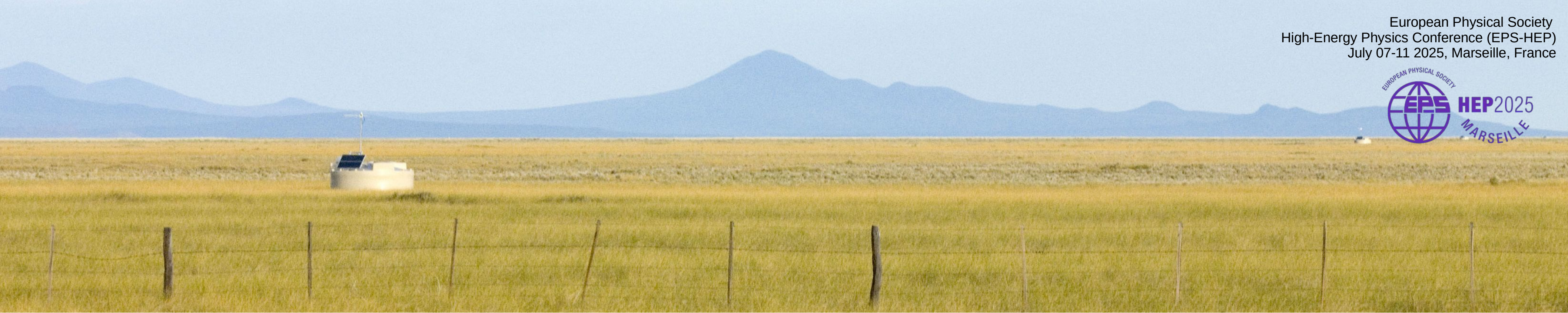
Searches for ultra-high-energy photons with the Pierre Auger Observatory

Nicolás González[1,2,3] for the Pierre Auger Collaboration[4]

[1] Università degli studi di Torino (UniTo)
[2] Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Torino
[3] Instituto de Tecnologías en Detección y Astropartículas (CNEA-CONICET-UNSAM), Argentina
[4] Observatorio Pierre Auger, Av. San Martín Norte 304, 5613 Malargüe, Argentina
Full author list available at https:/www.auger.org/archive/authors_2025_07.html

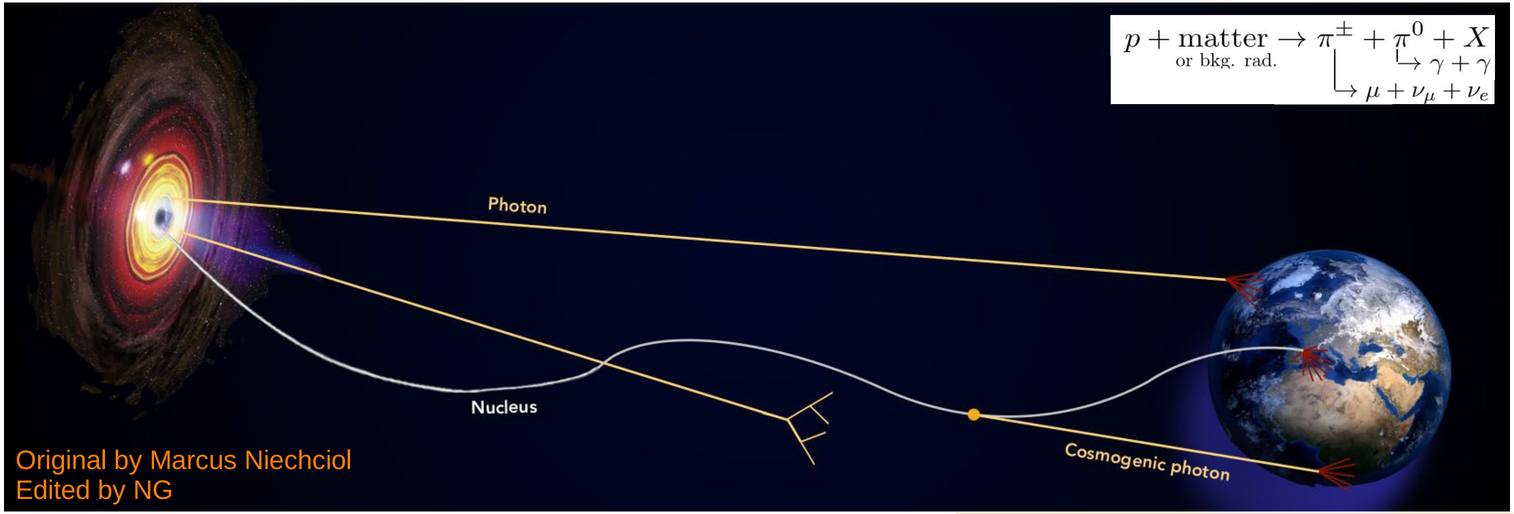


Neutral particles are probes of the Universe

- Produced in cosmic-ray acceleration sites (astrophysical fluxes), during cosmic-ray propagation (cosmogenic fluxes) or in the decay of dark matter particles

- Photons trace the local Universe while neutrinos travel through cosmological distances, both without deflection
  → complementary messengers of astrophysical steady and transient phenomena

- UHE ($E > 10^{17}$ eV) photon flux overwhelmed by cosmic rays → detection achievable with large exposures



Neutrinos discussed by Emanuele tomorrow

Nucl. Instrum. Meth. A 798 (2015) 172-213
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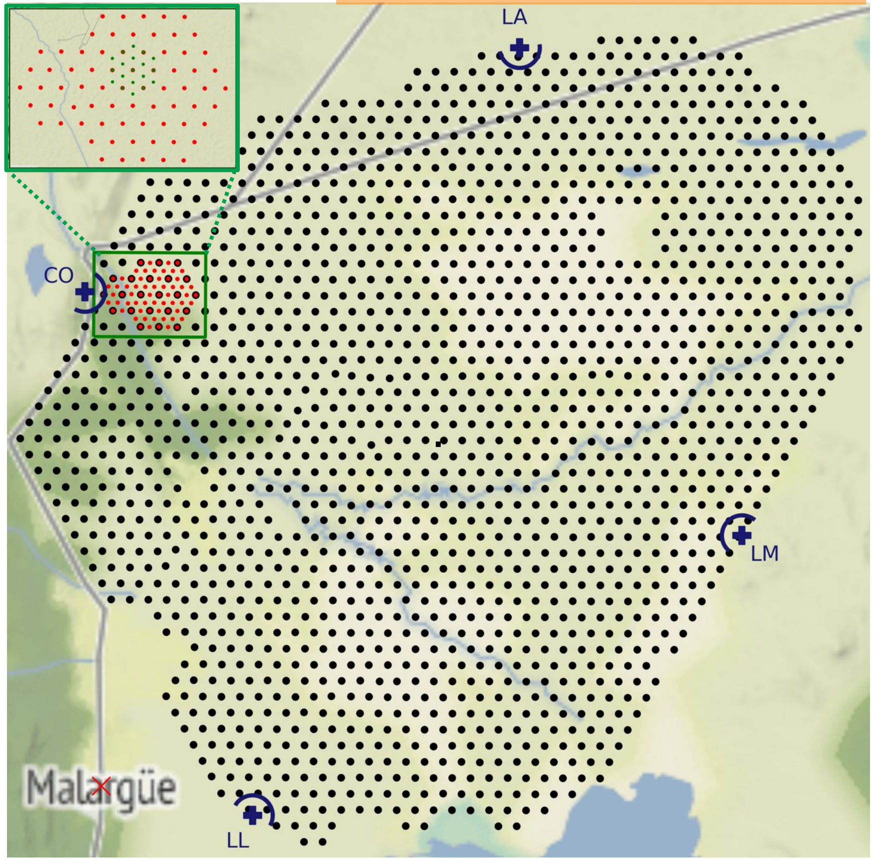
The Pierre Auger Observatory

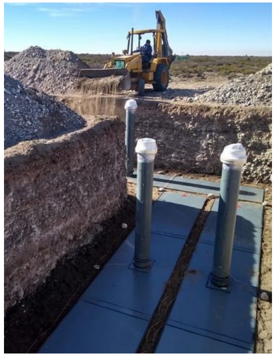
Surface detector (SD)
- 1500 m array
1661 stations (3000 km^2)
- 750 m array
61 stations (25 km^2)
- 433 m array
19 stations (2 km^2)

- Radio antennas
- Atmospheric monitoring facilities (CLF, XLF, Lidar)

Overwiew of Auger by Olivier this morning



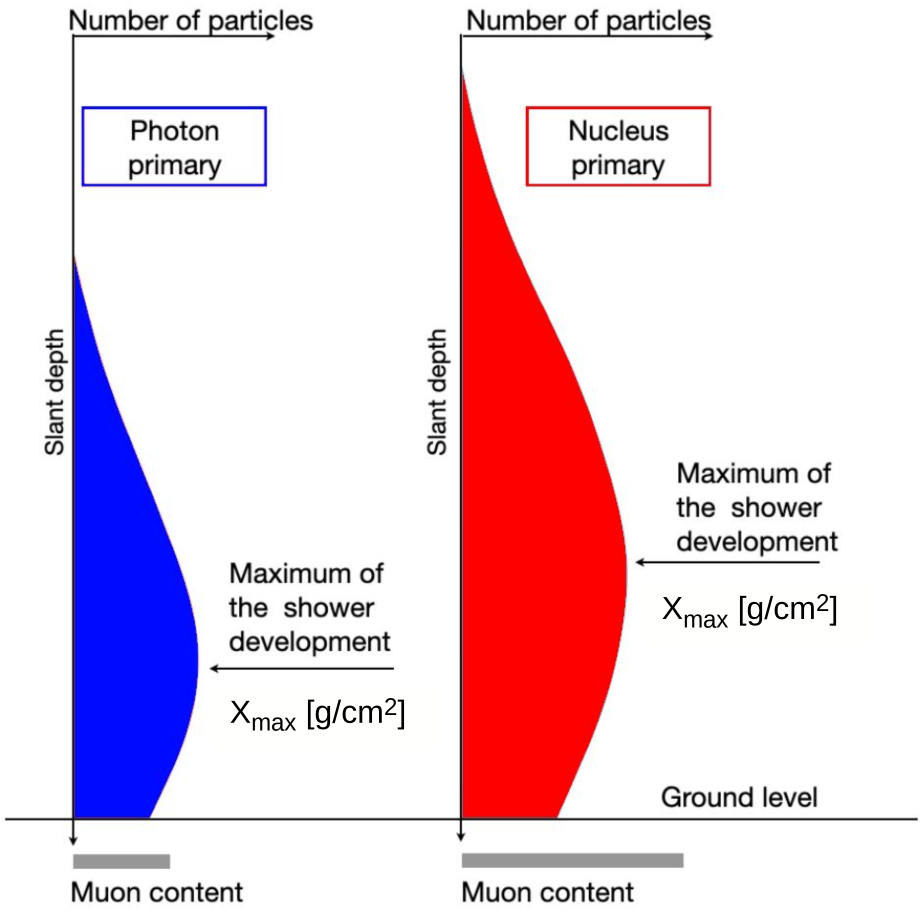
Unprecedented exposure to photons above 5 x 10^{16} eV



Underground muon detector (UMD)
48 (19) stations spaced by 750 m (433 m)

Fluorescence detector (FD)
27 telescopes across 4 sites

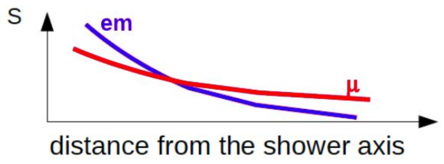
How can we identify a photon primary?



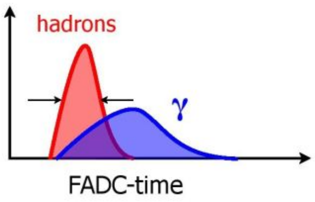
Air showers initiated by photon primaries follow a nearly purely electromagnetic (EM) development

► Deeper X_{max} due to lower multiplicity of EM interactions

► Less muon production due to suppressed $\pi^{\pm}$ generation channels



Steeper lateral spread of signals: absence of muons flattening the shower front



Longer rise-time: delayed arrival of broad EM shower front

► We exploit these features in all our searches

Photon search at 5×10^{16} eV – 2×10^{17} eV SD+UMD

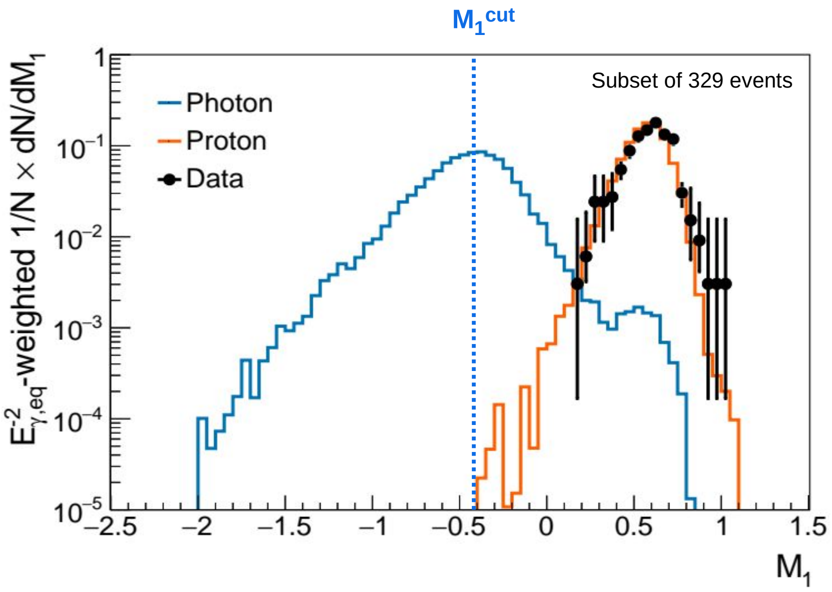
$$M_1 = \log_{10}\left(\sum_i \frac{\rho_\mu^i}{\rho_\mu^{\mathrm{p}}} \times \frac{r_i}{200\,\mathrm{m}}\right)$$

► **The observable** M_1 combines the high-energy muon densities, ρ_μ^i, measured at a distance r_i from the shower axis

► **The photon candidate cut** is a threshold value, M_1^{cut}, ensuring 50% photon selection efficiency

► **The background contamination** is the fraction of cosmic-ray events below M_1^{cut}

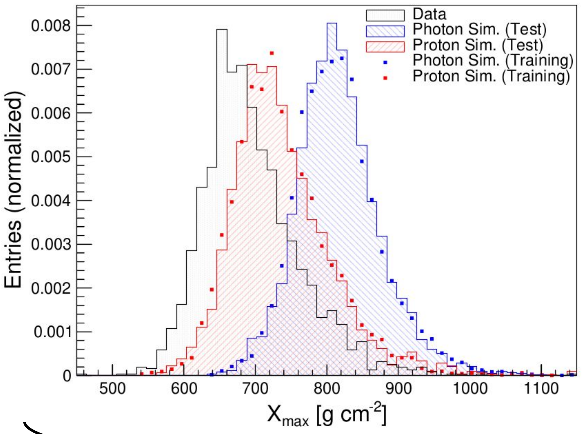
► 10^{-5} contamination assuming a pure-proton background (the most photon-like species)

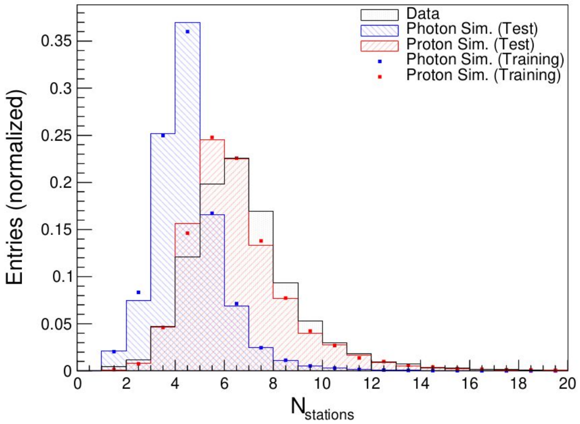


► Data set spans 15 months → ~ 0.6 km² sr yr

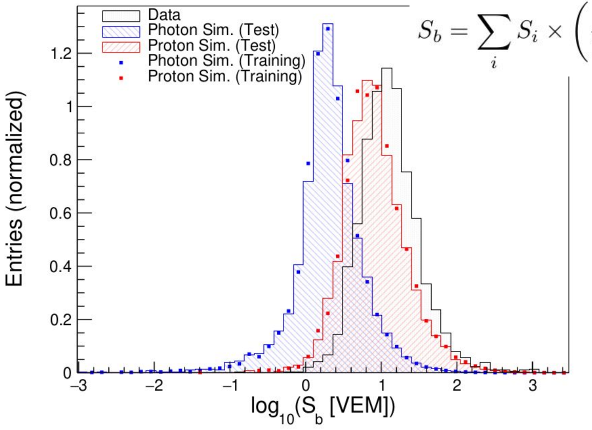
► 0 photon candidate events

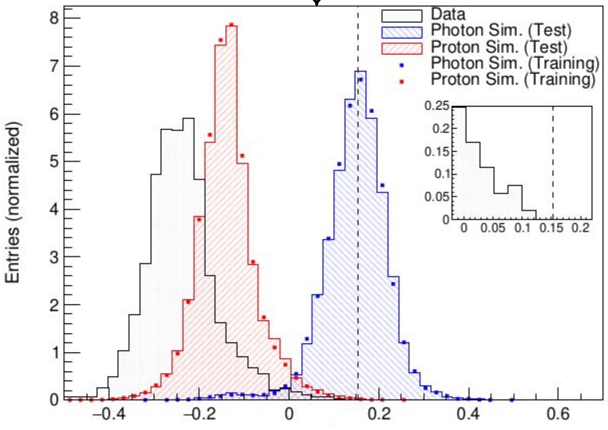
Photon search at 2×10^{17} eV – 10^{18} eV SD+FD





$$S_b = \sum_i S_i \times \left(\frac{R_i}{1000\,\mathrm{m}}\right)^b$$





Boosted decision trees observable

► X_{max} measured with FD, number of triggered stations and S_4 combined into a single observable with a boosted decision trees method.

► ~10^{-4} background contamination, i.e., 2 background events in data set, with 50% signal efficiency photon candidate cut

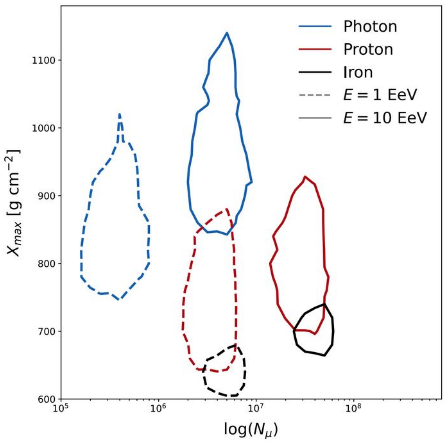
► Data set spanning 5.5 years → ~2.5 km² sr yr

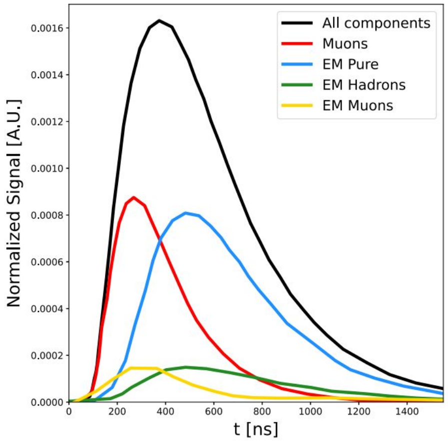
► 0 photon candidate events

Phys. Rev. D 110, 06205 (2024)

Photon search at 10^{18} eV – 10^{19} eV

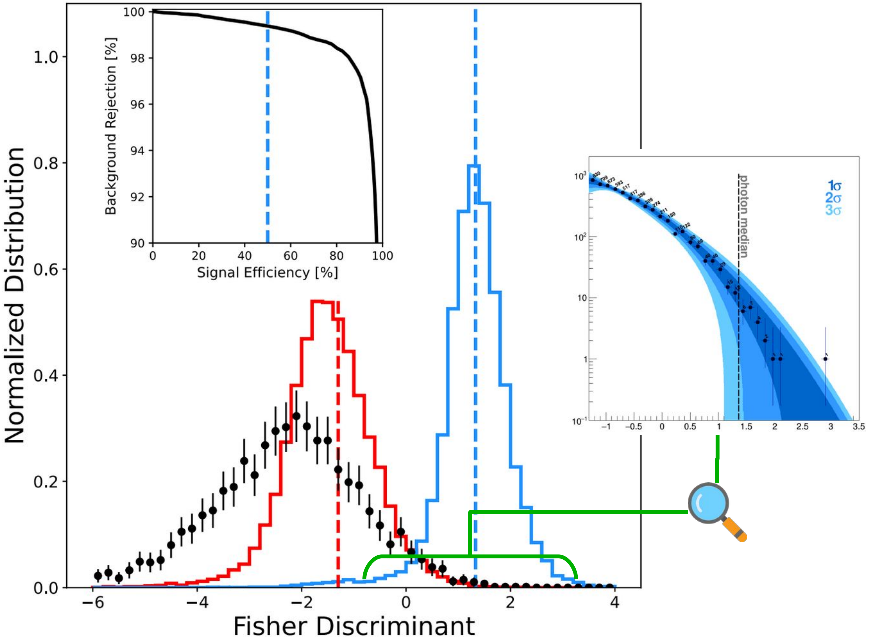
SD+FD





► Data set spans 12 years → ~1,000 km² sr yr

► 22 photon candidate events, but compatible with background of 30 ± 15 events estimated with data



► X_{max} measured with the FD. F_μ is a proxy of the muon content extracted from the SD signals

► Estimated by matching the measured signal in SD stations to S_{pred} which is a decomposition in EM and muonic components ($S_{i,comp}$)

$$S_{\text{pred}} = \sum_{i=1}^{4} S_i = \sum_{i=1}^{4} f_i(F_\mu) S_{i,\text{comp}}$$

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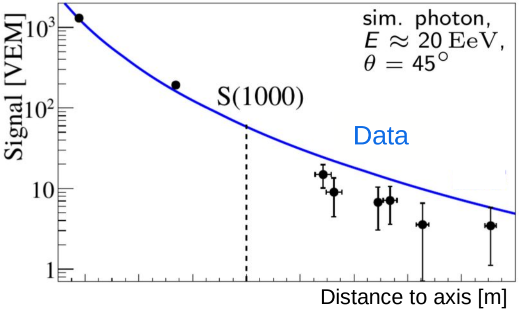
Photon search at > 10^{19} eV

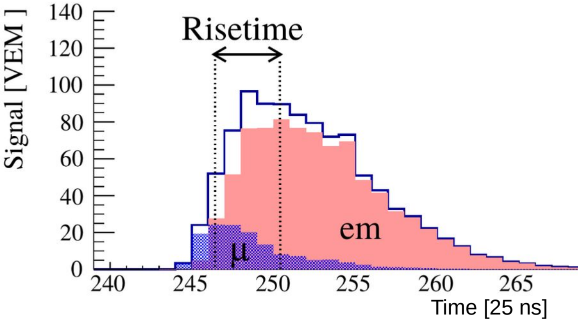
SD

Steeper lateral spread of particles (LDF)

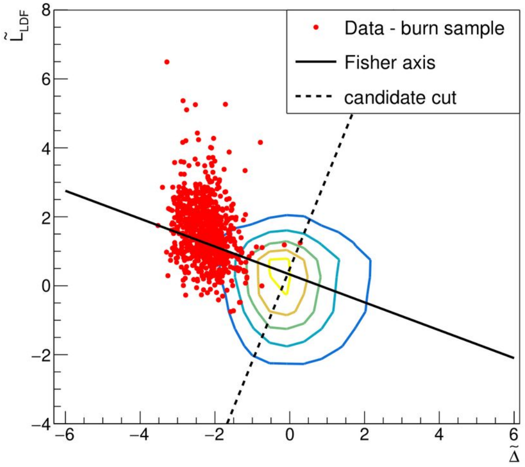


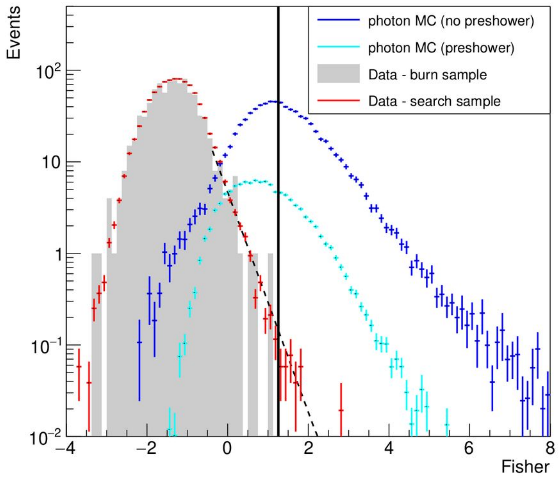
$$L_{\mathrm{LDF}} = \log_{10}\left(\frac{1}{N}\sum_{i=1}^{N}\frac{S_i}{S_{\mathrm{LDF}}(r_i)}\right)$$

Longer signal rise-time



$$\Delta = \frac{1}{N}\sum_{i=1}^{N}\frac{t_{1/2}^{i} - t_{1/2}^{\mathrm{bench}}}{\sigma_{t_{1/2}}^{i}}$$





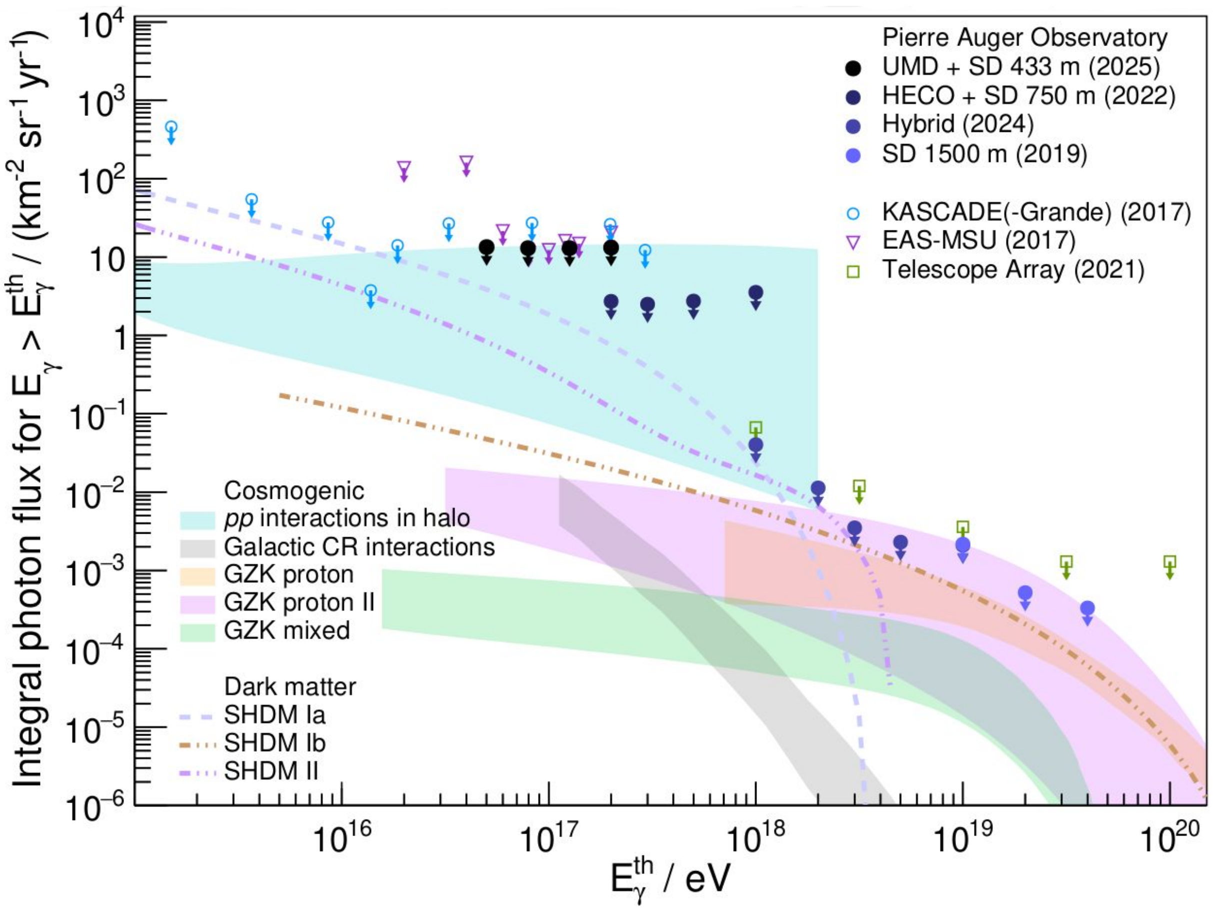
► Benchmarks $t_{1/2}^{\mathrm{bench}}$ and S_{LDF} obtained with data
→ method free of cosmic-ray composition assumptions

► Fisher analysis trained with photon simulations and a subset of data

► Data set spans 16 years → 17,000 km² sr yr

► 16 photon candidate events, but compatible with the background contamination

Upper limits to ultra-high-energy photons flux



► Most stringent limits across four decades in energy with 16 years of data

► Useful for constraining new physics, e.g., super-heavy dark matter models.

► Start closing the gap to the smaller air-shower experiments

► Predictions from most optimistic cosmogenic models of cosmic-ray propagation are within reach above 10^{18} eV

► Note that these are diffuse limits. What about directional and follow-up searches?

Astrophys. J. (2014) 789 160
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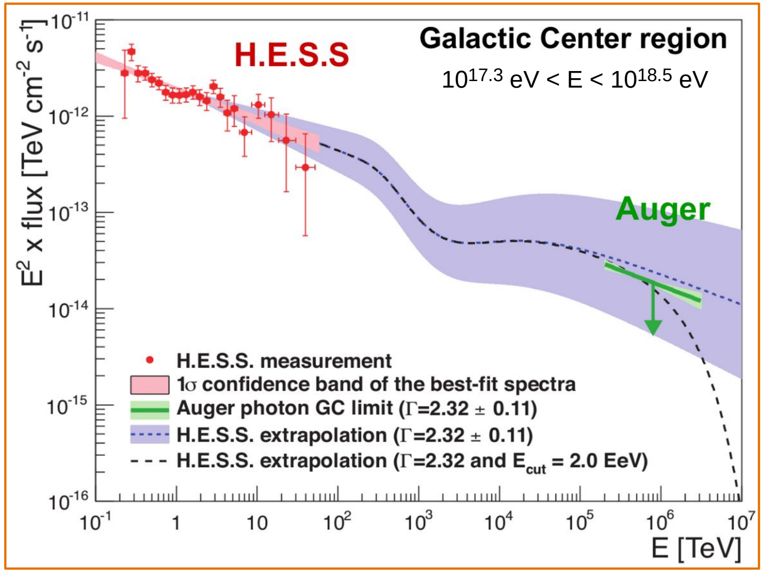
Targeted directional search

SD+FD

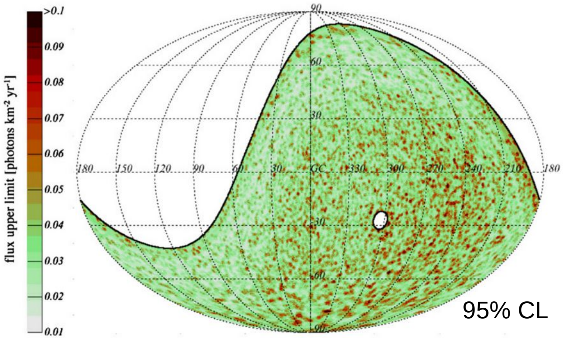
- ► Five mass-sensitive observables used to train a BDT
- ► Stacked analysis of 12 target sets (364 candidate sources) within few Mpc
- ► No evidence for **steady emission** of UHE photons from any target (stat. significance below 3σ)
- ► Upper limits obtained by Auger contrain the extrapolation of the measured TeV gamma-ray flux to EeV energies

(cut-off energy at 2×10^{18} eV)

Class	No.	$\mathcal{P}_w$	$\mathcal{P}$
msec PSRs	67	0.57	0.14
γ-ray PSRs	75	0.97	0.98
LMXB	87	0.13	0.74
HMXB	48	0.33	0.84
H.E.S.S. PWN	17	0.92	0.90
H.E.S.S. other	16	0.12	0.52
H.E.S.S. UNID	20	0.79	0.45
Microquasars	13	0.29	0.48
Magnetars	16	0.30	0.89
Gal. Center	1	0.59	0.59
LMC	3	0.52	0.62
Cen A	1	0.31	0.31



► Upper limits from blind search from any direction in the sky between -85° < δ < +20°



EPJ Web Conf., 283 (2023) 04004
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Multi-messenger follow-up studies

SD

- The Pierre Auger Observatory takes part in the multimessenger-astronomy networks GCN/TAN

- Follow-up photon searches in coincidence with 10 selected GWs from LIGO/VIRGO:

  - close-by, to avoid attenuation (III, IV)
  - distant but well-localized, to look for new physics (I, II)

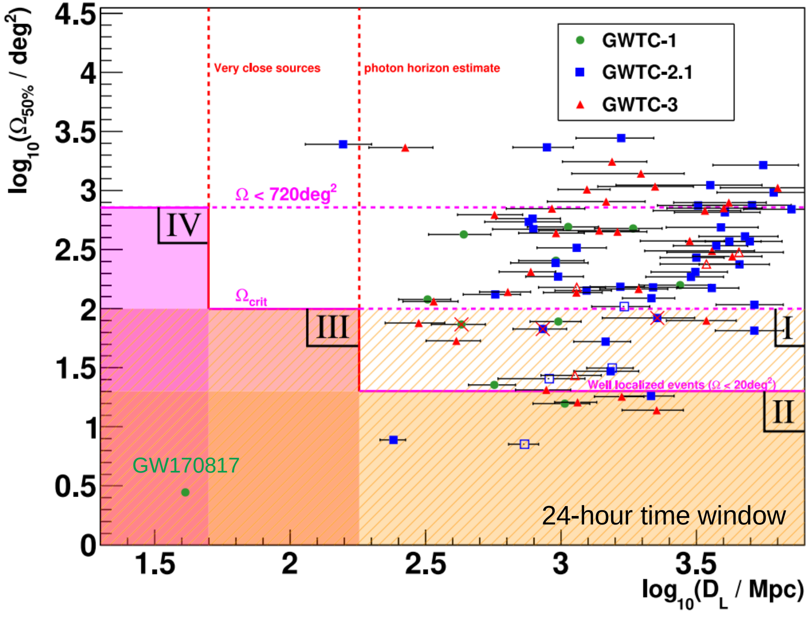
- Two time windows: ±500 s and +24 h from GW detection:

  - 7 visible in the long time window (1 BNS, 1 NSBH, 5 BBH)
  - 3 visible in the short time window (3 BBH)

- Event selection cuts: $E > 10^{19}$ eV, $\theta \in [30°,60°]$

- Photon-hadron discrimination based on LDF steepness and signal time structure (i.e., diffuse SD-only search)

$\Omega_{50\%}$: solid angle contour localization of GW



D_L: luminosity distance

Multi-messenger follow-up studies

SD

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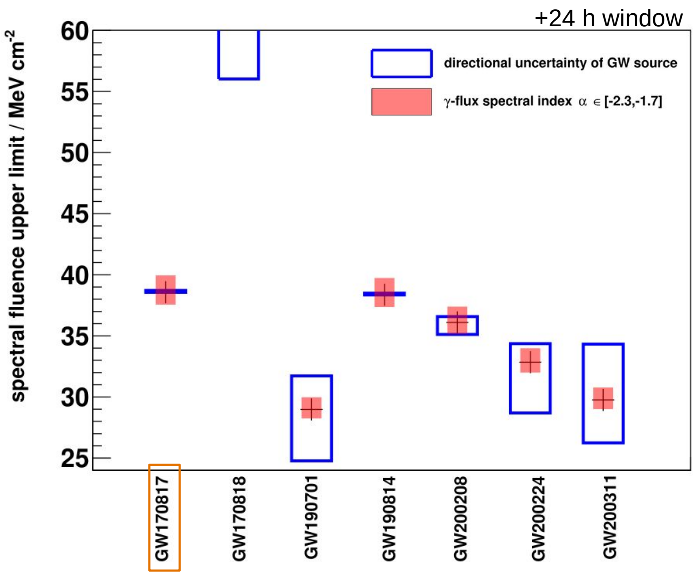
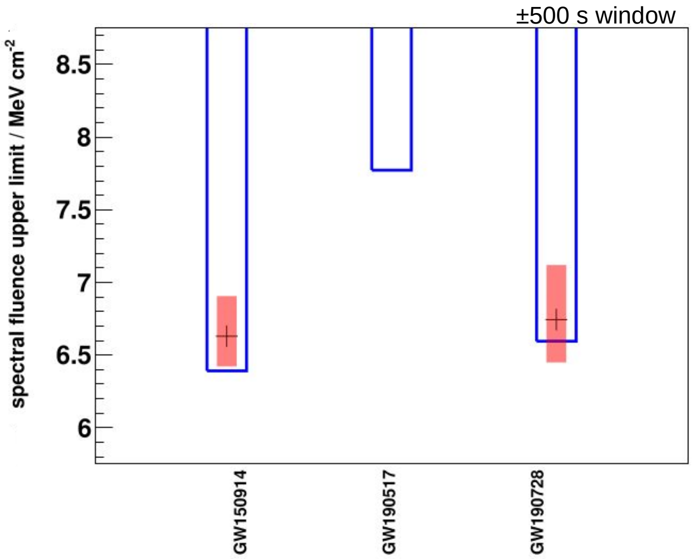




► Variations of the upper limits caused by:
- the finite source localization
- declination-dependent exposure to UHE photons

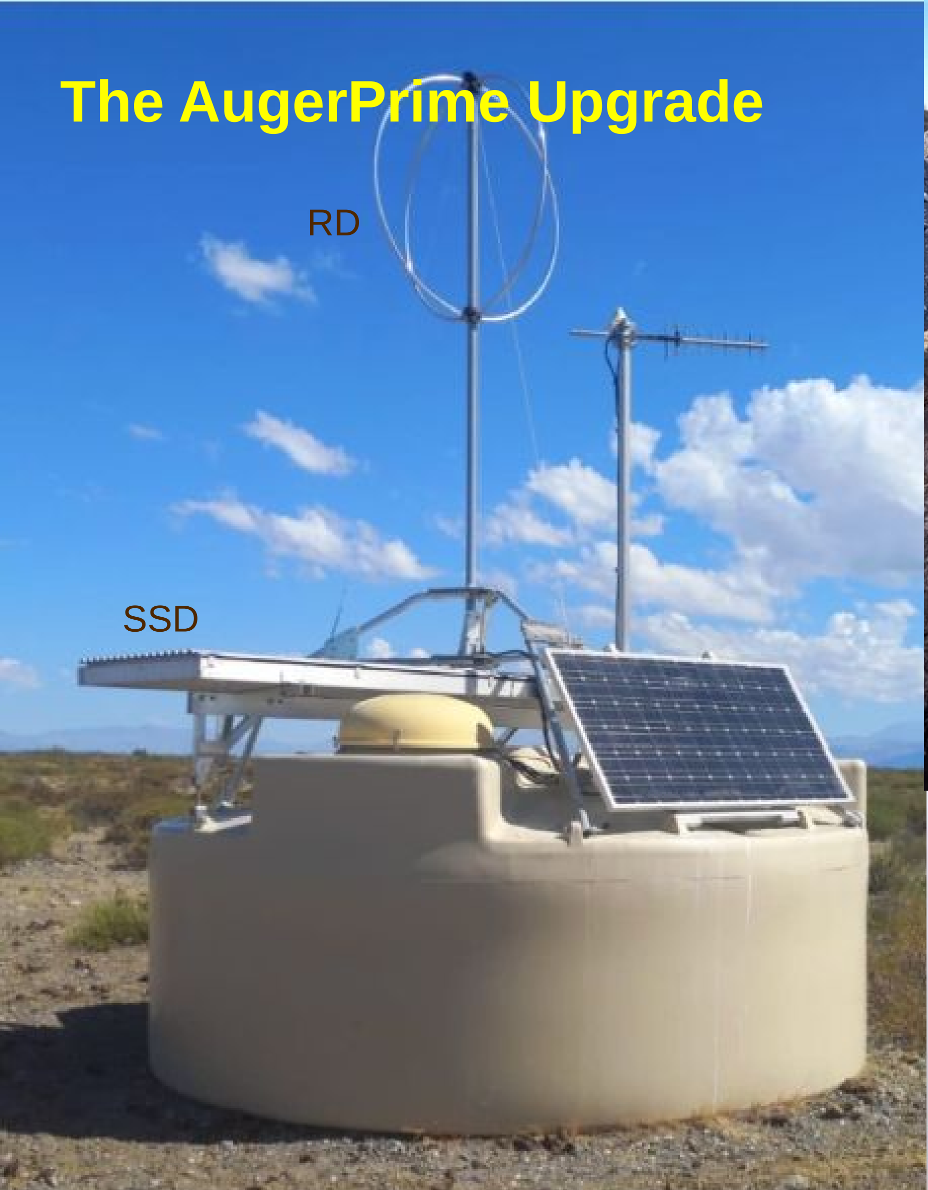
► First ever limits on the photon emission from GW events at UHEs

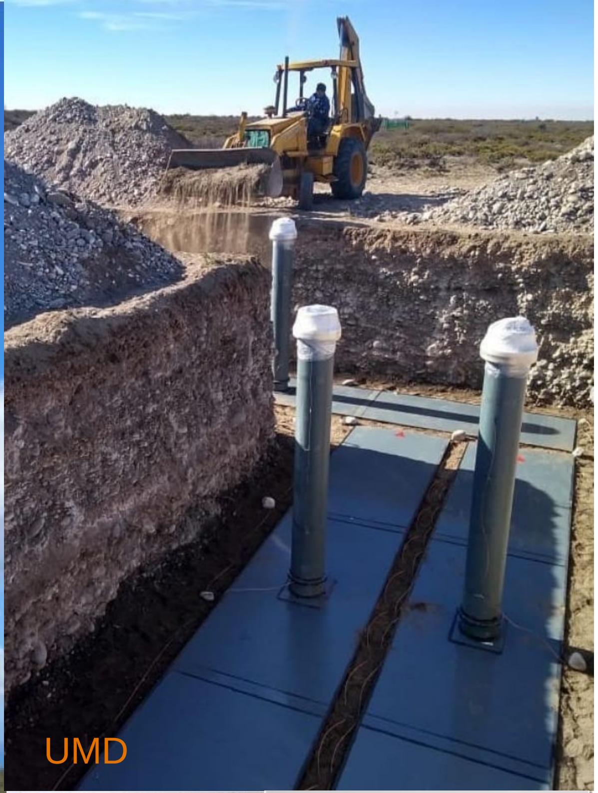
Auger limits on UHE neutrino emission too! (see backup)

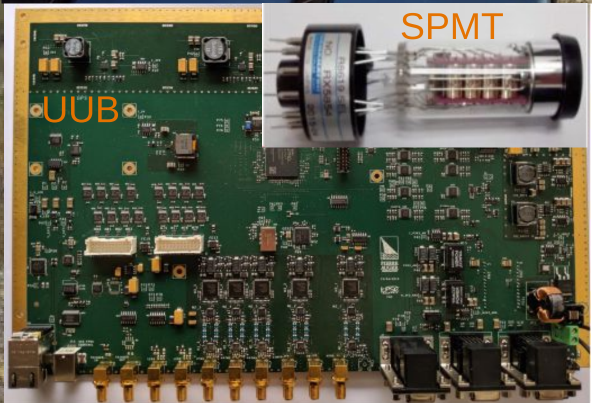
► < 20% energy transferred to UHE photons above 4×10^{19} eV from neutron star merger **GW170817** at ~40 Mpc

► Great improvement expected from closer GW events

The AugerPrime Upgrade





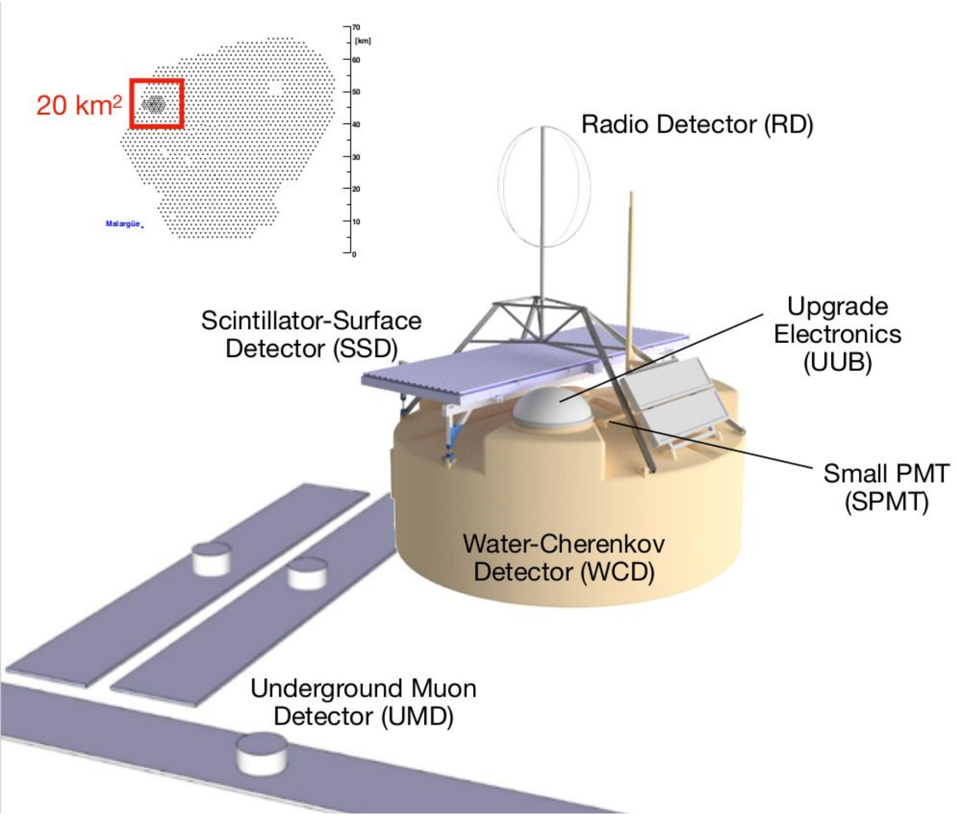


Multi-hybrid air-shower detection:

- ▶ 433 and 750 m SD arrays equipped with 3 x 10 m^2 UMD stations
- ▶ 4 m^2 plastic surface scintillation detectors (SSD)
- ▶ Measure radio emission from air showers with antennas (RD)
- ▶ Faster electronics (UUB) and larger dynamic range thanks to a small-area PMT (SPMT)

Aiming at a better composition sensitivity (including UHE γ)

The AugerPrime Upgrade



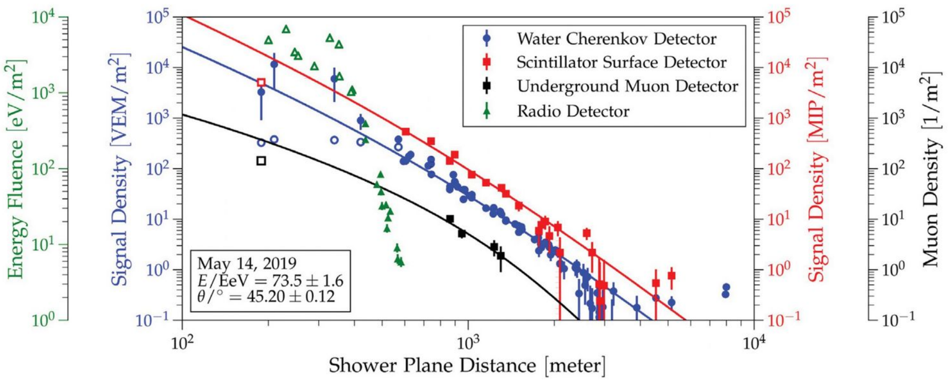
Credits to D. Schmidt (KIT)

► Data can be exploited to (re-)define discriminating observables:

- **e / μ decomposition using UMD/SSD (θ < 60°)**
- **shower development through radio measurements (θ > 60°)**
- **measured signals closer to the core with the SPMT**

► Observables can be combined using cutting-edge algorithms (neural networks, AI, etc)

► Extending mass sensitivity to the lower energies (< 10^{17} eV) and improving photon/hadron discrimination



DNN analyses discussed by Berenika this morning

Summary

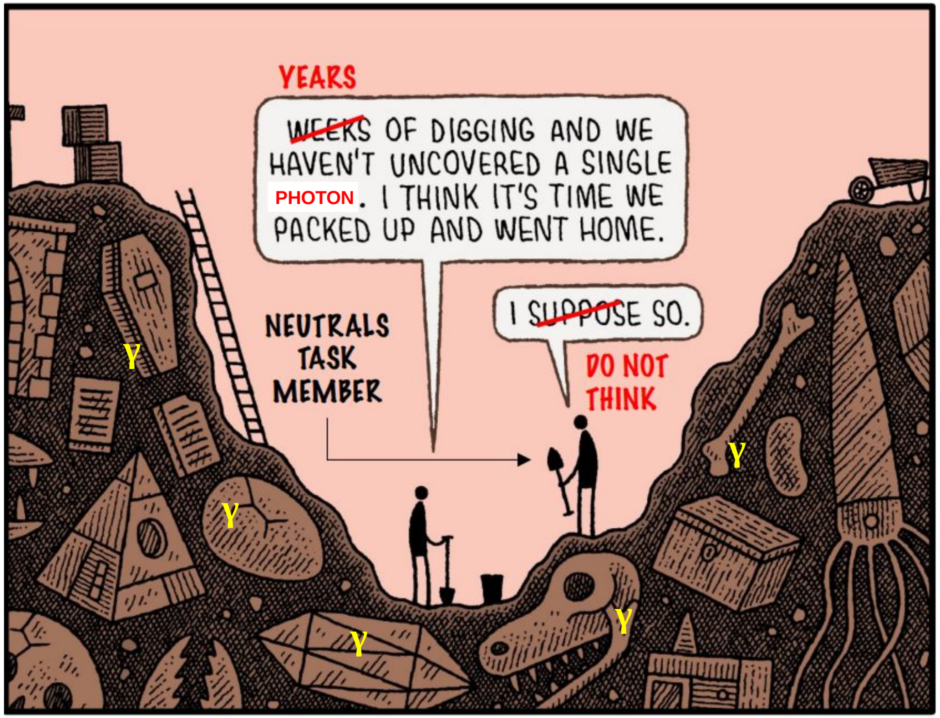
► Unrivalled exposure to photons: most stringent flux limits across four decades in energy above 5×10^{16} eV

► Upper limits can be used to constrain the parameter space of cosmogenic and super-heavy dark matter models

► The Pierre Auger Observatory is a key actor in the UHE multi-messenger astronomy thanks to its large sky coverage

→ thorough follow-up searches to transients

► Data acquired with upgraded detectors will not only refine existing constraints but may lead to the first observation of UHE photons

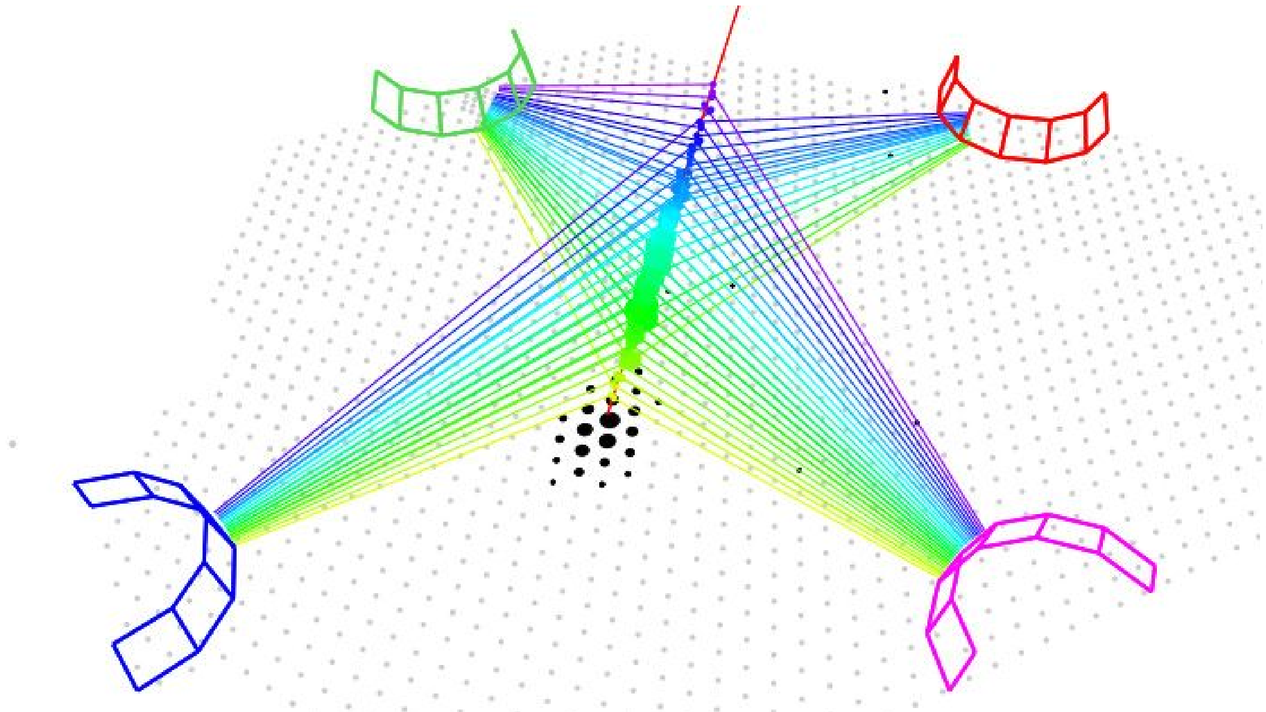


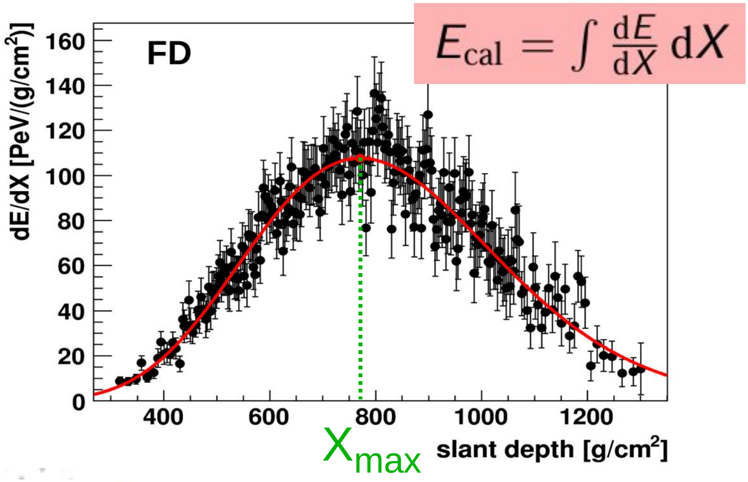
[Tom Gauld, Department of mind-blowing theories, Canongate Books, 2020]

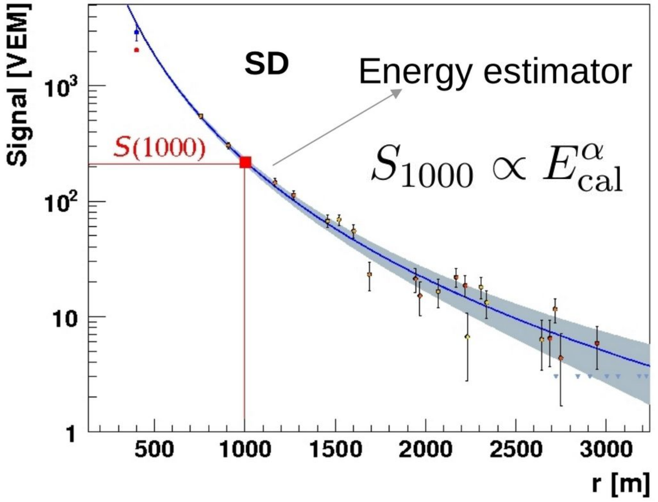
Edited by the Neutrals task

Backup

Hybrid Detection of Air Showers







- Primary energy from the FD measurements
- SD energy estimator calibrated against FD → SD-only reconstruction
- Maximum of shower development, X_{max}, is sensitive to the mass composition

Diffuse and directional photon searches

Our searches can be classified in three classes:

- **Diffuse**: Searches for an unresolved, direction-independent, flux of γ/ν
    - Tailored in different energy ranges
    - Exploiting different detection techniques
- **Point-source**: Searches for a flux of γ/ν in the direction of catalogued sources or regions
    - Dedicated to different type of sources
    - Sensitive to geometry resolution
- **Follow-up**: Searches for a flux of γ/ν in space-time coincidence to significant astrophysical events (e.g., gravitational waves)
    - Similar to point-source searches but with time dependence of the exposure (Earth's rotation)

Observables used in directional searches

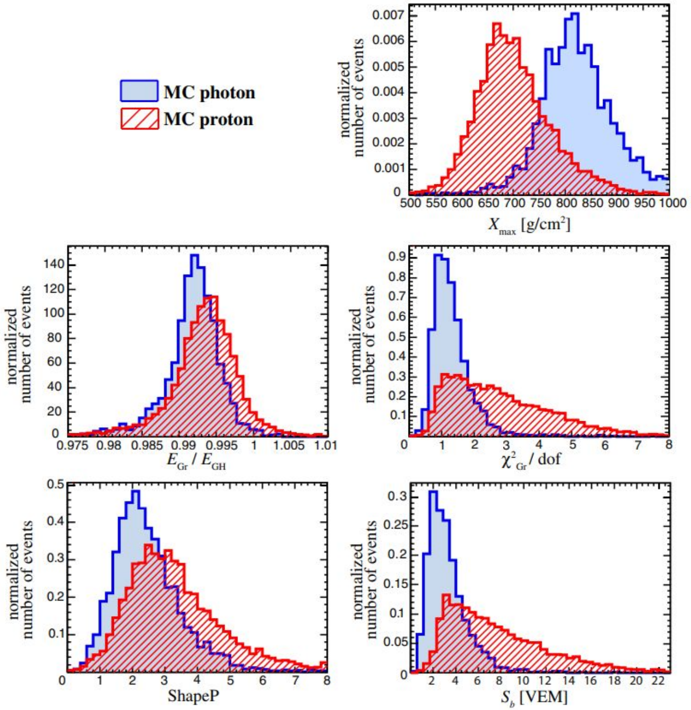


Figure 1. Distributions of photon (full blue) and proton (striated red) simulations of the introduced observables. The distributions are shown as examples for the energy range between $10^{17.6}$ eV and 10^{18} eV and zenith angle between 0° and 30°.

$$S_b = \sum_{i=1}^{N}\left[S_i \cdot \left(\frac{r_i}{1000\,\mathrm{m}}\right)^b\right]$$

$$\text{Shape P}(r,\theta) = \frac{S_{\text{early}}(r,\theta)}{S_{\text{late}}(r,\theta)}.$$

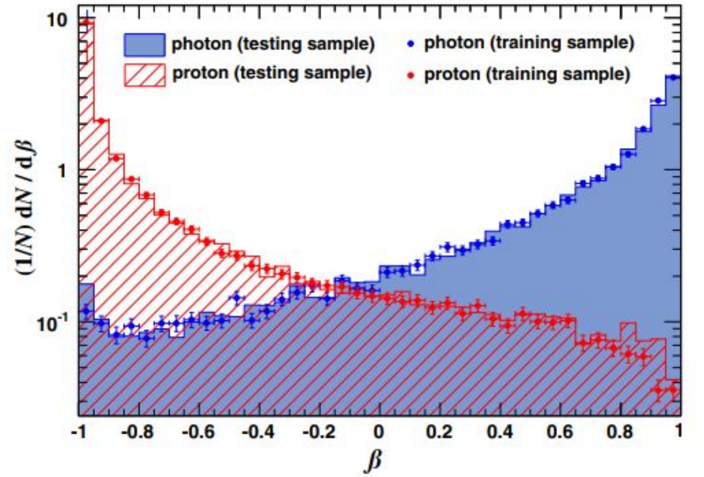


Figure 2. MVA response value β for photon and proton primaries using BDTs. During evaluation the MC sample is split half into a training (filled circles) and half into a testing sample (solid line).

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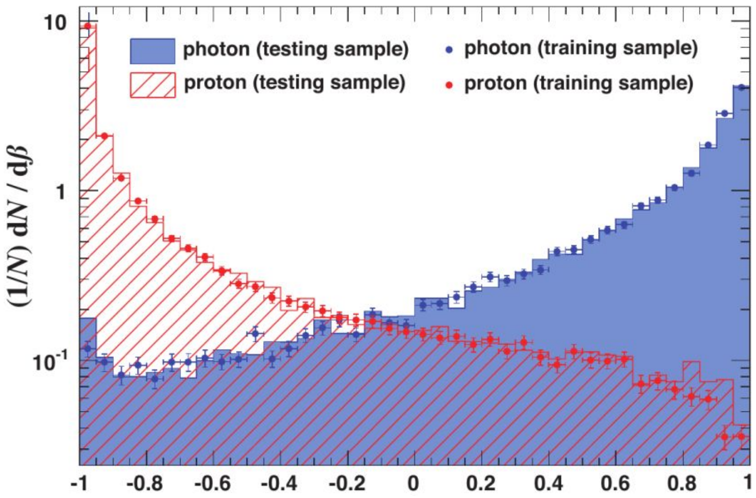
All-sky directional search

SD+FD

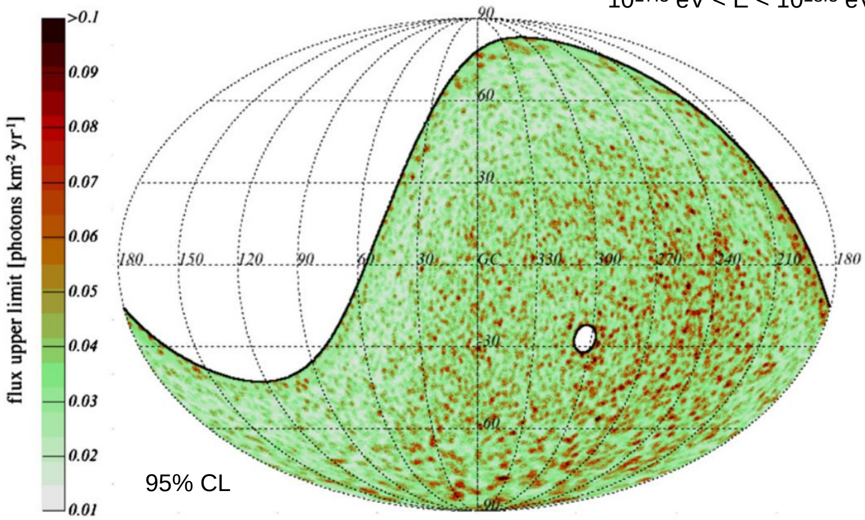
► Photon-hadron discrimination combining five SD and FD observables

► Photon candidate cut optimized by interplay of upper limits and signal efficiency



Boosted decision trees discriminator

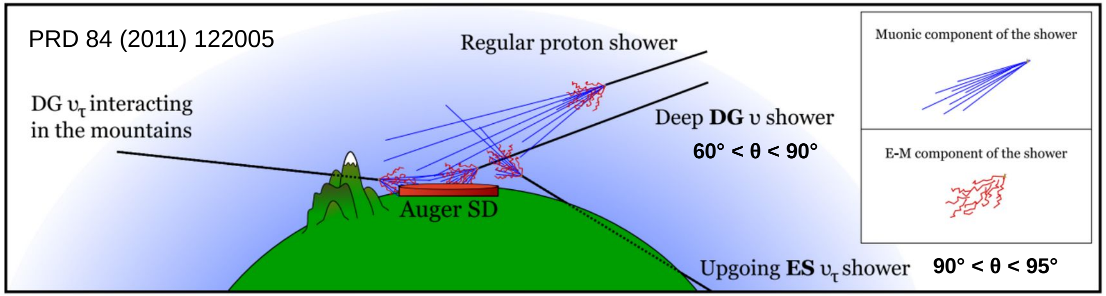
Jan 2005 – Sep 2011
$10^{17.3}$ eV < E < $10^{18.5}$ eV



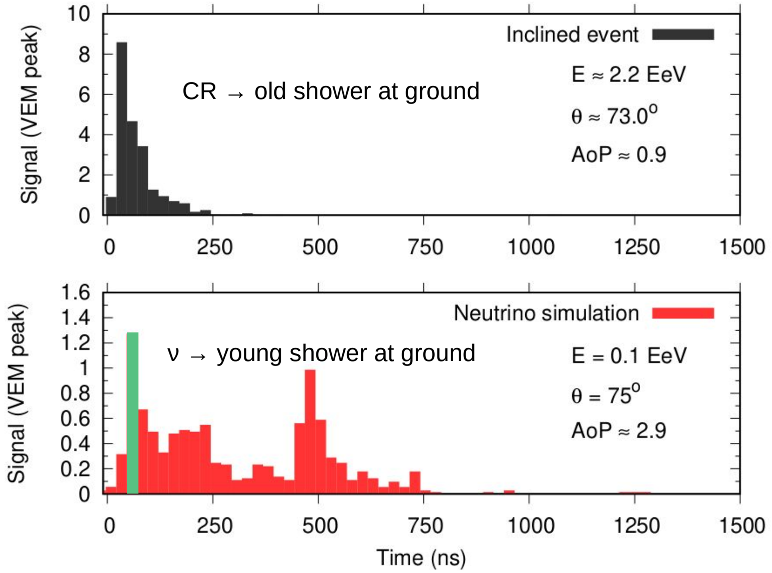
► No evidence for nearby photon-emitting steady sources from any direction in the sky between -85° < δ < +20°

► Upper limits compatible with either:
- extragalactic sources farther than 5 Mpc
- transient or opaque Galactic sources

How can we identify a neutrino primary?



JCAP10 (2019) 022



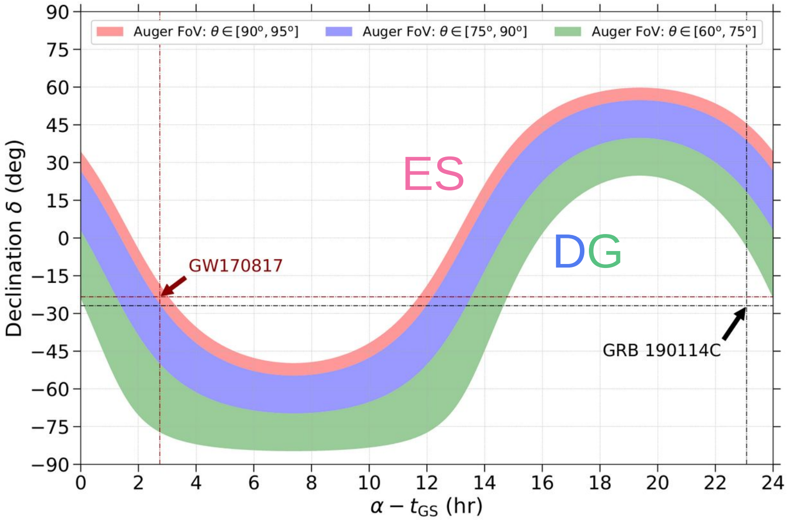
► Background composed by muon-dominated hadronic showers (EM component absorbed in the atmosphere)

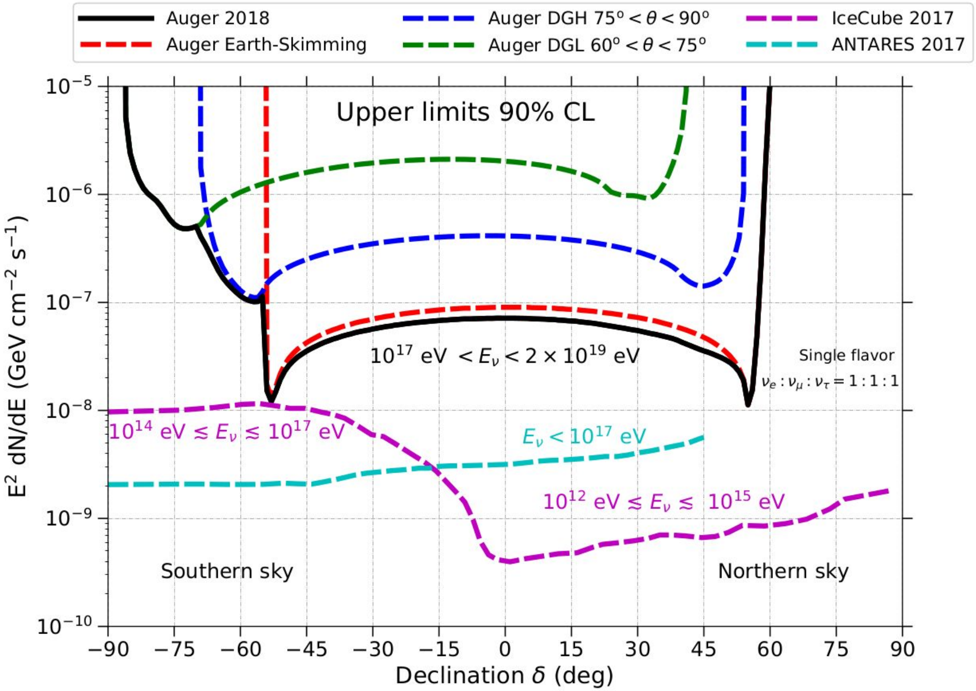
► Down-going (DG) channel: ν interacting deep in the atmosphere. Sensitive to all flavors

► Earth-skimming (ES) channel: ν_τ interacting in Earth's crust. τ lepton initiating an up-going shower close to the ground

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

Sensitivity to steady point sources





► Due to Earth's rotation, point sources transit through the field of view of each channel

► Longest daily transit 4-5 hours in ES channel or 6-11 hours in DG channel

► Total field of view covering δ (-85°,60°)

► Largest exposure for sources at around δ = ±55° because they remain the longest in the ES field-of-view

► Complementary energy ranges of experiments

Auger participation in follow-up campaigns

Astrophys. J. Lett. 850 (2017) L35
Astrophys. J. Lett. 902 (2020) 105
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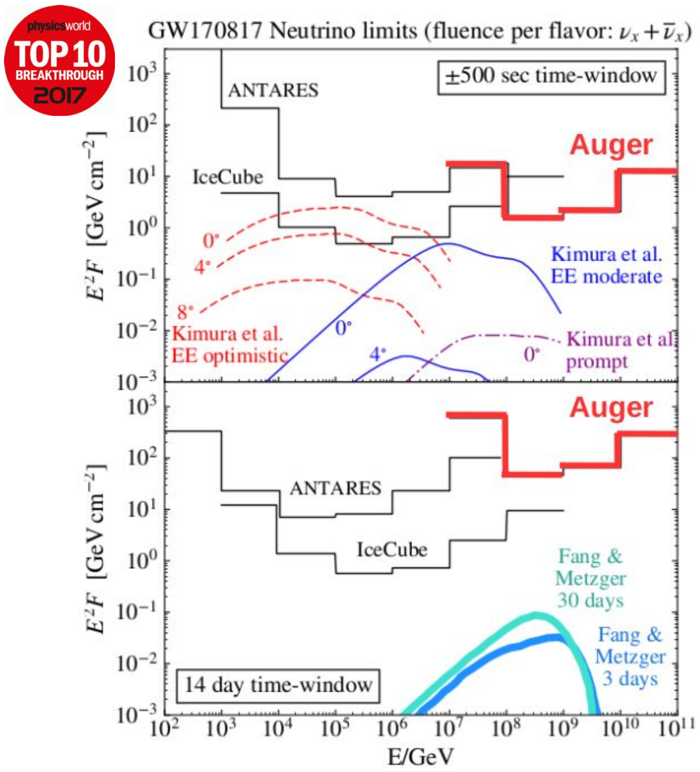

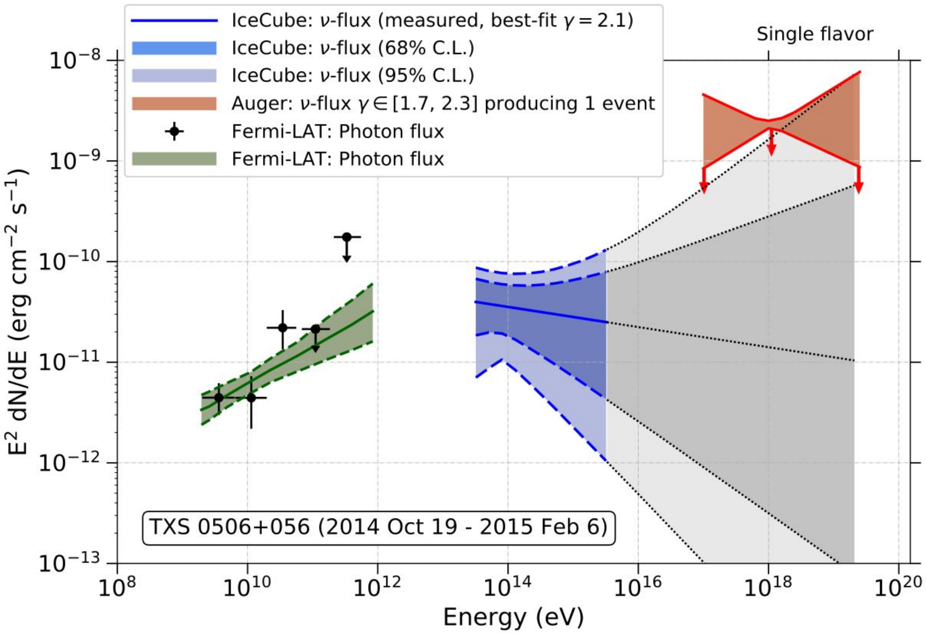

- ► Excellent visibility of the merger (ES channel)
- ► Upper limits consistent with an off-axis short GRB

- ► Blazar detected by Fermi-LAT and IceCube in Sep. 2017. Neutrino excess in IceCube archived data.
- ► Sub-optimal sensitivity of the source in all channels (δ = 5.7°)
- ► Auger would have detected 1 event at ~EeV if extrapolated neutrino spectrum were sufficiently hard (index > 1.5)

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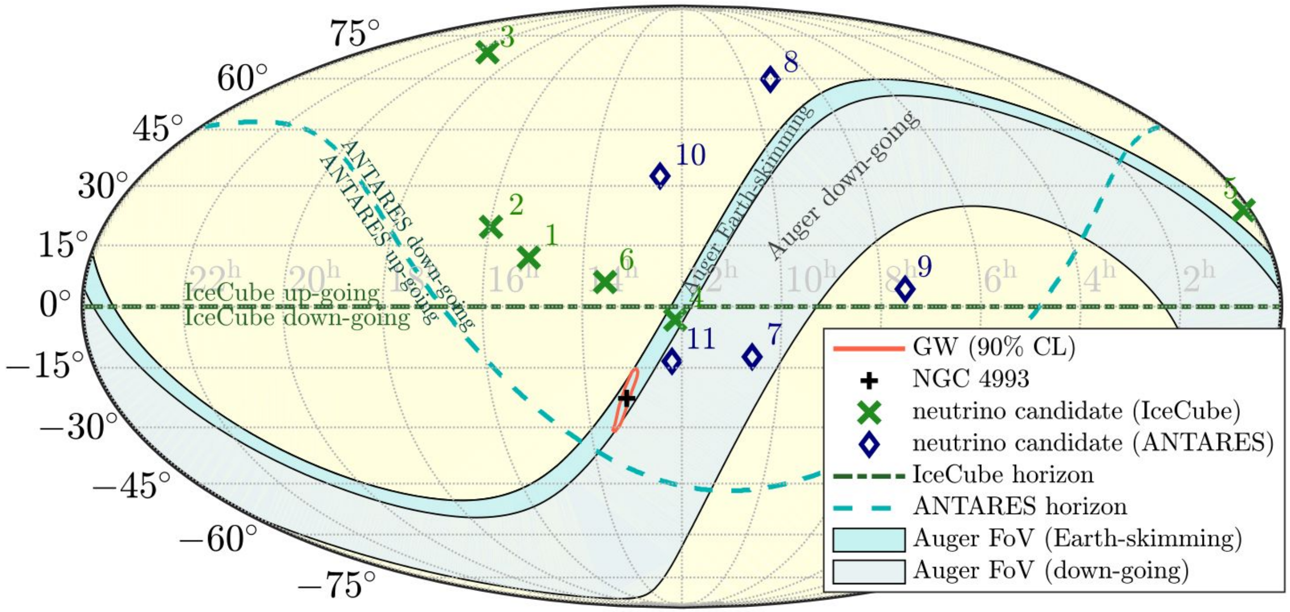
GW170817 in the Auger FoV



The BNS merger was in optimal position for the detection of UHE ν_τ from Auger at the instant of emission of GW170817

Figure 4. Left: Sensitive sky areas of ANTARES, IceCube and Auger at the time of the event GW170817 in Equatorial Coordinates. The red contour marks the 90% C.L. location of the event GW170817 [1, 18].