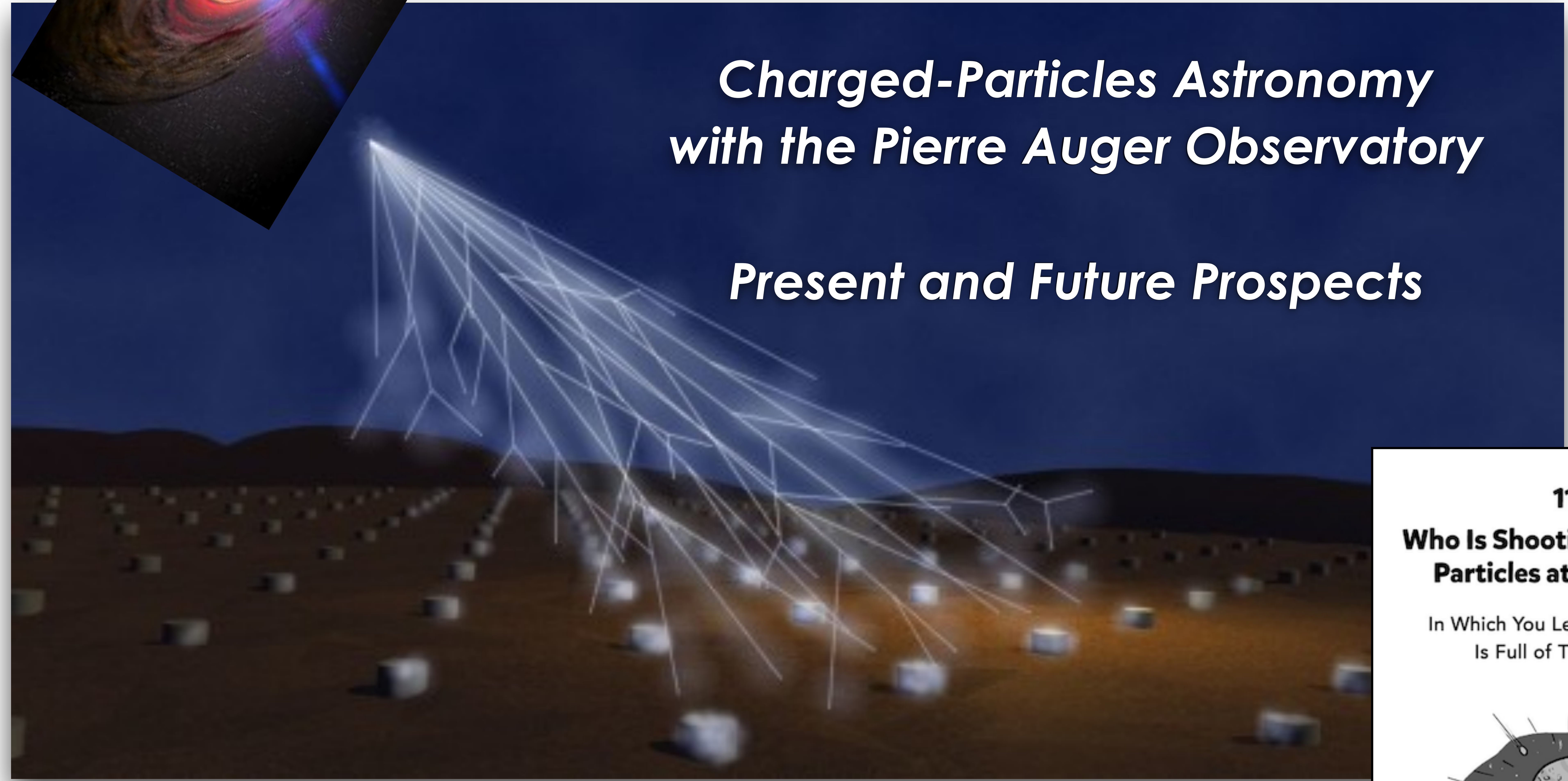


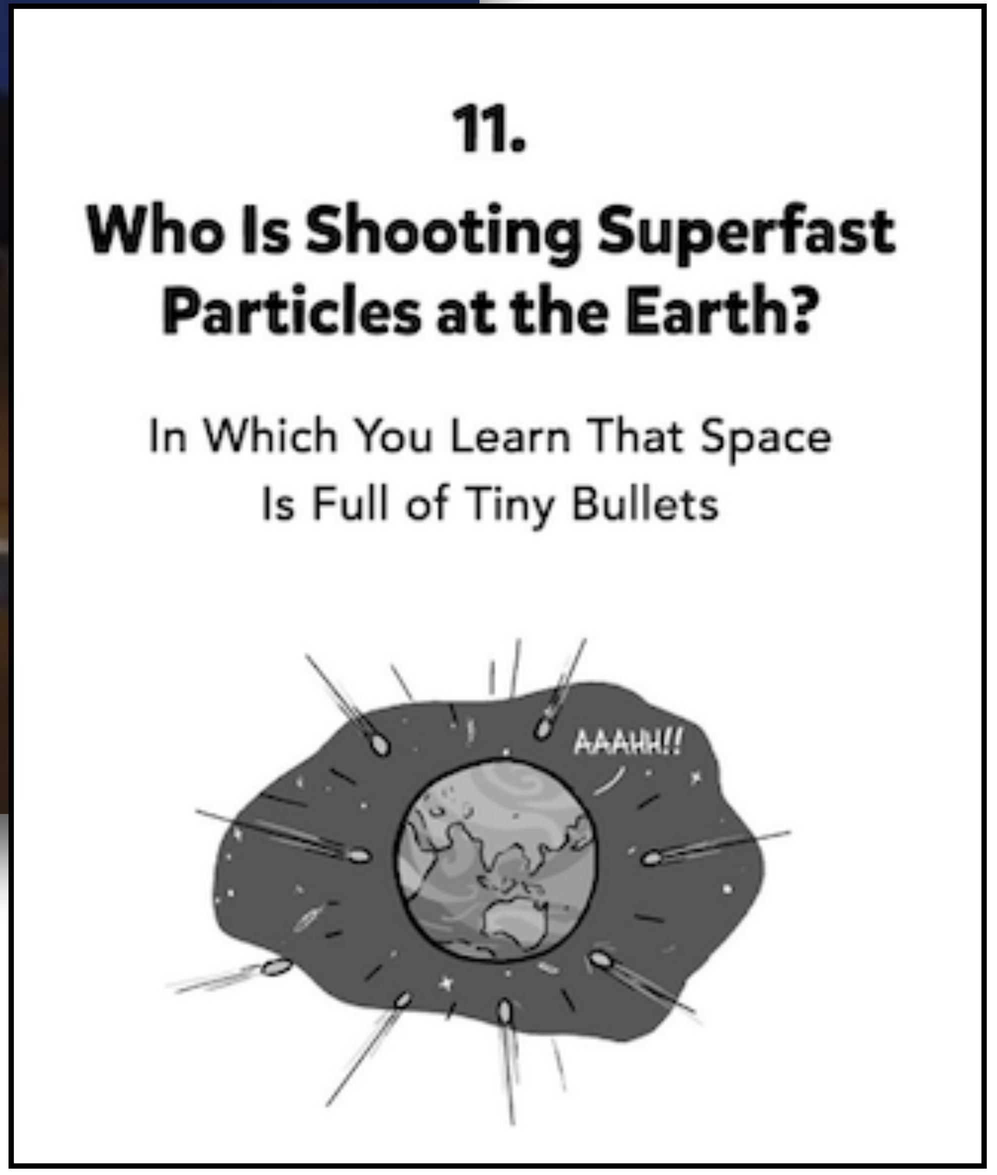
Charged-Particles Astronomy with the Pierre Auger Observatory

Present and Future Prospects

Ugo Giaccari

INFN Lecce

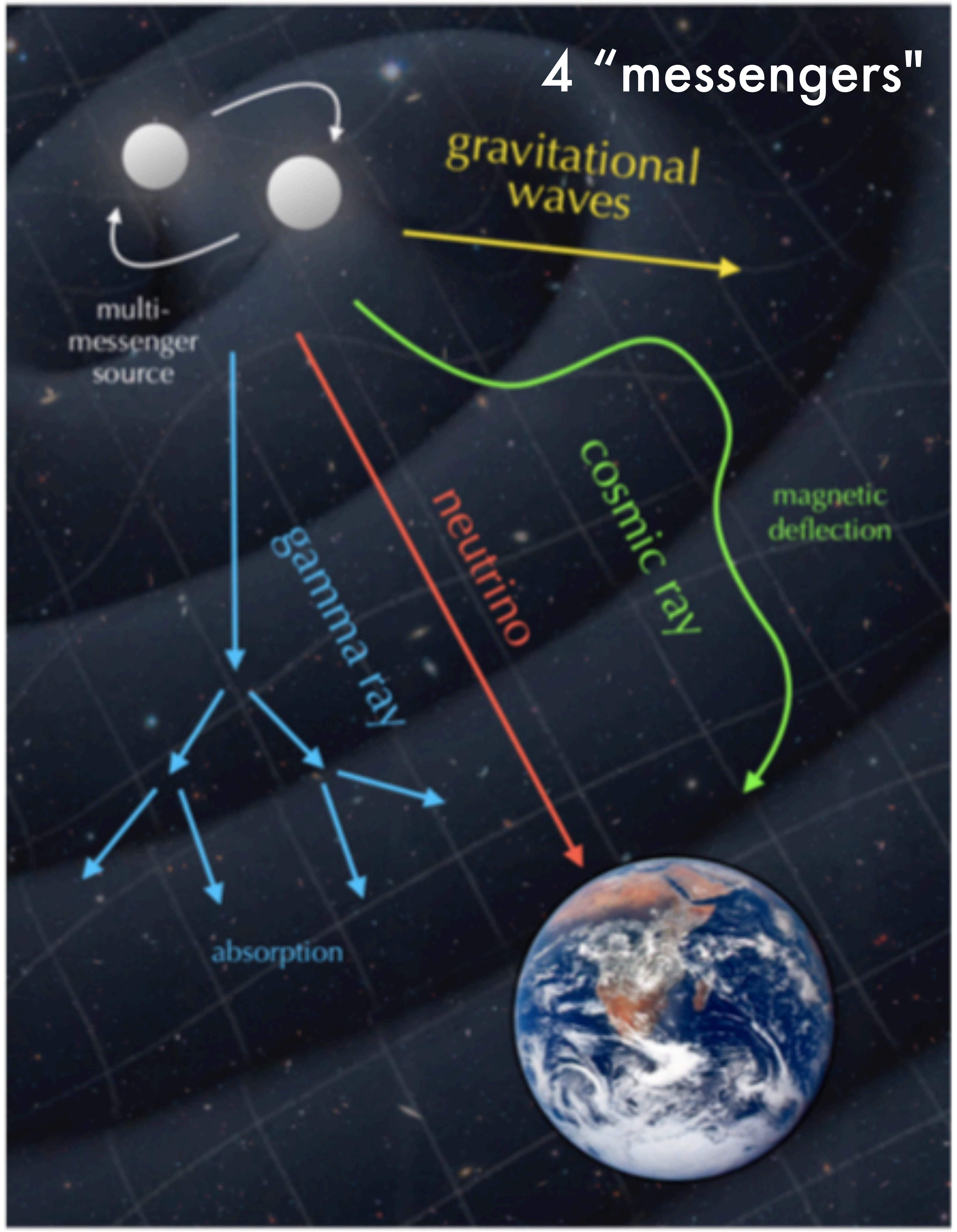
Multi-messengers program Jan 2024



http://phdcomics.com/noidea

PIERRE AUGER OBSERVATORY

Messengers for the Extreme Universe



Three messengers are tied together

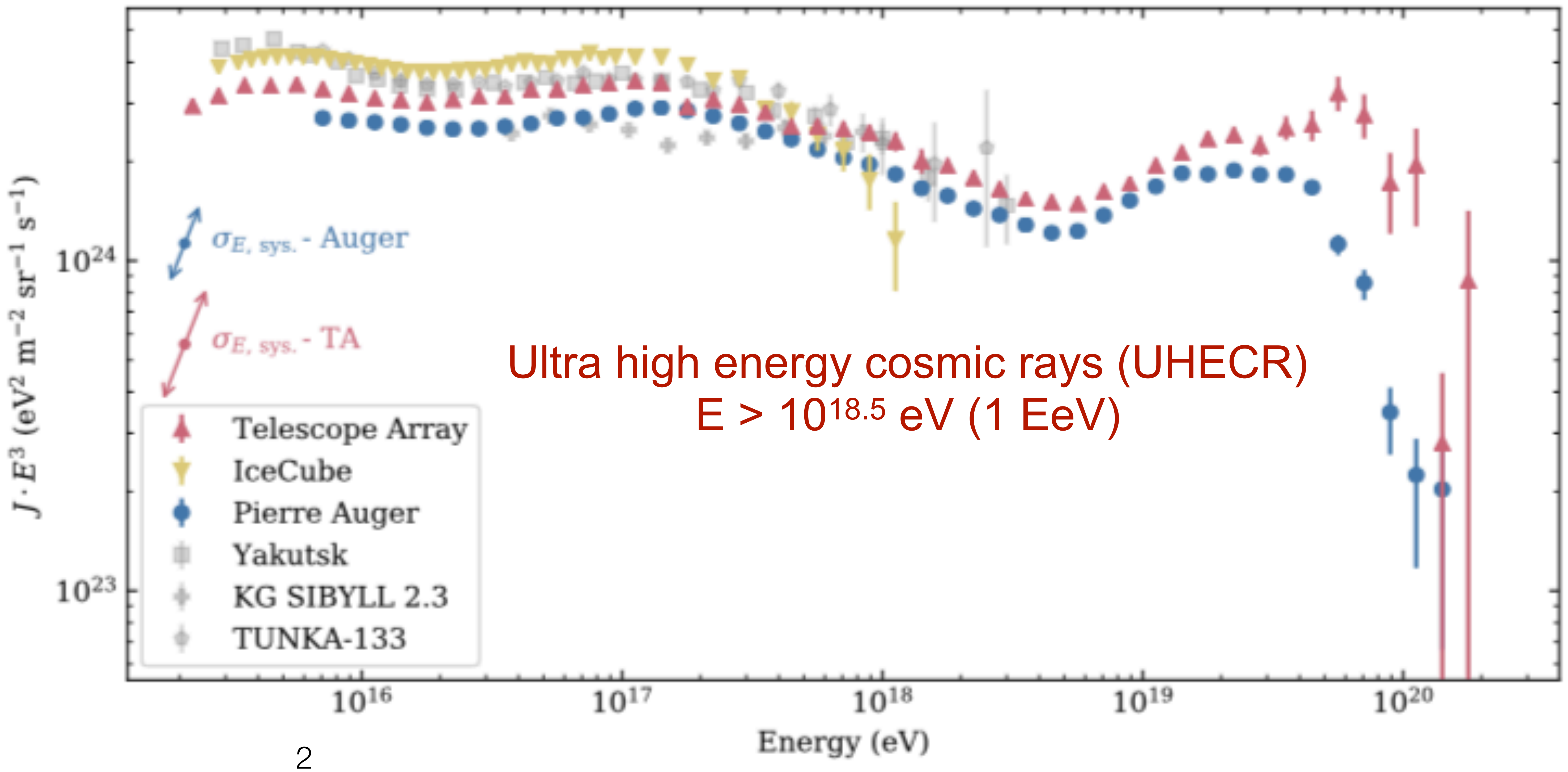
$$p + X \rightarrow \pi^+ \; \pi^- \; \pi^\circ \; ..$$

$$\pi^\circ \rightarrow \gamma \; \gamma$$

$$\pi^+ \rightarrow \mu^+ \; \nu_\mu$$

$$\hookrightarrow \; e^+ \; \nu_e \; \overline{\nu}_\mu$$

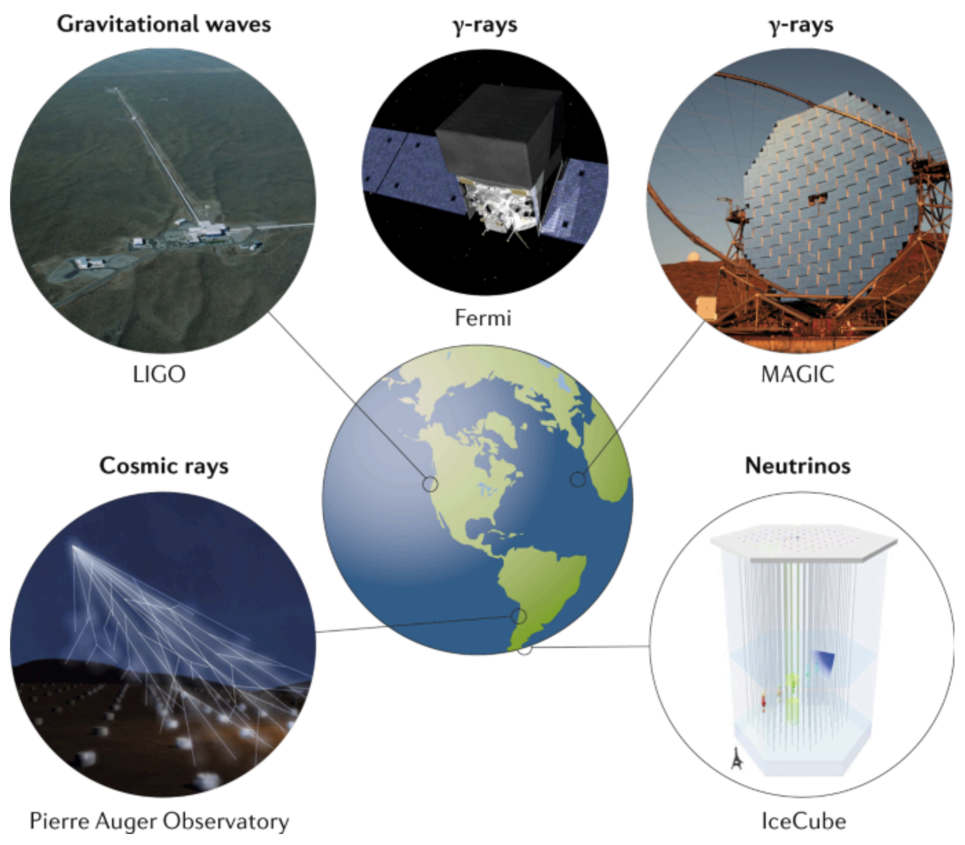
Cosmic-ray (protons or atomic nuclei)



2

ASTRONOMY NOT BASED ON THE ELECTROMAGNETIC SPECTRUM

- Gravitational-wave astronomy
- Neutrino astronomy
- Charged-particle astronomy



Multi-messenger astronomy

The pieces for charged-particles astronomy

Ballistic regime (magnetic deflection)

$$Rigidity\ R = \frac{E}{Z} \qquad R > 20 \times 10^{18} V$$

above ~30 EeV: deflections few degrees

Local Universe accessible

$$1\ Gpc \sim 10^{19} eV$$

$$100/200\ Mpc \sim 3 \times 10^{19} eV$$

Sites of acceleration

Active Galactic Nuclei, gamma-ray bust and energetic supernovae , star-forming galaxies, Galaxies clusters, pulsars….

Inhomogeneities in their spatial distribution

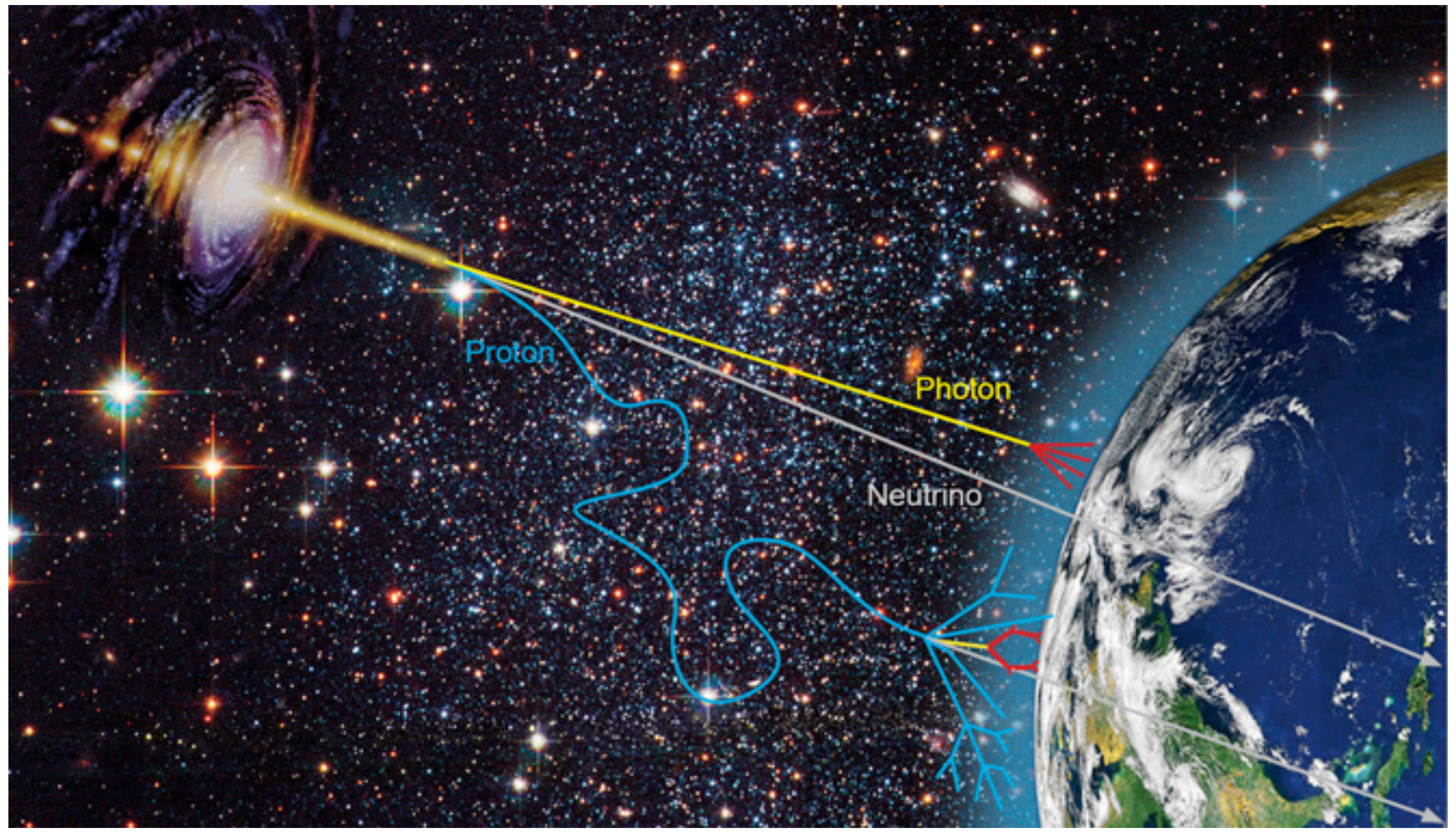
detection (> 5σ) of an charged-particle flux excess in the direction of a (few) prominent nearby source(s)

↓

Charged-particles astronomy

CHARGED-PARTICLE vs. NEUTRINO ASTRONOMY

Pros and Cons of a single messenger



Neutrinos

+ **not deflected by cosmic magnetic fields**

- **Angular resolution 1 deg** (at the best)

  Universe transparent for ν's

  (produced over cosmological distance)

- **Background** (atmospheric ν's)

Charged-particles at $E > 3 \times 10^{19}$ eV

— **deflected by cosmic B**

  (10 degree over 100 Mpc)

+ **Angular resolution 1 deg** (always)

  produced in the Local Universe

- **No background**

Despite routine detections of cosmic neutrinos

perform astronomy of a distance object with neutrinos is still an open issue

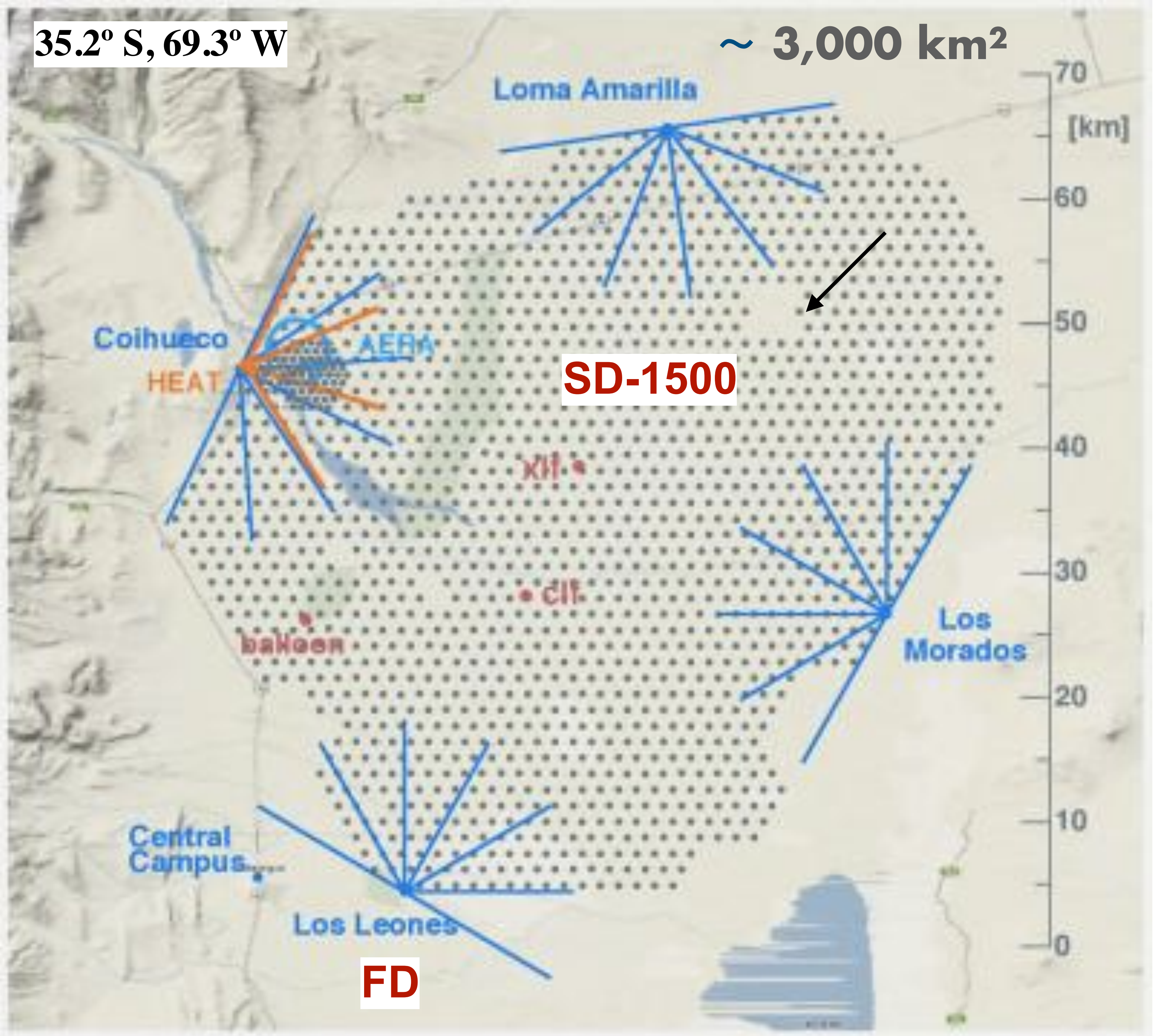
(like charged-particle astronomy)

The Observatory and the data set

From Surface Detector data ≈ 100% duty cycle (larger statistics), simpler exposure

Surface Detector: 1660 water-Cherenkov detectors (WCDs) on a triangular grid

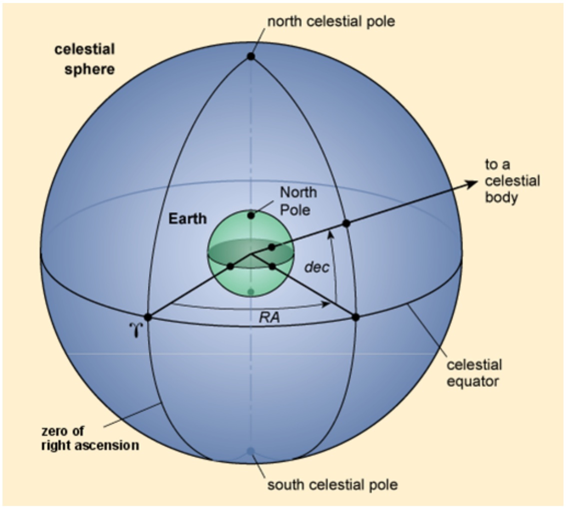
- ► **SD-1500: spacing 1500 m**
  - 1500 m vertical reconstruction (0º ≤ θ < 60º), full efficiency E ≥ 2.5 EeV
  - 1500 m inclined reconstruction (60º ≤ θ ≤ 80º), full efficiency E ≥ 4 EeV
- ► **Fluorescence Detector (FD)** → 27 telescopes in four buildings



- Small scale anisotropies above 32 EeV → SD-1500 vertical + inclined events (up to the end 2020), **≈ 122,000 km² sr yr**,
- **sky coverage ≈ 85%**

WATER CHERENKOV DETECTOR

Equatorial coordinates



more than 2,600 events above 32 EeV

The largest available dataset of ultra-high-energy cosmic rays above 32 EeV!

Angular resolution: ≈ 1˚. Energy resolution ≈ 7%

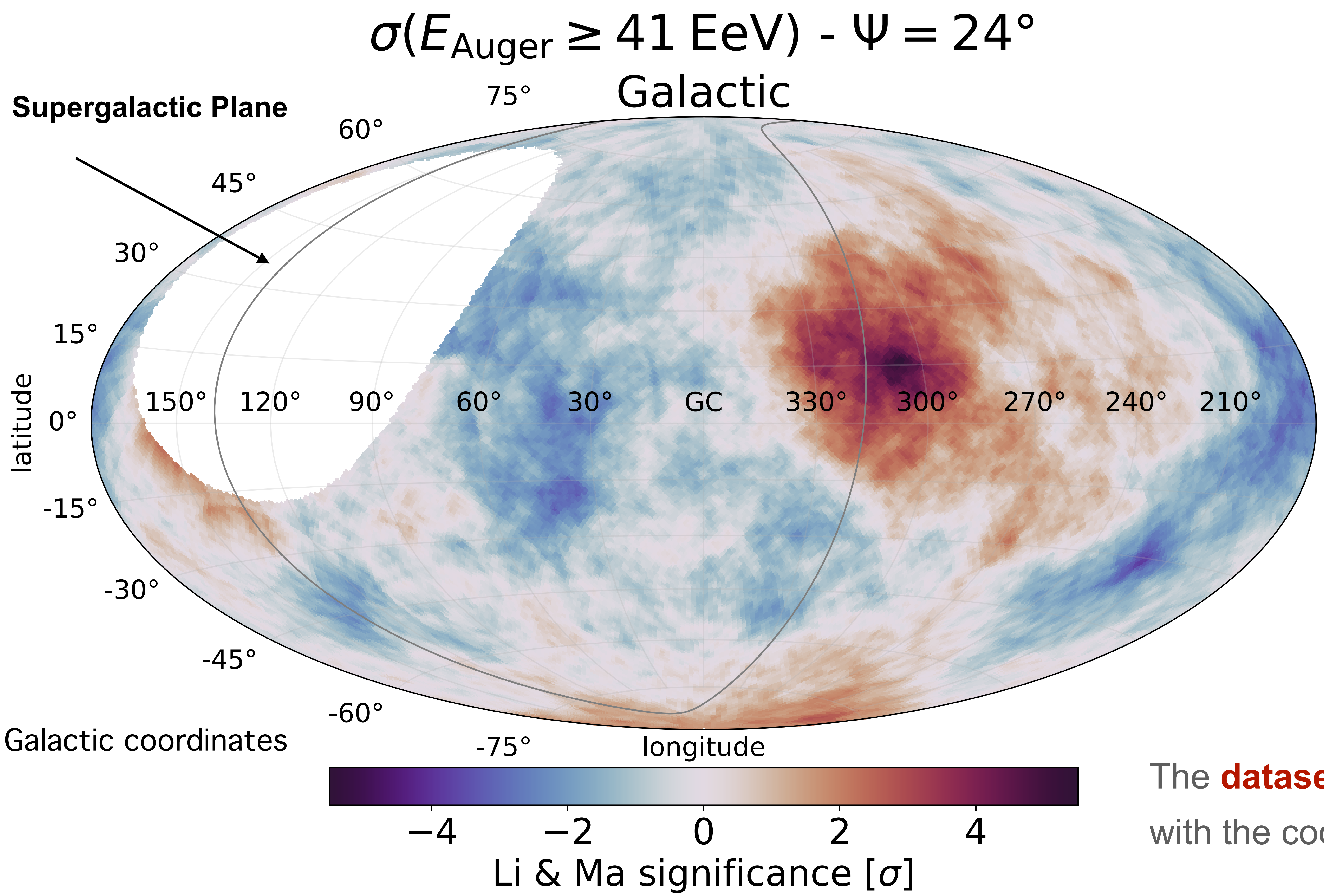
Calibration with the fluorescence detector: ≈ 14% systematic uncertainty

Arrival directions above 32 EeV

Pierre Auger Collab. The Astrophys. J. 935 (2022)170

Search for localized excesses

not specifying a priori the targeted regions of the sky



Approach

- ▶ Investigate binomial probability to measure the cumulative number of events (Nobs) given the expected on average from isotropic simulations (Nexp)
- ▶ **Scan in energy threshold in [32; 80] EeV, step of 1 EeV**
- ▶ **Scan in top-hat search angle Ψ in [1°; 30°], steps of 1°**

Most significant local excess over whole observable sky

$E_{th} \geq 41$ EeV, Ψ = 24°

(α, δ) = (196.3º, -46.6º), (l, b) = (305.4º, 16.2º)

Nobs = *153* events, Nexp = *97.7* events from isotropy

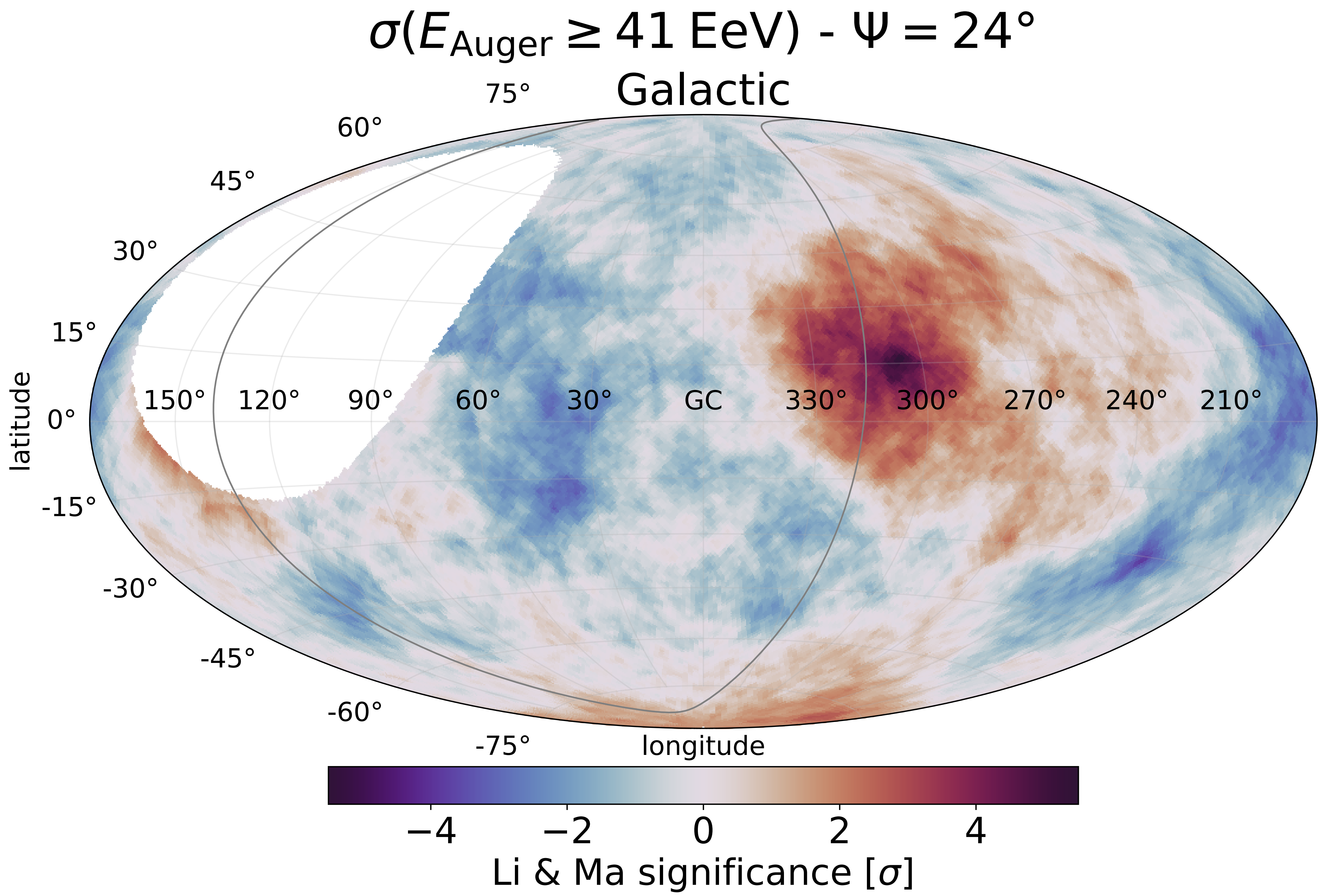
Local *p*-value 3.7 × 10^{-8} , Li&Ma significance = 5.4σ

Global *p*-value = 3%
(after accounting the scan, penalty factor $\sim O(10^5)$)

The **dataset above 32 EeV is available for public use** with the code to reproduce the results (here)

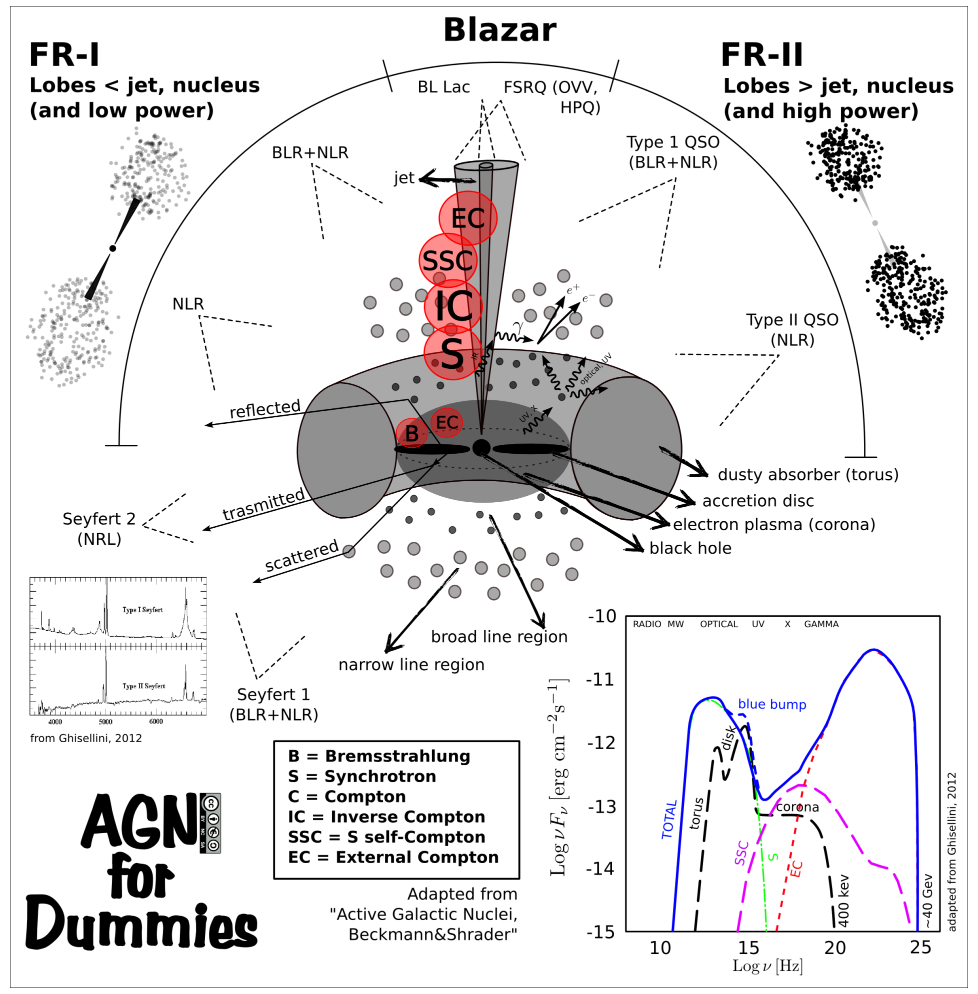
Significant interest in Centaurus A (NGC 5128)

Pierre Auger Collab. The Astrophys. J. 935 (2022)170

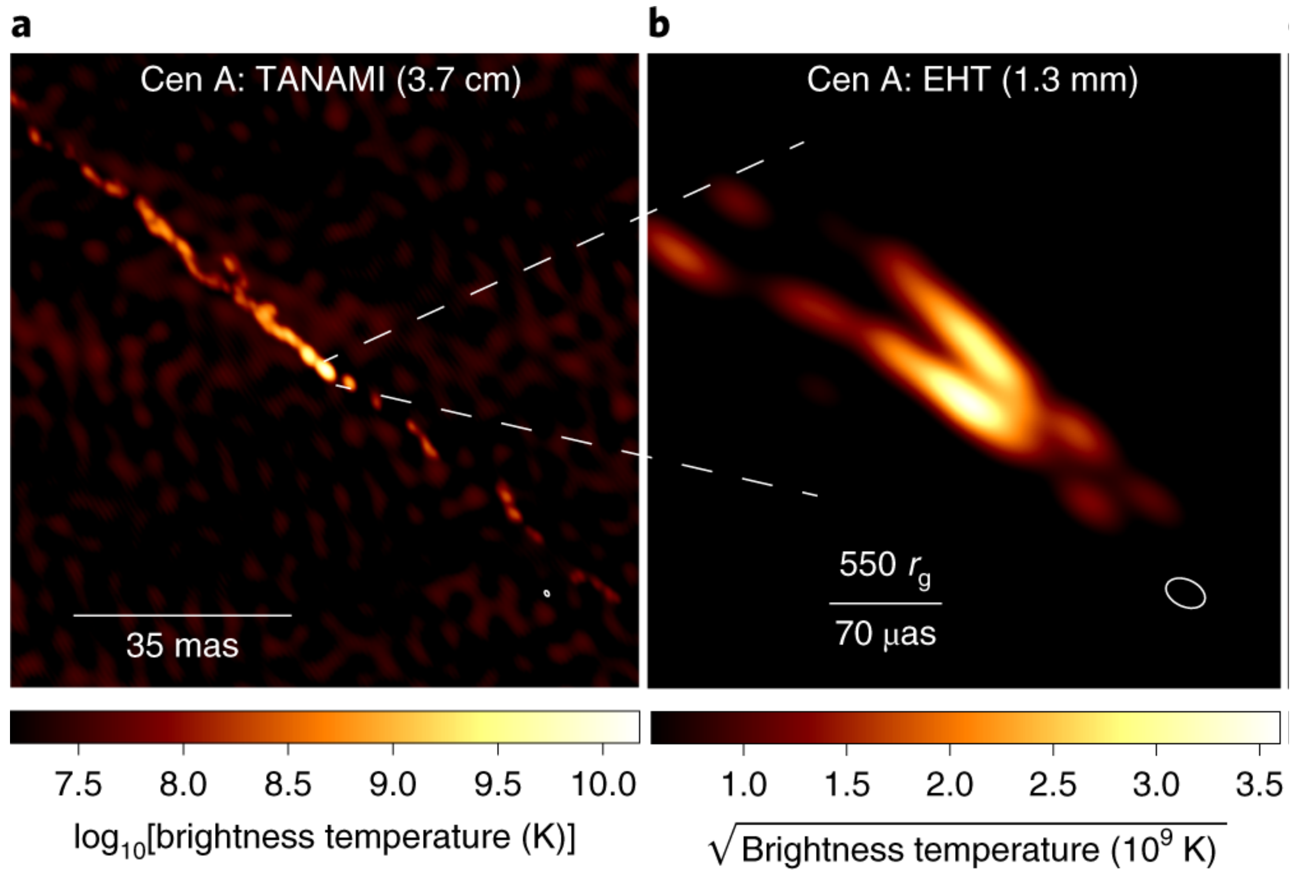


Is this the first image of an astronomical object taken with cosmic rays?!

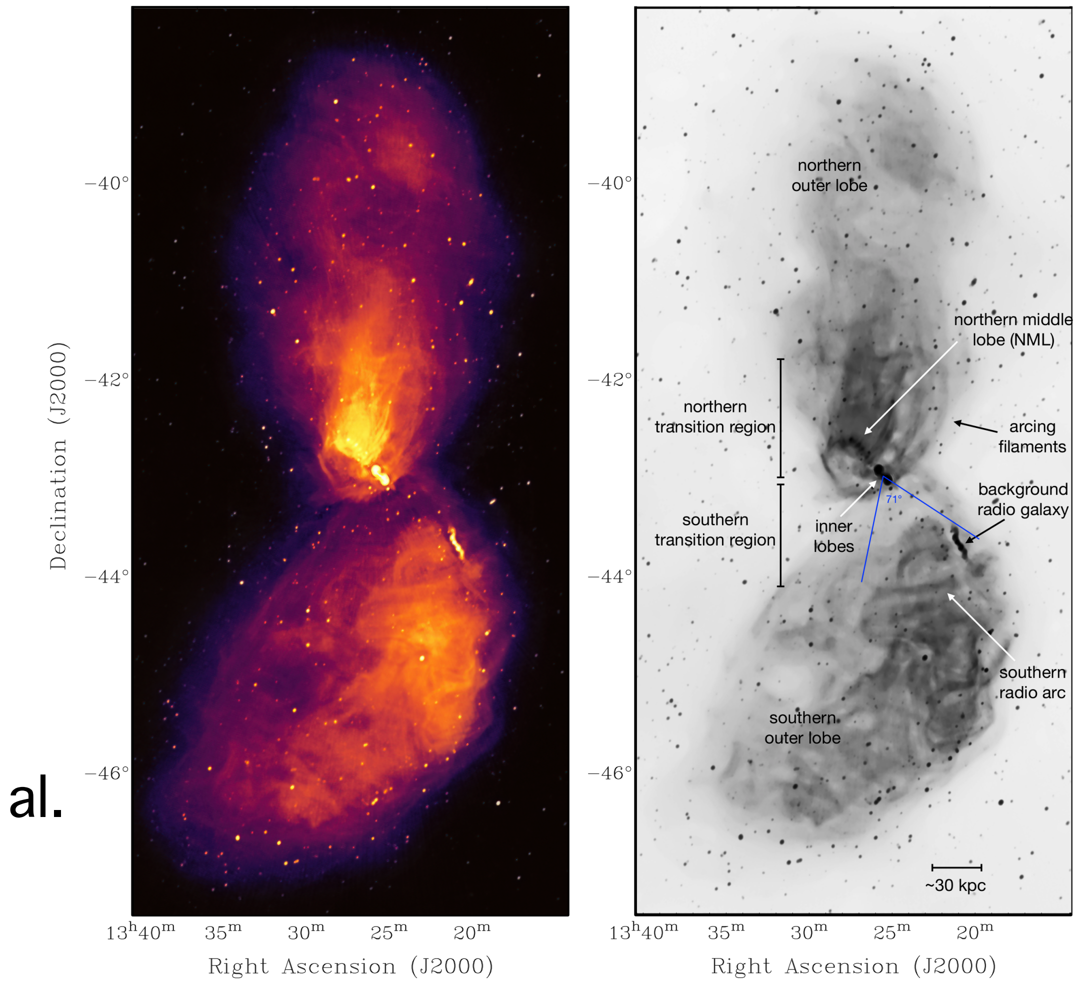
The closest (radio-loud)AGN



Janssen, M., Falcke, H., Kadler, M. et al. Nat Astron 5, 1017–1028 (2021)



McKinley, B., Tingay, S.J., Gaspari, M. et al. Nat Astron 6, 109–120 (2022)



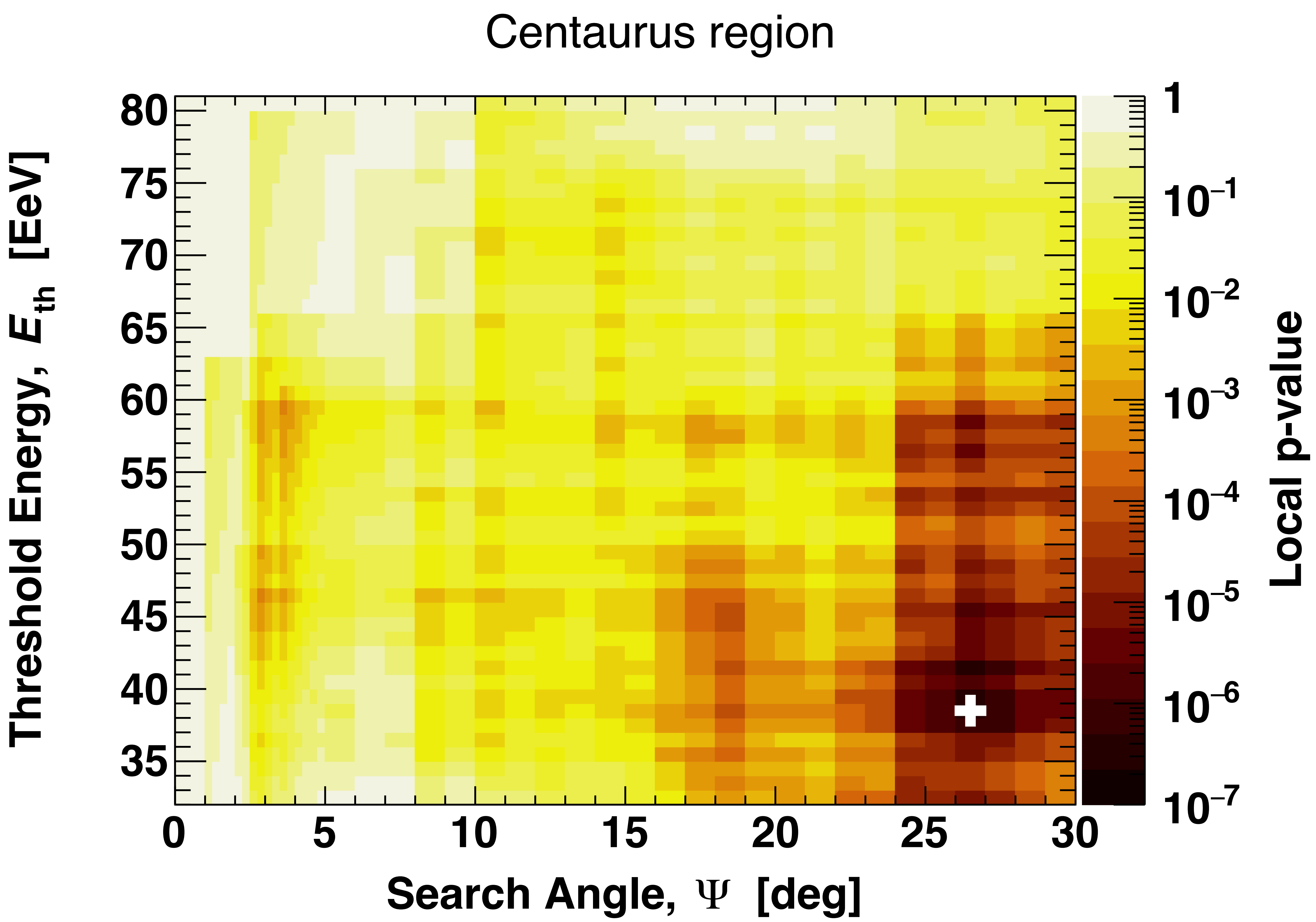
Excess in the Centaurus region

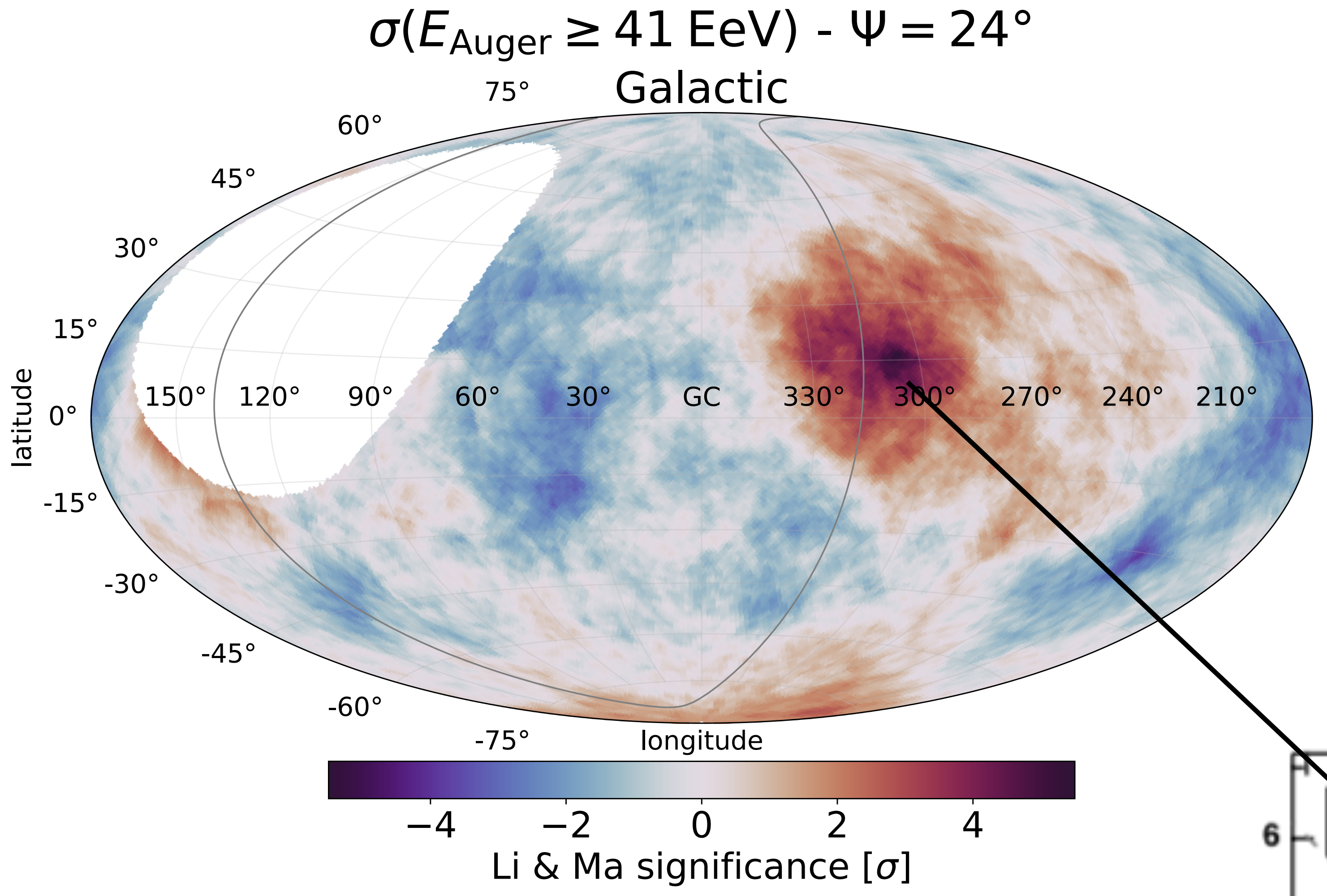
Method: Fix Centaurus A direction

► Compare the cumulative number of events (Nobs) with the expected on average from simulations assuming isotropy (Nexp)

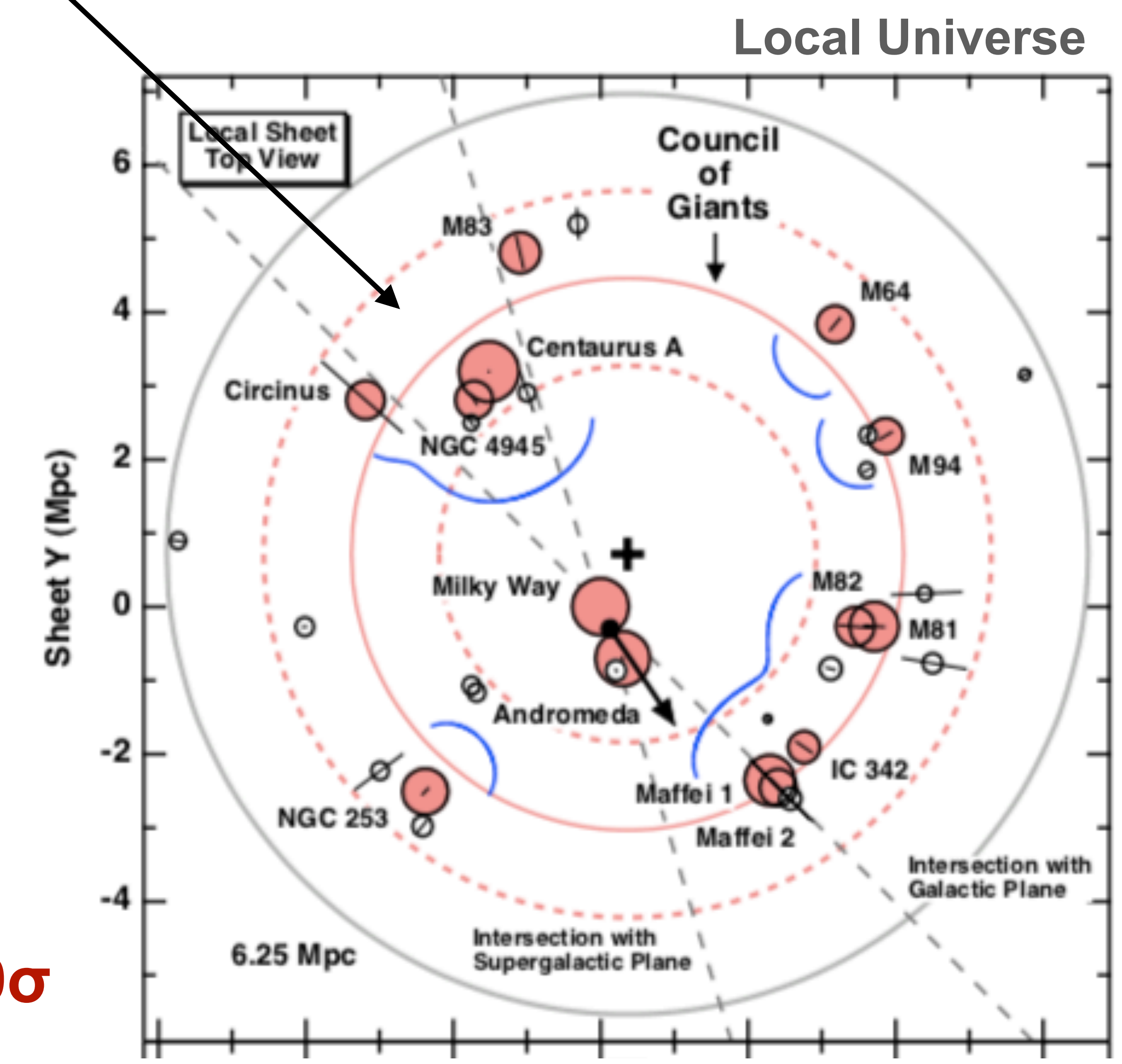
► Compute the cumulative binomial probability to measure Nobs given Nexp

► **Scan in energy threshold in step of 1 EeV, top-hat search angle Ψ in [1°; 30°] in steps of 0.25° up to 5°, 1° for larger angles**





Crowed region in the Local Group



M. L. McCall Astrophys. J. 891 (2020) 142

Most significance excess

$E_{th} \geq 41$ EeV, Ψ = 27°

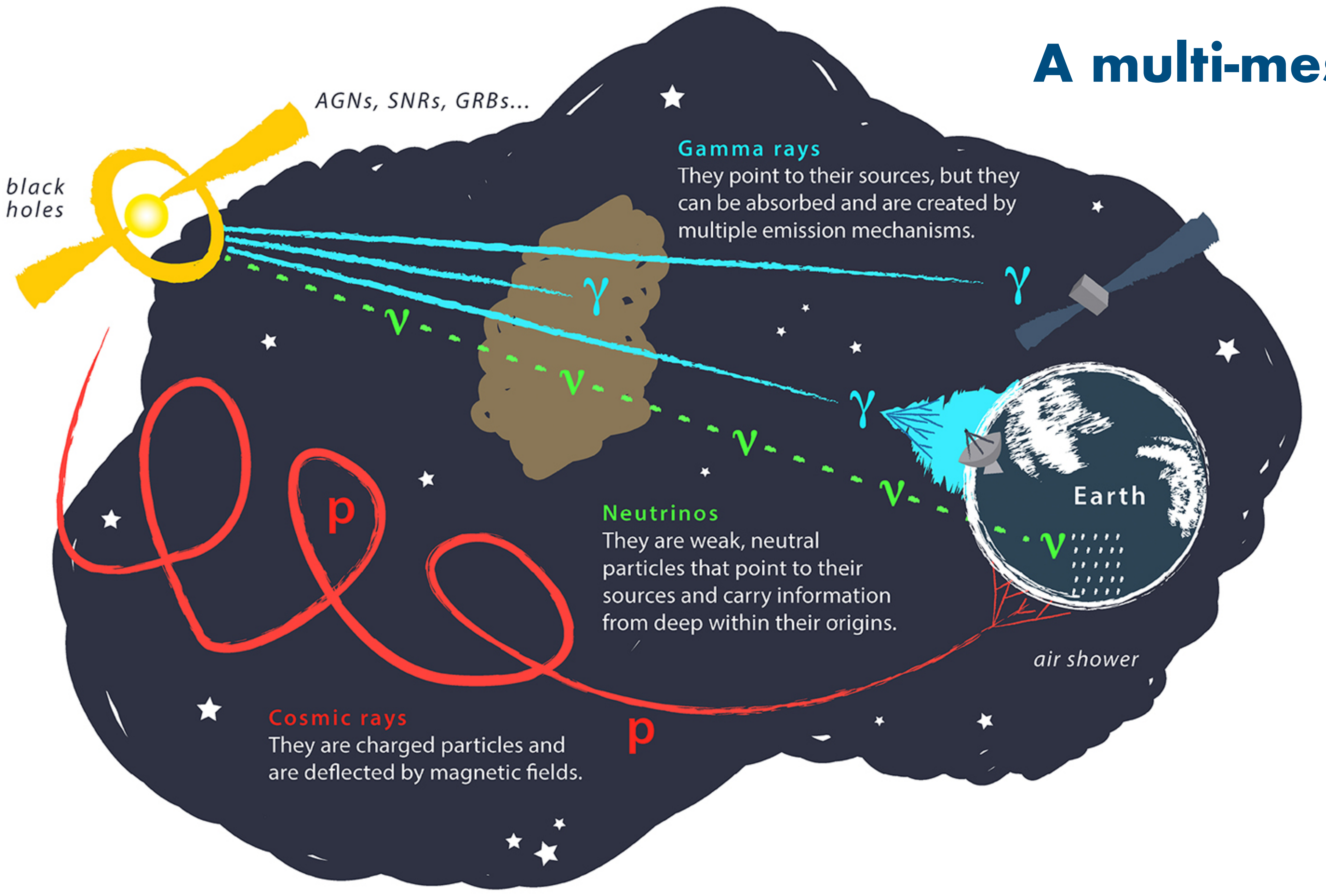
Nobs = 215, Nexp = 152

Local p-value 2.1× 10^{-7}

Global p-value 4.5× 10^{-5} , significance 3.9σ
(after accounting the scan)

⟹ search for correlation with extragalactic objects

Correlation with candidate sources

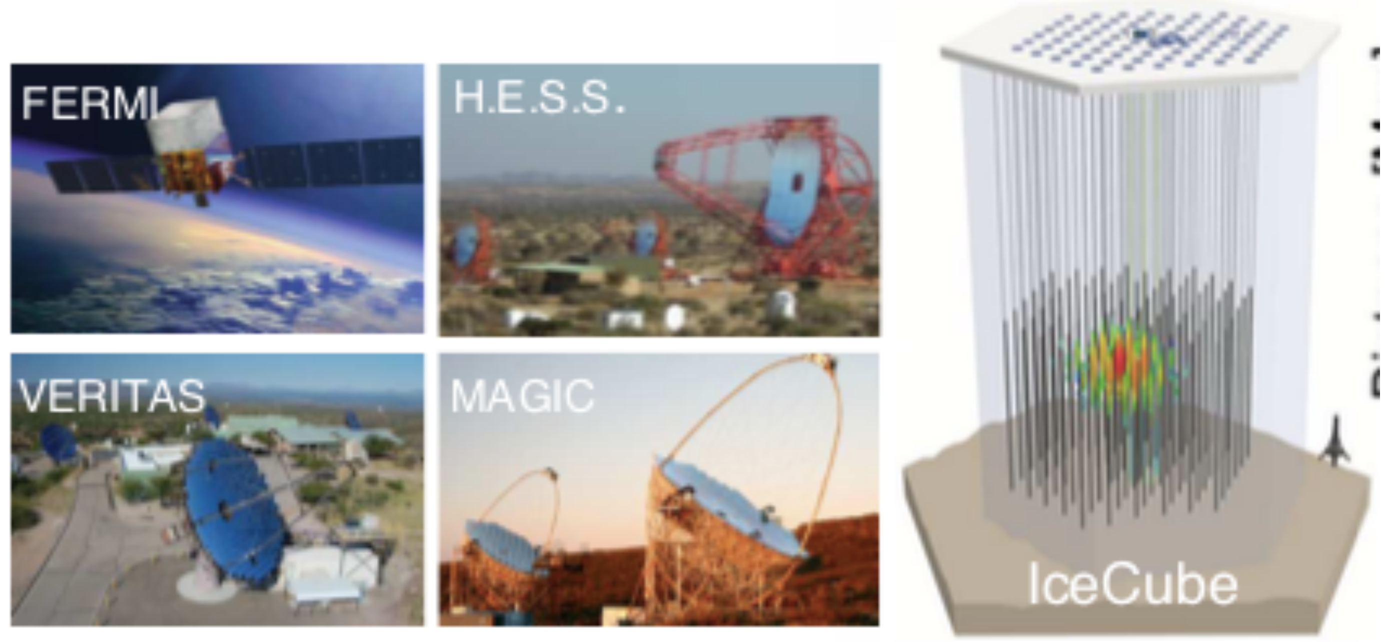


A multi-messenger approach

Traces of acceleration

Accelerators E > 10 EeV traces by PeV / TeV / GeV neutrals?

PeV : ν from IceCube
TeV : γ from HESS / MAGIC / VERITAS
GeV: γ from Fermi



Astrophysical limits

Accelerators E > 10 EeV traces by PeV / TeV / GeV neutrals?

PeV : ν few & diffusive, no point source yet
TeV : γ limited FoV, no full sky coverage
GeV: γ full sky + no absorption from nearby objects

Selection of non thermal sources

Four flux-limited catalogs - Jetted AGNs, all AGNs, Starburst galaxies, all galaxies

all galaxies from 2MASS

Assumption: UHECR flux ∝ stellar mass

Generic/stellar mass = IR from 2MRS (>40,000 galaxies 2.16 μm)

All AGNs observed with Swit-BAT

Assumption: UHECR flux ∝ hard-X rays flux

Accretion = X-rays from SwiftBAT (523 galaxies at 14-195 keV)

Starburst galaxies from JCAP, 2019 073 (Lunardini at al)

Assumption: UHECR flux ∝ star-forming activity

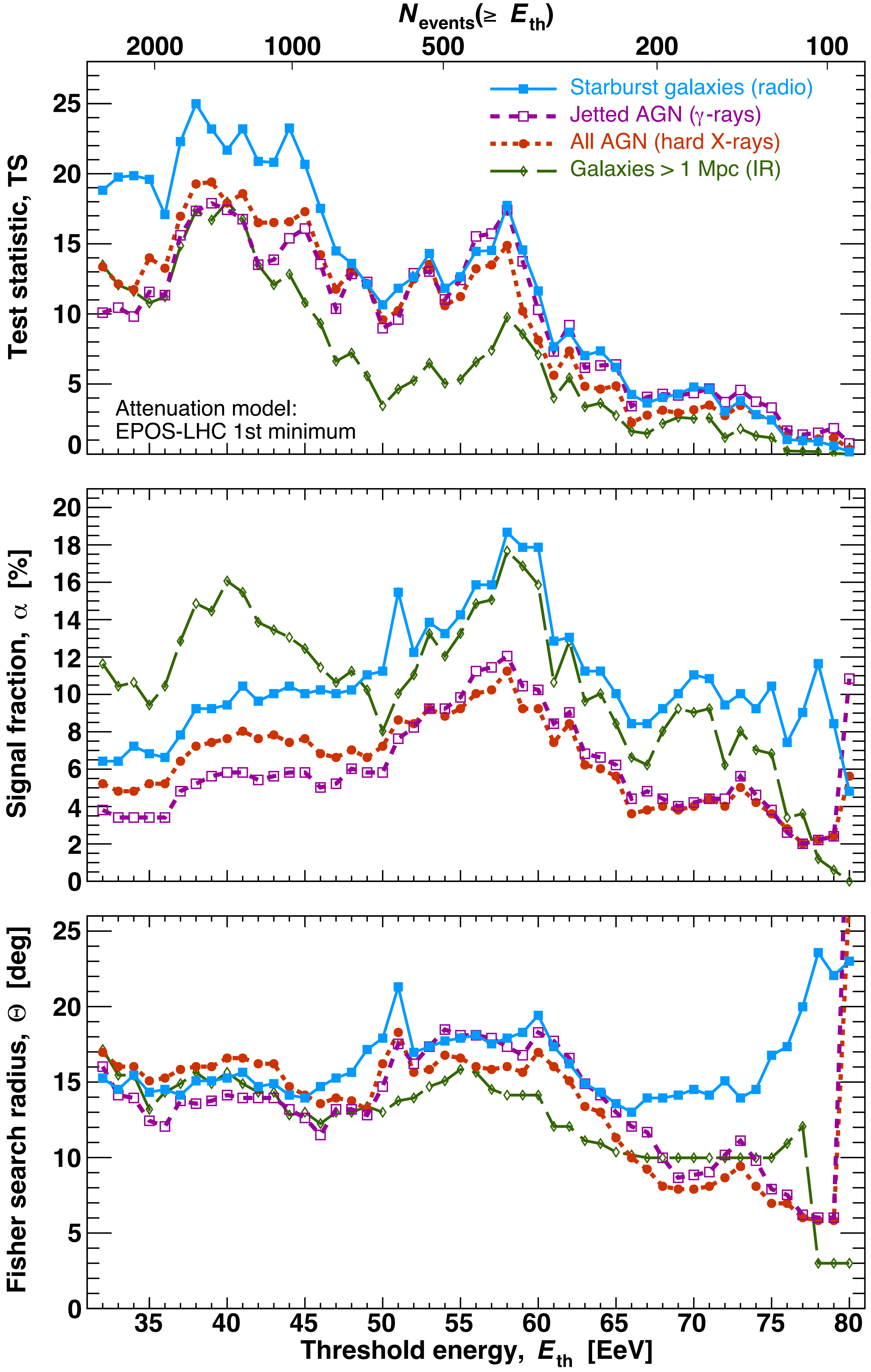
Burst = radio from Lunardini+19 (44 galaxies, 1.4 GHz)

Jetted AGNs from Fermi-LAT 3FHL catalog

Assumption: UHECR flux ∝ γ-rays flux

Jet = γ-rays from 3FHL (26 galaxies at 10 GeV-1 TeV)

Catalog-based searches



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Attenuation model: from best-fit escape spectrum of Auger spectral-composition modeling JCAP 03 (2018) E02

Method: Unbinned maximum likelihood analysis

UHECR sky model: isotropy + anisotropic component from candidate sources

Test statistic (TS) = LH ratio between H(UHECR sky model) and H(isotropy)

TS maximised vs Fisher search radius (Θ) and signal fraction (f) + energy scan

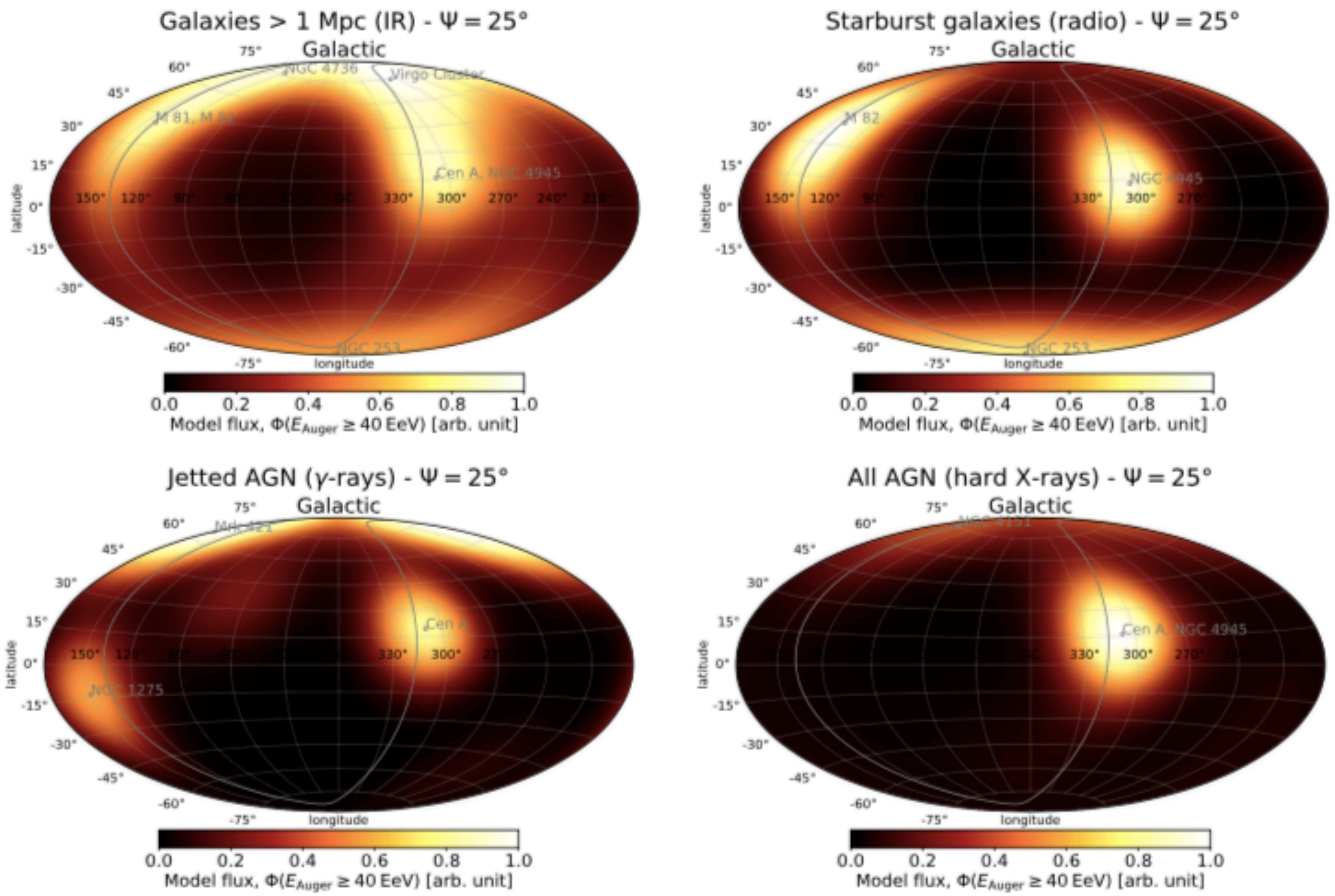
Best fit results at the global maximum

- **All galaxies, *E*th = 40 EeV, Θ = 16°, f = 16%, TS = 18.0, post-trial *p*-value = 7.9e−4 (3.2σ)**
- **Starburst, *E*th = 38 EeV, Θ = 15°, f = 9%, TS = 25.0, post-trial *p*-value = 3.2e−5 (4.0σ)**
- **All AGNs, *E*th = 39 EeV, Θ = 16°, f = 7%, TS = 19.4, post-trial *p*-value = 4.2e−4 (3.3σ)**
- **Jetted AGN, *E*th = 39 EeV, Θ = 14°, f = 6%, TS = 17.9, post-trial *p*-value = 8.3e−4 (3.1σ)**

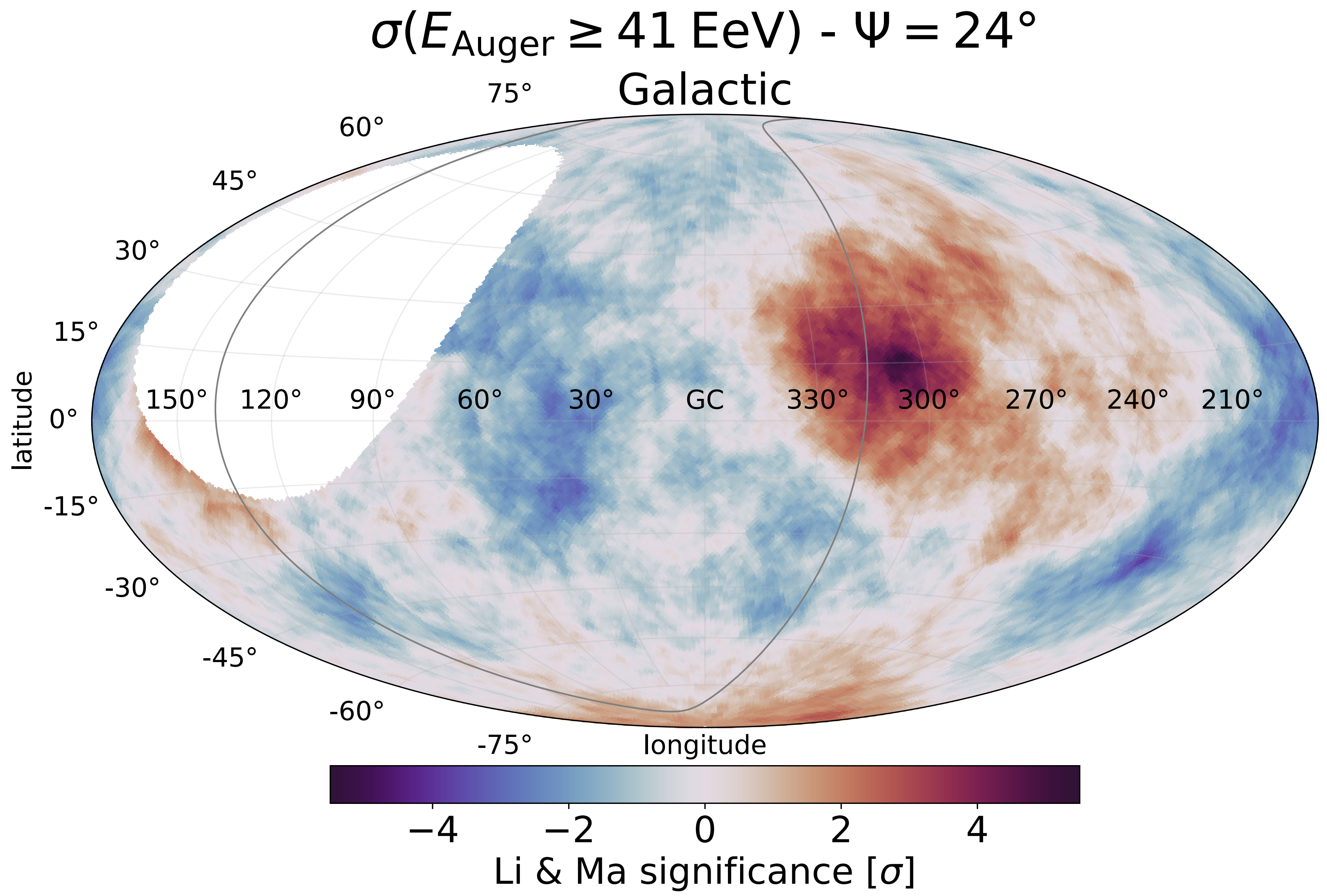
Comparison with starbust galaxies indicate
that isotropy is disfavored at a 4.0σ level (post-trial)
but no preference with a specific class of galaxies can be stated

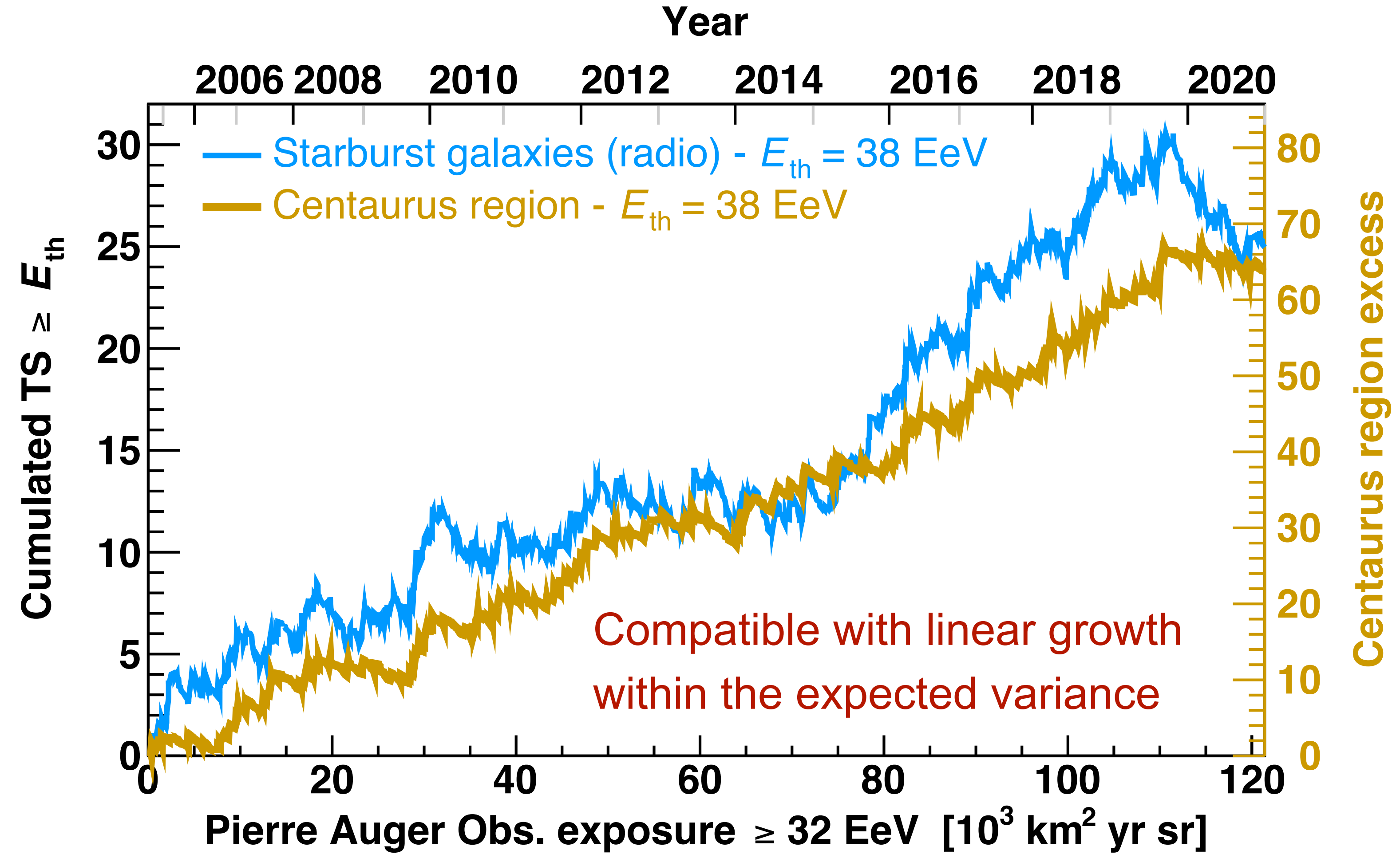
Comparing the sky models

Best fit model above 40 EeV



Observed above 41 EeV





- All models capture the hotspot in the **Centaurus region** (M83+ NGC4945 + CenA)
- The starburst model adds the excess in the Galactic South Pole (NGC253)
- **5 sigma deviation from isotropy at 2025 ± 2 years** (165,000 ± 15,000 km^2 sr yr (C.L. 68%))

Conclusion and prospect with Auger Phase 1 data

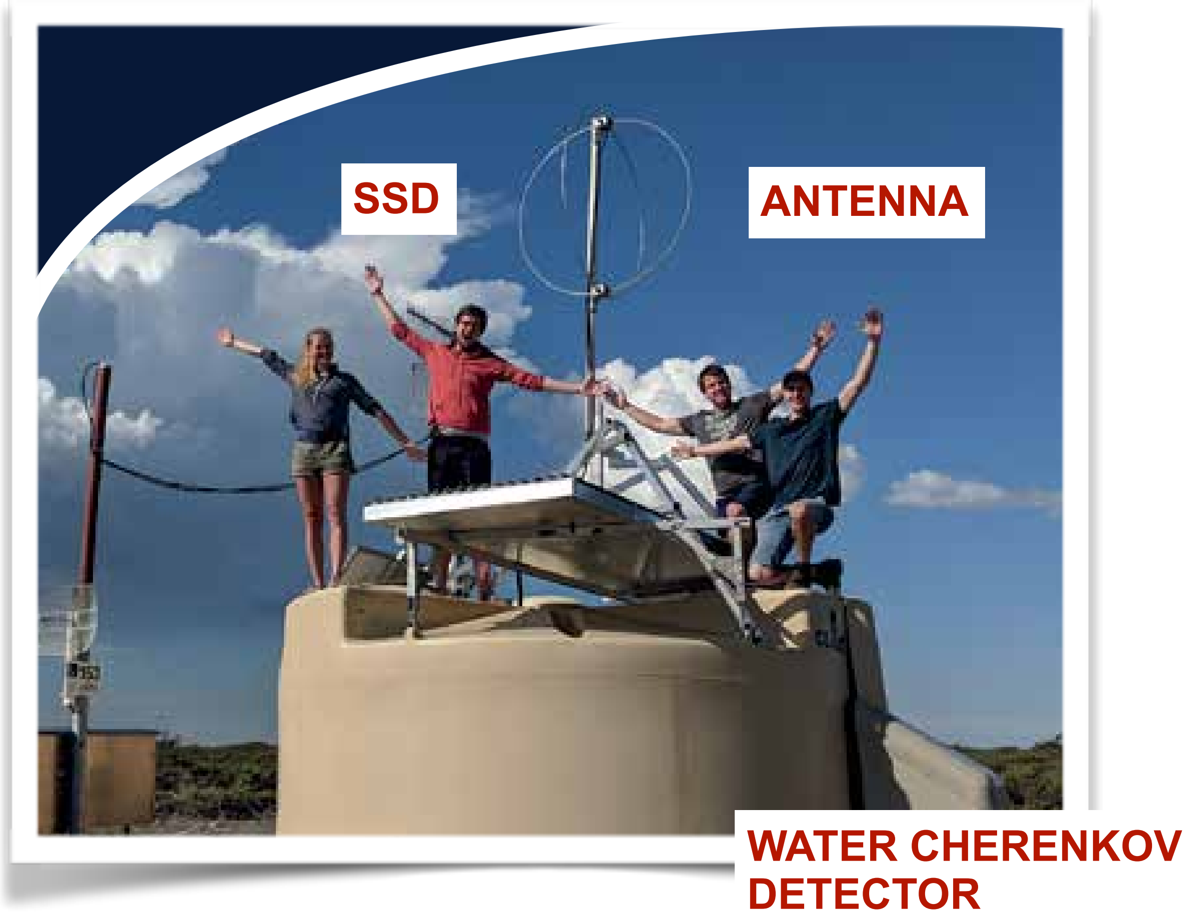
1/2004 to 12/2020 ⟹ AugerPhase 1

Towards charged-particles astronomy

- **Indication of departure from isotropy** ~4σ from search in Centaurus region confirmed also by catalog-based searches
- Starburst galaxy model provides the most significant indication that UHECRs are not isotropically distributed
- The **dataset above 32 EeV is available for public use with the code to reproduce the results** (here)

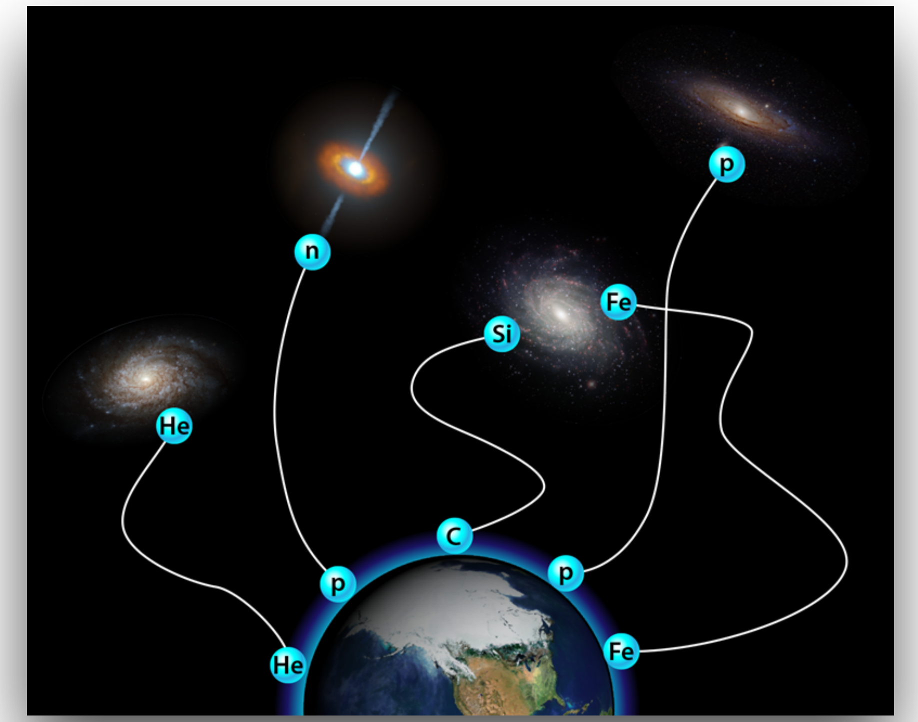
"AugerPrime"

12/2020 ⟹ AugerPhase 2



arXiv:1604.03637

- Looking at the sources using energies, positions and mass composition of the observed events (see Matteo's talk)



Perspectives

Increase sensitivities to Charged-particles Astronomy

Identify individual sources profit magnetic deflections ~ 1/E and perpendicular to B

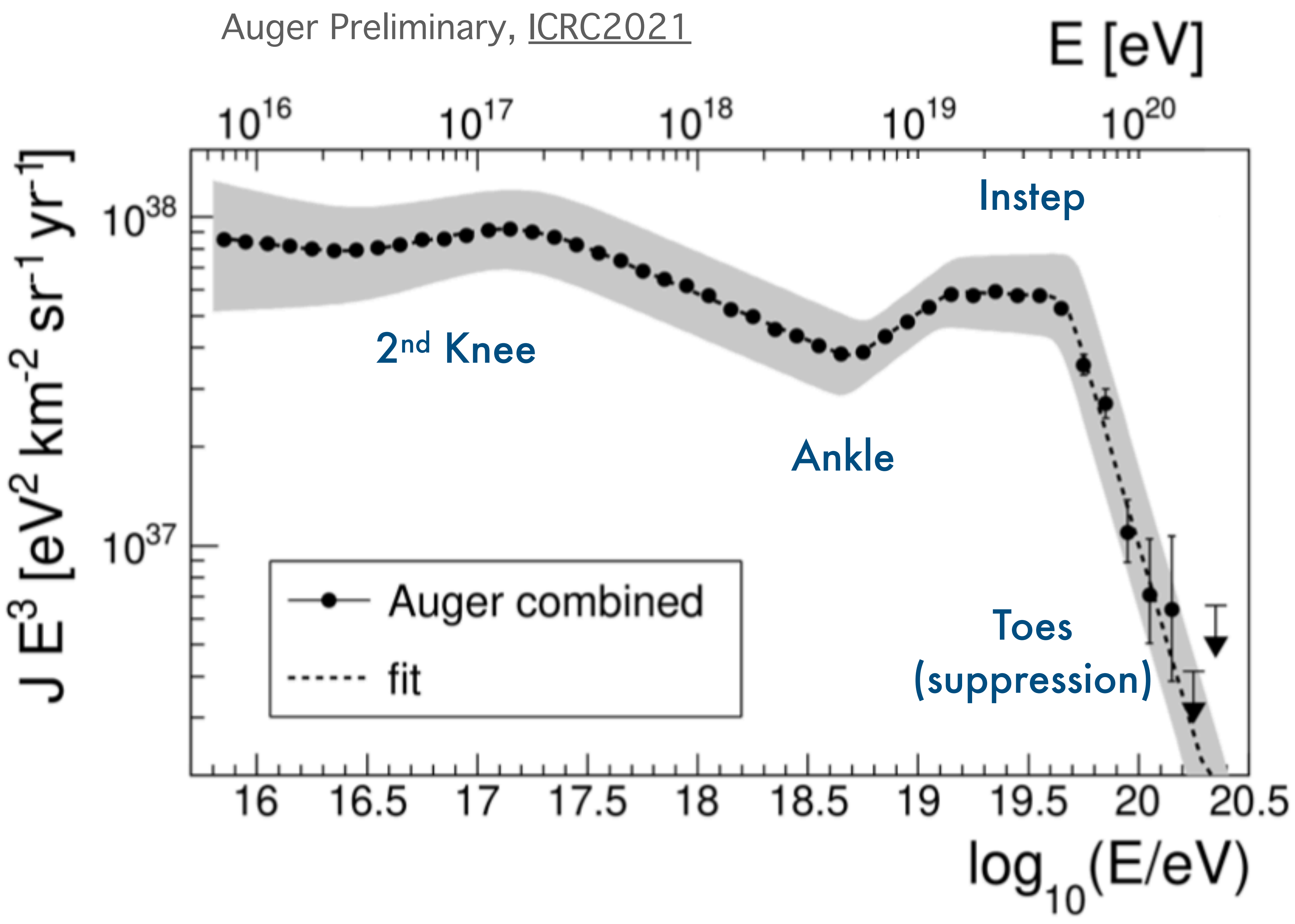
Identify acceleration mechanism(s)

Characterize Galactic and Extragalactic magnetic fields

Extra slides

Directional analyses at the Pierre Auger Observatory

Two lines of analyses since the beginning of our data taking



Large scale anisotropies can be present <u>at all energies</u>

- Propagation from extragalactic sources distributed anisotropically
- Diffusion from individual extragalactic sources
- Diffusive escape from Galaxy of CRs from Galactic sources
- Compton-Getting effect due to the Earth motion in the CR rest frame

Method: Rayleigh analysis in right ascension (and declination)

Challenge: control exposure and event rate down below < % level

Small-intermediate scale anisotropies can be present <u>in the suppression region</u>

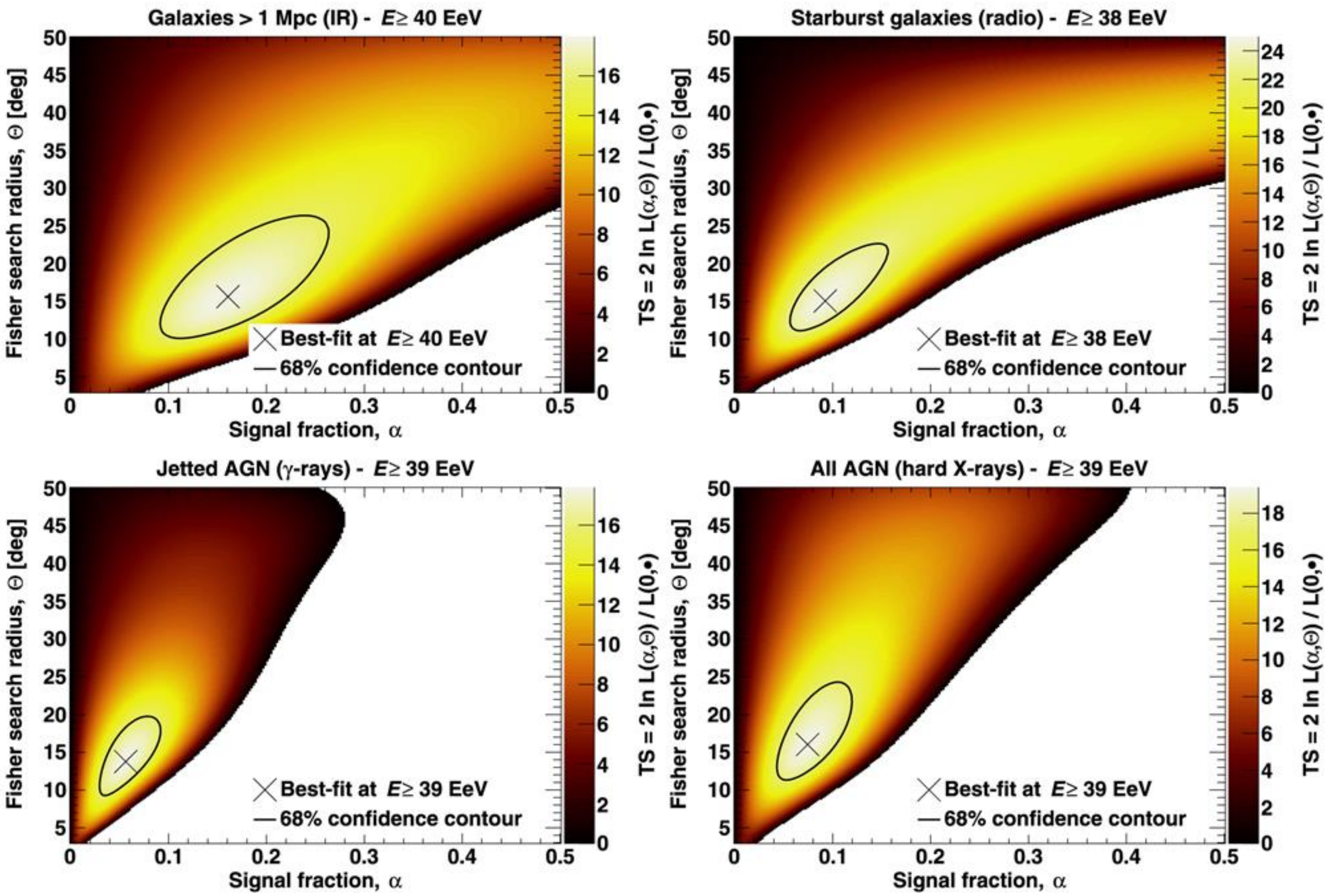
- At UHE, cosmic rays have reduced horizon and maybe enough rigidity ***to point back to their sources***

Method: Comparison of UHECR arrival directions with astronomical objects

Challenge: control of exposure and trial factor (energy, angle…)

Anisotropy studies over three decades in energy, from below the 2nd Knee to the suppression region

Catalog-based searches



Global maximum

Best-fit Results Obtained with the Four Catalogs at the Global (Upper) and Secondary (Lower) Maximum

Catalog	E_{th} [EeV]	Fisher Search Radius, Θ [deg]	Signal Fraction, α [%]	TS_{max}	Post-trial p-value
All galaxies (IR)	40	16^{+11}_{-6}	16^{+10}_{-7}	18.0	7.9×10^{-4}
Starbursts (radio)	38	15^{+8}_{-4}	9^{+6}_{-4}	25.0	3.2×10^{-5}
All AGNs (X-rays)	39	16^{+8}_{-5}	7^{+5}_{-3}	19.4	4.2×10^{-4}
Jetted AGNs (γ-rays)	39	14^{+6}_{-4}	6^{+4}_{-3}	17.9	8.3×10^{-4}
All galaxies (IR)	58	14^{+9}_{-5}	18^{+13}_{-10}	9.8	2.9×10^{-2}
Starbursts (radio)	58	18^{+11}_{-6}	19^{+20}_{-9}	17.7	9.0×10^{-4}
All AGNs (X-rays)	58	16^{+8}_{-6}	11^{+7}_{-6}	14.9	3.2×10^{-3}
Jetted AGNs (γ-rays)	58	17^{+8}_{-5}	12^{+8}_{-6}	17.4	1.0×10^{-3}

Correlation with Structures

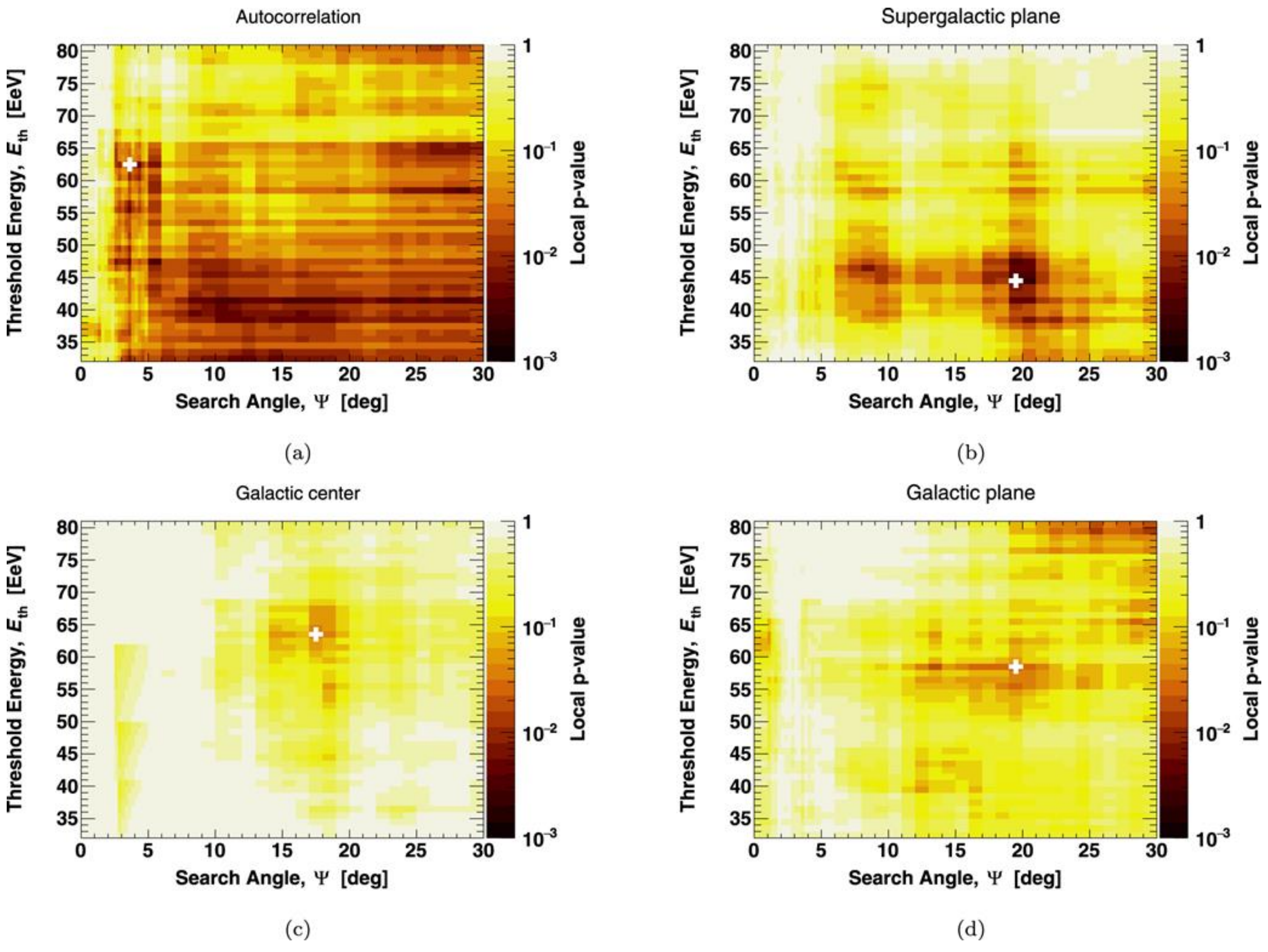
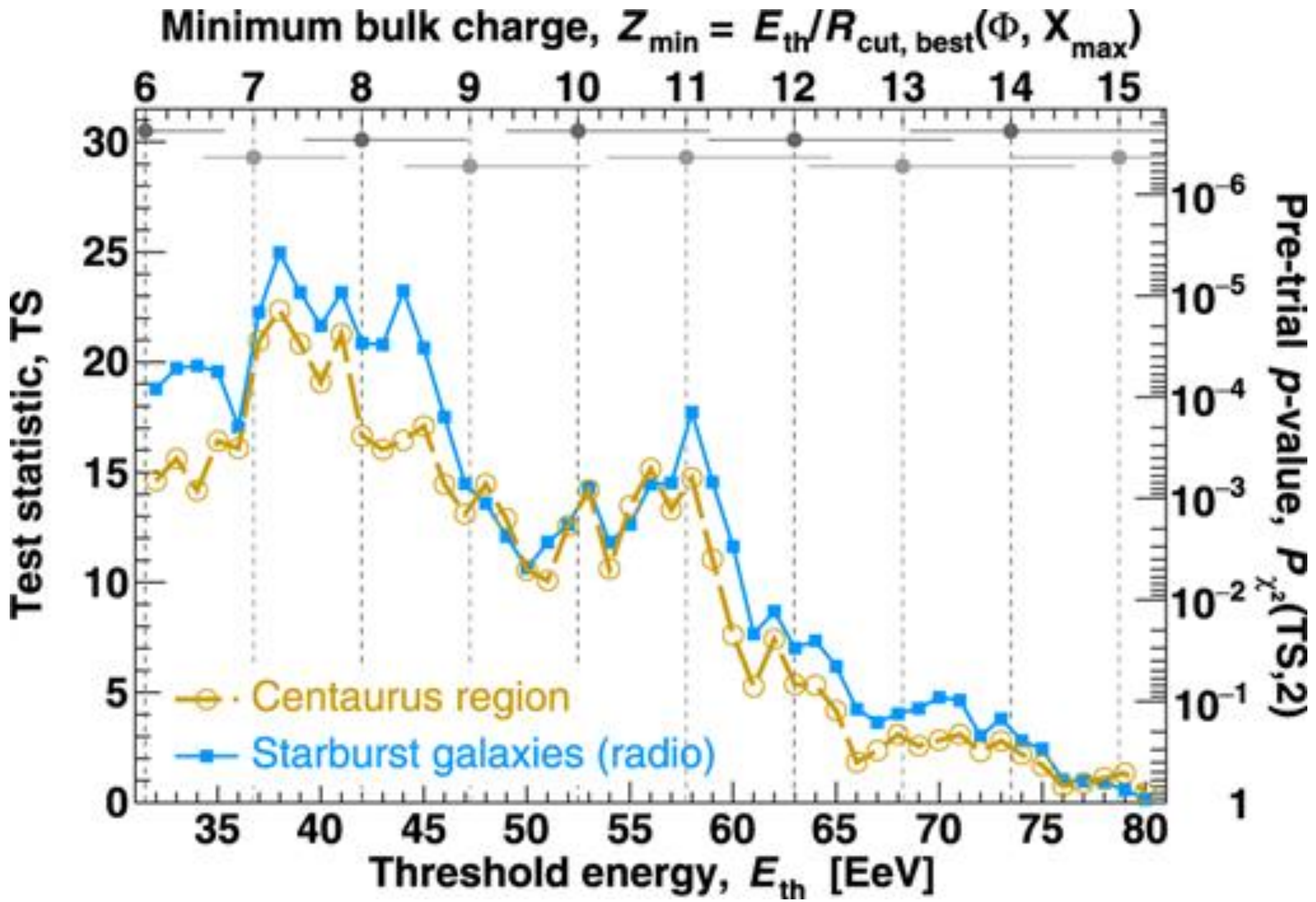


Table 1
Results of the Search for Autocorrelation and Correlation with Astrophysical Structures

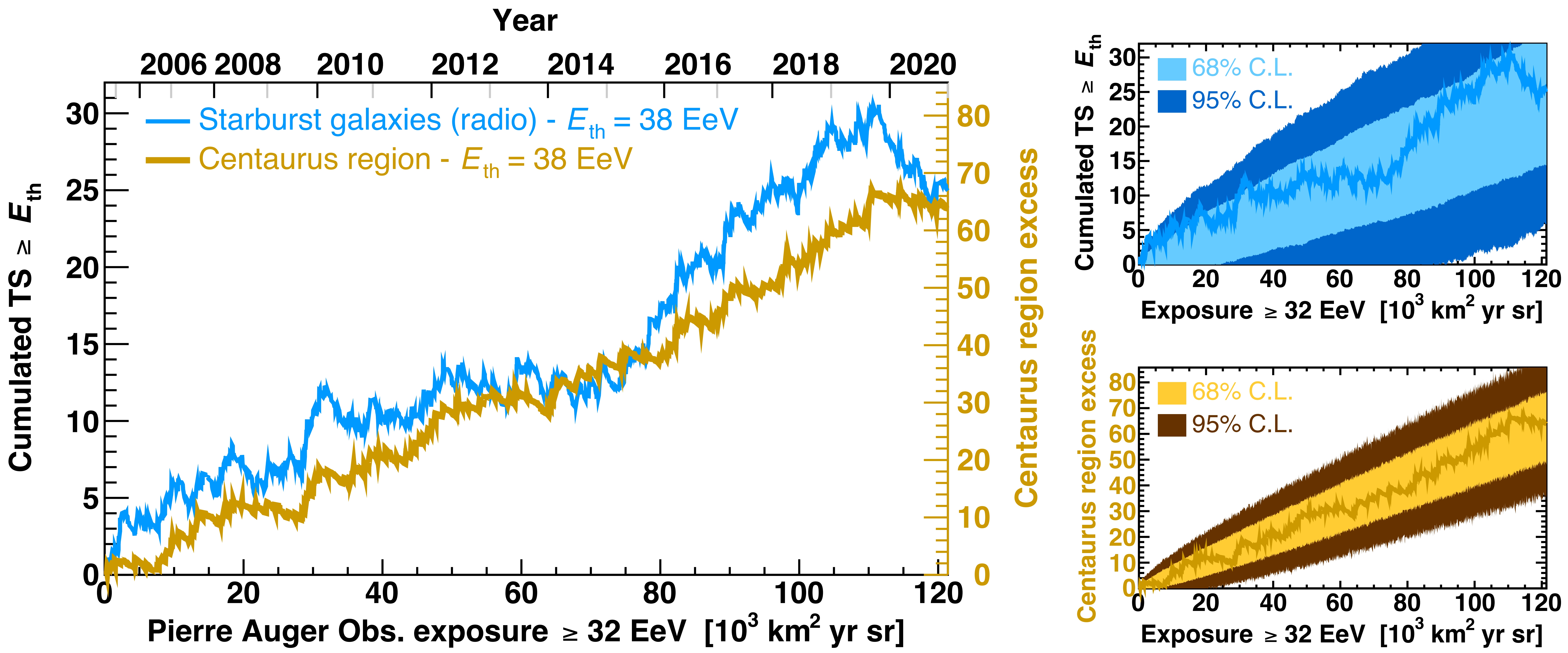
Search	E_{th} [EeV]	Angle, Ψ [deg]	N_{obs}	N_{exp}	Local p-value, f_{min}	Post-trial p-value
Autocorrelation	62	3.75	93	66.4	2.5×10^{-3}	0.24
Supergalactic plane	44	20	394	349.1	1.8×10^{-3}	0.13
Galactic plane	58	20	151	129.8	1.4×10^{-2}	0.44
Galactic center	63	18	17	10.1	2.6×10^{-2}	0.57

Starburst galaxies and Centaurus region



Evolution of the signal

Considering the best-fit parameters of the Centaurus region search



Compatible with linear growth within the expected variance

⟹ 5 sigma deviation from isotropy at 2025 ± 2 years

Correlation with candidate sources