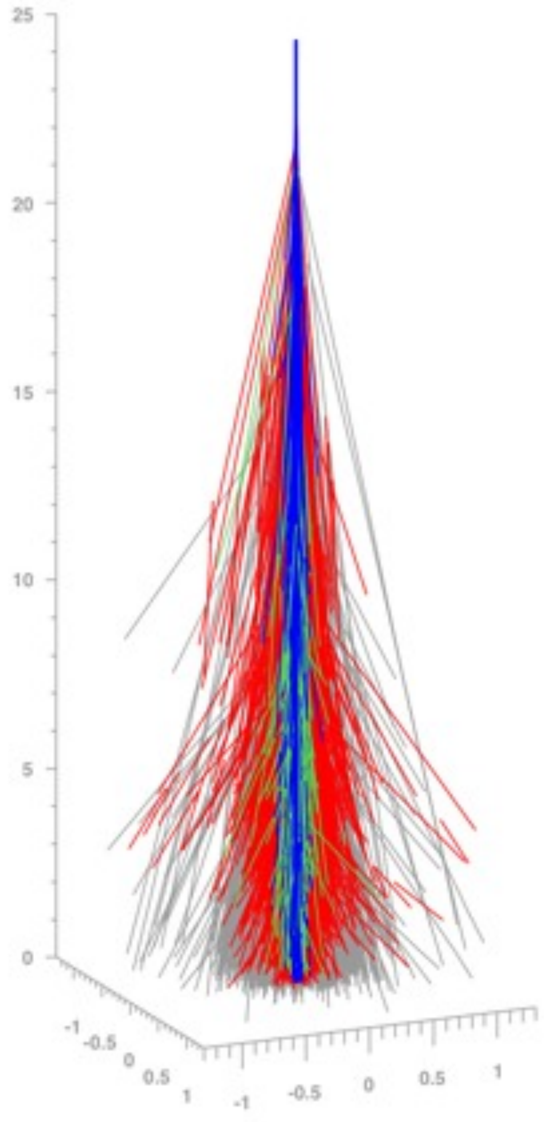
Cosmic Rays of Very High Energy

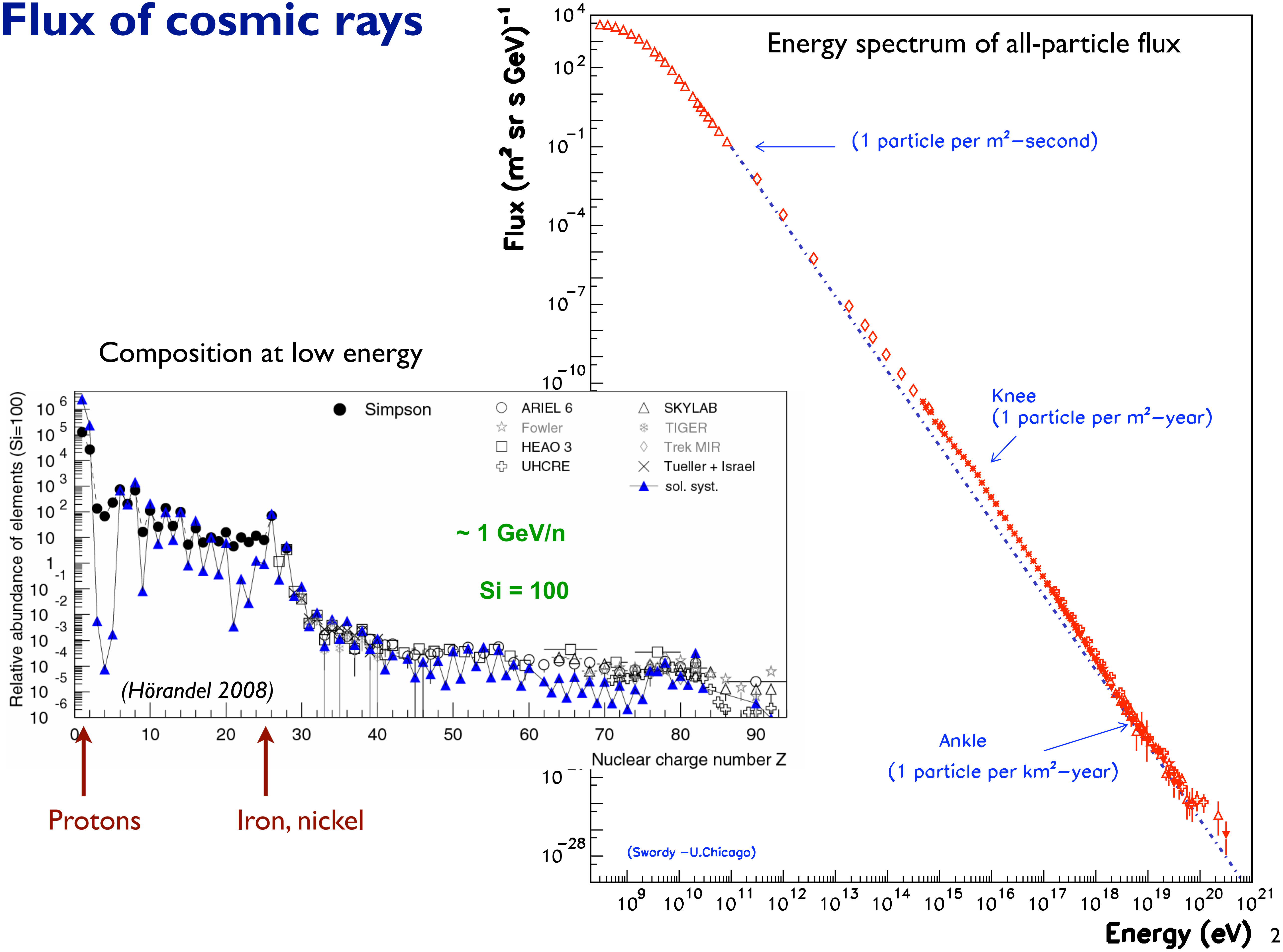


Ralph Engel

Karlsruhe Institute of Technology (KIT)

Karlsruhe Institute of Technology

Flux of cosmic rays



Energy spectrum of all-particle flux

(1 particle per m^2−second)

Knee
(1 particle per m^2−year)

Ankle
(1 particle per km^2−year)

(Swordy −U.Chicago)

Composition at low energy

~ 1 GeV/n

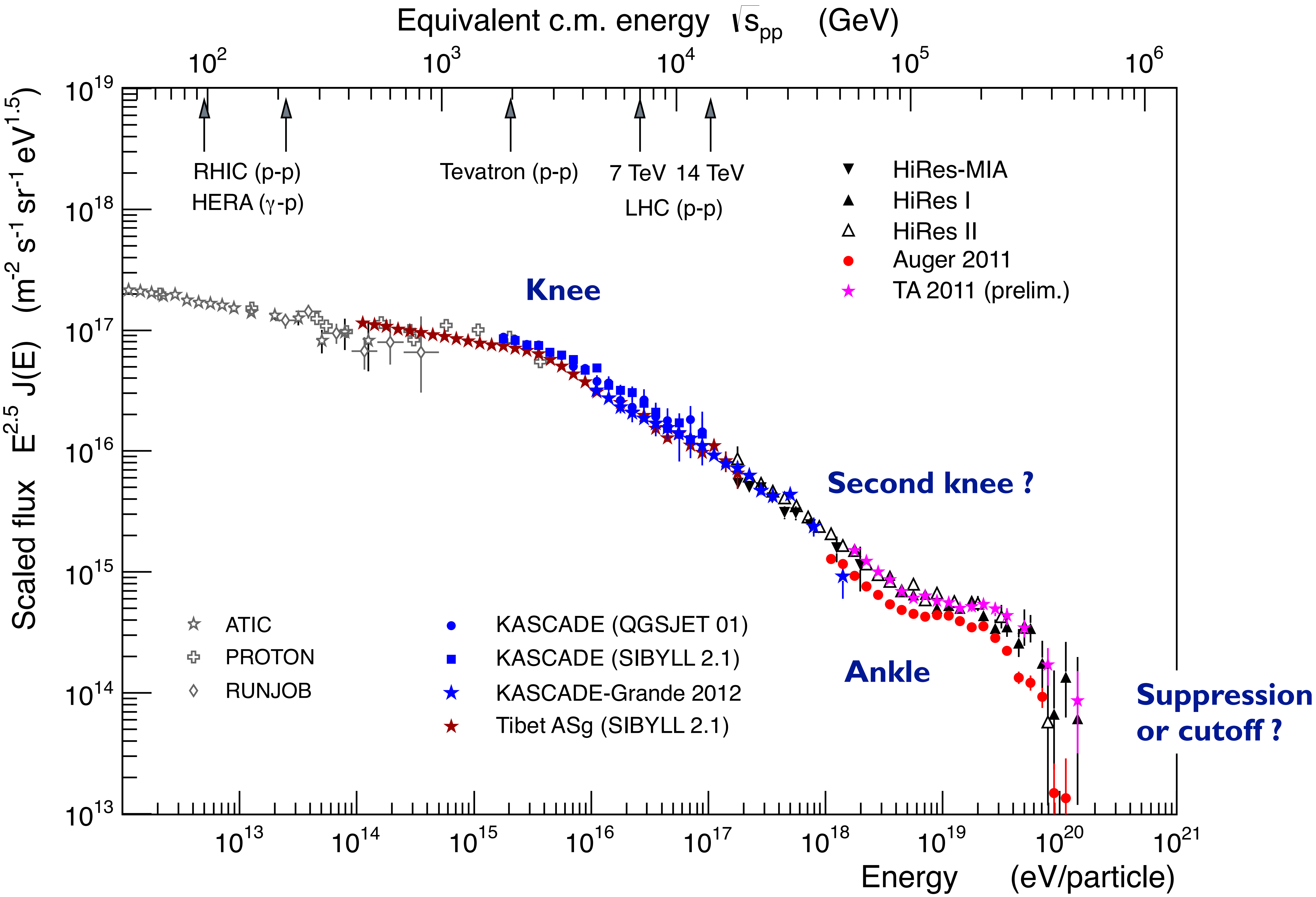
Si = 100

(Hörandel 2008)

Protons

Iron, nickel

General features of cosmic ray flux



Knee

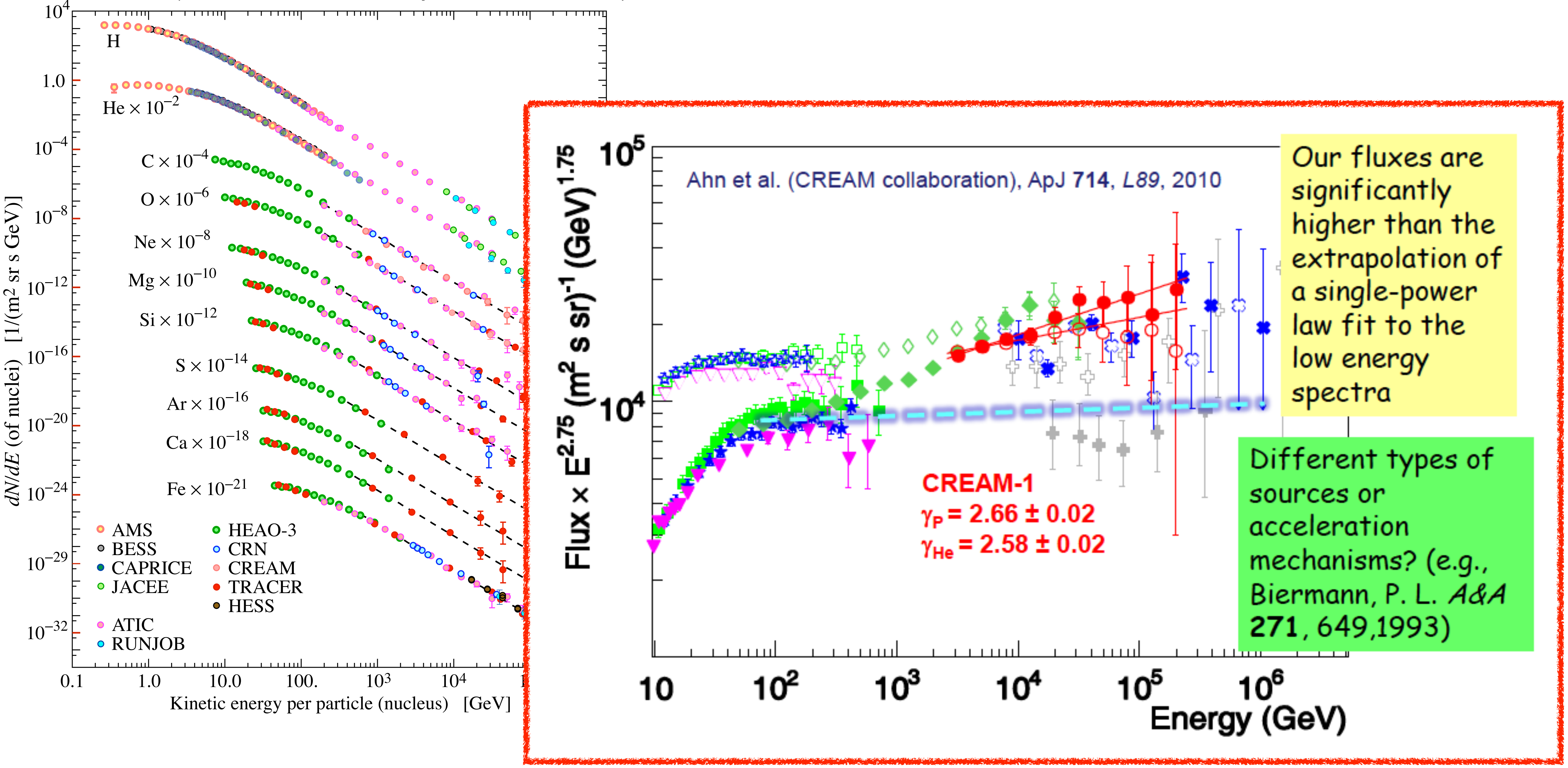
Second knee ?

Ankle

Suppression or cutoff ?

Direct measurements: Harder helium spectrum

(Particle Data Book, Boyle & Müller 2007)



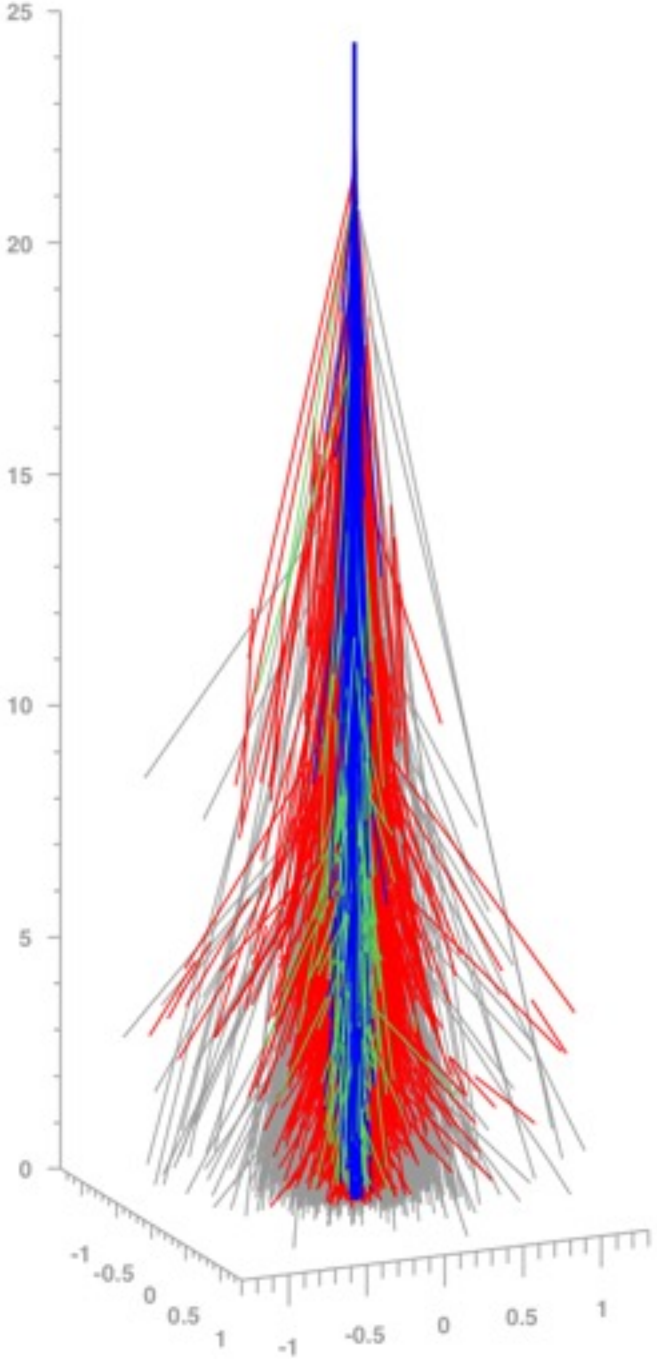
Ahn et al. (CREAM collaboration), ApJ **714**, *L89*, 2010

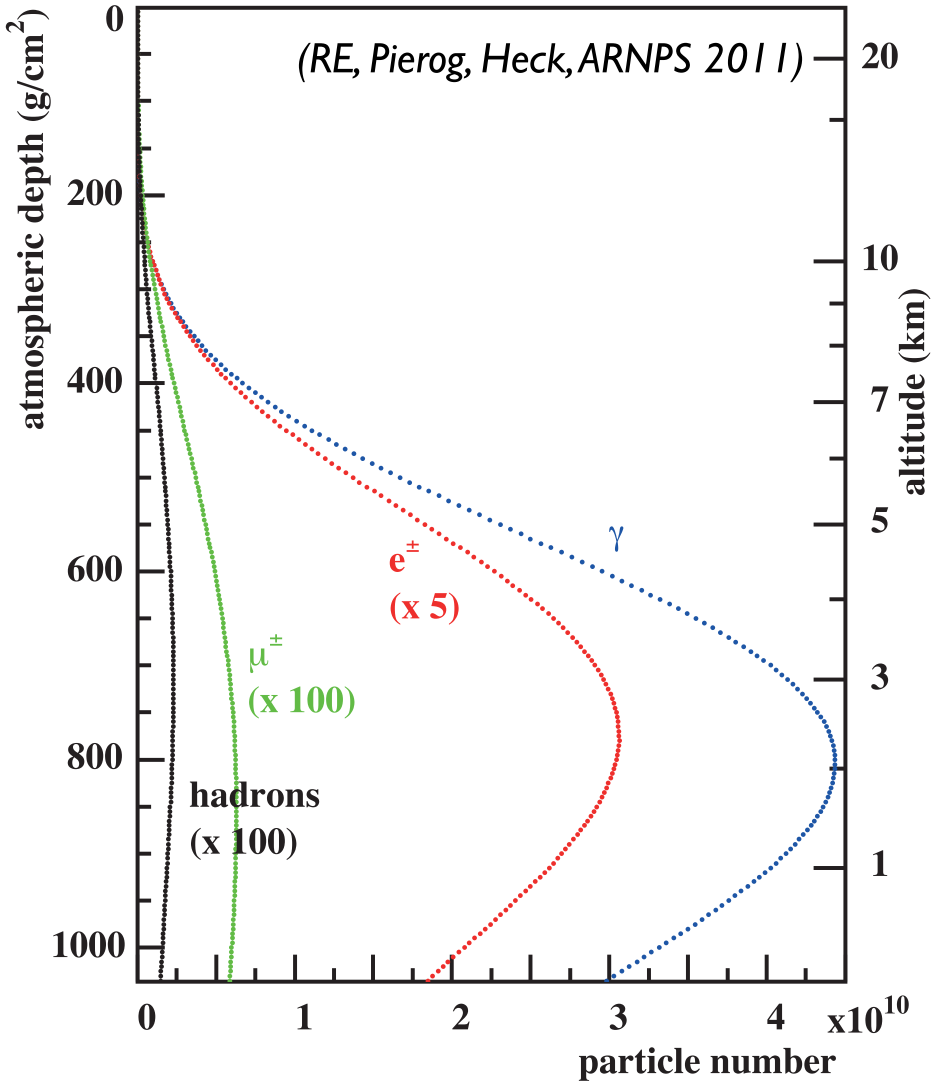
Our fluxes are significantly higher than the extrapolation of a single-power law fit to the low energy spectra

Different types of sources or acceleration mechanisms? (e.g., Biermann, P. L. *A&A* **271**, 649,1993)

Crossing of p and He fluxes cannot be explained with standard shock acceleration scenario

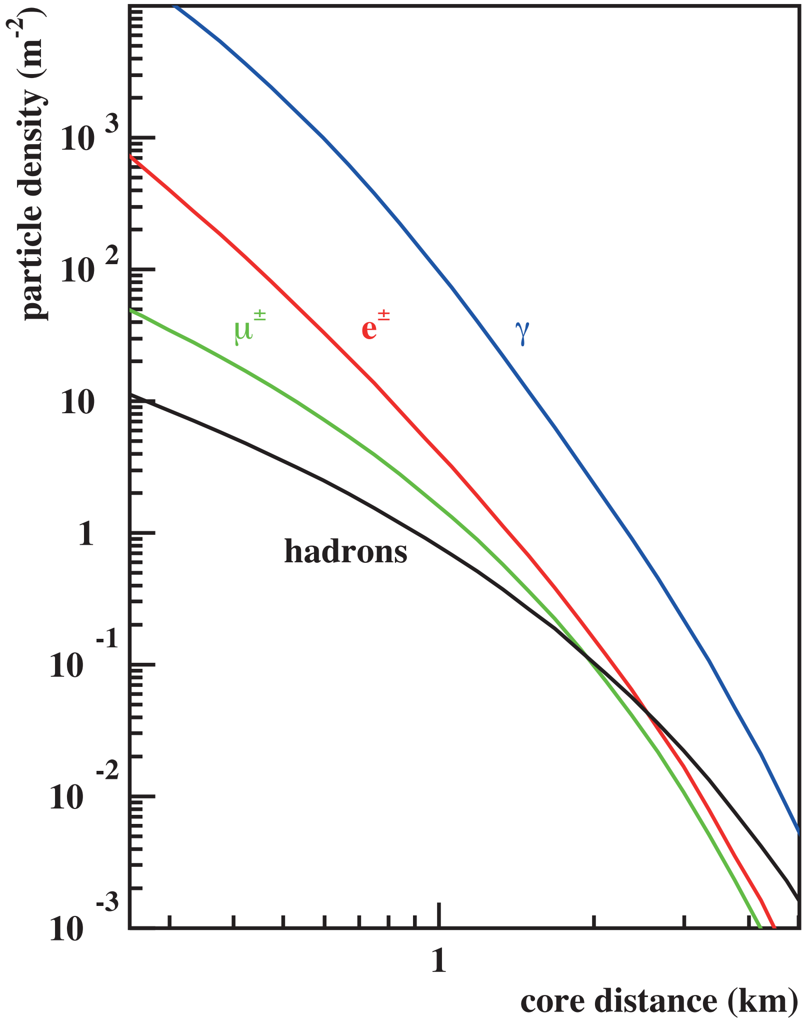
Measured components of air showers




(RE, Pierog, Heck, ARNPS 2011)

Longitudinal profile:

Cherenkov light
Fluorescence light
(bulk of particles measured)



Lateral profiles:

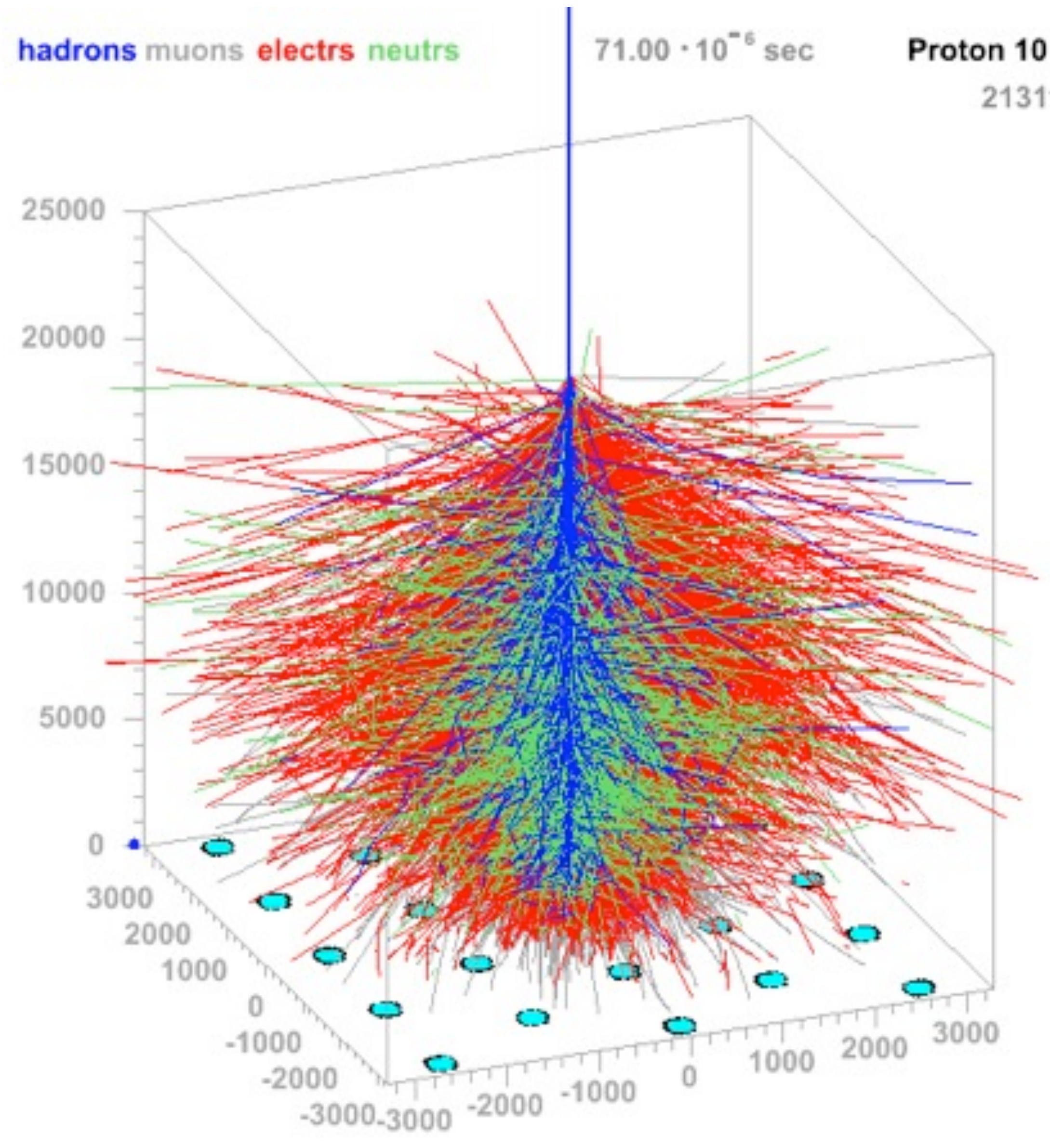
particle detectors at ground
(very small fraction of particles sampled)

KASCADE

Karlsruhe, Germany

Area ~ 0.04 km^2,
252 surface detectors

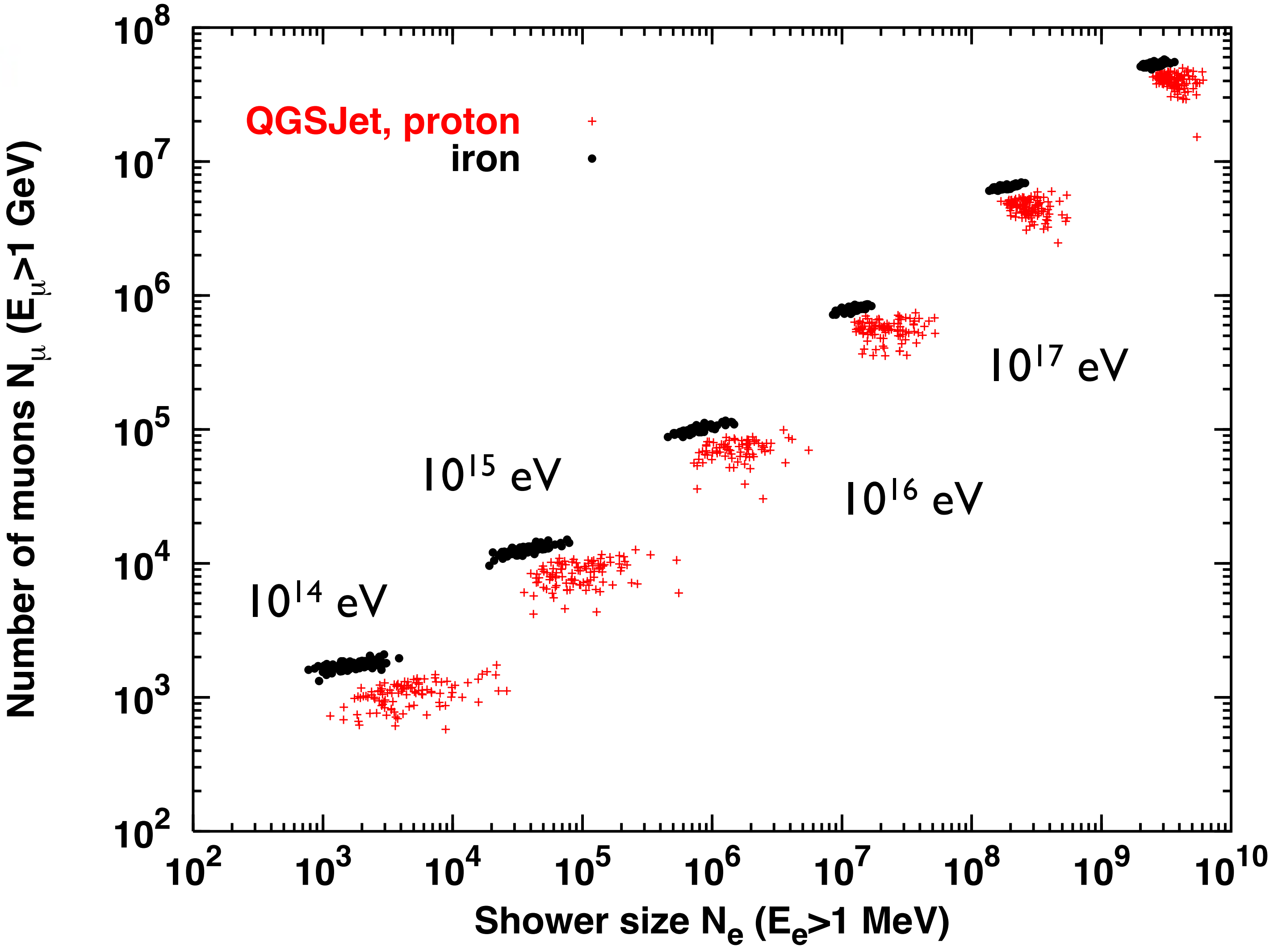
Air shower ground arrays



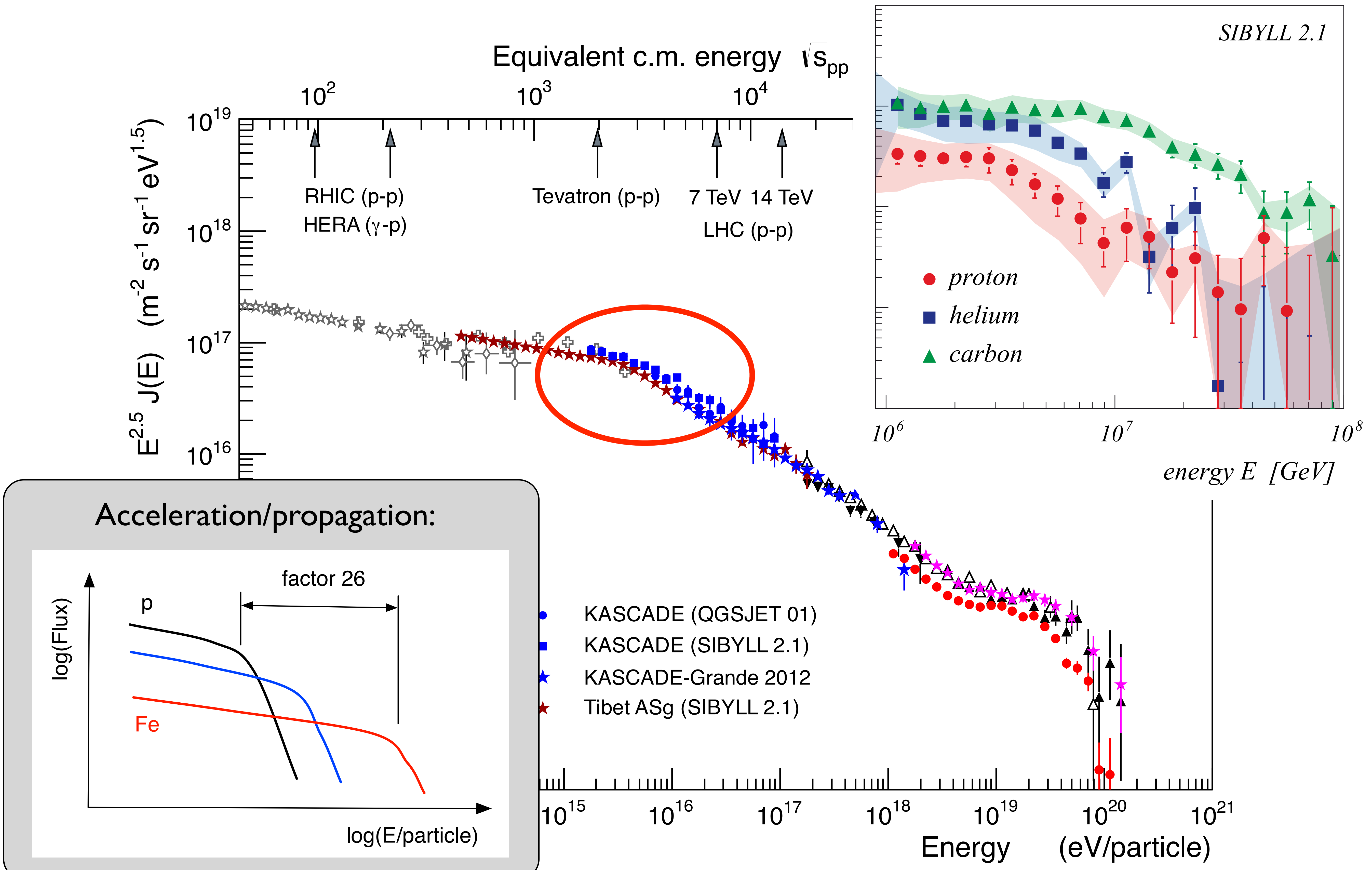
J.Oehlschlaeger,R.Engel,FZKarlsruhe

Example:
KASCADE-Grande (Karlsruhe)

Combined energy-composition analysis



Origin and physics of the knee

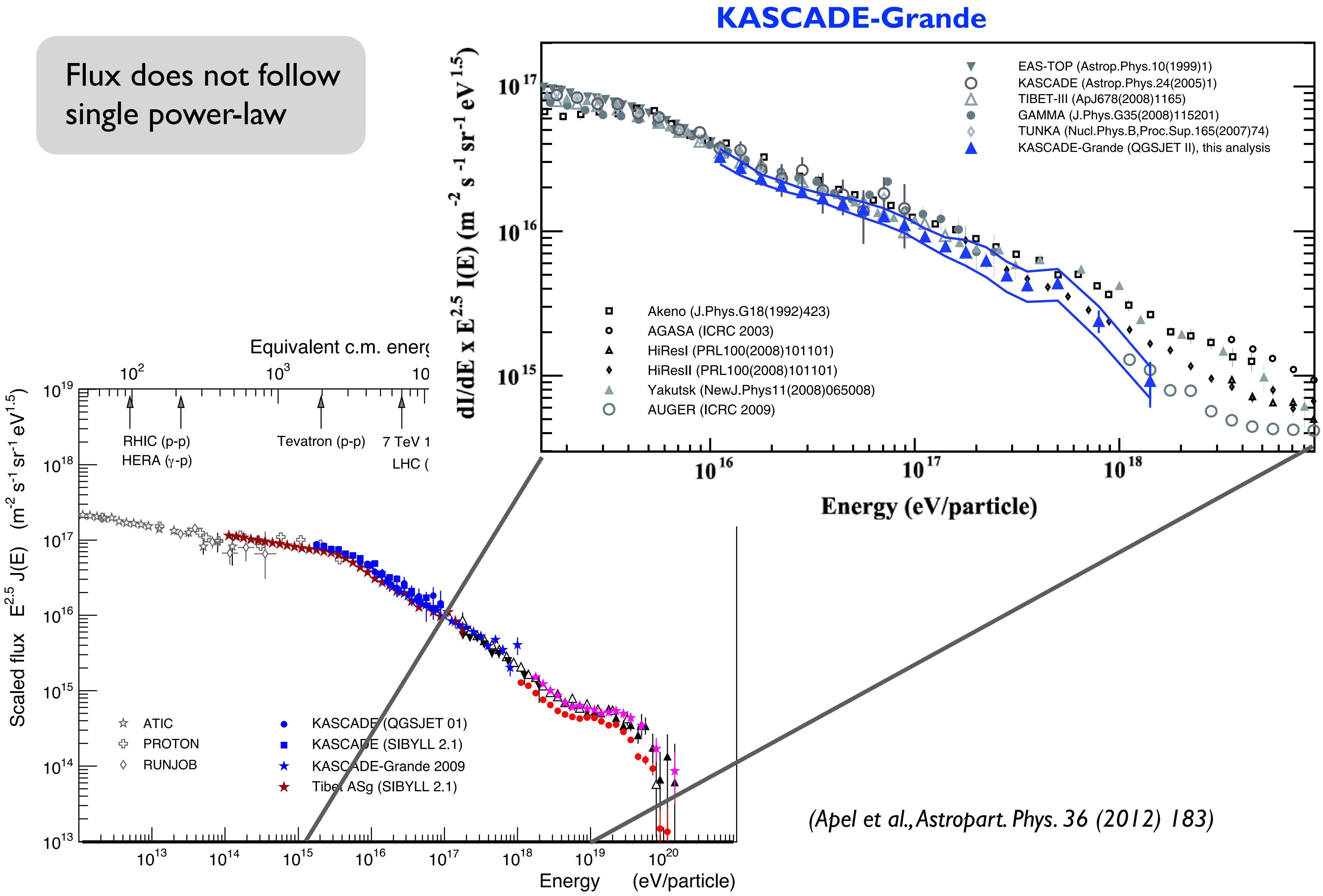


Acceleration/propagation:

(KASCADE, Astropart.Phys. 2005)

Structures above the knee (i)

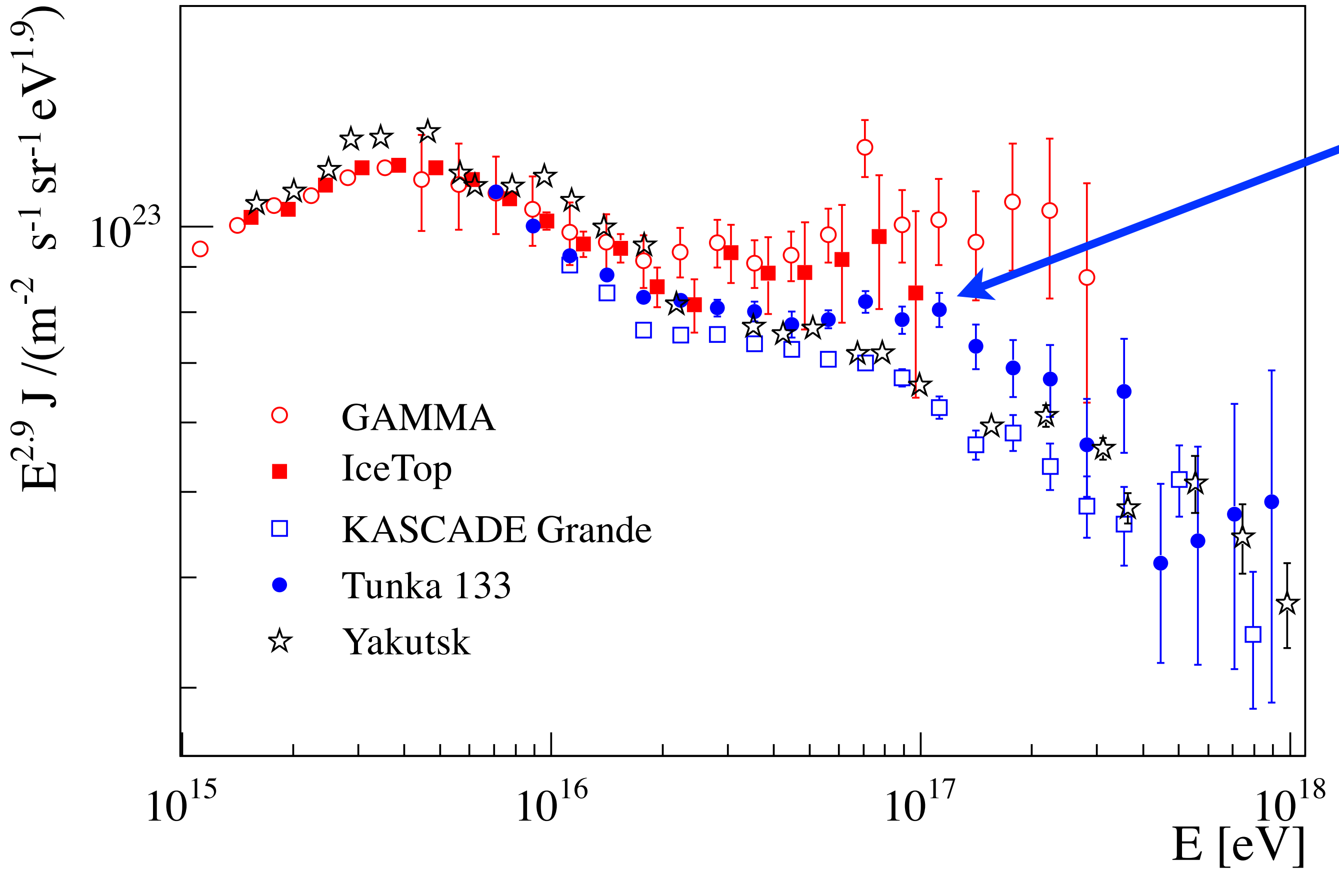
Flux does not follow single power-law



(Apel et al., Astropart. Phys. 36 (2012) 183)

Structures above the knee (ii)

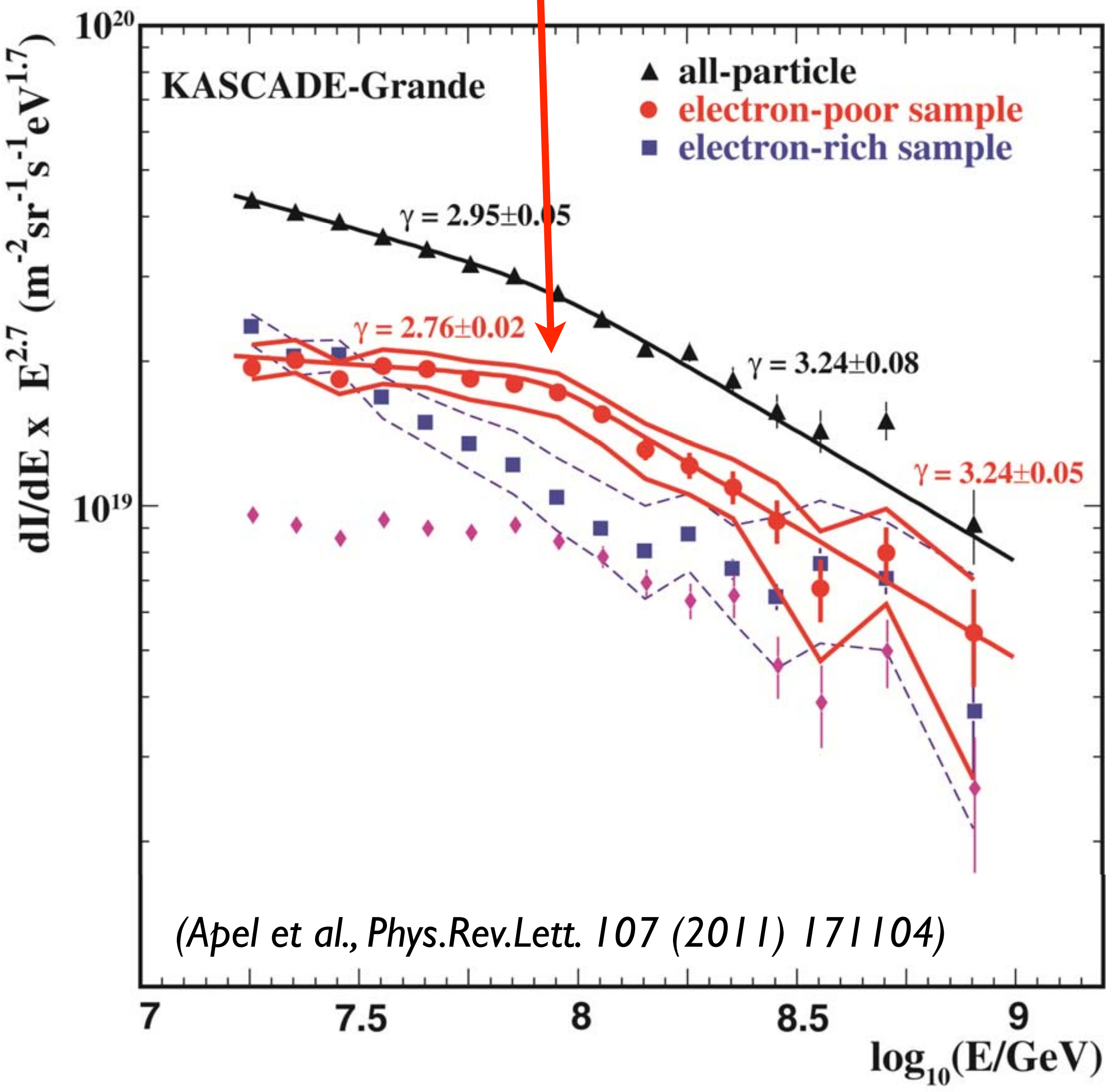
(Unger, rapporteur talk ICRC 2011)



knee of heavy elements

Structure in spectrum also found in other data sets (TUNKA, IceTop)

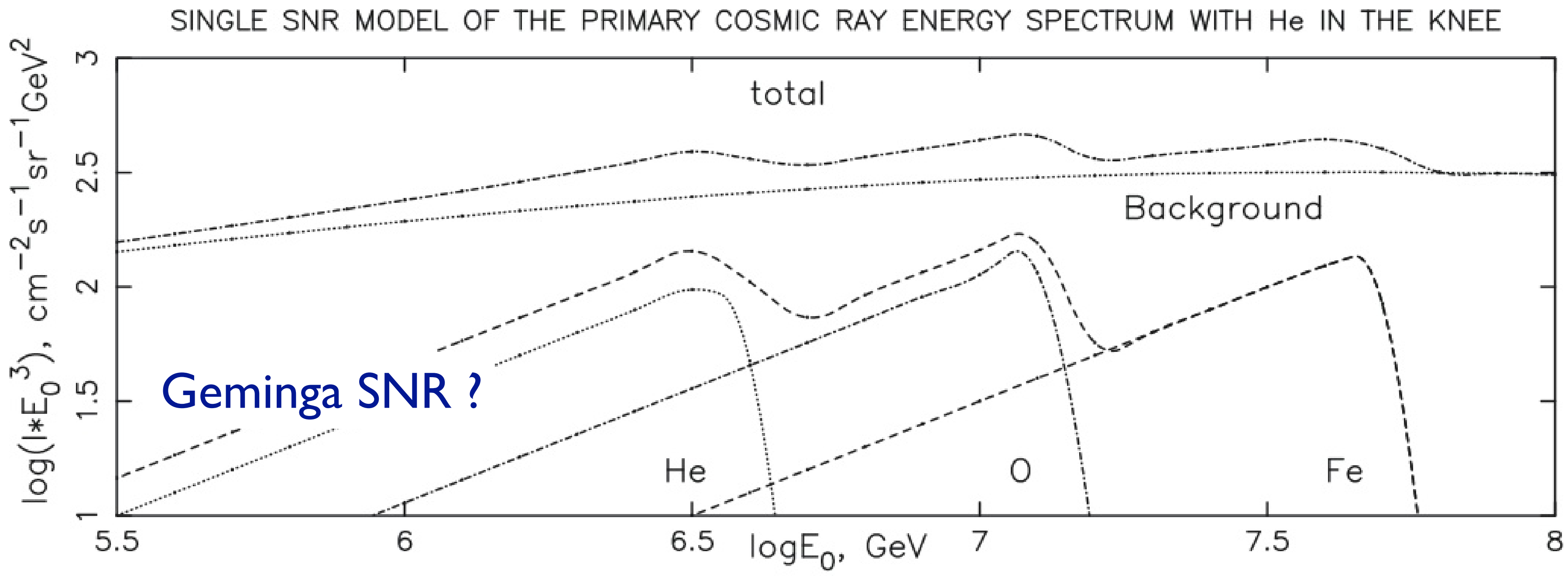
Composition estimate



(Apel et al., Phys.Rev.Lett. 107 (2011) 171104)

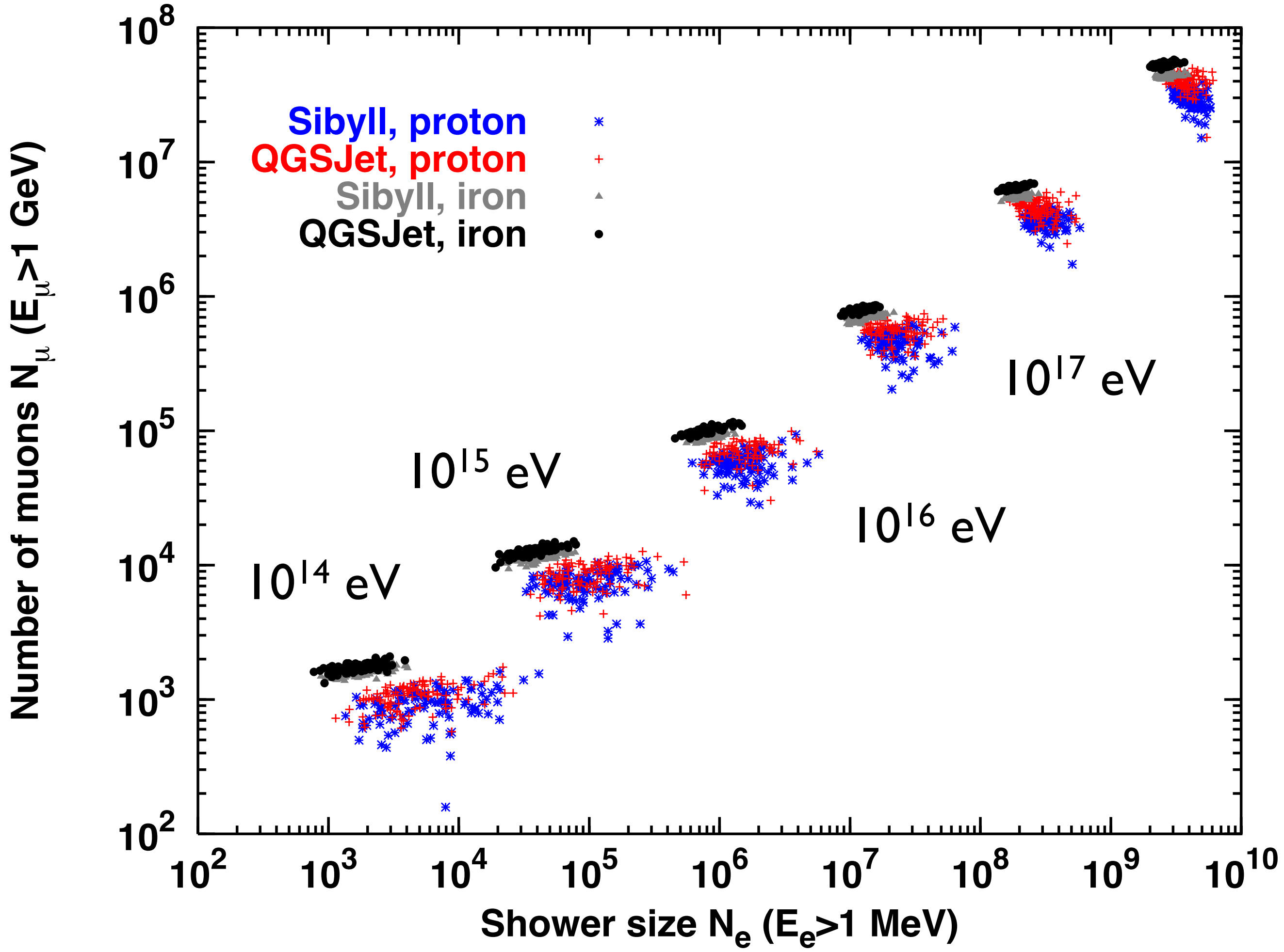
Example of model prediction: Local SNR

Erlykin & Wolfendale,
J.Phys.G32:1-8,2006



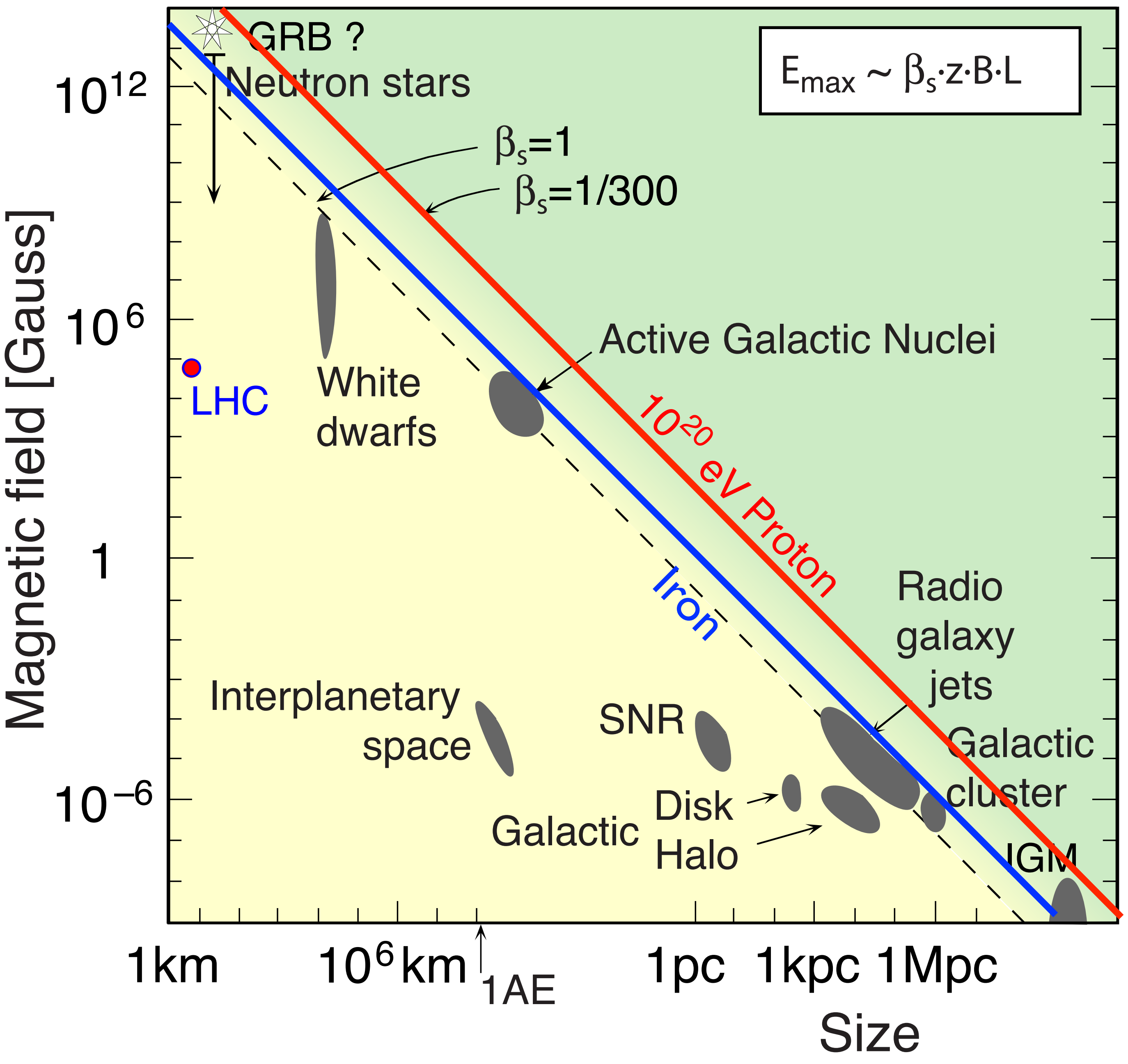
Geminga SNR ?

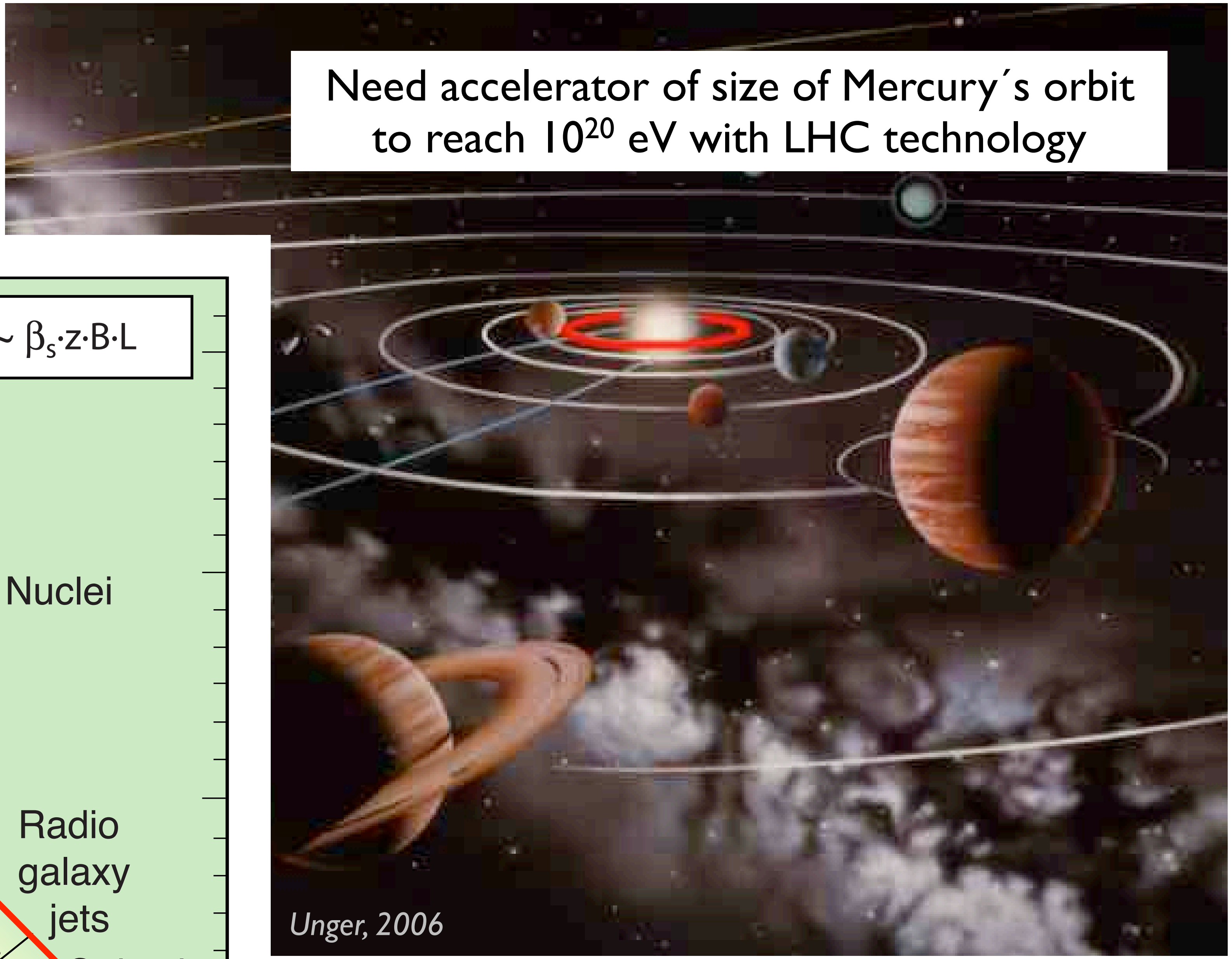
Problem: Main limitation of interpretation of air shower data stems from uncertainties in shower simulations



Ultra-high energies of order of 10^{20} eV

Hillas plot (1984)





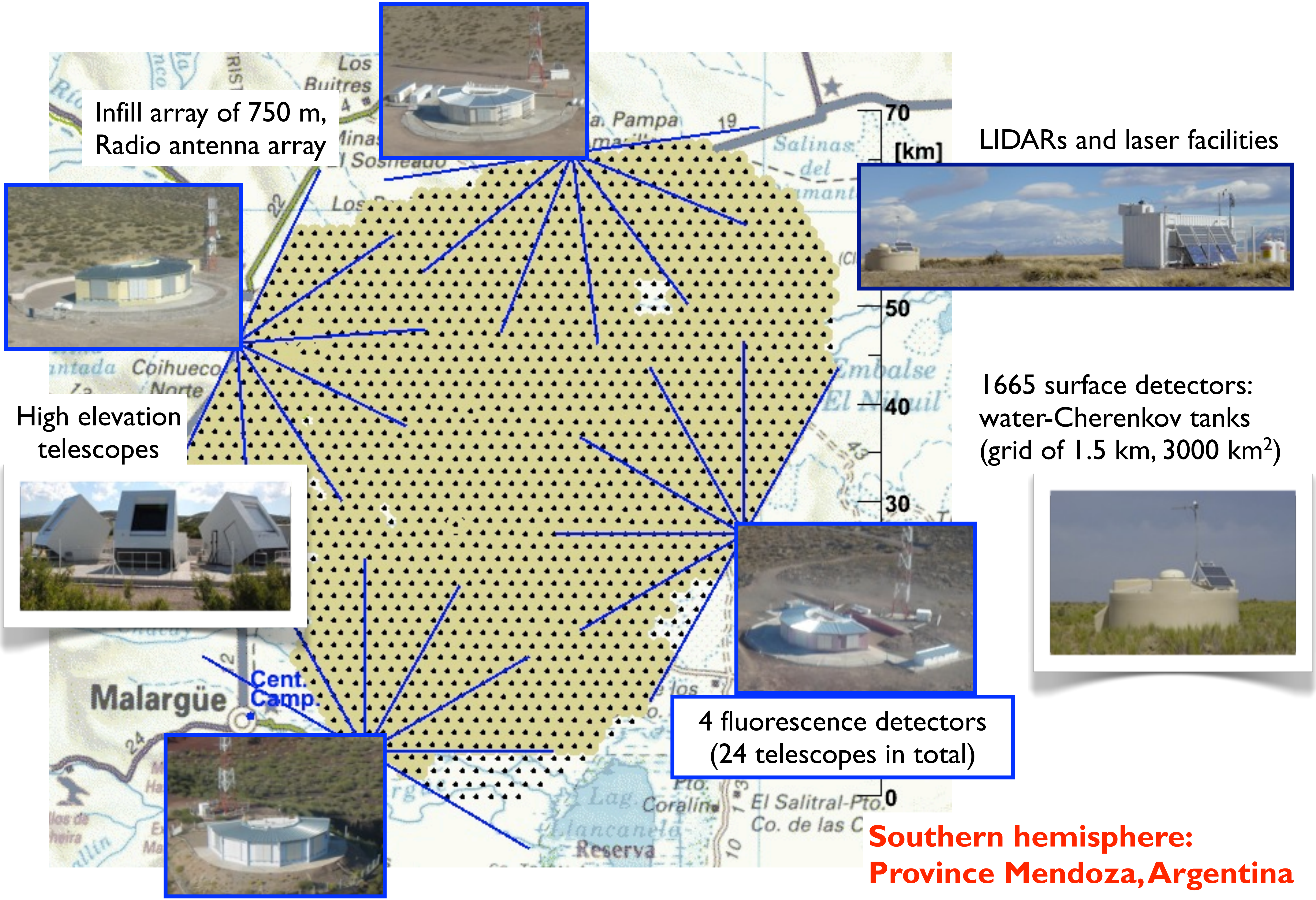
Need accelerator of size of Mercury´s orbit to reach 10^{20} eV with LHC technology

Unger, 2006

Realistic constraints more severe

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

The Pierre Auger Observatory



Infill array of 750 m,
Radio antenna array

High elevation
telescopes

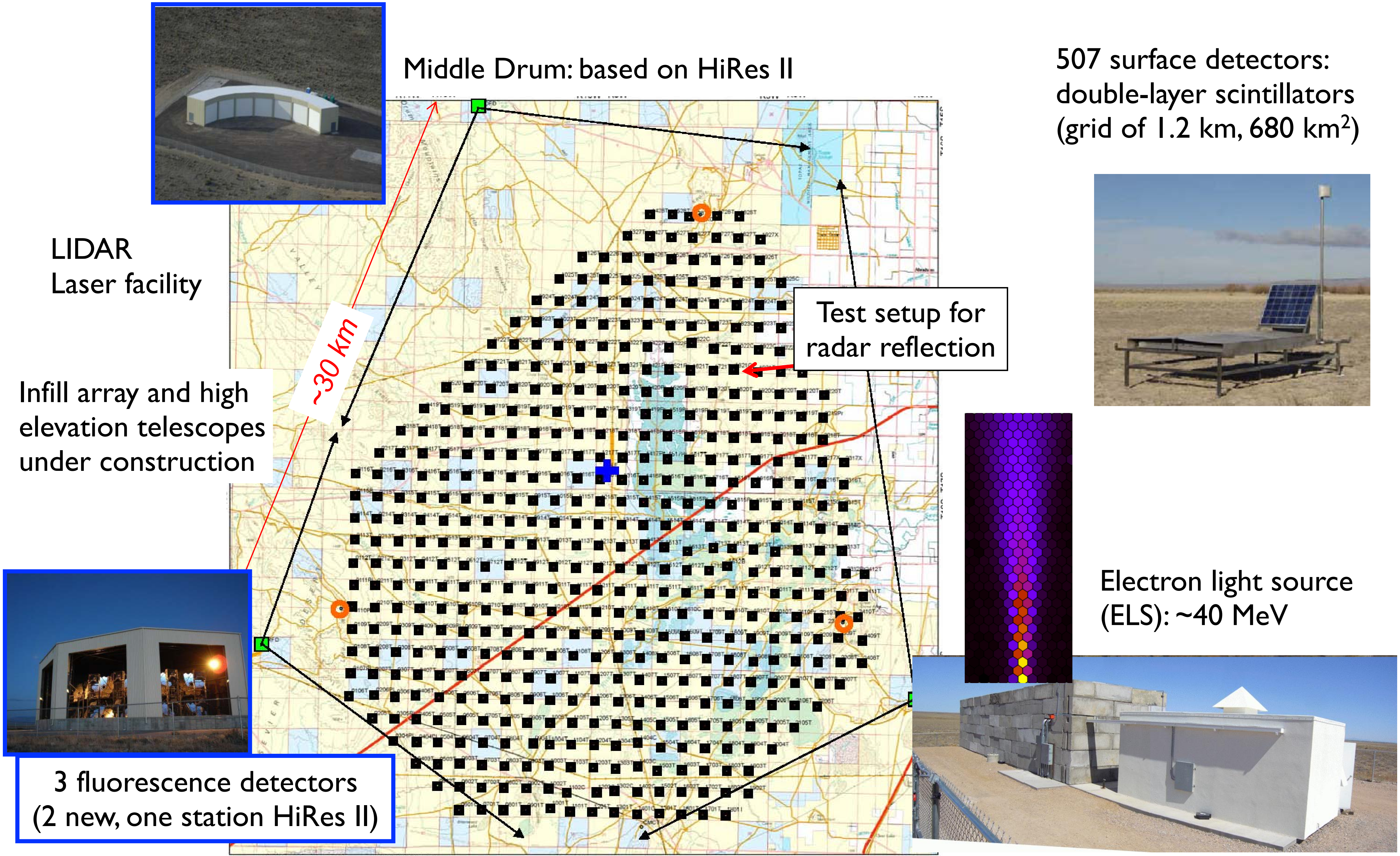
LIDARs and laser facilities

1665 surface detectors:
water-Cherenkov tanks
(grid of 1.5 km, 3000 km^2)

4 fluorescence detectors
(24 telescopes in total)

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, 680 km^2)

LIDAR
Laser facility

Test setup for radar reflection

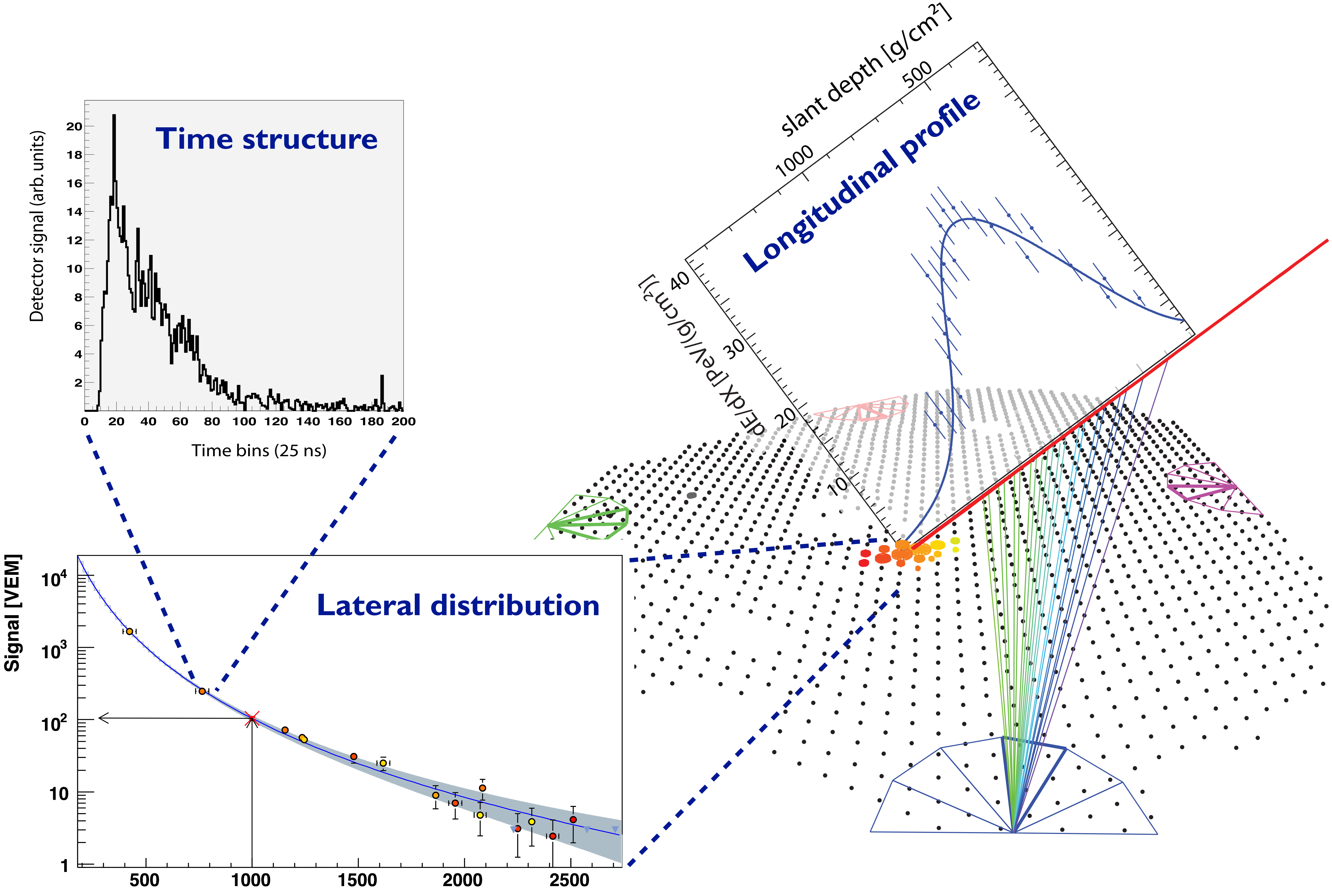
Infill array and high elevation telescopes under construction

Electron light source (ELS): ~40 MeV

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

Northern hemisphere: Utah, USA

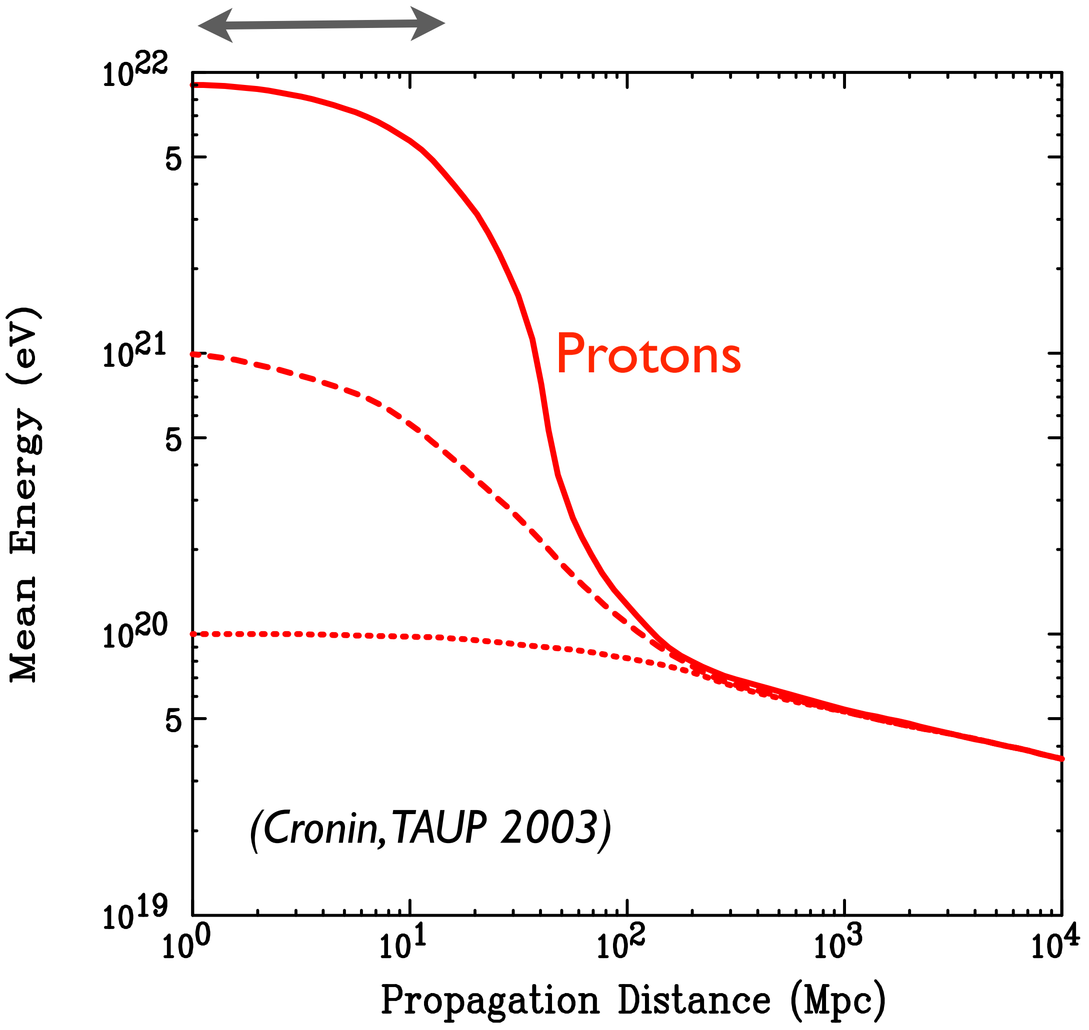
Several shower observables



Example: event observed by Auger

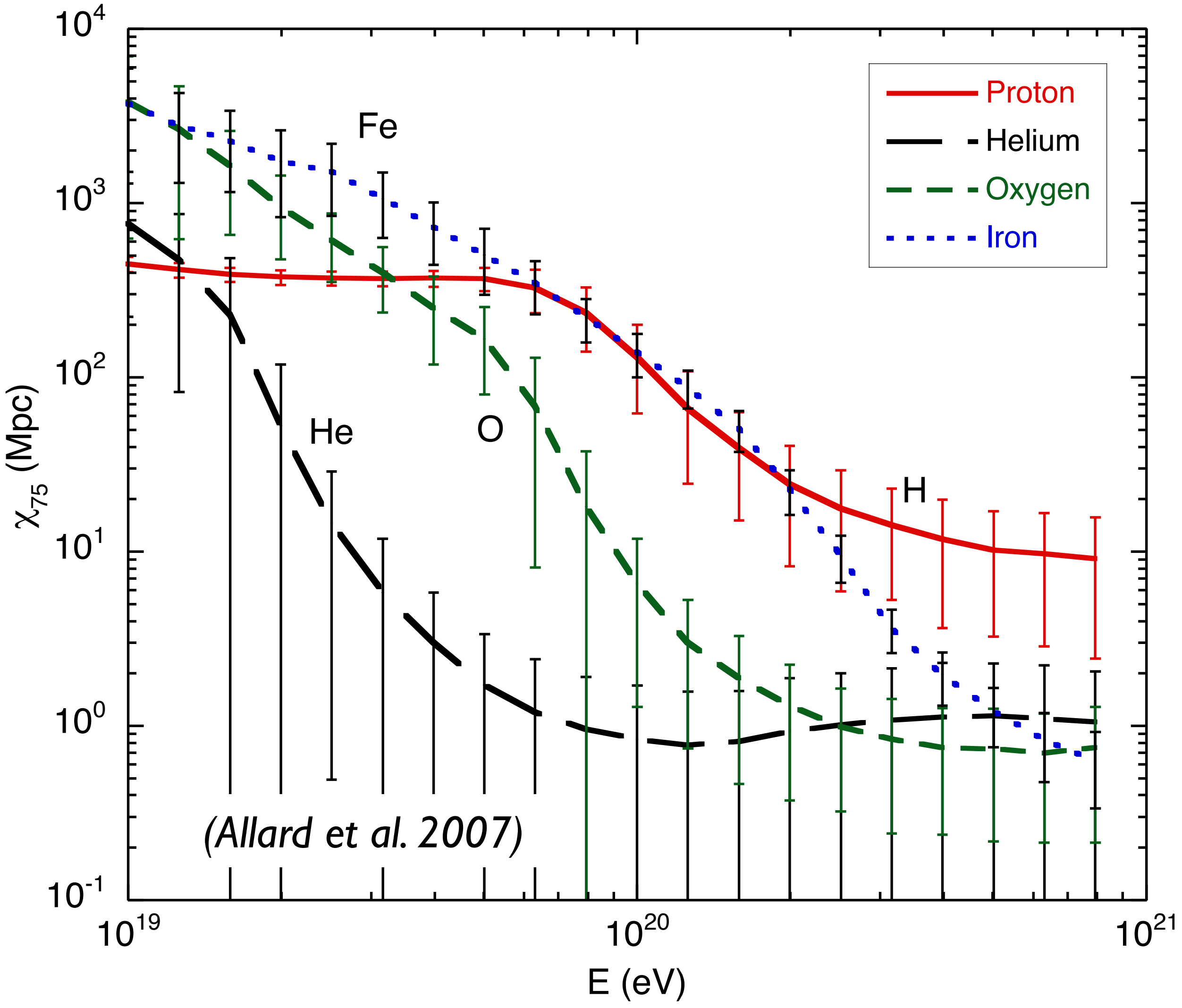
Problem 2: flux suppression due to GZK effect

Energy loss length



(Cronin, TAUP 2003)

Energy loss length



(Allard et al. 2007)

Greisen-Zatsepin-Kuzmin effect (1966)

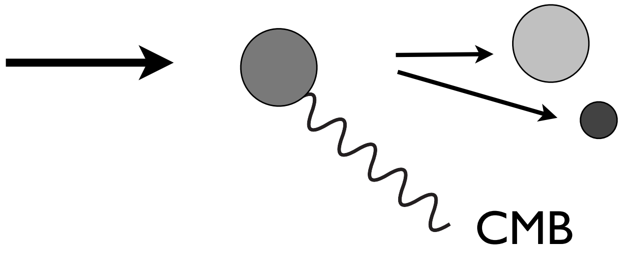
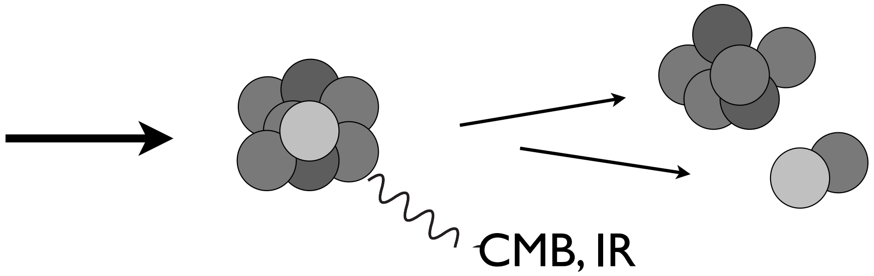


Photo-pion production

Photo-dissociation (giant dipole resonance)



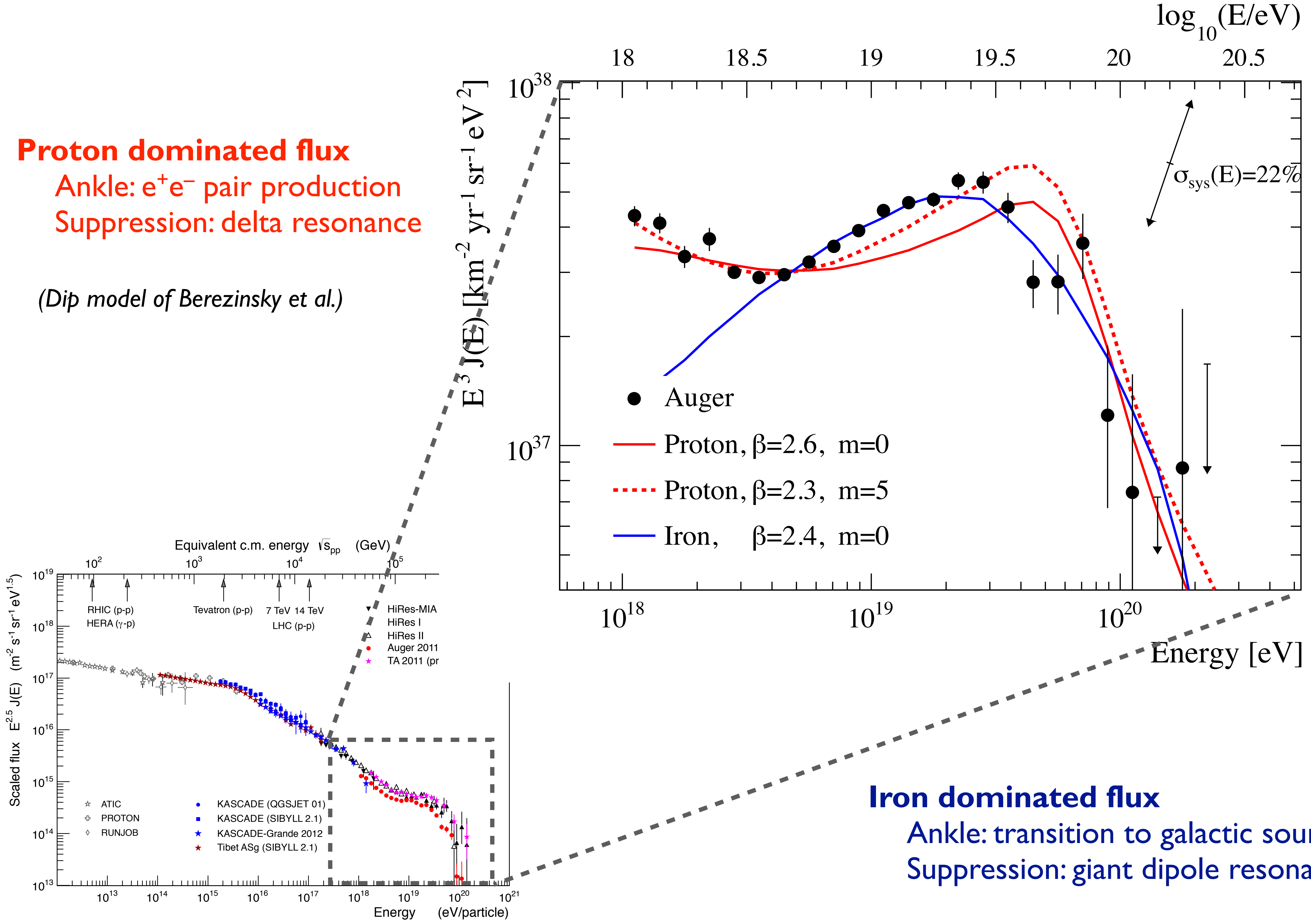
Flux suppression compatible with GZK effect ?

Proton dominated flux

Ankle: e⁺e⁻ pair production

Suppression: delta resonance

(Dip model of Berezinsky et al.)

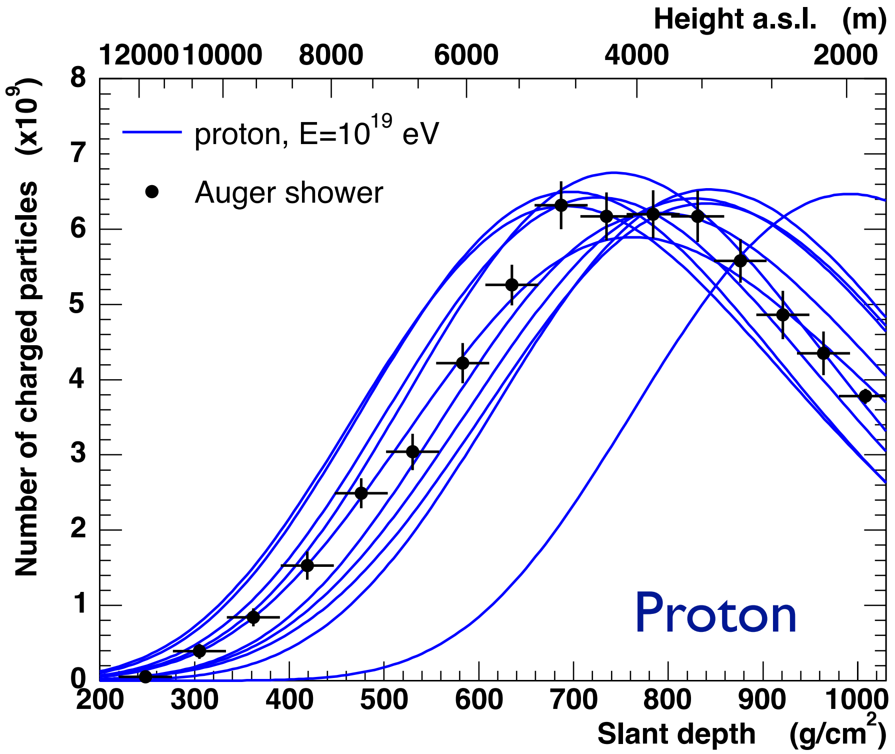


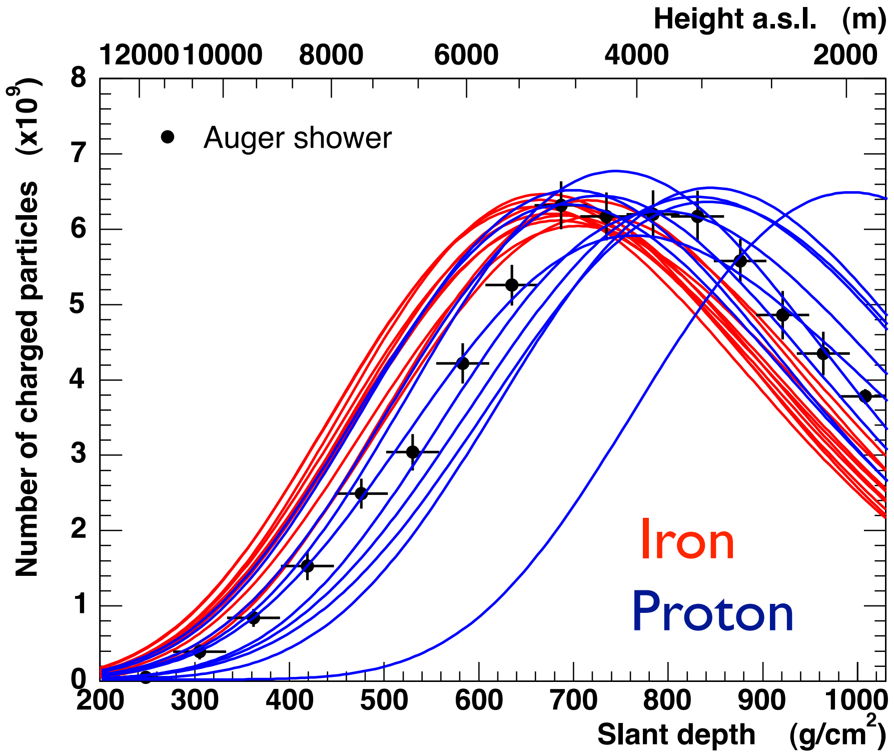
Iron dominated flux

Ankle: transition to galactic sources

Suppression: giant dipole resonance

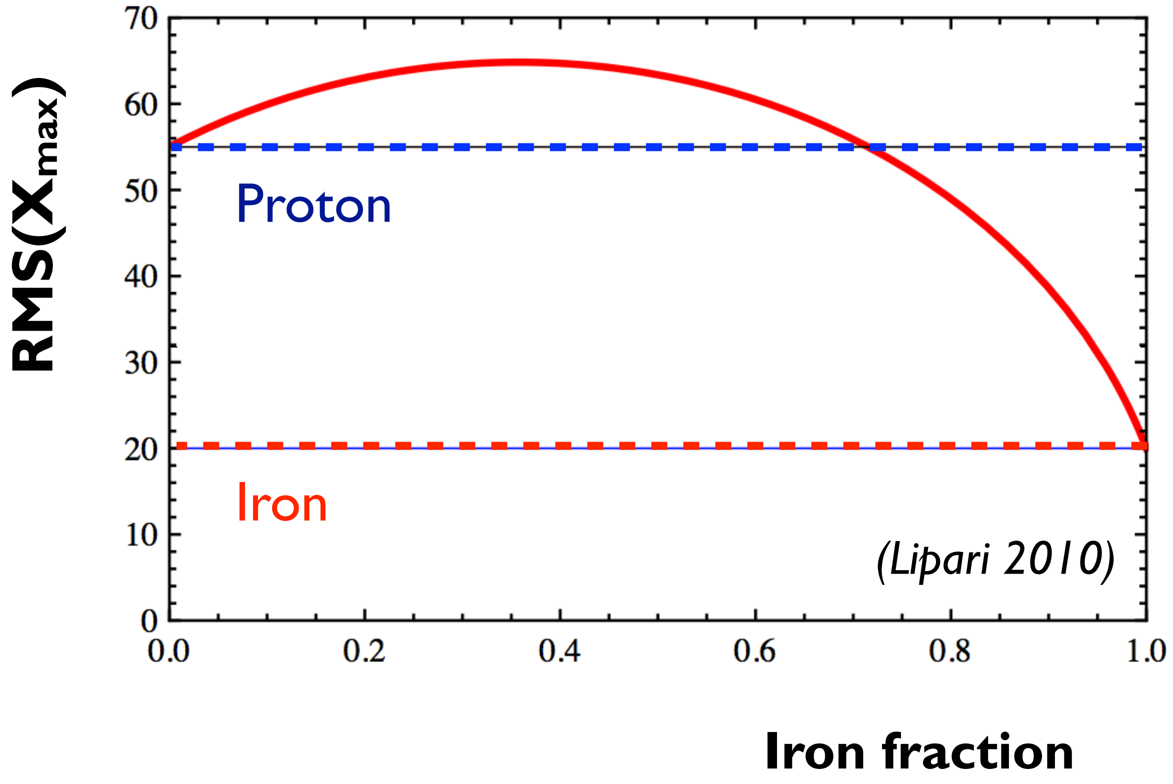
Auger data on shower profiles





Example: event measured by Auger Collab.

Fluctuations of depth of shower maximum



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

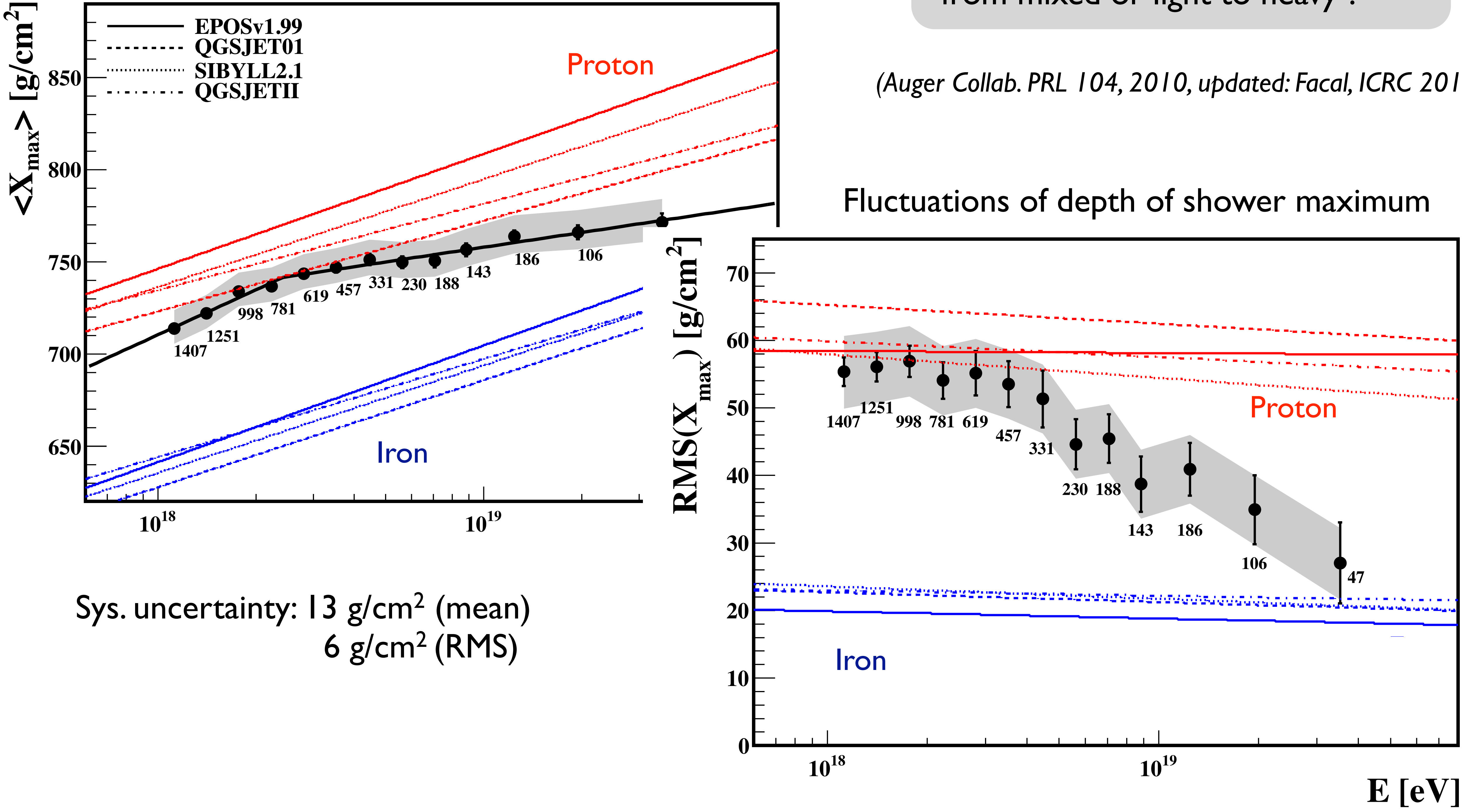
Auger Observatory: Composition data

Change of cosmic ray composition from mixed or light to heavy ?

(Auger Collab. PRL 104, 2010, updated: Facal, ICRC 2011)

Mean depth of shower maximum

Fluctuations of depth of shower maximum



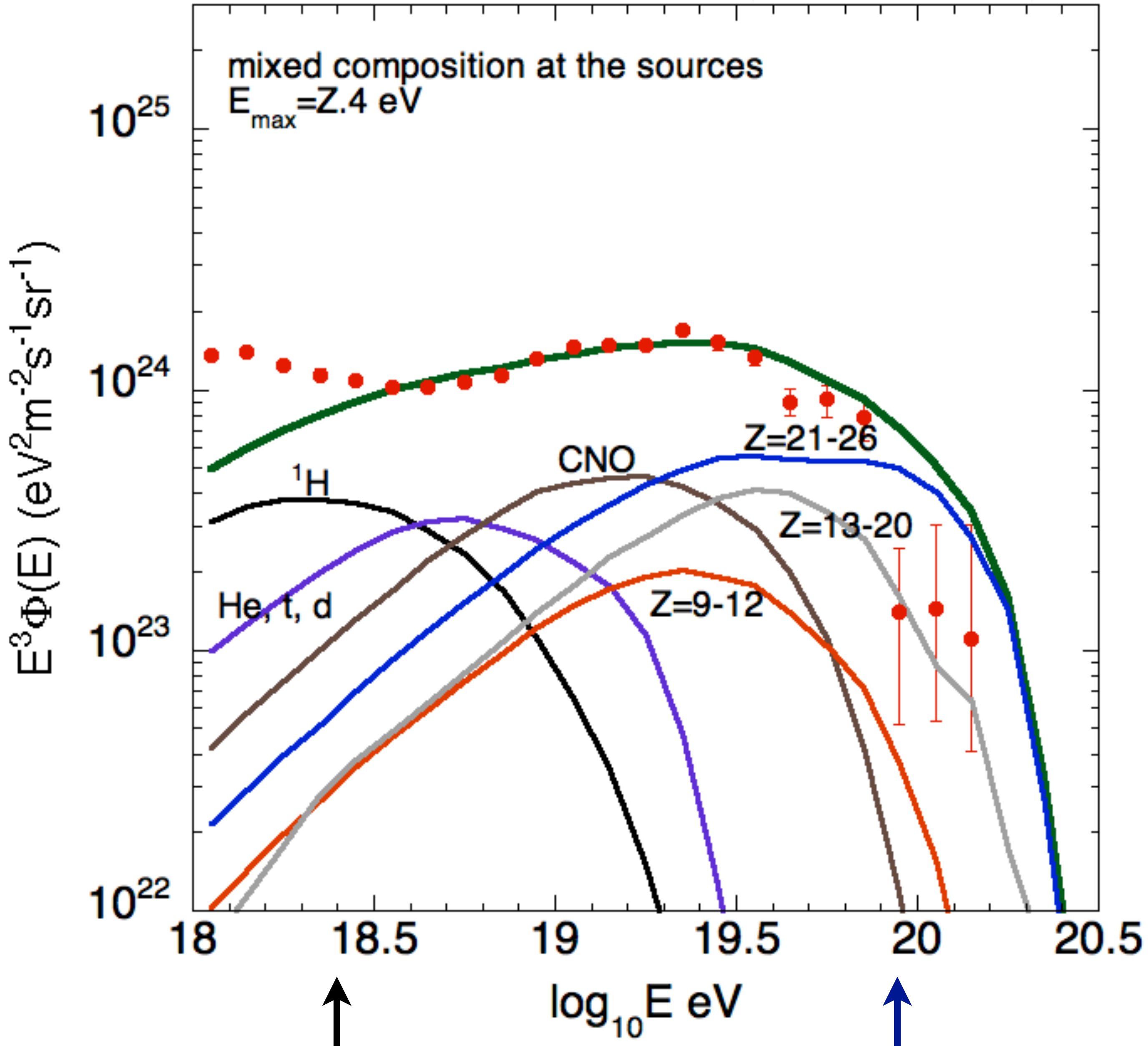
Sys. uncertainty: 13 g/cm^2 (mean)
6 g/cm^2 (RMS)

$$\sigma_X^2 = f_p\, \sigma_p^2 + (1-f_p)\, \sigma_{\rm Fe}^2 + f_p(1-f_p)\, \left(\langle X_p\rangle - \langle X_{\rm Fe}\rangle\right)^2$$

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

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

$$\frac{dN}{dE} \sim E^{-(1.0...1.6)}$$

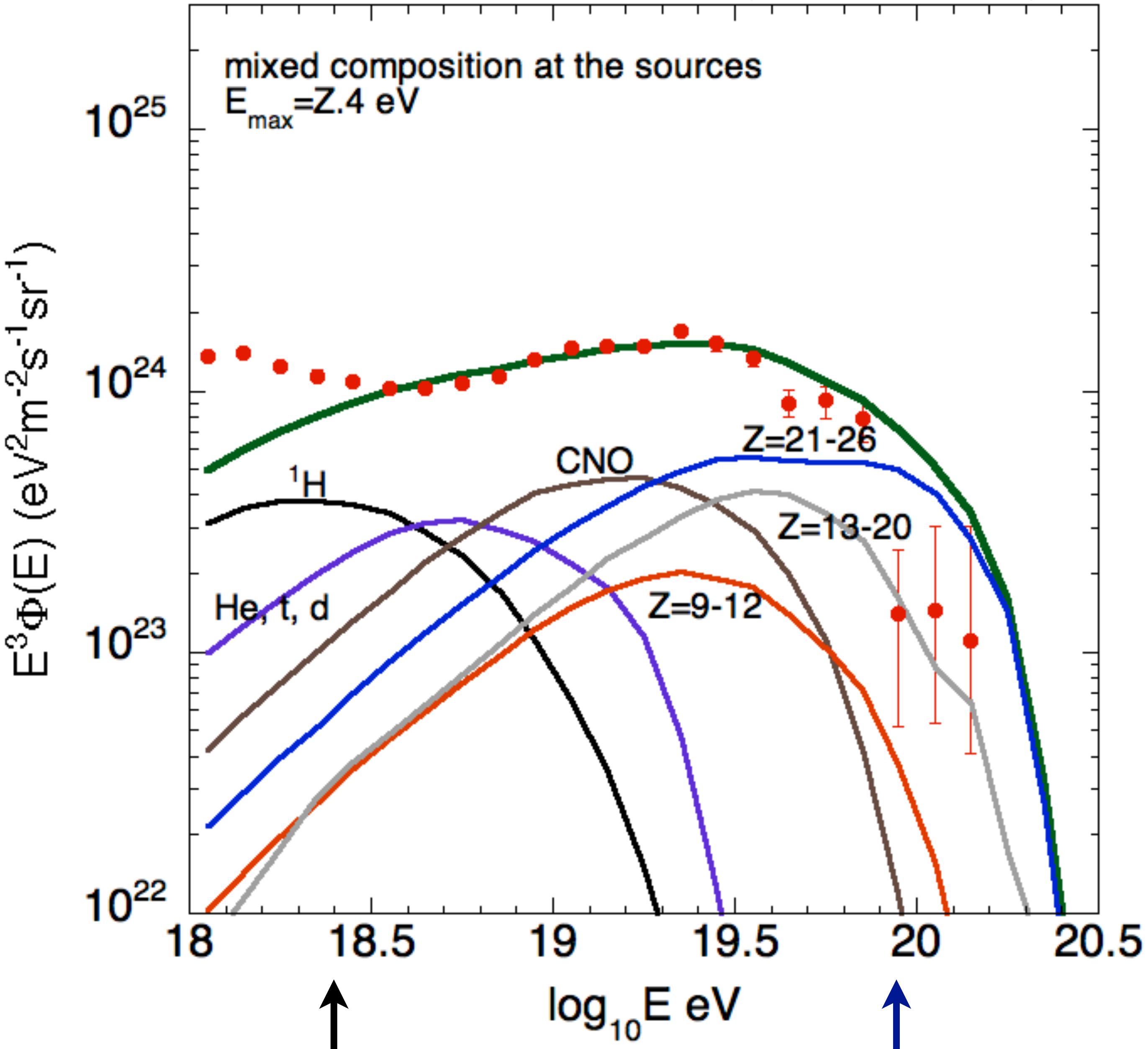
Astrophysics: very exotic result!

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

Upper end of source energy spectrum seen ?

Particle flux

(Allard, 1111.3290)



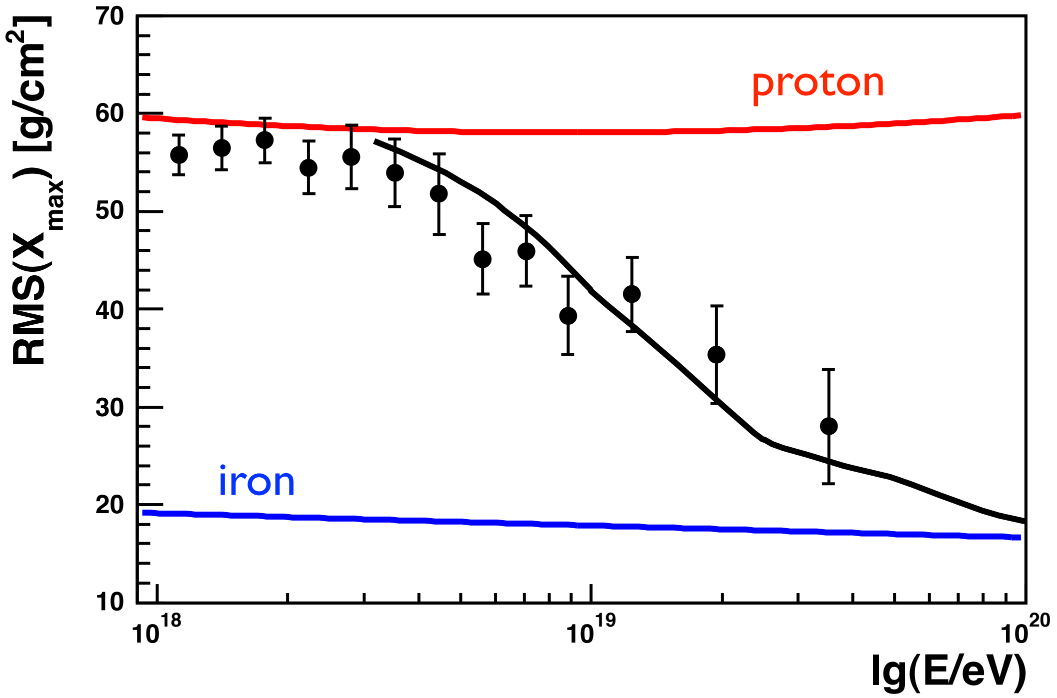
Protons $E_{max,p} = 10^{18.4}$ eV

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)

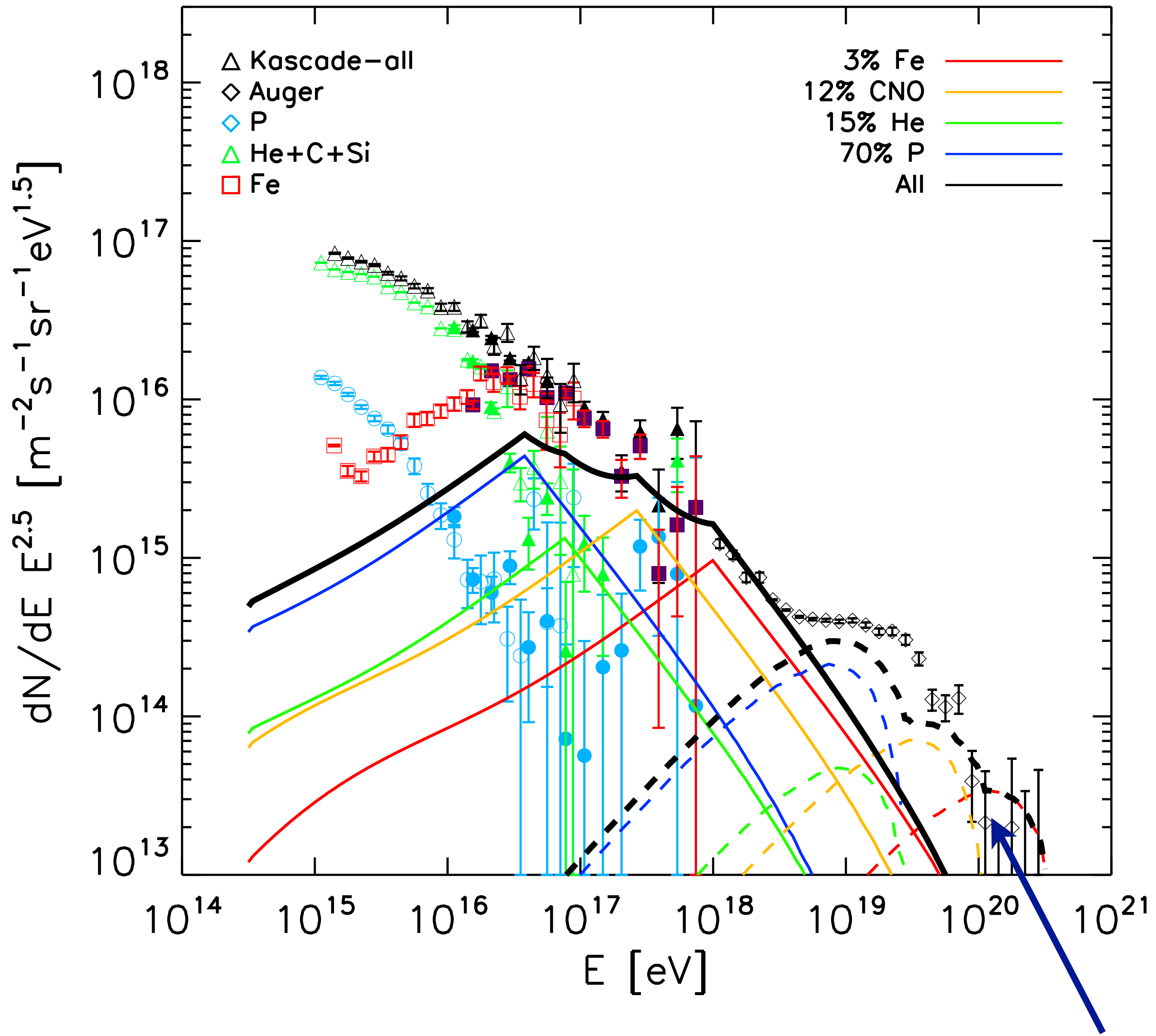


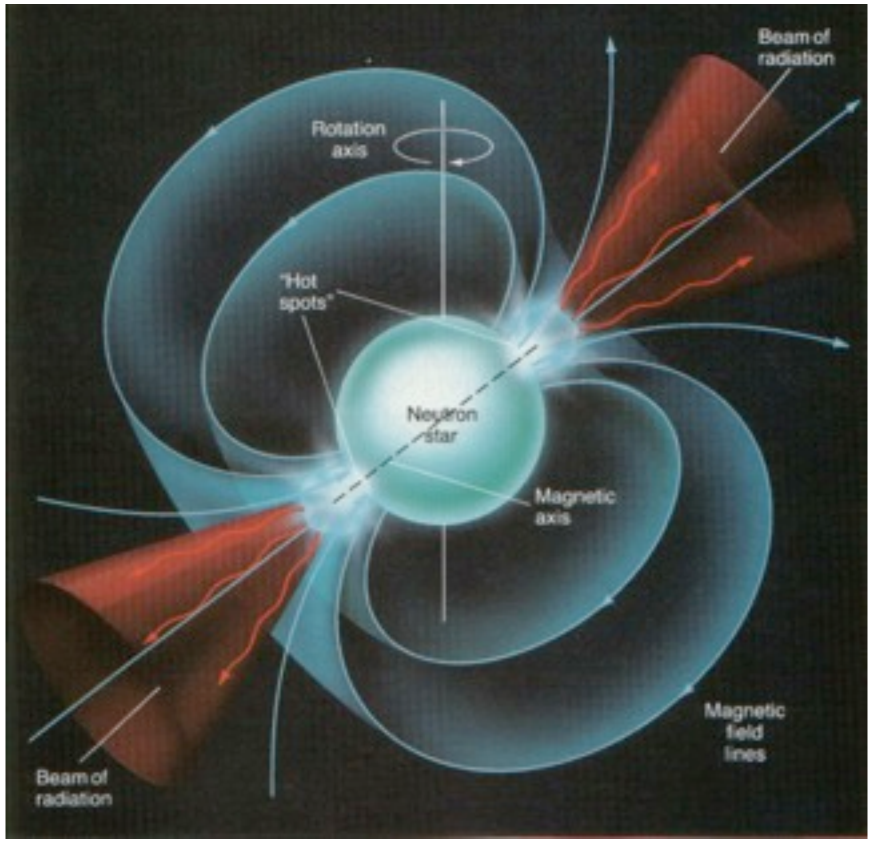
Different interpretation:
Suppression not due mainly to GZK energy-loss effect

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

Example: magnetar model

(Olinto, Kotera et al., 2012)





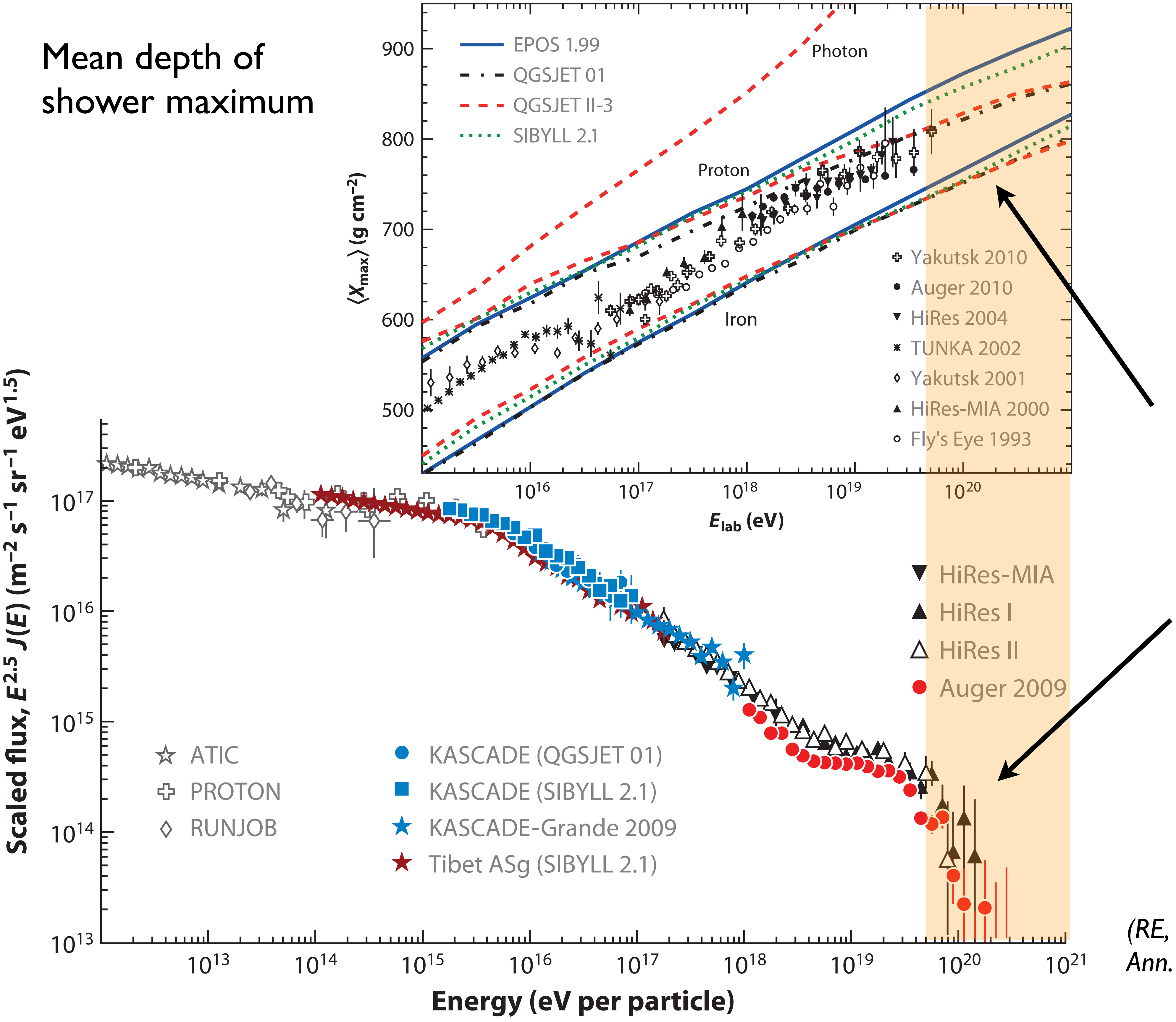
$$\frac{\mathrm{d}N_{\mathrm{inj}}}{\mathrm{d}E} \sim E^{-1}\left(1+\frac{E}{E_g}\right)^{-1}$$

Low-energy part:
many galactic magnetars

High-energy part:
extragalactic (extreme) magnetar

GZK suppression or maximum injection energy?

Mean depth of shower maximum



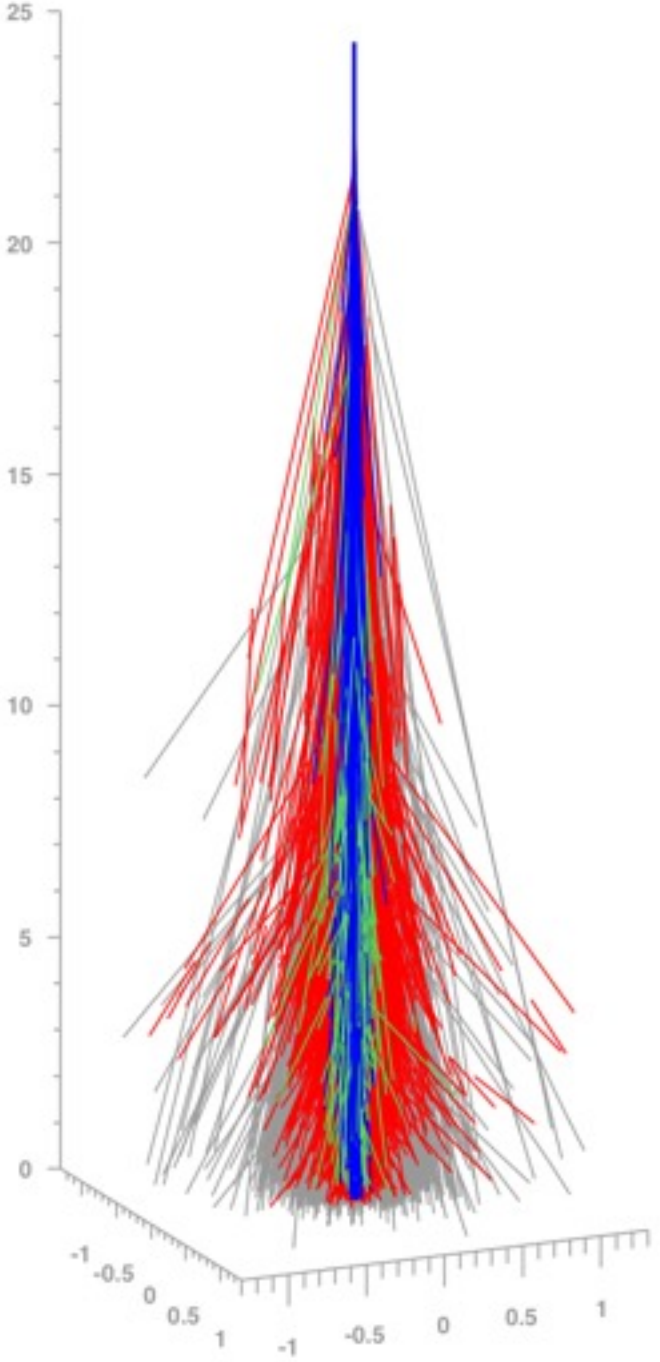
How to reduce uncertainties in shower predictions?

How to extend composition-sensitive measurements to higher energy?

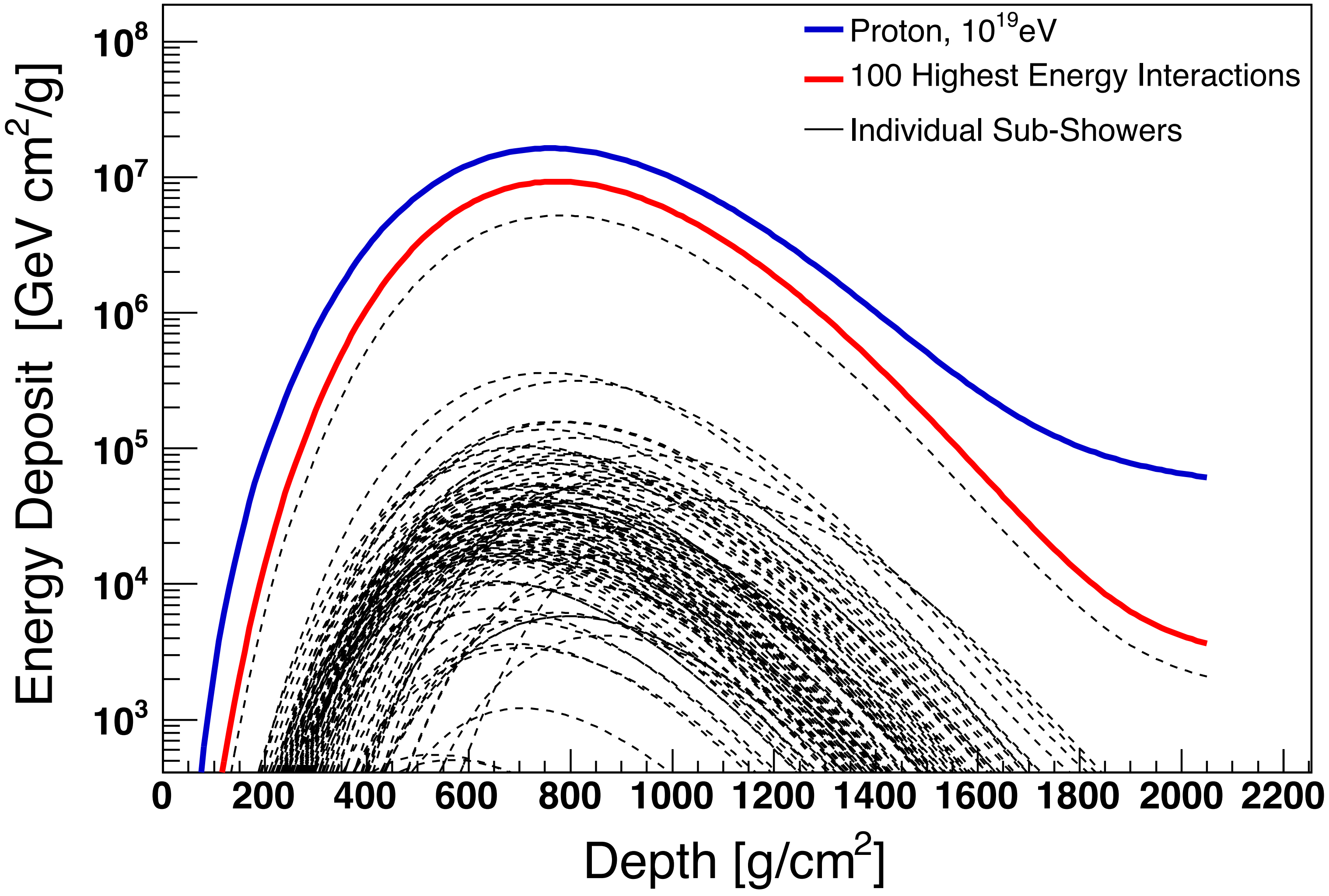
(RE, Heck & Pierog, Ann. Rev. Nucl. Part. Sci. 61, 2011)

How to improve reliability of Xmax predictions ?

Shower particles produced in 100 interactions of highest energy



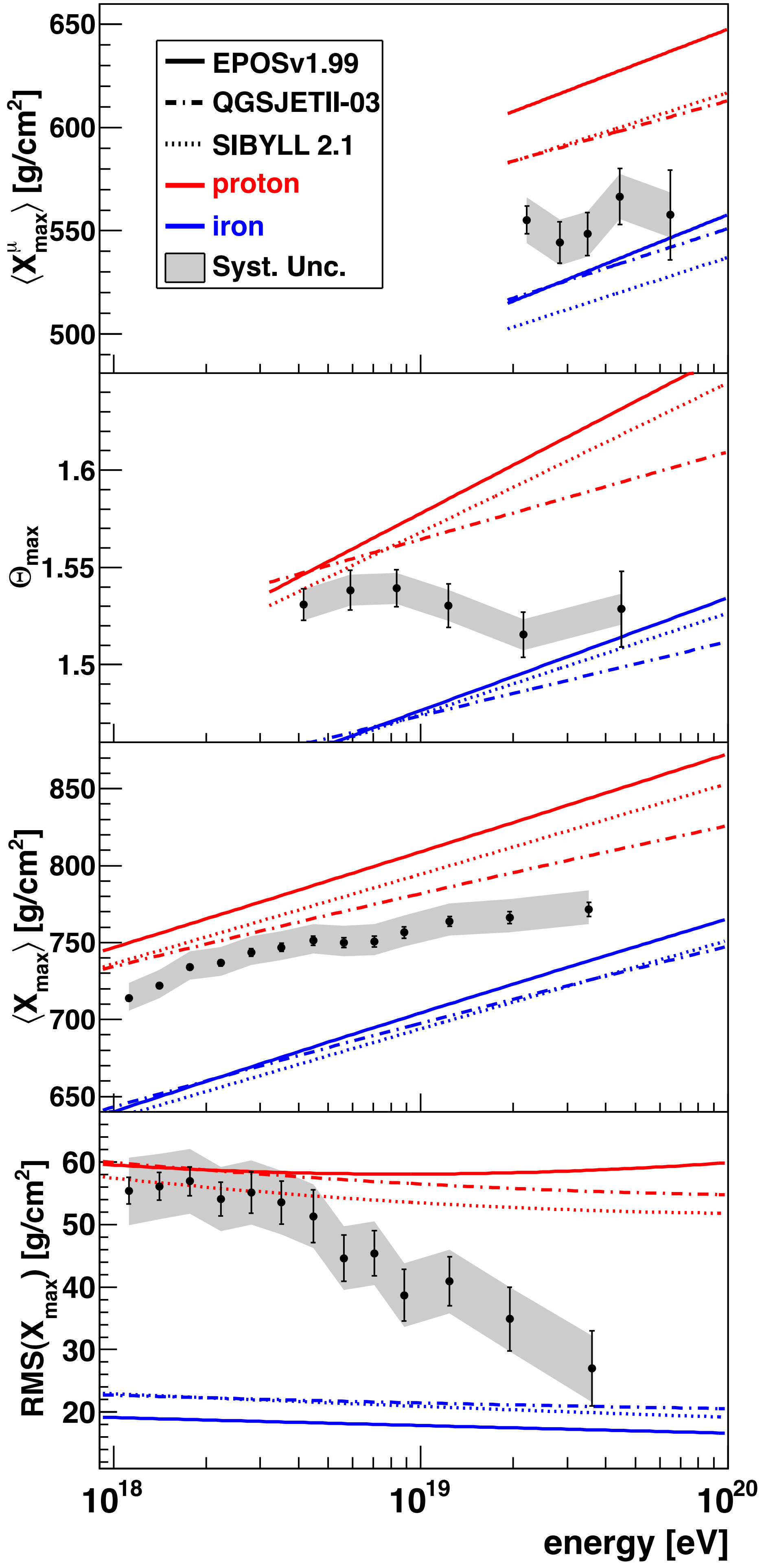
Depth of shower maximum



(Ralf Ulrich, 2012)

Electrons/photons:
high-energy interactions

How to push measurements to higher CR energies ?



100% duty cycle

Muon arrival times at large distance from shower core

Asymmetry in rise time of signal in surface detectors about shower core

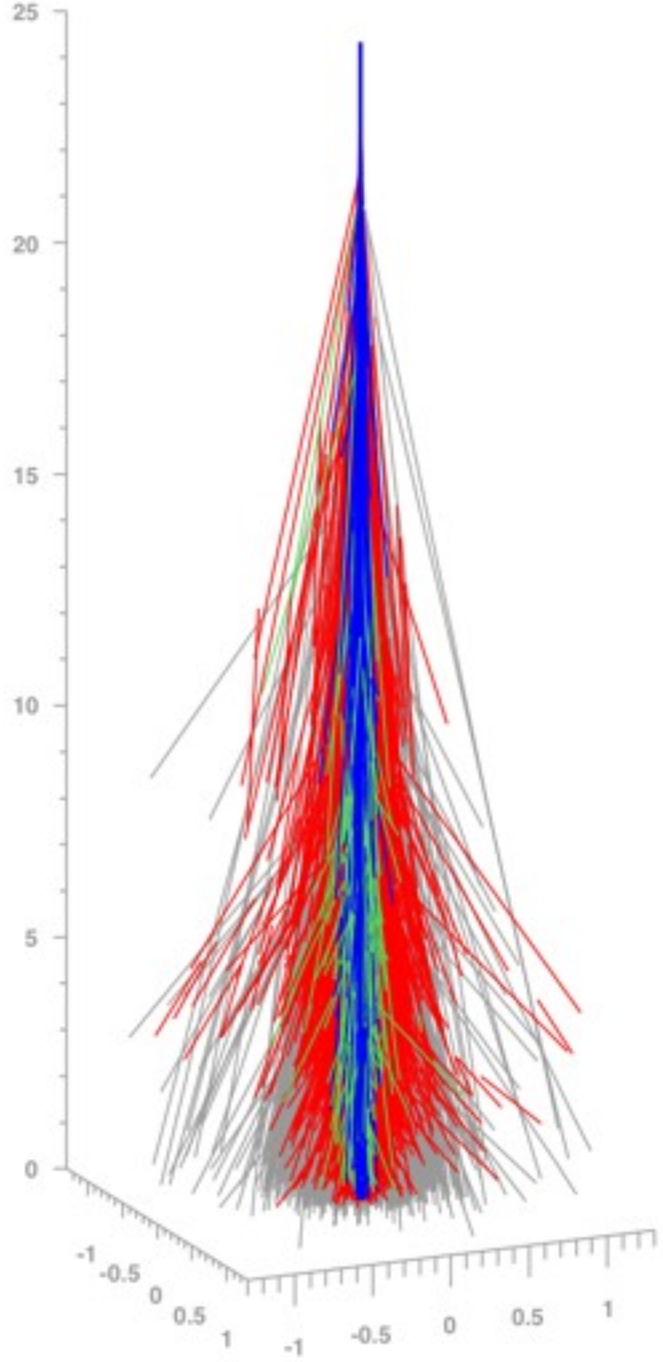
Average depth of shower maximum of charged particles

15% duty cylce

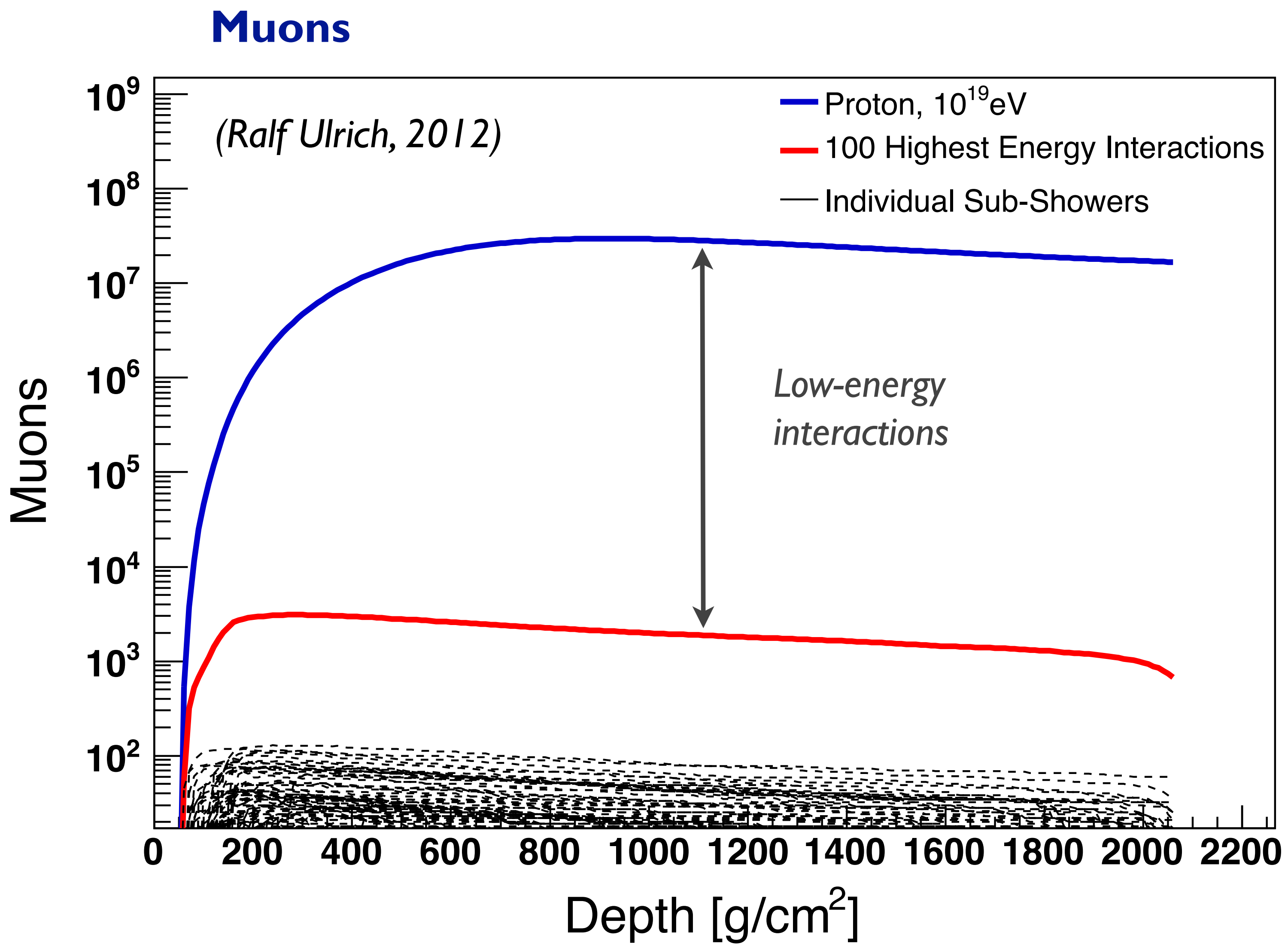
Shower-to-shower fluctuations of depth of shower maximum of charged particles

(Garcia-Pinto, Auger Collab., ICRC 2011 & 1107.4804)

How to improve predictions for muons ?



Shower particles produced in 100 interactions of highest energy


(Ralf Ulrich, 2012)

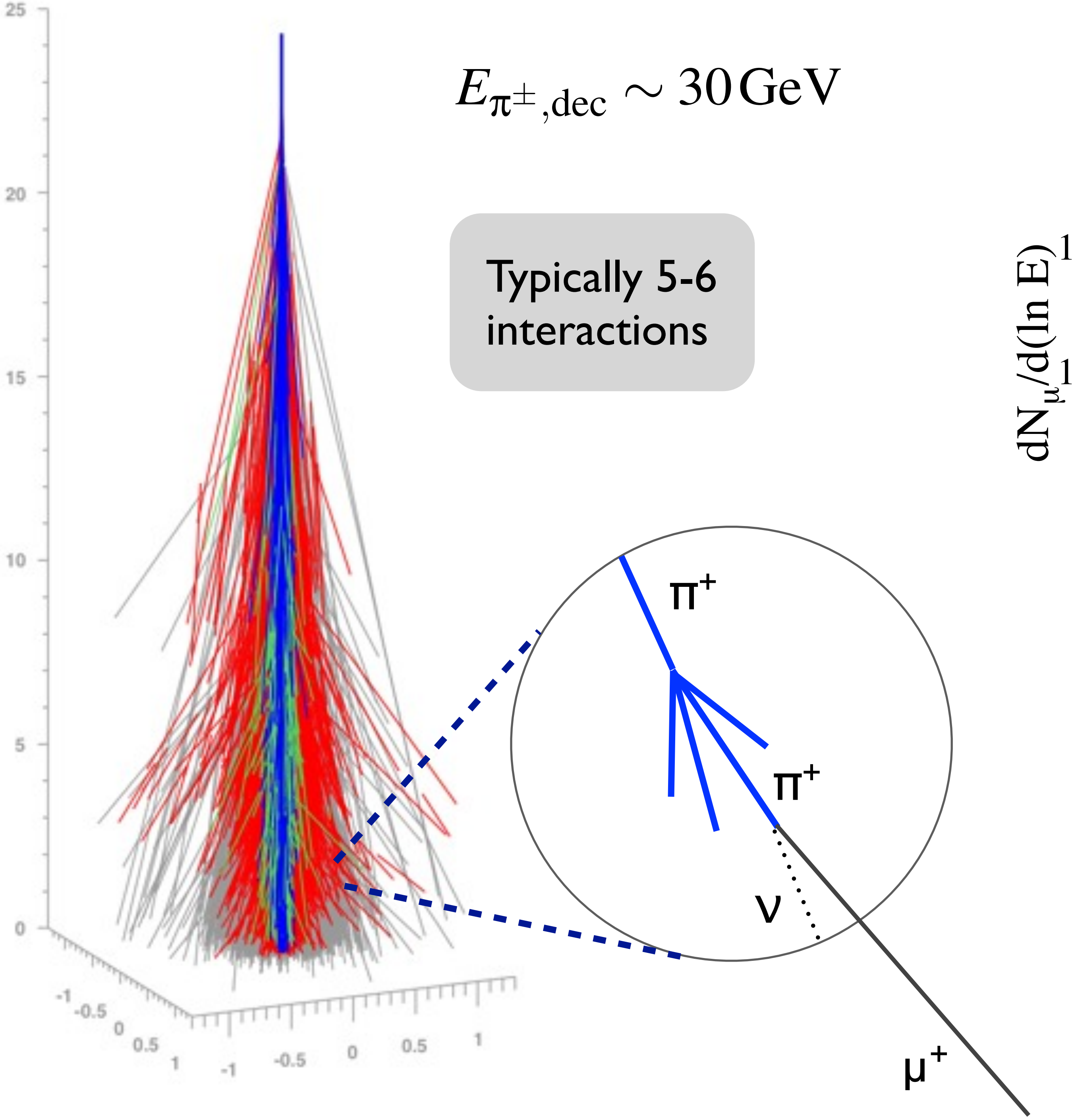
Low-energy interactions

Muons/hadrons: high- and low-energy interactions

Muon production at large lateral distance

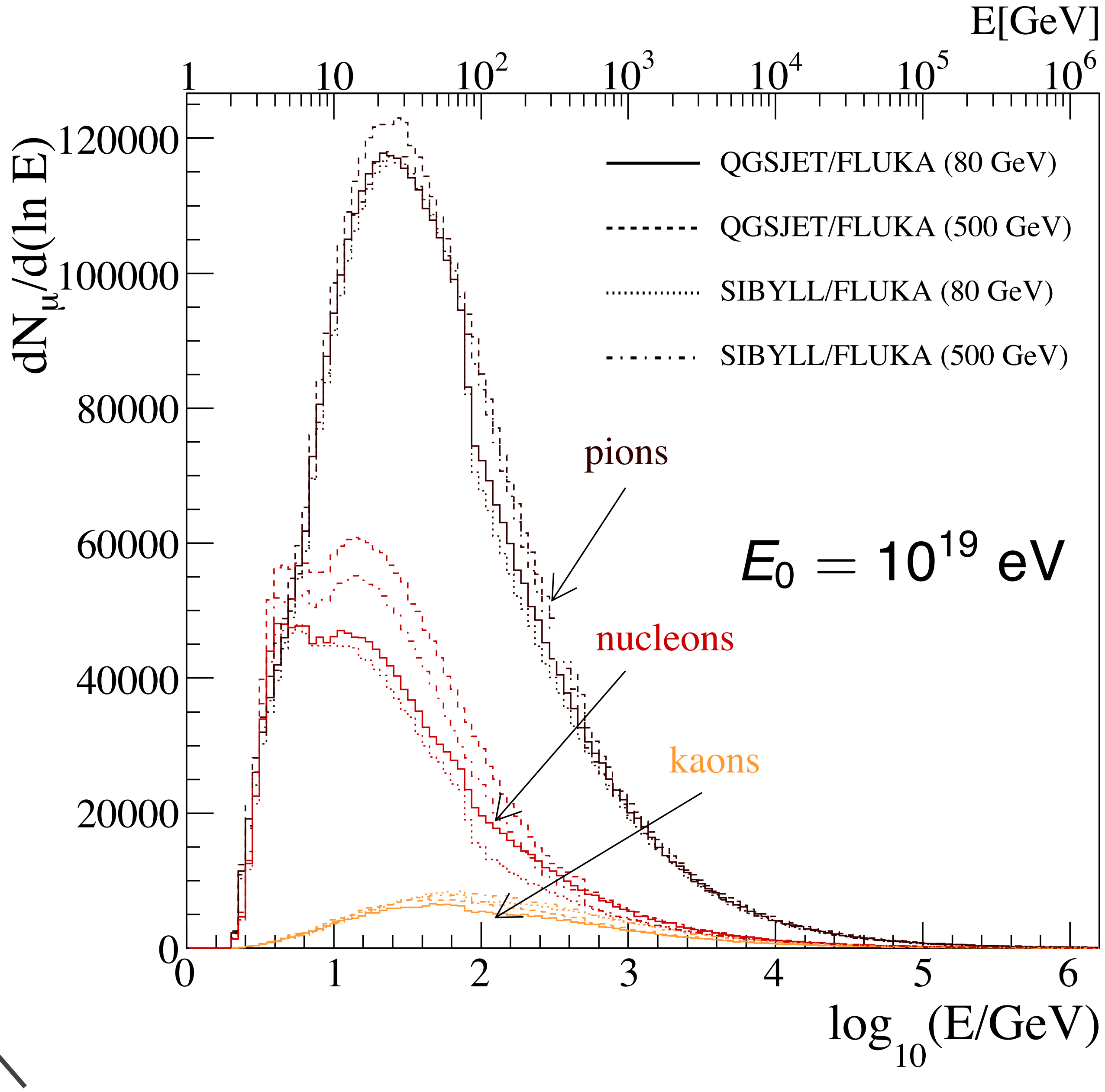
$E_{\pi^\pm,\mathrm{dec}} \sim 30\,\mathrm{GeV}$

Typically 5-6 interactions



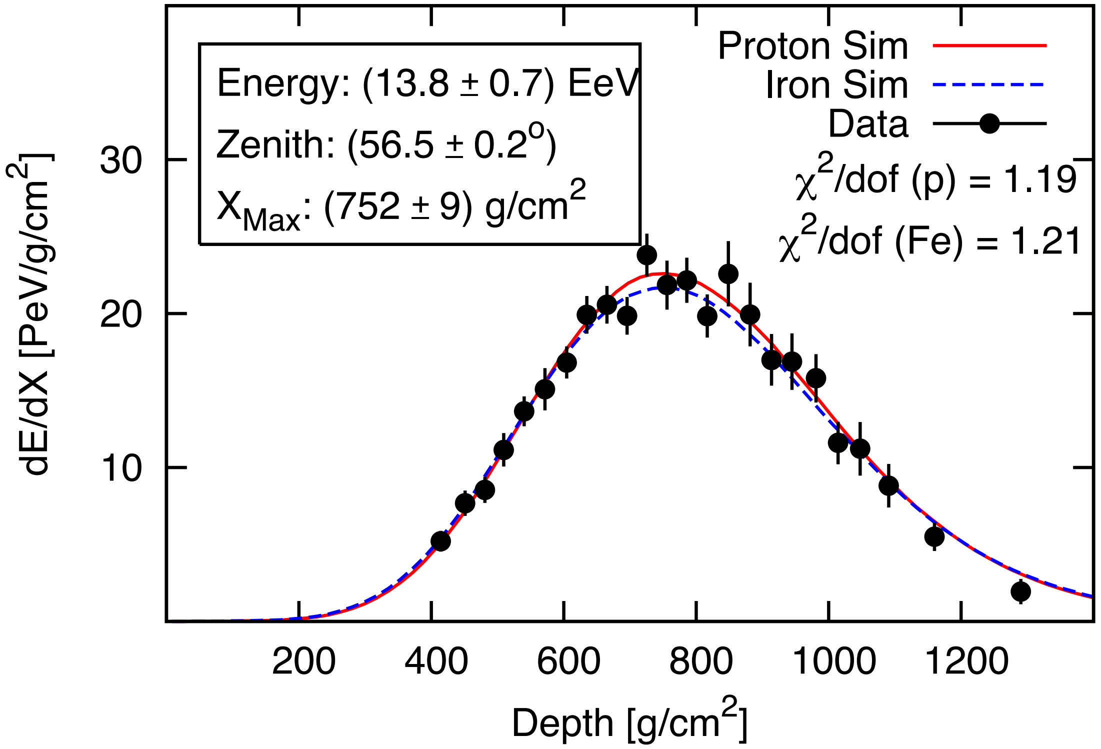
Muon observed at 1000 m from core

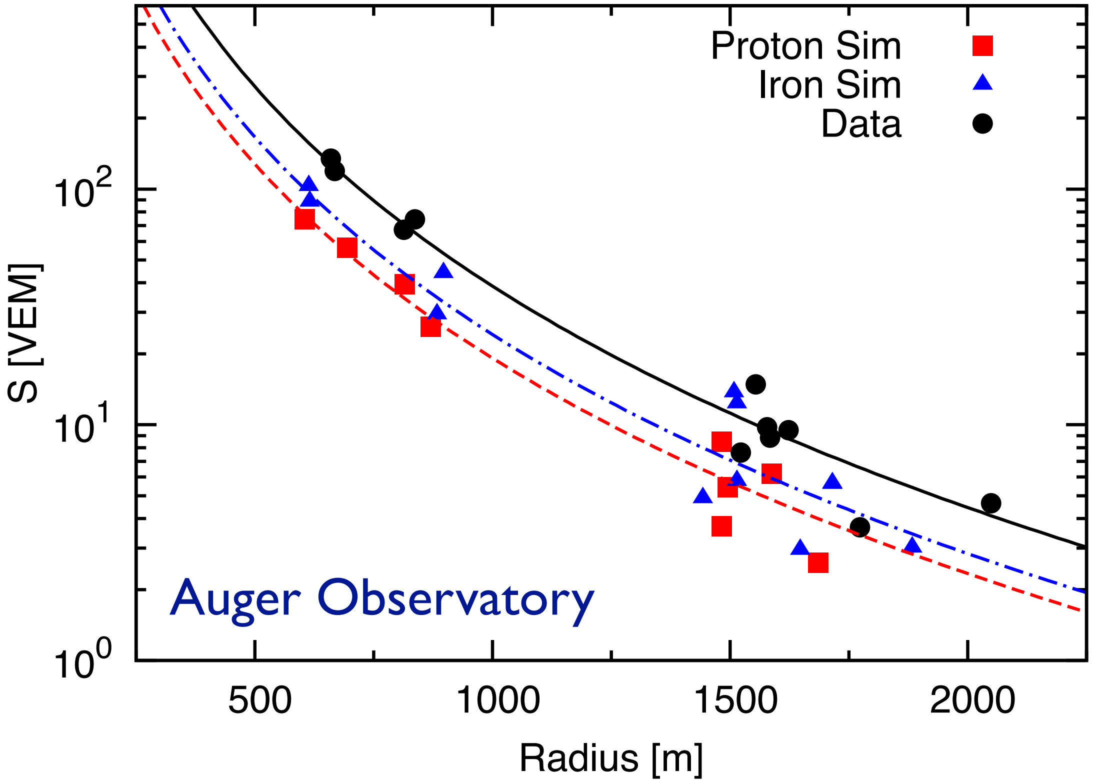
Energy distribution of last interaction that produced a detected muon



(Maris et al. ICRC 2009)

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

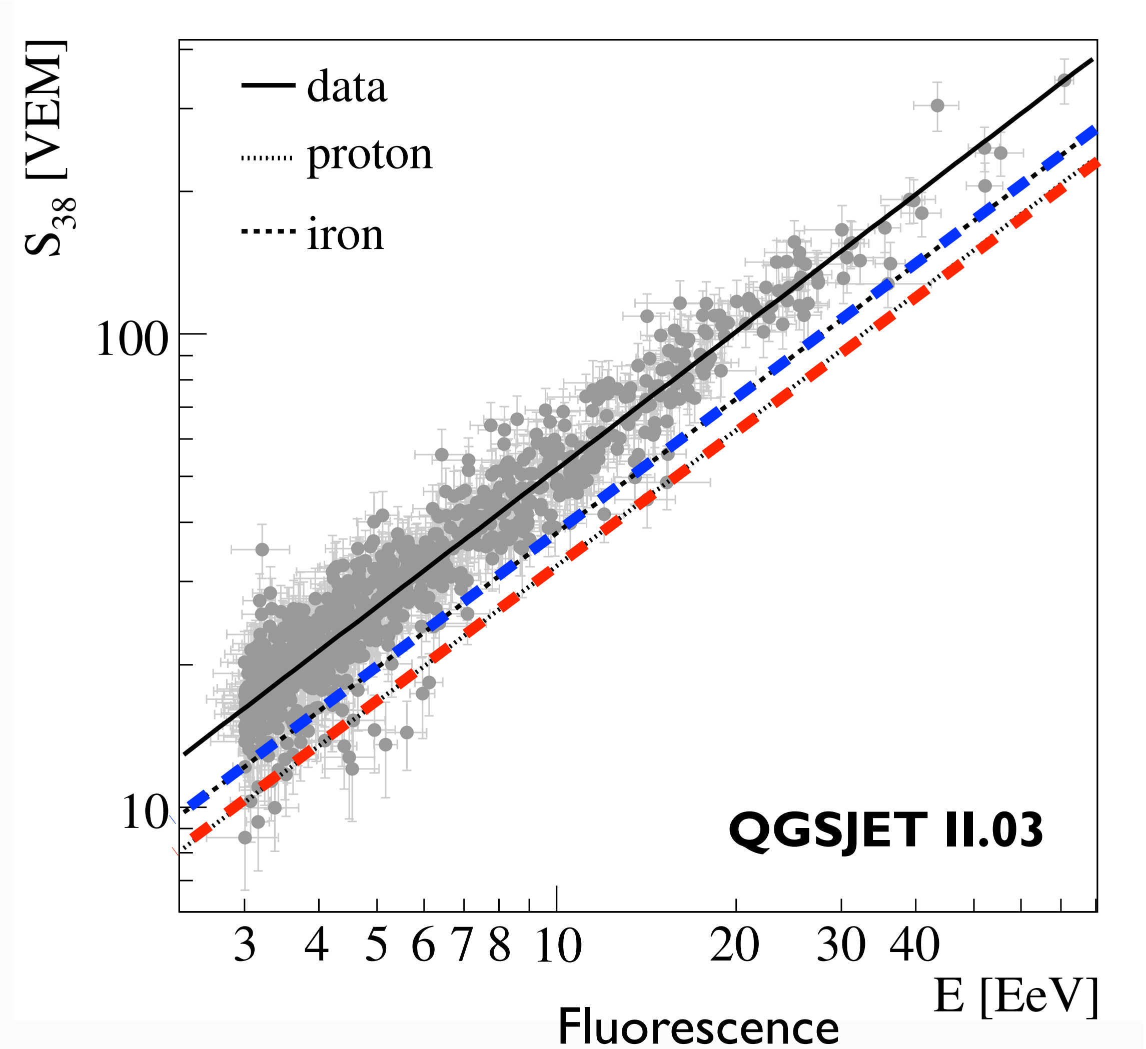
- Signal deficit found for **both** proton and iron like showers
- Showers with same X_{max} show only 10-15% variation
- Discrepancy much larger than 22% energy calibration uncertainty

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

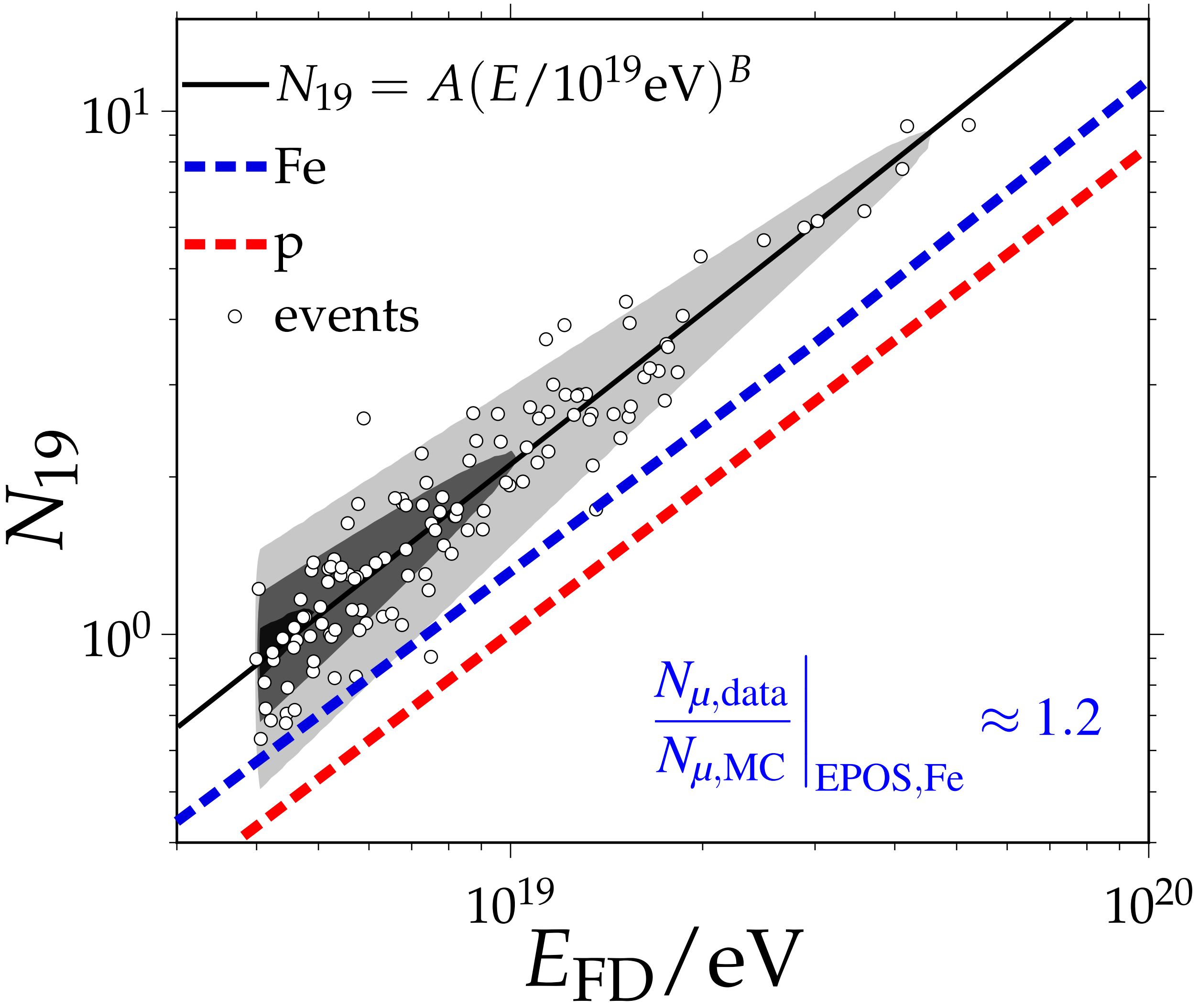
(Pierre Auger Collab. 1107.4804)

Auger: comparison of surface detector signals

Showers up to 60° zenith angle



Inclined showers (muon dominated)



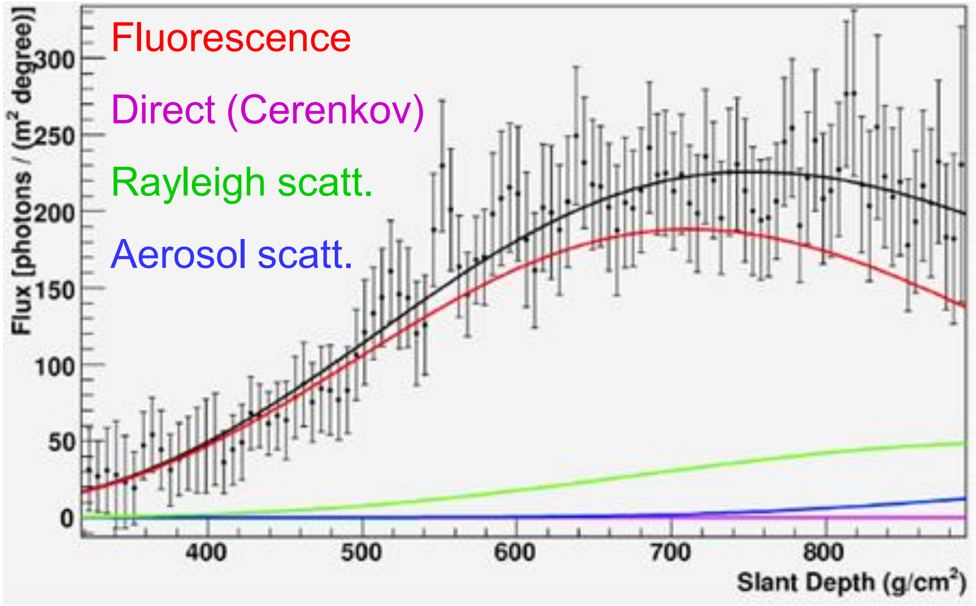
Discrepancy due mainly to muons

$$\left.\frac{N_{\mu,\mathrm{data}}}{N_{\mu,\mathrm{MC}}}\right|_{\mathrm{QGS,p}} = 2.13 \pm 0.04(\mathrm{stat}) \pm 0.11(\mathrm{sys})$$

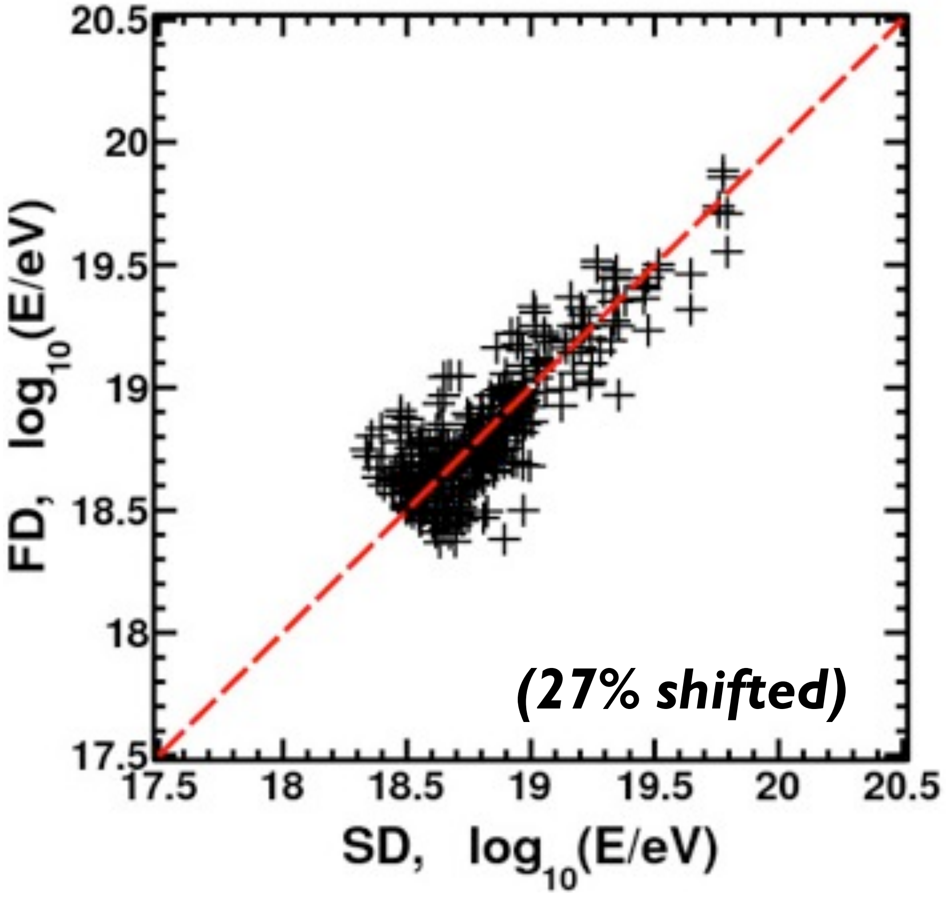
(Independent confirmation with several other observables)

(HadInt Working Group, UHECR 2012)

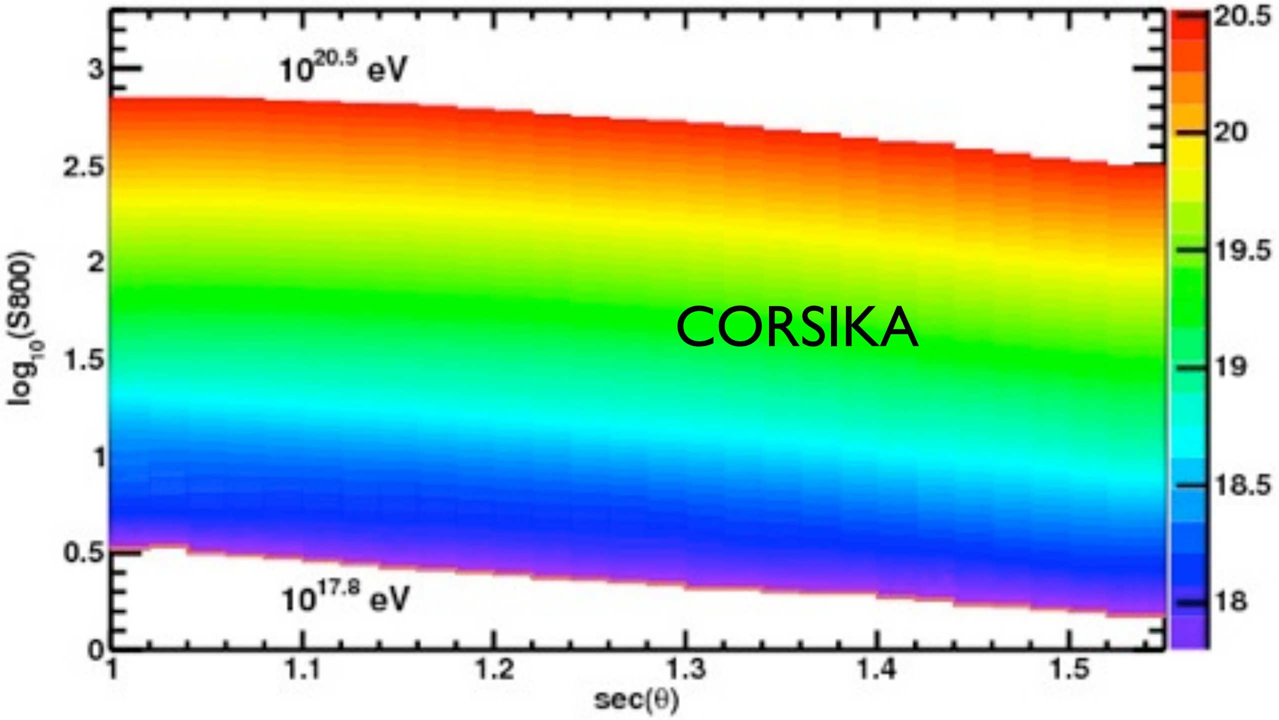
TA: comparison of energy scales



Energy derived from fluorescence light profile



(27% shifted)



Simulated SD signal at 800m used to determine SD energy

SD energies 27% higher than FD energies (QGSJET II, protons)

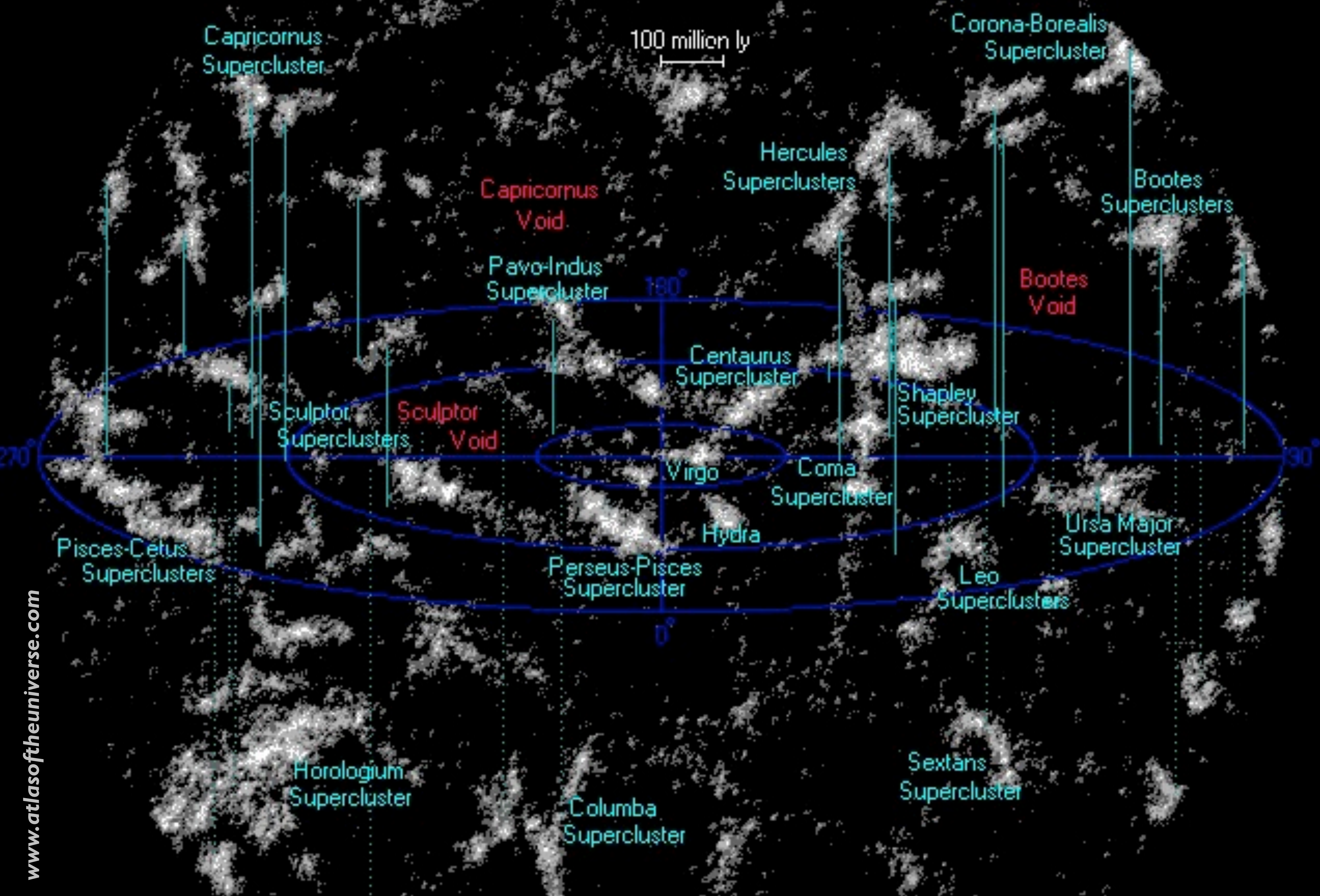
Summary and outlook

- New data in astrophysics indicate some radically new interpretations of observations
- Do we really observe the maximum injection energy of a source, or source population (possibly local) at the highest energies (and a ~10% background from other sources)?
- Interpretation of measurements of extensive air shower key to solving puzzles on astrophysics interpretations
- Large uncertainties in composition-sensitive observables (interaction physics?)
- Interaction models: first comparisons with LHC data very encouraging
- Current generation of models (pre-LHC) does not describe muon production sufficiently well (could be related to high- and/or low-energy interactions)
- **This is work in progress:** See talks tomorrow for importance of accelerator data and predictions of LHC-tuned model predictions

Backup slides:

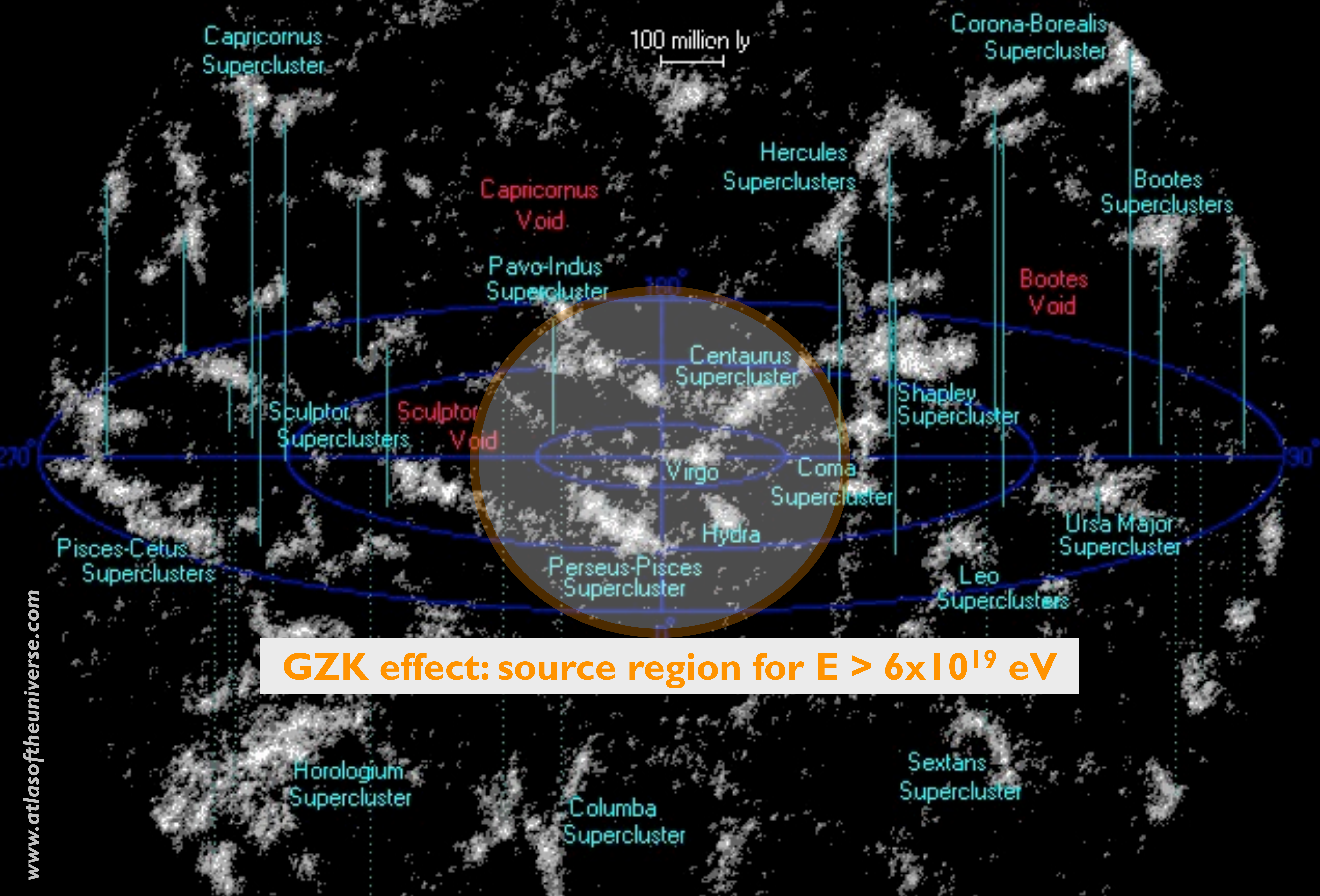
UHECR anisotropy and ~10% proton component

Problem 3: Arrival direction distribution



www.atlasoftheuniverse.com

GZK effect: anisotropy expected for light elements

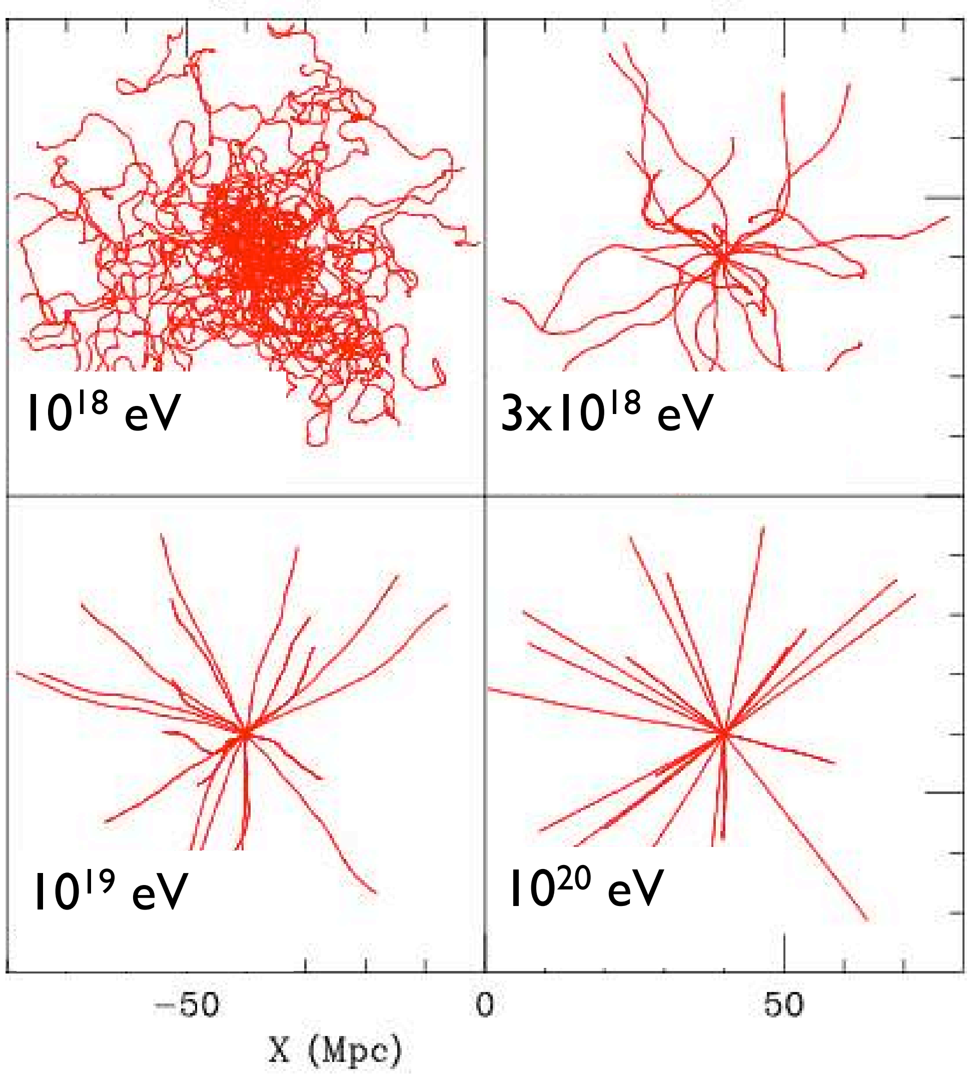


GZK effect: source region for E > 6×10^{19} eV

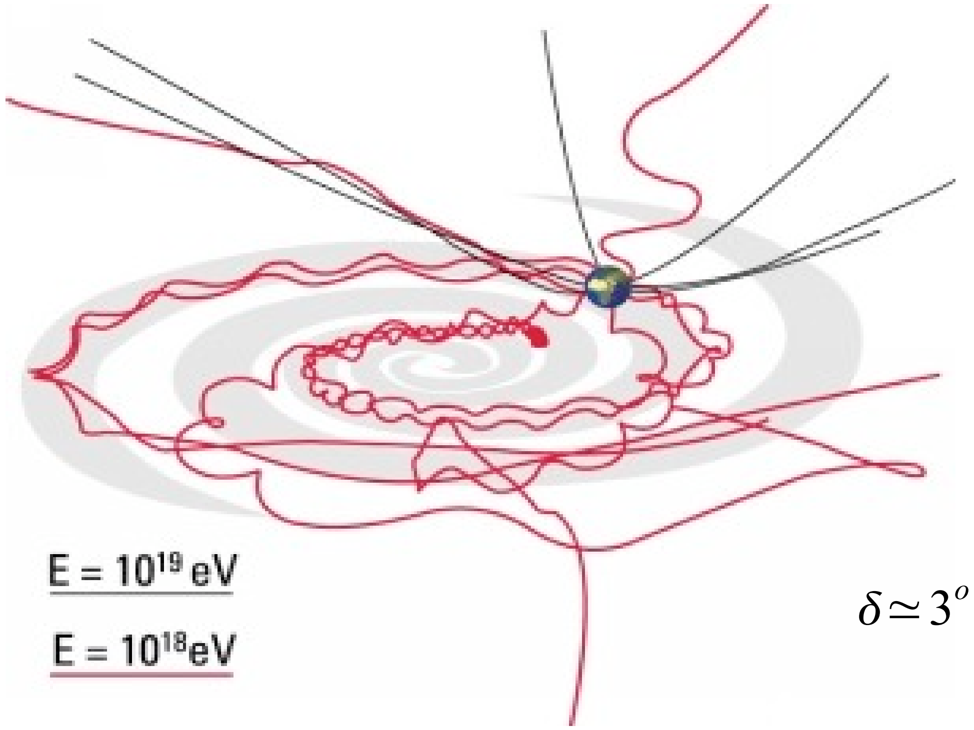
www.atlasoftheuniverse.com

Astrophysical magnetic fields

Extragalactic magnetic field



Galactic magnetic field

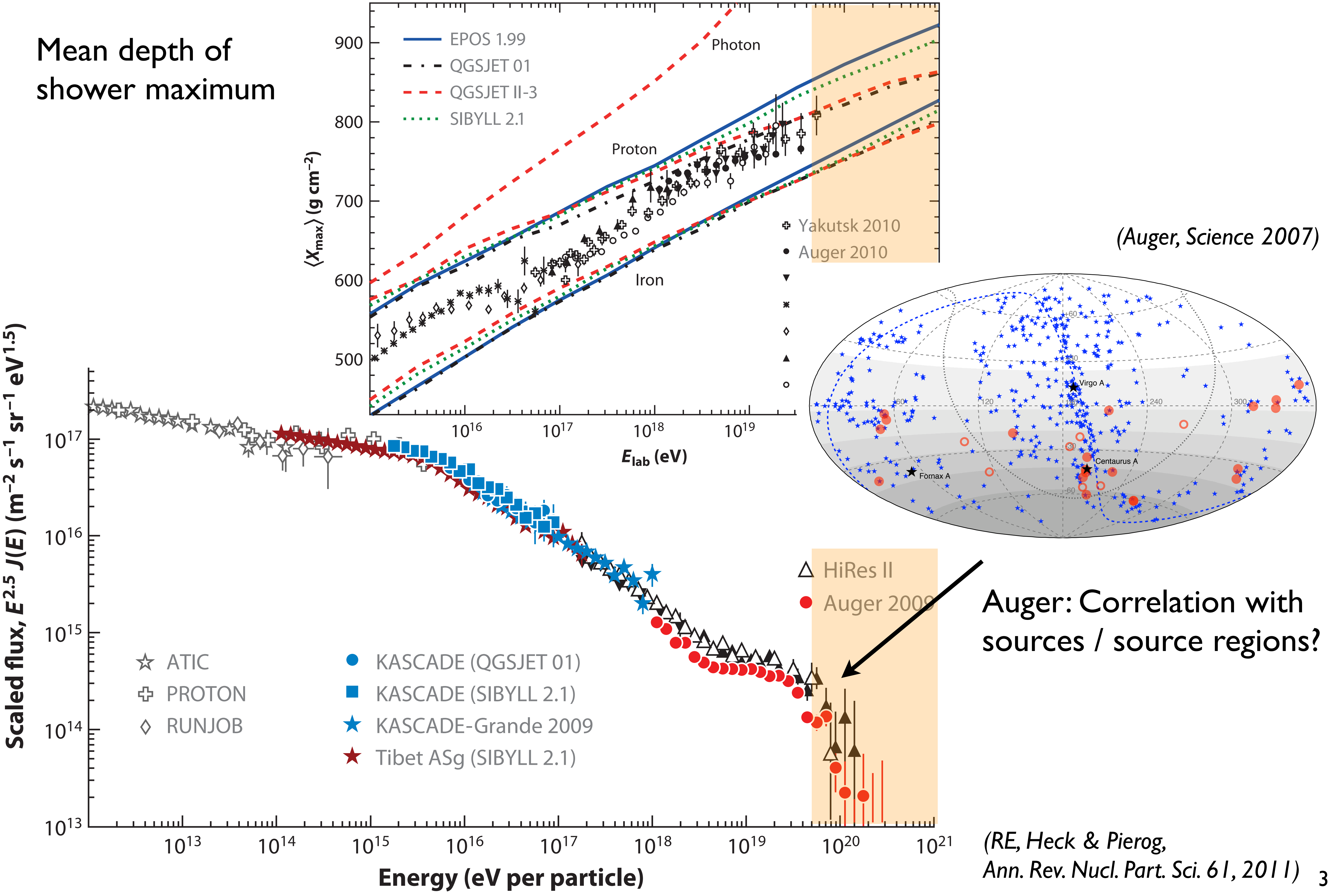


$$\delta \simeq 3^o \frac{B}{3\,\mu G}\,\frac{L}{kpc}\,\frac{6\times 10^{19}\,eV}{E/Z}$$

Deflection of a few degrees expected for protons

GZK suppression or maximum injection energy?

Mean depth of shower maximum

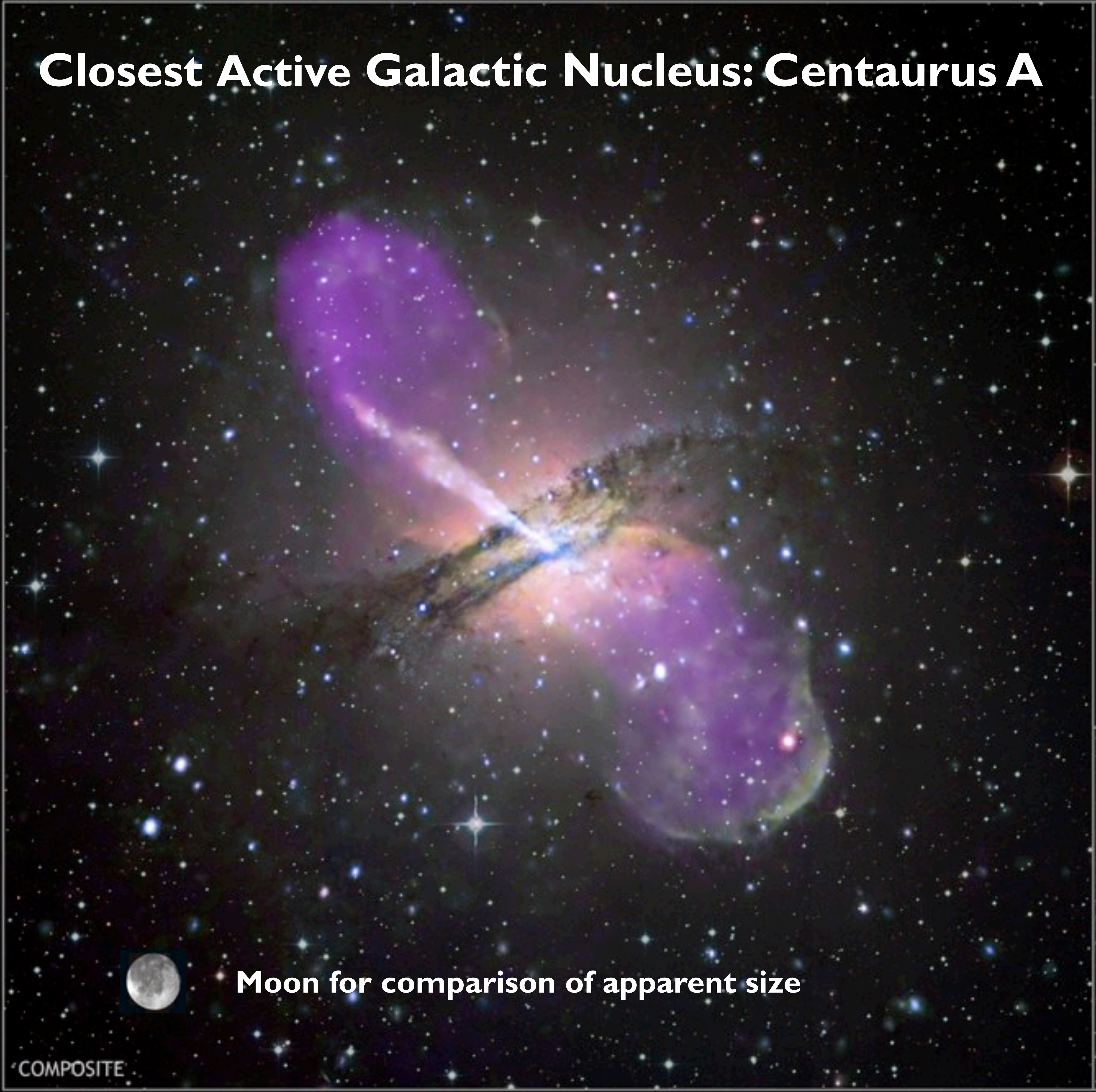


(Auger, Science 2007)

Auger: Correlation with sources / source regions?

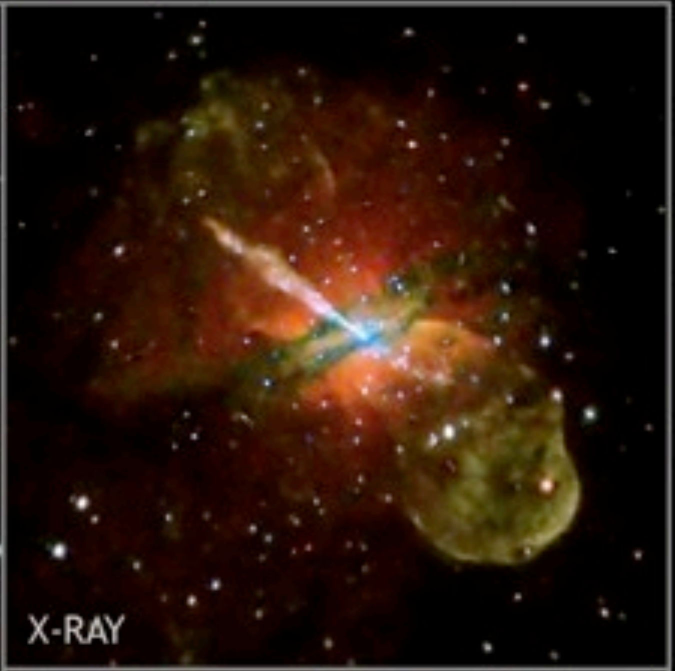
(RE, Heck & Pierog, Ann. Rev. Nucl. Part. Sci. 61, 2011)

Closest Active Galactic Nucleus: Centaurus A



Moon for comparison of apparent size

COMPOSITE



X-RAY

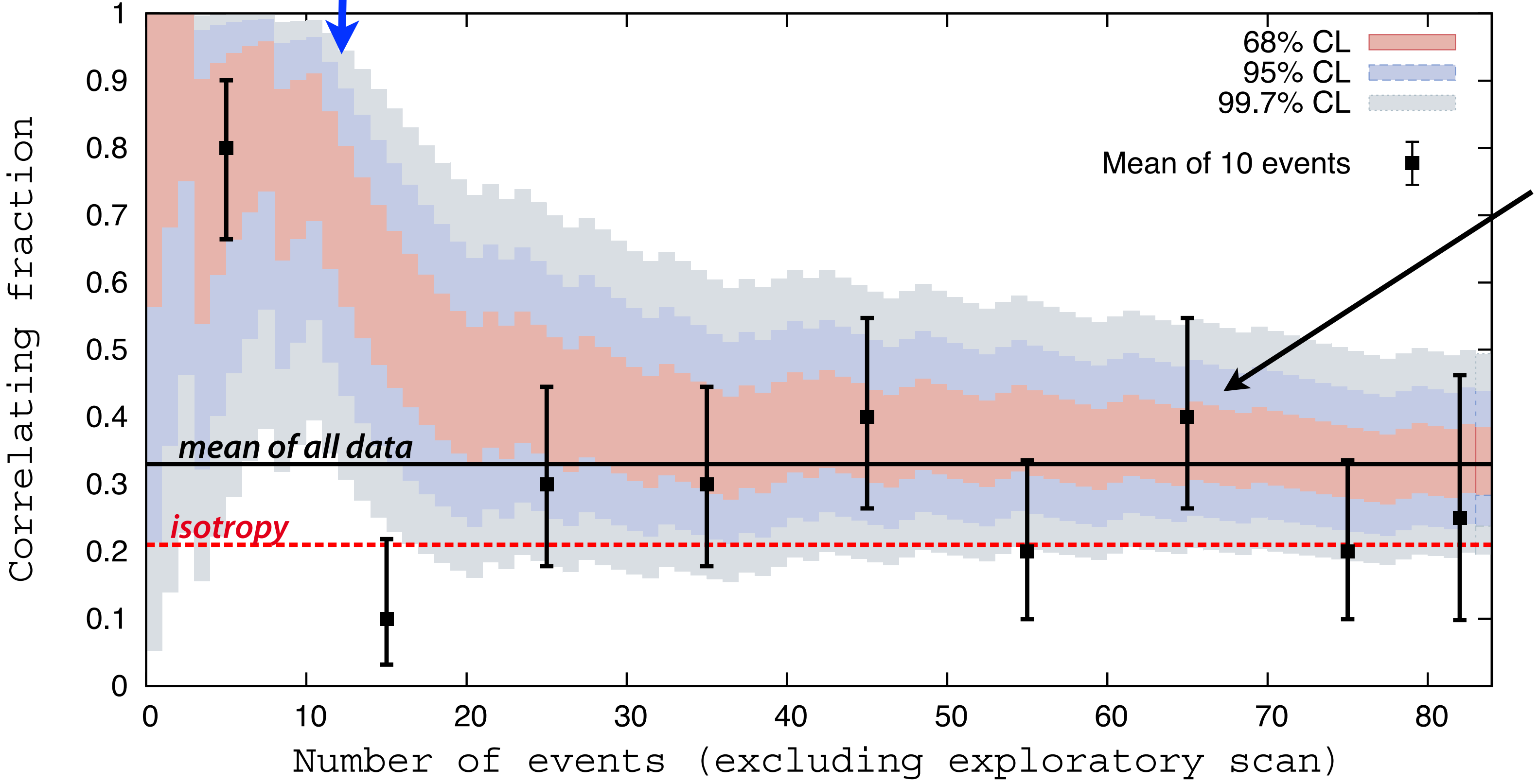
RADIO

OPTICAL

Current status of correlation with AGNs

Auger Observatory (2011)

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



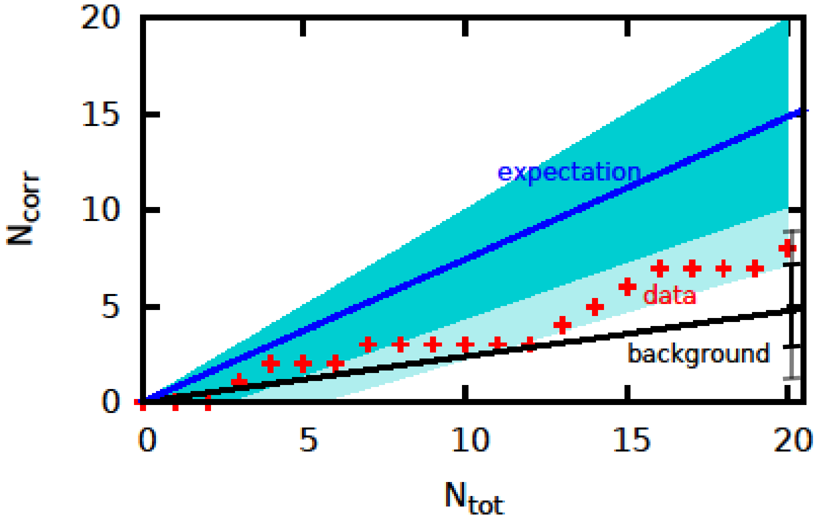
Differential estimate every 10 events

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

Telescope Array (2012)

Astrophys.J. **757** (2012) 26

11 out of 25, $P_{\text{chance}} = 2\%$



73%

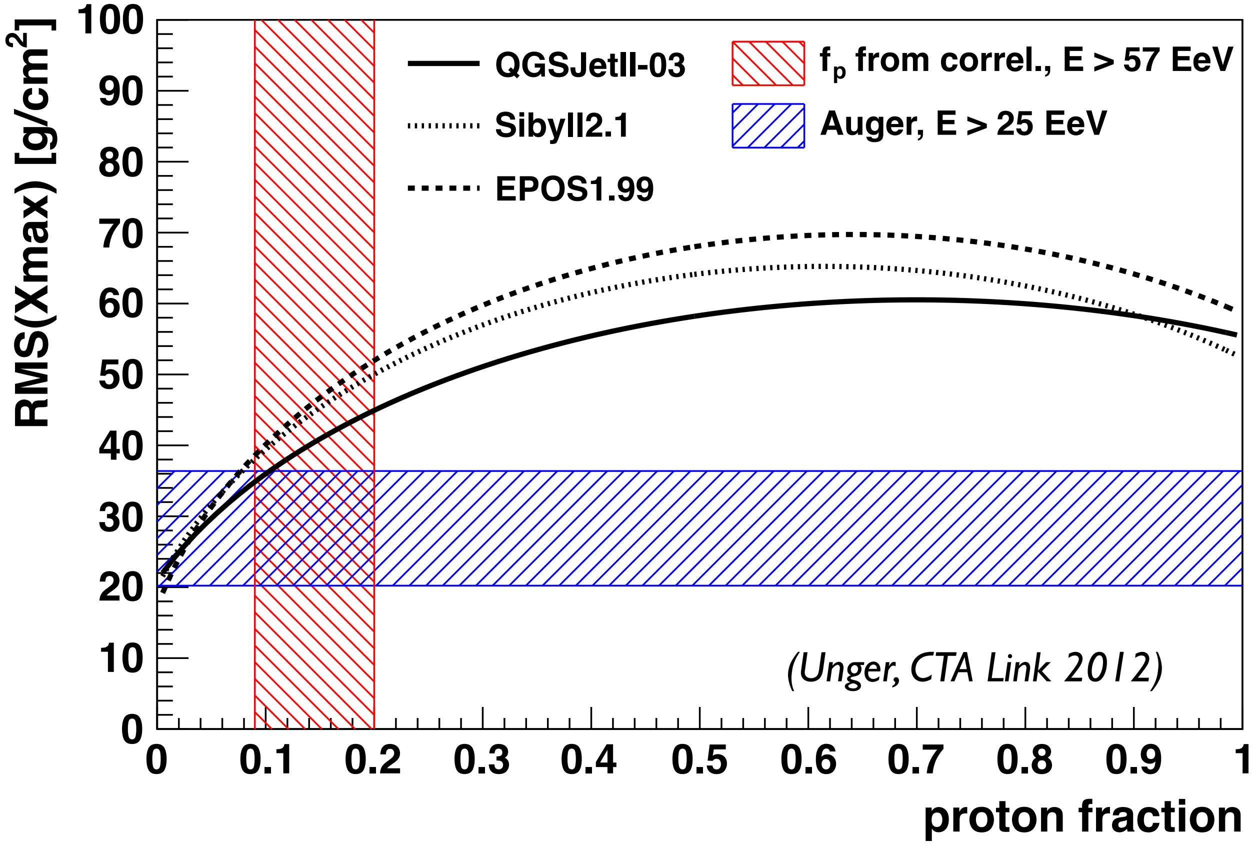
25%

Combined chance probability (isotropy) ~10^{-3} ?

Small fraction of protons even at highest energy ?

- fraction f_p of correlating protons
- $1 - f_p$ isotropized iron
- no intermediate nuclei (too small mean free path)
- Auger: $f_p = 12^{+7}_{-6}$ %, TA: $f_p = 20^{+15}_{-12}$ %

(Unger, CTA Link 2012)



Auger data

- compatible with ~15% protons
- anisotropy indicates ~15% protons

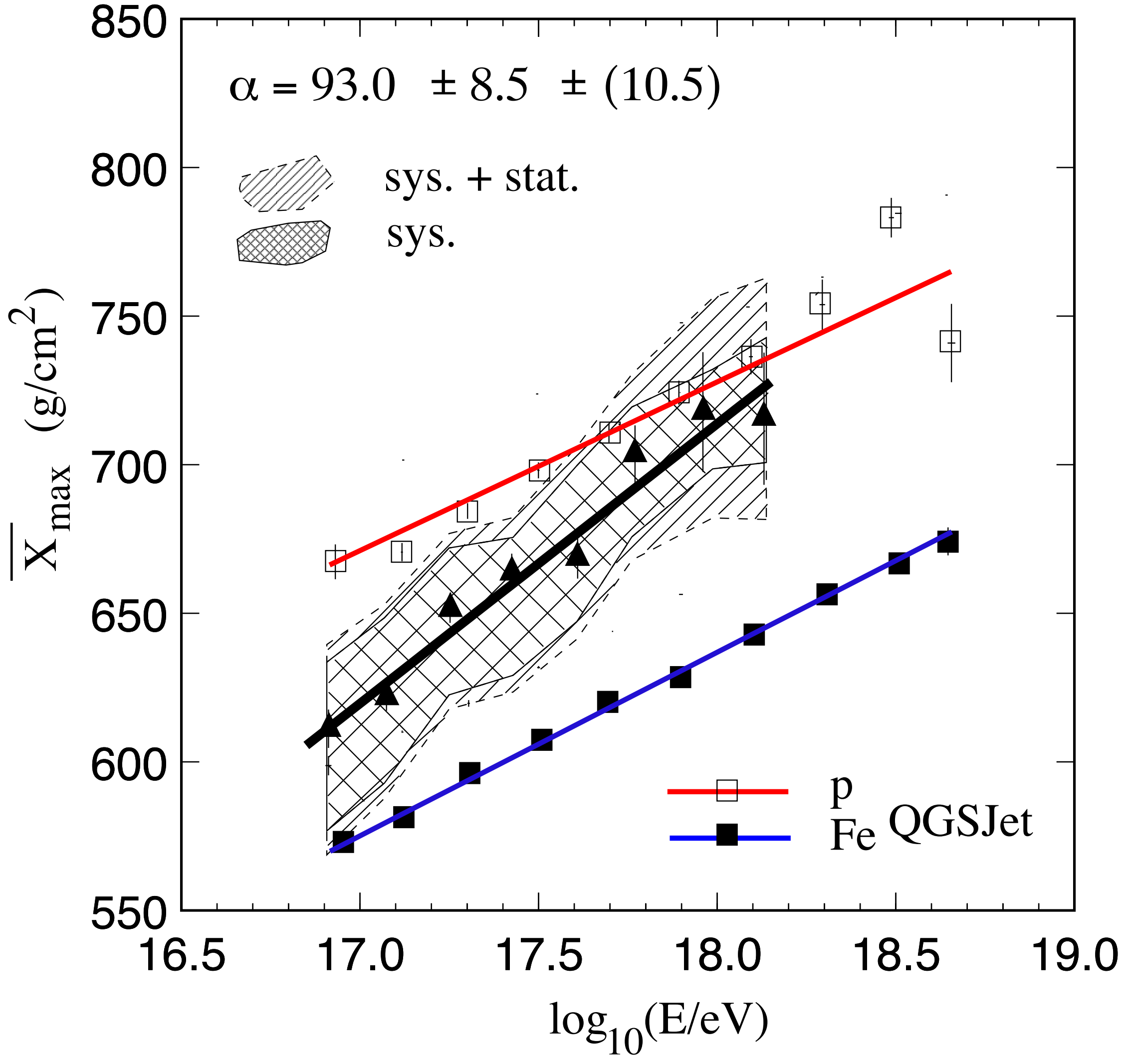
$$\langle f_p \rangle = 14^{+6}_{-5} \; \% \; (E > 57 \; \mathrm{EeV})$$

Backup slides:

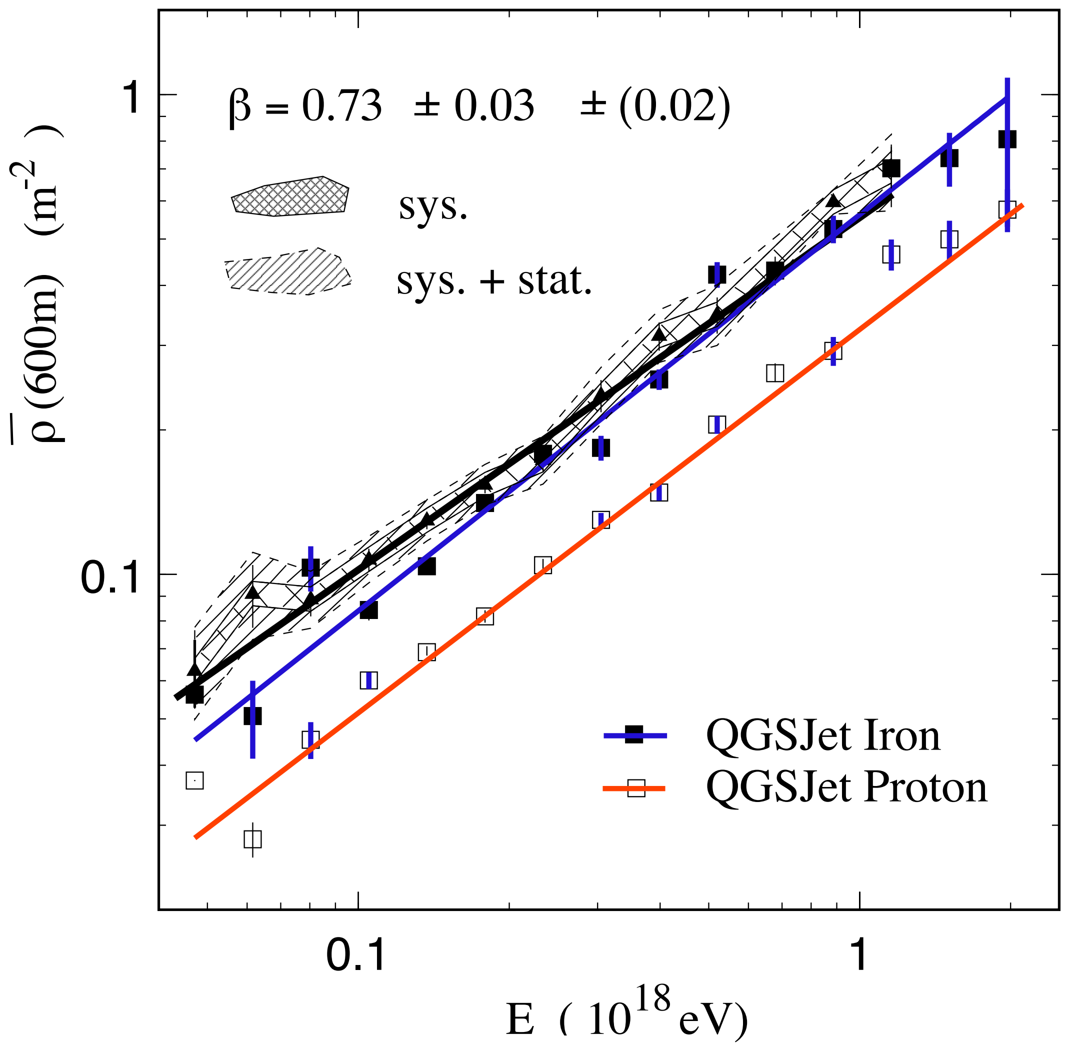
Muon discrepancy in extensive air showers

Same problem found also at lower energy

HiRes prototype + MIA



Muon density 600m from core

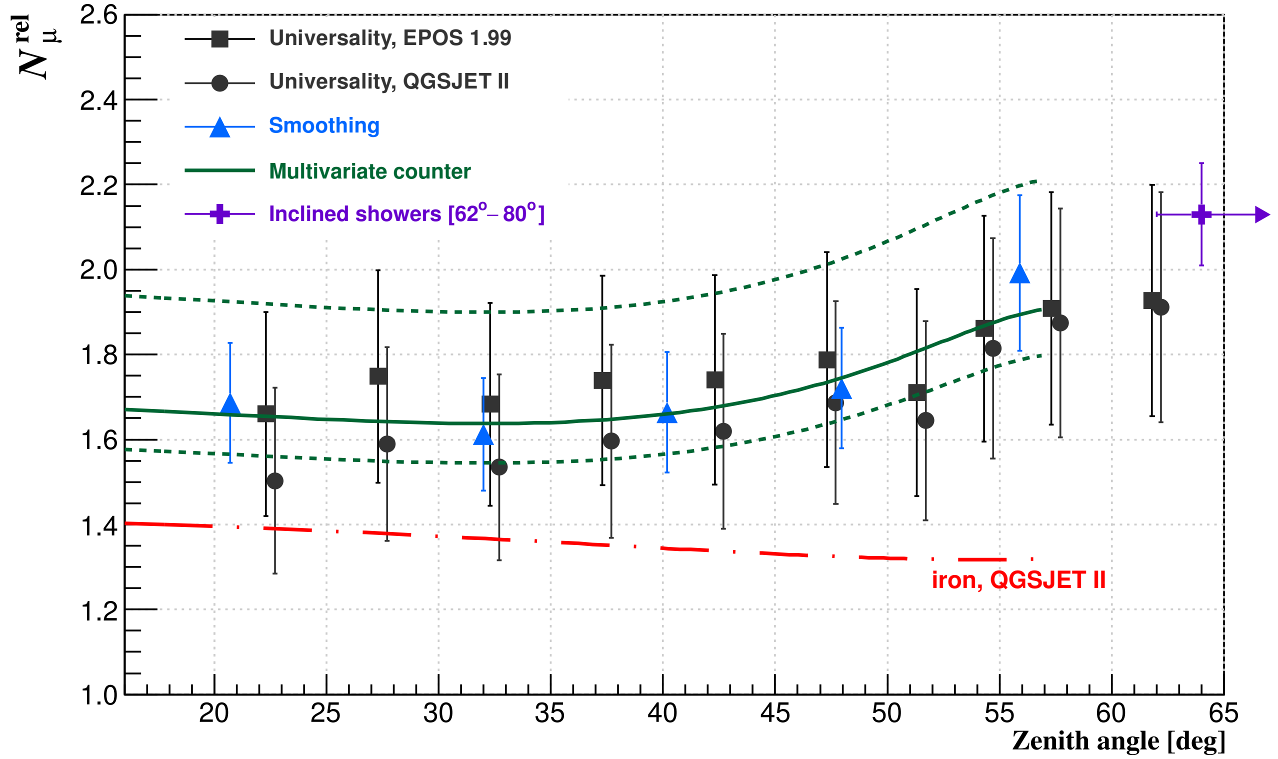


(HiRes Fly's Eye and MIA Collabs., Phys. Rev. Lett. 84, 2000)

At what energy does the muon problem appear ?

Auger results of related measurements

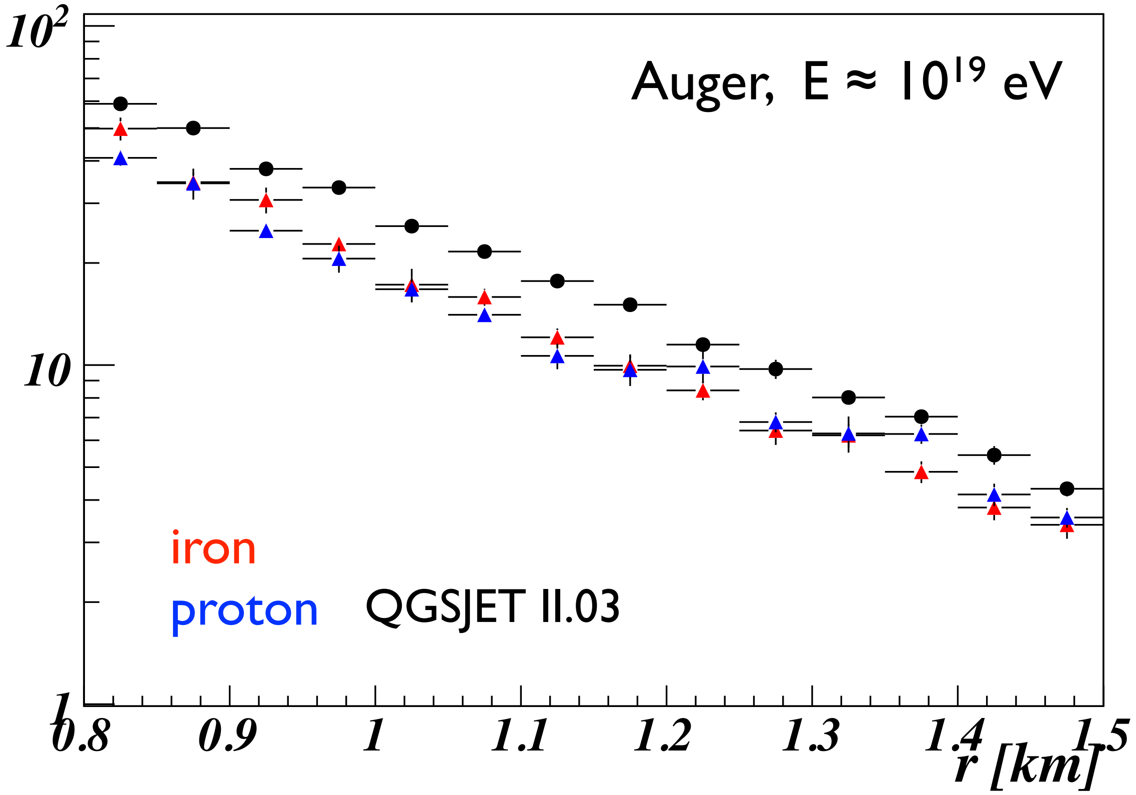
Different methods: **muon contribution**



(Yushkov, Auger UHECR 2012)

Energy uncertainty of 22% not included

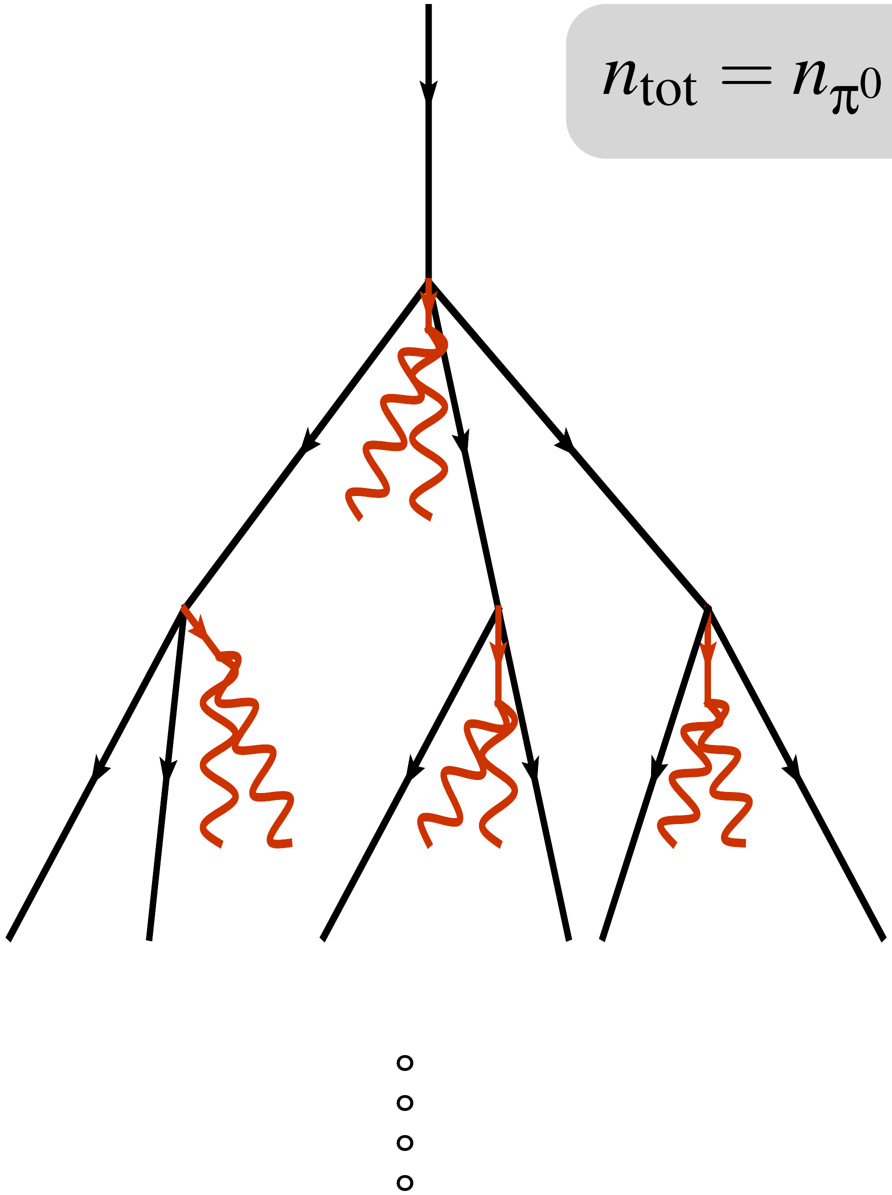
Em. component (smoothing method)



(Auger ICRC 2009)

Electromagnetic component:
25-30% more particles than QGSJET II.03?

Muon production in hadronic showers



$$n_{\text{tot}} = n_{\pi^0} + n_{\text{ch}}$$

Primary particle proton

π^0 decay immediately

$\pi^\pm$ initiate new cascades

Assumptions:

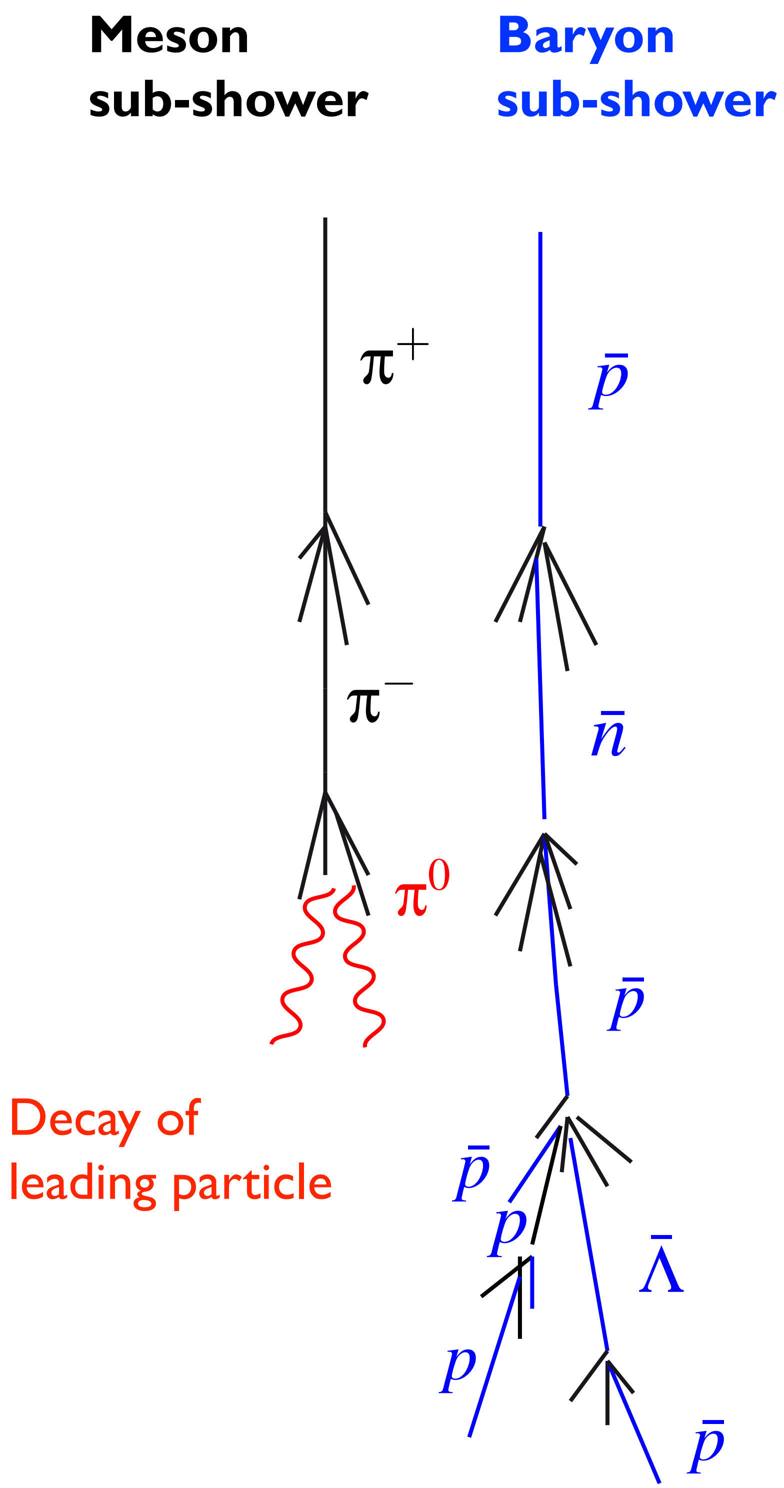
- cascade stops at $E_{\text{part}} = E_{\text{dec}}$
- each hadron produces one muon

In first approximation:

How fast and how much energy is transferred into em. shower part

(Matthews, Astropart.Phys. 22, 2005)

Enhancement of muon number in air showers



1 Baryon-Antibaryon pair production *(Pierog, Werner)*

- Baryon number conservation
- Low-energy particles: large angle to shower axis
- Transverse momentum of baryons higher
- **Enhancement of mainly low-energy muons**

2 Leading particle effect for pions *(Drescher, Ostapchenko)*

- Leading particle for a π could be ρ^0 and not π^0
- Decay of ρ^0 almost 100% into two charged pions

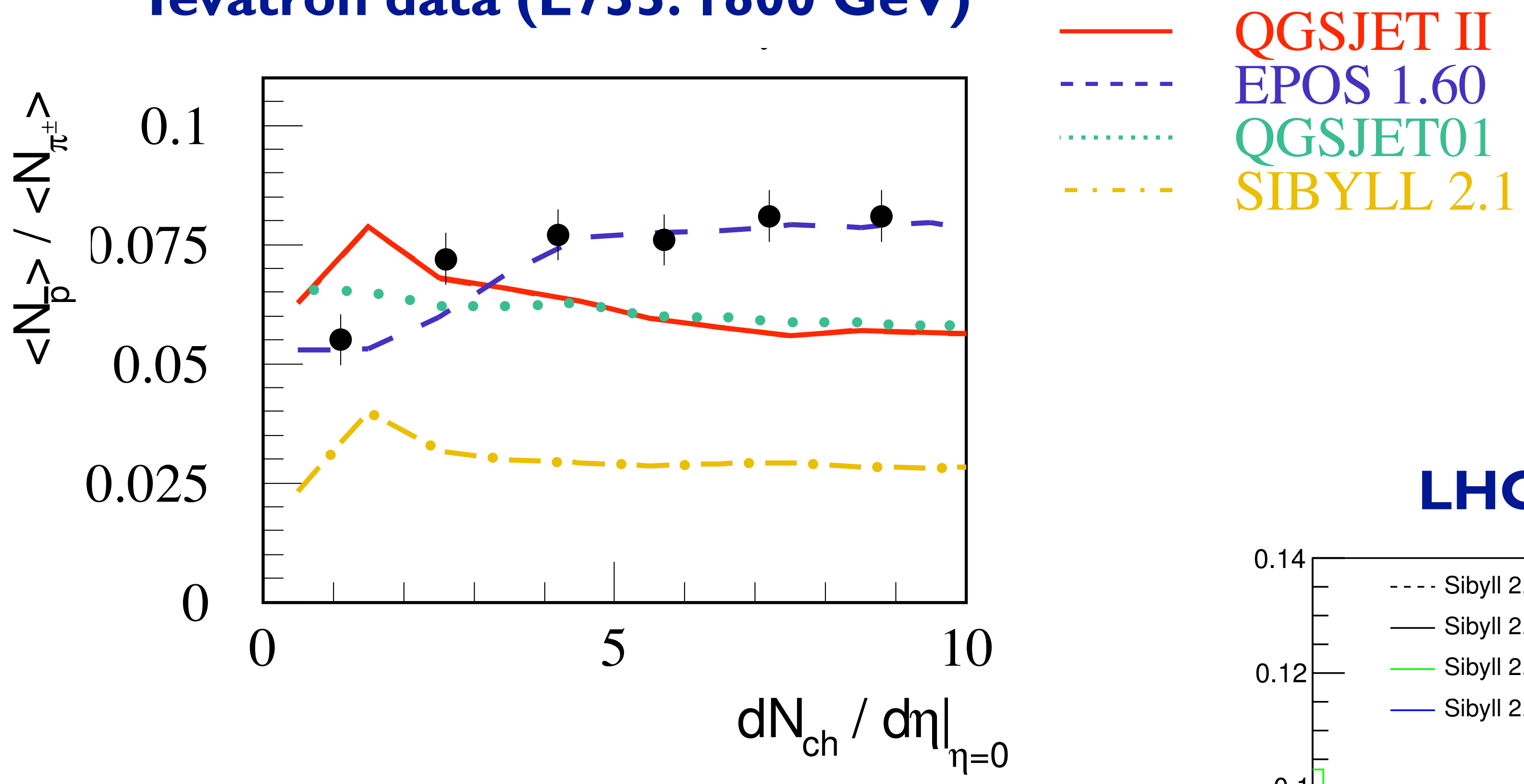
3 Chiral symmetry restoration *(Farrar, Allen)*

- **Proton primaries, applies above energy threshold**
- Pion production suppressed relative to baryons
- Large inelasticity of the events
- Faster increase of total cross section (reduction of fluctuations)

(Pierog, Werner PRL 101, 2008)

LHC data: Baryon production lower than assumed

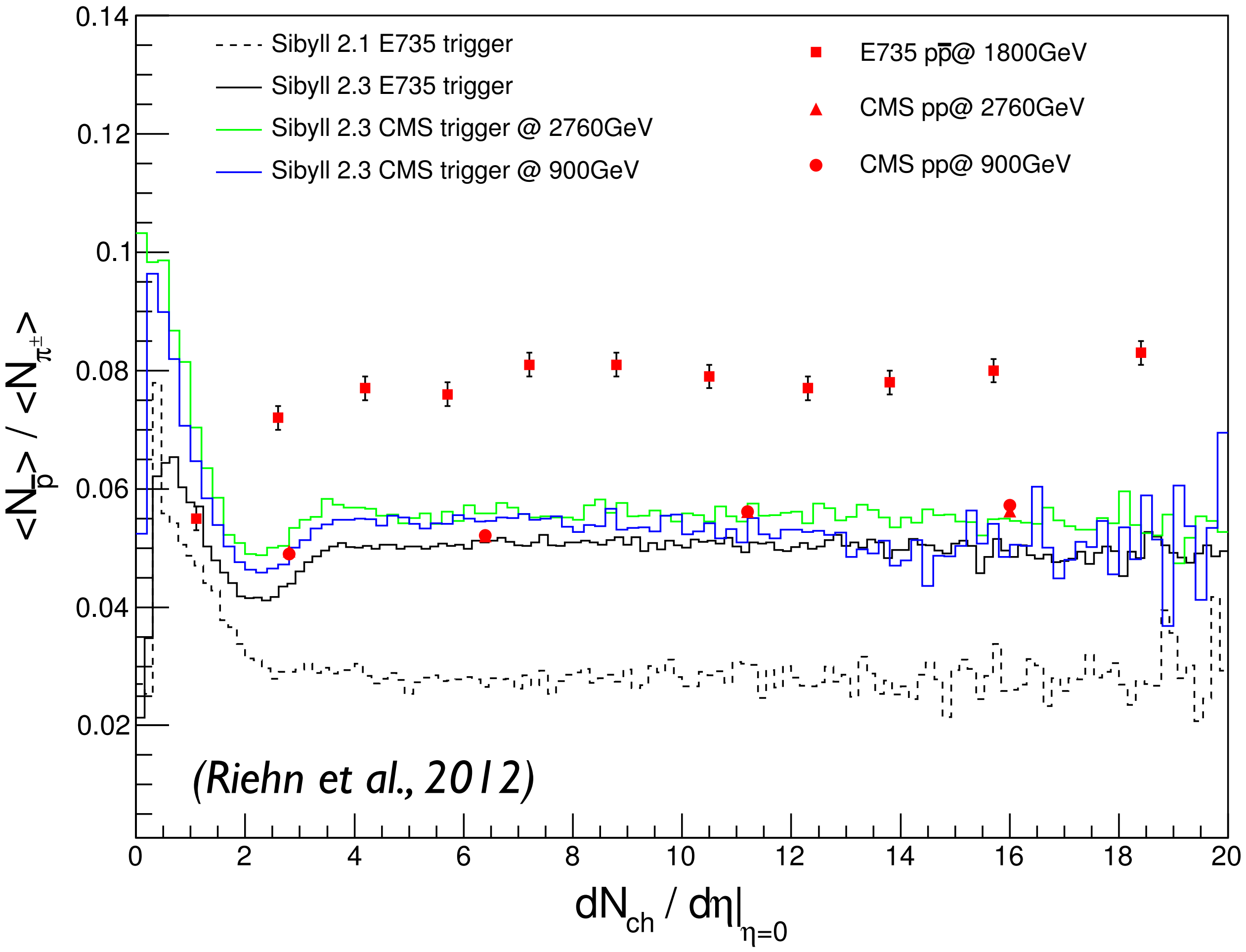
Tevatron data (E735: 1800 GeV)



(Pierog, Werner Phys. Rev. Lett. 101, 2008)

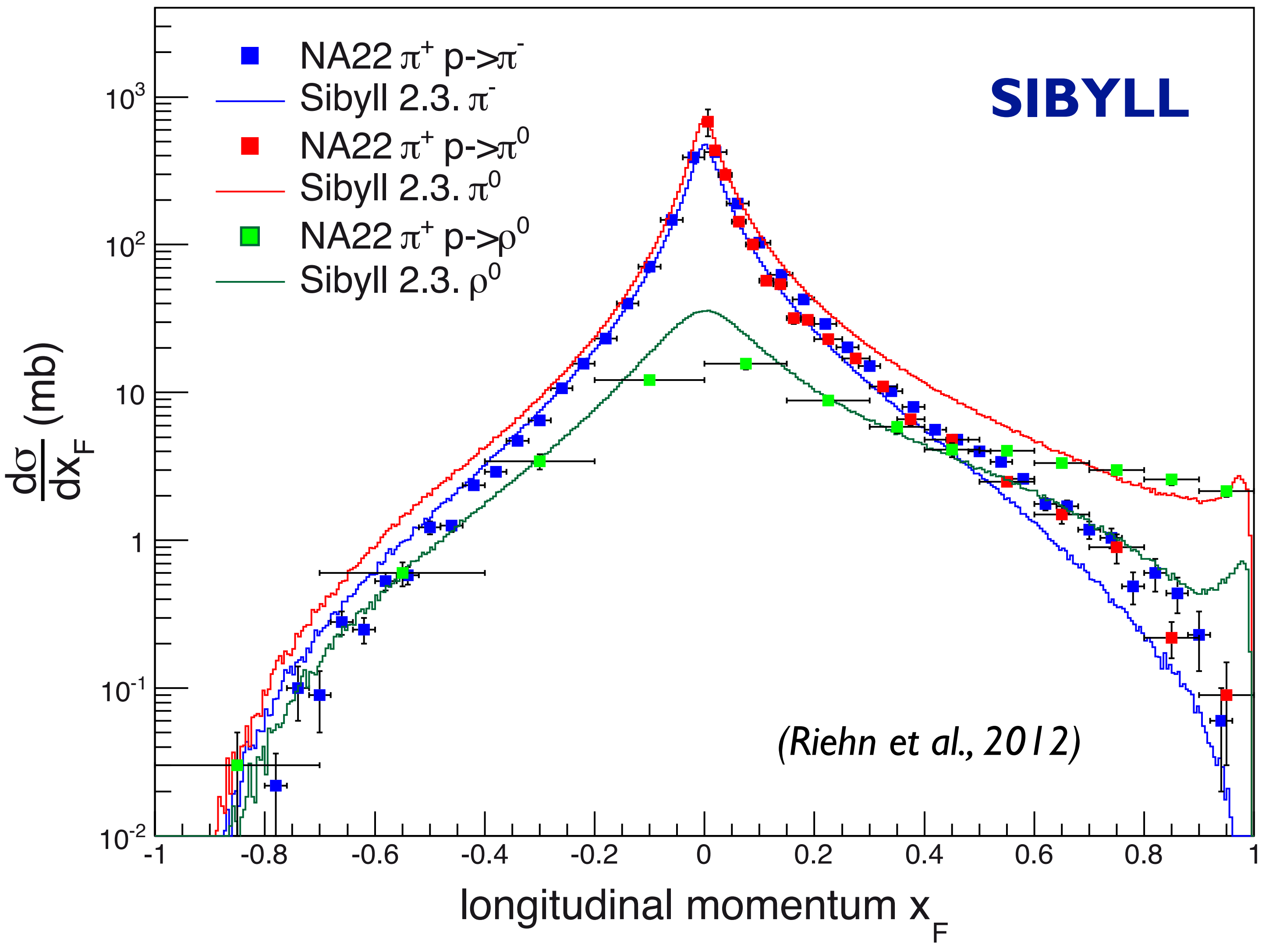
Baryon production rate not as high as expected from Tevatron data

LHC data (CMS: 900 and 2760 GeV)



(Riehn et al., 2012)

Leading particle for π-air interactions



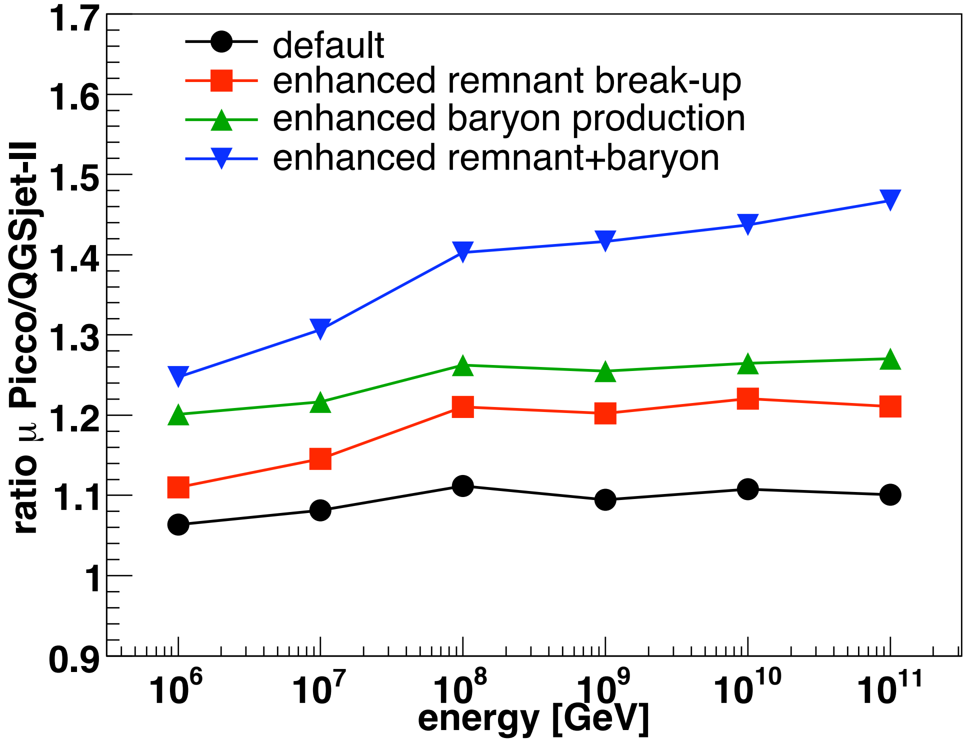
(Riehn et al., 2012)

Fixed-target data: NA22
at 250 GeV (22 GeV c.m.s.)

$$\rho^0 \longrightarrow \pi^+ \pi^-$$

$$\pi^0 \longrightarrow \gamma\,\gamma$$

More work needed to clarify situation (energy dependence?)



(Drescher Phys. Rev. D77, 2008)