Observation of Ultra-High Energy Cosmic Rays

Status and Prospects

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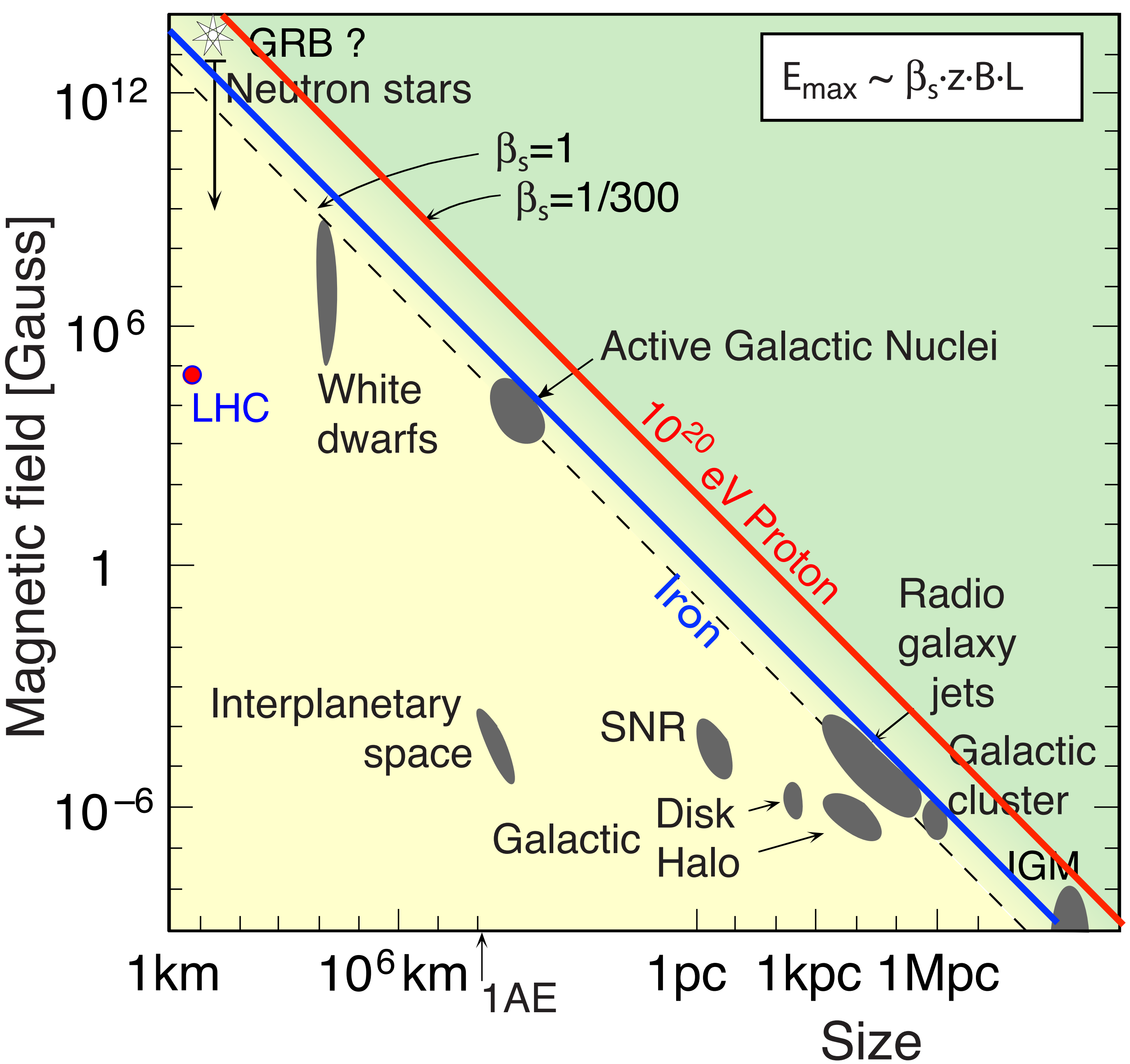
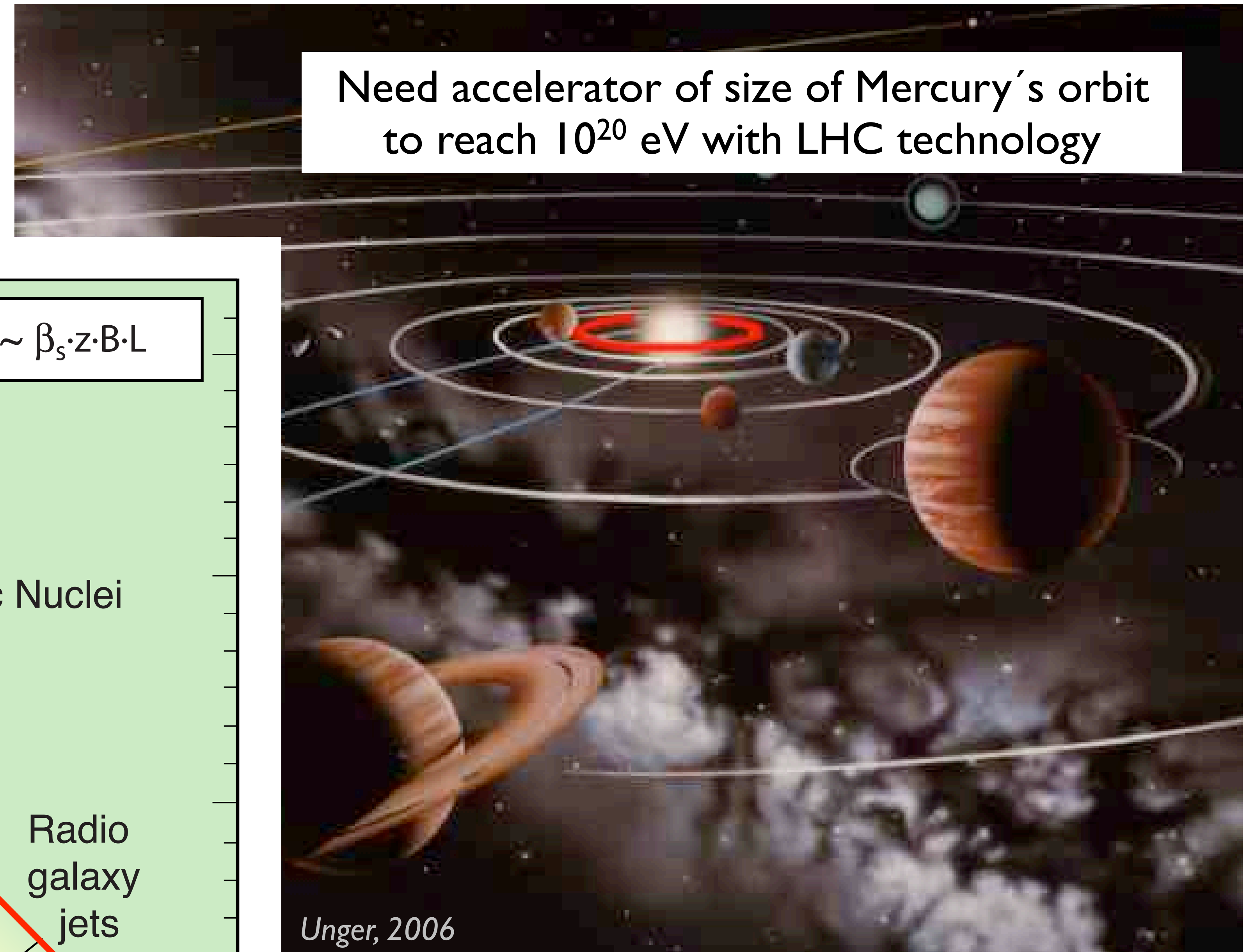
1. Ultra-high energy of 10^{20} eV

Hillas plot (1984)



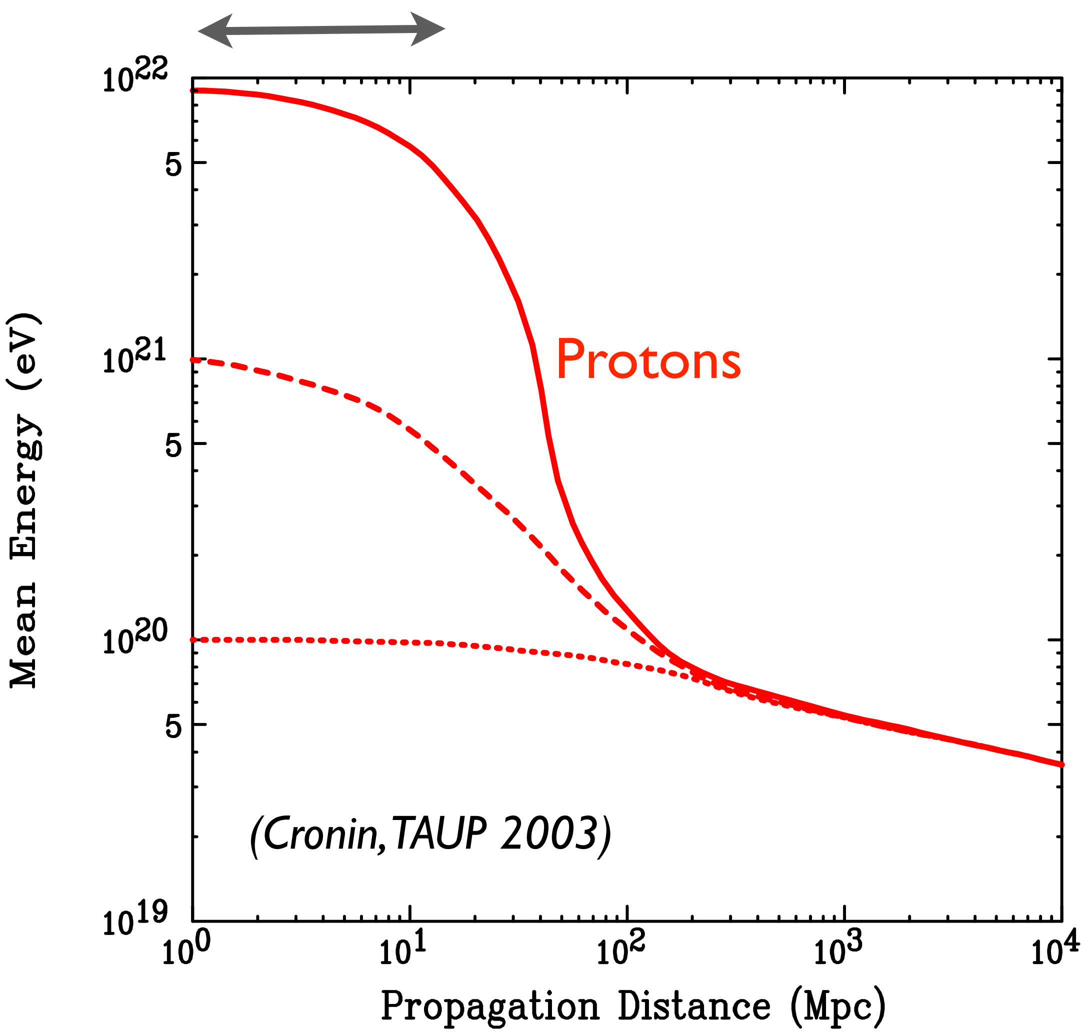


Realistic constraints more severe

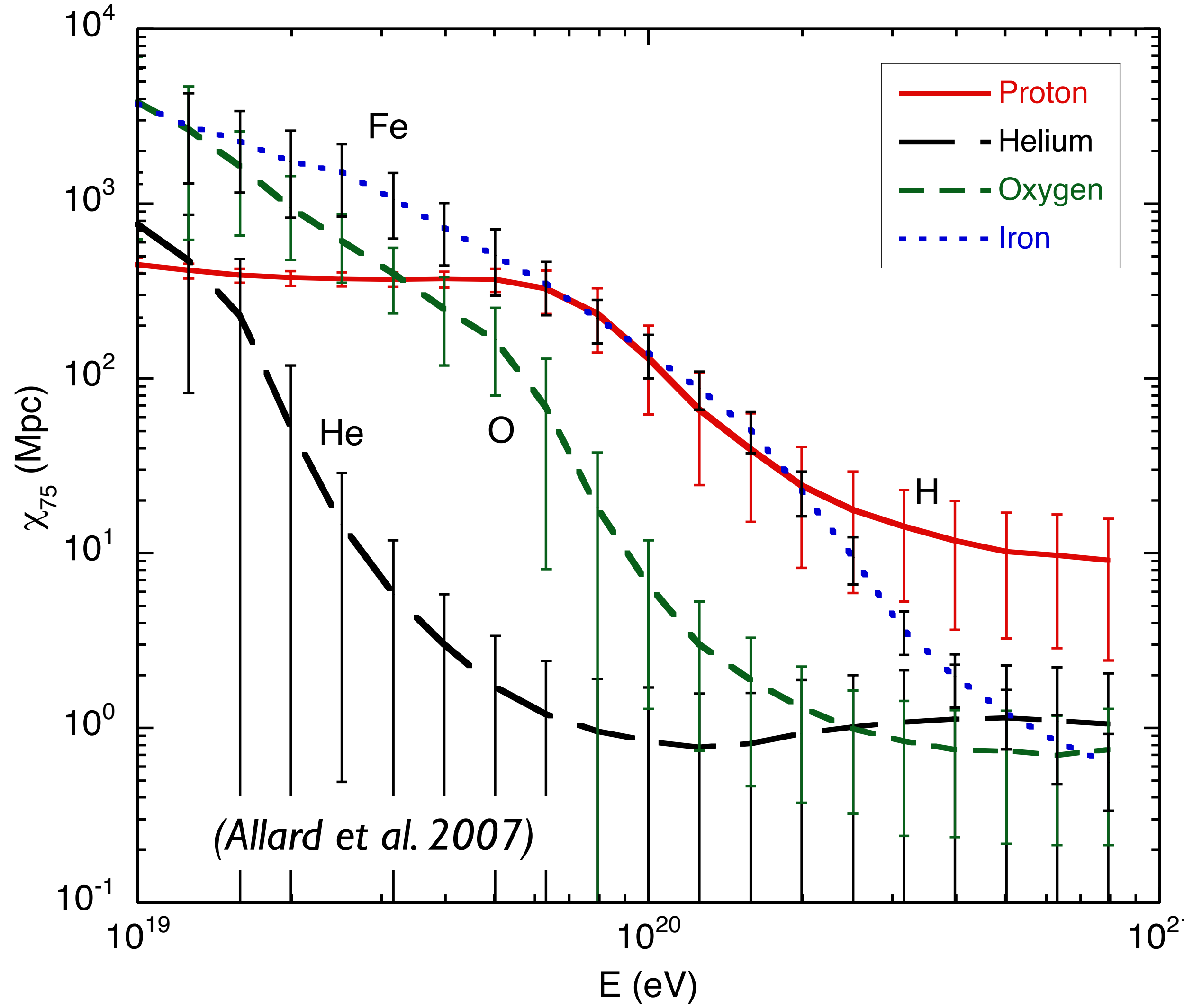
- small acceleration efficiency
- synchrotron & adiabatic losses
- interactions in source region

2. Flux suppression due to GZK effect

Energy loss length



Energy loss length



Greisen-Zatsepin-Kuzmin effect (1966)

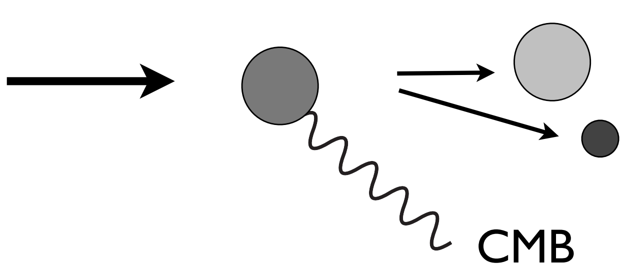
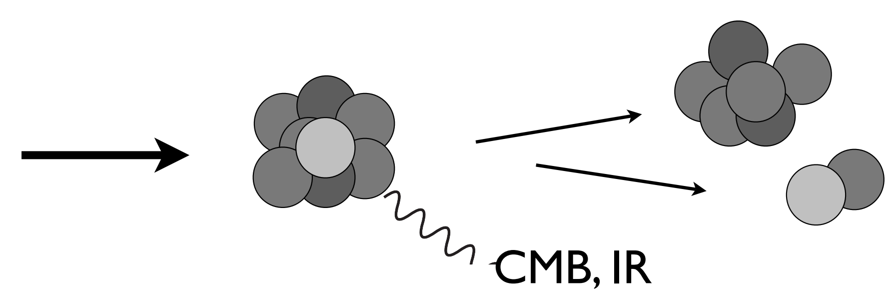
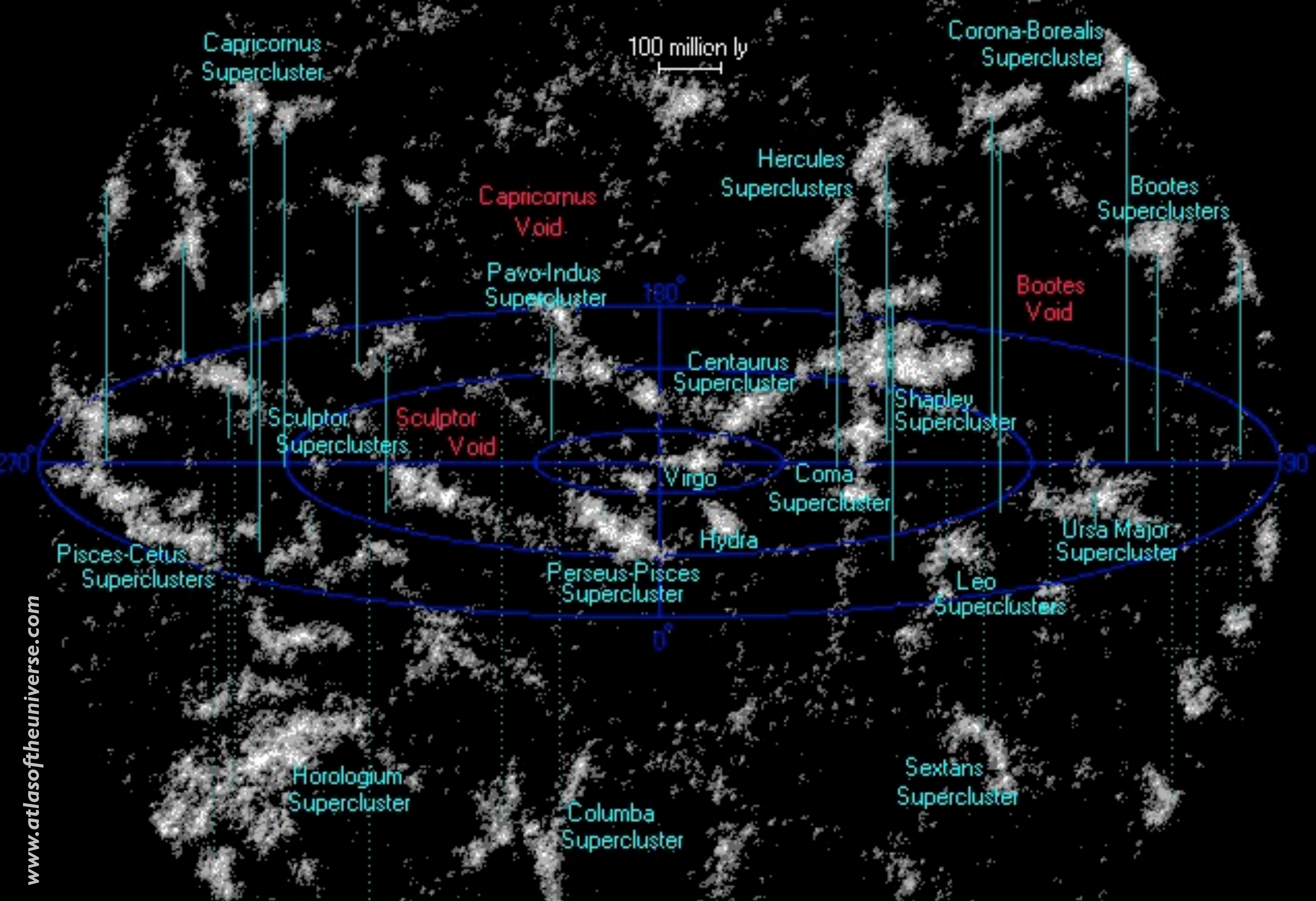


Photo-pion production

Photo-dissociation (giant dipole resonance)

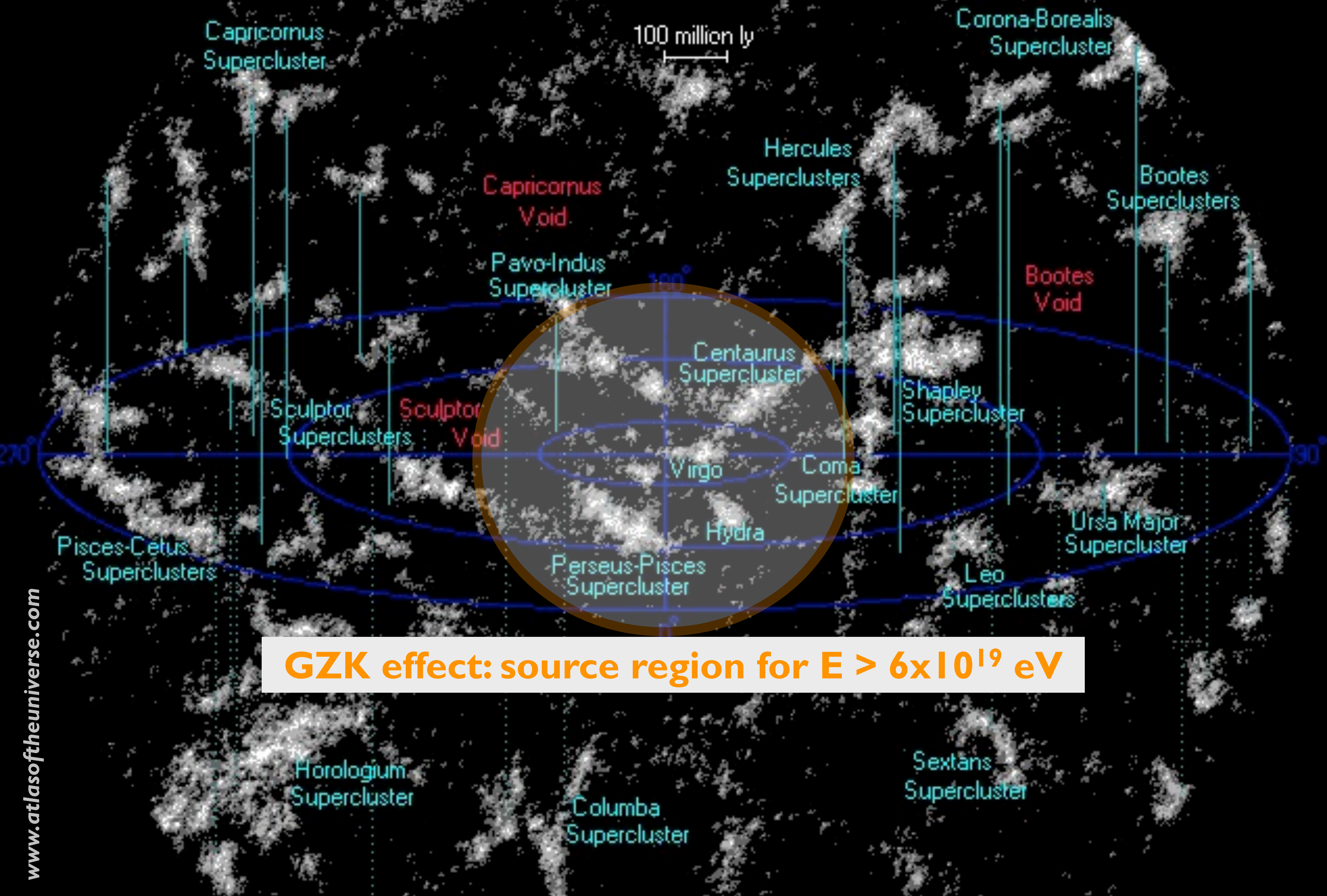


3. Arrival direction distribution

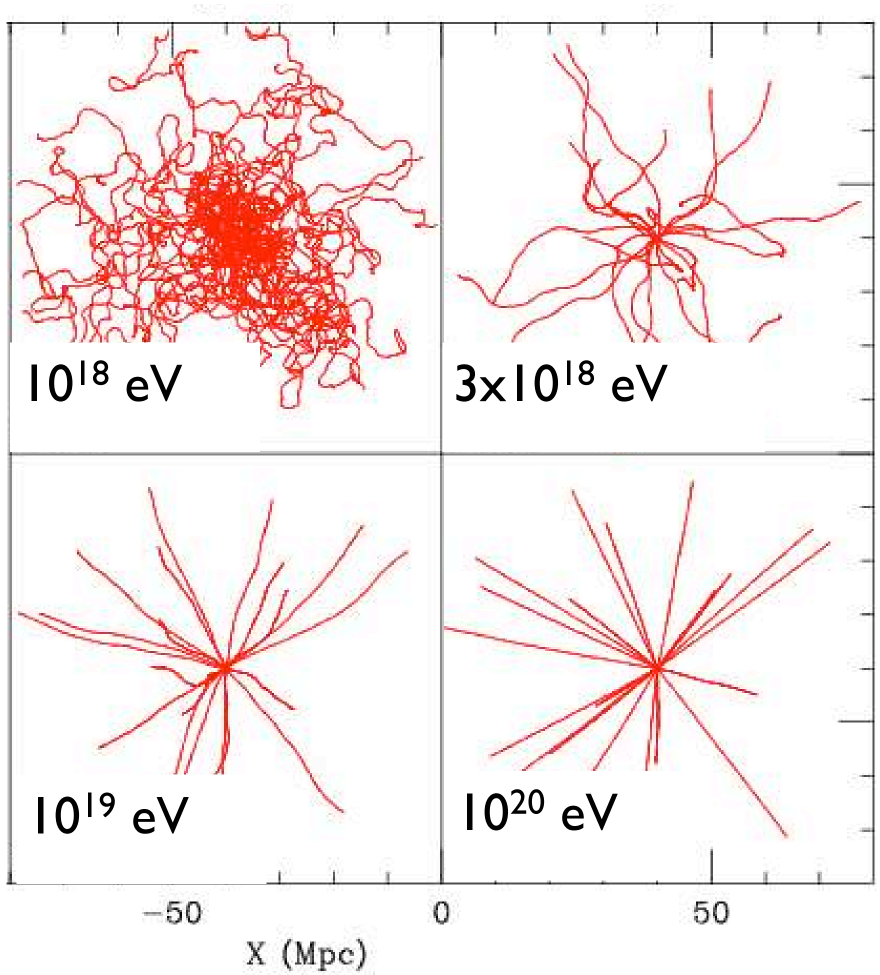


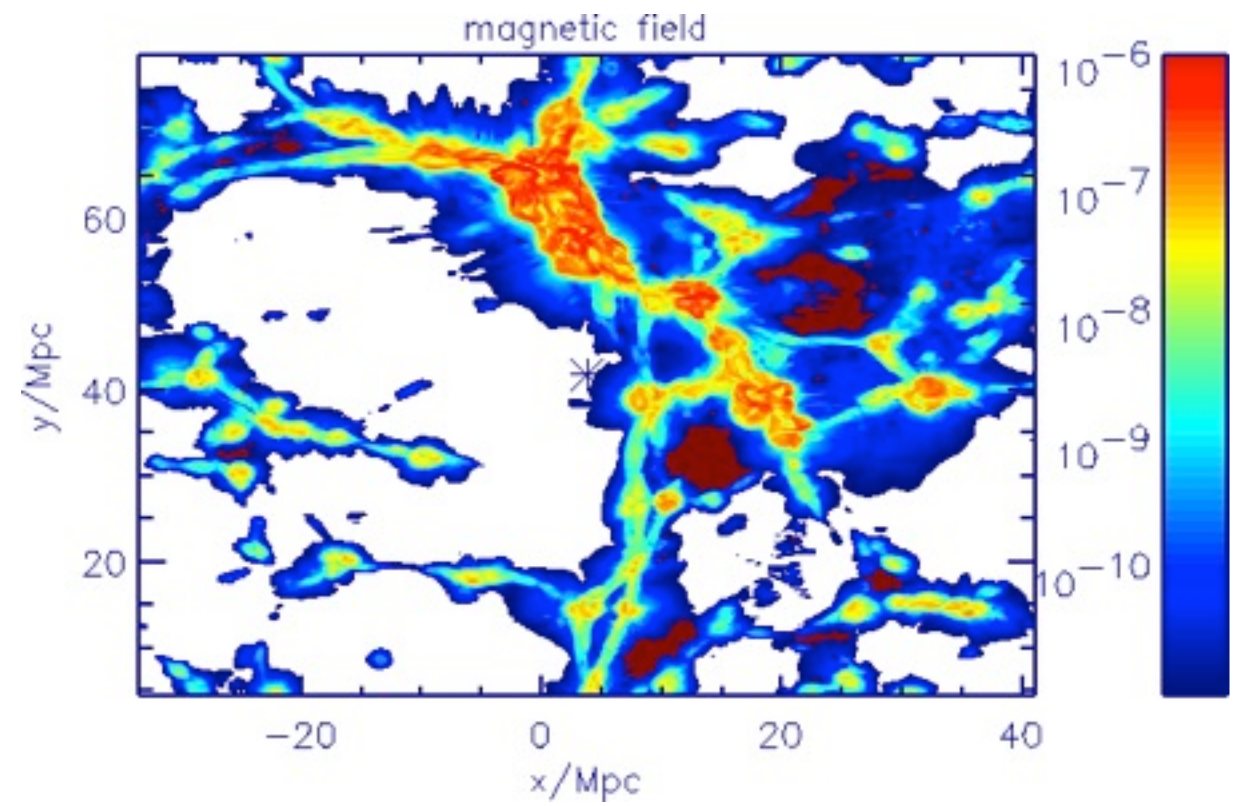
www.atlasoftheuniverse.com

GZK effect: anisotropy expected for light elements

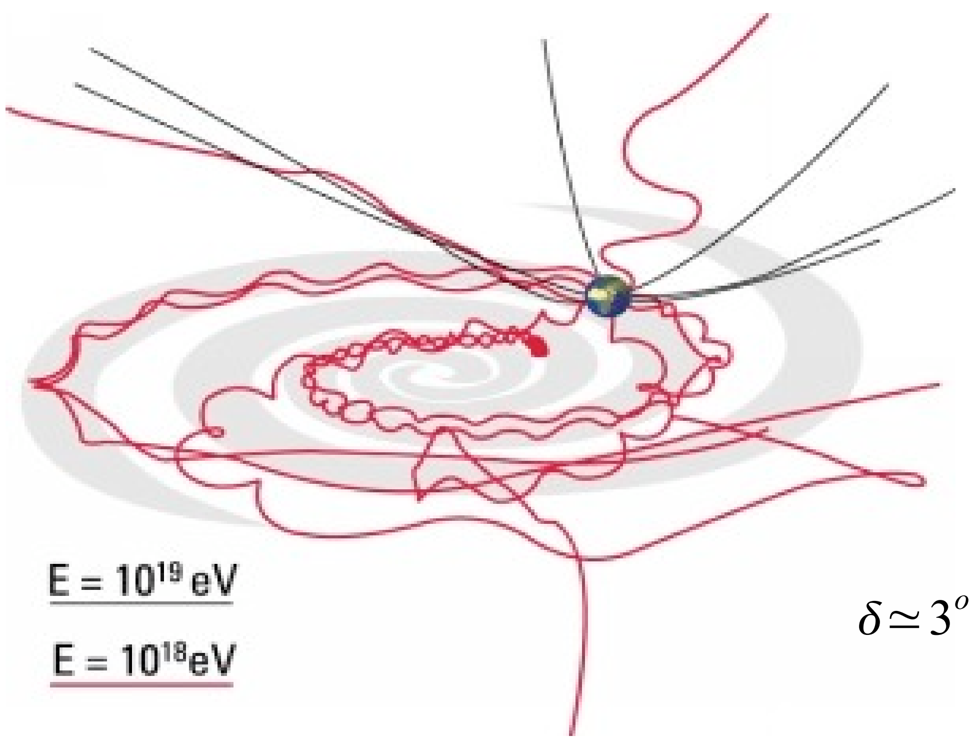


4. GZK horizon and magnetic field deflection





(Sigl, Miniati, Ensslin, PRD 68 (2003) 043002;PRD 70 (2004) 043007)



- Simple estimates: deflections ~ 3° - 10°
- Structures: dependence on source location, could be much larger

$$\delta \simeq 3^o \frac{B}{3\,\mu G}\,\frac{L}{kpc}\,\frac{6\times 10^{19} eV}{E/Z}$$

Current UHECR observatories

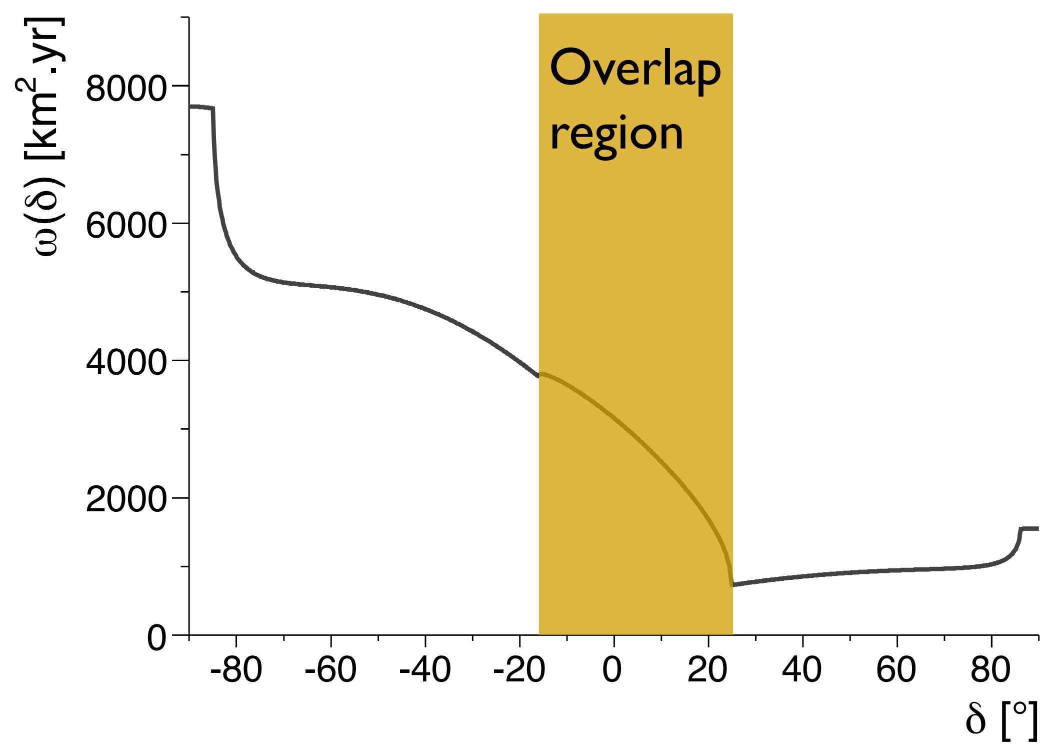
Telescope Array (TA)
Delta, UT, USA
507 detector stations, 680 km^2
36 fluorescence telescopes

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

E > 10^{19} eV

`[0-55°] for TA`

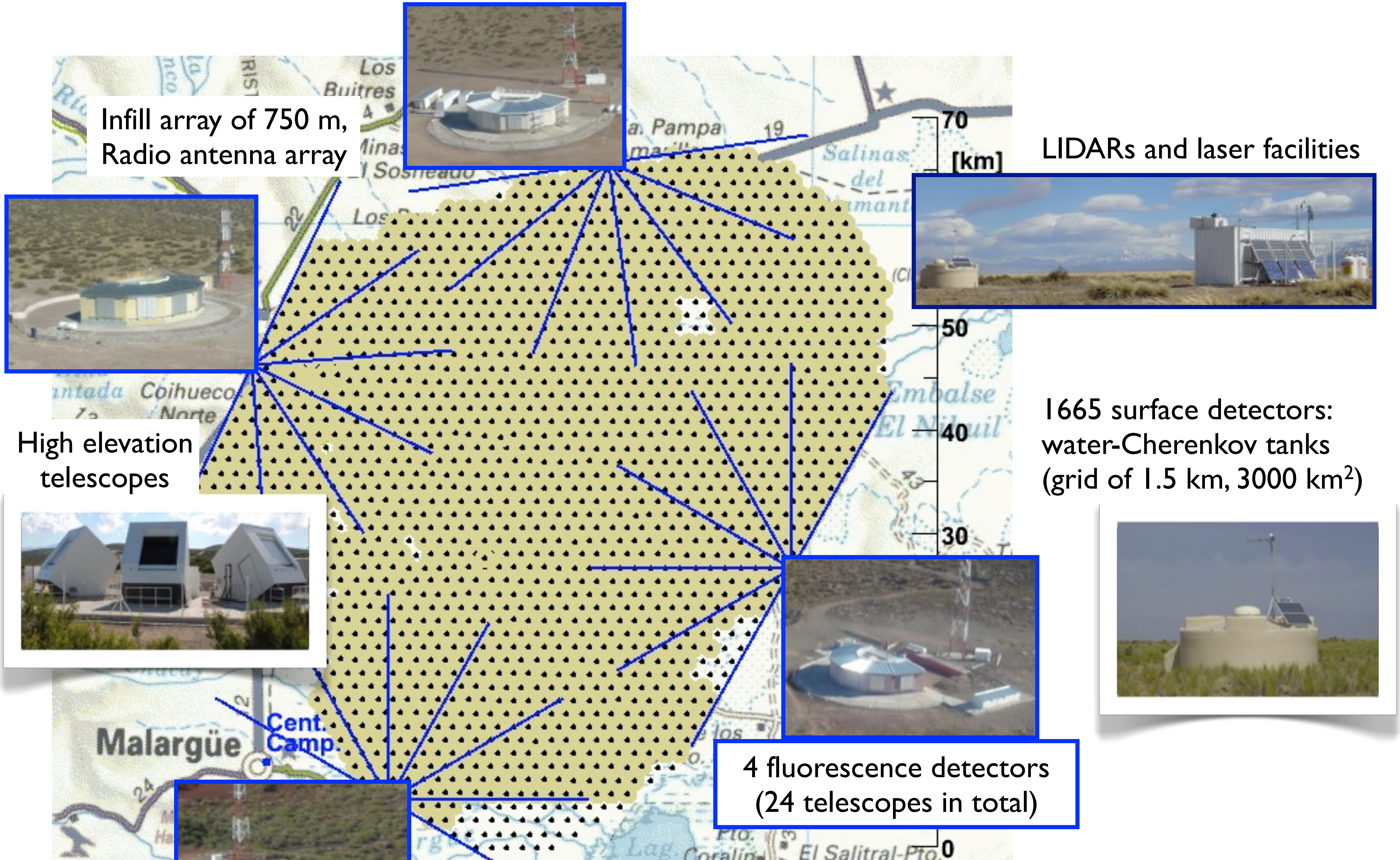
1,800 events
650 in overlap region



`[0-60°] for Auger`

10,900 events
3,400 in overlap region

The Pierre Auger Observatory



Southern hemisphere: Province Mendoza, Argentina

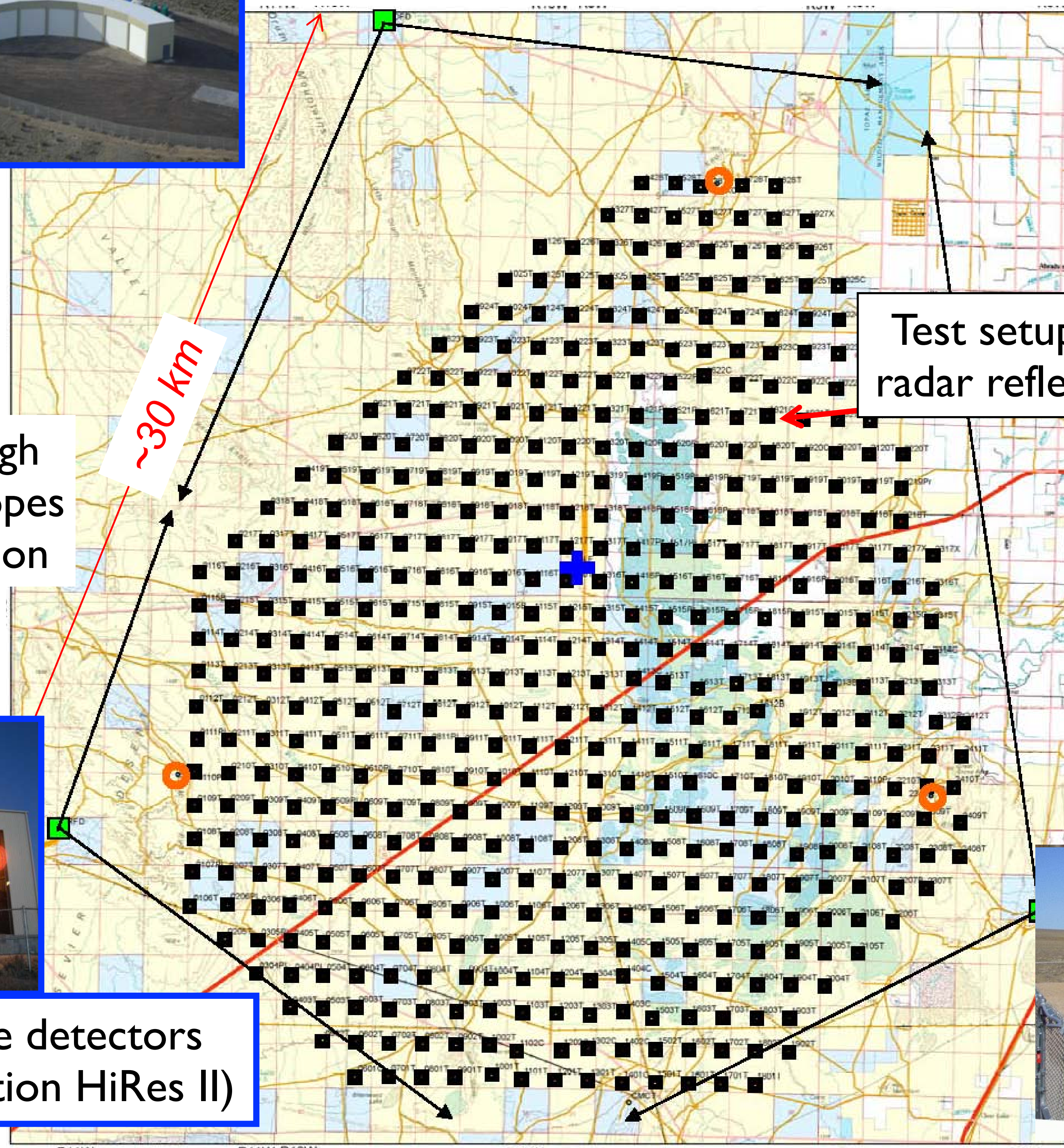
Telescope Array (TA)

Middle Drum: based on HiRes II

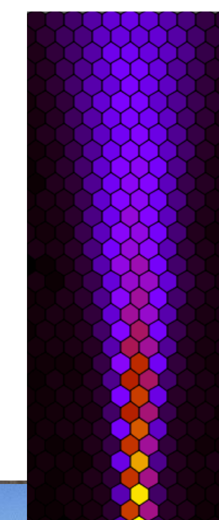
507 surface detectors:
double-layer scintillators
(grid of 1.2 km, 700 km^2)

LIDAR
Laser facility

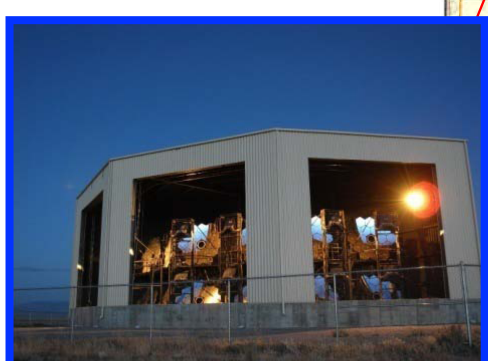
Infill array and high elevation telescopes under construction



Test setup for radar reflection



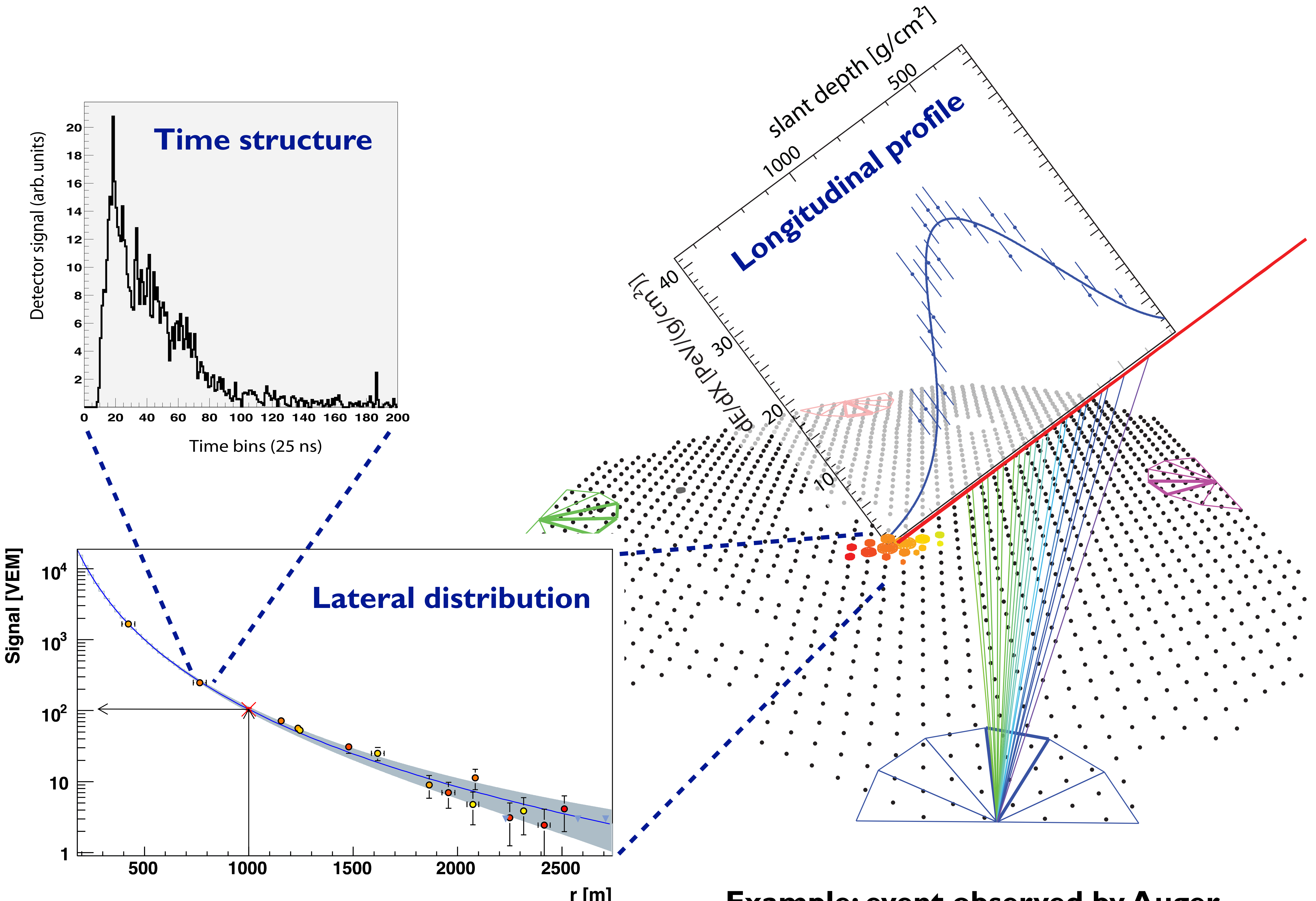
Electron light source (ELS): ~40 MeV



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

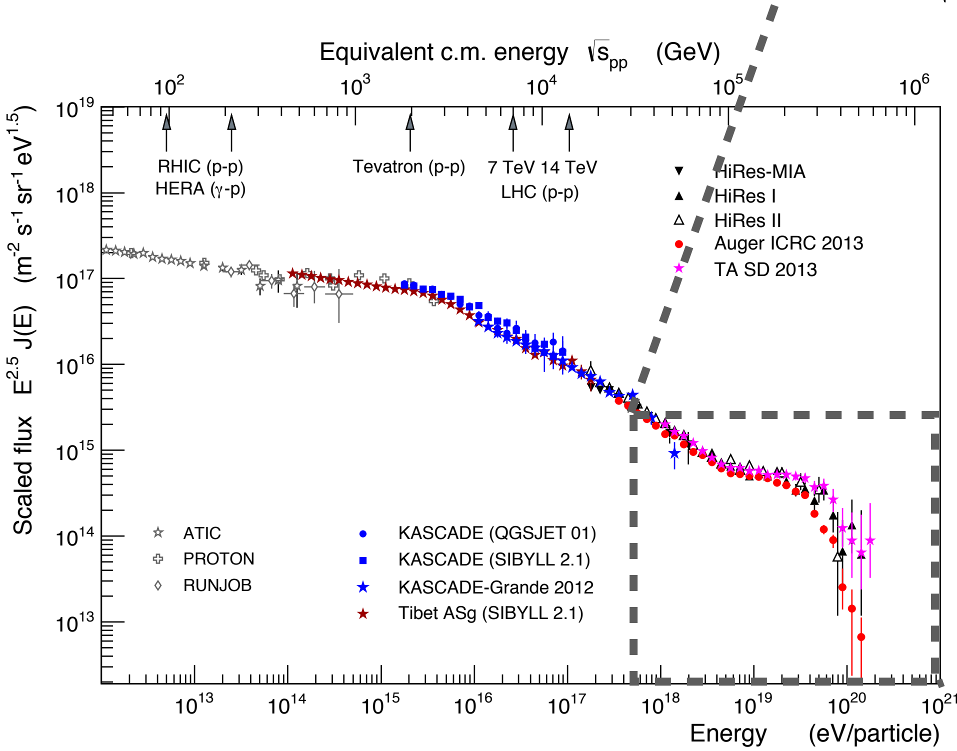
Northern hemisphere: Utah, USA

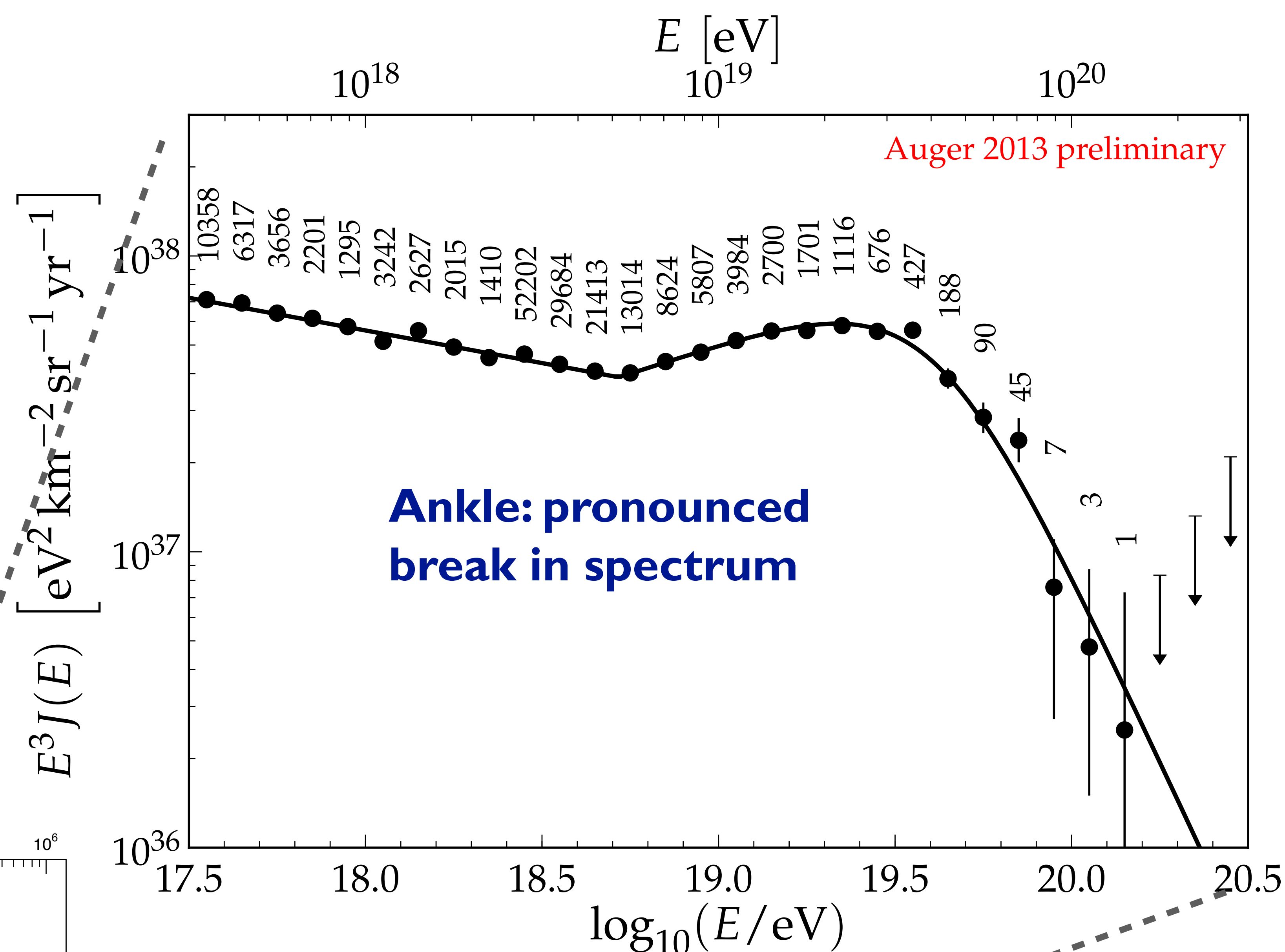
Measurement principle



Example: event observed by Auger

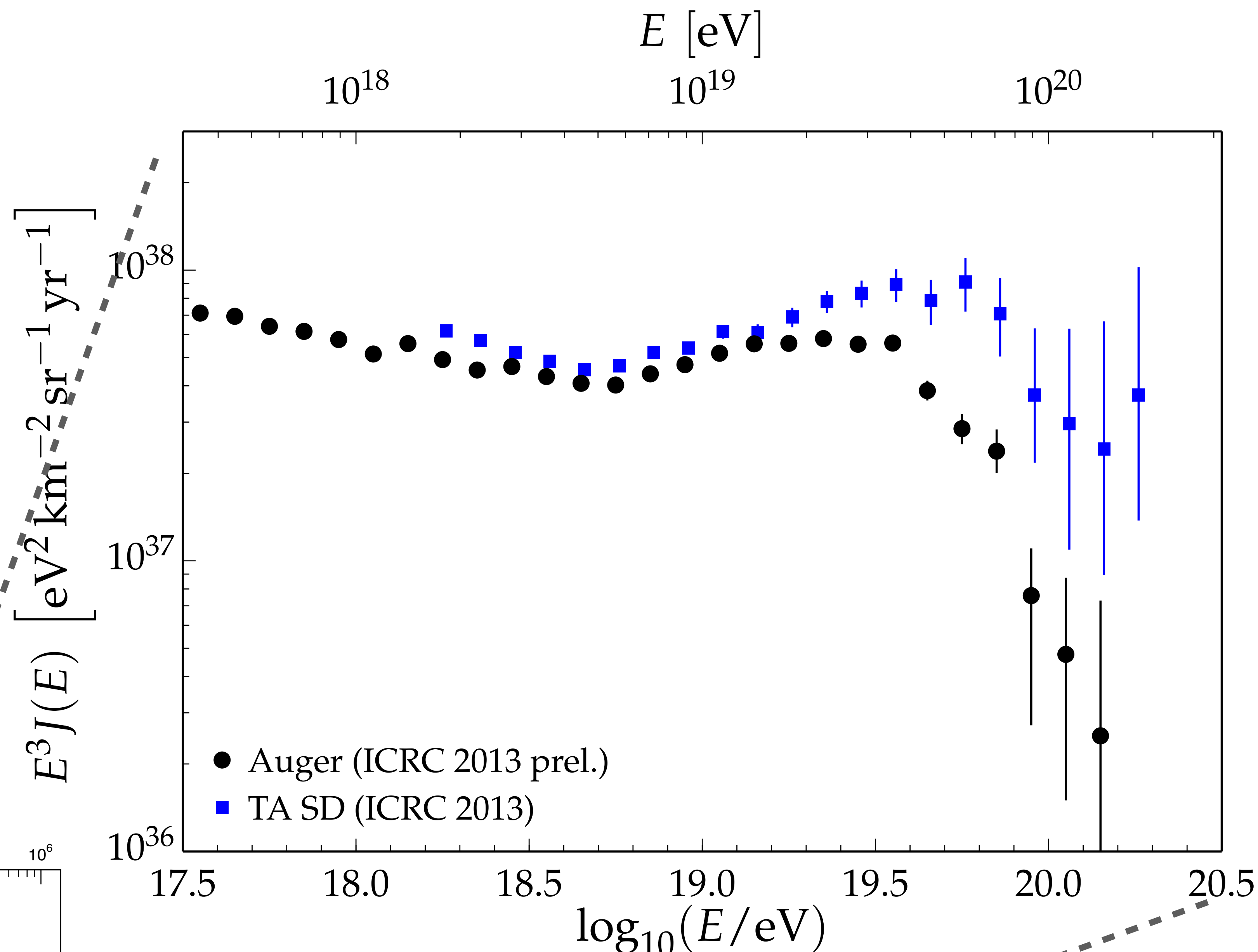
Energy spectrum: flux suppression



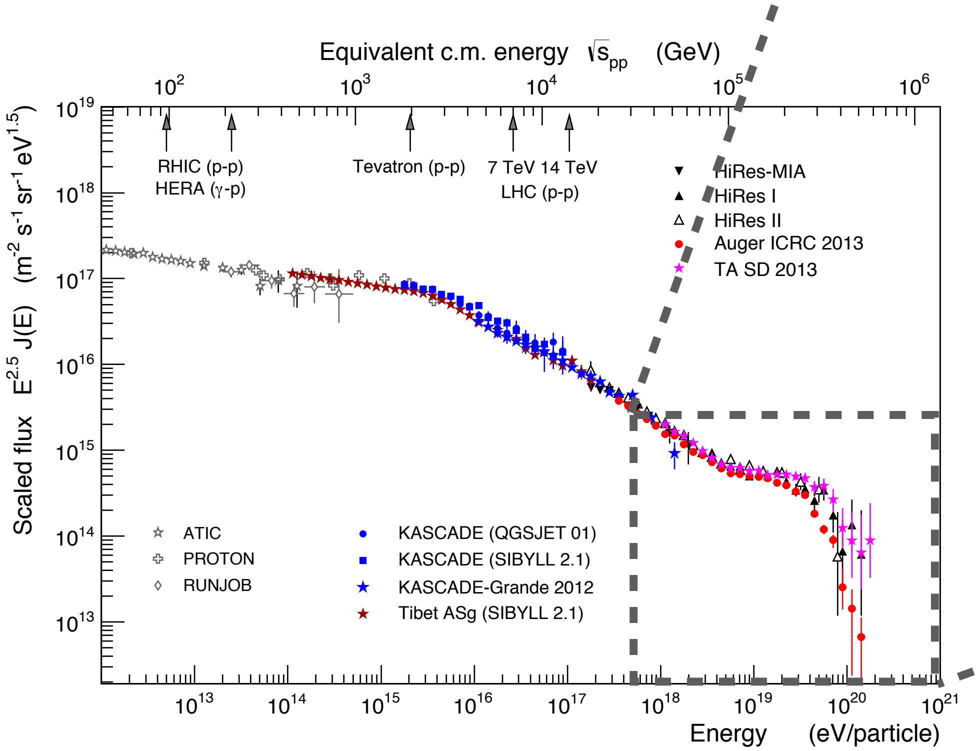


Suppression unambiguously established

Energy spectrum: flux suppression



Fluxes really different in suppression region ?



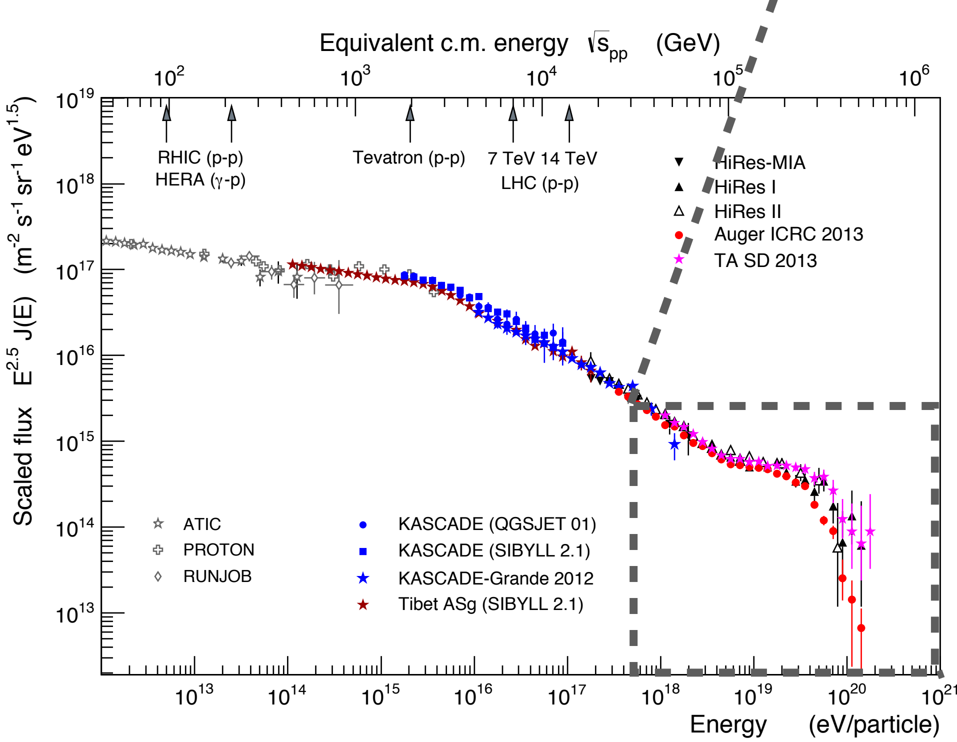
Energy spectrum: flux suppression

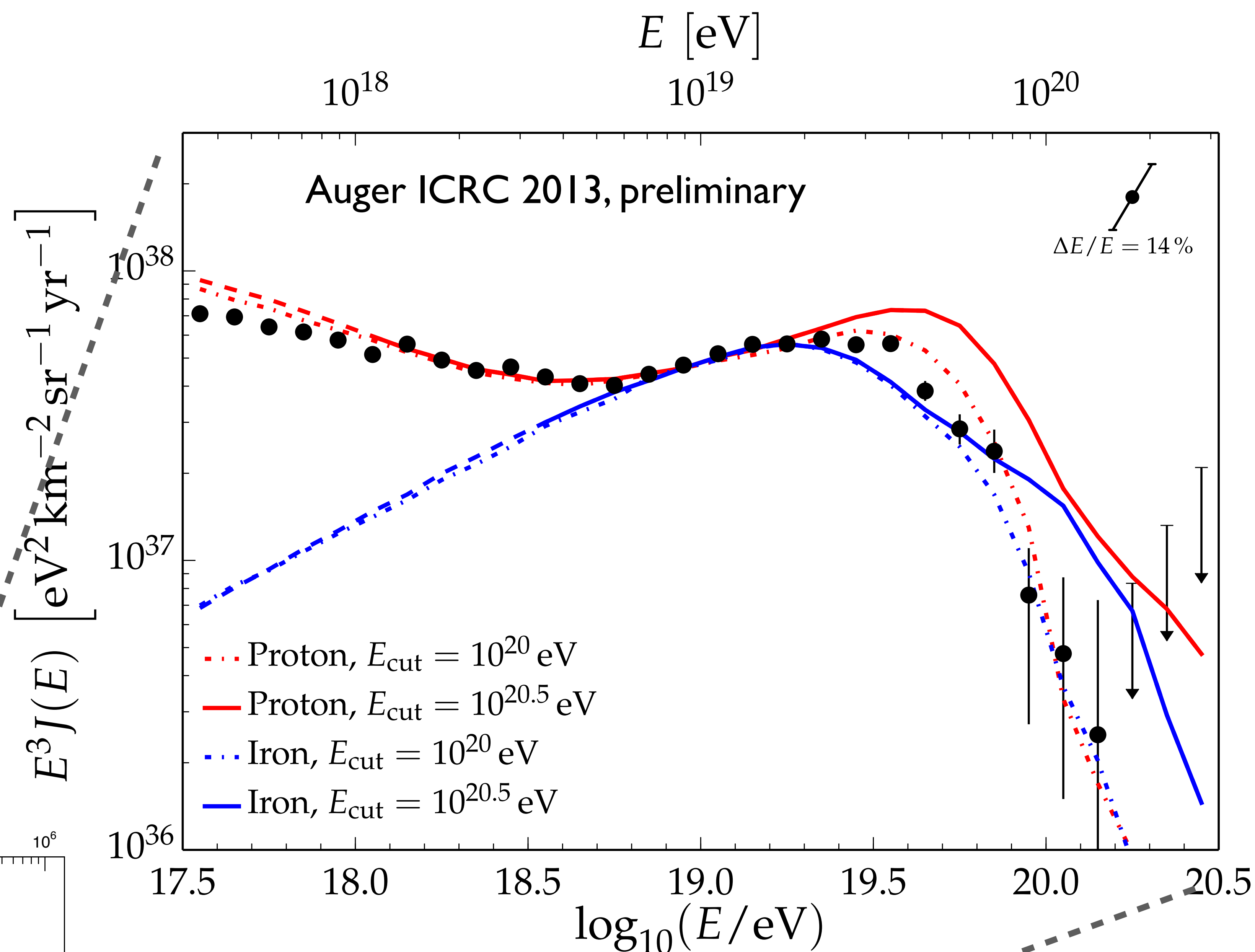
Proton dominated flux

Suppression: delta resonance

Ankle: e^+e^- pair production

(Dip model of Berezinsky et al.)





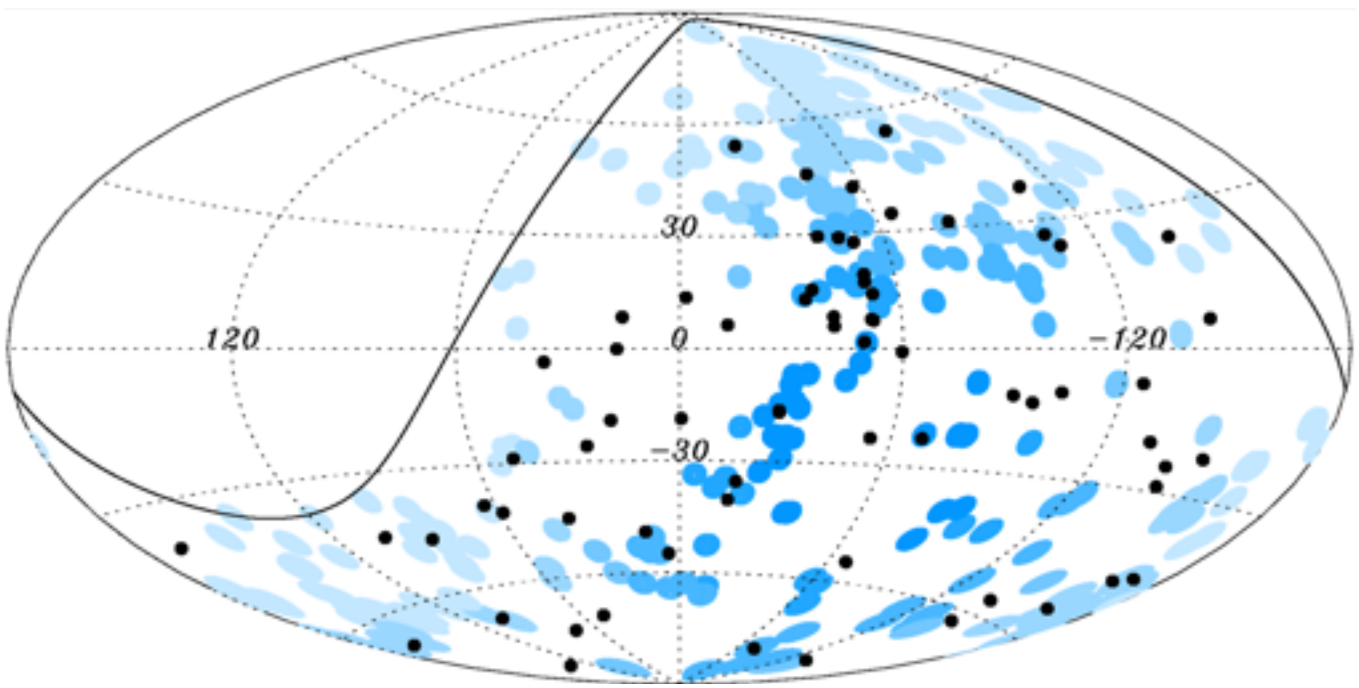
Iron dominated flux

Suppression: giant dipole resonance

Ankle: transition to galactic sources

Anisotropy at highest energies: source regions?

Auger Observatory (2011)

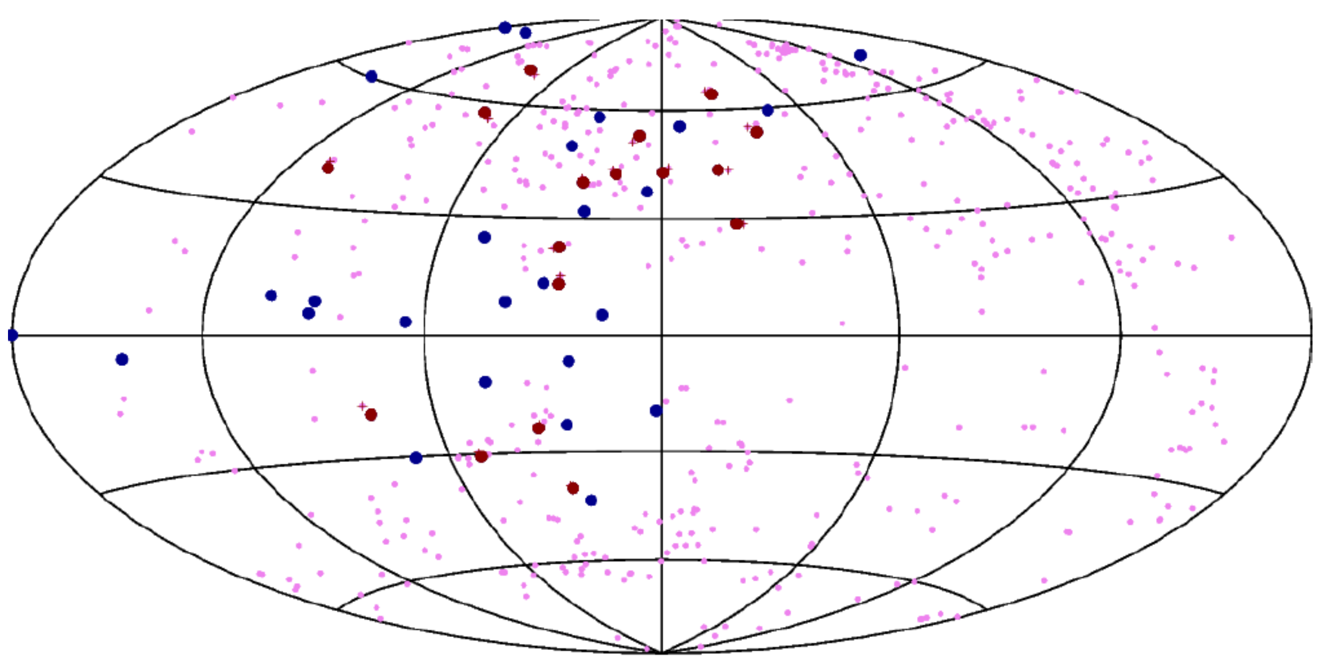


Correlation with AGNs *(Science 2007)*

z < 0.018 (75Mpc),
E > 5.5 10^{19} eV, $\Delta\theta \leq 3.1°$

Isotropy: 21% correlation expected
June 2011: 28 out of 84 correlated
estimate now 33 ± 5% (P = 0.006)

Telescope Array (2013)



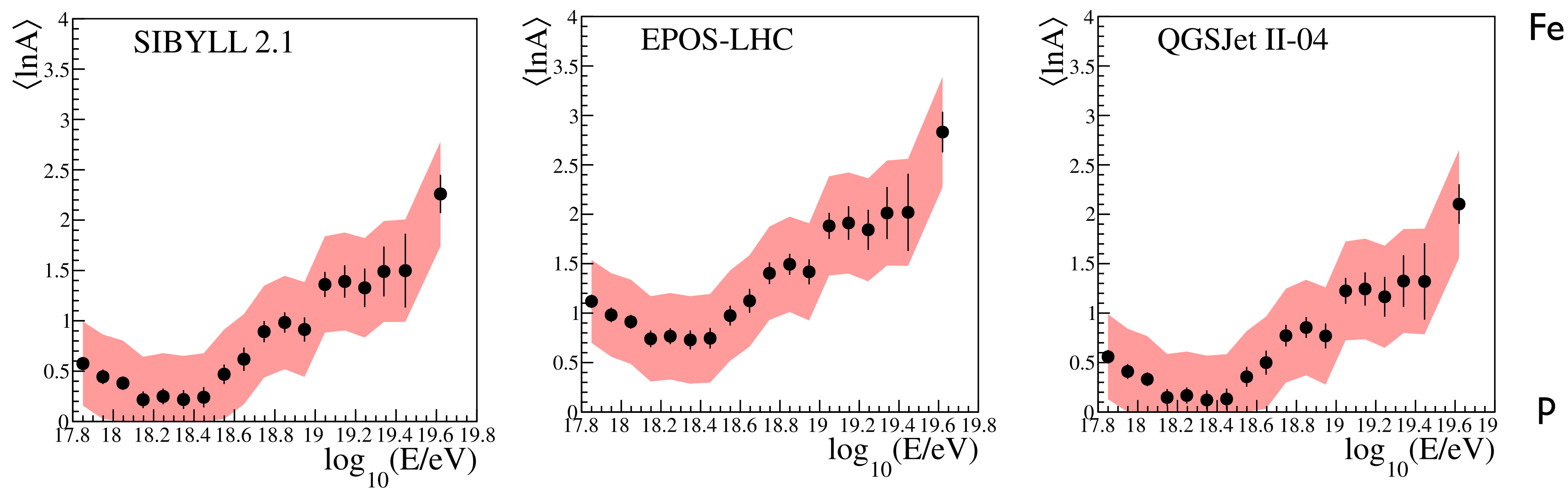
Isotropy: 24% correlation expected
June 2013: 17 out of 42 correlated
estimate now 40 ± 8% (P = 0.014)

In addition indications for correlation with large scale structure 2MASS Galaxies (3σ pre-trial)

Composition data: transition to heavier primaries

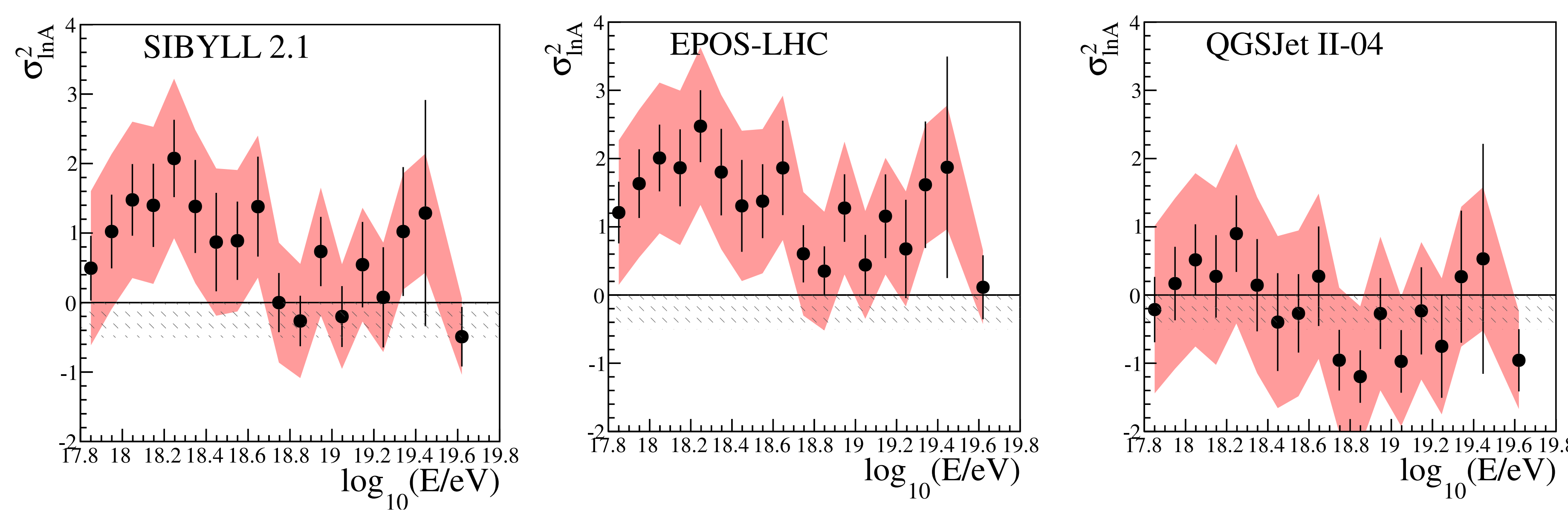
⟨ln A⟩: Transition from medium → light → heavy ?

$$\langle X_{\max} \rangle \approx \langle X^{p}_{\max} \rangle - D_p \langle \ln A \rangle$$



σ(ln A): Transition from proton dominated or mixed → approx. pure ?

$$\sigma(X_{\max})^2 \approx \langle \sigma_i^2 \rangle + D_p^2\, \sigma(\ln A)^2$$

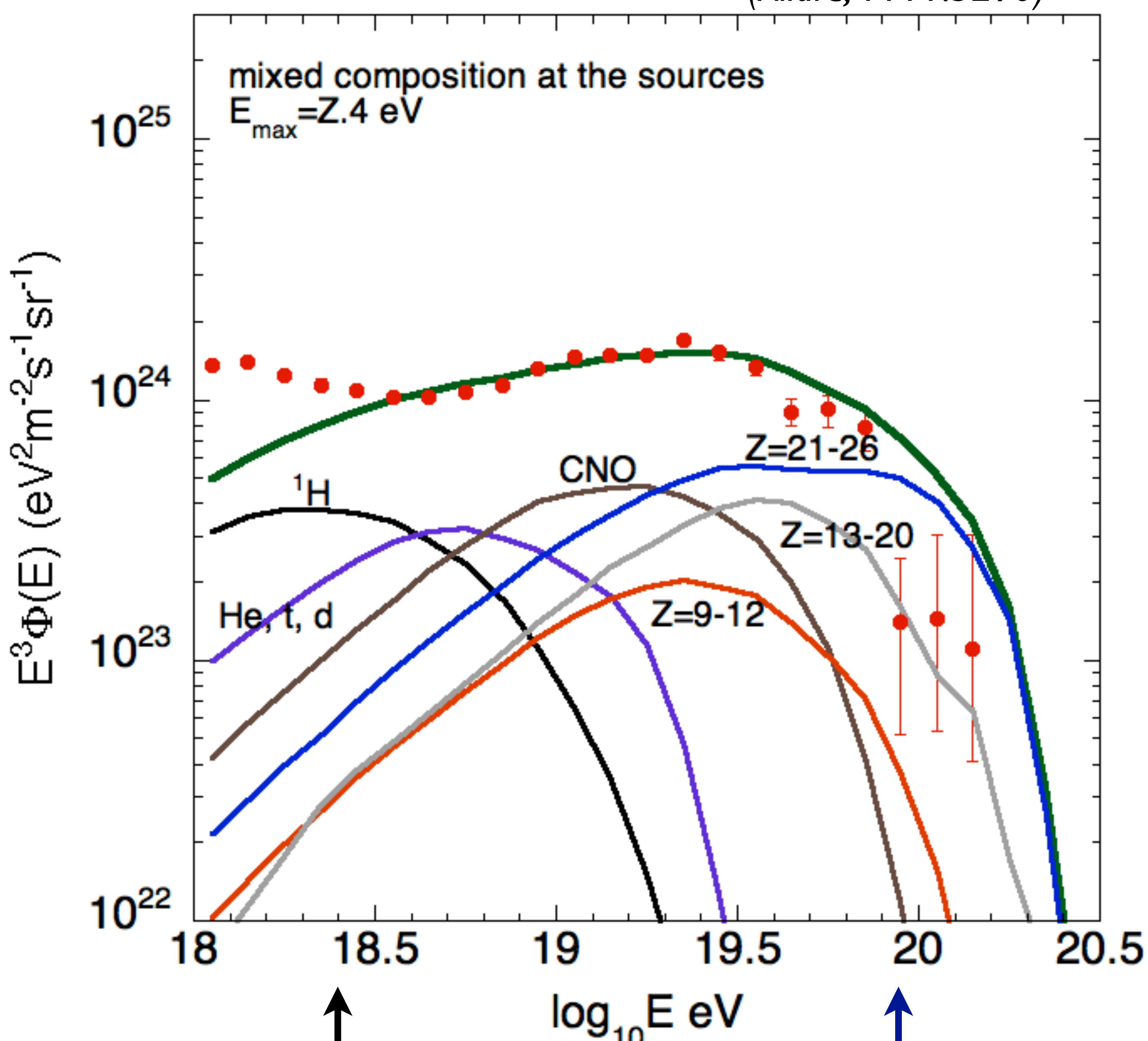


(Auger, JCAP 02 (2013) 026)

Upper end of source energy spectrum seen ?

Particle flux

(Allard, 1111.3290)

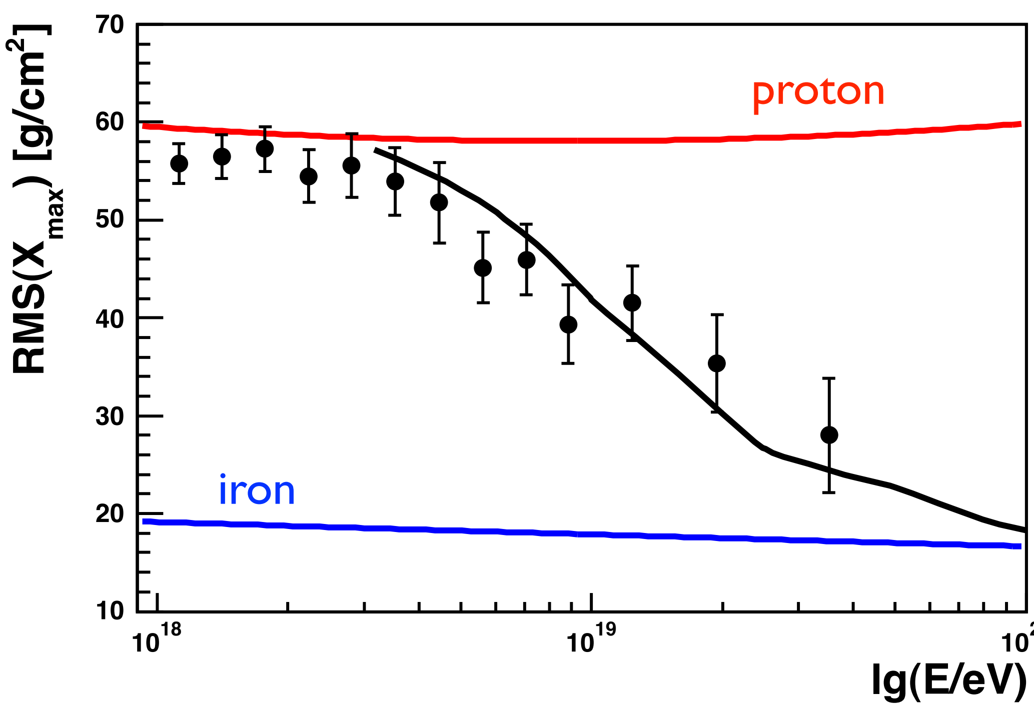


Protons $E_{max,p} = 10^{18.4}$ eV

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

Natural transition to heavier composition at high energy !

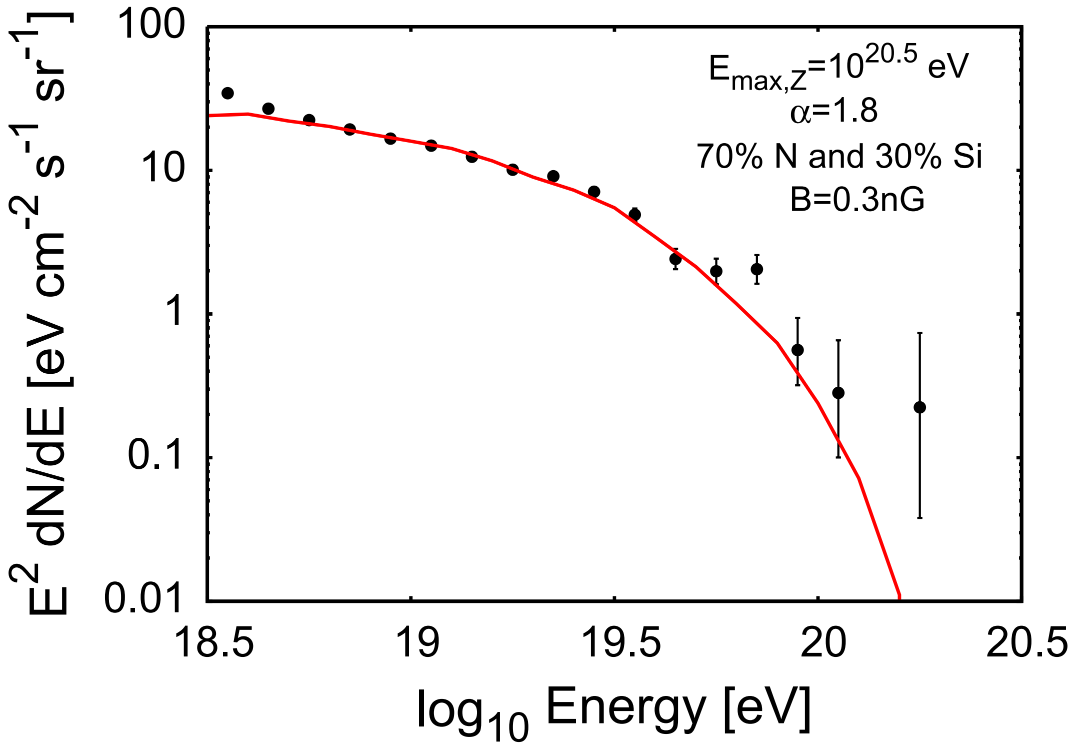
Fluctuations of X_{max} *(Unger 2012)*



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

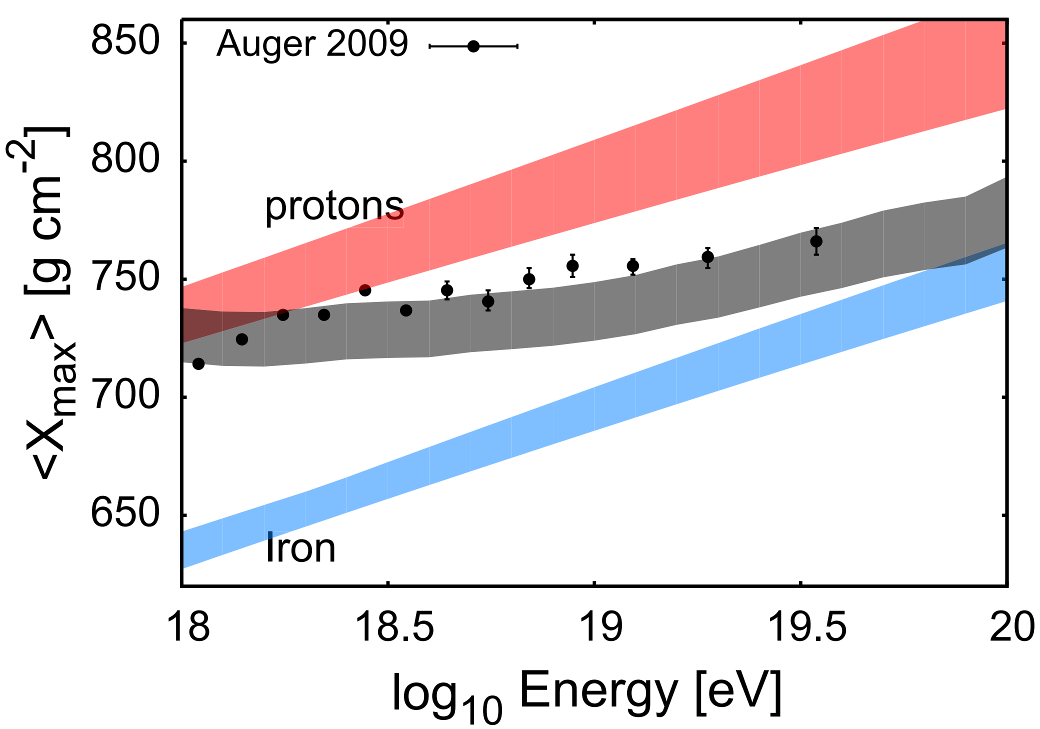
(see also Calvez et al. 2010, Aloisio et al. 2011)

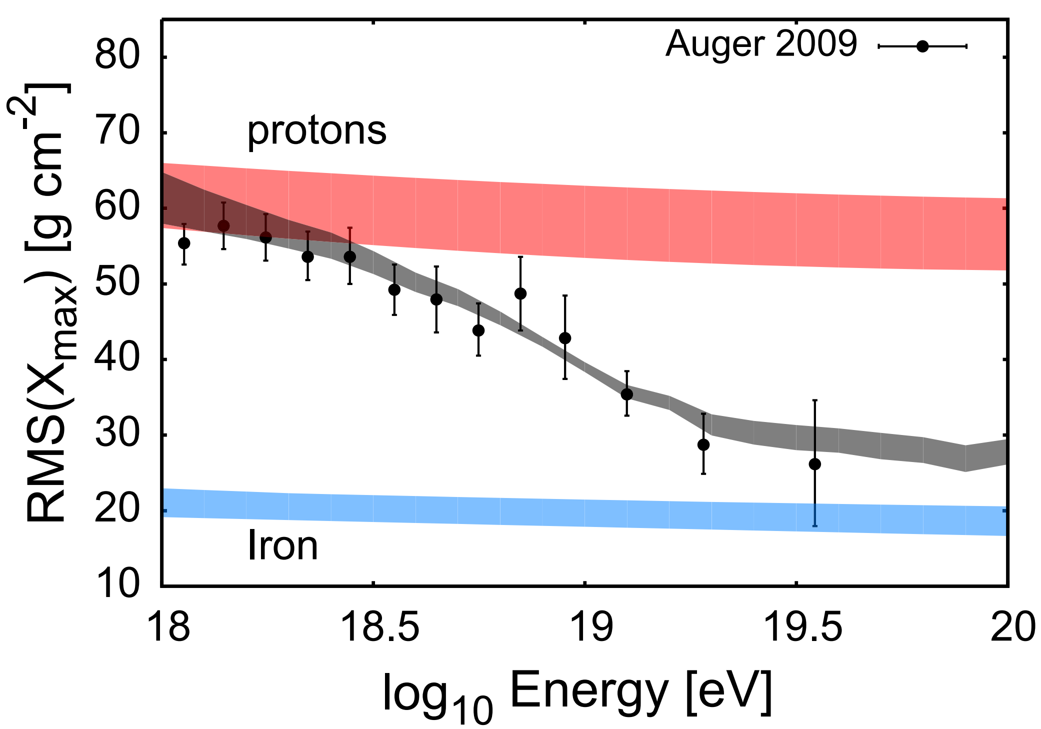
Photo-disintegration model



Main features

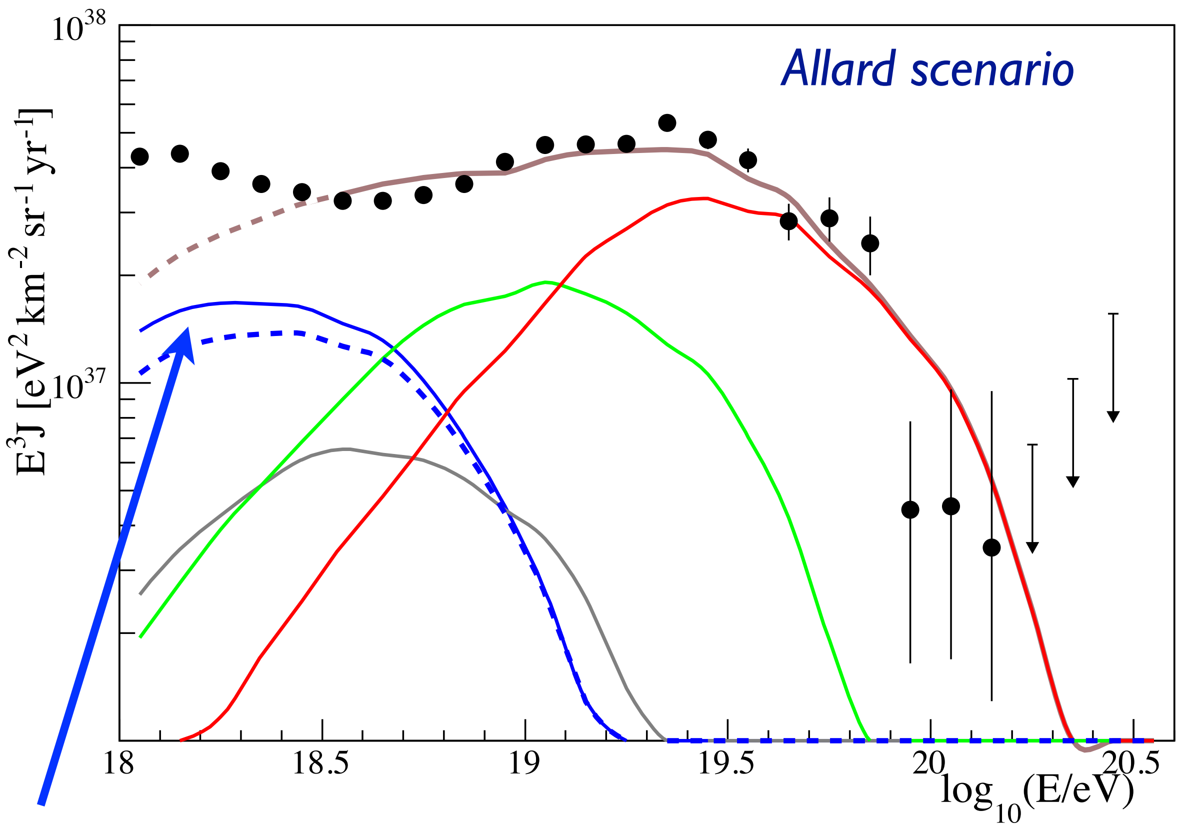
- Sources inject almost exclusively heavy elements (N, Si, Fe)
- Protons are produced by photodissociation (appear factor ~A lower in energy)
- Source max. energy cutoff for E_{Si} ~ 3×10^{20} eV, E_N ~ 1.5×10^{20} eV





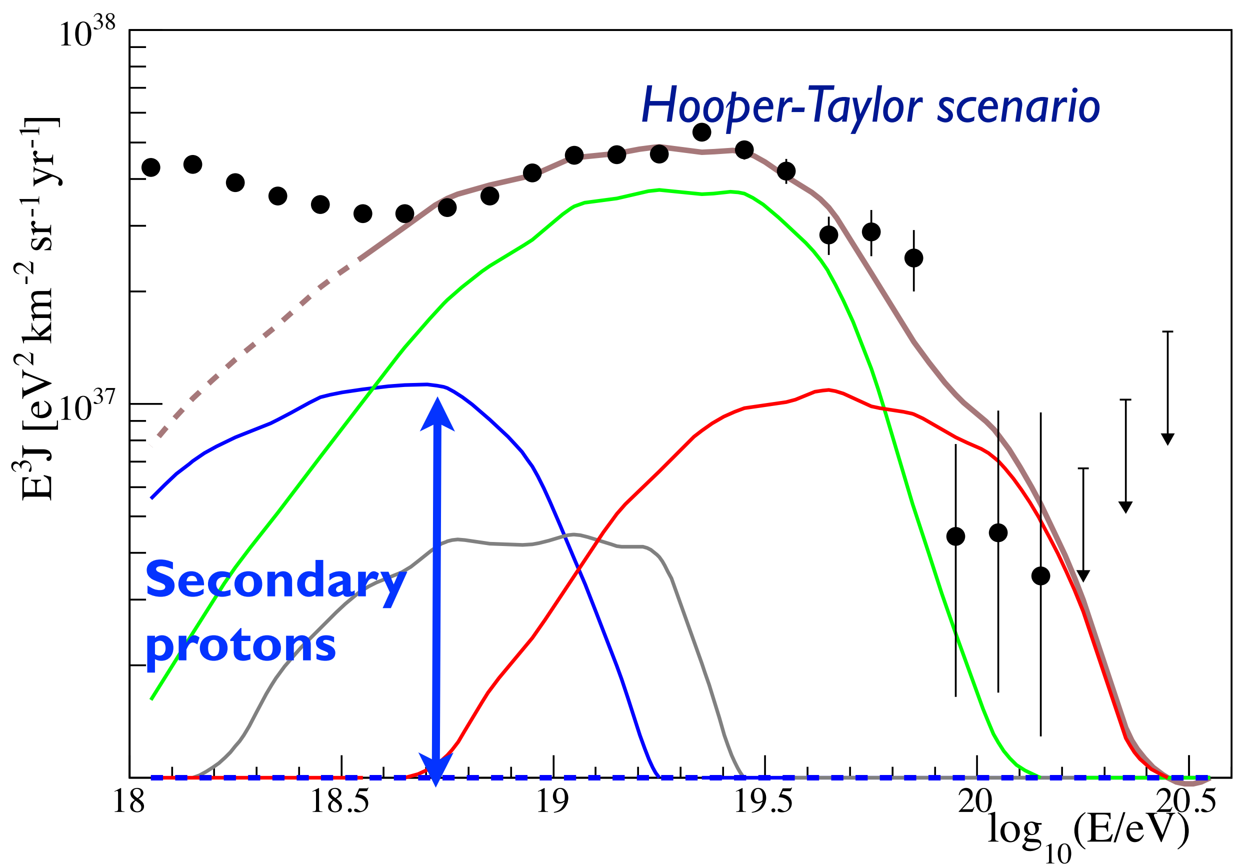
(Hopper, Taylor, Astropart. Phys. 2010)

Maximum-energy vs. energy-loss models



Difference: secondary protons

(*plots by Boncioli, Grillo, Petrera, 2012*)



Injection: Galactic composition with enhanced heavy elements

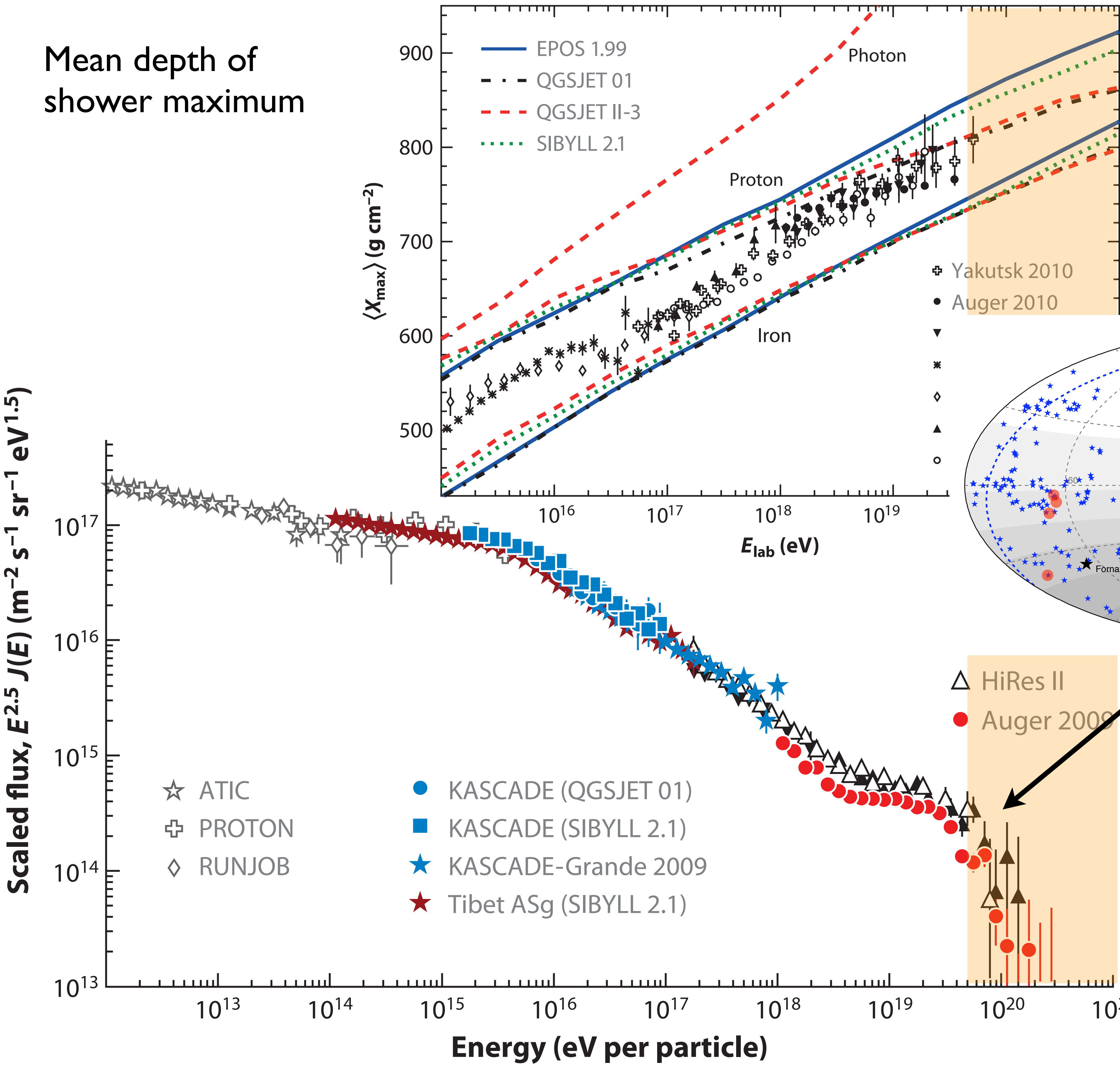
Injection: ~70% N or Si (almost no light elements)

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

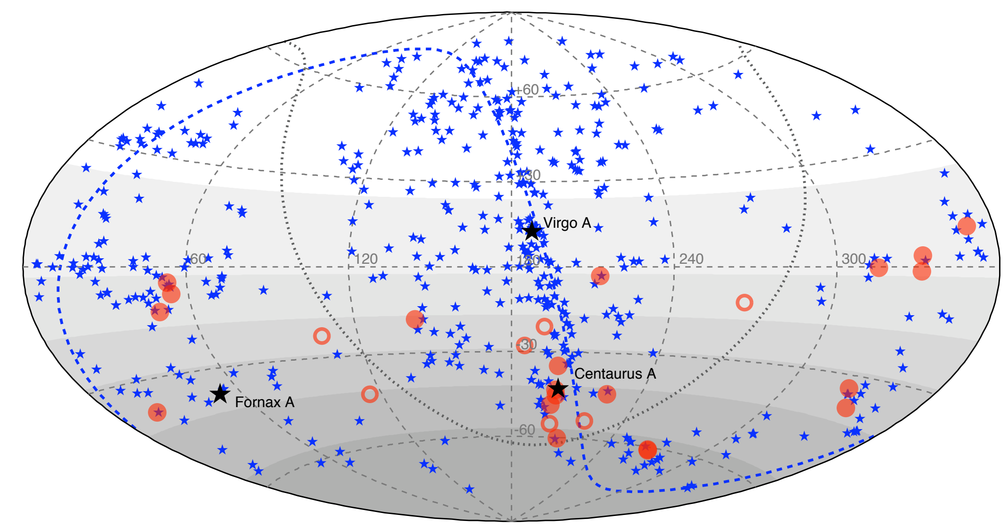
(Shaham & Prian, Phys. Rev. Lett. 110, 2013)

Sources and flux suppression by measuring composition

Mean depth of shower maximum



(Auger, Science 2007)



Auger: Correlation with sources / source regions?

(RE, Heck & Pierog, Ann. Rev. Nucl. Part. Sci. 61, 2011)

Complementary approaches

Composition measurement in flux suppression region

Pierre Auger Observatory

- Fluorescence detector: ~15%
- Surface detector ~100% (3000 km^2)
- Exposure (5400+1600) km2 sr yr per year
- Origin of flux suppression
- Composition-enhanced anisotropy (protons?)

Substantial increase of event statistics at highest energies

Telescope Array

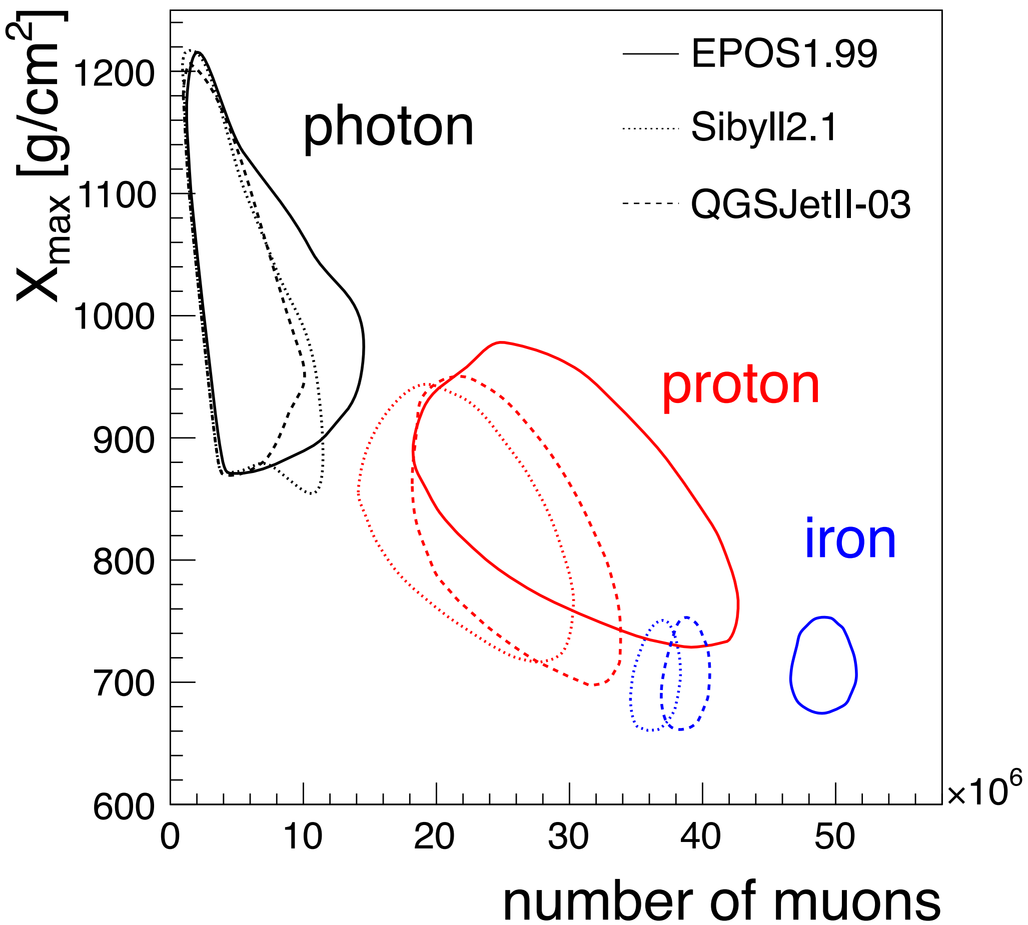
- Expansion of array by factor 5
- Larger station distance
- Increase energy threshold to ~$10^{19.5}$ eV

JEM-EUSO

- Instantaneously viewed volume 10^6 km^3
- Exposure 60,000 km^2 sr yr per year (nadir)
- Full sky coverage with same systematics

Pierre Auger Observatory: composition measurement

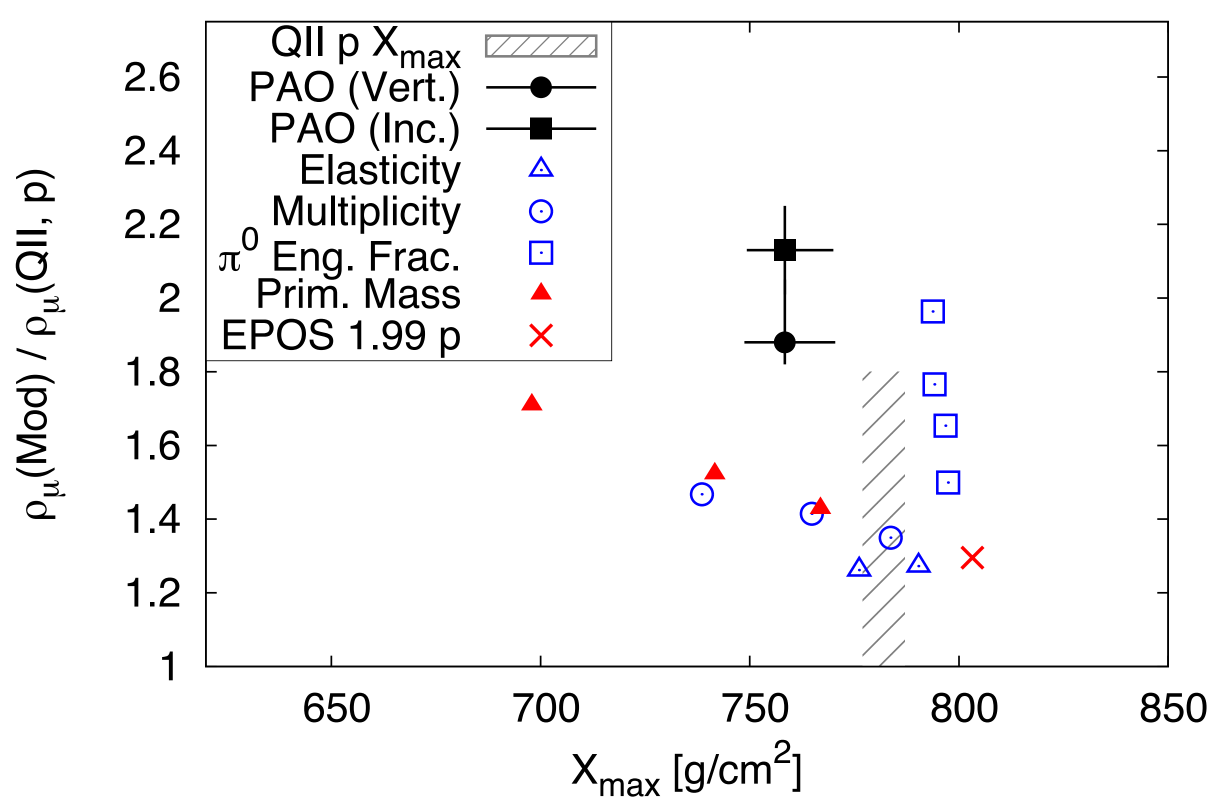
(Kampert & Unger, APP 35 (2012) 660)



Muon measurement with ground array

- good composition sensitivity
- event-by-event measurement
- overall interpretation model-dependent *(calibrate with X_{max} or understand better hadronic interactions)*

(Allen & Farrar, ICRC 2013 & 1307.7131)



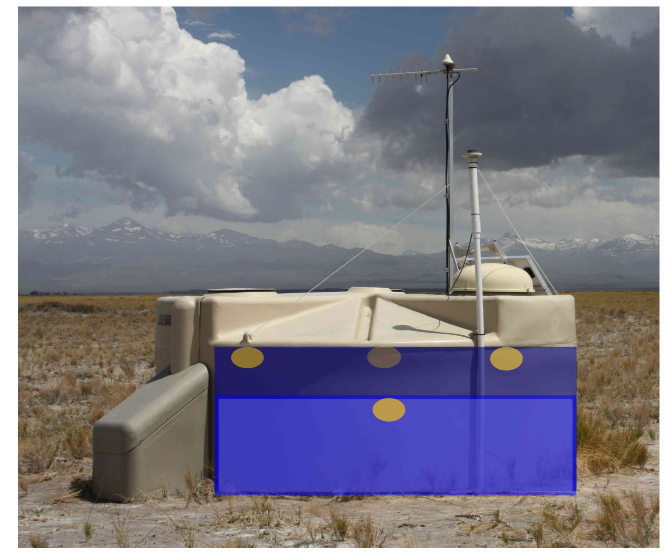
Event-by-event correlation Nμ – X_{max}

- hadronic interaction features
- new (exotic) hadronic interactions
- pure composition vs. mixture

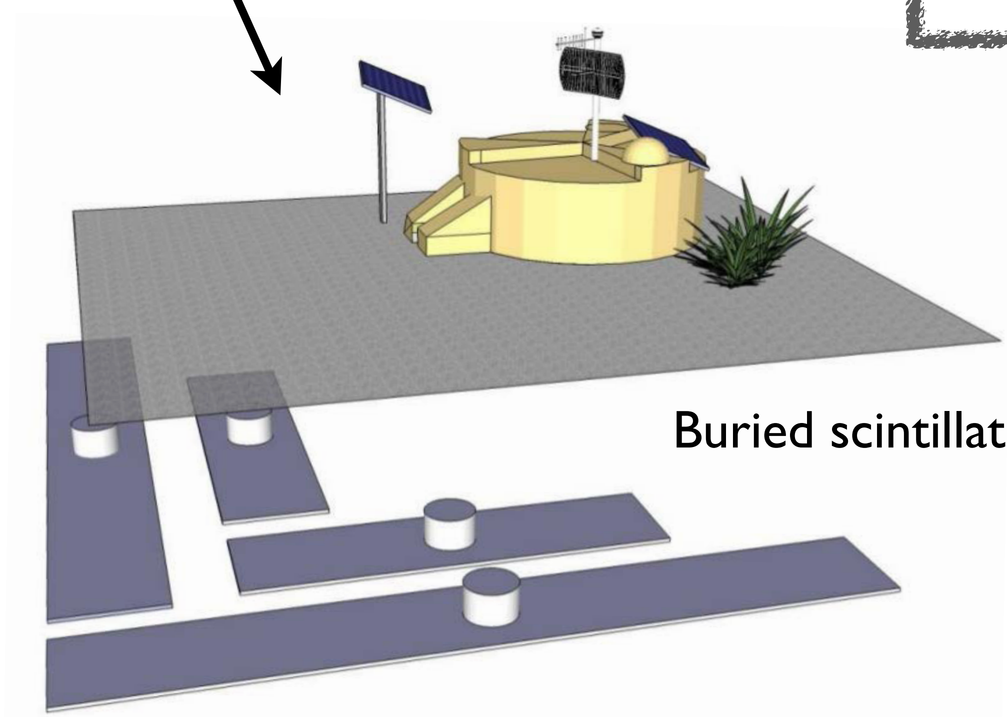
Measurement of muonic and em. shower components

Surface detector station of Auger array

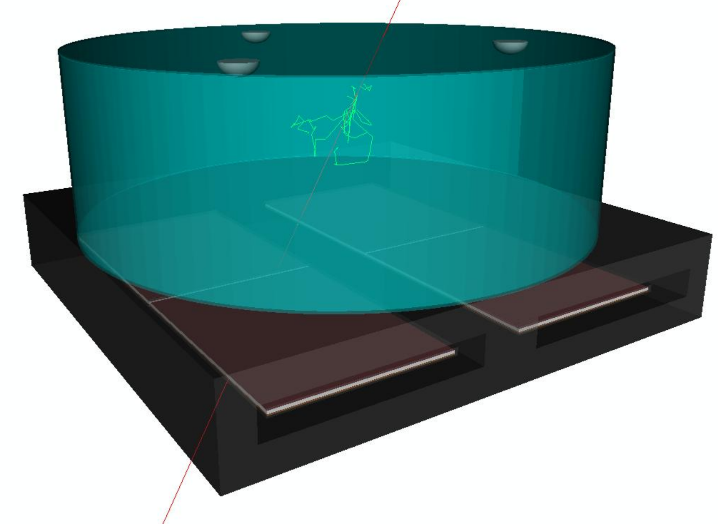
Segmented detectors
(upper part acts as absorber)



Engineering setups under investigation

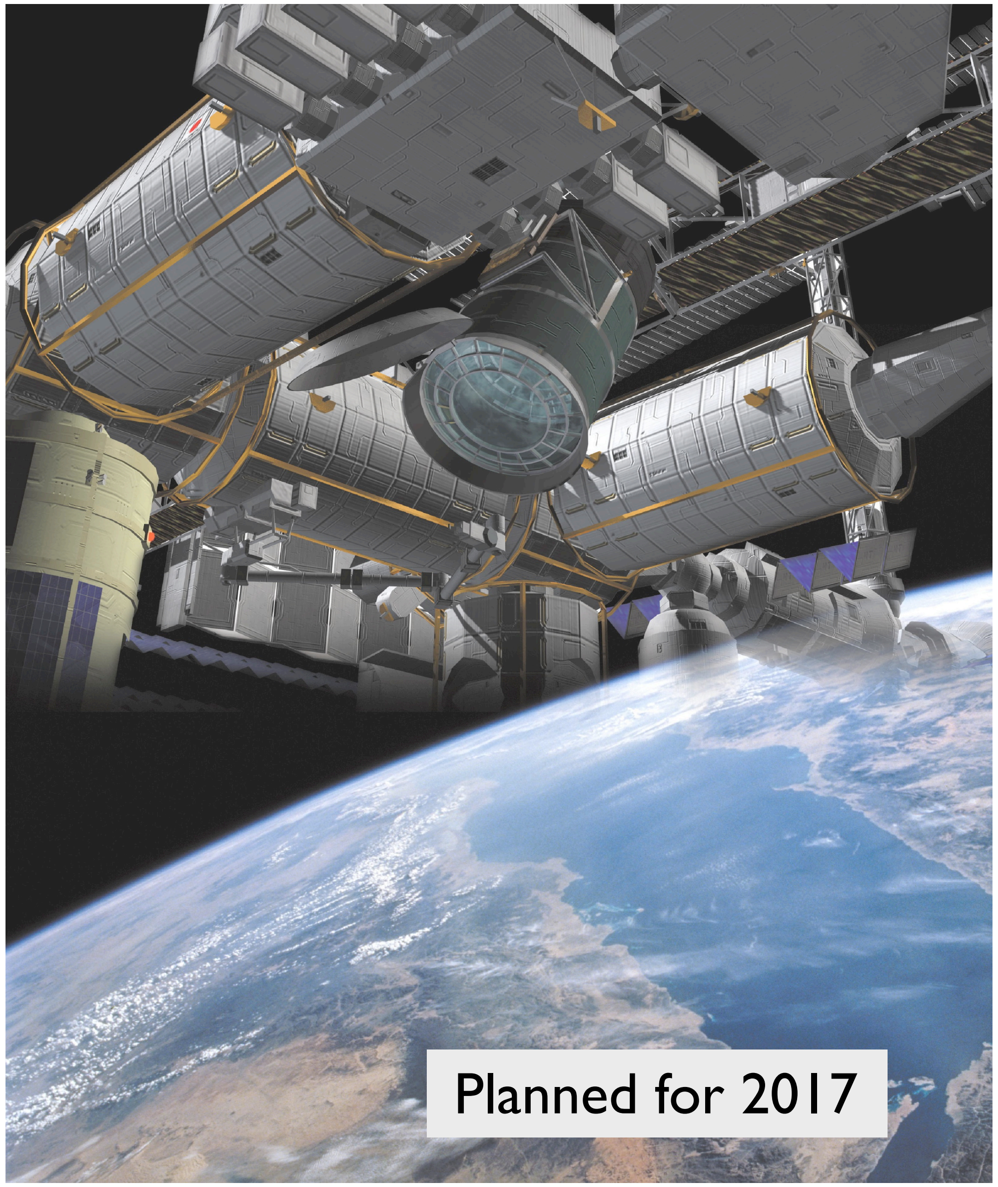


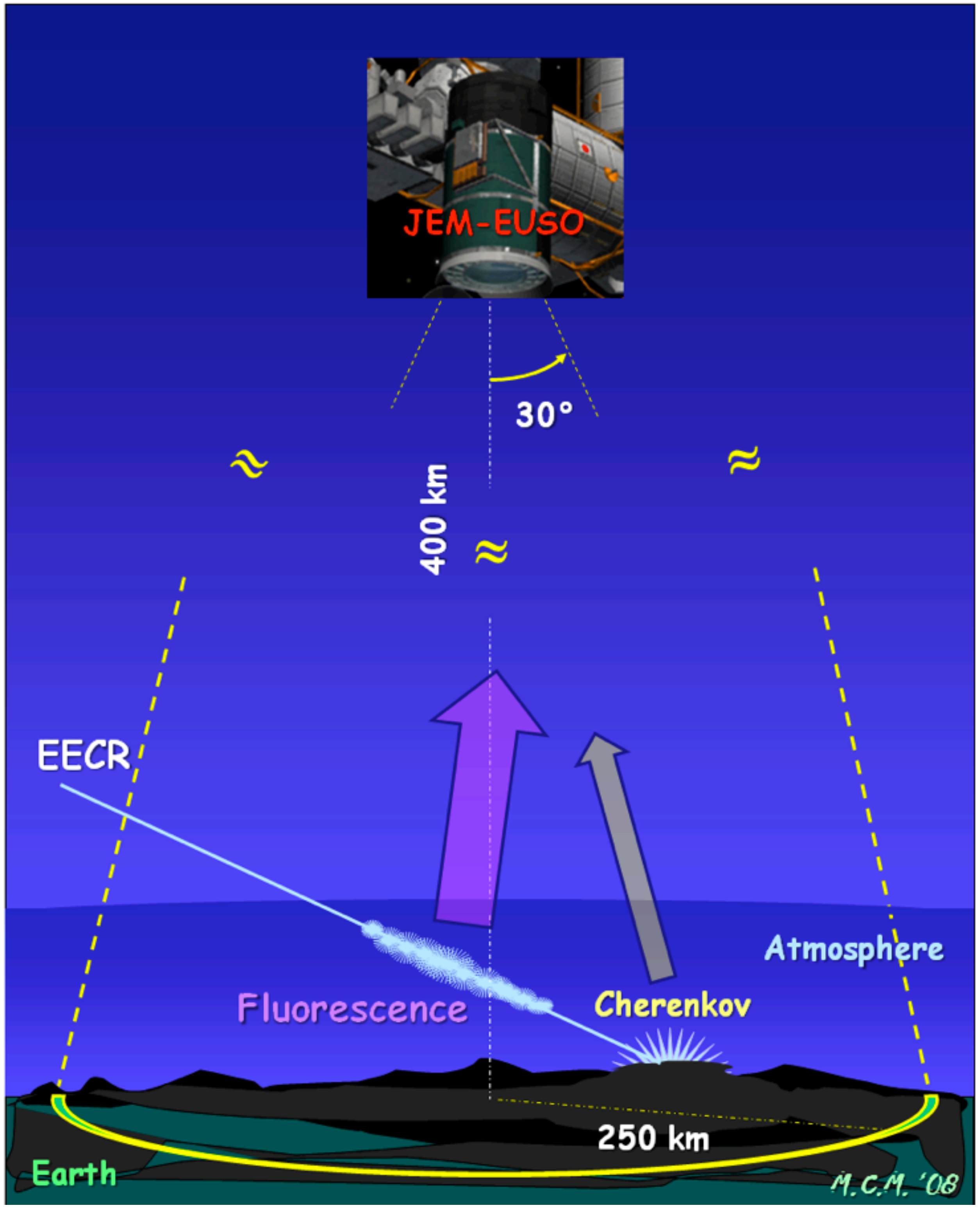
Place RPC detectors below existing detector stations



Upgraded array: 2017-2013
Data set will be doubled

JEM-EUSO: increase of statistics + full sky coverage





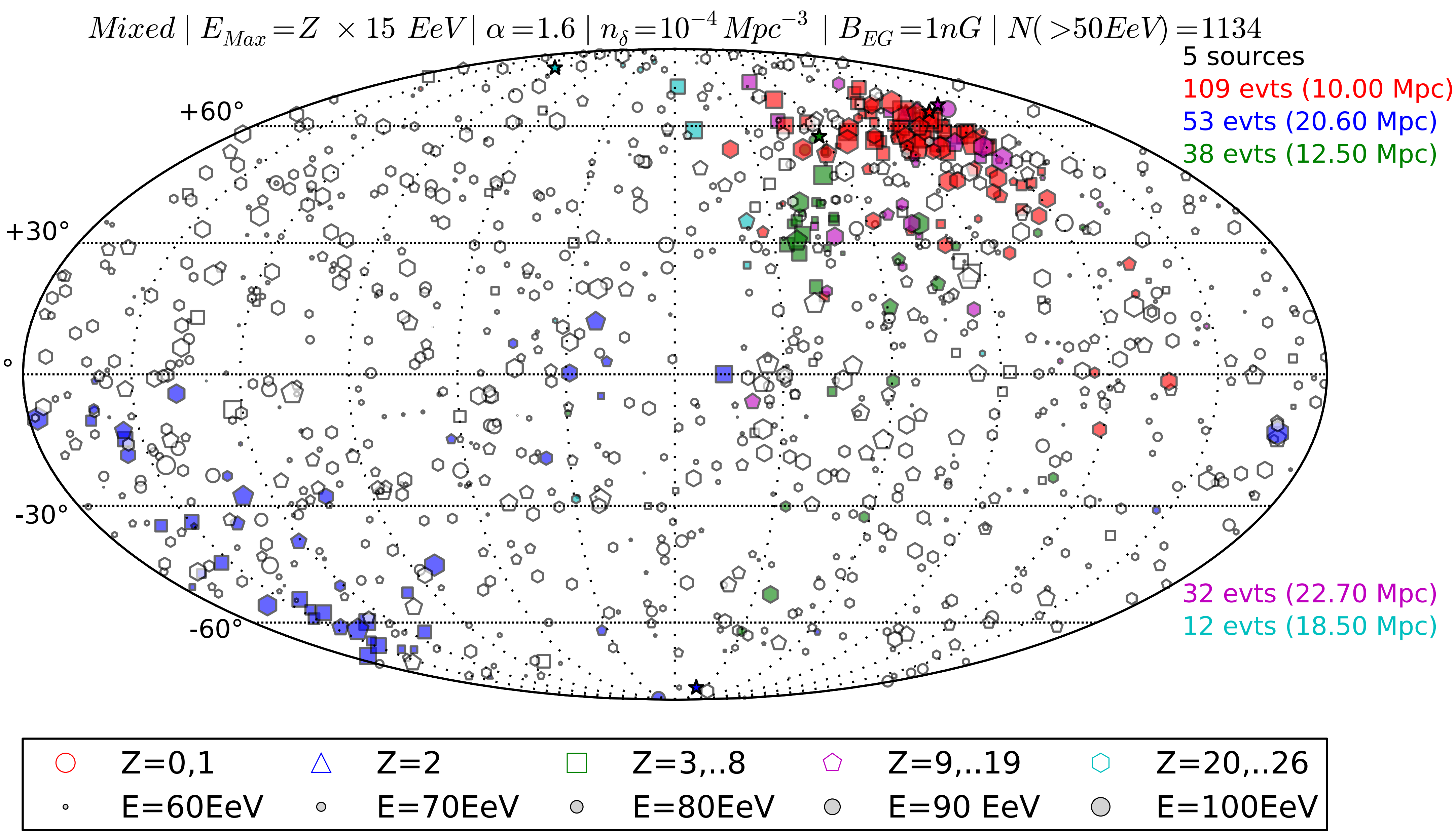
- Detection of fluorescence light and reflected Cherenkov light
- Exposure 300,000 km^2 sr yr
- Full sky coverage, $\Delta\theta \sim 3°$
- $E > 10^{19.7}$ eV, $\Delta E/E \sim 30\%$

(JEM-EUSO, Astropart. Phys. 44 (2913) 76)

Anisotropy studies with JEM-EUSO

Example for $E_{max}(p)$ = 15 EeV and $n_s = 10^{-4}$ Mpc^{-3}

“JEM-EUSO statistics”: 1100 events above 50 EeV (Auger energy scale)



(Rouille d´Orfeuil, Allard, Blaksley, Lauchard, Parizot, Nagataki ICRC 2013 #0984)

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

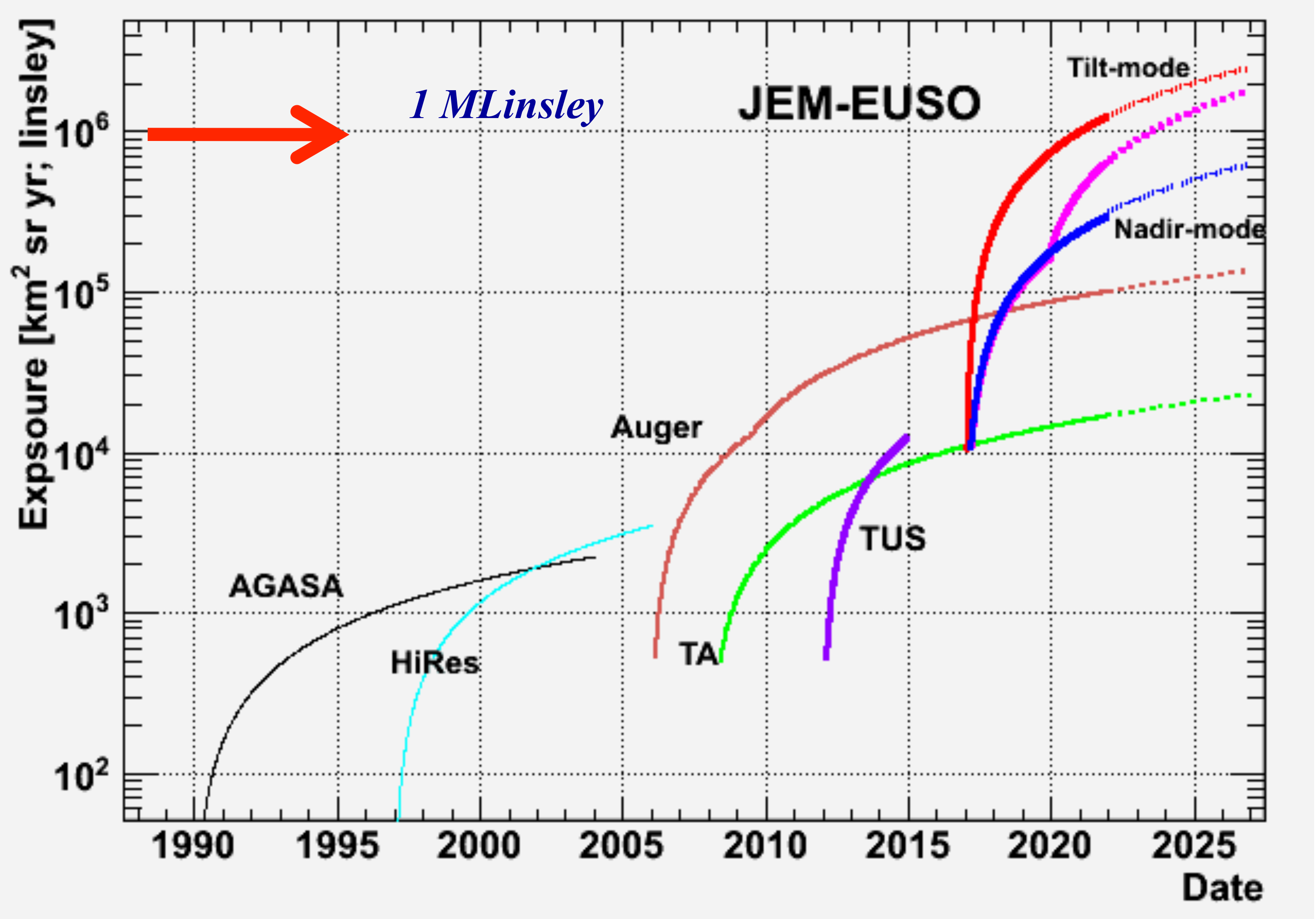
JEM-EUSO:

Observation from space from 2017 onwards

Anisotropy searches, spectrum at highest energies

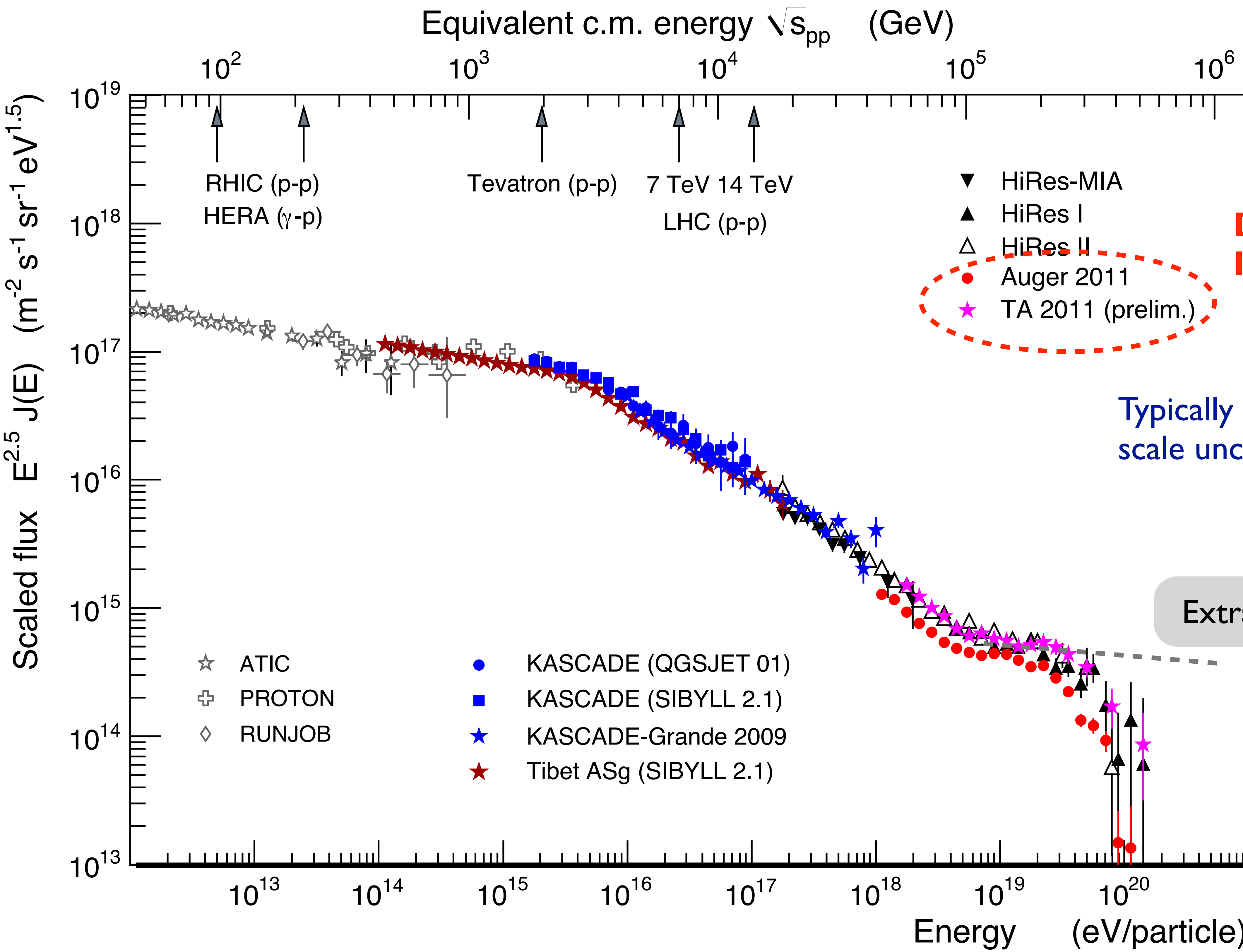
New technology: pathfinder for future missions

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



Backup slides

Unambiguous detection of flux suppression

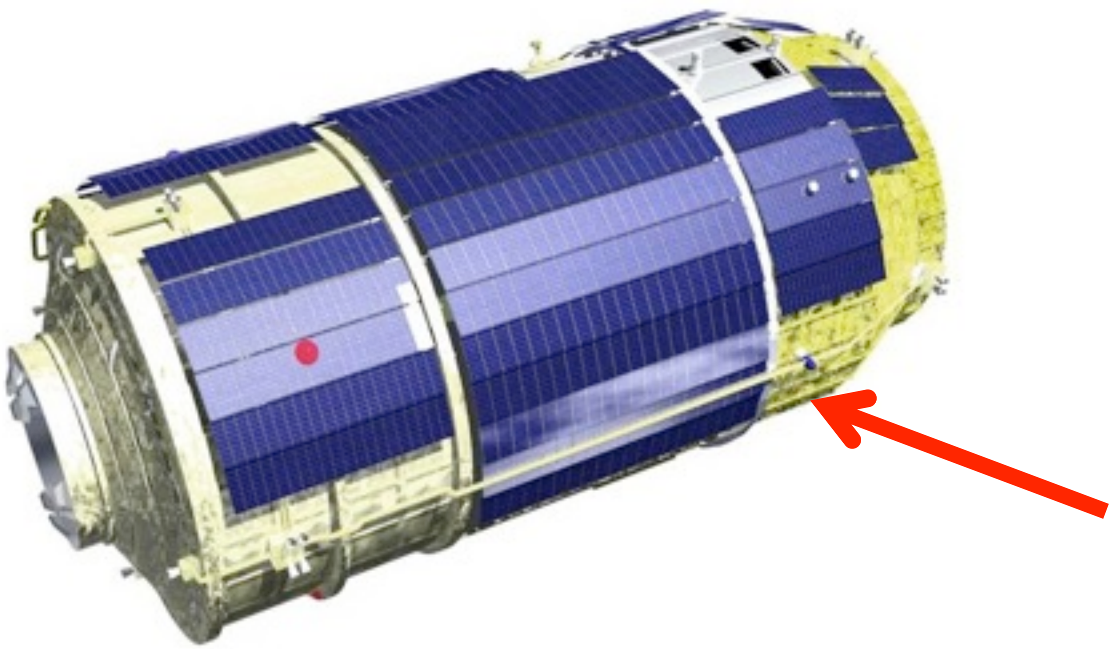


Data from ICRC 2011

Typically 20% energy scale uncertainty

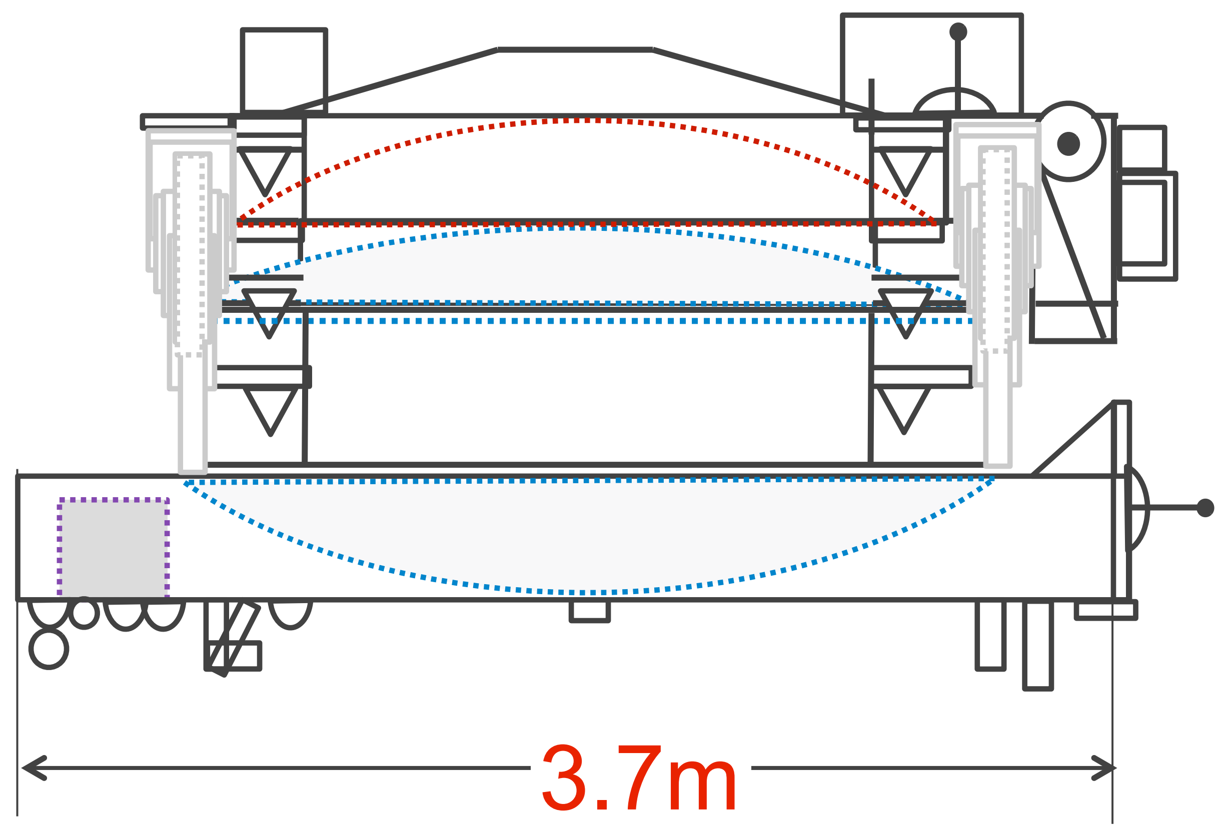
Extrapolated flux

Science Instrument on HTV



H2B Transfer Vehicle (HTV)

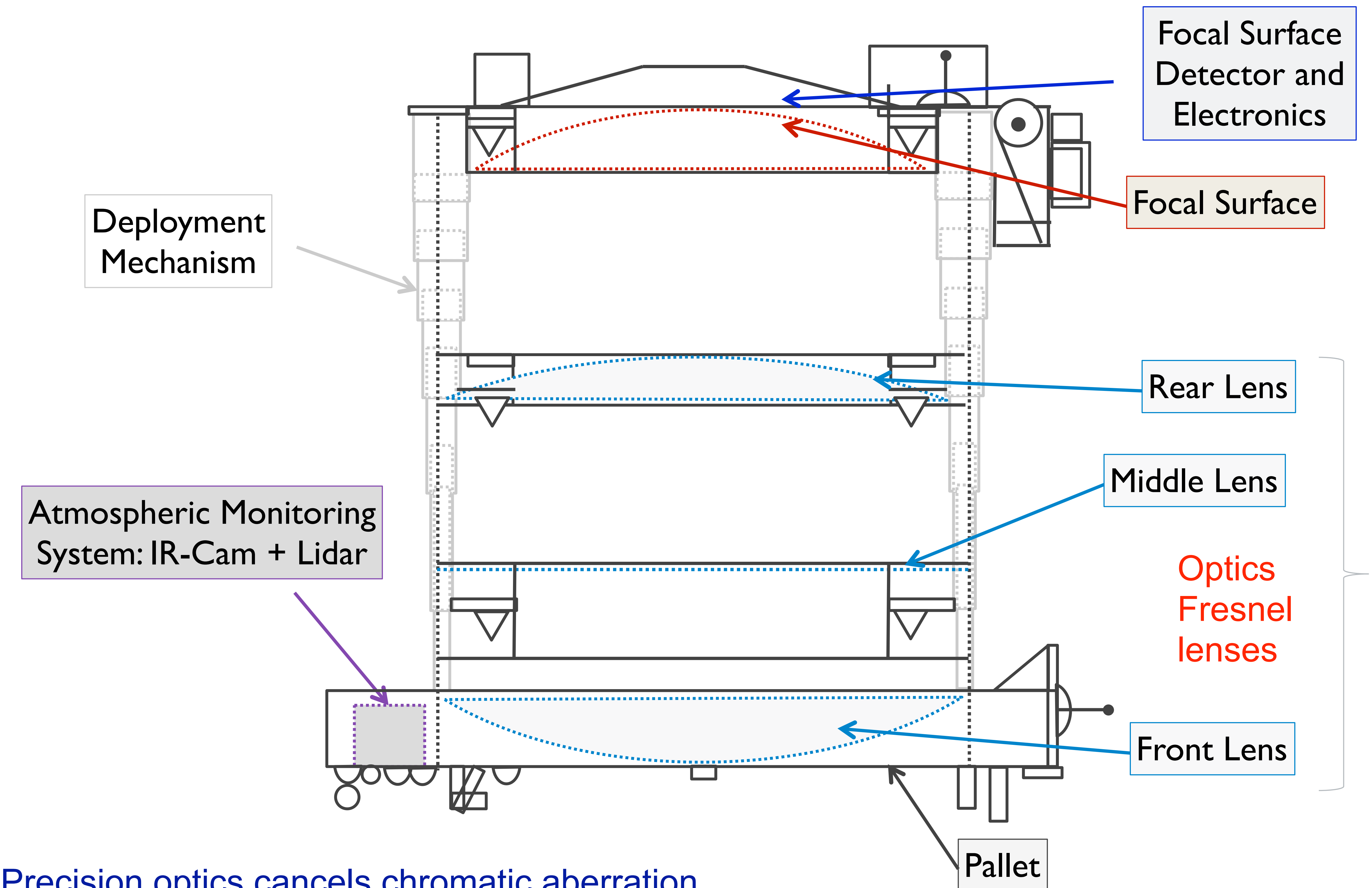
Side view



JEM-EUSO Telescope will be deployed after it is attached at the ISS

HTV was successfully launched on September 2009

Science Instrument: deployed



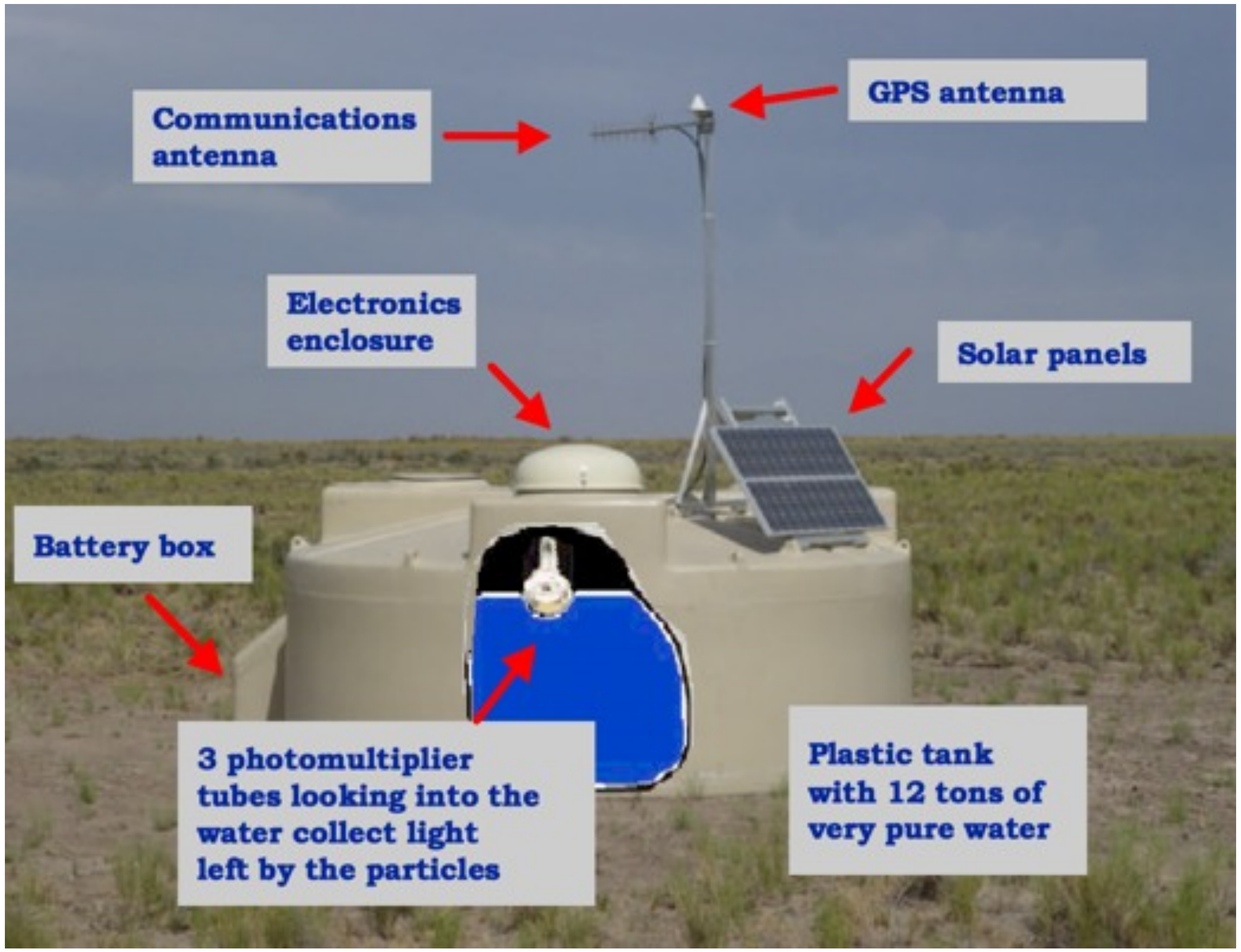
Precision optics cancels chromatic aberration.

Materials: PMMA+CYTOP

The UV Telescope Parameters

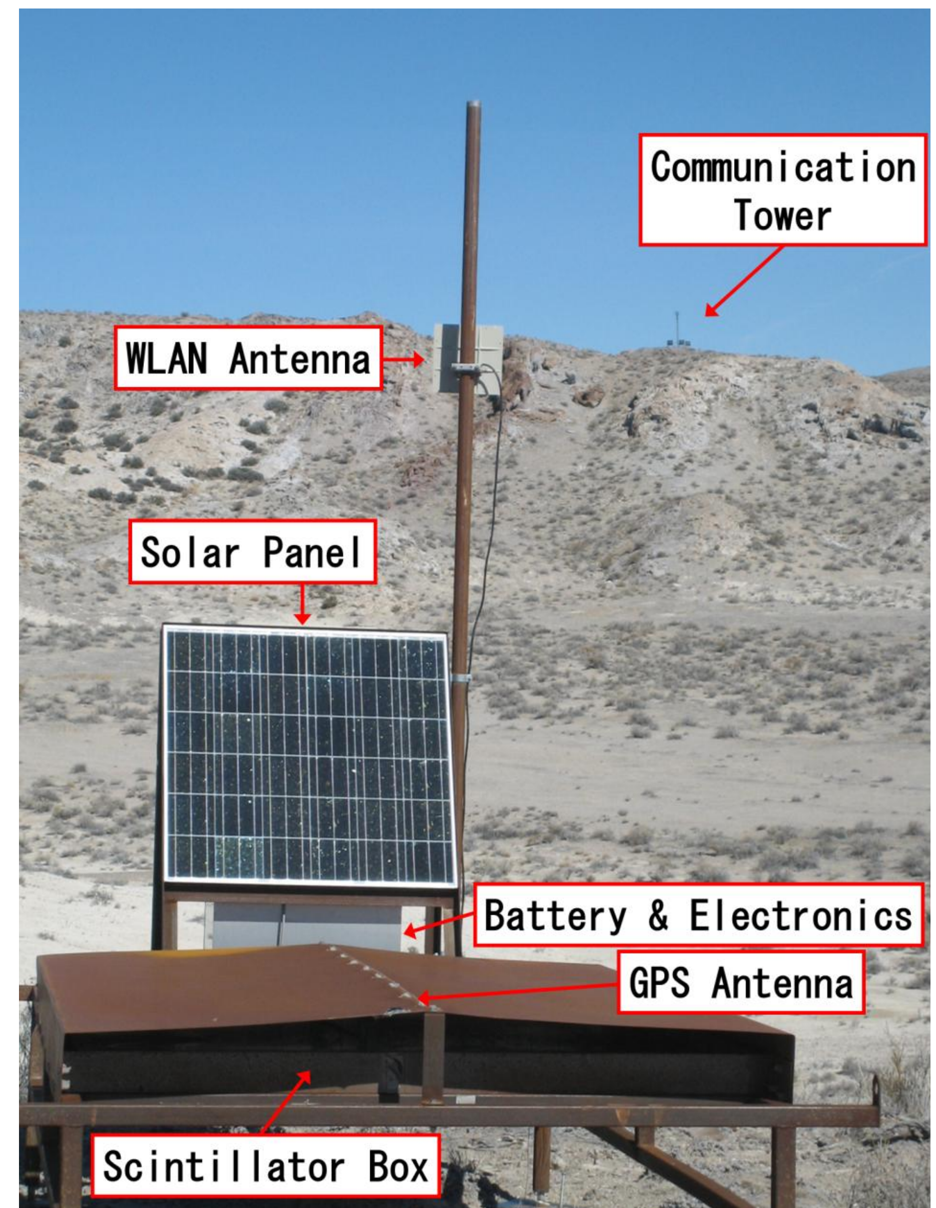
Parameter	Value
Field of View	**$\pm 30°$**
Monitored Area	**$>1.3\times10^5 km^2$**
Telescope aperture	**$\geq$2.5 m**
Operational wavelength	**300-400 nm**
Resolution in angle	**0.075°**
Focal Plane Area	**4.5 m^2**
Pixel Size	**<3 mm**
Number of Pixels	**$\approx 3\times10^5$**
Pixel size on ground	**$\approx$560 m**
Time Resolution	**2.5 μs**
Dead Time	**<3%**
Detection Efficiency	**$\geq$20%**

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)

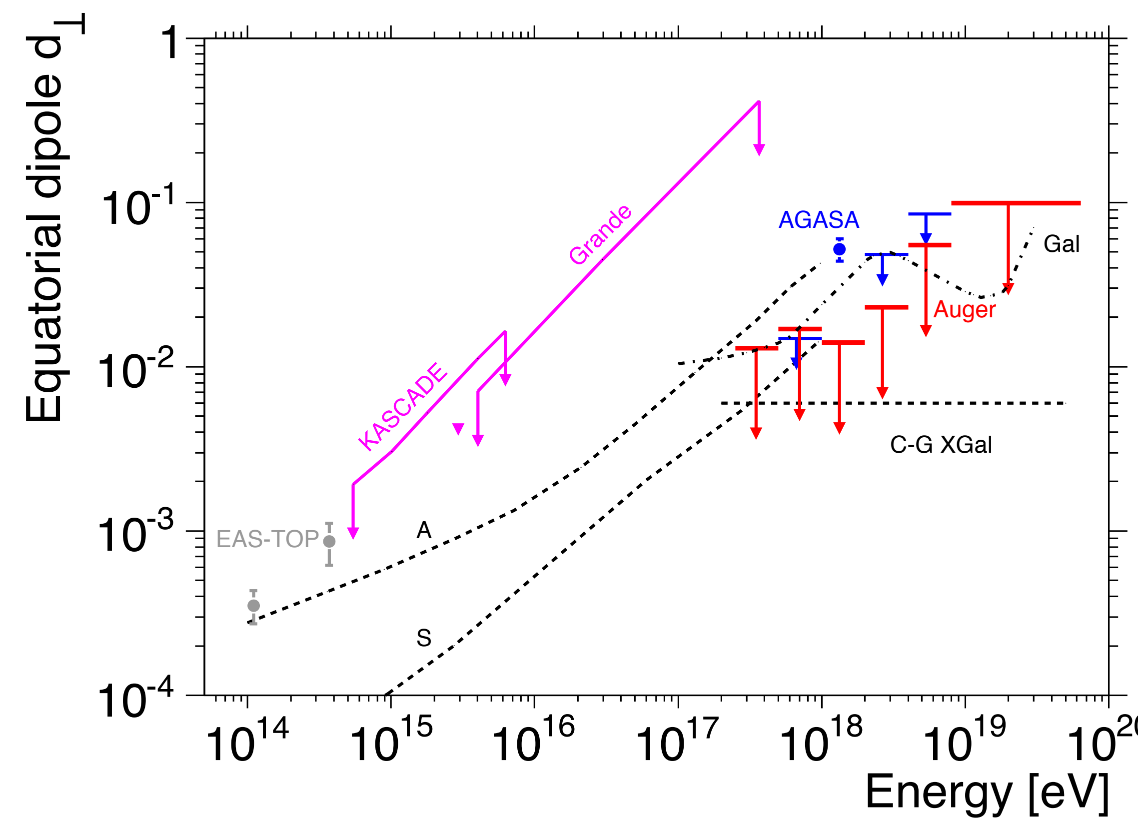


Complementary surface detector arrays

Anisotropy below and in ankle energy range

There found protons below $10^{18.5}$ eV but no significant anisotropy is measured

(Astropart. Phys. 34 (2011) 627)



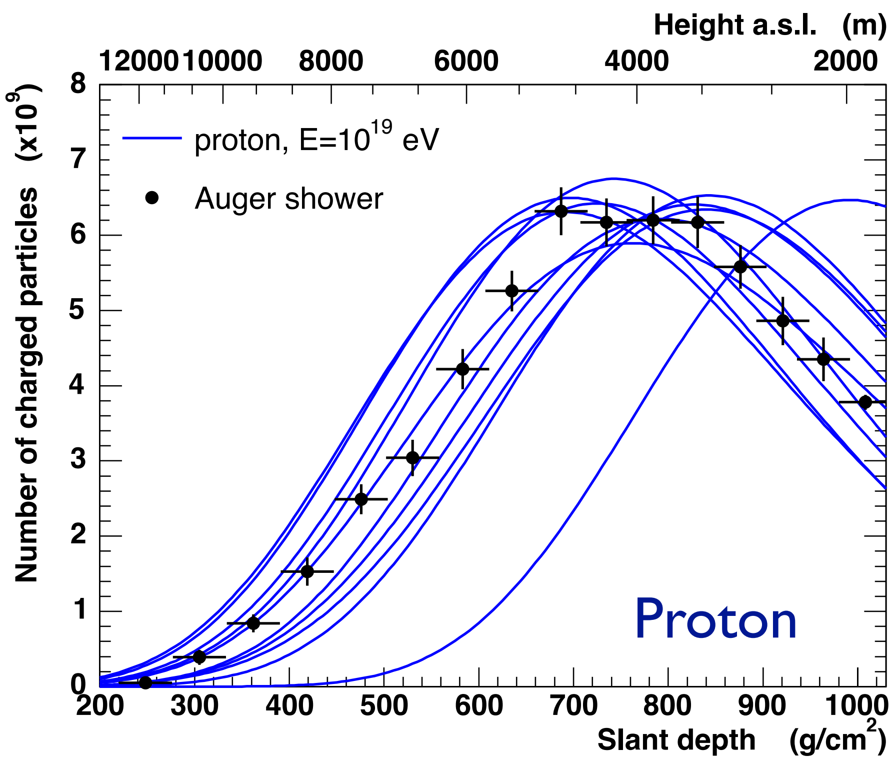
Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

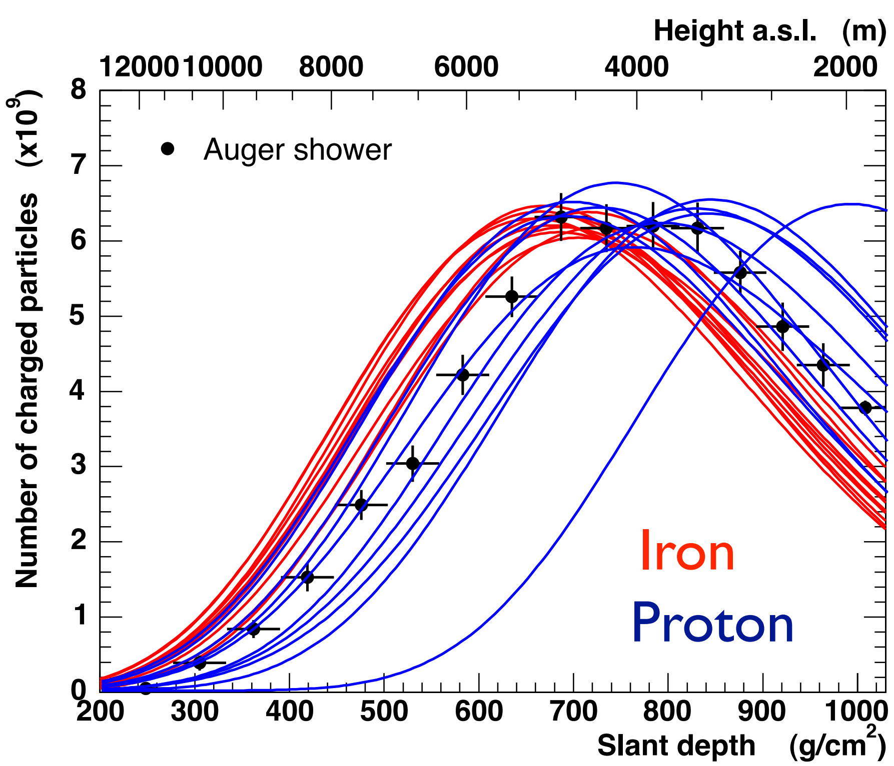
Cosmic ray anisotropy as signature for the transition from galactic to extragalactic cosmic rays

G. Giacinti,[a,b] M. Kachelrieß,[a] D.V. Semikoz[c,d] and G. Sigl[b]

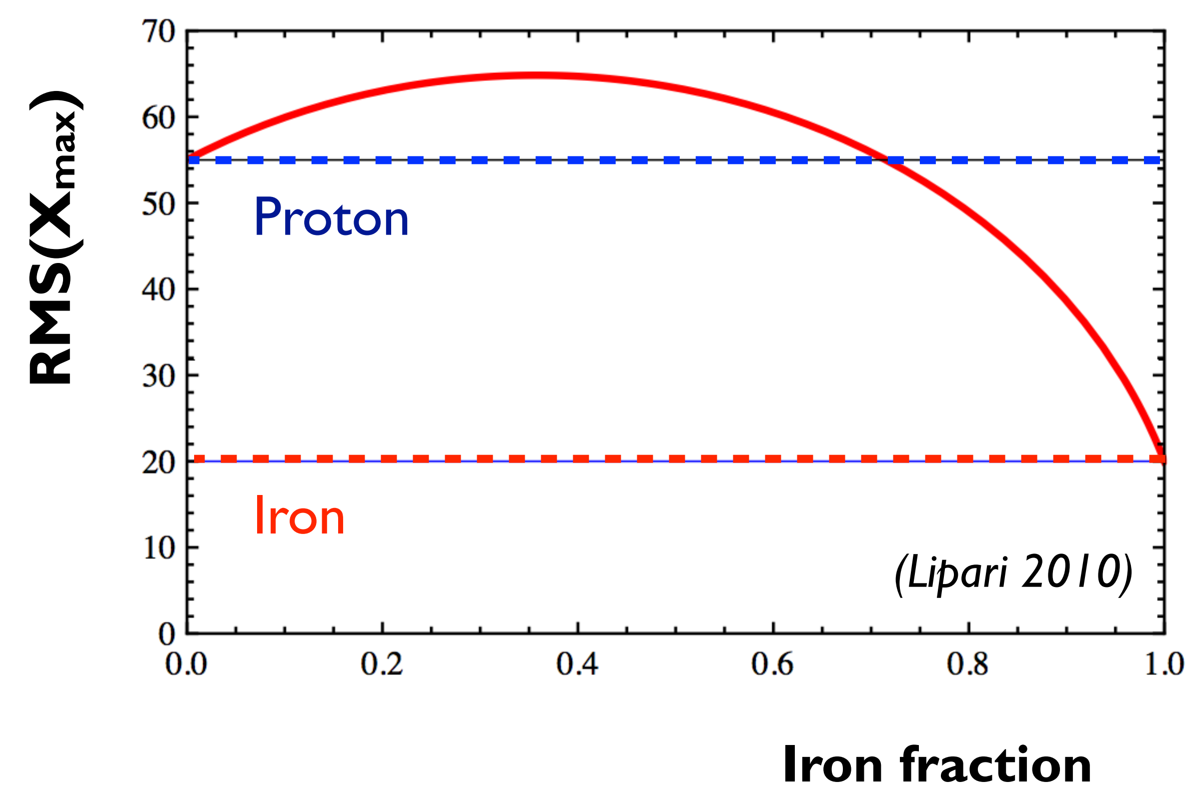
a nested grid which allows spatial resolution down to fractions of a parsec. Assuming sufficiently frequent Galactic CR sources, the dipole amplitude computed for a mostly light or intermediate primary composition exceeds the dipole bounds measured by the Auger collaboration around $E \approx 10^{18}$ eV. Therefore, a transition at the ankle or above would require a heavy composition or a rather extreme Galactic magnetic field with strength $\gtrsim 10\,\mu$G.

Auger data on shower profiles





Fluctuations of depth of shower maximum

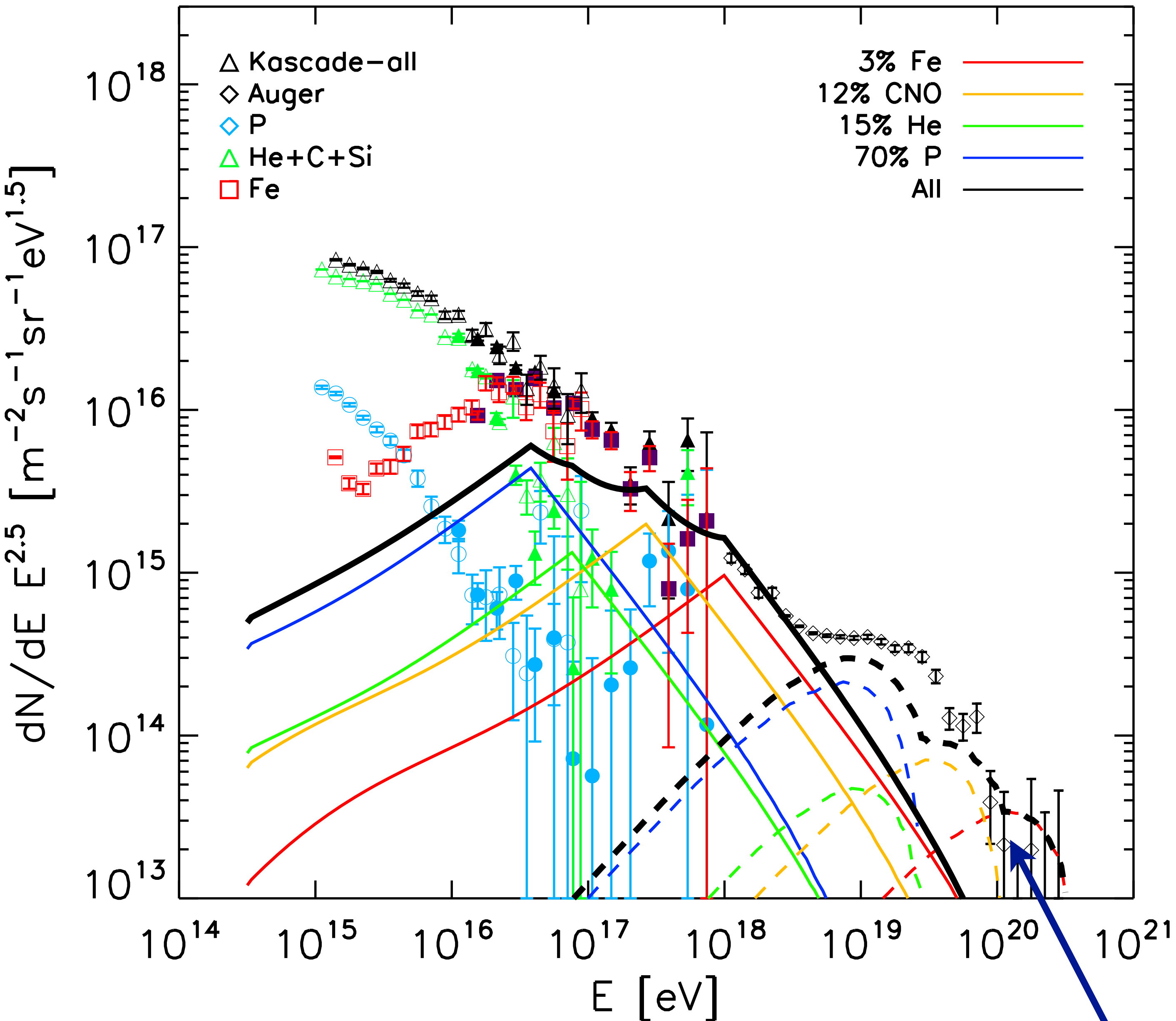


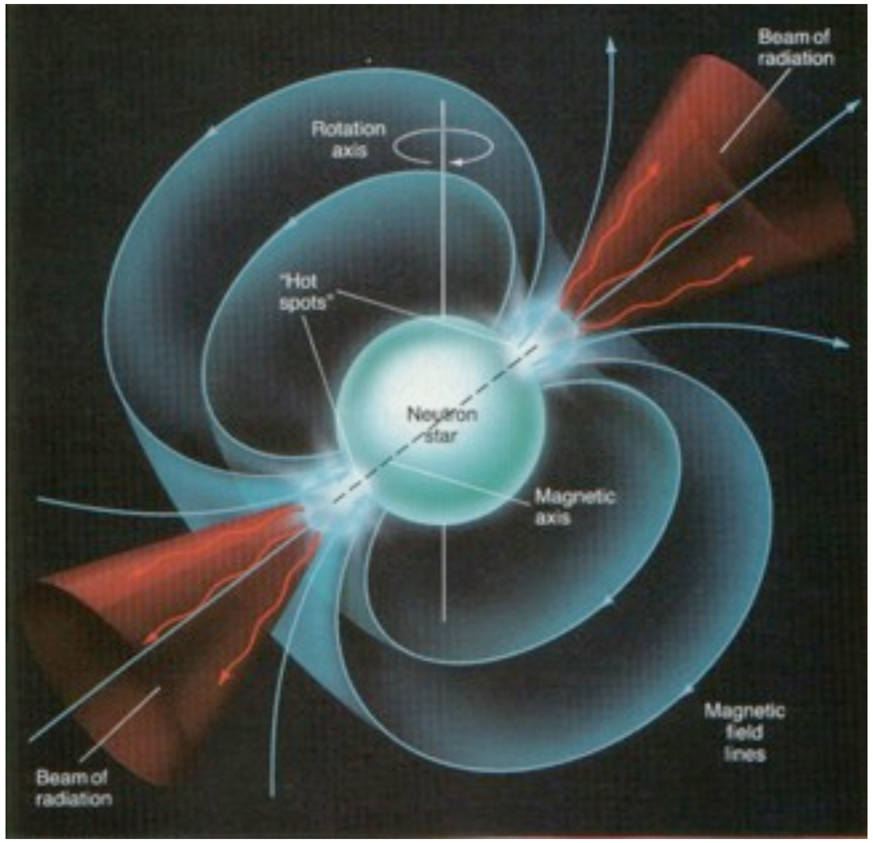
Mean depth of shower profiles and shower-to-shower fluctuations as measure of composition

Example: event measured by Auger Collab.

Example: magnetar model

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



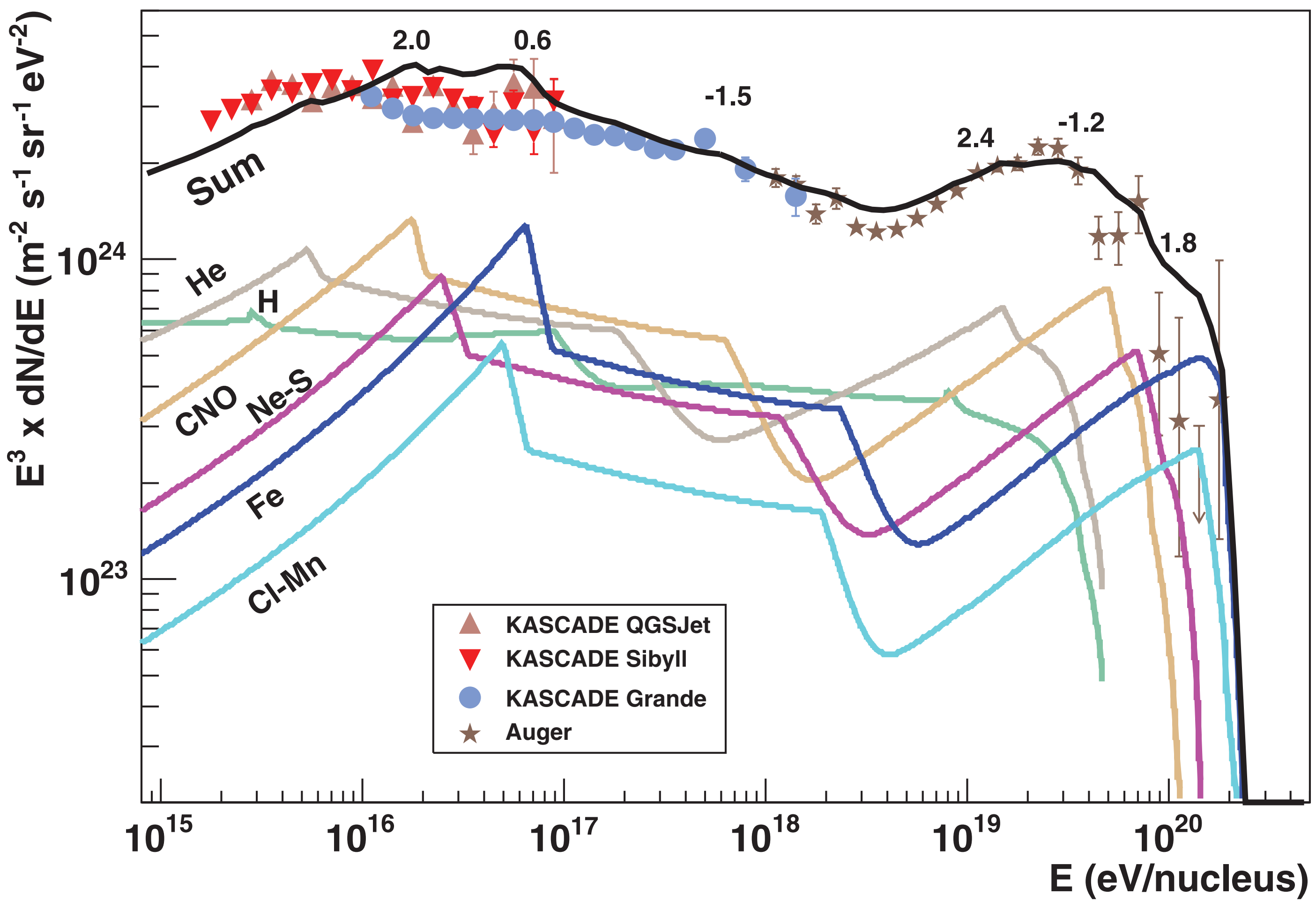


$$\frac{\mathrm{d}N_{\mathrm{inj}}}{\mathrm{d}E} \sim E^{-1}\left(1+\frac{E}{E_g}\right)^{-1}$$

Low-energy part:
many galactic magnetars

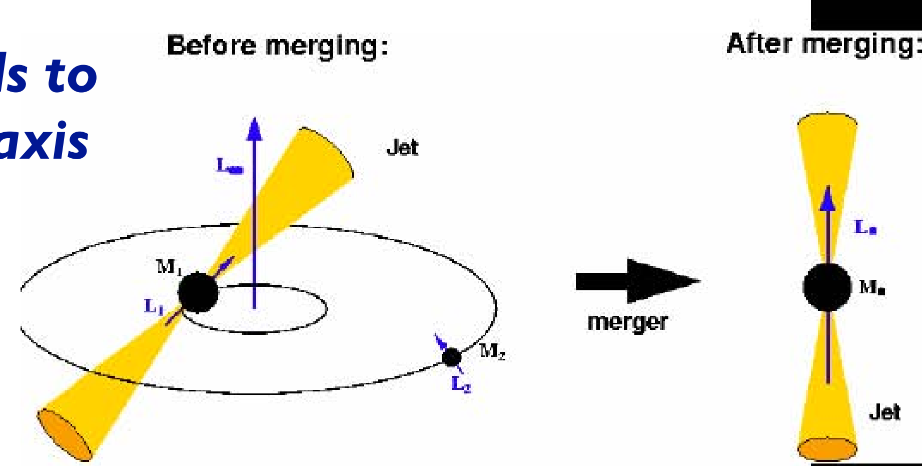
High-energy part:
extragalactic (extreme) magnetar

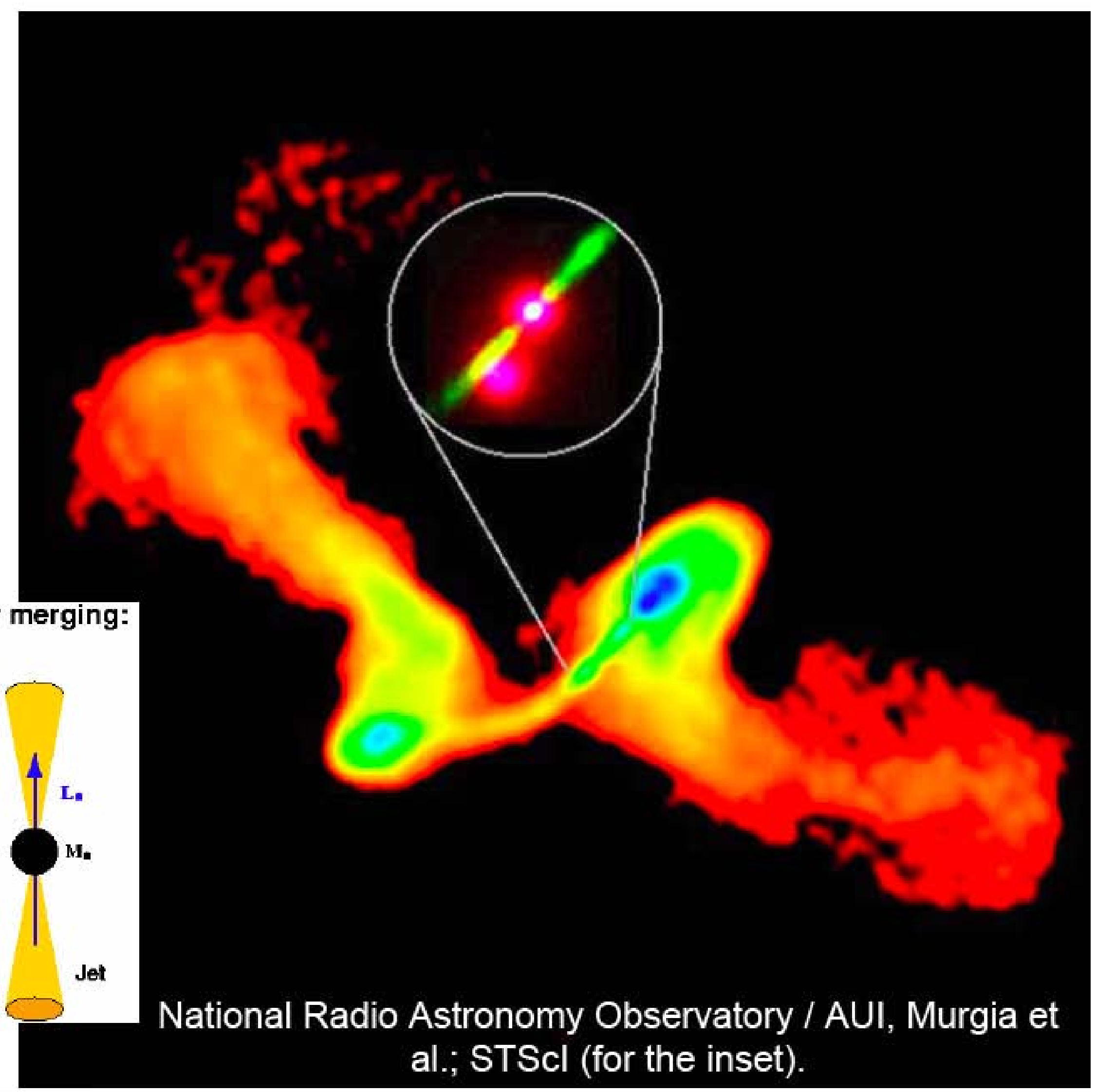
Centaurus A as dominating local source



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

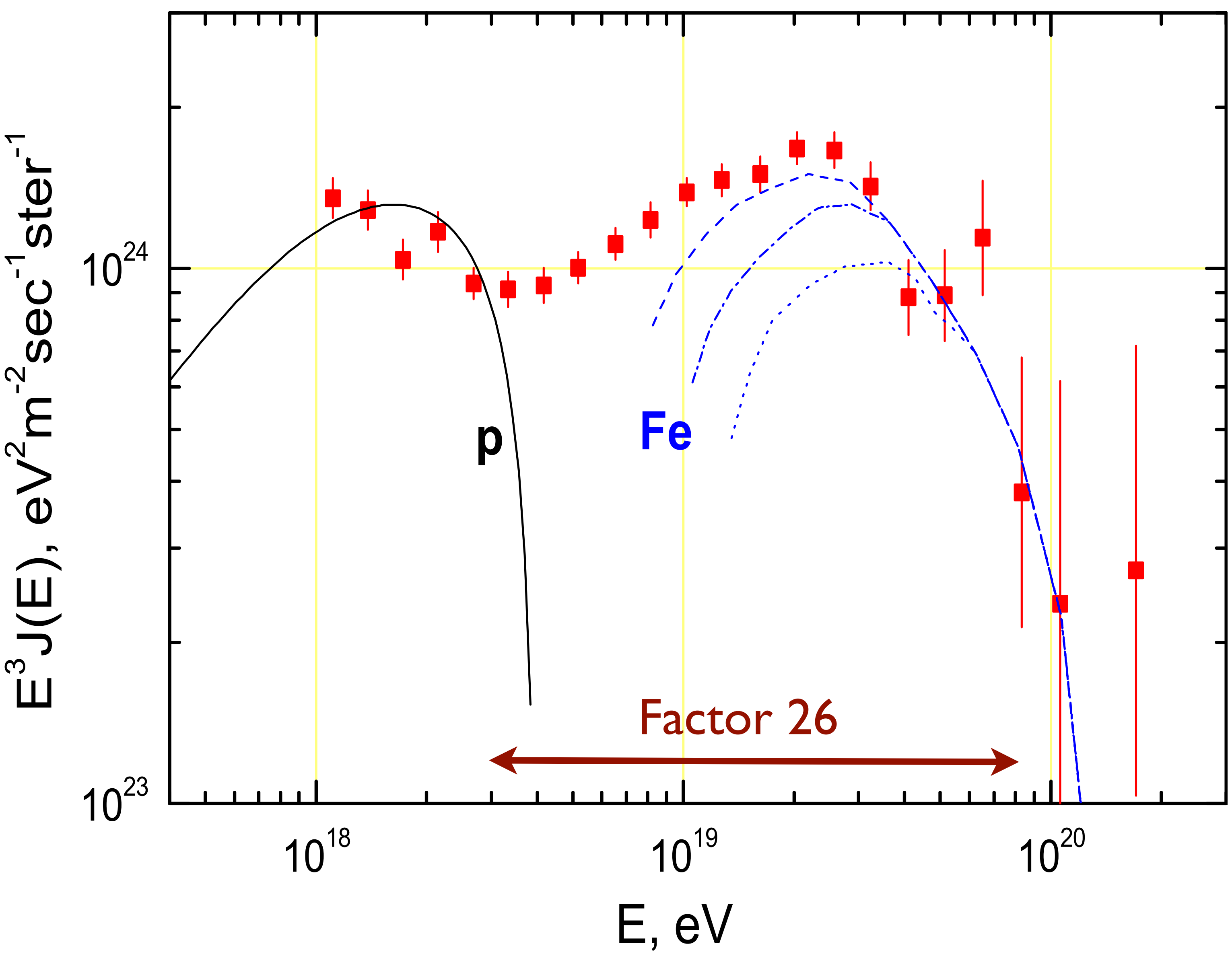
Spin flip of black hole leads to re-orientation of rotation axis





(Biermann et al. 2012)

Extreme scenario without any GZK suppression ?



(Aloisio, Berezinsky Astropart. Phys. et al. 2011)

Ankle would be transition between extragalactic protons and He/CNO

Single (local) source or class of sources dominating, could also be of galactic origin (GRB, termination shock, etc)

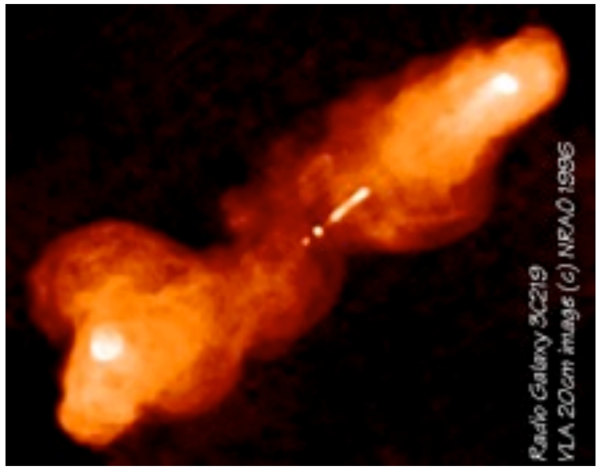
Second knee as transition from galactic to extragalactic sources

Protons at 10^{18} eV already of extragalactic origin

Energy loss effects unimportant

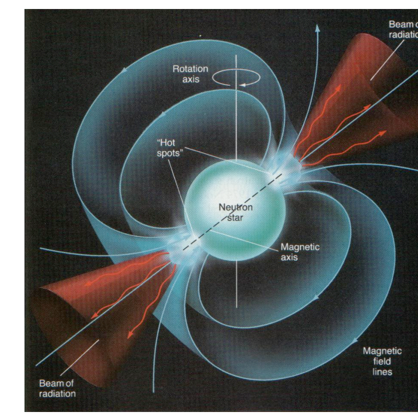
(see also Calvez et al. Phys. Rev. Lett. 2010, Aloisio et al. Astropart. Phys. 2011)

Exotic source and propagation scenarios ?



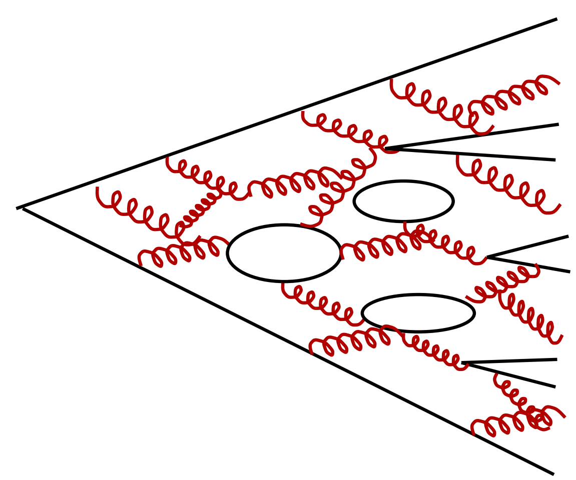
Active Galactic Nuclei (AGN):
Black Hole of ~10^9 solar masses

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 ~ 10^{23} - 10^{24} eV

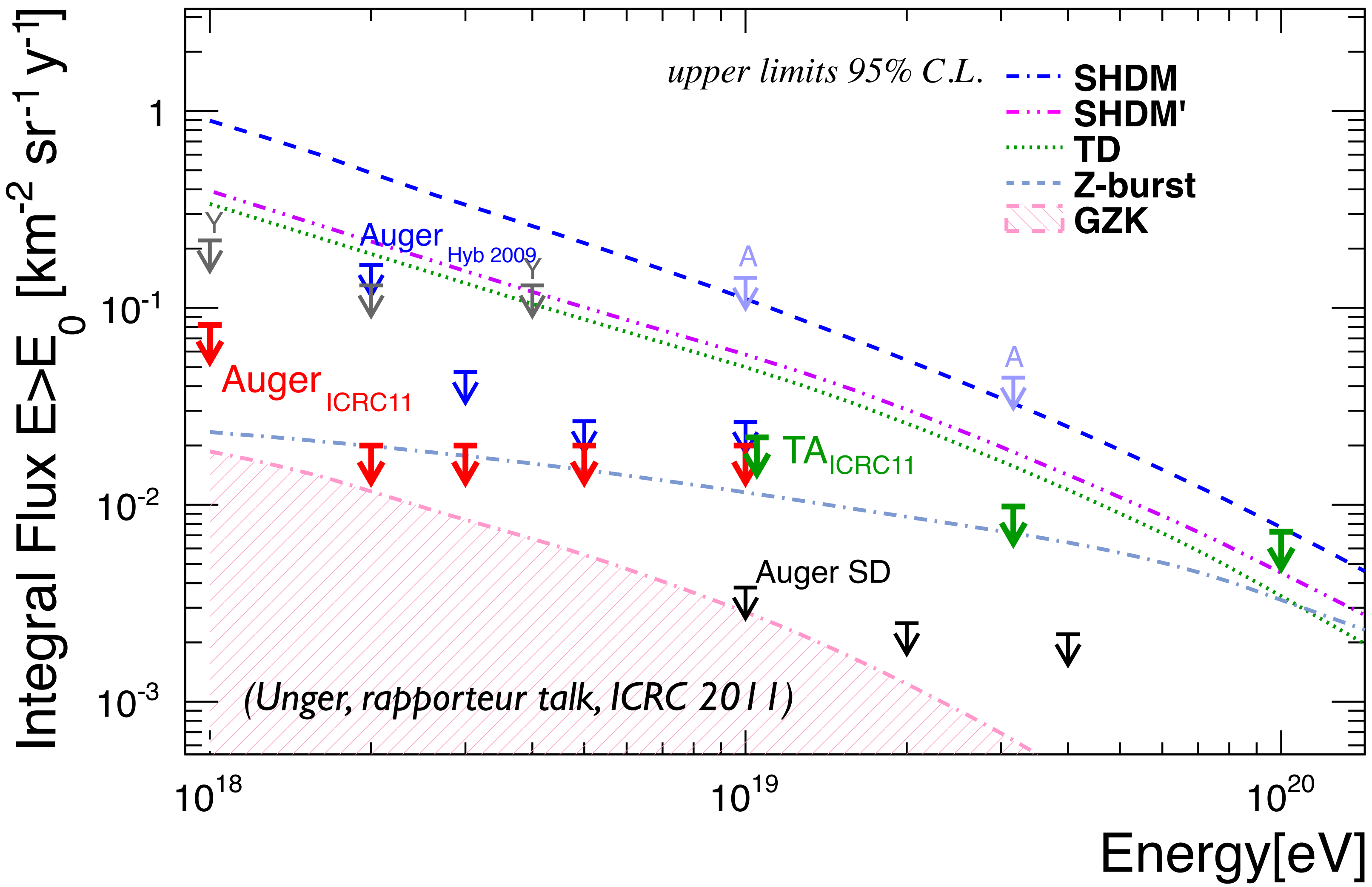


large fluxes of photons and neutrinos

(RE, Nijmegen Summer School, 2006)

Limits on exotic source scenarios

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

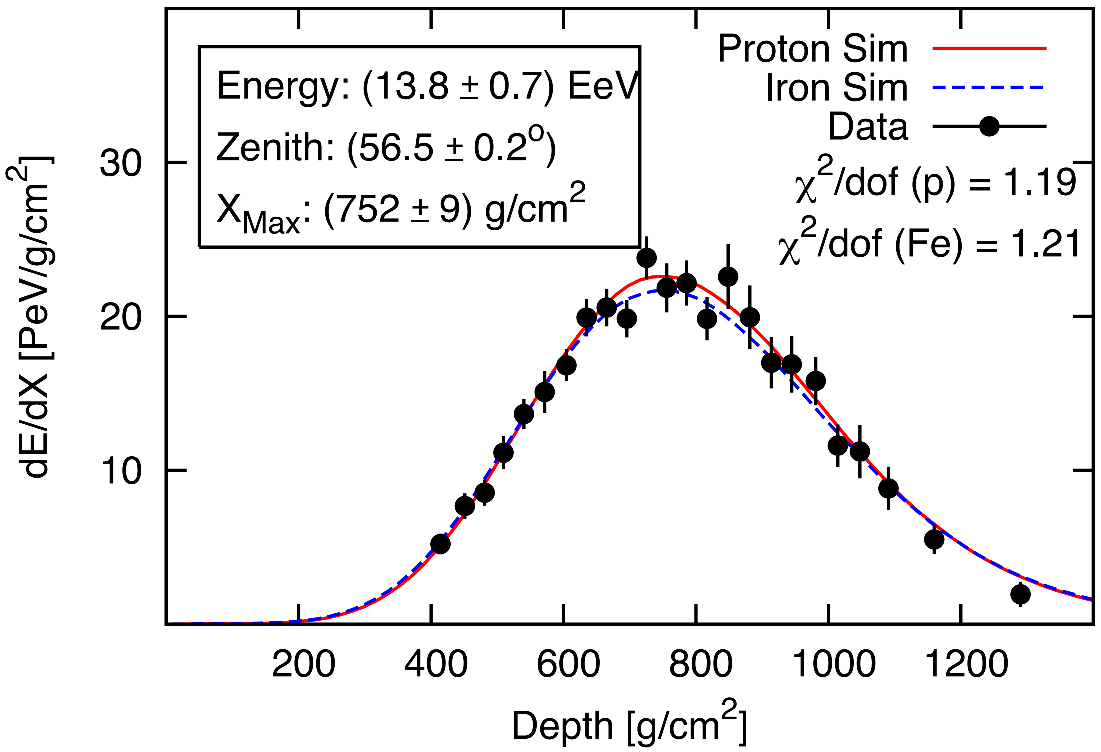


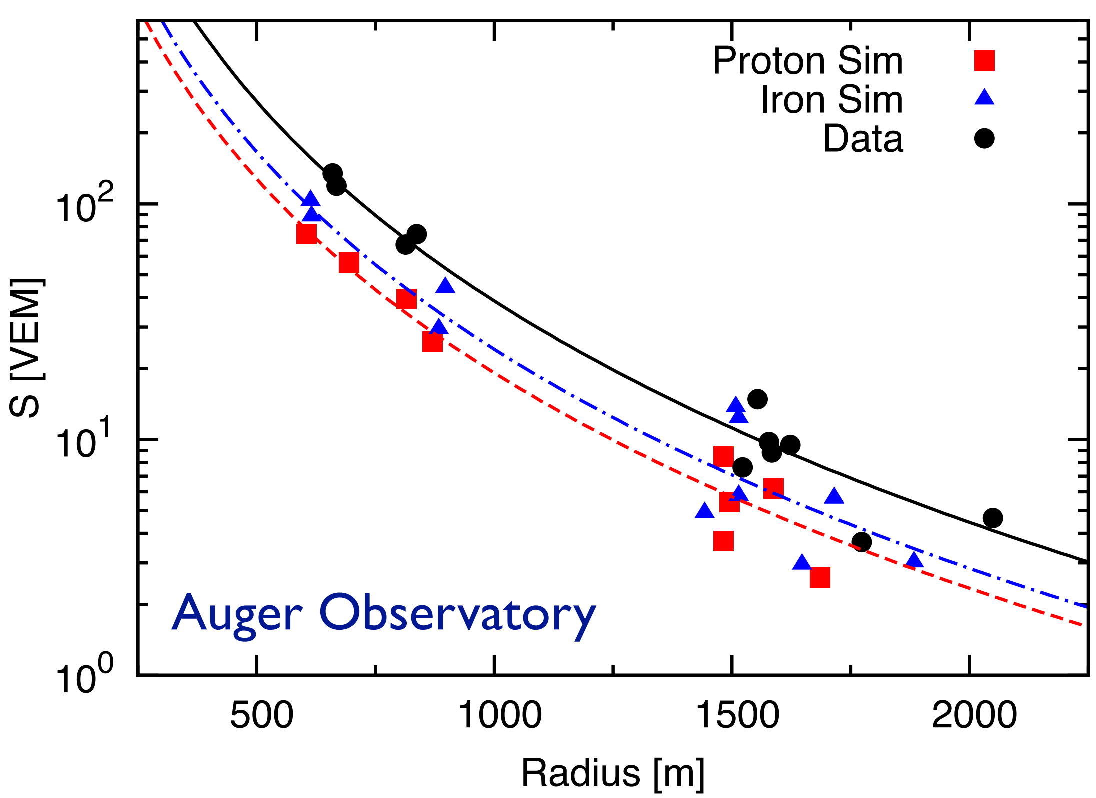
Super-heavy dark matter
Topological defects

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

Discrepancy between data and simulated showers





Procedure

- High-quality showers E ~10^{19} eV
- Proton or iron primaries
- surface detector simulation for best longitudinal profiles

Results

- Signal deficit found for **both** proton and iron like showers
- Showers with same X_{max} show only 10-15% variation
- Discrepancy much larger than 22% energy calibration uncertainty

Monte Carlo simulations cannot be used for energy calibration (reason for AGASA excess?)

(Pierre Auger Collab. 1107.4804)

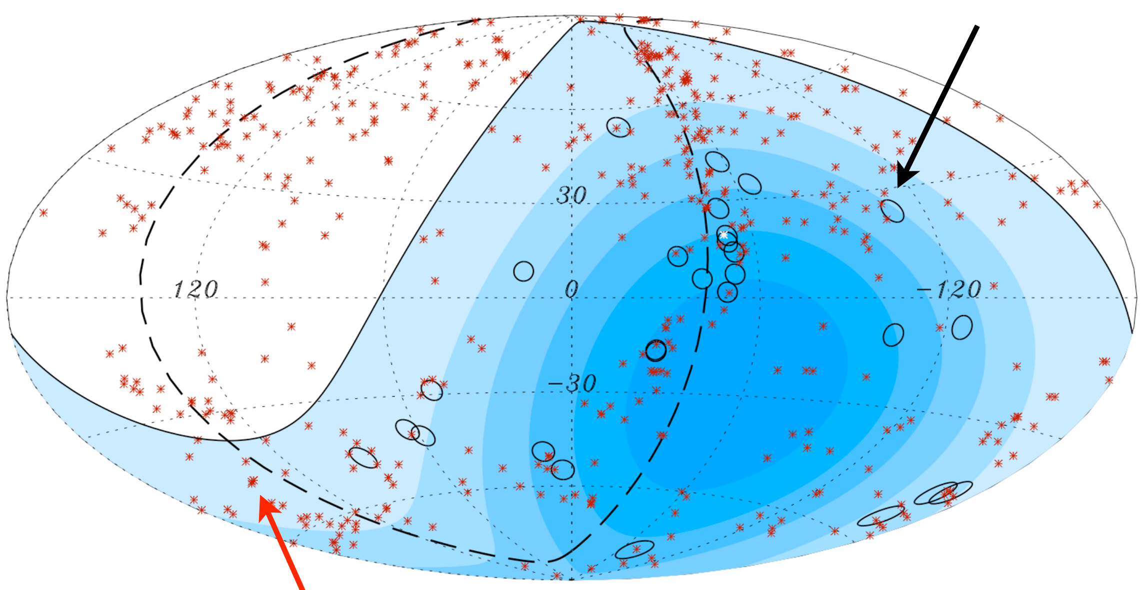
Correlation of arrival directions with AGNs

Auger Observatory (2007)

(Science 318, 2007)

Scan: 12 out of 15, prescription

Arrival direction of cosmic ray



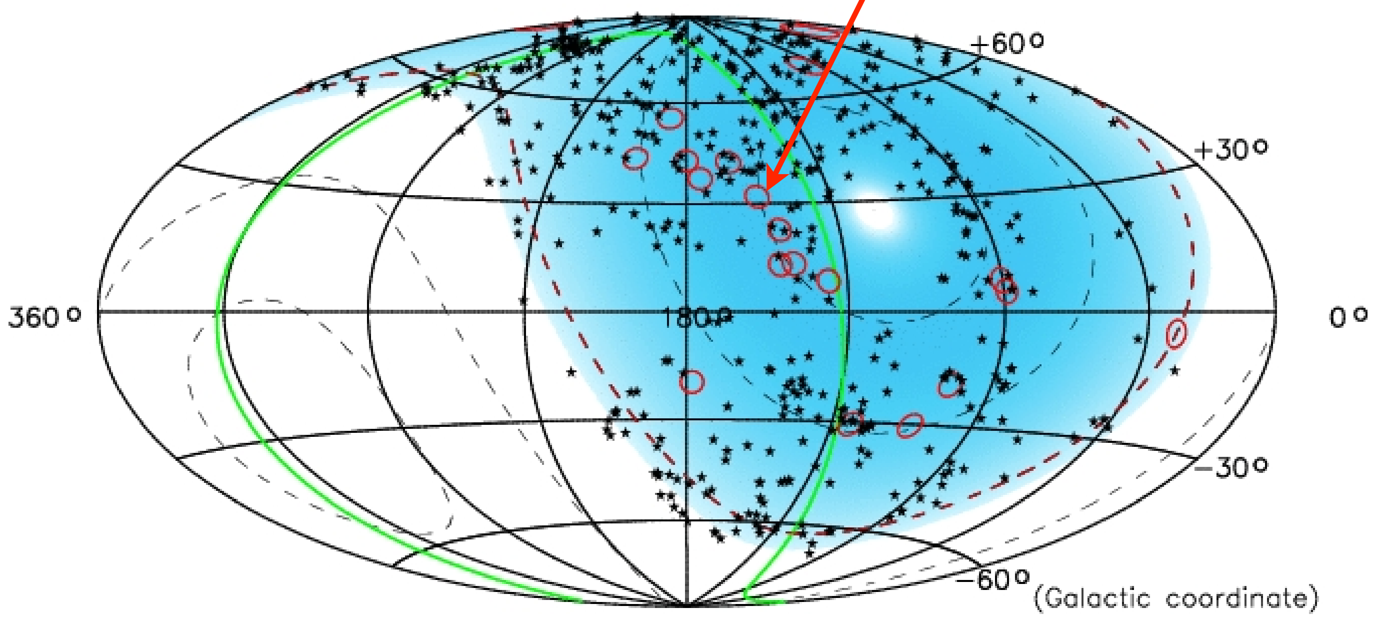
Active Galactic Nucleus (AGN) (Veron-Cetty & Veron catalog)

$E > 5.5 \times 10^{19}$ eV
$D < 75$ Mpc

20 out of 27, ~70% correlation, 21% expected

Telescope Array (2011)

Arrival direction of cosmic ray

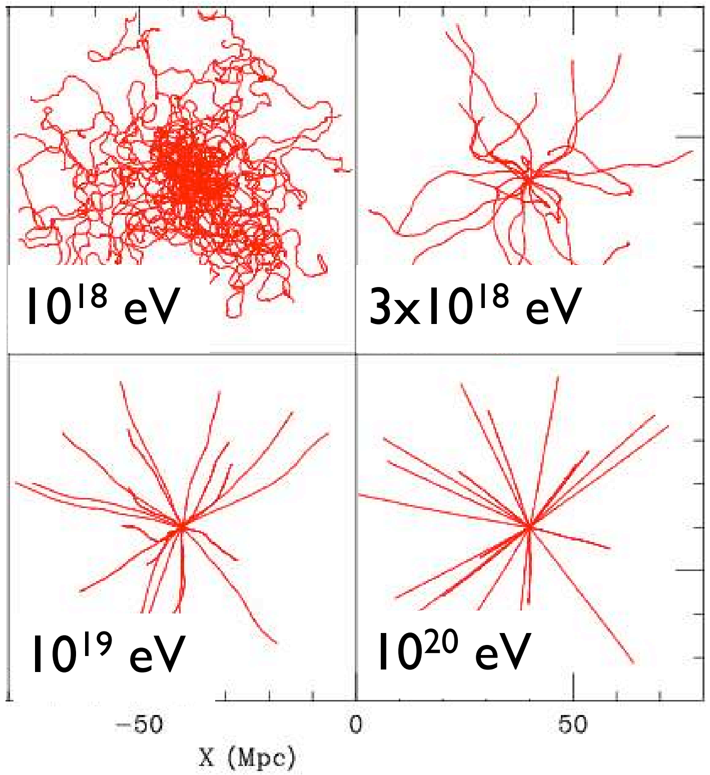


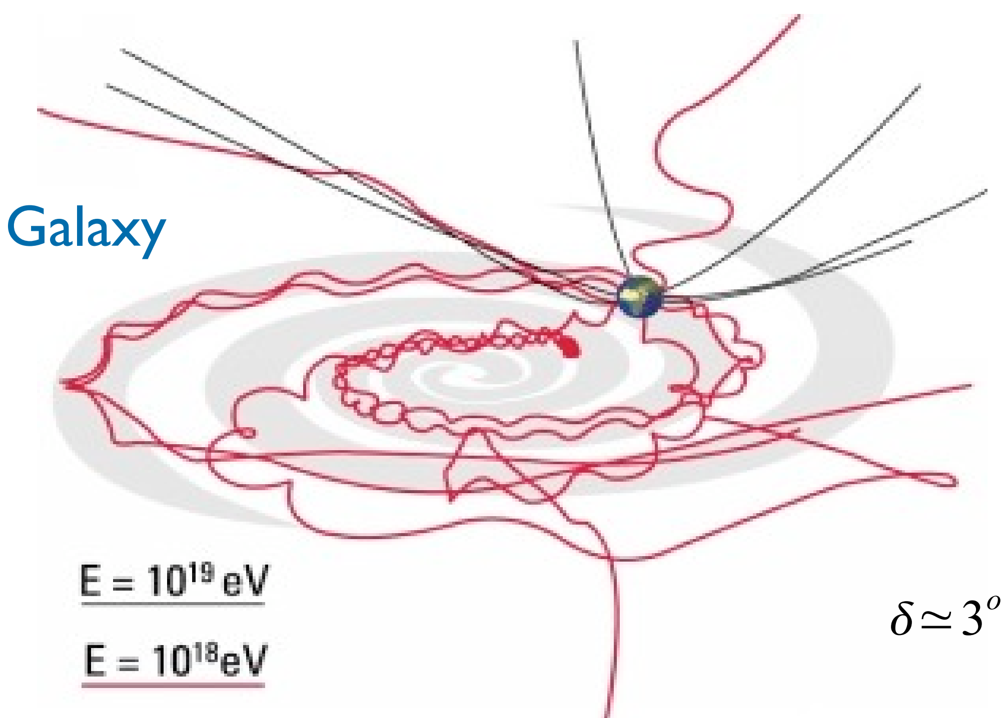
8 out of 20 events correlated, no stat. significant correlation found

Anisotropy only for source distances up to GZK sphere (as one would expect)
Small deflection angle indicates presence of **light elements** (protons?)

GZK horizon and magnetic field deflection

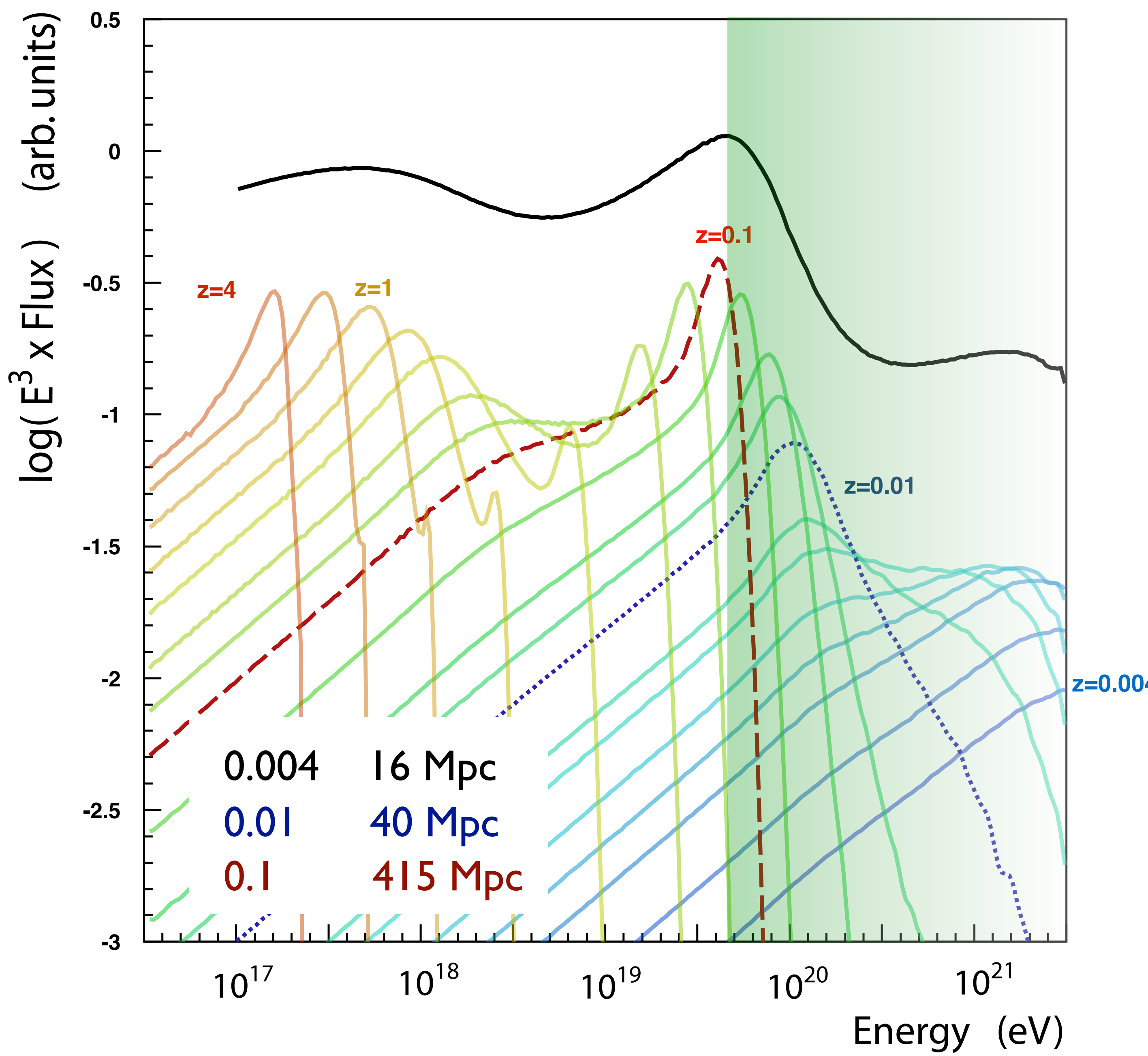
Extragalactic magnetic field





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

GZK horizon: energy-source relation



(Bergmann et al., PLB 2006)