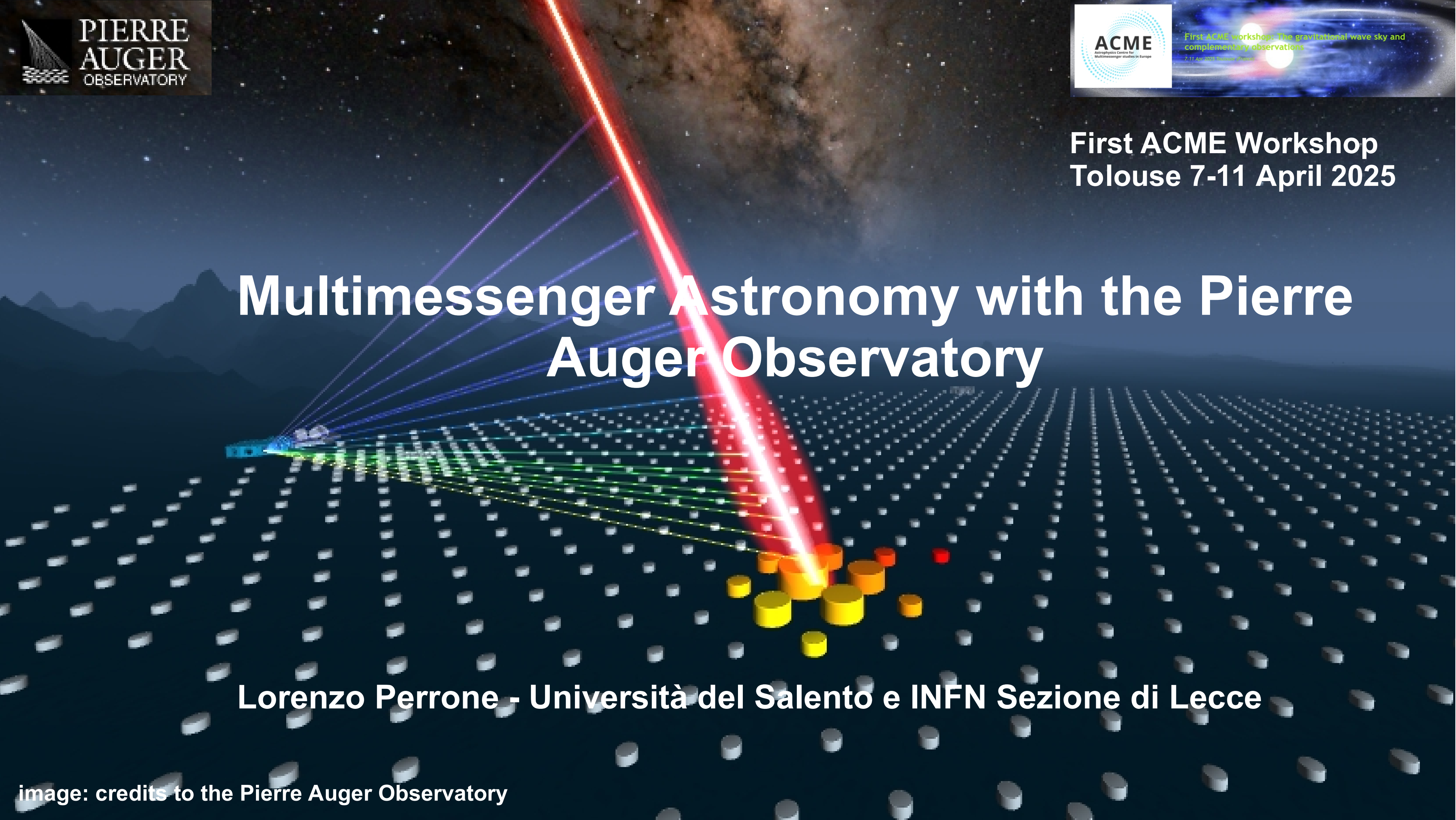


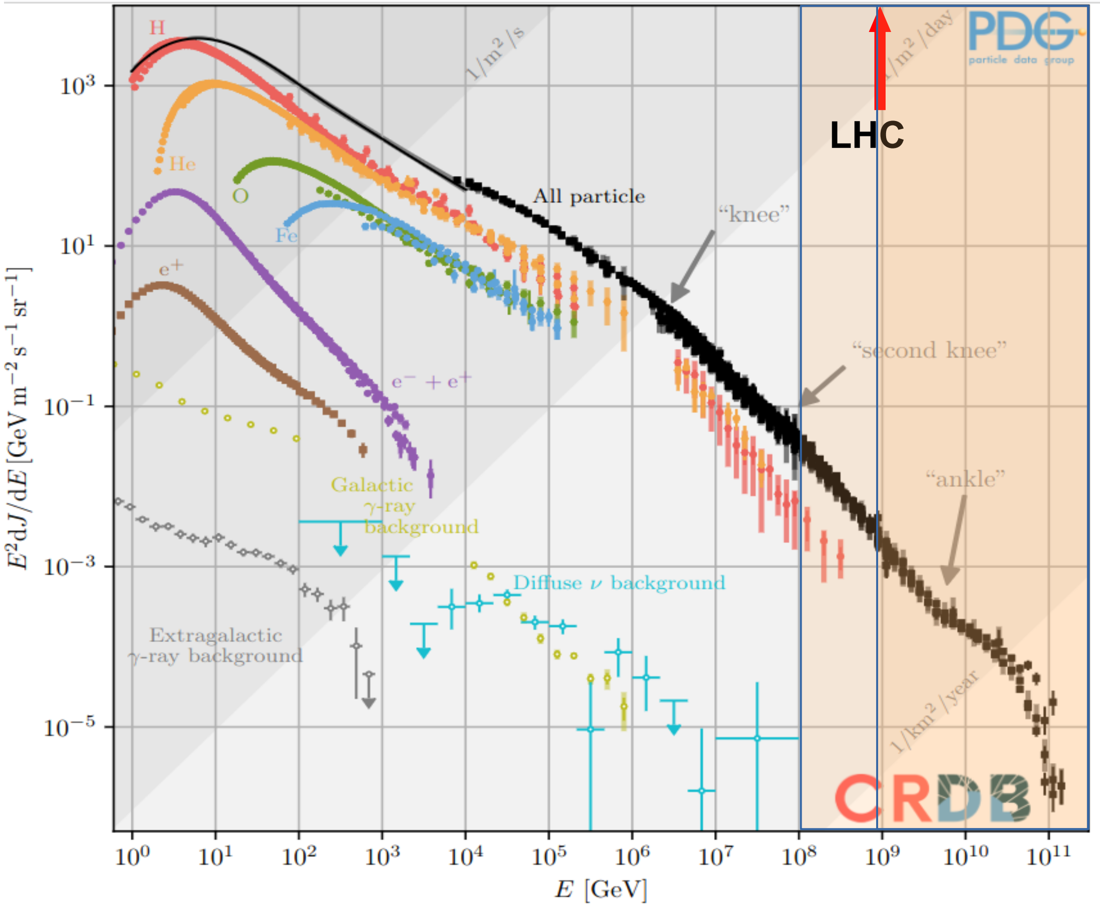
First ACME Workshop
Tolouse 7-11 April 2025

Multimessenger Astronomy with the Pierre Auger Observatory

Lorenzo Perrone - Università del Salento e INFN Sezione di Lecce

image: credits to the Pierre Auger Observatory

Ultra-high energies cosmic rays



Wide range of energy/flux

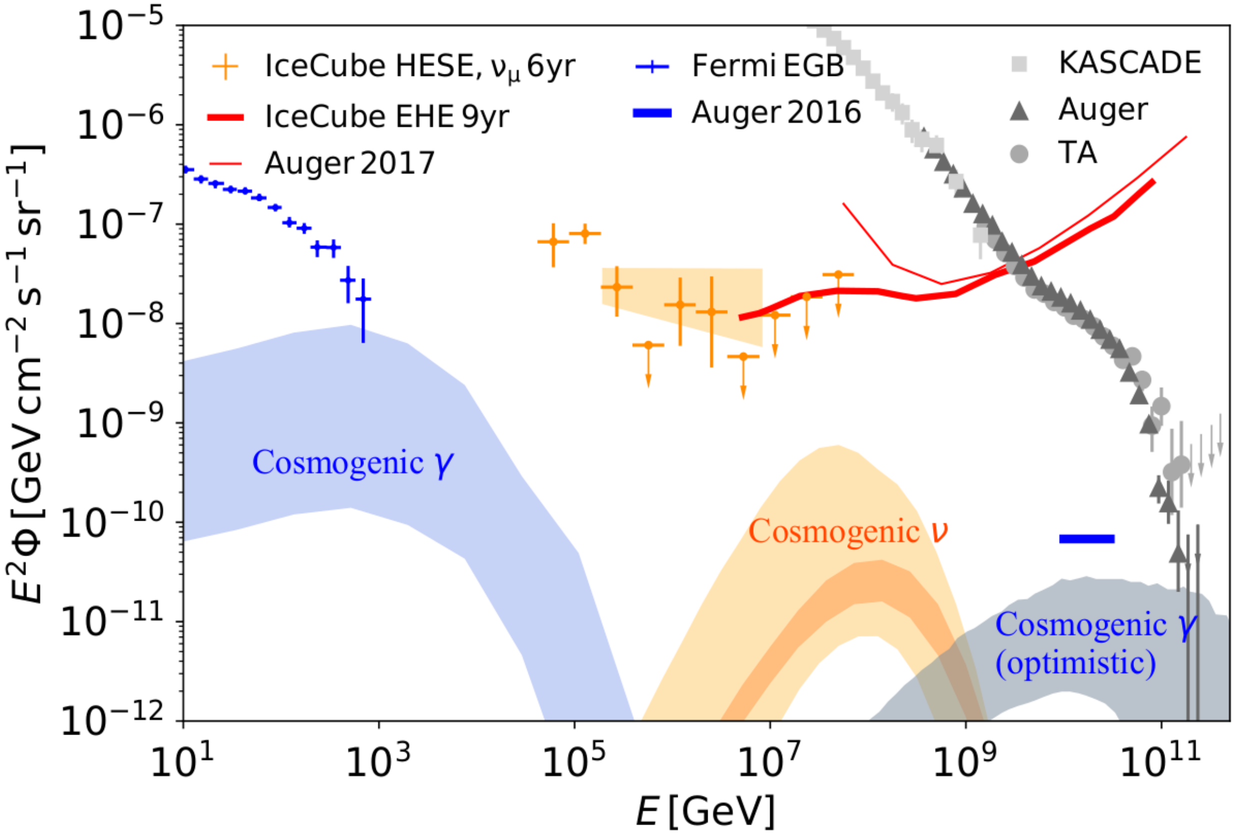
Diverse measurement techniques

Impressive improvement of the knowledge in the past decade still many open problems

Such as: origin and nature of ultra-high energy cosmic rays, acceleration mechanisms, propagation effects...

Unprecedented statistics and precision!

The multi-messenger astronomy landscape

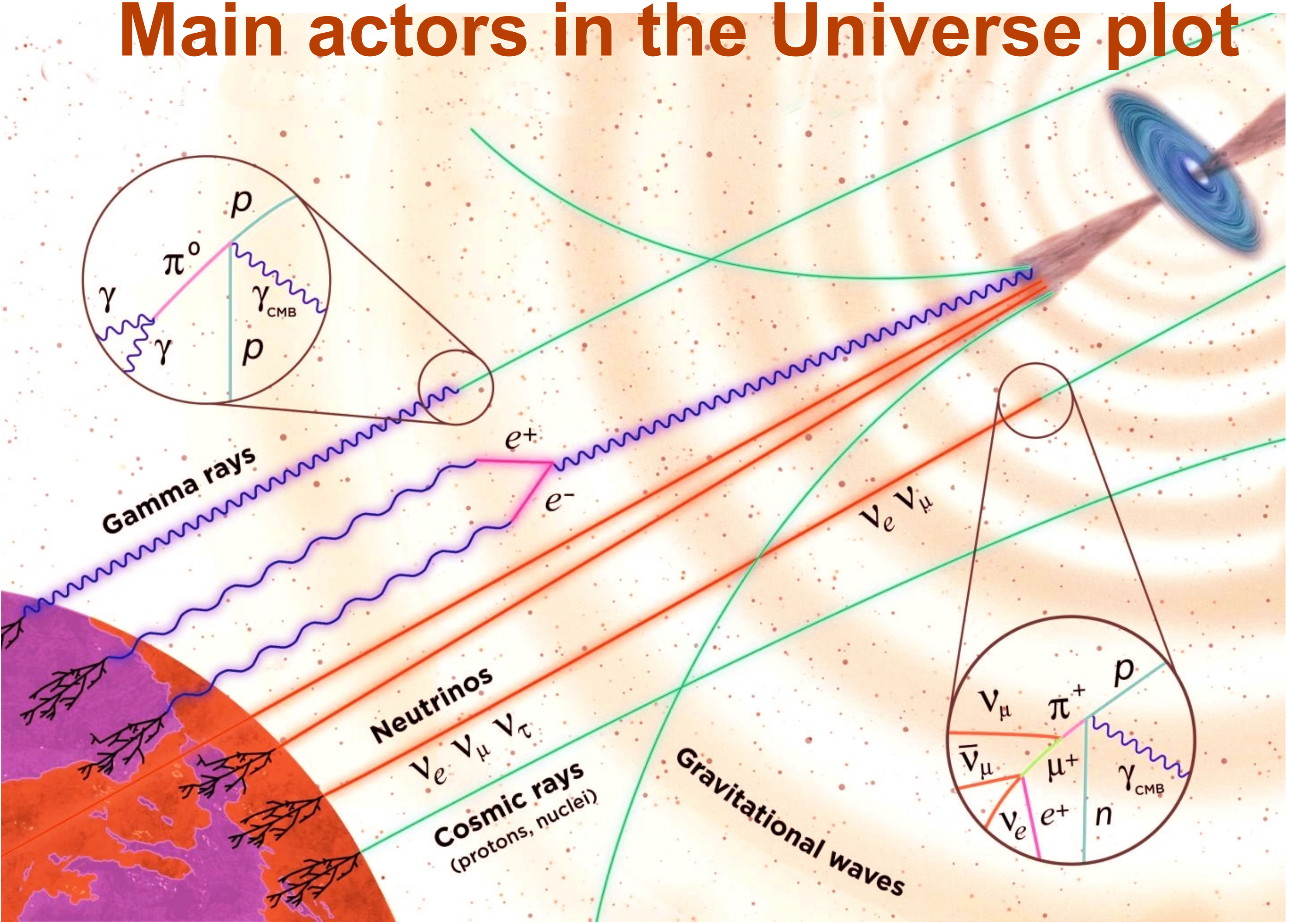


Strong interplay between different “cosmic” actors

Broader context is essential to have a scientifically coherent picture

Exploring and exploiting the potential of these tools in fundamental physics

Main actors in the Universe plot



Multi-Messenger astronomy with highest energy particles

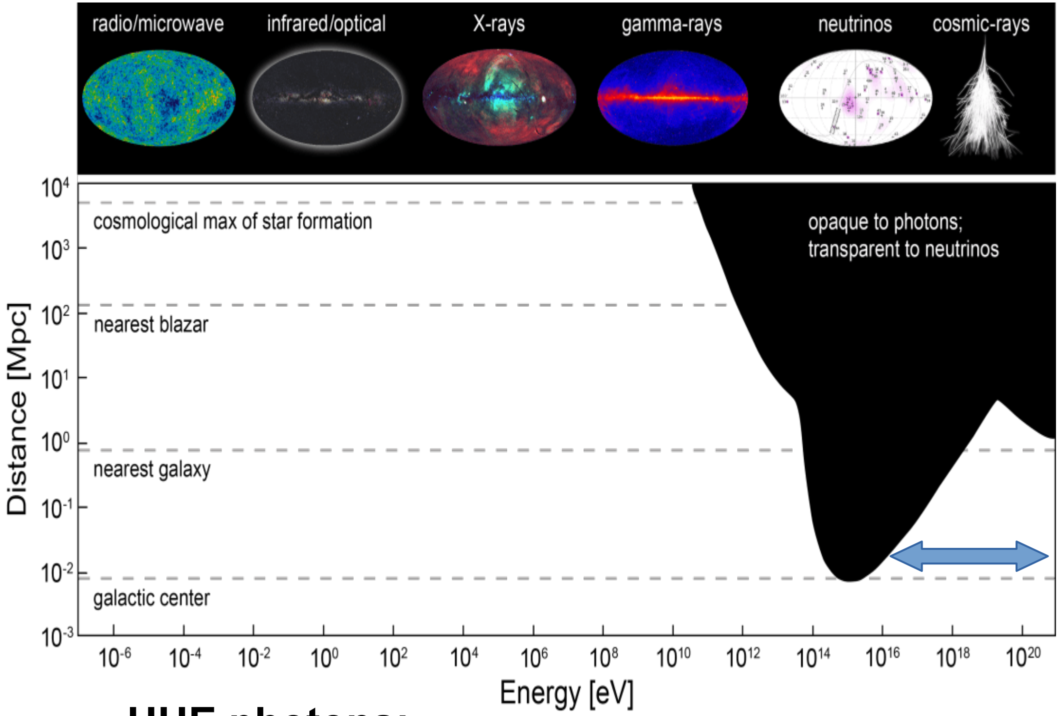
Gravitational Waves:
Multi wavelength searches in combination with mergers

→ **Charged CR:**
magnetic fields deflection

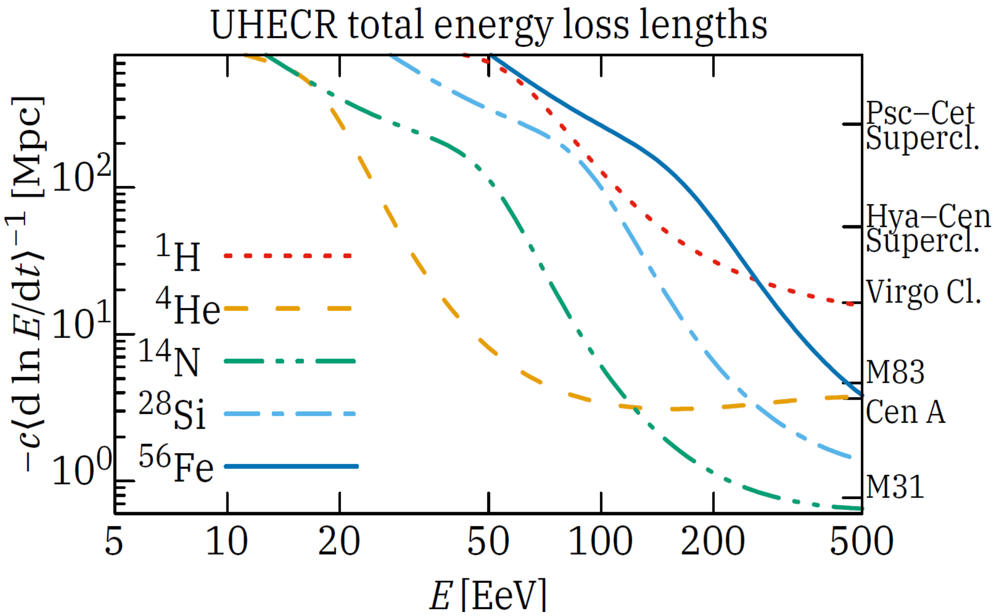
→ **UHE photons:**
limited horizon (local universe) or hints for new physics (SHDM, LIV)

→ **UHE neutrinos:** probing the most distant UHECR sources. Elusive particles need large exposure detectors

The cosmic horizon for the Pierre Auger Observatory



→ Charged CR:
magnetic fields deflection
propagation effect (~100 Mpc at 10^{20} eV)

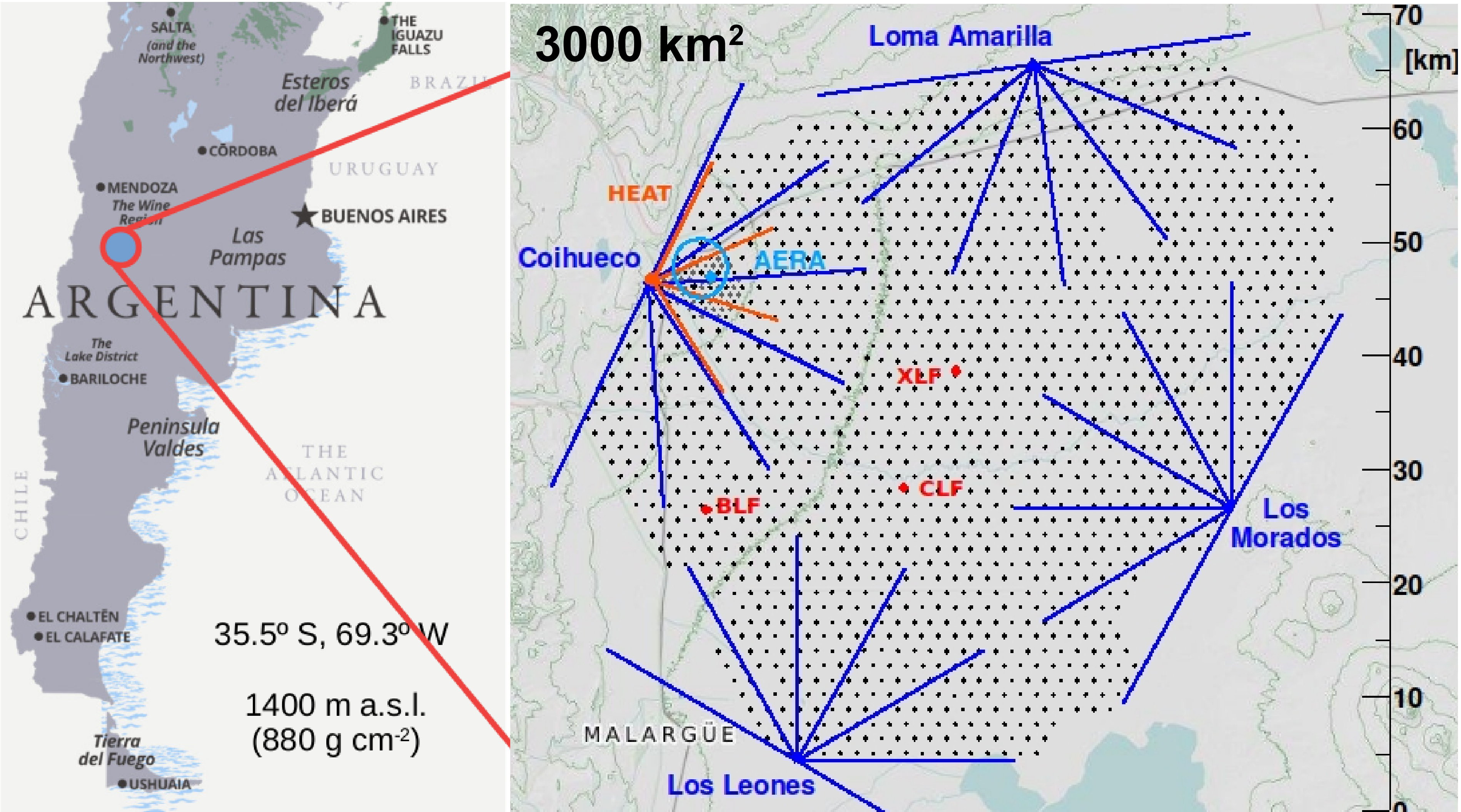


→ UHE photons:
limited horizon (local universe)
or hints for new physics (SHDM, LIV)

→ UHE neutrons: 15 min mean lifetime → 9.8 kpc (E/EeV)

→ UHE neutrinos: probing the most distant UHECR sources. Elusive particles need large exposure

The Pierre Auger Observatory



35.5º S, 69.3º W

1400 m a.s.l.
(880 g cm^{-2})

The Pierre Auger Observatory

PIERRE AUGER OBSERVATORY

Surface detector

~ 400 members, 17 countries

3000 km²

array of 1660 Cherenkov stations on a 1.5 km hexagonal grid of 3000 km²
Dense sub-array (750 m) of 24 km²

Fluorescence detector

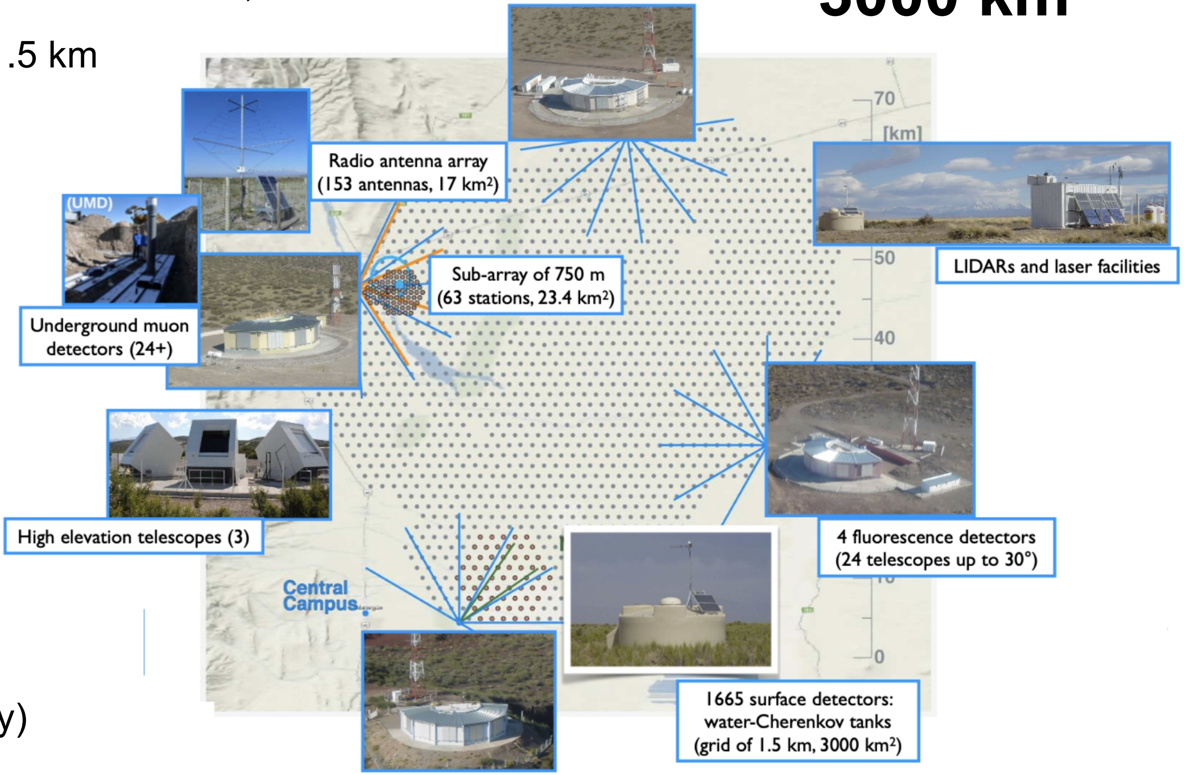
4+1 buildings overlooking the array
(24 + 3 HEAT telescopes)

Radio detector

153 Radio Antenna → AERA

Muon Detectors

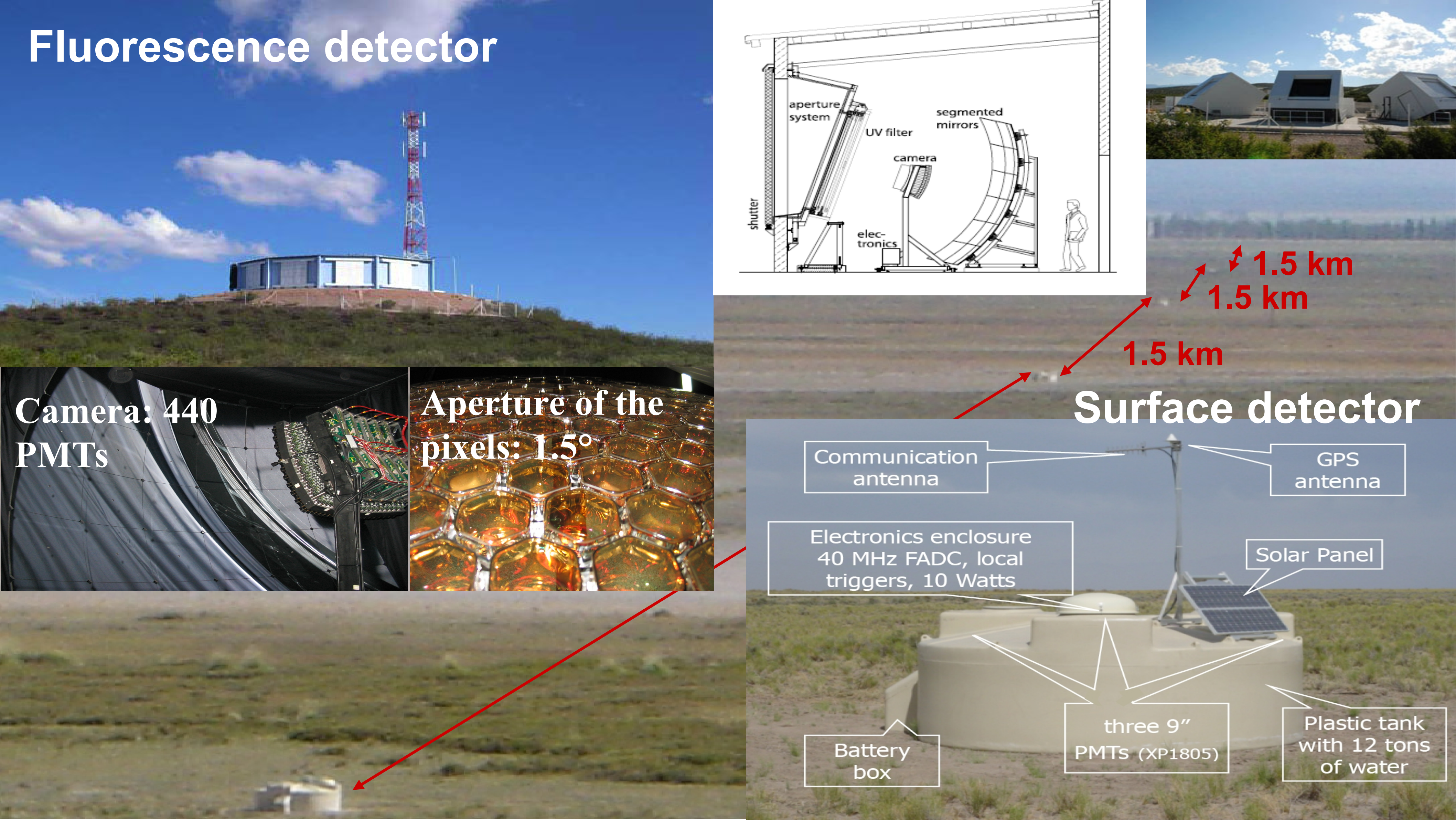
Buried scintillators (region of dense array)



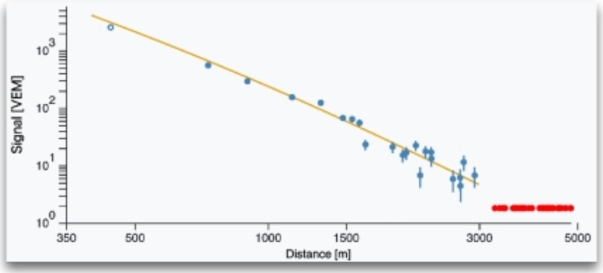
***Phase 1** : data taking from 2004 on*
(from 2008 with the full array in operation):

- Over 120.000 km² sr yr for anisotropy studies
- Over 80.000 km² sr yr for spectrum studies

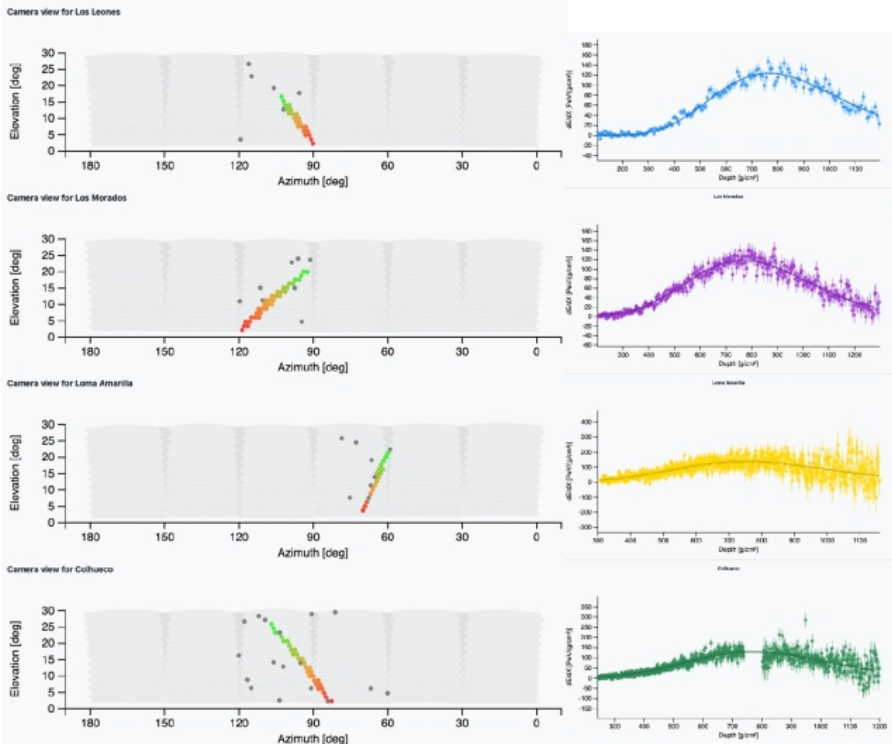
Phase 2 - the AugerPrime upgrade
Data taking from 2023 to 2035…
Multiple detectors

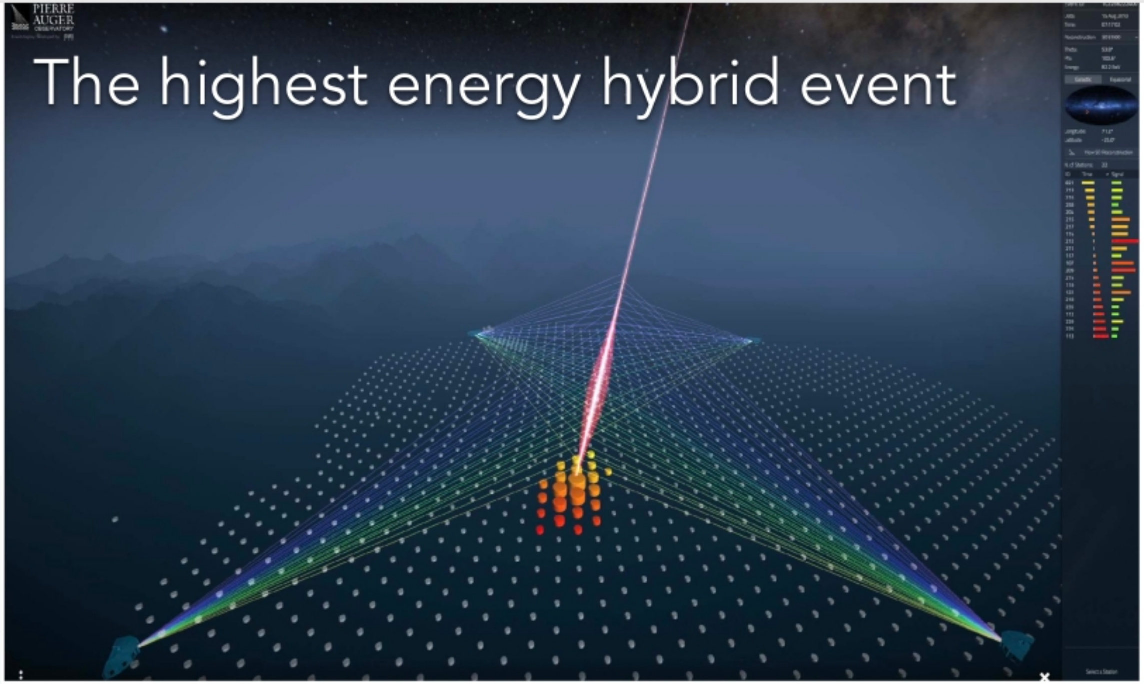

Fluorescence detector
aperture system
UV filter
segmented mirrors
camera
shutter
elec-
tronics
Camera: 440 PMTs
Aperture of the pixels: 1.5°
1.5 km
1.5 km
1.5 km
Surface detector
Communication antenna
GPS antenna
Electronics enclosure
40 MHz FADC, local triggers, 10 Watts
Solar Panel
Battery box
three 9” PMTs (XP1805)
Plastic tank with 12 tons of water

SD rec



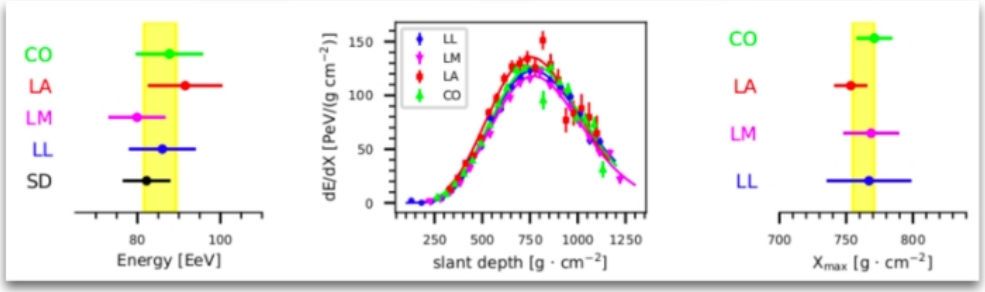
Energy	82±7 EeV
θ	53.8°
ϕ	100.6°
β	-2.1
$t_{1/2}(1000)$	127±5 ns
δ	17.8°
α	324.5°
Multiplicity	22



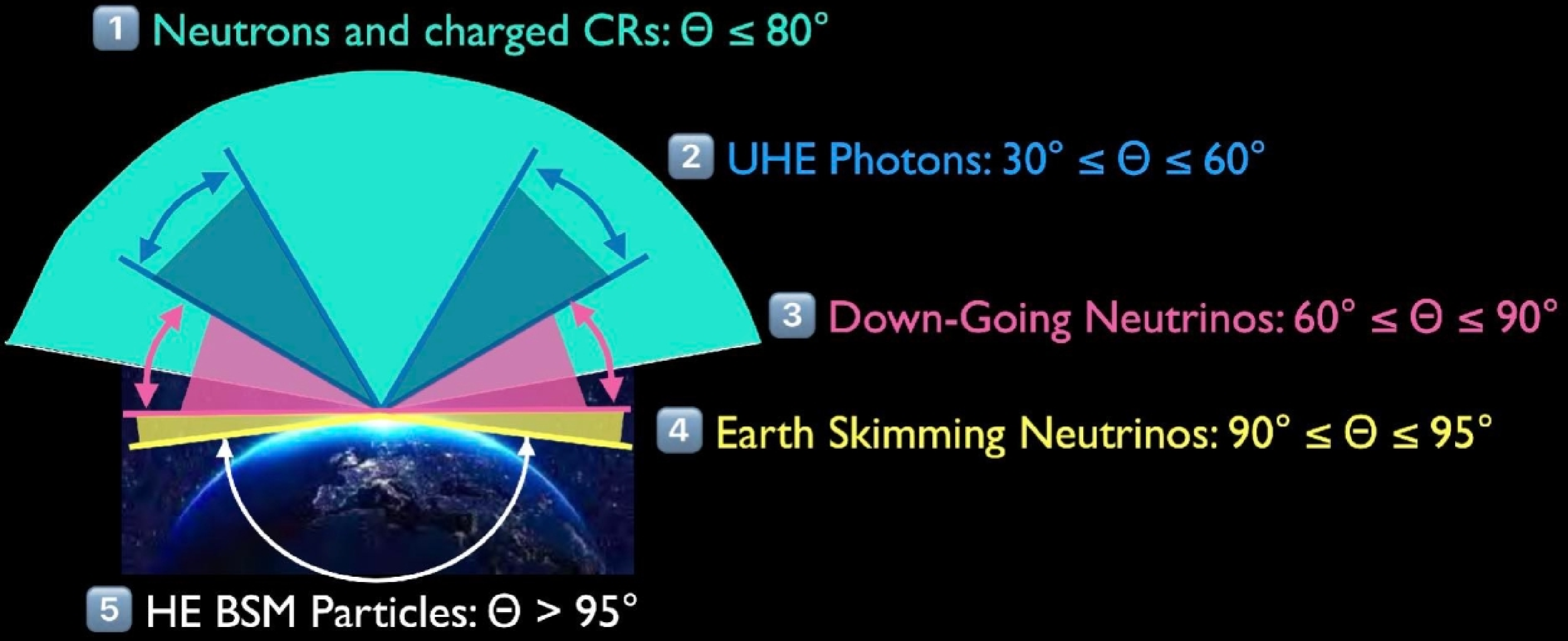


Astrophys. J. Suppl. S. 264 (2023) 50

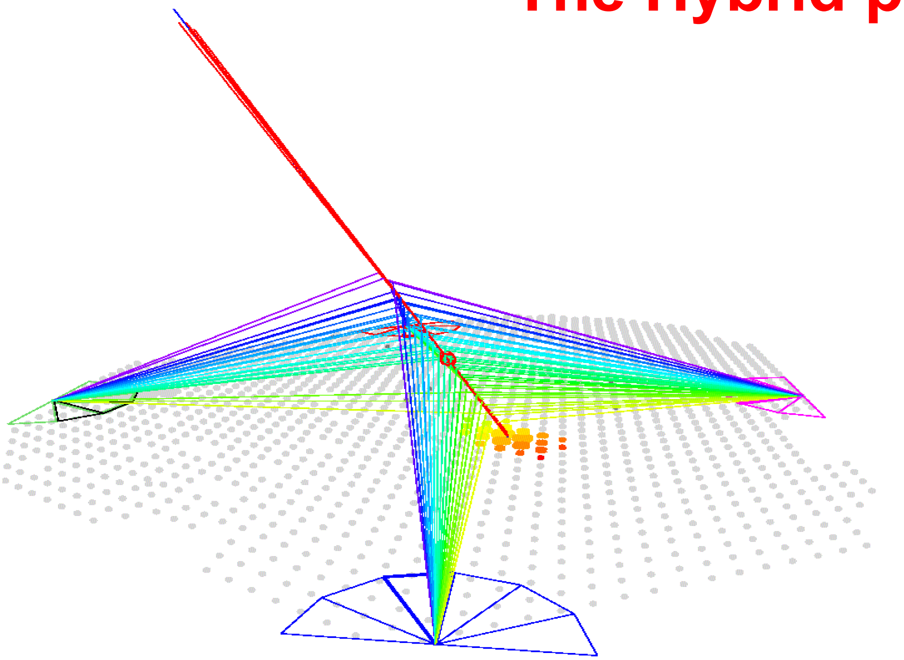
Hybrid rec

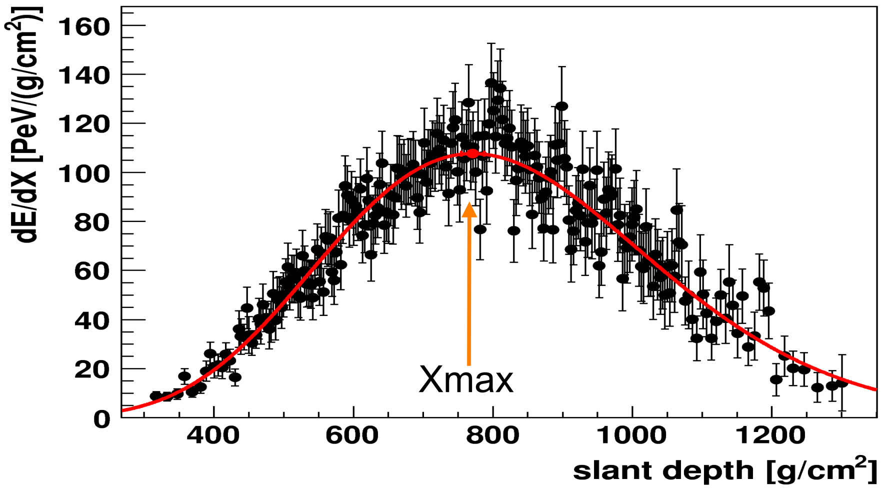


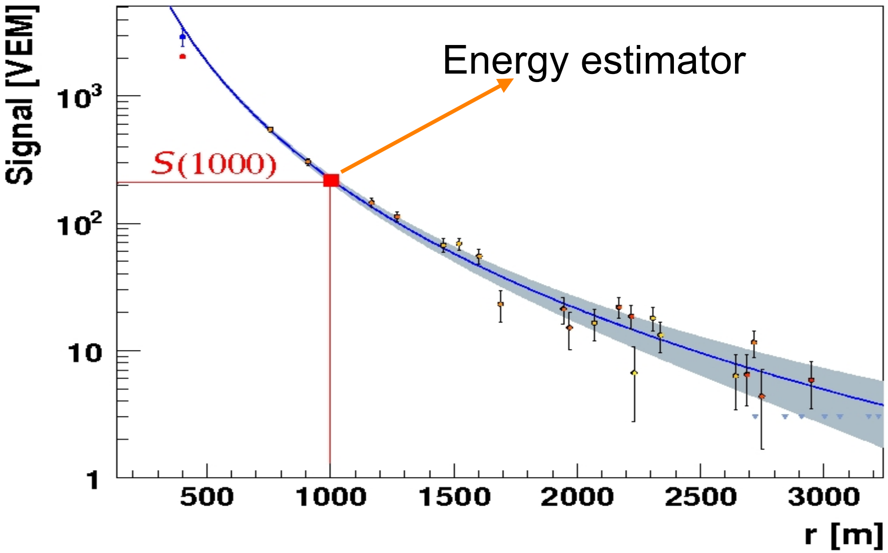
Auger: A 4π MM Observatory



The Hybrid paradigm







Longitudinal profile

FD - calorimetric measurement

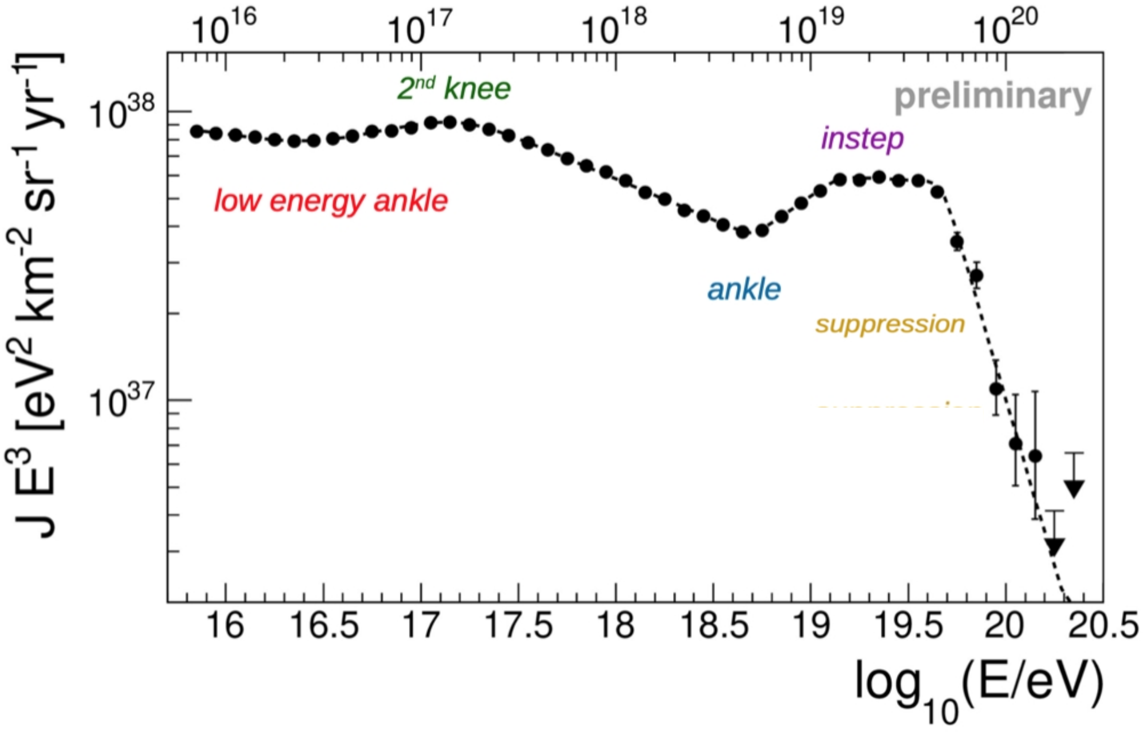
- duty cycle 15%
- Xmax (mass composition)

Density of particles at the ground

SD - duty cycle ~ 100%

Angular resolution ~ 1°

The Auger combined spectrum



Cutoff at ~ 5 10^{19} eV and **ankle** at ~ 5 10^{18} eV confirmed

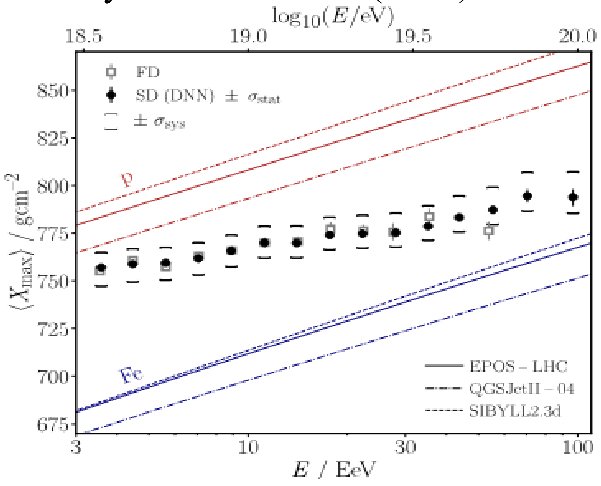
instep at ~ 10^{19} eV identified

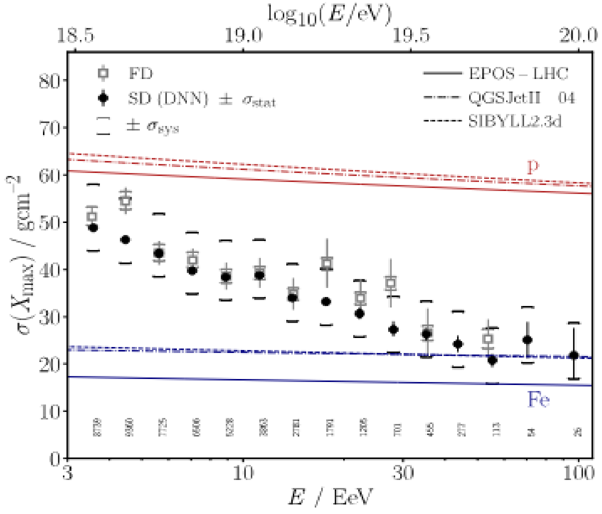
2nd knee observed, hint for a low energy ankle

Phys. Rev. D 102(2020) 062005, Phys. Rev. Lett. 125 (2020) 121106

<Xmax> and sigma

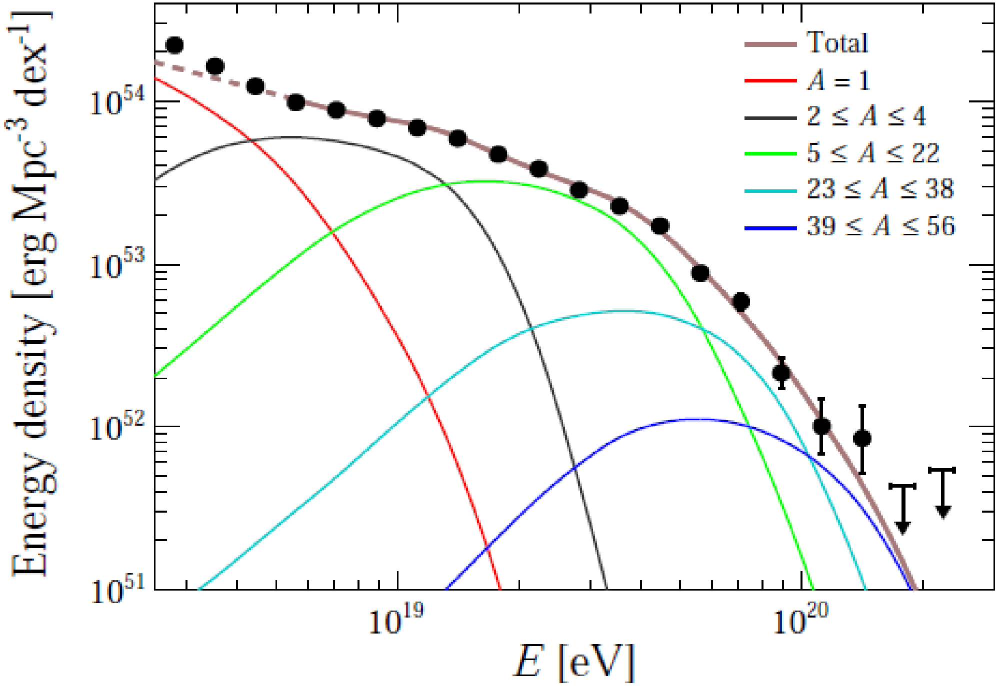
Phys Rev. D 111, 022003 (2025)
Phys.Rev. Lett. 134 (2025) 021001





Combined fit of Auger data (spectrum and X_{max} simultaneously) vs astrophysical scenarios

Phys. Rev. D 102(2020) 062005, Phys. Rev. Lett. 125 (2020) 121106



sources accelerating only protons → **disfavored**

uniformly distributed sources accelerating nuclei [rigidity dependent] → **favored**

indication that the new feature at 10^{19} eV may be due to the interplay of He and CNO components
(individual nearby source not favored, spectrum flat in declination)

additional component required below 5 10^{18} eV (possibly a tail from galactic CR)

energy density in CR above the ankle (5.66 ± 0.03 ± 1.40) 10^{53} erg Mpc^{-3}
this constraints the luminosity density for classes of extra-galactic

→ **sources such as AGN and SB match**

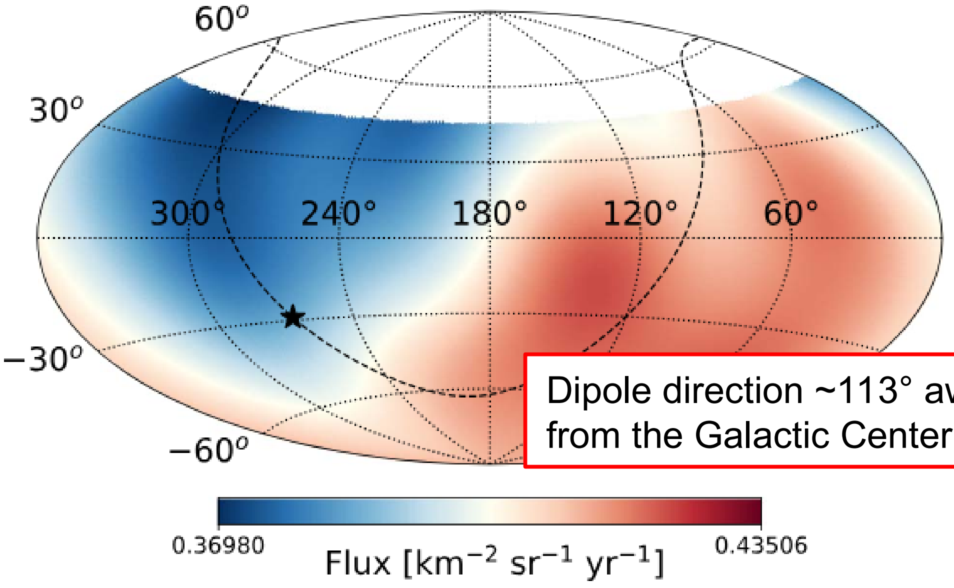
Large Scale anisotropy

E > 4 EeV, zenith < 80°
Exposure=123000 km²sr y!

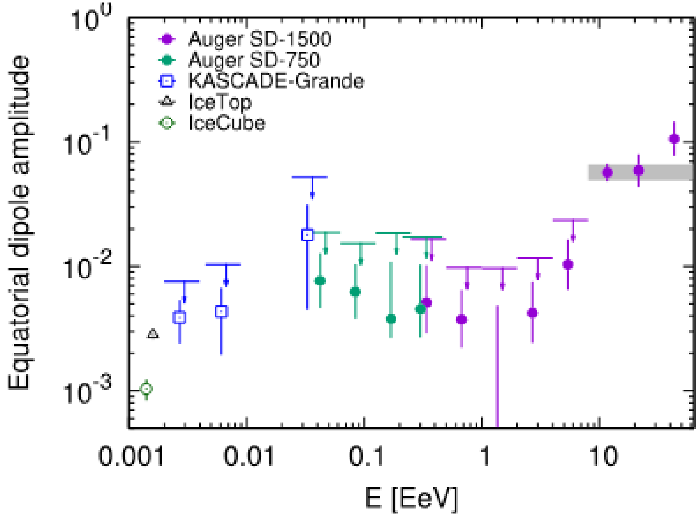
Observation of dipolar anisotropy for E≳8 10^{18} eV
Significance 6.9 σ above 8 EeV, 5.7σ at E=8-16 EeV

Can be interpreted as a signature of the local large scale distribution of matter.

Not consistent with pure protons above 8 EeV
Require mixed composition



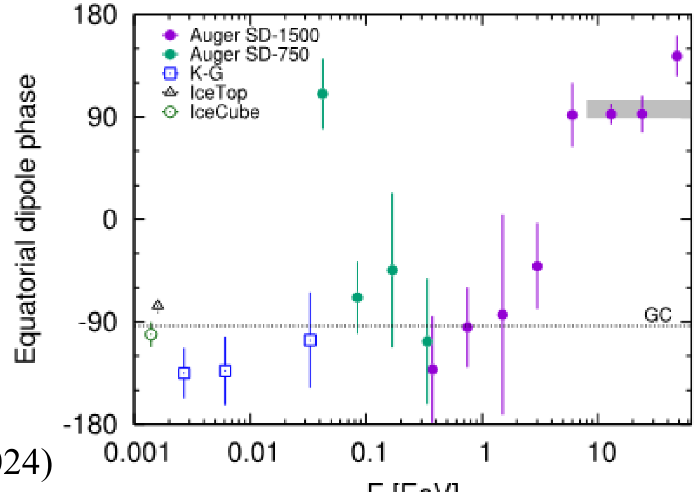
Dipole direction ~113° away from the Galactic Center



Dipole amplitude and phase

Evolution with energy of the dipole phase away from GC

→ Extragalactic origin of UHECR above 8 EeV

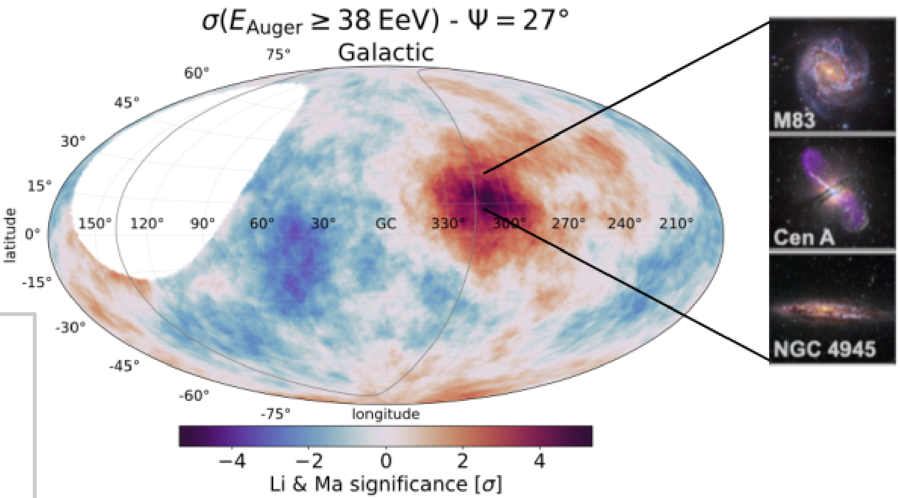


Science 315 (2017) 1266, APJ 976:48 (2024)

Anisotropy at intermediate scale

Blind search for overdensity

Energy [32-80] EeV
Zenith < 80° → 85% of the sky, declination [-90°, 45°]



Centaurus A region:
most significant excess, p-value 2% post trial, at ψ~24° E > 38 EeV
direction fixed at Cen A 4 σ post trial, at ψ~27° E > 38 EeV

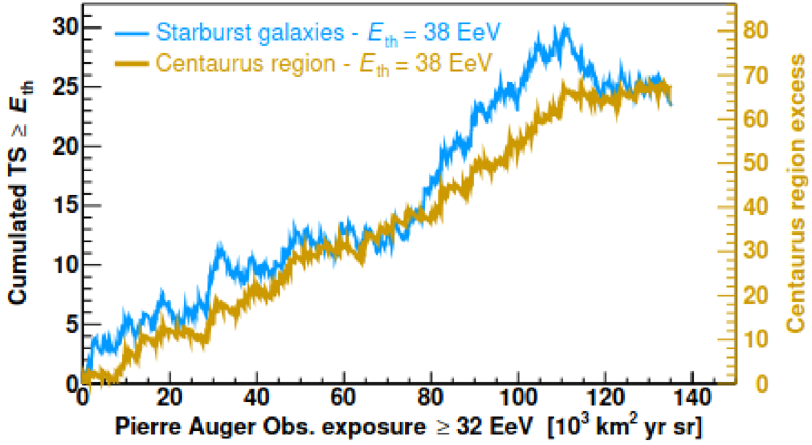
Autocorrelation with structures (GC, GP, SGP) not significant

Likelihood test for anisotropy with catalogs

Attenuation and relative weight of sources taken into account.

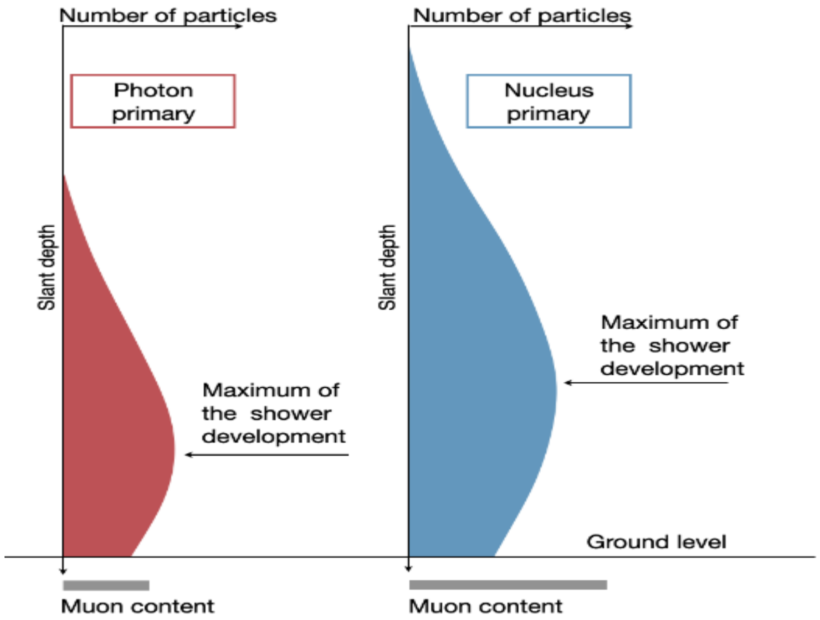
Catalog	E_{th} [EeV]	Ψ[°]	α[%]	TS	Post-trial p-value
All galaxies (IR)	38	24^{+15}_{-8}	14^{+8}_{-6}	18.5	6.3×10^{-4}
Starbursts (radio)	38	25^{+13}_{-7}	9^{+7}_{-4}	23.4	6.6×10^{-5}
All AGNs (X-rays)	38	25^{+12}_{-7}	7^{+4}_{-3}	20.5	2.5×10^{-4}
Jetted AGNs (γ-rays)	38	23^{+8}_{-7}	6^{+3}_{-3}	19.2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

Significance
3.8 σ for SB



The Astrophysical Journal 935 (2022)170, PoS(ICRC2023) 252

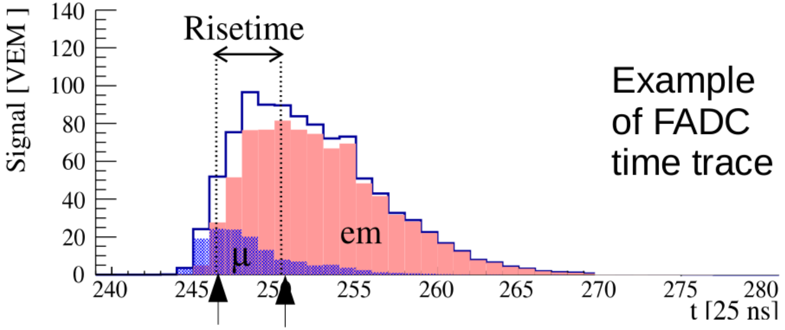
UHE Photon induced cascades



Photon EAS distintive signature:
→ delayed shower developement
→ smaller muon content

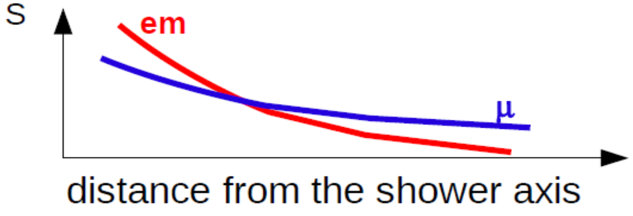
observable characteristics:

- deeper <Xmax>
- steeper LDF
- smaller footprint
- broader signal

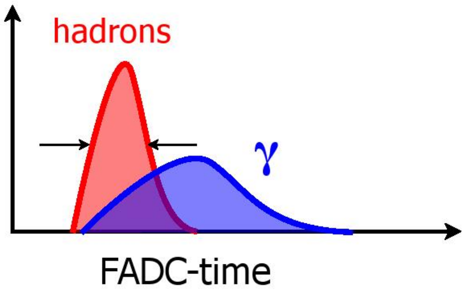


10% 50% quantiles

steeper LDF

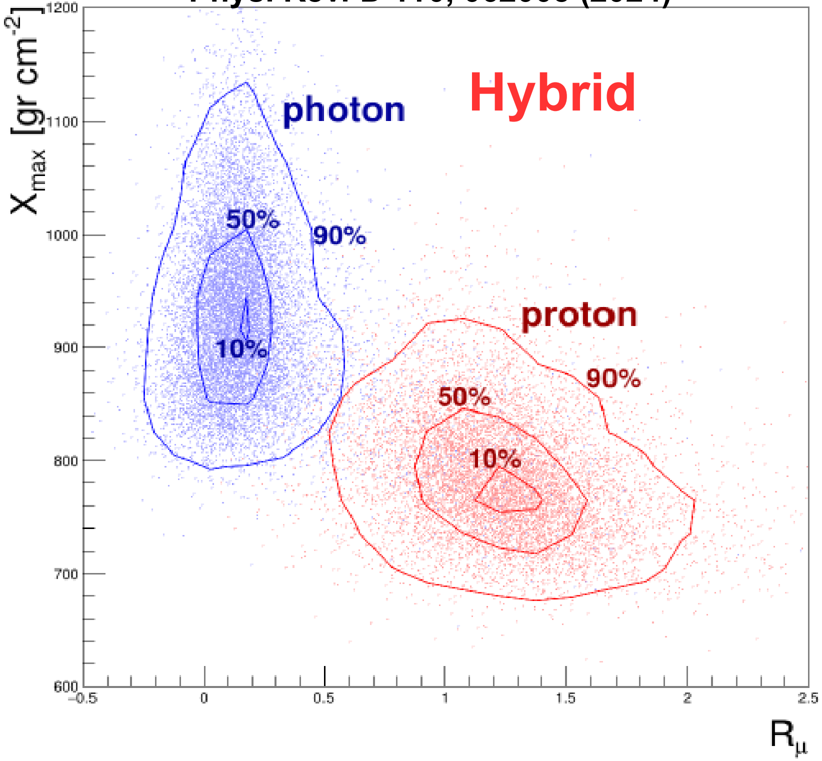


longer rise-time



Auger: Hybrid and SD photon search

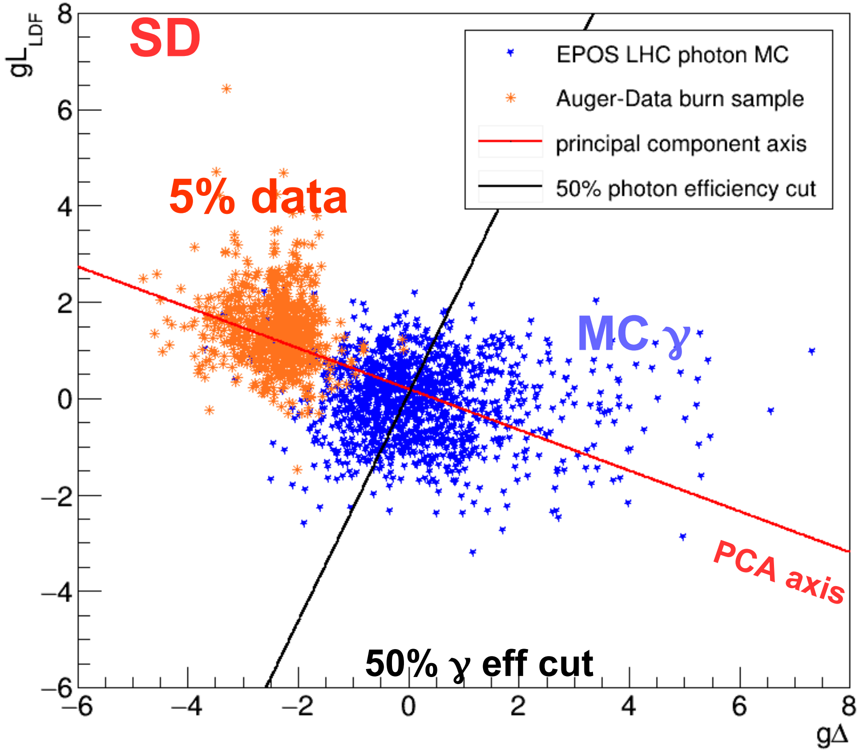
Phys. Rev. D 110, 062005 (2024)



Maximum of shower development: $\mathbf{X_{max}}$

Muon content of the shower (universality): R_μ

ApJ. 933 (2022)125

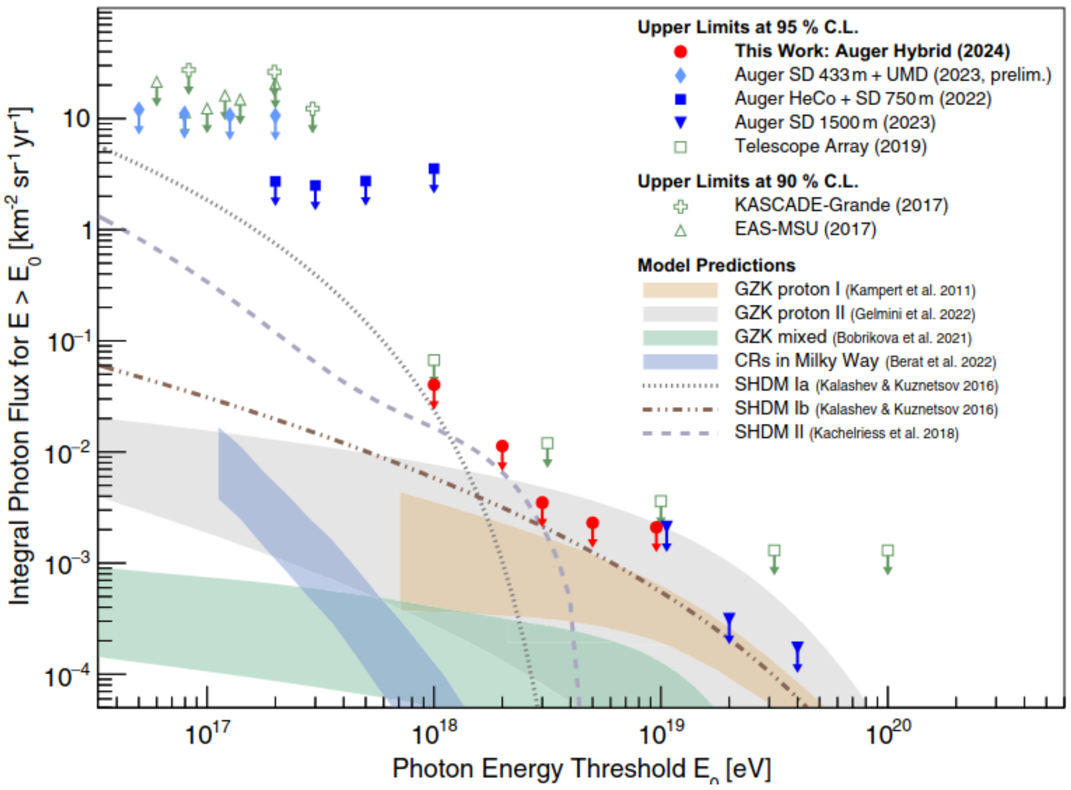


Deviation from data <LDF>: $\mathbf{gL_{LDF}}$

rise-time rel. event-wise quantity: $\mathbf{g_\Delta}$

Upper limits on diffuse photon flux

ApJ. 933 (2022)125
JCAP 05 (2023) 021
Phys. Rev. D 110, 062005 (2024)
To appear on JCAP (2025)



Strictest limits at E> 0.04 EeV

11 candidates > 10 EeV (SD)

22 candidates > 1 EeV (Hybrid)

Targeted search
- In coincidence of known sources including CenA and the Galactic Center [UL extrapolating HESS flux]
- GW follow-up

No candidates found

- Top-down model disfavored
- CR proton dominated scenario (also the most pessimistic cases) disfavoured
- constraining mass and lifetime of dark matter particles →
- Auger Phase II: additional information for better photon/hadron separation or photon discovery

Targeted searches: photons

Pierre Auger Coll., ApJL 837: L25 (2017)

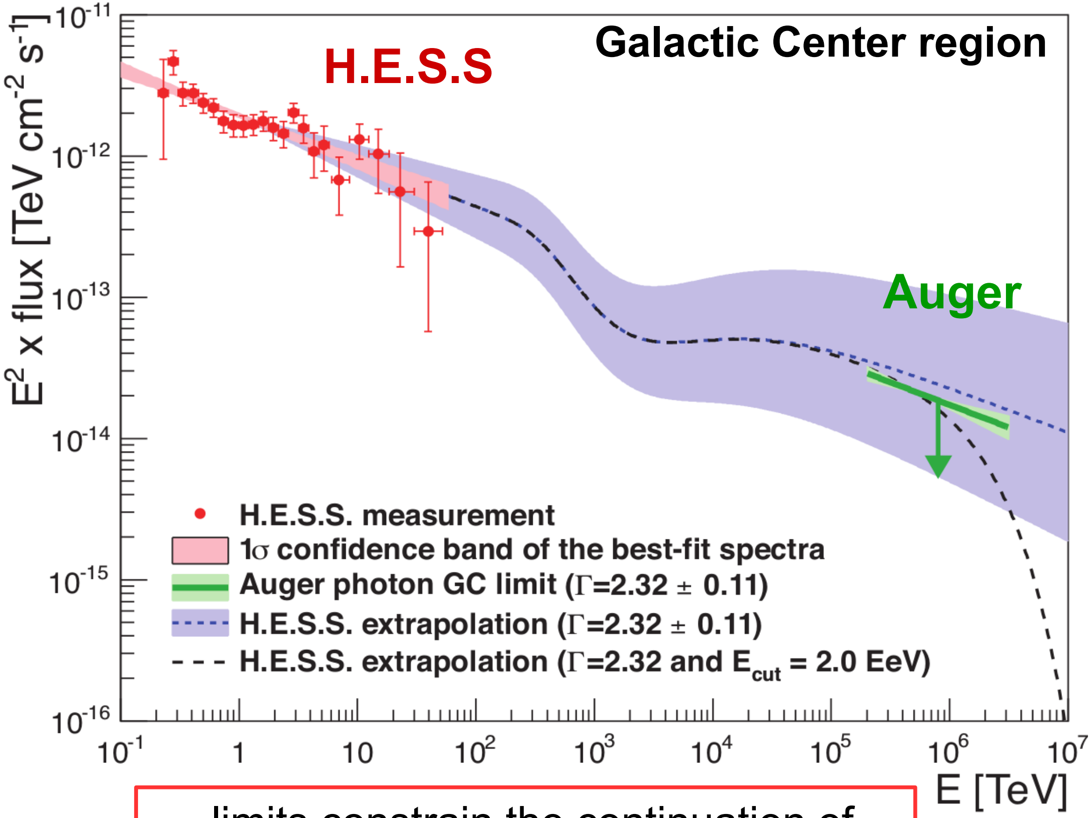
Previous blind search limits

12 target sets Galactic sources
(364 candidates sources)
- stacked analysis

→ complement targeted neutron searches

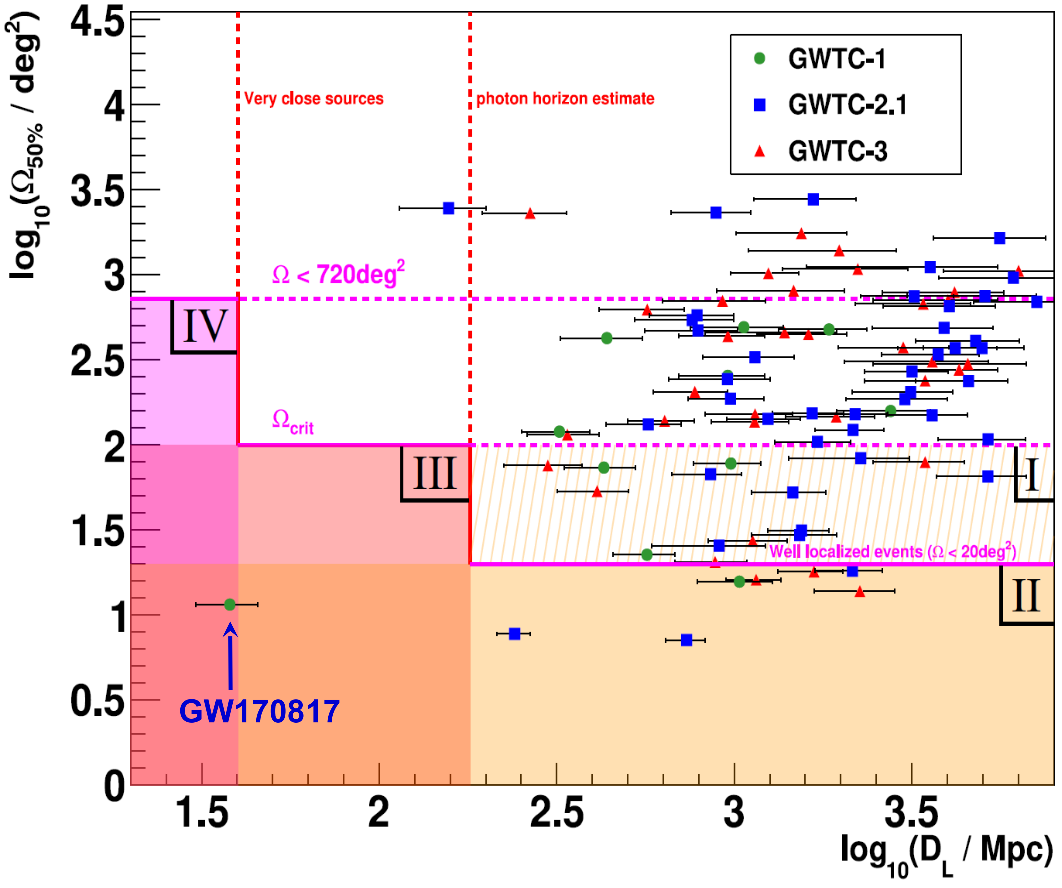
NO evidence for ***nearby*** photon-emitting ***steady*** sources in the EeV range

→ might be transients



→ limits constrain the continuation of measured TeV fluxes to EeV energies

GW follow-up photon searches



$$(D_L < \infty \quad \text{and} \quad \Omega_{50\%} < 100\,\text{deg}^2)_{\text{short}} \quad \text{“class I”}$$

$$(D_L < \infty \quad \text{and} \quad \Omega_{50\%} < 20\,\text{deg}^2)_{\text{long}} \quad \text{“class II”}$$

$$(D_L < 180\,\text{Mpc} \quad \text{and} \quad \Omega_{50\%} < 100\,\text{deg}^2)_{\text{long}} \quad \text{“class III”}$$

$$(D_L < 40\,\text{Mpc} \quad \text{and} \quad \Omega_{50\%} < 720\,\text{deg}^2)_{\text{long,short}} \quad \text{“class IV”}.$$

Search for time directional coincidence with 91 GW events from LIGO/Virgo

4 classes defined based on localization and distance
2 time windows: “short” Δt 1000s centered at t_{GW} and “long” Δt 1 day after it

Class IV best for γ sources, Classes I-II-III may point to new physics

Auger Coll., ApJ 952 (2023) 91

GW follow-up photon searches

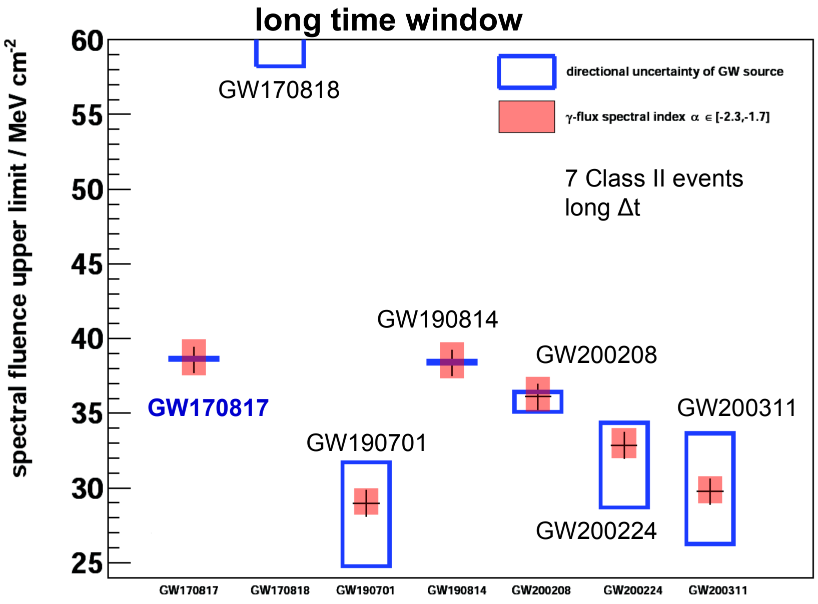
7 events in Class II, 3 in Class I

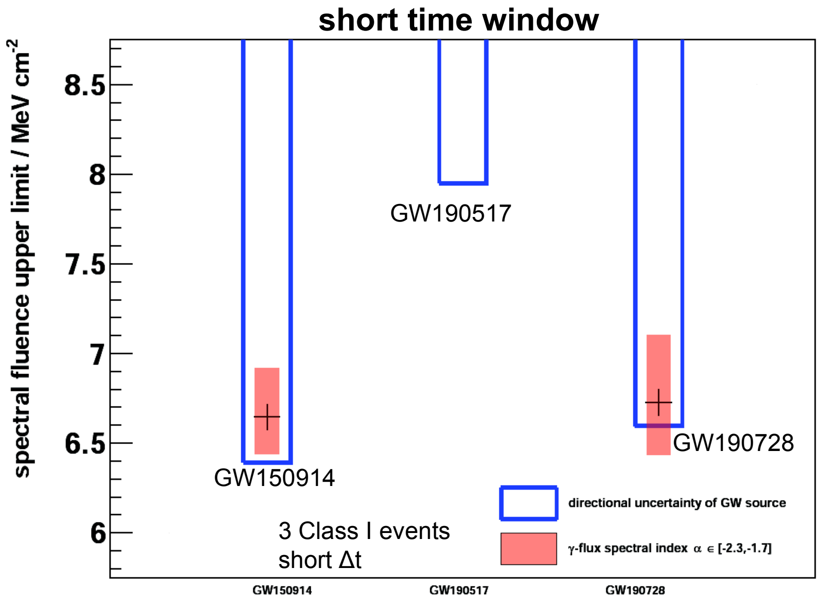
No candidate found for any GW event → flux upper limits

First ever limits on ɣ from GW at UHE

$$\frac{\mathrm{d}\Phi_\gamma^{\mathrm{GW}}}{\mathrm{d}E_\gamma}(E_\gamma) = k_\gamma E_\gamma^\alpha \longrightarrow k_\gamma^{\mathrm{UL}} = \frac{N_\gamma^{\mathrm{UL}}}{\int_{E_0}^{E_1} \mathrm{d}E_\gamma E_\gamma^\alpha \mathcal{E}(E_\gamma, \theta_{\mathrm{GW}}, \Delta t)}$$

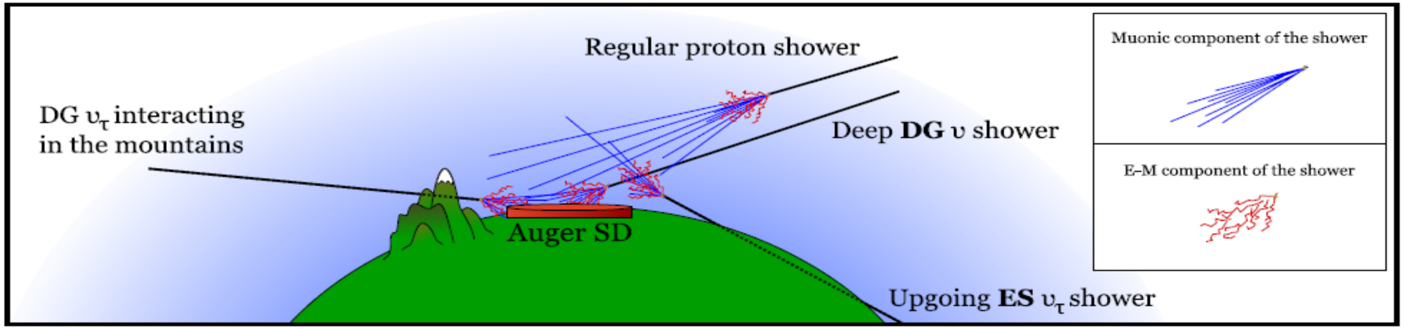
$$\mathcal{F}_\gamma^{\mathrm{UL}} = \int_{t_0}^{t_1}\int_{E_0}^{E_1} \mathrm{d}t\, \mathrm{d}E_\gamma\ E_\gamma\ \frac{d\Phi_\gamma^{\mathrm{GW}}}{dE_\gamma}$$

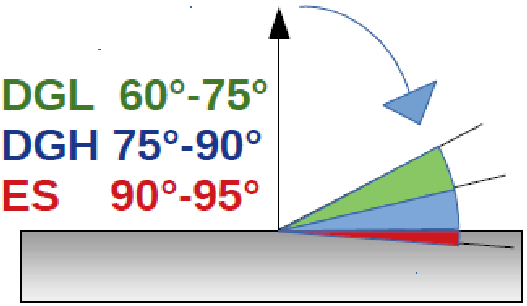


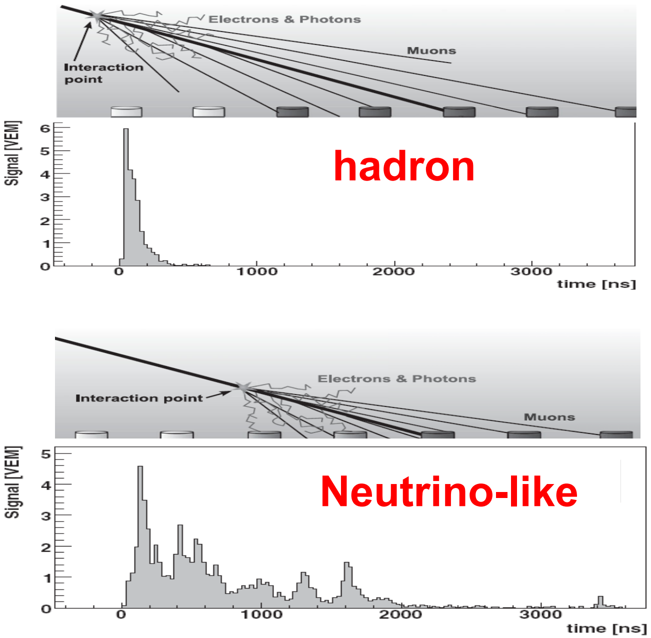


Auger Coll., ApJ 952 (2023) 91

Auger: UHE neutrinos with the SD

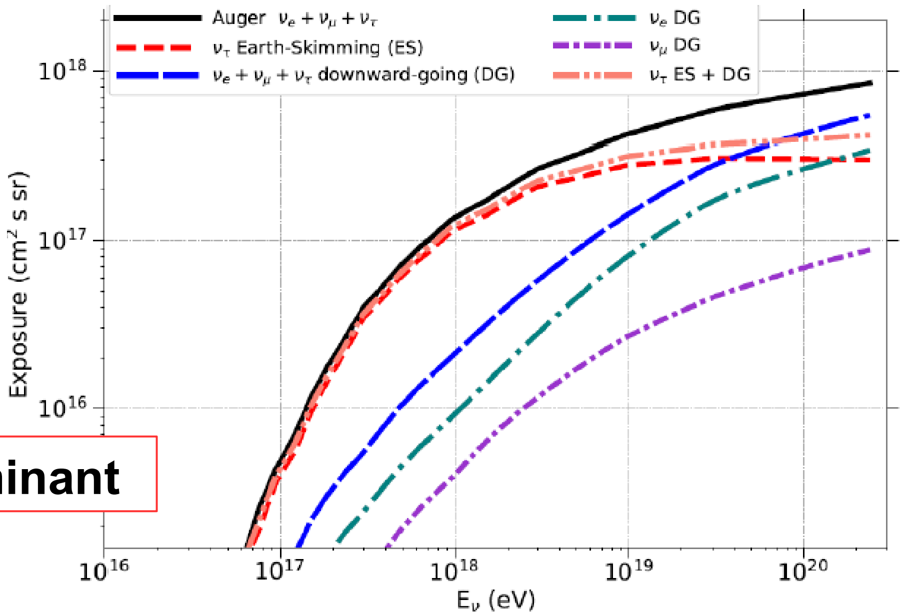






Sensitivity to different channels

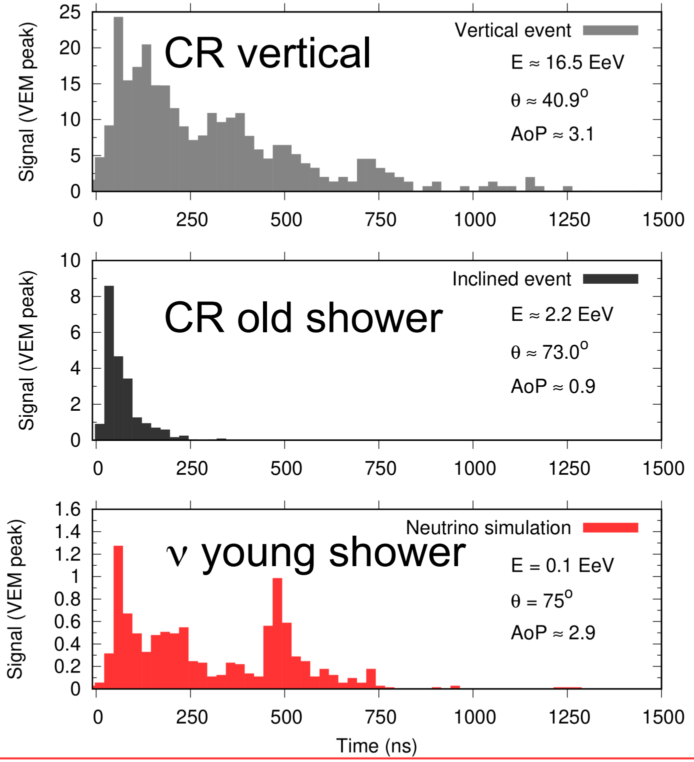
ES 79.4%
DGH 17.6%
DGL 3.0%



ν_τ ES sensitivity dominant

Search for neutrinos with the SD: signature

typical signal shapes

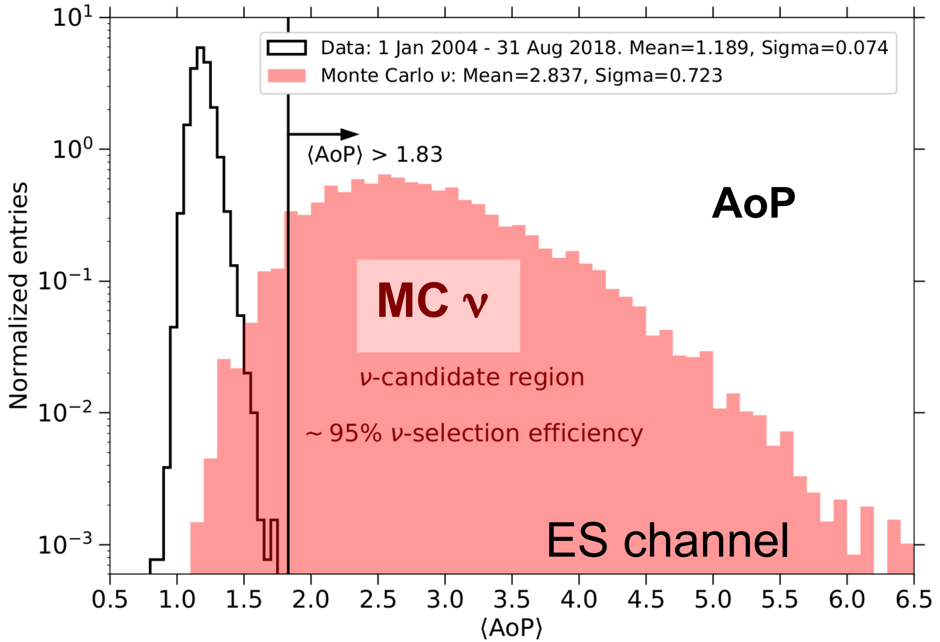


Signature:

"young shower" → with large electromagnetic component

inclined event with slow rising and broad signal

larger Area-over-Peak (**AoP**)



Data 2004 – 2018: 14.7 yr

→ **bkg expected: <1 event in 50 years!**

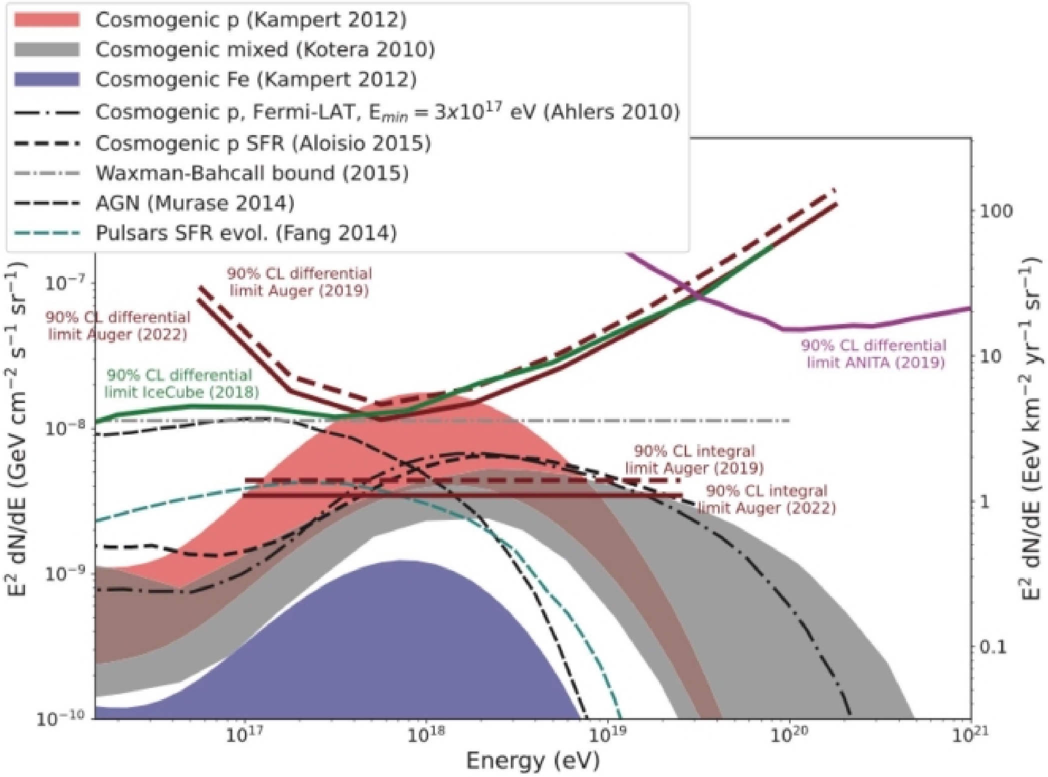
NO Candidates found

Bounds on neutrino fluxes from cosmic rays

tension with models assuming pure proton and spectrum shaped by GZK [up to 6 neutrino expected vs 0 observed]

Upper limits on the diffuse neutrino flux

Pierre Auger Coll., JCAP 10 (2019) 02, PoS(ICRC2023)1488



Maximum sensitivity **~ 1 EeV**

Point-like sources

also in coincidence with observations by other experiments

For example TXS 0506+056

Coincidence with GW

For example GW170817

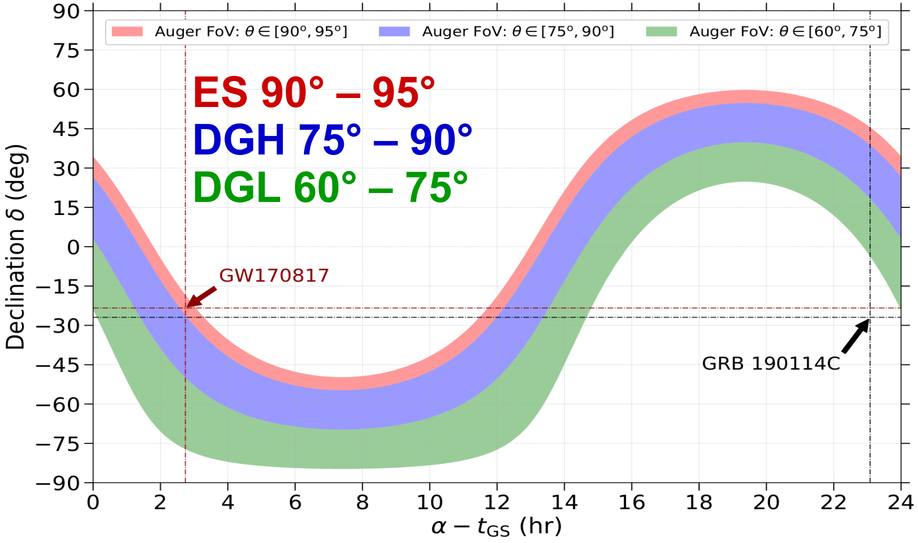
GW follow-up (62 events, stack analysis)

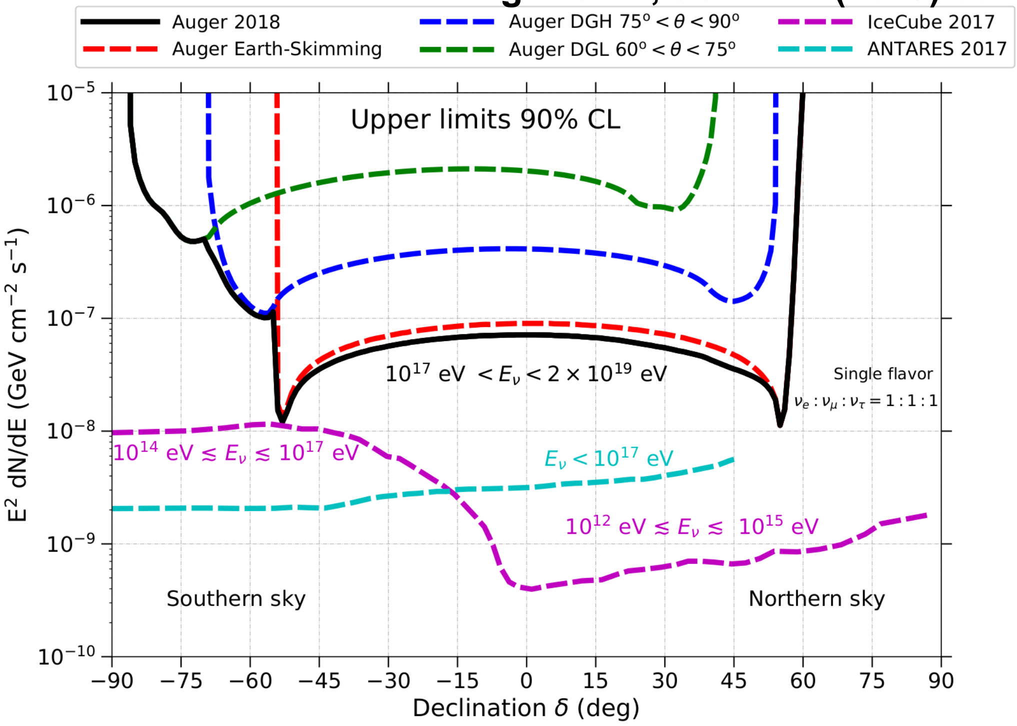
NO Candidates found

Constraining models assuming sources of CRs accelerating only protons

UHE neutrinos: point sources sensitivity

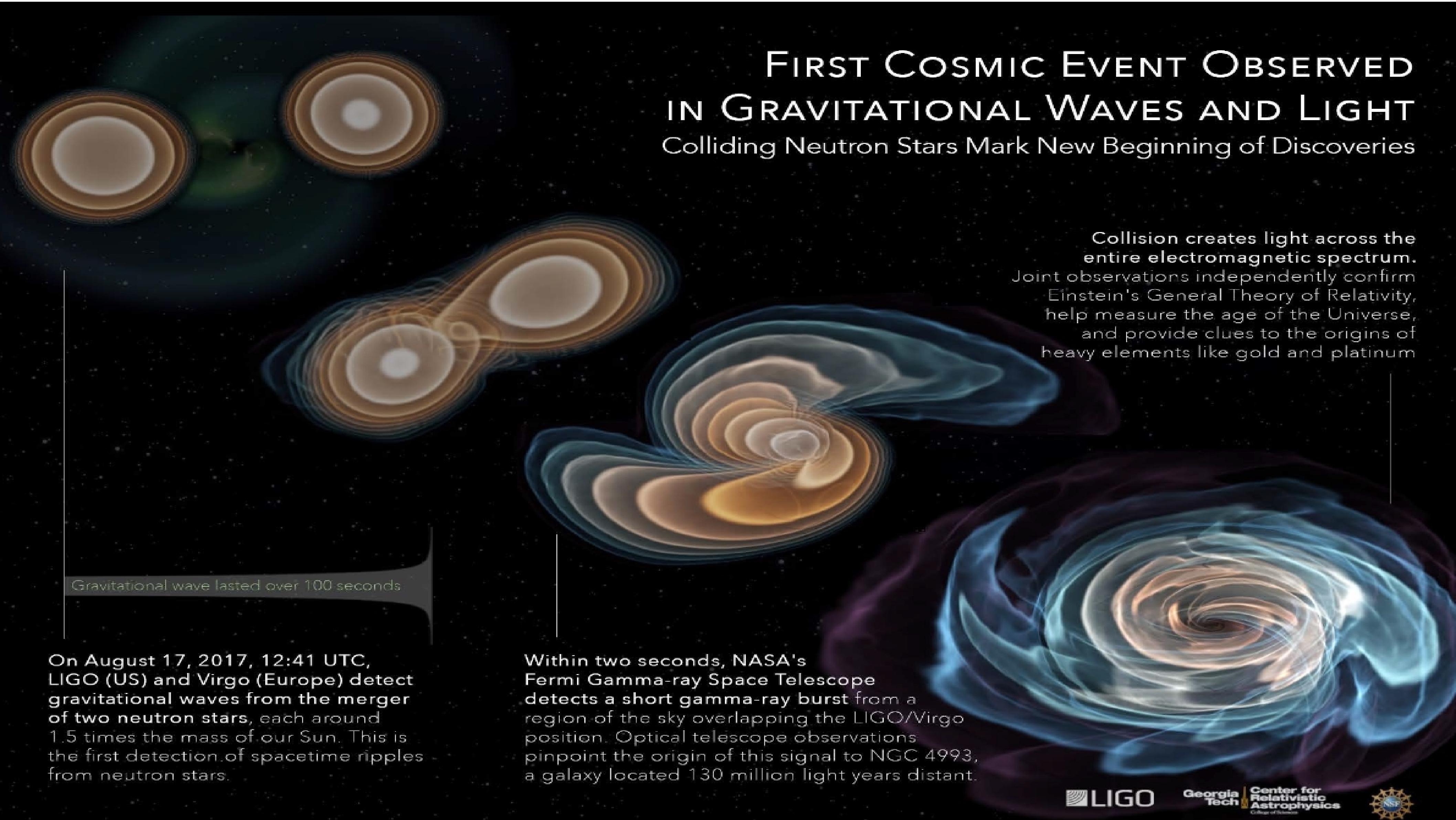
Pierre Auger Coll., JCAP 11 (2019) 004





point sources transit through the field of view of each detection channel

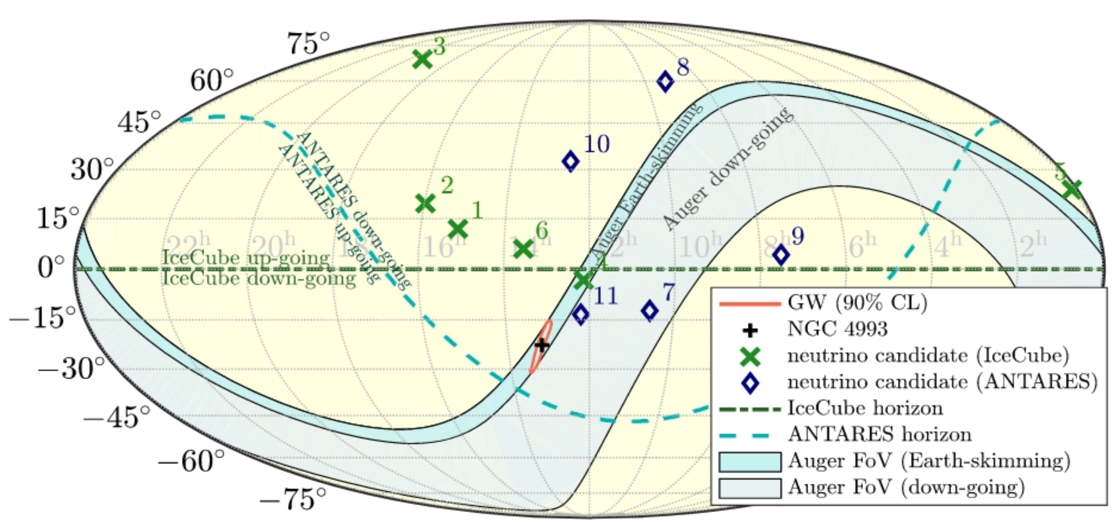
→ sensitivity strongly depends on source location and event timing



FIRST COSMIC EVENT OBSERVED
IN GRAVITATIONAL WAVES AND LIGHT
Colliding Neutron Stars Mark New Beginning of Discoveries
Collision creates light across the entire electromagnetic spectrum.
Joint observations independently confirm Einstein's General Theory of Relativity, help measure the age of the Universe, and provide clues to the origins of heavy elements like gold and platinum
Gravitational wave lasted over 100 seconds
On August 17, 2017, 12:41 UTC, LIGO (US) and Virgo (Europe) detect gravitational waves from the merger of two neutron stars, each around 1.5 times the mass of our Sun. This is the first detection of spacetime ripples from neutron stars.
Within two seconds, NASA's Fermi Gamma-ray Space Telescope detects a short gamma-ray burst from a region of the sky overlapping the LIGO/Virgo position. Optical telescope observations pinpoint the origin of this signal to NGC 4993, a galaxy located 130 million light years distant.
LIGO
Georgia Tech
Center for Relativistic Astrophysics

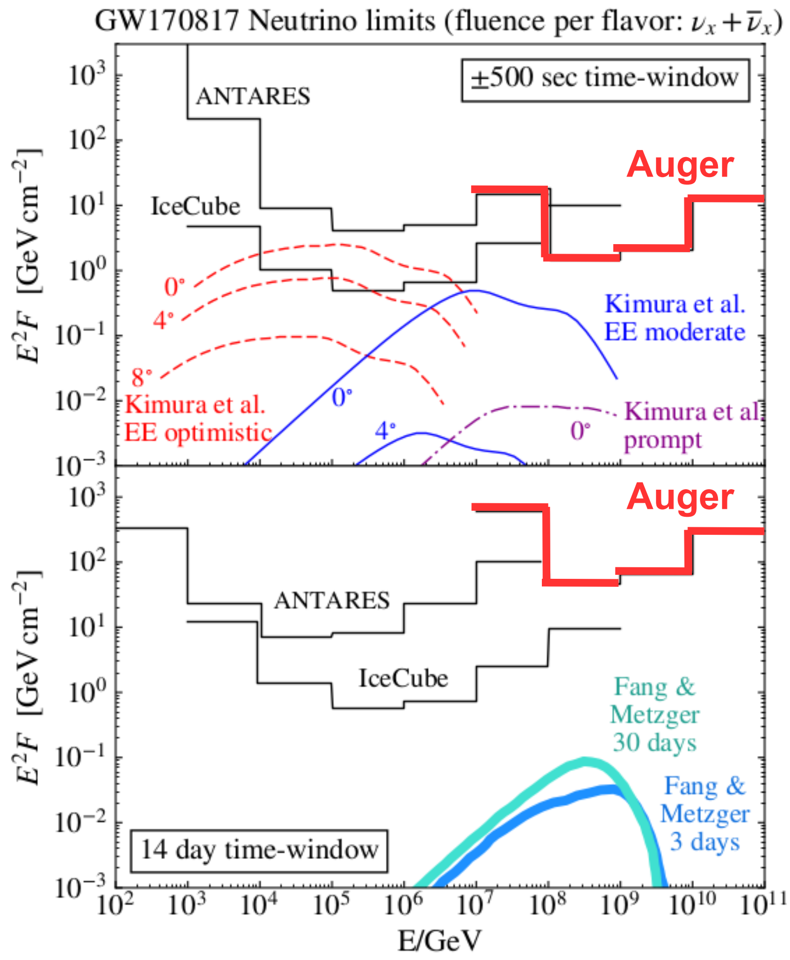
Follow-up searches: GW170817

LIGO/Virgo BNS GW170817 & Fermi sGRB 170817A
→ EM counterpart Optical/IR KiloNova AT2017GFO



→ excellent visibility of the merger:
90% CL GW event location in FoV of ES channel
→ time dependent exposure leads to substantially looser 14-day neutrino fluence limits wrt to prompt

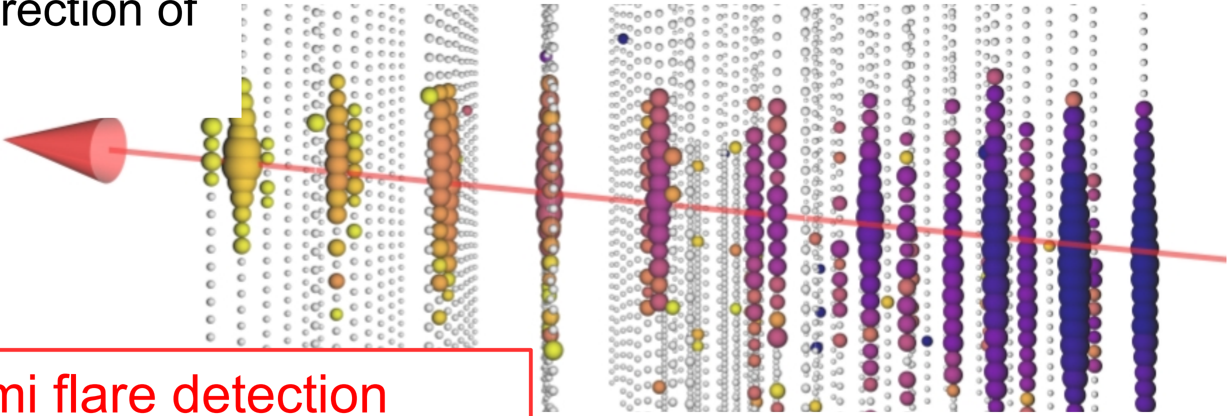
ApJL 850 L35 2017



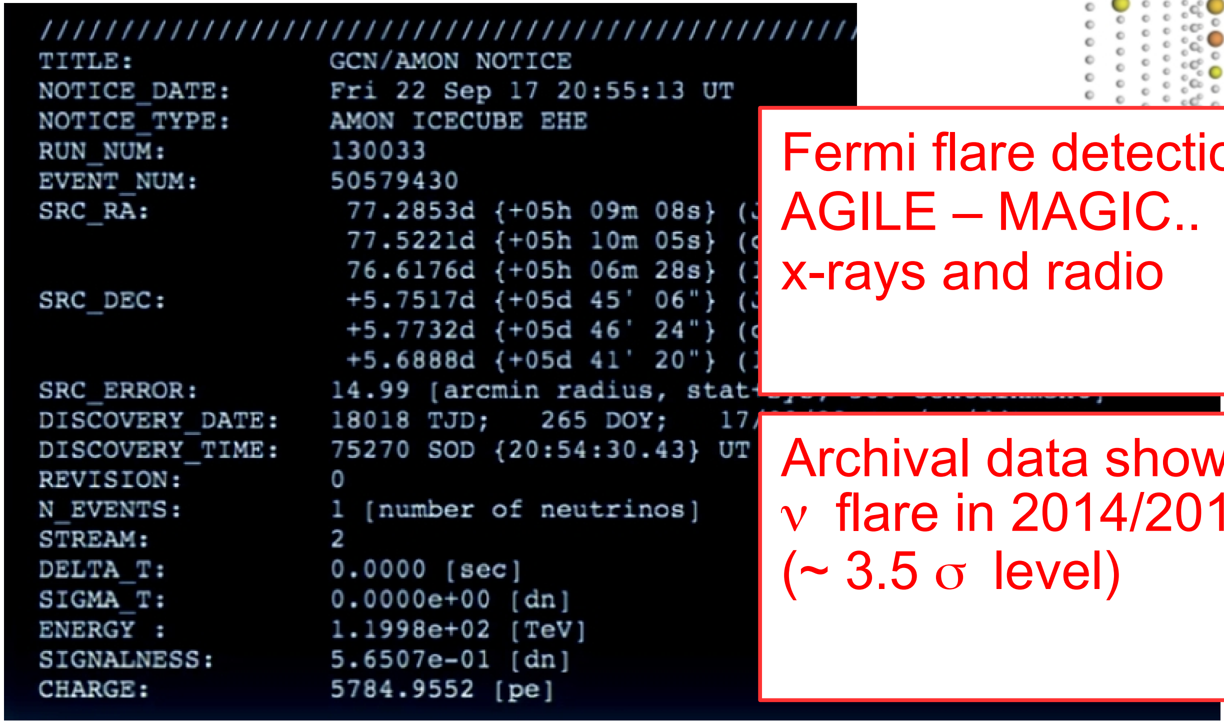
A source: TXS0506+056

Science 361, 146 (2018)

IceCube observed a 290 TeV ν in the direction of TXS0506+056 during flaring state



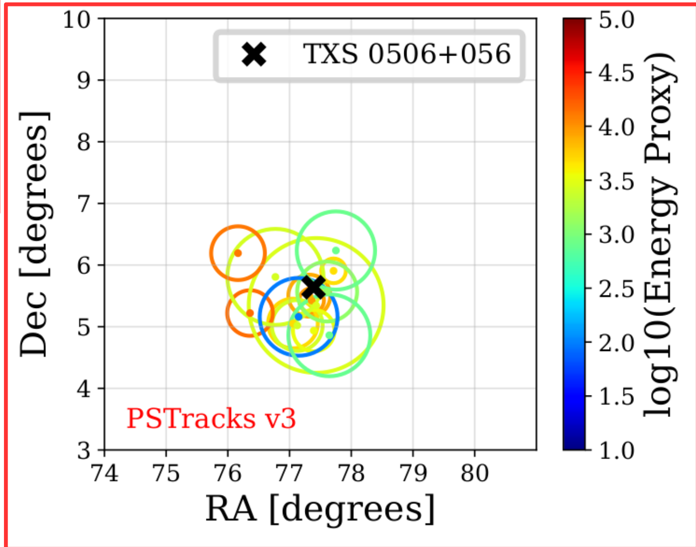
IceCube Alert IC170922A



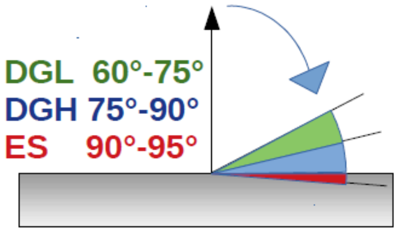
```
//////////////////////////////////////////////////////
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Fri 22 Sep 17 20:55:13 UT
NOTICE_TYPE:      AMON ICECUBE EHE
RUN_NUM:          130033
EVENT_NUM:        50579430
SRC_RA:            77.2853d {+05h 09m 08s} (J
                   77.5221d {+05h 10m 05s} (c
                   76.6176d {+05h 06m 28s} (1
SRC_DEC:           +5.7517d {+05d 45' 06"} (J
                   +5.7732d {+05d 46' 24"} (c
                   +5.6888d {+05d 41' 20"} (1
SRC_ERROR:        14.99 [arcmin radius, stat
DISCOVERY_DATE:   18018 TJD;   265 DOY;   17/
DISCOVERY_TIME:   75270 SOD {20:54:30.43} UT
REVISION:         0
N_EVENTS:         1 [number of neutrinos]
STREAM:           2
DELTA_T:          0.0000 [sec]
SIGMA_T:          0.0000e+00 [dn]
ENERGY :          1.1998e+02 [TeV]
SIGNALNESS:       5.6507e-01 [dn]
CHARGE:           5784.9552 [pe]
```

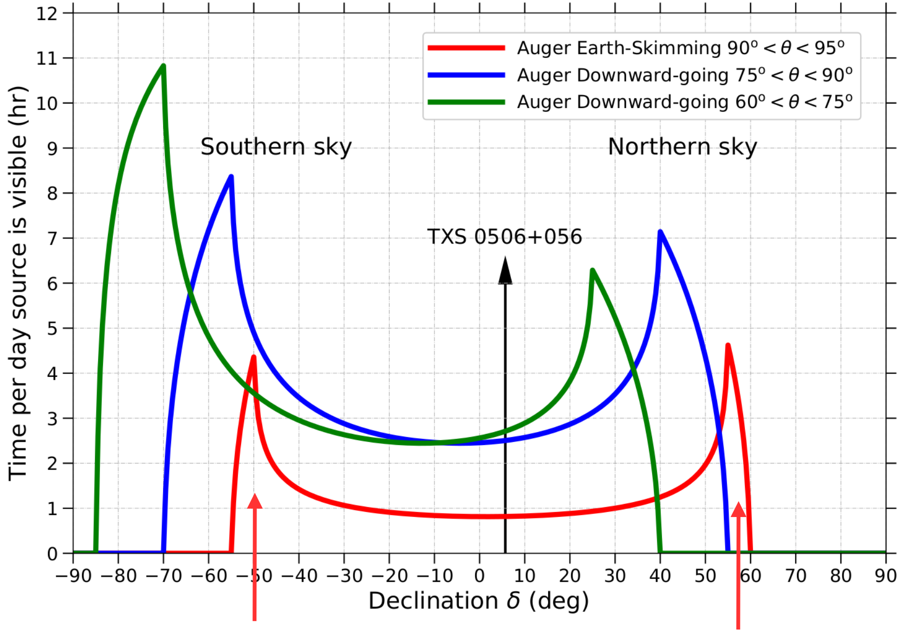
Fermi flare detection
AGILE – MAGIC.. then
x-rays and radio

Archival data shows
ν flare in 2014/2015
(~ 3.5 σ level)



Auger UHE window: TXS0506

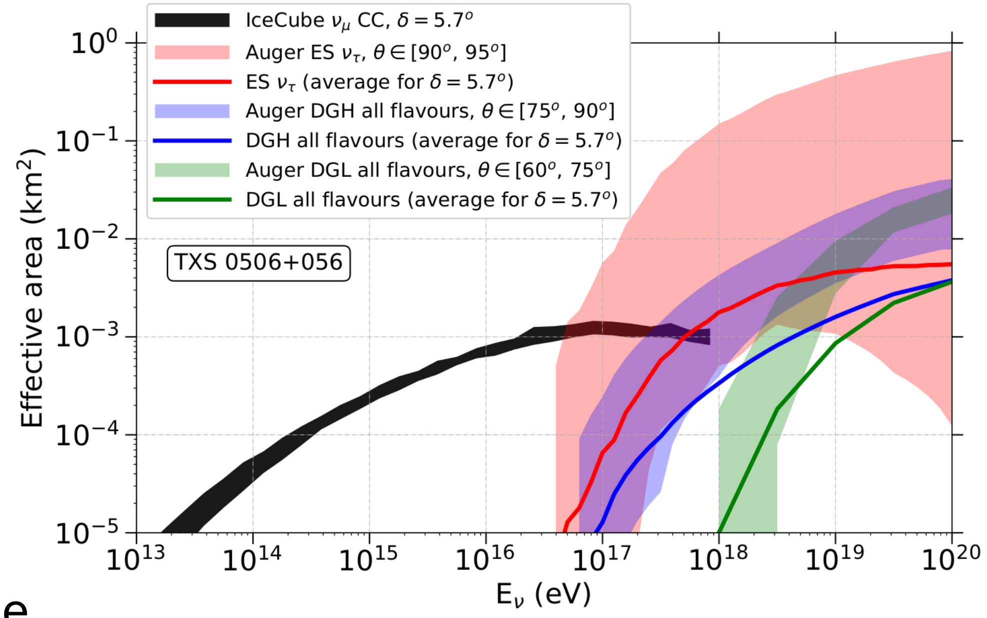




Optimal observation position: source δ in FOV of the Earth-skimming channel (right below the horizon)

TXS0506+056 declination = 5.7°

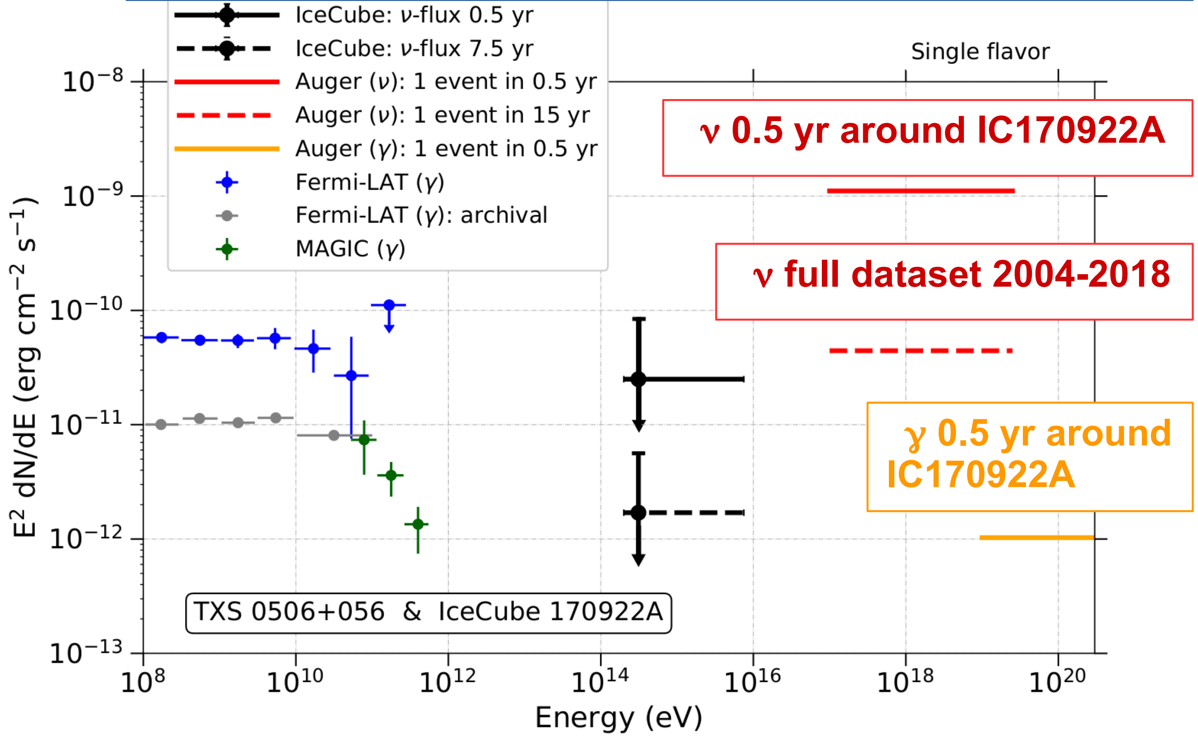
→ Non optimal sensitivity of the source in all channels



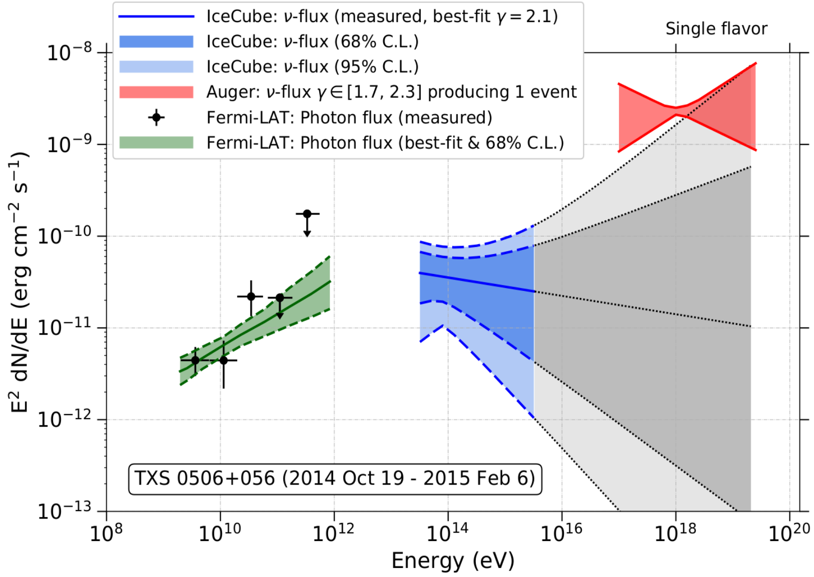
→ complementary to IceCube in the EeV range

Follow-up searches: TXS0506+056

IceCube observed a 290 TeV ν in the direction of TXS0506+056 during flaring state



Pierre Auger Coll., Ap. J., 902:105 (2020)

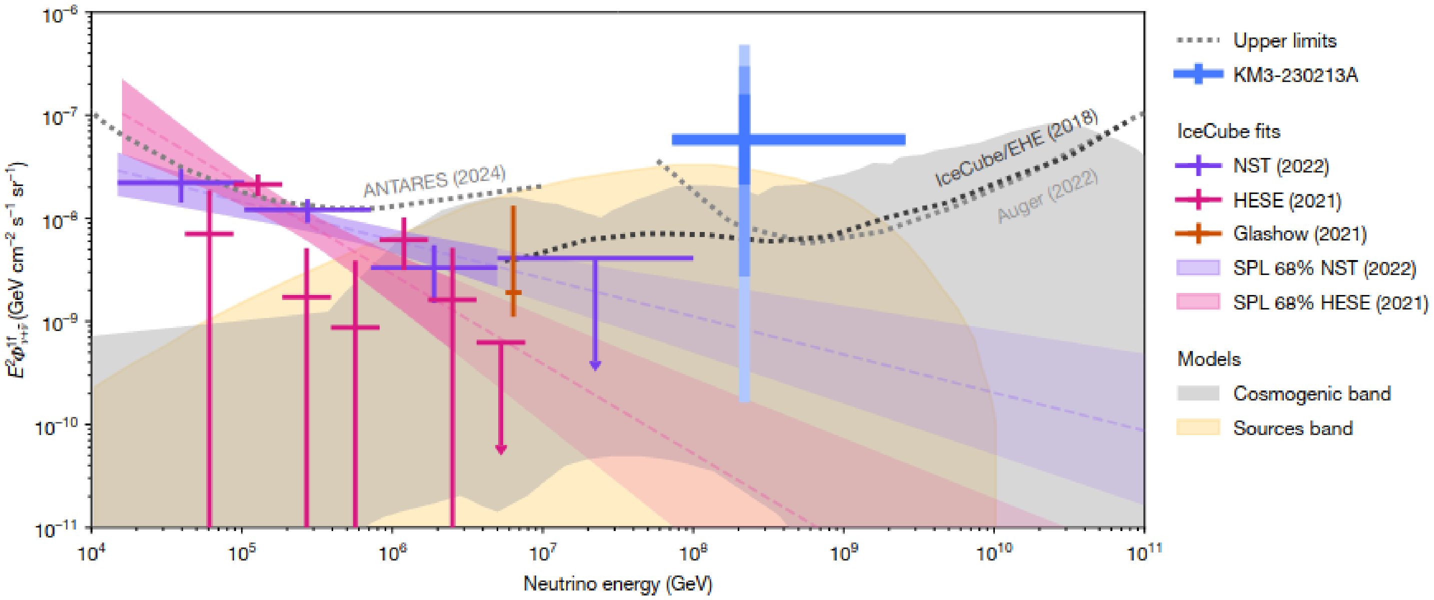


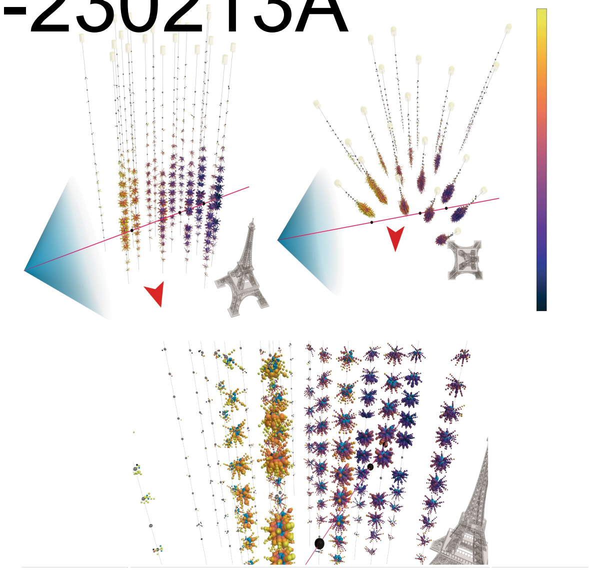
TXS0506 not in the most sensitive region

The neutrino event observed by KM3-230213A

Energy ~ 200 PeV !!

Nature | Vol 638 | 13 February 2025

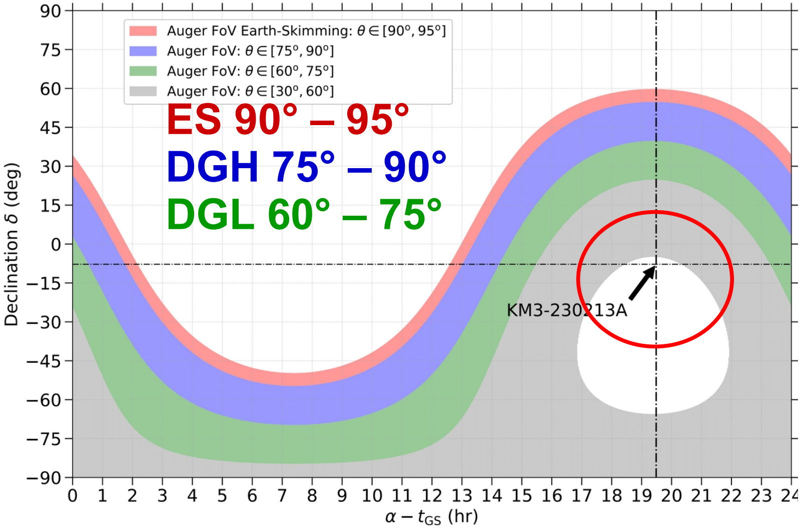




Astrophysical or cosmogenic?

→ **it's a breakthrough**

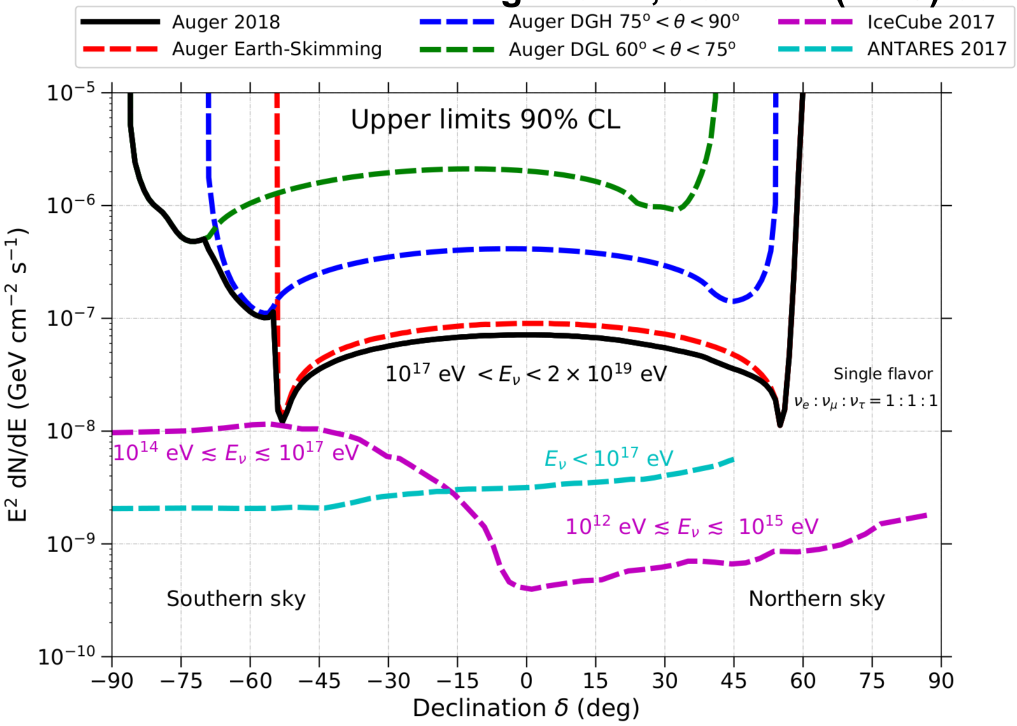
UHE neutrinos: KM3-230213A



point sources transit through the field of view of each detection channel

→ sensitivity strongly depends on source location and event timing

Pierre Auger Coll., JCAP 11 (2019) 004



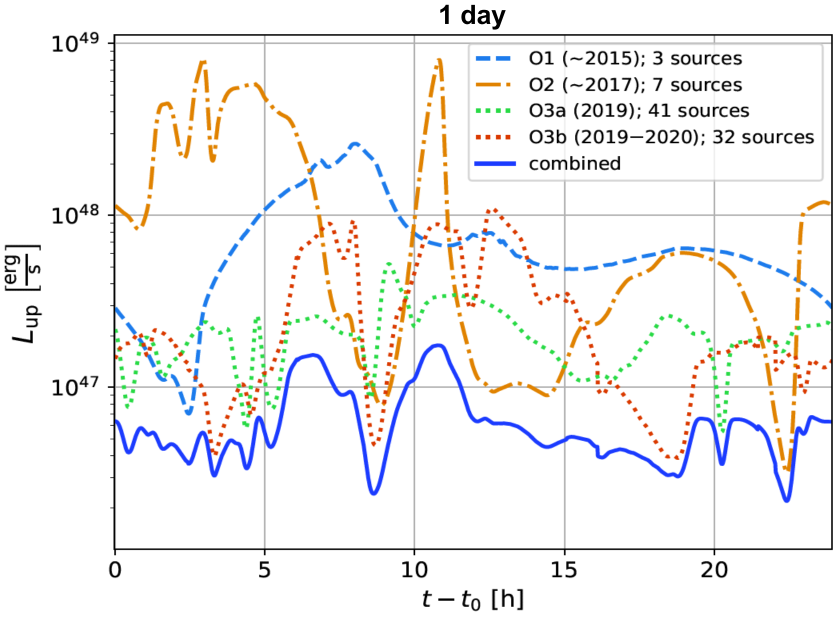
Vertical event ~ 27°

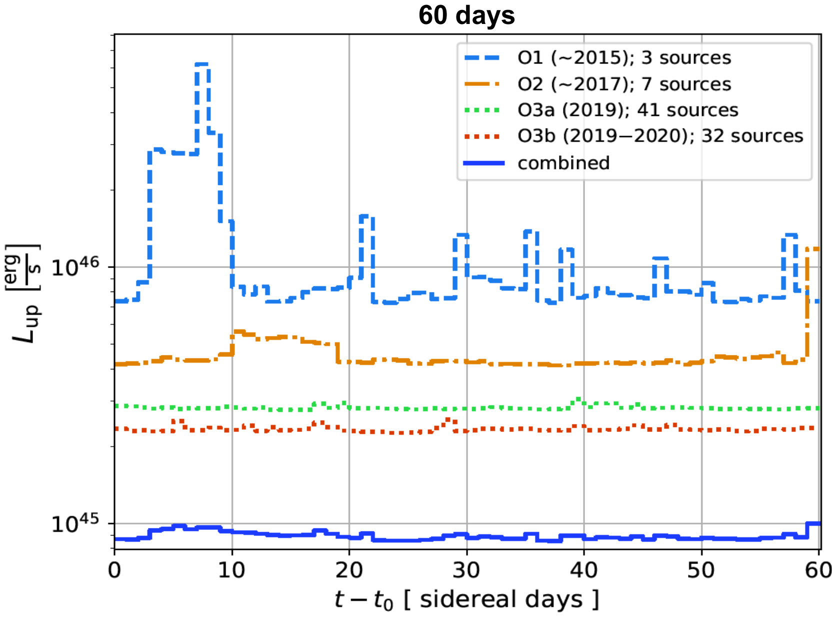
BBH follow-up: stacked ν searches

Look for time and directional coincidence with 93 BBH mergers from LIGO/Virgo runs O1-O3

No candidates found for any event inspected

Limits on the total energy emitted in neutrinos is <5.2x10^{51} erg → more than 2 orders or magnitude lower than the radiated GW energy



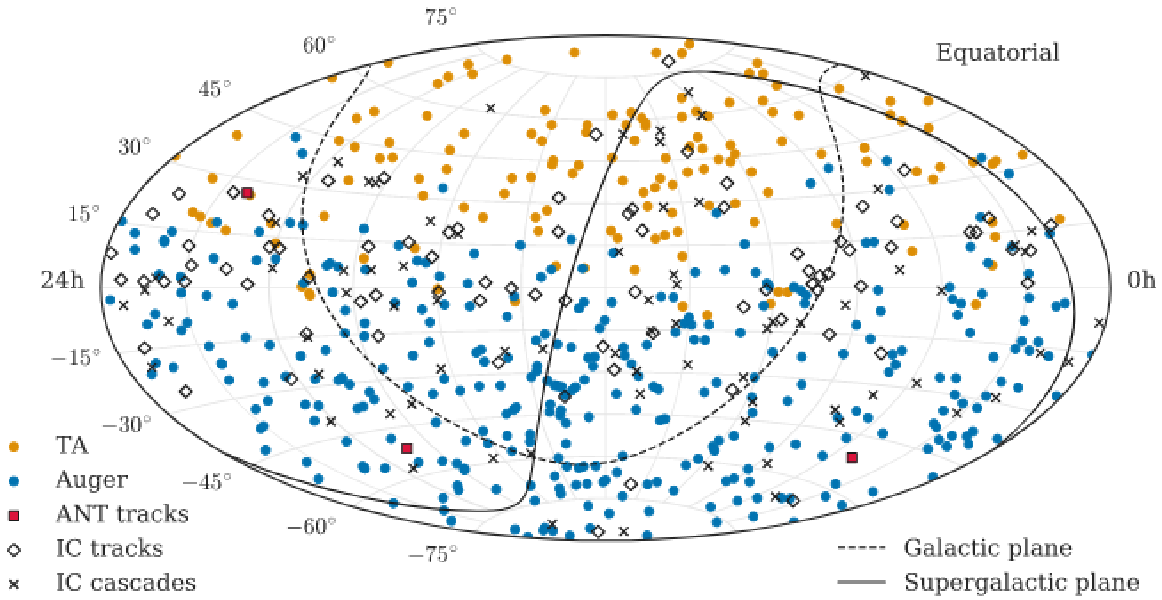


Auger Coll., PoS(ICRC2021) 968
Paper ready for submission

Joint searches (UHECR and neutrinos)

Antares, **I**ce**C**ube, **A**uger, **T**elescope **A**rray

APJ 934 (2022)164



Three analyses strategies:

- UHECR-neutrino cross-correlation
- Neutrino-stacking correlation with UHECRs
- UHECR-stacking correlation with neutrinos

All compatible with background

Searches for neutrons

→ neutron flux through an excess of cosmic ray events around a given direction

1500 m array

Most significant target from each target set – ≥ 1 EeV

Class	R.A. [deg]	Dec. [deg]	Flux U.L. [km^{-2} yr^{-1}]	E-Flux U.L. [eV cm^{-2} s^{-1}]
msec PSRs	286.2	2.1	0.026	0.19
γ-ray PSRs	296.6	−54.1	0.023	0.17
LMXB	237.0	−62.6	0.017	0.12
HMXB	308.1	41.0	0.13	0.97
H.E.S.S. PWN	128.8	−45.6	0.016	0.12
H.E.S.S. other	128.8	−45.2	0.014	0.11
H.E.S.S. UNID	305.0	40.8	0.15	1.1
Microquasars	308.1	41.0	0.13	0.95
Magnetars	249.0	−47.6	0.011	0.079
LHAASO	292.3	17.8	0.038	0.28
Crab	83.6	22.0	0.020	0.15
Gal. Center	266.4	−29.0	0.0053	0.039

E-Flux U.L. → Assuming an E^{-2} spectrum

No excess found

750 m array

Most significant target from each target set – ≥ 0.1 EeV

Class	R.A. [deg]	Dec. [deg]	Flux U.L. [km^{-2} yr^{-1}]	E-Flux U.L. [eV cm^{-2} s^{-1}]
msec PSRs	140.5	−52.0	1.7	12.5
γ-ray PSRs	288.4	10.3	5.3	38.9
HMXB	116.9	−53.3	2.1	15.1
H.E.S.S. PWN	277.9	−9.9	1.8	13.4
H.E.S.S. other	288.2	10.2	5.5	40.2
Magnetars	274.7	−16.0	1.6	11.8

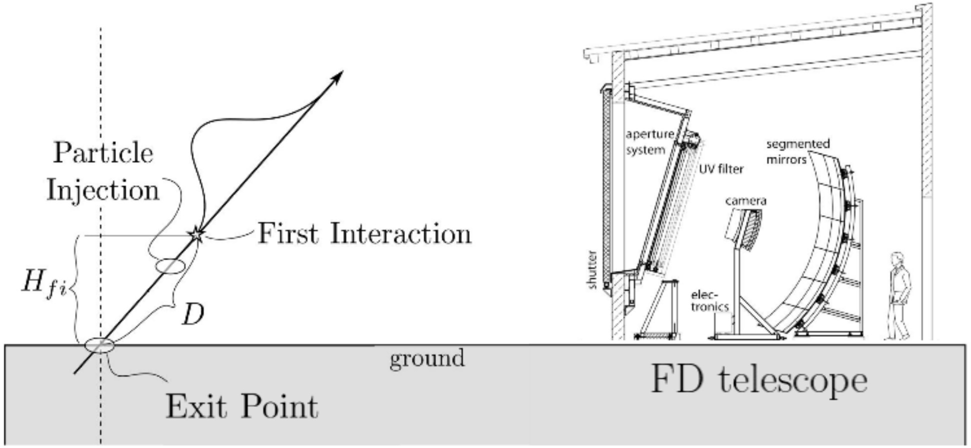
Search for upward-going air showers with Auger FD

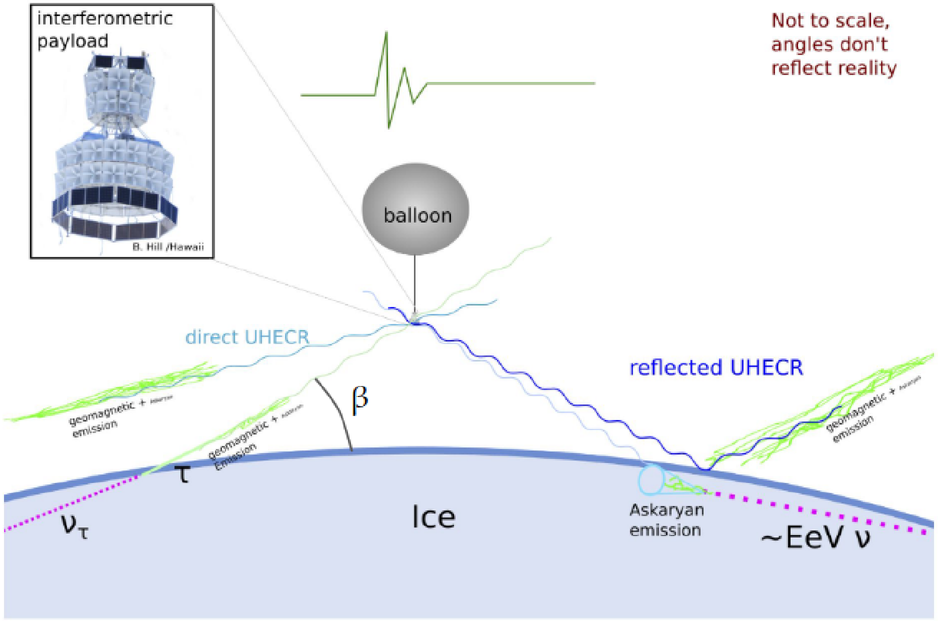
Two “anomalous” events detected by **ANITA** with non-inverted polarity
→ E ~ 0,2 EeV exit angle ~ 30°

Fervent debate about the interpretation

Highly inclined events cannot be observed with SD
→ Dedicated search using 14 years of FD data

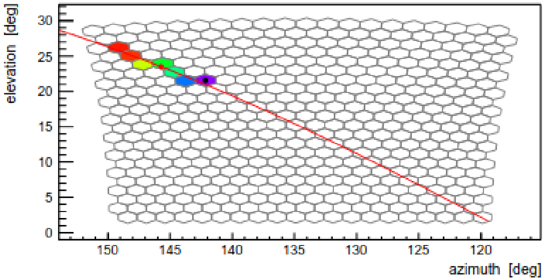
FD sensitivity depends on E and H_{fi} of the primary particle

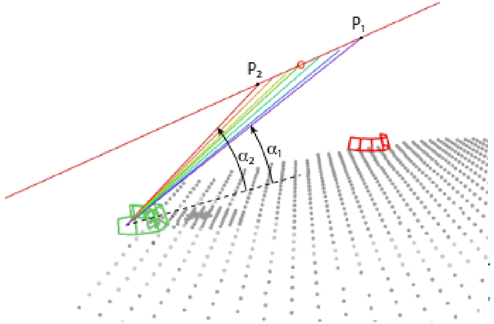




Search for upward-going air showers with Auger FD

FD Energy > 0.1 EeV, zenith > 110°, 14 years of FD data

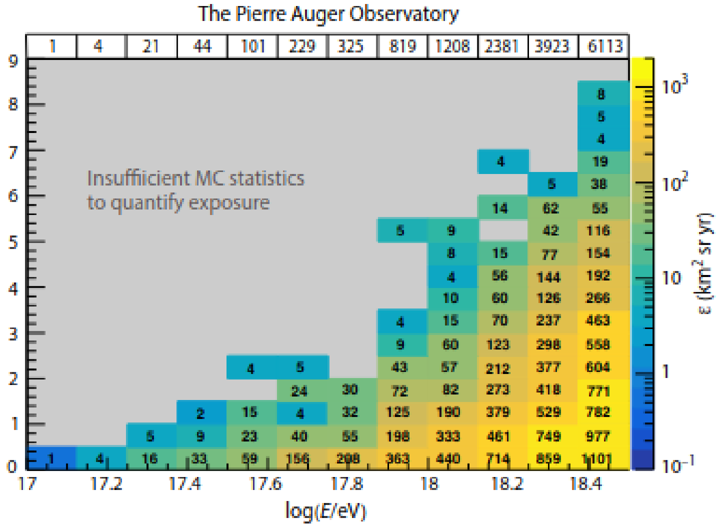




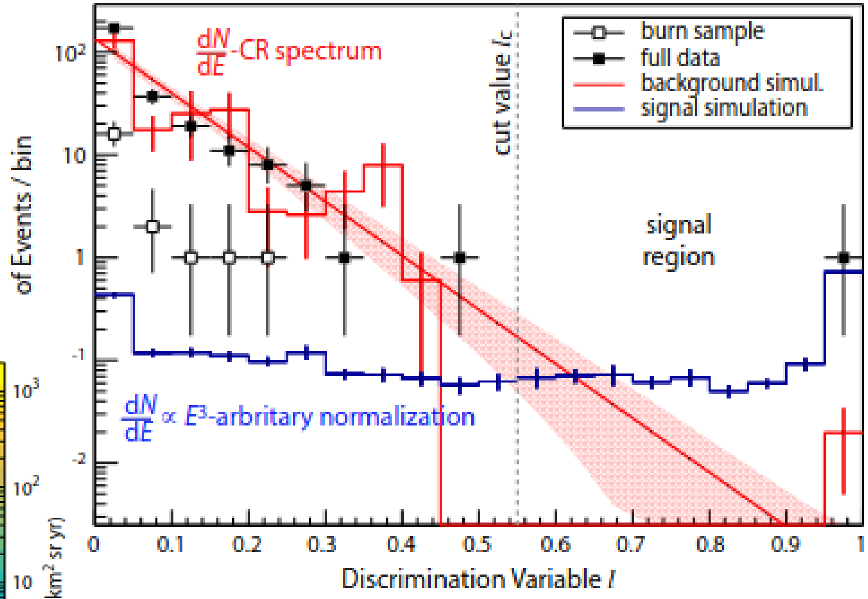
FD only reconstruction challenging for specific event topologies

Debate triggered by the claim done by the ANITA collaboration

Exposure (energy, height of first interaction)



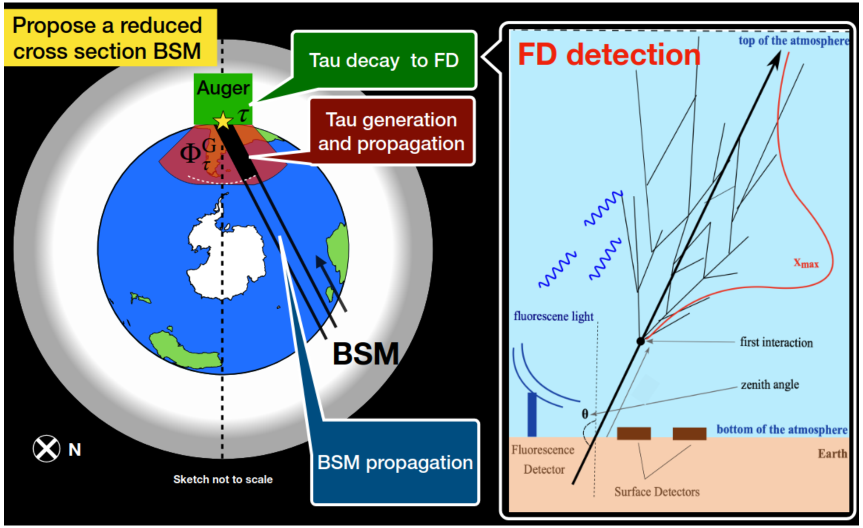
Accepted for publication on PRL 2025



1 candidate consistent with the background (~0.3)

Tau scenarios and BSM constrained (modified deep inelastic cross-sections)

Search for neutrinos using the FD detector

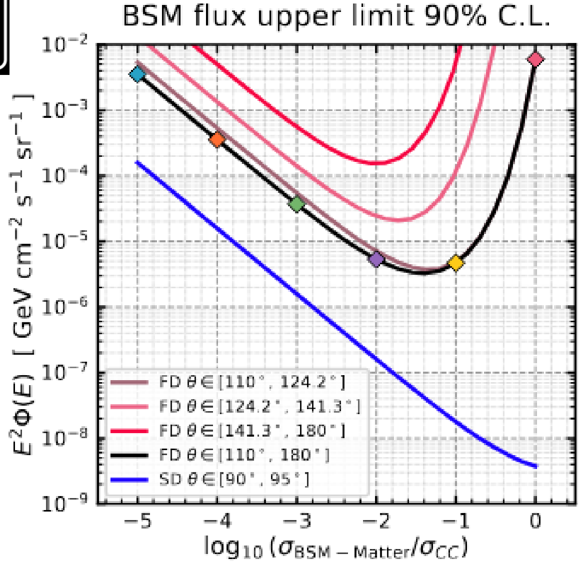


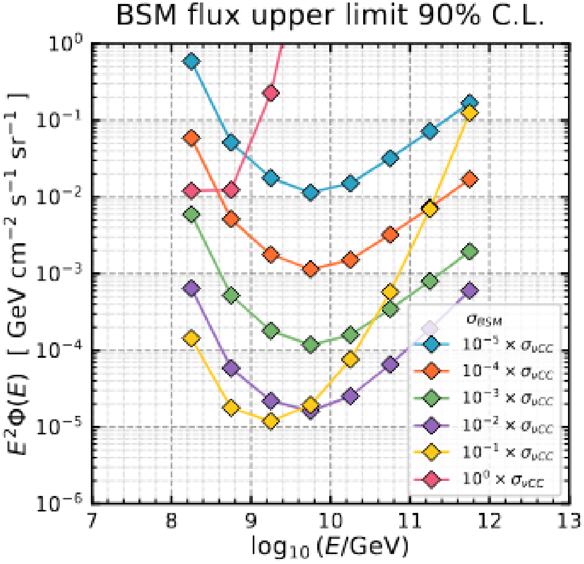
PoS(ICRC2023)1095

Upper limits for a specific tau scenario in the context of BSM

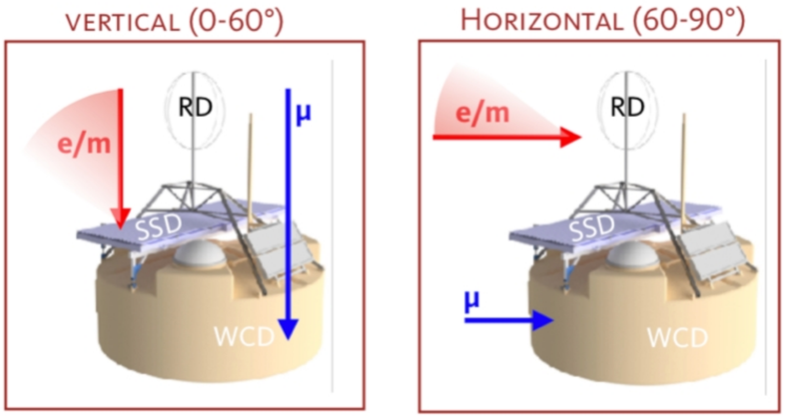
FD: best upper limits for a modified deep inelastic cross-section of about 3% of the standard charge current

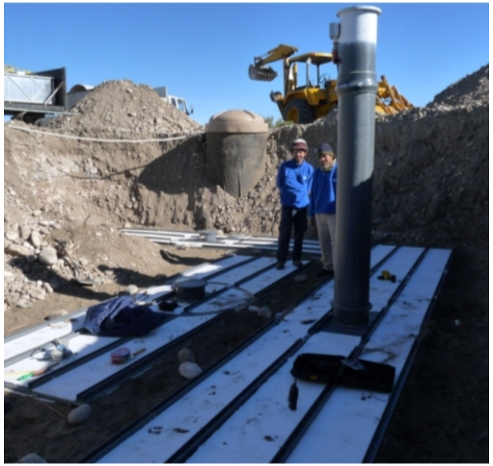
FD: zenith > 110°
SD: 90°<zenith<95°
→ complementary in zenith





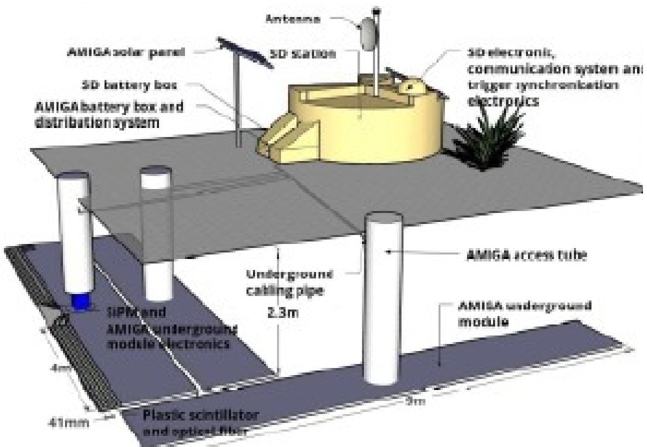
AugerPrime 2025→ 2035





Multi-hybrid measurements

scintillator layers added on top of WCD
→ better separation electromagnetic/muonic
faster electronics
→ improve on signal characterization, higher sensitivity
low gain PMTs added
→ measurement closer to shower axis
radio antennas
→ horizontal events
muon detectors in infill area (installed 75%)
→ direct measurement



Pierre Auger Observatory Open Data

March 2024 release

https://opendata.auger.org

doi 10.5281/zenodo.4487613

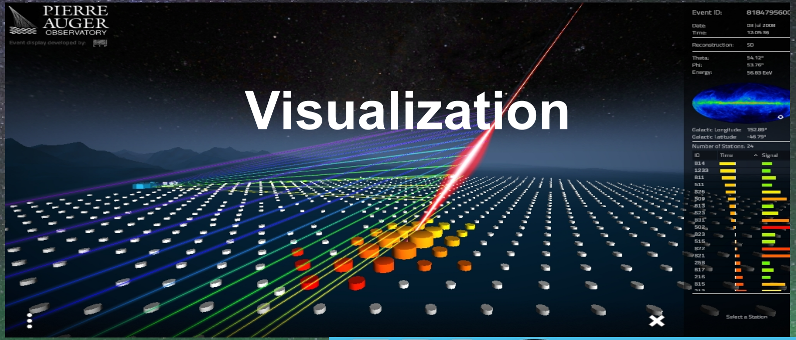
10% cosmic ray data → 30% at the end of 2024
100% atmospheric data

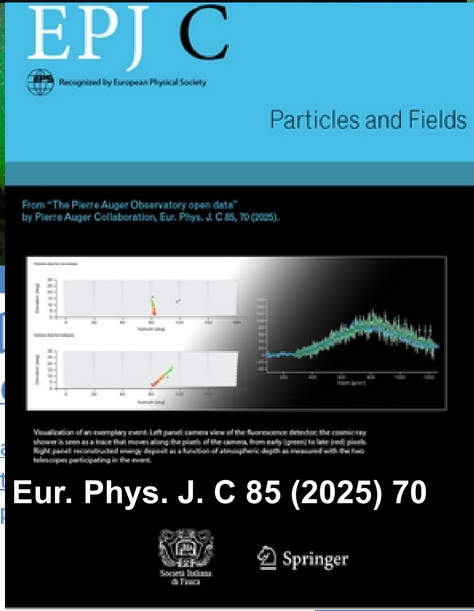
Close to raw data and higher level reconstruction

Surface and Fluorescence Detectors

JSON and summary CSV files

Python code for data analysis





Datasets

the released datasets and their complementary data

Visualize

an online look at the released pseudo raw cosmic-ray data

Analyze

example analysis codes in online python notebooks to run on the datasets

Conclusions

The Pierre Auger Observatory participates in the ongoing multi-messenger international effort to combine data from different experiments in complementary energy ranges

The Pierre Auger Observatory is a key detector at UHE energy:
→ **excellent sensitivity** to photons and neutrinos in the EeV range
→ stringent diffuse limits in the EeV range
→ constraining exotic scenarios and testing cosmogenic flux predictions
indirect hint on primary CR mass composition
→ **coverage of a large fraction of the sky** with targeted and joint searches
→ **follow-up searches** of LIGO/Virgo mergers

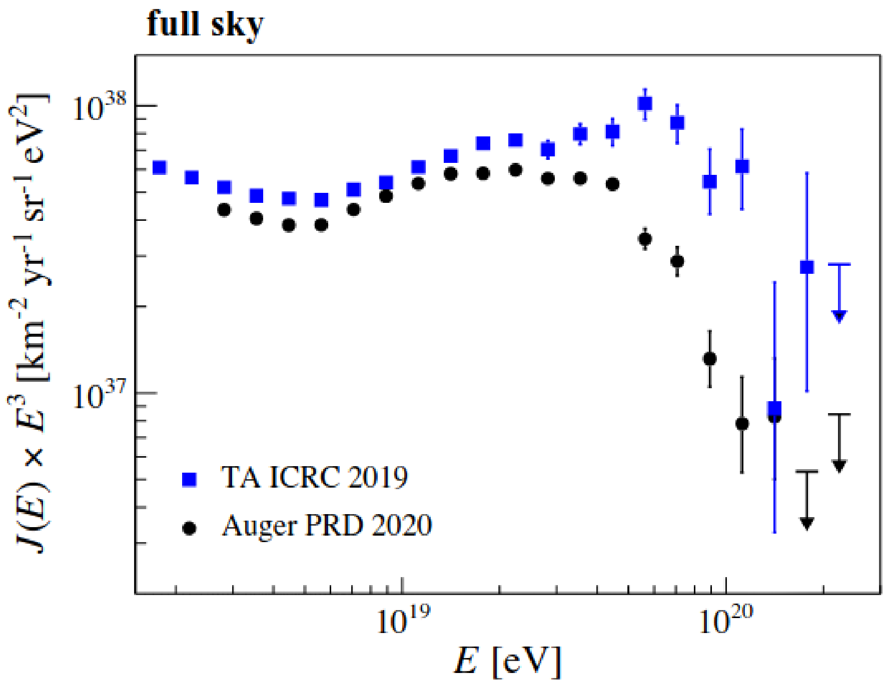
← Fast LVC alert follow-up infrastructure in place
→ GCN notices, streaming to AMON & DWF

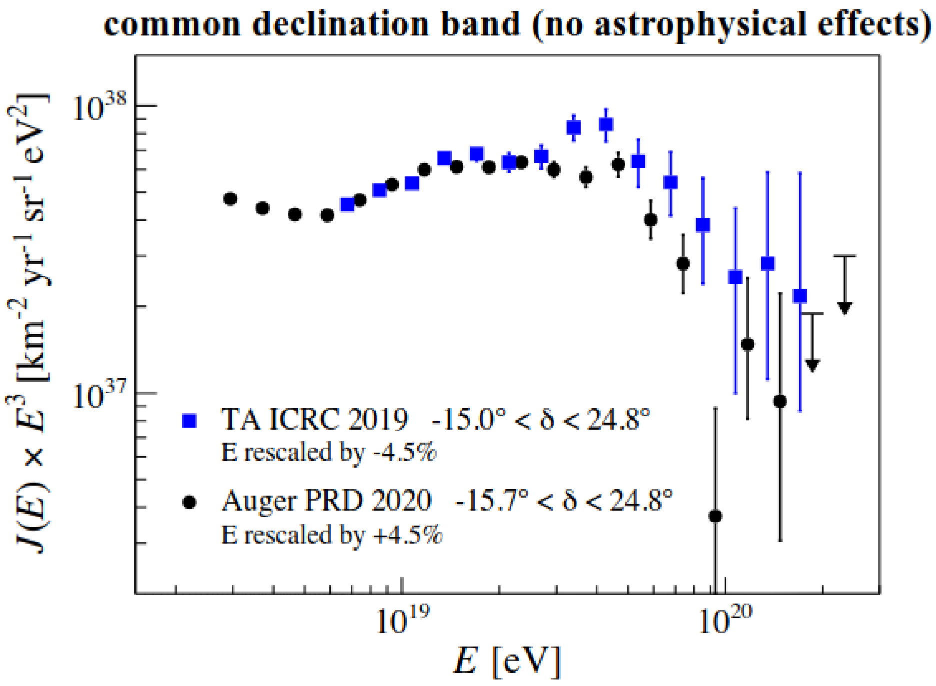
→ Pierre Auger Observatory upgrade will improve on sensitivity and background rejection

BACKUP

Joint Auger TA WG on the energy spectrum

Proper data combination requires understanding the differences in energy scales





Difference at highest energies ($\Delta E/E$ = 20%/decade) not understood

Extremely Energetic Events (> 10^{20} eV)

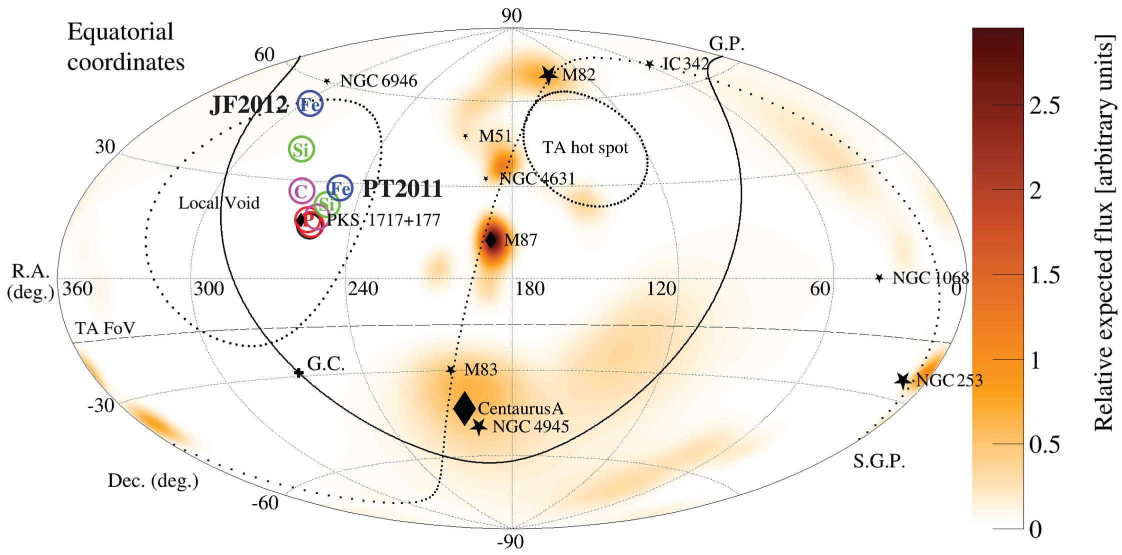
Amaterasu particle
244 EeV

TA, Science 382, 903–907 (2023)

Time (UTC)	Energy (EeV)	S_{800} (m^{-2})	Zenith angle	Azimuth angle	R.A.	Dec.
27 May 2021 10:35:56	244 ± 29 (stat.) $^{+51}_{-76}$ (syst.)	530 ± 57	38.6 ± 0.4°	206.8 ± 0.6°	255.9 ± 0.6°	16.1 ± 0.5°

common band !

From local void. Large magnetic deflections? Physics beyond SM?



166 EeV: most energetic Auger event

note: exposure Auger / TA ≈ 6,7 !

energy of the Amaterasu particle at the Auger energy scale would be 154 EeV

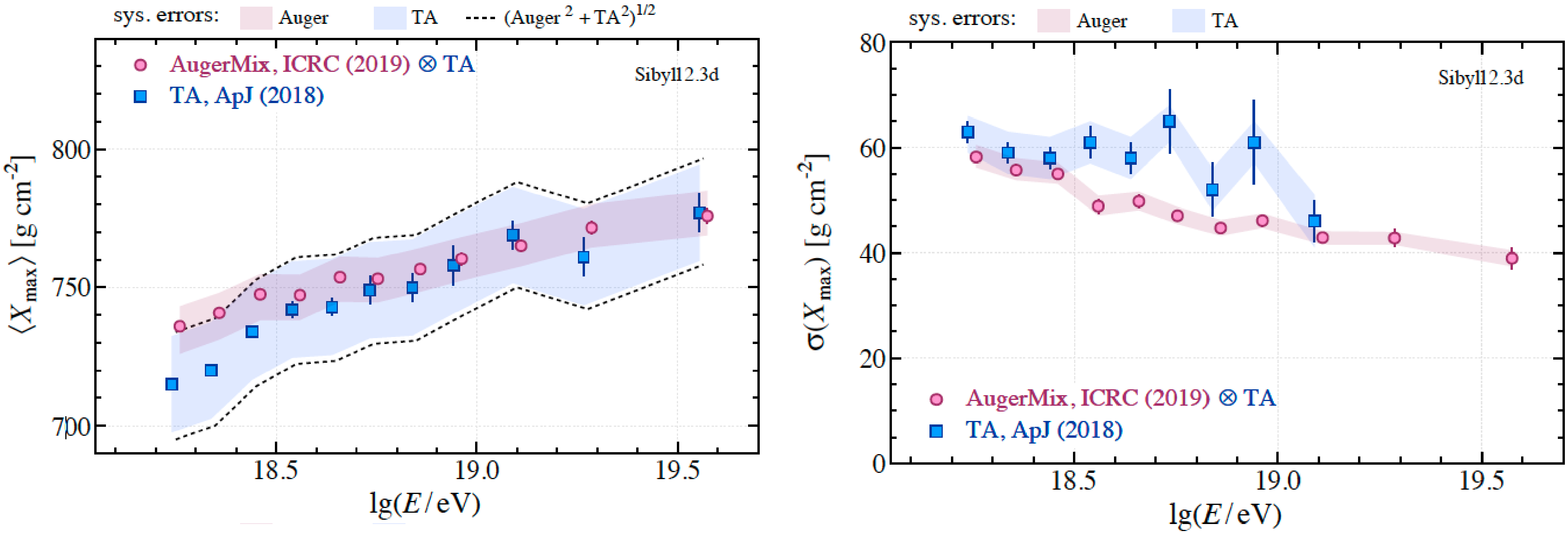
$$-9\% - 20\%(\log_{10}E - 19) = -37\%$$

	E [EeV]	Dec [deg.]
PAO191110	166	-52
PAO070114	165	-21
PAO200611	155	-48
PAO141021	155	-38
TA Amaterasu	154	16

Combining Auger and TA data at extreme energies very difficult due to the mismatch in the energy scales

Auger, Astrophys. J. Suppl. S. 264 (2023) 50 https://opendata.auger. org/catalog/

Joint Auger TA WG for mass composition



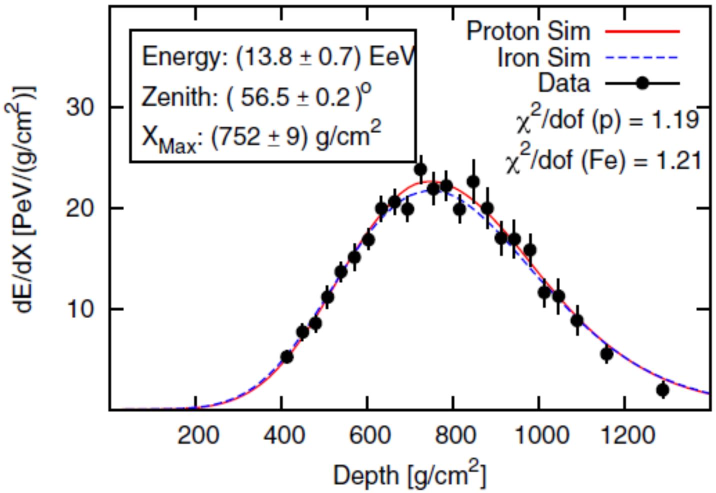
Consistency within uncertainties (larger for TA)

UHECR 2024 and paper under collaboration review

How well hadronic models match data?

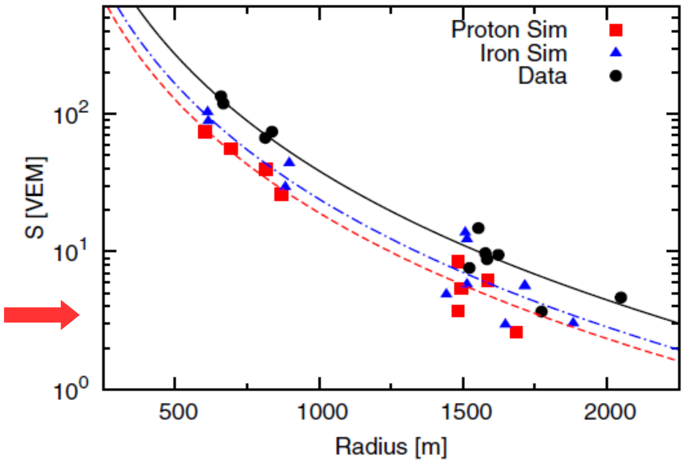
Hybrid events ~ 10^{19} eV, 0°< zenith 60°

PRL 117, 192001 (2016)



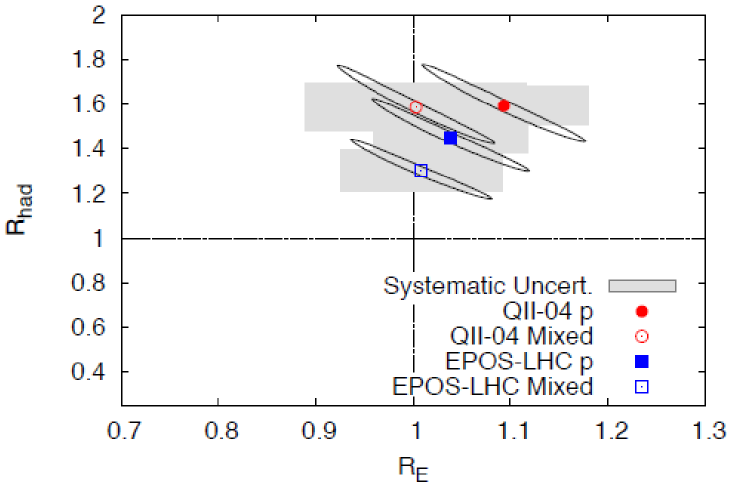
Observed longitudinal profile from FD is reproduced by simulations

Measured signal at the ground differ for data and simulations



R_{had} and R_E

Scaling factors to match data



Evidence of muon excess

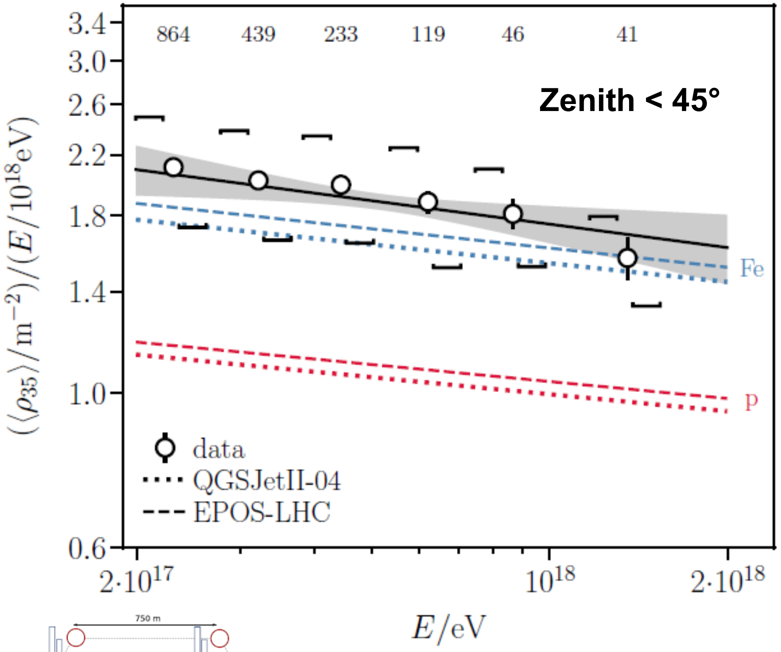
$1.3 < R_{had} < 1.6$

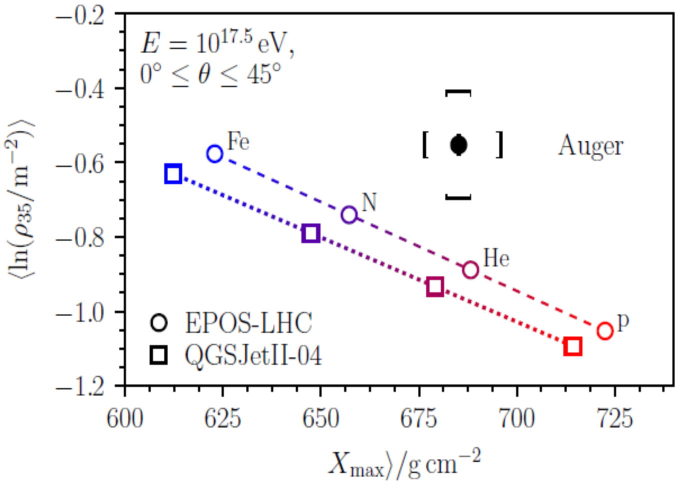
Insensitive to energy scale uncertainty

$R_E \sim 1$

Measurement of muon density and impact on models

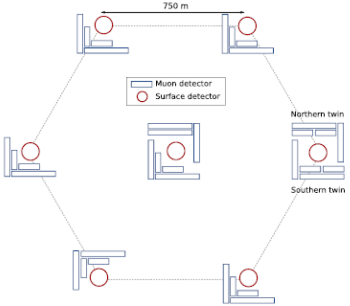
Eur. Phys J. C (2020) 80:751: first direct measurement of muon number with UMD at Auger





Data/Sims ~ 1.38 (1.50)
for EPOS-LHC (QGSJETII-04)

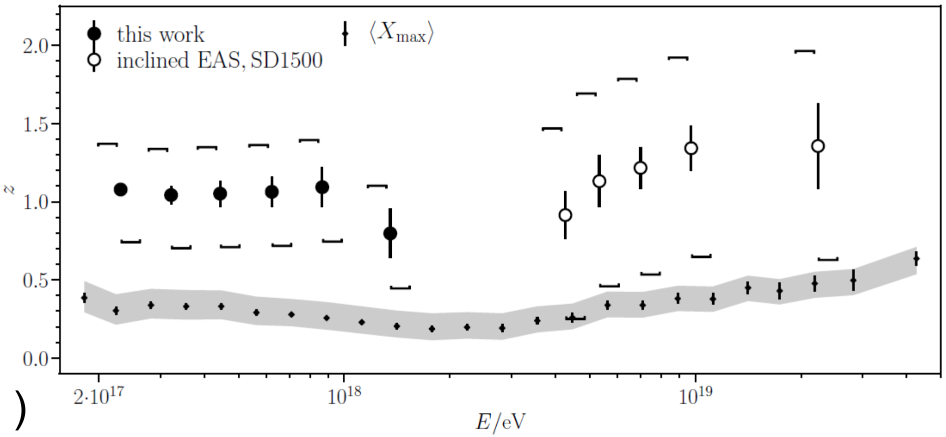
$$z = \frac{\langle \ln x \rangle - \langle \ln x \rangle_{\mathrm{p}}}{\langle \ln x \rangle_{\mathrm{Fe}} - \langle \ln x \rangle_{\mathrm{p}}}$$



Muon number from models in tension with data

Fluctuation in agreement
 (Phys. Rev. Lett. 126 (2021) 152002)

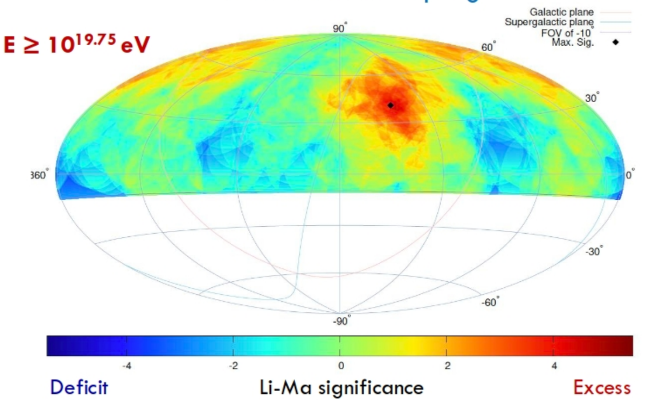
EPOS-LHC



TA Hotspot & Perseus-Pisces supercluster excess

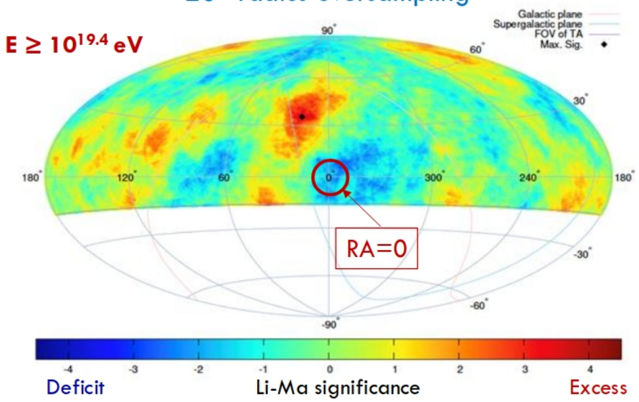
J. Kim, PoS(ICRC2023)244

25°-radius oversampling



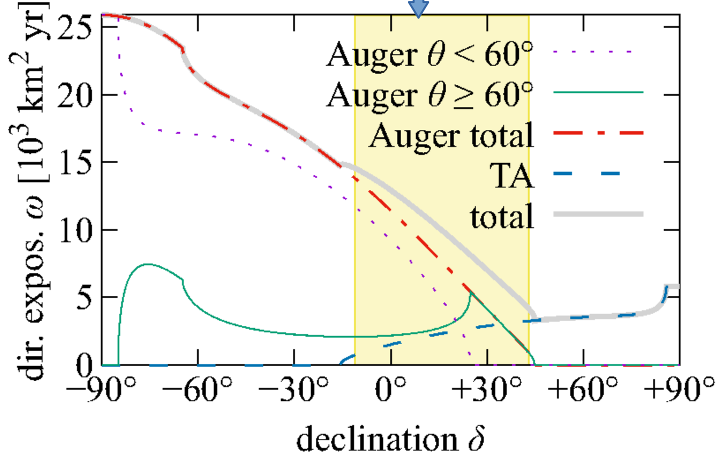
- 216 events (15-year TA SD data)
- Max local sig.: **4.8σ** at (144.0°, 40.5°)
- Post-trial prob.: $P(S_{MC} > 4.8\sigma)$=2.7×10^{-3}→ **2.8σ**

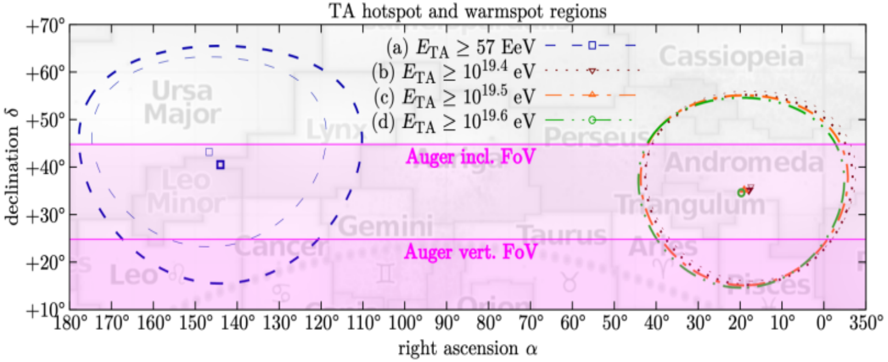
20°-radius oversampling



- 1125 events (15-year TA SD data)
- Max local sig.: **4.0σ** at (17.9°, 35.2°)
- Chance probability of having equal or higher excess close to the PPSC → **3.3σ**

Declination Auger/TA common band





TA "Hot Spot" and PPSC excess not confirmed by Auger

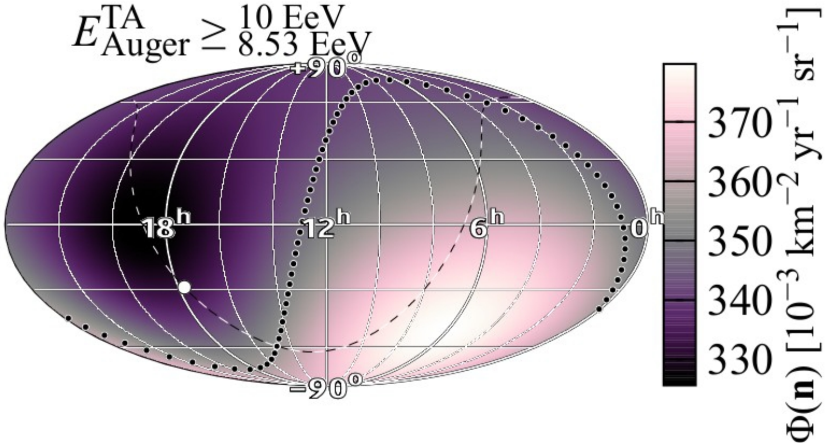
PoS(ICRC2023) 252

	$(\alpha_0, \delta_0)\,[°]$	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

Joint Auger TA WG in the search for anisotropy signals

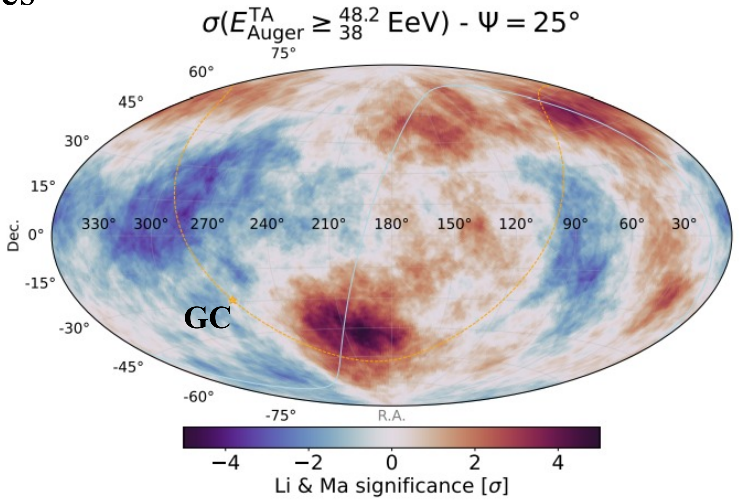
Reports at UHECR and ICRC conferences, journal publications

large scale (dip. + quad.)



equatorial coordinates

medium scale



Cen A

studies limited by TA statistics

Correlation with starburst galaxies $1\,\mathrm{Mpc} \leq D < 130\,\mathrm{Mpc}$ (Lunardini+ '19 catalog)

dataset	E^{min}_{Auger}	E^{min}_{TA}	Θ	f	TS	post-trial
ICRC 2023	38 EeV	48.2 EeV	$(15.4^{+5.2}_{-3.0})°$	$(11.7^{+4.7}_{-2.9})\%$	30.5	4.6σ
UHECR 2024	38 EeV	47.8 EeV	$(15.0^{+5.0}_{-2.9})°$	$(11.1^{+4.4}_{-2.8})\%$	29.5	4.4σ

TAx4 under construction

ICRC2023, UHEC2024

Starburst galaxies: Auger only 4σ Auger+TA 4.4σ

Beyond the standard model

Search for Lorentz invariance violation

Effects suppressed for low energy and short travel distances : UHECRs !!!

$$E_i^2 - p_i^2 = m_i^2 + \sum_{n=0}^{N} \delta_i^{(n)} E_i^{2+n} = m_i^2 + \eta_i^{(n)} \frac{E_i^{2+n}}{M_{Pl}^n}$$

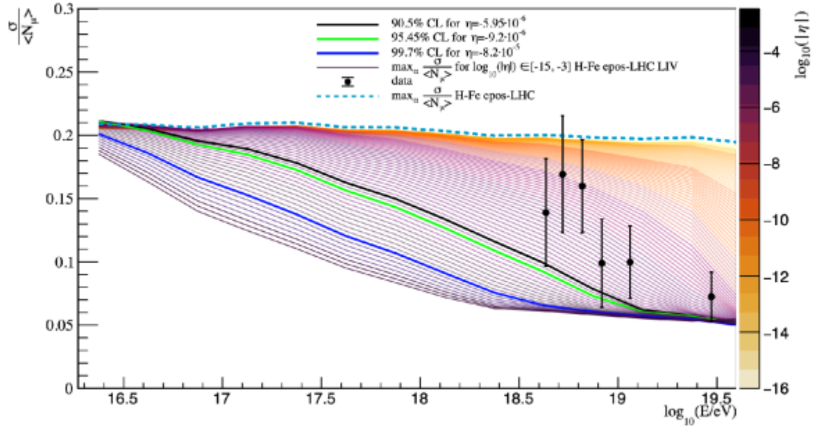
$$\gamma_{\mathrm{LIV}} = \frac{E}{m_{\mathrm{LIV}}} \qquad \tau = \gamma_{\mathrm{LIV}} \tau_0$$

In air shower development

for $\eta^{(n)}<0$, decay of π^0 forbidden

EM component decreasing, hadronic one increasing

$$\pi^0 \to \gamma\gamma \qquad \boxed{\tau_0 = 8.4 \cdot 10^{-17}\mathrm{s}}$$



C.Trimarelli, EPJ Web of Conf. ***283****, 05003 (2023)*

Auger Coll., JCAP 01 (2022) 023

Super-heavy dark matter searches

Overdensity of SHDM in the galatic halo:

$$\delta = \frac{\delta_X^{halo}}{\rho_X^{extr}} = \frac{\rho_{DM}^{halo}}{\Omega_{DM}\rho_c} \simeq 2 \times 10^5$$

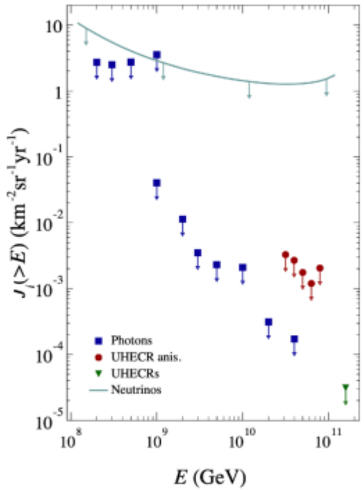
Berezinsky V. et al., Phys.Rev.Lett.79 (1997) 4302

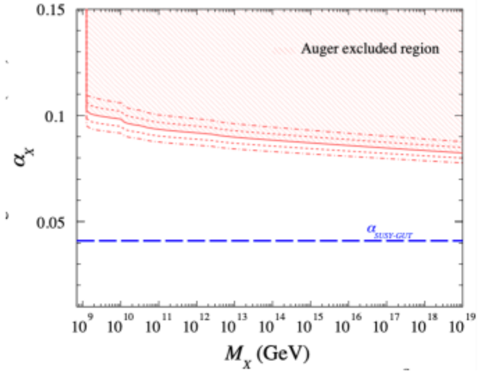
Flux of secondaries from SHDM decay ($i = \gamma, \nu, \bar{\nu}, N, \bar{N}$):

$$J_i^{\mathrm{gal}}(E) = \frac{1}{4\pi M_X c^2 \tau_X} \frac{\mathrm{d}N_i}{\mathrm{d}E} \int_0^\infty \mathrm{d}s\ \rho_{\mathrm{DM}}(\mathbf{x}_\odot + \mathbf{x}_i(s;\mathbf{n})).$$

Free parameters

$$\tau_X = \hbar M_X^{-1} \exp(4\pi/\alpha_X)$$



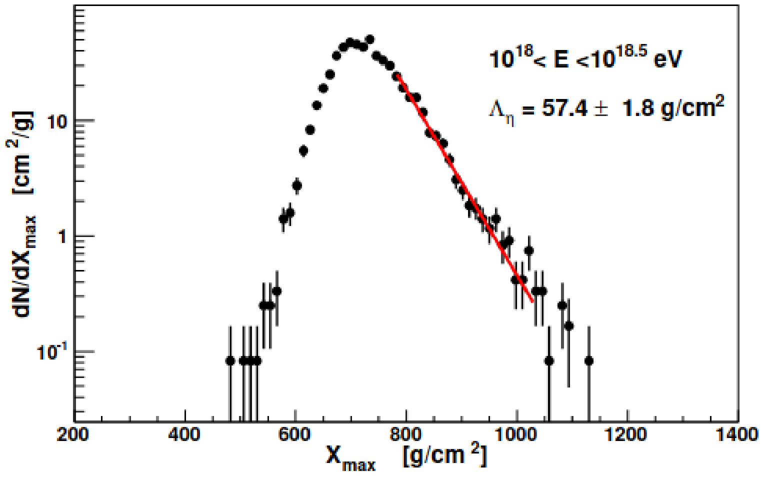


Auger Coll., Phys. Rev. D 107 (2023) 042002

Auger Coll., Phys. Rev. Lett. 130 (2023) 061001

Auger Coll., Phys. Rev. D 109 (2024) L081101

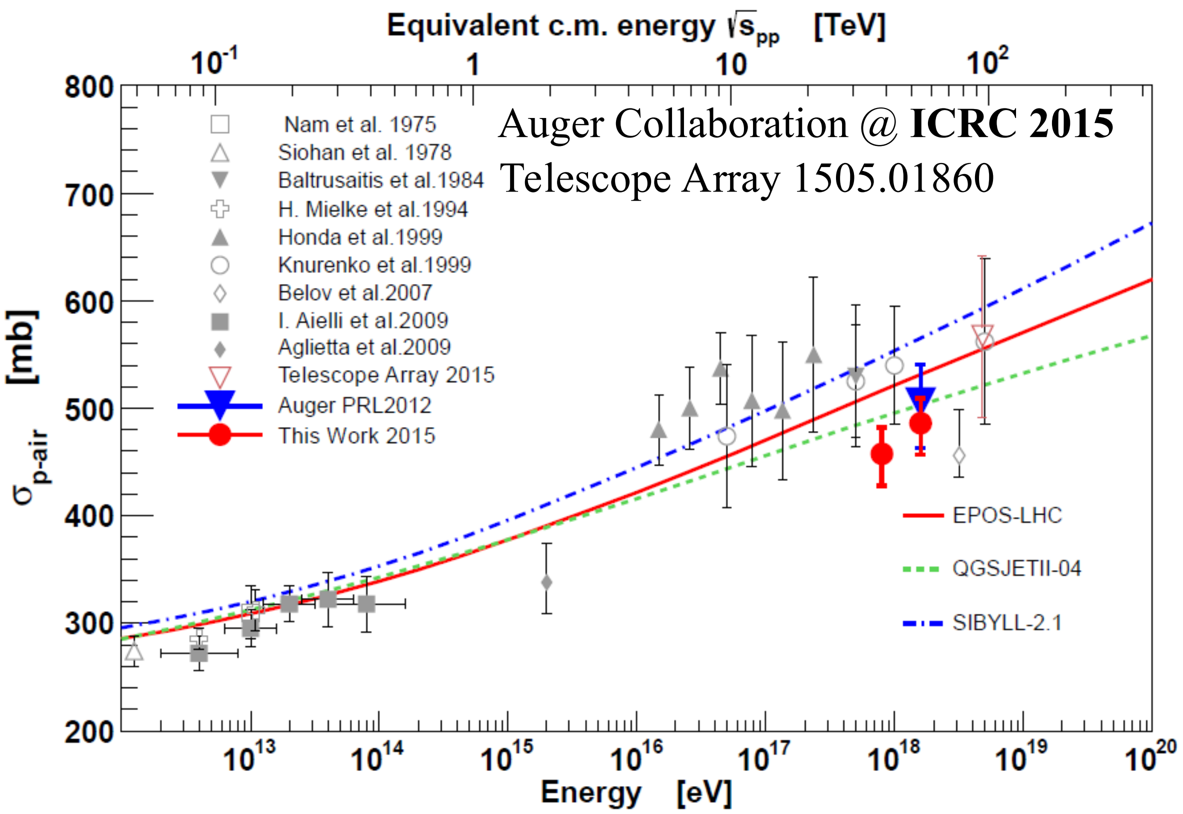
proton-air cross-section



Fit to the tail of the Xmax distribution and converting into cross-section using simulations

- depends on composition

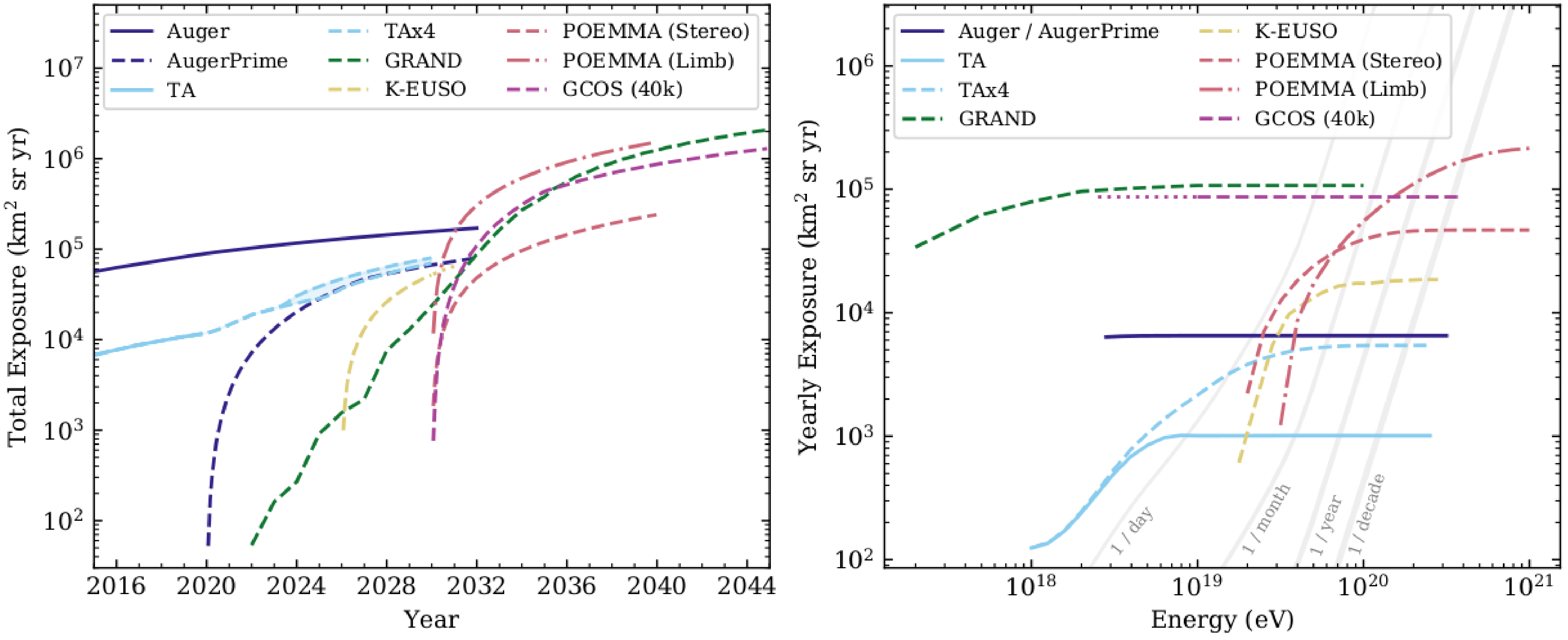
- depends on model



Lower energy [457 ± 18(stat)+19/-25(syst)] mb
Higher energy [486 ± 16(stat)+19/-25(syst)] mb

A look into the future for UHECRs

EPJ Web of Conferences 283, 01001 (2023)



Summary of main facts for UHECRs

UHECRs NOT predominantly protons, fraction of heavier nuclei increases with energy above ~2 EeV
→ spectrum features reflect the evolution of mass composition
→ different and independent measurements
→ non observation of photons and neutrinos from CRs

Spectrum features are clearly identified without relying on hypotheses on composition or sources
The shape of the spectrum reflects the different contributions in mass

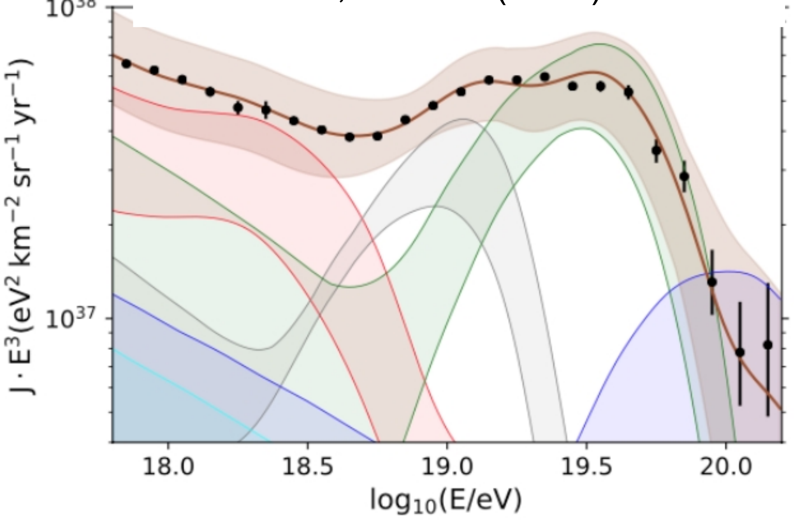
Observation of a dipolar anisotropy > 8 EeV → EG origin
no hints for anisotropy in Northern sky up to 45° in declination (vertical+inclined events)
hints of correlation with the SBGs above 40 EeV

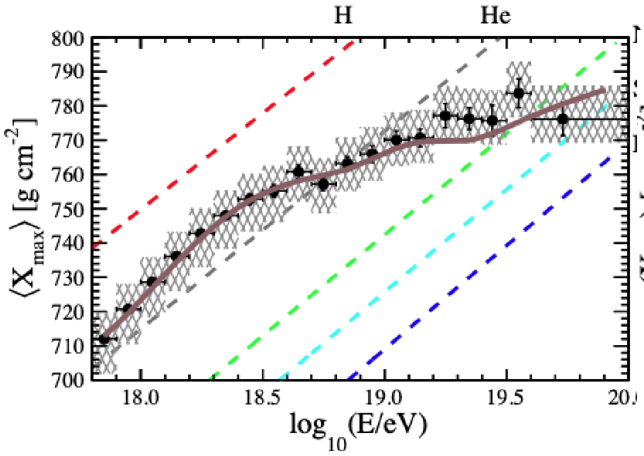
No composition difference from Northern to Southern hemisphere below $10^{19.5}$ eV
The transition region is placed around the second knee. Supported by
— the measured composition, which becomes lighter above the 2nd knee up to $\sim 2\times10^{18}$ eV
— the smooth transition from isotropy to a dipolar anisotropy above 8 EeV
— the exclusion of H+He mix in the ankle region at >5σ

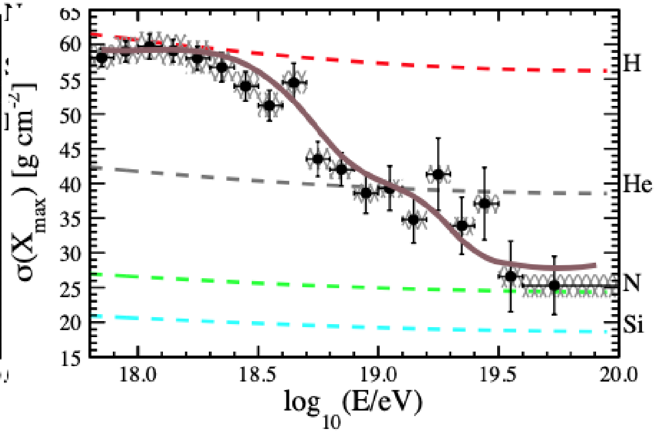
Valuable information about hadronic interactions at UHE:
μ deficit in models due to pile-up effects along the shower development

Constraints to effects of **physics beyond standard model**

ICRC 2021, JCAP05(2023)024







BEST FIT

1) EG: hard HE component + soft LE component
2) possible Galactic component (N)

Scenarios compatible within systematics

Dominant experimental systematics
Only propagation, no magnetic fields

	1st scenario		2nd scenario	
Galactic contribution (at Earth)	N+Si		-	
J_0^{gal} [eV^{-1} km^{-2} sr^{-1} yr^{-1}]	$(1.07 \pm 0.06) \cdot 10^{-13}$		-	
$\log_{10}(R_{cut}^{gal}/V)$	17.48 ± 0.02		-	
f_N (%)	93.0		-	
EG components (at the sources)	Low energy	High energy	Low energy	High energy
$\mathcal{L}_0$ [erg Mpc^{-3} yr^{-1}]	$7.28 \cdot 10^{45}$	$4.4 \cdot 10^{44}$	$1.7 \cdot 10^{46}$	$4.5 \cdot 10^{44}$
γ	3.30 ± 0.05	-1.47 ± 0.12	3.49 ± 0.02	-1.98 ± 0.10
$\log_{10}(R_{cut}/V)$	24 (lim.)	18.19 ± 0.02	24 (lim.)	18.16 ± 0.01
I_H (%)	100 (fixed)	0.0	49.87	0.0
I_{He} (%)	-	27.17	10.92	28.60
I_N (%)	-	69.86	36.25	69.05
I_{Si} (%)	-	0.0	0.0	0.0
I_{Fe} (%)	-	2.97	2.96	2.35
D_J (N_J)	49.5 (24)		60.1 (24)	
$D_{X_{max}}$ ($N_{X_{max}}$)	593.8 (329)		554.8 (329)	
D (N)	643.3 (353)		614.9 (353)	