Are There Photons Among **U**ltra-**H**igh-**E**nergy **C**osmic **R**ays?

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N01/NZ15
Seminarium dla Młodych
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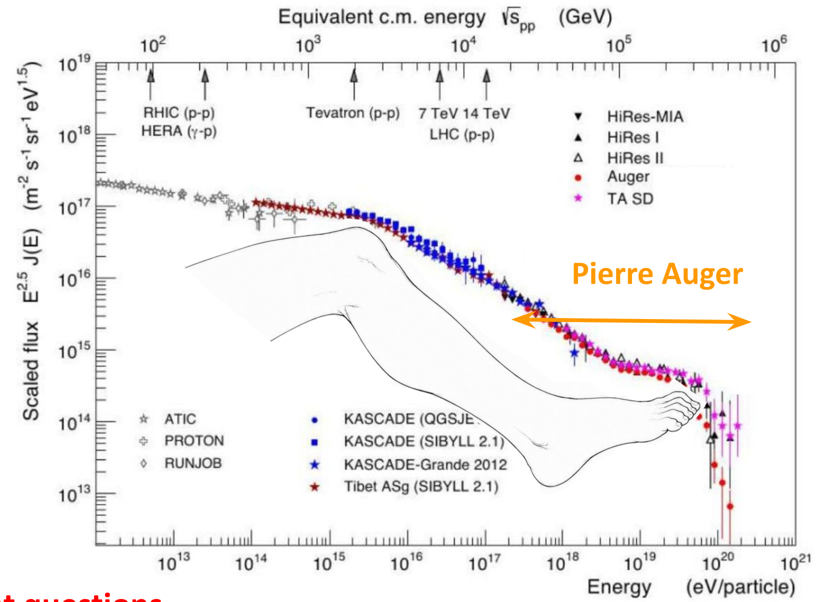
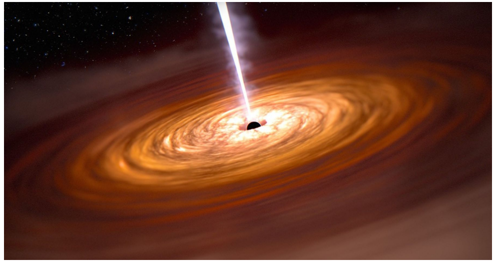
What are Cosmic Rays?

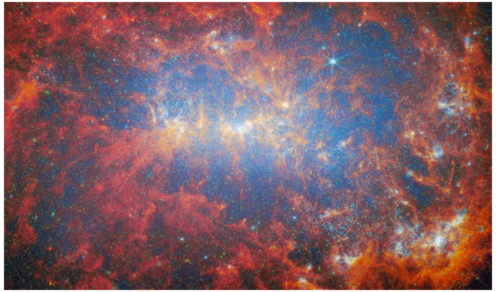
Cosmic rays, are **highly energetic particles**, like protons, heavier nucleons, leptons, or neutral particles, etc, coming from space.



Some of the possible sources of Ultra-High-Energy Cosmic Rays (UHECRs), E ≥ 10^{17} eV



Active Galactic Nuclei
Credit: NASA/ESA/CSA, Joseph Olmsted (STScI)



Starburst Galaxy
Credit: NASA/ESA/CSA James Webb Space Telescope

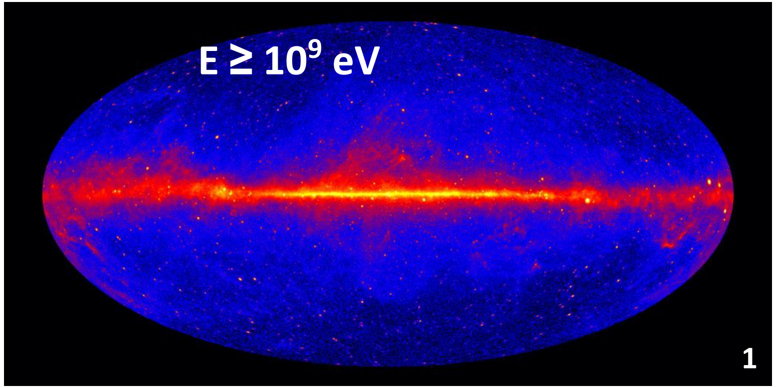
Hot questions -

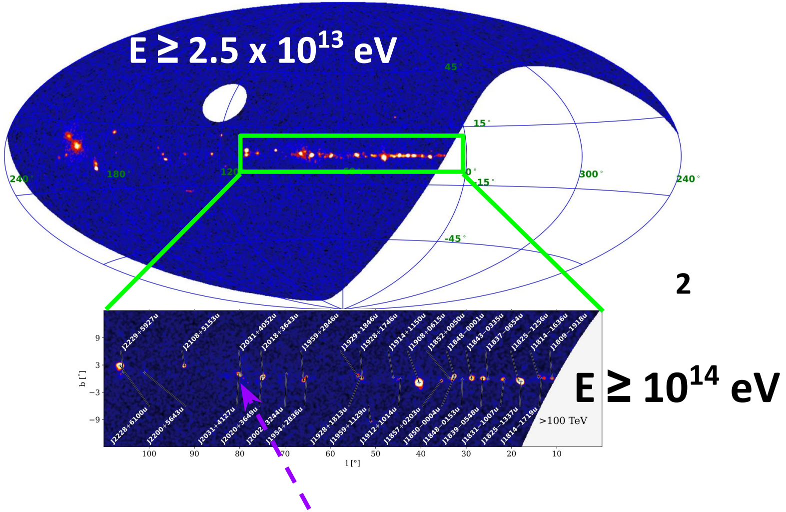
- **Anisotropy in arrival directions**
- **Features of the energy spectrum at extreme energies**
- **Particle composition**
- **Are photons or neutrinos a part of UHECRs?**

Origin of UHE photons

- Acceleration sites (**astrophysical**)
  - Particle jets - steady or **transient (flare)**
  - Fermi acceleration
  - Magnetic Reconnection
  - …
- Produced during CR propagation (**cosmogenic**)
  - UHE charged particles interacting with **Cosmic Microwave Background** photons (~10^{-4} eV) - **Greisen-Zatsepin-Kuzmin (GZK)** effect
- Decay of metastable **Super-Heavy Dark Matter (SHDM)** particles
- …

Seeing the sky in high-energy light





1. 15 years of all-sky Fermi-Large Area Telescope gamma-ray map. Credit: [NASA/DOE/Fermi-LAT Collaboration]
2. 1st catalog of gamma-ray sources by Large High Altitude Air Shower Observatory (LHAASO). Credit: [ApJS 271 (2024) 25]

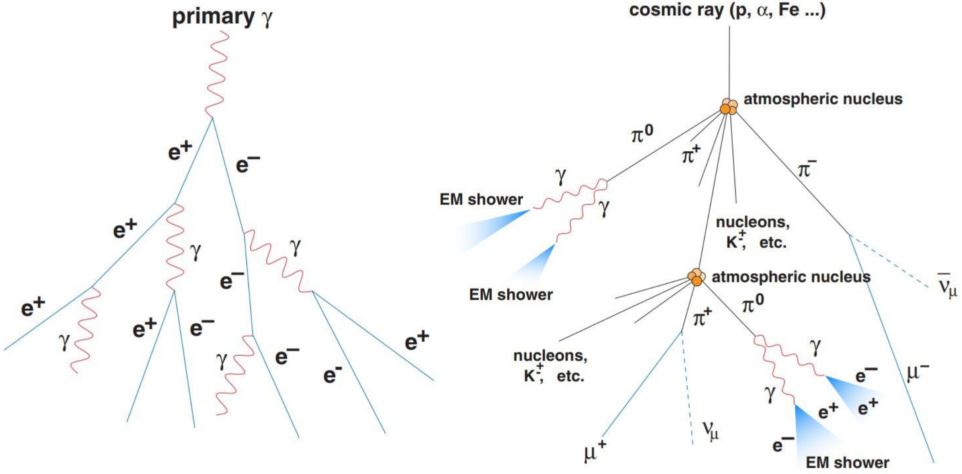
The highest energy of photons measured, E ~2.5 x 10^{15} eV

([Sci Bull, 69 (2024), pp. 449-457])

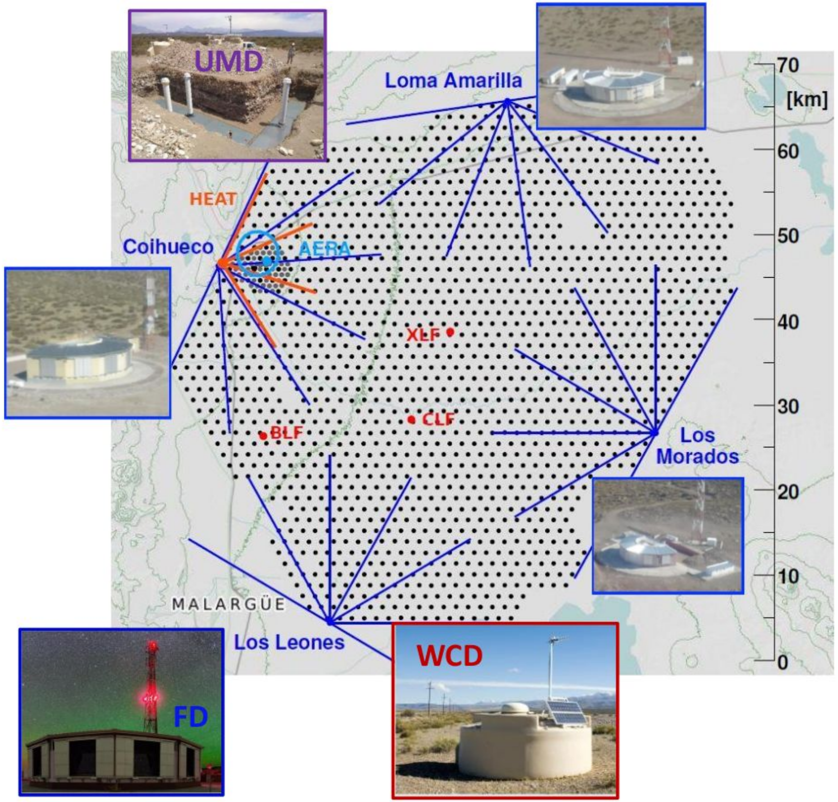
Can we see higher energy photons?

Detection of Cosmic Rays

- The flux of UHECRs falls down to **one per century per km^2**
- We detect cosmic rays from the ground, by detecting the **Extensive Air Showers –** particle cascade initiated by a **primary cosmic ray particle** interacting with the **atmosphere**
- The **lateral and longitudinal profiles** of the particle cascade depends on the **primary cosmic ray particle**
- The particle cascade produce **Cherenkov radiation**, as the particles travel *faster than the speed of light* in air



Pierre Auger Observatory
The largest observatory of UHE Cosmic Rays

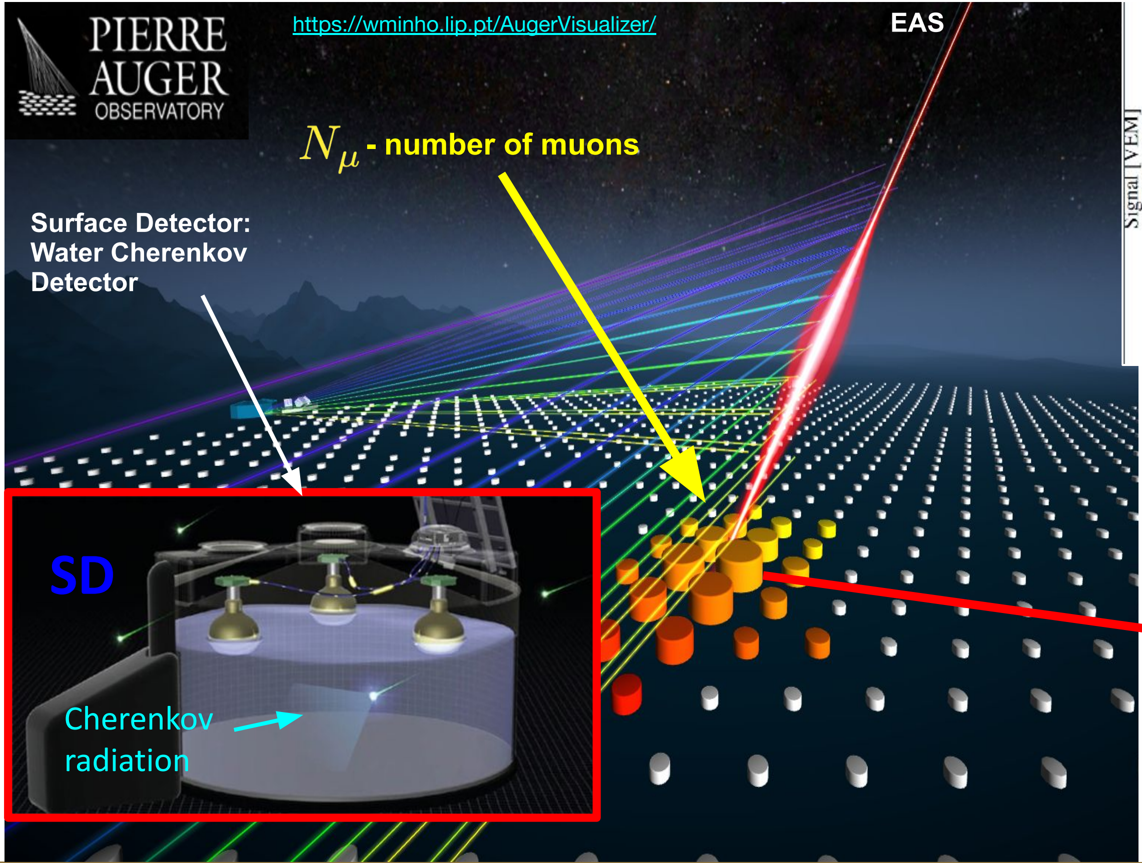


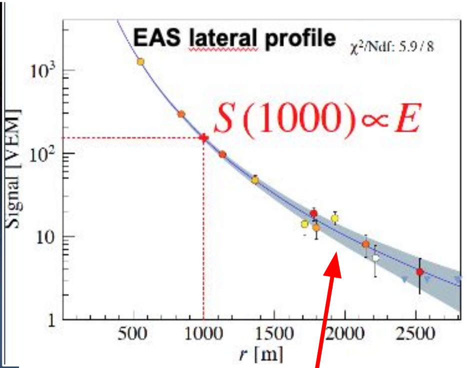
Multi hybrid detector
Phase I (2004-2023)
Phase II (2023-)

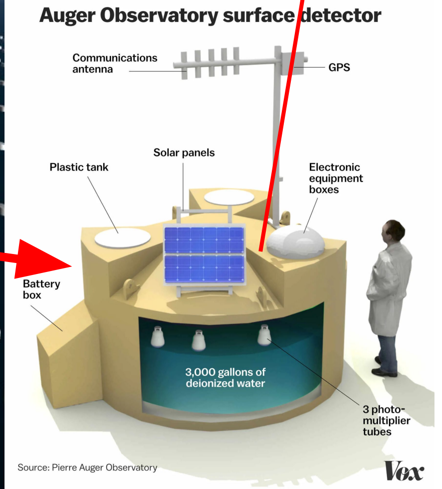
- **Surface Detector (SD)**
  - **Water-Cherenkov detectors (WCD)**
    - ~1600 stations, 1.5 km grid, **3000 km²**
    - 2 additional grids of 750 m and 433 m spacing
  - **Scintillator Surface Detector (SSD)**
  - **Radio Detector (RD)**
- **Fluorescence Detector (FD)**
  - 4 sites, 27 telescopes
- **Underground Muon Detector (UMD)**

\+ Atmospheric monitoring devices

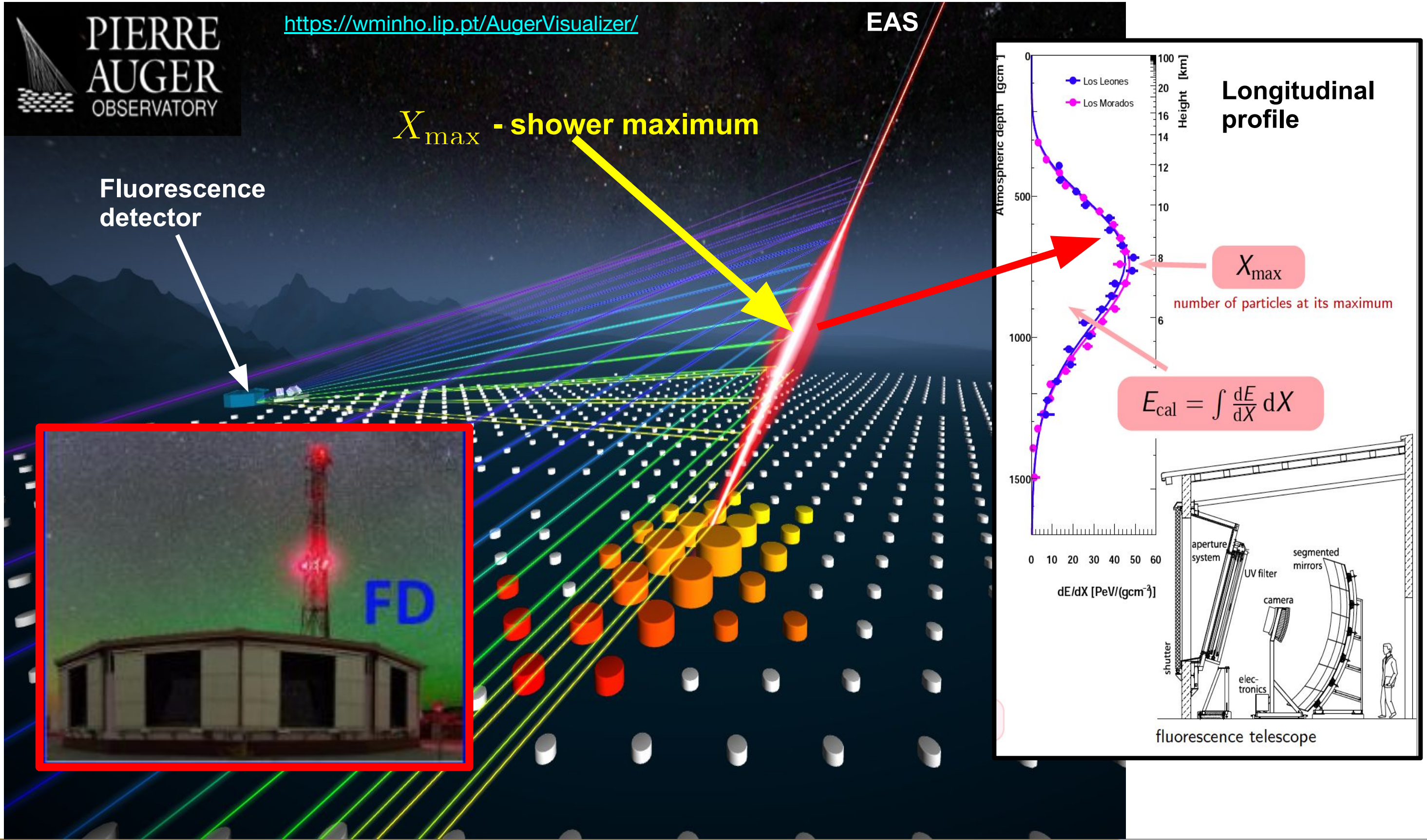
Detection with Pierre Auger







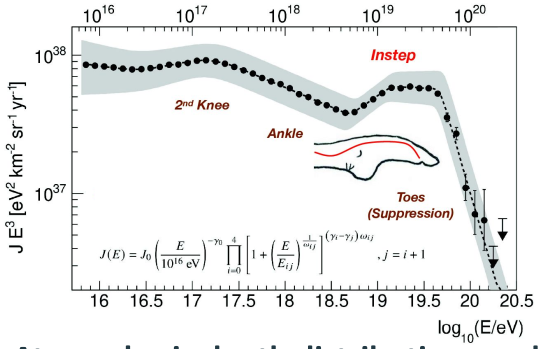
Detection with Pierre Auger



Pierre Auger: Main results Phase I (2004-2023)

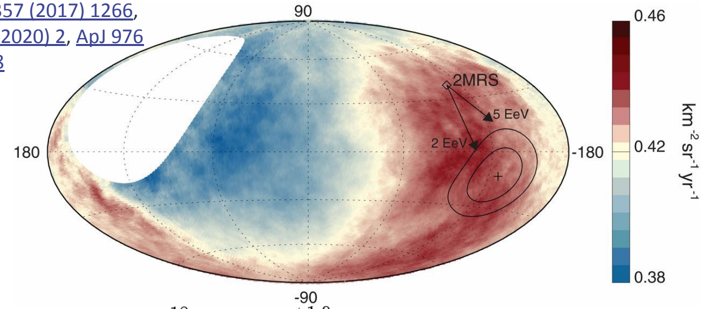
Energy Spectrum

PRD 125 (2020) 121106, PRD 102 (2020) 062005, Eur. Phys. J. C. 81 (2021) 966, ASR 72 (2023) 3531-3537



Large-scale Anisotropy above 8 x 10^{18} eV

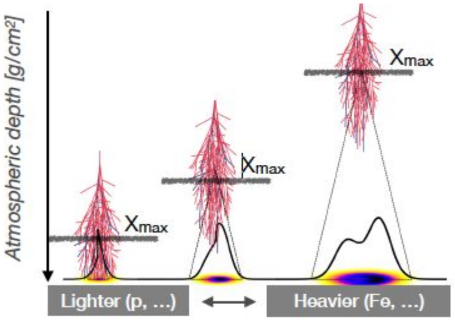
Science 357 (2017) 1266, ApJ 891 (2020) 2, ApJ 976 (2024) 48

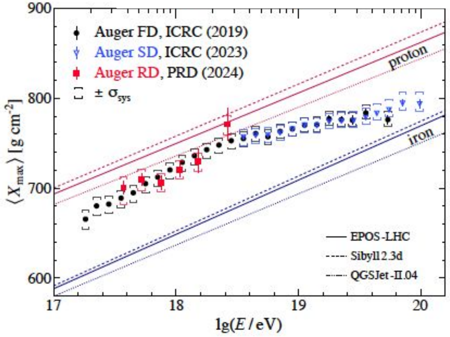


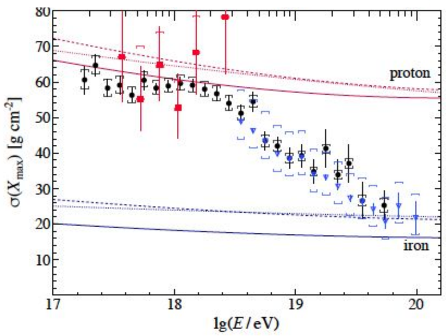
$$\mathrm{Amplitude}(E \geq 8 \times 10^{18} eV) : 7.4^{+1.0}_{-0.8}\%; 6.8\sigma_{stat}$$

Atmospheric depth distributions and shift in Mass composition at higher energies

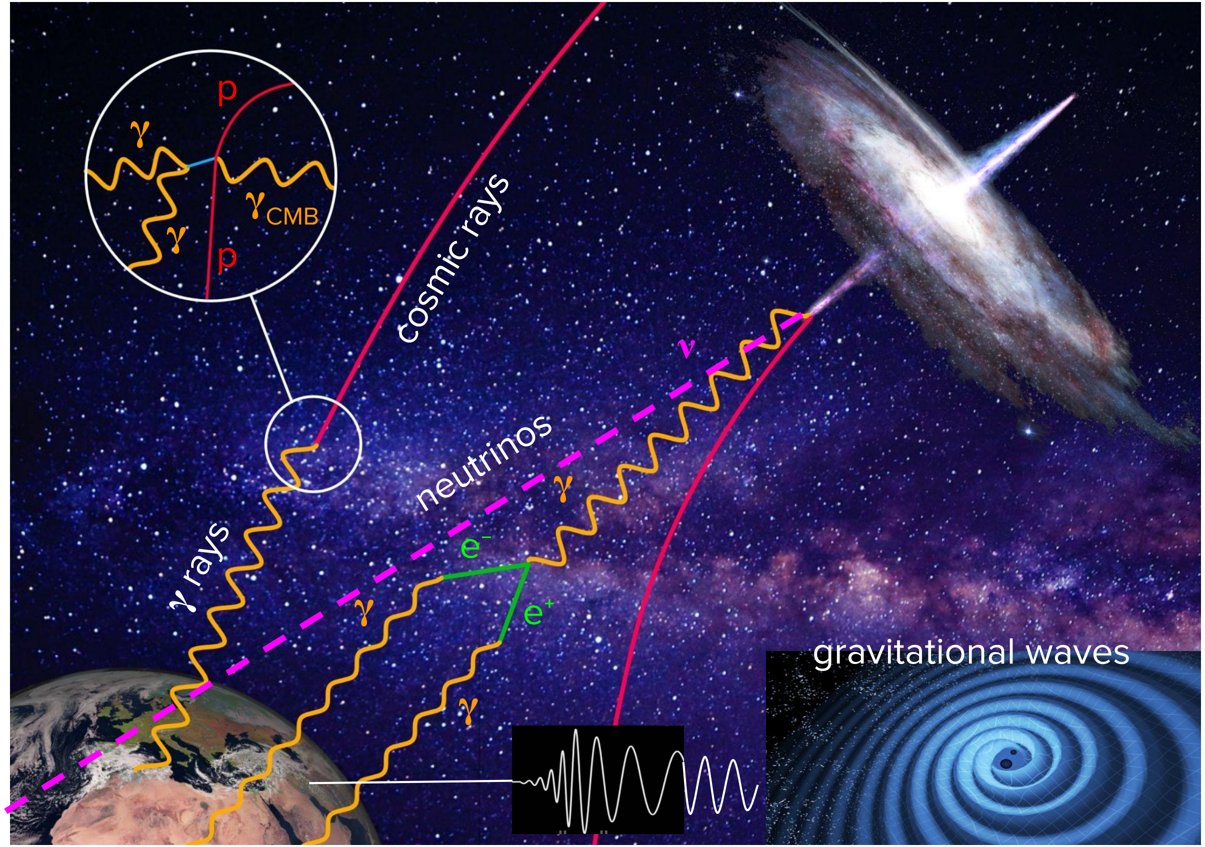
PRD 90 (2014) 122005, PRD 96 (2017) 122003, PRL 134 (2025) 021001







Multi-messenger Astronomy

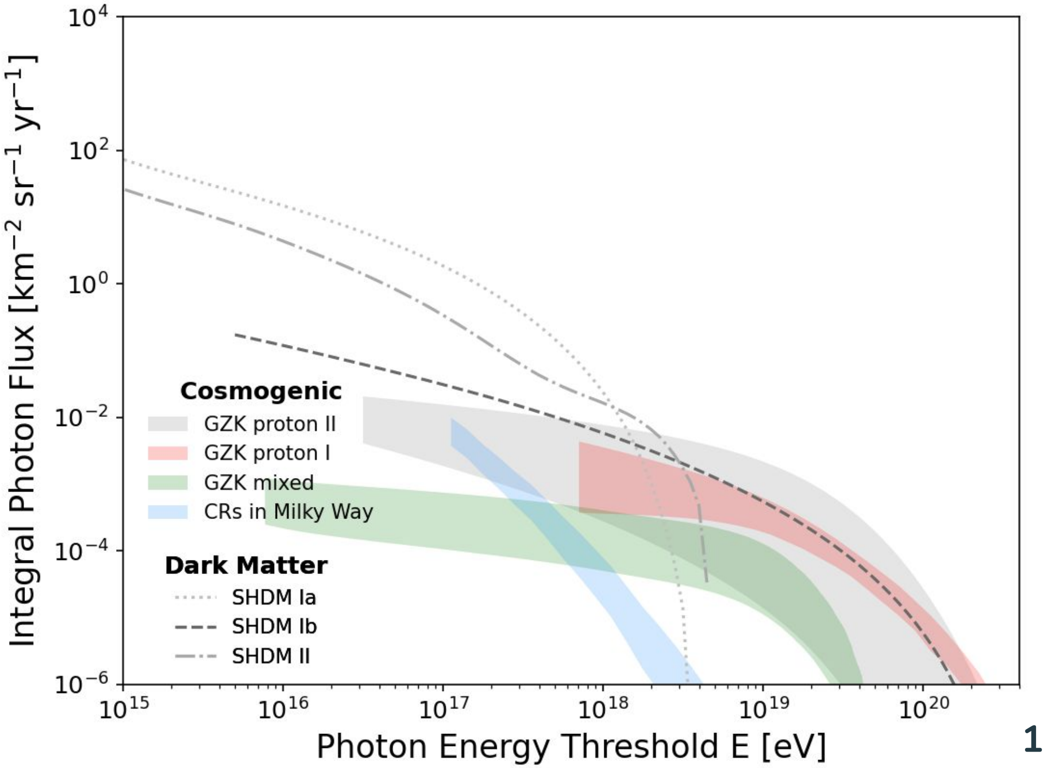


1. Electromagnetic radiation - photons
2. Cosmic Rays
3. Neutrinos
4. Gravitational Waves

Diffuse flux searches

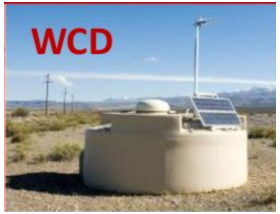
Theoretical predictions:

- **Cosmogenic** with different UHE mass compositions interacting with CMB photons - **GZK effect**
- Cosmic Rays interacting with **Galactic disk matter**
- **Super Heavy Dark Matter** models

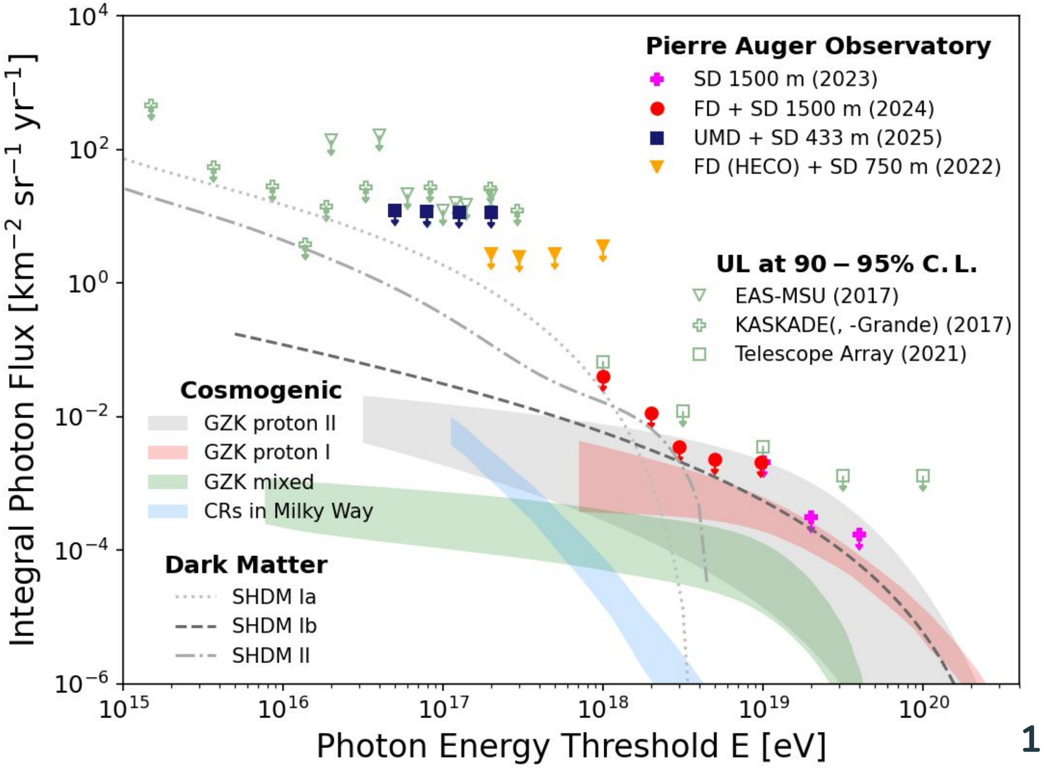


Diffuse flux searches

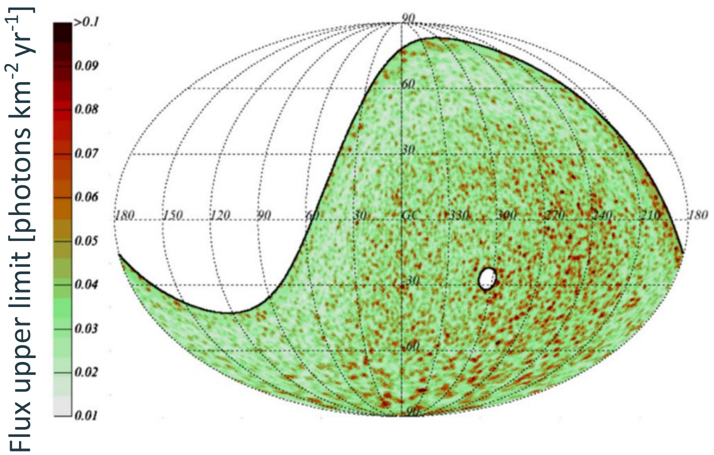
- **No photon candidates found**
- Super-Heavy Dark Matter models are **strongly constrained by Auger limits**
- Significant increase of exposure needed to constrain GZK proton scenarios



ApJ 933 (2022) 125, PRD 110 (2024) 062005, JCAP 05 (2023) 021, JCAP 05 (2025) 061



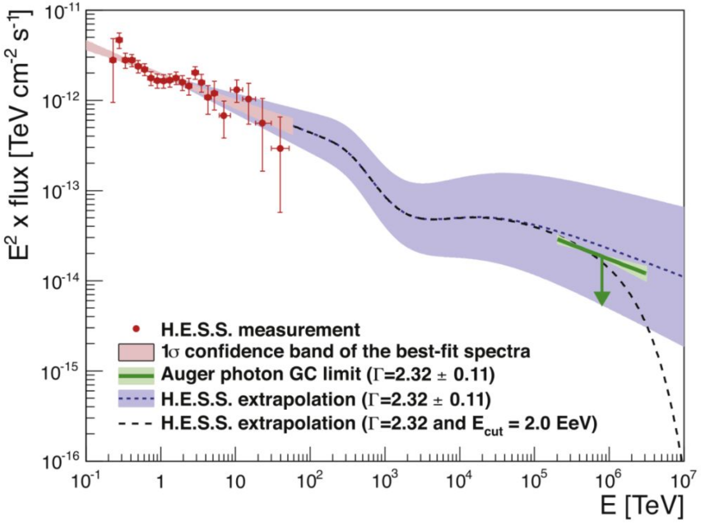
Direct searches: Blind and Targeted



Blind search of visible sky

2005 - 2011

(ApJ 789 (2014) 160)



Galactic Center

Targeted search of 364 sources

2005 - 2014

(ApJL 837 (2017) L25)

No photon candidates found

NZ15 group work: Direction-Time Clustering

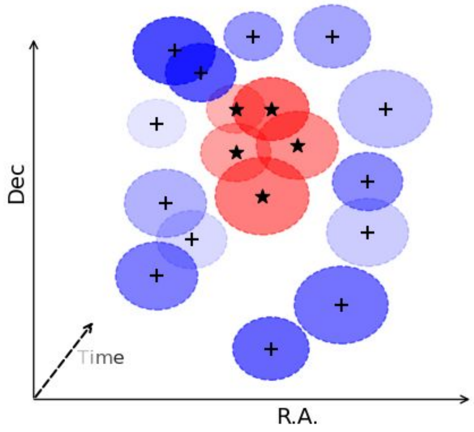
- Developed **unbinned likelihood methods** to search for clusters of UHE photons
- Validated the algorithm with **MC simulation** of signal events
- Performed preliminary search of sources of UHE photons with **real data**

Direction-Time Clustering

Identification of **astrophysical flare/flares** from a point source can be performed by **unbinned likelihood method** with search for **direction-time correlation**, in the following ways,

- **Multiplet (Braun 2008)** - for all possible multiplets, **time integrated**
- **Multiplet (Braun 2010)** - for all possible multiplets
- **Stacking (Góra 2011)** - for only doublets, can search for **multiple flares**

We created a **Python** package UHECluster to **generalize** these algorithms and use them in an *open-source, modular, and experiment-independent way*.



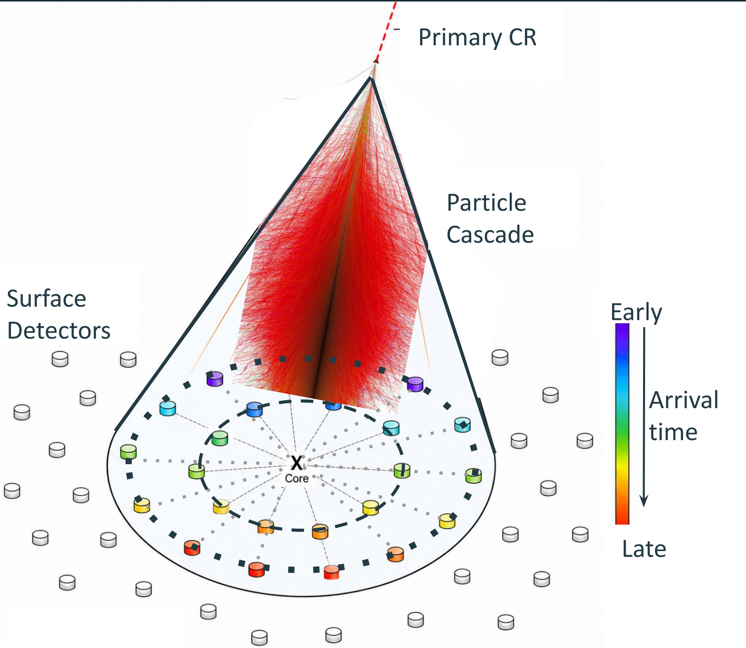
ICRC 501 (2025) 400

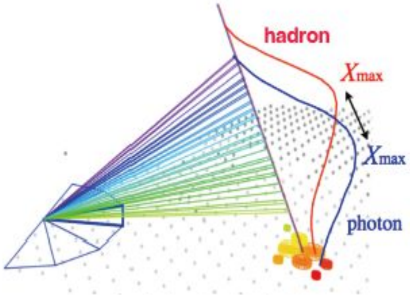
ICRC 501 (2025) 199

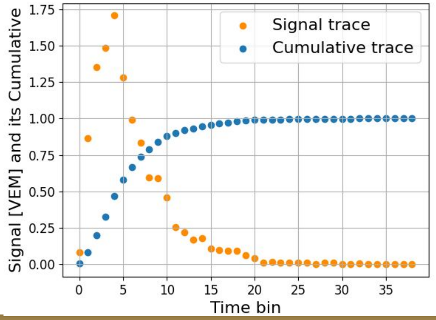
Photon Tags

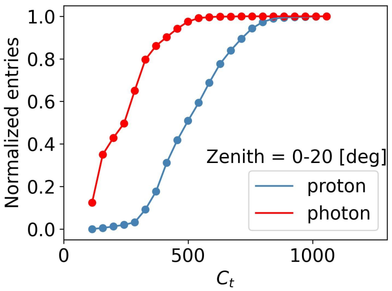
Among the various photon/hadron discriminant observables, we consider:

1) $S_{b=4}$ --> Summation of **total** signal from *k* stations, at a distance R_k from the shower axis
2) C_t --> Summation of the **cumulative trace** signal from *M active* stations, over *N* time bins.
3) X_{max} –> Atmospheric depth of the **shower maximum**









Unbinned Likelihood Method

Input event parameters:
1. Arrival Time
2. Arrival Direction
3. Photon Tag score

$$\mathcal{S}_i^{direction} = \frac{1}{2\pi\sigma_i^2} exp\Big(-\frac{|\vec{r_i} - \vec{r_s}|^2}{2\sigma_i^2}\Big)$$

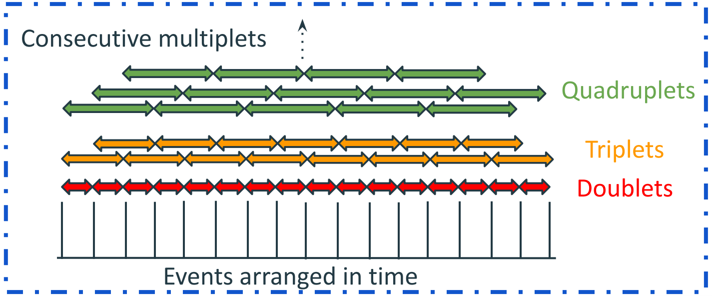
$$\mathcal{S}_i^{time} = \frac{H(t_j^{max} - t_i)H(t_i - t_j^{min})}{\Delta t_j}$$

$$\mathcal{S}_i = \mathcal{S}_i^{direction} \cdot \mathcal{S}_i^{time} \cdot \mathcal{S}_i^{PhTag}$$

$$\mathcal{B}_i^{direction} = \frac{1}{\Delta\Omega}$$

$$\mathcal{B}_i^{time} = \frac{1}{\Delta T}$$

$$\mathcal{B}_i = \mathcal{B}_i^{direction} \cdot \mathcal{B}_i^{time} \cdot \mathcal{B}_i^{PhTag}$$



Final result:
1. **TS(max)**
2. **# signal events**
3. **Flare duration**

$$\mathcal{L}(n, \Delta t_j, \vec{r_s}) = \prod_{i=1}^{N} \Big(\frac{n}{N}\mathcal{S}_i + (1 - \frac{n}{N})\mathcal{B}_i\Big)$$

$$TS(n) = -2\log\left[\frac{\mathcal{L}(0, \Delta t_j, \vec{r_s})}{\mathcal{L}(n, \Delta t_j, \vec{r_s})}\right]$$

$$TS(n) = 2\sum_{i=1}^{N}\left[\log\Big(\frac{n}{N}(\frac{\mathcal{S}_i}{\mathcal{B}_i} - 1) + 1\Big)\right]$$

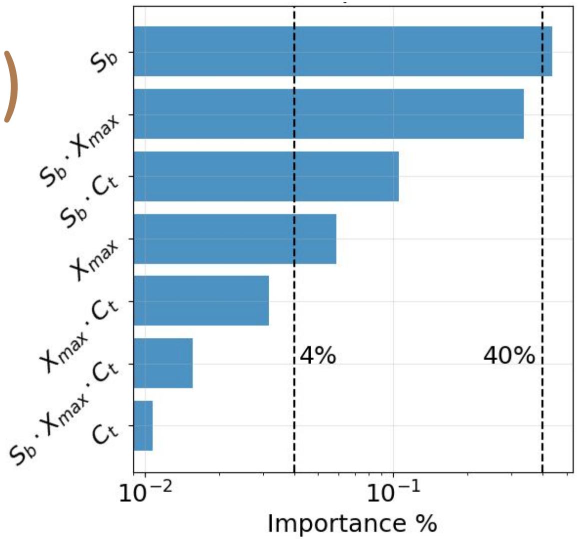
Evaluate the **likelihood** and maximize the Likelihood Ratio Test based **TS**

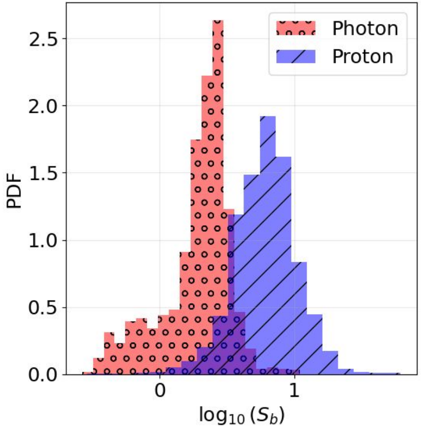
⟶Also apply a pre-selection cut on $S^{direction}S^{PhTag}/B^{direction}B^{PhTag}$ to select ***more* signal-like** events

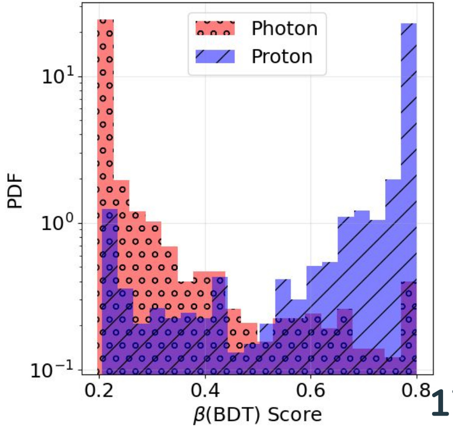
Enhancement of the algorithm ➡ **Directional correlation** › **Temporal correlation** › **Photon Tag** › **S/B threshold**

Boosted Decision Tree (BDT)

- Combining the individual observables and their products by **training a BDT model**, using XGBoost to discriminate between **γ** and **p**
- The AUC value of the ROC curve of β (BDT) score and S_b, are **0.964** and 0.947, respectively
- The Merit factor of β(BDT) score and S_b, **quantifying the separation power**, are **2.03** and 1.31, respectively



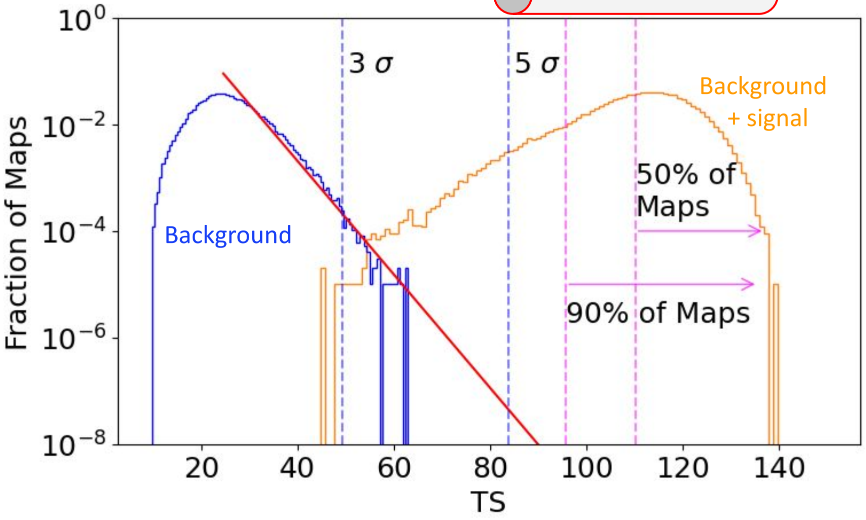




Discovery and Sensitivity Thresholds

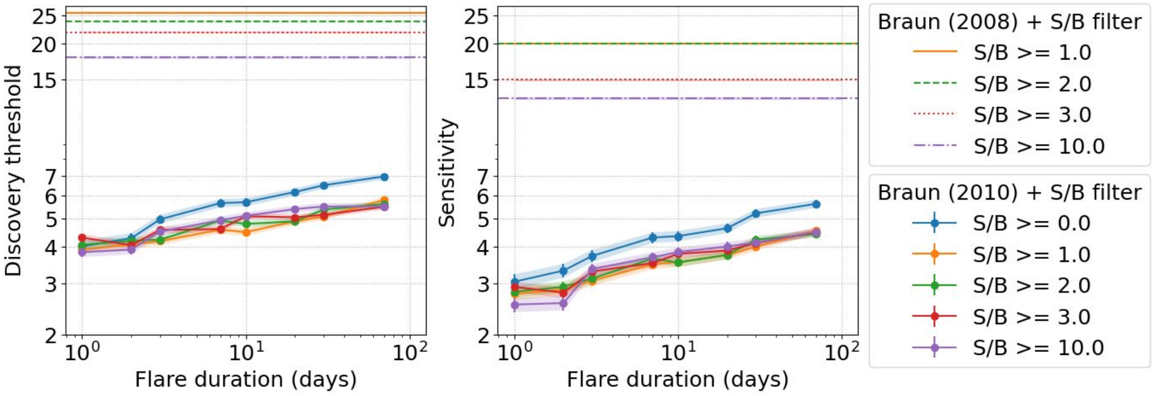
- **Scrambling** of cosmic ray data, assuming **isotropic distribution of background CRs**. Scrambling (multiple maps) gives a statistical distribution to compare with.
- The **discovery potential** is the number of signal events required to achieve a **one-sided 5σ** in 50% of the maps.
- The **sensitivity threshold**, similarly corresponds to a **one-sided 3σ** in 90% of the maps.

Scrambled parameters:
1. Arrival Time
2. Arrival Direction
3. Photon Tag score



Validation by MC study

- Parameters used:
  - Background of **~1000 events** in **9 deg radial sky region** around a target, over **14 years** of data.
  - Signal events for *different* flare durations.
- **Scrambled 10^5 times** to get good statistical estimation.
- Compared different multiplet methods



Braun (2010) + BDT + S/B filter needs only **4-6 signal events to reach 5σ** for 1-100 day flares!! Without **temporal** correlation, we need **20-25** signal events!

Directional correlation → **Temporal correlation** → **Photon Tag** → **S/B threshold**

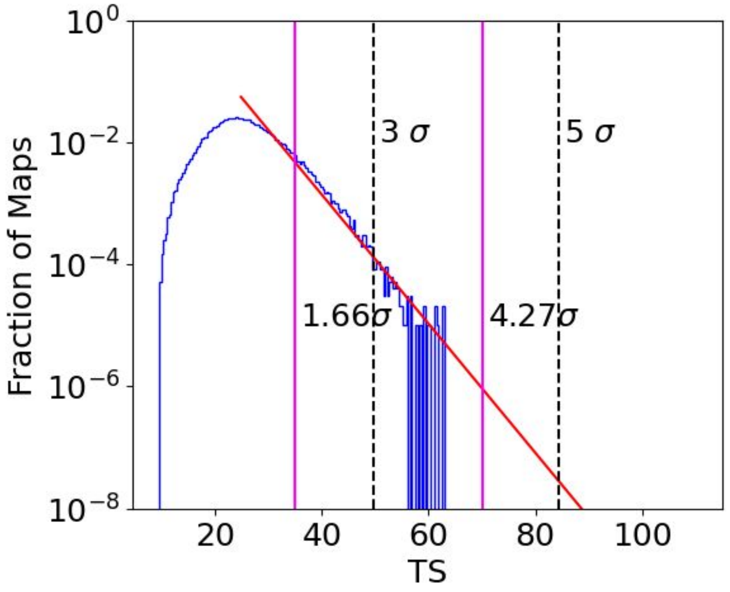
Case study: Targeted search on select sources

- We analyzed **364 sources** (12 categories), used in ApJL 837 (2017) L25 with the direction-time clustering algorithm, using
  - **Braun (2010) multiplets** algorithm
  - **S/B >= 1**
  - Maximum flare duration = **90 days**
  - **β (BDT)** photon tag
- We test with the events of the Auger Burnt Sample, collected with **~10% of SD-1500 (2004-2018)**

1. Milli-second Pulsars
2. Gamma-ray **(10^9eV)** Pulsars
3. Low-Mass **X-ray** Binaries
4. High-Mass **X-ray** Binaries
5. H.E.S.S. **(10^{12}eV)** Pulsar Wind Nebulae
6. H.E.S.S. **(10^{12}eV)** “Other” - Uncommon categories
7. H.E.S.S. **(10^{12}eV)** “UNID” - Unidentified sources
8. Microquasars
9. Magnetars
10. Galactic Center
11. Large Magellanic Cloud
12. Centaurus A

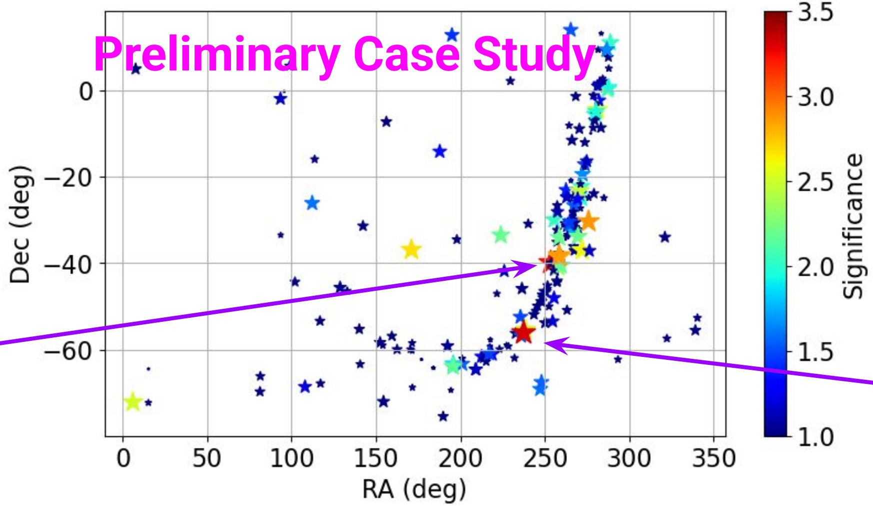
Analysis steps

1. Run the multiplet algorithm **once**, to get reconstructed N_{sig}, Flare Duration, and **TS**
2. **Scramble 10^5** times (# of Maps) the dataset, to get a uniform **background TS distribution**
3. Get the **p-value** and statistical **significance** for each search



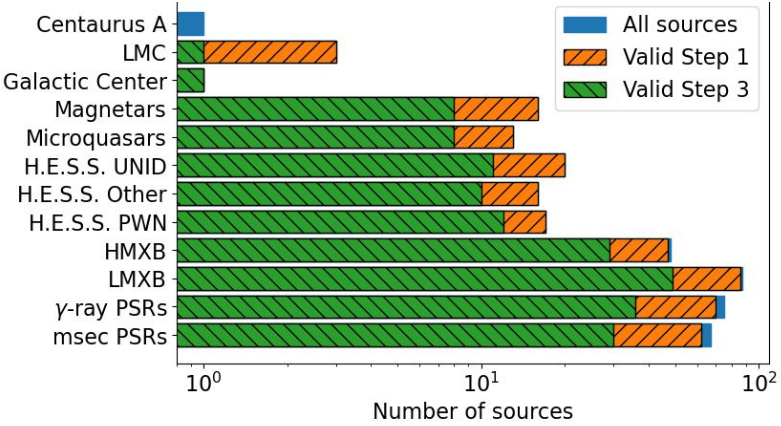
Sample distribution

Results



GRO J1655−40
Low-Mass X-ray Binary Microquasar
~3.3σ
6 events
38.7 days flare

XTE J1550−564
Low-Mass X-ray Binary **Microquasar**
~3.3σ
5 events
67.8 days flare



194/**364** sources with valid estimations in **Step 1 and 3**

Summary

- The **Pierre Auger Observatory** provides the **strongest upper limits** on the **diffuse fluxes of photons** in the energy range between **5×10^{16} - 10^{20} eV**
- Search for **point-sources** using **blind** and **targeted** methods were also performed (No candidates found)
- **Direction-Time Clustering algorithms** offers a significant improvement in searching for UHE photon flaring sources
- Addition of photon tag based on **Boosted Decision Tree**, increases the sensitivity of the method
- The analysis chain has been defined and is powerful enough to **enable discovery** of **Ultra-High-Energy photons amongst the Cosmic Rays**
- For more in-depth inter-departmental discussions on multi-messenger astrophysics, find us at the IFJ Astrophysics Forum (https://astrophys.ifj.edu.pl/)!