Search for photons beyond PeV

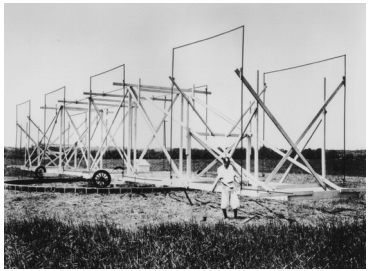
Markus Risse
University of Siegen

14th CosPa Meeting
Brussels, 27 Oct 2025

An (attempted) overview talk

Some details, many omissions (sorry!)

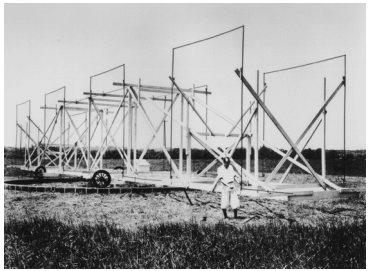
Photons from the Universe: new windows - new discoveries

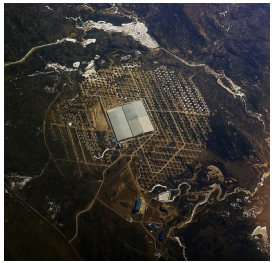



radio MW sub-mm IR **opt** UV x-ray γ-ray 10^{12} 10^{15} 10^{18} 10^{21} eV

pulsars *CMB* *dark matter* *collaps.* *γ-ray* *EBL*
radio galaxies *starburst galaxies* *binaries* *bursts*

Photons from the Universe: new windows - new discoveries



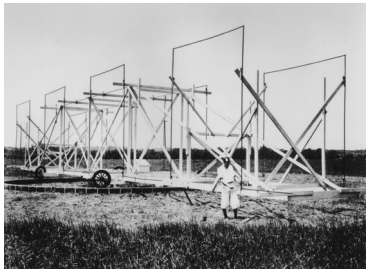



radio MW sub-mm IR **opt** UV x-ray γ-ray 10^{12} 10^{15} 10^{18} 10^{21} eV

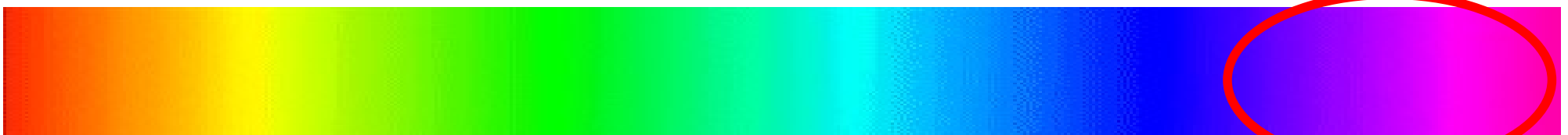
pulsars
radio galaxies
CMB
starburst galaxies
dark matter
collaps.
binaries
γ-ray
bursts
EBL

Photons beyond PeV ?

Photons from the Universe: new windows - new discoveries




radio MW sub-mm IR **opt** UV x-ray γ-ray 10^{12} 10^{15} 10^{18} 10^{21} eV



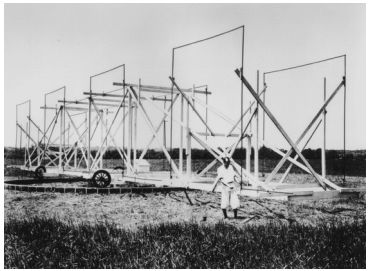
pulsars
radio galaxies
CMB
starburst galaxies
dark matter
collaps.
binaries
γ-ray
bursts
EBL

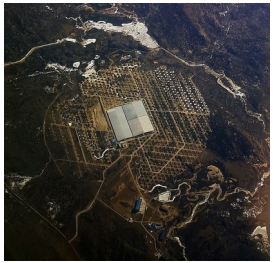
photon sources >10^{15} eV !

Photons beyond PeV ?

- PeV photon sources w/o cutoff: how far do they continue (see later)

Photons from the Universe: new windows - new discoveries



radio MW sub-mm IR **opt** UV x-ray γ-ray 10^{12} 10^{15} 10^{18} 10^{21} eV

pulsars *CMB* *dark matter* *collaps.* *γ-ray* *EBL*
radio galaxies *starburst galaxies* *binaries* *bursts*

photon sources >10^{15} eV !

cosmic rays of >10^{20} eV !

Photons beyond PeV ?

- PeV photon sources w/o cutoff: how far do they continue (see later)
- CR: energy per nucleon ~few EeV: secondary photons of (few) 100 PeV expected

Production of UHE photons

From π^0 decay, e.g.:

$p\,\gamma_{CMB} \rightarrow \Delta^+ \rightarrow p\,\pi^0$ ("GZK photons")

or decay chain of SHDM ($M \gg 10^{18}$ eV)

For PeV photons also leptonic processes

Production of UHE photons ... and propagation

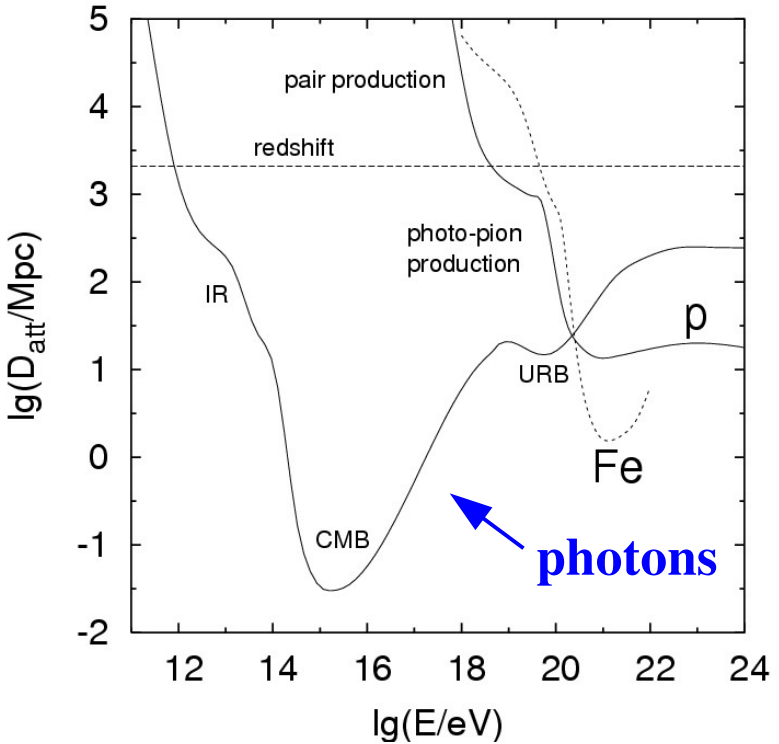
From π^0 decay, e.g.:

$p\,\gamma_{CMB} \rightarrow \Delta^+ \rightarrow p\,\pi^0$ ("GZK photons")

or decay chain of SHDM ($M \gg 10^{18}$ eV)

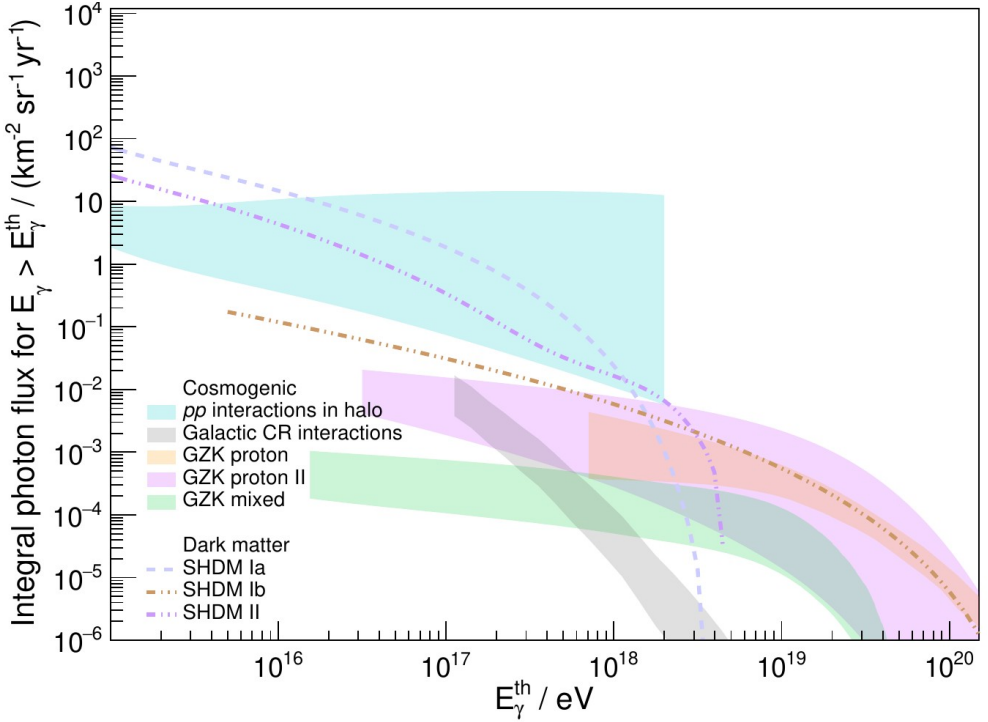
For PeV photons also leptonic processes

energy loss length



- **pair production** with background photons
- **galactic scale @ few PeV** with CMB
- **10-20 Mpc @ UHE** with URB (uncertainty!)

Photons at Earth: how much expected?



[Auger, JCAP 2025, N. Gonzalez]

GZK photons: sensitive to composition (protons!)

Galactic CR interactions (disk)

pp interaction in halo: normalized to IceCube ν-flux and extrapolated in energy

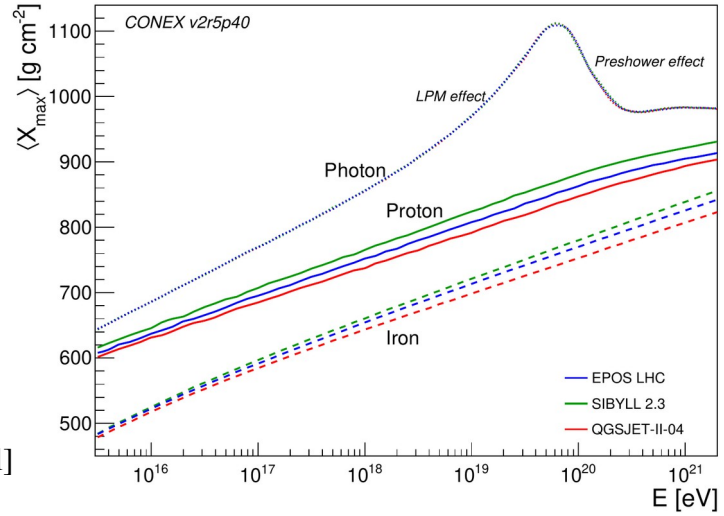
SHDM: e.g. $M \simeq 10^{19}$ eV, $\tau \simeq 3 \cdot 10^{21}$ yr. (see later)

(Photon) air showers

and measurements

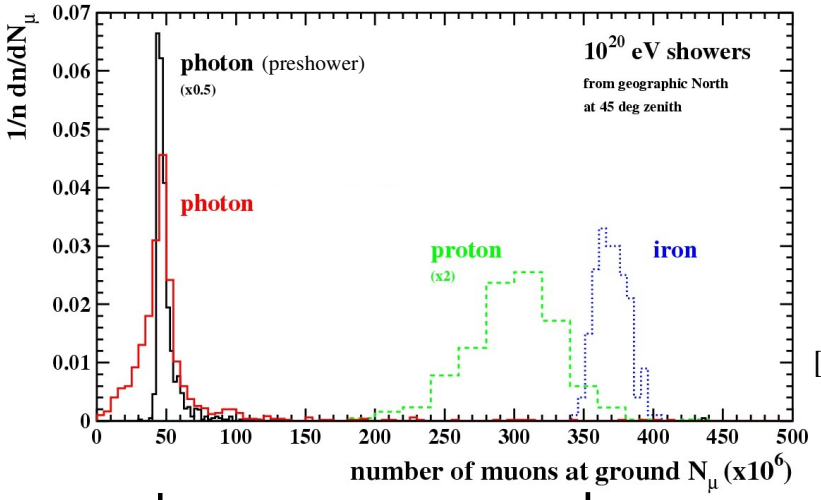
Photon air showers ... differ from hadron showers

deeper X_{max}



[M. Niechciol]

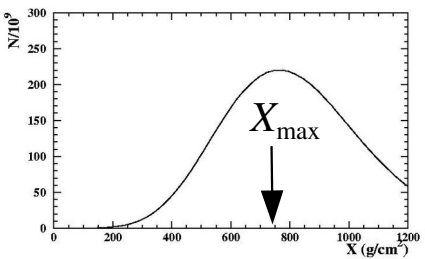
fewer muons



[Homola et al., ApP 2007]

factor 6-8

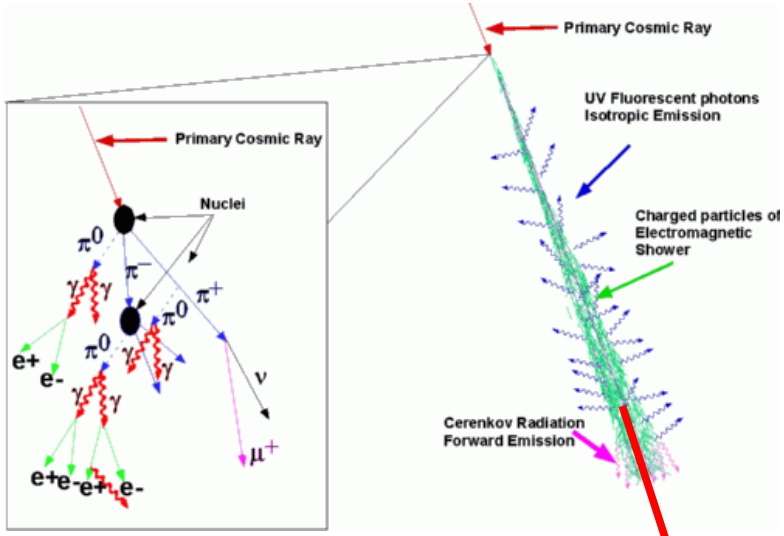
shower profile



And observables related to these two (or combinations of):
lateral distributions, signal timings ...

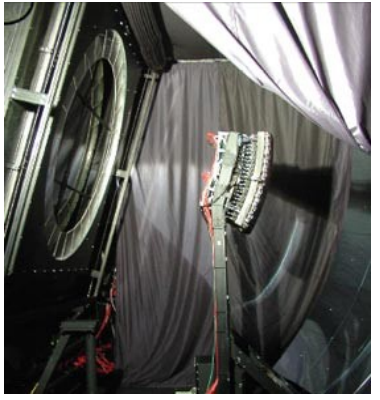
note: only minor uncertainty from hadronic interaction models!

Air shower measurements



- collisions in atmosphere
- → secondary particle cascades
- → direction ~1°, energy ~20%

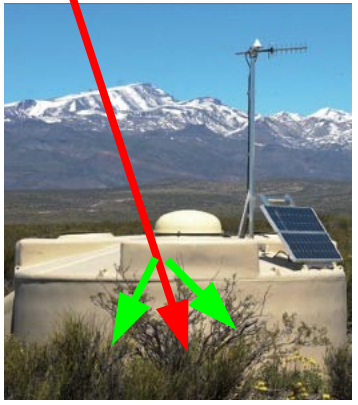
fluorescence light



only in clear nights (~10%)

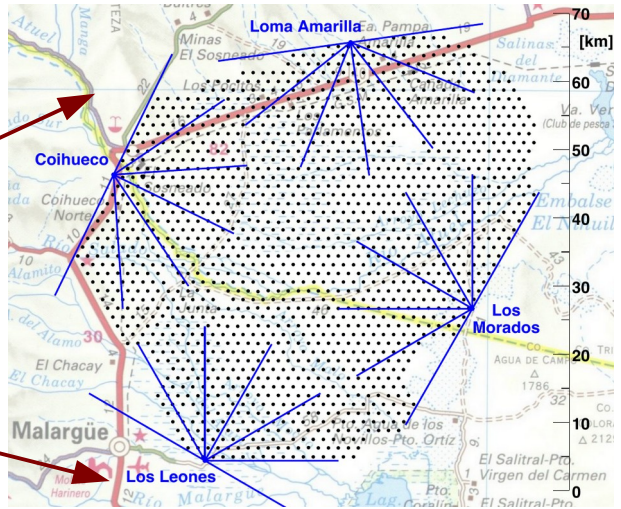
particles on ground

e.g. water detectors ⇒
Cherenkov light

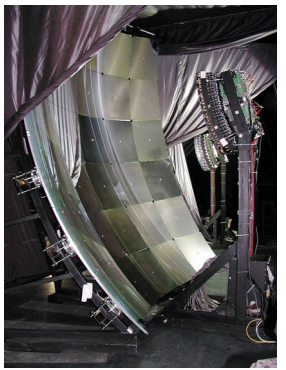


plus muon / radio detectors

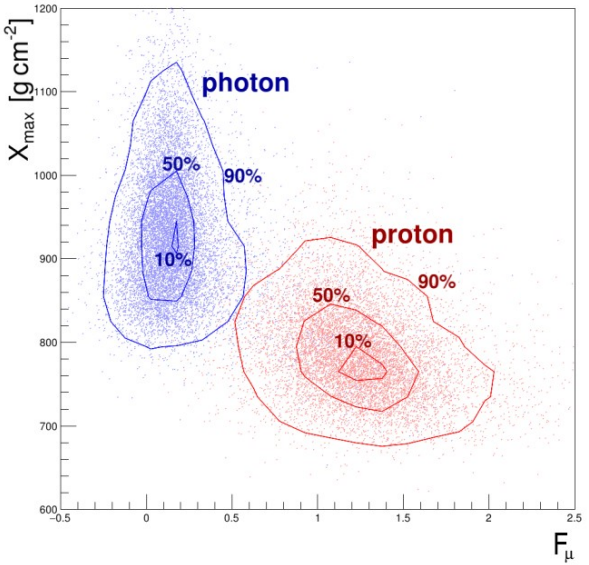
Pierre Auger Observatory

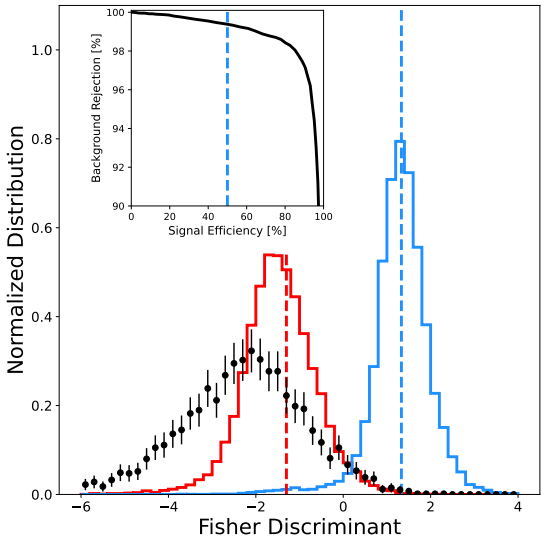


- 1660 **water Cherenkov tanks ⇒ 3000 km²**
  1.5 km spacing (sub-arrays: 750 m, 433 m)
- 27 fluorescence **telescopes** in 4 stations
- physics data since **2004**
- **AugerPrime upgrade**



Example of photon search: Auger hybrid (array plus telescopes)





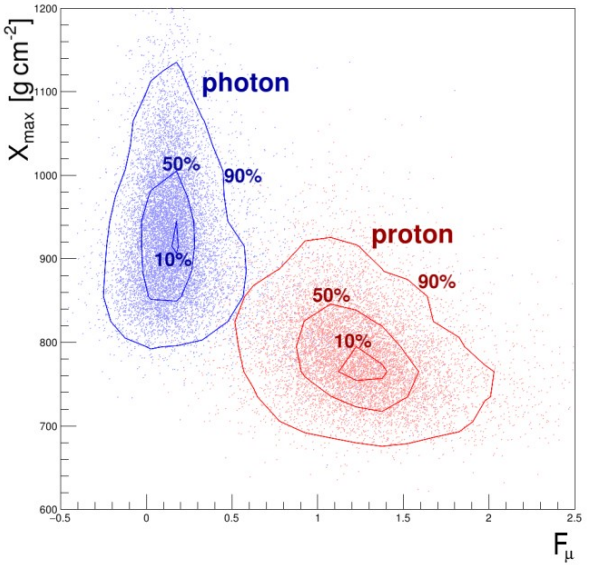
$E \geq 10^{18}$ eV

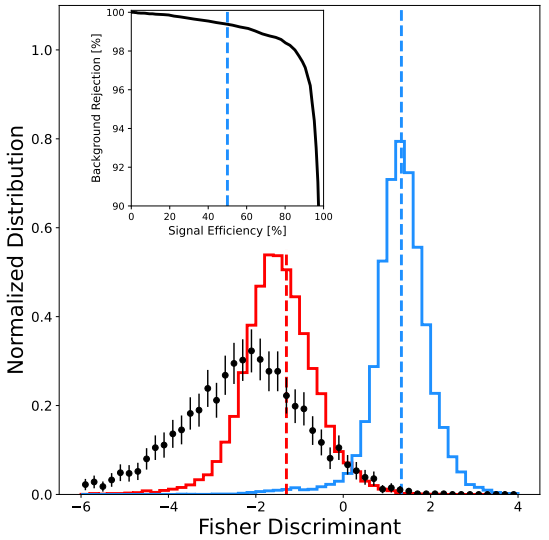
X_{max} combined with F_μ (muon proxy): discriminant observable

if value above photon median:
event counted as “photon candidate“

[Auger, PRD 2024]

Example of photon search: Auger hybrid (array plus telescopes)





$E \geq 10^{18}$ eV

X_{max} combined with F_μ (muon proxy): discriminant observable

if value above photon median: event counted as "photon candidate"

[Auger, PRD 2024]

data: number of photon candidates is 22 above 10^{18} eV

2 above $2 \cdot 10^{18}$ eV, 0 above $3 \cdot 10^{18}$ eV

compatible with background expectation

⇒ upper limit on photon flux:

u.l. number photon candidates

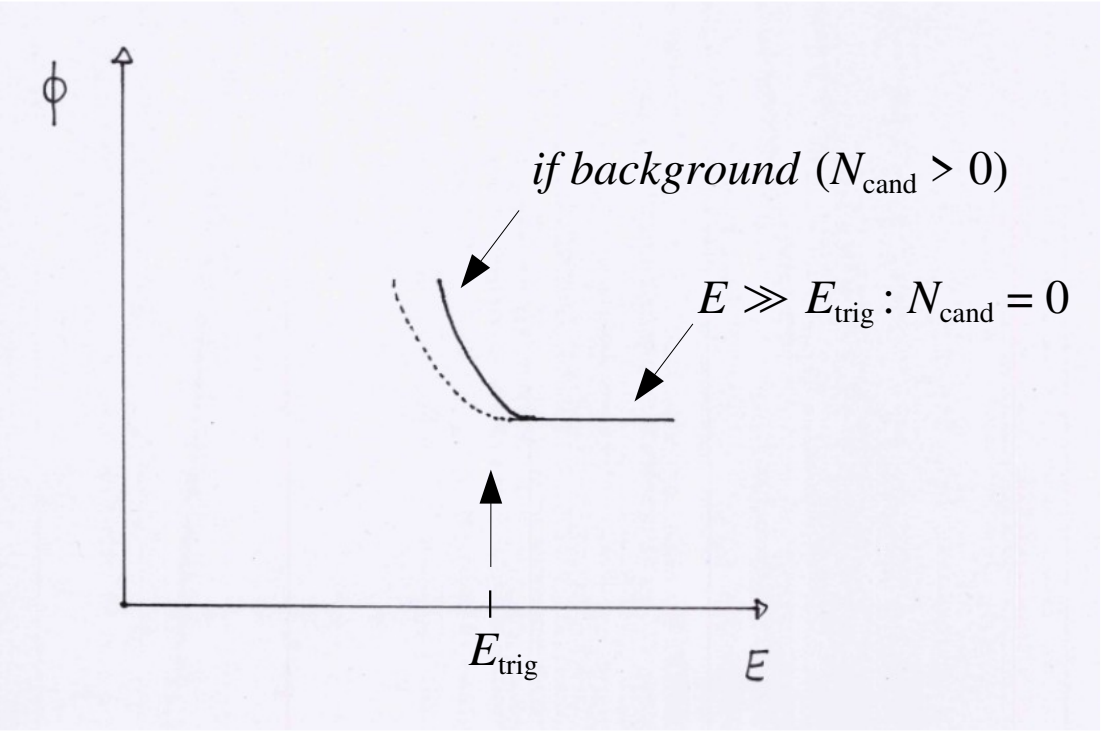
$$\Phi_\gamma^{\mathrm{CL}}(E_\gamma > E_\gamma^0) = \frac{N_\gamma^{\mathrm{CL}}(E_\gamma > E_\gamma^0)}{\mathscr{E}_\gamma(E_\gamma > E_\gamma^0)}$$

exposure

Photon search: experimental results

(1) Diffuse photon flux

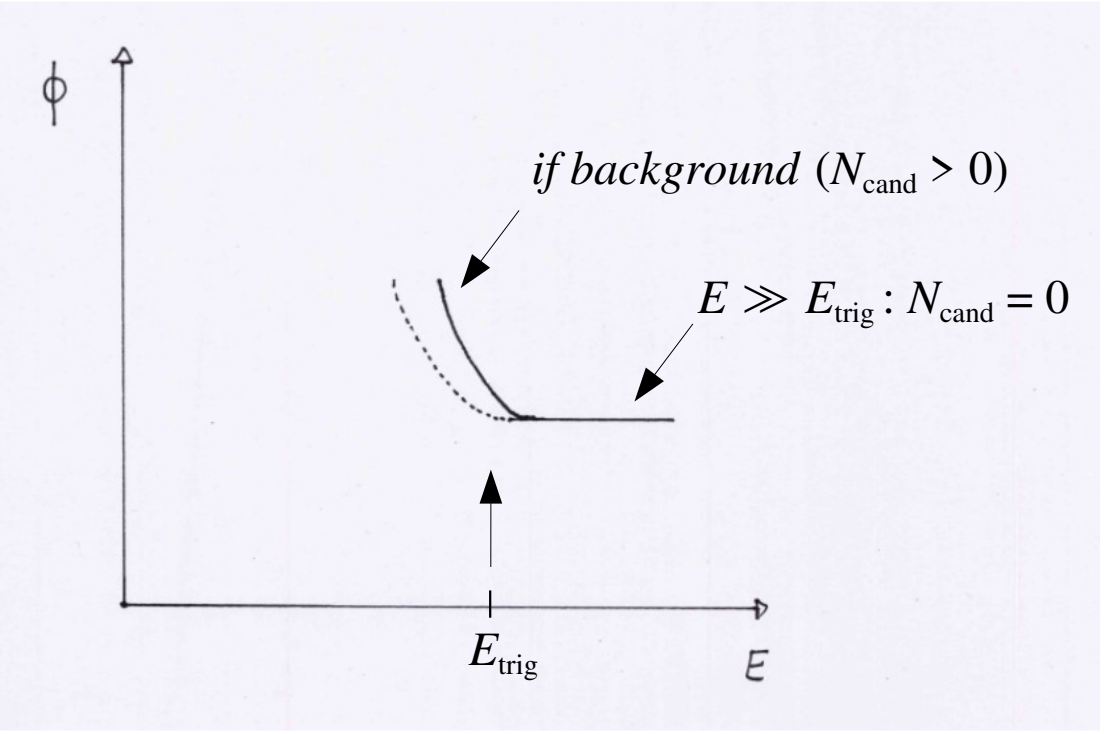
Typical shape of limits (simplified)



trigger
threshold

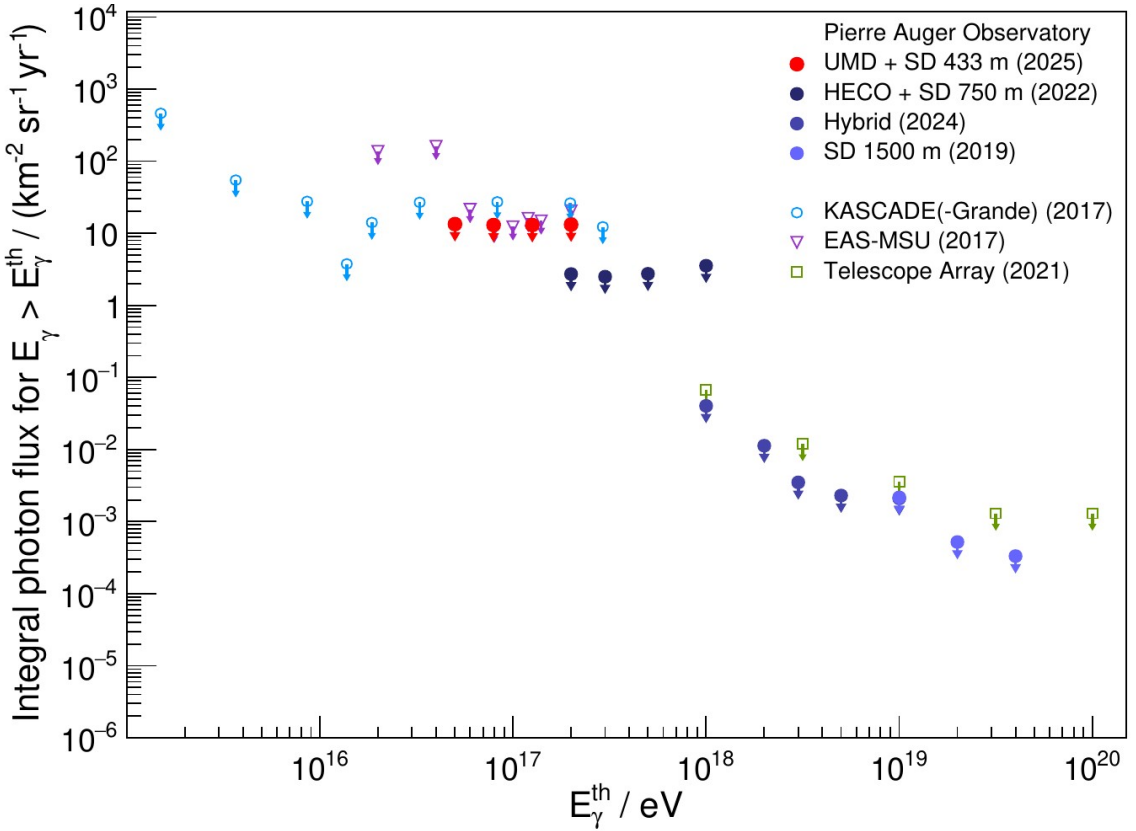
Typical shape of limits (simplified)

How to improve:
- larger exposure
- lower threshold
- better separation

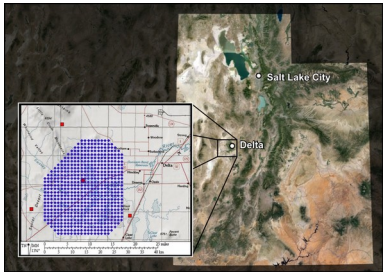


trigger
threshold

Limits on diffuse photon flux



[Auger, JCAP 2025 / N. Gonzalez]



Telescope Array hybrid, 730 km^2

Auger moving towards (multi-)PeV range

KA/-Grande 0.04 km^2 / 0.5 km^2

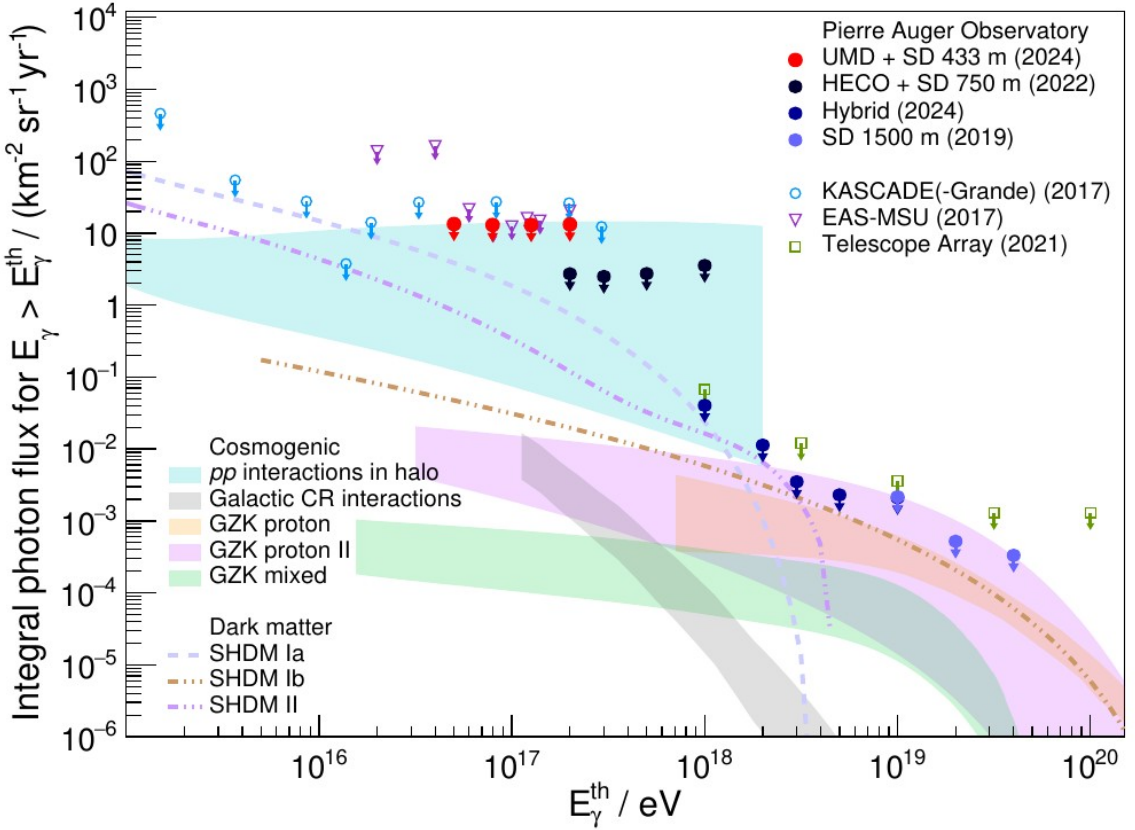
array 2 km^2 +muon

hybrid 27.5 km^2

hybrid 3000 km^2

array 3000 km^2

Limits on diffuse photon flux

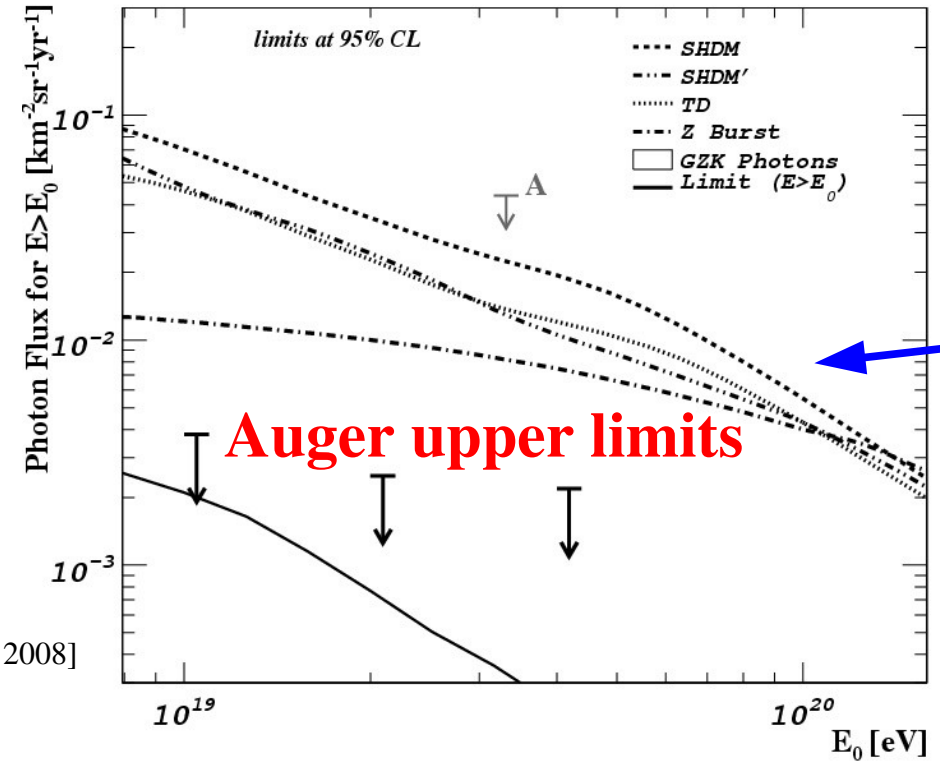


[Auger, JCAP 2025]

start constraining “GZK proton“, “pp int. halo“

continue constraining “SHDM residuals“

Reminder 2008: “top-down models“ try explain UHECR



[Auger, ApP 2008]

… but predict way too many photons

top-down predictions

E.g. SHDM:
only partial contribution to cosmic rays from residual phase space

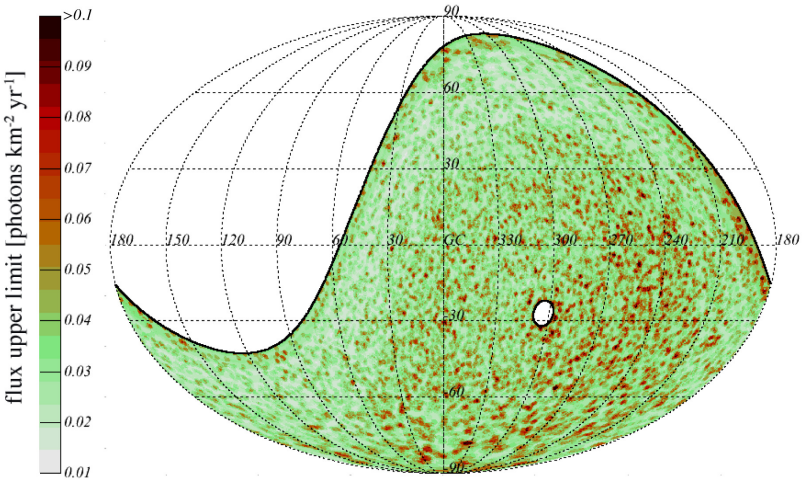
Photon search: experimental results

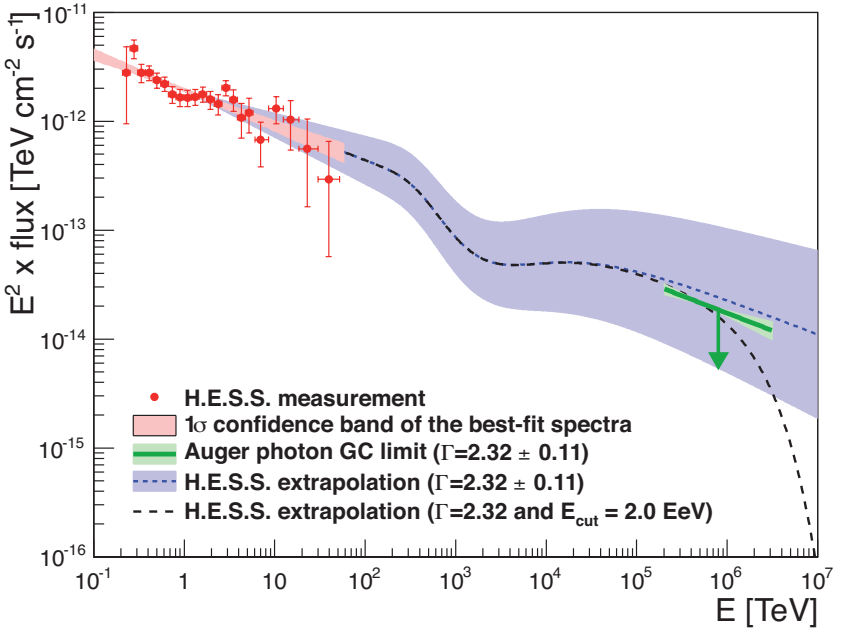
✓ (1) Diffuse photon flux

Since photons are neutral ...

(2) Directional excesses

Directional search for photons: Auger Observatory





***E* = 10$^{17.3}$ - 10$^{18.5}$ eV**, hybrid

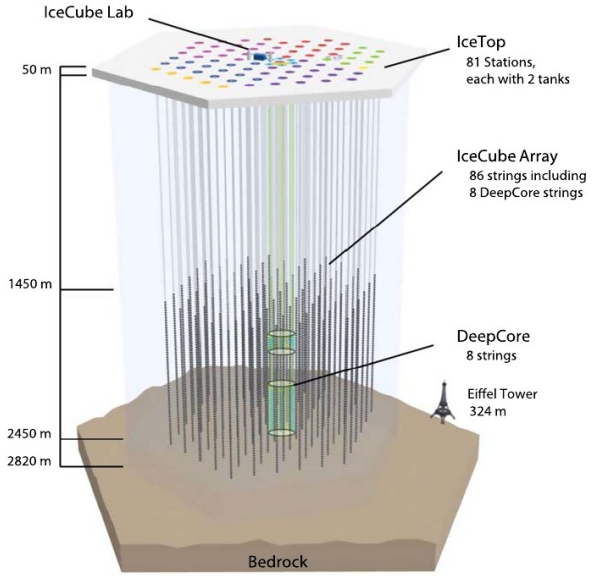
search for excess of photon-like events (no sign. excess)

directional upper limits

[Auger, ApJ 2014, ApJL 2017]

constrains high-energy extrapolations of gamma-ray sources (here: GC)

Directional search for photons: IceCube



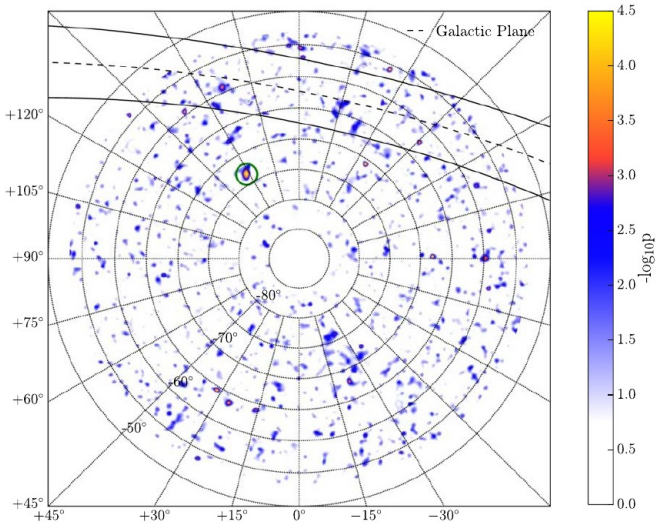


Figure 13. All-sky likelihood scan pretrial *p*-values shown projected from the South Pole in equatorial units. The R.A. is labeled along the figure axes, with the interior text denoting decl. bands. The green circle highlights the hottest spot in the scan. The Galactic plane region (>5° in Galactic latitude) is also shown.

[IceCube, ApJ 2020]

$E \simeq 2$ PeV

IceTop (surface array, ~1 km^2) plus IceCube (as muon veto)
search for excess of photon-like events (no sign. excess)
galactic plane slice of ~50 deg

Photon search: experimental results

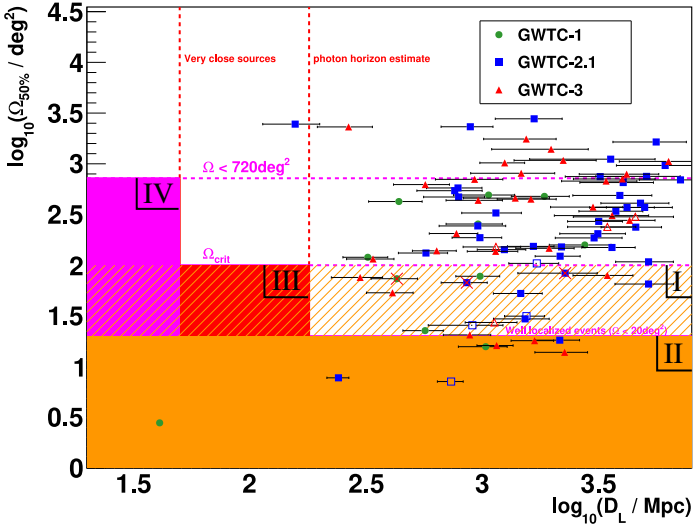
✓ (1) Diffuse photon flux

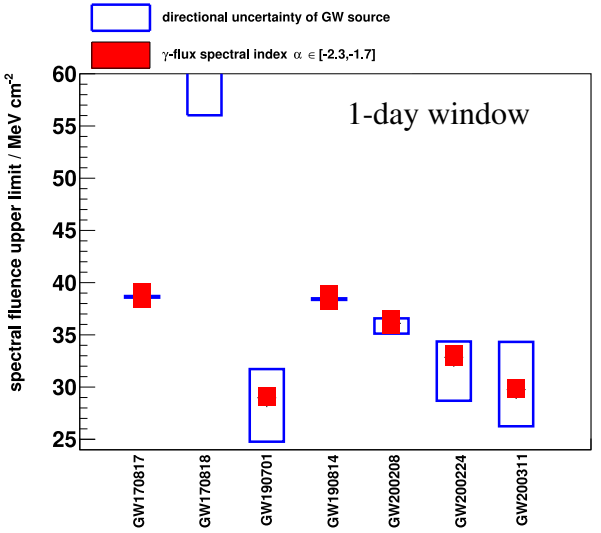
Since photons are neutral ...

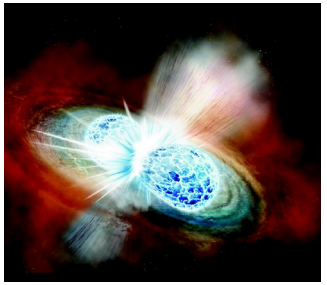
✓ (2) Directional excesses

(3) Transients (excess in direction and time)

Search for photons from transients







[Auger, ApJ 2023]

$E \geq 10^{19}$ eV, array; LIGO/Virgo runs O1-O3 (91 events)

elaborated GW event selections (preferred: small distance, well localized)

search for time-directional correlation

limits on UHE photon fluence from GW mergers ("proof-of-principle")

distant sources: signal would indicate new physics (e.g. LV)

Photons and fundamental physics:

does Lorentz invariance hold?

Lorentz invariance violation

Lorentz invariance: fundamental pillar of physics

quantum gravity models: violation (LV) well possible

Lorentz invariance violation

Lorentz invariance: fundamental pillar of physics

quantum gravity models: violation (LV) well possible

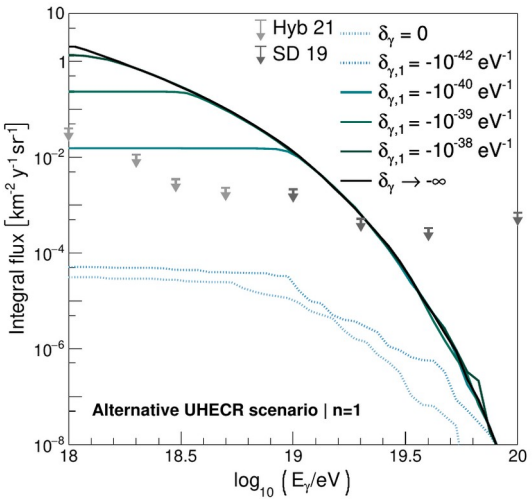
(1) Suppression of SM interactions? E.g. pair production ⇒ accumulation of UHE photons?

photon limits lead to LV constraints

caveat "conditional constraints" (UHE proton component?)

[e.g. Galaverni, Sigl, PRL 2008
Auger, JCAP 2022]

[Auger, JCAP 2022]



Lorentz invariance violation

Lorentz invariance: fundamental pillar of physics

quantum gravity models: violation (LV) well possible

(1) Suppression of SM interactions? E.g. pair production ⇒ accumulation of UHE photons?

photon limits lead to LV constraints

caveat "conditional constraints" (UHE proton component?)

[e.g. Galaverni, Sigl, PRL 2008
Auger, JCAP 2022]

(2) Appearance of BSM interactions? E.g. photon decay $\gamma \rightarrow e^+ + e^-$

photon observations lead to LV constraints

example: a ~10^{18} eV photon would improve related LV parameter by almost 4 orders of magnitude

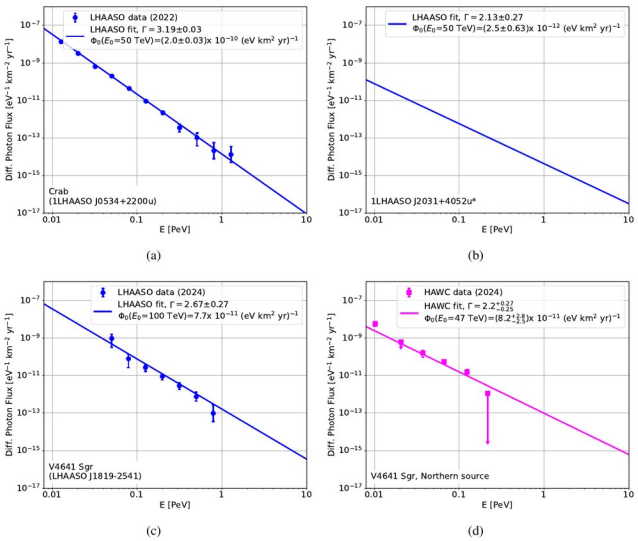
[e.g. Klinkhamer, Schreck 2008,
MR, CPT 2022]

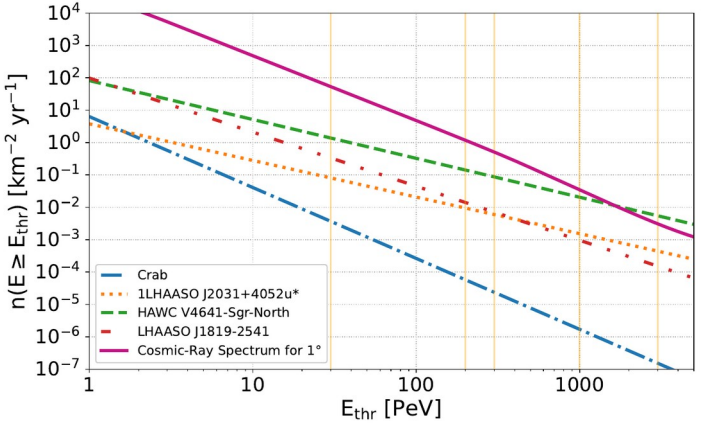
PeV photon sources w/o cutoff

How far in energy do the continue?

→ Can shower observatories test high-energy extrapolations?

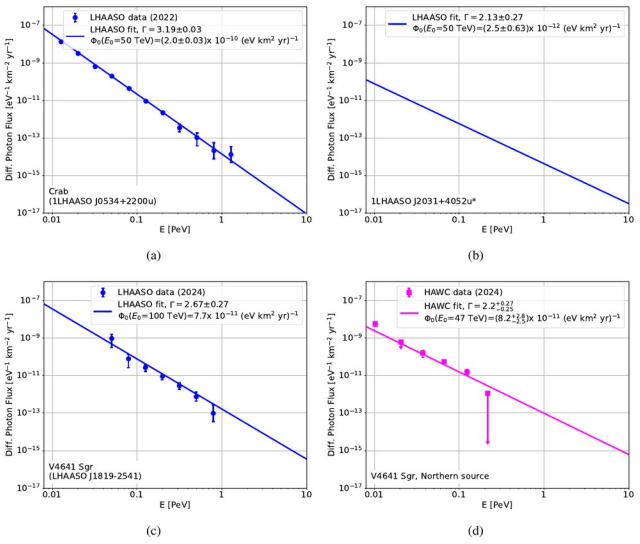
Benchmarking: extrapolate PeV photon spectra

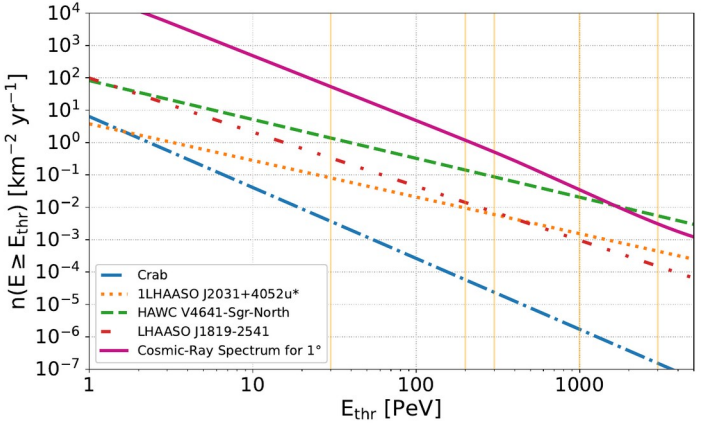




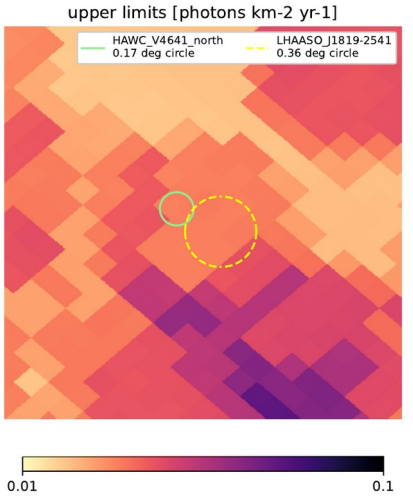
[Papior, Niechciol, MR, ApP 2024 and ICRC 2025]

Benchmarking: extrapolate PeV photon spectra





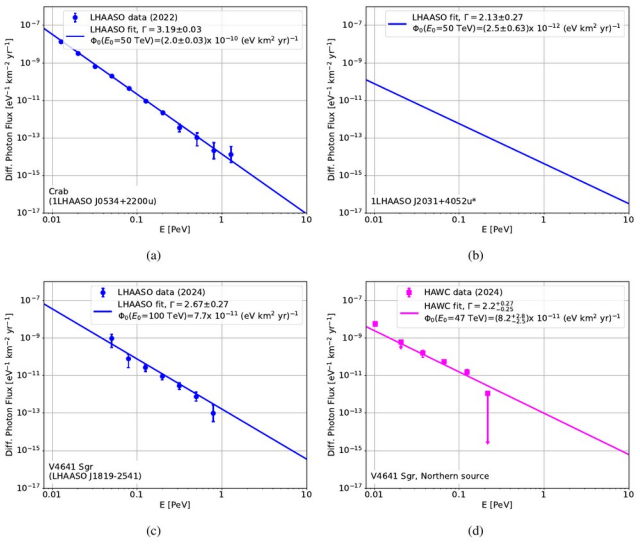
[Papior, Niechciol, MR, ApP 2024 and ICRC 2025]

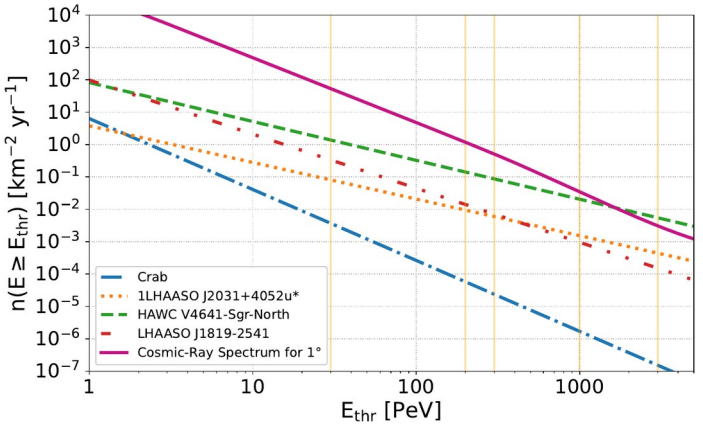


Certain tests **possible already** with present air shower setups, e.g.:

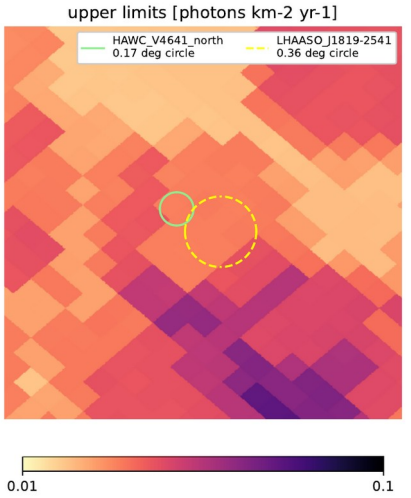
For V4641 Sgr, Auger directional limits at $E = 10^{17.3}$ - $10^{18.5}$ eV constrain power-law extrapolation harder than -2,2

Benchmarking: extrapolate PeV photon spectra





[Papior, Niechciol, MR, ApP 2024 and ICRC 2025]



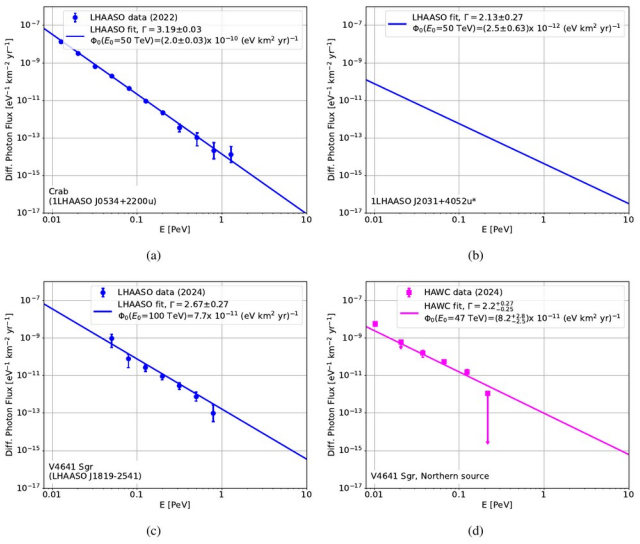
Certain tests **possible already** with present air shower setups, e.g.:

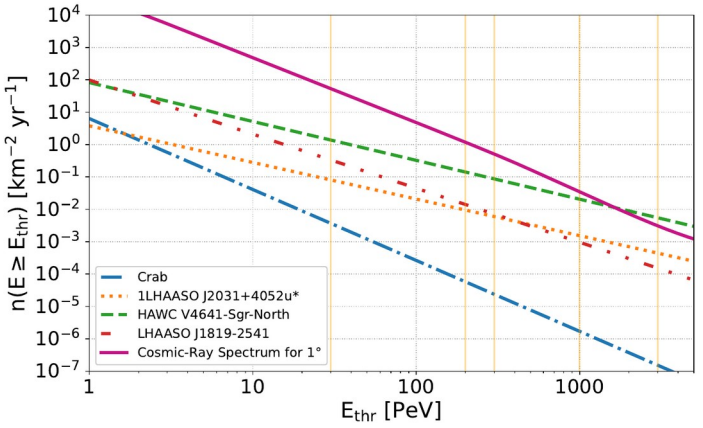
For V4641 Sgr, Auger directional limits at $E = 10^{17.3}$ - $10^{18.5}$ eV constrain power-law extrapolation harder than -2,2

However, unless hard spectra to energies ≫PeV: **event rate challenging** for present air shower setups, e.g.:

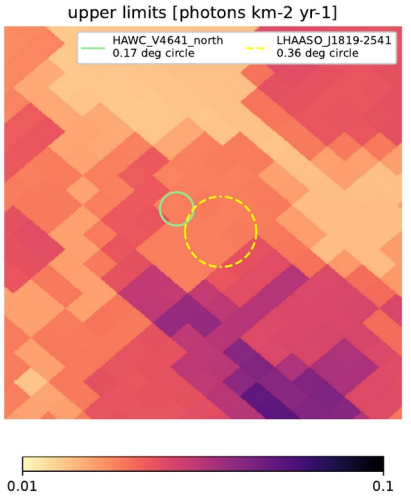
For 30 PeV threshold, ~1 photon/yr from (currently) brightest sources

Benchmarking: extrapolate PeV photon spectra





[Papior, Niechciol, MR, ApP 2024 and ICRC 2025]



Certain tests **possible already** with present air shower setups, e.g.:

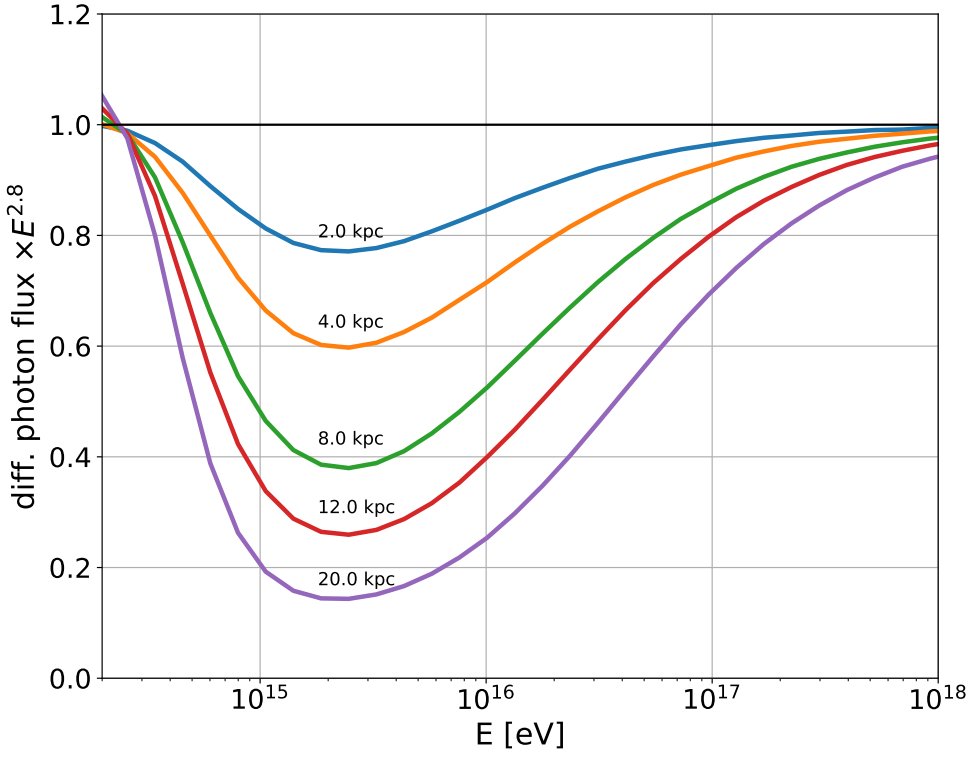
For V4641 Sgr, Auger directional limits at $E = 10^{17.3}$ - $10^{18.5}$ eV constrain power-law extrapolation harder than -2,2

However, unless hard spectra to energies ≫PeV: **event rate challenging** for present air shower setups, e.g.:
For 30 PeV threshold, ~1 photon/yr from (currently) brightest sources

→ lower threshold (towards PeV), effective size O(10 km^2)

→ *PEPS (talk by Ioana)*

If power-law >10 PeV: observe spectral suppression !?



CRPropa simulations:

photon emission spectrum $E^{-2.8}$

[C. Papior]

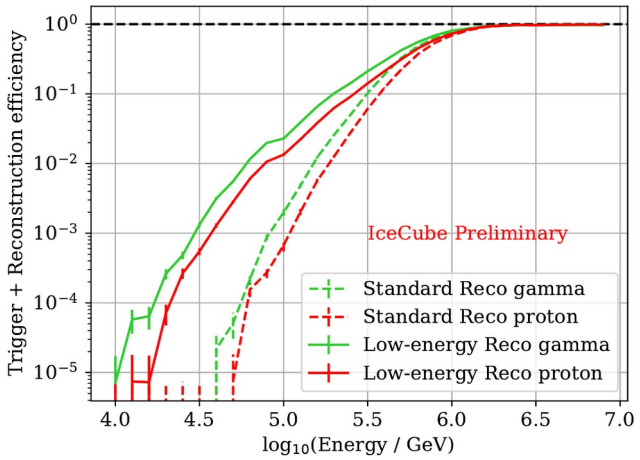
From galactic propagation (pair-production with CMB):
Expect suppression towards ~3 PeV, then (relative) recovery
Test of Lorentz invariance, galactic transparency, ...

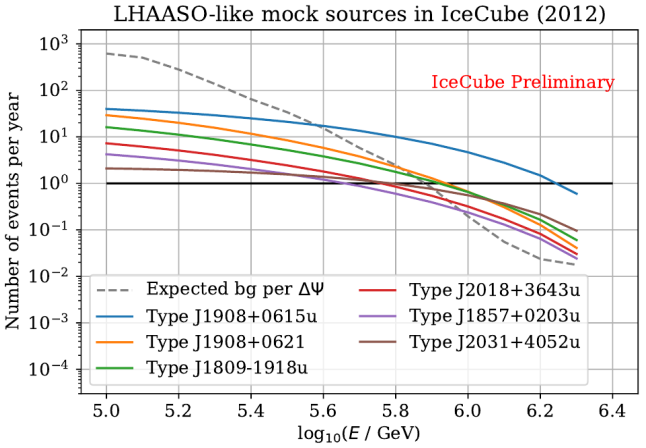
(Present) future:

Experimental Upgrades

IceCube

[IceCube, ICRC 2025]



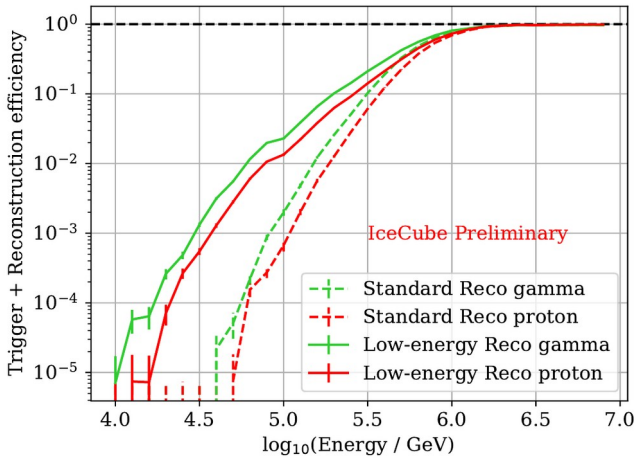


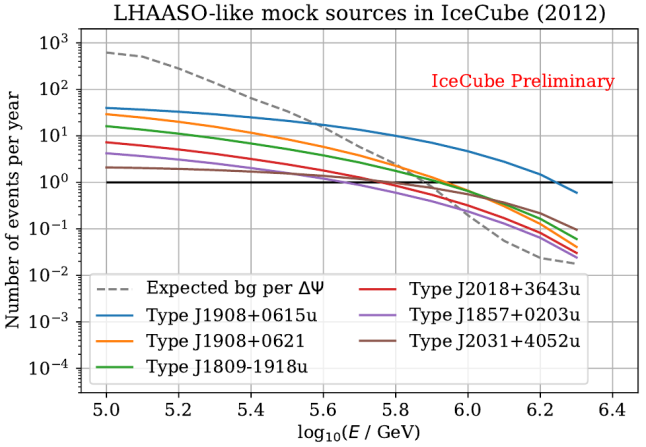
improving analysis:
- better separation
- lower threshold (sub-PeV)

discovery potential

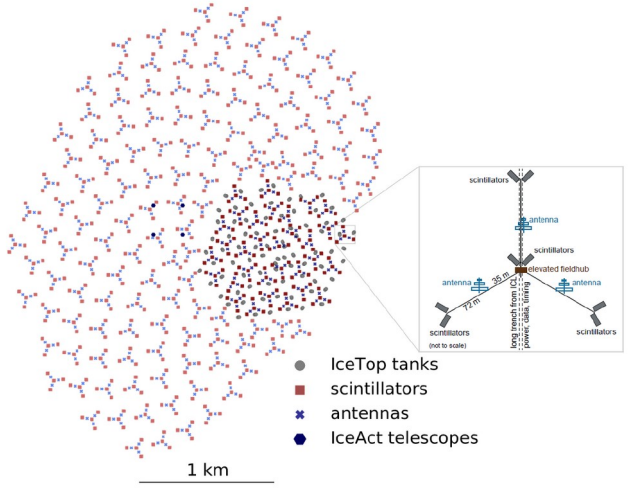
IceCube(-Gen2)

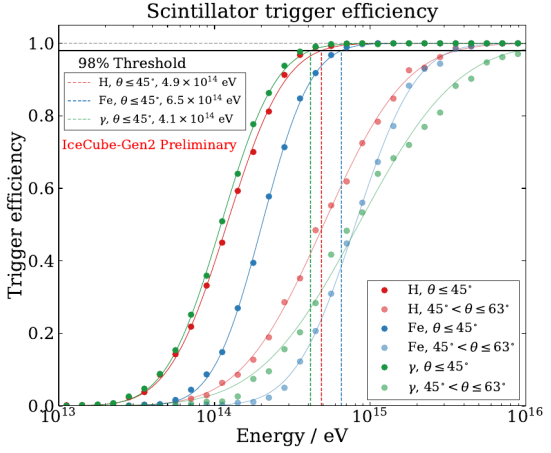
[IceCube, ICRC 2025]

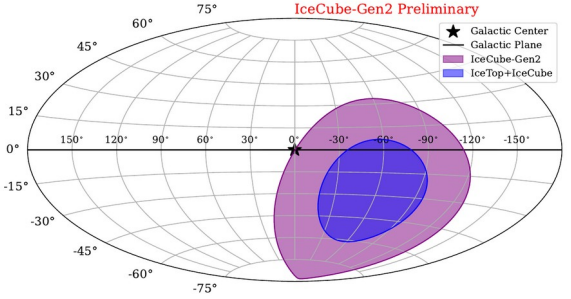




improving analysis:
- better separation
- lower threshold (sub-PeV)
discovery potential

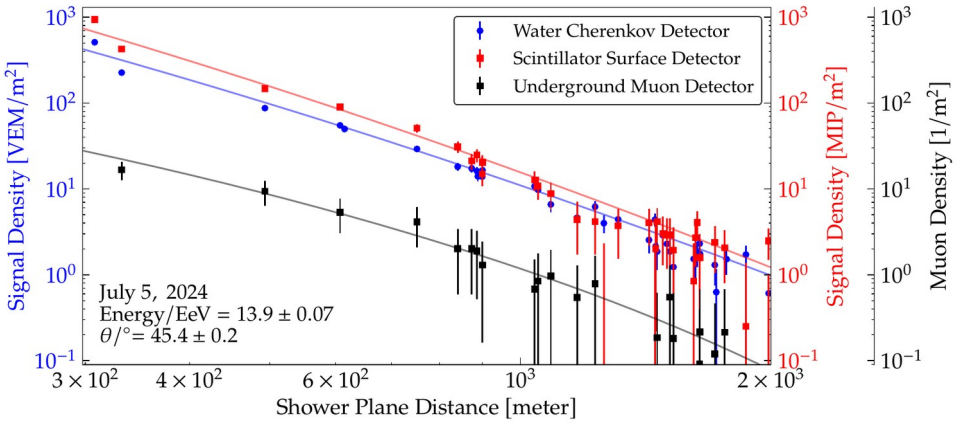






IceCube-Gen2:
- larger array (~6 km^2)
- increased FoV (gal. plane!)

Pierre Auger Observatory



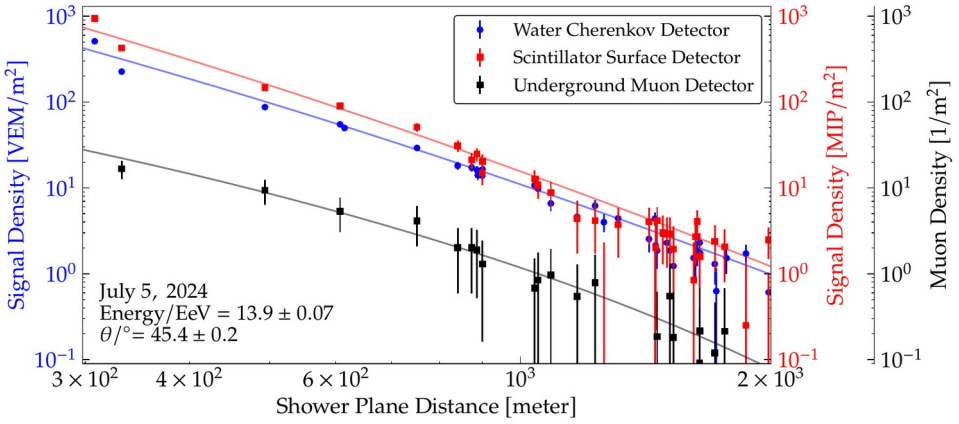
[Auger, ICRC 2025 and JCAP 2025]

data taking → 2035

AugerPrime upgrade: scintillation and radio detector on each tank, ... ⇒ improving separation

Pierre Auger Observatory

[Auger, ICRC 2025 and JCAP 2025]



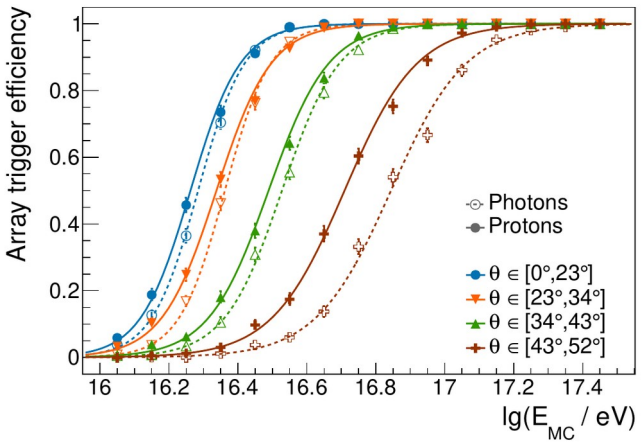
data taking
→ 2035

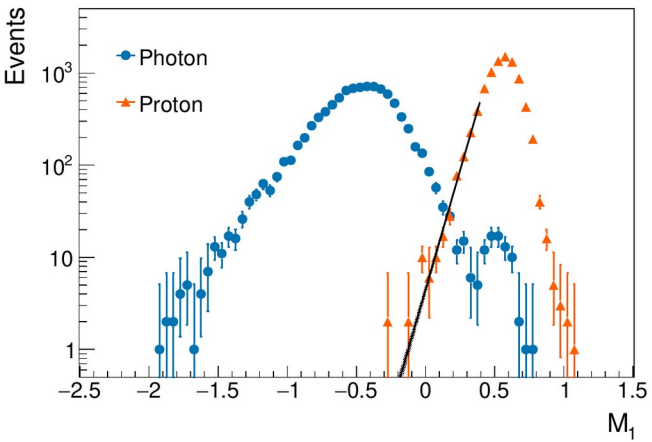
AugerPrime upgrade: scintillation and radio detector on each tank, ... ⇒ improving separation

Completing UMD
(muons on 2 km^2 array)

towards ~20 PeV

excellent separation





Search for photons beyond PeV: summary

- they should exists (factor >100 above current E_{max})
- neutral ⇒ directional pointing (source identification)
- neutral ⇒ transients (flaring vs. steady sources)
- relation to cosmic rays (particularly composition)
- tracers of matter and fields during propagation
- testing more local universe (complementary to neutrinos)
- the only gauge boson among astroparticles
- observation by showers: similar to “normal“ ones
- quite precise simulation of cascading (EM dominates)
- potential tracers of BSM physics

historical view on the conquest of new windows:

Search for photons beyond PeV: summary

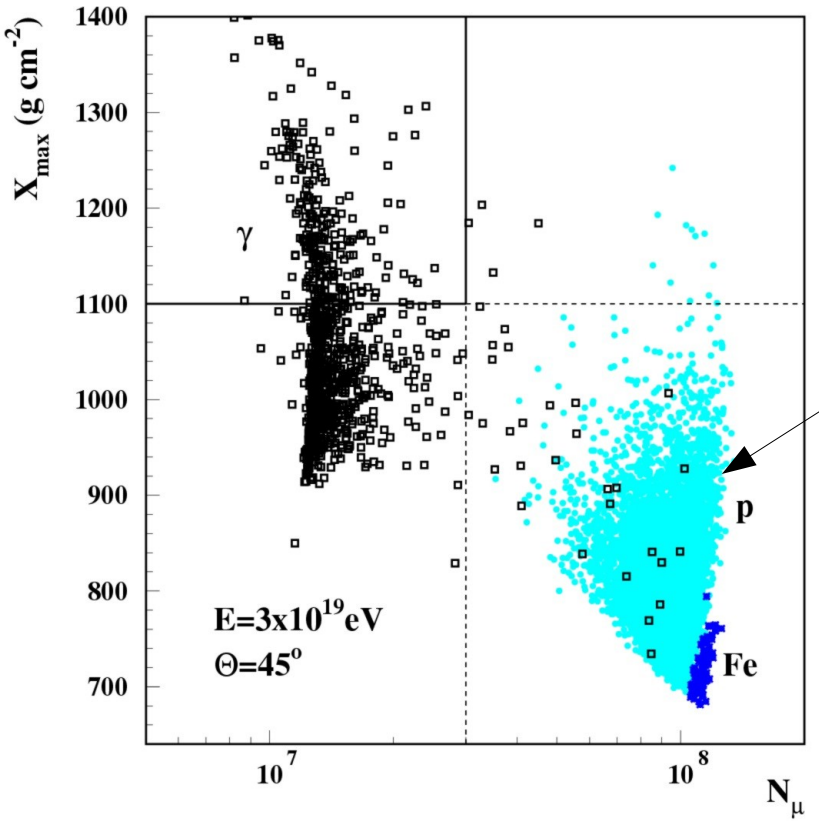
- they should exists (factor >100 above current E_{max})
- neutral ⇒ directional pointing (source identification)
- neutral ⇒ transients (flaring vs. steady sources)
- relation to cosmic rays (particularly composition)
- tracers of matter and fields during propagation
- testing more local universe (complementary to neutrinos)
- the only gauge boson among astroparticles
- observation by showers: similar to “normal“ ones
- quite precise simulation of cascading (EM dominates)
- potential tracers of BSM physics

historical view on the conquest of new windows:

question is not if, but when ...

OK OK OK OK OK OK OK OK OK OK OK ? ? ?

Photon-hadron discrimination. How good with showers?



air shower simulation only

10,000 protons

Proton fluctuations may depend on hadron model. Photon simulations are almost model-independent!

(MR & Homola 2007)

- **mis-identification rates** (proton-photon) **~0.1%** **(X_{max}), ~0.01%** **(N_μ)**