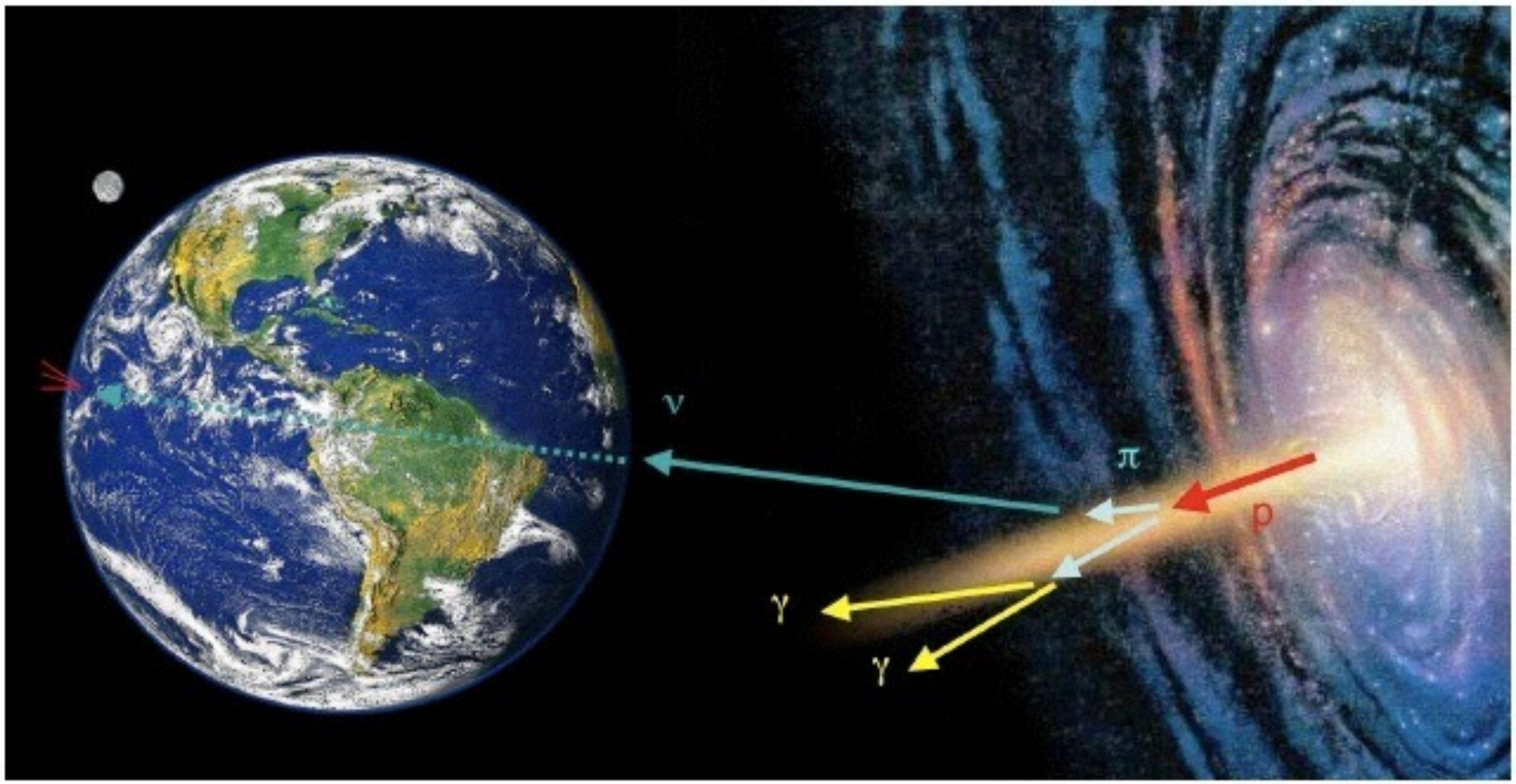
Teilchenphysik mit kosmischen und mit erdgebundenen Beschleunigern



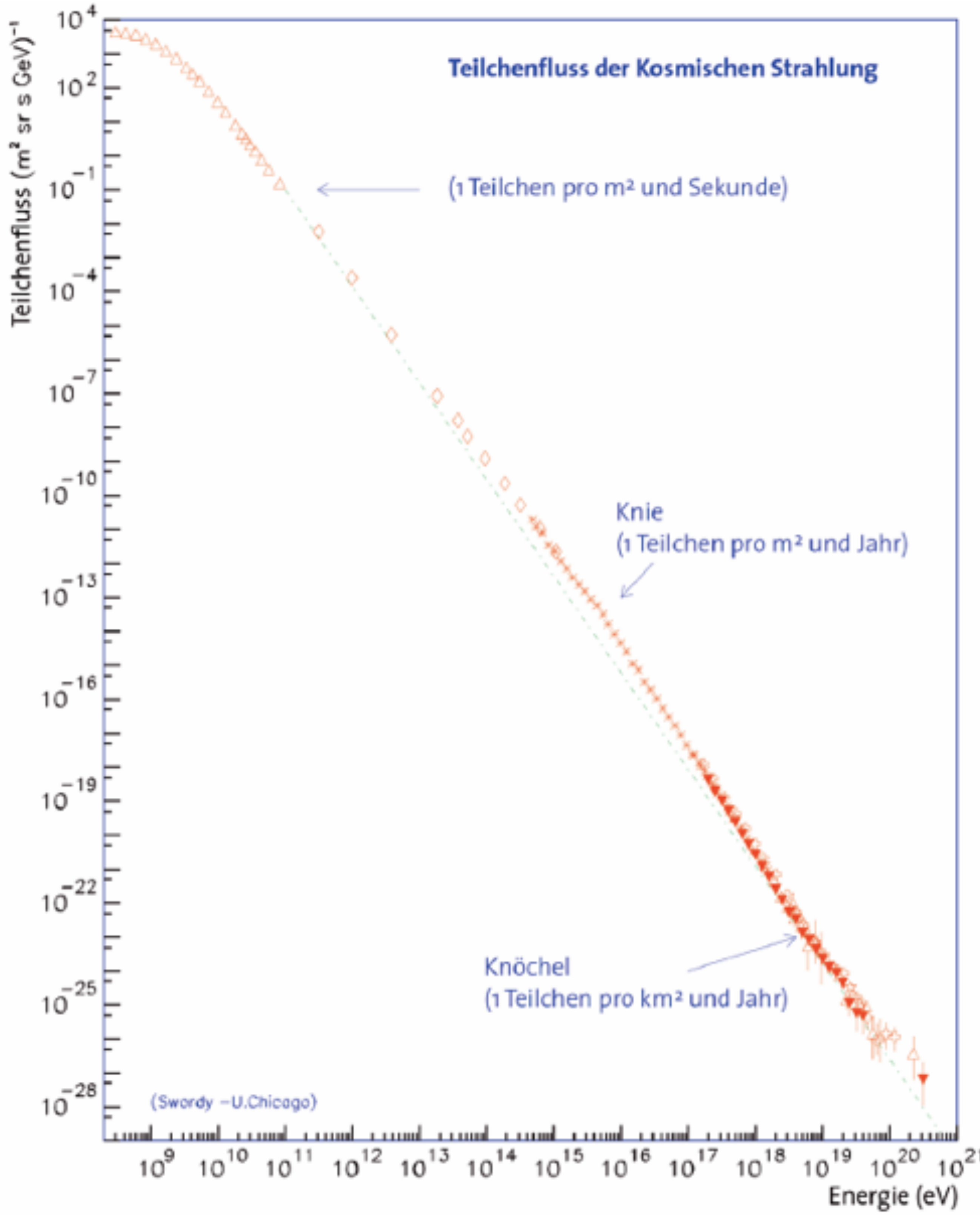
09. Cosmic Rays I

13.06.2016

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Prof. Dr. Siegfried Bethke
Dr. Frank Simon

Cosmic Rays: Spectrum



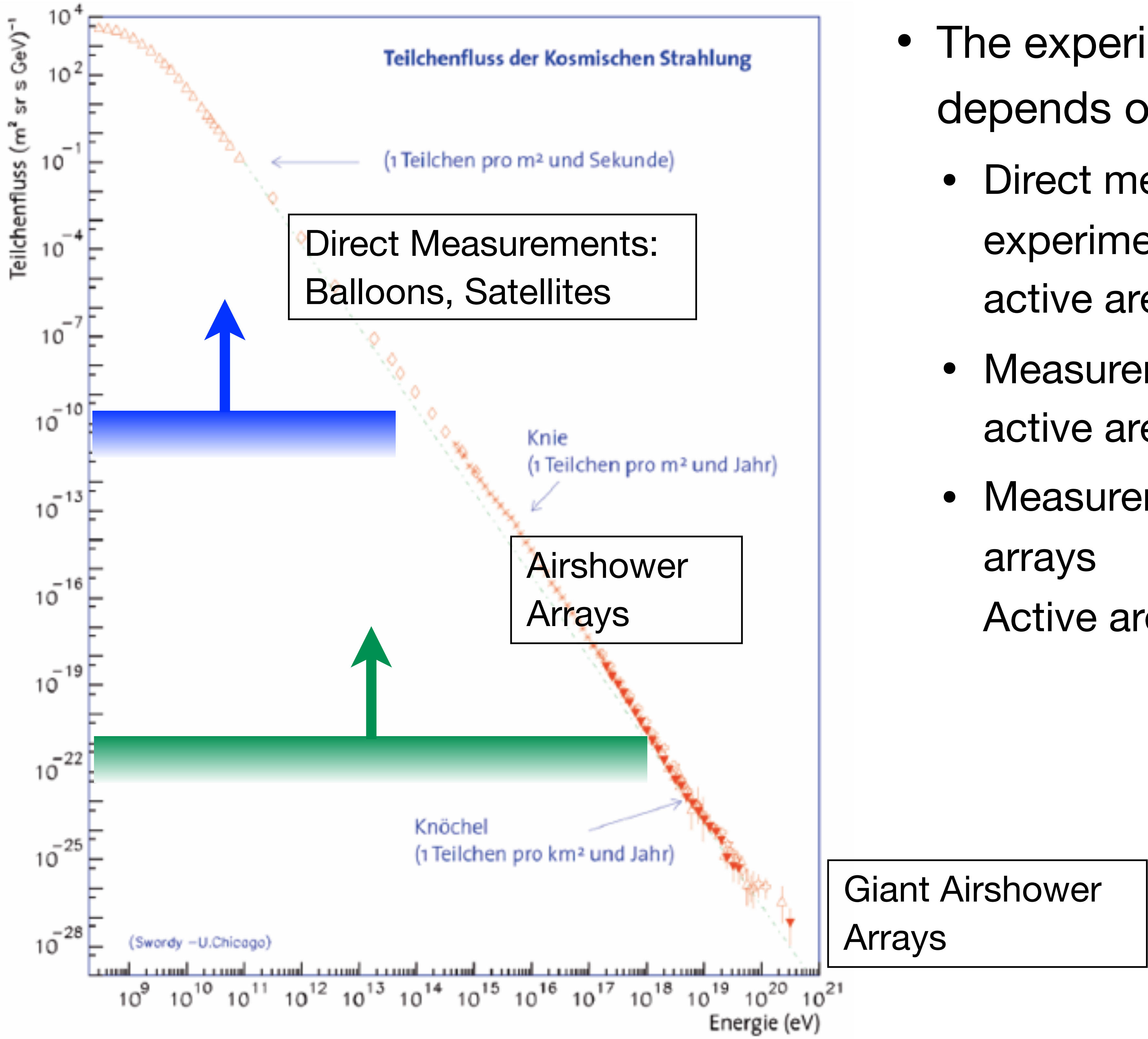
- Extends over many orders of magnitude in energy and flux:
  - GeV (10^9 eV) - ZeV (10^{21})
  - >1 $cm^{-2}s^{-1}$ - < 1 km^{-2} per century

- Follows a power law:

$$\frac{dN}{dE} \propto E^{-\gamma}$$

- $\gamma \sim 2.7$ $E < 10^{15}$ eV
- $\gamma \sim 3.0$ 10^{15} eV < $E < 10^{18}$ eV
- $\gamma \sim 2.7$ 10^{18} eV < E

Cosmic Rays: Spectrum & Experiments



- The experimental technique used depends on particle energy and flux
  - Direct measurement via balloon experiments and satellites, active area ~ 1 m^2
  - Measurement with airshower arrays active area ~ 10 000 m^2
  - Measurement with giant airshower arrays Active area ~ 1000 km^2

Air Showers: The Atmosphere as Calorimeter

- Nuclear interaction length λ_I ~ 90 g/cm^2
- Radiation length X_0 ~ 36.6 g/cm^2
- Density of the atmosphere: ~ 1035 g/cm^2

▸ ~ 11 λ_I, ~ 28 X_0

Reminder:

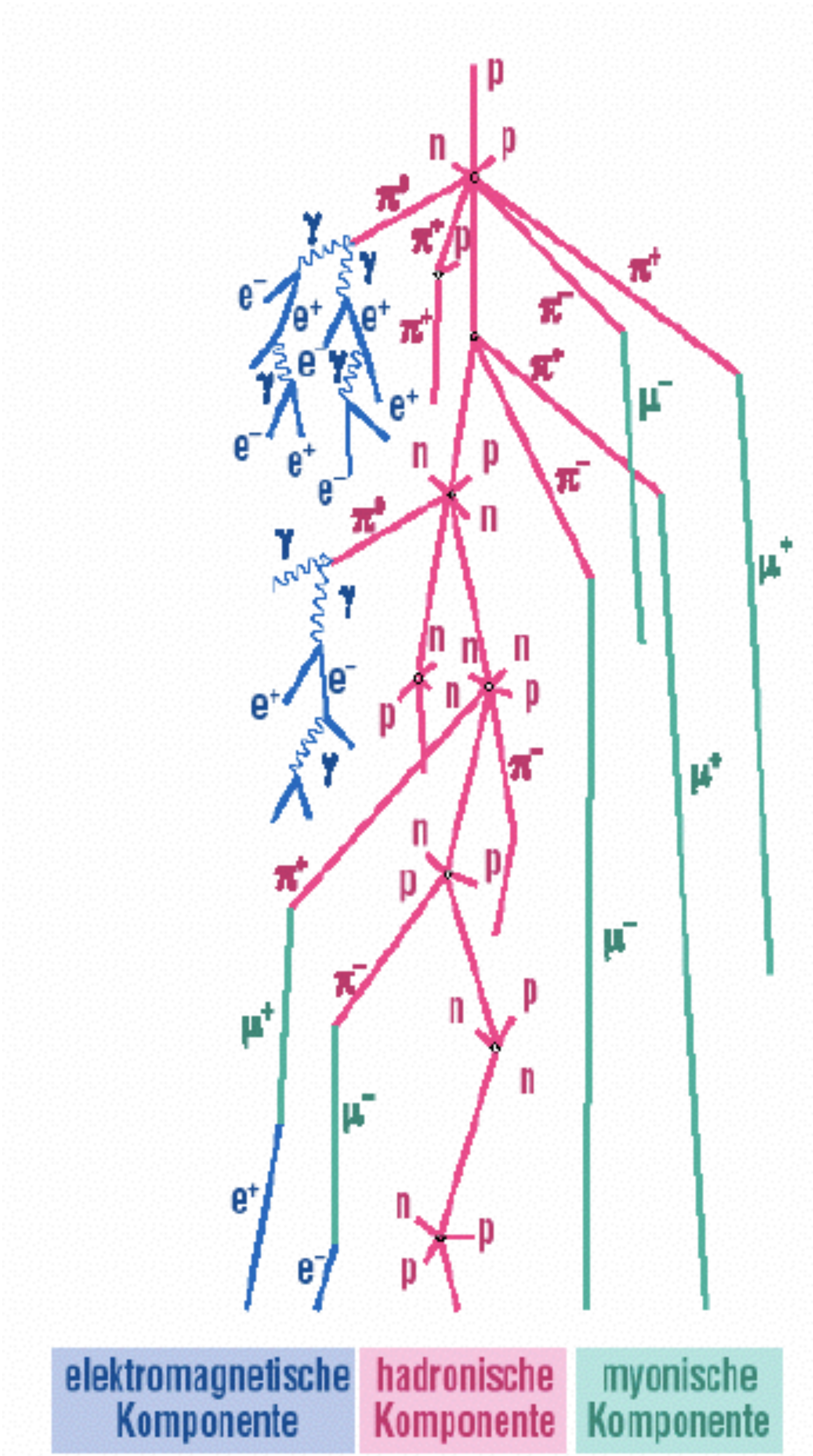
Radiation length: Energy loss of electrons in matter:

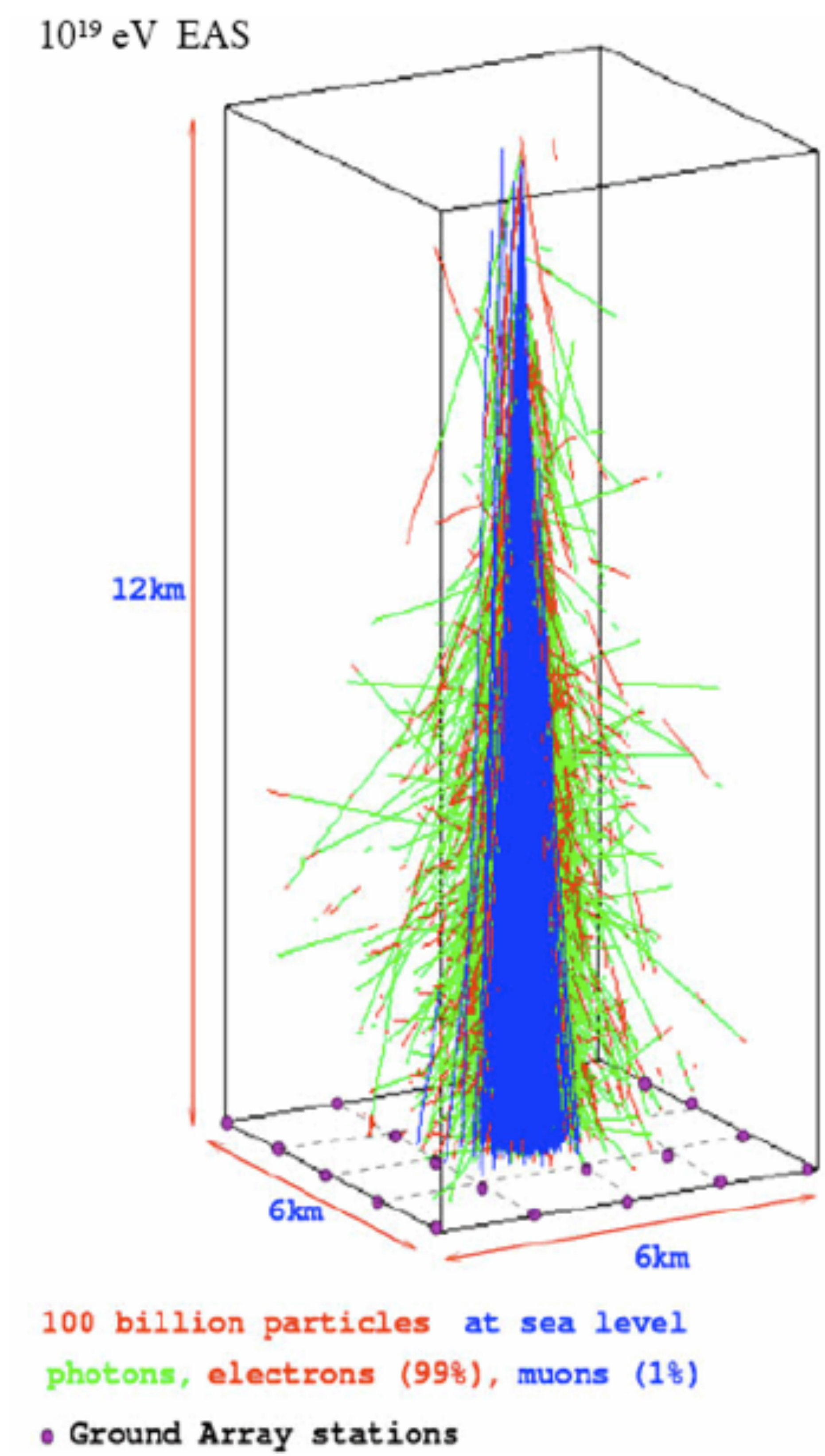
$$\langle E_e(x) \rangle \propto e^{\frac{x}{X_0}}$$

Nuklear interaction length: Typical mean free path between nuclear reactions, Probability that no interaction is taking place:

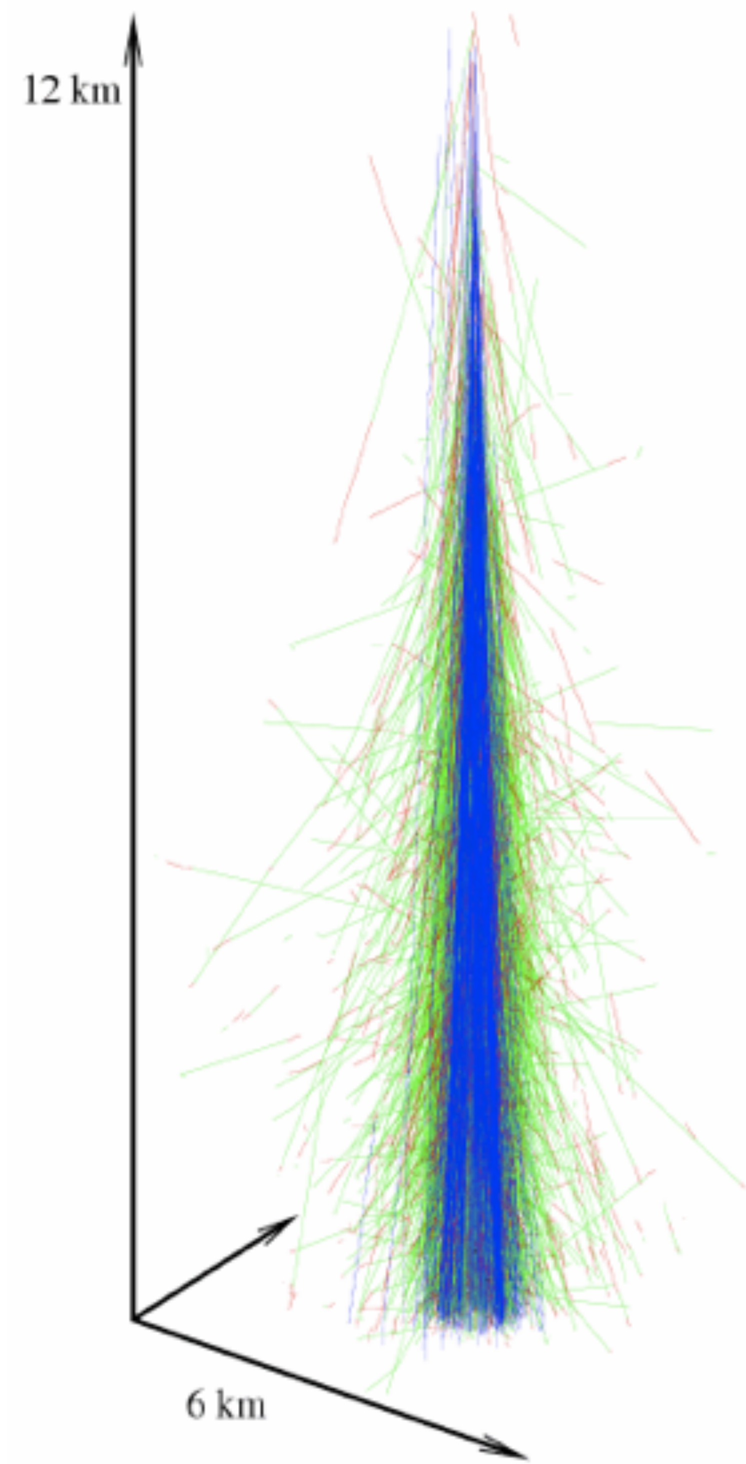
$$P(x) = e^{\frac{-x}{\lambda_I}}$$

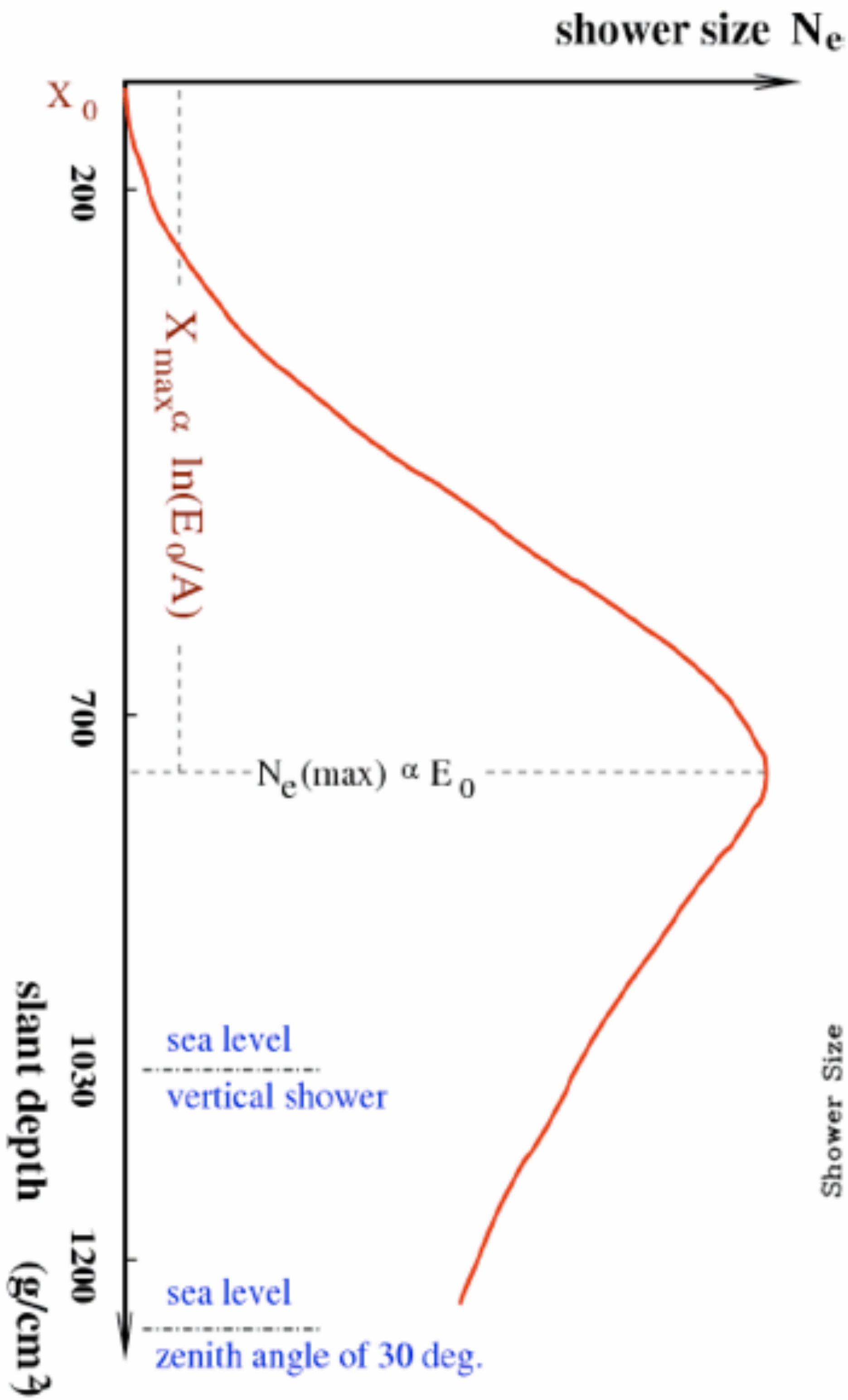
Extended Air Showers (EAS)



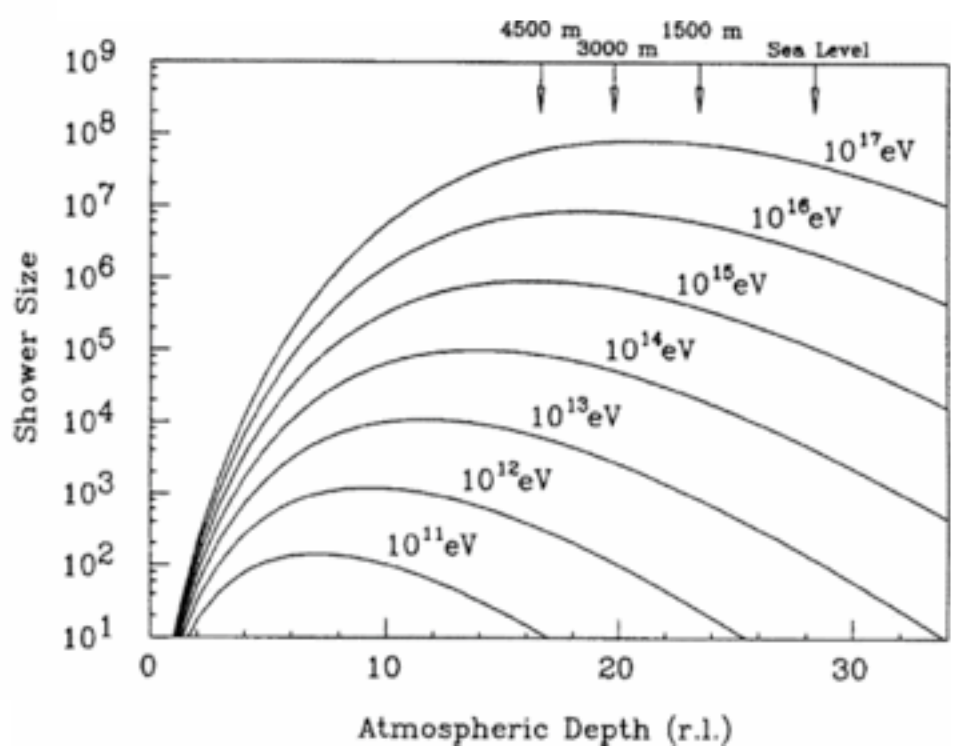


EAS: In the Atmosphere





- Mainly electromagnetic: photons, electrons
- Shower maximum: ~ $\ln(E_0/A)$



R.Engel, ISAPP2005

EAS: Hadronic Component

- Inelastic reactions of the incoming hadron (proton, nucleus) with nuclei in the atmosphere after ~ 1 λ_I, typically energy loss of 40%-60%, production of secondary hadrons: p, n, π^0, $\pi^\pm$, $K^\pm$, ...

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  - electromagnetic shower

- Charged pions: $\pi^\pm \rightarrow \mu^\pm \nu_\mu, \ \tau \sim 2.6 \times 10^{-8} s \ (c\tau \sim 8\,m)$
  - Hadronic interaction before decay, or decay into muon + neutrino (at energies of ~ 10 - 20 GeV the range is ~ 1 λ_I)
  - Muonic component is integrating: Muon decay irrelevant on shower time scale, lifetime ~ 2 x 10^{-6} s
  - The production of additional hadrons dominates early in the shower, towards the end decay into muons is more probable

EAS: Electromagnetic Component

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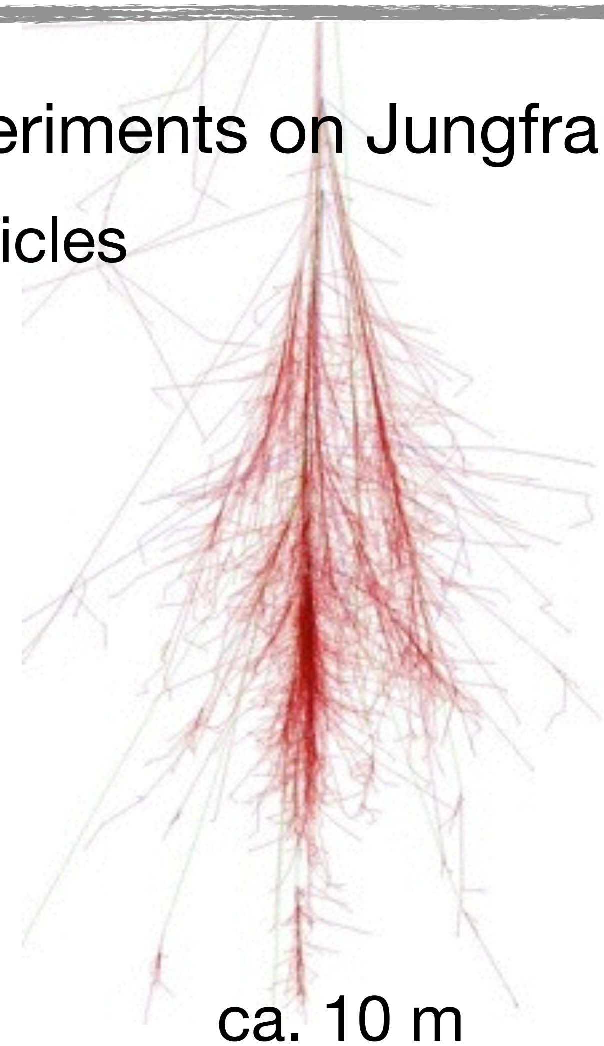
- Continuation of the cascade until

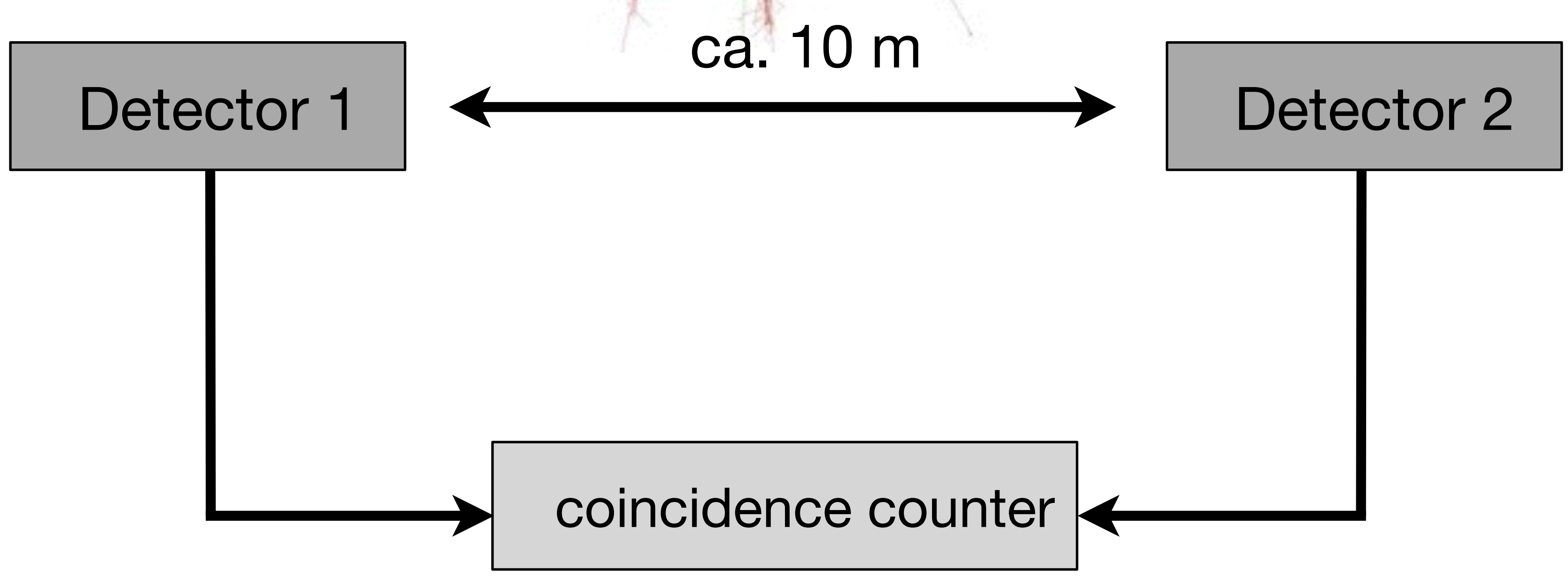
$$\left(\frac{dE}{dx}\right)_{ion} > \left(\frac{dE}{dx}\right)_{brems}$$

- Highest particle number in the shower maximum, reduction afterwards

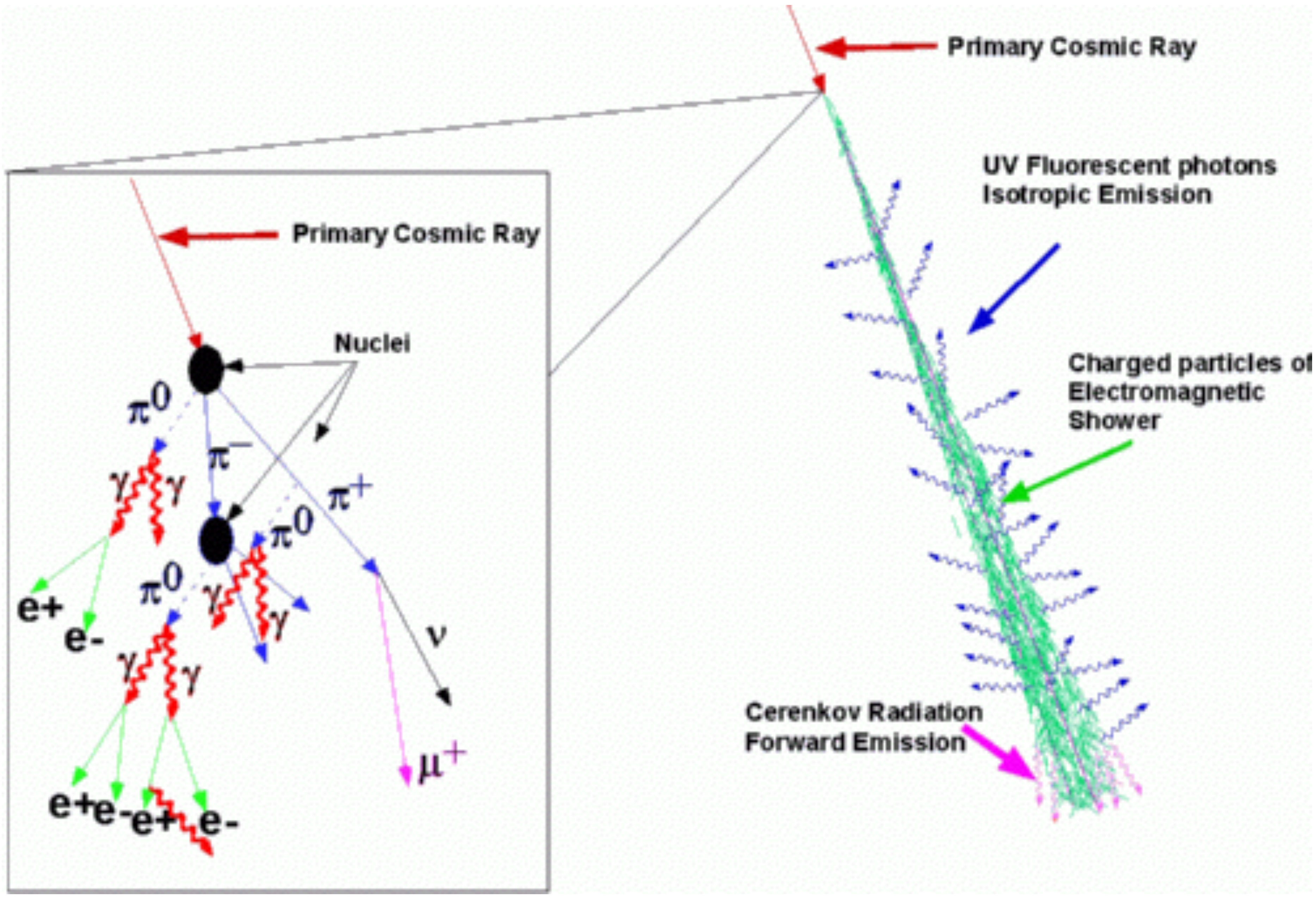
Extended Air Showers: Discovery

- Pierre Auger, 1935 with experiments on Jungfraujoch
  - Detection of coincident particles over large areas
  - ‣ Highly energetic primary particle!





EAS: Measurement

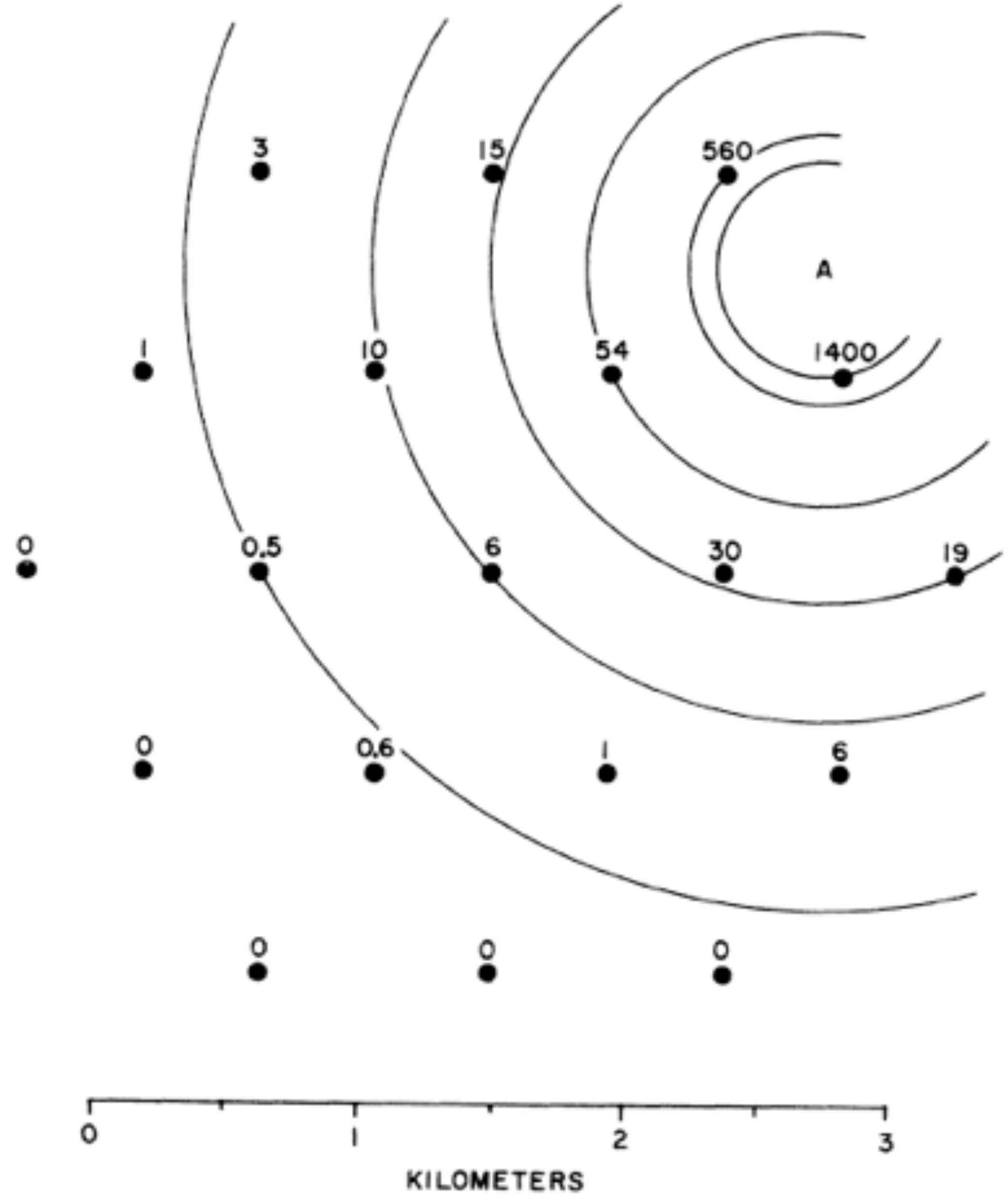


- Detection of charged particles on the surface in “ground arrays”
- Measurement of flourescence light
- Measurement of Cherenkov light

Ultra-High Energy Cosmic Rays: Discovery

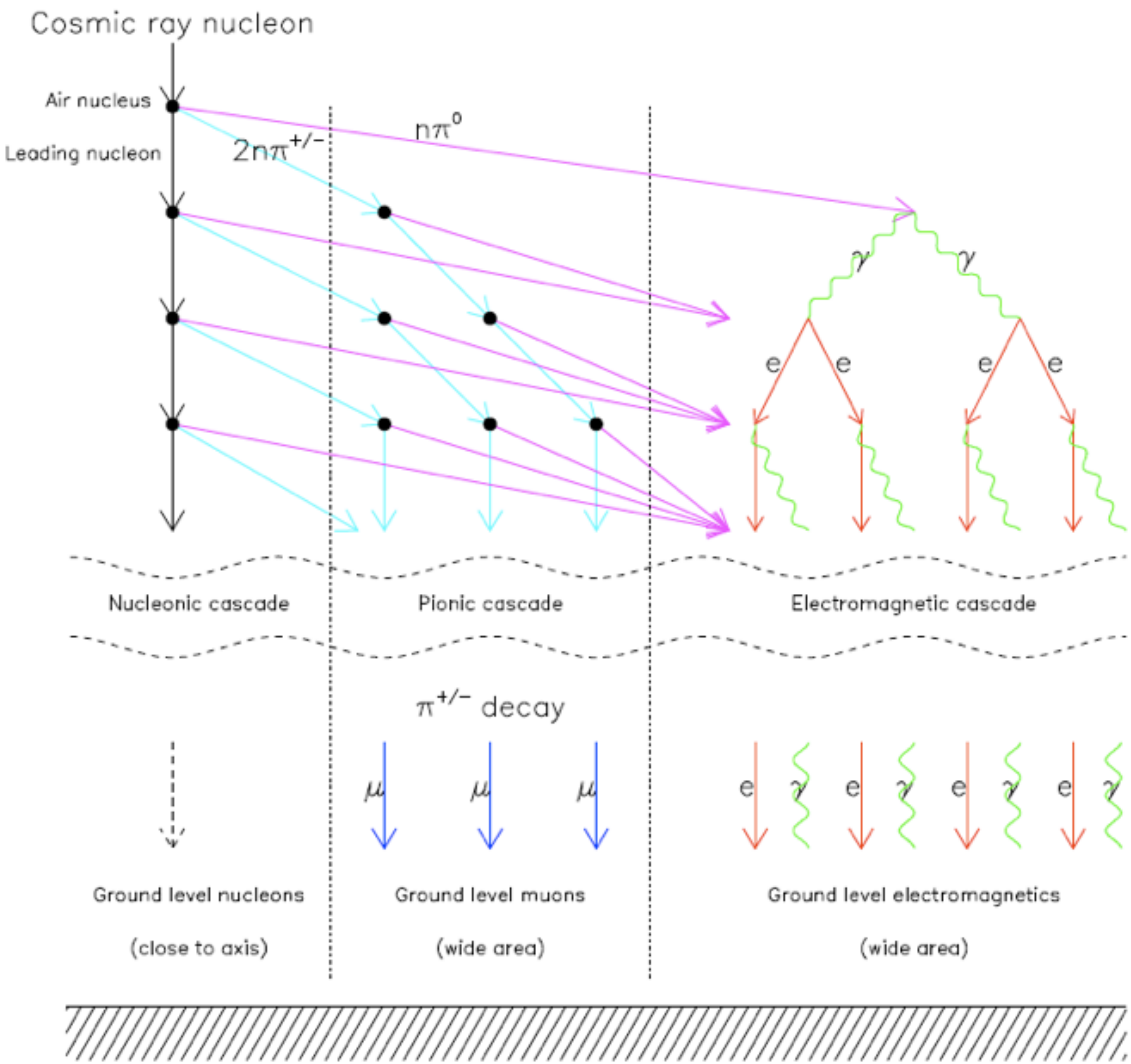
- John Linsley et. al, 1962, MIT Volcano Ranch Array, NM, USA
- ~8 km^2, 19 Detectors a 3.3 m^2 (Scintillation Counters)
- Determination of primary energy based on shower size (Number of particles) on ground

- Primary energy determined to be **10^{20} eV**



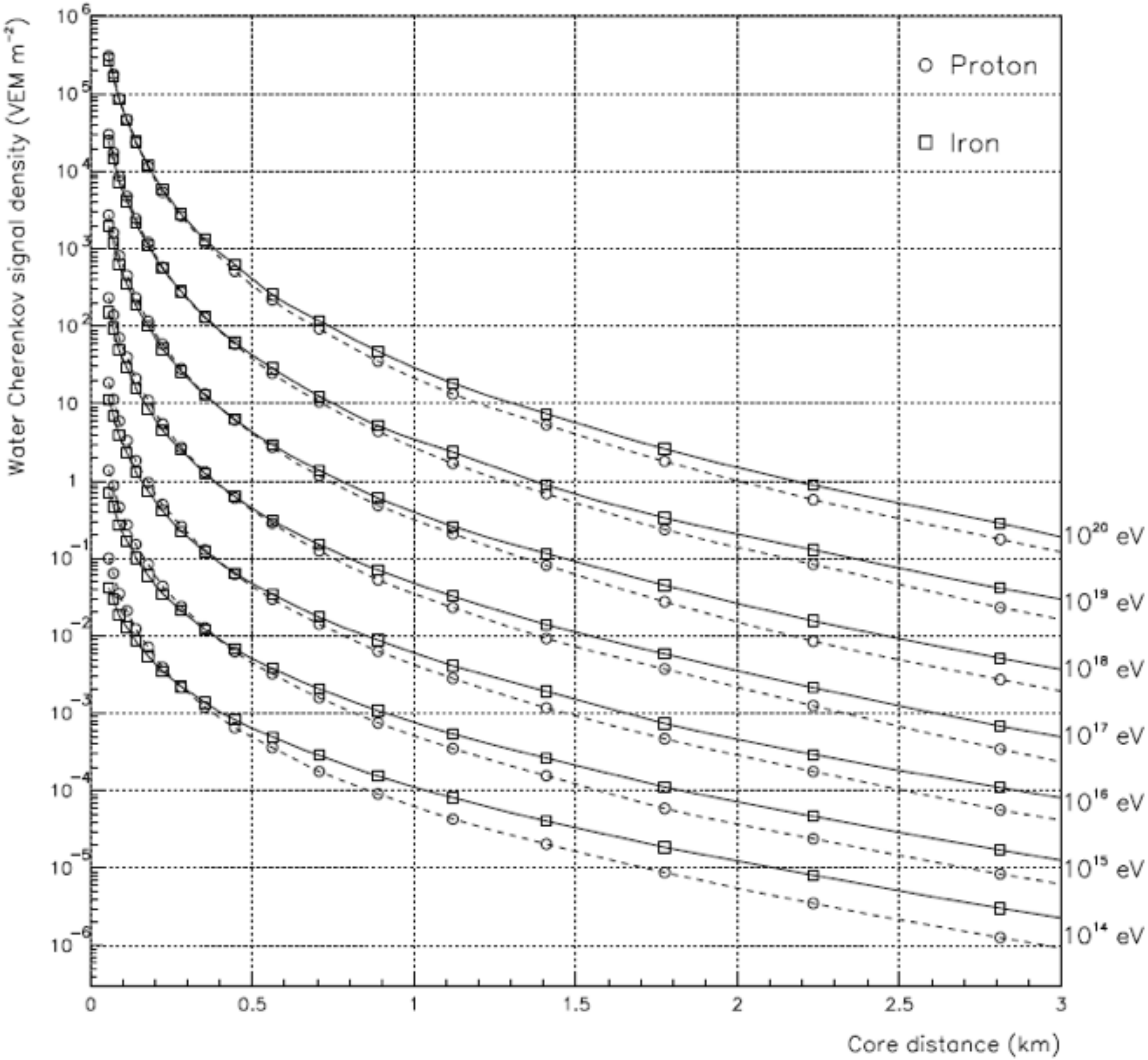
Phys. Rev. Lett. 10, 146 (1963)

Extended Air Showers



AUGER TDR

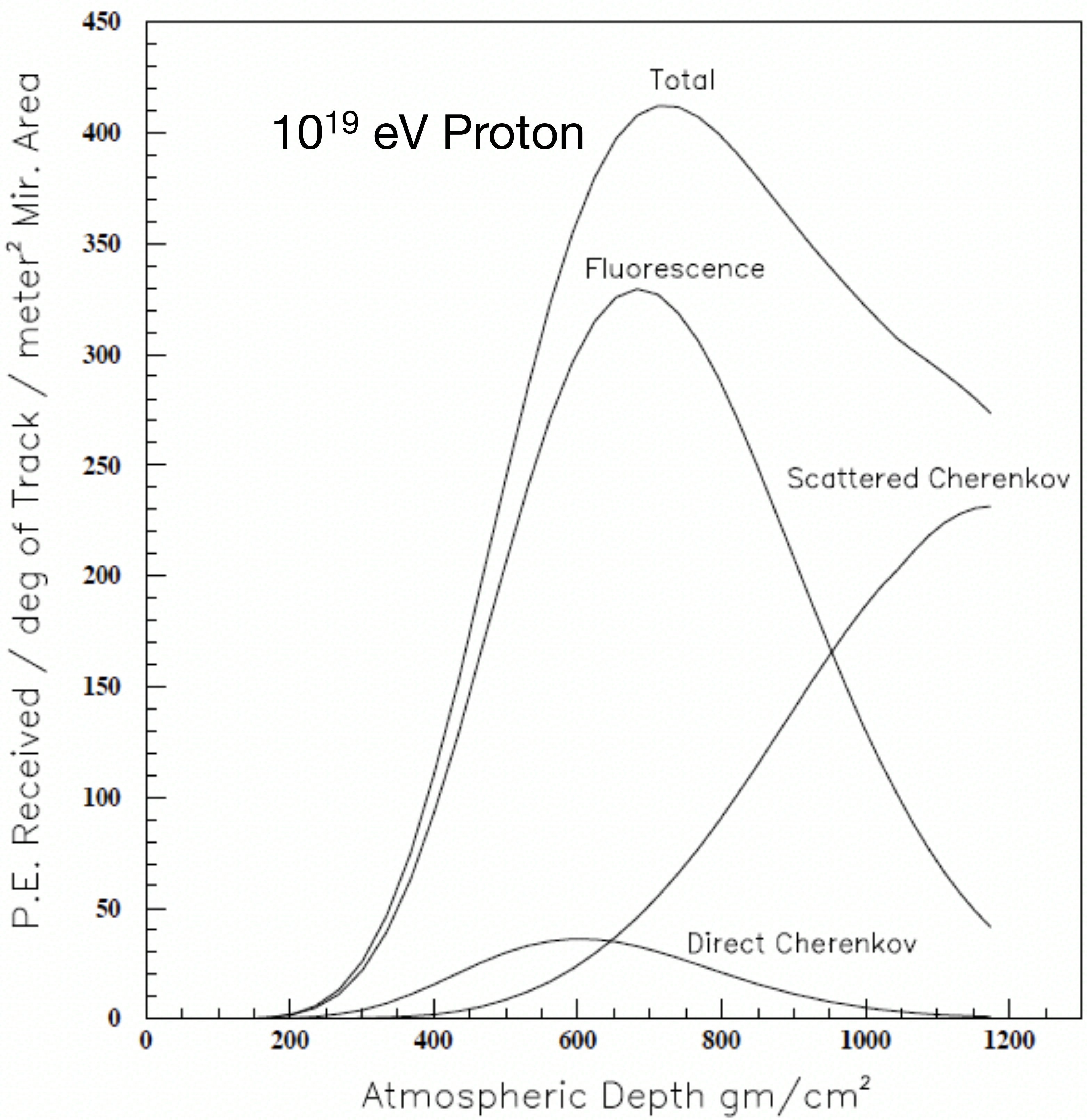
Shower Multiplicity and Energy



- Particle density on ground at different distances from the shower core is a good measure for the total energy

AUGER TDR

EAS: Light Measurement



- Detection of fluorescence and Cherenkov light used to measure energy
- Also serves to reconstruct details of the shower development in the atmosphere!

AUGER TDR

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- First and foremost: What type of objects are capable to generate such high energies?

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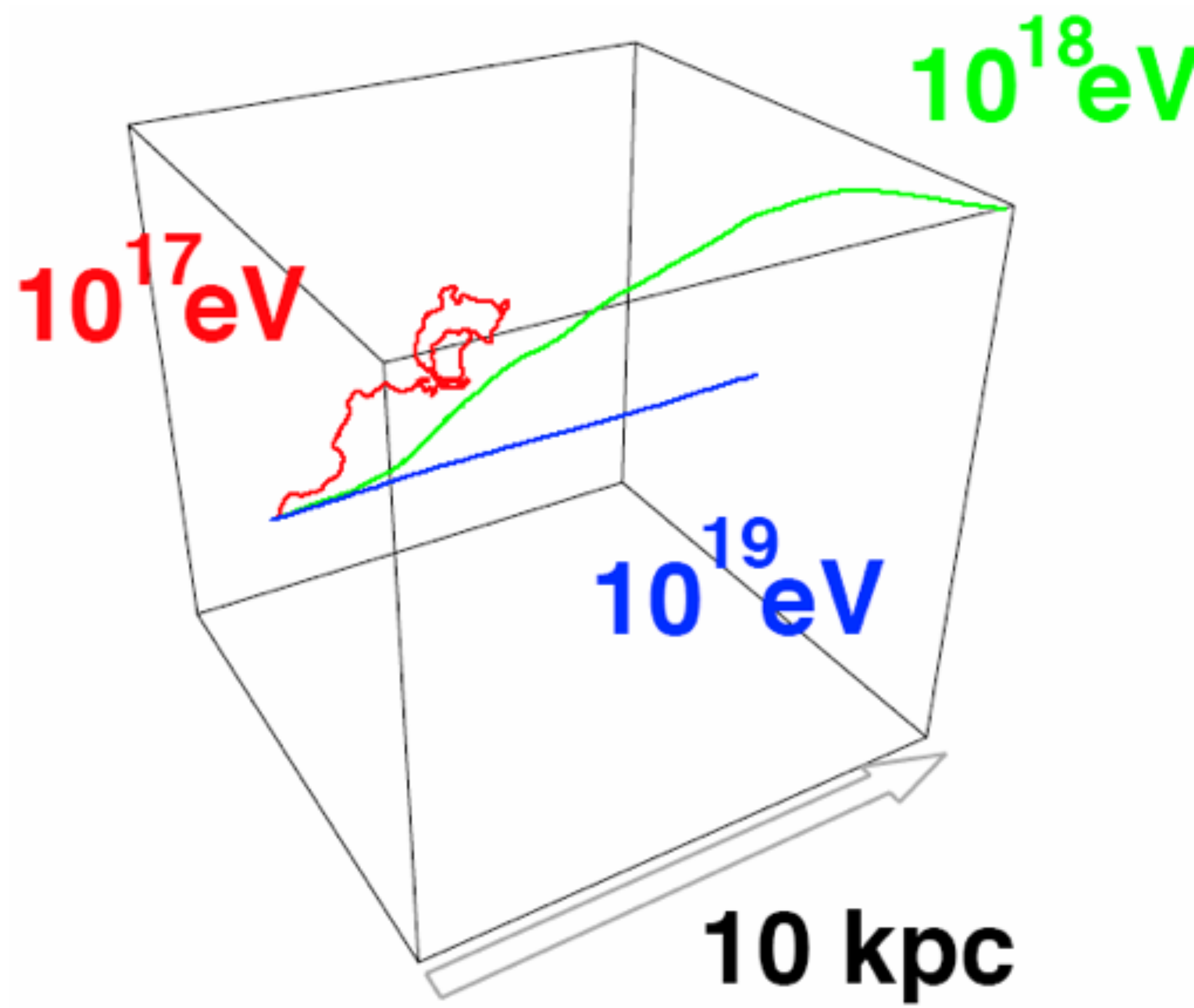

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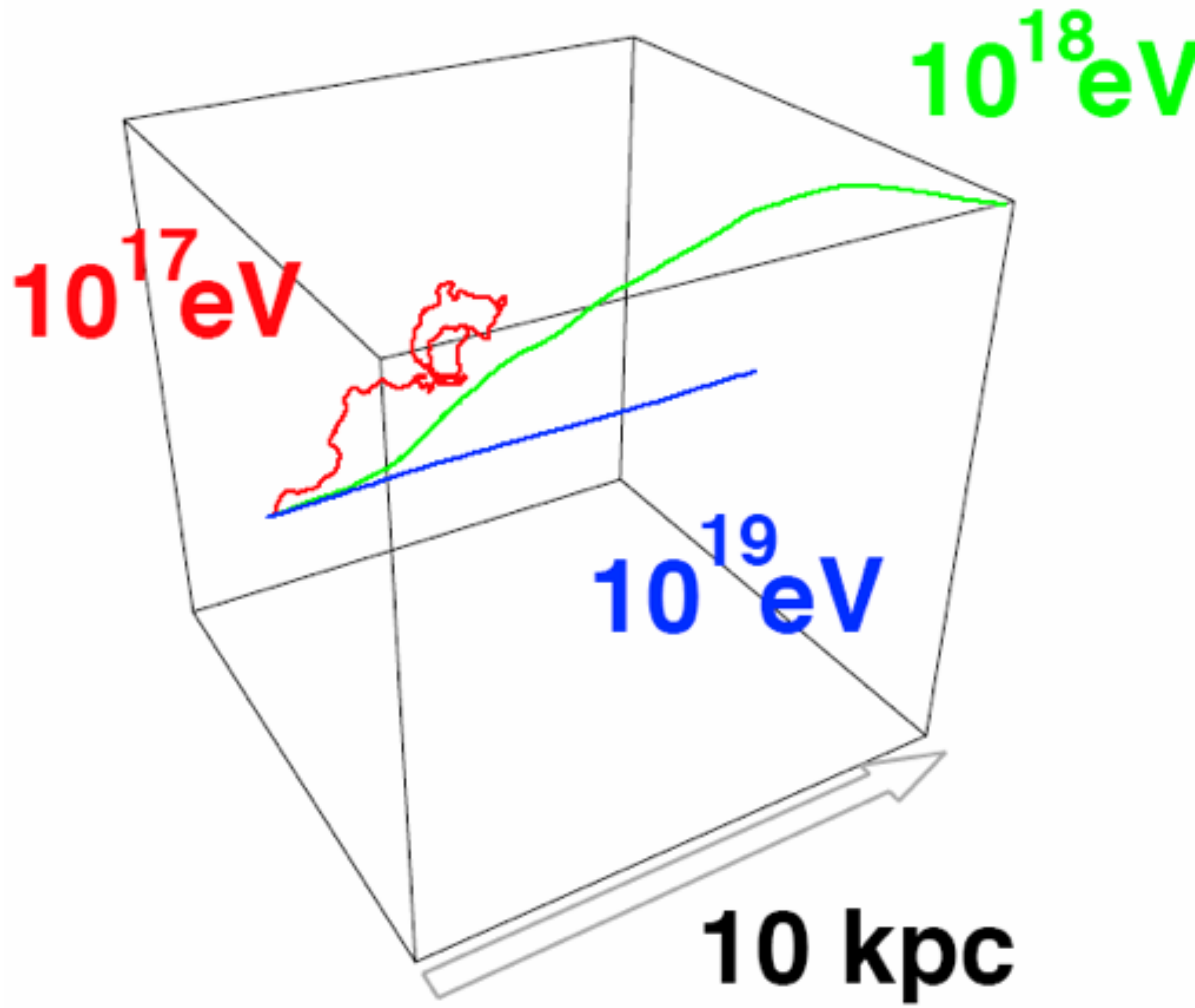
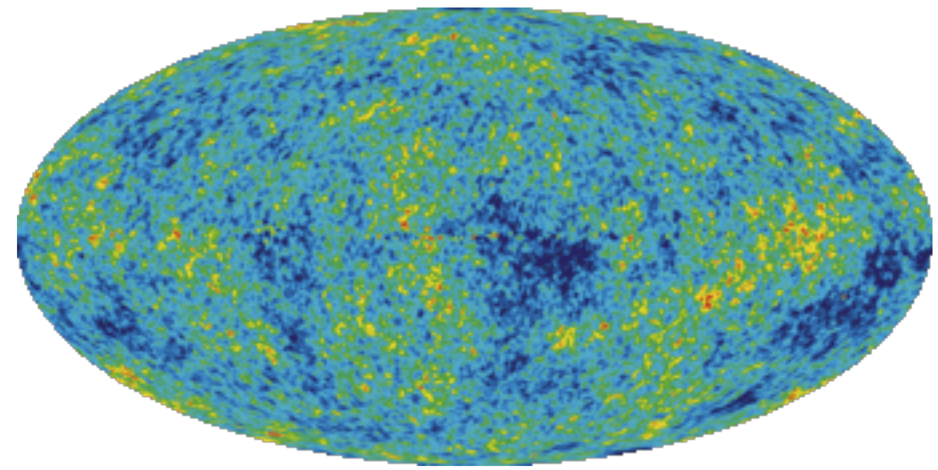


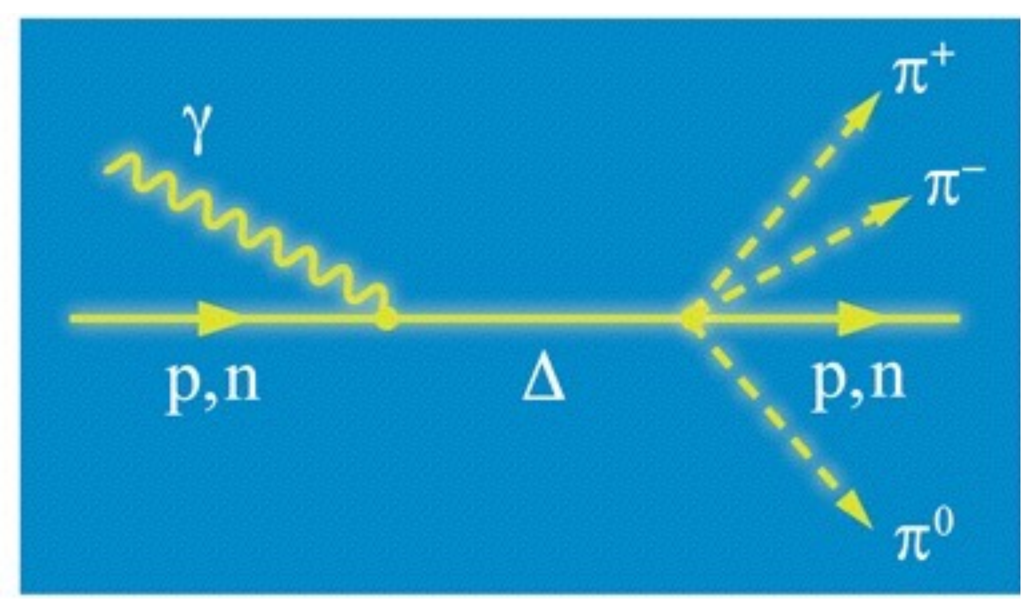
➯ The beginning of "particle astronomy" ?

Cosmic Speed Limit?



- Greisen - Zatsepin - Kuzmin Cutoff (1966):
  - Interaction of cosmic particles with photons of the CMB
  - Mean free path between two collisions: ~ 50 Mpc
  - At (very) high energies: Possibility for pion production:

$$p + \gamma \ \rightarrow \ p + \pi^0, \ n + \pi^+$$



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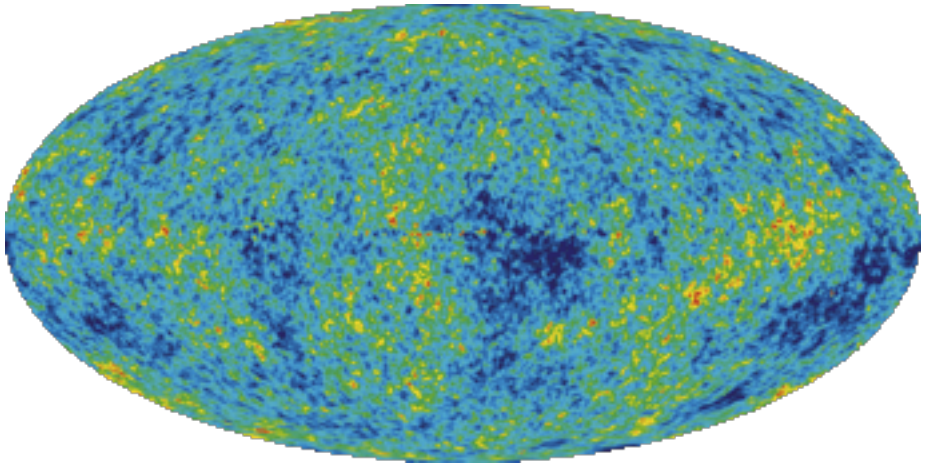

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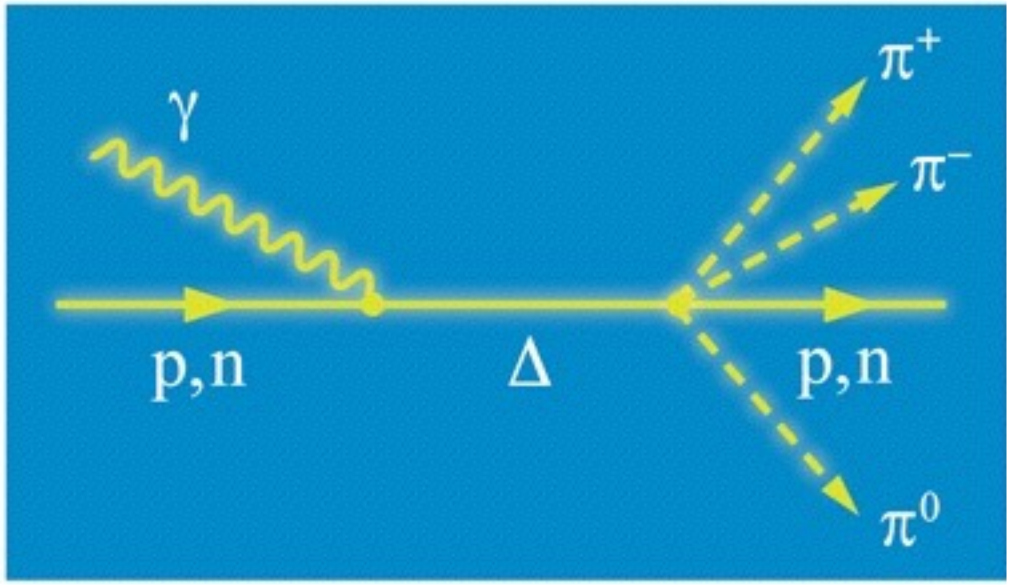
Center-of-mass energy of the reaction

$$\sqrt{s} = \sqrt{m_p^2 + 2E_pE_\gamma(1 - cos\alpha)}$$



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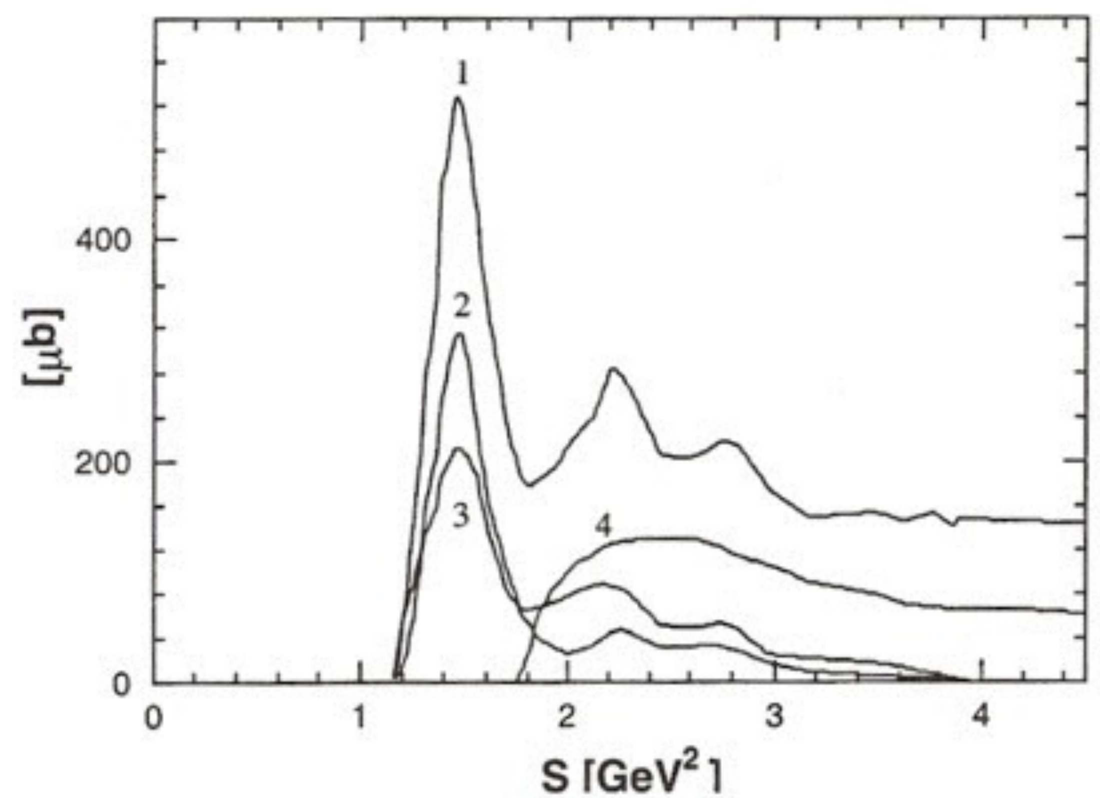

FIG. 3.2: Cross sections for photopion production [9]. **1** denotes the summation of all channels, **2** $\gamma p \rightarrow p\pi^0$, **3** $\gamma p \rightarrow n\pi^+$, and **4** $\gamma p \rightarrow p +$ *double pion*.

S. Yoshida, "Ultra-High Energy Particle Astrophysics"

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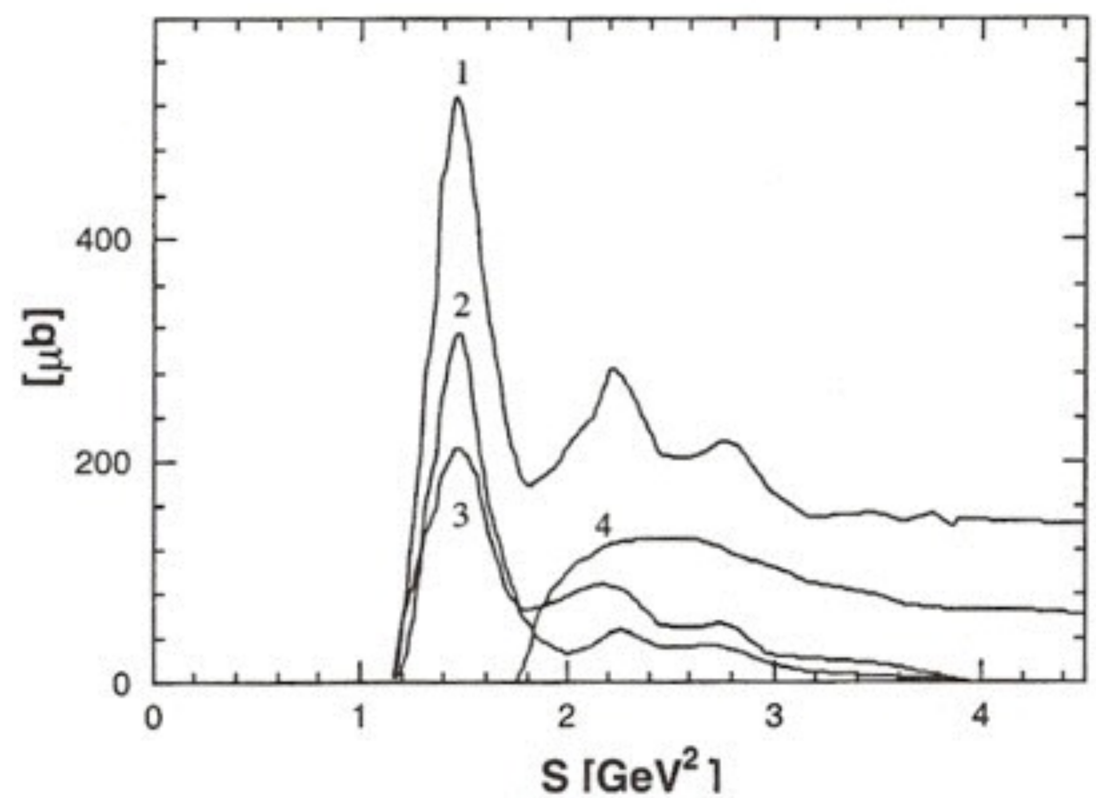
- Cosmic Microwave Background: black body with 2.7 K, ~ 2.3 x 10^{-4} eV
  - Photons up to ~ 10^{-3} eV
- Cosmic "speed limit" at **~ 7 x10^{19} eV**



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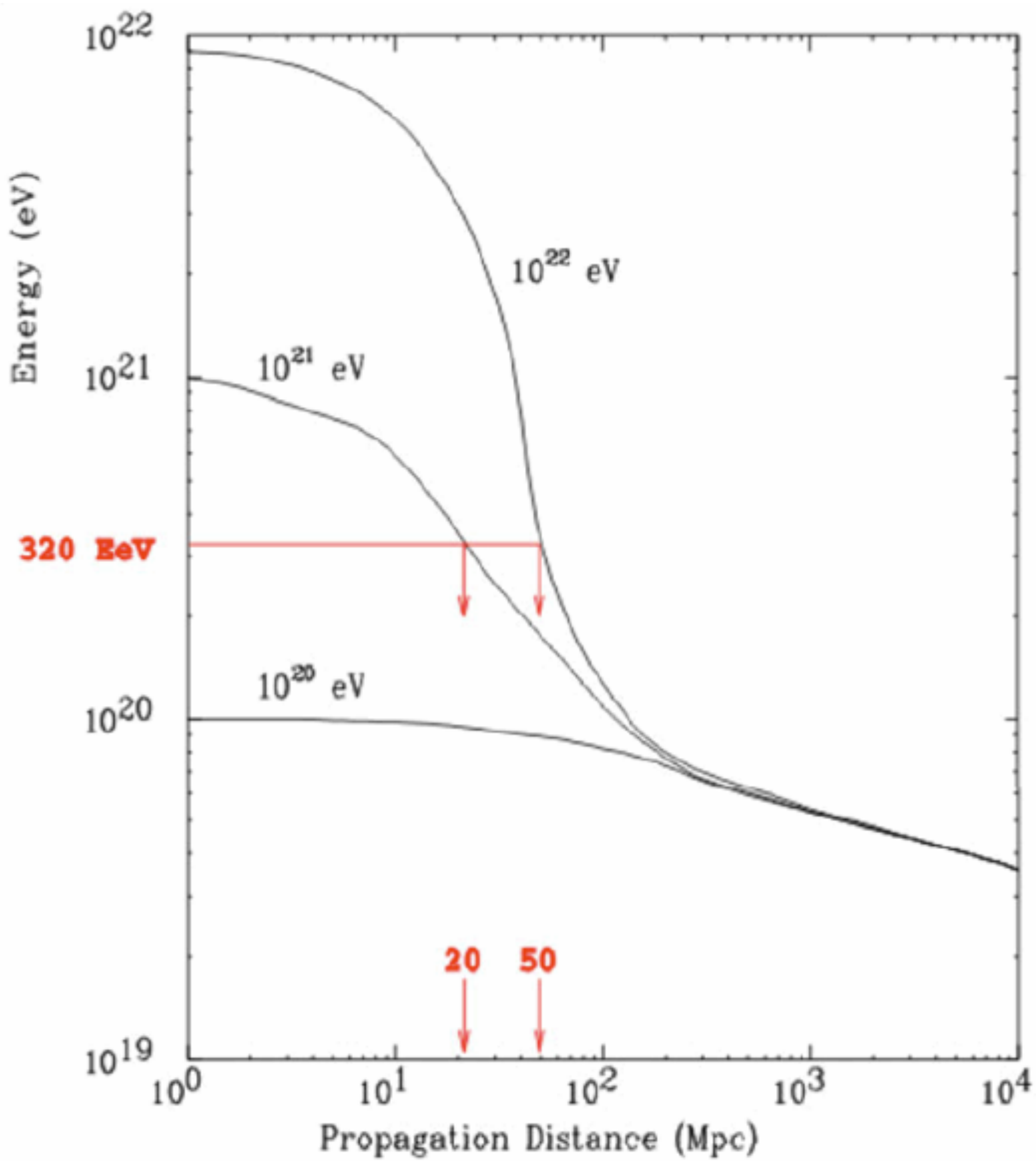
Energy Evolution due to GZK Effect



- Highly energetic particles rapidly loose energy through photo-pion production:
  - Per interaction ~ 30% of the total energy are lost
- Range of particles with energies above ~10^{20} eV is limited to < 100 Mpc

GZK on Nuclei, and other Processes

- The GZK cutoff should be even more dramatic for nuclei than for protons: photo disintegration!

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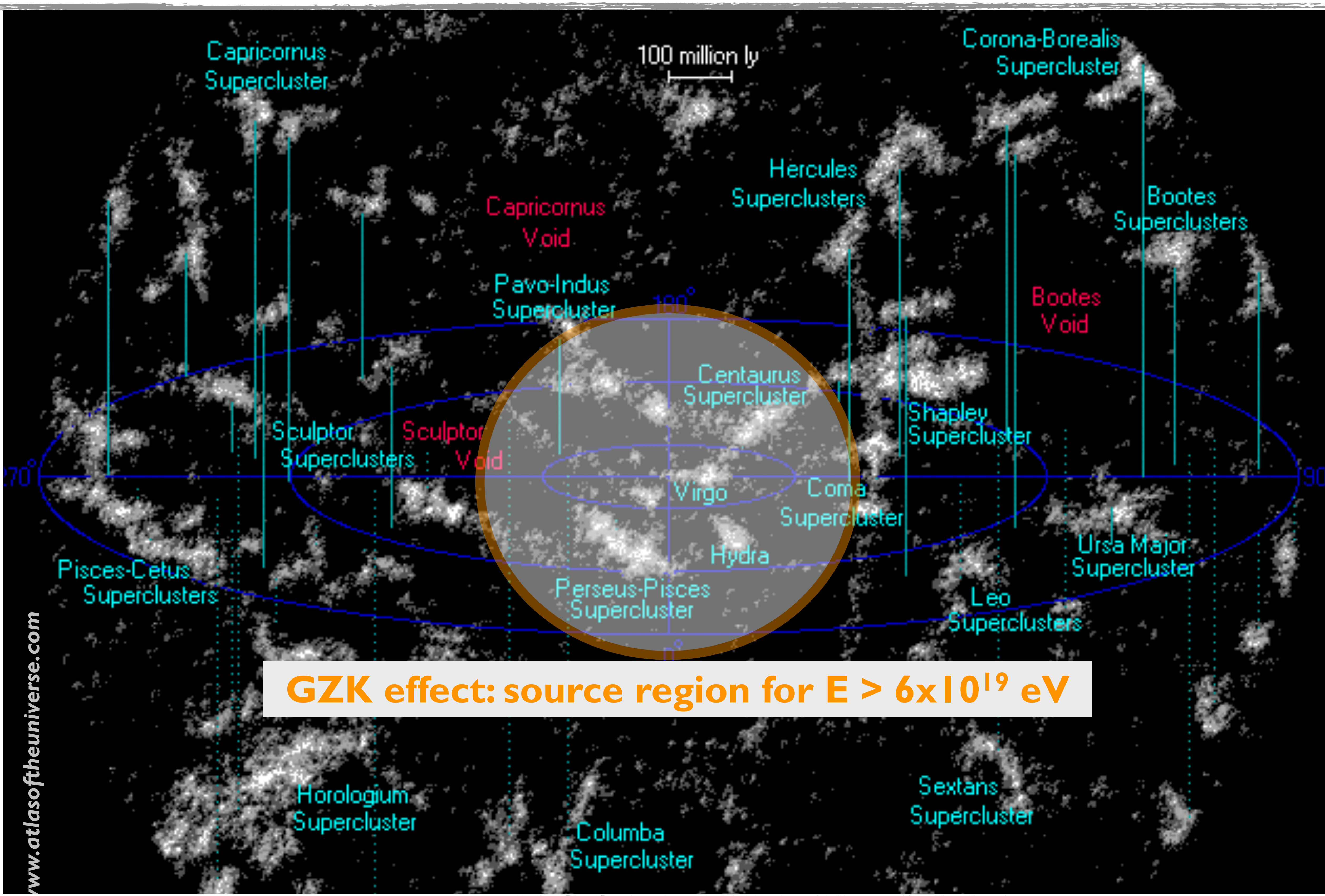
But: Typically only small energy loss: $2m_e/m_p \sim 10^{-3}$, at high energies even lower. For comparison: GZK events result in an energy loss of 30% or more!

➪ Only small effect on spectrum

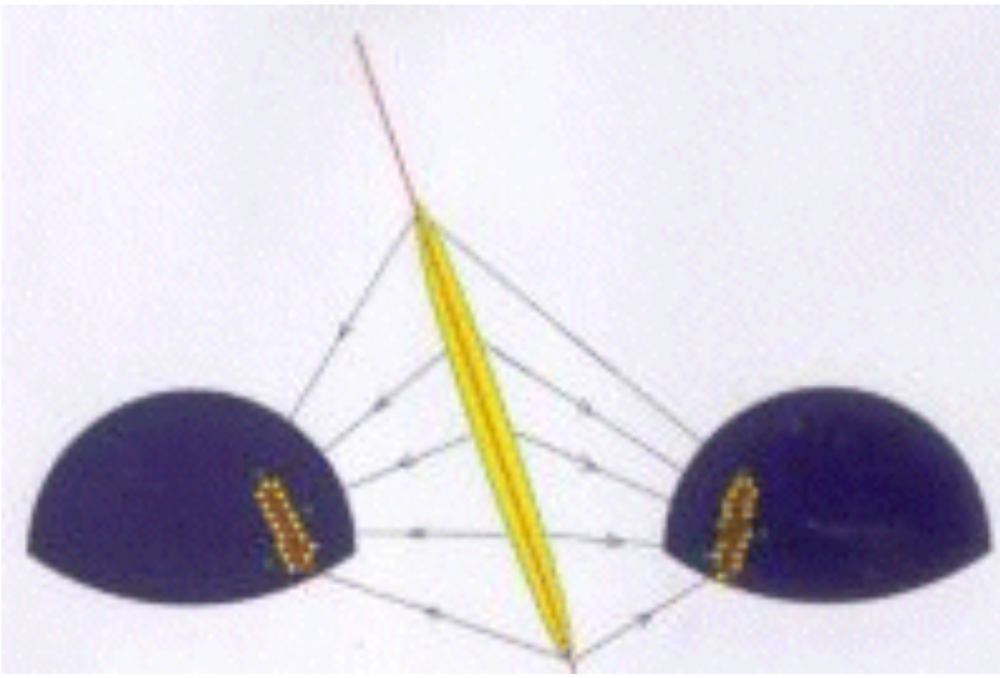
GZK Effect: Limited Source Region: ~ 75 Mpc



Fly's Eye

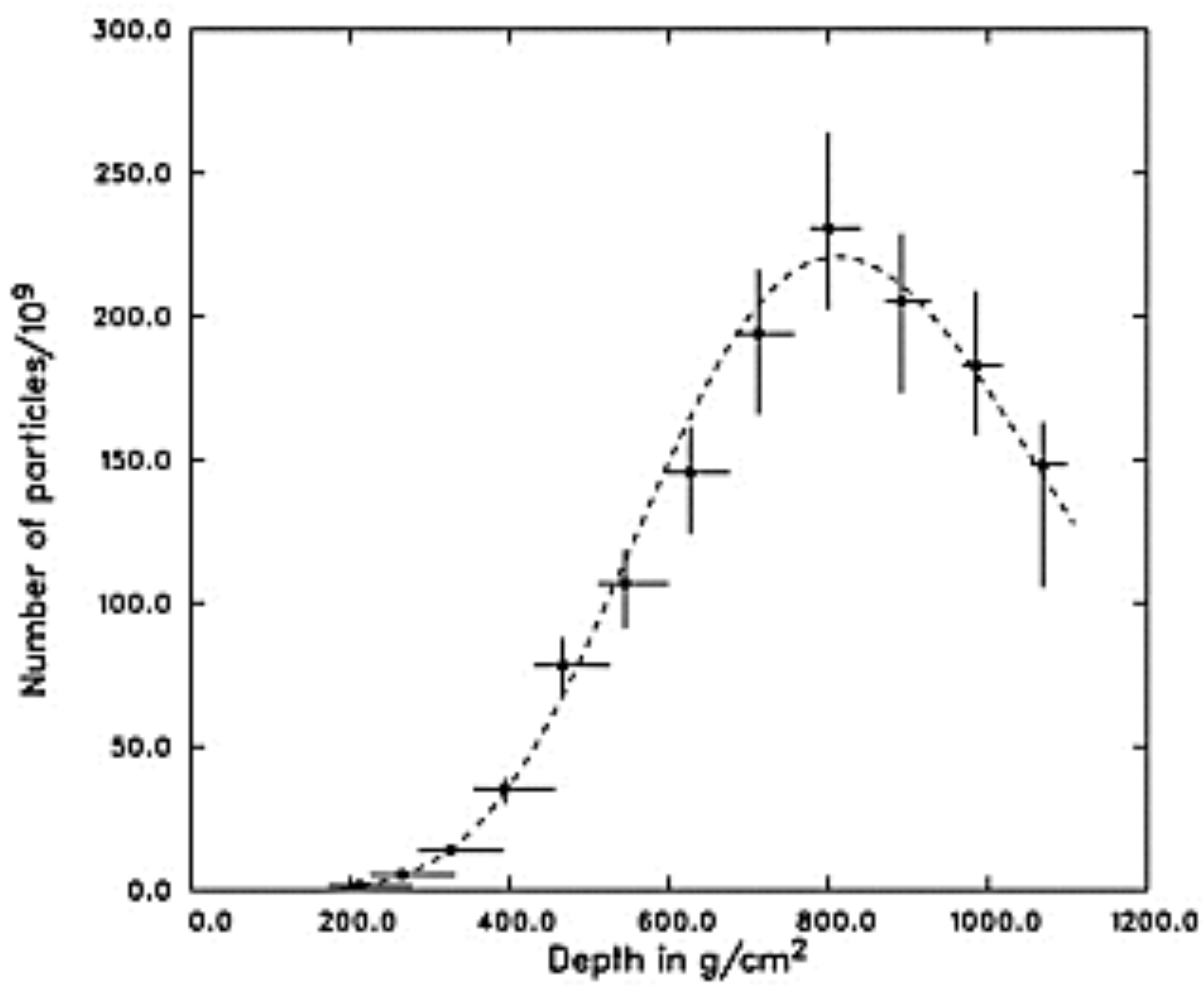
- Measurement of fluorescence light in the atmosphere

Fly's Eye: The highest-energy Particles



- Stereo-Observation with two detector stations permits a precise determination of the shower direction and profile

- The highest-energy particle ever detected on earth:
  15.10.1991, Utah:
  Energy ~ 3 x 10^{20} eV



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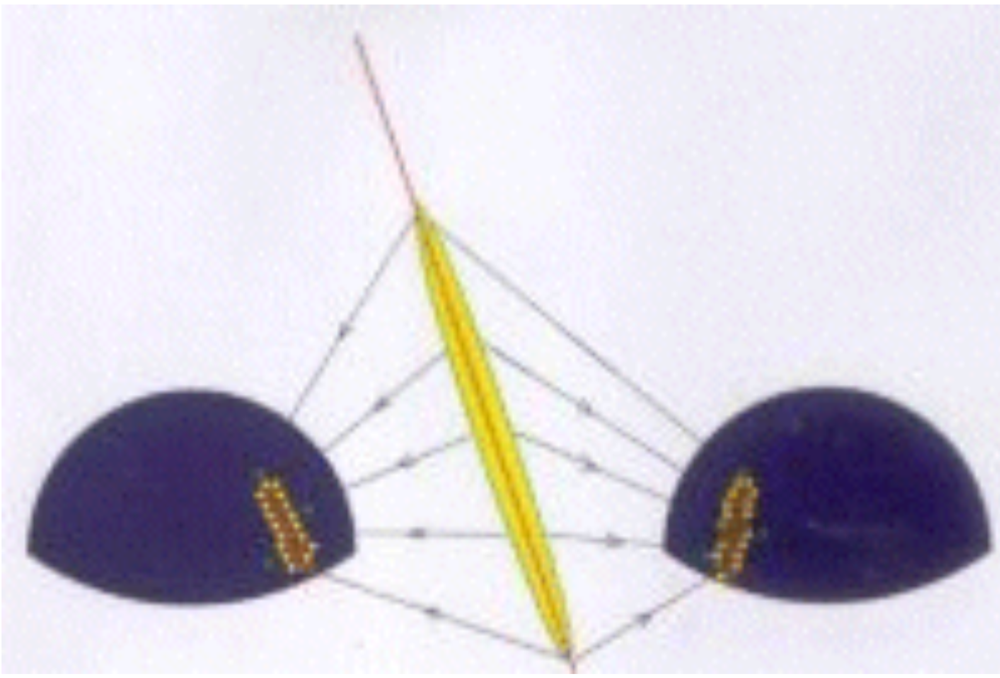

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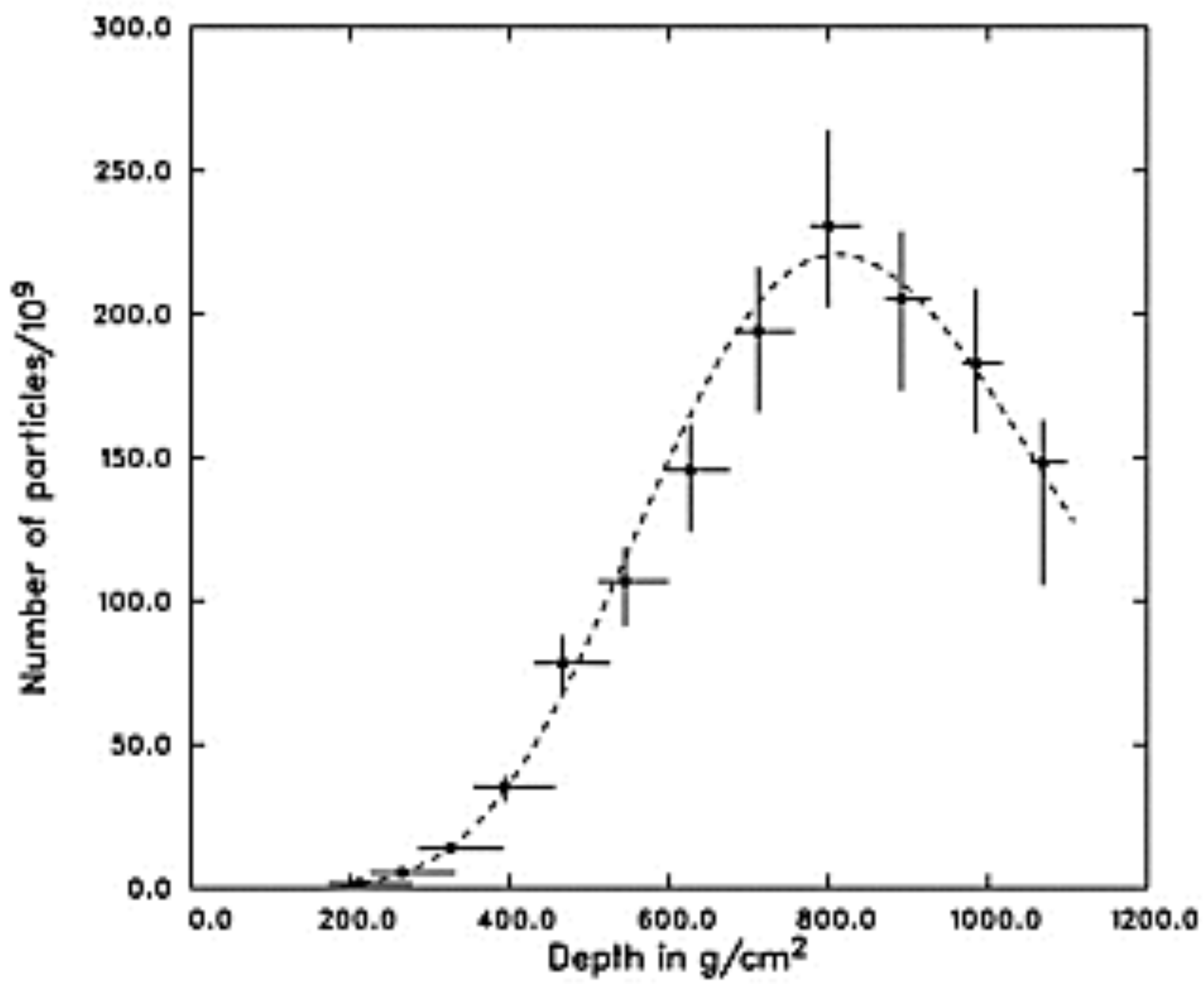
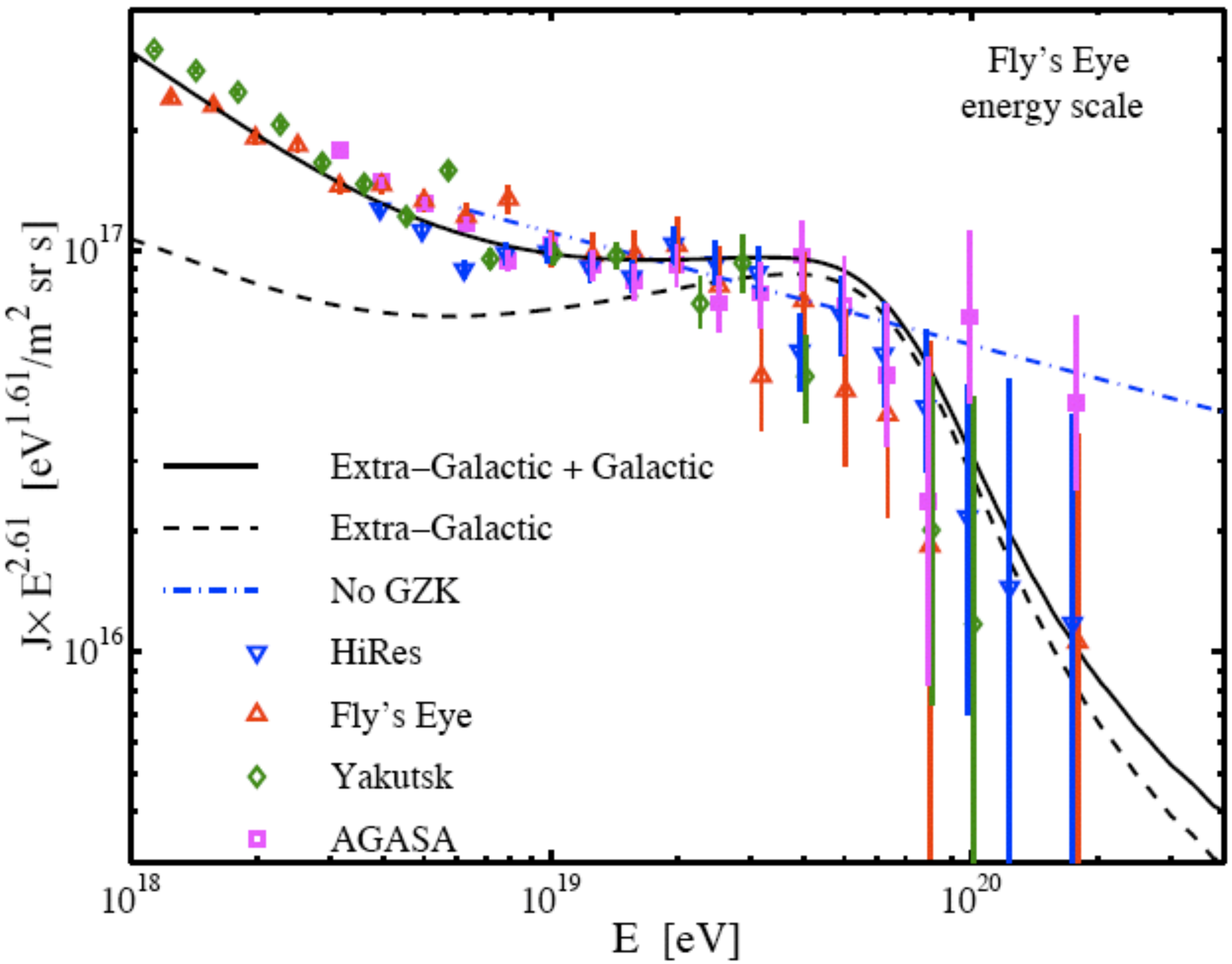
50 J !
"Oh-my-God particle"



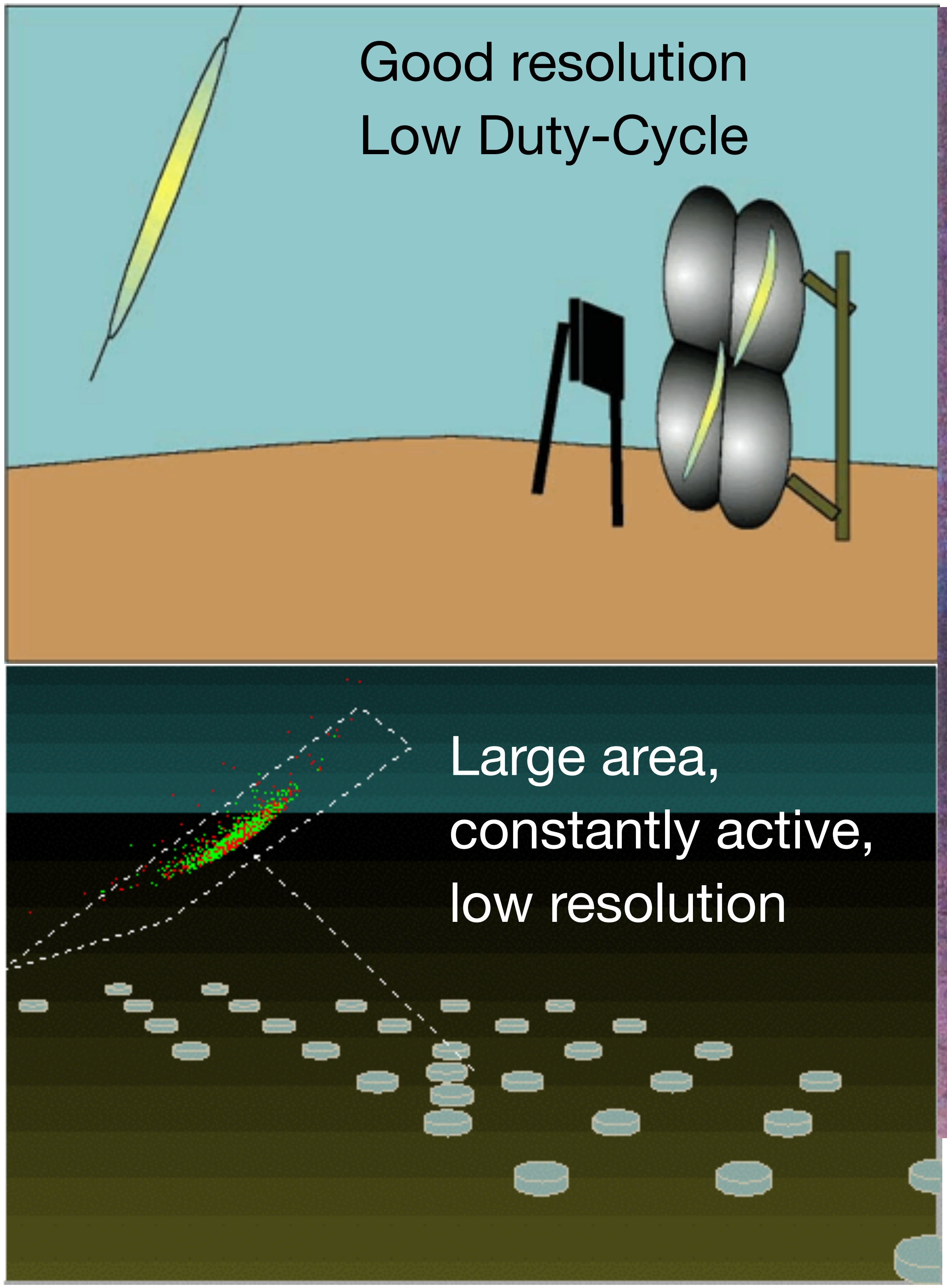
GZK-Cutoff: Status - 2003

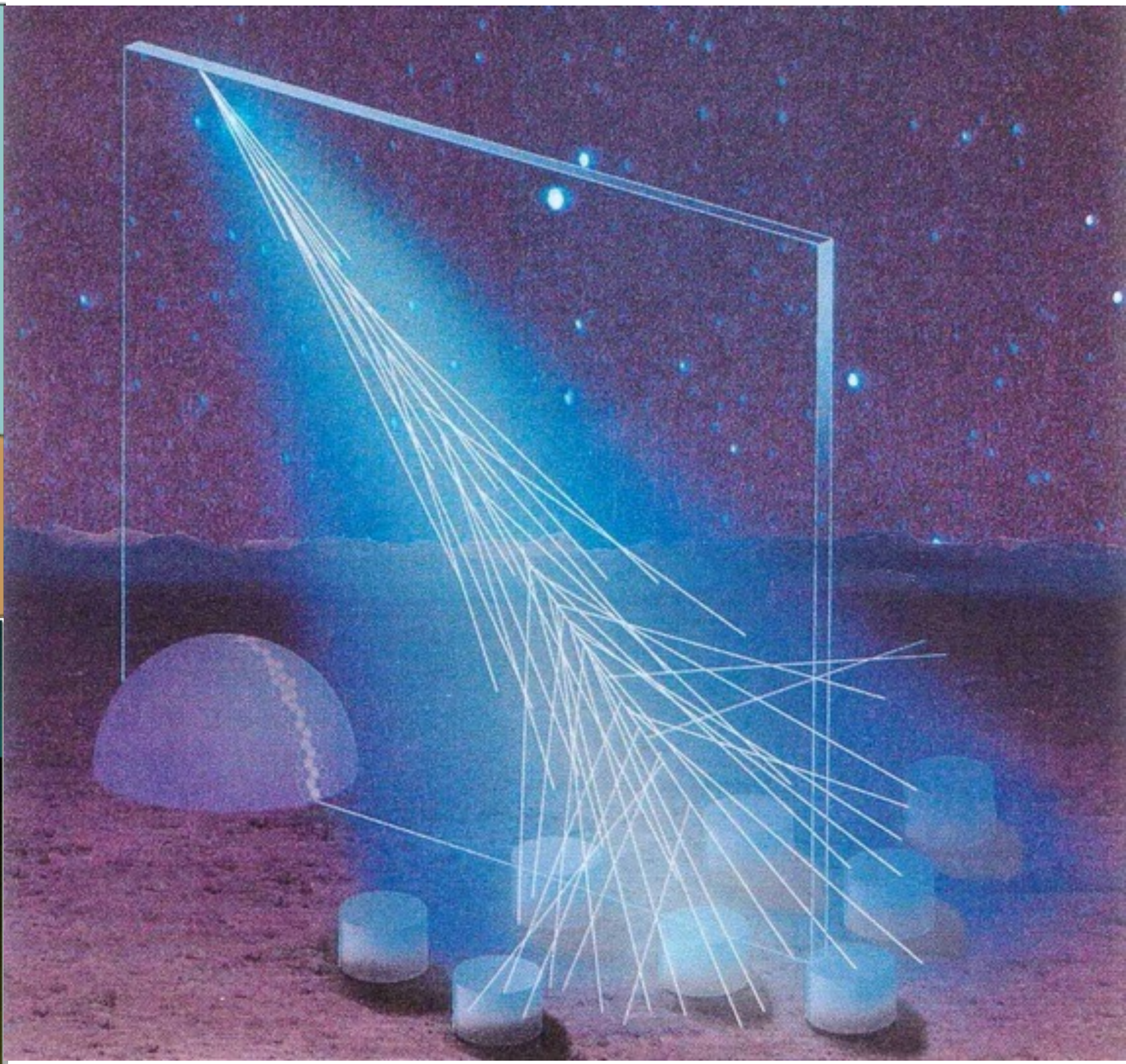


Nucl. Phys. B556, 1 (2003)

- To alleviate apparent discrepancy between different experiments: Shift of individual energy scales , so that all agree at 10^{19} eV with Fly's Eye
- ‣ Strong indication for the existence of the GZK Cutoff

AUGER: Combination of two Techniques

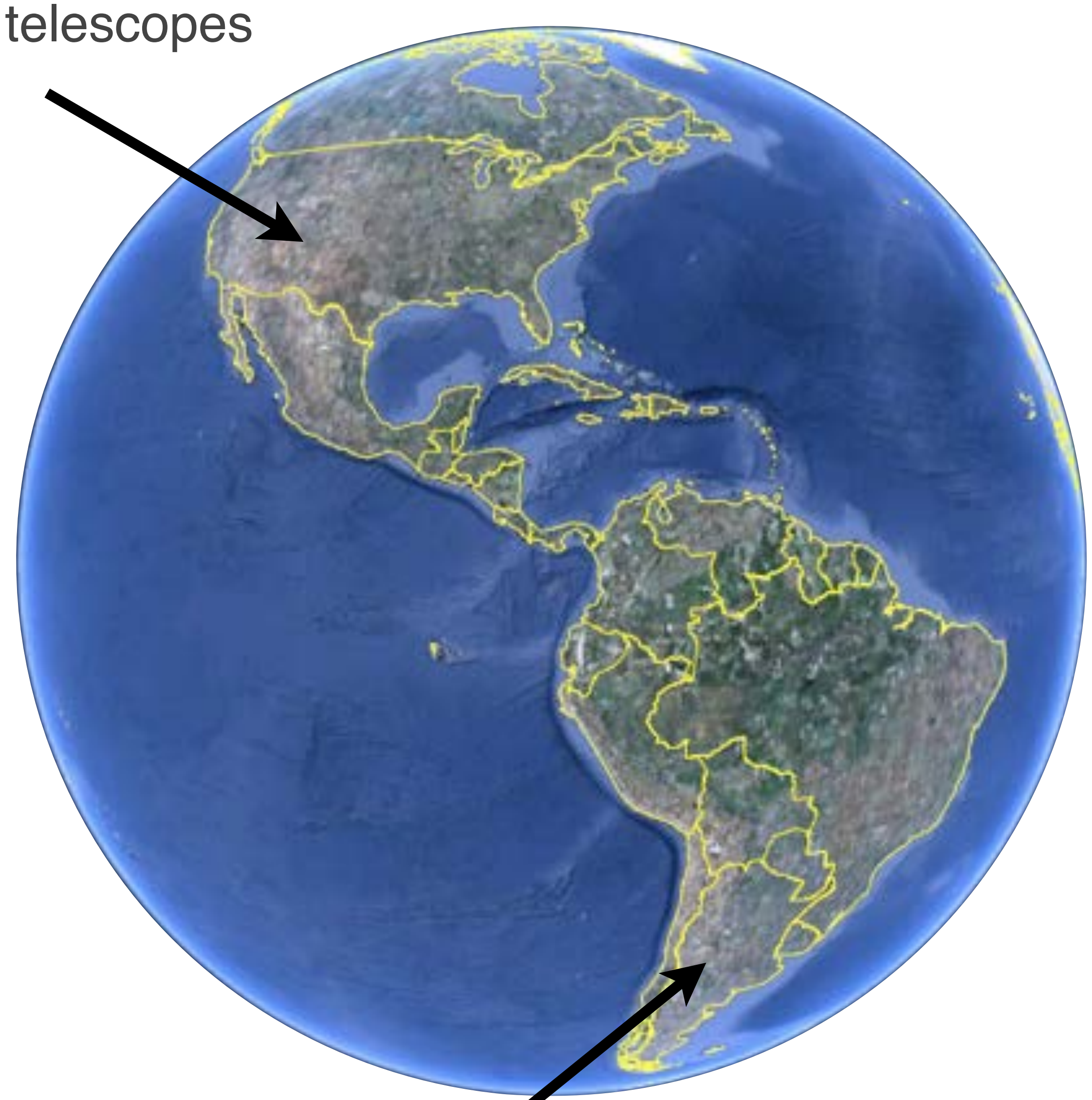




- Now state of the art for UHECR Observatories

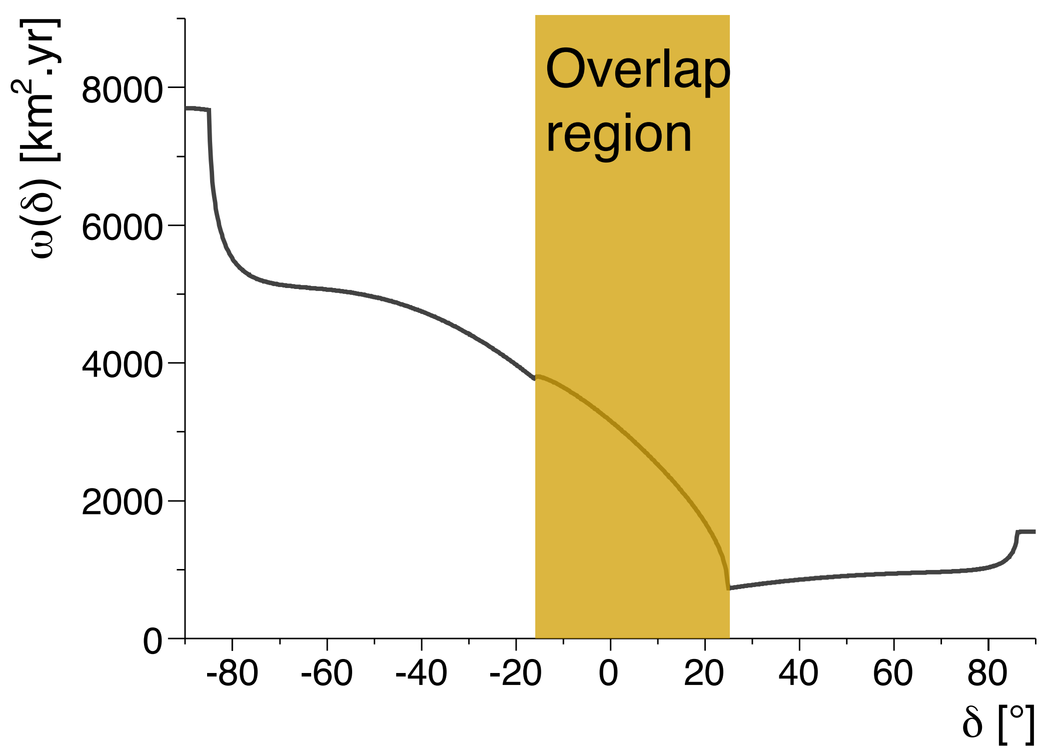
UHECR Observatories Today

Telescope Array (TA)
Delta, UT, USA
507 detector stations, 680 km²
36 fluorescence telescopes



E > 10^{19} eV

[0-55°] for TA
1,800 events
650 in overlap region

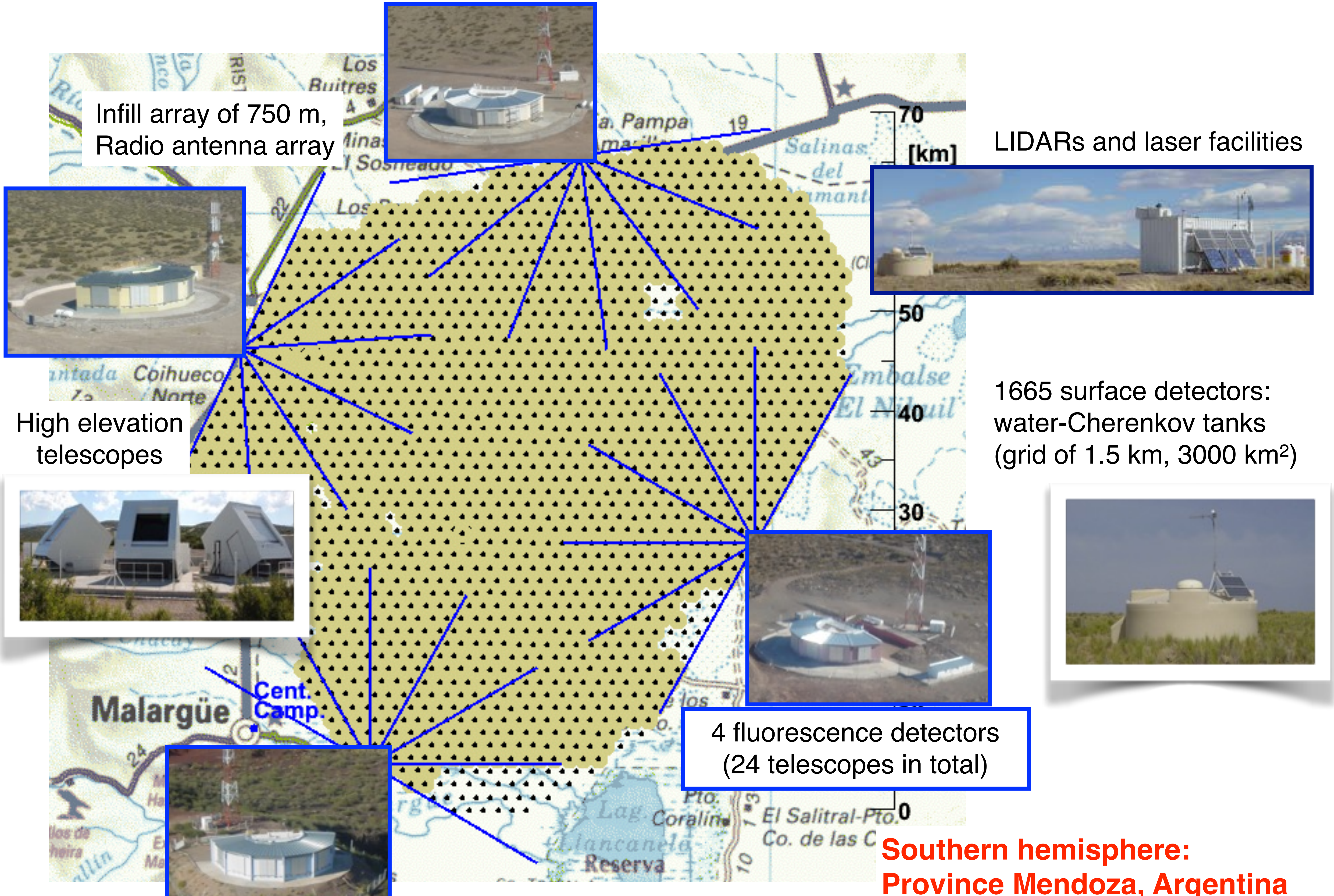


[0-60°] for Auger
10,900 events
3,400 in overlap region

Pierre Auger Observatory
Province Mendoza, Argentina
1660 detector stations, 3000 km²
27 fluorescence telescopes

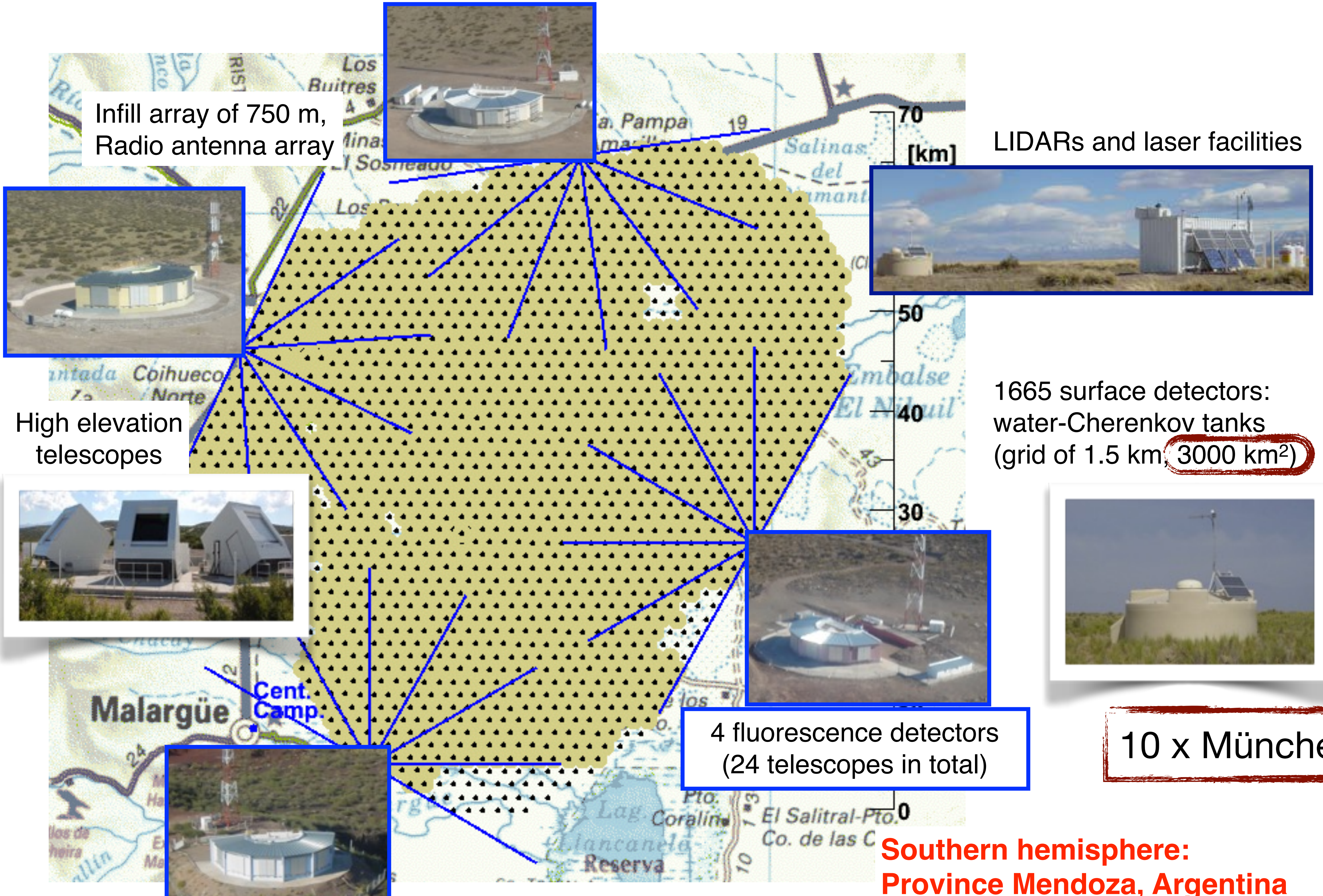
Exposures *Auger: 32,000 km² sr yr* *TA: 3,700 km² sr yr*

AUGER: In the Argentinian Pampa



Southern hemisphere:
Province Mendoza, Argentina

AUGER: In the Argentinian Pampa



Infill array of 750 m,
Radio antenna array

High elevation telescopes

LIDARs and laser facilities

1665 surface detectors:
water-Cherenkov tanks
(grid of 1.5 km, 3000 km²)

4 fluorescence detectors
(24 telescopes in total)

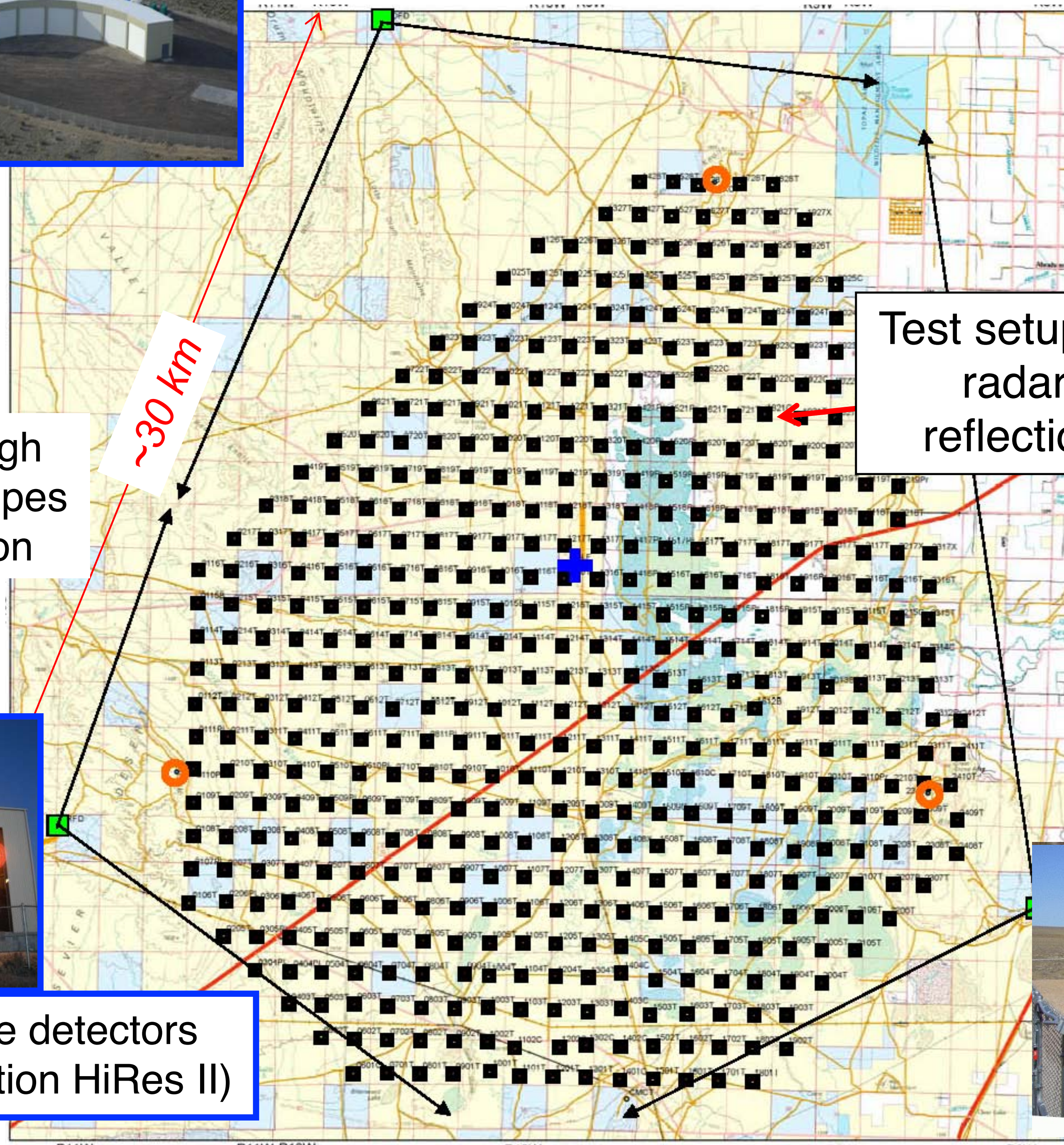
10 x München

Southern hemisphere:
Province Mendoza, Argentina

Telescope Array: Covering the North

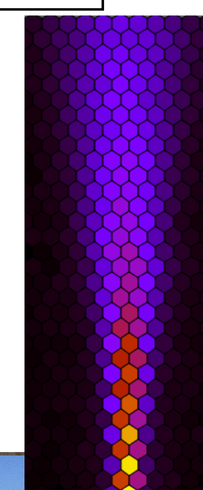
Middle Drum: based on HiRes II

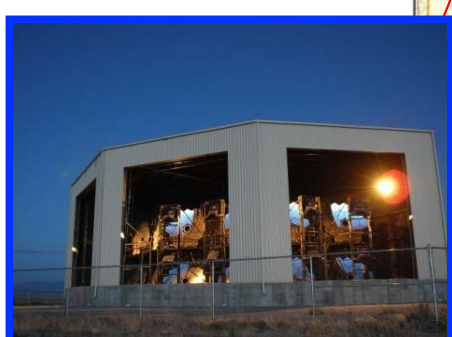
507 surface detectors: double-layer scintillators (grid of 1.2 km, 680 km²)



LIDAR
Laser facility

Infill array and high elevation telescopes under construction





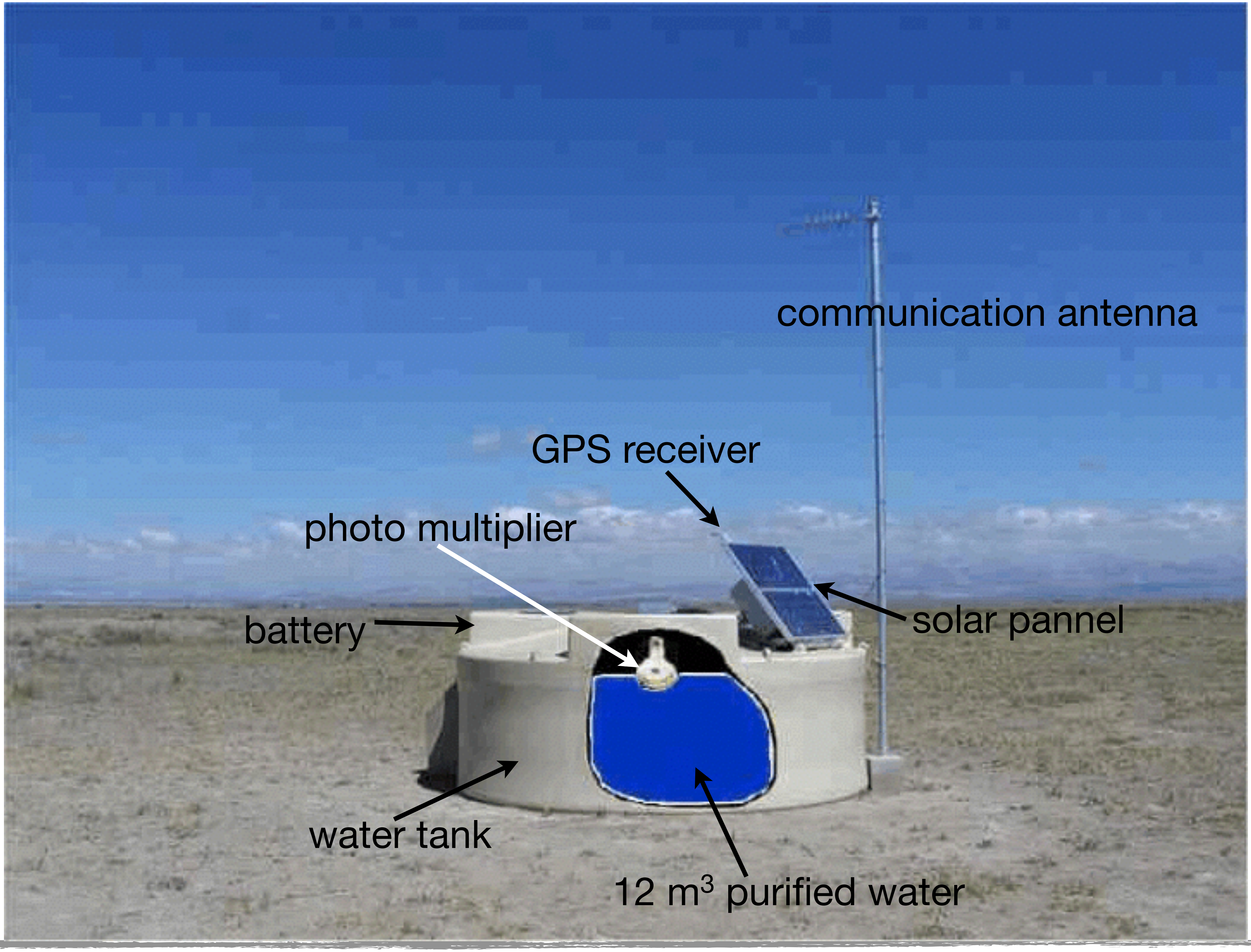
Electron light source (ELS): ~40 MeV

3 fluorescence detectors (2 new, one station HiRes II)

Northern hemisphere: Utah, USA

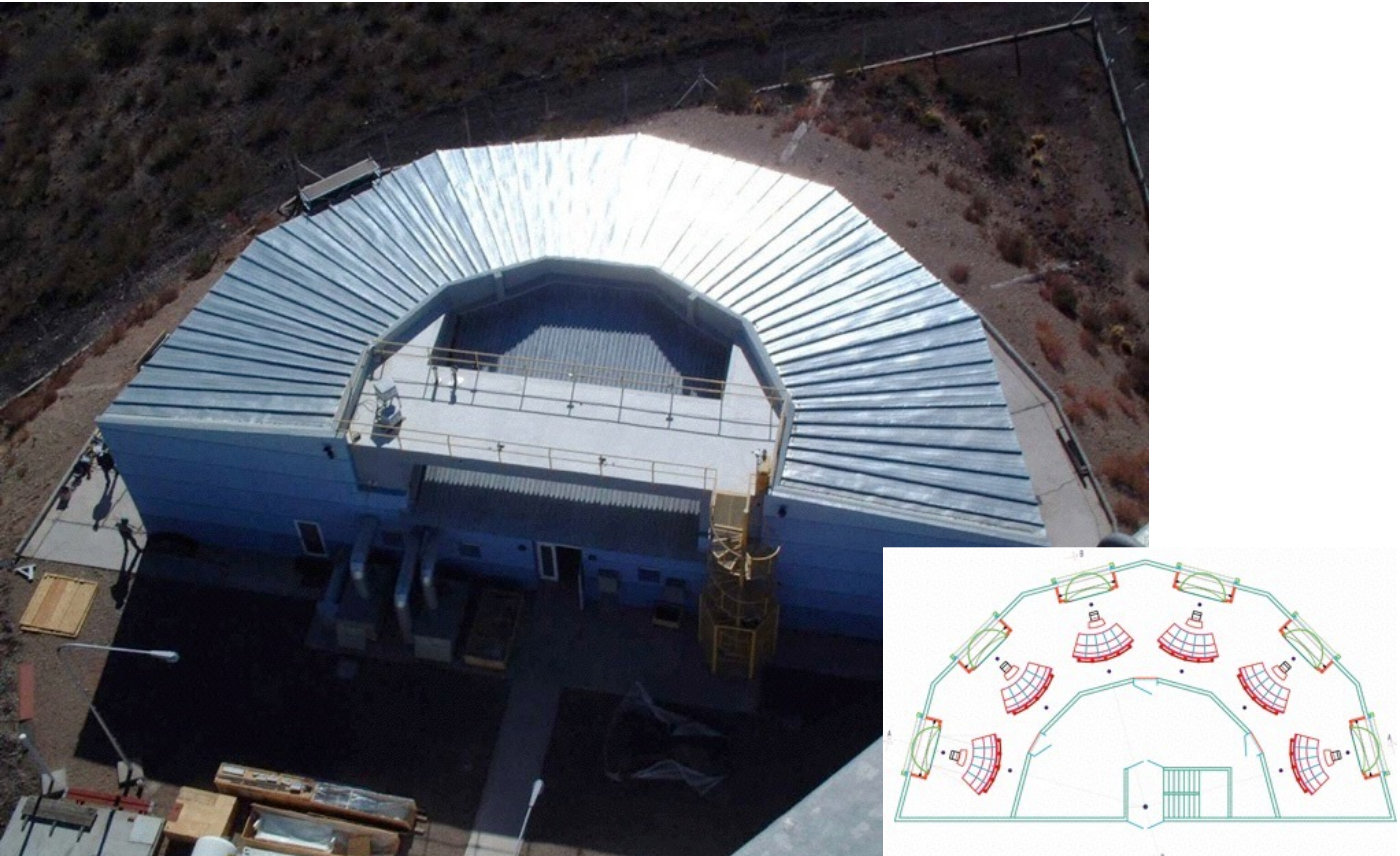
Frank Simon (fsimon@mpp.mpg.de)

AUGER Detector: Ground Array

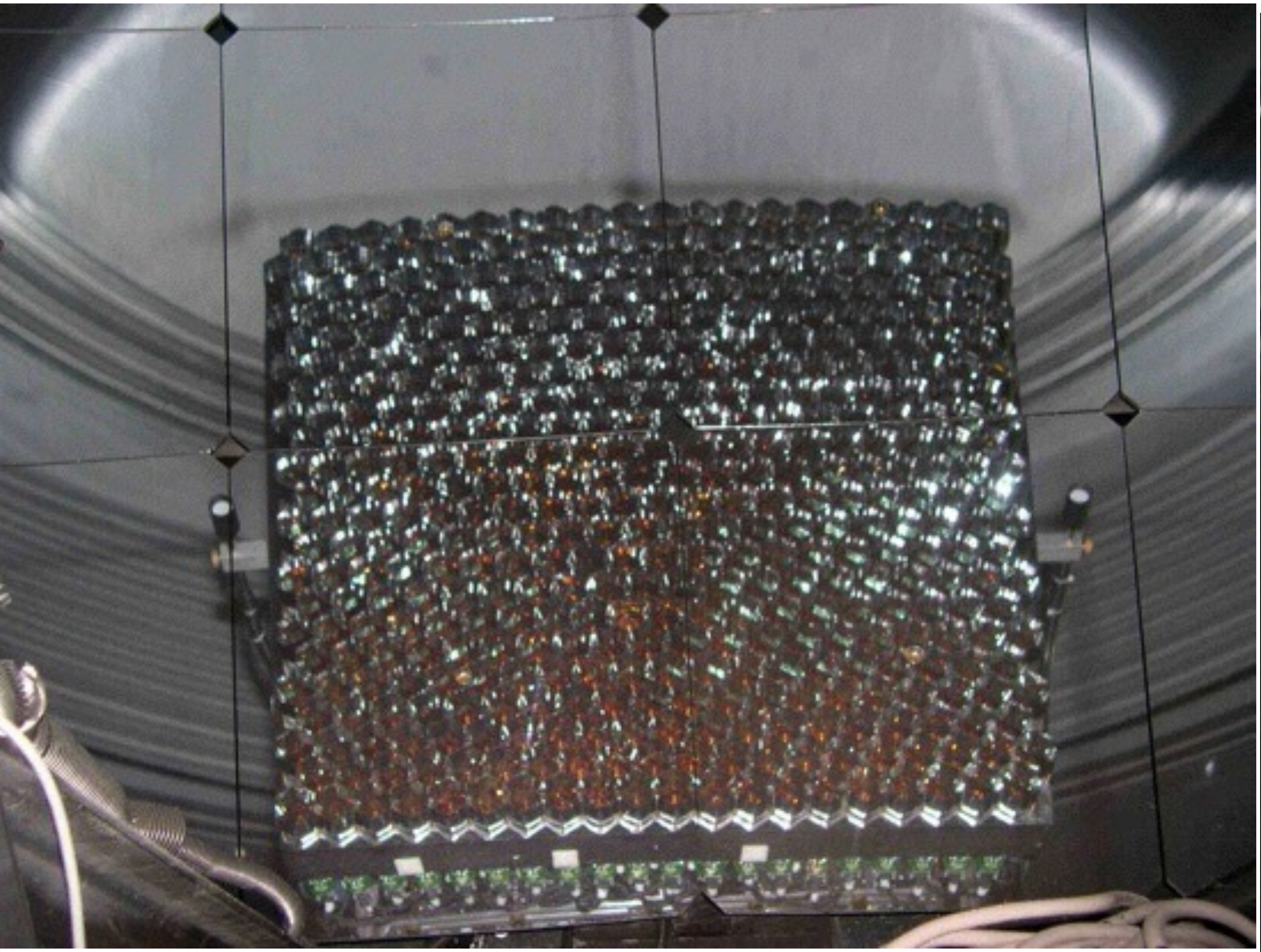


AUGER Installation

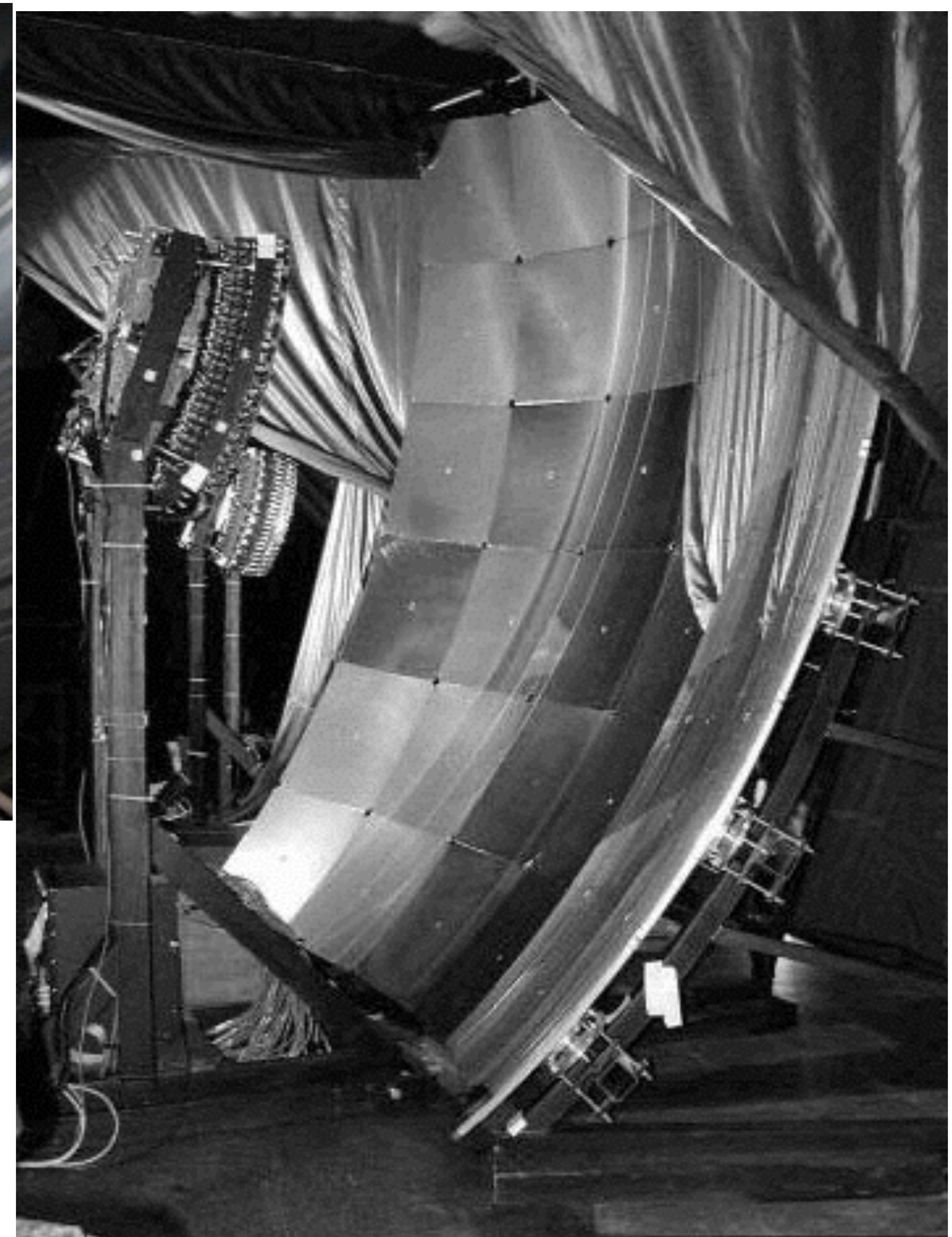
AUGER Fluorescence Telescopes



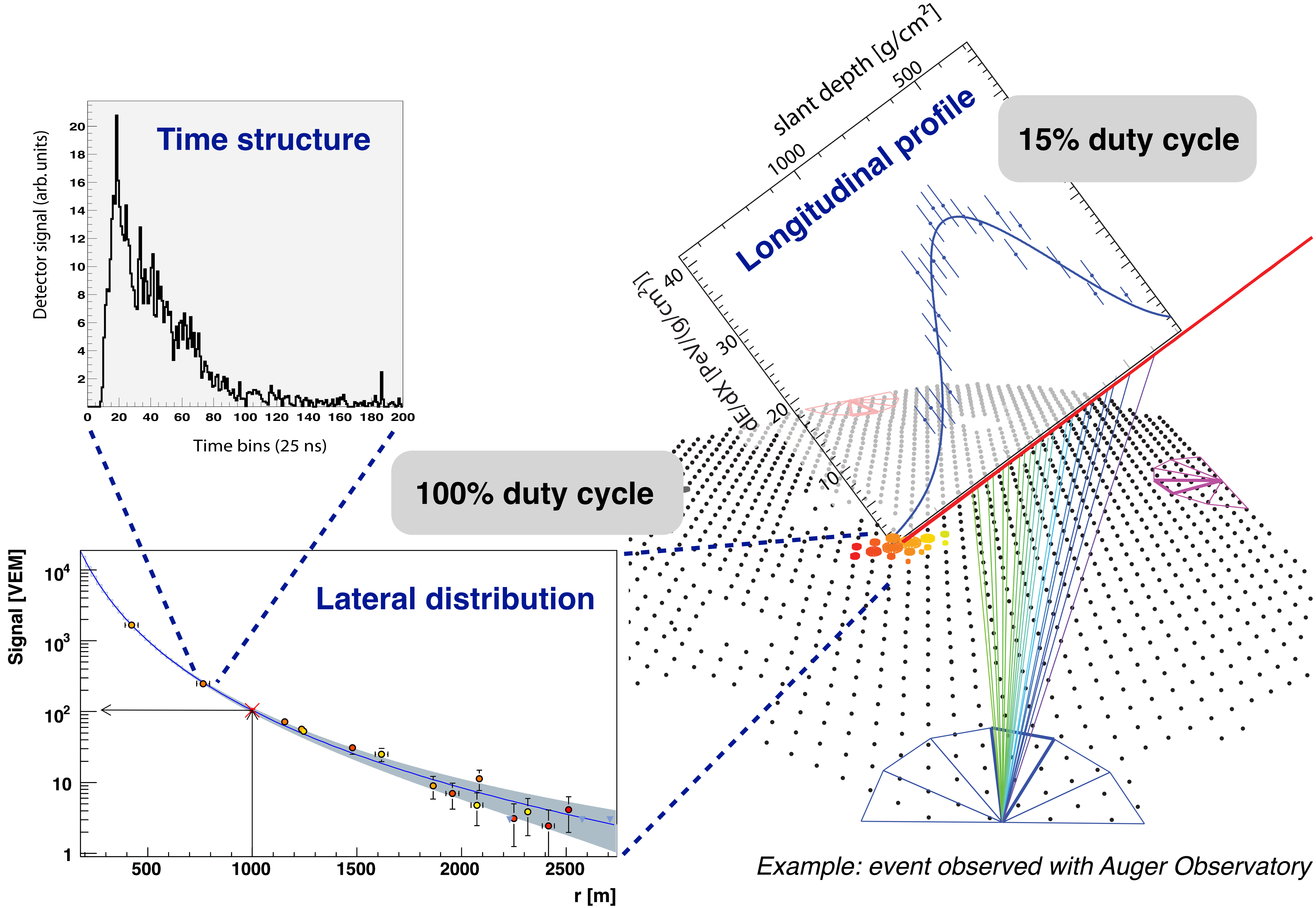
AUGER Fluorescence Telescopes



- 440 PMTs, 1.5° per Pixel

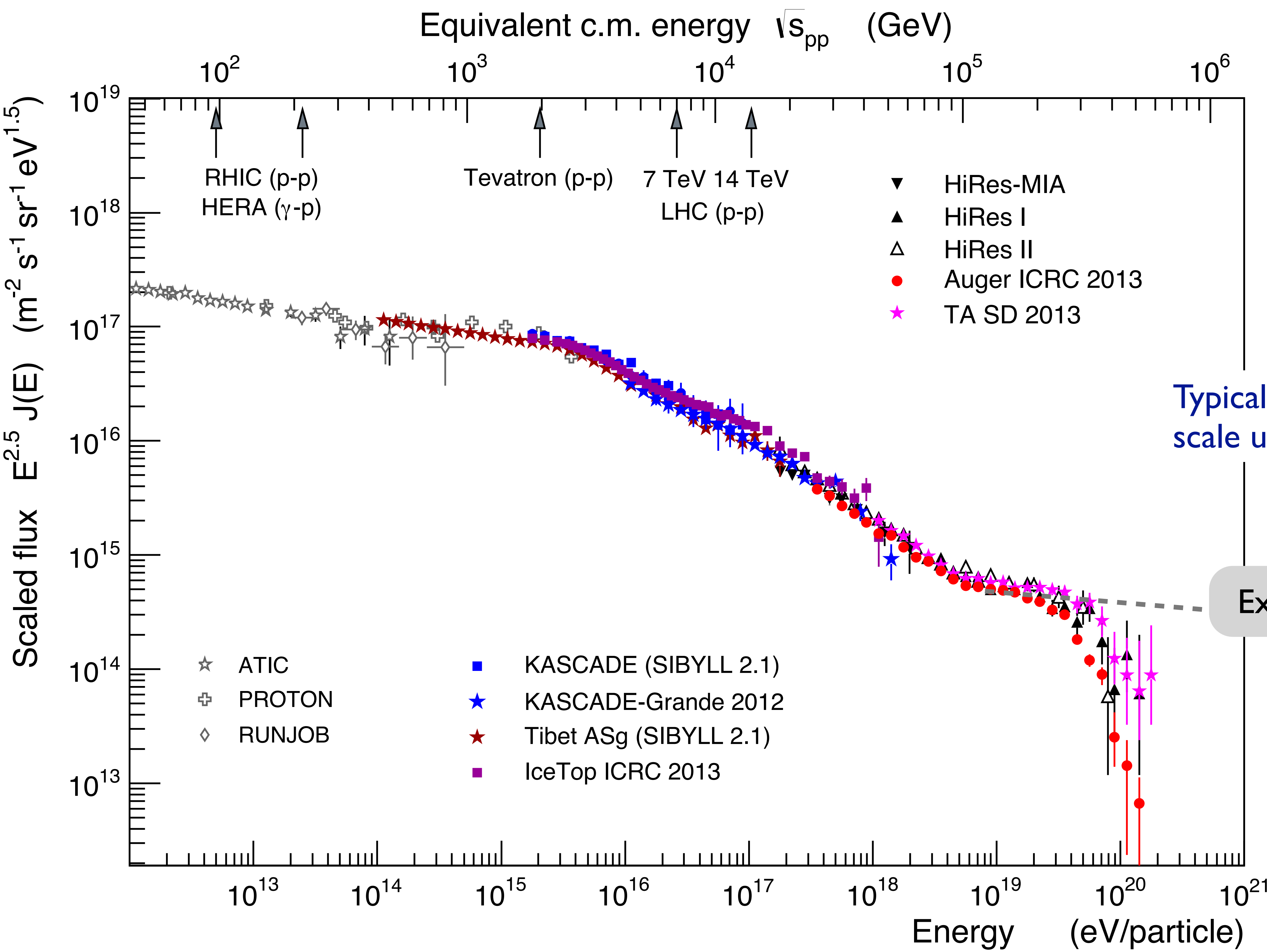


Typical AUGER Events



Example: event observed with Auger Observatory

The Spectrum at Highest Energies



Auger Coll. (ICRC 2013)

Typically 15-20% energy scale uncertainty

Extrapolated flux

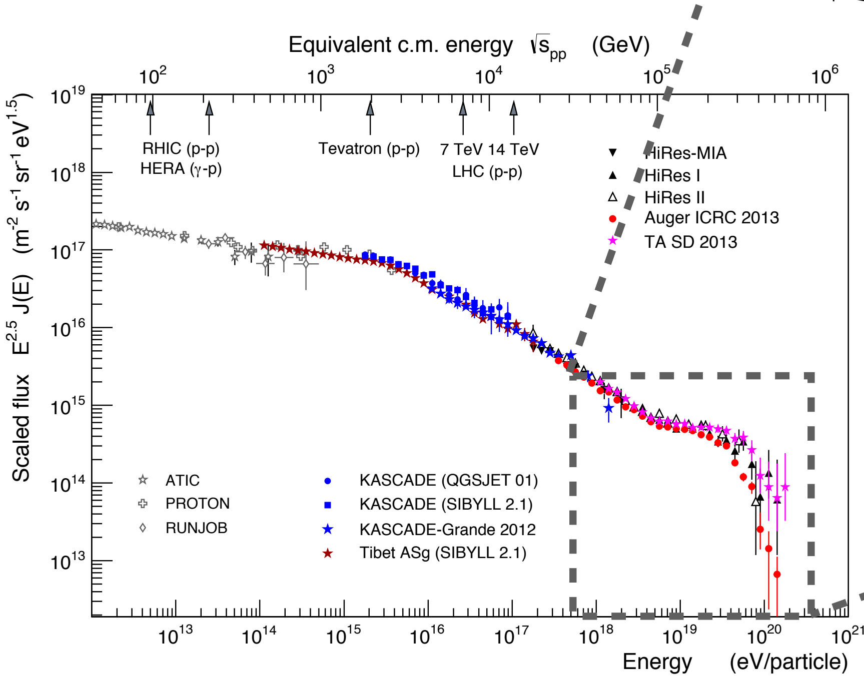
The Spectrum at Highest Energies

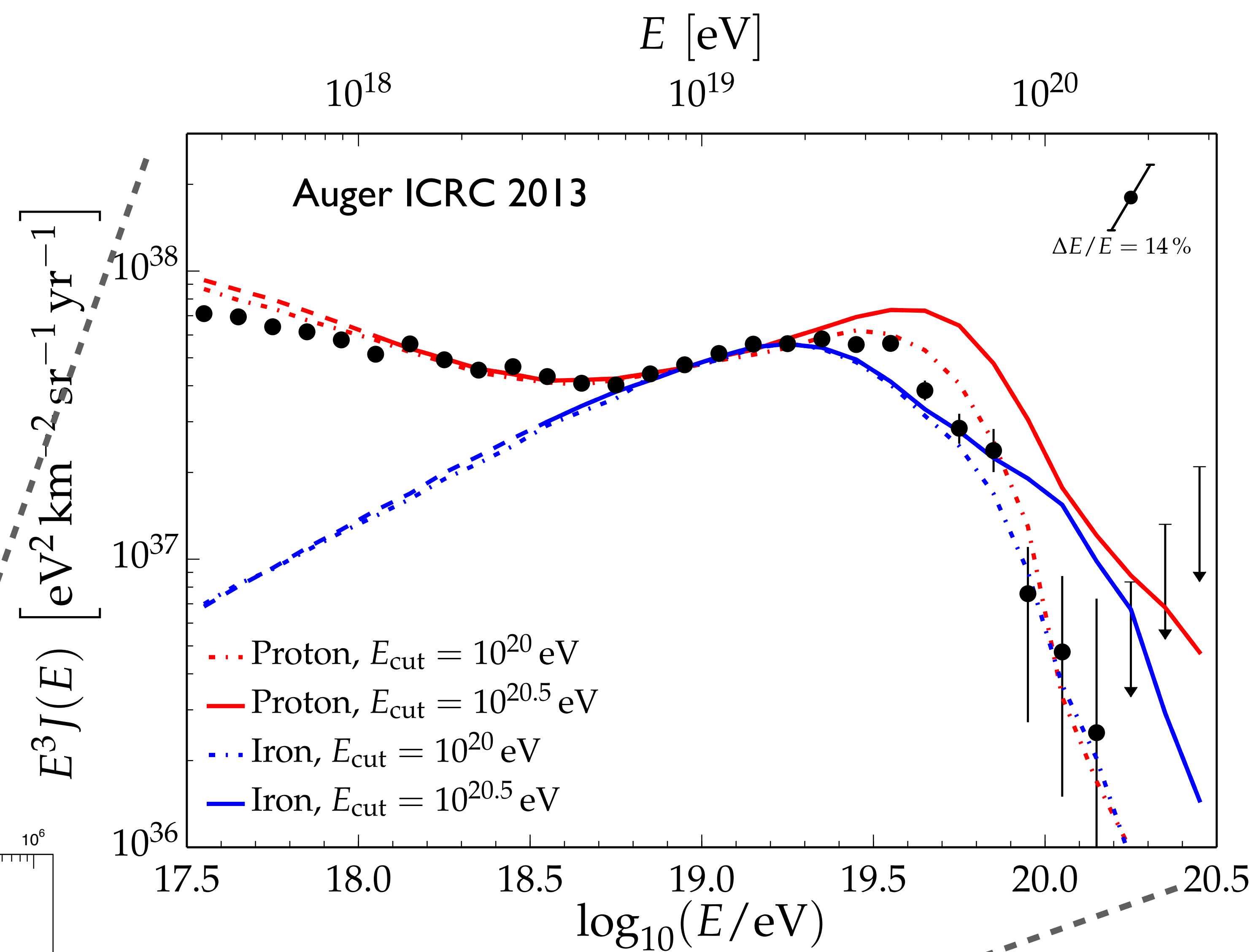
Proton dominated flux

Suppression: delta resonance

Ankle: e^+e^- pair production

(Dip model of Berezinsky et al.)





Iron dominated flux

Suppression: giant dipole resonance

Ankle: transition to galactic sources

The Spectrum at Highest Energies

Proton dominated flux

Suppression: delta resonance

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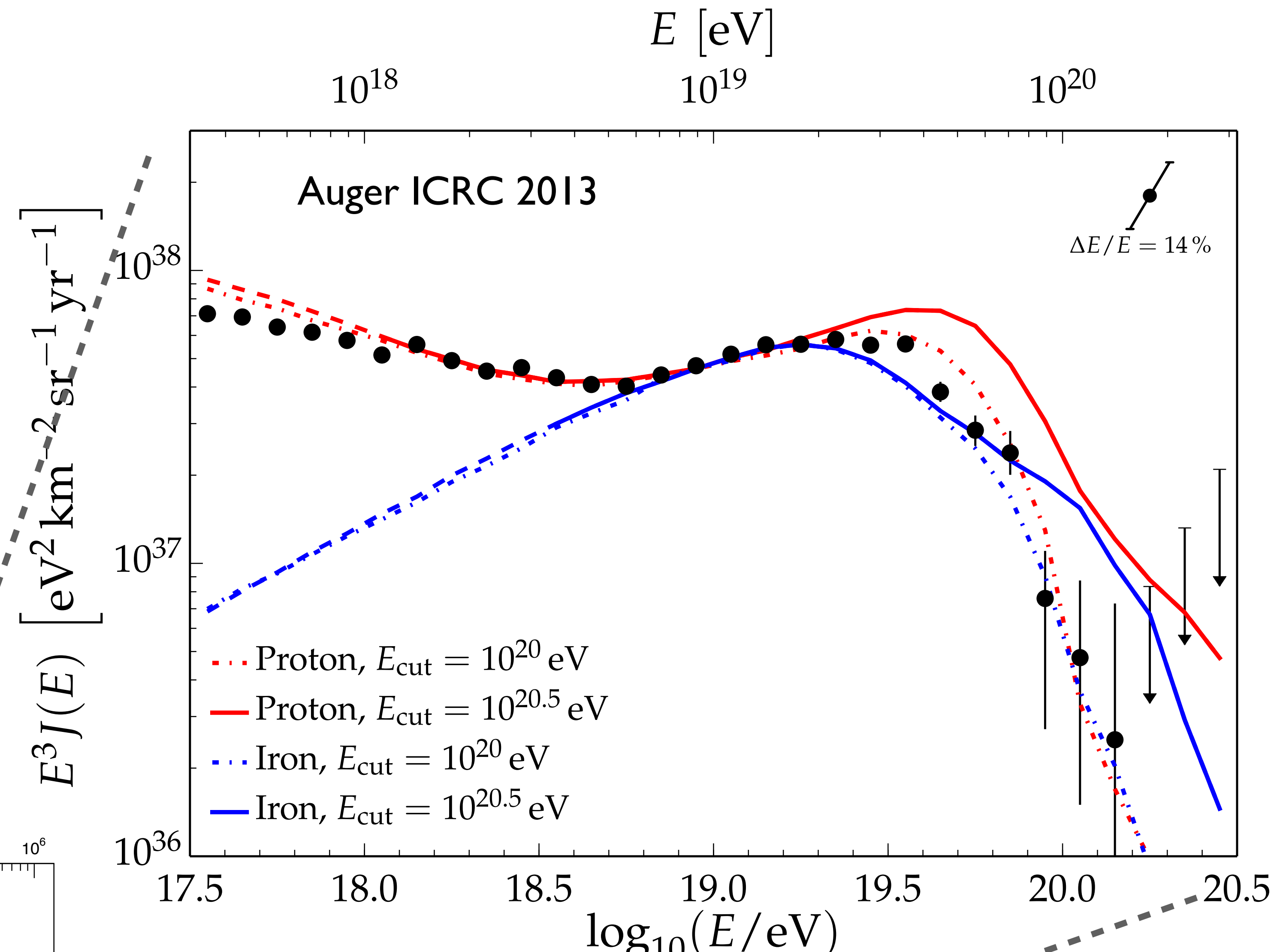
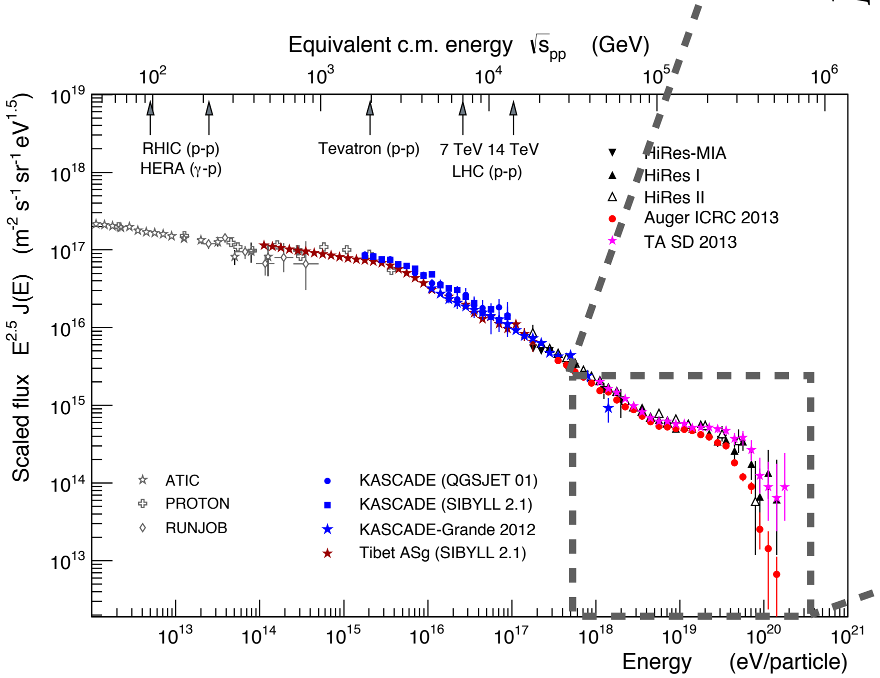




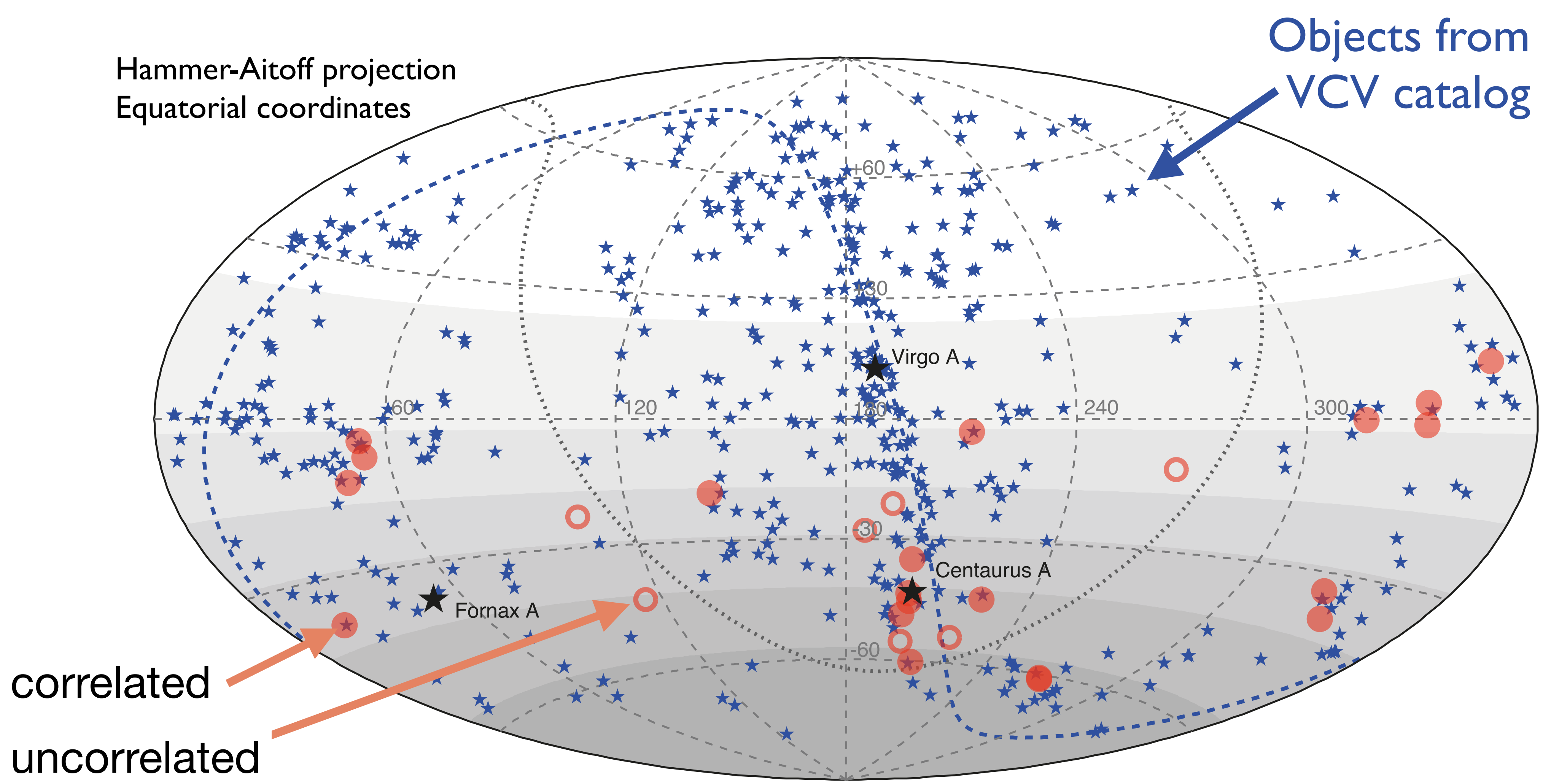
Compatible with expectations from GZK effect!

Iron dominated flux

Suppression: giant dipole resonance

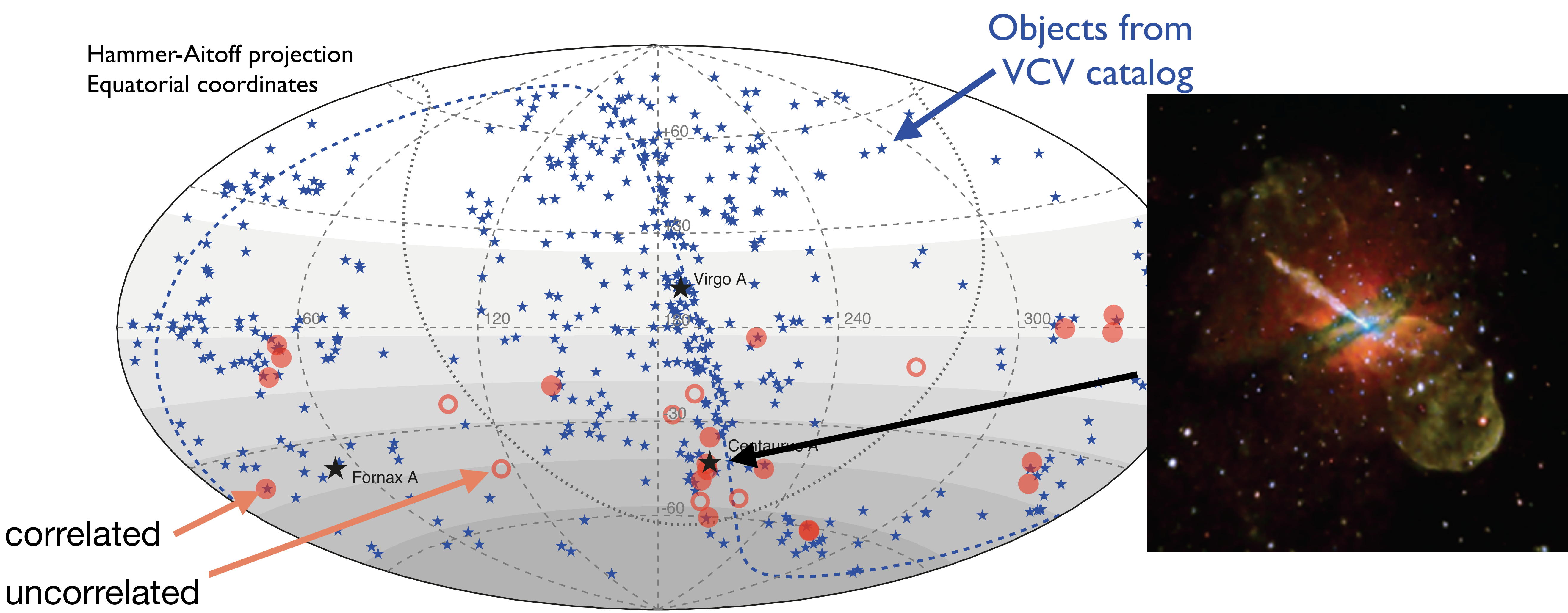
Ankle: transition to galactic sources

AUGER: Sources for UHECRs - 2007



- Highest-energy particles are not distributed isotropically
- Correlation with known close-by AGNs and with “supergalactic plane”
  - Initially 70% of particles observed to be correlated to AGNs

AUGER: Sources for UHECRs - 2007



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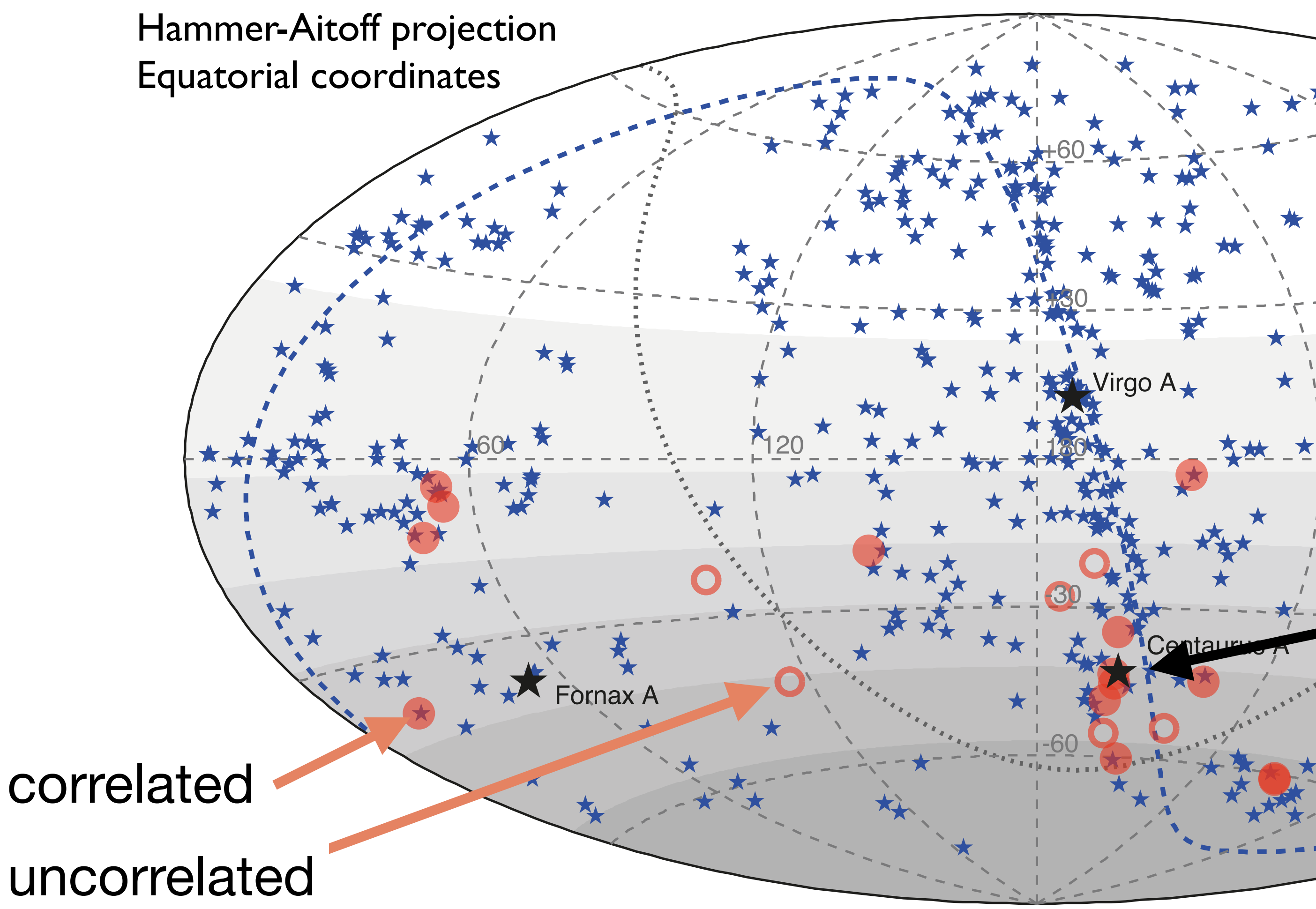
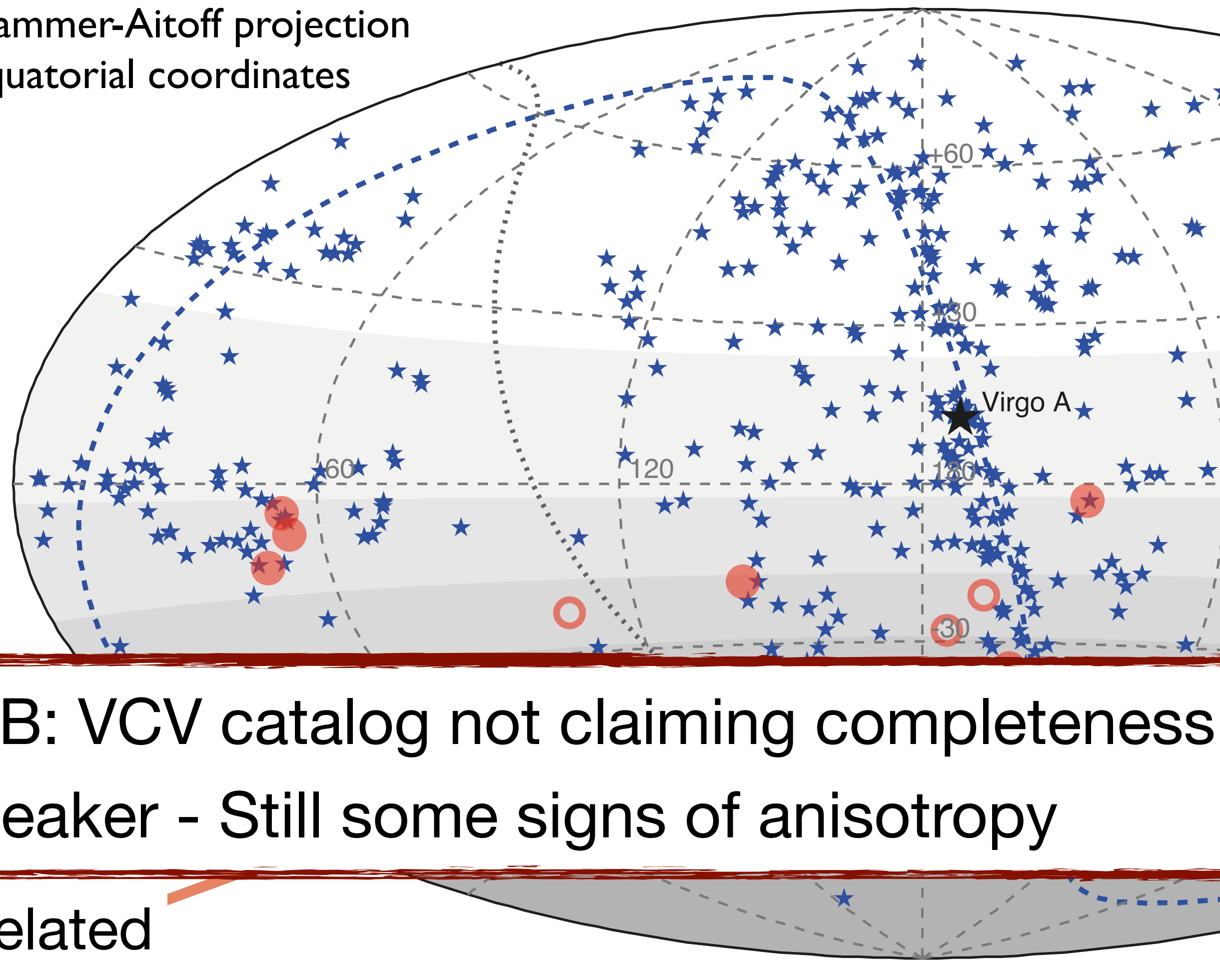


- Highest-energy particles are not distributed is
- Correlation with known close-by AGNs and wi
  - Initially 70% of particles observed to be cor

AUGER: Sources for UHECRs - 2007



- NB: VCV catalog not claiming completeness - and with more data the correlation got weaker - Still some signs of anisotropy

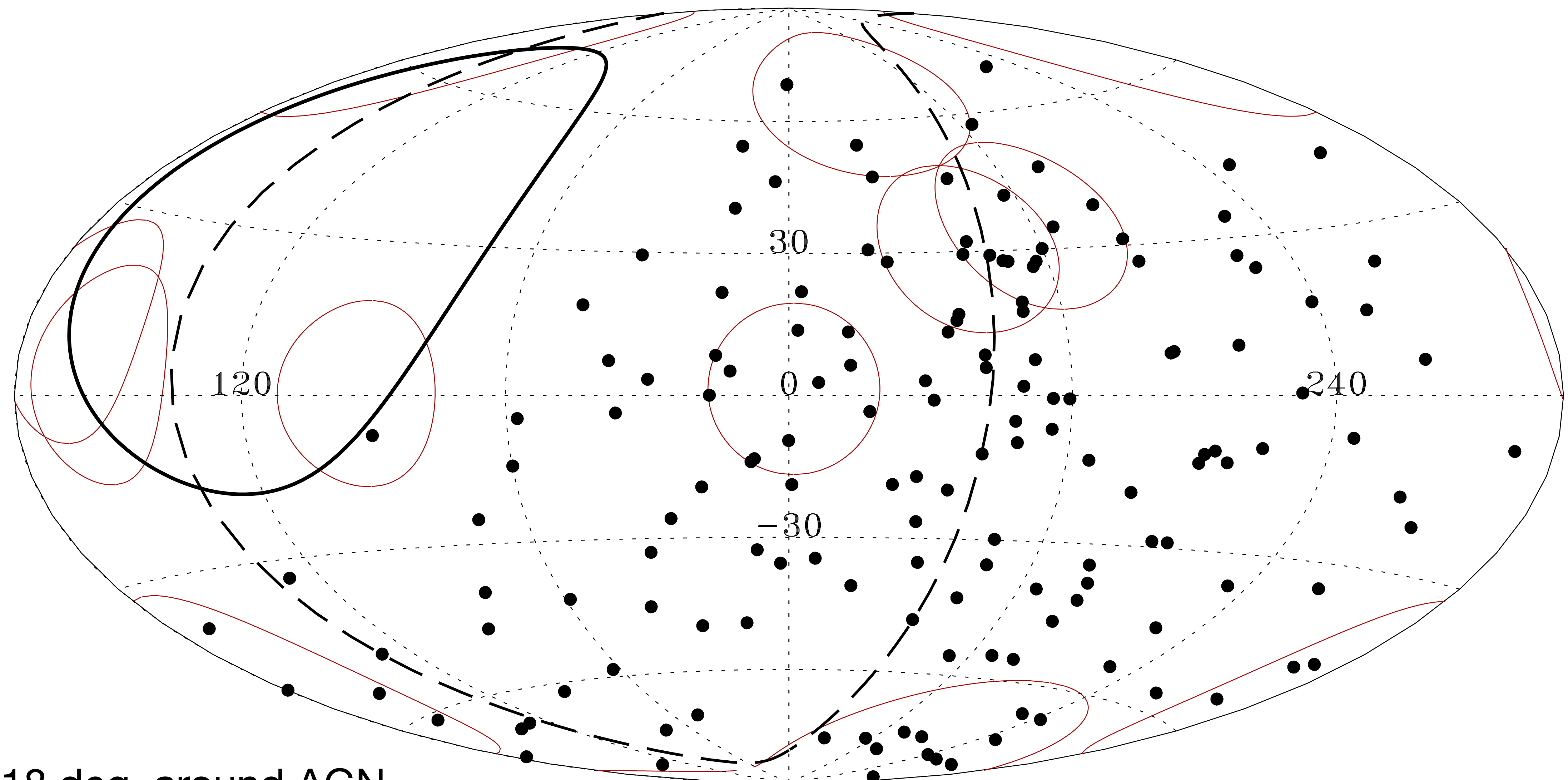
uncorrelated

- Highest-energy particles are not distributed is
- Correlation with known close-by AGNs and wi
  - Initially 70% of particles observed to be cor

One of the Top 10 Science Stories of the Year 2007

Correlation with AGNs: Current Status

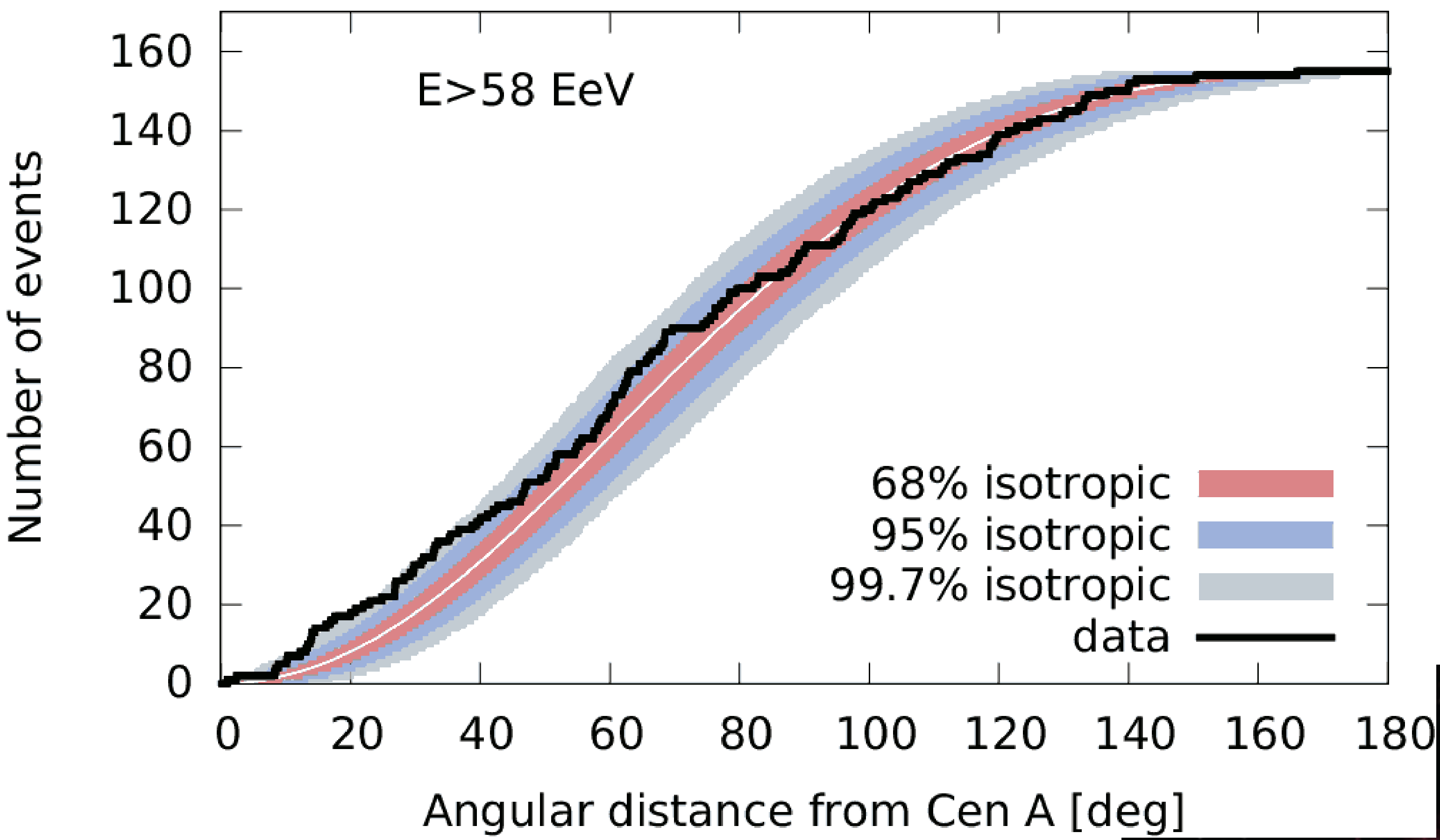
- Mild correlation of observed CRs with $E > 5.8 \times 10^{19}$ eV and very luminous AGNs closer that 130 Mpc.
  - The probability to get the same (or higher) correlation with an isotropic distribution is 1.3%



circles show 18 deg. around AGN
dots show CRs

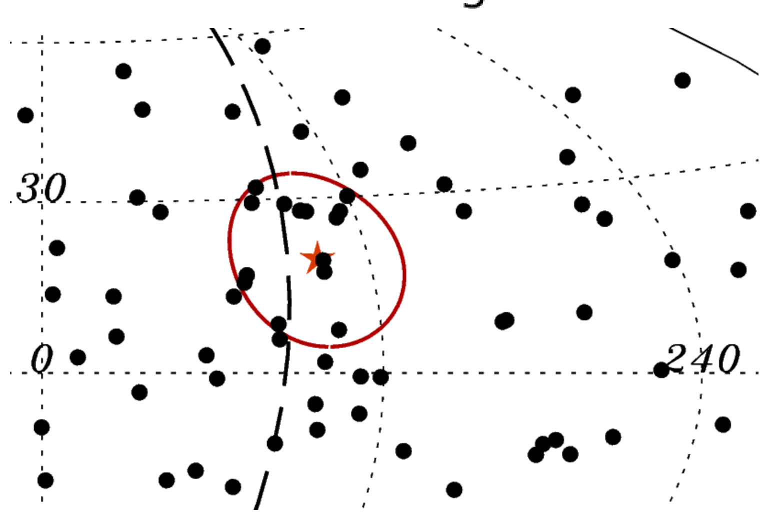
AUGER: A Closer Look at Cen A

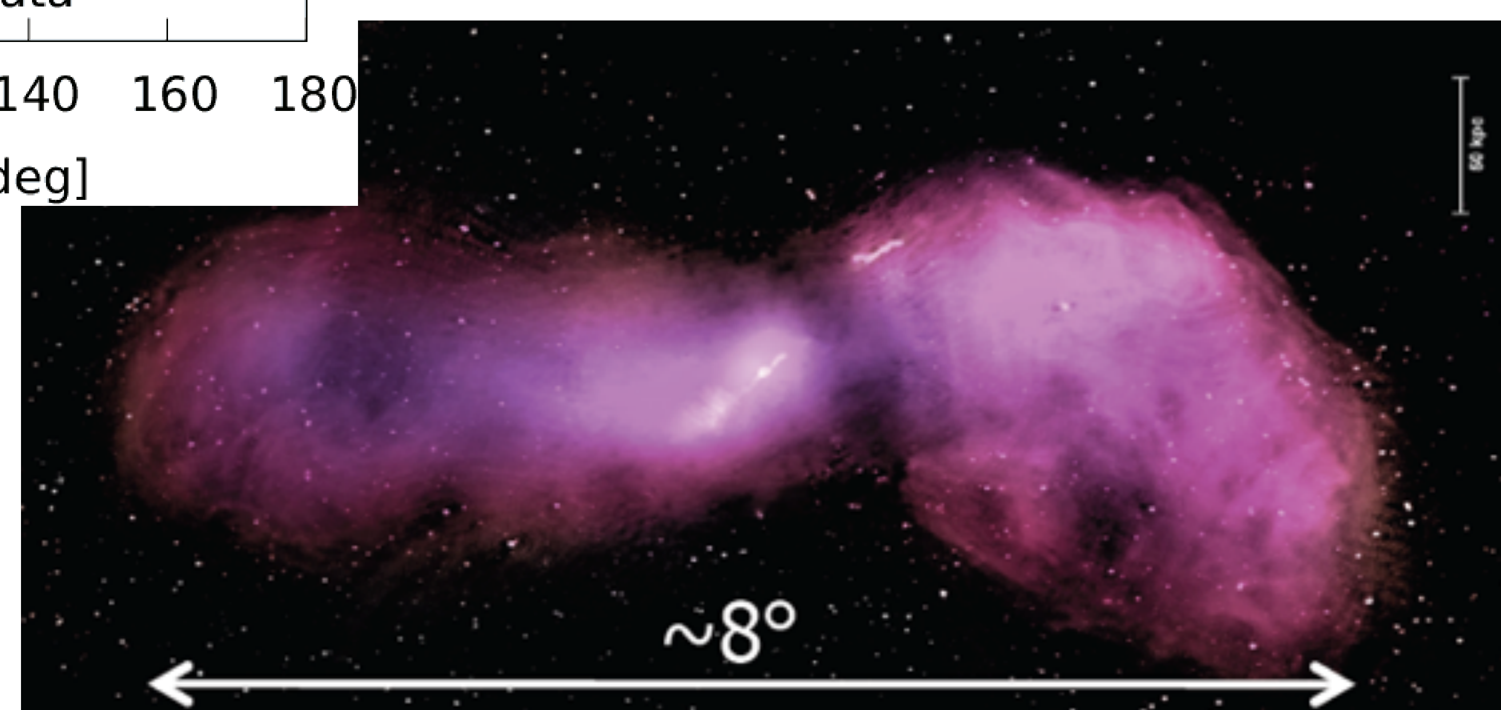
- A possible source: Centaurus A (4.2 Mpc away)
    - Active galaxy, well in AUGER field of view



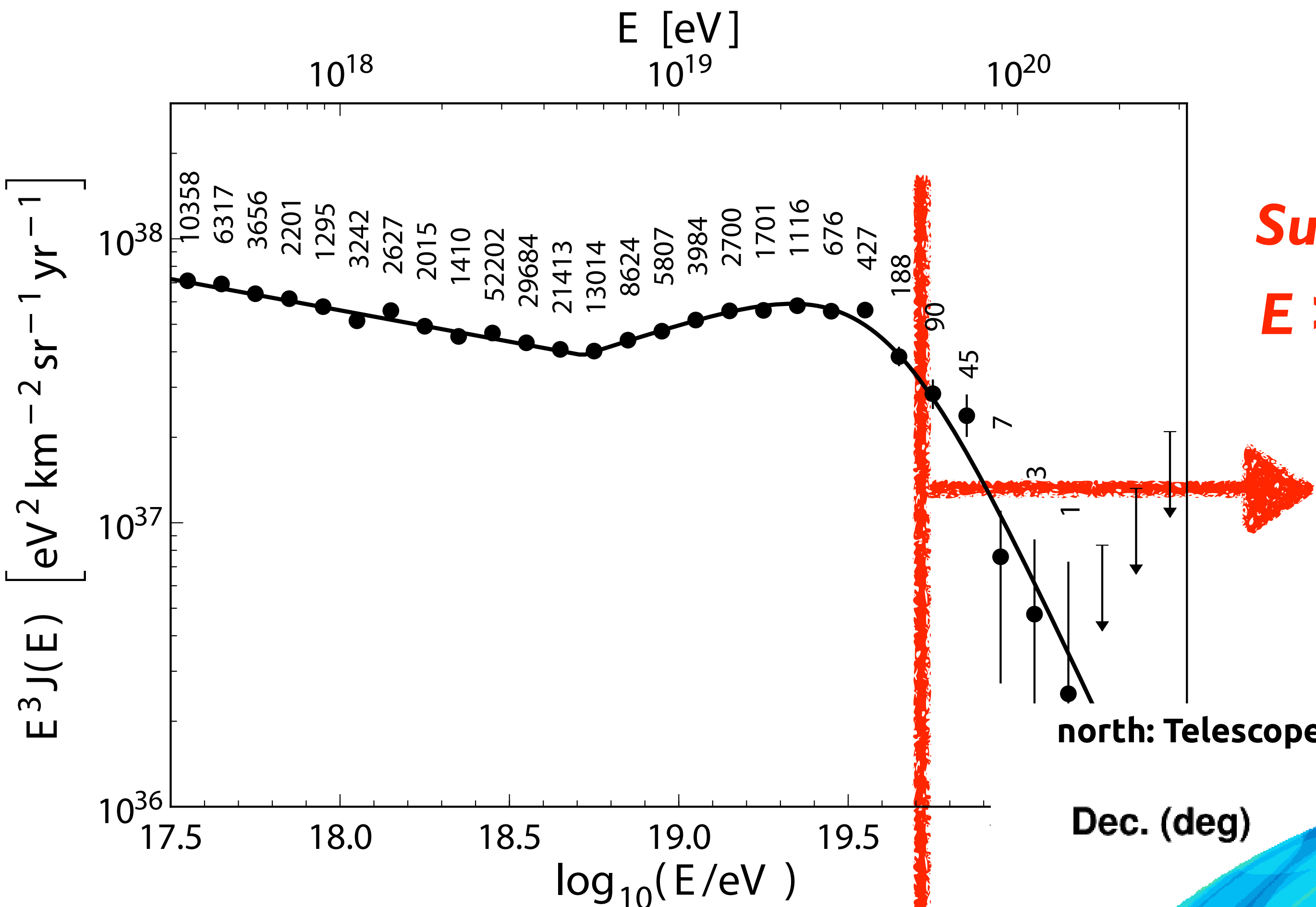
Cumulative event number (E > 58 EeV) as a function of the angle to Cen A.

14 events within 15°
(4.5 expected) - Probability to get this (or more) for an isotropic distribution is 1.4%





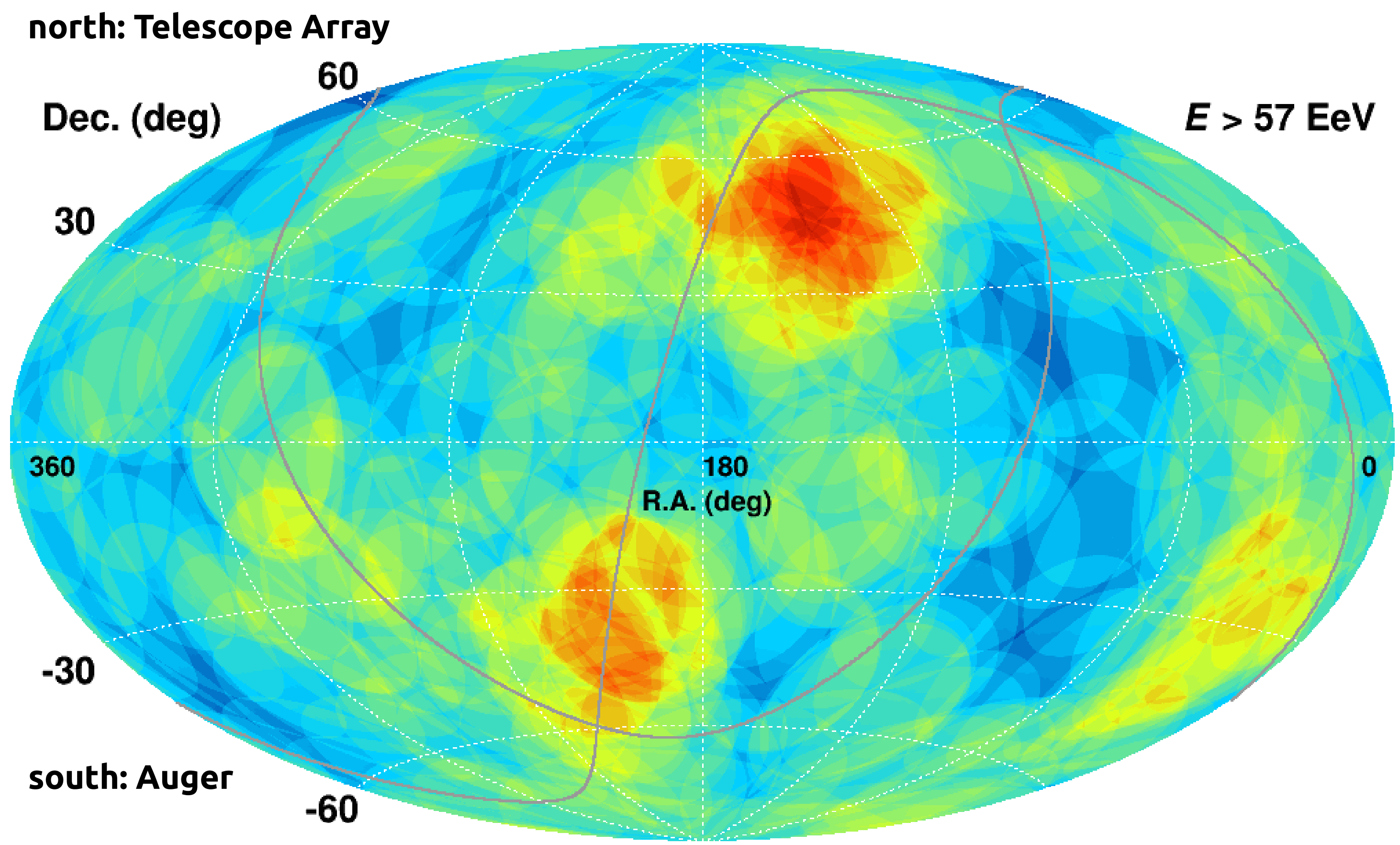
AUGER and TA - The Latest Status



Suppression region

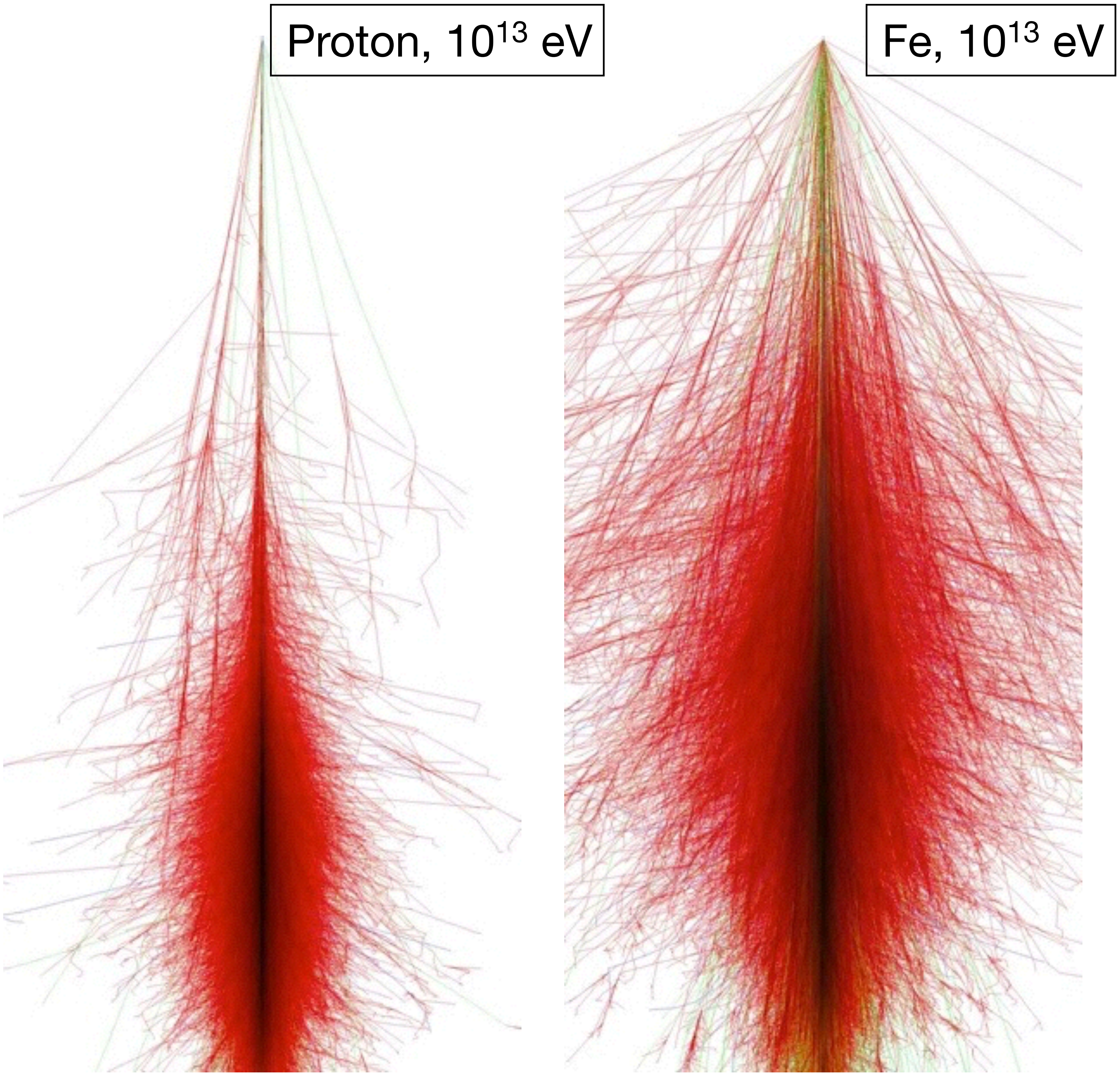
E > 5.7x10^19 eV

Telescope Array:
hotspot (20°), source unknown
(arXiv:1404.5890)



Auger Observatory:
warm spot (18°), probably Cen A

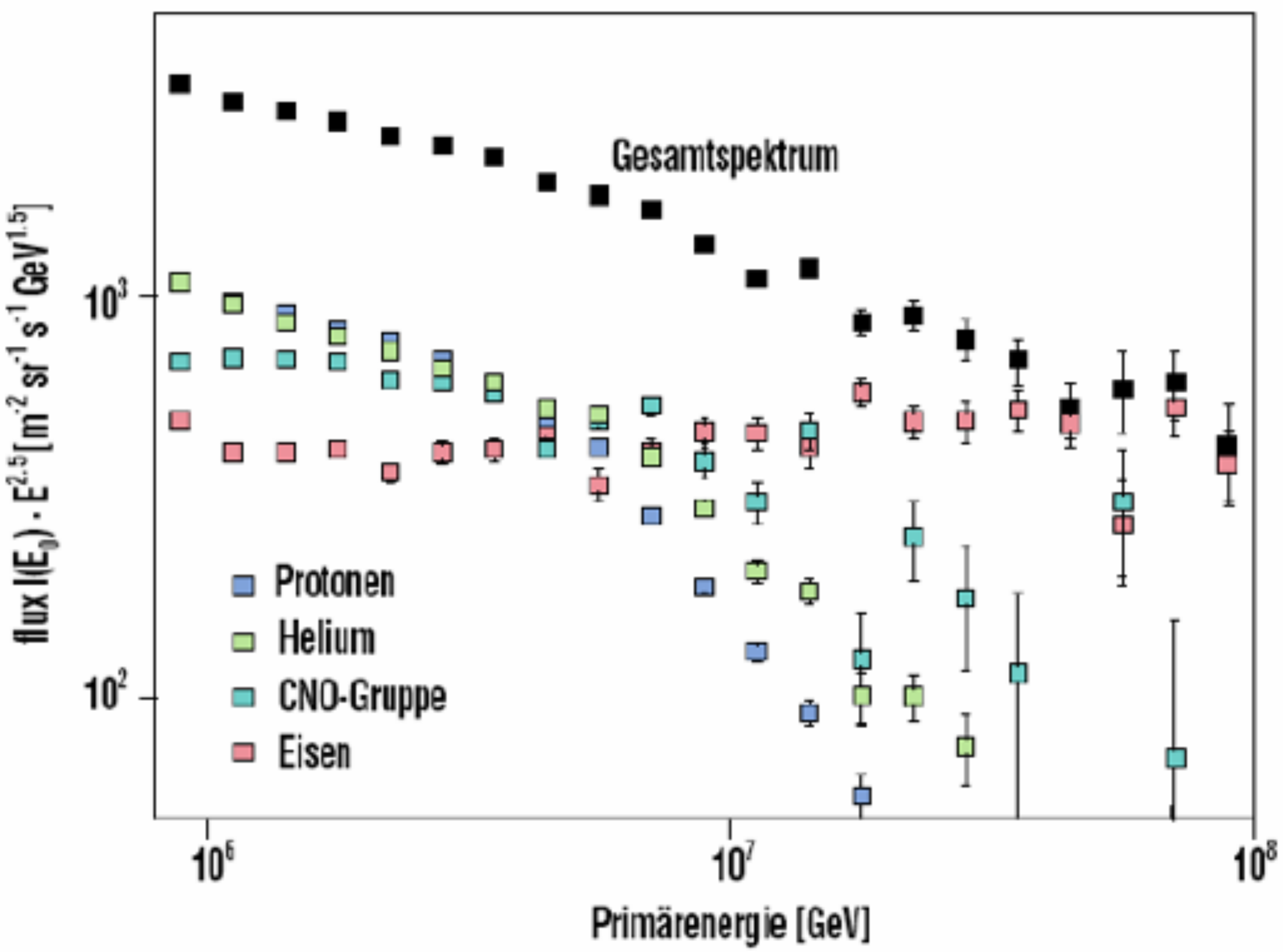
Composition of UHECRs: Protons vs Fe



- Distinction of primary particles possible based on shower structure:
  - Showers of heavy nuclei start “faster” and reach an earlier shower maximum

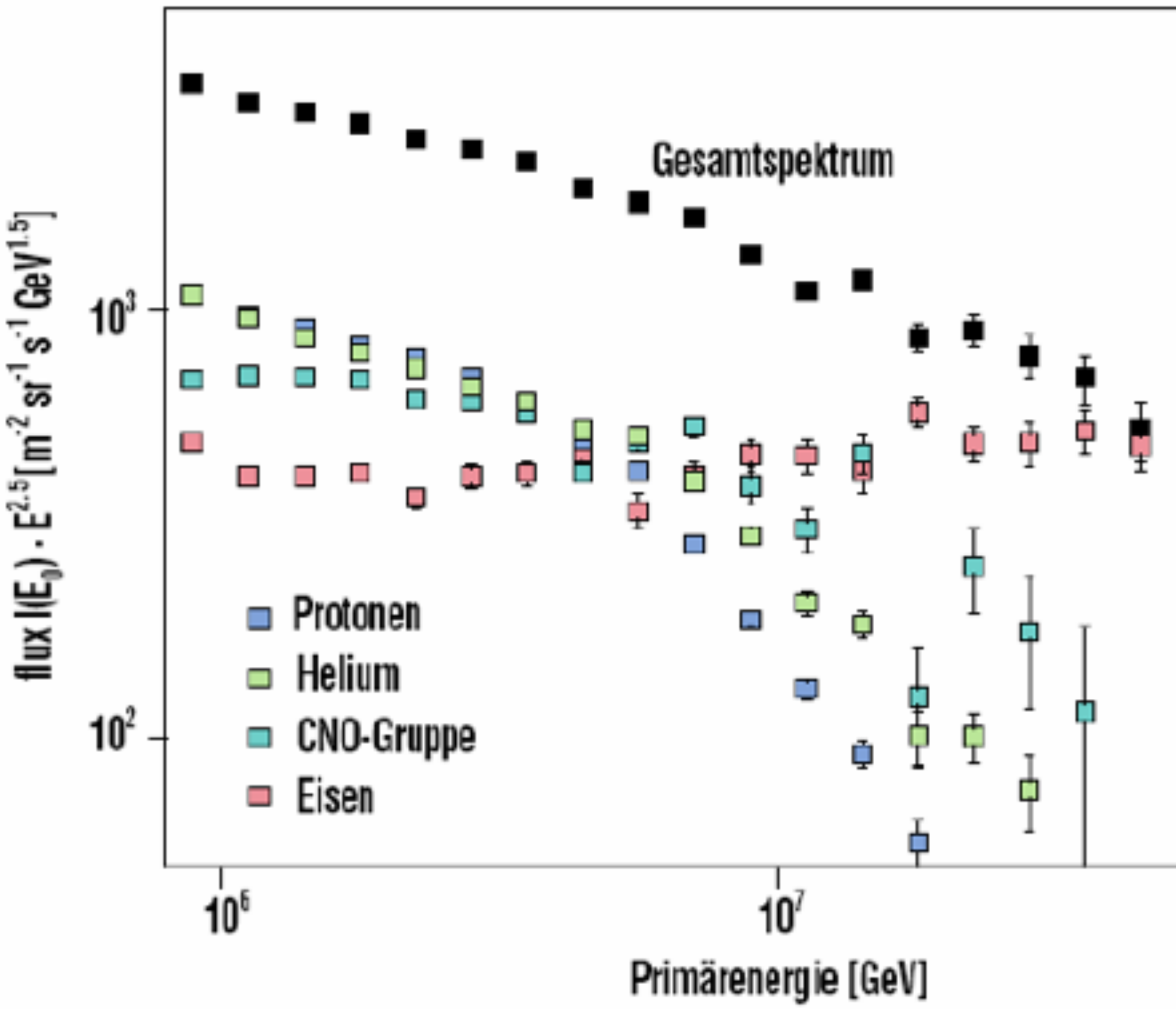
http://www.ast.leeds.ac.uk/~fs/showerimages.html

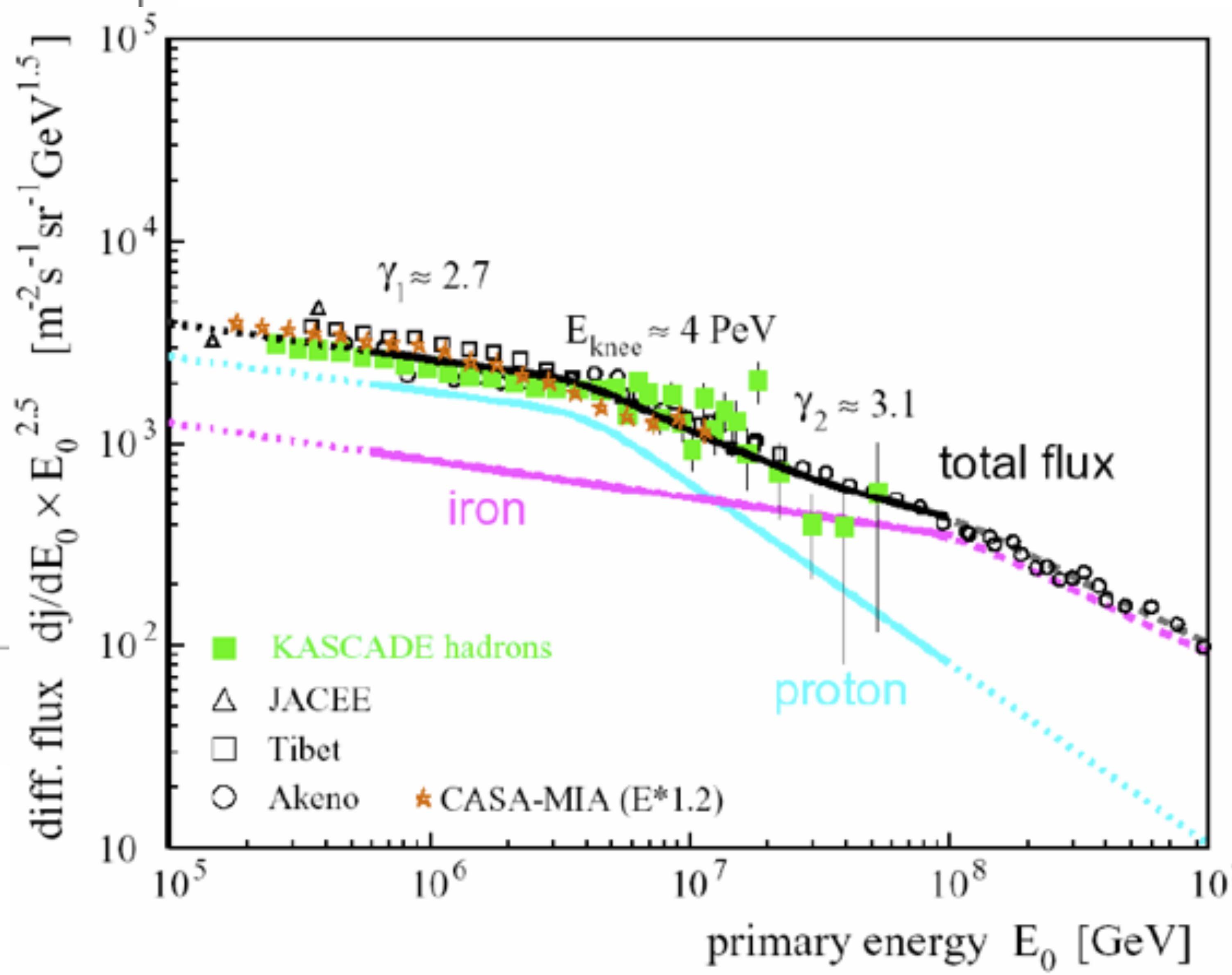
Composition around the Knee of the Distribution



- Position of the knee depends on the element: for heavy nuclei it is at higher energy
  - Fits the current understanding of acceleration mechanisms
- At higher energies heavy elements dominate (for example Fe)

Composition around the Knee of the Distribution





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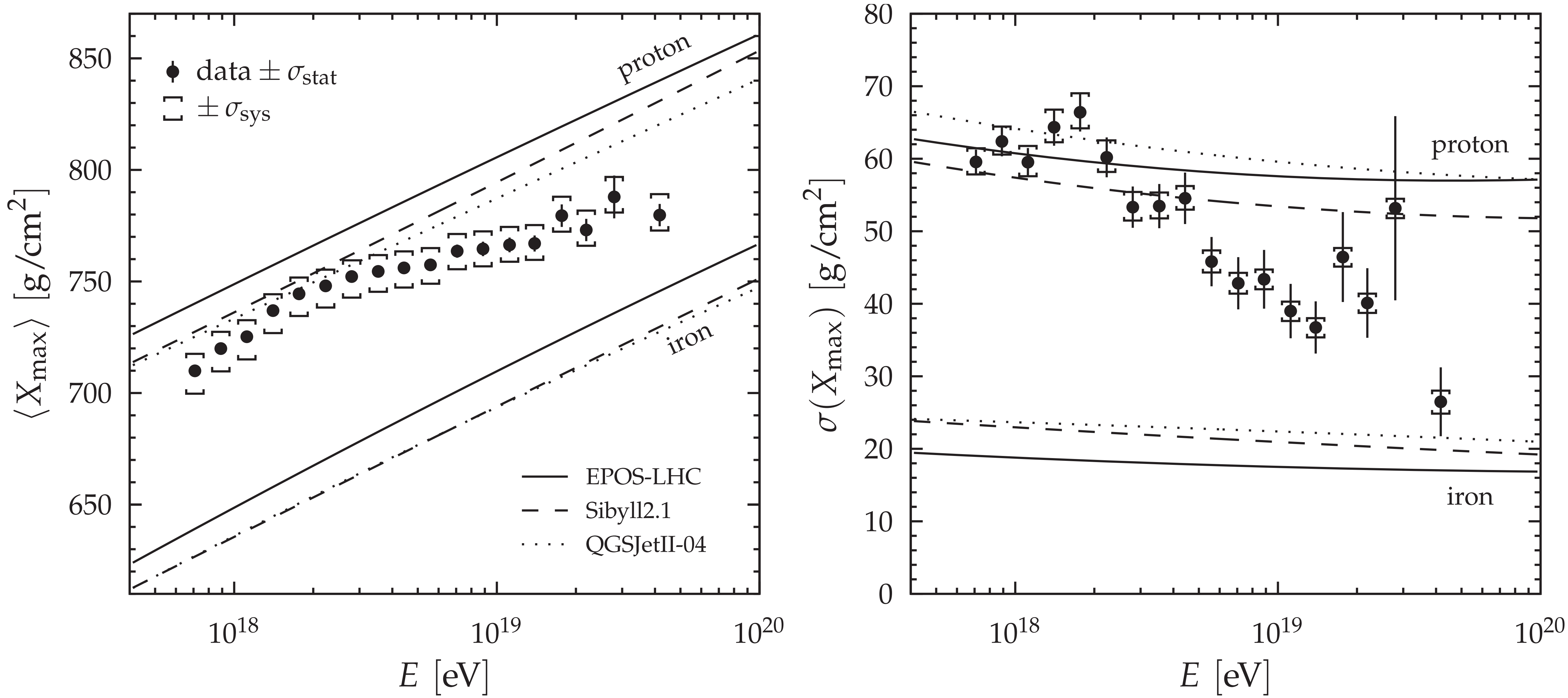
Composition at High Energies

- Determined from shower profile

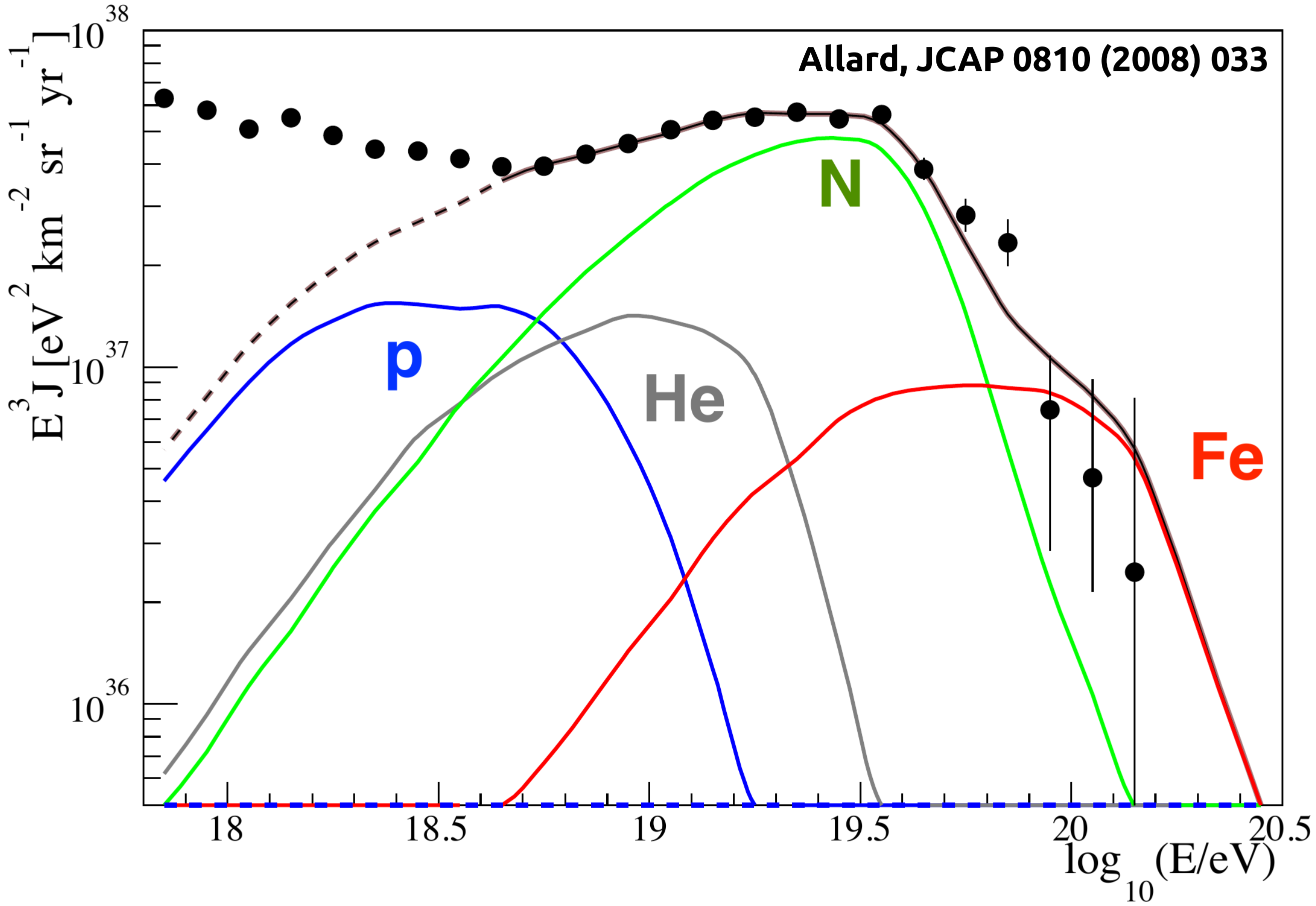
Phys. Rev. D90, 122006 (2014)



- Composition get more iron-like at high energies - Data still missing at the very highest energies (> 10^{20} eV)
  - Can also be interpreted as an energy limit in the sources

Composition and Suppression Scenarios

Scenario 1

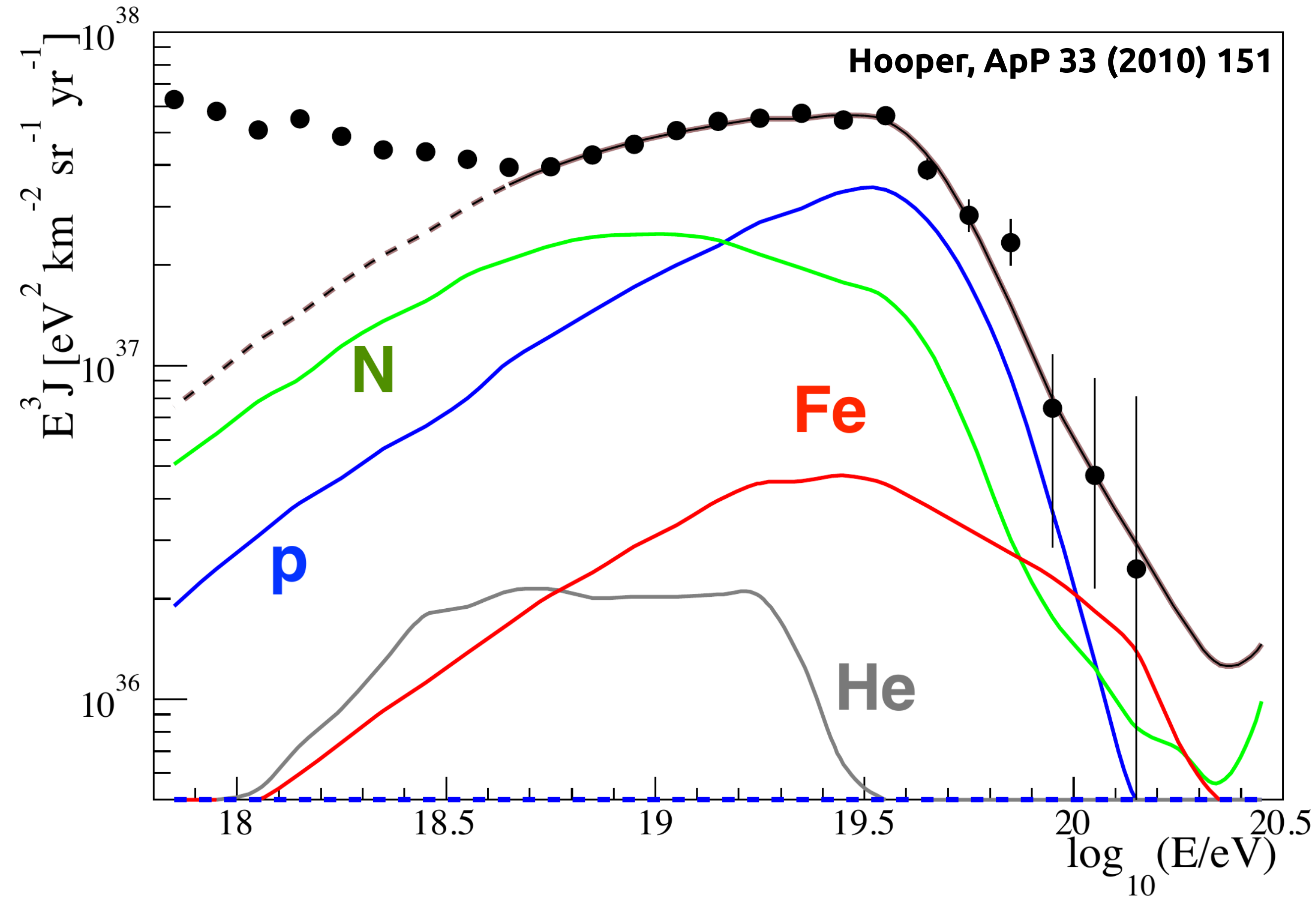


sources accelerate to maximum rigidity (“tired” sources)

energies shifted up by *Z*

heavy injection Si-Fe

Scenario 2



(mostly) photo-disintegration

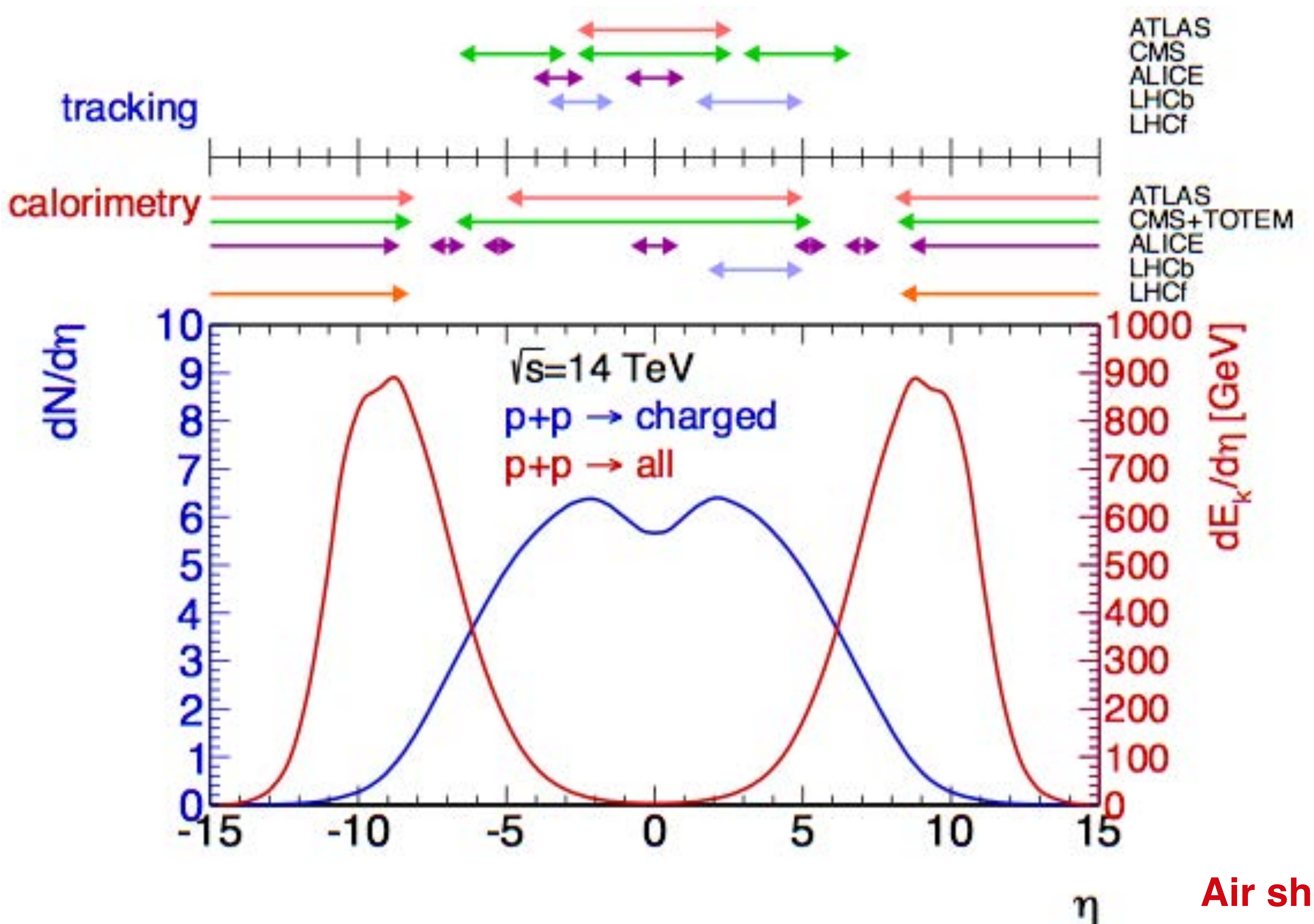
energies shifted down by *A*

light elements come from heavy

CR astronomy still possible

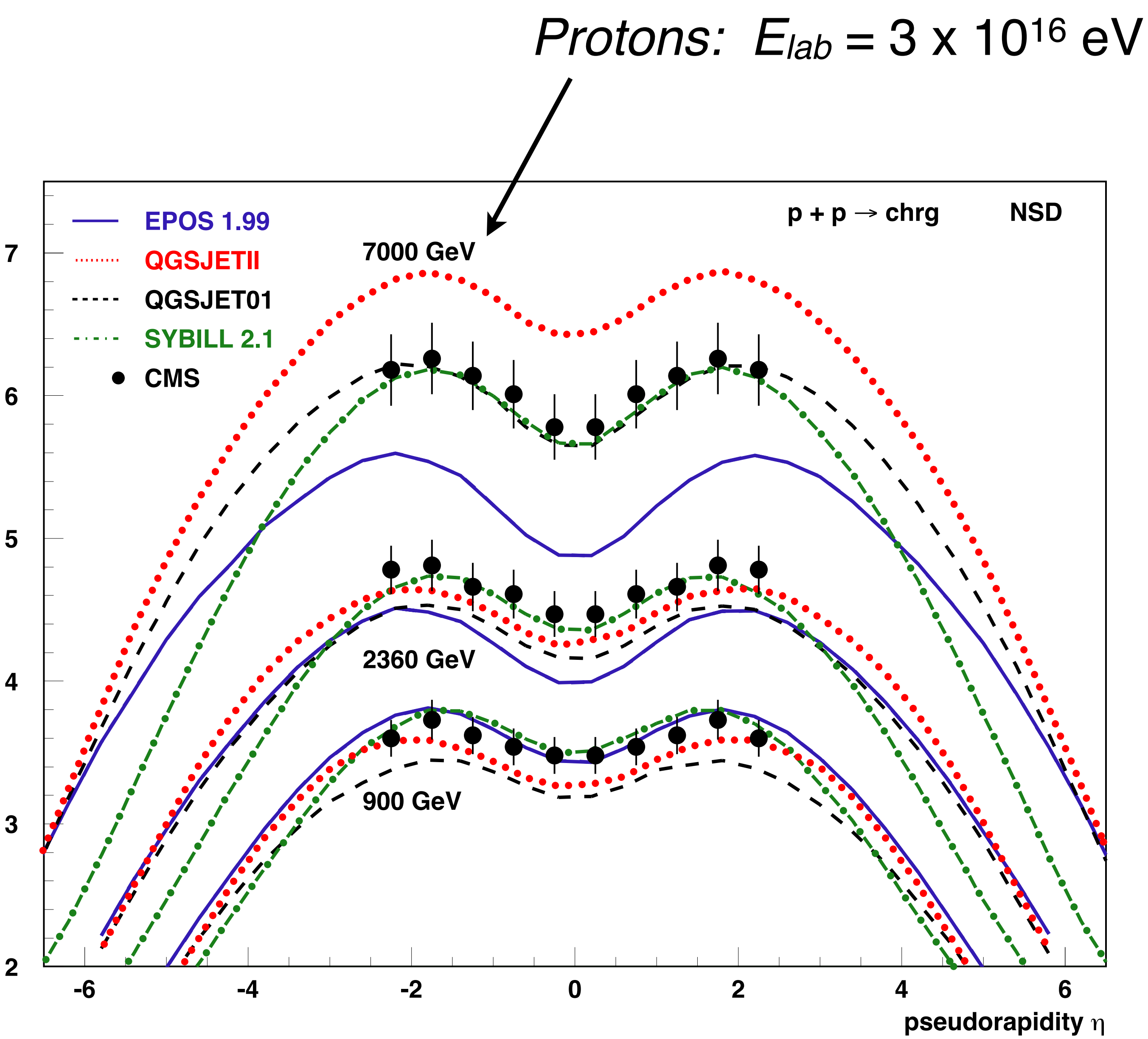
Connection to Collider Physics

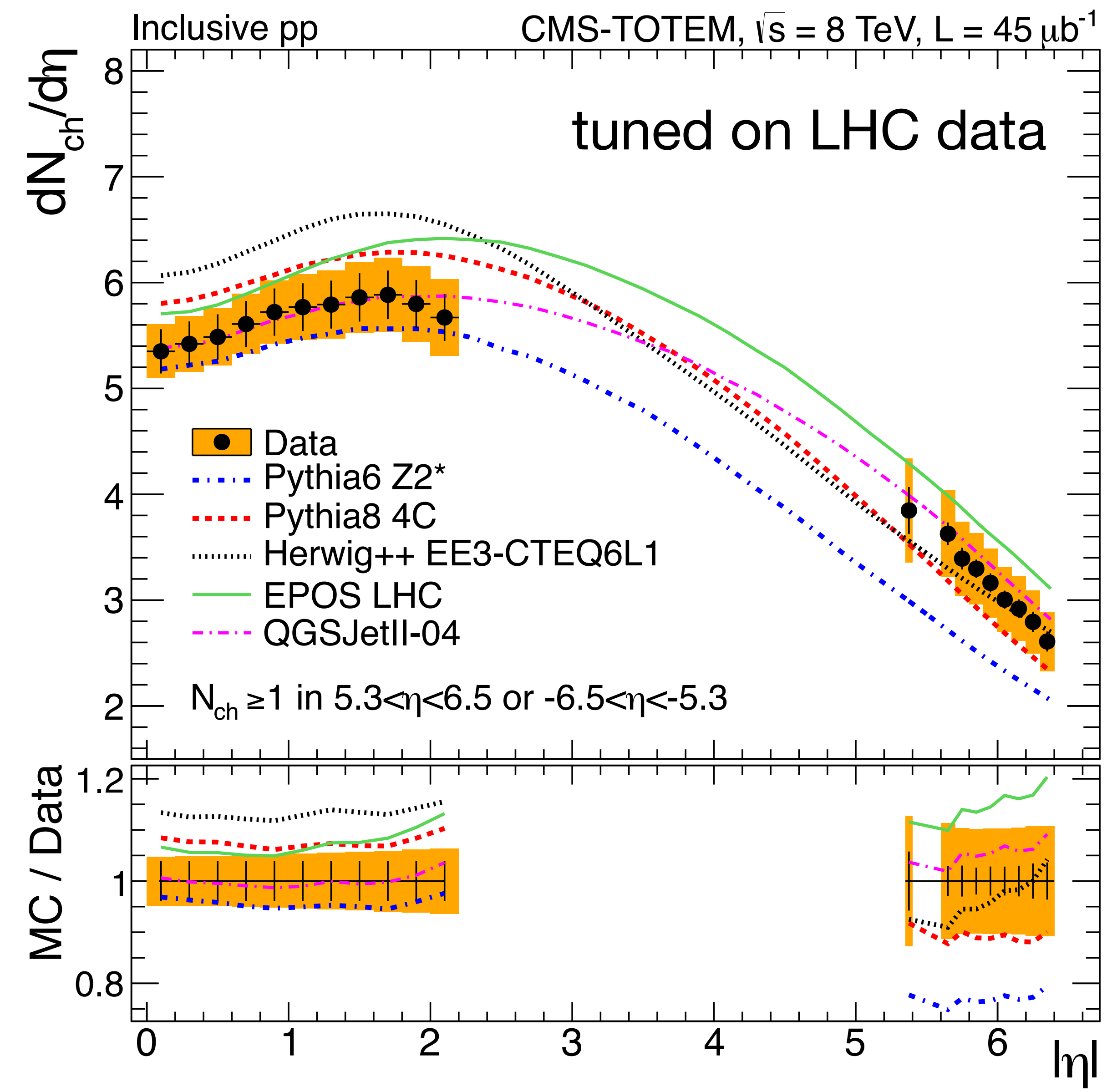
- Different LHC experiments covering most of the relevant phase space



Air showers: Particles of highest energy most important

Connection to Collider Physics

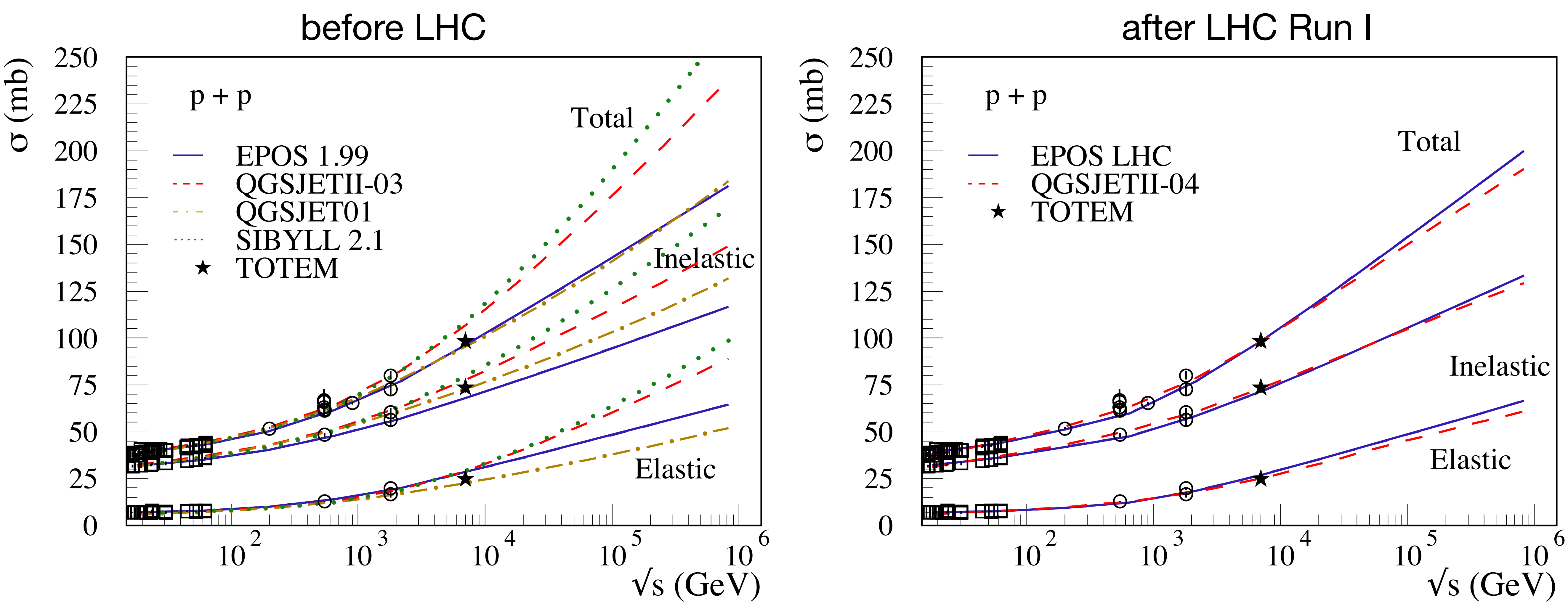




- LHC data has provided substantial input, used to tune and improve the models

Connection to Collider Physics

- One example: Evolution of cross section with energy - crucial for shower evolution



Summary

- Ultra-high energy cosmic rays create particle showers in the atmosphere
  - Detection via particle multiplicity on ground and via fluorescence light
- Particles with energies up to 3 x 10^{20} eV have been observed

- Interactions of charged particles with photons of the cosmic microwave background introduce an energy limit for particles over long distance scales
  - The GZK - Cutoff: ~ 7 x 10^{19} eV for protons, experimentally well established

- The search for sources is going on: Indications of anisotropic distribution, possible correlation with AGN
  - Centaurus A is one possible candidate

- Composition of cosmic rays at high energies is unclear - LHC data, including specialized experiments help to improve the simulation models

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Next Lecture: 20.06., "Cosmic Rays II", F. Simon

Topics - Overview

11.04.	Einführung / Introduction
18.04.	Erdgebundene Beschleuniger / Accelerators
25.04.	Detektoren in der Nicht-Beschleuniger-Physik / Detectors
02.05.	Kosmische Beschleuniger / Cosmic Accelerators
09.05.	Das Standardmodell / The Standard Model
16.05.	Pfingsten - Keine Vorlesung! No Lecture
23.05.	QCD und Jet Physik an Lepton Beschleunigern / QCD and Jets
30.05.	Präzisionsexperimente (g-2) / Precision Experiments
06.06.	Gravitationswellen / Gravitational Waves
13.06.	Kosmische Strahlung I / Cosmic Rays I
20.06.	Kosmische Strahlung II / Cosmic Rays II
27.06.	Dunkle Materie & Dunkle Energie / Dark Matter & Dark Energy
04.07.	Neutrinos I
11.07.	Neutrinos II