Latest Results from the Searches for Photons at the Highest Energies with the Pierre Auger Observatory

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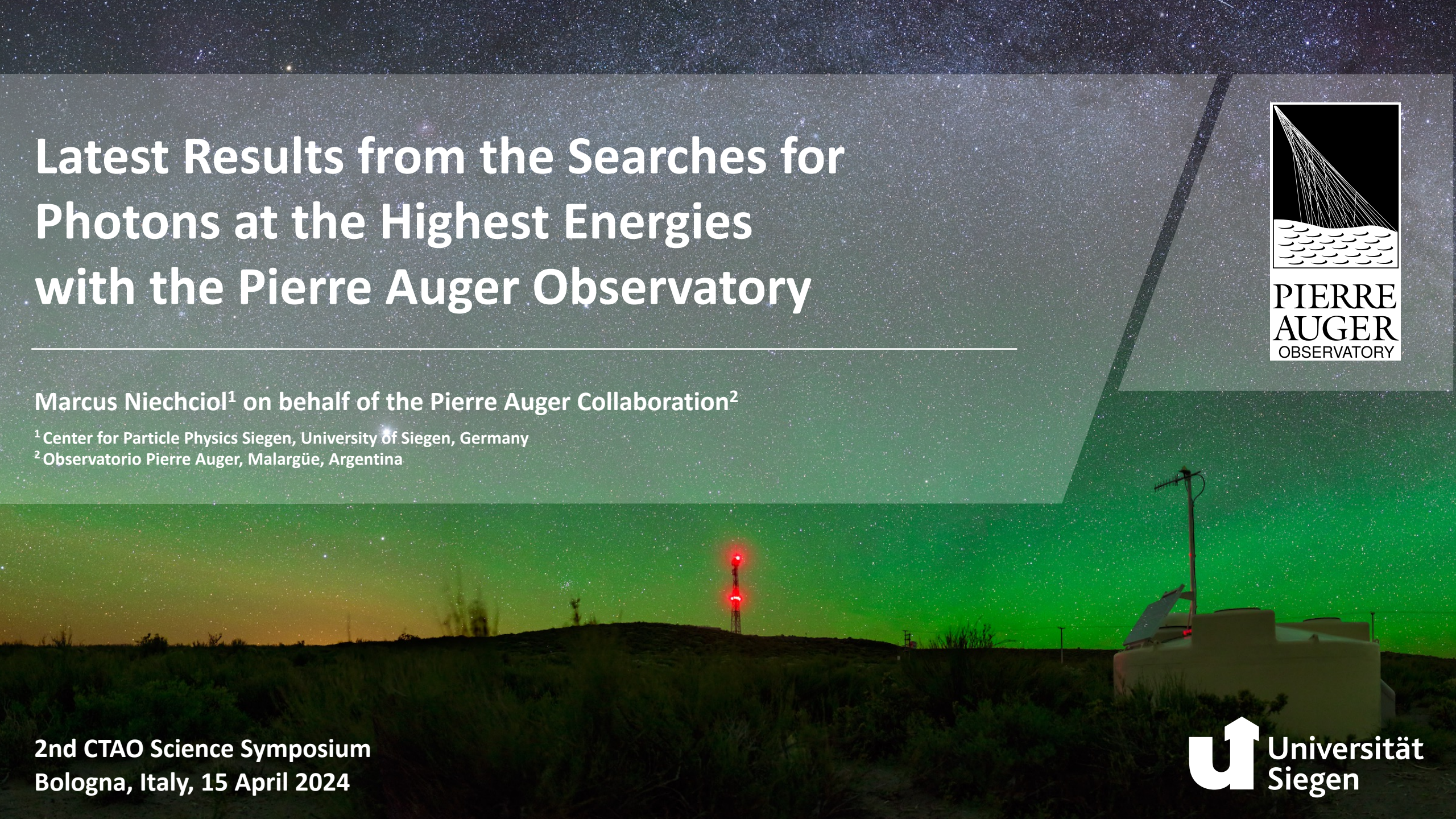

2nd CTAO Science Symposium
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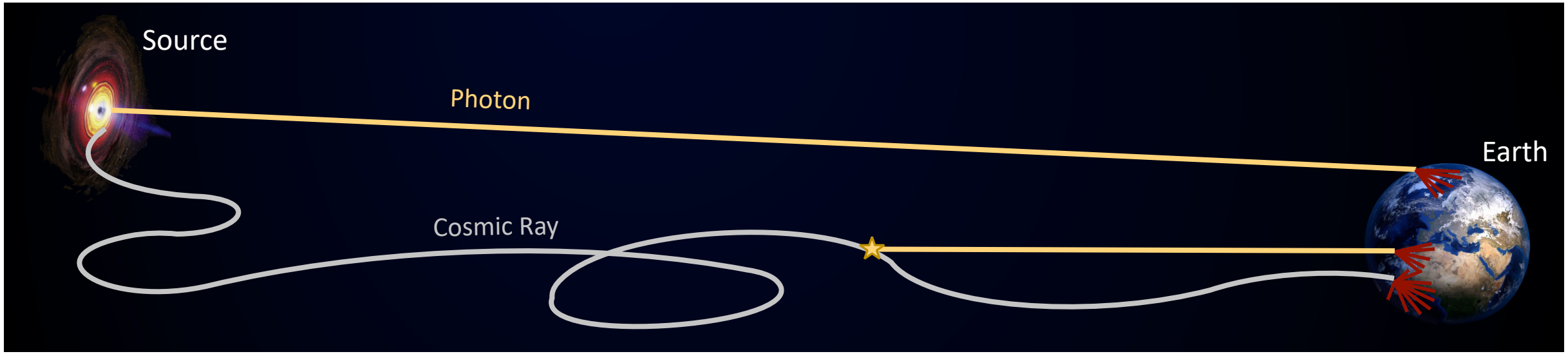
PIERRE AUGER OBSERVATORY

Universität Siegen

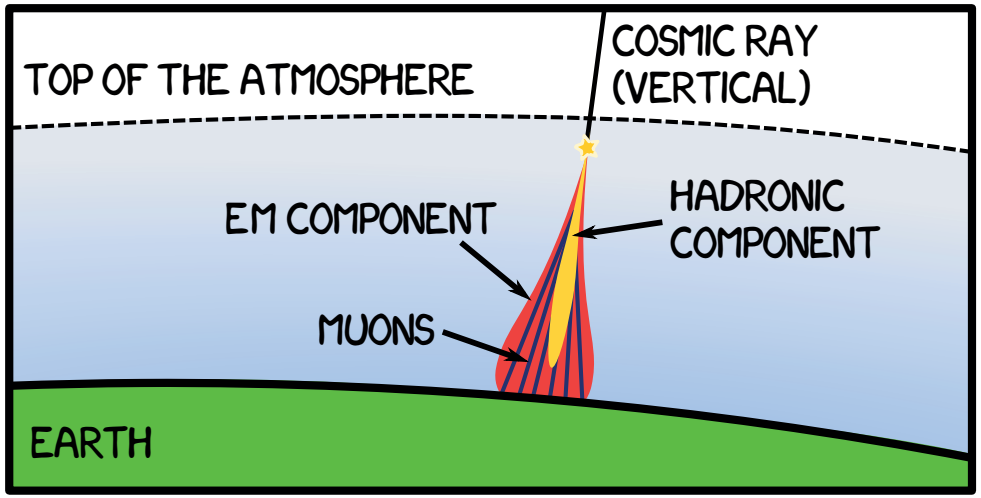
Why Search for UHE Photons?

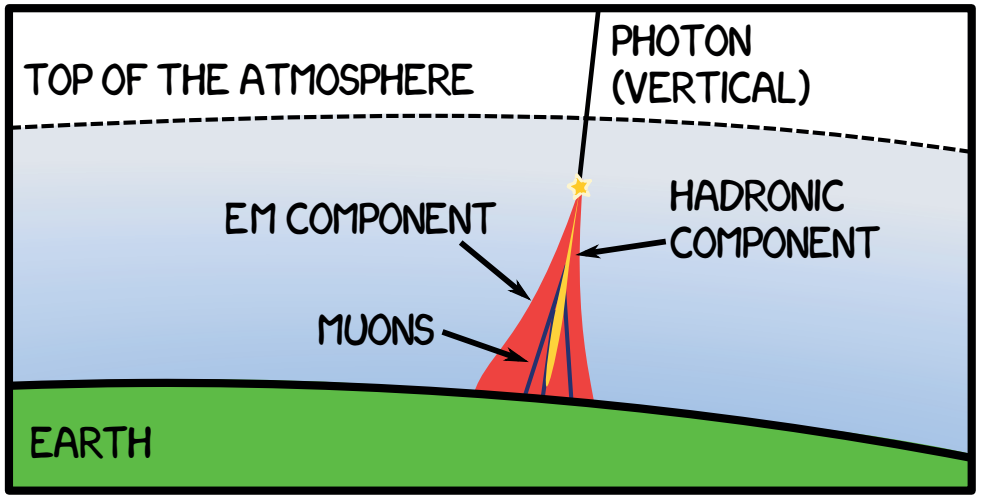
- Photons play a **crucial role** for **multimessenger astronomy** at ultra-high energies (UHE, $E \gtrsim 10^{17}$ eV)
  - One of the **main goals**: understanding where and how UHE cosmic rays (UHECRs) are produced
  - **Intimate connection** between UHE photons and UHECRs
    - Can be produced either directly at the sources of UHECRs or during their propagation through the Universe, for example in interactions with the CMB



How to Identify UHE Photons?

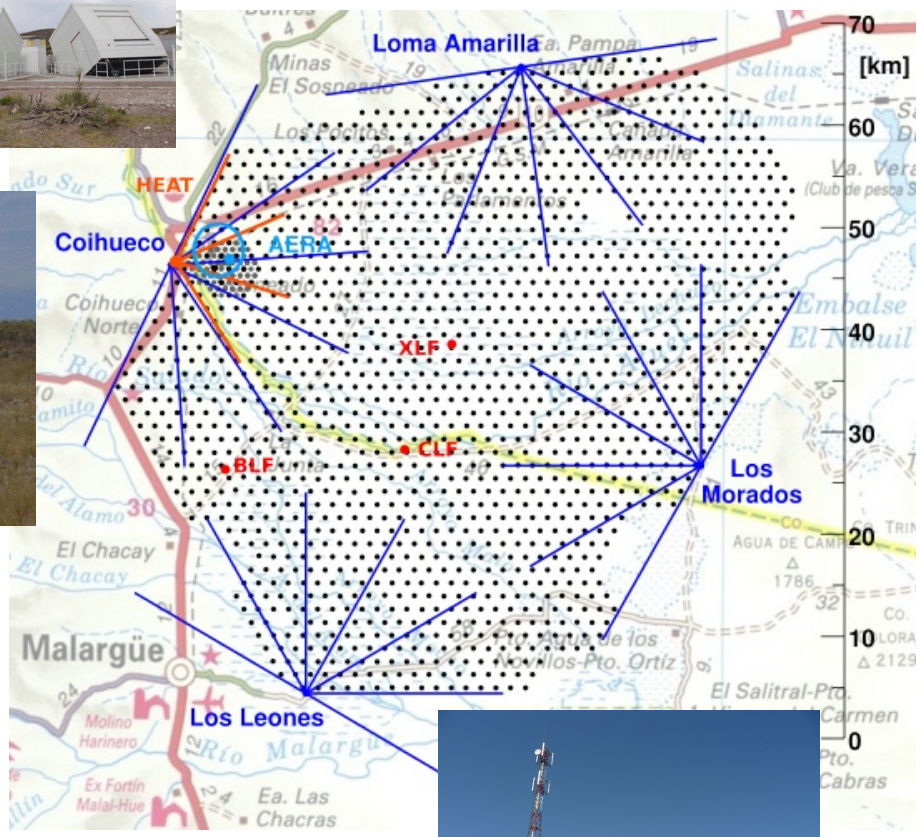
- Photons entering the Earth's atmosphere can **initiate extensive air showers**, just like charged cosmic rays – making indirect detection possible
  - **Main challenge**: distinguishing photon-induced air showers from the **vast background** of showers initiated by cosmic protons and heavier nuclei
  - **In a nutshell:** Searching for UHE photons means looking for **deeper (vertical) showers with fewer muons**





Pierre Auger Observatory

- Located near **Malargüe, Argentina**
- **Surface detector array (SD)**
  - ~1660 water Cherenkov detectors (WCDs) covering a total area of ~3000 km^2
  - Measuring **secondary particles on ground**
- **Fluorescence detector (FD)**
  - 4 stations with 27 telescopes, overlooking the SD
  - Measuring the **longitudinal development** in the atmosphere
- **Additional detector systems** complementing the main SD and FD (e.g., radio antennas, underground muon detectors…)



[Pierre Auger Coll., NIM A 798 (2015) 172]

Searching for Photons at the Pierre Auger Observatory

[Pierre Auger Coll., Universe 8 (2022) 579]

- Searches for a **diffuse (i.e., direction-independent, unresolved)** flux of photons
  - Different energy ranges using data from different detector systems: [P. Savina (Pierre Auger Coll.), PoS (ICRC 2021) 373]
    - Above 10^{19} eV: 1500 m SD array [Pierre Auger Coll., JCAP 05 (2023) 021]
    - 10^{18} to 10^{19} eV: FD + 1500 m SD array (hybrid data) [P. Savina (Pierre Auger Coll.), PoS (ICRC 2021) 373]
    - 2×10^{17} to 10^{18} eV: HEAT/Coihueco + 750 m SD array (hybrid data) [Pierre Auger Coll., ApJ 933 (2022) 125]
    - Below 2×10^{17} eV (down to tens of PeV): 433 m SD array + UMD; preliminary results shown at the last ICRC

[N. González (Pierre Auger Coll.), PoS (ICRC 2023) 238]

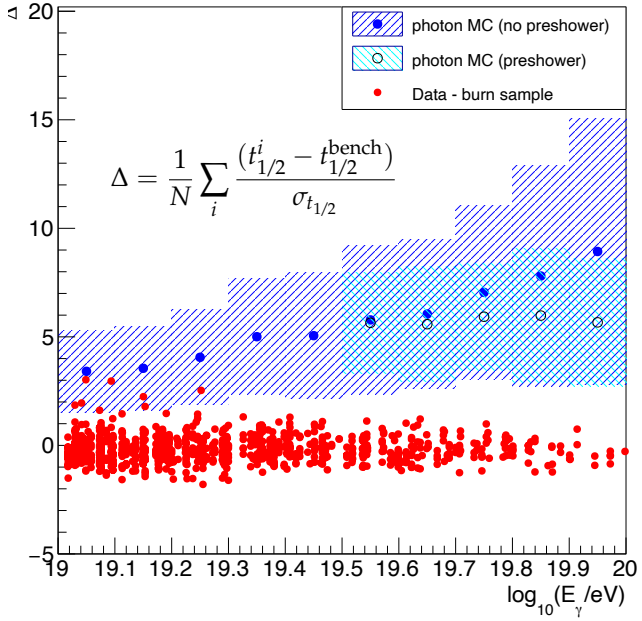
- Searches for **point sources** of photons
  - **Blind search** covering the full field of view [Pierre Auger Coll., ApJ 789 (2014) 160]
  - **Targeted search** involving different classes of potential sources [Pierre Auger Coll., ApJL 837 (2017) L25]

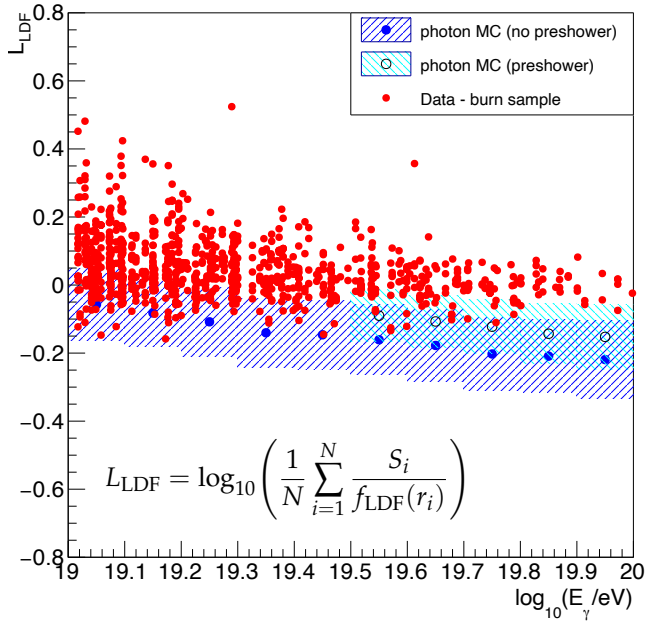
- **Follow-up search** for UHE photons in coincidence with gravitational-wave events

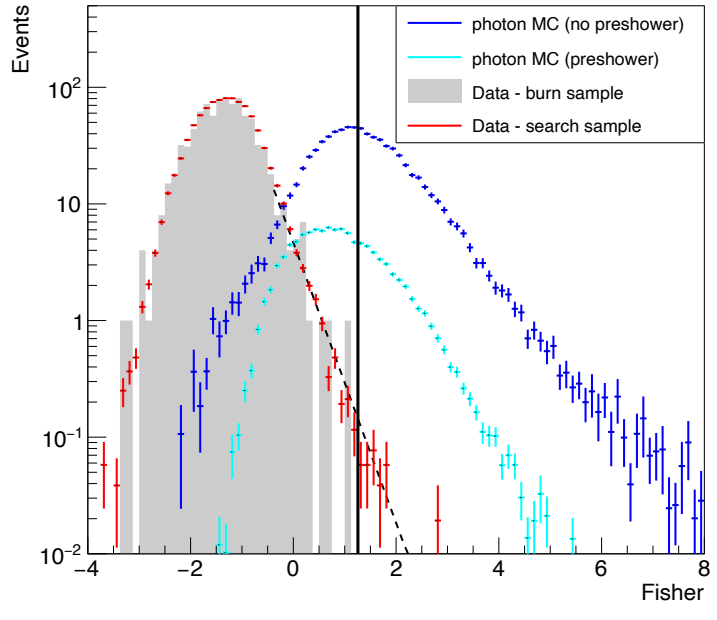
[Pierre Auger Coll., ApJ 952 (2023) 91]

Search for Photons above 10^{19} eV

- Analysis uses **two observables**, both based on ”benchmarks” obtained from data
  - **No assumptions** needed on the cosmic-ray composition
  - Combination in a **Fisher analysis** trained with photon simulations and a fraction of the data sample
- **Data period:** 01/2004 – 06/2020, exposure: ~17000 km^2 sr yr
- **16 events pass the candidate cut**, consistent with the background expectation

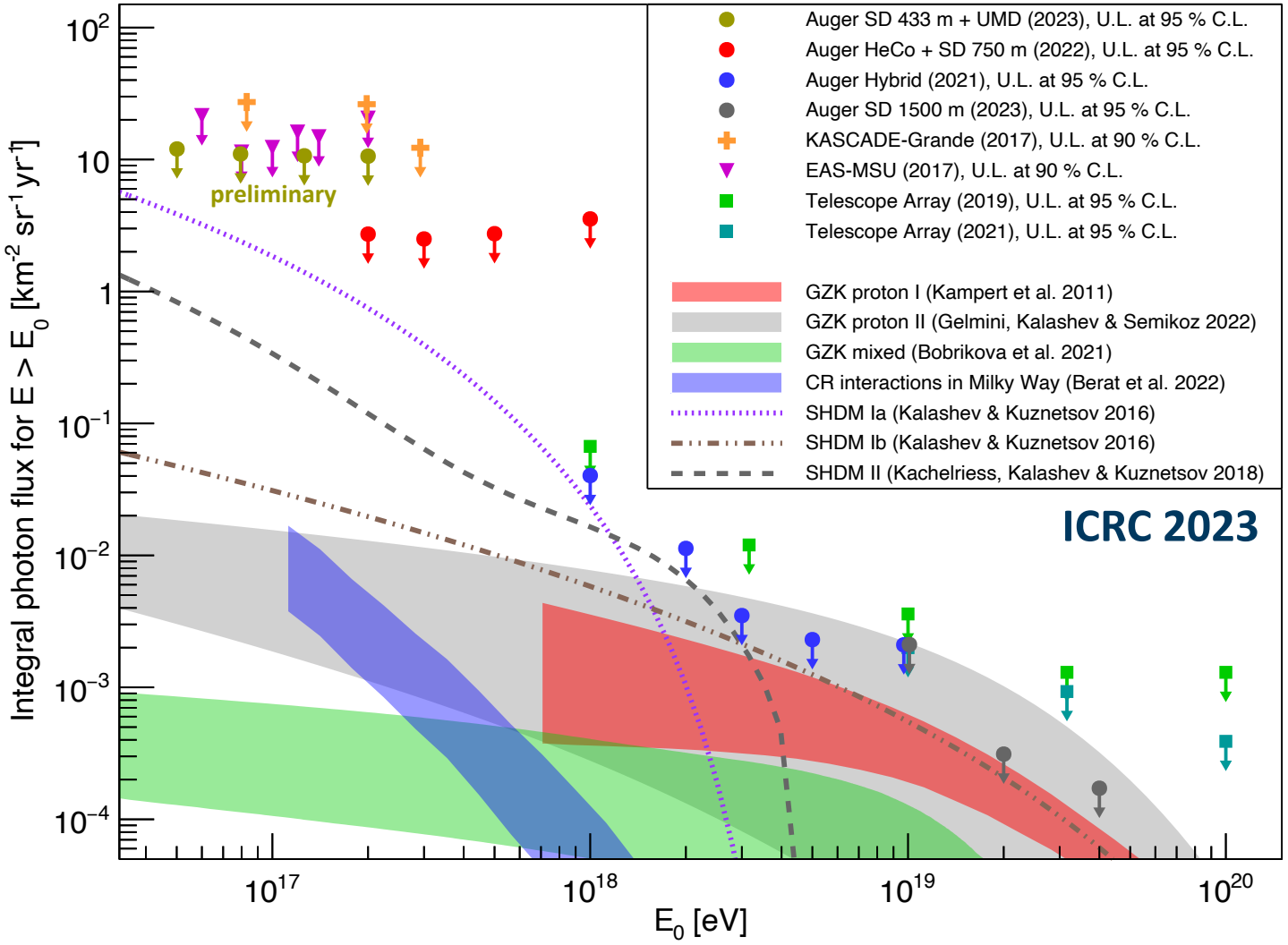






[Pierre Auger Coll., JCAP 05 (2023) 021]

Upper Limits on the Diffuse Flux of UHE Photons



[M. Niechciol (Pierre Auger Coll.), PoS (ICRC 2023) 1488]

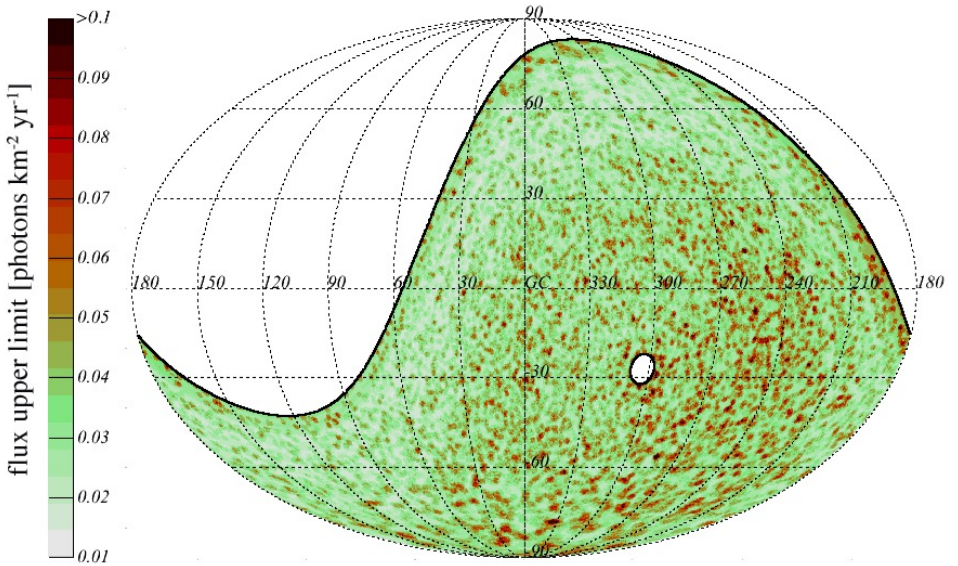
- **No primary UHE photon** could be unambiguously identified so far
- **Most stringent limits** on the diffuse flux of photons over a wide energy range come from Auger
- Predictions of some **theoretical models** (e.g., involving GZK interactions) are within reach
- Limits also useful to constrain BSM models involving **SHDM particles**

[Pierre Auger Coll., PRL 130 (2023) 061001]
[Pierre Auger Coll., PRD 107 (2023) 042002]

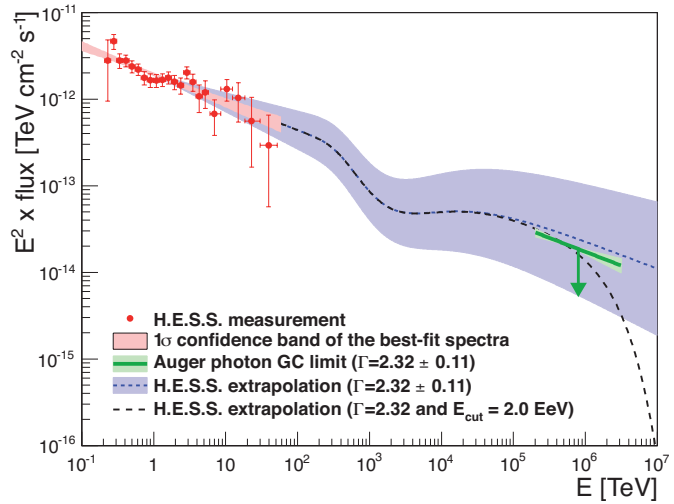
Searches for Point Sources of UHE Photons

- Search for an **excess of photon-like events** from any direction in the (visible) sky
  - Energy range $10^{17.3}$ eV to $10^{18.5}$ eV, data period 01/2005 to 09/2011, declination range -85° and +20°
  - **No evidence** for such an excess from any direction
- Reduce the statistical penalty by **restricting the analysis to specific classes** of potential (mostly galactic) sources only
  - **No compelling evidence** for photon-emitting sources in the EeV range
  - Upper limit on the flux useful to constrain the extrapolation of **H.E.S.S. measurements of the galactic center region**

[H.E.S.S. Coll., Nature 531 (2016) 476]



[Pierre Auger Coll., ApJ 789 (2014) 160]

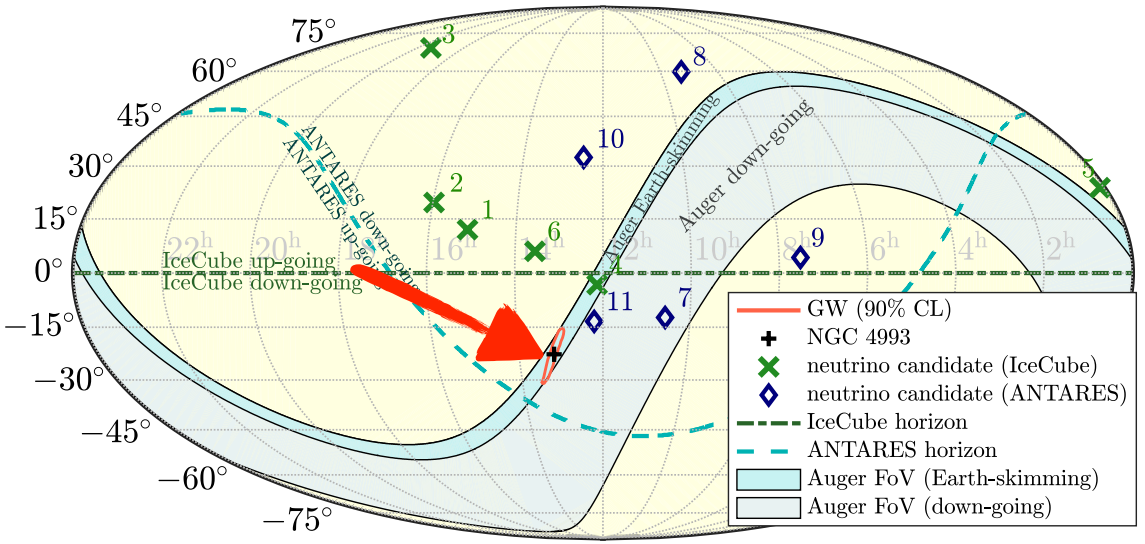


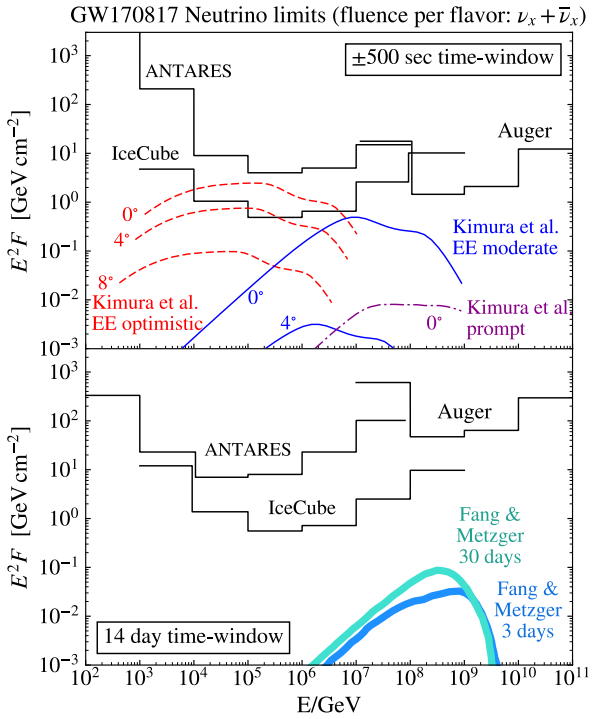
[Pierre Auger Coll., ApJL 837 (2017) L25]

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) by reacting to the corresponding **alerts**
- One example: **GW170817 neutrino follow-up** (BNS merger)

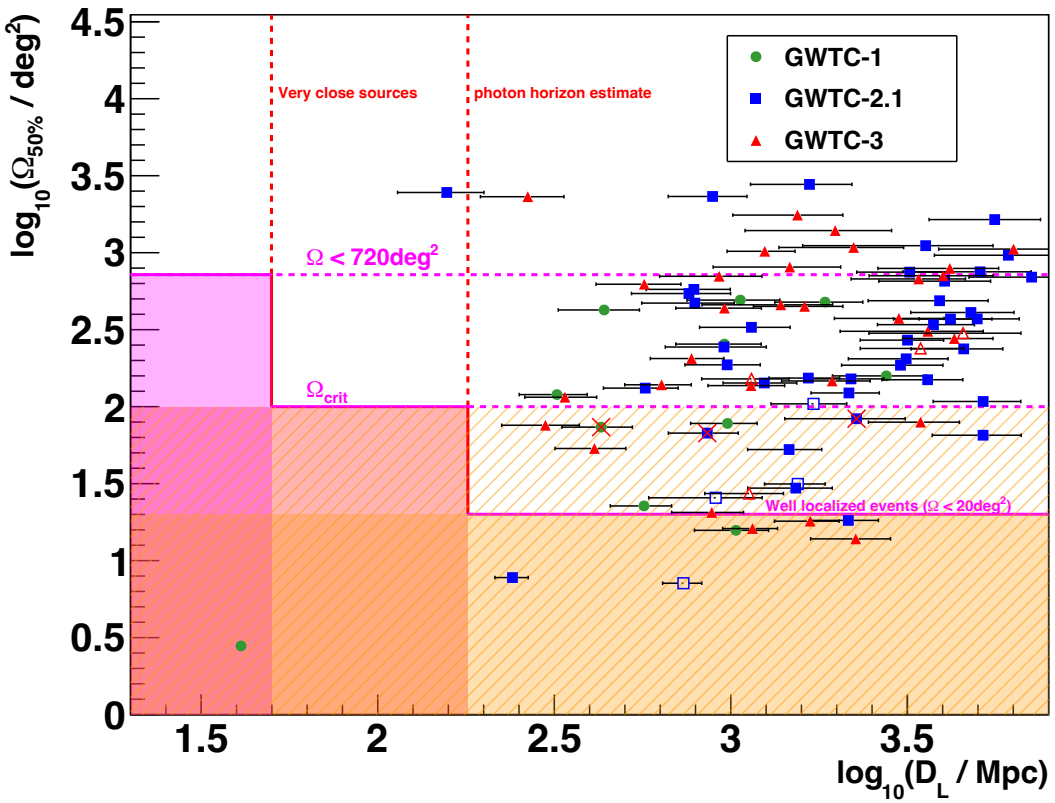
[Antares, IceCube, Pierre Auger, Ligo Scientific and Virgo Colls., ApJL 850 (2017) L35]





Follow-Up Search for UHE Photons

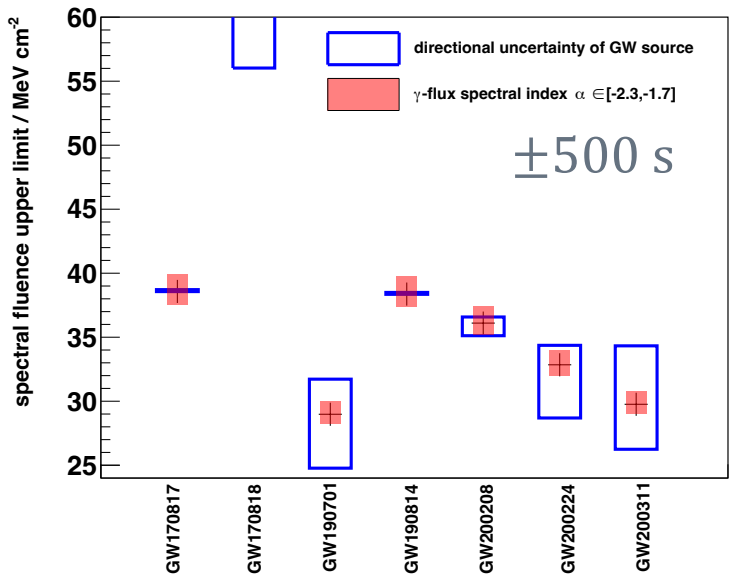
- Search for UHE photons with energies above 10^{19} eV in **coincidence with GW events**
- Use **data from the 1500 m SD array**, same observables as in the standard analysis
- Background has to be taken into account: **only follow up selected GW events** to reduce the rate of false-positive detections
- Focus on **close and/or well-localized GW events** measured by LIGO/Virgo
  - Selection also includes whether an event (region) was inside the Auger FoV during one of the **two search windows** (± 500 s and $+1$ day around the time of the event)

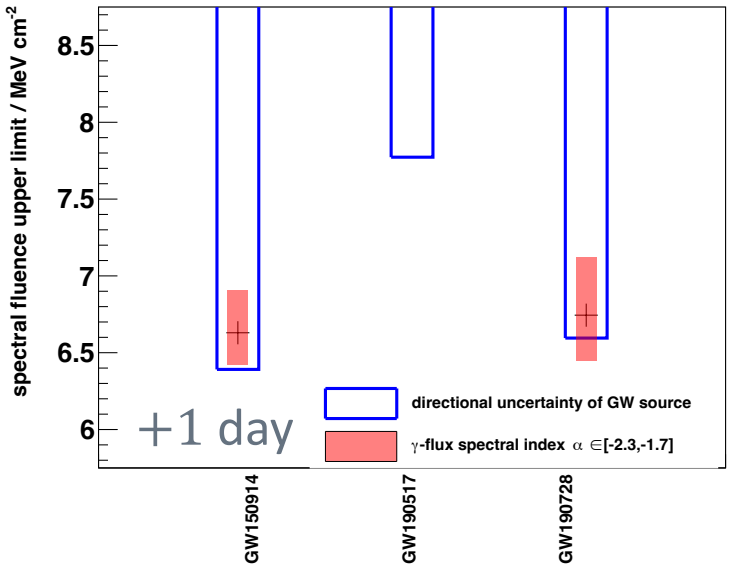


[Pierre Auger Coll., ApJ 952 (2023) 91]

Follow-Up Search for UHE Photons

- **10 GW events** from GWTCs 1, 2.1 and 3 passed the selection and were followed up
- **No coincident photons** were identified for any of the 10 selected GW events: determine upper limits on the spectral fluence
  - Closer look at **GW170817**: energy transferred into UHE photons above 40 EeV constrained to be less than 20% of its total energy





[Pierre Auger Coll., ApJ 952 (2023) 91]

AugerPrime: Upgrade of the Pierre Auger Observatory

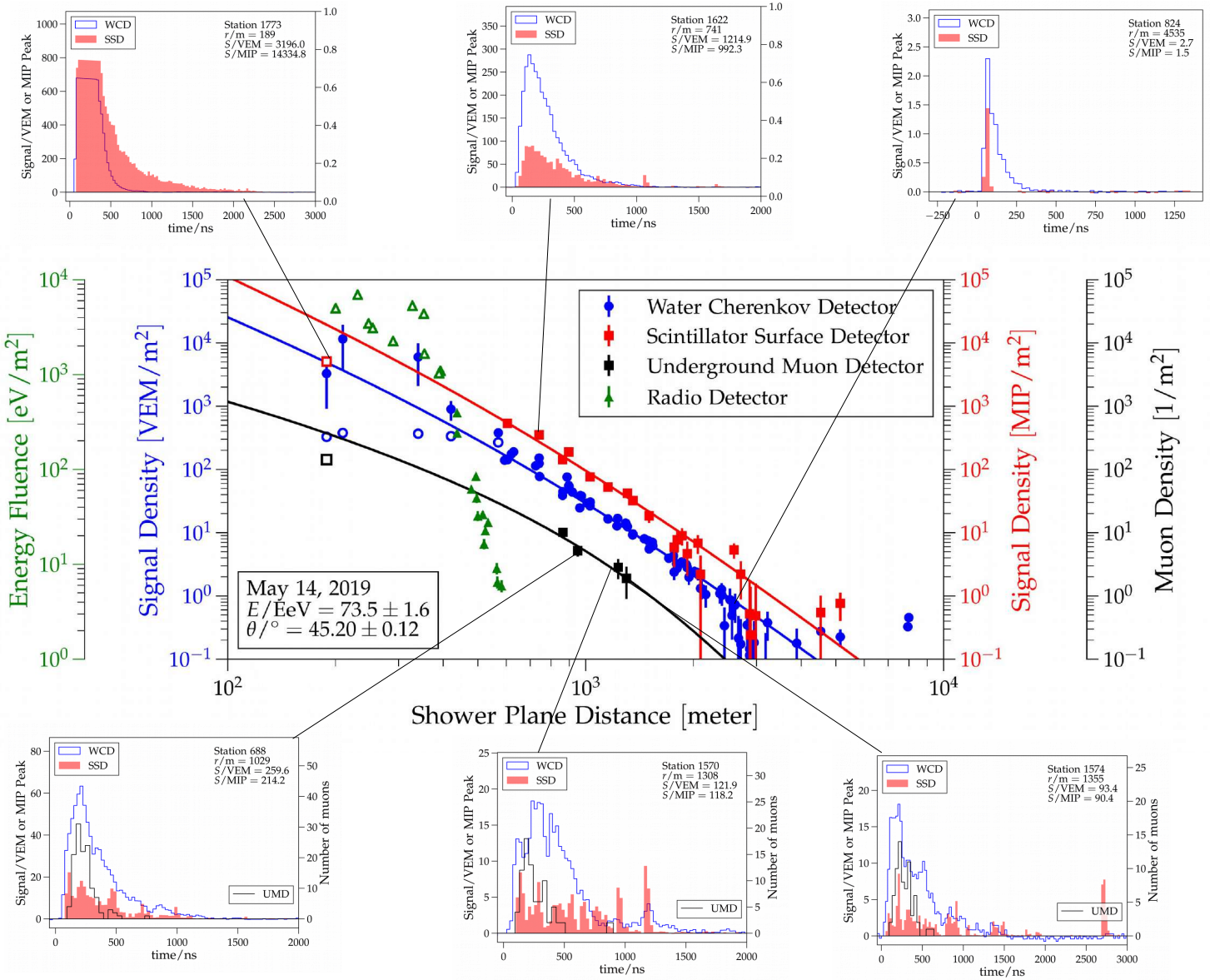
- **Main components** of the upgrade:
  - **Modify existing WCDs**: improved electronics, additional small PMT...
  - **Add new detectors:** scintillation detector (SSD) on top of every WCD, radio antennas (RD)…
- Goal: **increase composition sensitivity** (including sensitivity to UHE photons) through multi-hybrid measurements
  - **Example:** WCDs are more sensitive to muons, SSD more sensitive to electrons/photons; combine measurements from both to better disentangle the different shower components
- **Phase II of the Pierre Auger Observatory**: take data with the upgraded detector systems until 2035 (at least)

Summary

- 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

Appendix

Multi-Hybrid Measurements of Air Showers



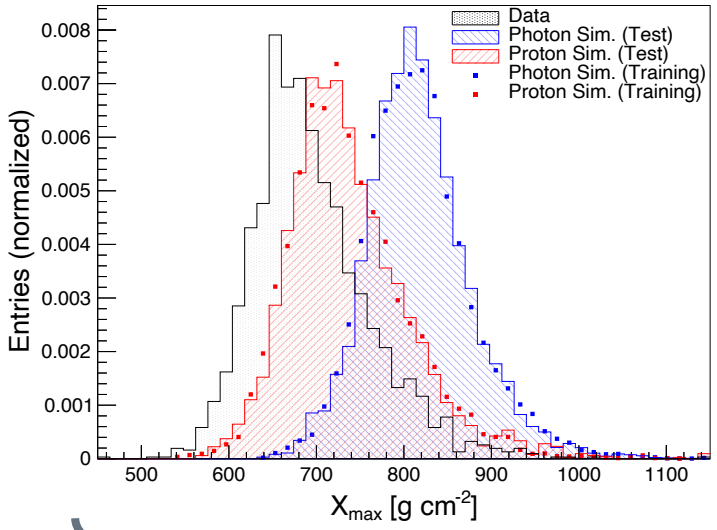
“Phase II” of Auger

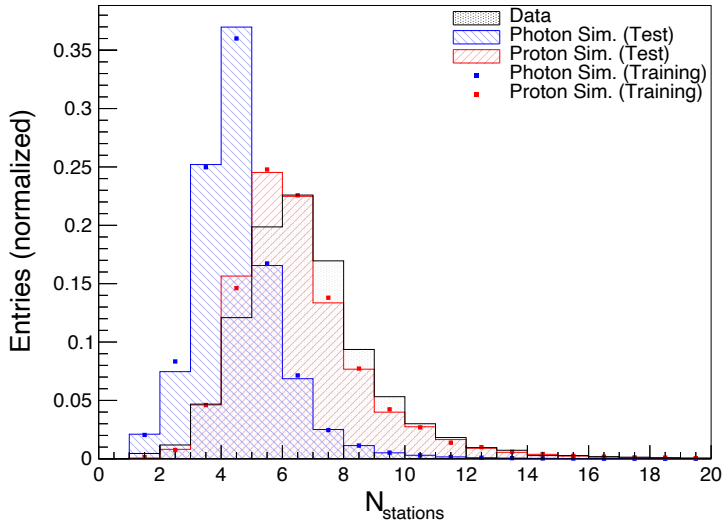
- Data taking 2022/2023 – 2035
- Collected exposure after 8 years for $\theta < 60°$: 40,000 km^2 yr sr (”Phase I”: 80,000 km^2 yr sr)
- Re-analysis of the ”old” data set using machine learning

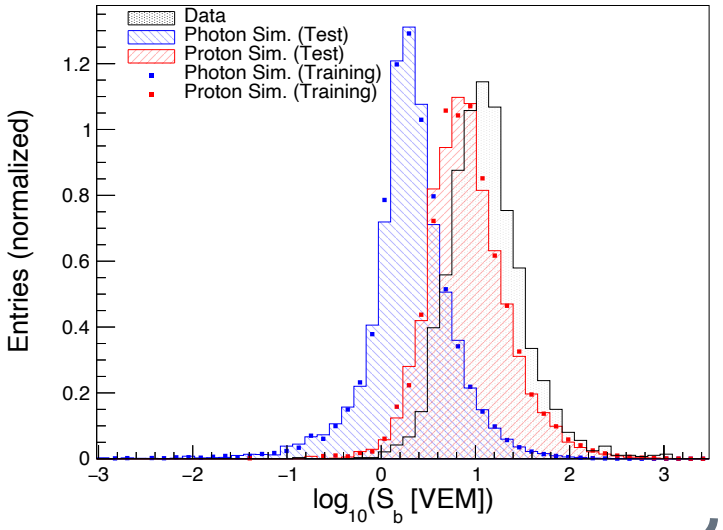
Search for photons between 2×10^{17} and 10^{18} eV

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

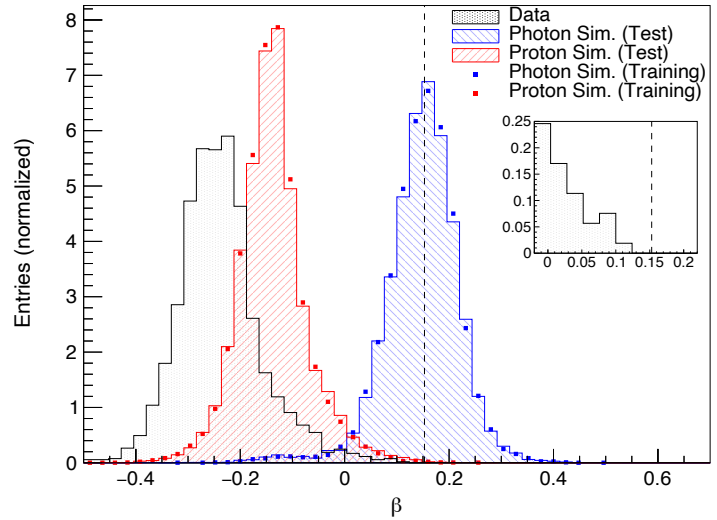
Observables







MVA (BDT)

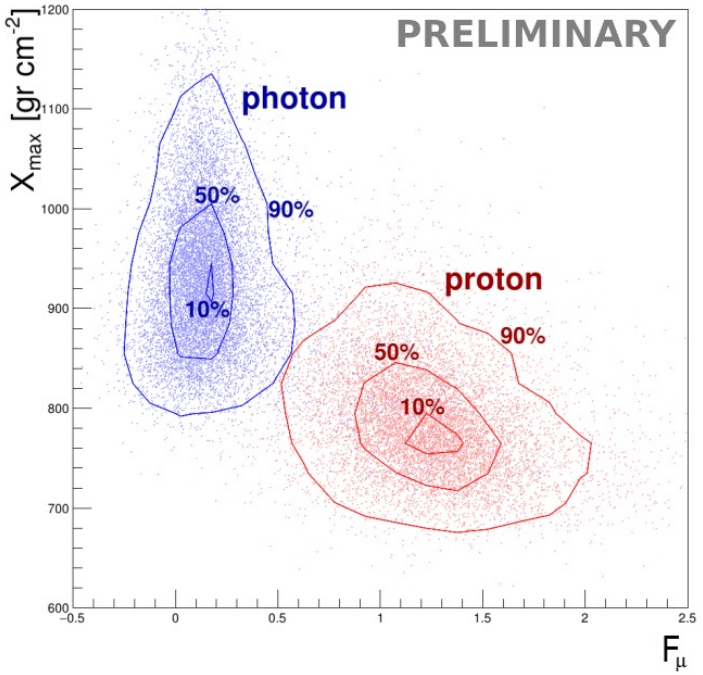


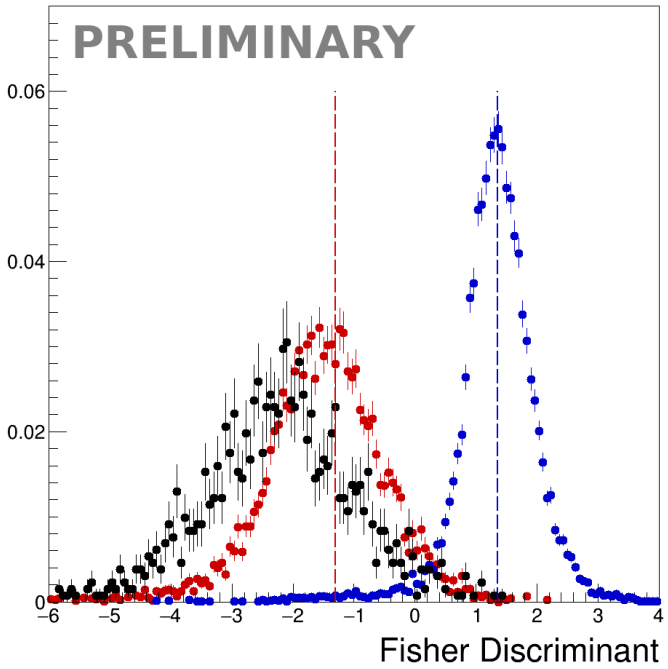
- **Photon candidate cut** chosen to ensure 50 % signal efficiency, leading to ~99.9 % background rejection
- **Data period:** 1 Jun 2010 – 31 Dec 2015
- **Exposure** to photons (from simulations): ~2.5 km^2 sr yr
- **No events** pass the candidate cut

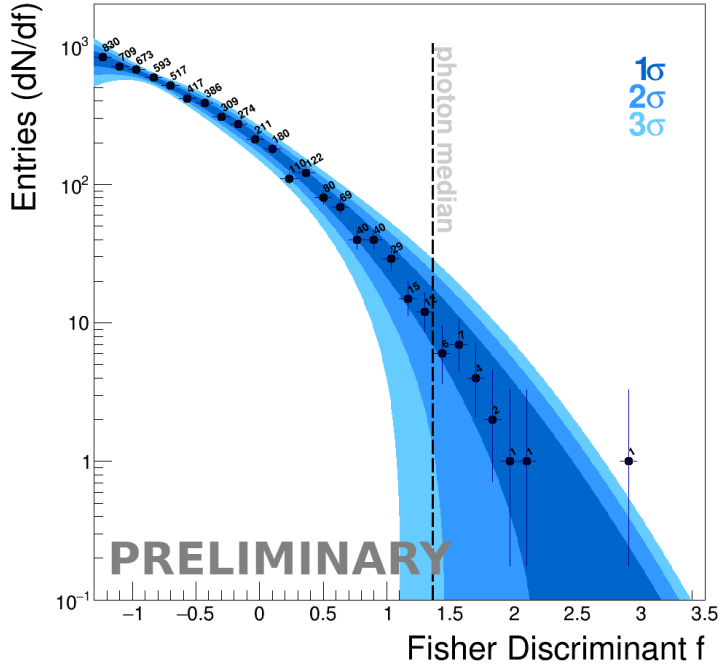
[Pierre Auger Coll., ApJ 933 (2022) 125]

Search for photons between 10^{18} and 10^{19} eV

- The **observable F_μ** is used as a proxy for the muon content calculated using a model based on **air-shower universality**
- Overall background rejection ~99.9 %
- **Data period:** 1 Jan 2005 – 31 Dec 2017; ~1000 km^2 sr yr







- **22 candidate events**, consistent with the expectation of 30±15, estimated using data