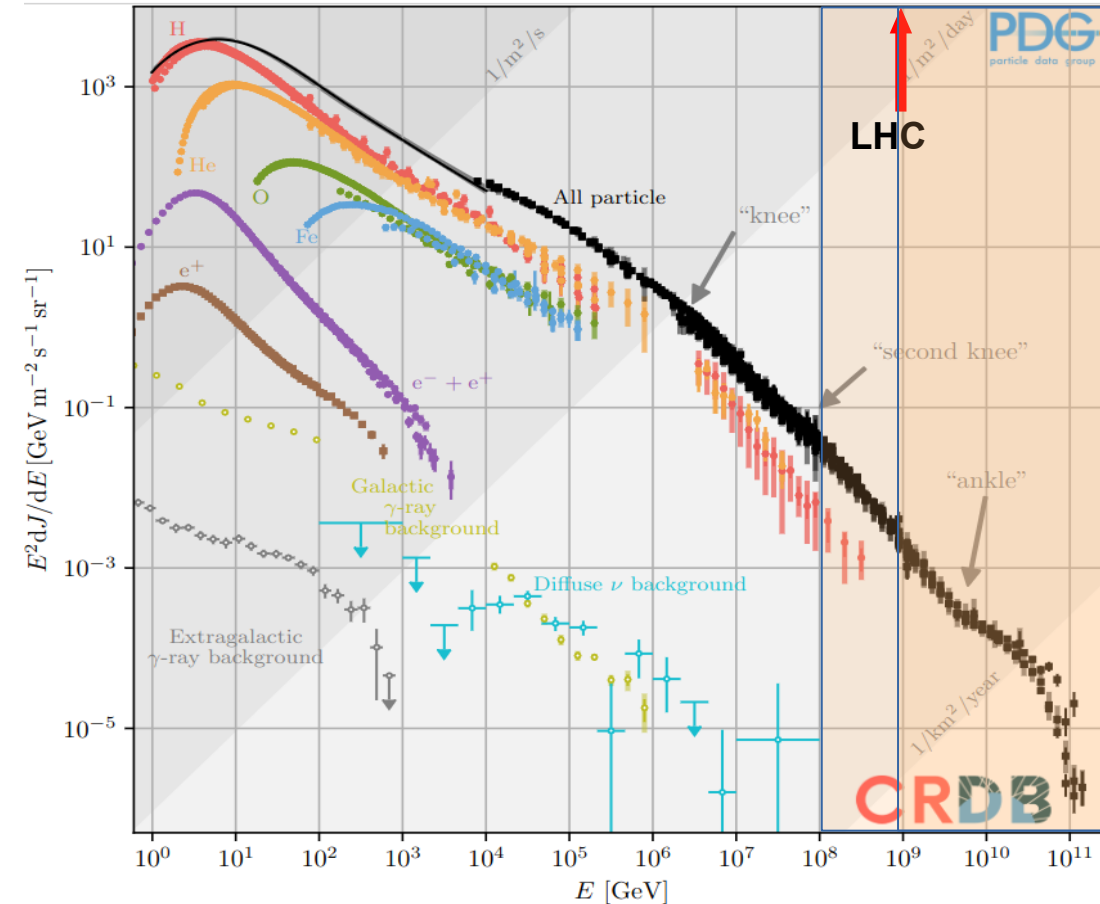


Results from the Pierre Auger Observatory

Lorenzo Perrone - Università del Salento e INFN Sezione di Lecce

Ultra-high energies cosmic rays



Wide range of energy/flux

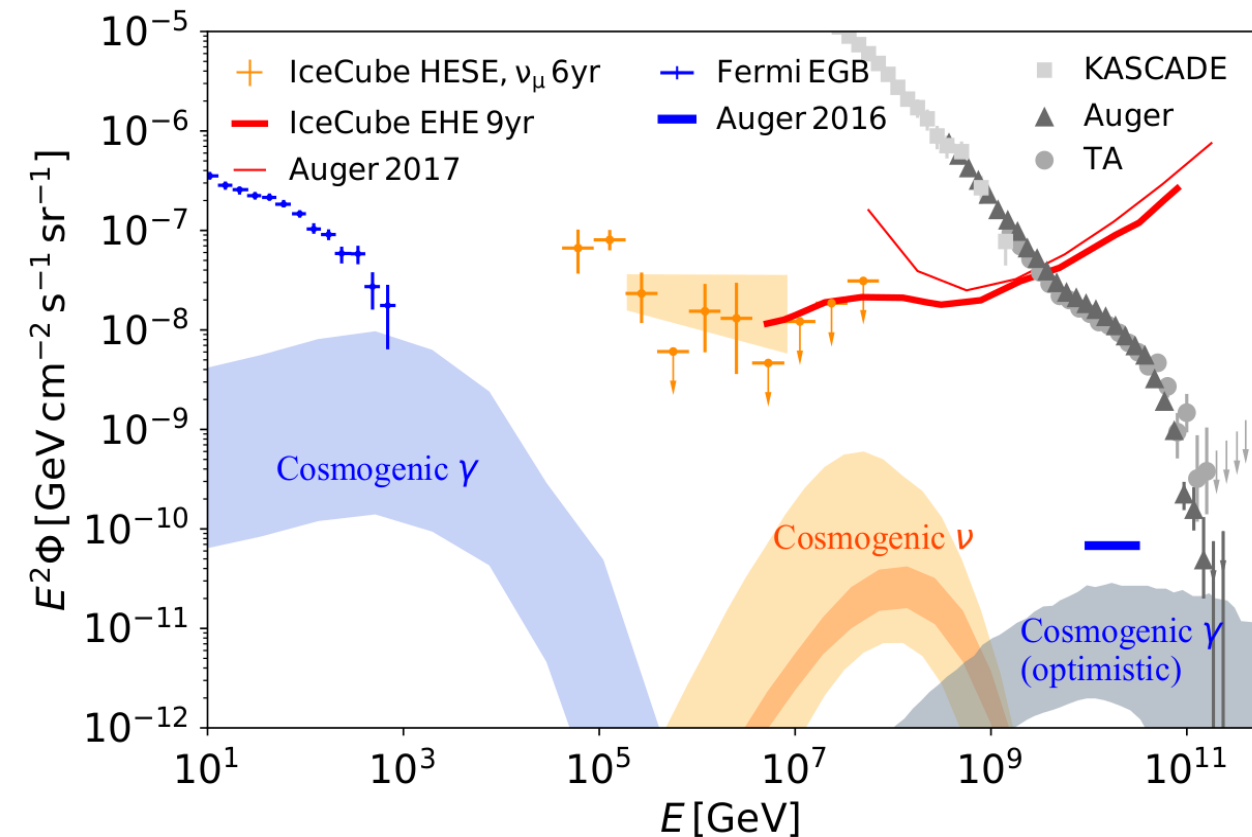
Diverse measurement techniques

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

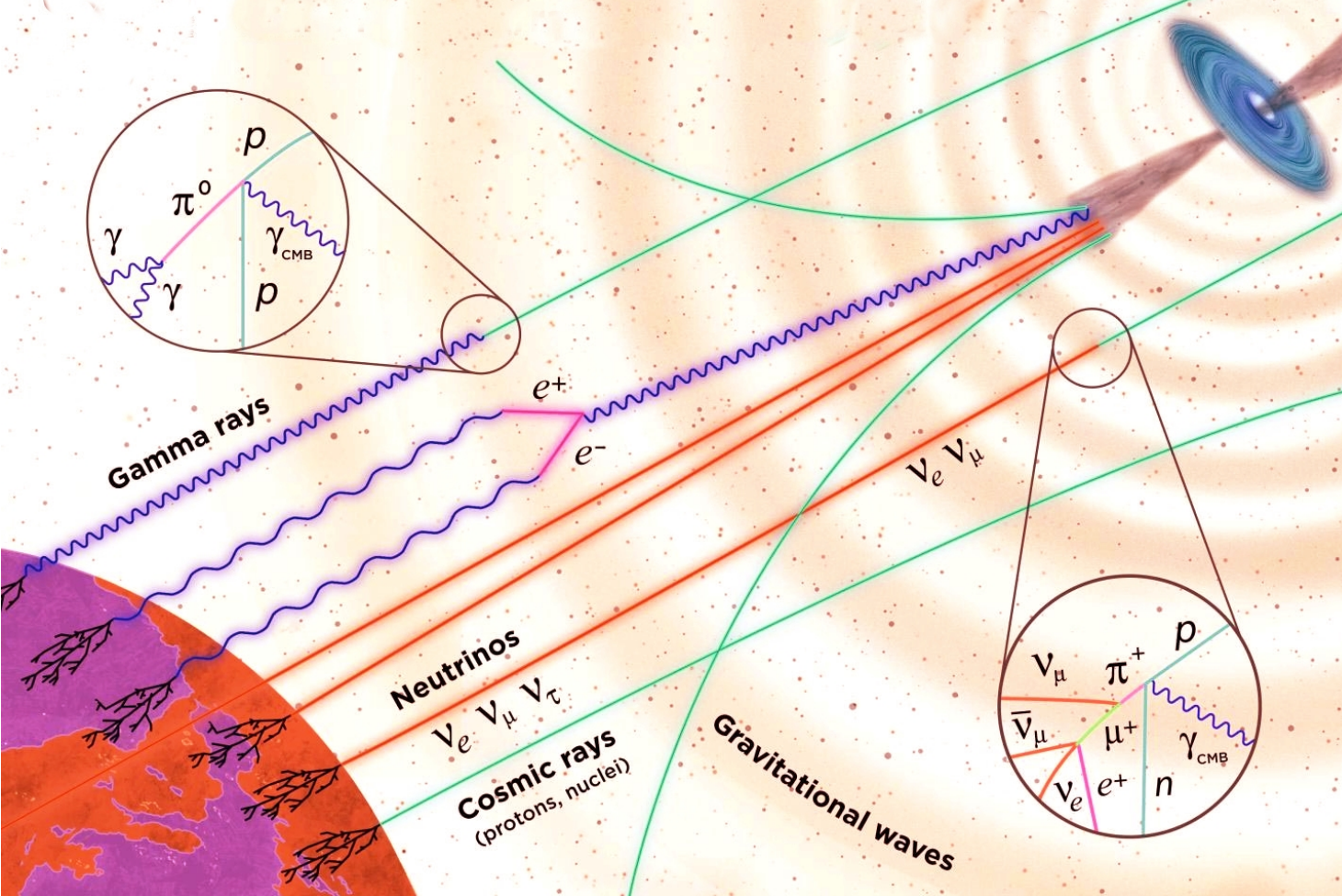


Strong interplay between different “cosmic” actors

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:

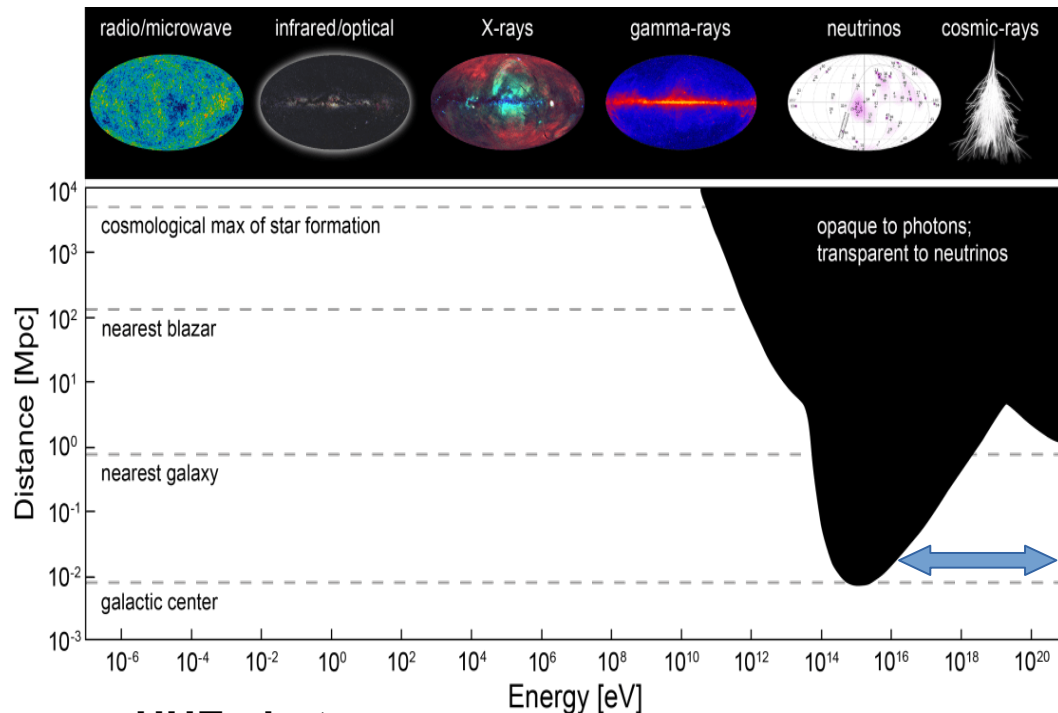
magnetic fields deflection

→ UHE photons:

limited horizon (local universe)
or hints for new physics
(SHDM, BSM)

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

The cosmic horizon for the Pierre Auger Observatory

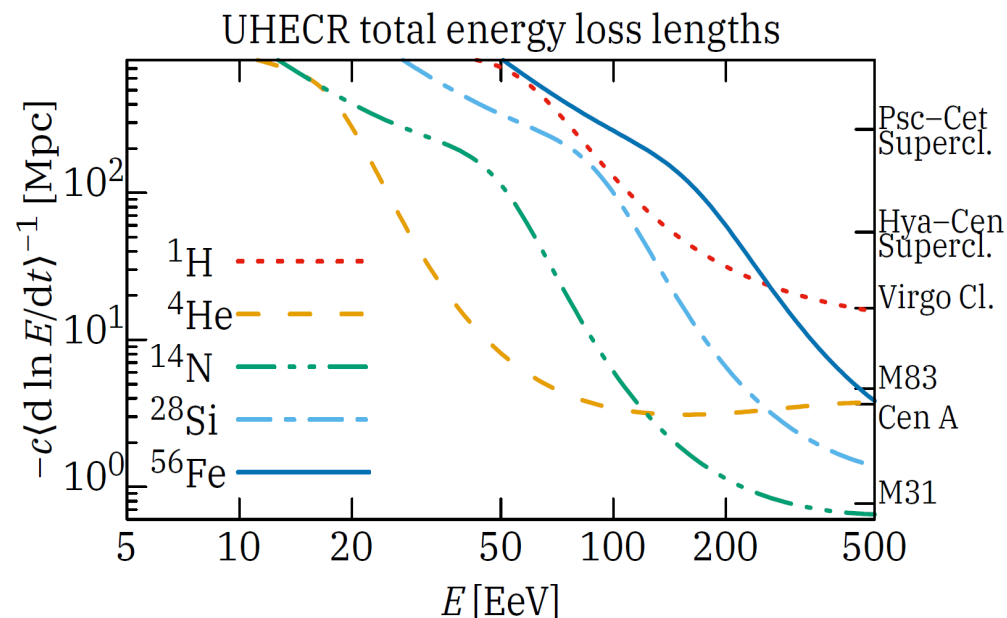


→ **UHE photons:**
limited horizon (local universe)
or hints for new physics (SHDM, BSM)

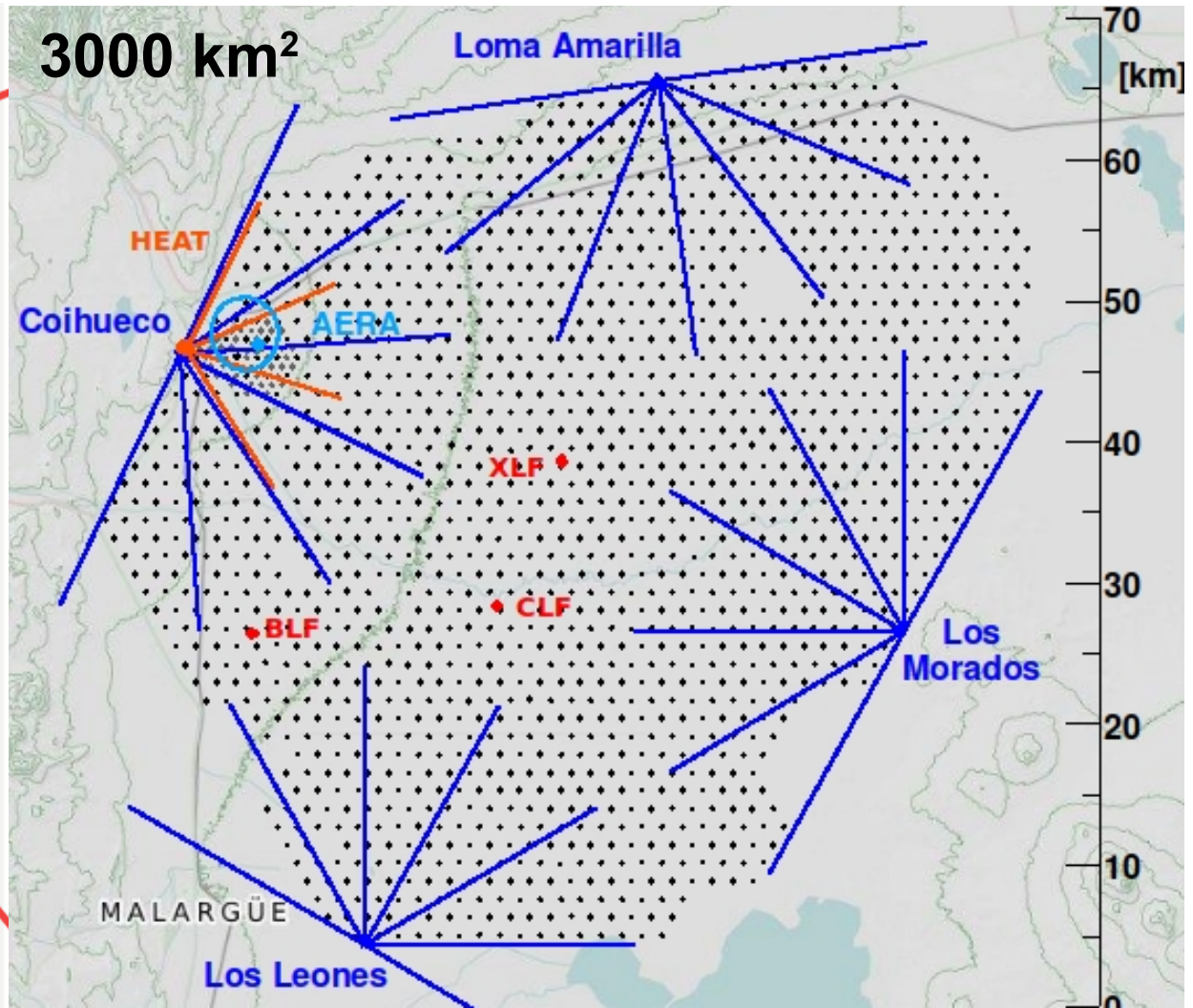
→ **UHE neutrons:** 15 min mean lifetime → 9.8 kpc (E/EeV)

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

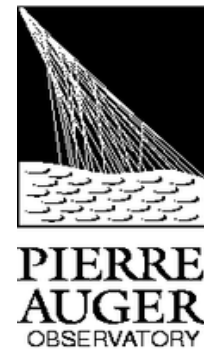
→ **Charged CR:**
magnetic fields deflection
propagation effect (~ 100 Mpc at 10^{20} eV)



The Pierre Auger Observatory



The 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 (61,750 m) of 24 km²

Very Dense array (19, 433 m) of 2 km²

Fluorescence detector

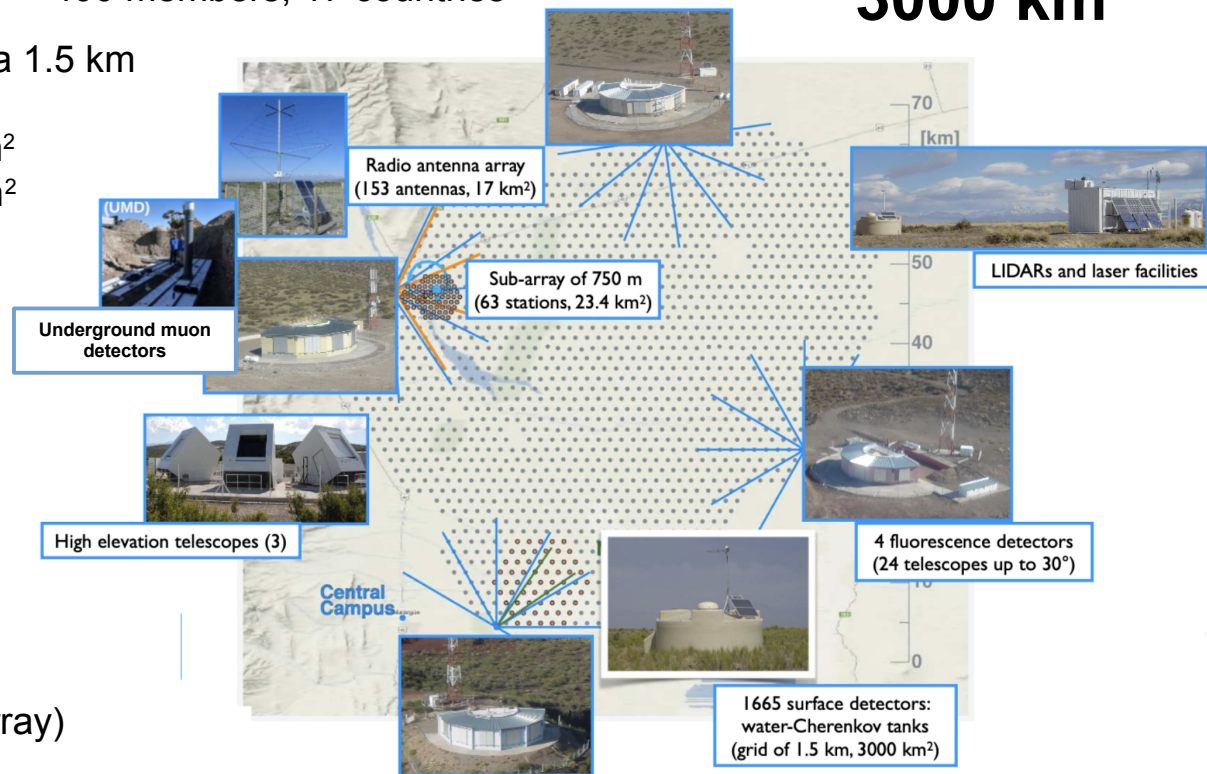
4+1 buildings overlooking the array
(24 + 3 HEAT telescopes)

Radio detector

153 Radio Antenna, 17 km² → AERA

Muon Detectors

Buried scintillators (region of dense array)

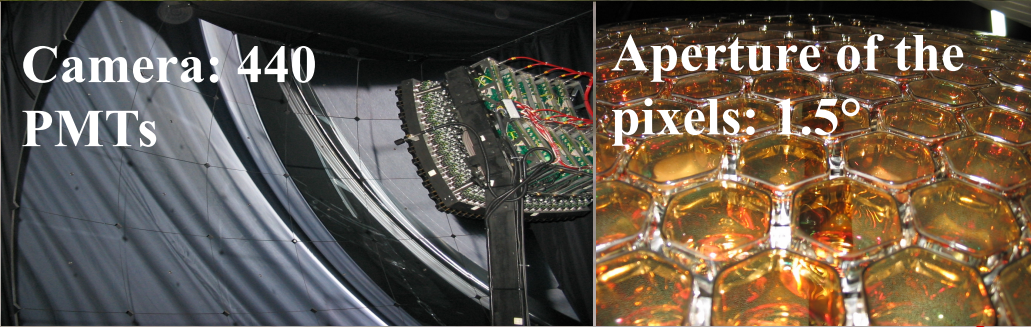


Phase 1 : data taking from 2004 on
(from 2008 with the full array in operation):

- Over 120.000 km² sr yr for anisotropy studies
- Over 100.000 km² sr yr for spectrum studies

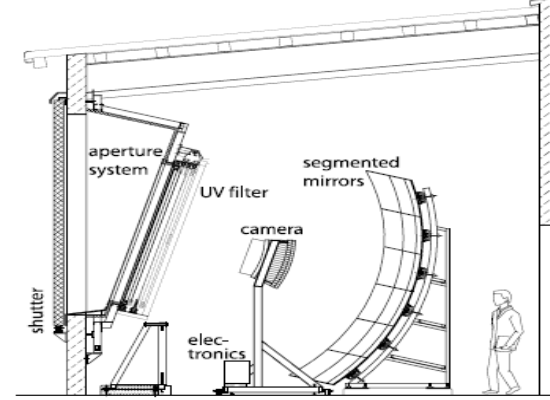
Phase 2 - the AugerPrime upgrade
Data taking until 2035
Multiple detectors

Fluorescence detector

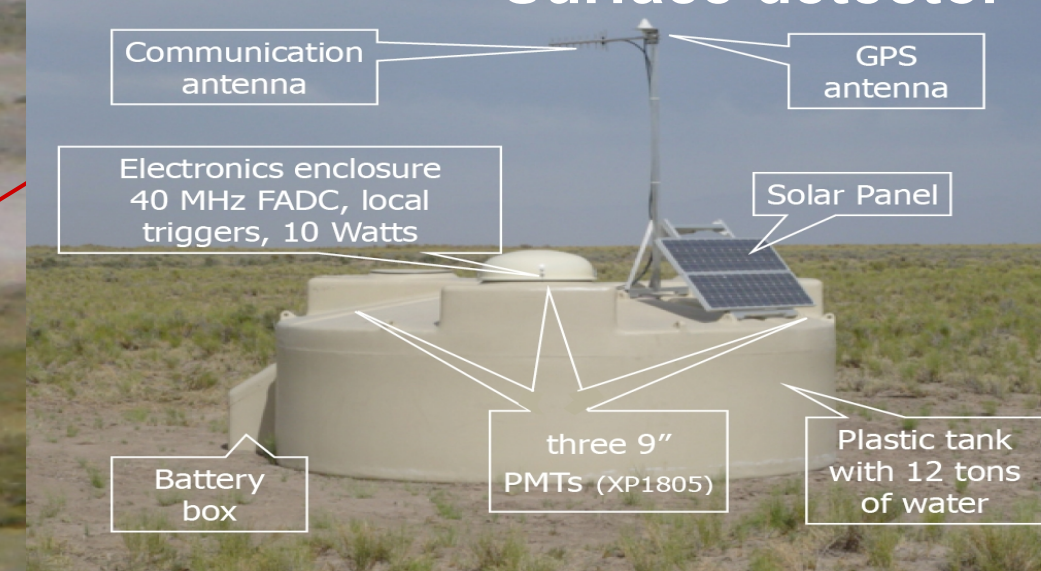


Camera: 440
PMTs

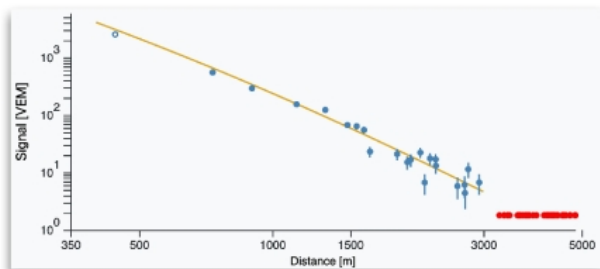
Aperture of the
pixels: 1.5°



Surface detector

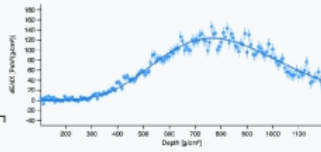
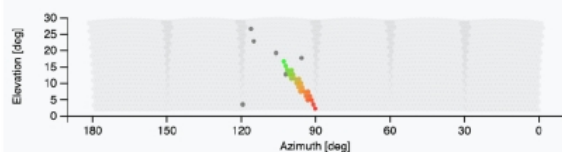


SD rec

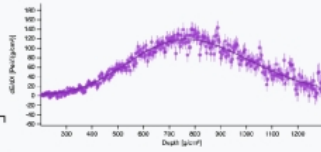
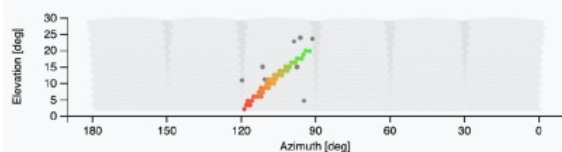


Energy	82±7 EeV
θ	53.8°
ϕ	100.6°
β	-2.1
$t_{1/2}(1000)$	127±5 ns
δ	17.8°
α	324.5°
Multiplicity	22

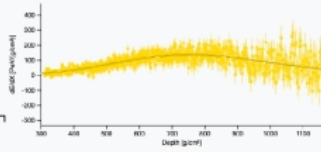
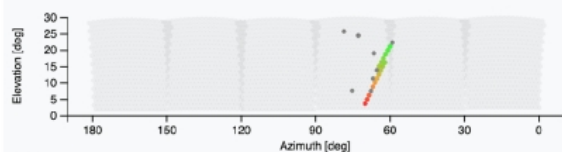
Camera view for Los Leones



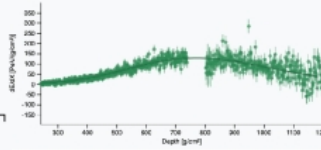
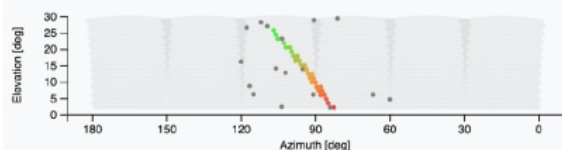
Camera view for Los Morados



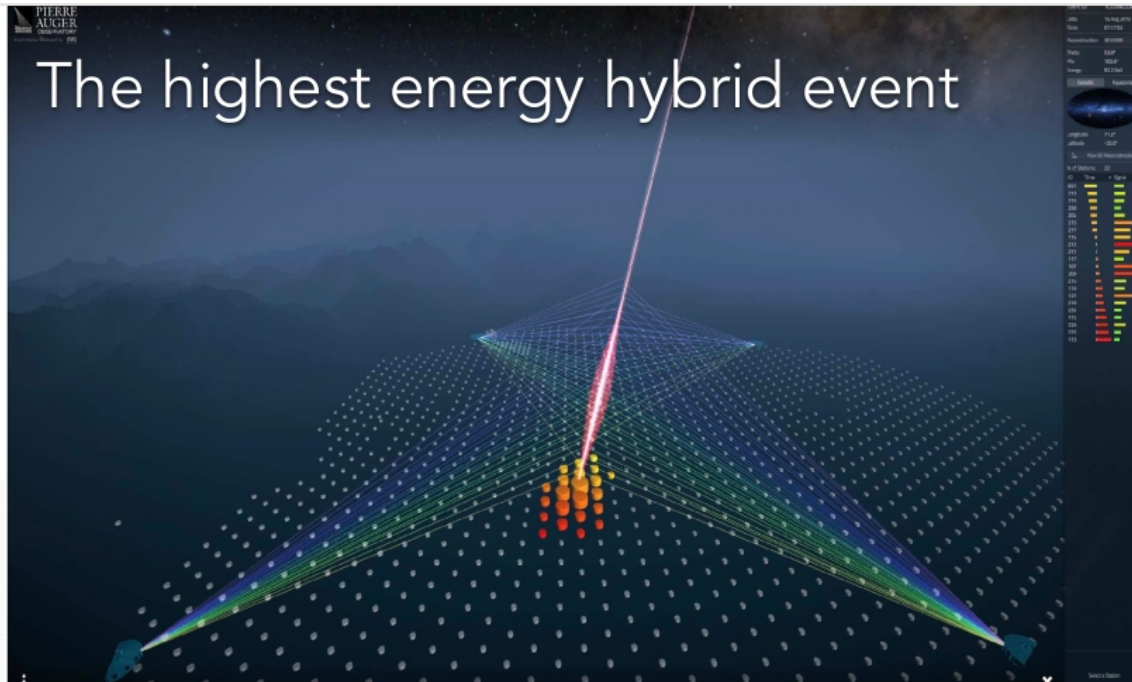
Camera view for Loma Amarilla



Camera view for Colihueco

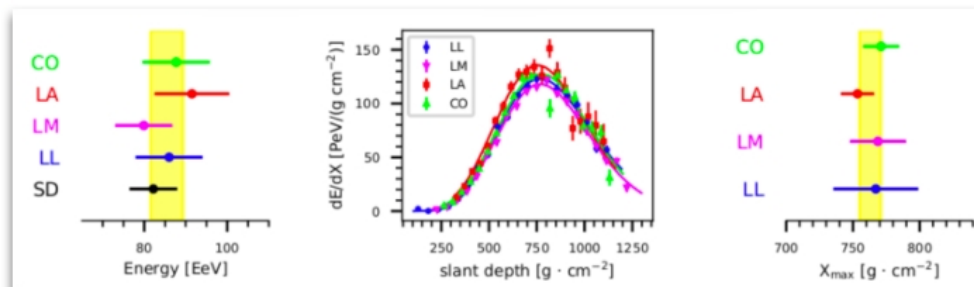


The highest energy hybrid event



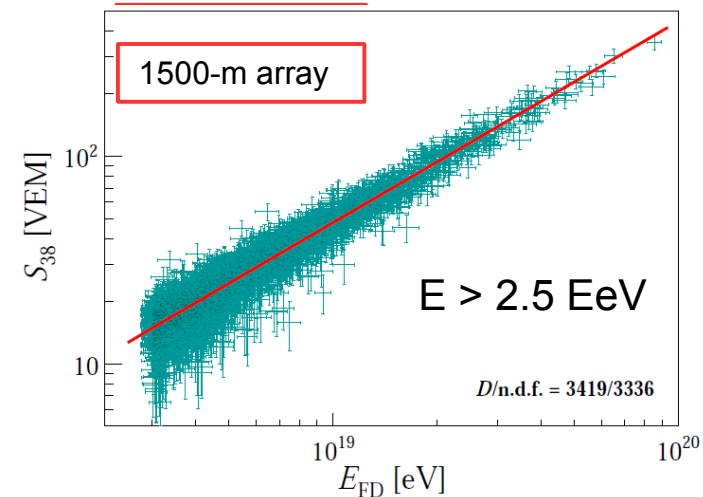
Astrophys. J. Suppl. S. 264 (2023) 50

Hybrid rec



Auger: calibration with the FD energy scale

Phys. Rev. D 102 (2020) 062005

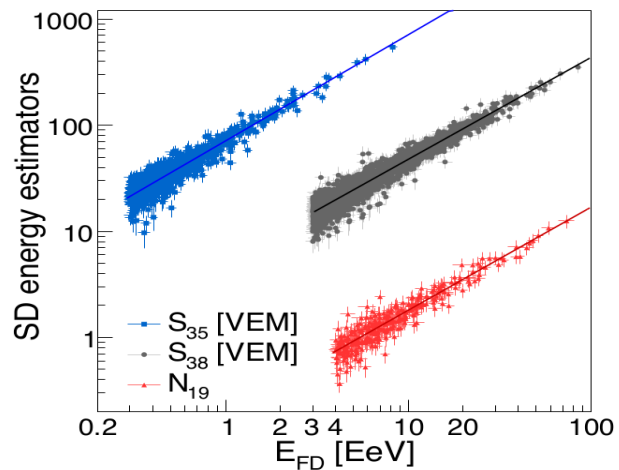
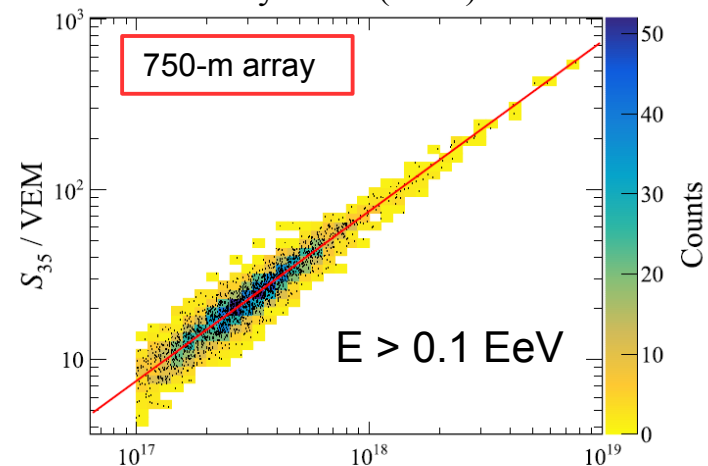


Systematic uncertainty in the energy scale

ICRC 2013

Fluorescence yield	3.6%
Atmosphere	3.4% – 6.2%
FD calibration	9.9%
FD profile recon.	6.5% – 5.6%
Invisible energy	3% – 1.5%
Stability of energy scale	5%
TOTAL	14%

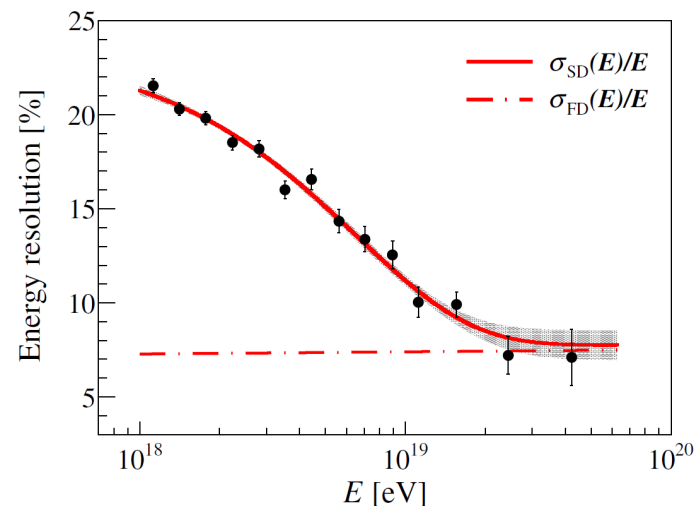
Eur. Phys J C. (2021) 81:966



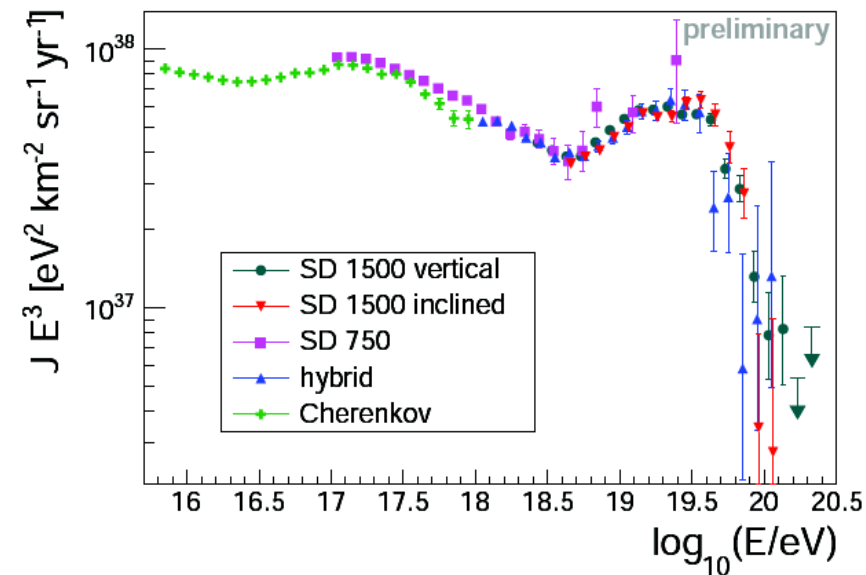
Energy resolution

SD: < 20% (zenith < 60° and)

Hybrid: 6-8 % [ICRC 2019]



The Auger combined spectrum



Cutoff at $\sim 5 \cdot 10^{19}$ eV confirmed

ankle at $\sim 5 \cdot 10^{18}$ eV confirmed

instep at $\sim 10^{19}$ eV identified

2nd knee observed, hint for a low energy ankle

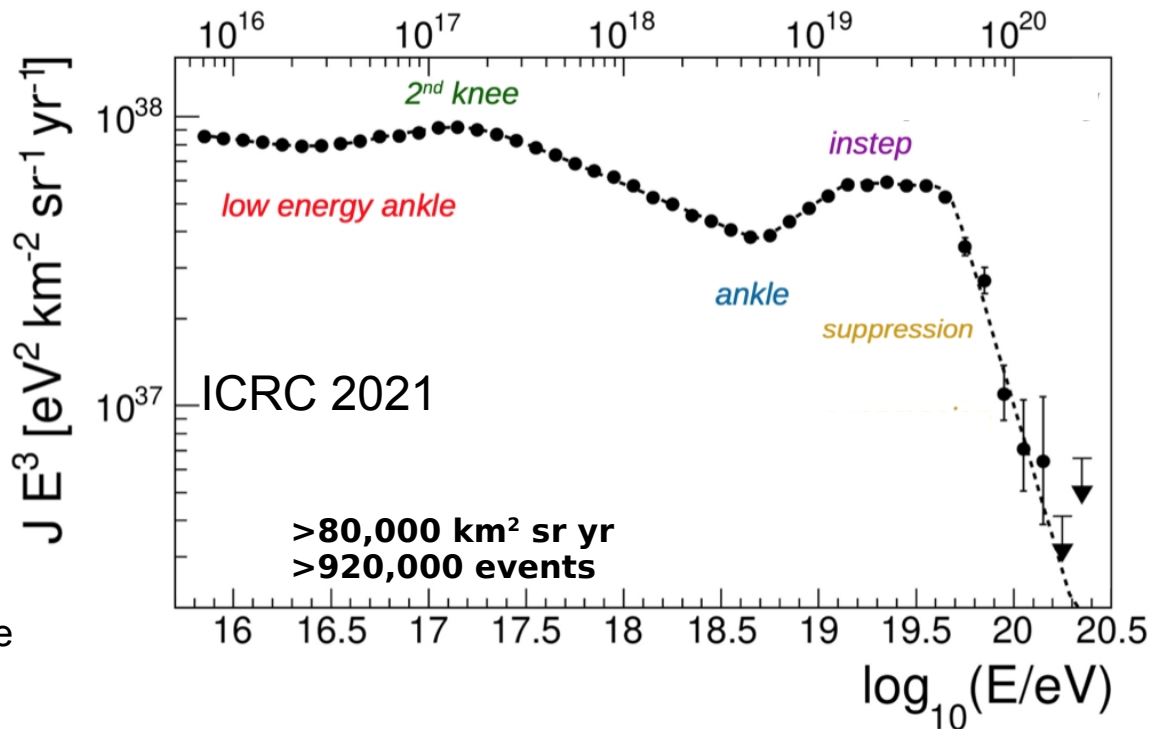
Five measurements

more than 3 order of magnitudes

same energy scale

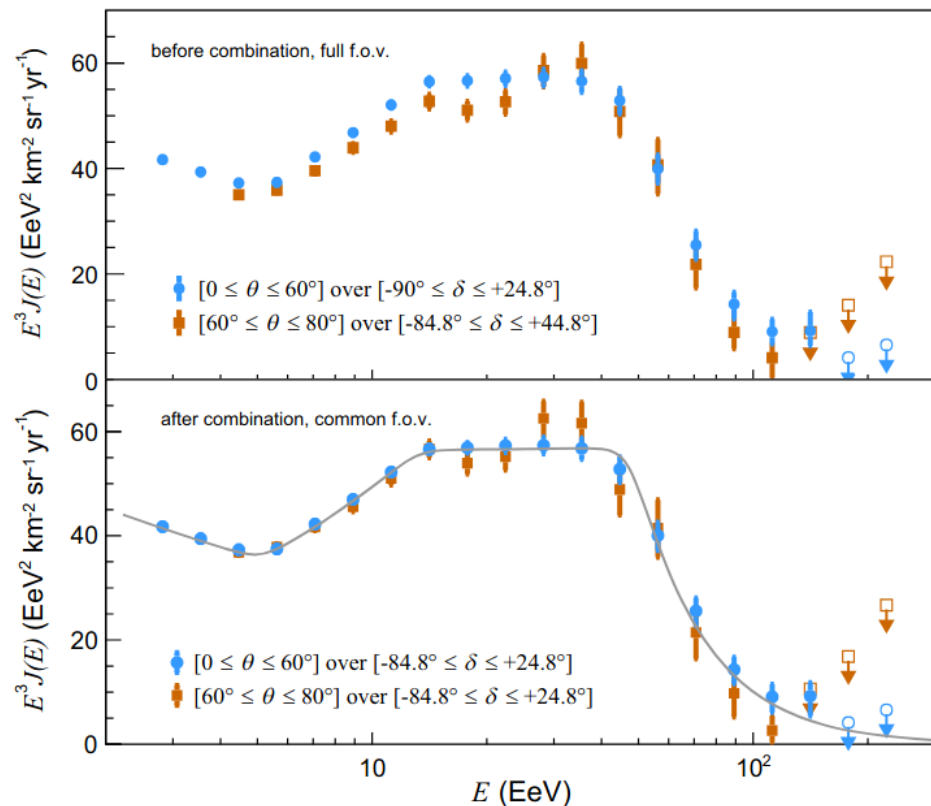
Fluxes in agreement

within systematic uncertainties



Independent of mass composition and model assumptions

Energy spectrum across declination -90° and $+44.8^\circ$



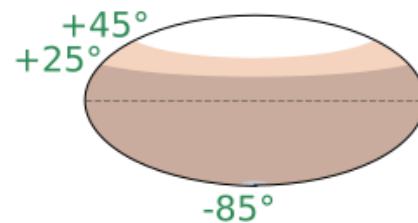
Phys. Rev. Lett. 135, 241002 (2025)

19 years of data, zenith up to 80°

- exposure of **104900 km sr yr**

- **instep** significance $\sim 5.5 \sigma$

Combined spectrum
for δ in $[-85^\circ, 45^\circ]$
Equatorial coordinates

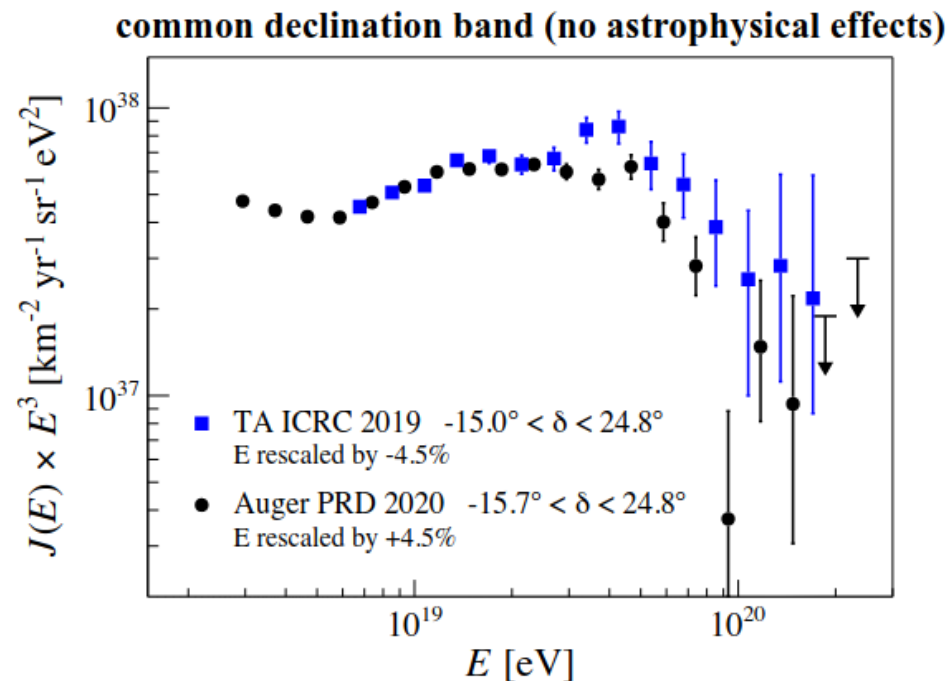
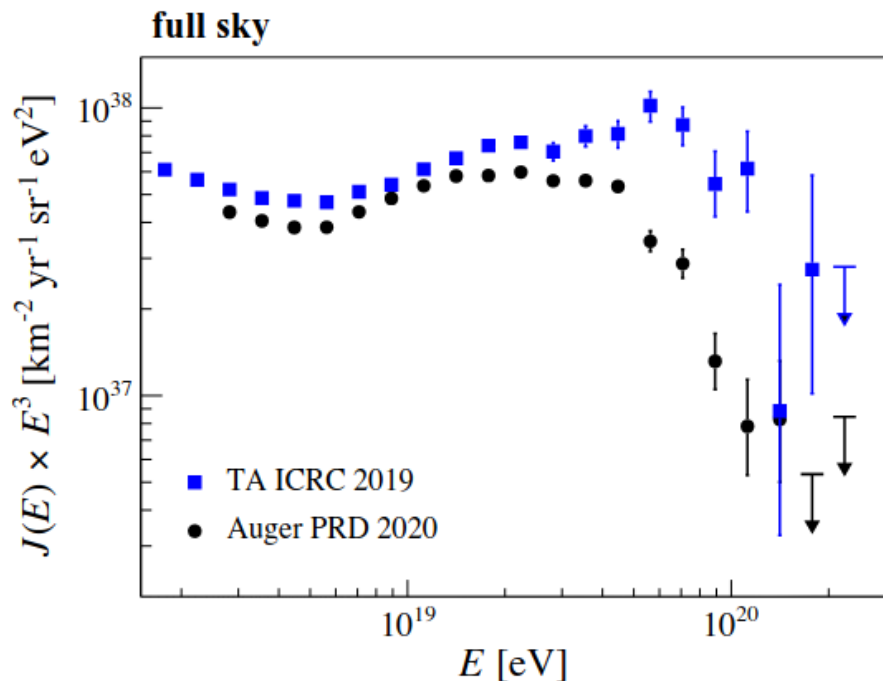


No significant dependence on declination
dipolar non-uniformity doesn't modify the picture

→ disfavor instep feature as due to one/few foreground sources

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

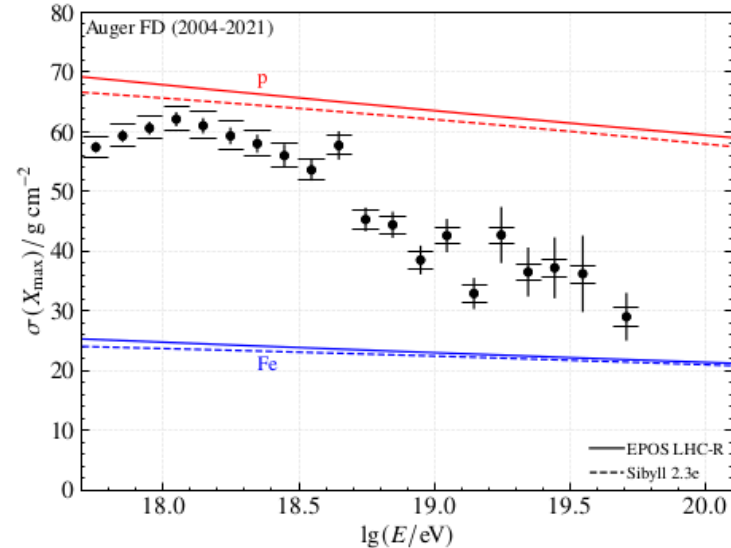
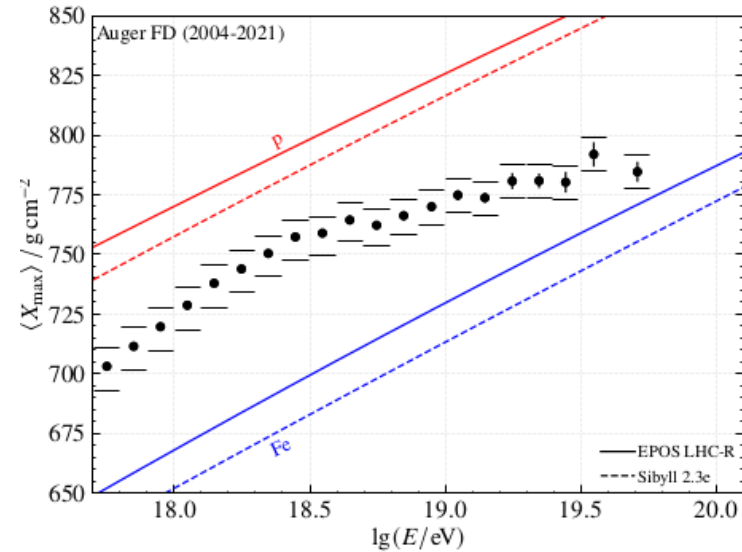
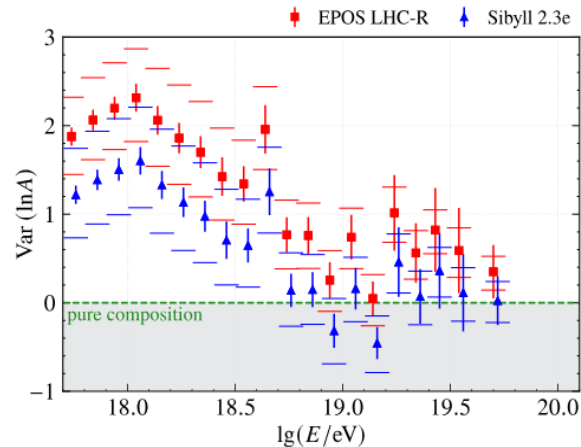
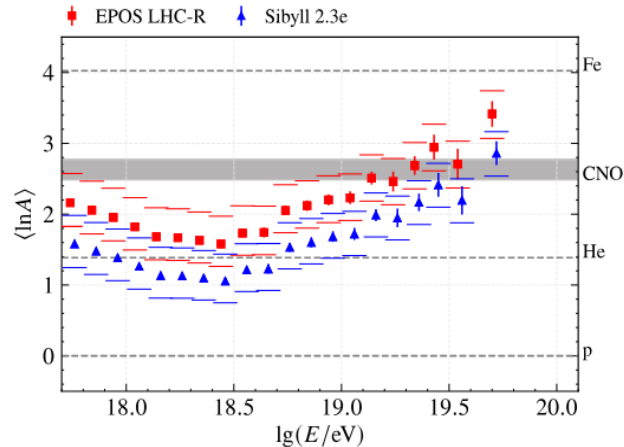
The ultra-high energy mass composition

Phys. Rev. D 114, 043016 (2026)

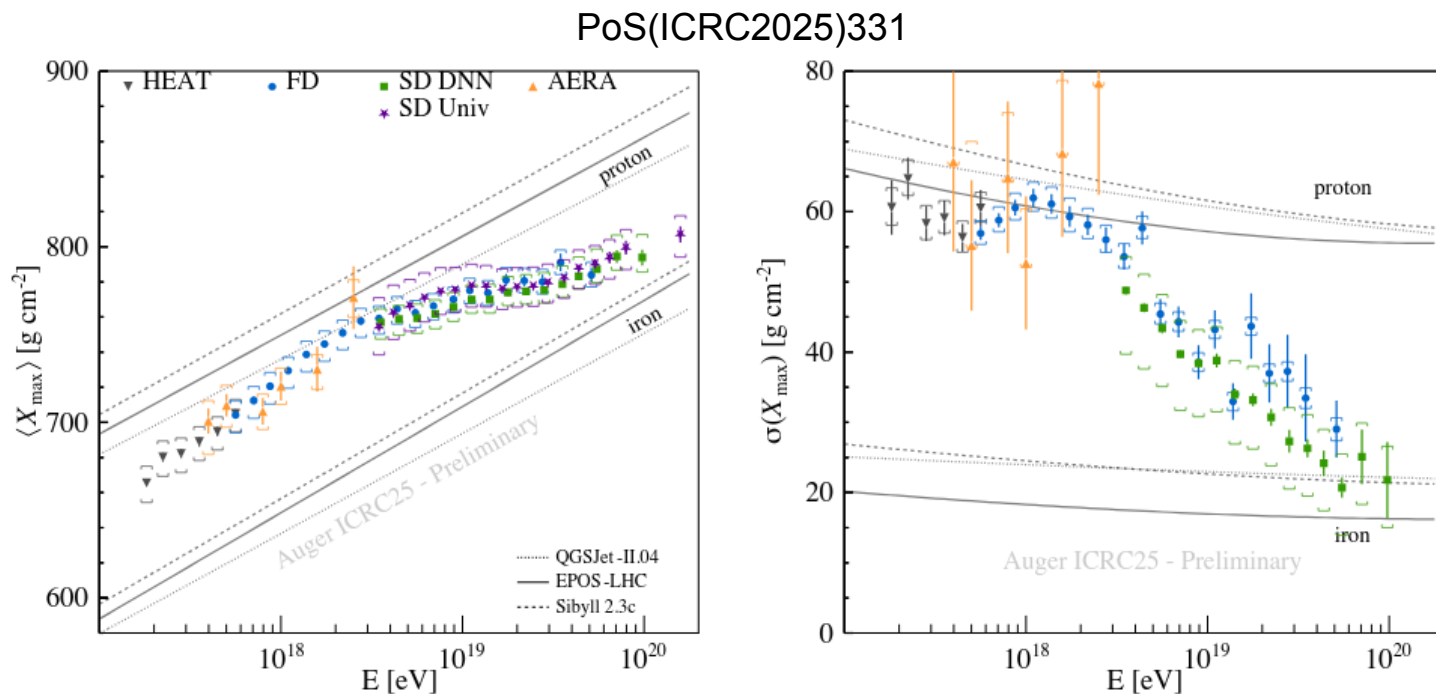
Fluorescence Detector → longitudinal profile

$\langle X_{\max} \rangle$ resol. 15 g/cm² at the highest energies

- $\langle X_{\max} \rangle$ gets lighter up to $\sim 2 \cdot 10^{18}$ eV and heavier above incompatible with pure composition
- $\sigma(X_{\max})$ at the highest energy excludes a large fraction of protons and proton GZK as a dominant reason for the spectral cutoff



The ultra-high energy mass composition: adding SD and Radio



Surface detector → temporal and lateral distributions + DNN or Universality
<Xmax> resol. 30 g/cm² at the highest energies

RADIO (AERA) → footprint at ground
<Xmax> resol. 15 g/cm² (energy dependent)

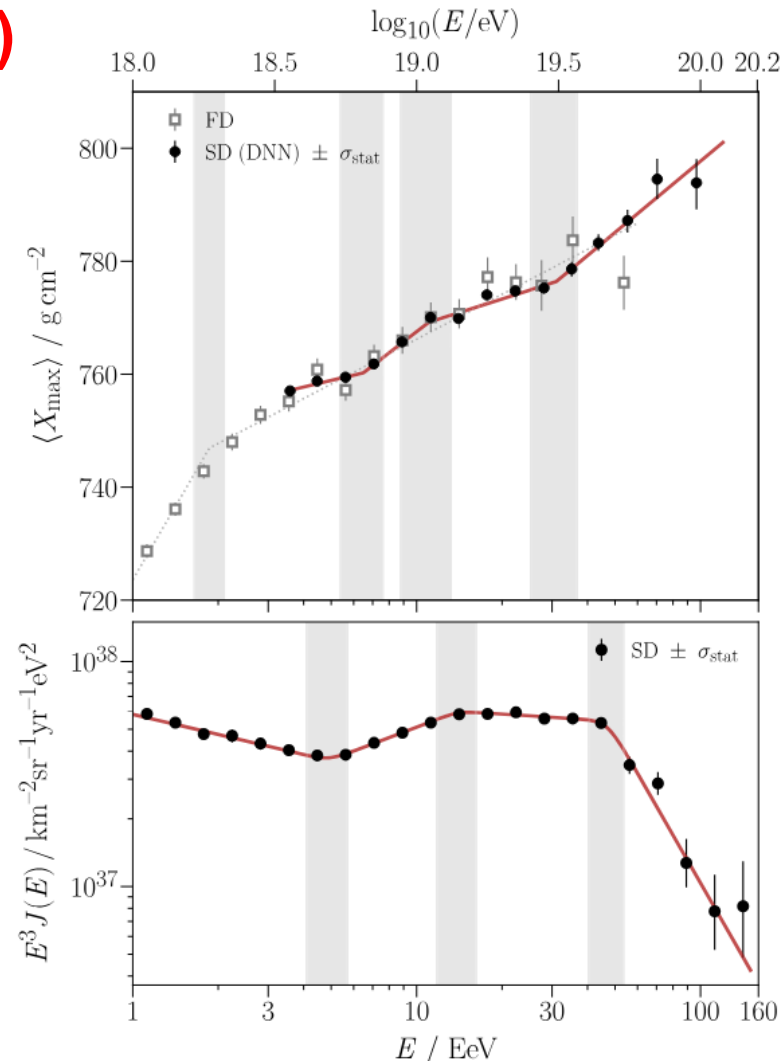
Change in the Elongation rate (SD + DNN)

Extending the ER measurement using DNN

→ same FD Xmax scale

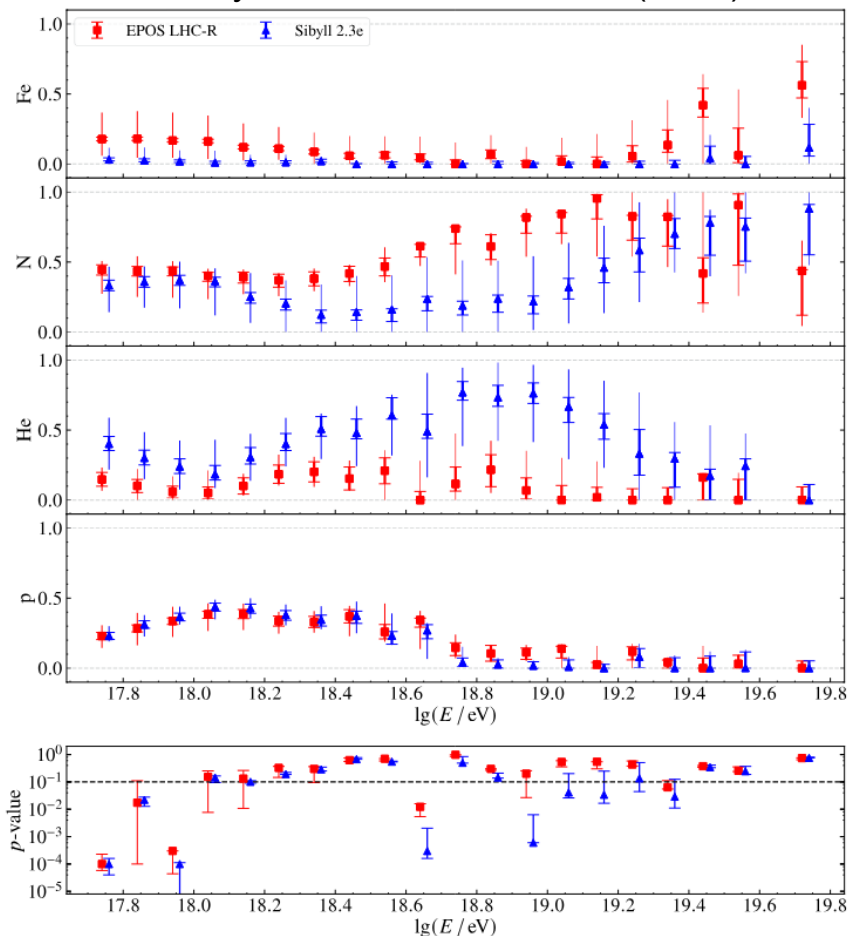
Parameter	3-Break model	Energy spectrum
val $\pm \sigma_{\text{stat}} \pm \sigma_{\text{syst}}$	val $\pm \sigma_{\text{stat}} \pm \sigma_{\text{syst}}$	val $\pm \sigma_{\text{stat}} \pm \sigma_{\text{syst}}$
$b/\text{g cm}^{-2}$	$750.5 \pm 3 \pm 13$	
$D_0/\text{g cm}^{-2} \text{ decade}^{-1}$	$12 \pm 5 \pm 6$	
E_1/EeV	$6.5 \pm 0.6 \pm 1$	$4.9 \pm 0.1 \pm 0.8$
$D_1/\text{g cm}^{-2} \text{ decade}^{-1}$	$39 \pm 5 \pm 14$	
E_2/EeV	$11 \pm 2 \pm 1$	$14 \pm 1 \pm 2$
$D_2/\text{g cm}^{-2} \text{ decade}^{-1}$	$16 \pm 3 \pm 6$	
E_3/EeV	$31 \pm 5 \pm 3$	$47 \pm 3 \pm 6$
$D_3/\text{g cm}^{-2} \text{ decade}^{-1}$	$42 \pm 9 \pm 12$	

Constant ER rejected at $4.4 \sigma \rightarrow$ **incompatible with pure composition**
kinks resembling the spectrum feature



Fractions of elements

Phys. Rev. D 114, 043016 (2026)

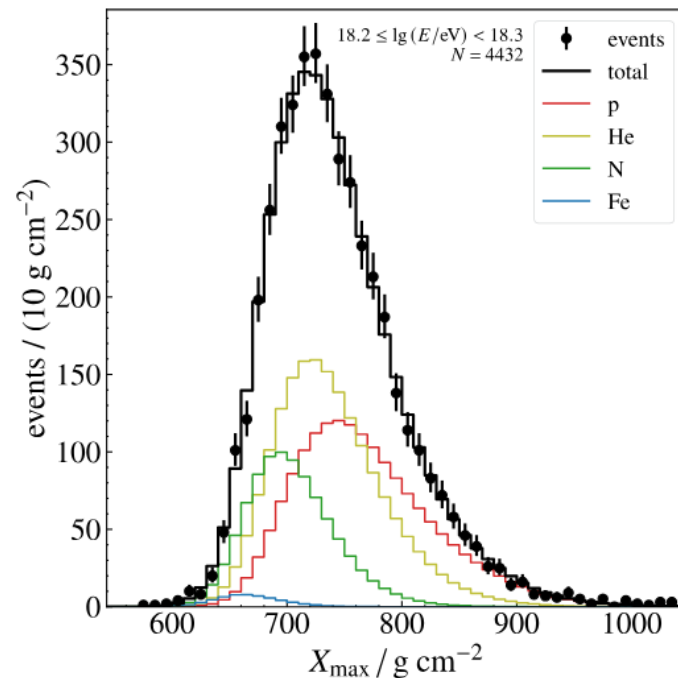


iron

nitrogen

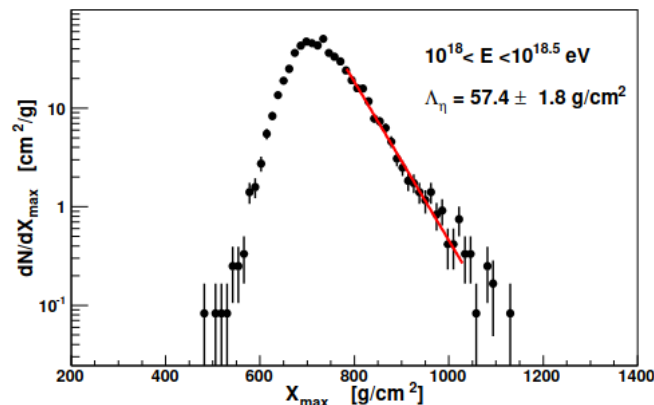
helium

proton



Example of the fit of composition fractions of the mass groups (H, He, N, Fe) with SIBYLL 2.3e in the energy range $18.2 \leq \lg(E/\text{eV}) < 18.3$

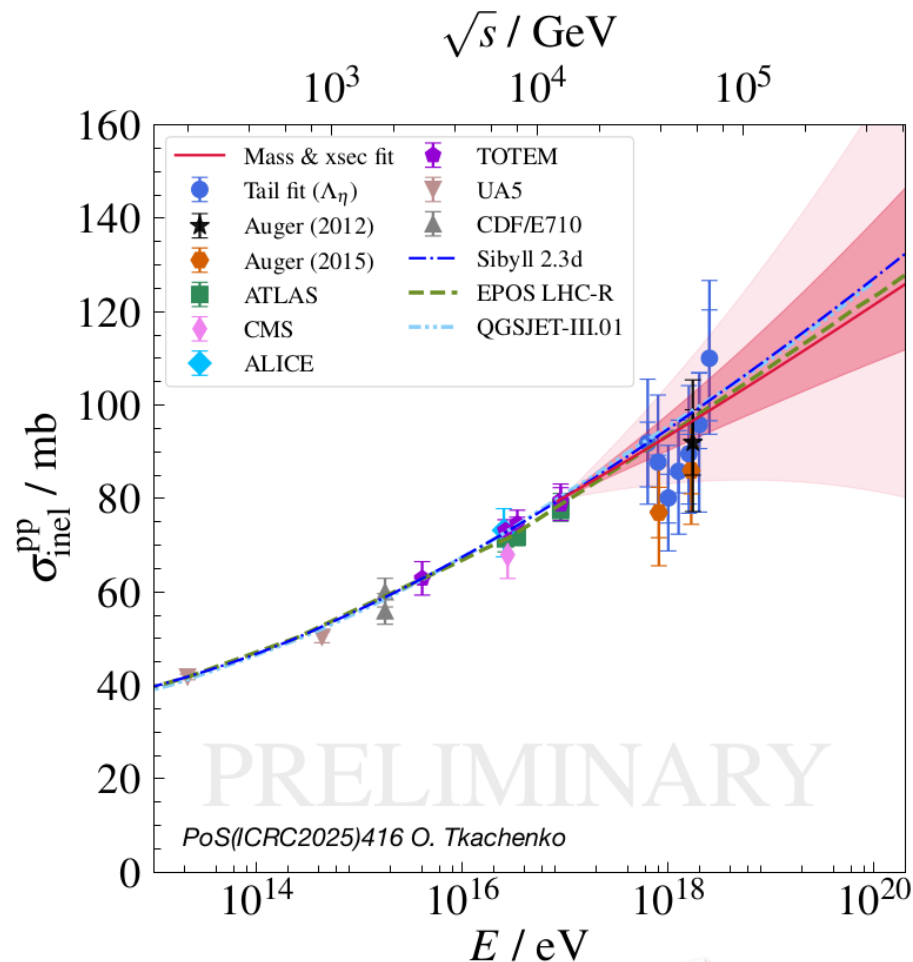
proton-proton cross-section at $\sqrt{s} > 40$ TeV



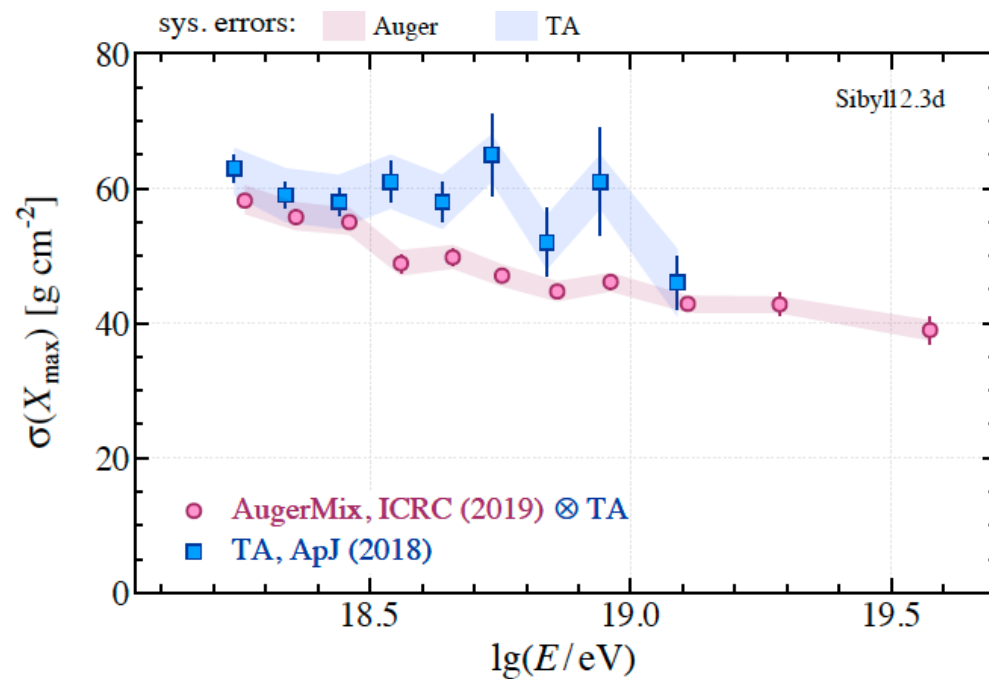
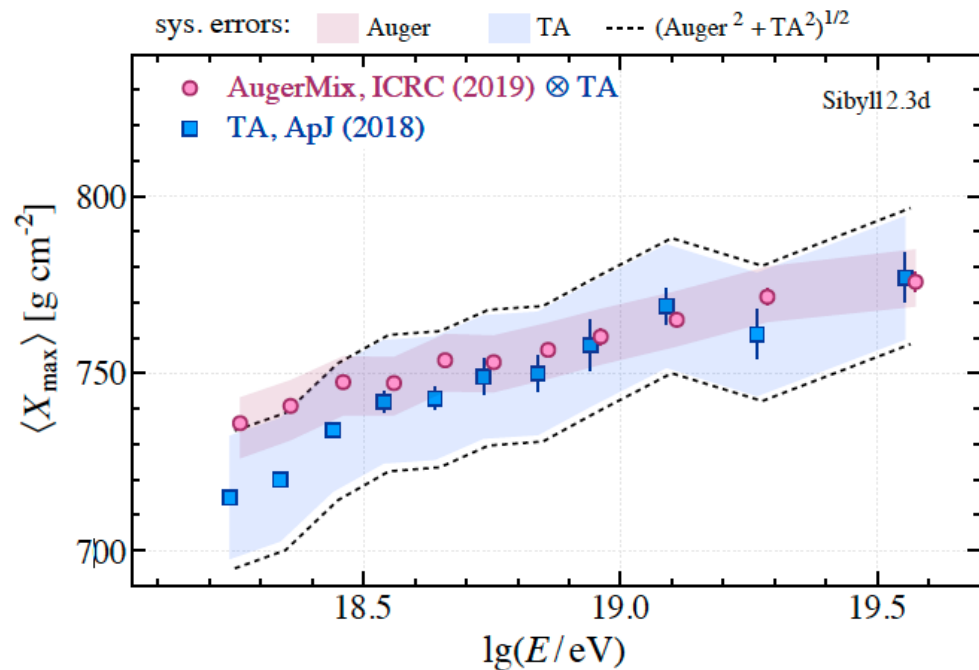
Traditional method

→ fitting the tail of $X_{\max}$ distribution

Alternative Method: simultaneous fit to $X_{\max}$ distributions and cross-section, $X_{\max}$ scale as free parameter



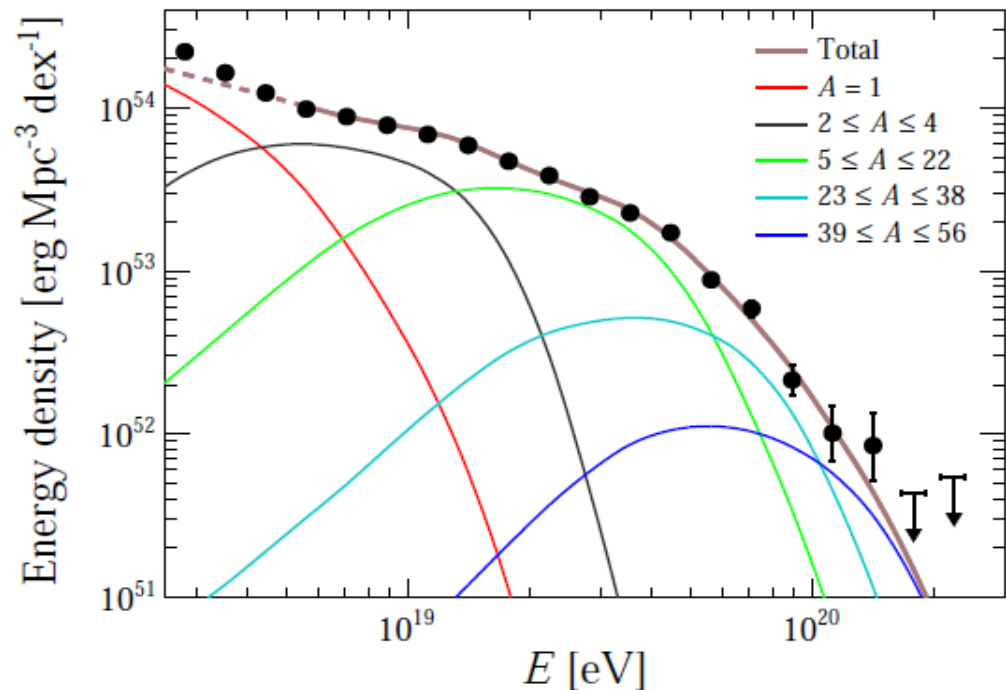
Joint Auger TA WG for mass composition



Consistency within uncertainties (larger for TA)

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**

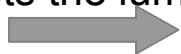
uniformly distributed sources accelerating
nuclei [rigidity dependent] → **favorable**

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 $5 \cdot 10^{18}$ eV (possibly a tail from galactic CR)

energy density in CR above the ankle $(5.66 \pm 0.03 \pm 1.40) \cdot 10^{53}$ erg Mpc⁻³

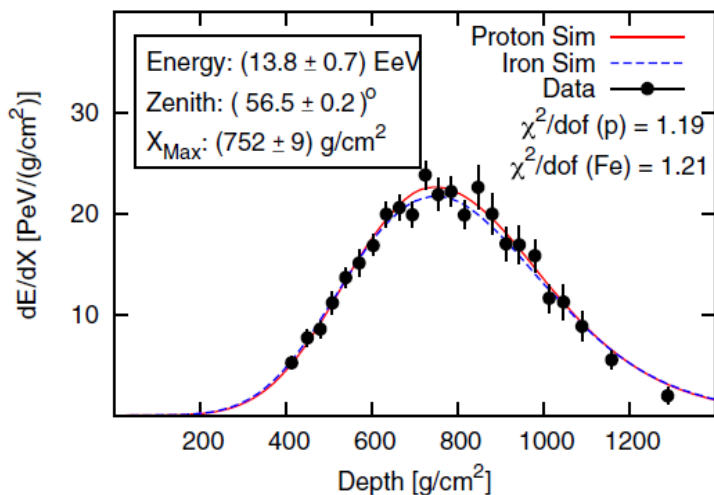
this constraints the luminosity density for classes of extra-galactic



sources such as AGN and SB match

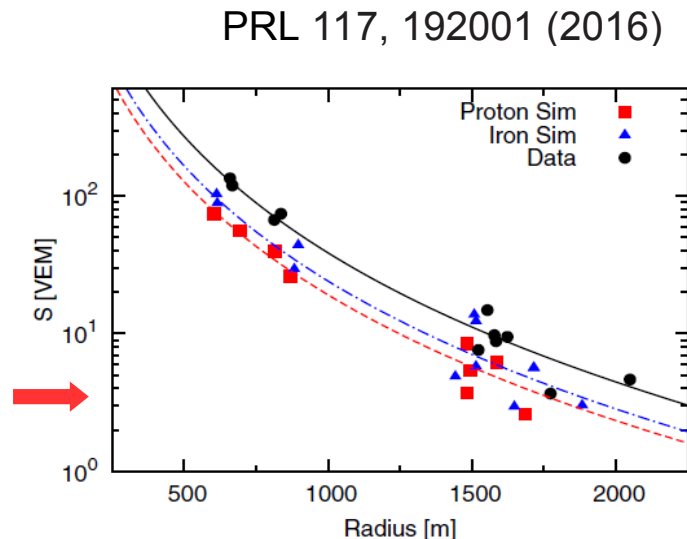
How well hadronic models match data?

Hybrid events $\sim 10^{19}$ eV, $0^\circ < \text{zenith} < 60^\circ$



Observed longitudinal profile from FD is reproduced by simulations

Measured signal at the ground differ for data and simulations



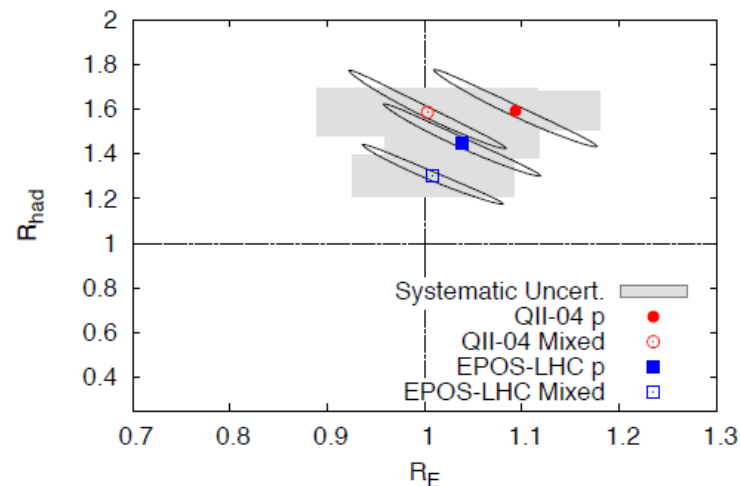
R_{had} and R_E
Scaling factors to match data

Evidence of muon excess

$$1.3 < R_{\text{had}} < 1.6$$

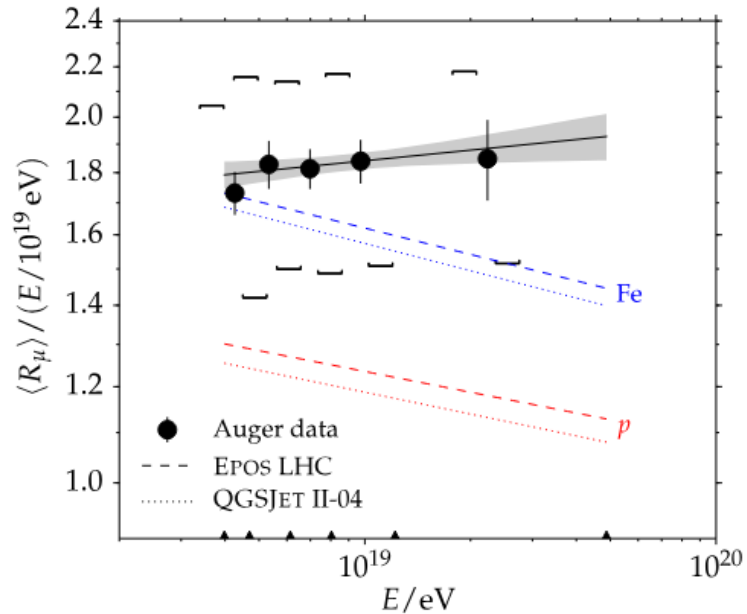
Insensitive to energy scale uncertainty

$$R_E \sim 1$$



Muon Number and its fluctuation in inclined air-showers

Phys Rev. D 91, 032003 (2015)

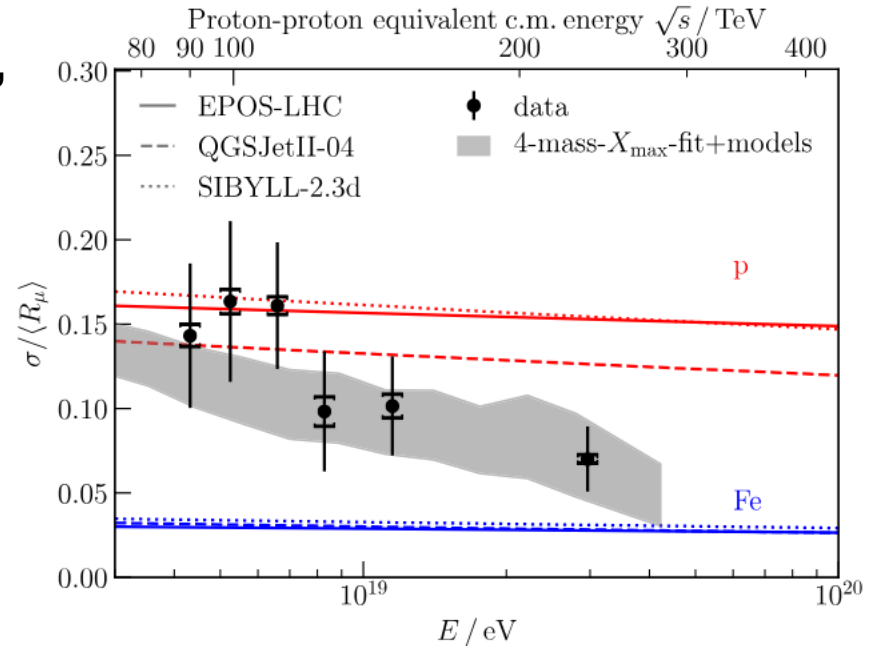


“Muon puzzle”

mean muon
number non
consistent with
prediction

Fluctuation
compatible

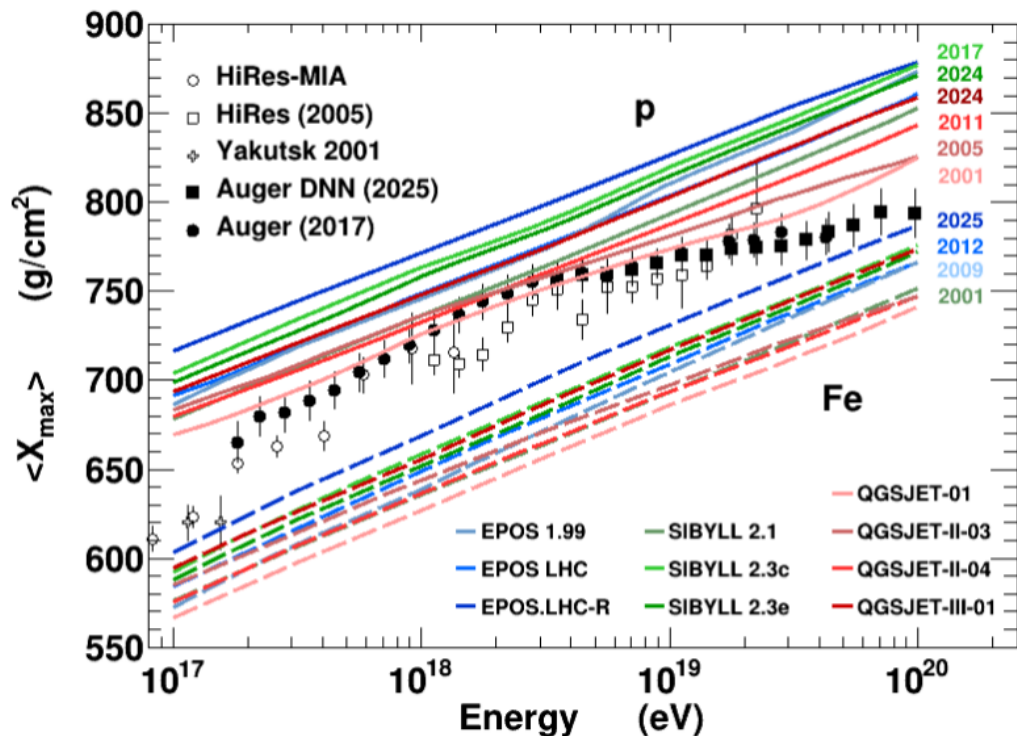
Phys Rev. Lett. 126, 152002 (2021)



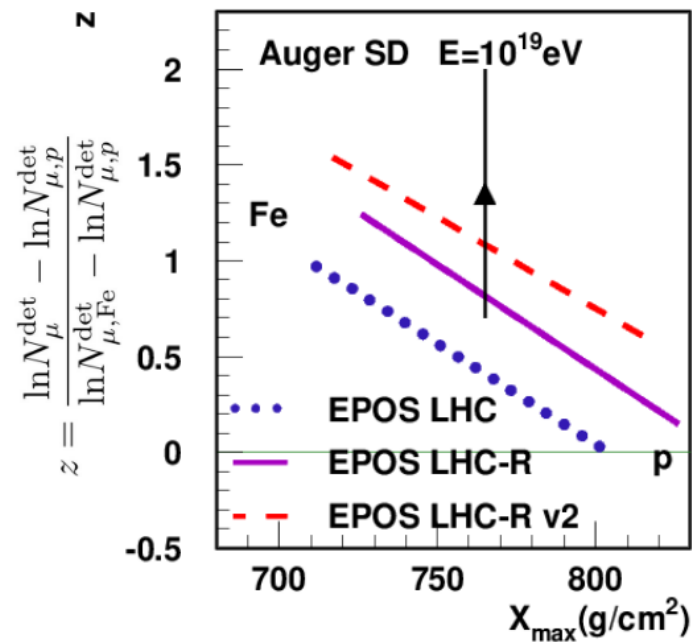
Muon problem not due to the modeling of the first interaction (contributing at most at the overall fluctuation), most likely due to accumulation of small effects along the cascade

Muon puzzle... many recent progresses

T. Pierog @ ISVHECRI 2026



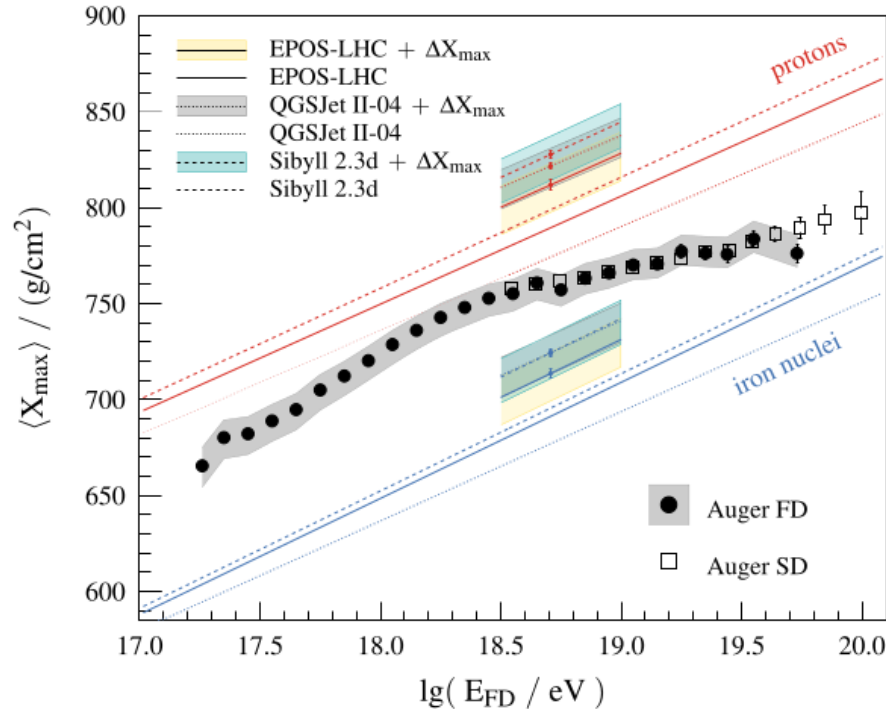
New data from accelerators pO and OO



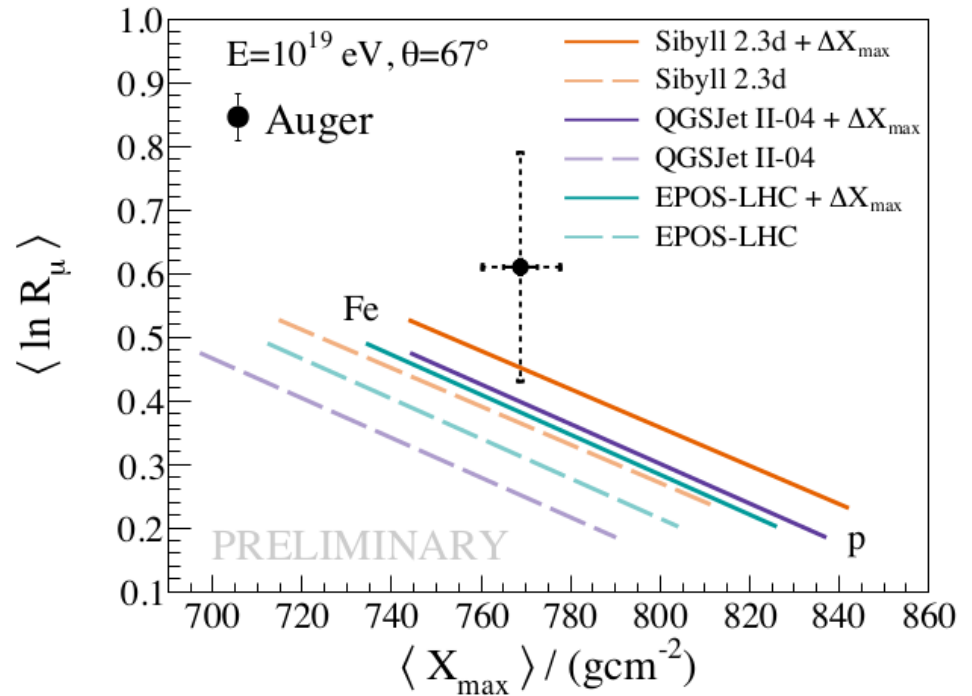
Modeling relevant to the interpretation and understanding of the implication of UHECRs data

Physics implications

PRD 109(2024)102001

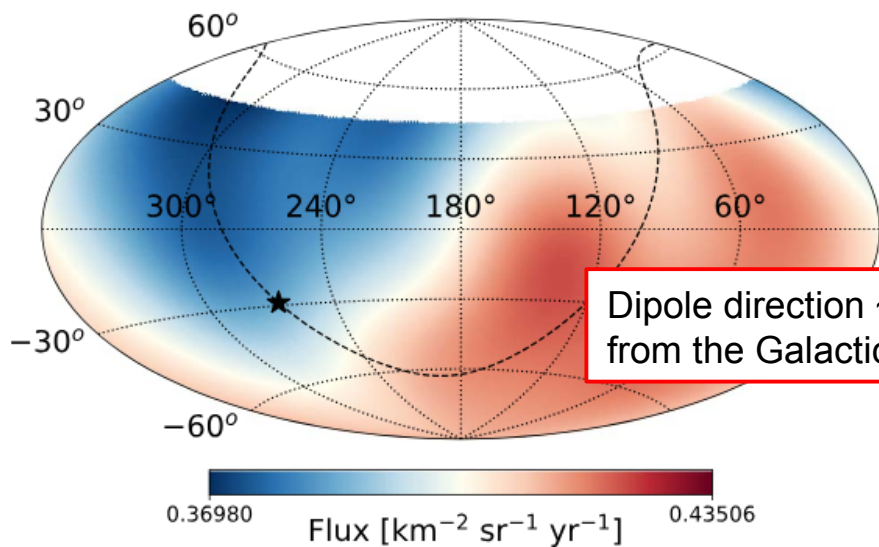


The deeper $X_{\max}$ prediction for all models implies a **heavier mass composition** inferred from the data



For inclined showers, the muon scale underestimation is reduced to about 15-25%

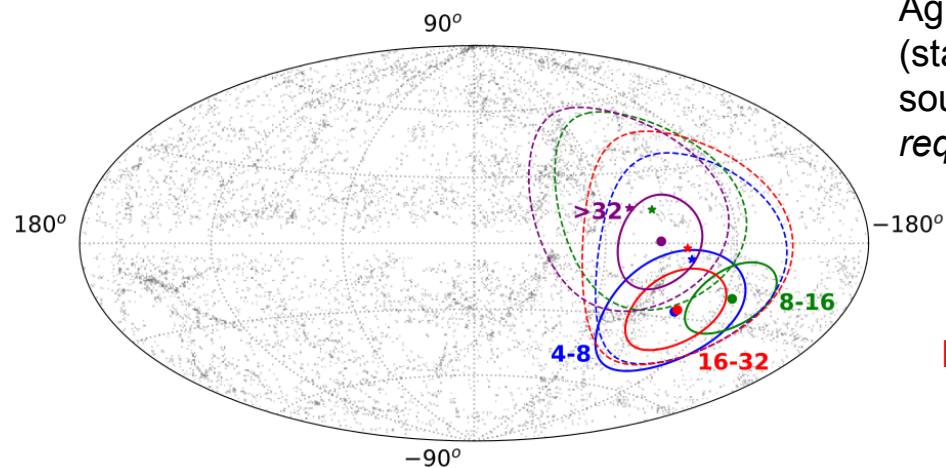
Large Scale → 3D dipole above 8 EeV



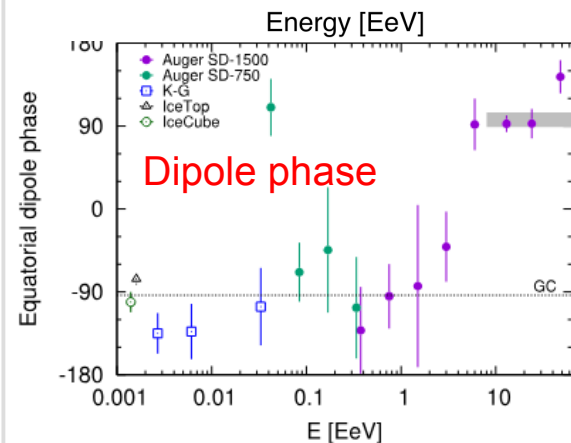
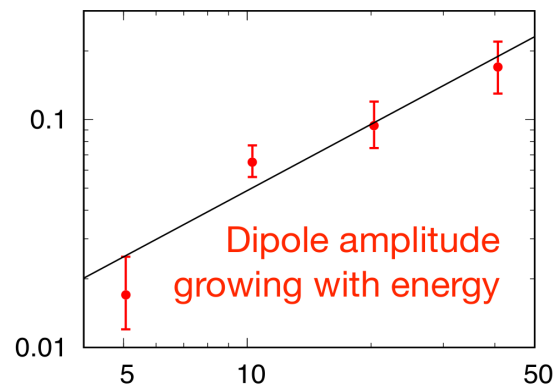
Exposure=123000 km²sr y!

6.5% at 6.8 σ level

Dipole direction $\sim 113^\circ$ away from the Galactic Center (*)



Agreement with prediction (stars) of 103 realizations of source distribution (10^{-4} Mpc⁻³) require mixed composition



Amplitude and phase evolution may reflect the distribution of matter in the the local universe

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 $\psi \sim 24^\circ$ $E > 38$ EeV
direction fixed at Cen A 4 σ post trial, at $\psi \sim 27^\circ$ $E > 38$ EeV

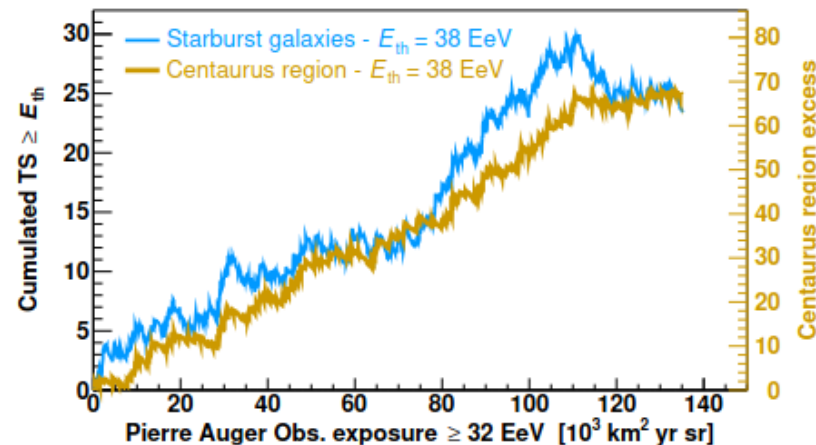
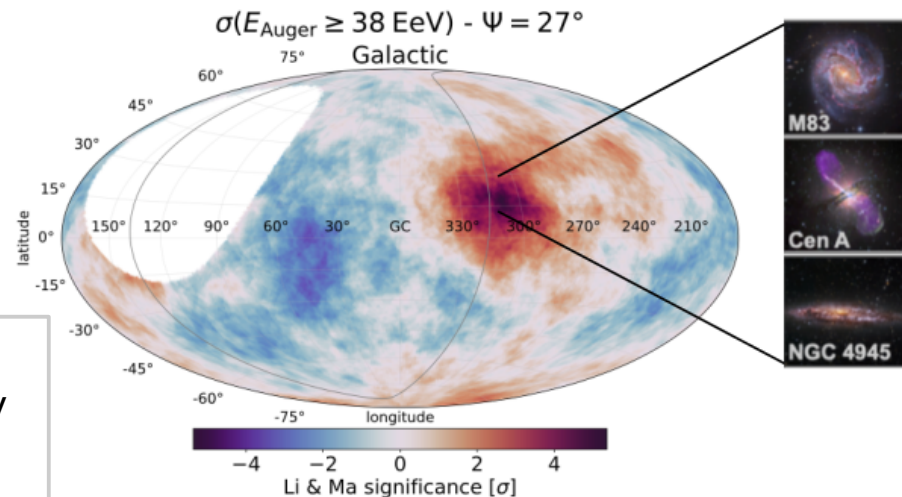
Autocorrelation with structures (GC, GP, SGP) not significant

Likelihood test for anisotropy with catalogs

Attenuation and relative weight of sources taken into account.

Significance
3.8 σ for SB

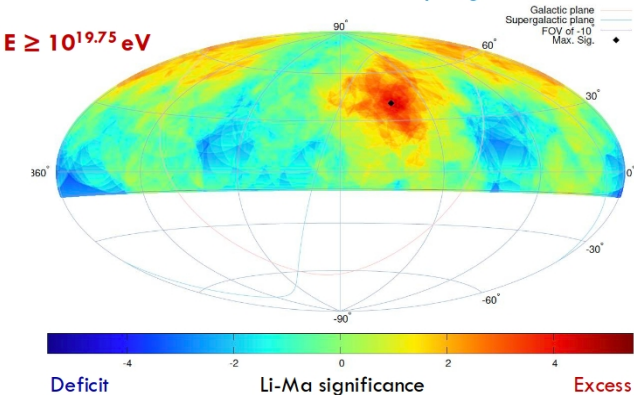
Catalog	E_{th} [EeV]	Ψ [°]	α [%]	TS	Post-trial p -value
All galaxies (IR)	38	24^{+15}_{-8}	14^{+8}_{-6}	18.5	6.3×10^{-4}
Starbursts (radio)	38	25^{+13}_{-7}	9^{+7}_{-4}	23.4	6.6×10^{-5}
All AGNs (X-rays)	38	25^{+12}_{-7}	7^{+4}_{-3}	20.5	2.5×10^{-4}
Jetted AGNs (γ -rays)	38	23^{+8}_{-7}	6^{+3}_{-3}	19.2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



TA Hotspot & Perseus-Pisces supercluster excess

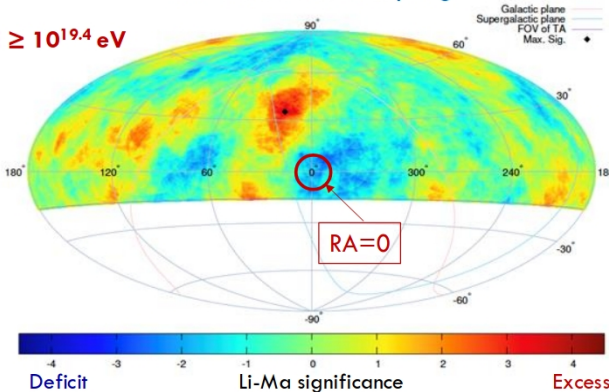
J. Kim, PoS(ICRC2023)244

25°-radius oversampling



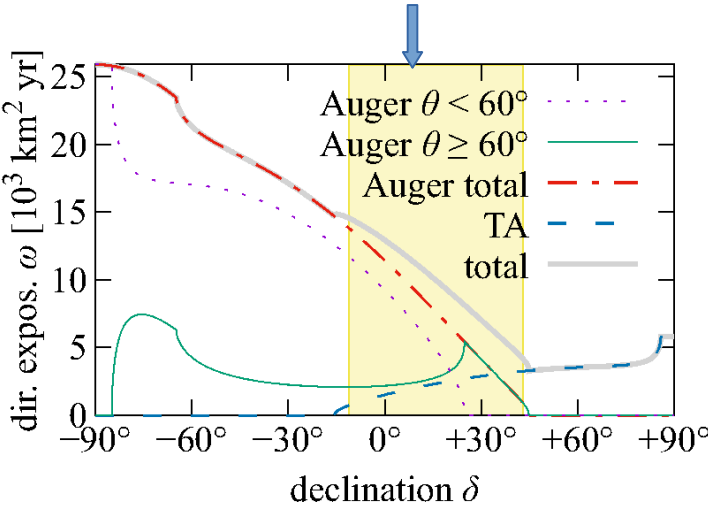
- 216 events (15-year TA SD data)
- Max local sig.: **4.8σ at (144.0°, 40.5°)**
- Post-trial prob.: $P(S_{MC} > 4.8\sigma) = 2.7 \times 10^{-3} \rightarrow$ **2.8σ**

20°-radius oversampling

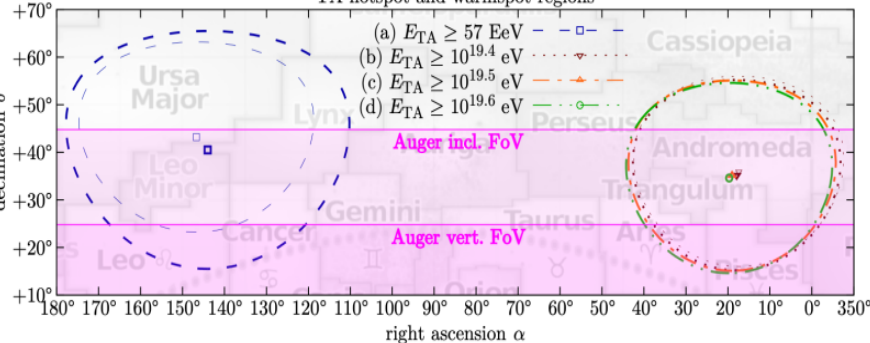


- 1125 events (15-year TA SD data)
- Max local sig.: **4.0σ at (17.9°, 35.2°)**
- Chance probability of having equal or higher excess close to the PPSC $\rightarrow$ **3.3σ**

Declination Auger/TA common band



TA hotspot and warmspot regions



TA “Hot Spot” and PPSC excess not confirmed by Auger

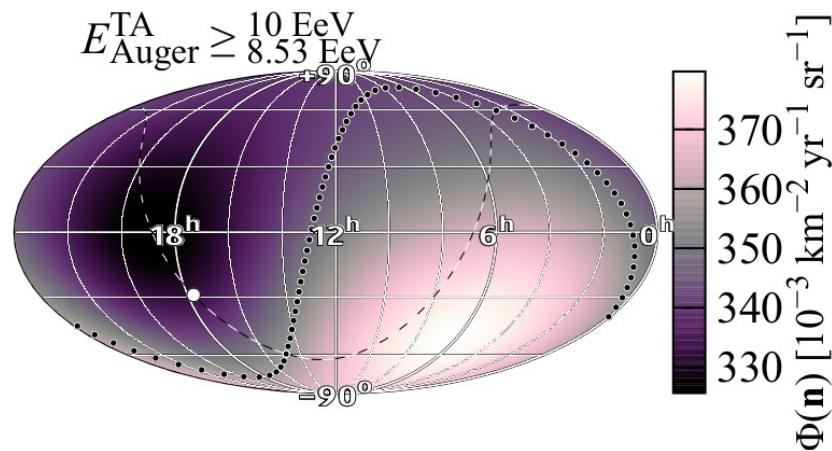
PoS(ICRC2023) 252

	$(\alpha_0, \delta_0) [^\circ]$	E^{TA}	N_{obs}^{TA}	N_{exp}^{TA}	σ_{post}^{TA}	E^{Auger}	N_{obs}^{Auger}	N_{exp}^{Auger}	σ_{Li-Ma}^{Auger}
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

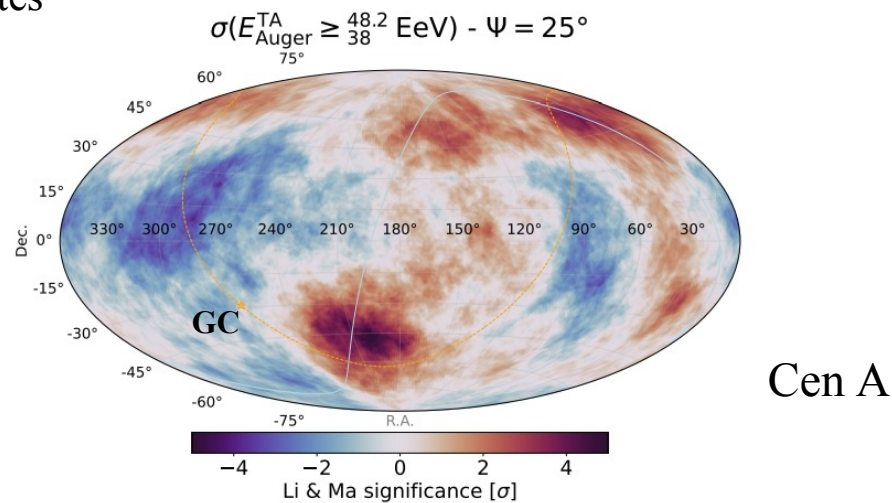
Reports at UHECR and ICRC conferences, journal publications

large scale (dip. + quad.)



equatorial
coordinates

medium scale



studies limited by TA statistics

TAx4 under construction

ICRC2023, UHEC2024

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

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

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

Multi-messenger physics (diffuse, targeted and follow up)

Sensitivity on a wide energy range to photons and neutrinos

Mass composition

Fundamental physics

- BSM
- exotic physics
- dark matter
- LIV

Gamma rays

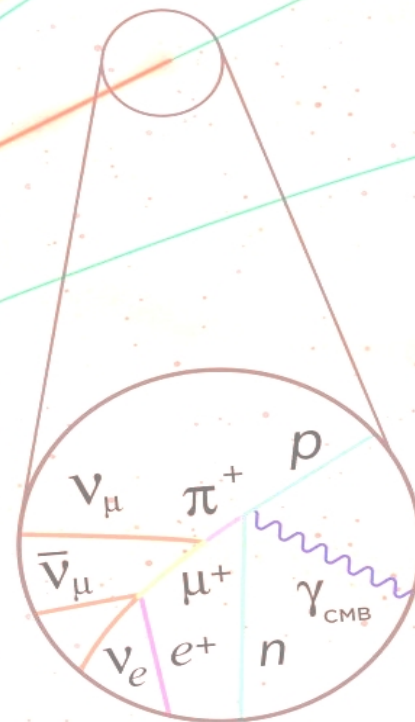
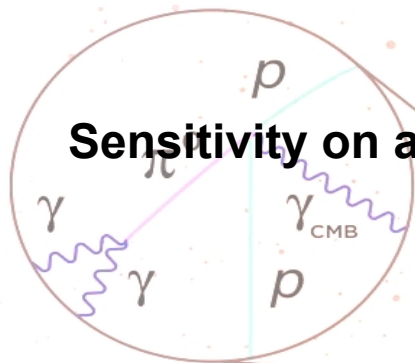
Neutrinos

$\nu_e \nu_\mu \nu_\tau$

Cosmic rays
(protons, nuclei)

Gravitational waves

$\nu_e \nu_\mu$



Auger: A 4π MM Observatory

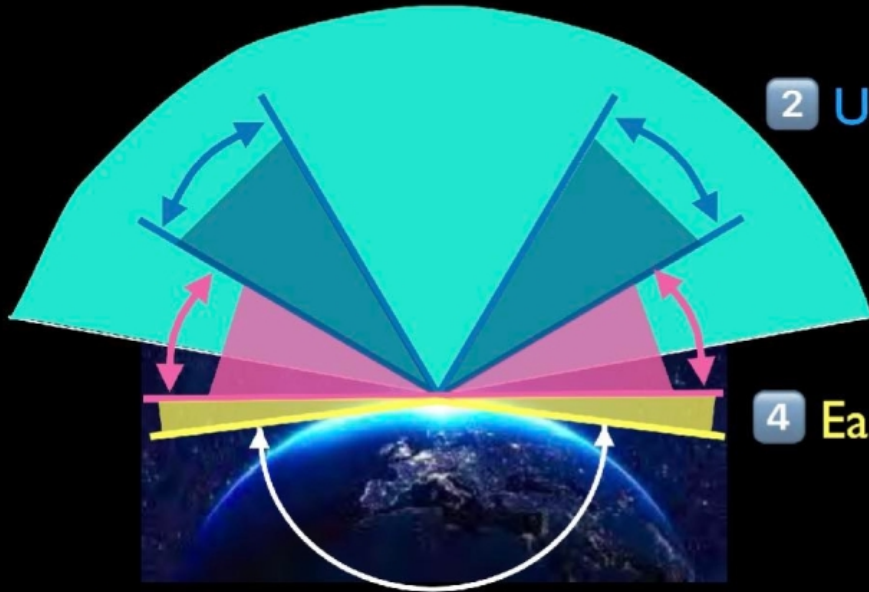
1 Neutrons and charged CRs: $\Theta \leq 80^\circ$

2 UHE Photons: $30^\circ \leq \Theta \leq 60^\circ$

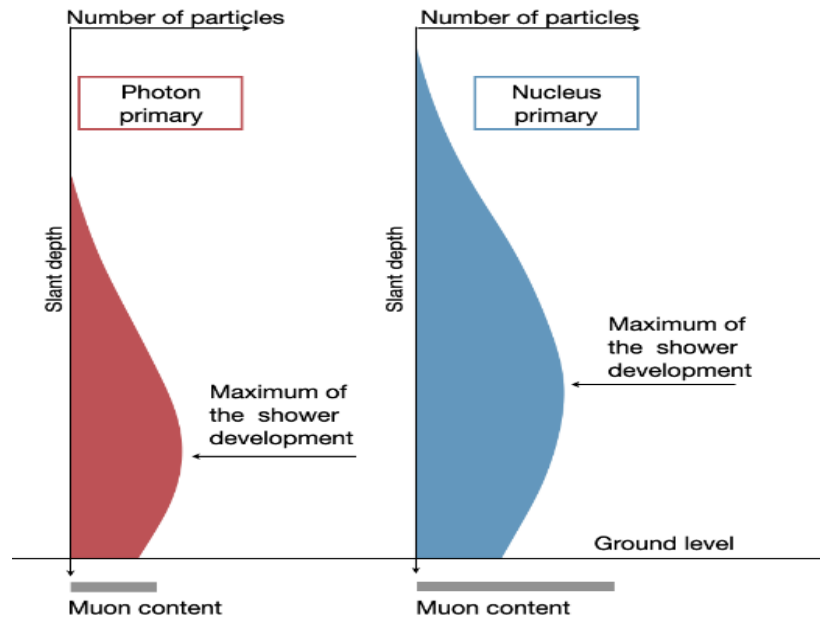
3 Down-Going Neutrinos: $60^\circ \leq \Theta \leq 90^\circ$

4 Earth Skimming Neutrinos: $90^\circ \leq \Theta \leq 95^\circ$

5 HE BSM Particles: $\Theta > 95^\circ$



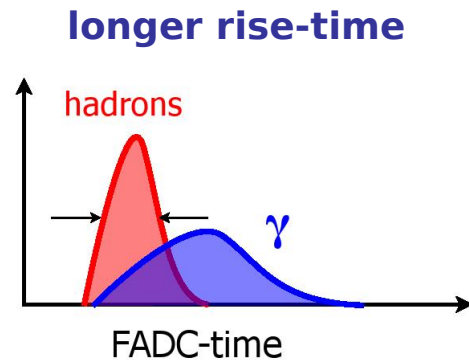
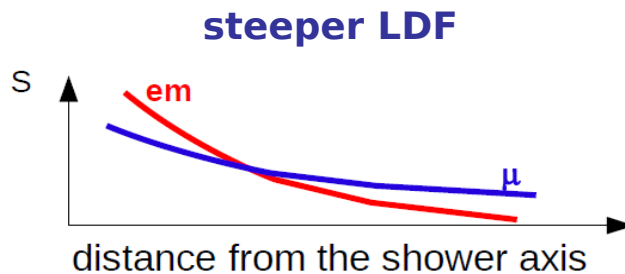
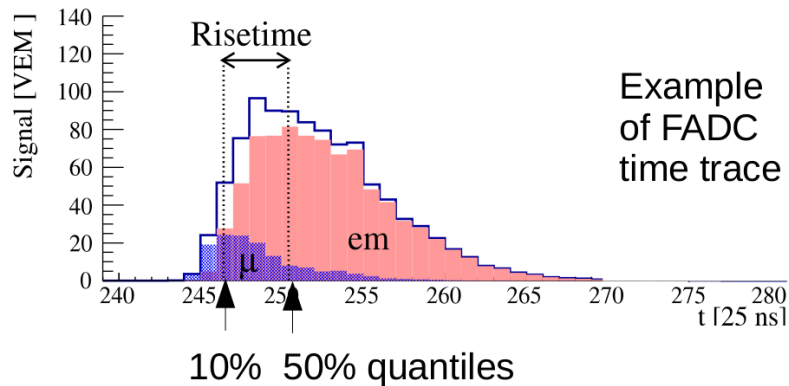
UHE Photon induced cascades



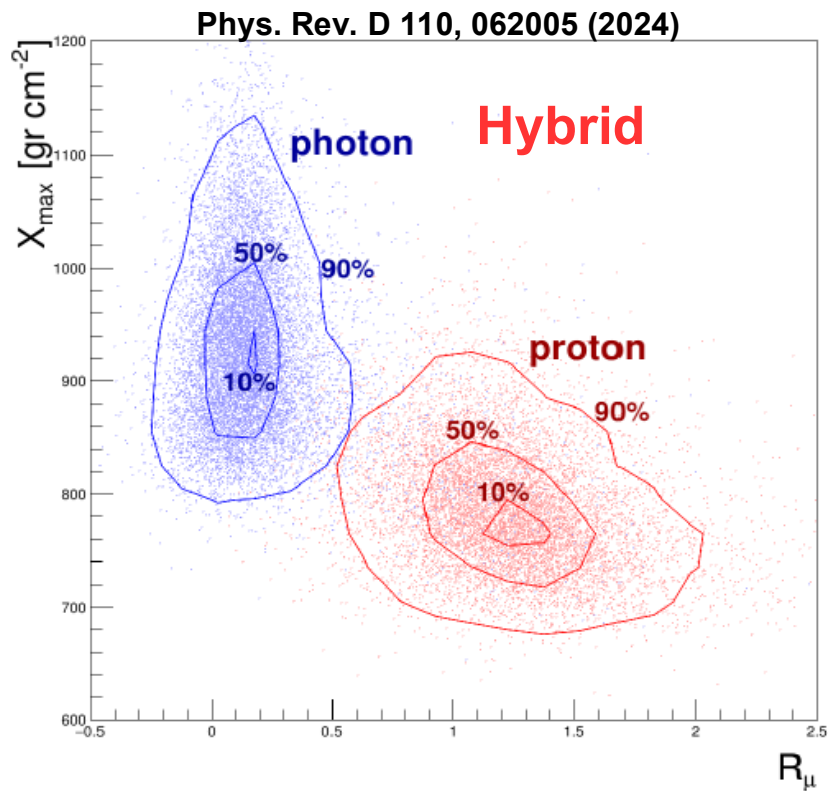
Photon EAS distinctive signature:
 → delayed shower development
 → smaller muon content

observable characteristics:

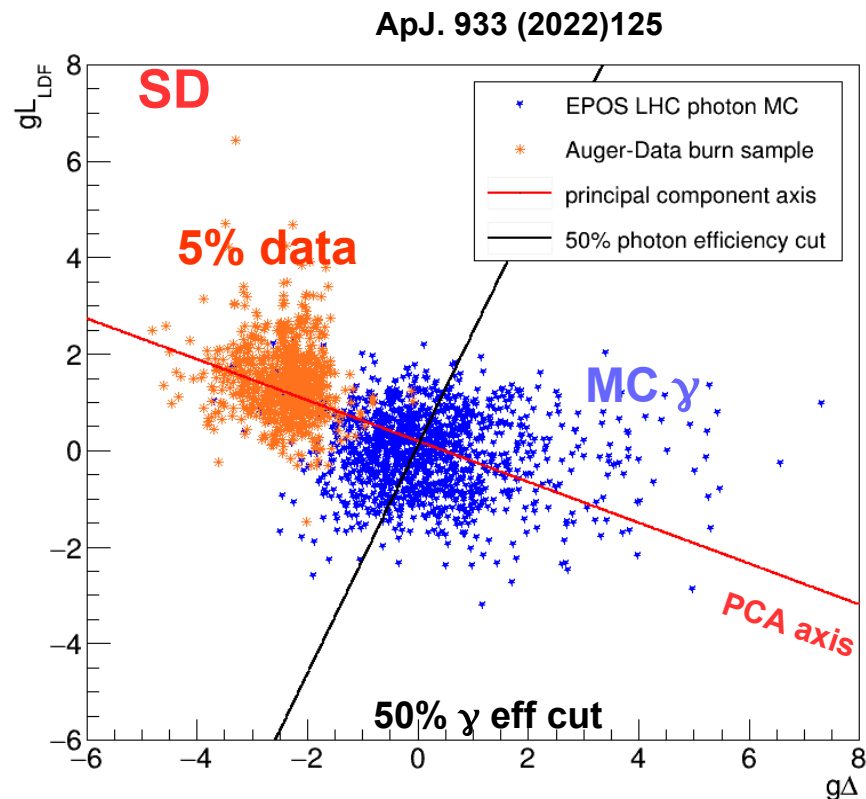
- deeper $\langle X_{\max} \rangle$
- steeper LDF
- smaller footprint
- broader signal



Auger: Hybrid and SD photon search

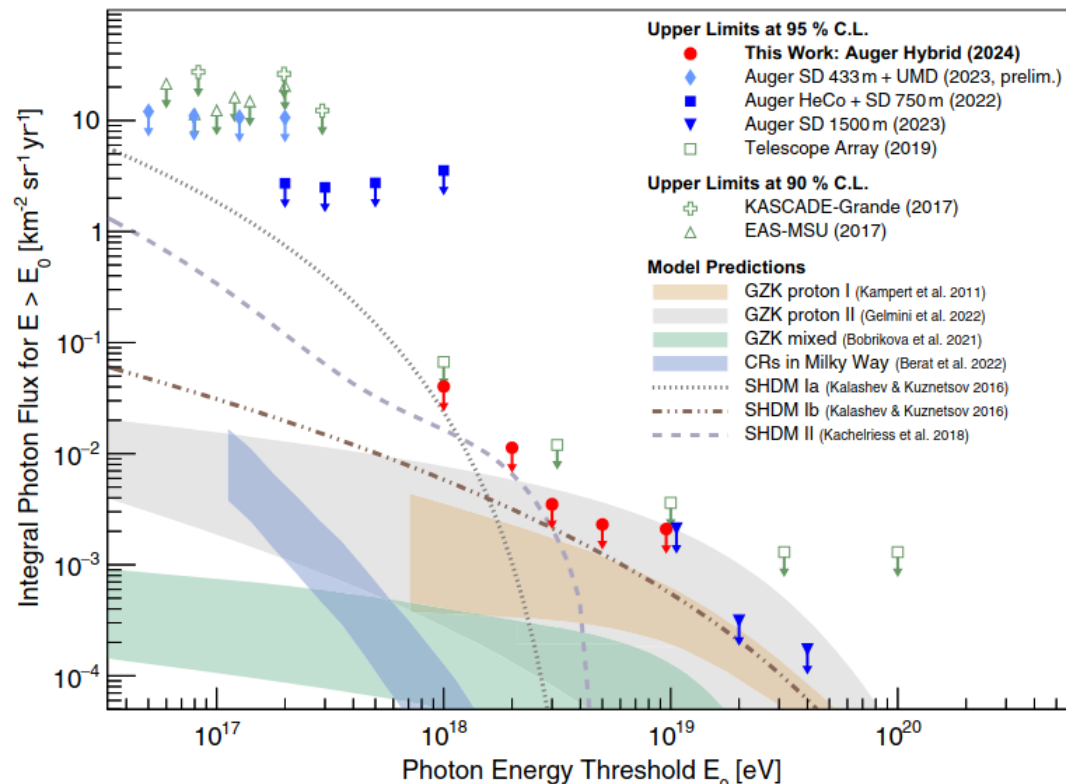


Maximum of shower development: $X_{\max}$
 Muon content of the shower (universality): R_{μ}



Deviation from data <LDF>: gL_{LDF}
 rise-time rel. event-wise quantity: g_{Δ}

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 $E > 0.04 \text{ EeV}$

11 candidates $> 10 \text{ EeV}$ (SD)

22 candidates $> 1 \text{ EeV}$ (Hybrid)

Targeted search

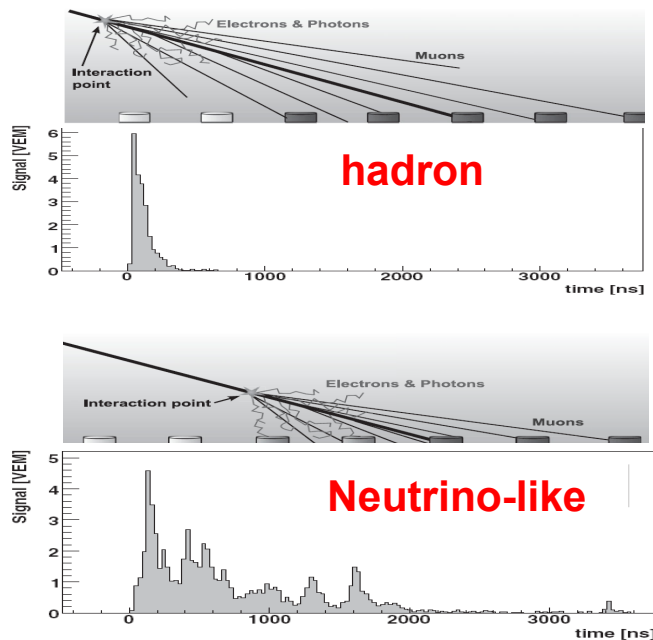
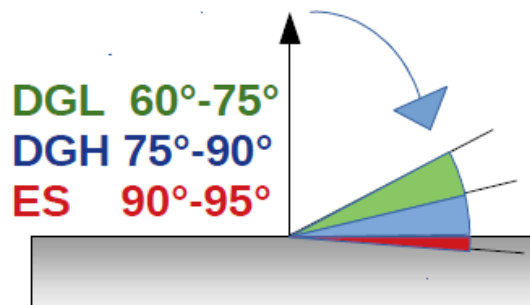
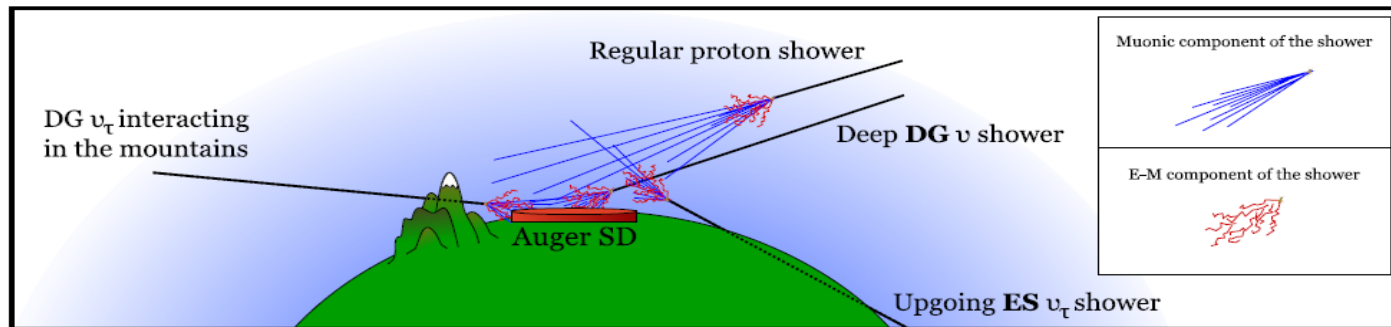
- In coincidence of known sources including CenA and the Galactic Center [UL extrapolating HESS flux]
- GW follow-up

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

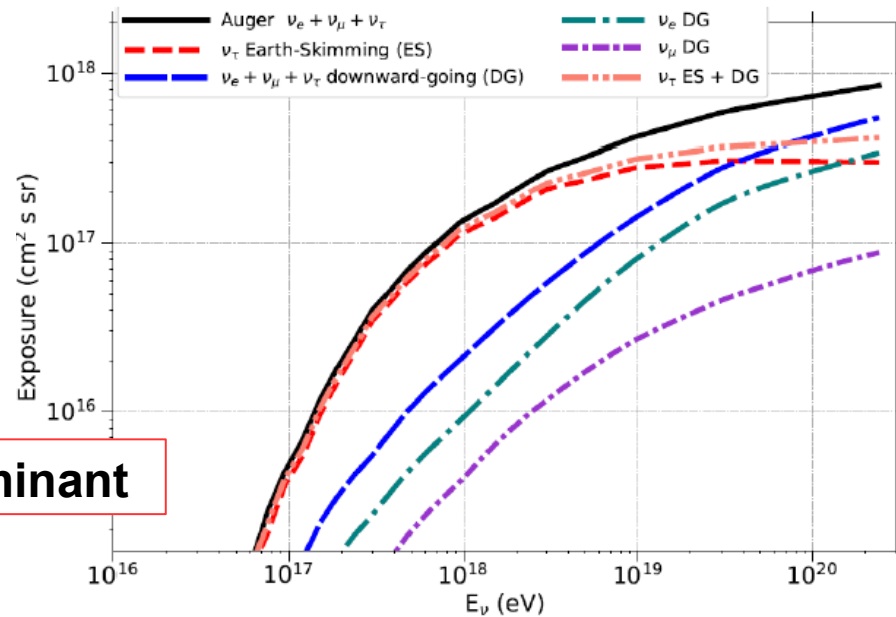
Auger: UHE neutrinos with the SD



Sensitivity to different channels

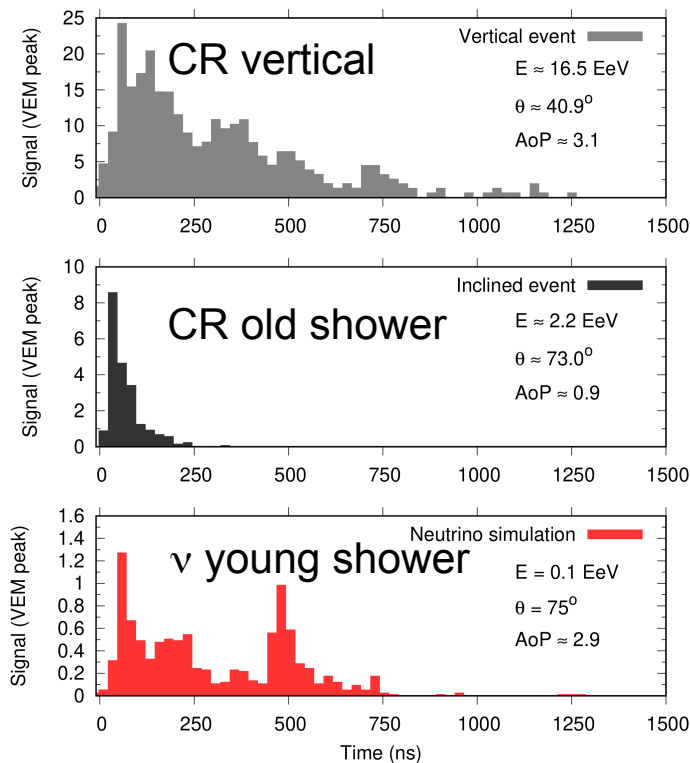
ES 79.4%
DGH 17.6%
DGL 3.0%

ν_τ ES sensitivity dominant



Search for neutrinos with the SD: signature

typical signal shapes

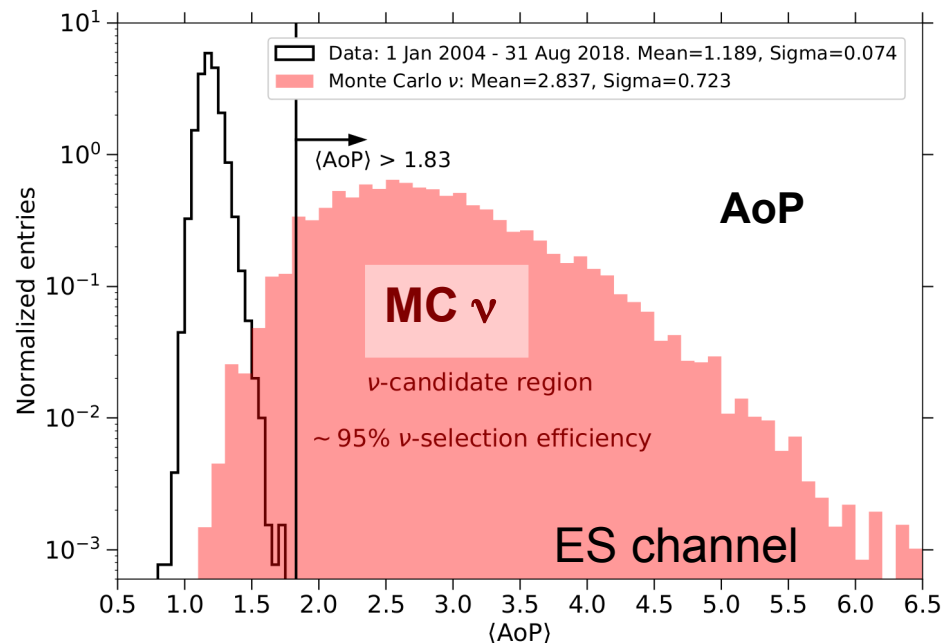


Signature:

“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

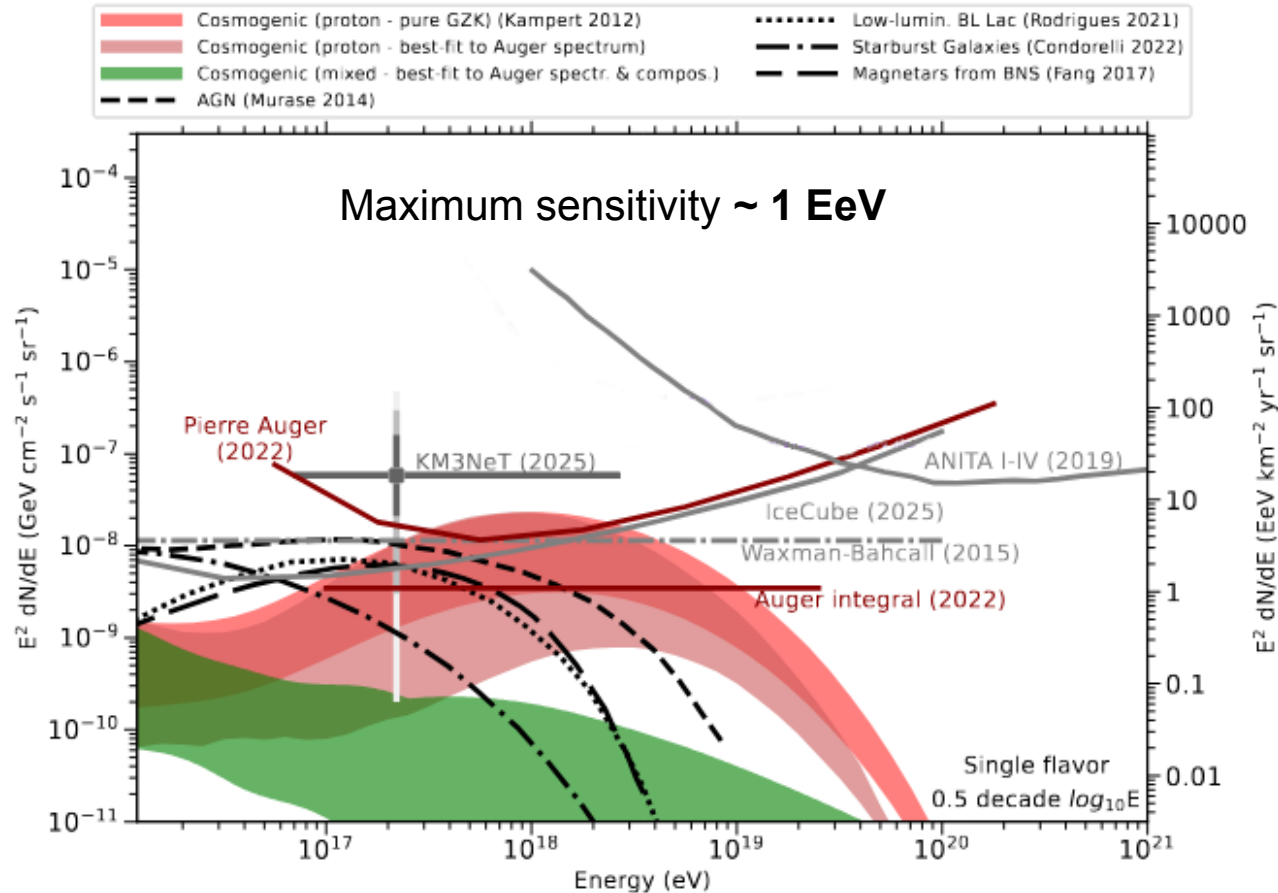
→ **bkg expected: <1 event in 50 years!**

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

JCAP 10 (2019) 02, PoS(ICRC2025)1170



Point-like sources

also in coincidence with observations
by other experiments
For example TXS 0506+056

Coincidence with GW

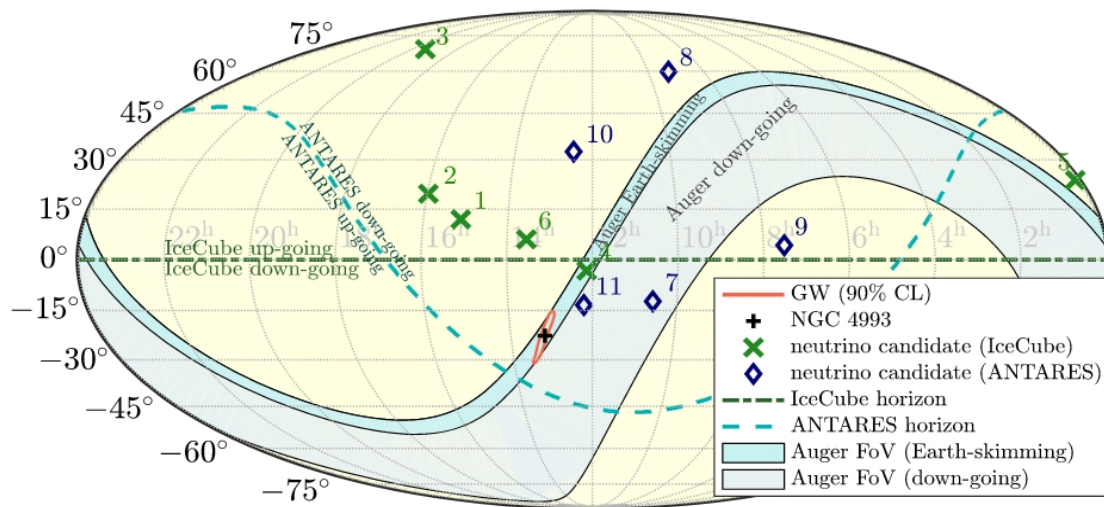
For example GW170817
GW follow-up (62 events, stack
analysis)

NO Candidates found

Constraining models assuming sources of CRs accelerating only protons

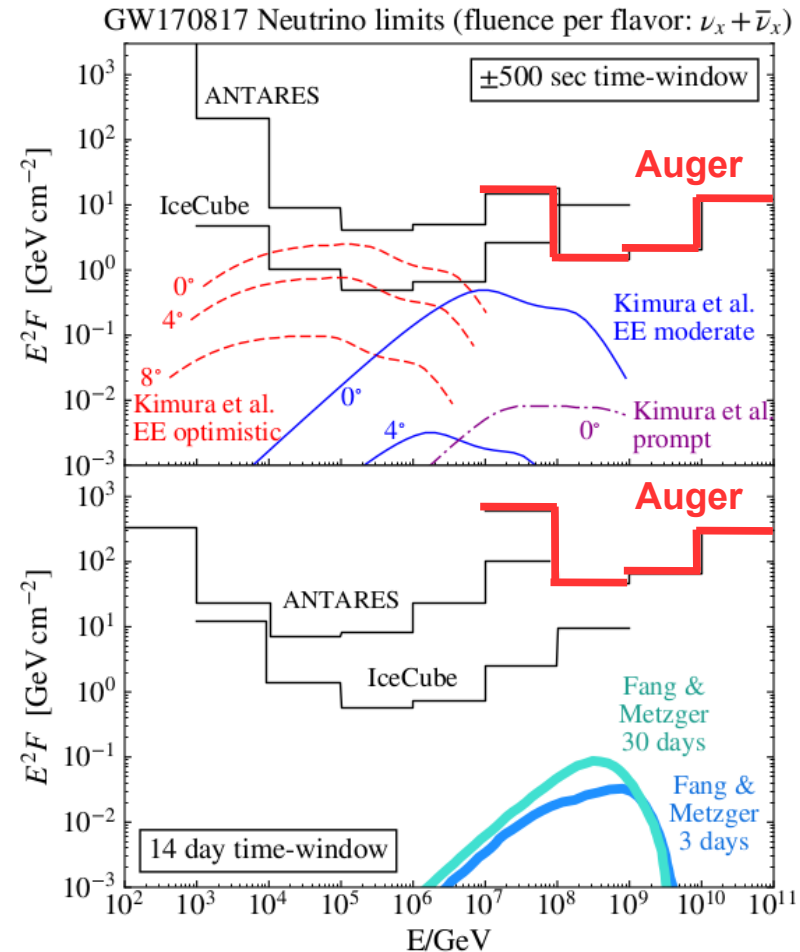
Follow-up searches: GW170817

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



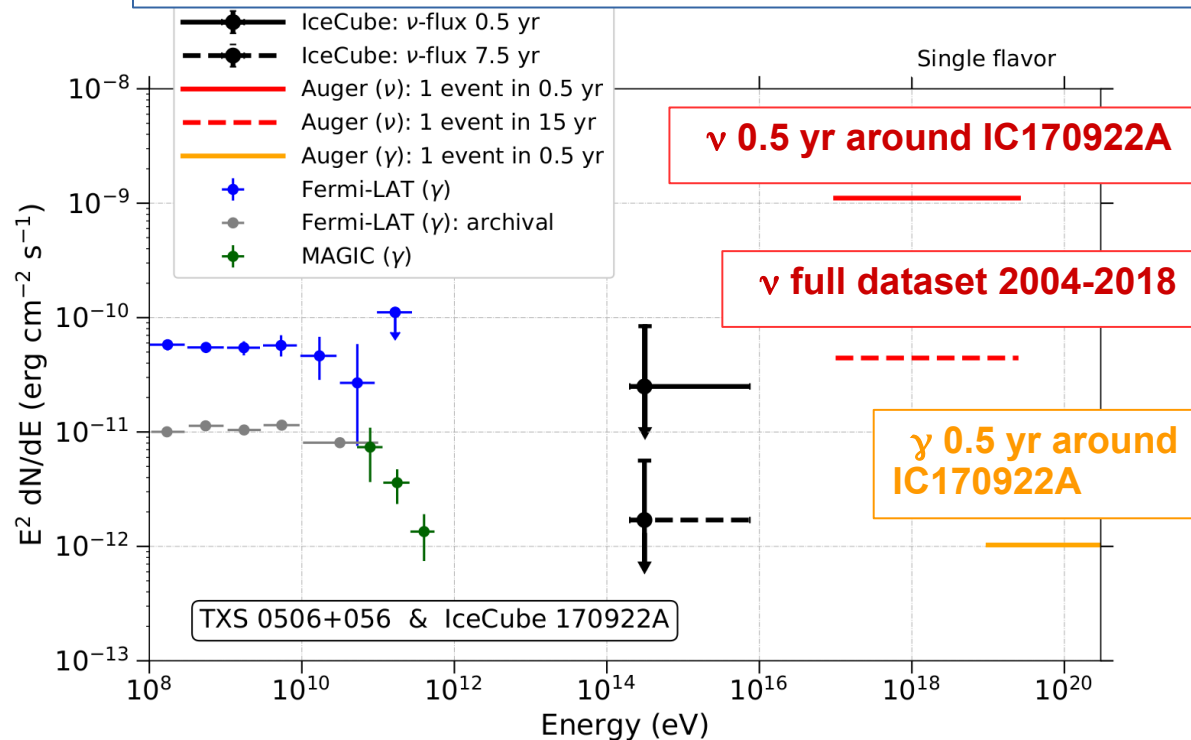
- excellent visibility of the merger:
90% CL GW event location in FoV of ES channel
- time dependent exposure leads to substantially looser 14-day neutrino fluence limits wrt to prompt

ApJL 850 L35 2017

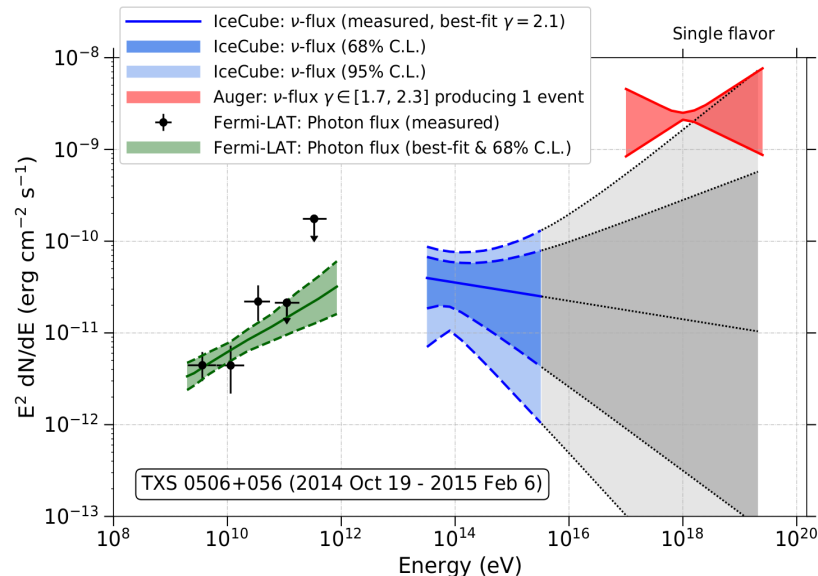


Follow-up searches: TXS0506+056

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

Search for neutrons

ApJ 99 (2026) 168

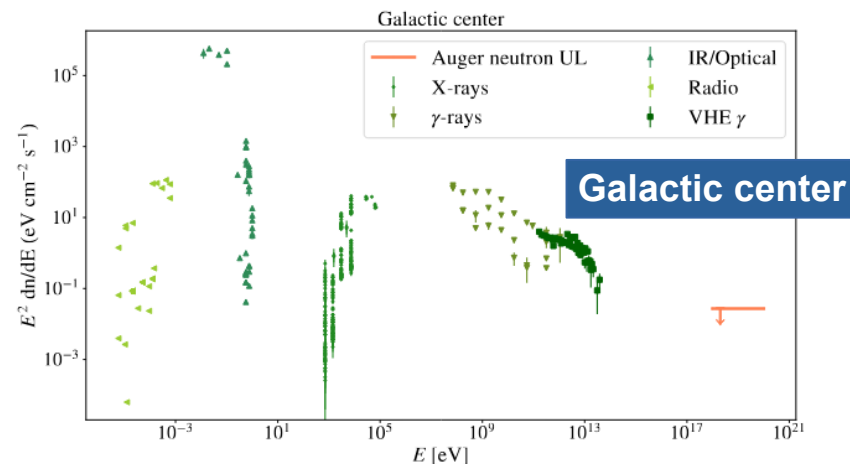
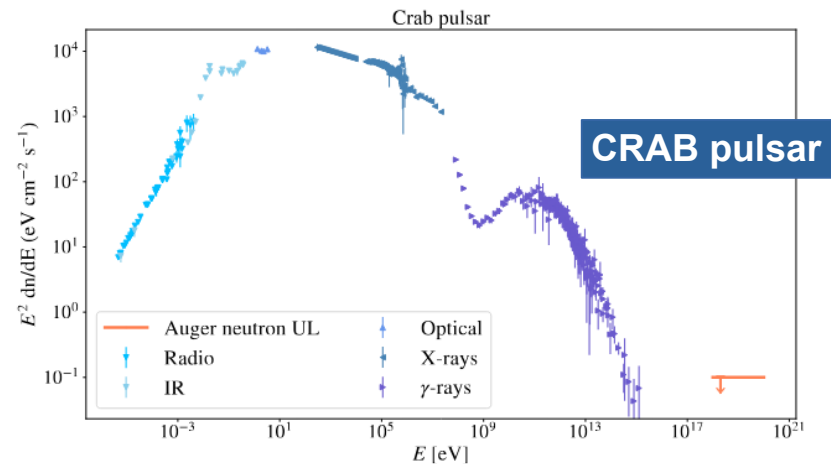
Neutron produced by hadrons interaction with ambient photon or nuclei

Travelled distance $\sim 9.2 (E/\text{EeV}) \text{ kpc}$

Method

→ define targets (1092) and look for excess
SD1500/SD750 Phase 1 data up to 2022

most stringent direct constraints on hadronic acceleration in Galactic sources above 100 PeV

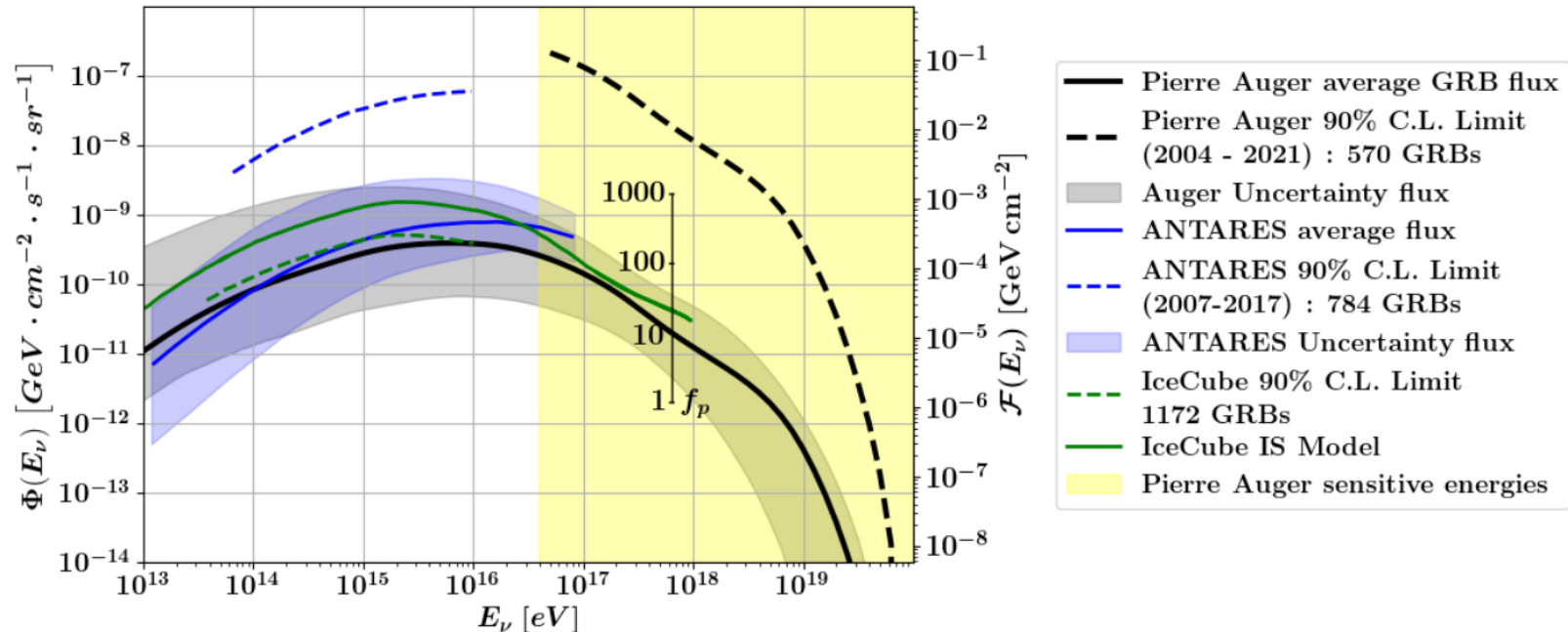


Neutrino search from GRBs

No neutrino candidates found in coincidence with GRBs

Upper bounds to prompt neutrino fluence:

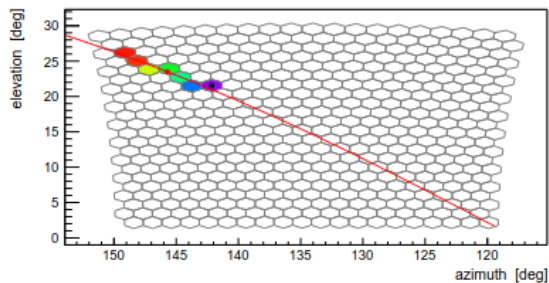
- stacking approach (570 sources in Auger neutrino FoV) using NeuCosmA for each source
- best limit above 10^{17} eV, in comparable scale with ANTARES at lower energies



Search for upward-going air showers with Auger FD

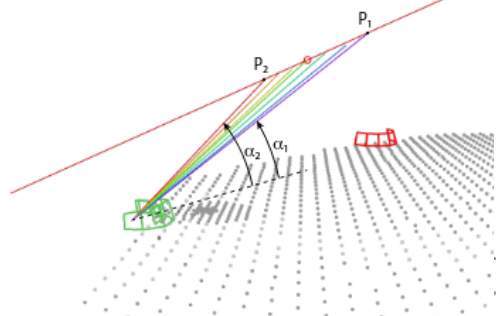
FD Energy > 0.1 EeV, zenith > 110°, 14 years of FD data

Phys. Rev. Lett. 134 (2025) 121003

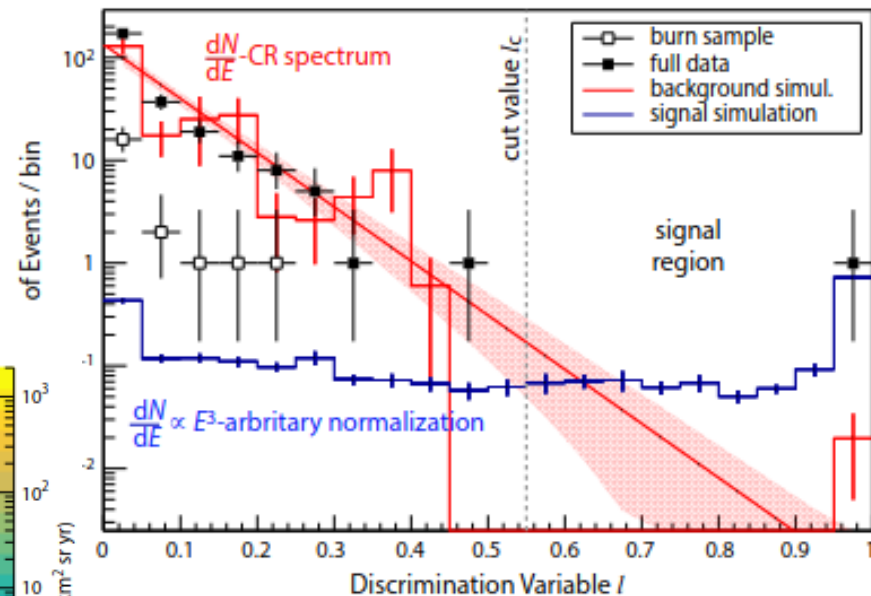
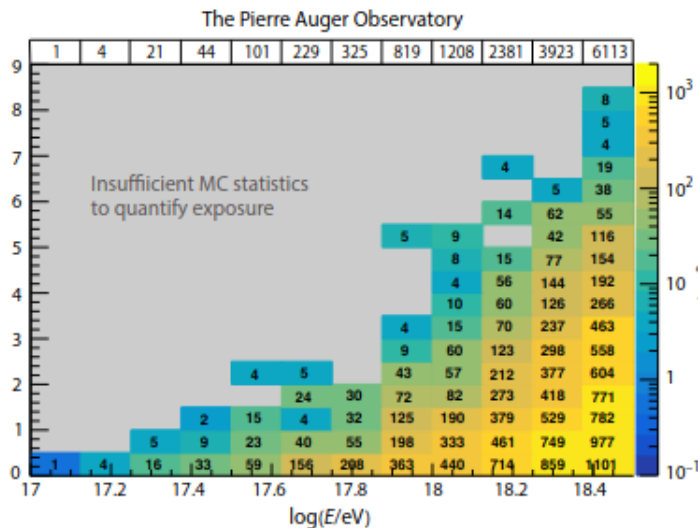


Debate triggered by the claim done by the ANITA collaboration

Exposure (energy, height of first interaction)



FD only reconstruction challenging for specific event topologies

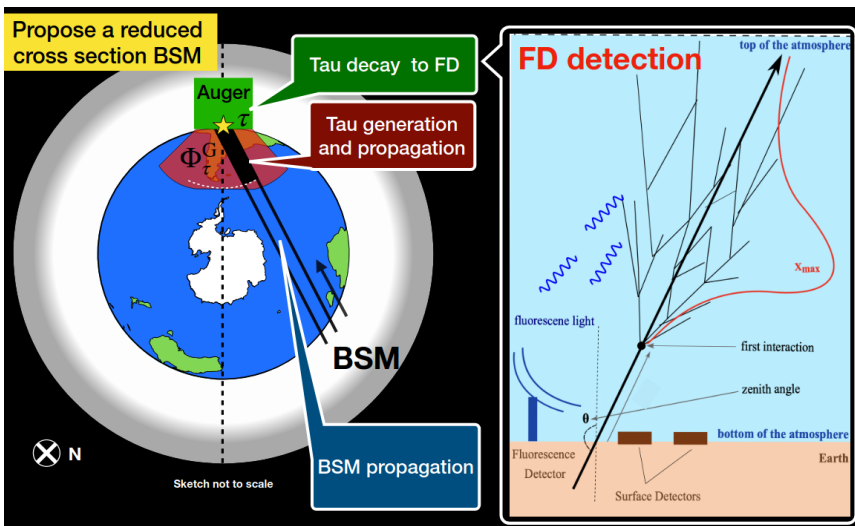


1 candidate consistent with the background (~ 0.3)

Auger should have seen from 8 to ~ 70 events

Probing BSM scenarios

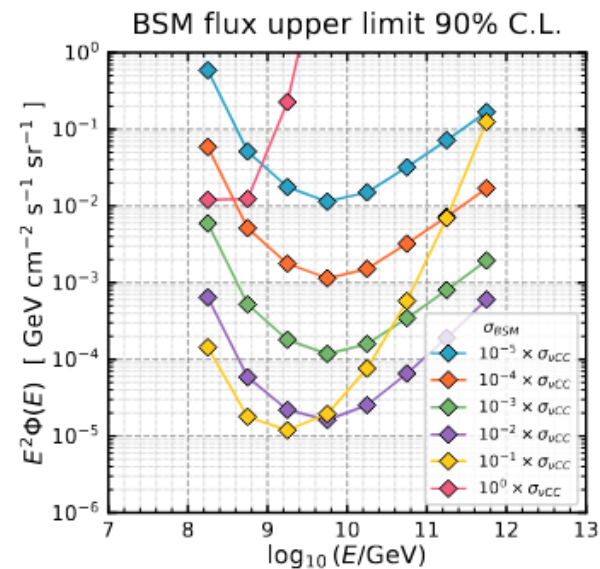
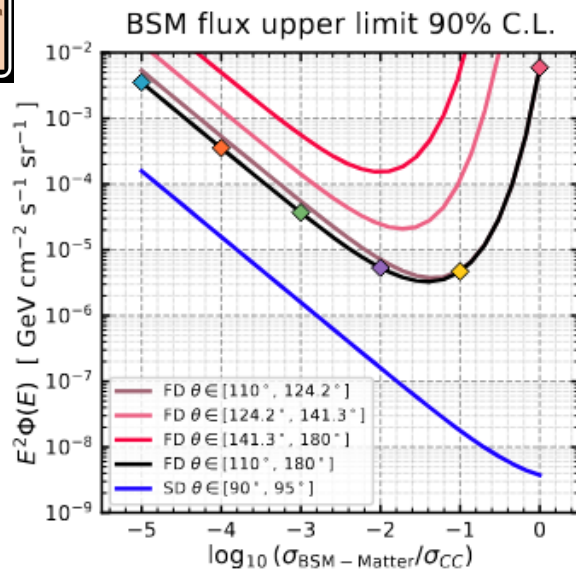
PoS(ICRC2023)1095



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 $> 110^\circ$
SD: $90^\circ < \text{zenith} < 95^\circ$
→ complementary in zenith

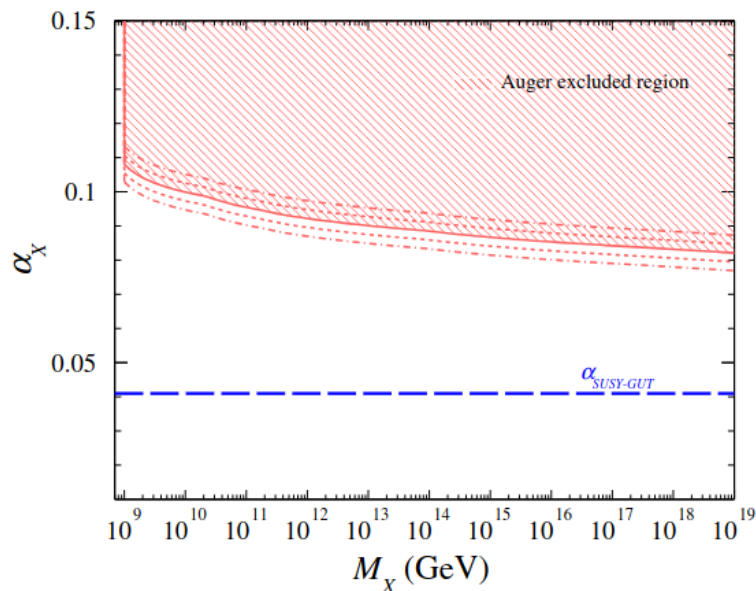


A deep insight into the BSM physics

Bounds on photons and neutrinos used to explore fundamental physics (see talk by O. Deligny)

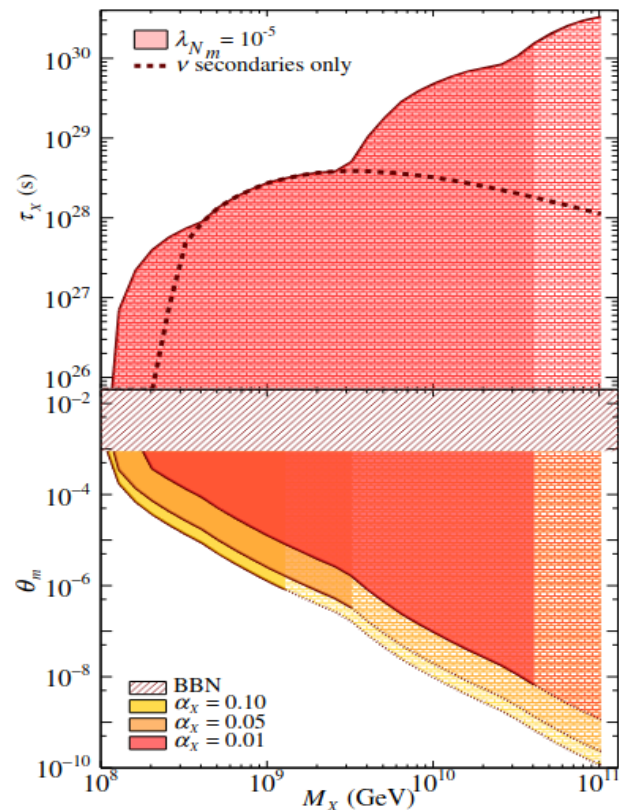
SHDM particles in the Galactic halo decay into SM particles and photons.

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



Constrain a specific extension of the SM, coupling the sterile neutrinos to SHDM candidate

→ stringent limit on the angle θ_m mixing sub-eV sterile and active neutrinos



Phys. Rev. Lett. 130 (2023) 061001

Phys. Rev. D 107 (2023) 042002

Phys. Rev. D 109 (2024) L081101

Search for Lorentz Invariance Violation

$$E^2 - p^2 = m^2 + \eta^{(n)} \frac{p^{n+2}}{M_{\text{Pl}}^n},$$

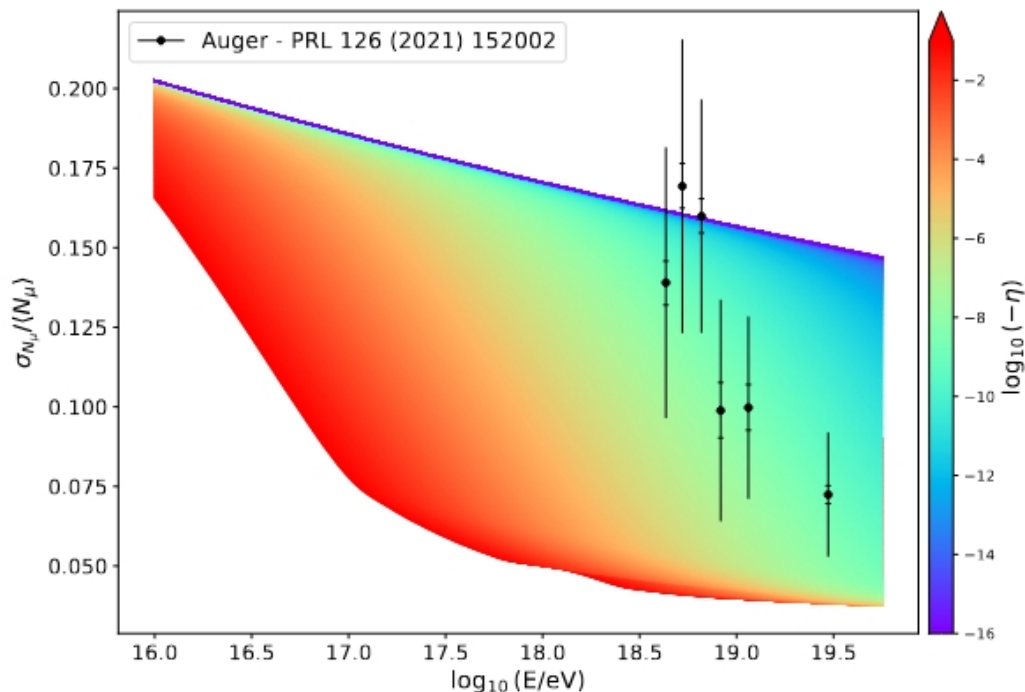
Negative value of η tend to increase the lifetime of π_0 , favoring interaction over decay.

→ LIV leads then to a moderate muon excess (increased hadronic component) and reduced fluctuations due to limited stochastic leakage in the first interaction

Muon fluctuation used to derive stringent upper limit for LIV

Improvement expected from AugerPrime (UMD and Radio)

To appear on Phys. Rev. Lett. 2026



Pierre Auger Observatory Open Data

March 2024 release

<https://opendata.auger.org>

doi 10.5281/zenodo.4487613

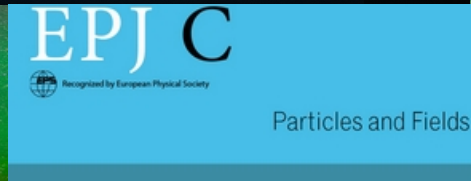
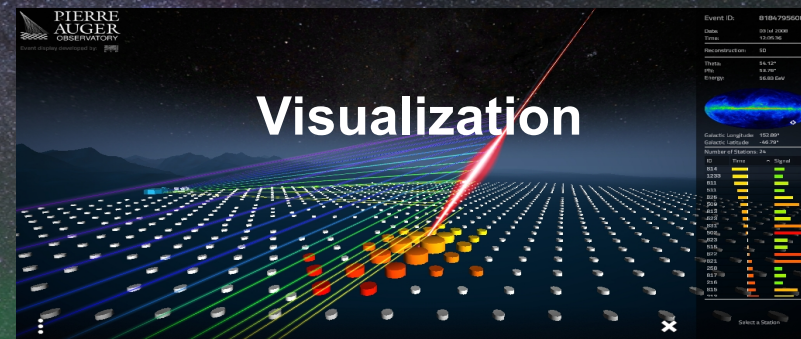
10% cosmic ray data → release of 30% is imminent
100% atmospheric data

Close to raw data and higher level reconstruction

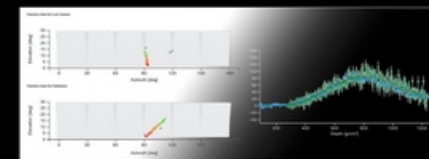
Surface and Fluorescence Detectors

JSON and summary CSV files

Python code for data analysis



From "The Pierre Auger Observatory open data"
by Pierre Auger Collaboration, Eur. Phys. J. C 85, 70 (2025).



Visualization of an exemplary event. Left panel: camera view of the fluorescence detector; the cosmic ray shower is seen as a trace that moves along the points of the camera, from early (green) to late (red) pixels. Right panel: reconstructed energy deposit as a function of atmospheric depth as measured with the two telescopes participating in the event.

Eur. Phys. J. C 85 (2025) 70



Springer



Datasets

[the released datasets and their complementary data](#)



Visualize

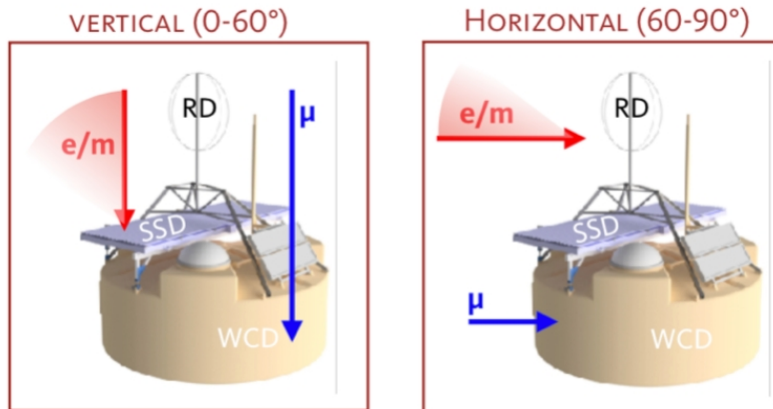
[an online look at the released pseudo raw cosmic-ray data](#)



Analyze

[example analysis codes in online python notebooks to run on the datasets](#)

The future: AugerPrime



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

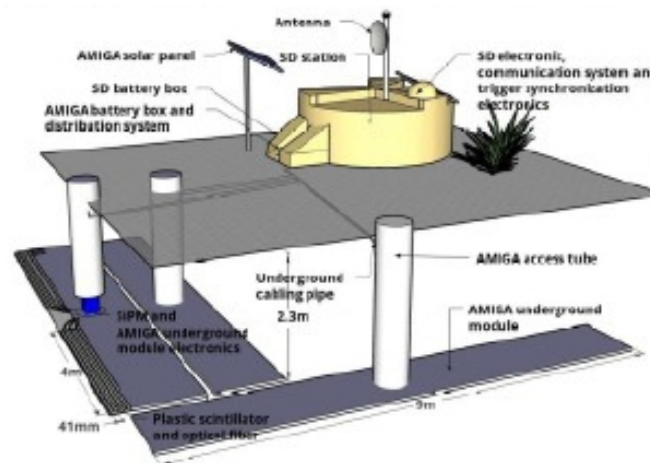
→ measurement closer to shower axis

radio antennas

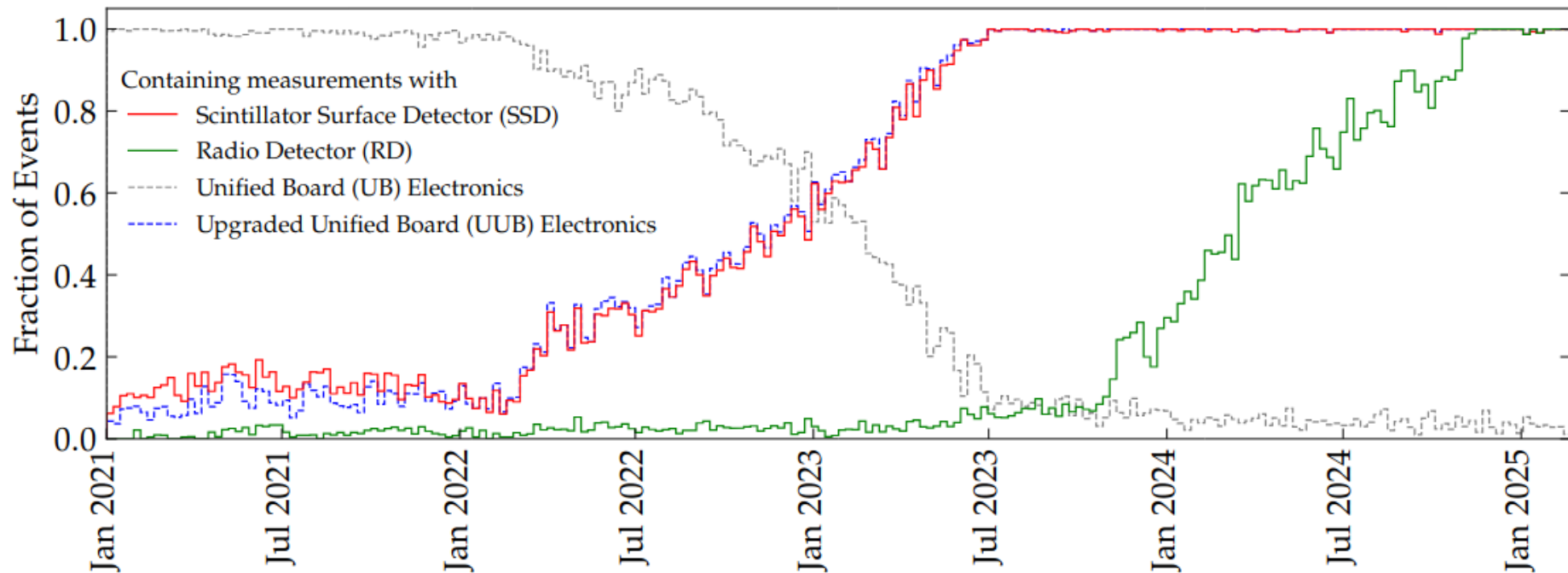
→ horizontal events

muon detectors in infill area (installed 75%)

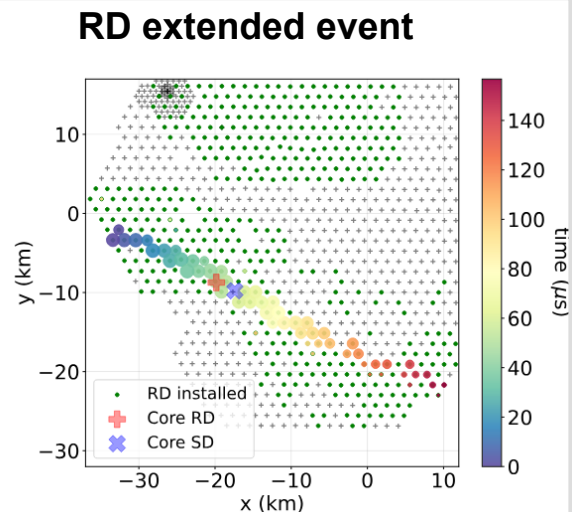
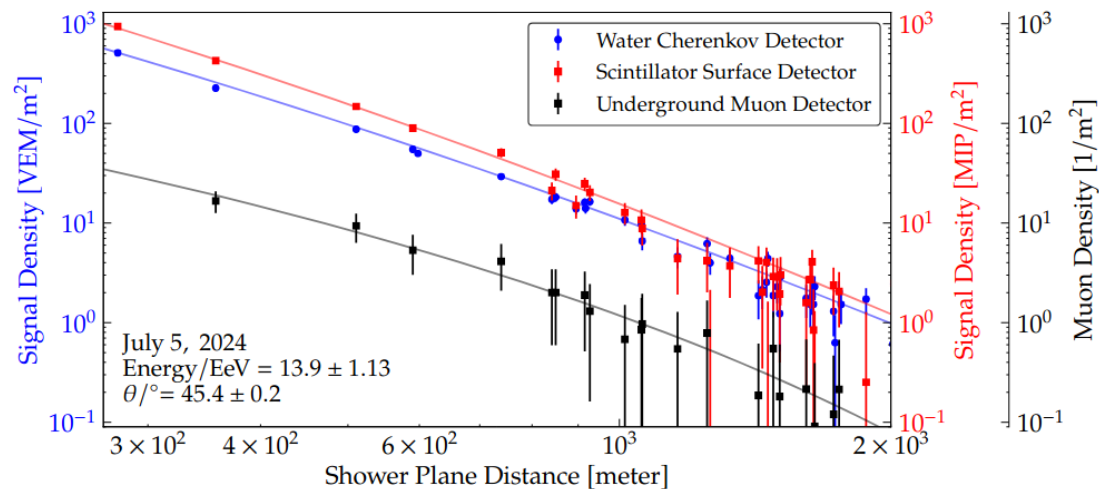
→ direct measurement



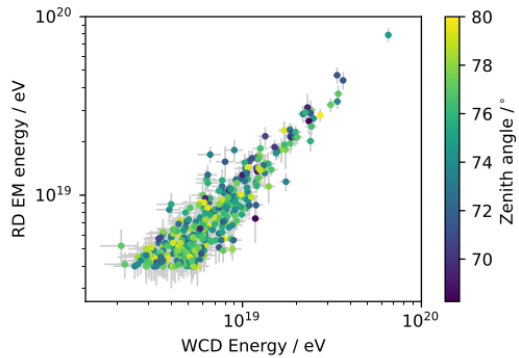
Transition to AugerPrime: timeline



The future is multi-hybrid



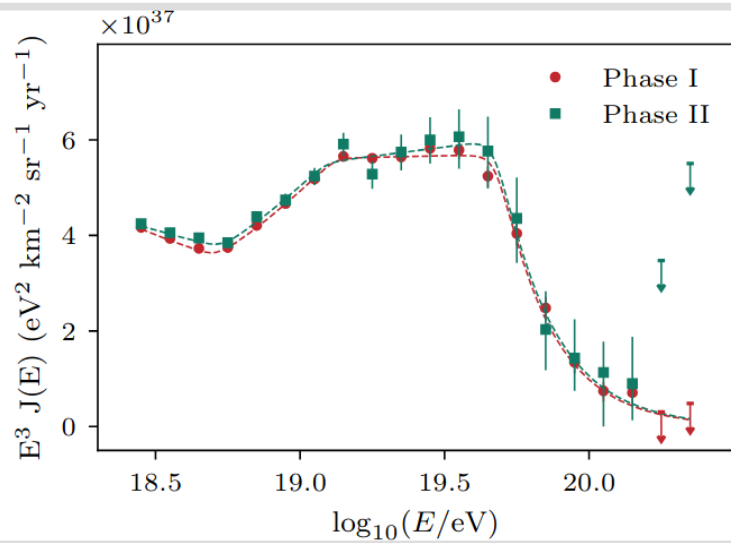
	RD	SD
Azimuth (deg)	156.9±0.1	156.8±0.1
Zenith (deg)	84.8±0.1	84.7±0.1
Energy (EeV)	32±4	29±2



Checking the compatibility
 same analysis chain of Phase 1

Exposure 9200 ± 300 km² sr yr
 (10% of Phase 1)

Consistent results

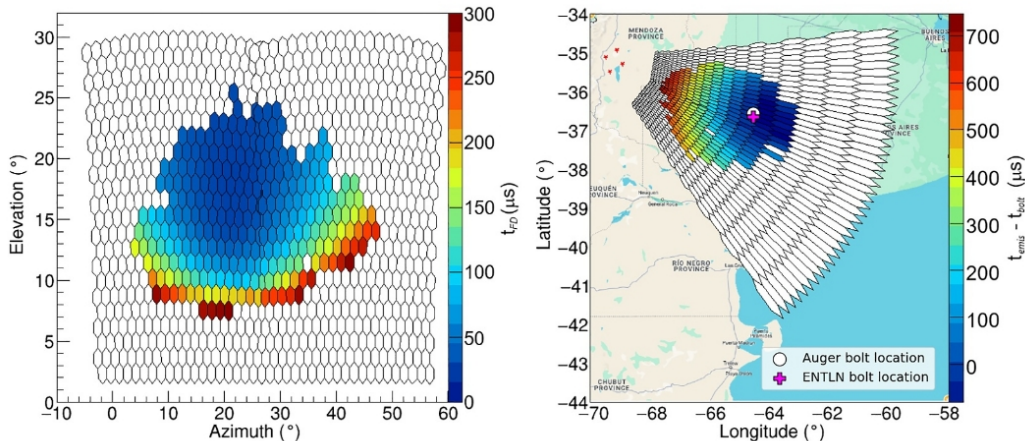


PoS(ICRC2025)370

PoS(ICRC2025)385/294

Interdisciplinary science at the observatory

Earth and Space Science 12 (2025) e2025EA004321



Elves in the FD camera:

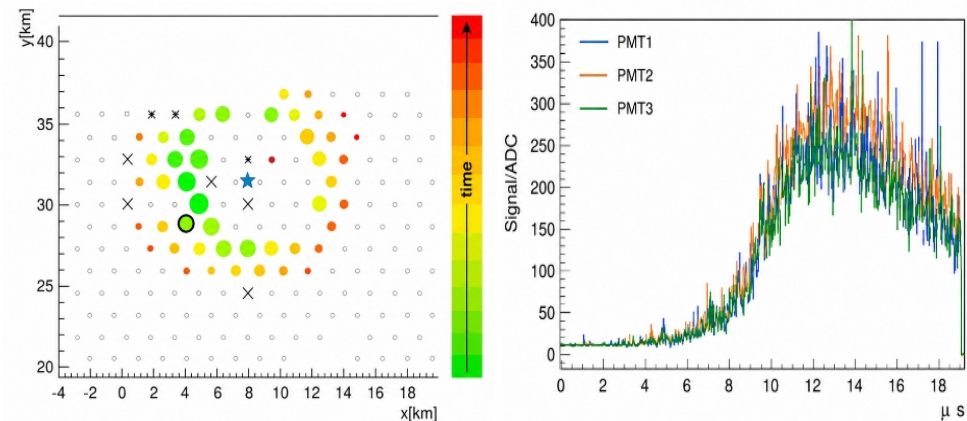
electromagnetic pulse from an intense lightning strike reaching the lower ionosphere
Characterization of elves with multiple rings

SD Scaler rate

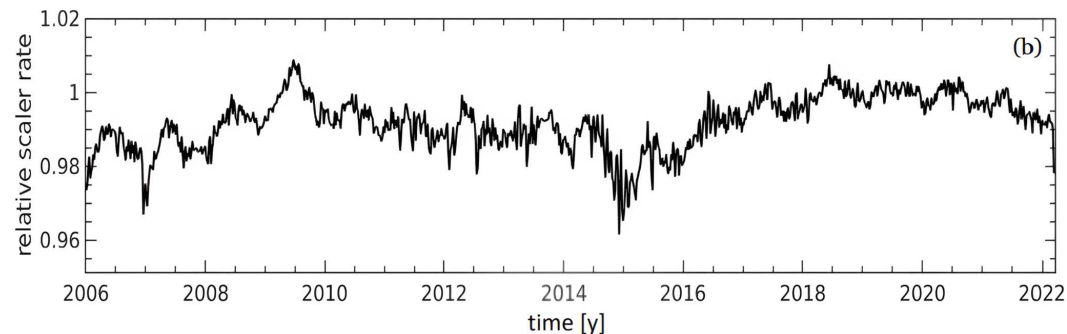
Study of the solar activity, influence of the solar wind on galactic cosmic rays

The Astrophysical Journal, 987 2025

arXiv:2608.28885v1 submitted to JGR



Terrestrial Gamma-ray Flashes (TGFs) in the SD
short, intense bursts of gamma rays associated with lightning



The Pierre Auger Observatory as test bed infrastructure

PoS(ICRC2023)303 F. Bradfield

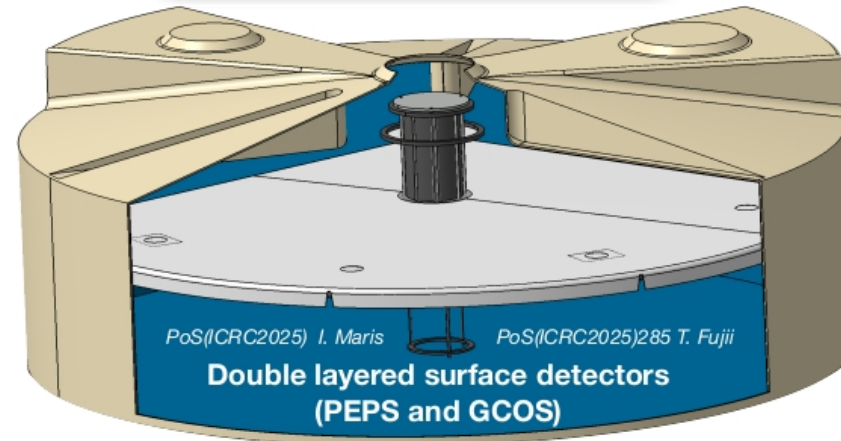


PoS(ICRC2025)1024 B. de Errico

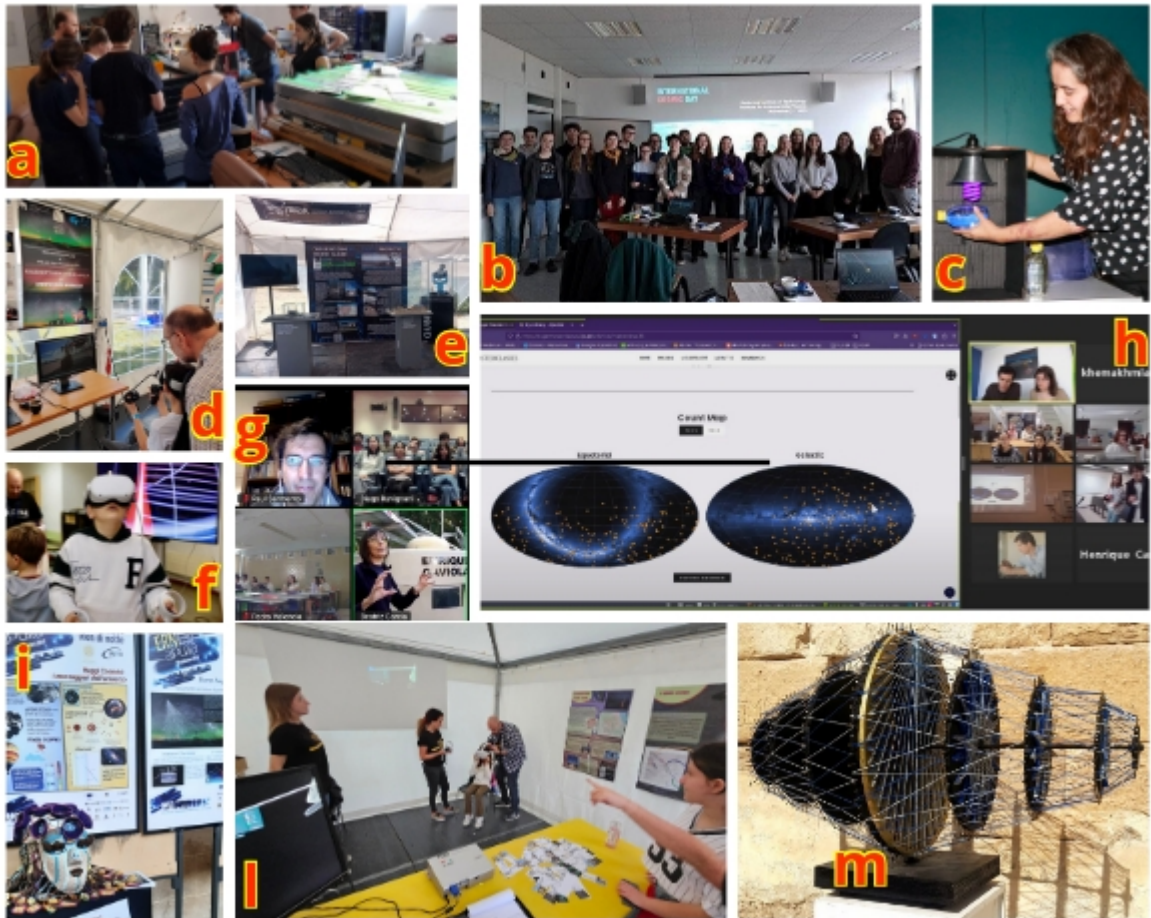


M. Roth
ISVHECRI 2026

PoS(ICRC2025)387 F. Schröder



Outreach activities at the Pierre Auger Observatory



Auger Master Classes
(member of the IPPOG
collaboration)

International Cosmic Day

Women and Girls in Science

Dedicated activities at the
Observatory site in Malargue

Science Fair

Art and Science

.....

Wrap-up of some evidences

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)

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 $\sim 2 \times 10^{18}$ eV
- the smooth transition from isotropy to a dipolar anisotropy above 8 EeV
- towards deeper $X_{\max}$ scales of models, implying heavier mass composition

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**

Wrap-up of the MM observed landscape

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 (ν candidates), streaming to AMON & DWF

ACME (Astrophysics Center for MM studies in Europe)

- Funded under EU Horizon Research and innovation Program till 2028
- Auger is one of the 12 offered research infrastructures
- Accepted proposals will be given expert support, improved access to data

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

Summary

The Pierre Auger Observatory is now going through Phase II

- the upgrade is implemented and performing as expected

First data are encouraging, heading towards collecting multi-hybrid events

Fundamental physics can be investigated using a multi-messenger approach

- hadronic interactions at energies larger than LHC
- exotic physics and BSM studies in a poorly populated phase space

The Pierre Auger Observatory is involved in the multi-messenger effort

- participate in several alert network and makes joint proposals
- providing open data and open to society

It offers a unique infrastructure for the future of the field

The future has already begun!

- many connections with other collaborations
- testing current and new detectors in the field

BACKUP

Targeted searches: photons

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

Previous blind search limits

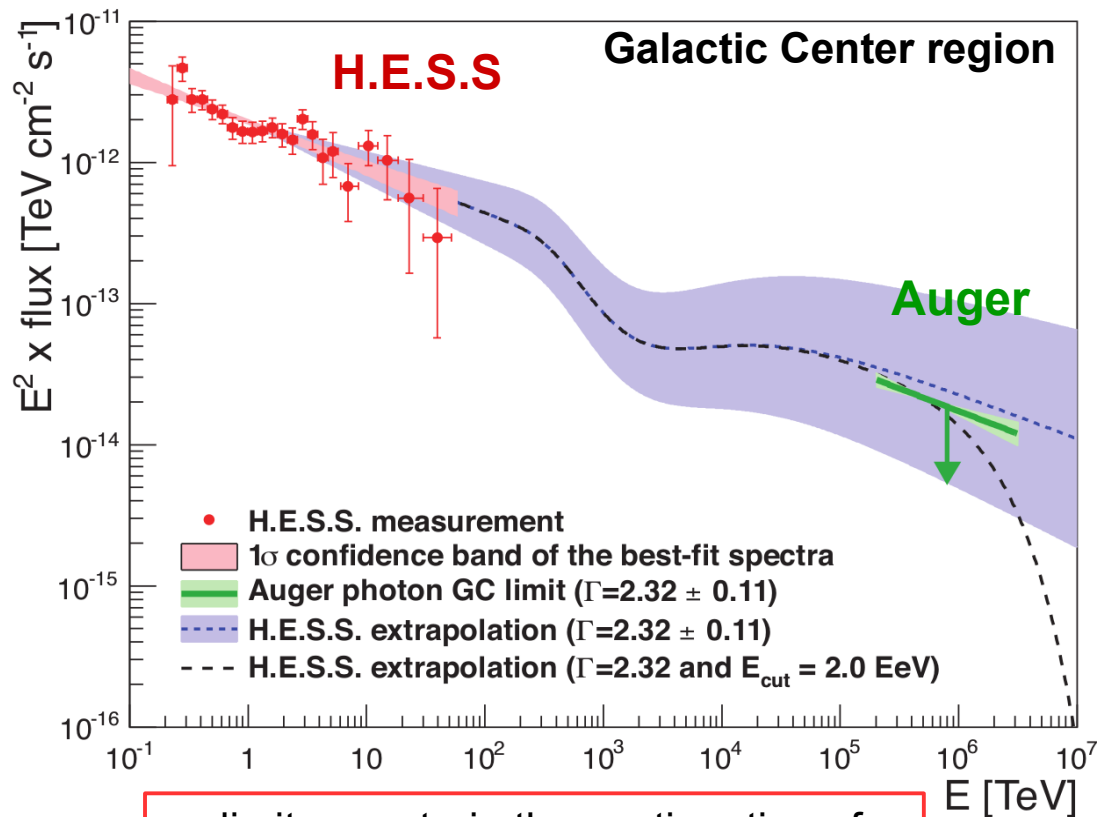
12 target sets Galactic sources
(364 candidates sources)

- stacked analysis

→ complement targeted neutron searches

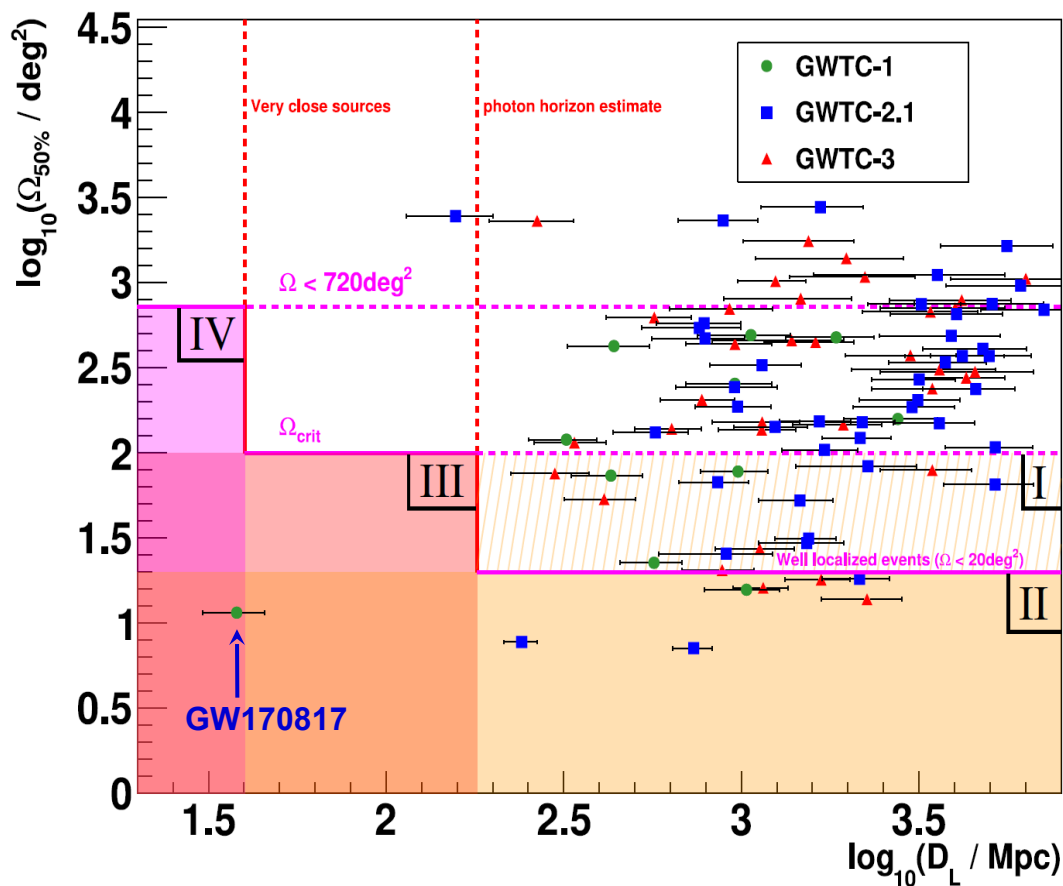
NO evidence for *nearby* photon-emitting *steady* sources in the EeV range

→ might be transients



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

GW follow-up photon searches



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

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

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

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

GW follow-up photon searches

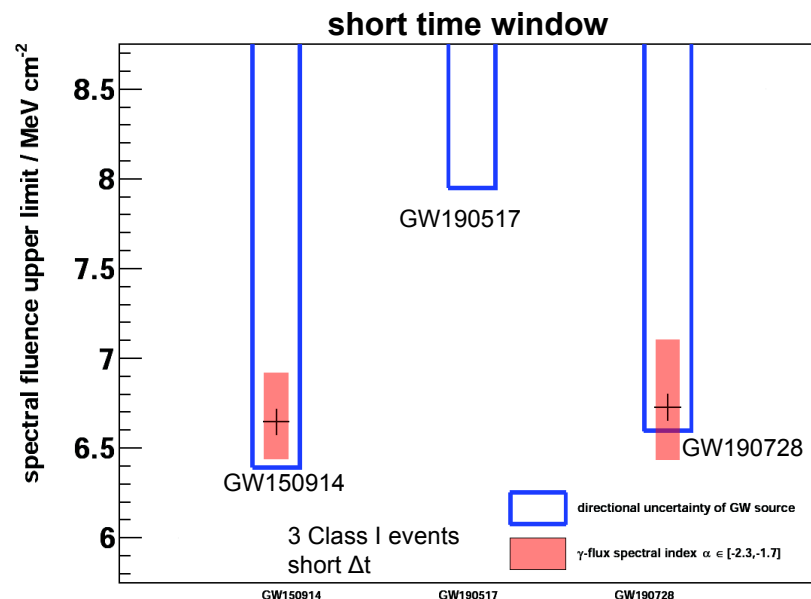
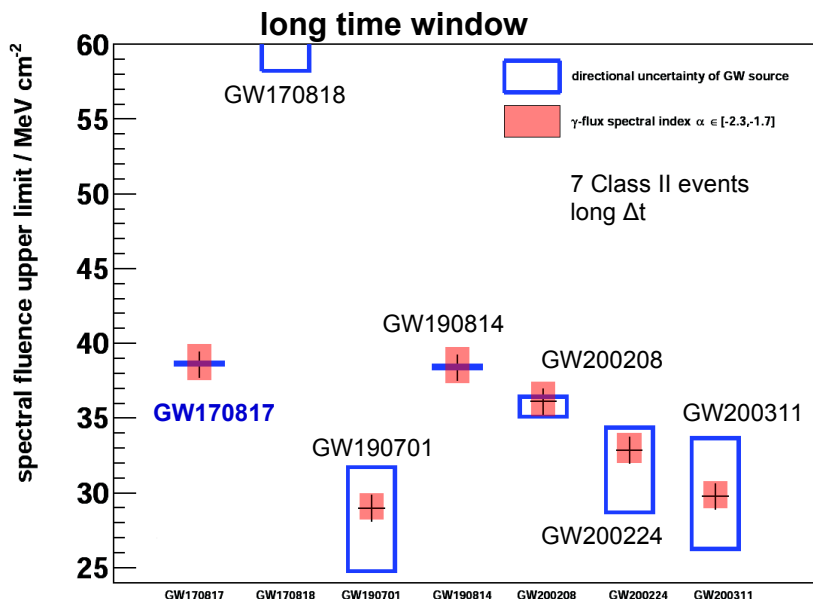
7 events in Class II, 3 in Class I

No candidate found for any GW event $\rightarrow$ flux upper limits

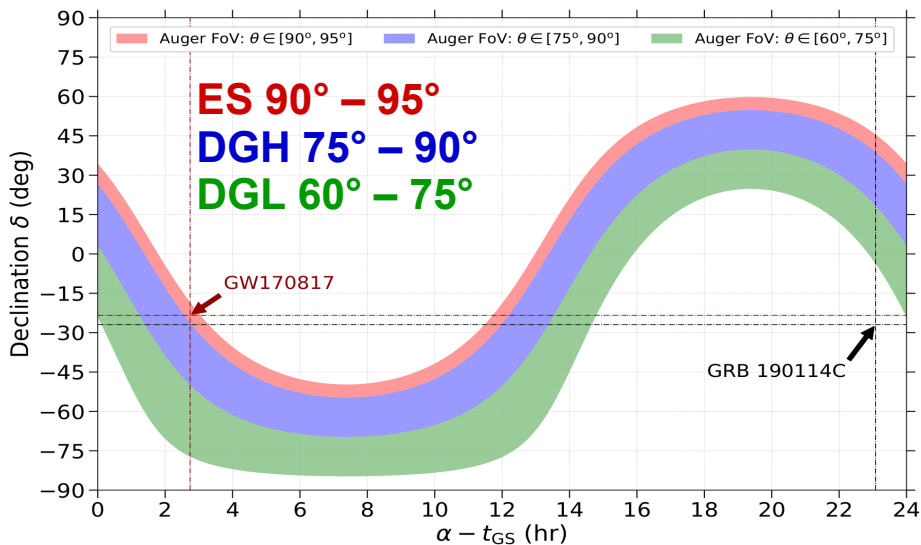
First ever limits on γ from GW at UHE

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

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

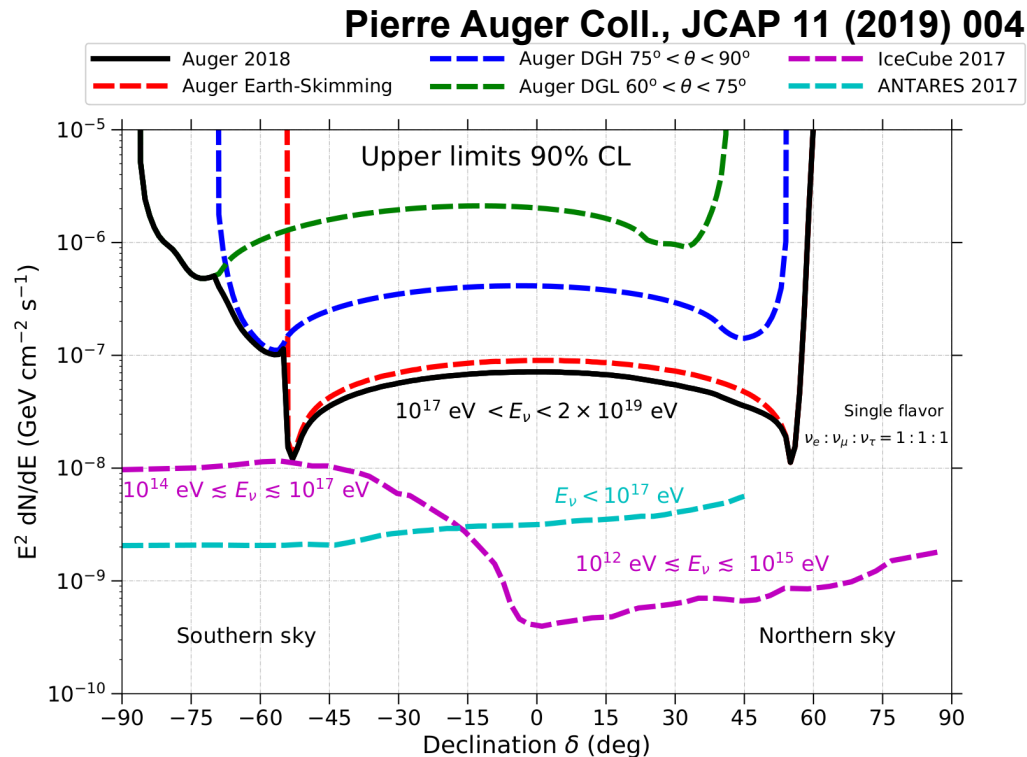


UHE neutrinos: point sources sensitivity



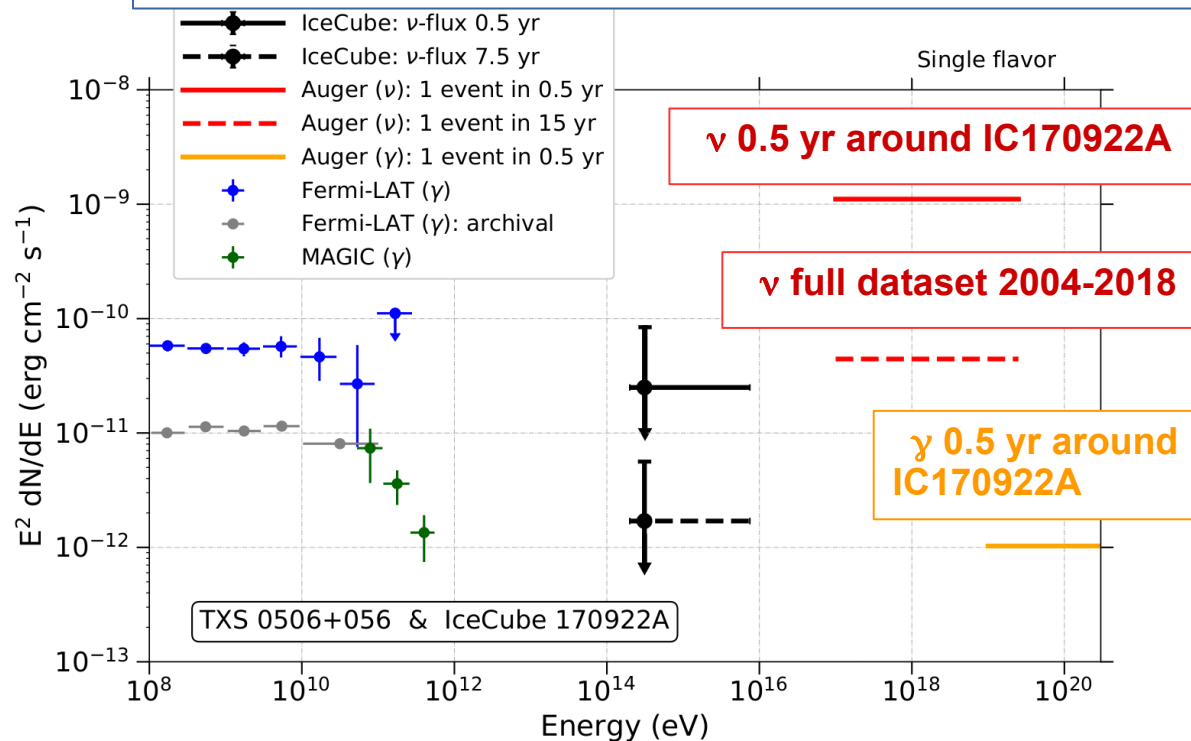
point sources transit through the field of view of each detection channel

→ sensitivity strongly depends on source location and event timing

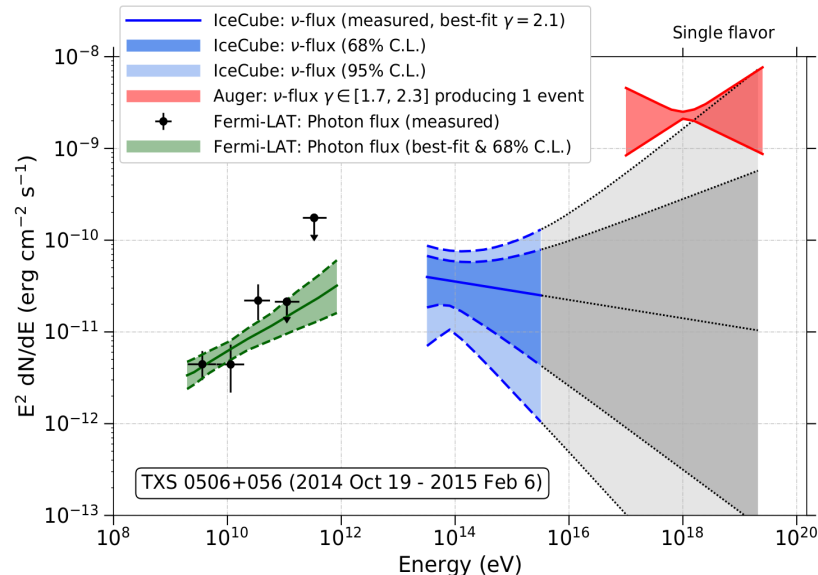


Follow-up searches: TXS0506+056

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

Search for upward-going air showers with Auger FD

Two “anomalous” events detected by **ANITA** with non-inverted polarity

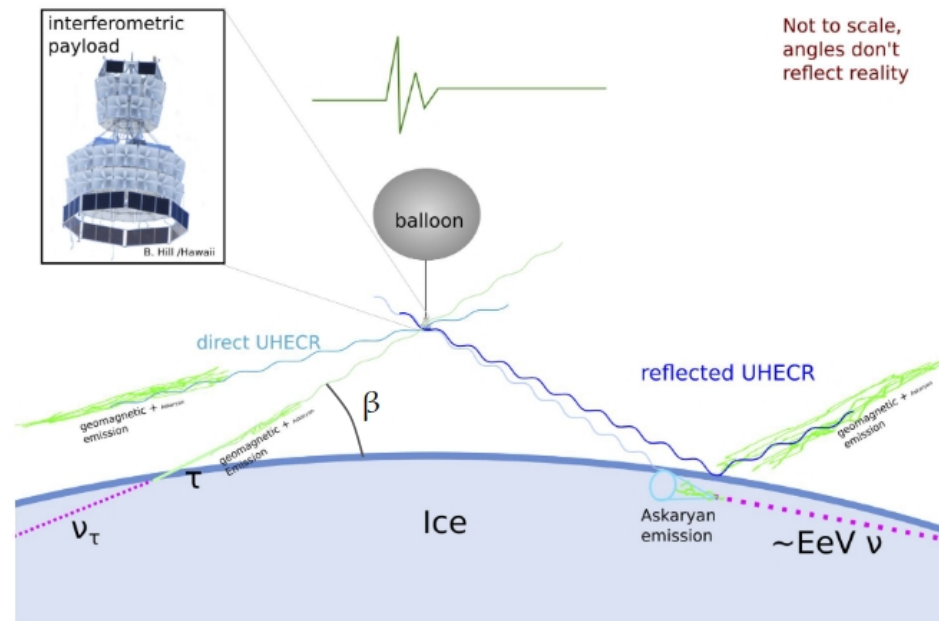
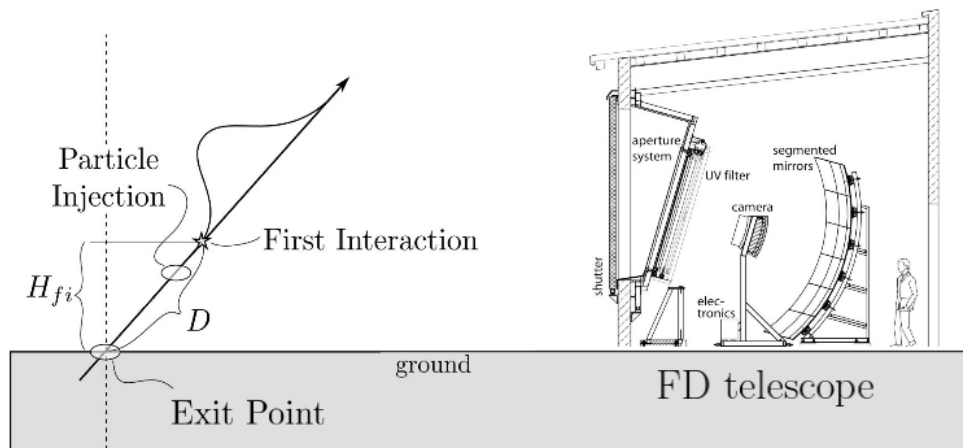
→ $E \sim 0,2 \text{ EeV}$ exit angle $\sim 30^\circ$

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



The Pierre Auger Observatory as part of the multimessenger network

Automatic Global Coordinate Network (GCN) alerts listener

- SD events update every 15', 3 neutrino reconstruction analyses running

-

-

Read GCN alerts and look for neutrino candidates in 90% CL region

Automatic alert if any findings and possible GCN notice if confirmed

AMON and DWF triggering and follow-up partner

- Alerts from private or GammaCN notices

- High quality SD events shared every few minutes

- SD events in DWF field of view shared

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- Funded under EU Horizon Research and innovation

Program till 2028

- Auger is one of the 12 offered research infrastructures

- Accepted proposals will be given expert support, improved access to data

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

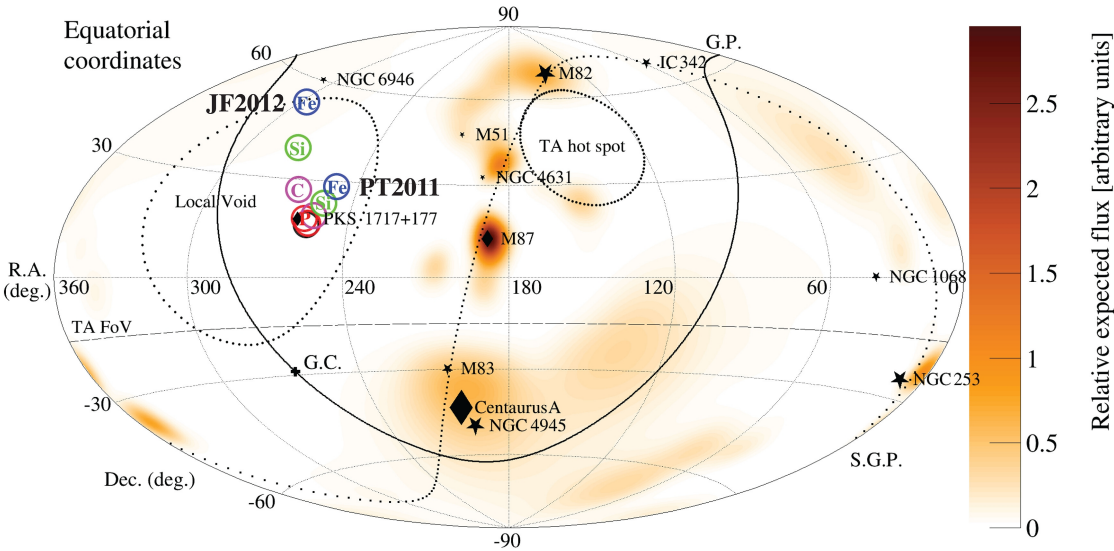
Amaterasu
particle
244 EeV

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	$38.6 \pm 0.4^\circ$	$206.8 \pm 0.6^\circ$	$255.9 \pm 0.6^\circ$	$16.1 \pm 0.5^\circ$

common
band !

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



166 EeV: most energetic Auger event
note: exposure Auger / TA $\approx 6,7$!

energy of the Amaterasu particle at the
Auger energy scale would be 170 EeV

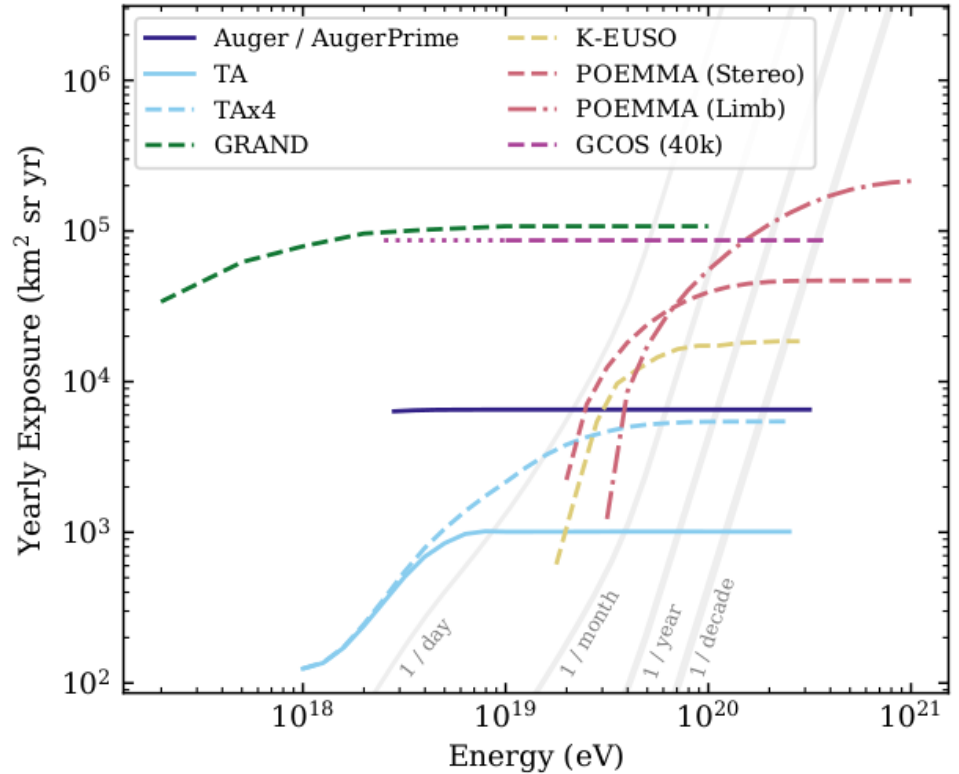
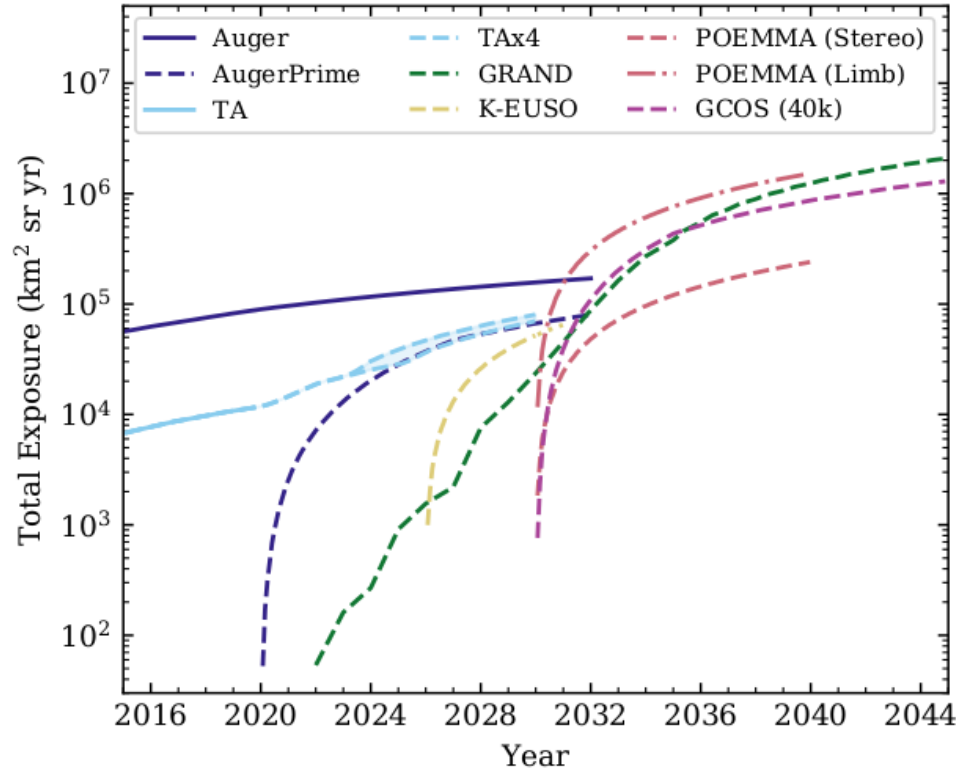
$$-9\% - 20\%(\log_{10} E - 19) = -37\%$$

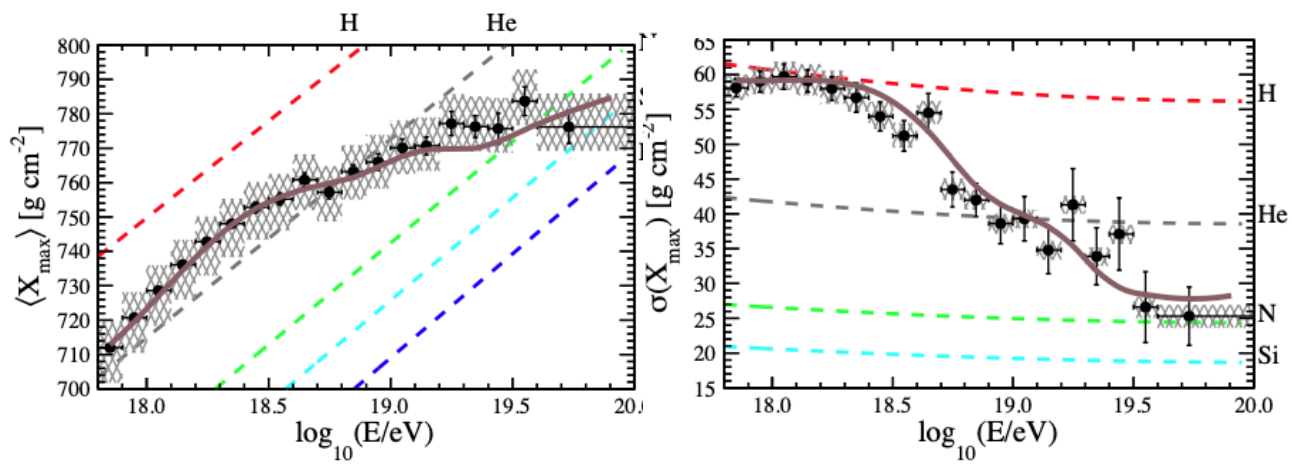
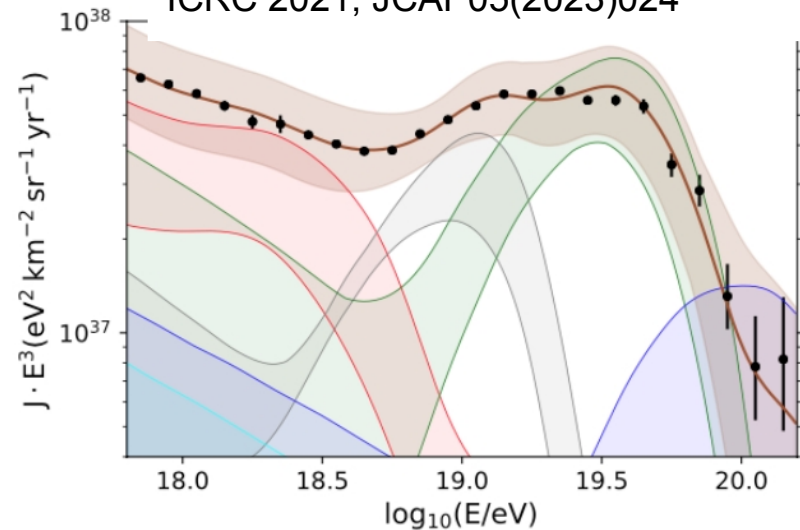
	E [EeV]	Dec [deg.]
PAO191110	166	-52
PAO070114	165	-21
PAO200611	155	-48
PAO141021	155	-38
TA Amaterasu	154	16

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

A look into the future for UHECRs

EPJ Web of Conferences 283, 01001 (2023)





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]	$(1.07 \pm 0.06) \cdot 10^{-13}$		-	
$\log_{10}(R_{\text{cut}}^{\text{gal}}/V)$	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
$\log_{10}(R_{\text{cut}}/V)$	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)	
$D_{X_{\text{max}}}$ ($N_{X_{\text{max}}}$)	593.8 (329)		554.8 (329)	
D (N)	643.3 (353)		614.9 (353)	

The ultra-high energy mass composition

FD → longitudinal profile

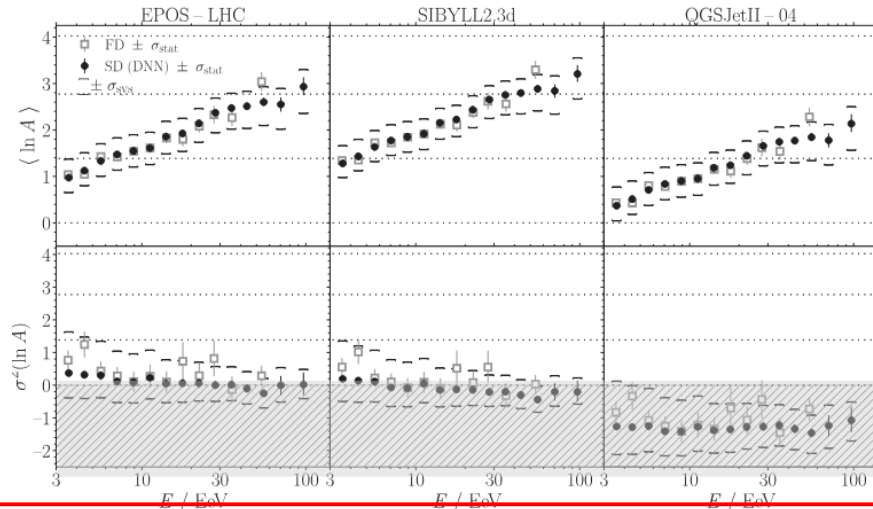
$\langle X_{\max} \rangle$ resol. 15 g/cm² at the highest energies

SD → temporal and lateral distributions + **DNN**

$\langle X_{\max} \rangle$ resol. 30 g/cm² at the highest energies

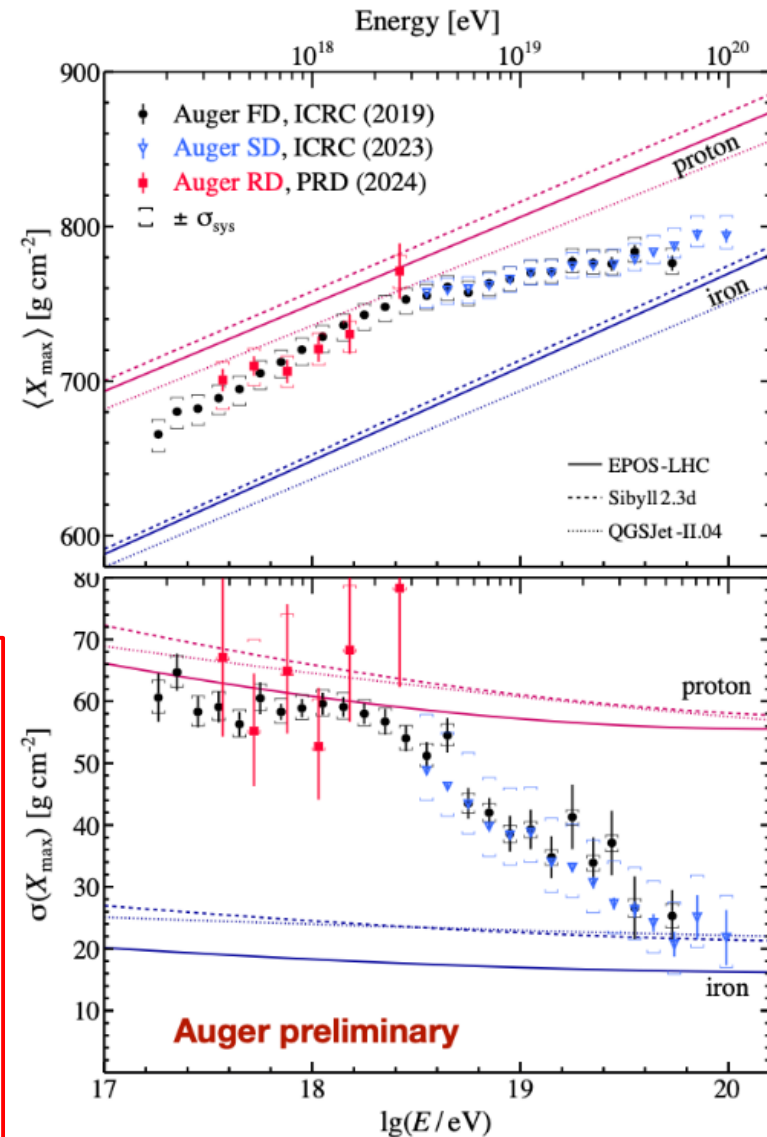
- $\langle X_{\max} \rangle$ gets lighter up to $\sim 2 \cdot 10^{18}$ eV and heavier above incompatible with pure composition
- $\sigma(X_{\max})$ at the highest energy excludes a large fraction of protons and proton GZK as a dominant reason for the spectral cutoff

**WITH
RD!**

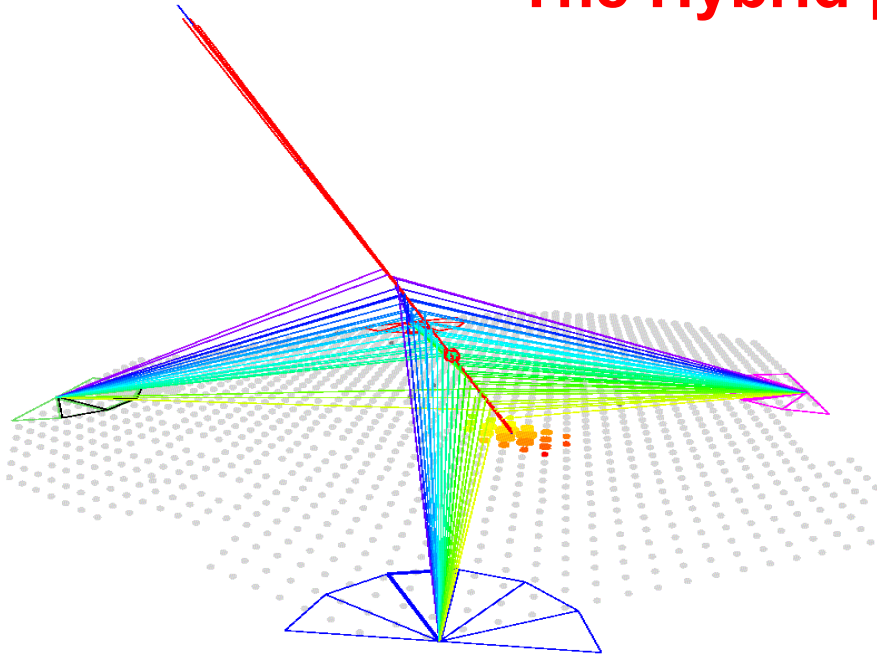


Tension with
some hadronic
interaction
models

unphysical



The Hybrid paradigm



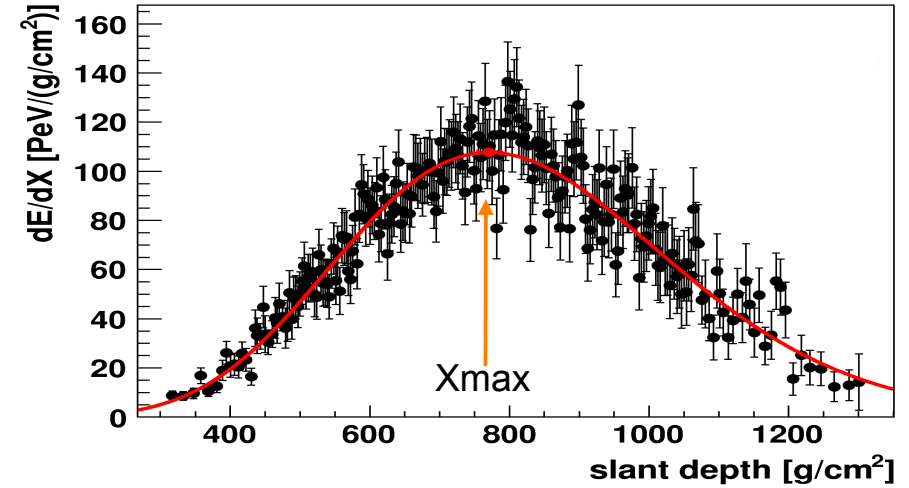
Longitudinal profile

FD - calorimetric measurement

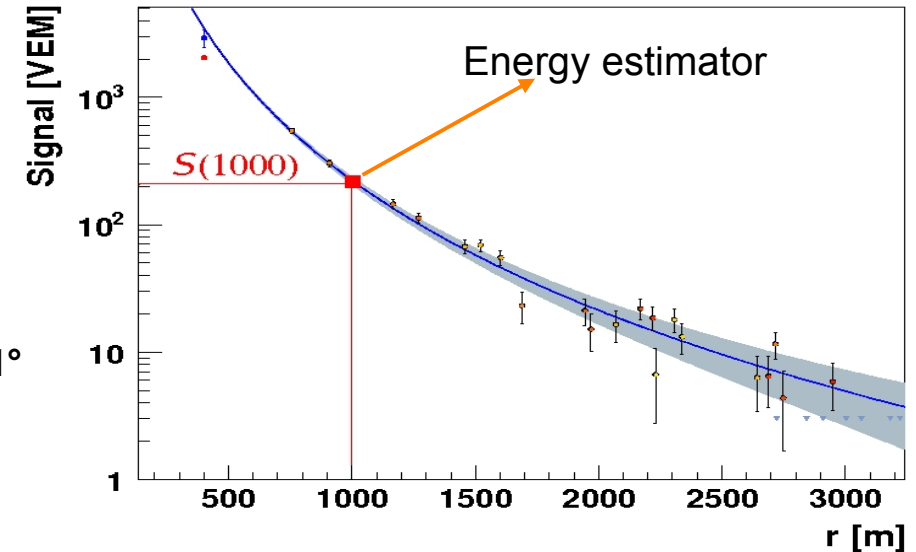
- duty cycle 15%
- X_{max} (mass composition)

Density of particles at the ground

SD - duty cycle $\sim 100\%$



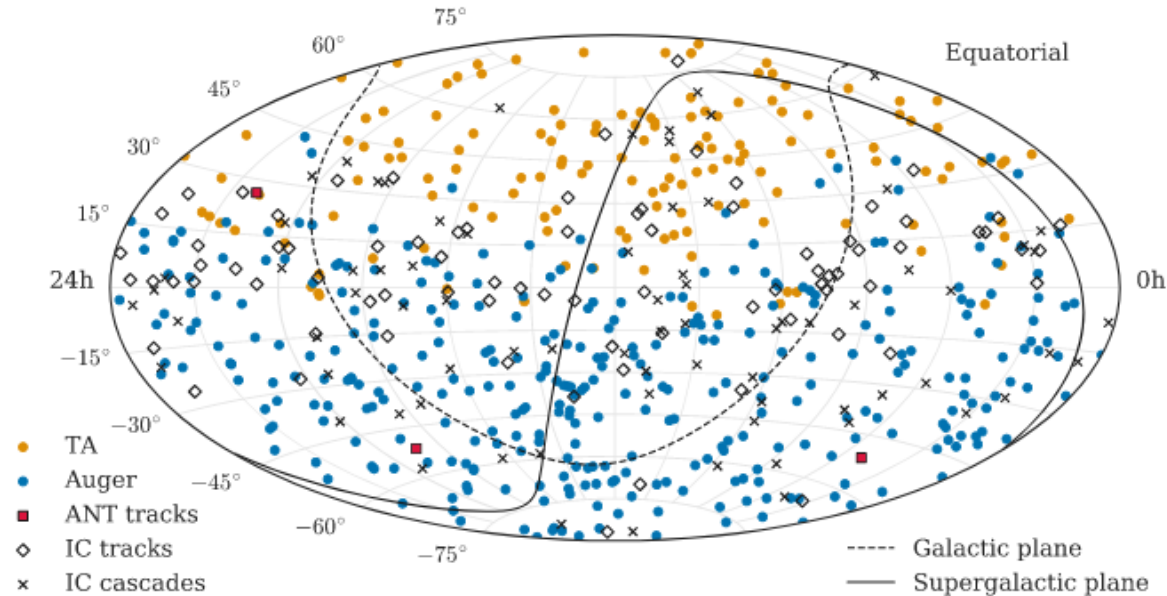
Angular
resolution $\sim 1^\circ$



Joint searches (UHECR and neutrinos)

Antares, IceCube, Auger, Telescope Array

APJ 934 (2022)164



Three analyses strategies:

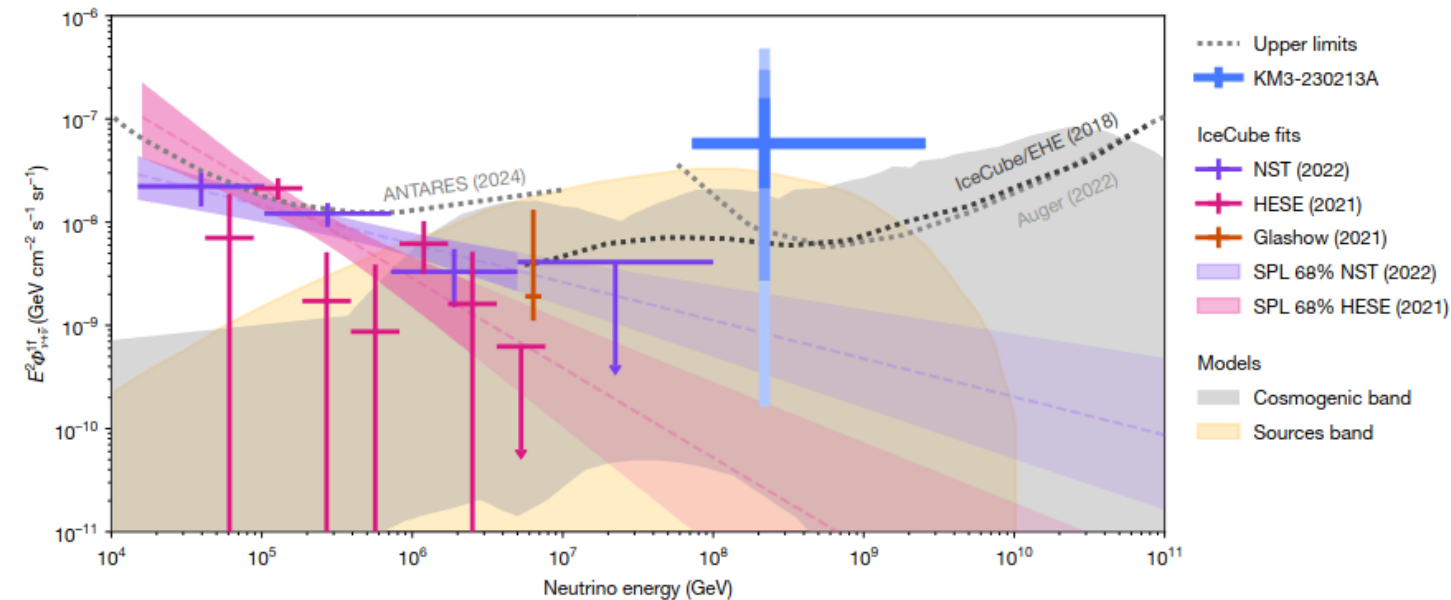
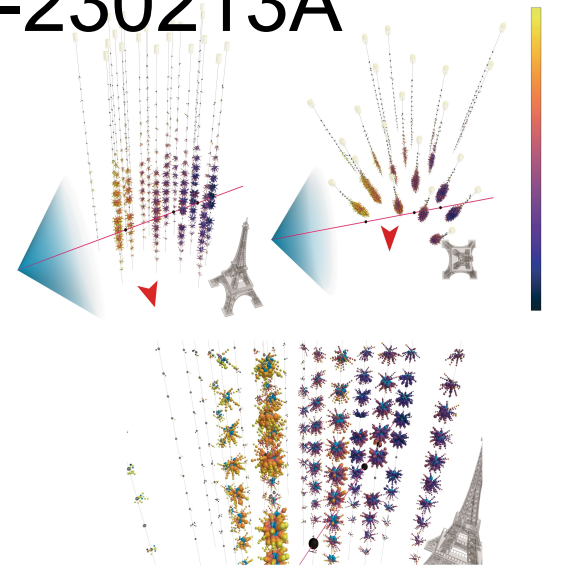
- UHECR-neutrino cross-correlation
- Neutrino-stacking correlation with UHECRs
- UHECR-stacking correlation with neutrinos

All compatible with background

The neutrino event observed by KM3-230213A

Energy ~ 200 PeV !!

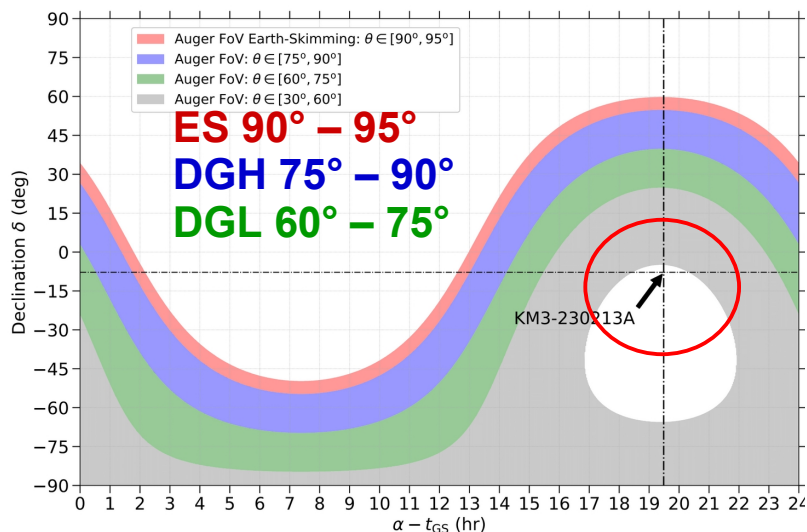
Nature | Vol 638 | 13 February 2025



Astrophysical or
cosmogenic?

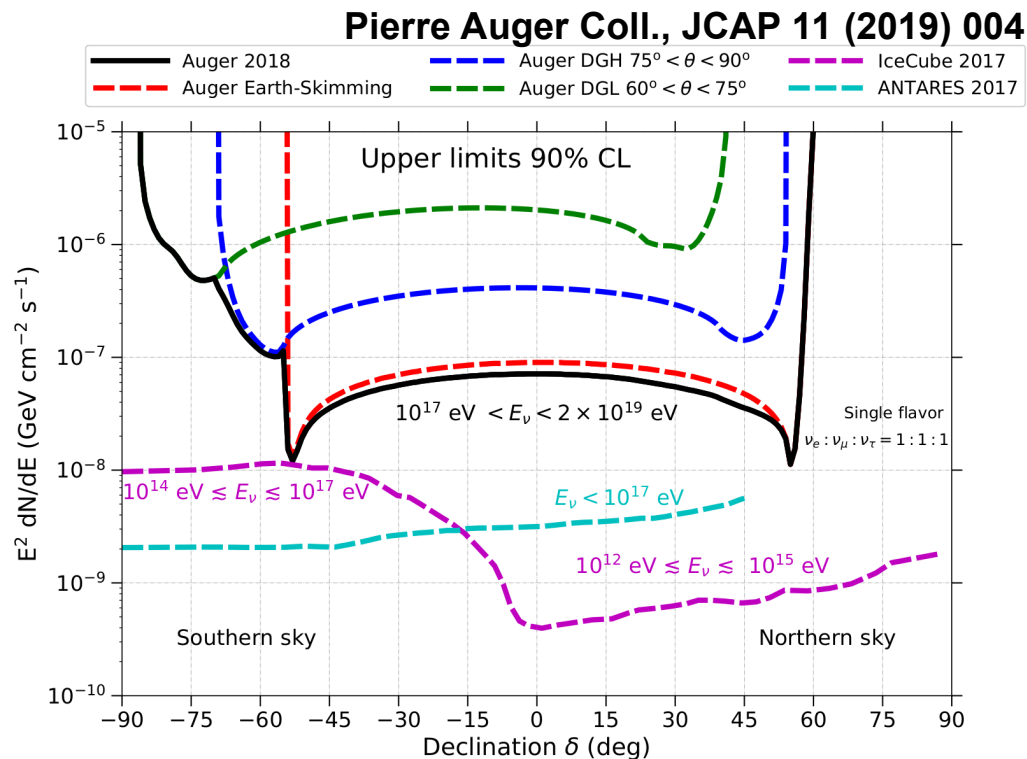
→ **it's a breakthrough**

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

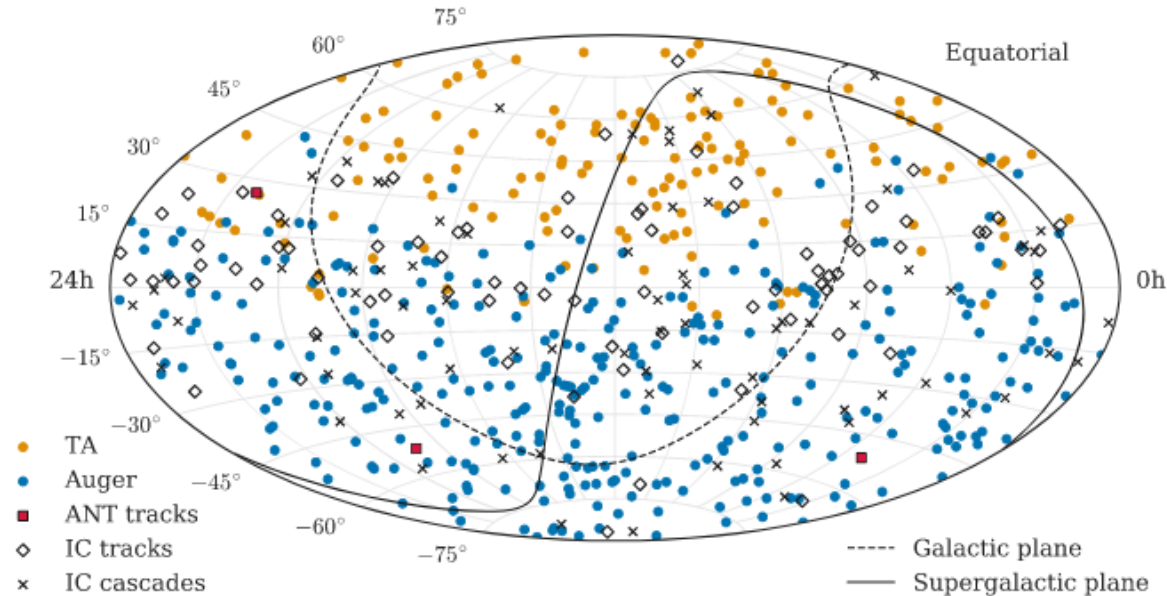


Vertical event ~ 27°

Joint searches (UHECR and neutrinos)

Antares, IceCube, Auger, Telescope Array

APJ 934 (2022)164



Three analyses strategies:

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

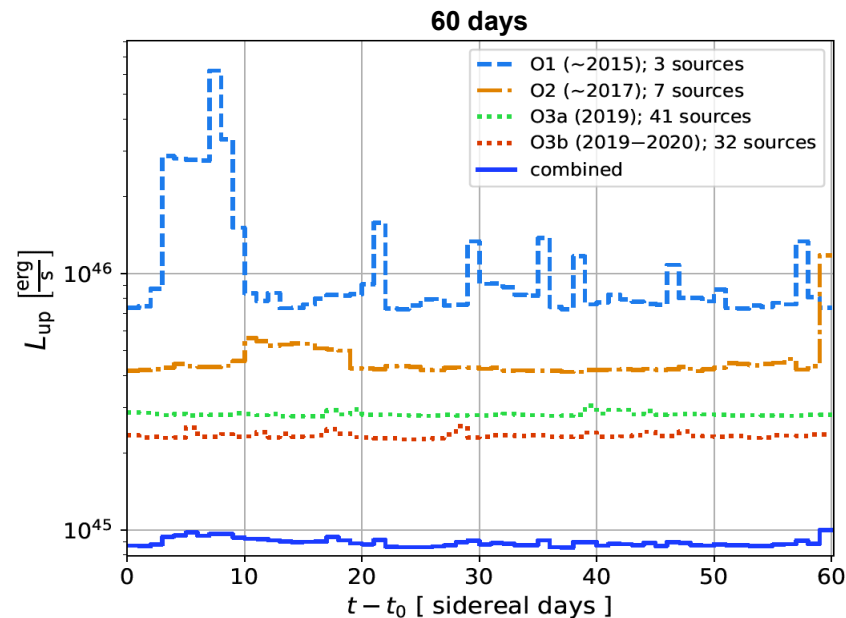
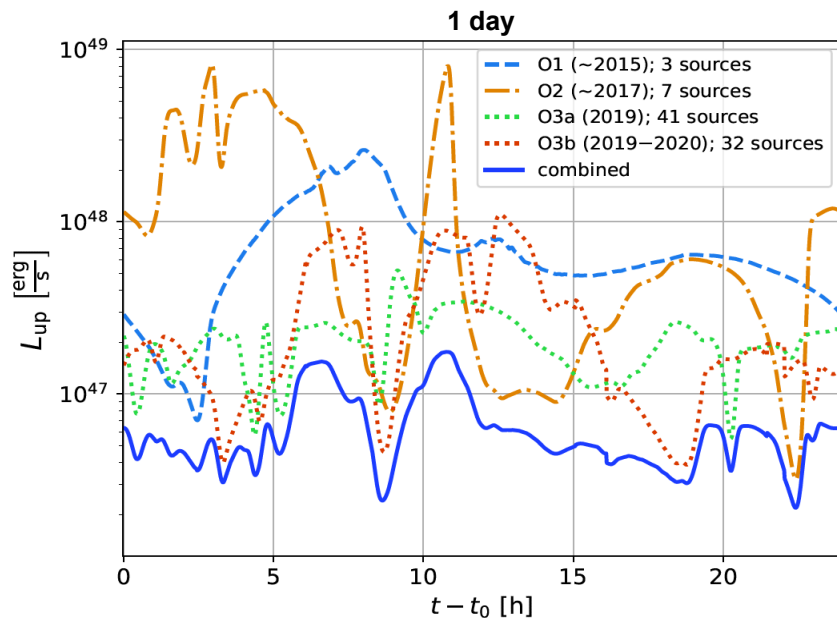
All compatible with background

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 $<5.2 \times 10^{51}$ erg $\rightarrow$ more than 2 orders of magnitude lower than the radiated GW energy



A source: TXS0506+056

Science 361, 146 (2018)

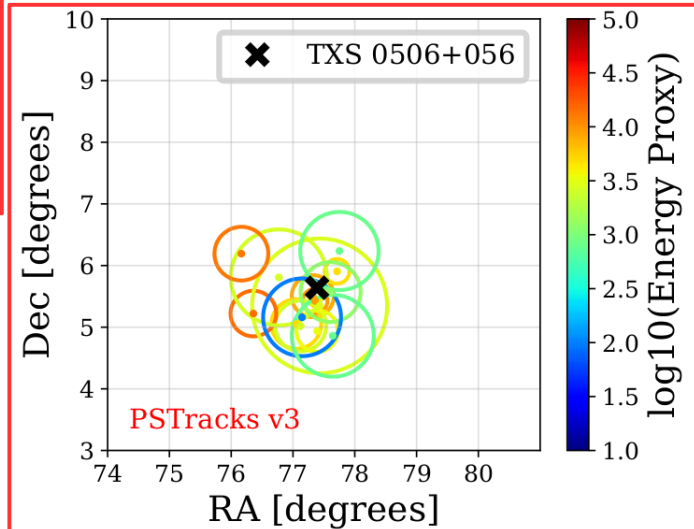
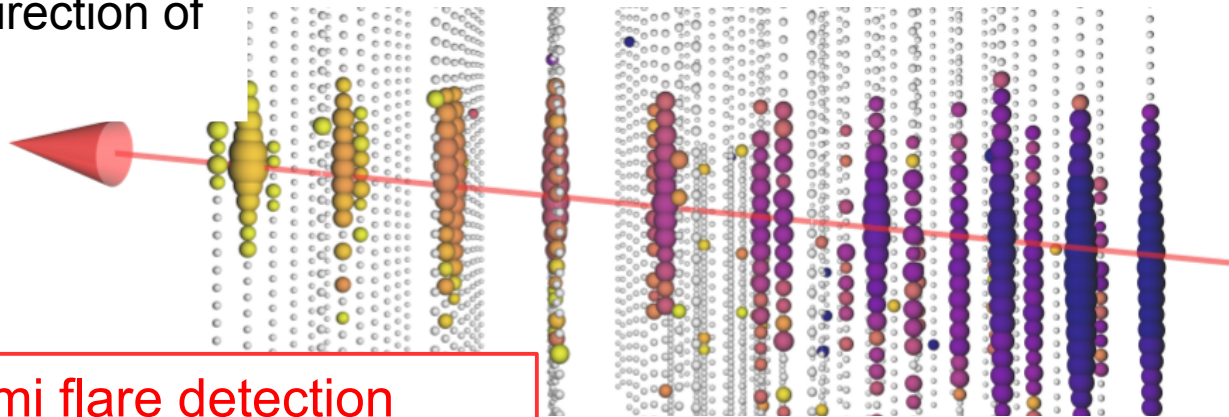
IceCube observed a 290 TeV ν in the direction of TXS0506+056 during flaring state

IceCube Alert IC170922A

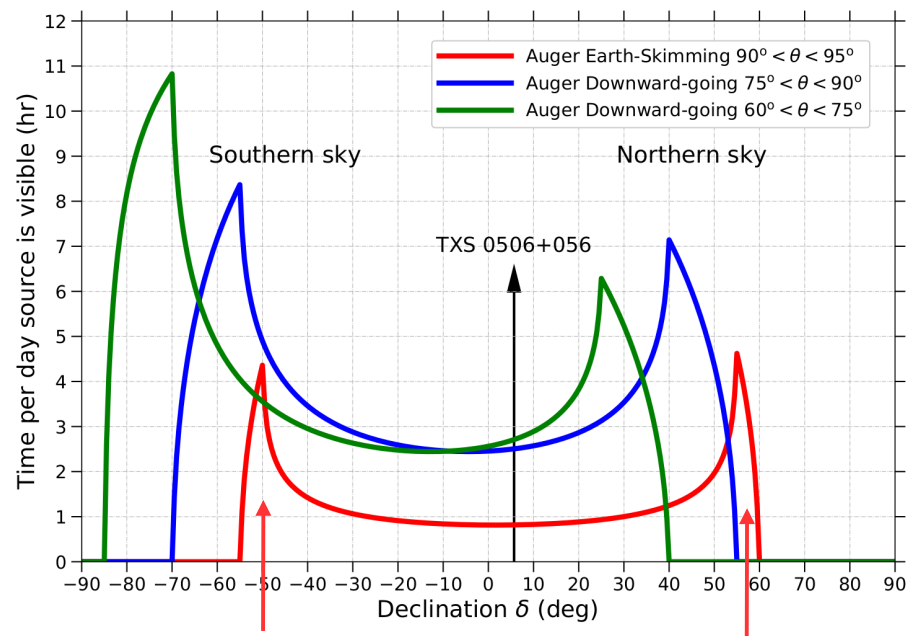
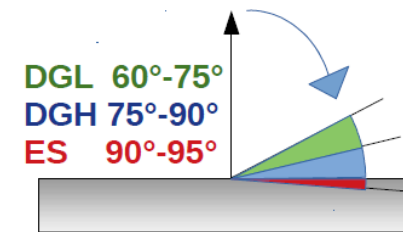
```
////////////////////////////////////  
TITLE:          GCN/AMON NOTICE  
NOTICE_DATE:    Fri 22 Sep 17 20:55:13 UT  
NOTICE_TYPE:    AMON ICECUBE EHE  
RUN_NUM:       130033  
EVENT_NUM:     50579430  
SRC_RA:        77.2853d {+05h 09m 08s} (J2000)  
              77.5221d {+05h 10m 05s} (J2000)  
              76.6176d {+05h 06m 28s} (J2000)  
SRC_DEC:       +5.7517d {+05d 45' 06"} (J2000)  
              +5.7732d {+05d 46' 24"} (J2000)  
              +5.6888d {+05d 41' 20"} (J2000)  
SRC_ERROR:     14.99 [arcmin radius, stat_1sig, 95% containment]  
DISCOVERY_DATE: 18018 TJD; 265 DOY; 17 SEP 2017  
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
($\sim 3.5 \sigma$ level)



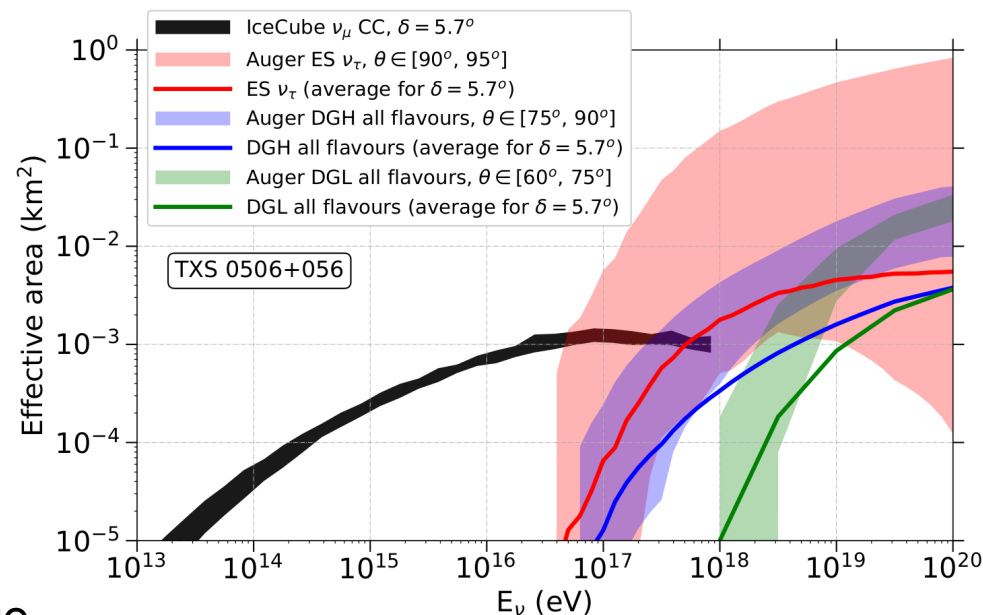
Auger UHE window: TXS0506



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

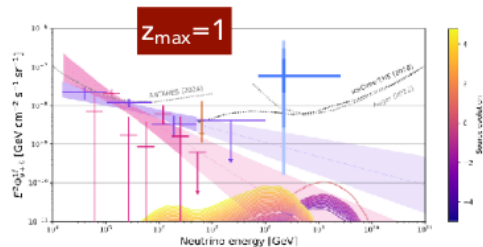
→ complementary to IceCube in the EeV range

TXS0506+056 declination = 5.7°
→ Non optimal sensitivity of the source in all channels

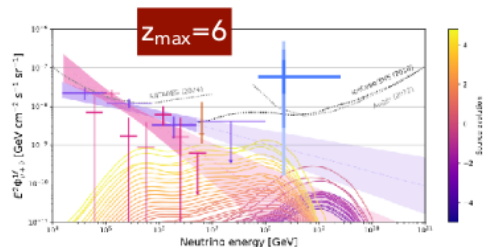


MM analyses to explain the Km3Net event

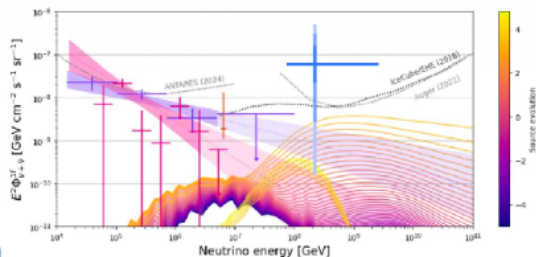
Auger spectrum+composition information above and below the ankle plus limits on ϕ_ν



If the KM3Net-230213A event is cosmogenic, higher probability to come from distant sources



With an even small proton fraction below the ankle, better agreement



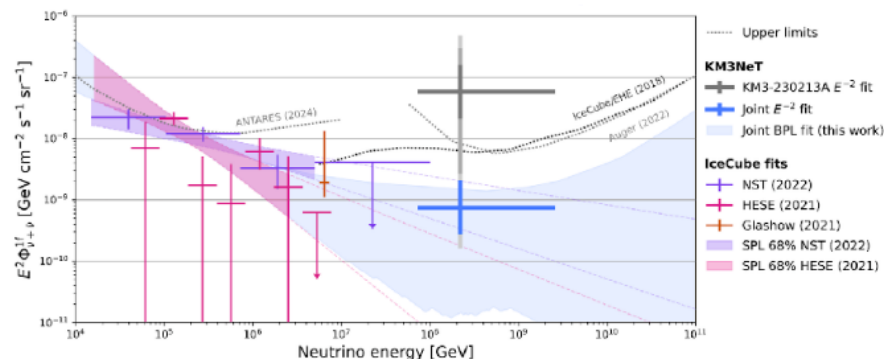
Adriani et al., ApJL 984:L41 (2025)

Is the KM3Net-230213A event compatible with the non observation of EHE neutrinos by IceCube and Auger?

Km3Net-only flux $E^2\Phi = 5.8 \times 10^{-8} \text{ GeV cm}^{-2} \text{ sr}^{-1}$

Joint E-2 fit (Km3Net + IceCube EHE + UHE Auger)

$E^2\Phi = 7.5 \times 10^{-10} \text{ GeV cm}^{-2} \text{ sr}^{-1}$



Mild to moderate tension 1.6-2.9 σ

most plausible explanation upward fluctuation of a UHE ν flux

Adriani et al., PRX 15 (2025) 031016