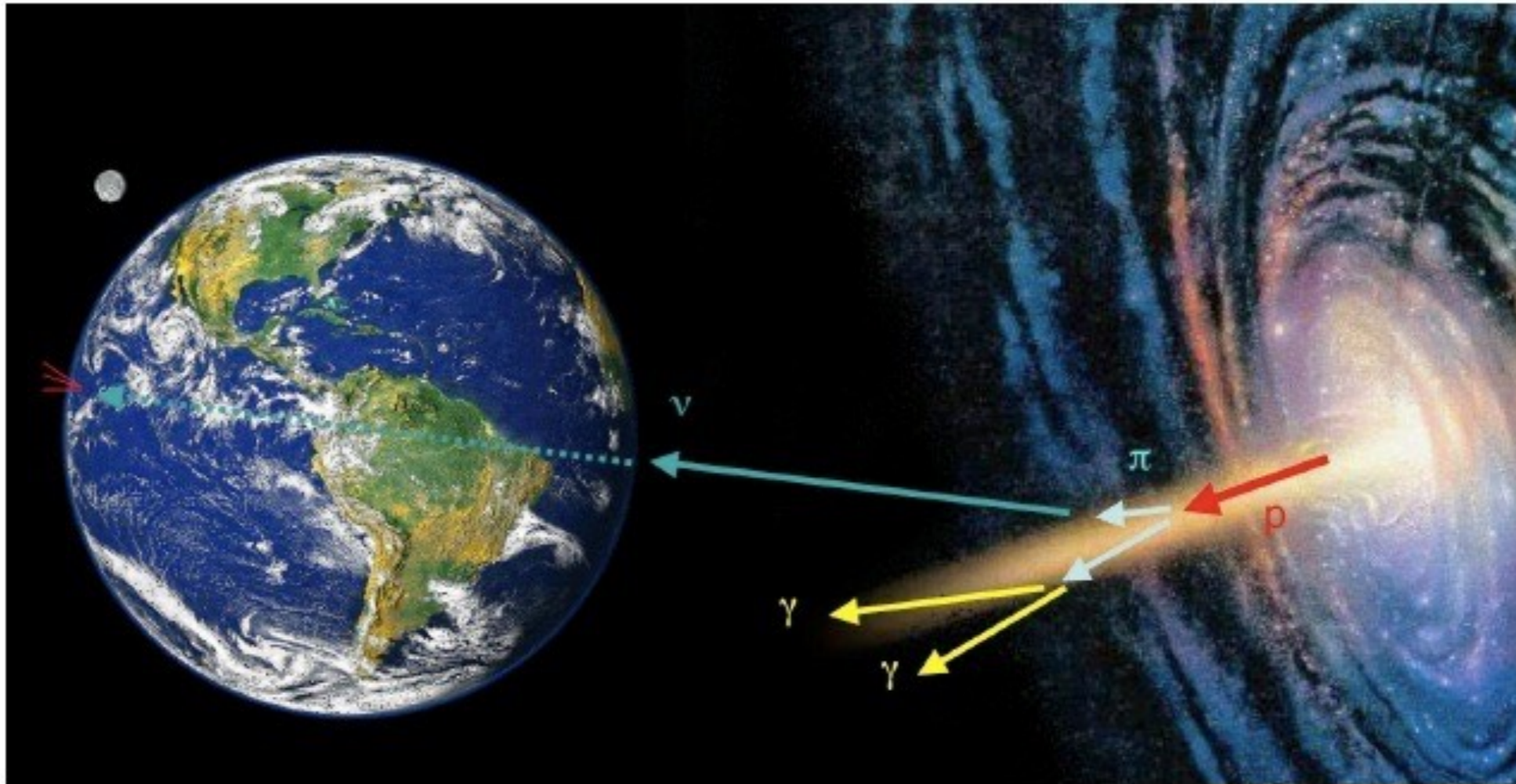


Teilchenphysik mit kosmischen und mit erdgebundenen Beschleunigern

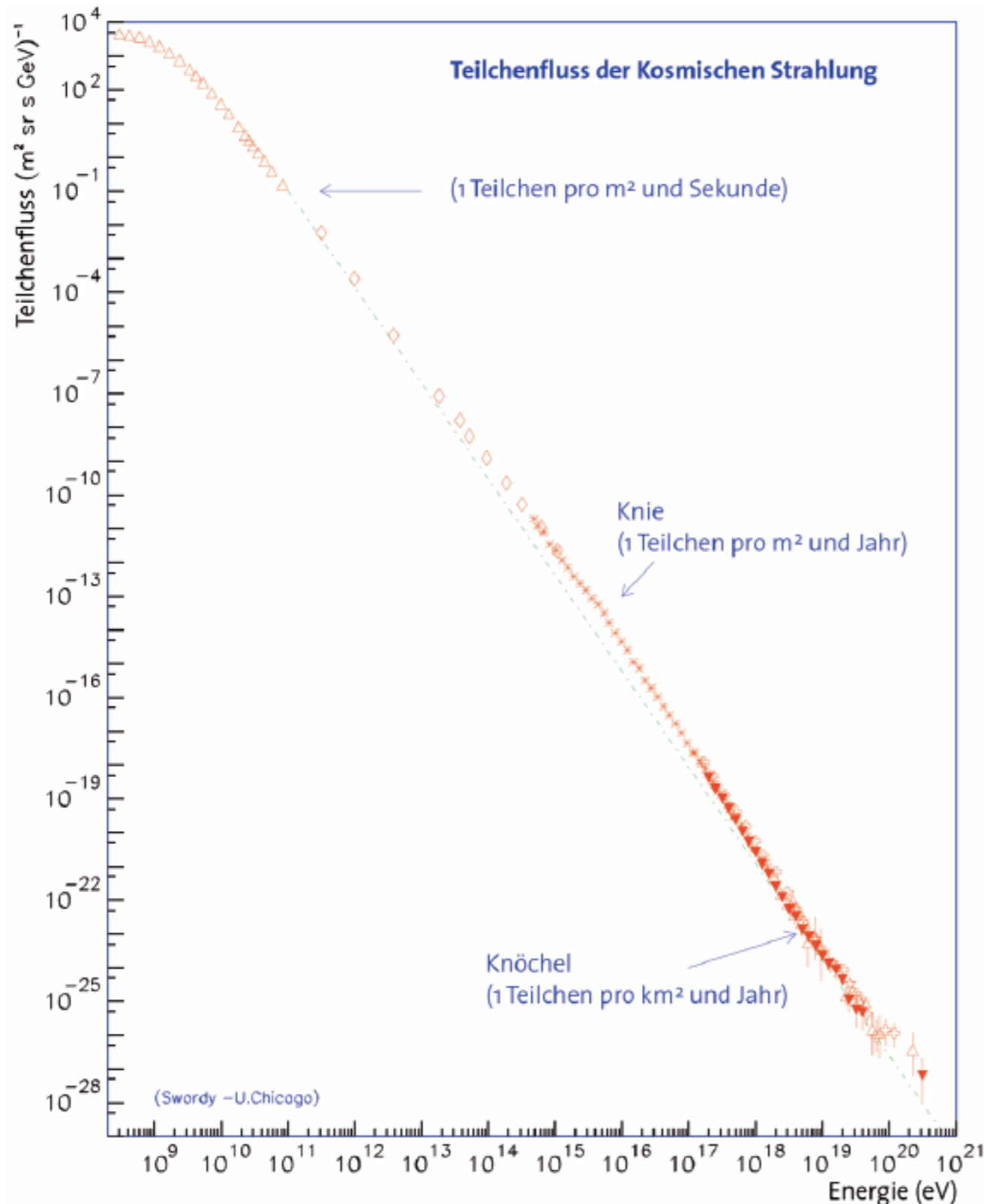


09. Cosmic Rays I

11.06.2018



Reminder: Cosmic Rays - Spectrum



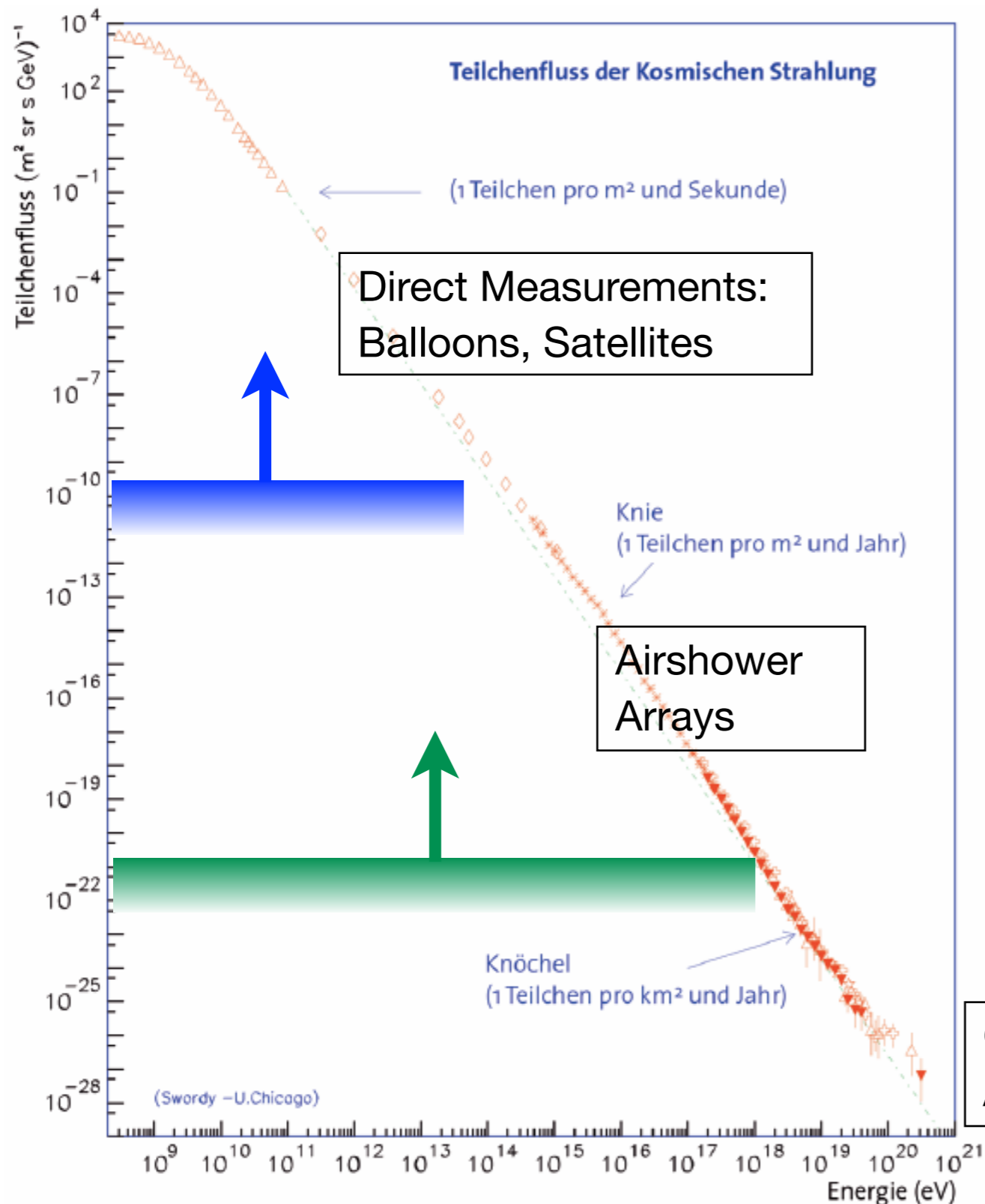
- Extends over many orders of magnitude in energy and flux:
 - ▶ GeV (10⁹ eV) - ZeV (10²¹)
 - ▶ >1 cm⁻²s⁻¹ - < 1 km⁻² per century

- 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 m²
 - Measurement with airshower arrays active area ~ 10 000 m²
 - Measurement with giant airshower arrays Active area ~ 1000 km²

Air Showers: The Atmosphere as Calorimeter

- Nuclear interaction length $\lambda_I \sim 90 \text{ g/cm}^2$
- Radiation length $X_0 \sim 36.6 \text{ g/cm}^2$
- Density of the atmosphere: $\sim 1035 \text{ g/cm}^3$
- ▶ $\sim 11 \lambda_I, \sim 28 X_0$

Reminder:

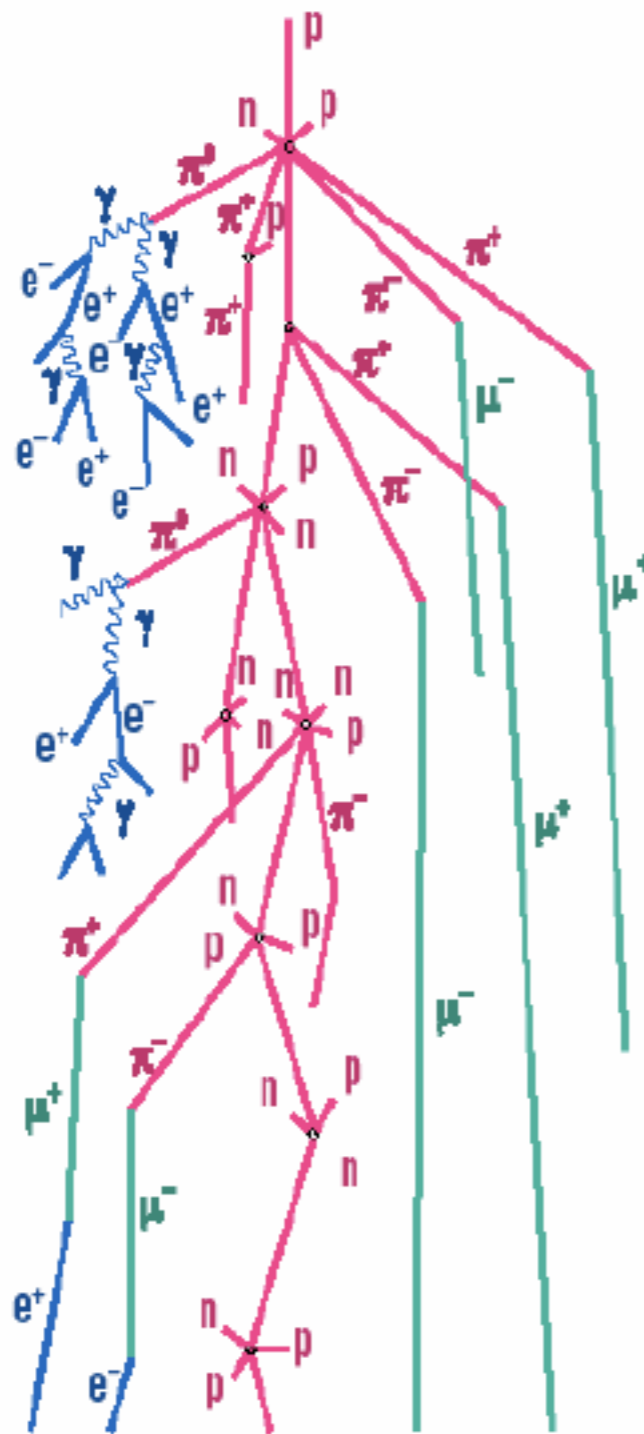
Radiation length: Energy loss of electrons in matter:

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

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

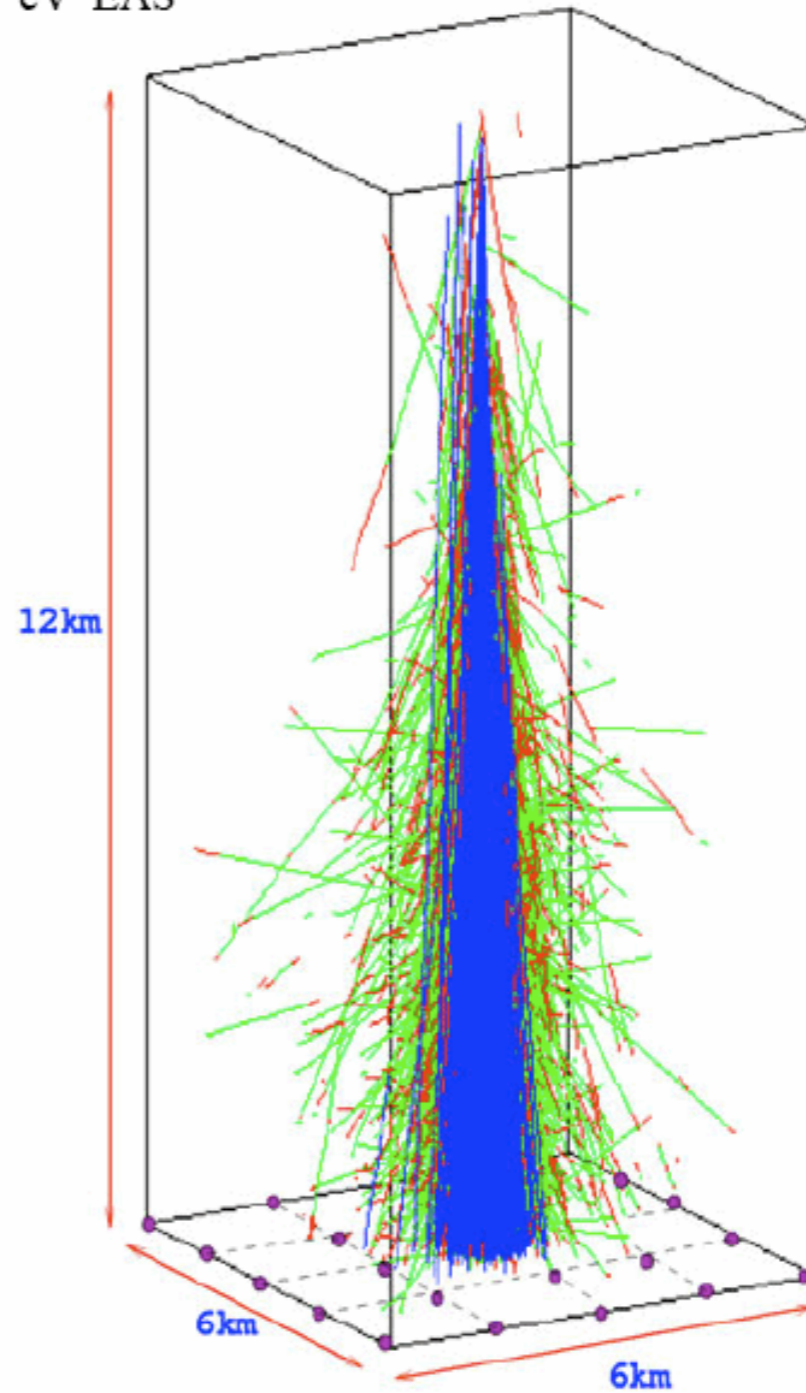
$$P(x) = e^{-\frac{x}{\lambda_I}}$$

Extended Air Showers (EAS)



elektromagnetische Komponente
hadronische Komponente
myonische Komponente

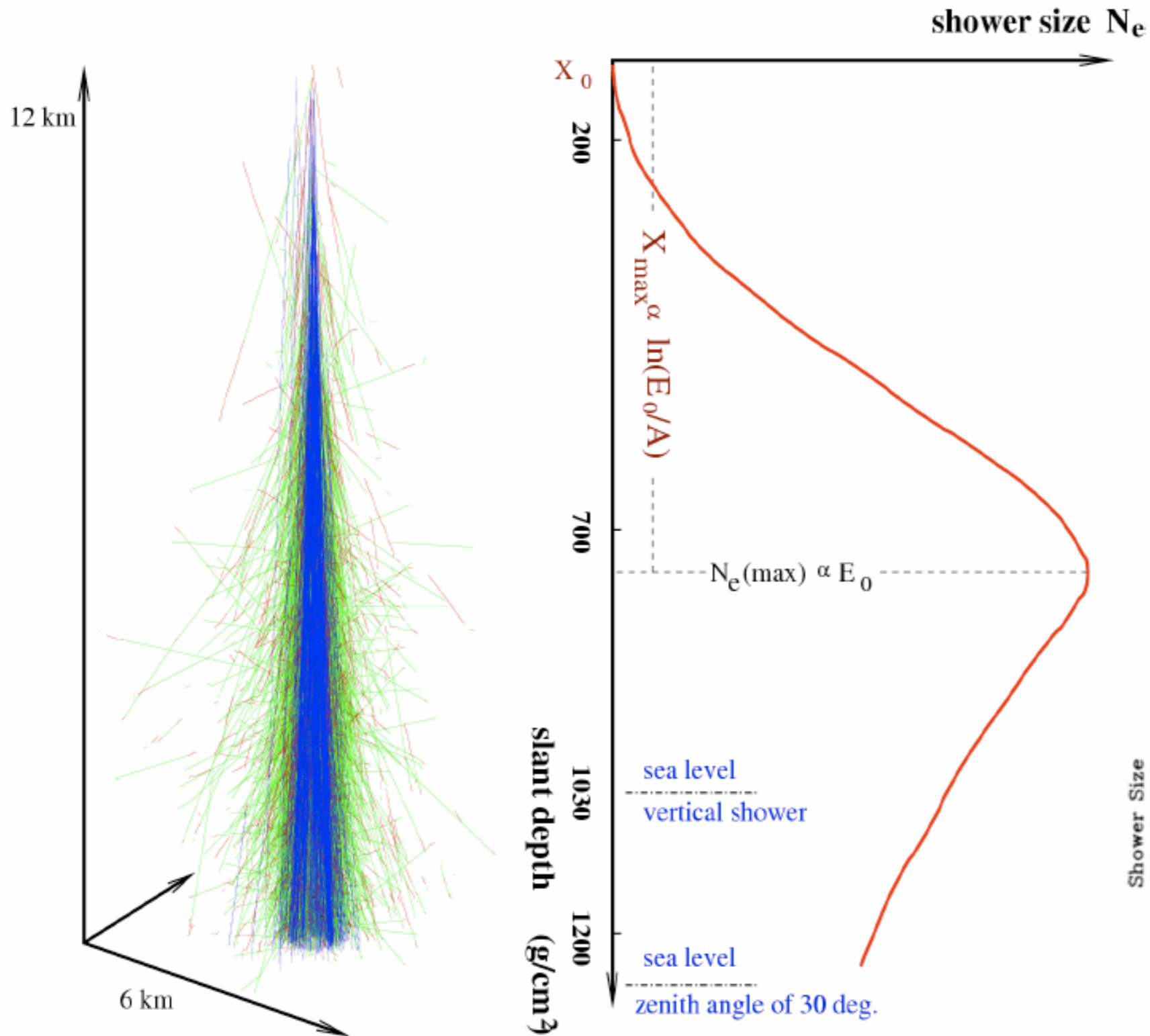
10^{19} eV EAS



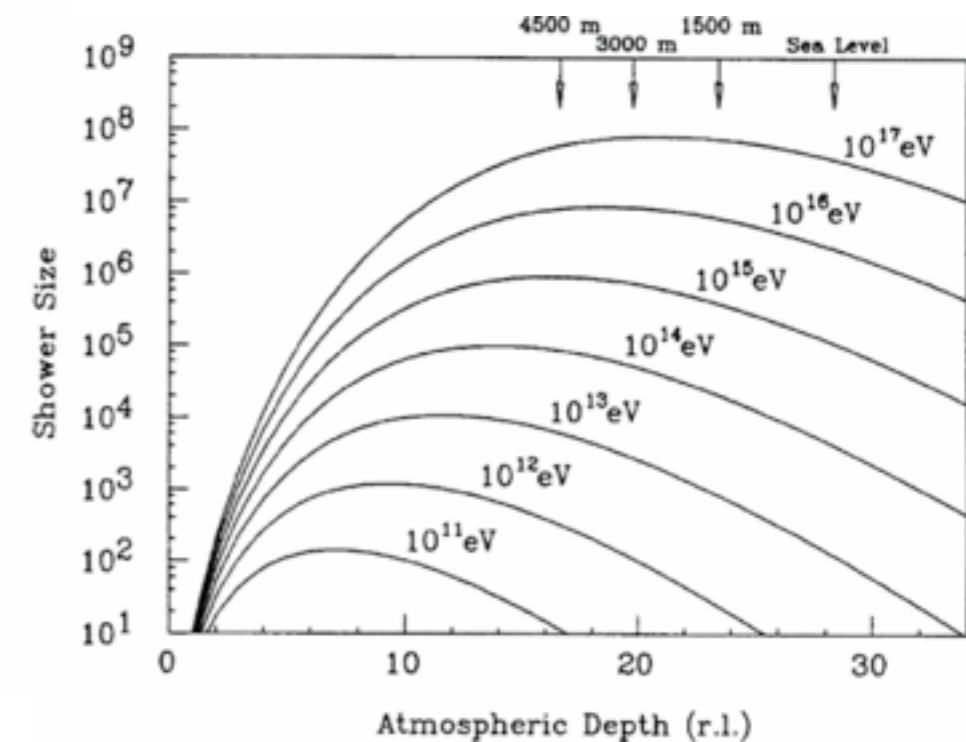
100 billion particles at sea level
 photons, electrons (99%), muons (1%)
 ● Ground Array stations



EAS: In the Atmosphere



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



R.Engel, ISAPP2005

EAS: Hadronic Component

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

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▶ electromagnetic shower

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▶ Neutral pions: $\pi^0 \rightarrow \gamma\gamma, \tau \sim 10^{-16} s$

▶ 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 $\sim 10 - 20$ GeV the range is $\sim 1 \lambda_I$)

▶ Muonic component is integrating: Muon decay irrelevant on shower time scale, lifetime $\sim 2 \times 10^{-6} s$

▶ The production of additional hadrons dominates early in the shower, towards the end decay into muons is more probable

EAS: Electromagnetic Component

- Pair production of photons from pion decay (or primary photon):

$$\gamma \rightarrow e^+ + e^-$$

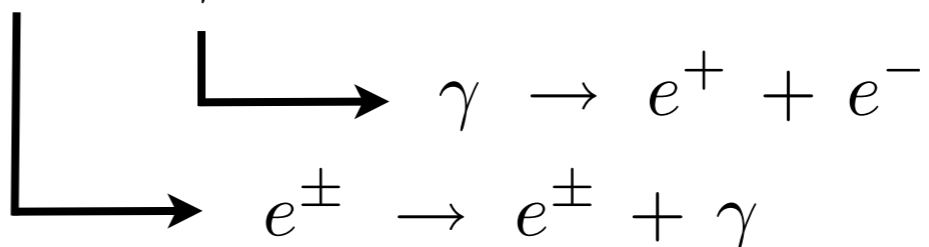
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- Bremsstrahlung in the field of nuclei

$$e^\pm \rightarrow e^\pm + \gamma$$



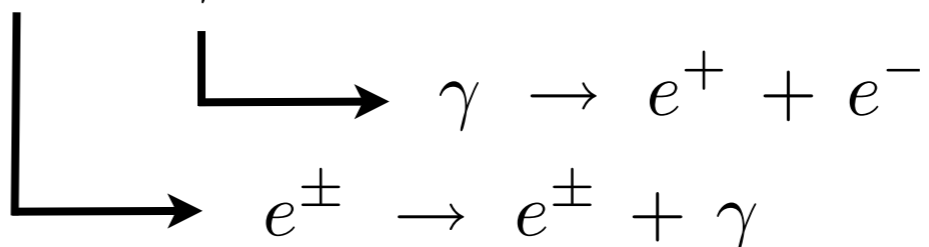
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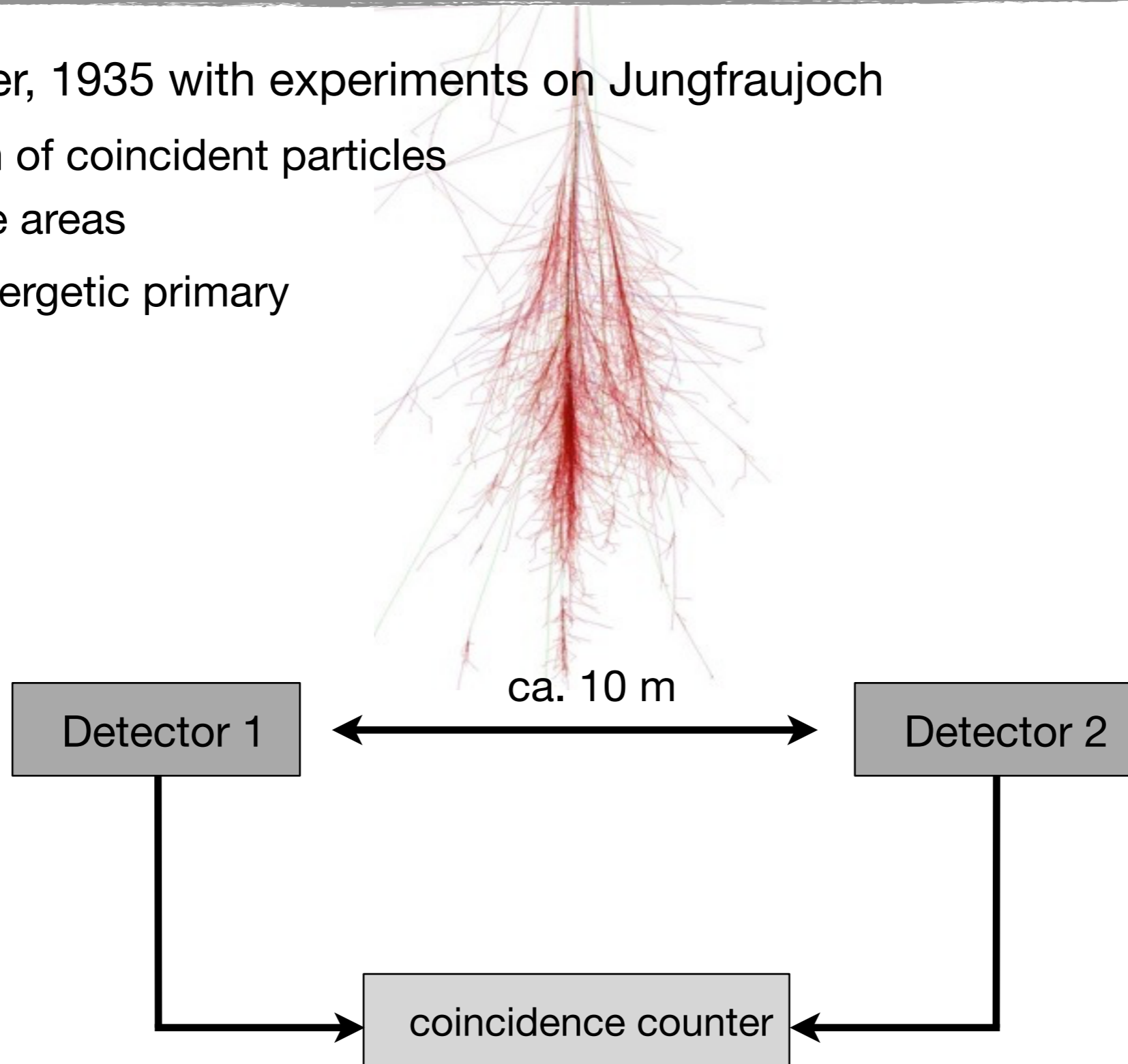
- Continuation of the cascade until

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

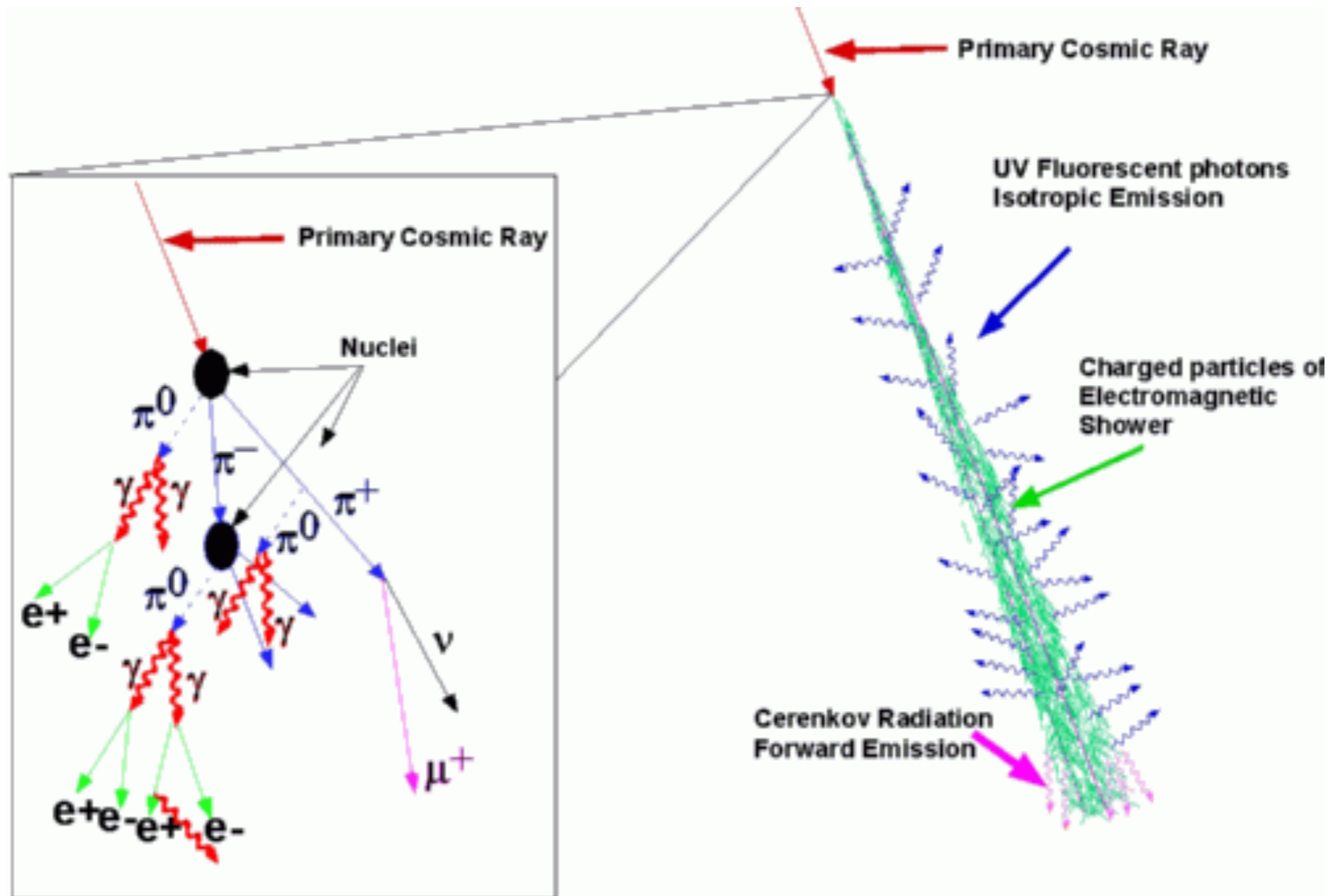
- Highest particle number in the shower maximum, reduction afterwards

Extended Air Showers: Discovery

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



EAS: Measurement

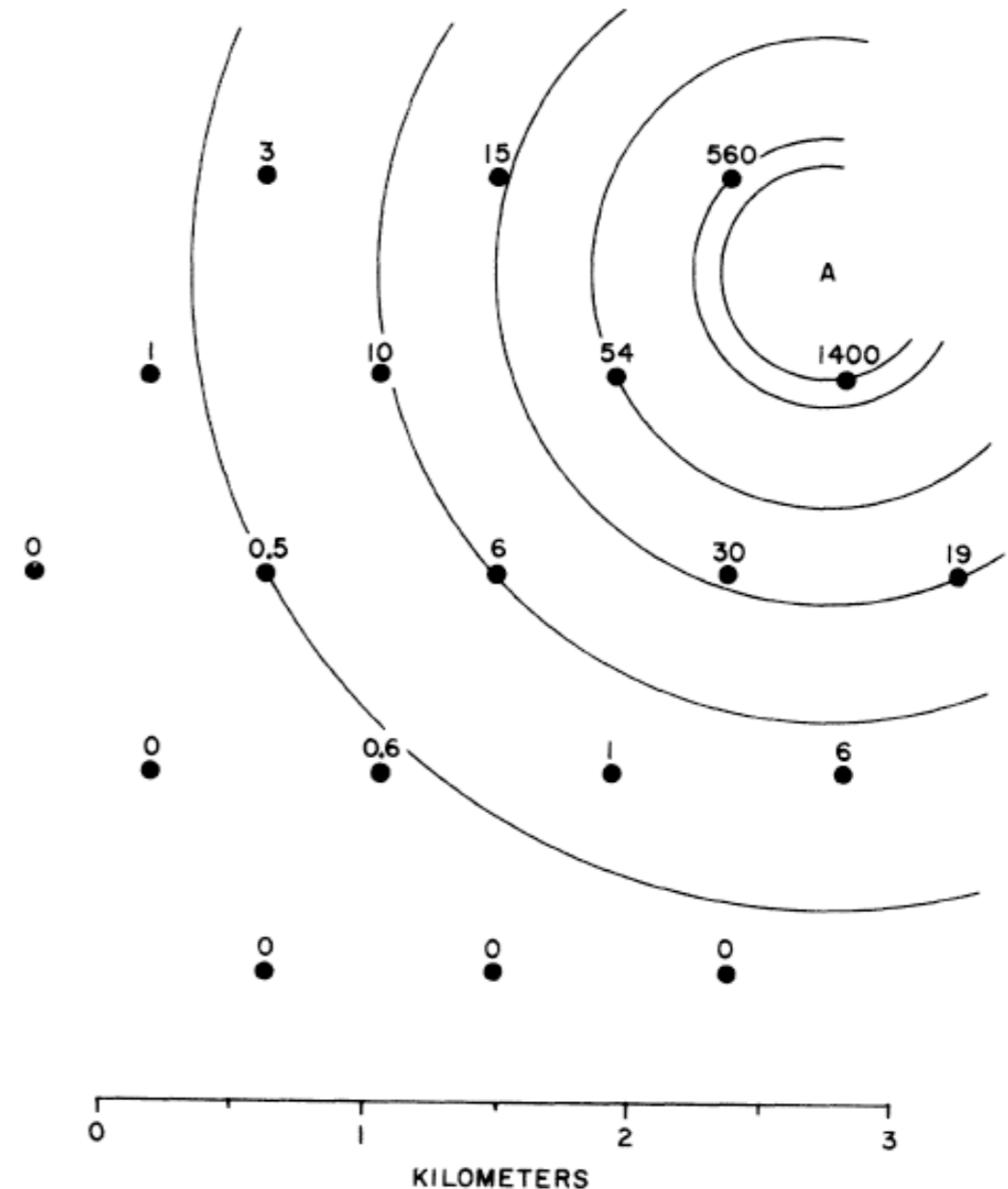


- Detection of charged particles on the surface in “ground arrays”
- Measurement of fluorescence light
- Measurement of Cherenkov light

Ultra-High Energy Cosmic Rays: Discovery



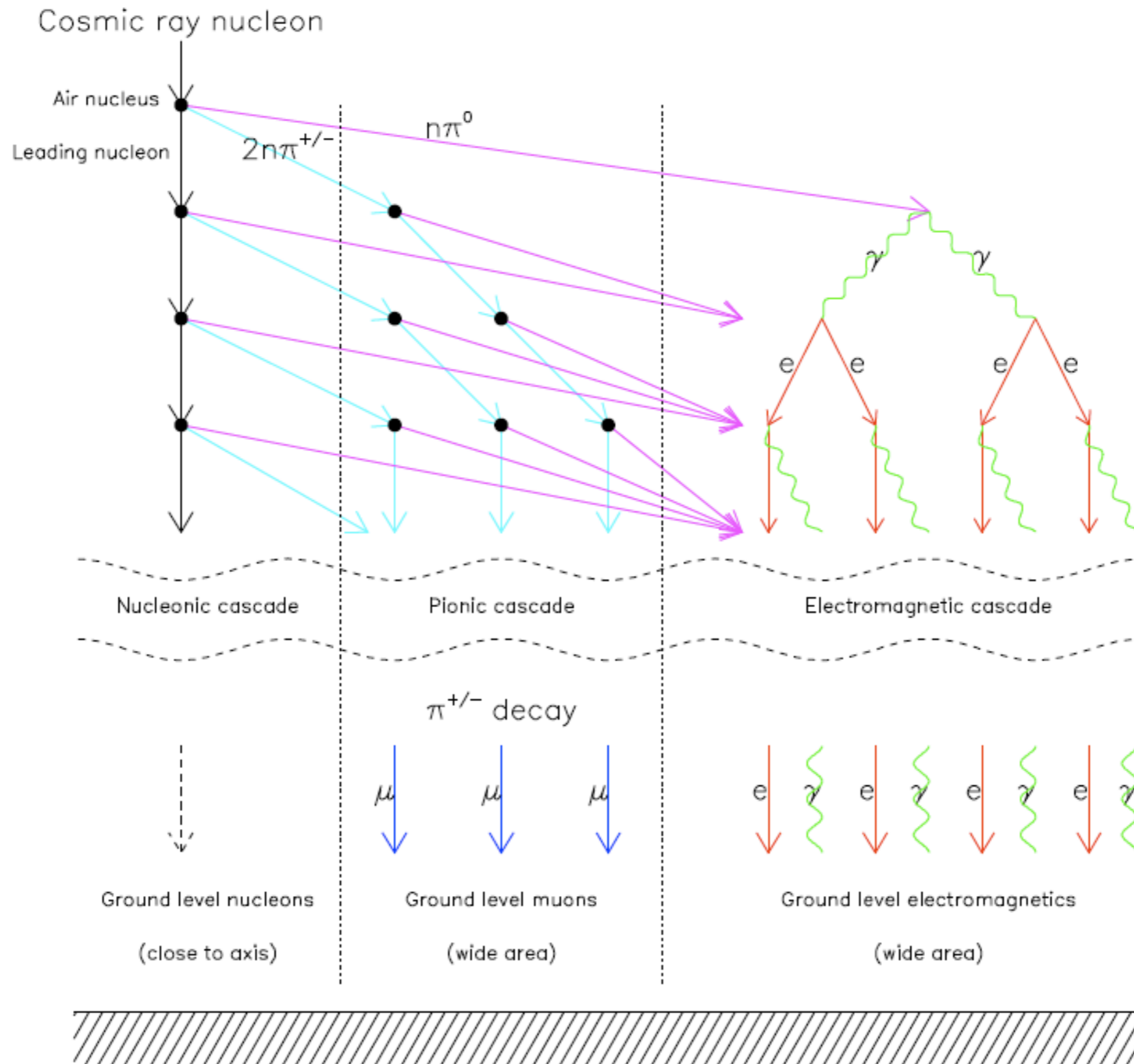
- Primary energy determined to be **10^{20} eV**



- John Linsley et. al, 1962, MIT Volcano Ranch Array, NM, USA
- ~8 km², 19 Detectors a 3.3 m² (Scintillation Counters)
- Determination of primary energy based on shower size (Number of particles) on ground

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

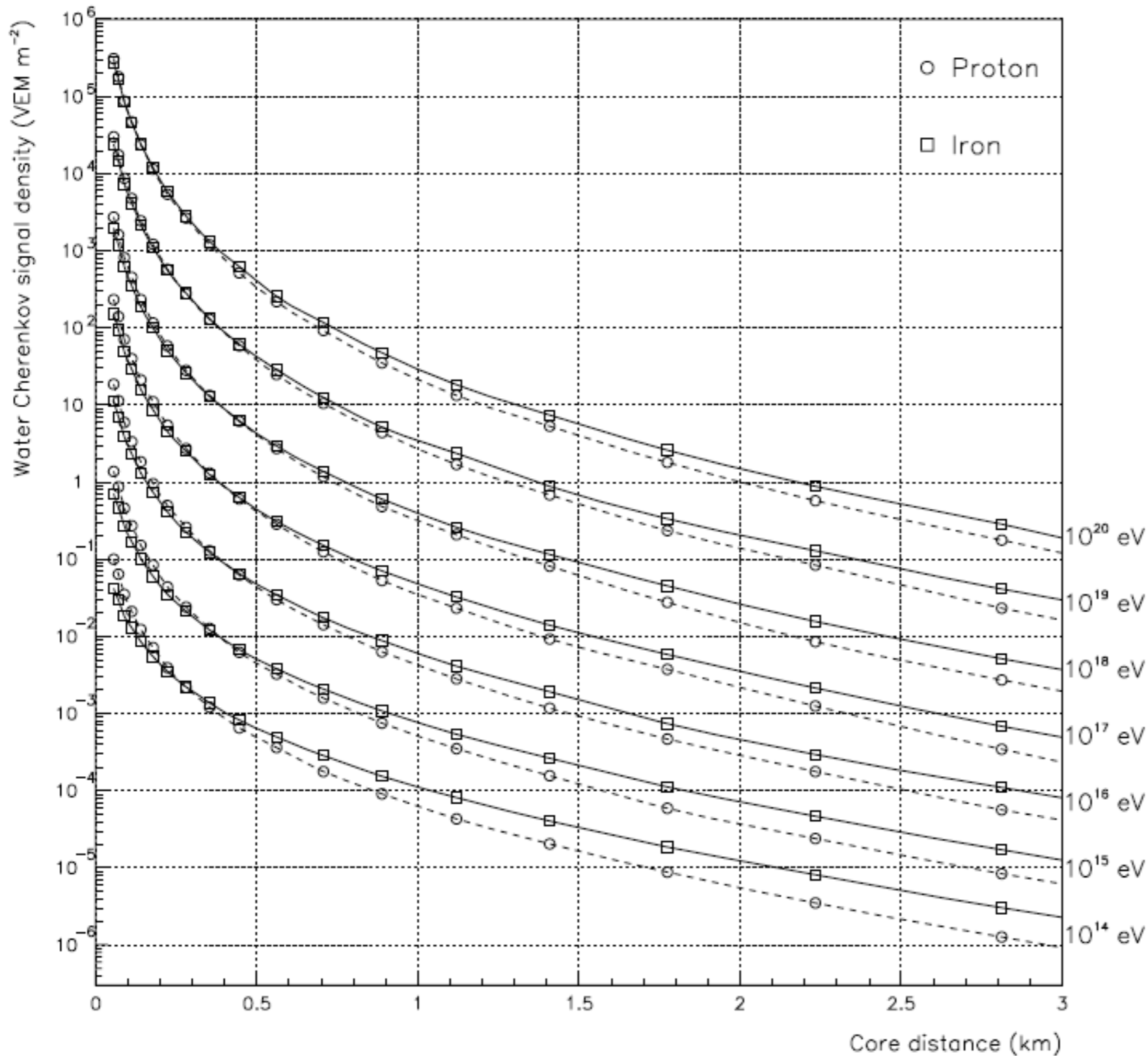
Extended Air Showers



AUGER TDR



Shower Multiplicity and Energy

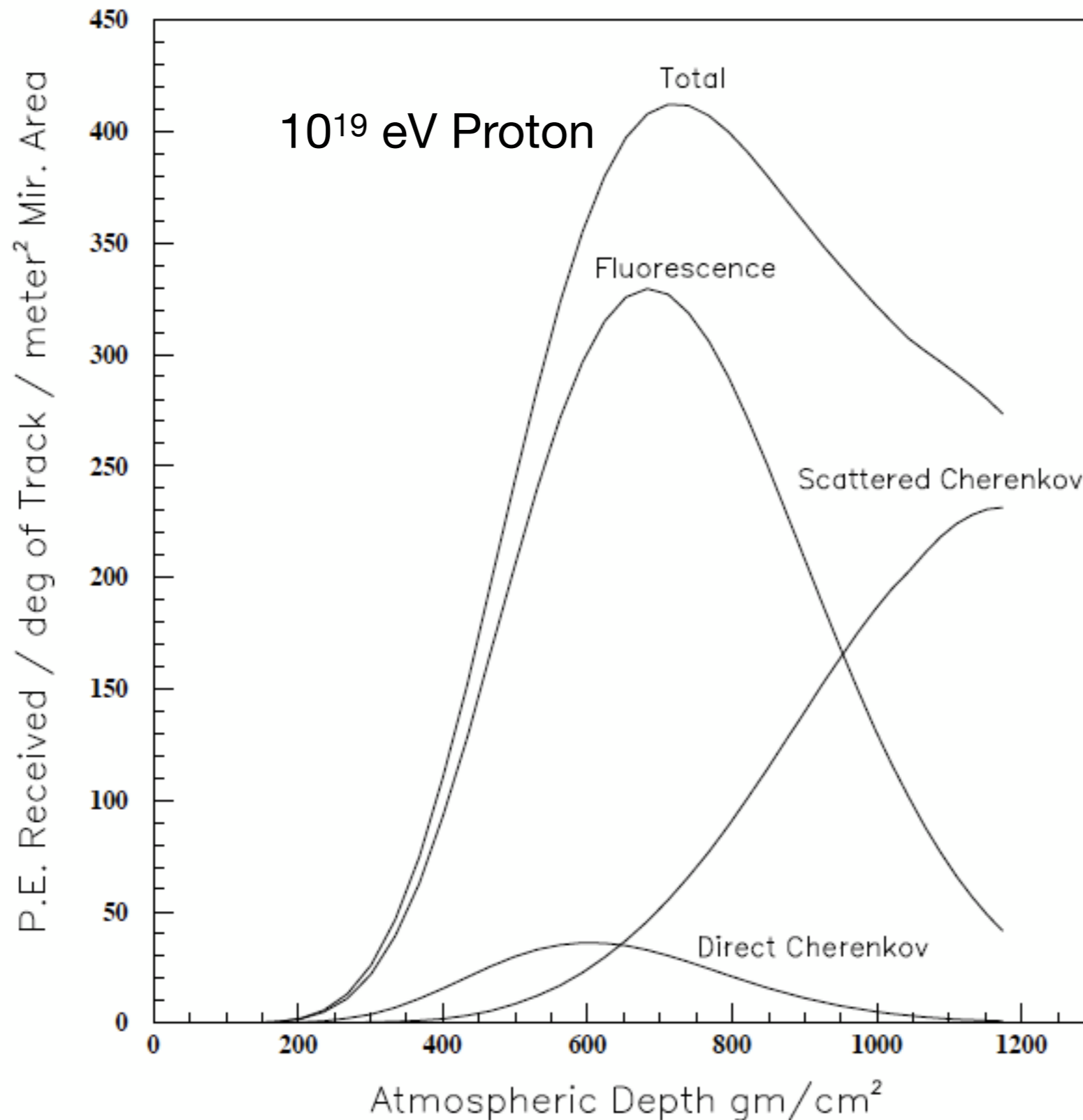


- Particle density on ground at different distances from the shower core is a good measure for the total energy

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

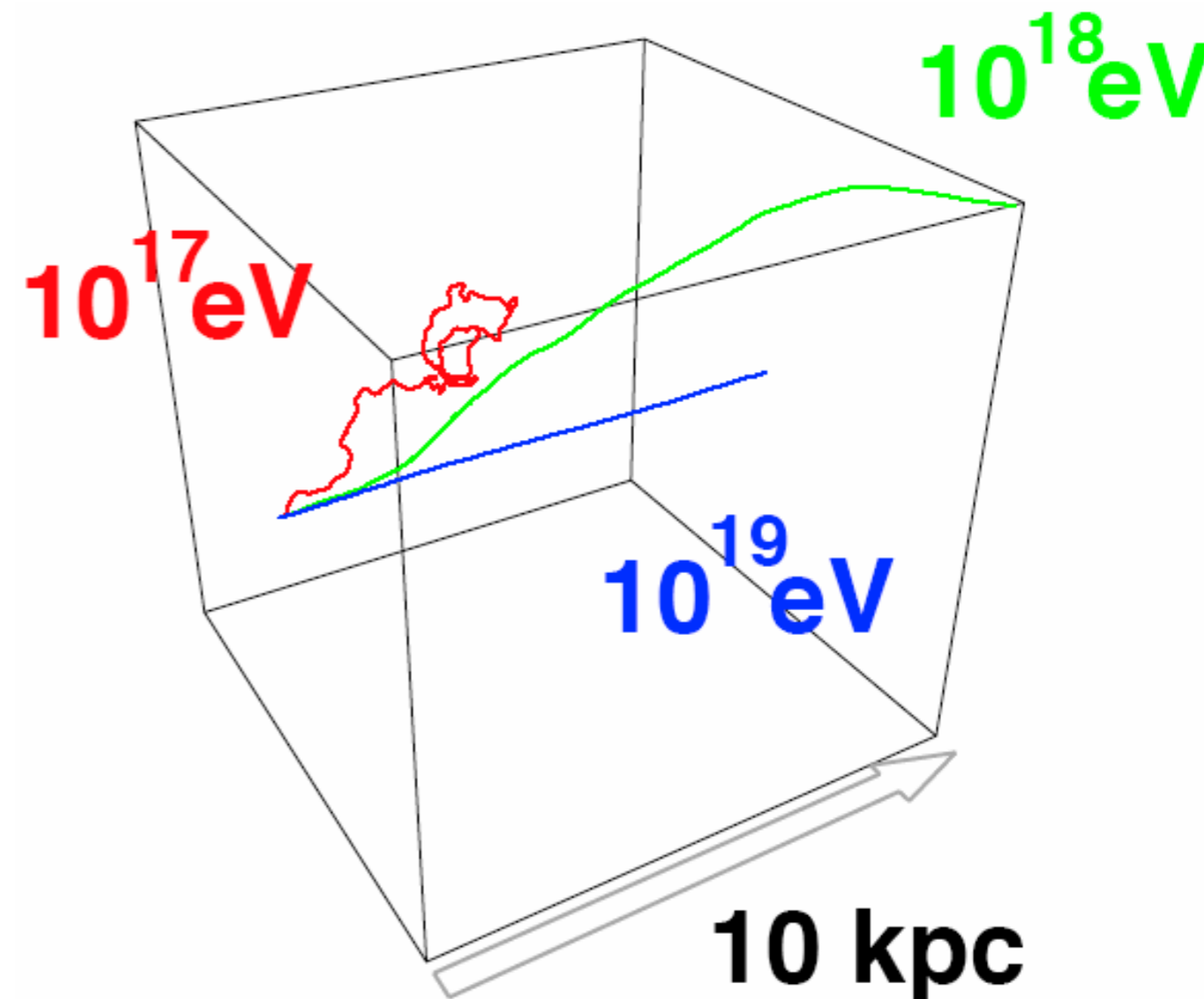
Why are the highest Energies interesting?

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

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Almost no deflection in magnetic fields, these particles could point to their sources!

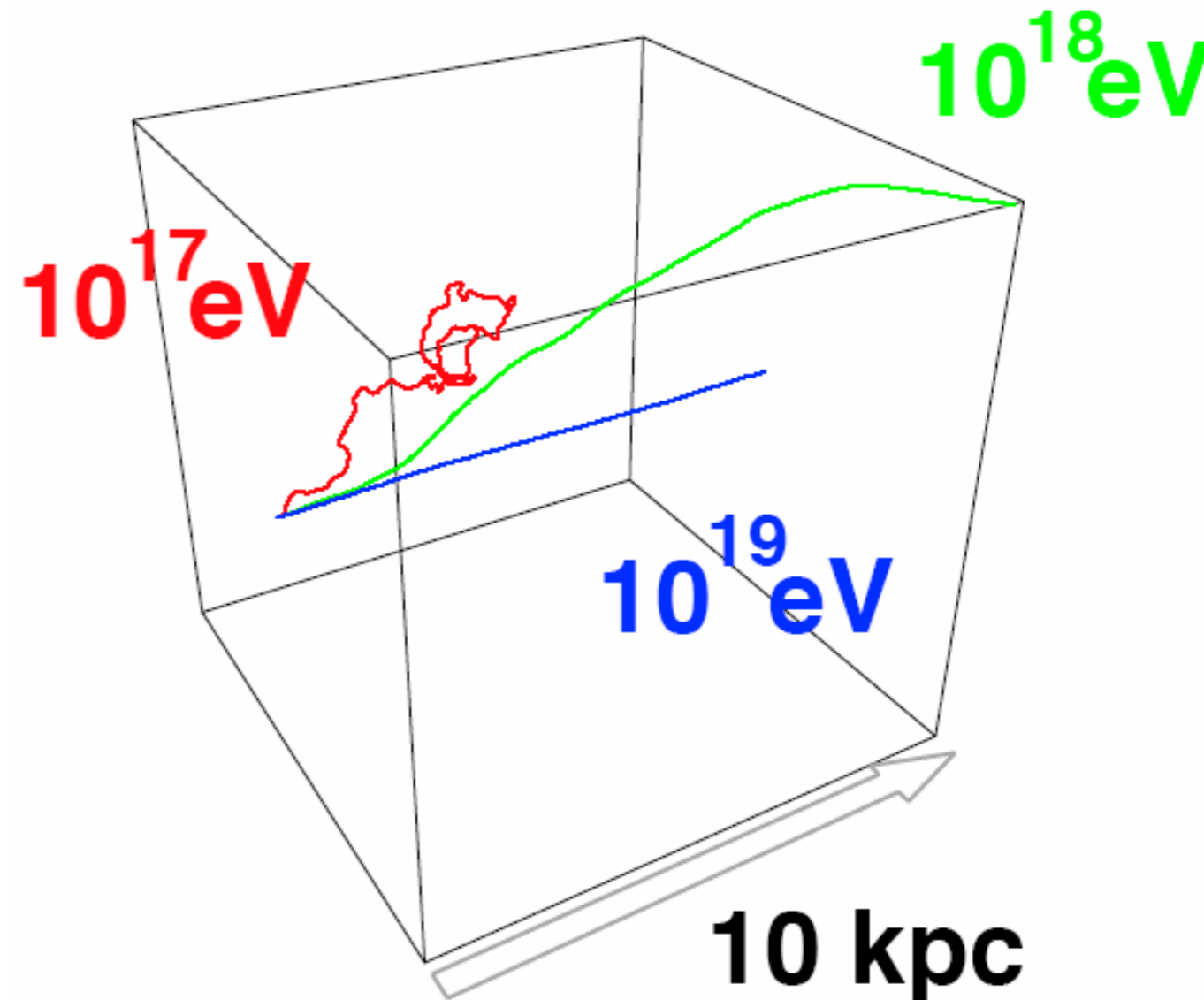


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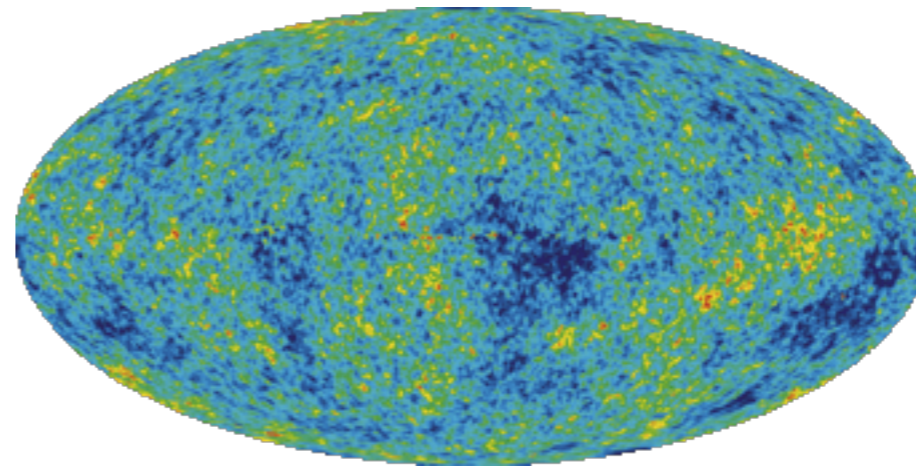
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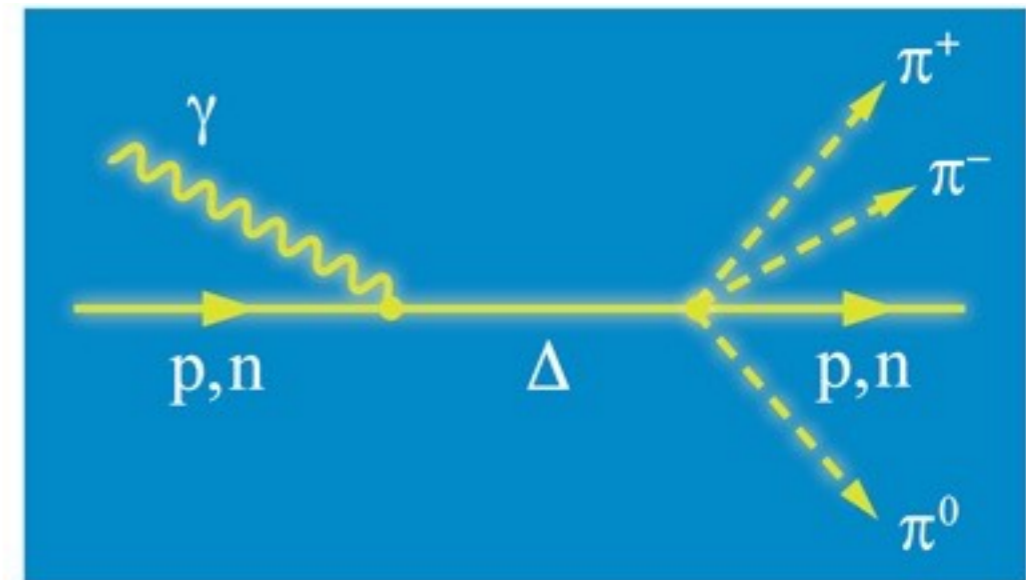
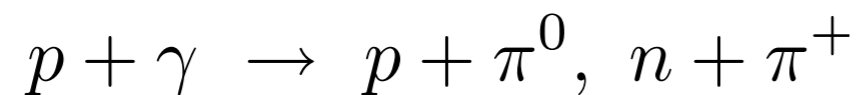
⇒ The beginning of “particle astronomy” ?



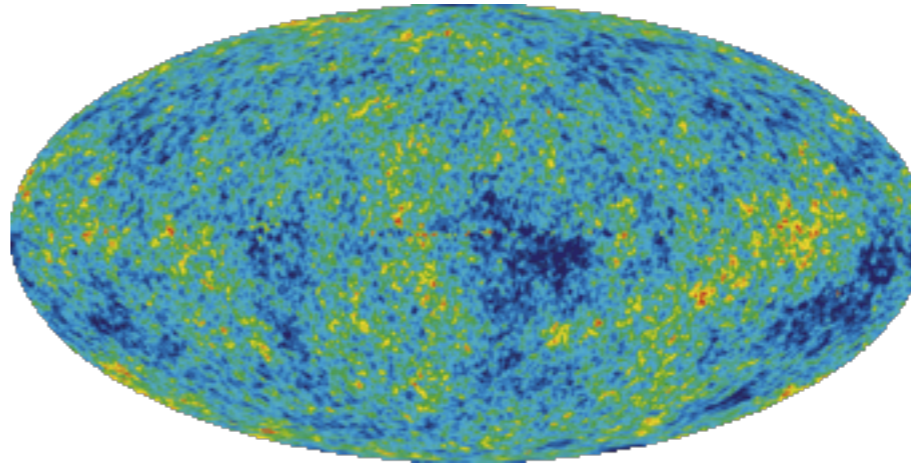
Cosmic Speed Limit?



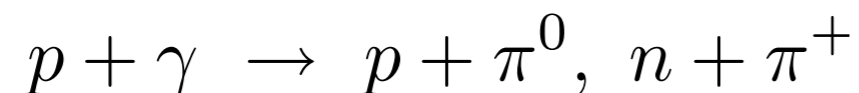
- Greisen - Zatsepin - Kuzmin Cutoff (1966):
 - Interaction of cosmic particles with photons of the CMB
 - Mean free path between two collisions: ~ 50 Mpc
 - At (very) high energies: Possibility for pion production:



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Center-of-mass energy of the reaction

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

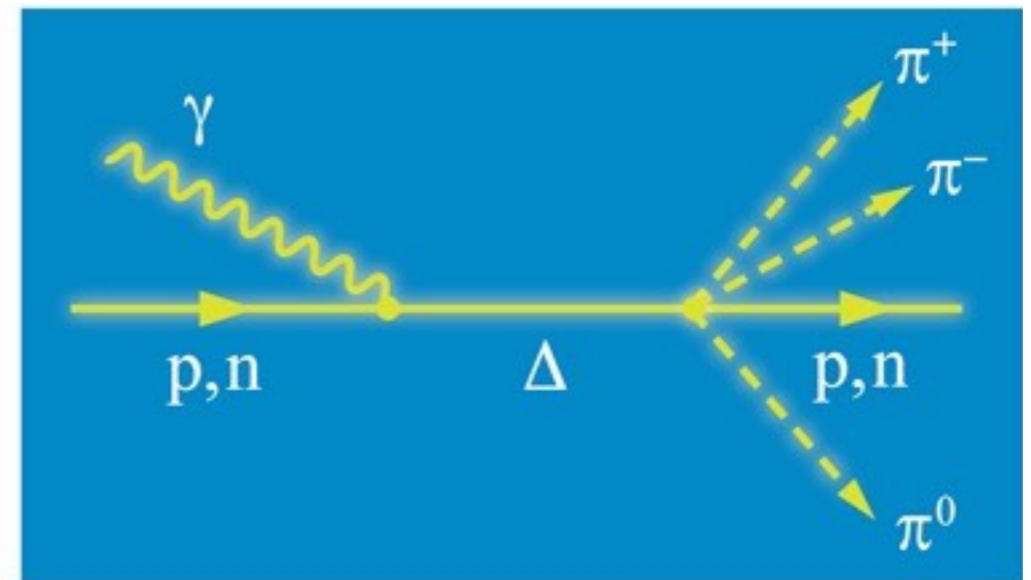


Photo-Pion Production with CMB Photons

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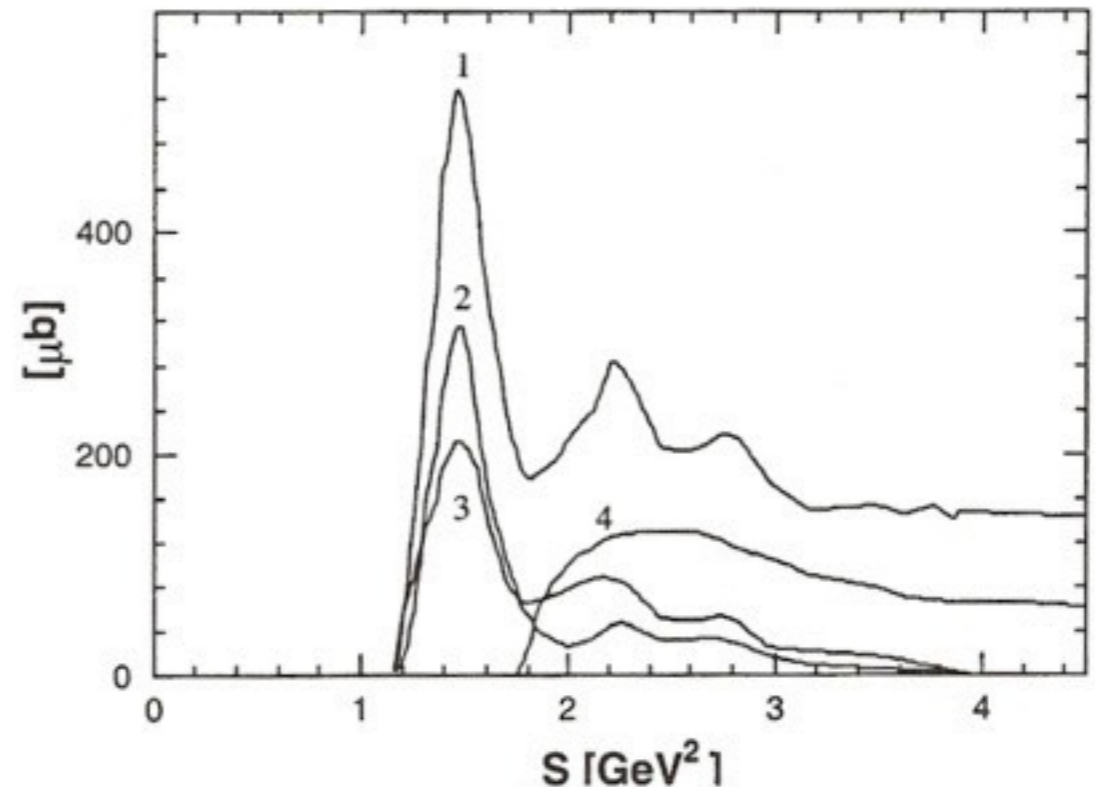


FIG. 3.2: Cross sections for photopion production [9]. 1 denotes the summation of all channels, 2 $\gamma p \rightarrow p\pi^0$, 3 $\gamma p \rightarrow n\pi^+$, and 4 $\gamma p \rightarrow p + \text{double pion}$.

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

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- Cosmic Microwave Background: black body with 2.7 K, $\sim 2.3 \times 10^{-4}$ eV
 - ▶ Photons up to $\sim 10^{-3}$ eV
 - ▶ Cosmic “speed limit” at $\sim 7 \times 10^{19}$ eV

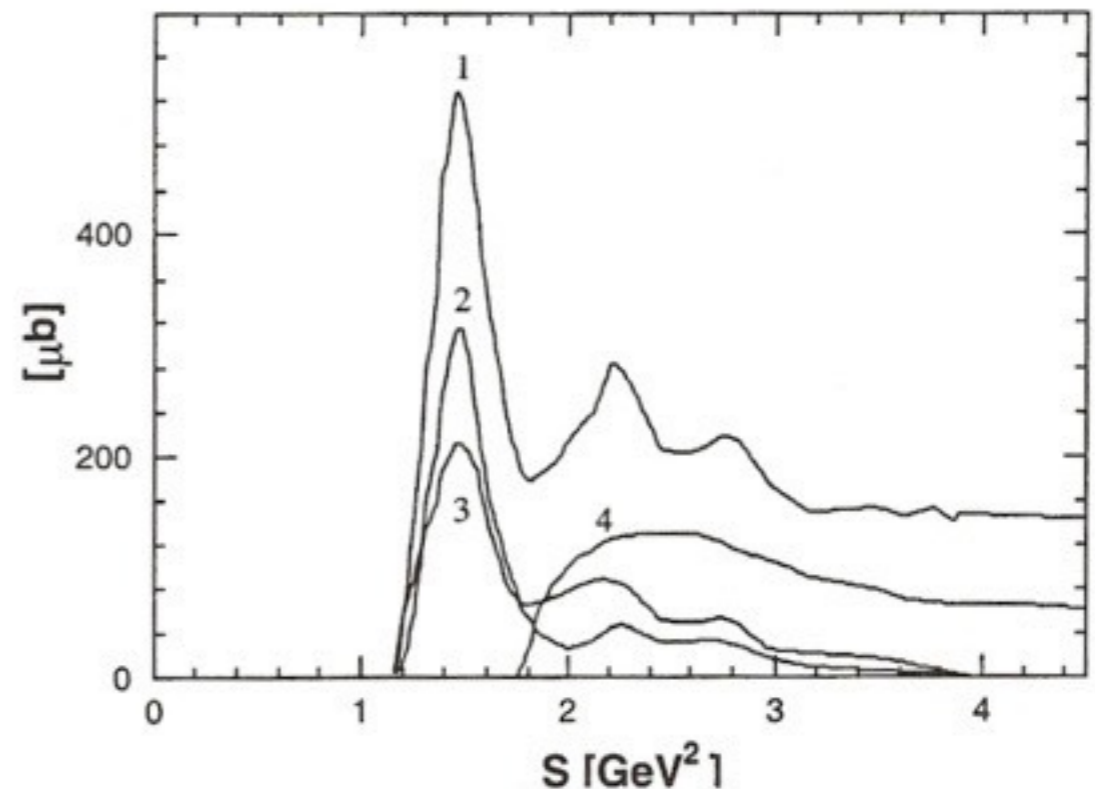
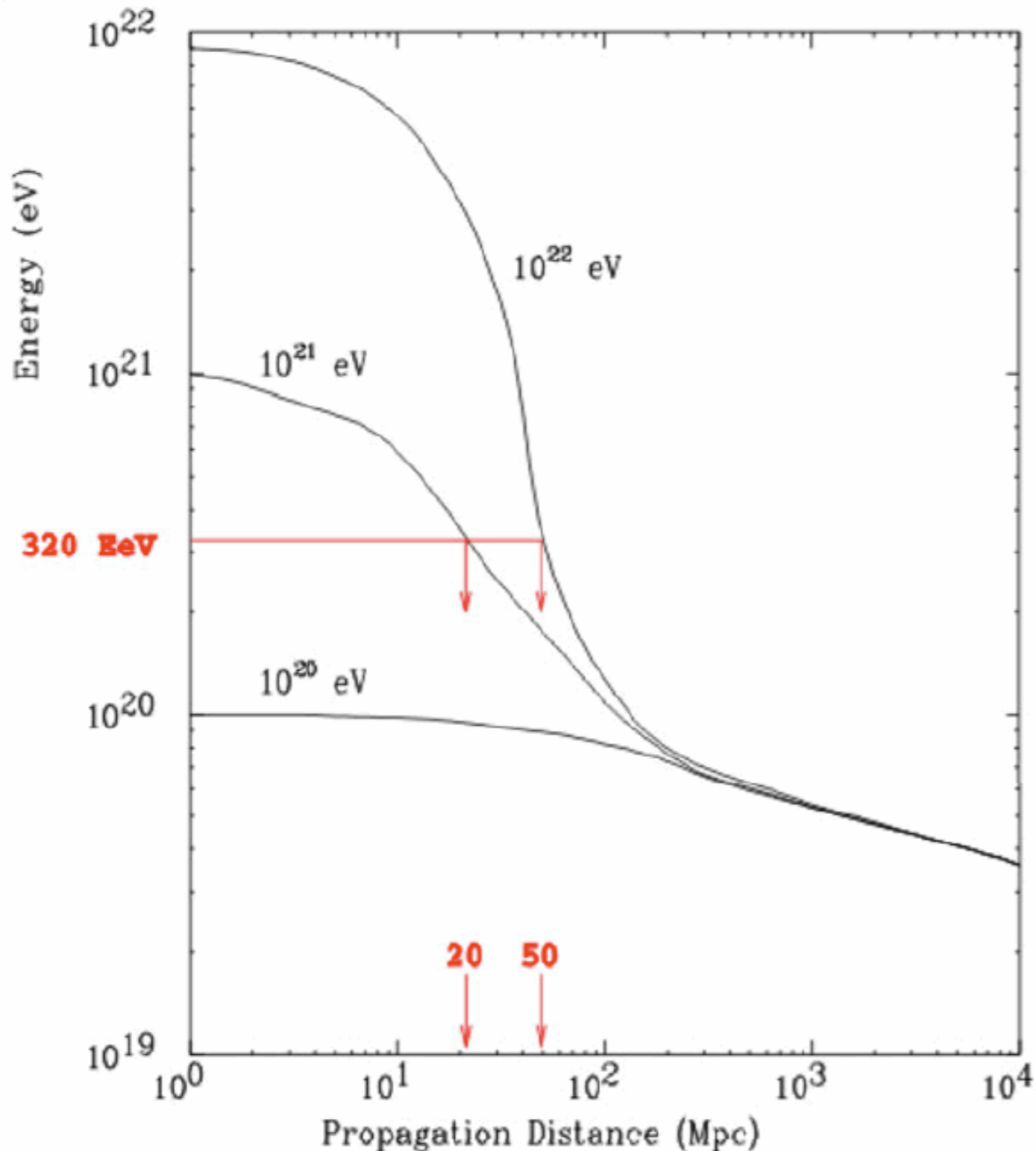


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Energy Evolution due to GZK Effect



- ▶ Highly energetic particles rapidly lose energy through photo-pion production:
 - Per interaction $\sim 30\%$ of the total energy are lost
- ▶ Range of particles with energies above $\sim 10^{20}$ 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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In addition: e^+e^- - pair production with CMB photons (Bethe-Heitler-Process, analogous to Bremsstrahlung): Low energy threshold in the region of a few 10^{17} eV

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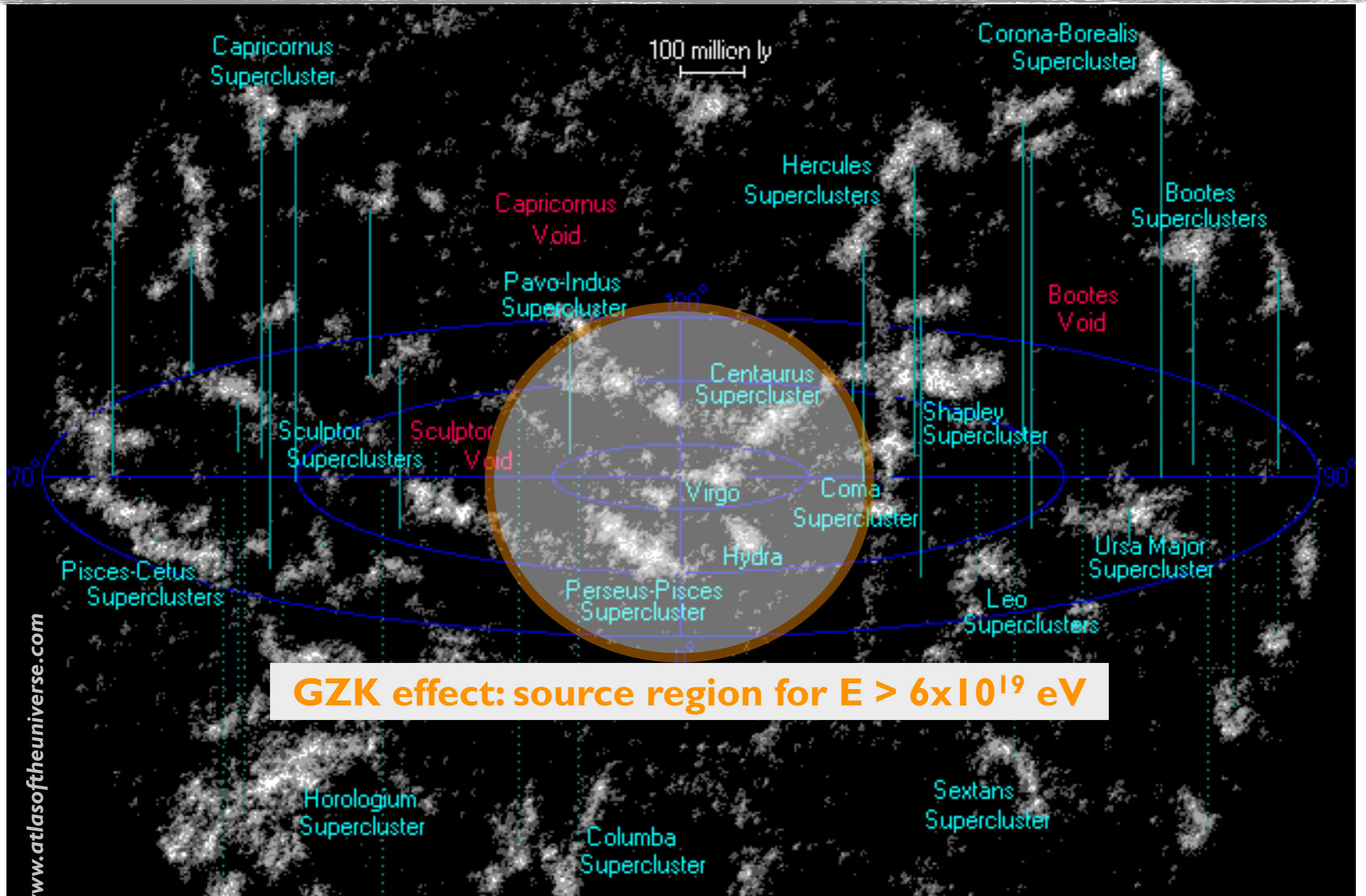
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But: Typically only small energy loss: $2m_e/m_p \sim 10^{-3}$, at high energies even lower. For comparison: GZK events result in an energy loss of 30% or more!

⇒ Only small effect on spectrum

GZK Effect: Limited Source Region: ~ 75 Mpc



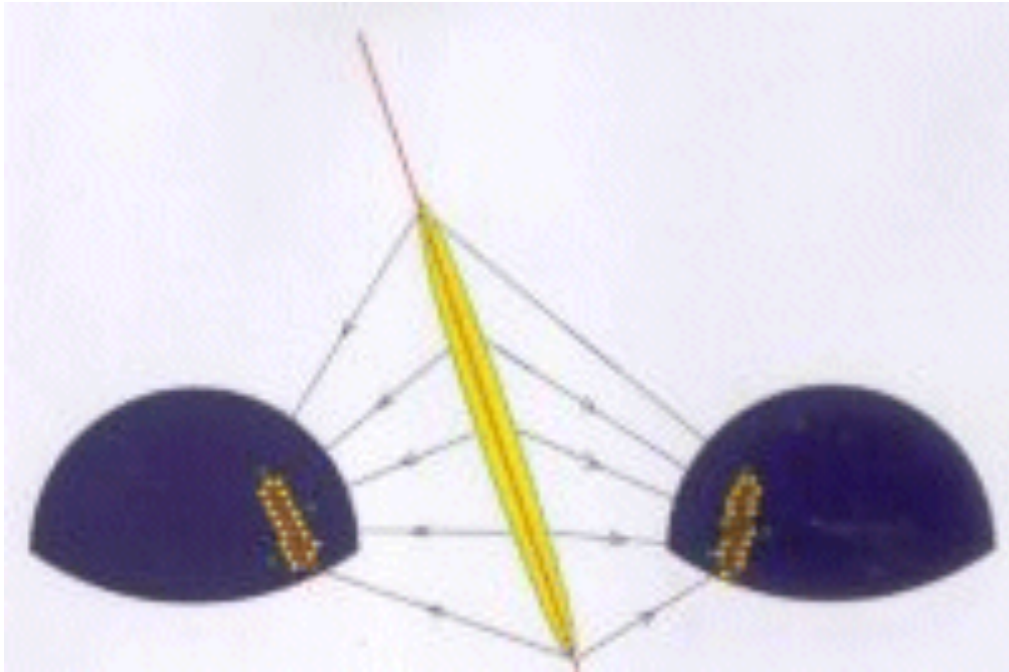
GZK effect: source region for $E > 6 \times 10^{19}$ eV

Fly's Eye



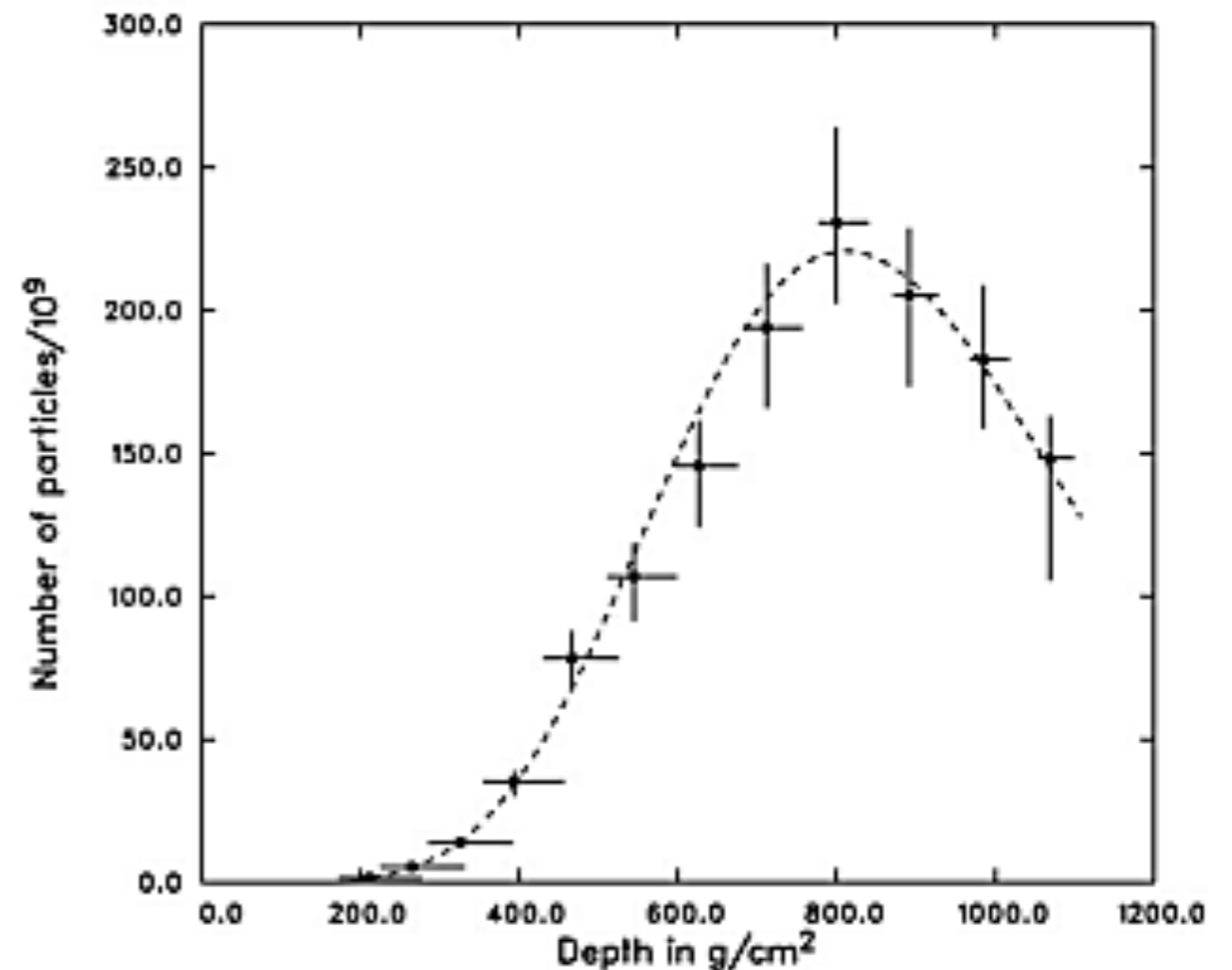
- Measurement of fluorescence light in the atmosphere

Fly's Eye: The highest-energy Particles

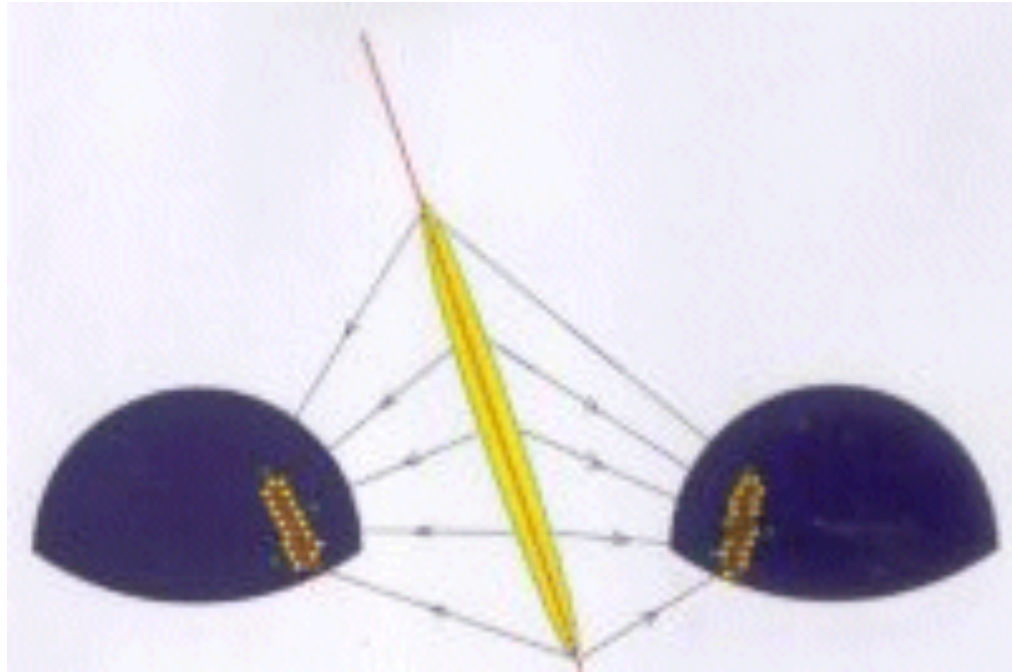


- Stereo-Observation with two detector stations permits a precise determination of the shower direction and profile

- The highest-energy particle ever detected on earth:
15.10.1991, Utah:
Energy $\sim 3 \times 10^{20}$ eV



Fly's Eye: The highest-energy Particles

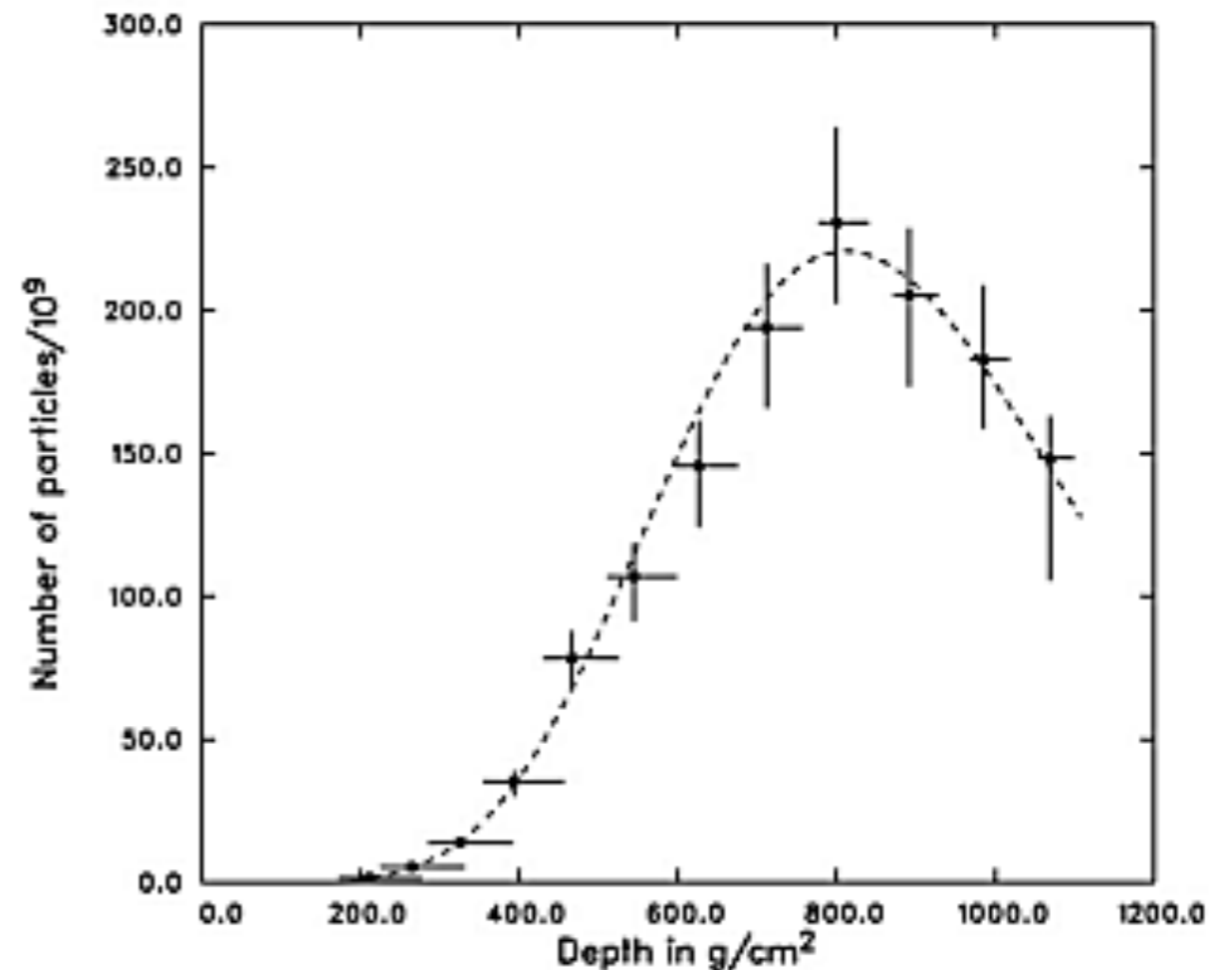


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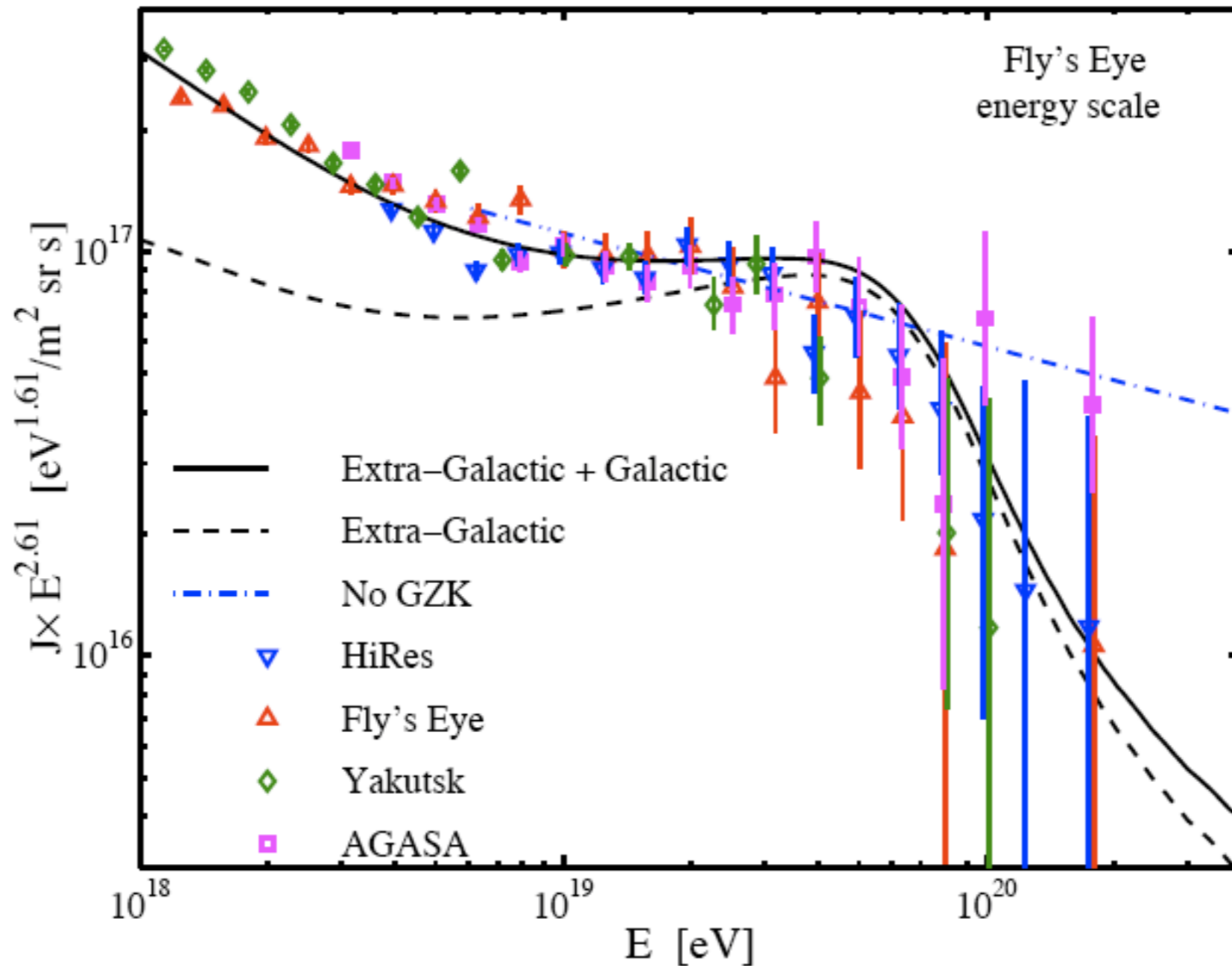
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50 J !

“Oh-my-God particle”



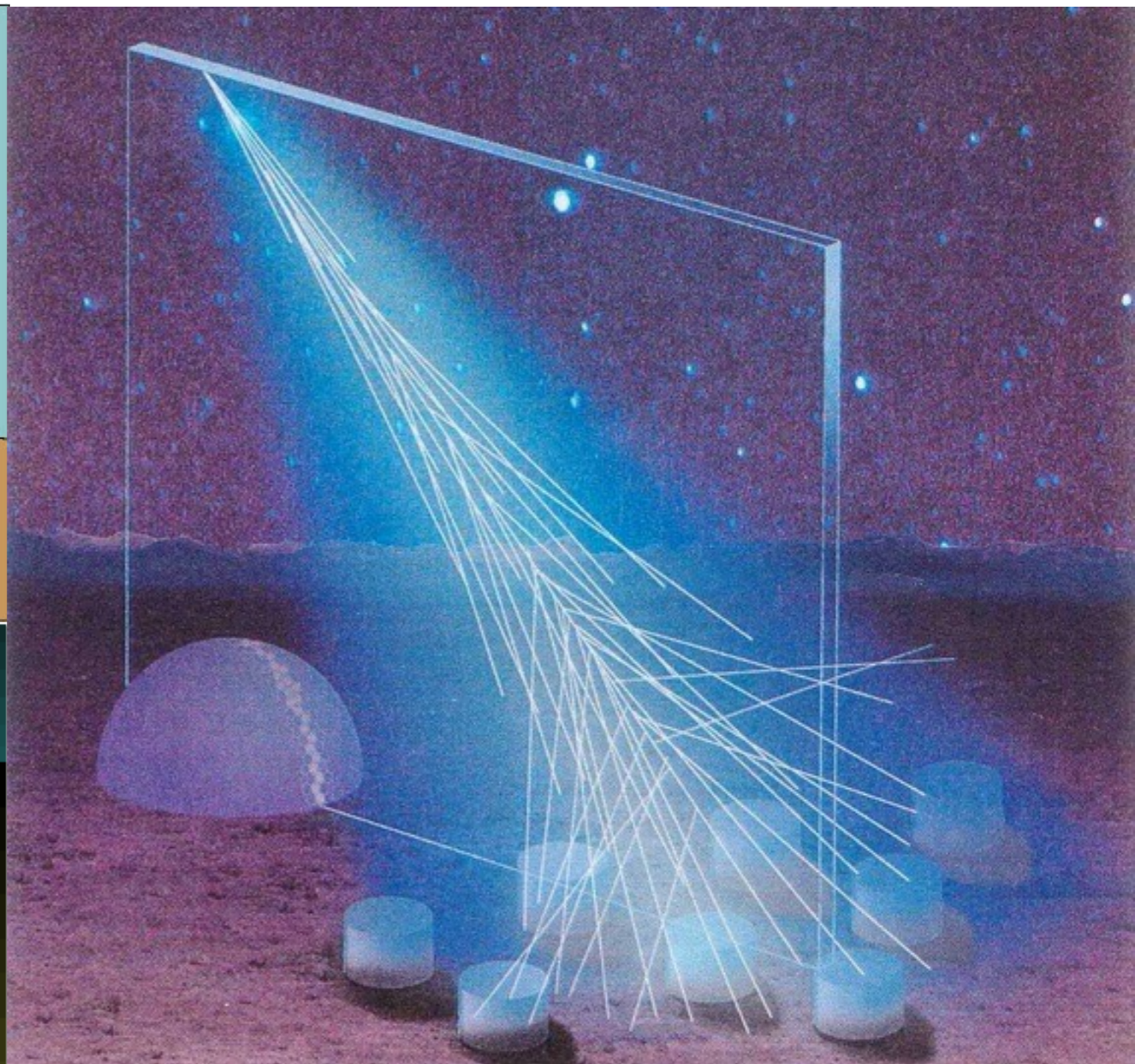
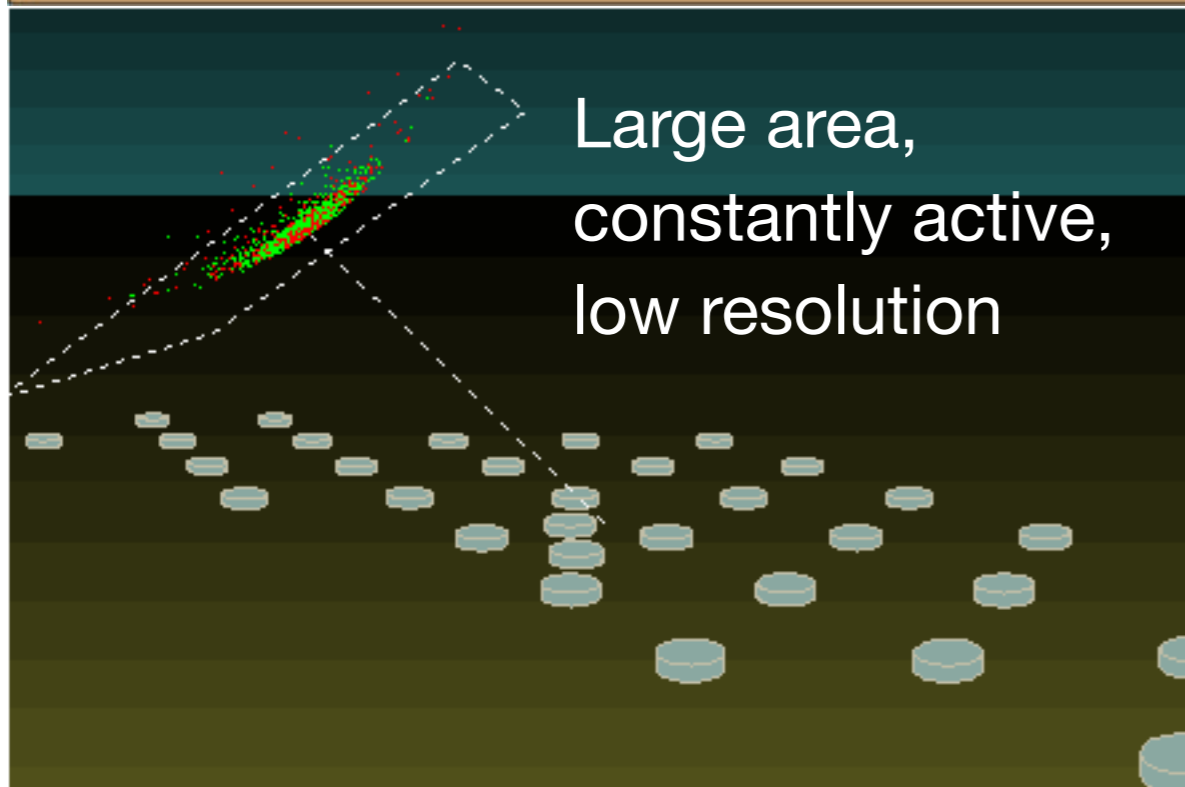
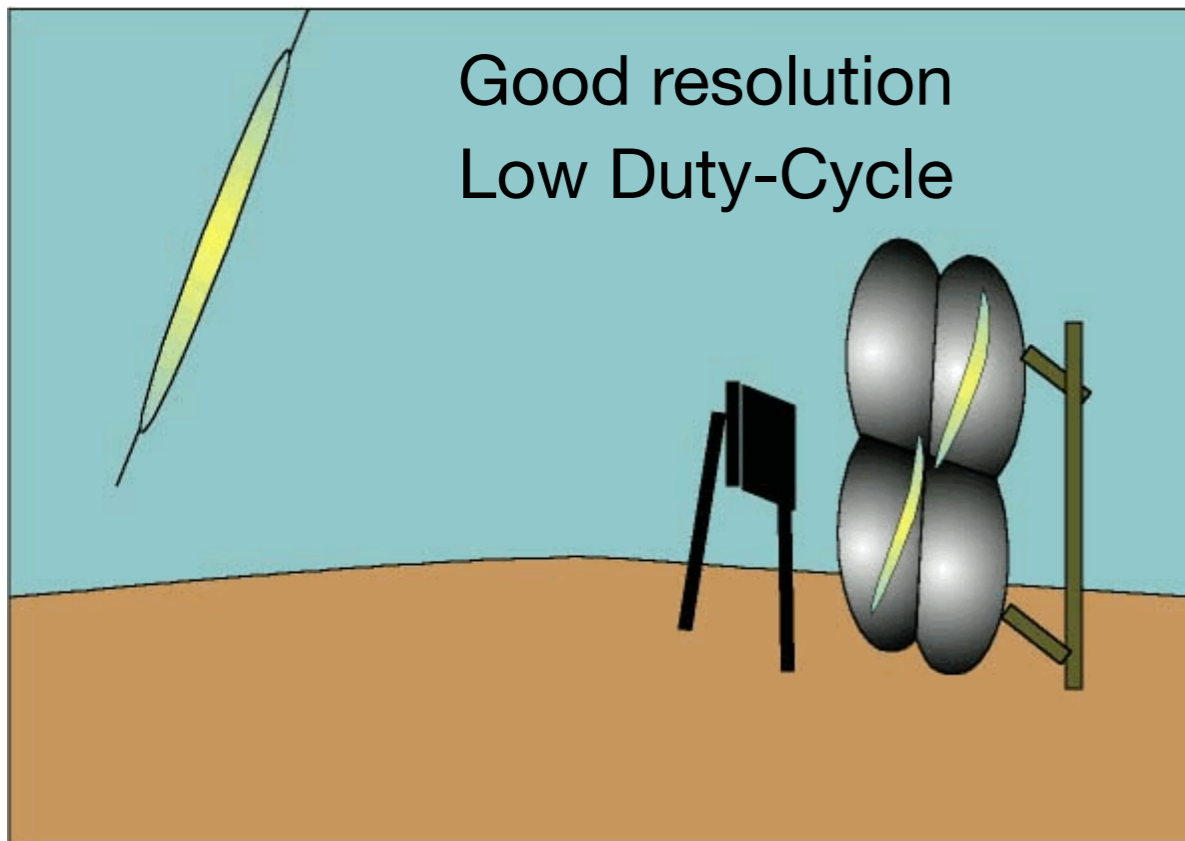
GZK-Cutoff: Status - 2003



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

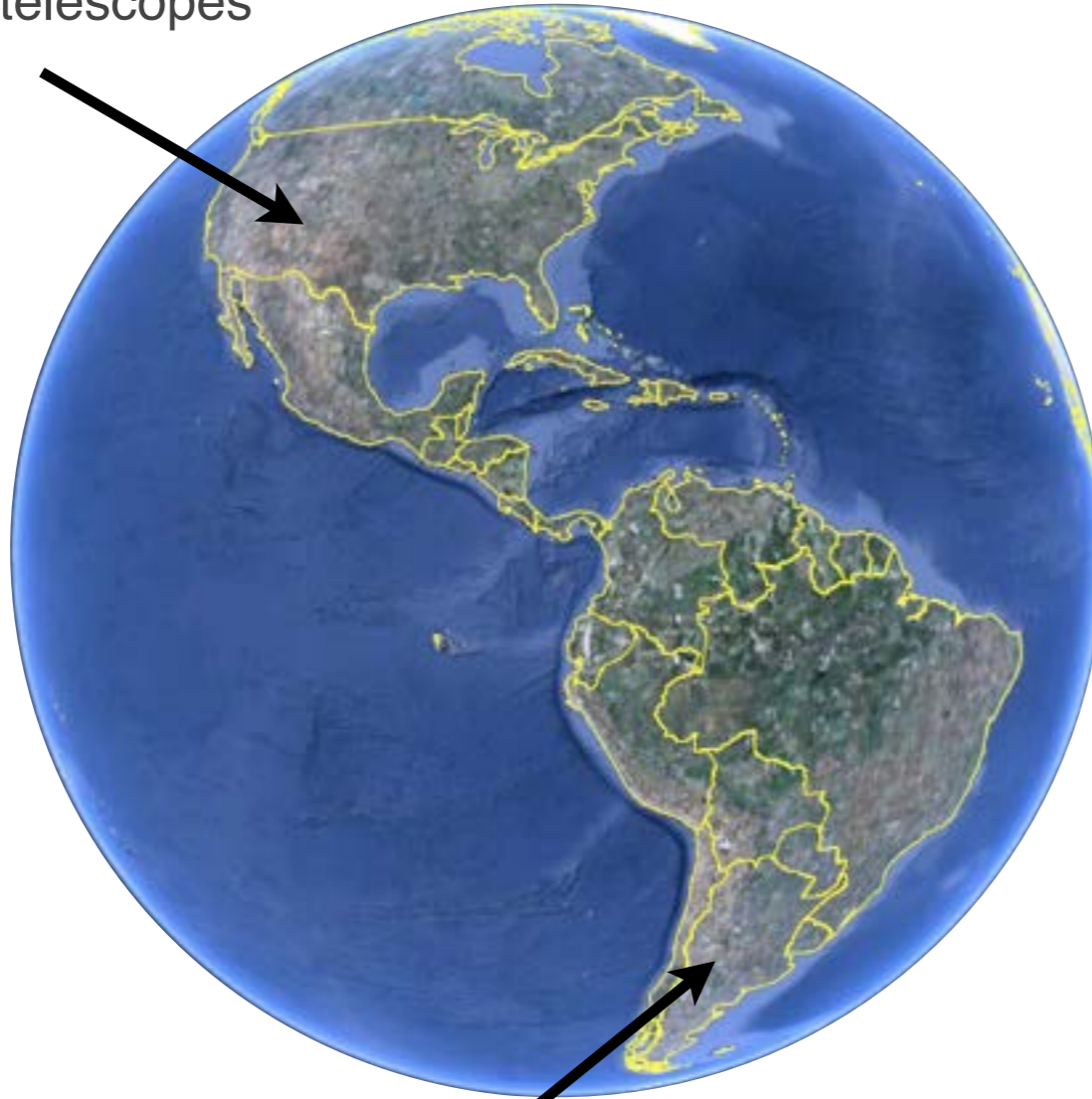
UHECR Observatories Today

Telescope Array (TA)

Delta, UT, USA

507 detector stations, 680 km²

36 fluorescence telescopes



Pierre Auger Observatory

Province Mendoza, Argentina

1660 detector stations, 3000 km²

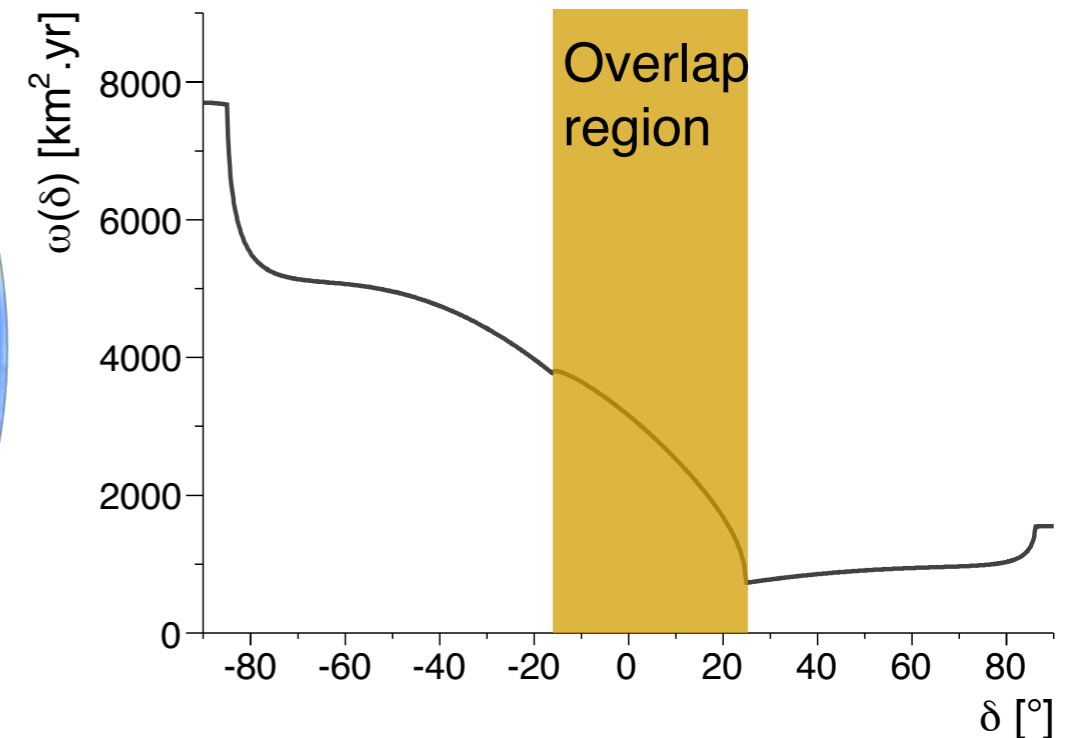
27 fluorescence telescopes

$E > 10^{19}$ eV

[0-55°] for TA

1,800 events

650 in overlap region



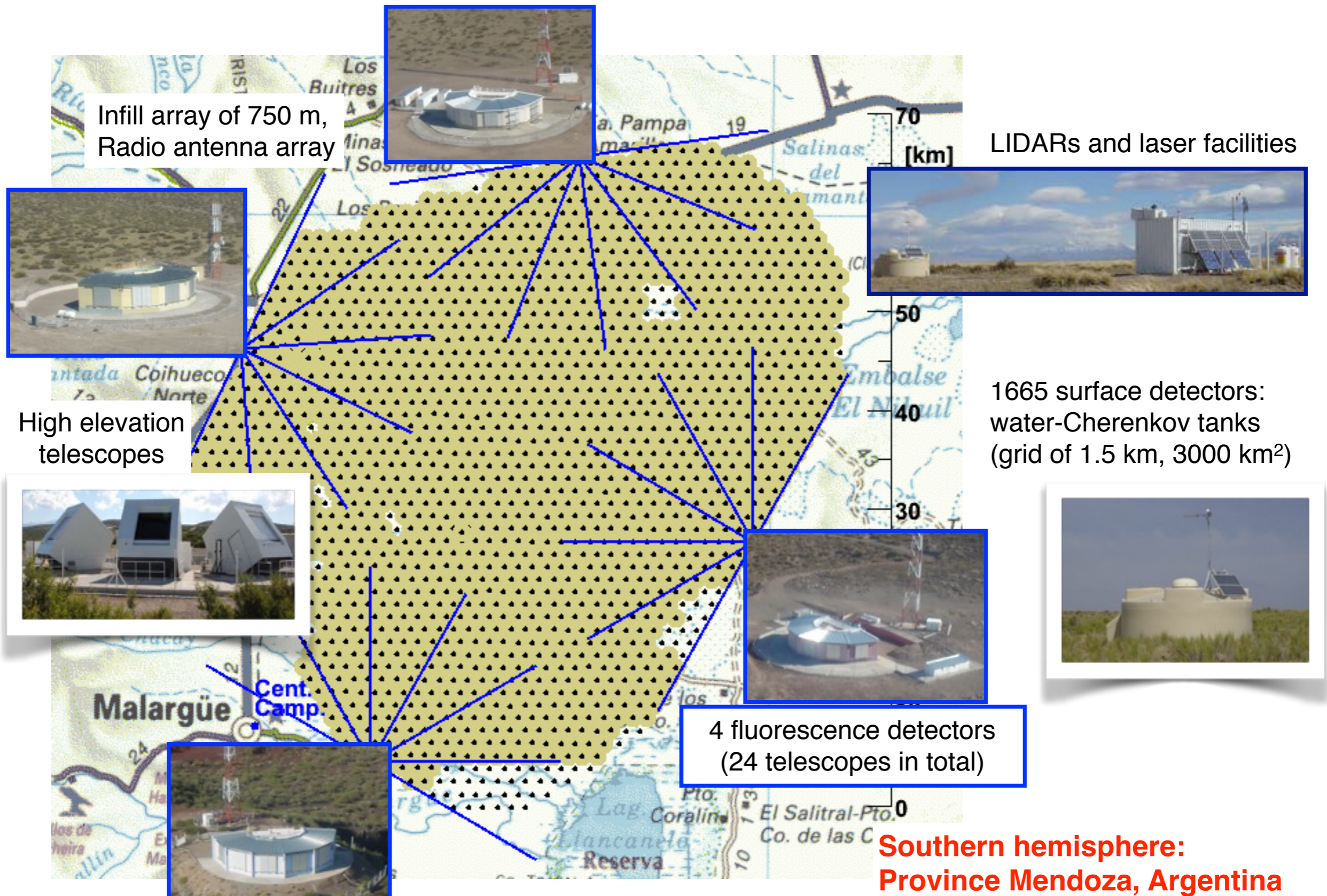
[0-60°] for Auger

10,900 events

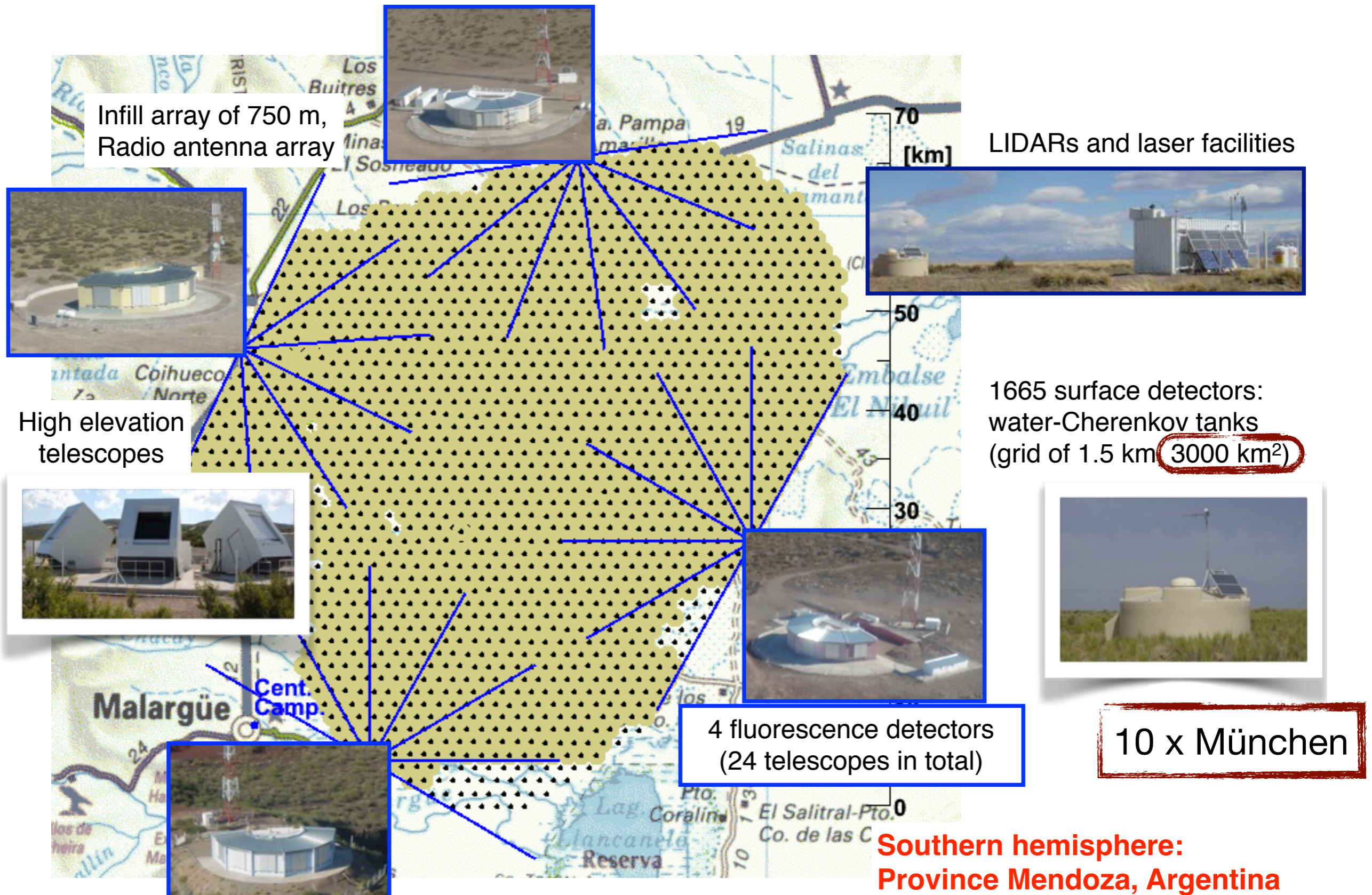
3,400 in overlap region

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

AUGER: In the Argentinian Pampa



AUGER: In the Argentinian Pampa



Telescope Array: Covering the North

Middle Drum: based on HiRes II

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



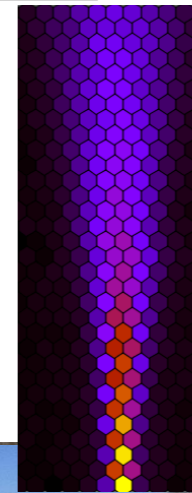
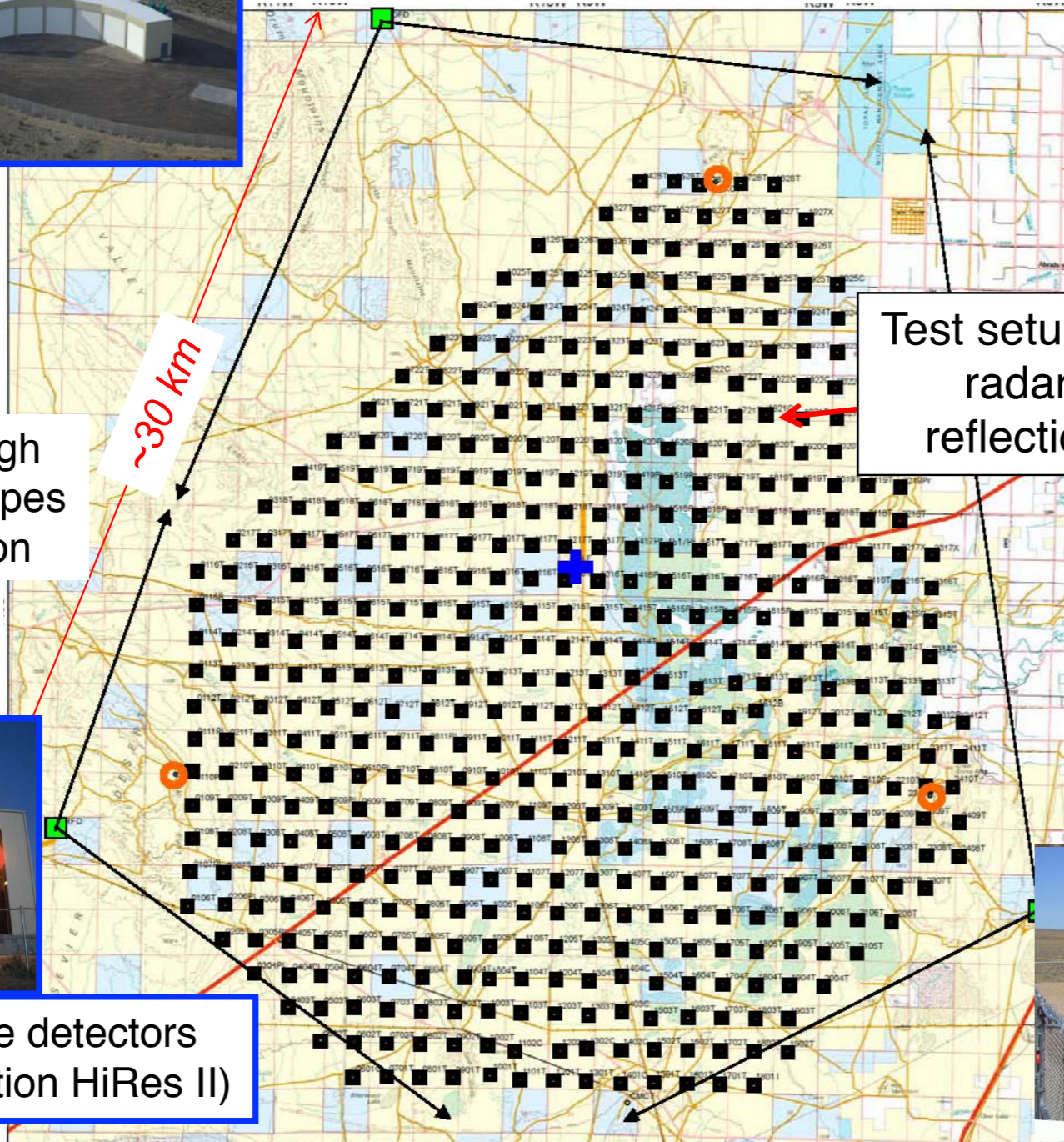
LIDAR
Laser facility



Test setup for
radar
reflection

Infill array and high
elevation telescopes
under construction

~30 km



Electron light source
(ELS): ~40 MeV

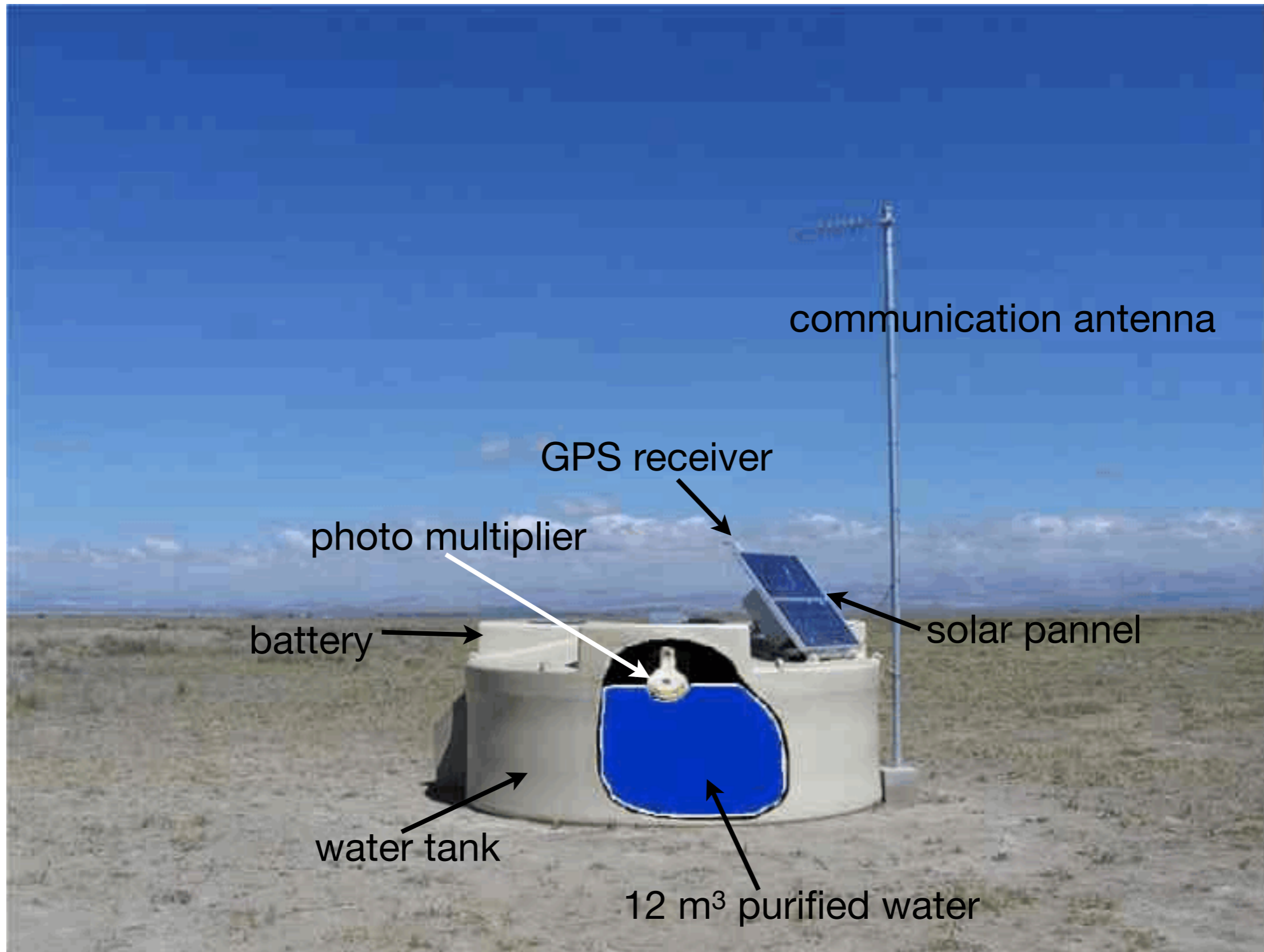


3 fluorescence detectors
(2 new, one station HiRes II)



Northern hemisphere: Utah, USA

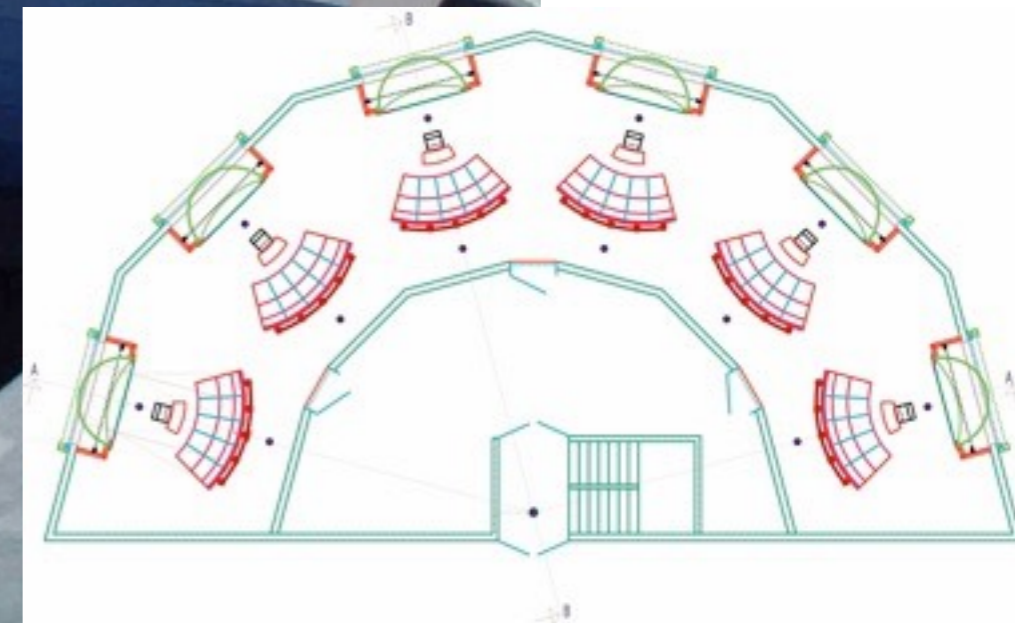
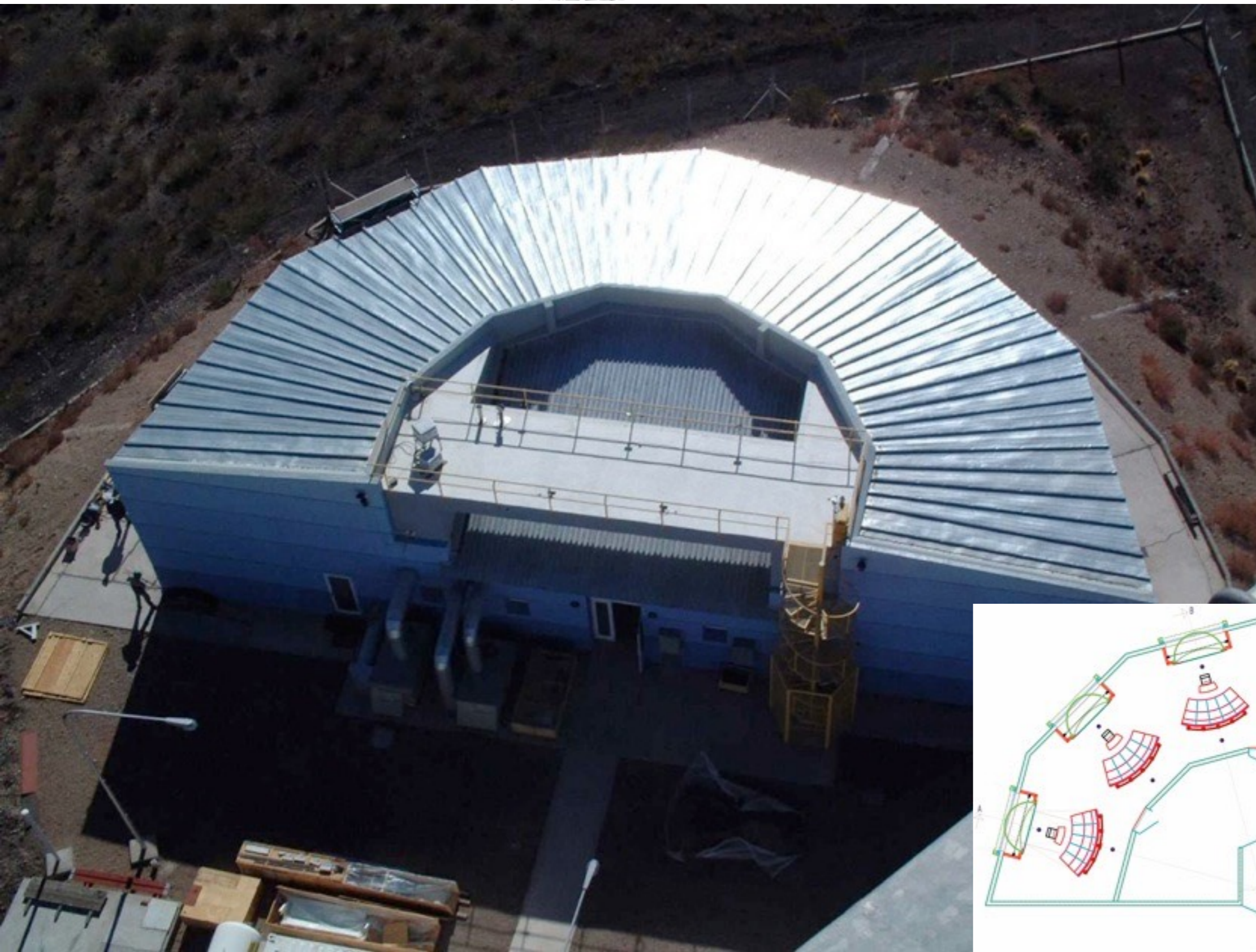
AUGER Detector: Ground Array



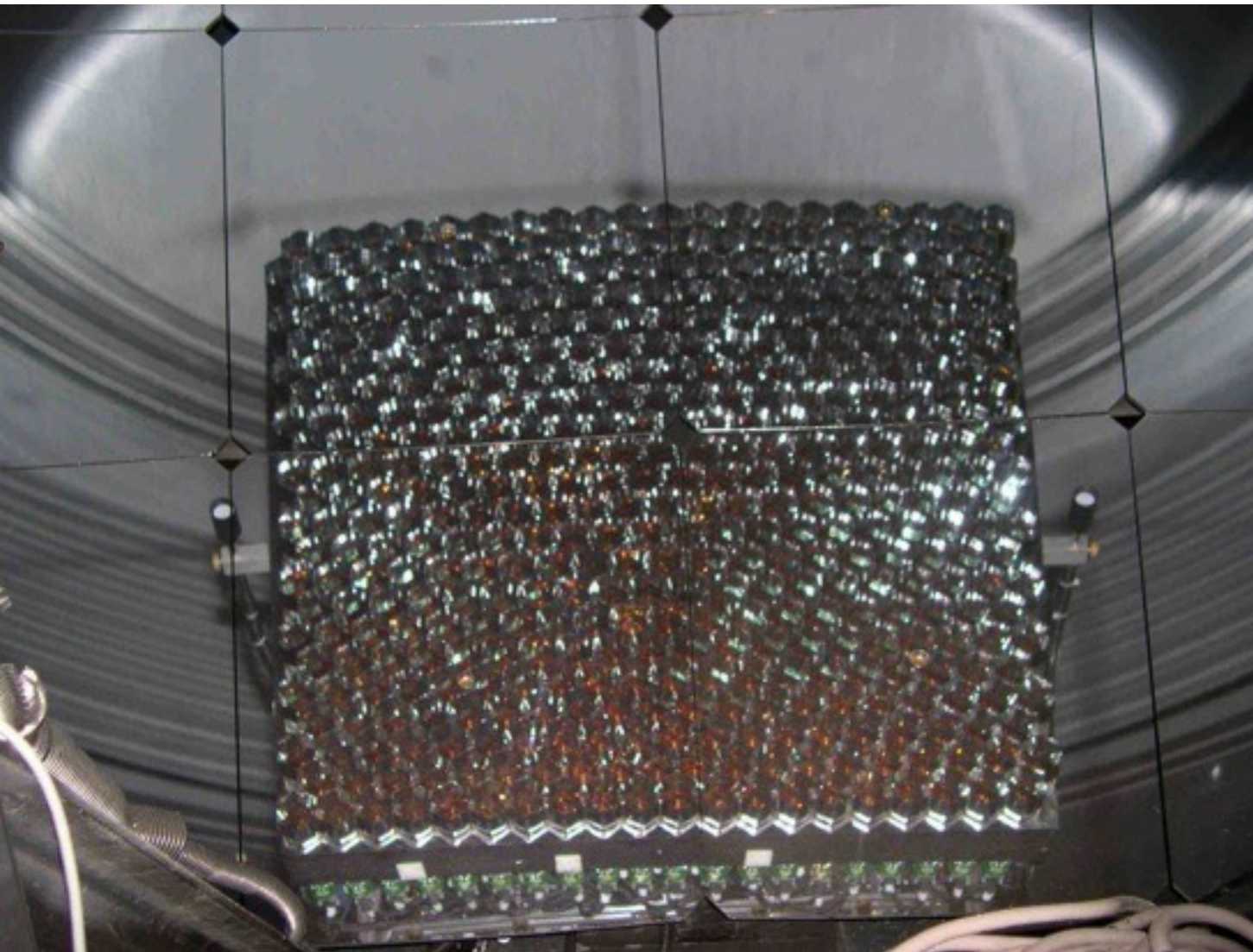
AUGER Installation



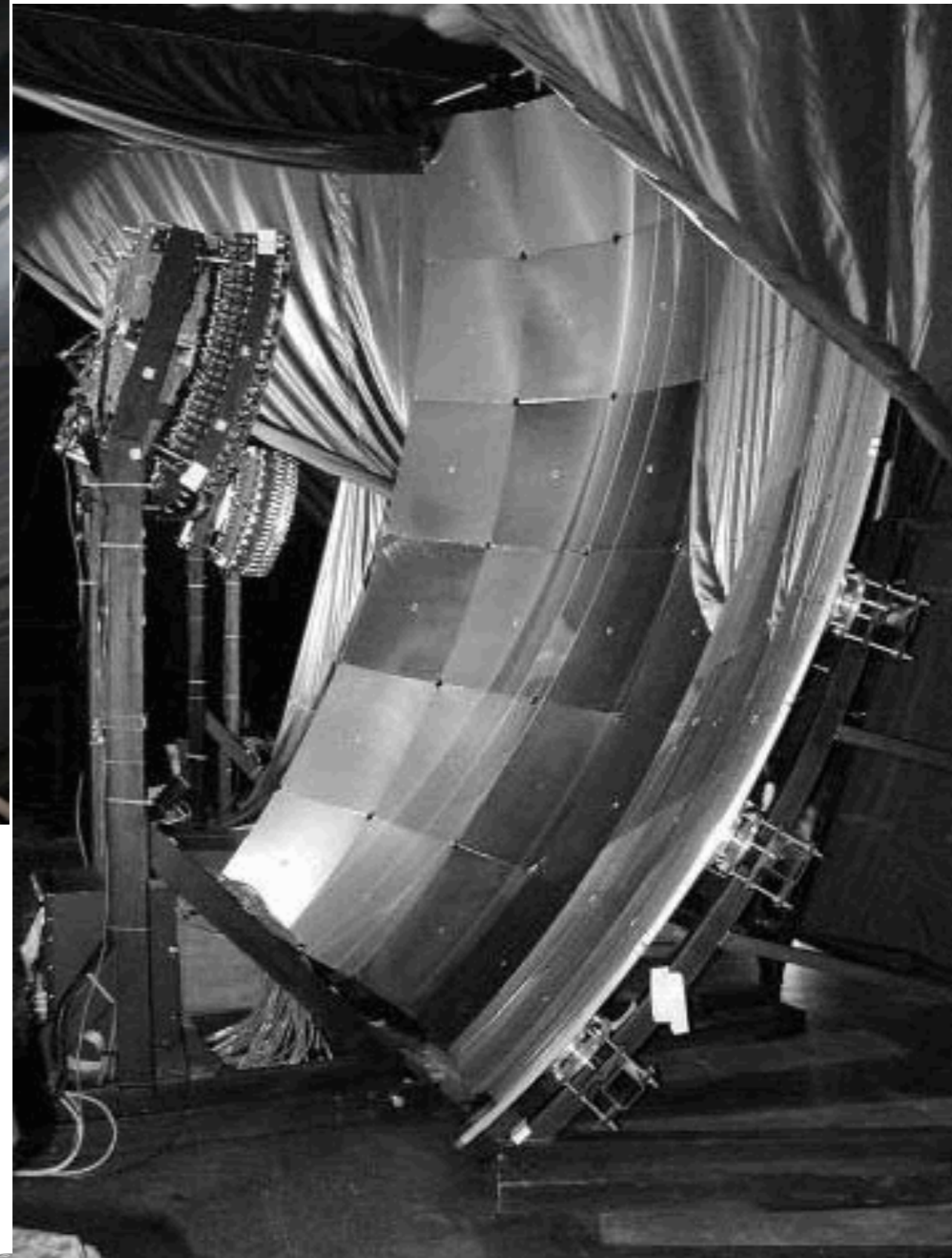
AUGER Fluorescence Telescopes



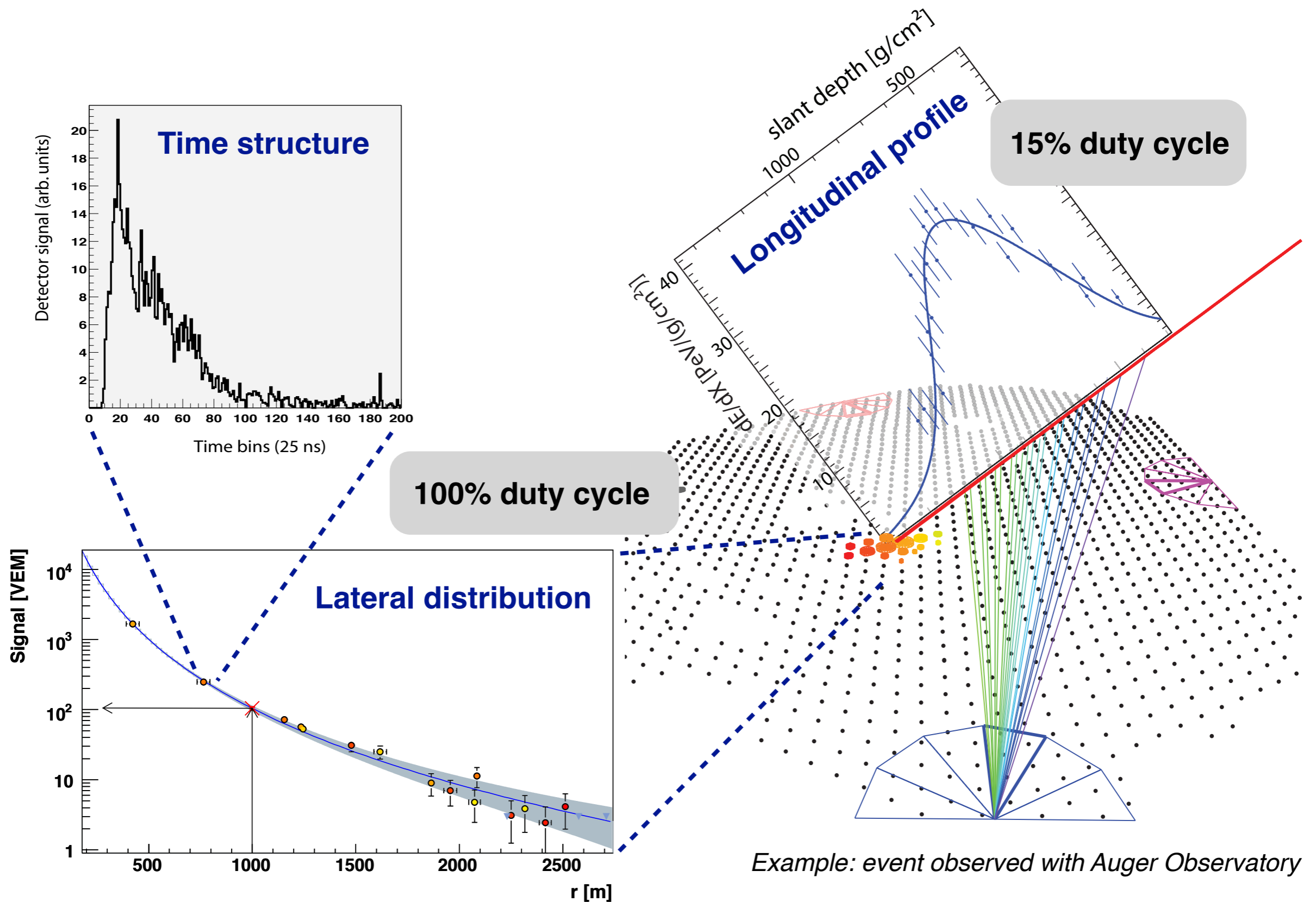
AUGER Fluorescence Telescopes



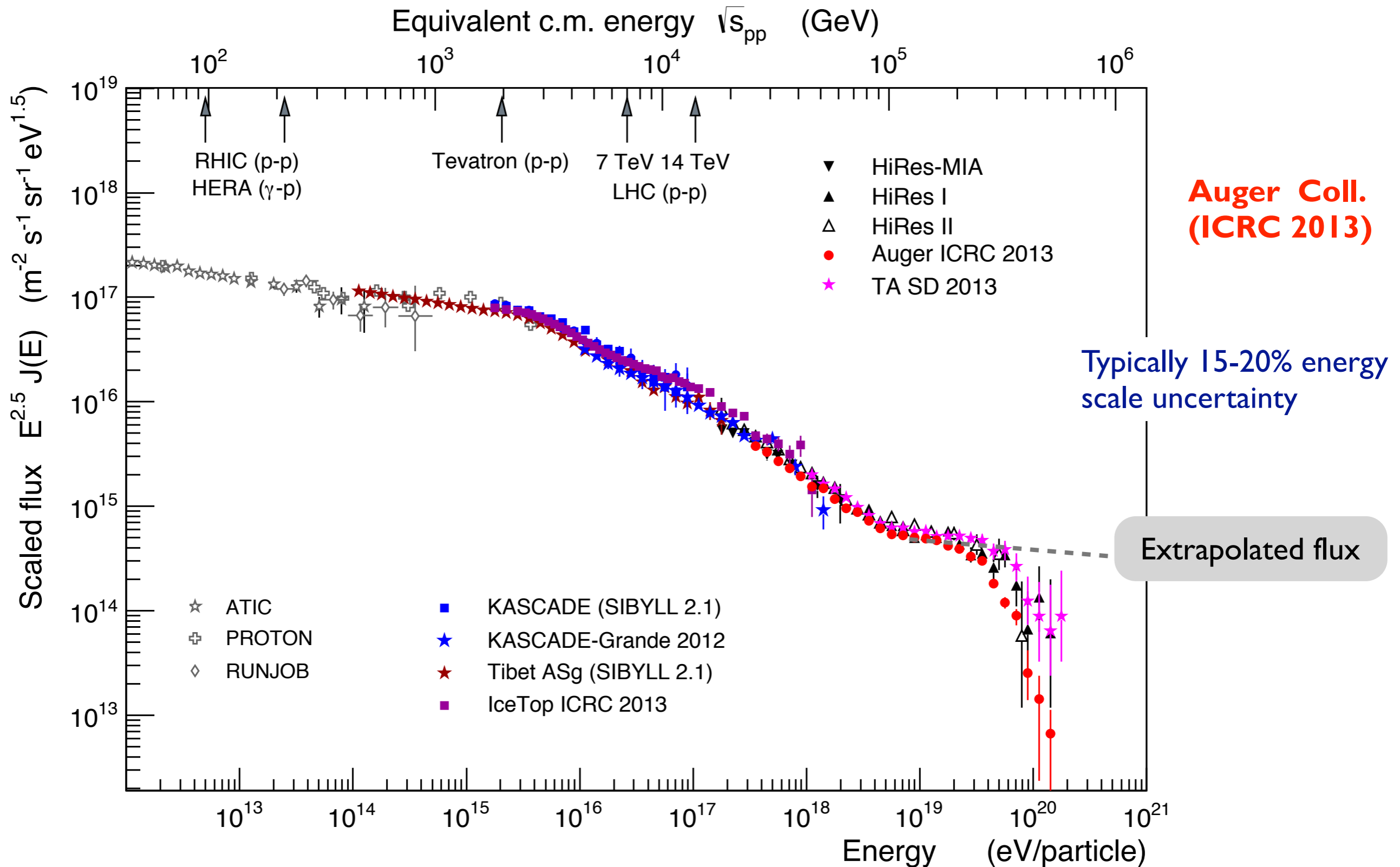
- 440 PMTs, 1.5° per Pixel



Typical AUGER Events



The Spectrum at Highest Energies

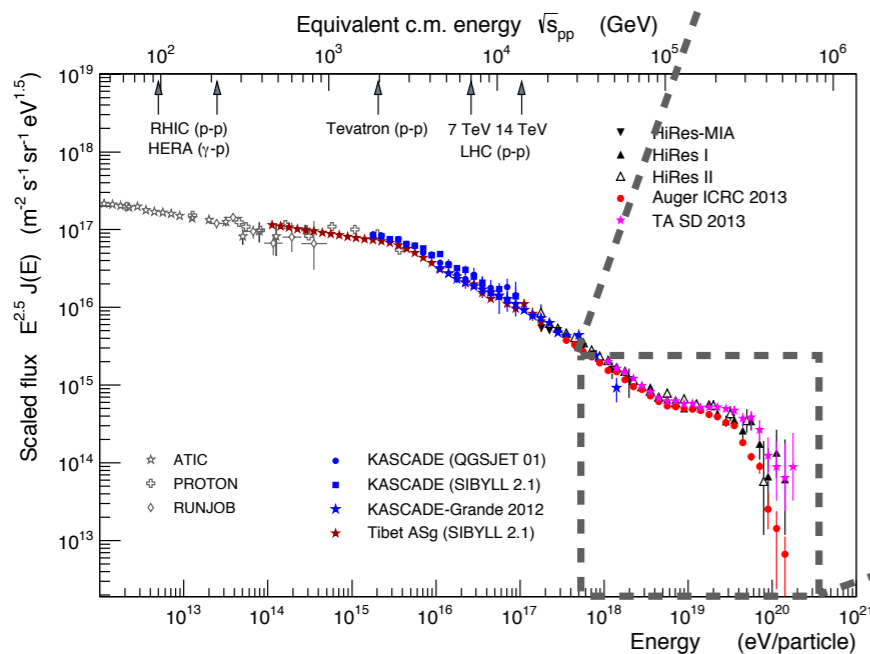
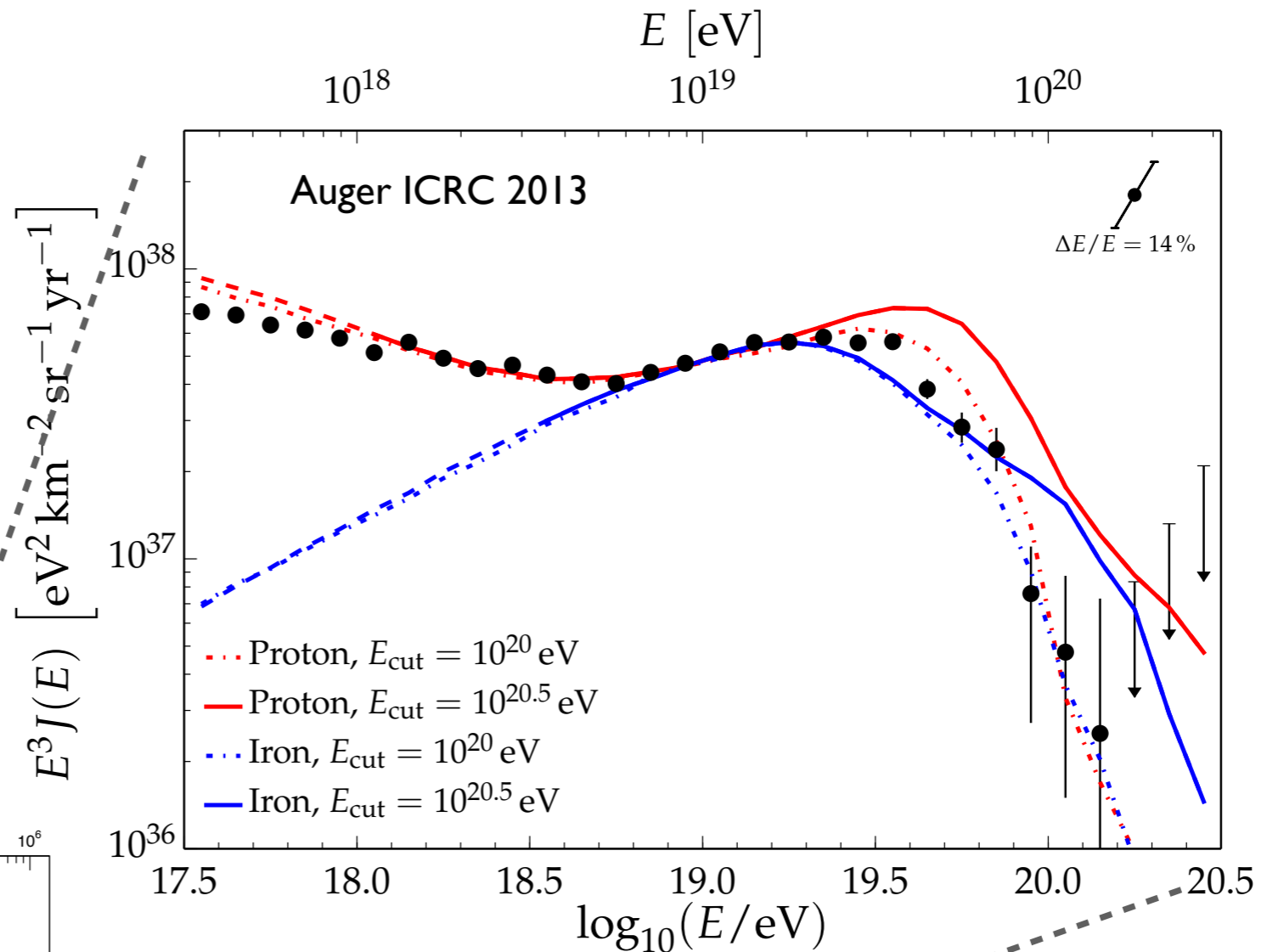


The Spectrum at Highest Energies

Proton dominated flux

Suppression: delta resonance
Ankle: e^+e^- pair production

(Dip model of Berezhinsky et al.)



Iron dominated flux

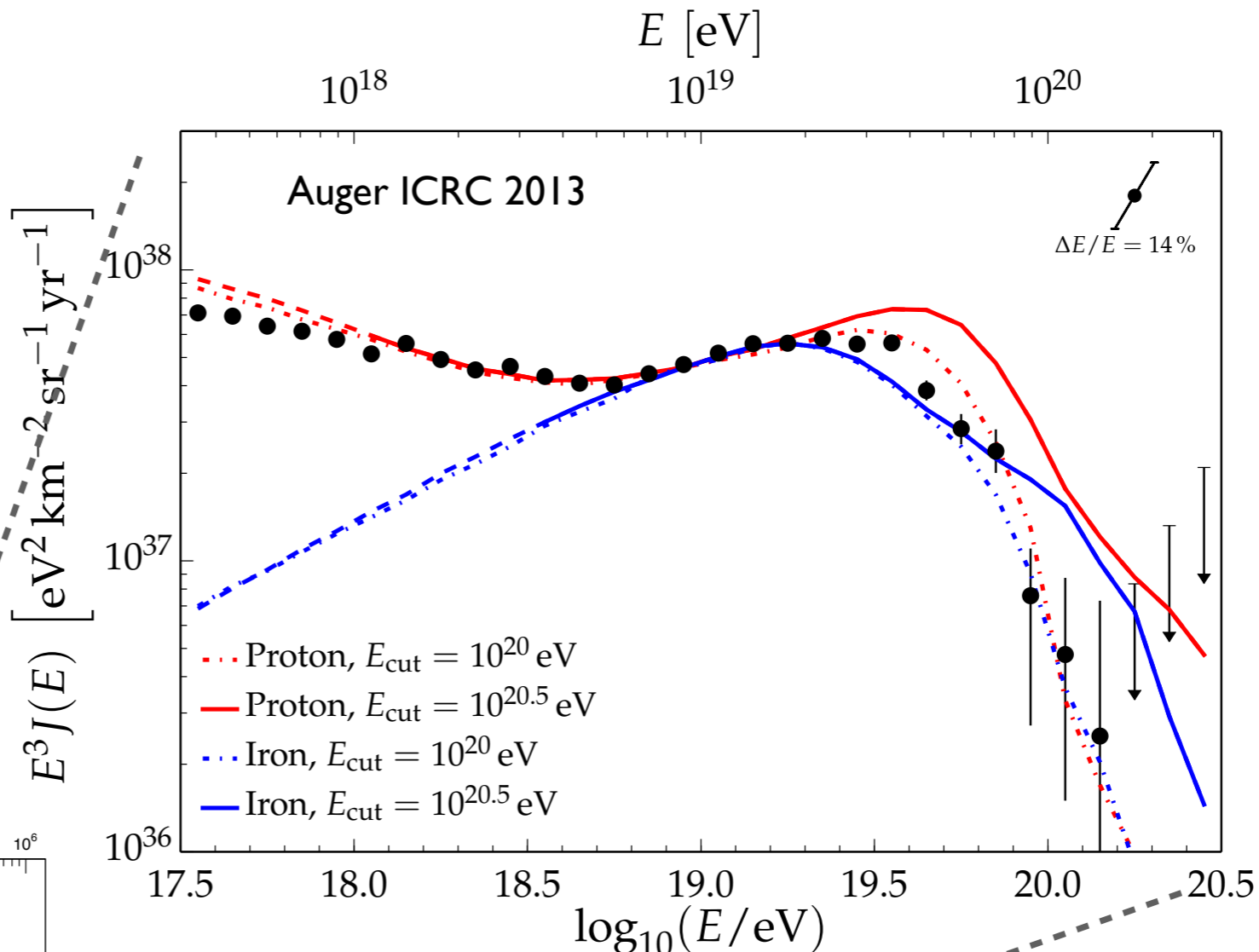
Suppression: giant dipole resonance
Ankle: transition to galactic sources

The Spectrum at Highest Energies

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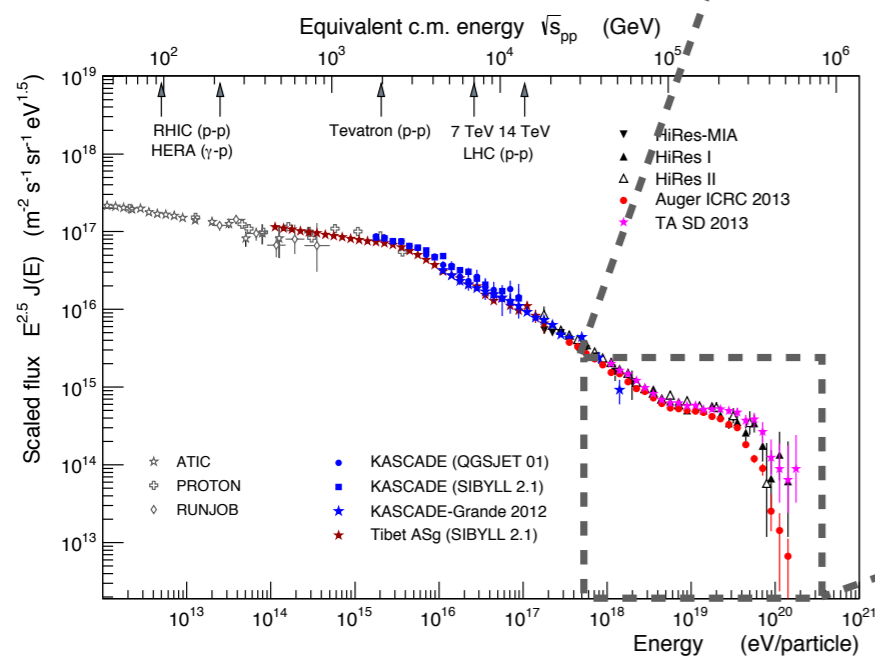
(Dip model of Berezhinsky et al.)



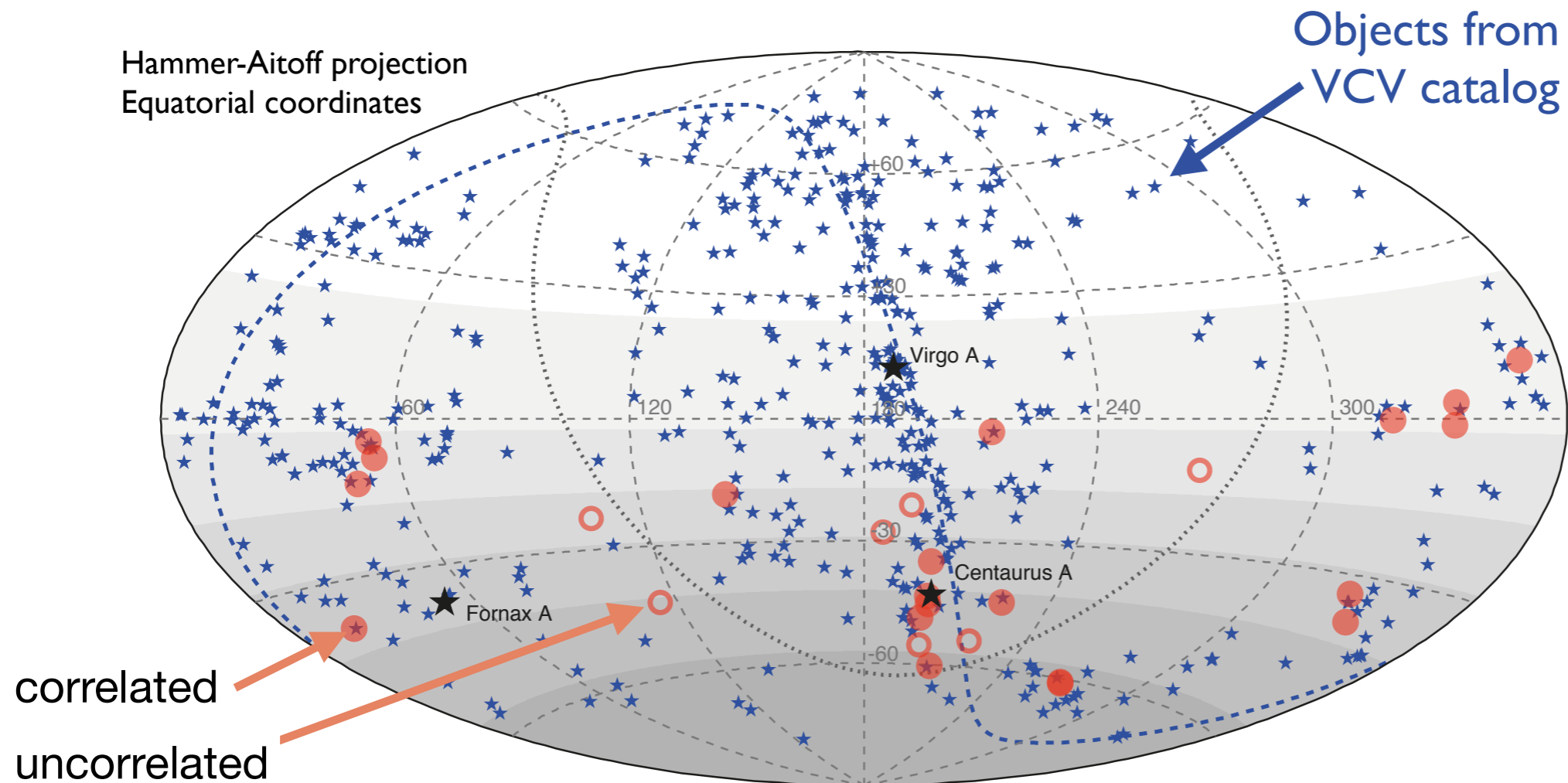
Compatible with expectations from GZK effect!

Iron dominated flux

Suppression: giant dipole resonance
Ankle: transition to galactic sources

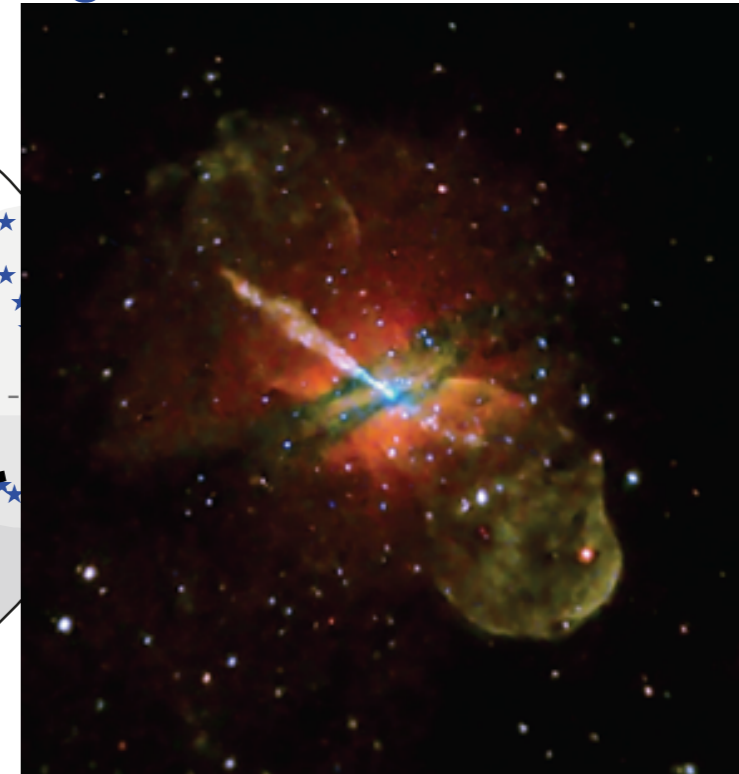
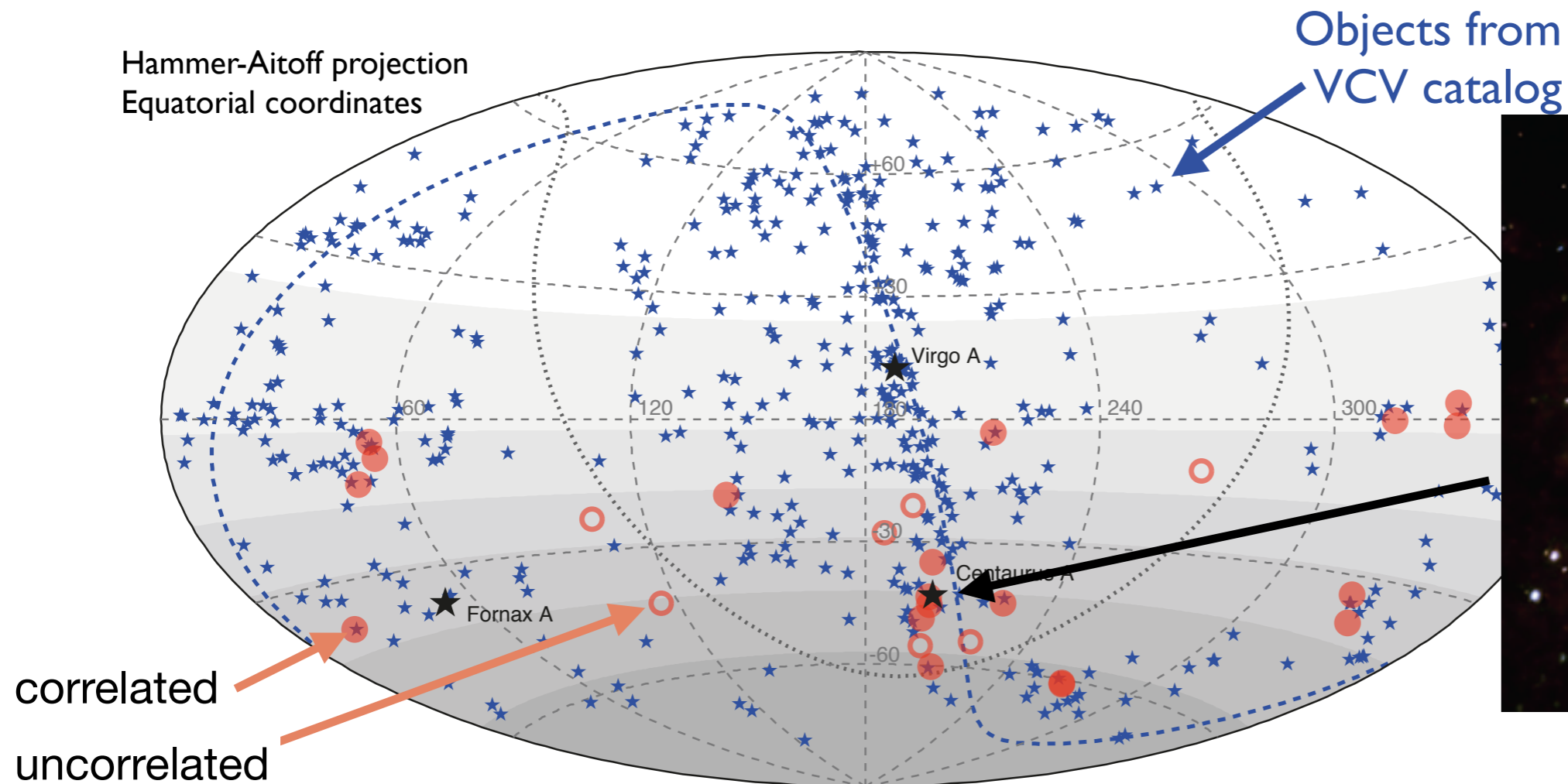


AUGER: Sources for UHECRs - 2007



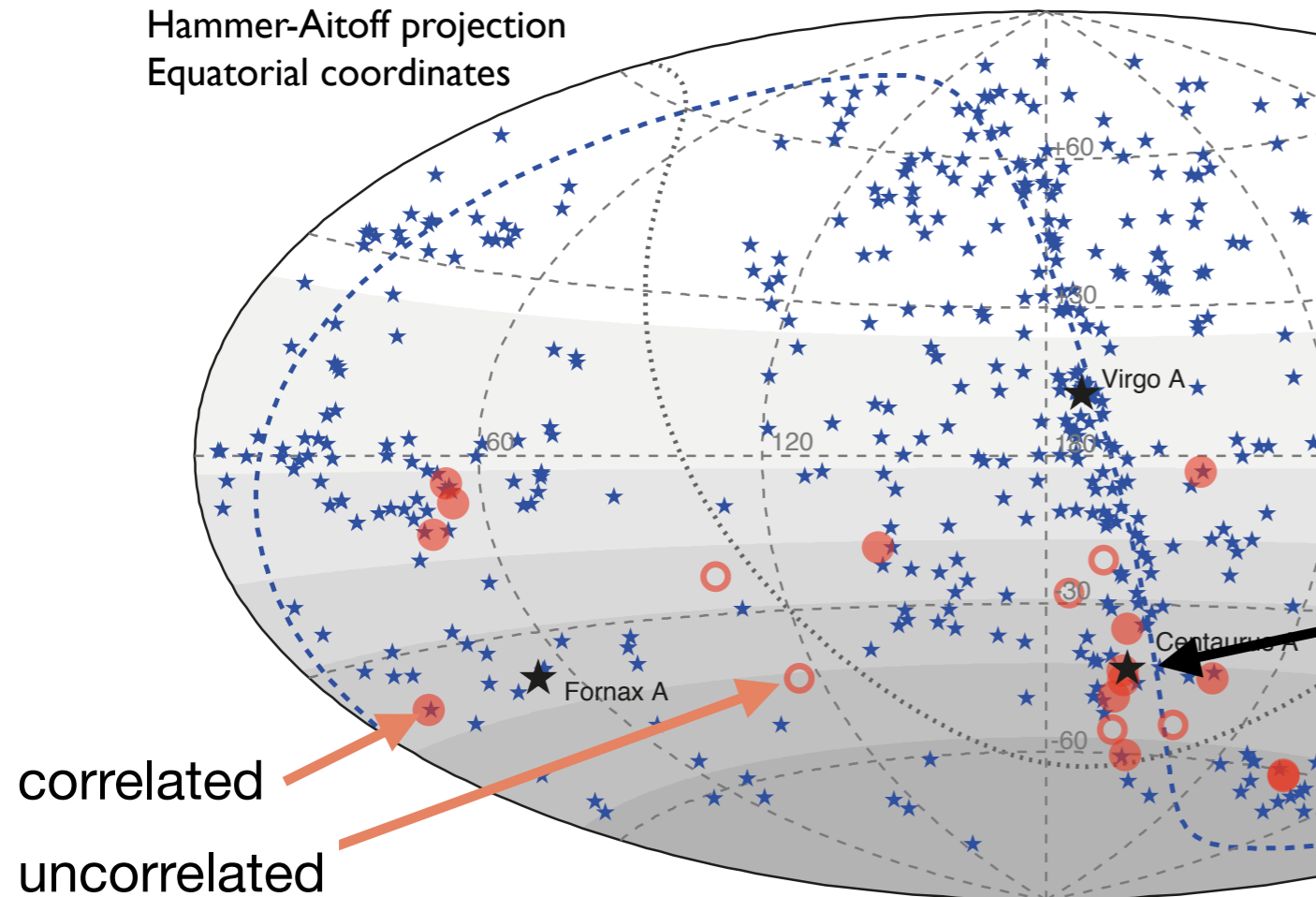
- Highest-energy particles are not distributed isotropically
- Correlation with known close-by AGNs and with “supergalactic plane”
 - Initially 70% of particles observed to be correlated to AGNs

AUGER: Sources for UHECRs - 2007



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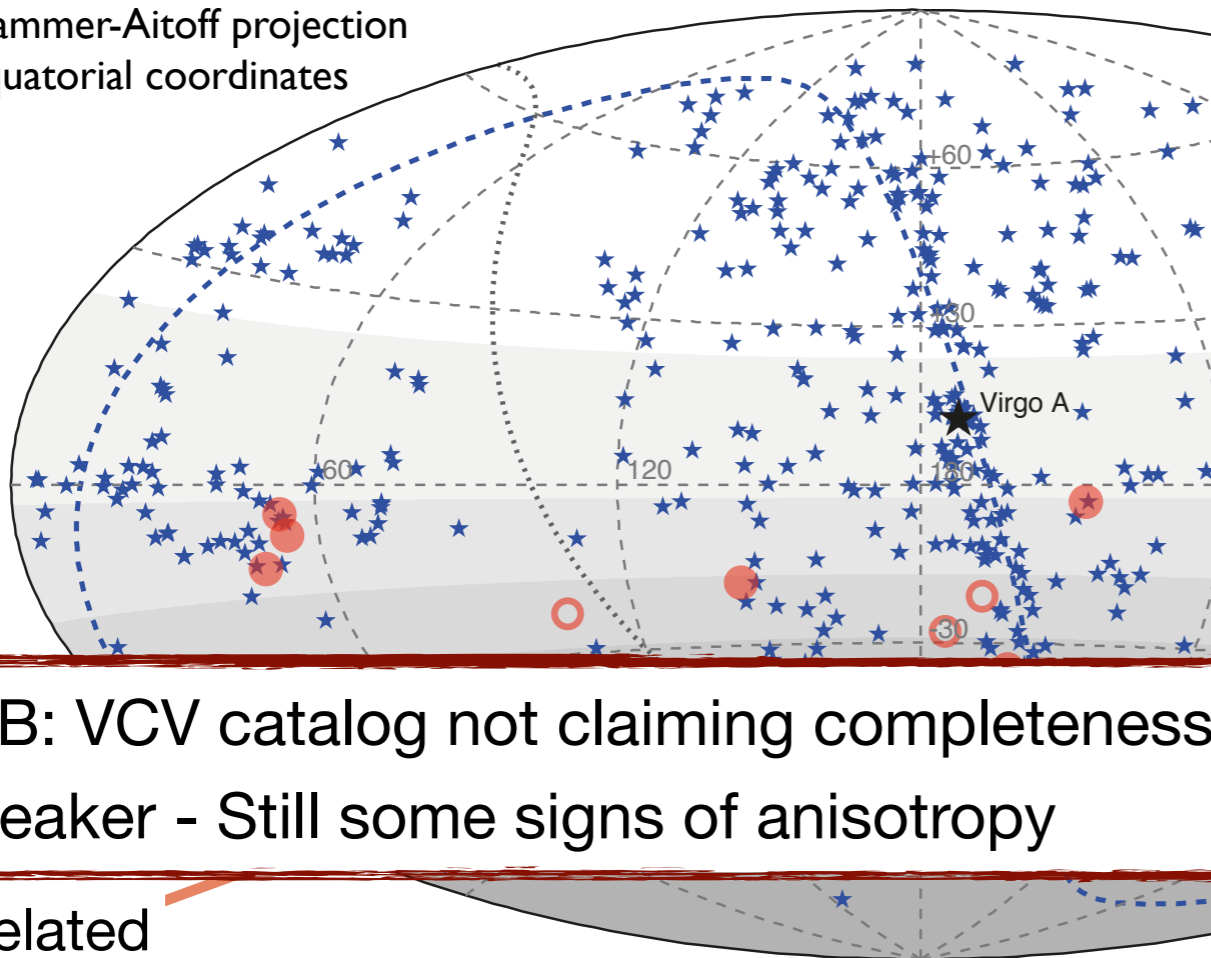


- Highest-energy particles are not distributed isotropically
- Correlation with known close-by AGNs and with the Galactic plane
 - Initially 70% of particles observed to be correlated



AUGER: Sources for UHECRs - 2007

Hammer-Aitoff projection
Equatorial coordinates



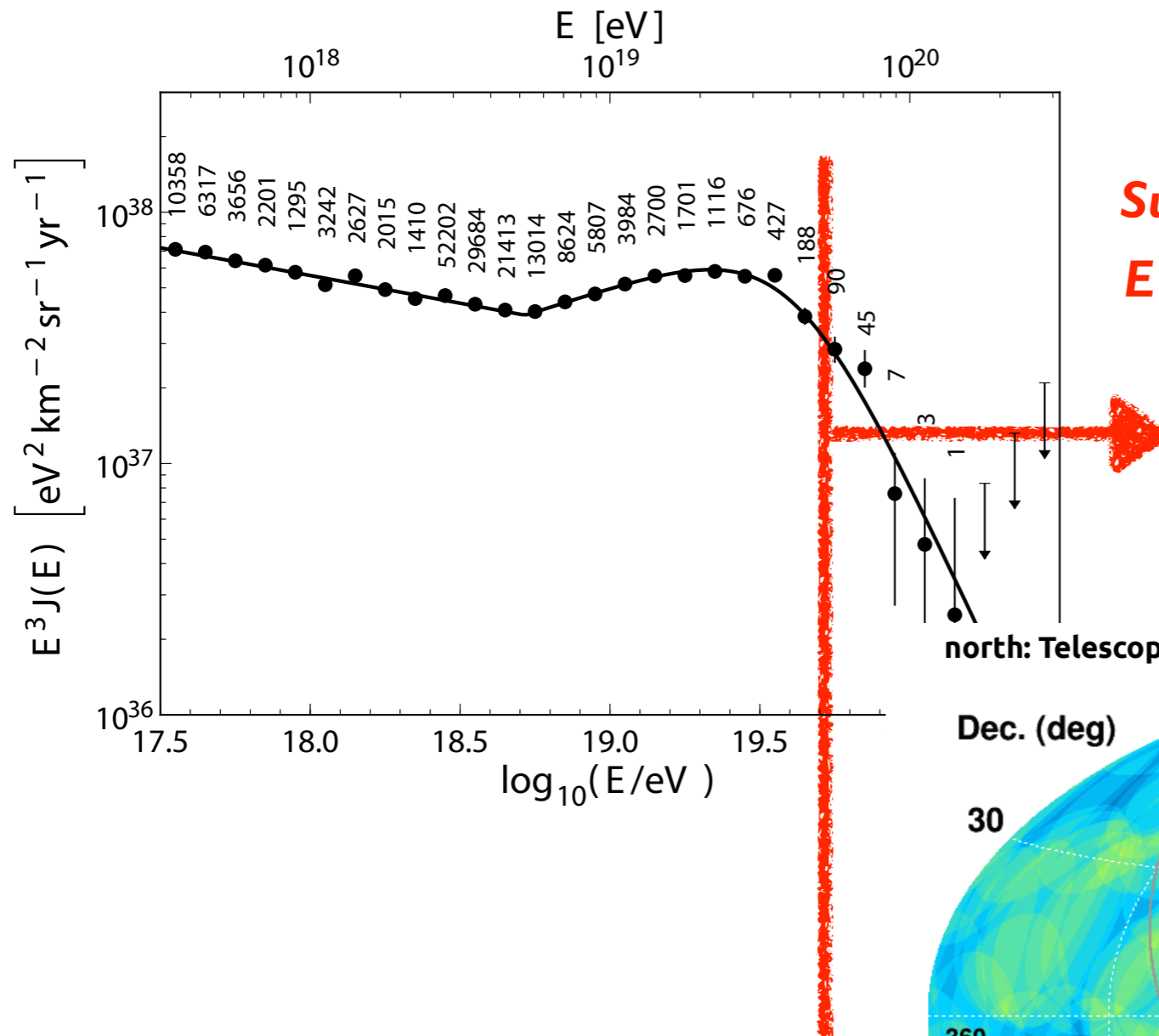
- NB: VCV catalog not claiming completeness - and with more data the correlation got weaker - Still some signs of anisotropy

uncorrelated

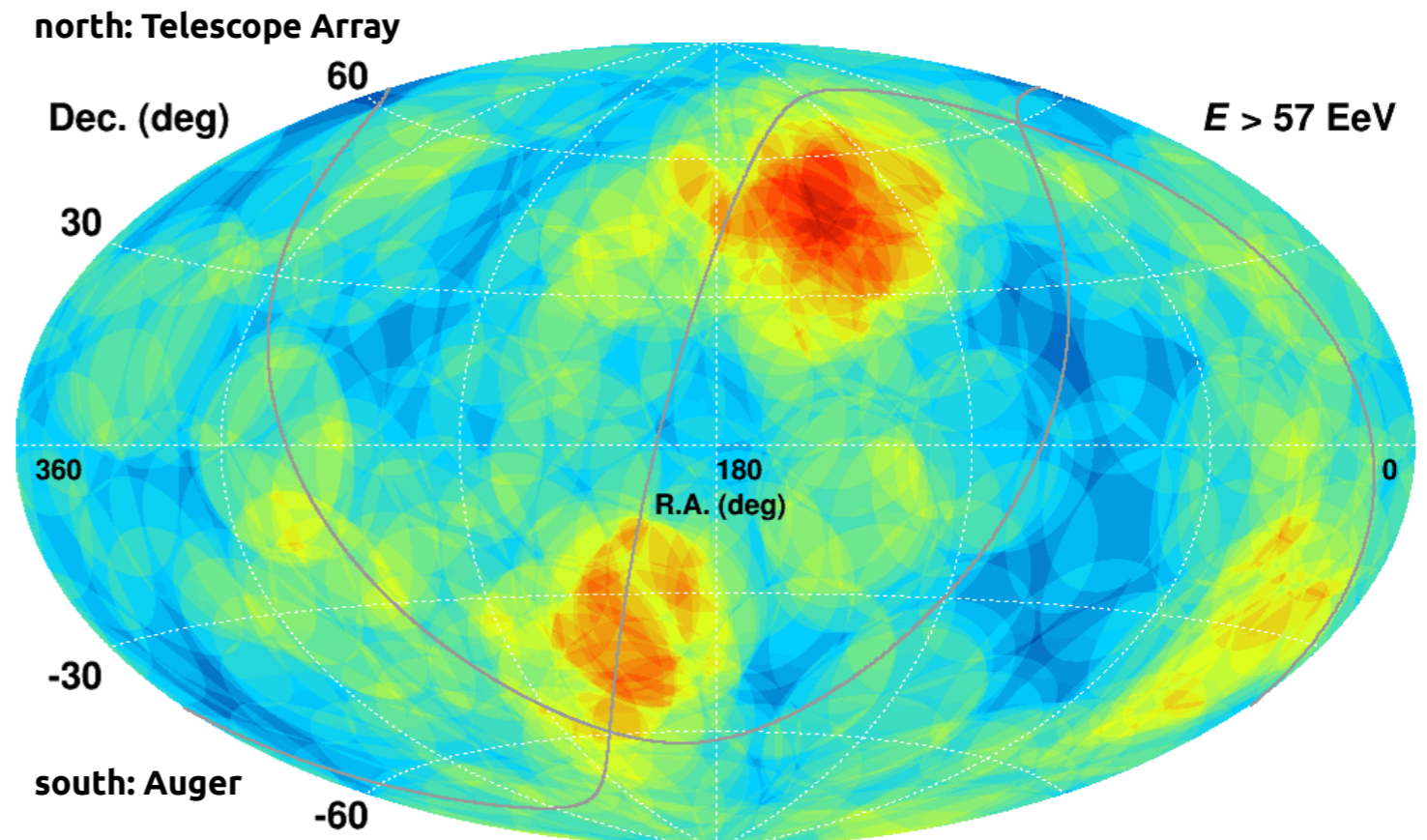
- Highest-energy particles are not distributed isotropically
- Correlation with known close-by AGNs and with the Virgo A cluster
- Initially 70% of particles observed to be correlated



AUGER and TA - The Latest Status



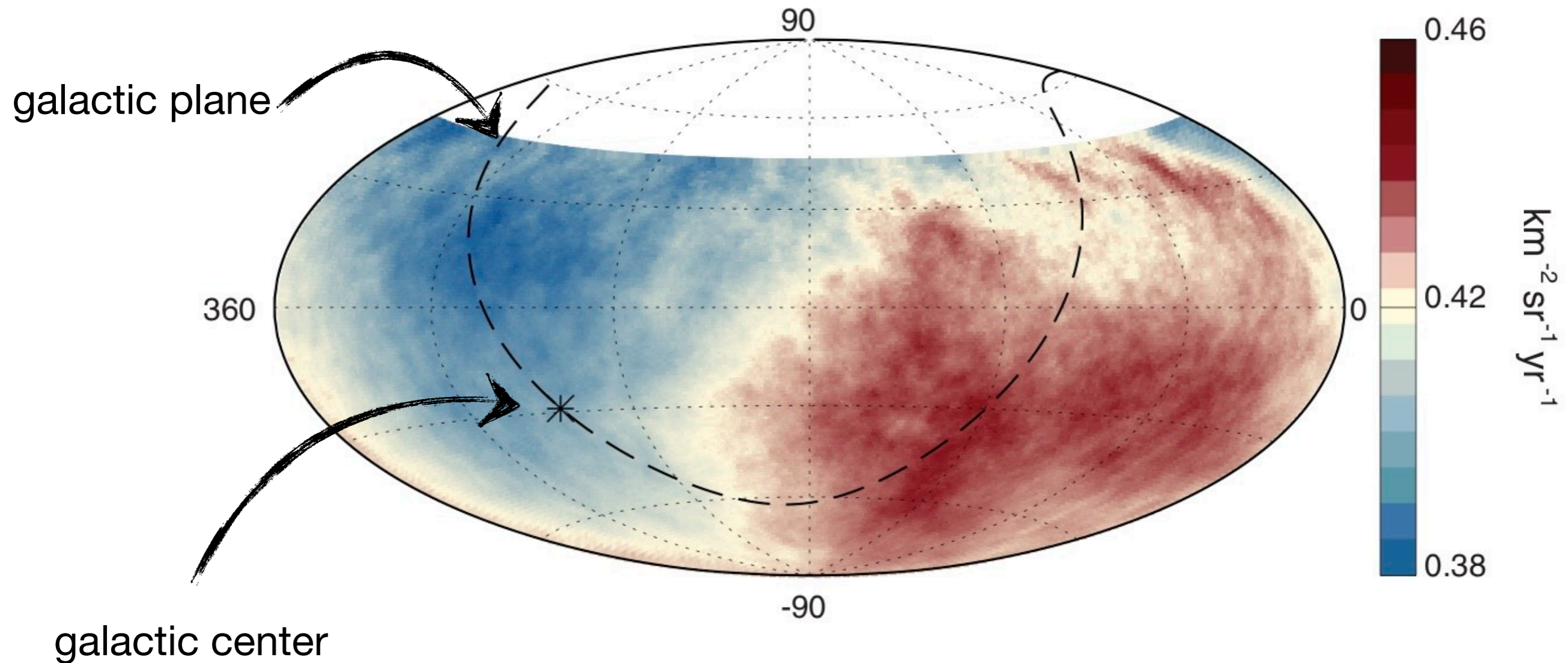
Telescope Array:
hotspot (20°), source unknown
(arXiv:1404.5890)



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

Origin of Cosmic Rays: A Continuing Story...

- Updated AUGER results:



- Proof that UHECRs are of extragalactic origin

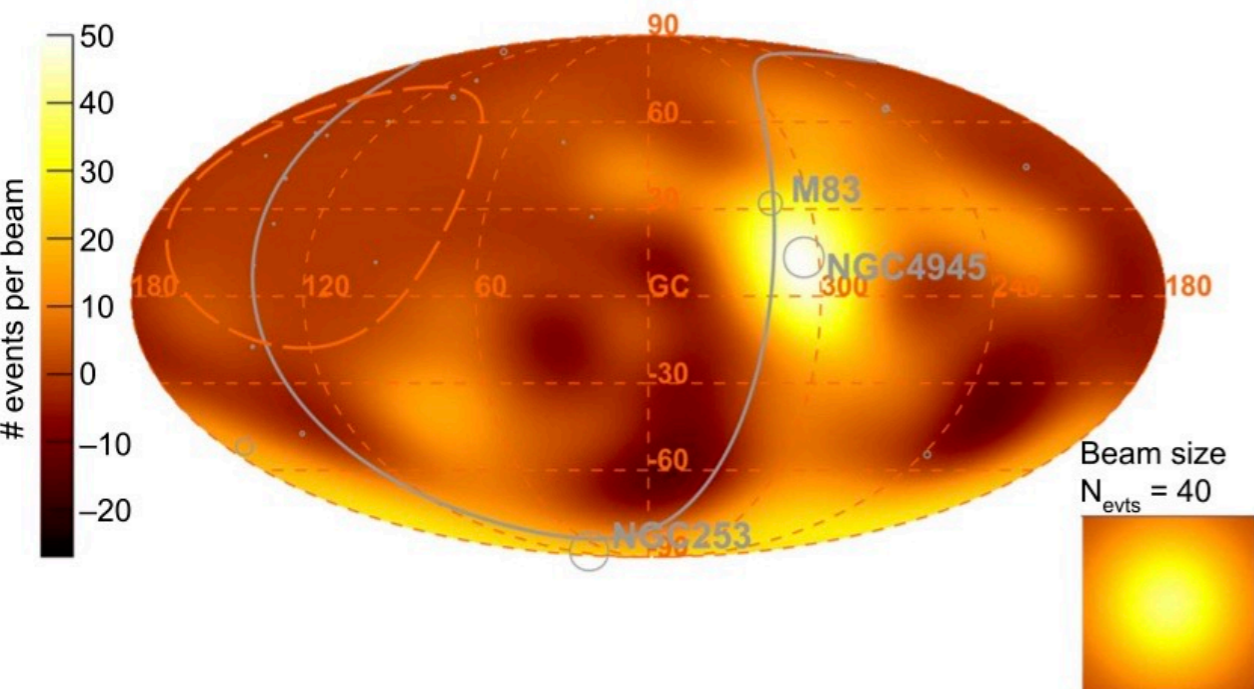
Science 357, 1266 (2017)

Origin of Cosmic Rays: A Continuing Story...

- Taking Telescope Array and new AUGER data together:
Best-matching hypothesis is that “starburst galaxies” are the main responsible for UHECRs

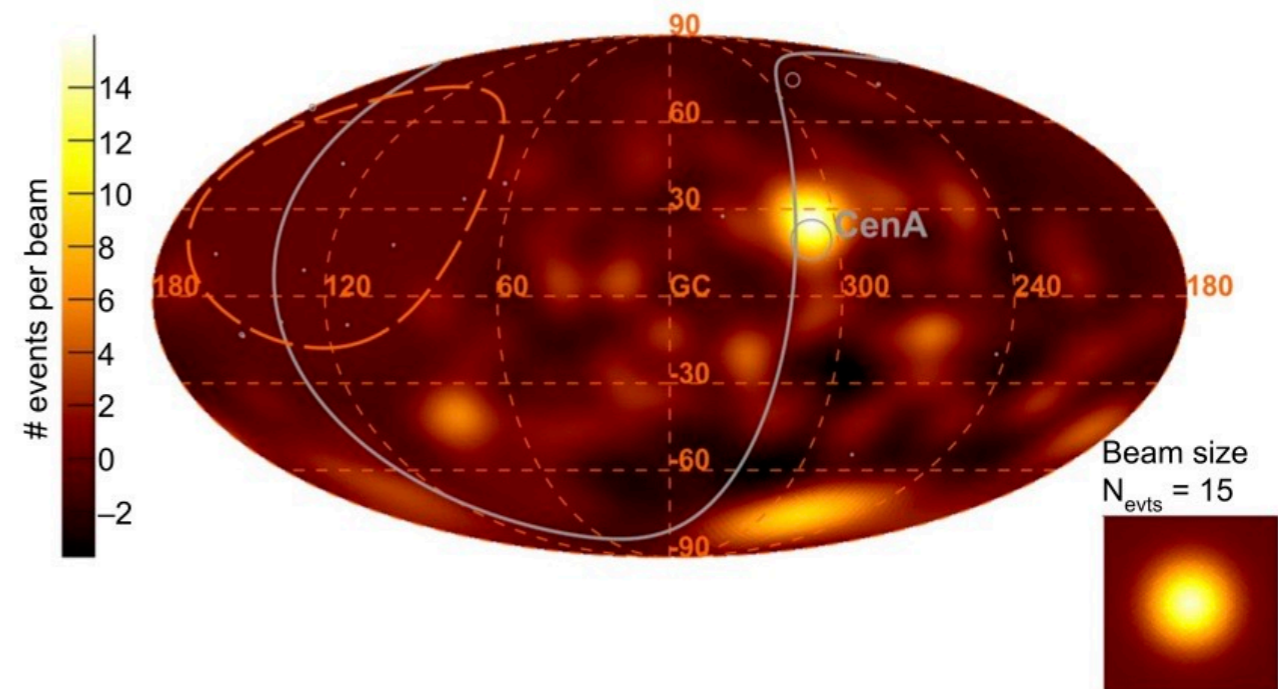
AUGER measurement

Observed Excess Map - $E > 39$ Eev



starburst galaxies

Observed Excess Map - $E > 60$ Eev



active galactic nuclei

N.B.: Different coordinate system than on previous slides
- galactic center now in origin

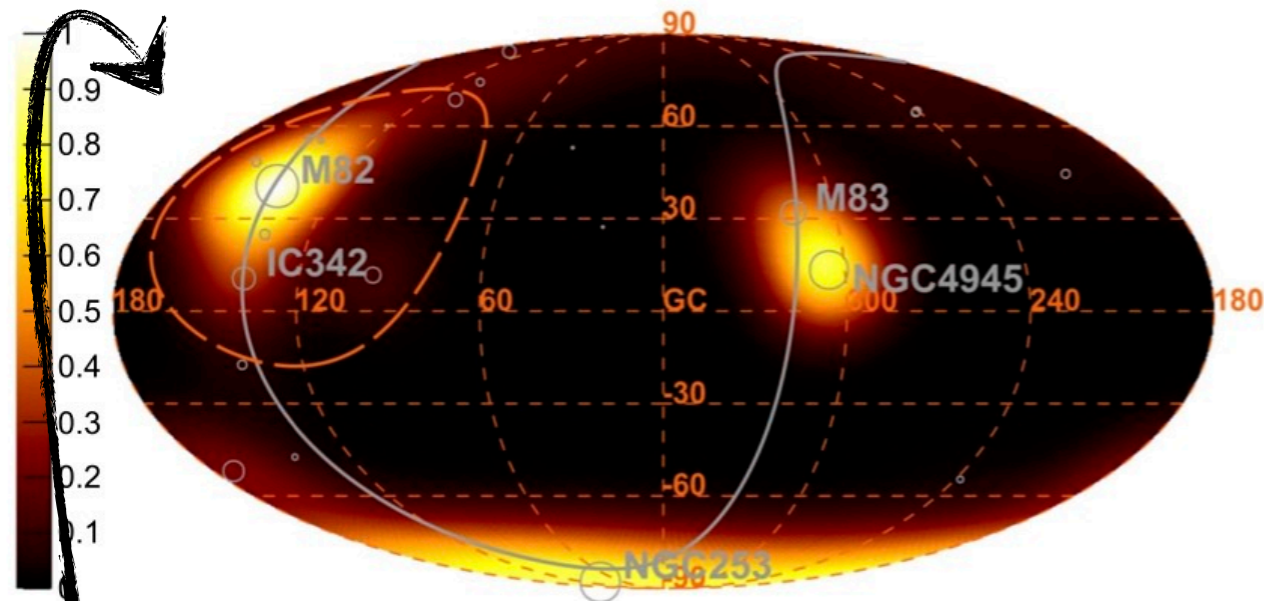
ApJL 853, L29 (2018)

Origin of Cosmic Rays: A Continuing Story...

- Taking Telescope Array and new AUGER data together:
Best-matching hypothesis is that “starburst galaxies” are the main responsible for UHECRs

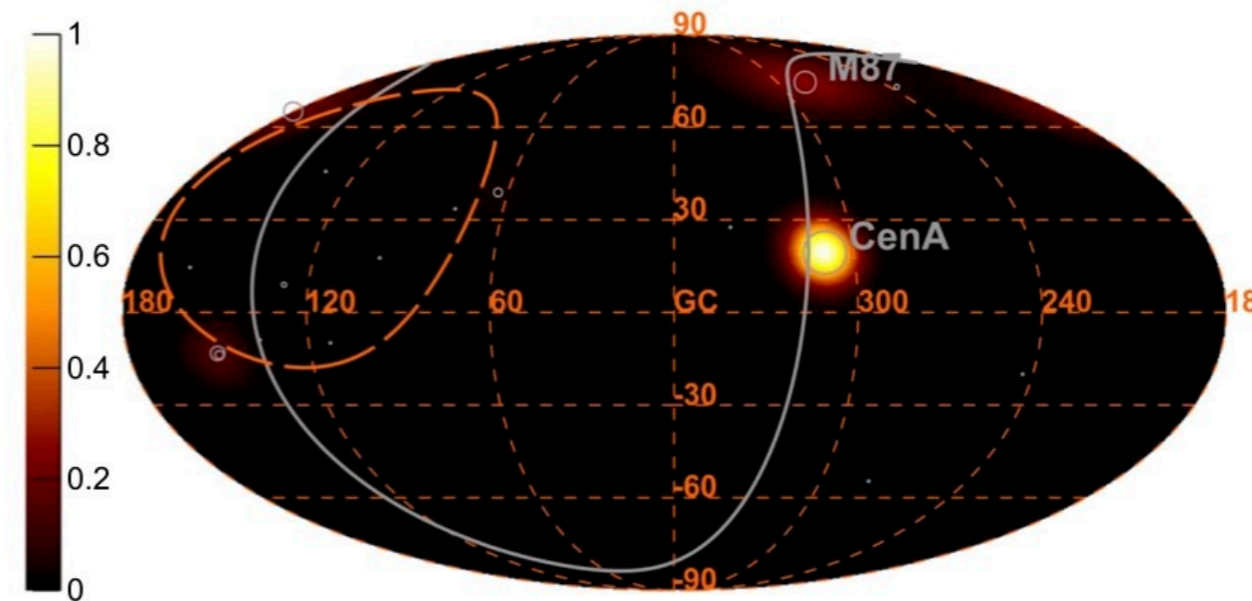
Predictions of models:

Model Flux Map - Starburst galaxies - $E > 39$ EeV



starburst galaxies

Model Flux Map - Active galactic nuclei - $E > 39$ EeV



active galactic nuclei

This is where the TA excess is!

N.B.: Different coordinate system than on previous slides
- galactic center now in origin

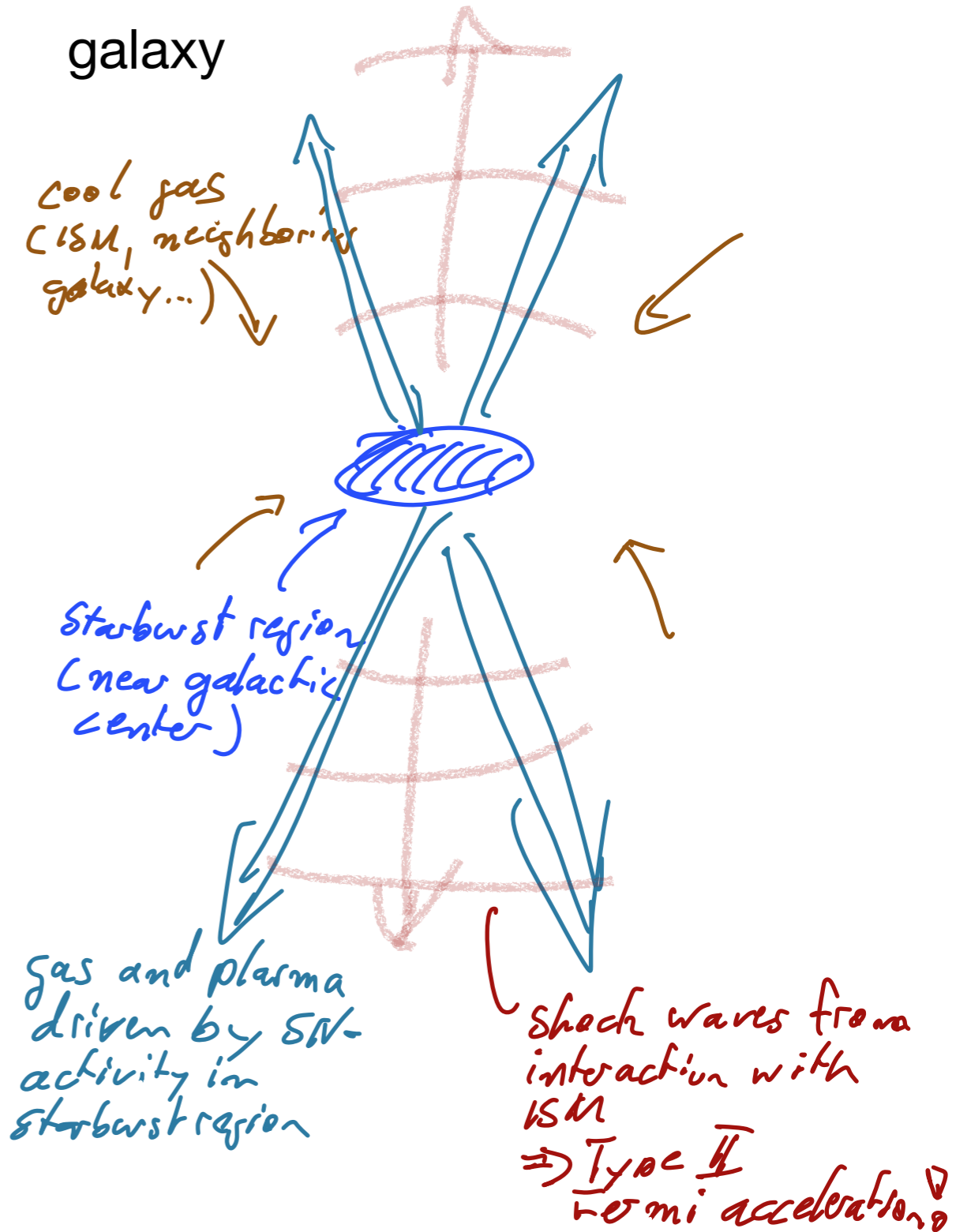
ApJL 853, L29 (2018)

The Latest Candidates: Starburst Galaxies



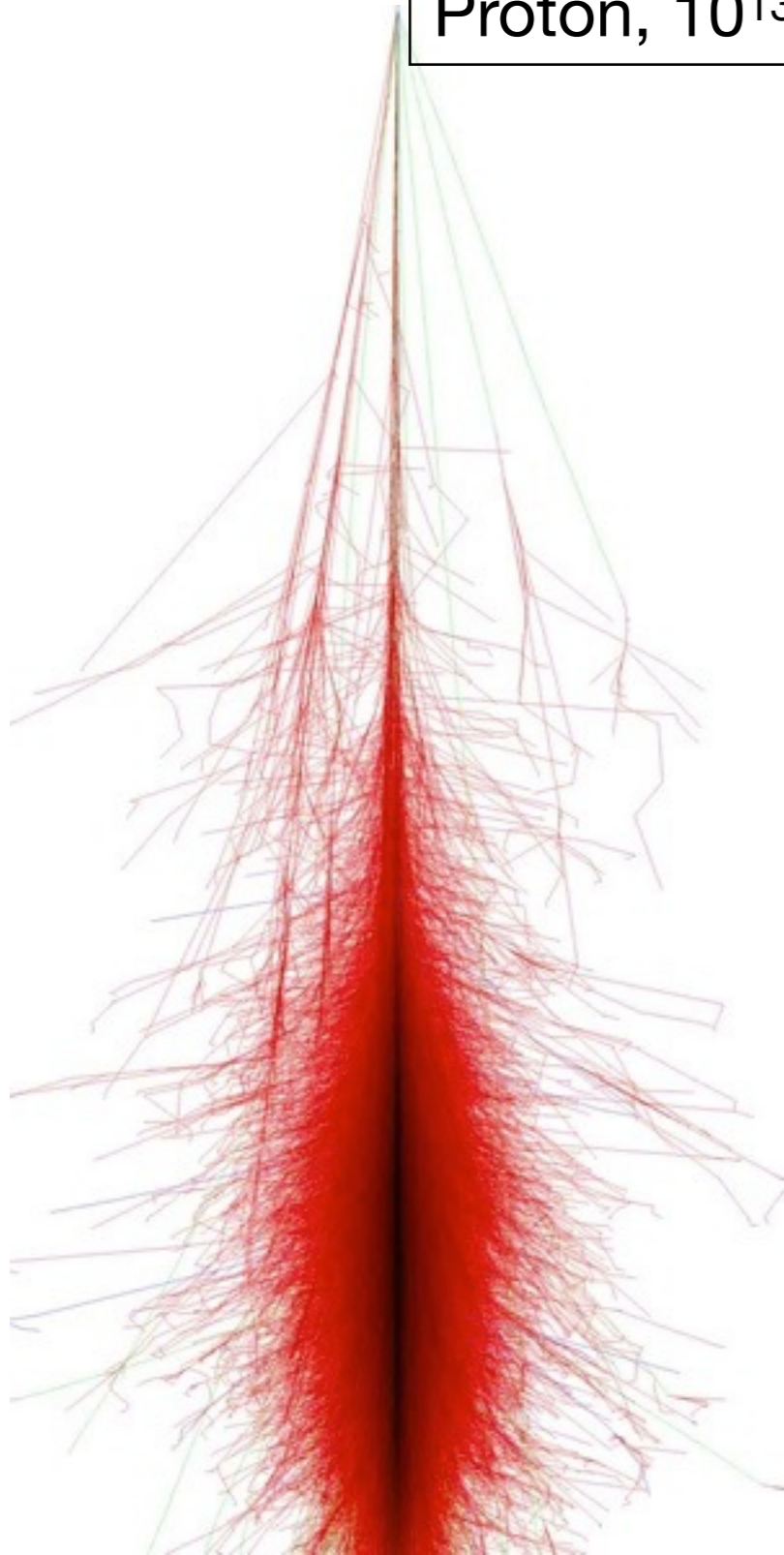
M82 directly in field of view of TA
(not AUGER)

- M82: the closest starburst galaxy



Composition of UHECRs: Protons vs Fe

Proton, 10^{13} eV



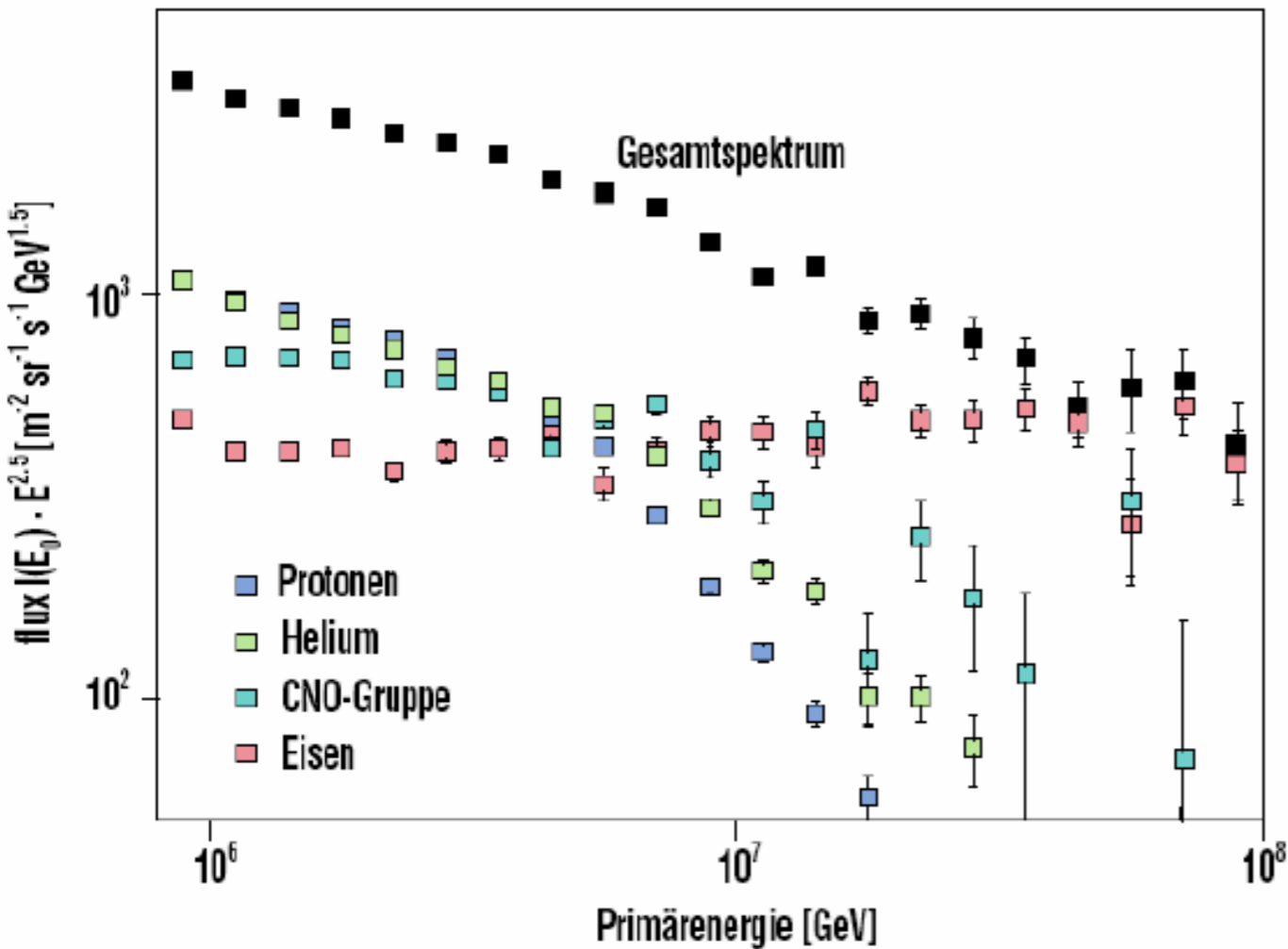
Fe, 10^{13} eV



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

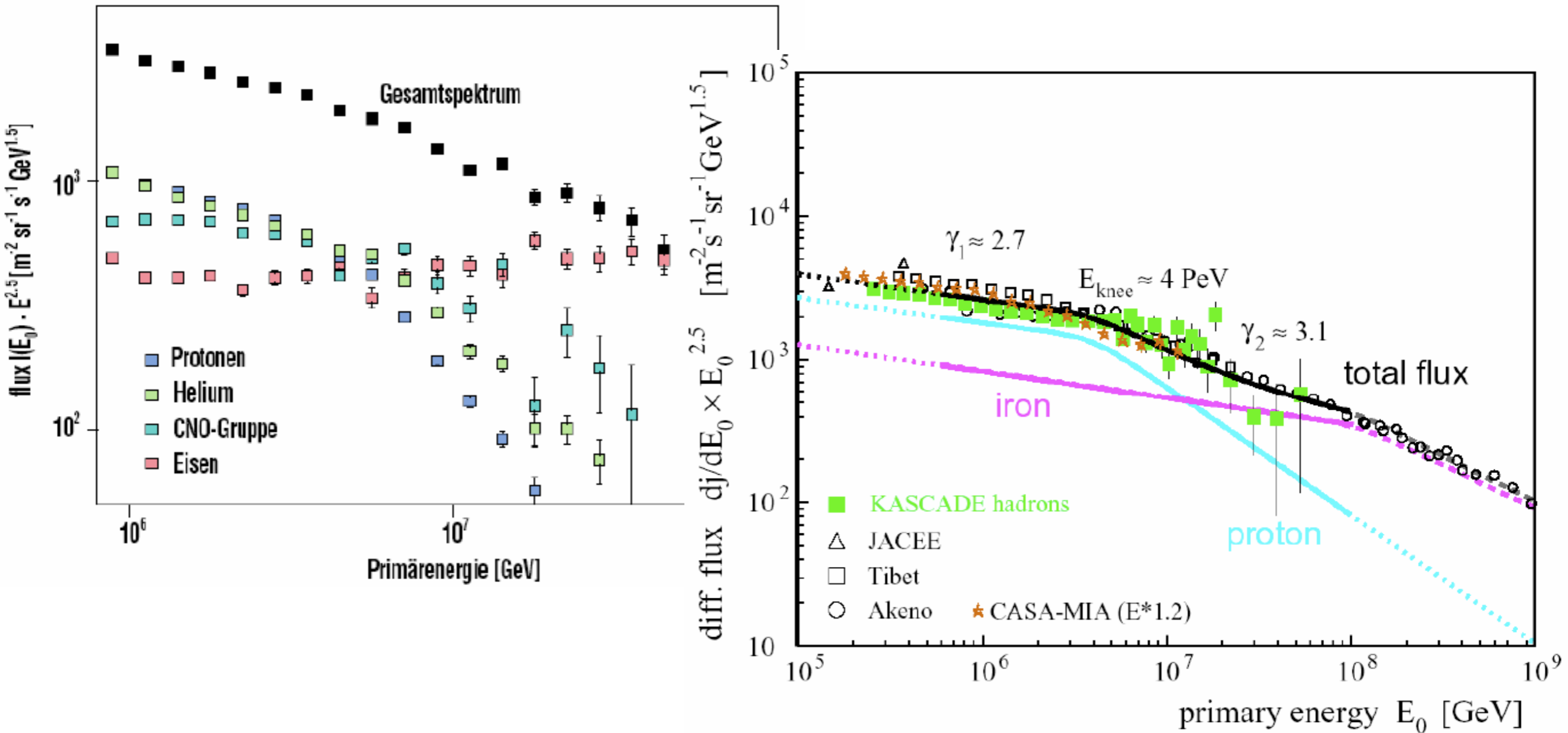
<http://www.ast.leeds.ac.uk/~fs/showerimages.html>

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)

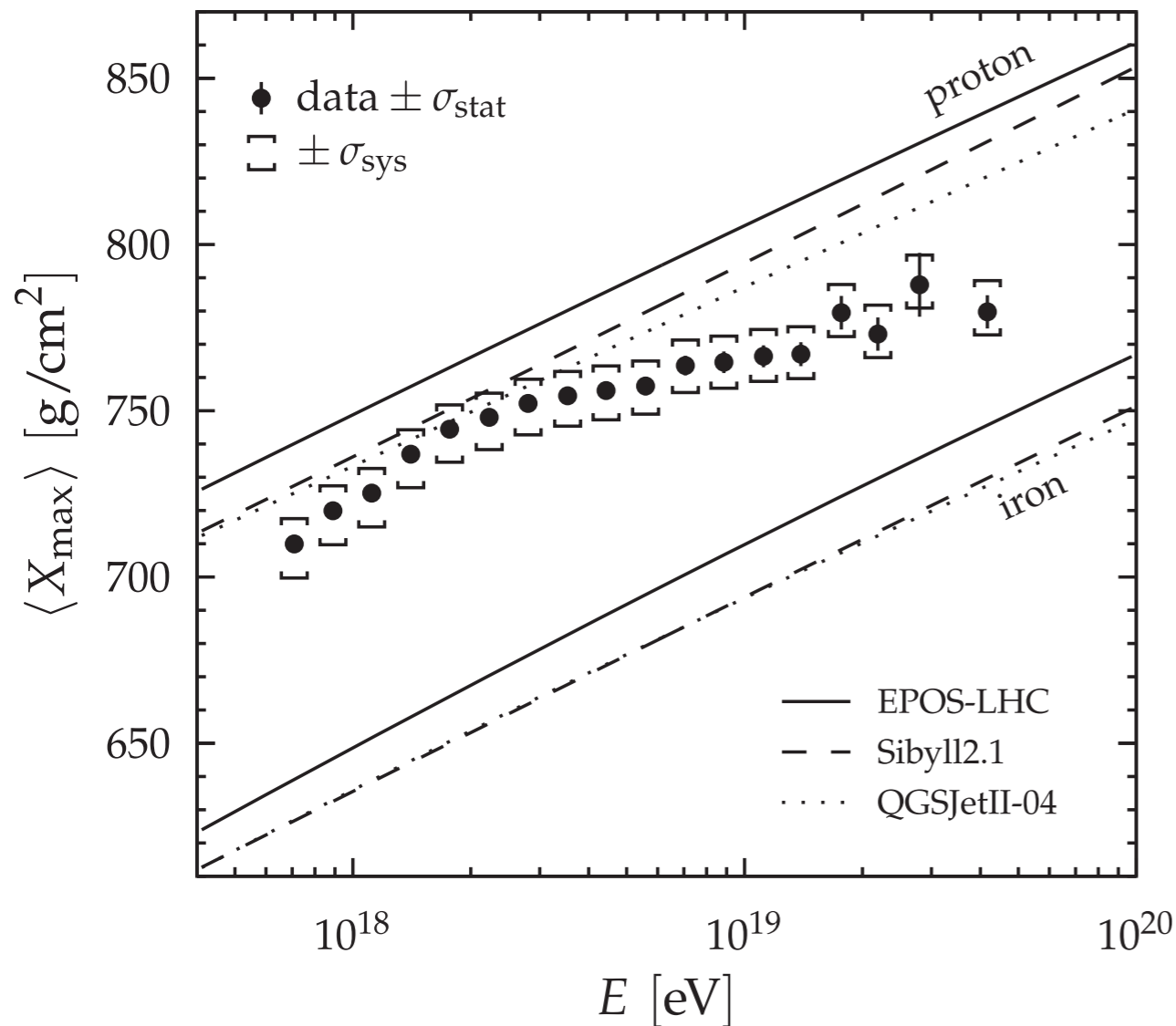
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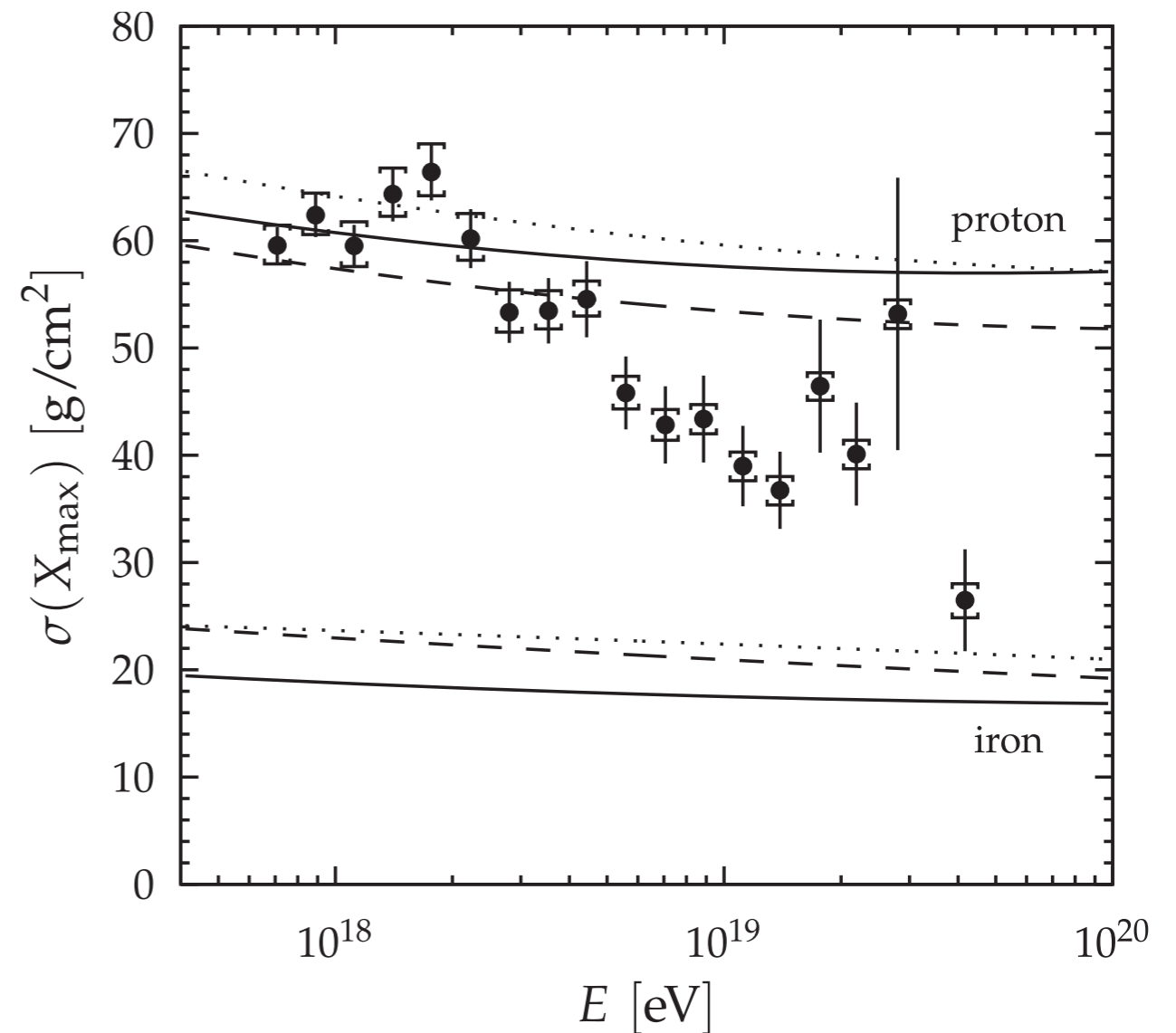
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Composition at High Energies

- Determined from shower profile



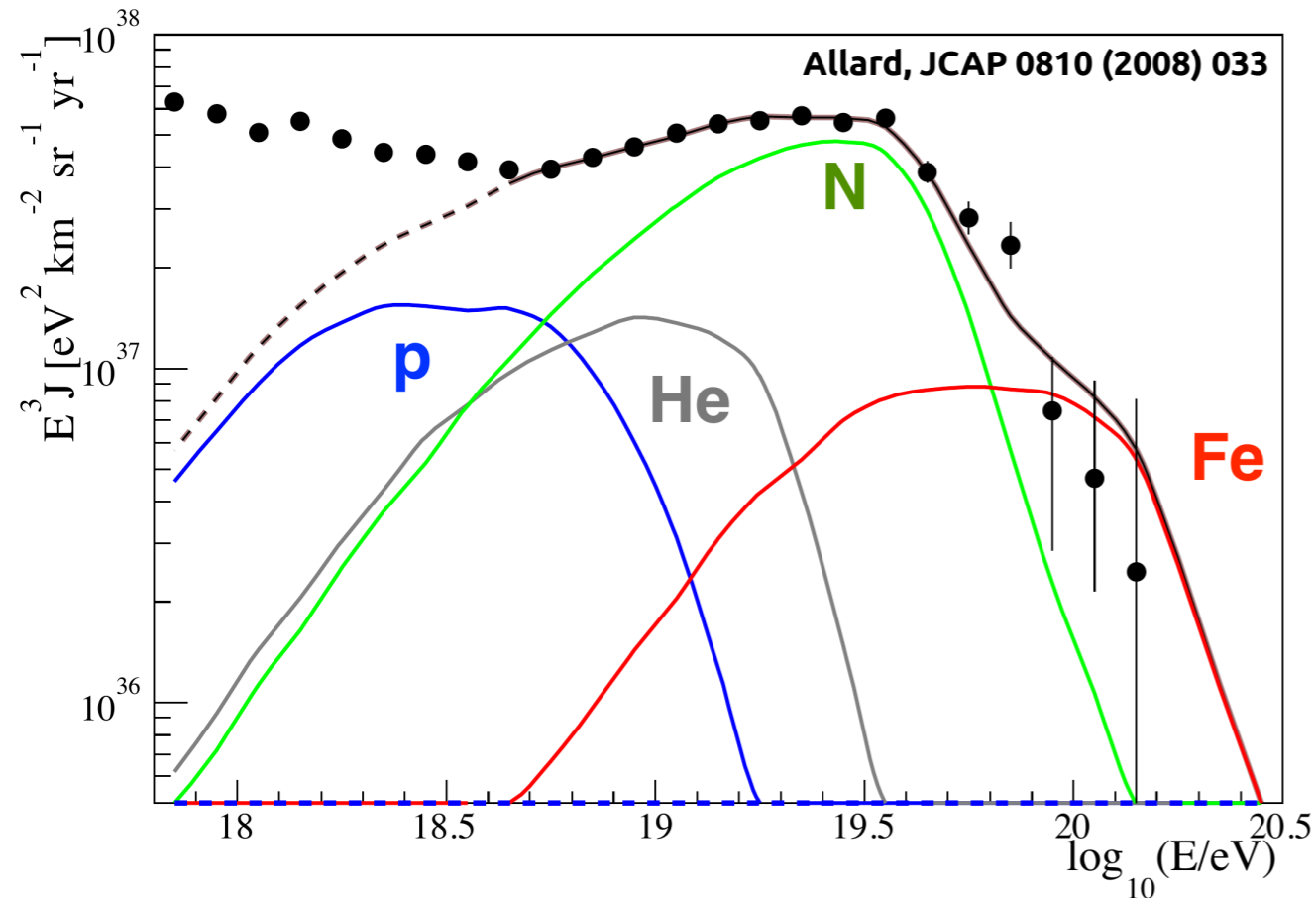
Phys. Rev. D90, 122006 (2014)



- 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

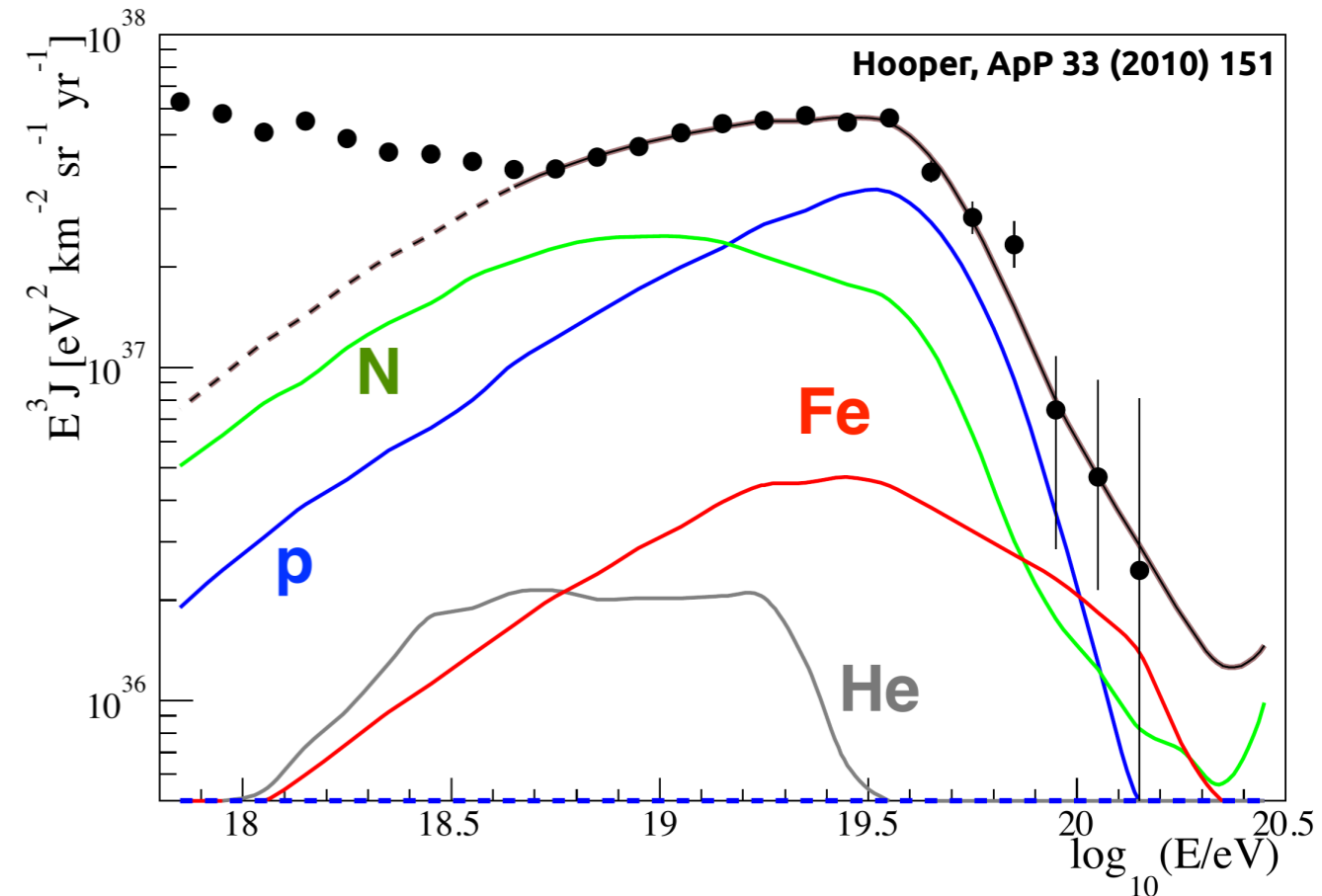
Composition and Suppression Scenarios

Scenario 1



sources accelerate to maximum rigidity ("tired" sources)
 energies shifted up by Z
 heavy injection Si-Fe

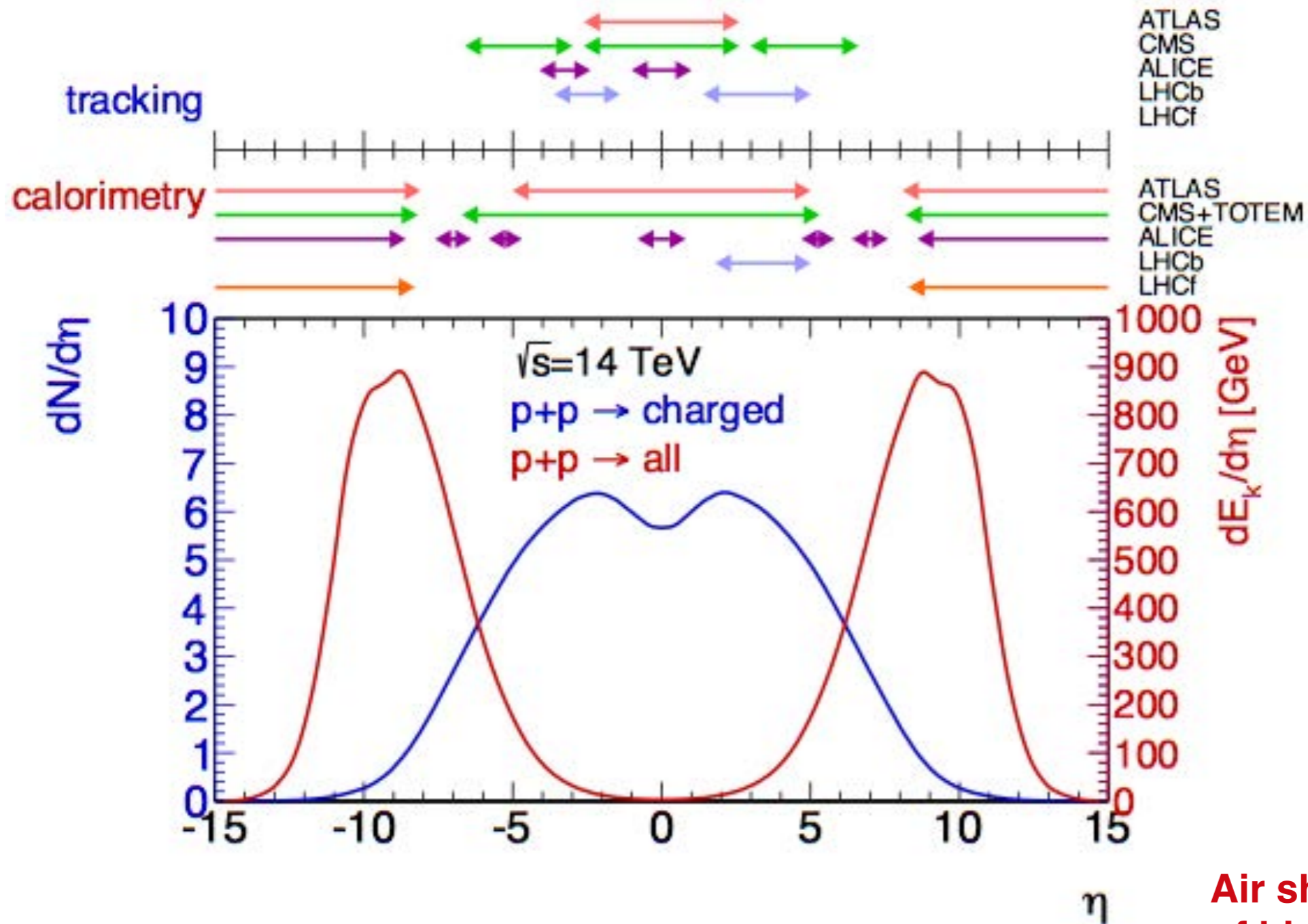
Scenario 2



(mostly) photo-disintegration
 energies shifted down by A
 light elements come from heavy
 CR astronomy still possible

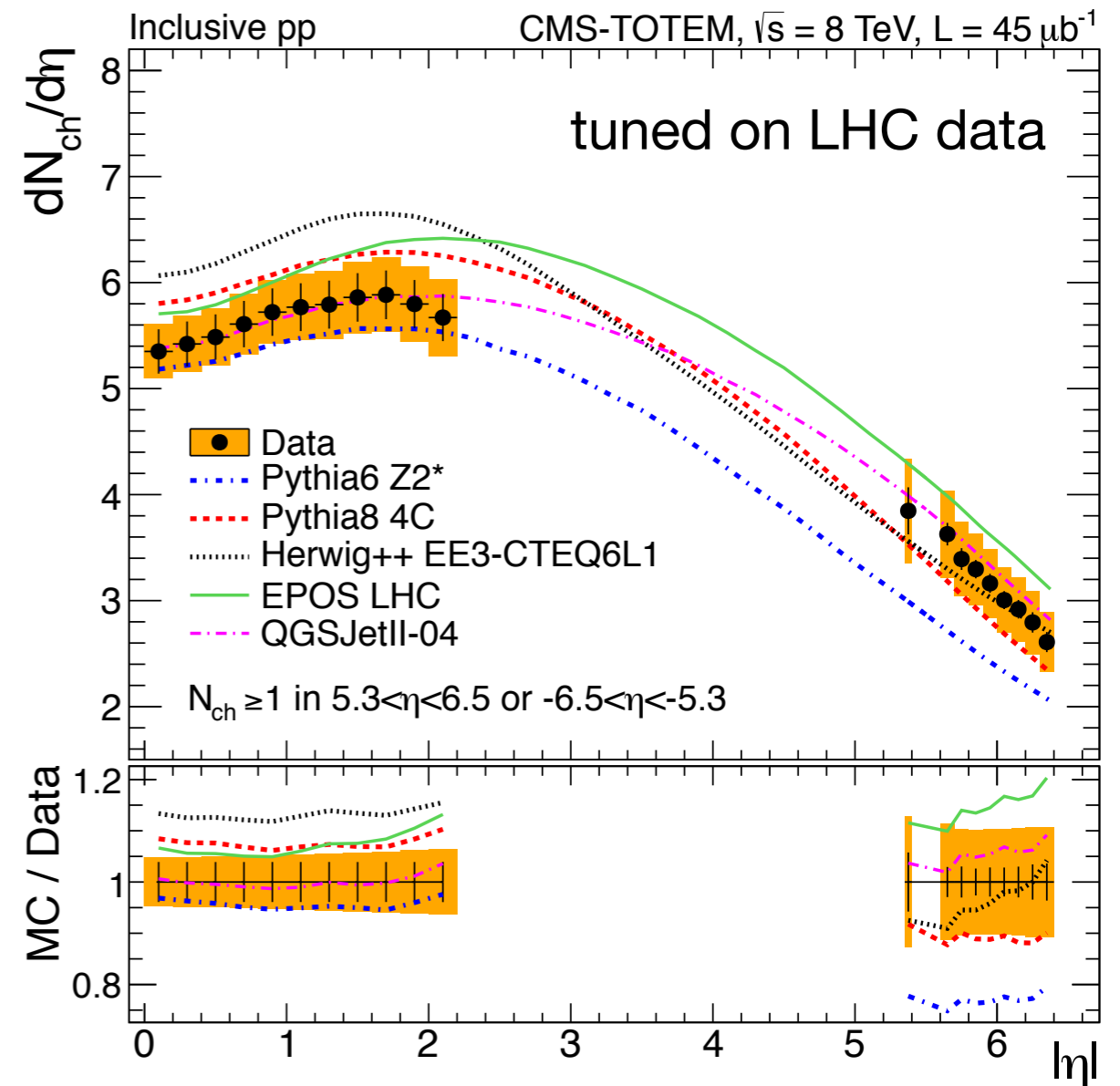
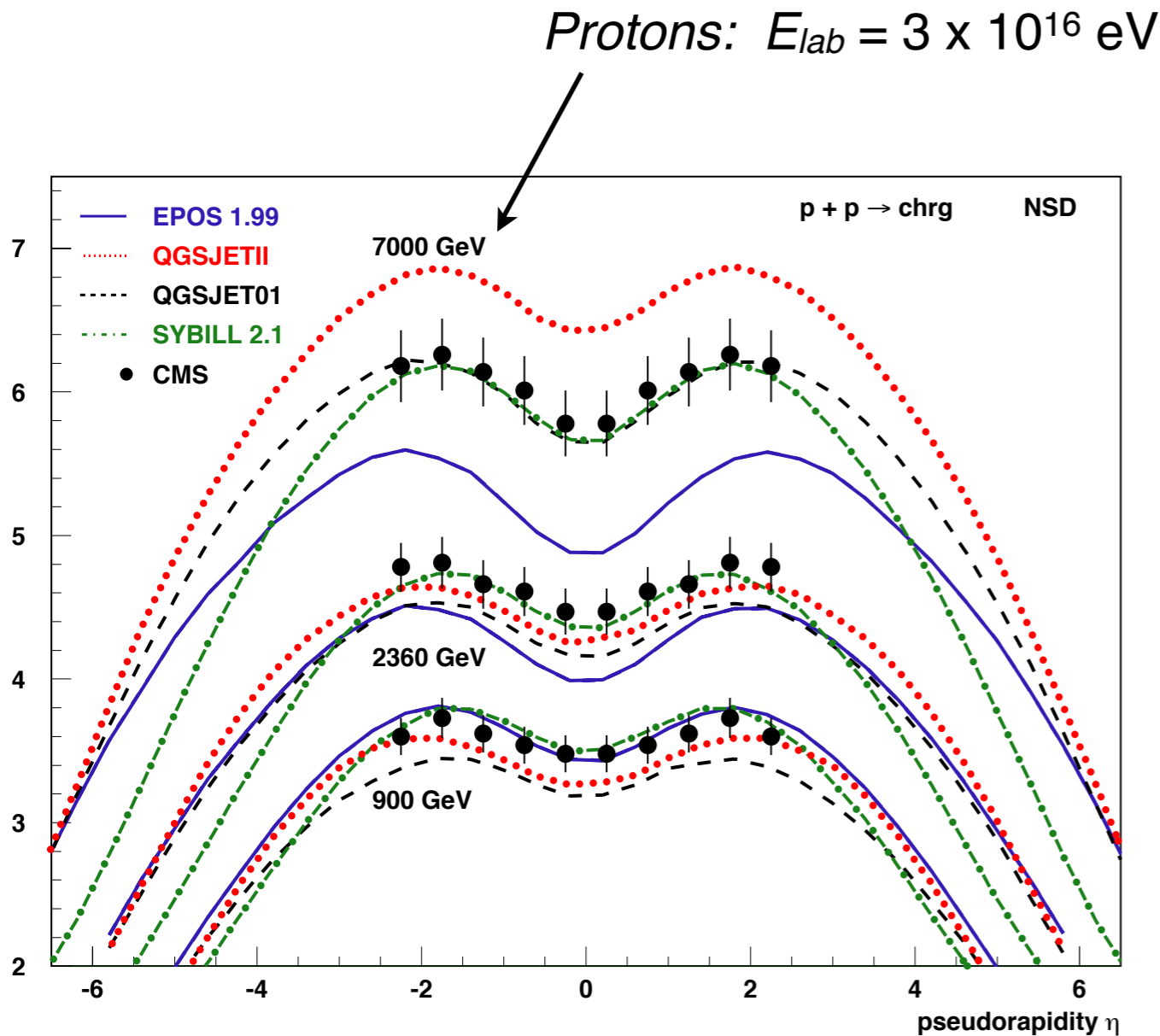
Connection to Collider Physics

- Different LHC experiments covering most of the relevant phase space



Air showers: Particles of highest energy most important

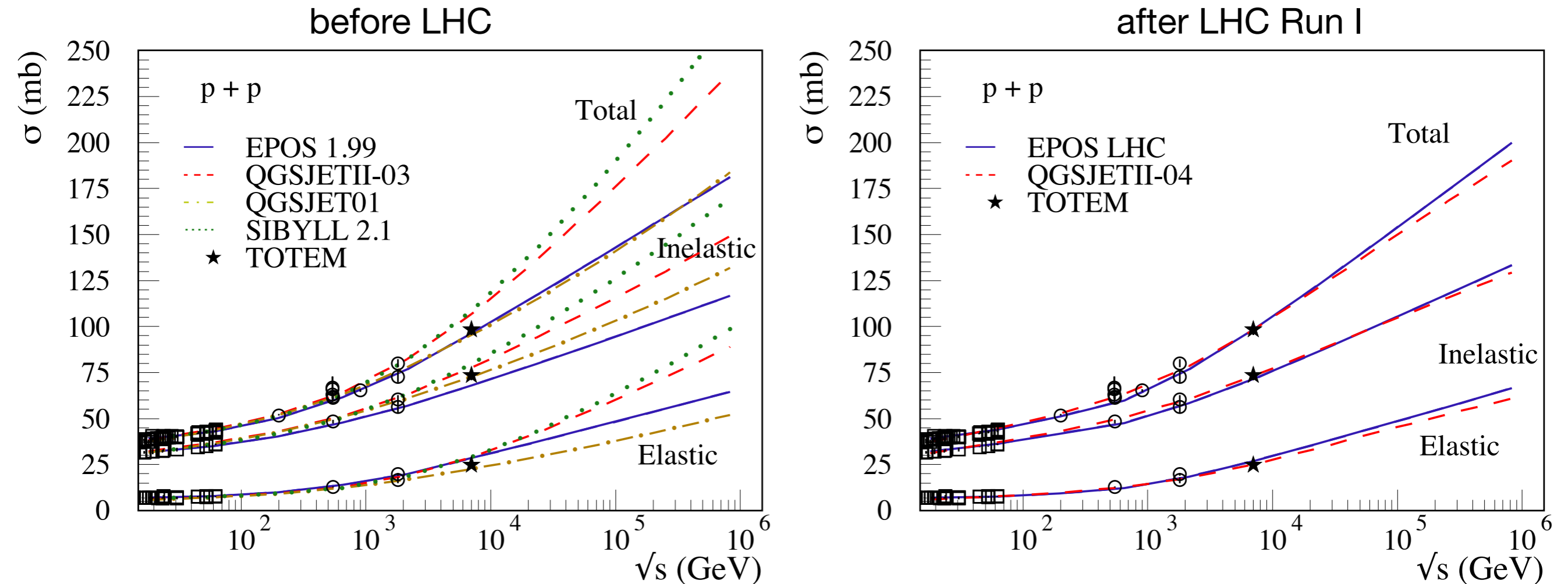
Connection to Collider Physics



- 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 3×10^{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: $\sim 7 \times 10^{19}$ eV for protons, experimentally well established
- The search for sources is going on: Indications of anisotropic distribution, best correlation with starburst galaxies
 - M82 closest starburst galaxy - excess seen by Telescope Array
- 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: 18.06., “Cosmic Rays II”, F. Simon

Lecture Overview

09.04.	Einführung / Introduction
16.04.	Ground-based Accelerators
23.04.	Cosmic Accelerators
30.04.	Detectors in Astroparticle Physics
07.05.	The Standard Model
14.05.	QCD and Jets at e^+e^- Colliders
21.05.	Holiday - No Lecture
28.05.	Precision Experiments with low-energy accelerators
04.06.	Dark Matter & Dark Energy
11.06.	Cosmic Rays I
18.06.	Cosmic Rays II
25.06.	Gravitational Waves, Neutrino Introduction
02.07.	Neutrinos I
09.07.	Neutrinos II