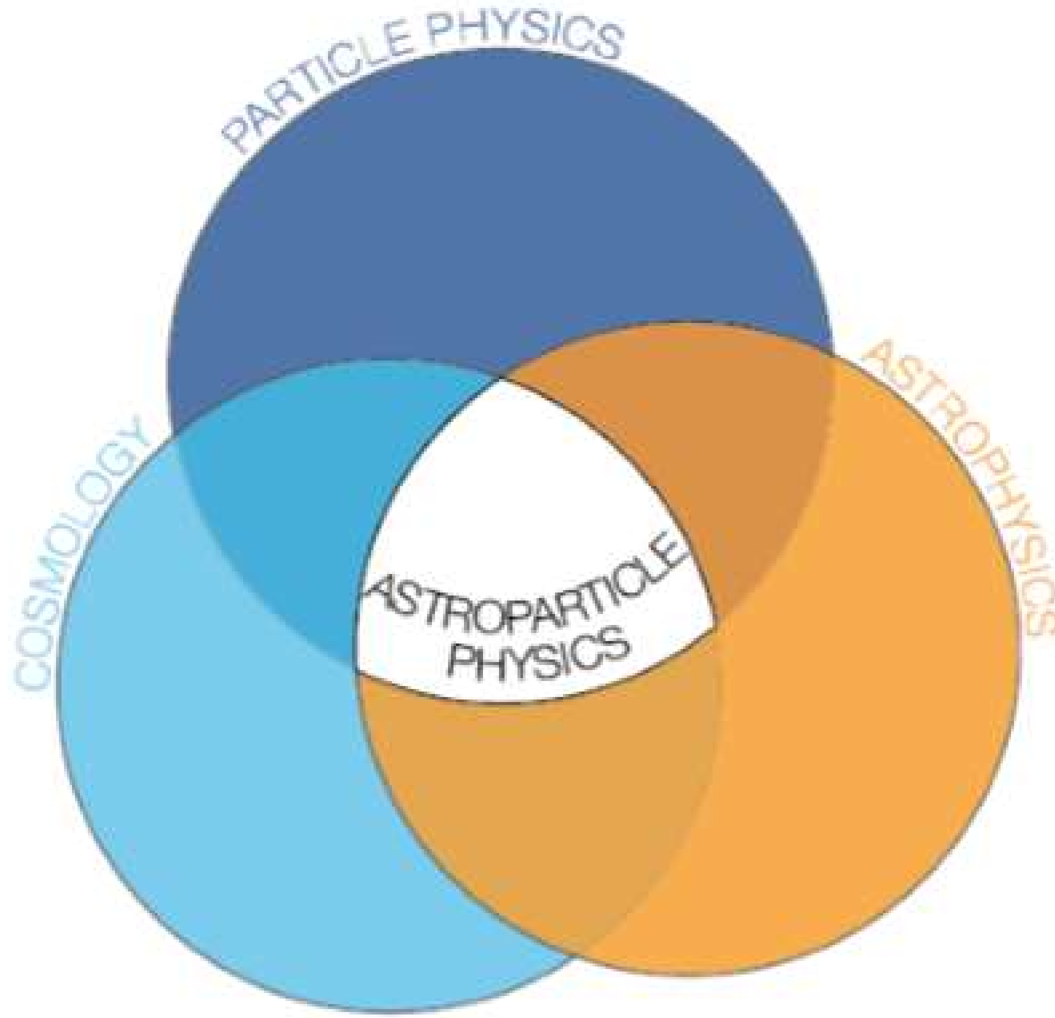
Pierre Auger Observatory – physics

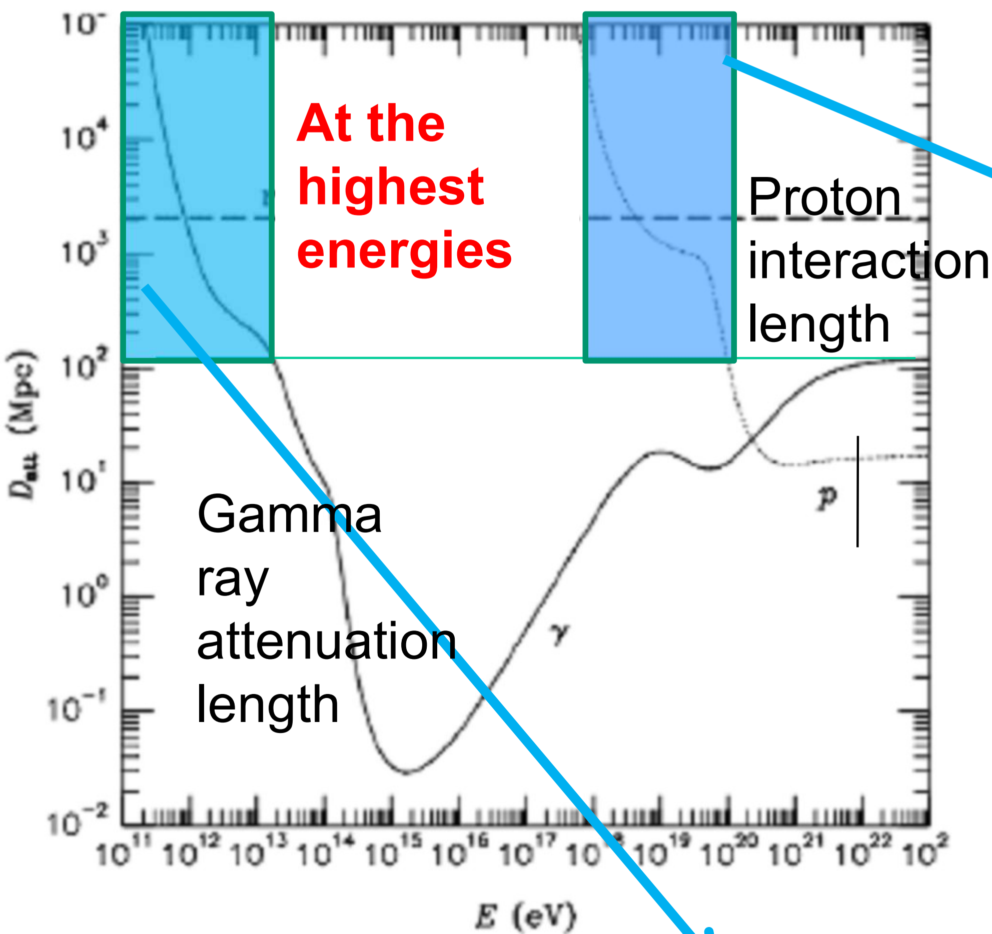
Triggering Discoveries in High Energy Physics III, High Tatras

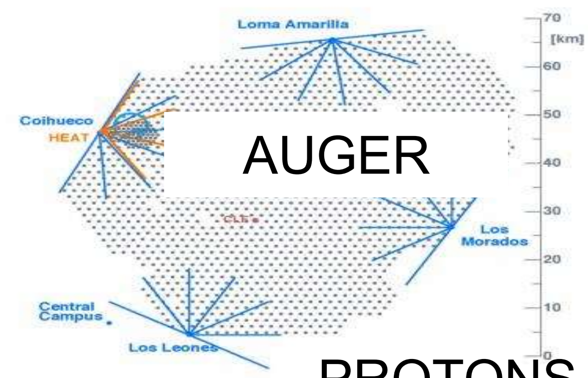
Michael Prouza
FZU - The Institute of Physics of the Czech Academy of Sciences
Prague, Czech Republic

What is ASTROPARTICLE PHYSICS?



Pierre Auger Observatory and Cherenkov Telescope Array

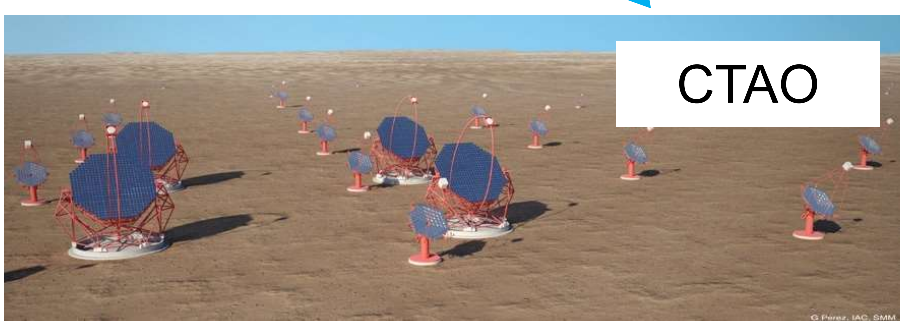




PROTONS, NUCLEI

AUGER – AugerPrime,
AugerPhase II has started

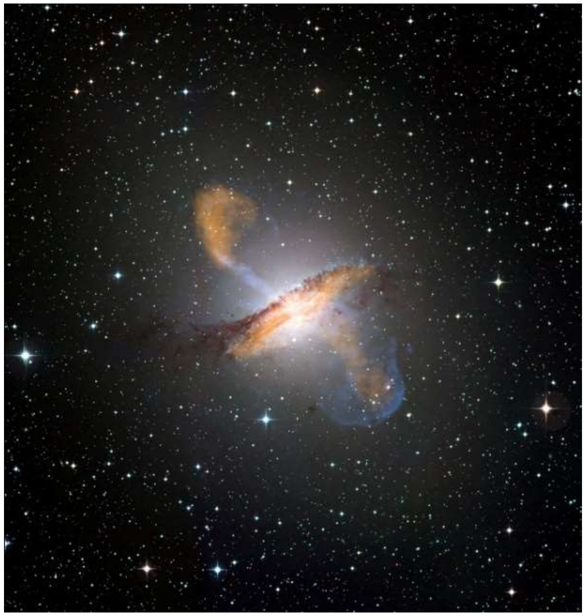
CTAO - construction, ready for operation in 2024



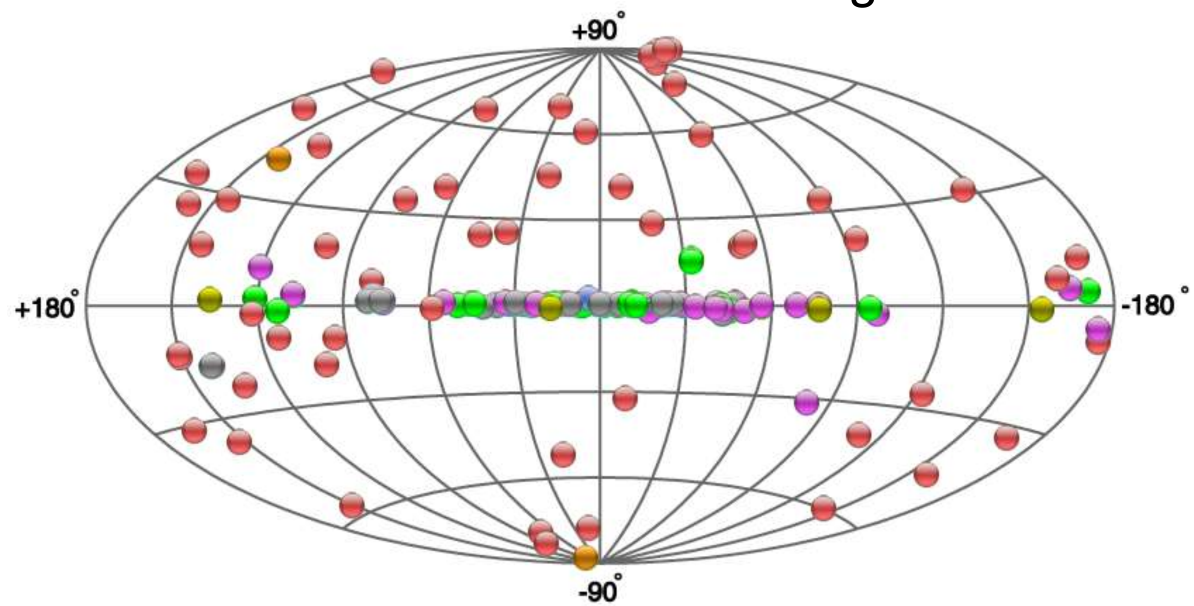
PHOTONS

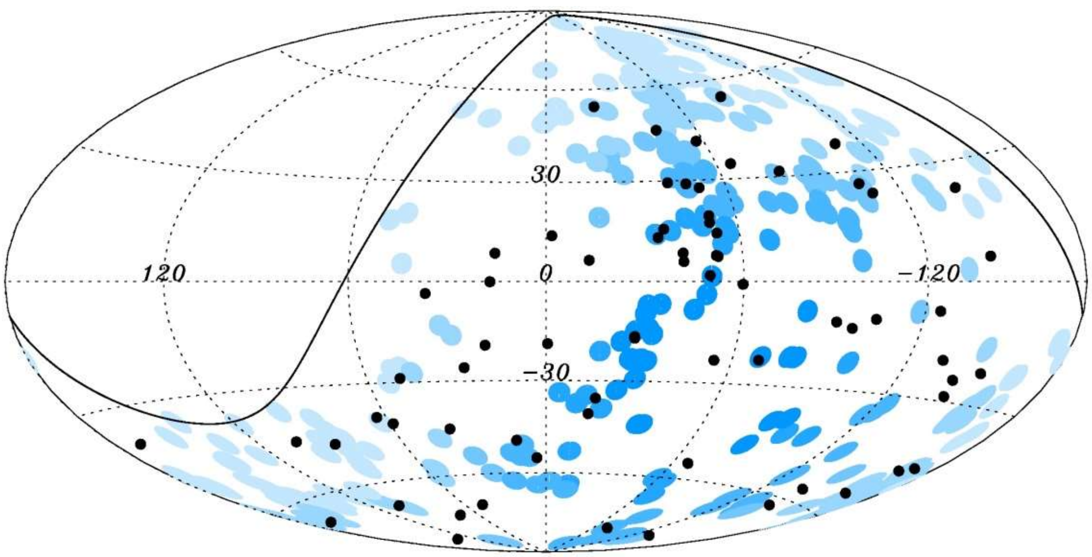
FZU - Team of more than 20 people, AUGER, CTAO, SWGO + SST1M (Patrik)

Motivation



Gamma TeV energies





Hadrons > 55 EeV energies

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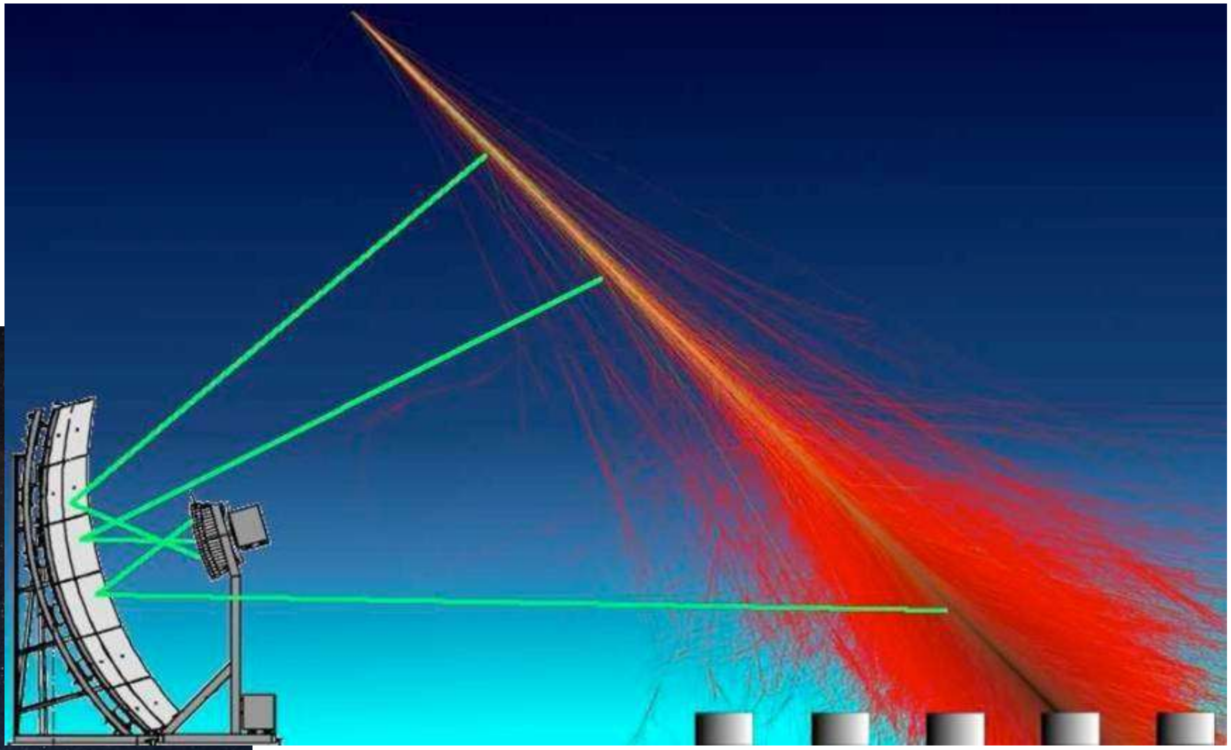
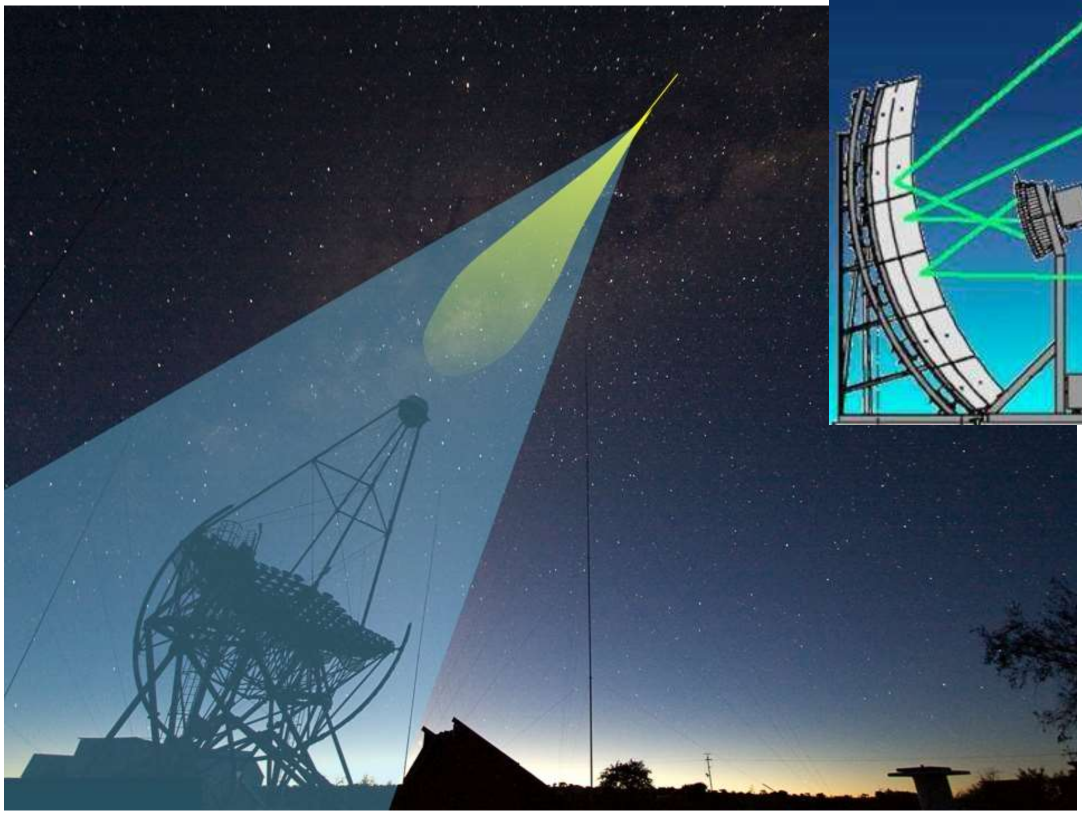
Similar sources !?

Motivation

Fluorescence detection - Auger



Cherenkov detection - CTA



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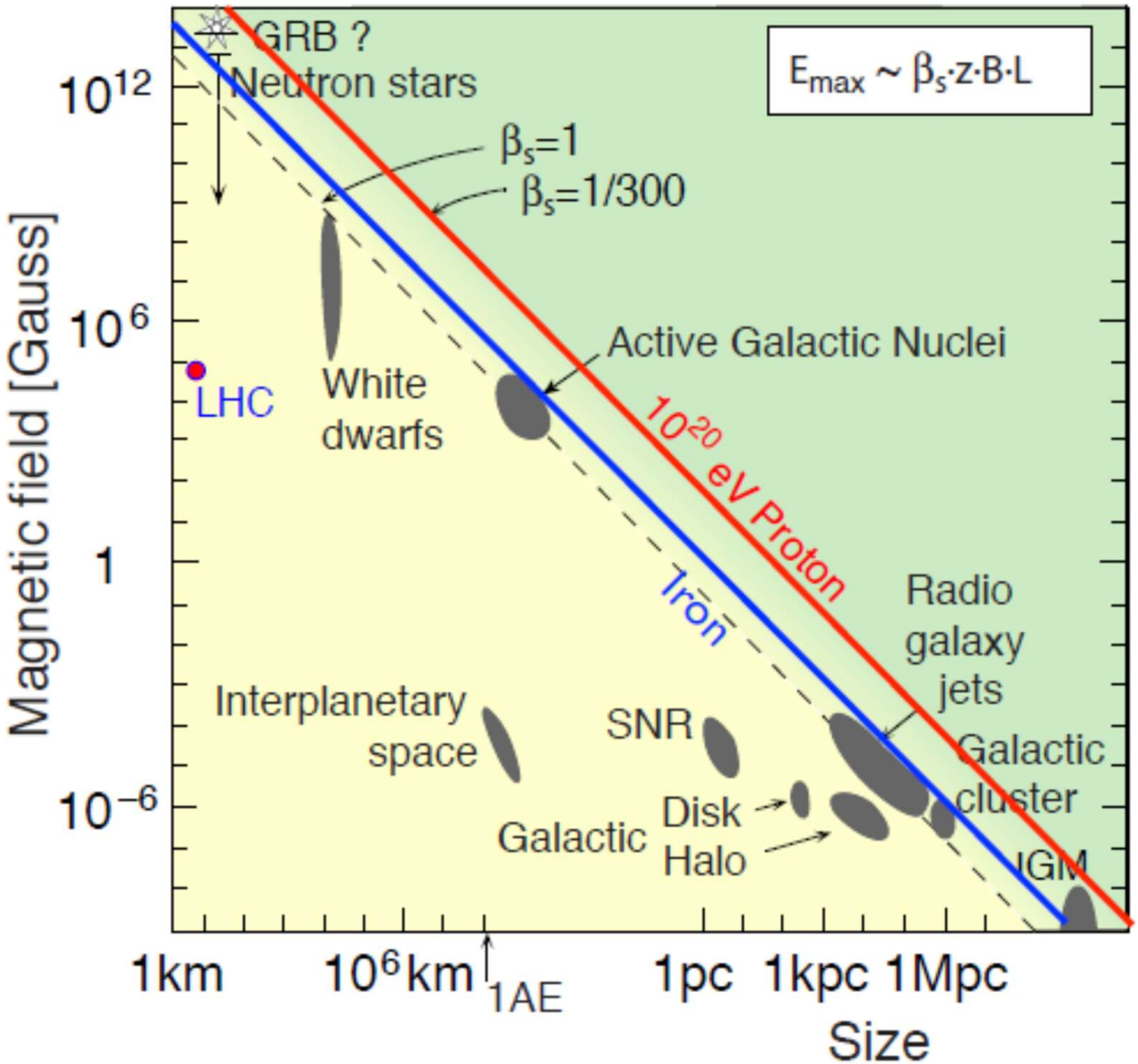
What are the sources of the highest energies?

Direct observation, gammas, CTA

Indirect hints from hadrons, AUGER :

- energy spectrum
- mass composition
- anisotropy searches



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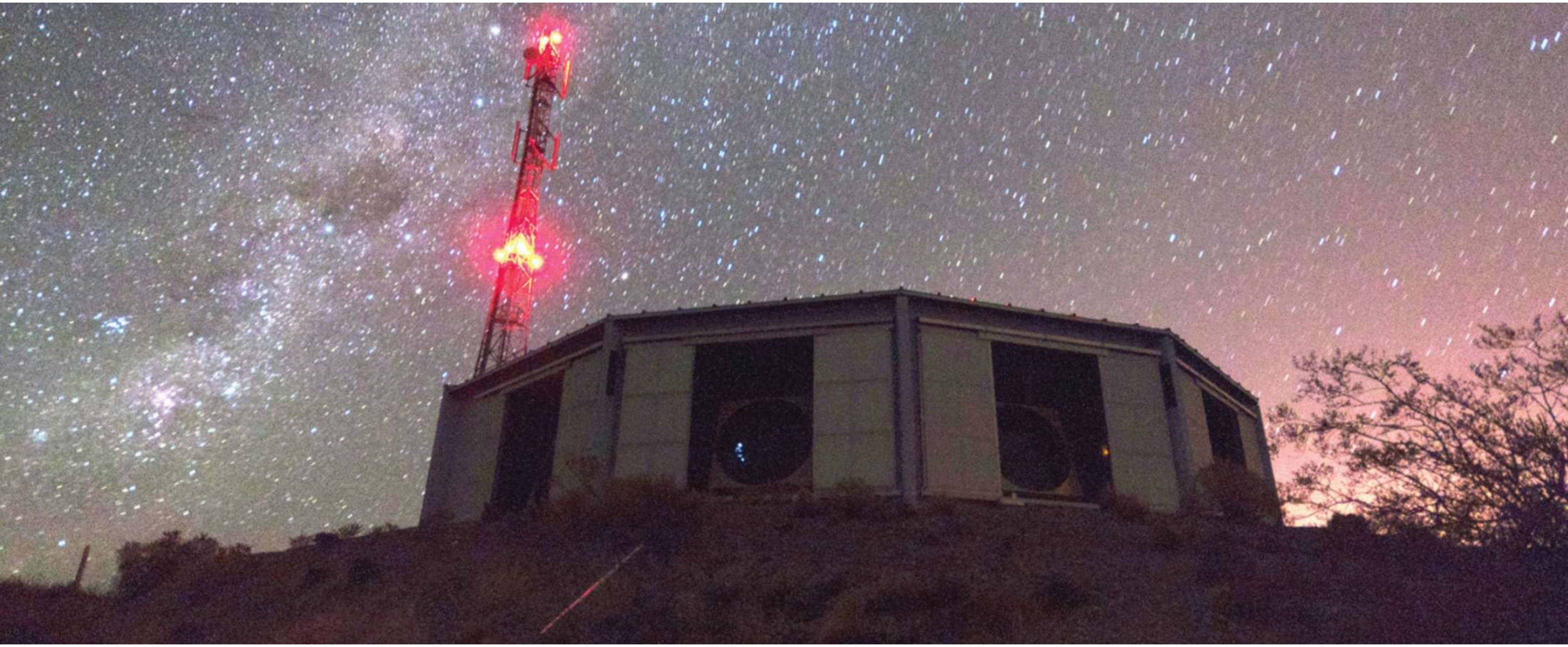
Most energetic particles - The Pierre Auger Observatory (AUGER)



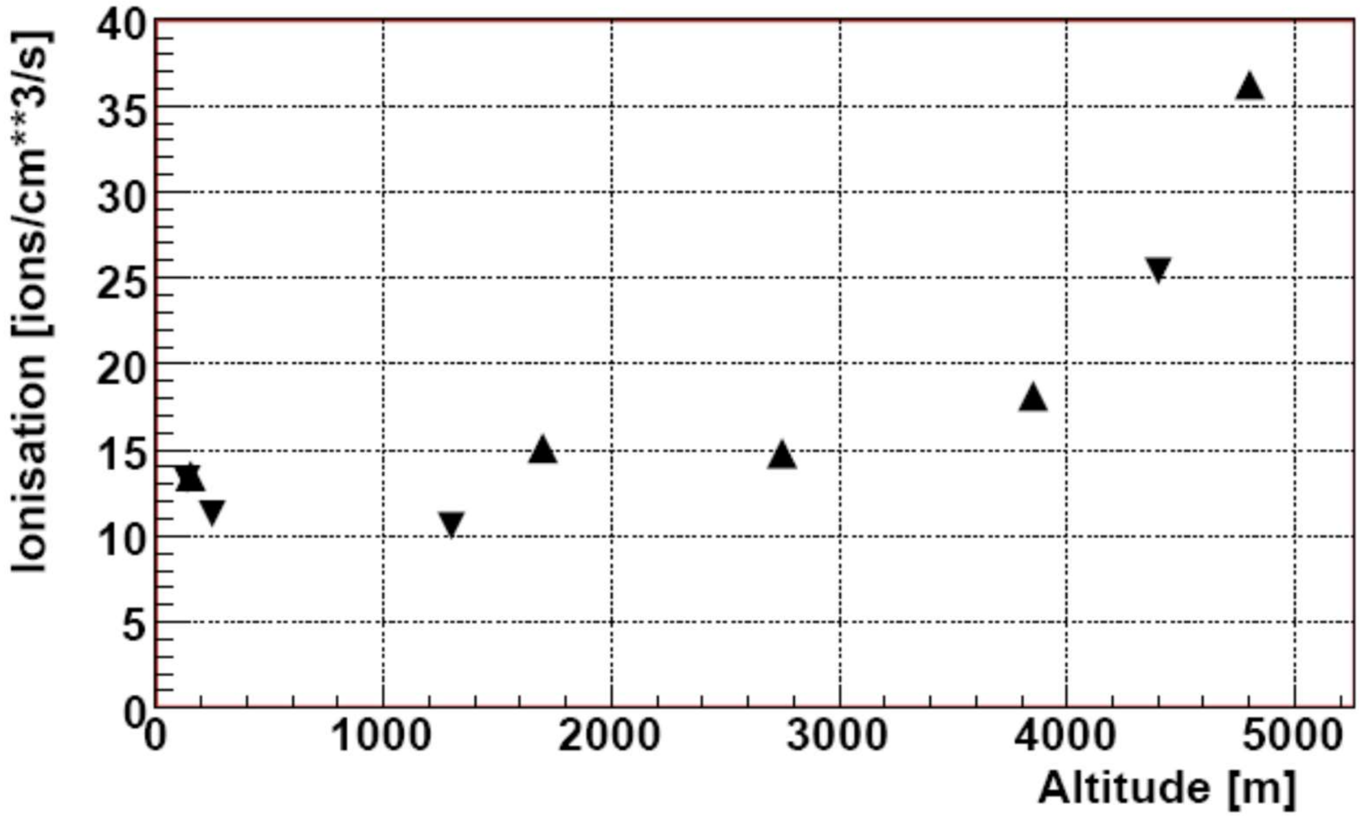
History: Discovery of cosmic rays

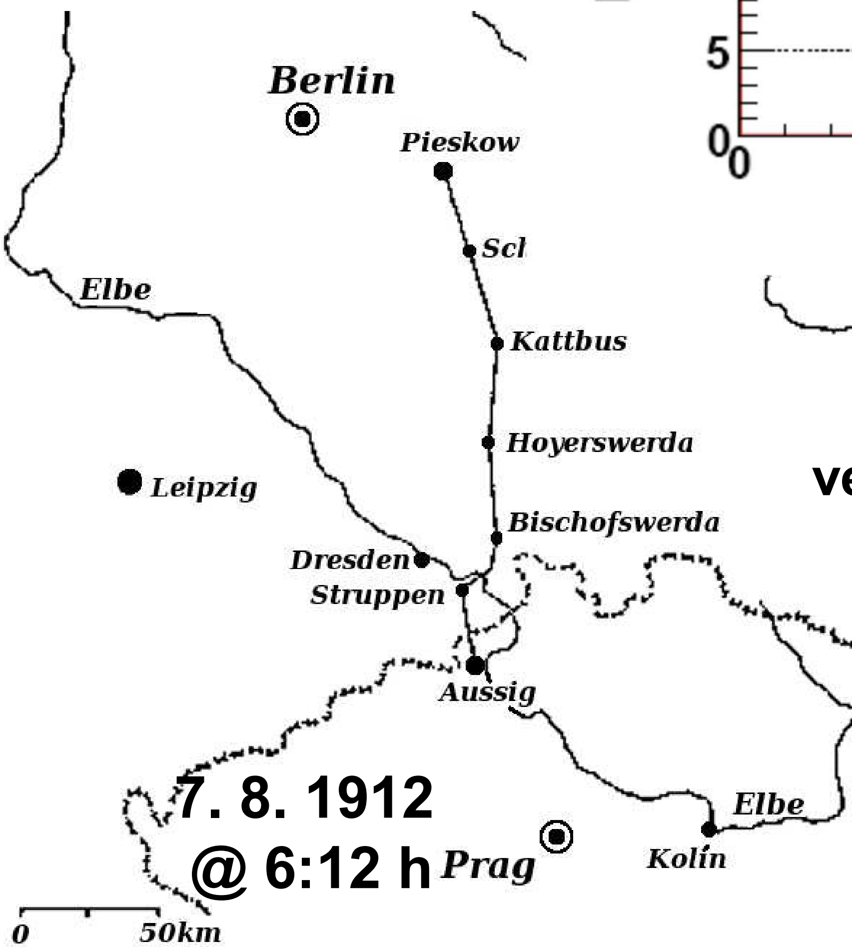
1912

Viktor Hess has discovered cosmic rays.

Some of his balloon flights starting from Bohemia.

1936 – Nobel Prize

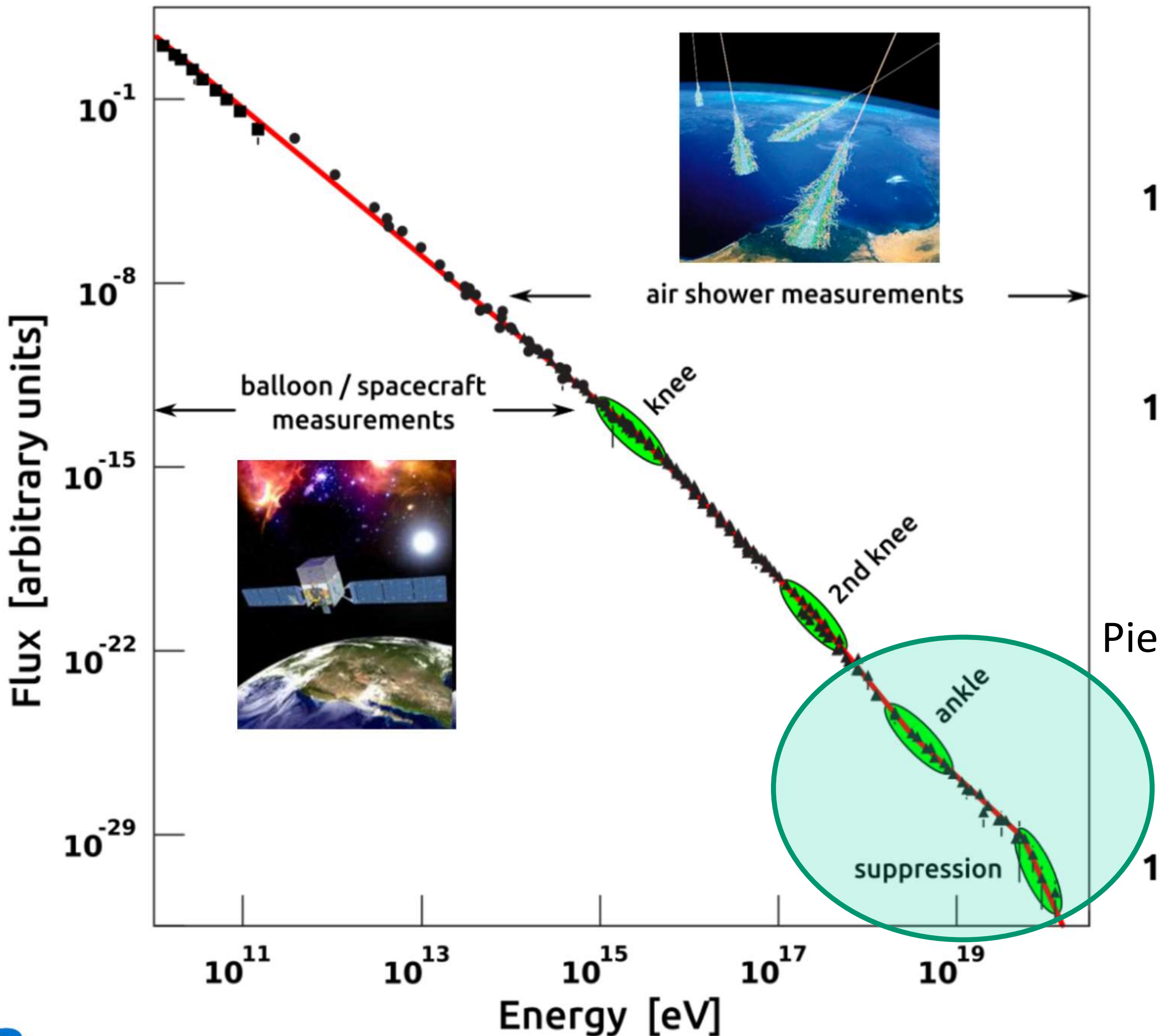




7. 8. 1912
@ 6:12 h

… radiation of
very high penetrating power enters the atmosphere
from above, and
still produces in the lower layers a part of the
ionization observed . . . ”
(V. Hess 1912).

Cosmic ray flux



1 particle/m²/second

1 particle/m²/year

Pierre Auger Observatory
~ 3000 km²

1 particle/km²/century

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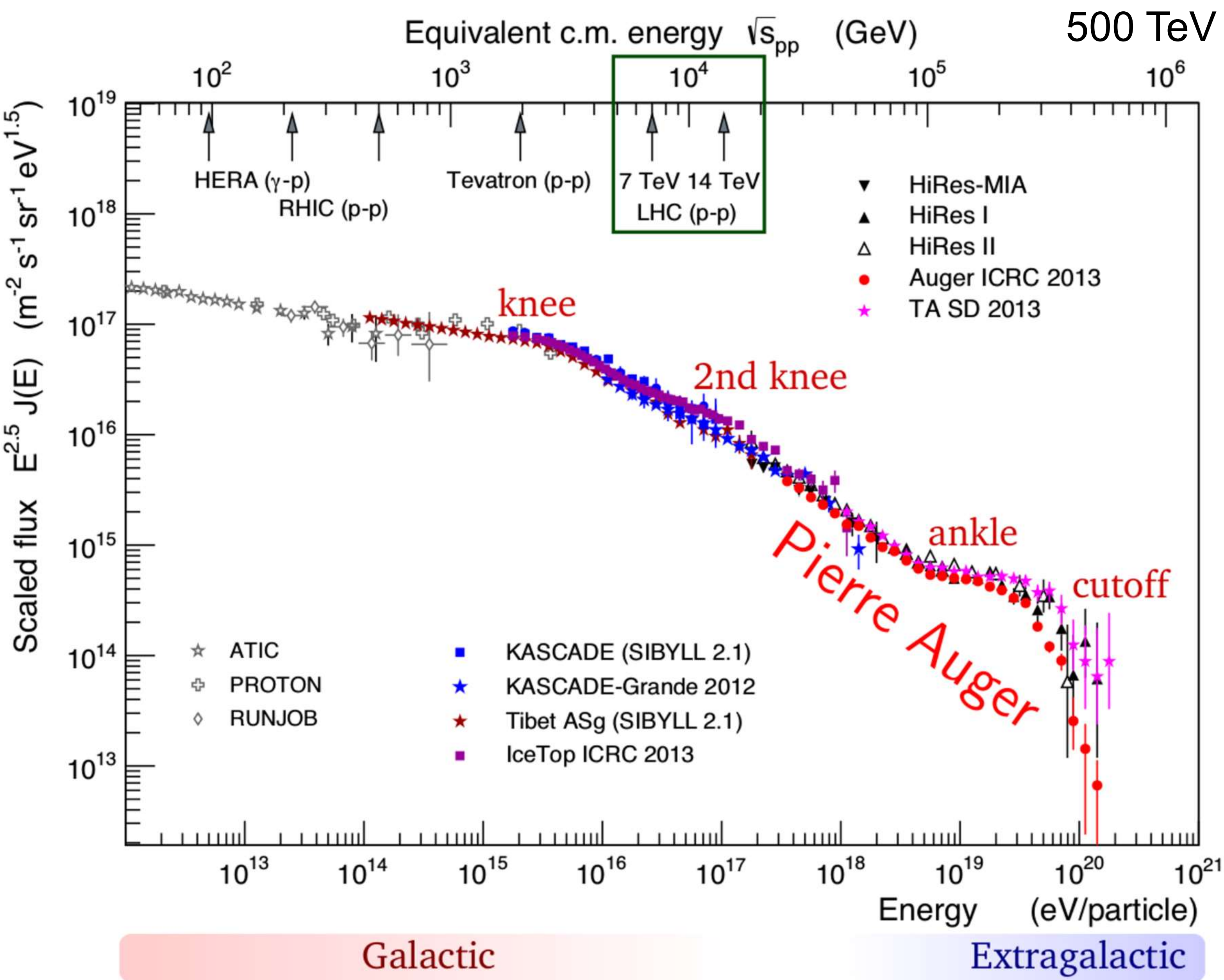
Scaled cosmic ray flux



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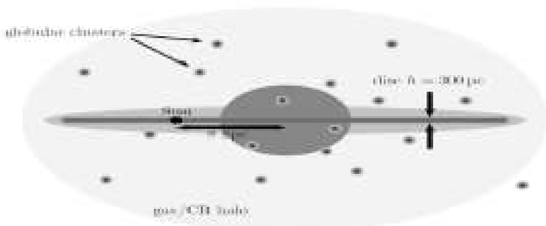
Distortions in Magnetic Fields

$$r_l[kpc] = \frac{E[10^{18} eV]}{Z \cdot B[\mu G]}$$

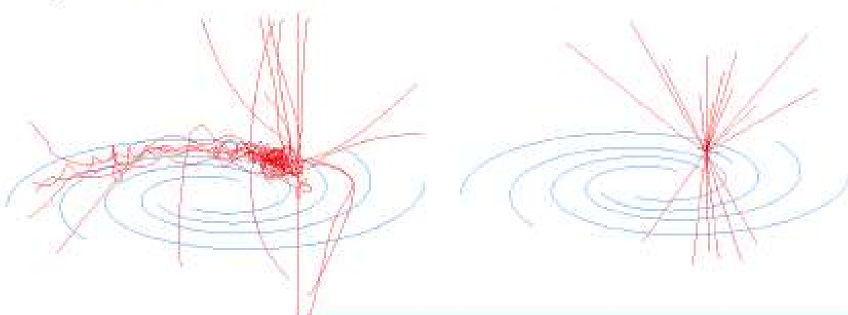
Galactic field

- $B_G \approx 3\mu G$
- Proton with E ~ 10^{18} eV
  => r_l = 0.3 kpc (disc thickness)



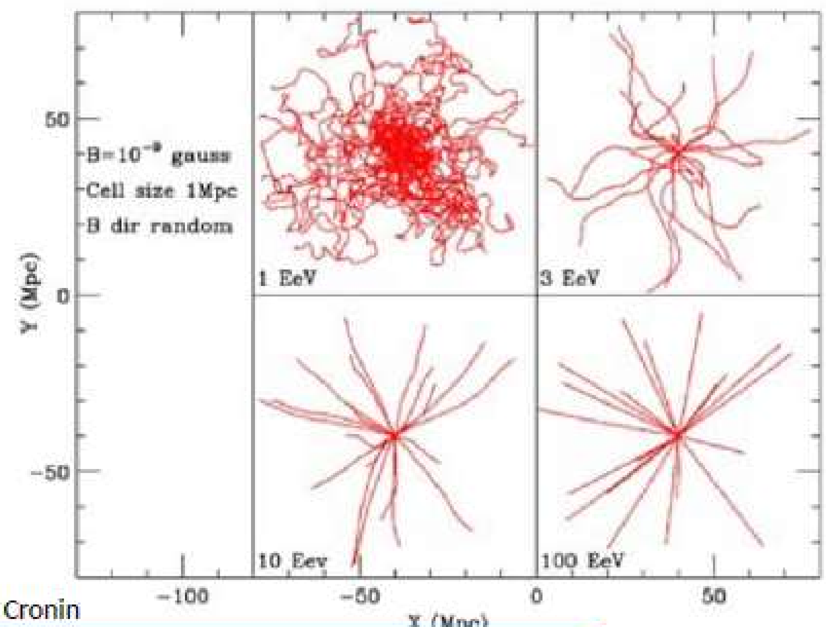
p 10^{18} eV

p 10^{20} eV



Extragalactic field

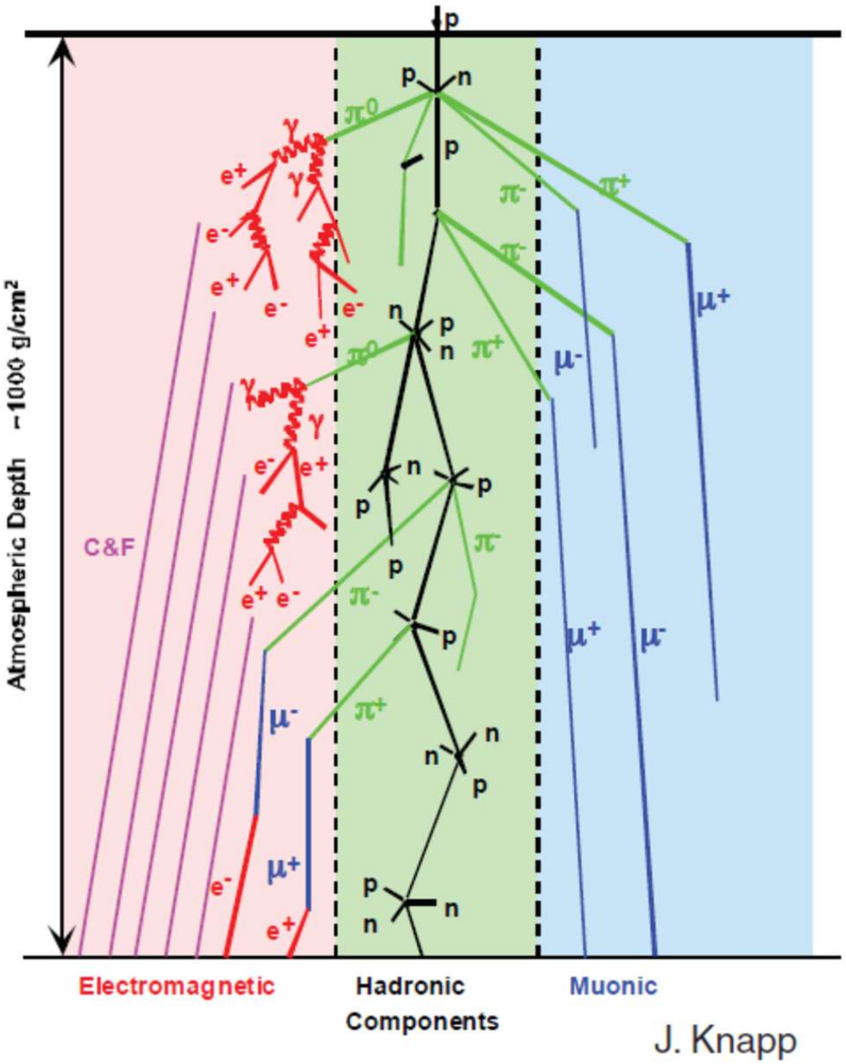
- Extragalactic field $B_{EG} \leq$ nG
- The closest AGN is Centaurus A (≈ 4 Mpc)

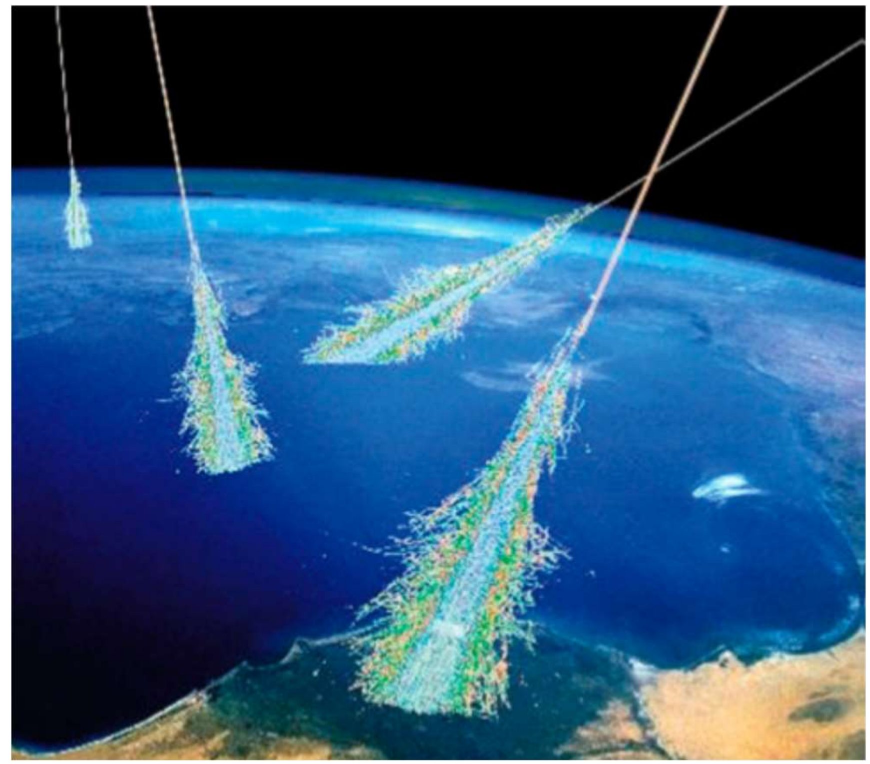


J. Cronin

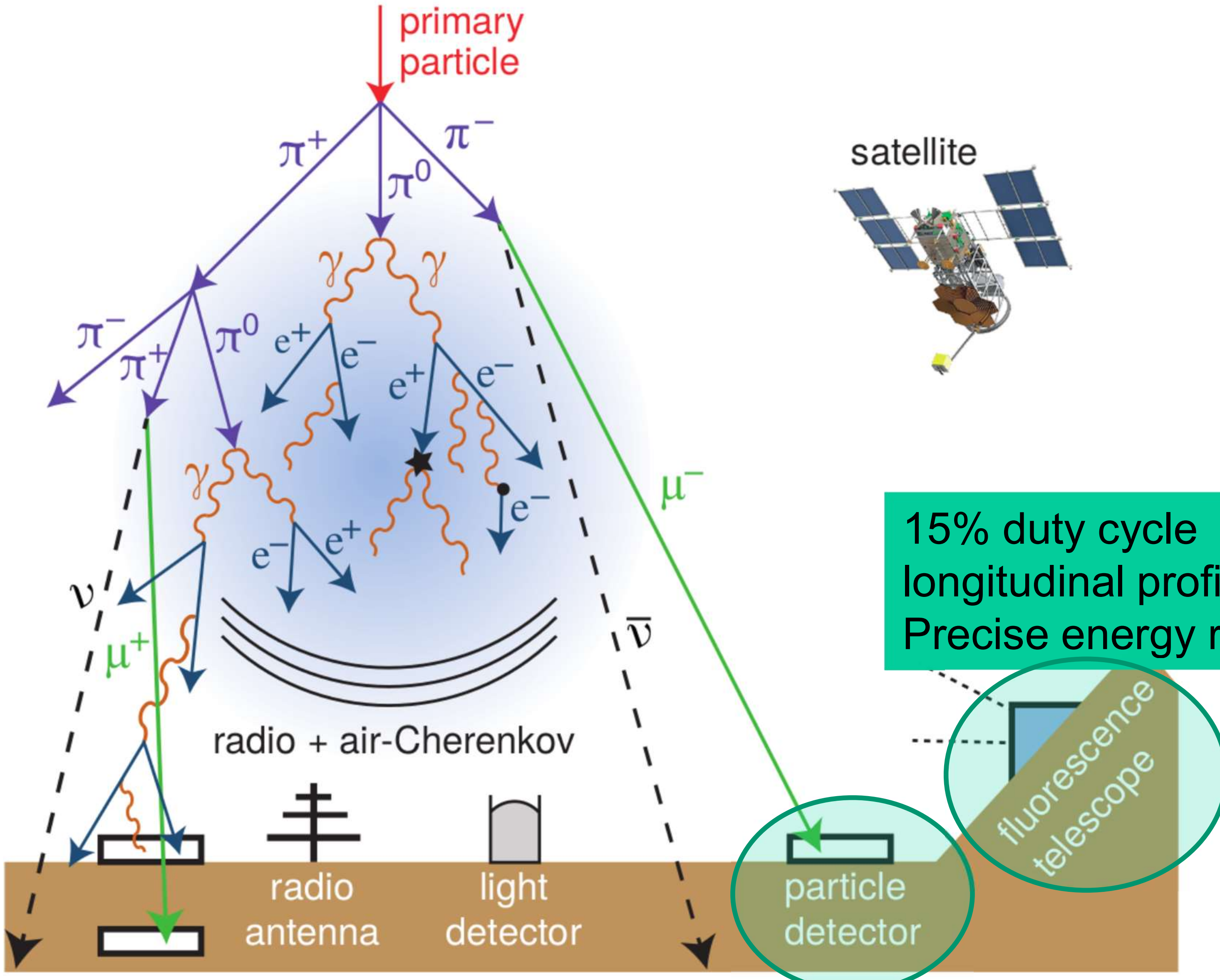
few deg expected for 50 EeV protons

Indirect detection – extensive air showers





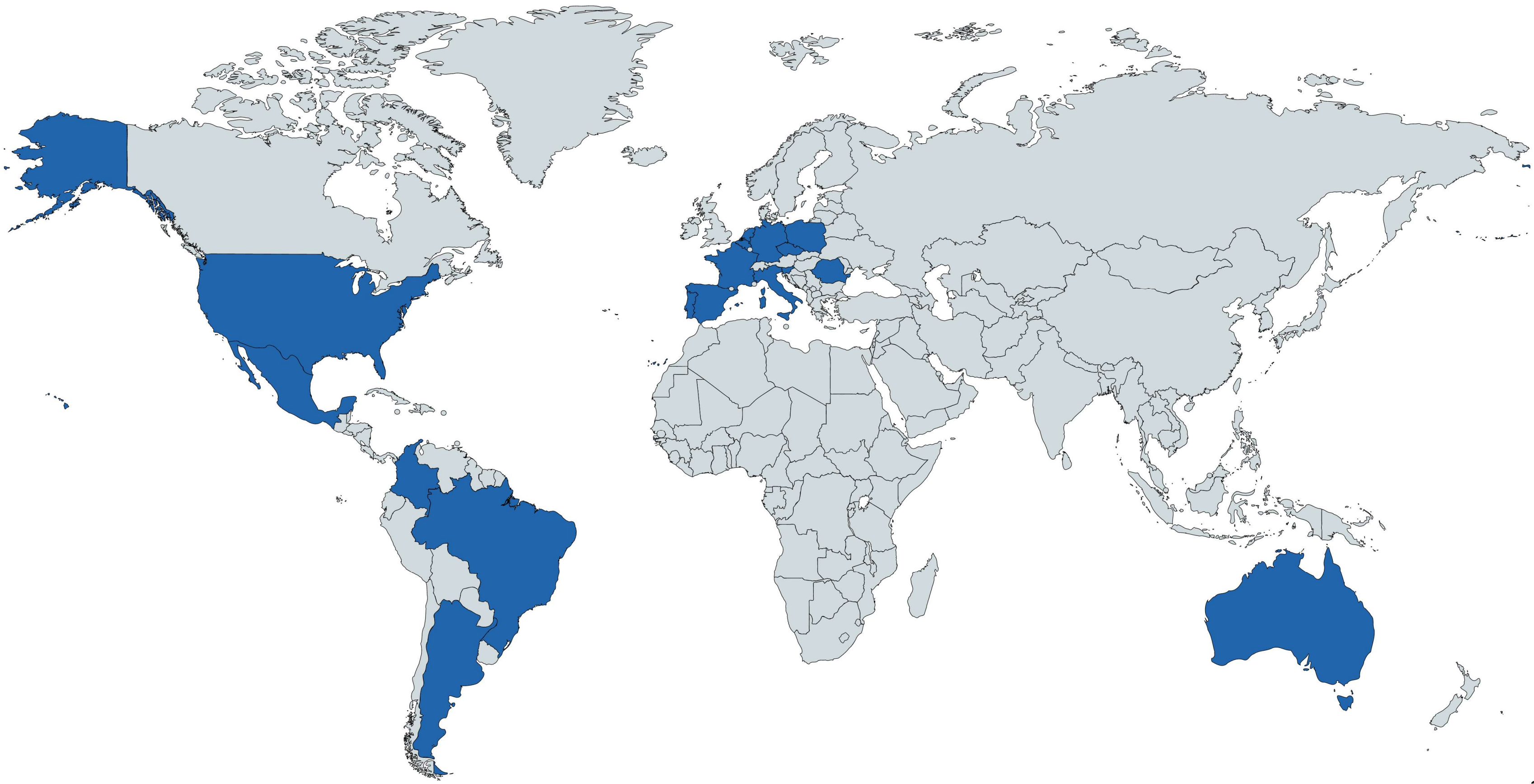
Detection of athmospheric showers

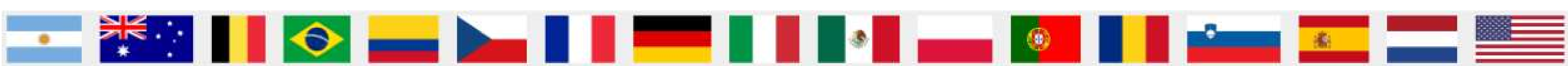


15% duty cycle
longitudinal profile
Precise energy reconstruction

100% duty cycle
Lateral profile only

Pierre Auger collaboration





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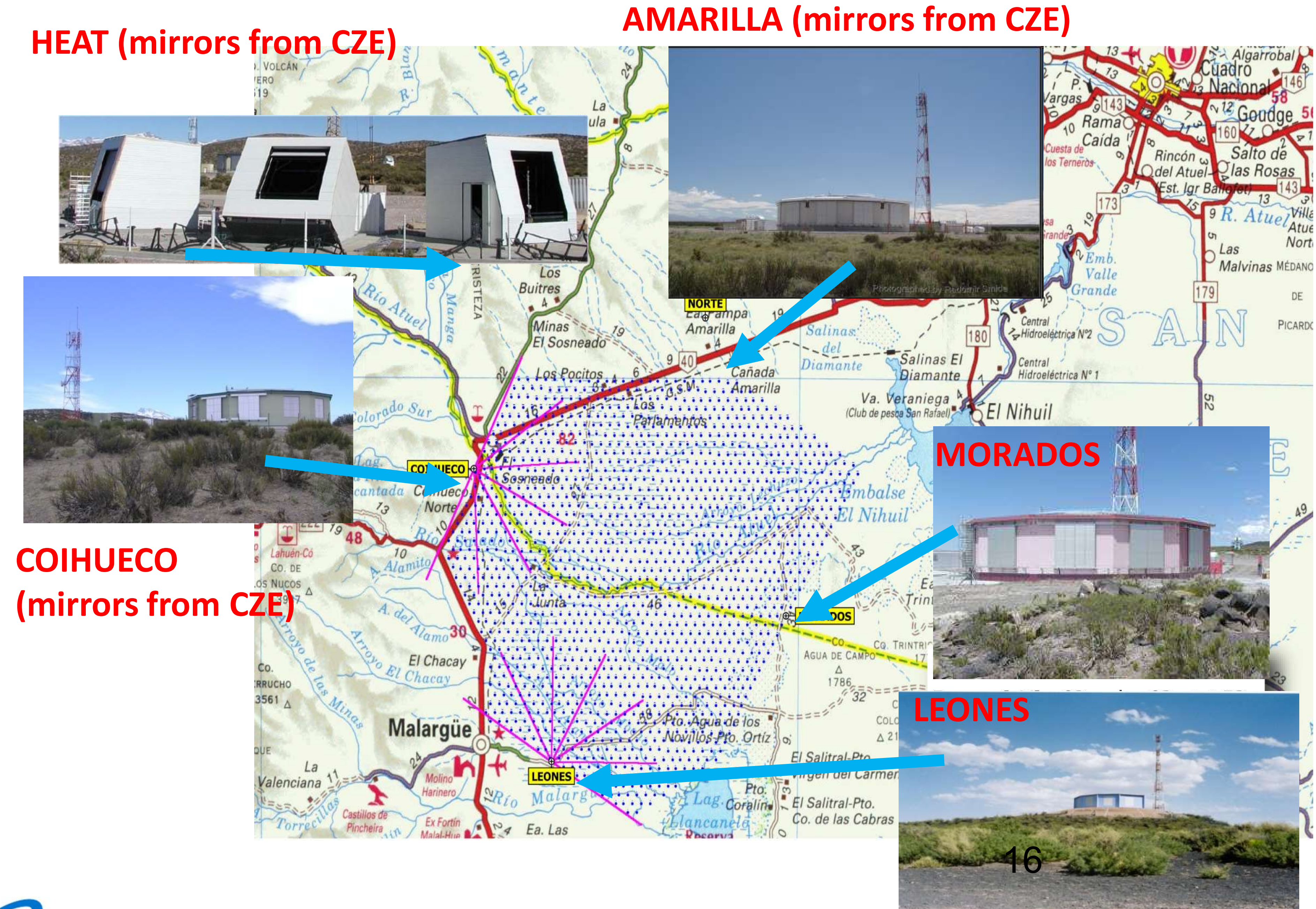

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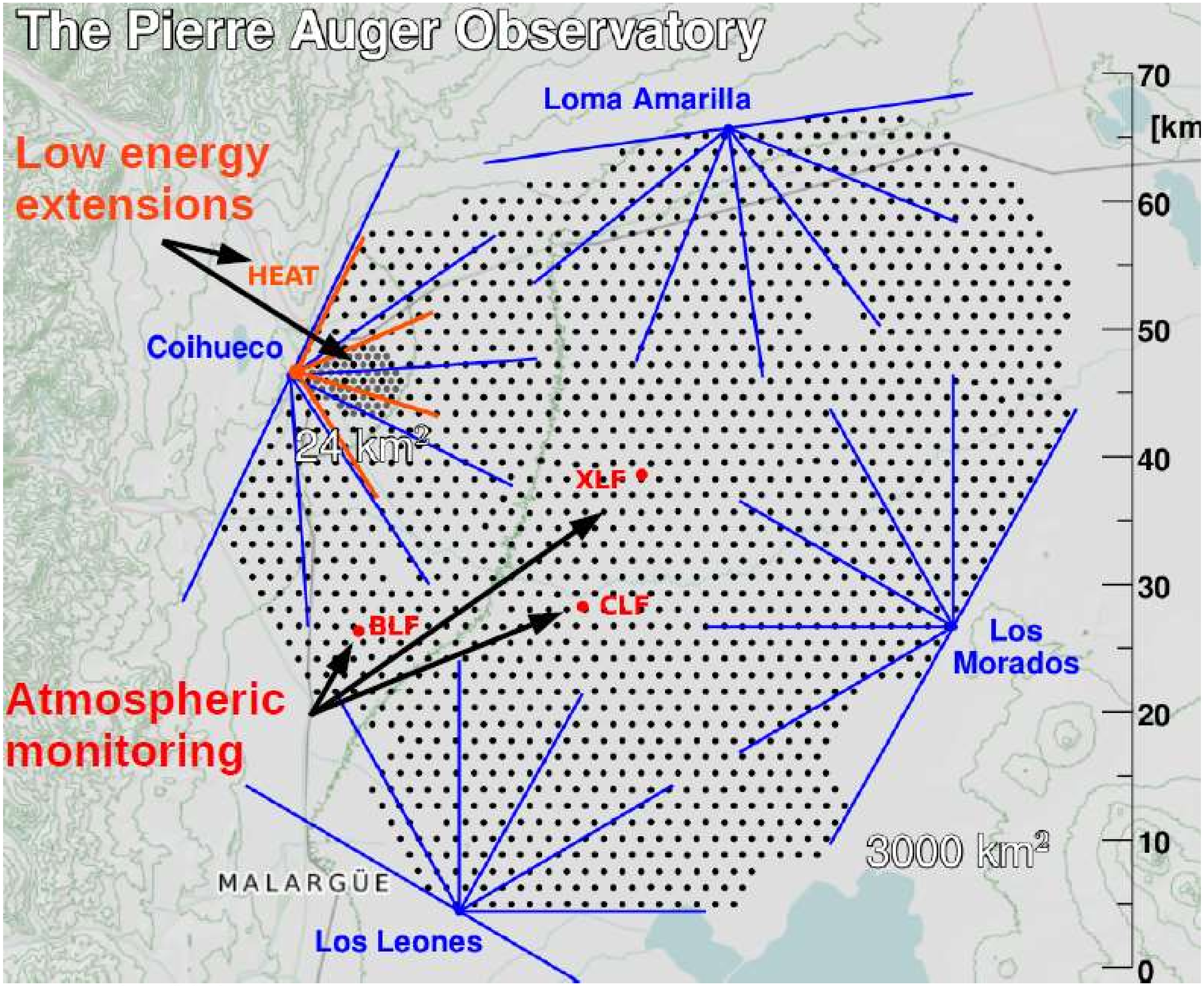
Pierre Auger Observatory



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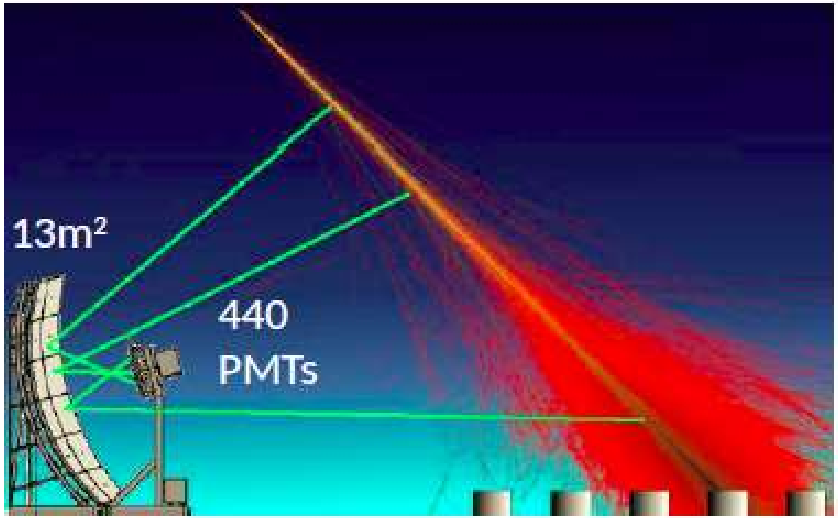
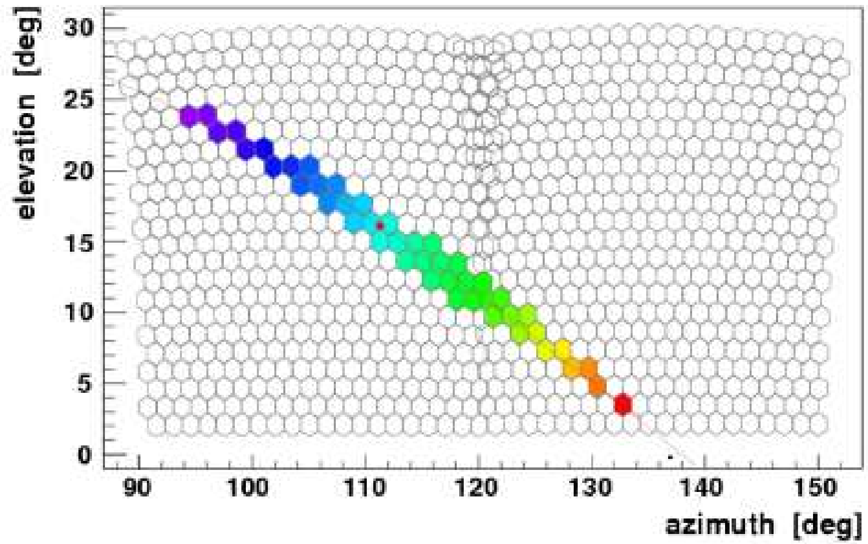
ODK12
ORION OPTICS

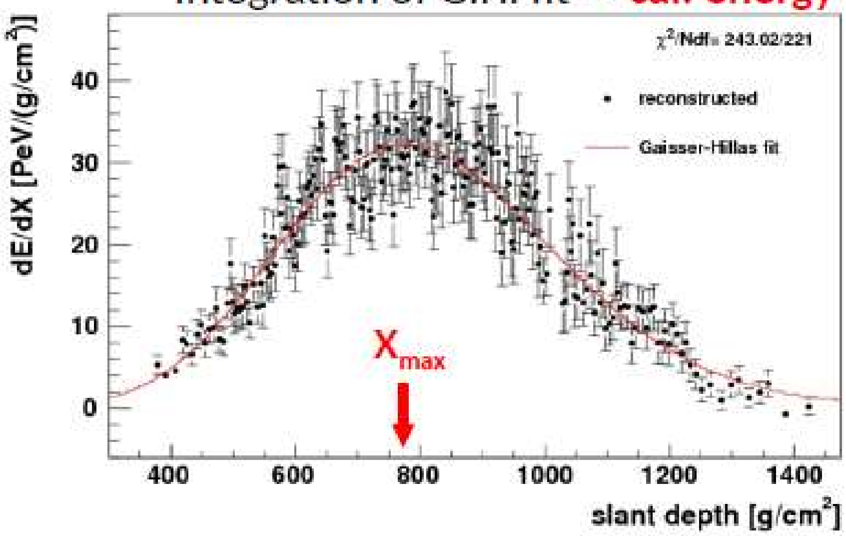
Fluorescence detector



- **Calorimetric** measurement
  (+ correction for invisible energy)
- **13%** duty cycle
- Hybrid detection improves the precision of shower reconstruction



Integration of G.H. fit -> cal. energy



- Observation of X_{max} in FOV
- Energy resolution **7-8%**
- Sys. uncertainty decreased to **14%**

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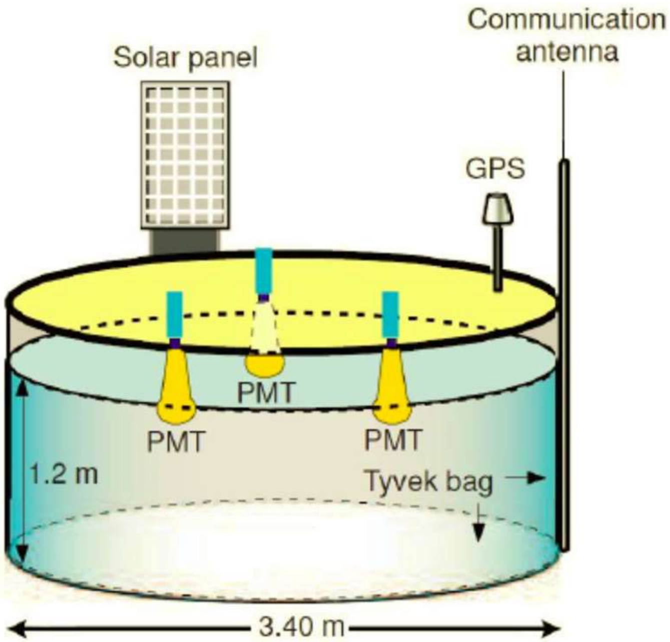
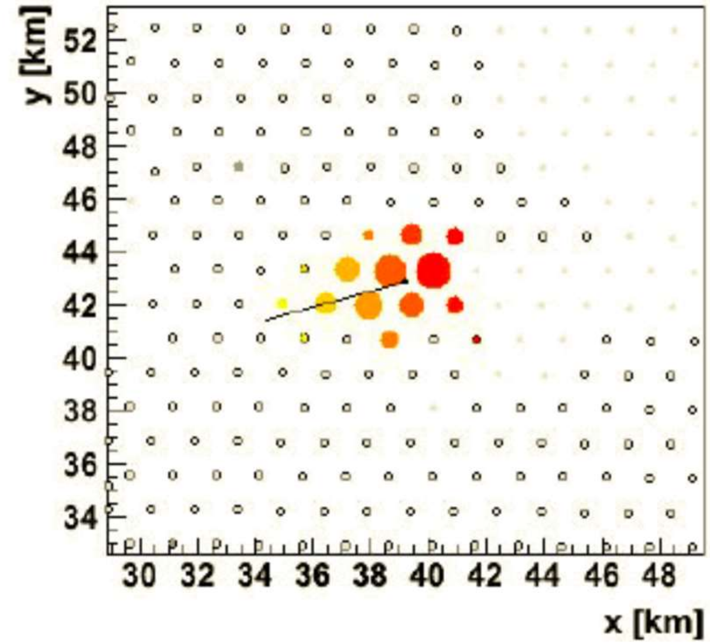
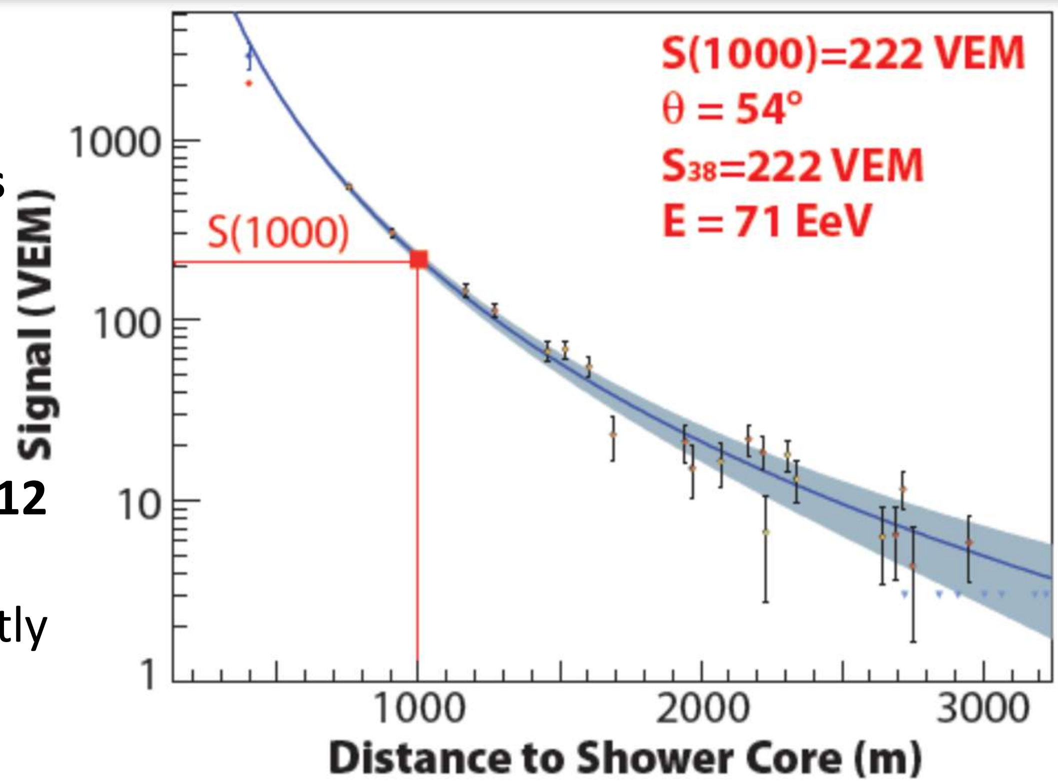
Surface detector







- Water Cherenkov tanks sensitive to **muons and EM** component
- **100% duty cycle**
- Signal attenuation corrected by the CIC method (data driven)
- Energy calibration using FD, resolution **17-12 %**, angular < 1° above 10 EeV
- For zenith angles **> 60°** SD signal dominantly from **muon** component

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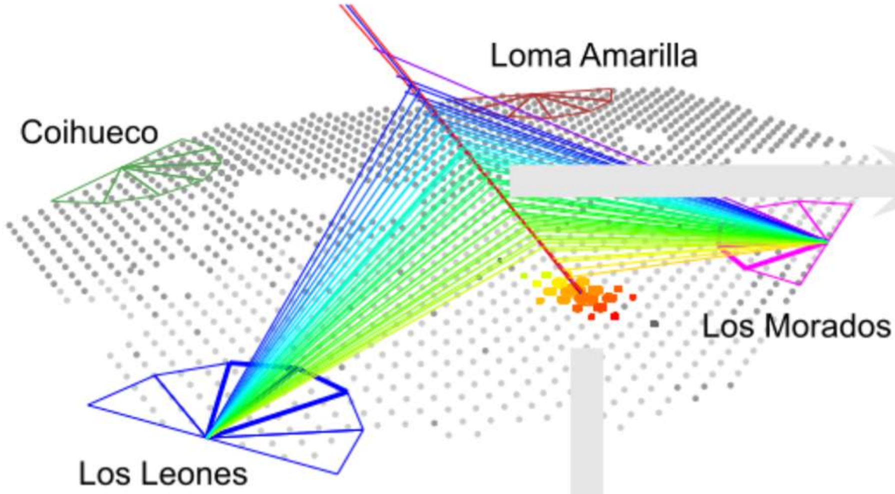
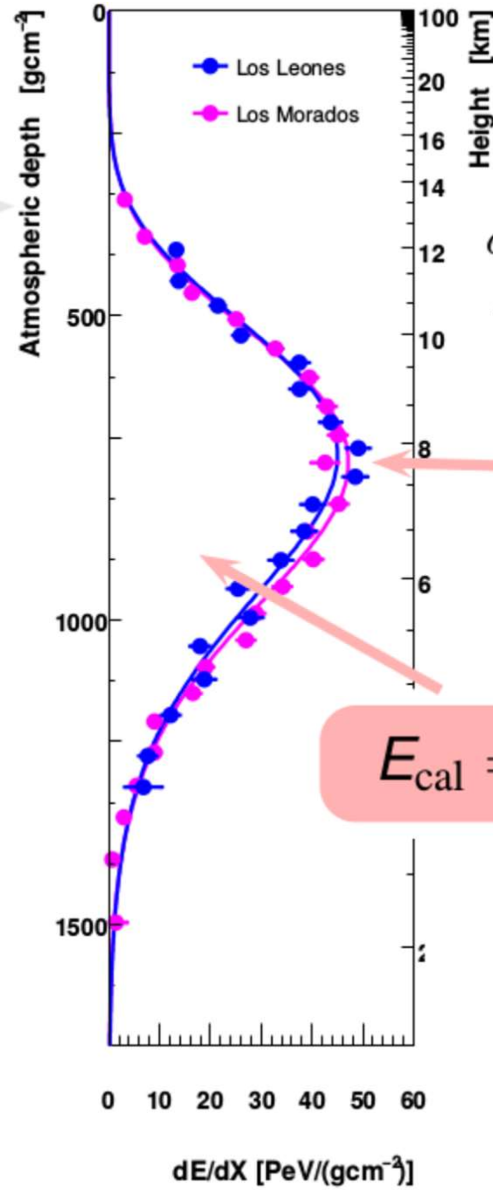
Measurement principle



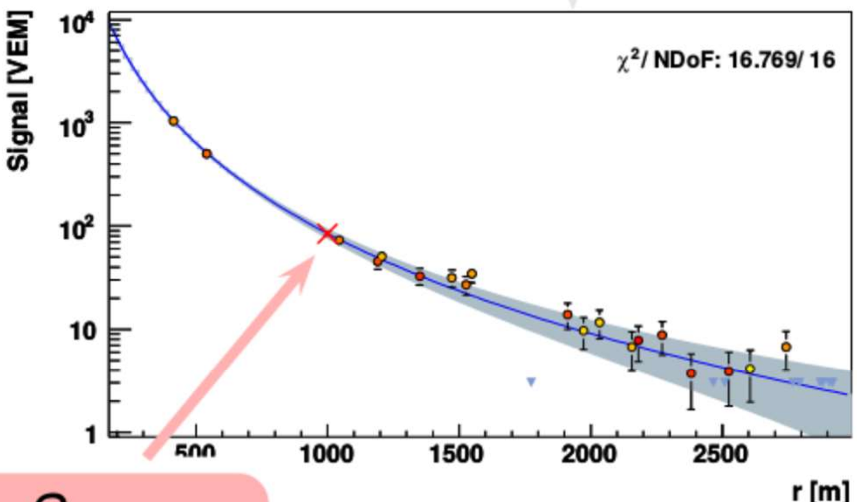


$\sigma_{X_{\mathrm{max}}} \leq 20\,\mathrm{g/cm^2}$
$\Delta_{\mathrm{sys}} \leq 10\,\mathrm{g/cm^2}$

X_{max}

$E_{\mathrm{cal}} = \int \frac{\mathrm{d}E}{\mathrm{d}X}\,\mathrm{d}X$

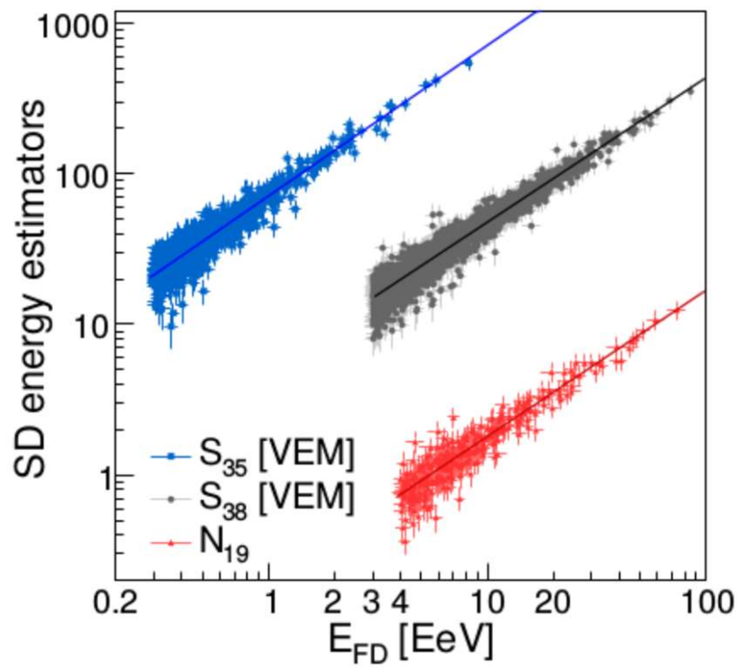
$\sigma_E/E \sim 8\,\%$
$\Delta_{\mathrm{sys}} \approx 15\,\%$

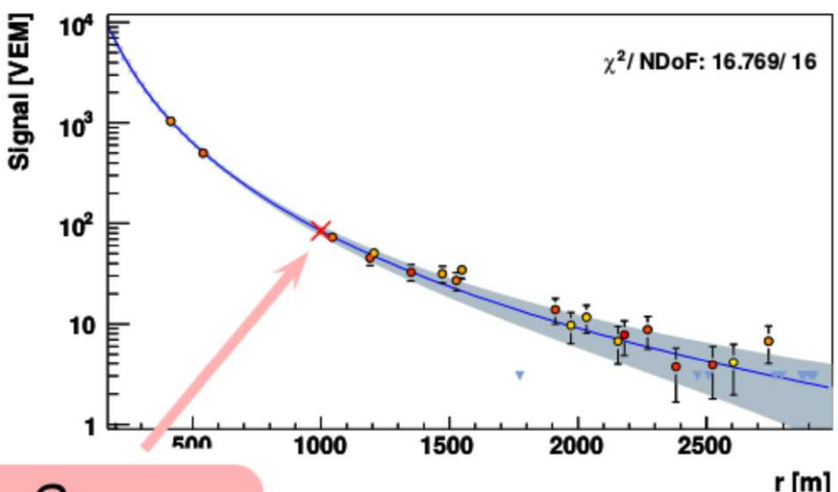


S_{1000}

$E_{\mathrm{surface}} = f(S_{1000},\, \theta)$

Measurement principle





S_{1000}

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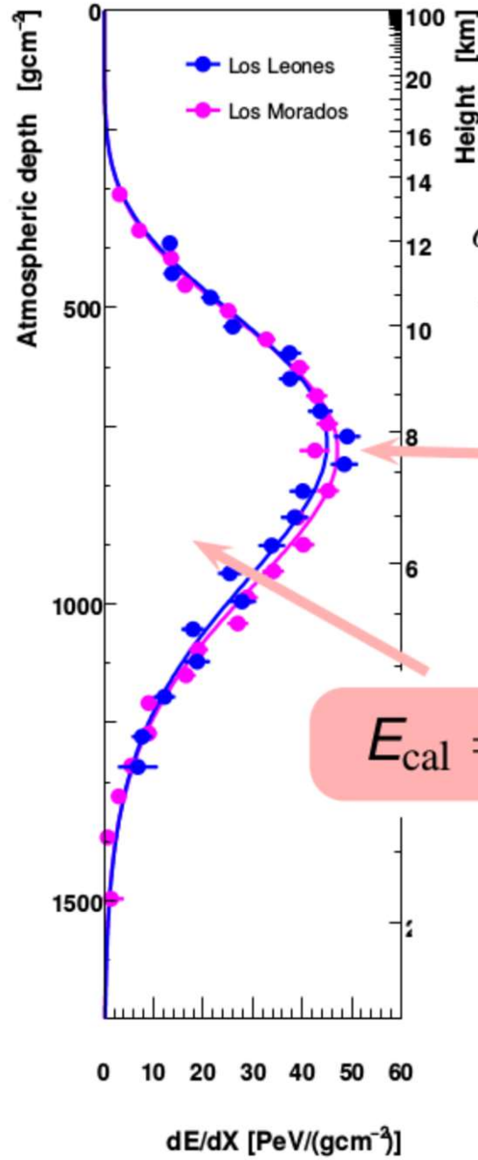

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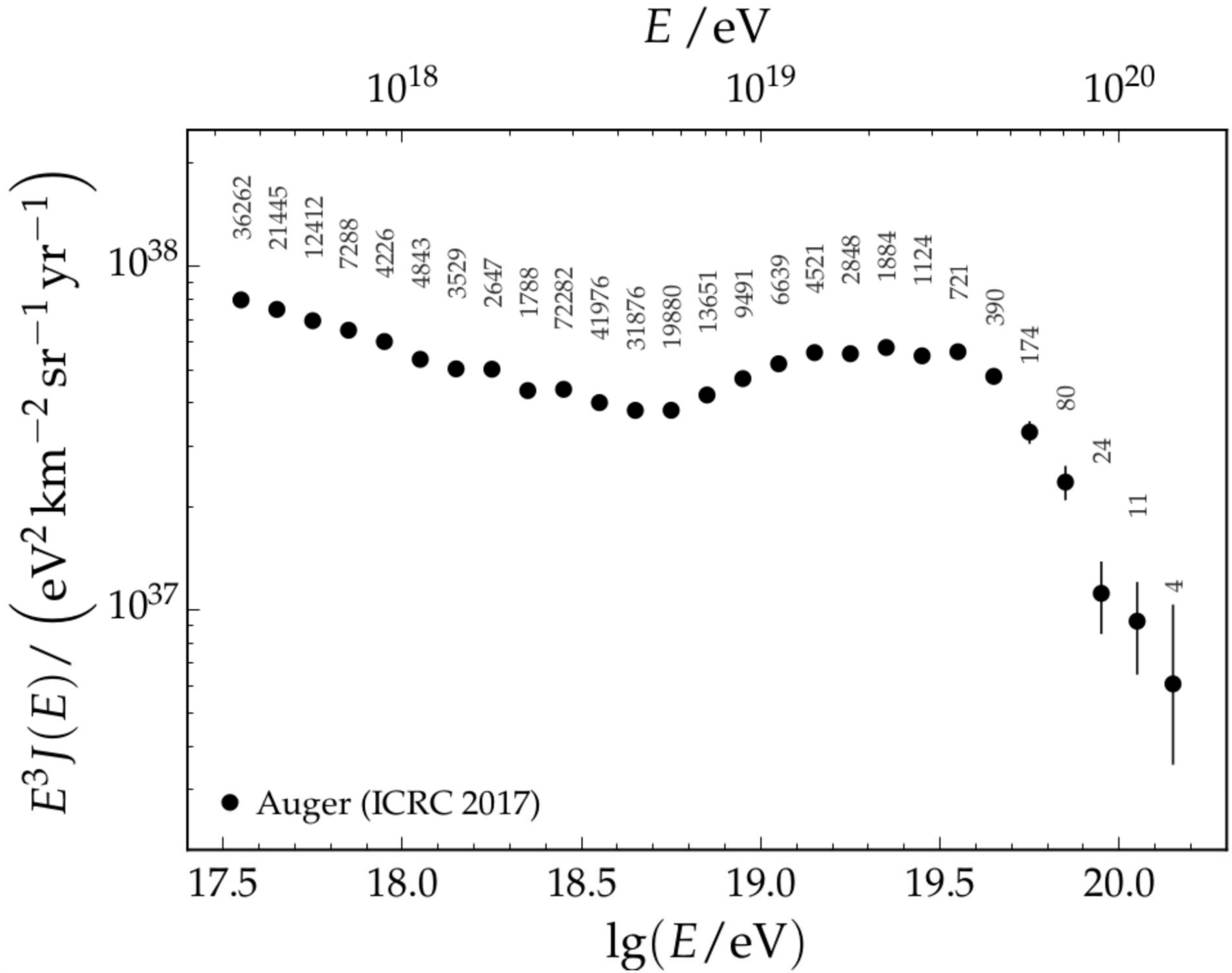
Our data



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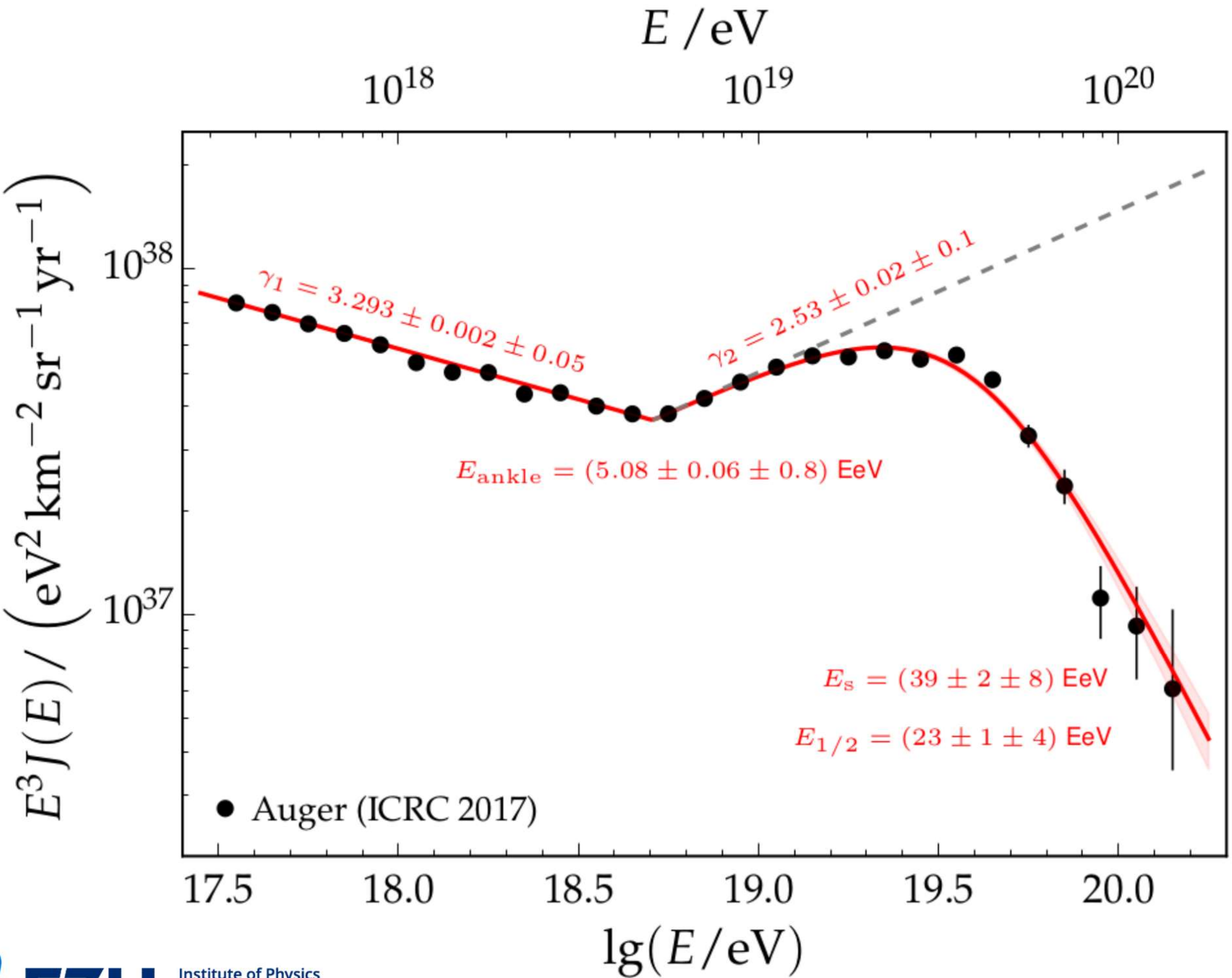
Spectral features



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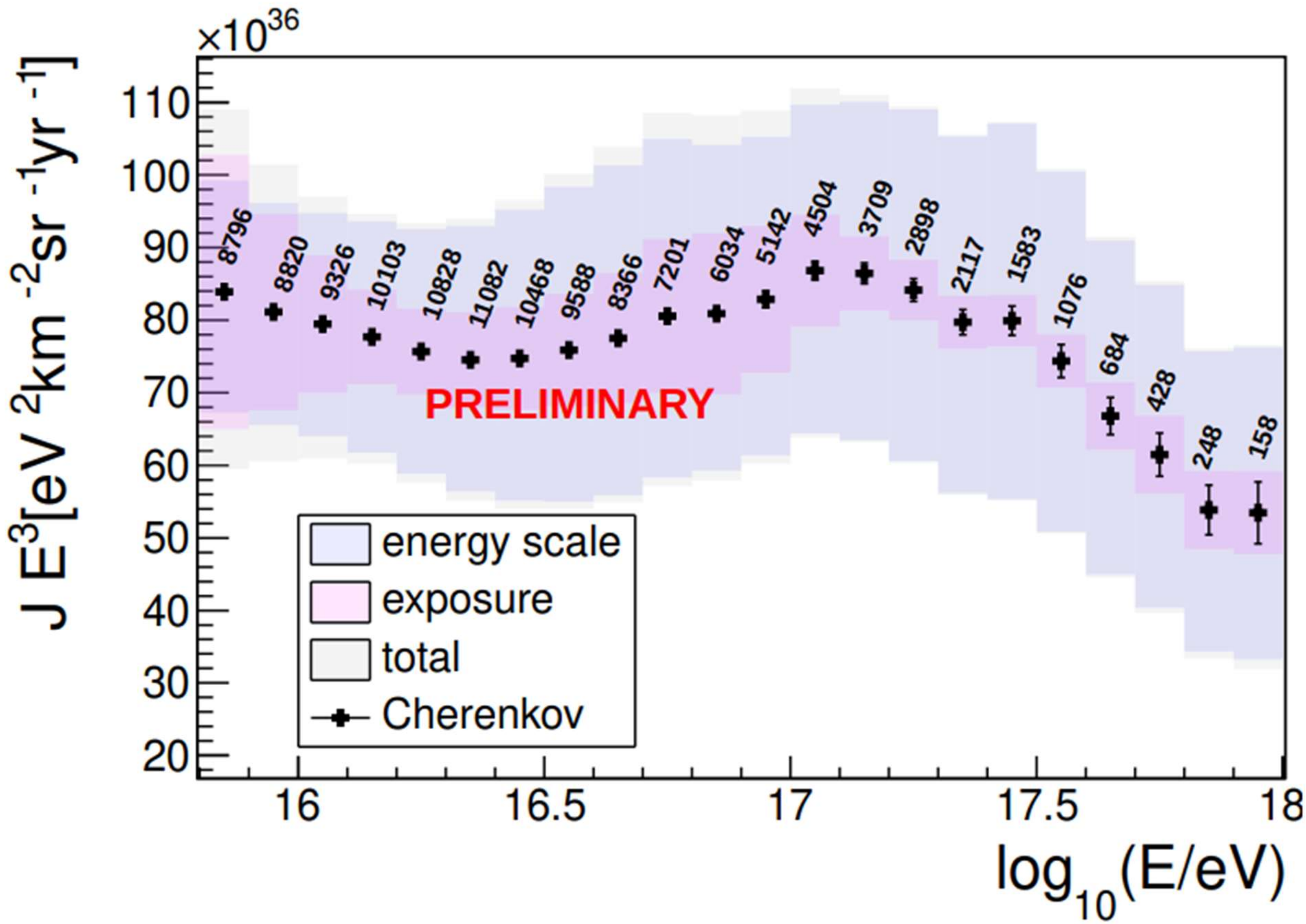
Low energy spectrum



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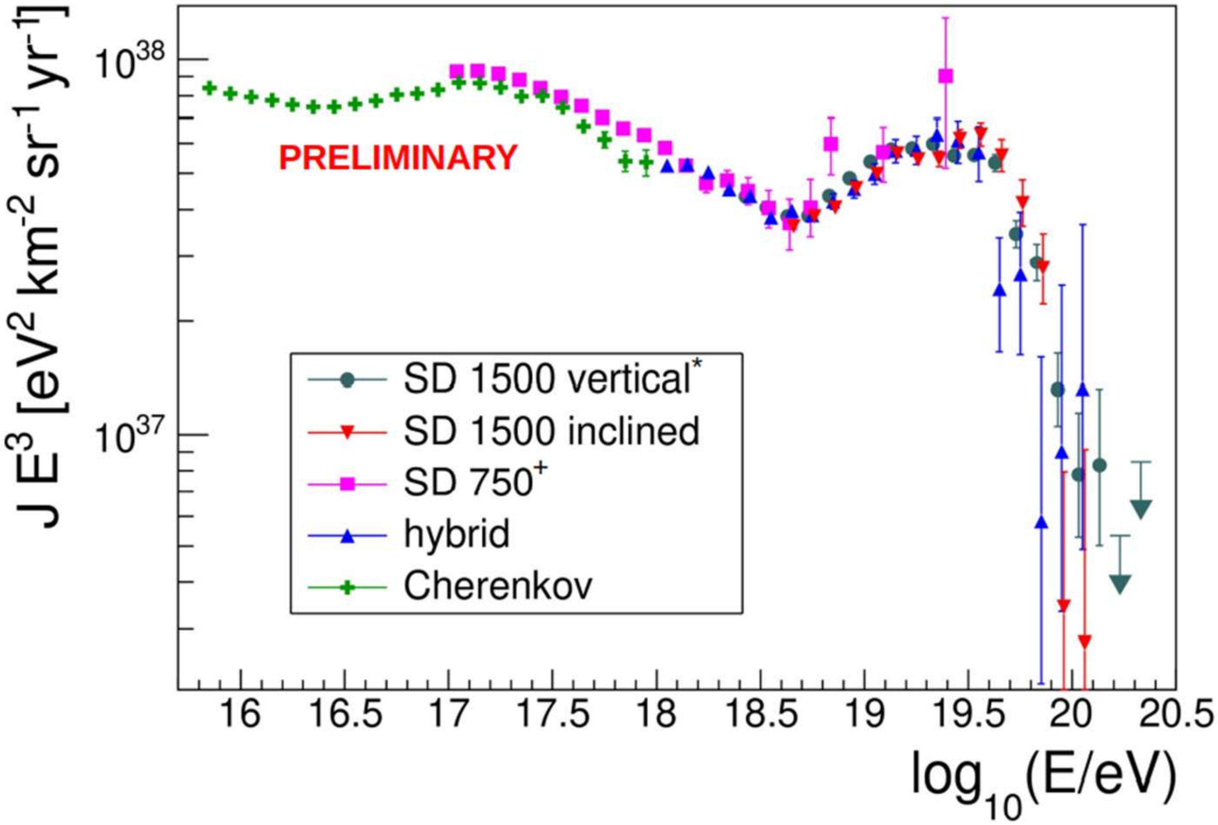
Combined spectrum

compatible within uncorrelated uncertainties



normalization shifts after comb.:

SD 1500 m	<1 %
SD 750 m	-2 %
SD 1500 m inclined	+5 %
Hybrid	<1 %
Cherenkov	+7 %

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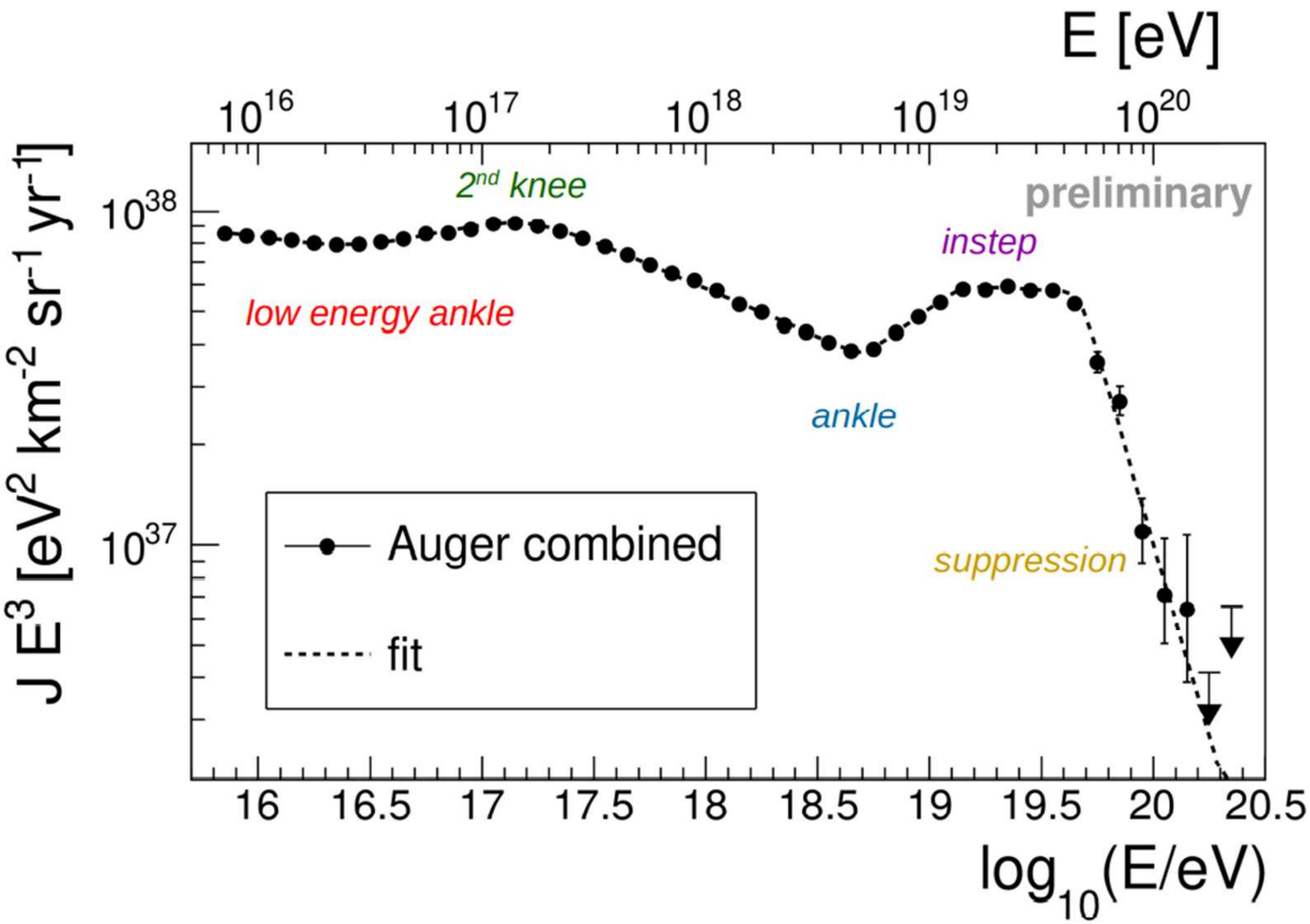
Spectrum features



fit parameters (± stat. ± syst.)

$\gamma_0 = 3.09 \pm 0.01 \pm 0.10$

$E_{01} = (2.8 \pm 0.3 \pm 0.4) \times 10^{16}$ eV

$\gamma_1 = 2.85 \pm 0.01 \pm 0.05$

$E_{12} = (1.58 \pm 0.05 \pm 0.2) \times 10^{17}$ eV

$\gamma_2 = 3.283 \pm 0.002 \pm 0.10$

$E_{23} = (5.0 \pm 0.1 \pm 0.8) \times 10^{18}$ eV

$\gamma_3 = 2.54 \pm 0.03 \pm 0.05$

$E_{34} = (1.4 \pm 0.1 \pm 0.2) \times 10^{19}$ eV

$\gamma_4 = 3.03 \pm 0.05 \pm 0.10$

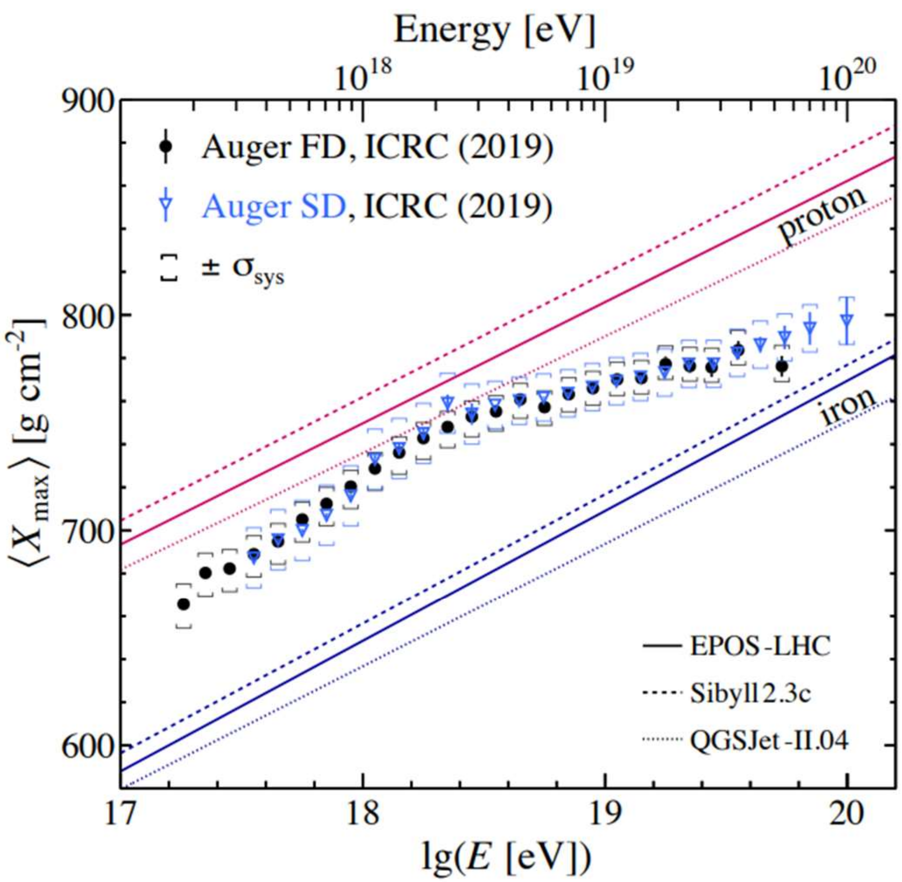
$E_{45} = (4.7 \pm 0.3 \pm 0.6) \times 10^{19}$ eV

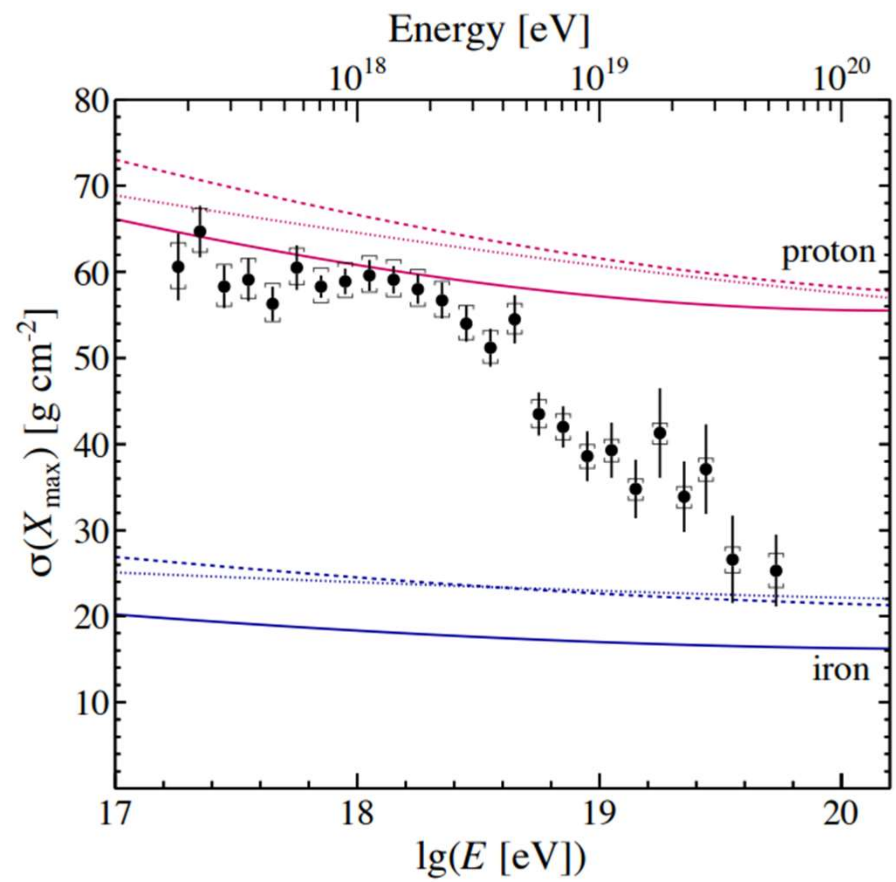
$\gamma_5 = 5.3 \pm 0.3 \pm 0.1$

$J_0 = (8.34 \pm 0.04 \pm 3.40) \times 10^{-11}$ km^{-2} sr^{-1} yr^{-1} eV^{-1}

14

Mass composition





Models of hadronic interactions tuned to the LHC data (Run I)

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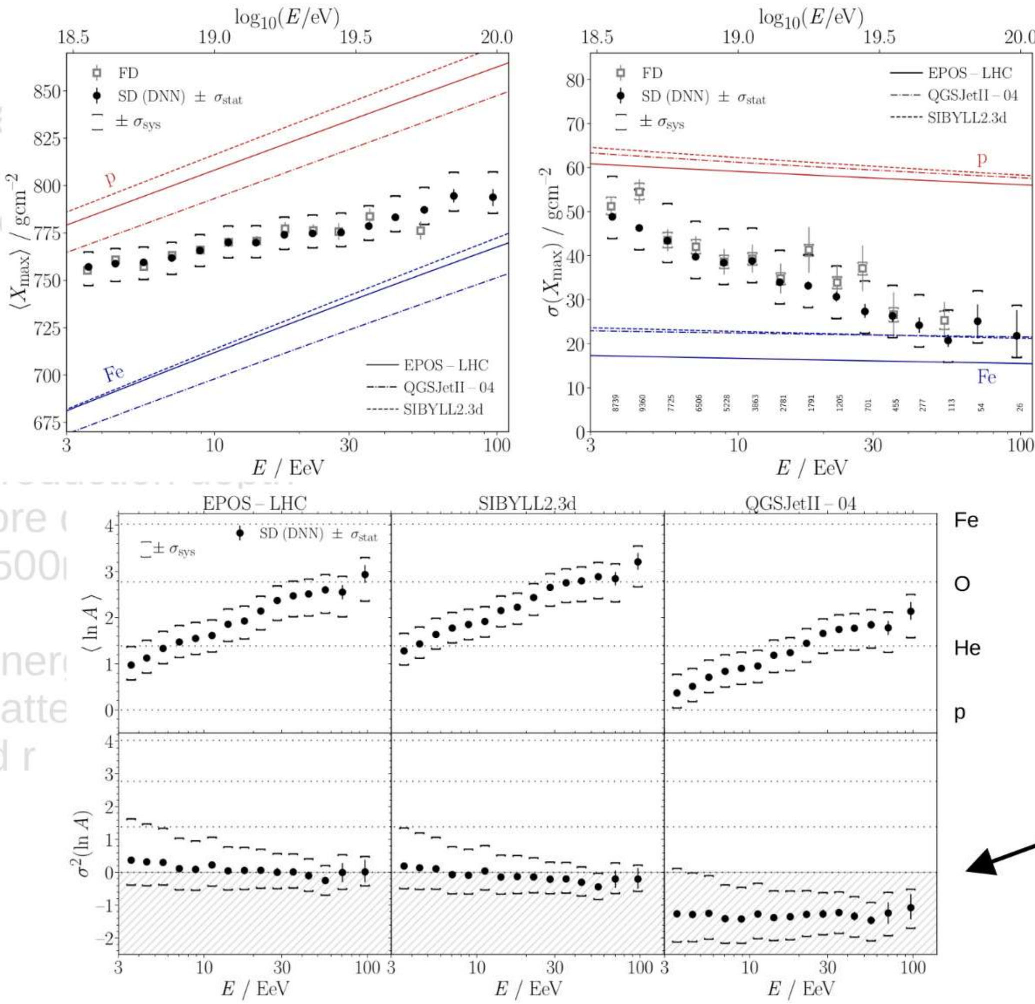
Observables relevant to hadronic interaction models

[accepted in PRD, arXiv:2406.06319]

SD signa

- muon c
  - from
  - scinti
  - from
- muon p
  - for core
  - r > 1500
- muon ener
  - from atte
  - θ and r



$10^{18.5\text{-}20.0}$ eV

FD longitudinal profile

- estimation of primary masses from X_{max} fits
- interpretation of X_{max} moments using ln A
- p-air cross-section from tail of X_{max} distribution

showers

Indication of too shallow predictions of $\langle X_{max} \rangle$ for all three models !

J. Vícha, UHECR 2024, Nov 2024

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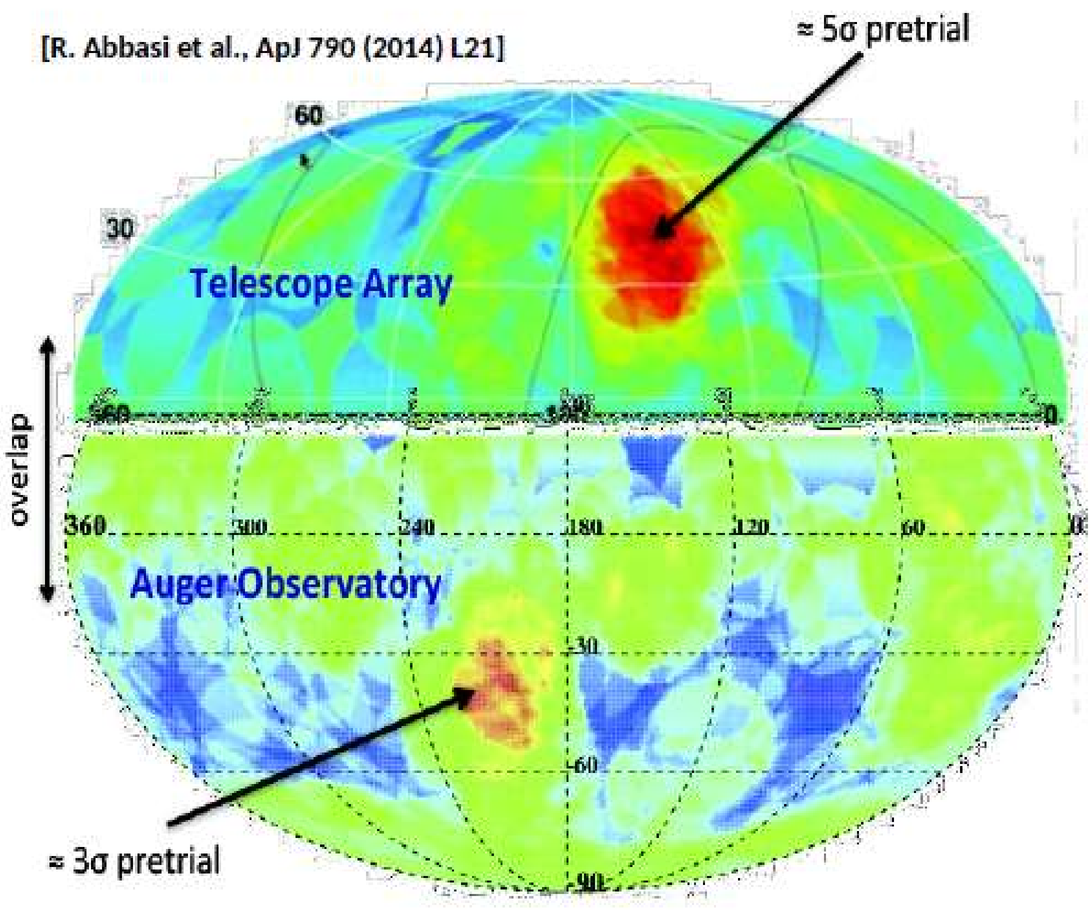
Anisotropies at the Highest Energies (above ~ 50 EeV)

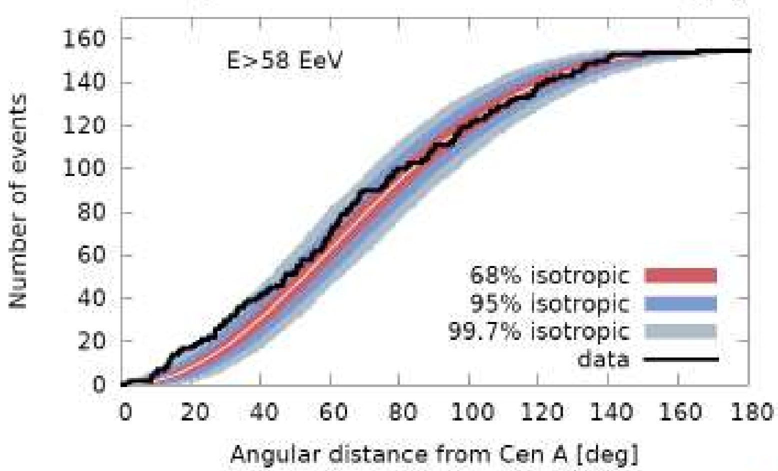


Equatorial coordinates [A. Aab et al., ApJ 804 (2015) 15]

~ 5-σ local significance
(no obvious source nearby)

~20 deg hot spots!

~ 3-σ local significance
(around Cen A – AGN 4 Mpc)



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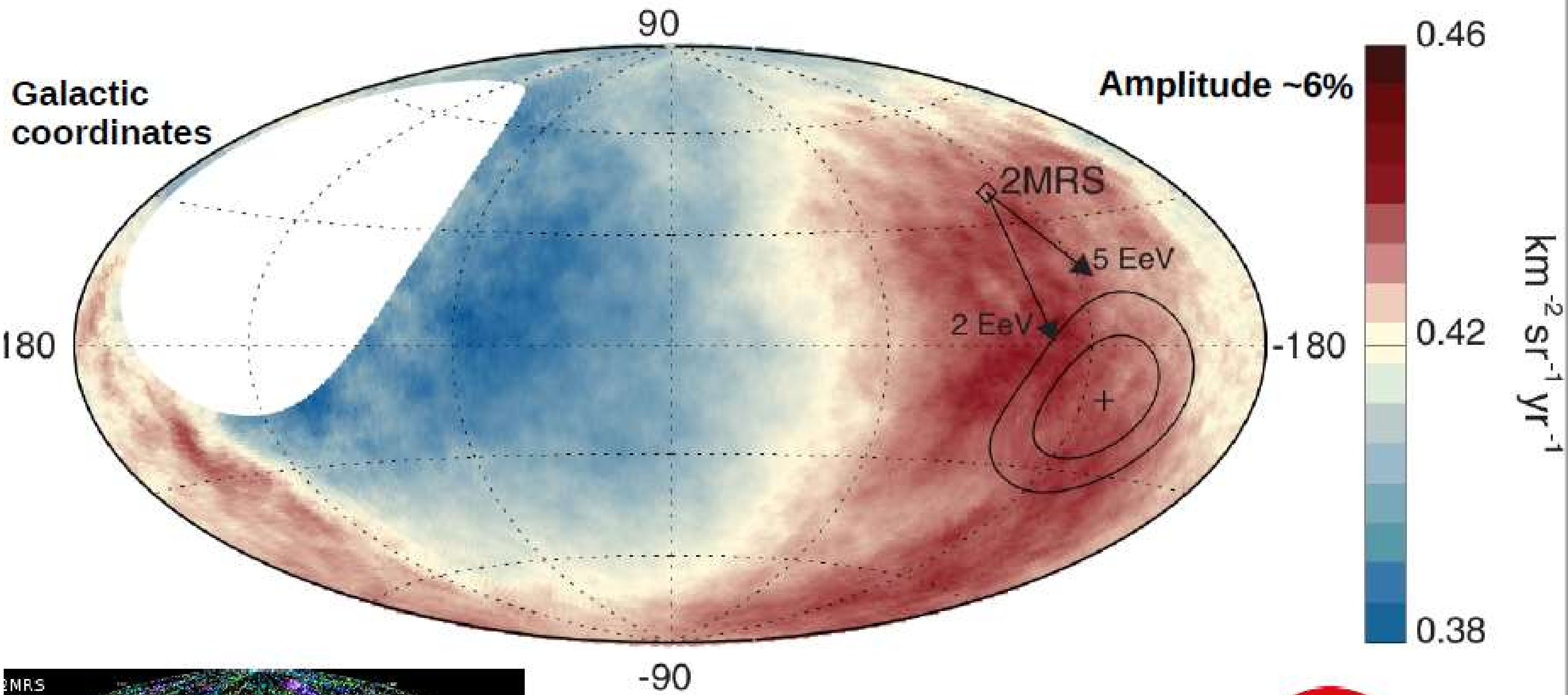
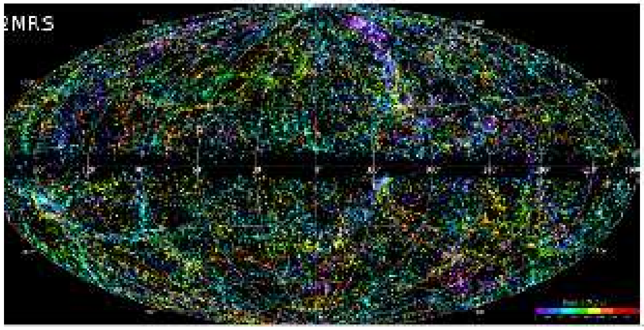
Large-scale Dipole - 5 σ discovery!

[Science 57 (2017) 1266-1270]

PIERRE AUGER OBSERVATORY

Energy above 8 EeV, 5.2 σ after all penalizations from more than 32 000 events





Extragalactic origin!

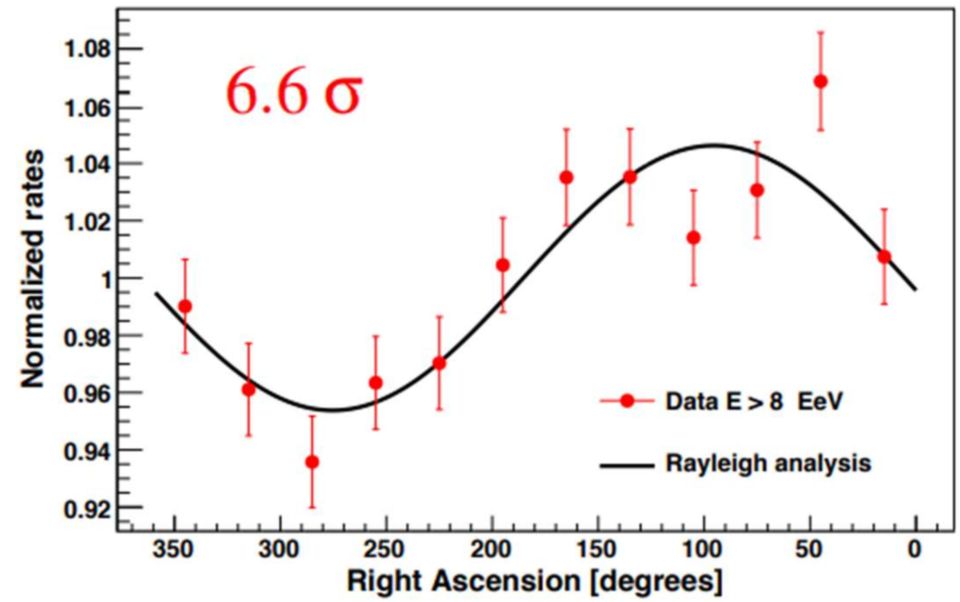
~125° from the Galactic Center

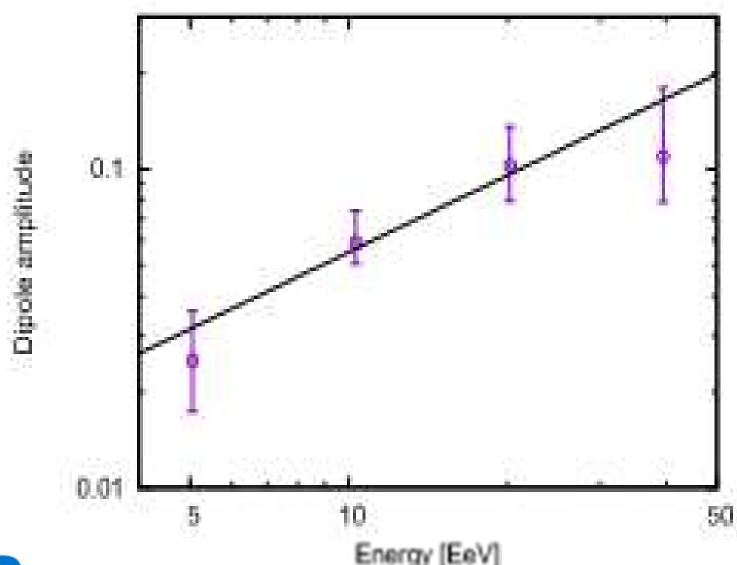
physicsworld TOP 10 BREAKTHROUGH 2017

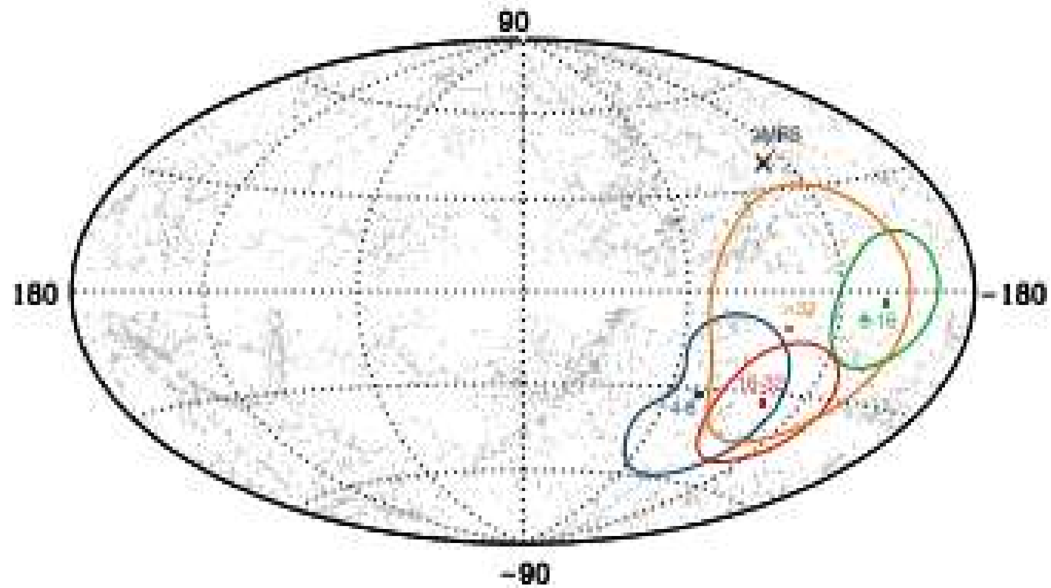
Jakub Vícha

Energy evolution of the anisotropy

Large-scale cosmic-ray anisotropies above 4 EeV measured by the Pierre Auger Observatory
ApJ 868 (2018) 4







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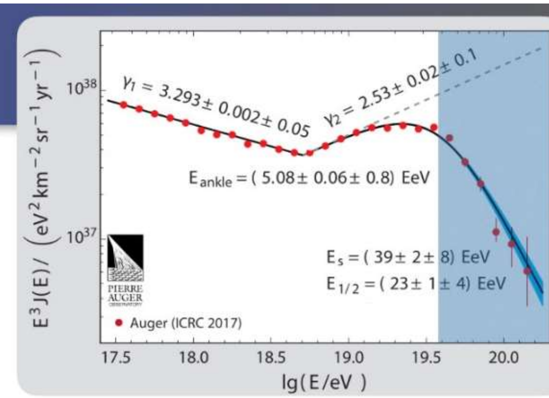
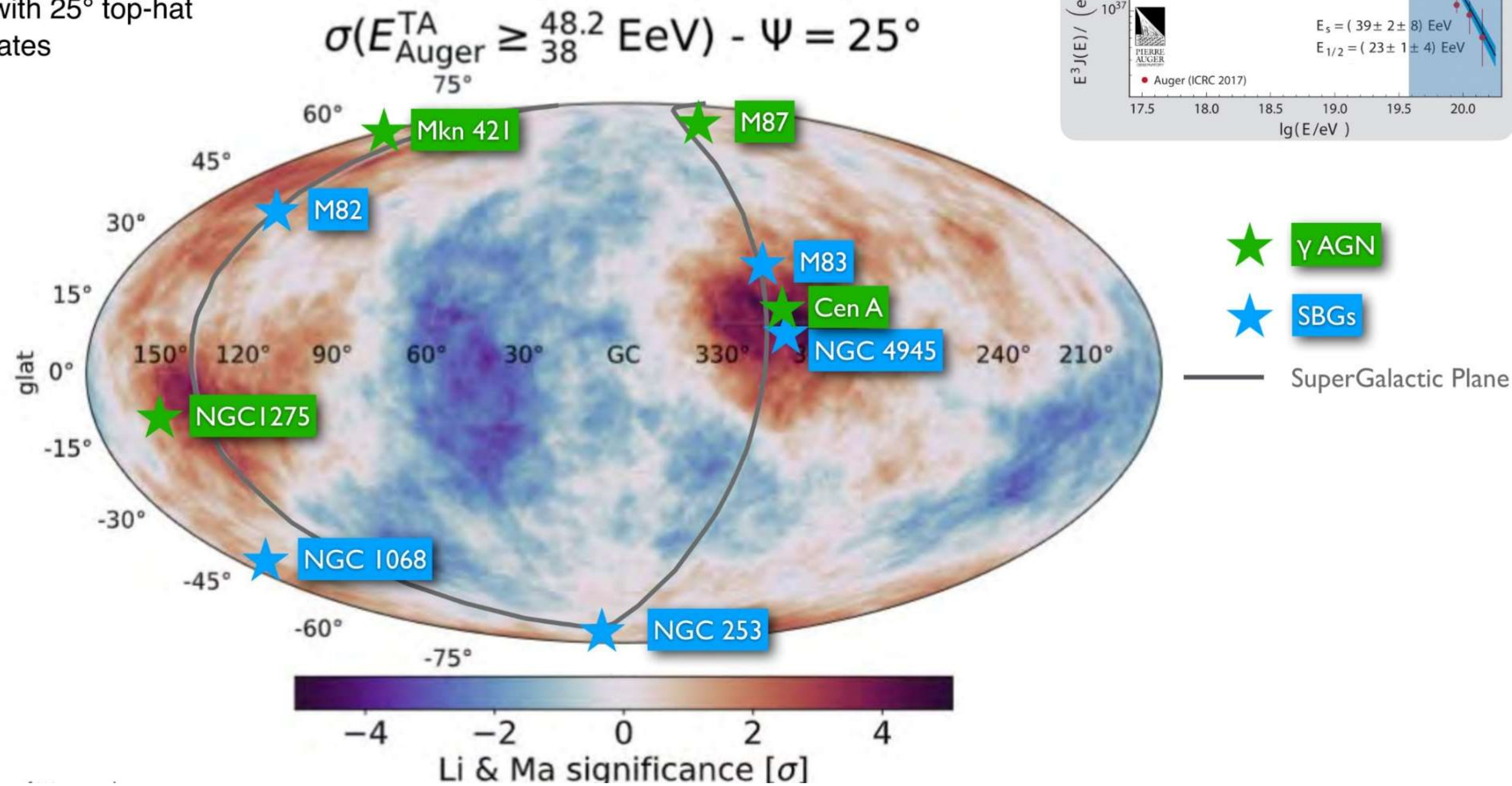
Auger combined with TA: > 38 EeV



Auger Collaboration, PoS(ICRC2023)544

map smoothed with 25° top-hat
Galactic coordinates



K.-H. Kampert, HEACOSS 2024, Oct 2024

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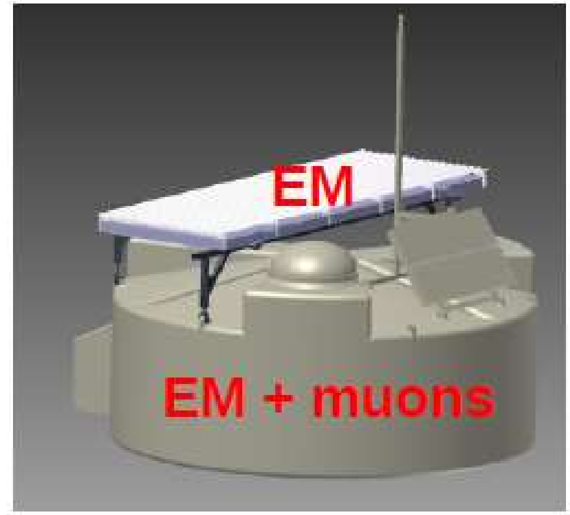
Questions

- What is the origin of the flux suppression?
- What is the proton fraction at the end of E spectrum?
- Is there an energy dependence of anisotropies?
- What about hadronic physics at highest energies?

We need a large-exposure detector with good composition sensitivity!

AugerPrime – Upgrade of the Pierre Auger Observatory, finished November 2024

- Instalation of 1660 **scintillation detectors** (3.8 m^2, 1 cm thick, 3000 km^2)
- Instalation of **new electronics** (40 Mhz → 120 MHz all stations)
- Instalations of small **PMTs** (all stations saturation of SD signal from 500 m to 300 m from the shower core for log(E/eV)>19.5)
- **Cross check** with 61 **muon detectors** (30m^2 2.3m under ground - AMIGA, 750m spacing, 23.4 km^2)
- **Increase of FD exposure** by 50% at the highest energies decreasing HV on PMT
- Installation of 1660 **radio antennas** to improve detection of inclined showers



Pierre Auger Observatory 2018

- AUGERPrime – upgrade of the Observatory

- 30 SSDs in the field

R&D and Pierre Auger Observatory 2018

- FAST – simplified (future) FD
- telescope at TA in Utah since Oct. 2018
- FAST telescope at Pierre Auger Observatory since 2019, further three to come in 2025