Istituto Nazionale di Fisica Nucleare

RICAP 2022

Arrival Directions of Cosmic Rays above 32 EeV from Phase One of the Pierre Auger Observatory

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PIERRE AUGER OBSERVATORY

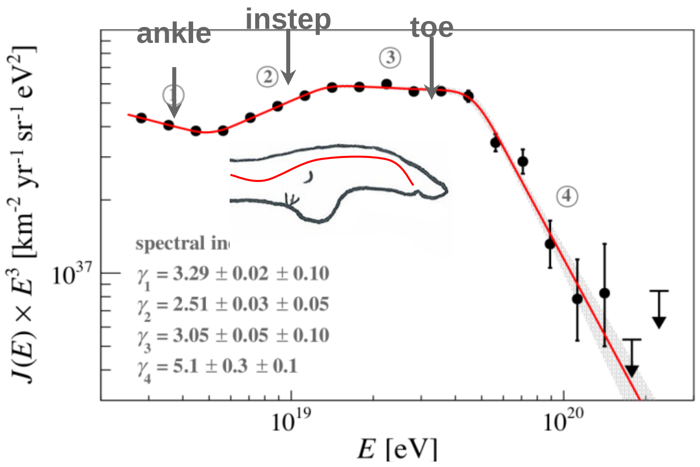
Introduction

Present the results of the paper «Arrival Directions of Cosmic Rays above 32 EeV from Phase One of the Pierre Auger Observatory» 2022 *ApJ* **935** 170 doi:10.3847/1538-4357/ac7d4e

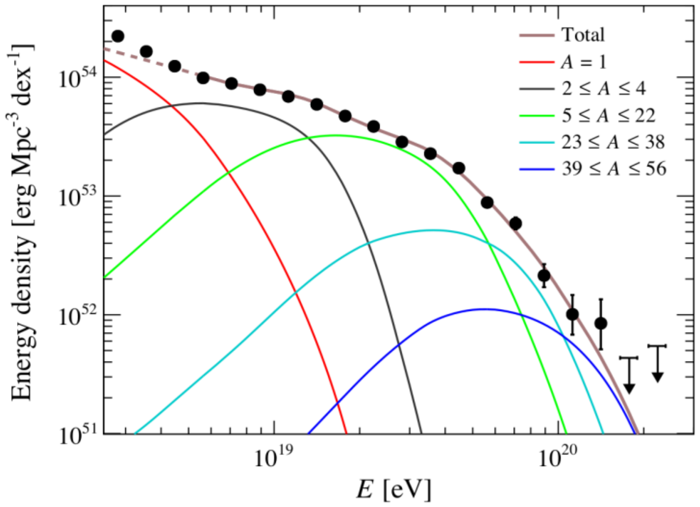
Aim: Release and study the arrival directions of the **highest energy cosmic rays (E>32 EeV)**, at **small and intermediate scale (≲30°)**

Context (spectrum and composition):

- 4 features observed in the spectrum at the highest energies:
  ankle, ~5 EeV (possible transition from Galactic to extra-galactic sources)
  instep 10-15 EeV (possibly effect of Peters cycle, i.e. primary mass sequence)
  toe 40-50 EeV UHECR horizon (GZK) or source exhaustion



Composition measurements from Auger suggest that the average composition **grows** with energy
(see also talks by L. Perrone, E. Guido, A. Condorelli…)



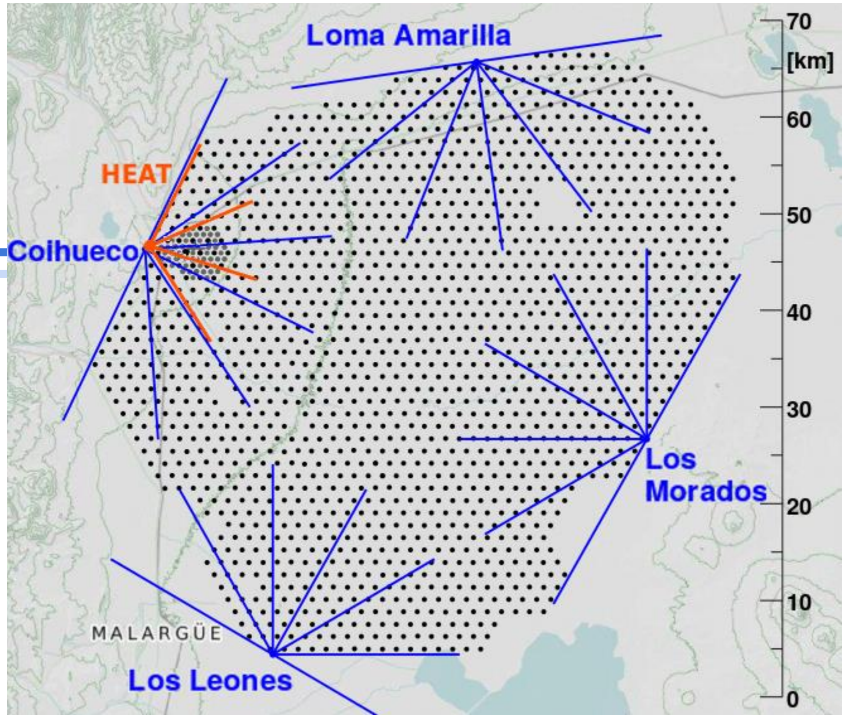
The Pierre Auger Observatory

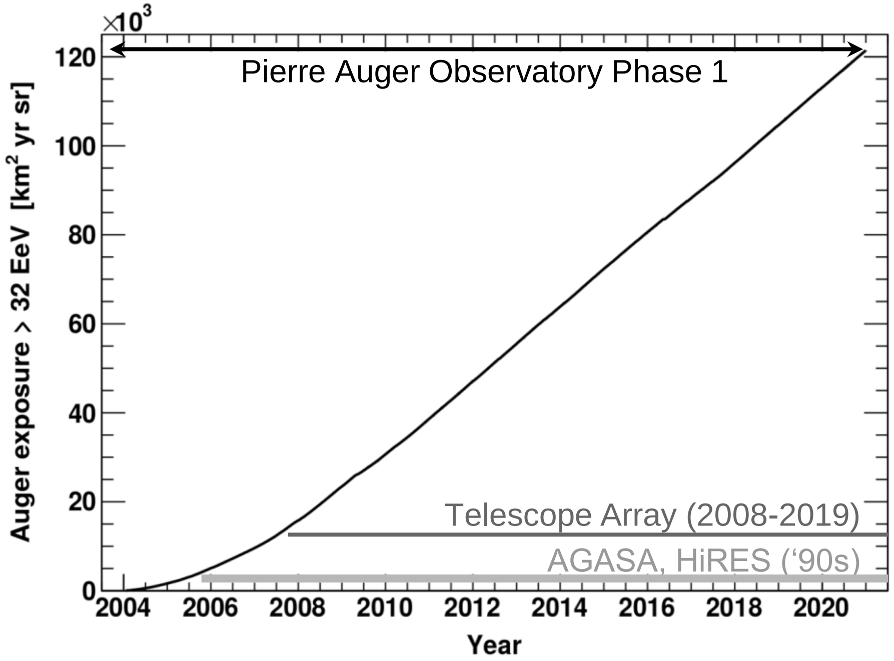
The largest UHECR observatory ever built - 3000 km (~Luxembourg)

1600 water Cherenkov detectors to sample the shower plane at earth (SD)

Hybrid design

24 fluorescence telescopes in 4 sites (FD)





Now undergoing an upgrade: «**Auger Prime**»: here we consider data from **phase 1** (i.e. before Prime)

85% of sky coverage, angular resolution <1° above the ankle

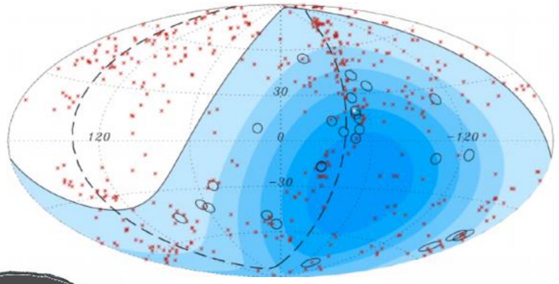
Exposure at the highest energies/loosest cuts: **120000 km2 yr sr** 2004-2020

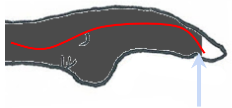
40-70x larger than previous experiments (AGASA, HiRES)

9x larger than the northern complementary TA

Previous anisotropy results from Auger

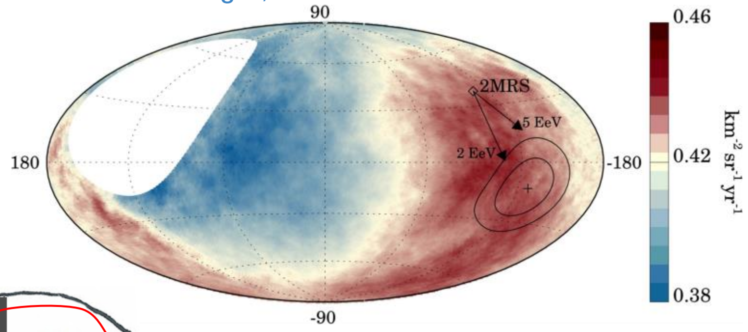
Auger, Science 2007

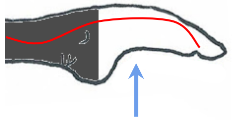




~ 27 evts ≥ 57 EeV

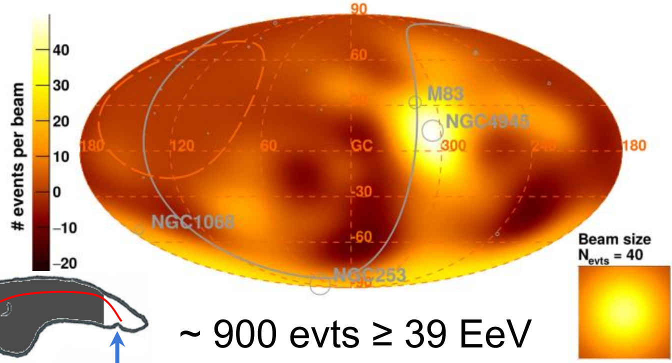
Auger, Science 2017

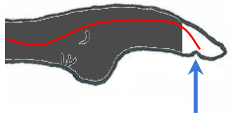




~ 32,000 evts ≥ 8 EeV

Auger, ApJL 2018





~ 900 evts ≥ 39 EeV

2020

2600 evts ≥ 32 EeV

2007

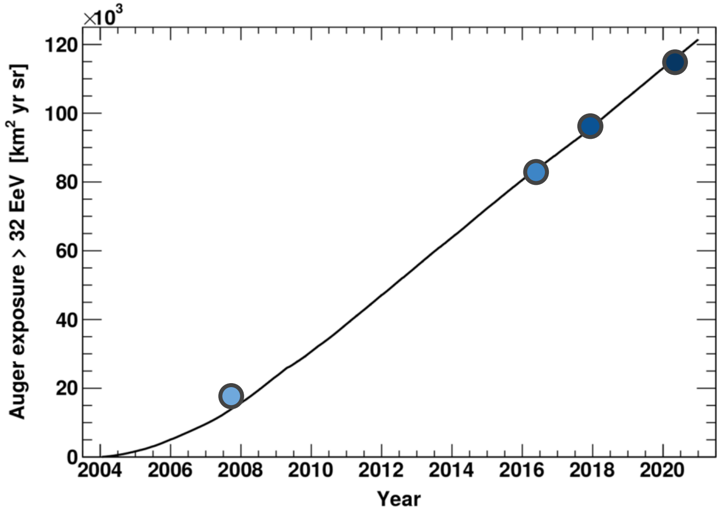
27 events > 57 EeV

20/27 within 3°

of nearby galaxies

10 clustered

in the **Centaurus region**



2017

32,000 evts ≥ 8 EeV

>5σ dipolar-like flux

In line with nearby **galaxy stellar mass distribution** (2MRS)

2018

900 evts ≥ 39 EeV

4σ evidence for correlation with nearby **starforming galaxies**

3σ level for other types of galaxies

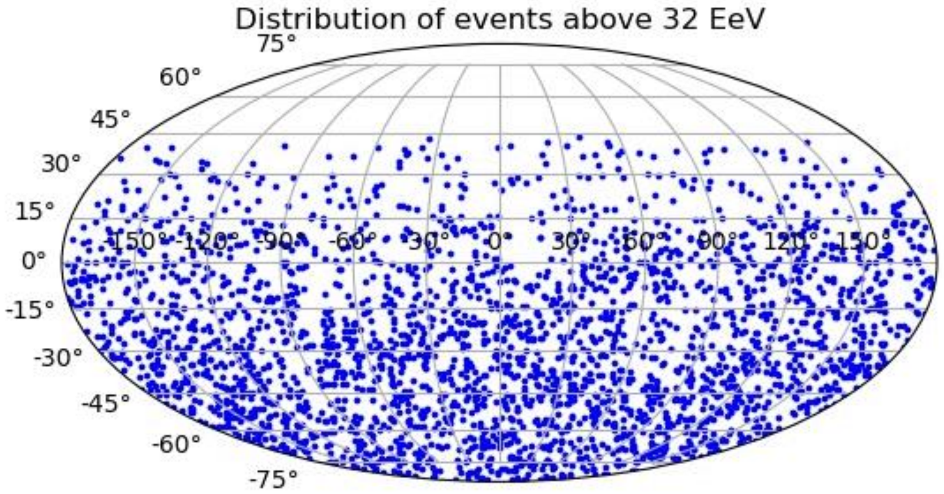
The dataset

- Largest dataset so far of events at the highest energies
- Events measured by the Surface Detector of Auger, reconstructed **Energy $\geq$32 EeV**
- From the **1st of January 2004** to the **31st of December 2020**
- Two different sets of events each with its proper **selection** and **reconstruction**:
  - **2040 'Vertical'** events: zenith angle $\leq$60°.
  - **595 'Inclined'** events: 60°< zenith angle $\leq$ 80°

  Selected when the station with the highest signal is surrounded by at least 5 active stations

Total exposure: 120,000 km² sr yr

Total number of events: 2635



32 chosen as the highest energy range for dipolar searches

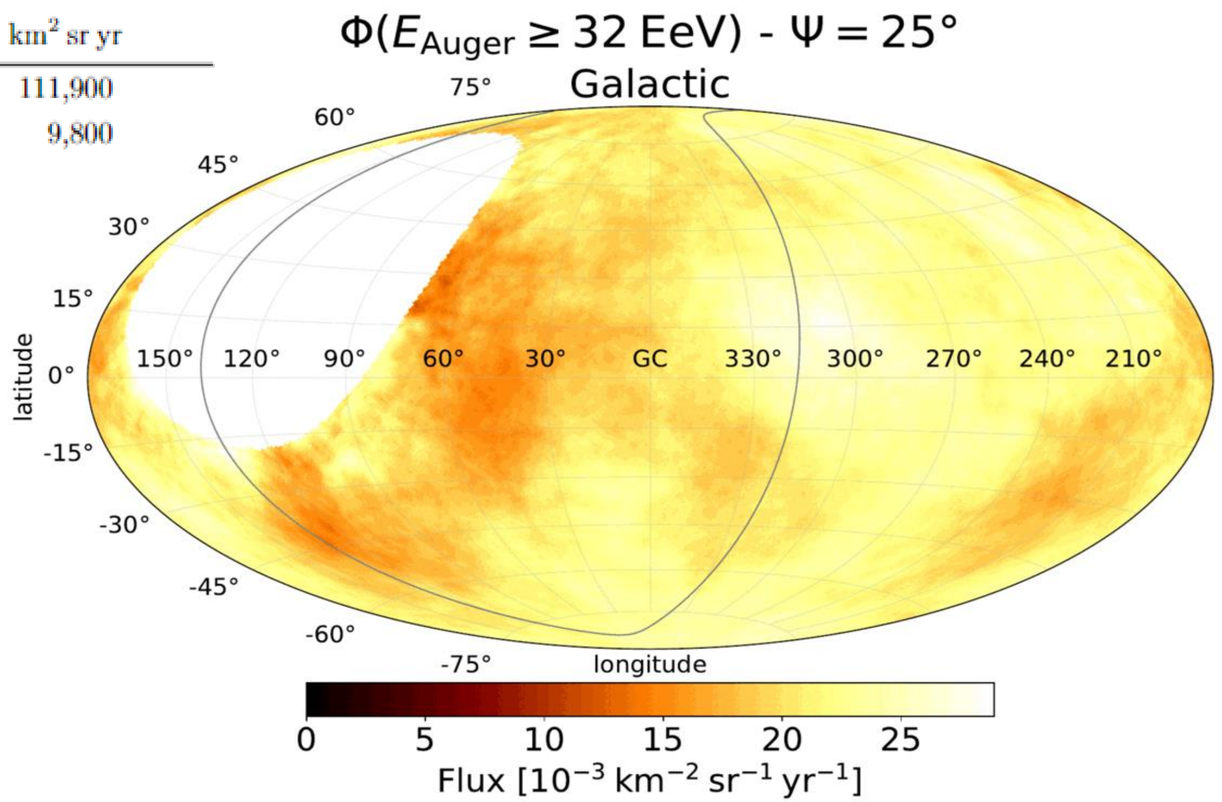
2635 above 32 EeV
647 above 50 EeV
261 above 64 EeV
36 above 100 EeV (0.1 ZeV!)
Most energetic event: 165 EeV

The dataset

- The dataset, together with the code used for the analyses presented in the following slides is **public**
  https://doi.org/10.5281/zenodo.6504276

Year	JD	UTC	Zenith angle, θ	Azimuth angle, ϕ	R.A., α	Dec, δ	E	Cumulative exposure
		s	°	°	°	°	EeV	km^2 sr yr
2019	314	1573399408	58.6	−135.6	128.9	−52.0	166	111,900
2007	13	1168768186	14.2	85.6	192.9	−21.2	165	9,800

Feel free to use it!

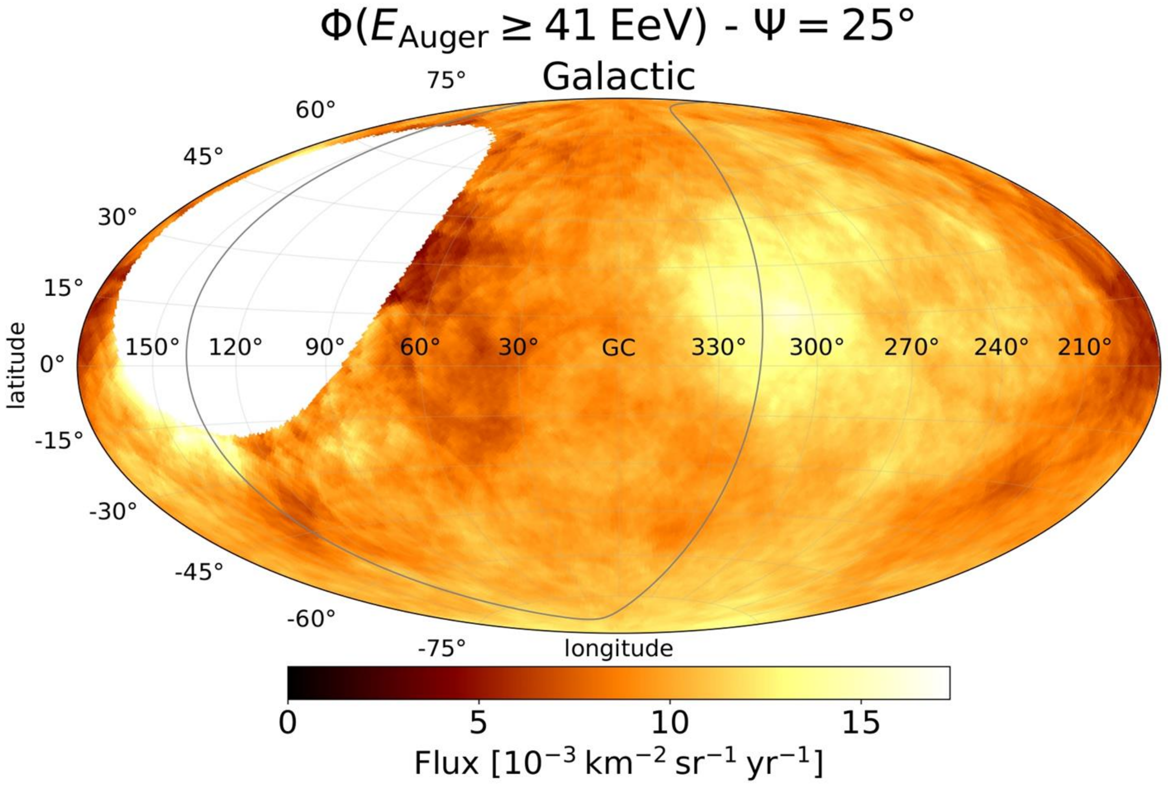


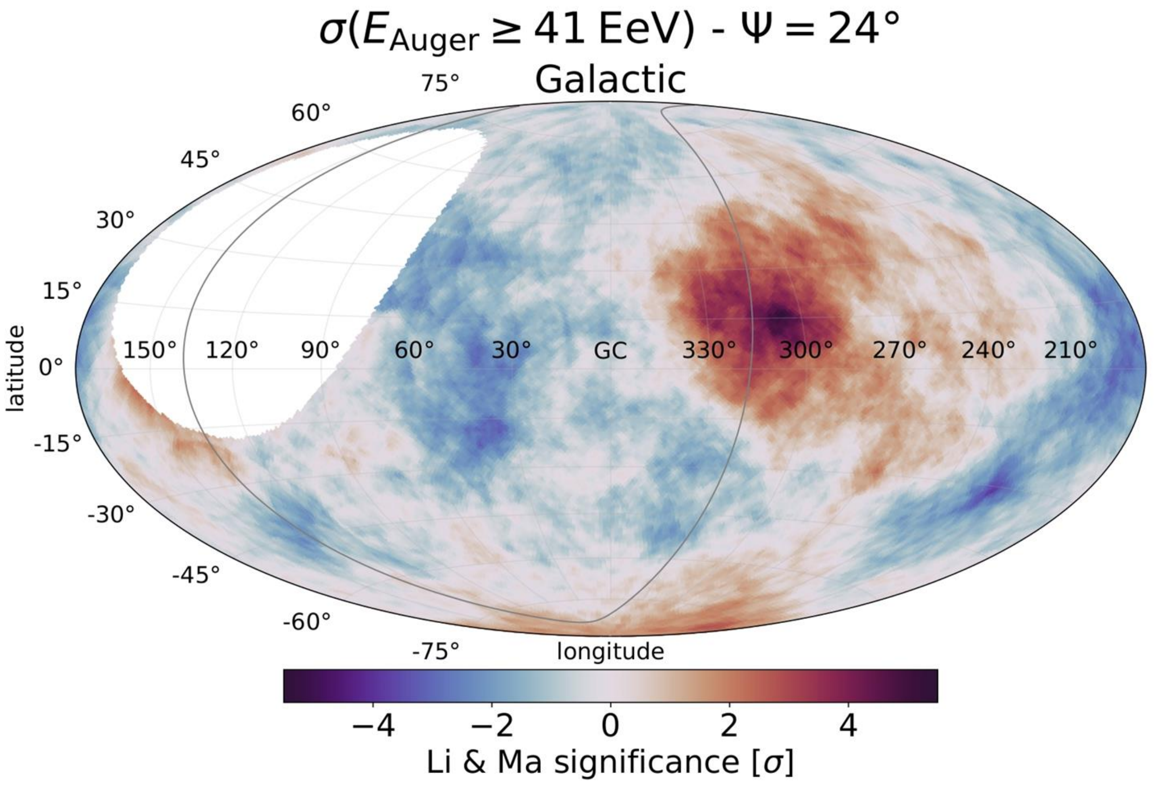
Blind search

Search with little to **no *a priori***: most prominent overdensity in the whole observable sky

Parameter space is scanned in
- Direction (R.A., Dec)
- Threshold energy 32 EeV $\leq$ Eth $\leq$ 80 EeV
- Top-Hat angular scale 1° $\leq \psi \leq$ 30°

Largest significance post-trial **2.2σ**
found at (RA, dec)=(196.3°, -46.6°) or (l, b)=(305.4°, 16.2°)
Nobs = 156 vs Nexp=98 at Eth 41 EeV and Ψ=24°





Autocorrelation and correlation with astrophysical structures

Structures

Events in proximity of local astrophysical structures

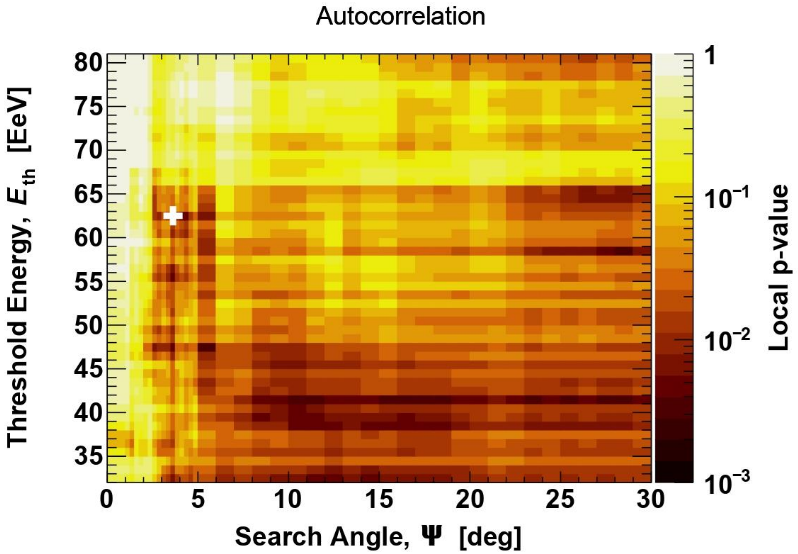
Scan in threshold energy, angle Ψ

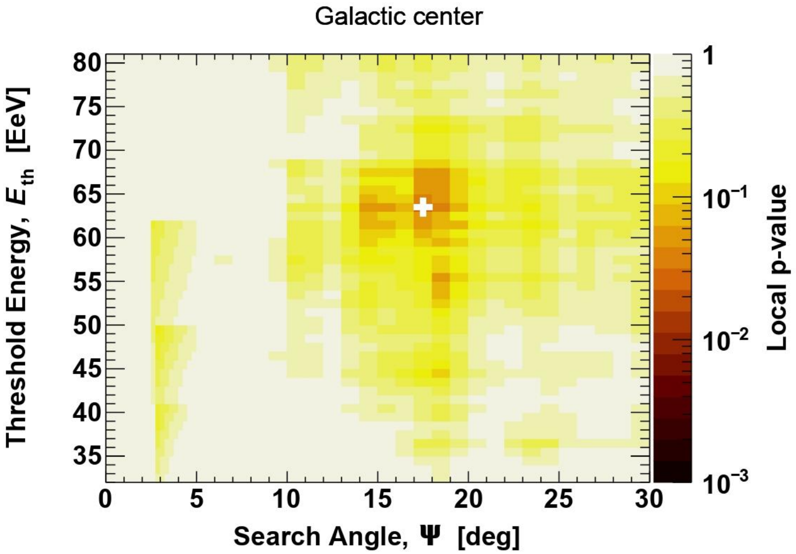
Autocorrelation

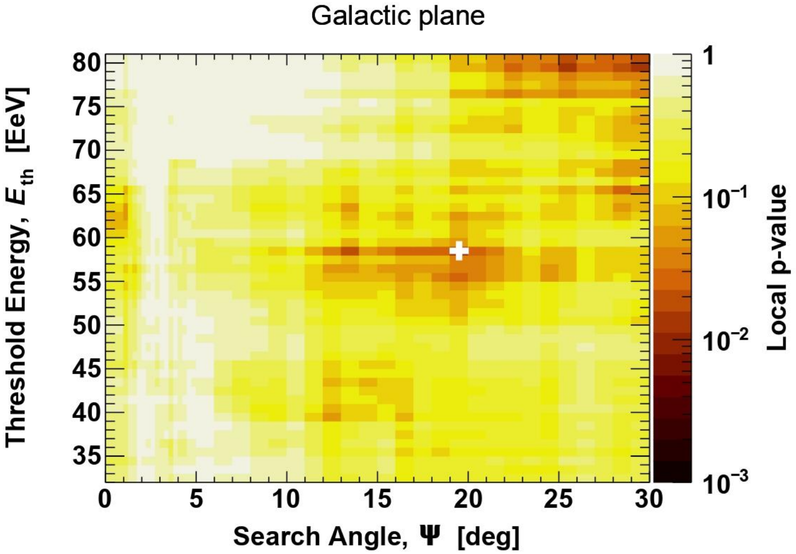
Pairs of events separated by given angular distance

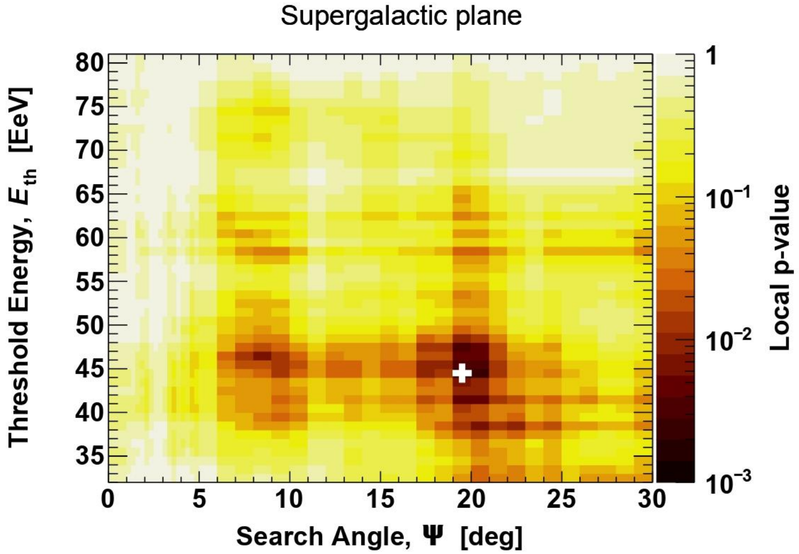
Scan in threshold energy, angle Ψ

Search	E_{th} [EeV]	Angle, Ψ [deg]	N_{obs}	N_{exp}	Local p-value, f_{min}	Post-trial p-value
Autocorrelation	62	3.75	93	66.4	2.5×10^{-3}	0.24
Supergalactic plane	44	20	394	349.1	1.8×10^{-3}	0.13
Galactic plane	58	20	151	129.8	1.4×10^{-2}	0.44
Galactic center	63	18	17	10.1	2.6×10^{-2}	0.57









Catalog-based searches

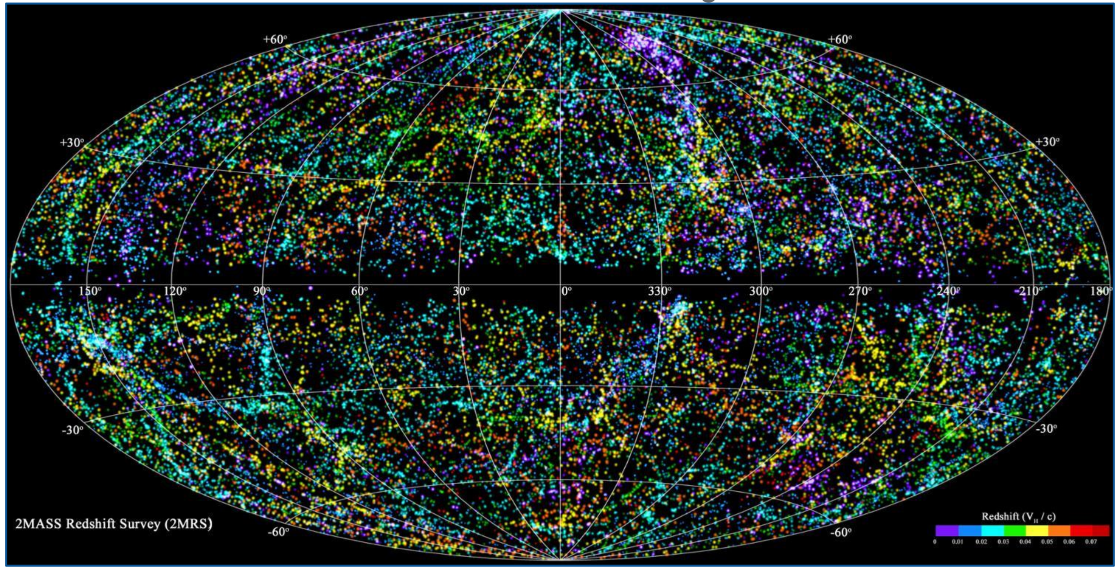
CenA, jetted AGN

NGC415, non-jetted AGN

M82, starburst

Each source weighted based on
- **luminosity distance** to account for propagation effects (supposing an average composition above 32 EeV)
- **electromagnetic emission** to estimate UHECR flux

Uncut 2MRS catalog color coded in redshift



AGN activity

Accretion = X-rays from SwiftBAT (523 galaxies at 14-195 keV)
Jet = γ-rays from 3FHL (26 galaxies at 10 GeV-1 TeV)

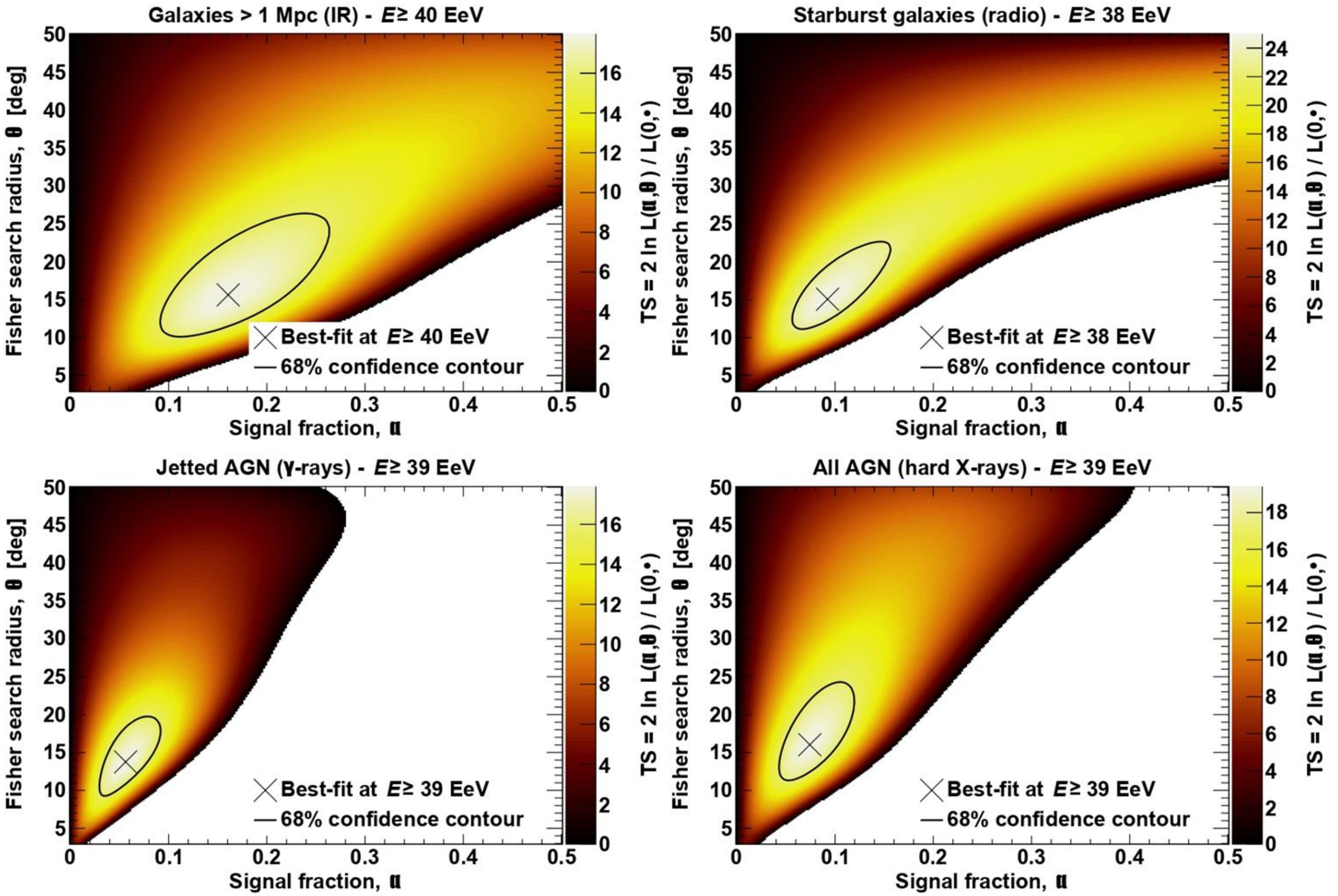
Star formation

Generic/**stellar mass = IR** from 2MRS (>40'000 galaxies 2.2 μm)
Burst = radio from Lunardini+19 (44 galaxies, 1.4 GHz)

Result: 4 flux-limited samples - Jetted AGNs, all AGNs, Starburst galaxies, all galaxies

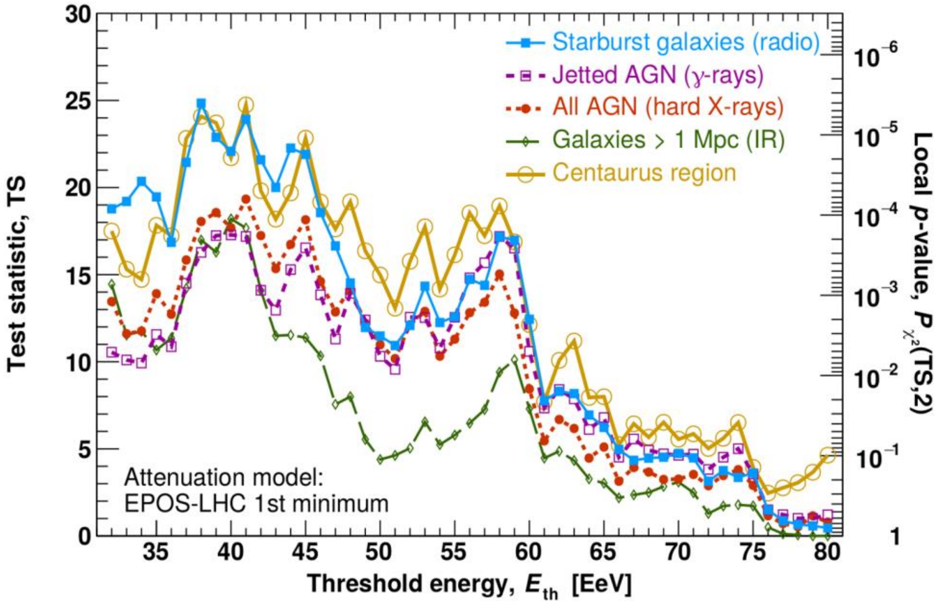
Catalog-based searches

Maximum likelihood fit with 2 free parameters:
- signal fraction α= (1-isotropic fraction)
- gaussian smoothing size



All catalogs have highest test statistics at Eth=38-41 EeV, scale Ψ=23°-27°, signal fraction α=6-15%

Post-trial significance 3.1σ for jetted AGNs, **4.0σ for Starburst galaxies**



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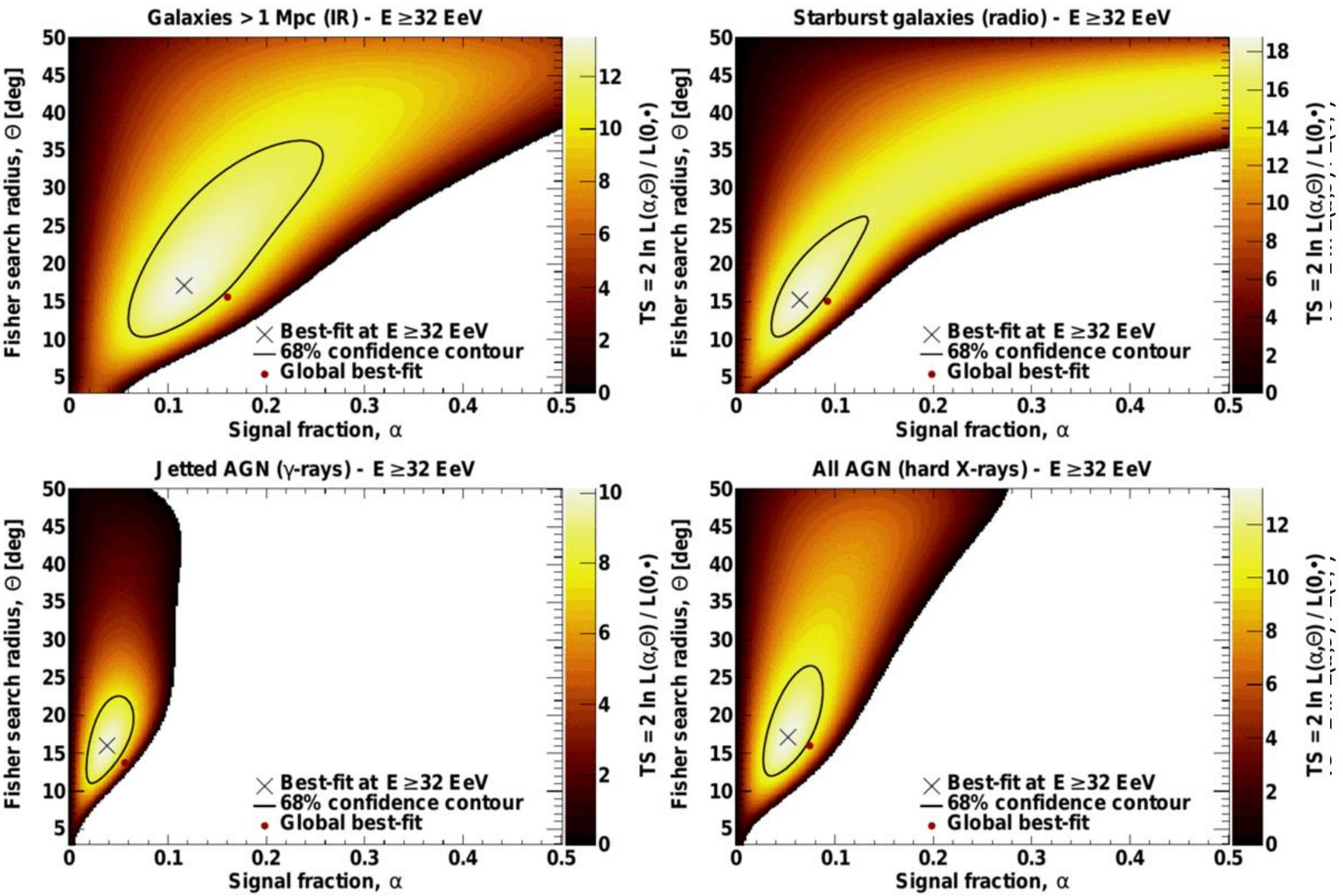

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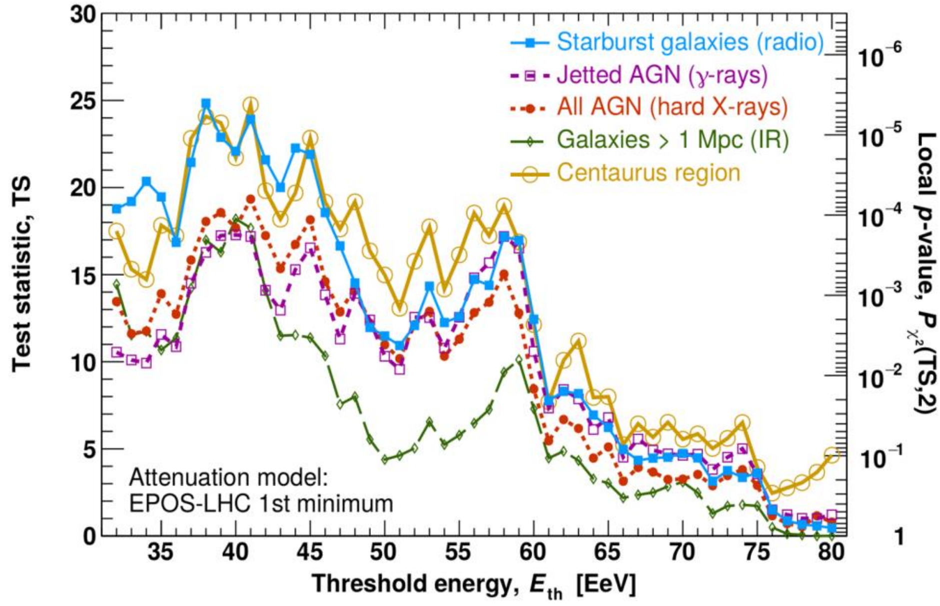


Centaurus region

A priori motivation for a targeted search in this area:

A priori: prominent area in the **Council of Giants**

Flagged area since the first anisotropy results (7% of current exposure) Auger, Science 2007

Most significant overdensity present in the blindsearch

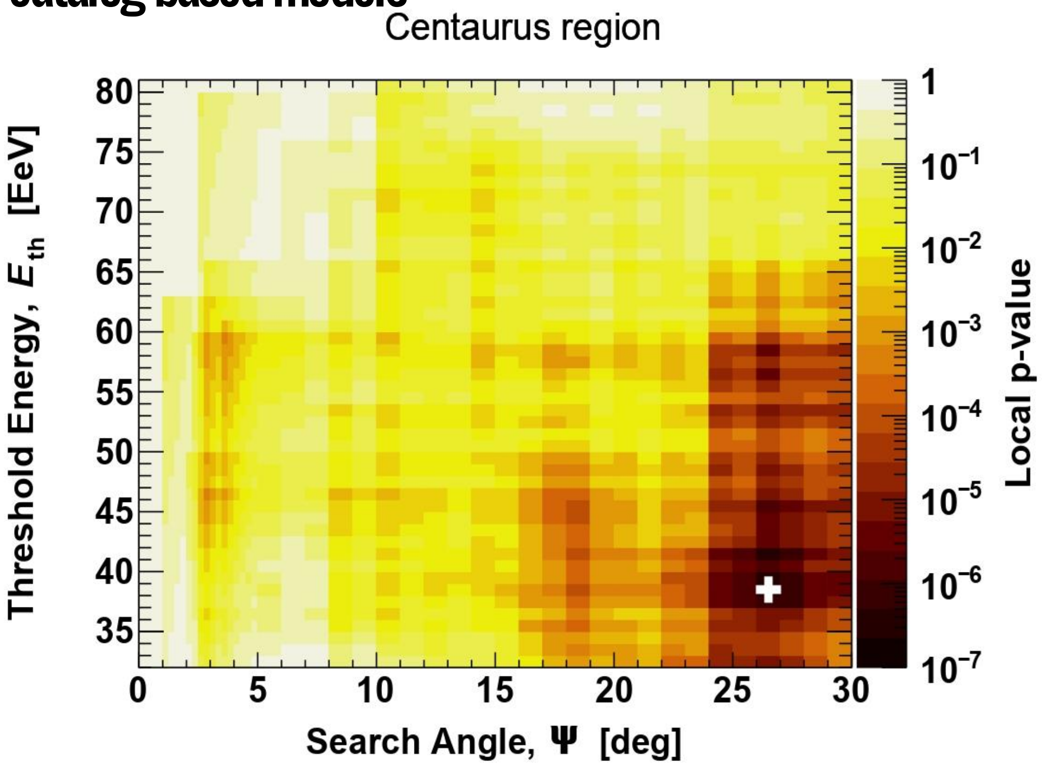
Driving hotspot in all the catalog based models

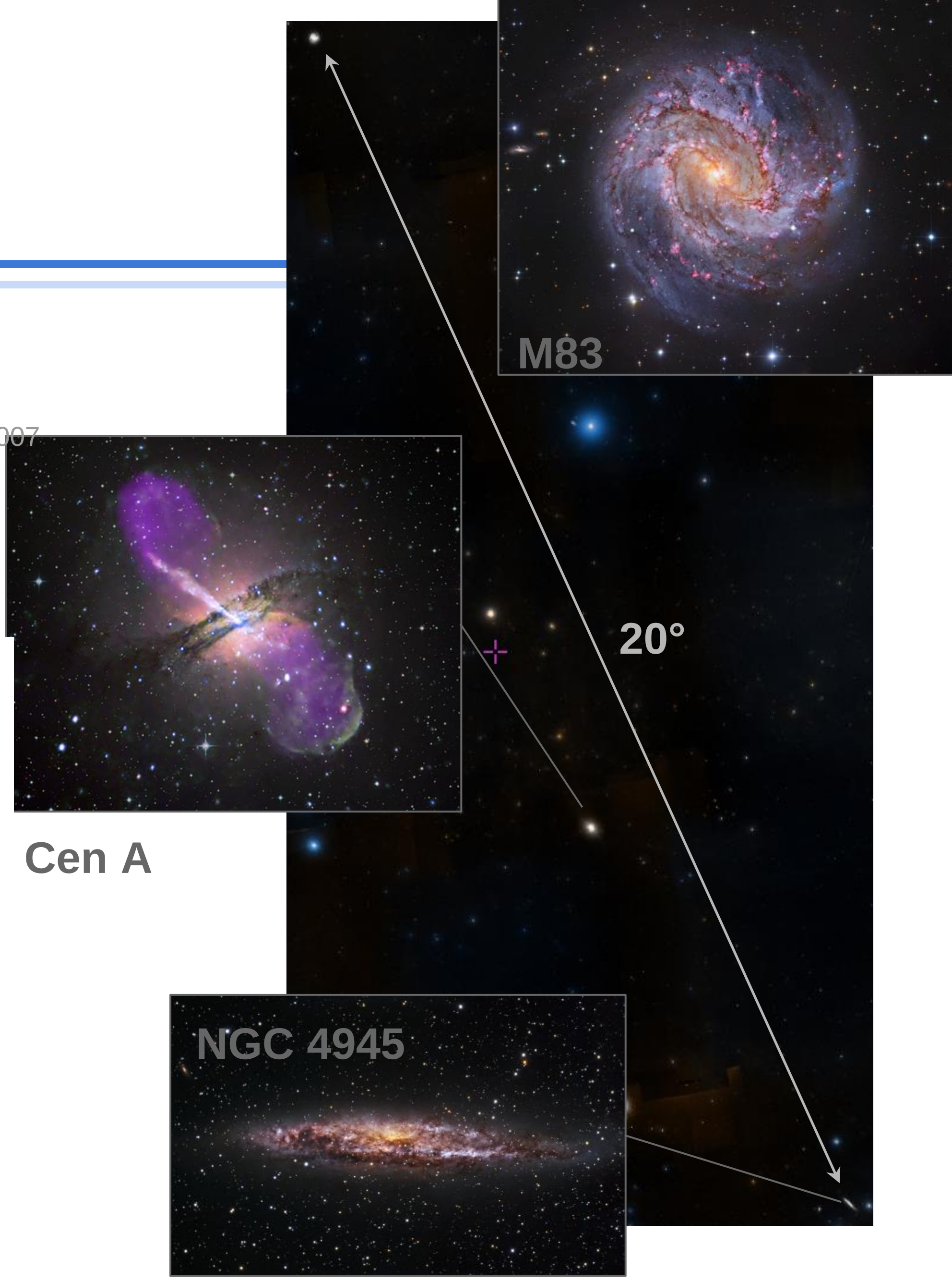
Direction fixed to CenA, scan in threshold energy and angle Ψ

3.9σ post-trial

for Eth=38 EeV, Ψ=27°

Excess=Nobs-Nexp=215-152=63



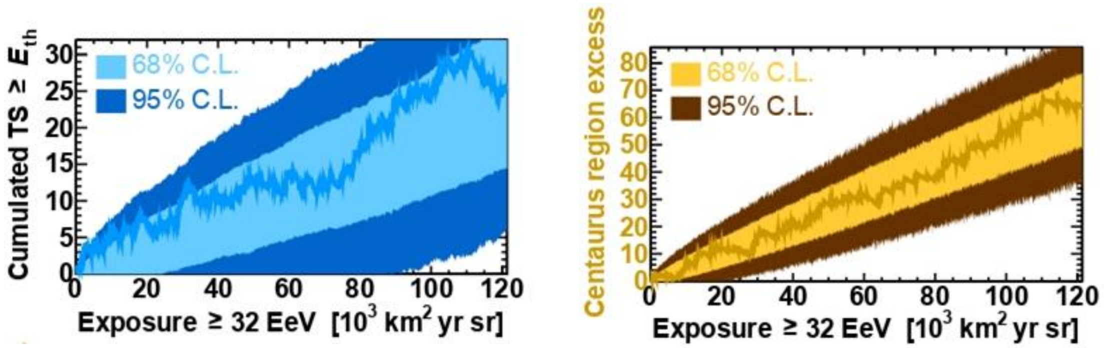


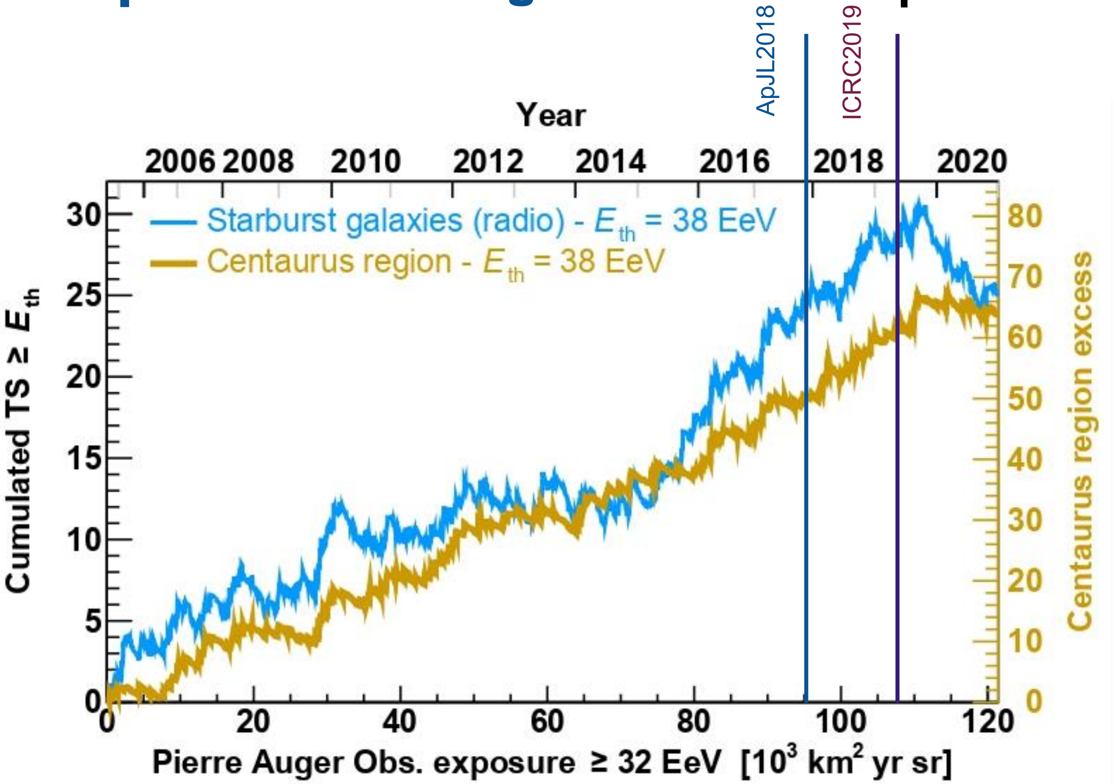
Evolution of the signals

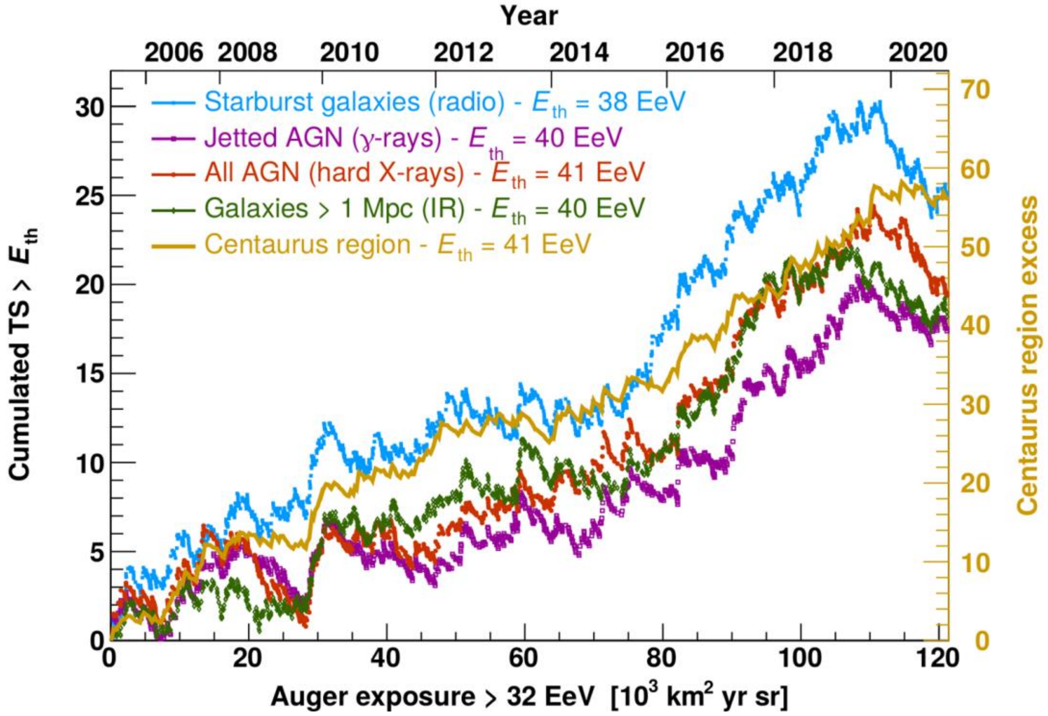
Starburst significance was 4.0σ in ApJL2018, 4.5σ at ICRC2019

Drop in significance coincidet with a plateau of the Centaurus excess

Compatible with linear growth within the expected variance







Summary and outlook

We have built and released the largest dataset of cosmic rays at the highest energies (above 32 EeV, «toe region»)

Search for anisotropy in their arrival directions lead to:
~4σ from search in Centaurus region, confirmed by catalog-based searches.
Largest signal from starbursts, mild catalog preference compared to others

Extra: neutrons (and photons)

Another source of anisotropy could come from **neutrons** from nearby (Galactic) sources.

Additional information and data

With AugerPrime addition of composition information: celect the lighter, less deflected component
"Dumb test": removing 25% simulated heaviest component gives 5σ significance in the Centaurus region analysis

TS growth rate ~ 2 units / year With TS(5σ) ~ 35
⇒ **Auger-only discovery without composition information in 2025-2030**

Full-sky coverage

Auger only sees 85% of the sky

⇒ Combination with Telescope Array (10% of Auger exposure) promising with the upgrades AugerPrime and TAx4

See Armando Di Matteo's talk!

Connection with large scales

Interconnection at the instep of the large (ankle) and small/intermediate (toe) scales

Connect sky pattern maps in the local universe with UHECR flux maps

The next years look very promising for this field!

Backup slides

Public data and code

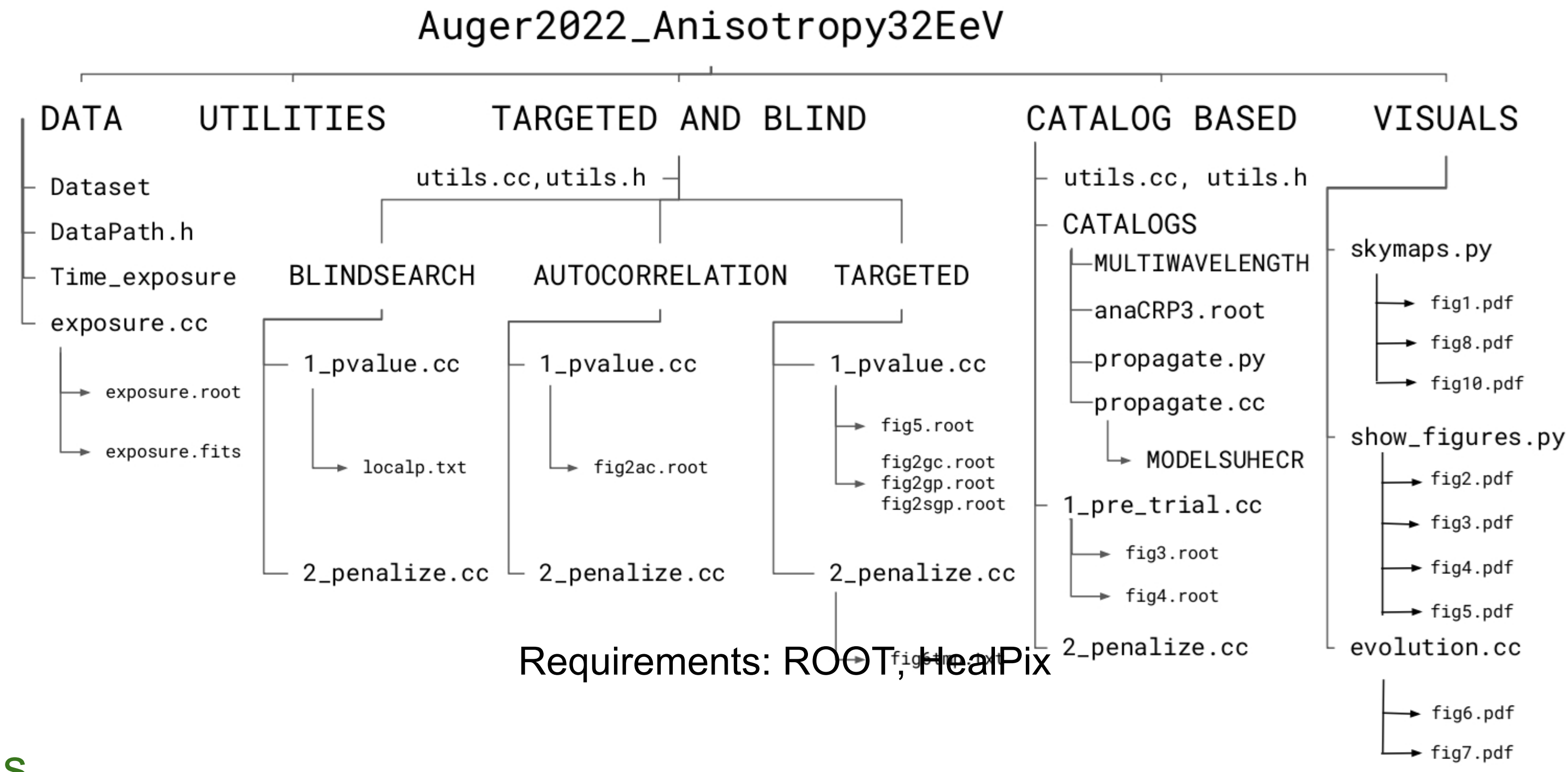
https://doi.org/10.5281/zenodo.6504276

The **dataset is available for public use** with the code to reproduce the results

The different analyses are split in two subgroups:

- Targeted and Blind for blindsearch, autocorrelation, astrophysical structures, Centaurus region
- Catalog Based

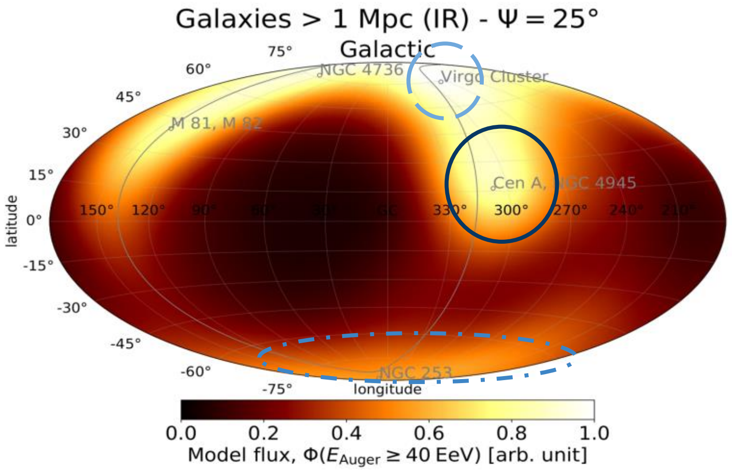
Plots are produced by the scripts in Visuals

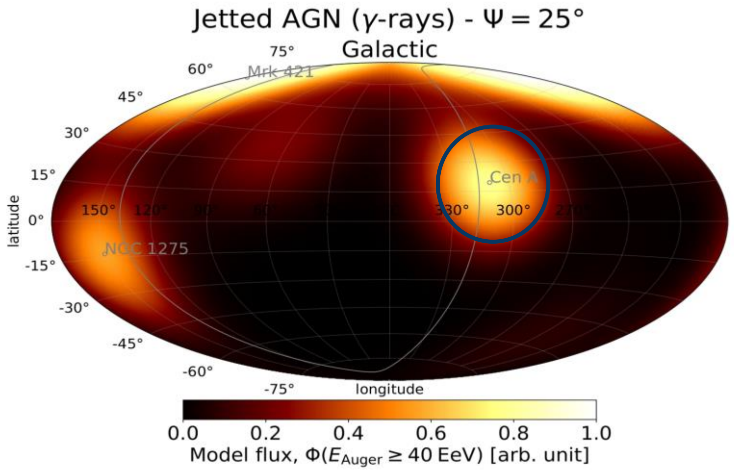


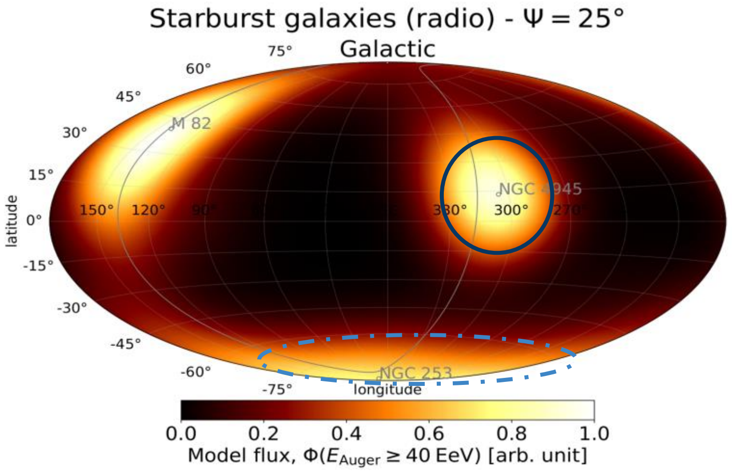
Requirements: ROOT, HealPix

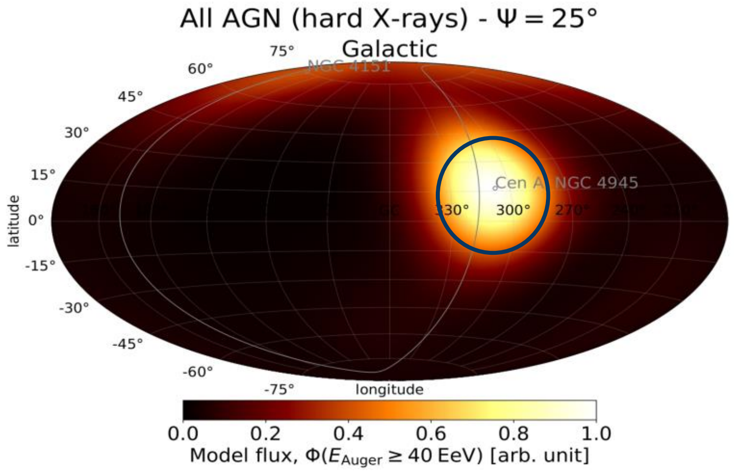
The code adapts to different datasets, provided the source is changed in Data/DataPath.h

Sky models comparison





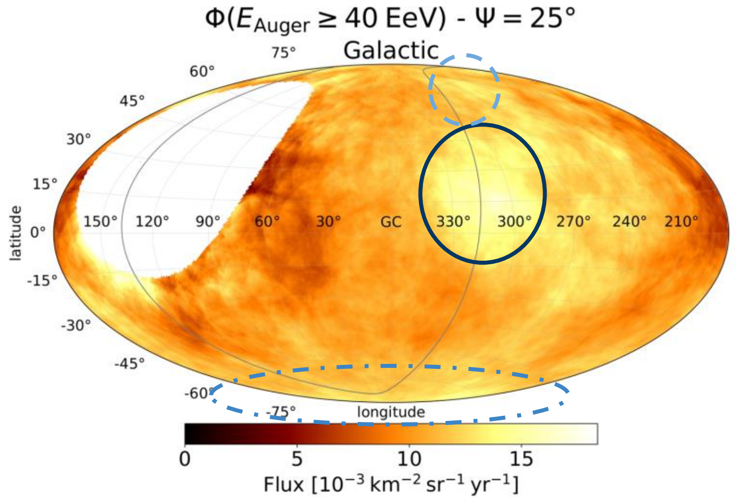




All models capture the hotspot in the **Centaurus region** (M83+NGC4945+CenA)

The starburst model adds the “warm-spot” in the **galactic south pole** (NGC253)

Hotspot missing in the **Virgo Cluster** (l,b) (280°, 75°) in the IR galaxies model



Direct comparison between models shows **mild preference for including** vs excluding **SBGs** (2-3σ)

Likelihood computation

TS evaluation

$$\mathrm{TS} = 2\sum_i k_i \times \ln \frac{n^{H_1}(\mathbf{u}_i)}{n^{H_0}(\mathbf{u}_i)}. \qquad (4)$$

$$n^{H_1}(\mathbf{u}) = (1-\alpha) \times n^{H_0}(\mathbf{u}) + \alpha \times \frac{\sum_j s_j(\mathbf{u};\Theta)}{\sum_i \sum_j s_j(\mathbf{u_i};\Theta)}, \quad (2)$$

Signal fraction

Contribution from each galaxy

$$s_j(\mathbf{u};\Theta) = \omega(\mathbf{u}) \times \phi_j a(d_j) \times \exp\left(\frac{\mathbf{u}\cdot\mathbf{u}_j}{2(1-\cos\Theta)}\right). \quad (3)$$

Count density in the H1 (signal) hypothesis

$$n^{H_0}(\mathbf{u}) = \frac{\omega(\mathbf{u})}{\sum_i \omega(\mathbf{u}_i)}, \qquad (1)$$

Directional exposure of the observatory

Count density in the H0 (isotropy) hypothesis

Evolution of signal

Evolution of TS, Signal fraction and search radius as a function of Threshold energy

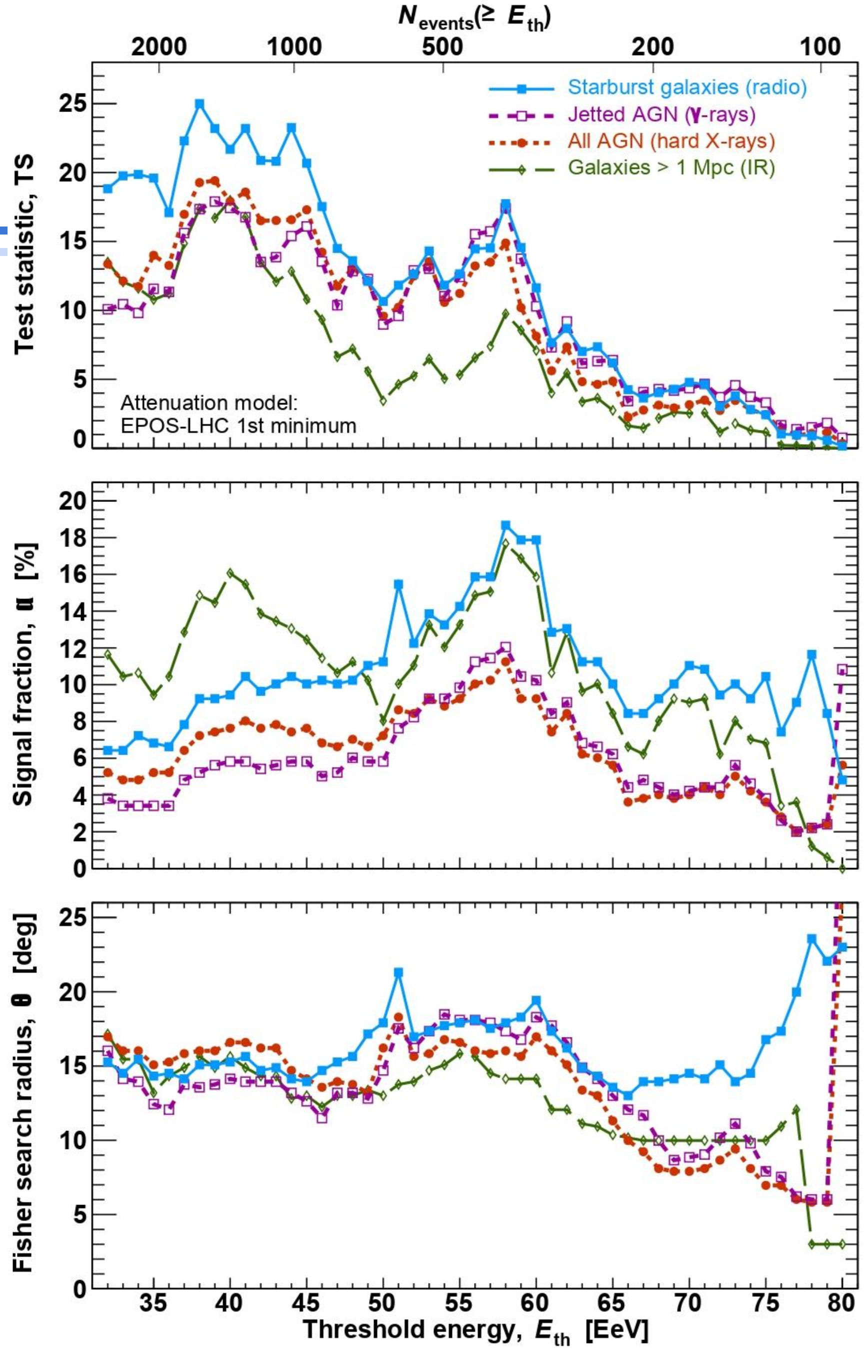


Table 4. Galaxies (2MASS(K<11.75) × HyperLEDA).

PGC	Counterpart	Object Type	R.A.	Dec	$(m-M)$	$\sigma(m-M)$	d_L	$\sigma(d_L)/d_L$	K_t	$\sigma(K_t)$
			°	°	mag	mag	Mpc		mag	mag
29128	NGC3109	G	150.78	-26.16	25.56	0.02	1.29	0.007	9.57	0.4
29653	PGC029653	G	152.75	-4.69	25.59	0.03	1.31	0.013	11.31	0.56
28913	UGC05373	G	150.0	5.33	25.79	0.01	1.44	0.006	10.76	0.23
100169	PGC100169	G	31.52	69.0	26.15	0.2	1.7	0.092	9.69	0.24
67908	IC5152	G	330.67	-51.3	26.46	0.03	1.96	0.012	9.05	0.36
3238	NGC0300	G	13.72	-37.68	26.53	0.02	2.03	0.007	6.58	0.36
1014	NGC0055	G	3.72	-39.2	26.62	0.01	2.11	0.006	6.34	0.18
9140	PGC009140	G	36.18	-73.51	26.63	0.07	2.12	0.032	10.83	0.1
13115	UGC02773	G	53.03	47.79	26.69	0.2	2.18	0.092	9.8	0.1
39573	IC3104	G	184.69	-79.73	26.86	0.02	2.36	0.007	9.24	0.14
60849	IC4662	G	266.79	-64.64	27.03	0.01	2.55	0.006	9.45	0.21
47495	UGC08508	G	202.68	54.91	27.07	0.02	2.6	0.011	11.51	0.1
40904	UGC07577	G	186.92	43.5	27.08	0.02	2.6	0.011	10.45	0.2
54392	ESO274-001	G	228.56	-46.81	27.24	0.06	2.8	0.026	8.3	0.39
51472	UGC09240	G	216.18	44.53	27.25	0.02	2.82	0.008	10.89	0.13
39023	NGC4190	G	183.44	36.63	27.26	0.04	2.83	0.02	11.4	0.77
14241	PGC014241	G	59.96	67.14	27.37	0.03	2.98	0.012	8.24	0.16
4126	NGC0404	G	17.36	35.72	27.37	0.02	2.98	0.007	7.53	0.02
39225	NGC4214	G	183.91	36.33	27.37	0.01	2.98	0.002	8.09	0.21
38881	NGC4163	G	183.04	36.17	27.38	0.02	2.99	0.007	10.92	0.08
15488	NGC1560	G	68.2	71.88	27.38	0.1	2.99	0.046	9.07	0.22
49050	ESO383-087	G	207.32	-36.06	27.52	0.02	3.19	0.007	9.91	0.14
15439	PGC015439	G	68.01	63.62	27.53	0.05	3.2	0.024	10.97	0.17
21396	NGC2403	G	114.21	65.6	27.53	0.01	3.2	0.004	6.24	0.14
47762	NGC5206	G	203.43	-48.15	27.53	0.01	3.21	0.005	8.39	0.25
...	...	...	...	...	...	...	...	...	...	...
127001	PGC127001	G	67.39	-61.25	36.99	0.07	249.7	0.03	11.72	0.18

NOTE—44,113 entries within 250 Mpc. 17,143 entries at $d_L < 100$ Mpc, 39,563 at $d_L < 200$ Mpc.

Table 5. Starburst galaxies (Lunardini+ '19).

Lunardi Name	Counterpart	Host Type	R.A.	Dec	$(m-M)$	$\sigma(m-M)$	d_L	$\sigma(d_L)/d_L$	Φ(1.4 GHz)	$\sigma(\Phi)$	flag: in Aab+ '18?
			°	°	mag	mag	Mpc		Jy	Jy	(No/Yes/Xcheck)
NGC0055	NGC0055	SBm	3.72	-39.2	26.62	0.01	2.11	0.005	0.37	N/A	N
NGC1569	NGC1569	IB	67.7	64.85	27.53	0.05	3.21	0.023	0.4	N/A	X
NGC2403	NGC2403	SABc	114.21	65.6	27.53	0.01	3.21	0.005	0.39	N/A	X
IC342	IC342	SABc	56.7	68.1	27.68	0.03	3.44	0.014	2.25	N/A	Y
NGC4945	NGC4945	Sbc	196.37	-49.47	27.7	0.02	3.47	0.009	6.6	N/A	Y
NGC3034(M82)	M82	S?	148.97	69.68	27.79	0.01	3.61	0.005	7.29	N/A	Y
NGC0253	NGC253	SABc	11.89	-25.29	27.84	0.02	3.7	0.009	6.0	N/A	Y
N/A	Circinus	Sb	213.29	-65.34	28.12	0.36	4.21	0.166	1.5	N/A	Y
NGC5236(M83)	M83	Sc	204.25	-29.87	28.45	0.02	4.9	0.009	2.44	N/A	Y
Maffei2	Maffei2	Sbc	40.48	59.6	28.79	0.12	5.73	0.055	1.01	N/A	X
NGC6946	NGC6946	SABc	308.72	60.15	29.14	0.05	6.73	0.023	1.4	N/A	Y
NGC4631	NGC4631	SBcd	190.53	32.54	29.33	0.02	7.35	0.009	1.12	N/A	Y
NGC5194(M51)	M51	SABb	202.48	47.2	29.67	0.02	8.59	0.009	1.31	N/A	Y
NGC5055(M63)	NGC5055	Sbc	198.96	42.03	29.78	0.01	9.04	0.005	0.35	N/A	Y
NGC2903	NGC2903	Sbc	143.04	21.5	29.85	0.11	9.33	0.051	0.44	N/A	Y
NGC891	NGC891	Sb	35.64	42.35	29.94	1.72	9.73	0.792	0.7	N/A	Y
NGC1068	NGC1068	Sb	40.66	0.0	30.12	0.34	10.6	0.157	4.85	N/A	Y
NGC3628	NGC3628	SBb	170.07	13.59	30.21	0.34	11.0	0.157	0.47	N/A	Y
NGC4818	NGC4818	SABa	194.2	-8.53	30.27	0.33	11.3	0.152	0.45	N/A	N
NGC3627	NGC3627	Sb	170.06	12.99	30.3	0.04	11.5	0.018	0.46	N/A	Y
NGC1808	NGC1808	Sa	76.93	-37.51	30.45	0.36	12.3	0.166	0.5	N/A	X
NGC4303	M61	Sbc	185.48	4.47	30.45	0.1	12.3	0.046	0.44	N/A	X
NGC3521	NGC3521	SABb	166.45	-0.04	30.47	0.29	12.4	0.134	0.35	N/A	N
NGC0660	NGC660	Sa	25.76	13.65	30.5	1.31	12.6	0.603	0.37	N/A	Y
NGC4254	NGC4254	Sc	184.71	14.42	30.77	1.13	14.3	0.52	0.37	N/A	N
...	...	...	...	...	...	...	...	...	...	...	...
NGC6240	NGC6240	S0-a	253.26	2.4	35.18	0.15	108.6	0.069	0.65	N/A	Y

NOTE—44 entries within 250 Mpc. 43 entries at $d_L < 100$ Mpc, 44 at $d_L < 200$ Mpc.

Table 6. Jetted and non-jetted AGNs (*Swift*-BAT 105 months).

BAT105 Name	Counterpart	AGN Type	R.A.	Dec	$(m-M)$	$\sigma(m-M)$	d_L	$\sigma(d_L)/d_L$	$\Phi(14-195$ keV$)$	$\sigma(\Phi)$	flag: ref. $(m-M)$
			°	°	mag	mag	Mpc		10^{-12} erg cm^{-2} s^{-1}	10^{-12} erg cm^{-2} s^{-1}	(HyperLEDA/NED)
J1305.4-4928	NGC4945	Sy2	196.37	-49.47	27.7	0.02	3.47	0.009	282.1	N/A	H
J0955.5+6907	M81	Sy1.9	148.94	69.06	27.78	0.01	3.6	0.005	20.3	N/A	H
J1325.4-4301	CenA	BeamedAGN	201.37	-43.02	27.83	0.03	3.68	0.014	1346.3	N/A	H
J1412.9-6522	Circinus	Sy2	213.29	-65.34	28.12	0.36	4.21	0.166	273.2	N/A	H
J1210.5+3924	NGC4151	Sy1.5	182.64	39.41	28.39	1.65	4.76	0.76	618.9	N/A	H
J1202.5+3332	NGC4395	Sy2	186.45	33.53	28.39	0.01	4.76	0.005	27.5	N/A	H
J0420.0-5457	NGC1566	Sy1.5	64.96	-54.94	29.13	1.16	6.7	0.534	19.5	N/A	H
J1219.4+4720	M106	Sy1.9	184.75	47.29	29.41	0.01	7.62	0.005	23.0	N/A	H
J1329.9+4719	M51	Sy2	202.48	47.2	29.67	0.02	8.59	0.009	13.3	N/A	H
J0242.6+0000	NGC1068	Sy1.9	40.66	0.0	30.12	0.34	10.6	0.157	37.9	N/A	H
J1717.1-6249	NGC6300	Sy2	259.25	-62.83	30.15	0.09	10.7	0.041	96.4	N/A	H
J1203.0+4433	NGC4051	Sy1.5	180.78	44.52	30.28	0.35	11.4	0.161	42.5	N/A	H
J1652.0-5915B	NGC6221	Sy2	253.18	-59.23	30.34	0.62	11.7	0.286	22.4	N/A	H
J1209.4+4340	NGC4138	Sy2	182.35	43.7	30.7	0.25	13.8	0.115	24.4	N/A	H
J1157.8+5529	NGC3998	Sy1.9	179.46	55.44	30.73	0.19	14.0	0.087	13.2	N/A	H
J2235.9-2602	NGC7314	Sy1.9	338.95	-26.05	31.03	0.25	16.1	0.115	57.4	N/A	H
J1432.8-4412	NGC5643	Sy2	218.19	-44.15	31.03	1.0	16.1	0.461	16.8	N/A	H
J1001.7+5543	NGC3079	Sy2	150.46	55.67	31.16	0.32	17.1	0.147	36.7	N/A	H
J1341.9+3537	NGC5273	Sy1.5	205.47	35.66	31.16	0.12	17.1	0.055	16.0	N/A	H
J1207.8+4311	NGC4117	Sy2	181.95	43.12	31.18	0.94	17.2	0.433	12.9	N/A	H
J0333.6-3607	NGC1365	Sy2	53.39	-36.14	31.19	0.02	17.3	0.009	63.5	N/A	H
J0241.3-0816	NGC1052	BeamedAGN	40.29	-8.24	31.22	0.11	17.5	0.051	31.4	N/A	H
J1132.7+5301	NGC3718	Sy1.9	173.22	53.02	31.25	0.89	17.8	0.41	12.2	N/A	H
J1206.2+5243	NGC4102	Sy2	181.59	52.71	31.29	0.25	18.1	0.115	32.1	N/A	H
J2318.4-4223	NGC7582	Sy2	349.6	-42.37	31.41	0.1	19.1	0.046	82.3	N/A	H
...	...	...	...	...	...	...	...	...	...	...	...
J0534.8-6026	2MASXJ05343093-6016153	Sy1	83.7	-60.27	36.98	0.06	248.9	0.028	10.7	N/A	H

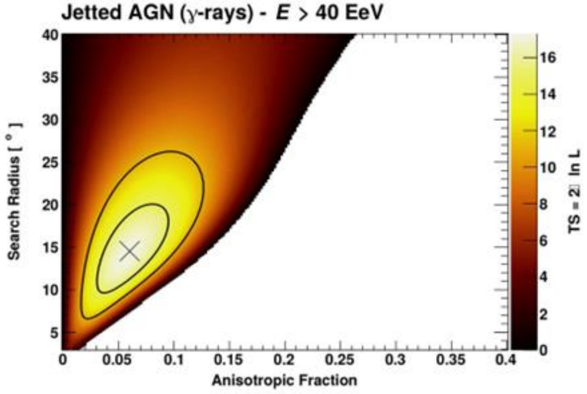
NOTE—523 entries within 250 Mpc. 201 entries at $d_L < 100$ Mpc, 458 at $d_L < 200$ Mpc.

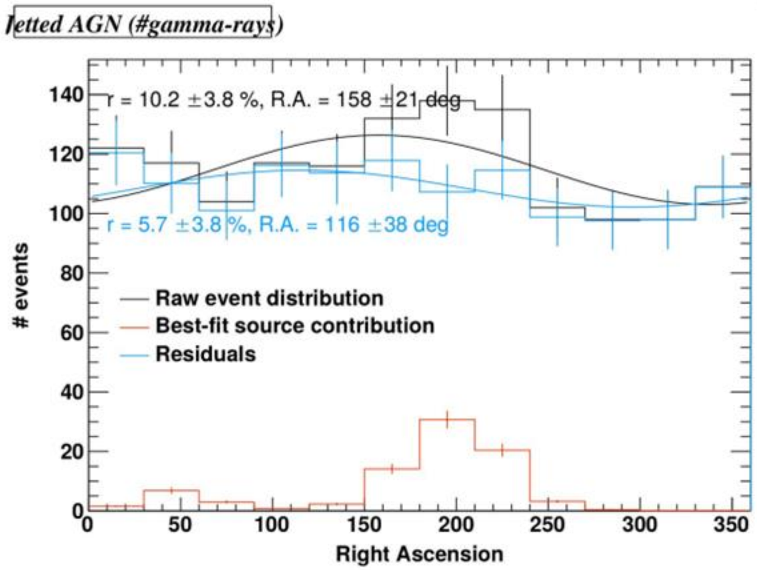
Table 7. Jetted AGNs (*Fermi*-LAT 3FHL).

3FHL Name	Counterpart	Jetted AGN Type	R.A.	Dec	$(m-M)$	$\sigma(m-M)$	d_L	$\sigma(d_L)/d_L$	$\Phi(0.01-1\ \mathrm{TeV})$	$\sigma(\Phi)$	flag: in Aab+ '18?
			°	°	mag	mag	Mpc		$10^{-10}\ \mathrm{cm^{-2}\ s^{-1}}$	$10^{-10}\ \mathrm{cm^{-2}\ s^{-1}}$	(No/Yes)
J1325.5-4300	CenA	RDG	201.37	-43.02	27.83	0.03	3.68	0.014	1.54	0.25	Y
J1230.8+1223	M87	RDG	187.71	12.39	31.12	0.06	16.7	0.028	0.98	0.2	Y
J0322.6-3712e	FornaxA	RDG	50.67	-37.21	31.55	0.03	20.4	0.014	0.48	0.16	N
J1346.2-6026	CenB	RDG	206.7	-60.41	33.71	0.29	55.2	0.134	0.64	0.18	N
J0319.8+4130	NGC1275	RDG	49.95	41.51	34.46	0.08	78.0	0.037	14.17	0.67	Y
J0316.6+4120	IC310	RDG	49.18	41.32	34.6	0.19	83.2	0.087	0.43	0.13	Y
J0153.5+7115	TXS0149+710	BCU	28.36	71.25	35.07	0.15	103.3	0.069	0.44	0.12	Y
J0308.4+0408	NGC1218	RDG	47.11	4.11	35.48	0.13	124.7	0.06	0.54	0.16	N
J1104.4+3812	Mkn421	BLL	166.1	38.21	35.63	0.12	133.7	0.055	59.35	1.38	Y
J1653.8+3945	Mkn501	BLL	253.47	39.76	35.91	0.1	152.1	0.046	19.17	0.76	Y
J0131.1+5546	TXS0128+554	BCU	22.81	55.75	36.06	0.1	162.9	0.046	0.33	0.12	N
J1543.6+0452	CGCG050-083	BCU	235.89	4.87	36.26	0.09	178.6	0.041	0.69	0.17	N
J0223.0-1119	1RXSJ022314.6-111741	BLL	35.81	-11.29	36.31	0.09	182.8	0.041	0.4	0.13	N
J2347.0+5142	1ES2344+514	BLL	356.76	51.69	36.47	0.08	196.8	0.037	3.32	0.31	Y
J0816.4-1311	PMNJ0816-1311	BLL	124.11	-13.2	36.51	0.08	200.4	0.037	2.71	0.33	N
J1136.5+7009	Mkn180	BLL	174.11	70.16	36.54	0.08	203.2	0.037	1.74	0.21	Y
J1959.9+6508	1ES1959+650	BLL	299.97	65.16	36.63	0.08	211.8	0.037	8.43	0.46	Y
J1647.6+4950	SBS1646+499	BLL	251.9	49.83	36.64	0.08	212.8	0.037	0.48	0.12	N
J1517.6-2422	APLibrae	BLL	229.42	-24.37	36.68	0.07	216.8	0.032	3.76	0.37	Y
J0214.5+5145	TXS0210+515	BLL	33.55	51.77	36.7	0.11	218.8	0.051	0.42	0.12	Y
J1806.8+6950	3C371	BLL	271.71	69.82	36.77	0.07	225.9	0.032	1.3	0.18	N
J1353.0-4413	PKS1349-439	BLL	208.24	-44.21	36.79	0.07	228.0	0.032	0.33	0.12	N
J0200.1-4109	1RXSJ020021.0-410936	BLL	30.09	-41.16	36.85	0.07	234.4	0.032	0.51	0.14	N
J0627.1-3528	PKS0625-35	BLL	96.78	-35.49	36.89	0.07	238.8	0.032	1.81	0.26	Y
J2039.4+5219	1ES2037+521	BLL	309.85	52.33	36.89	0.07	238.8	0.032	0.58	0.15	N
J0523.0-3627	PKS0521-36	BLL	80.76	-36.46	36.91	0.07	241.0	0.032	1.17	0.21	N

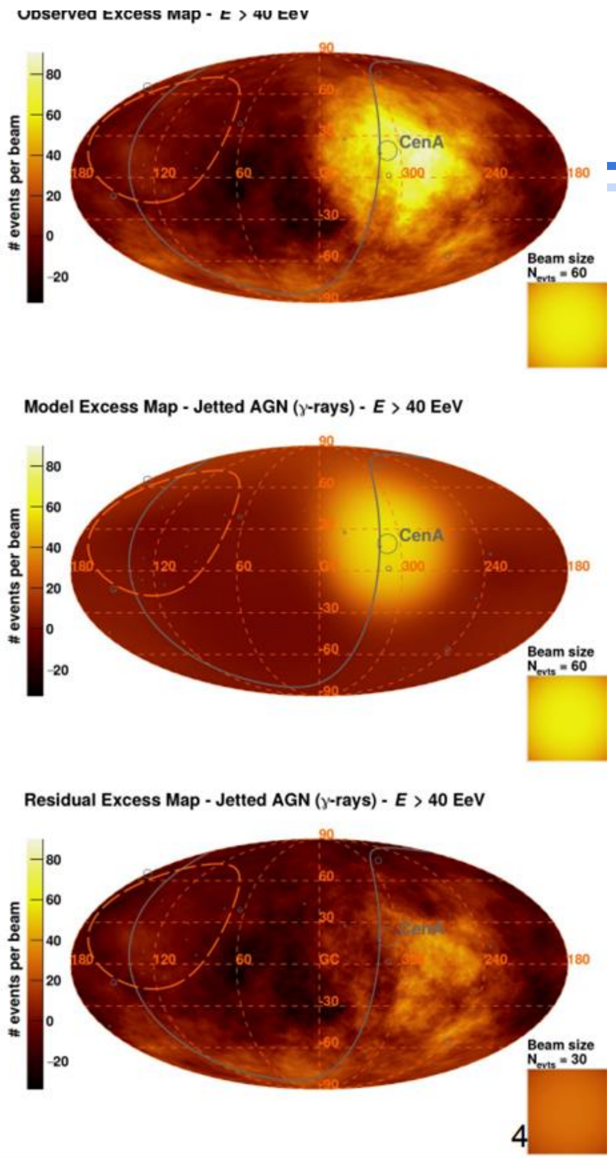
NOTE—26 entries within 250 Mpc. 6 entries at $d_L < 100$ Mpc, 14 at $d_L < 200$ Mpc.

Jetted AGN model (EPO1st)



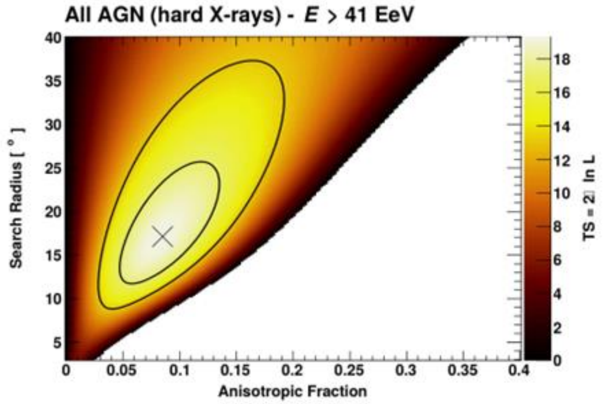


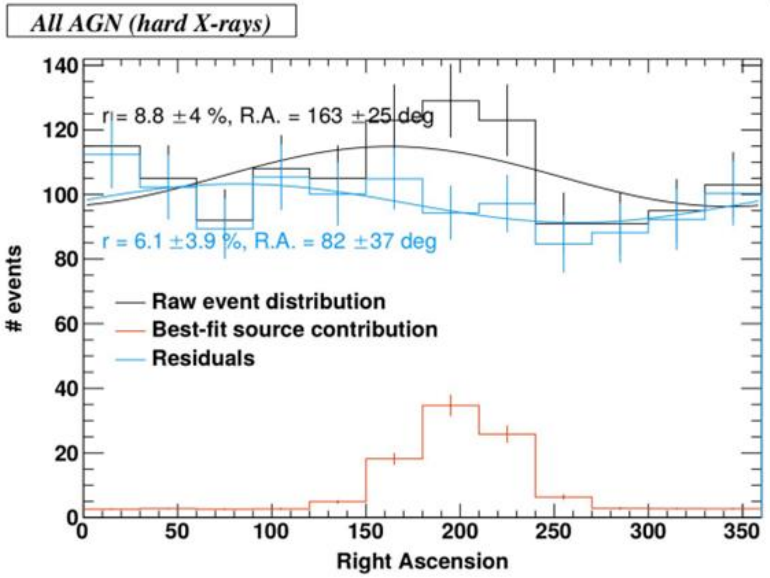
Note: 2MRS dipole at R.A. ~ 155°

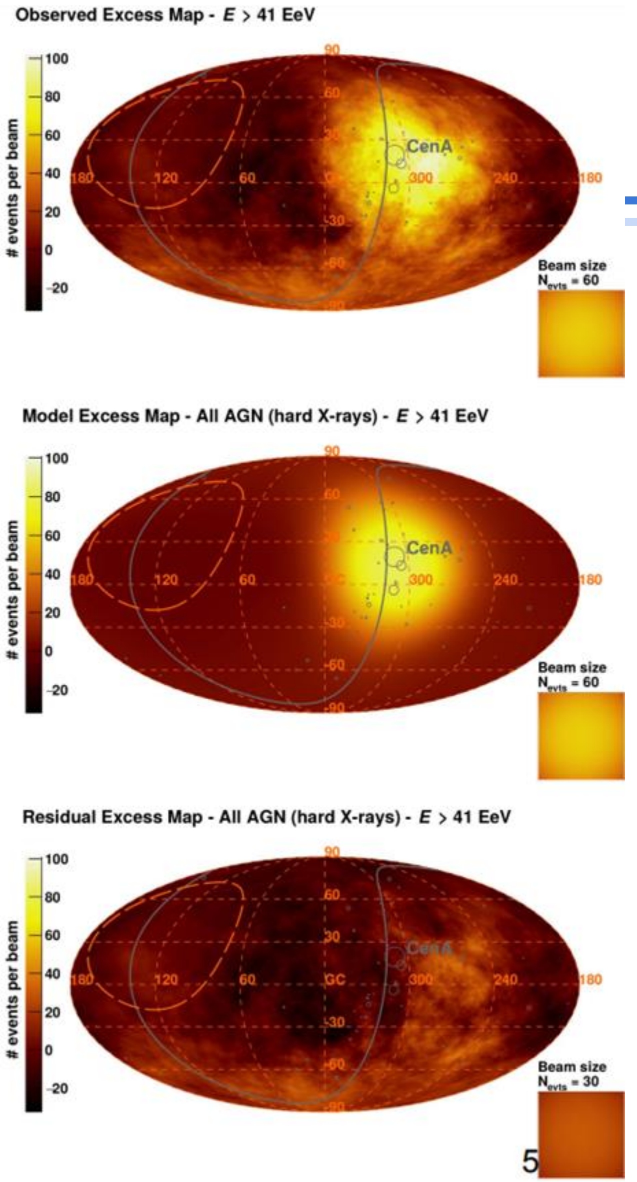


Courtesy of J. Biteau

All AGN model (EPO1st)



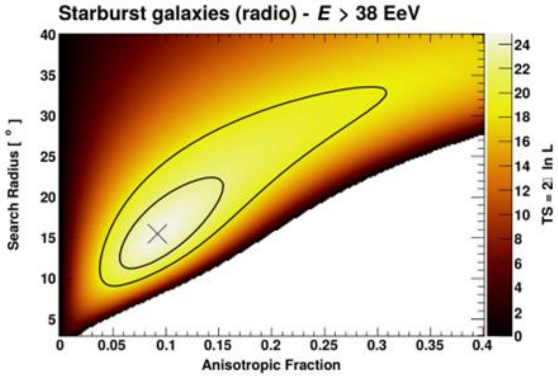


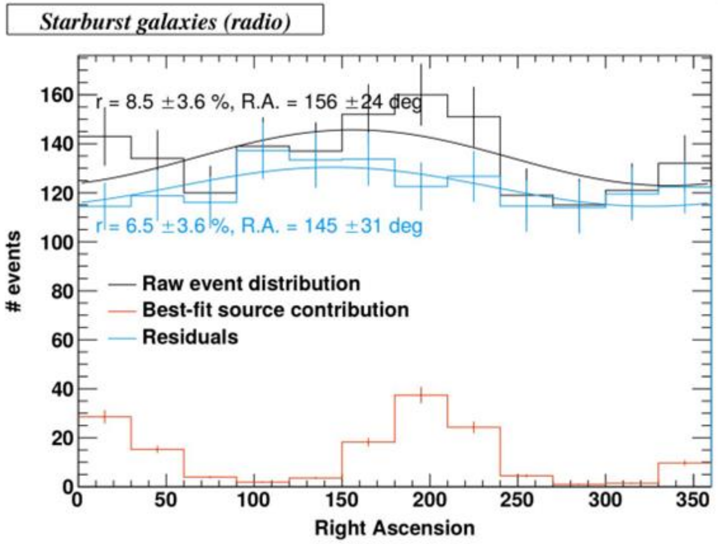


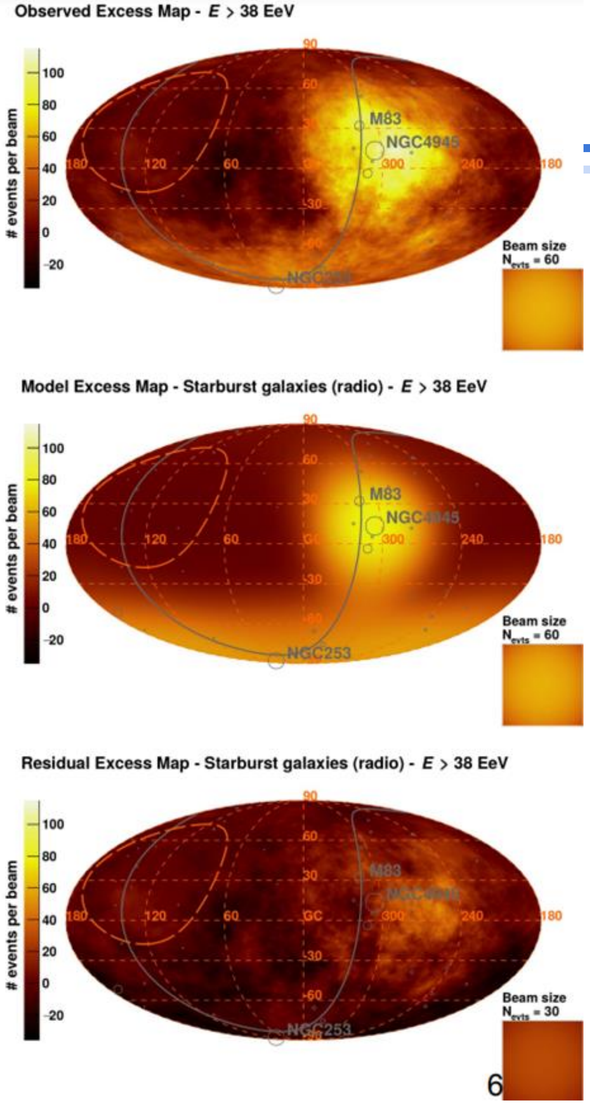
Note: 2MRS dipole at R.A. ~ 155°

Courtesy of J. Biteau

Starburst model (EPO1st)



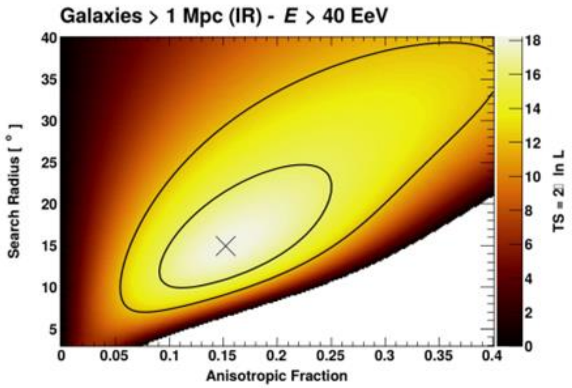


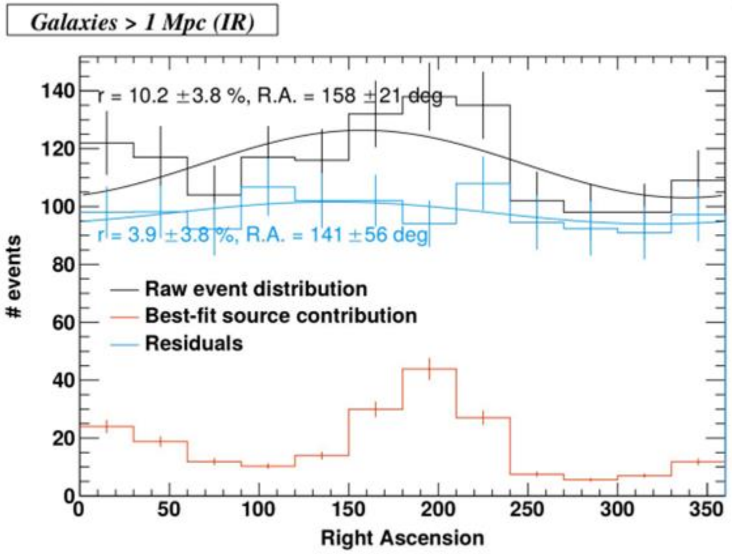


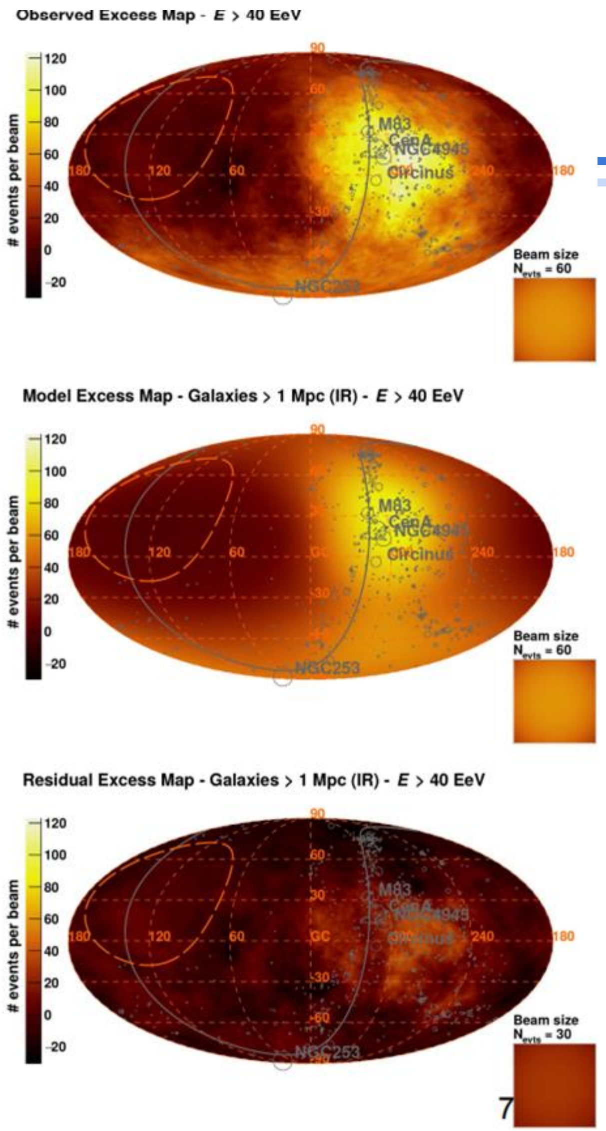
Note: 2MRS dipole at R.A. ~ 155°

Courtesy of J. Biteau

All Galaxies model (EPO1st)







Note: 2MRS dipole at R.A. ~ 155°

Courtesy of J. Biteau

Summary

amplitude	**Intermediate-scale signal, α**	**Large-scale R.A. residual modulation, r**
SBG	9%	7%
All Galaxies	15%	4%
Jetted AGN	6%	6%
All AGNs	8%	6%
typical uncertainty	± 5%	± 4%

pros/cons	**Intermediate-scale signal, α**	**Large-scale R.A. residual modulation, r**
SBG	Best match (TS~25)	Inferior match (r=0 within 1.5-2σ) Compatible with 2MRS
All Galaxies	Inferior match (TS~18) due to Virgo excess	Best match (r=0 within 1σ)
Jetted AGN	Inferior match (TS~17) due tepid spot deficit	Inferior match (r=0 within 1.5) Incompatible with 2MRS
All AGNs	Inferior match (TS~19) due tepid spot deficit	Inferior match (r=0 within 1.5) Compatible with 2MRS

Likelihood test for anisotropy with astrophysical catalogs

We expect that **brighter** objects contribute more to the flux, and we want to take into account **interaction**:

➤ **Likelihood Method** (for details see The Pierre Auger Collaboration - ApJL, 853:L29 (2018))

Probability maps built including:

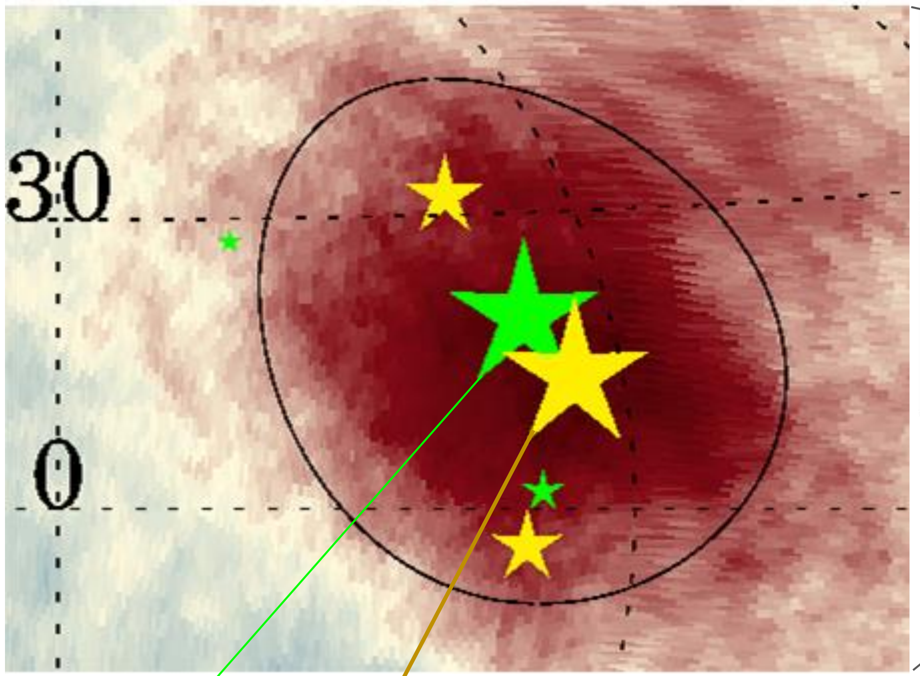
- Weight objects by their relative flux in the corresponding electromagnetic wavelength
- Different attenuation due to different distances to sources taken into account
- A smearing angle θ around each object to take into account magnetic deflections ➤ **First free parameter**
- Source fraction (rest isotropic) ➤ **Second free parameter (f_{aniso})**
- Directional exposure normalized to the total number of events

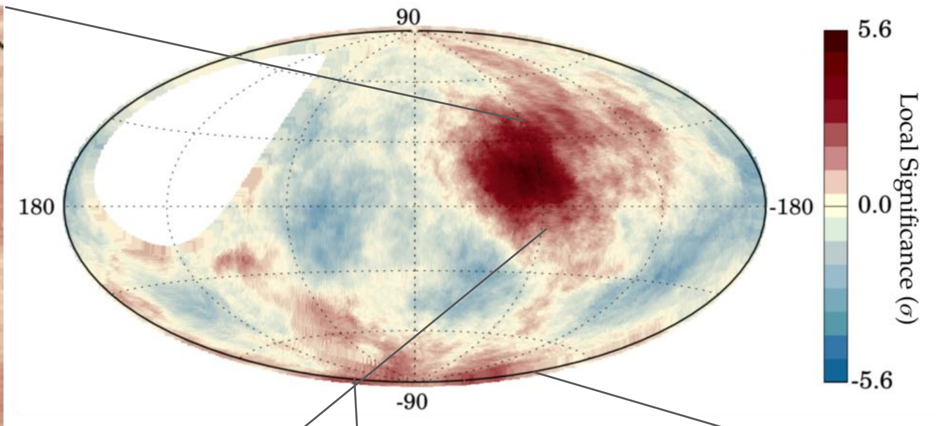
Test statistic defined as the ratio of likelihoods: $TS = 2 \text{ Log} [\mathscr{L}(\psi, f_{aniso})/\mathscr{L}(f_{aniso} = 0)]$

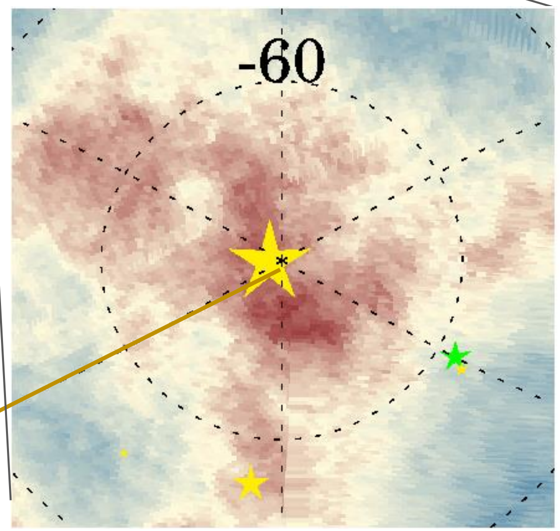
Scan in energy thresholds **32 EeV $\leq$ Eth $\leq$ 80 EeV [1 EeV steps]**

Test 4 different catalogs

Discussion







Cen A

Most contributing source to 2MRS, γ-AGNs and Swift-BAT

NGC 4945

Most contributing source to starburst

NGC 253

2nd-most contributing source to starburst

Model Excess Map