Search for Ultra-High Energy Photons with the Pierre Auger Observatory

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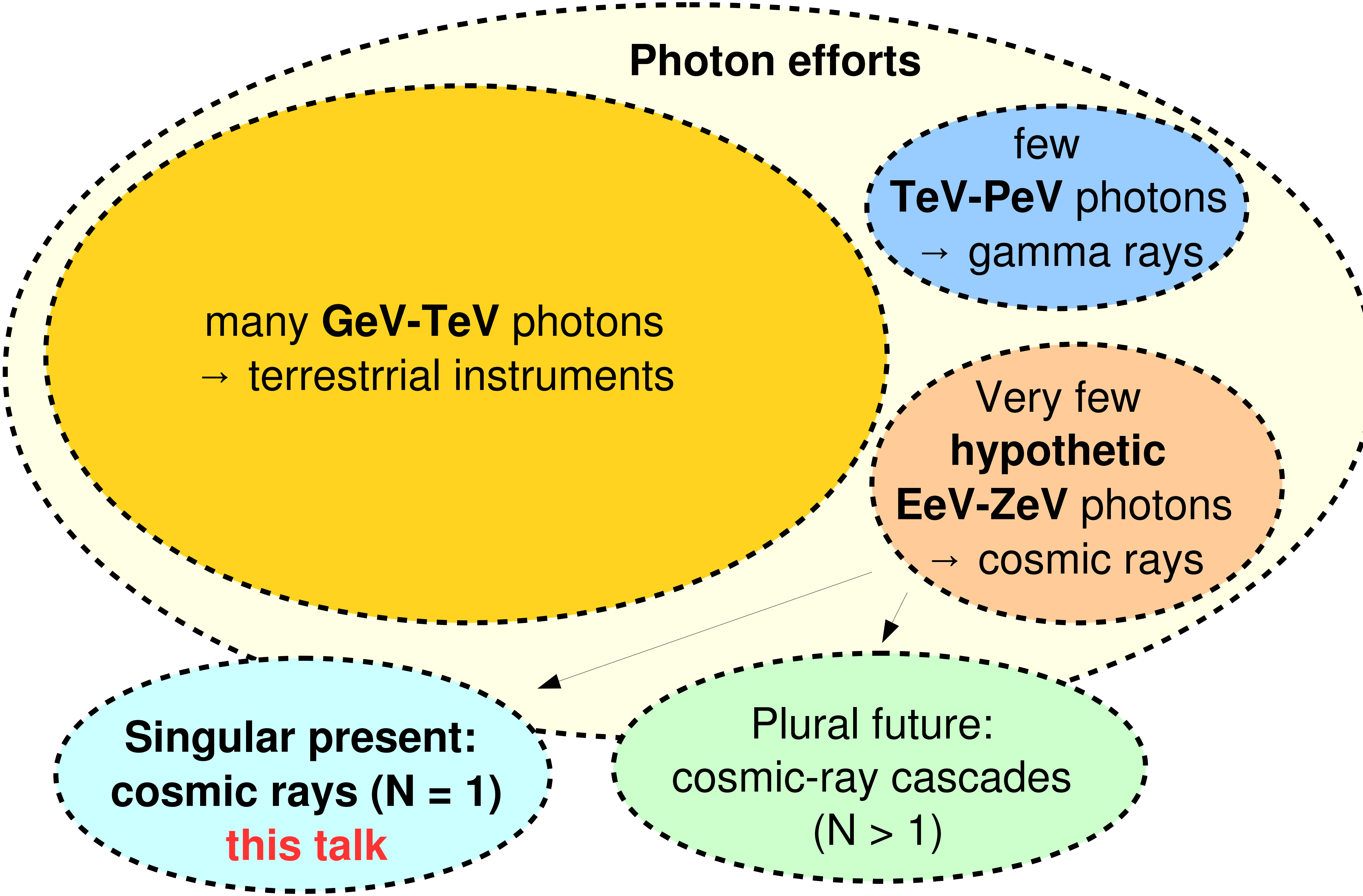
Photon 2017, CERN, 25.05.2017

photo by theoryandpractice.org

Understanding the Photon Structure



N: number of cosmic ray particles correlatated in time

Short history of ultra-high energy cosmic rays (UHECR)

Particles coming to Earth from Space

1912. Electroscopes discharge faster with increasing altitude → rays of extraterrestrial origin: V. Hess (Nobel prize 1936).

1932. Discovery of antimatter (positron): C. Anderson (Nobel prize 1936).

1937. Discovery of muons: S. Neddermeyer and C. Anderson → particle physics begins.

1938. Extensive air showers (EAS) → $E > 10^{15}$ eV: P. Auger

1962. First EAS at 10^{20} eV: J. Linsley
→ what and why can have so huge energies???

.... high time for a next breakthrough?

Energy spectrum of cosmic rays

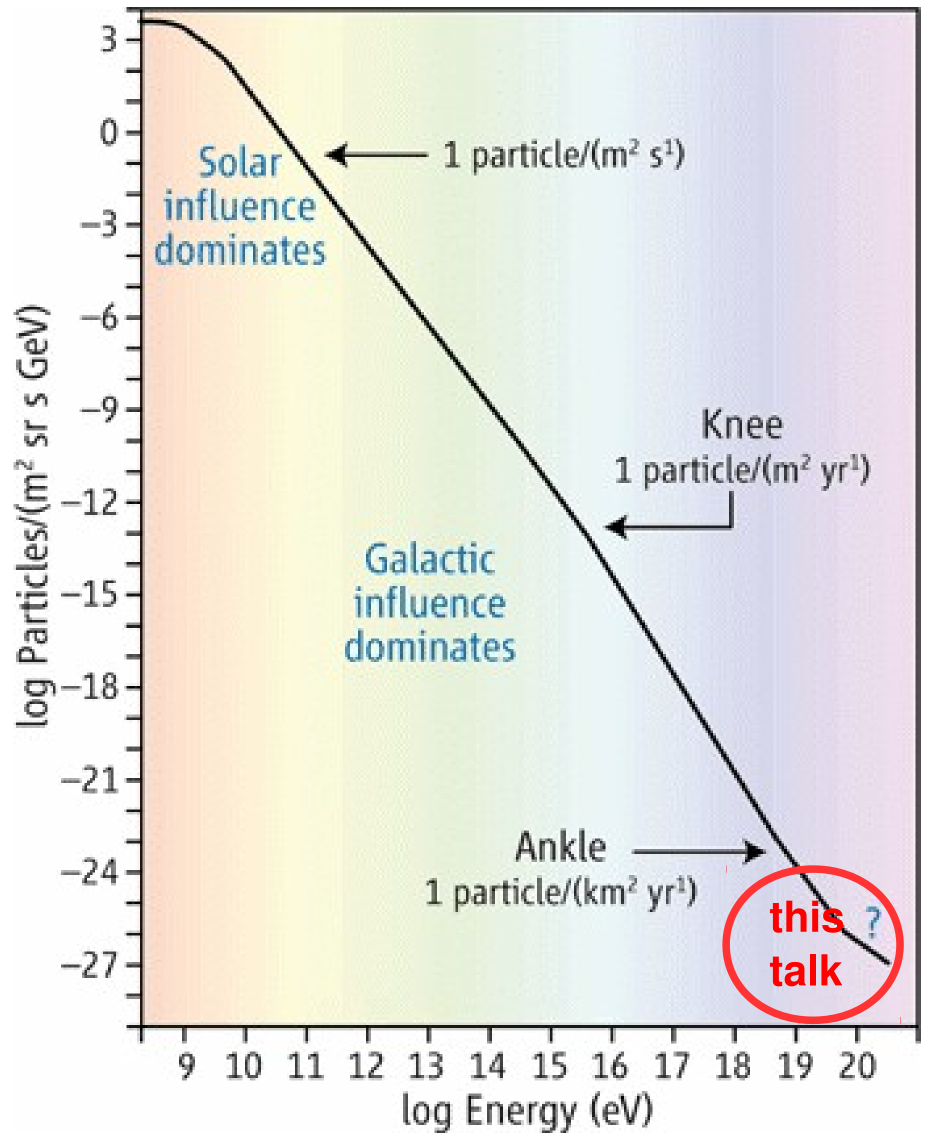
Ranges:
energy: > 10 orders of magnitude
flux: > 30 orders of magnitude
→ diverse physics (sources)
→ diverse detection techniques

Flux rapidly decreases with energy (~10^{-3}),
Highest energies → the most demanding challenges:

→ technical:
extremely low flux (at E=10^{20}eV
1 particle / km^2 millenium), but now:
the Pierre Auger Observatory (~3000 km^2)

→ scientific:
What are UHECR? Where they come from?
How do they propagate?

Do photons contribute to the UHECR flux?



UHECR propagation: no source candidates?

UHECR protons of high energies (E > ~ 5 $\times 10^{19}$eV) should interact with background radiation (CMBR):

$$p\gamma_{CMBR} \rightarrow p\pi^0 / n\pi^+$$

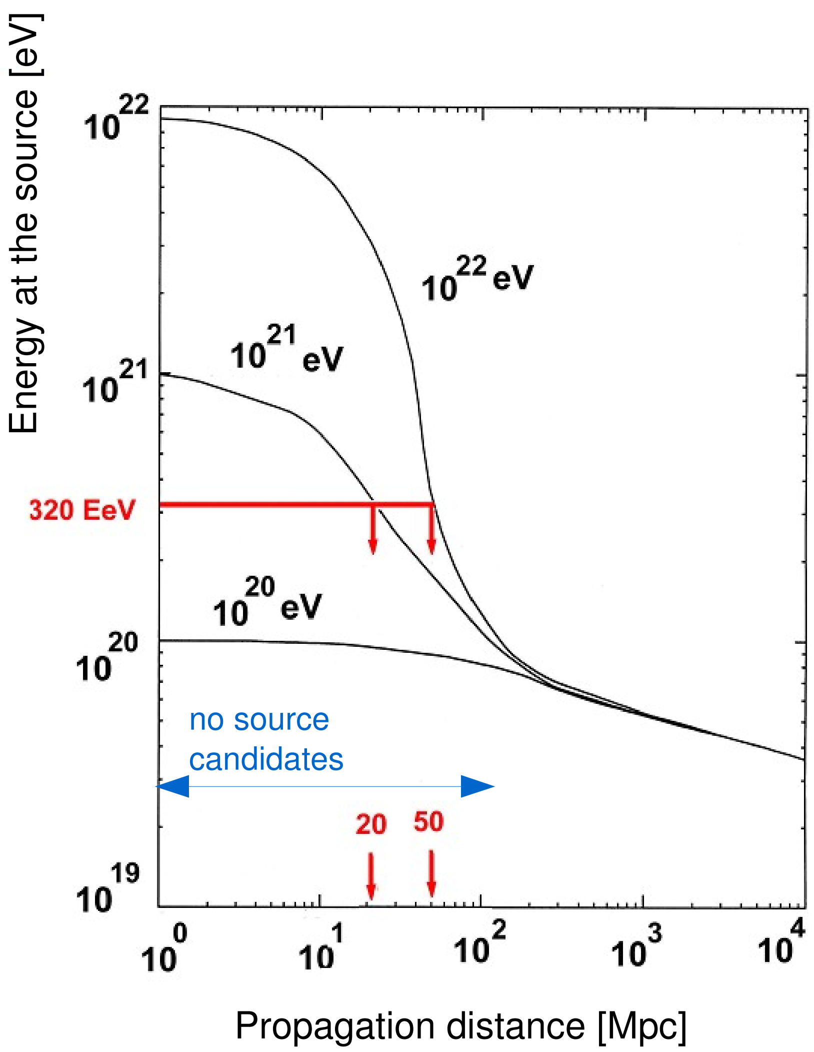
$\hookrightarrow$ γ (GZK photons)

→ proton energy reduced, mean free path limited
→ characteristic cut-off of the energy spectrum

effect predicted in 1966 by
K. Greisen, G. T. Zatsepin, V. A. Kuzmin

GZK photons guaranteed if protons contribute to UHECR flux...

Testing GZK effect through photons:
→ nuclear interactions at highest energies,
source distribution or maximum source energies



Photons as UHECR: testing astrophysical scenarios

Astrophysical scenarios

acceleration of nuclei (e.g. by shock waves)
+ „conventional interactions”, e.g. with CMBR

- sufficently efficent astrophysical objects difficult to find
- small fractions of photons and neutrinos – mainly nuclei expected

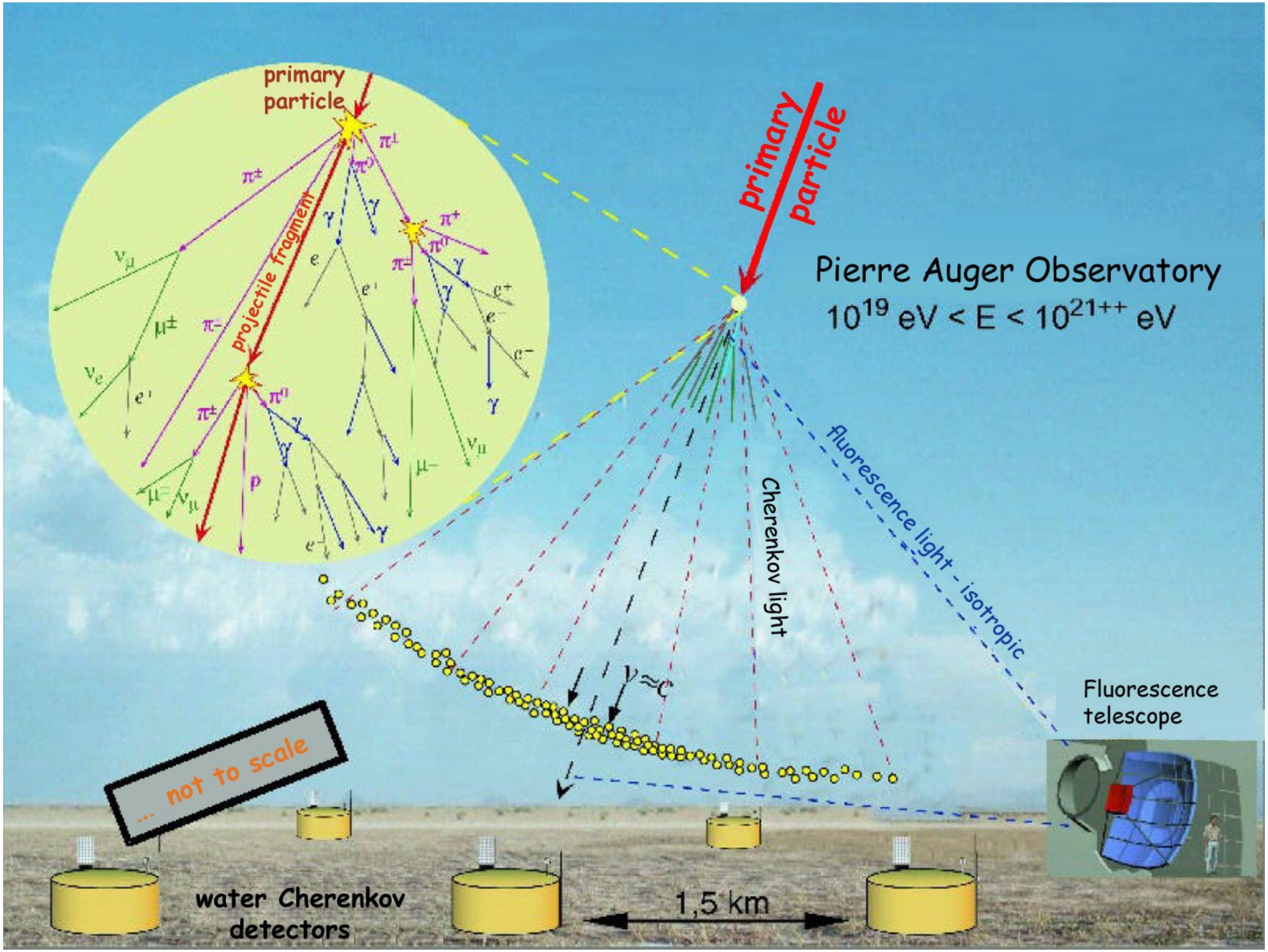
??? Exotic scenarios (particle physics) ???

Decay or annihilation the early Universe relics
→ hypothetic supermassive particles of energies $\sim 10^{23}$ eV
→ decay to quarks and leptons → hadronization (mainly pions)

- large fraction of photons and neutrinos in UHCER flux

↘ not the case?

Detection of UHECR at the Pierre Auger Observatory



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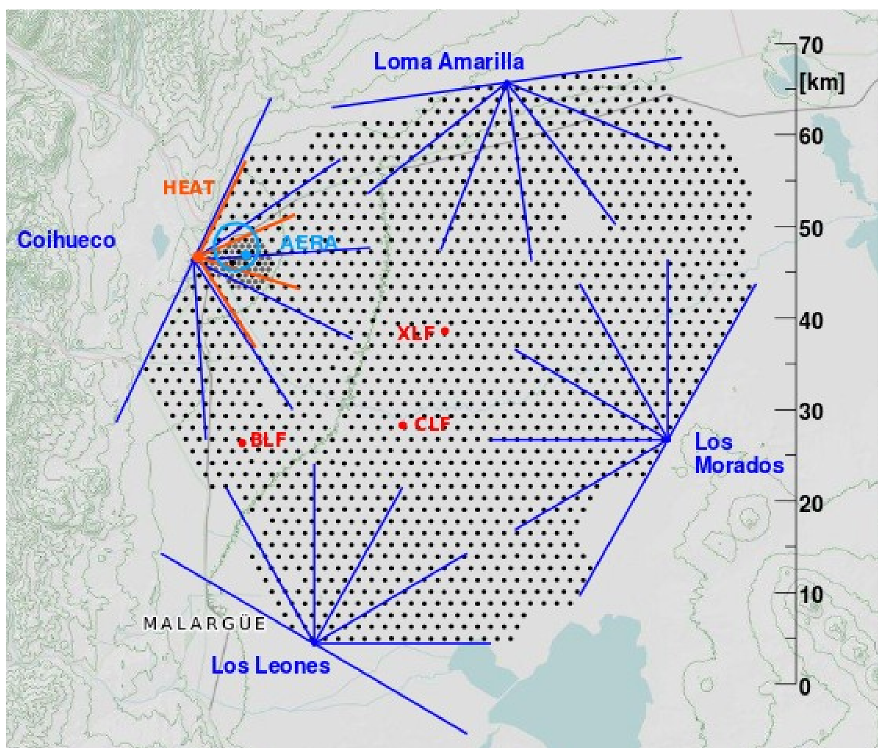


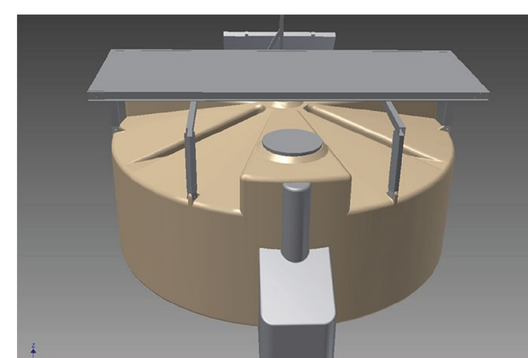
Surface Detector:

→ 1600 stations (3000 km^2)

Fluorescence Telescopes:

→ 27 (5 stations)

being upgraded: **AugerPrime**



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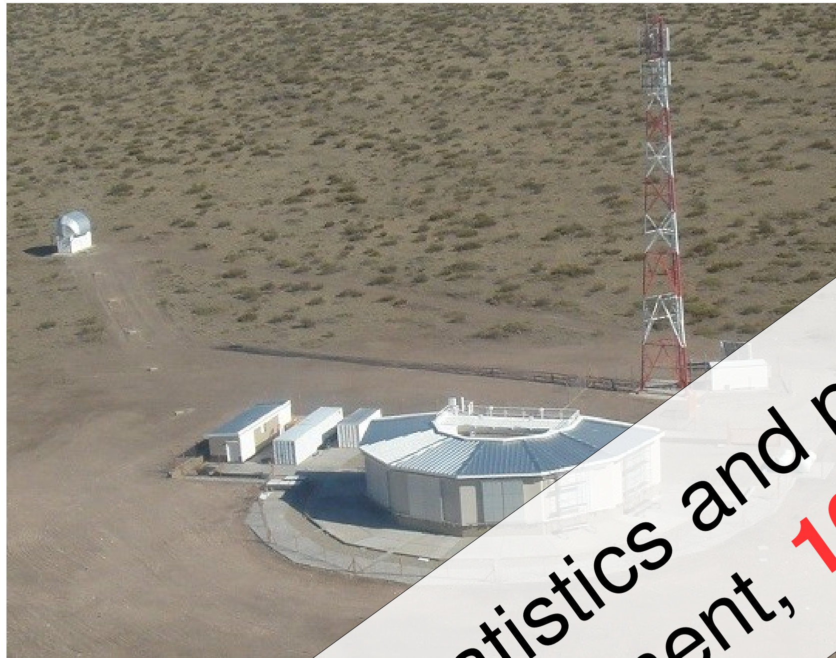
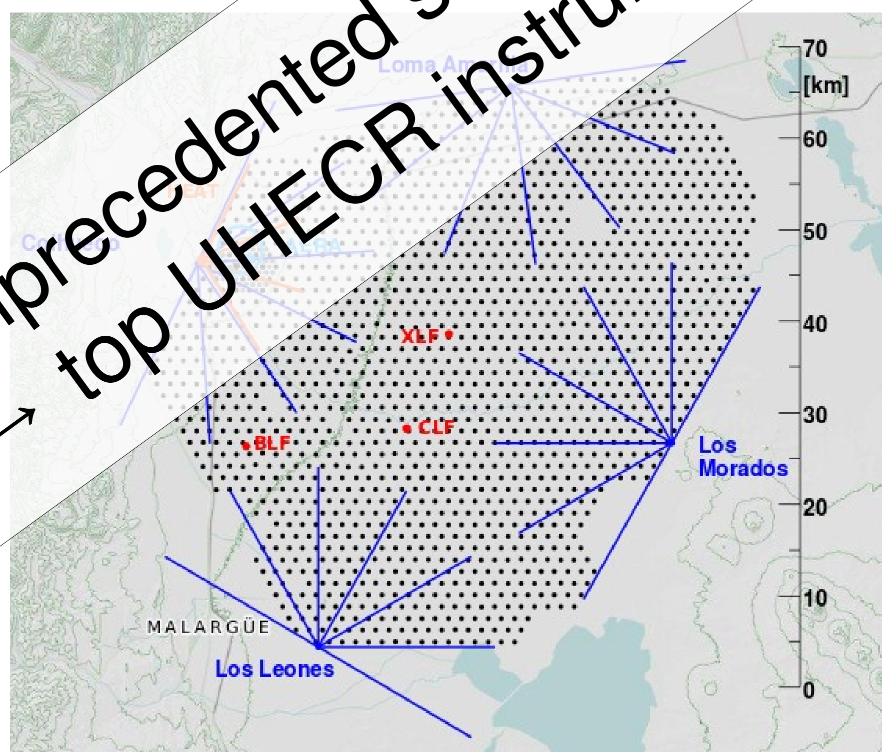


Unprecedented statistics and precision

→ top UHECR instrument, 10^{20} eV!!!



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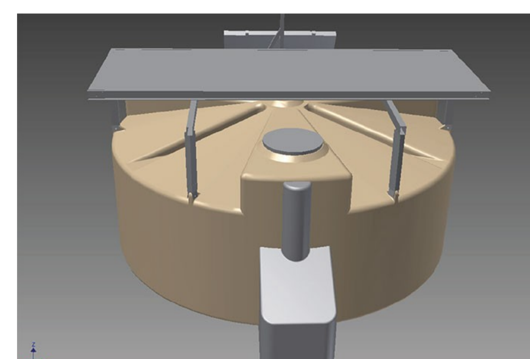
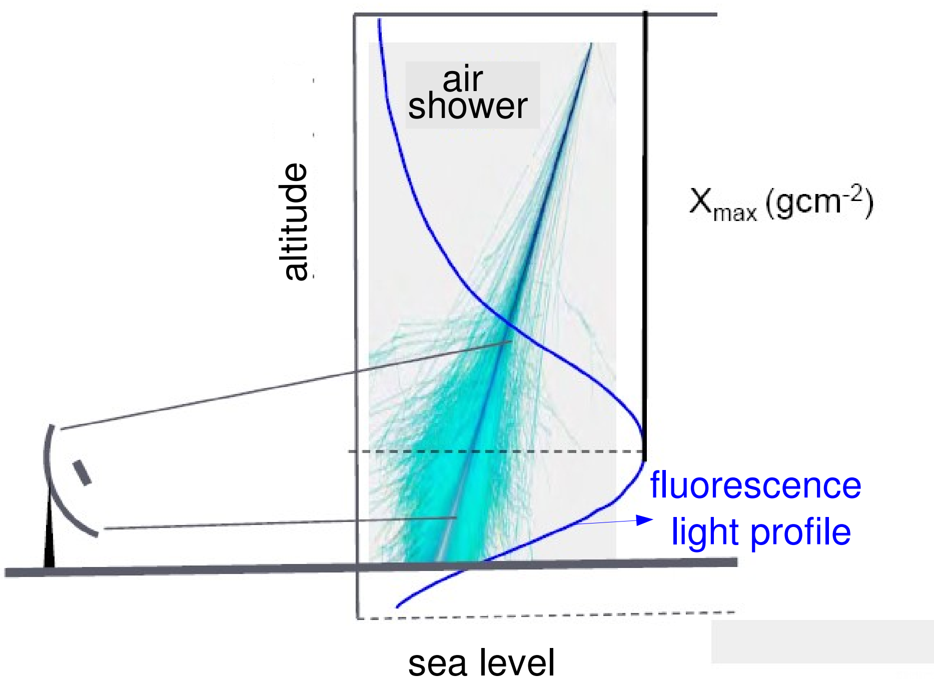
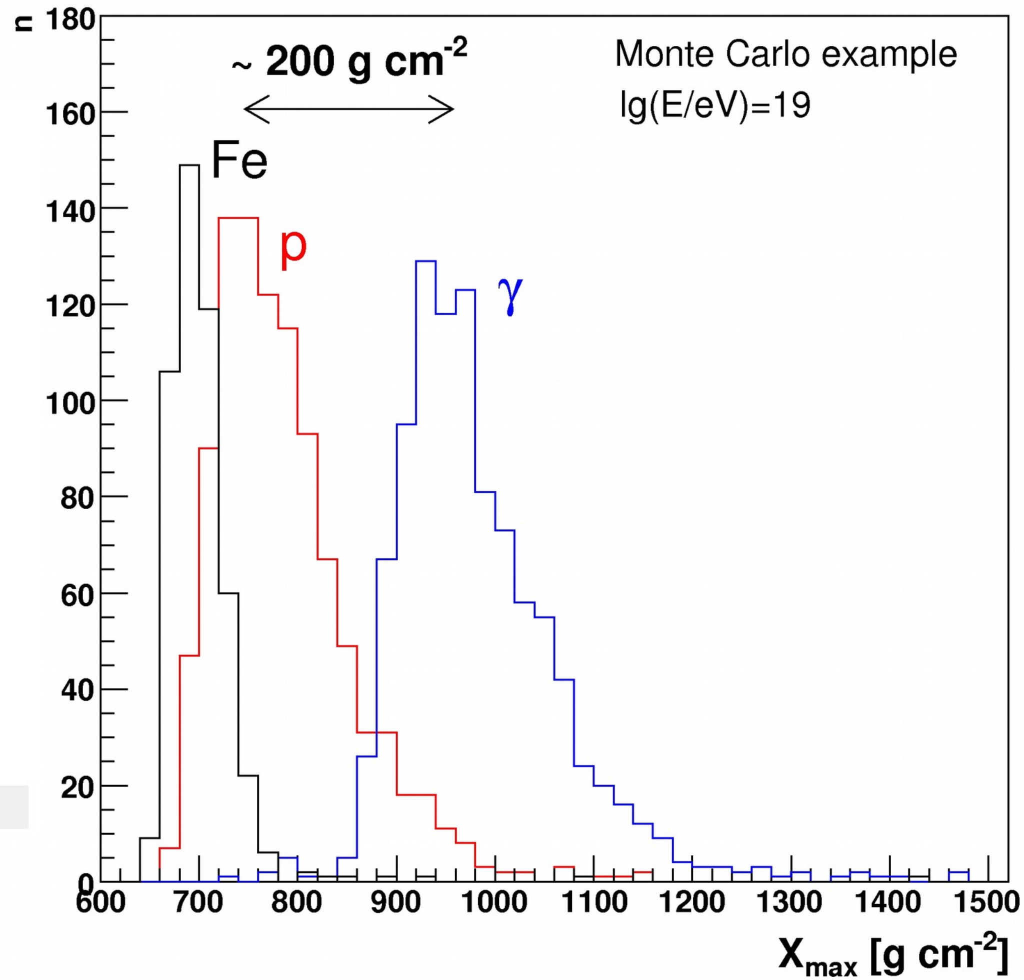


UHECR photon identification: X_{max}





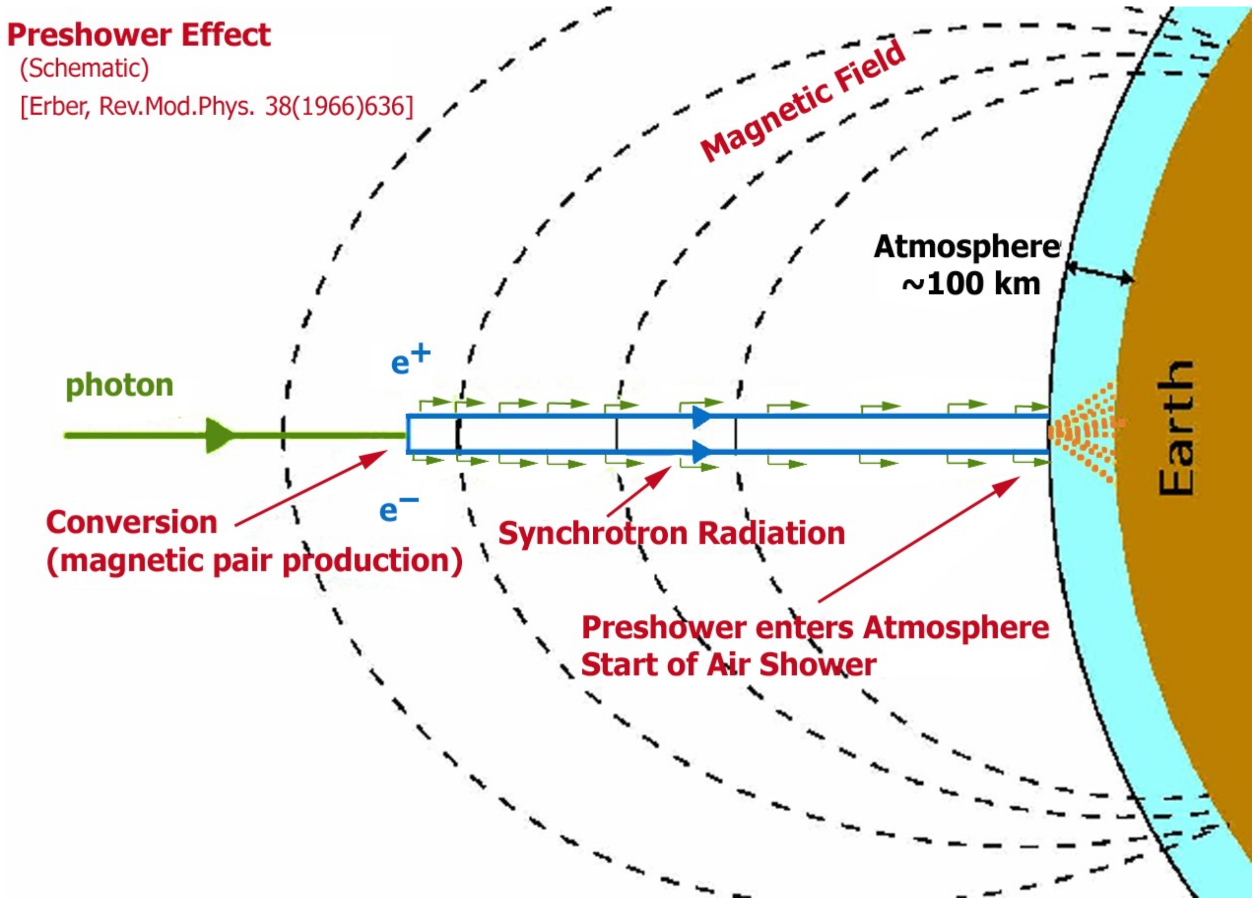
X_{max}: atmospheric depth of shower maximum development

$\rightarrow \langle X_{max}(Fe) \rangle < \langle X_{max}(p) \rangle < \langle X_{max}(\gamma) \rangle$

Preshowers: a must to study UHE photons

Preshower (important for $E_\gamma > 10^{19}$ eV):

→ contains typically 100 particles
(created at around 1000 km a.s.l.)



→ dependence on E and $B_\perp$ (to be seen in data?)

Landau-Pomeranchuk-Migdal (LPM) effect

LPM effect:
Pair prodution formation length $\geqslant$ mean free path → destructive interference from several scattering centers: $\gamma \not\rightarrow e^+e^-$

Bremsstrahlung supressed as well. Confirmed by experiments.

Formation lenght: the lenght of the photon trajectory over which pair production happens
Pair production formation length icreases with photon energy $\mathbf{E_\gamma}$
Photon mean free path decreases with medium density ϱ

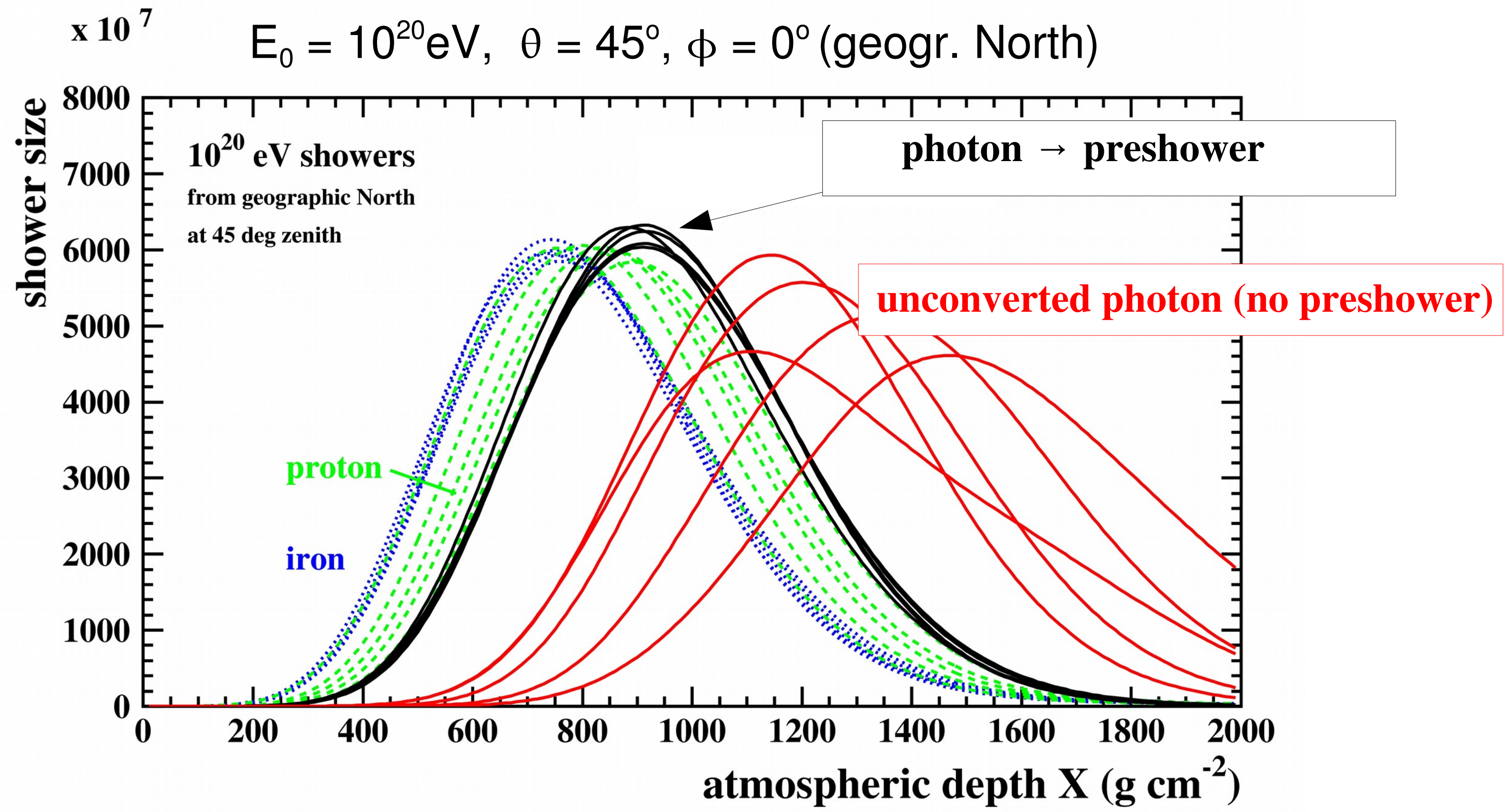
→ the **Bethe-Heitler cross-section** for pair production by photons, σ_{BH} (in air $\sigma_{BH} \approx$ 0.51 b), can be **reduced** when $\mathbf{E_\gamma}$ and/or medium density ϱ **high**

$\kappa = E_\gamma E_{LPM}/[E_e(E_\gamma - E_e)]$, $E_{LPM} = m_e^2 c^3 \alpha X_0/(4\pi\hbar\varrho) \approx$ (7.7 TeV/cm) $\times X_0/\varrho$, $X_0 \sim 37$ g cm^{-2}
E_γ - photon energy, E_e - electron energy, ϱ - medium density, X_0 - radiation length

Approximation for $\kappa<1$: $\boldsymbol{\sigma_{LPM} = \sigma_{BH}\, \kappa^{1/2} \propto (\varrho\, E_\gamma)^{-1/2}}$
→ σ_{BH}/σ_{LPM} largest for a symmetric energy partition in the electron pair, $E_e \approx E_\gamma/2$

Numerical examples:
$\mathbf{E_{LPM} \sim 10^{19}}$ **eV in the upper atmosphere**, $E_{LPM} \sim 2.8 \times 10^{17}$ eV at 300 m a.s.l.

Preshowers and EAS development



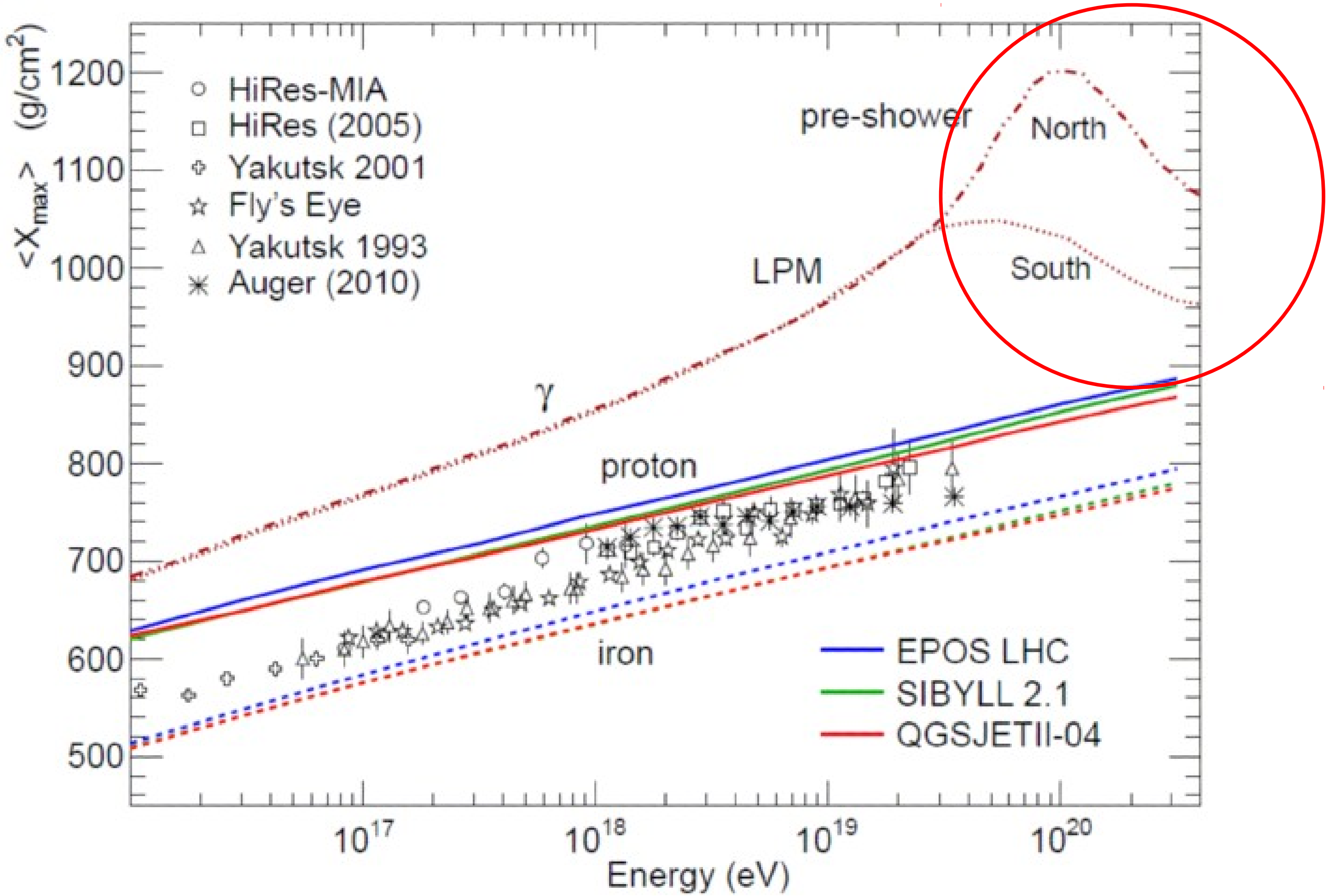
LPM (in top layers of atmosphere is important for $E_\gamma > 10^{19}$ eV):

→ **deep** X_{max}, **large** fluctuations of X_{max}

PRESHOWER (primary E_γ split into preshower particles):

→ **shallow** X_{max}, **small** fluctuations of X_{max}

Identification of photon-induced air showers: X_{max} vs. E_γ



M. Settimo for the Pierre Auger Collaboration, Proceedings of Photon 2013 Conference

Preshower effect:

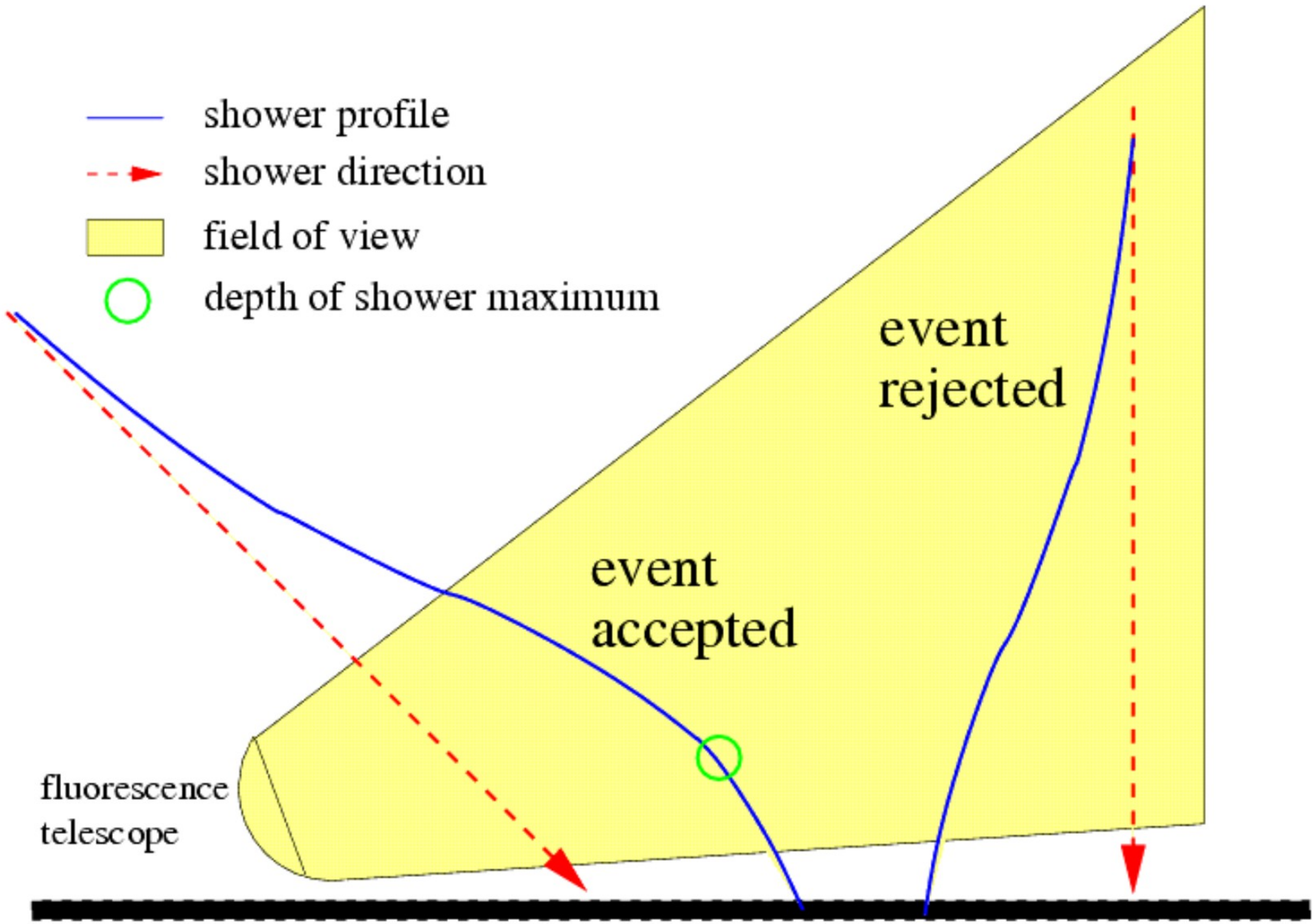
→ **negative** elongation rate!

→ dependence on arrival direction

→ no X_{max} values typical for unconverted photons and preshowers

Data selection example

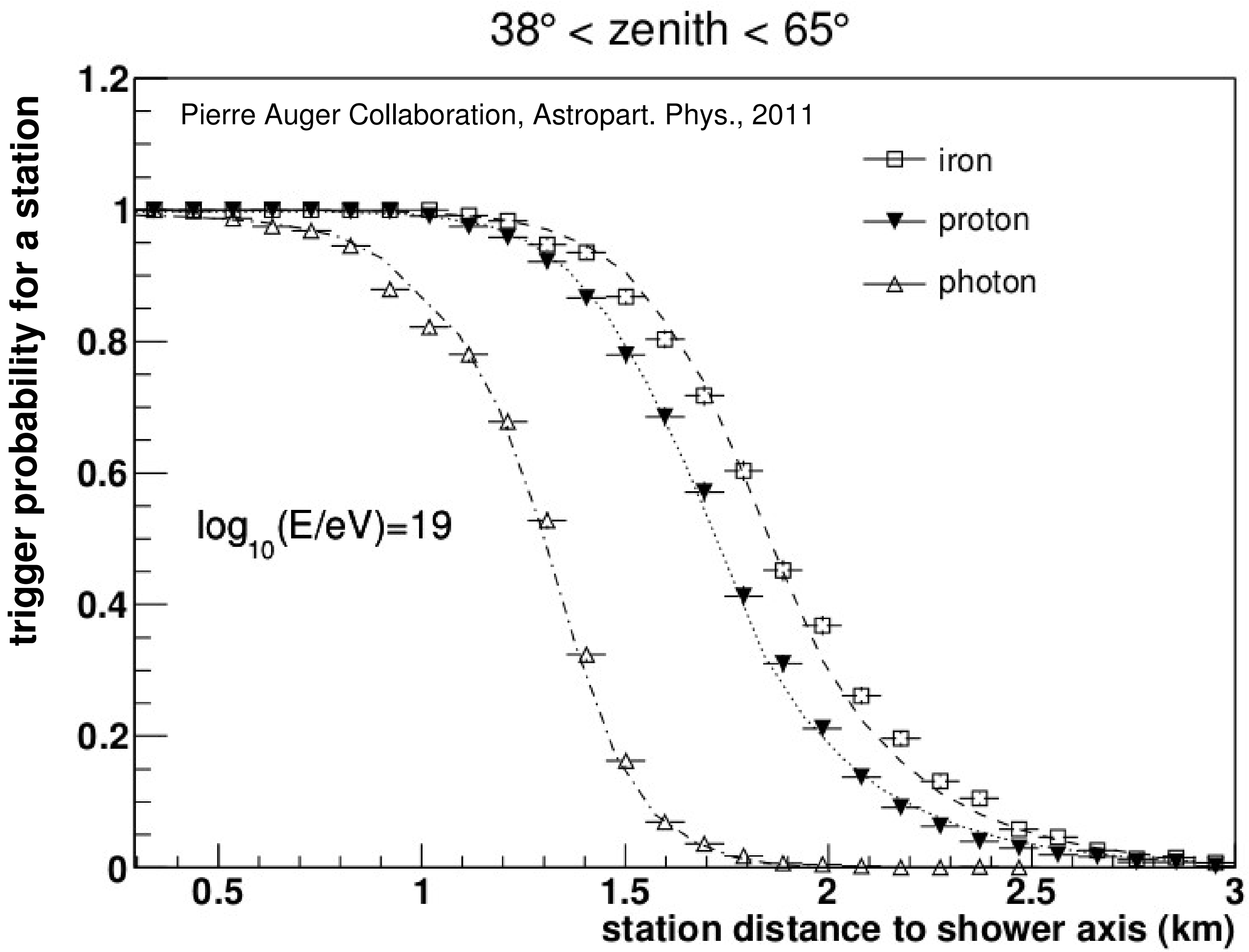
X_{max} in the field of view of fluorescence telescope



Auger Surface Detector UHE photon observables

Smaller footprint of photon-induced showers:

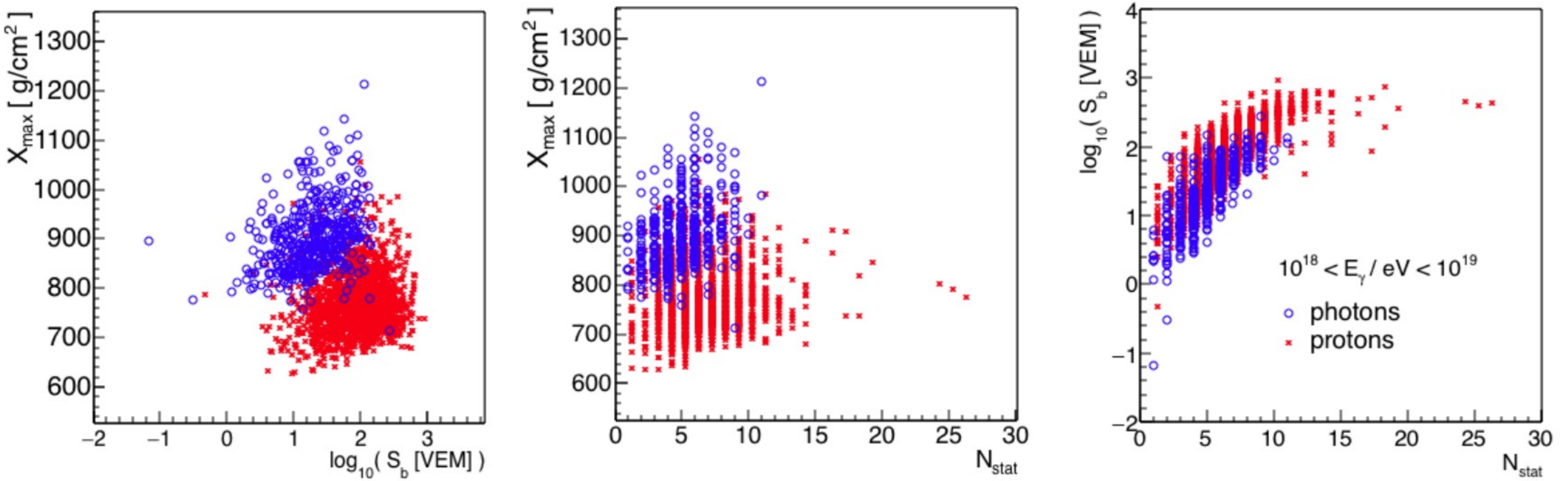
$N_{stations}$(photon) < $N_{stations}$(hadron): N_{stat} ; $Signal_{R0}$(photon) < $Signal_{R0}$(hadron): $S_b = \sum_i^N S_i \left(\frac{R_i}{R_0}\right)^b$



Diffuse UHE photon search: mulitvariate

Pierre Auger Collaboration, JCAP 2017

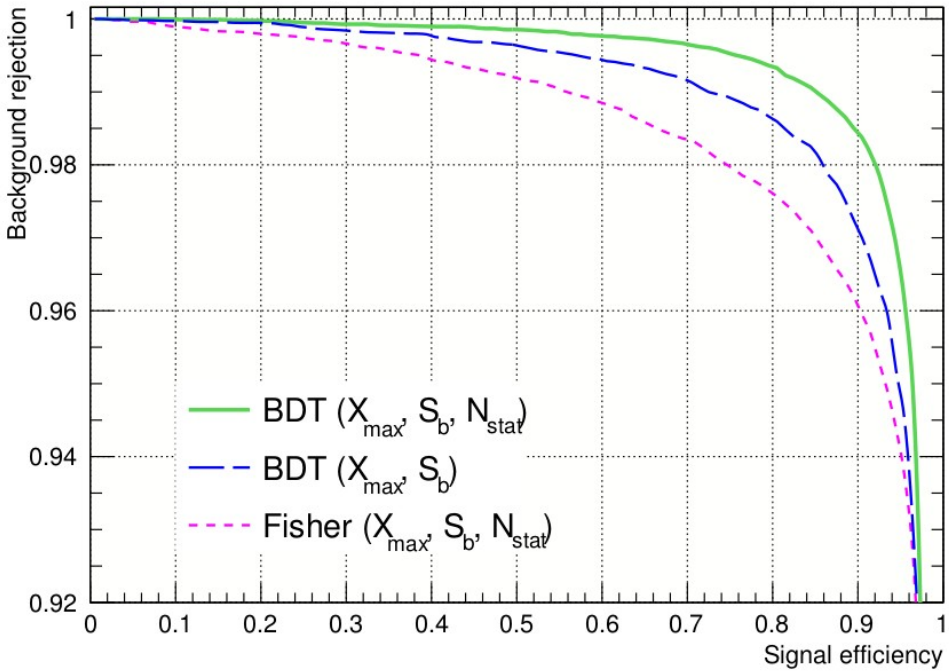
X_{max} S_b N_{stat}

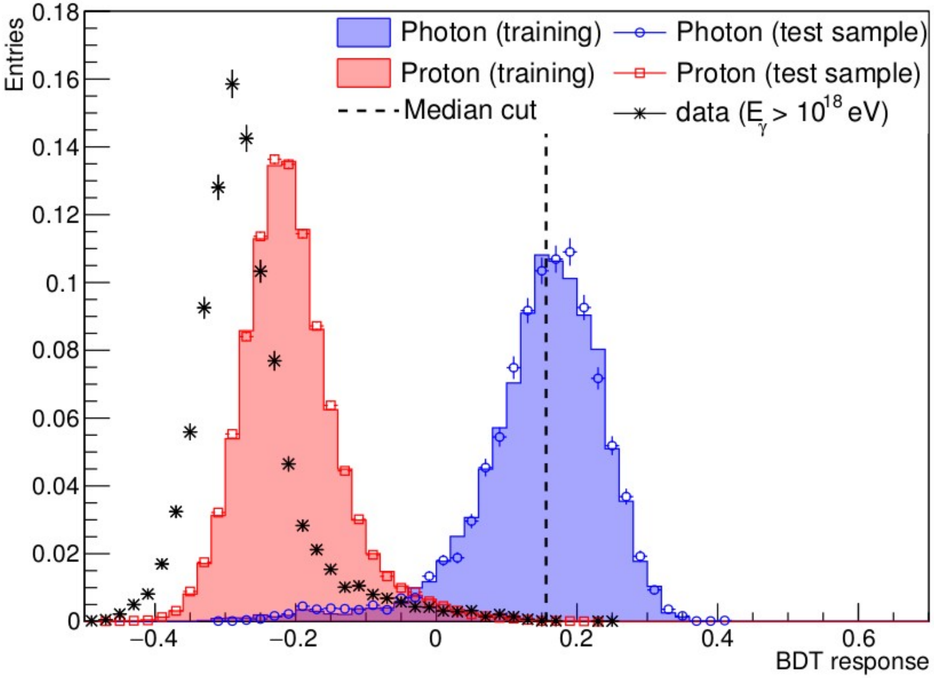


VEM: vertical equivalent muon

Diffuse UHE photon search: candidates

Pierre Auger Collaboration, JCAP 2017

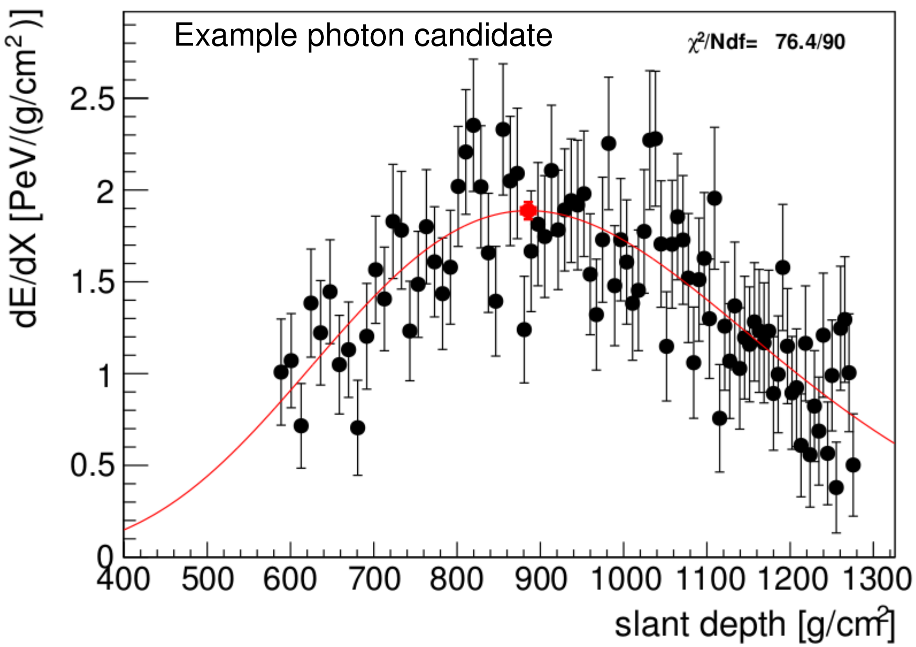


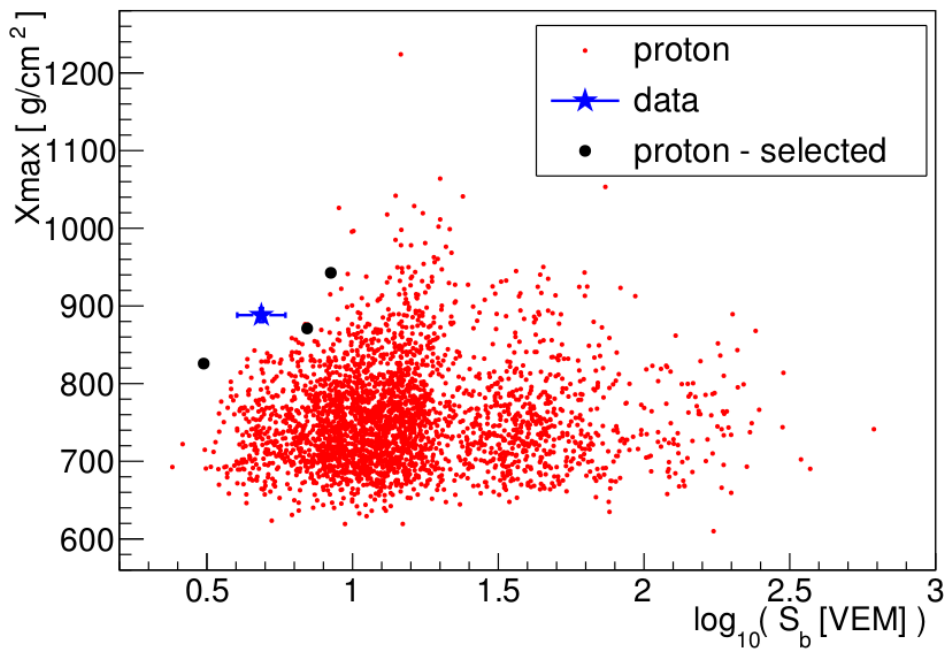


BDT: Boosted Decision Tree

Diffuse UHE photon search: proton background

Pierre Auger Collaboration, JCAP 2017

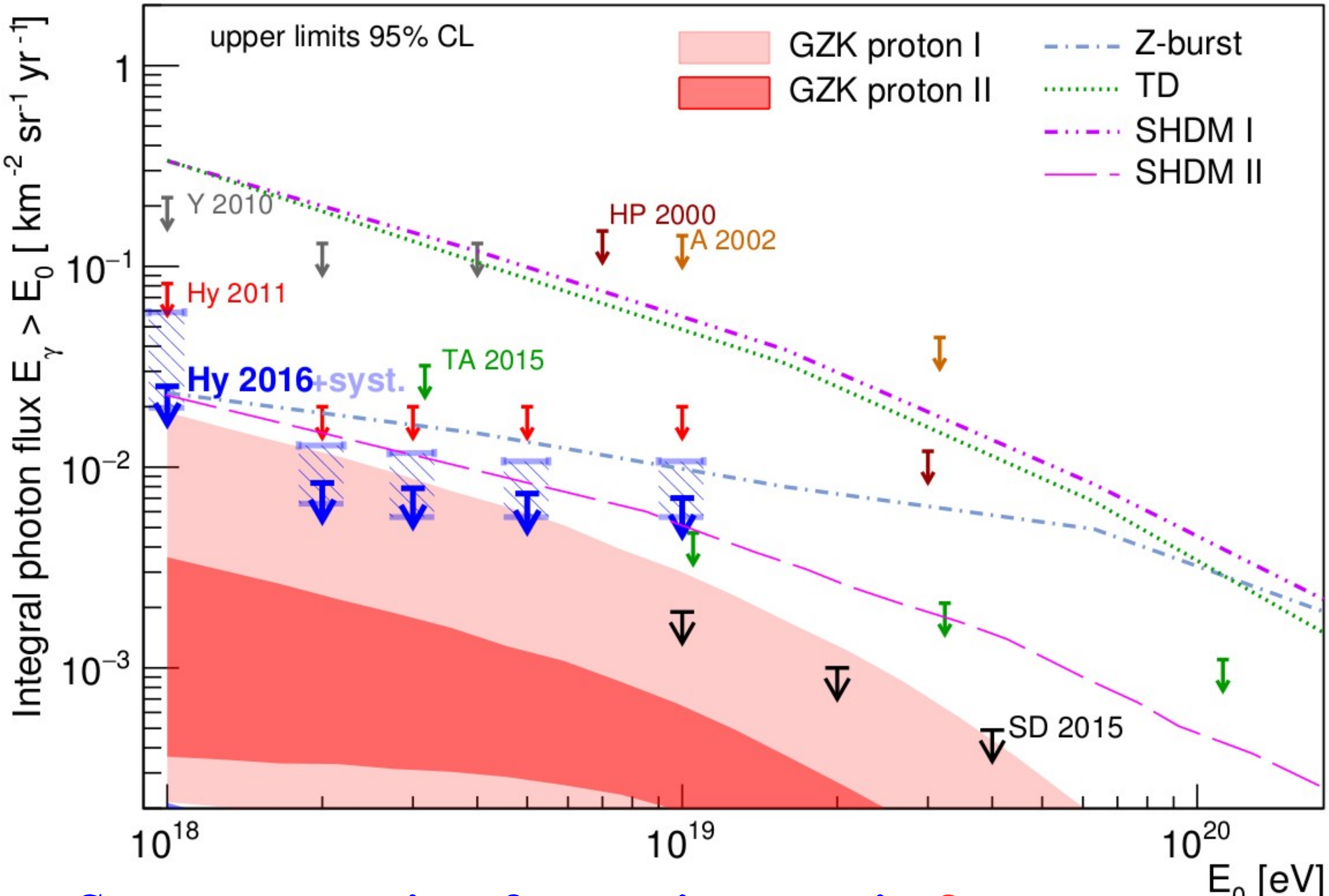




3 photon candidates (1 < E/EeV < 2), consistent with proton background

Diffuse UHE photon search: hybrid limits

Pierre Auger Collaboration, JCAP 2017



→ **Severe constraints for exotic scenarios?**

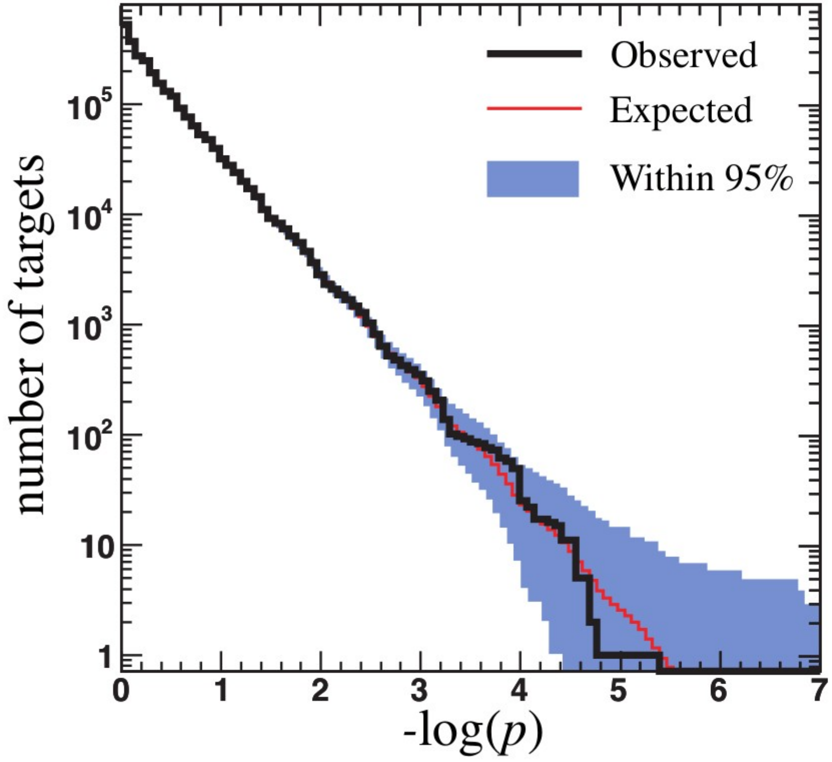
→ **and for (special) Lorentz Invariance Violation?**

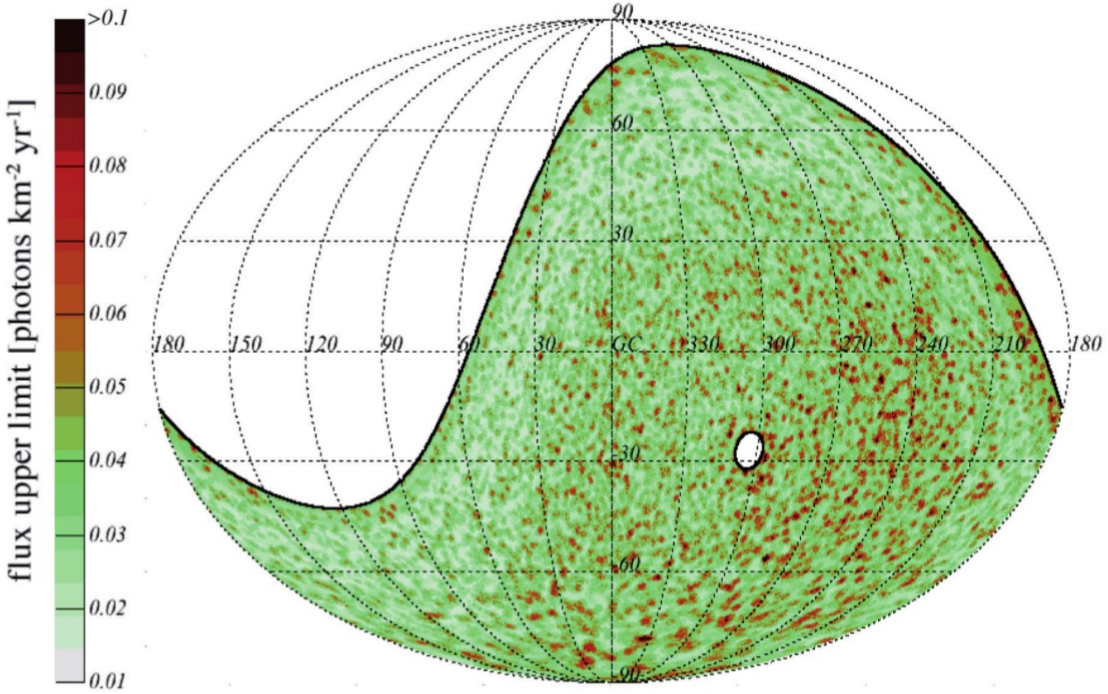
Directional (blind) UHE photon search

Pierre Auger Collaboration, ApJ 2014:

- Photons are neutral → undeflected

- only photon-like events → reduce nuclear background





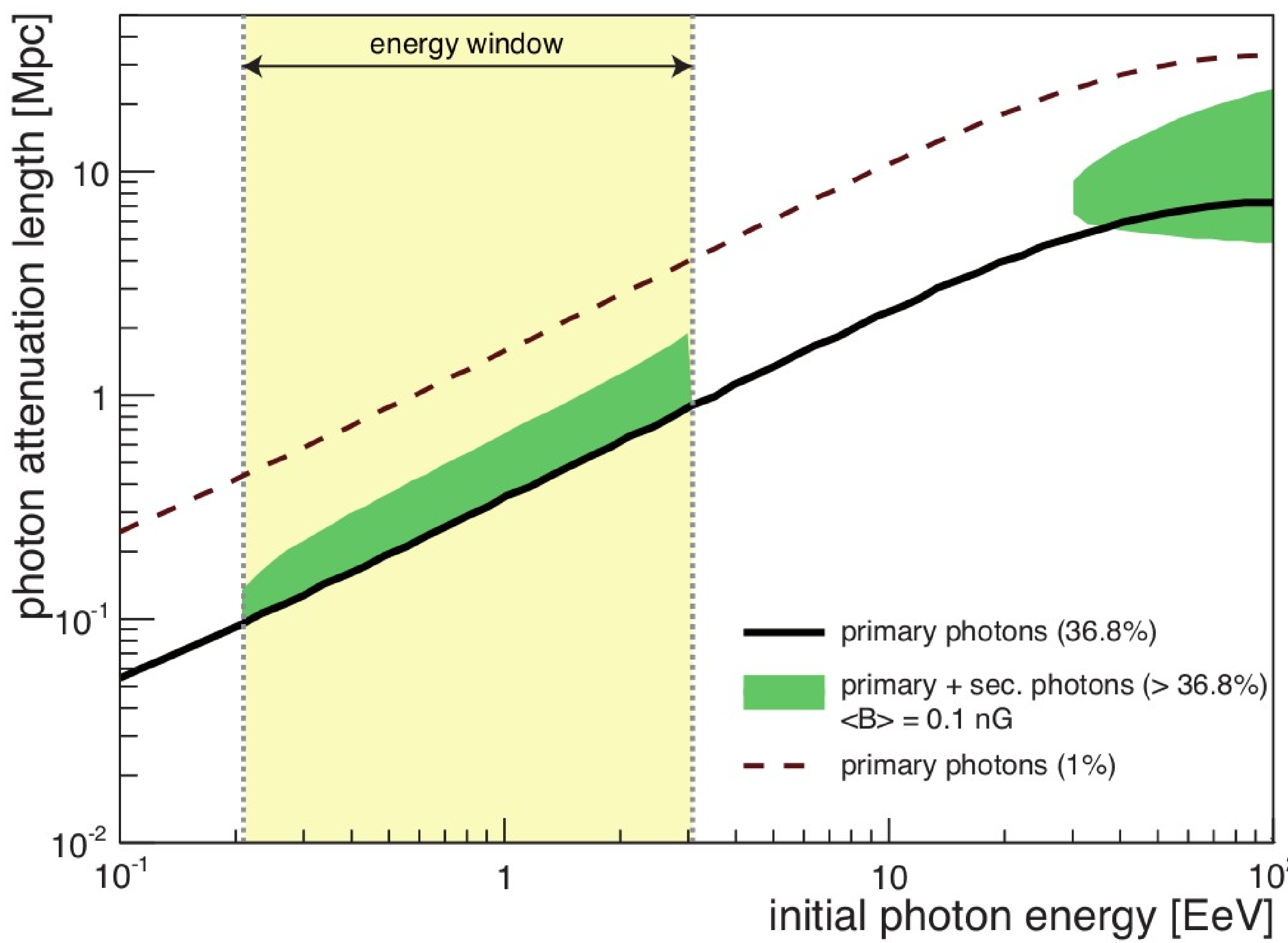
No indications for nearby photon emitters in the EeV energy range

→ directional (point sources) upper limits

Targeted UHE photon search: horizon

Pierre Auger Collaboration, ApJL 2017

Sources distant by < 1 Mpc



Targeted UHE photon search: source classes

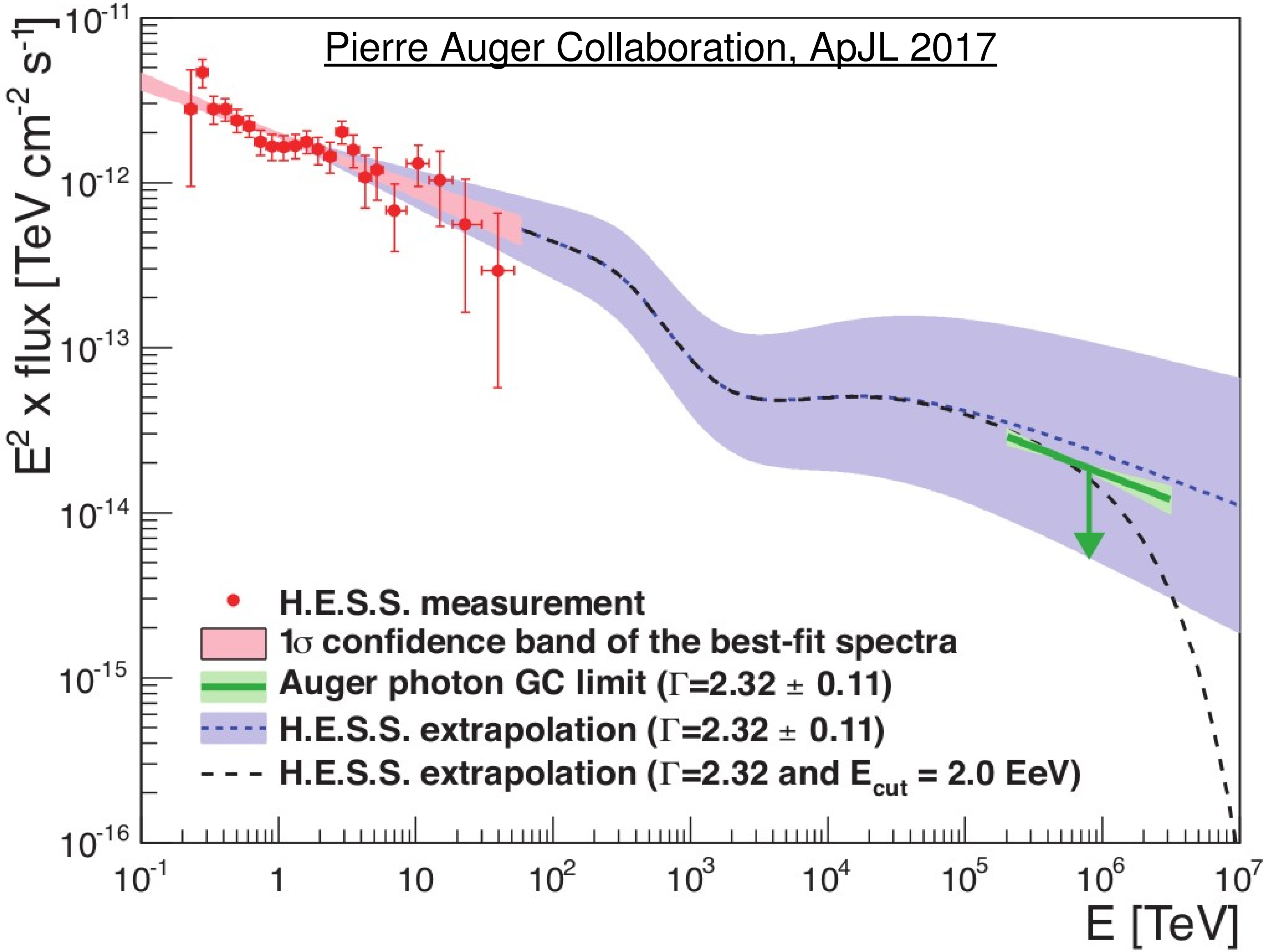
Pierre Auger Collaboration, ApJL 2017

Groupping sources in classes

Class	No.	$\mathcal{P}_w$	$\mathcal{P}$
msec PSRs	67	0.57	0.14
γ-ray PSRs	75	0.97	0.98
LMXB	87	0.13	0.74
HMXB	48	0.33	0.84
H.E.S.S. PWN	17	0.92	0.90
H.E.S.S. other	16	0.12	0.52
H.E.S.S. UNID	20	0.79	0.45
Microquasars	13	0.29	0.48
Magnetars	16	0.30	0.89
Gal. Center	1	0.59	0.59
LMC	3	0.52	0.62
Cen A	1	0.31	0.31

Minimum p-values statistically insignificant

Targeted UHE photon search: constraints



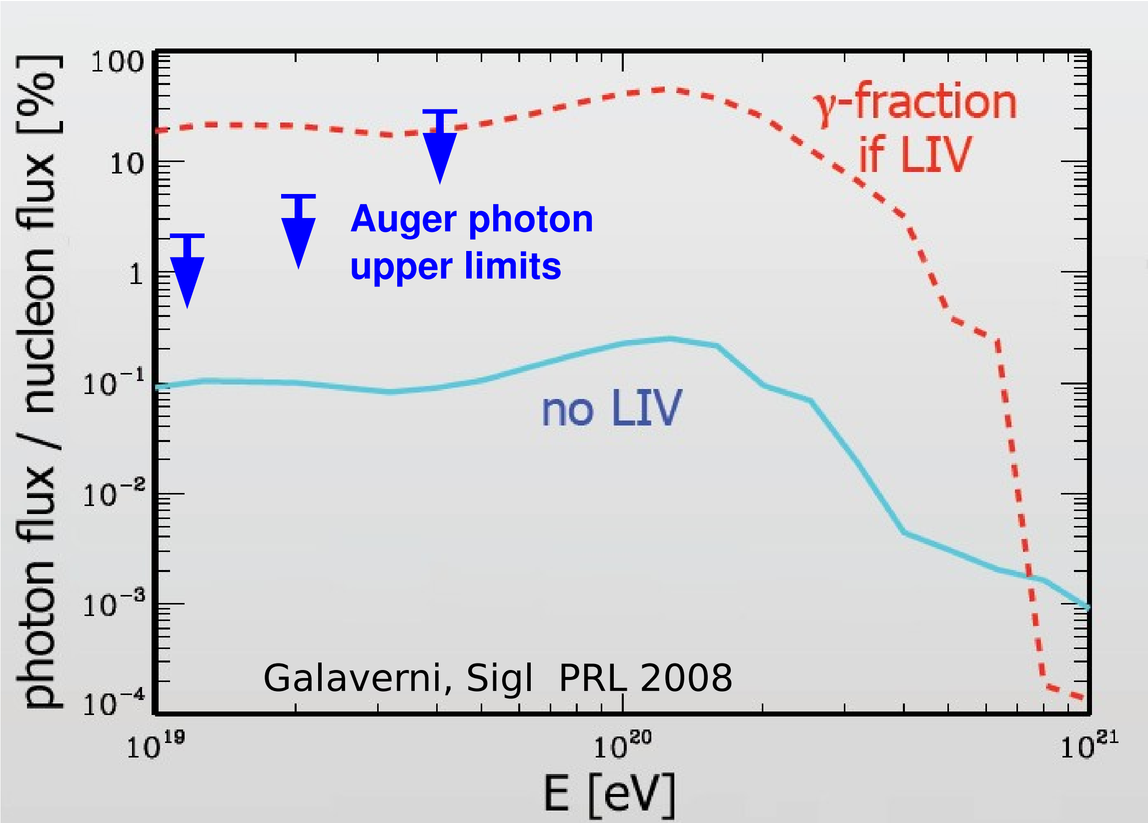
Constraining astrophysics: e.g. extrapolations of fluxes from the TeV range

Probing fundamental physics: example

Testing Lorentz Invariance Violation (LIV) → photon dissperssion relation modified?

$\omega^2 = k^2 + \xi_n k^2 (k/M_{Pl})^n$ → e^+e^- production threshold modified

e.g. $\pi^0 \rightarrow \gamma\gamma$ $\quad \gamma \not\rightarrow e^+e^-$ cascading of photons supressed



If LIV:

$\xi_1, \xi_2 > 0$

Upper limits based on UHECR observations:

$\xi_1 < 2.4\times10^{-15}$
$\xi_2 < 2.4\times10^{-7}$

Lorentz invariance violation and photon limits

Isotropic, nonbirefringent LV

UNIVERSITÄT SIEGEN

- κ endows the vacuum with an effective index of refraction, leading to a **modification of the photon dispersion relation**

$$\omega(q) = \frac{1}{n_{\mathrm{eff}}} q = \sqrt{\frac{1-\kappa}{1+\kappa}}\, q$$

- This modification allows for processes which are **kinematically forbidden** in the conventional Lorentz-invariant theory
  - $\kappa > 0$: **vacuum Cherenkov radiation** possible above a threshold $E_{\mathrm{thr}}(\kappa)$

$$f \to f + \tilde{\gamma}$$

    efficient energy loss mechanism for charged particles, current constraints ($\kappa < 6 \times 10^{-20}$ at 98% C.L.) derived from **observations of UHECRs** [Klinkhamer & Risse 2008] [Klinkhamer & Schreck 2008]

  - $\kappa < 0$: **photon becomes unstable** above a threshold $\omega_{\mathrm{thr}}(\kappa)$

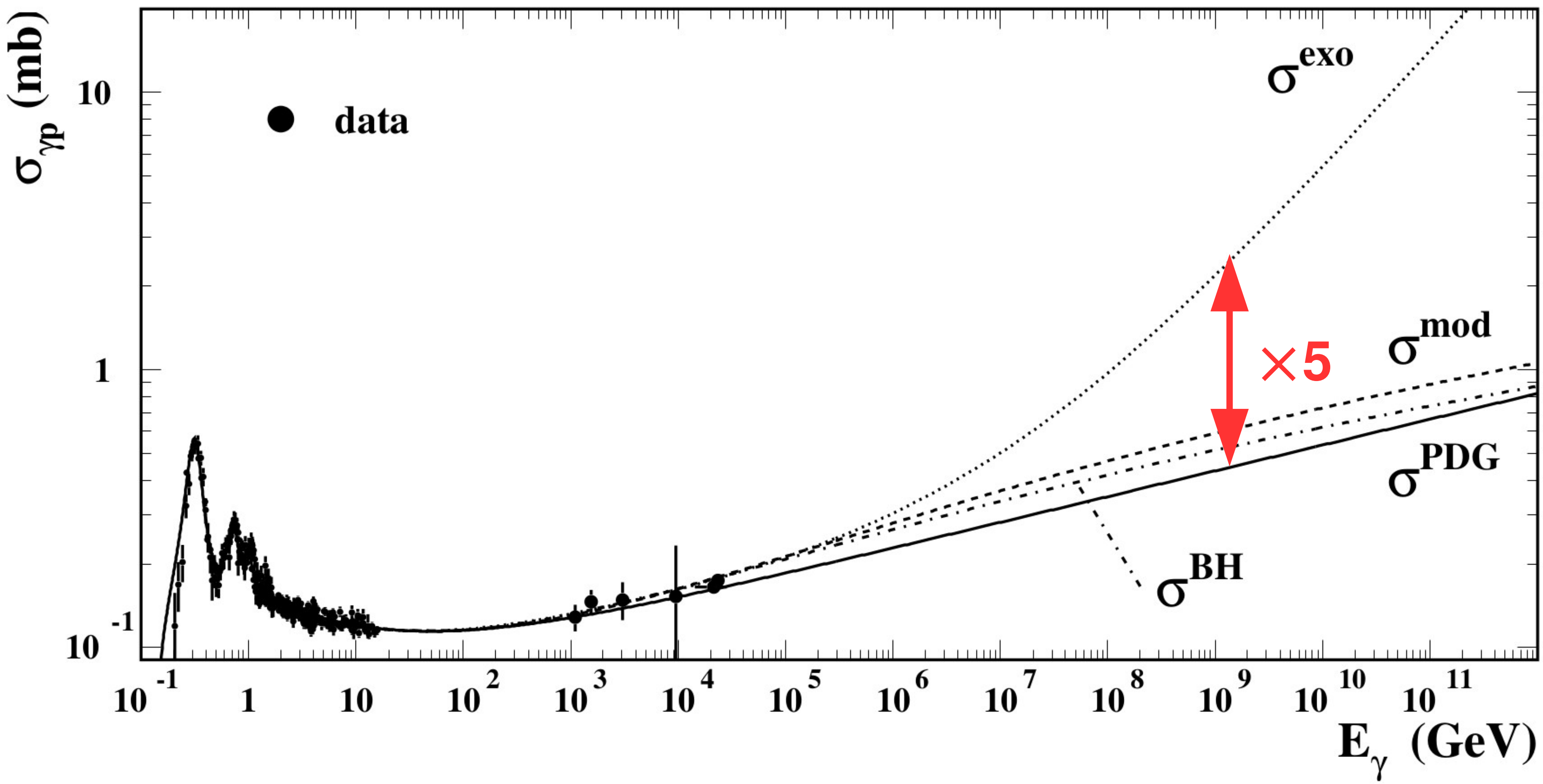
$$\tilde{\gamma} \to e^{+} + e^{-}$$

    decay length is very small, current constraints ($\kappa > -9 \times 10^{-16}$ at 98% C.L.) derived from **gamma-ray astronomy** [Klinkhamer & Schreck 2008]

UHE photons cascade immediately!!!

Low N_μ in photon induced showers? What if...

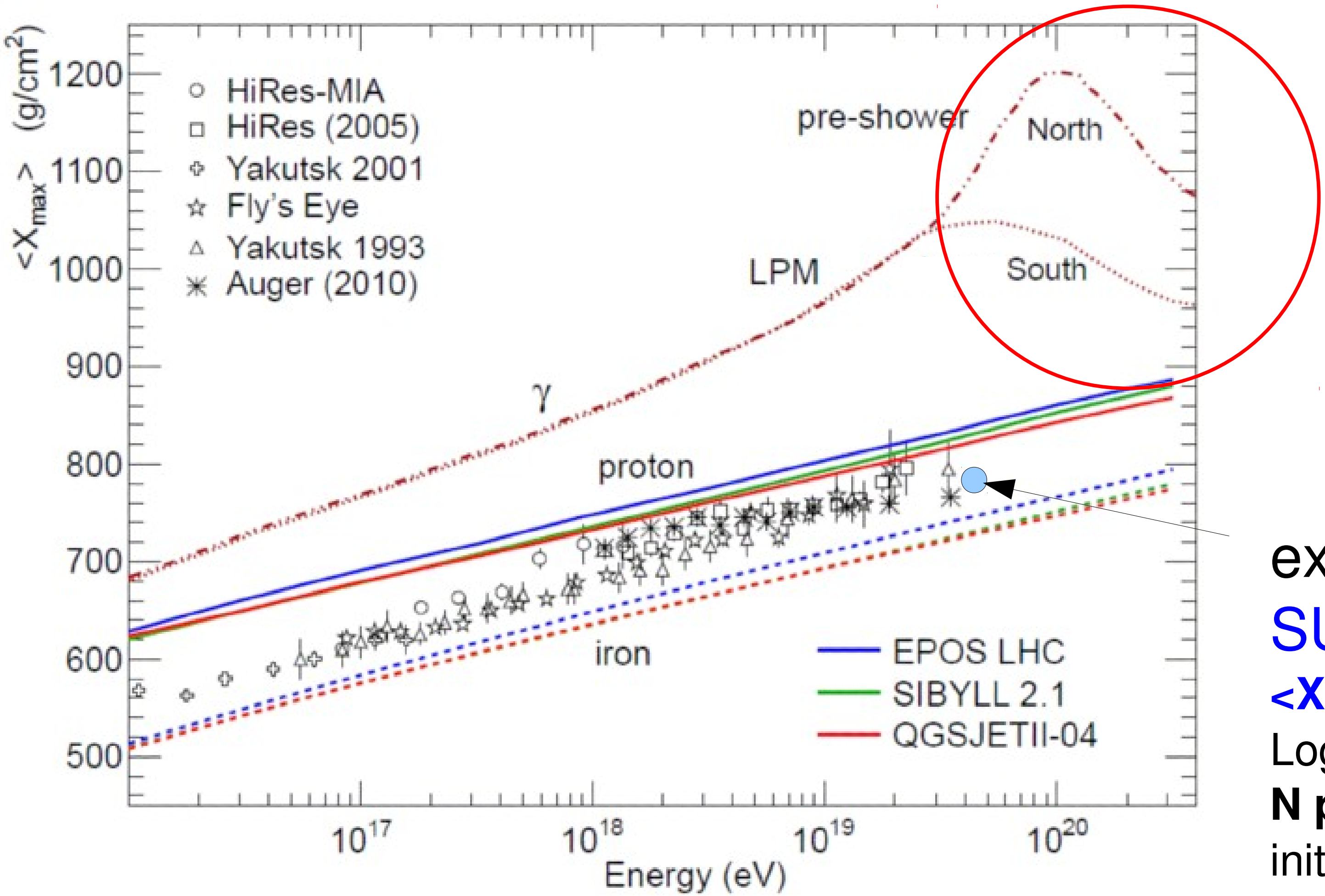
Risse et al., 2006



→ keeping in mind uncertainty about $\sigma_{\gamma p}$

→ **AugerPrime will help!** Better primary mass discrimination

No deep X_{max} observed? What if...



M. Settimo for the Pierre Auger Collaboration, Proceedings of Photon 2013 Conference

Preshower effect:

→ **negative** elongation rate!

→ dependence on arrival direction

example

SUPER-preshower:

<Xmax>=783±3g/cm²

LogE=19.6

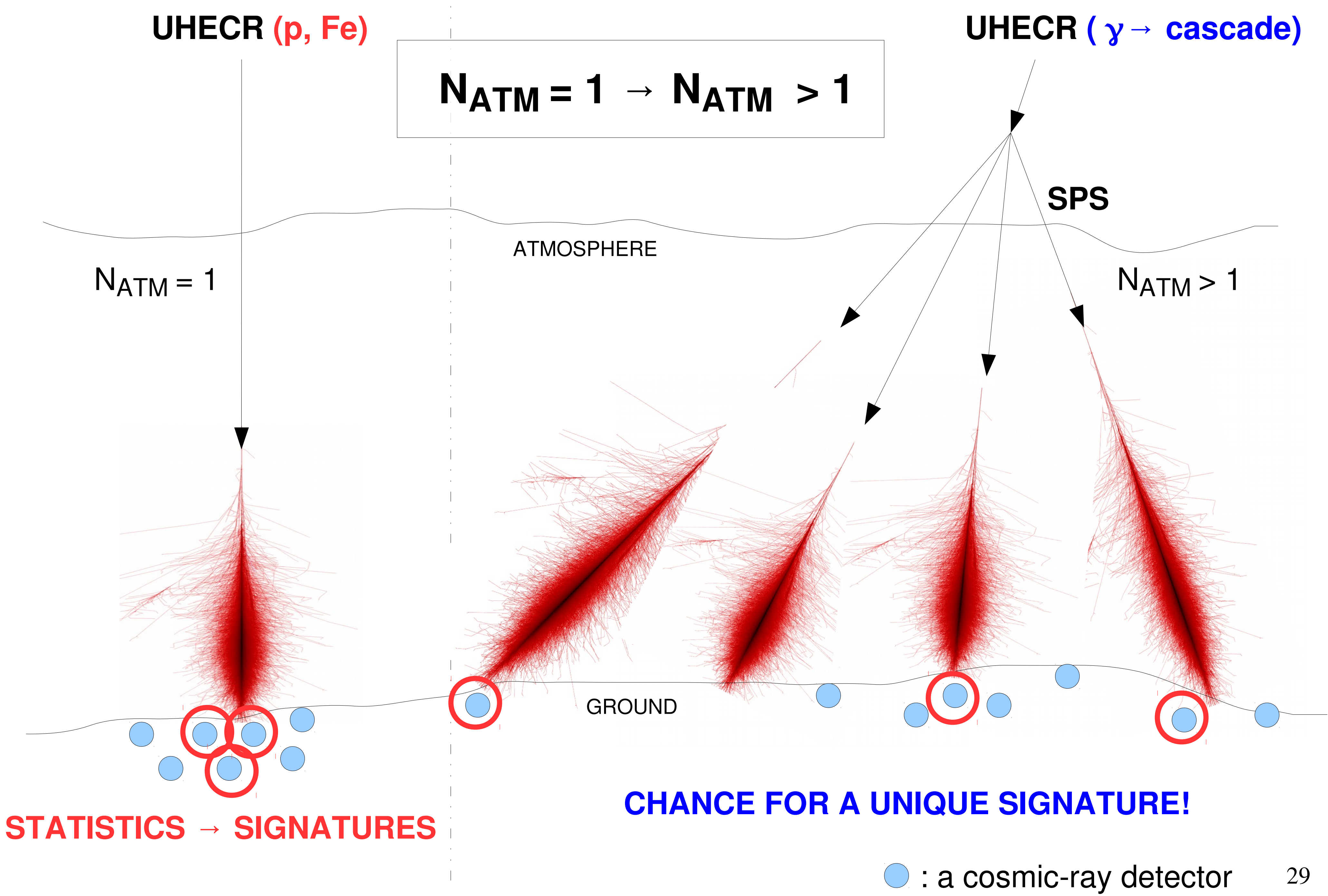
N particles =1500

initiated at 17000 km a.s.l.

→ search dedicated to SUPER-preshowers???

→ **AugerPrime** will offer new observables...

Extension of the UHE photon search horizon?



UHE photons summary

- no evidence for existence useful!

→ constraints on special LIV

→ constrain astrophysical scenarios
(fluxes extrapolations from TeV range)

- perspectives to continue the search:

→ a room for a better understanding of extensive air showers
(AugerPrime – better primary mass sensitivity)

→ plural approach: extensive photon cascades?
(see PH talk on CREDO)