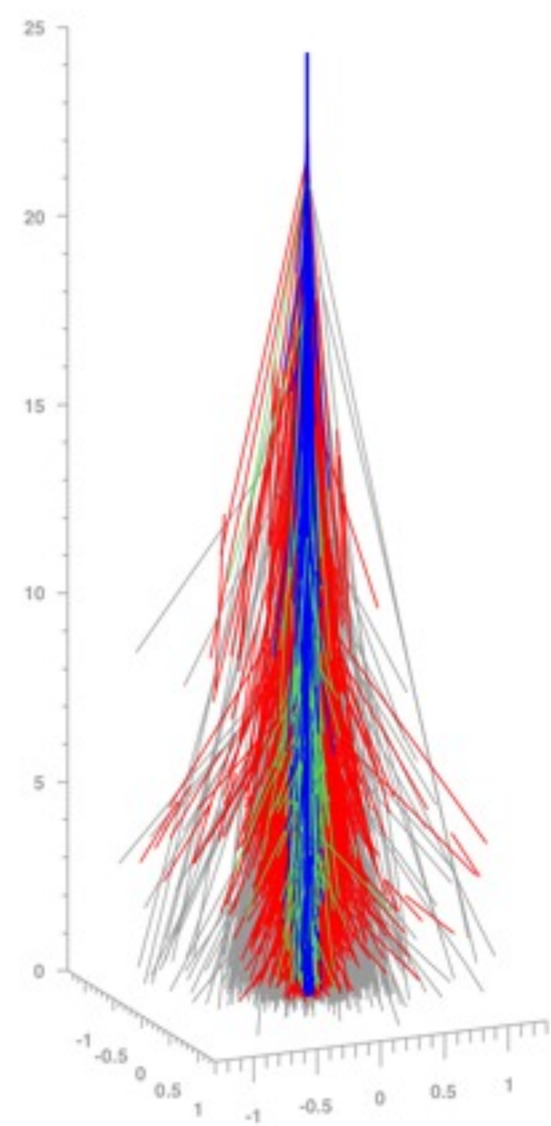
Ultra-High Energy Cosmic Rays

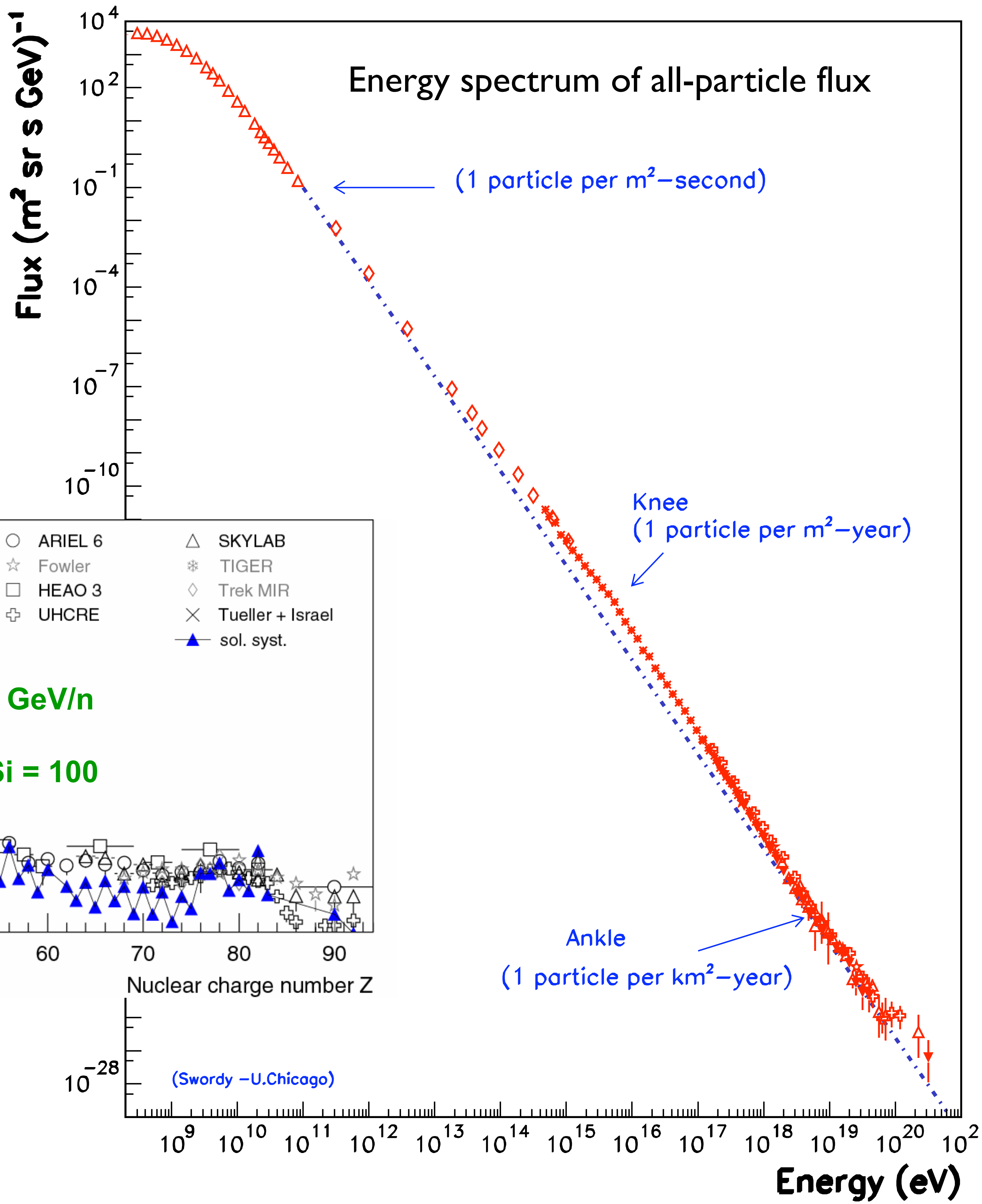
First Answers and New Puzzles

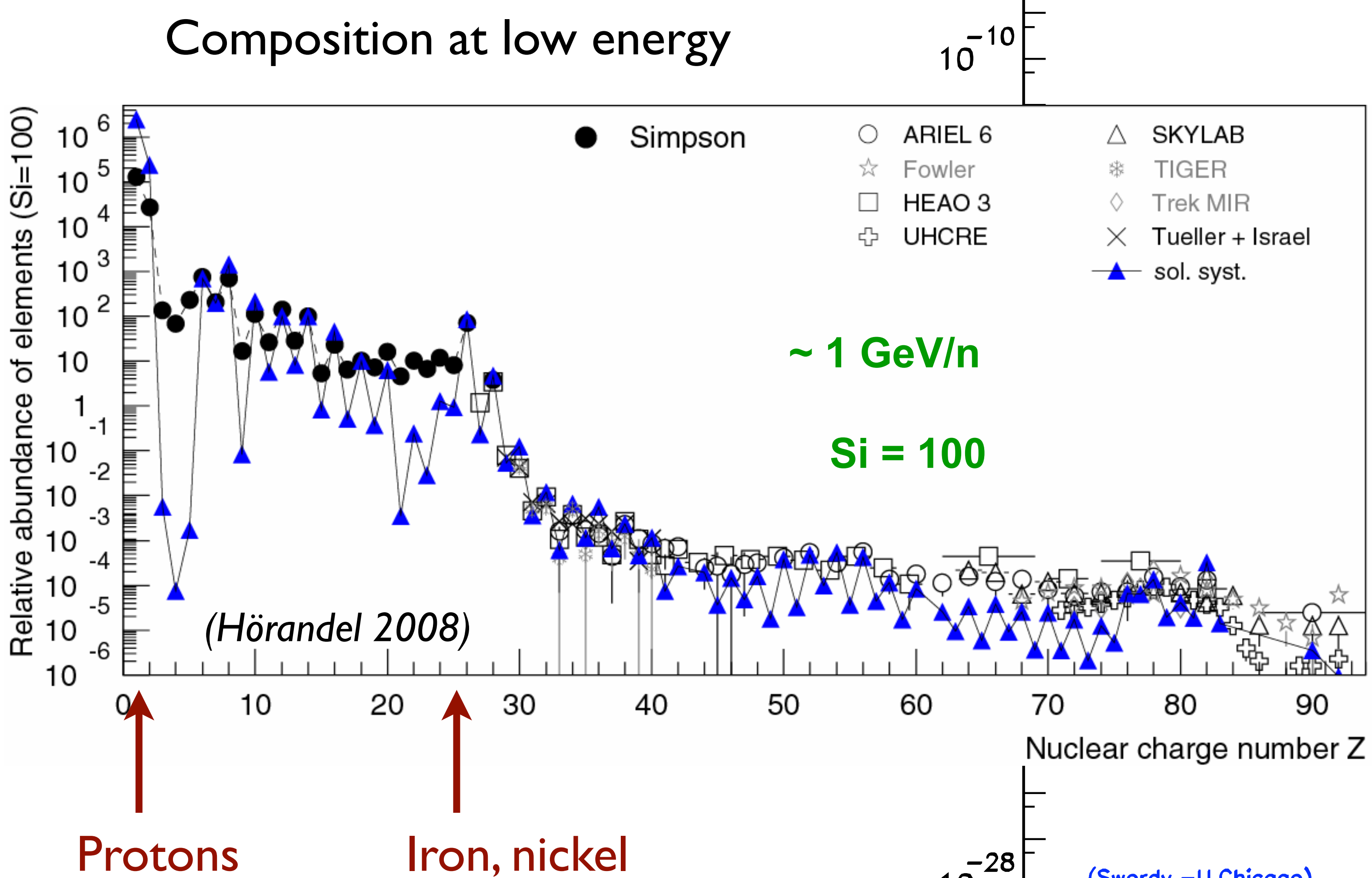


Ralph Engel

Karlsruhe Institute of Technology (KIT)

Flux of cosmic rays





Outline

Physics of ultra-high energy cosmic rays

Results obtained before 2004

New generation of cosmic ray detectors

New data – **first answers**

New data – **new puzzles**

Summary & outlook

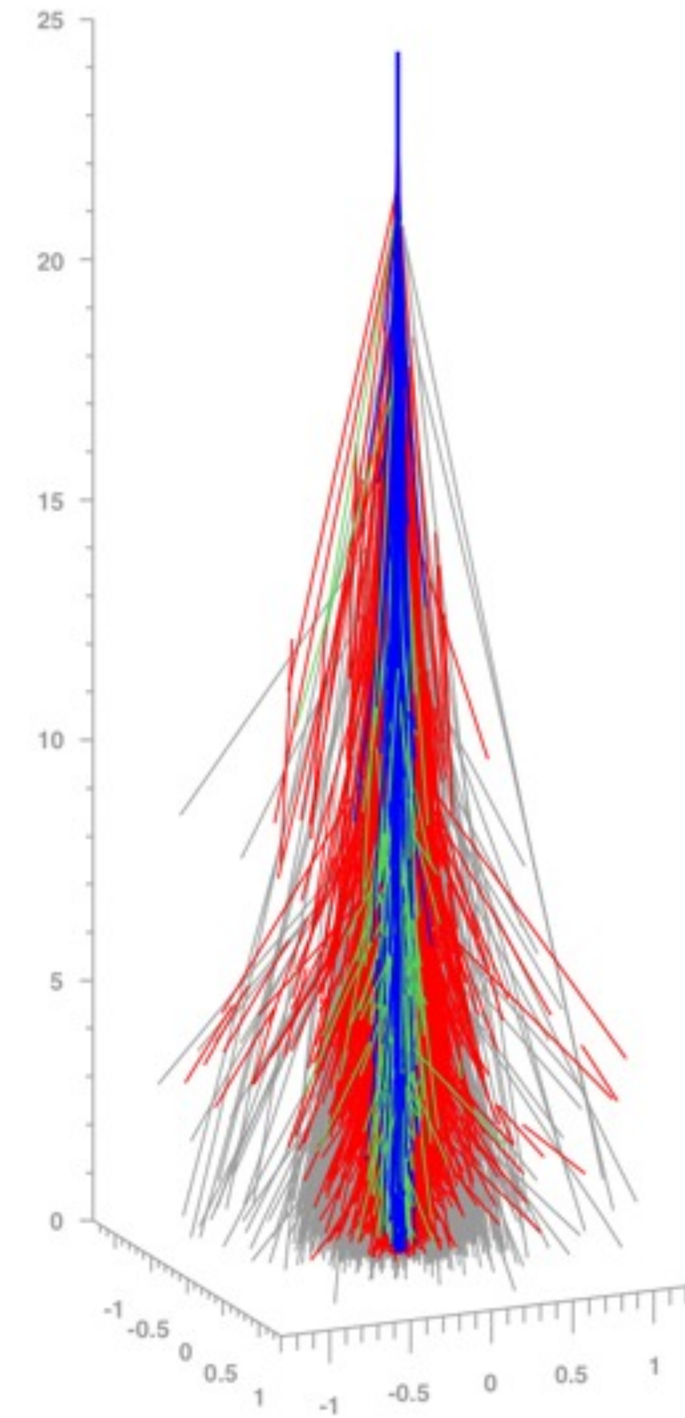
Physics of ultra-high energy cosmic rays

The first really big event

VOLUME 10, NUMBER 4 PHYSICAL REVIEW LETTERS 15 FEBRUARY 1963

EVIDENCE FOR A PRIMARY COSMIC-RAY PARTICLE WITH ENERGY 10^{20} eV†

John Linsley
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 10 January 1963)



Array of particle detectors at ground

Cosmic rays of 10^{20} eV exist !

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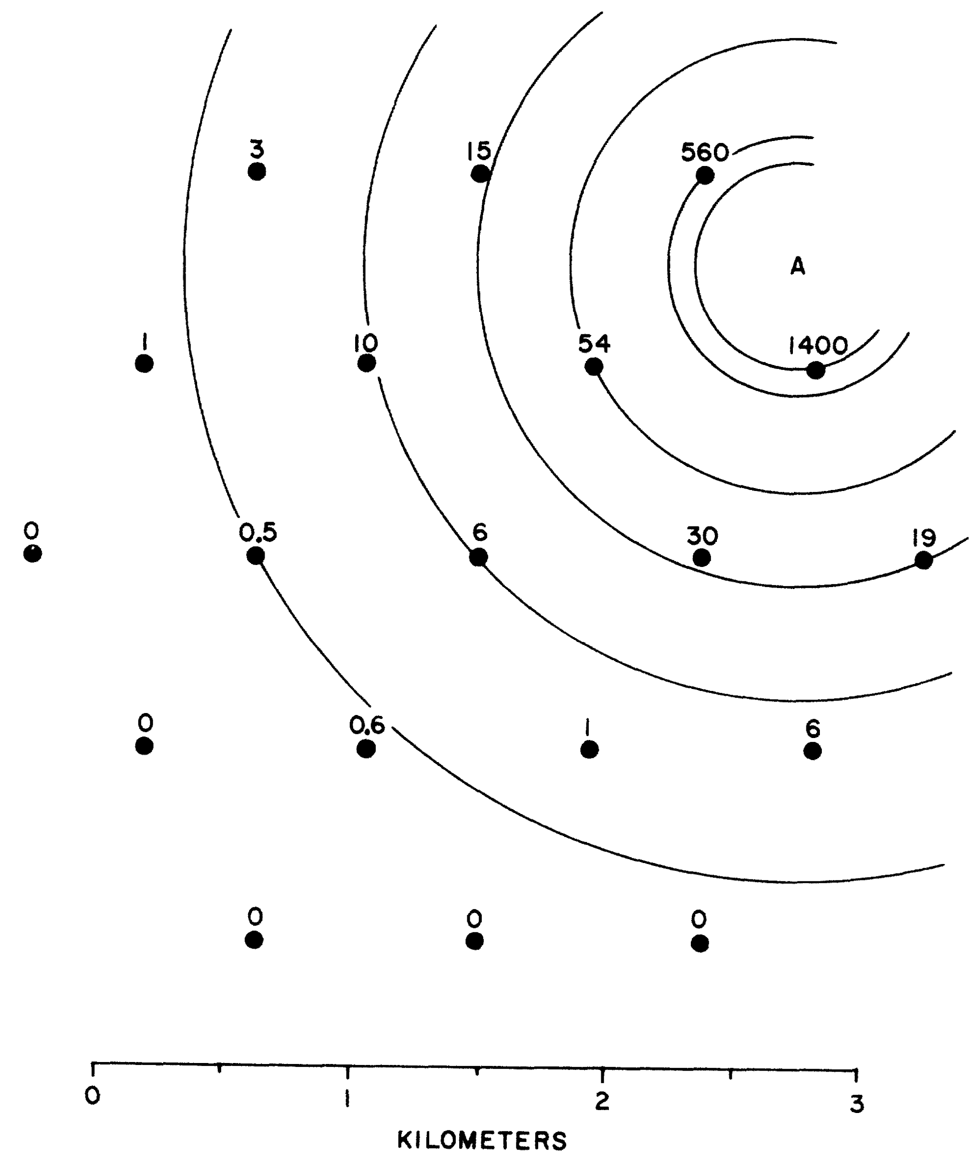
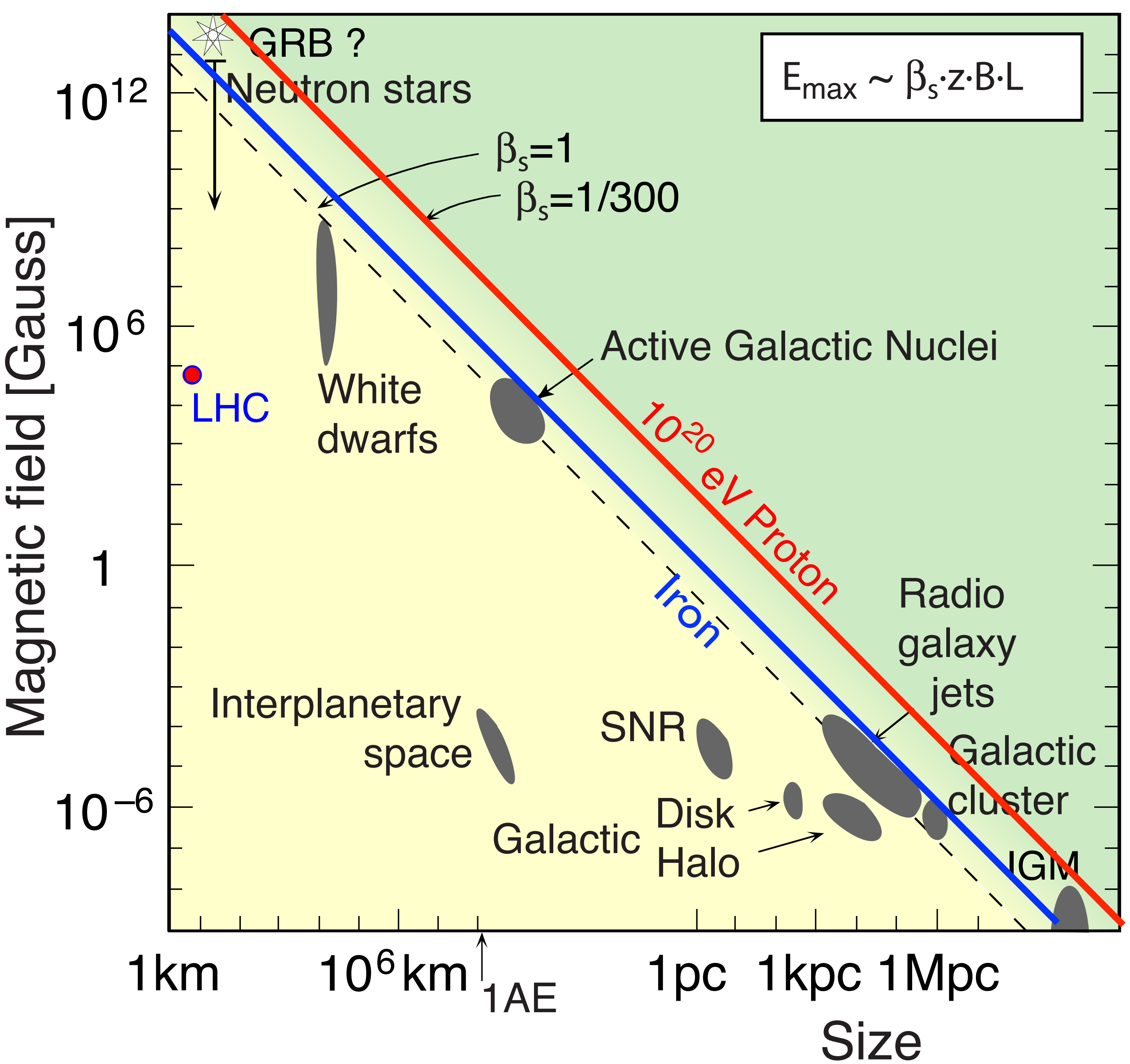
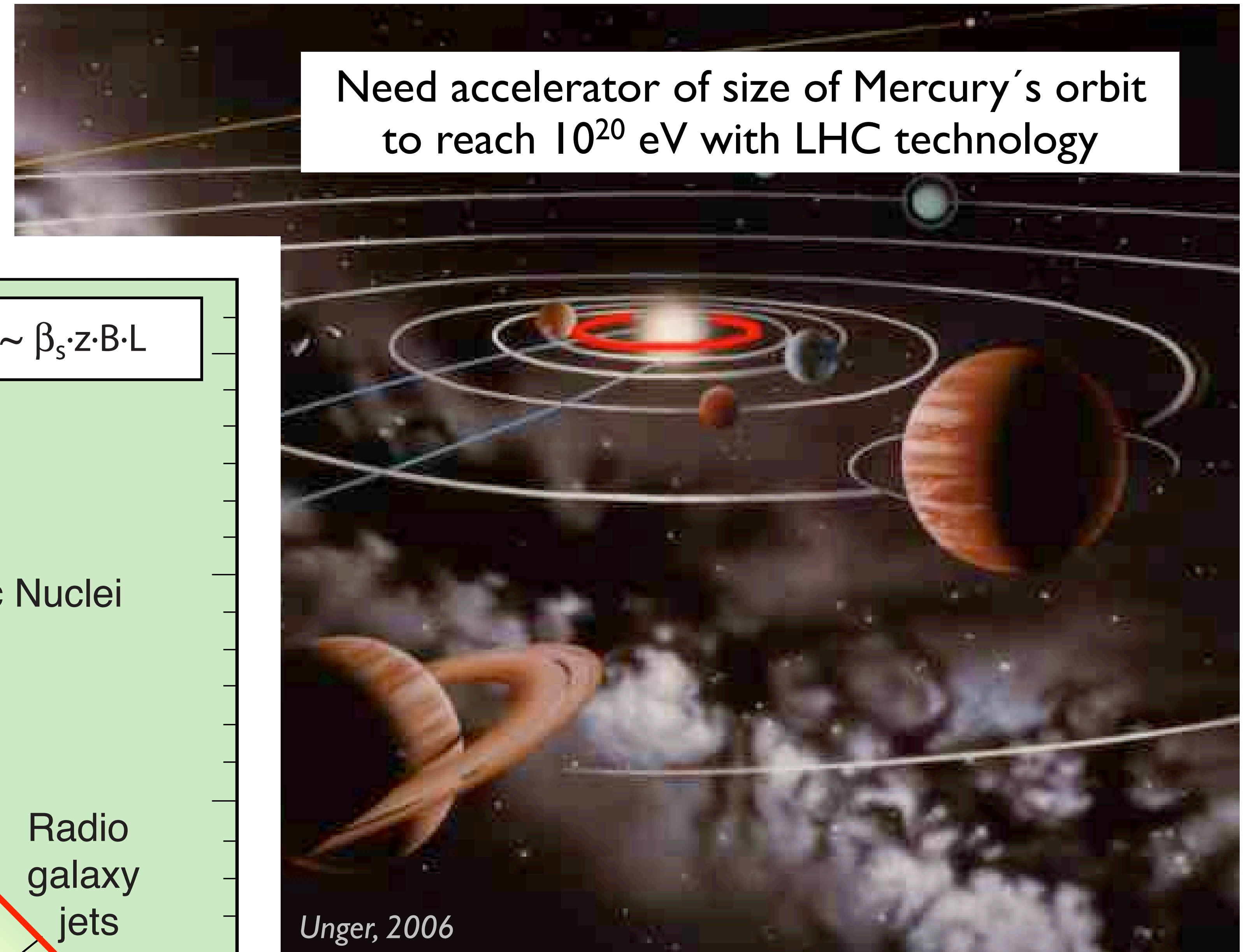


FIG. 1. Plan of the Volcano Ranch array in February 1962. The circles represent 3.3-m^2 scintillation detectors. The numbers near the circles are the shower densities (particles/m^2) registered in this event, No. 2-4834. Point "*A*" is the estimated location of the shower core. The circular contours about that point aid in verifying the core location by inspection.

Challenge: Sources of 10^{20} eV particles

Hillas plot (1984)



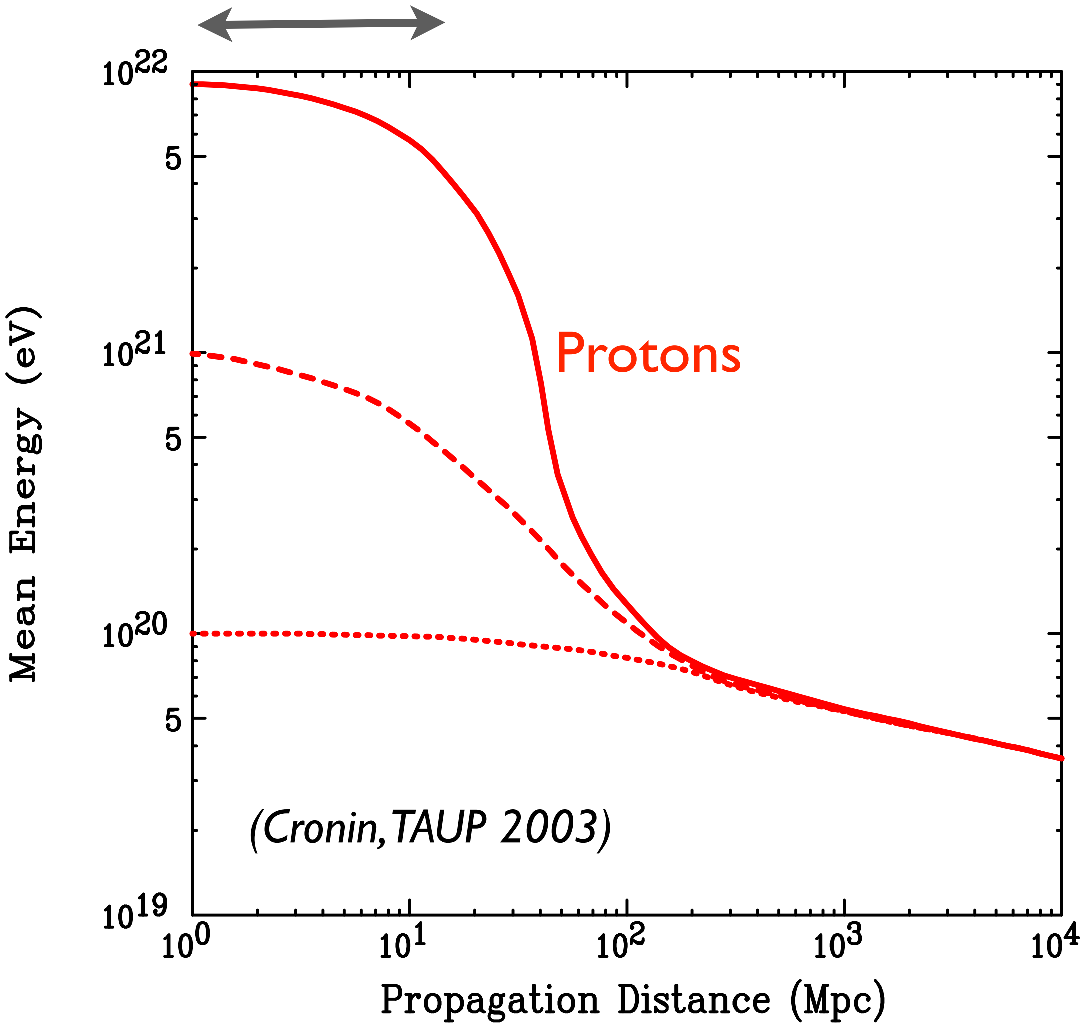


Realistic constraints more severe

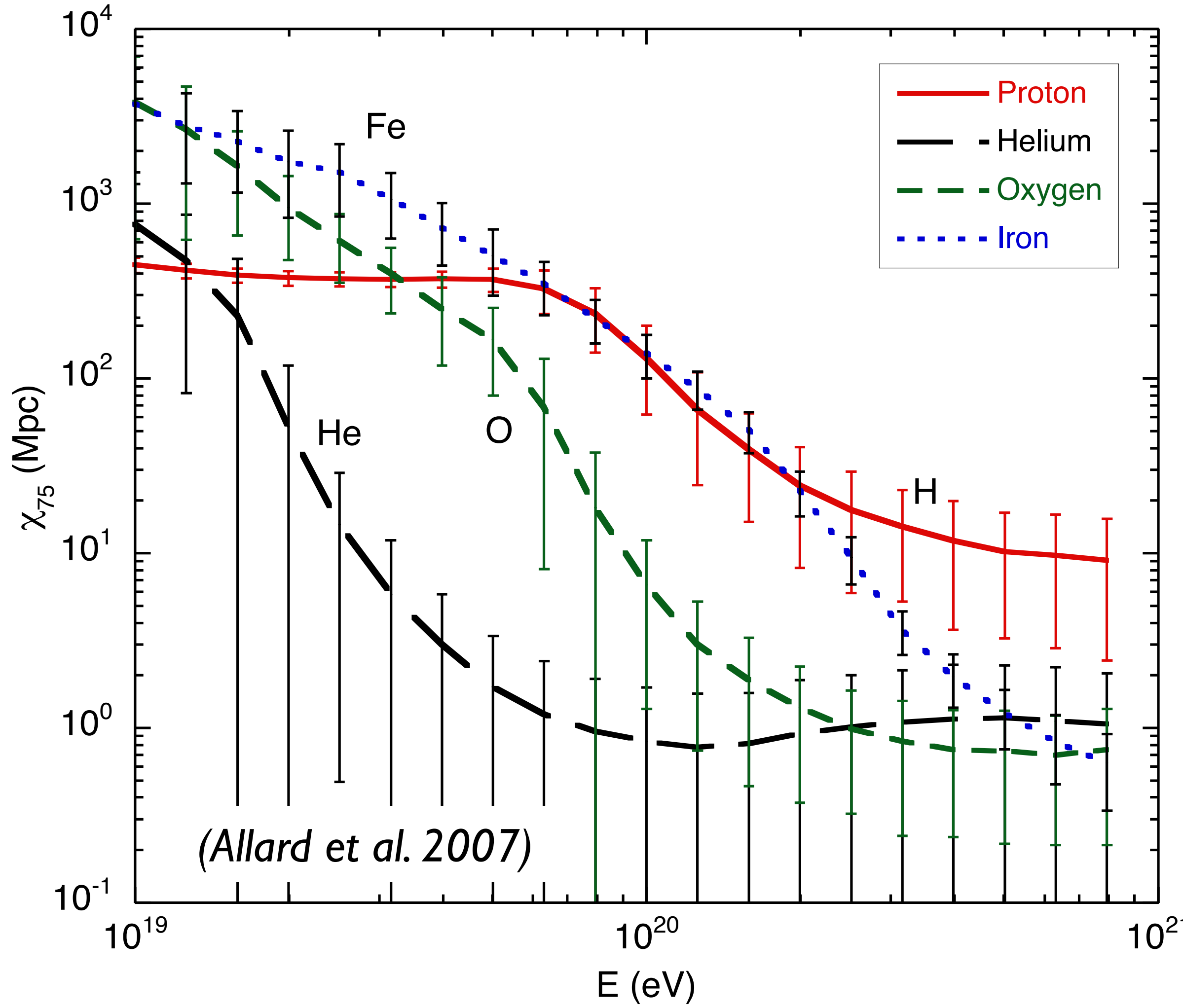
- small acceleration efficiency
- synchrotron & adiabatic losses
- interactions in source region

Energy loss: Flux suppression due to GZK effect

Energy loss length



Energy loss length



Greisen-Zatsepin-Kuzmin effect (1966)

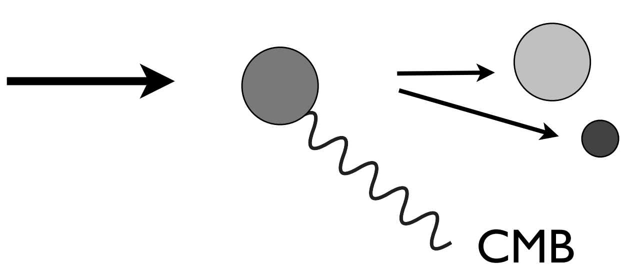
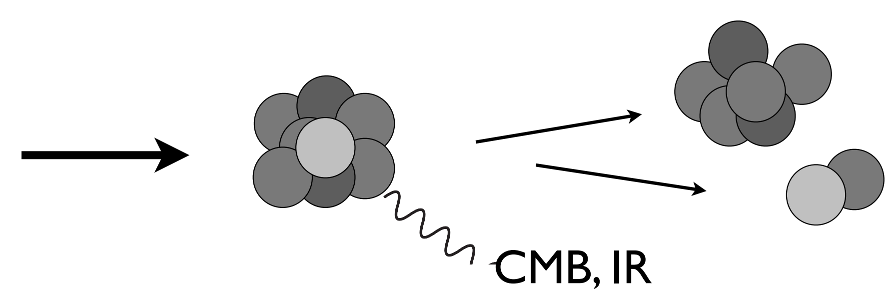


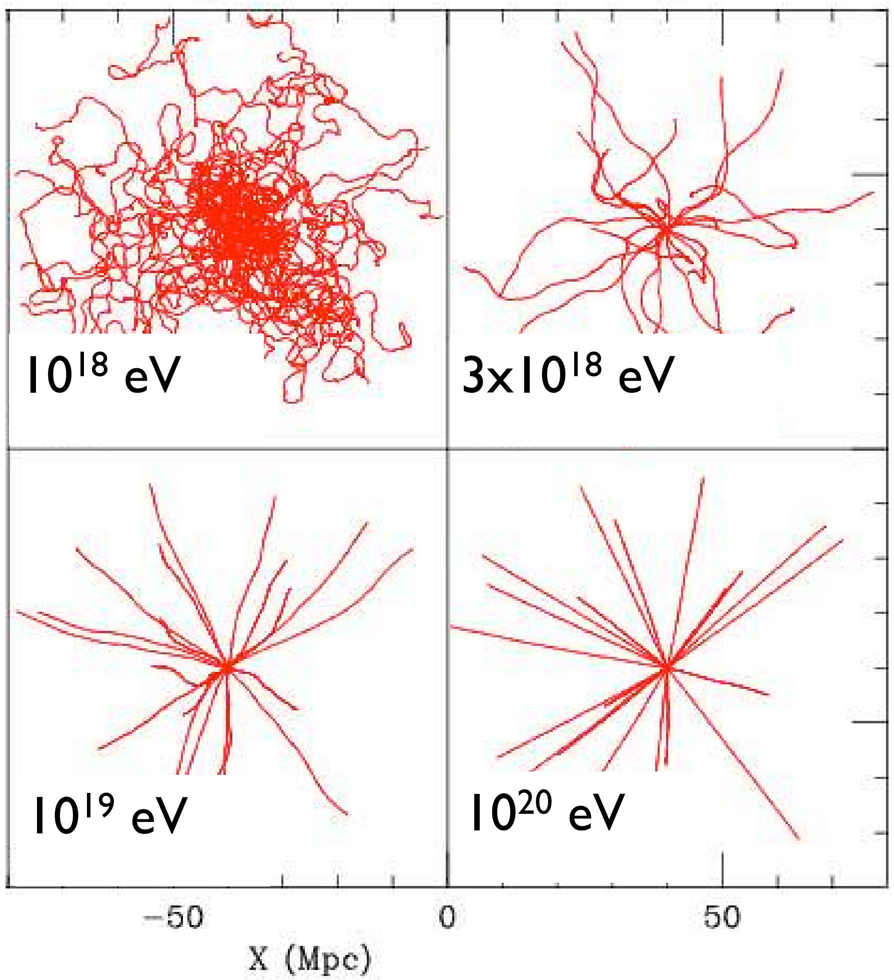
Photo-pion production

Photo-dissociation (giant dipole resonance)

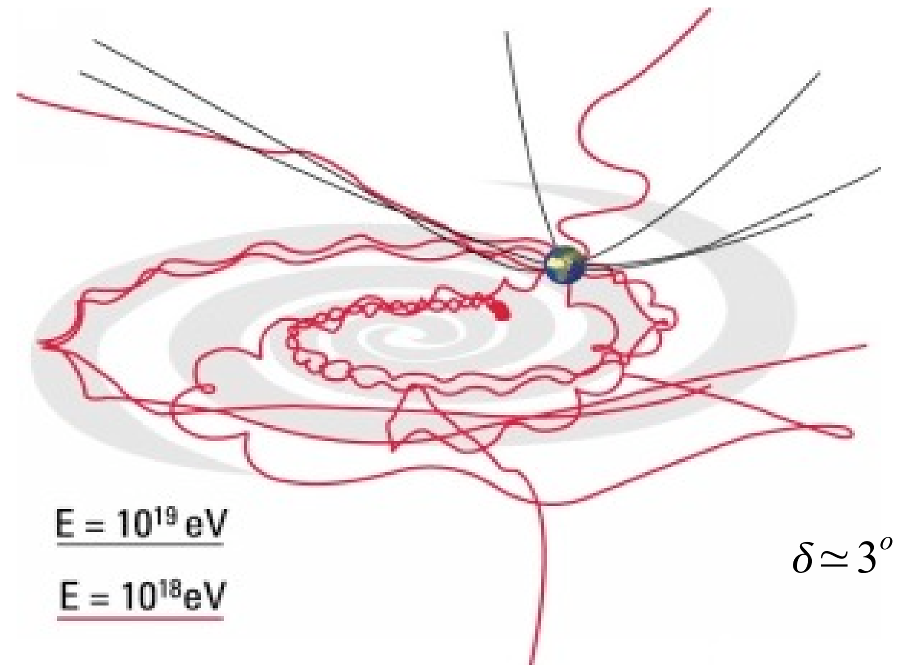


Deflection by magnetic fields small (Z=1)

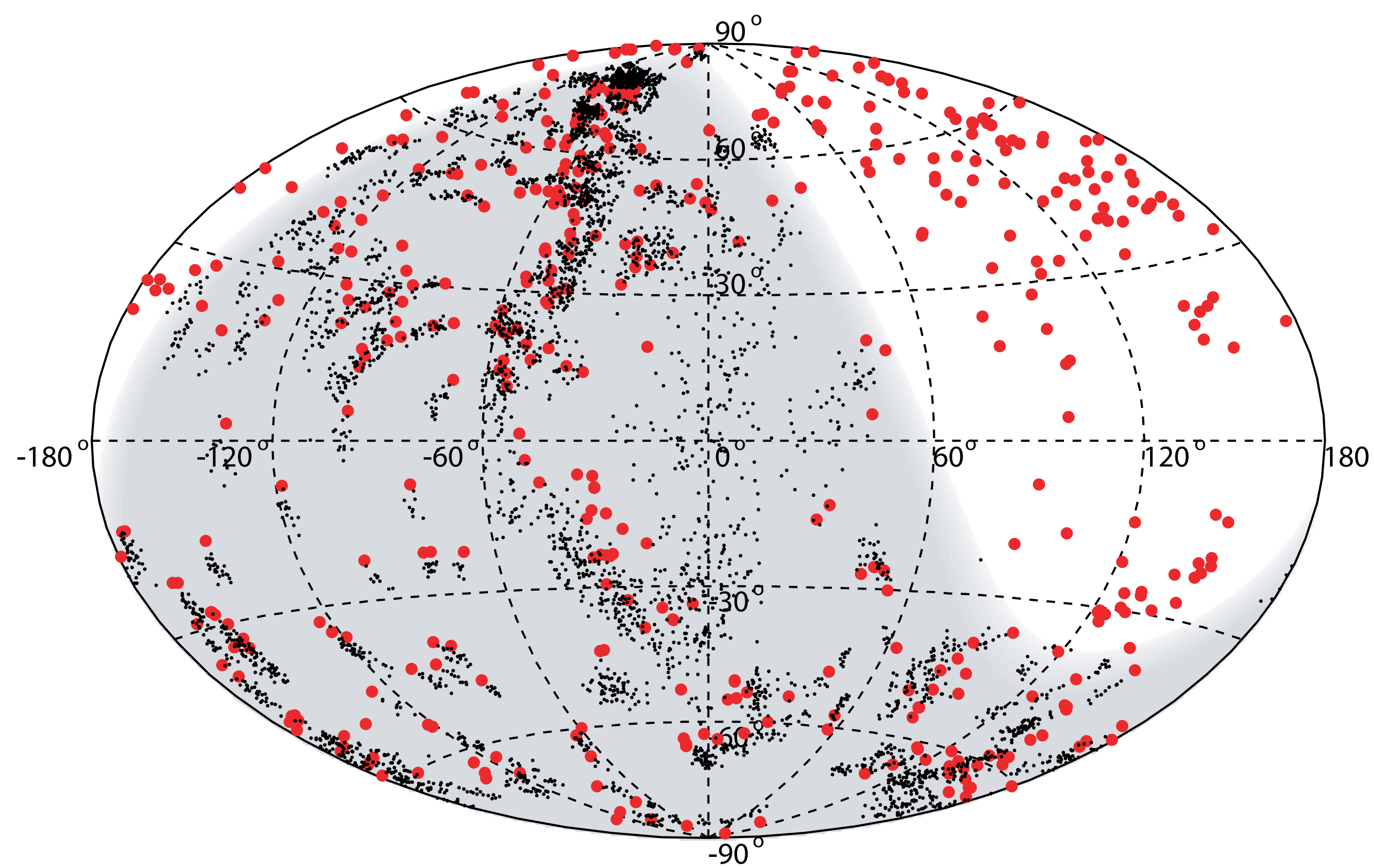
Extragalactic contribution



Galactic contribution

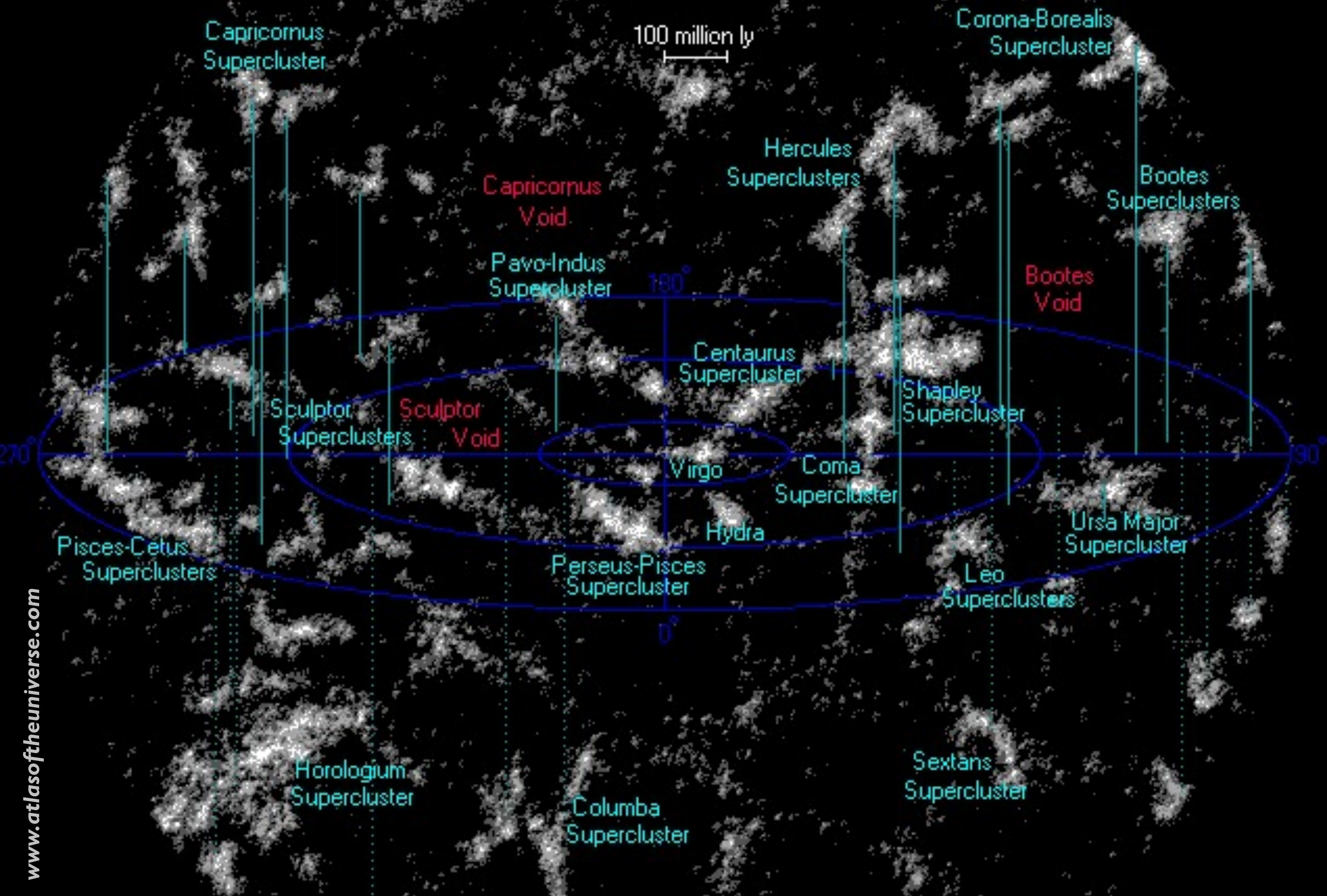


$$\delta \simeq 3^o \frac{B}{3\,\mu G}\frac{L}{kpc}\frac{6\times10^{19}eV}{E/Z}$$

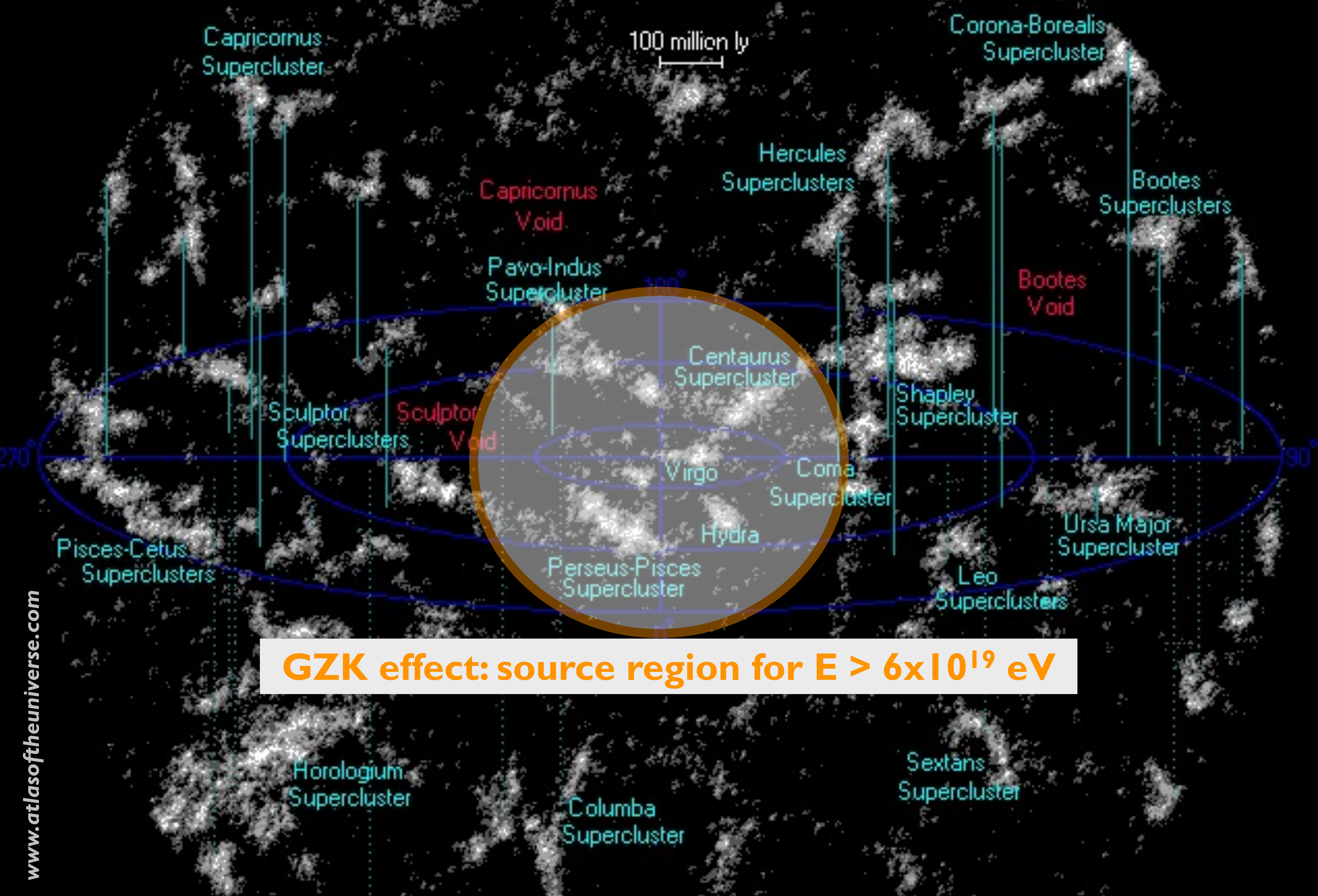


Ideal case of protons (Z=1) and very high statistics

Arrival direction distribution

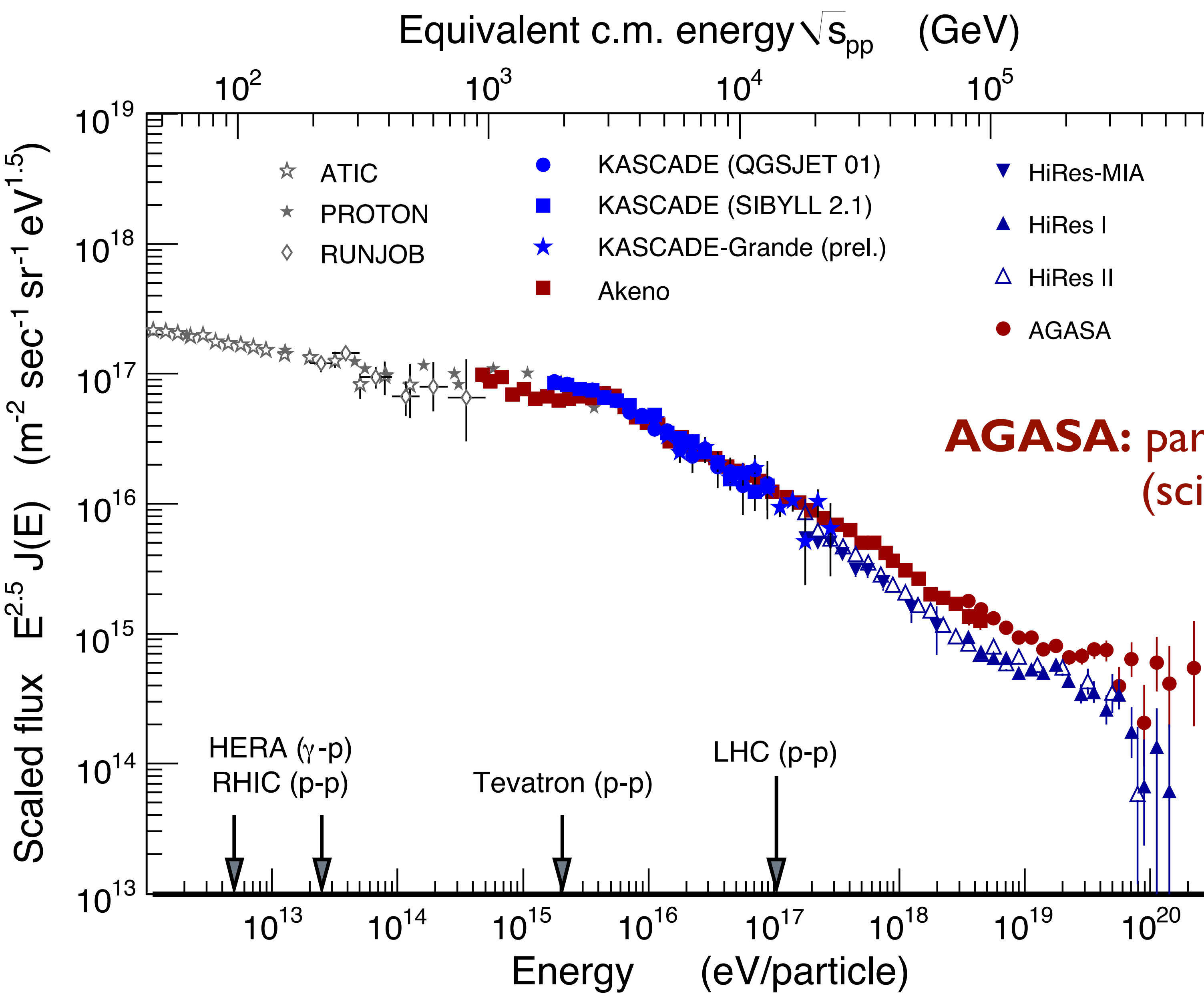


GZK effect: anisotropy expected for light elements



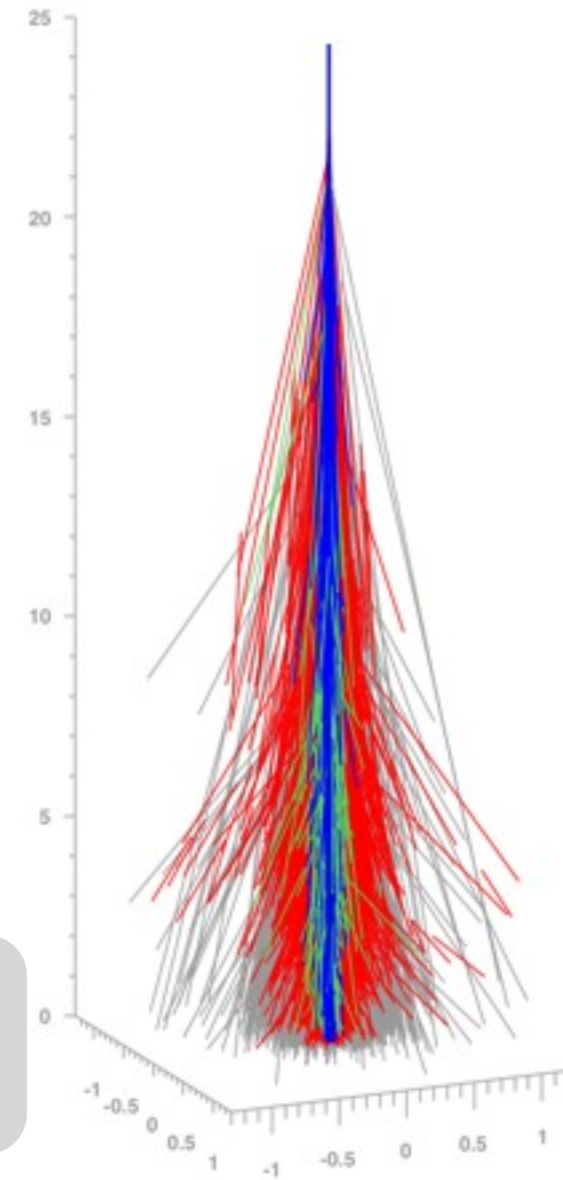
Data available as of 2004

Status of some years ago



AGASA: particles at ground (scintillator array)

Does GZK suppression exist ?

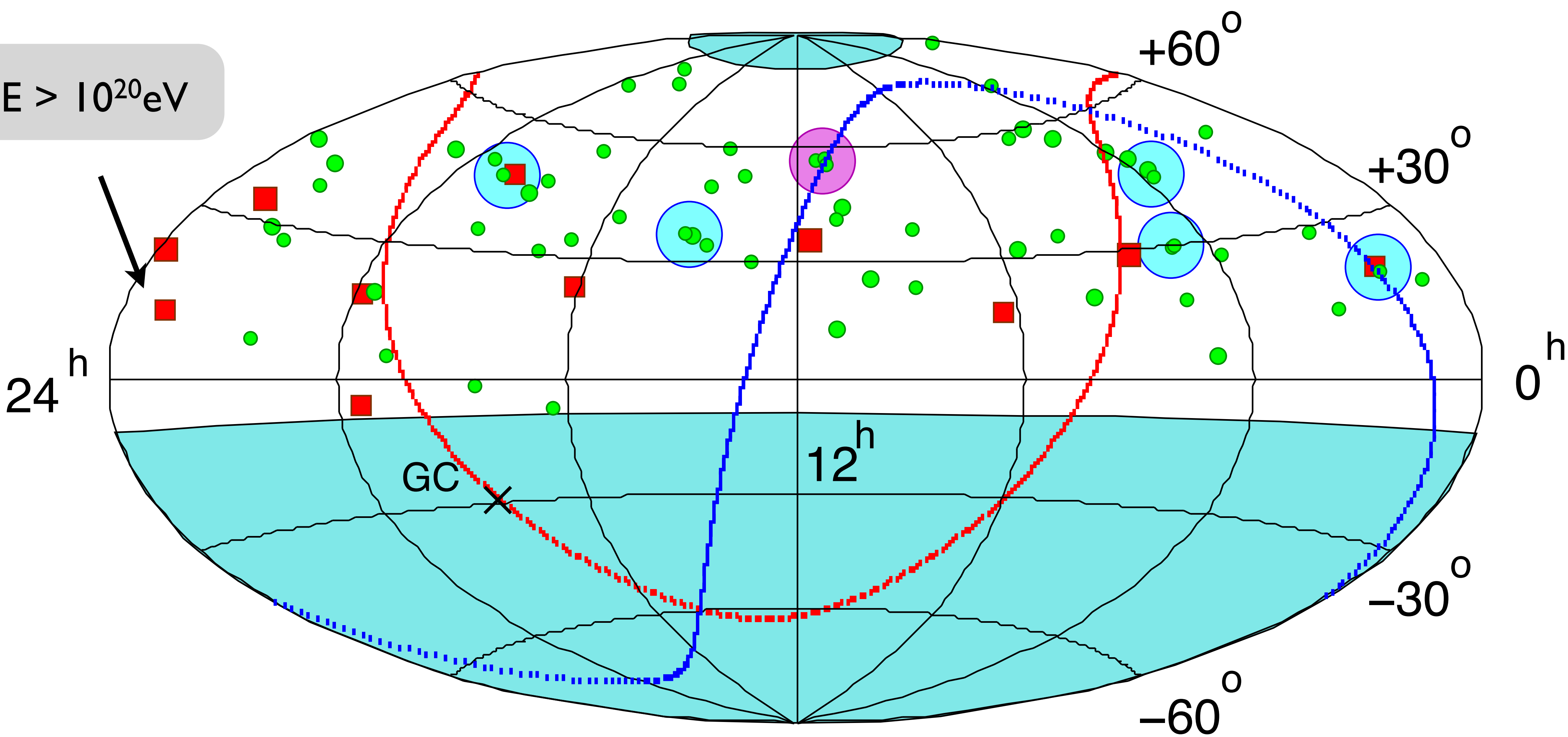


HiRes Fly´s Eye: longitudinal shower profile (fluorescence telescopes)

- **Flux data contradictory**
- **Composition: protons ?**
- **Apparent isotropy**

Arrival direction distribution

E > 10^{20}eV

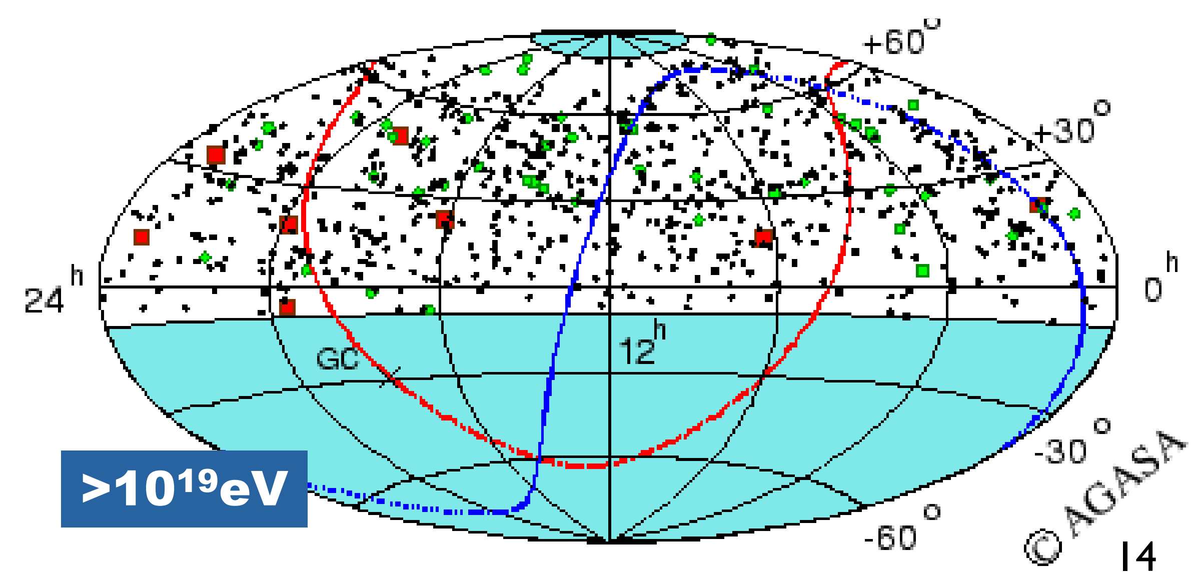


AGASA:

5 doublets, 1 triplet for
$\Delta\theta < 2.5°$, E > 4×10^{19}eV

HiRes:

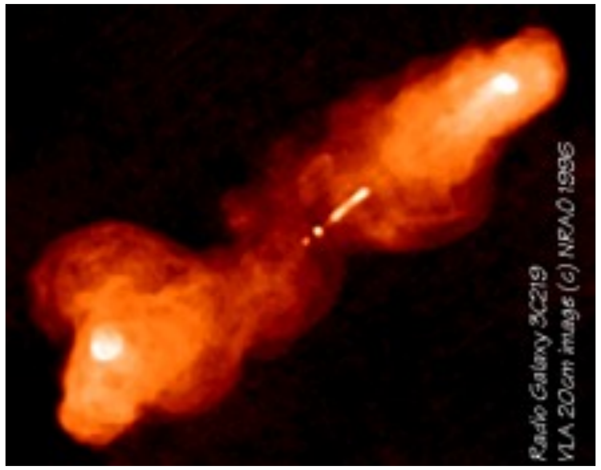
no confirmation (different statistics & systematics)



>10^{19}eV

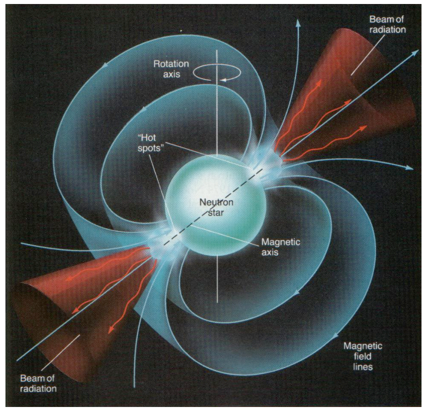
(RE, Nijmegen Summer School, 2006)

Exotic source and propagation scenarios ?



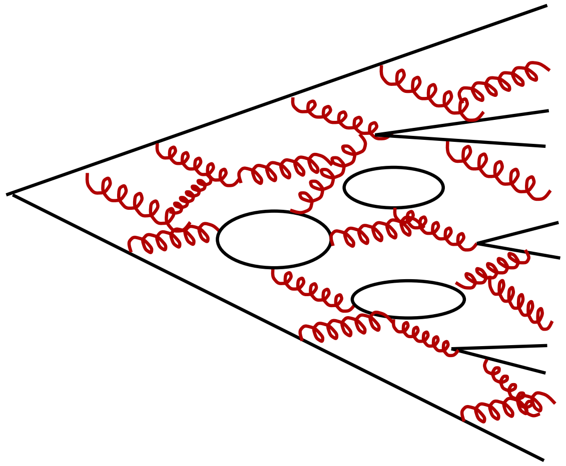
Active Galactic Nuclei (AGN):
Black Hole of ~10^9 solar masses

Magnetars:
magnetic field up to ~10^{15} G



	Process	Distribution	Injection flux
AGNs, GRBs, ... (☆)	Diffuse shock acceleration	Cosmological	p ... Fe
Young pulsars (☆☆)	EM acceleration	Galaxy & halo	mainly Fe
X particles (☆☆☆)	Decay & particle cascade	(a) Halo (SHDM) (b) Cosmological	ν, γ-rays and p
Z-bursts (☆☆☆☆)	Z^0 decay & particle cascade	Cosmological & clusters	ν, γ-rays and p

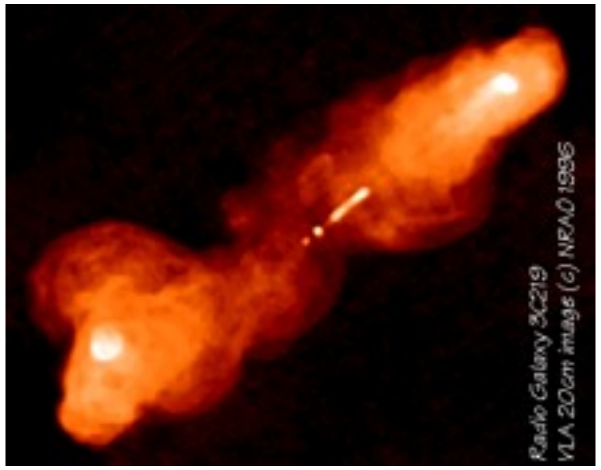
Super-heavy particles, topological defects:
$M_X \sim 10^{23}$ - 10^{24} eV



large fluxes of photons and neutrinos

(RE, Nijmegen Summer School, 2006)

Exotic source and propagation scenarios ?



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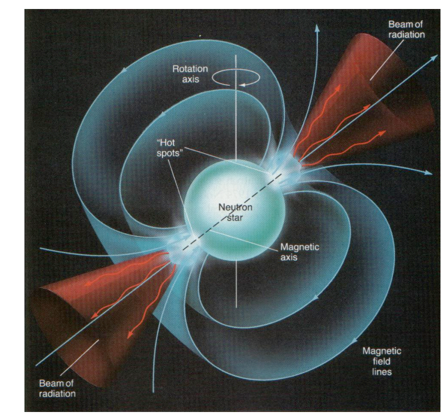

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AGNs, GRBs, ... (☆)	Diffuse shock acceleration	...logical	p ... Fe
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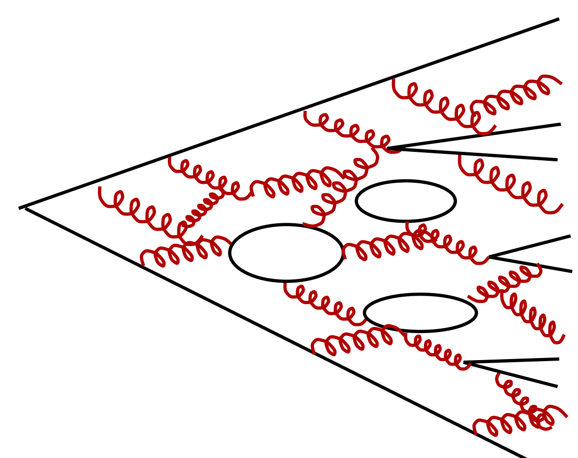
Z-bu... (...	Z^0 decay & particle cascade	Cosmological & clusters	ν, γ-rays and p

Golden age of speculative theories

Super-heavy particles, topological defects:
M_X ~ 10^{23} - 10^{24} eV

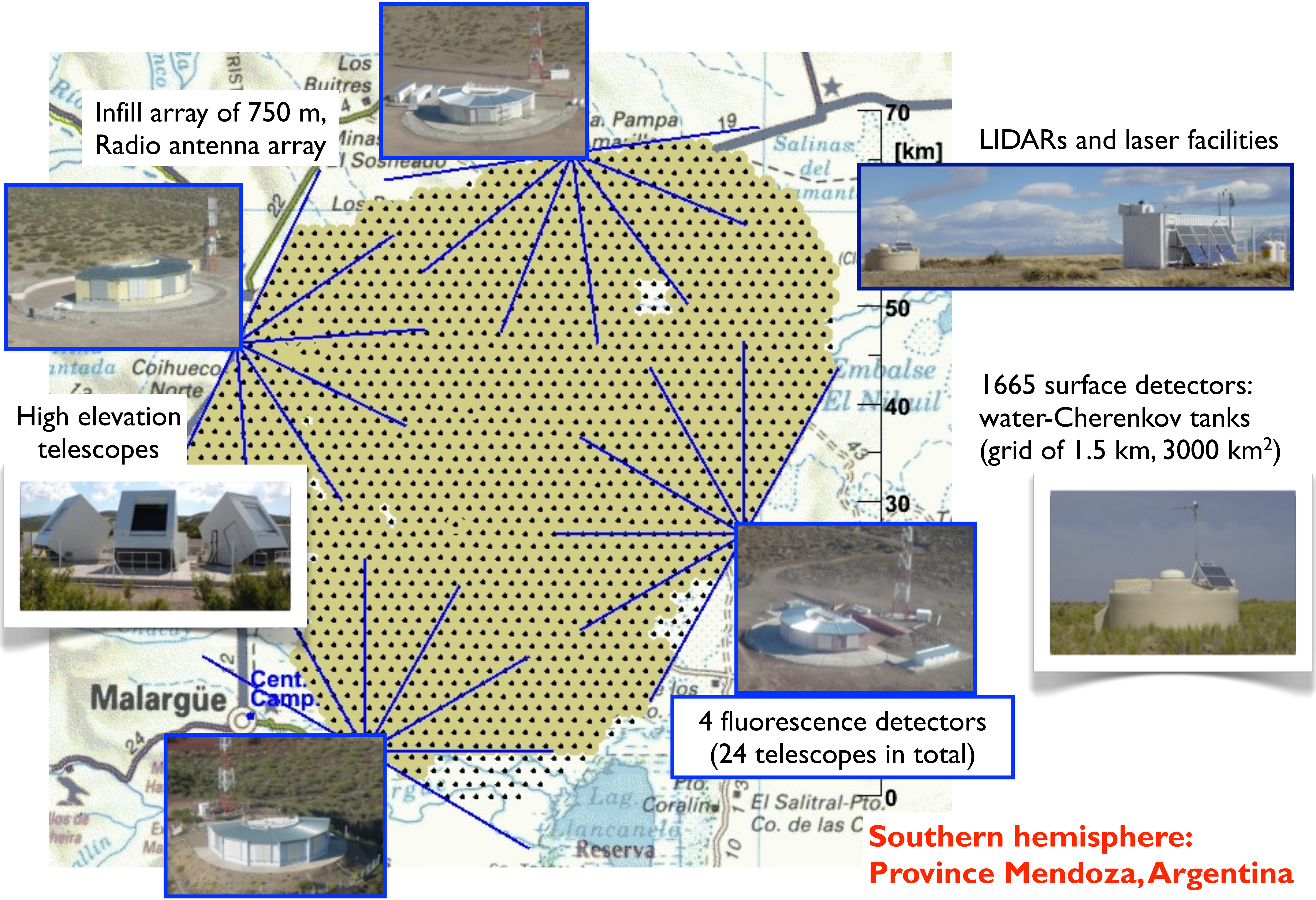


large fluxes of photons and neutrinos

(RE, Nijmegen Summer School, 2006)

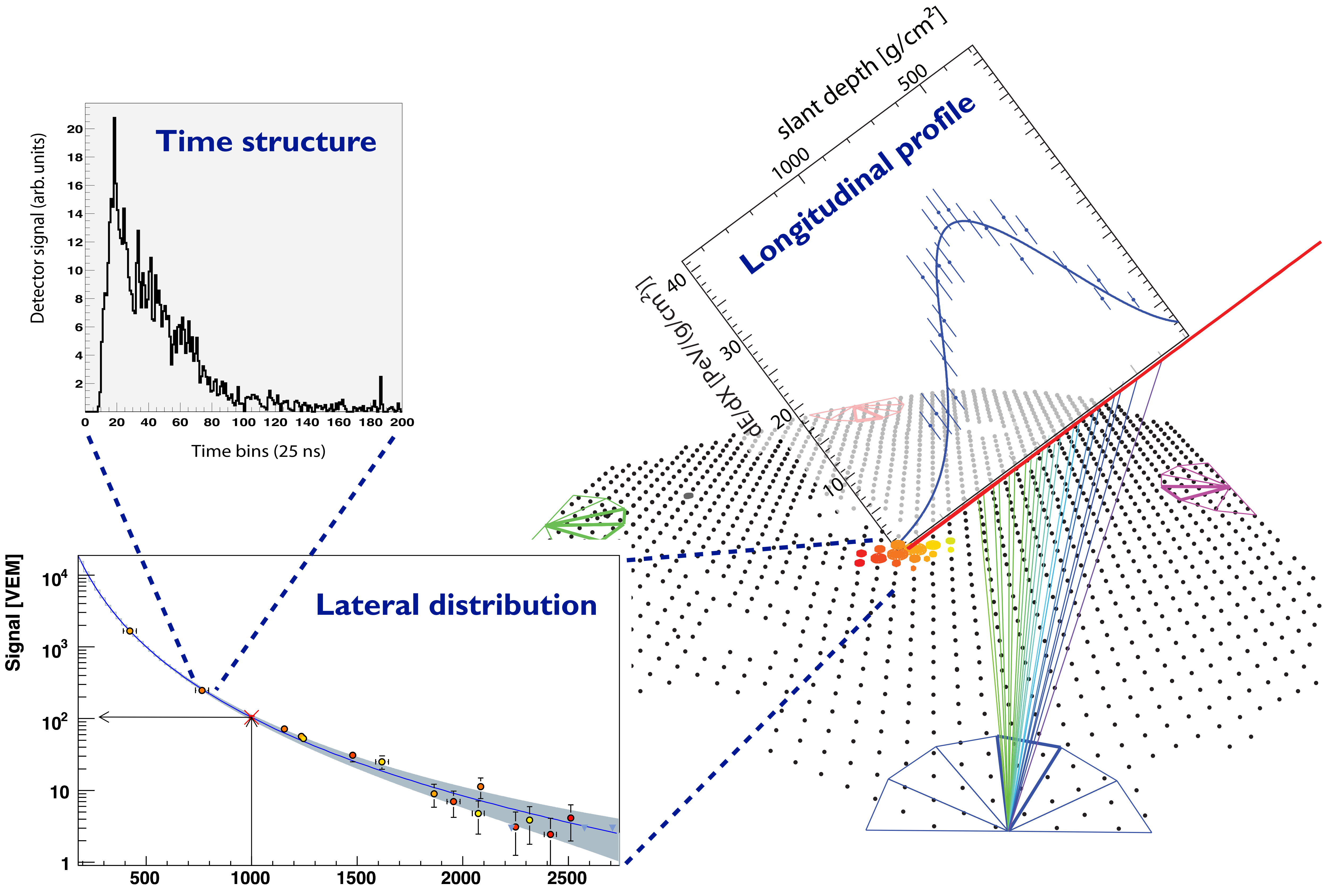
New generation of cosmic ray detectors

The Pierre Auger Observatory



Southern hemisphere: Province Mendoza, Argentina

Several shower observables



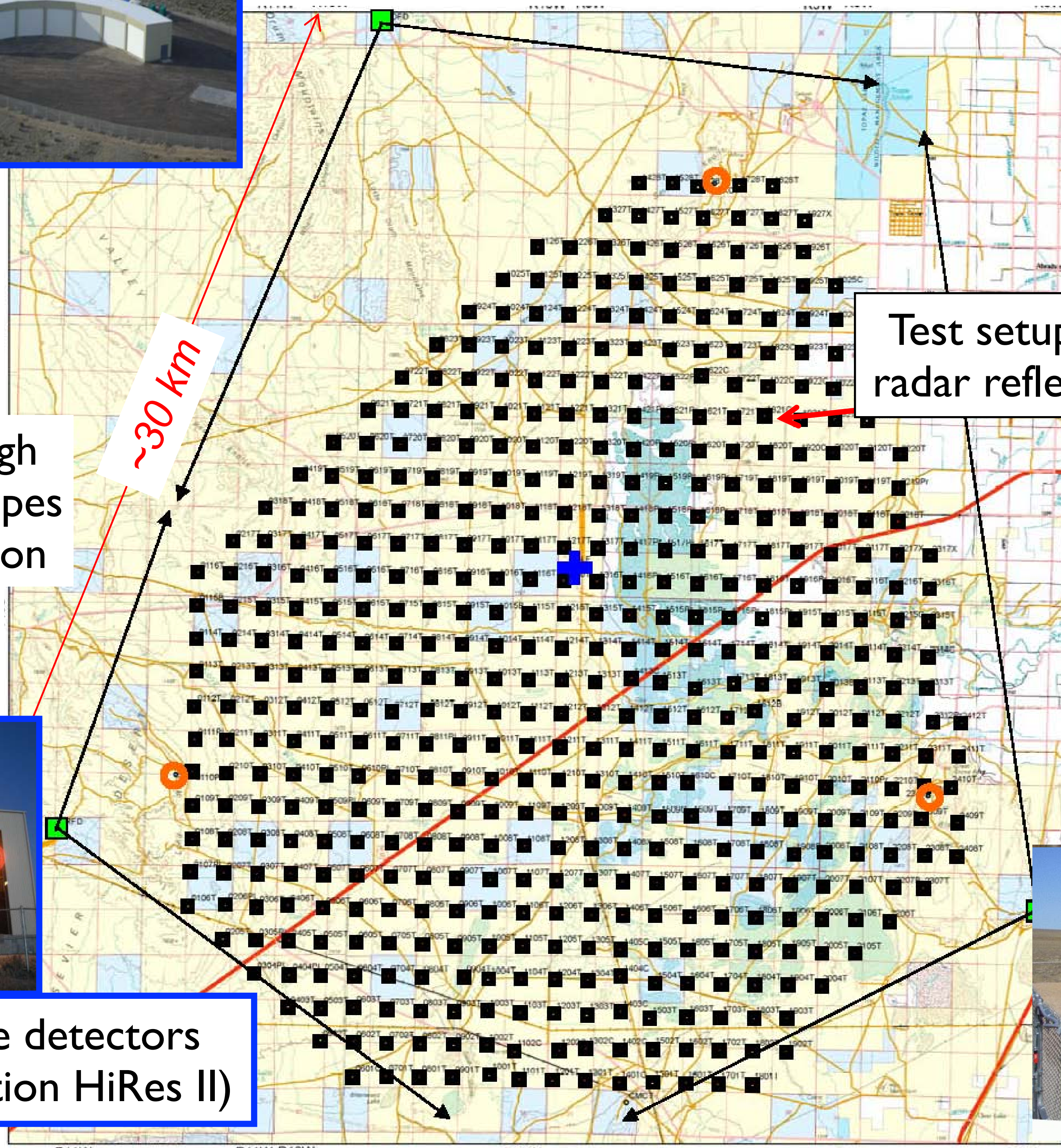
Example: event observed by Auger

Telescope Array (TA)

Middle Drum: based on HiRes II

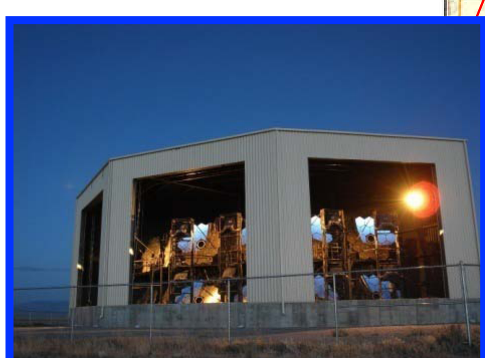
507 surface detectors: double-layer scintillators (grid of 1.2 km, 680 km^2)

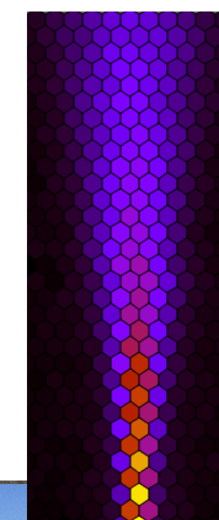
LIDAR
Laser facility



Test setup for radar reflection

Infill array and high elevation telescopes under construction



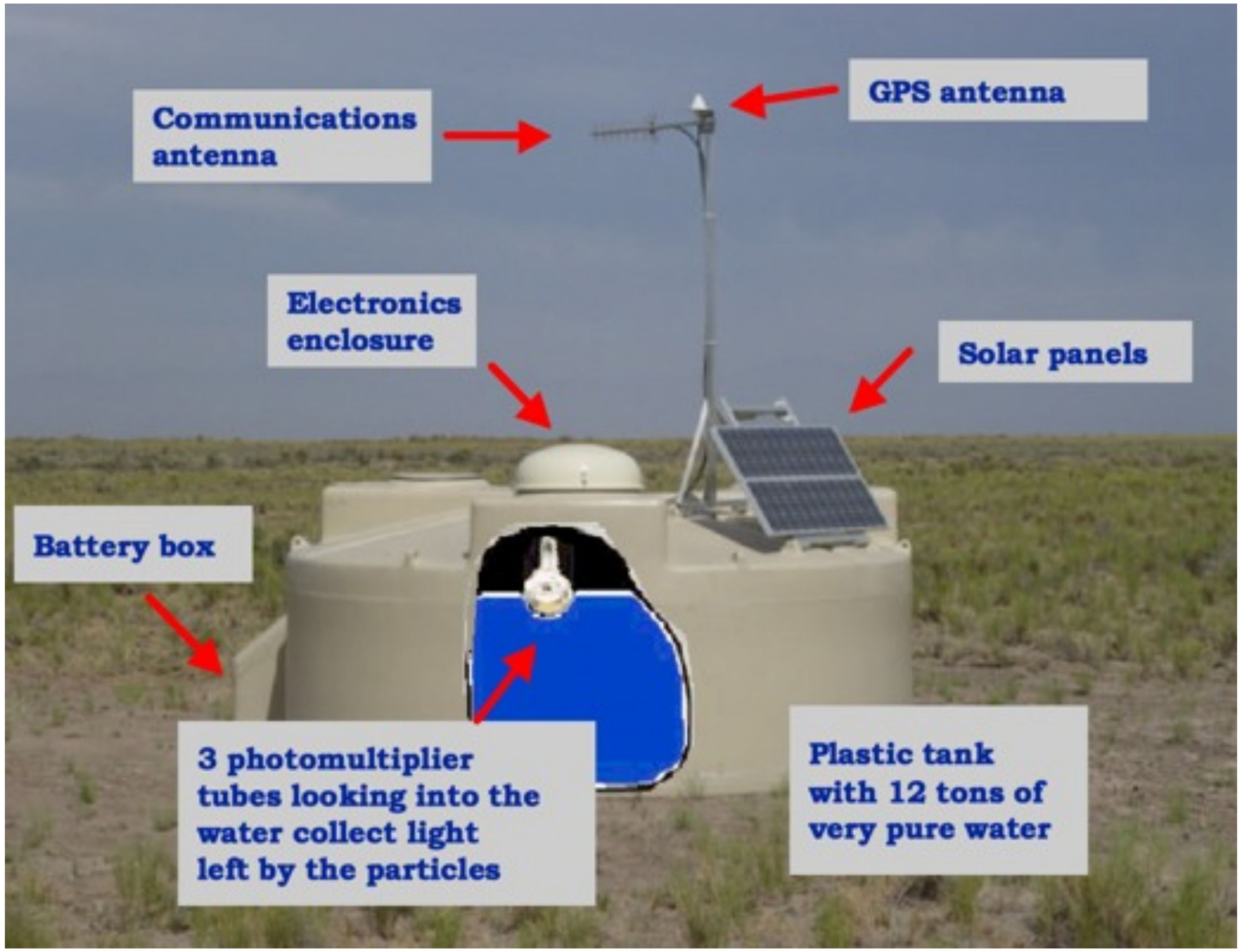


Electron light source (ELS): ~40 MeV

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

Northern hemisphere: Utah, USA

Comparison of surface detectors

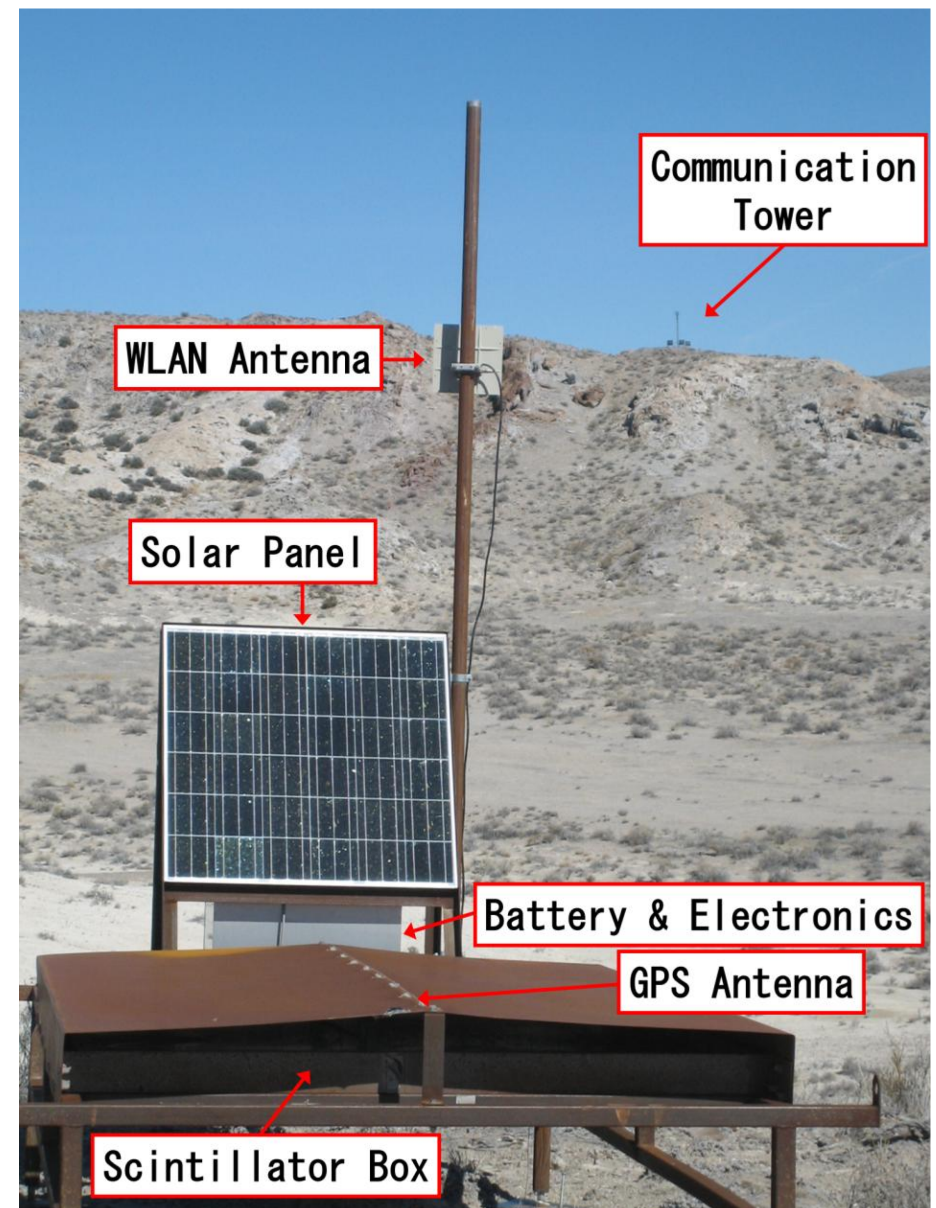


Auger: thick water-Cherenkov detectors

- large part of signal due to muons
- large acceptance to inclined showers

Telescope Array: thin scintillators

- main part of signal due to em. particles
- low sensitivity to muons



Complementary surface detector arrays

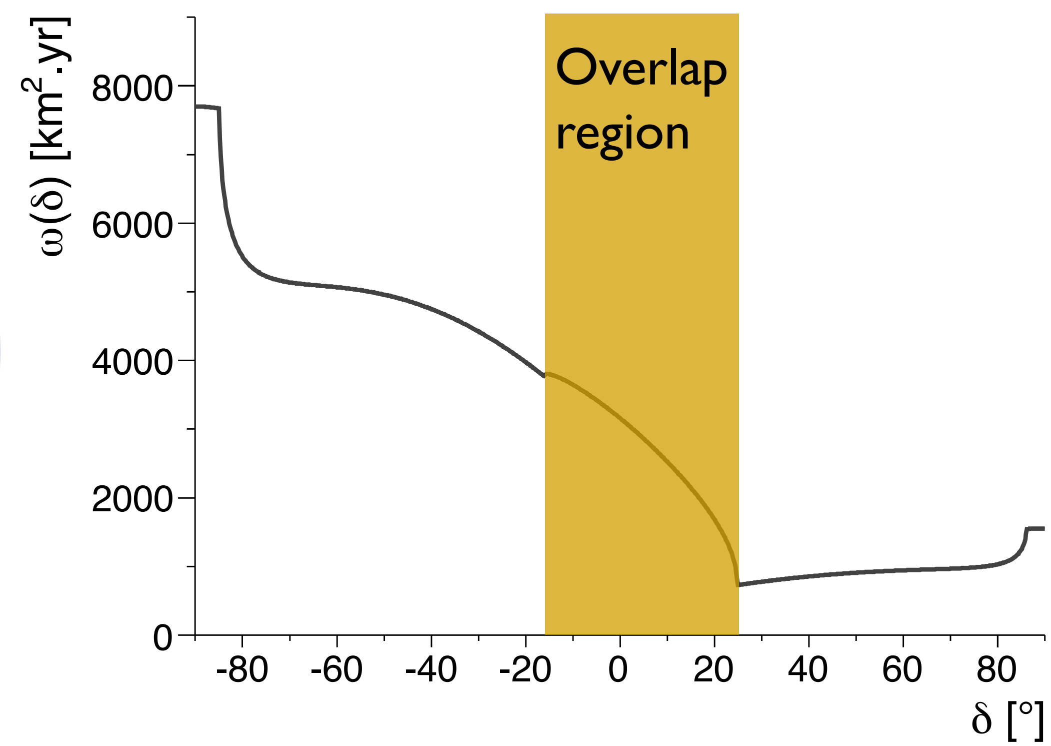
Exposures of UHECR observatories

Telescope Array (TA)
Delta, UT, USA
507 detector stations, 680 km^2
36 fluorescence telescopes

Pierre Auger Observatory
Province Mendoza, Argentina
1660 detector stations, 3000 km^2
27 fluorescence telescopes

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

E > 10^{19} eV

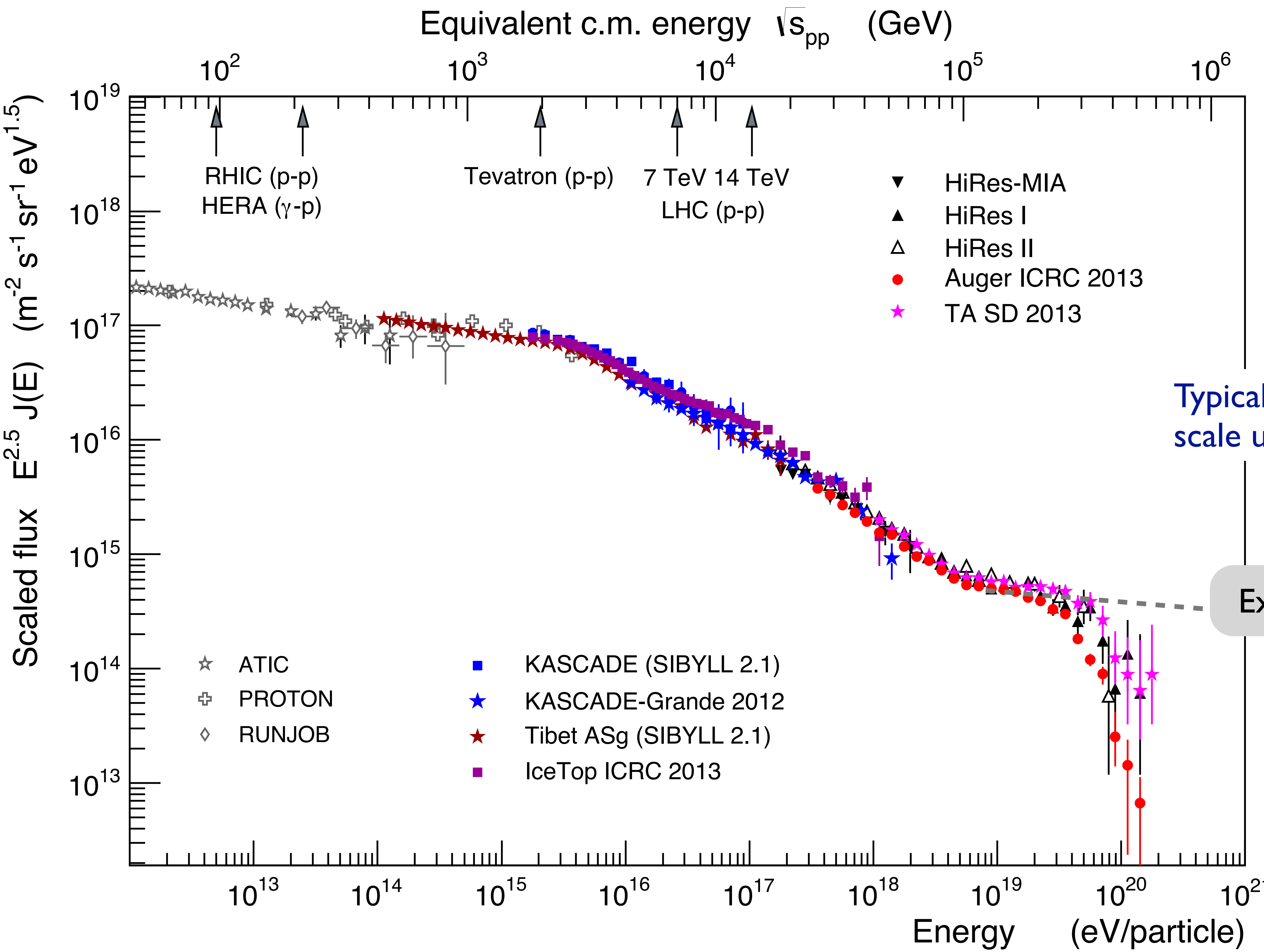


[0-60°] for Auger
10,900 events
3,400 in overlap region

New results on ultra-high energy cosmic rays:

First answers

Answer 1: The flux is suppressed



Data from ICRC 2013

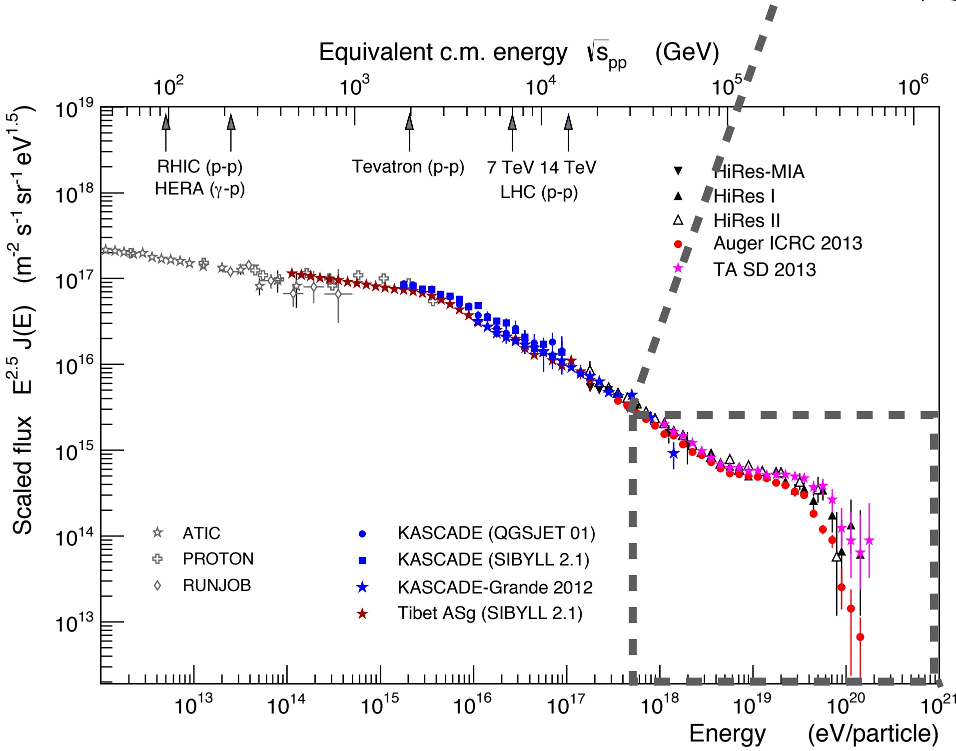
Typically 15-20% energy scale uncertainty

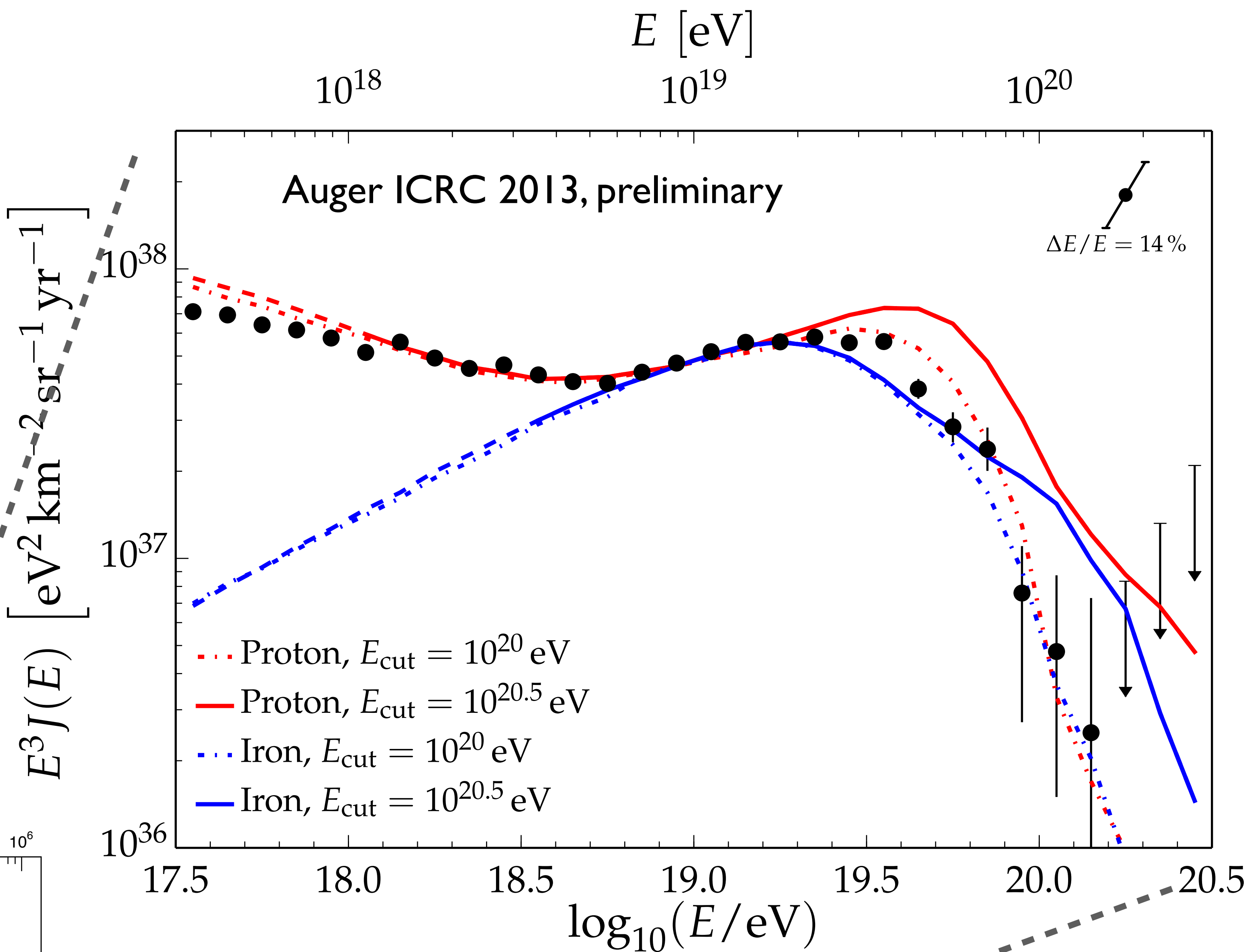
Extrapolated flux

Energy spectrum: expected flux suppression

Proton dominated flux
Suppression: delta resonance
Ankle: e^+e^- pair production

(Dip model of Berezinsky et al.)

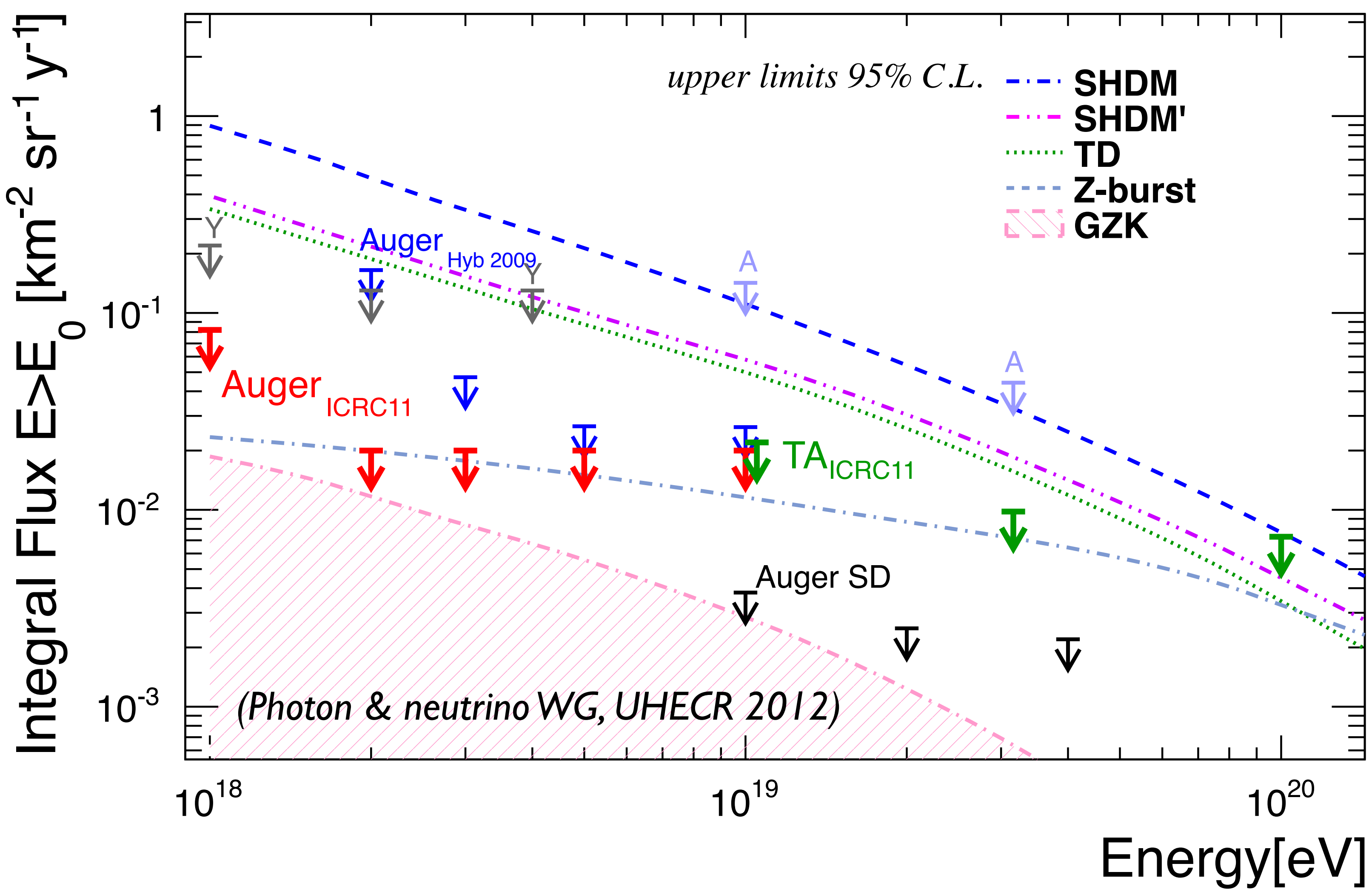




Iron dominated flux
Suppression: giant dipole resonance
Ankle: transition to galactic sources

Answer 2: Most exotic source models excluded

Searches for photon- and neutrino-induced showers: integral limits



Super-heavy dark matter
Topological defects

Photon showers penetrate deeper in the atmosphere, contain almost no muons

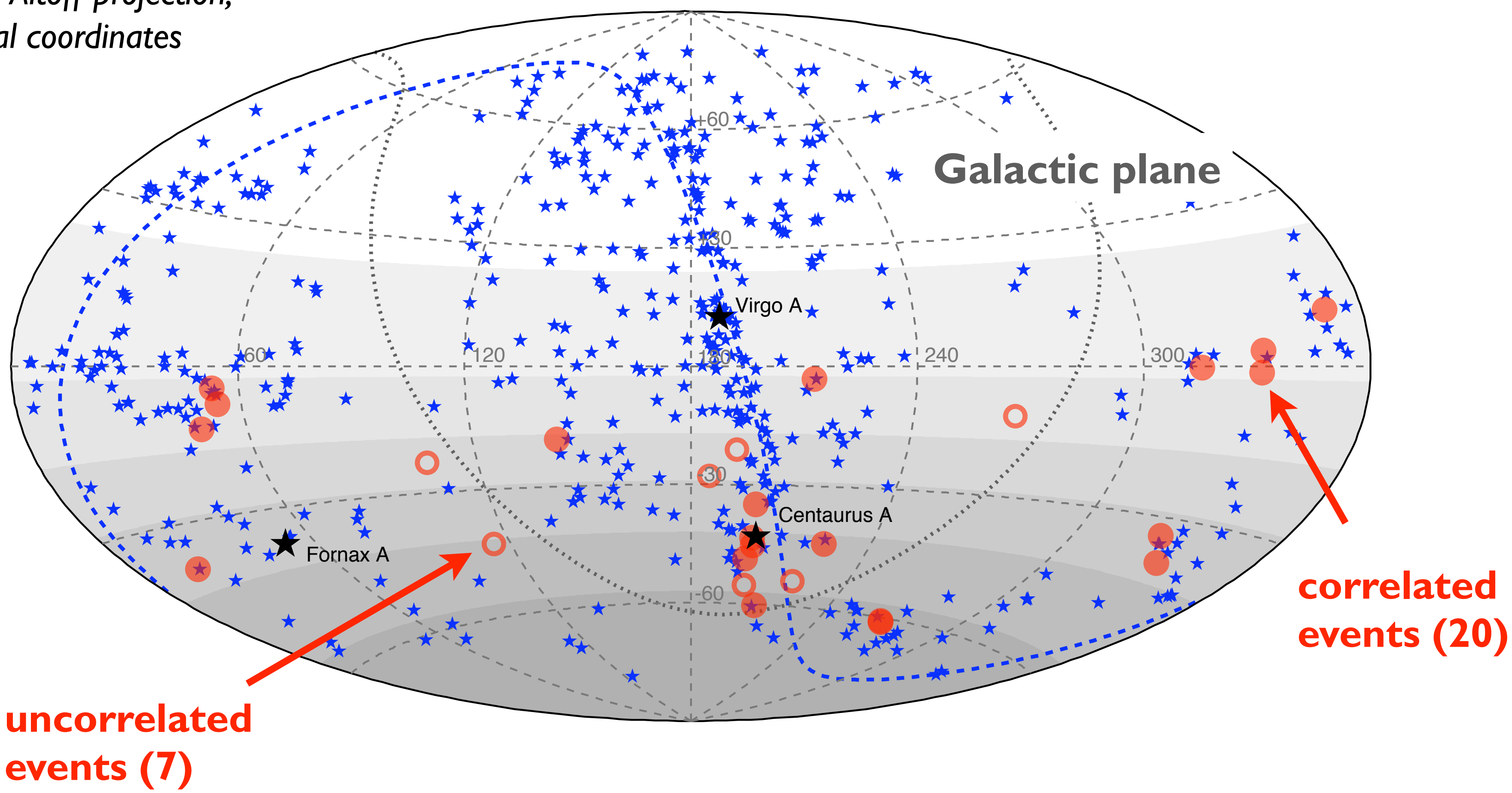
Most exotic source scenarios excluded or strongly disfavoured, similar results for ultra-high energy neutrino searches

Answer 3: Arrival direction distribution is anisotropic

Less than 1% chance probability

Hammer-Aitoff projection,
Equatorial coordinates

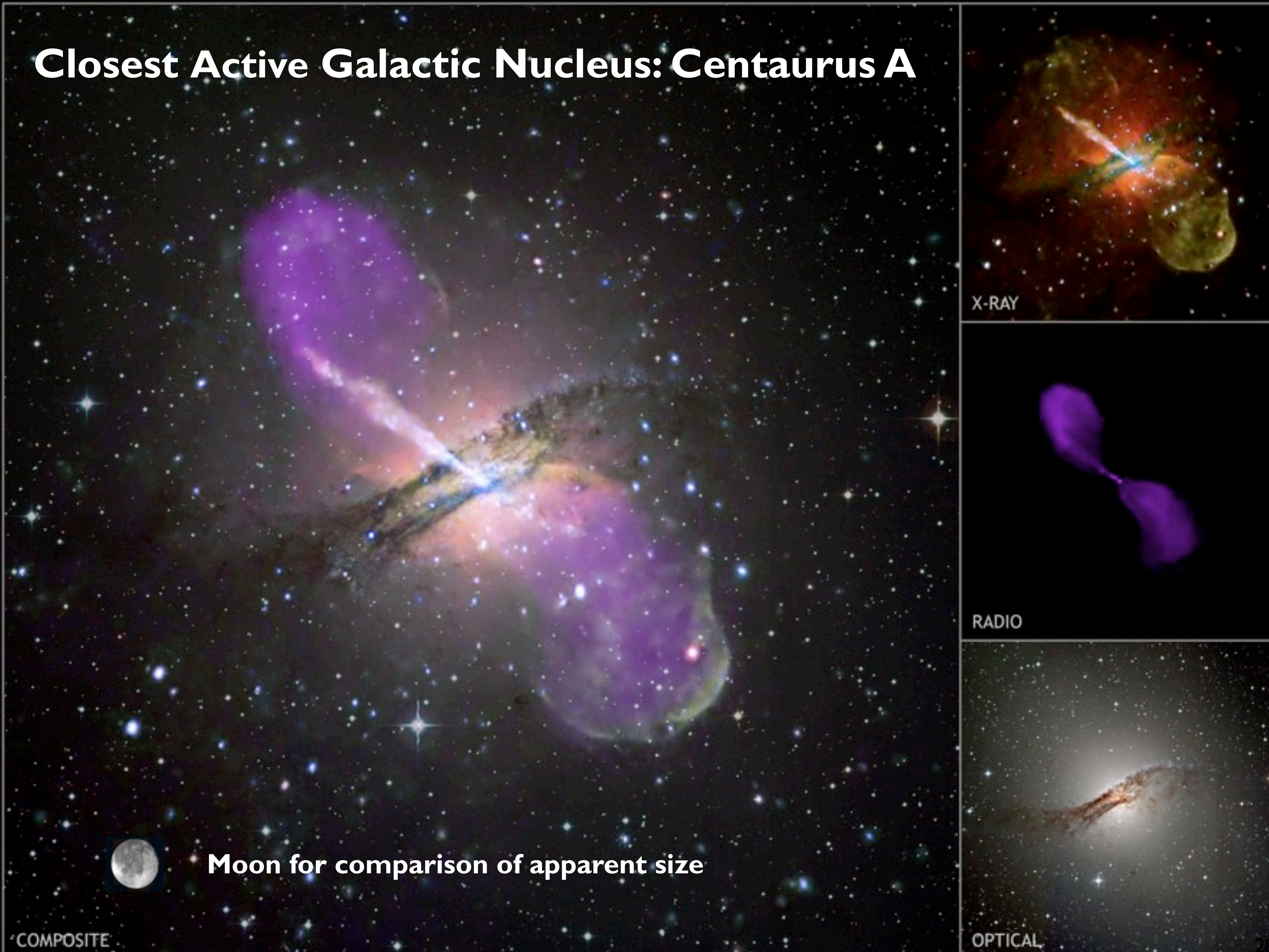
Auger Collab. 2007



70% of particles with E > 5.5 10^{19} eV correlated with AGNs (D < 75 Mpc) within 3.1°, 21% expected

Active Galactic Nuclei: sources or tracer of sources
Small magnetic deflection: protons or light nuclei

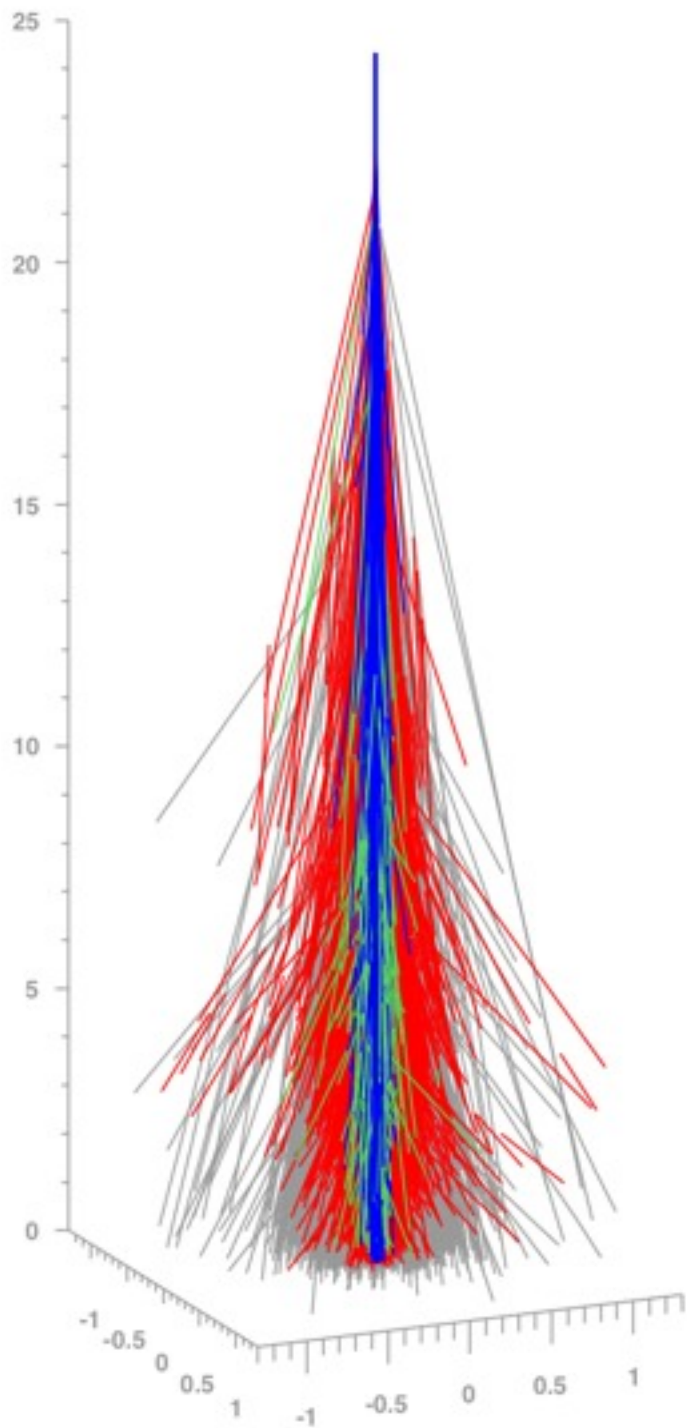
Closest Active Galactic Nucleus: Centaurus A

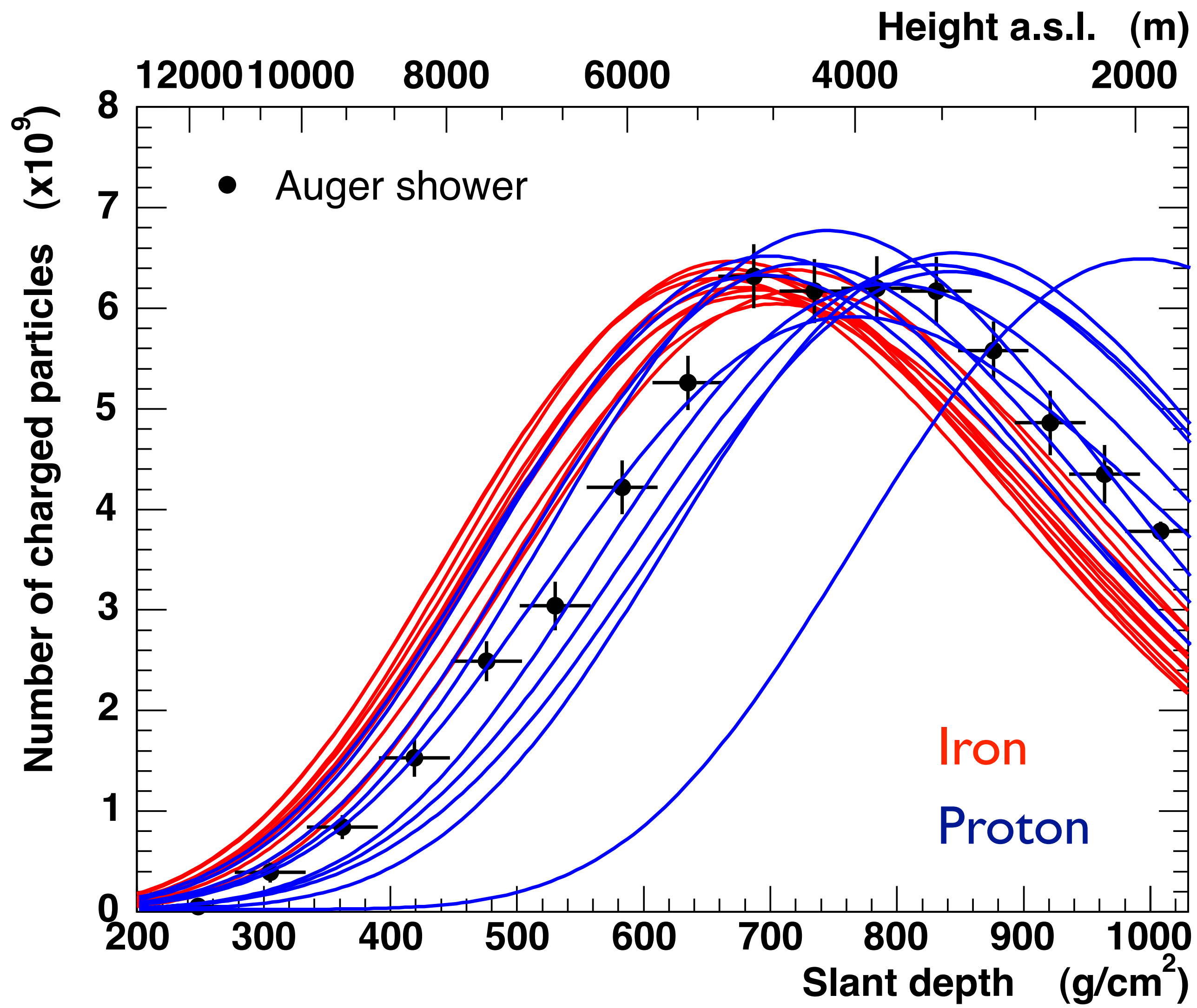


New results on ultra-high energy cosmic rays:

New puzzles

Composition from longitudinal shower profile

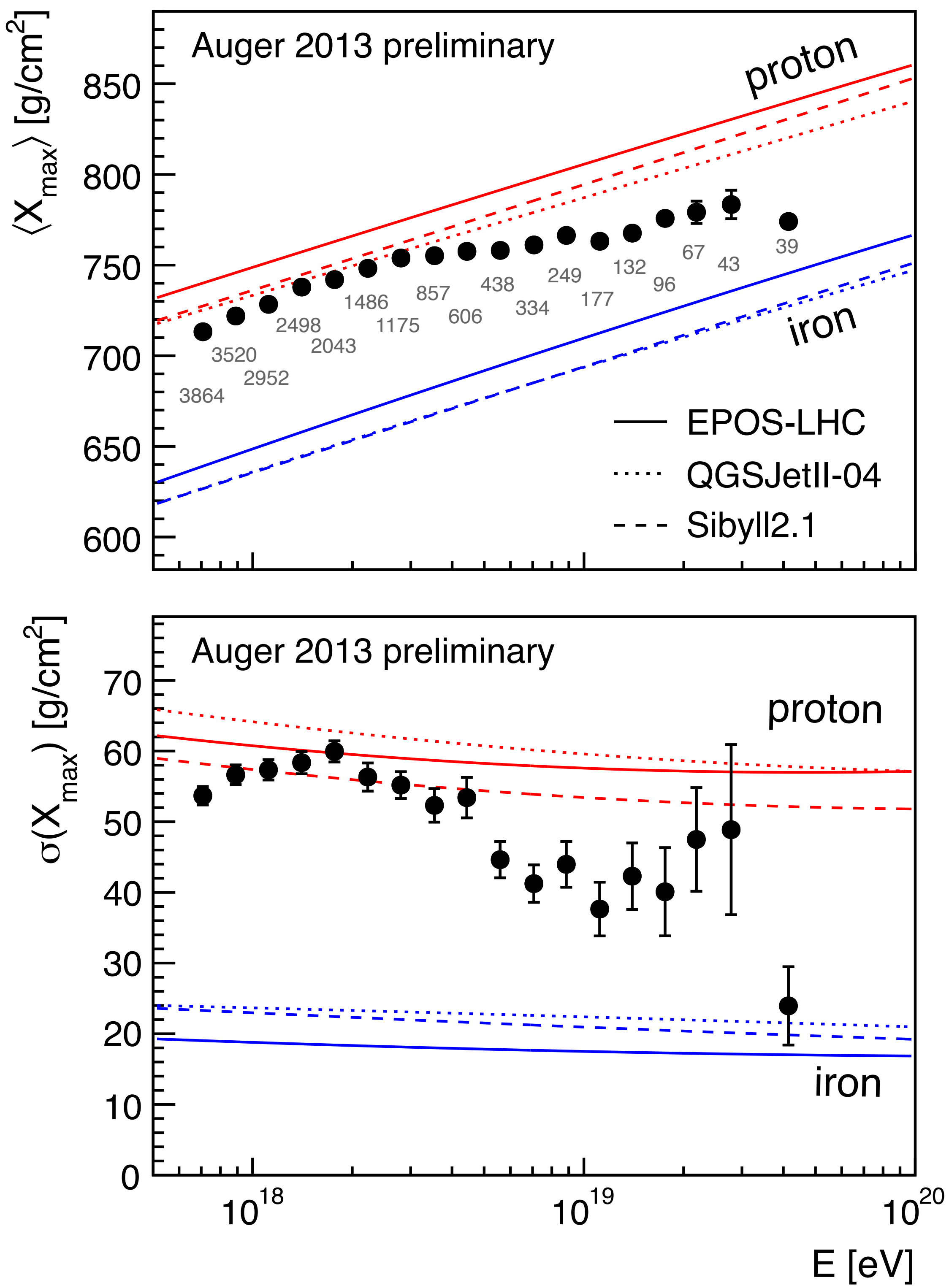




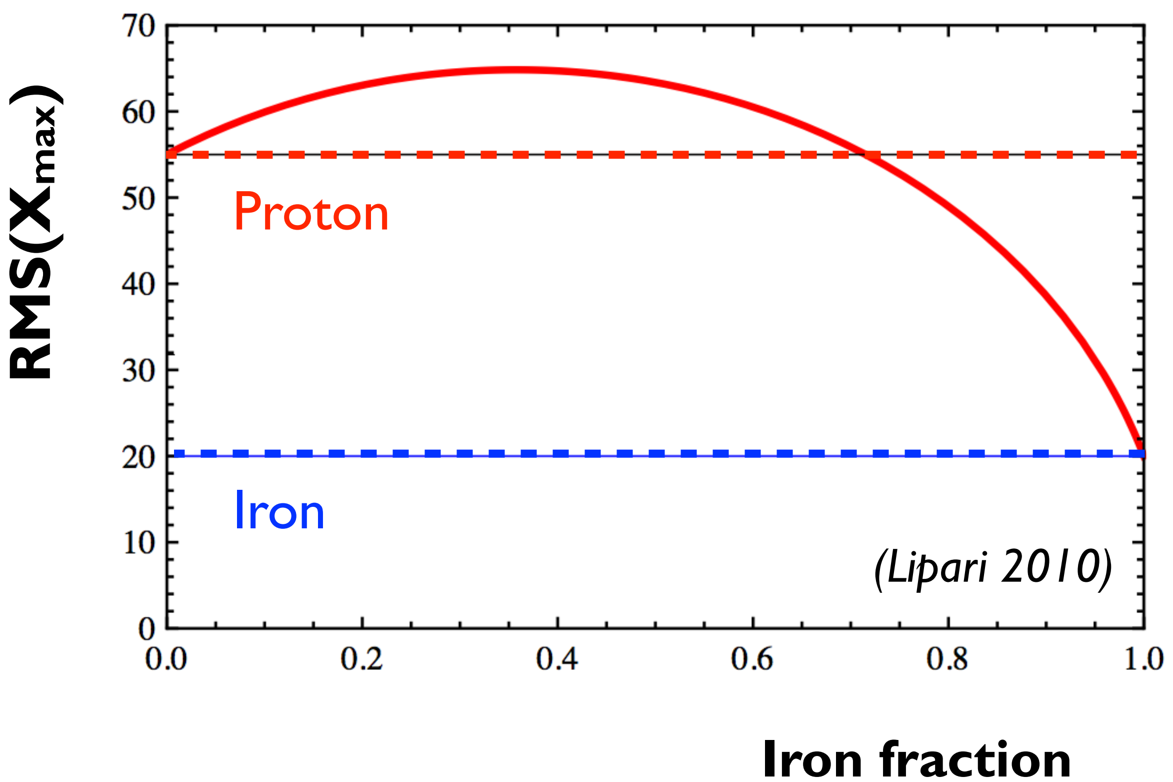
Mean depth of shower profiles and shower-to-shower fluctuations as measure of composition

Example: event measured by Auger Collab.

Mass composition from shower profile



Example: proton-iron mixture

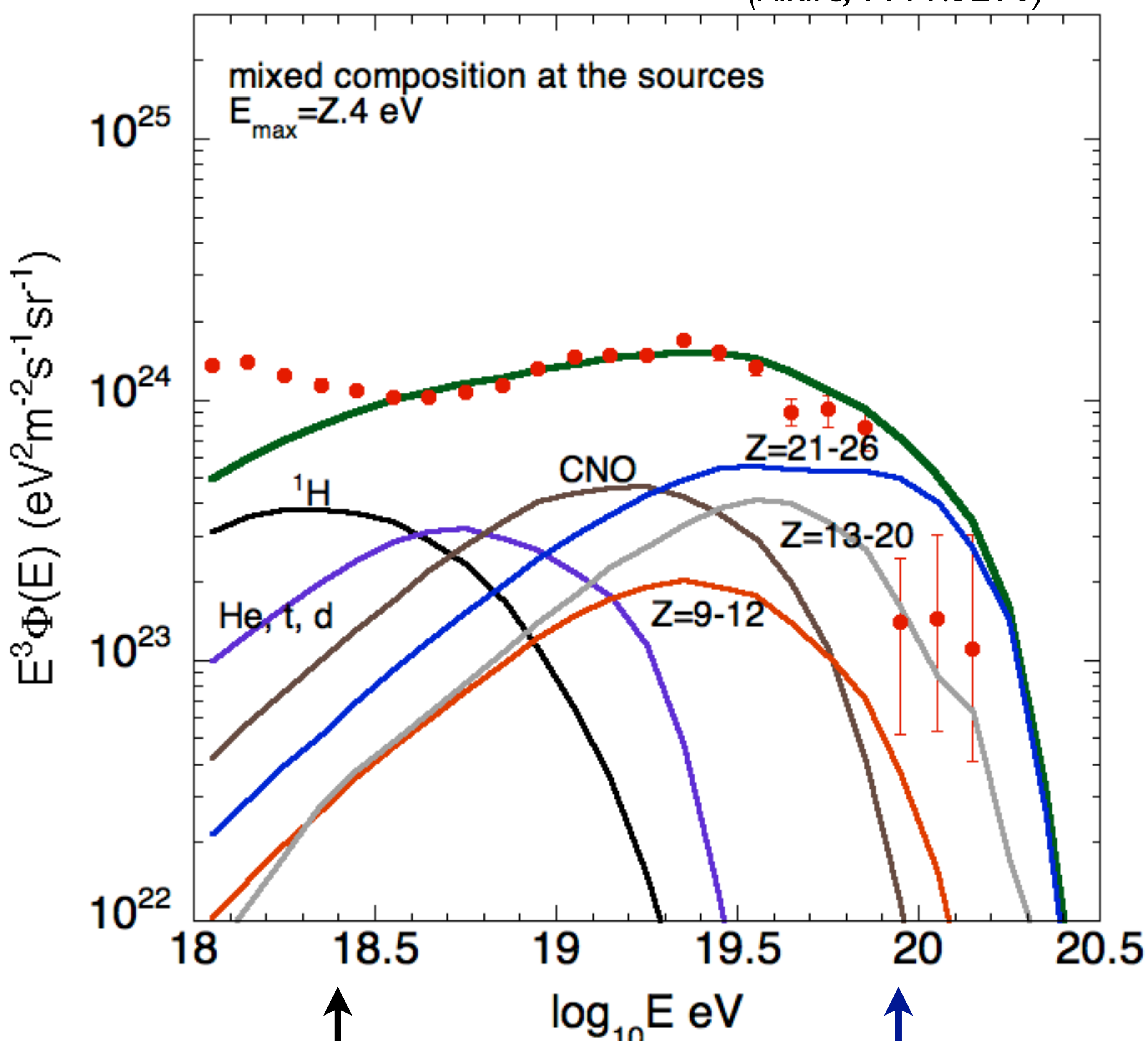


Independent confirmation from other composition indicators

(Auger Collab. PRL 104, 2010, updated: ICRC 2013)

Upper end of source energy spectrum seen ?

Particle flux *(Allard, 1111.3290)*

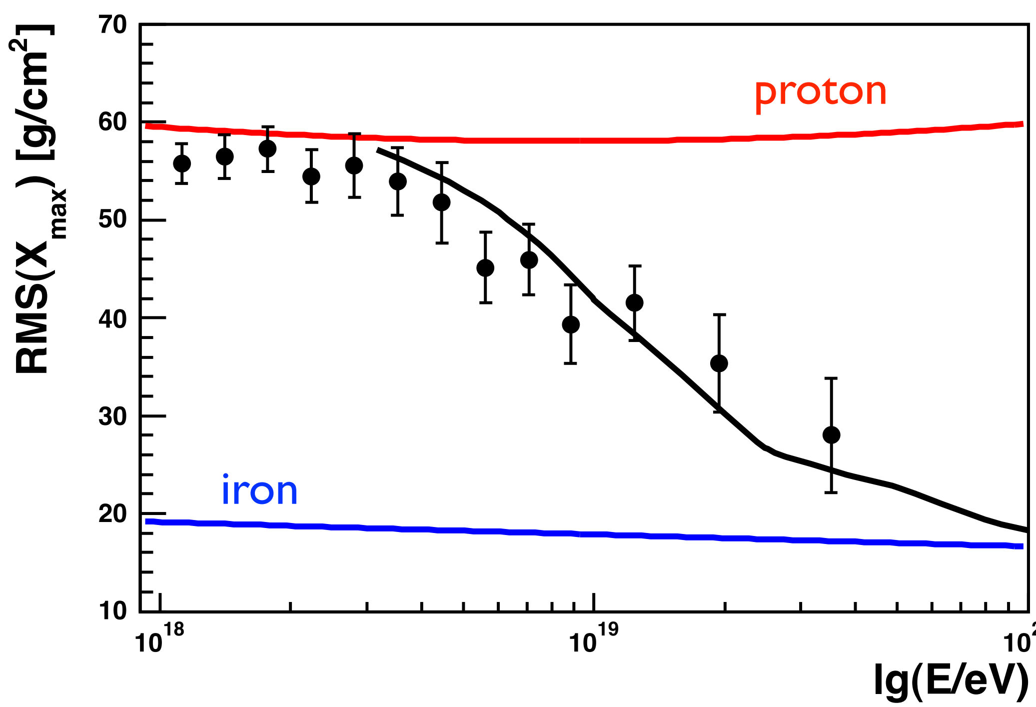


Protons $E_{max,p} = 10^{18.4}$ eV

Iron $E_{max, Fe}$ = 26 $E_{max,p}$ = 10^{20} eV

Natural transition to heavier composition at high energy !

Fluctuations of X_{max} *(Unger 2012)*



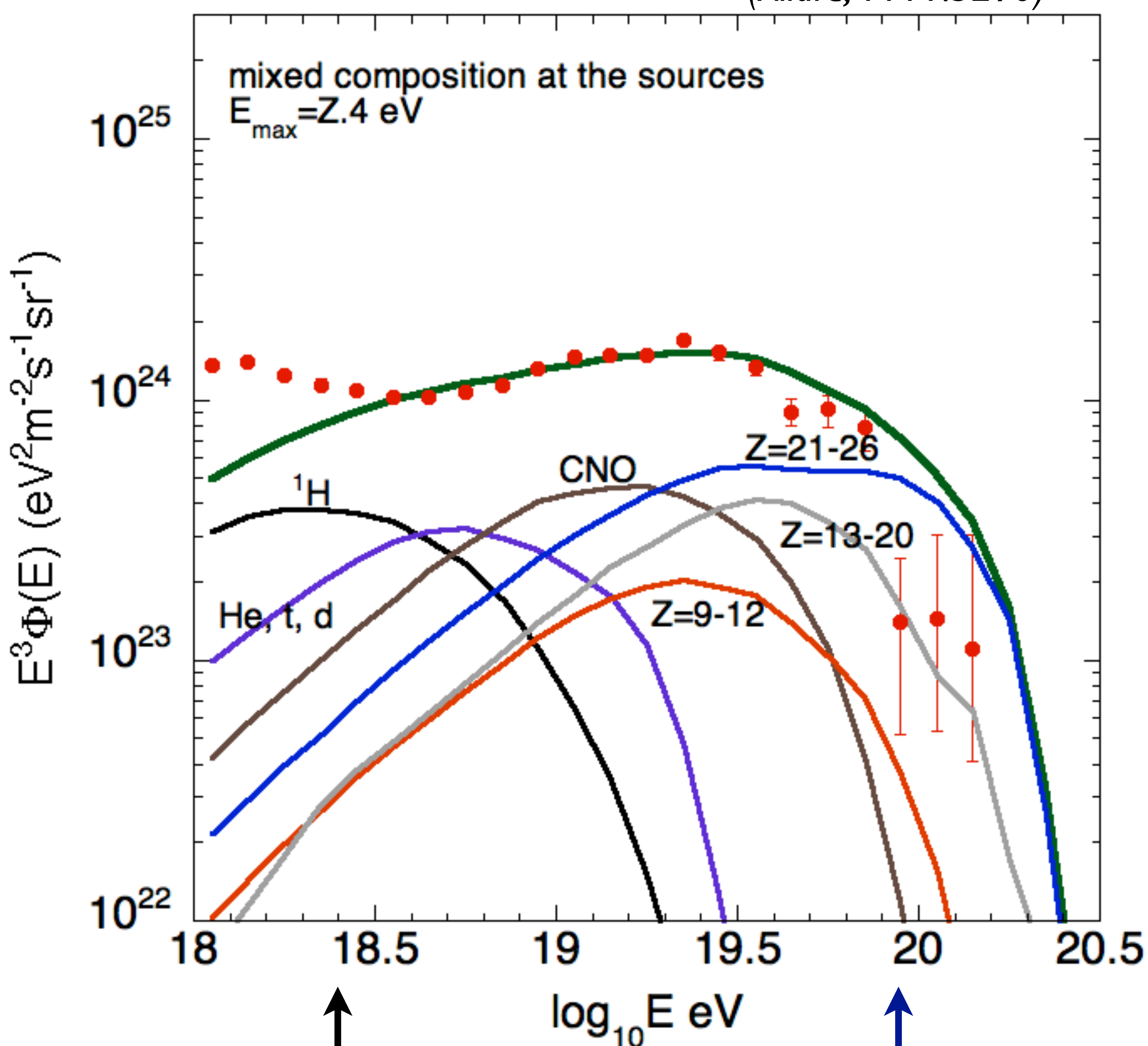
Different interpretation:
Suppression not due mainly to GZK energy-loss effect

(see also Calvez et al. 2010, Aloisio et al. 2011)

Upper end of source energy spectrum seen ?

Particle flux

(Allard, 1111.3290)



- Rigidity-dependent maximum injection energy
- Galactic composition
- Hard source injection spectrum

$$\frac{dN}{dE} \sim E^{-(1.0...1.7)}$$

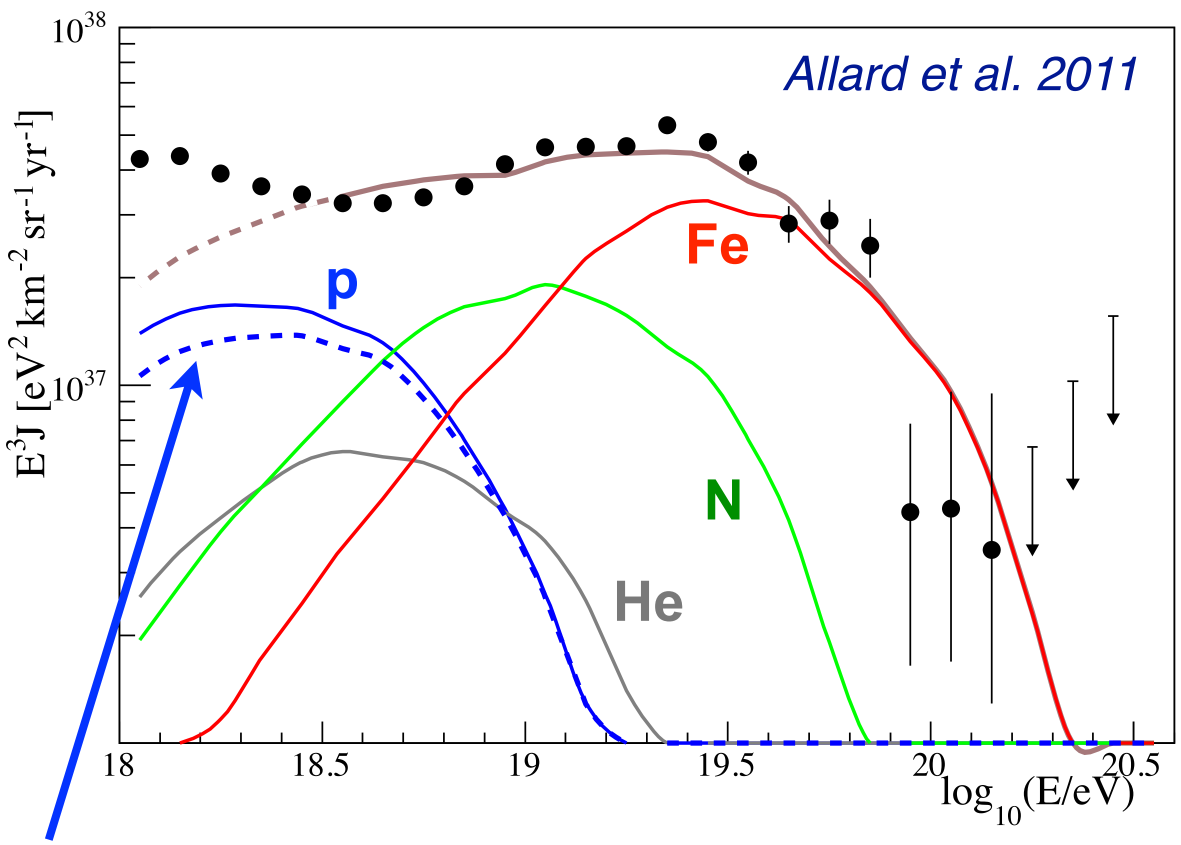
Astrophysics: very exotic result!

Protons $E_{max,p} = 10^{18.4}$ eV

Iron $E_{max,Fe} = 26\ E_{max,p} = 10^{20}$ eV

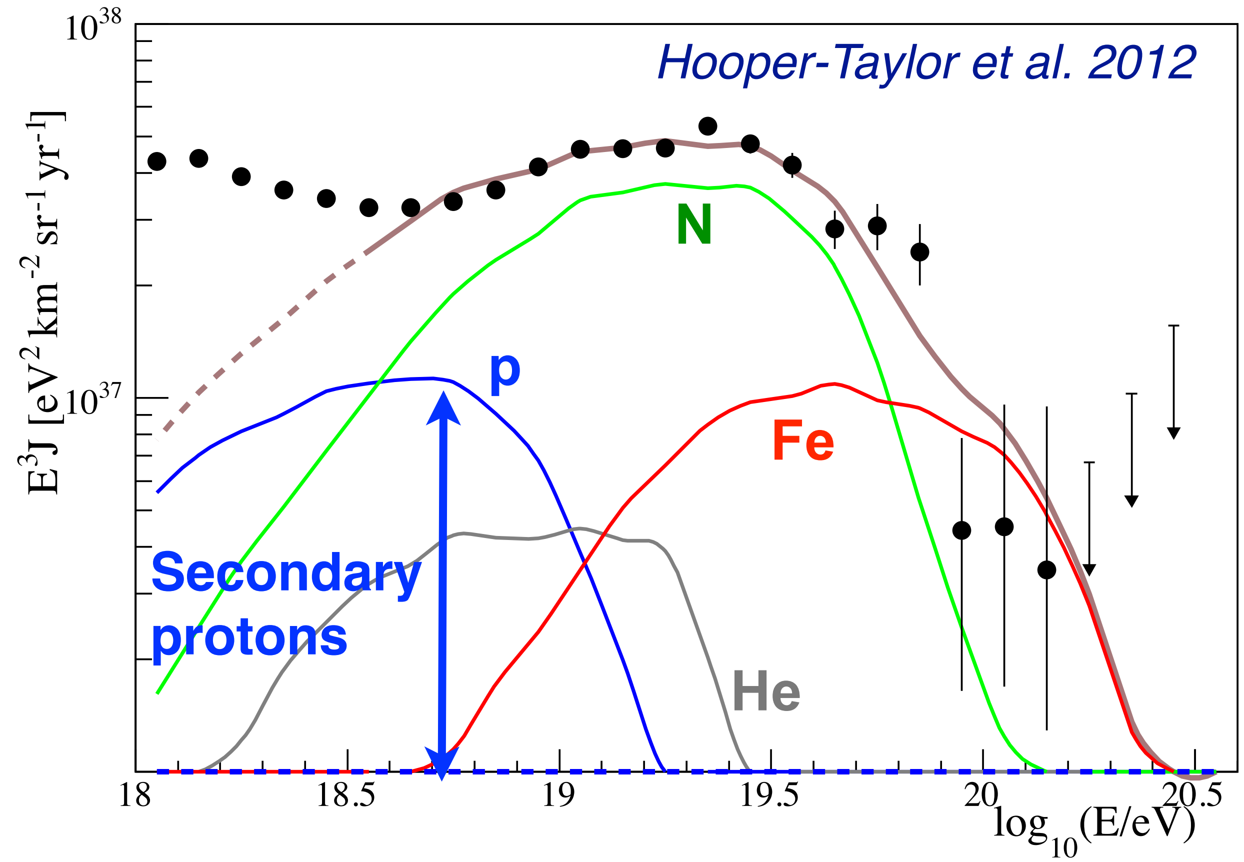
(see also Calvez et al. 2010, Aloisio et al. 2011)

Puzzle 1: Maximum-energy or GZK energy-loss ?



Protons injected from sources

(Sergio Petrera et al.)



Injection: Galactic composition with enhanced heavy elements

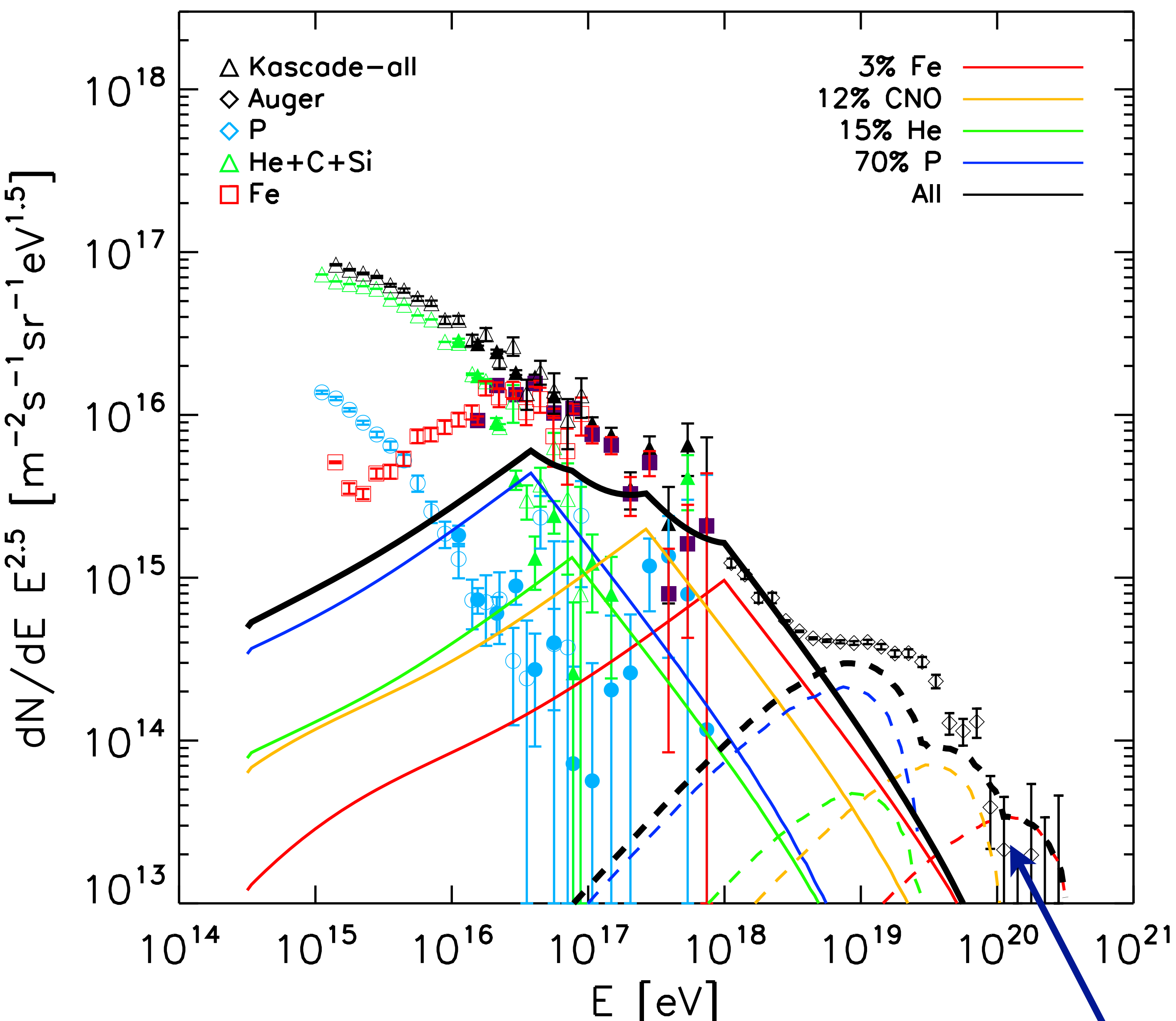
Injection: ~70% N or Si (almost no light elements)

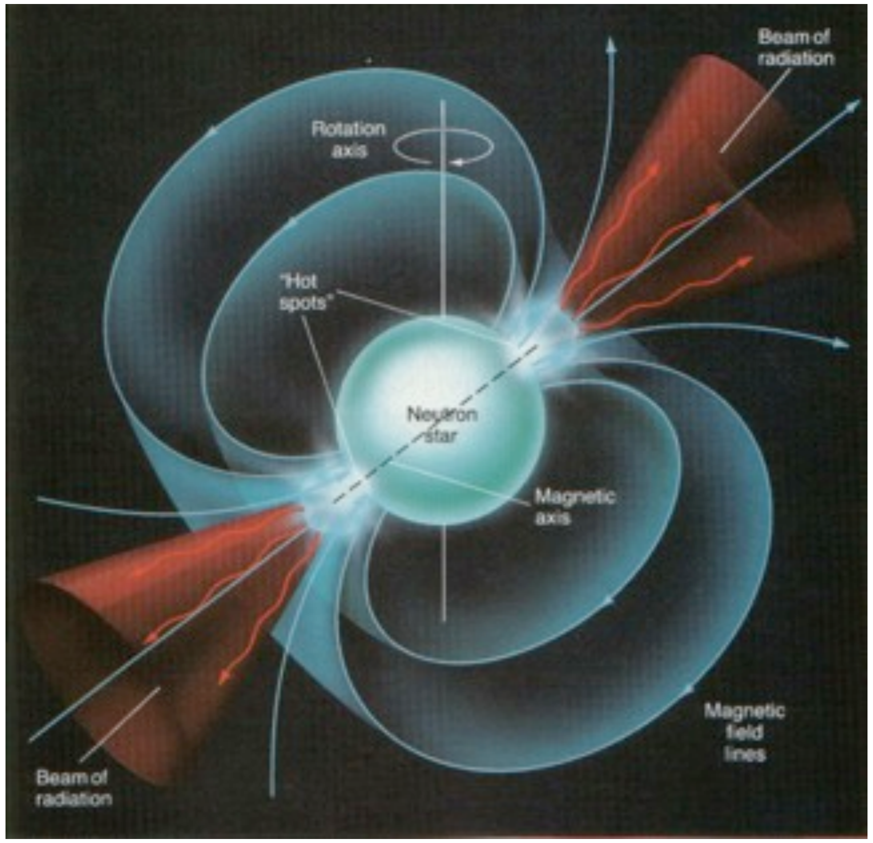
Difference: scaling with charge Z or mass number A
Both scenarios: hard injection spectrum and heavy source composition

(Shaham & Prian, Phys. Rev. Lett. 110, 2013)

Puzzle 2: source models with hard spectrum

(Aron 2003, Olinto, Kotera et al., 2012, Fang et al. 2013)



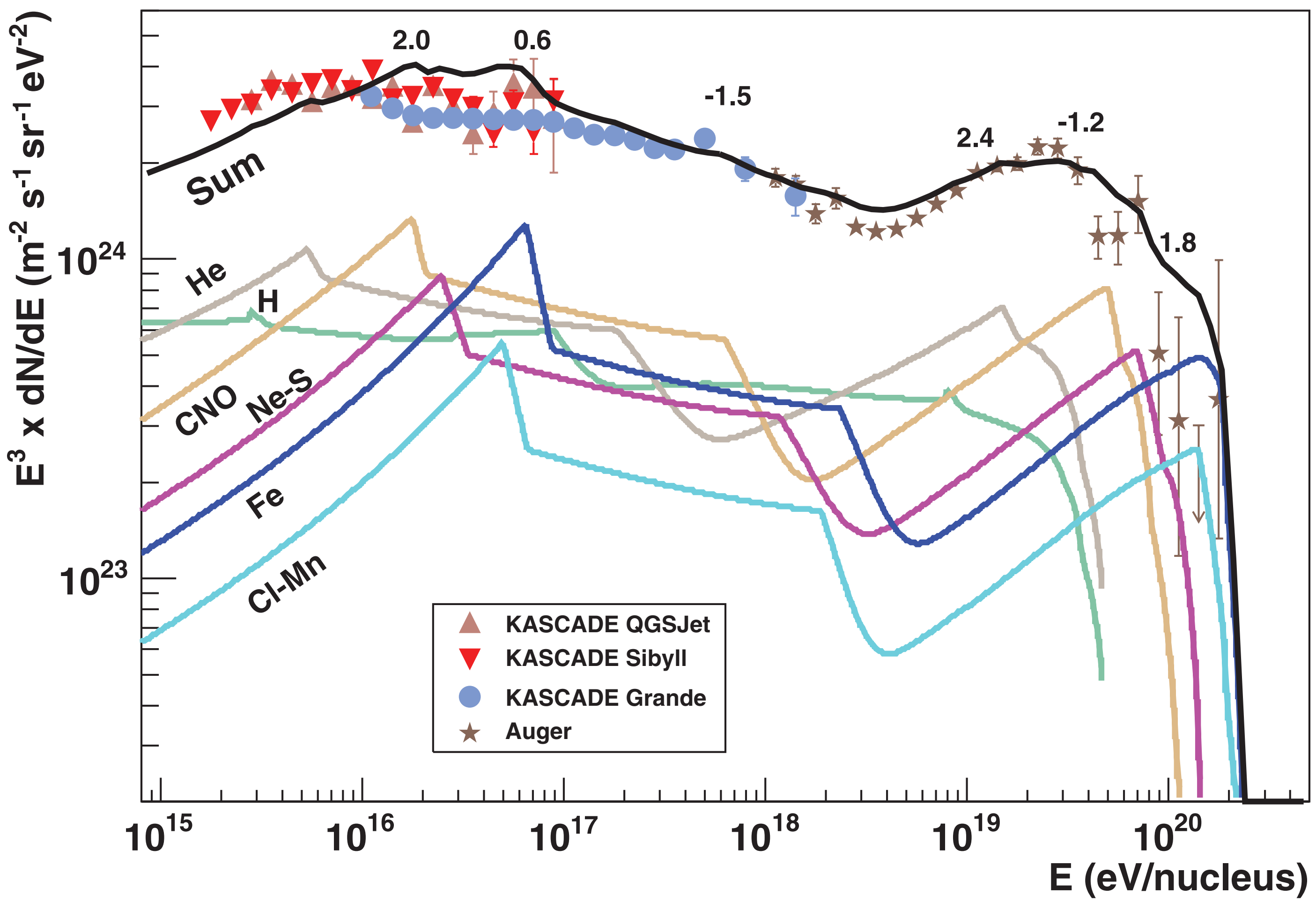


$$\frac{\mathrm{d}N_{\mathrm{inj}}}{\mathrm{d}E} \sim E^{-1}\left(1+\frac{E}{E_g}\right)^{-1}$$

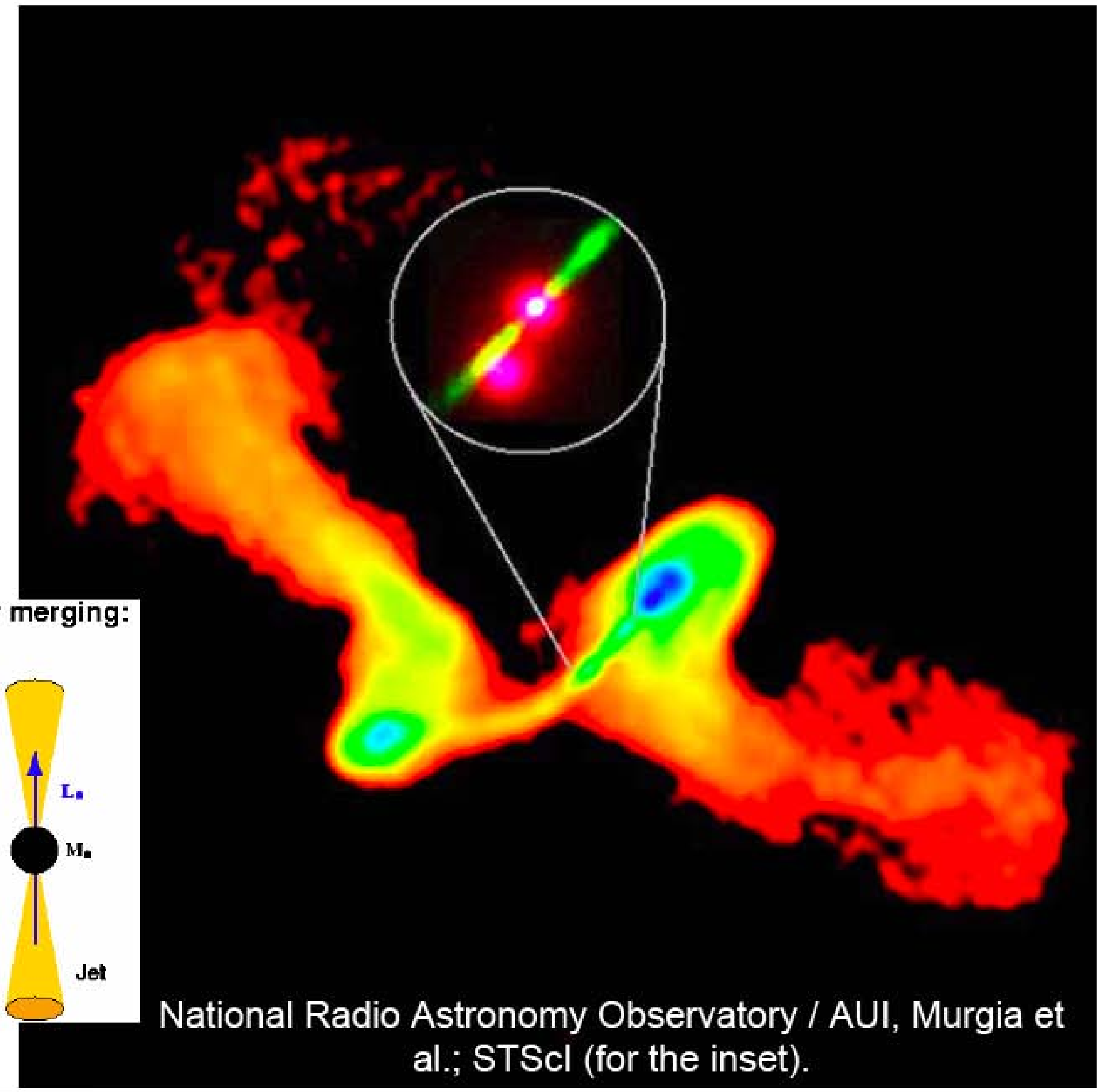
Low-energy part:
many galactic magnetars

High-energy part:
extragalactic (extreme) magnetar

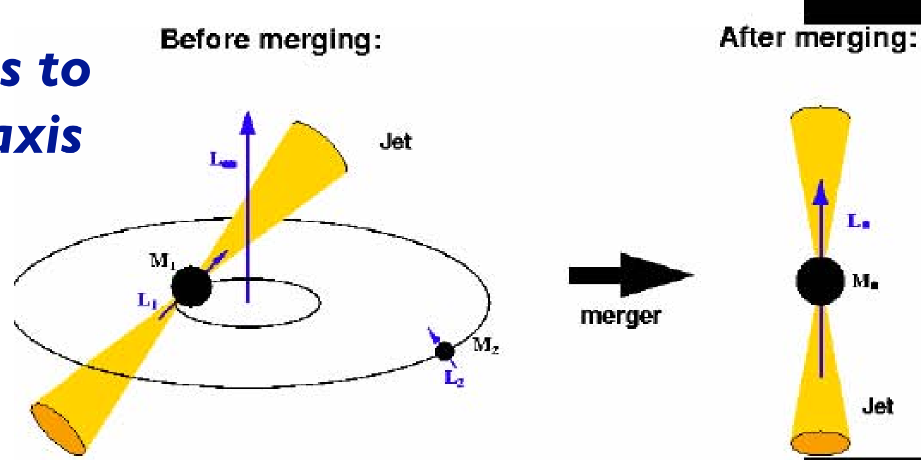
Centaurus A as dominating local source



Single reflection of galactic population of cosmic rays on ultra-relativistic shock front of AGN jet



Spin flip of black hole leads to re-orientation of rotation axis

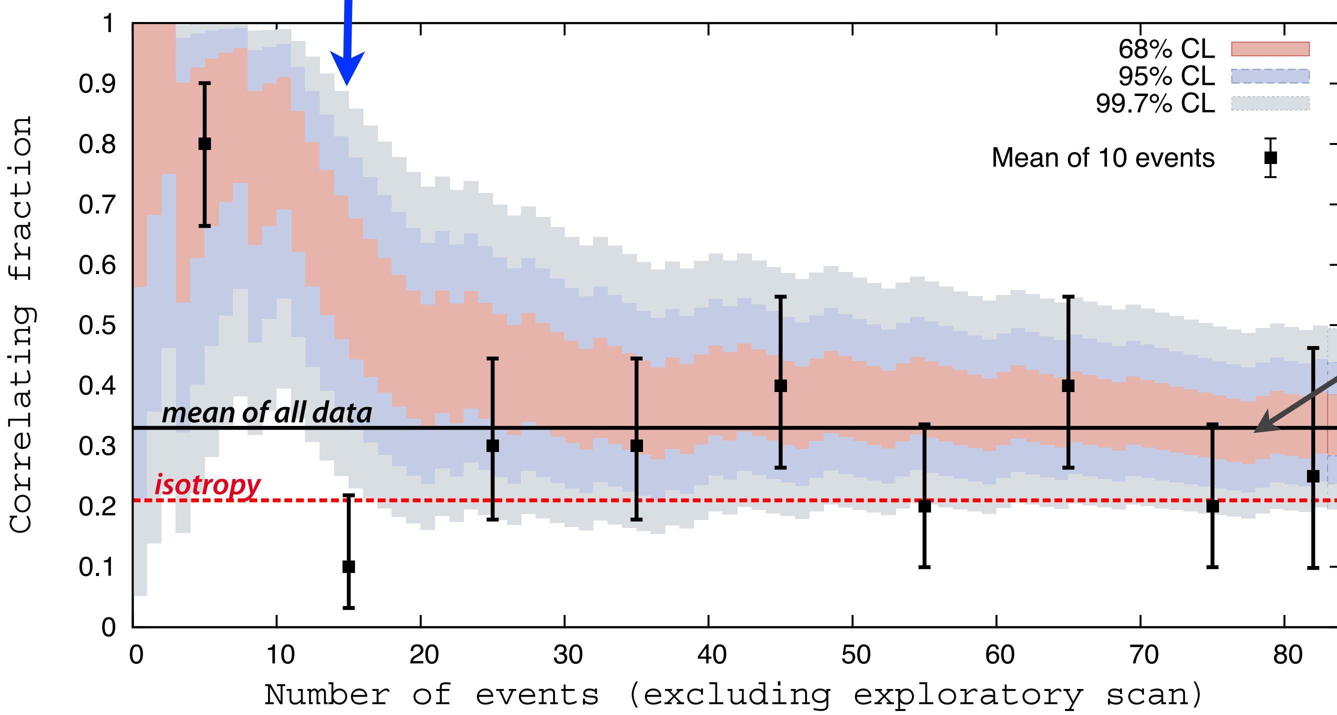


(Biermann et al. 2012)

Puzzle 3: Heavy elements and anisotropy ?

Auger Observatory (2011)

Science publication: 9/13 events ~69% correlated, expectation for isotropy 21%

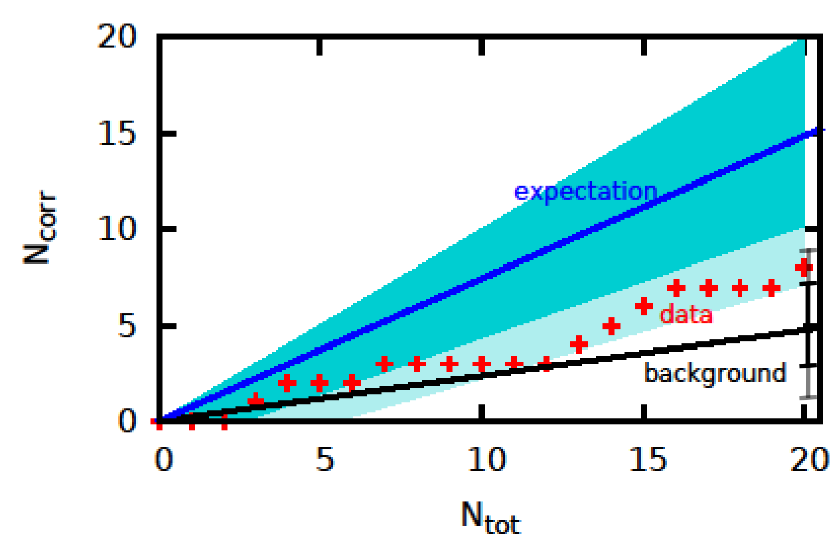


Differential estimate every 10 events

June 2011: 28 out of 84 correlated estimate now 33 ± 5% (P = 0.006)

Telescope Array (2011)

Expectation comes from Auger 69% (=9/13) which is converted to northern sky 73%. The background chance probability is 25%



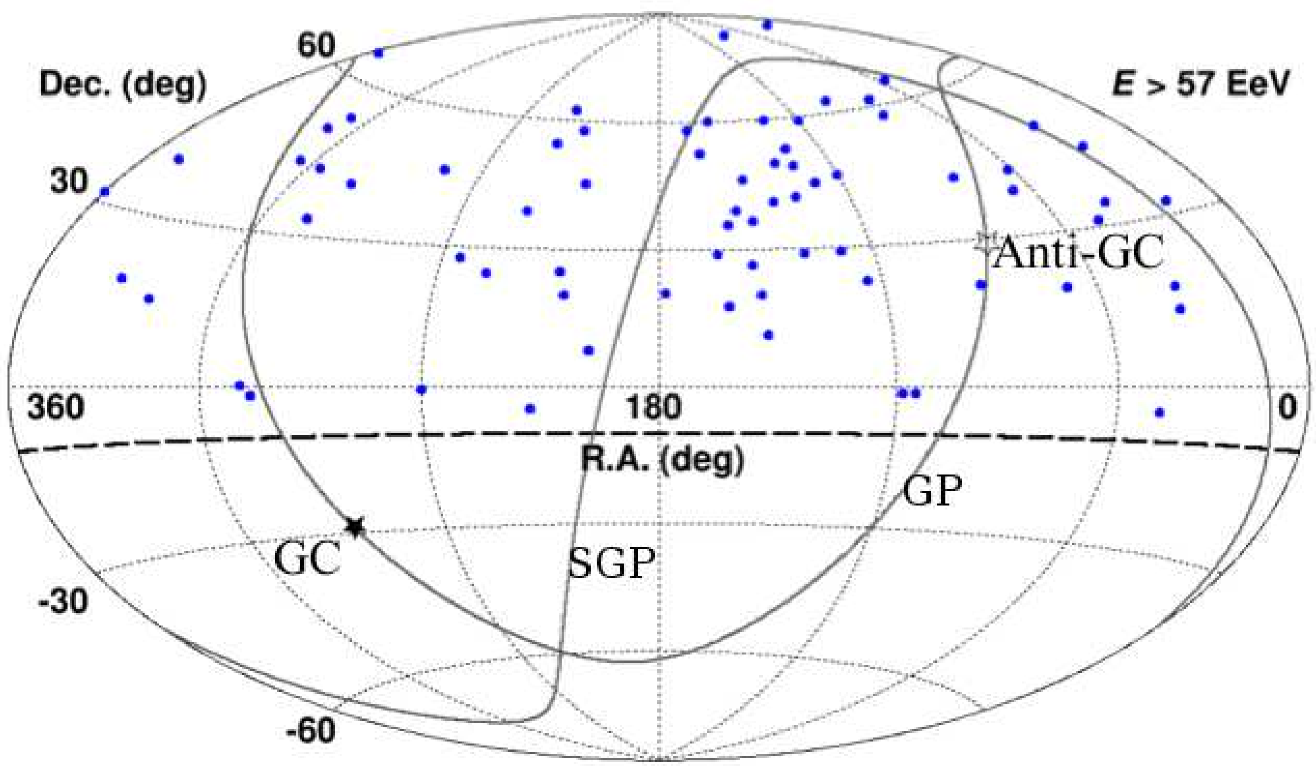
73%

25%

Auger data

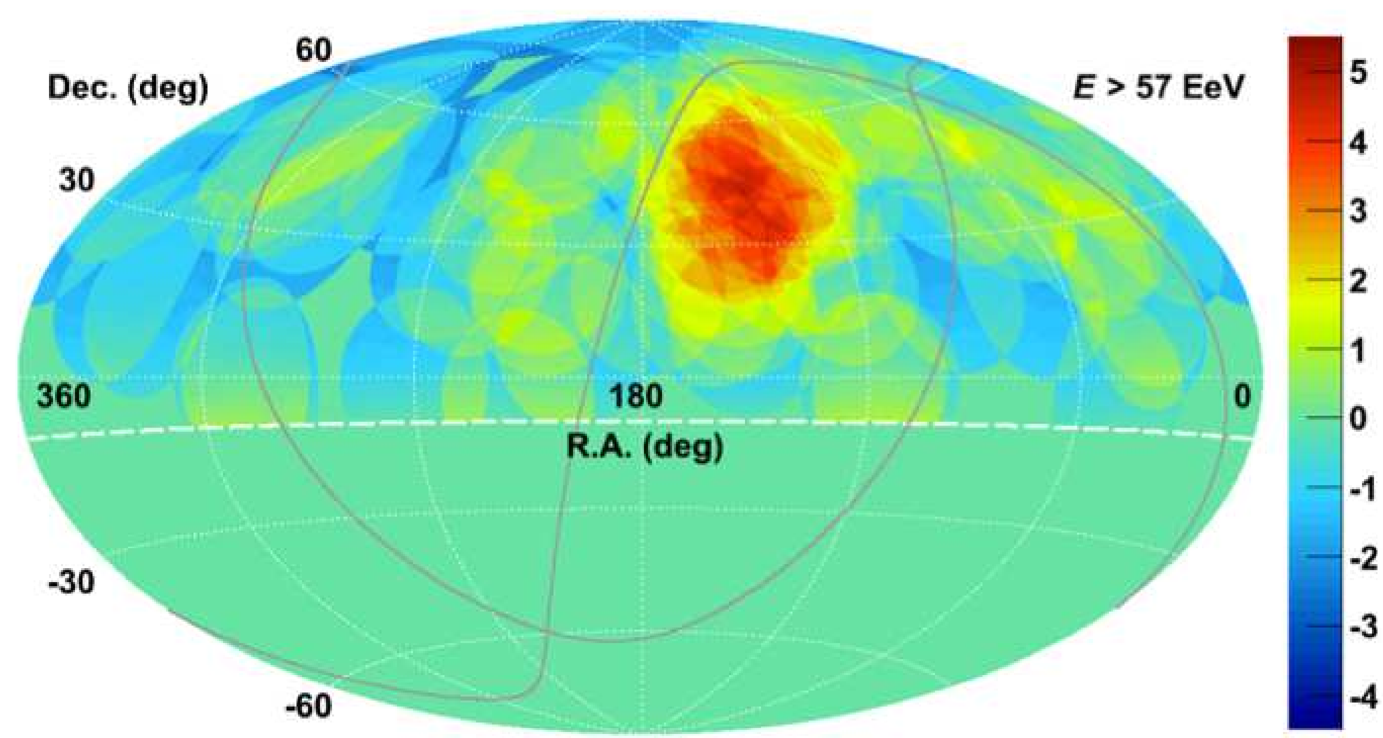
- compatible with ~10% protons
- anisotropy could come from ~10% protons

Latest data from TA: source region in northern sky



Part of sky not seen by Auger Observatory

Source region on 20° smearing, appox. 5 sigma

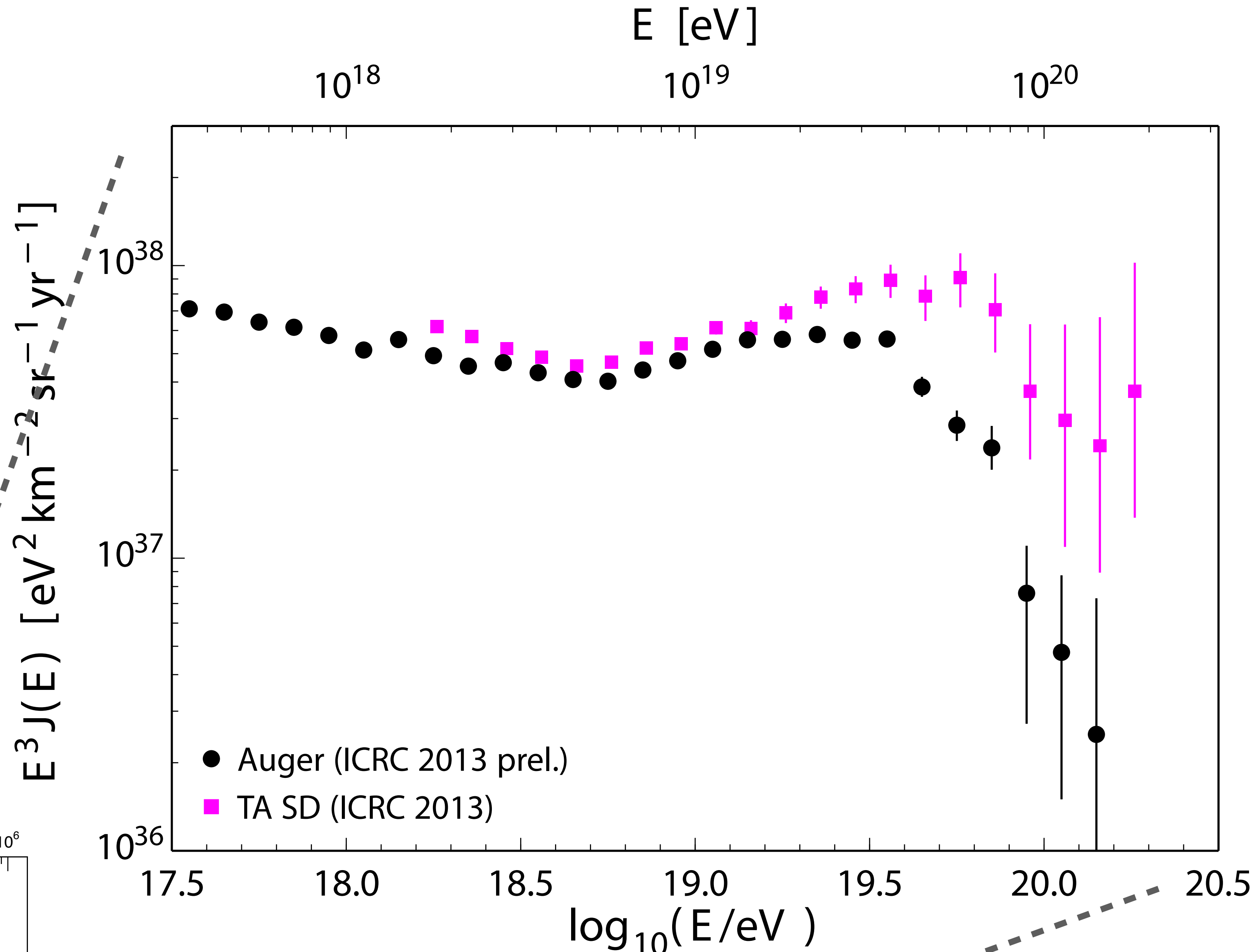


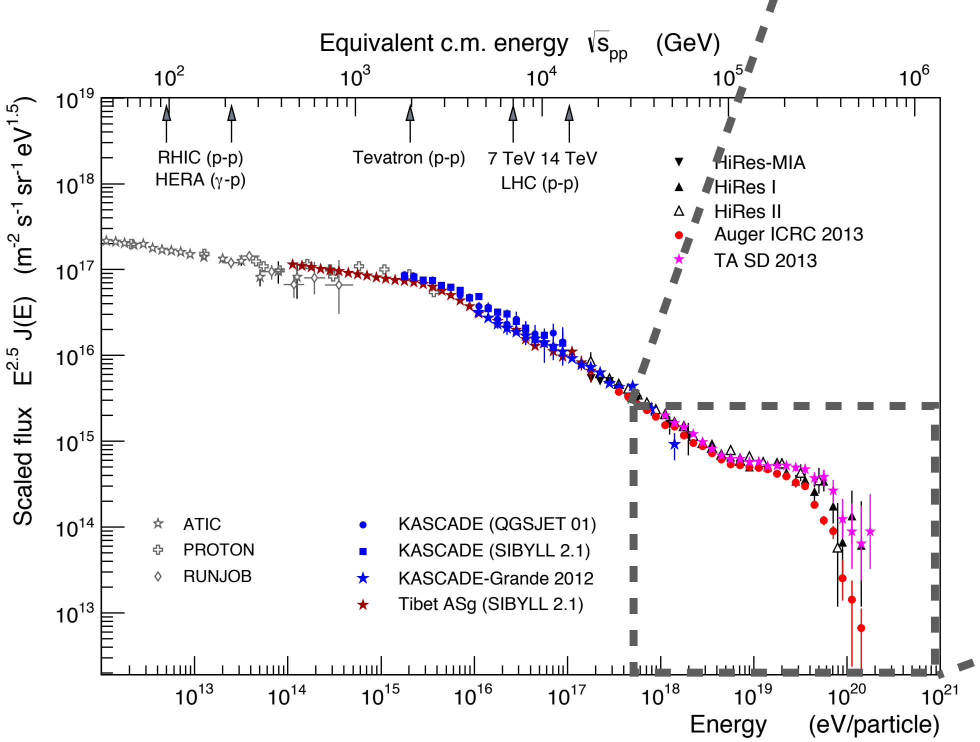
Chance probability to find equivalent excess if isotropy is assumed ~3.6 sigma, 1.4 10^{-4}

(TA Collab., 1404.5890)

Puzzle 4: Flux suppression not universal ?

Fluxes really different in suppression region ?





Summary

First answers

- **Flux suppression unambiguously established**
  - Indications for charge-dependent max. injection energy
  - Importance of possible GZK suppression of flux unclear
- **Exotic sources of ultra-high energy particles strongly disfavoured**
- **Anisotropy found at $E > 5.7\ 10^{19}$ eV**
- **Mixed or heavy composition favoured at very high energy**
  - Dependence on modelling hadronic interaction (LHC data)
  - No composition data for highest energies available

New puzzles

- **Flux suppression due to energy loss or maximum injection energy ?**
- **Sources with hard injection spectrum and very heavy composition ?**
- **New proton component appearing at highest energies ?**
- **Particle physics extrapolation to 400 TeV cms energy ?**

Outlook

Telescope Array:

Extension of existing array by factor ~5 (comparable to existing Auger array)

Auger Observatory:

Upgrade of detector array to be operated 2017 – 2023

Measurement composition up to highest energies, composition-enhanced anisotropy

Study of hadronic interactions in air showers, muon counting

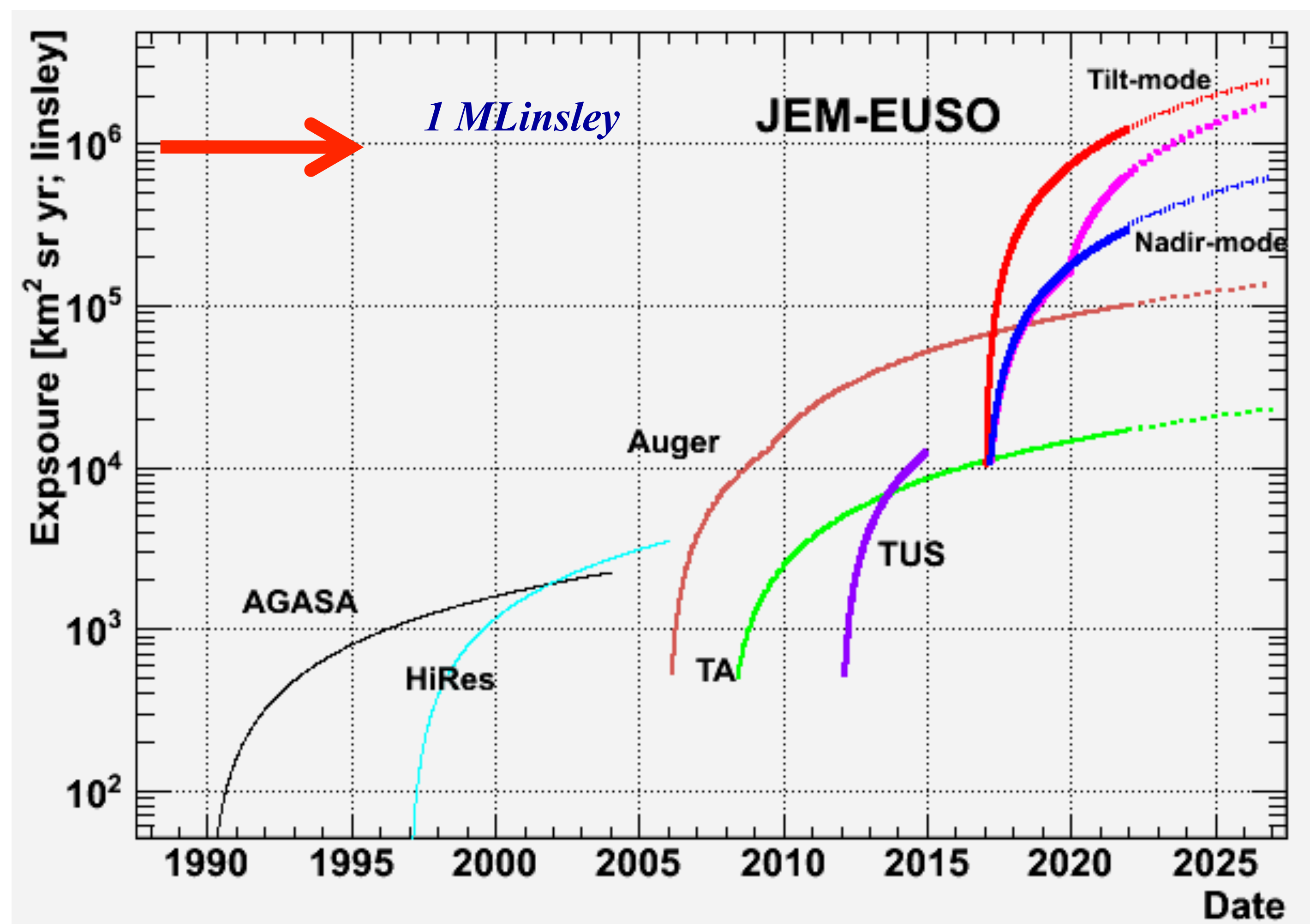
JEM-EUSO:

Anisotropy searches, spectrum at highest energies

New technology: pathfinder

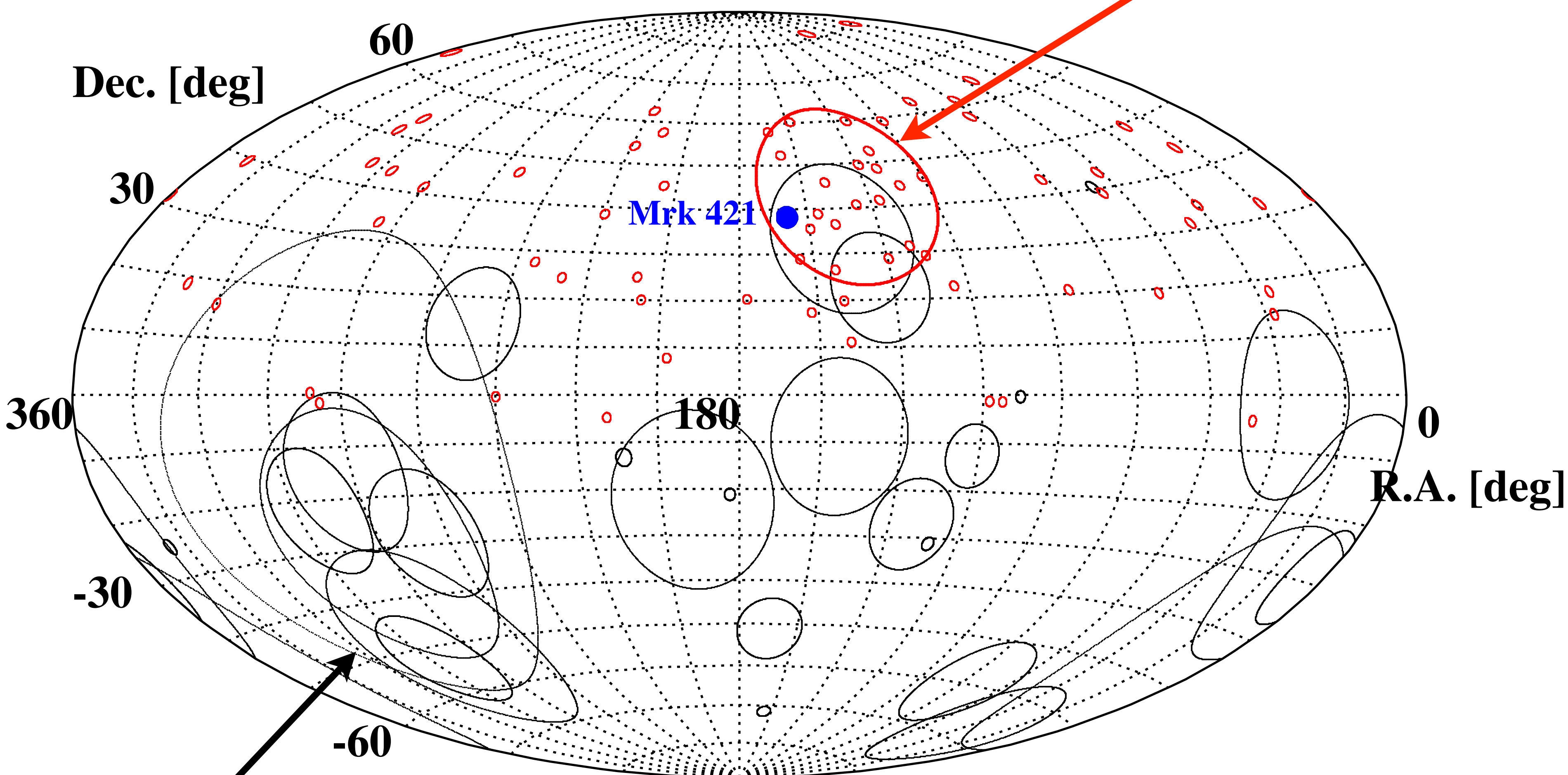
for future missions

In addition: multi-messenger information from neutrino and gamma ray observations



Mulit-messenger: work driven by new data

TA excess region



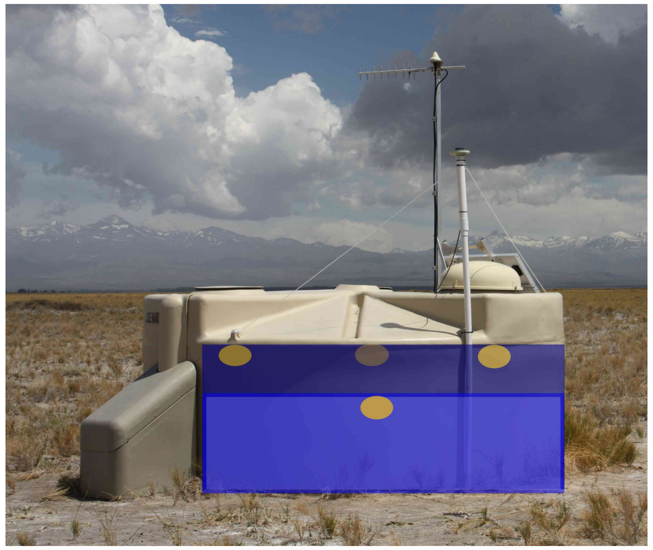
IceCube high-energy neutrinos

Work from today morning:
Fang et al. 1404.6237

Correlation at 2 sigma level

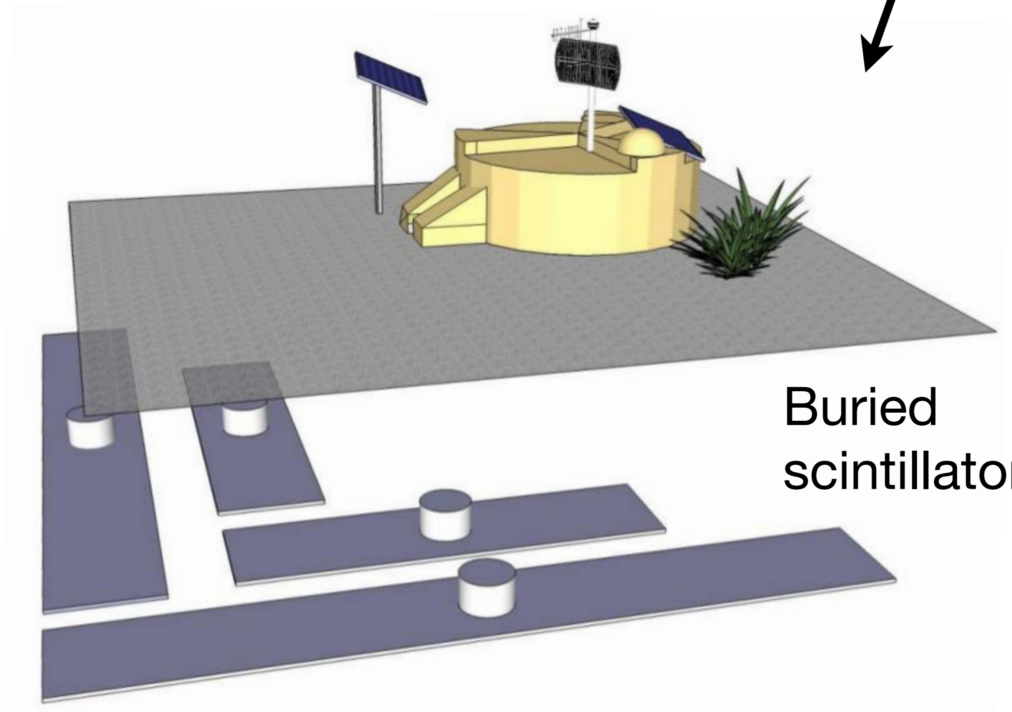
Auger upgrade – muonic and em. shower components

Surface detector station of Auger array

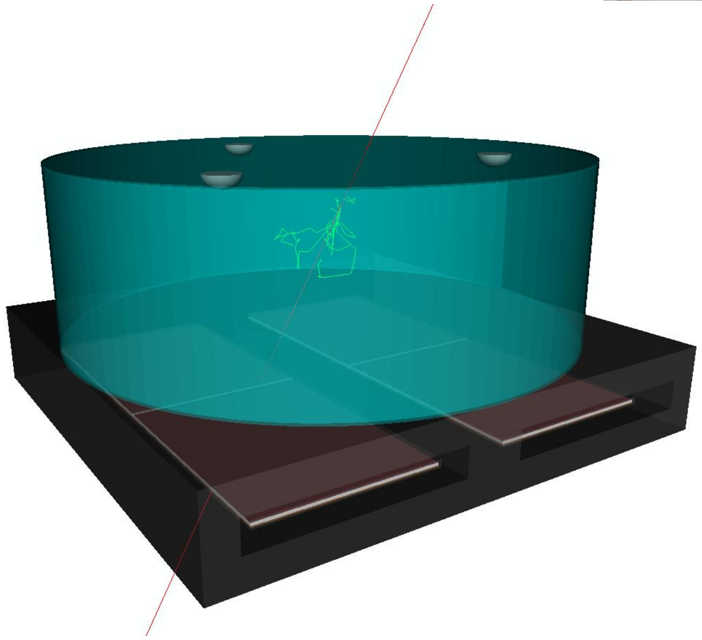


Segmented detectors (upper part acts as absorber)

Scintillators on top of existing stations



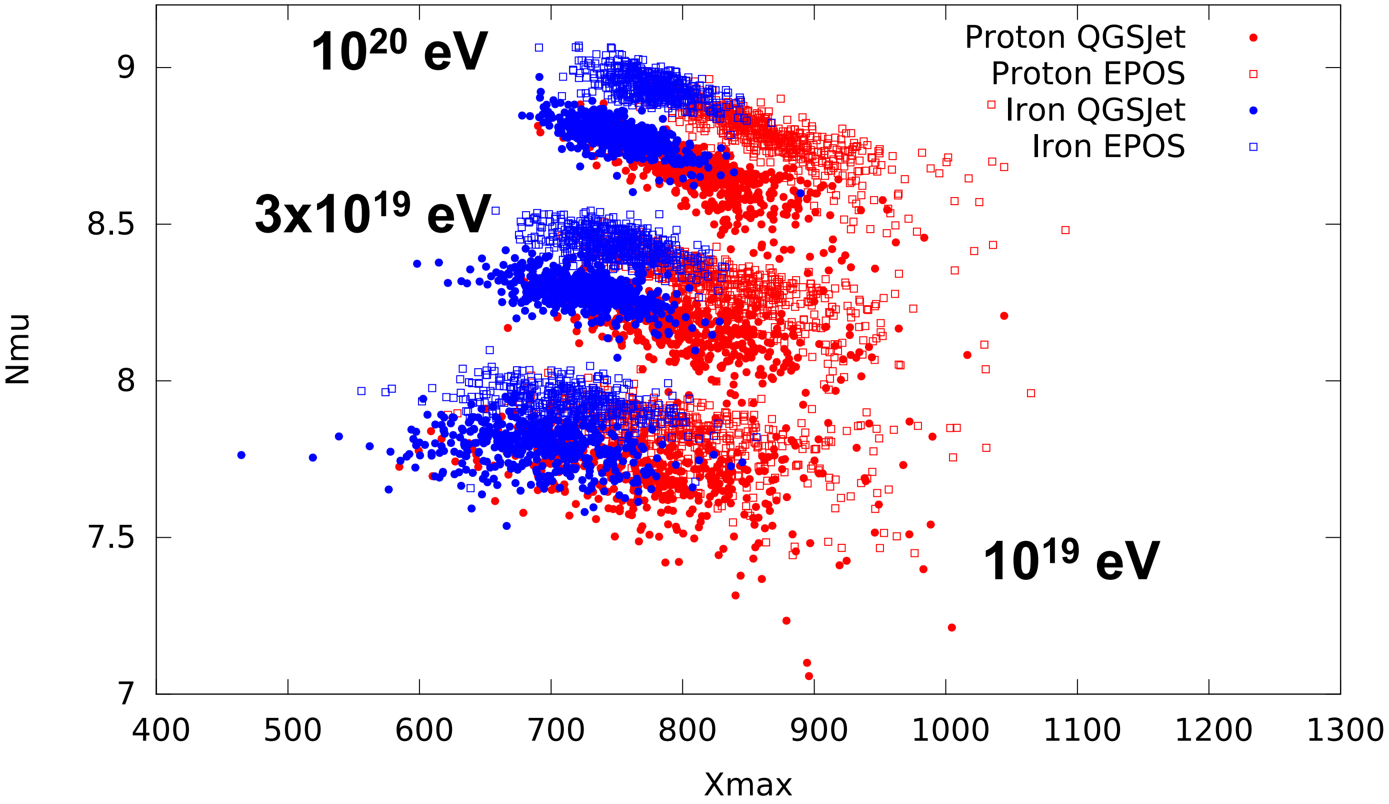
Buried scintillators



RPC detectors or scintillators placed below existing detector stations

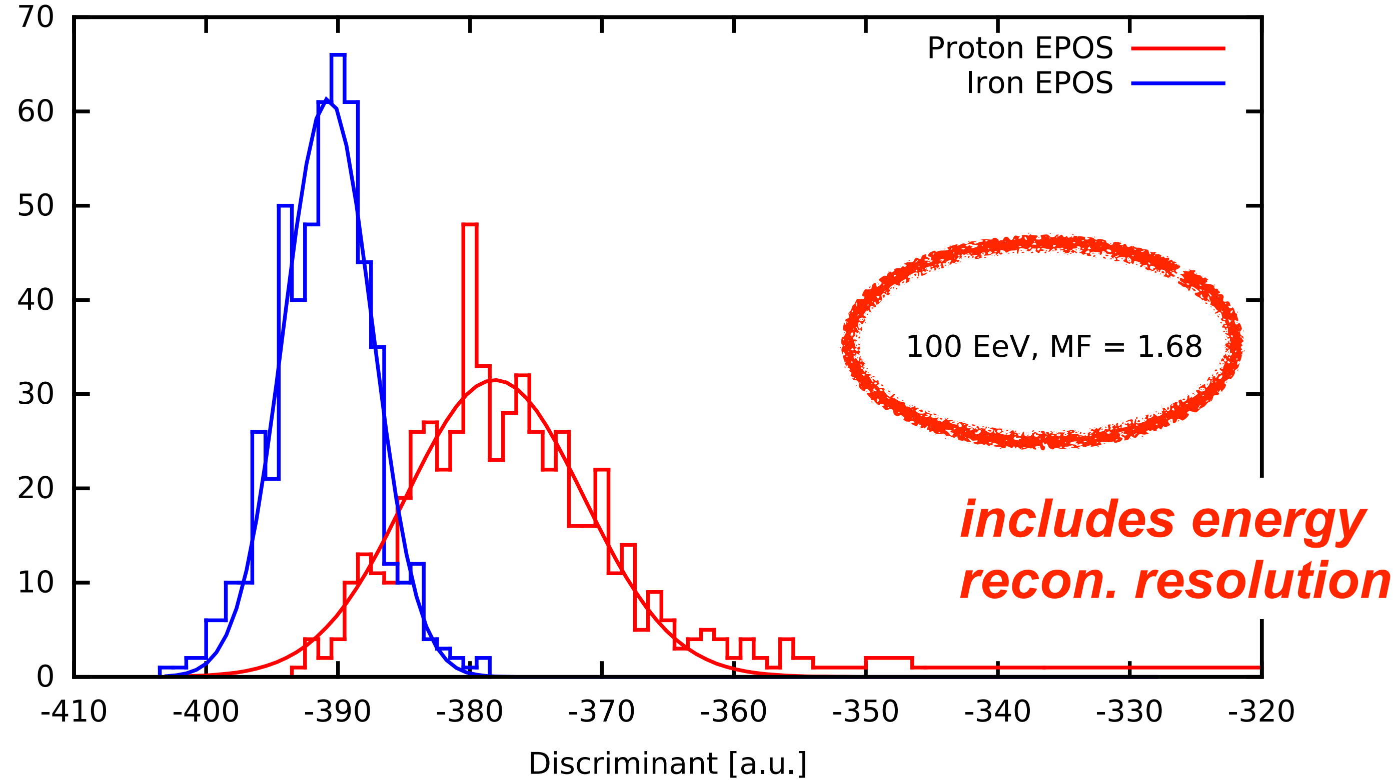
Auger upgrade: scintillators above each detector

Simulated configuration:
2 m² scintillator on top of tank

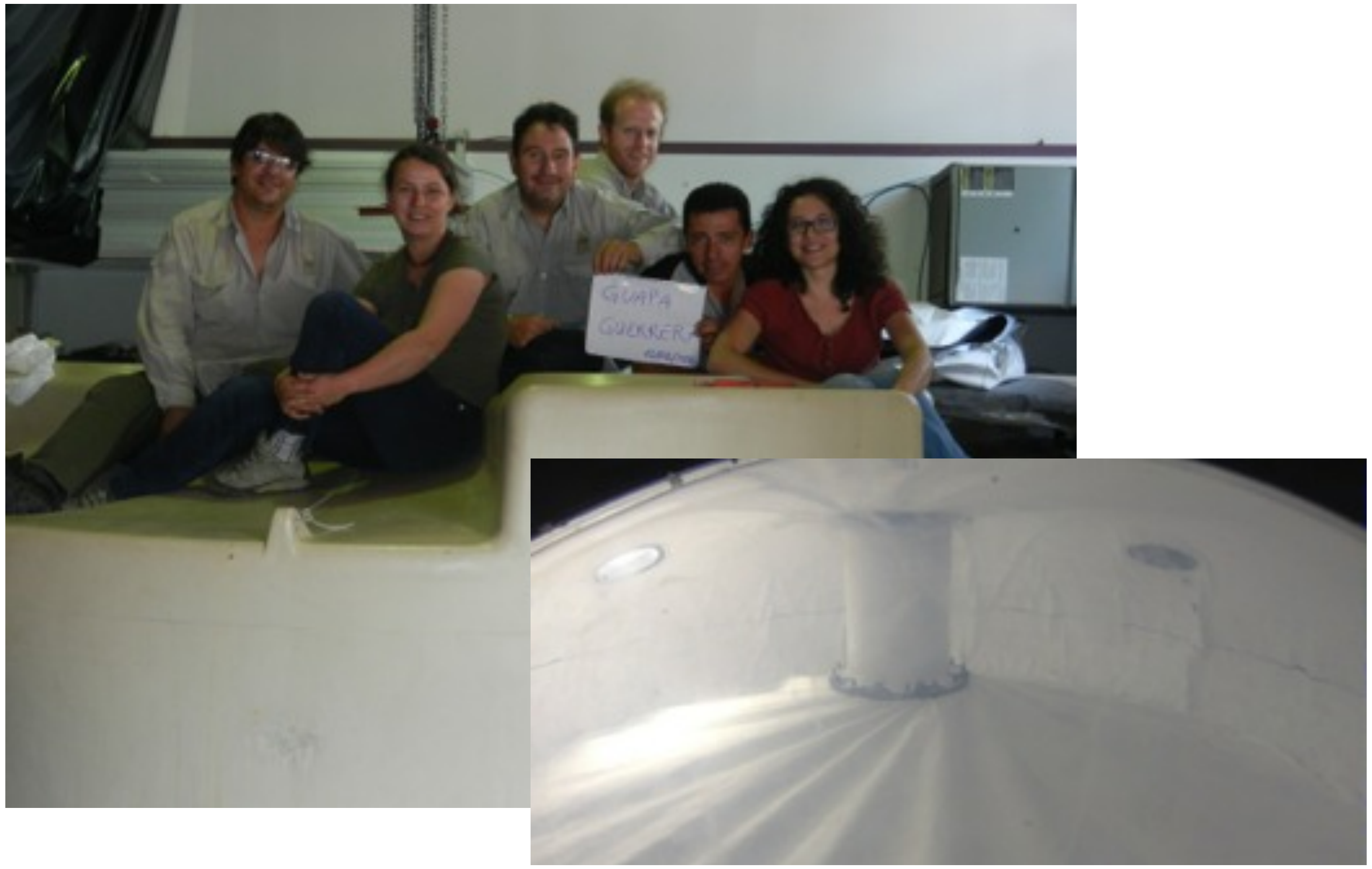


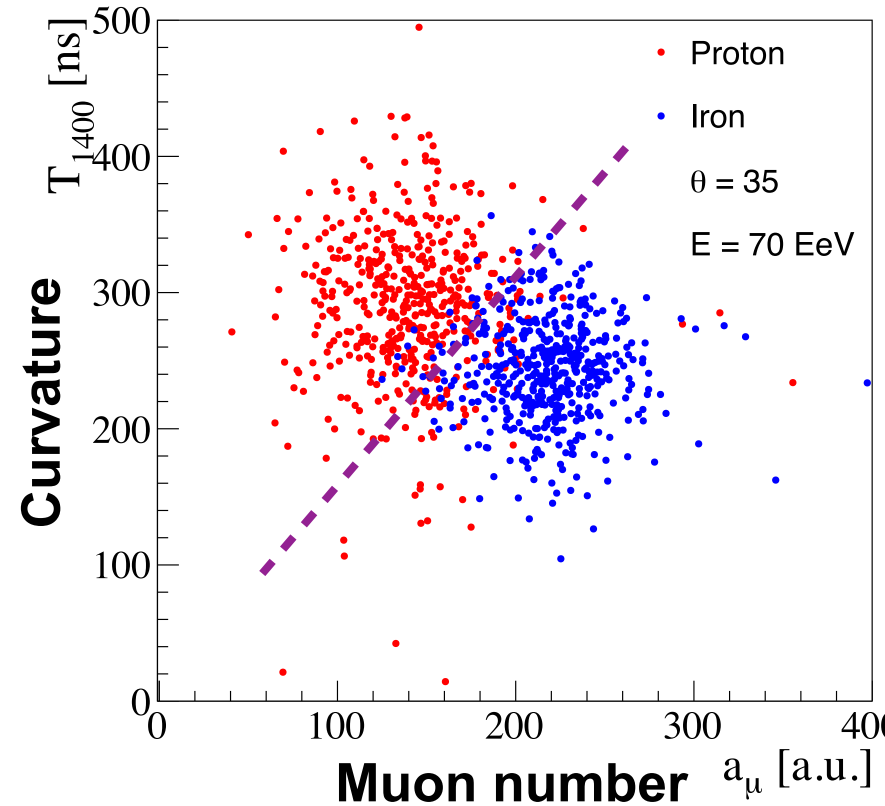
Merit factor
(discrimination power)

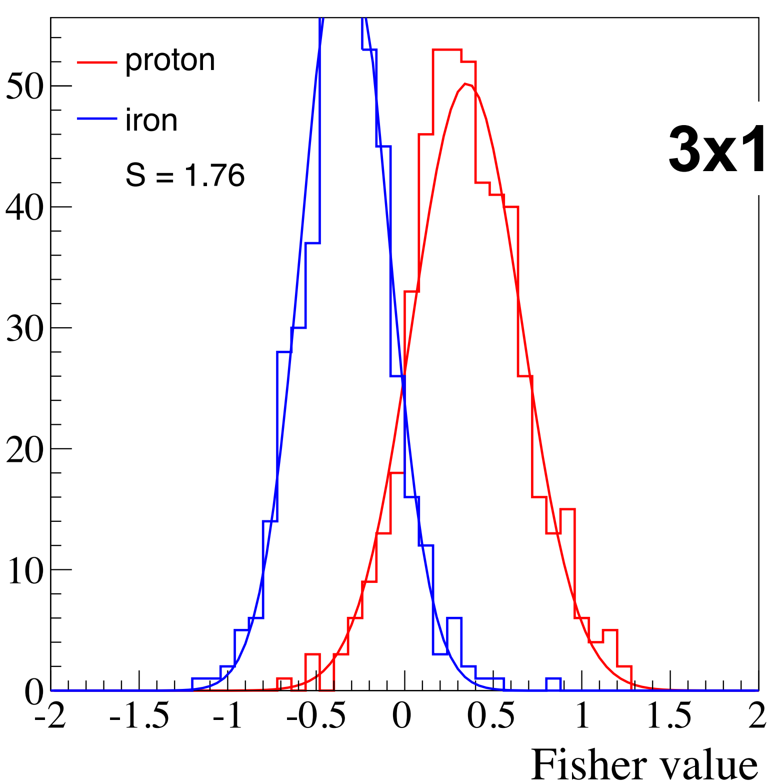
$$f_{\mathrm{p,Fe}} = \frac{|\langle S_{\mathrm{Fe}}\rangle - \langle S_{\mathrm{p}}\rangle|}{\sqrt{\sigma^2{}_{\mathrm{Fe}} + \sigma^2{}_{\mathrm{p}}}}$$



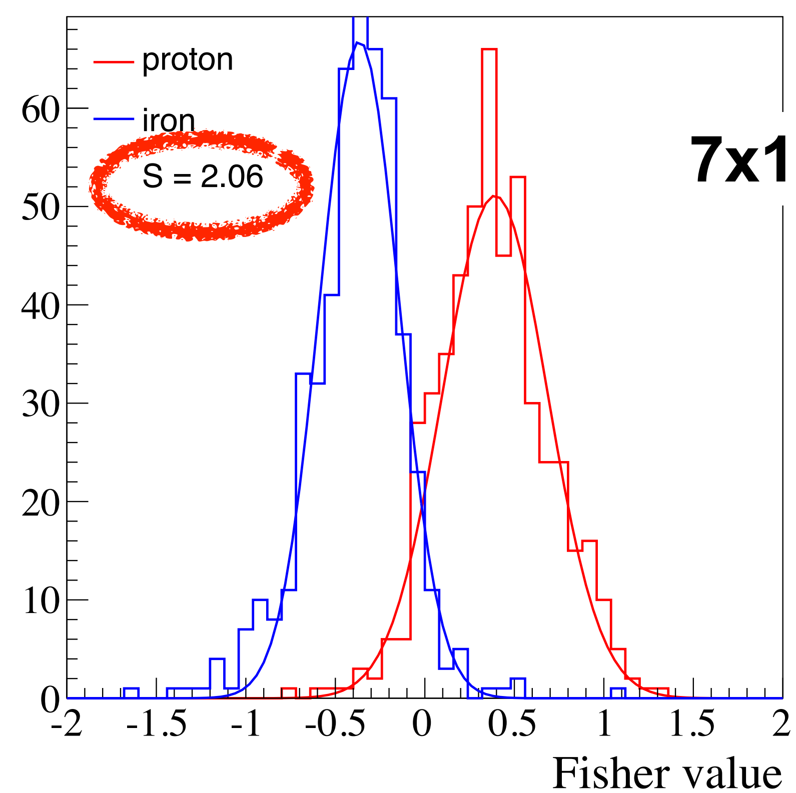
Auger upgrade: layered surface detector





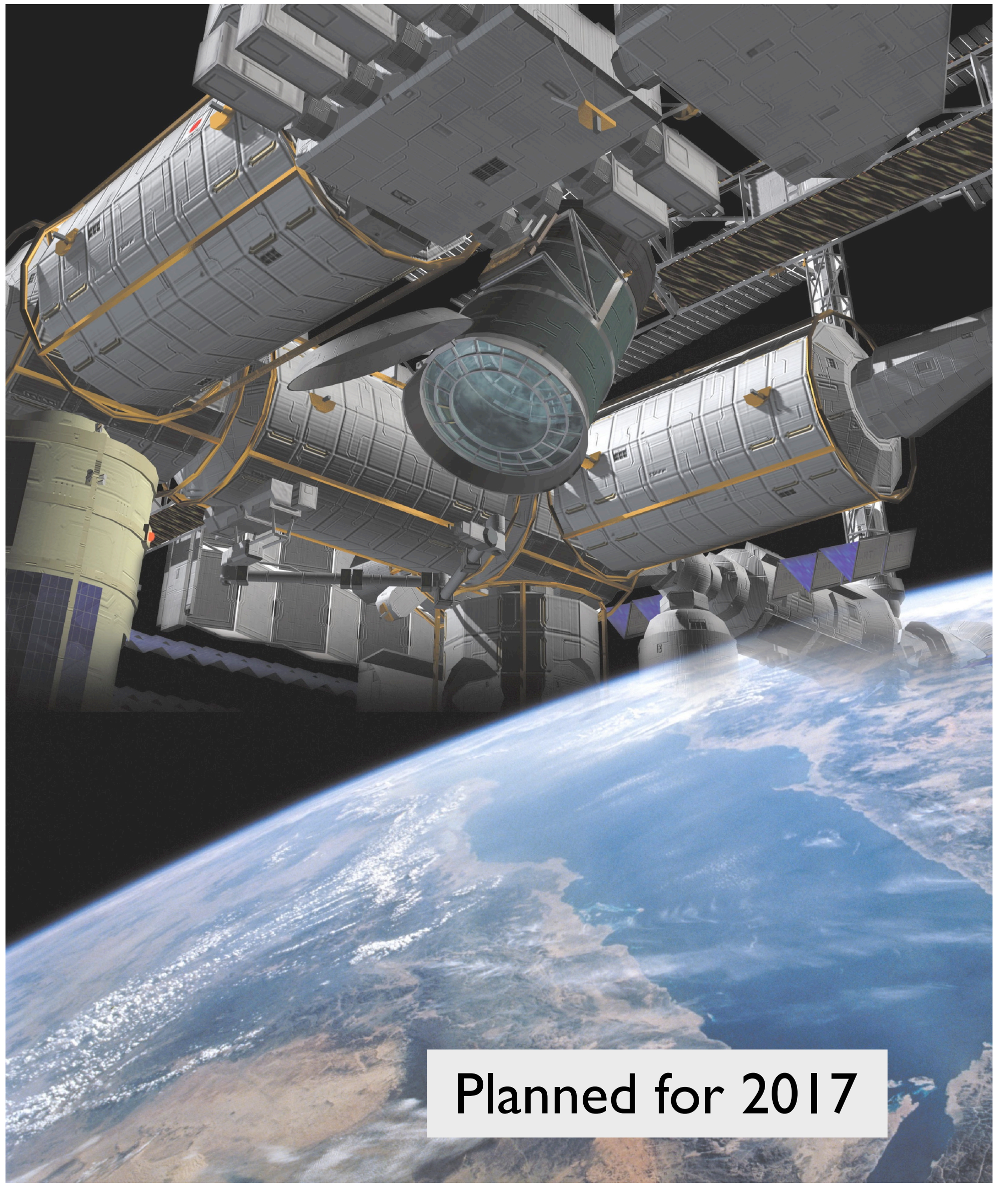


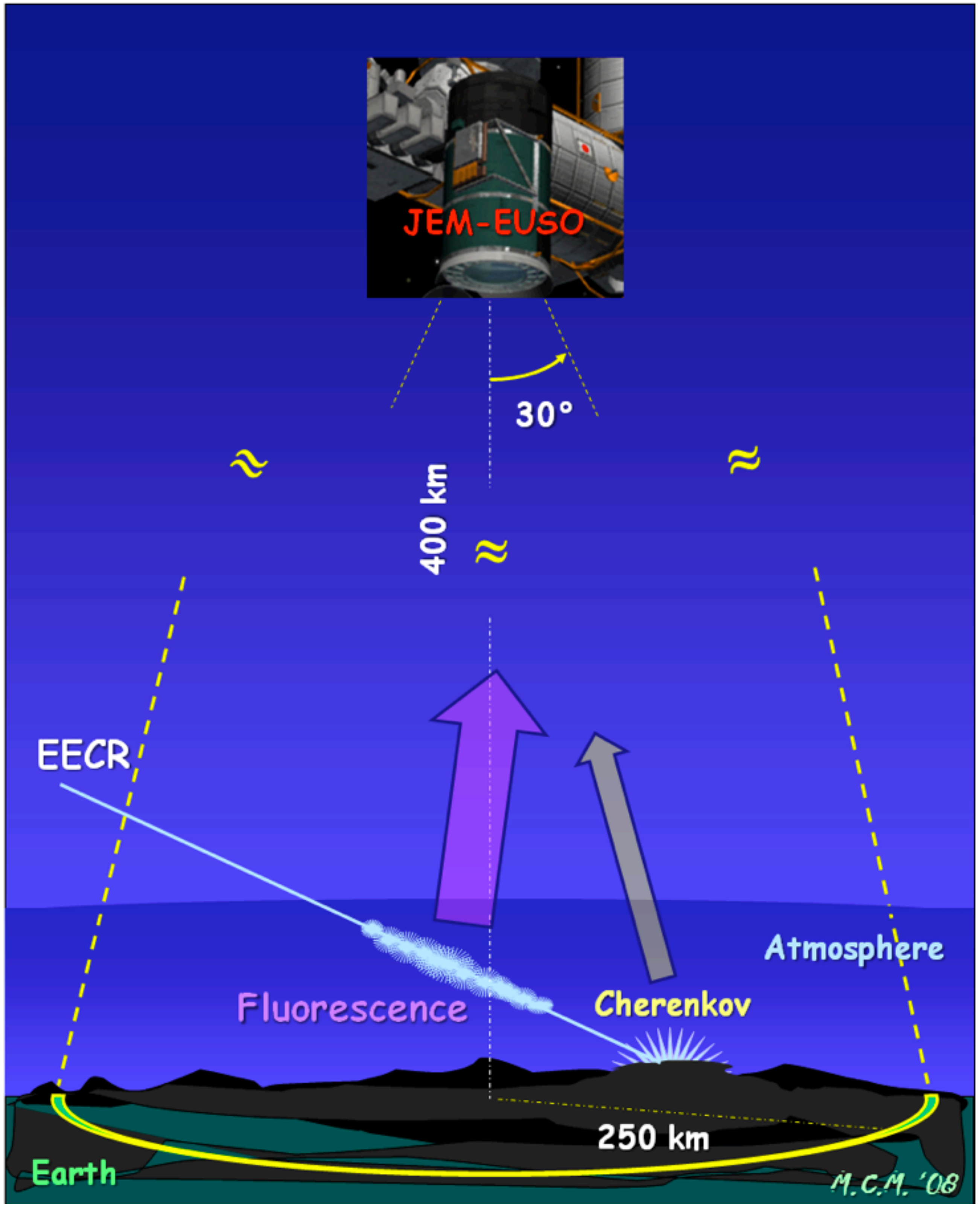
$3x10^{19}$ eV



$7x10^{19}$ eV

Observation from space: JEM-EUSO





- Detection of fluorescence light and reflected Cherenkov light
- Energy threshold $10^{19.7}$ eV
- Full sky coverage