Anisotropy searches of cosmic rays at the highest energy with the Pierre Auger Observatory

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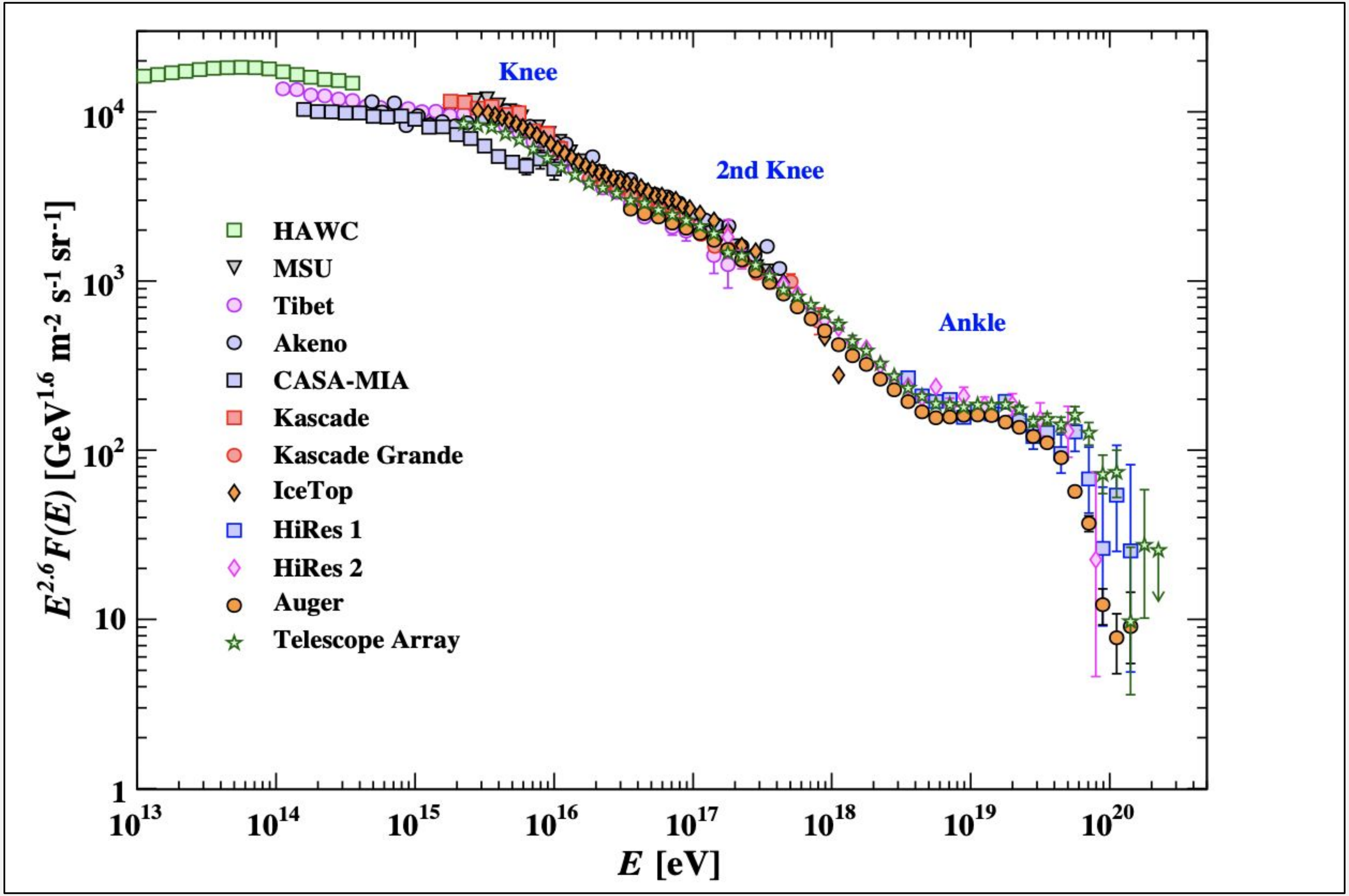
AUGER MILANO
PIERRE AUGER OBSERVATORY

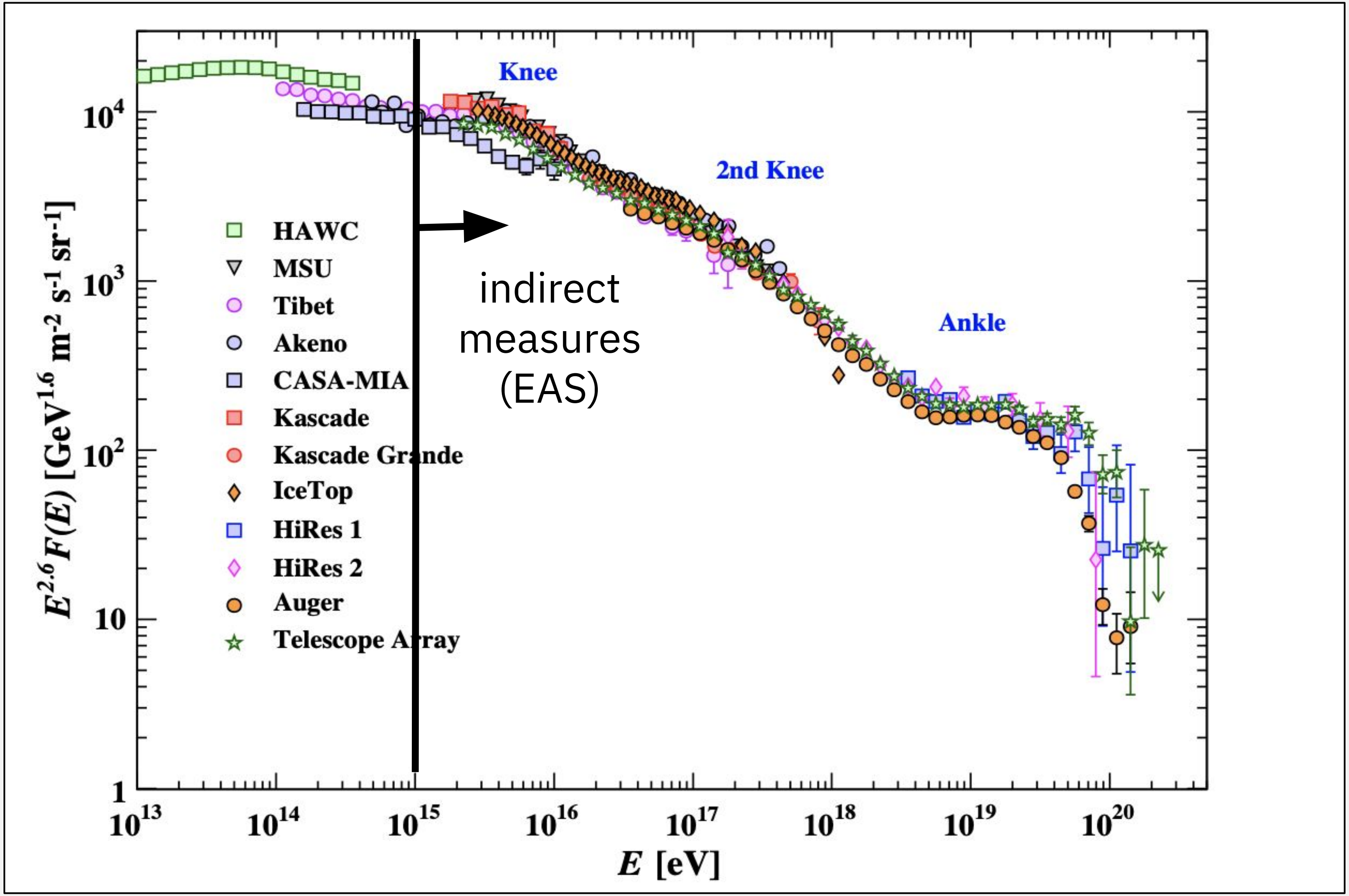
Cosmic rays

- Cosmic rays are massive and charged particles coming from the Galaxy or outside the Galaxy reaching the Earth's atmosphere.

- Cosmic rays can be detected by direct or indirect techniques, depending on the energy range studied.

- Composition over the entire energy range: 90% protons, 9% He nuclei, less 1% heavier nuclei, electrons, positrons


Knee
2nd Knee
Ankle
HAWC
MSU
Tibet
Akeno
CASA-MIA
Kascade
Kascade Grande
IceTop
HiRes 1
HiRes 2
Auger
Telescope Array
$E^{2.6}F(E)$ [GeV$^{1.6}$ m^{-2} s^{-1} sr^{-1}]
E [eV]
1
10
10^2
10^3
10^4
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}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2nd Knee
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indirect measures (EAS)
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MSU
Tibet
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CASA-MIA
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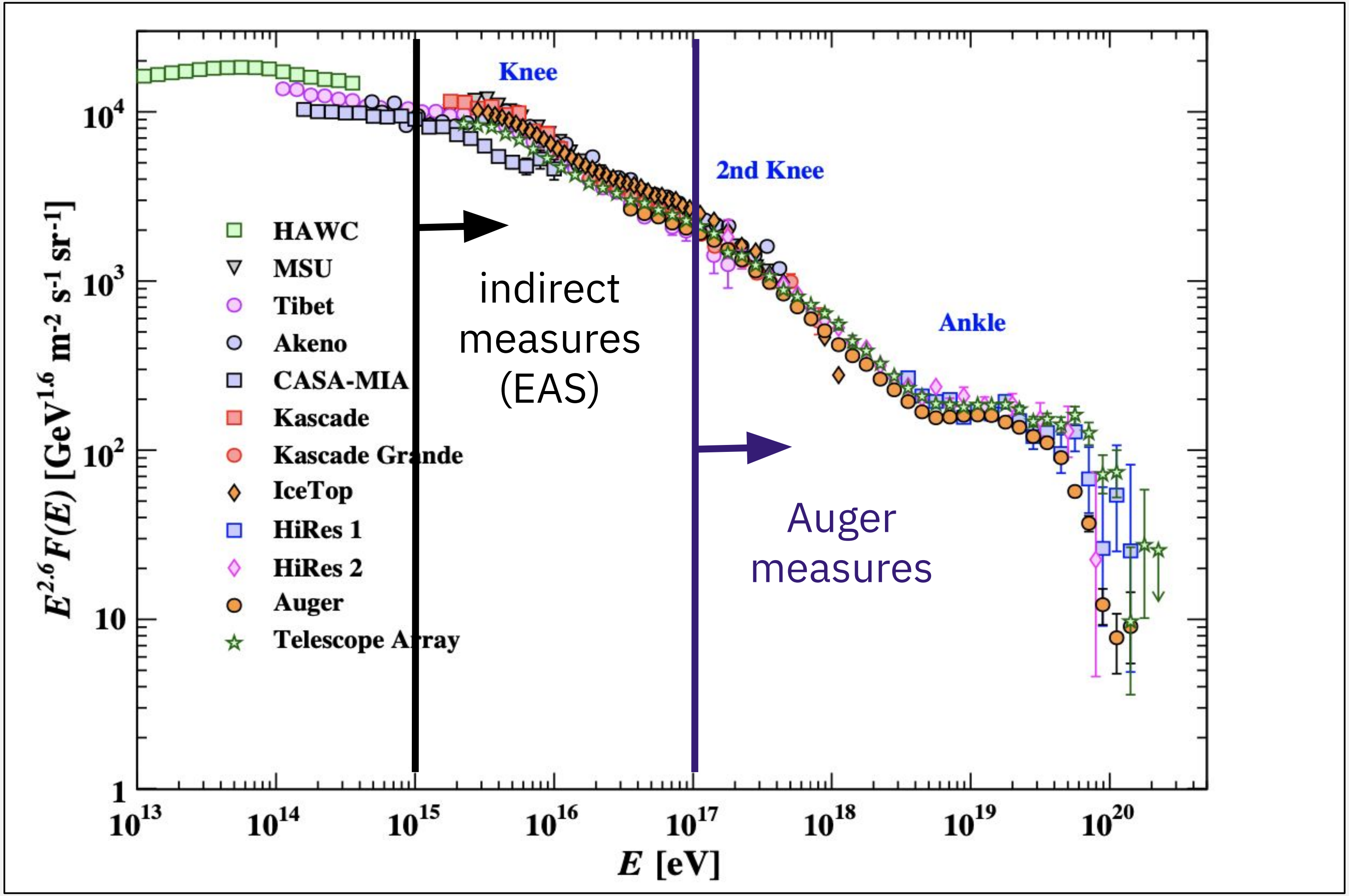
$E^{2.6}F(E)$ [GeV$^{1.6}$ m^{-2} s^{-1} sr^{-1}]
E [eV]
10^{4}
10^{3}
10^{2}
10
1
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}



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Auger measures
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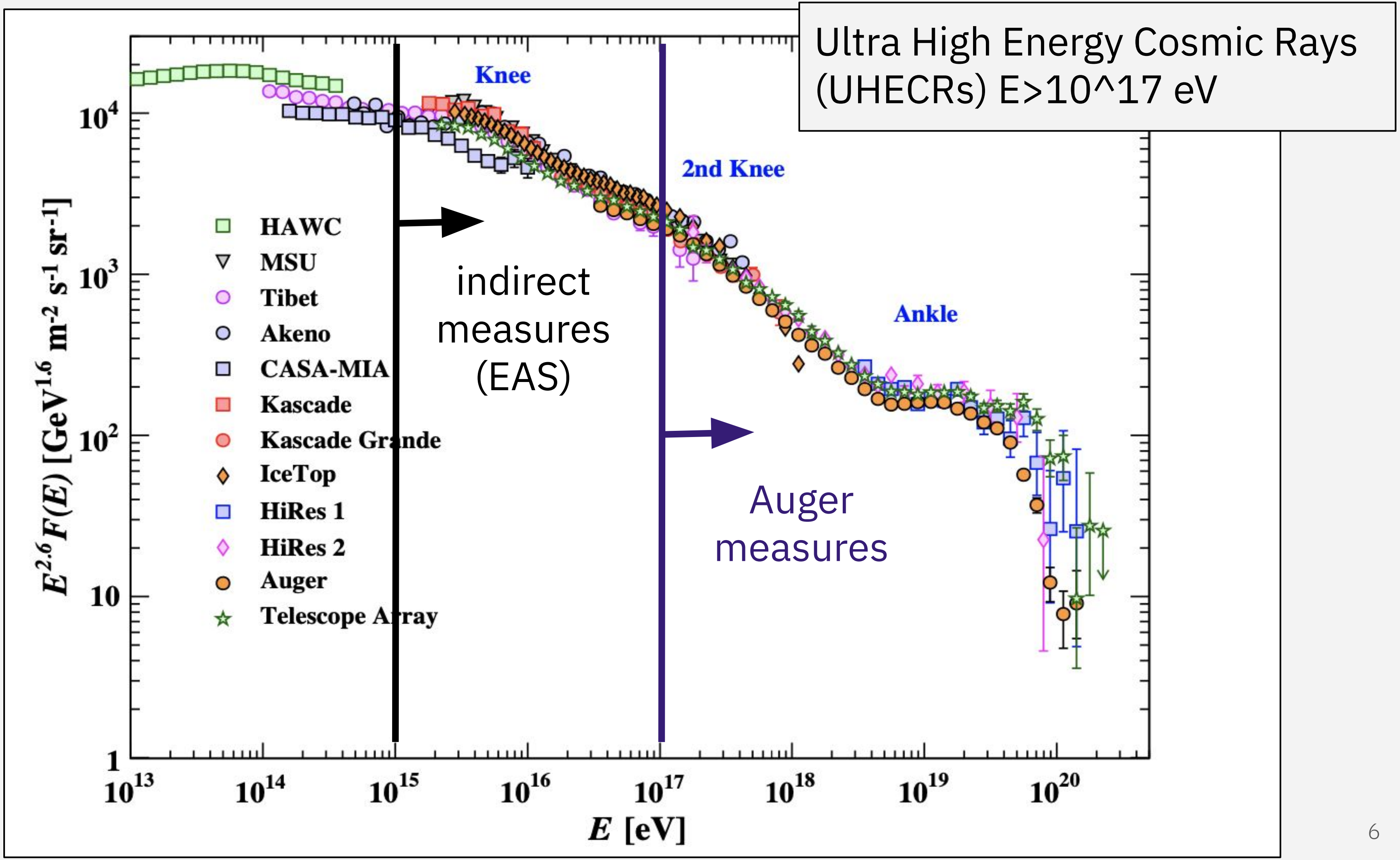
E [eV]


Ultra High Energy Cosmic Rays
(UHECRs) E>10^17 eV
Knee
2nd Knee
Ankle
indirect
measures
(EAS)
Auger
measures
HAWC
MSU
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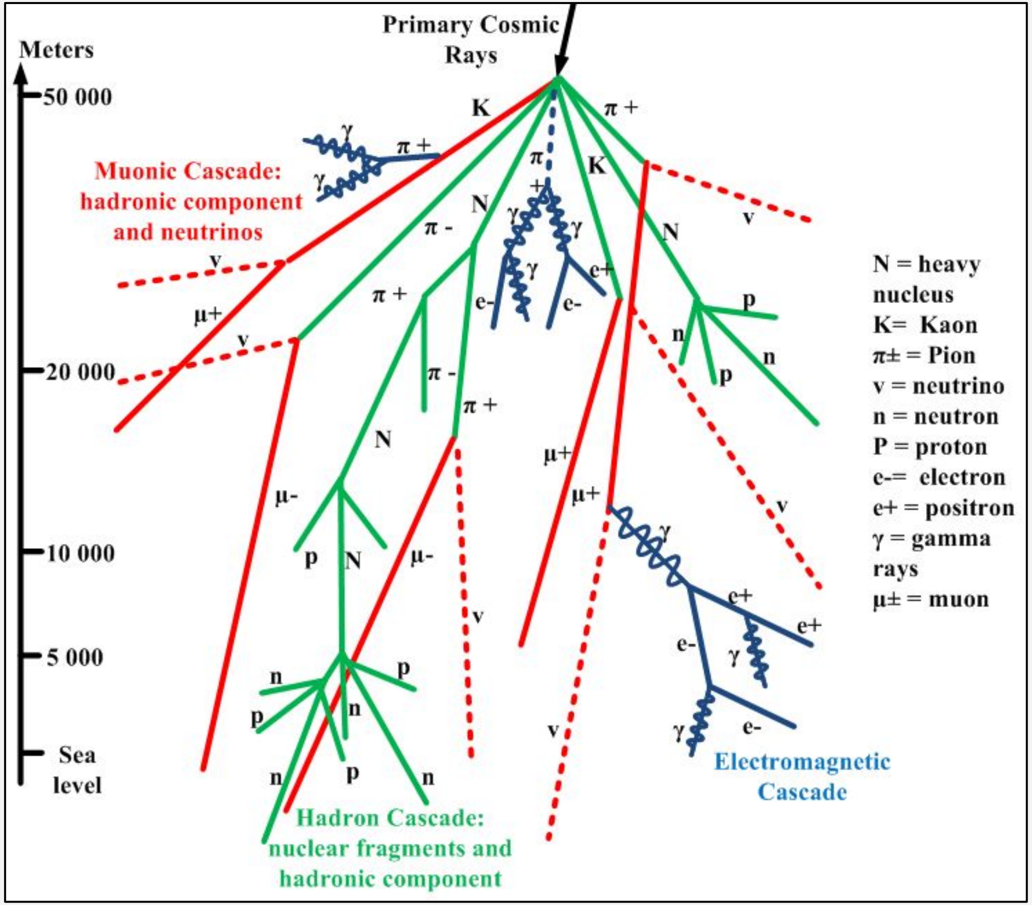
Auger
Telescope Array
E^2.6 F(E) [GeV^1.6 m^-2 s^-1 sr^-1]
E [eV]

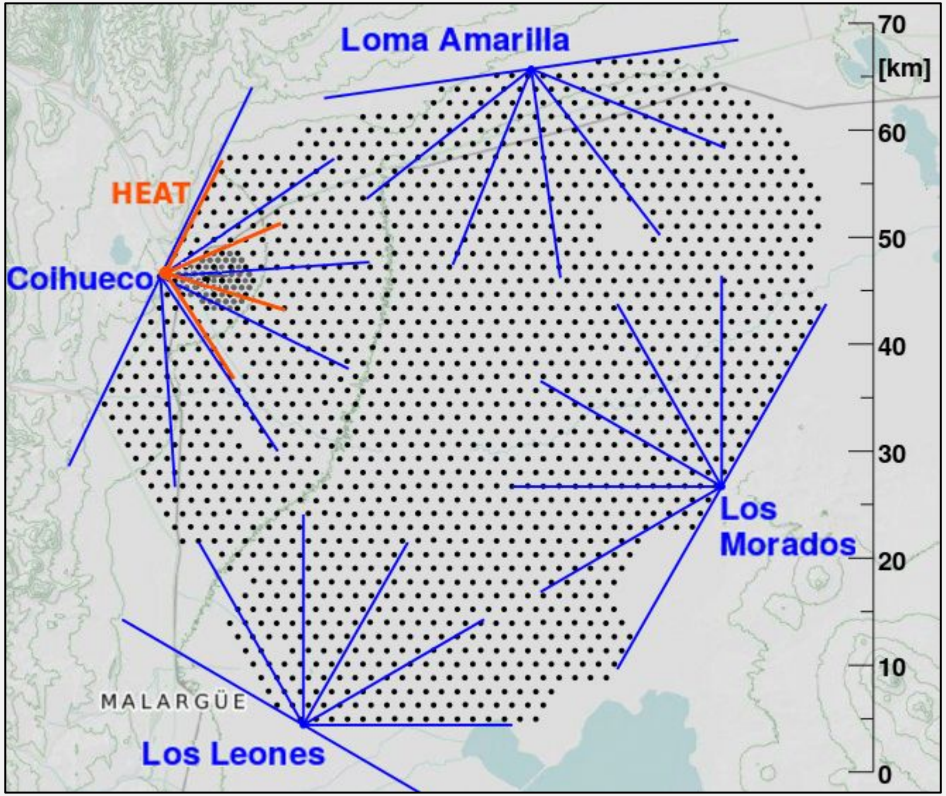
Extensive air showers

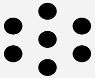


The Pierre Auger Observatory

The largest UHECRs *hybrid* observatory ever built - 3000 km^2 (~Luxembourg)

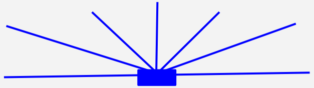
- Active since 2004
- Malargüe Argentina, at a Latitude of 35.2° S
- 85% of sky coverage, angular resolution ~1°
- 1400 m asl (880 g/cm^2 atmosferic depth)





Surface Detector (SD):

1660 water Cherenkov detectors to sample the shower plane at earth

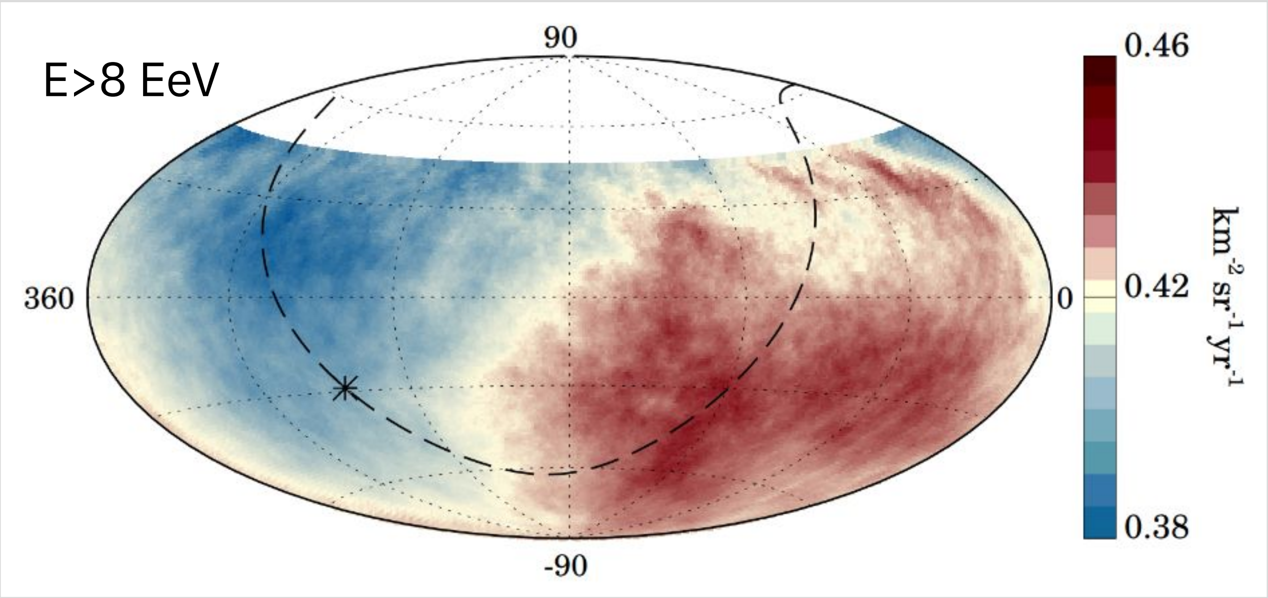


Fluorescence Detector (FD):

27 fluorescence telescopes in 4 sites (5 buildings)

Large-scale analysis E>4 EeV

Combined Fourier analysis in R.A (sensitive to the equatorial component $d_\perp$) and azimuth (sensitive to the N-S one d_z) with weights that account for the small variations in coverage and the tilt of the array



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E [EeV]	N	$d_\perp$	d_z	d	α_d [°]	δ_d [°]	P($\geq d_\perp$)	
4-8	118,835	$0.010^{+0.006}_{-0.004}$	-0.014 ± 0.008	$0.017^{+0.008}_{-0.005}$	91 ± 30	-53^{+21}_{-19}	0.15	
≥8	49,710	$0.058^{+0.009}_{-0.008}$	-0.045 ± 0.012	$0.073^{+0.010}_{-0.008}$	97 ± 8	-37^{+9}_{-9}	7.4×10^{-12}	6.9σ
8-16	36,683	$0.057^{+0.010}_{-0.009}$	-0.030 ± 0.014	$0.065^{+0.012}_{-0.009}$	92 ± 10	-28^{+11}_{-12}	1.2×10^{-8}	5.7σ
16-32	10,288	$0.059^{+0.020}_{-0.015}$	-0.07 ± 0.03	$0.094^{+0.026}_{-0.019}$	93 ± 18	-51^{+13}_{-13}	4.5×10^{-3}	
≥32	2,739	$0.11^{+0.04}_{-0.03}$	-0.13 ± 0.05	$0.17^{+0.05}_{-0.04}$	143 ± 19	-51^{+14}_{-13}	8.4×10^{-3}	

~113° away from the GC

At high energy the distribution of the UHECRs arrival directions might show anisotropy at intermediate angular scales, mirroring the inhomogeneous distribution of the nearby extra-galactic matter.

This analysis has been complemented in Auger by the search for anisotropy at intermediate angular scales

- Blind searches
- Catalog based searches
- Autocorrelation and correlation with structures

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With the largest dataset ever built at the extreme energies: 2635 events with energy above 32 EeV available for public use https://doi.org/10.5281/zenodo.6504276

"Vertical"
2040 with zenith angle θ<60°

"Inclined"
595 with zenith angle θ>60°

36 above 100 EeV (0.1 ZeV!)
Highest energy event: 165 EeV

Blind search for overdensity

Search for the most prominent overdensity in the whole observable sky by Auger

Parameter space

- Direction
- Threshold energy $E_{\mathrm{th}} = \{32, 80\}$ EeV
- Top-Hat angular scale Ψ

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Search for the most prominent overdensity in the whole observable sky by Auger

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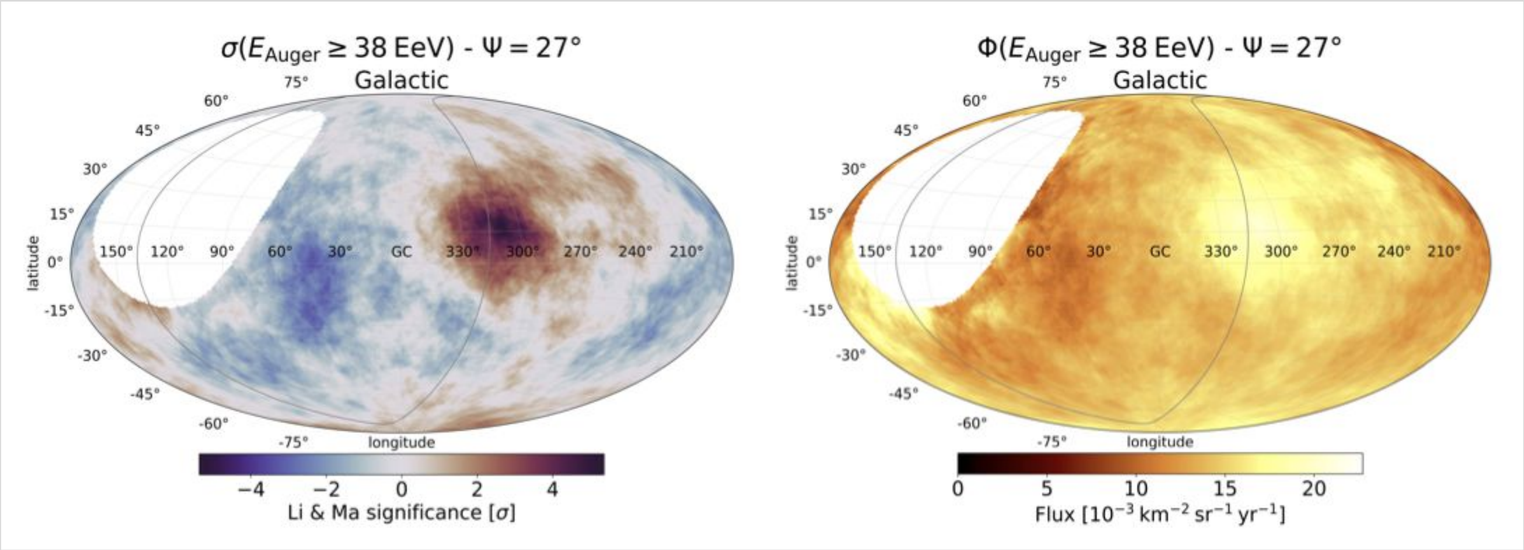
Largest significance post-trial 2.1σ
2° away from CenA
E_{th} = 38 EeV
Ψ=27°



Catalog based searches

Probability maps built weighing objects by their relative fux in the corresponding e.m. band and an attenuation due to their different distances (Auger spectral-composition modeling)

Parameters space: Fisher search radius θ and the signal fraction; scan in E_{th} in [32, 80] EeV, steps of 1 EeV

Catalogs (and their fux proxy):

- all galaxies (IR) from 2MRS (K-band)
- starbursts (radio) based on Lunardini+19 (1.4 GHz)
- all AGNs (X-rays) from Swift-BAT (14-195 keV)
- jetted AGNs (g-rays) from Fermi 3FHL (E>10 GeV)

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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}
Starbursts (radio)	38	25^{+13}_{-7}	9^{+7}_{-4}	23.4	6.6×10^{-5}
All AGNs (X-rays)	38	25^{+12}_{-7}	7^{+4}_{-3}	20.5	2.5×10^{-4}
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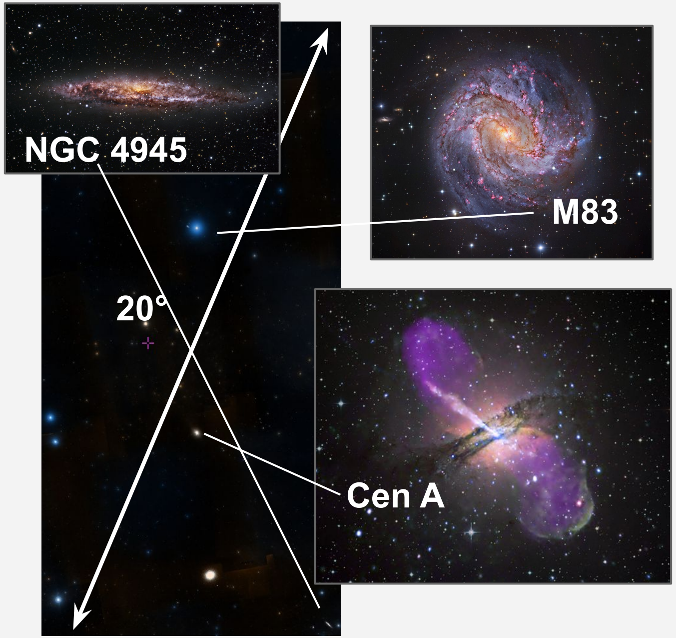
3.8σ

Centaurus region

The Centaurus region is particularly promising for many reasons:

- Is a flagged area since the first anisotropy results of the Pierre Auger Observatory
- Is the most significant overdensity present in the blindsearch is in this direction
- Cen A region is the driving hotspot in all the catalog based models



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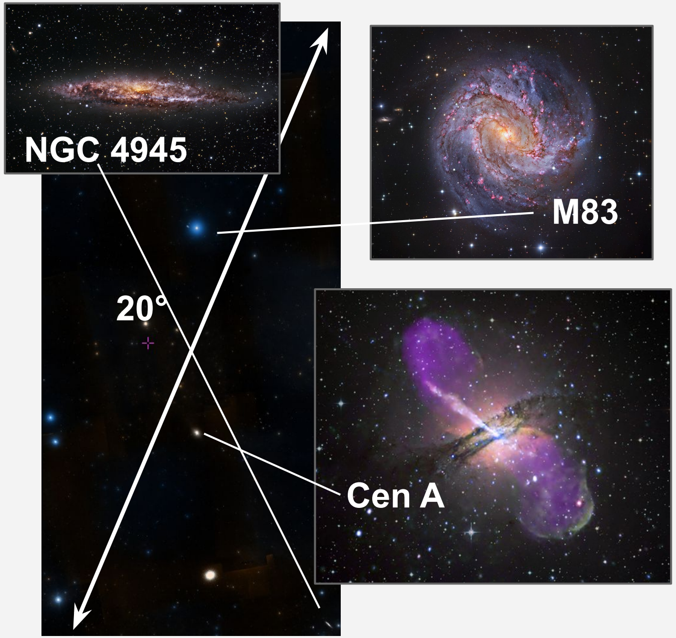
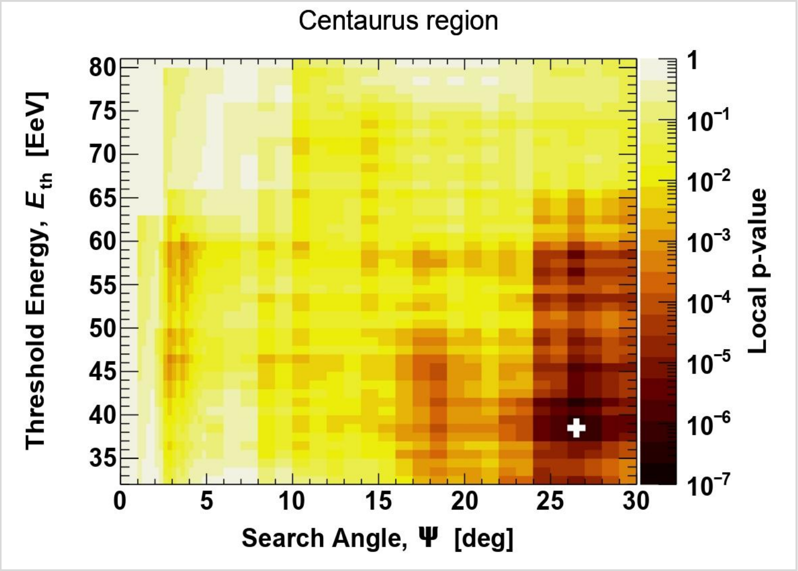




4.0σ post-trial for E_{th}=38 EeV, Ψ=27°

Autocorrelation

Autocorrelation

Pairs of events separated by given angular distance, scan in threshold energy, angle Ψ

Autocorrelation and correlation with structures

Autocorrelation

Pairs of events separated by given angular distance, scan in threshold energy, angle Ψ

Structures

Events in proximity of local astrophysical structures, scan in threshold energy, angle Ψ

Autocorrelation and correlation with structures

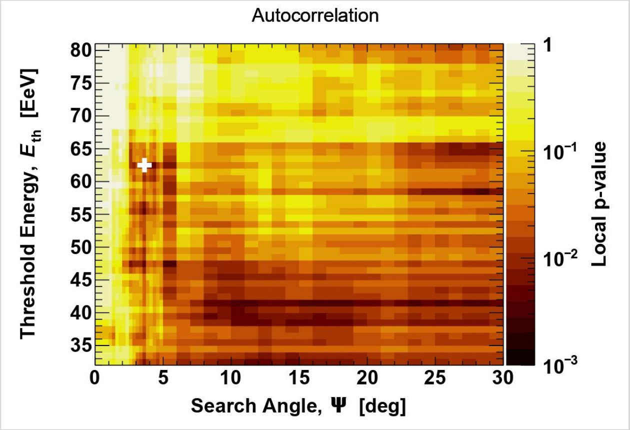
Autocorrelation

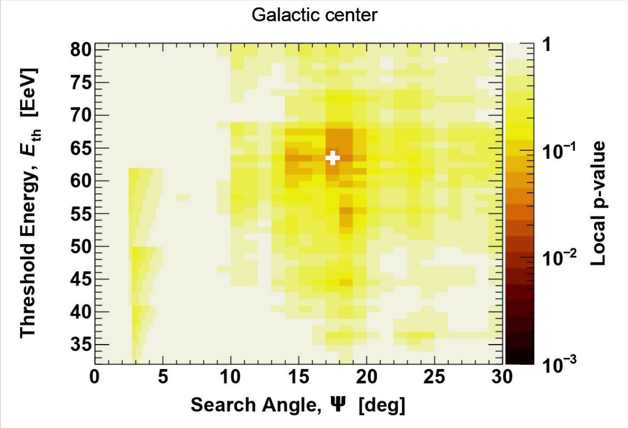
Pairs of events separated by given angular distance, scan in threshold energy, angle Ψ

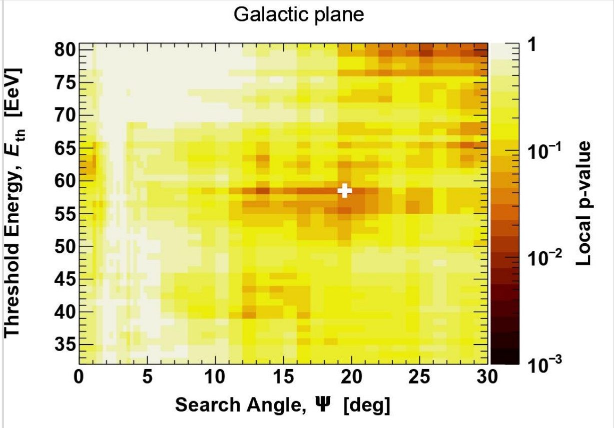
Structures

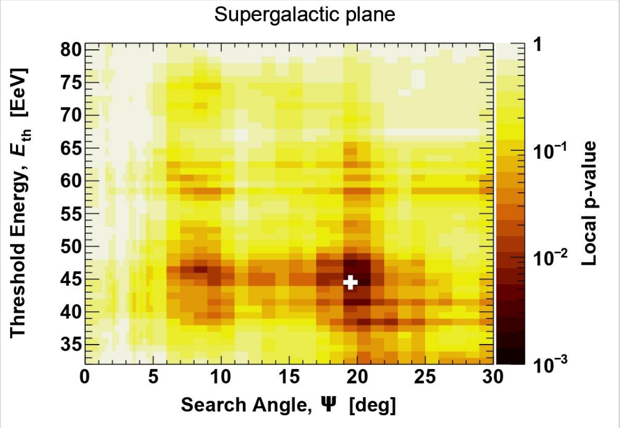
Events in proximity of local astrophysical structures, scan in threshold energy, angle Ψ

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









UHECRs can produce secondary neutrinos, photons and neutrons near their sources or during propagation through Universe

$$p + \gamma \rightarrow n + \pi^+$$

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

$$\mu^+ \rightarrow \mathrm{e}^+ + \bar{\nu}_\mu + \nu_\mathrm{e}$$

$$n \rightarrow p + \mathrm{e}^- + \bar{\nu}_\mathrm{e}$$

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

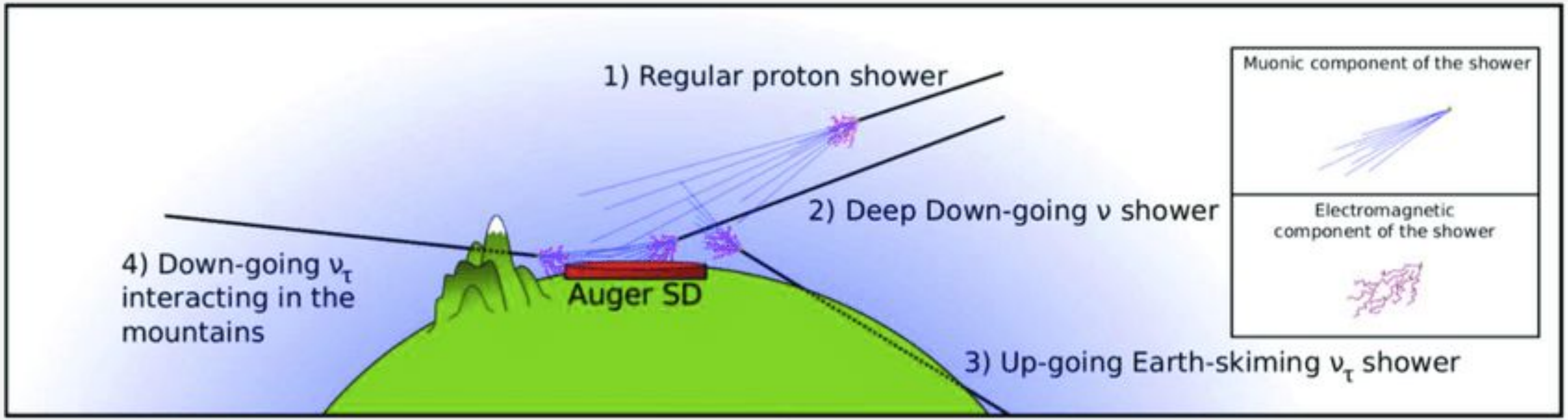
$$\pi^0 \rightarrow \gamma + \gamma$$

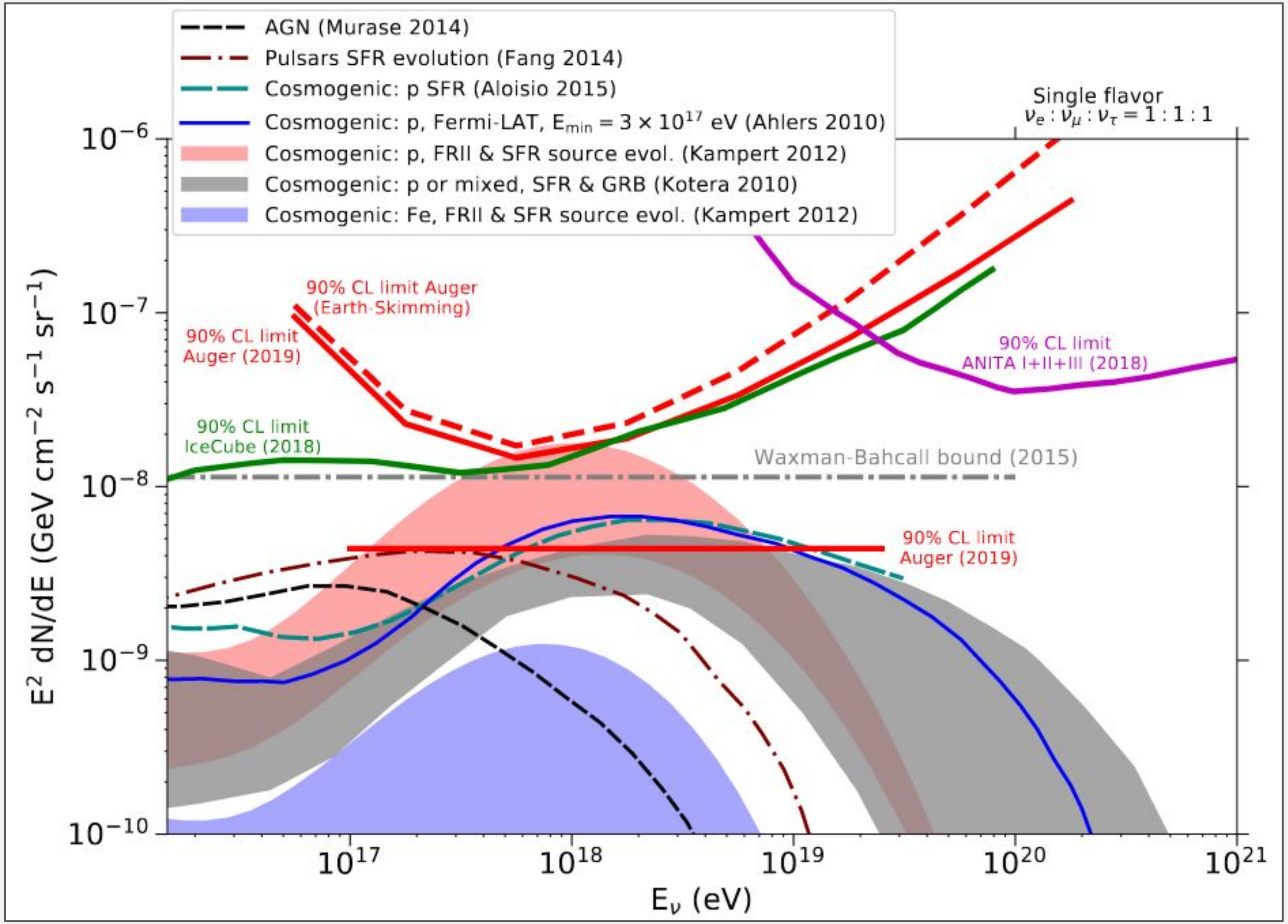
UHE protons in interactions with CMB can produce neutrinos of energies typically 1/20 of the proton energy and in greater quantities than the heavier primaries

- study of neutrino flux gives information on the nature of the primaries

In auger we look for neutrino by researching:

- Deep down-going inclined shower, with a considerable electromagnetic component (sensible to all flavors)
- Up-going earth-skimming showers (tau flavored neutrinos)




AGN (Murase 2014)
Pulsars SFR evolution (Fang 2014)
Cosmogenic: p SFR (Aloisio 2015)
Cosmogenic: p, Fermi-LAT, $E_{min} = 3 \times 10^{17}$ eV (Ahlers 2010)
Cosmogenic: p, FRII & SFR source evol. (Kampert 2012)
Cosmogenic: p or mixed, SFR & GRB (Kotera 2010)
Cosmogenic: Fe, FRII & SFR source evol. (Kampert 2012)
Single flavor
$\nu_e : \nu_\mu : \nu_\tau = 1:1:1$
90% CL limit Auger (Earth-Skimming)
90% CL limit Auger (2019)
90% CL limit IceCube (2018)
90% CL limit ANITA I+II+III (2018)
Waxman-Bahcall bound (2015)
90% CL limit Auger (2019)
E^2 dN/dE (GeV cm^{-2} s^{-1} sr^{-1})
E_ν (eV)

Neutrons

Charged cosmic rays can produce neutrons in interactions near the acceleration source

		mean lifetime		mean traveled distance
Neutron	→	15 minutes	→	$9.2\ E$ kpc
				Energy / EeV (1 EeV = 10^{18} eV)

We can look for neutron sources within the Galaxy

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	mean lifetime		mean traveled distance
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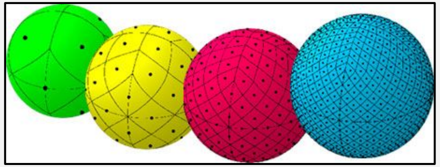
We can look for neutron sources within the Galaxy

It is not possible to distinguish between an air shower initiated by a proton or a neutron.

We identify a neutron flux through an excess of cosmic ray events around a given direction in small angular scale

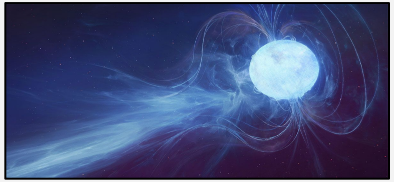
Blind search

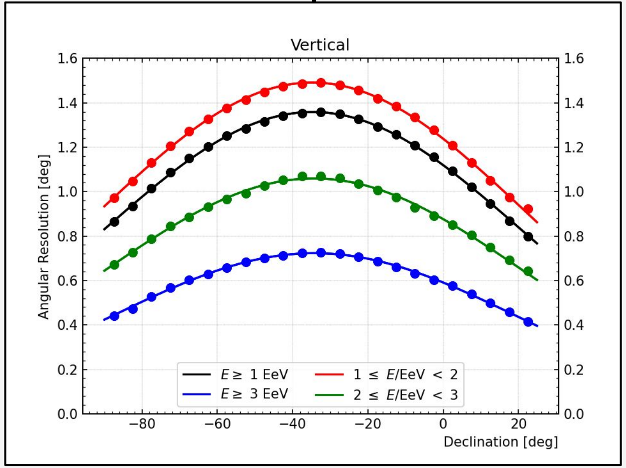
Look for overdensity in the whole observable sky by dividing it in target directions



Targeted search

Look for excesses in direction of candidate sources selected from catalogs of Galactic compact objects

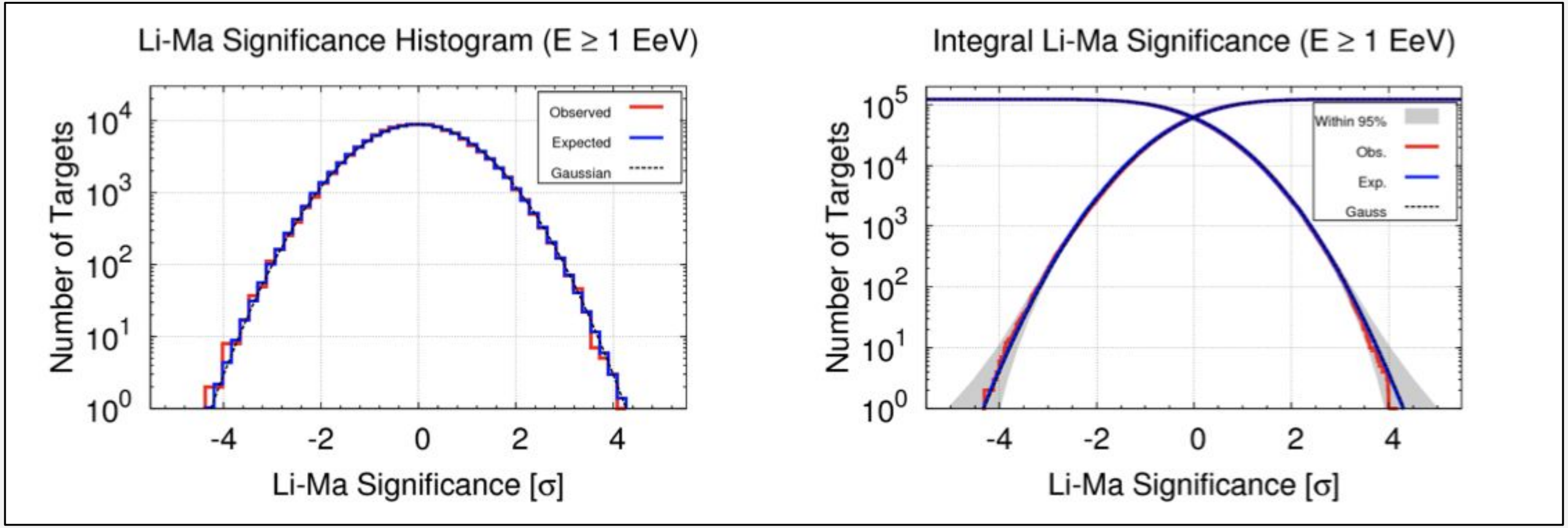


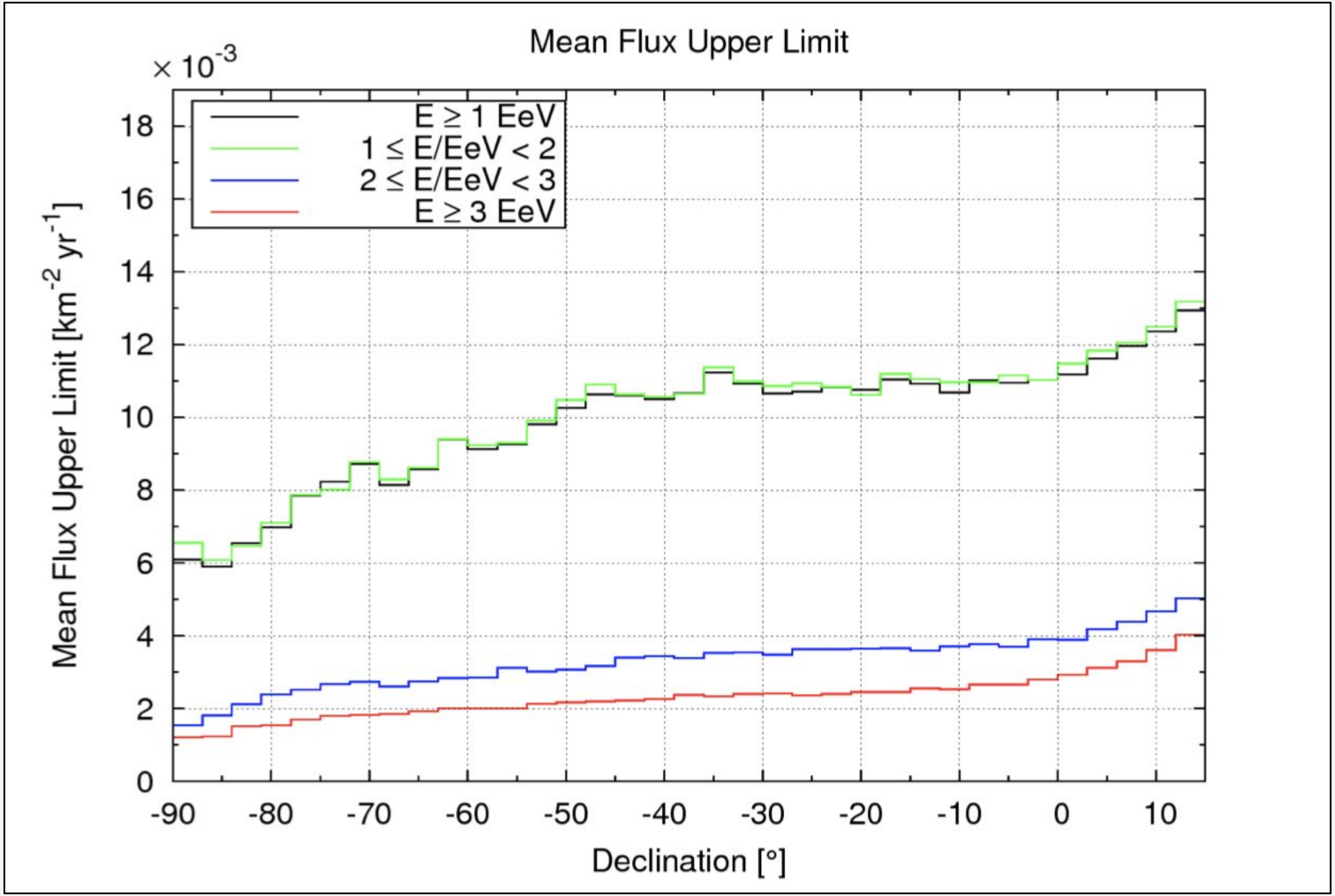


Sensitivity to point sources is optimized by choosing a target size according to the angular resolution of the SD number of events inside the target region using the observed data set

$$S = \frac{n-b}{|n-b|}\sqrt{2}\left\{ n\ln\left(\frac{n+\alpha n}{b+\alpha n}\right) + \frac{b}{\alpha}\ln\left(\frac{b+\alpha b}{b+\alpha n}\right)\right\}^{1/2}$$

expected number of events inside the target region




Mean Flux Upper Limit
× 10^-3
E ≥ 1 EeV
1 ≤ E/EeV < 2
2 ≤ E/EeV < 3
E ≥ 3 EeV
Mean Flux Upper Limit [km^-2 yr^-1]
Declination [°]
18
16
14
12
10
8
6
4
2
0
-90
-80
-70
-60
-50
-40
-30
-20
-10
0
10

Class	RA [°]	Dec [°]	Obs	Exp	Flux U.L. [km^{-2} yr^{-1}]	E-Flux U.L. [eV cm^{-2} s^{-1})]	p-value	p-value (penalized)
msec PSRs	260.27	-24.95	237	214	0.019	0.14	0.058	0.98
γ-ray PSRs	8.59	-5.58	176	149	0.024	0.18	0.016	0.70
LMXB	264.57	-26.99	265	219	0.028	0.20	0.0012	0.10
HMXB	152.45	-58.29	283	248	0.019	0.14	0.014	0.49
H.E.S.S. PWN	128.75	-45.60	275	248	0.018	0.13	0.043	0.53
H.E.S.S. other	269.72	-24.05	235	211	0.019	0.14	0.054	0.59
H.E.S.S. UNID	266.26	-30.37	251	227	0.018	0.13	0.055	0.57
Microquasars	262.75	-26.00	247	216	0.022	0.16	0.020	0.23
Magnetars	81.50	-66.08	268	241	0.016	0.11	0.040	0.48
Gal. Center	266.42	-29.01	234	223	0.014	0.10	0.24	-
Gal. Plane	$\lvert Gal.\ lat. \rvert < 1.17°$		16965	17197	0.077	0.56	0.96	-

Summary

During Phase I of the Pierre Auger Observatory several research analyzes of directions of arrival of UHECRs were carried out:

- Large scale anisotropy studies
  - Dipole effect of the flux for E>8 EeV
  - Extragalactic origin of UHECRs for E>8 EeV
- Small and intermediate scale anisotropies
  - most significant results for blind search and catalog based analysis highlighted the Centaurus region as a hotspot of interest
- Search for neutral particles
  - Produced by the interaction of CRs near their sources and with Galactic and Extragalactic background and undeflected
  - Possibility of study their flux to put constraint to the origin of UHECRs and on the properties of the sources