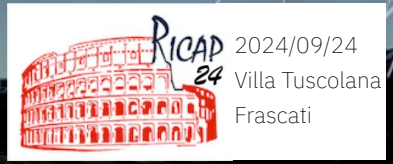
Anisotropy searches at the highest energy cosmic rays with the Pierre Auger Observatory Phase I



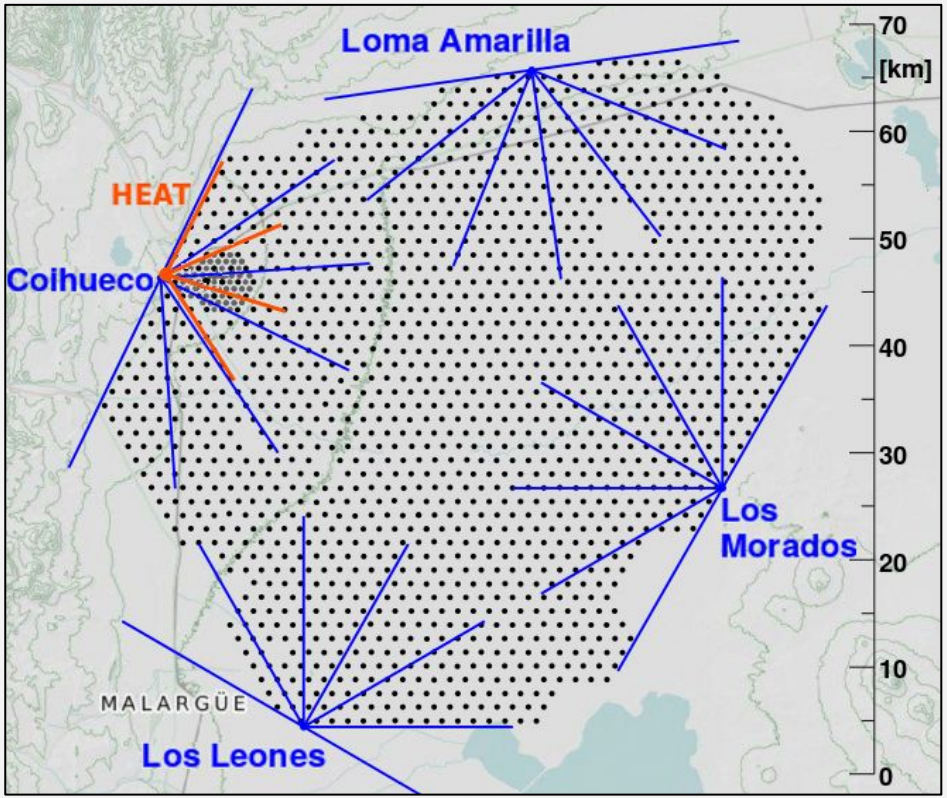
2024/09/24
Villa Tuscolana
Frascati

Federico Maria Mariani
federicomaria.mariani@unimi.it

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)

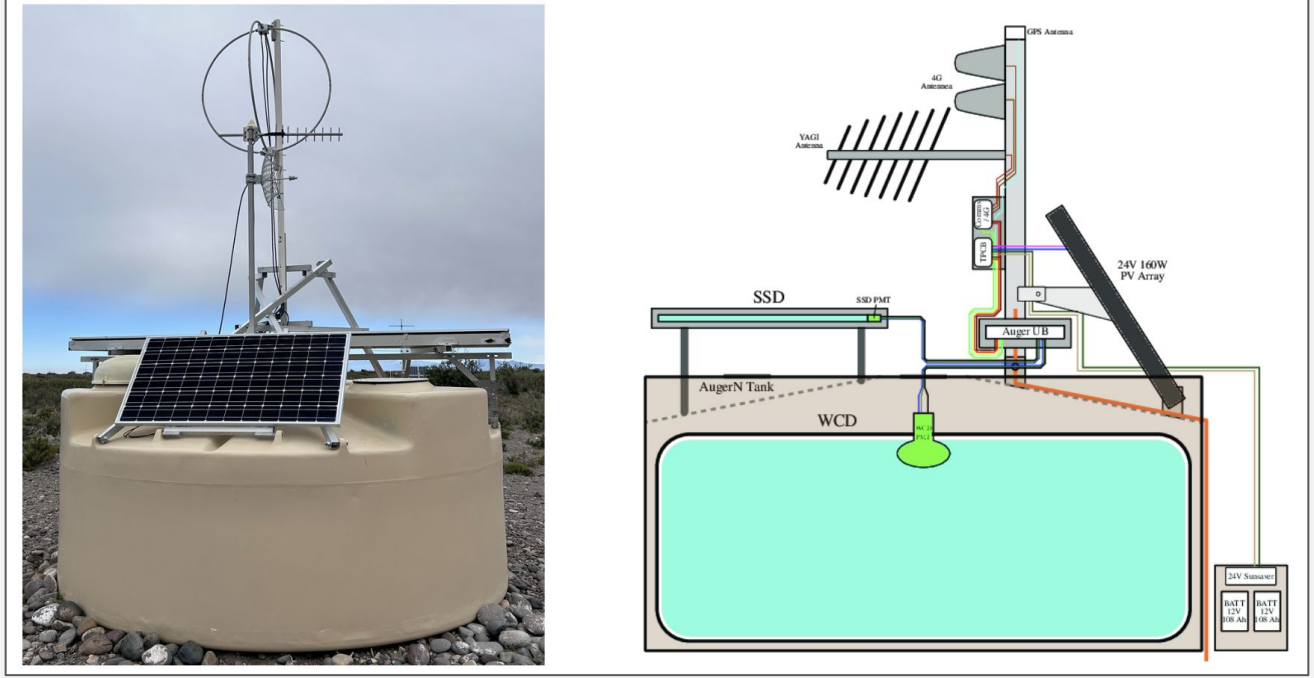


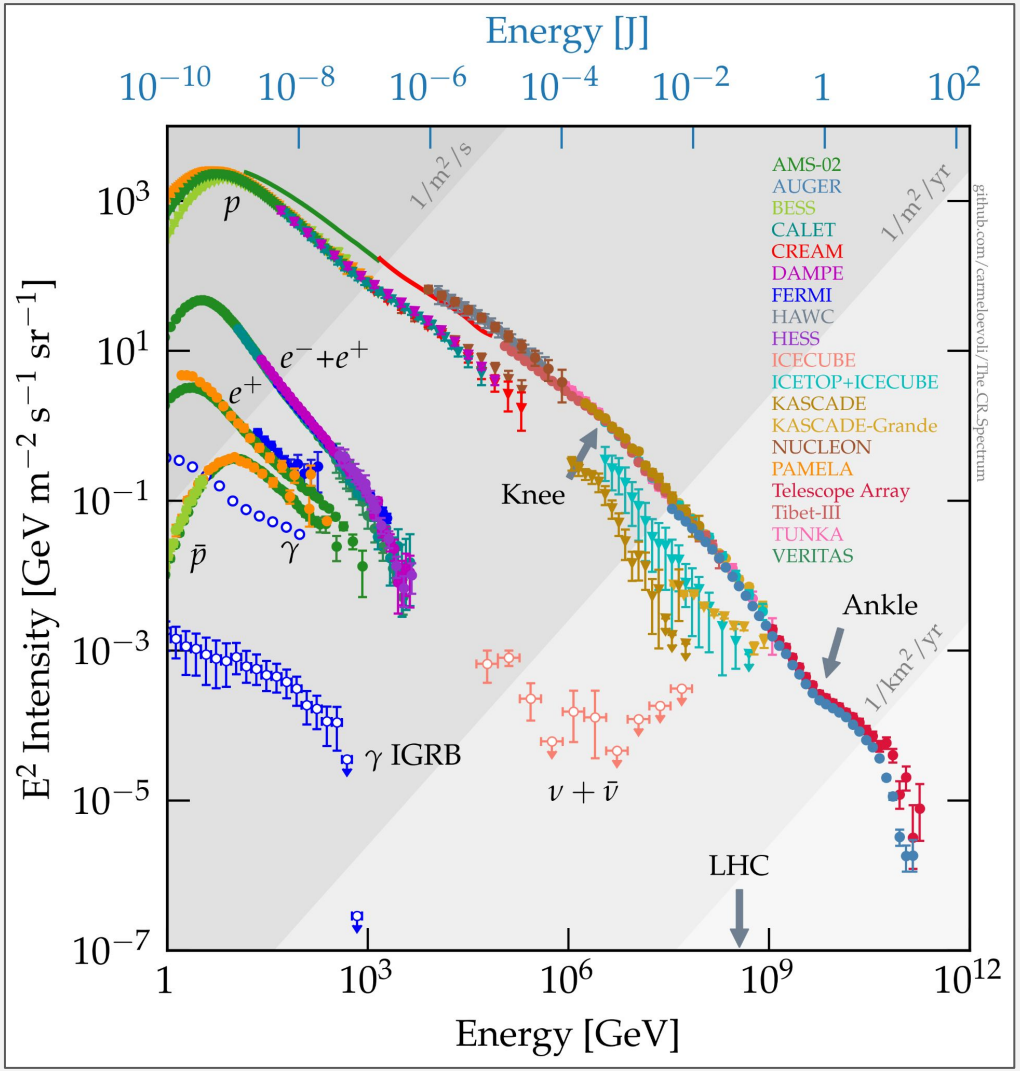
Surface Detector (SD):
1660 water Cherenkov detectors to sample the shower plane at earth

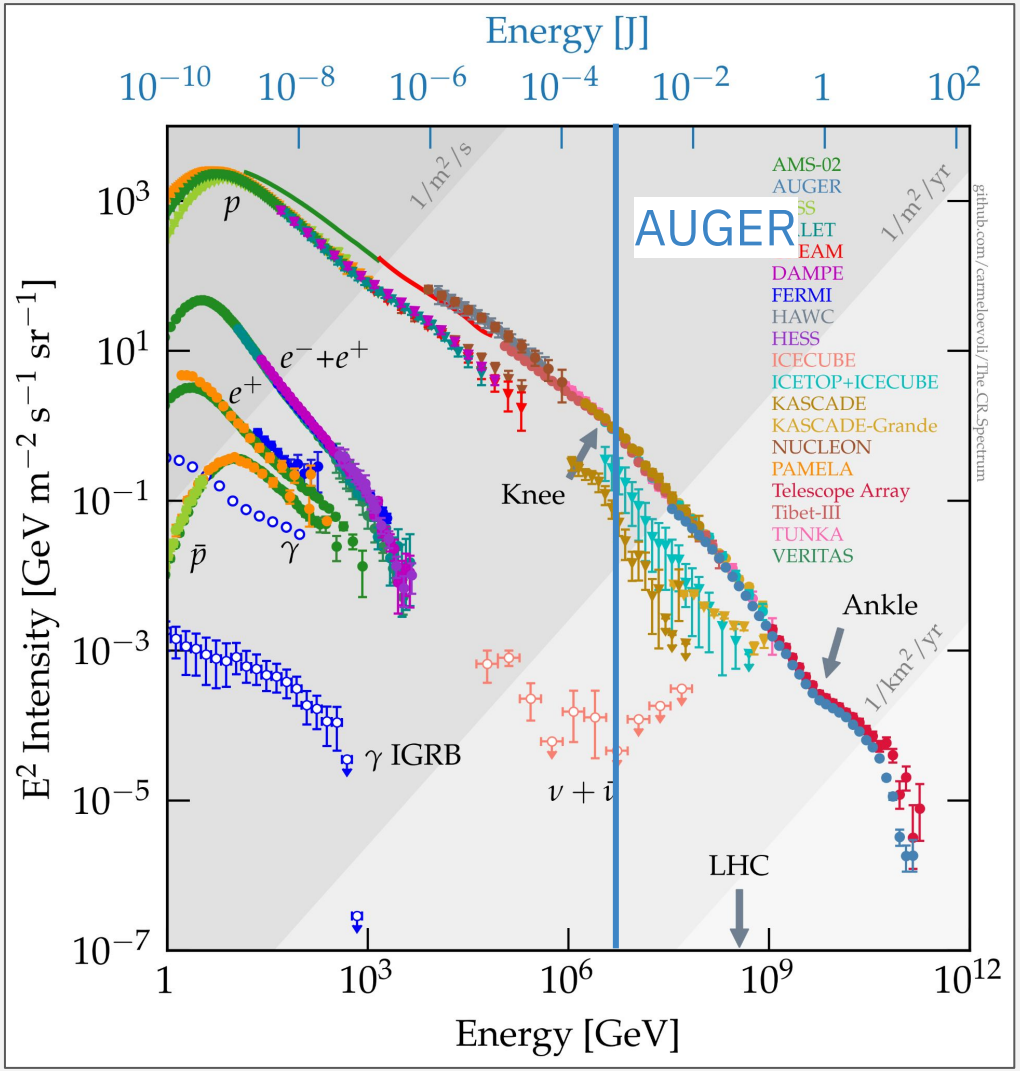
Fluorescence Detector (FD):
27 fluorescence telescopes in 4 sites (5 buildings)

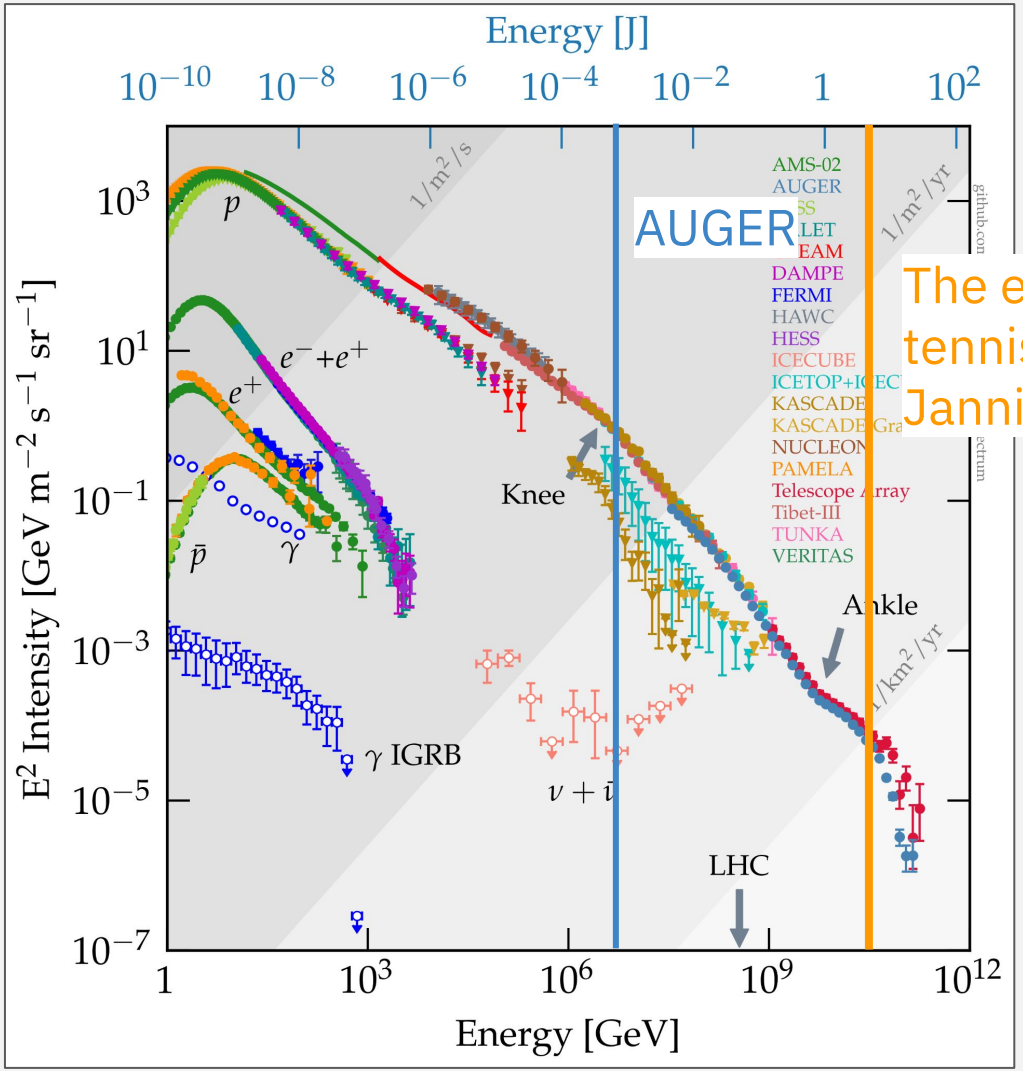
Pierre Auger Observatory Phase I

Phase I: 2004 (first data acquisition) - 2022 (deployment of the upgrade AugerPrime)




Energy [J]
10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 1 10^{2}
10^{3} 10^{1} 10^{-1} 10^{-3} 10^{-5} 10^{-7}
E^2 Intensity [GeV m^{-2} s^{-1} sr^{-1}]
1 10^{3} 10^{6} 10^{9} 10^{12}
Energy [GeV]
$1/m^2/s$
$1/m^2/yr$
$1/km^2/yr$
p
e^-+e^+
e^+
$\bar{p}$
γ
γ IGRB
$\nu+\bar{\nu}$
Knee
Ankle
LHC
AMS-02
AUGER
BESS
CALET
CREAM
DAMPE
FERMI
HAWC
HESS
ICECUBE
ICETOP+ICECUBE
KASCADE
KASCADE-Grande
NUCLEON
PAMELA
Telescope Array
Tibet-III
TUNKA
VERITAS
github.com/carmeloevoli/The.CR.Spectrum

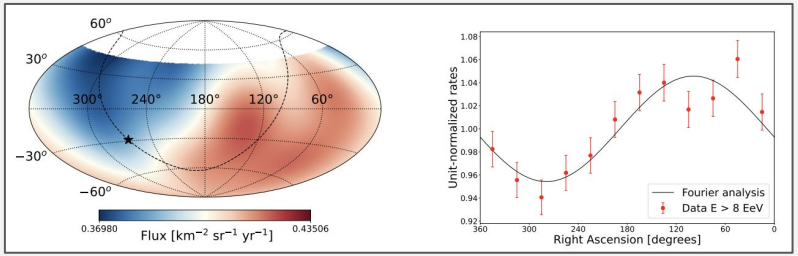

Energy [J]
10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 1 10^{2}
$1/m^2/s$
$1/m^2/yr$
$1/km^2/yr$
AUGER
AMS-02
AUGER
SS
LET
EAM
DAMPE
FERMI
HAWC
HESS
ICECUBE
ICETOP+ICECUBE
KASCADE
KASCADE-Grande
NUCLEON
PAMELA
Telescope Array
Tibet-III
TUNKA
VERITAS
github.com/carmeloevoli/The.CR.Spectrum
p
$e^- + e^+$
e^+
$\bar{p}$
γ
γ IGRB
$\nu + \bar{\nu}$
Knee
Ankle
LHC
E^2 Intensity [GeV m^{-2} s^{-1} sr^{-1}]
10^{3} 10^{1} 10^{-1} 10^{-3} 10^{-5} 10^{-7}
1 10^{3} 10^{6} 10^{9} 10^{12}
Energy [GeV]



The energy of a tennis ball hit by Jannik Sinner

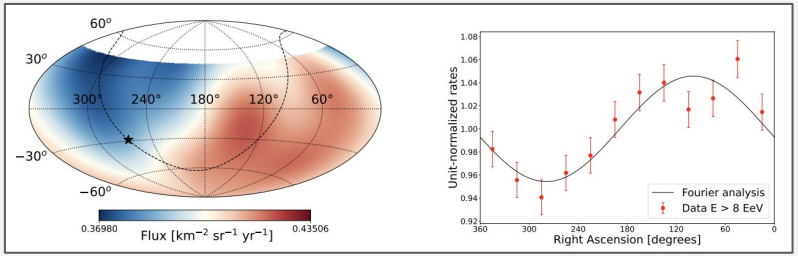
Anisotropy studies at the Pierre Auger Observatory

For large scale anisotropy studies see **Marta Bianciotto**'s talk



Anisotropy studies at the Pierre Auger Observatory

For large scale anisotropy studies see **Marta Bianciotto**'s talk



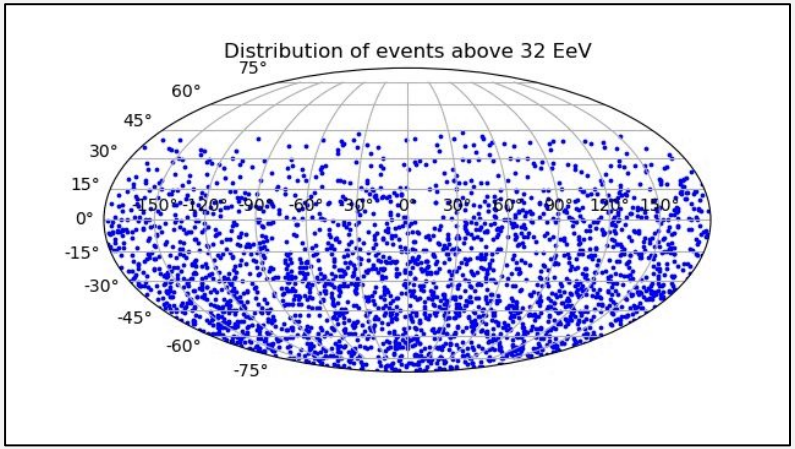
Magnetic deflections are proportional to Z/E, and cosmic rays have a reduced horizon at ultrahigh energies

- The resistance of UHECRs to deections due to magnetic fields is express in terms of rigidity R = E/eZ
- We search for small and intermediate-angular-scale anisotropies with the highest-energy events that could help to trace their sources

Dataset

Largest dataset ever built at the extreme energies (>2500 events)

- E>32 EeV
- SD data
- From 2004/01 to 2022/12 (up to 2020 availiable for public use https://doi.org/10.5281/zenodo.6504276)
- θ<80°
- exposure 135 000 km^2 sr yr



2635 above 32 EeV
647 above 50 EeV
261 above 64 EeV
36 above 100 EeV (0.1 ZeV!)
Highest energy event: 165 EeV

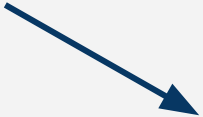
Anisotropy searches at the intermediate scale

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

Blind search for overdensity

Search for the most prominent overdensity in the whole observable sky by Auger
Binomial probability to measure N_{obs}, inside a circular window, compared to N_{exp} from isotropic simulations

Parameter space

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

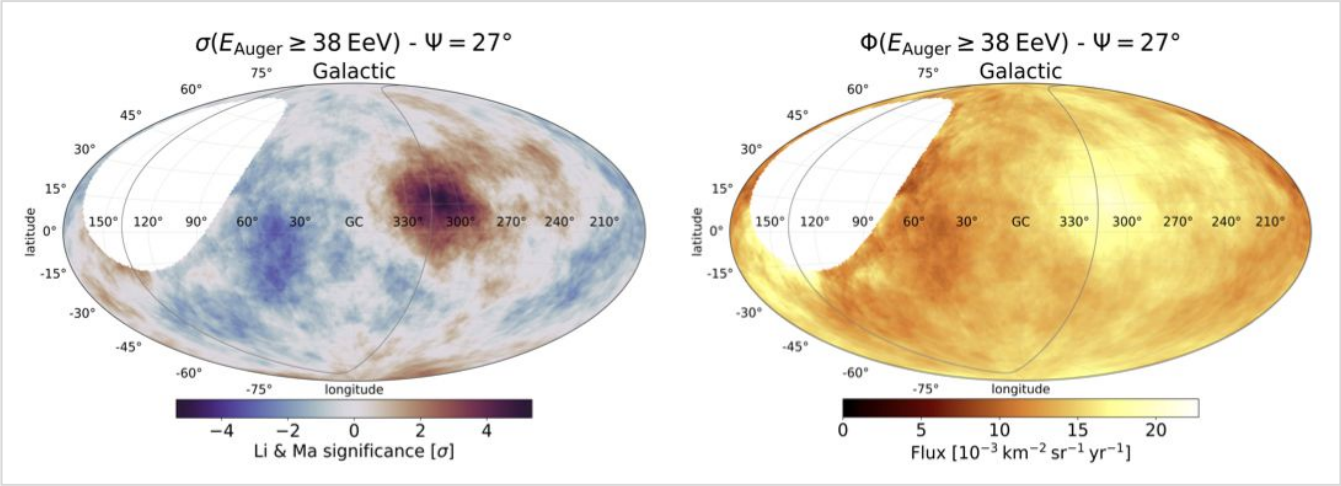
Blind search for overdensity

Search for the most prominent overdensity in the whole observable sky by Auger
Binomial probability to measure N_{obs}, inside a circular window, compared to N_{exp} from isotropic simulations

Parameter space

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

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 flux in the corresponding e.m. band and an attenuation due to their different distances (Auger spectral-composition modeling)

Parameters space: Fisher search radius θ (Ψ=1.59θ) and the signal fraction; scan in $E_{\rm th}$ in [32, 80] EeV, steps of 1 EeV

Catalogs (and their flux 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)

Catalog based searches

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

Parameters space: Fisher search radius θ (Ψ=1.59θ) and the signal fraction; scan in $E_{\rm th}$ in [32, 80] EeV, steps of 1 EeV

Catalogs (and their flux 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)

Catalog	$E_{\rm th}$ [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}
Jetted AGNs (γ-rays)	38	23^{+8}_{-7}	6^{+3}_{-3}	19.2	4.6×10^{-4}

Catalog based searches

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

Parameters space: Fisher search radius θ (Ψ=1.59θ) and the signal fraction; scan in $E_{\rm th}$ in [32, 80] EeV, steps of 1 EeV

Catalogs (and their flux 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)

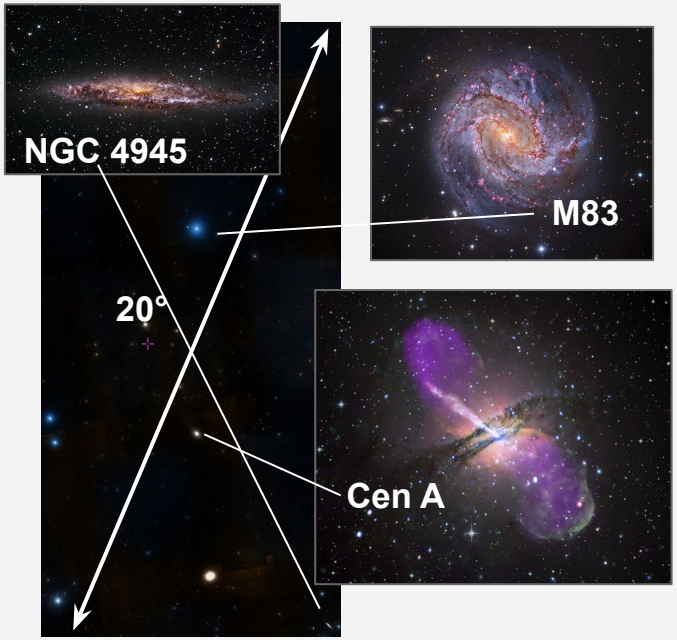
Catalog	$E_{\rm th}$ [EeV]	Ψ [°]	α [%]	TS	Post-trial p-value
All galaxies (IR)	38	24^{+15}_{-8}	14^{+8}_{-6}	18.5	6.3×10^{-4}
Starbursts (radio)	38	25^{+13}_{-7}	9^{+7}_{-4}	23.4	6.6×10^{-5}
All AGNs (X-rays)	38	25^{+12}_{-7}	7^{+4}_{-3}	20.5	2.5×10^{-4}
Jetted AGNs (γ-rays)	38	23^{+8}_{-7}	6^{+3}_{-3}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

3.8σ

Centaurus region

The Centaurus region is particularly promising for many reasons:

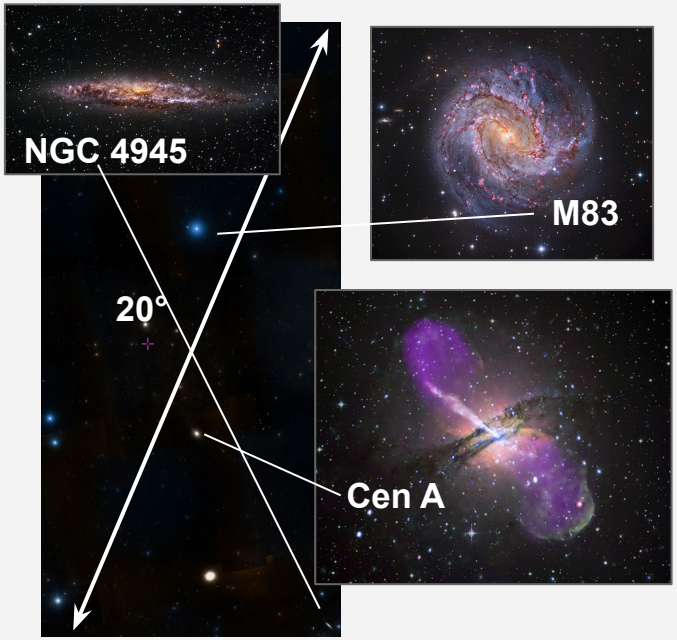
- Is a flagged area since the first anisotropy results of the Pierre Auger Observatory
- Is the most significant overdensity present in the blindsearch is in this direction
- Cen A region is the driving hotspot in all the catalog based models

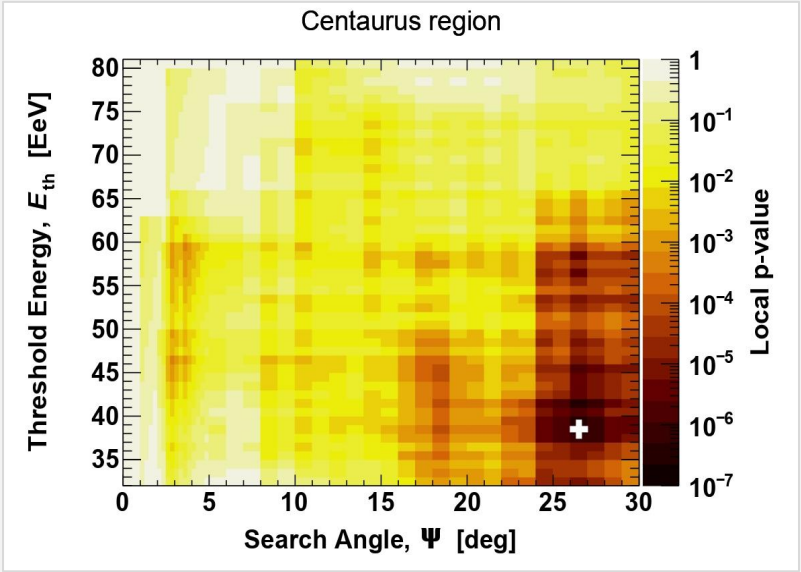


Centaurus region

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





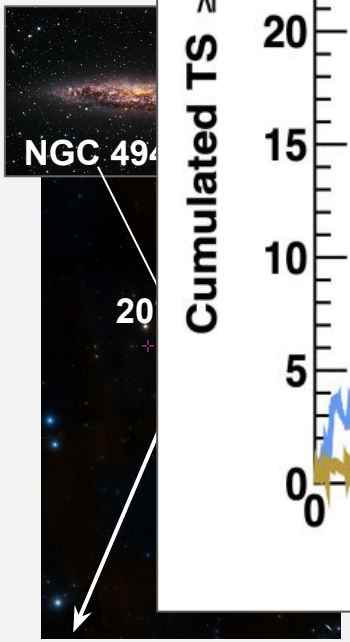
4.0σ post-trial for E_{th}=38 EeV, Ψ=27°

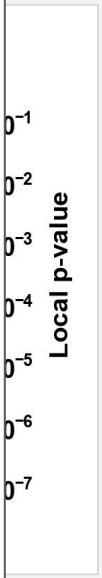
Centaurus region

The Cent

- Is a
- Is t
- Cer

ory





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

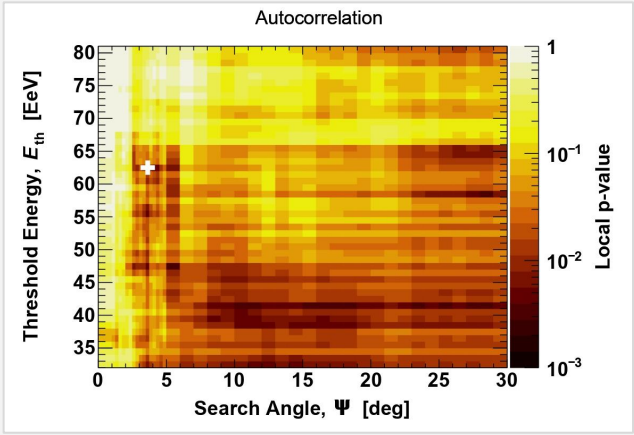
Autocorrelation

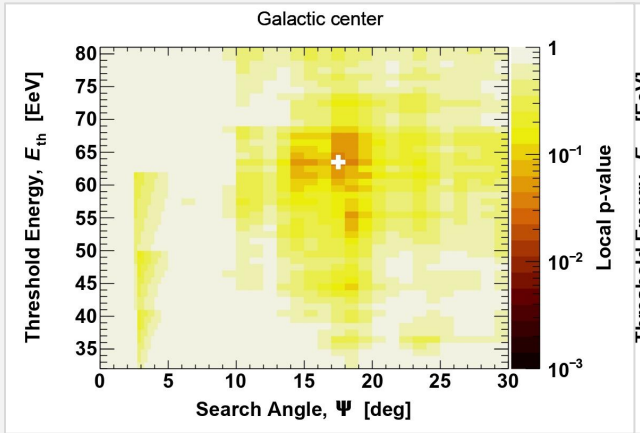
Pairs of events separated by given angular distance, scan in threshold energy, angle Ψ

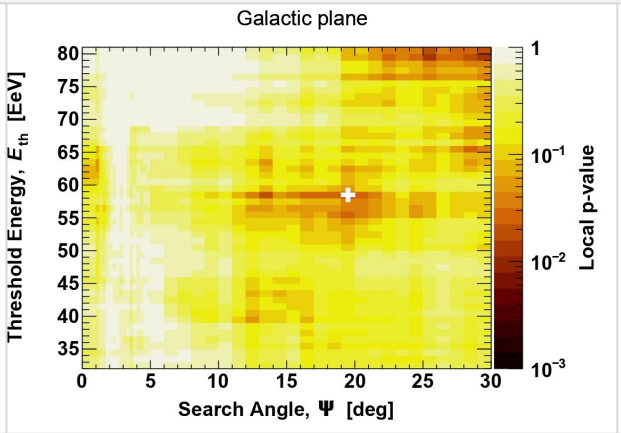
Structures

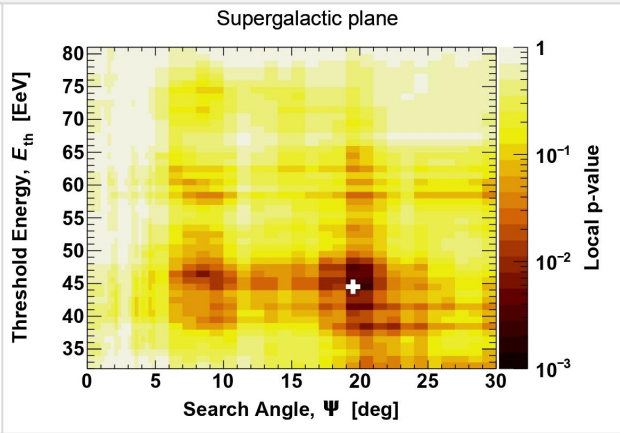
Events in proximity of local astrophysical structures, scan in threshold energy, angle Ψ

Search	$E_{\rm th}$ [EeV]	Angle, Ψ [deg]	$N_{\rm obs}$	$N_{\rm exp}$	Local p-value, $f_{\rm min}$	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









Regions of Telescope Array excesses with Auger data

We study the regions of the sky where the Telescope Array Collaboration has reported excesses in their data

- overdensities close to the Perseus-Pisces supercluster (PPSC)
- TA hot spot, the higher-energy excess

	$(\alpha_0, \delta_0)[^\circ]$	E^{TA}	$N^{\mathrm{TA}}_{\mathrm{obs}}$	$N^{\mathrm{TA}}_{\mathrm{exp}}$	$\sigma^{\mathrm{TA}}_{\mathrm{post}}$	E^{Auger}	$N^{\mathrm{Auger}}_{\mathrm{obs}}$	$N^{\mathrm{Auger}}_{\mathrm{exp}}$	$\sigma^{\mathrm{Auger}}_{\mathrm{Li-Ma}}$
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

energy rescaled by ~20%, taking into account the cross-calibration of the energy scale

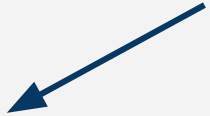
Summary & conclusion

- We search for small and intermediate-angular-scale anisotropies with the highest-energy events that could help to trace their sources
  - UHECRs arrival directions might show anisotropy at intermediate angular scales, mirroring the inhomogeneous distribution of the nearby extra-galactic matter

Summary & conclusion

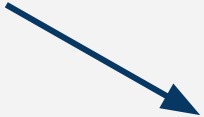
- We search for small and intermediate-angular-scale anisotropies with the highest-energy events that could help to trace their sources
  - UHECRs arrival directions might show anisotropy at intermediate angular scales, mirroring the inhomogeneous distribution of the nearby extra-galactic matter

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



Blind searches

Catalog based searches

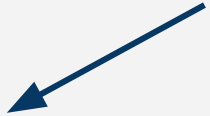


Autocorrelation and correlation with structures

Summary & conclusion

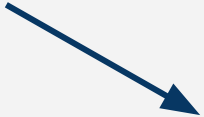
- We search for small and intermediate-angular-scale anisotropies with the highest-energy events that could help to trace their sources
  - UHECRs arrival directions might show anisotropy at intermediate angular scales, mirroring the inhomogeneous distribution of the nearby extra-galactic matter

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

Centaurus region at 4.0σ

- could reach 5.0σ by (165,000 ± 15,000) km2 sr yr

SBG catalog at 3.8σ