image credit: Steven Saffi, Pierre Auger Collaboration

Universität Siegen | HEP Experimental High Energy Physics | CPPS Center for Particle Physics Siegen

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PIERRE AUGER OBSERVATORY

Searches for ultra-high-energy photons with the Pierre Auger Observatory: Current status and future perspectives

XIII International Conference on New Frontiers in Physics
26 Aug - 4 Sep 2024, OAC, Kolymbari, Crete, Greece

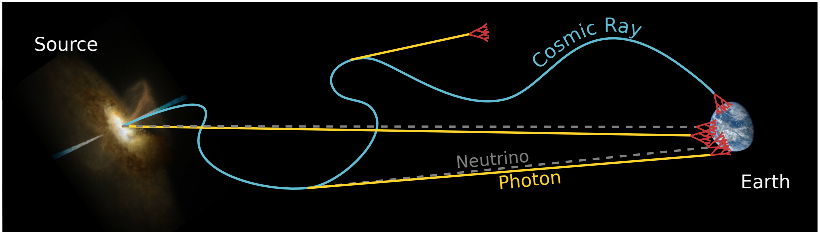
Tim Fehler[1] on behalf of the Pierre Auger Collaboration[2]

[1] Center for Particle Physics Siegen, University of Siegen, Germany

[2] Observatorio Pierre Auger, Malargüe, Argentina

28 Aug 2024

UHE photons as messengers of the Universe



- Open question in astrophysics: **Origin** and **nature** of ultra-high-energy (UHE, $E \gtrsim 10^{17}$ eV) cosmic rays?
  - **Problem:** Magnetic deflection
- UHE photons (and neutrinos) produced in interactions of cosmic radiation
  - Near sources (dense regions): Neutral particles point right back at their sources!
  - Background fields: CMB $\rightarrow$ GZK effect, ...? Photon flux sensitive to cosmic-ray composition
- Other possiblities: BSM processes (SHDM), ...
- Photons themselves can interact with background fields: **Effective UHE photon horizon** at the order of Mpc (10^{18} eV)

M. Risse and P. Homola, Mod. Phys. Lett. A **22**, 749–766 (2007)

Detecting UHE photons with air-shower detectors

- Photons initiate air showers in the atmosphere, just like hadronic cosmic rays
- Information about primary particle is coded in shower development (composition)
  - Depth of shower maximum X_{max}
  - Muon content N_μ
- Central challenge: **Distinguishing photon-induced showers from vast background of hadronic showers**

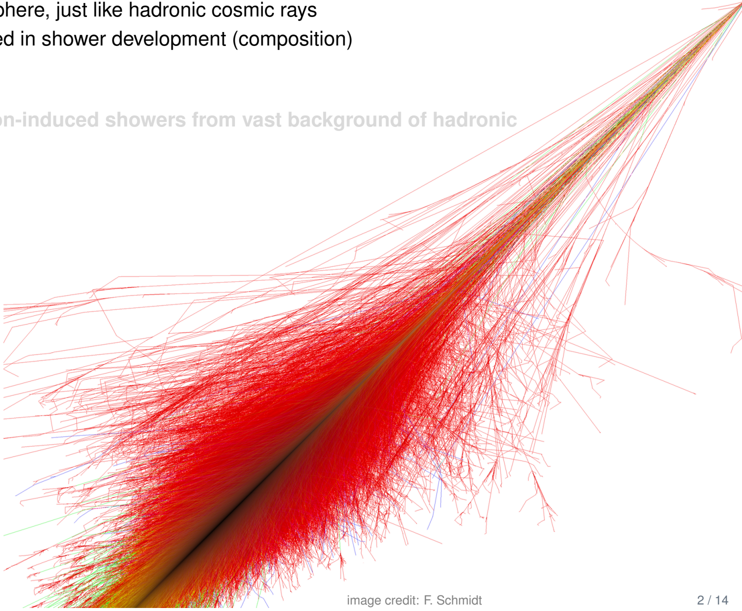


image credit: F. Schmidt

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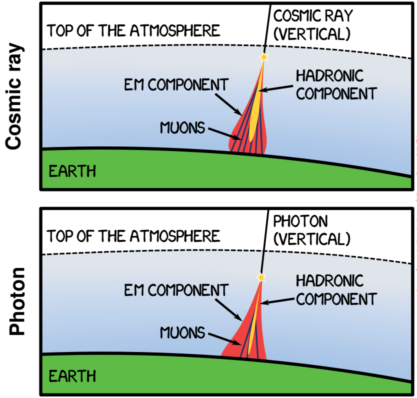


image credit: M. Niechciol

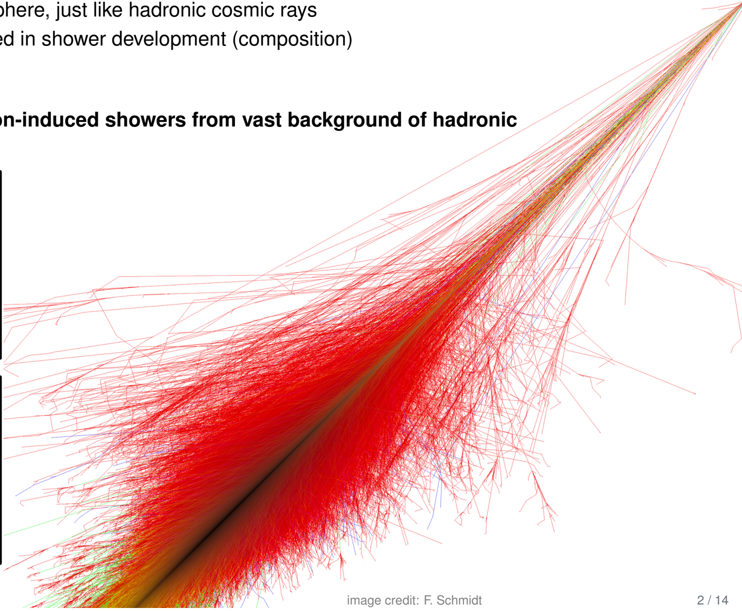
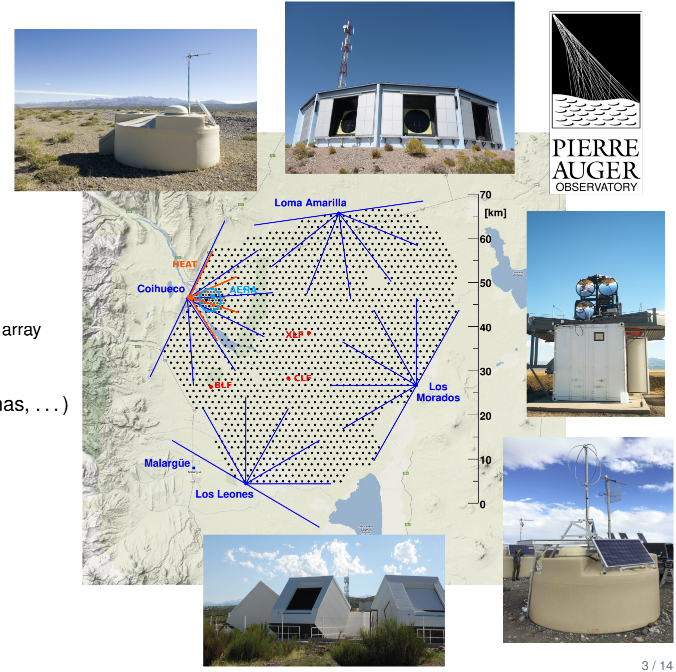


image credit: F. Schmidt

Pierre Auger Observatory

- Largest **cosmic-ray observatory** in the world
- Located near Malargüe, Argentina
- Energy range: 10^{17} eV to $> 10^{20}$ eV
- **Hybrid detector**
- **Surface detector array (SD)**
  - 1660 water-Cherenkov detectors over $3000\,\text{km}^2$
  - Footprint of shower
- **Fluorescence detector (FD)**
  - 27 telescopes distributed over 4 sites overlooking SD array
  - Longitudinal shower development
  - $\sim 15\%$ duty cycle
- Auxiliary detector systems (infill arrays, radio antennas, . . .)
- Atmospheric monitoring (LIDAR, laser facilities, . . .)
- Currently: **AugerPrime upgrade**
  - Primary mass estimate on shower-by-shower basis



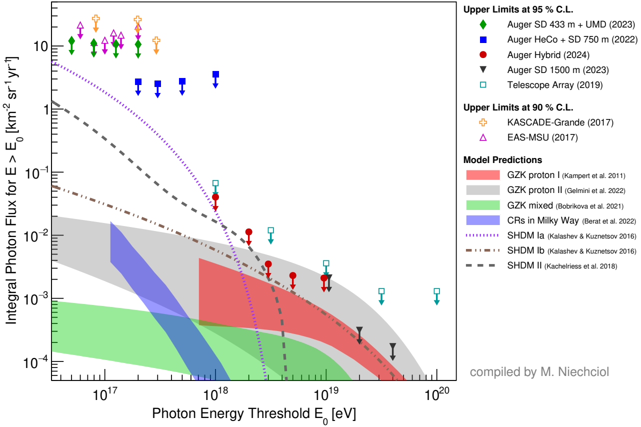
Talk by **V. de Souza**
today, 28 Aug, 09:30

Pierre Auger Coll., NIMA **798**, 172–213 (2015)

Map of recent UHE photon searches

Map of recent UHE photon searches

- **No UHE photon unambiguously identified so far**
- Limits on diffuse integral flux of photons



① SD 433 m + UMD — N. González, Pierre Auger Coll. PoS(ICRC2023) **444**, 238 (2023)
② HeCo + SD 750 m — Pierre Auger Coll., ApJ **933**, 125 (2022)
③ Hybrid — Pierre Auger Coll., (2024), arXiv:2406.07439 [astro-ph.HE], acc. by PRD
④ SD — Pierre Auger Coll., JCAP **2023**, 021 (2023)

see also overview: Pierre Auger Coll., Universe **8**, 579 (2022)

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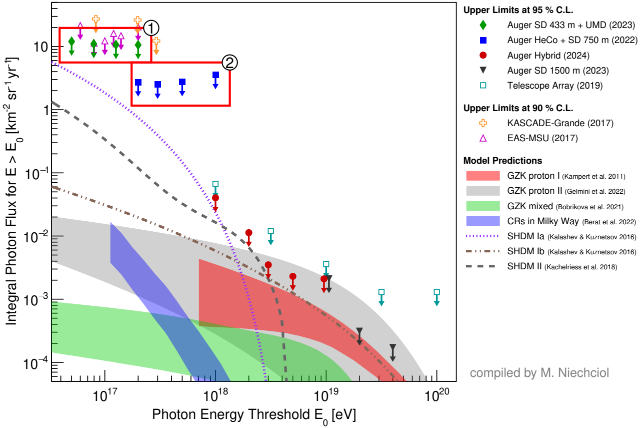

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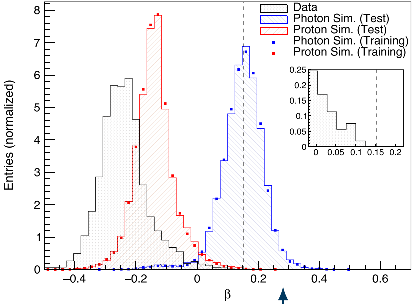
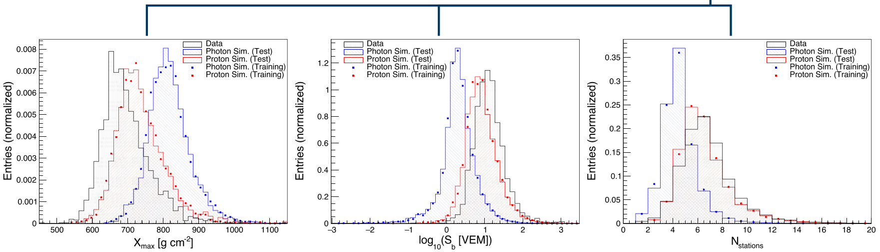
“Low”-energy: HeCo + SD 750 m

- **Low-energy hybrid extensions** of Observatory
- $E \geq 2 \times 10^{17}$ eV
- MVA with three observables (X_{max}, S_b, N_{stations}) employing **BDT**
- **Photon candidate threshold** at 50% signal efficiency
  - $\sim 99.9\%$ background rejection
- **Data period:** 1 June 2010 – 31 December 2015, exposure: $\sim 2.5\,\text{km}^2$ sr yr
- No candidate events observed



$$S_b = \sum_{i=1}^{N_{\text{stations}}} S_i \times \left(\frac{r_i}{1000\,\text{m}}\right)^b$$



Pierre Auger Coll., ApJ **933**, 125 (2022)

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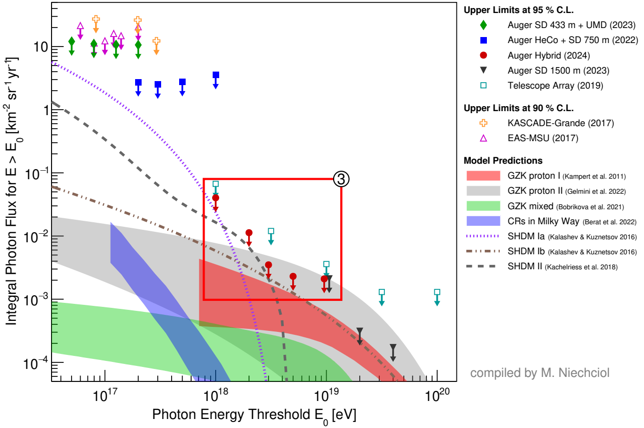

compiled by M. Niechciol

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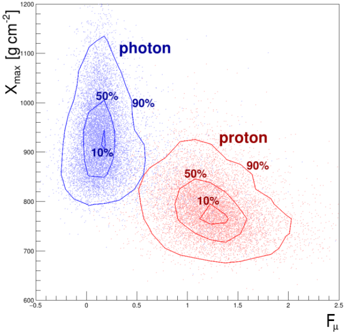
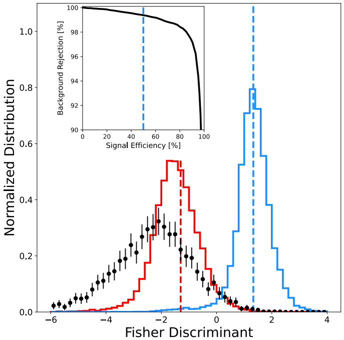
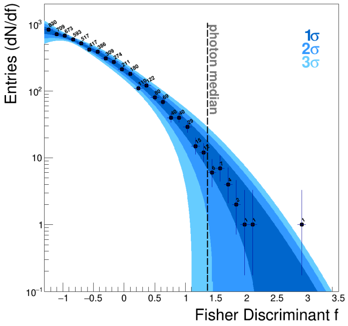
“Medium”-energy: Hybrid







- $E \geq 10^{18}$ eV
- Observable F_μ as proxy for muon content (**air-shower universality**)
- Combining $X_{\rm max}$ and F_μ with **Fisher analysis** to single discriminant
- Photon candidate threshold at 50% signal efficiency
- **Data period:** 1 January 2005 – 31 December 2017, exposure: ~ 1000 km^2 sr yr
- 22 candidate events (consistent with background expectation from data)

Pierre Auger Coll., (2024), arXiv:2406.07439 [astro-ph.HE], acc. by PRD

Map of recent UHE photon searches

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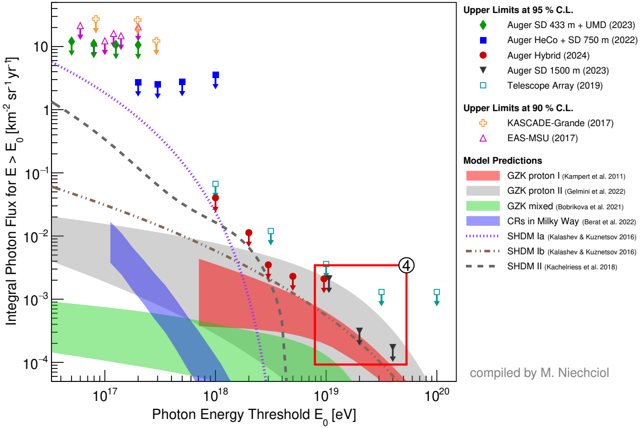

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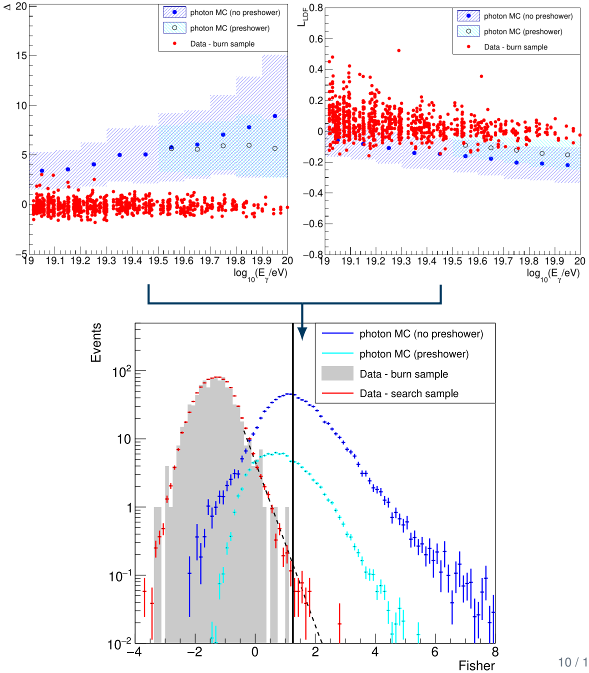
④ SD — Pierre Auger Coll., JCAP **2023**, 021 (2023)

see also overview: Pierre Auger Coll., Universe **8**, 579 (2022)

“High”-energy: SD

- $E \geq 10^{19}$ eV
- Two **benchmark observables** from SD:
  - Δ Signal risetime
  - L_{LDF} Steepness of lateral distribution of signal
- Combination to discriminant with **Fisher analysis**
- Candidate threshold at 50% signal efficiency
- **Data period:** 1 January 2004 – 30 June 2020, exposure: $\sim 17\,000$ km^2 sr yr
- 16 events pass candidate cut (consistent with background expectation from data)
- Established upper limits already approach most optimistic model of cosmogenic photon flux



Pierre Auger Coll., JCAP **2023**, 021 (2023)

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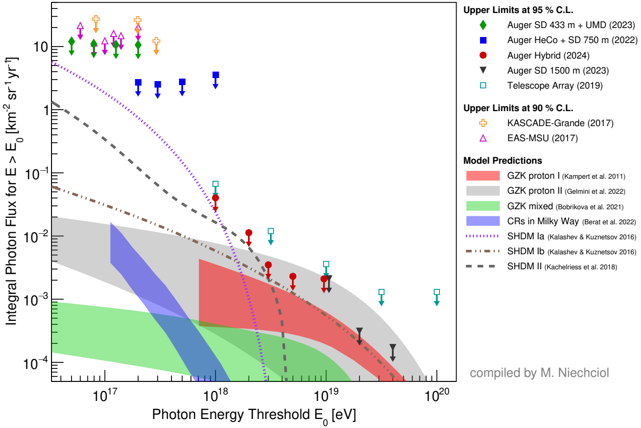

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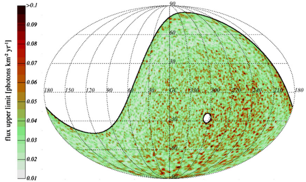
see also overview: Pierre Auger Coll., Universe **8**, 579 (2022)

- Directional efforts (blind and targeted)
  - Pierre Auger Coll., ApJ **789**, 160 (2014)



  - Pierre Auger Coll., ApJL **837**, L25 (2017)

Class	N	$\mathscr{P}$	$\mathscr{P}_w$	p	p^*	$f_{UL}^{0.95}$ [km^{-2} yr^{-1}]
msec PSRs	67	0.14	0.57	0.010	0.476	0.043
γ-ray PSRs	75	0.98	0.97	0.007	0.431	0.045
LMXB	87	0.74	0.13	0.014	0.718	0.046
HMXB	48	0.84	0.33	0.040	0.856	0.036
H.E.S.S. PWN	17	0.90	0.92	0.104	0.845	0.038
H.E.S.S. other	16	0.52	0.12	0.042	0.493	0.040
H.E.S.S. UNID	20	0.45	0.79	0.014	0.251	0.045
Microquasars	13	0.48	0.29	0.037	0.391	0.045
Magnetars	16	0.89	0.30	0.115	0.858	0.031
Gal. Center	1	0.59	0.59	0.471	0.471	0.024
LMC	3	0.62	0.52	0.463	0.845	0.030
Cen A	1	0.31	0.31	0.221	0.221	0.031

- Multimessenger efforts (GW follow-up)

Talk by **J. P. Lundquist**
on Wed, 04 Sep, 10:00

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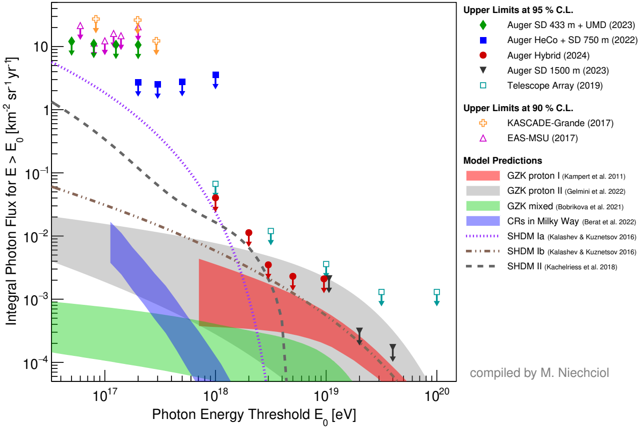

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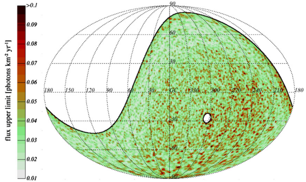

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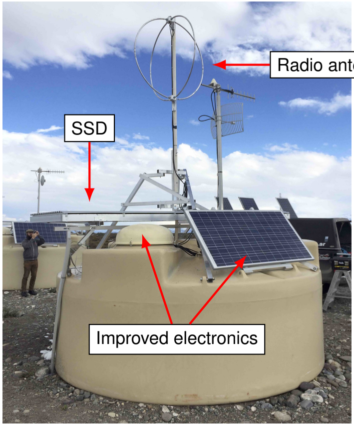
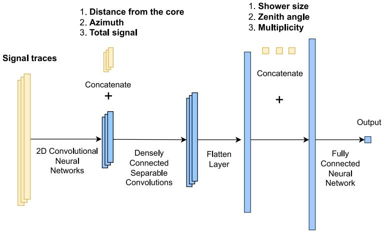
Future perspectives



- Constant increase in exposure
- **AugerPrime** upgrade → Talk by **D. Schmidt** on Tue, 3 Sep, 12:20
  A. Castellina, Pierre Auger Coll. EPJ Web Conf. **210**, 06002 (2019),
  Pierre Auger Coll., (2016), arXiv:1604.03637 [astro-ph]
  - **Composition sensitivity:** Scintillator (SSD) on every station
  - Full-scale **radio detector** (RD)
  - Improved electronics/software, additional small PMT (dynamic range), . . .
  - Running in Phase II until at least 2035
- New **analysis approaches**: Deep learning, air-shower universality, . . .



e.g. E. Guido et al., PoS(ICRC2023), 191 (2023)

Summary

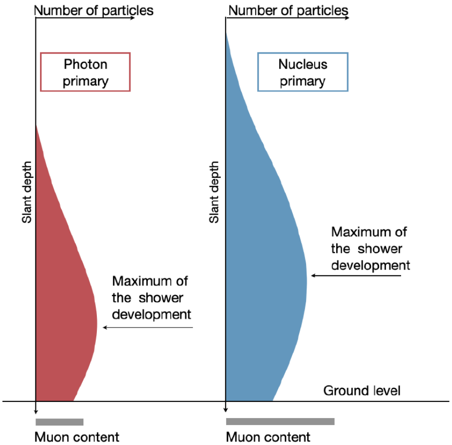
- UHE photons are connected to diverse astrophysical processes and can provide unique insights into the Universe (in our "galactic neighborhood")
- No UHE photon unambiguously identified so far
- Pierre Auger Collaboration has established most stringent upper limits on UHE photon flux across more than three orders of magnitude in energy (5×10^{16} eV to $> 10^{20}$ eV)
- Major advances with additional equipment (AugerPrime upgrade) and refined analysis techniques expected in the future

Thank you for your attention!

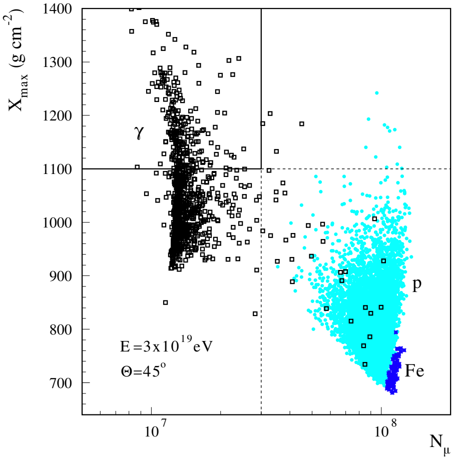
image credit: Pierre Auger Collaboration

BACK UP

How to identify UHE photon primaries



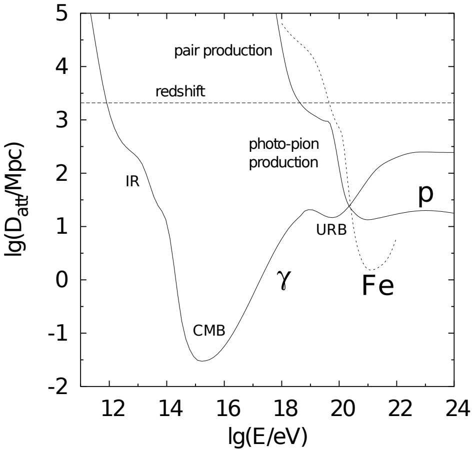
Pierre Auger Coll., Universe **8**, 579 (2022)



M. Risse and P. Homola, Mod. Phys. Lett. A **22**, 749–766 (2007)

Effective UHE photon horizon

Energy loss length of photons in background fields



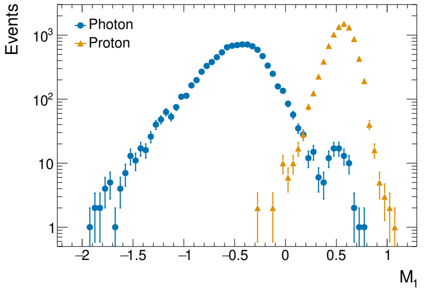
M. Risse and P. Homola, Mod. Phys. Lett. A **22**, 749–766 (2007)

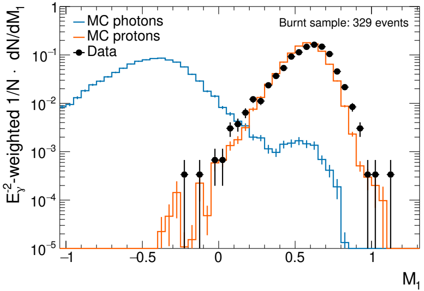
"Low"-energy: SD 433 m + UMD

- Based on low-energy extension of Observatory
  - 433 m SD infill array
  - Underground Muon Detectors (UMD)
- $E \geq 5 \times 10^{16}$ eV
- Customized photon energy scale for all events
- Key observable M_b (lateral muon density)

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

- Candidate threshold at 50% signal efficiency
- **Data period:** 17 December 2020 – 31 March 2022, exposure: $\sim 0.6\,\mathrm{km}^2$ sr yr
- No candidate events observed





N. González, Pierre Auger Coll. PoS(ICRC2023) **444**, 238 (2023)

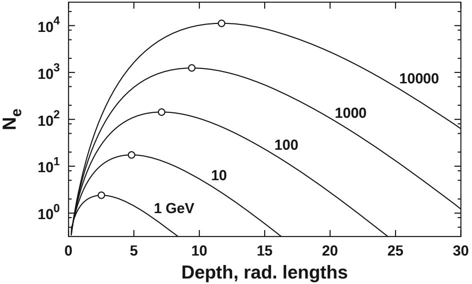
Air-shower universality

- **General idea:** Energy spectrum of secondary particles, angular and lateral distributions depend only on energy of primary and stage of shower development
- **Consequence:** (Electromagnetic part of) shower development can be described by $\vec{n}_{\mathrm{arrival}}$, $\vec{x}_{\mathrm{core}}$ E_{primary}, $X_{\max}$, (N_μ)
- General model of signal in SD stations

  M. Ave et al., Astroparticle Physics **87**, 23–39 (2017)

  M. Ave et al., Astroparticle Physics **88**, 46–59 (2017)

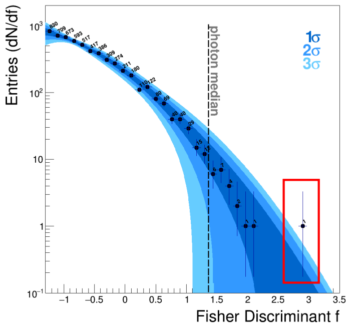
  M. Stadelmaier et al., Phys. Rev. D **110**, 023030 (2024)
- Missing quantities can be calculated from the other ones!

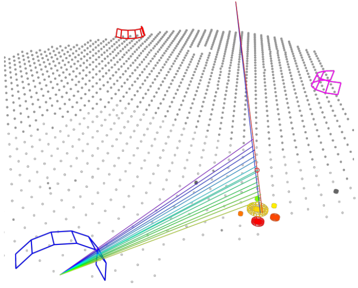


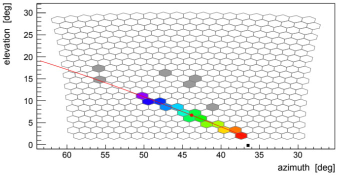
T. Stanev, High Energy Cosmic Rays, 3rd ed. (Springer Int. Pub., 2021)

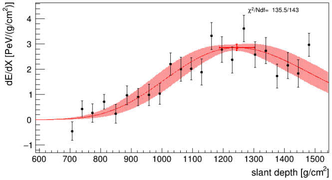
Investigating the outlier in the hybrid search

Pierre Auger Coll., (2024), arXiv:2406.07439 [astro-ph.HE], acc. by PRD









- Proton primary cannot be significantly excluded
- Also have to consider empty bins to estimate significance of this excess