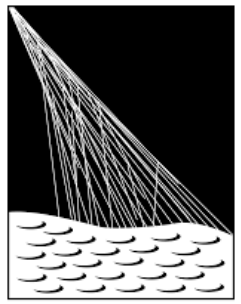
ICRC 2019 - Madison, USA

Anisotropies of the highest energy cosmic-ray events recorded by the Pierre Auger Observatory in 15 years of operation

Lorenzo Caccianiga for the Pierre Auger Collaboration



PIERRE
AUGER
OBSERVATORY

Introduction

Aim:

study the arrival directions of the **highest energy cosmic rays (E>32 EeV)**, above the observed cutoff, at **small and intermediate scale (≤30°)**

Previous results:

- excess when looking at events with E ≥58 EeV within 15° from the position of **Centaurus A**

➤ ~3 σ post-trial significance (Ugo Giaccari for the Pierre Auger Collaboration - ICRC 2017)*

- indication of anisotropy in the UHECRs sky at E ≥39 EeV when comparing with the position of **Starburst Galaxies**

➤ ~4 σ post-trial significance (The Pierre Auger Collaboration - ApJL, 853:L29 (2018))

➤ Update these results with the largest dataset of events above the flux suppression ever produced (nearly 15 years)

* scan performed in the 40-80 EeV range

The dataset

- Largest dataset so far of events above the observed flux suppression
- Events measured by the **Surface Detector** of Auger, reconstructed **Energy ≥32 EeV**
- From the **1st of January 2004** to the **31st of August 2018**
- Two different sets of events each with its proper **selection** and **reconstruction**:
  - **1672 'Vertical'** events: zenith angle ≤60°.
    Selected when the station with the highest signal is surrounded by at least 4 active stations and the core falls in an equilateral or isosceles triangle of active stations
  - **485 'Inclined'** events: 60°< zenith angle ≤ 80°
    Selected when the station with the highest signal is surrounded by at least 5 active stations
- Total **exposure: 101,400 km^2 sr yr**
- **Total number of events: 2157**

For more details about the two different reconstructions, see Valerio Verzi's talk - CRI7e PoS(ICRC2019)450

Search for overdensites

Blind search - whole sky 1°x 1° grid

Scan:

$1° \leq \psi \leq 30°$

$32\ \text{EeV} \leq E_{th} \leq 80\ \text{EeV}$

Most significant excess:

R.A.=202. Dec=-45.

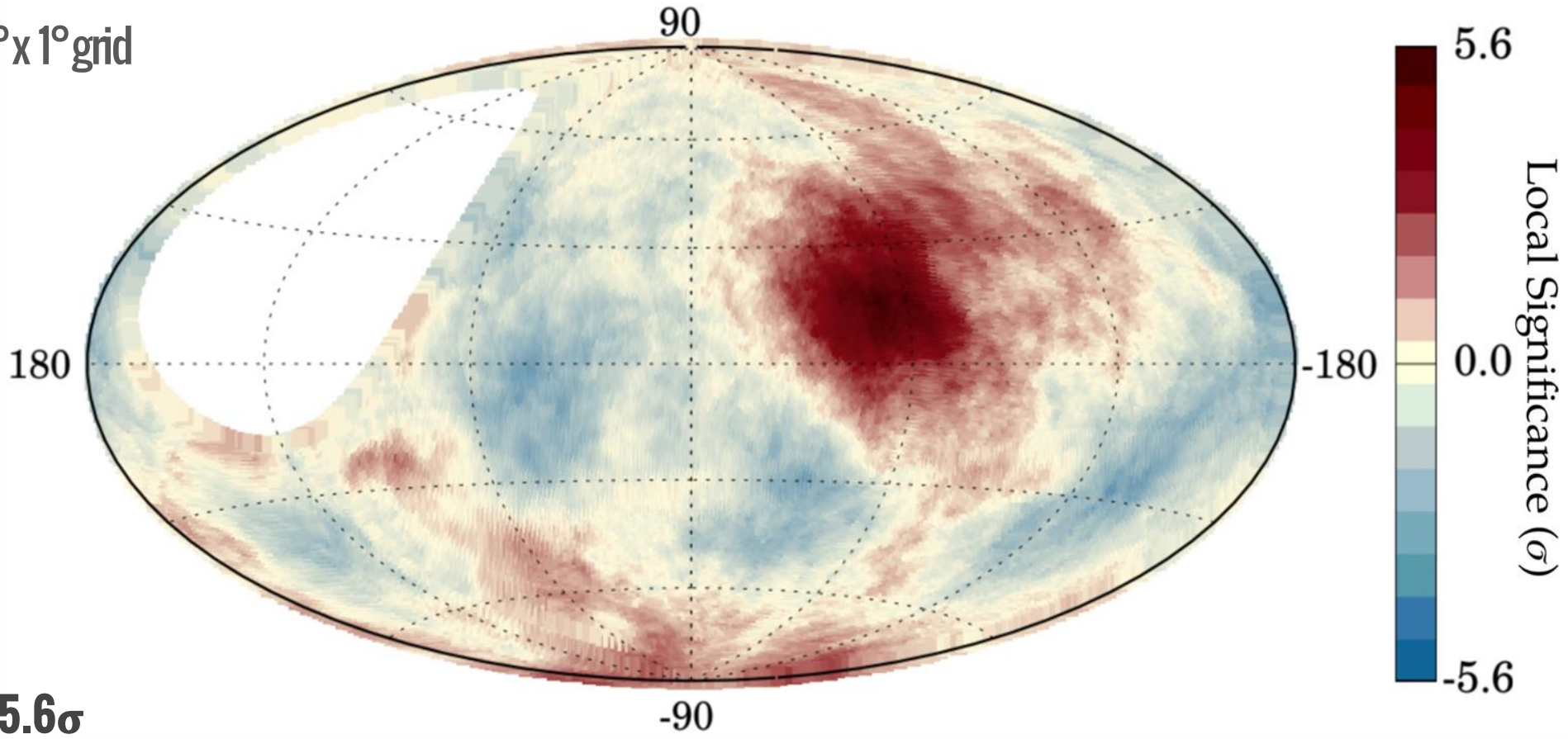
$E_{th} = 38\ \text{EeV}$

$\psi = 27°$

$n_{obs} = 188 \quad n_{exp} = 125$

local Li-Ma significance=5.6σ

post-trial p-value=2.5%



See also **Armando di Matteo**'s talk CRI11b-PoS(ICRC2019)439 for a **whole-sky** search using **Auger** and **TA**

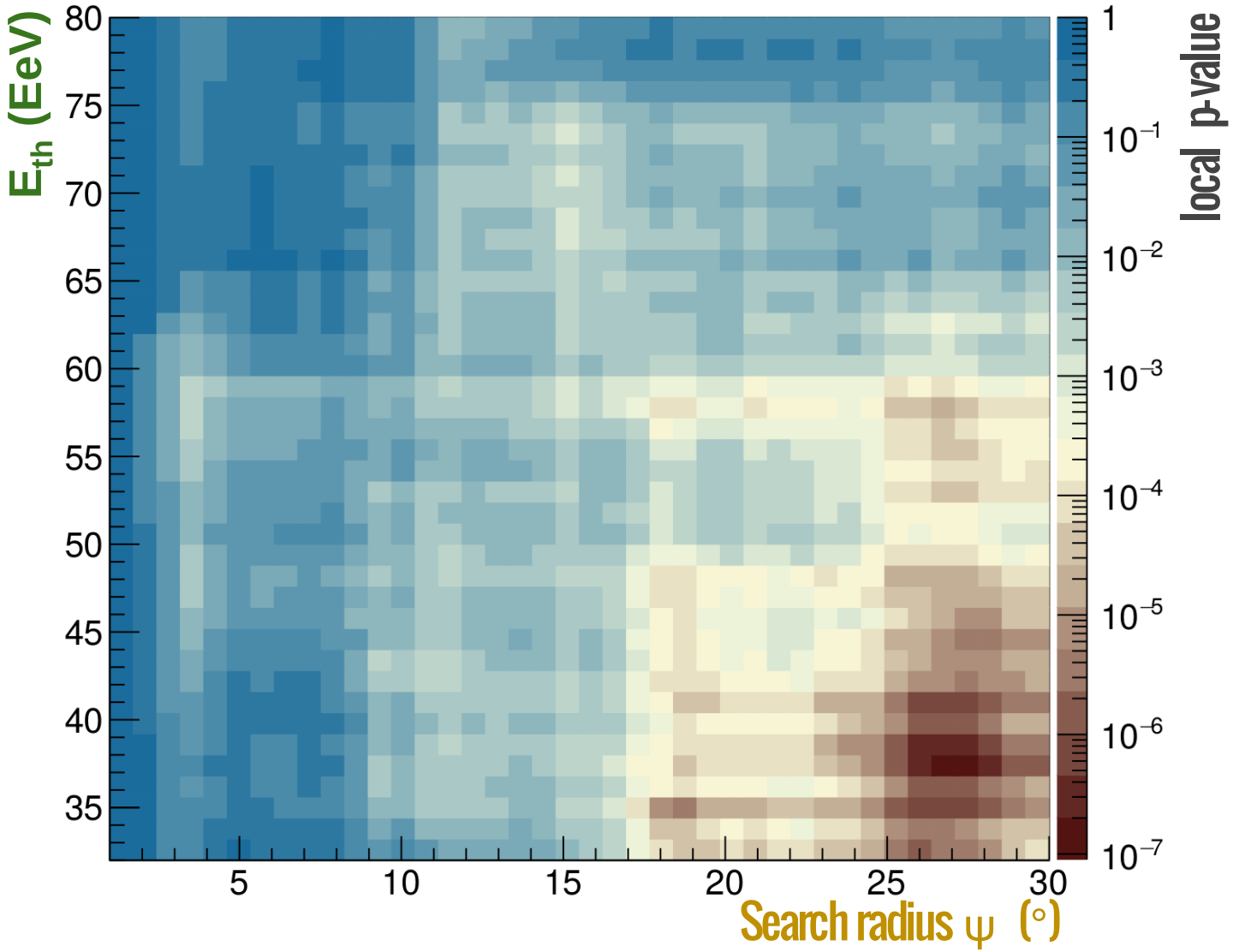
Note: the Auger dataset used here covers a wider time and energy range than the one used in the combined analysis

The Centaurus A region

Cen A is the closest radiogalaxy
D~3.6 Mpc

Scan:
$1° \leq \psi \leq 30°$
$32\ \text{EeV} \leq E_{th} \leq 80\ \text{EeV}$

Most significant excess:
$E_{th} = 37$ EeV
$\psi = 28°$
$n_{obs} = 203 \quad n_{exp} = 141$
local p-value=1.5×10^{-7}
post-trial : 3.9σ



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**

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 **$32 \text{ EeV} \leq \text{Eth} \leq 80 \text{ EeV}$ [1 EeV steps]**

Test 4 different catalogs

Likelihood test for anisotropy with astrophysical catalogs

γ-emitting AGNs

- Selected using Fermi 3FHL (was 2FHL)
- UHECR flux proxy: Φ(E>10 GeV)
- 33 sources (including Cen A, Fornax A, M87, Mkn421)
- Majority blazars of BL-Lac type and radio-galaxies of FR-I type

Starburst Galaxies

- UHECR flux proxy Φ(1.4 Ghz)
- Selection based on *Ackermann+ 12* and *Becker+ 09*, with the addition of data from HEASARC Radio Master Catalog
- 32 sources (including Circinus, M82 M83…)

Swift-BAT

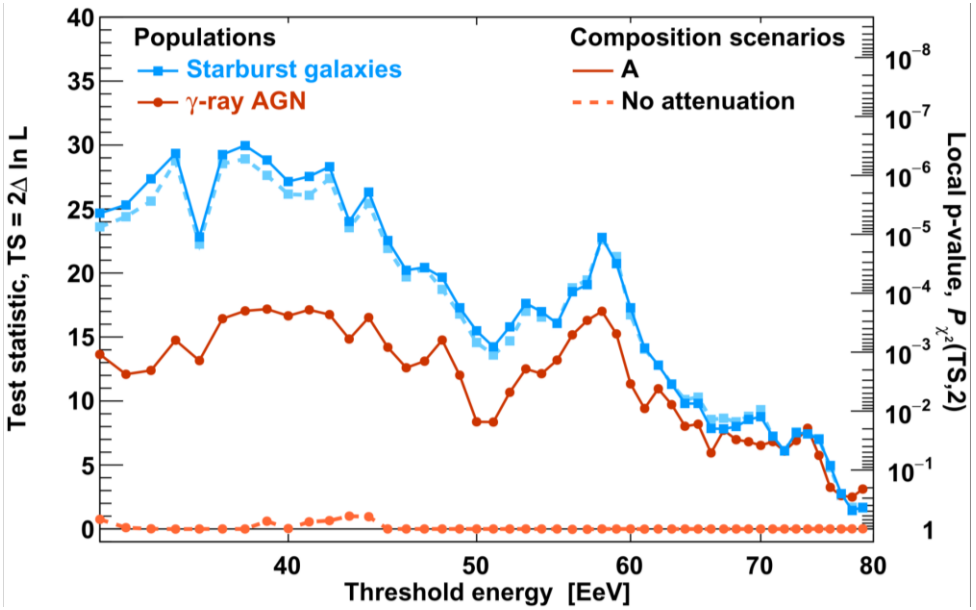
- UHECR flux proxy: Φ(14-195 keV)
- Different AGN sample than previous one (both radio loud and quiet)
- >300 sources

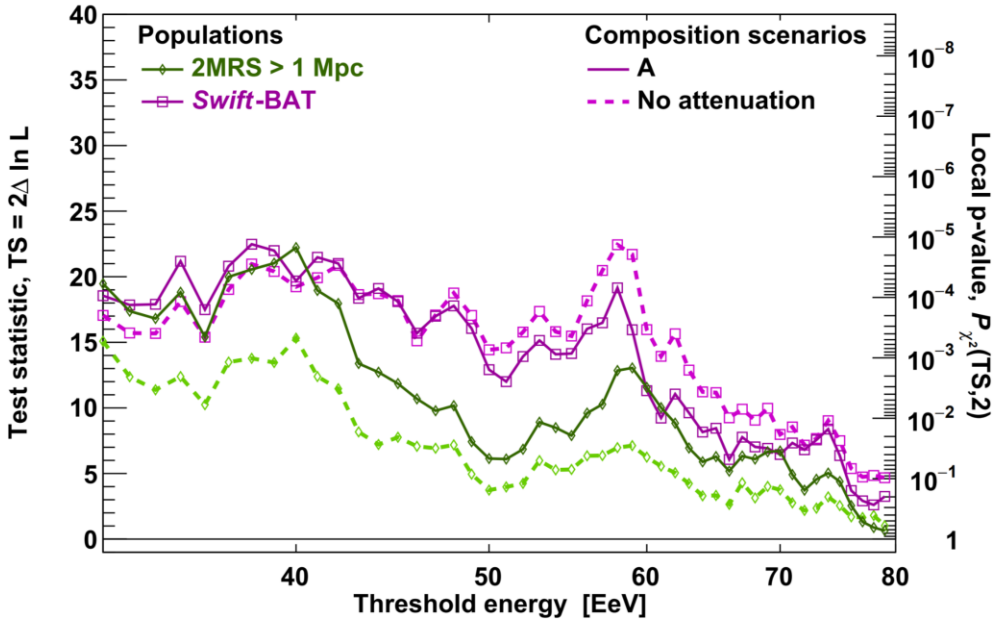
2MRS

- UHECR flux proxy Φ(k-band)
- Traces local matter (some 10^4 sources)
- Local group taken away by selecting only events with D>1Mpc

More details about catalog selection in ApJL, 853:L29 (2018)

Likelihood test for anisotropy with astrophysical catalogs





Catalog	E_{th}	θ	f_{aniso}	TS	Post-trial
Starburst	38 EeV	$15^{+5}_{-4}°$	$11^{+5}_{-4}\%$	29.5	$4.5\,\sigma$
γ-AGNs	39 EeV	$14^{+6}_{-4}°$	$6^{+4}_{-3}\%$	17.8	$3.1\,\sigma$
Swift-Bat	38 EeV	$15^{+6}_{-4}°$	$8^{+4}_{-3}\%$	22.2	$3.7\,\sigma$
2MRS	40 EeV	$15^{+7}_{-4}°$	$19^{+10}_{-7}\%$	22.0	$3.7\,\sigma$

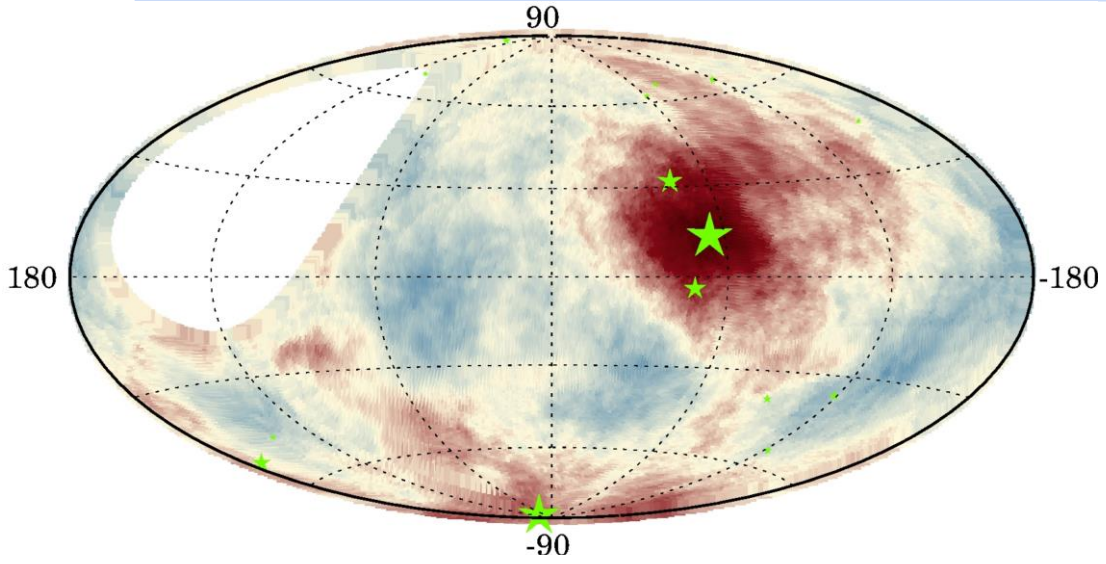
Highest TS = 29.5 found for starburst galaxies with E_{th}=38 EeV

All the most significant excesses happen at similar E_{th} and angular scale

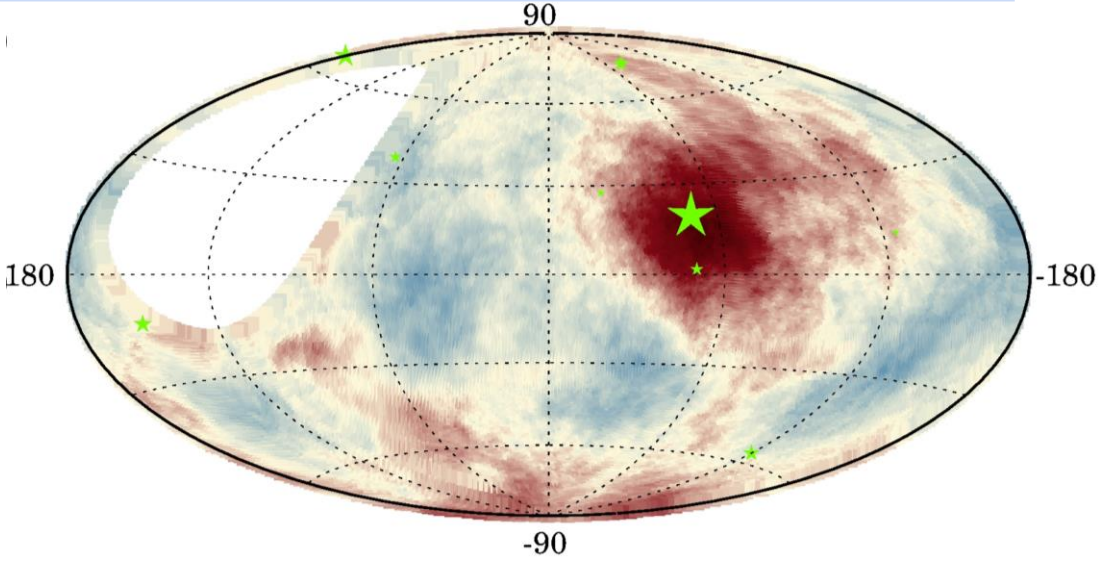
Note: 15° smeared Fisher-Von Misses distribution ~1.59×15°=24±8° top-hat

Discussion

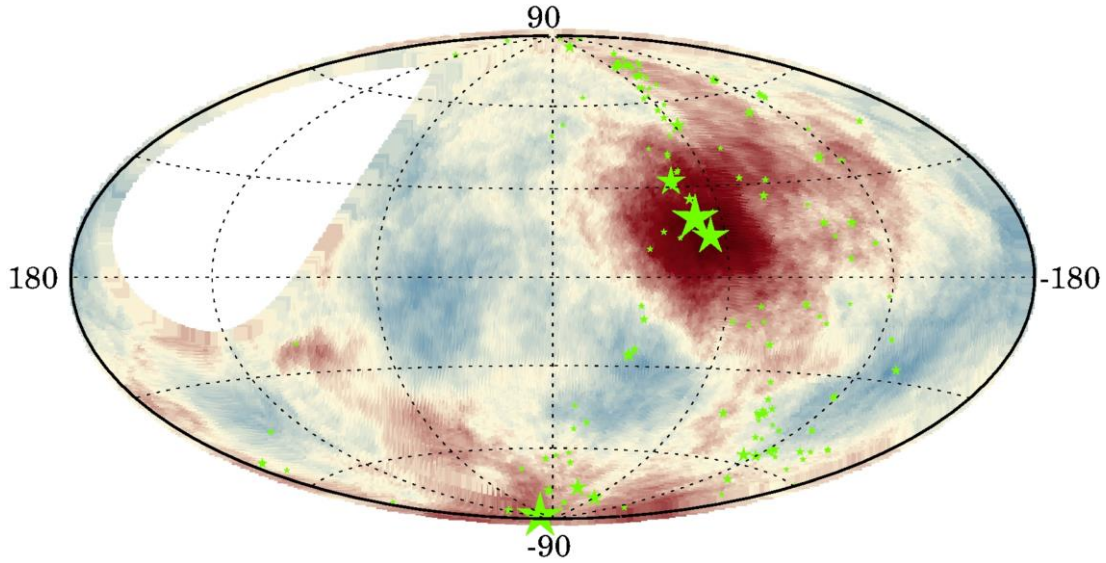
Starburst Galaxies



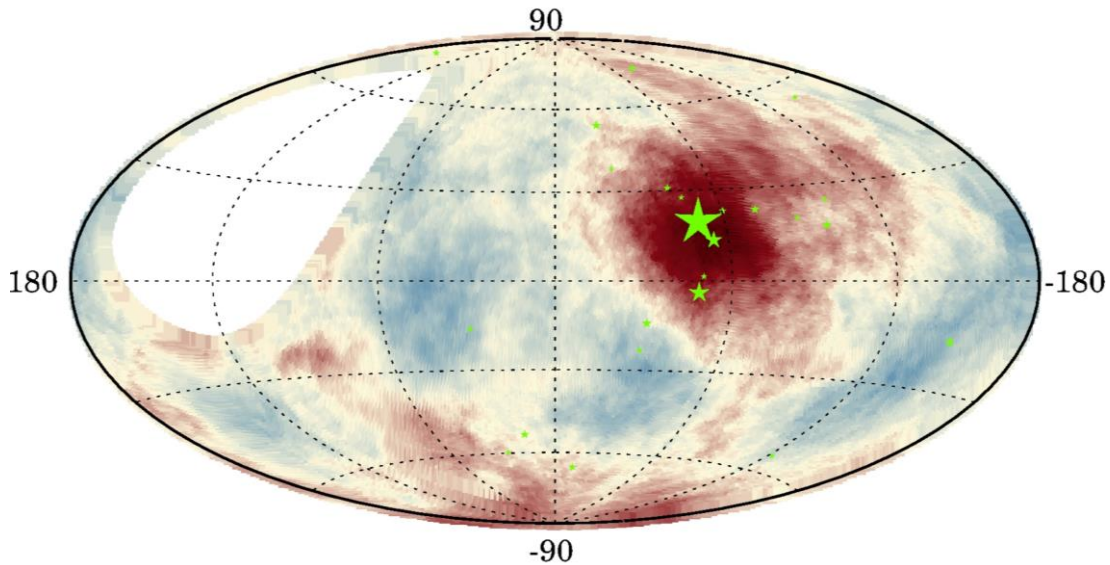
γ-emitting AGNs



2MRS



Swift-BAT



Conclusions and outlook

Update of the two most significant results of previous analyses with new data:

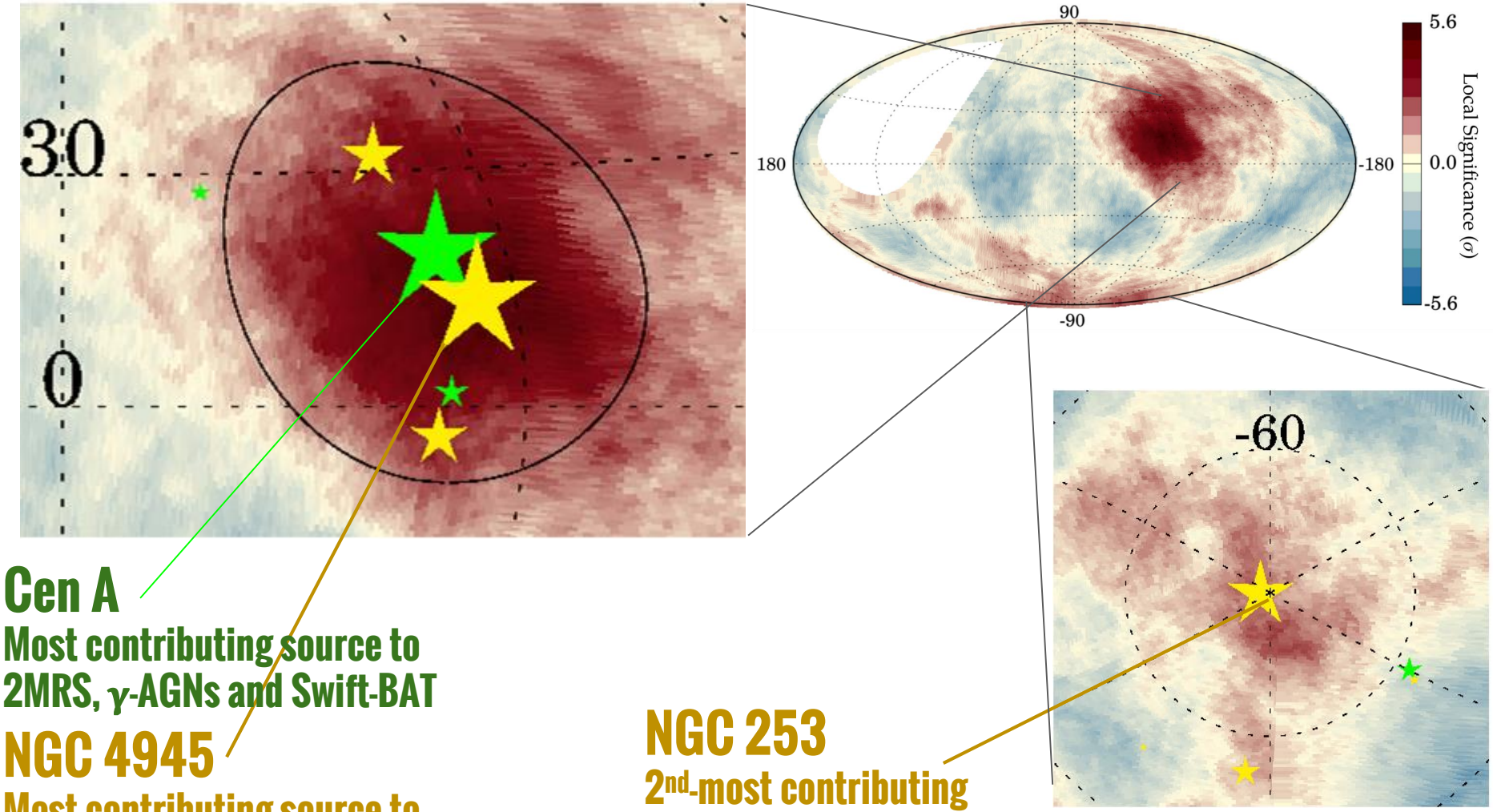
- **Centaurus A**: most significant excess at E_{th}=37 EeV ψ= 28°
  3.9 σ post-trial significance
- **Starburst Galaxies**: best rejection of pure isotropic hypothesis at
  E_{th} = 38 EeV f_{aniso}= 11% θ= 15° 4.5 σ post-trial significance
- The region around the most significant excess is populated by a number of highly contributing candidate sources in the considered catalogs
- **Note**: in penalized p-values only the clearly accountable trials (scans) are taken into account. There is no rigorous way of taking into account the penalization due to other searches performed within the Auger Collaboration and outside

We look forward to increasing our dataset even more and see if the significance continues to grow, as expected if what we see is a real signal and not a fluctuation

Data from **Auger Prime** will help anisotropy studies in the next years

Backup slides

Discussion

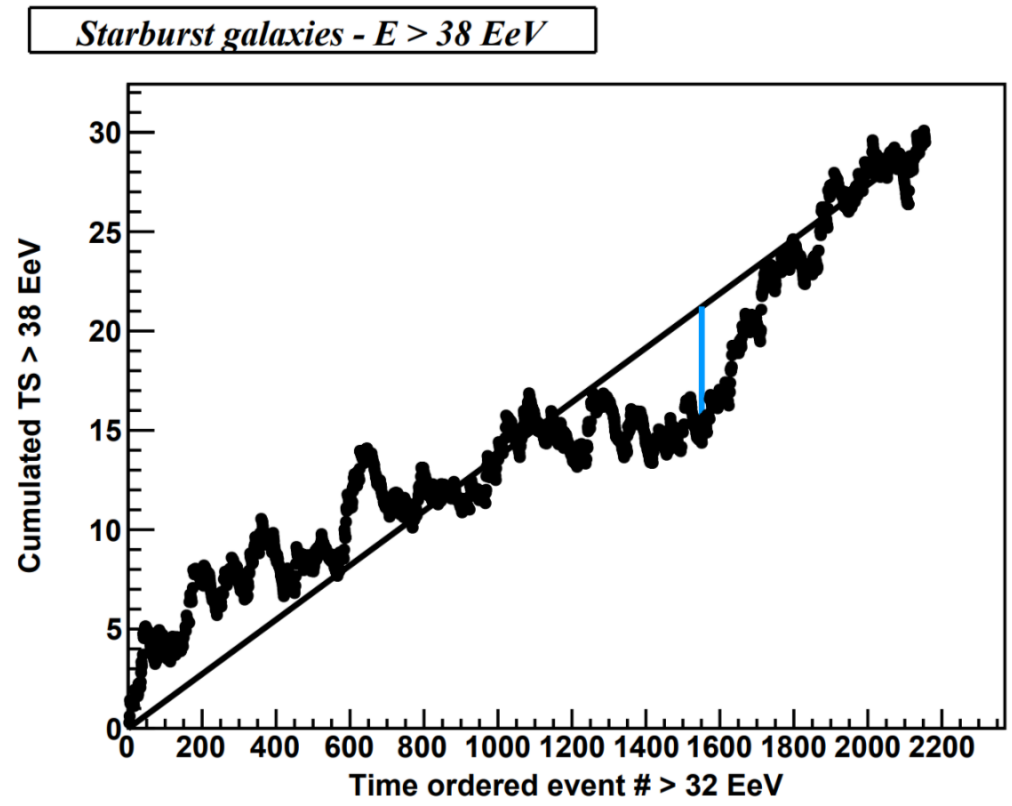


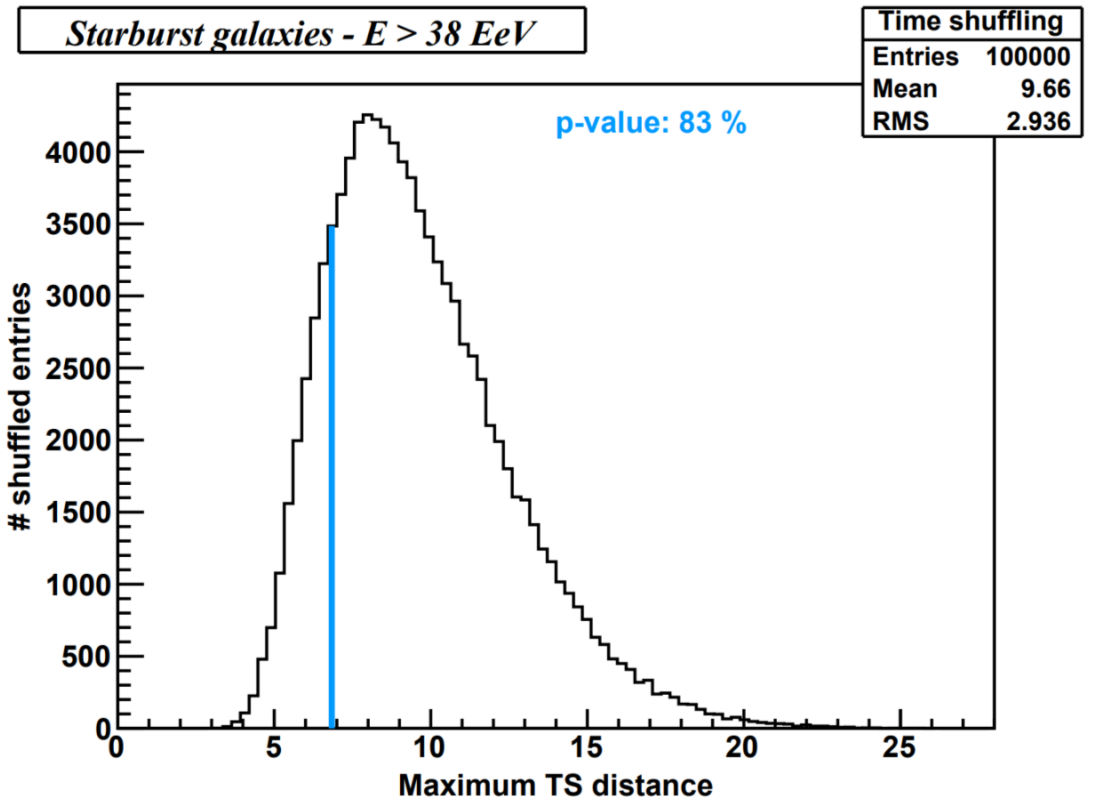
Cen A
Most contributing source to 2MRS, γ-AGNs and Swift-BAT

NGC 4945
Most contributing source to starburst

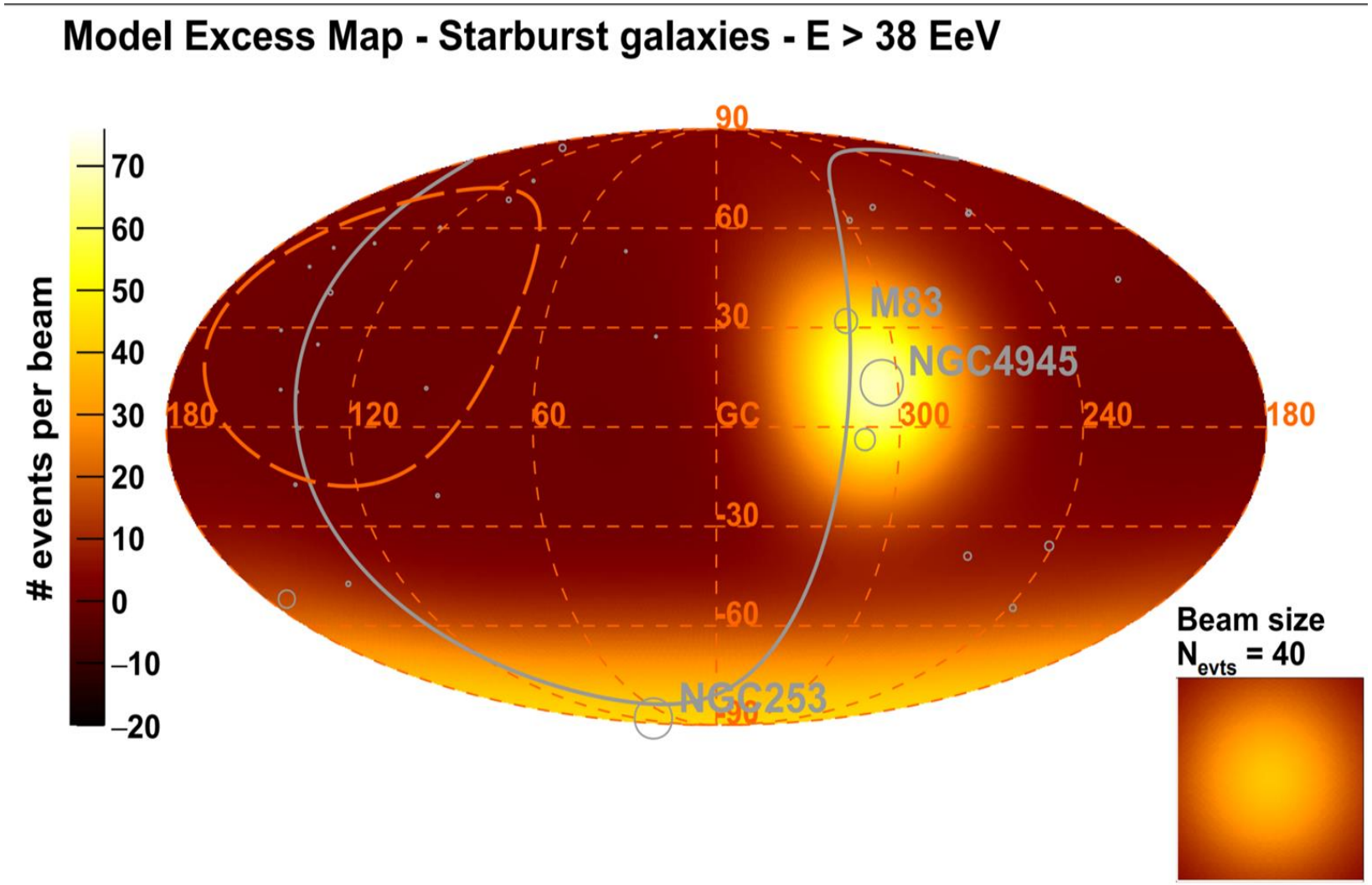
NGC 253
2nd-most contributing source to starburst

Evolution in time

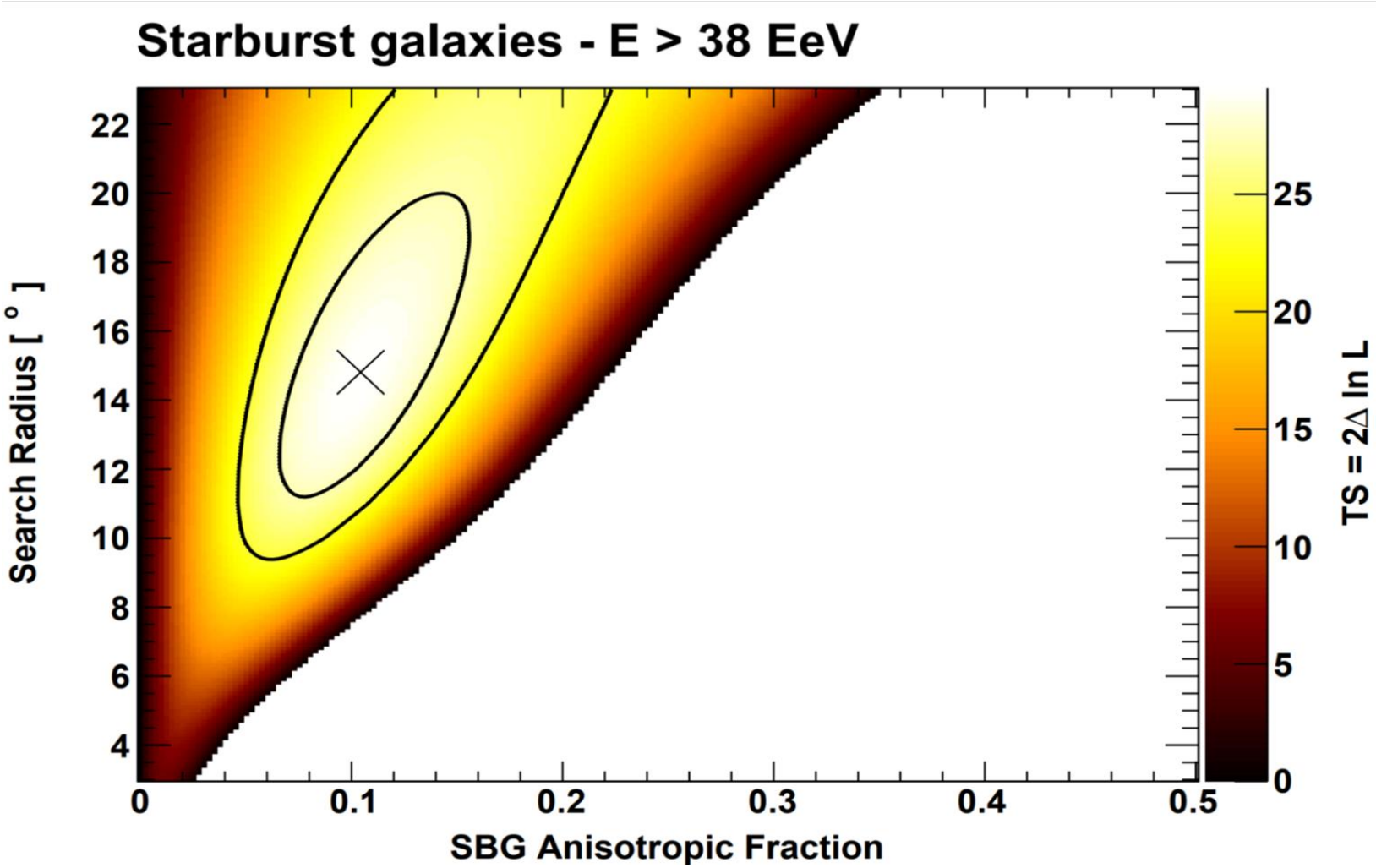




Model Excess Map



Parameter space



Sources most contributing to the likelihood analysis

Starburst Galaxies

Src	l	b	excess-weight
NGC4945	305.27	13.34	100.0%
NGC253	97.36	-87.97	77.7%
M83	314.58	31.97	27.7%
Circinus	311.33	-3.81	22.4%
NGC1068	172.10	-51.93	14.8%
NGC1808	241.21	-35.90	3.8%
NGC1672	268.78	-38.99	2.8%
NGC4631	142.81	84.22	2.2%
NGC1365	237.96	-54.60	2.1%
NGC4666	299.54	62.37	1.3%
M61	284.37	66.28	1.3%
NGC3627	241.96	64.42	1.3%
NGC2903	208.71	44.54	1.2%
M51	104.85	68.56	1.1%
NGC660	141.61	-47.35	1.1%
NGC3628	240.85	64.78	1.1%

γ-emitting AGNs

Src	l	b	excess-weight
CenA	309.52	19.42	100.0%
Mkn421	179.83	65.03	22.6%
NGC1275	150.58	-13.26	14.2%
FornaxA	240.16	-56.69	11.0%
M87	283.78	74.49	11.0%
CenB	309.72	1.73	7.3%
Mkn501	63.60	38.86	5.7%
APLibrae	340.68	27.58	2.3%
PMNJ0816-1311	234.80	12.12	1.6%

Swift-BAT

Src	l	b	excess-weight
CenA	309.52	19.42	100.0%
Circinus	311.33	-3.81	18.0%
NGC4945	305.27	13.34	12.9%
NGC2110	212.93	-16.55	3.8%
NGC6300	328.49	-14.05	3.3%
NGC5506	339.15	53.81	3.2%
MCG-05-23-016	262.74	17.23	3.0%
NGC7172	15.13	-53.07	2.5%
NGC3783	287.46	22.95	2.5%
NGC4507	299.64	22.86	2.1%
IC4329A	317.50	30.92	2.1%
NGC4388	279.12	74.34	2.1%
NGC7582	348.08	-65.70	1.9%
NGC4151	155.08	75.06	1.8%
ESO103-035	329.78	-23.18	1.4%
NGC1365	237.96	-54.60	1.4%
NGC6814	29.35	-16.01	1.3%
4U1344-60	309.77	1.51	1.3%
NGC3081	259.02	25.03	1.2%
NGC7314	27.14	-59.74	1.1%
NGC3227	216.99	55.45	1.1%
NGC3281	273.01	19.78	1.1%
NGC5728	337.32	38.10	1.1%
MCG-06-30-015	313.29	27.68	1.0%

Scenario A for attenuation

Mass composition model following best fit in JCAP 04 (2017) 38:

EPOS-LHC

γ = 1

log10(Rcut/V) = 18.68

fH (%)= 0

fHe (%) = 67.3

fN (%) = 28.1

fSi (%) = 4.6

fFe (%) = 0

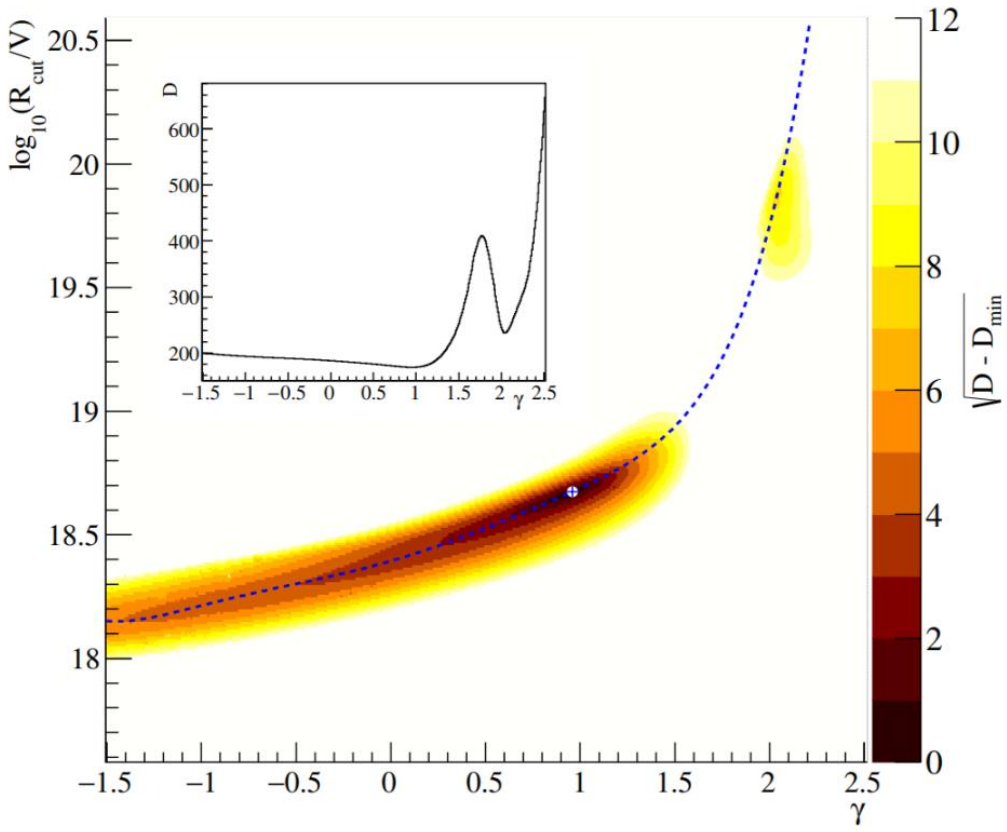


Figure 1. Deviance $\sqrt{D - D_{\rm min}}$, as function of γ and $\log_{10}(R_{\rm cut}/{\rm V})$. The dot indicates the position of the best minimum, while the dashed line connects the relative minima of D (valley line). In the inset, the distribution of $D_{\rm min}$ in function of γ along this line.