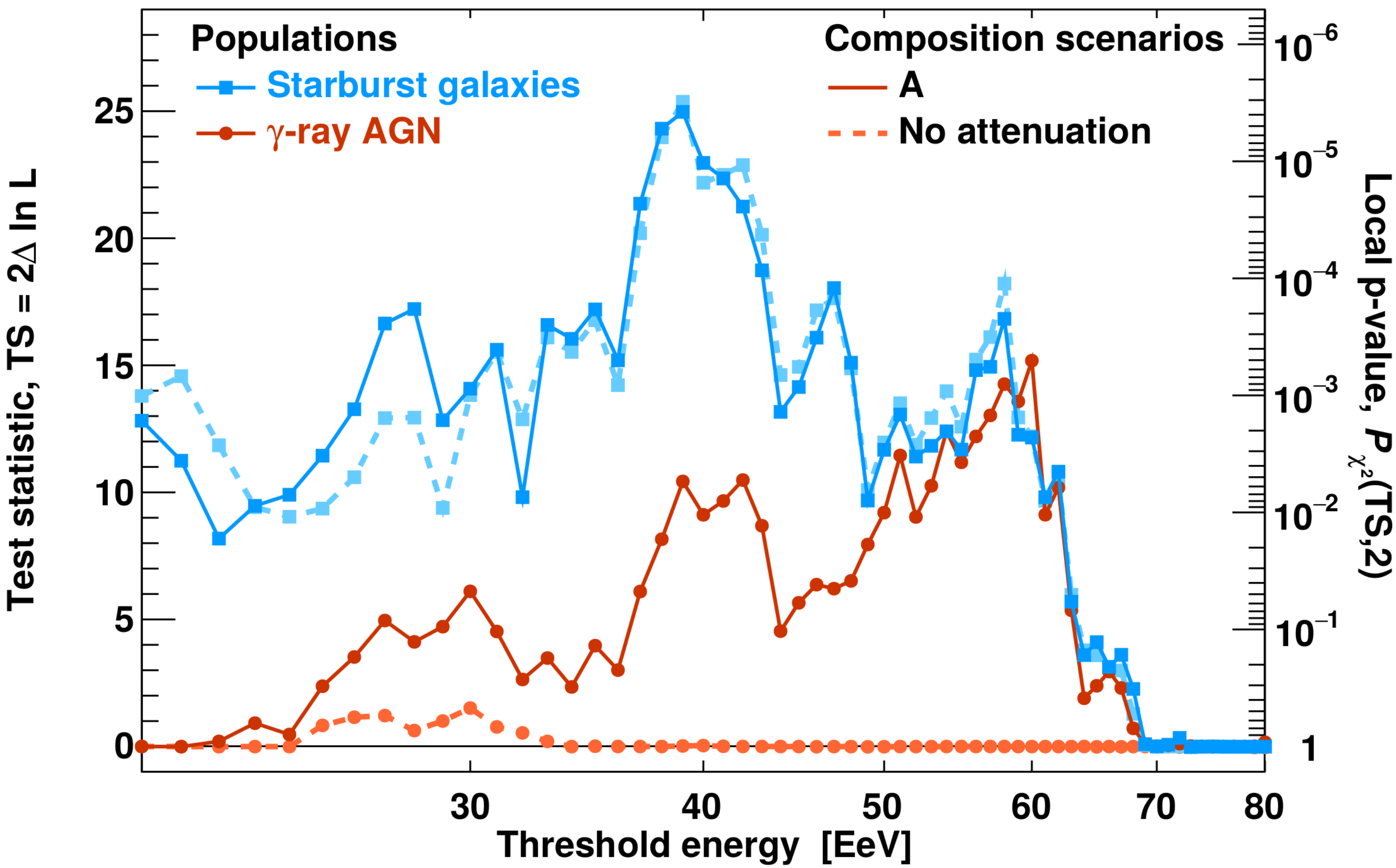
Test hypothesis	Null hypothesis	Threshold energy[a]	TS	Local p-value $\mathcal{P}_{\chi^2}(\mathrm{TS}, 2)$	Post-trial p-value	1-sided significance	AGN/other fraction	SBG fraction	Search radius
SBG + ISO	ISO	39 EeV	24.9	3.8×10^{-6}	3.6×10^{-5}	$4.0\,\sigma$	N/A	9.7 %	12.9°
γAGN + SBG + ISO	γAGN + ISO	39 EeV	14.7	N/A	1.3×10^{-4}	$3.7\,\sigma$	0.7 %	8.7 %	12.5°
γAGN + ISO	ISO	60 EeV	15.2	5.1×10^{-4}	3.1×10^{-3}	$2.7\,\sigma$	6.7 %	N/A	6.9°
γAGN + SBG + ISO	SBG + ISO	60 EeV	3.0	N/A	0.08	$1.4\,\sigma$	6.8 %	0.0 %[b]	7.0°
Swift-BAT + ISO	ISO	39 EeV	18.2	1.1×10^{-4}	8.0×10^{-4}	$3.2\,\sigma$	6.9 %	N/A	12.3°
Swift-BAT + SBG + ISO	*Swift*-BAT + ISO	39 EeV	7.8	N/A	5.1×10^{-3}	$2.6\,\sigma$	2.8 %	7.1 %	12.6°
2MRS + ISO	ISO	38 EeV	15.1	5.2×10^{-4}	3.3×10^{-3}	$2.7\,\sigma$	15.8 %	N/A	13.2°
2MRS + SBG + ISO	2MRS + ISO	39 EeV	10.4	N/A	1.3×10^{-3}	$3.0\,\sigma$	1.1 %	8.9 %	12.6°

[a] For composite model studies, no scan over the threshold energy is performed.

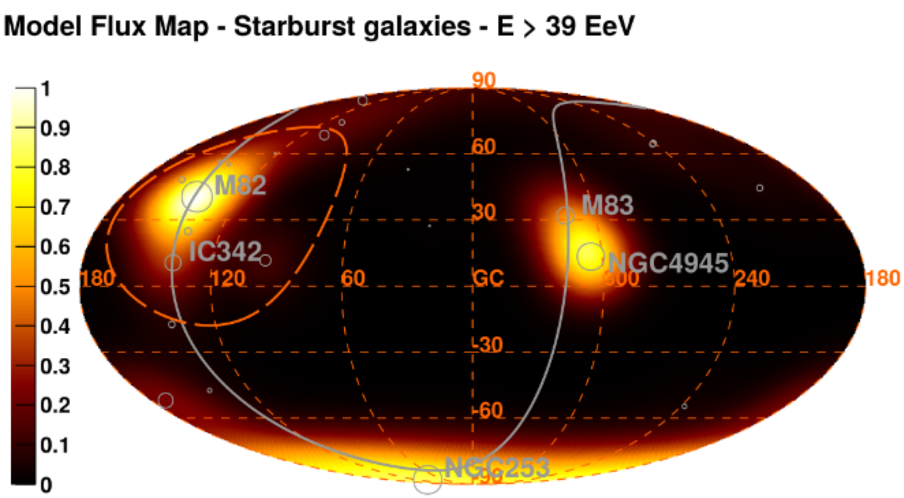
[b] Maximum TS reached at the boundary of the parameter space.

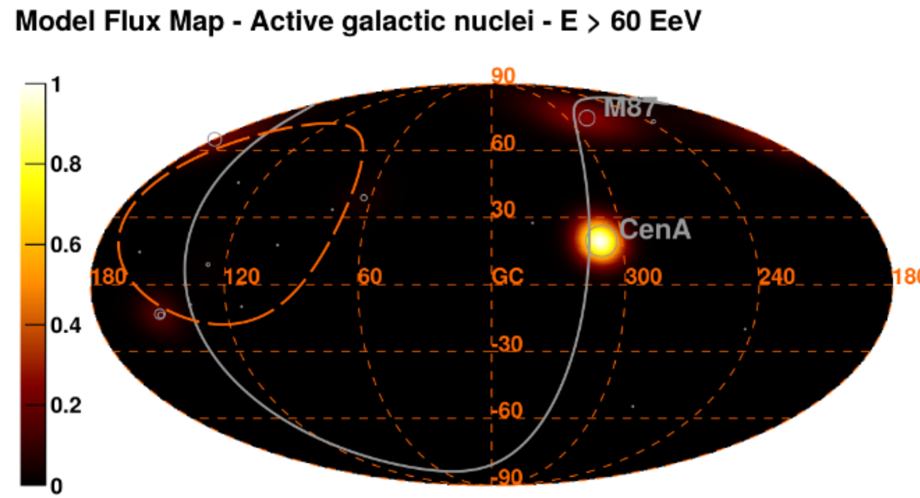
ISO: isotropic model.

TS with attenuation



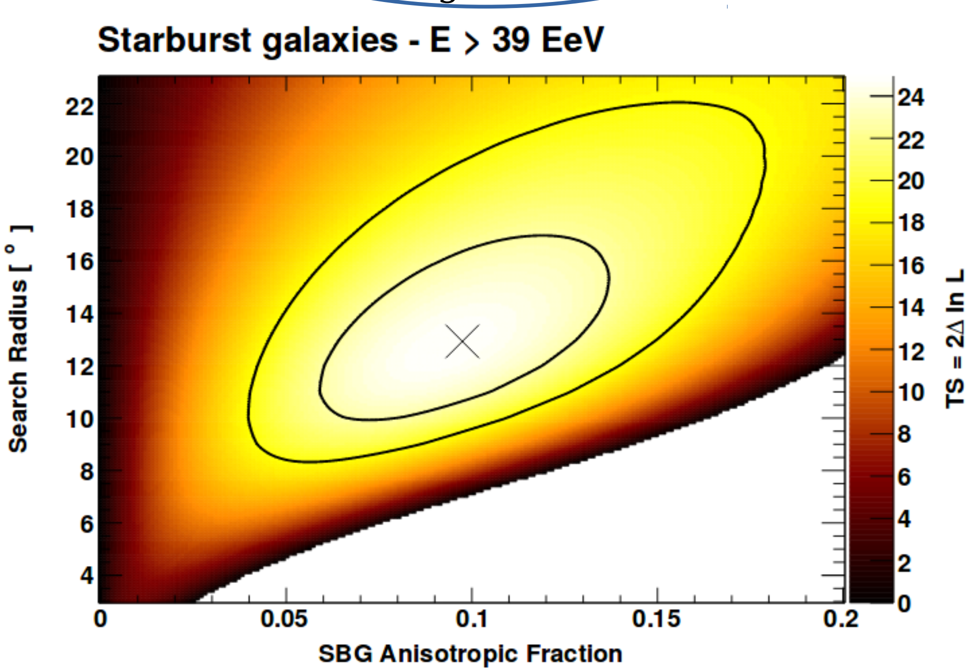
Model flux maps

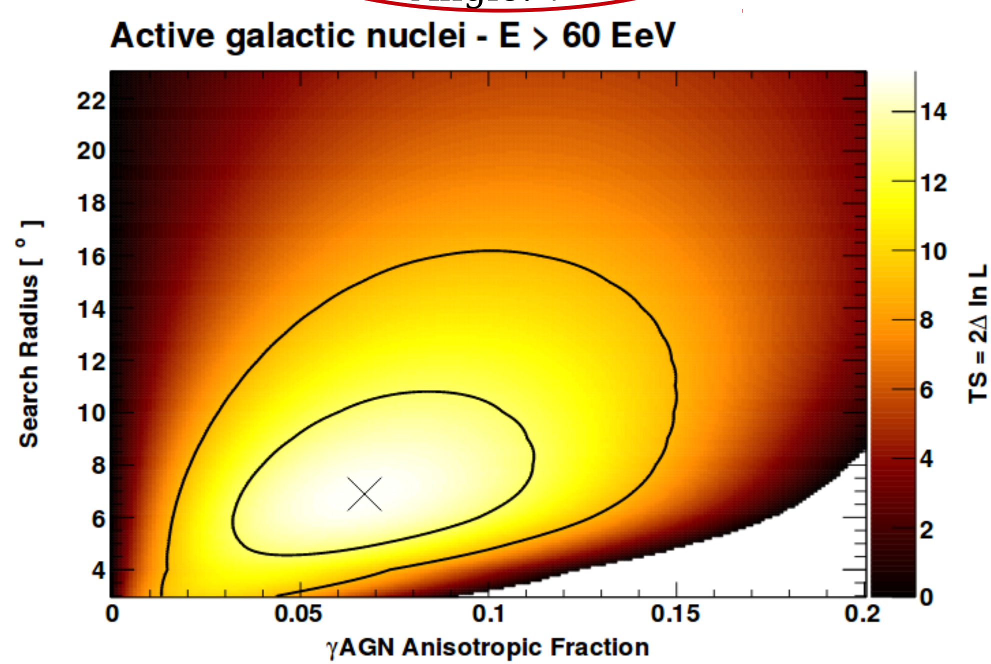




4.0σ post-trial
Fraction: 10%
Angle: 13°

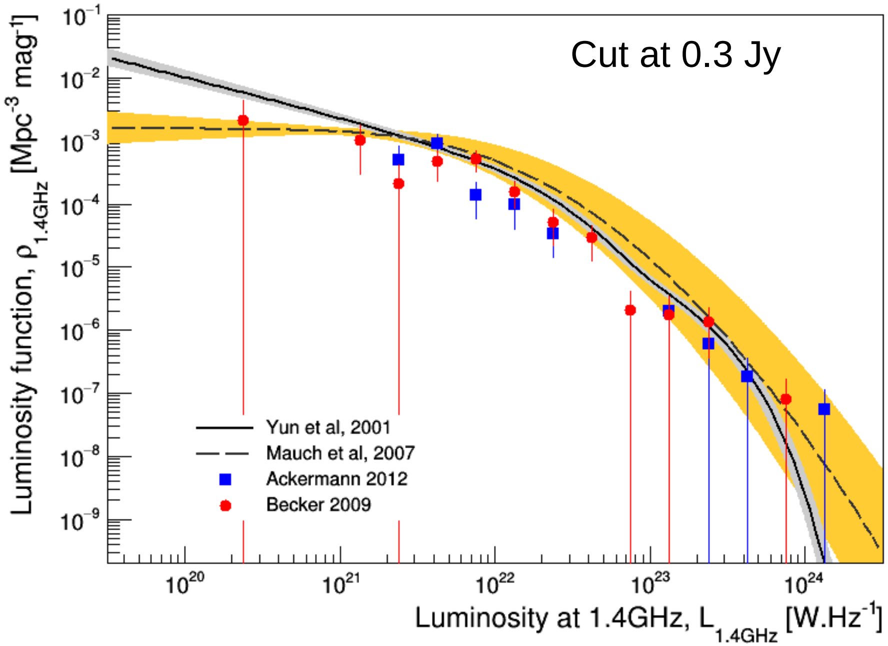
2.7σ post-trial
Fraction: 7%
Angle: 7°

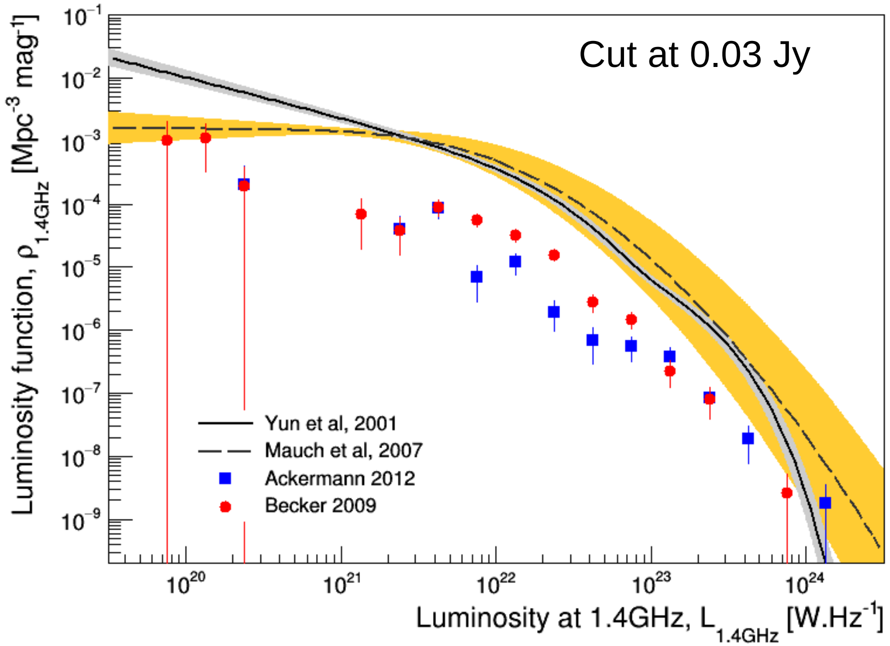


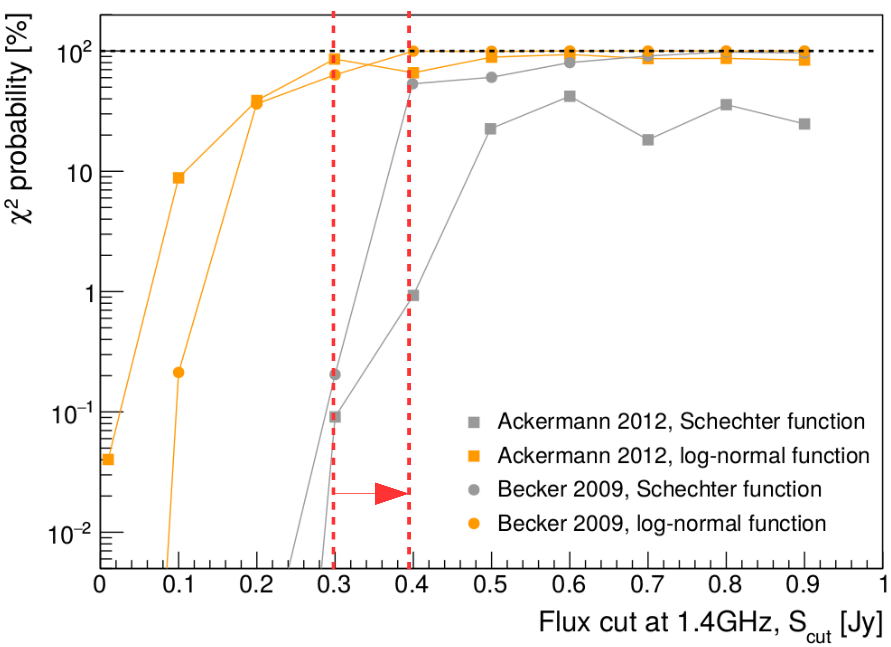


Flux limited starburst catalog?

Construction of the catalog by excluding **galactic plane** and with a poor exposure below **declination of -35°** → incompleteness of startburst catalog?







Reconstruct luminosity functions of starburst catalogs Ackermann et al. (2012) and Becker et al. (2009)
Model of luminosity functions from flux-limited sample in Yun et al. (2001) and Mauch et al. (2007)

Cut at 0.4 Jy = best compromise
→ Removal of **4%** of total cumulated flux from faint sources
→ Do not influence the previous results