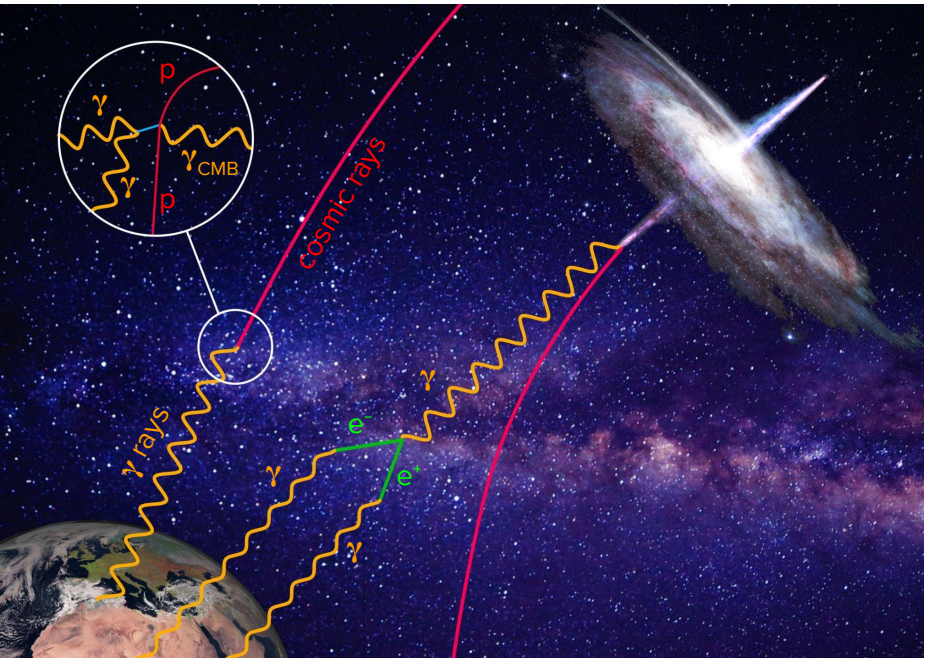
Ultra-High-Energy Photon Searches with the Pierre Auger Observatory: Constraints, Multi-messenger Synergies, and Future Prospects

Chaitanya Priyadarshi[1] on behalf of the **Pierre Auger Observatory**[2]

[1] Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
[2] Observatorio Pierre Auger, Malargüe, Argentina

TeV Particle Astrophysics 2025, Valencia

Searching for UHE photons



Origin of UHE photons:

- Acceleration sites (**astrophysical**)
- Produced during CR propagation (**cosmogenic**)
- Decay of metastable SHDM particles

The maximum energy of photons we have measured is about 2.5 PeV by LHAASO (Phys. Rev. Lett. 131 (2023) 151001)

Can we see higher energy photons?

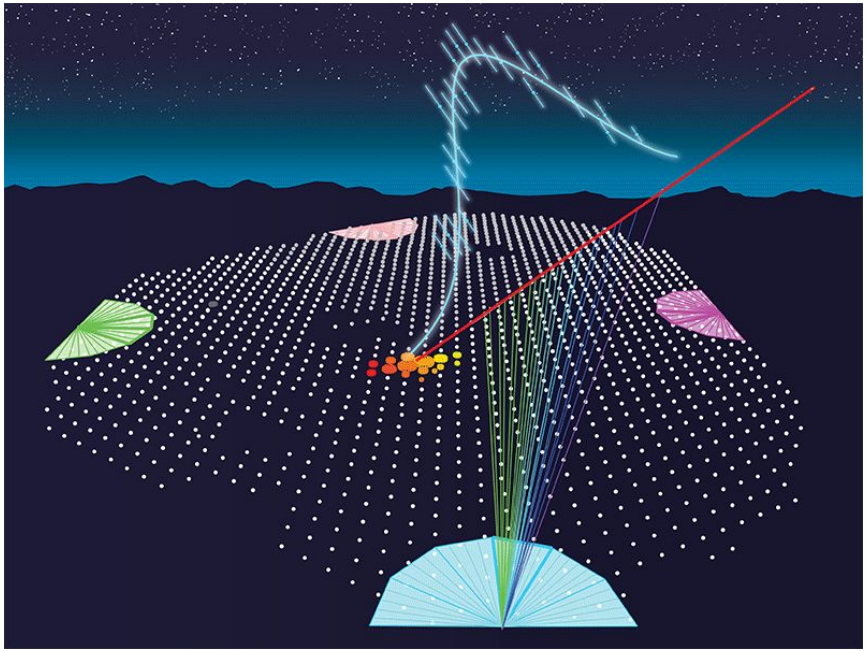
Pierre Auger Observatory

Complex hybrid detector -

- Surface Detector
- Fluorescence Detectors
- Underground Muon Detectors
- Radio Detectors

Background (CRs) rejection using air-shower observables:

- Lateral spread of particles on ground, S_b
- Depth of the air-shower maximum
- Muon content



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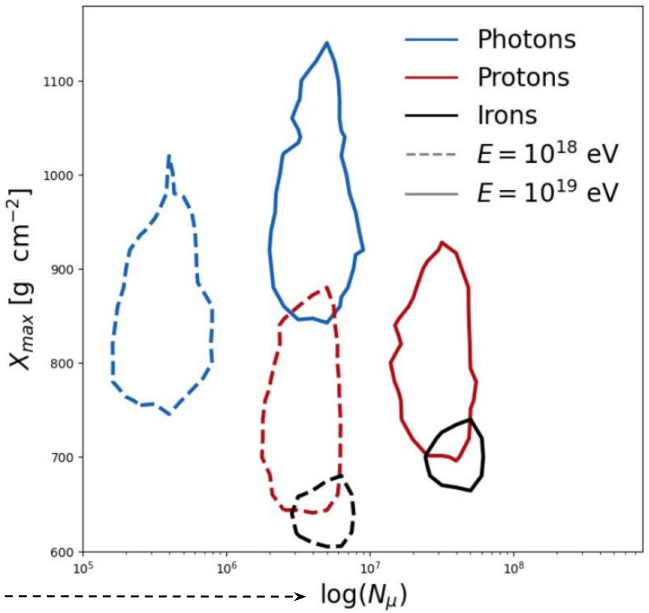


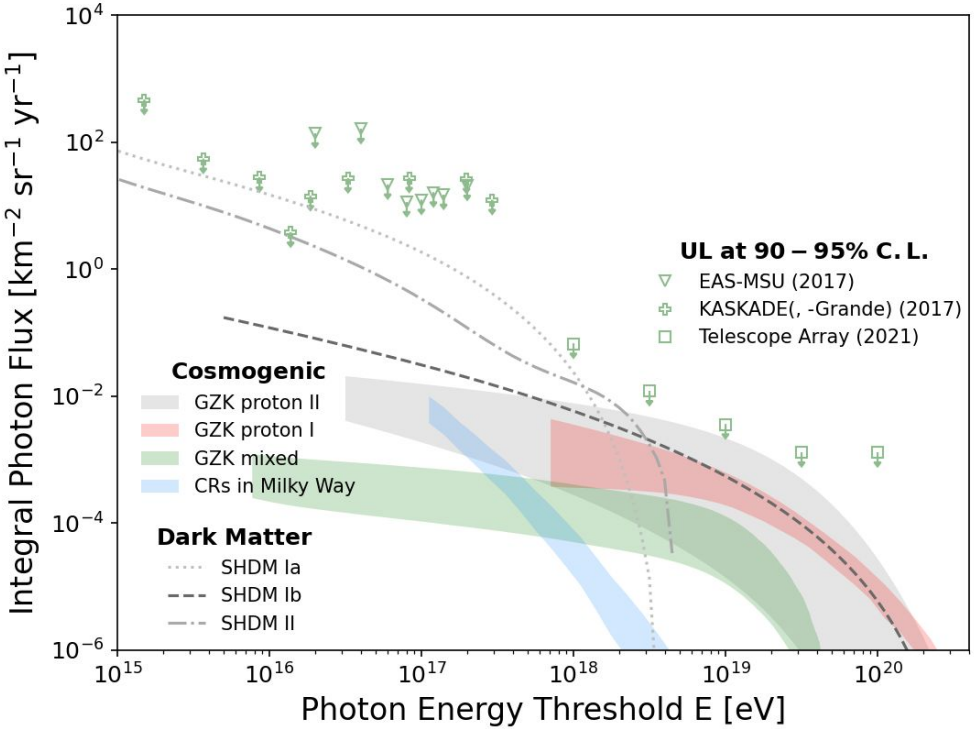
Diffuse photon flux searches

Theoretical predictions:

- Cosmogenic with different UHE mass compositions
- CRs + Galactic disk matter
- Super Heavy DM models

Searches from other experiments above 10^{16} eV: EAS - MSU, KASKADE, TA

The **Pierre Auger Observatory** provides upper limits over **~4 energy ranges** using analyses based on data from different detectors.

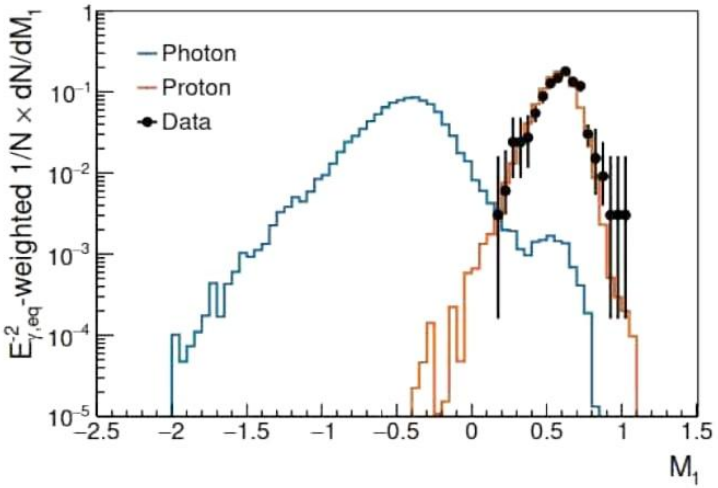


E > 5x10^{16} eV | SD-433 + Underground Muon Detector

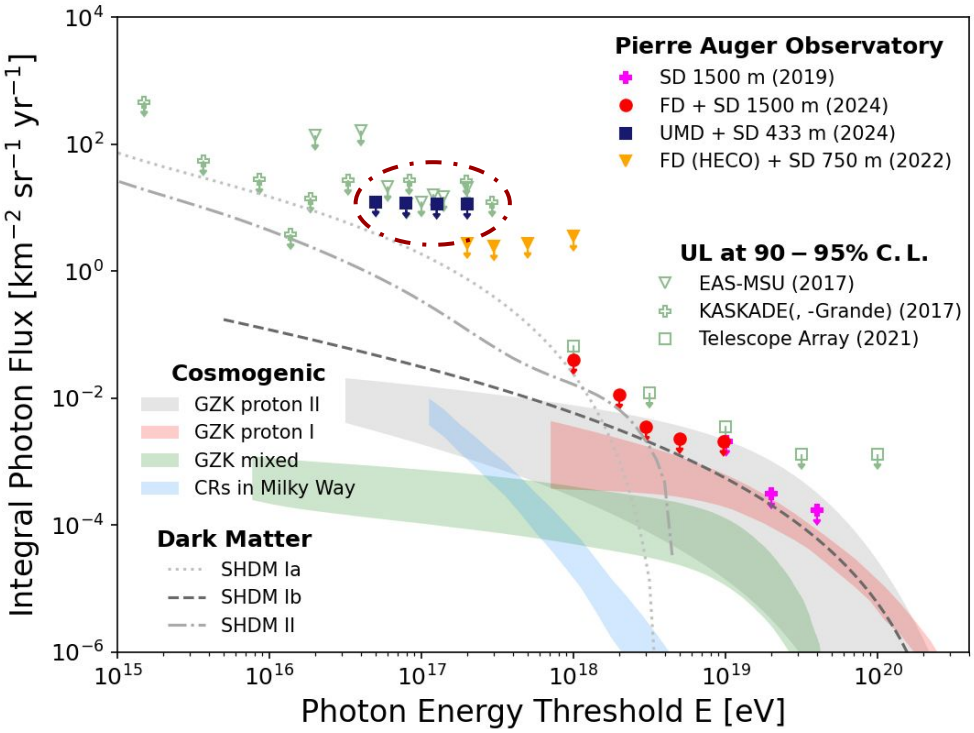
Data period: 2021 - 2022

Observable: M_1 muon content estimator

Separation power smaller than 10^{-5}



0 candidates



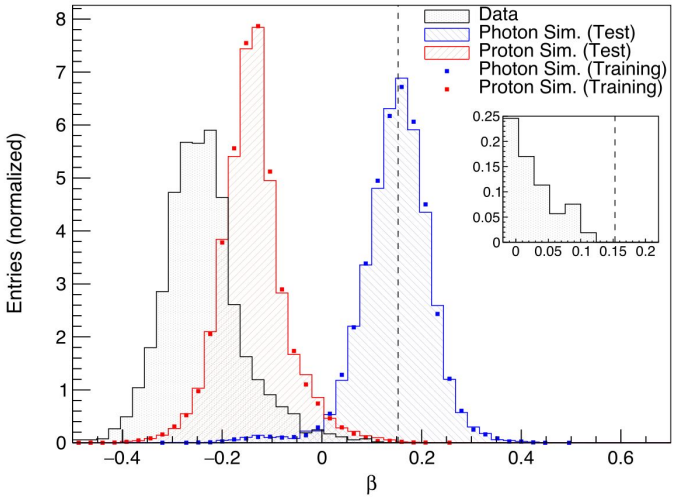
(JCAP 05 (2025) 061)

E: 2×10^{17} - 10^{18} eV | SD-750 + Fluorescence Detector

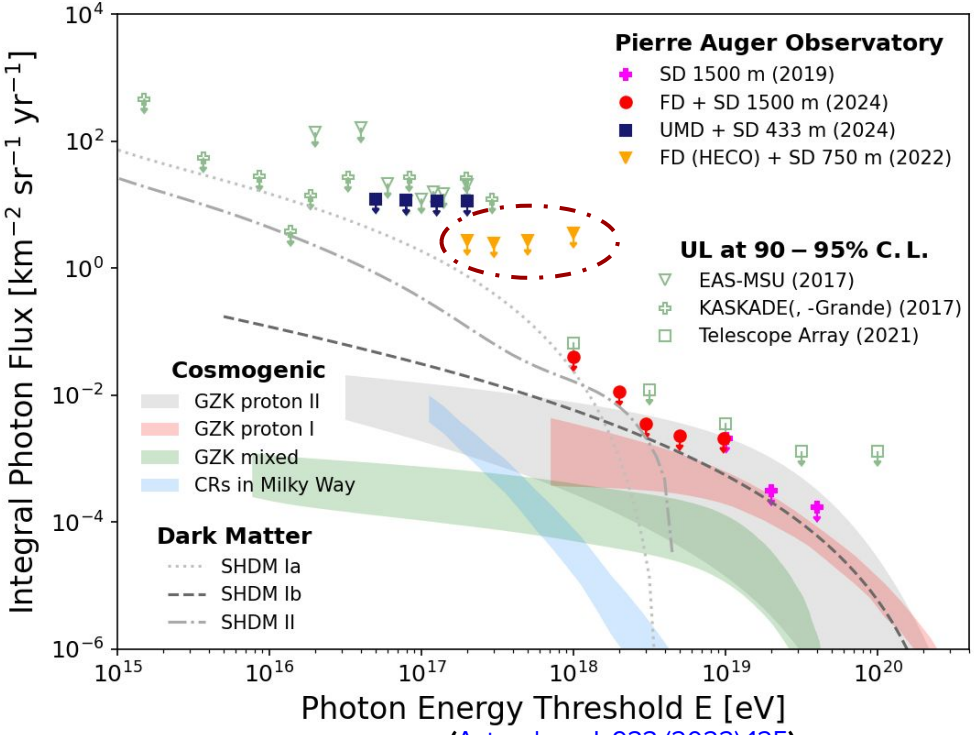
Data period: 2010 - 2016

Multivariate analysis: X_{max} , S_b , $N_{stations}$

Combined by Boosted Decision Tree, β



0 candidates



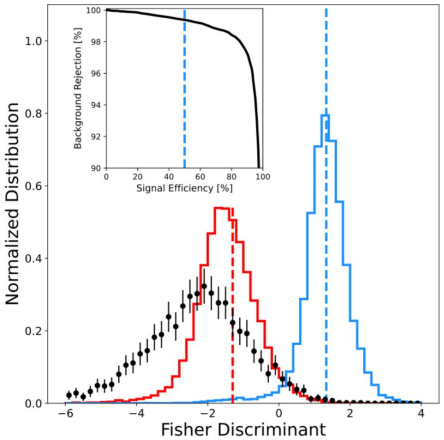
(Astrophys. J. 933 (2022) 125)

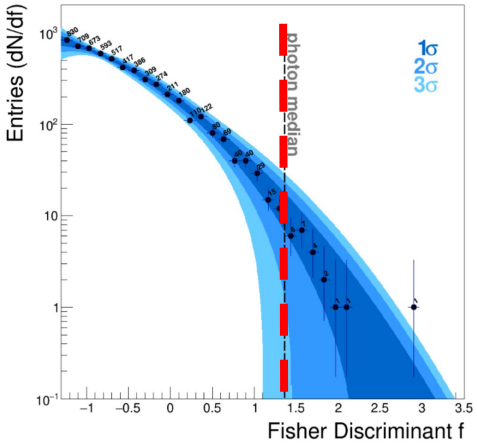
E: 10^{18} - 10^{19} eV | SD-1500 + Fluorescence Detector

Data period: 2005 - 2018

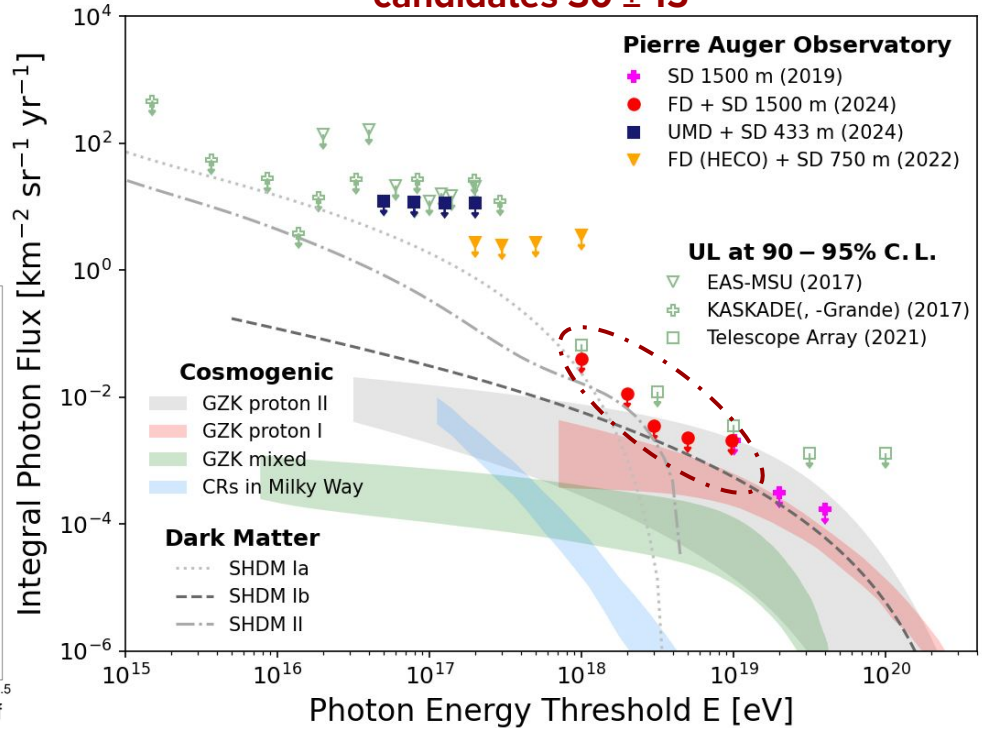
Observables: X_{max} , F_{μ} proxy for muon content

Combined in a Fisher discriminant, *f*





22 candidates, with expectation of false candidates 30 ± 15



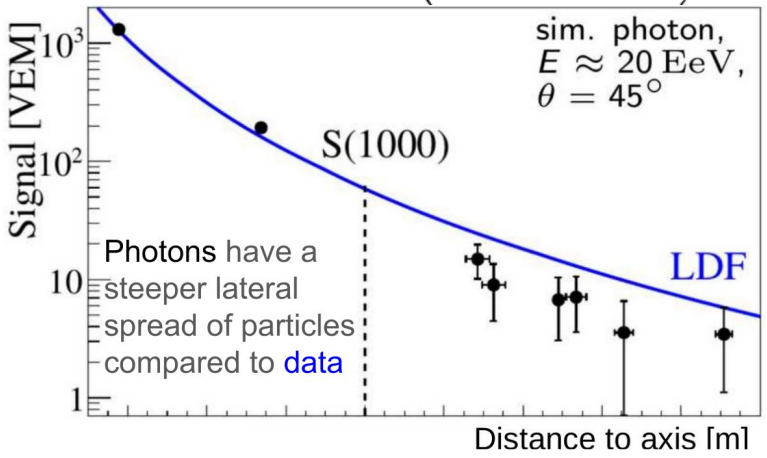
([PRD 110, 062005 (2024)](PRD 110, 062005 (2024)))

$E > 10^{19}$ eV | SD-1500

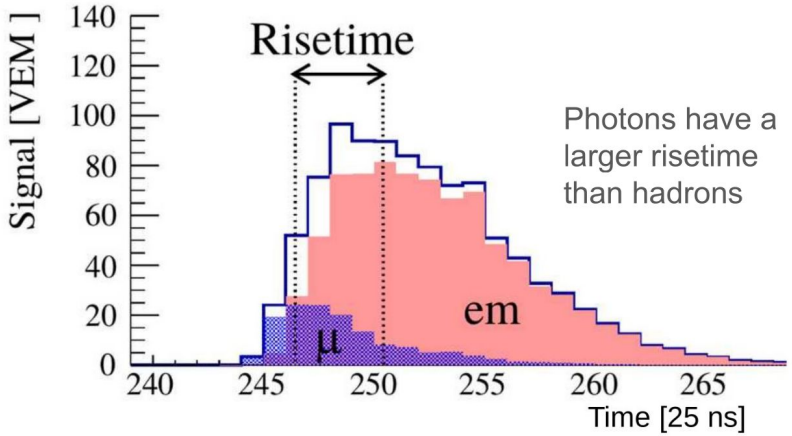
Data period: 2004 - 2020

Observables: Deviation from the “benchmark” values for photons,

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



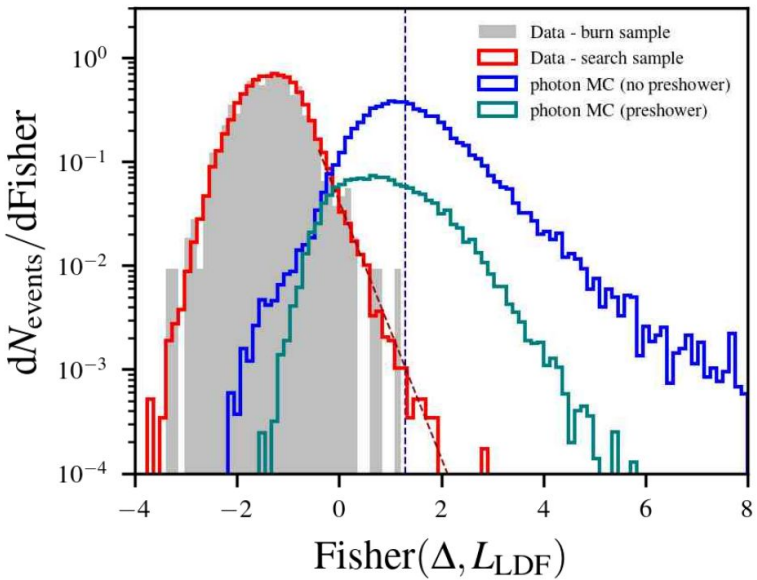
2) $$\Delta = \frac{1}{N}\sum_{i=1}^{N}\frac{(t^i_{1/2} - t^{bench}_{1/2})}{\sigma_{t_{1/2}}}$$



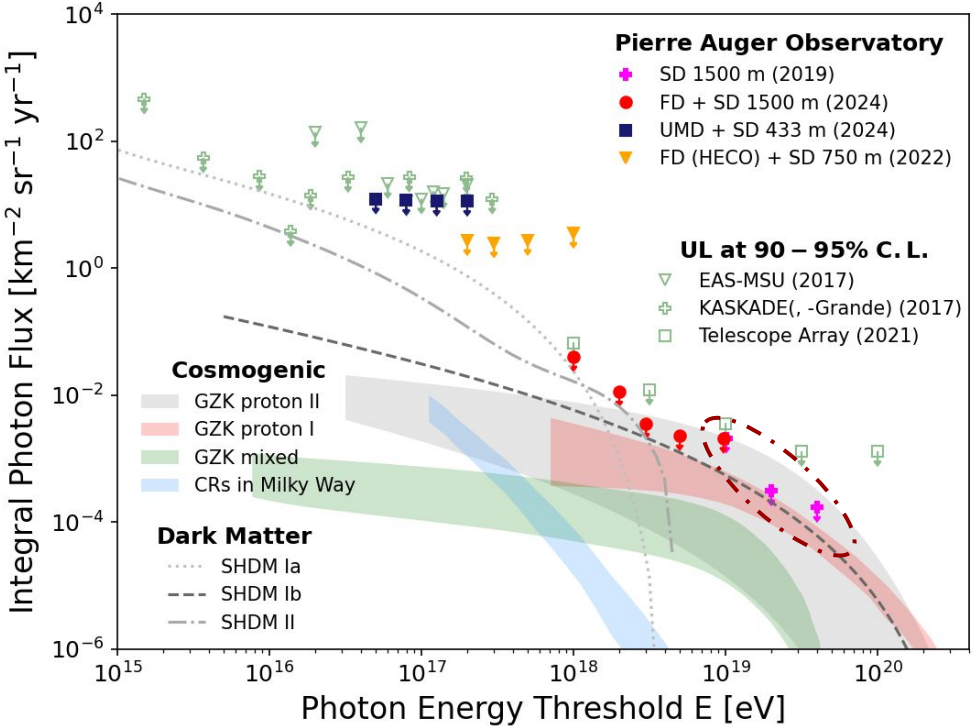
(JCAP 05 (2023) 021)

$E > 10^{19}$ eV | SD-1500

Combined by Fisher discriminant, *f*



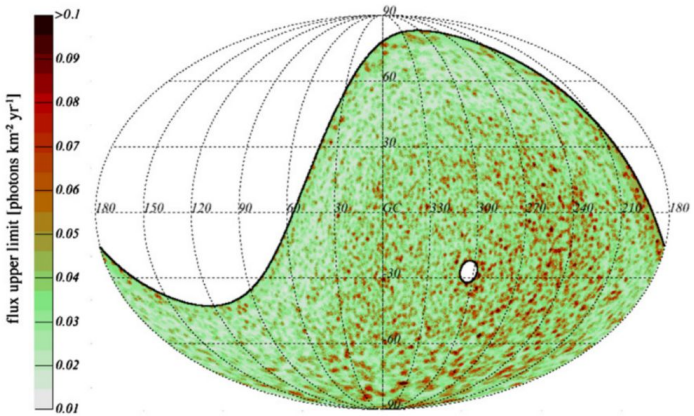
16 candidates compatible with background



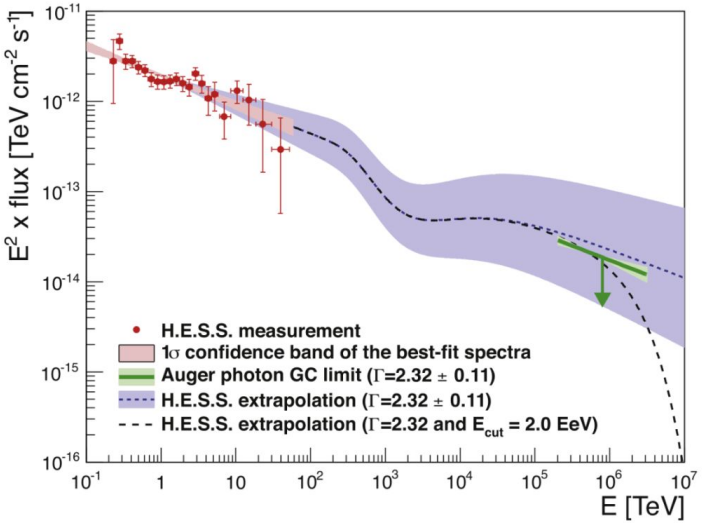
(JCAP 05 (2023) 021)

Direct searches: Blind and Targeted

Combination of 5 observables from SD-1500 and fluorescence detectors



Blind search - 2005 - 2011
([ApJ 789 (2014) 160](ApJ 789 (2014) 160))



Targeted search of Galactic Center - 2005 - 2014 (ApJL 837 (2017) L25)

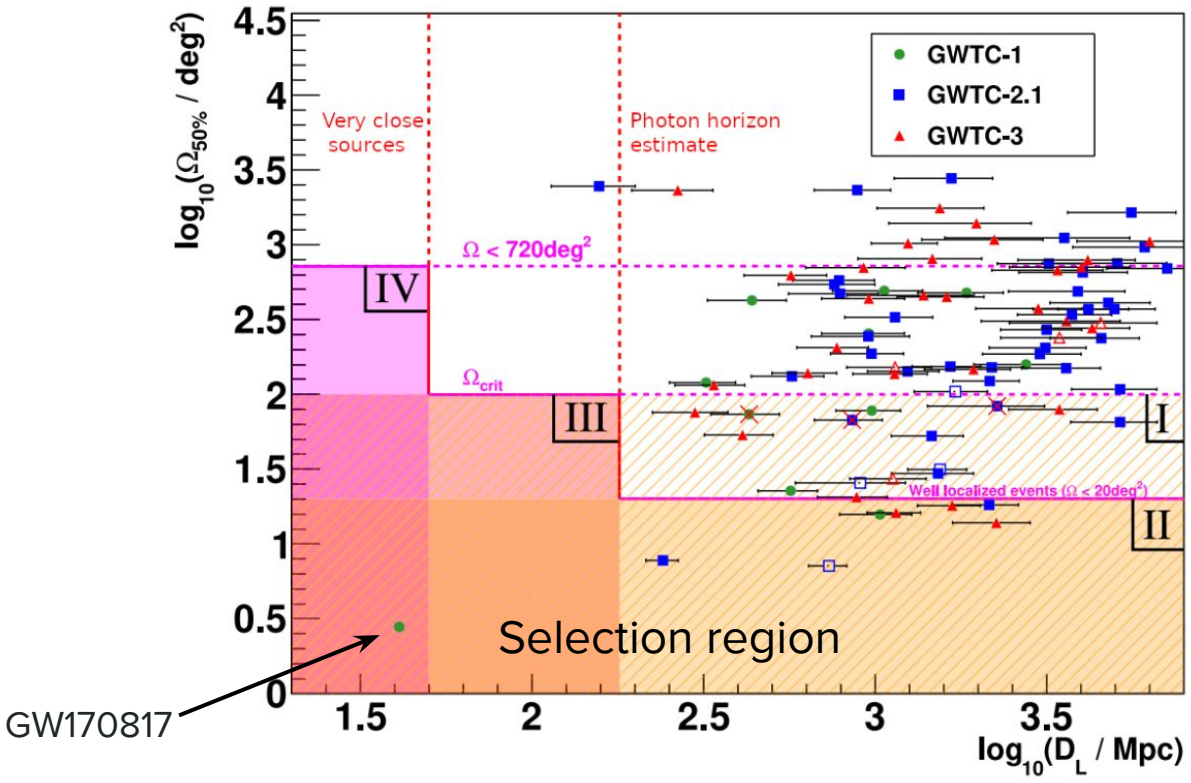
0 candidates found

Search for time-direction correlations with GWs

GW seen by **LIGO/Virgo** (O1: O3 runs)

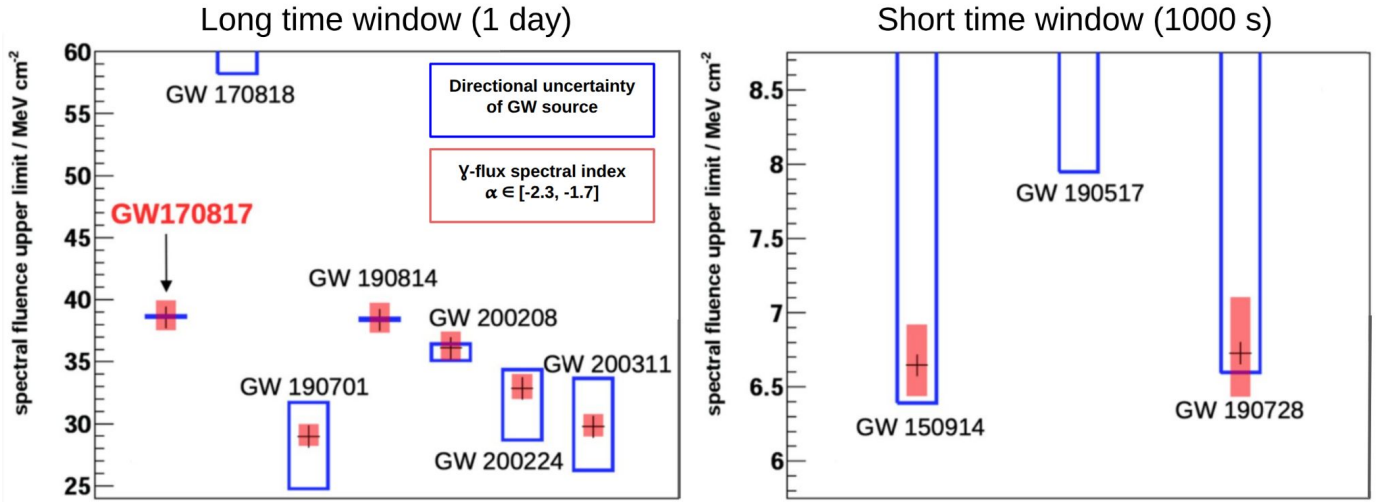
Auger events measured with SD-1500 (ApJ 952 (2023) 91)

10 events were selected, which are either nearby or well-localized on the sky



Search for time-direction correlations with GWs

For GW170817, the energy transferred into UHE photons above 4 x 10^{19} eV, was constrained to be < 20% of its total GW energy



0 coincident photons found

Future Analyses

Pierre Auger Observatory upgrade (finished in 2024)

- Improved sensitivity with the new detectors: Scintillators and Radio Antennas on top of the Water Cherenkov Detectors, and the completed deployment of the Underground Muon Detectors.
- More than 10 years of data to be taken (operation time at least until 2035) with increased angular observation range.

Future activities to extend towards lower energies - PEPS*

*See talk by I. Maris on Monday

Conclusions

- The Pierre Auger Observatory provides the strongest upper limits on the **diffuse fluxes** in the energy range between 5 x 10^{16} - 10^{20} eV.
- It searches for **point-sources** using blind and targeted methods (No candidates found).
- Multi-messenger: **follow-up searches** to GW events.
- Auger Phase II data is expected to further enhance the **sensitivity.**

Can we see UHE photons in the next 10 years? Maybe... Stay tuned!