The search for ultra-high-energy photons at the Pierre Auger Observatory

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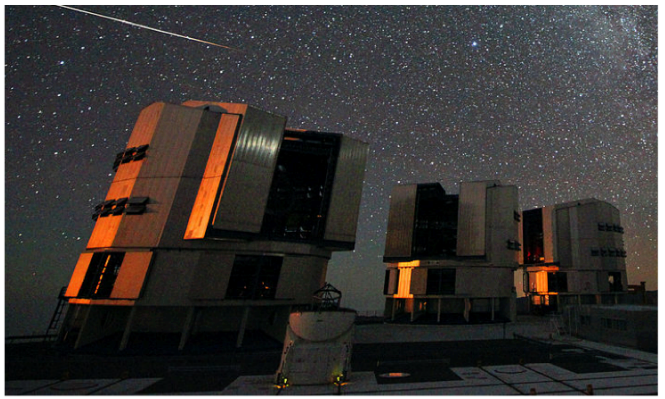
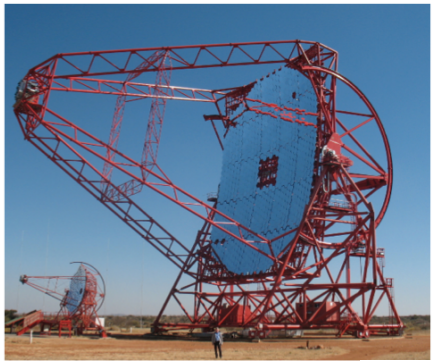
Electromagnetic spectrum



Very Large Telescope (VLT)



High Energy Stereoscopic System (H.E.S.S.)

Highest-energy photons so far: **≈ 100 TeV**

Visible light

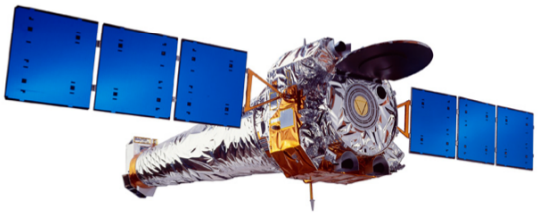
Gamma-rays

E_γ / eV: 10^{-3} 1 10^{4} 10^{12} 10^{20} ?

Radio

X-rays

Atacama Large Millimeter Array (ALMA)



Chandra X-ray Observatory

- **Cosmic rays** have been observed up to **3×10^{20} eV**
- **Observation of photons** in this energy range would open a **new window to the Universe** (“EeV Astronomy”)
- **Direct impact** on astro- and particle physics

UHE photons: motivation

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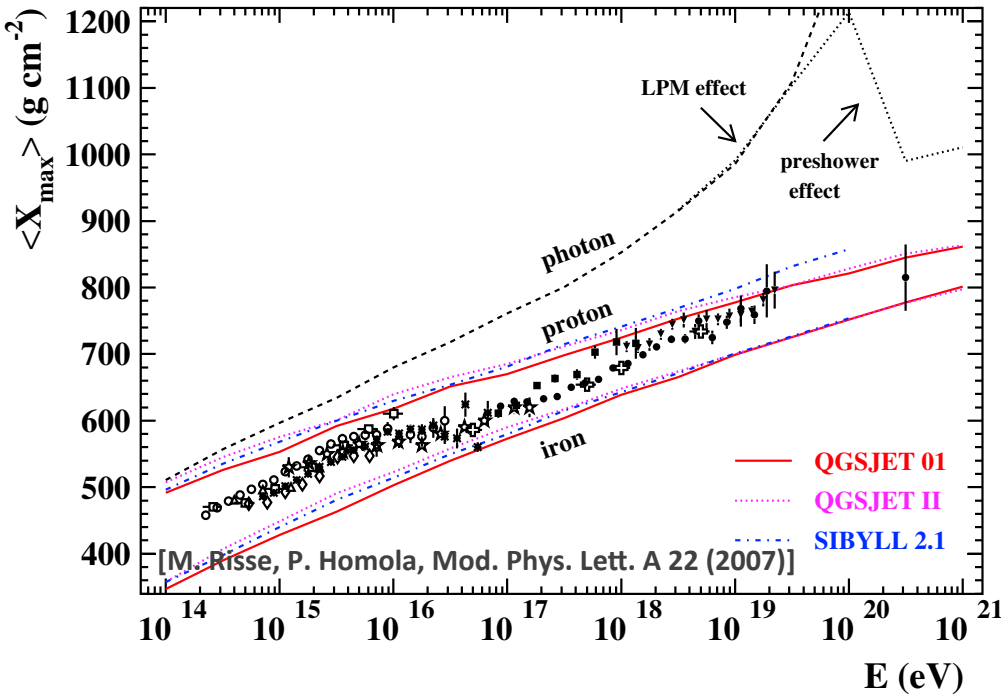
- **Distinguish** between **different models** for the **origin** of ultra-high-energy cosmic rays (UHECR)
  - **Bottom-up** (e.g. AGN): **small fraction** of UHE photons
  - **Top-down** (e.g. SHDM): **larger** fraction
- **Probe the GZK effect**: is it really the reason for the observed suppression in the UHECR energy spectrum?
  - Greisen, Zatsepin, Kuzmin (1966): UHE protons lose energy via **resonant photo-pion production** with photons from the cosmic microwave background (CMB)

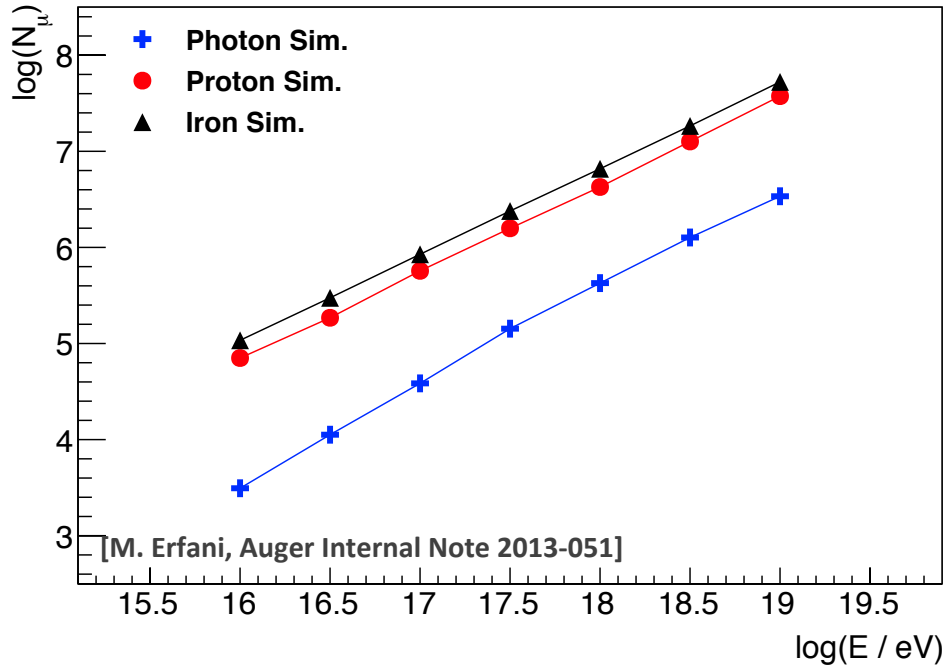
$$p + \gamma_{\mathrm{CMB}} \longrightarrow p + \pi^0 \hookrightarrow \gamma_{\mathrm{UHE}} + \gamma_{\mathrm{UHE}}$$

- Search for **sources of UHECR**
  - Photons: no deflection in (extra)galactic magnetic fields
- Probe **fundamental physics**
  - Tests of Lorentz invariance and QED / QCD at the highest energies

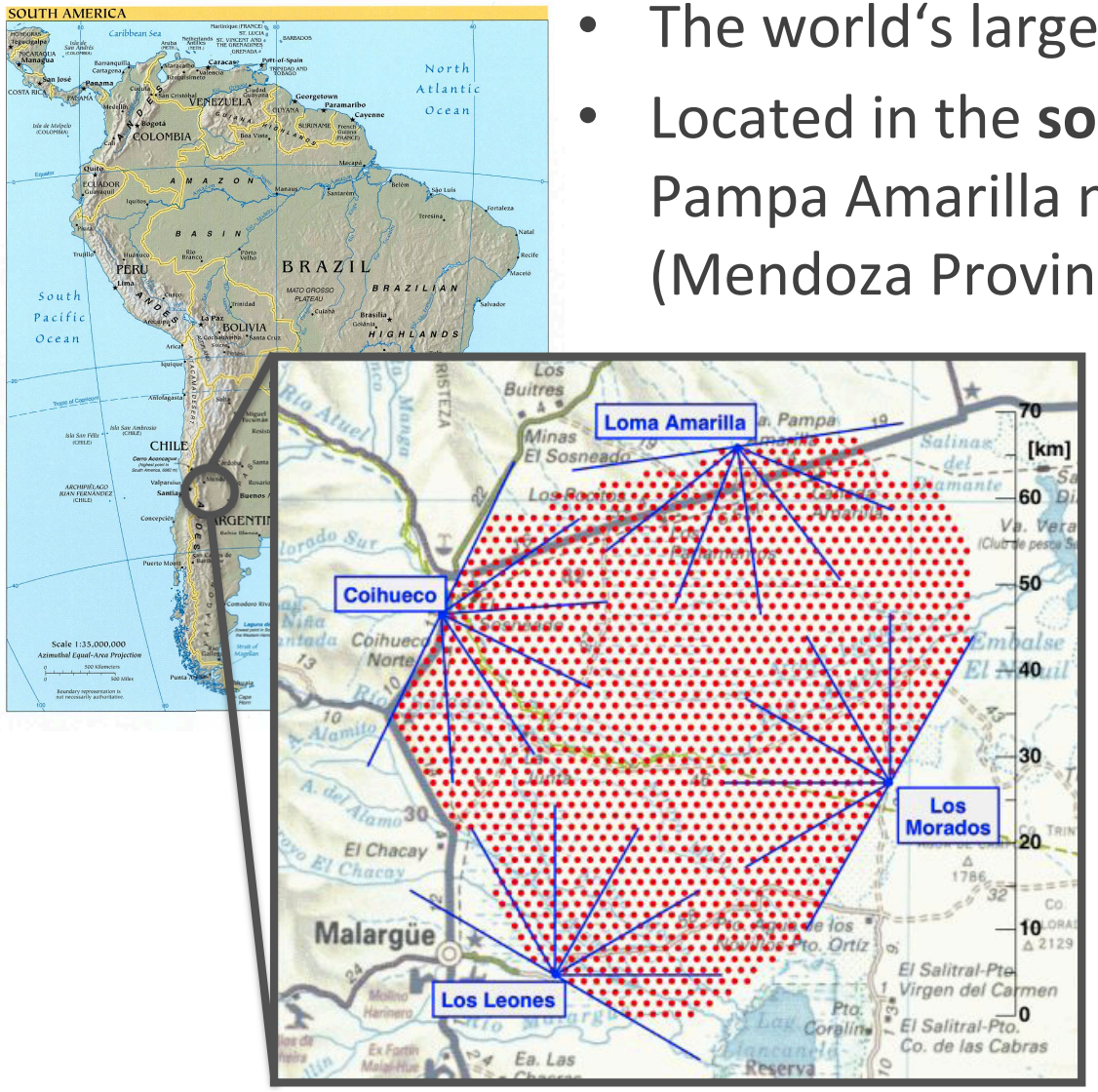
Photon-induced air showers

- Deeper development in the atmosphere (larger X_{max}) compared to hadron-induced showers
  - At larger energies (> 10^{19} eV) additional QED effects (LPM effect and preshowering) have to be taken into account
- Fewer muons (smaller N_μ) due to the small photonuclear cross-sections (at 10 EeV: 10 mb; pair production: 500 mb)





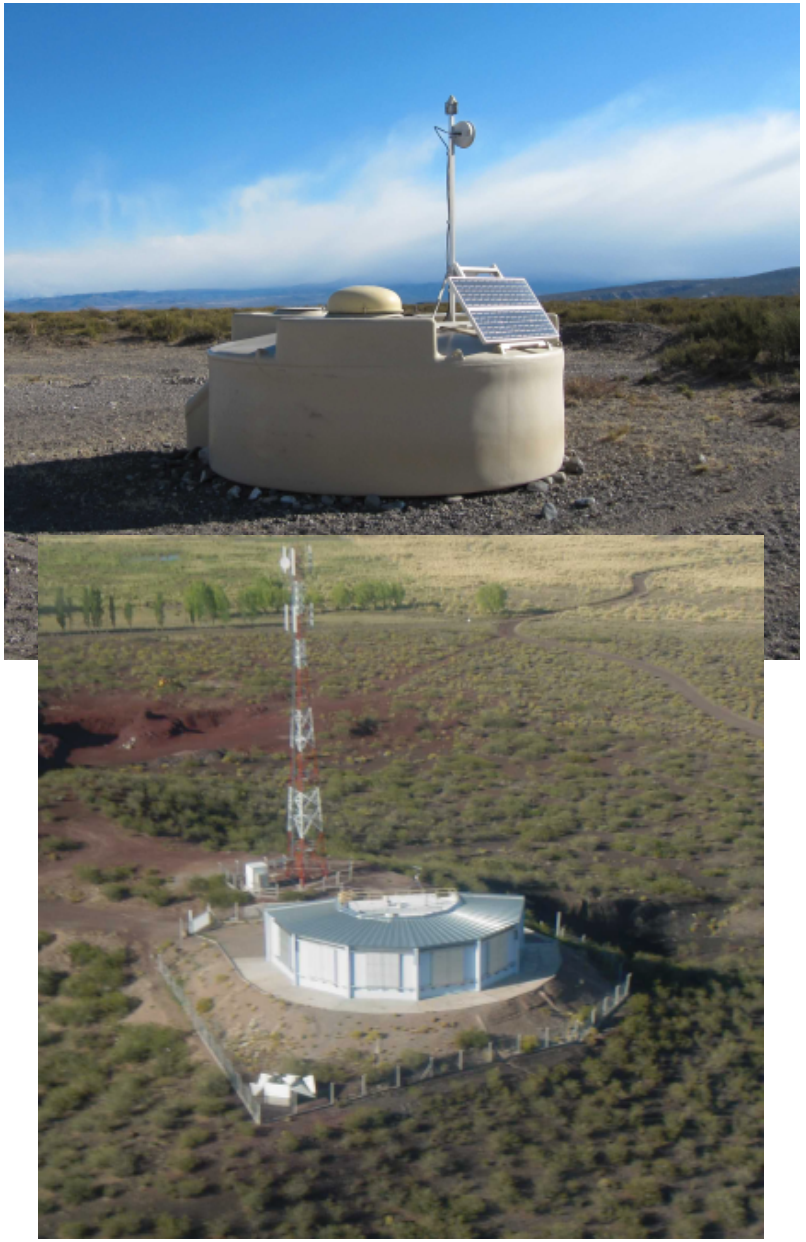
The Pierre Auger Observatory (I)



- The world‘s largest **air shower experiment**
- Located in the **southern hemisphere** in the Pampa Amarilla near the town of **Malargüe** (Mendoza Province, Argentina)

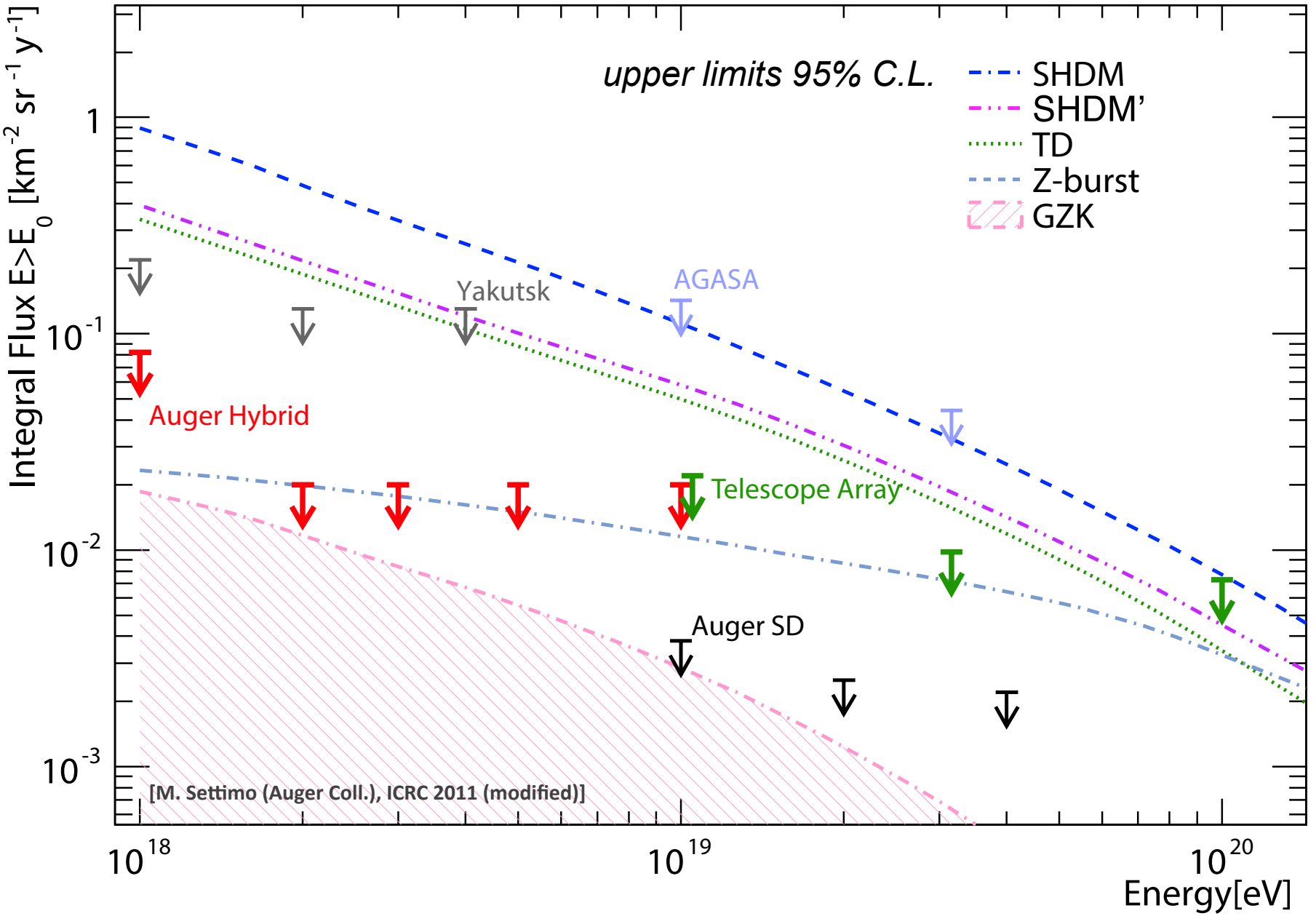
- Planned since 1992; **start of physics data taking**: 2004
- **Unprecedented exposure** for UHECR: > 150 events above 50 EeV so far
- **Hybrid concept**: two **independent** and **complementary** detector systems

The Pierre Auger Observatory (II)



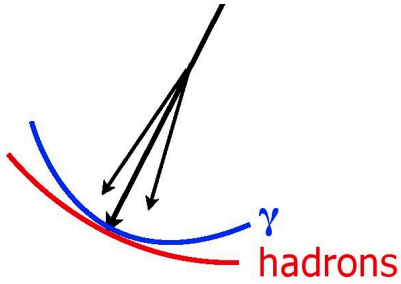
- **Surface Detector (SD)**
  - 1660 water Cherenkov detector stations covering 3000 km^2
  - **100 % duty cycle**
  - Measuring the **lateral shower profile** at ground level
- **Fluorescence Detector (FD)**
  - 27 fluorescence telescopes overlooking the SD array
  - **15 % duty cycle**
  - Measuring the **longitudinal shower development** in the atmosphere
- **Enhancements**:
  - Radio antennas
  - Dedicated muon detectors

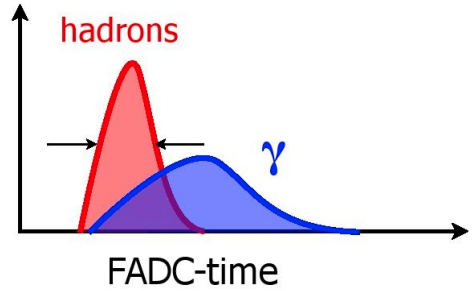
UHE photon limits: status

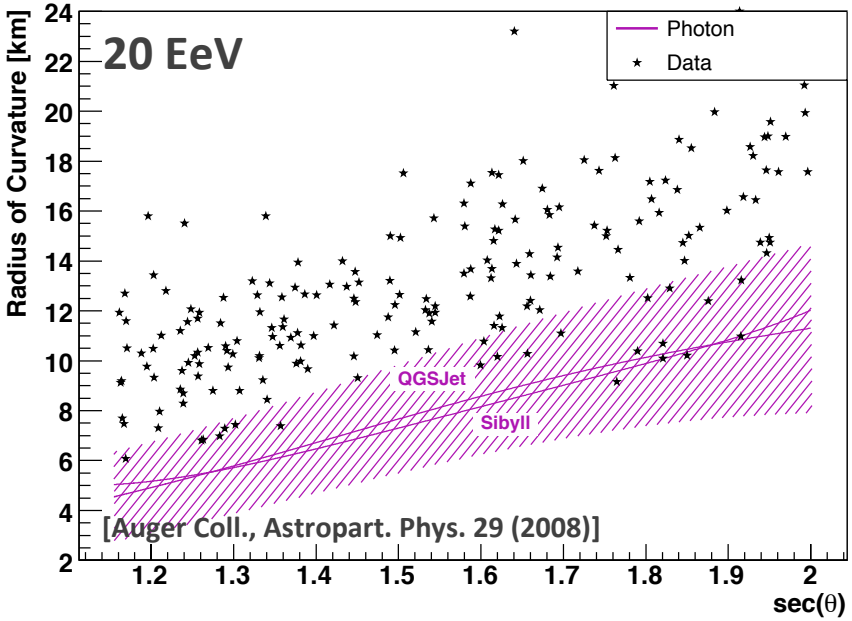


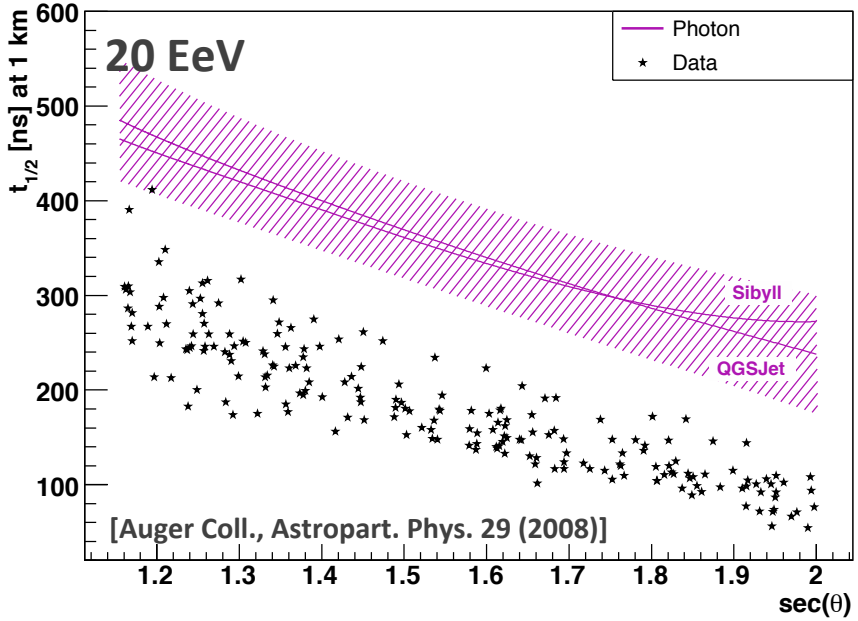
SD-only search (I)

- Observables used for photon identification in the SD-only search:
  - R_c: reconstructed radius of curvature of the shower front
  - $t_{1/2}(1000)$: interpolated risetime of the signals in the SD stations at 1000 m distance from the shower axis



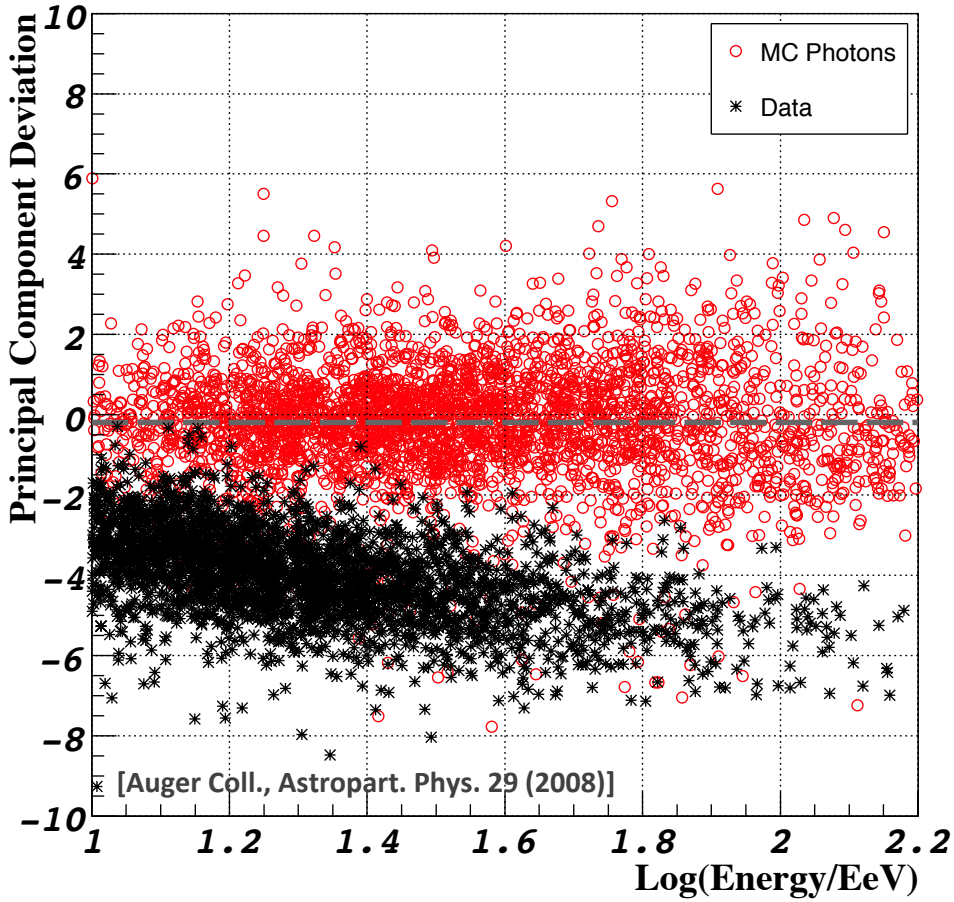




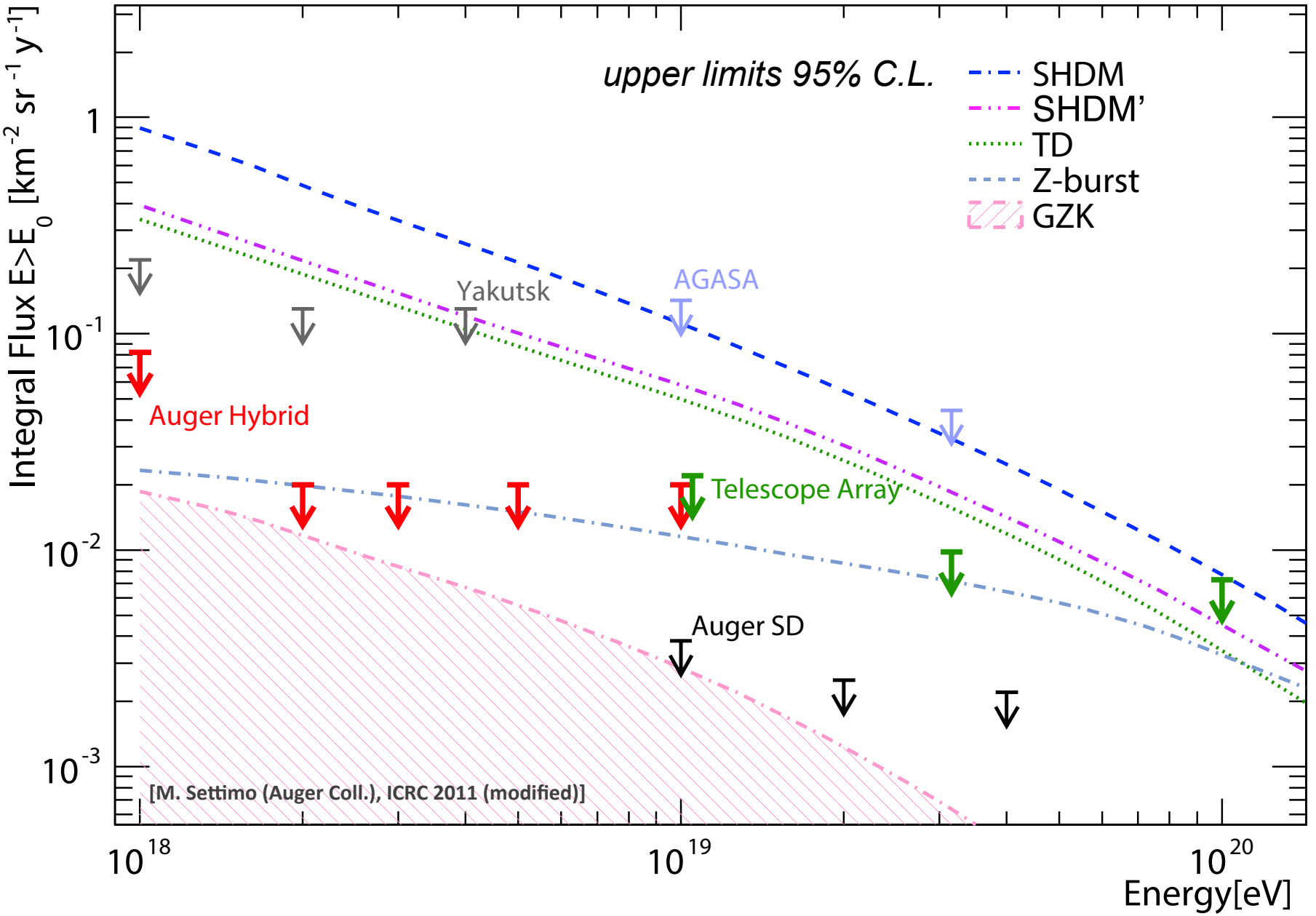


SD-only search (II)

- Combine R_c and $t_{1/2}(1000)$ in a **principal component analysis**
- Analysis of data restricted to $E > 10$ EeV and $30° < \theta < 60°$
- **A-priori candidate cut** at the median of the photon distribution
- Data and MC photons **well separated**; no photon candidates at highest energies
- Calculate **upper limits** using photon efficiency (from simulations) and detector exposure (from geometrical calculations)



UHE photon limits: status



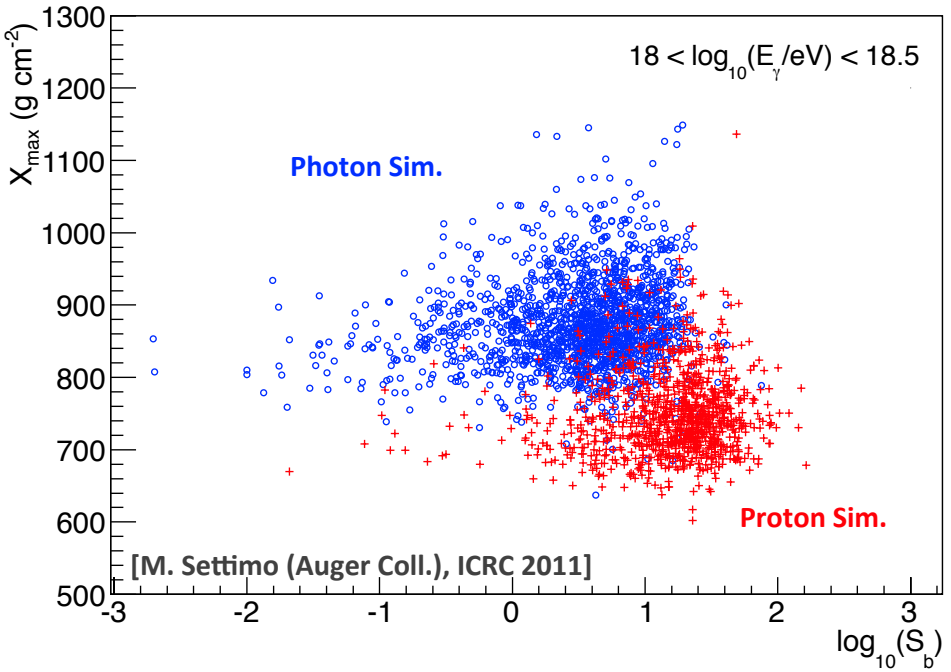
Hybrid search (I)

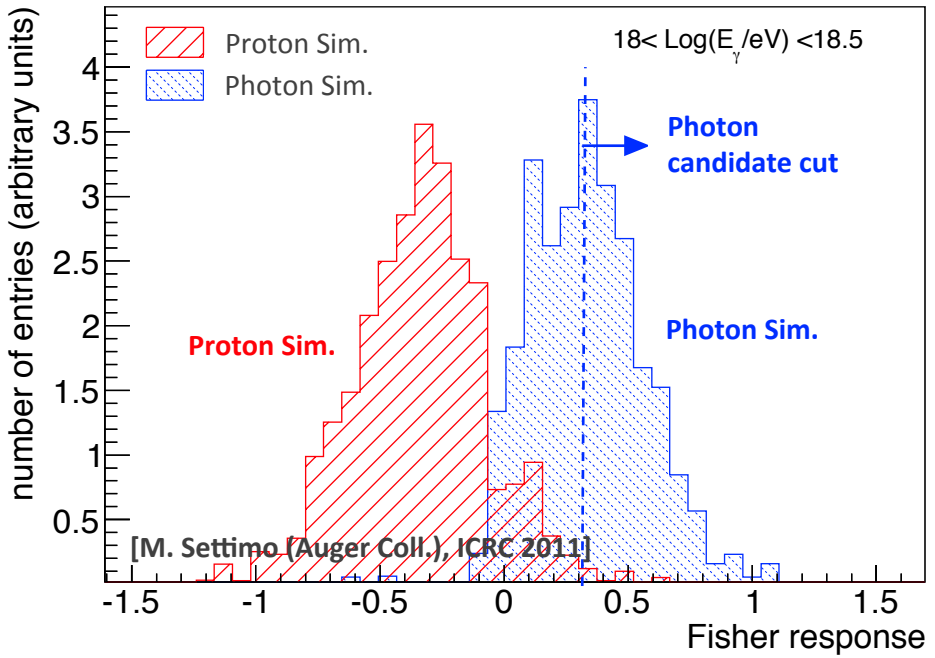
- Combination of **simultaneous measurements of SD and FD**
  - **Limited statistics** due to low FD duty cycle: not feasible at higher energies
  - Observables: X_{max} (FD) and S_b (SD)
  - S_b exploits the **steeper lateral distribution** of photon showers

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

S_i: measured signal in the SD station *i*
R_i: distance to the shower axis
[G. Ros *et al.*, Astropart. Phys. 47 (2013)]

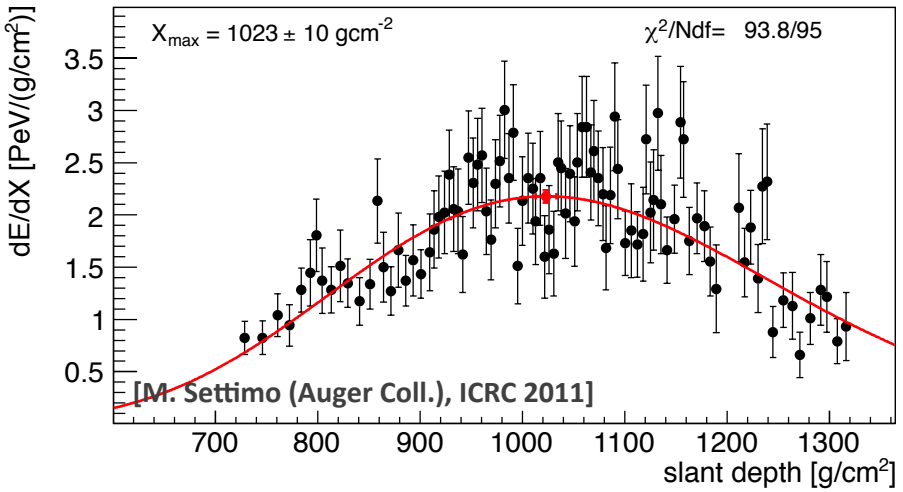
  - Combination of both observables in a **Fisher discriminant analysis**

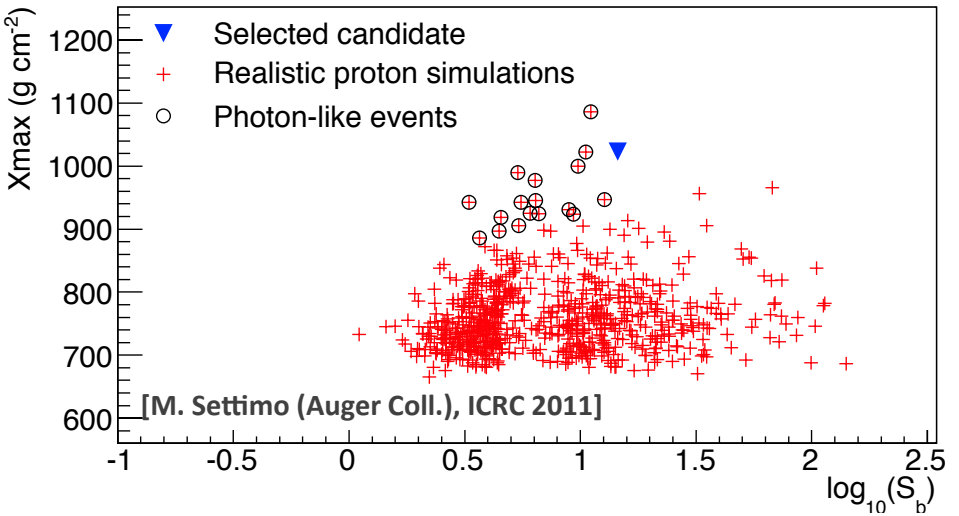




Hybrid search (II)

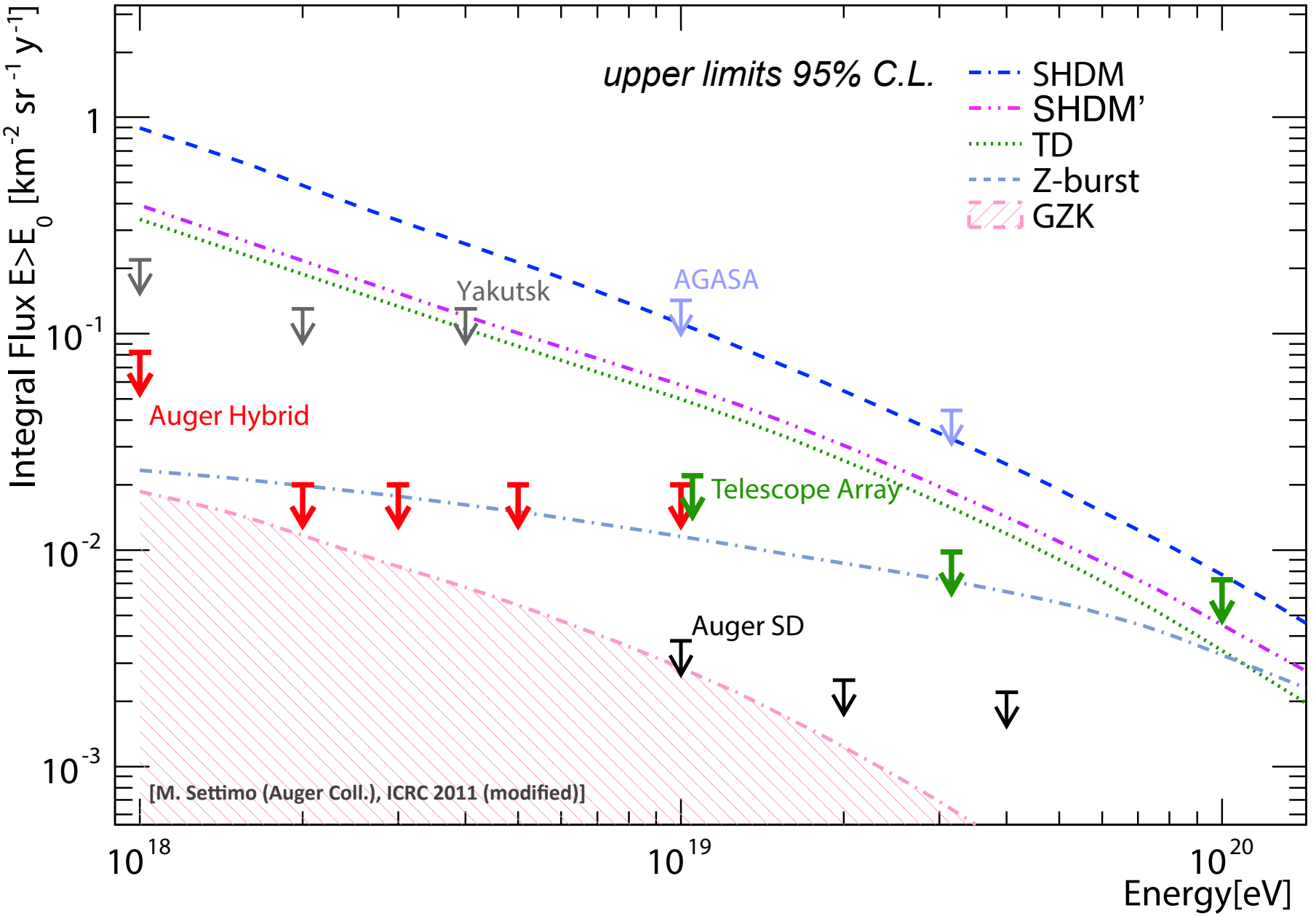
- Data analysis restricted to $1 < E < 10$ EeV and $0° < \theta < 60°$
  - **6 photon candidates** between 1 and 2 EeV; 0 above
  - Number of photon candidates is **consistent with the expected hadron background**; checked with dedicated simulations





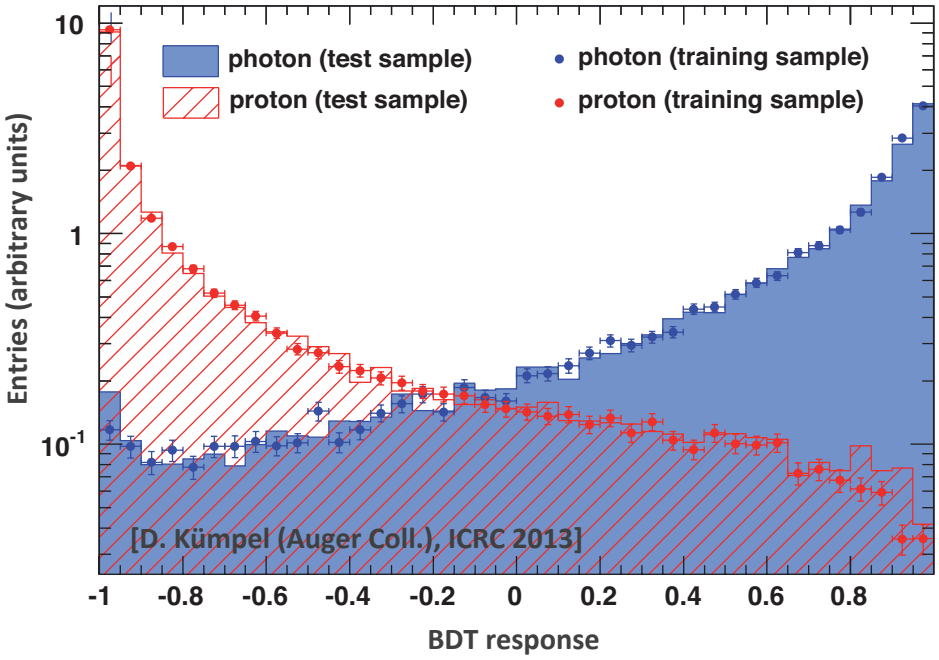
- **Conservative determination of the upper limits** on the photon flux: no background subtraction and minimal hybrid exposure for photons

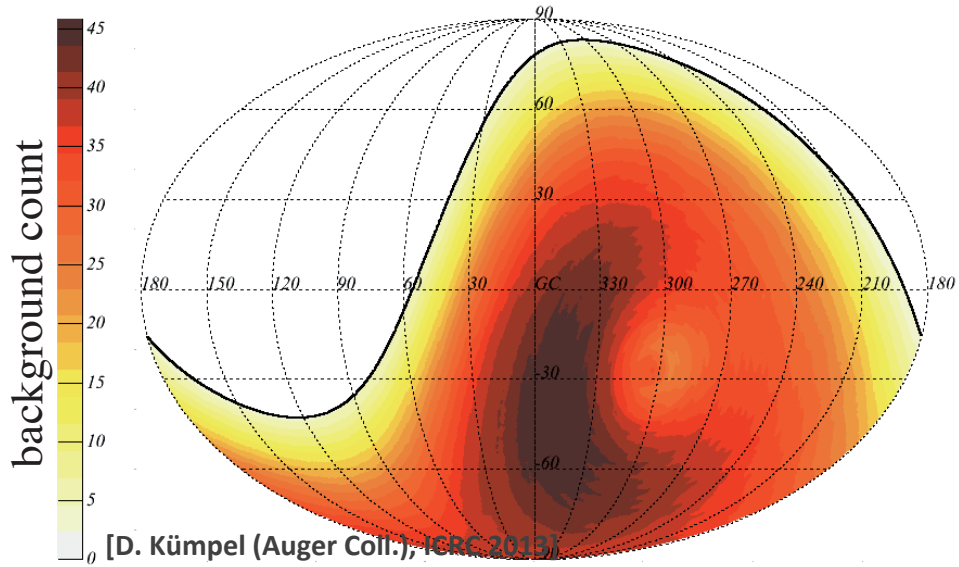
UHE photon limits: status



Directional search (I)

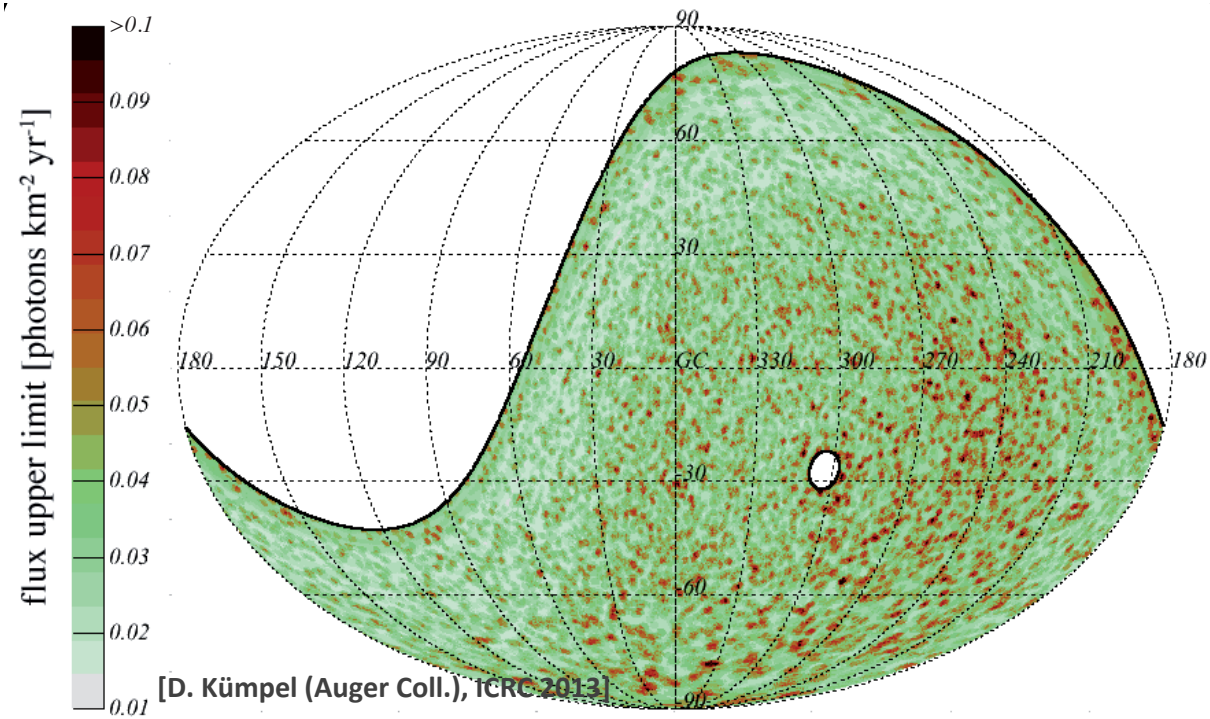
- Search for **photon point sources** by looking for an **excess of photon events** from a certain direction in the sky
- First step in the analysis: Selection of a **subset of photon-like events** using boosted decision trees; input variables: X_{max}, S_b, …
- Data analysis restricted to $0.2 < E < 3.2$ EeV and $0° < \theta < 60°$
- Determine **background expectation** using scrambling technique

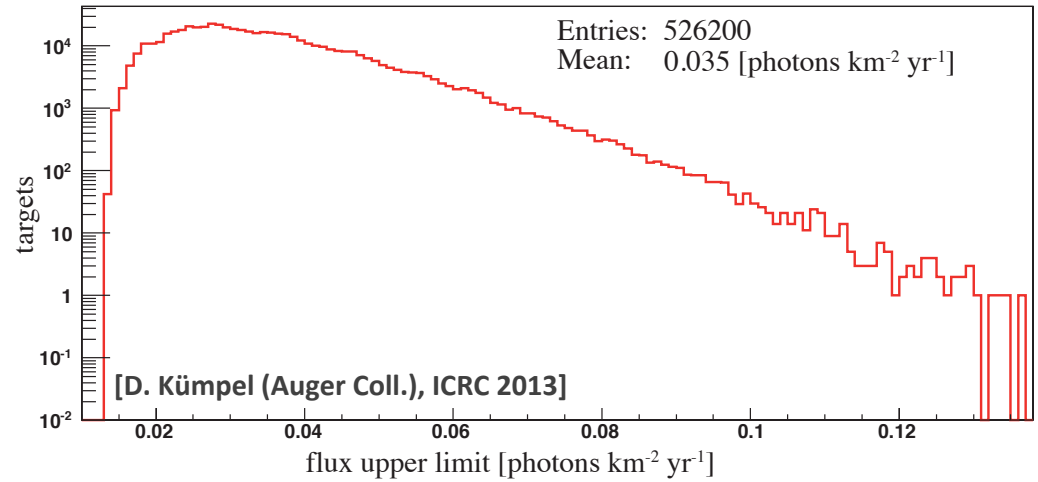




Directional search (II)

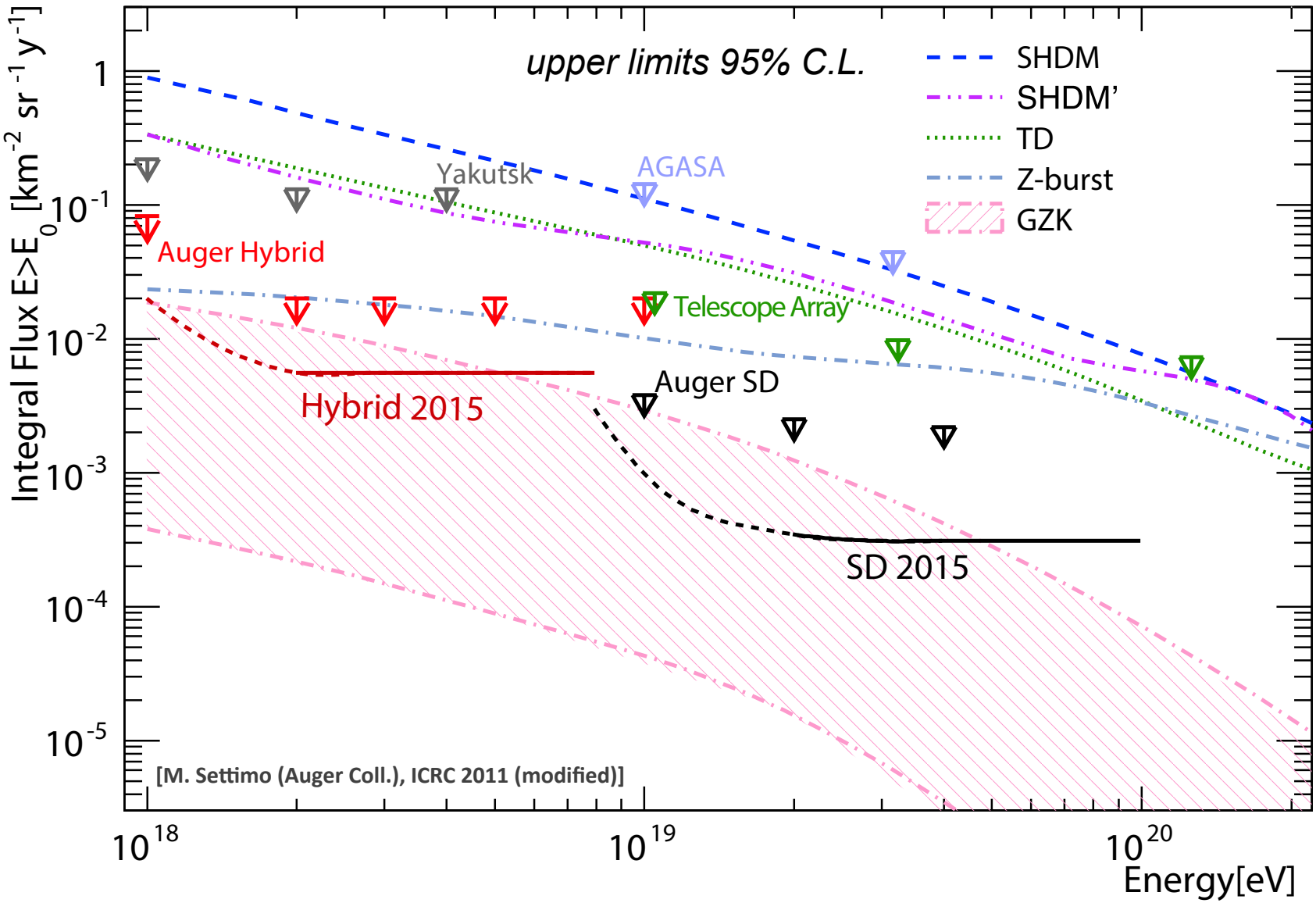
- **Optimize selection direction-wise** taking into account the background expectation
- **No significant excess** of photon-like events observed: **no photon point sources**
- **Determine sky map of upper limits** for the directional photon fluxes





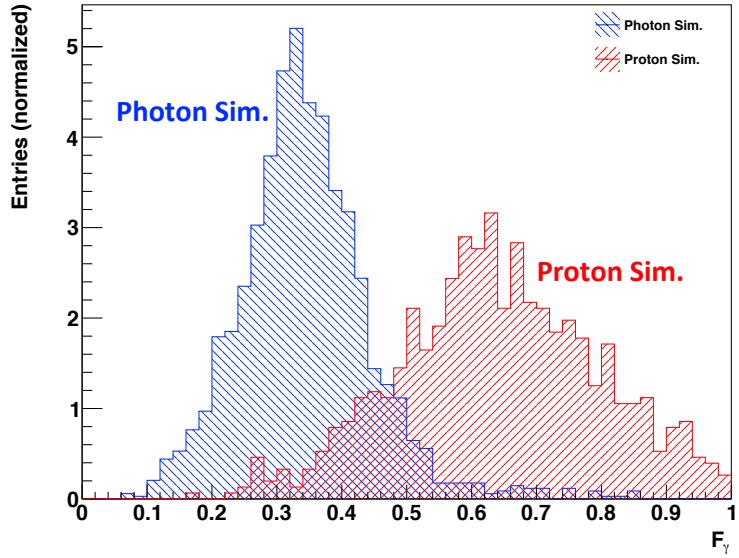
Outlook (I)

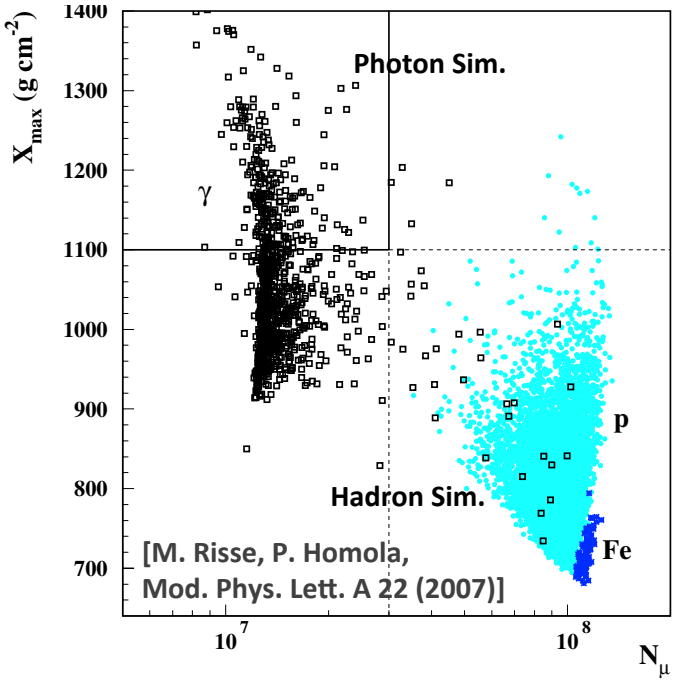
- Extrapolated development of the upper limits:



Outlook (II)

- **Improvement** of the presented analyses by choosing variables with **higher discrimination power**
  - SD: e.g. using the **shapes of the time traces** in the single SD stations
  - Hybrid: e.g. **photon-optimized likelihood fit** to the measured lateral distribution (F_γ parameter)
- Photon search will profit from a **direct measurement of the muon number N_μ**





Summary

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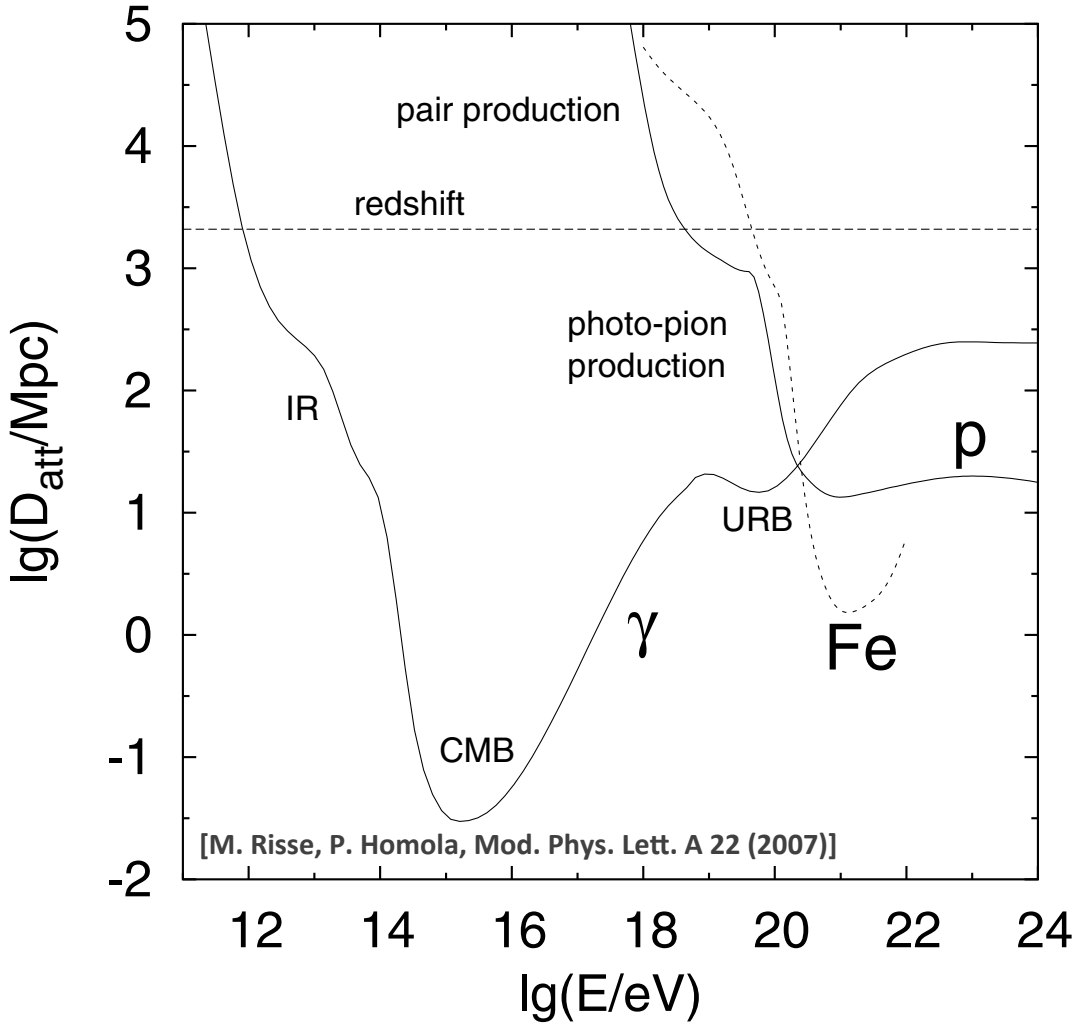
- **The search for ultra-high-energy photons:**
  - The **Pierre Auger Observatory offers unique capabilities**, both in quantity and quality of the recorded data
  - **Upper limits on diffuse photon fluxes** above the EeV range have been set using hybrid and SD-only analyses
  - Upper limits **severely constrain** theoretical models for the origin and acceleration of UHECR
  - **Directional analysis** to identify possible photon point sources: **no significant excess** of photon-like events observed
  - **GZK region is within reach** in the next few years using improved analyses and larger statistics

Backup slides

Windows on the Universe

- Attenuation length for different particles propagating through the Universe as a function of their energy

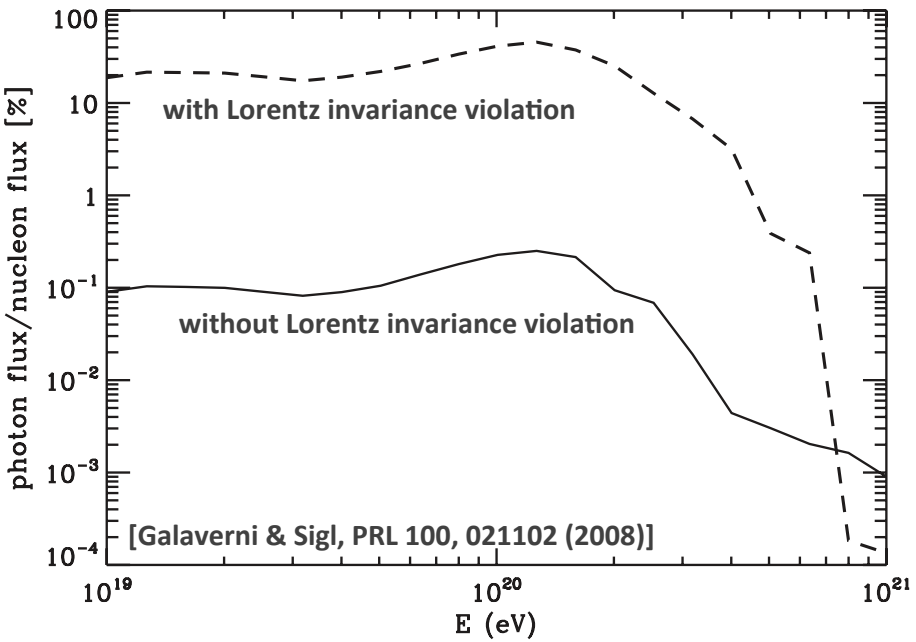


Lorentz invariance violation

- Lorentz invariance violation can lead to modified photon dispersion relation

$$\omega^2 = k^2 + \xi_n k^2 (k/M_{Pl})^n$$

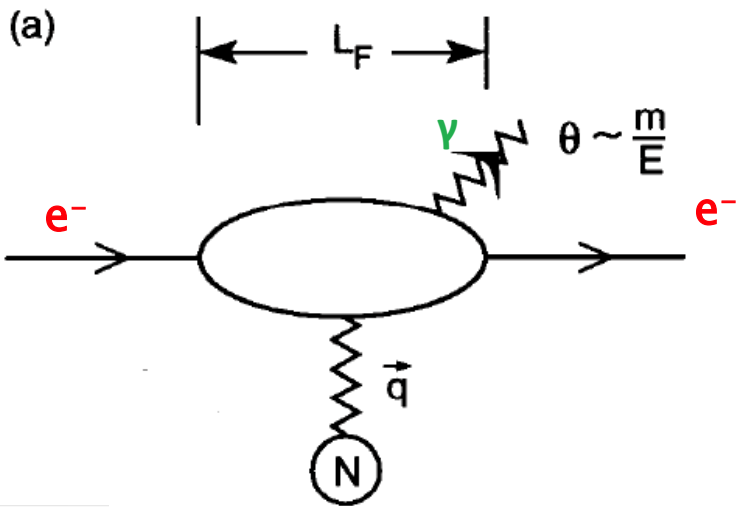
- Modified e^+e^- pair production threshold: suppression of the cascading of e.g. GZK photons

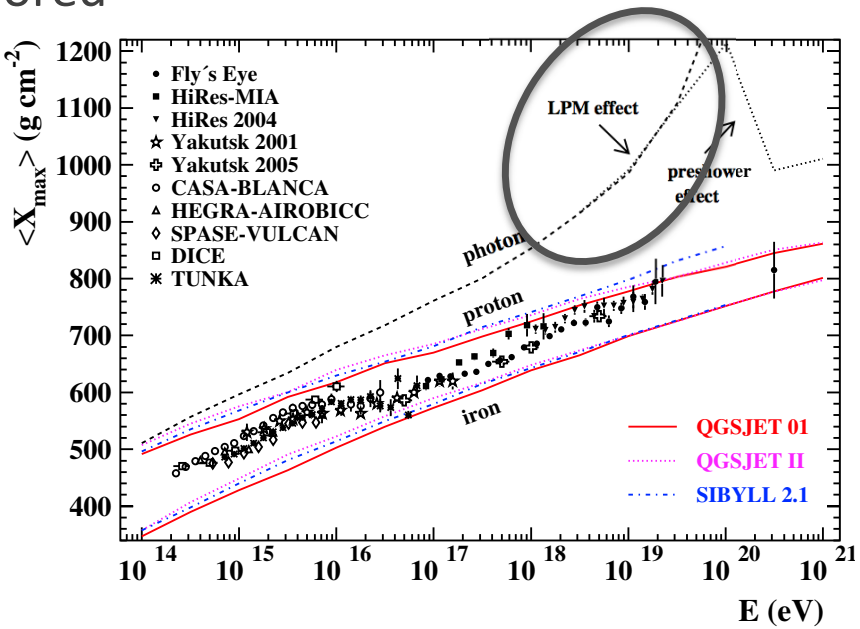


- If Lorentz invariance violated, $\xi_{1/2} > 0$ expected
- Best upper limits so far (from UHECR observations):
  - $\xi_1 < 2.4 \times 10^{-15}$
  - $\xi_2 < 2.4 \times 10^{-7}$

LPM effect

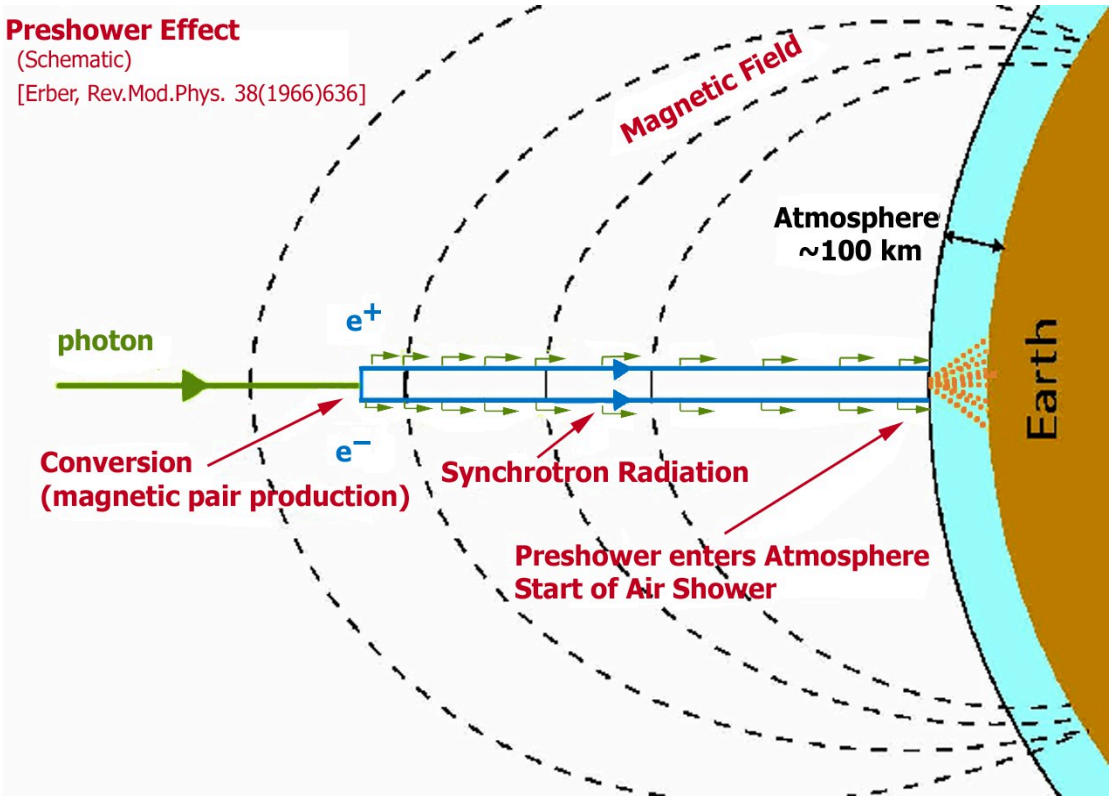
- Landau, Pomeranchuk (1953); Migdal (1956):
  - Bremsstrahlung and pair production are not point interactions, but occur in a formation zone
  - When the formation zone becomes macroscopic: interference effects
  - Bremsstrahlung and pair production cross-sections are reduced prop. to 1/sqrt(ρE) in the high-energy limit; effect increases with air density and particle energy
  - Asymmetric energy distribution favored

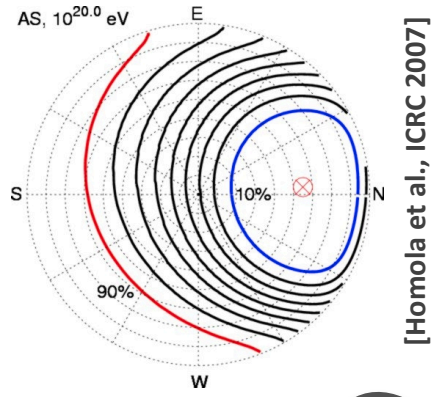


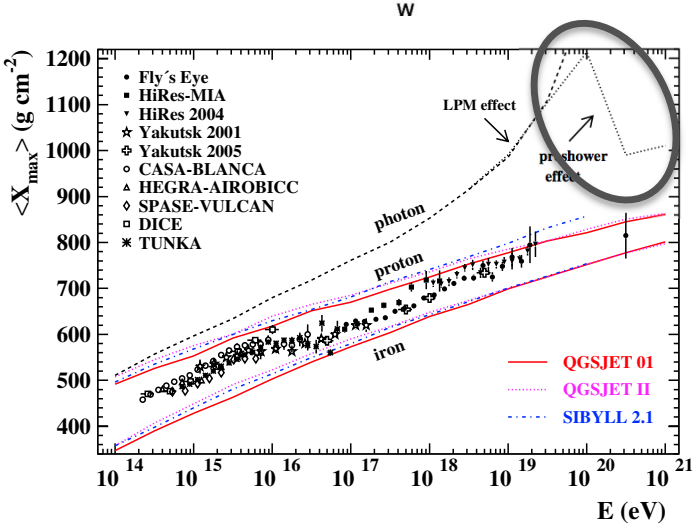


Preshowering

- Electromagnetic cascade in the geomagnetic field before the “normal” air shower

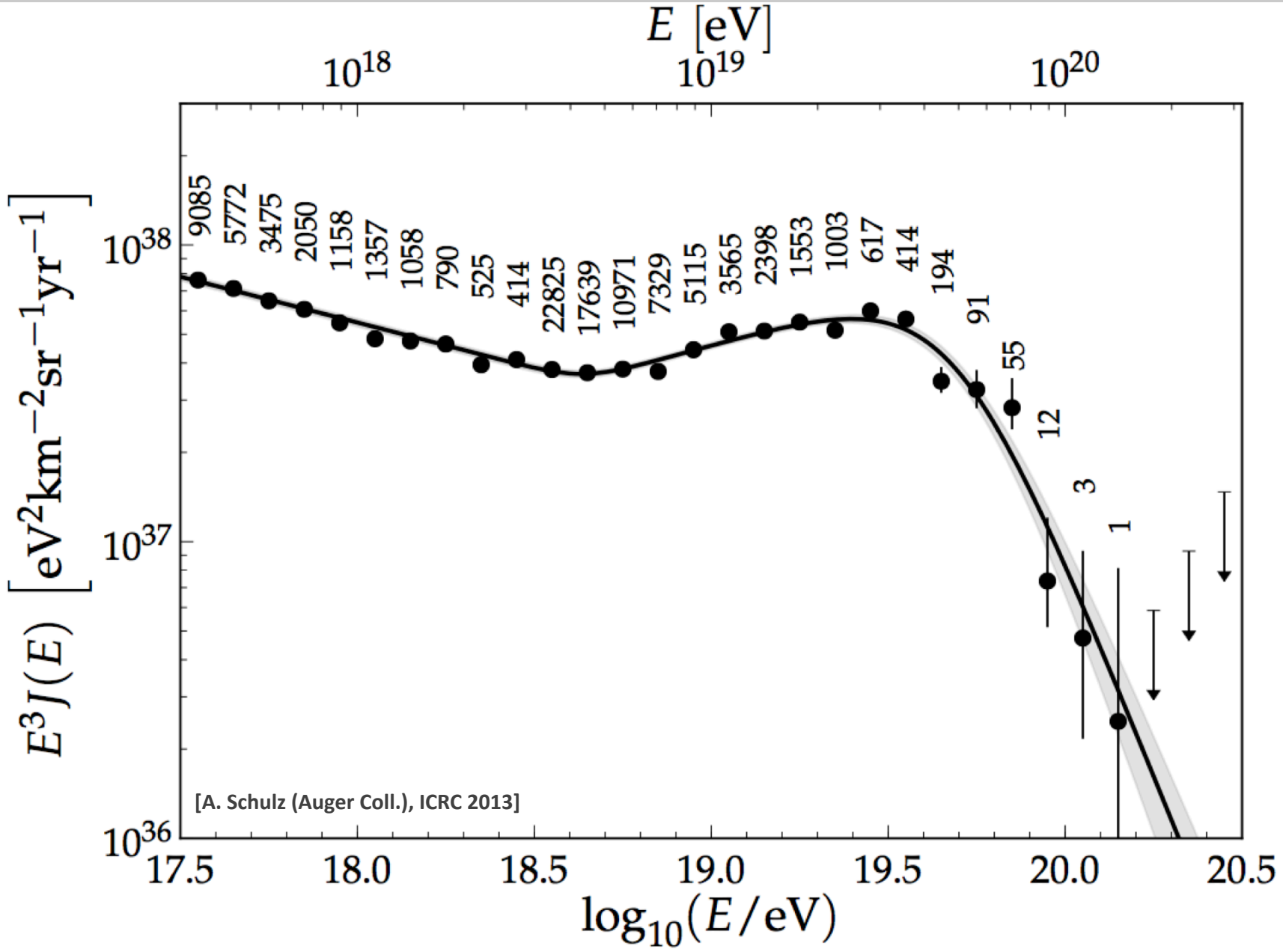






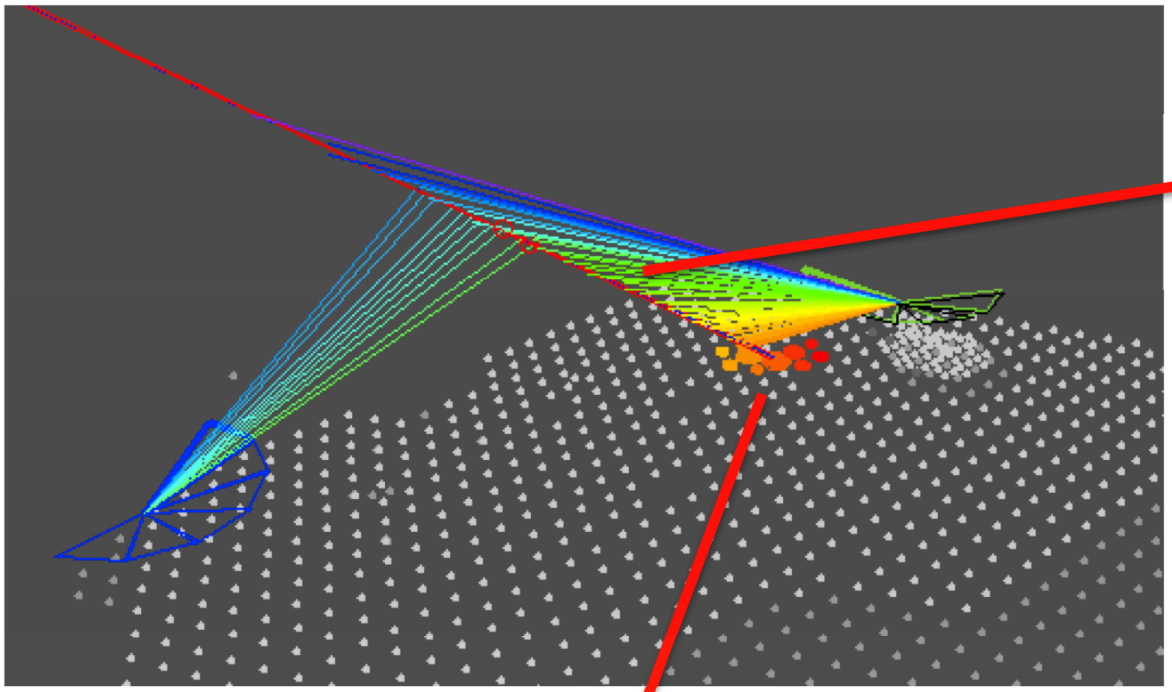
- Probability for a preshower depends on the energy and the transverse magnetic field, i.e. the incoming direction of the photon

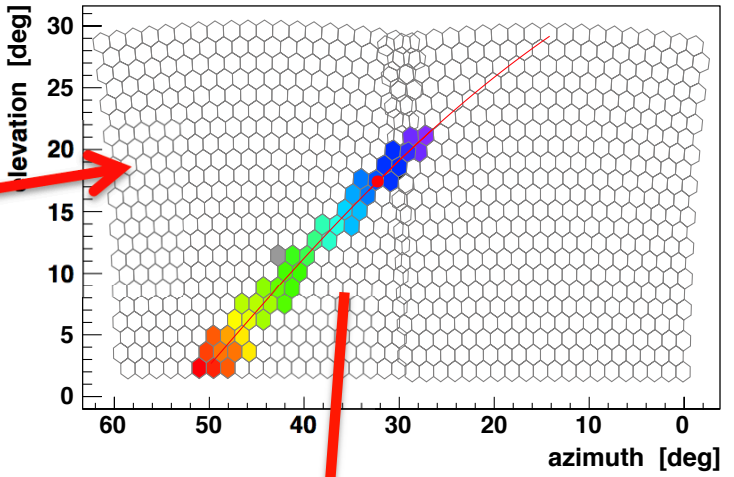
Auger spectrum (ICRC 2013)

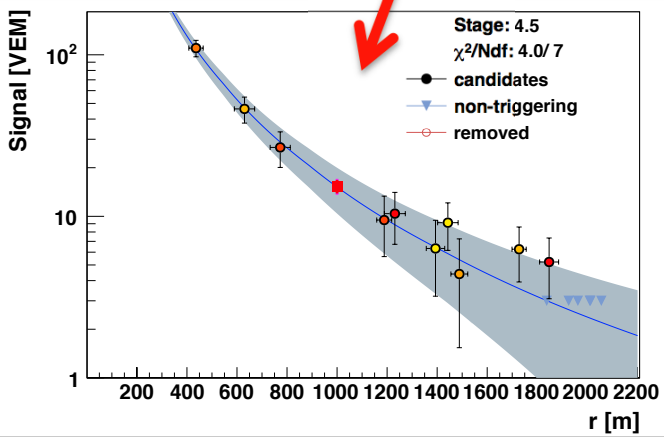


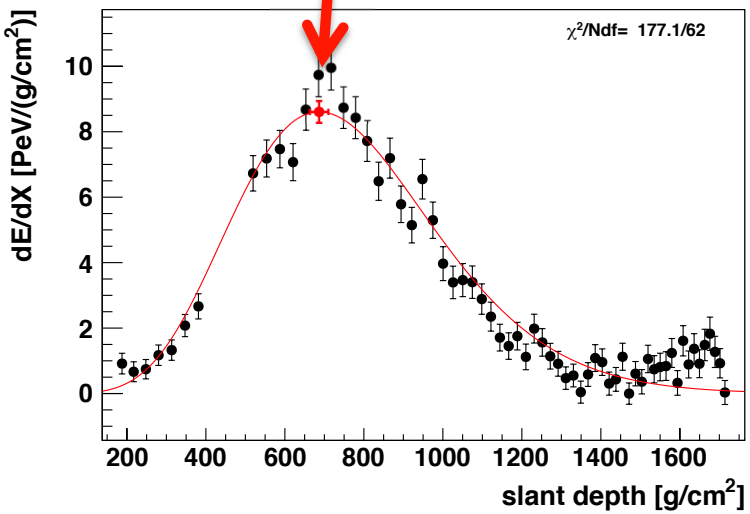
Example hybrid event

Stereo event from 19.03.2012; $\theta = 62°$, $E = 6$ EeV, $X_{max} = 687$ g/cm^2

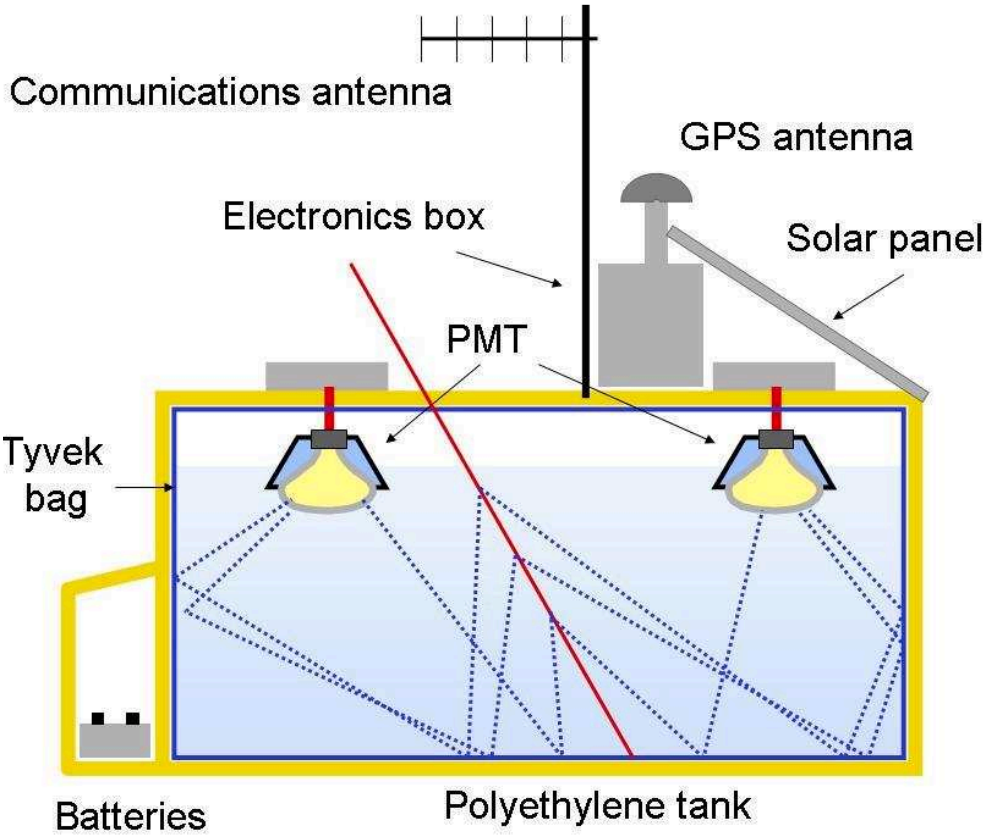




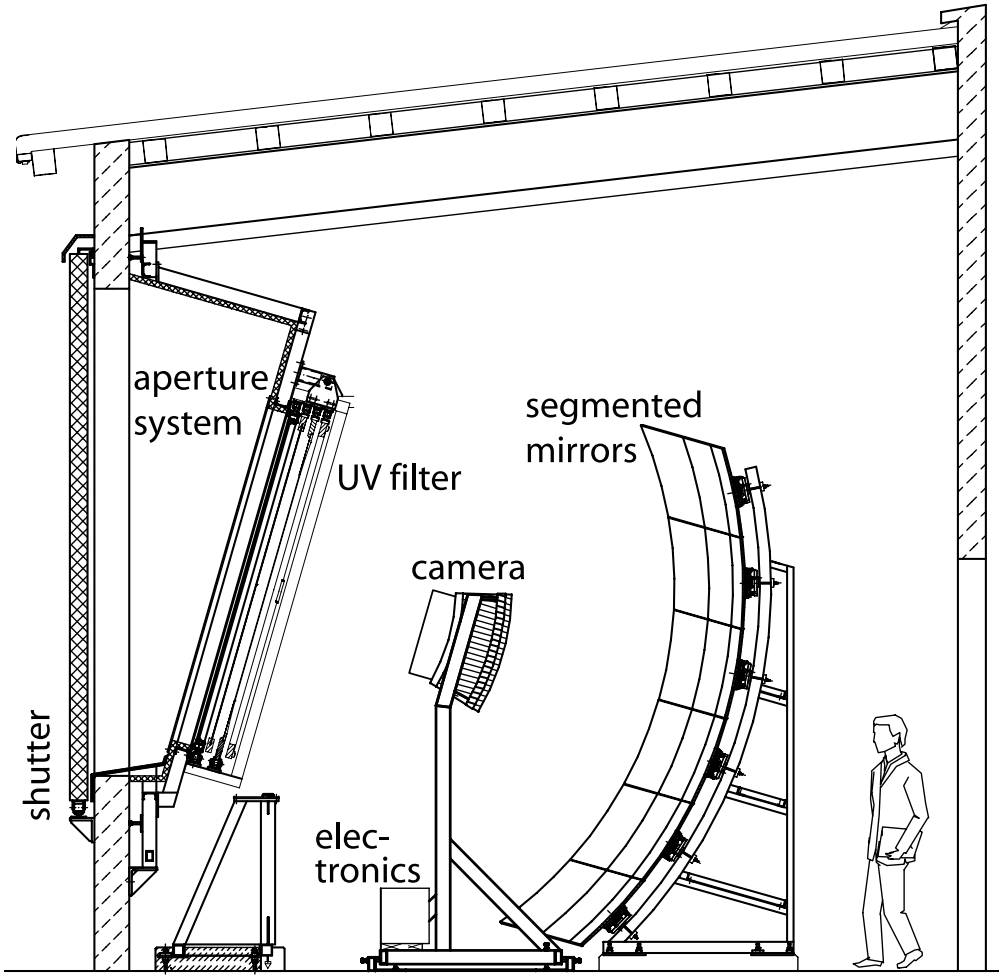




SD and FD

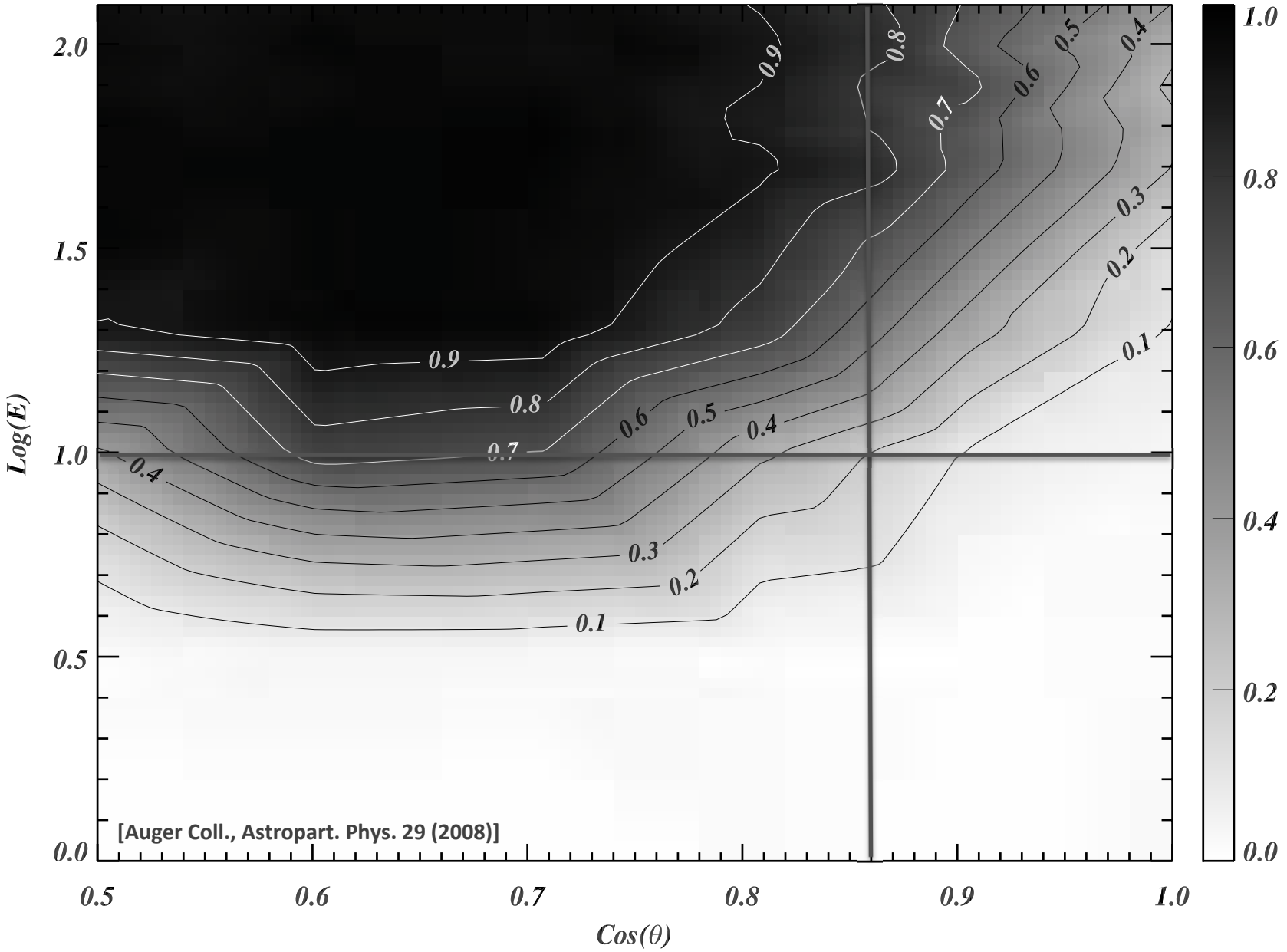


SD



FD

Photon efficiency of the SD



Hybrid exposure for photons