The UHECR sky above 32 EeV viewed from the Pierre Auger Observatory

The quest for UHECR origins

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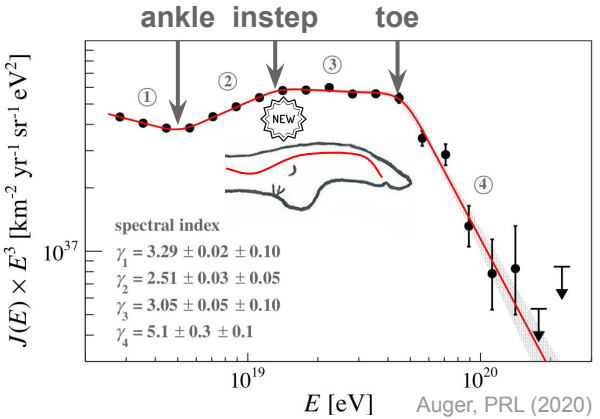
Ultra-high energy cosmic rays (UHECR)

Long thought to be of **extragalactic origin > 5 EeV** (0.8 J!), marking the **ankle**

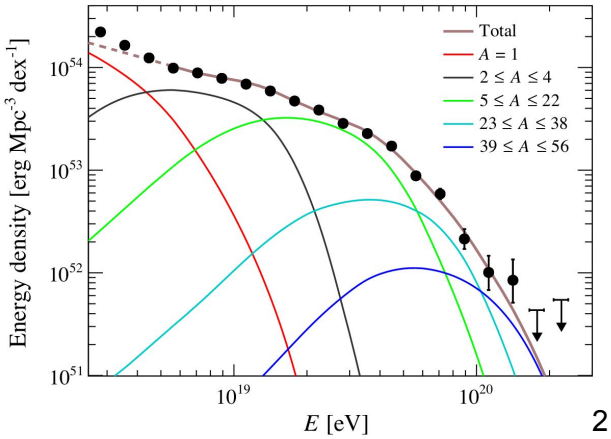
Observed spectral features: **instep at 10-15 EeV**, **toe at 40-50 EeV**
→ markers of Peters cycle (**acceleration**) and UHECR horizon (**propagation**) based on joint spectral-composition modeling

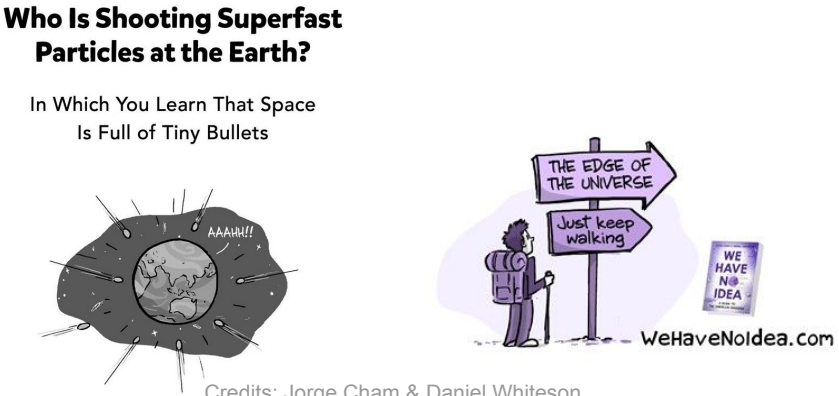
Spectral and composition observables integrated over the sphere
→ help constrain **source distance** distribution & source **escape spectrum**

Anisotropy observables
→ break down the flux (and composition) vs **arrival direction**: **pinpoint sources?**



Auger, PRL (2020)





Credits: Jorge Cham & Daniel Whiteson

The largest UHECR observatory ever built

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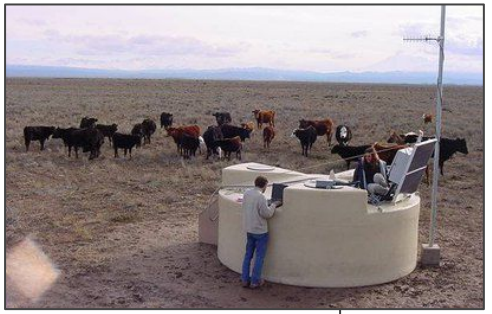
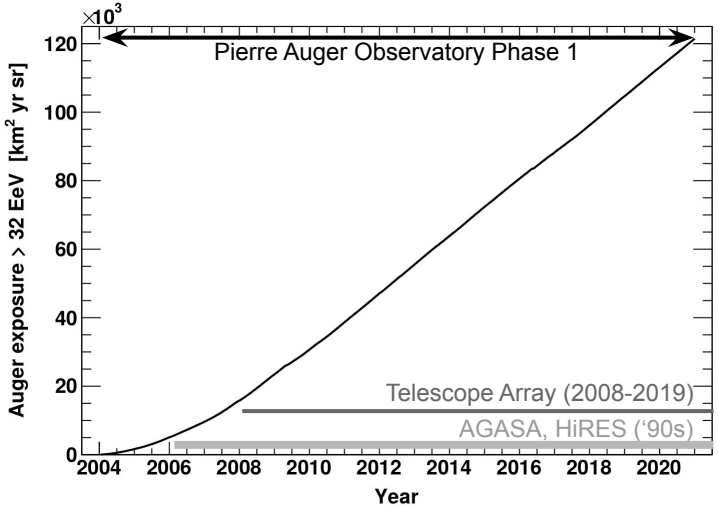
The Pierre Auger Observatory

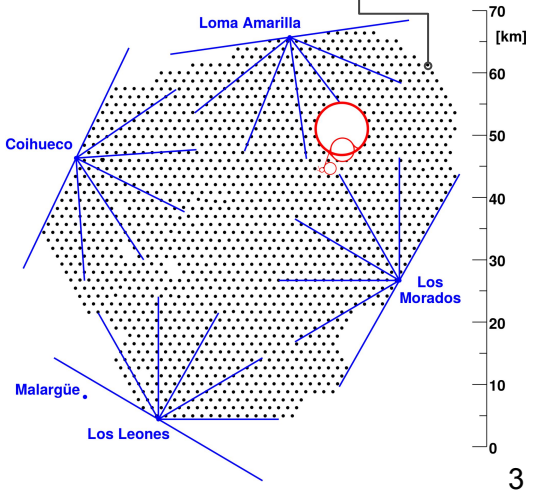
West Argentina at 1,400m a.s.l., **spread over 3,000 km²** (~ Luxembourg or Rhode Island)

1600 water Cherenkov detectors (12t each) to measure secondary particles in air showers
→ **85% of the sky covered** with angular resolution < 1° above the ankle

Exposure at the highest energies (loosest cuts): **120,000 km² yr sr in 2004-2020**
→ **40-70x larger than previous generation** experiments (AGASA, HiRES)
→ **9x larger than complementary Northern hemisphere** experiment (Telescope Array)







Some landmarks in Auger anisotropy studies

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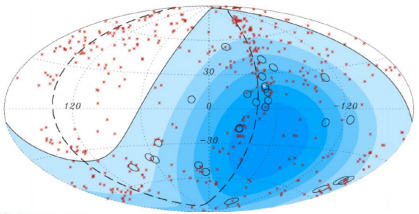
Auger, Science 2007



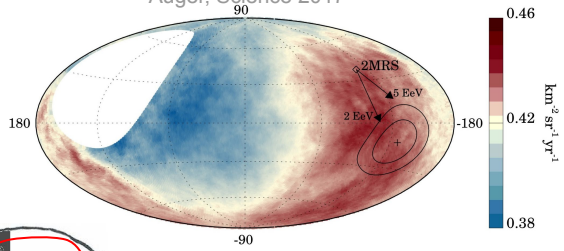
First steps: hint

20 out of 27 evts within 3° of nearby galaxies → was ~3σ

10 evts in particular clustered in the **Centaurus region**

~ 27 evts ≥ 57 EeV

Auger, Science 2017

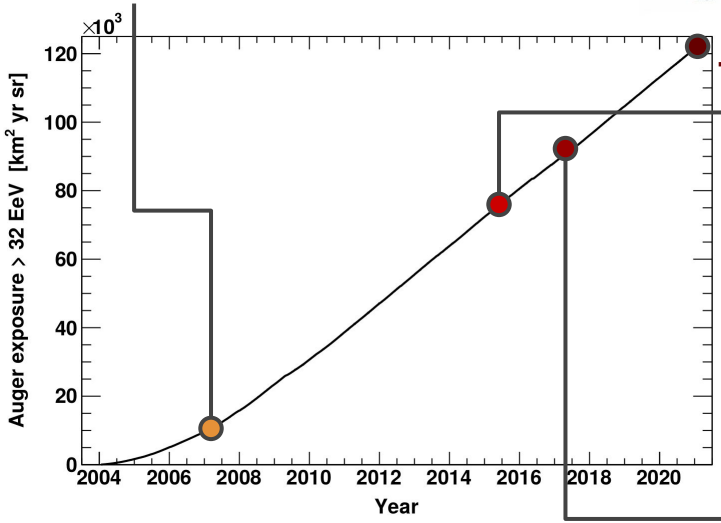


Maturity: discovery

>5σ dipolar-like flux

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

~ 32,000 evts ≥ 8 EeV



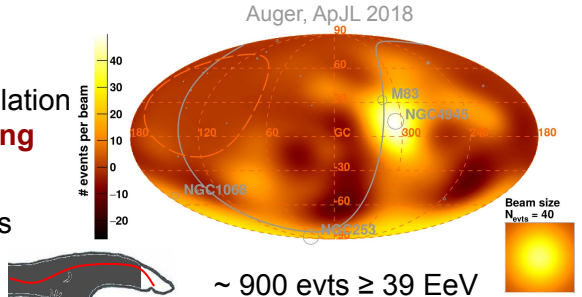
Today

Revival: a trail?

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

3σ level for other types of galaxies

Auger, ApJL 2018



~ 900 evts ≥ 39 EeV

“Blind” searches in the toe region

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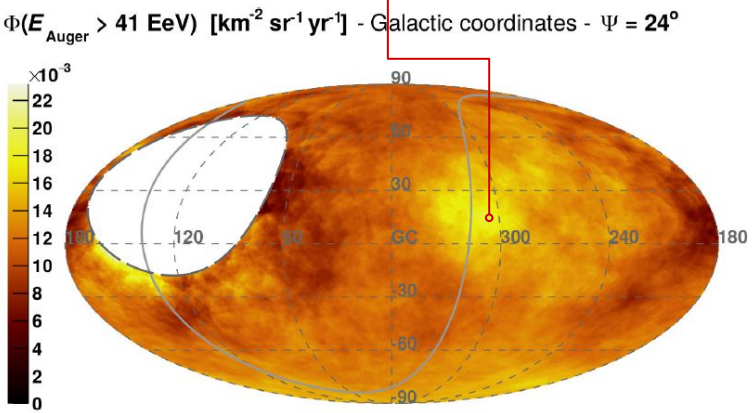
Dataset > 32 EeV from Auger phase 1 (Jan. 2004 - Dec. 2020)

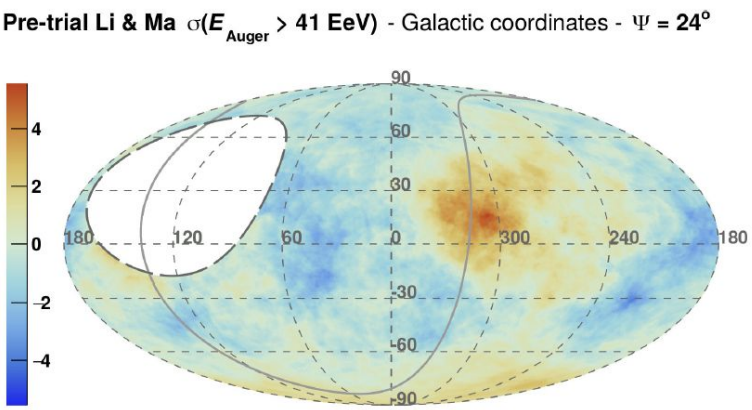
Minimum energy threshold for search: highest energy range for dipolar searches (where dipole significance drops)

~ 2,600 events at E_{th} > 32 EeV, ~ 740 events at E_{th} > 48 EeV, **~ 260 events at E_{th} > 64 EeV**

Searches with little *a priori* : singlemost overdensity, autocorrelation, supergalactic plane, Galactic plane & center

High-dimensional parameter space: E_{th} = {32, 33, …, 80} EeV, direction (R.A., dec), top-hat angular scale Ψ
→ largest **post-trial significance** (**2.2σ**, $\#_{observed}$= 156 vs $\#_{expected}$= 98) from localized overdensity at E_{th} > 41 EeV and Ψ = 24°





Stronger *a priori*: the Centaurus region

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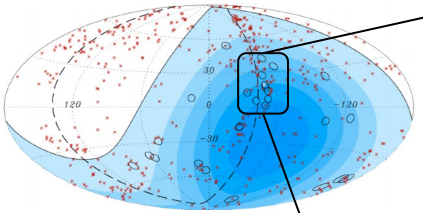
Motivation

Early-day flagging of Centaurus region (7% current exposure)

Crowded area in the **Council of Giants** (3-6 Mpc)

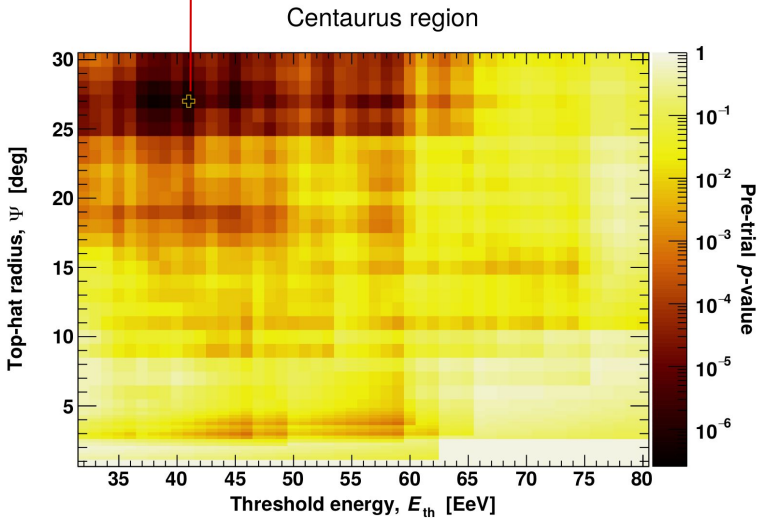


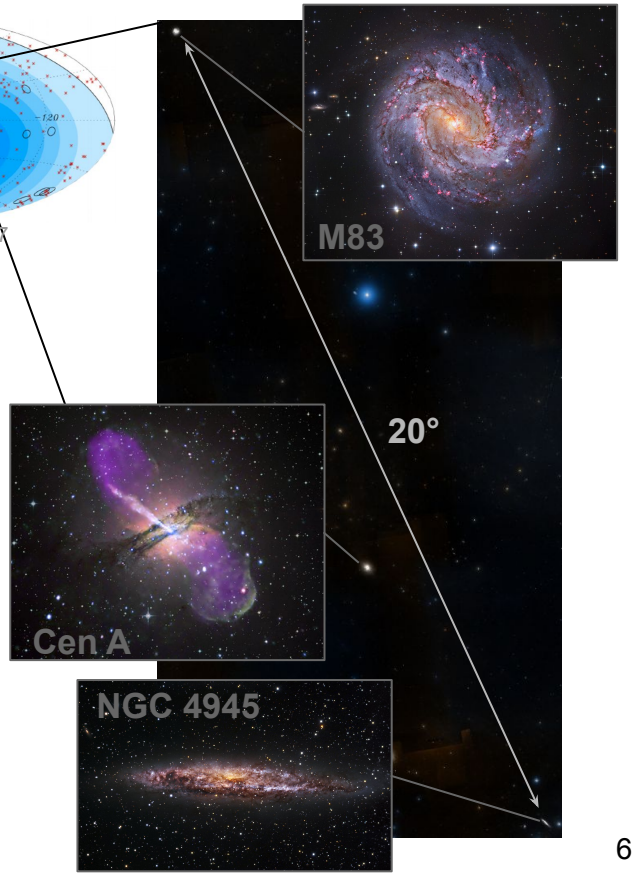
Auger, Science 2007

Method & Result

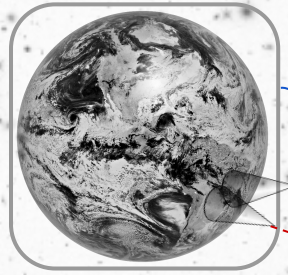
Direction fixed to that of Cen A, free E_{th} and Ψ

E_{th} > 41 EeV, Ψ = 27°: **3.9σ post-trial** deviation from isotropy (5% excess)





Which sources, which galaxies?

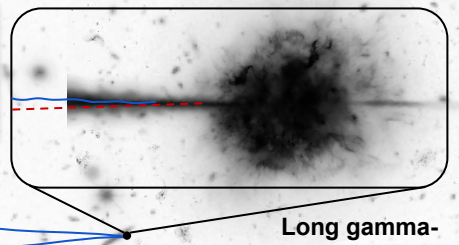


CMB
meV photons

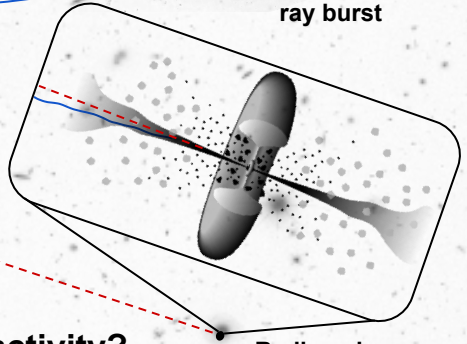
EBL
eV photons

EeV-ZeV
cosmic rays

Attenuation weights:
from best-fit escape spectrum of Auger spectral-composition modeling



Long gamma-ray burst



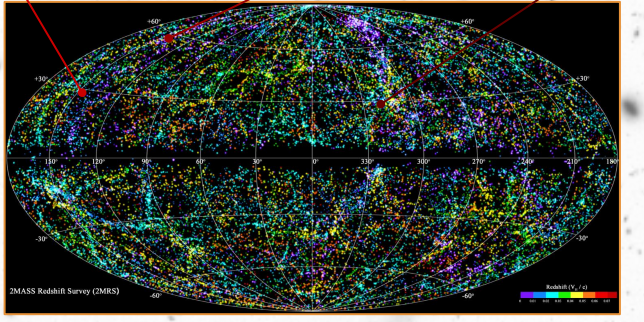
Radio galaxy

electromagnetic emission

M82, starburst

NGC 4151, non-jetted AGN

Cen A, jetted AGN



UHECR flux ∝ star formation / AGN activity?

Star formation (e.g. long GRB):
- integral = **stellar mass**: **infrared** from revised 2MRS (44,113 gal. at 2.2 μm)
- **instantaneous**: **radio** based on Lunardini+ 19 (44 gal. at 1.4 GHz)

Jetted / non-jetted **AGN** (e.g. radio galaxies, blazars / Seyferts):
- **accretion** w. or w./o. jets: **X-rays** *Swift*-BAT 105 months (523 gal. at 14-195 keV)
- **jets**: **γ-rays** from *Fermi*-LAT 3FHL (26 gal. at 10 GeV - 1 TeV)

Catalog-based searches

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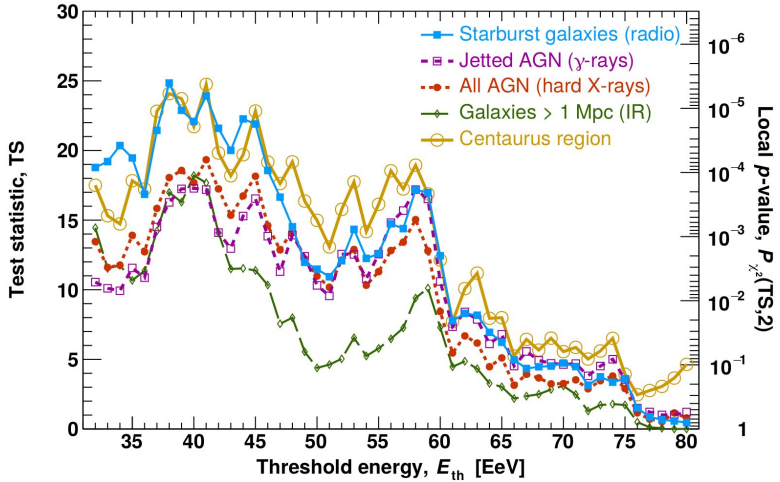
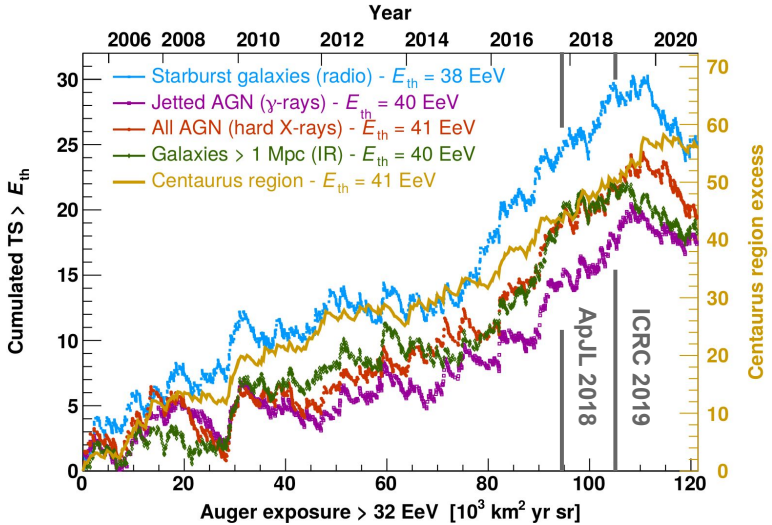
Best-fit parameters and threshold energy

Fit of attenuated flux pattern + isotropy to data with variable signal fraction and smoothing scale above E_{th} = {32, 33, …, 80} EeV
For all four catalogs: most significant signal at E_{th} = 38-41 EeV on top-hat scale Ψ = 23-27° with signal fraction α = 6-15%
Post-trial deviation from isotropy: from **3.1σ (jetted AGN)** up to **4.0σ (starbursts)**.

Evolution of signal with exposure

Starbursts significance: 4.0σ in ApJL 2018, 4.5σ at ICRC2019 (similar α, Ψ above 38-41 EeV).
Compatible with **linear growth within expected variance**





A closer look at the catalog-based models

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Which UHECR overdensities do the models grasp?

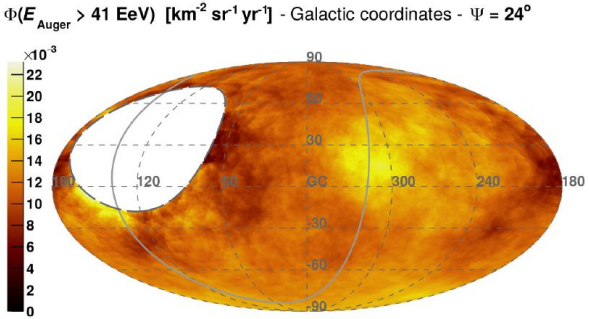
Centaurus region in all models (M83 + Cen A + NGC 4945 at ~4 Mpc)

Galactic-South-pole tepid spot in starburst model (NGC 253 at ~4 Mpc)

No hotspot at (l,b) ~ (280°,75°) from IR model (Virgo cluster at ~16 Mpc)

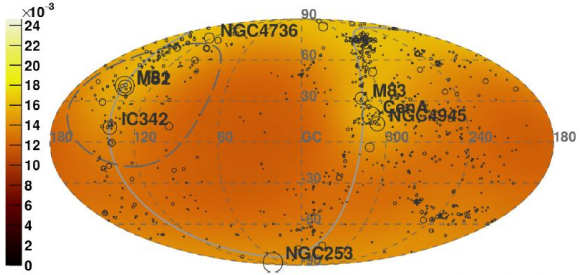
Disclaimer: qualitative comparison
Starbursts + IR/X-ray/γ-ray vs IR/X-ray/γ-ray
yield **only mild (2-3σ) preference for starbursts**

Observed > 41 EeV

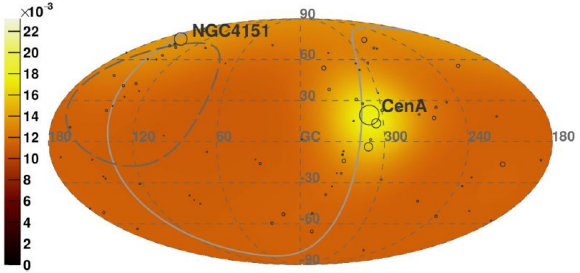


Best-fit models > 38-41 EeV

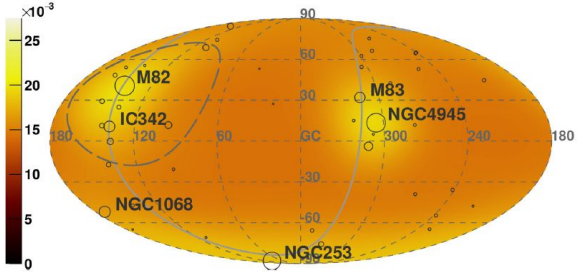
Galaxies > 1 Mpc (IR) - expected $\Phi(E_{Auger} > 40\ EeV)$ [km^{-2} sr^{-1} yr^{-1}]



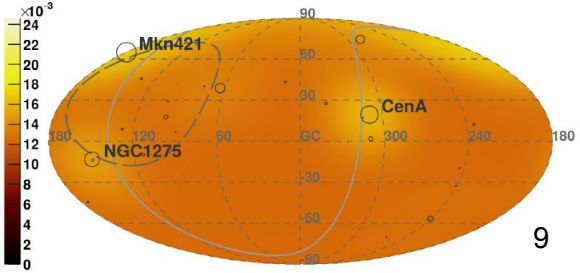
All AGN (hard X-rays) - expected $\Phi(E_{Auger} > 41\ EeV)$ [km^{-2} sr^{-1} yr^{-1}]



Starburst galaxies (radio) - expected $\Phi(E_{Auger} > 38\ EeV)$ [km^{-2} sr^{-1} yr^{-1}]



Jetted AGN (γ-rays) - expected $\Phi(E_{Auger} > 40\ EeV)$ [km^{-2} sr^{-1} yr^{-1}]



Status and near future: what are the ideas?

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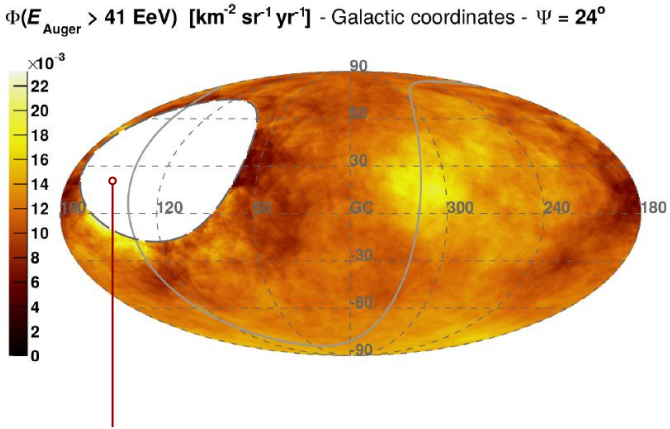
Anisotropies in the toe region with Auger phase 1 data

~4σ from search in Centaurus region, confirmed by catalog-based searches.

Largest signal from starbursts w/o compelling evidence for catalog preference

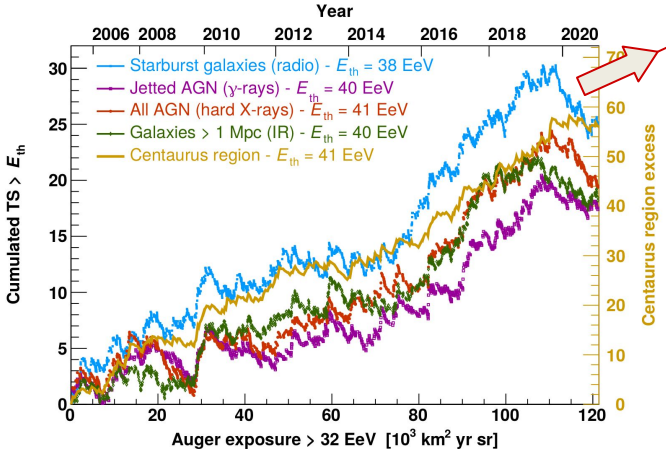


Extension 1: Data quality & quantity

Promising inclusion of **X_{max} information** (*see Bister's and Mayotte's contributions*), particularly in the context of ongoing AugerPrime upgrade

TS growth at a rate of ~ 2 units / year (full array), with TS(5σ) ~ 35

⇒ **Auger-only discovery with current approach in 2025-2030**



Extension 2: Full-sky coverage

Auger-only: 85% of the sky

⇒ **combination with Telescope Array** exposure (**~10% that of Auger**, *see di Matteo's contribution*, promising future for such studies with TA x 4)

Extension 3: From the toe down to the ankle

Significant **large-scale signal in instep region** (*see de Almeida's contribution*)

Promising tomographic mappings of matter in 1 Gyr to **connect sky patterns** (*see Ding's and Biteau's contributions*)