Riunione con i referees
Napoli 4 Luglio 2025

Search for photons and neutrinos with the Pierre Auger Observatory

Lorenzo Perrone - Università del Salento e INFN Sezione di Lecce

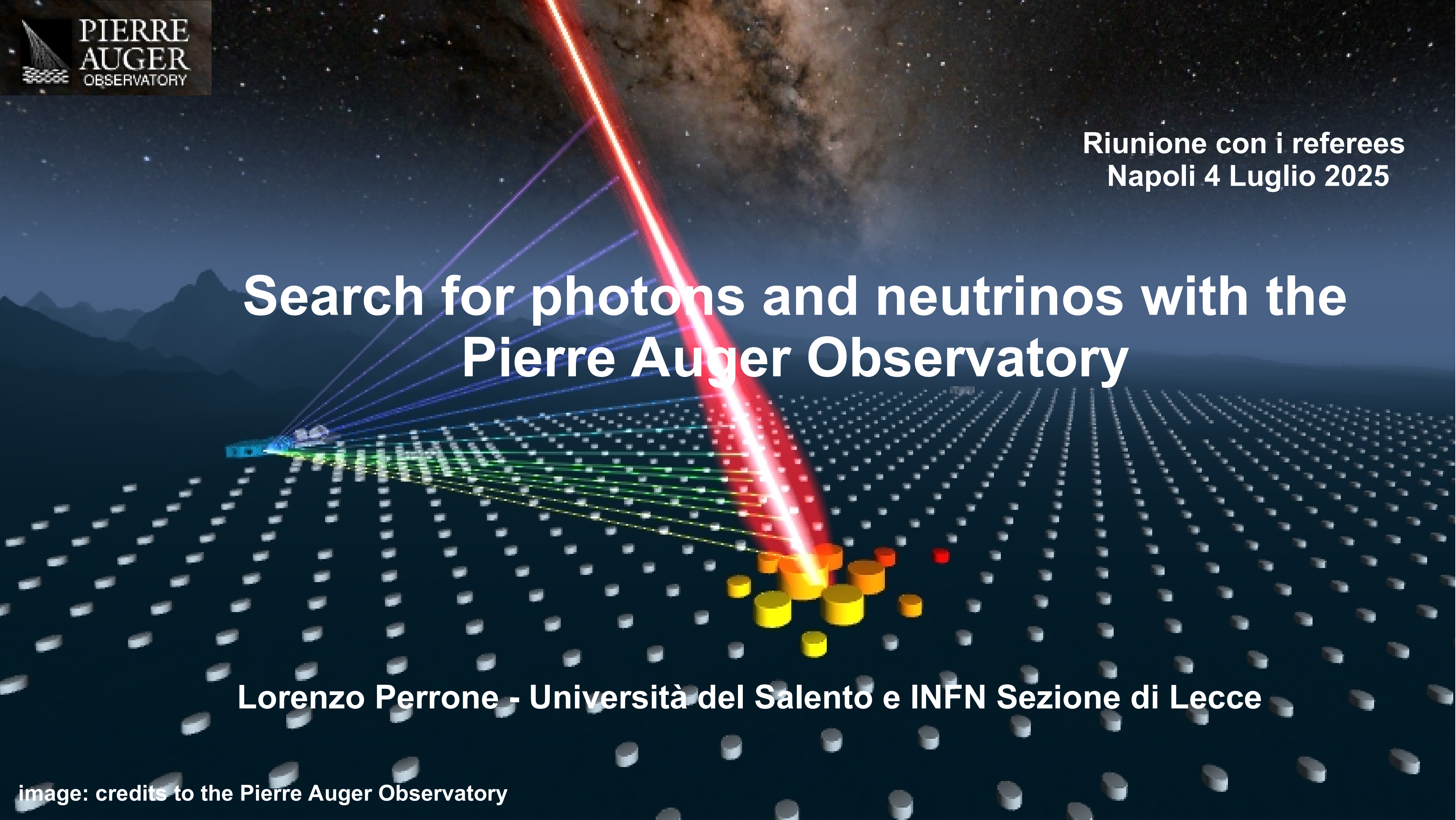
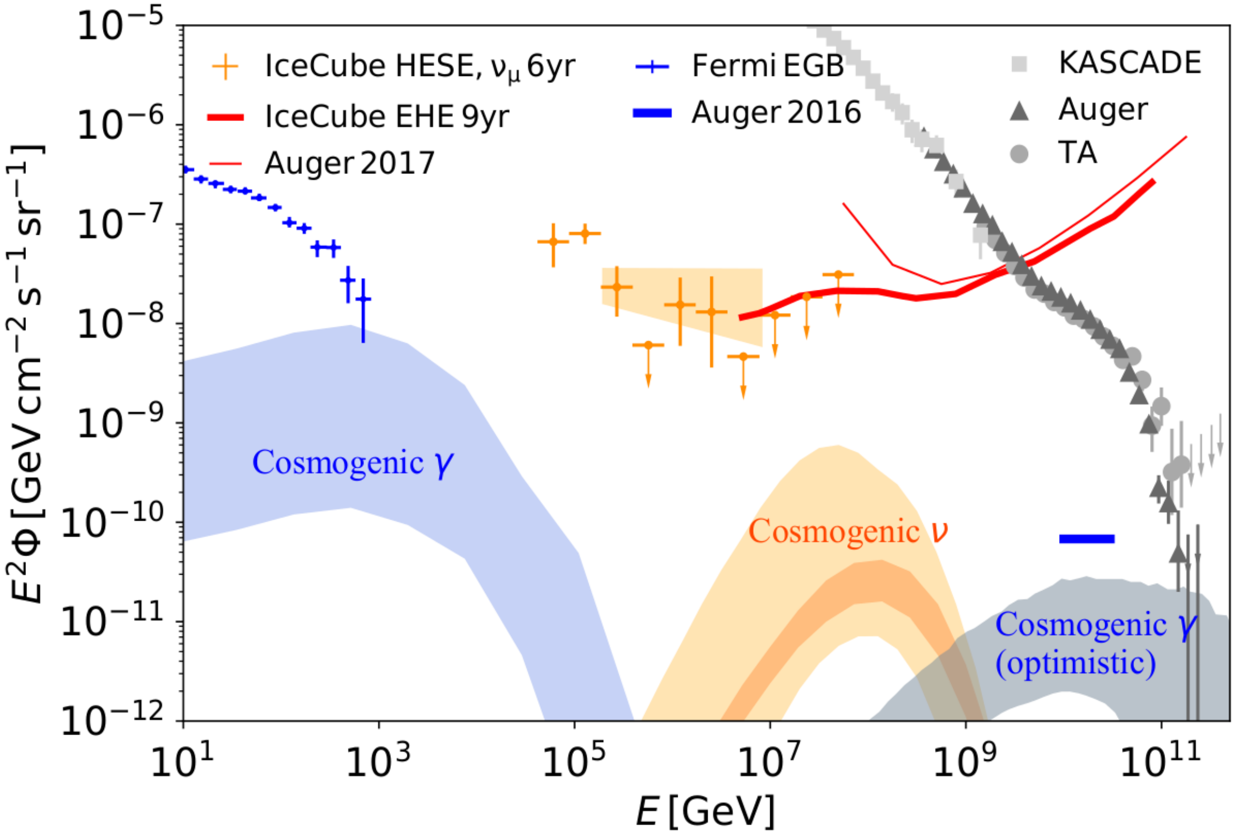


image: credits to the Pierre Auger Observatory

The multi-messenger astronomy landscape

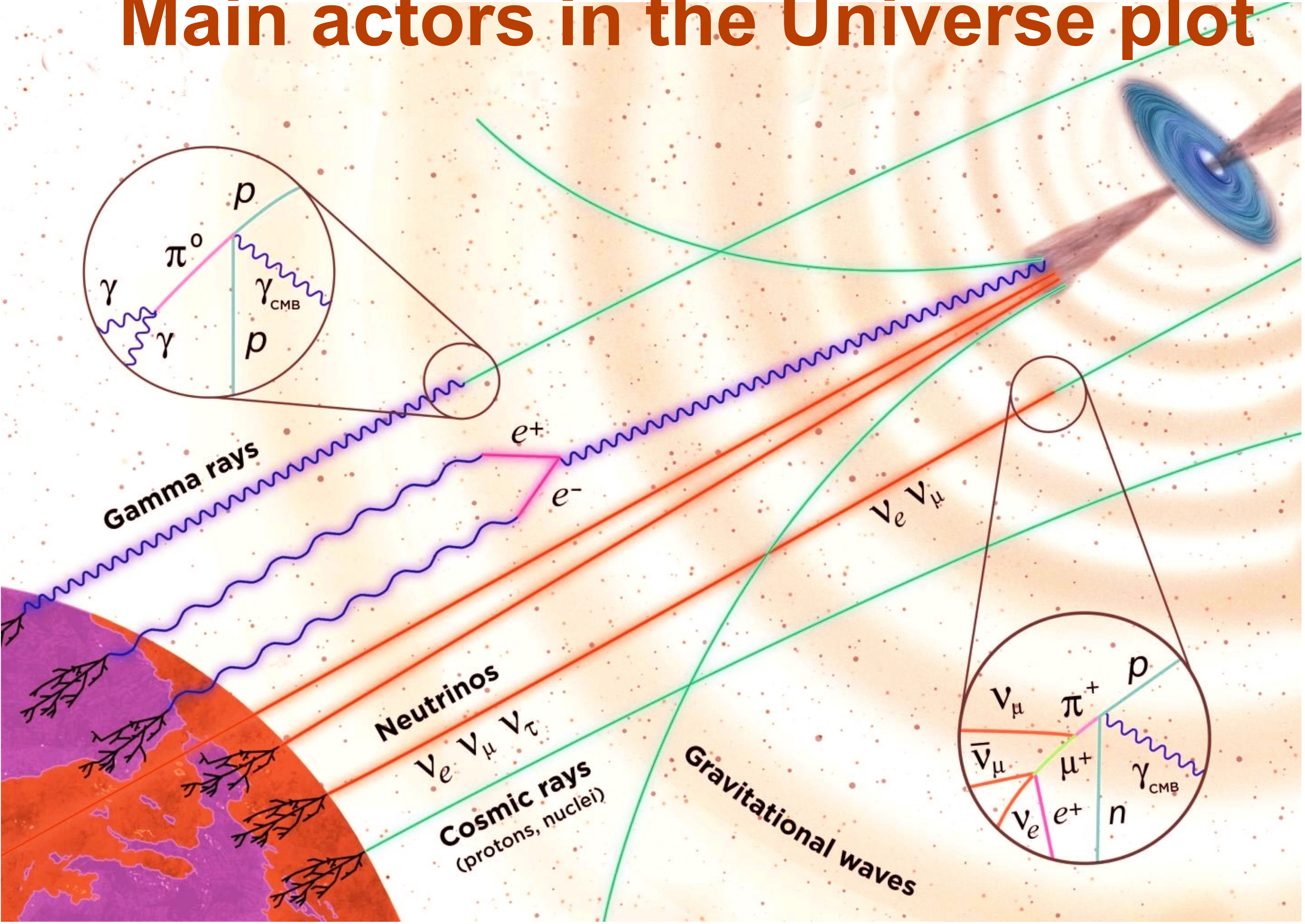


Strong interplay between different "cosmic" actors

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

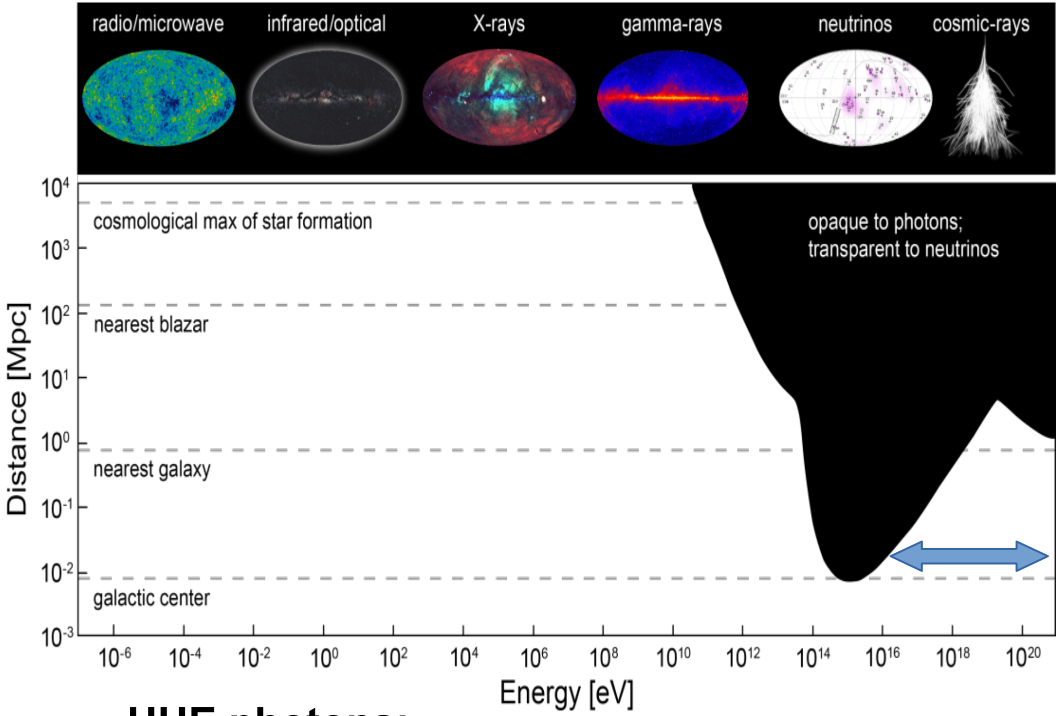
Gravitational Waves:
Multi wavelength searches in combination with mergers

→ **Charged CR:**
magnetic fields deflection

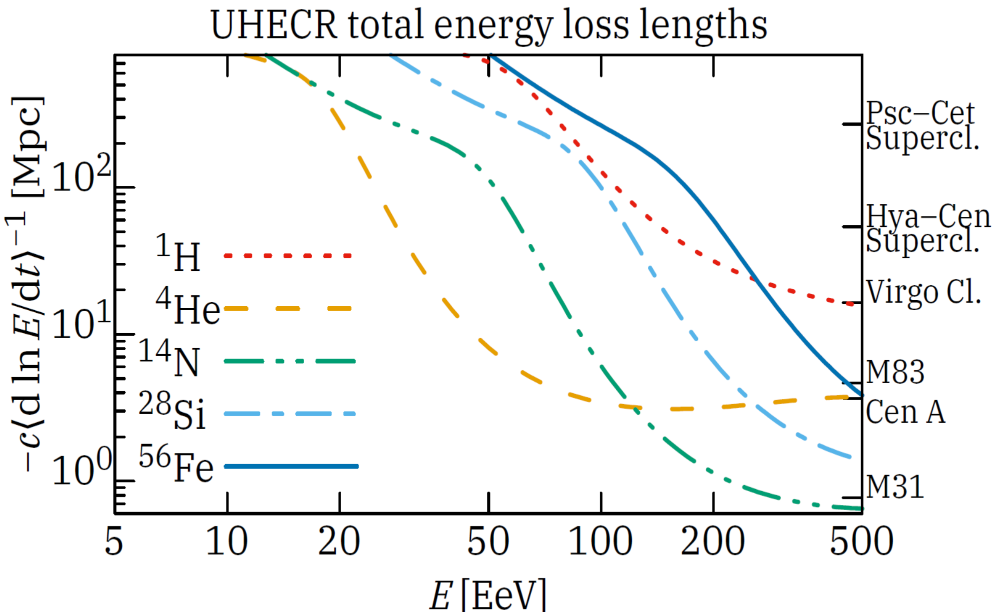
→ **UHE photons:**
limited horizon (local universe) or hints for new physics (SHDM, LIV)

→ **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)



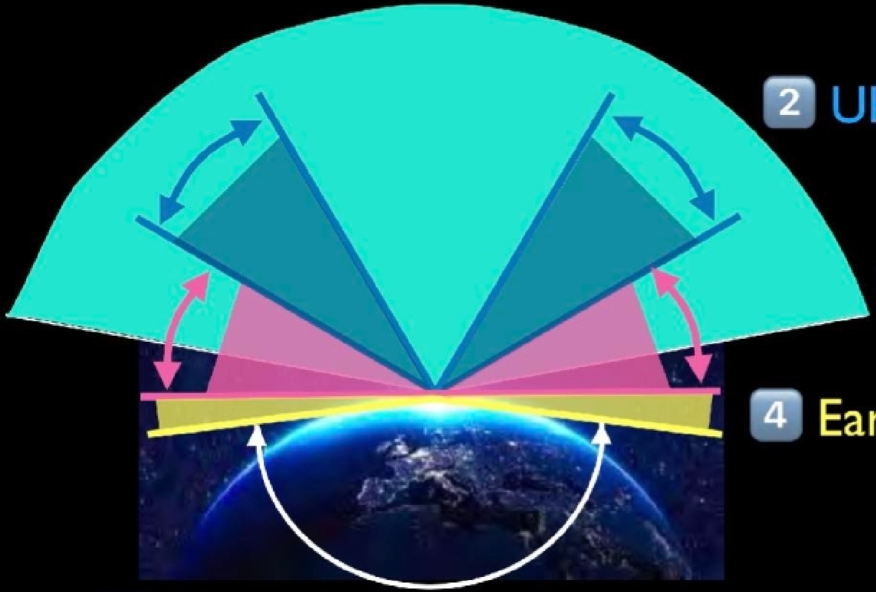
→ **UHE photons:**
limited horizon (local universe)
or hints for new physics (SHDM, LIV)

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

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

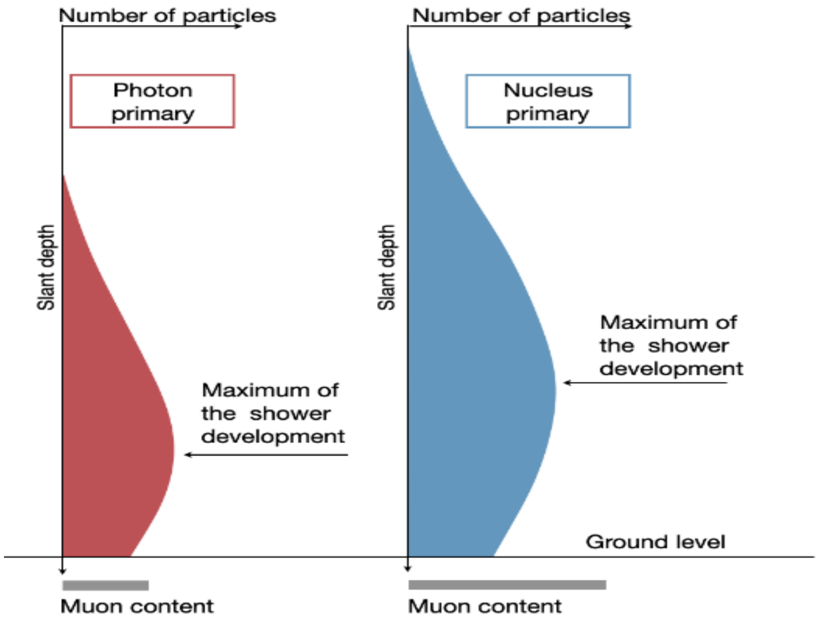
Auger: A 4π MM Observatory

1. Neutrons and charged CRs: $\Theta \leq 80°$



2. UHE Photons: $30° \leq \Theta \leq 60°$
3. Down-Going Neutrinos: $60° \leq \Theta \leq 90°$
4. Earth Skimming Neutrinos: $90° \leq \Theta \leq 95°$
5. HE BSM Particles: $\Theta > 95°$

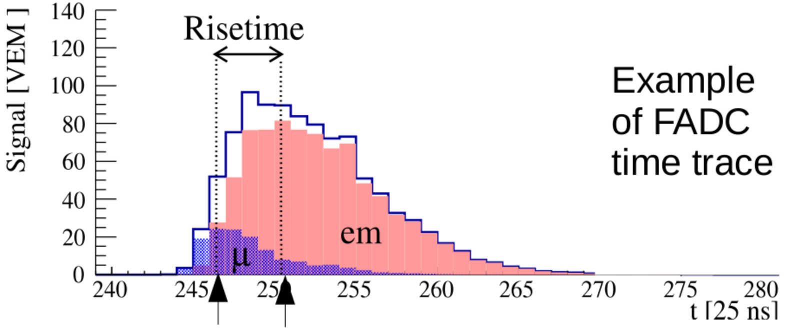
UHE Photon induced cascades



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

observable characteristics:

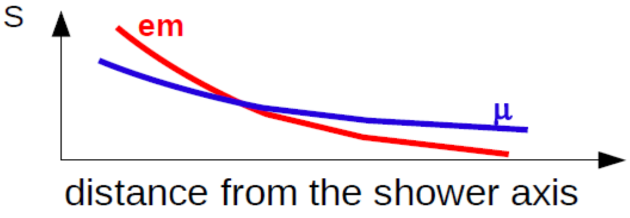
- deeper <Xmax>
- steeper LDF
- smaller footprint
- broader signal



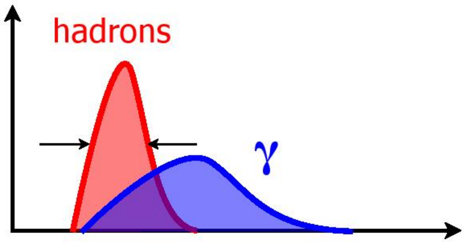
Example of FADC time trace

10% 50% quantiles

steeper LDF



longer rise-time

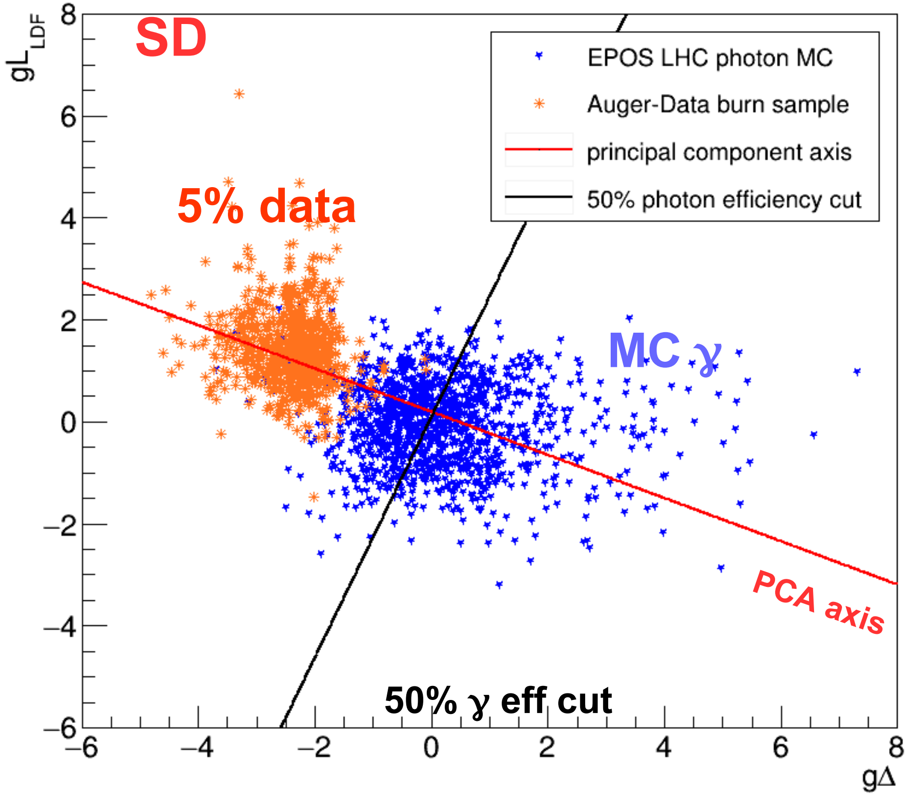


FADC-time

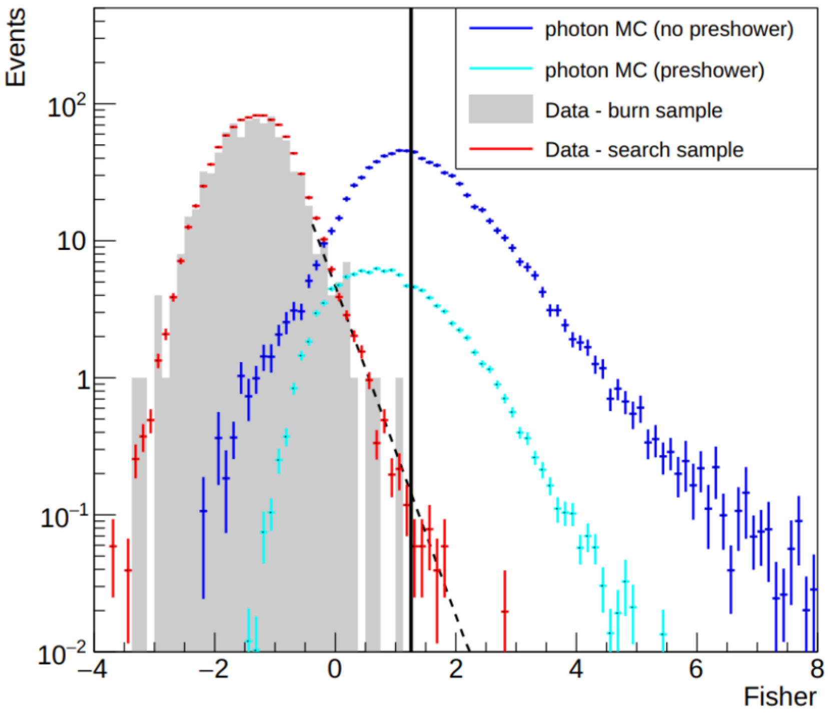
Auger SD photon search

JCAP05(2023)021

E > 10^{19} eV
SD-1500



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

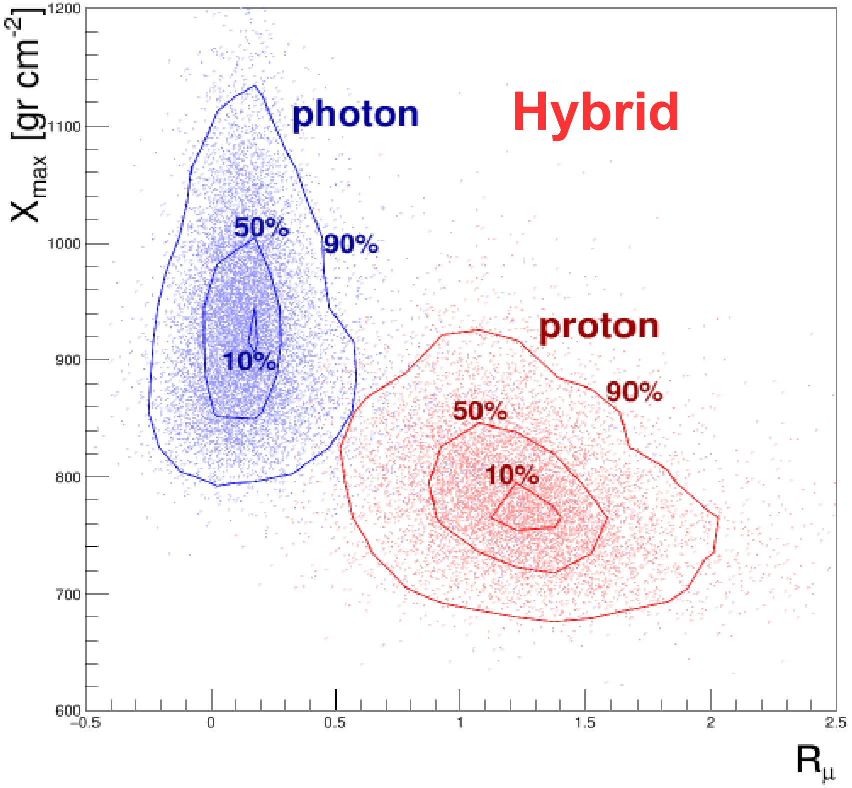


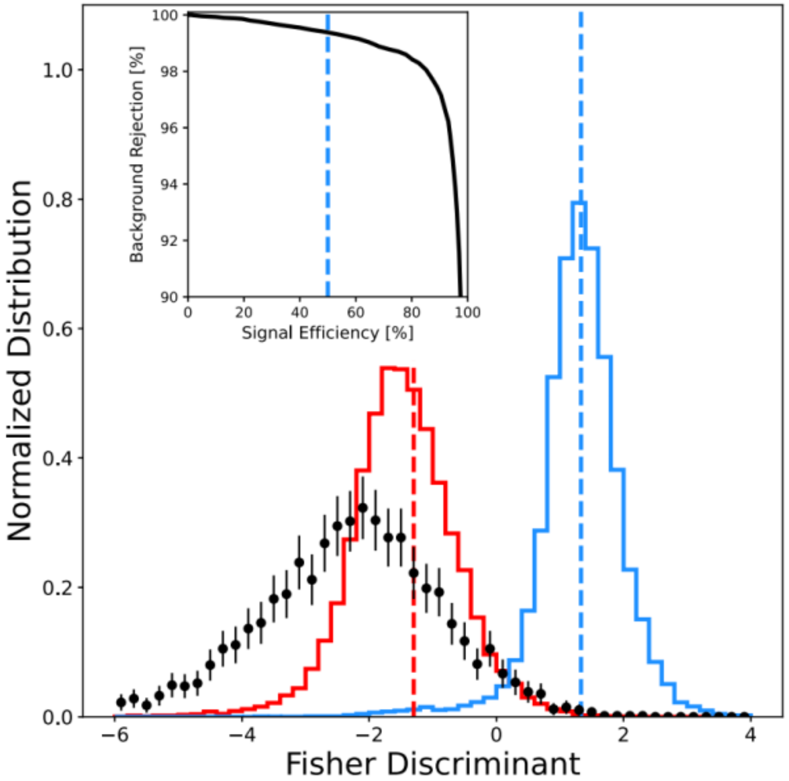
16 Candidates, consistent with the expected background

Auger: Hybrid photon search

Phys. Rev. D 110, 062005 (2024)

E > 10 [18] eV
FD+ SD1500





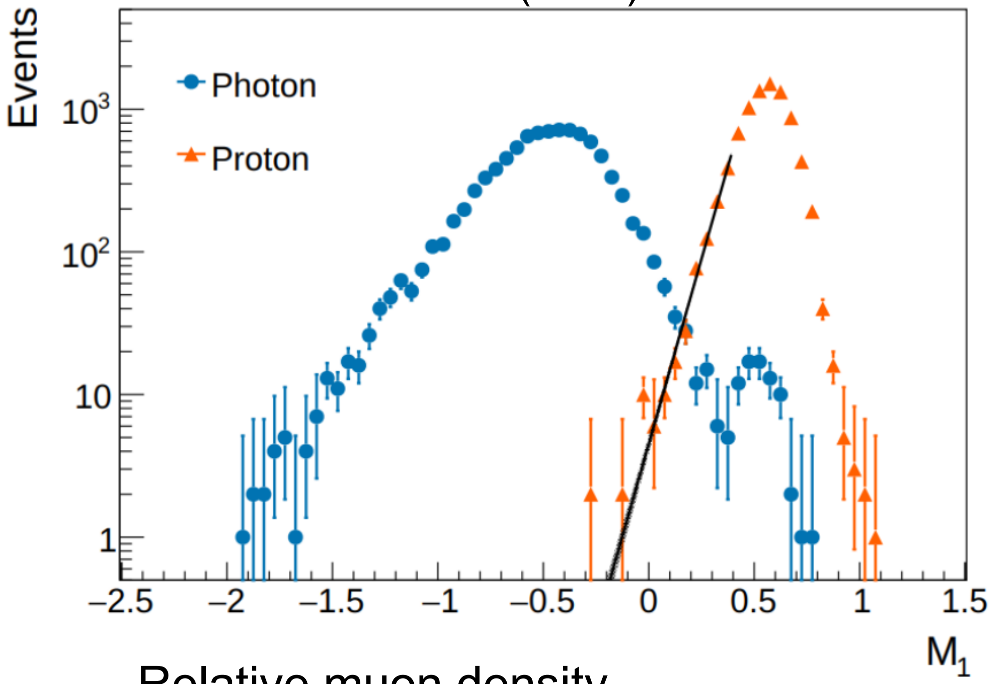
Maximum of shower development: $\mathbf{X_{max}}$
Muon content of the shower (universality): R_μ

22 Candidates, consistent with the expectation of 30 ± 15

Auger photon search at lower energies

Above 5 10 [16] eV:
SD433 + UMD 19 stations

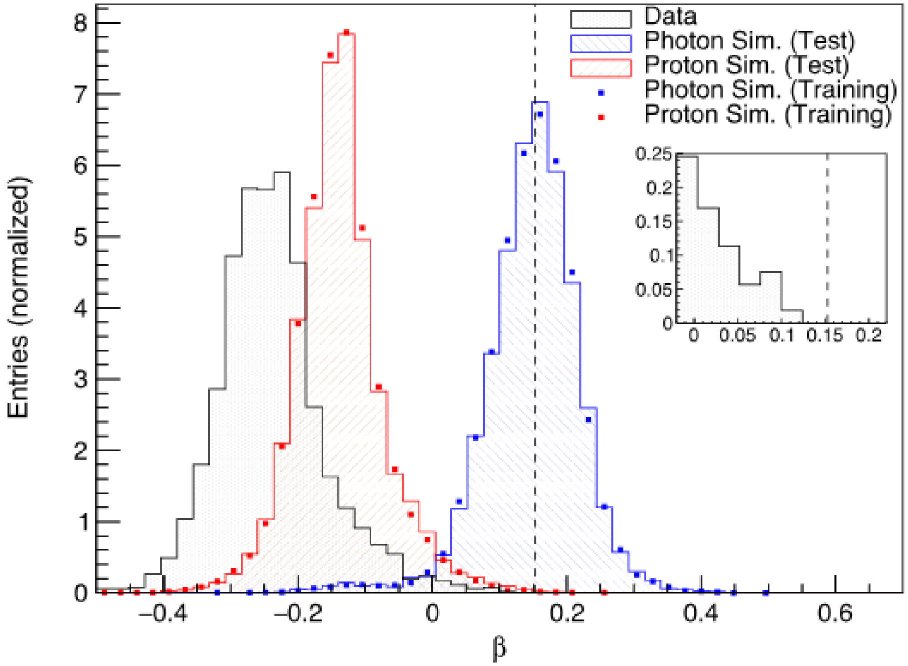
JCAP 05 (2025) 061



Relative muon density
0 candidates found

10^{17} - 10^{18} eV
FD HEAT + SD750

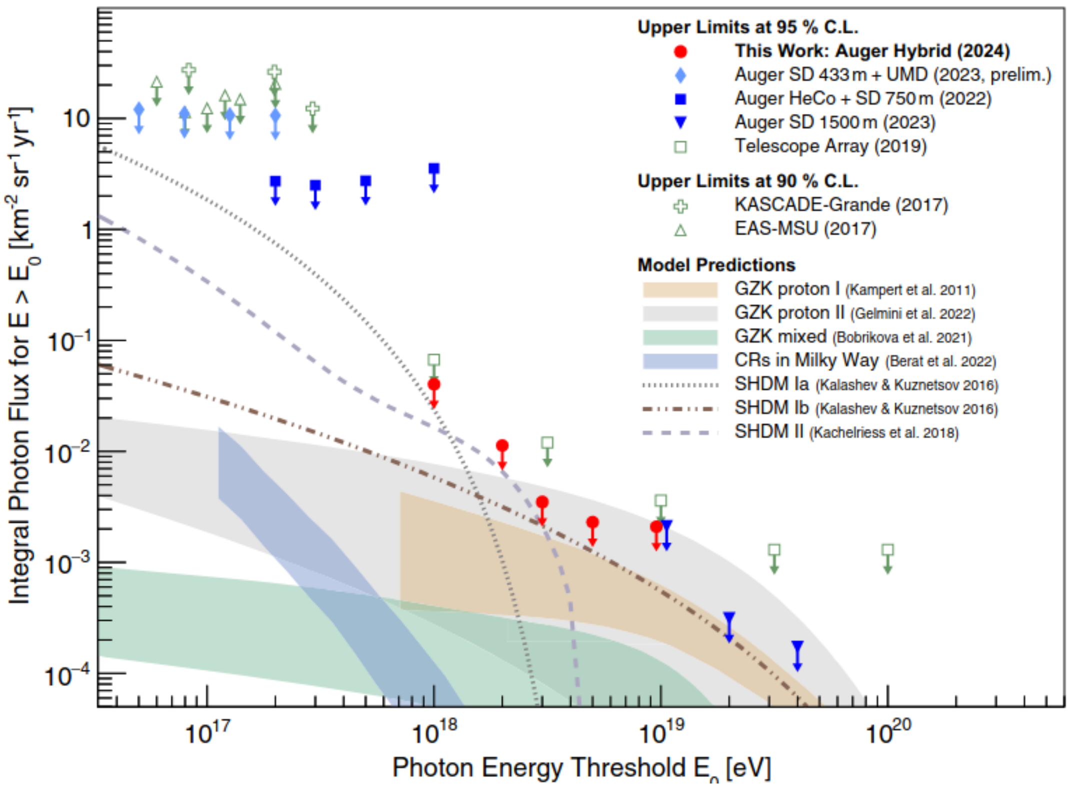
Astrophys. J. 933 (2022) 125



BDT → Xmax and Sb [signal size]
0 candidates found

Upper limits on diffuse photon flux

ApJ. 933 (2022)125
JCAP 05 (2023) 021
Phys. Rev. D 110, 062005 (2024)
JCAP05(2025)061



Strictest limits at E> 40 PeV

16 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

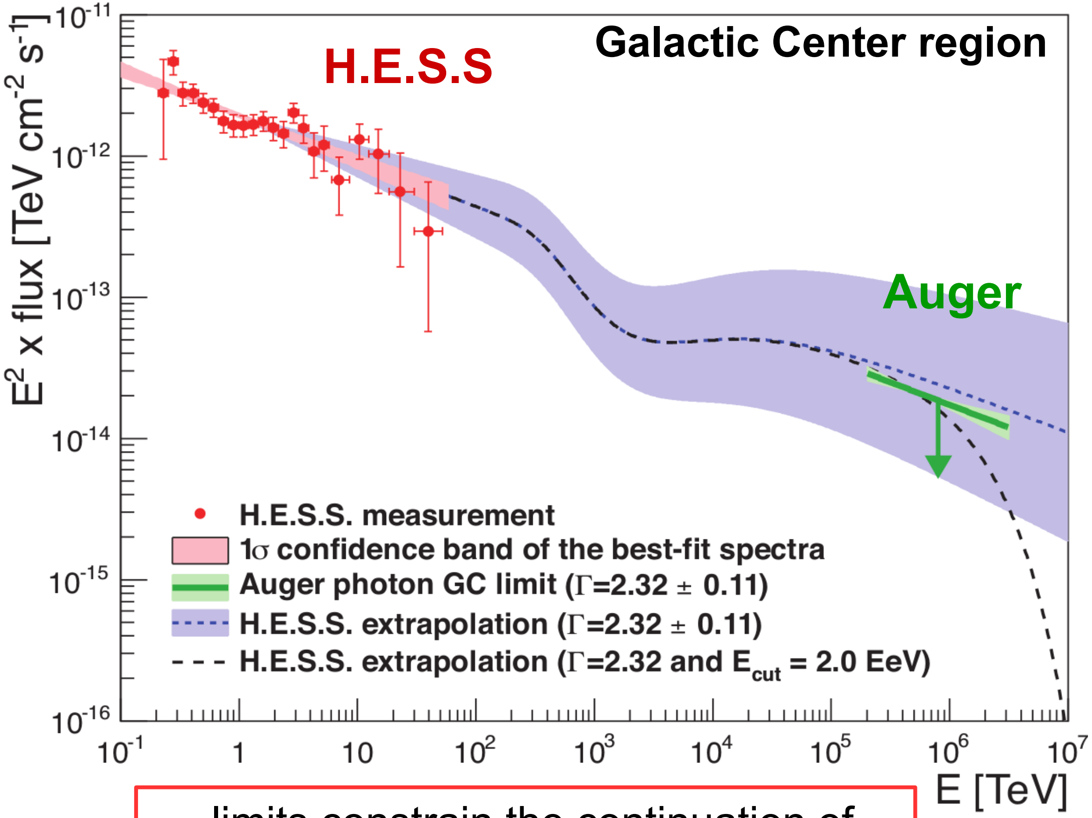
Pierre Auger Coll., ApJL 837: L25 (2017)

Previous blind search limits

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

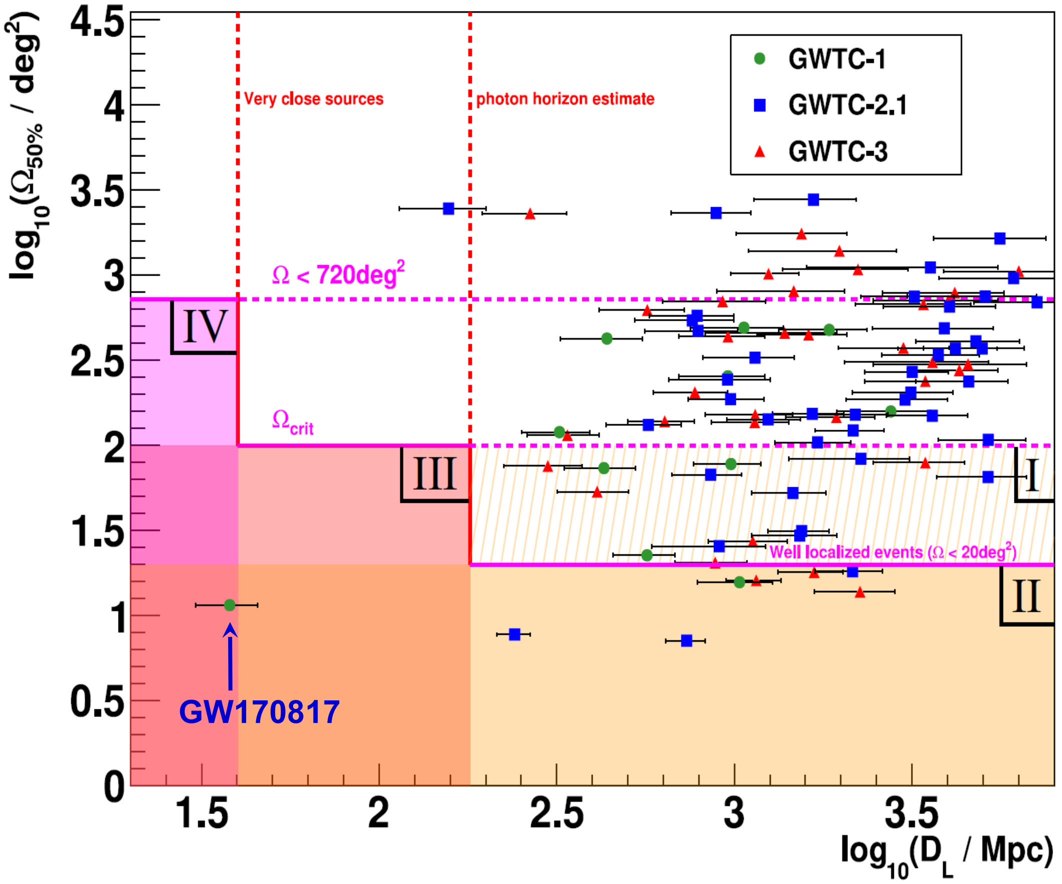
→ complement targeted neutron searches

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

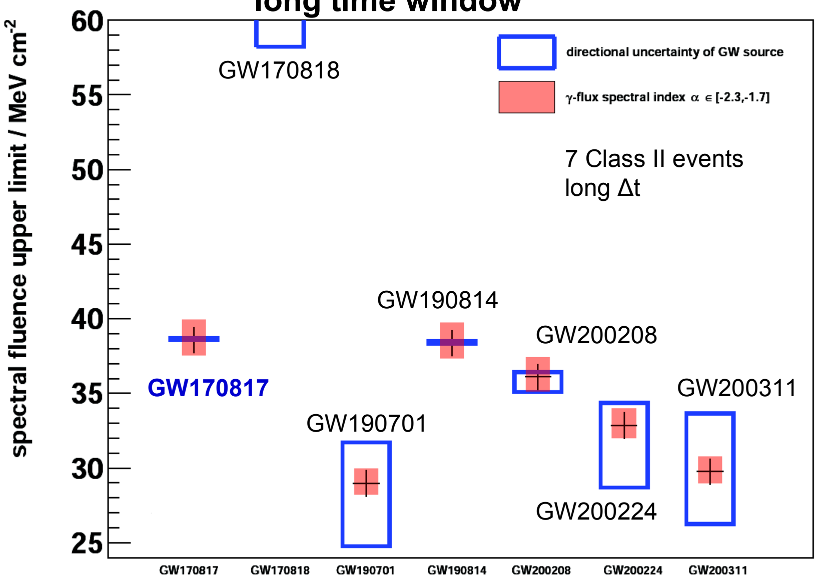
No candidate found for any GW event → flux upper limits

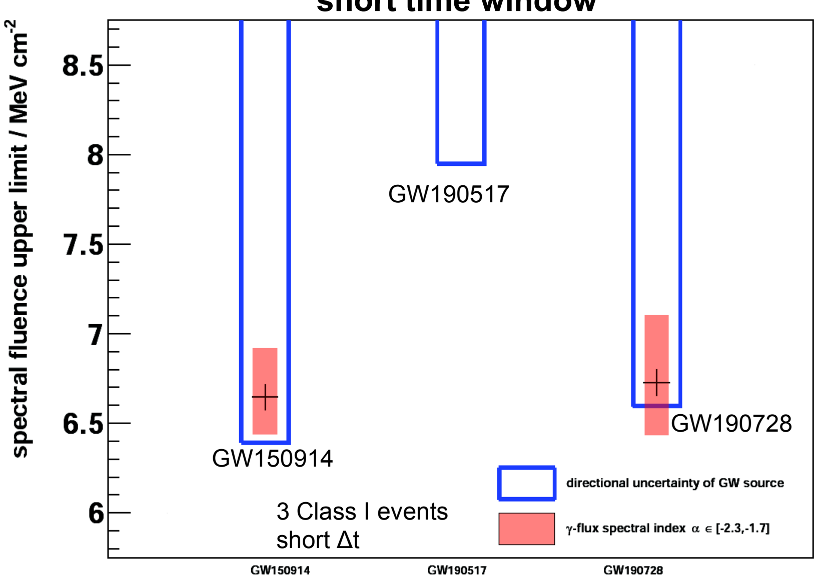
First ever limits on γ from GW at UHE

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

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

Auger Coll., ApJ 952 (2023) 91





GW170817: energy transferred into UHE-photons above 40 EeV constrained to be less than 20% of its total energy

Gruppi italiani tradizionalmenti coinvolti in prima linea nelle analisi della ricerca dei fotoni

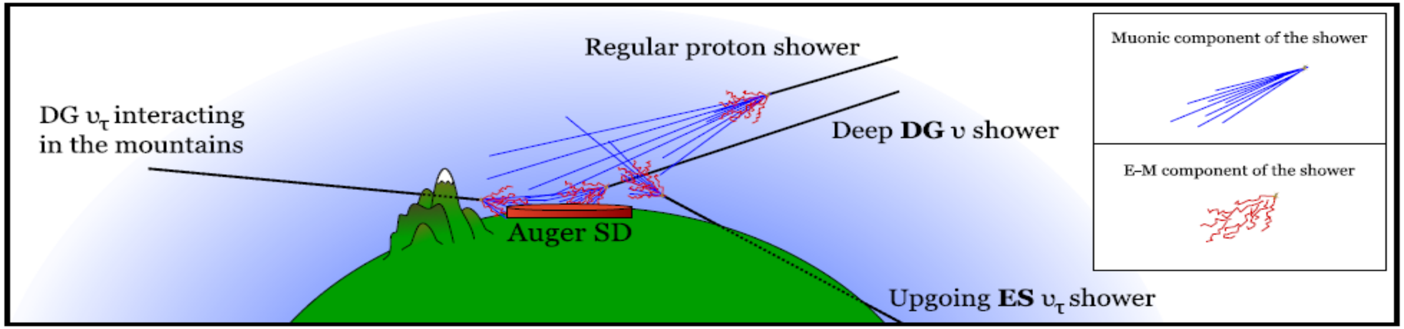
Analisi ibrida basata su universalità
FD + SD1500 (hybrid data) [PRD 110, 062005 (2024)] (Lecce)

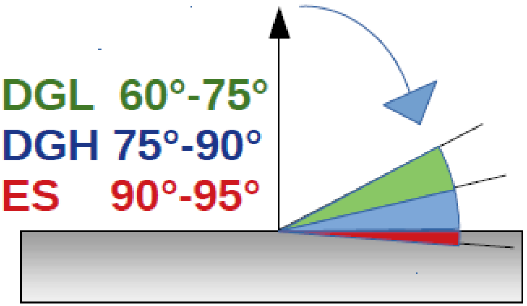
Contributo di Lecce nell'analisi SD SD1500 [JCAP 05 (2023) 021]
Contributo dell'Aquila in HEAT/Coihueco + SD75 [Astrophys. J. 933 (2022) 125]
Contributo di Torino in SD433 + UMD [JCAP 05 (2025) 061]

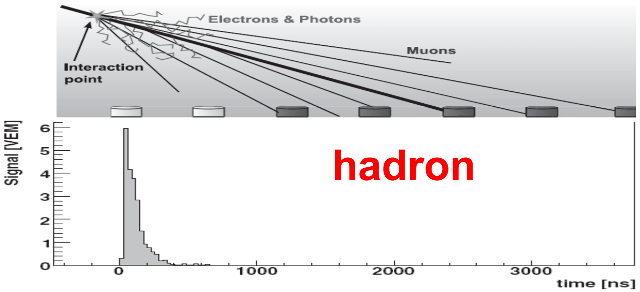
Implicazioni limiti fotoni e neutrini su fisica fondamentale (GSSI, Torino)
PRD 109, L081101 (2024)
PRL130, 061001 (2023)

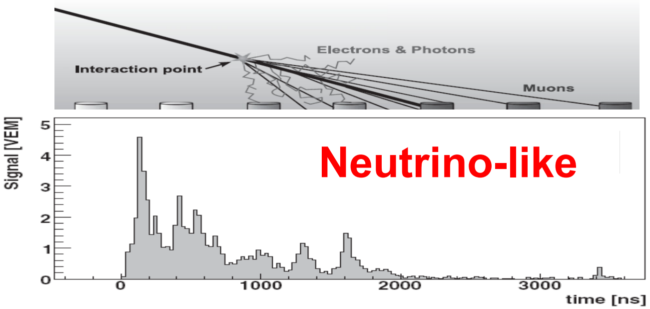
Lavoro in progress (Lecce, Napoli, Torino)
Aggiornare analisi ibrida con una migliore stima del background
Sfruttare i rivelatori di AugerPrime per migliorare la capacità di separazione fotoni/adroni

Auger: UHE neutrinos with the SD



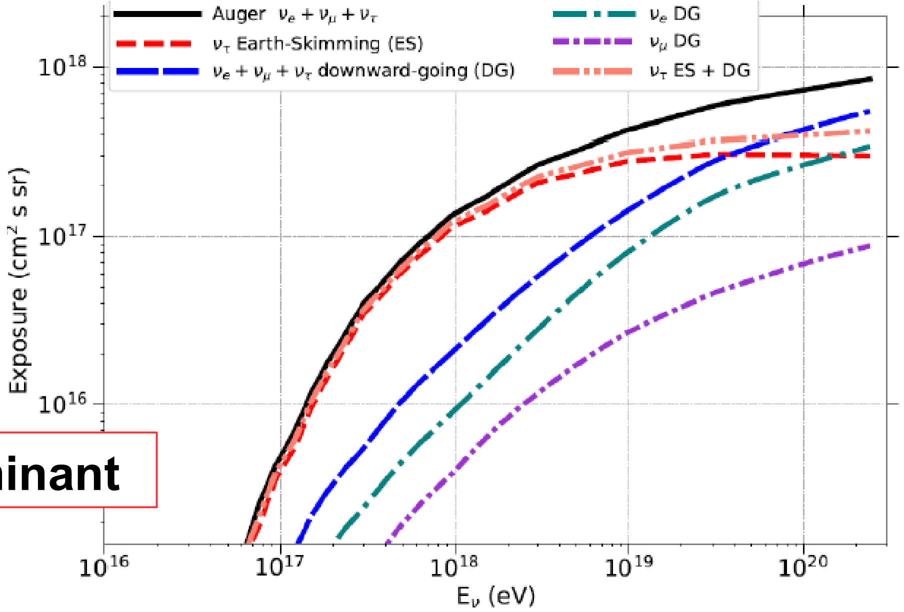






Sensitivity to different channels

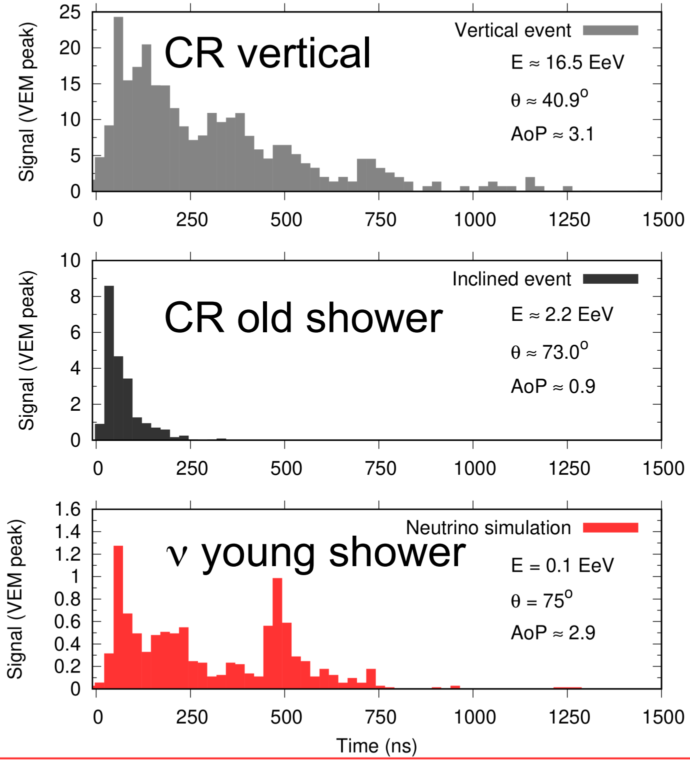
ES 79.4%
DGH 17.6%
DGL 3.0%



ν_τ ES sensitivity dominant

Search for neutrinos with the SD: signature

typical signal shapes

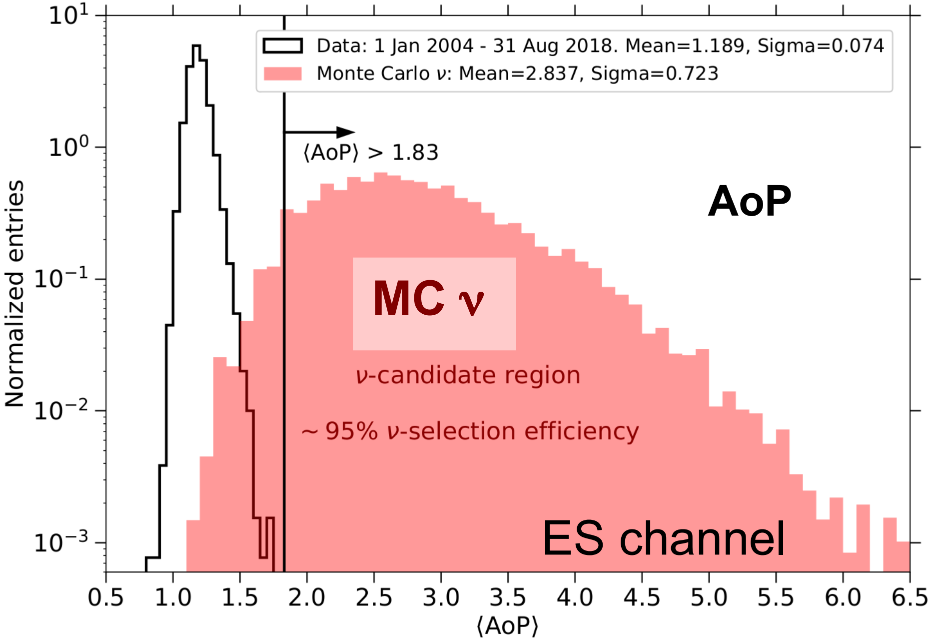


Signature:

"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!**

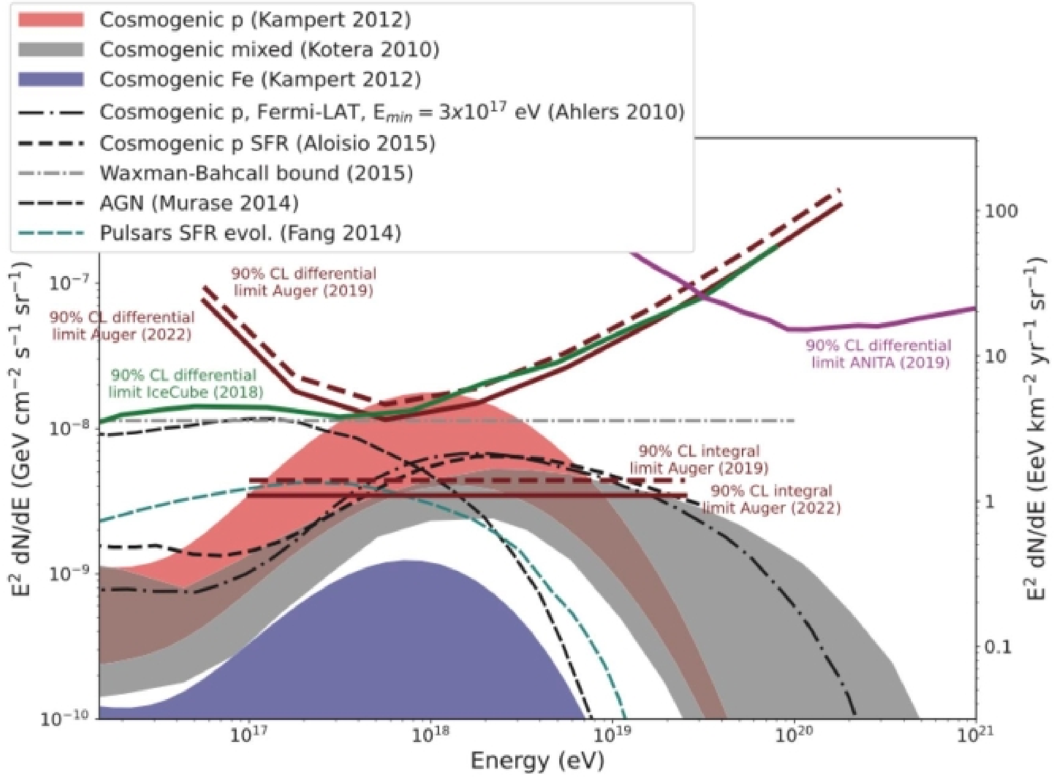
NO Candidates found

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



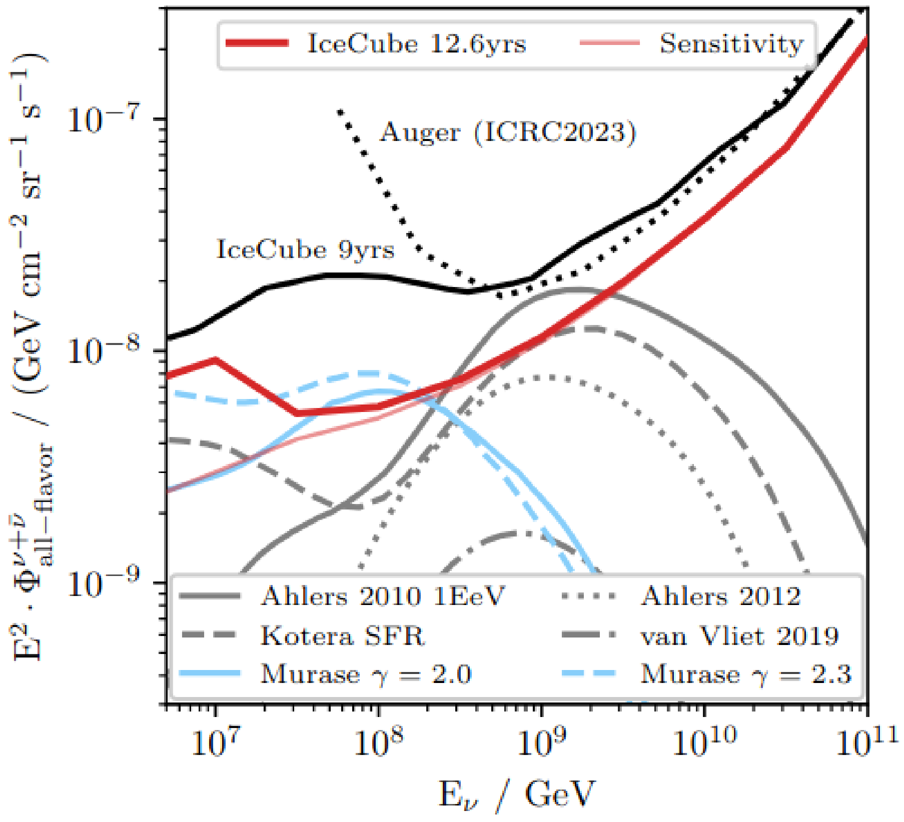
Maximum sensitivity ~ **1 EeV**

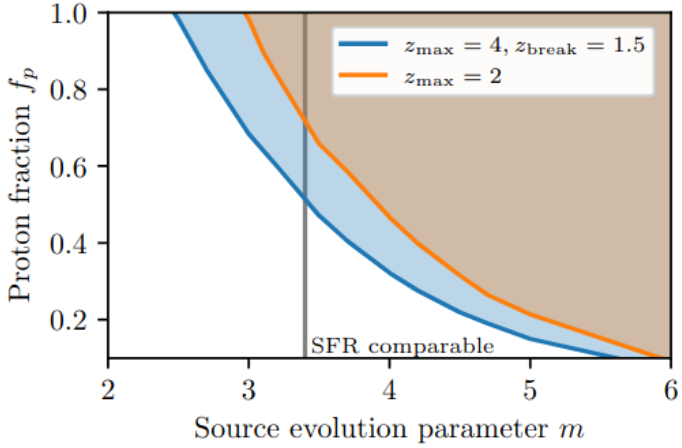
Point-like sources
also in coincidence with observations by other experiments
For example TXS 0506+056

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 https://arxiv.org/pdf/2502.01963

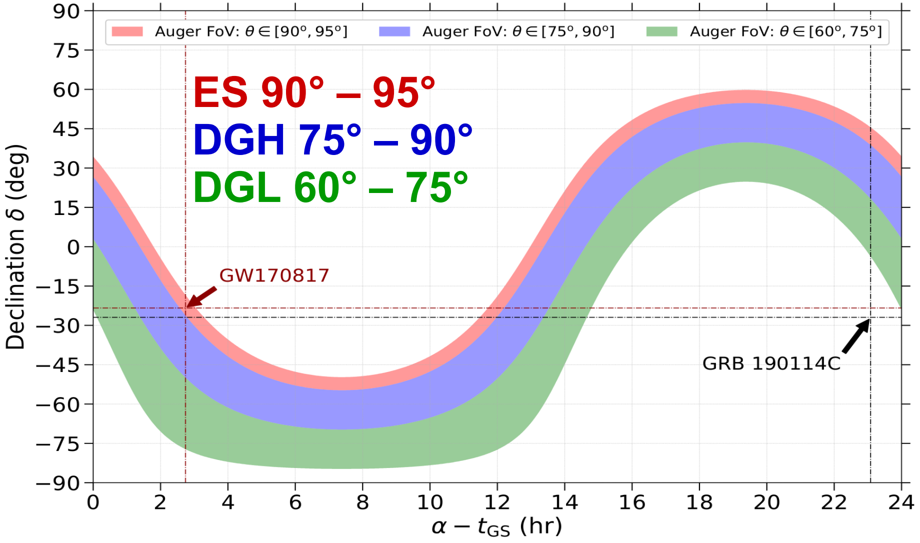




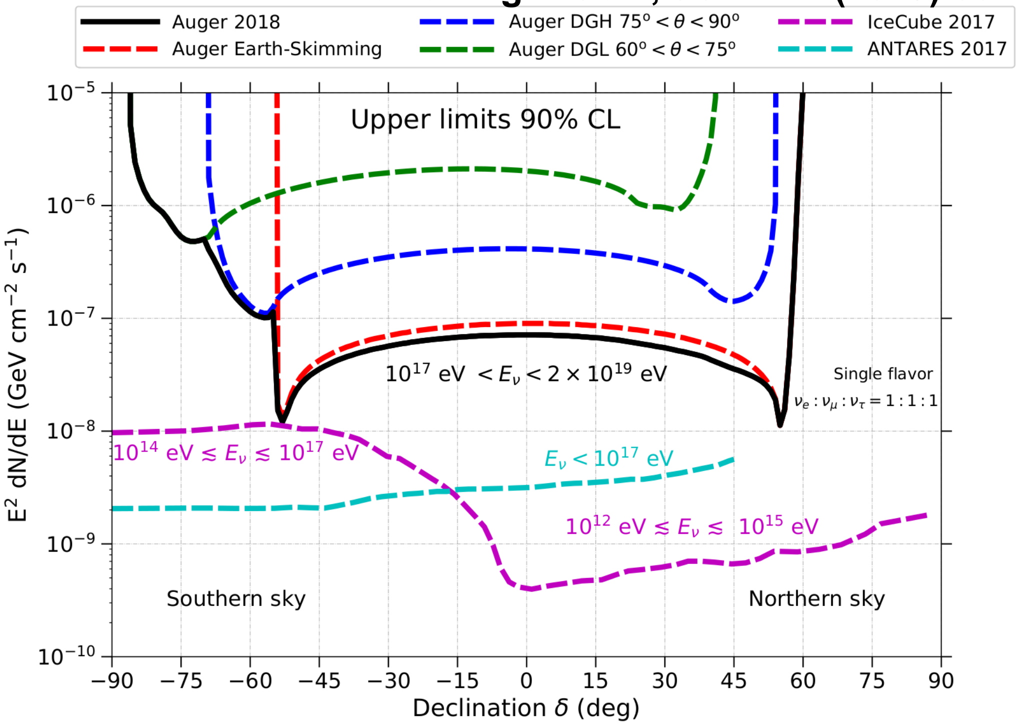
Constrain the proton fraction
<~ 70% above 30 EeV

disfavor the “proton-only” hypothesis for UHECRs using neutrino data.
(not relying on hadronic models)

UHE neutrinos: point sources sensitivity



Pierre Auger Coll., JCAP 11 (2019) 004

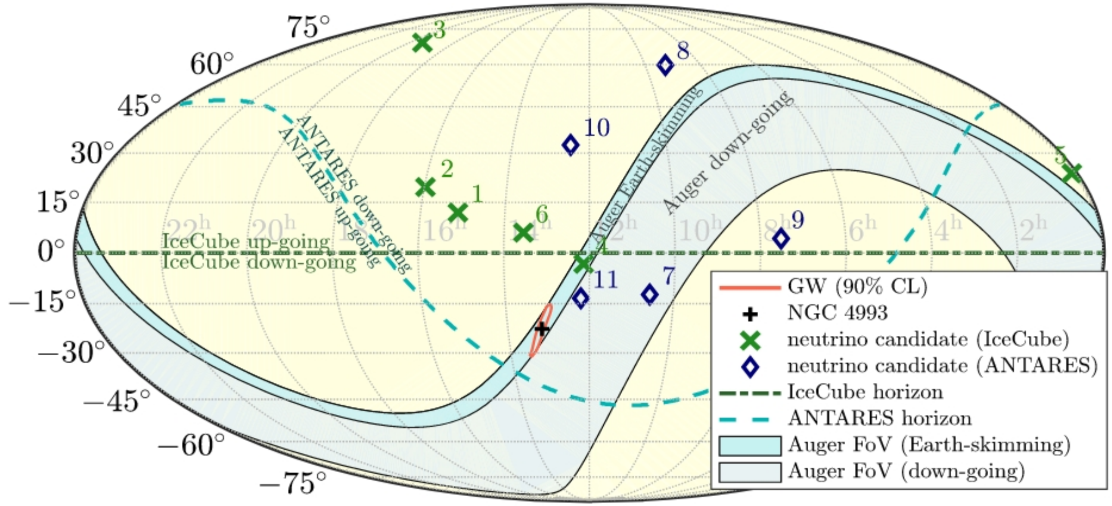


point sources transit through the field of view of each detection channel

→ sensitivity strongly depends on source location and event timing

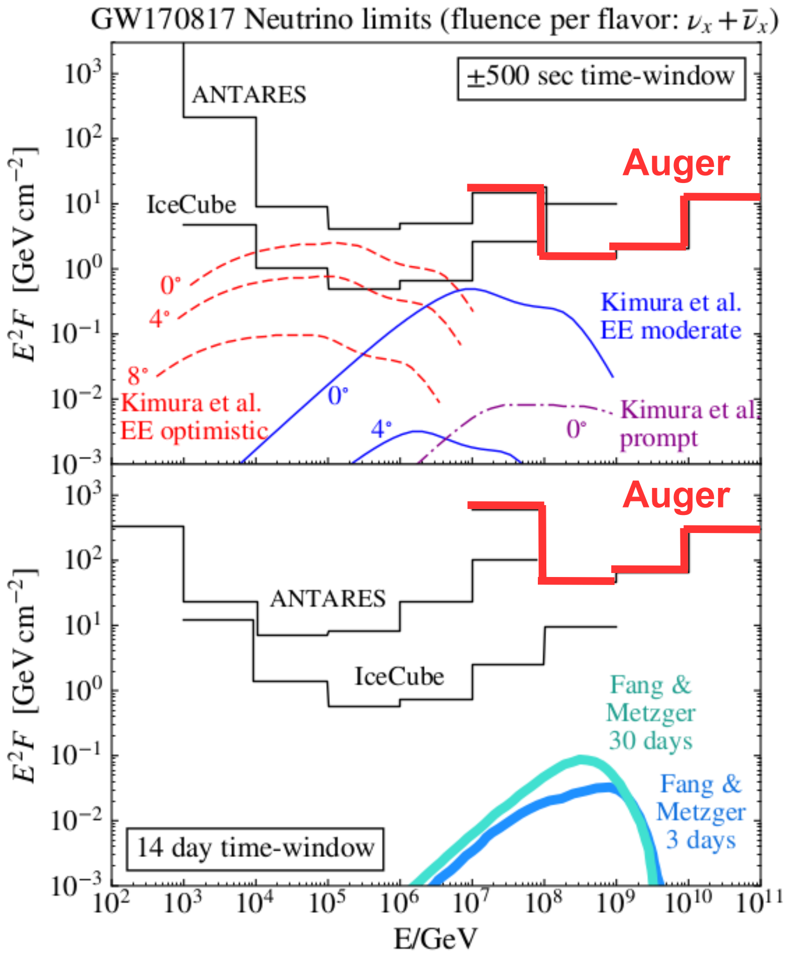
Follow-up searches: GW170817

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

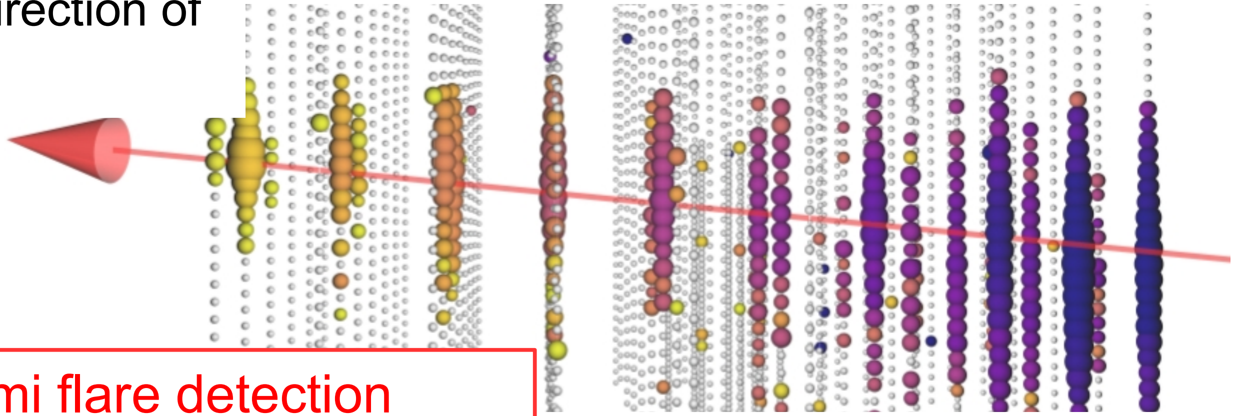
ApJL 850 L35 2017



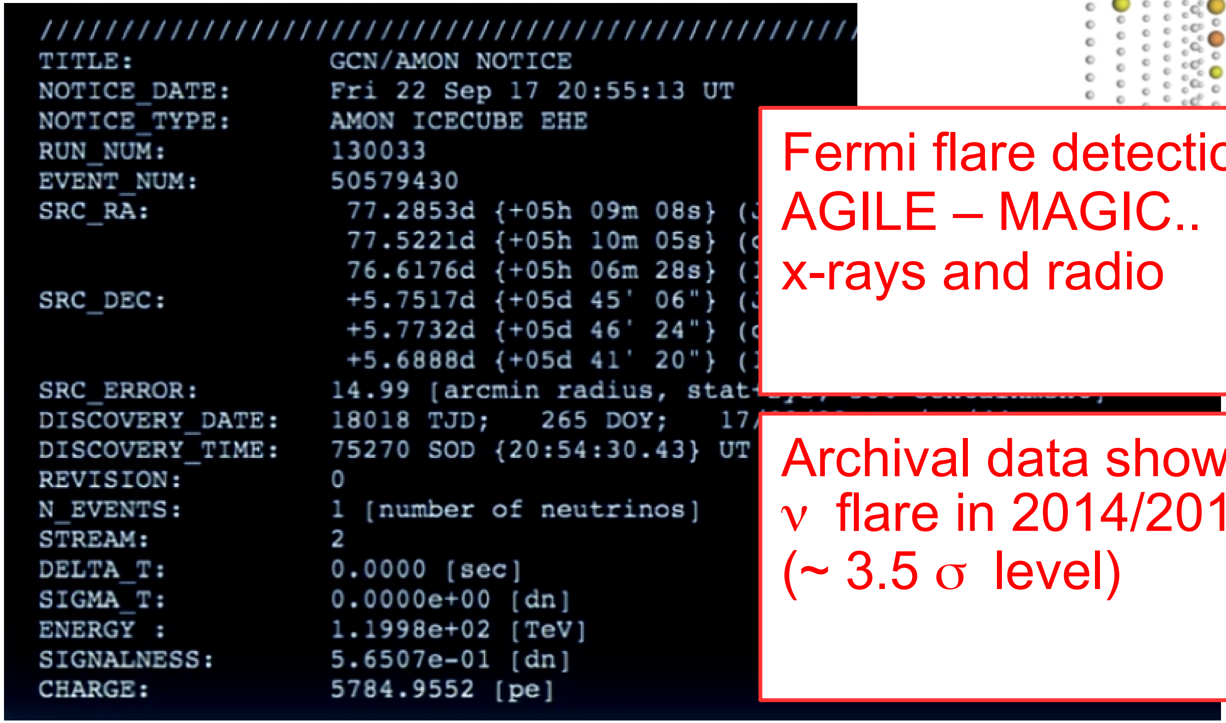
A source: TXS0506+056

Science 361, 146 (2018)

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



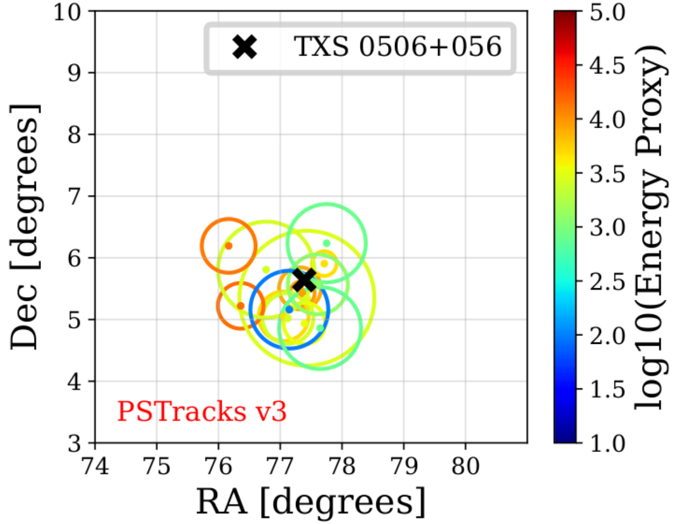
IceCube Alert IC170922A



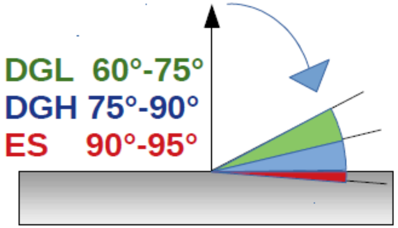
```
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Fri 22 Sep 17 20:55:13 UT
NOTICE_TYPE:      AMON ICECUBE EHE
RUN_NUM:          130033
EVENT_NUM:        50579430
SRC_RA:            77.2853d {+05h 09m 08s} (J
                   77.5221d {+05h 10m 05s} (
                   76.6176d {+05h 06m 28s} (
SRC_DEC:           +5.7517d {+05d 45' 06"} (J
                   +5.7732d {+05d 46' 24"} (
                   +5.6888d {+05d 41' 20"} (
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

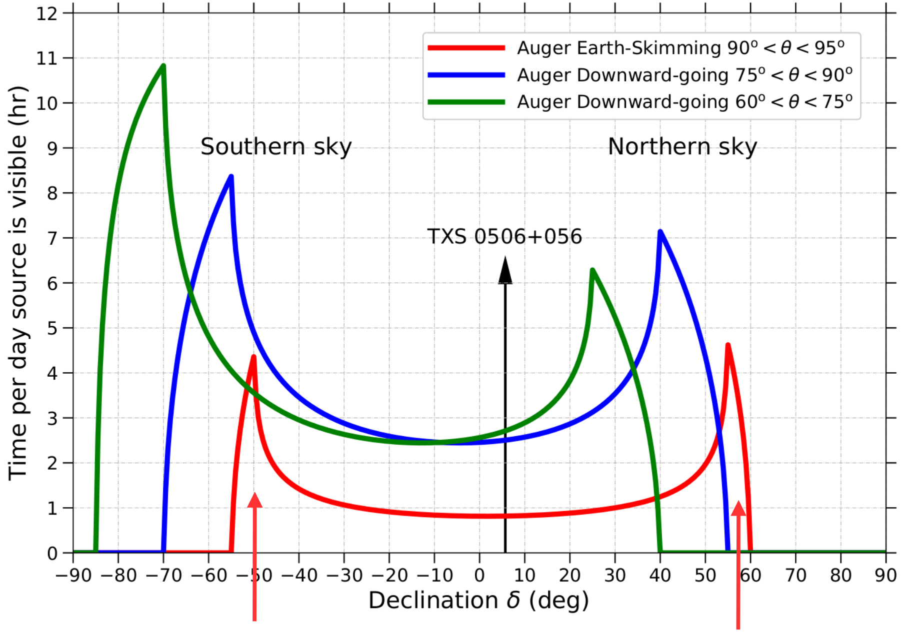
Archival data shows
ν flare in 2014/2015
(~ 3.5 σ level)



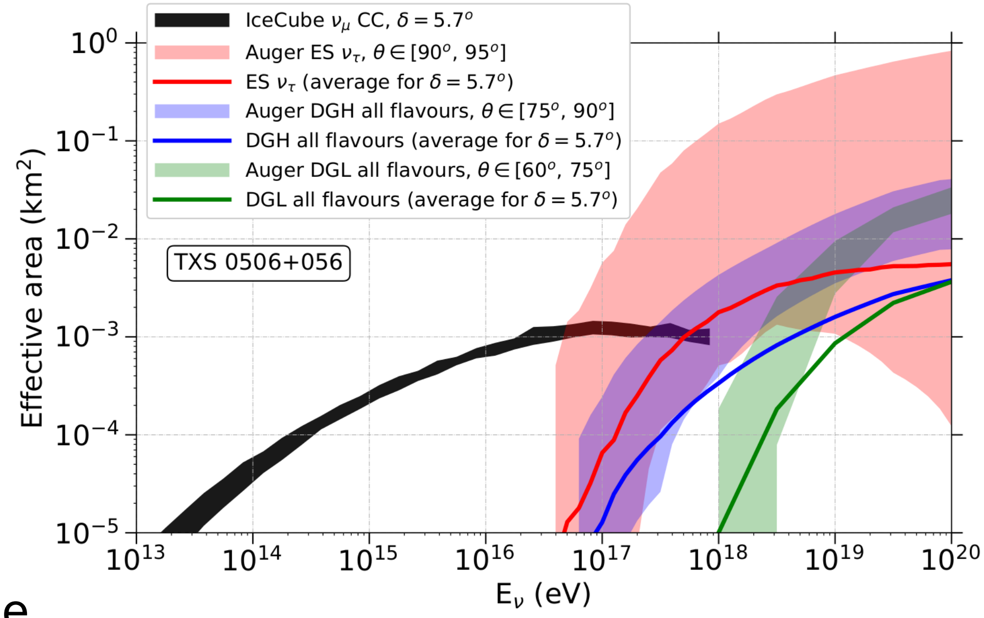
Auger UHE window: TXS0506



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



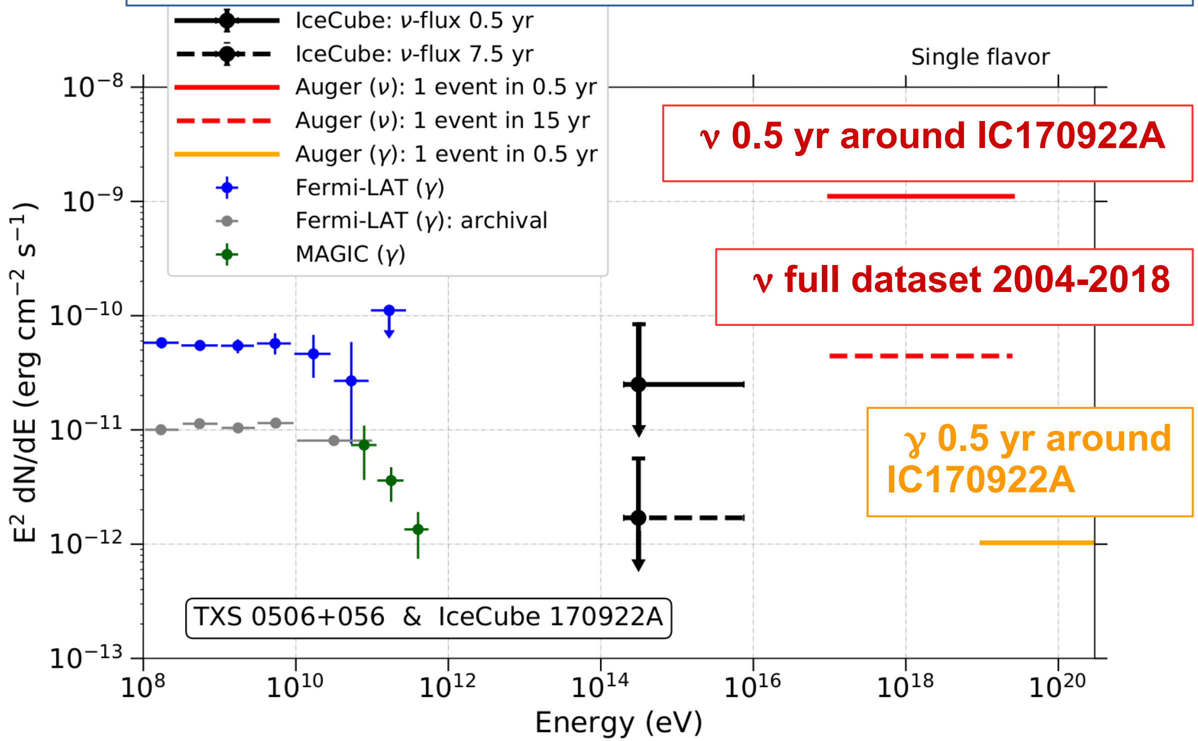
Optimal observation position: source δ in FOV of the Earth-skimming channel (right below the horizon)



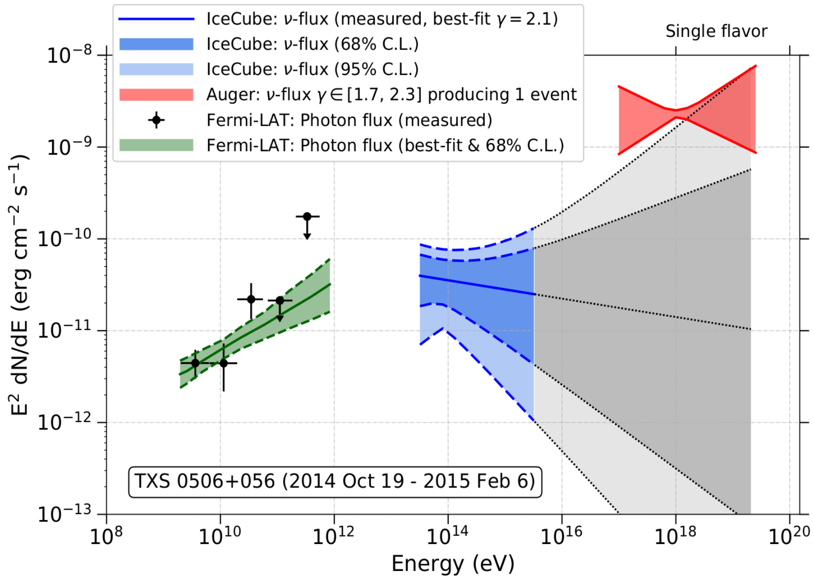
→ complementary to IceCube in the EeV range

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)

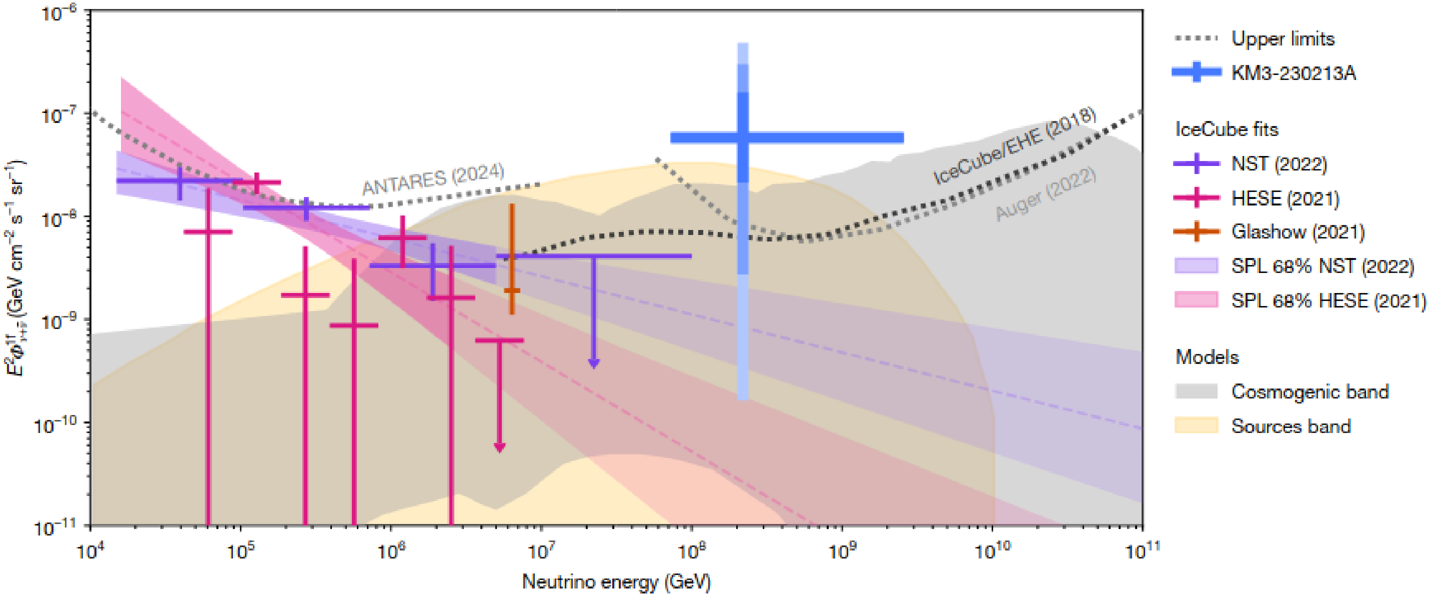


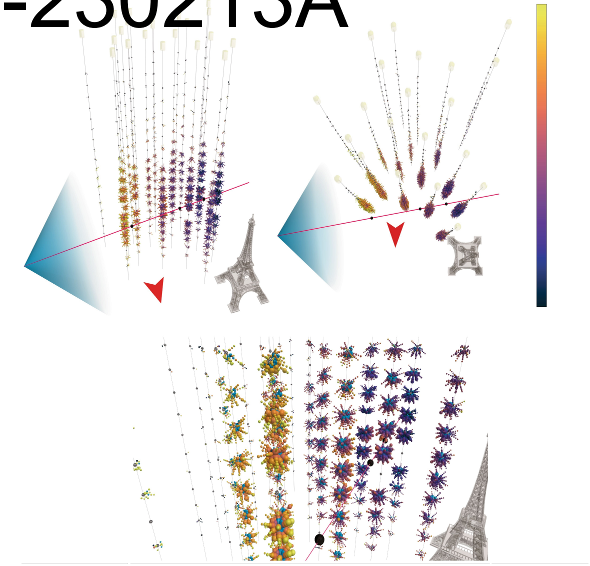
TXS0506 not in the most sensitive region

The neutrino event observed by KM3-230213A

Energy ~ 200 PeV !!

Nature | Vol 638 | 13 February 2025

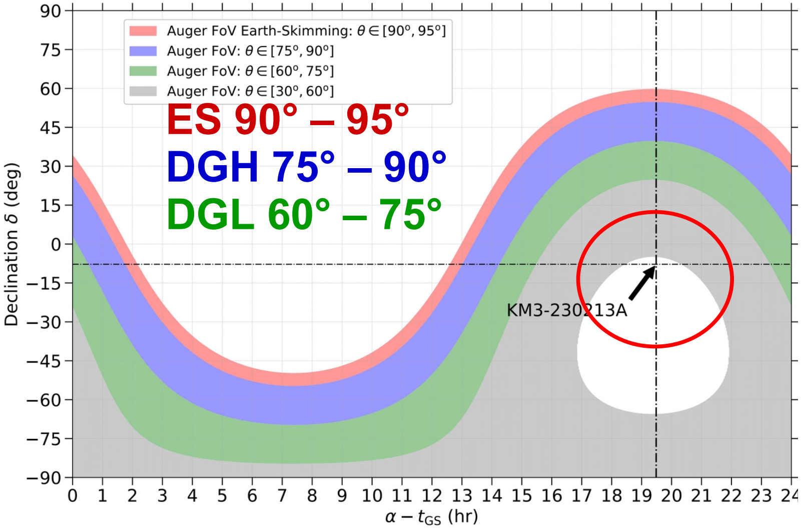




Astrophysical or cosmogenic?

→ **it's a breakthrough**

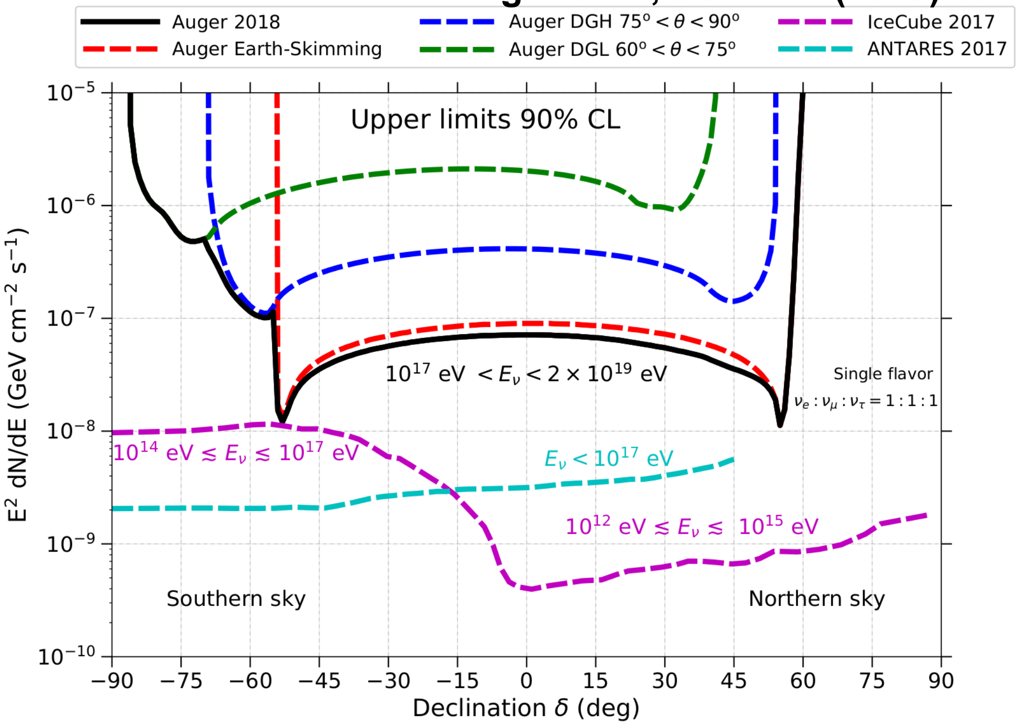
UHE neutrinos: KM3-230213A



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



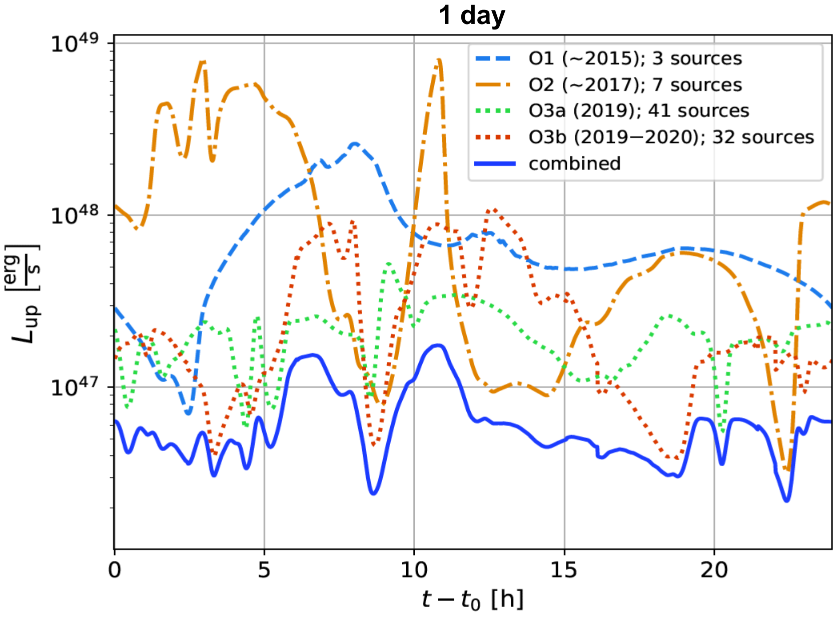
Vertical event ~ 27°

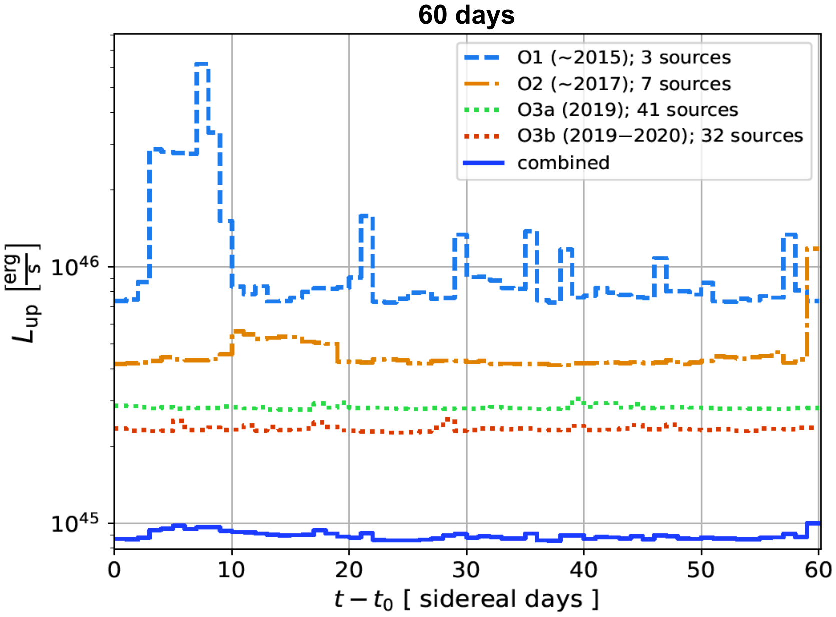
BBH follow-up: stacked ν searches

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 $<5.2\times10^{51}$ erg → more than 2 orders or magnitude lower than the radiated GW energy





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

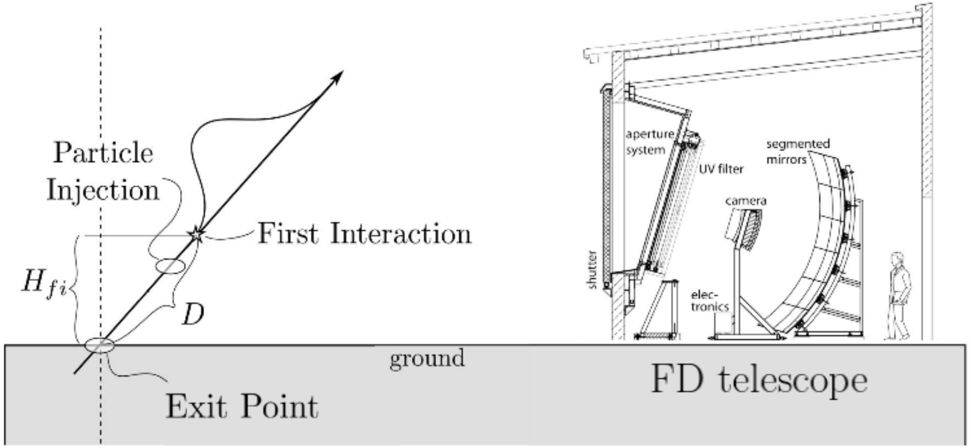
Search for upward-going air showers with Auger FD

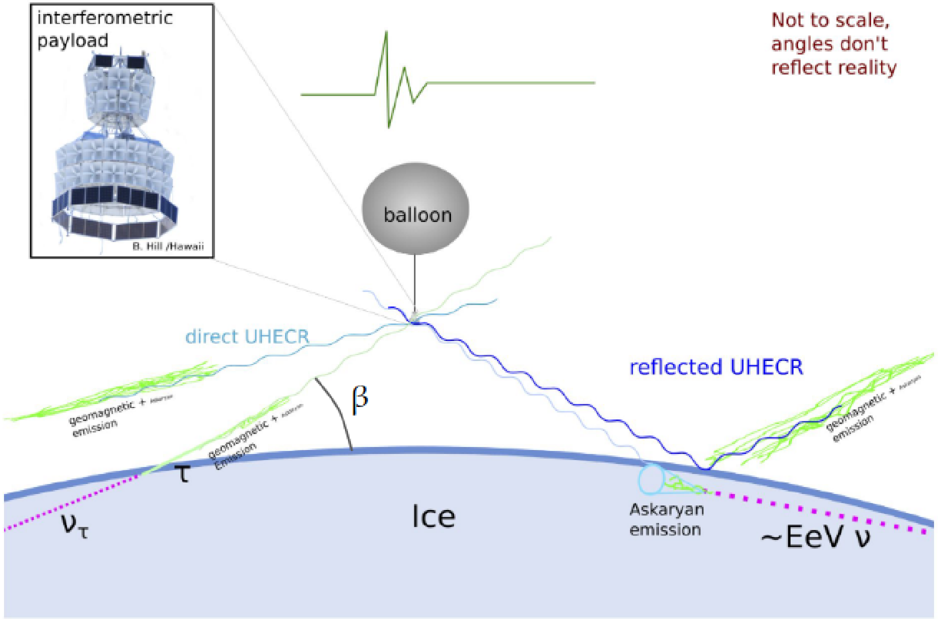
Two “anomalous” events detected by **ANITA** with non-inverted polarity
→ E ~ 0,2 EeV   exit angle ~ 30°

Fervent debate about the interpretation

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

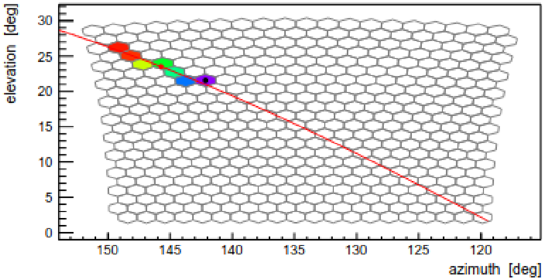
FD sensitivity depends on E and H_{fi} of the primary particle

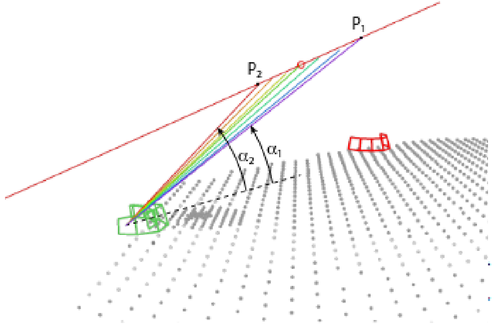




Search for upward-going air showers with Auger FD

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

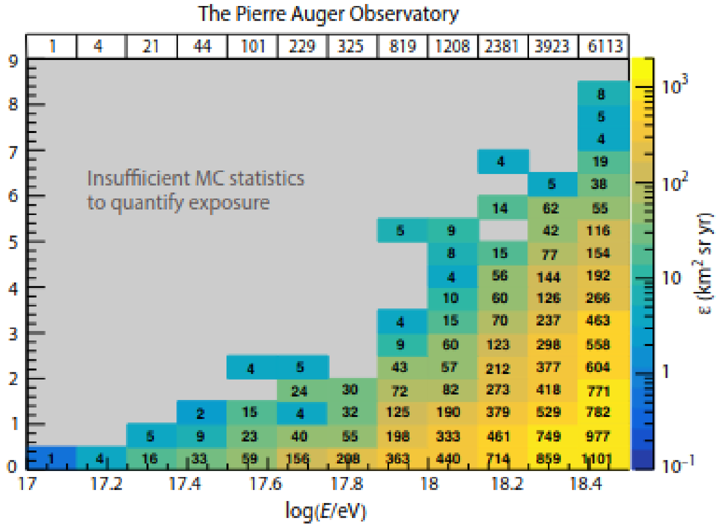




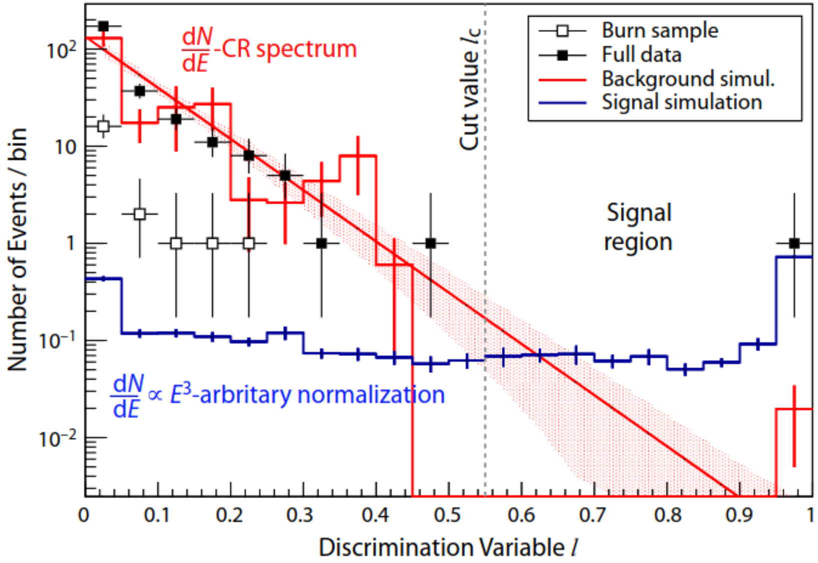
FD only reconstruction challenging for specific event topologies

Debate triggered by the claim done by the ANITA collaboration

Exposure (energy, height of first interaction)



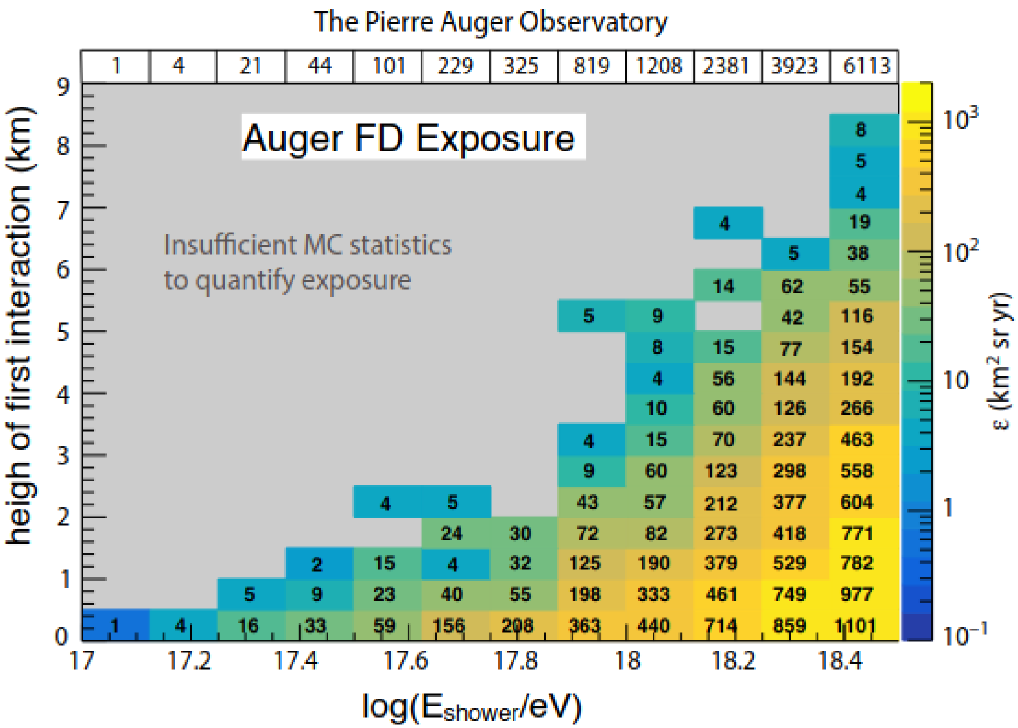
PRL 134, 121003 (2025)



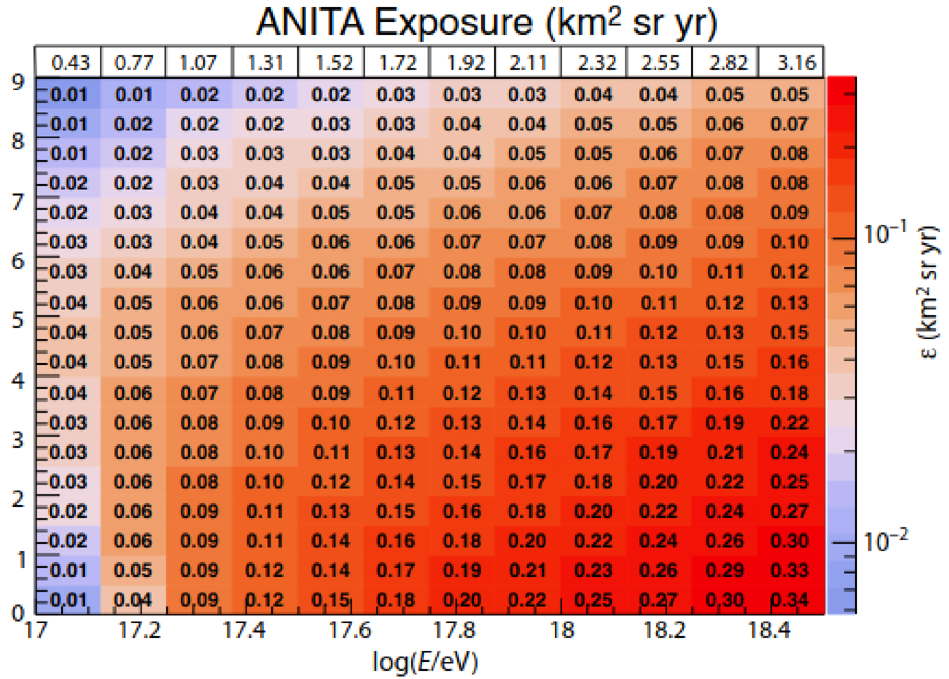
1 candidate consistent with the background (~0.3)

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

Auger Exposure: time dependent simulation



ANITA Exposure analytically calculated

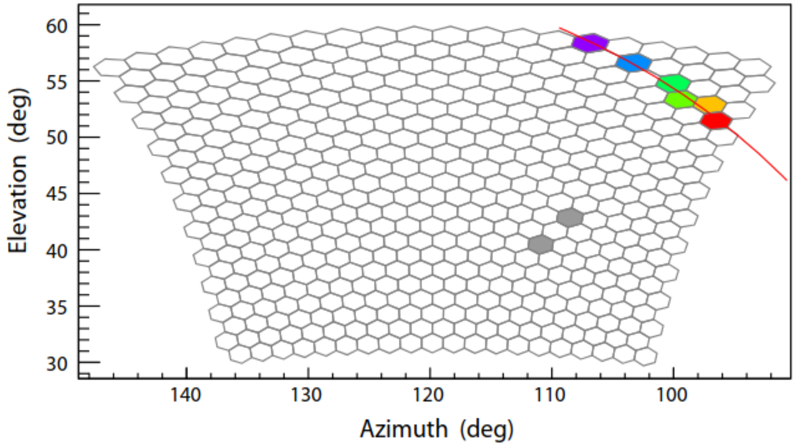


Expected 59 (69) events for E^{-3} , flat in height
Expected 12 (8) events for E^{-5} , flat in height
Expected 18 (11) events for E^{-3} , tau-like decay

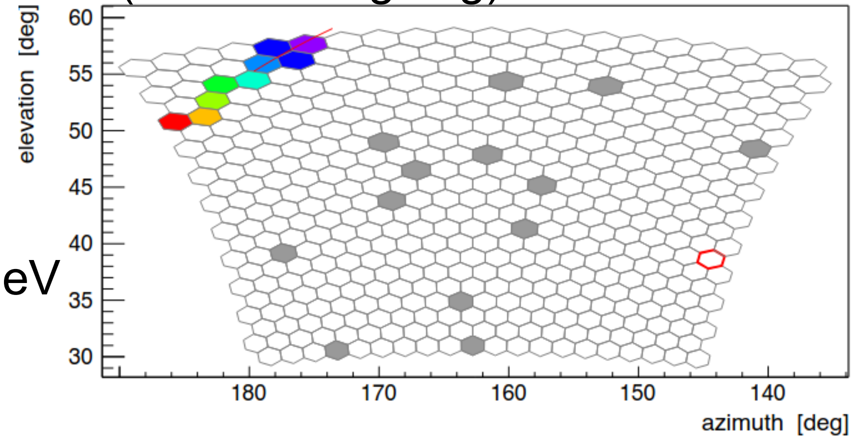
Anita I (Anita III)

Auger results in strong tension with ANITA, even for very conservative assumptions

Data: candidate

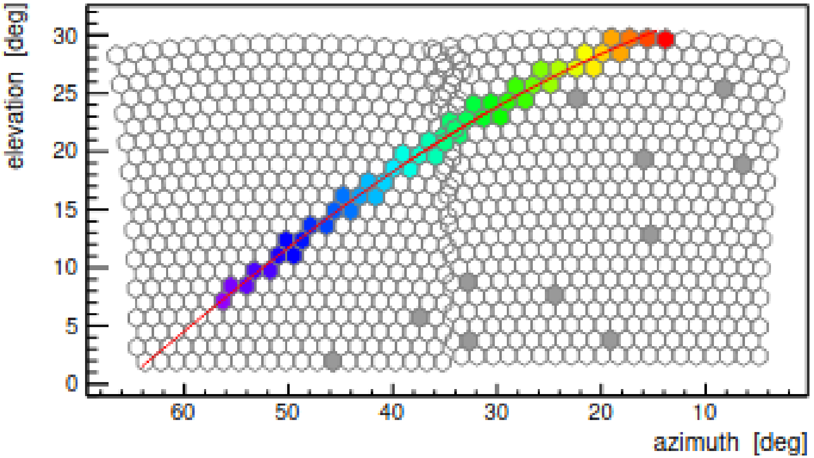


Background:
(downward-going) simulation



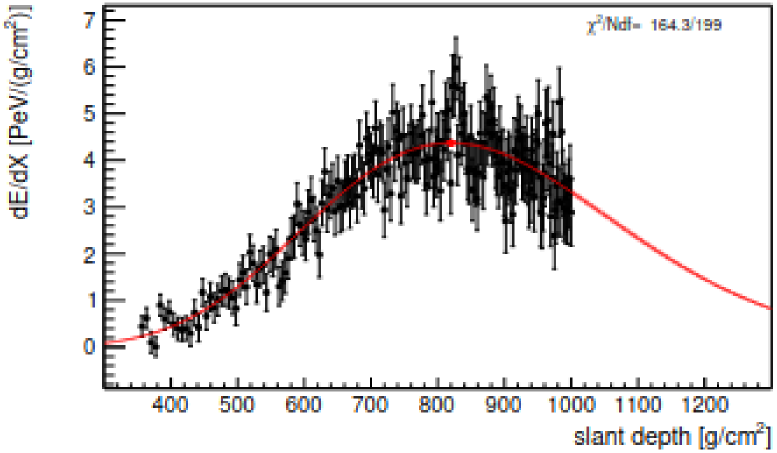
E~ 6.6 EeV
θ ~ 82°

Signal simulation: upward event



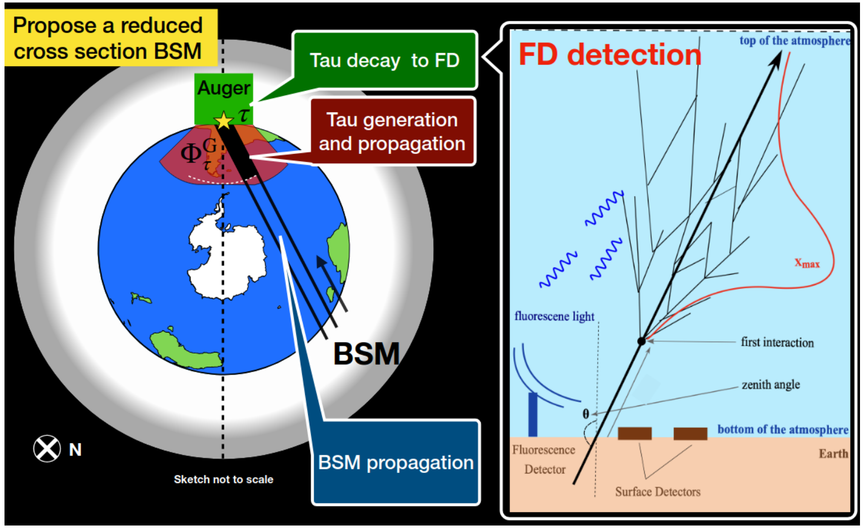
E~ 3 EeV

θ ~ 114°

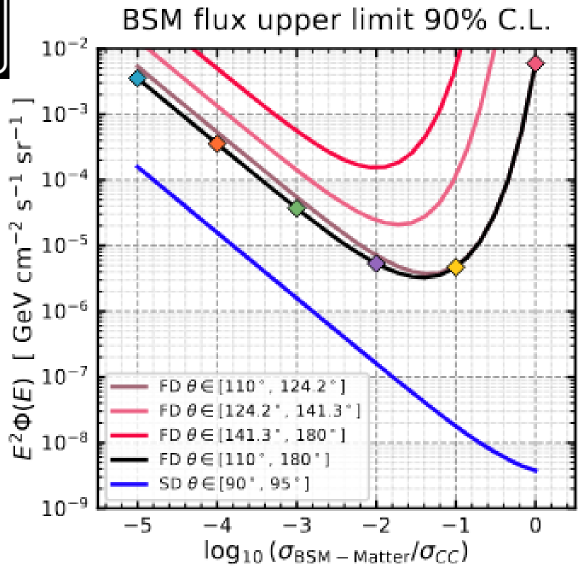


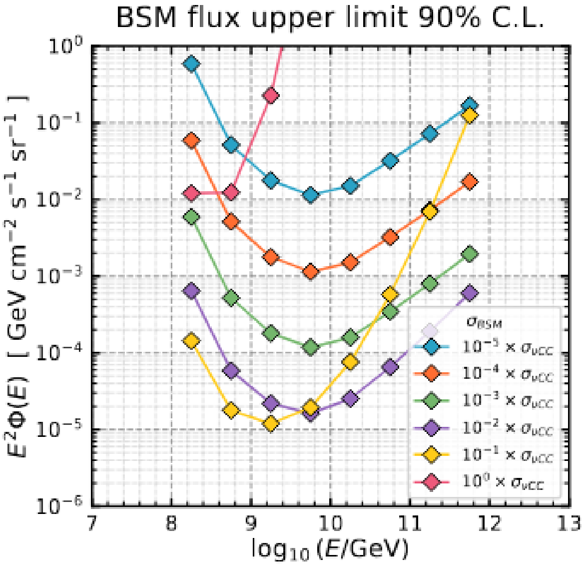
Search for neutrinos using the FD detector

PoS(ICRC2023)1095



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



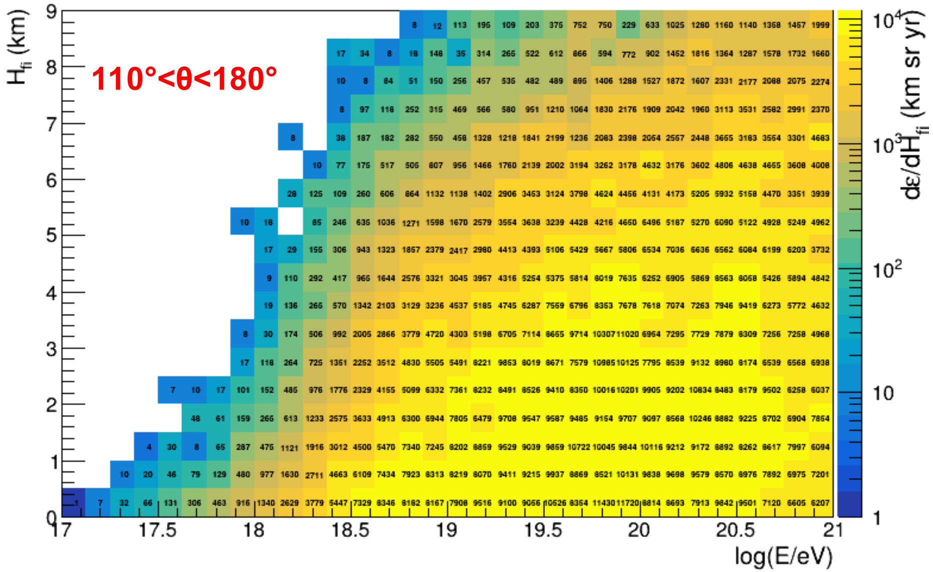


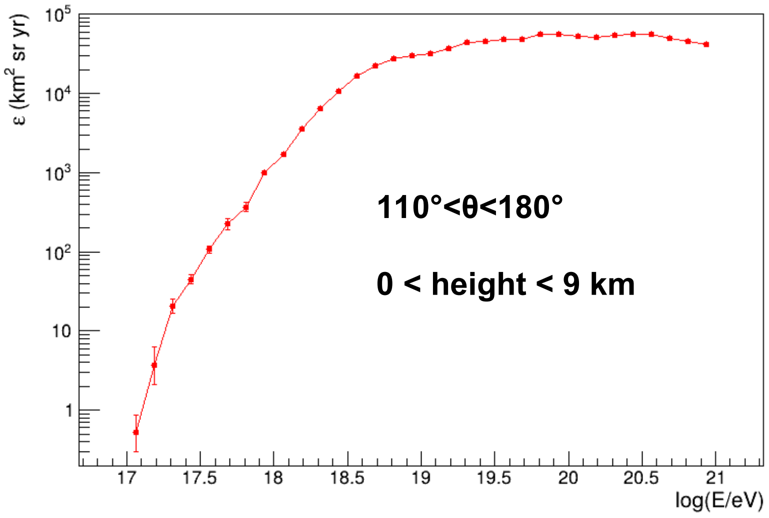
FD: best upper limits for a modified deep inelastic cross-section of about 3% of the standard charge current

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

Perspectives

Exposure up to 10^{21} eV for the BSM paper delivered (internal to the collaboration)

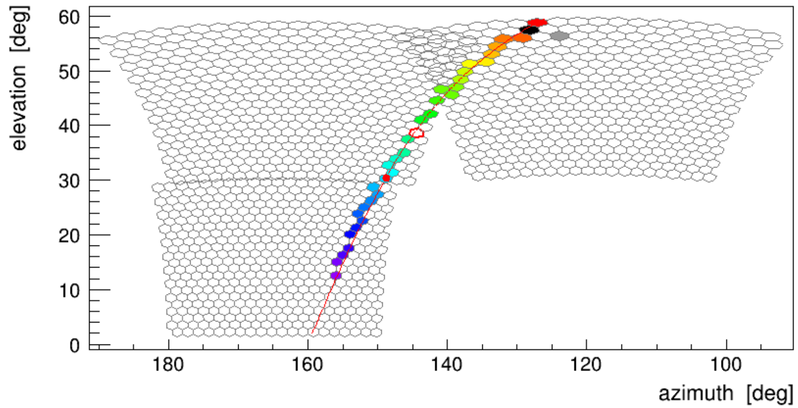


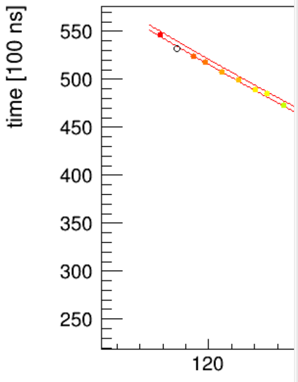


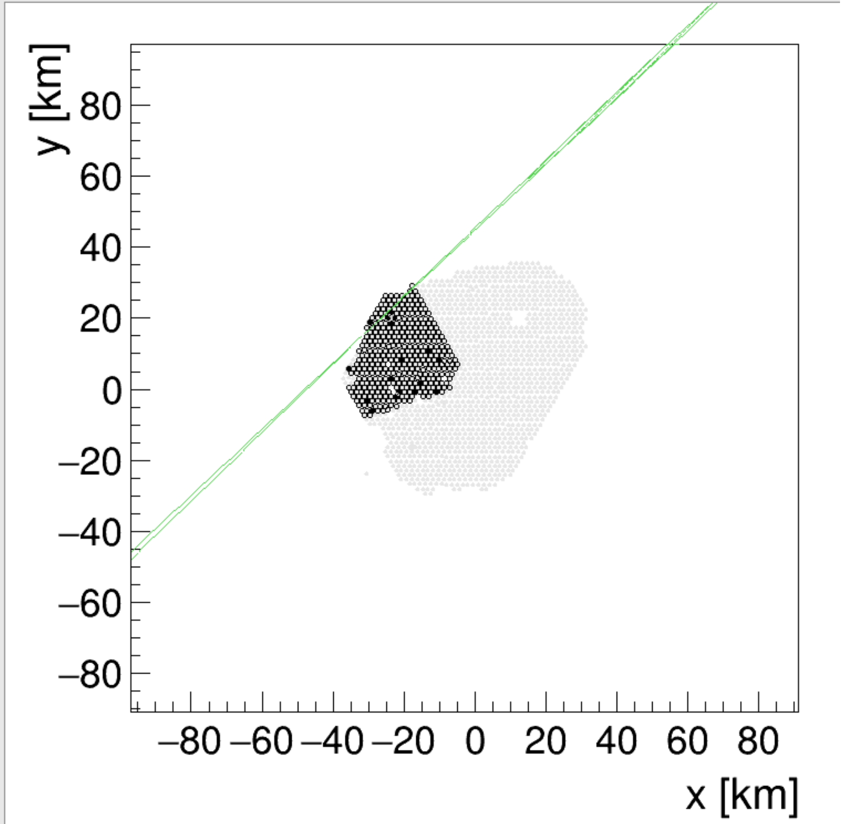
Extending the zenith angle range towards horizontal events

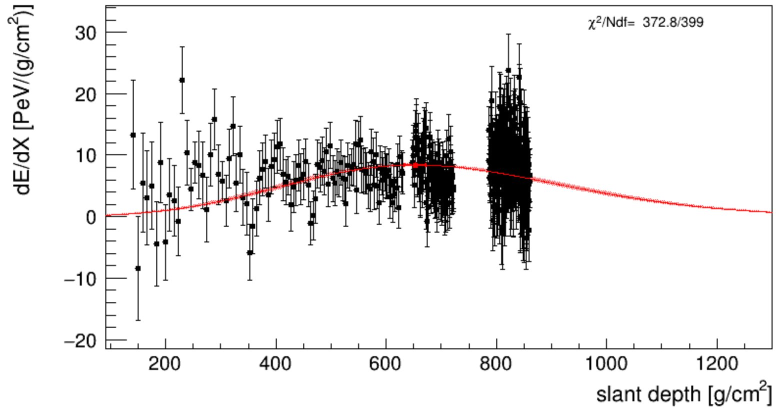
Very inclined, most likely Earth-missing event

Zenith~90°, ~ 6 EeV passing over Coihueco at a height of about 18km (not in current analysis)









Event Info | Pixels | PCGF

run 5929, event 5729

time stamp: 1123909401 s 40159081

Trigger: unknown, 'Shower Candidate

in MegaEye mirror 24 26 27 (in DAQ: 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27)

geometry: Profile-Constrained

(θ, ϕ) = (89.2±0.4, 40.5±0.1) deg

(x, y) = (-238.44±27.67, -179.53±26.22) km

R_p = 18.14 ± 0.03 km

profile: 4-parameter Gaisser-Hillas (type: USP)

E = (6.37 ± 0.26 ± 0.39) × 10^{18} eV

X_{max} = 653 ± 20 g/cm^2

$(dE/dX)_{max}$ = 8.39 ± 0.20 PeV/(g/cm^2)

(λ, X_0, L) = (49, -642, 252±7) g/cm^2, R = 0.19±0.05

Cherenkov-fraction = 1%, mva=7 deg.

databases:

Mie attenuation: measured (h<16.3 km, VAOD at 3km: 0.00)

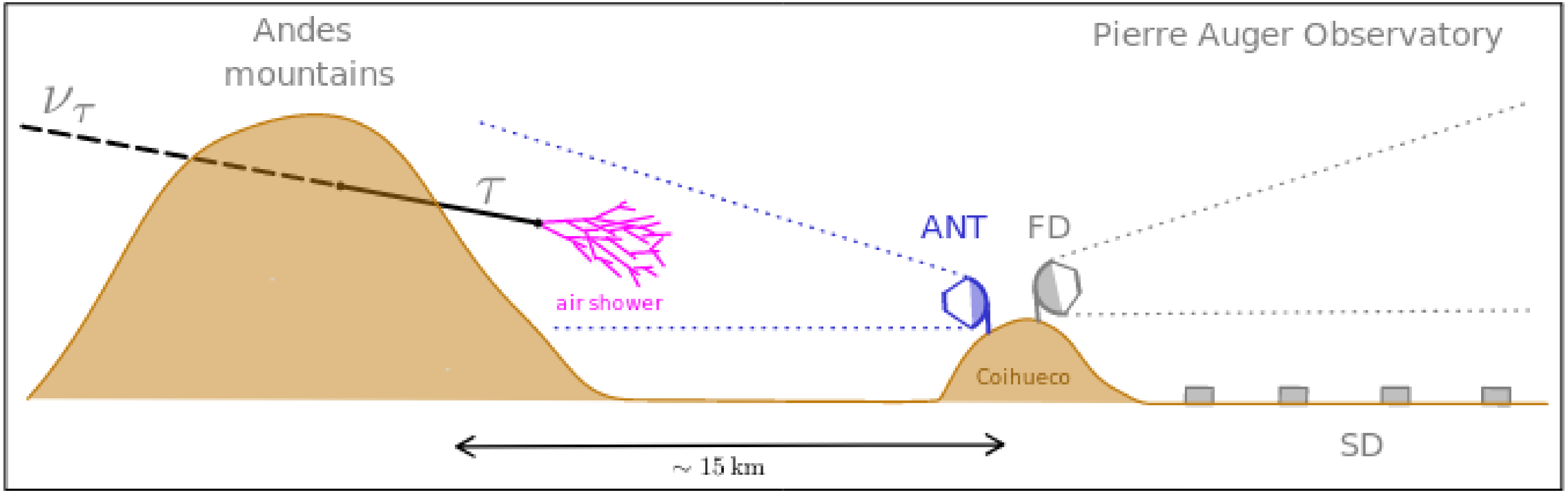
LIDAR: no data ; CloudCam: max(ζ)=(0/0)% (elev>5.5^°); CloudMap: max=0%

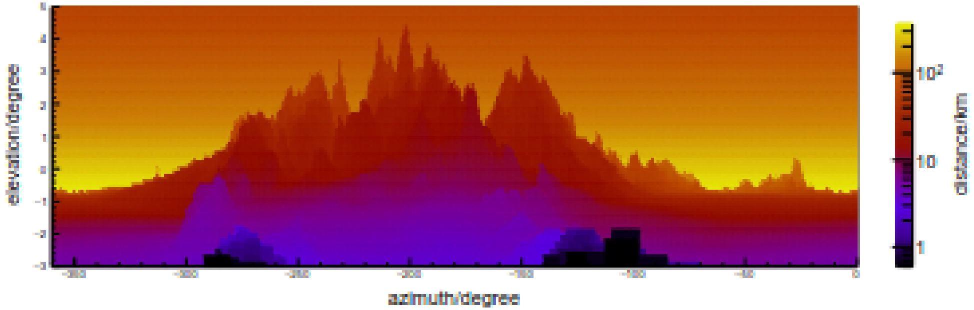
molecular profile: GDAS; time correction: good

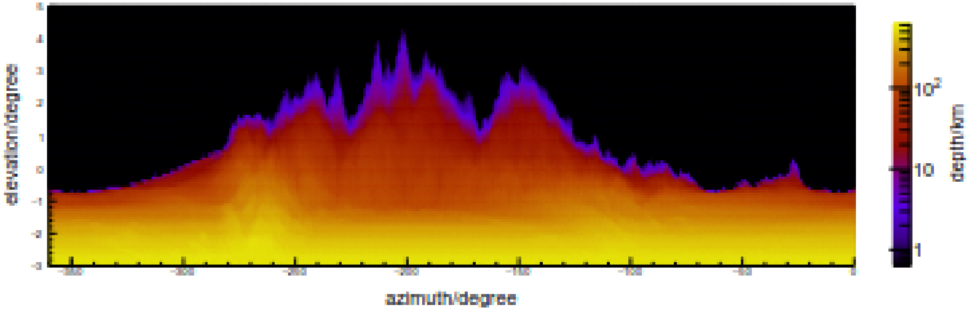
M. Unger, KIT
internal to the collaboration

ANT – Auger Neutrino Telescope

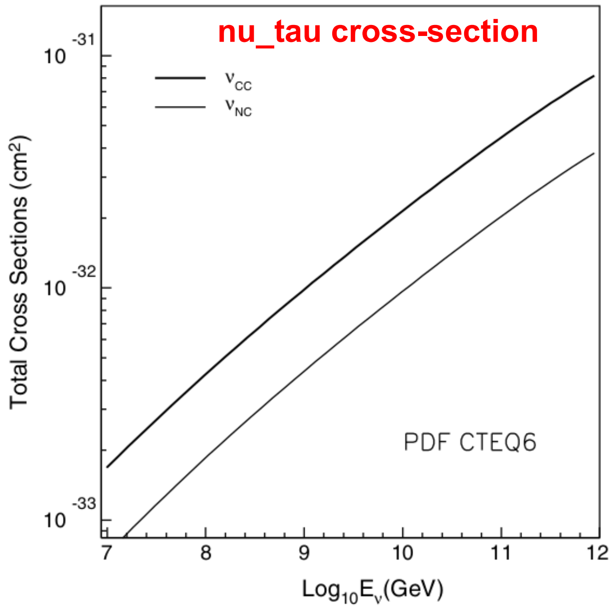
detect UHECR source neutrinos at $E_\nu = 1/20\, E_p = 10^{17}$ eV

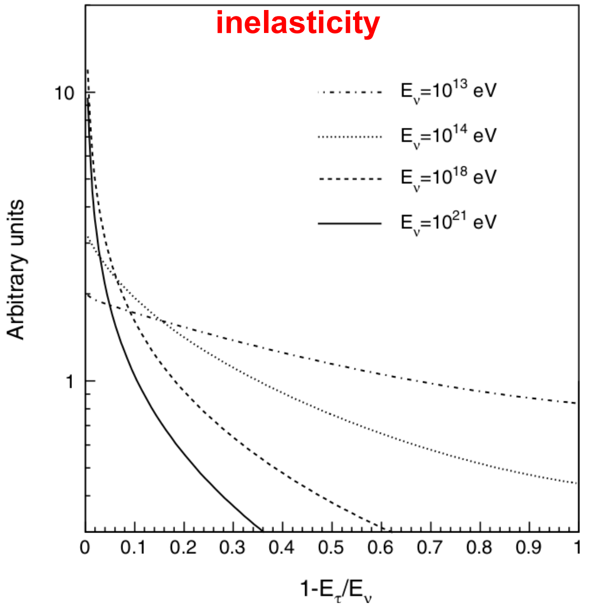






Astroparticle Physics 23 (2005) 65–77

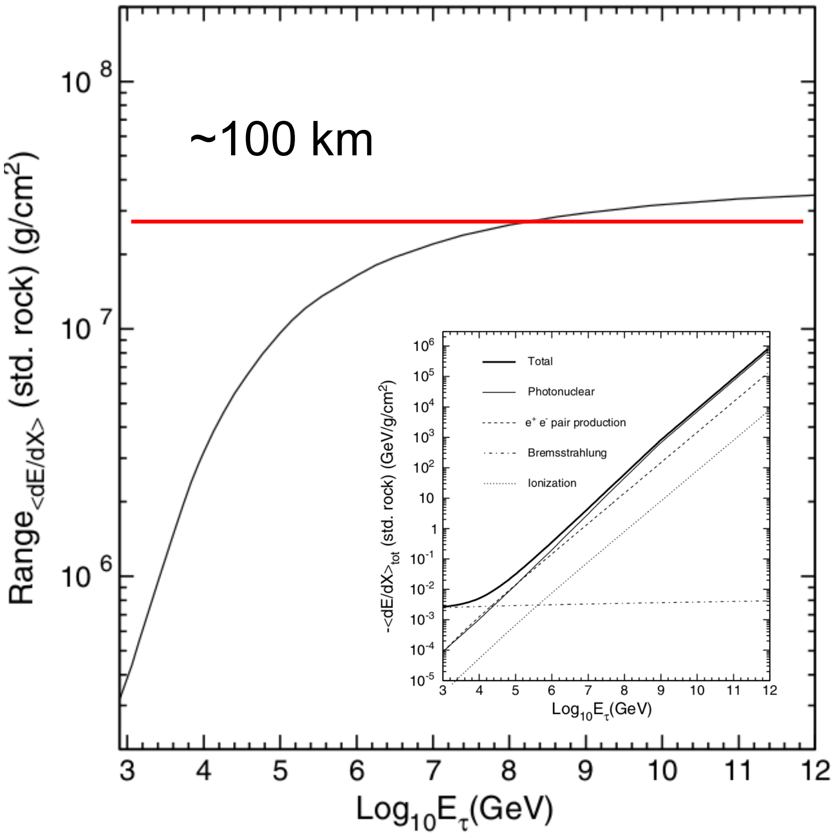




simplified assumption for now y ~ 0.8

Need accurate knowledge of the mountain profiles (traversed rock for different elevations and azimuth)

Tau range in standard rock



τ branching ratios:

if tau decays in air →

- 18% $\mu \rightarrow$ no shower
- 18% $e \rightarrow \frac{1}{3}E_\tau$
- 64% $h \rightarrow \frac{2}{3}E_\tau$

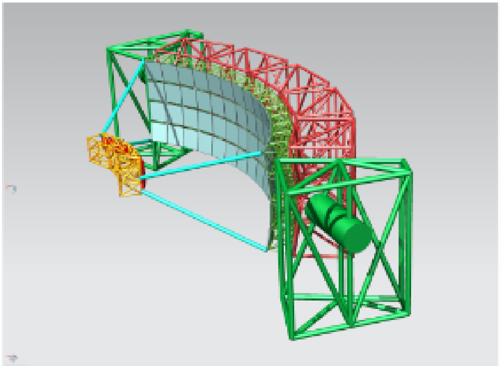
Simplified Simulation of Detection

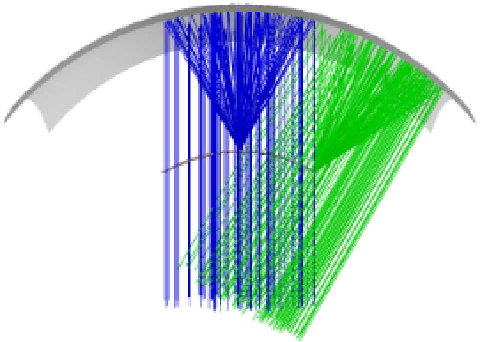
M. Unger, KIT internal to the collaboration

- $5^\circ \times 160^\circ$ FOV
- $\theta_{\rm pix} = 0.3^\circ$
- aperture area $A = 1\,\mathrm{m}^2$
- NSB from mountain: 0.1 NSB Auger
- 4 pixels for trigger

sensitive assumption

e.g.:

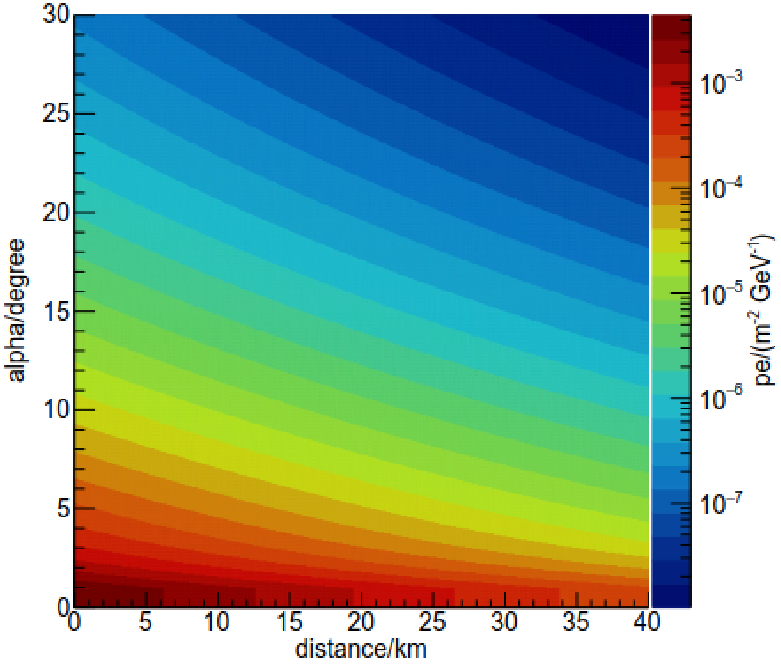




left: MACHETE design (Otte et al), right: ray-tracing (L. Scherne, BSc Thesis, KIT)

parametrization of $n_{\rm pe}$ from Cherenkov

N. Otte PRD 2018

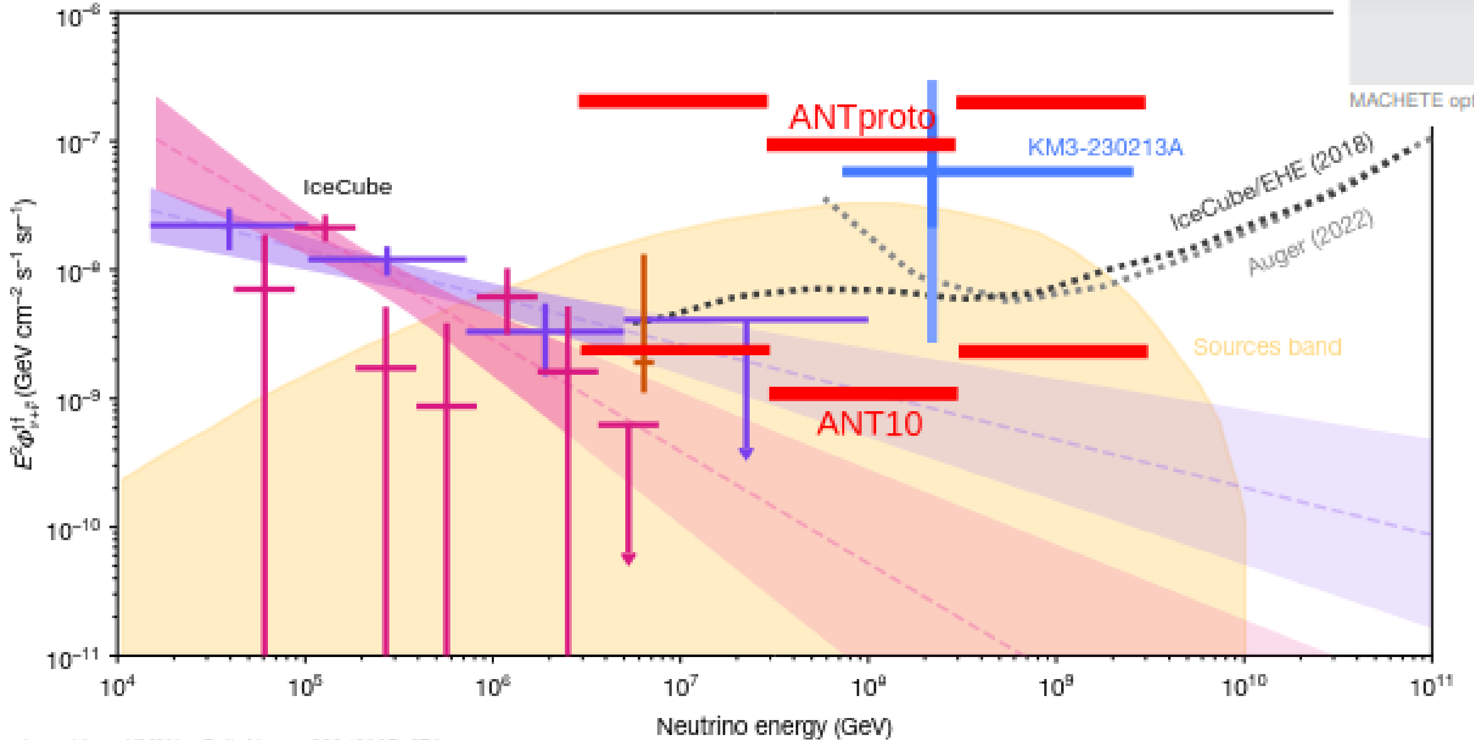


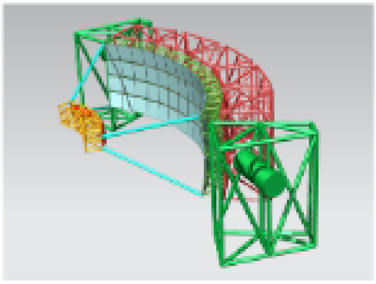
M. Unger, KIT internal to the collaboration

ANT – Auger Neutrino Telescope

M. Unger (IAP, KIT)

preliminary sensitivity using wide-field Cherenkov telescope(s)





MACHETE optics (Cortina et al., Otte et al.)

adapted from KM3Net Coll. Nature 638 (2025) 376

Gruppi italiani coinvolti in prima linea nelle analisi della ricerca dei neutrini con il rivelatore FD

PRL 134, 121003 (2025) Lecce e l'Aquila, 2 tesi di dottorato, EB
Collaborazione con Torino e Napoli

Lavoro in progress (Lecce, Torino)

Estendere statistica zenith ed energia.

Interesse per l'ipotesi di un telescopio Cherenkov per neutrini @ Auger

Primo passo:
- Misura del background fondo cielo
- Richiesti fondi per partecipare alla campagna di misura (Iniziativa Auger)

Gruppi interessati: Lecce, L'Aquila, Torino,….

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

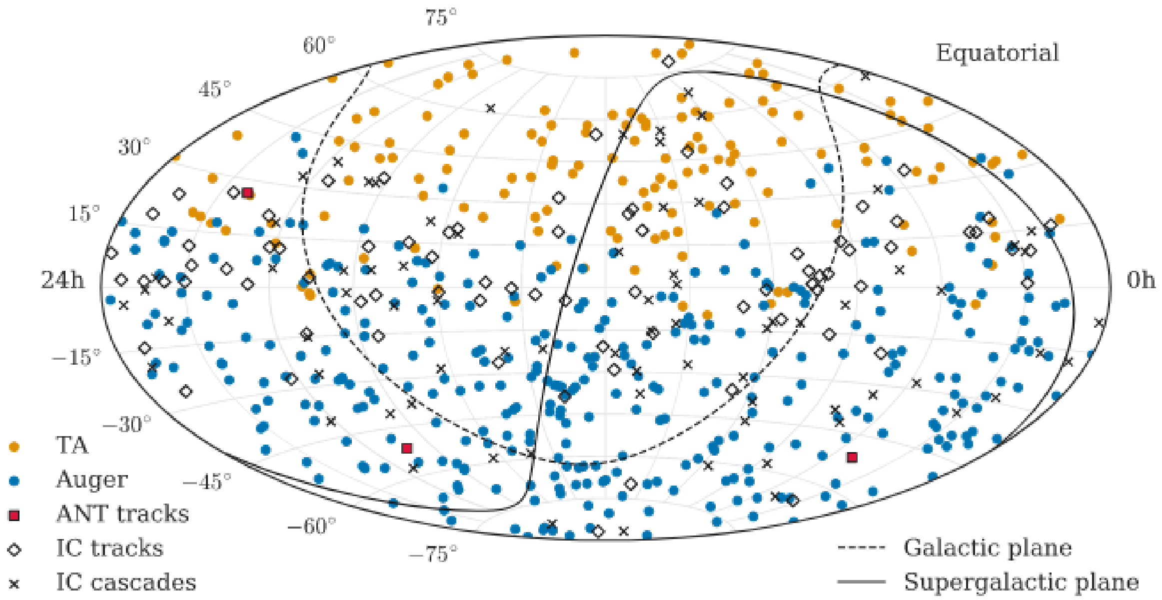
→ Pierre Auger Observatory upgrade will improve on sensitivity and background rejection

BACKUP

Joint 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

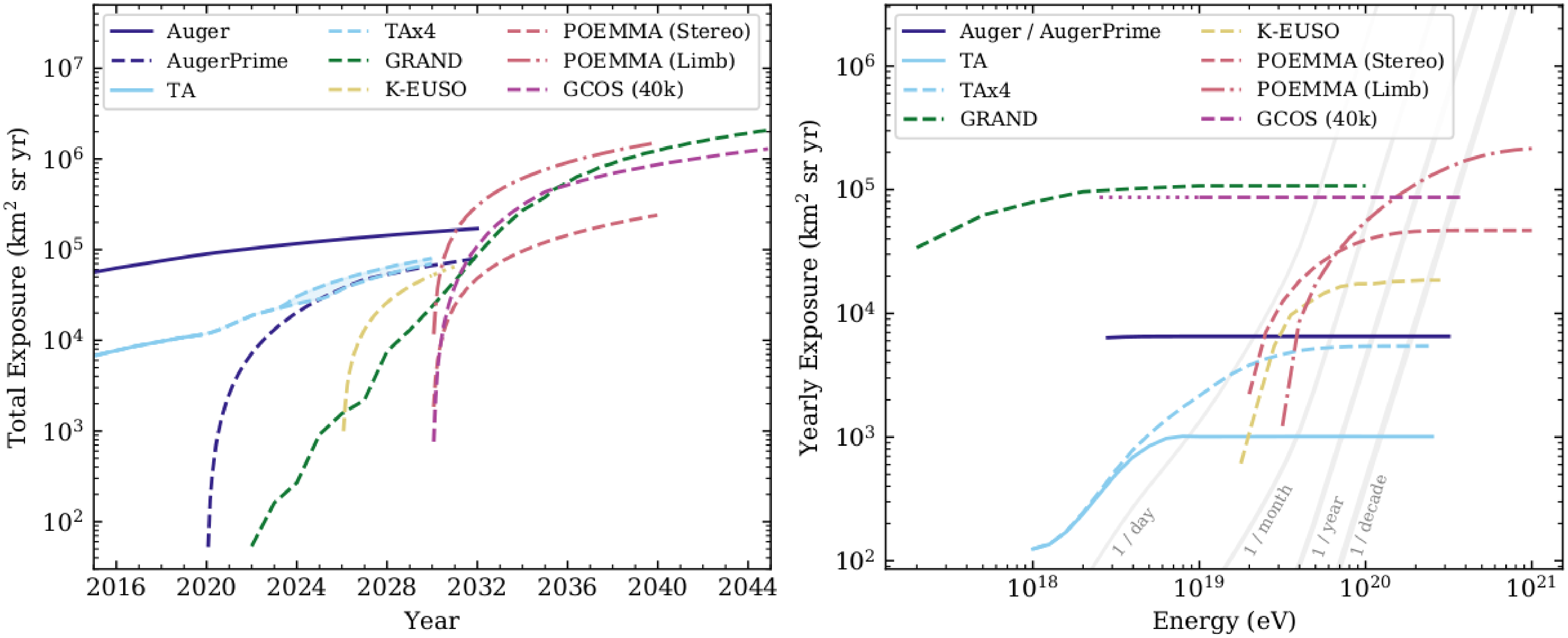
No excess found

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

A look into the future for UHECRs

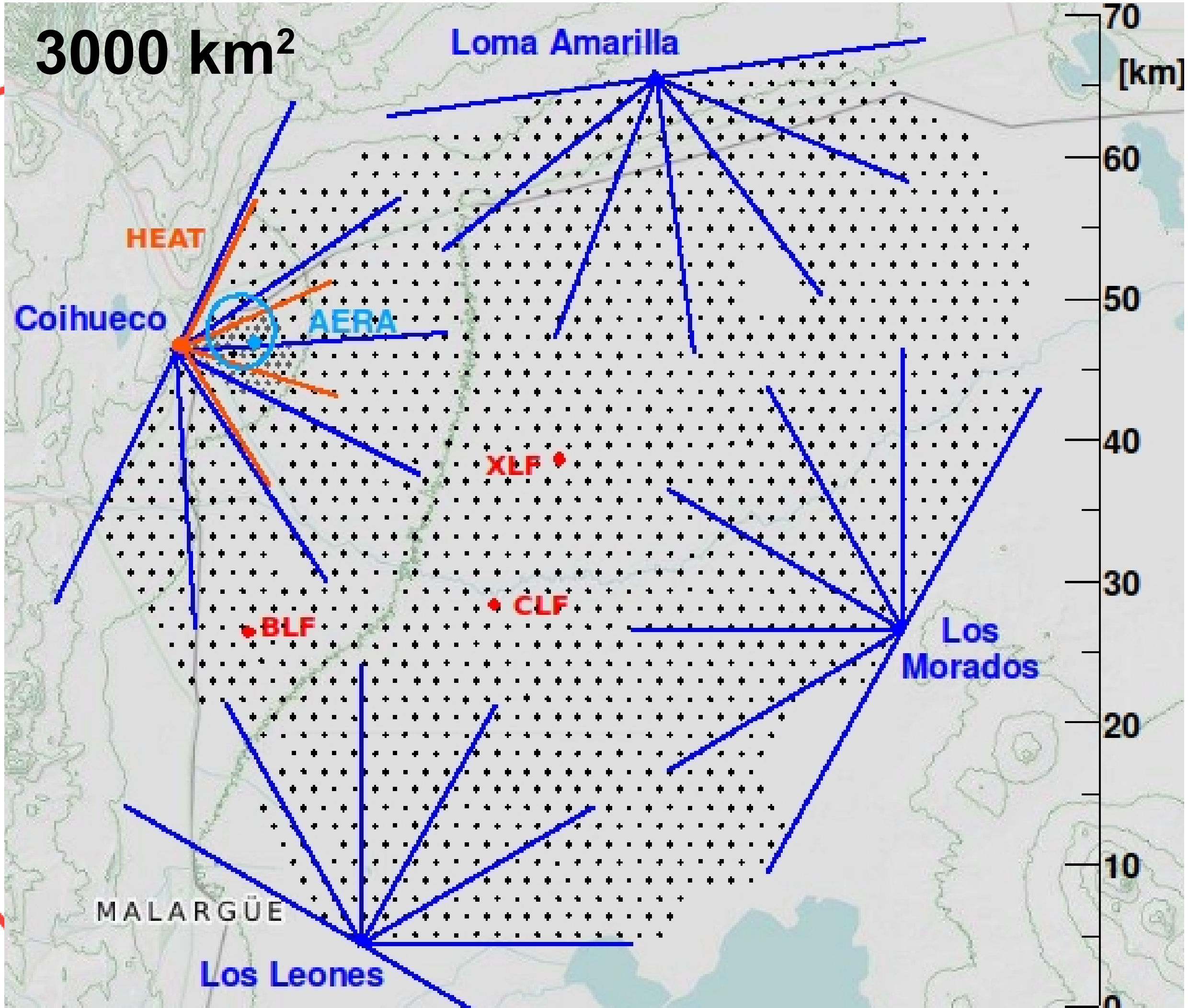
EPJ Web of Conferences 283, 01001 (2023)



The Pierre Auger Observatory

35.5º S, 69.3º W

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



The Pierre Auger Observatory

~ 400 members, 17 countries

3000 km²

Surface detector

array of 1660 Cherenkov stations on a 1.5 km hexagonal grid of 3000 km^2
Dense sub-array (750 m) of 24 km^2

Fluorescence detector

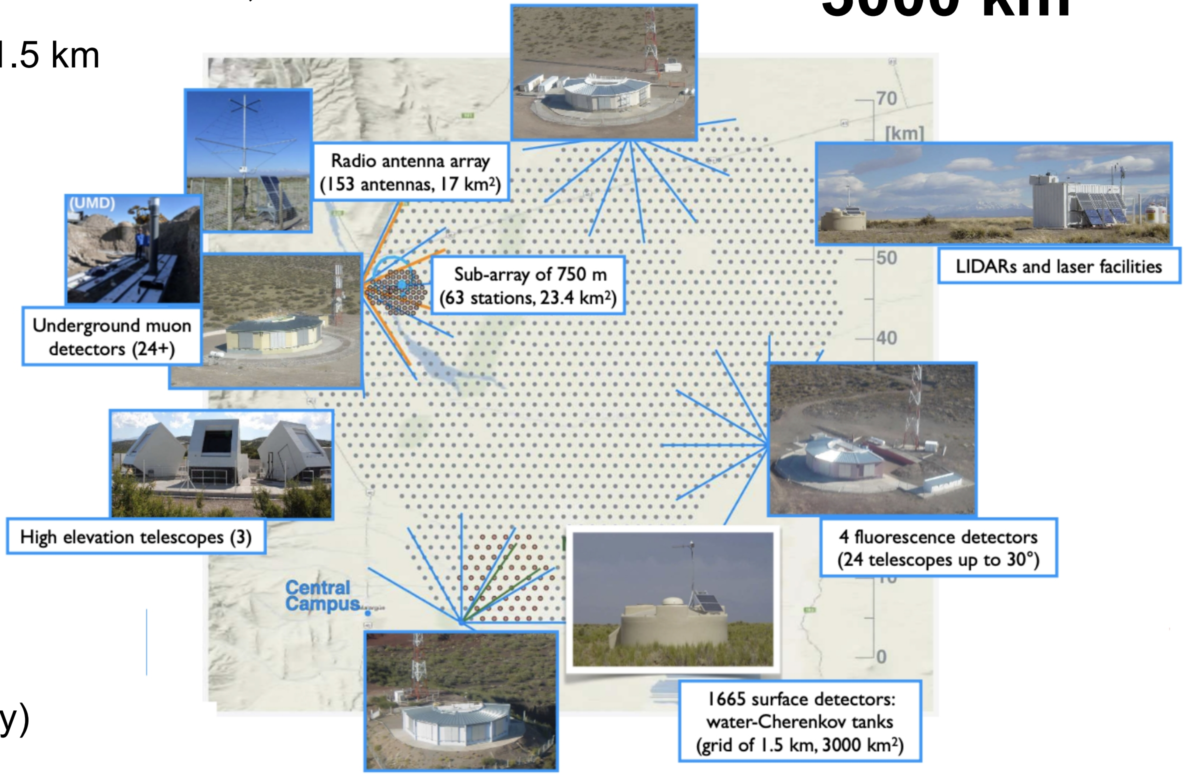
4+1 buildings overlooking the array
(24 + 3 HEAT telescopes)

Radio detector

153 Radio Antenna → AERA

Muon Detectors

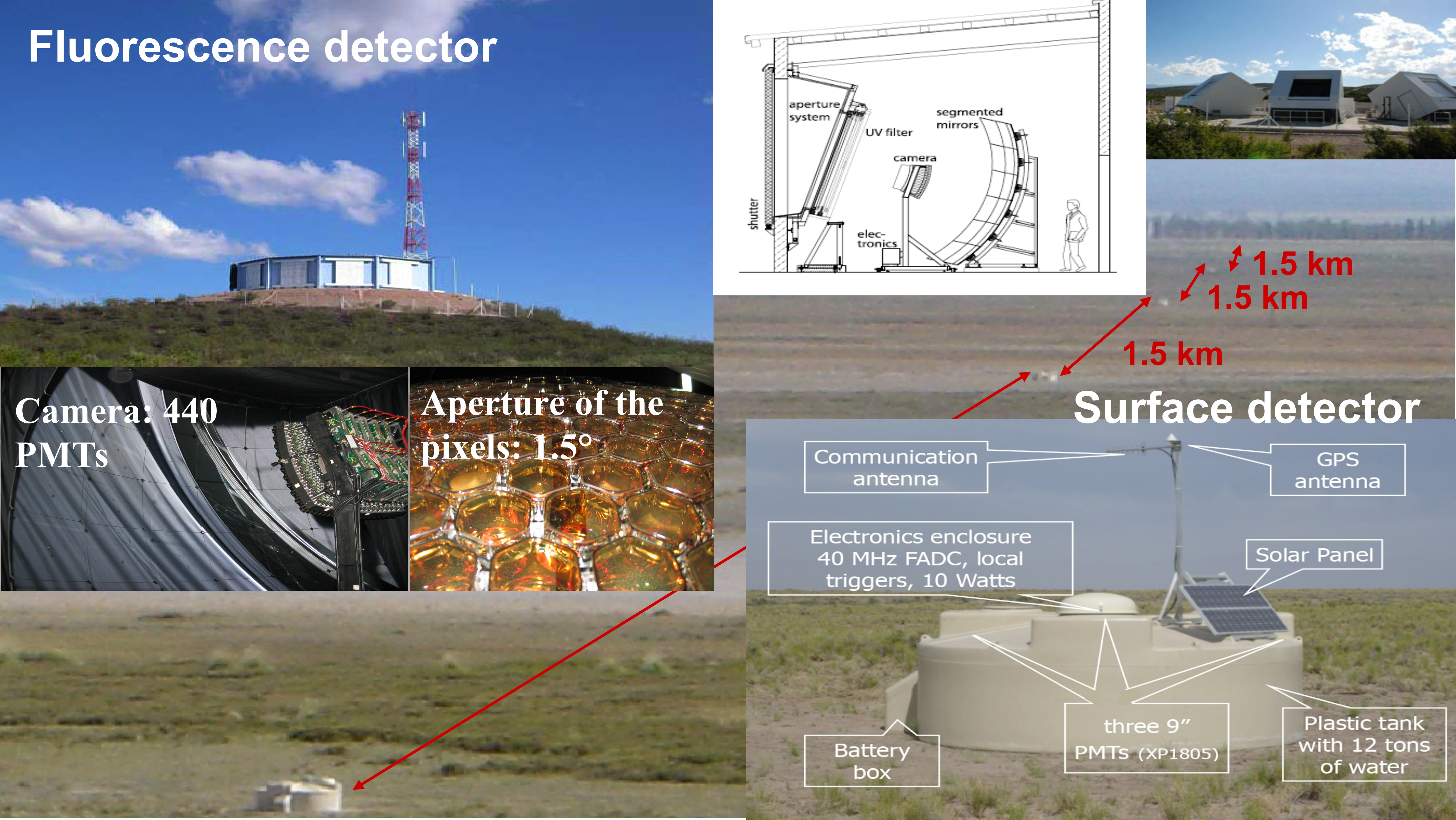
Buried scintillators (region of dense array)



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

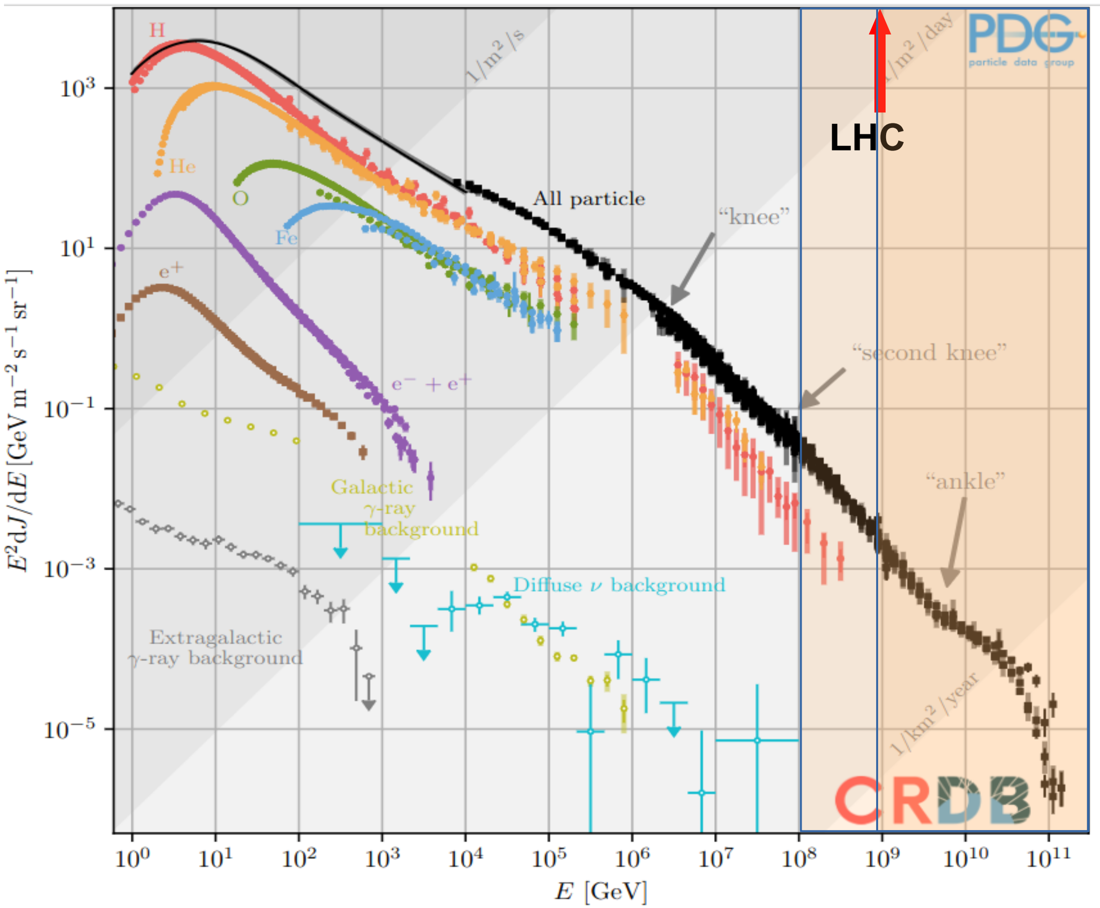
- Over 120.000 km^2 sr yr for anisotropy studies
- Over 80.000 km^2 sr yr for spectrum studies

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
1.5 km
1.5 km
1.5 km
Camera: 440 PMTs
Aperture of the pixels: 1.5°
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

Ultra-high energies cosmic rays



Wide range of energy/flux

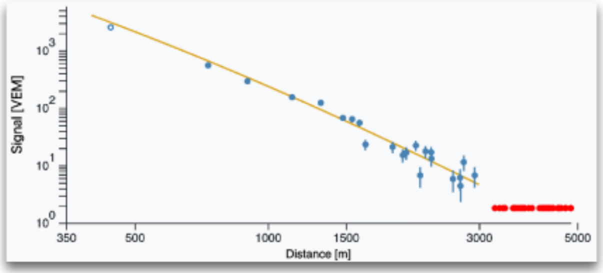
Diverse measurement techniques

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

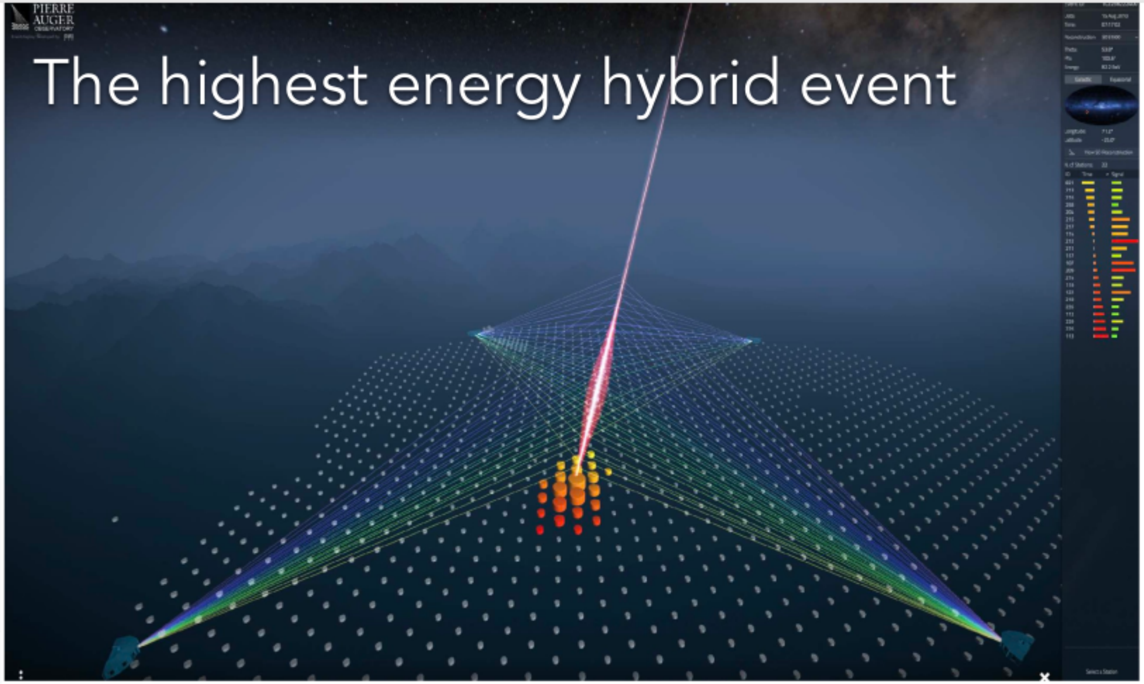
Such as: origin and nature of ultra-high energy cosmic rays, acceleration mechanisms, propagation effects...

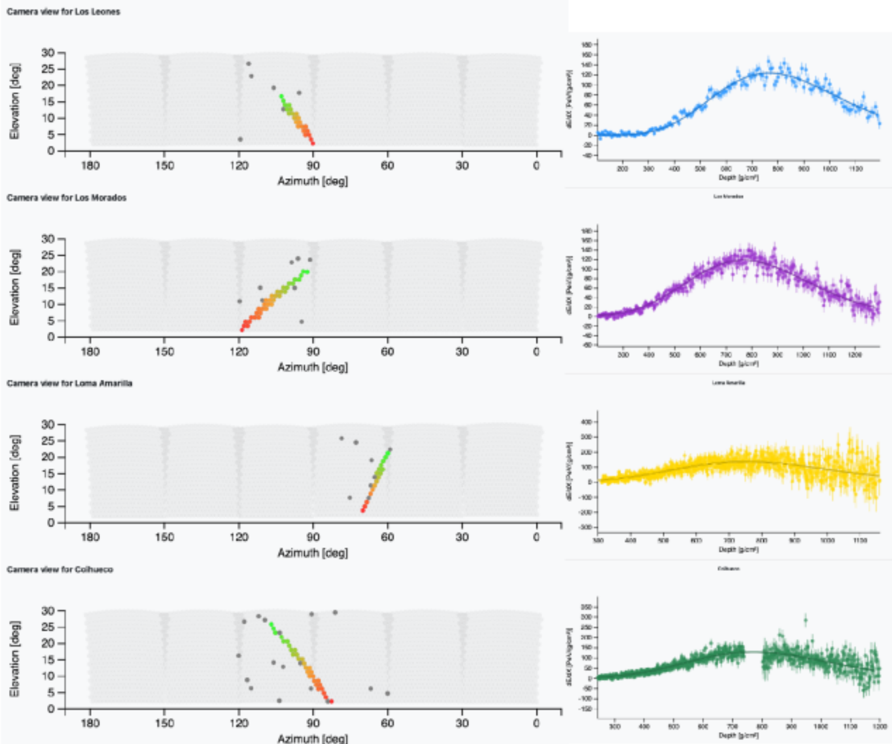
Unprecedented statistics and precision!

SD rec



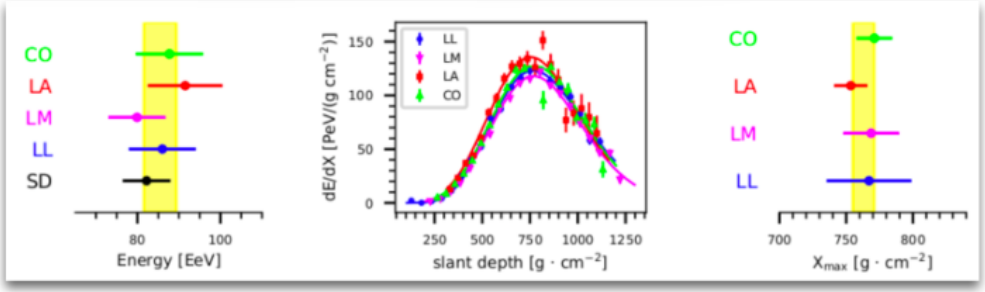
Energy	82±7 EeV
θ	53.8°
ϕ	100.6°
β	-2.1
$t_{1/2}(1000)$	127±5 ns
δ	17.8°
α	324.5°
Multiplicity	22



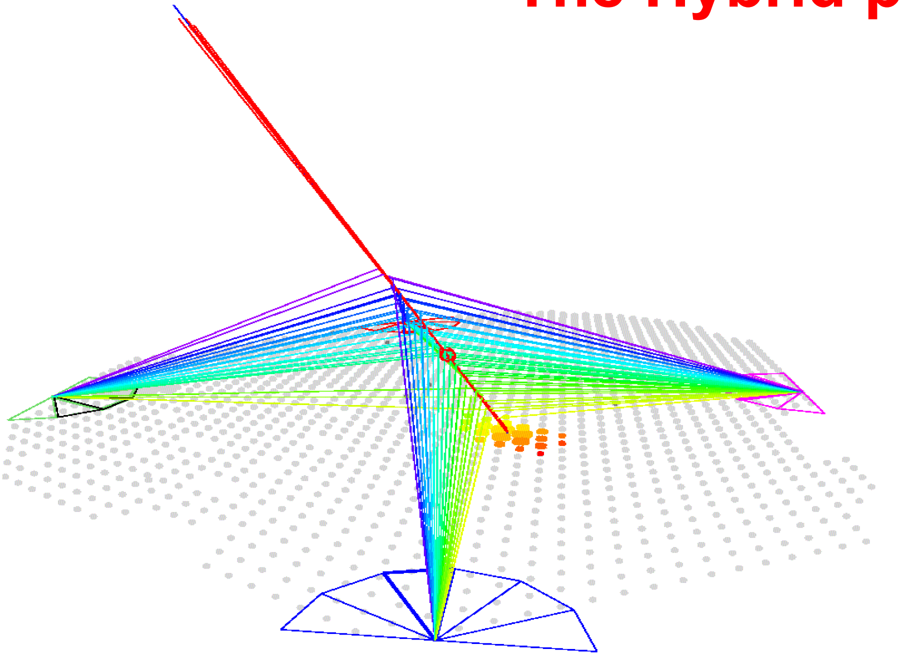


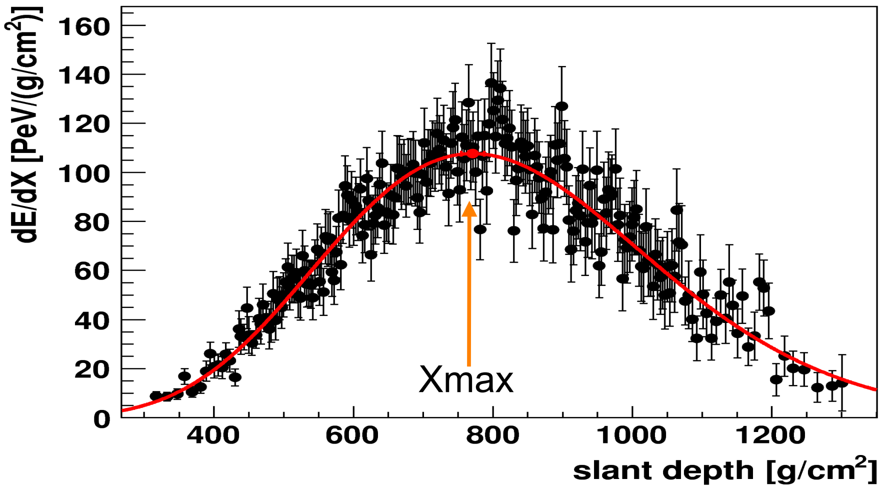
Astrophys. J. Suppl. S. 264 (2023) 50

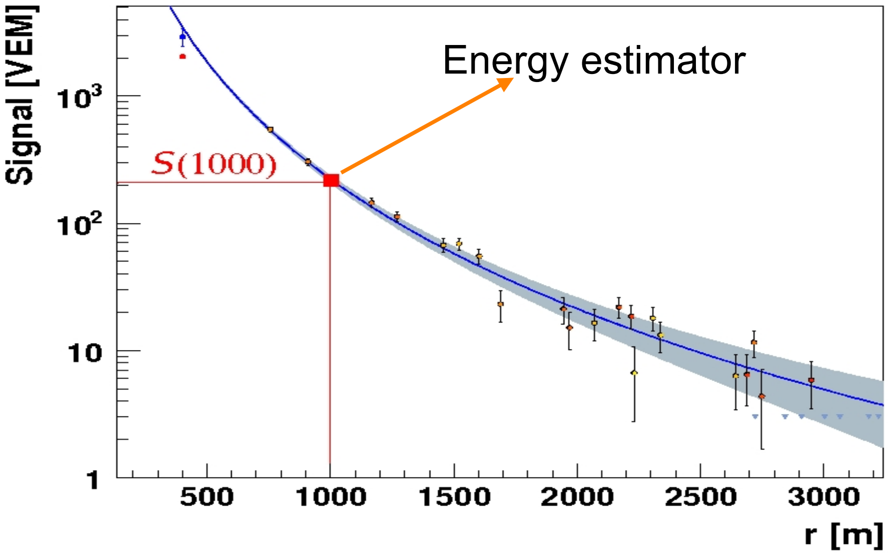
Hybrid rec



The Hybrid paradigm







Longitudinal profile

FD - calorimetric measurement

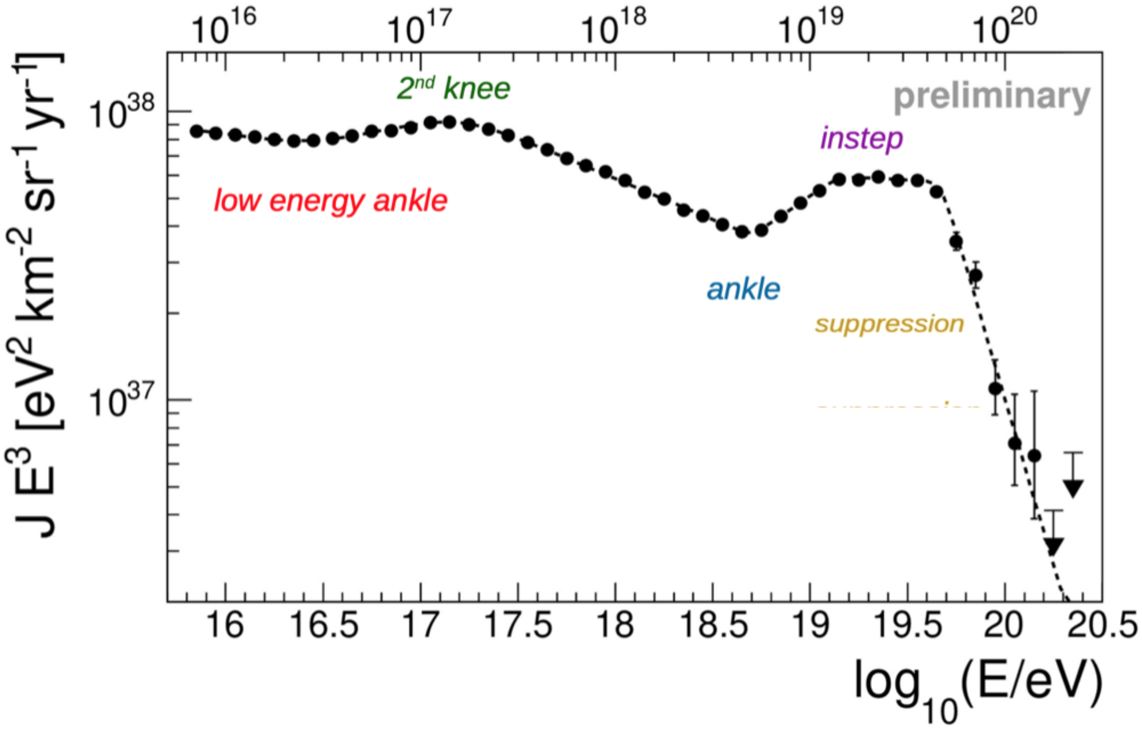
- duty cycle 15%
- Xmax (mass composition)

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

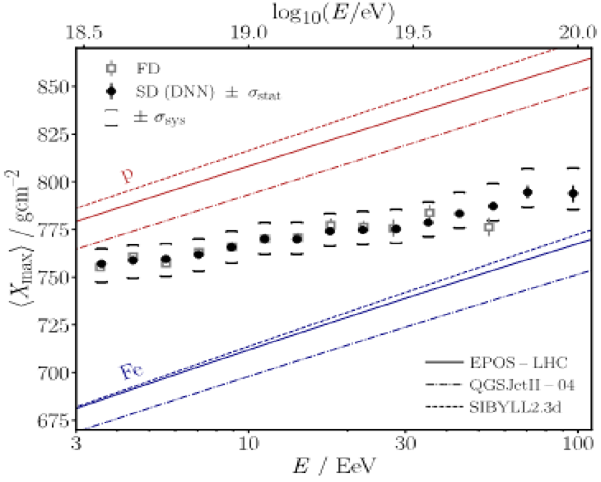
2nd knee observed, hint for a low energy ankle

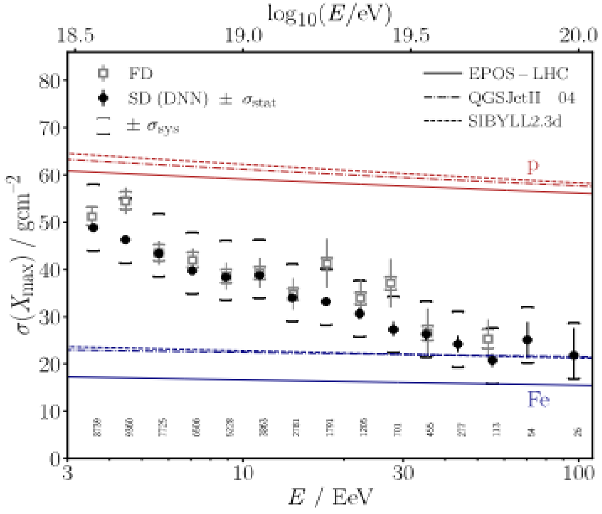
Phys. Rev. D 102(2020) 062005, Phys. Rev. Lett. 125 (2020) 121106

<Xmax> and sigma

Phys Rev. D 111, 022003 (2025)

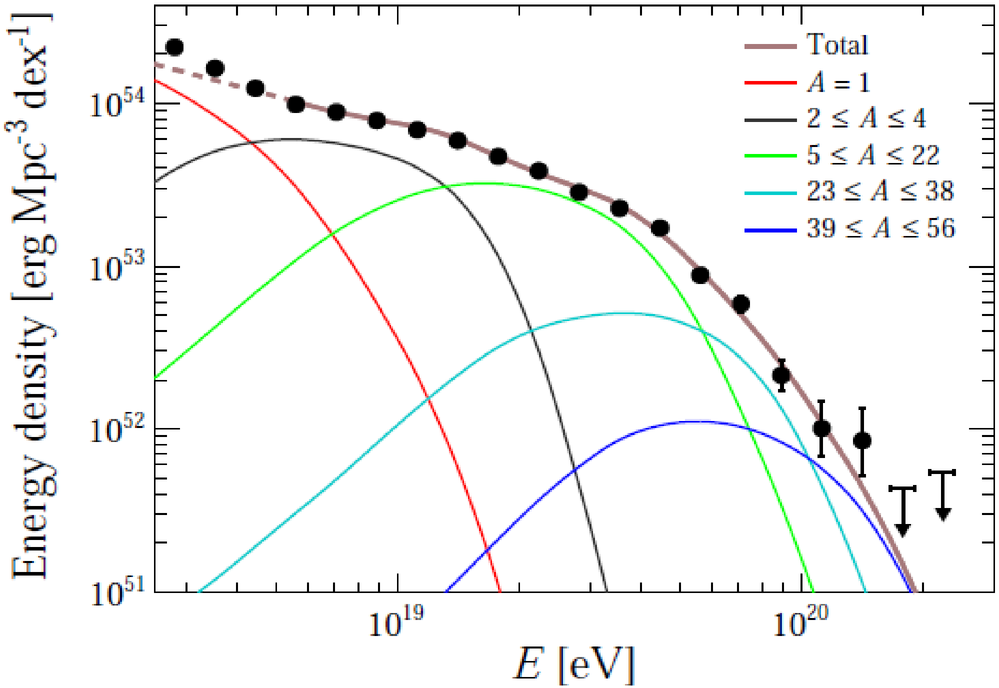
Phys.Rev. Lett. 134 (2025) 021001





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**

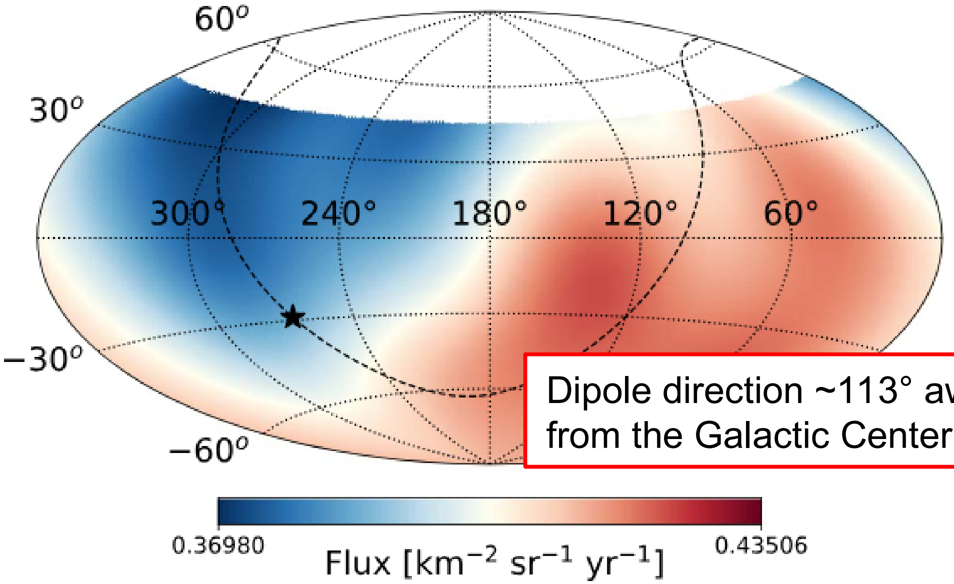
Large Scale anisotropy

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

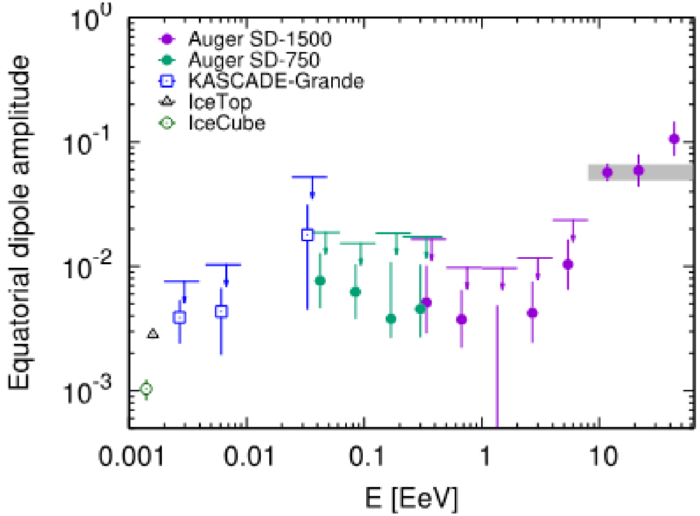
Observation of dipolar anisotropy for E≳8 10^{18} eV
Significance 6.9 σ above 8 EeV, 5.7σ at E=8-16 EeV

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



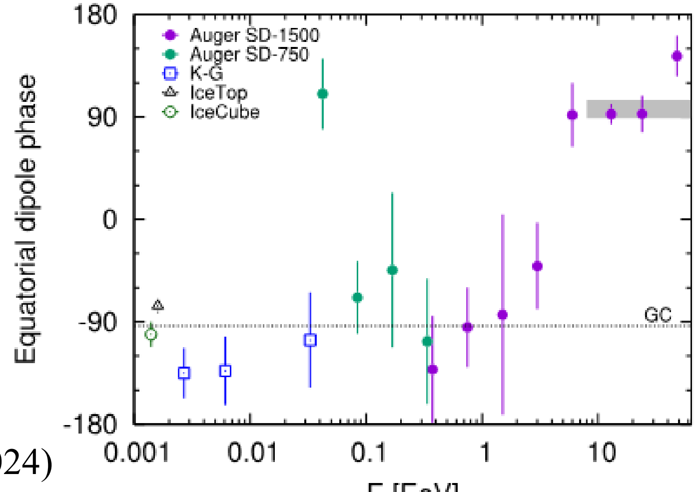
Dipole direction ~113° away from the Galactic Center



Dipole amplitude and phase

Evolution with energy of the dipole phase away from GC

→ **Extragalactic origin of UHECR above 8 EeV**

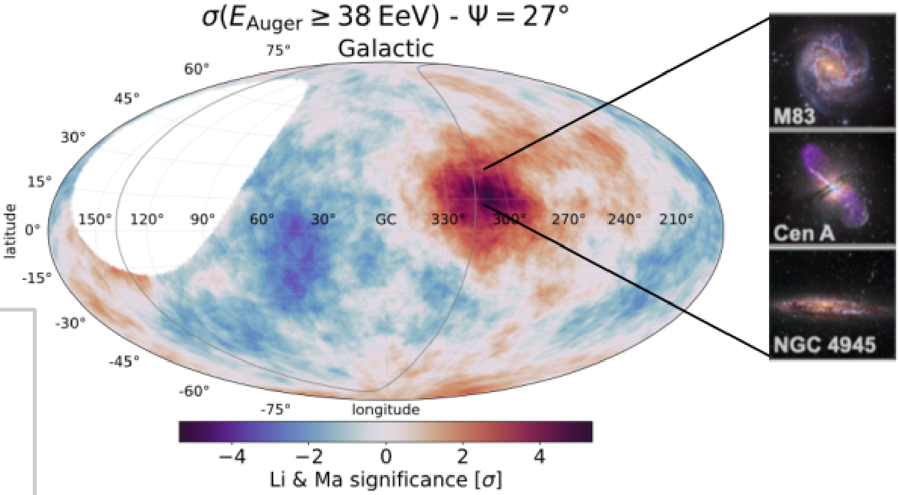


Science 315 (2017) 1266, APJ 976:48 (2024)

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

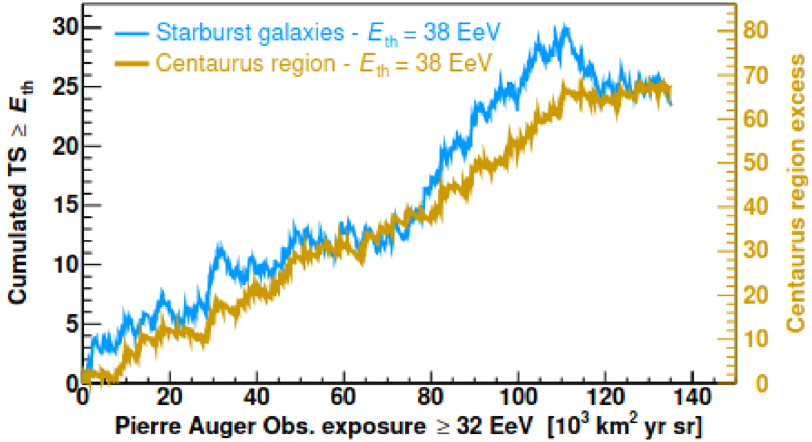
Autocorrelation with structures (GC, GP, SGP) not significant

Likelihood test for anisotropy with catalogs

Attenuation and relative weight of sources taken into account.

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}

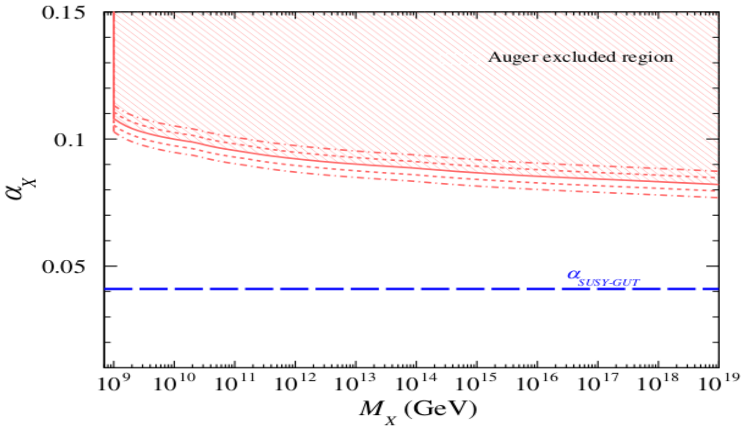


The Astrophysical Journal 935 (2022)170, PoS(ICRC2023) 252

PHYSICAL REVIEW D **107**, 042002 (2023)

Cosmological implications of photon-flux upper limits at ultrahigh energies in scenarios of Planckian-interacting massive particles for dark matter

Using the data of the Pierre Auger Observatory, we report on a search for signatures that would be suggestive of super-heavy particles decaying in the Galactic halo. From the lack of signal, we present upper limits for different energy thresholds above $\gtrsim 10^8$ GeV on the secondary by-product fluxes expected from the decay of the particles. Assuming that the energy density of these super-heavy particles matches that of dark matter observed today, we translate the upper bounds on the particle fluxes into tight constraints on the couplings governing the decay process as a function of the particle mass. Instantons, which are nonperturbative solutions to Yang-Mills equations, can give rise to decay channels otherwise forbidden and transform stable particles into metastable ones. Assuming such instanton-induced decay processes, we derive a bound on the reduced coupling constant of gauge interactions in the dark sector: $\alpha_X \lesssim 0.09$, for $10^9 \lesssim M_X/\text{GeV} < 10^{19}$. Conversely, we obtain that, for instance, a reduced coupling constant $\alpha_X = 0.09$ excludes masses $M_X \gtrsim 3 \times 10^{13}$ GeV. In the context of dark matter production from gravitational interactions alone during the reheating epoch, we derive constraints on the parameter space that involves, in addition to M_X and α_X, the Hubble rate at the end of inflation, the reheating efficiency, and the nonminimal coupling of the Higgs with curvature.



SHDM scenario assuming dark matter interaction (lifetime stabilized) with SM particles using photon upper limits

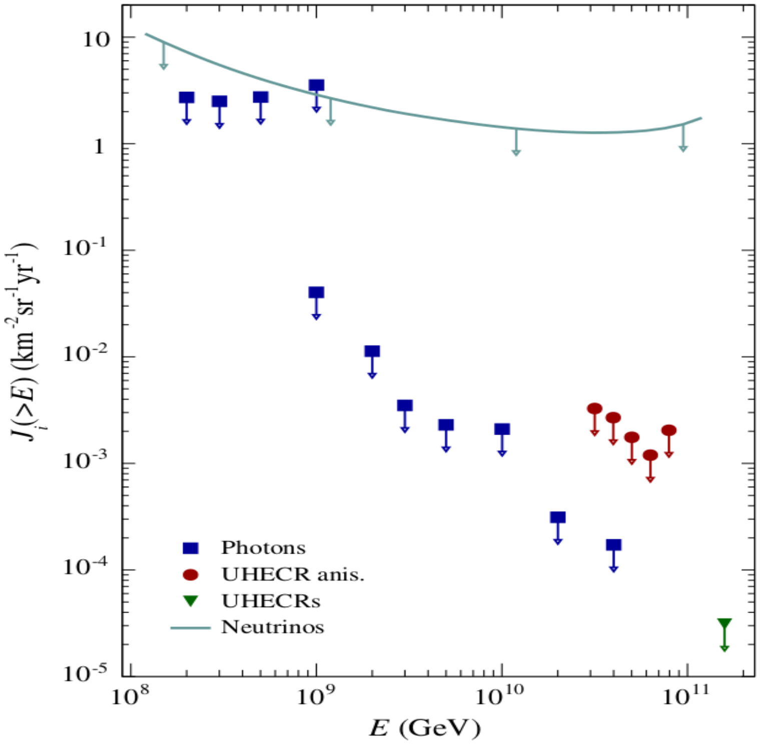
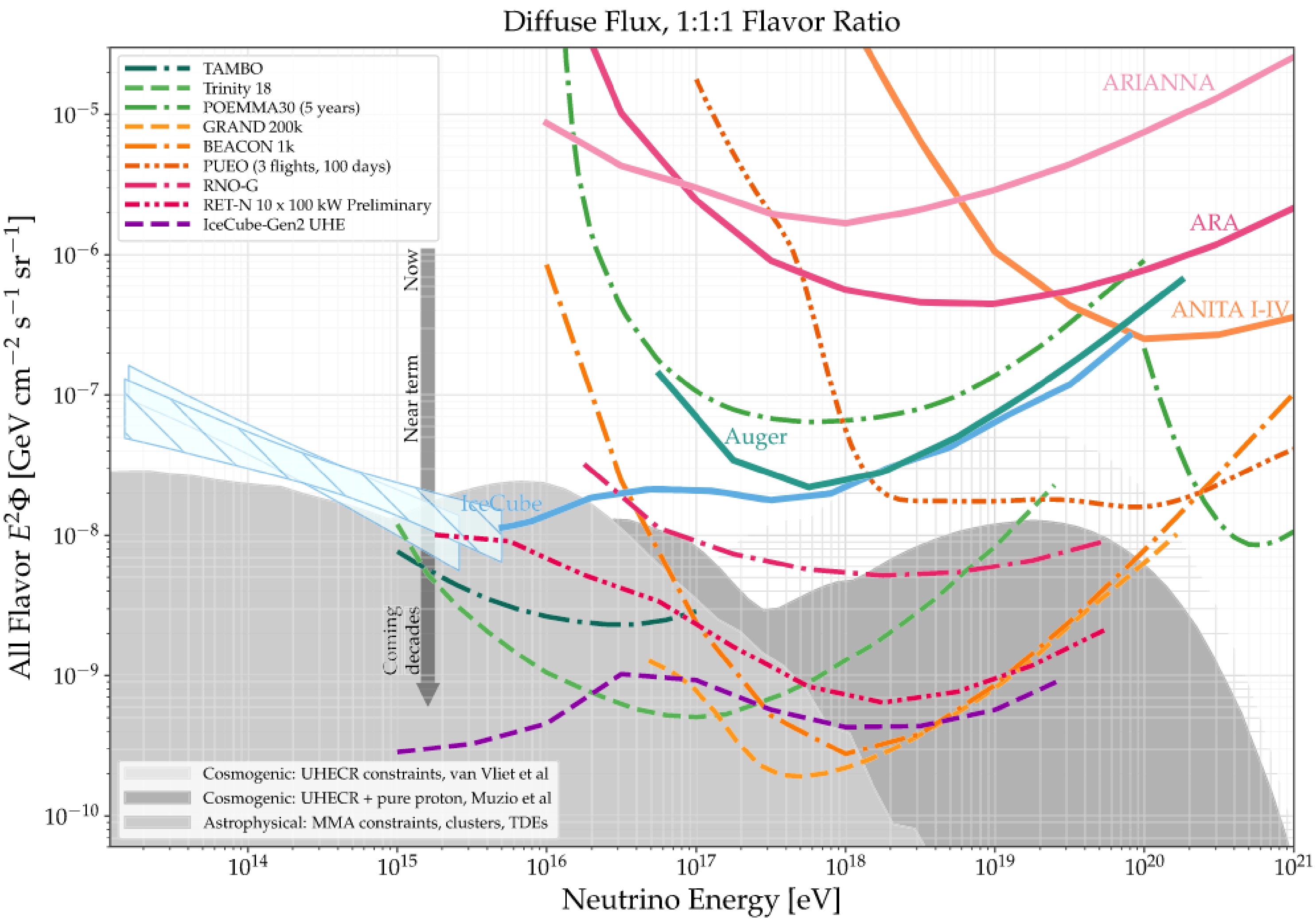


FIG. 3. Upper limits on secondaries produced from the decay of SHDM particles.

Defining an exclusion region in the **coupling-mass** phase space



Ackermann+ Snowmass 2022