What we know about ultra-high-energy cosmic rays after 20 years of operation of the Pierre Auger Observatory

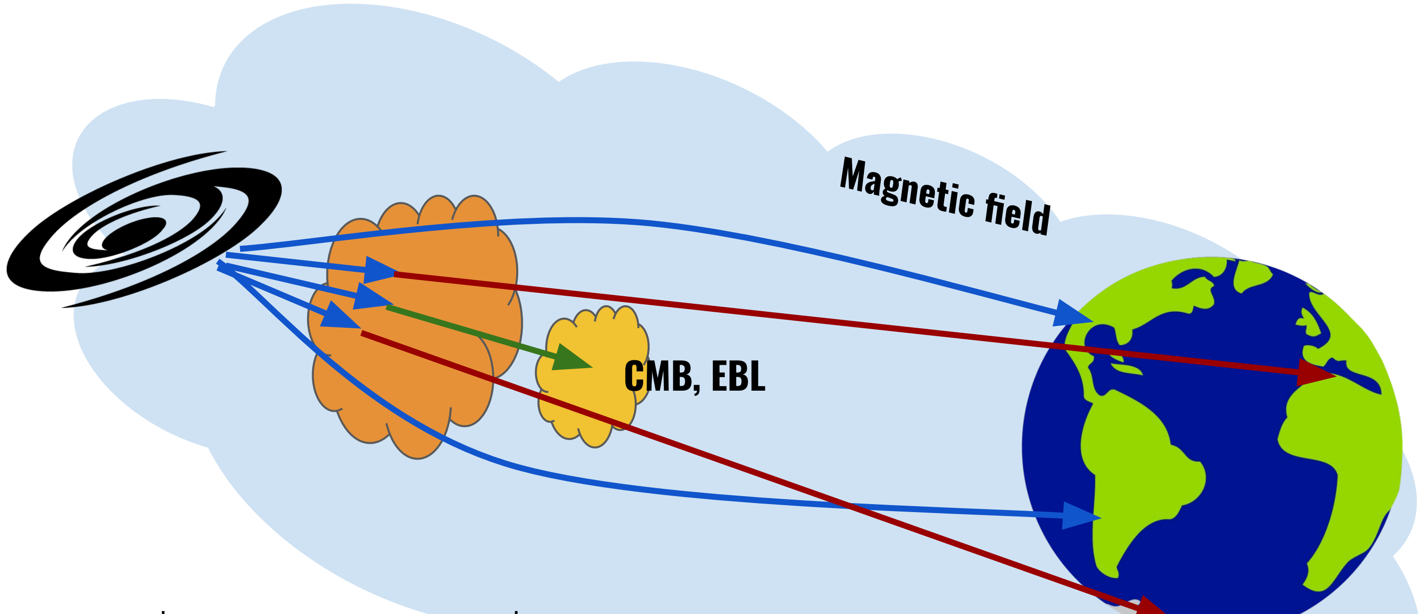
Lorenzo Caccianiga, for the **Pierre Auger Collaboration**

Introduction

Gamma and **neutrino** emissions are strictly related to **cosmic rays**

At the highest energies the **flux** of cosmic rays is **extremely low** (less than 1 per km^2 per century)

→ need for huge detectors... and patience



$$p + \gamma/p \longrightarrow \pi^+ + n \longrightarrow \mu^+ + \nu_\mu + n \longrightarrow e^+ + \nu_\mu + \nu_e + \nu_\mu + n$$

$$\longrightarrow \pi^0 + p \longrightarrow \gamma + \gamma + p$$

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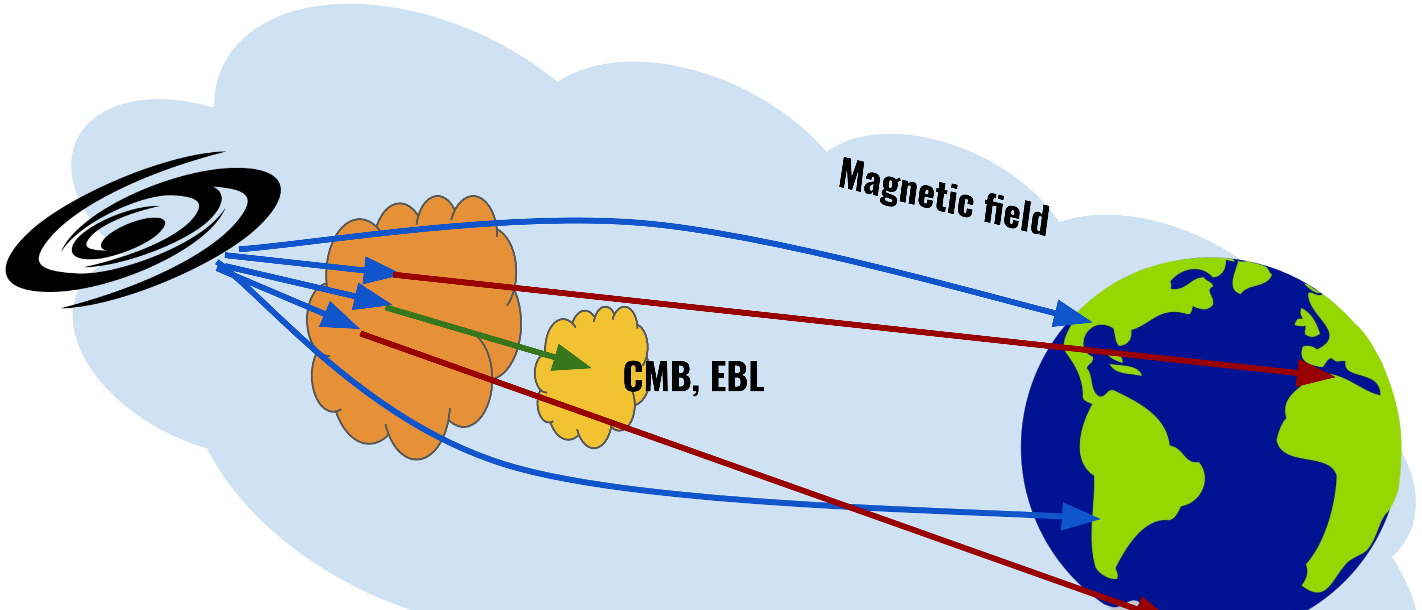
The Pierre Auger Observatory has a **detection area of 3000 km^2** and started taking data in **2004**, 20 years ago.

20 years is a long time



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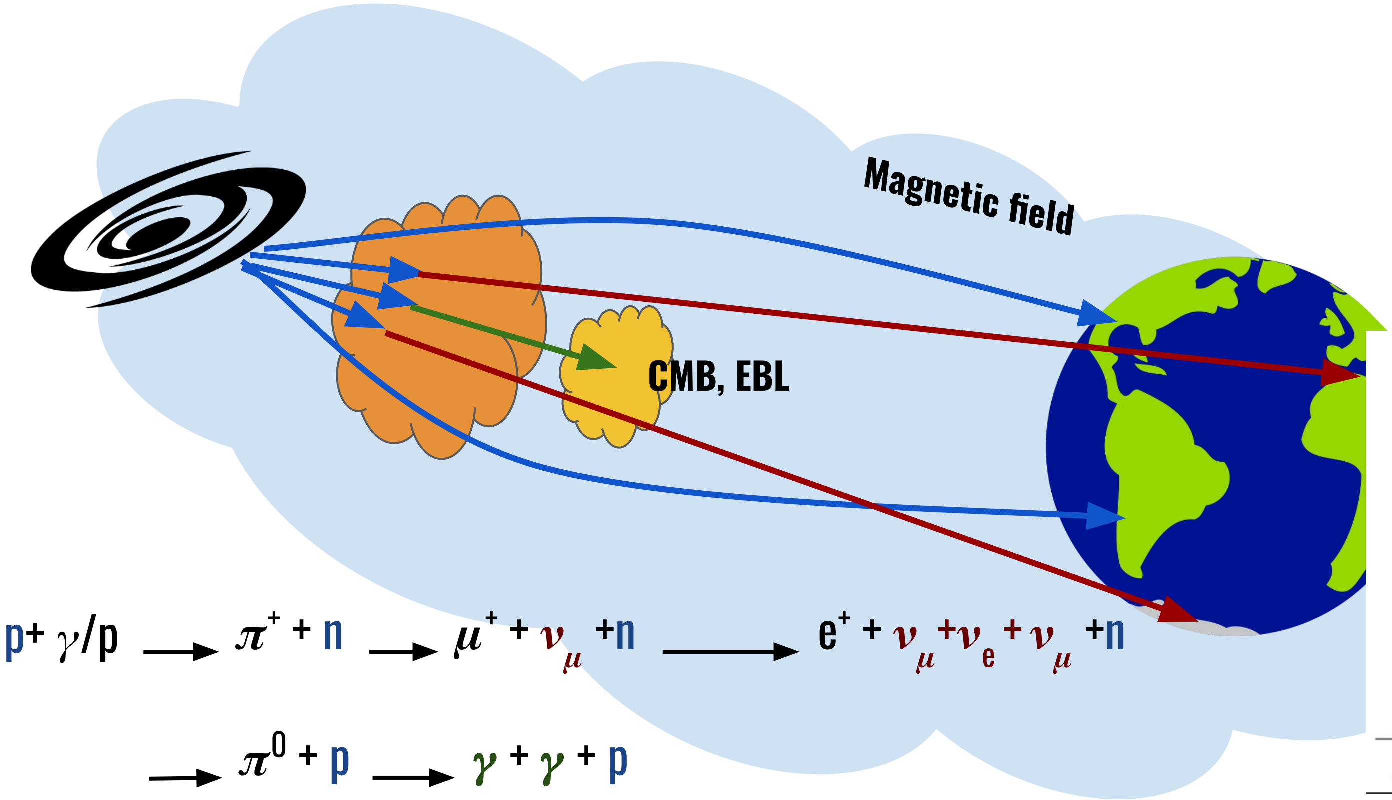

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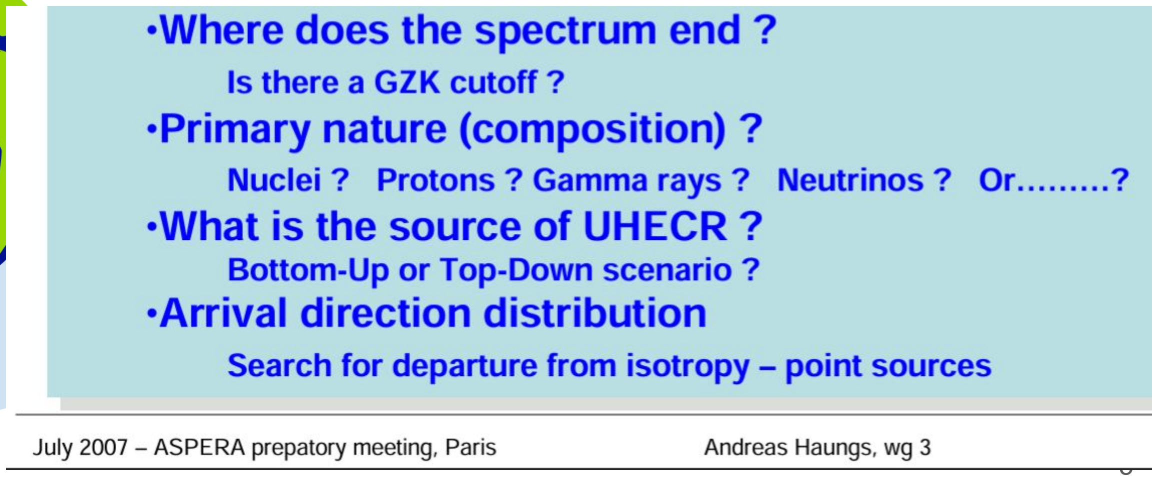


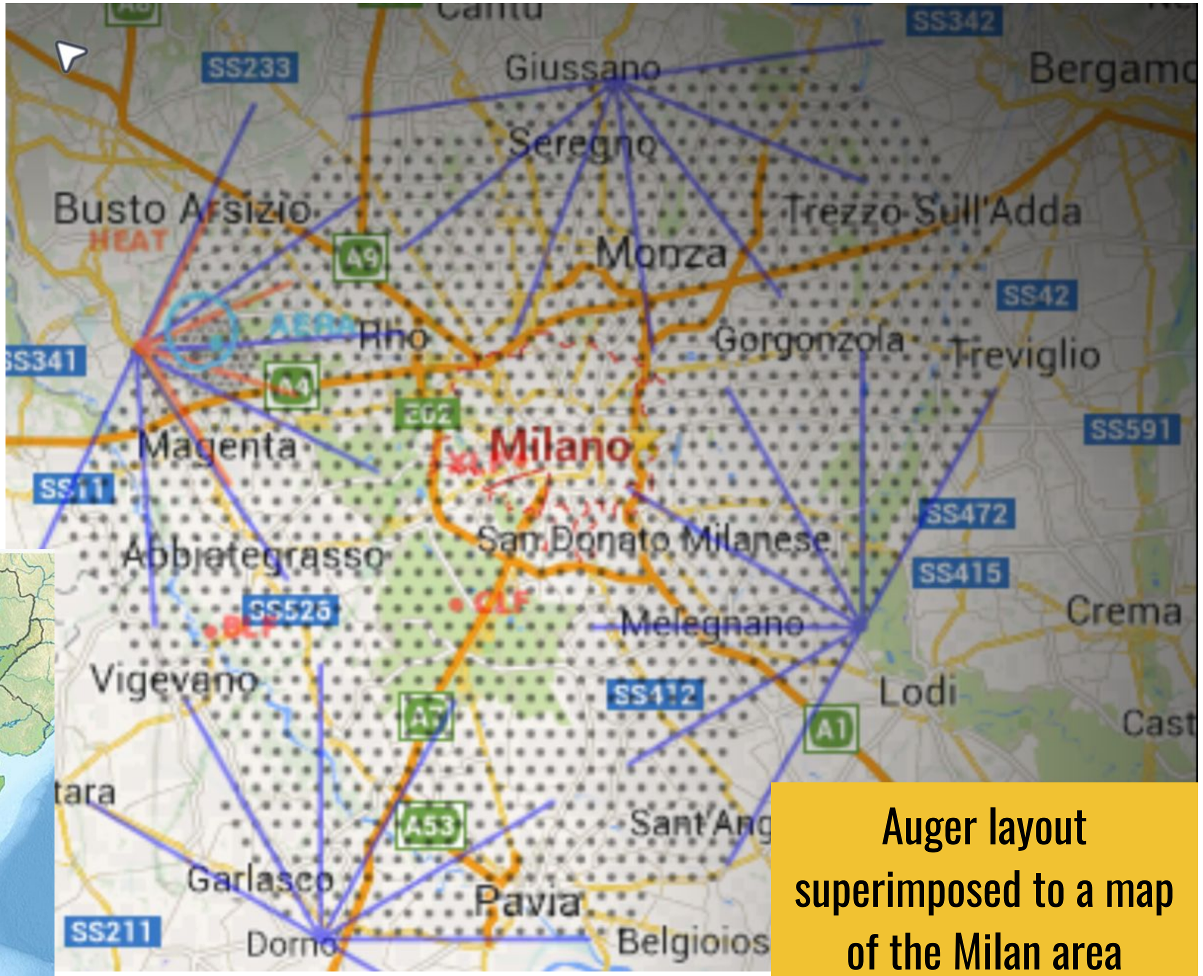
- **Where does the spectrum end ?**
  - Is there a GZK cutoff ?
- **Primary nature (composition) ?**
  - Nuclei ? Protons ? Gamma rays ? Neutrinos ? Or………?
- **What is the source of UHECR ?**
  - Bottom-Up or Top-Down scenario ?
- **Arrival direction distribution**
  - Search for departure from isotropy – point sources

July 2007 – ASPERA prepatory meeting, Paris Andreas Haungs, wg 3

The Pierre Auger Collaboration

~400 members from 18 countries and

The Pierre Auger Observatory



Auger layout superimposed to a map of the Milan area

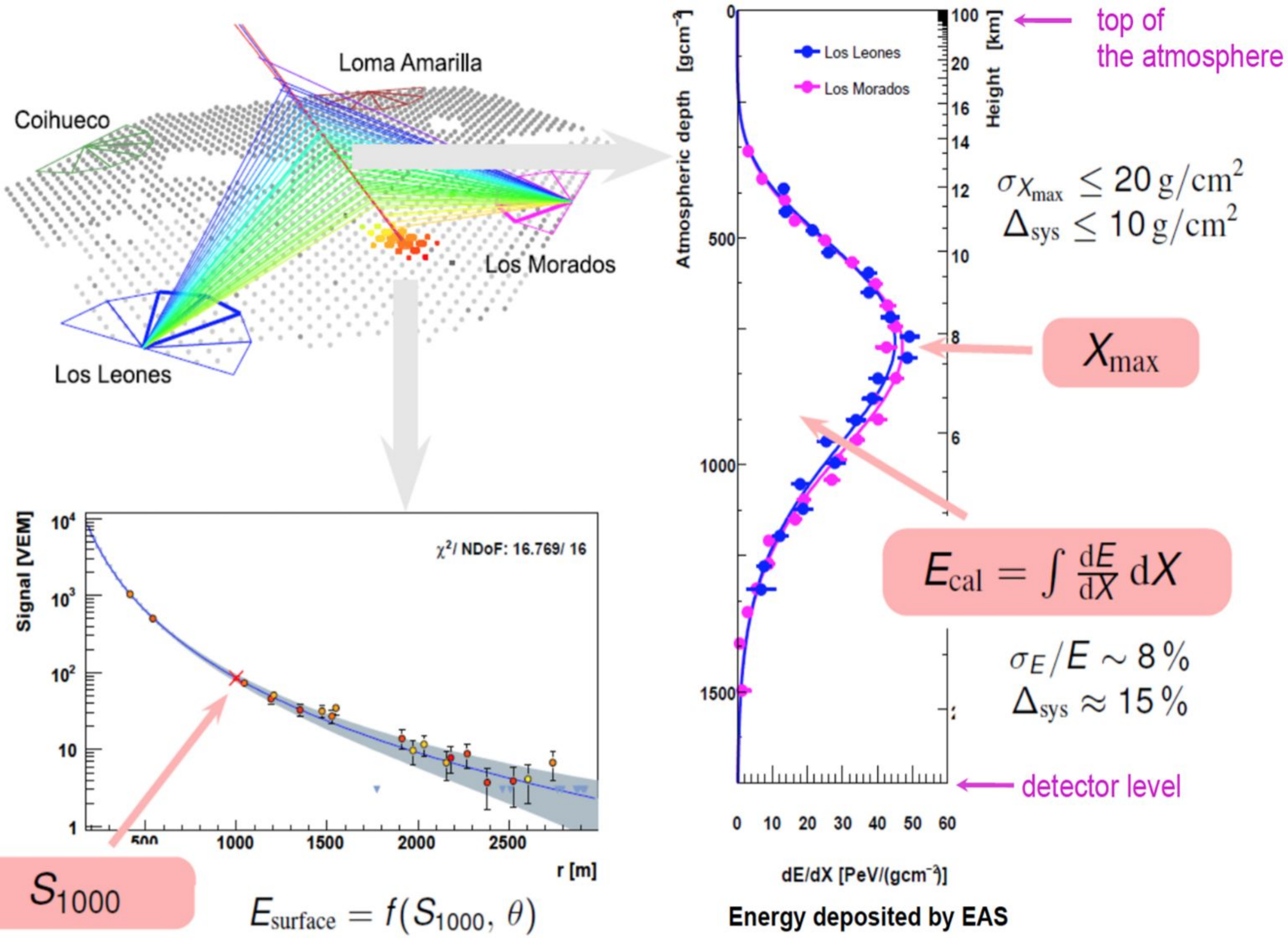
Located in **Argentina**, in the Pampa Amarilla, around 1400 m of altitude

Operating since 2004, full array completed in 2008.

Largest detector of UHECR

energy range $10^{17(16)}$-10^{20} eV

The Pierre Auger Observatory



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SD - Array of 1660 water cherenkov detectors (100% duty cycle)

FD - 27 fluorescence telescopes (10-15% DC)

The Pierre Auger Observatory... upgraded

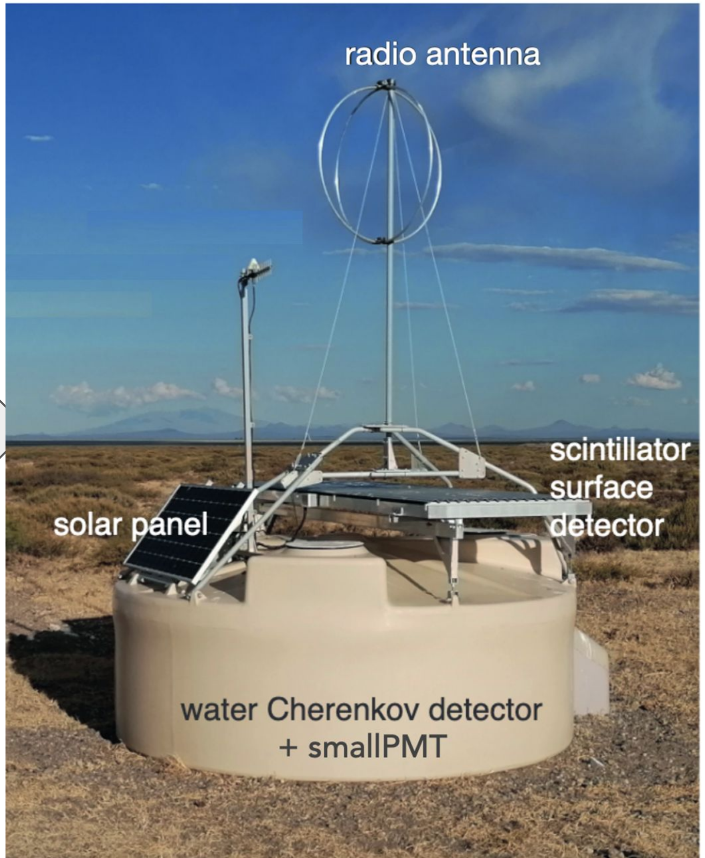
Between 2019 and 2023 Auger underwent a huge upgrade:

- New electronics for SD stations, with a new (smaller) PMT and a scintillator and a radio antenna
- Extended FD operation

2004 →2021
Auger "phase 1"

2021 →2023
Transition phase

2024 →2035
Auger Prime (Phase 2)



Cosmic rays, how many of them?

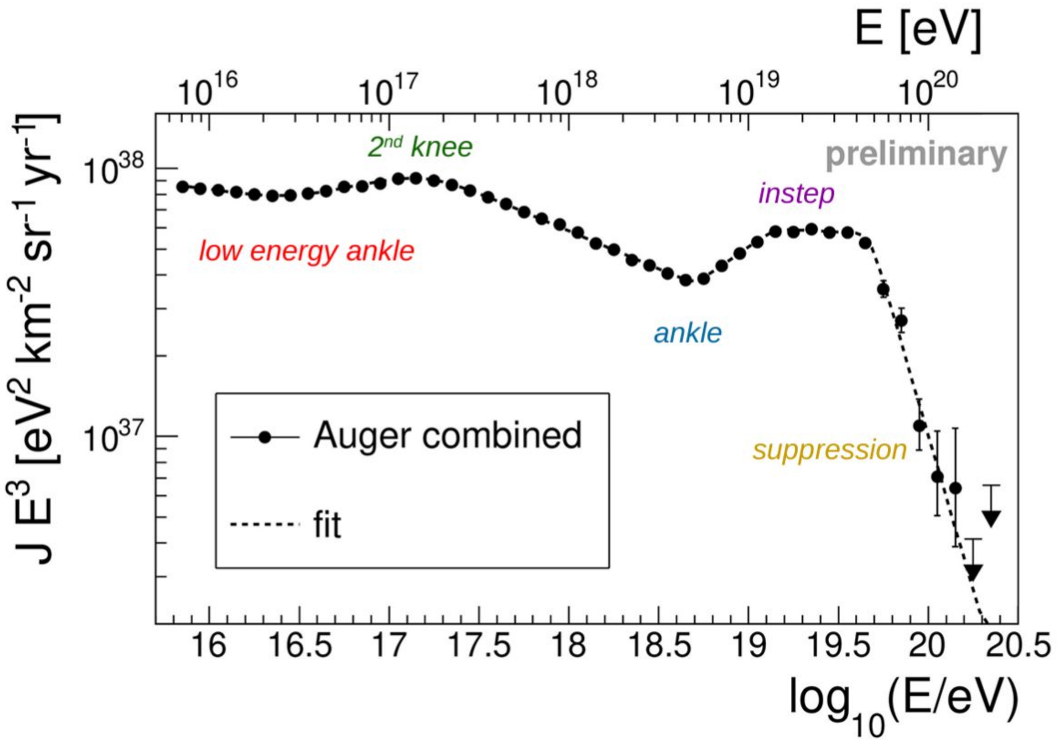
Energy spectrum estimated from 5 measurements

three from SD – precisely defined exposure, large statistics

two from FD – nearly calorimetric measurement of energy

Exposure >80,000 km^2 sr yr

>920,000 events



fit parameters (± stat. ± syst.)

$\gamma_0 = 3.09 \pm 0.01 \pm 0.10$

$E_{01} = (2.8 \pm 0.3 \pm 0.4) \times 10^{16}$ eV

$\gamma_1 = 2.85 \pm 0.01 \pm 0.05$

$E_{12} = (1.58 \pm 0.05 \pm 0.2) \times 10^{17}$ eV

$\gamma_2 = 3.283 \pm 0.002 \pm 0.10$

$E_{23} = (5.0 \pm 0.1 \pm 0.8) \times 10^{18}$ eV

$\gamma_3 = 2.54 \pm 0.03 \pm 0.05$

$E_{34} = (1.4 \pm 0.1 \pm 0.2) \times 10^{19}$ eV

$\gamma_4 = 3.03 \pm 0.05 \pm 0.10$

$E_{45} = (4.7 \pm 0.3 \pm 0.6) \times 10^{19}$ eV

$\gamma_5 = 5.3 \pm 0.3 \pm 0.1$

$J_0 = (8.34 \pm 0.04 \pm 3.40) \times 10^{-11}\ km^{-2}\ sr^{-1}\ yr^{-1}\ eV^{-1}$

Auger Coll., Phys.Rev.D102 (2020) 062005 Auger Coll., Phys.Rev.Lett. 125 (2020) 121106 Auger Coll., Eur. Phys. J. C 81 (2021) 966
V.Novotny, PoS(ICRC2021) 324 A.Brichetto, PoS(ICRC2023) 398

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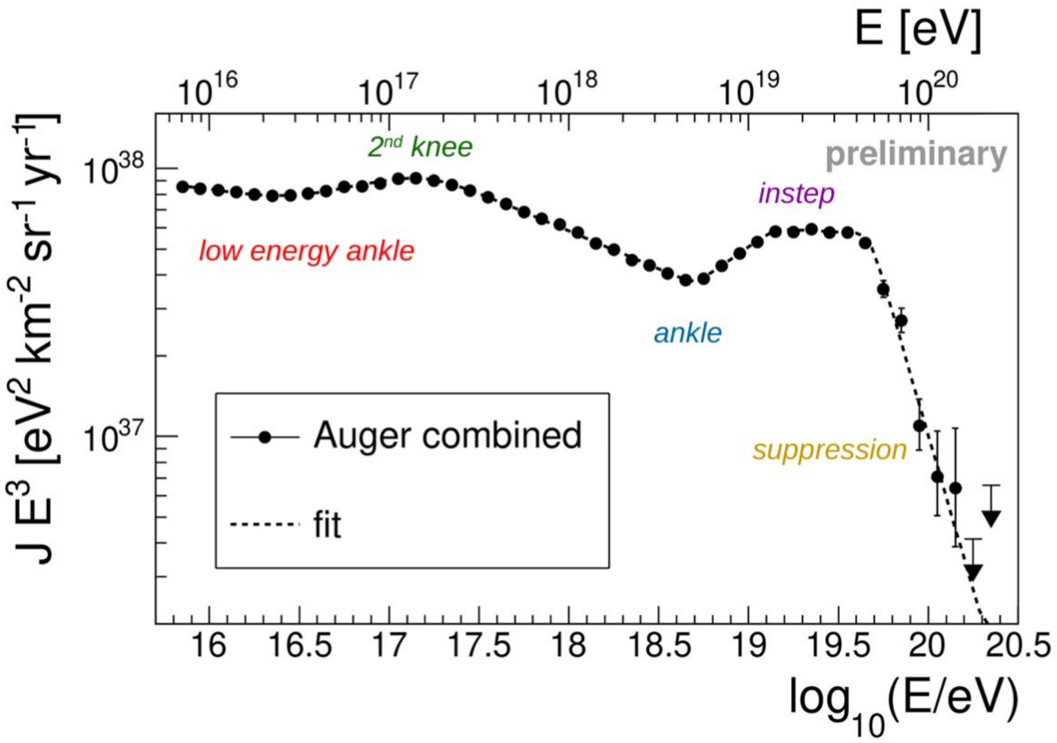

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- We **confirm** the existence of a suppression starting around 50 EeV
- Unprecedented precision in measuring the position of the different features
- Brand new features like the **instep**!
- Extension to **very low energy** (10 PeV) thanks to dedicated FD detectors (HEAT) and **Cherenkov measurements**

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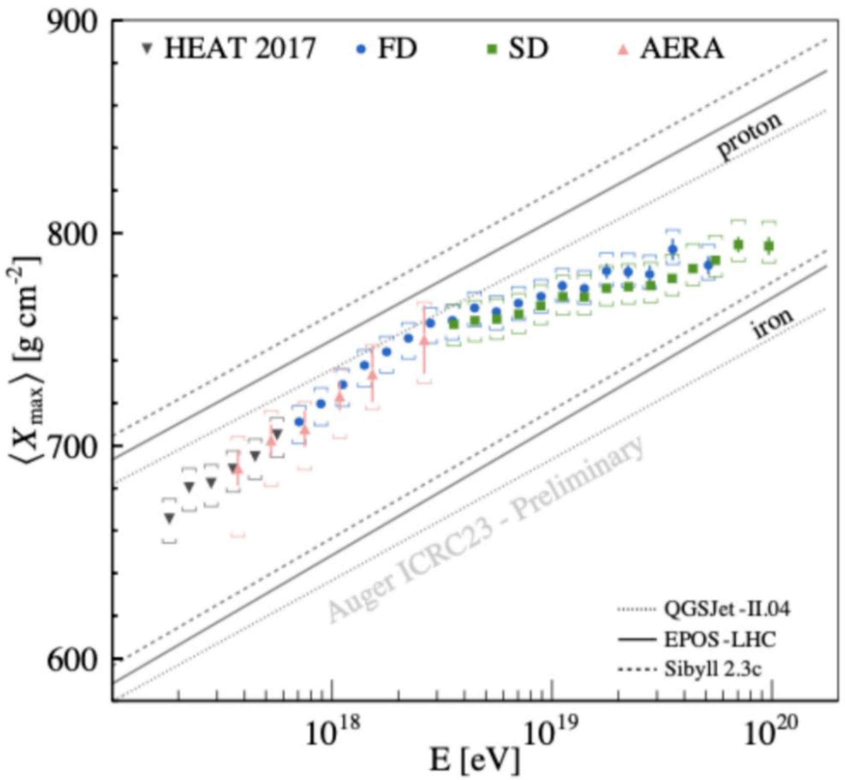
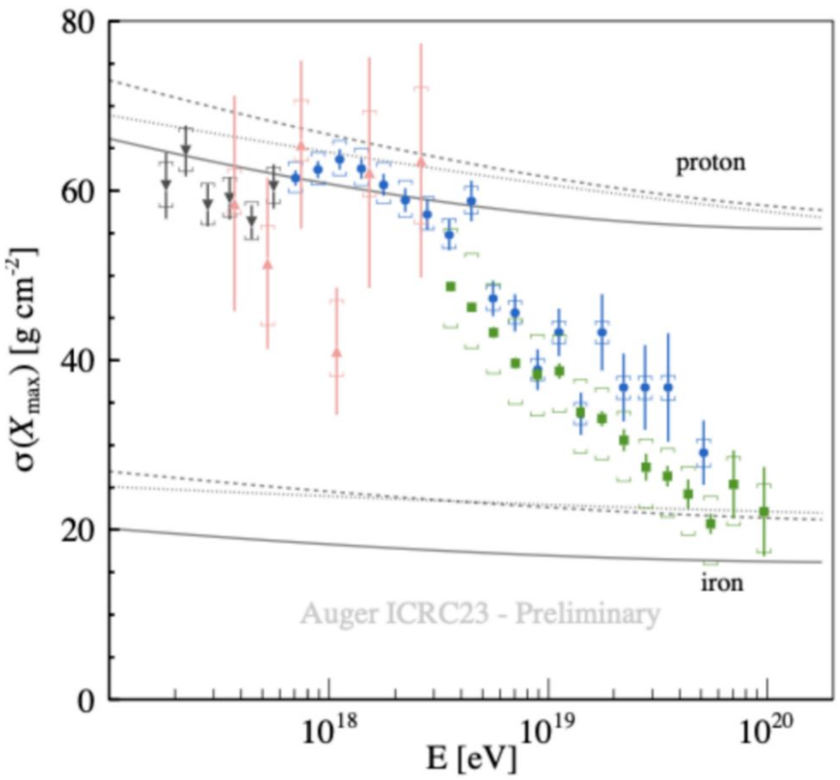
Cosmic rays, what are they?

Depth of the shower maximum measured with FD, the most direct but with only ∽ 10% duty cycle

Shower characteristics at ground measured with SD and fitted to reconstruct Xmax - recently achieved (also with ML), 100% duty cycle

Radio footprint (RD, 100% duty cycle) completely independent and nicely agree with the “standard” ones





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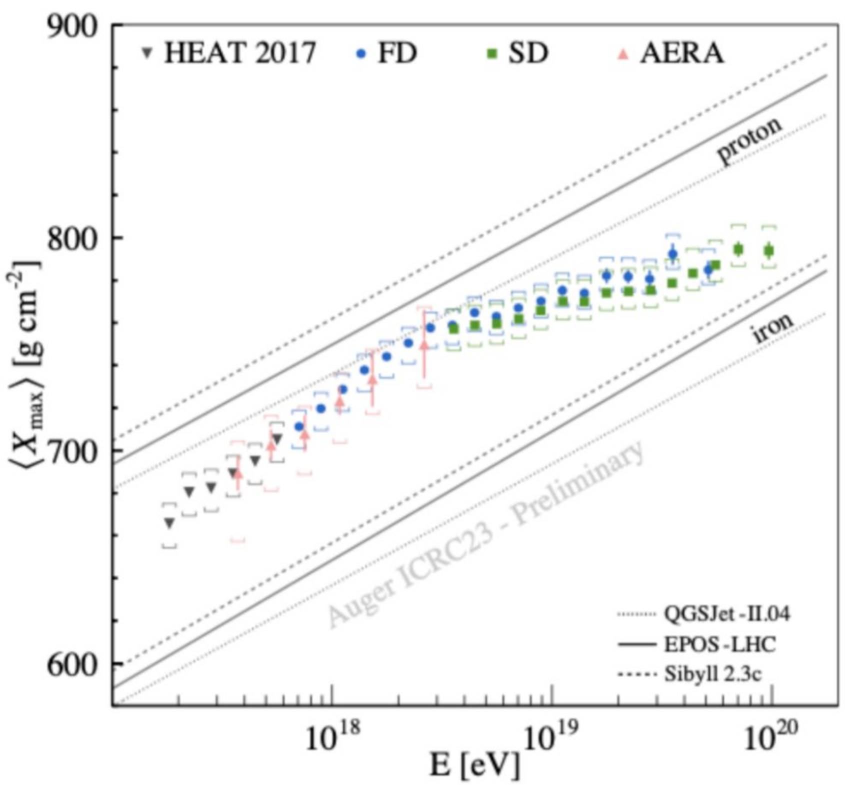
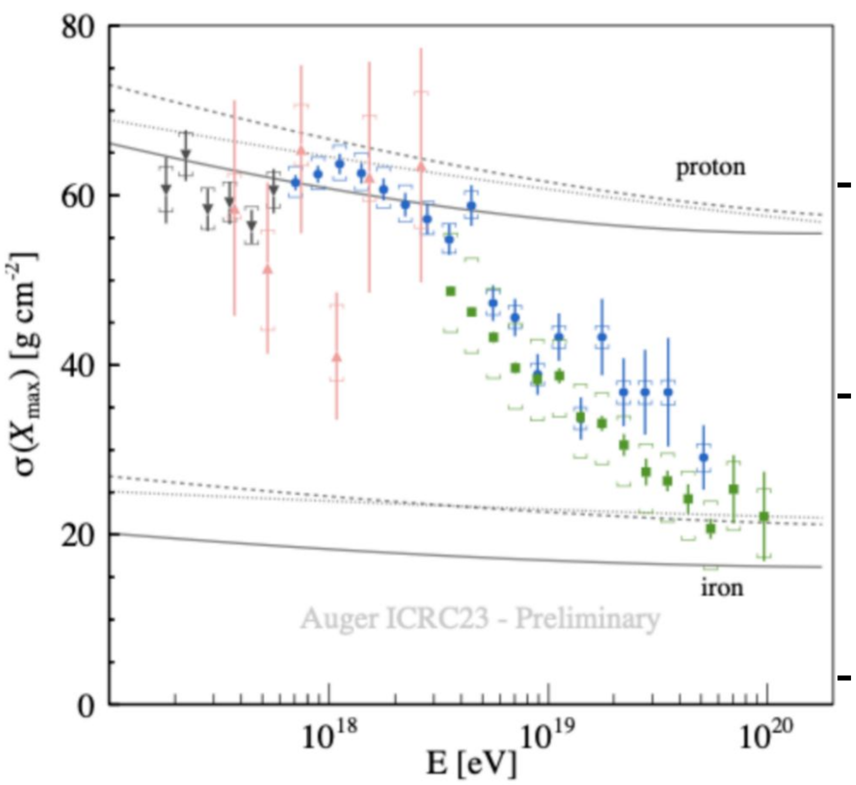




- Composition gets **lighter** up to few 10^{18} eV and **heavier** above this energy
- At the **highest energies**, we can exclude a **large fraction of protons**
- Converting this in **actual mass** (thus charge) requires **hadronic interaction models**, tuned at much **lower energies** (LHC)
- So far, “mass” information **not** used **event-by event**

The Pierre Auger Observatory… a multi-purpose experiment!

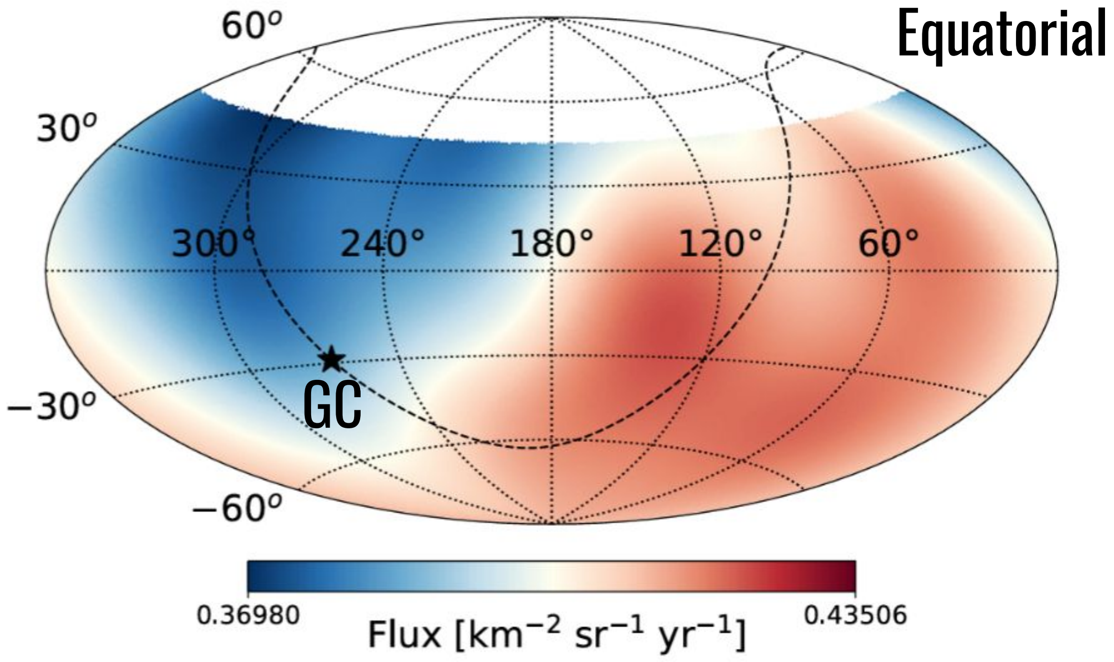
Things that I don't have time to discuss:

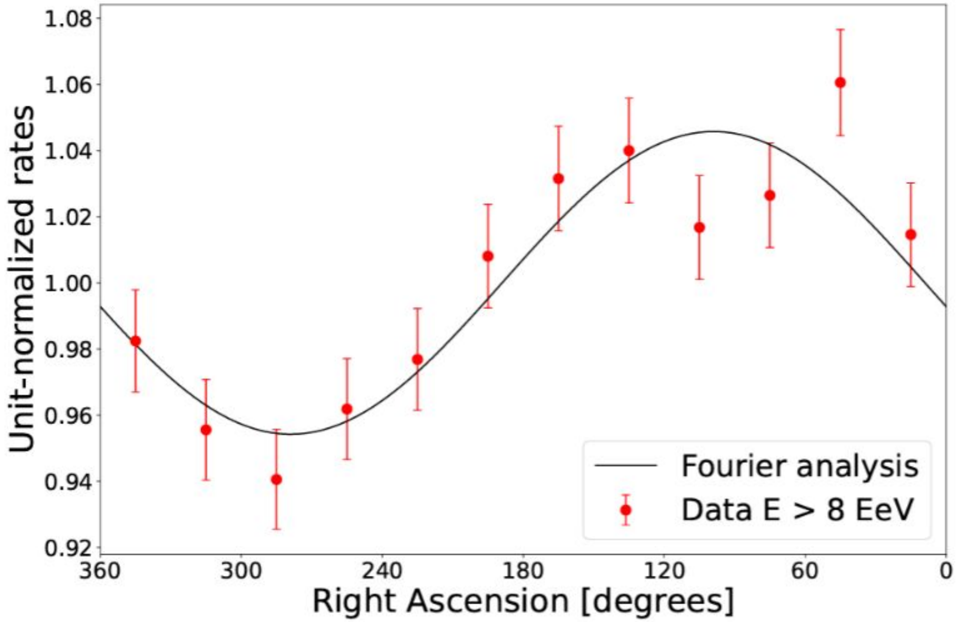
- **The Muon puzzle: why do we observe less muons than predicted in hadronic interaction models?** *Auger Coll., PRD91 (2015) 032003+059901 Auger Coll., PRL 126 (2021) 152002*
- **Particle physics results: p-air cross section and shower development Auger Coll.,** *Phys.Rev.D109 (2024) 102001*
- **Atmospheric studies with the Observatory: ELVES and other magical creatures** *Earth Space Sci. 7 (2020) e2019EA000582*
- **Search for Lorenz invariance violation in air showers and CR propagation:** *Auger Coll., JCAP01 (2022) 023 C.Trimarelli (Auger Coll.), UHECR2022*
- **Search for Super-Heavy Dark Matter** *Auger coll., PRD 109 (2024) L081101; Auger coll., PRL 130 (2023) 061001; Auger coll., PRD 107 (2023) 042002*

What I will focus on:

- **Arrival direction studies: large scale, small/intermediate scale, search for neutrons**
- **Search for neutrinos:** with the Observatory we can detect UHE neutrinos better than most experiments
- **Search for gamma:** we can try and distinguish showers induced by photons from the dominant hadronic background

Where do cosmic rays come from? - Large scale





- Well established **dipolar feature** observed **above 8 EeV** (> 6 σ) - *Science 357 (2017) 1266-1270*
- Points **away from the Galactic Center**, suggesting **extragalactic origin**
- **No** significant **dipole** observed in the **4-8 EeV energy bin**, despite much larger statistics
- **No** significant **higher multipole** found in any energy bin

All plots and results for large scale analyses are from the new work: Large-scale cosmic ray anisotropies with 19 years of data from the Pierre Auger Observatory, arXiv:2408.05292 submitted to ApJ

Where do cosmic rays come from? - Large scale

E [EeV]	N	$d_\perp$ [%]	d_z [%]	d [%]	α_d [°]	δ_d [°]	$P(\geq r_1^\alpha)$
4-8	118,722	$1.0^{+0.6}_{-0.4}$	-1.3 ± 0.8	$1.7^{+0.8}_{-0.5}$	92 ± 28	-52^{+21}_{-19}	0.14
≥8	49,678	$5.8^{+0.9}_{-0.8}$	-4.5 ± 1.2	$7.4^{+1.0}_{-0.8}$	97 ± 8	-38^{+9}_{-9}	8.7×10^{-12}
8-16	36,658	$5.7^{+1.0}_{-0.9}$	-3.1 ± 1.4	$6.5^{+1.2}_{-0.9}$	93 ± 9	-29^{+11}_{-12}	1.4×10^{-8}
16-32	10,282	$5.9^{+2.0}_{-1.8}$	-7 ± 3	$9.4^{+2.6}_{-1.9}$	93 ± 16	-51^{+13}_{-13}	4.3×10^{-3}
≥32	2,738	11^{+4}_{-3}	-13 ± 5	17^{+5}_{-4}	144 ± 18	-51^{+14}_{-14}	9.8×10^{-3}

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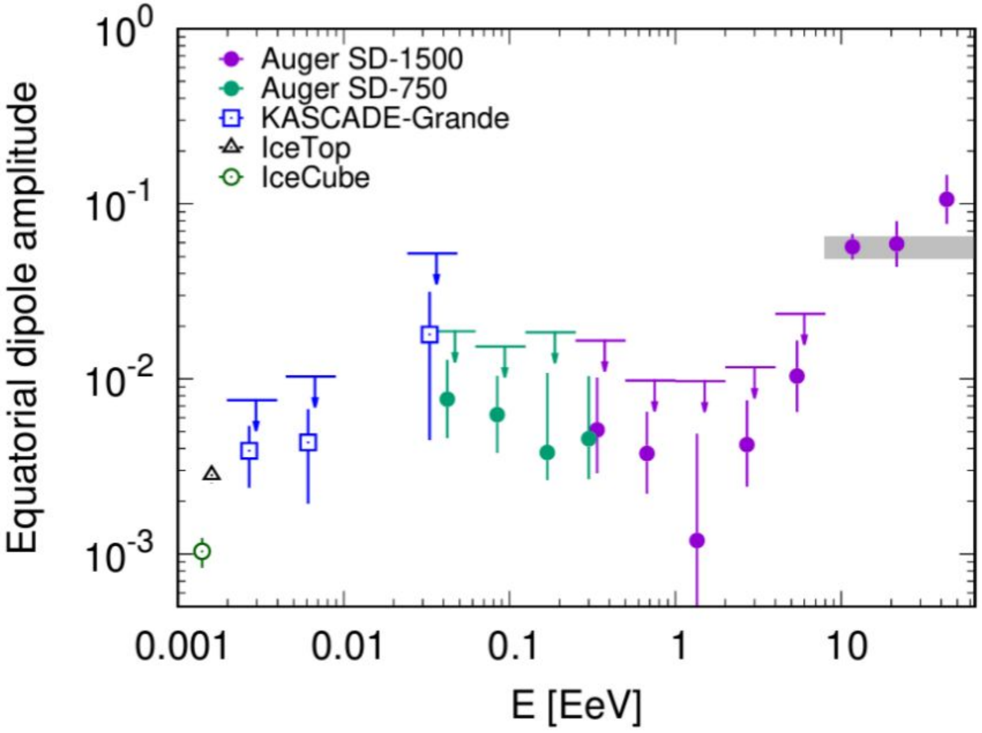
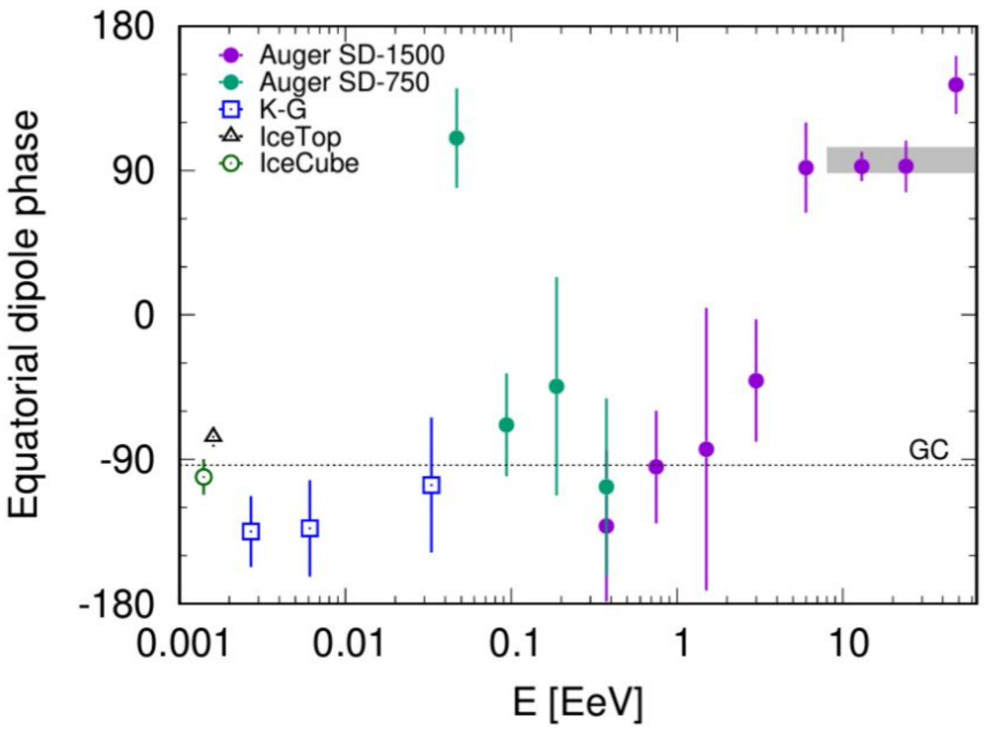


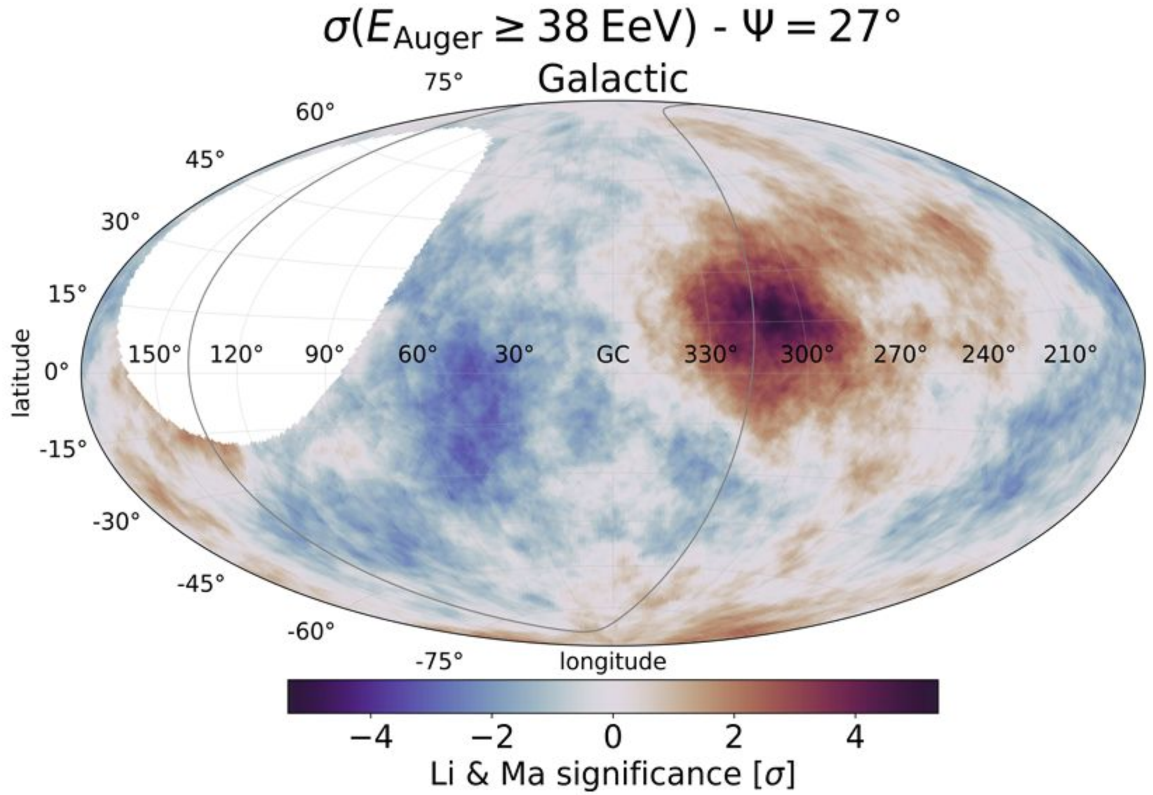


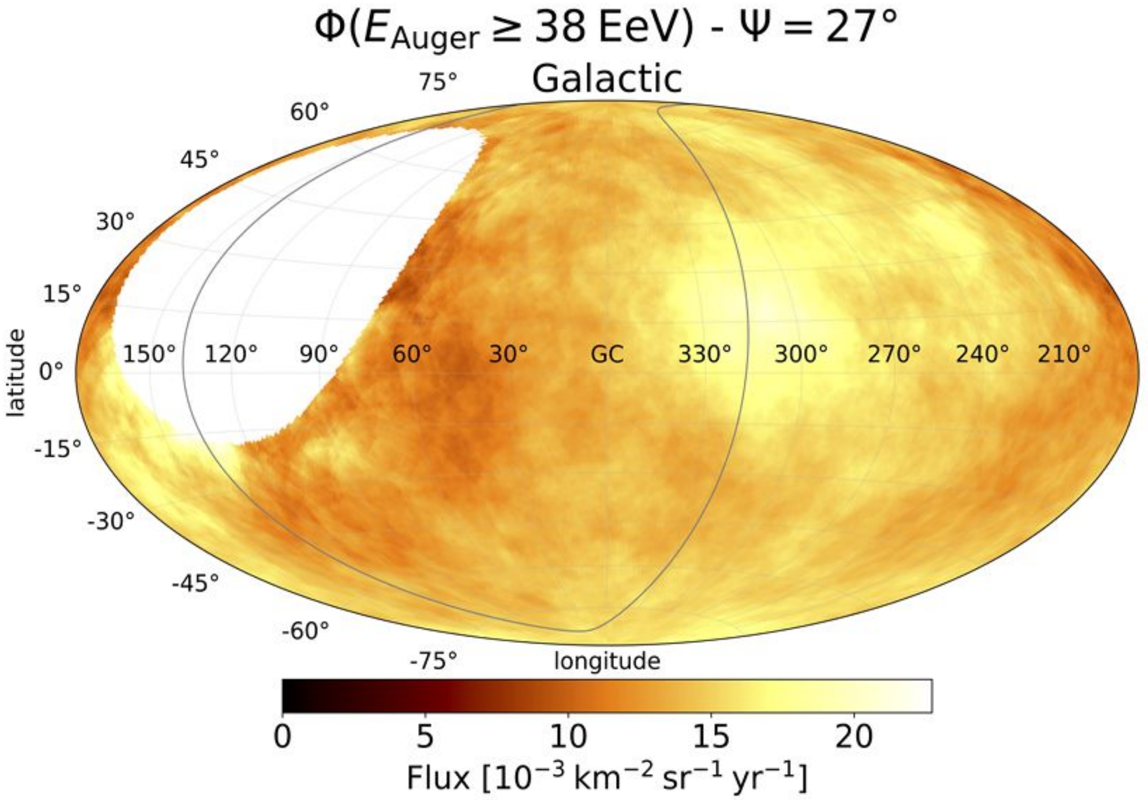
- **The phase shift** around **3-4 EeV** may be a suggestion for where the **transition between galactic and extragalactic** happens
- we found no significant dipole below 8 EeV

Where do cosmic rays come from? Small/intermediate scale

Results of a scan in energy threshold (from 32 EeV) and angle (1°-30°) around the position of CenA

→**4σ post trial excess** in a 27° top-hat region for events above 38 EeV





G. Golup for the Auger coll. PoS(ICRC2023)252 - Astrophys. J. 935 (2022) 170

Where do cosmic rays come from? Small/intermediate scale

Search for correlation with **extragalactic catalogs** using a **likelihood analysis**, considering probability maps built weighting objects by their relative fux in the corresponding e.m. band and an attenuation due to their different distances

Free parameters: Energy threshold, fisher smearing angle and anisotropic fraction.

Catalog	E_{th} [EeV]	Ψ [°]	α [%]	TS	Post-trial p-value	
All galaxies (IR)	38	24^{+15}_{-8}	14^{+8}_{-6}	18.5	6.3×10^{-4}	► 3.2σ
Starbursts (radio)	38	25^{+13}_{-7}	9^{+7}_{-4}	23.4	6.6×10^{-5}	► 3.8σ
All AGNs (X-rays)	38	25^{+12}_{-7}	7^{+4}_{-3}	20.5	2.5×10^{-4}	► 3.5σ
Jetted AGNs (γ-rays)	38	23^{+8}_{-7}	6^{+3}_{-3}	19.2	4.6×10^{-4}	► 3.3σ

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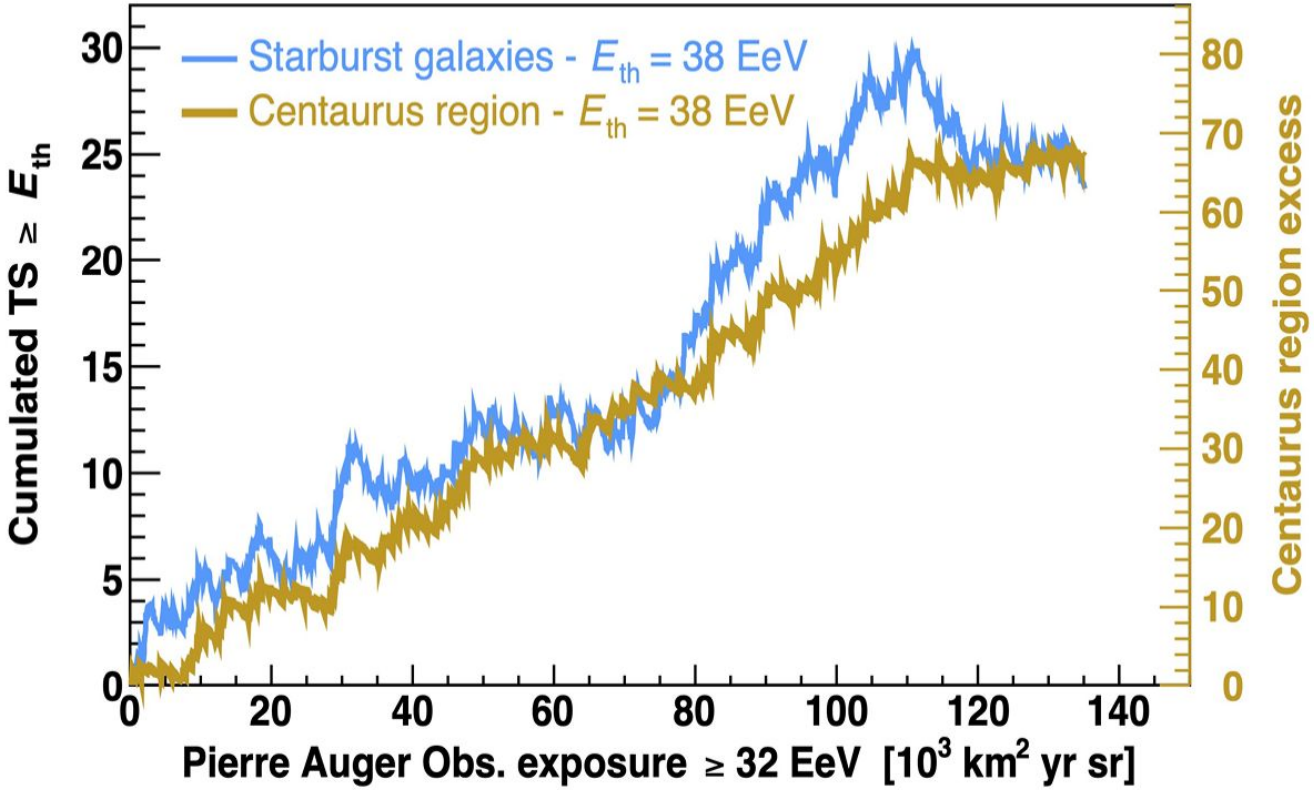

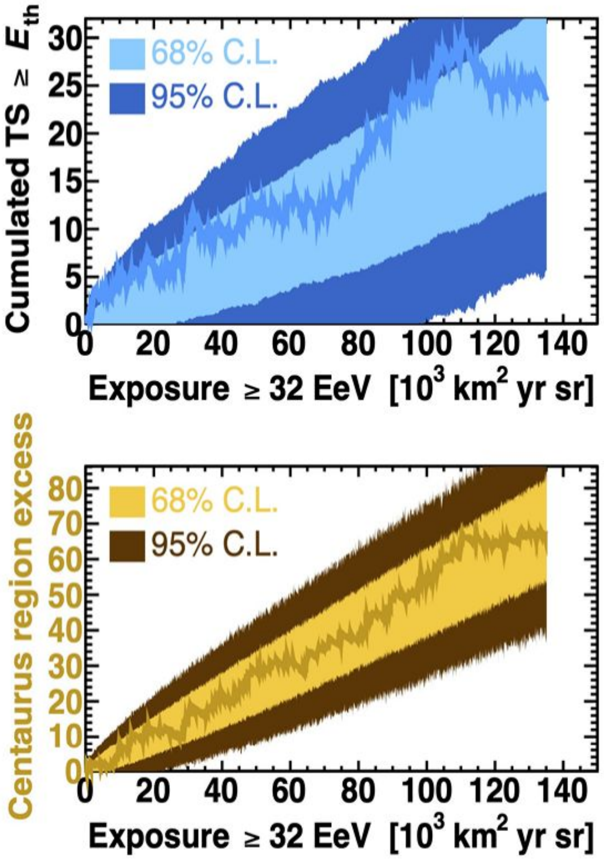

Cata	
All g	3.2σ
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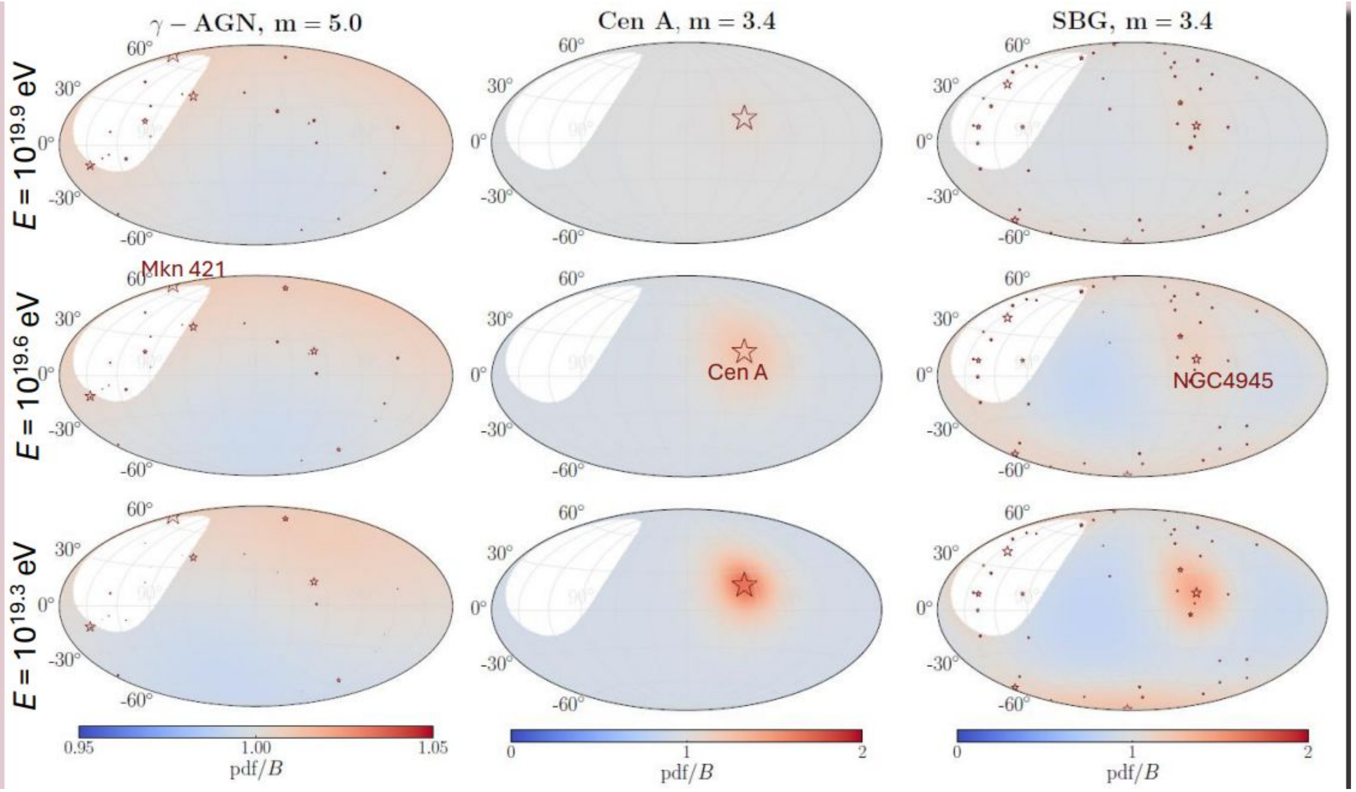
We also searched for correlations between **UHECRs** observed by **Auger** and **TA** and **UHE neutrinos** from **IceCube** and **ANTARES**, found none. *Astrophys. J. 934 (2022) 164*

Fitting all we know: a combine fit of spectrum, mass and arrival directions

With some assumption, we can try and fit together the information from different observables.
→ fit to **spectrum**, **shower depths** & **energy-dependent arrival directions** (no coherent field)



Auger Coll., JCAP 01 (2024) 022

- **AGNs disfavored**
- **SBG model describes data very well**
  → 4.5σ significance compared to model with only homogeneously distributed sources
  - best-fit: ~20% from SBGs at 40 EeV, ~20° blurring for proton at 10 EeV
- **Centaurus region** well described by local source at ~4 Mpc

Where do cosmic ray come from? Neutrons

Neutrons can be produced near the **source**, they **decay** but they can travel **9.2 kpc** per **EeV of energy**

- we search for excesses at the scale of **Auger's angular resolution** (which varies... generally ~1°)
- first results published in 2014, now being updated with higher sky coverage and lower threshold energy
- **12 target sets** resulting in a total of **888 sources** with a declination **up to +45°**. Of those, 166 are within a distance $\leqslant$ 1 kpc and have a declination up to 20° (suitable for search below EeV).

- Millisecond Pulsars
- γ-ray Pulsars
- Low Mass X-ray Binaries
- High Mass X-ray Binaries
- γ TeV emitters - Pulsar Wind Nebulae
- γ TeV emitters - Other

- γ TeV emitters - UNIDentified
- Microquasars
- Magnetars
- **LHAASO PeVatrons**
- **Crab Nebula**
- Galactic Center

Where do cosmic ray come from? Neutrons

No significant excess found, we can put **upper limits**

→ here you can see the UL for the most significant source in each catalog

Class	R.A. [deg]	Dec. [deg]	Flux U.L. [km^{-2} yr^{-1}]	E-Flux U.L. [eV cm^{-2} s^{-1}]	p-value	p^*
msec PSRs	286.2	2.1	0.026	0.19	0.0075	0.88
γ-ray PSRs	296.6	−54.1	0.023	0.17	5.0×10^{-5}	0.013
LMXB	237.0	−62.6	0.017	0.12	0.0069	0.51
HMXB	308.1	41.0	0.13	0.97	0.014	0.57
TeV γ-ray - PWN	128.8	−45.6	0.016	0.12	0.0070	0.18
TeV γ-ray - other	128.8	−45.2	0.014	0.11	0.022	0.63
TeV γ-ray - UNID	305.0	40.8	0.15	1.1	0.0066	0.31
Microquasars	308.1	41.0	0.13	0.95	0.014	0.19
Magnetars	249.0	−47.6	0.011	0.079	0.15	0.99
LHAASO	292.3	17.8	0.038	0.28	0.024	0.20
Crab	83.6	22.0	0.020	0.15	0.71	0.71
Galactic Center	266.4	−29.0	0.0053	0.039	0.86	0.86

PoS

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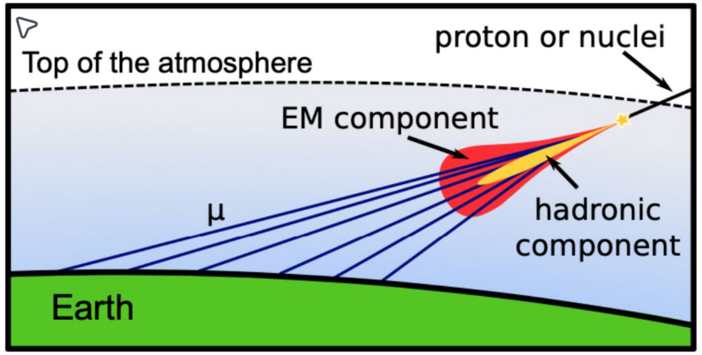
PoS

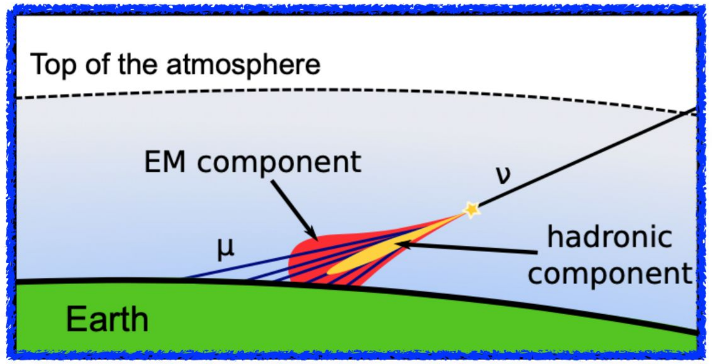
A paper is in preparation, hopefully out by the end of the year.

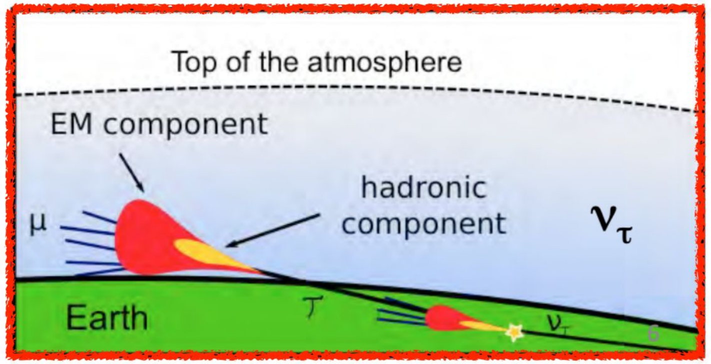
Following that, we plan on doing:

- a **blind search on all sky**
- a **correlation with Galactic Plane**
- a **space-time correlation** with variable sources

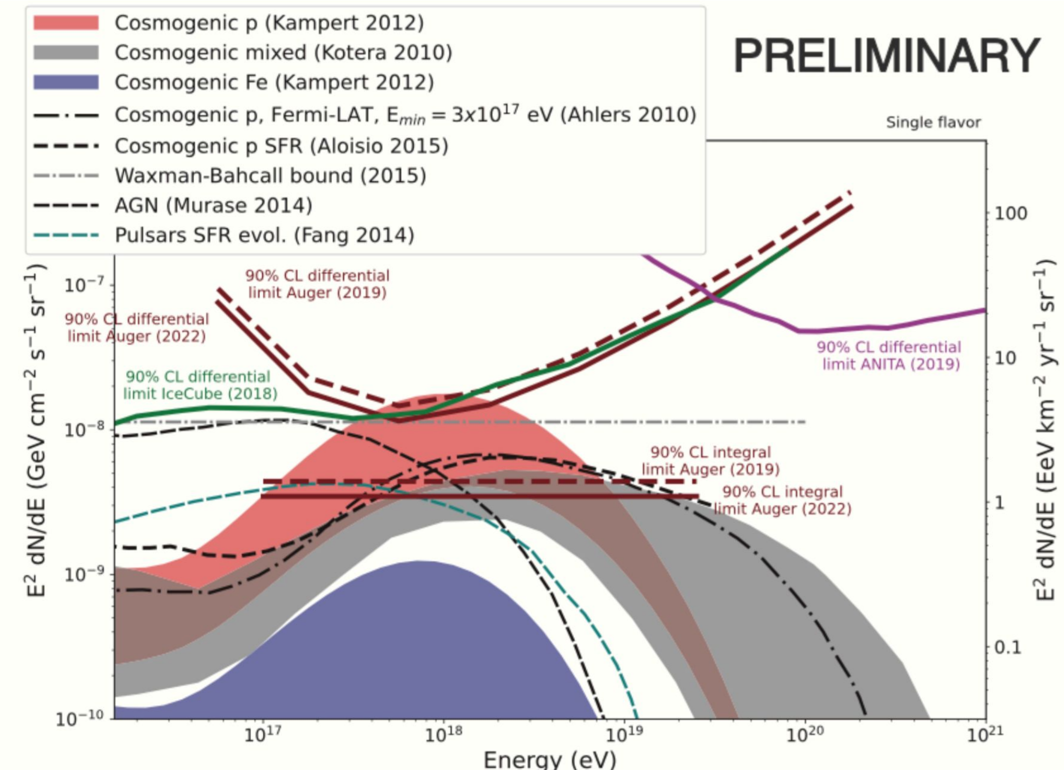
not only cosmic rays: neutrino detection







- No candidates found: upper limits put
- best sensitivity around 10^{18} eV
- practically no background → limited by exposure
- Constraints on models assuming proton composition



Auger Coll., JCAP 10 (2019) 022 UHECR2022

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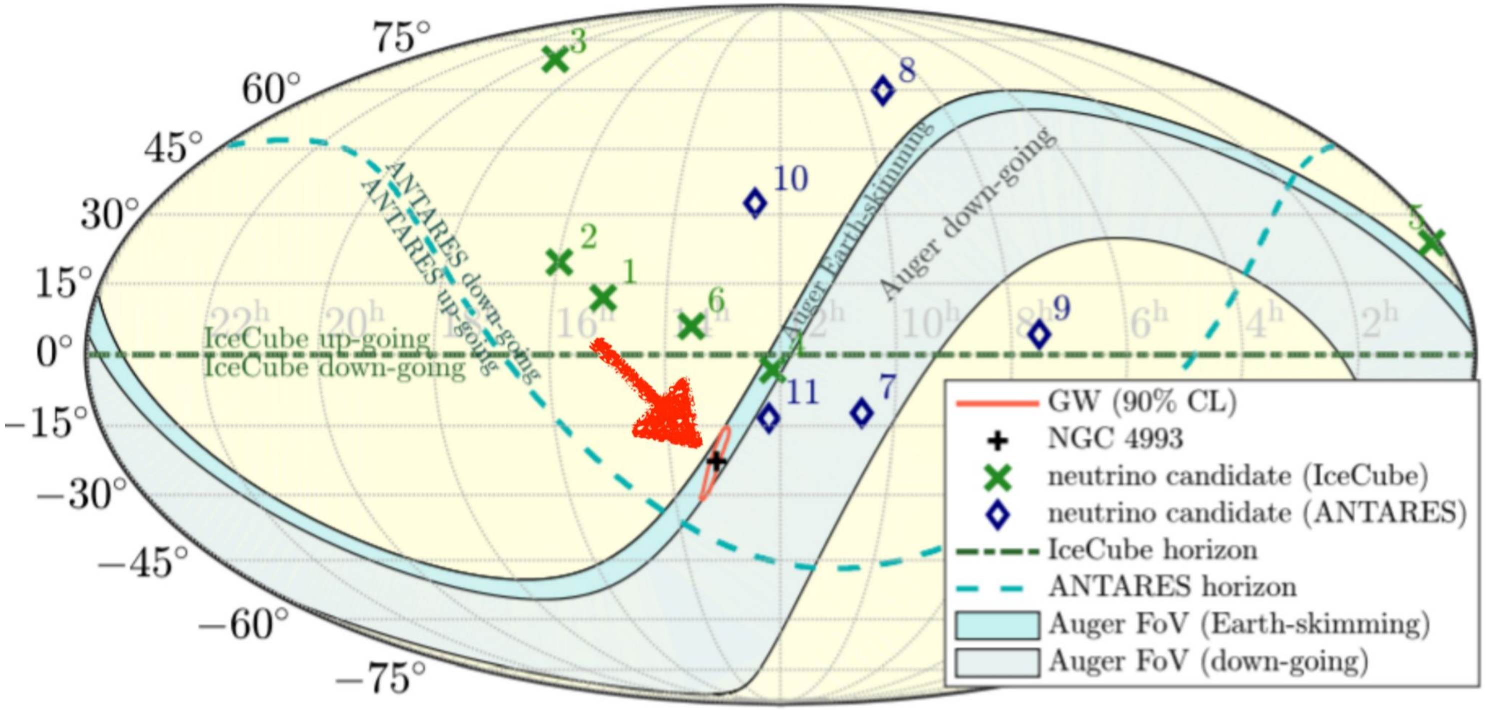
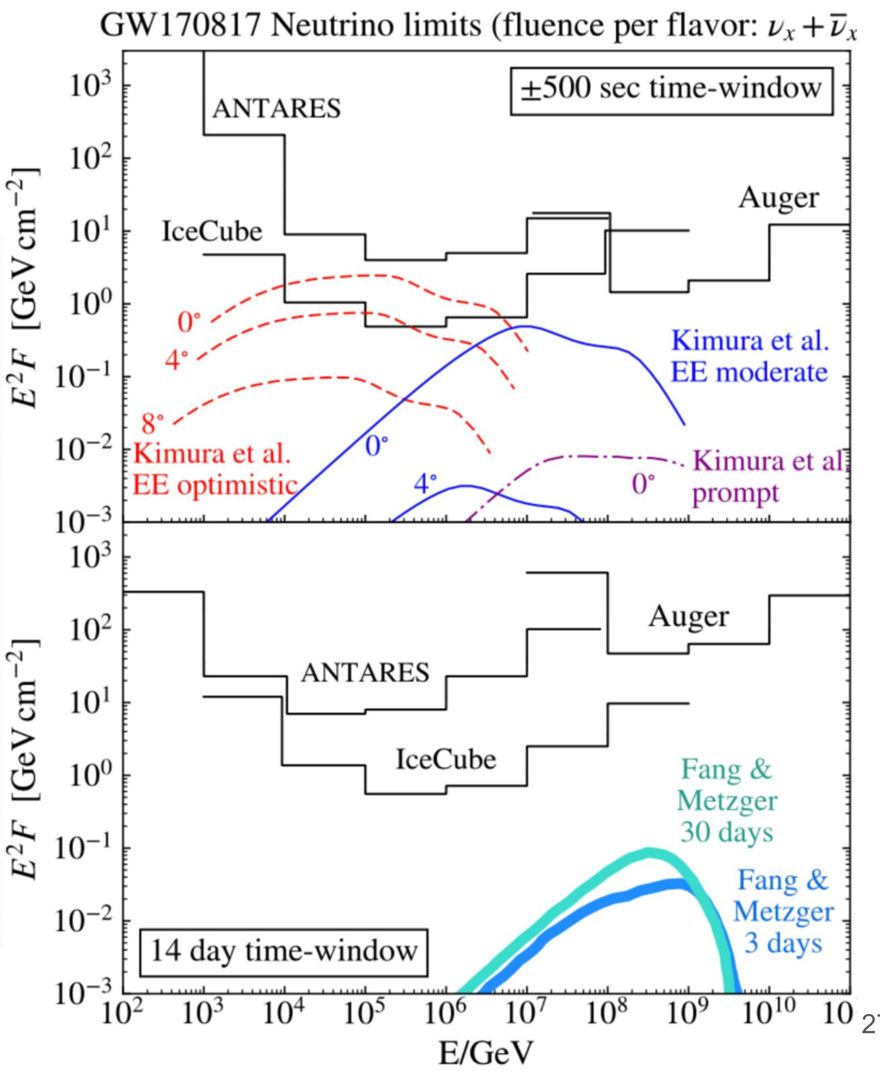
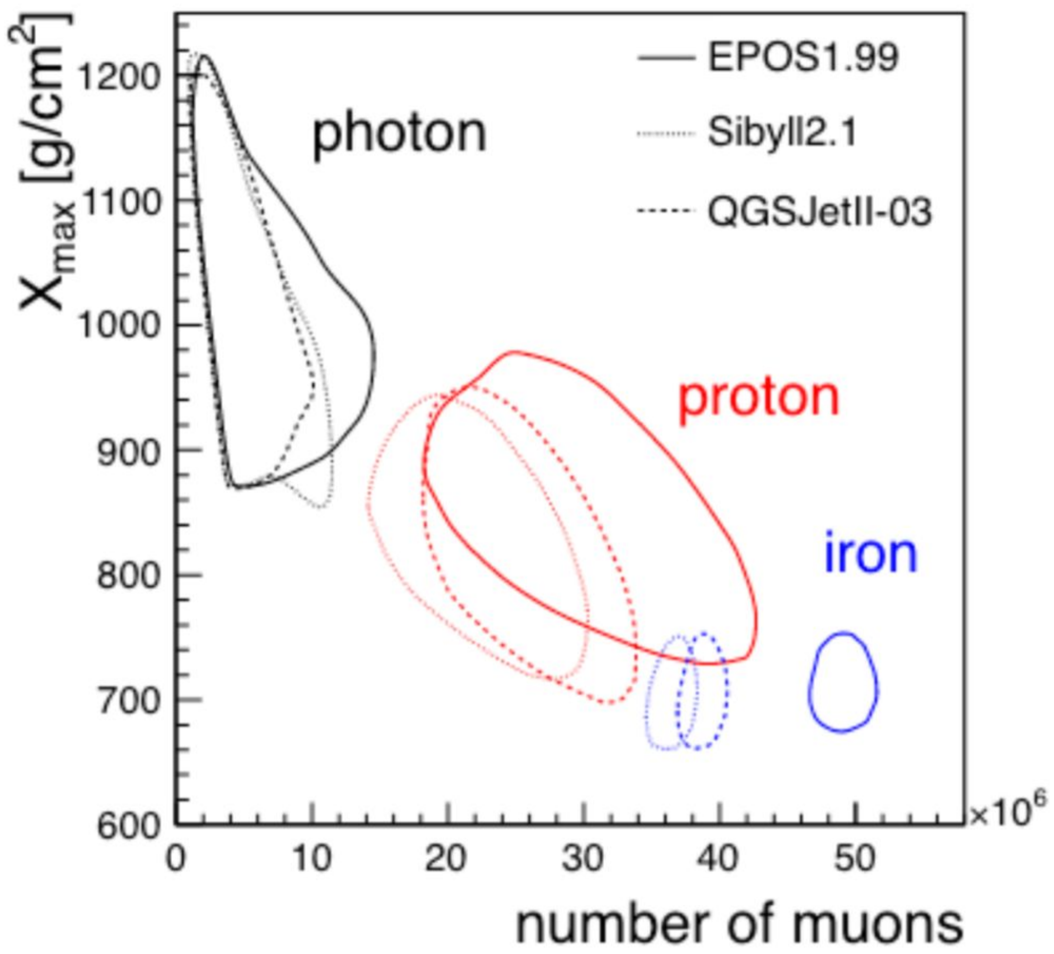


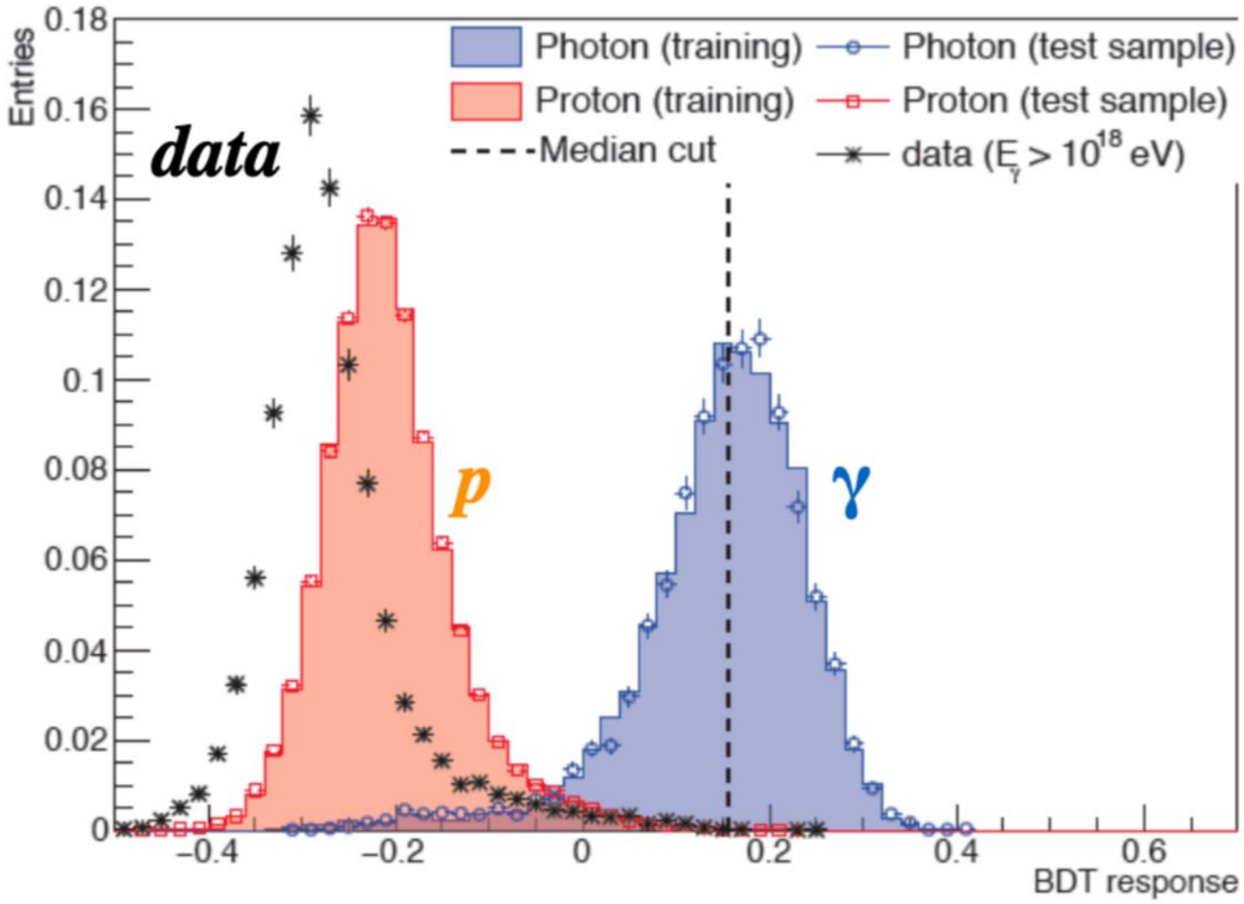


- Search for neutrinos from the NS-NS merger GW170817 Astrophys. J. Lett. 850 (2017) L35
- But also from TXS 0506+056 Astrophys. J. 902 (2020) 105

not only cosmic rays: gamma detection

- Showers induced by gammas are basically purely electromagnetic, so we can try to distinguish them!





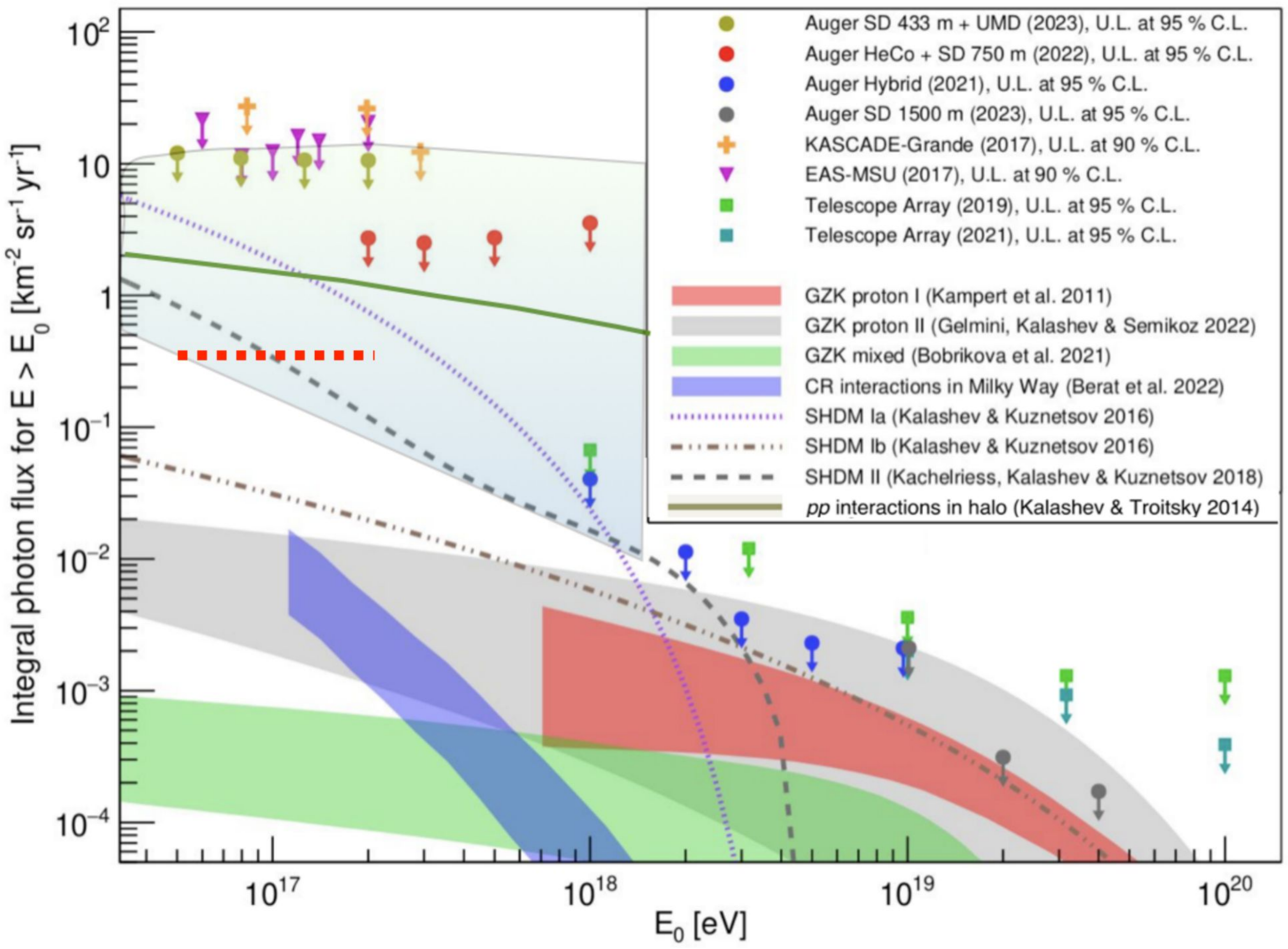
not only cosmic rays: gamma detection

- Showers induced by gammas are basically purely electromagnetic, so we can try to distinguish them!

Method	Energy range [eV]	Detectors	Exposure [km^2 sr yr]	Observables	Cit.
1	>5 10^{16}	UMD - SD433	0.6	Muon densities in SD433	Proc. of Science 444, 238 (2023)
2	>0.2 10^{18}	SD750 and FD	2.5	X_{max}, N_{st}, SD750 signals	Astrophys. J. 933 (2022) 125
3	>10^{18}	SD1500 and FD	1000	X_{max}, F_{μ} (SD1500)	arXiv:2406.07439 subm.PRD
4	>10^{19}	SD1500	17000	LDF, risetime in SD1500	JCAP 05 (2023) 021

Thanks to A. Castellina

not only cosmic rays: gamma detection



We can put limits from **less than 100 PeV** to **100 EeV**

Also these results goes **against a pure proton composition at the highest energies**

We also searched for gammas from **target sources** Astrophys. J. Lett. 837 (2017) L25
and in **space-time coincidence with GW events** *Auger Coll., Astrop.J.952 (2023) 91*

Public data

https://opendata.auger.org/ contains **10% of our data** down to a **nearly-raw level**

- Not only CR, but also **environmental** and **space-weather** data
- Citable via a zenodo DOI https://zenodo.org/records/10488964
- Includes a detailed description of the **100 most energetic events** (not only 10% of them!) *Astrophys. J. Suppl. S. 264 (2023) 50*
- Includes some ipython **notebooks** for standard analyses, for outreach, but not only!

In addition to this, we released the **energy** and **arrival directions** of all* our **2635 events above 32 EeV**, together with the code used to analyse them: https://zenodo.org/records/6759610

*until the end of 2020

Conclusions and outlook

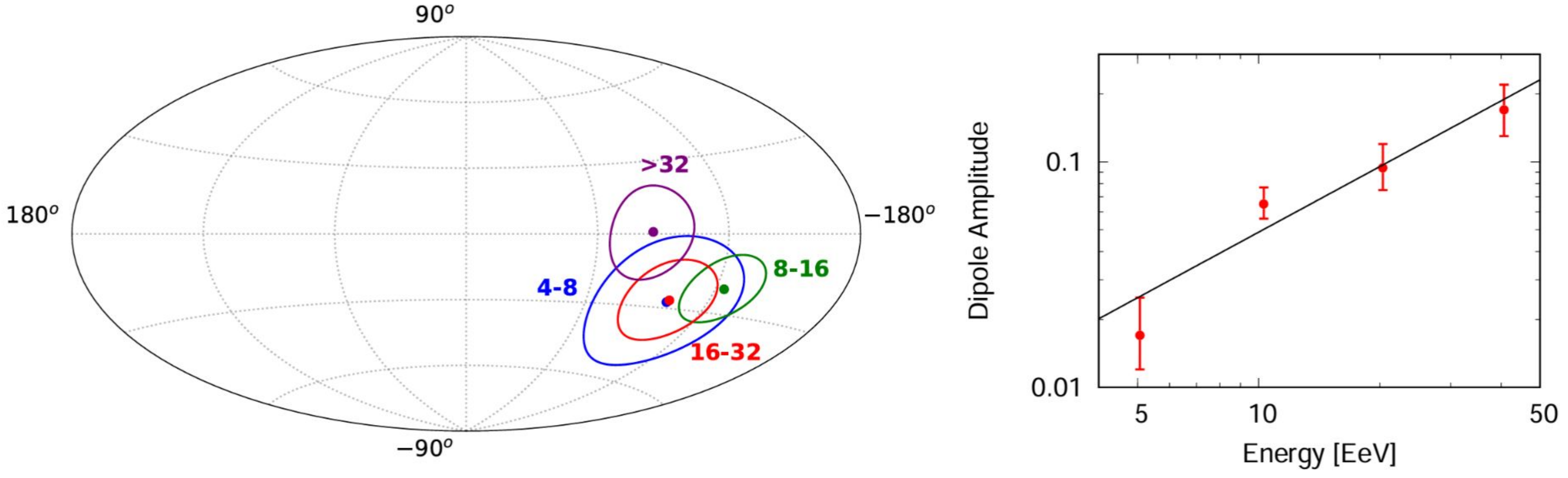
- The **Pierre Auger Observatory** has gathered an unprecedented dataset of cosmic rays above **few hundreds of PeV and up to more than 150 EeV**
- Our data suggests that the majority of UHECR sources **is extragalactic above few EeV**
- **No UHE photon or neutrino observed** so far, limits on cosmogenic production of these particles were placed… we hope to have a signal in the future!

- With **Auger Prime**, from now **until 2035** better mass discrimination will improve arrival direction studies and the search for neutral particles
- Even before, the application of **new analyses** to Phase 1 data (including ML) will give us the possibility of making **anisotropy studies** only on the "**lightest**" UHECR (nice results coming soon!)
- Even without mass estimation, **we will confirm** or exclude some results such as **the centaurus region excess** in a few years **just with new statistics**

Backup Slides

Where do cosmic ray come from?

Large-scale cosmic ray anisotropies with 19 years of data from the Pierre Auger Observatory, arXiv:2408.05292 submitted to ApJ



(a) (b)

Figure 3. (a) Map with the directions of the 3D dipole for different energy bins, in Galactic coordinates. The contours of equal probability per unit solid angle, marginalized over the dipole amplitude, that contain the 68% CL range are shown. (b) The evolution of the dipole amplitude with energy, for the four energy bins considered (4-8, 8-16, 16-32, ≥ 32) EeV.

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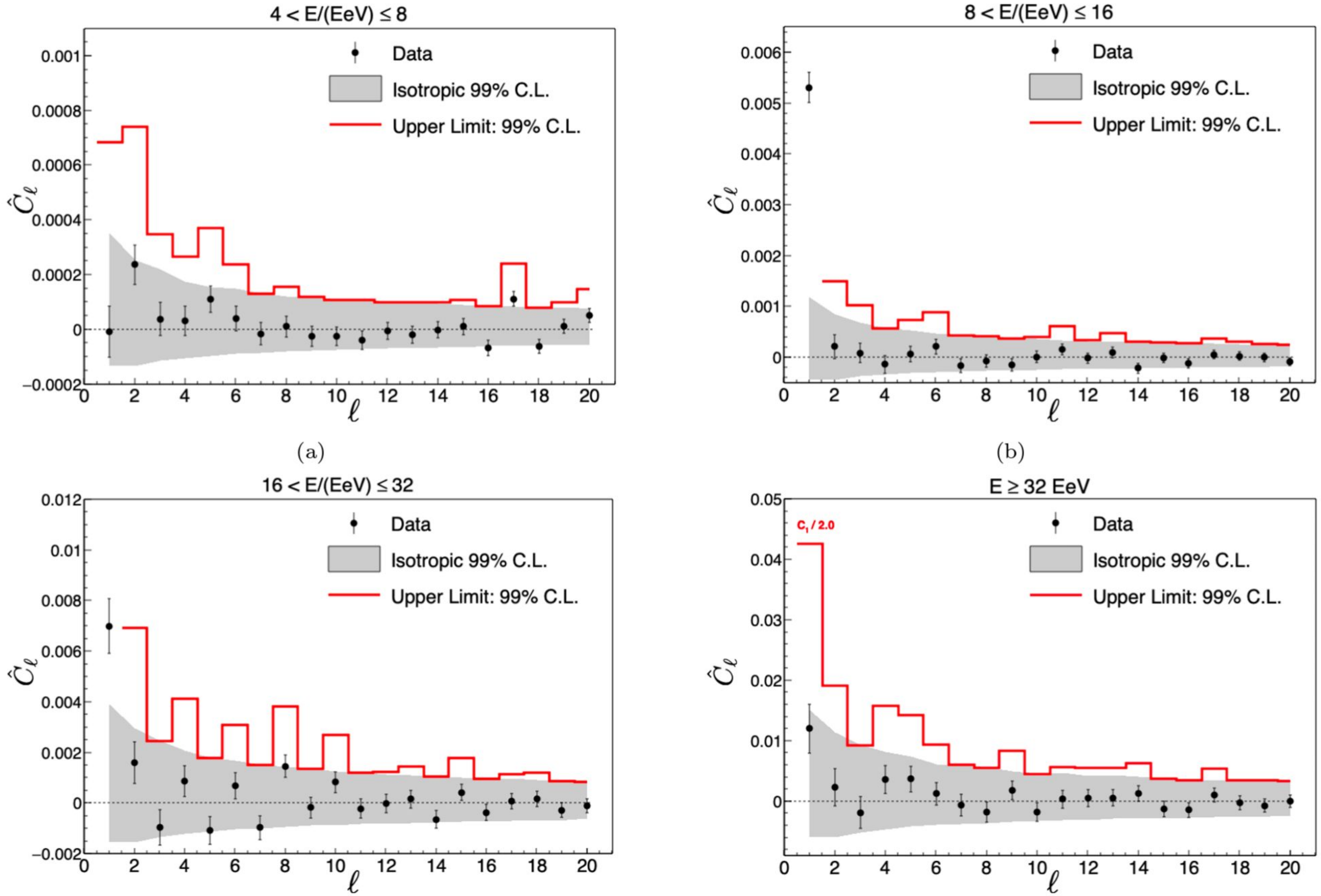


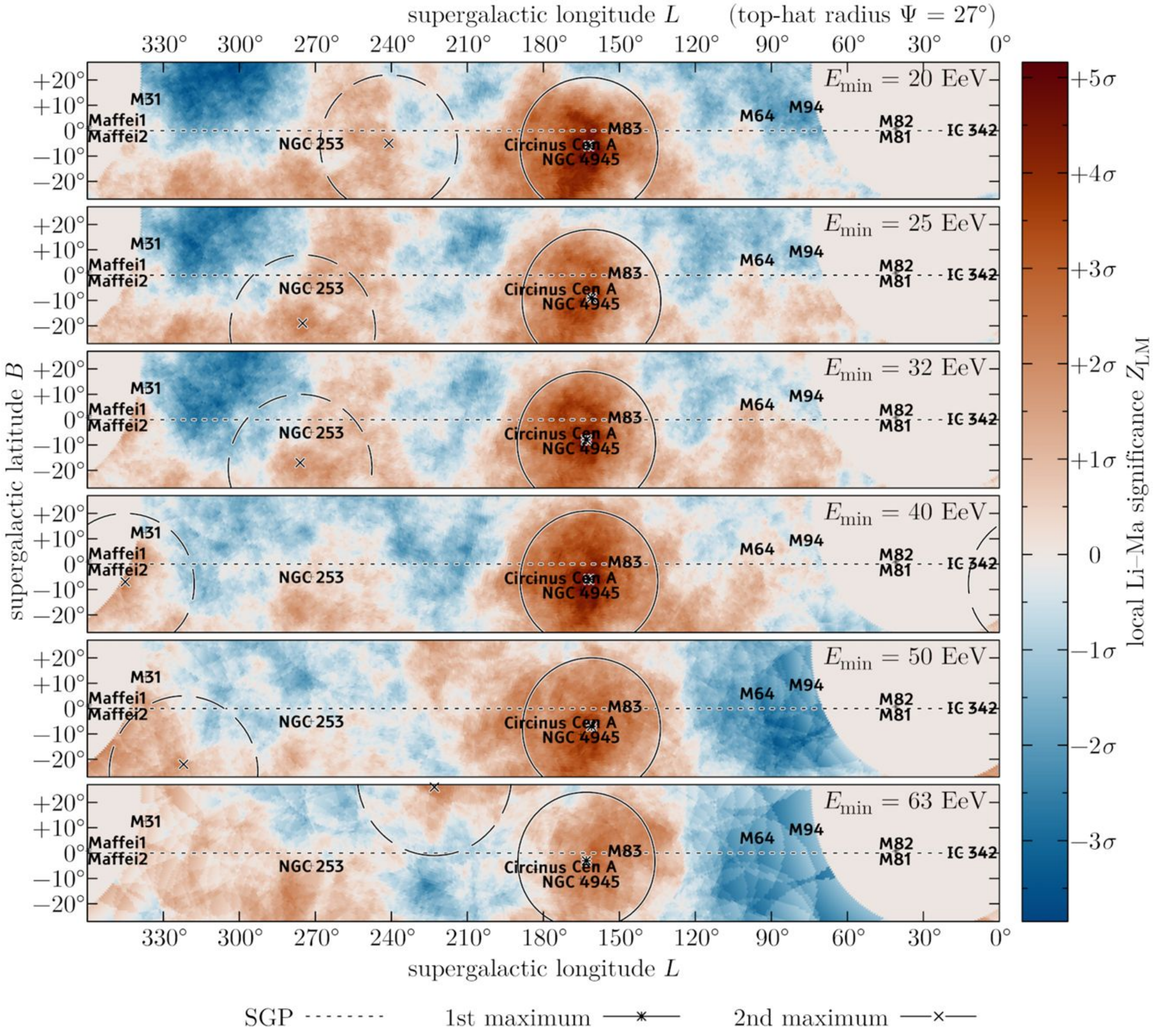
ate scale

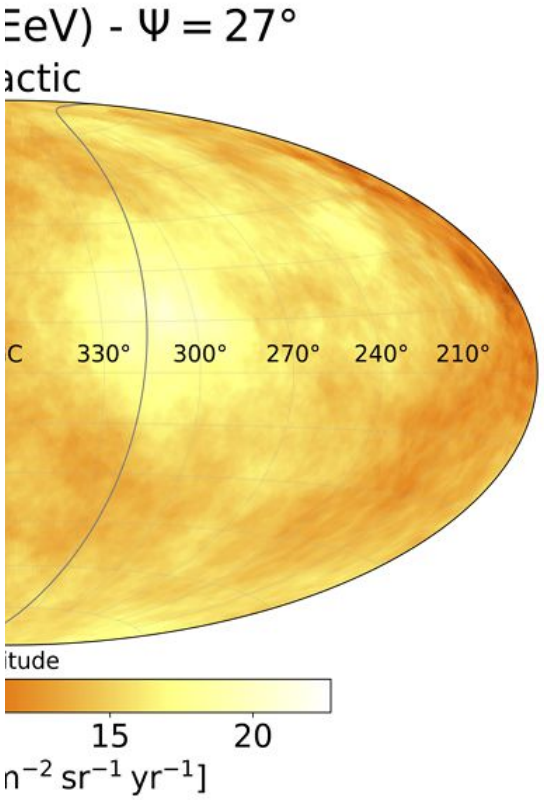
Res

- 4σ

ne position of CenA

or events above 38 EeV

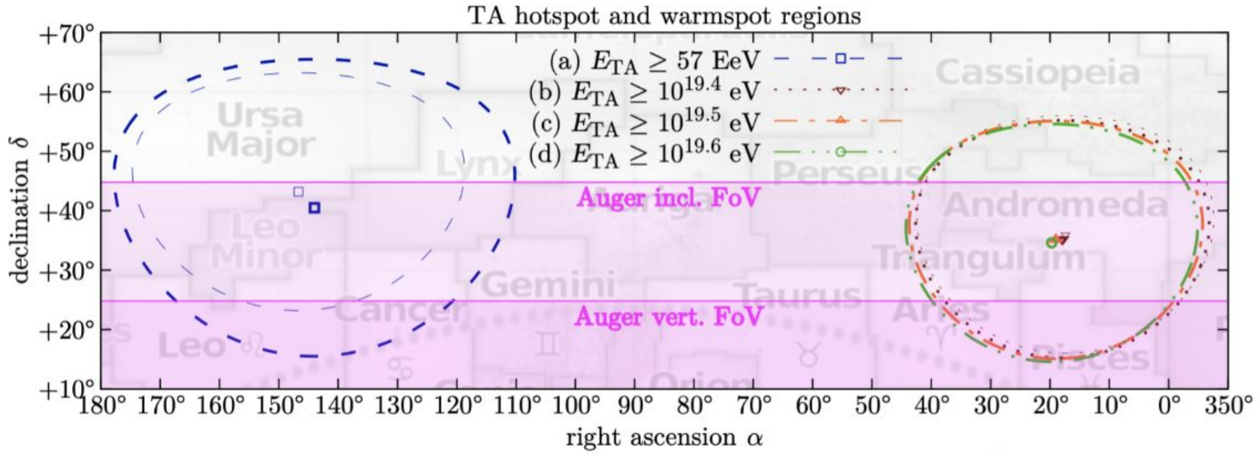


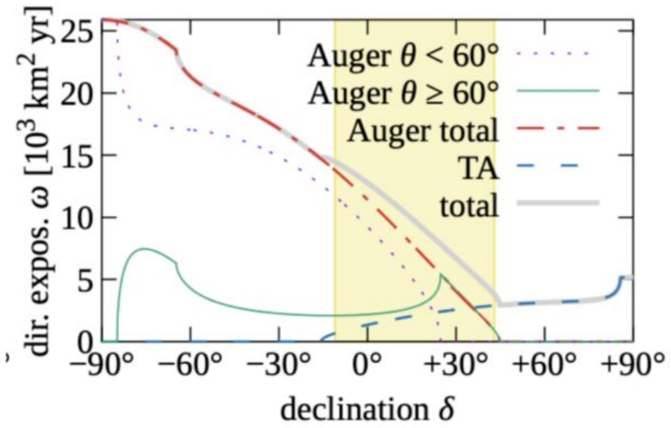


G. Golup for the Auger coll. PoS(ICRC2023)252 - Astrophys. J. 935 (2022) 170

What about the northern sky?

Using vertical+inclined events we have partial coverage of the Northern sky





G.Golup, PoS(ICRC2023) 252
Auger Coll., subm.ApJ

	(α_0, δ_0) [°]	E^{TA}	N^{TA}_{obs}	N^{TA}_{exp}	σ^{TA}_{post}	E^{Auger}	N^{Auger}_{obs}	N^{Auger}_{exp}	σ^{Auger}_{Li-Ma}
PPSC	(17.4, 36.0)	25.1	95	61.4	3.1σ	20.1	68	69.3	−0.2σ
	(19.0, 35.1)	31.6	66	39.1	3.2σ	25.3	40	45.2	−0.8σ
	(19.7, 34.6)	39.8	43	23.2	3.0σ	31.8	27	26.5	0.1σ
TA hot spot	(144.0, 40.5)	57	44	16.9	3.2σ	45.6	7	10.1	−1.0σ

➡️confirmation of the Centaurus region as most significant excess (4.0σ post-trial), extended to lower energies (20 EeV)

➡️no hints for excesses in the TA "spots" with data of comparable size —> at variance with the claim of TA that the declination dependence of the UHECR energy spectrum is due to the presence of excesses in particular regions of the Northern sky

Large scale anisotropies

We can see the whole sky: better reconstruction of large scales structures

no assumption needed on higher ℓ when measuring the dipole and quadrupole amplitudes (unlike in Auger-only or TA-only studies)

$E^{\mathrm{TA}}_{\mathrm{Auger}}$ [EeV]	$^{10}_{8.55} \leq E \leq {}^{19.4}_{16}$	$^{19.4}_{16} \leq E \leq {}^{40.2}_{32}$	$E \geq {}^{40.2}_{32}$	$E \geq {}^{10}_{8.55}$
d_x [%]	$-0.5 \pm 1.0 \pm 0.0$	$+0.3 \pm 1.8 \pm 0.0$	$-5.3 \pm 3.5 \pm 0.1$	$-0.7 \pm 0.9 \pm 0.0$
d_y [%]	$+5.3 \pm 1.0 \pm 0.0$	$+4.0 \pm 1.8 \pm 0.0$	$+9.3 \pm 3.4 \pm 0.0$	$+5.2 \pm 0.9 \pm 0.0$
d_z [%]	$-3.3 \pm 1.2 \pm 1.2$	$-7.7 \pm 2.2 \pm 1.3$	$+4.7 \pm 4.3 \pm 3.5$	$-3.8 \pm 1.0 \pm 1.1$
$Q_{xx} - Q_{yy}$ [%]	$-4.5 \pm 4.4 \pm 0.0$	$+12.7 \pm 7.7 \pm 0.0$	$+31.2 \pm 14.4 \pm 0.1$	$+1.7 \pm 3.7 \pm 0.0$
Q_{xz} [%]	$-2.1 \pm 2.6 \pm 0.0$	$+5.9 \pm 4.6 \pm 0.0$	$+4.6 \pm 9.5 \pm 0.1$	$+0.1 \pm 2.2 \pm 0.0$
Q_{yz} [%]	$-5.2 \pm 2.6 \pm 0.0$	$-6.9 \pm 4.5 \pm 0.1$	$+12.0 \pm 8.9 \pm 0.2$	$-4.5 \pm 2.2 \pm 0.0$
Q_{zz} [%]	$+0.5 \pm 3.0 \pm 1.5$	$+5.5 \pm 5.3 \pm 1.5$	$+25.2 \pm 10.2 \pm 4.3$	$+3.2 \pm 2.5 \pm 1.4$
Q_{xy} [%]	$+2.0 \pm 2.2 \pm 0.0$	$-1.6 \pm 3.9 \pm 0.0$	$+4.7 \pm 7.5 \pm 0.0$	$+1.3 \pm 1.9 \pm 0.0$

Fitting all we know: a combine fit of spectrum, mass and arrival directions

With some assumption, we can try and fit together the information from different observables.

nearby source candidates [5] + homogeneous background sources

- active galactic nuclei (AGNs), flux weighted by ɣ-ray flux + bg with m=5
- starburst galaxies (SBGs) + bg with m=3.4 (star formation rate)
- nearby radio galaxy Centaurus A + different bgs

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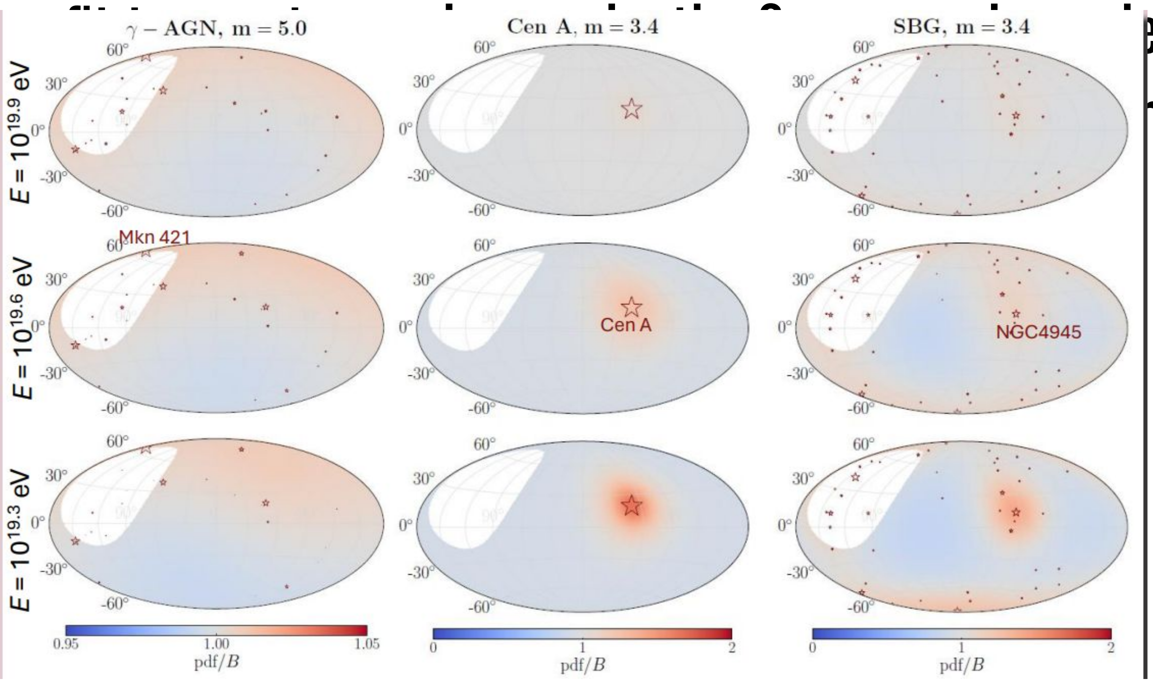

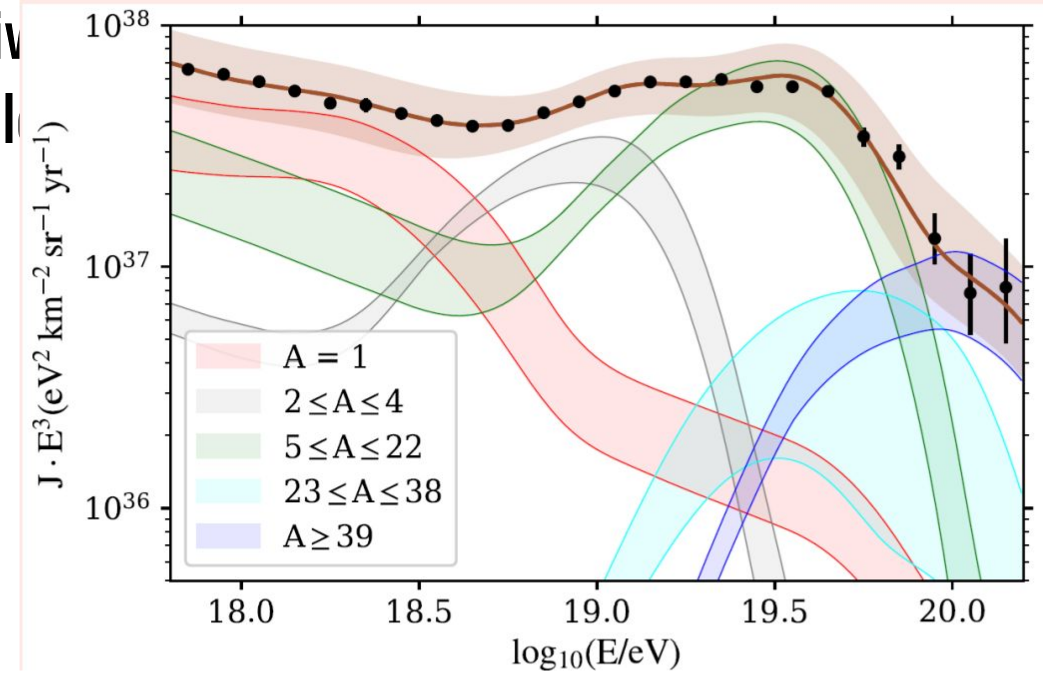

Targeted search for photons

Astrophys. J. Lett. 837 (2017) L25

Table 1
Combined Unweighted Probabilities $\mathcal{P}$ and Weighted Probabilities $\mathcal{P}_w$ for the 12 Target Sets

Class	No.	$\mathcal{P}_w$	$\mathcal{P}$	R.A. (°)	Decl. (°)	Obs	Exp	Exposure (km^2 yr)	Flux UL (km^{-2} yr^{-1})	E-flux UL (eV cm^{-2} s^{-1})	p	p^*
msec PSRs	67	0.57	0.14	286.4	4.0	5 (7, 9^*)	1.433	236.1	0.043	0.077	0.010	0.476
γ-ray PSRs	75	0.97	0.98	312.8	−8.5	6 (8, 10^*)	1.857	248.1	0.045	0.080	0.007	0.431
LMXB	87	0.13	0.74	258.1	−40.8	6 (8, 11^*)	2.144	233.9	0.046	0.083	0.014	0.718
HMXB	48	0.33	0.84	285.9	−3.2	4 (7, 9^*)	1.460	235.2	0.036	0.066	0.040	0.856
H.E.S.S. PWN	17	0.92	0.90	266.8	−28.2	4 (8, 10^*)	2.045	211.4	0.038	0.068	0.104	0.845
H.E.S.S. other	16	0.12	0.52	258.3	−39.8	5 (8, 10^*)	2.103	233.3	0.040	0.072	0.042	0.493
H.E.S.S. UNID	20	0.79	0.45	257.1	−41.1	6 (8, 10^*)	2.142	239.2	0.045	0.081	0.014	0.251
Microquasars	13	0.29	0.48	267.0	−28.1	5 (8, 10^*)	2.044	211.4	0.045	0.080	0.037	0.391
Magnetars	16	0.30	0.89	257.2	−40.1	4 (8, 10^*)	2.122	253.8	0.031	0.056	0.115	0.858
Gal. Center	1	0.59	0.59	266.4	−29.0	2 (8, 8^*)	2.048	218.9	0.024	0.044	0.471	0.471
LMC	3	0.52	0.62	84.4	−69.2	2 (8, 9^*)	2.015	180.3	0.030	0.053	0.463	0.845
Cen A	1	0.31	0.31	201.4	−43.0	3 (8, 8^*)	1.948	214.1	0.031	0.056	0.221	0.221

Note. In addition, information on the most significant target from each target set is given. The number of observed (Obs) and expected (Exp) events and the corresponding exposure are shown. The numbers in brackets in the observed number of events column indicate the numbers of events needed for a 3σ observation unpenalized and penalized (*). Upper limits (UL) are computed at the 95% confidence level. The last two columns indicate the p-value unpenalized (p) and penalized (p^*). Due to the discrete distribution of p-values arising in isotropic simulations, $\mathcal{P}$ can differ from p in the sets that contain only a single target.

Targeted search for photons

Astrophys. J. Lett. 837 (2017) L25