Pierpaolo Savina[1] on behalf of the **Pierre Auger Collaboration**[2]

[1] Gran Sasso Science Institute, L'Aquila, Italy; INFN Laboratori Nazionali del Gran Sasso, Assergi, Italy
[2] Observatorio Pierre Auger, Malargüe, Argentina

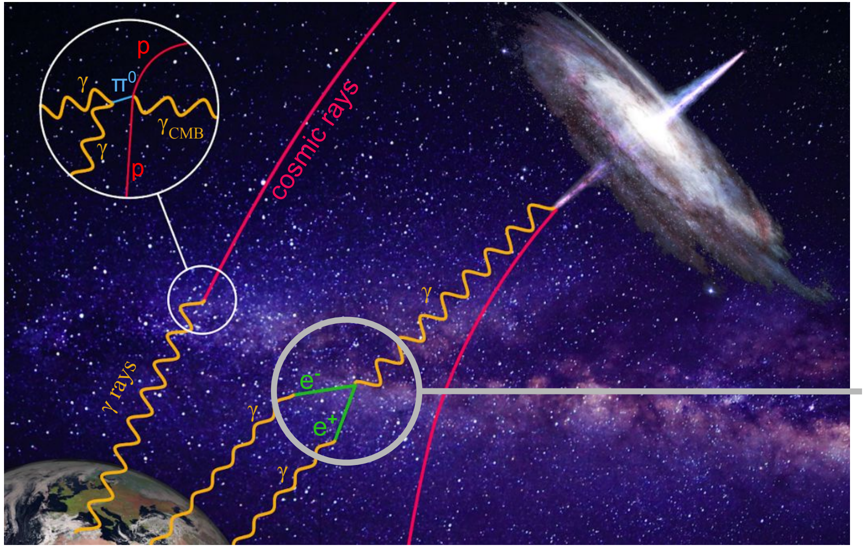
Latest results from the searches for ultra-high-energy photons at the Pierre Auger Observatory

RICAP 2024, Frascati, Italy

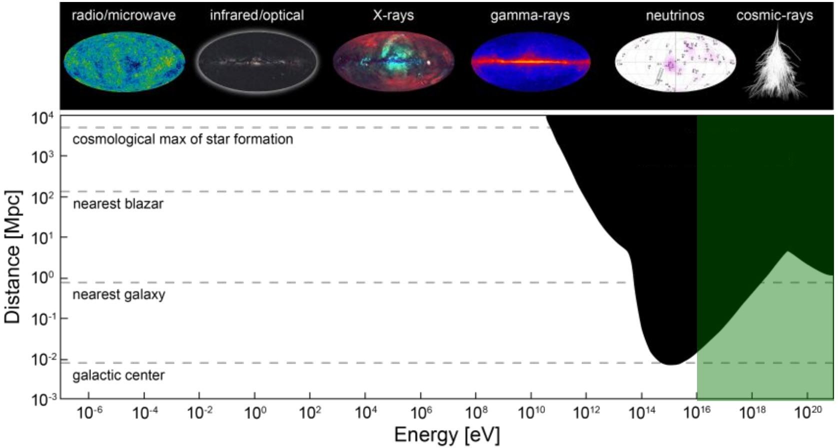
UHE-PHOTONS AS A PROBE OF THE UNIVERSE

UHE-Photons can be produced:

- in **acceleration sites** (astrophysical fluxes)
- during **cosmic-ray propagation** (cosmogenic fluxes)
- decay of putative **dark matter particles**



Universe not transparent to UHE-photons:
Track local Universe
Probe Dark Matter models (Galactic Center)



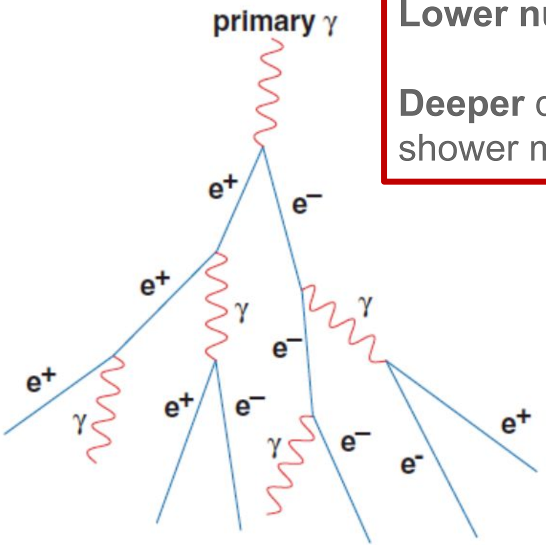
SIGNATURES OF A **PHOTON-INITIATED** SHOWER

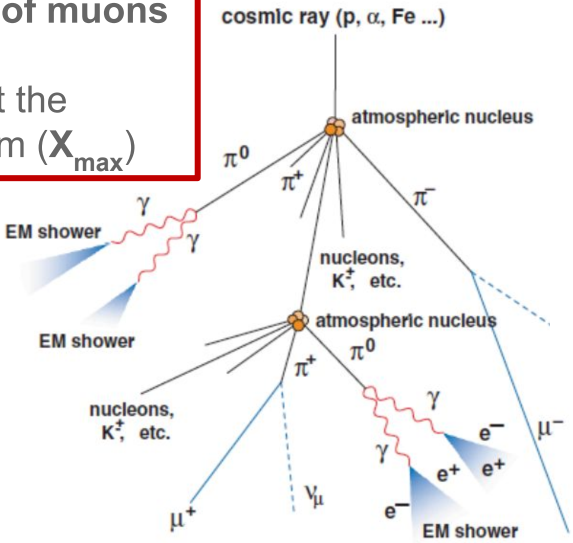
Steeply falling spectrum requires **large detector areas**.
Ground based experiments measure secondary products generated by primary cosmic rays in atmosphere

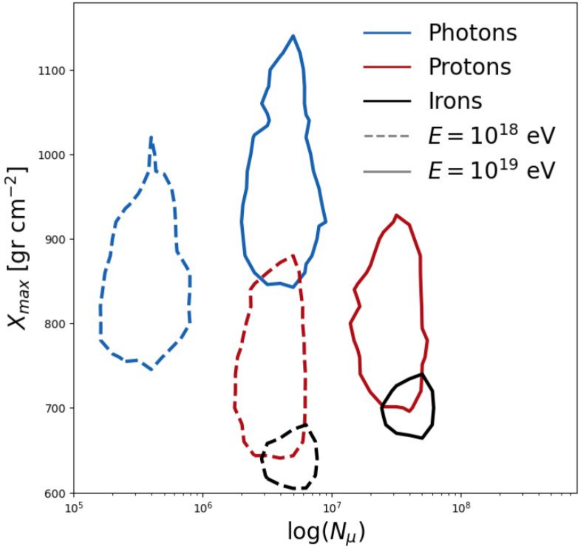
Separation exploiting the **different nature** of the **interactions**

Lower number of muons

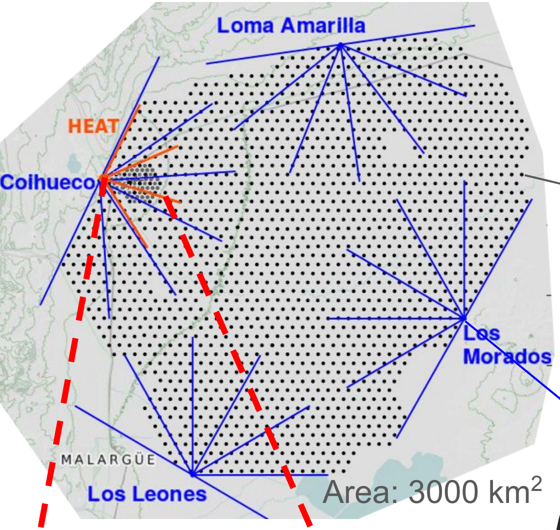
Deeper depth at the shower maximum (**X_{max}**)



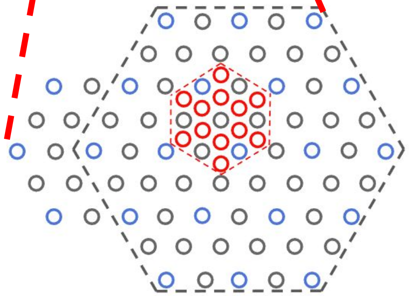




THE PIERRE AUGER OBSERVATORY



Area: 3000 km^2



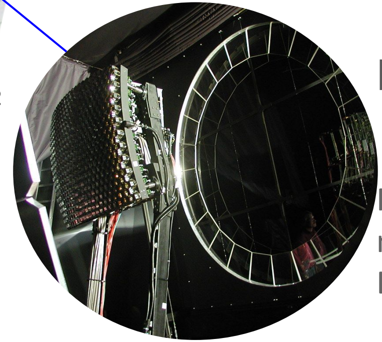
Surface Detector (SD)

1661 Water-Cherenkov stations

- SD1500: 1600 stations - 1.5 km grid
- SD750: 61 stations - 750 m grid
- SD433: 19 stations - 433 m grid

Samples secondary particles that reach the ground

Duty cycle: 100%



Fluorescence Detector (FD)

- FD: 24 telescopes (across 4 sites) - 0°-30° FOV
- HEAT: 3 telescopes - 30°-60° FOV

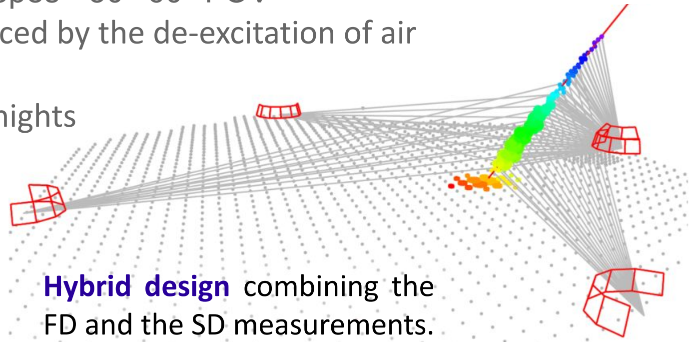
Measuring light produced by the de-excitation of air nitrogen molecules.

Duty cycle: moonless nights

Additional detector systems:

complementing main SD and FD

radio antennas, underground muon detectors



Hybrid design combining the FD and the SD measurements.

SEARCHES AT THE PIERRE AUGER OBSERVATORY

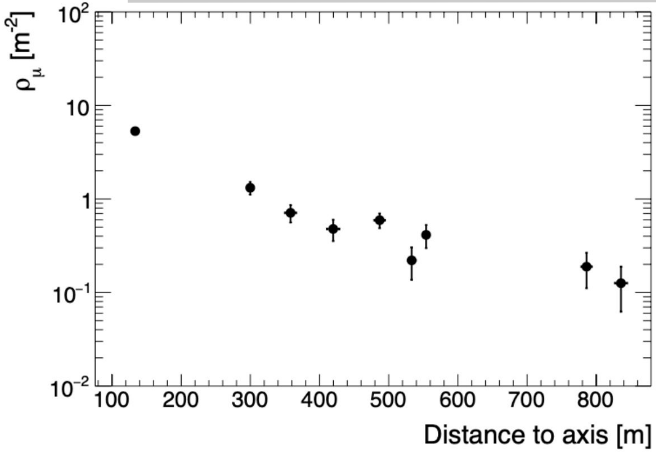
Searching for a **diffuse** flux of photons [Universe 8 (2022) 579]

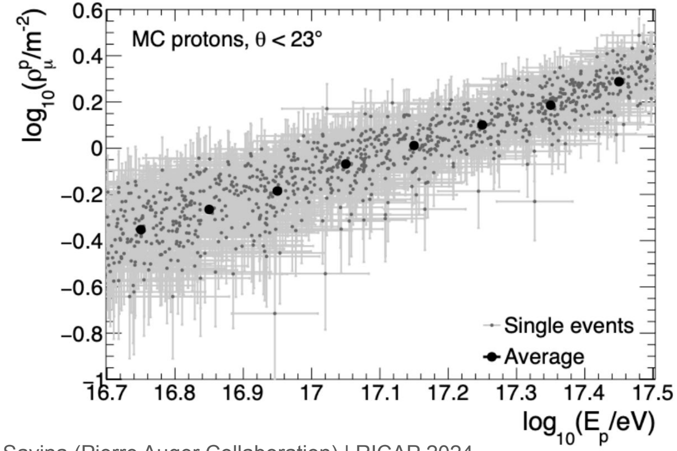
- Different energy ranges using data from different detector systems:
  - Below 2 x 10^{17} eV: SD433 [Proc. of Science 444, 238 (2023)]
  - 2 x 10^{17} to 10^{18} eV: HEAT/Coihueco + SD750 (hybrid data) [Astrophys. J. 933 (2022) 125]
  - 10^{18} to 10^{19} eV: FD + SD1500 (hybrid data) [arXiv:2406.07439 accepted.PRD]
  - Above 10^{19}: SD1500 [JCAP 05 (2023) 021]

Follow-us search for UHE photons in coincidence with gravitational-wave events

PHOTONS: THE > 5 x 10^{16} ENERGY RANGE

Proc. of Science 444, 238 (2023)





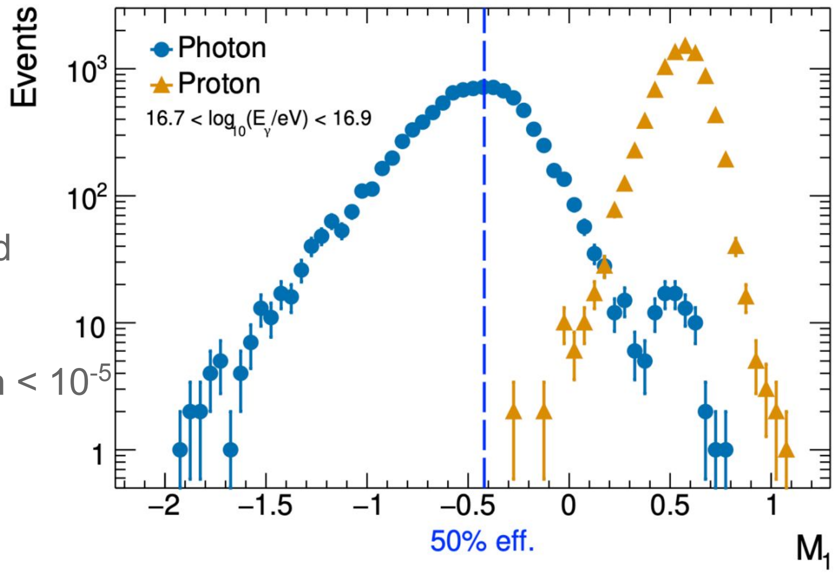
$$M_1 = \log_{10}\left(\sum_i \frac{\rho_\mu^i}{\rho_\mu^p} \times \frac{r_i}{200\,\mathrm{m}}\right)$$

M_1 <0 for photons

Data based on SD433 + UMD*: 2204 events selected

From simulations: background rejection < 10^{-5}

0 candidates found



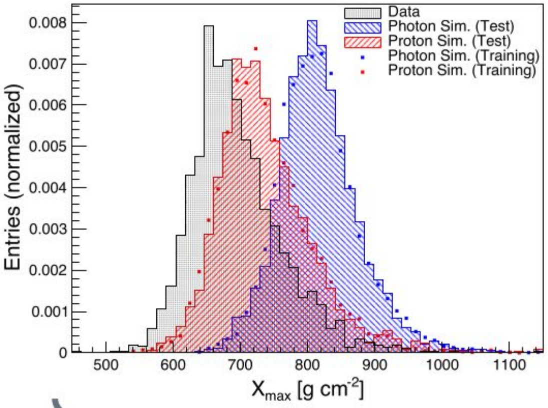
First measurement of the diffuse photon flux from the Southern hemisphere

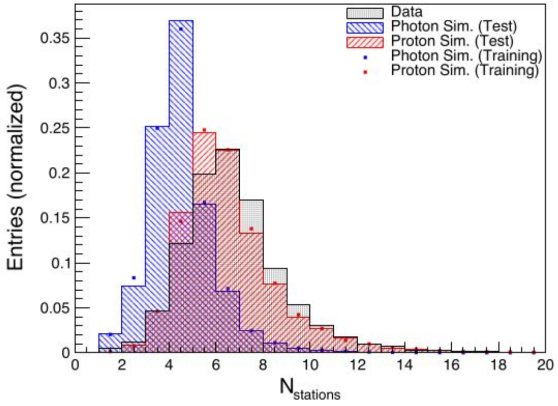
*UMD: Underground muon detector

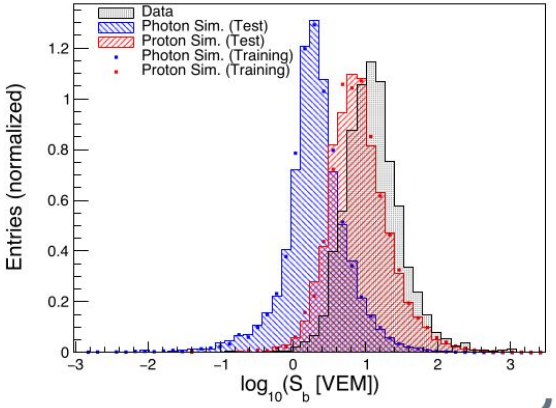
PHOTONS: THE **2 x 10^{17} - 10^{18} eV** ENERGY RANGE

ApJ. 933 (2022) 125

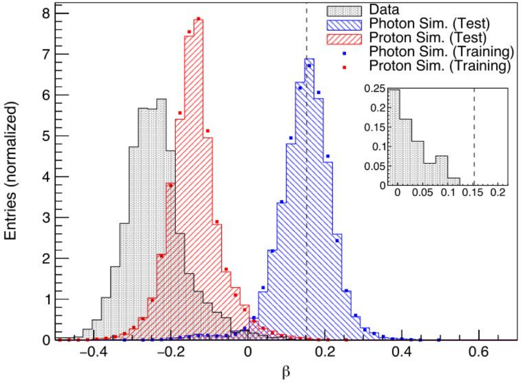
Observables







MVA (BDT)



- Photon candidate **cut**: **50% signal** efficiency, ~99.9% background rejection
- **Data**: 1 Jun 2010 - 31 Dec 2015
- Exposure from simulations: ~ 2.5 km^2 sr yr

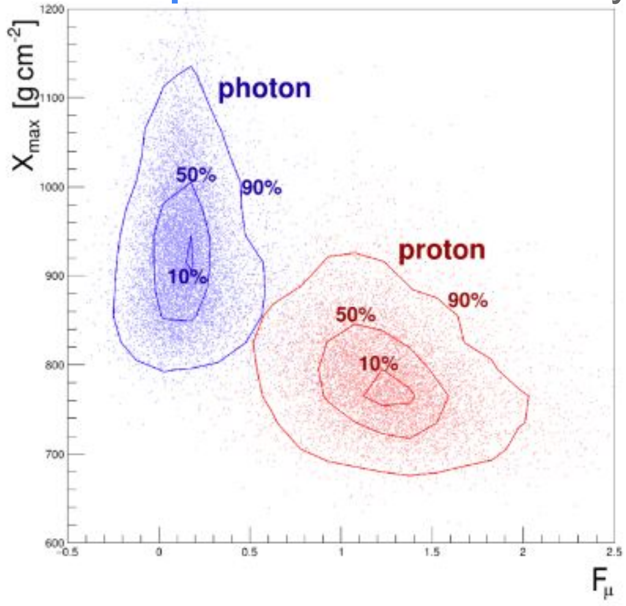
No photon candidate identified

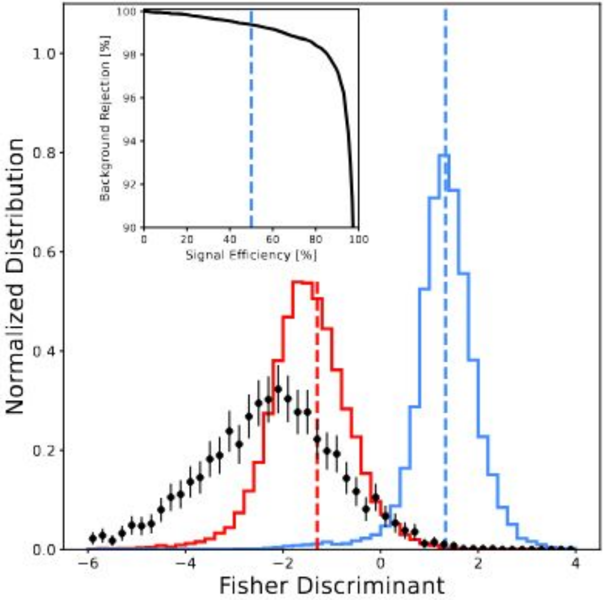
PHOTONS: THE 10^{18} - 10^{19} eV ENERGY RANGE

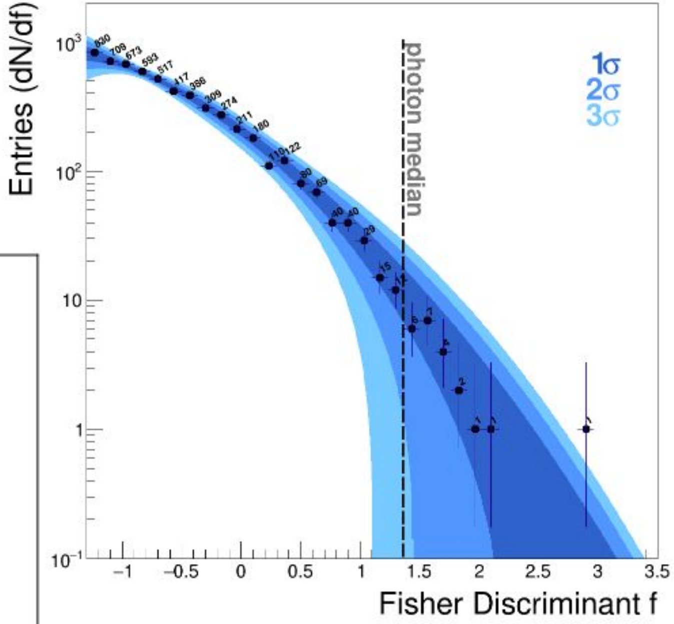
PRD 110, 062005 (2024)

PIERRE AUGER OBSERVATORY

- **F_μ**, calculated using a model based on air-shower universality, is used as a **proxy for the muon content.**
- Signal Efficiency 50%, background rejections 99.9%;
- **Data**: 1 Jan 2005 - 31 Dec 2017
- **Exposure**: ~ 1000 km^2 sr yr



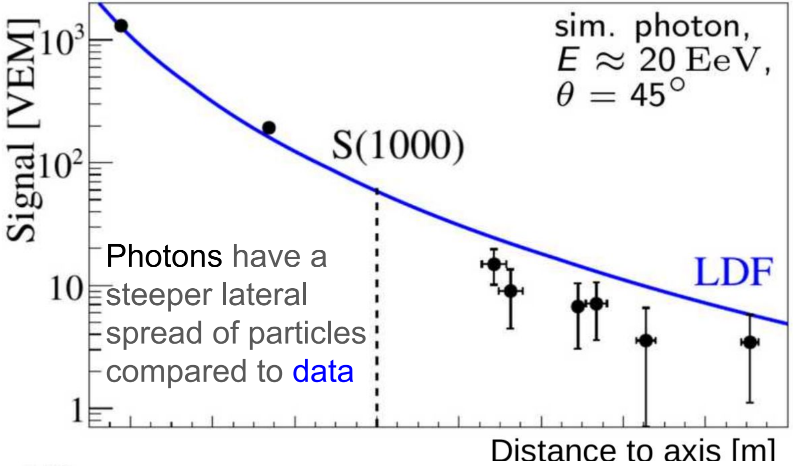


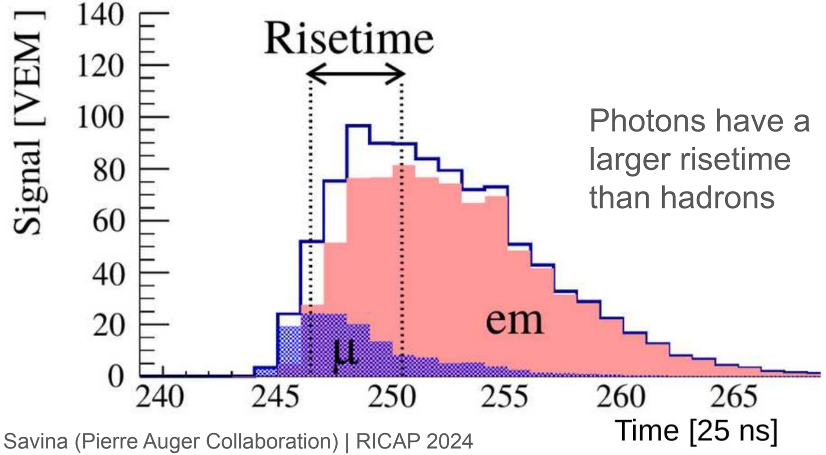


22 Candidates, consistent with the **expectation of 30 ± 15,** estimated using 5% of the data

PHOTONS: THE > 10^{19} eV ENERGY RANGE

JCAP 05 (2023) 021





Analysis on **2 observables**, both based on “**benchmarks**” obtained from data

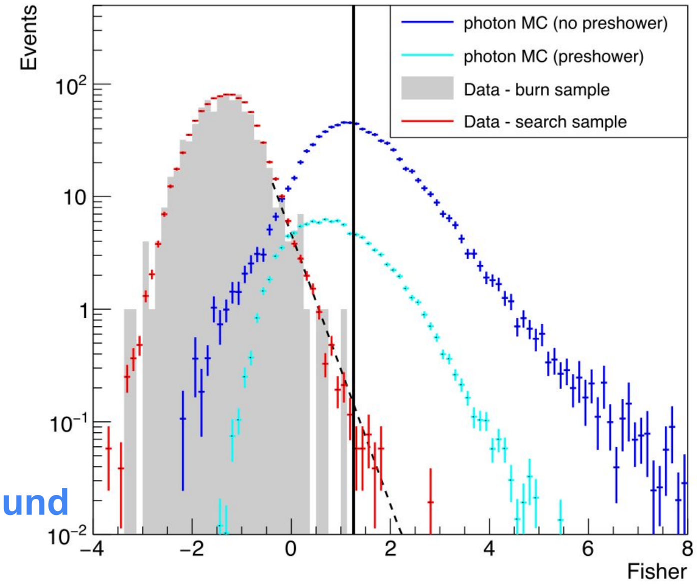
$$L_{\rm LDF} = \log_{10}\left(\frac{1}{N}\sum_{i=1}^{N}\frac{S_i}{f_{\rm LDF}(r_i)}\right) \qquad \Delta = \frac{1}{N}\sum_i \frac{(t^i_{1/2} - t^{\rm bench}_{1/2})}{\sigma_{t_{1/2}}}$$

(Method free from composition assumptions).

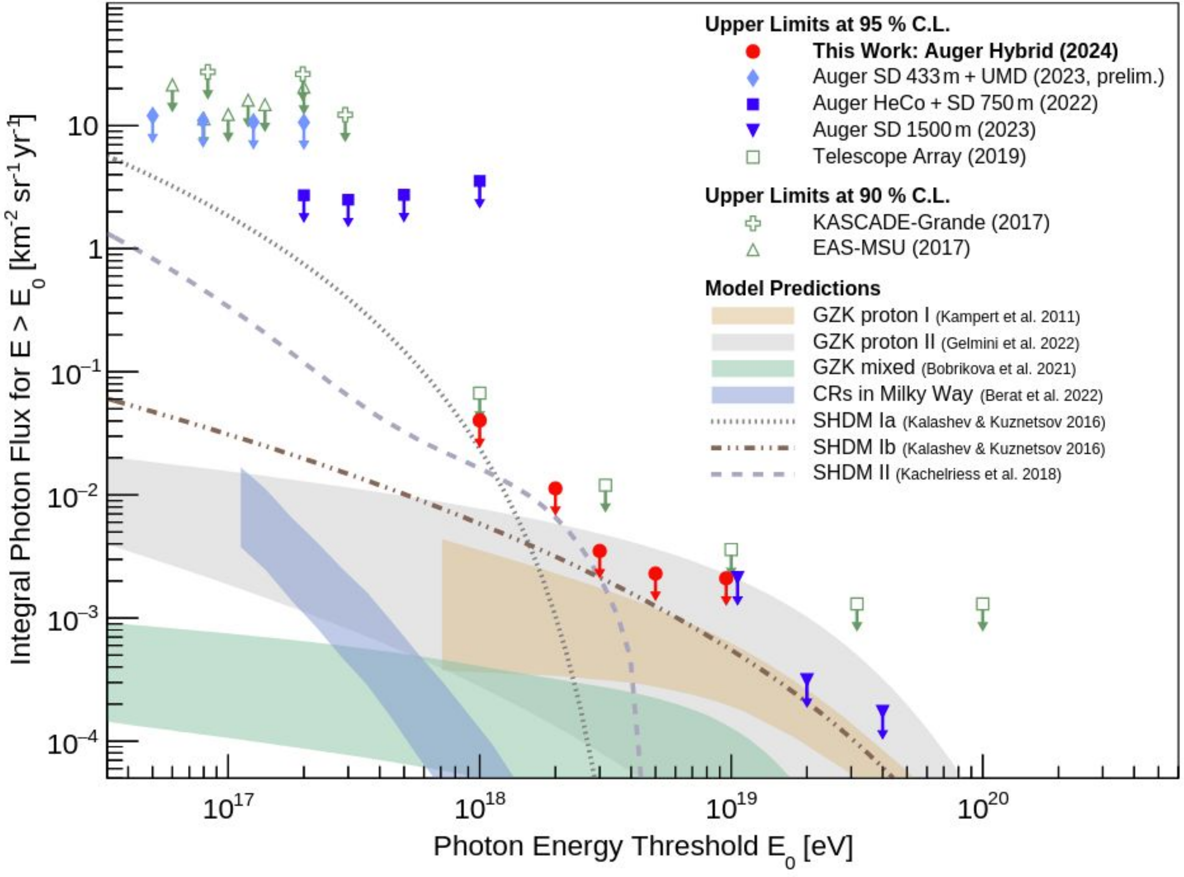
Data:
01/2004 - 06/2020

Exposure:
~17000 km^2 sr yr

16 Candidates, consistent with the expected **background**



UPPER LIMITS ON THE DIFFUSE UHE-PHOTON FLUX



No primary UHE-photon unambiguously identified so far

Most stringent limits on the diffuse flux of photons over a wide energy range come from Auger

Predictions of some **theoretical models** are within reach

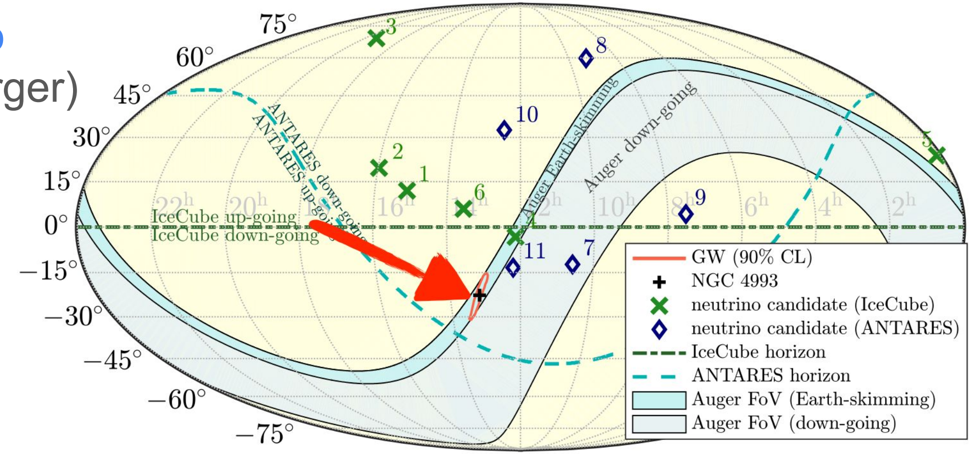
Limits can **constrain SHDM models**

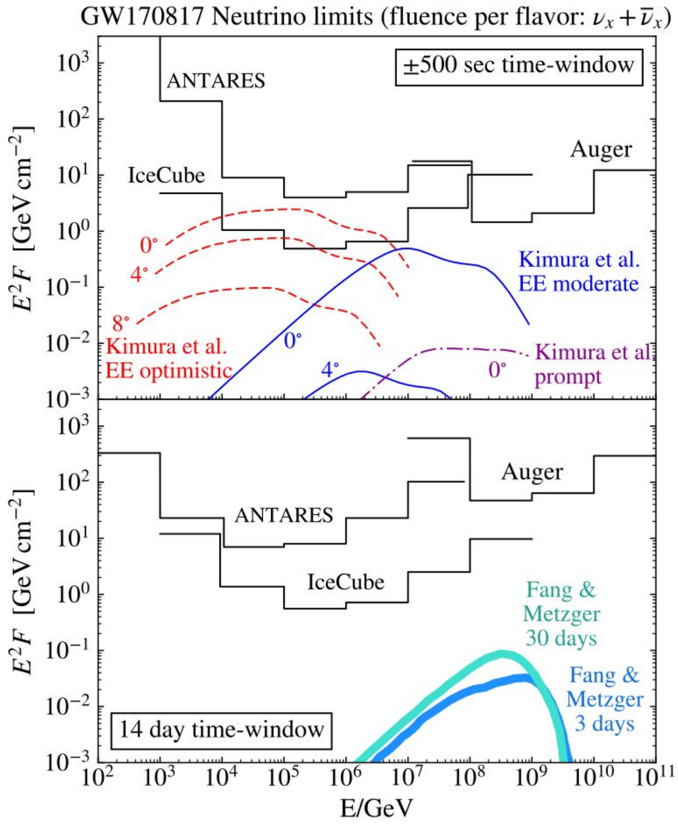
FOLLOW-UP STUDIES TO TRANSIENT EVENTS

The Pierre Auger Observatory takes part in the **multimessenger-astronomy networks GCN/TAN** and **AMON** [https://gcn.nasa.gov/] [https://www.amon.psu.edu]

Enables **direct follow-up studies** to transient events (e.g., compact binary mergers)

GW170817 neutrino follow-up [Antares, IceCube, Pierre Auger, Ligo Scientific and Virgo Colls., ApJL 850 (2017) L35]
(BNS merger)





FOLLOW-UP SEARCH FOR UHE PHOTONS (I)

[ApJ 952 (2023) 91]

Search for UHE-photons with energies above 10^{19} eV in **coincidence with GW events**

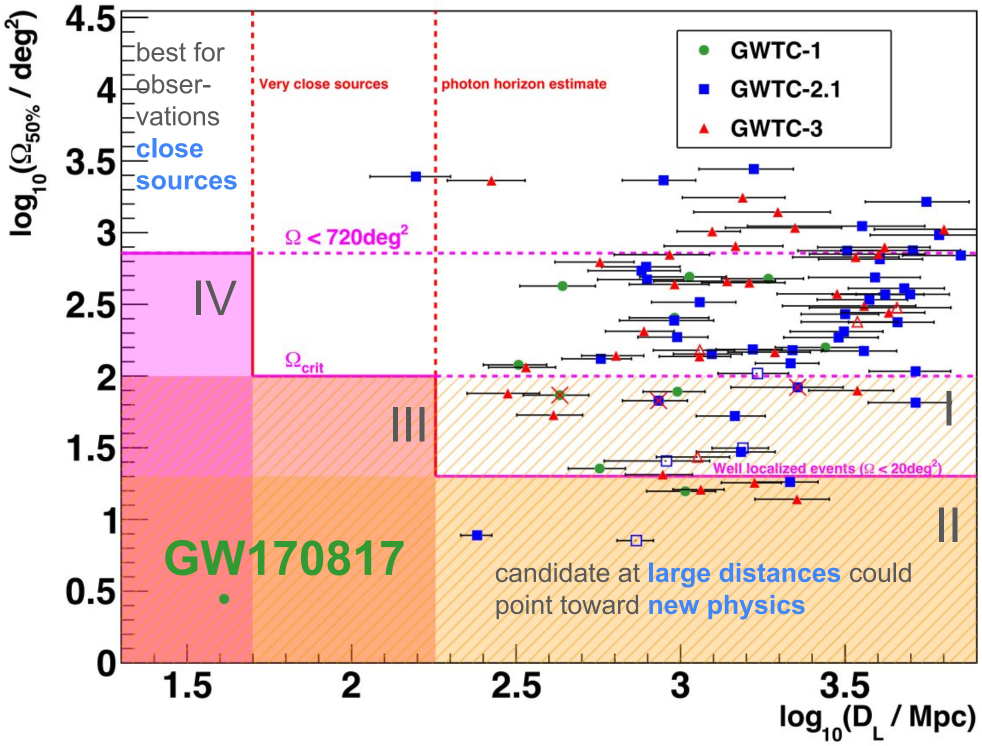
Use **data from 1500 m SD array**, same observables as in the standard analysis

91 follow-up selected GW events to reduce the rate of false-positive detections

Close and/or **well-localized GW** measured by LIGO/VIRGO

$$(D_L < \infty \text{ and } \Omega_{50\%} < 100\ \text{deg}^2)_s \text{ “class I”}$$
$$(D_L < \infty \text{ and } \Omega_{50\%} < 20\ \text{deg}^2)_l \text{ “class II”}$$
$$(D_L < 180\ \text{Mpc and } \Omega_{50\%} < 100\ \text{deg}^2)_l \text{ “class III”}$$
$$(D_L < 50\ \text{Mpc and } \Omega_{50\%} < 720\ \text{deg}^2)_{l,s} \text{ “class IV”}$$

2 search windows (±500 s or +1 day around the time of the event)



FOLLOW-UP SEARCH FOR UHE PHOTONS (II)

[ApJ 952 (2023) 91]

10 GW events passed the selection and were followed up

No coincident photons were identified -> upper limits

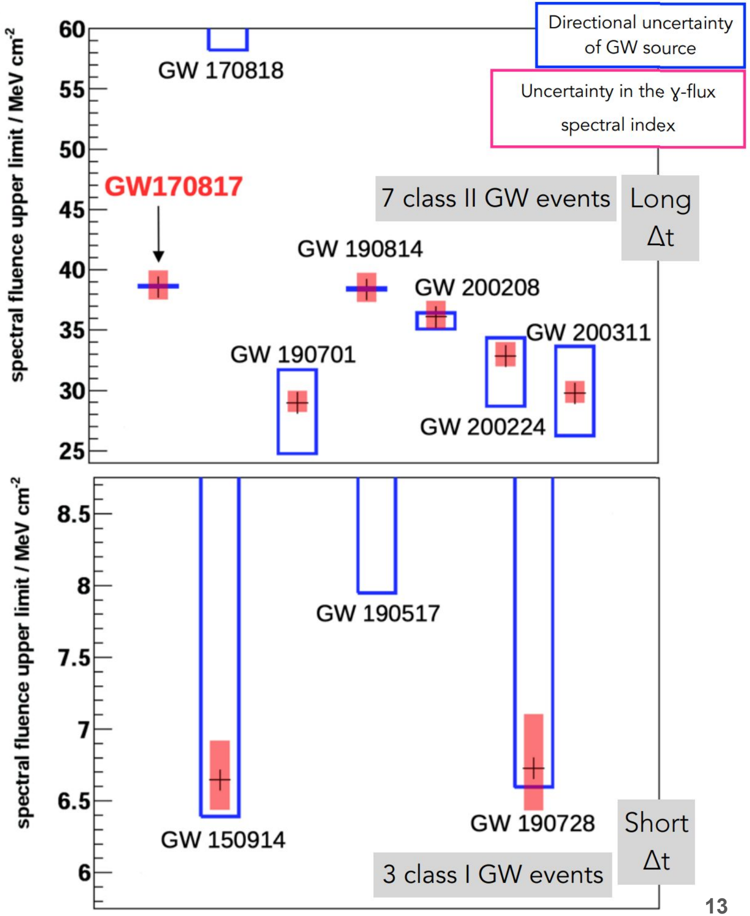
GW170817: energy transferred into UHE-photons above 40 EeV constrained to be **less than 20%** of its total energy

$$\frac{\mathrm{d}\Phi_\gamma^{\mathrm{GW}}}{\mathrm{d}E_\gamma}(E_\gamma) = k_\gamma E_\gamma^\alpha$$

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

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

Spectral γ fluence



AugerPrime: UPGRADE OF THE OBSERVATORY

WCD/SSD/RD can collect multi-hybrid events with a 100% duty cycle

Separation of shower components can be obtained:
- by WCD/SSD for events up to ~60°
- by WCD/RD for inclined events > 60°
- by WCD/SSD/UMD extending the mass sensitivity to the lower energies and improving photon/hadron separation

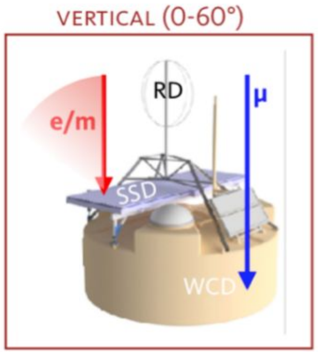
4 m^2 scintillators

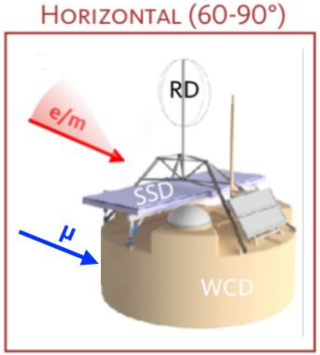
+ faster electronics and extended dynamic range for the SD

30 m^2 buried scintillators

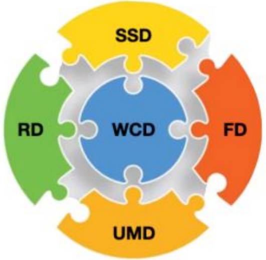
Radio antennas

EPJ Web Conf. 145 (2017) 05001





With the new electronics we will enhance the sensitivity of triggers to electromagnetic signals, specifically for photons and neutrinos



CONCLUSIONS

The Pierre Auger Observatory offers an **unprecedented exposure** not only to UHECRs, but also to UHE photons

Stringent upper limits on the diffuse fluxes of UHE photons

Thorough follow-up searches to gravitational wave events

The Pierre Auger Observatory is a key actor in **multimessenger astronomy** at ultra-high energies – even more so with the upcoming **AugerPrime** upgrade