On the search for the most energetic photons in the Universe

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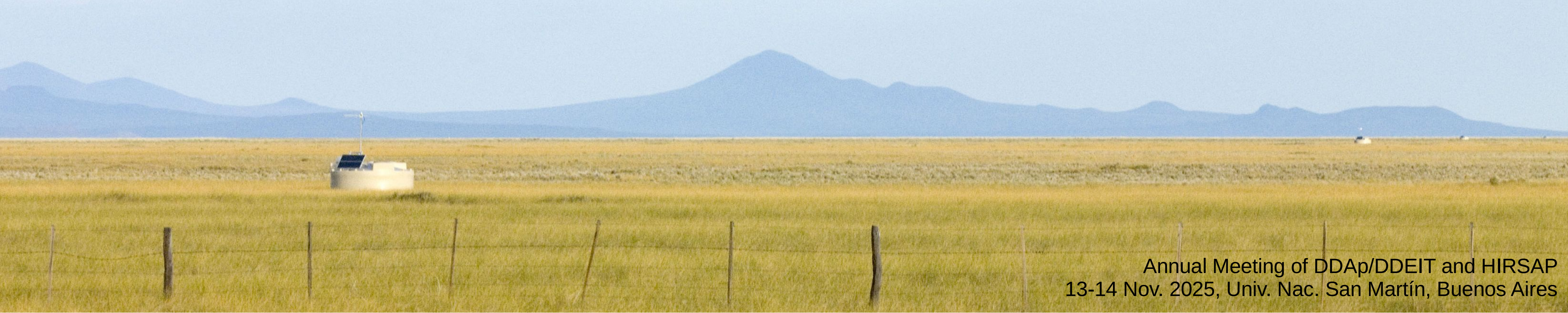
Istituto Nazionale di Fisica Nucleare (INFN)

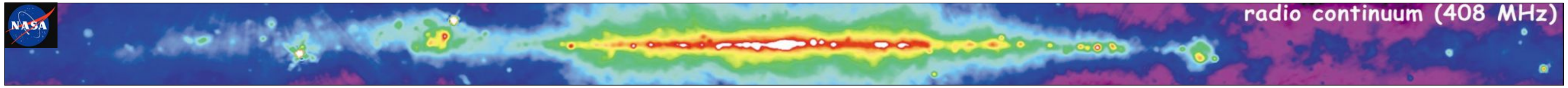


Annual Meeting of DDAp/DDEIT and HIRSAP
13-14 Nov. 2025, Univ. Nac. San Martín, Buenos Aires

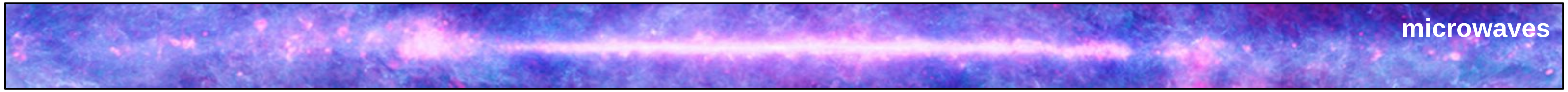

gettyimages

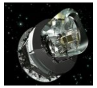
Light comes in different flavours

Energy



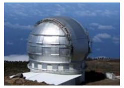
Deep Space Antenna



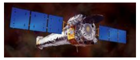


Planck satellite

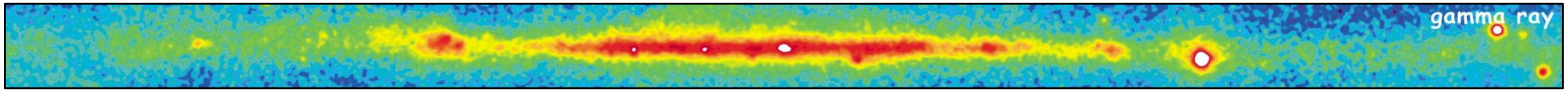
James Webb Space Telescope

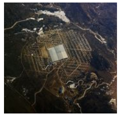


Gran Telescopio Canarias



Chandra mission

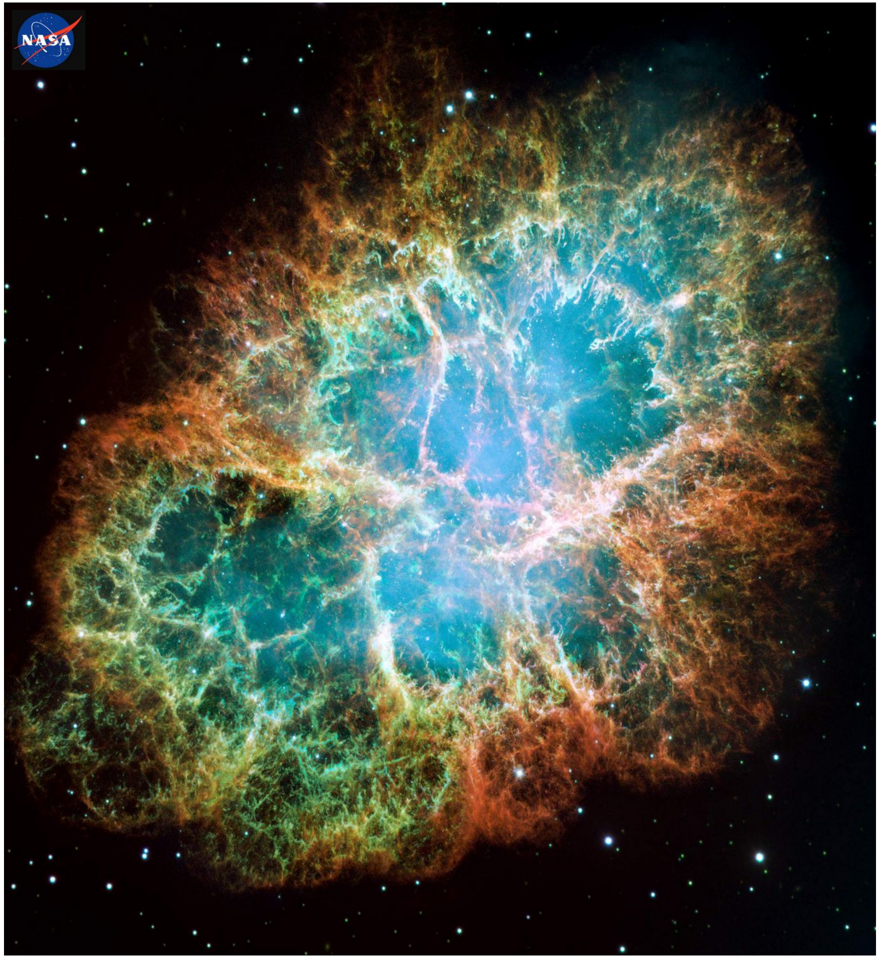


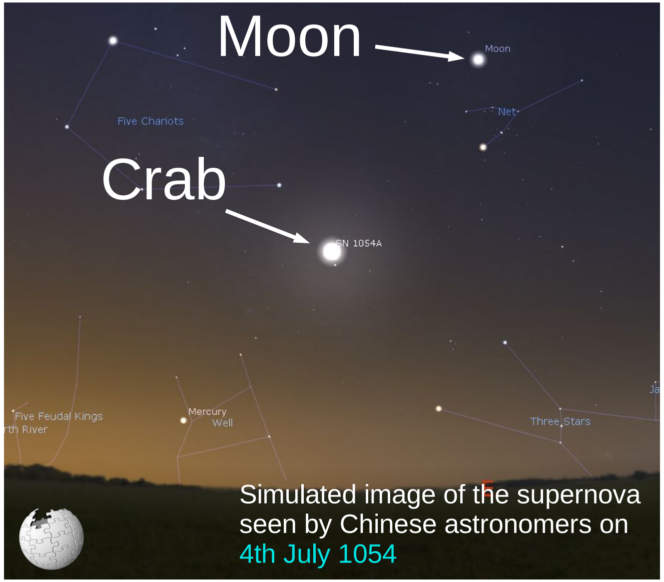


LHAASO Observatory

? ? ?

Crab Nebula, the most studied gamma-ray source



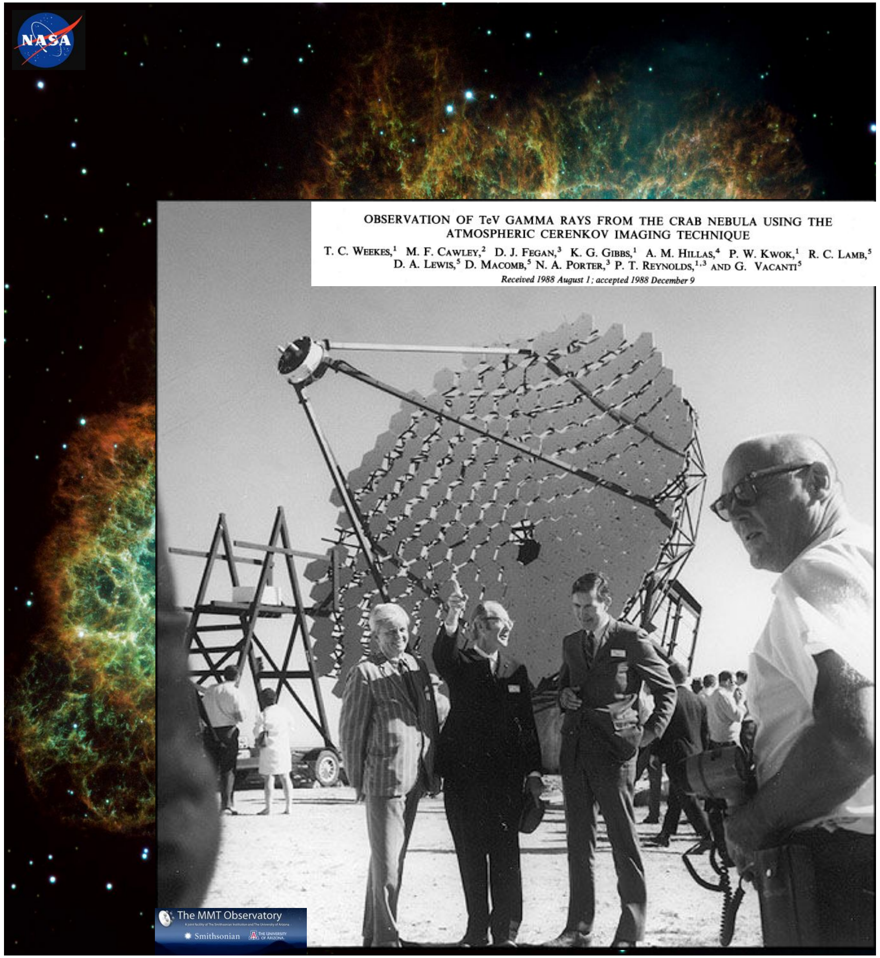


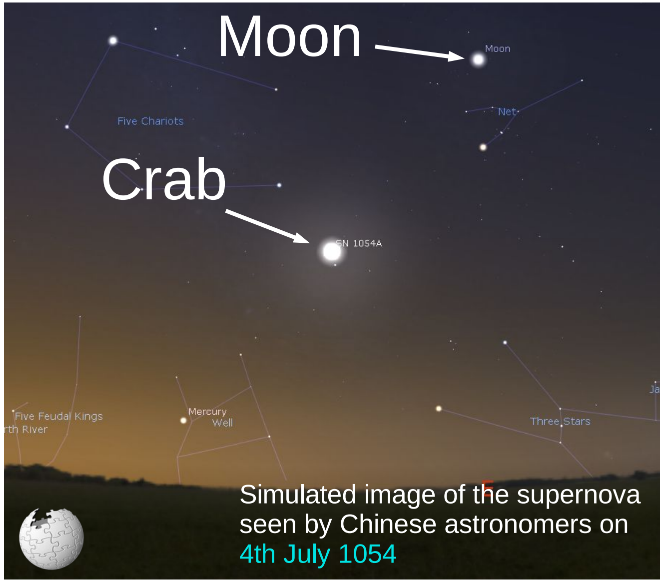
Simulated image of the supernova seen by Chinese astronomers on 4th July 1054

Holy Roman Emperor Henry III before Tivoli pointing up at a new star (Univ. Heidelberg)

- ► Remnants of a star explosion leaving behind a rotating neutron star
- ► 42 gamma-rays per second hitting an equivalent area of Buenos Aires
- ► Steep energy spectrum: the higher the energy of the gamma-ray, the more difficult to produce it

TeV photons from Crab (1989)





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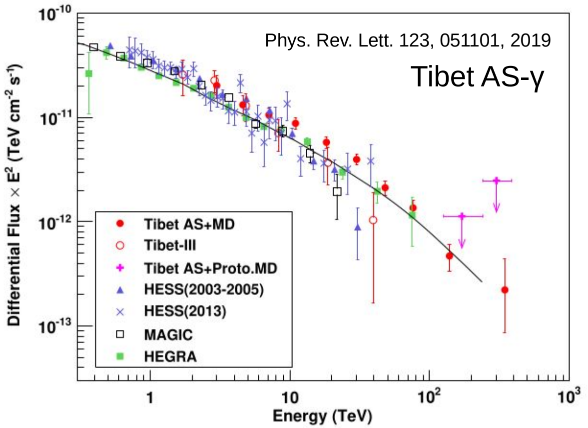
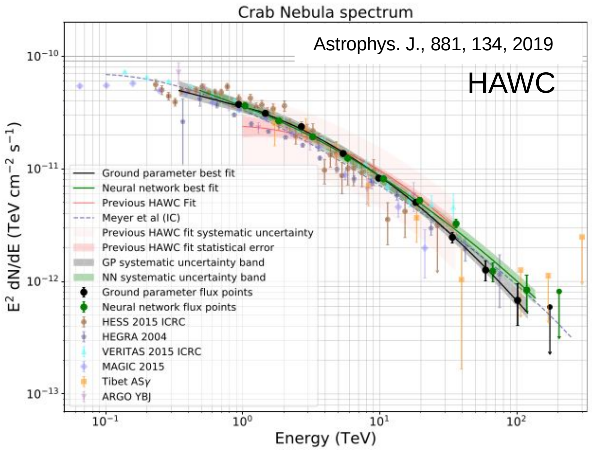
- ► Remnants of a star explosion leaving behind a rotating neutron star
- ► 42 gamma-rays per second hitting an equivalent area of Buenos Aires
- ► Steep energy spectrum: the higher the energy of the gamma-ray, the more difficult to produce it
- ► TeV gamma-ray source discovery by Whipple, an imaging Cherenkov telescope with a 10-m reflector and a multi-pixel camera, in 1989

(Astrophys. J. 342 (1989) 379)

100 TeV photons from Crab (2019)



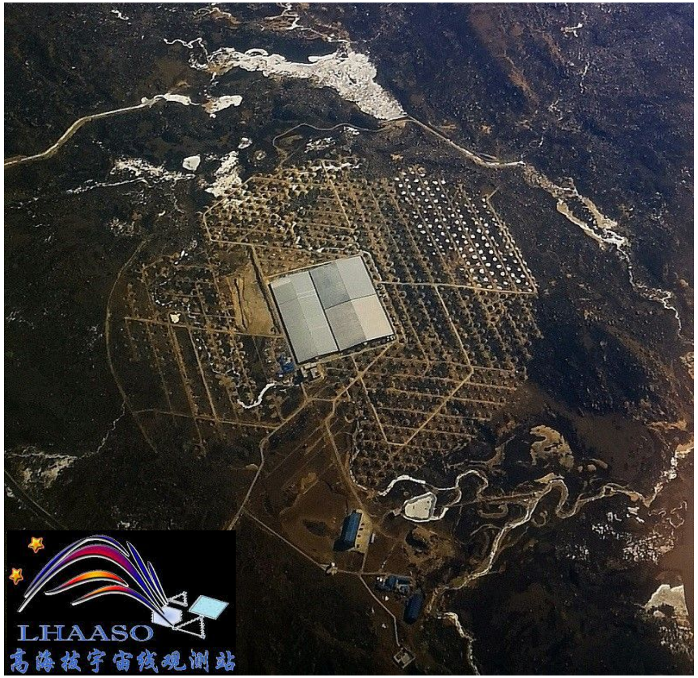
4300 m above sea level
(Yangbajing, Tibet)



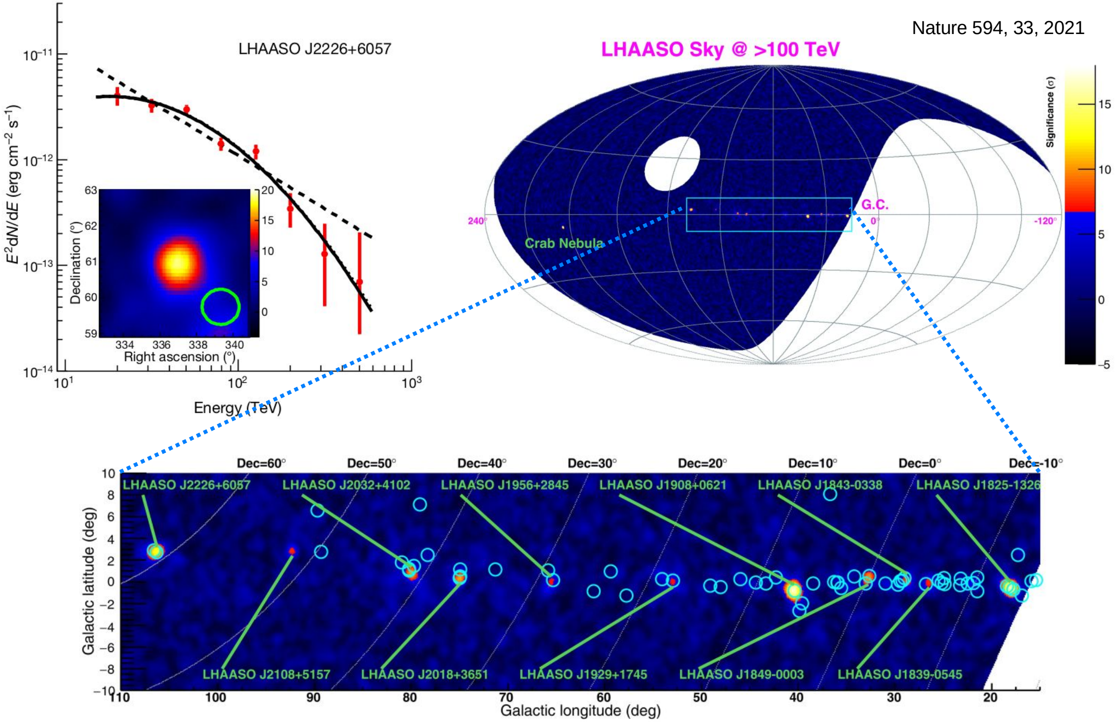
4100 m above sea level
(Puebla, Mexico)

1 PeV photons from Crab! (2021)

4400 m above sea level (Sichuan, China)



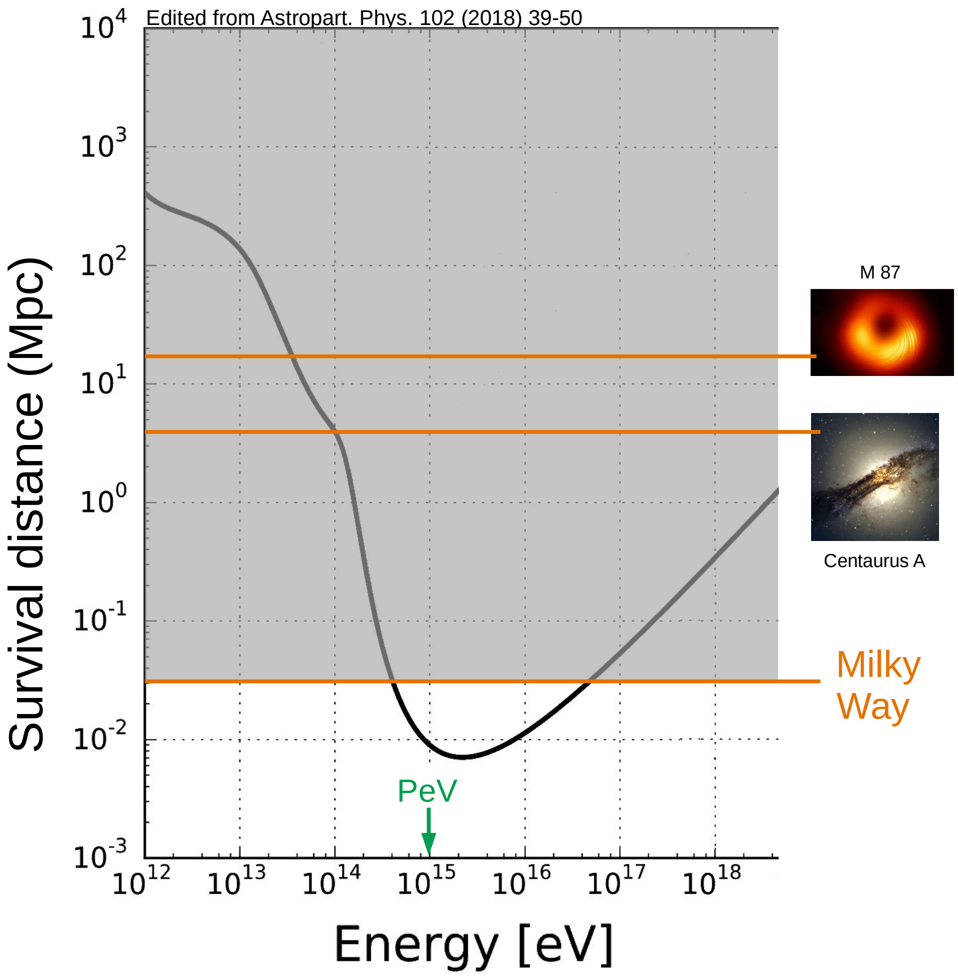
May 2021: 12 sources of gamma-rays with energies up to 1 PeV



Feb 2024: catalog of 90 gamma-ray sources sources by LHAASO (ApJS 271, 25, 2024)

What is the situation at higher energies?

Ultra-high-energy photons



Gamma-rays with energies above few PeV are usually called "ultra-high-energy photons" (UHE)

► Between 1-100 PeV, photons trace the local Universe → messengers of Galactic phenomena

► Produced in cosmic-ray acceleration sites, during cosmic-ray propagation or in the decay of dark matter

► They carry information about:

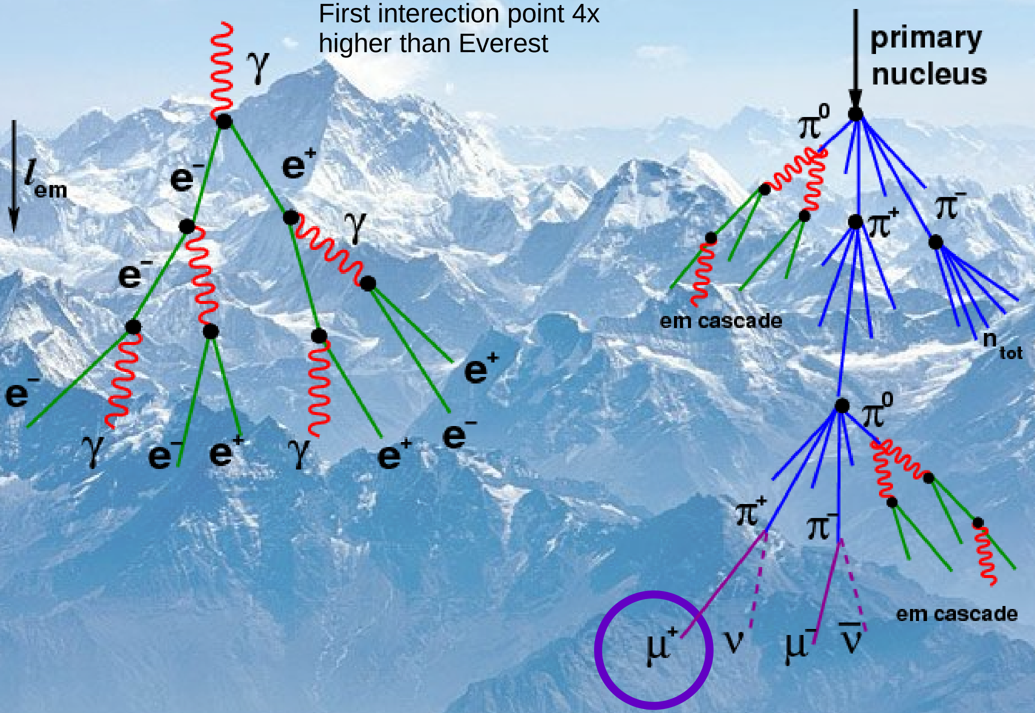
→ **high-energy particle interactions**
→ **Galactic matter and radiation fields**
→ **beyond standard model Physics**

► Their detection is not an easy task: less than 1 UHE photon per year hitting an equivalent area of Buenos Aires (E > 50 PeV)

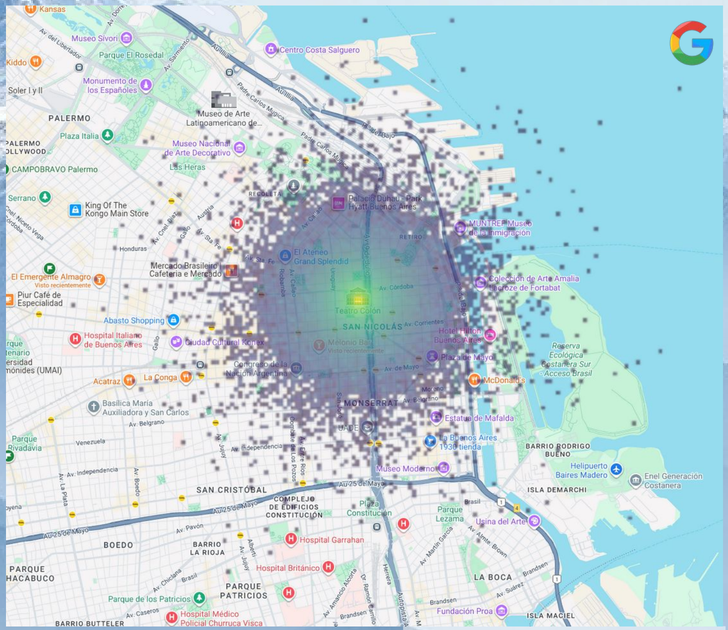
Then, how could we study them?

Is this a lottery for ultra-high-energy photons?

First interection point 4x higher than Everest



► Astroparticles at ultra-high energies interact with the atmosphere initiating a cascade of secondary leptons and hadrons



10^{17} eV photon shower on BA

► Cosmic rays outnumber photons in at least 1:100,000 (same odds to winning the roulette three times in a row)

► Cosmic rays produce hadronic cascades with a rich muon component

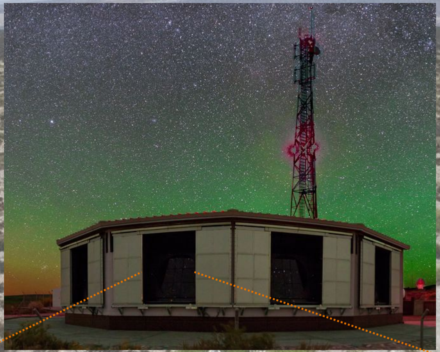
We can discover ultra-high-energy photons by measuring air-shower muons

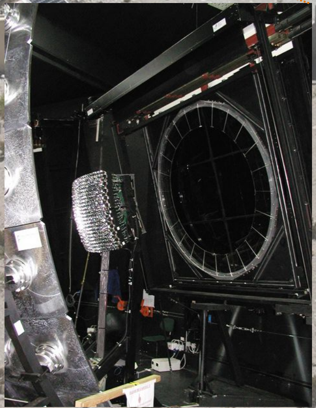
Credit: Julius Zetzsche/Unsplash

Nucl. Instrum. Meth. A 798 (2015) 172-213

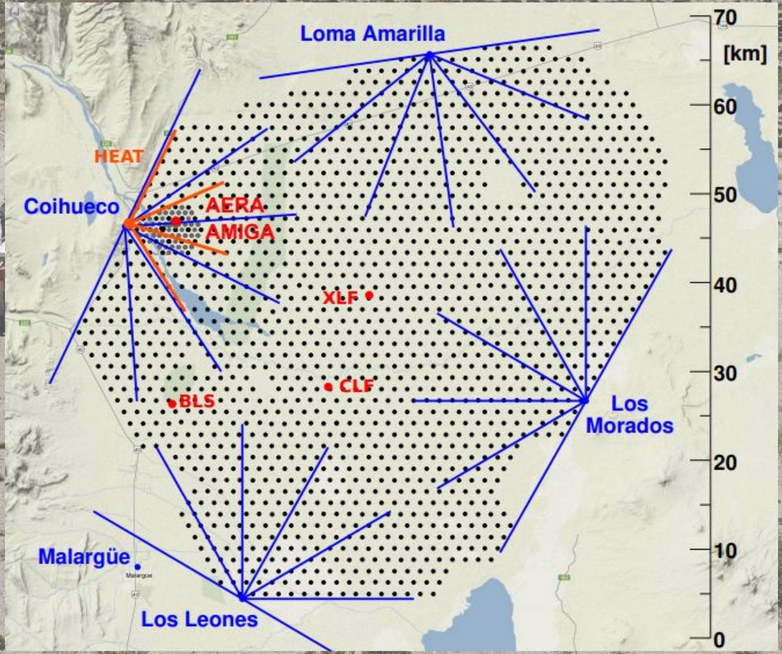
The Pierre Auger Observatory

27 fluorescence telescopes across four sites





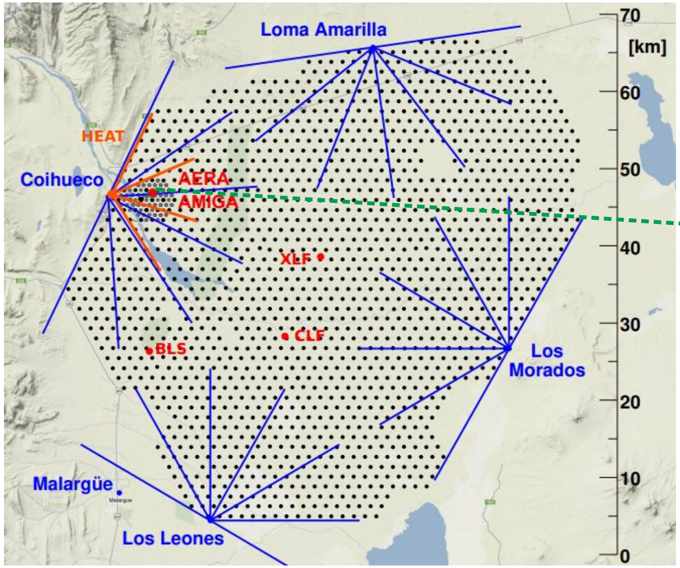
Built and operated by a scientific Collaboration of 400 members, 98 institutions and 17 countries

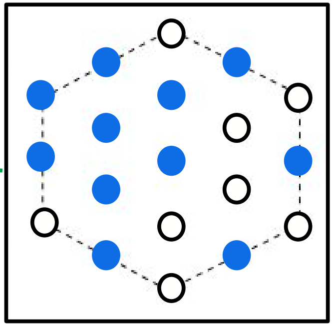


Surface detector (SD) stations filled with 12 tons of hyper-pure water

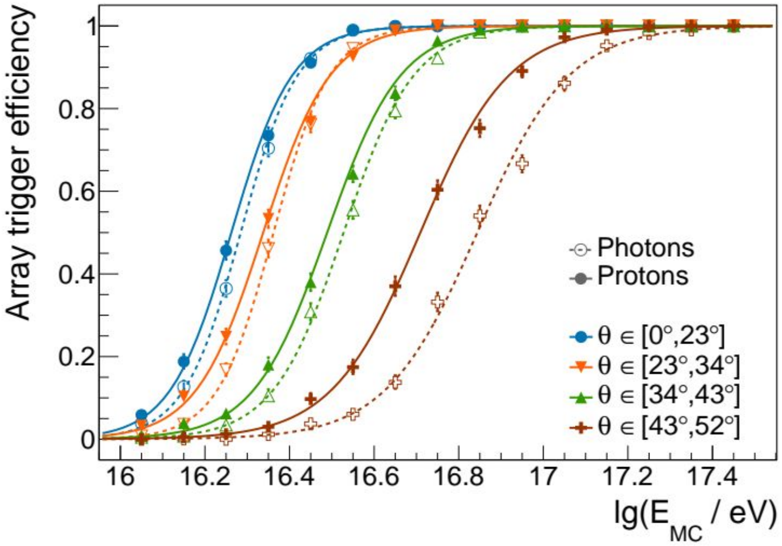
- ► 1500 m array (3000 km²): 1661 stations
- ► 750 m array (25 km²): 61 stations
- ► 433 m array (2 km²): 19 stations

Cosmic-ray detection above 30 PeV with the SD-433





19-station 433 m
SD array



► Significant air-shower detection probability above 30 PeV
→ **we can infer the features of the primary particle with the SD-433**

► Direct muon measurement with one of the detectors of the AugerPrime upgrade: **the Underground Muon Detector (UMD)**

The AugerPrime Upgrade

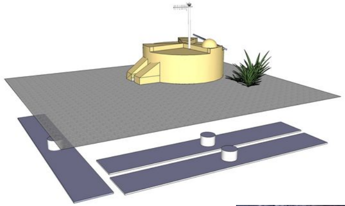
Multi-hybrid air-shower detection:

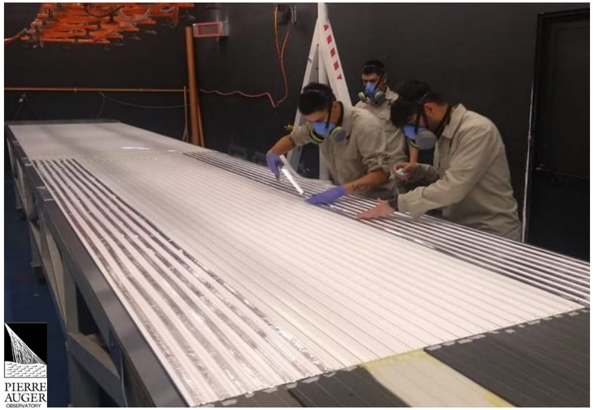
- ► 433 and 750 m SD arrays equipped with 3 x 10 m^2 UMD stations
- ► 4 m^2 plastic surface scintillation detectors (SSD)
- ► Measure radio emission from air showers with antennas (RD)
- ► Faster electronics (UUB) and larger dynamic range thanks to a small-area PMT (SPMT)

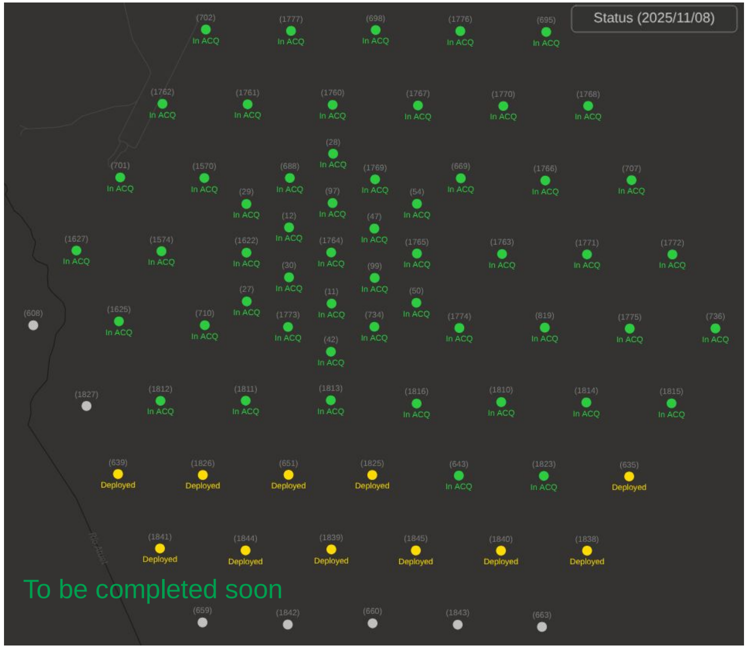
Aiming at a better composition sensitivity (including UHE γ)

Using buried scintillators to win the lottery

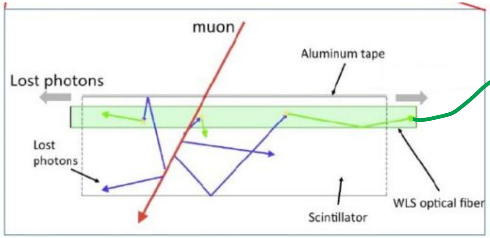
3x10 m^2 plastic scintillators composed by 64 scintillation bars

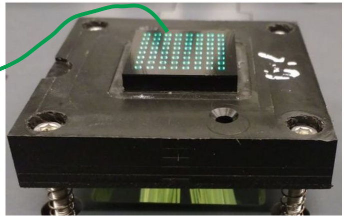






- ► All charged particles from the air-shower are filtered in the ground, except muons with kinetic energies above 1 GeV
- ► Plastic scintillation material emits fluorescence light when a muon transverses it
- ► Single-pixel silicon photomultipliers (SiPM) as optosensors

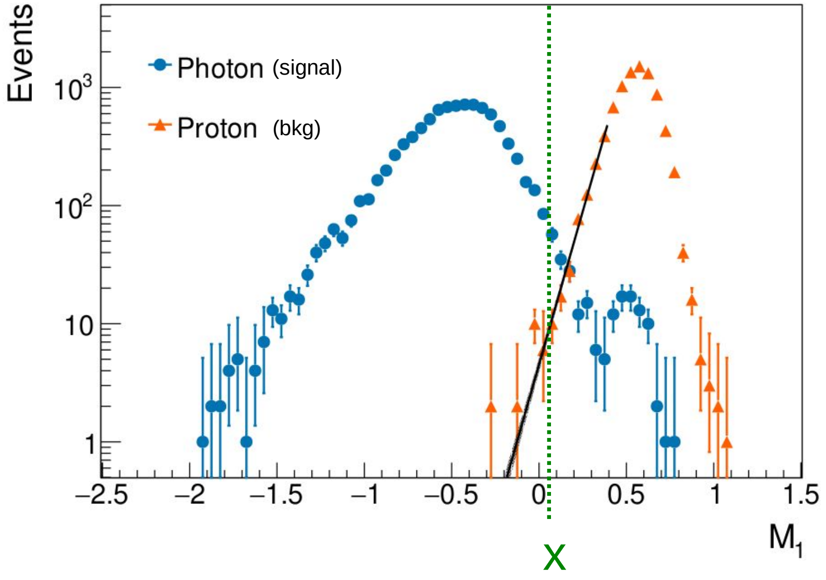




How we searched for photons at tens of PeV

- Discrimination based on the muon density (ρ_i) measured by the UMD stations
- The normalization factor ρ_{pr} is the expected muon density for proton events at r_{pr} = 200 m

$$\boxed{M_1 = \lg\left(\sum_i \frac{\rho_i}{\rho_{\mathrm{pr}}} \times \left(\frac{r_i}{r_{\mathrm{pr}}}\right)\right)}$$



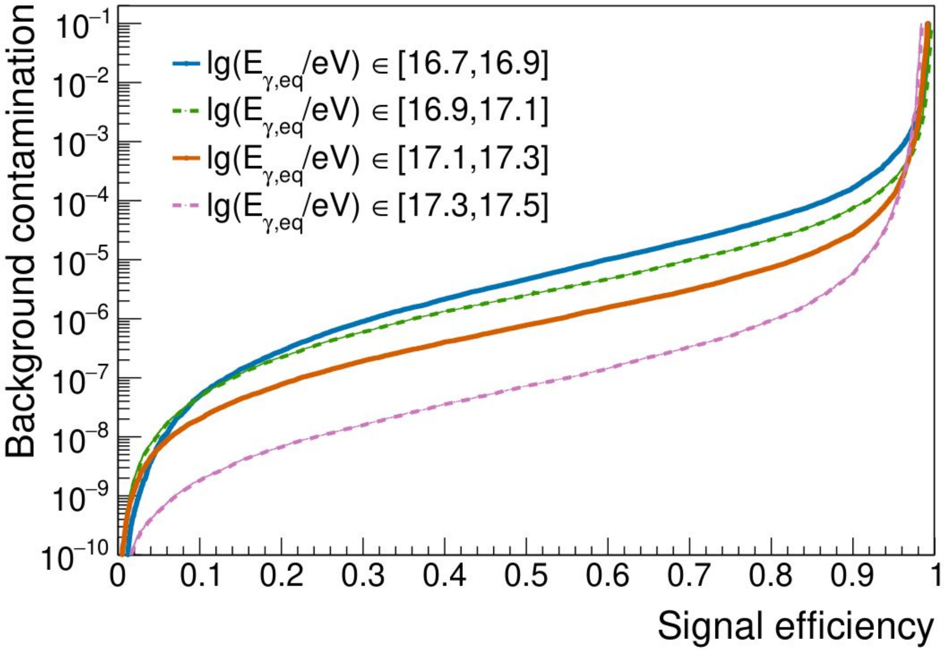
- Two metrics characterize the discrimination performance:

$$\text{sig. efficiency} = \int_{-\infty}^{x} f_\gamma(M_1)dM_1$$

$$\text{bkg. contamination} = \int_{-\infty}^{x} f_{\mathrm{pr}}(M_1)dM_1$$

M_1: the discrimination observable

► Discrimination based on the muon density (ρ_i) measured by the UMD stations



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$$\text{sig. efficiency} = \int_{-\infty}^{x} f_\gamma(M_1)dM_1$$

$$\text{bkg. contamination} = \int_{-\infty}^{x} f_{\text{pr}}(M_1)dM_1$$

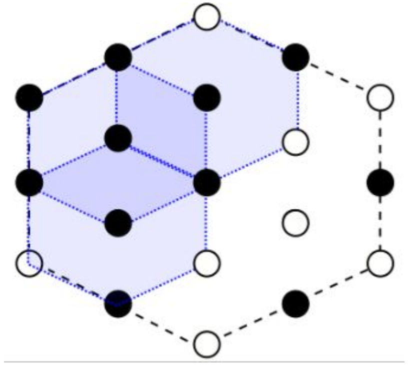
► Contamination decreases with increasing primary energy due to the larger air-shower muon content

► Larger signal efficiency at the expense of larger contamination

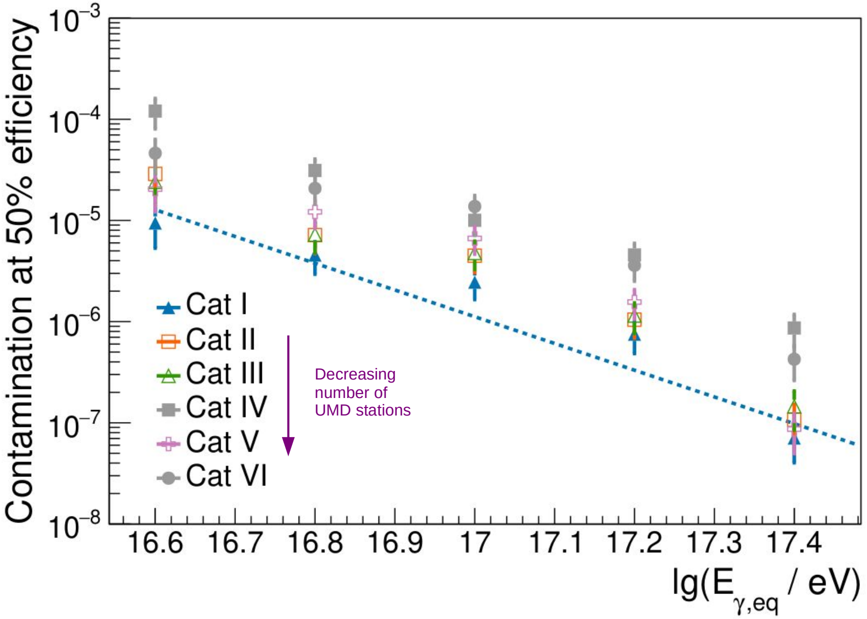
Background contamination

- ► M_1 calculated with the UMD stations of the hottest hexagon
- ► Since M_1 scales with the number of muon density measurements, any missing UMD station would bias M_1

→ **event classification in six "categories" based on number and placement of available UMD stations**



SD-433+UMD (2020-2022)



► Contamination increases for decreasing number of UMD stations

► Very low contamination!

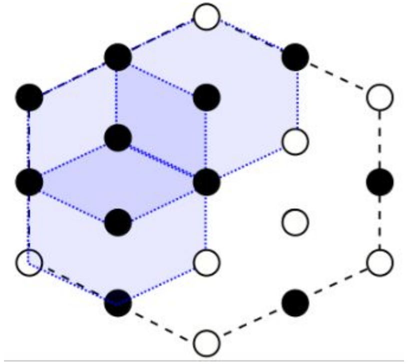
1 bkg event misidentified as a photon every 106 years in Cat I (NW hexagon)

Photon candidate cuts

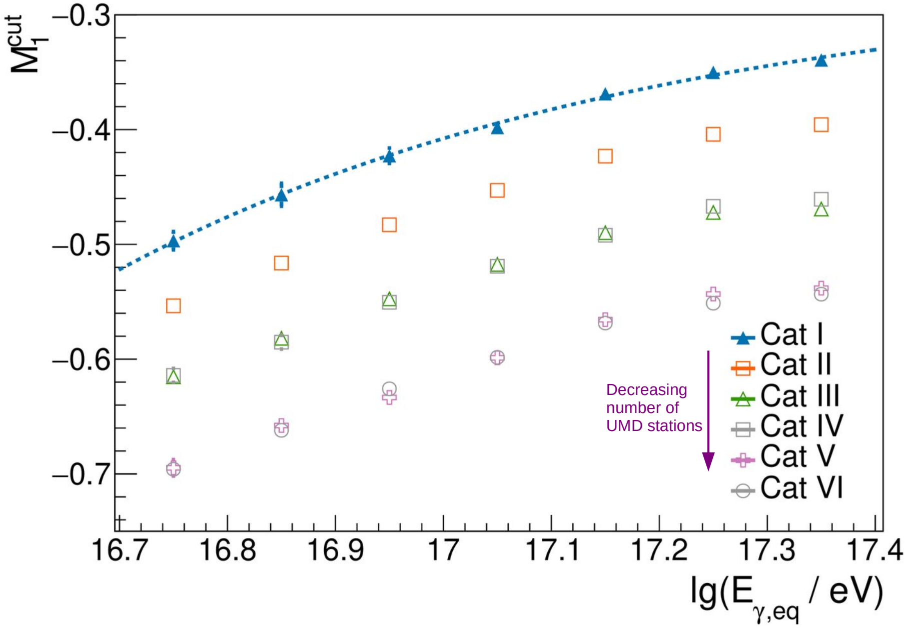
► M_1 calculated with the UMD stations of the hottest hexagon

► Since M_1 scales with the number of muon density measurements, any missing UMD station would bias M_1

→ **event classification in six "categories" based on number and placement of available UMD stations**



SD-433+UMD (2020-2022)



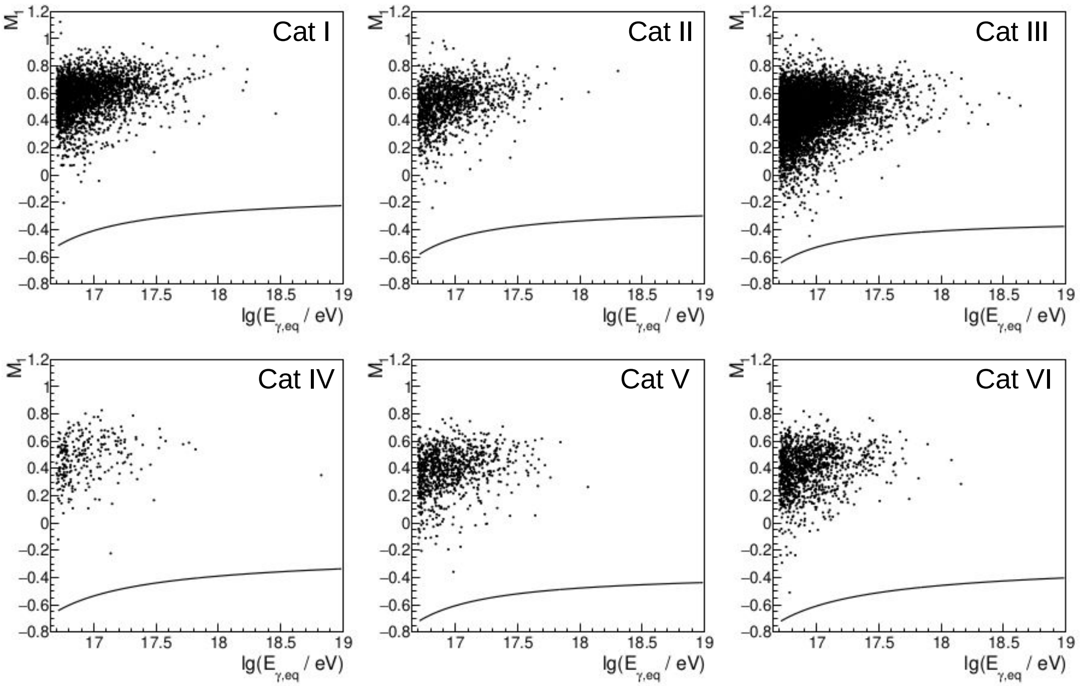
► M_1^{cut} is the "photon candidate cut"

► It is threshold value at which a 50% signal efficiency is reached

► M_1^{cut} scales with the event muon footprint, i.e., with the primary energy and the number of UMD stations

Full data-set unblinding: no photon candidates

► Events for each of the six categories. Lines correspond to the parametrized M_1^{cut} (the "photon candidate cuts")



► No events below the photon candidate cuts
→ upper limits to the photon flux, Φ_γ, above an energy E_γ^{th}

$$\Phi_\gamma < \frac{3.095}{(1 - f_{\mathrm{burnt}}) \times f_{\mathrm{cut},\gamma} \times \epsilon_\gamma}$$

► f_{burnt} = 0.1 (fraction of burnt data)
► $f_{cut,\gamma}$ = 0.504 (signal efficiency)
► ε_γ, exposure to photons

E_γ^{th} (PeV)	ϵ_γ (km^2 sr yr)	Φ_γ (km^{-2} sr^{-1} yr^{-1})	$\Phi_\gamma + \sigma_{\mathrm{sys}}$ (km^{-2} sr^{-1} yr^{-1})
50	(0.58 ± 0.02)	12.3	13.8
80	(0.61 ± 0.03)	11.7	13.5
120	(0.63 ± 0.03)	11.3	13.3
200	(0.63 ± 0.03)	11.3	13.6

► Upper limits increased by:
- energy bias of the photon-equivalent scale (12-17)%
- variations in the spectral index (0.8-2.2)%

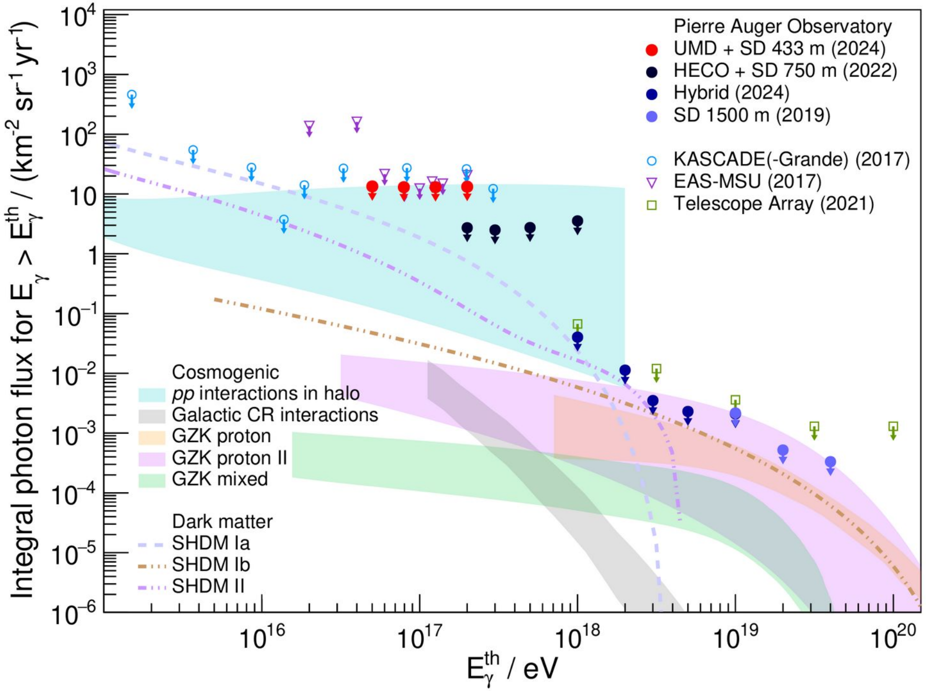
► No impact from muon deficit or UMD simulation

Upper limits to the diffuse photon flux

► First search for a diffuse flux of primary photons above between 50 and 200 PeV from the Southern Hemisphere

► Opportunity to constrain the mass-lifetime phase-space for specific super-heavy dark matter models and to explore the photon flux from proton-proton interactions in the Galactic halo

► Groundwork for a nearly real-time search for primary photons in the tens of PeV domain



Search for a diffuse flux of photons with energies above tens of PeV at the Pierre Auger Observatory

The Pierre Auger Collaboration
E-mail: auger_spokespersons@fnal.gov

Abstract. Diffuse photons of energy above 0.1 PeV, produced through the interactions between cosmic rays and either interstellar matter or background radiation fields, are powerful tracers of the distribution of cosmic rays in the Galaxy. Furthermore, the measurement of a diffuse photon flux would be an important probe to test models of super-heavy dark matter decaying into gamma-rays. In this work, we search for a diffuse photon flux in the energy range between 50 PeV and 200 PeV using data from the Pierre Auger Observatory. For the first time, we combine the air-shower measurements from a 2 km^2 surface array consisting of 19 water-Cherenkov surface detectors, spaced at 433 m, with the muon measurements from an array of buried scintillators placed in the same area. Using 15 months of data, collected while the array was still under construction, we derive upper limits to the integral photon flux ranging from 13.3 to 13.8 $km^{-2}\,sr^{-1}\,yr^{-1}$ above tens of PeV. We extend the Pierre Auger Observatory photon search program towards lower energies, covering more than three decades of cosmic-ray energy. This work lays the foundation for future diffuse photon searches: with the data from the next 10 years of operation of the Observatory, this limit is expected to improve by a factor of ~ 20.

JCAP 05 (2025) 061

► Currently, the Auger photon search programme covers three orders of magnitude in energy

► Searches at higher energies exploit the air-shower longitudinal development and integrated signals and timing observables from the larger SD arrays (see backup)

A key ingredient: the DDAp programme

Karlsruhe Institute of Technology

UNIVERSIDAD
NACIONAL DE
SAN MARTÍN

► Very important regarding the academic and professional development

► Unique opportunity to explore a variety of cultures and get to know many wonderful persons!

Unveiling a new face of the Milky Way

What's next?:

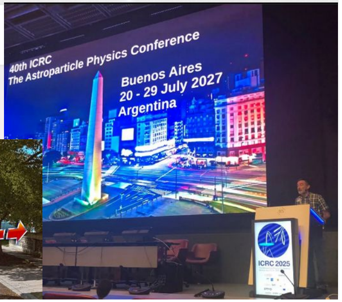
► More than three more years of data have been acquired after the unblinded data (Dic 2020 – March 2022)

► Full deployment of UMD stations in the SD-433 array in 2022-2023 enables the use of all seven hexagons in the array for photon searches

► **Phase II photon search is in progress:**

- Information about the electromagnetic component measured by AugerPrime detectors

- Lower the energy threshold towards super-heavy dark matter predictions



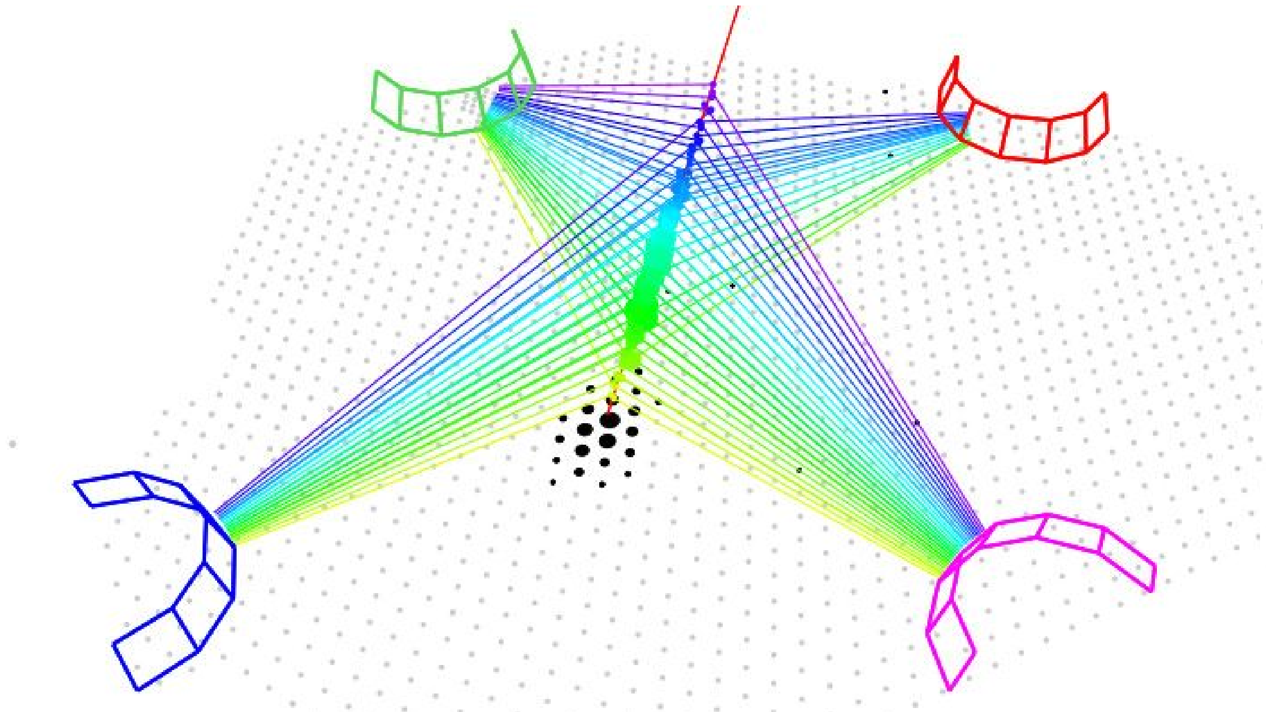
"Question is not 'if', but 'when'"
Markus Risse

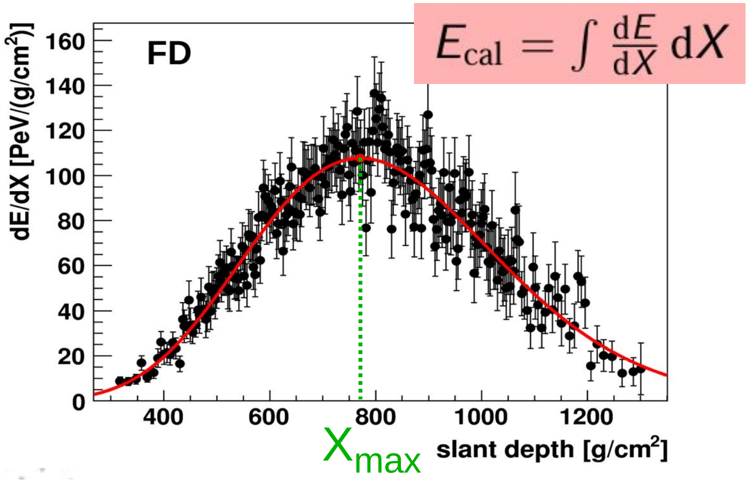
? ? ?

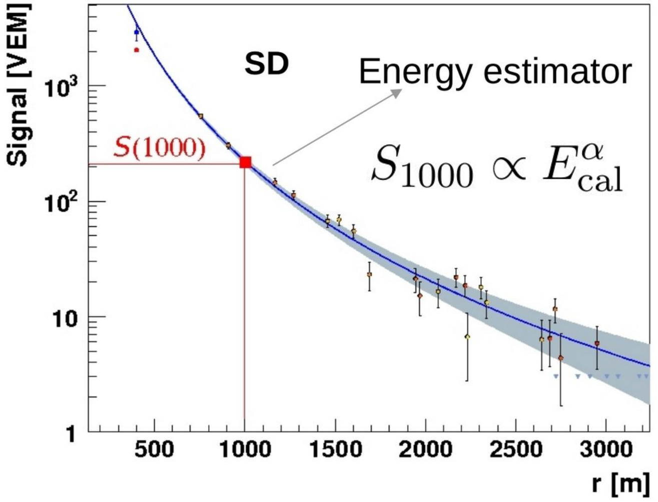
Ultra-high-energy photons

Backup

Hybrid detection of air showers





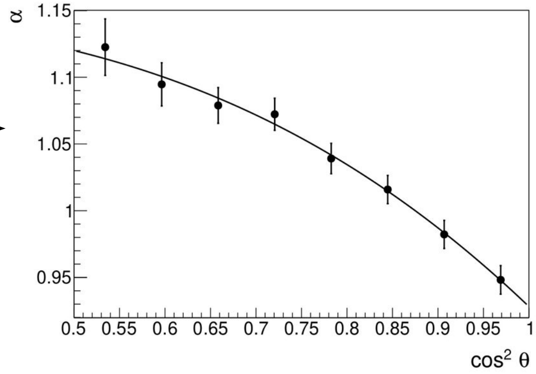


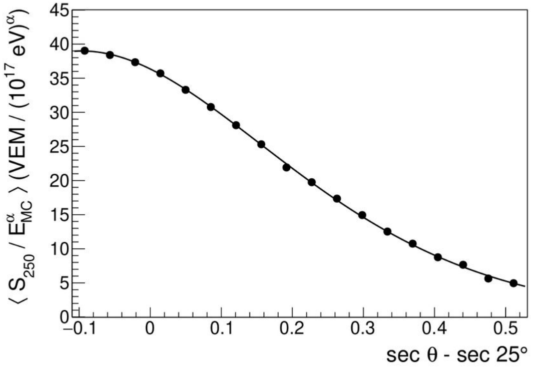
- ► Primary energy from the FD measurements
- ► SD energy estimator calibrated against FD → SD-only reconstruction
- ► Maximum of shower development, X_{max}, is sensitive to the mass composition

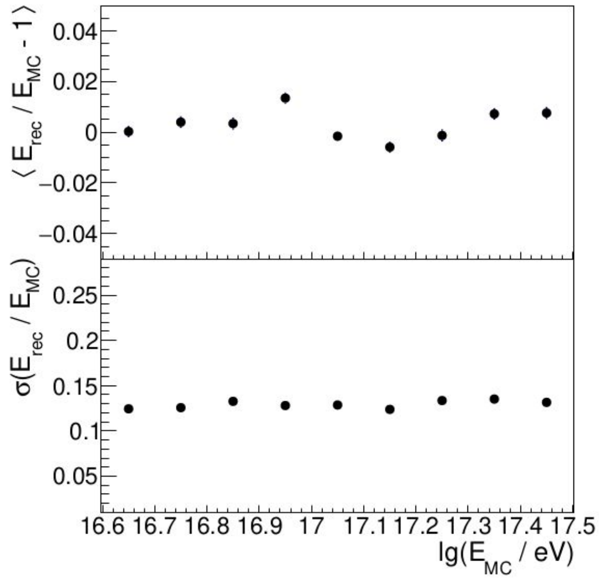
Photon energy reconstruction

- ► NKG with one slope parameter (β) used to reconstruct the LDF
- ► Dedicated parametrization of β for photon primaries
- ► Gaisser-Hillas attenuation function g(θ)
- ► Energy calibration with E_{MC}

$$\frac{S(250)}{g(\theta)} = \left(\frac{E_{\mathrm{MC}}}{10^{17}\,\mathrm{eV}}\right)^{\alpha(\theta)}$$







- ► <2% bias, 12% resolution

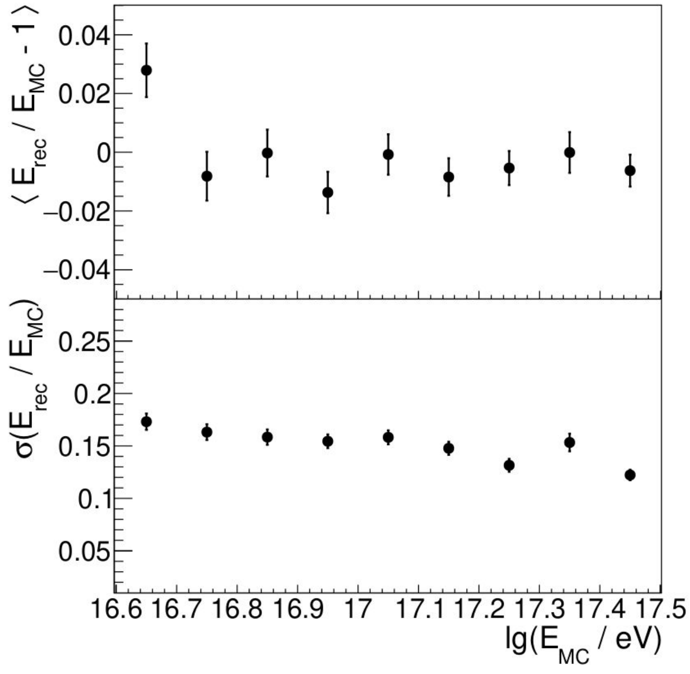
Proton energy reconstruction

► LDF model developed with Phase I data
► Attenuation function g'(θ) resembling CIC
► Direct energy calibration: unbinned likelihood to estimate the five free parameters

$$\frac{S(250)}{g'(\theta)} = \left(\frac{E_{\mathrm{MC}}}{10^{17}\,\mathrm{eV}}\right)^{\underline{\alpha'}}$$

$$g'(\theta) = \underline{a'} \times (1 + \underline{b'} \times x + \underline{c'} \times x^2 + \underline{d'} \times x^3)$$

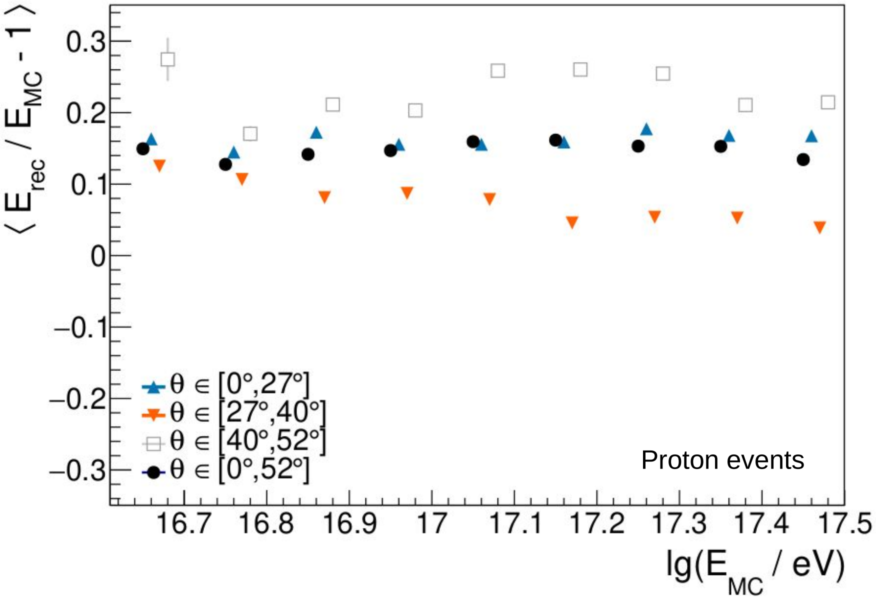
$$x = \cos^2\theta - \cos^2 30\,^\circ$$



► <2% bias, 18% to 13% resolution

Photon-equivalent energy scale

► A unified energy scale is essential for accurately comparing events initiated by different primary species



► If reconstructed with the photon scale, proton events have a 15% bias (due to muonic component in hadronic showers)

► Noticeable angular dependence → photon and proton showers attenuate differently in the atmosphere

→ idea: let's combine the photon and proton energy calibrations!

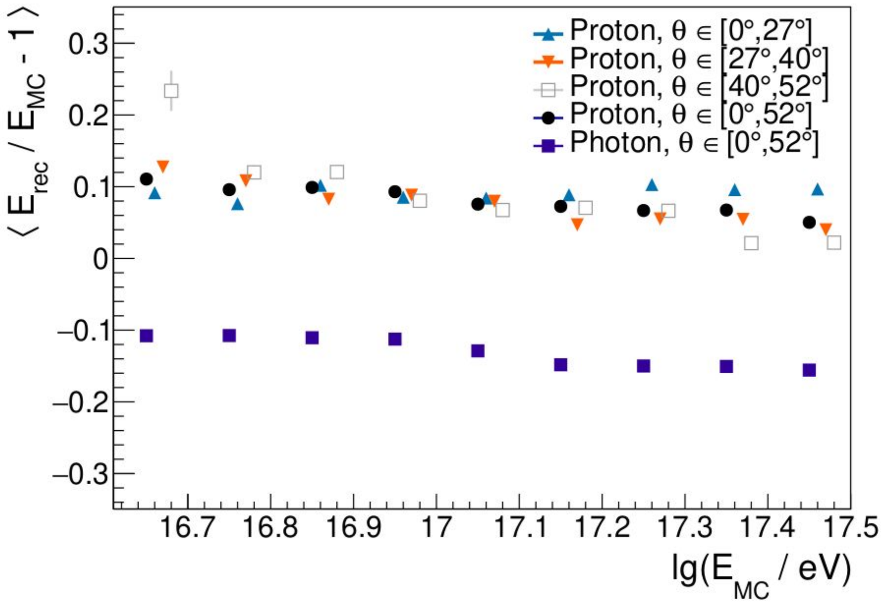
Photon

$$\frac{S(250)}{g'(\theta)} = \left(\frac{E_{\mathrm{MC}}}{10^{17}\,\mathrm{eV}}\right)^{\alpha(\theta)}$$

Proton

Photon-equivalent energy scale

► A unified energy scale is essential for accurately comparing events initiated by different primary species



► **Proton events** reconstructed with the photon-equivalent scale are assigned energies **between 5% and 10% higher than E_{MC}**

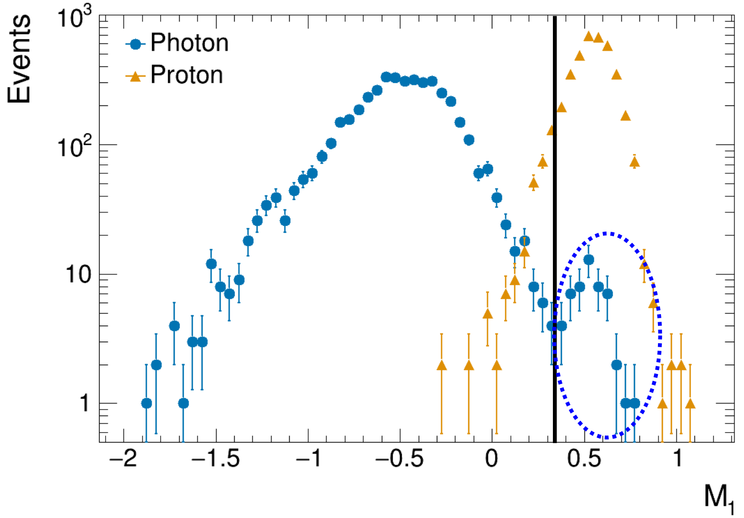
► **Photon events** reconstructed with the photon-equivalent scale are assigned energies **between 10% and 15% lower than E_{MC}**

► In a given $E_{\gamma,eq}$ bin, protons with lower true energy coexist with photons with higher true energy

→ a conservative scenario for discrimination

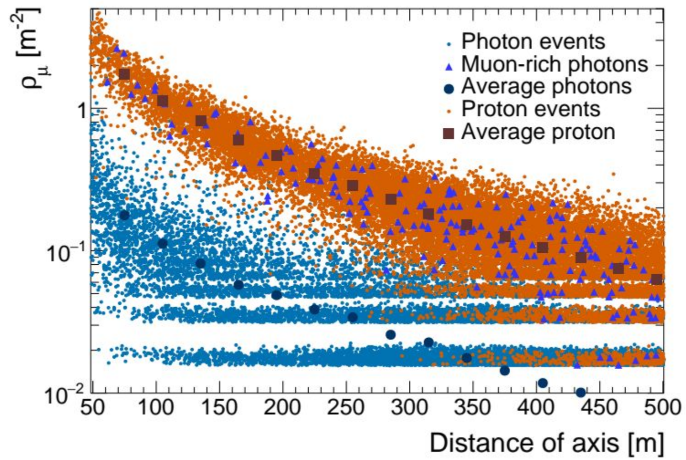
Muon-rich photon showers between $10^{16.7}$ eV and $10^{16.8}$ eV

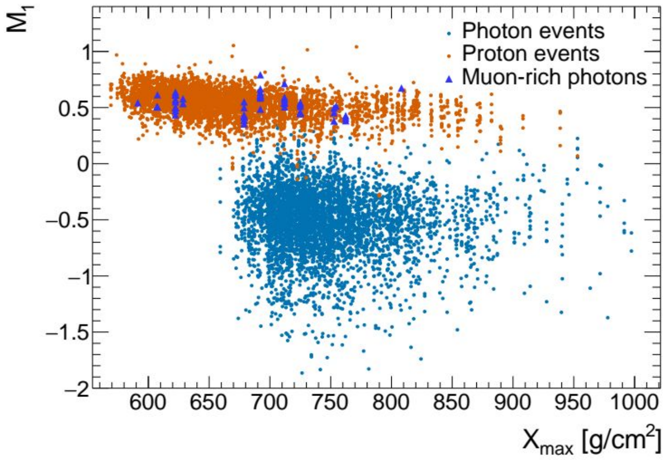
► Muon-rich photon showers are defined as those producing events with $M_1 > 0.35$ (~ bkg median)



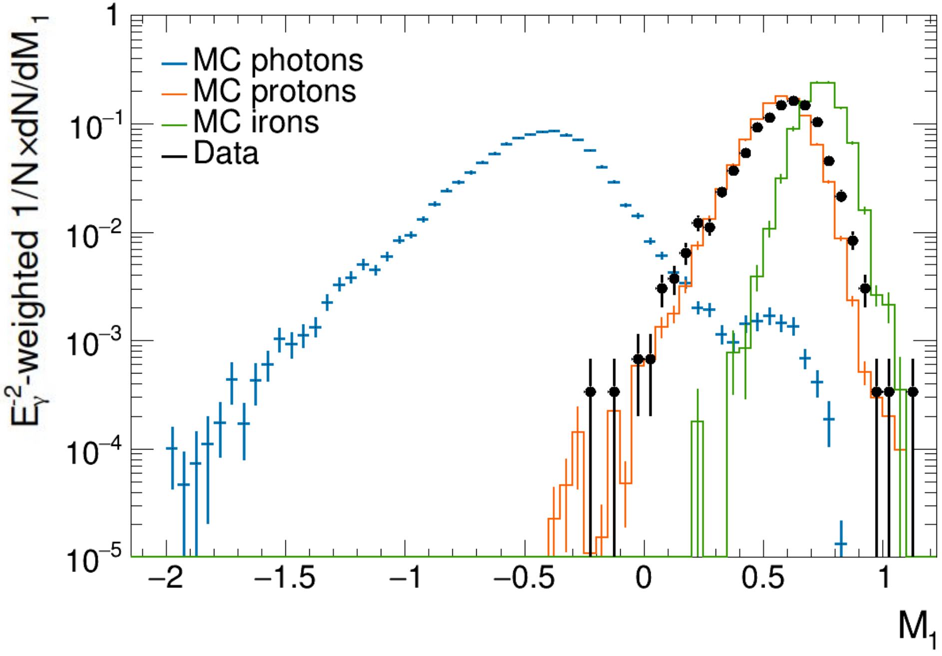
► Muon-rich photon showers have a muon content and a longitudinal development compatible with an average proton shower

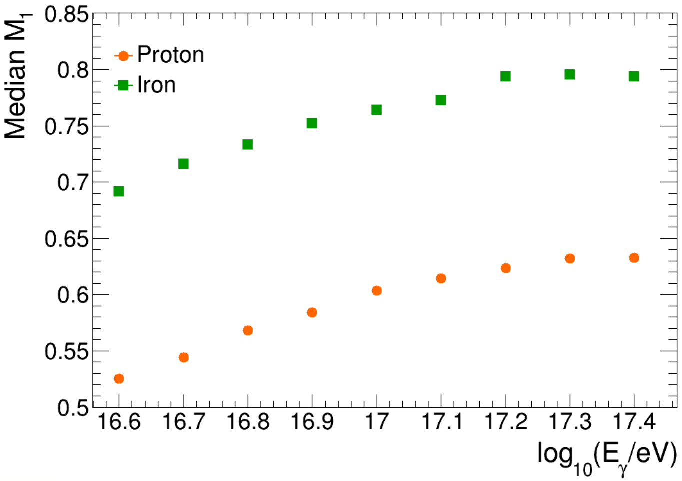
► These special showers have a leading $\pi^{\pm}$ at the first stages of the development

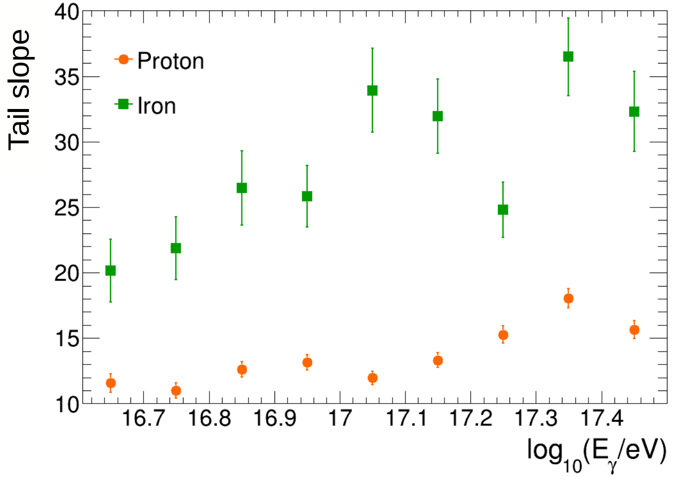




M_1 iron distributions







- Iron showers have more muons and fewer fluctuations
→ larger M_1 and steeper tail slopes
- Both features lead to smaller bkg contamination
- Note that iron MC set size is 25% of the protons one

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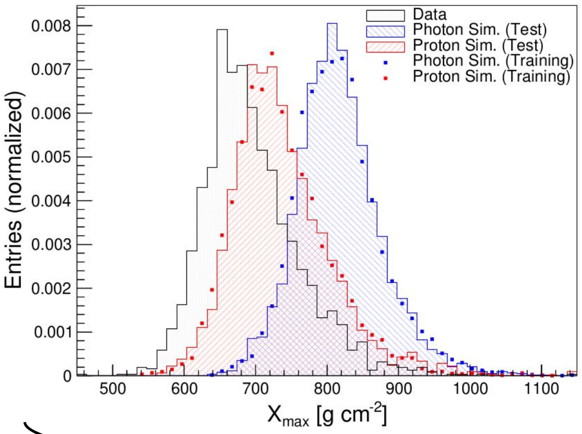
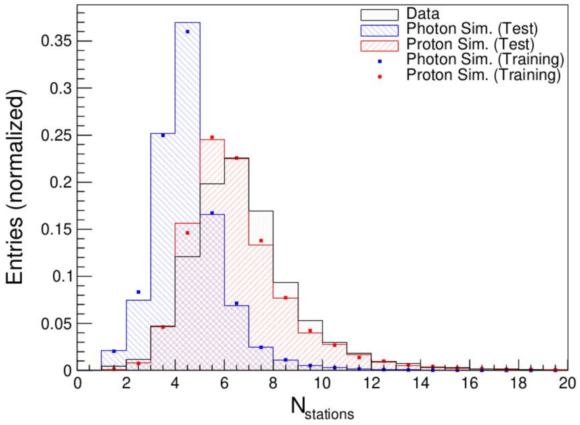
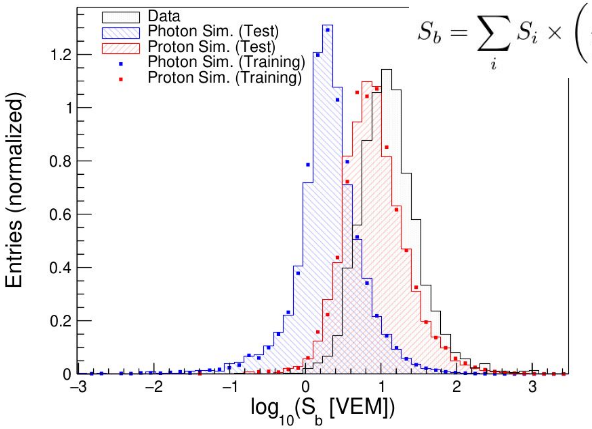
Photon search at 2×10^{17} eV – 10^{18} eV

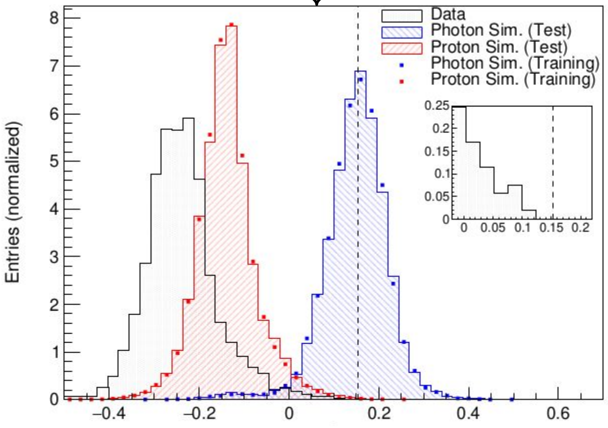
SD+FD







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



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

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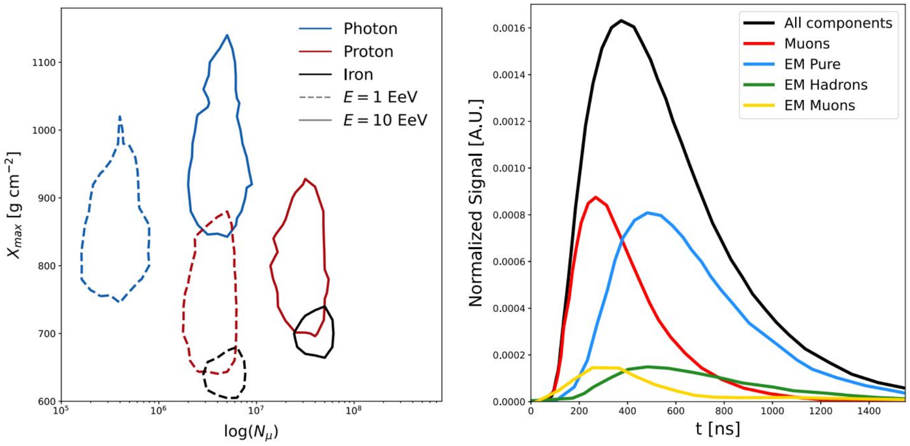
Photon search at 10^{18} eV – 10^{19} eV

SD+FD



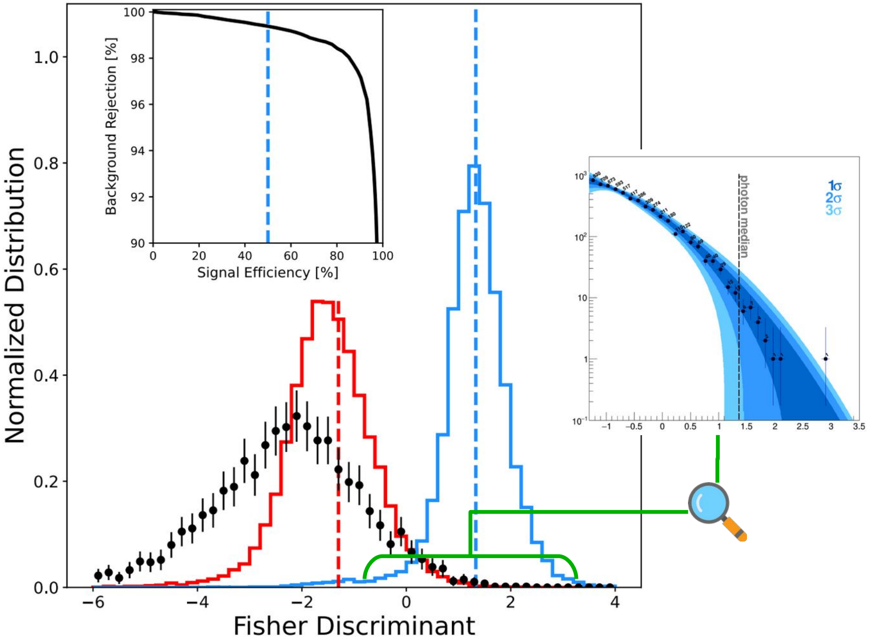
► X_{max} measured with the FD. F_μ is a proxy of the muon content extracted from the SD signals

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

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

► 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



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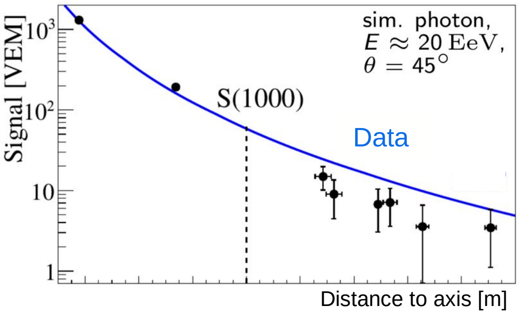
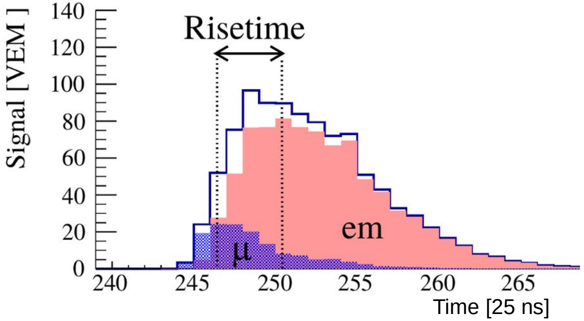
Photon search at > 10^{19} eV SD

Steeper lateral spread of particles (LDF)

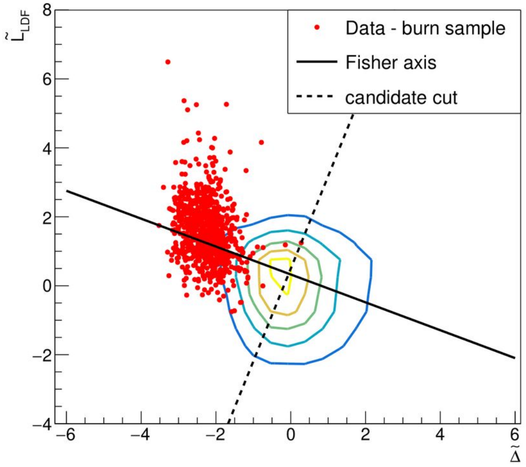


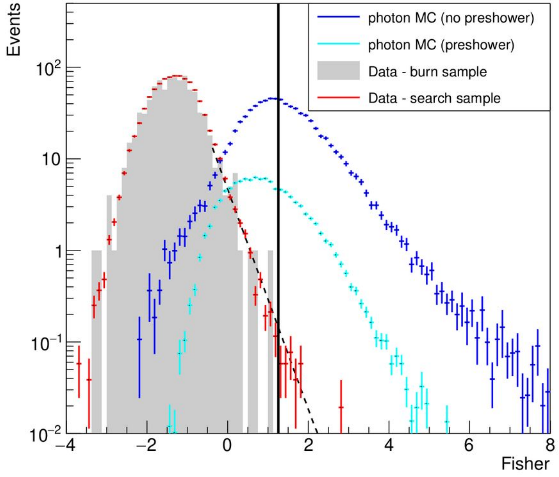
$$L_{\mathrm{LDF}} = \log_{10}\left(\frac{1}{N}\sum_{i=1}^{N}\frac{S_i}{S_{\mathrm{LDF}}(r_i)}\right)$$

Longer signal rise-time



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





► 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

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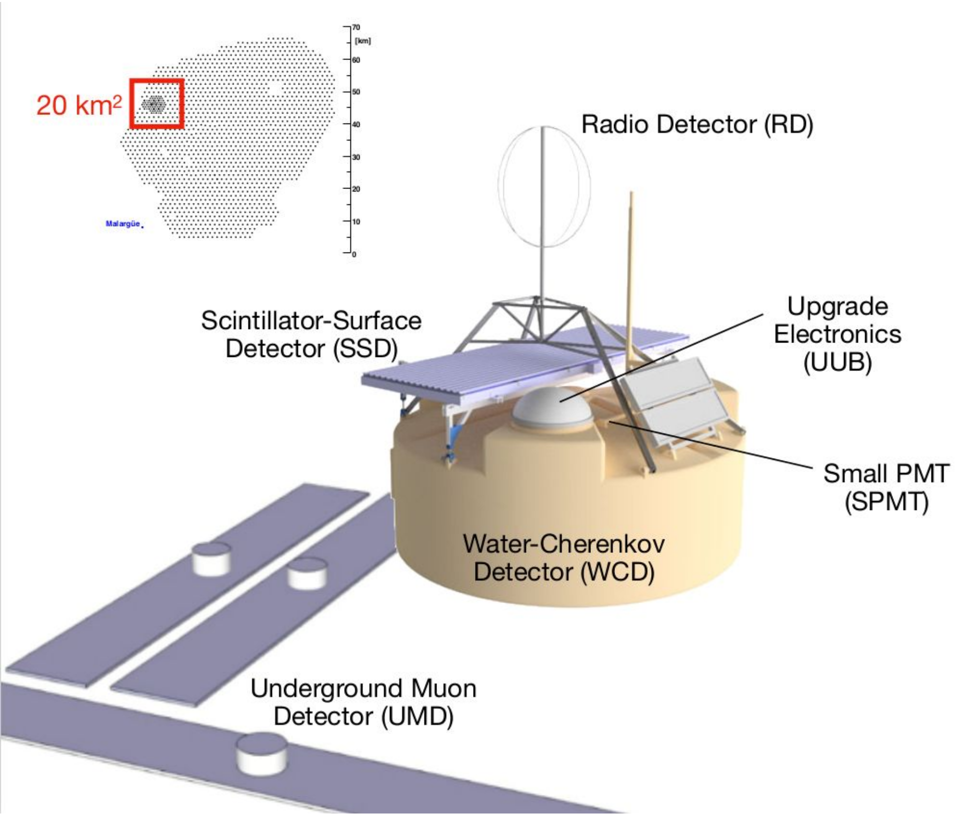
The AugerPrime Upgrade



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