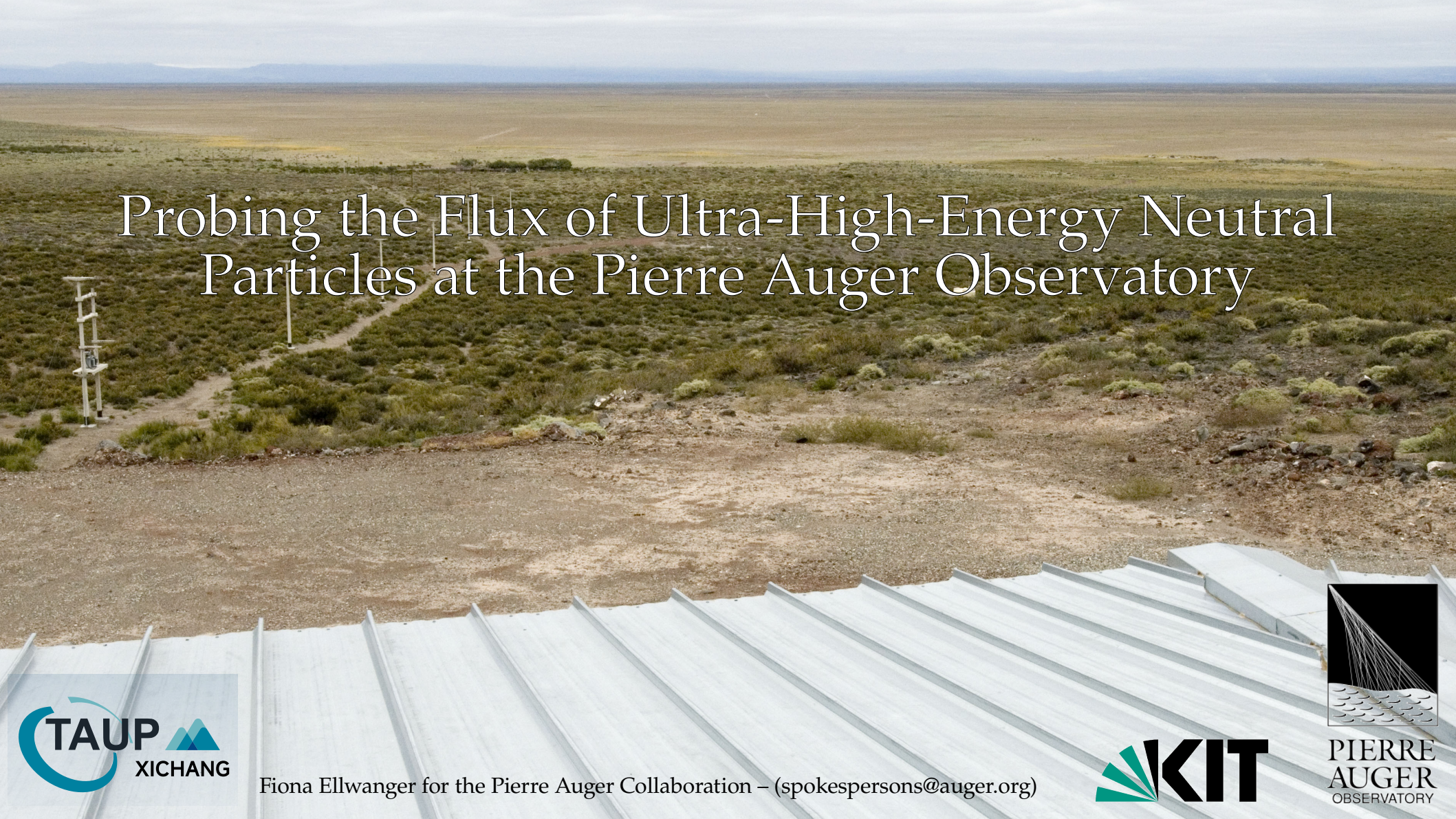
Probing the Flux of Ultra-High-Energy Neutral Particles at the Pierre Auger Observatory



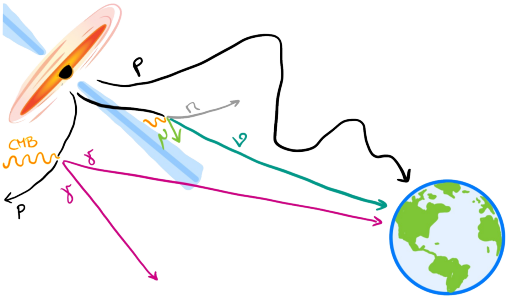
Fiona Ellwanger for the Pierre Auger Collaboration – (spokespersons@auger.org)

Production of Ultra-High Energy Photons/Neutrinos

➔ *Astrophysical:* sources of cosmic rays also produce γ and ν

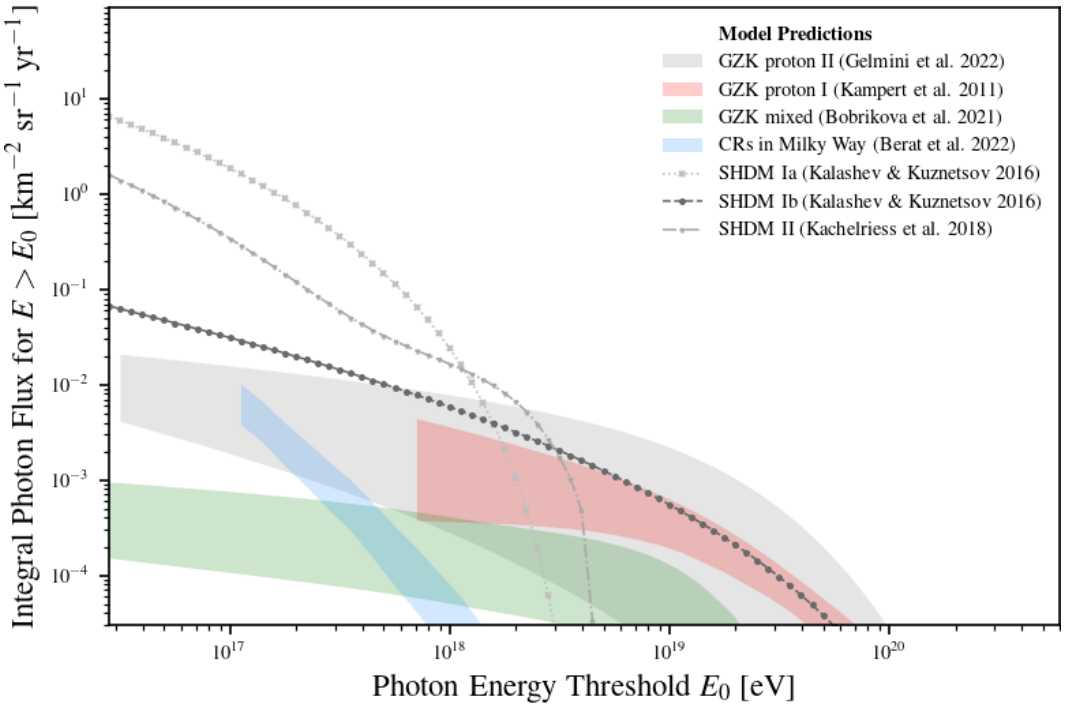
➔ *Cosmogenic:*

- interaction with CMB (GZK)
- interaction with matter (e.g. in galactic disk)
- decay of super-heavy dark matter

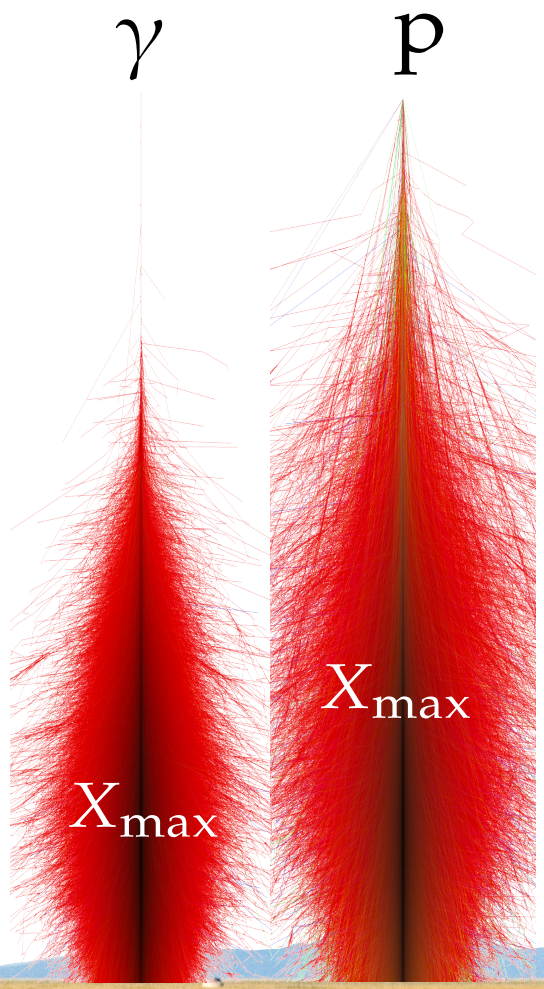


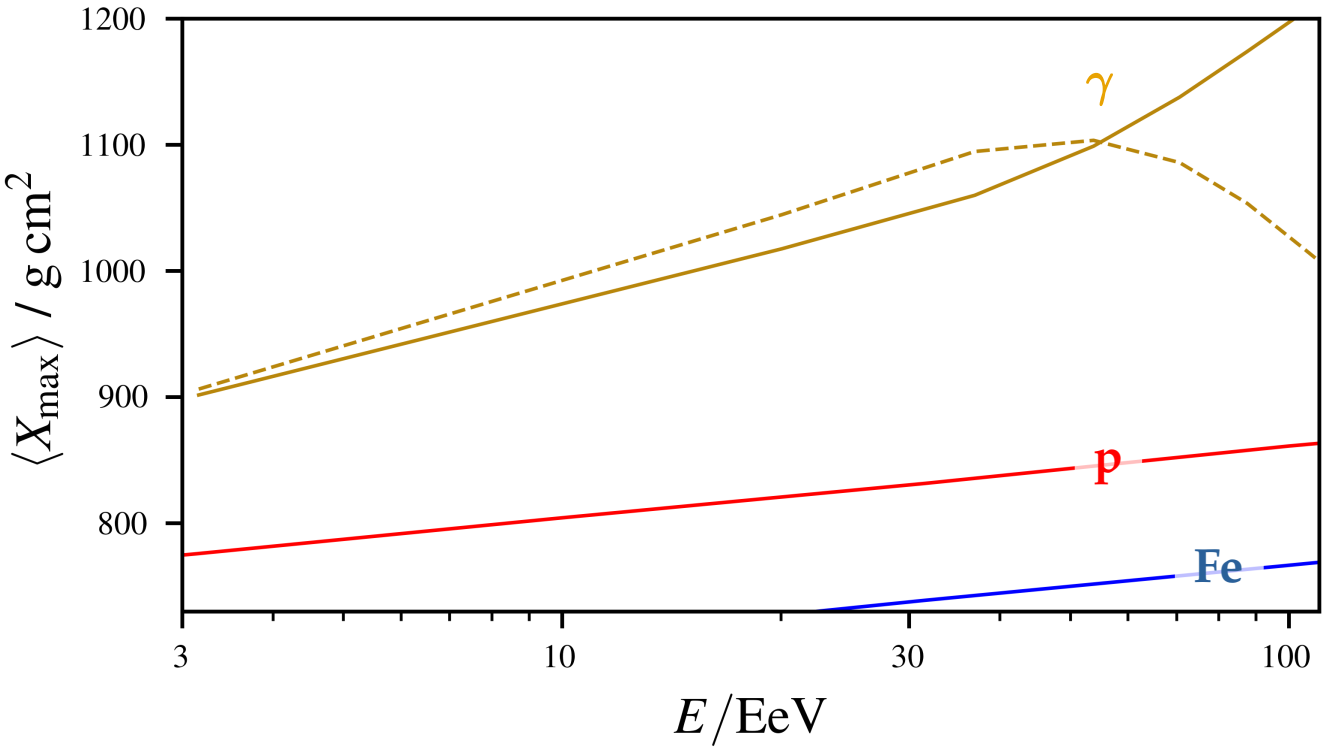
$$p + p/\gamma \rightarrow \pi^0 + X$$
$$\rightarrow 2\gamma$$

$$p + p/\gamma \rightarrow \pi^{\pm} + X$$
$$\rightarrow \mu^{\pm} + \nu_\mu/\bar{\nu}_\mu$$
$$\rightarrow e^{\pm} + \bar{\nu_\mu}/\nu_\mu + \nu_e/\bar{\nu}_e$$



Photon induced air showers





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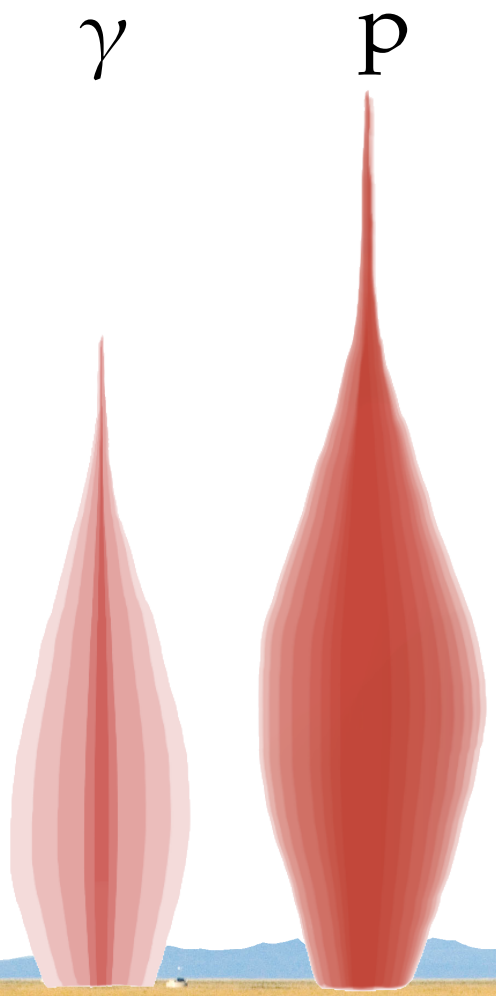
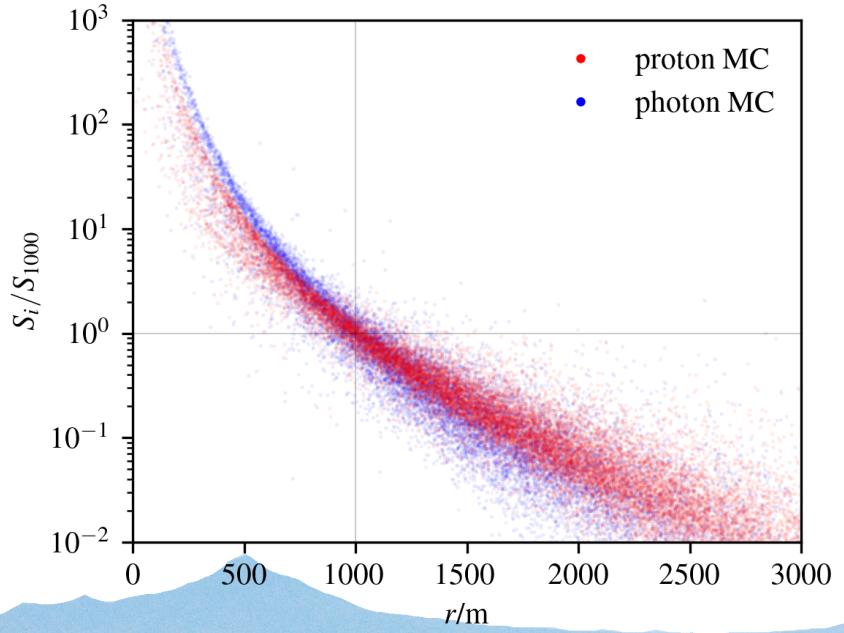


→ deeper maximum of the shower X_{max}
→ steeper lateral distribution of particles



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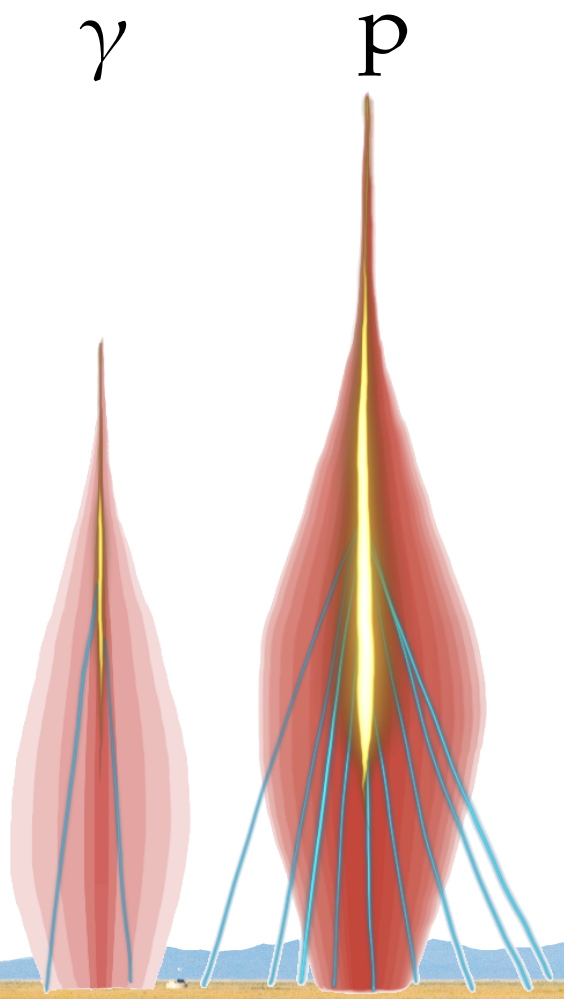
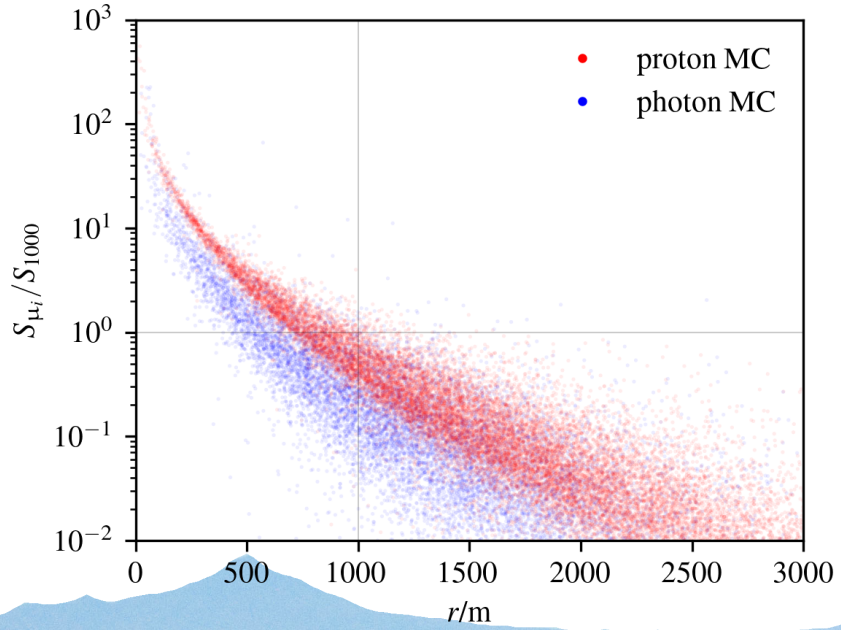
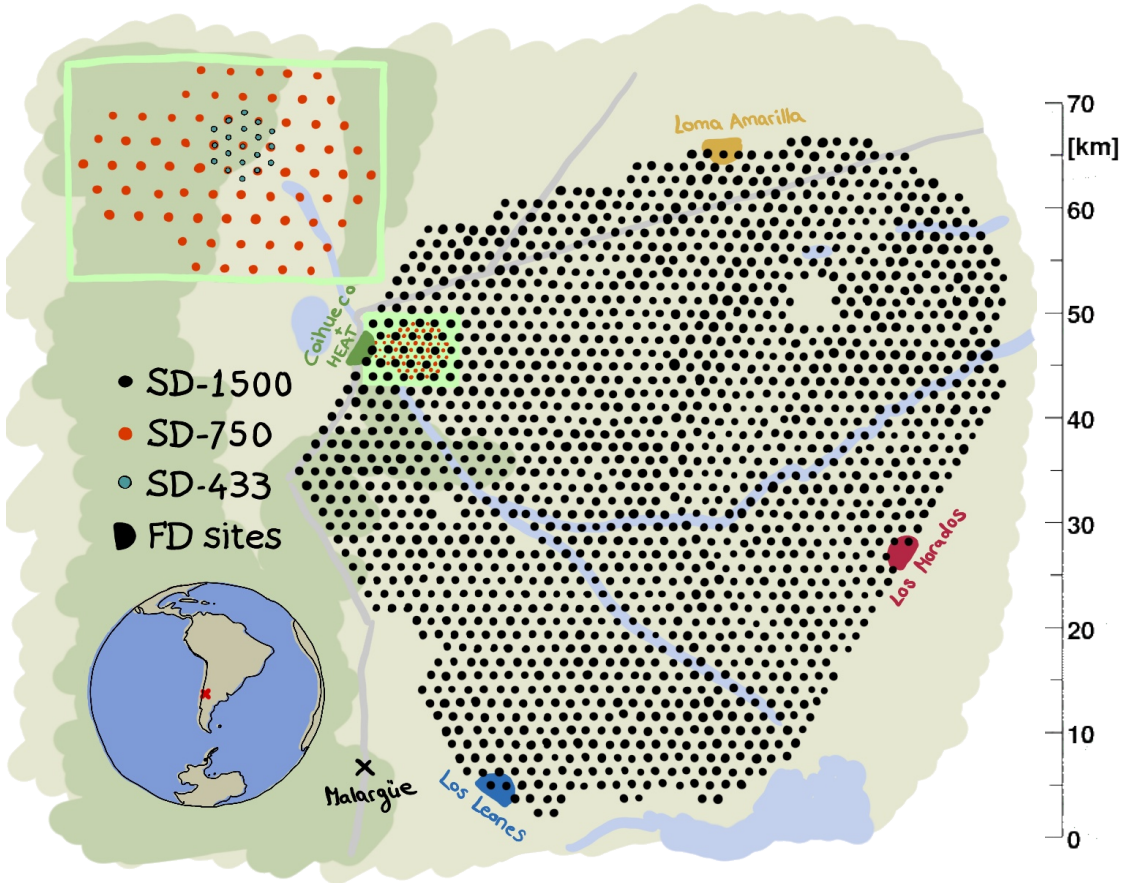


→ deeper maximum of the shower X_{max}
→ steeper lateral distribution of particles
→ reduced hadronic component
→ suppressed muonic component



The Pierre Auger Observatory

- ➔ 1400m altitude
- ➔ 3000 km^2
- ➔ Designed to detect secondary particles of extensive air showers
- ➔ Hybrid detector layout
  - Fluorescence Detector
  - Surface Detector



The Surface Detector (SD)

- ➜ >1600 water-Cherenkov detector stations
- ➜ triangular grid
- ➜ 3 arrays with different densities
  - 1500 m spacing
  - 750 m spacing
  - 433 m spacing
- ➜ 100% duty-cycle
- ➜ Calibrated with atmospheric muons

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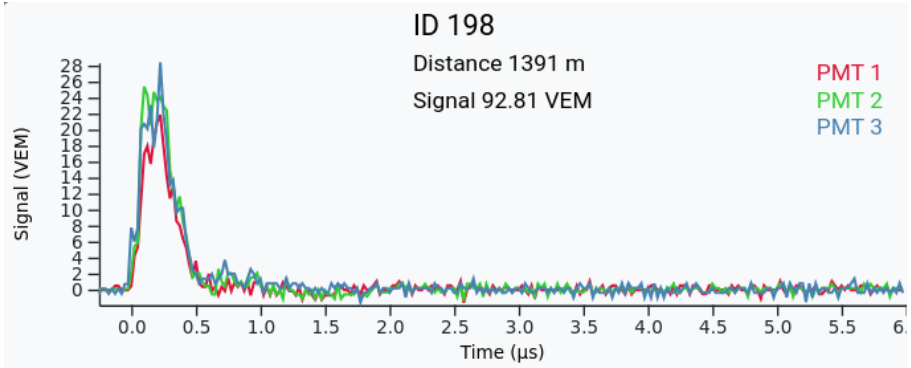
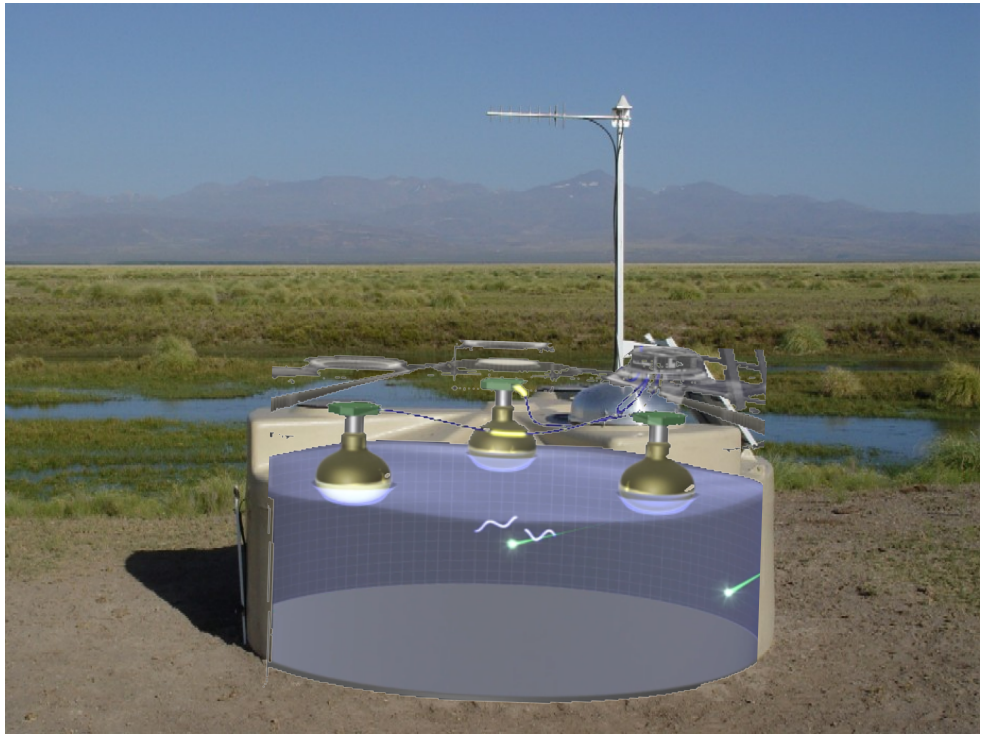
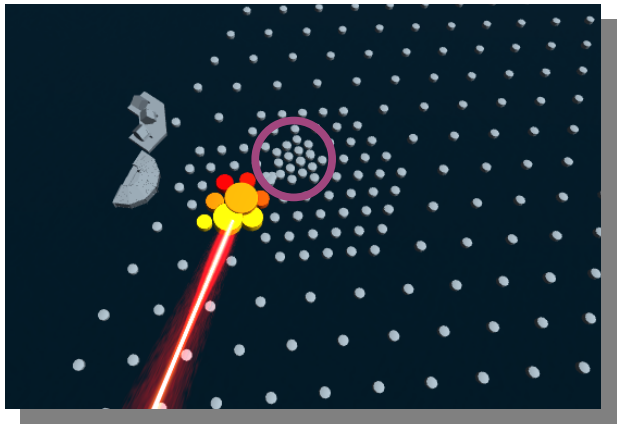


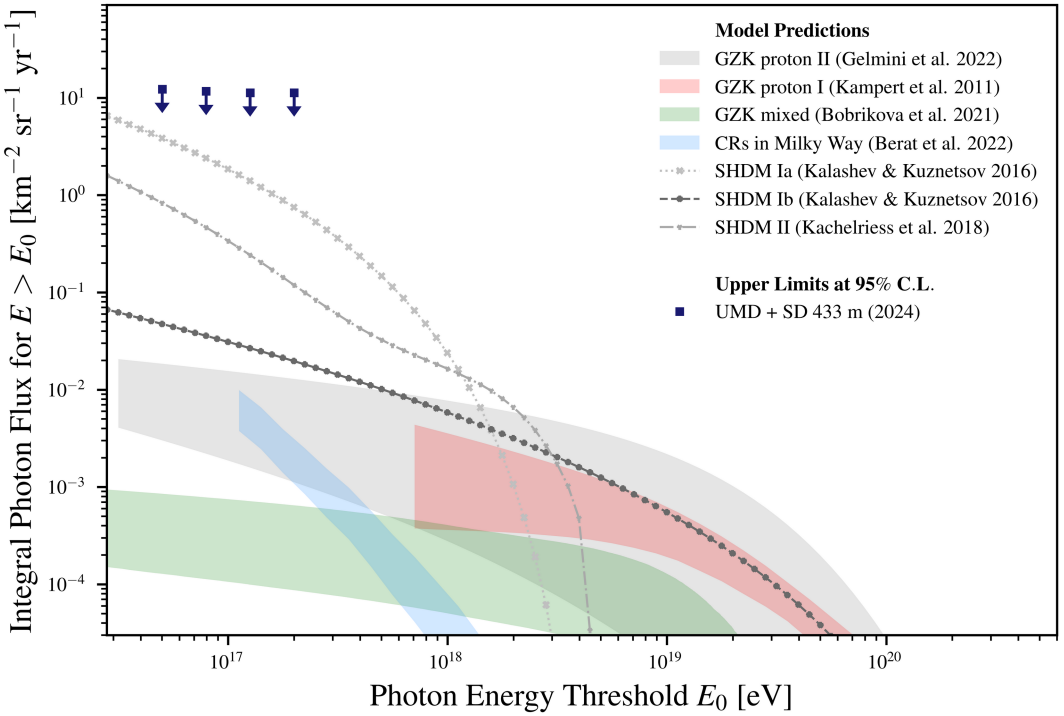


Diffuse flux of photons with energies above tens of PeV

JCAP05(2025)061

➔ Estimate on muon density, ρ_μ, from **underground muon detectors** (UMD)

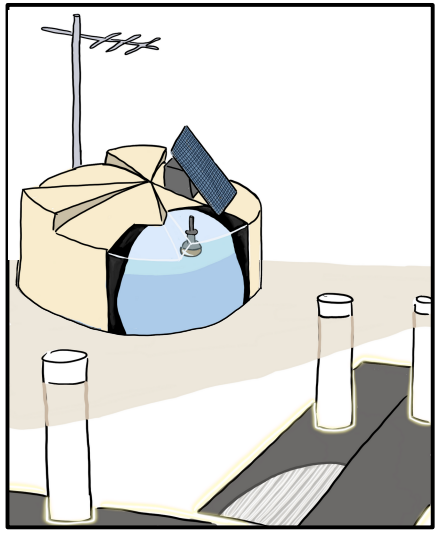




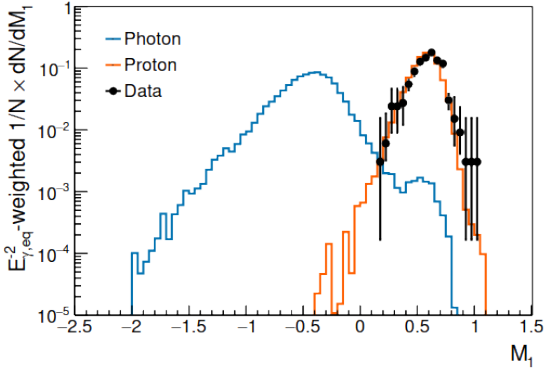
Diffuse flux of photons with energies above tens of PeV

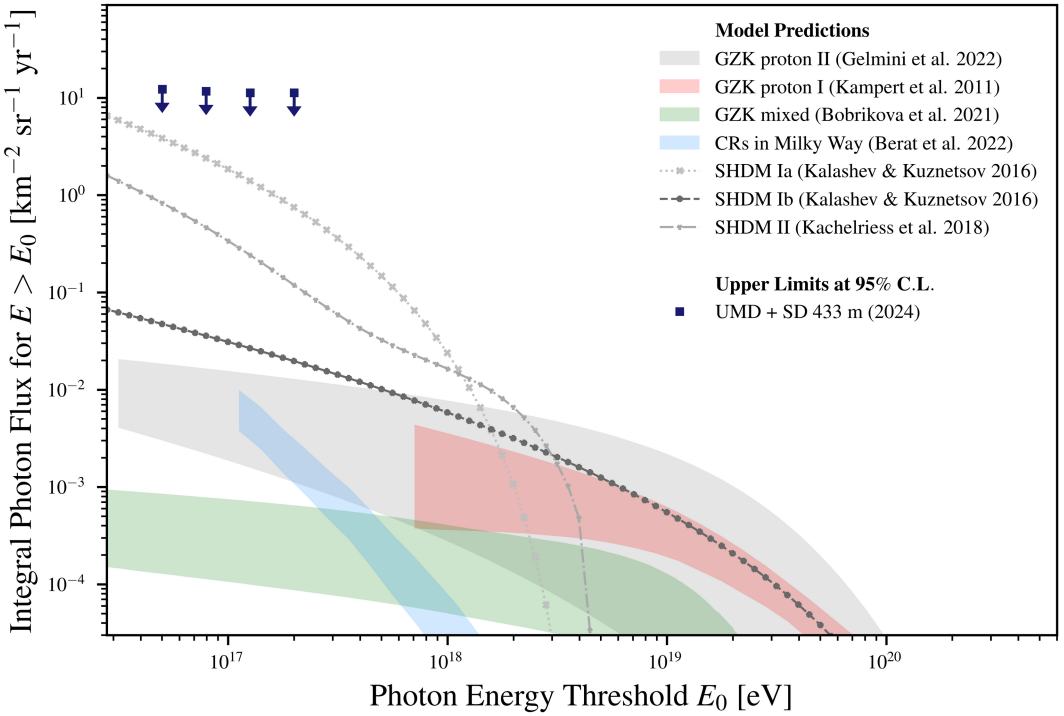
JCAP05(2025)061

- ➔ Estimate on muon density, ρ_μ, from **underground muon detectors** (UMD)
- ➔ No candidate γ found



$$M_1 = \lg\left(\sum_i^{\text{stations}} \frac{\rho_\mu(r_i)}{\rho_\mu^{\text{proton}}(r_{\text{ref}})} \left(\frac{r_i}{r_{\text{ref}}}\right)\right)$$

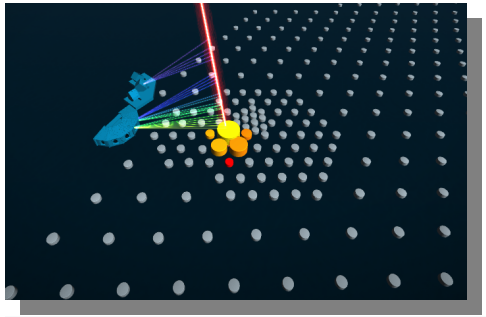


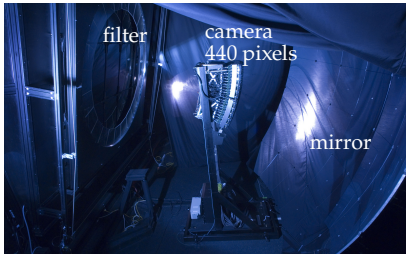


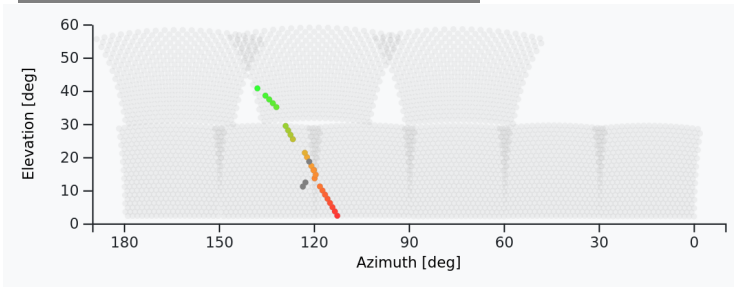
Diffuse flux of photons with energies above tens of 2×10^{17}eV

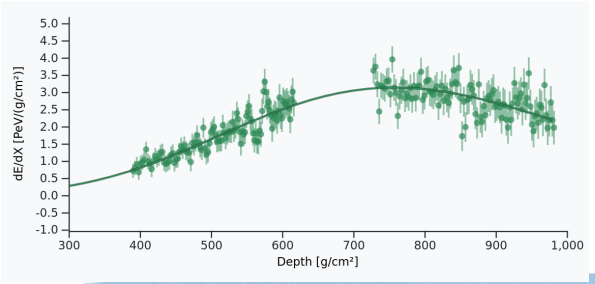
ApJ 933 (2022) 125

→ hybrid data from the low-energy extensions

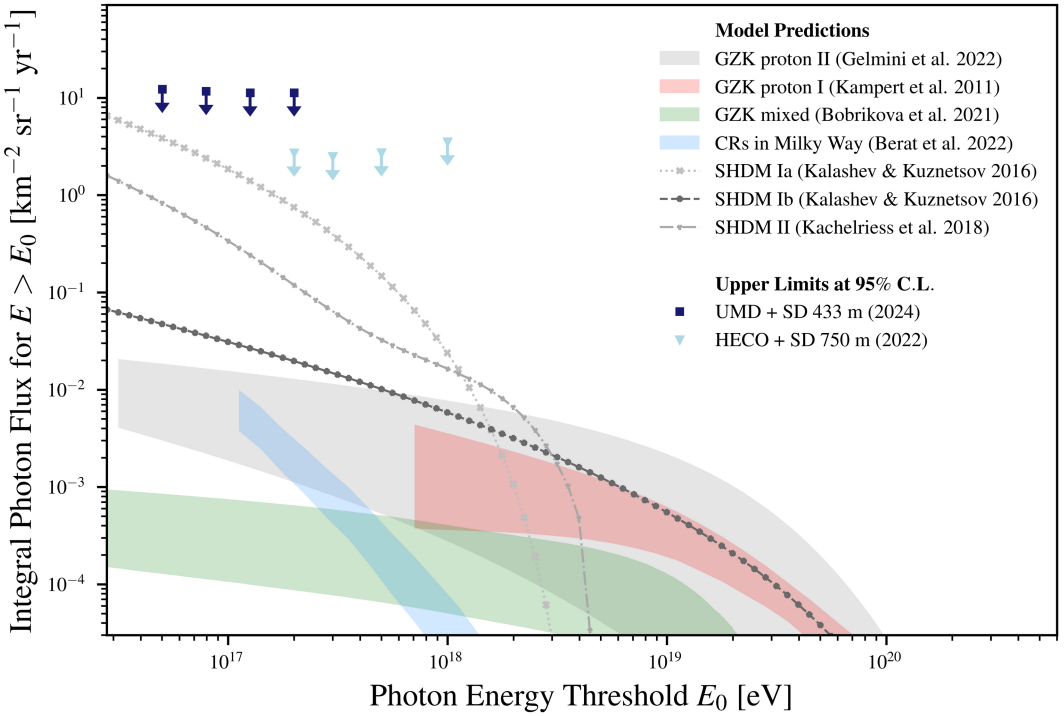








→ X_{max}



Diffuse flux of photons with energies above tens of 2×10^{17}eV

ApJ 933 (2022) 125

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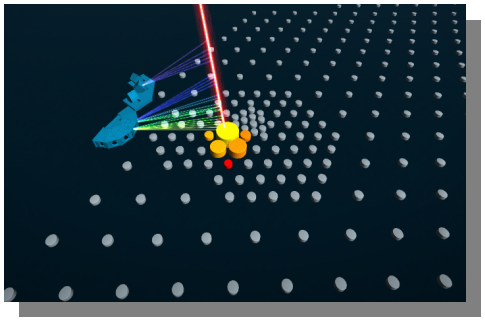


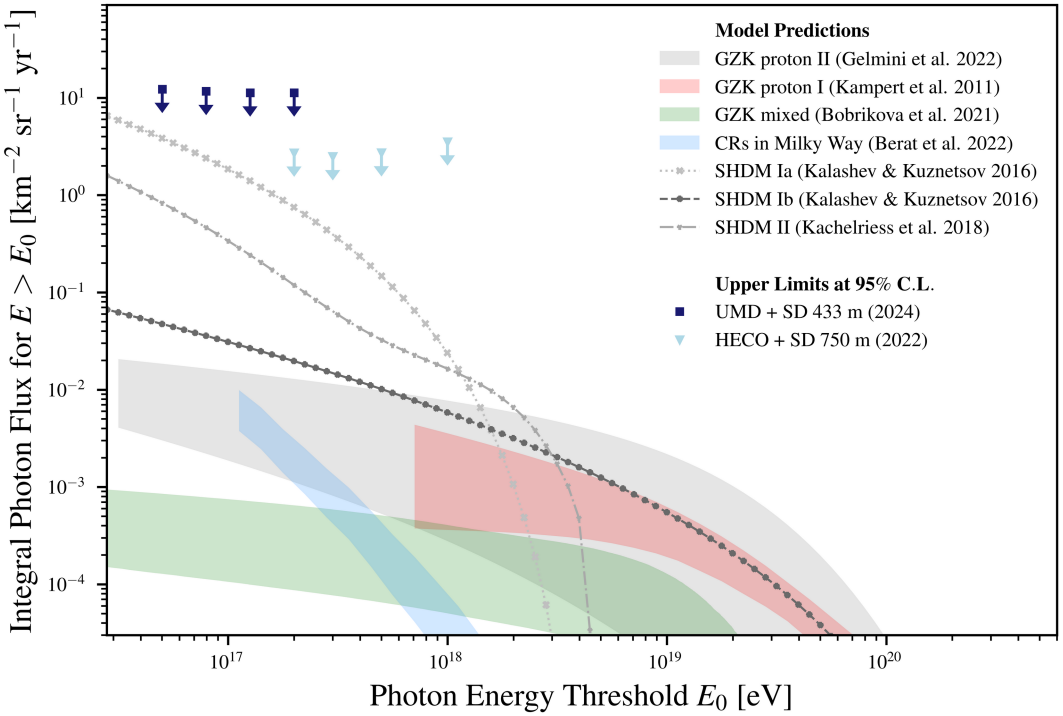
➔ BDT analysis

- X_{max} from FD
- Steepness of the LDF

$$S_4 = \sum_{i}^{\text{stations}} S_i \left(\frac{r_i}{1000\,m}\right)^4$$

- Number of stations, N_{stations}

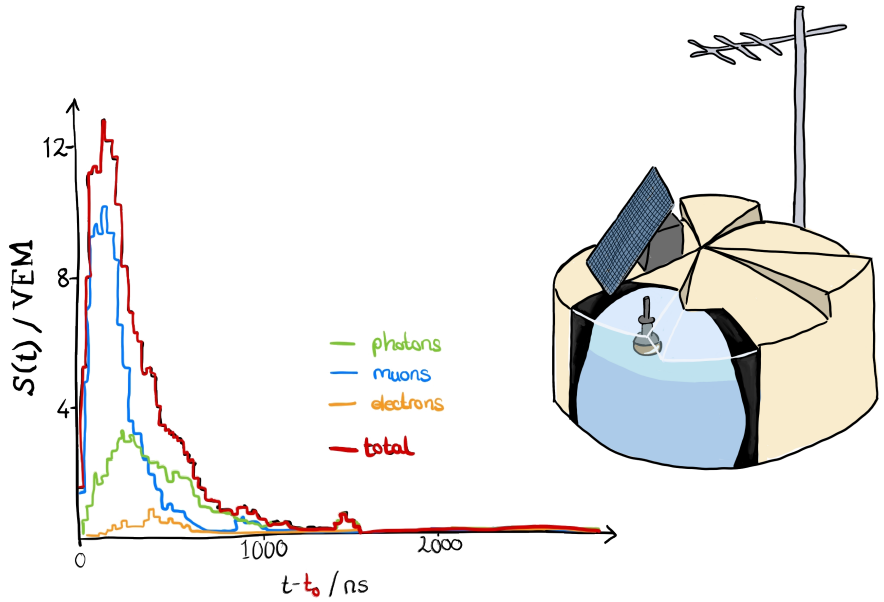
➔ No γ candidates found

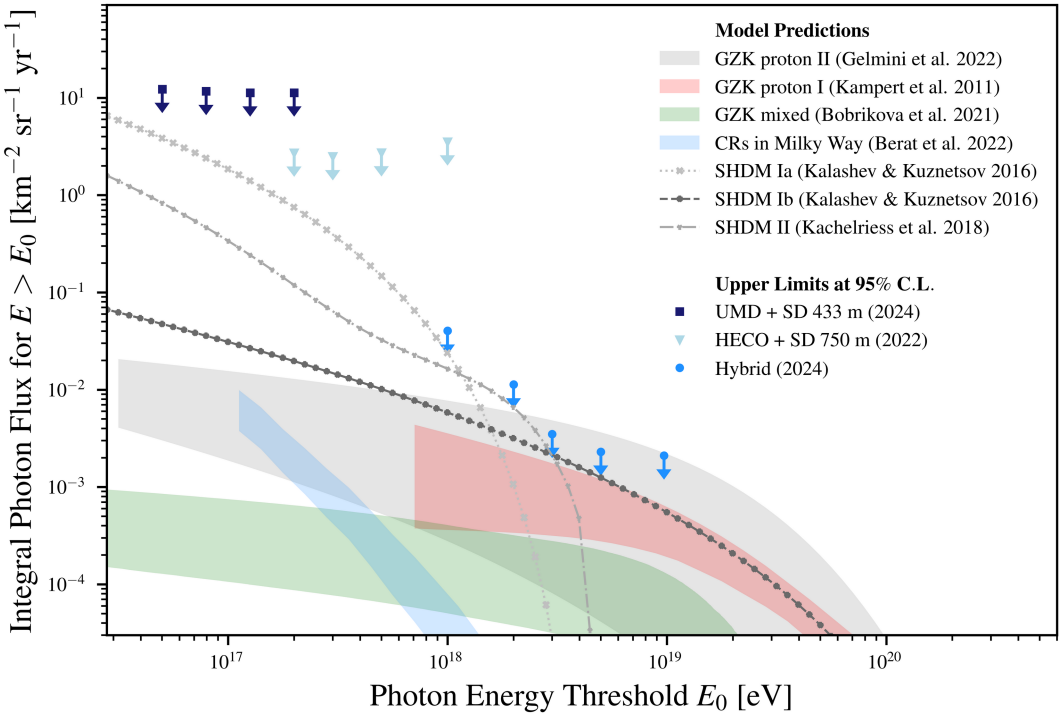


Diffuse flux of photons with energies above tens of 10^{18}eV

PRD 110 (2024) 062005

- ➜ Hybrid data
- ➜ Fluorescence detector ➜ $E, \mathbf{X}_{\max}, (\theta, \phi)$
- ➜ At least one SD station
  - ➜ shower universality model ➜ $\mathbf{F}_{\mu}$





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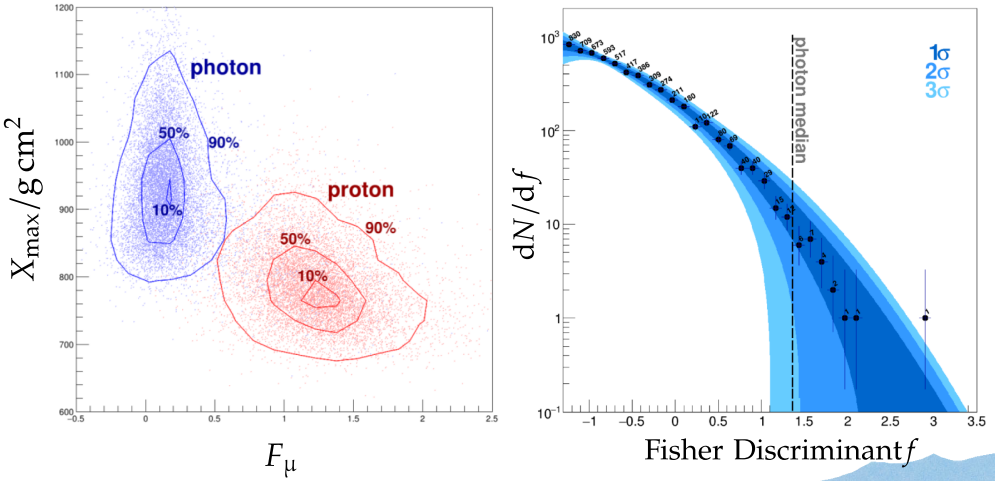
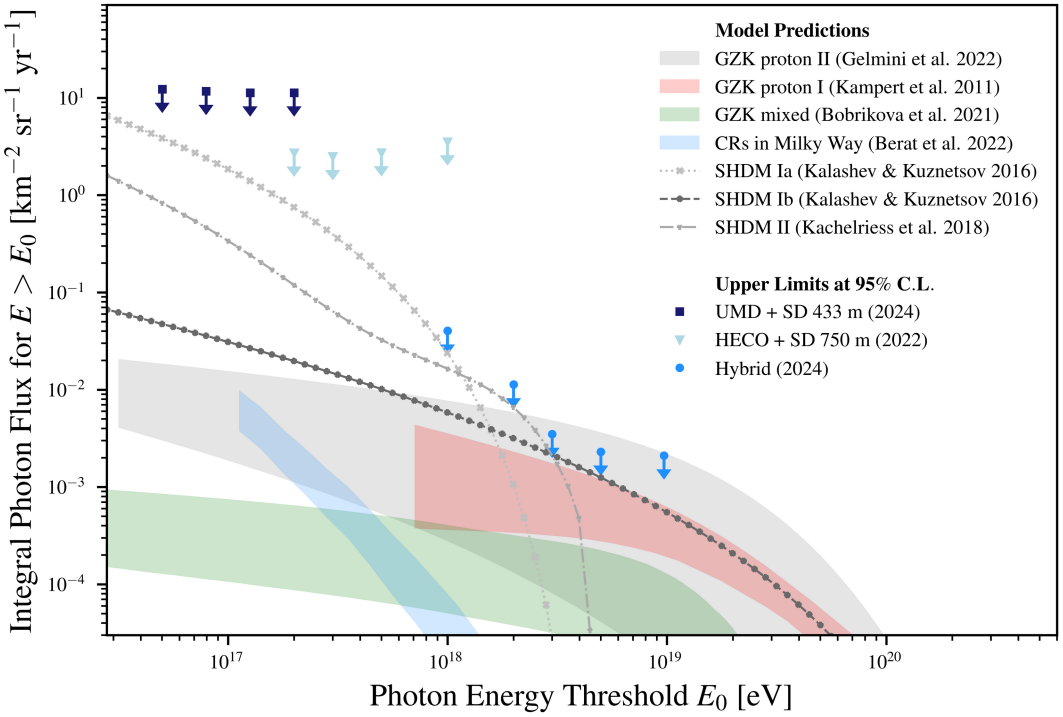
$$F_\mu = \frac{S_\mu}{S_\mu(\text{proton})}.$$

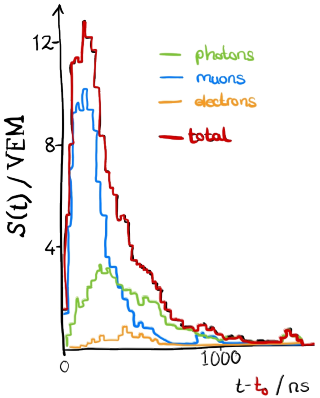


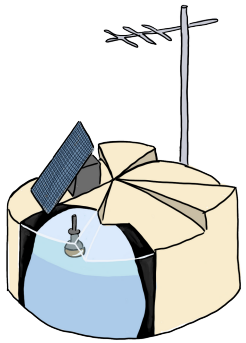


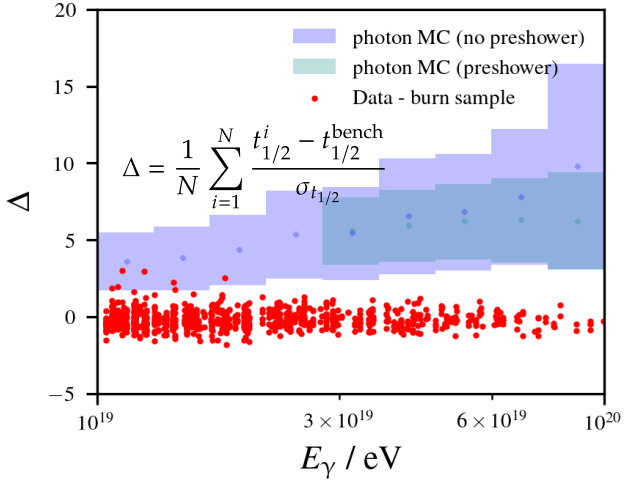
- ➔ 22 candidates, consistent with expected background (30±15)

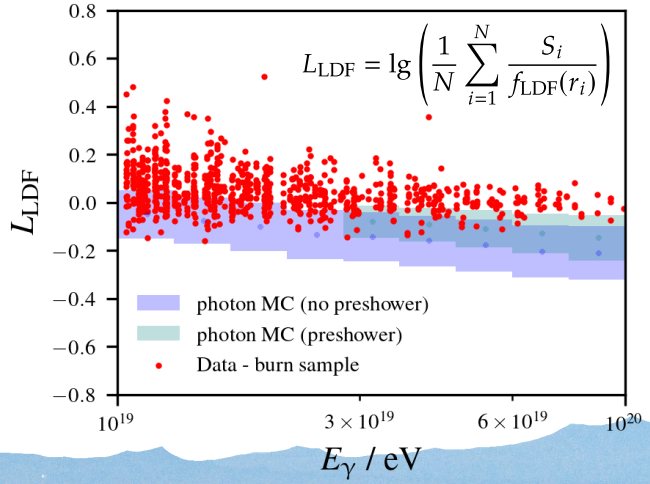
Diffuse flux of photons with energies above 10^{19}eV

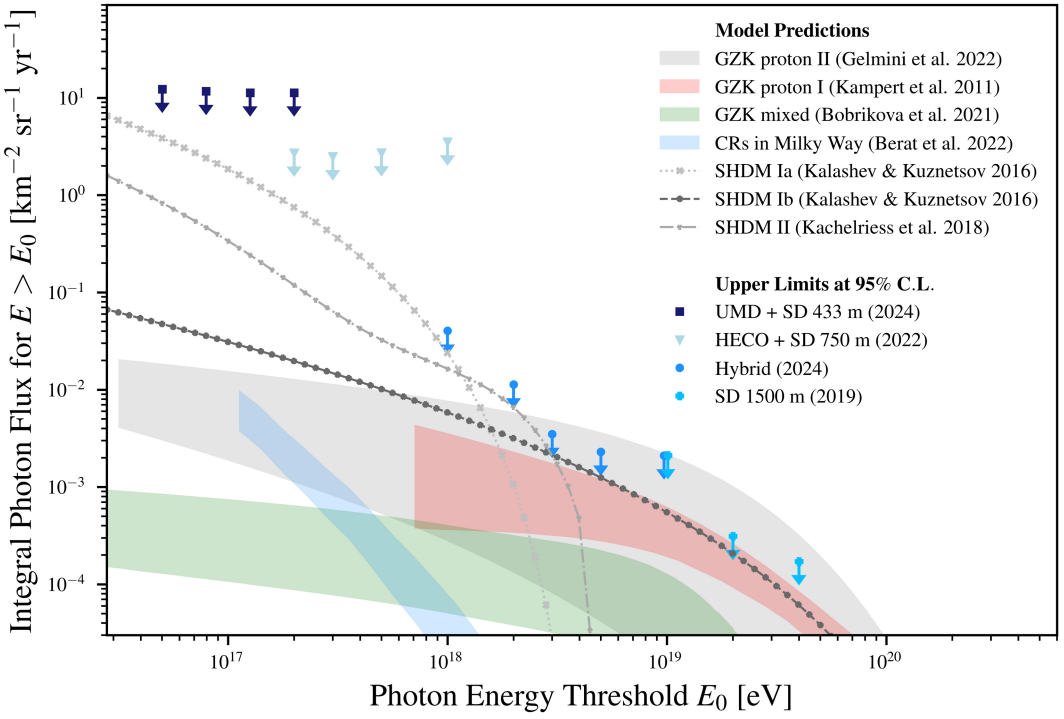
JCAP 05 (2023) 021





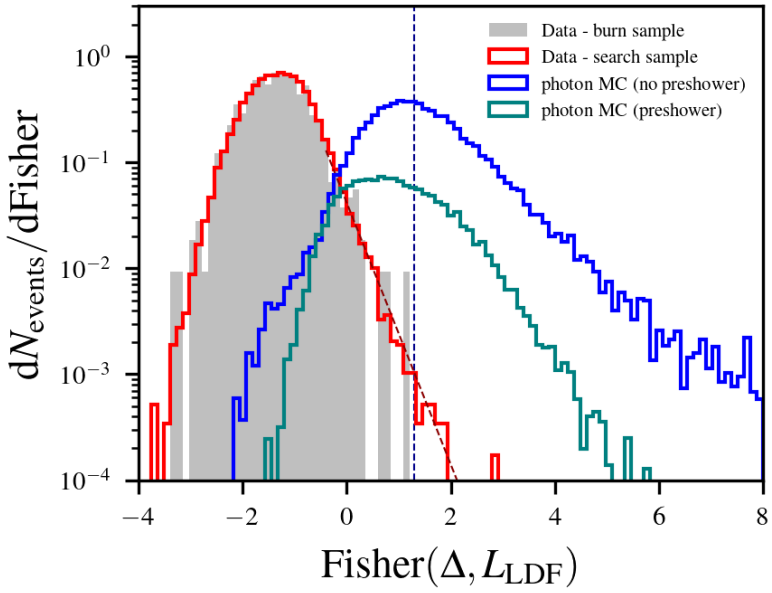


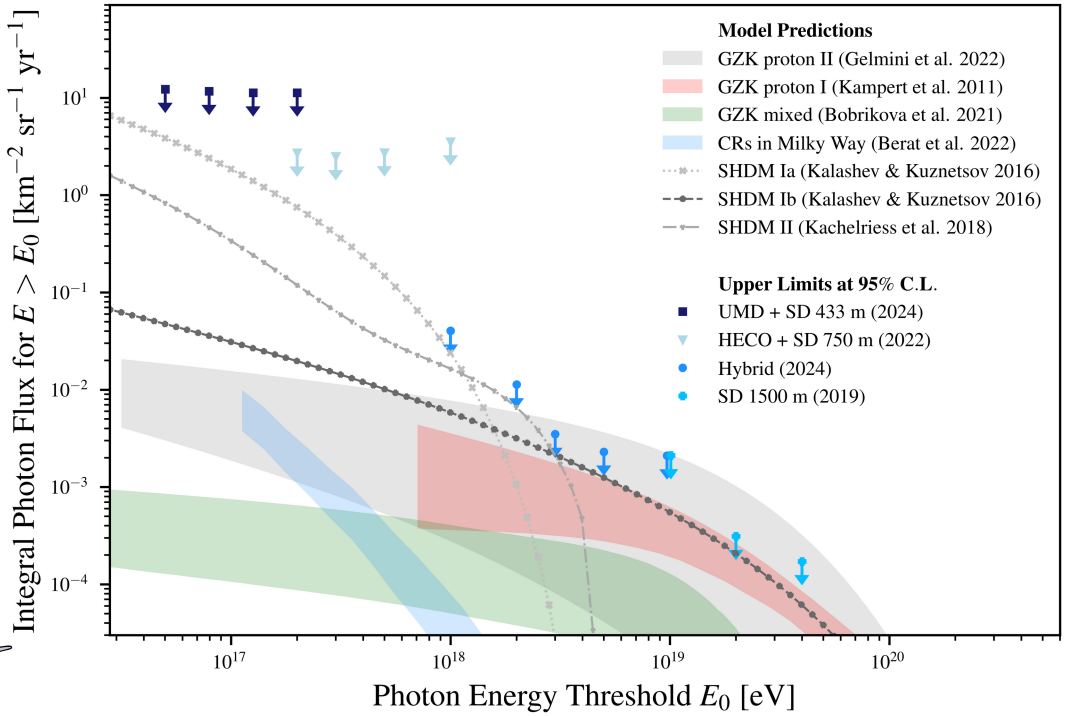




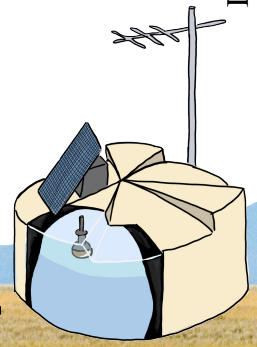
Diffuse flux of photons with energies above 10^{19}eV

JCAP 05 (2023) 021





→ 16 candidates, consistent with expected background



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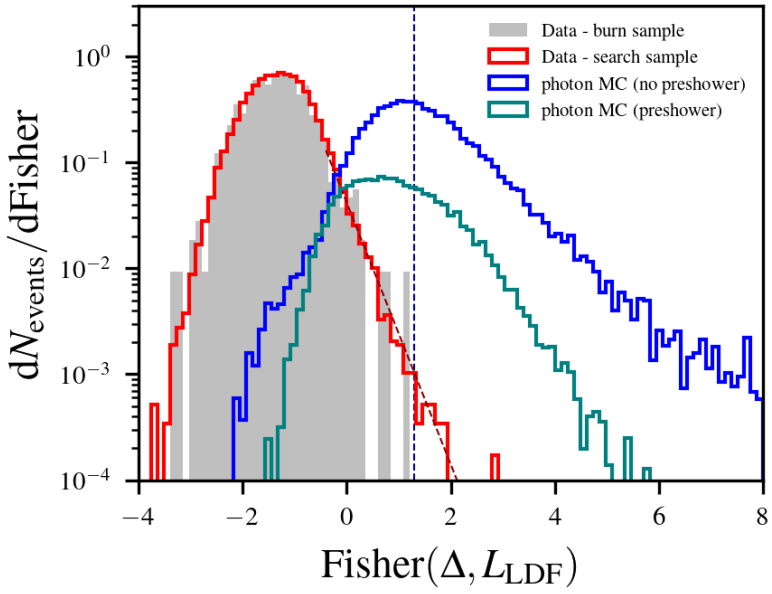
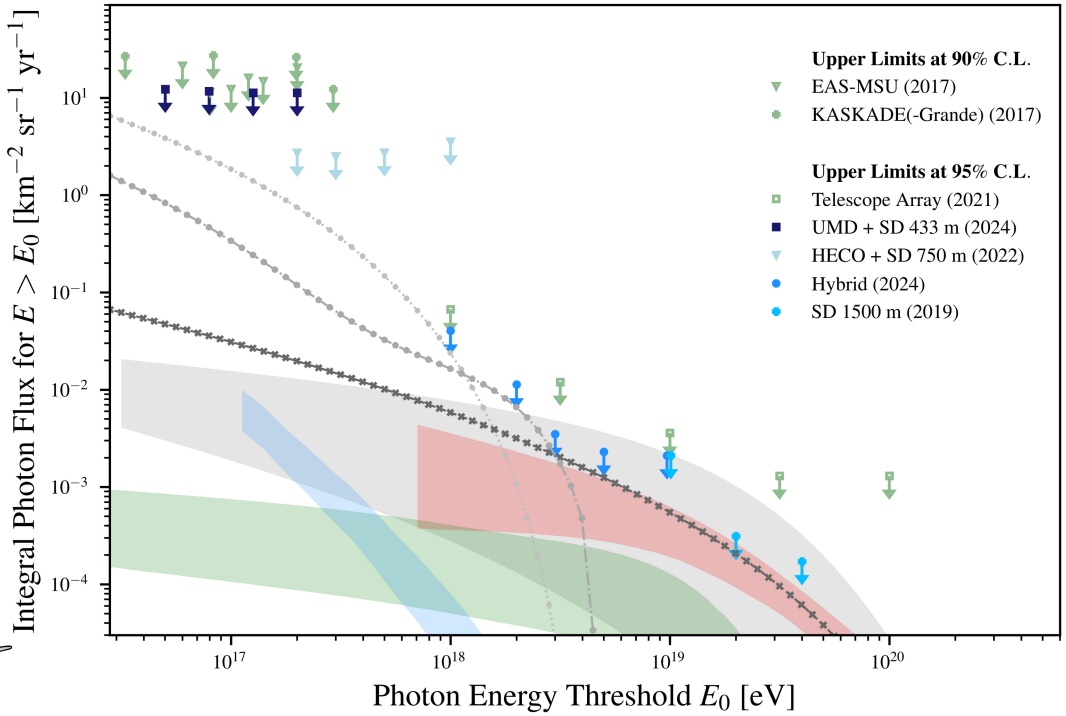
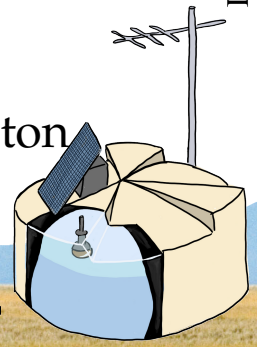
JCAP 05 (2023) 021





→ 16 candidates, consistent with expected background

→ world leading limits on UHE photon flux



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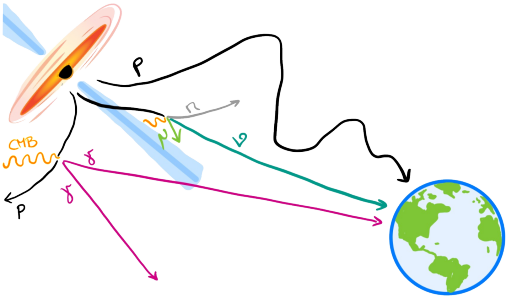

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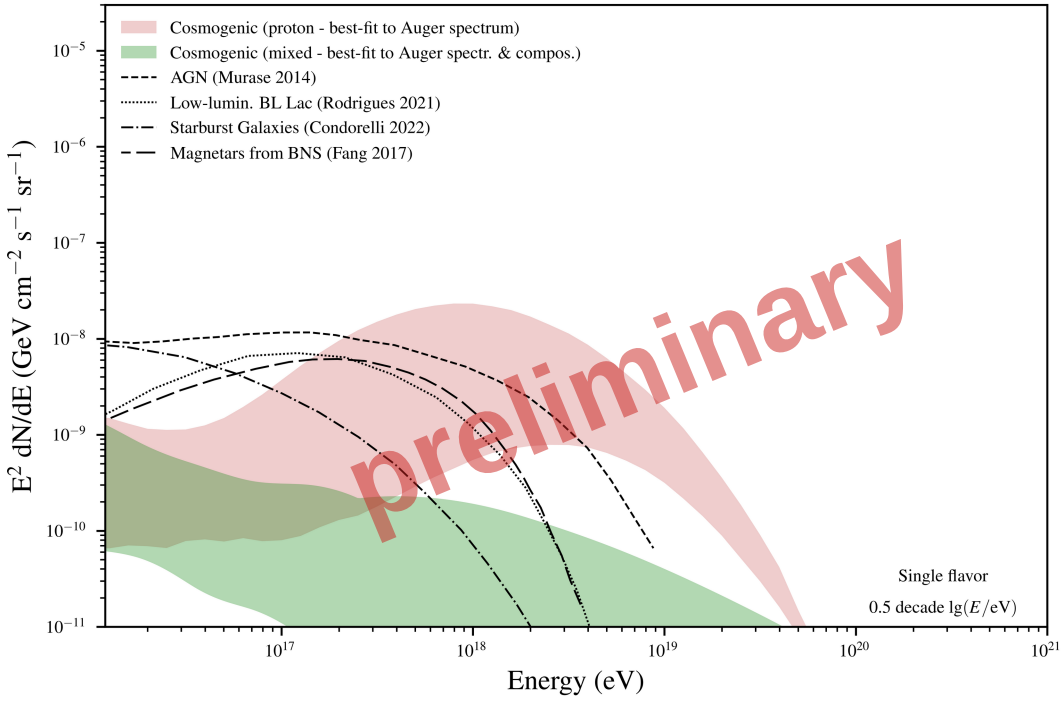
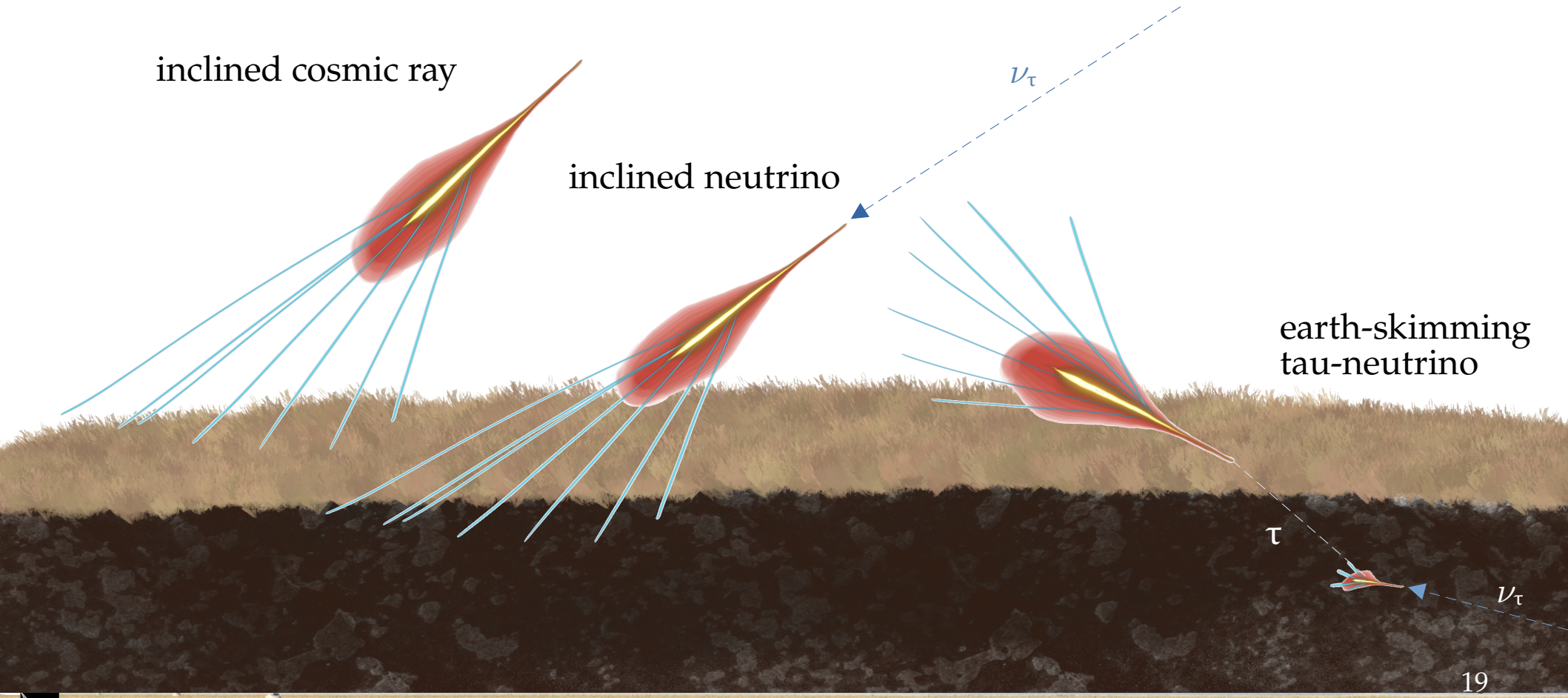
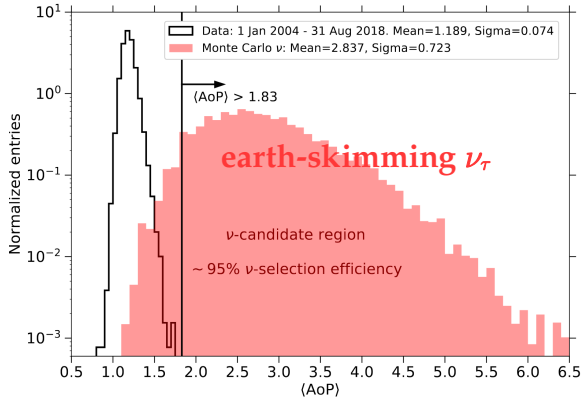


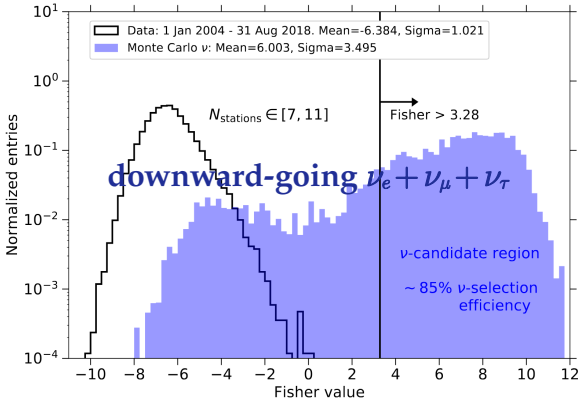
Neutrino induced air showers

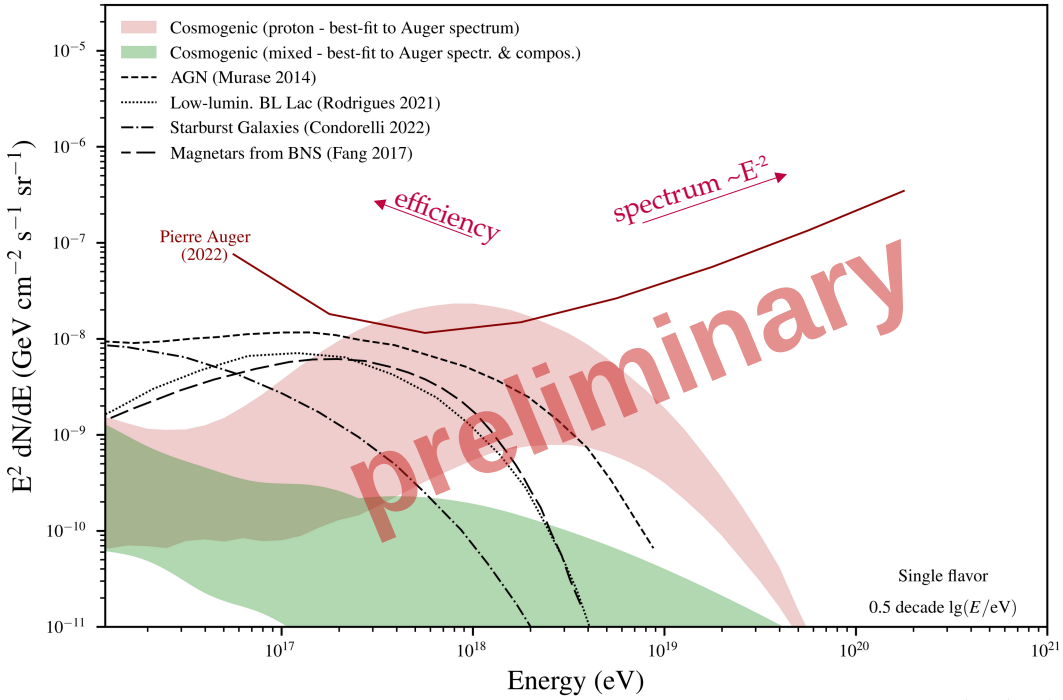


Neutrinos in the EeV Energy Range

JCAP 10 (2019) 022





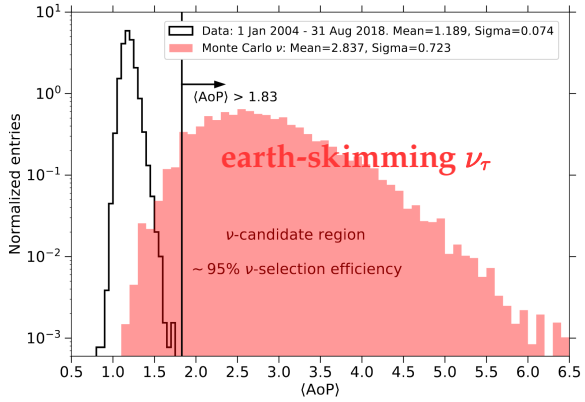


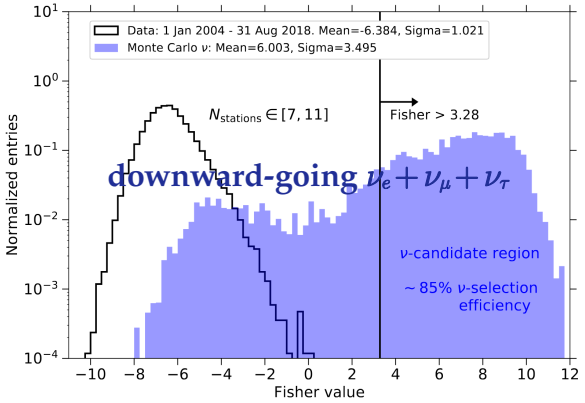
$\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$

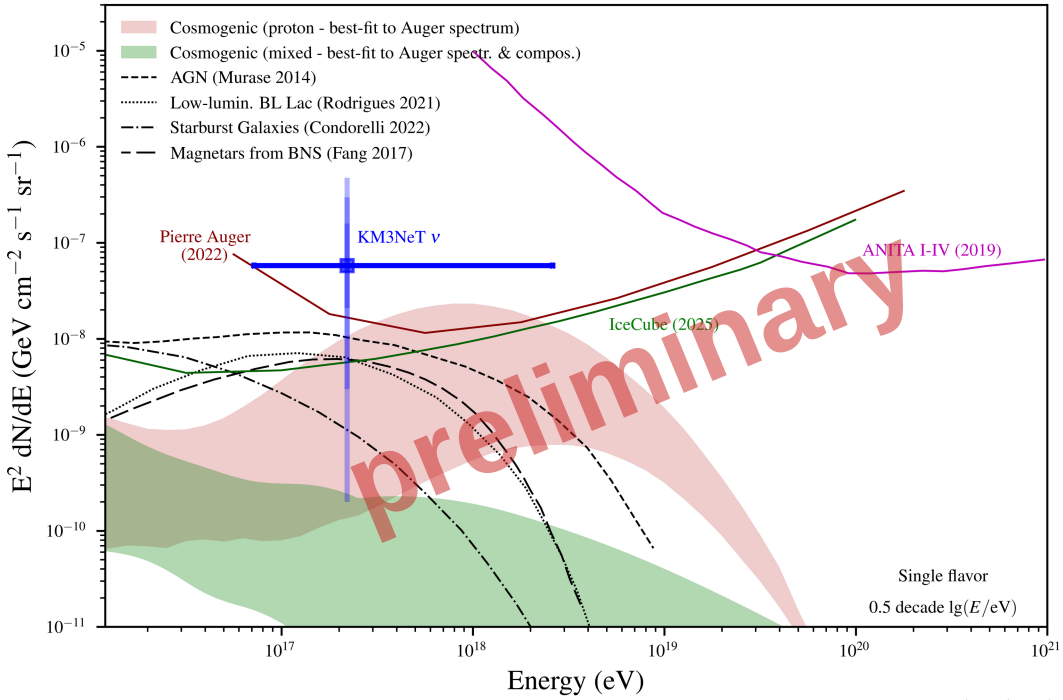
➔ No candidate ν found

Neutrinos in the EeV Energy Range

JCAP 10 (2019) 022







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Summary

➔ The Pierre Auger Observatory is a **observatory for UHE photons and neutrinos** as well
➔ **Stringent upper limits** on the diffuse γ and ν flux have been set
➔ **Follow-up searches** to transient events (e.g. gravitational wave events)
➔ The **AugerPrime** upgrade has the potential to further increase our sensitivity