Search for ultra-high energy photons and neutrinos in the multi-messenger context at the Pierre Auger Observatory

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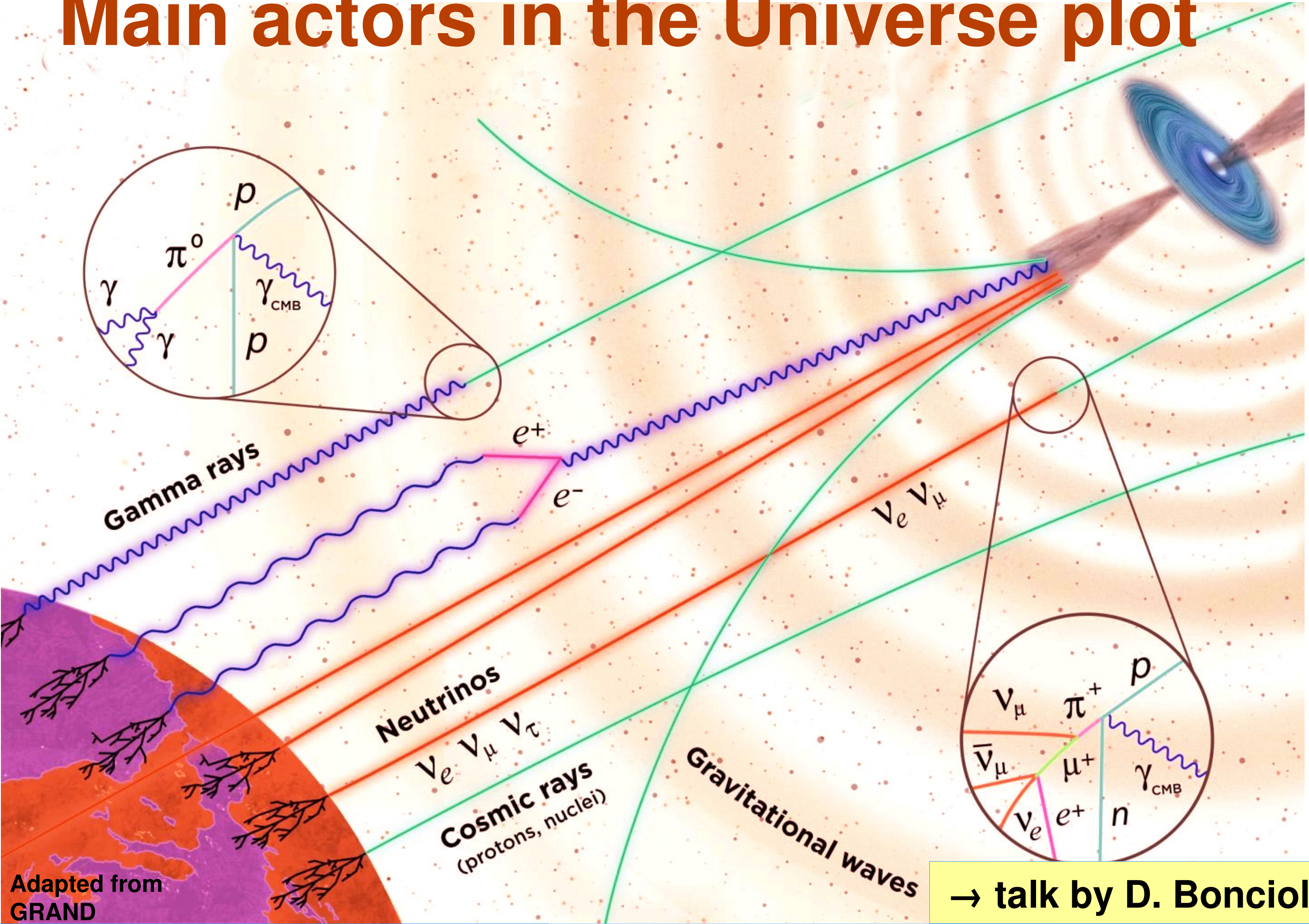
* Università del Salento and INFN Lecce, Italy

Main actors in the Universe plot



→ talk by D. Boncioli

→ **Gravitational Waves:** Multi wavelenght searches in combination with mergers

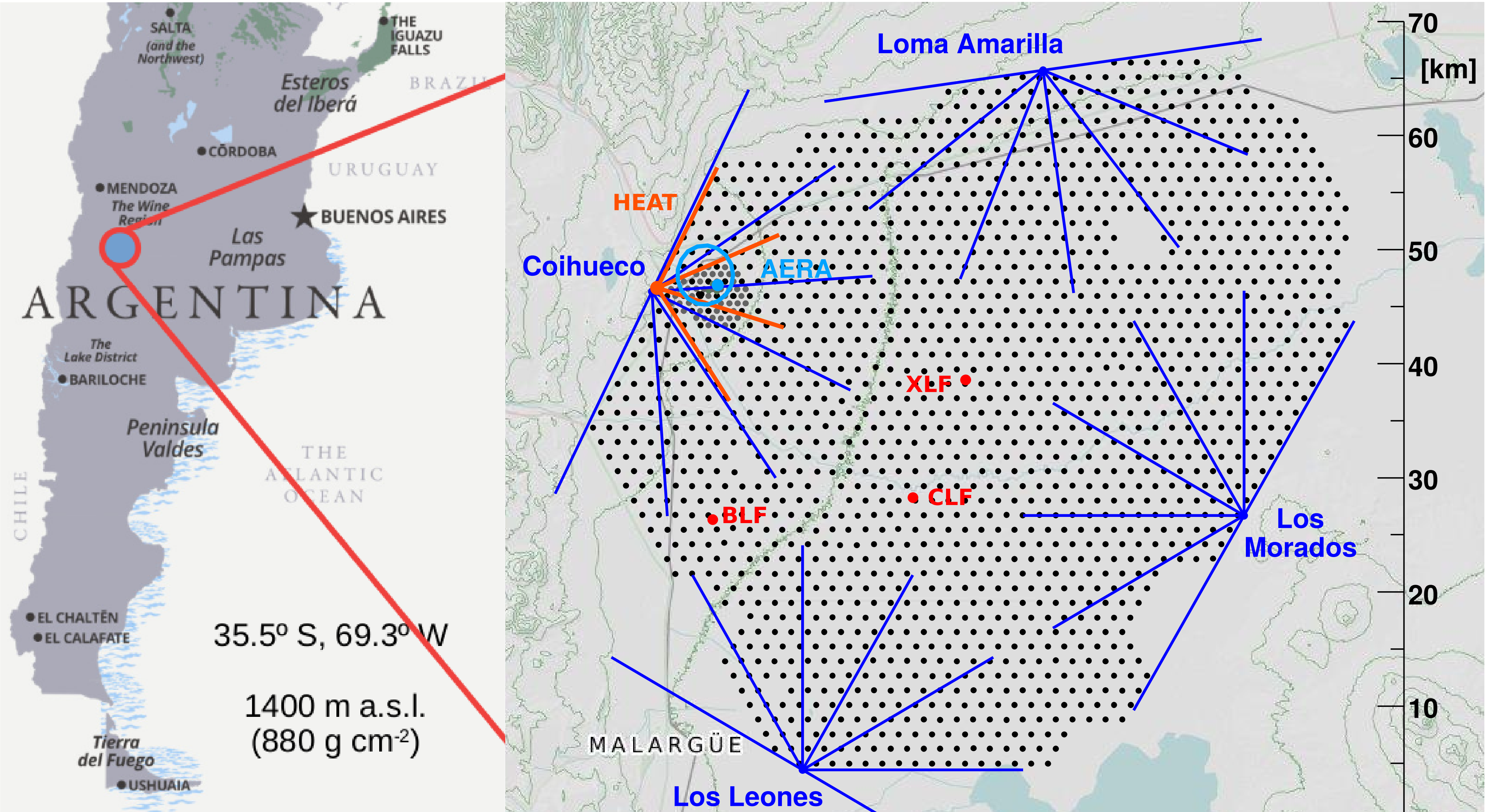
→ **Charged UHECR:** magnetic fields deflection

→ **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

explore the intimate connection between UHECR and neutrals sources & propagation

The Pierre Auger Observatory

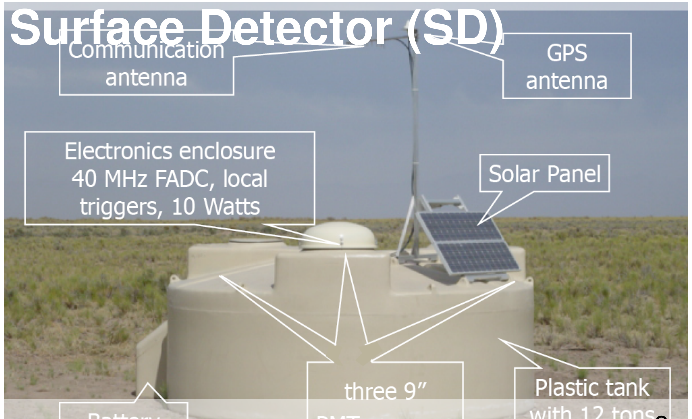


The Pierre Auger Observatory

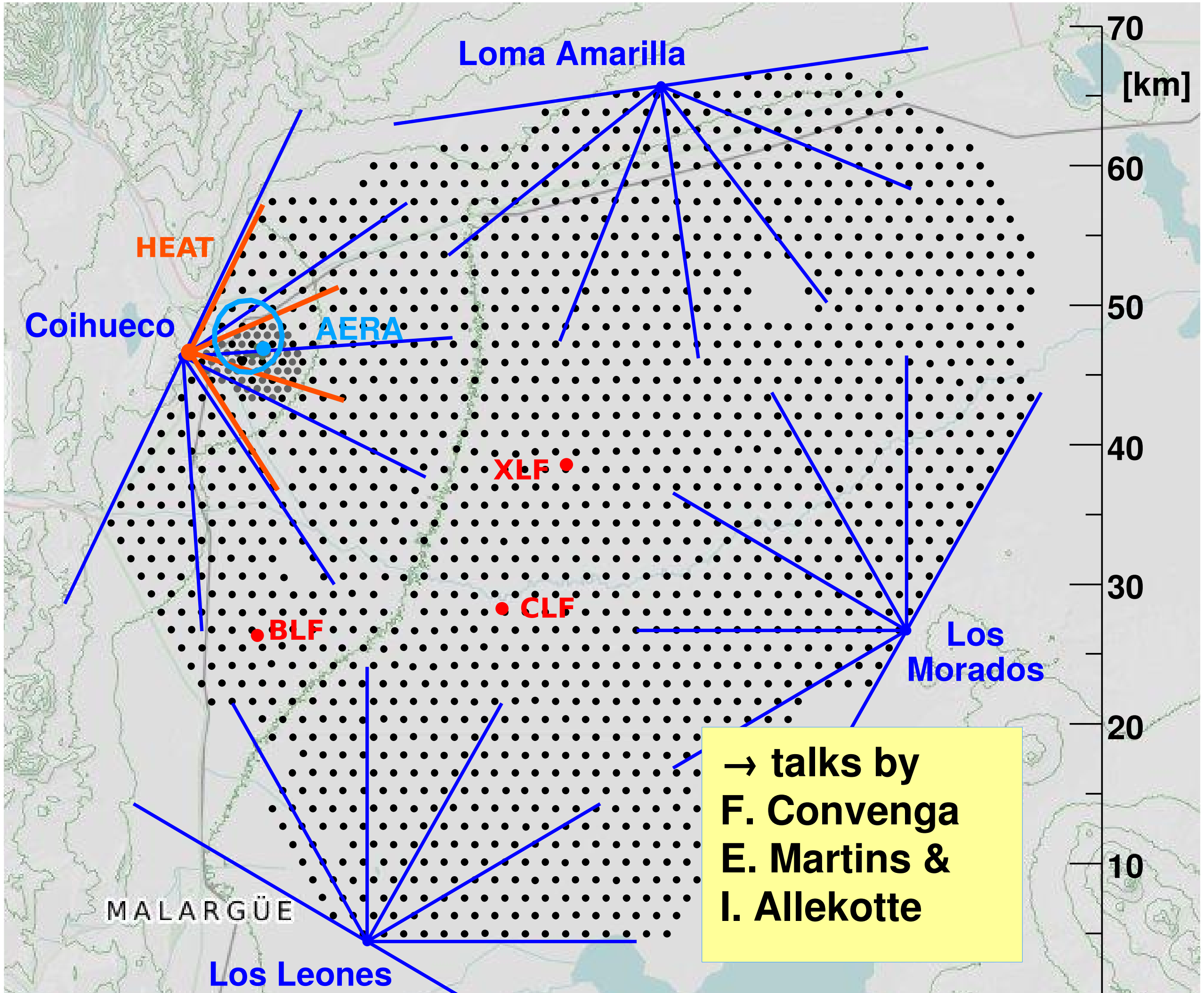
Fluorescence Detector (FD)

24 Tel. @ 4 sites, 1°-30° FoV
3 Tel. (HEAT), 30°-60° FoV

Surface Detector (SD)

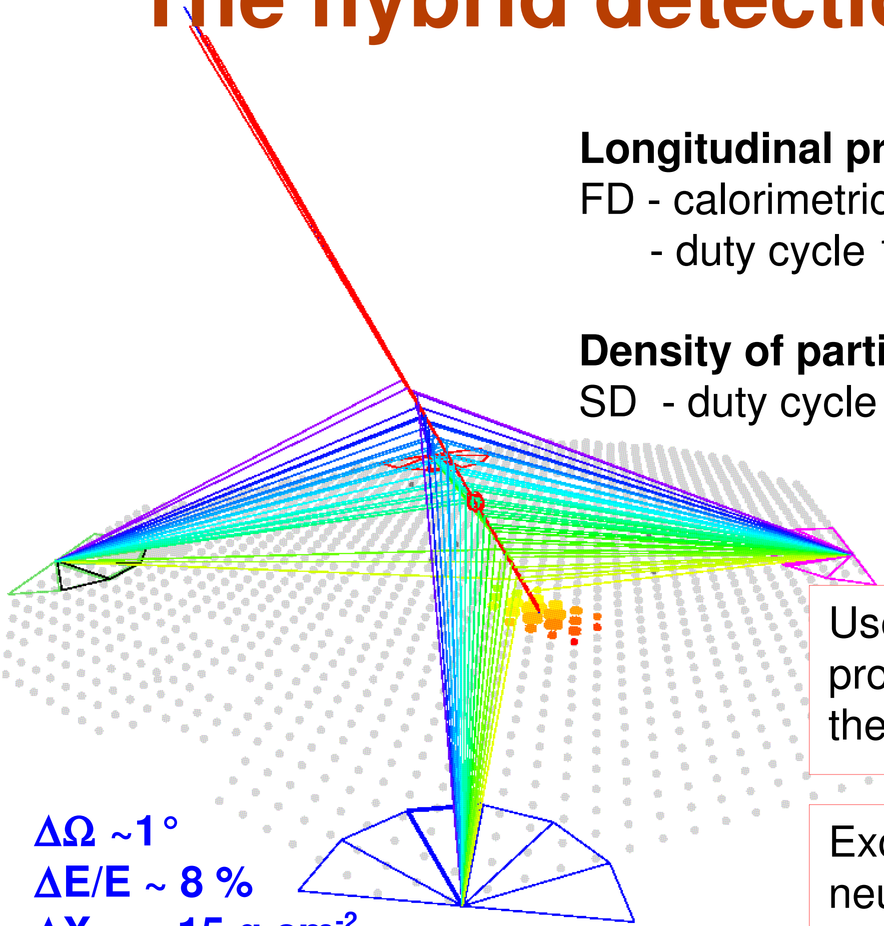


1600 stations @ 1.5 km, 3000 km^2
61 stations @ 0.75 km, 25 km^2



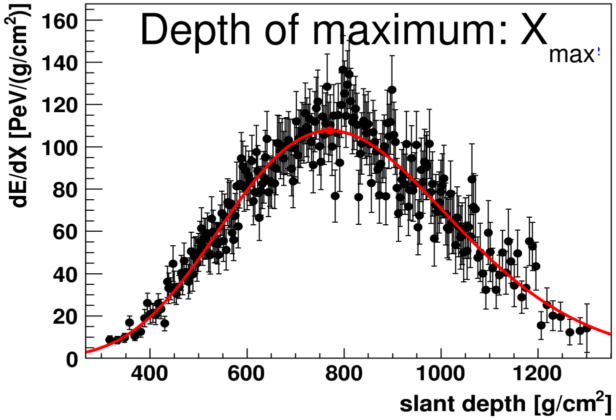
→ talks by
F. Convenga
E. Martins &
I. Allekotte

The hybrid detection of cosmic rays

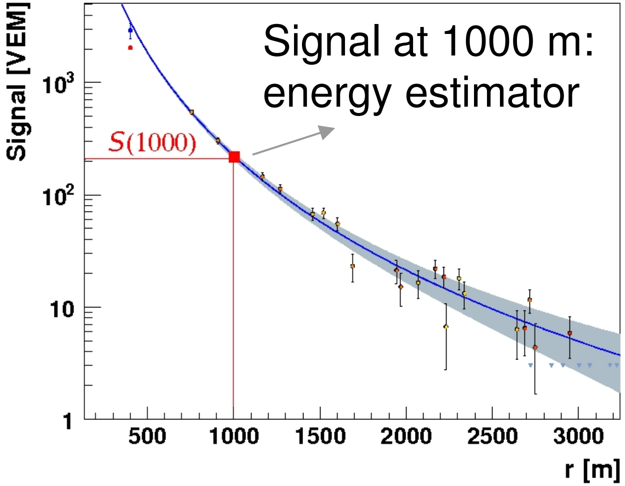


Longitudinal profile
FD - calorimetric measurement
- duty cycle 15%

Density of particles at the ground
SD - duty cycle ~ 100%



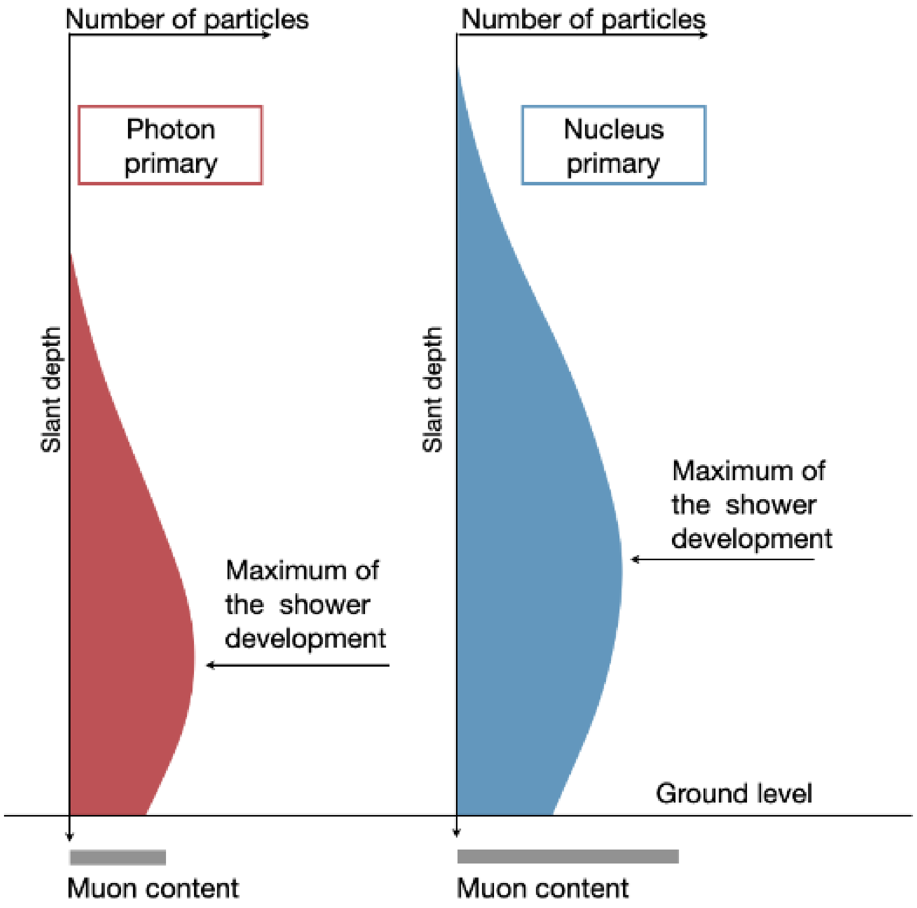
Use the energy scale provided by FD to calibrate the entire SD data sample



Excellent sensitivity also to neutral primaries in the EeV energy range

$\Delta\Omega$ ~1 °
$\Delta E/E$ ~ 8 %
ΔX_{max} ~15 g cm^{-2}

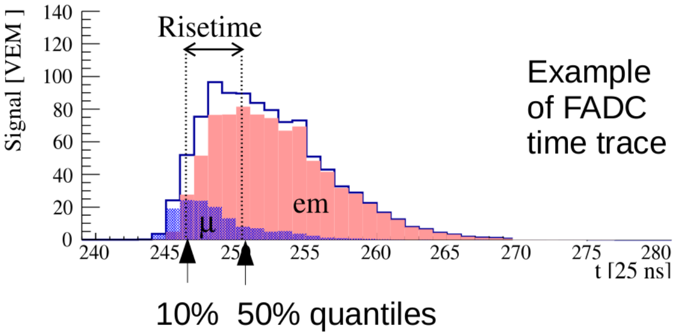
UHE Photon induced cascades



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

observable characteristics:

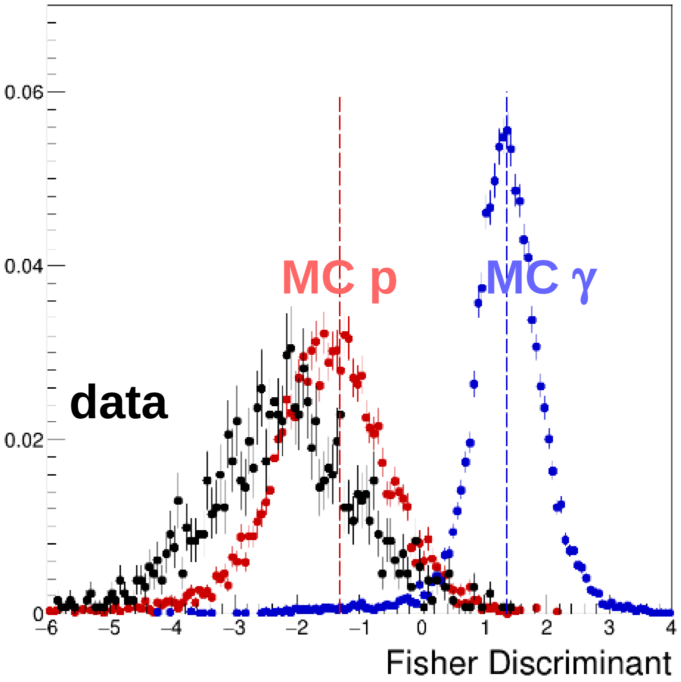
- deeper <Xmax>
- steeper LDF
- smaller footprint
- broader signal traces



Example of FADC time trace

Photons: HYB and SD data selection

Hybrid selection: Fisher response

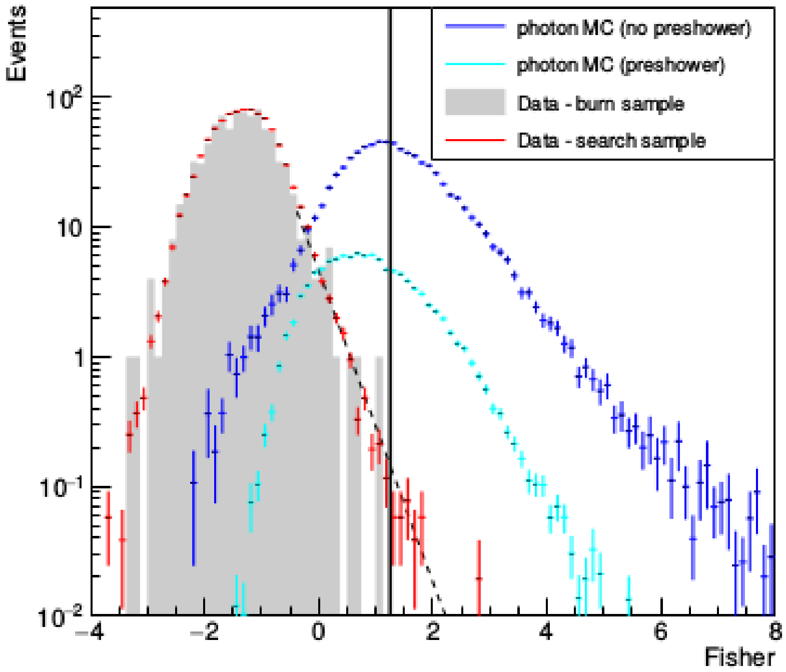


→ Maximum of shower development: $\mathbf{X}_{max}$

→ Muon content of the shower (universality): F_μ

PoS(ICRC2021)373, paper in preparation

SD selection: Fisher response



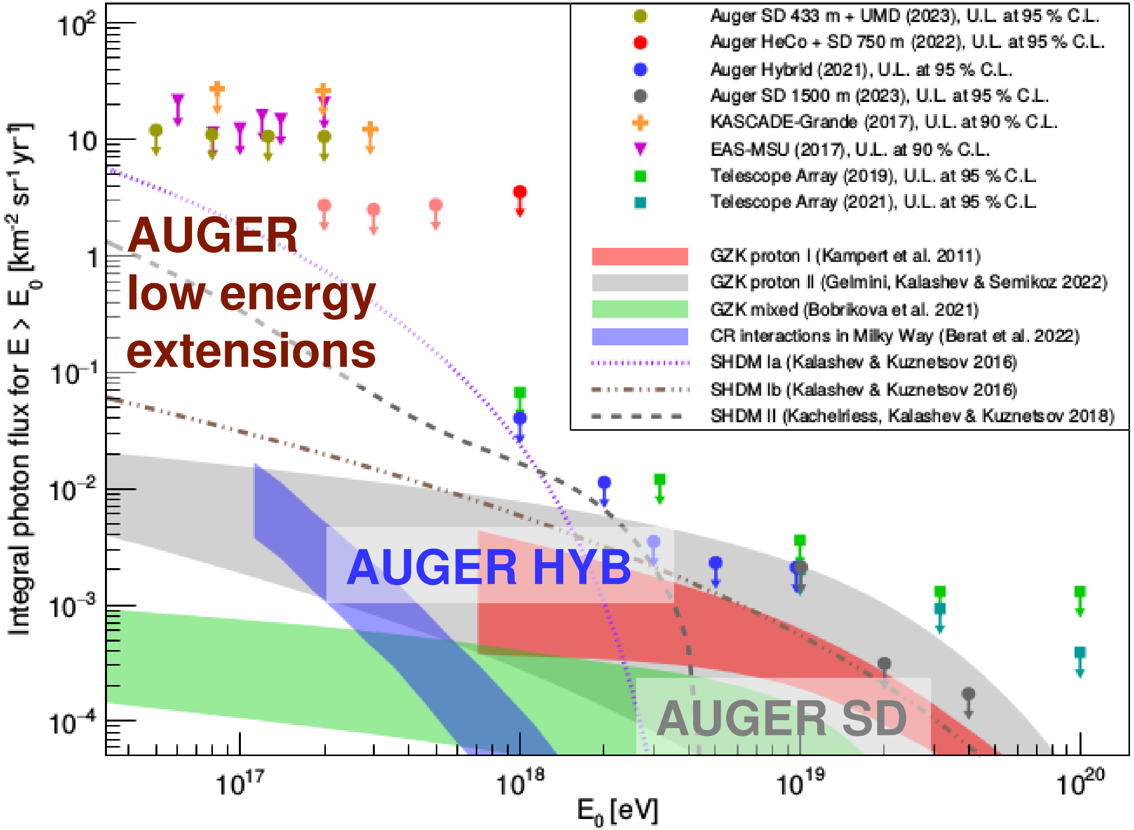
deviation from benchmark obtained from data:

→ based on LDF: $\mathbf{L}_{LDF}$

→ based on rise-time: **Δ**

JCAP 05 (2023) 021

Photon flux upper limits



Ap. J. 933 (2022)125
PoS (ICRC 2021) 373
JCAP 05 (2023) 021
PoS(ICRC2023)1488

→ measurements over ~4 decades

→ constraining cosmogenic predictions
→ disfavouring most top-down models
→ constraining mass and lifetime of dark matter particles

→ talk by O. Deligny

Phys. Rev. Lett., 130(6):061001, 2023
Phys. Rev. D, 107(4):042002, 2023

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

ApJL. 837: L25 (2017)

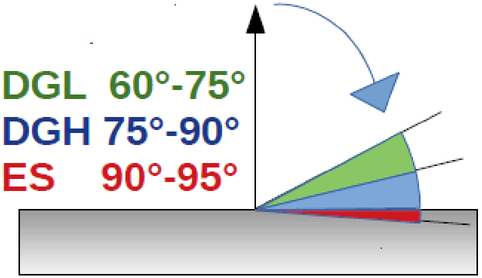
→ Auger Phase II started in 2022 additional information for better photon/hadron separation or... photon discovery!

UHE neutrinos: detection channels

Earth-skimming (ES):
upward going τ neutrinos CC
zenith angle 90° ÷ 95°

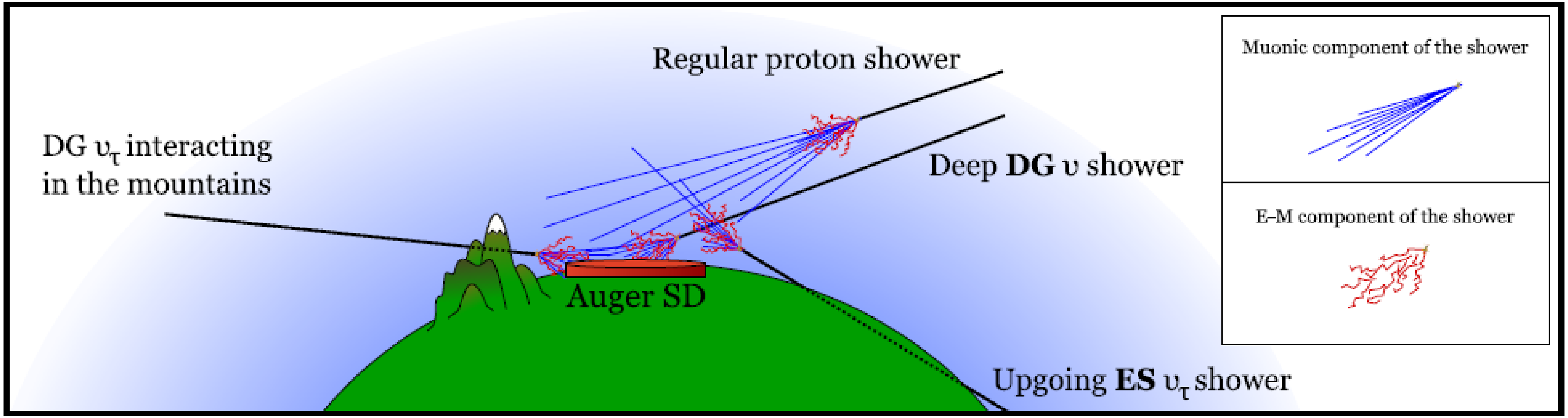
→ τ can emerge from the Earth crust and decay close to the detector

D. Fargion, Astrophys. J. 570, 909 (2002)
A. Letessier-Selvon, AIP Conf. Proc. 566, 157 (2001)

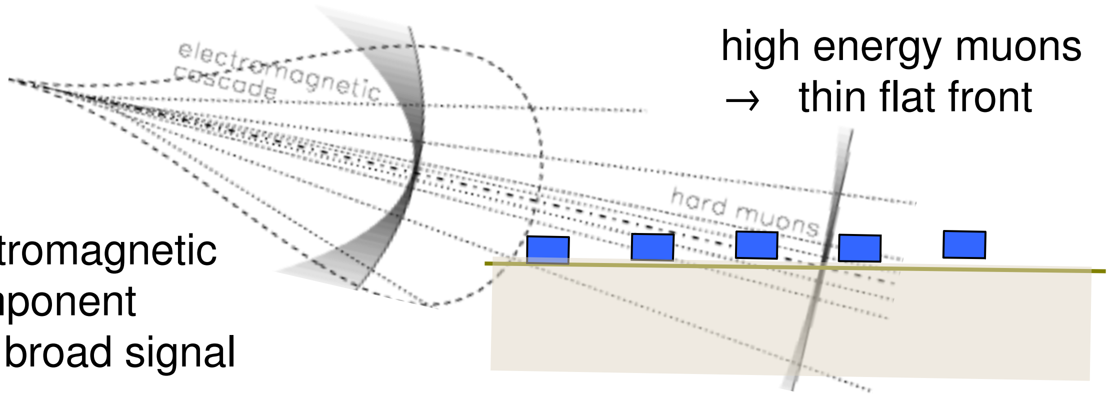


Downward Going (DG):
deeply interacting ν CC & NC
DGL 60°÷75° - DGH 75°÷90°

Sensitivity to ALL ν flavours and ALL interaction channels



UHE neutrinos: signature



high energy muons
→ thin flat front

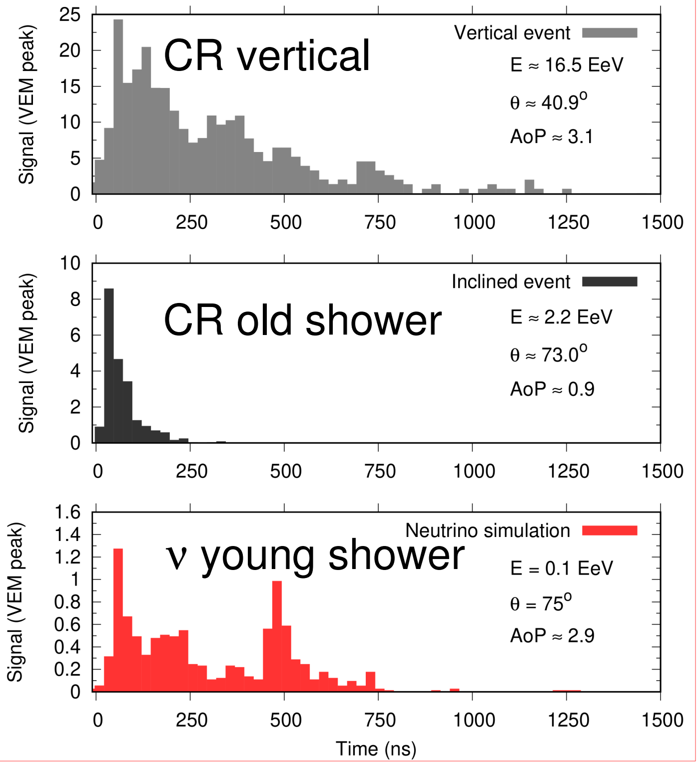
elettromagnetic component
→ broad signal

young shower i.e. with large electromagnetic component
→ inclined event with slow rising and broad signal

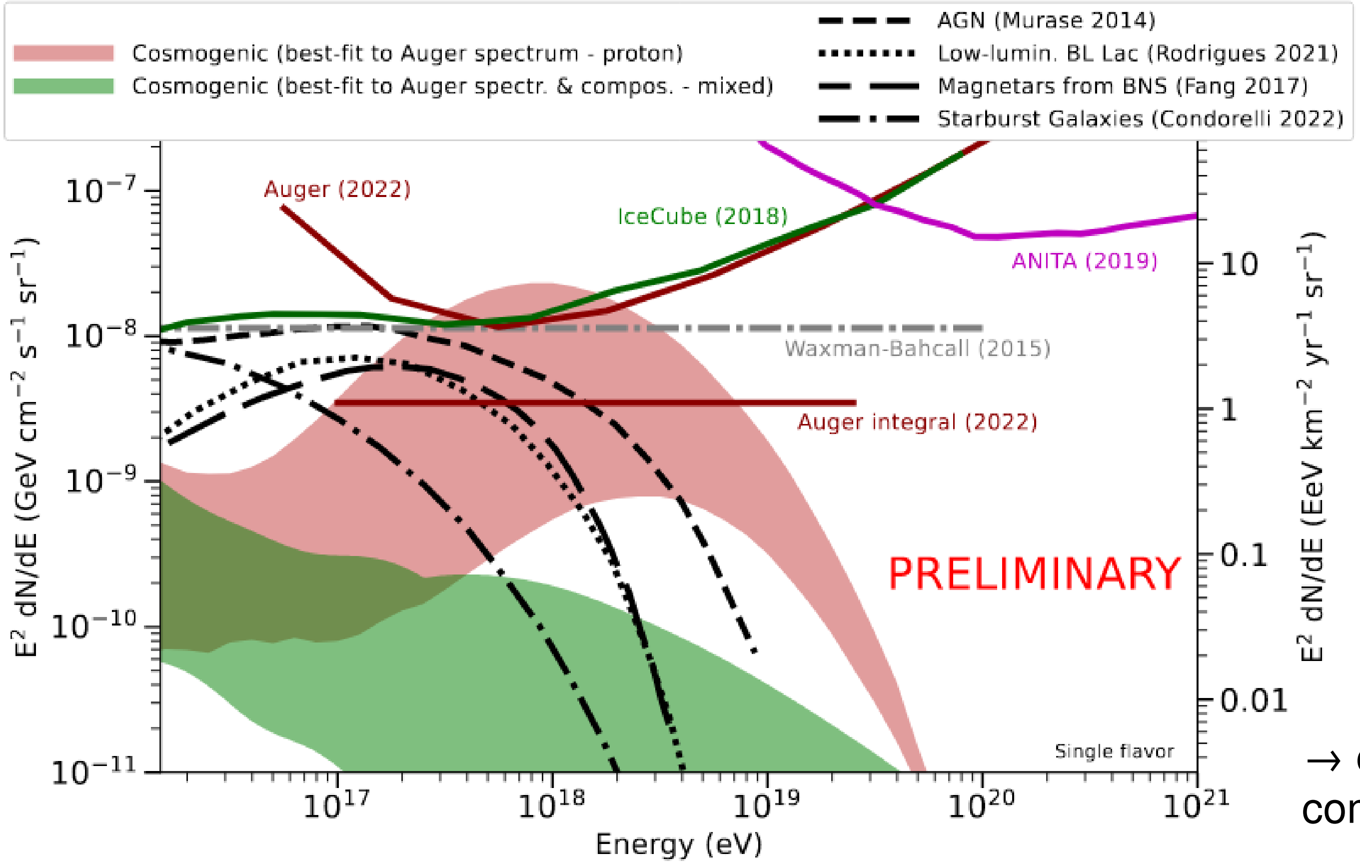
background composed by **muon-dominated hadronic showers** (EM component absorbed in the atmosphere)

discrimination relies on the **different SD signal shapes** between hadronic and neutrino events
→ Area-over-Peak

typical signal shapes



UHE neutrinos: diffuse flux limits



Pierre Auger Coll., JCAP 10 (2019) 022
EPJ Web Conf. 283 (2023) 04003

SD data from 1 January 2004 until 31 December 2021

NO Candidates found

Max sensitivity ~ **1 EeV**

Integral UL normalization factor
k ~ 3.5 x 10^{-9} [GeV cm^{-2} s^{-1} sr^{-1}]

pure-proton scenario disfavoured

factor 3 exposure for probing mixed-composition scenarios

→ corresponding limits on point sources complement IceCube and ANTARES

→ activity ongoing on transients

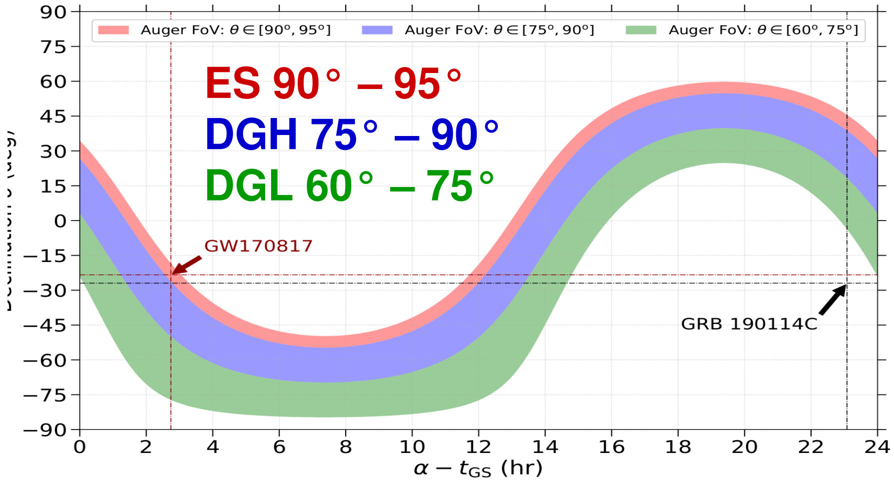
GW follow-up: ν searches

Routine in place to follow-up GW alerts

→ search for time-directional coincidence with 83 BBH events from LIGO/Virgo

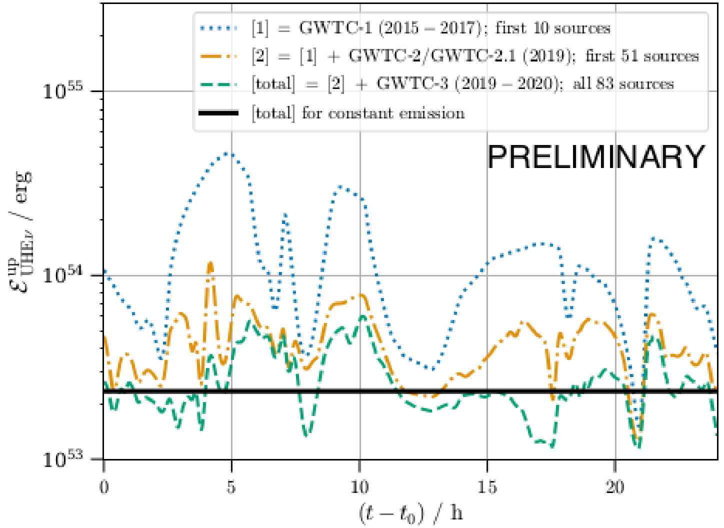
→ sensitivity strongly depends on source location and event timing

→ number of neutrinos per source proportional to weighted overlap area integrated over time



GW170817 with IceCube ANTARES, ApJL850 (2017) L35

stacked analysis: PoS(ICRC2021)968, paper in prep. (2023)



$$L_{\mathrm{up},i} = \frac{N_{\mathrm{up},\nu} \,/\, T}{\sum_s P_{\mathrm{BBH},s} \sum_{p \in \Omega_{90}(s)} \rho_{p,s} \mathcal{A}_{p,i} \int_0^\infty \frac{\Pi_{p,s}(r)}{r^2(1+z(r))}\,\mathrm{d}r}$$

No UHE-neutrino events found for 83 GW events

upper limit on neutrino emission: Eν ~ 2 x10^{53} erg

→ well below the radiated GW energy

GW follow-up: γ searches

- focus on nearby and/or well localised sources
- window open to potential new physics

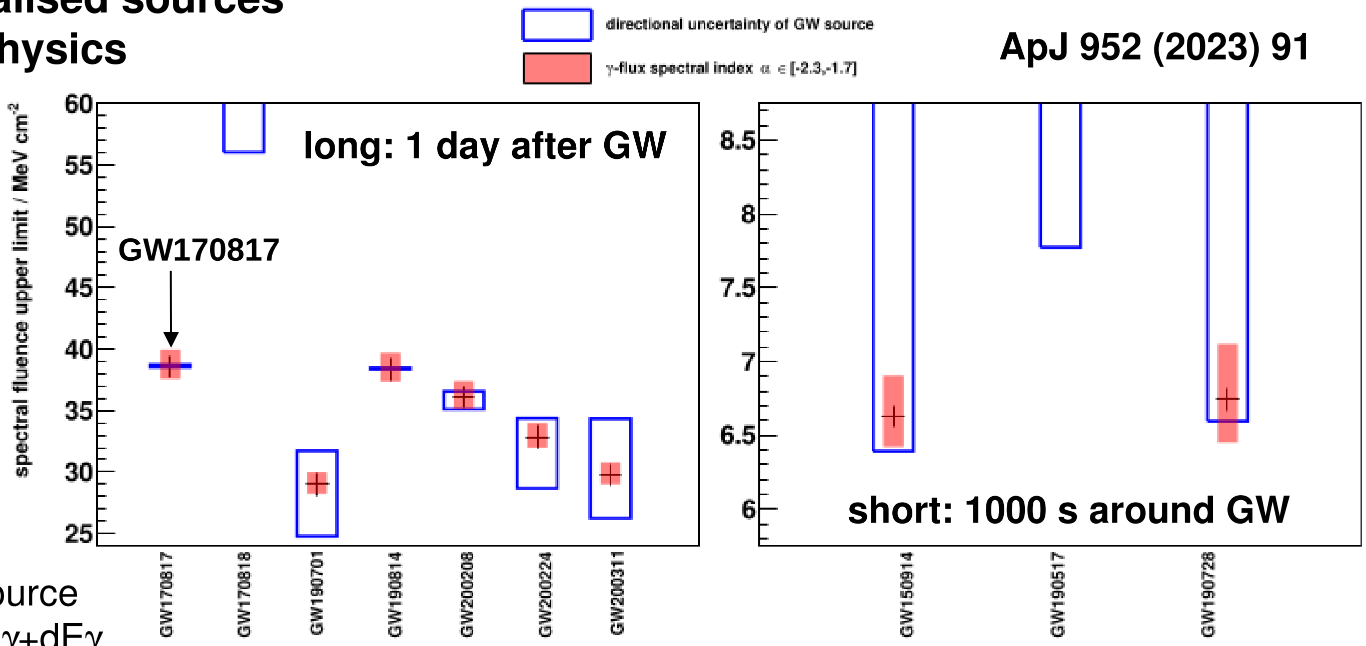
ApJ 952 (2023) 91

CLASS I (short)
D < ∞   Ω < 100 deg²

CLASS II (long)
D < ∞   Ω < 20 deg²

CLASS III (long)
D < 180 Mpc   Ω < 100 deg²

CLASS IV (long-short)
D < 50Mpc   Ω < 720 deg²



Assuming constant flux $k \cdot E_\gamma^{\alpha}$
Number of photons arriving from GW source per unit time & area in the interval E_γ ,$E_\gamma+dE_\gamma$

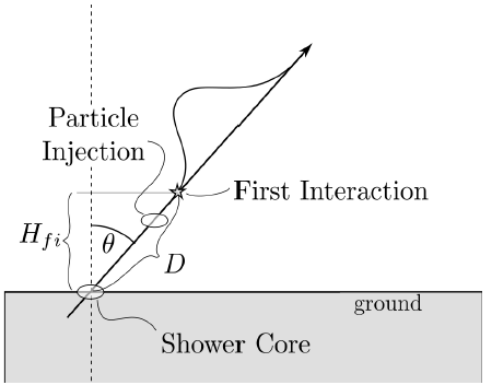
$$\mathcal{F}_\gamma^{\mathrm{UL}} = \int_{t_0}^{t_1}\int_{E_0}^{E_1} \mathrm{d}t\,\mathrm{d}E_\gamma\; E_\gamma\, \frac{d\Phi_\gamma^{\mathrm{GW}}}{dE_\gamma}$$

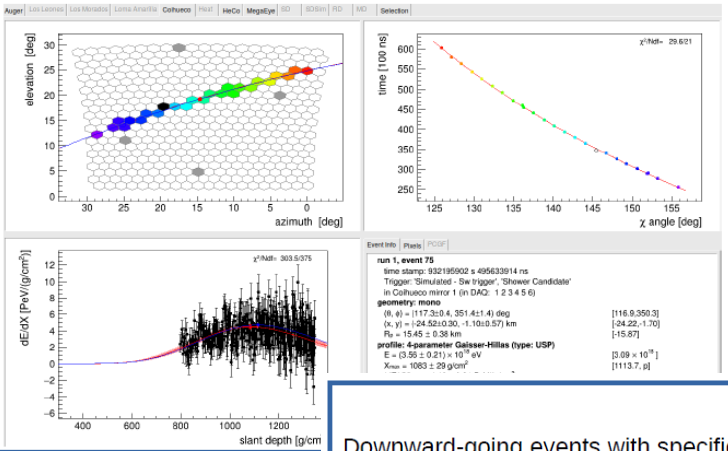
No coincident photon candidate identified
→ upper limits on spectral fluence ~ 7 MeV cm $^{-2}$ and ~35 MeV cm $^{-2}$
→ constrain energy transferred into photons to < 20% for GW170817

Search for upward-going events with the FD

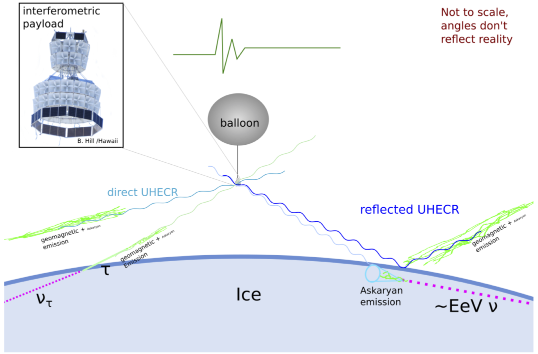
Blind analysis searching for upward-going air showers with the Fluorescence Detector PoS(ICRC2023)1099, paper in prep.

SIGNAL SIMULATION





Zenith [110°- 180°]
log10 (E/eV) [16.5-18.5]



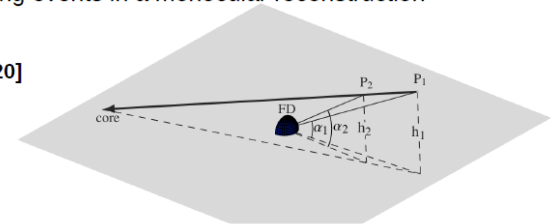
ANITA Observation:

$E_{1,2} \gtrsim 0.2$ EeV, exit angle $\approx 27°, 35°$

BACKGROUND SIMULATION

Downward-going events with specific geometries can mimic upward-going events in a monocular reconstruction

Zenith [0°- 90°]
log10 (E/eV) [17-20]



$\alpha_1 < \alpha_2$
$h_1 > h_2$

Signal from P_1 reaches the FD before the signal from P_2 → downward-going event reconstructed as upward-going

Also events with a core far away from the array can produce background and need to be simulated

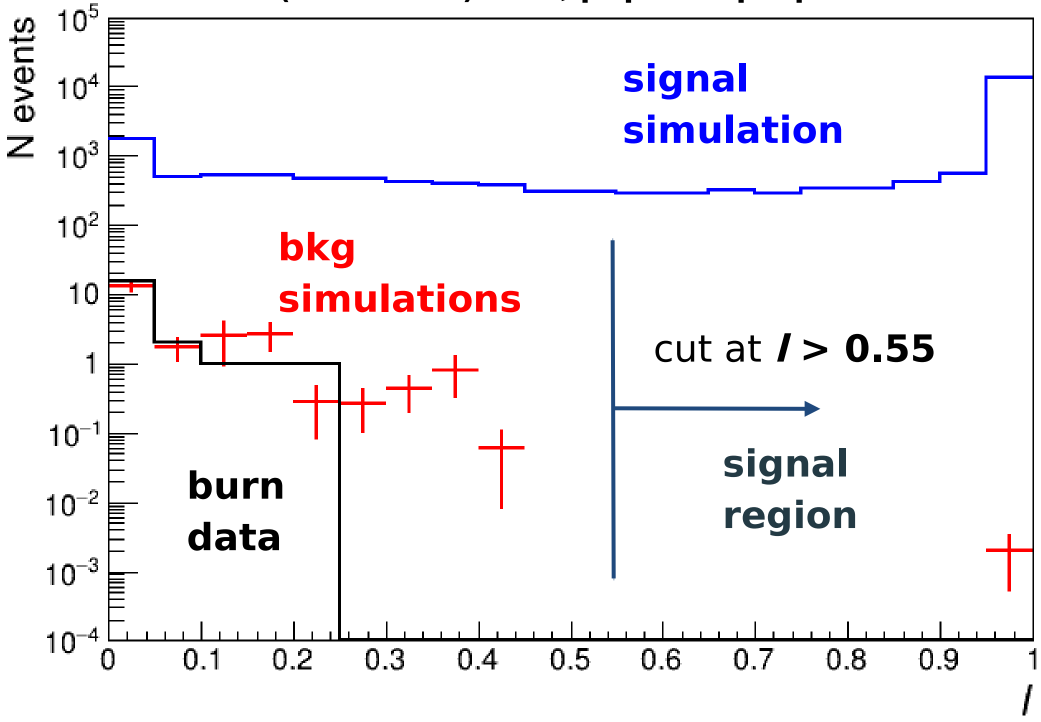
Quantify the sensitivity of the FD to upward-going showers

→ **derive the FD exposure as a function of shower energy and height of first int.**

→ **MC estimate of the expected background**

Search for upward-going events

PoS(ICRC2023)1099, paper in prep.



$$l = \frac{\arctan\left(-2\log\left(L_{down}/\max\left\{L_{down}, L_{up}\right\}\right)/50\right)}{\pi/2}$$

Signal simulations: protons, log(E/eV) [16.5, 19] zenith [110°, 180°] - h [0, 9] km - spectrum E^{-1}
→ 6.5 x 10^7 showers

Background simulations: protons He, N, Fe, log(E/eV) [17, 19], zenith[0°, 90°] - CRspectrum
→ 2.5 x 10^8 showers

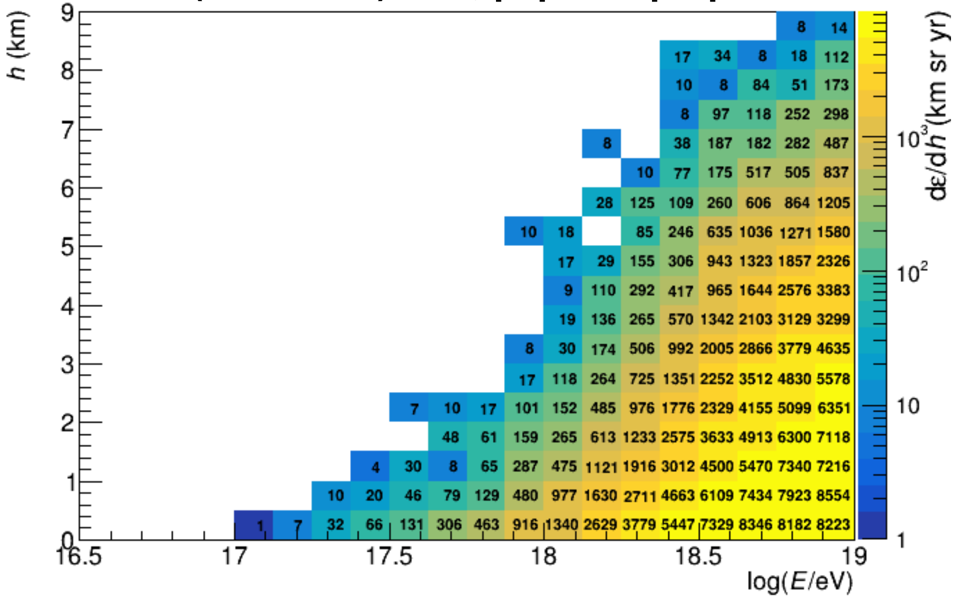
Data: 10% burn sample defining selection criteria

testing upward and downward reconstructions:
l = 0 downward favored, l → 1 upward favored

Full data sample 2004-2021:
1 candidate event found
→ consistent with background (~0.3 evts ± 0.12)

Search for upward-going events

PoS(ICRC2023)1099, paper in prep.



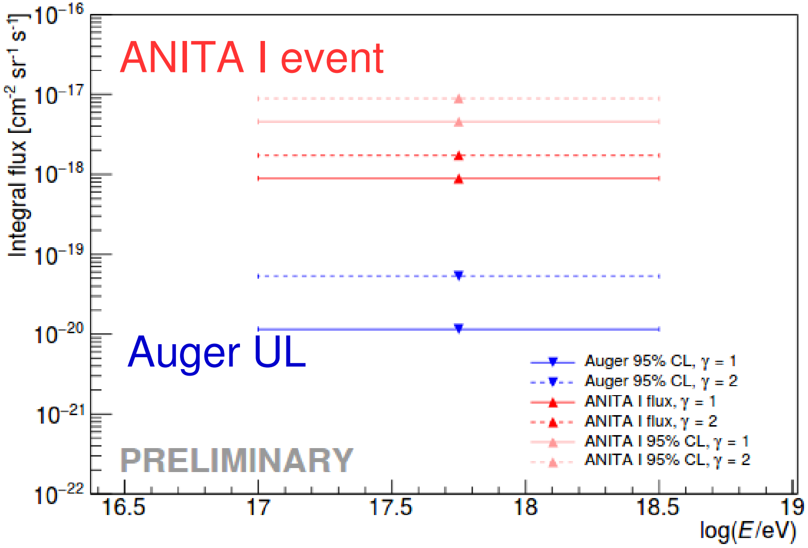
Integral upper limit above 10^{17} eV:

→ $(7.2 \pm 0.2)\times10^{-21}$ cm^{-2} s^{-1} sr^{-1}, E^{-1} spectrum

→ $(3.6 \pm 0.2)\times10^{-20}$ cm^{-2} s^{-1} sr^{-1}, E^{-2} spectrum

Upward-going shower detection efficiency can be used for testing BSM scenarios **PoS(ICRC2023)1095**

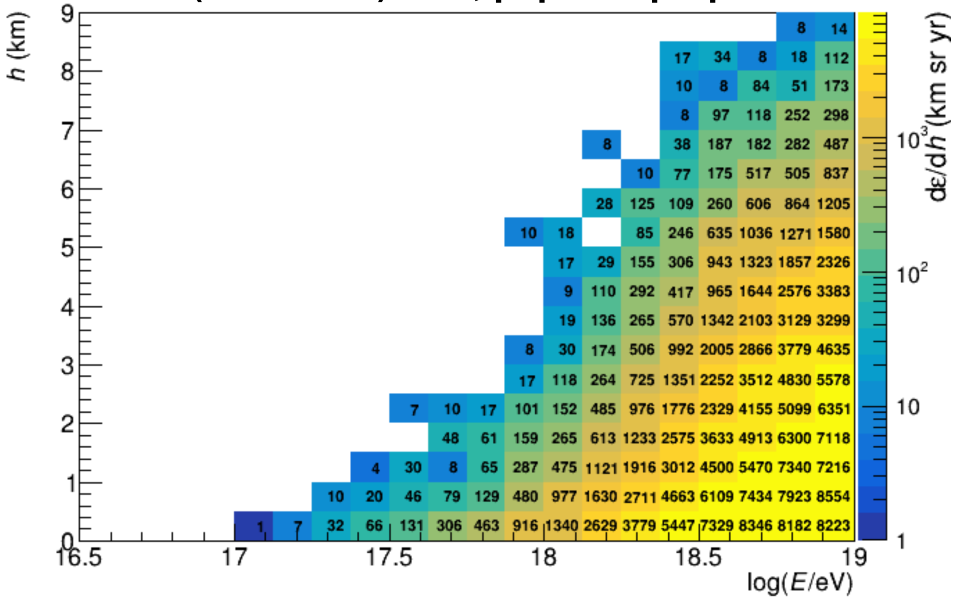
Joint work Auger-ANITA for calculating and comparing exposures



→ Auger limits are a factor ~100 (30) lower than ANITA fluxes, assuming E^{-1} (E^{-2}) spectrum

Search for upward-going events

PoS(ICRC2023)1099, paper in prep.



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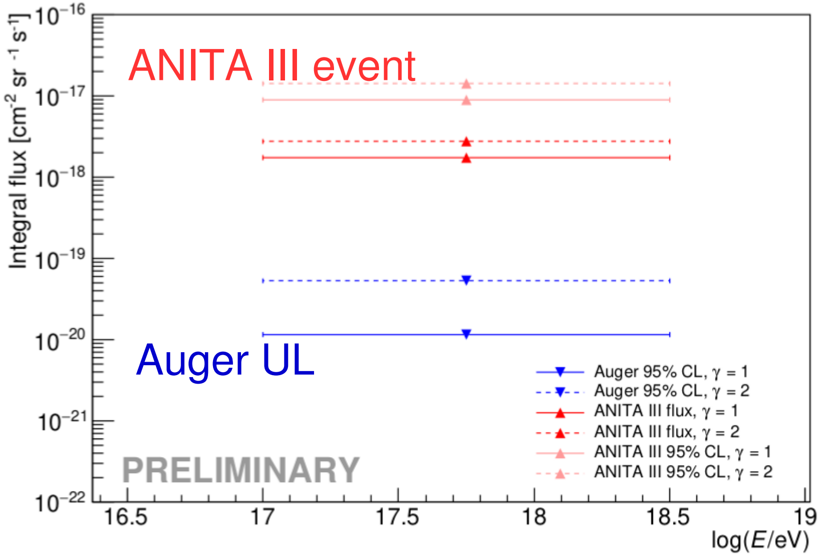


→ Auger limits are a factor ~100 (30) lower than ANITA fluxes, assuming E^{-1} (E^{-2}) spectrum

Outlook

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, the largest detector for UHECR:

→ **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 searches / transients

→ **follow-up searches** of LIGO/Virgo mergers

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

→ **upward-going searches** bounds to anomalous ANITA events & test BSM scenarios

→ The AugerPrime upgrade will improve on sensitivity and background rejection

Pierre Auger Observatory Open Data

December 2022 release

http://www.opendata.auger.org

The Pierre Auger Open Data is the public release of 10% of the Pierre Auger Observatory cosmic-ray data published in recent scientific papers and at International conferences , following the Auger Collaboration Open Data Policy. The release also includes 100% of weather and space-weather data collected until 31 December 2020. This website hosts the datasets for download. Brief overviews of the Pierre Auger Observatory and of the Auger Open Data are set out below. An online event display to explore the released cosmic-ray events, and example analysis codes are provided. An outreach section dedicated to the general public is also available.

catalog of the 100 highest energy events

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

Datasets

the released datasets

Visualize

an online look at the released

Analyze

example

codes in

Catalog

of the

energy

Outreach

a page

to the

increase CR fraction from 10% to 30% in 2024

backup slides

Targeted searches: photons

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

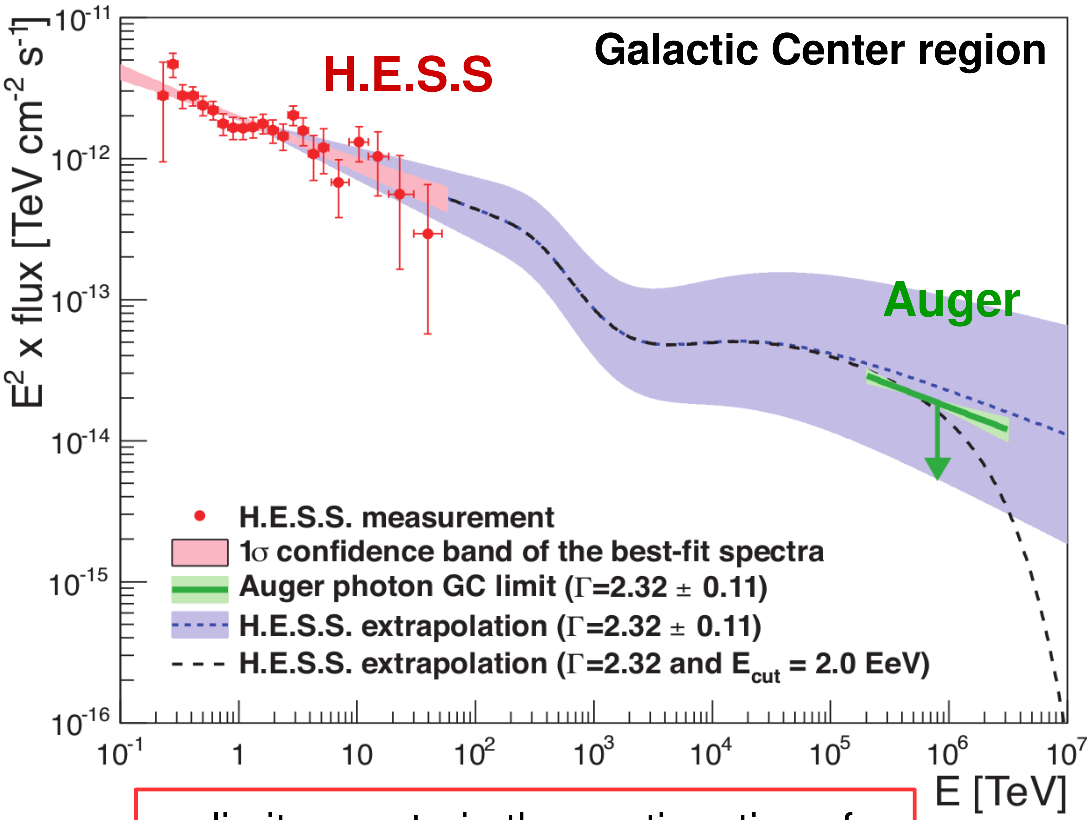
Previous blind search limits

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

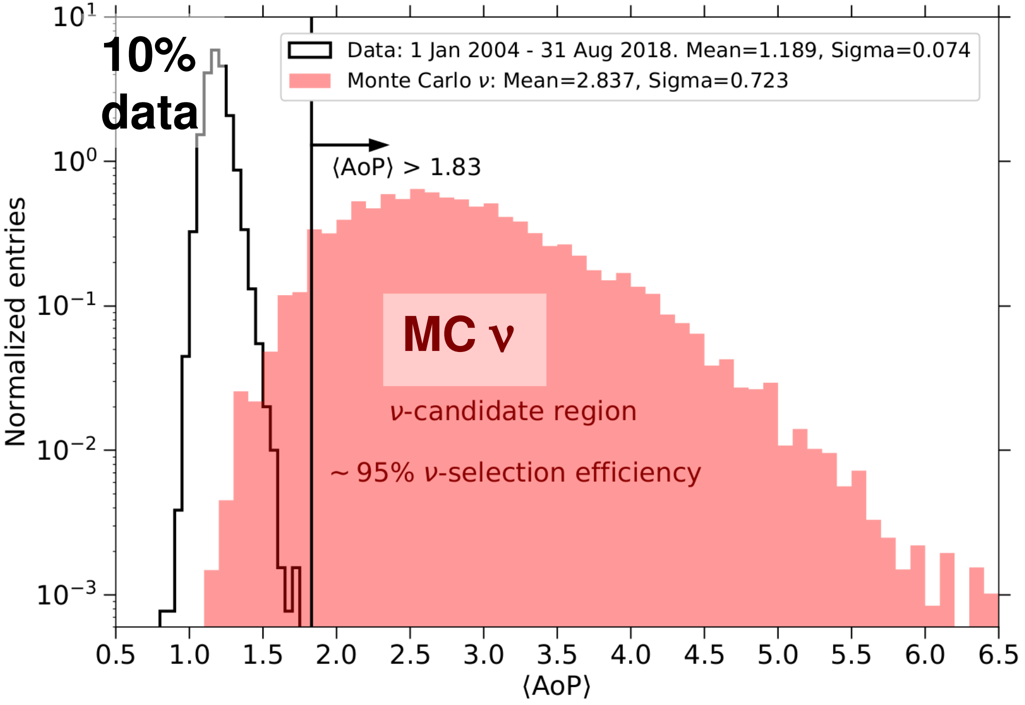
→ might be transients

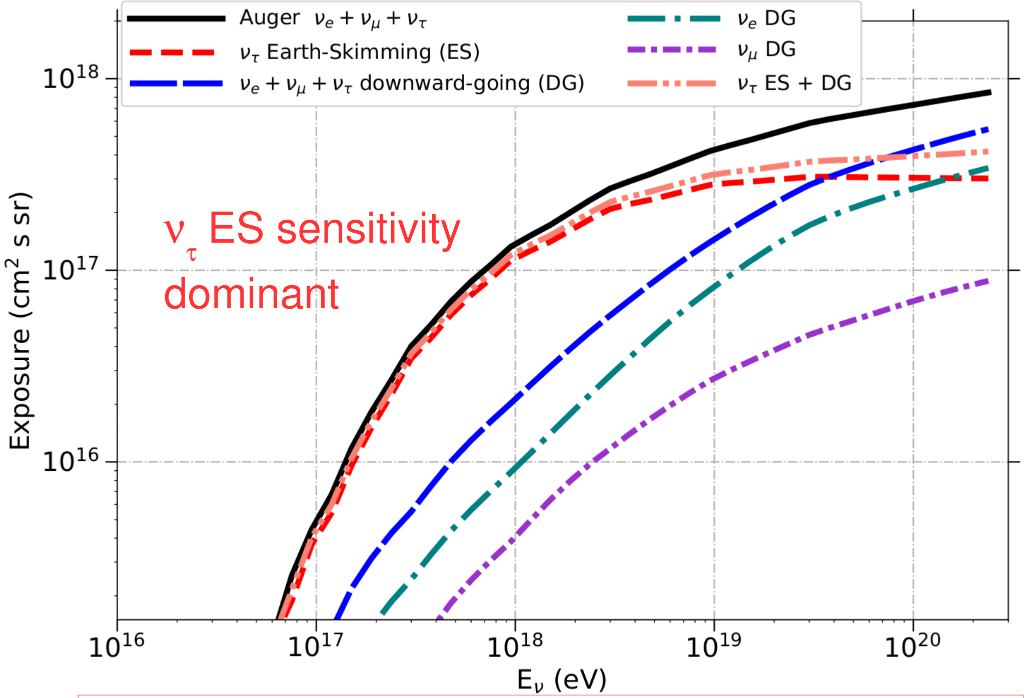


→ limits constrain the continuation of measured TeV fluxes to EeV energies

UHE neutrinos: data selection

Pierre Auger Coll., JCAP 10 (2019) 022

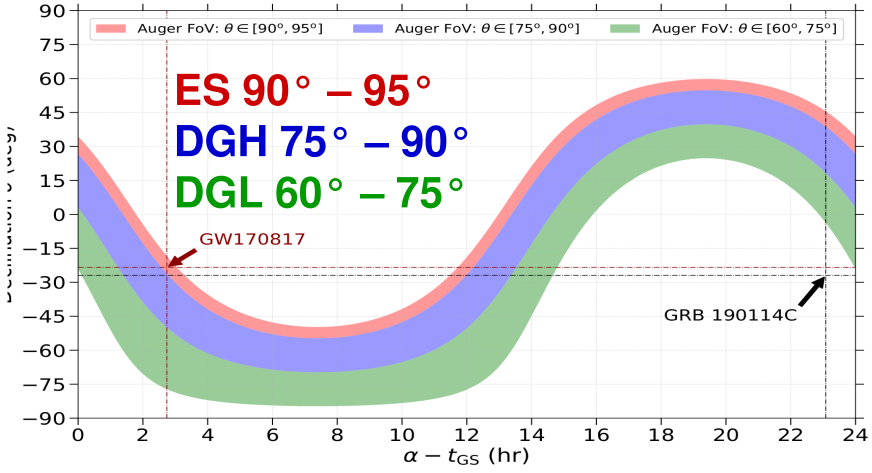




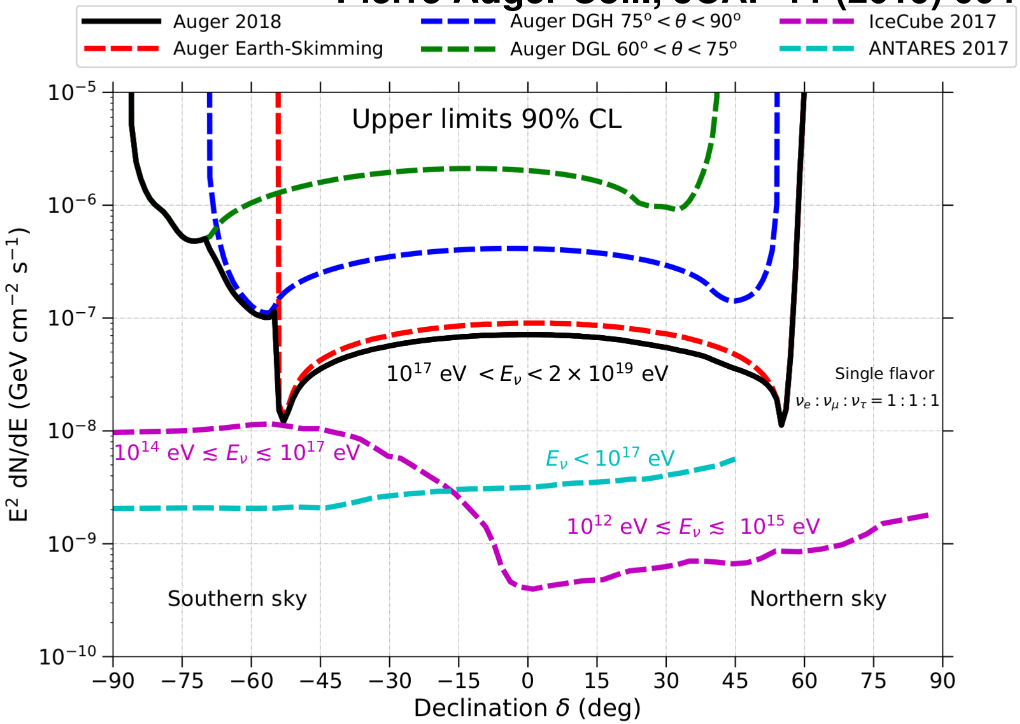
- Data 2004 – 2018: 14.7 yr of stable operation
  → **bkg expected: <1 event in 50 years**
- Selection tuned on the different det. channels

Contribution by channel:	Contribution by flavour:
ES 79.4%	τ 86.1%
DGH 17.6%	e 10.1%
DGL 3.0%	μ 3.8%

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

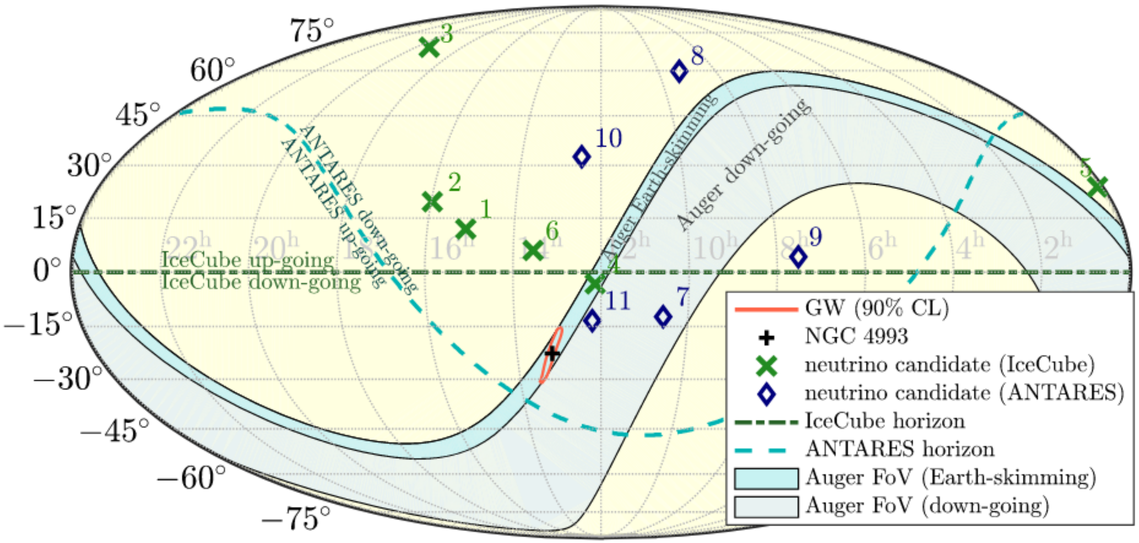
→ good sensitivity in the EeV range in a broad range of declinations

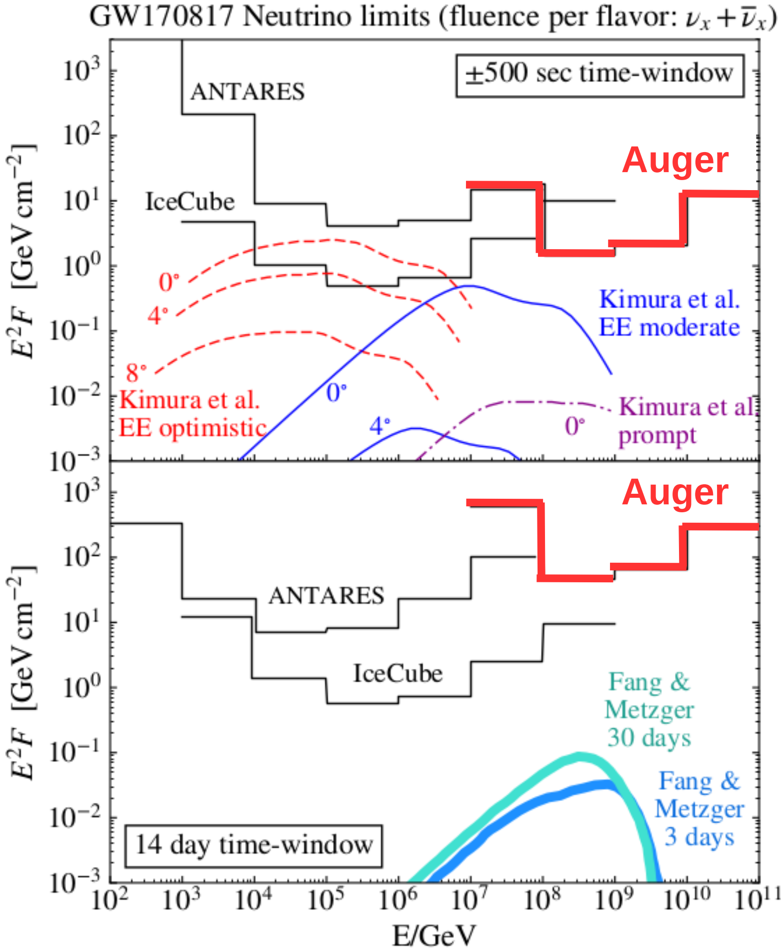
→ complementary energy range: $10^{17} \div 2 \cdot 10^{19}$ eV

Follow-up searches: GW170817

ApJL 850 L35 2017

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





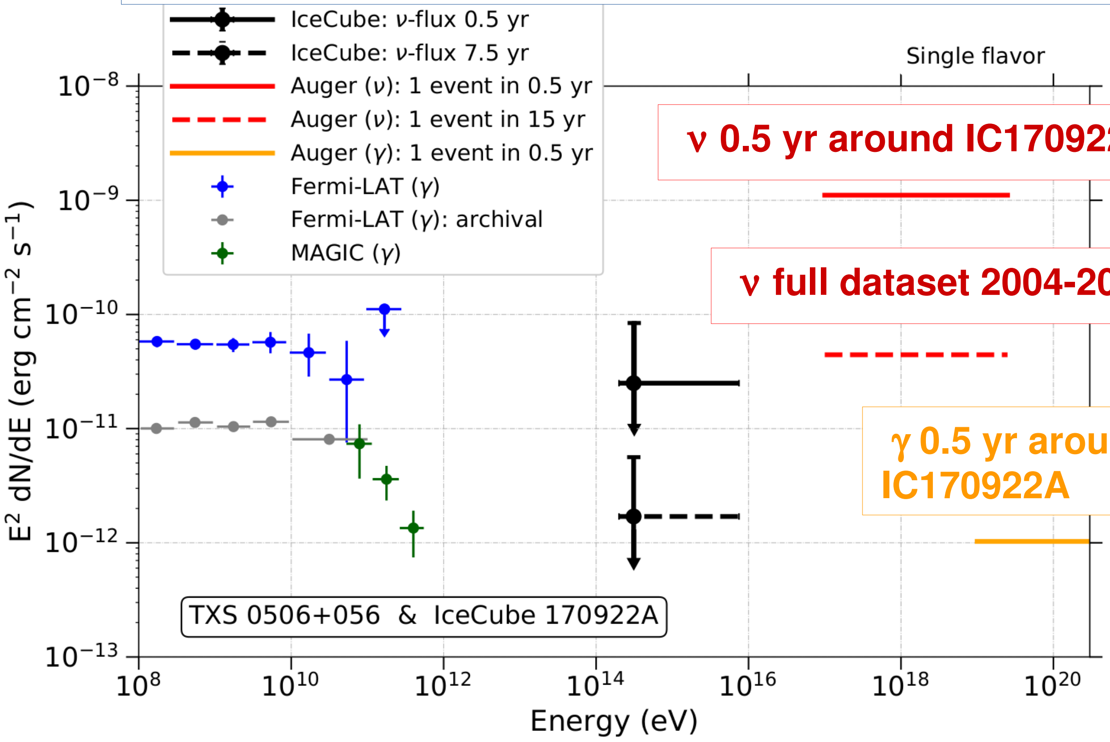
→ excellent visibility of the merger:
90% CL GW event location in FoV of ES channel

→ time dependent exposure leads to substantially lower 14-day neutrino fluence limits wrt to prompt

Follow-up searches: TXS0506+056

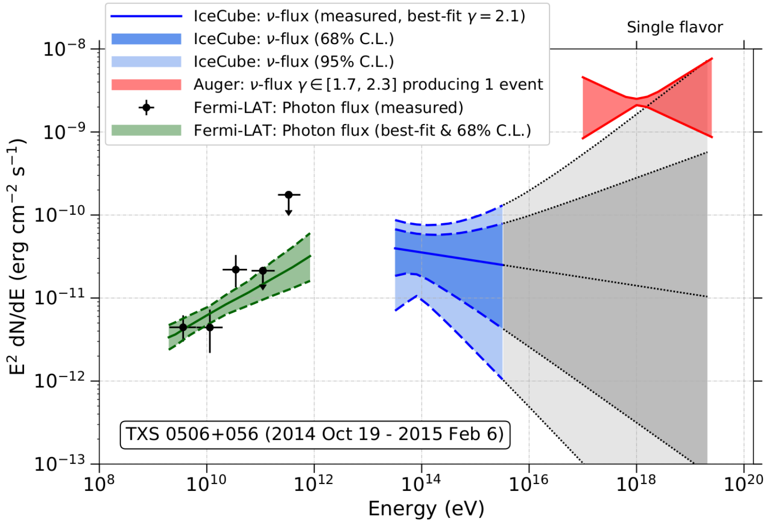
Science 361, 146 (2018)

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



Reference flux for 1 event @ Auger

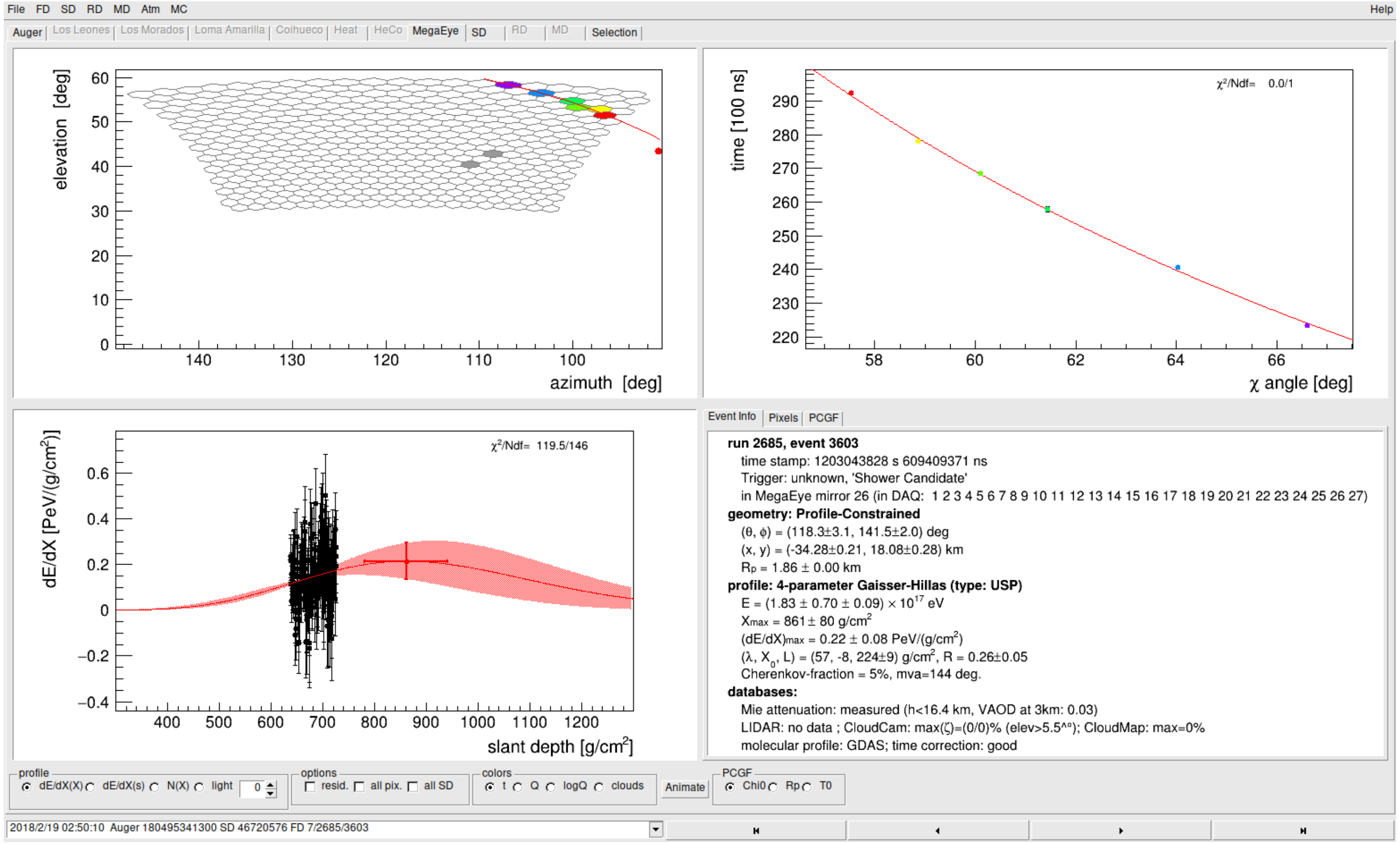
Pierre Auger Coll., Ap. J., 902:105 (2020)



TXS0506 not in the most sensitive region

→ complementary to IceCube in the EeV range
→ observation only if hard (>1.5) spectral index up to EeV range

FD upward candidate event



Few pixels at the border of the FD camera

$\theta \simeq 118°$

Short profile

Core is behind the FD telescope