Introduction to Cosmic Rays

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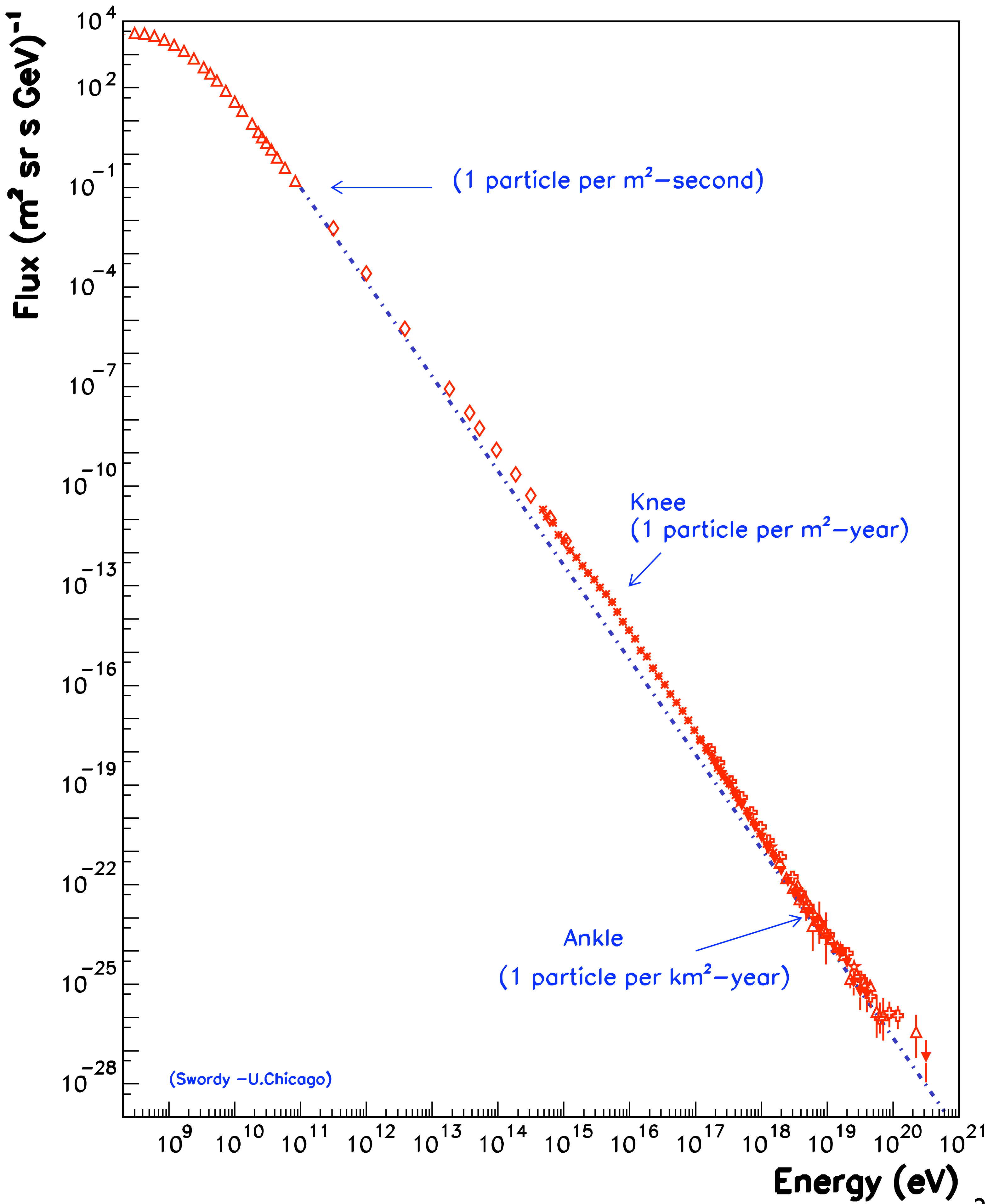
Flux of cosmic rays



Flux follows power law

$$\frac{dN}{dE\,d\Omega\,dA\,dt} \propto E^{-\gamma}$$

$$\gamma \approx 2.7 \qquad 10^{11}\,\text{eV} < E < 10^{15.5}\,\text{eV}$$
$$\approx 3.1 \qquad 10^{15.5}\,\text{eV} < E < 10^{18.5}\,\text{eV}$$

Energy spectrum of all-particle flux

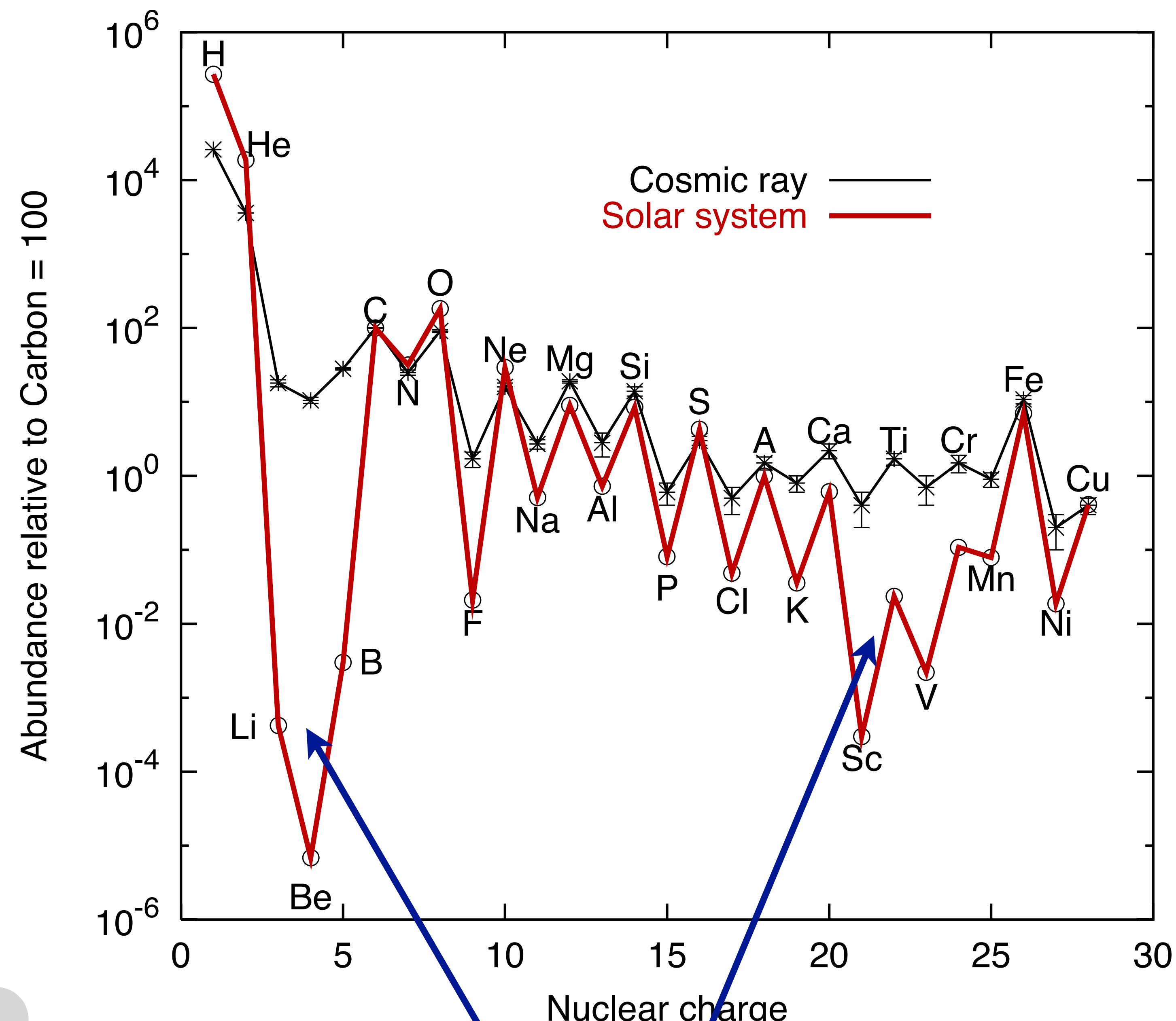
Direct measurement (balloons, satellites)

Measurement in upper atmosphere

Traversed column depth $$X = \int_h^\infty \rho(h)\,dl$$

Total atmosphere (vertical) $X_{atm} \approx 1030\ \mathrm{g/cm^2}$

Nuclear abundance: cosmic rays compared to solar system

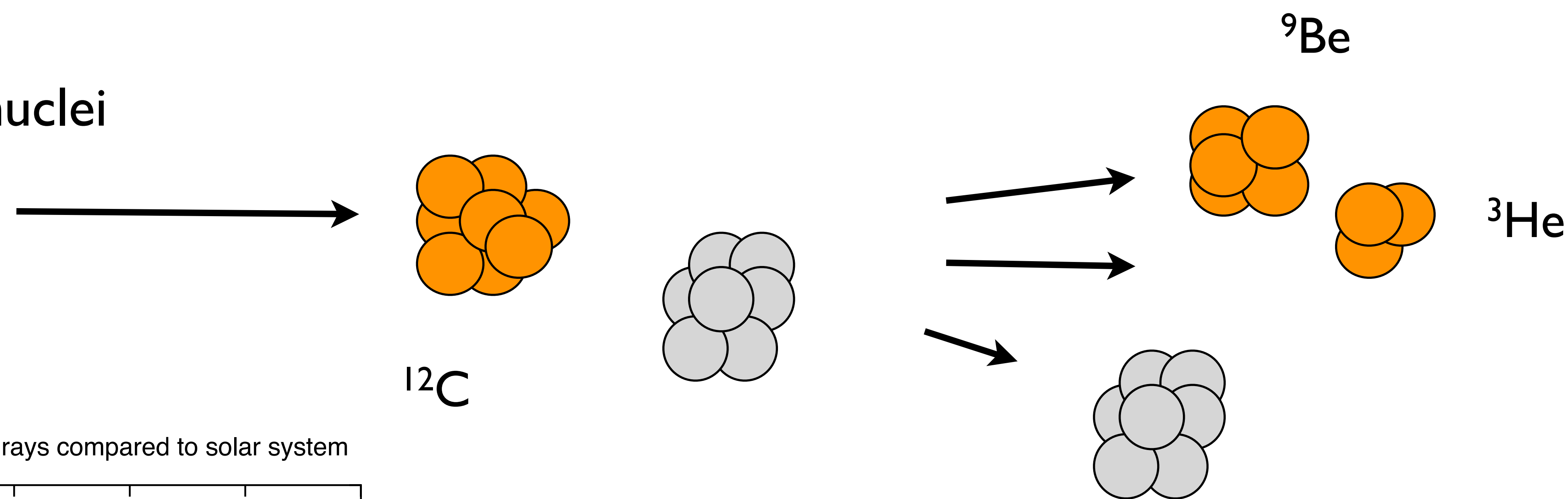


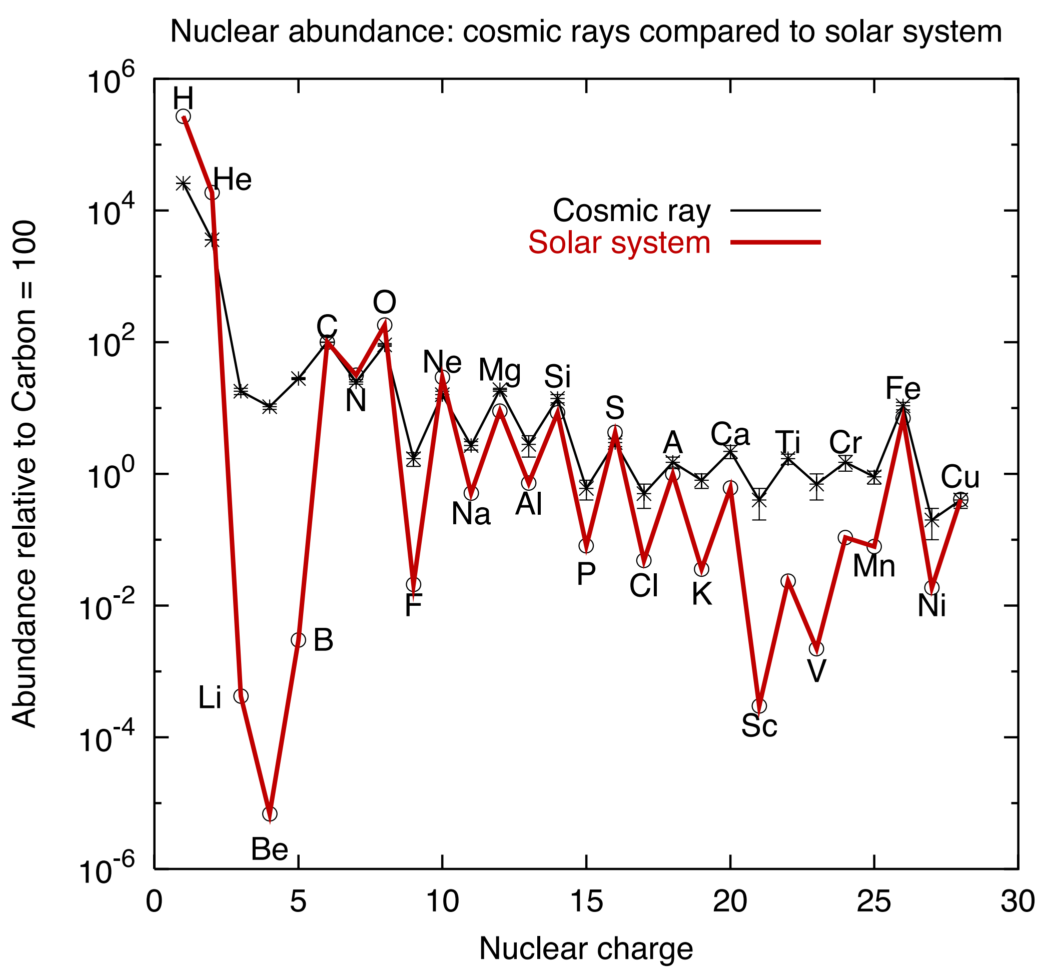
Not typical products of Supernova explosions

Cross check of model with secondary elements

Interstellar medium in galaxy: ~1 atom /cm^3

Spallation of nuclei





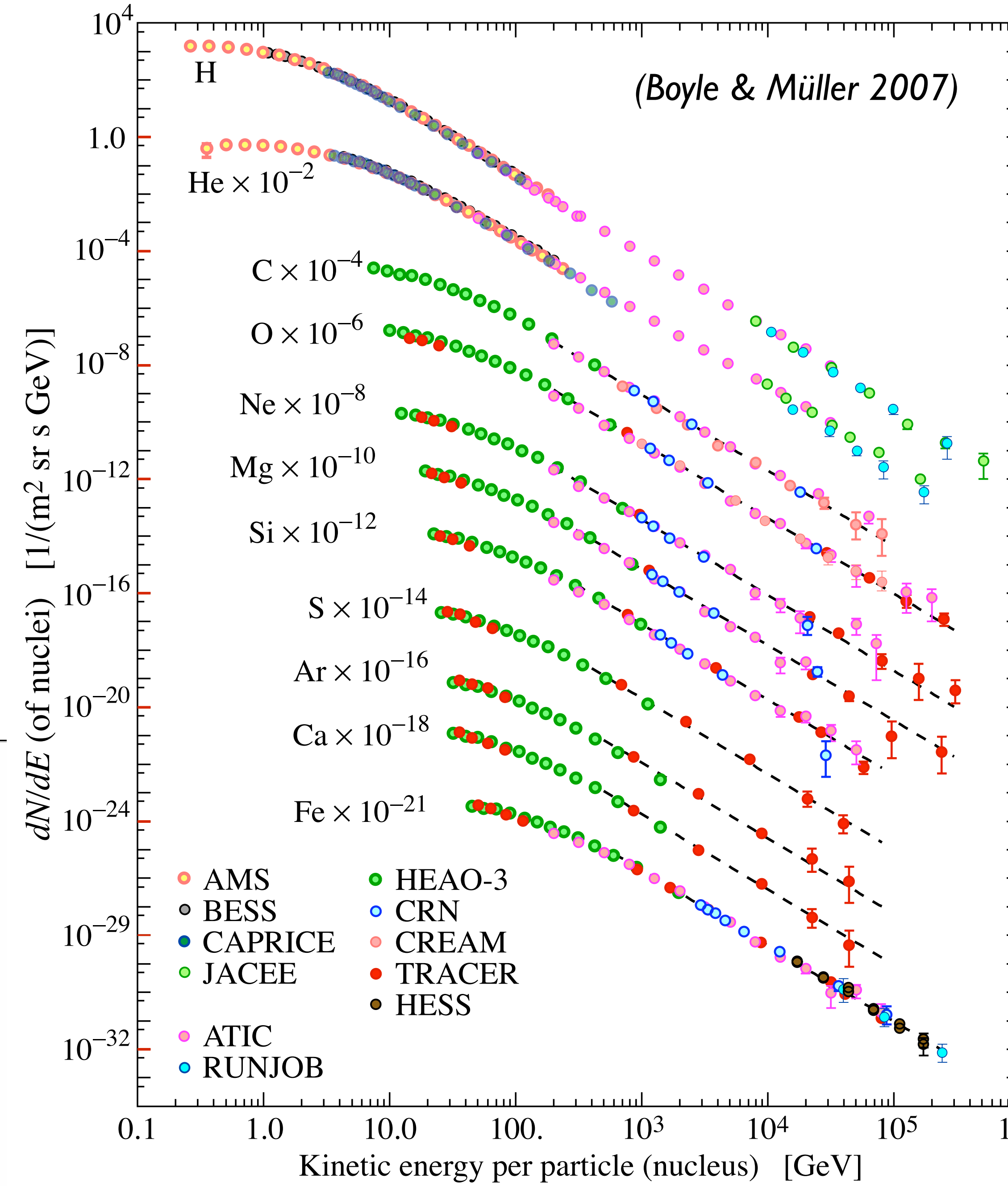
- Explanation of differences of abundances
- Energy dependence through τ_{esc} predicted

Composition of cosmic rays at low energy

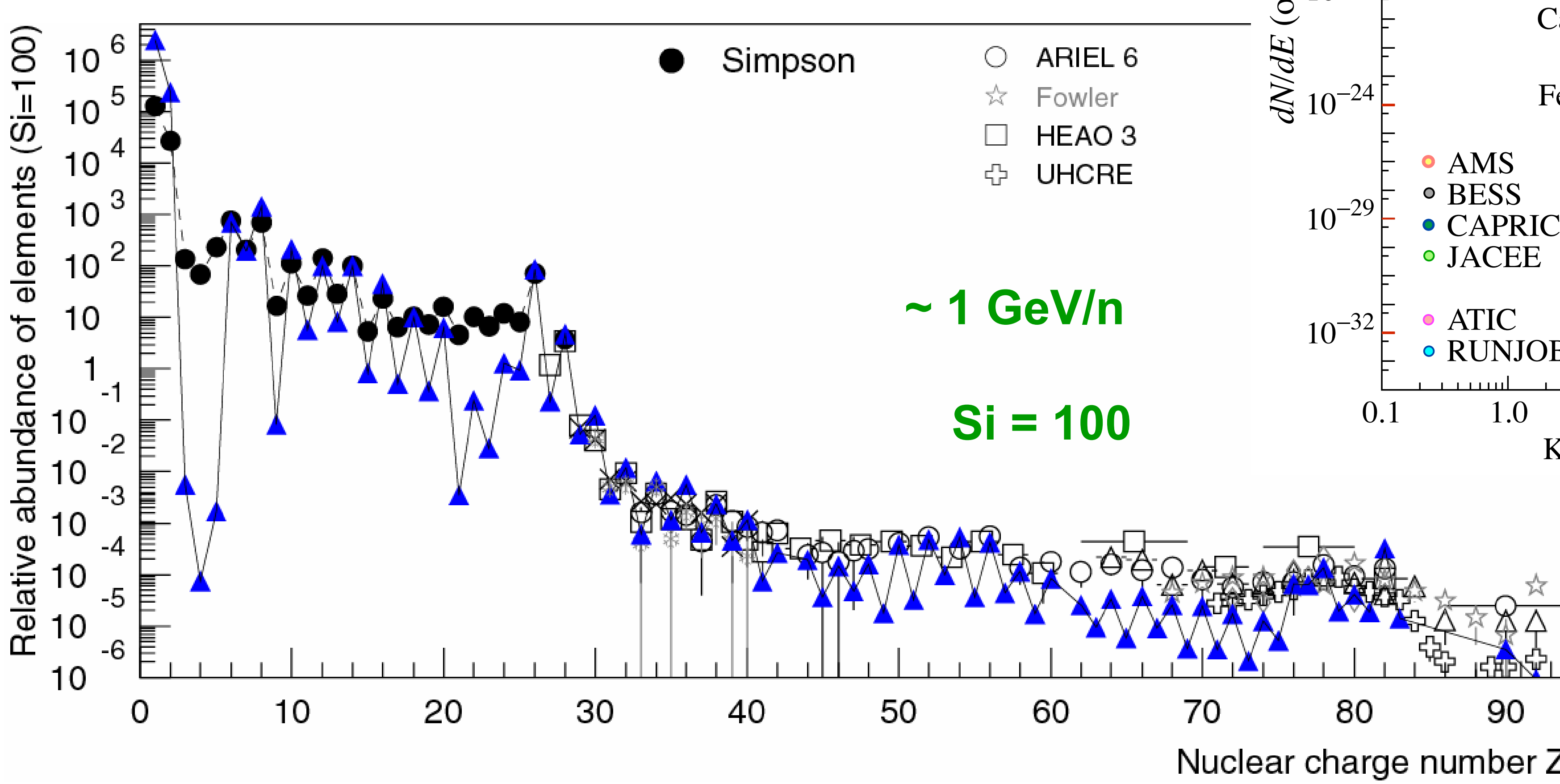
Most frequent elements: H ... Fe/Ni
Often only H and Fe considered

Relative abundance of nuclei

H	He	Z= 6-9	10-20	21-30
1	0.38	0.22	0.15	0.4



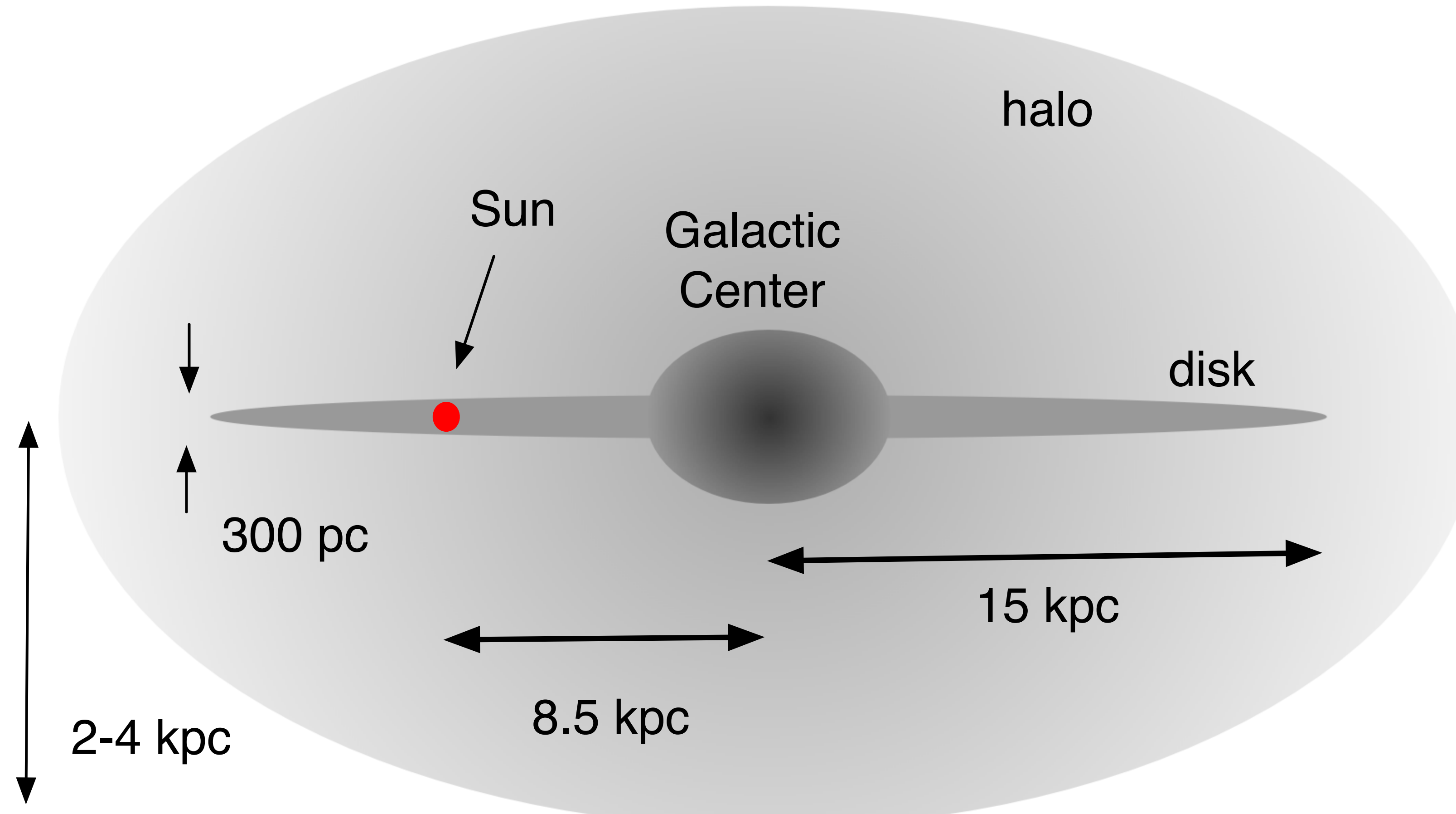
(Hörandel, 2005)



Galaxy and galactic magnetic fields

(Andromeda, M31)

1 pc = 3.26 ly = 3.08 10^{16} m



Magnetic field not well known,
B = 3 μG = 30 nT close to Solar System

$$R_L \simeq 1\,\mathrm{pc} \times \left(\frac{E}{10^{15}\,\mathrm{eV}}\right)\left(\frac{\mu\mathrm{G}}{ZB}\right)$$

Diffusion: distance scales ~ $(\mathrm{time})^2$ → Extragalactic sources unlikely

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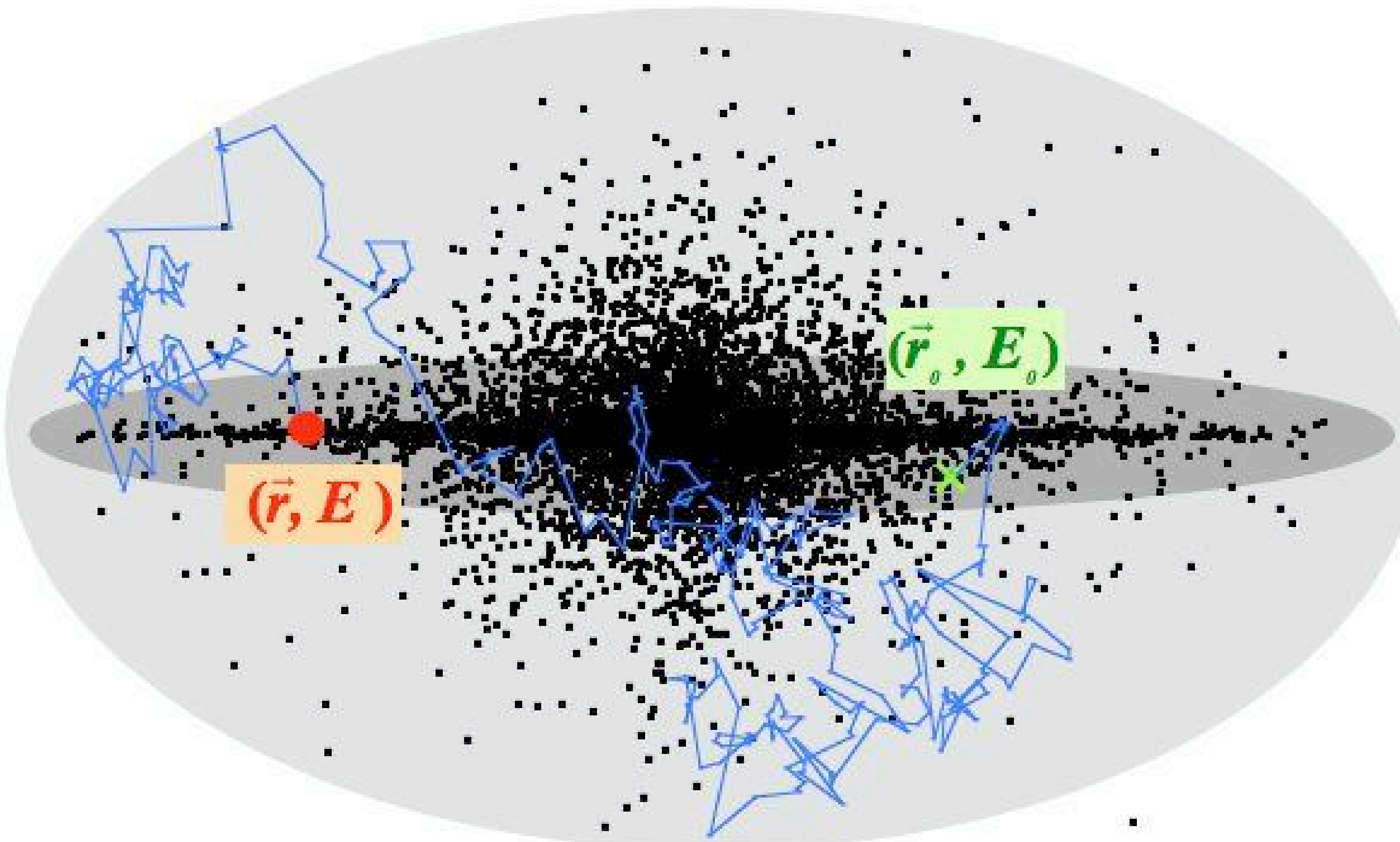

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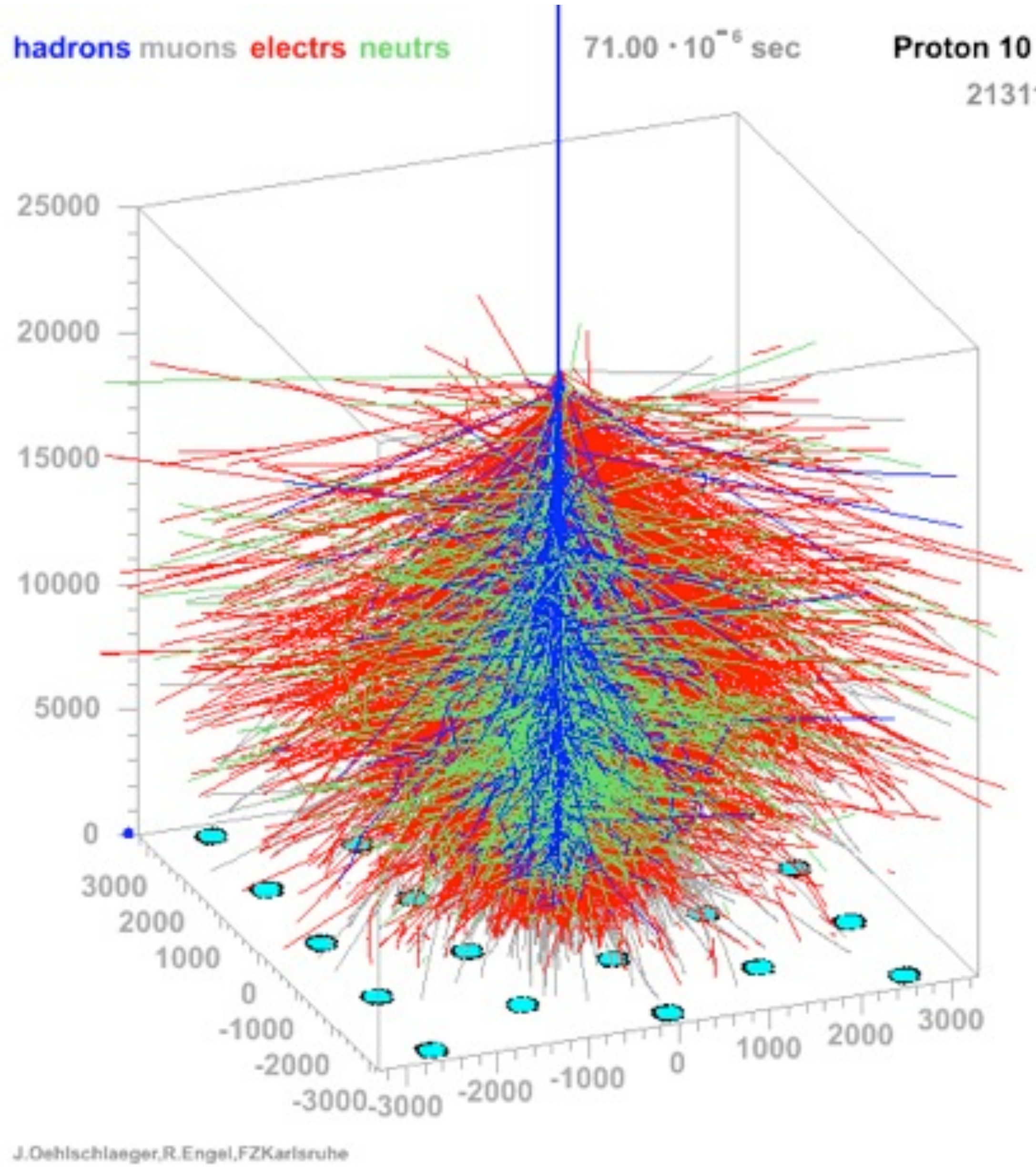
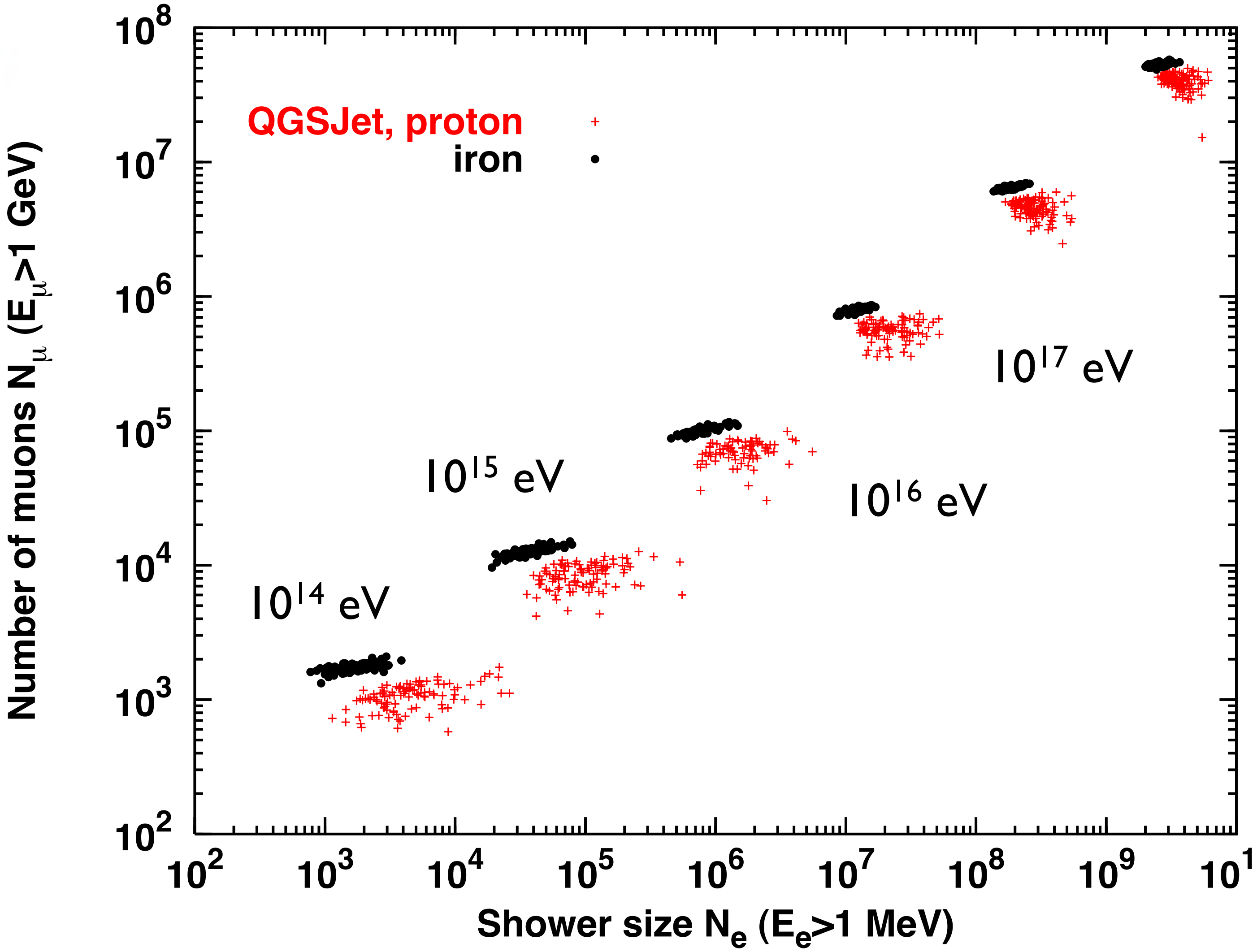
Air shower ground arrays

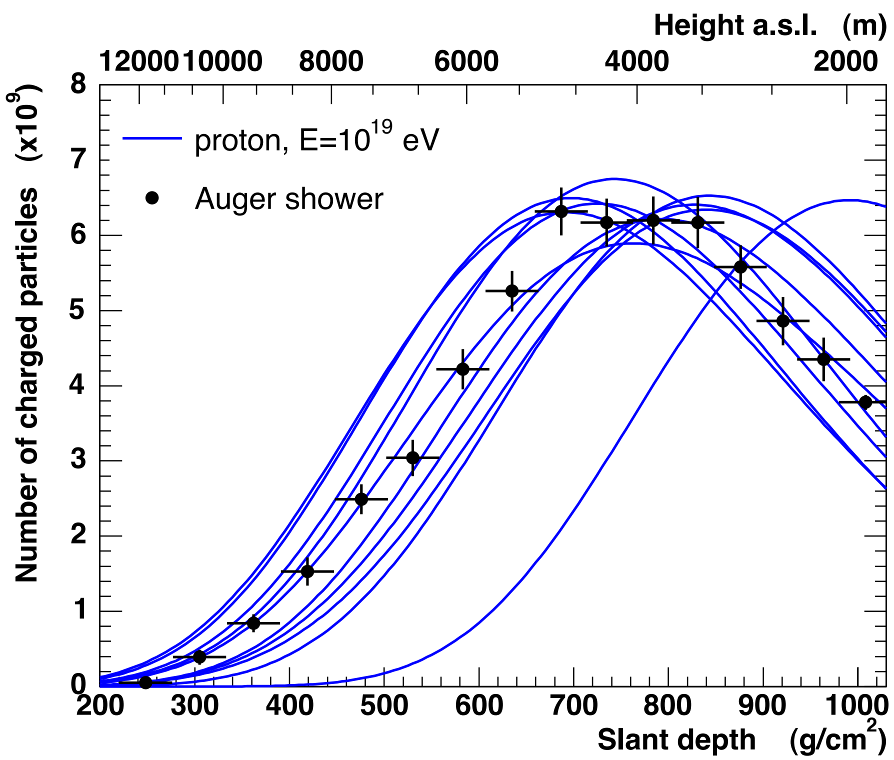


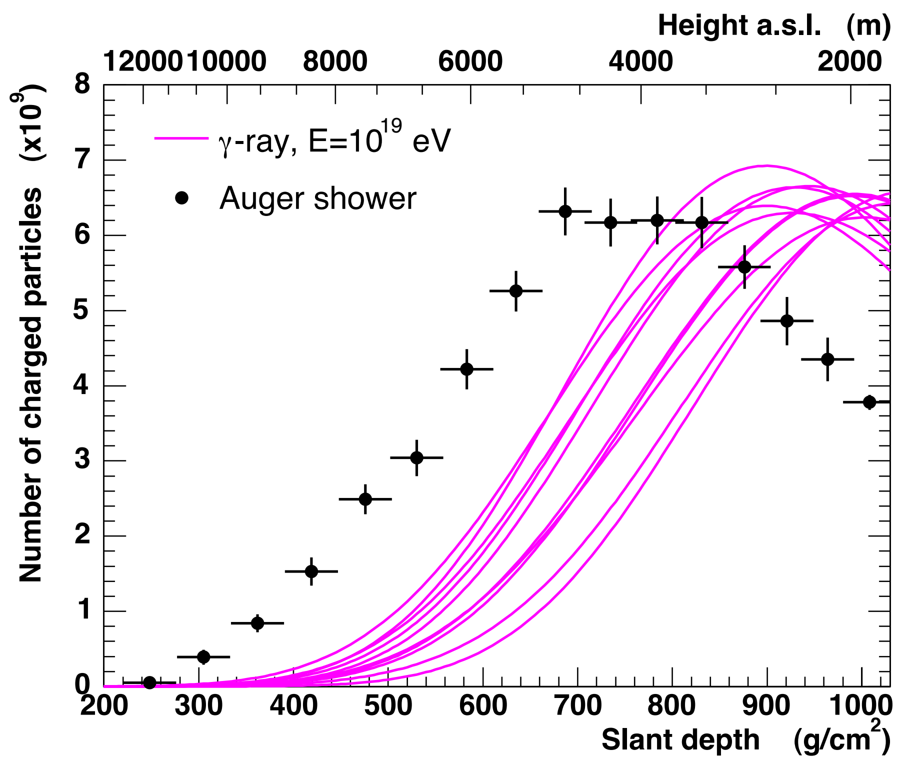
Example:
KASCADE-Grande (Karlsruhe)

Combined energy-composition analysis

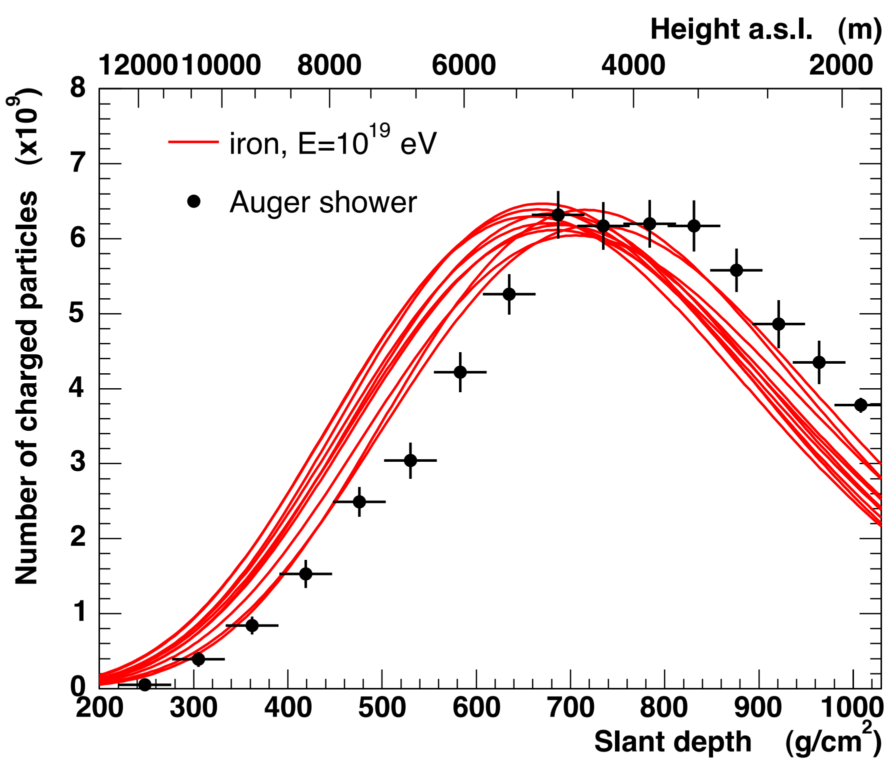


Energy / composition analysis using shower profiles



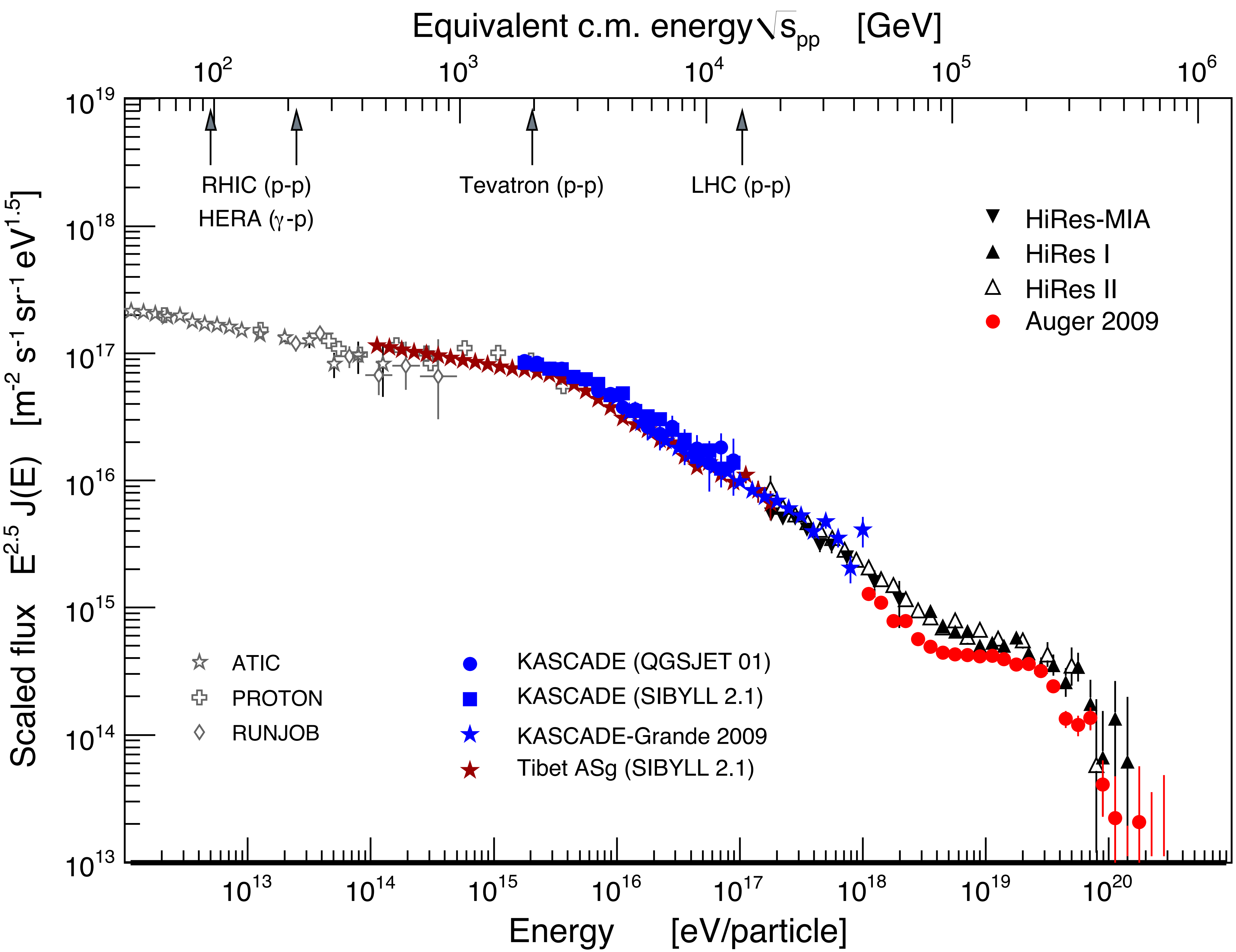


Example: event measured by Auger Collab. (ICRC 2003)

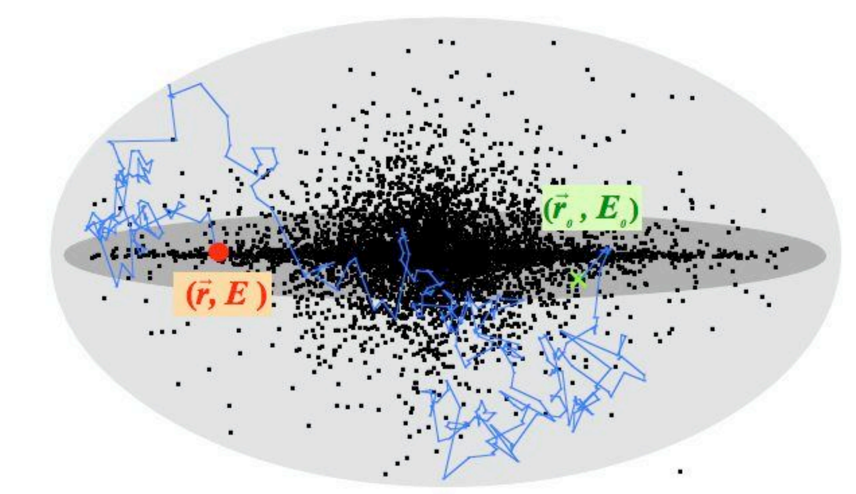


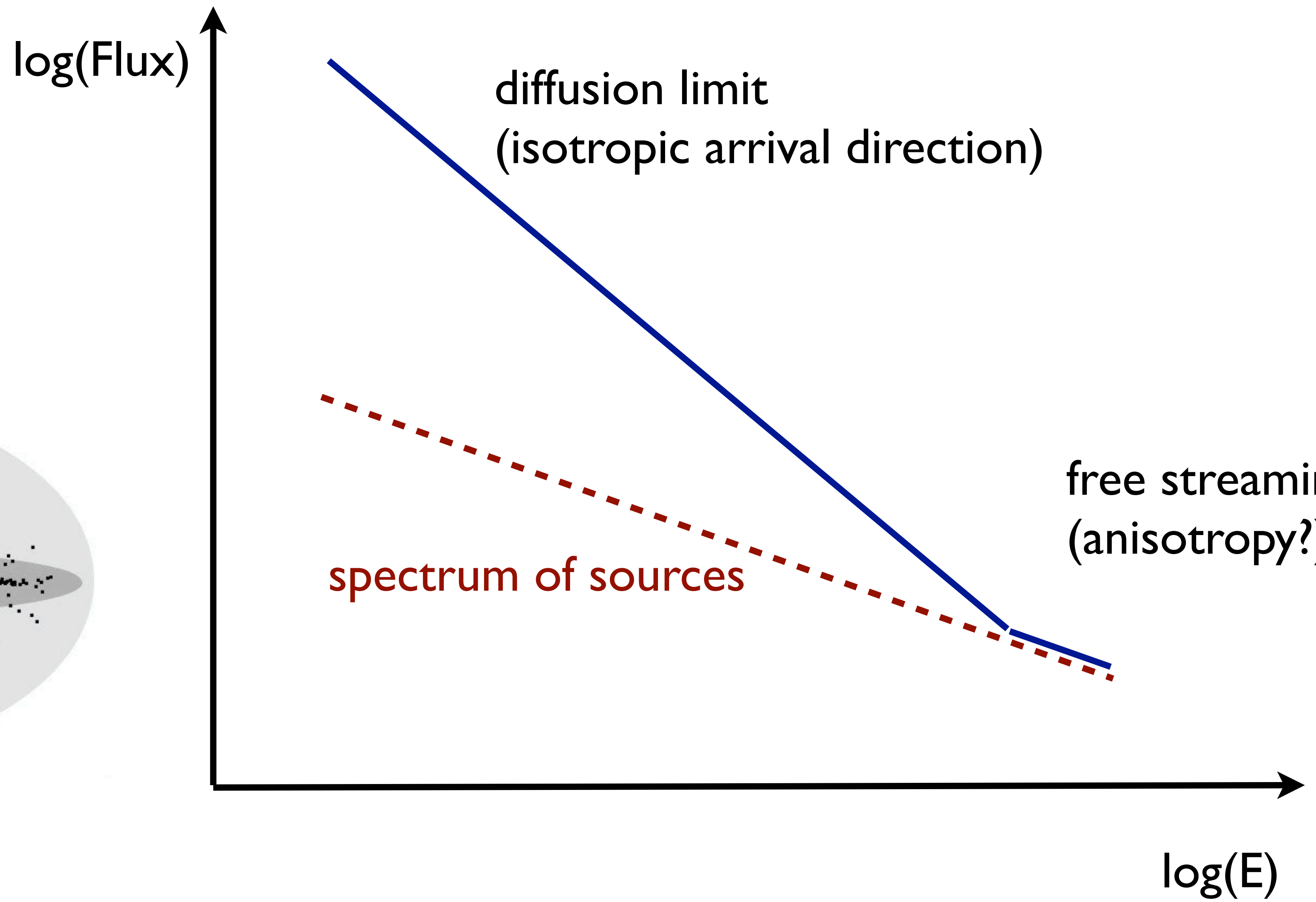
- Energy well determined
- Primary particle type: mean and fluctuations of shower depth of maximum

Success: all-particle flux



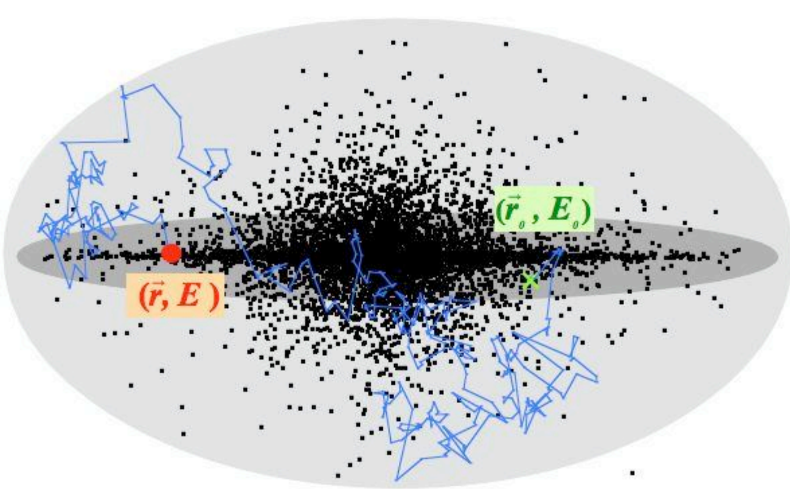
Magnetic fields: Confinement in the Galaxy (i)

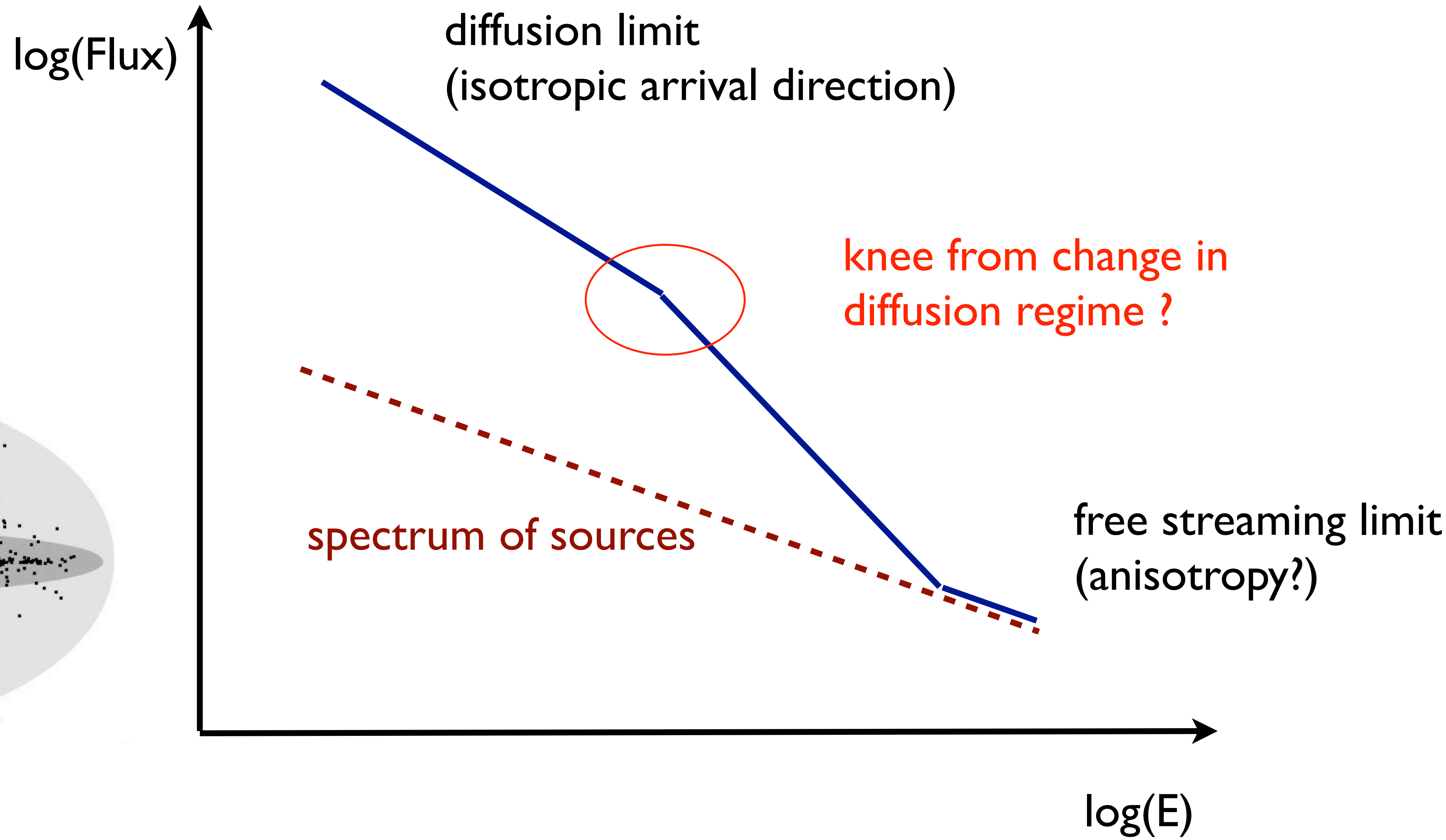




Observed spectrum softer than injection spectrum

Magnetic fields: Confinement in the Galaxy (ii)





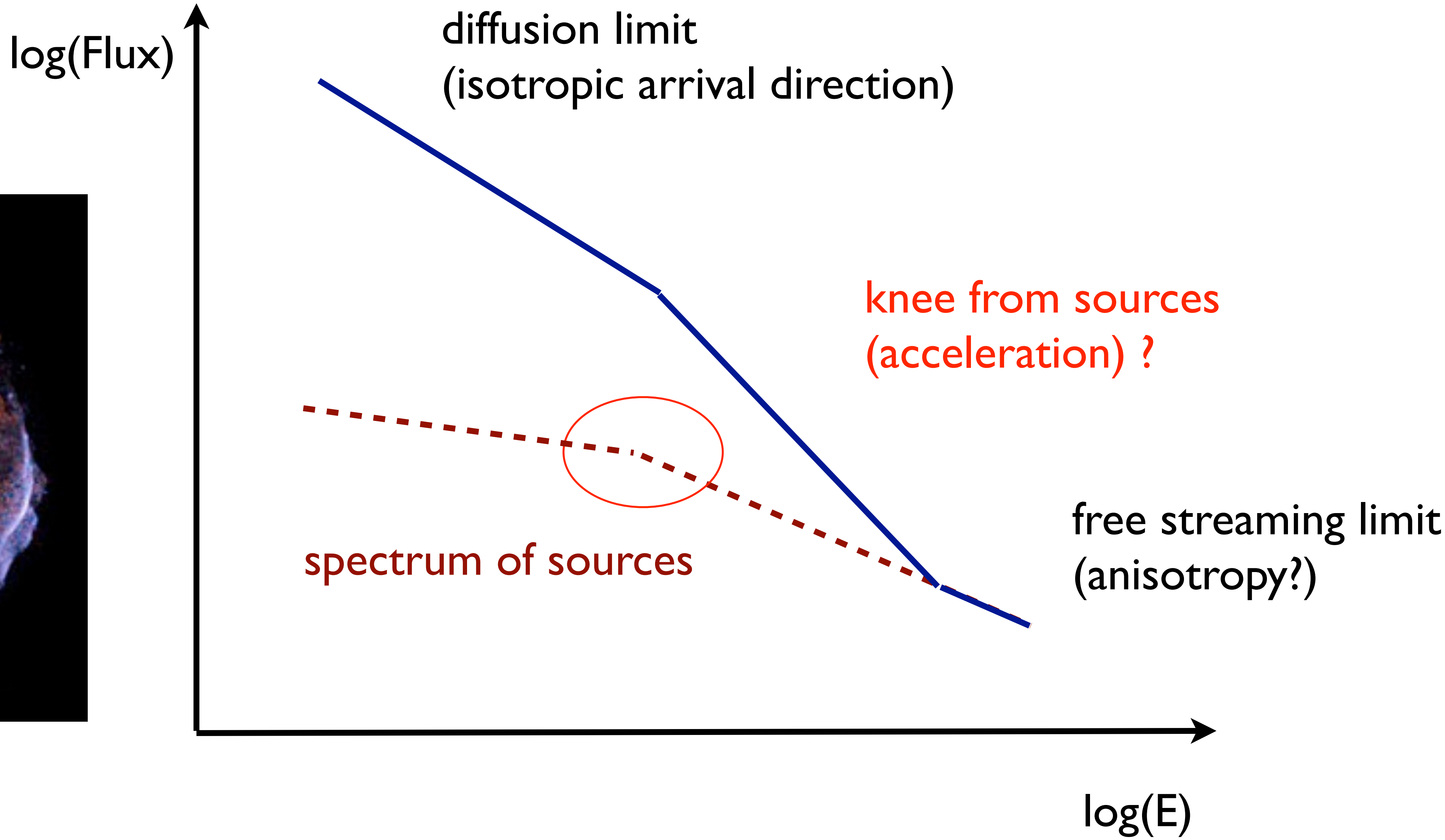
Diffusion: same behaviour for different elements at same rigidity $p/Z \sim E/Z$

Magnetic fields: Confinement in sources

SN remnant 1006

Distance ~ 2.2 kpc

20 pc



Acceleration: same behaviour for different elements at same rigidity $p/Z \sim E/Z$

Exotic models for interpretation

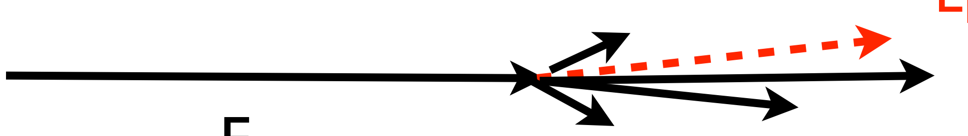
The knee and unusual events at PeV energies

A.A.Petrukhin[a]

Nuclear Physics B (Proc. Suppl.) 151 (2006) 57–60

[a]Experimental Complex NEVOD, Moscow Engineering Physics Institute,
Kashirskoe shosse, 31, Moscow 115409, Russia

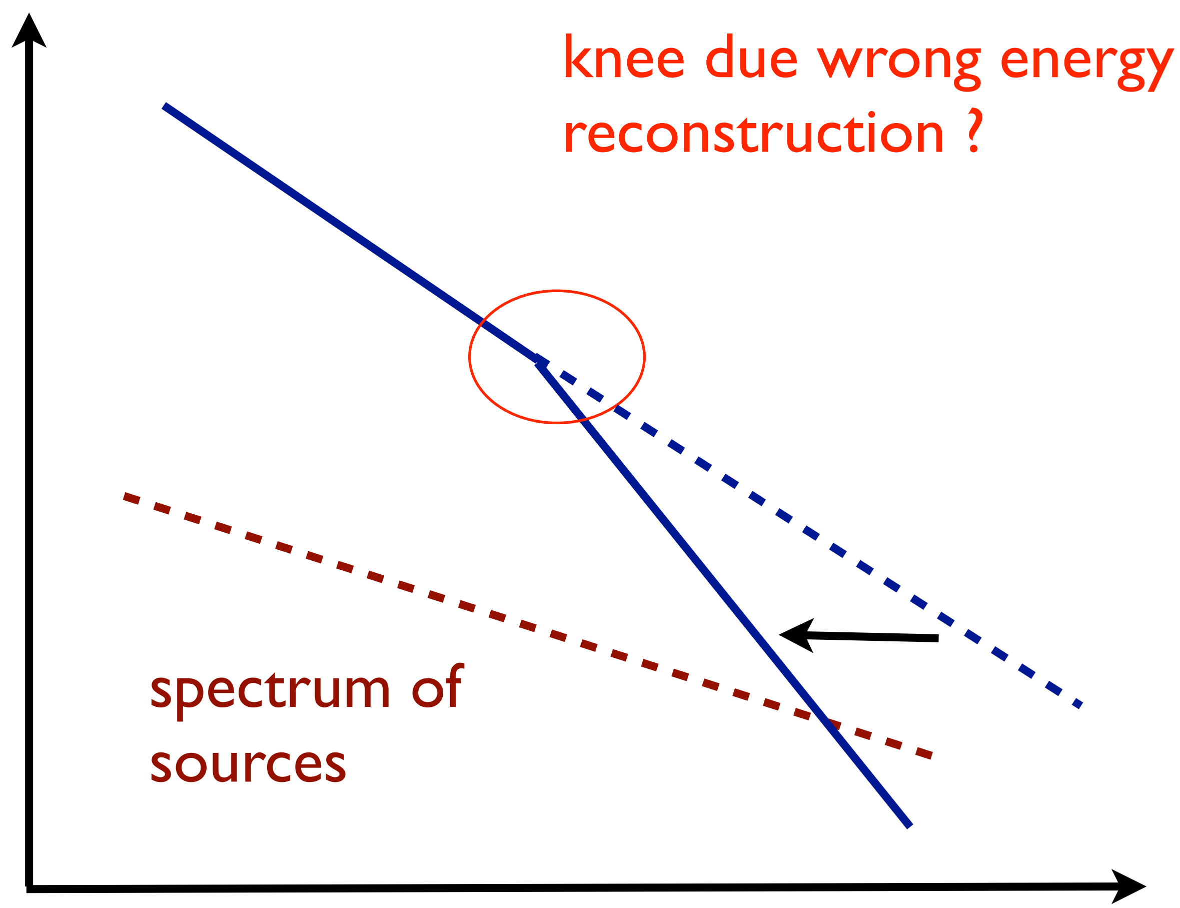
The appearance of the knee in EAS energy spectrum in the atmosphere in PeV energy interval and observation of various types of unusual events approximately at same energies are considered as evidence for new physics. Some ideas about possible new physical processes at PeV energies are described. Perspectives to check these ideas and their consequences for experiments at higher energies are discussed.



New physics, the cosmic ray spectrum knee, and *pp* cross section measurements

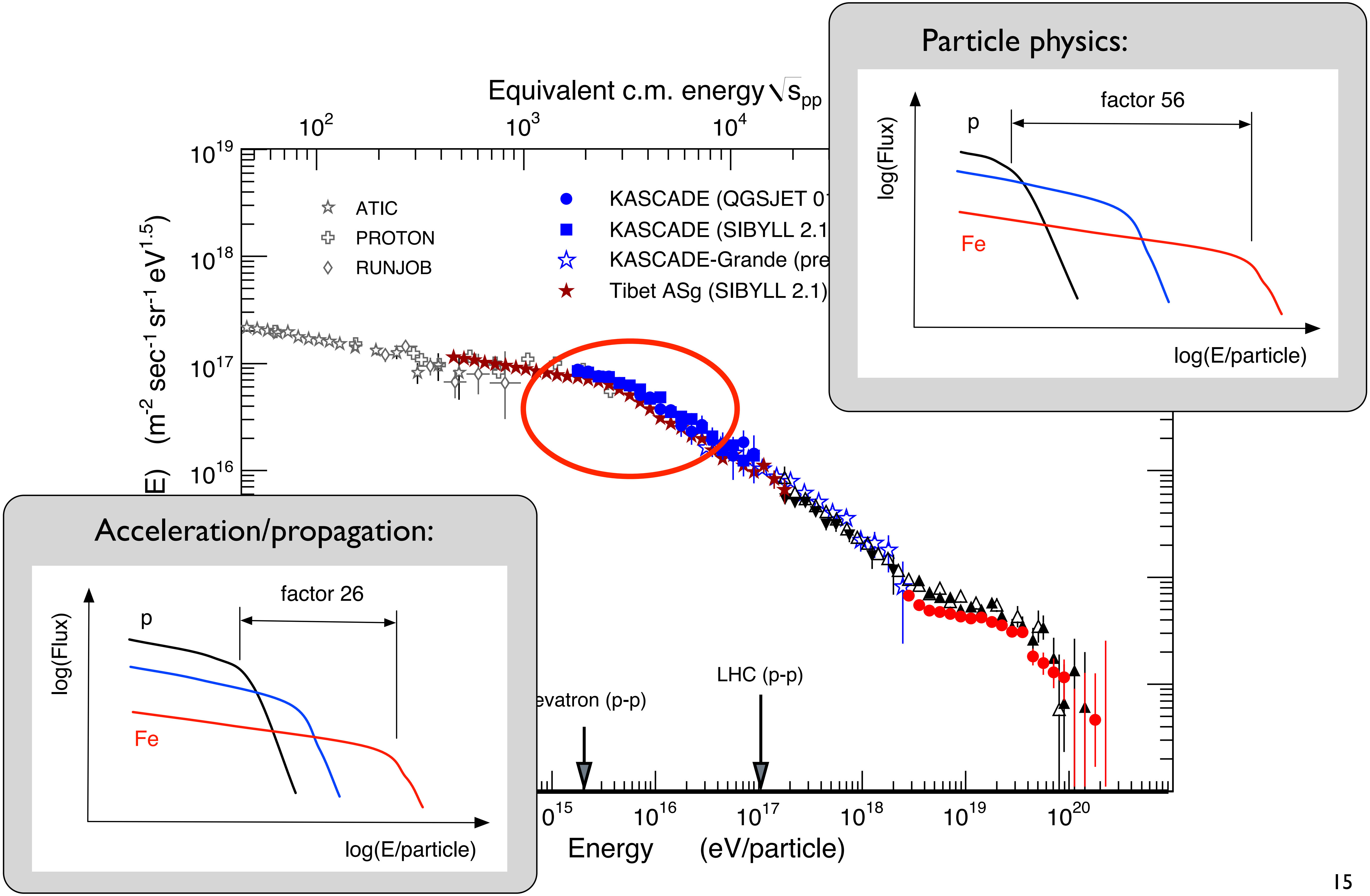
Aparna Dixit[1], Pankaj Jain[2], Douglas W. McKay[3], and Parama Mukherjee[4]

December 7, 2009



New physics: scaling with nucleon-nucleon cms energy

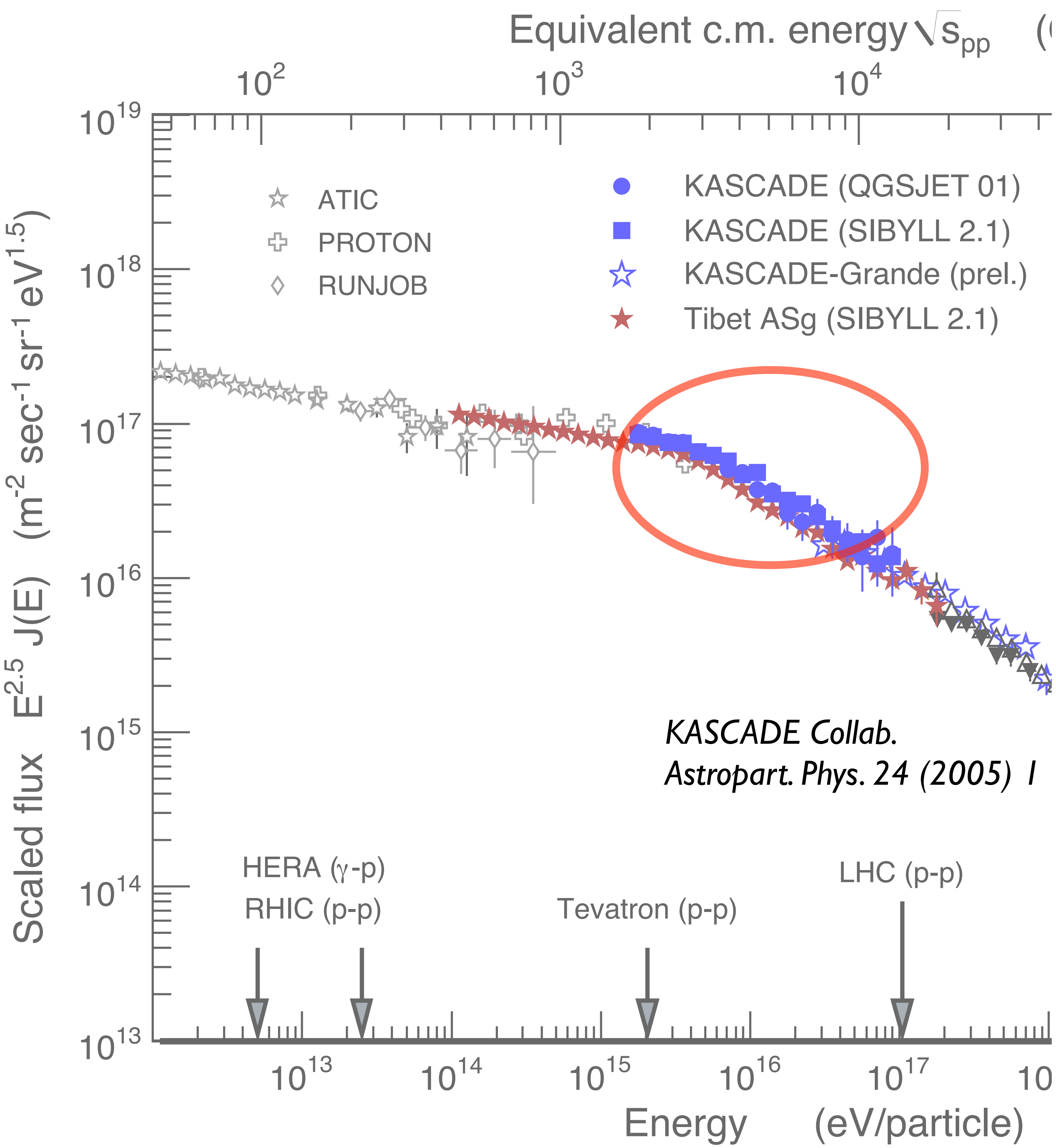
Origin and physics of the knee

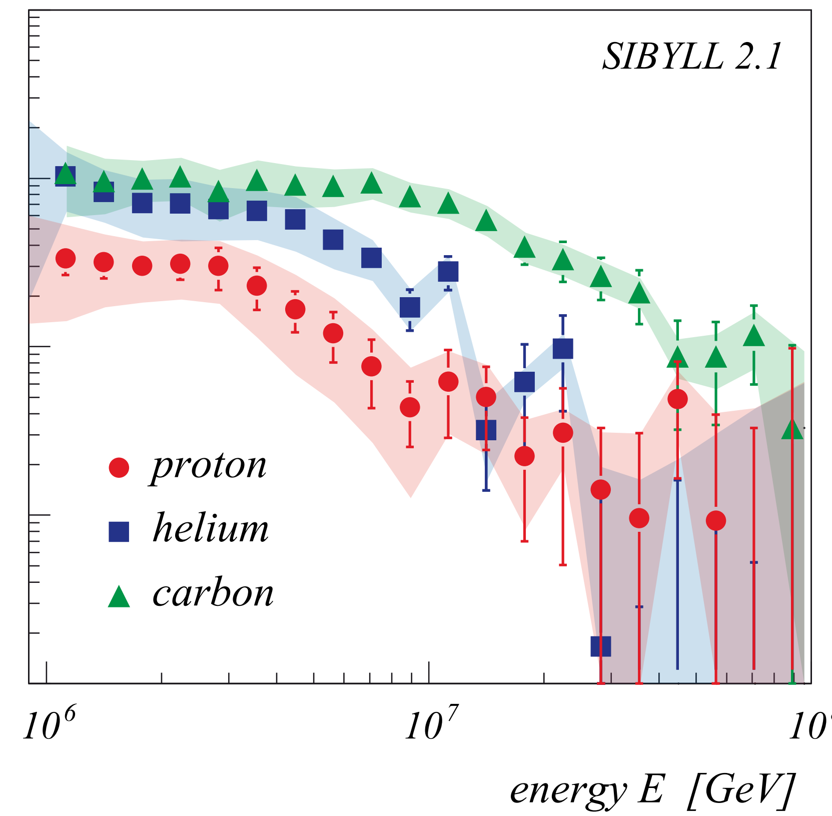


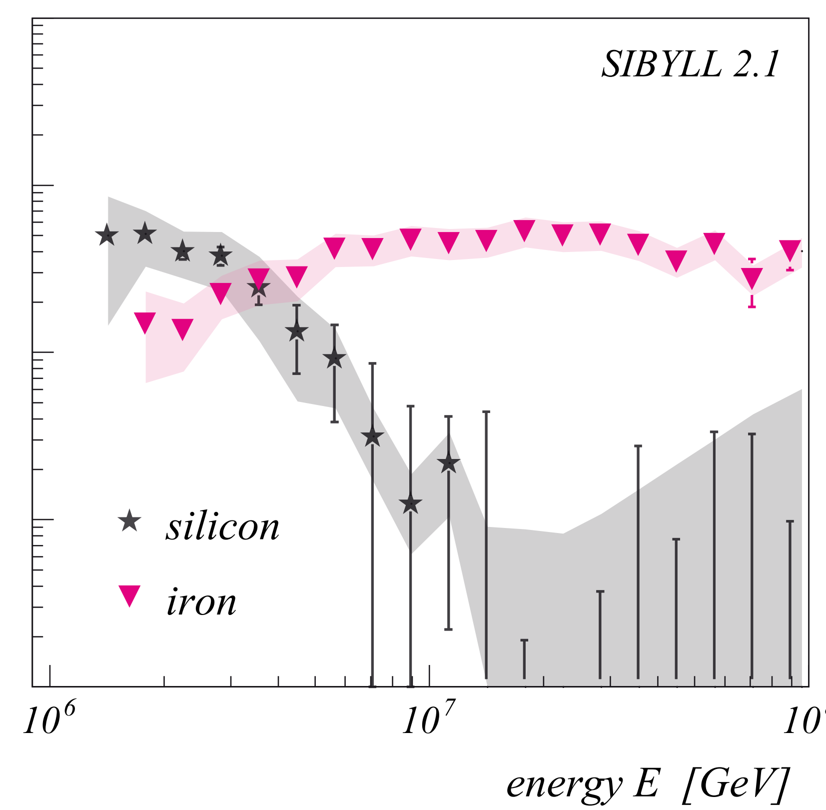
KASCADE

Area ~ 0.04 km^2,
252 surface detectors

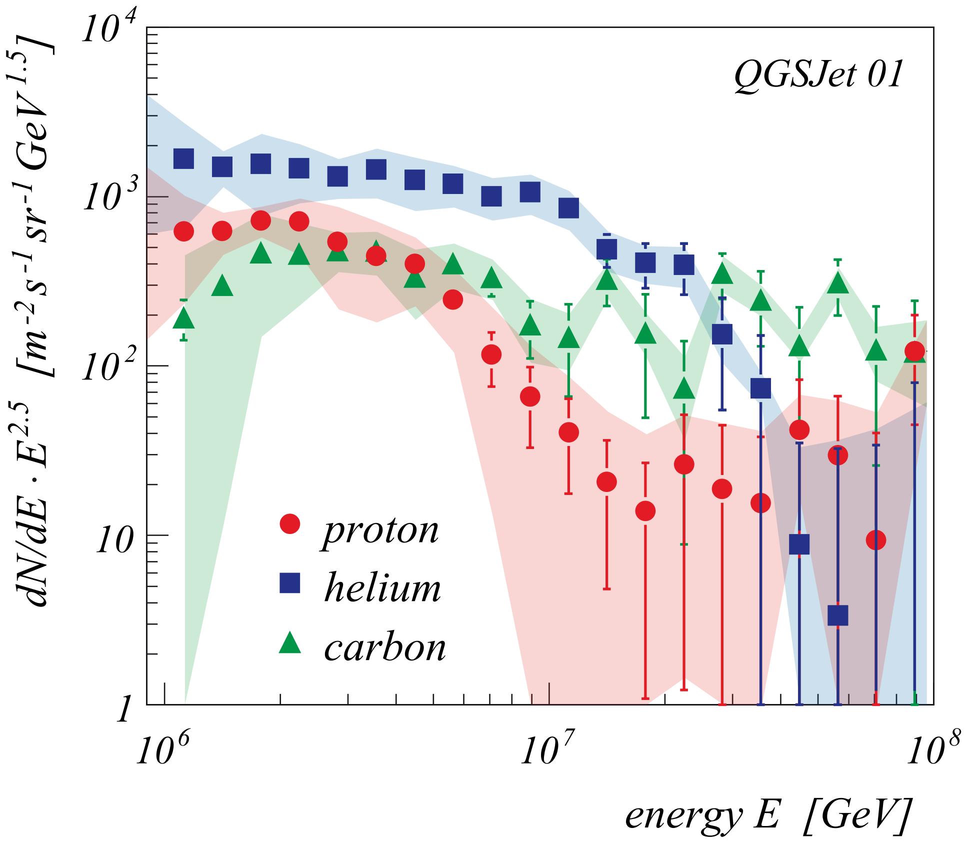
Composition in Knee region (i)

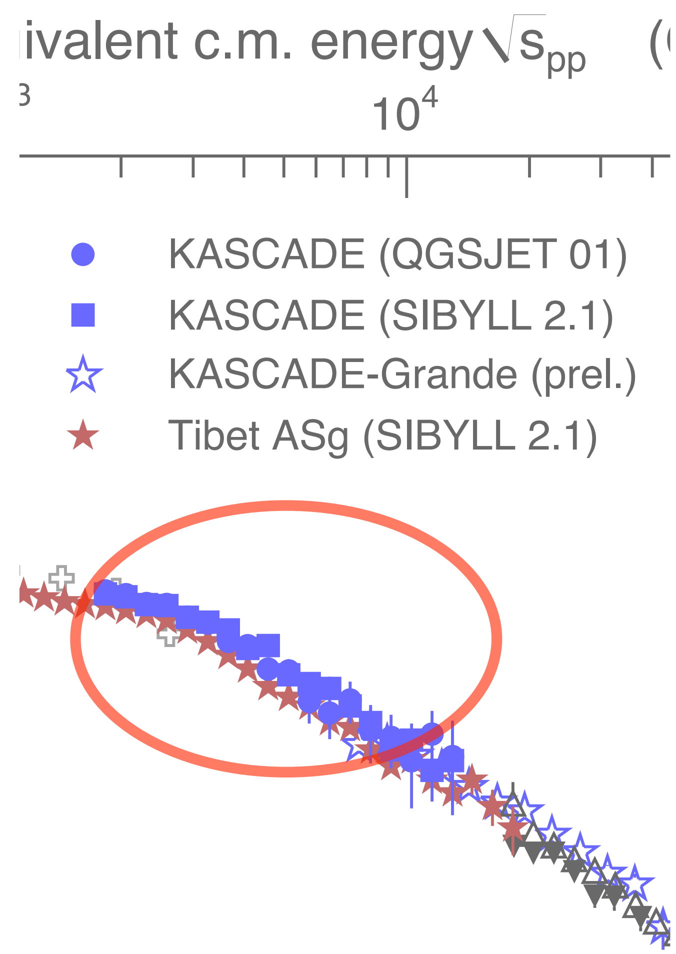




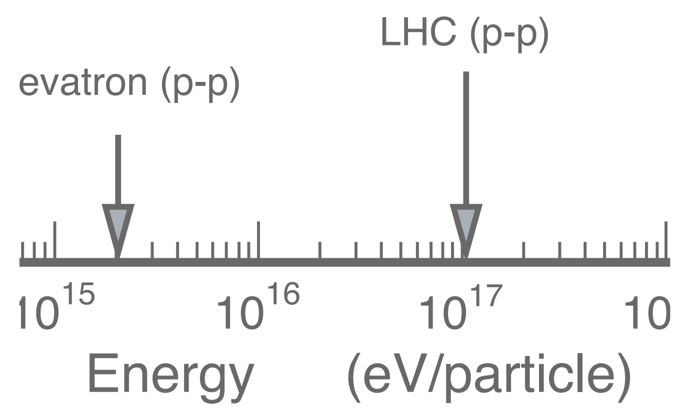


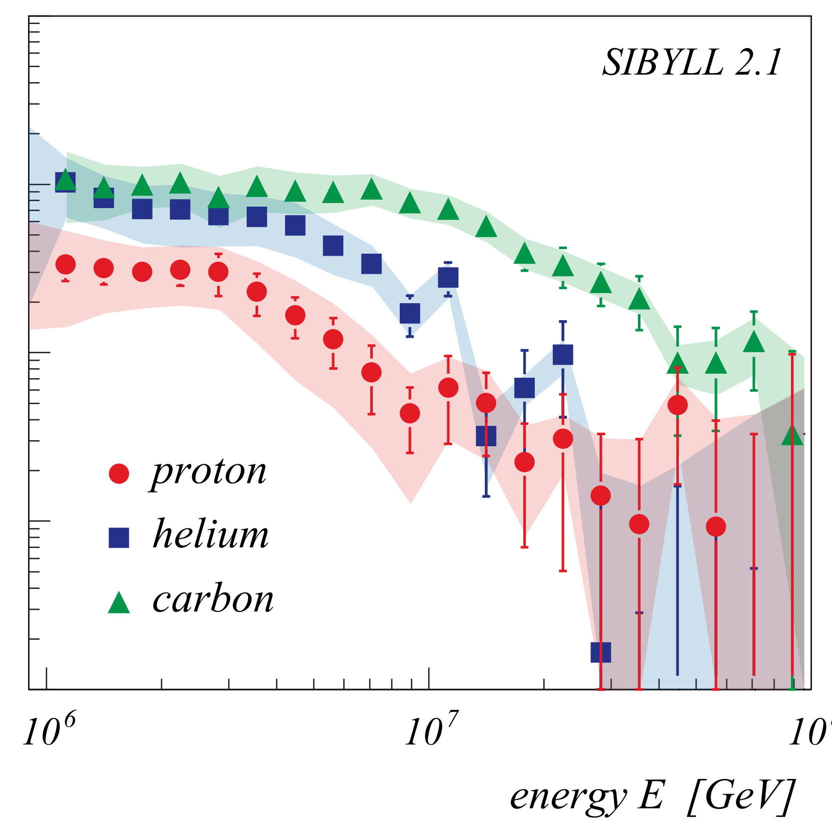
Composition in Knee region (ii)

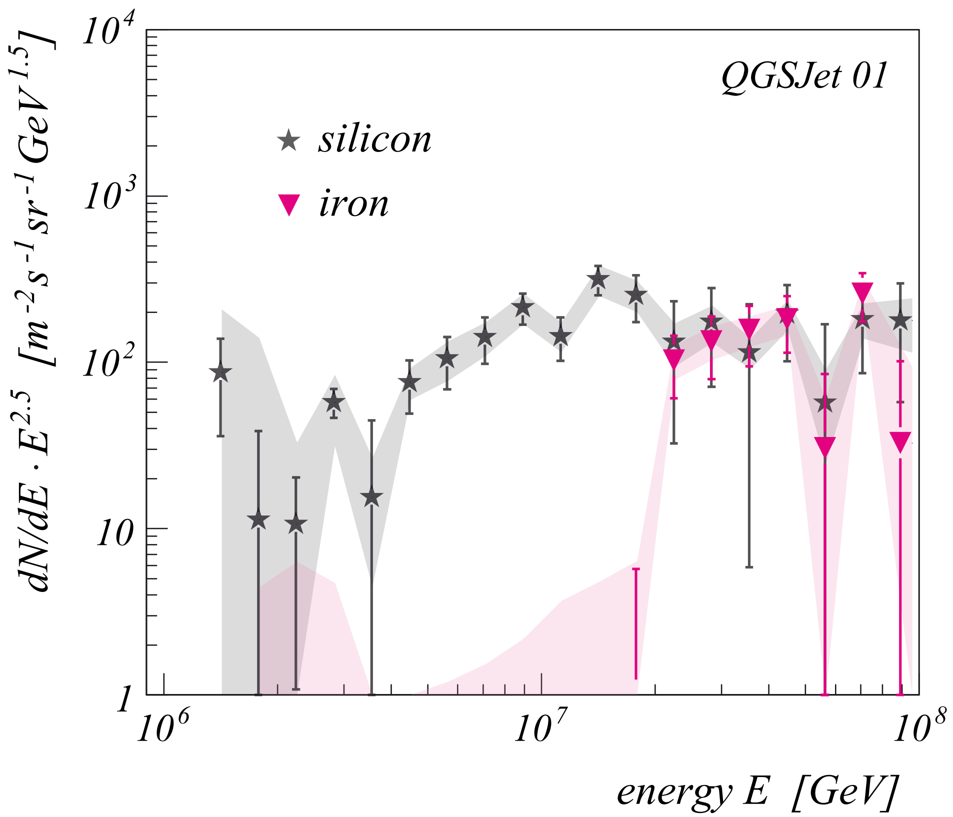


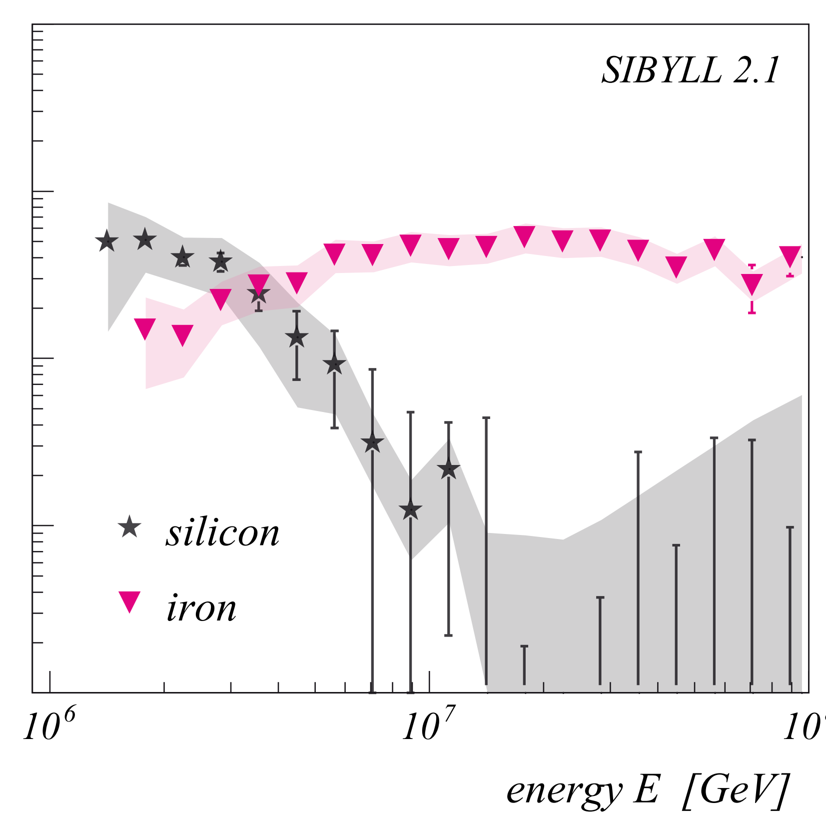


KASCADE Collab.
Astropart. Phys. 24 (2005) 1

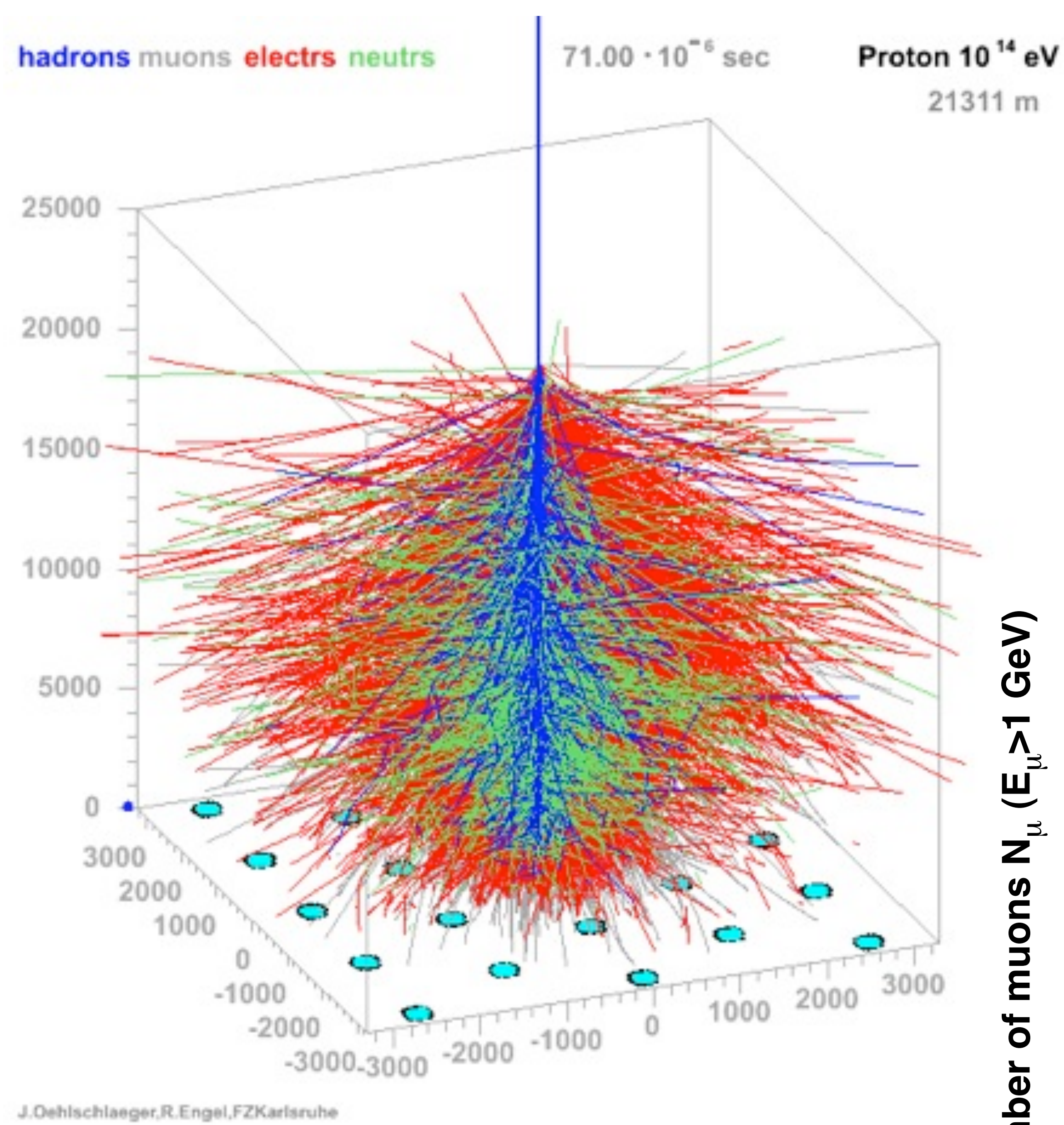








Air shower ground arrays



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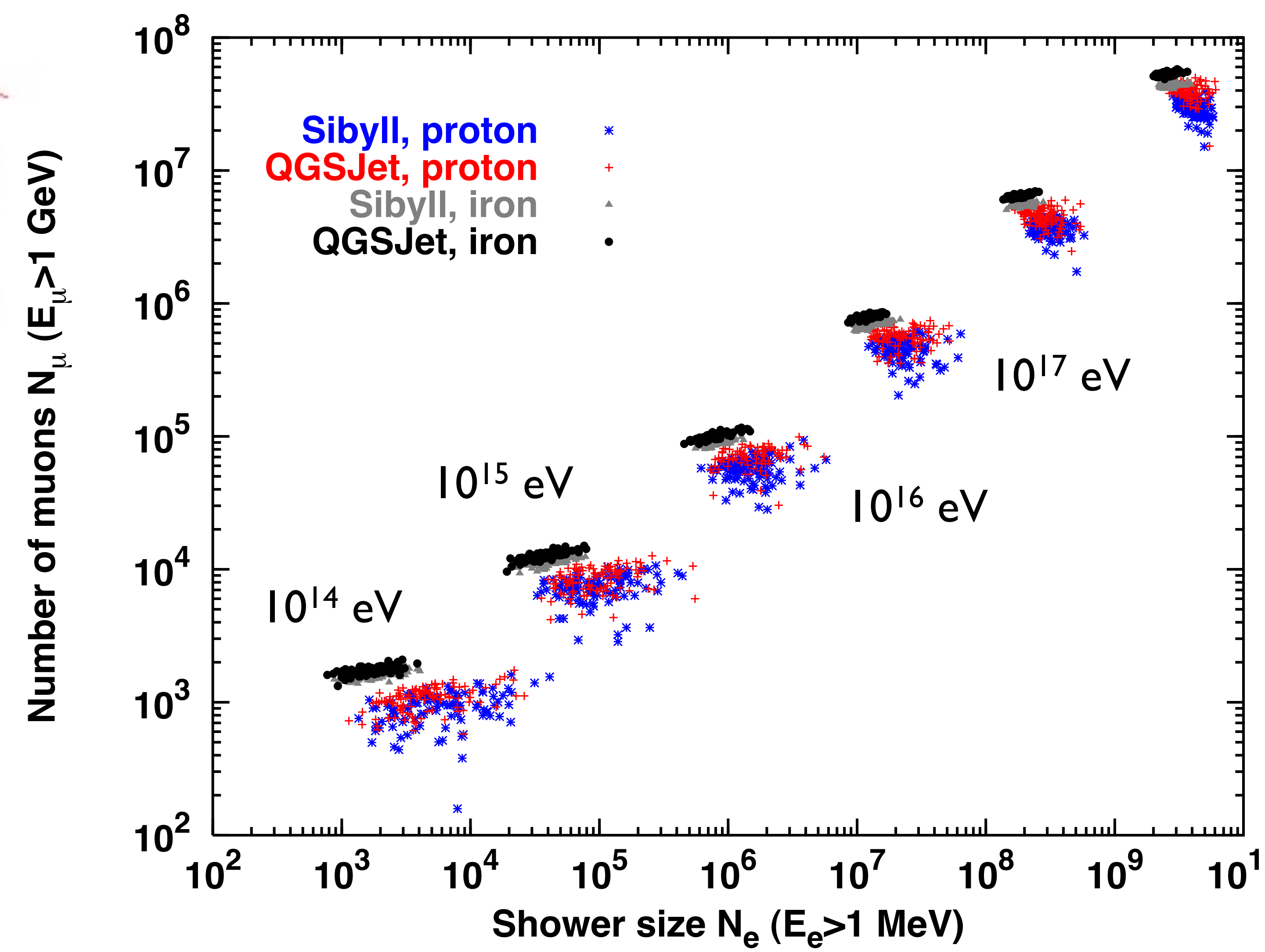
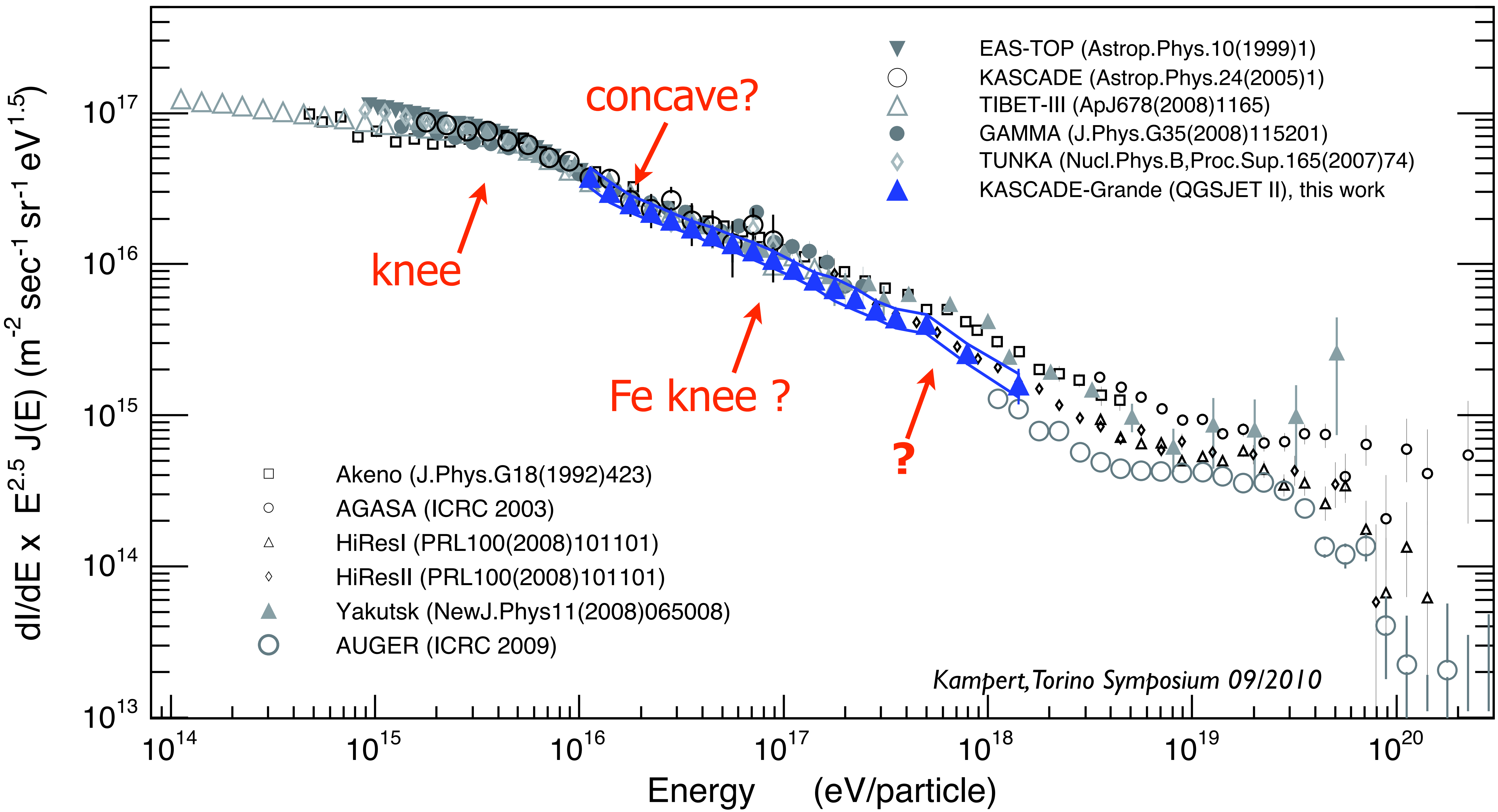
Combined energy-composition analysis

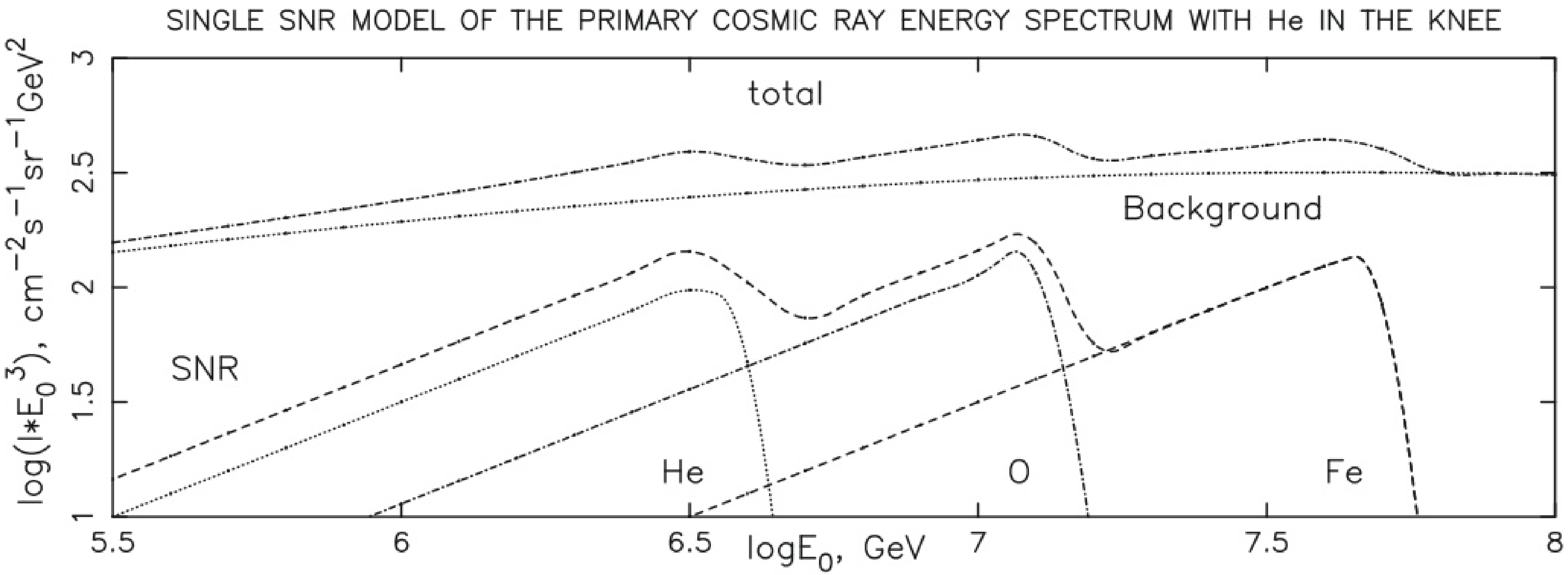


Energy spectrum really just a broken power law ?



KASCADE-Grande, ECRS 2010 (paper in preparation)

Curvature in power law of flux



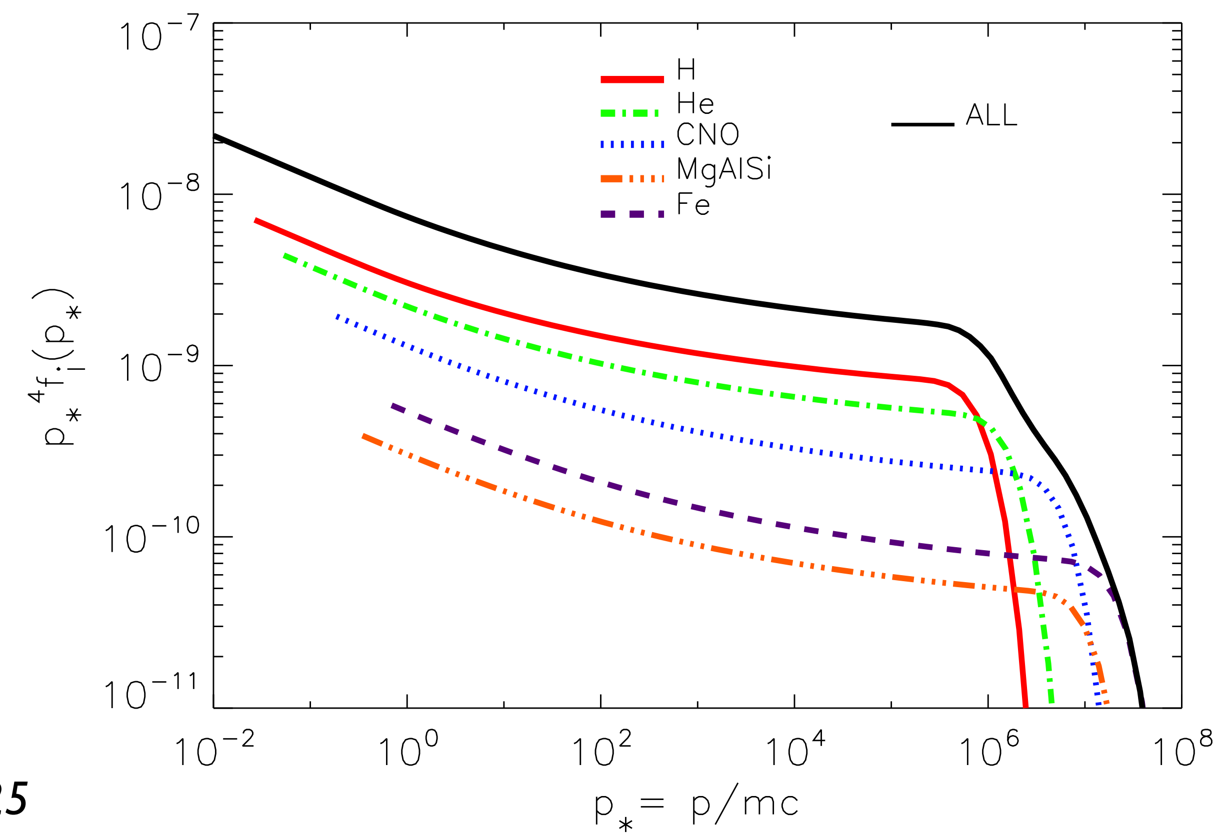
Anisotropy likely at some level

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

Non-linear shock acceleration

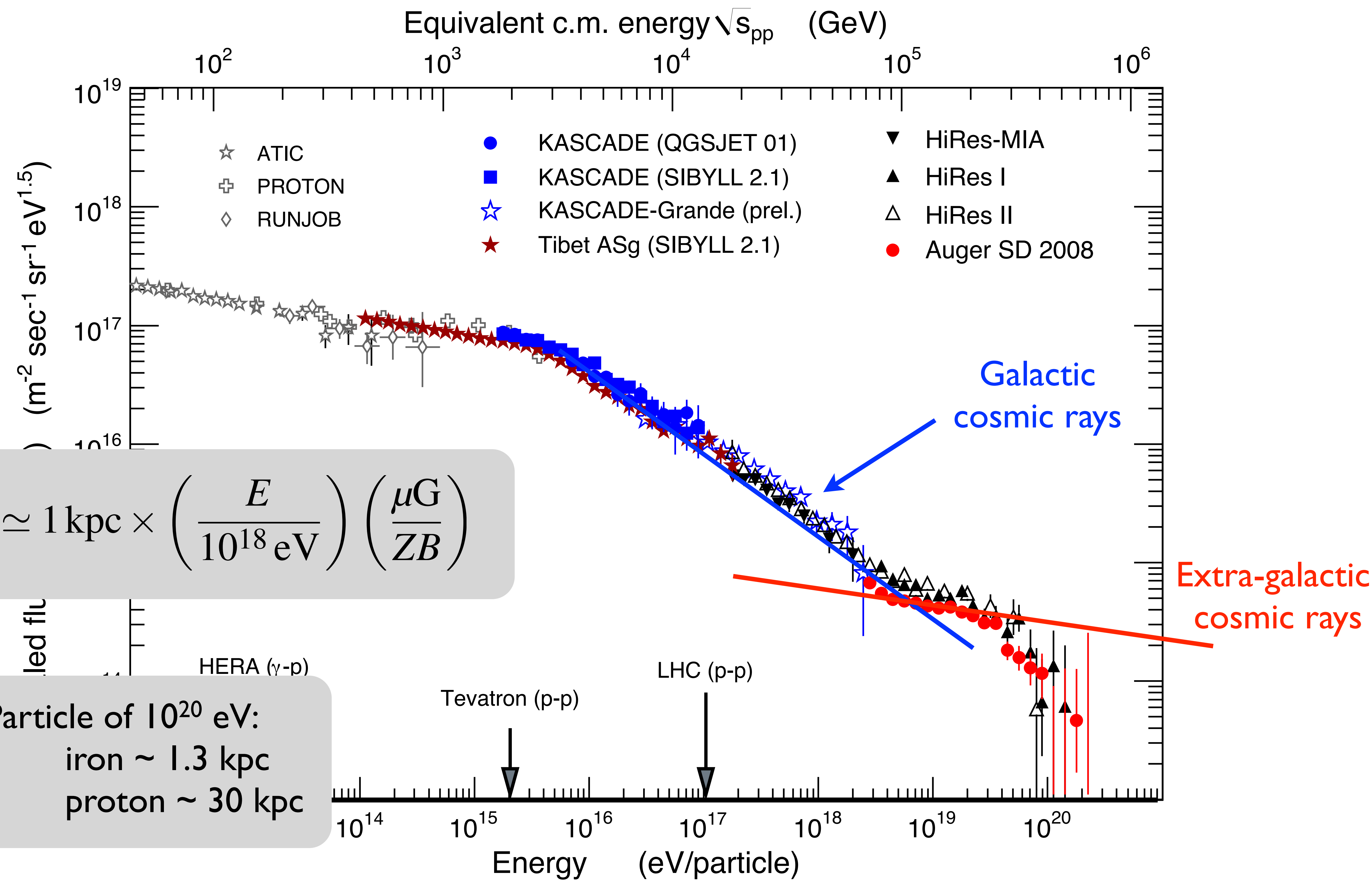
Bell & Lucek, 2001 (several papers)
Berezhko, Völk, ...

Magnetic field amplification, similar end values for different environments



Caprioli, Blasi, Amato, astro-ph/1007.1925

Transition to extra-galactic sources ?



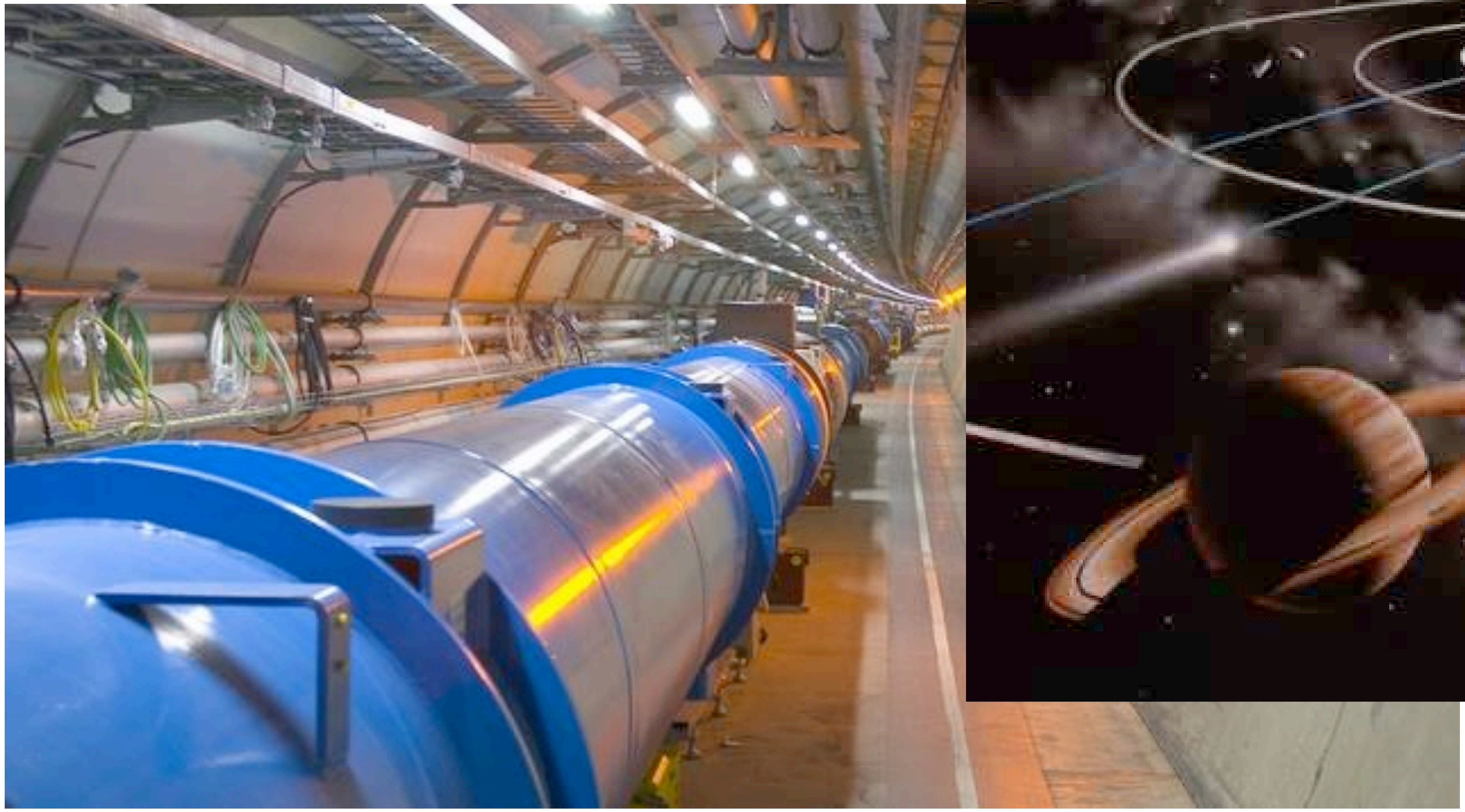
$$r_g \simeq 1\,\mathrm{kpc} \times \left(\frac{E}{10^{18}\,\mathrm{eV}}\right)\left(\frac{\mu\mathrm{G}}{ZB}\right)$$

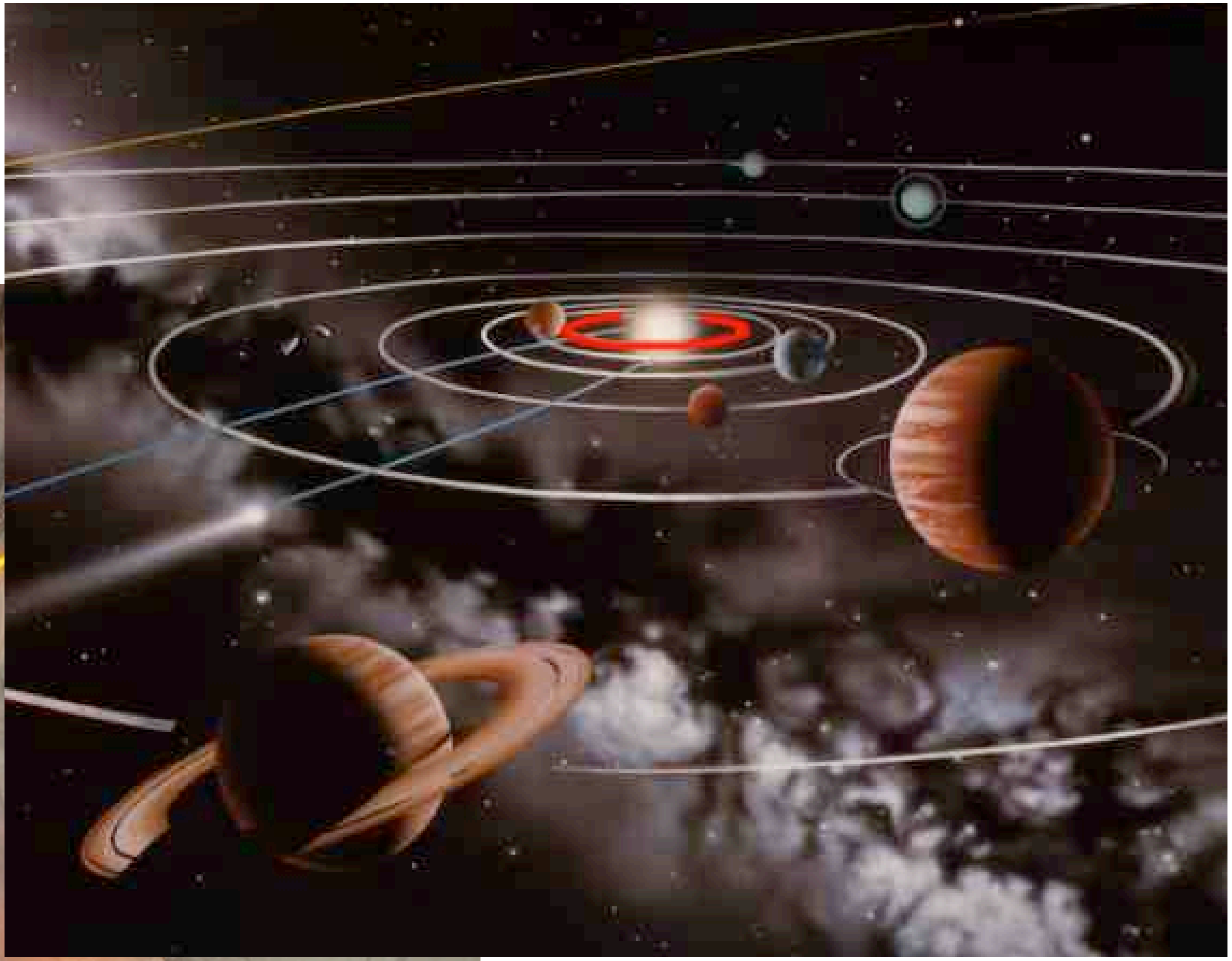
Particle of 10^{20} eV:
iron ~ 1.3 kpc
proton ~ 30 kpc

Ultra-high energy: 10^{20} eV

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

Large Hadron Collider (LHC),
27 km circumference,
superconducting magnets





(M. Unger, 2006)

Acceleration time for LHC: 815 years

Source: diffuse shock acceleration?

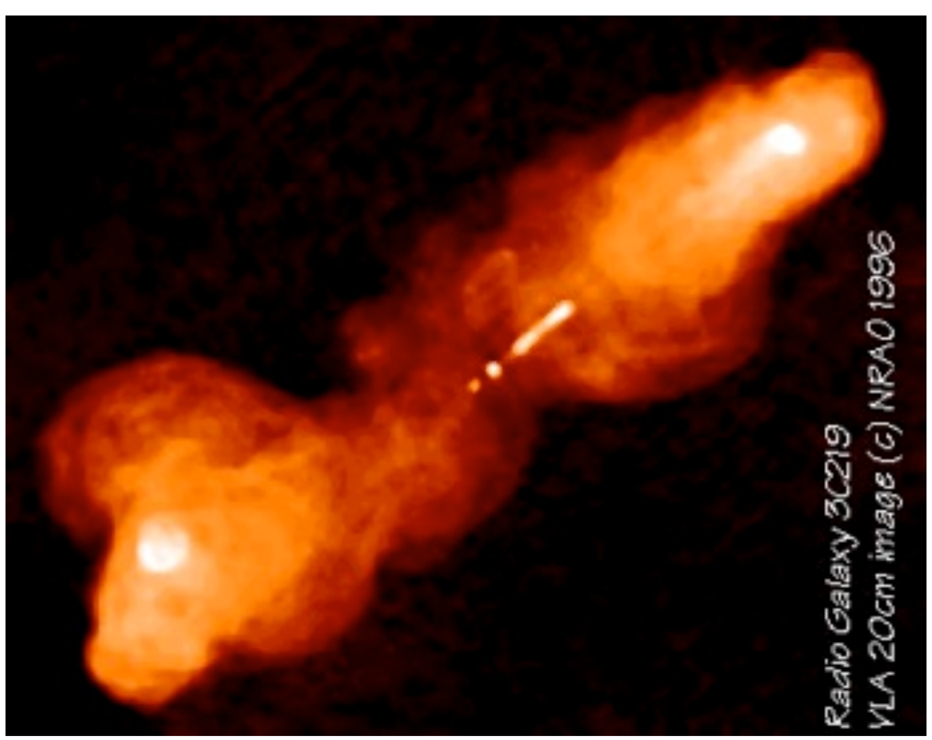
Hillas 1984:

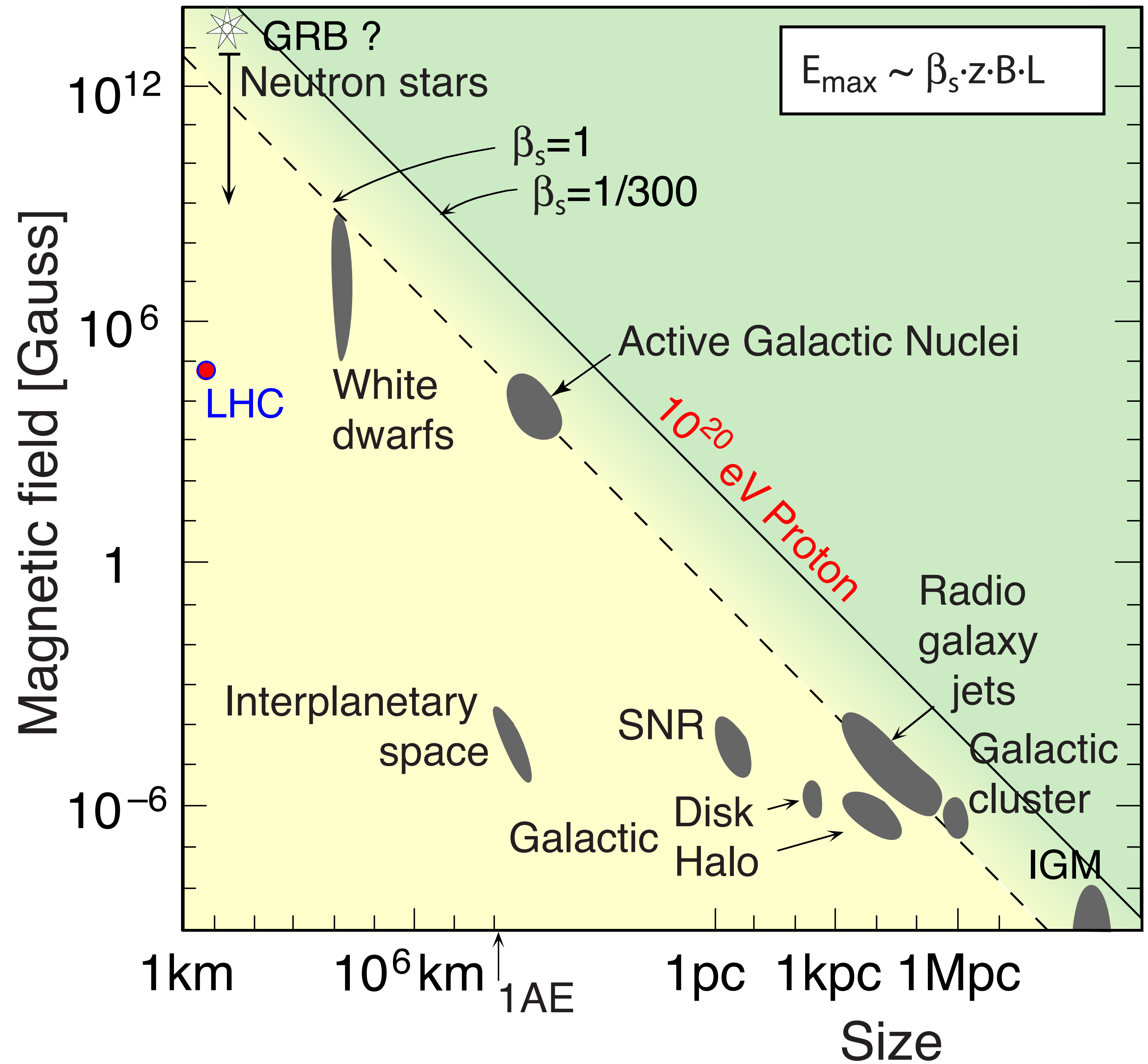
$$E_{\max} \simeq 10^{18}\,\text{eV}\, Z\, \beta \left(\frac{R}{\text{kpc}}\right)\left(\frac{B}{\mu\text{G}}\right)$$

shock velocity

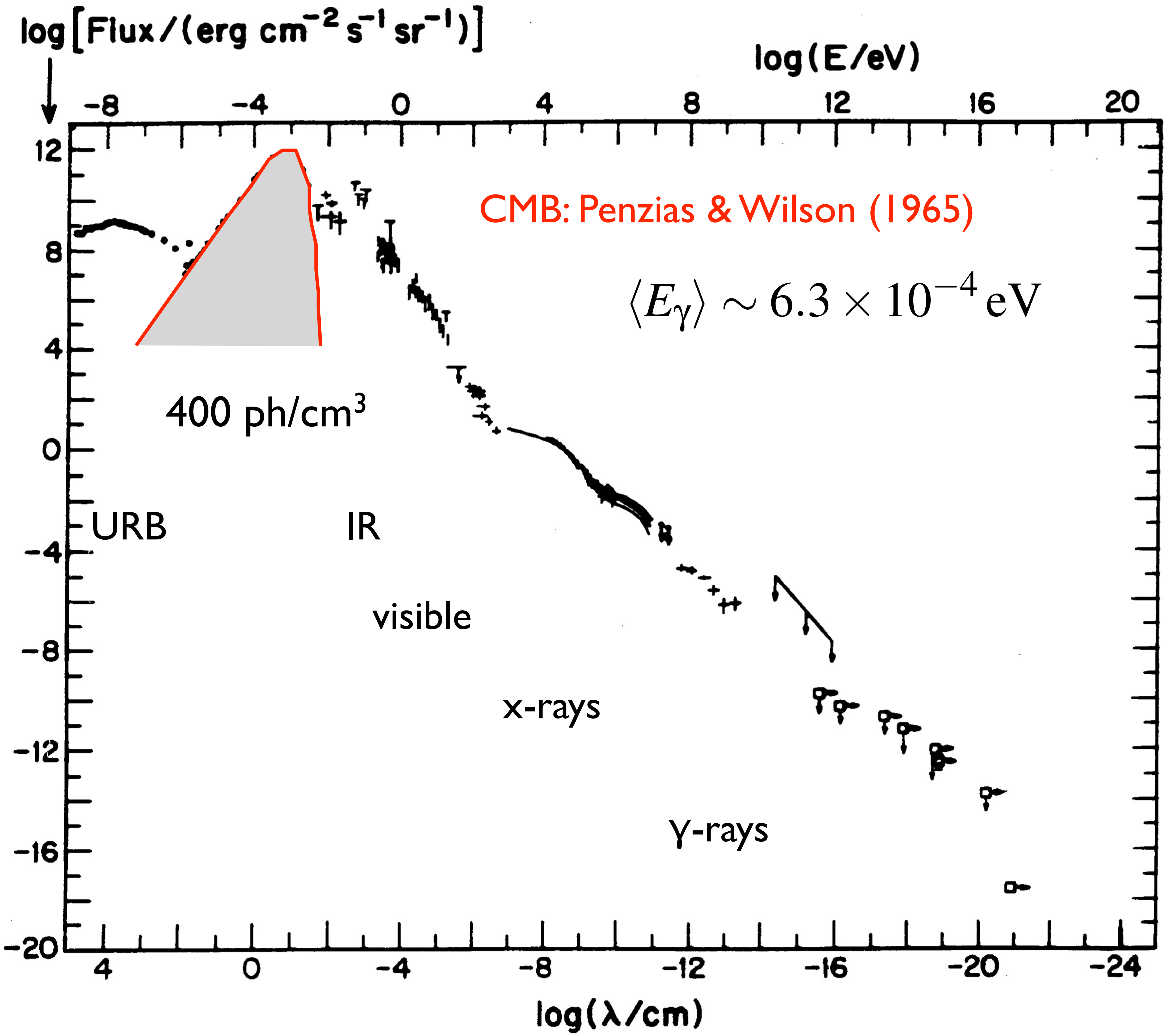
size of acc. region

mag. field strength





Greisen-Zatsepin-Kuzmin (GZK) effect

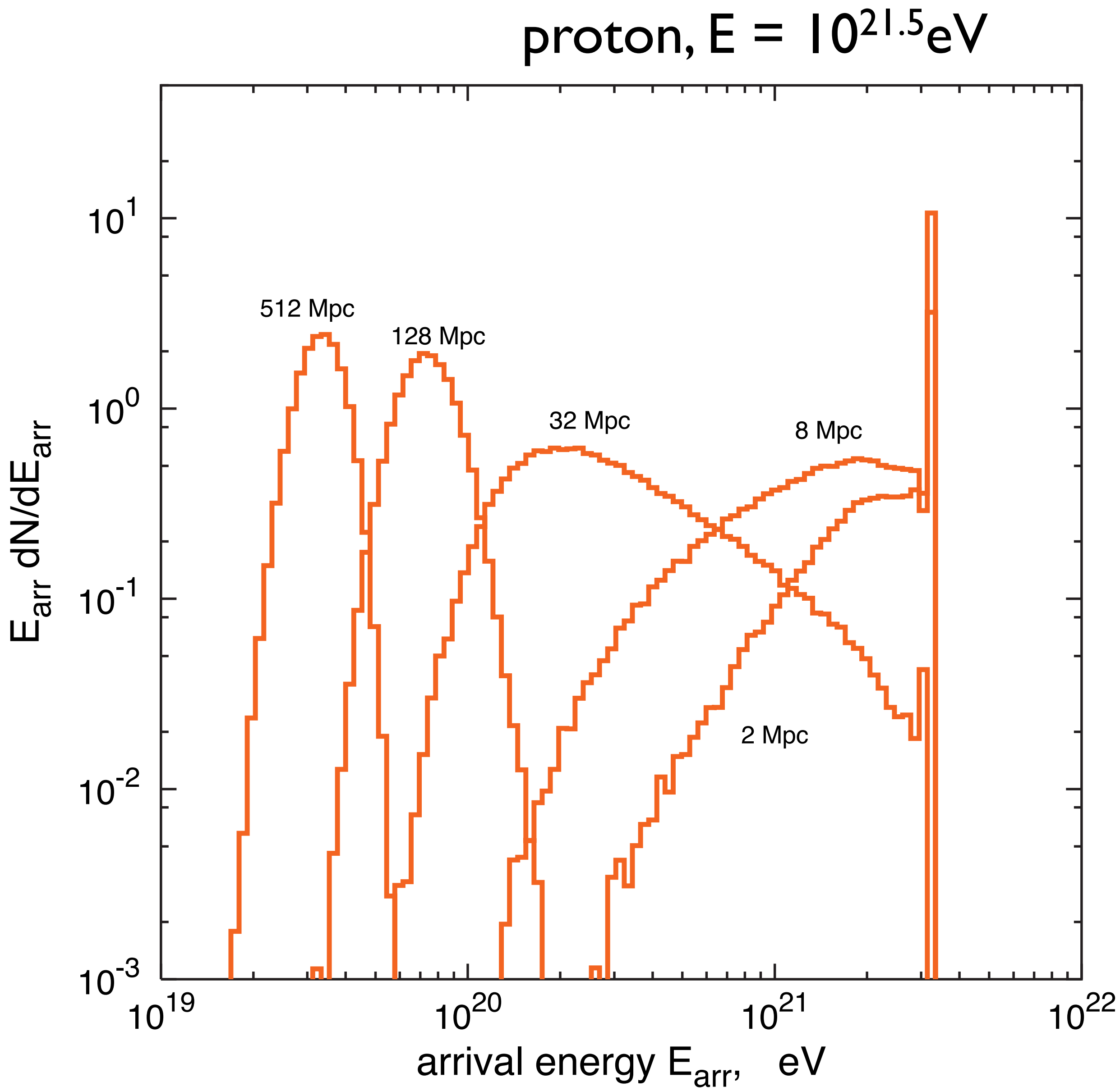


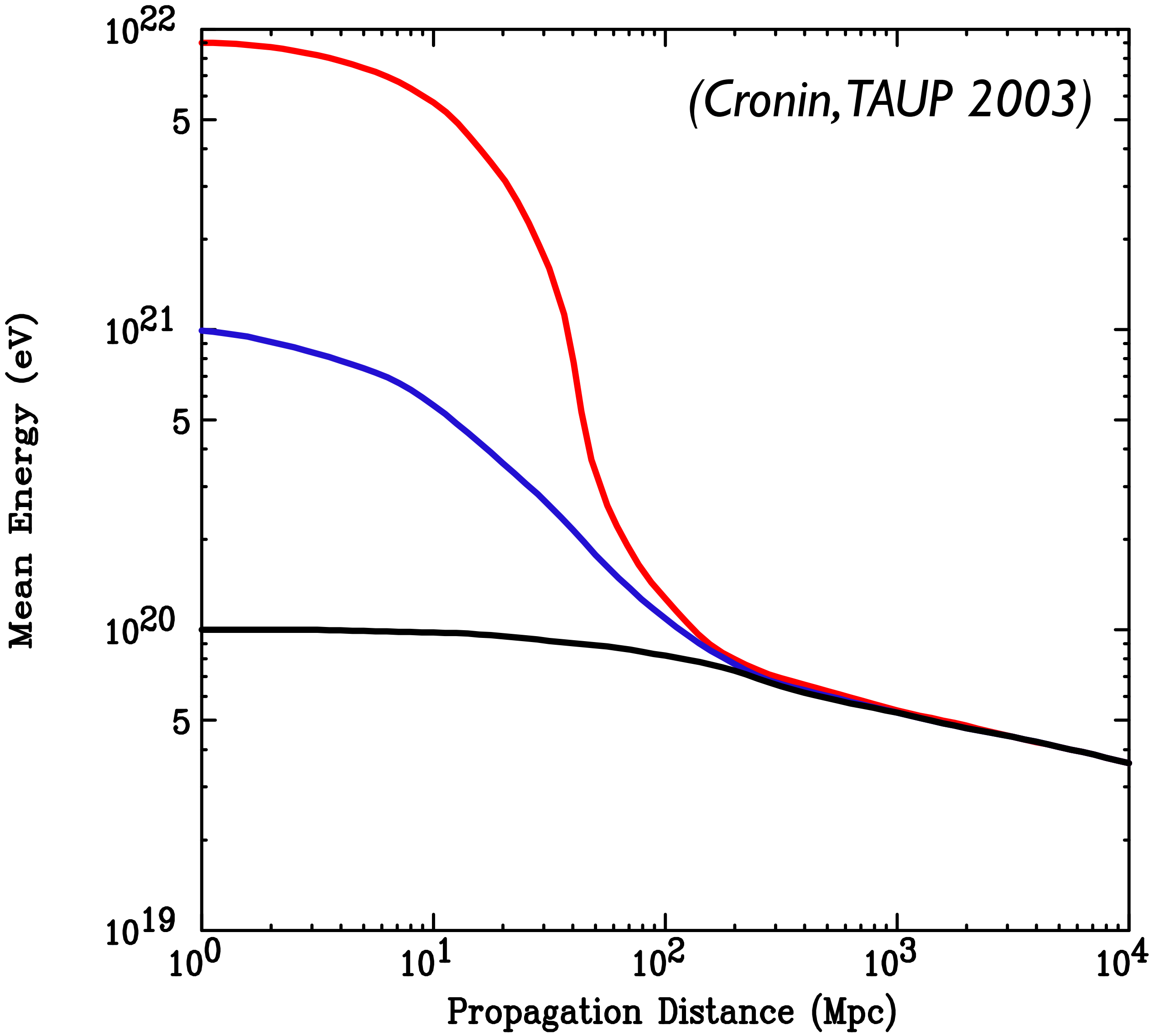
Greisen, Zatsepin & Kuzmin (1966)

$$p\,\gamma \rightarrow p\,\pi^0$$
$$p\,\gamma \rightarrow n\,\pi^+$$
$$A\,\gamma \rightarrow (A-1)\,n$$
$$A\,\gamma \rightarrow (A-2)\,(pn)$$

Universe opaque for p with E > 10^{20} eV

Example: Energy loss of protons





Hadronic energy loss: stochastic process

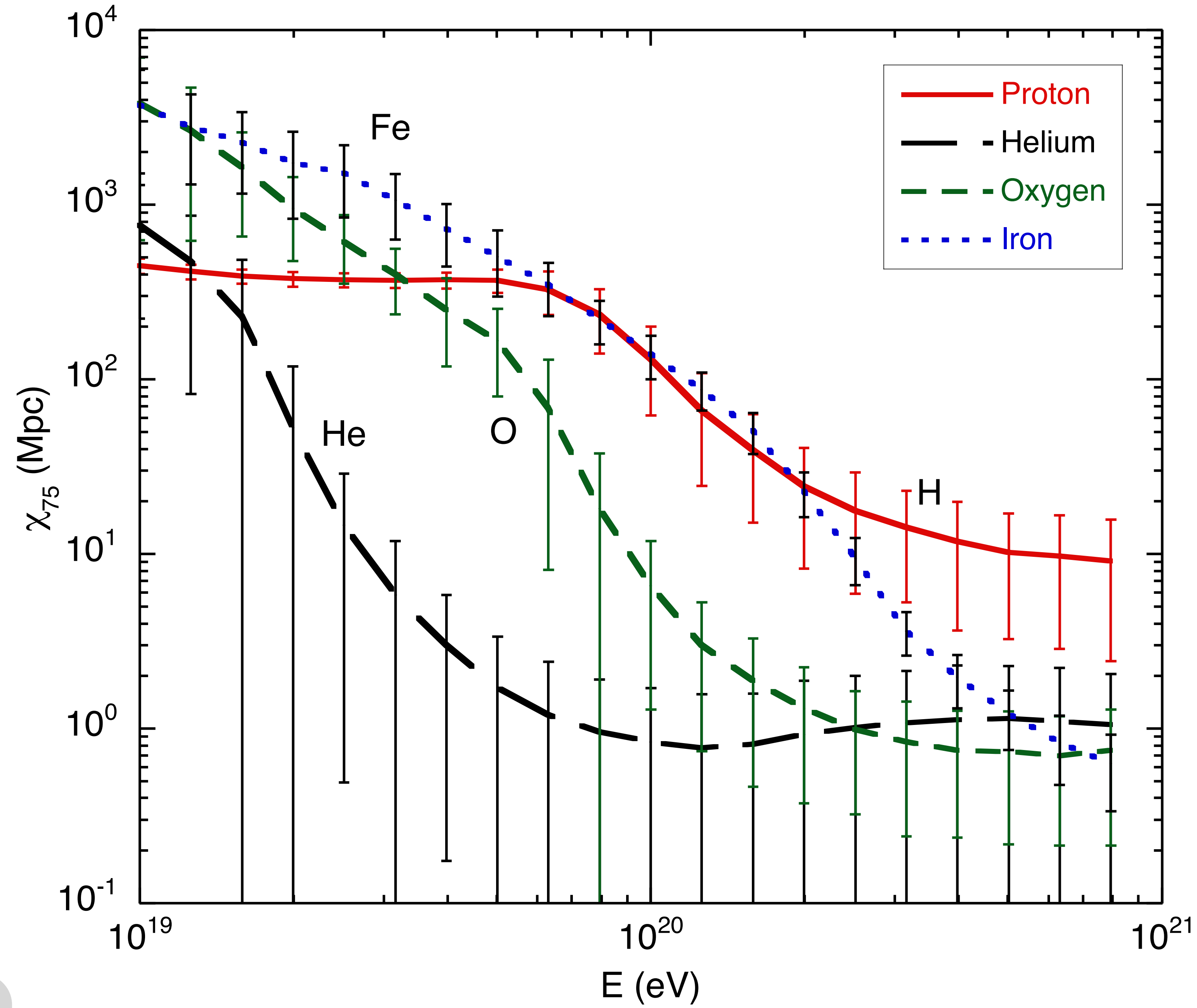
(Achterberg 1999,
Stanev et al., PRD62, 2000)

Loss length comparison: protons vs. nuclei

Loss length here defined for 25% loss of initial energy

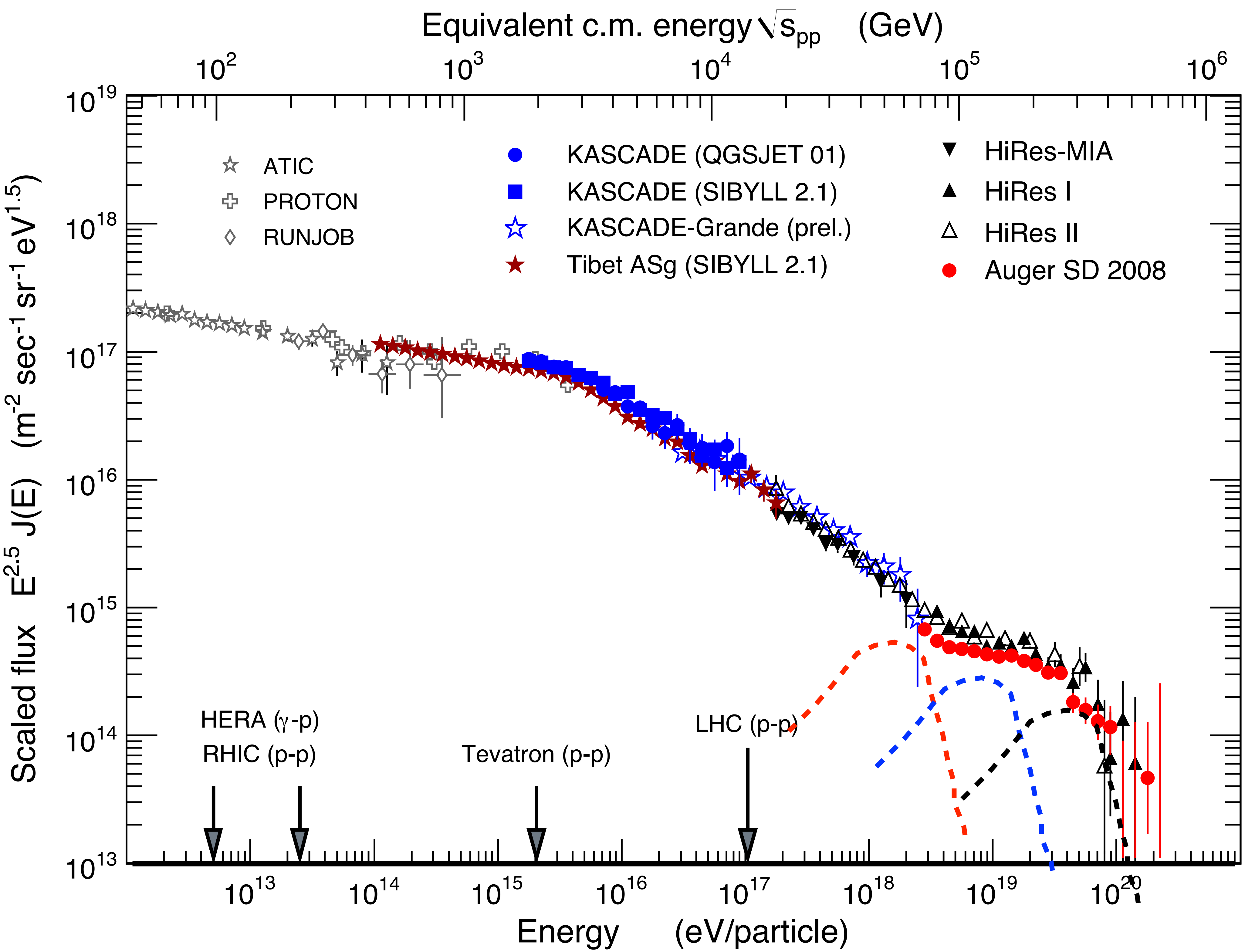
Nuclei subject to energy loss similar to nucleons

Proton and iron propagate over largest distance



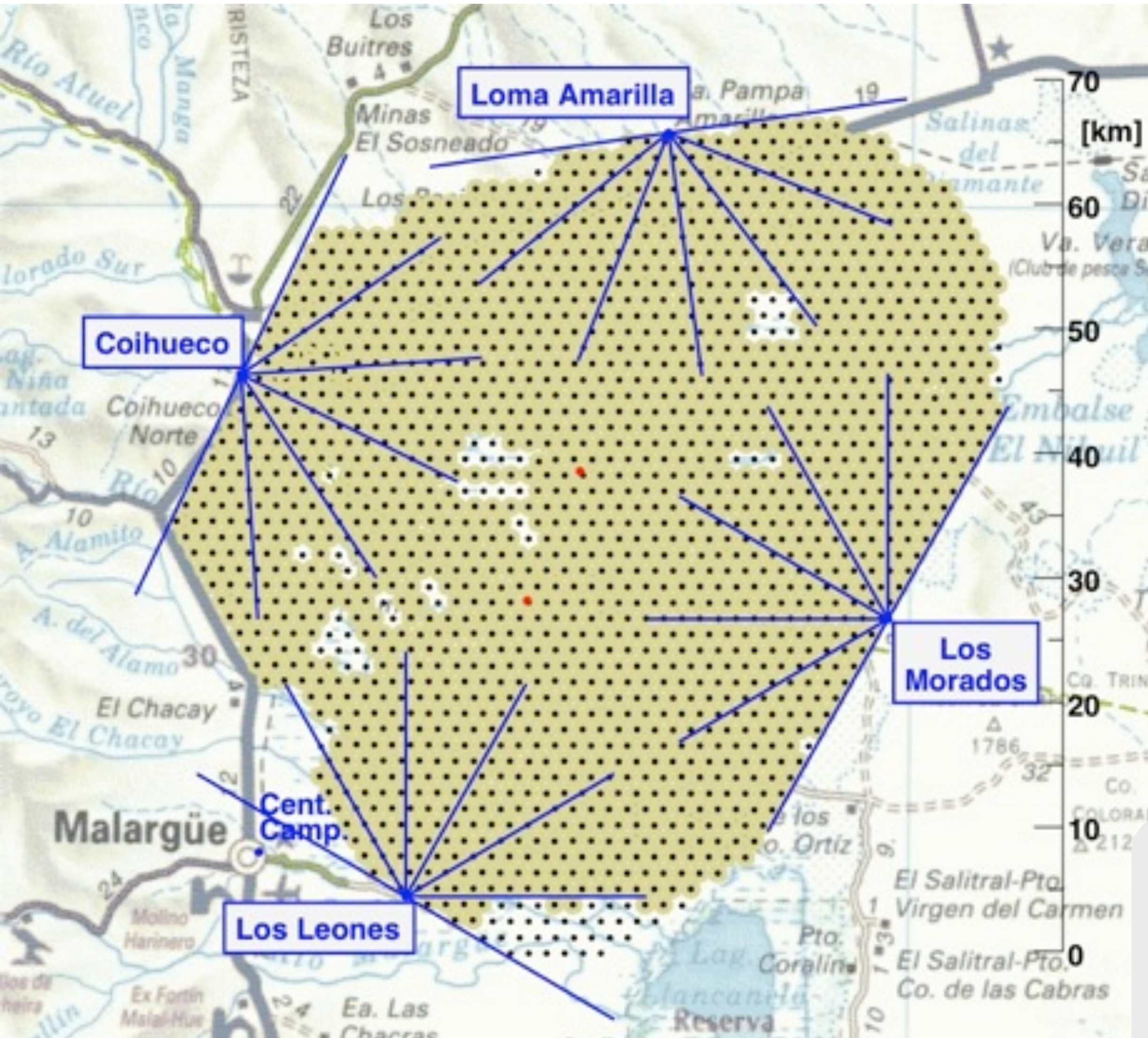
(Allard et al., 2005)

Origin of flux suppression: GZK effect vs. max. energy



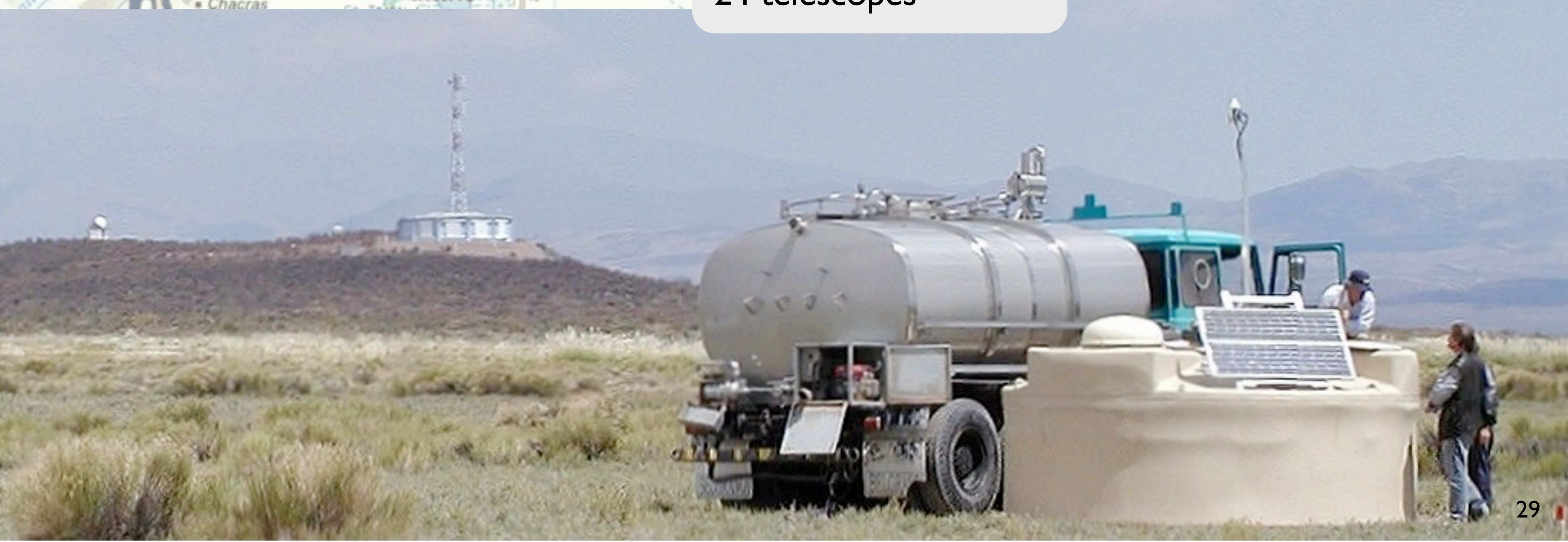
Change of had. interaction chracteristics could explain data

Max. energy scenario naturally predicts change in composition & very steep suppression



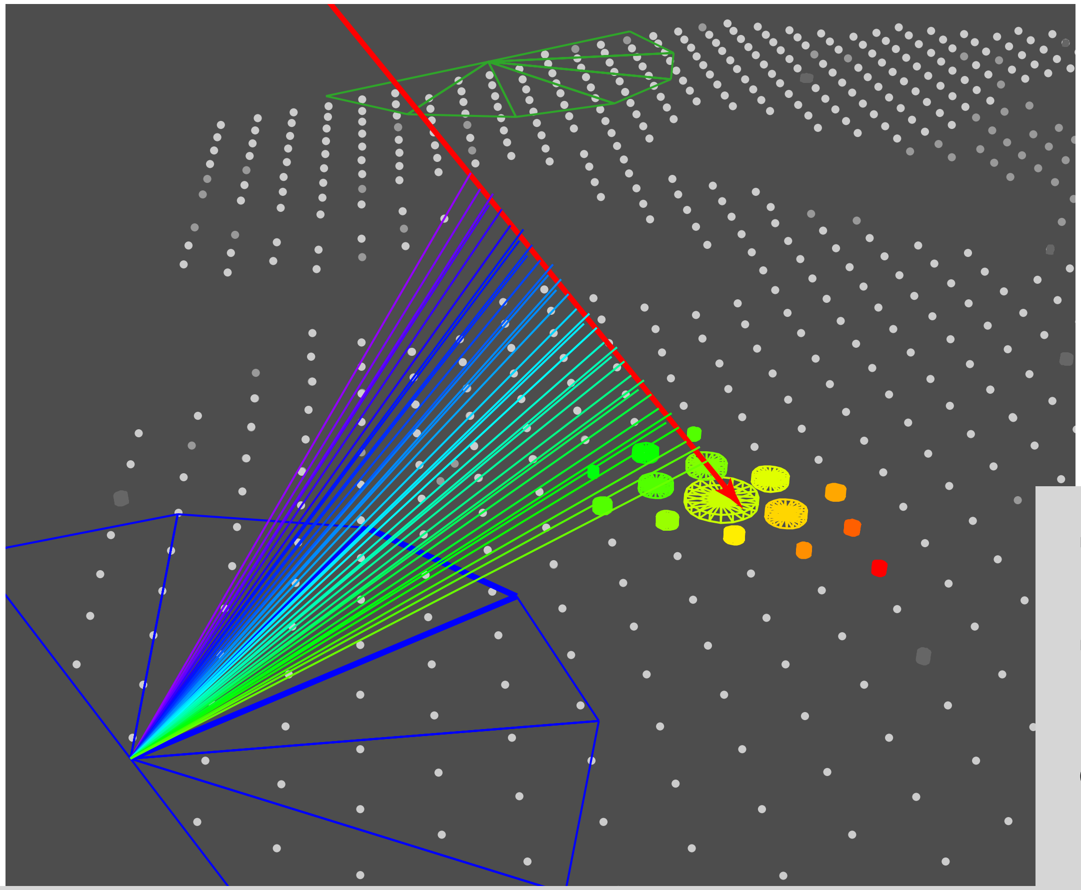
Southern Pierre Auger Observatory

Malargue, Argentina

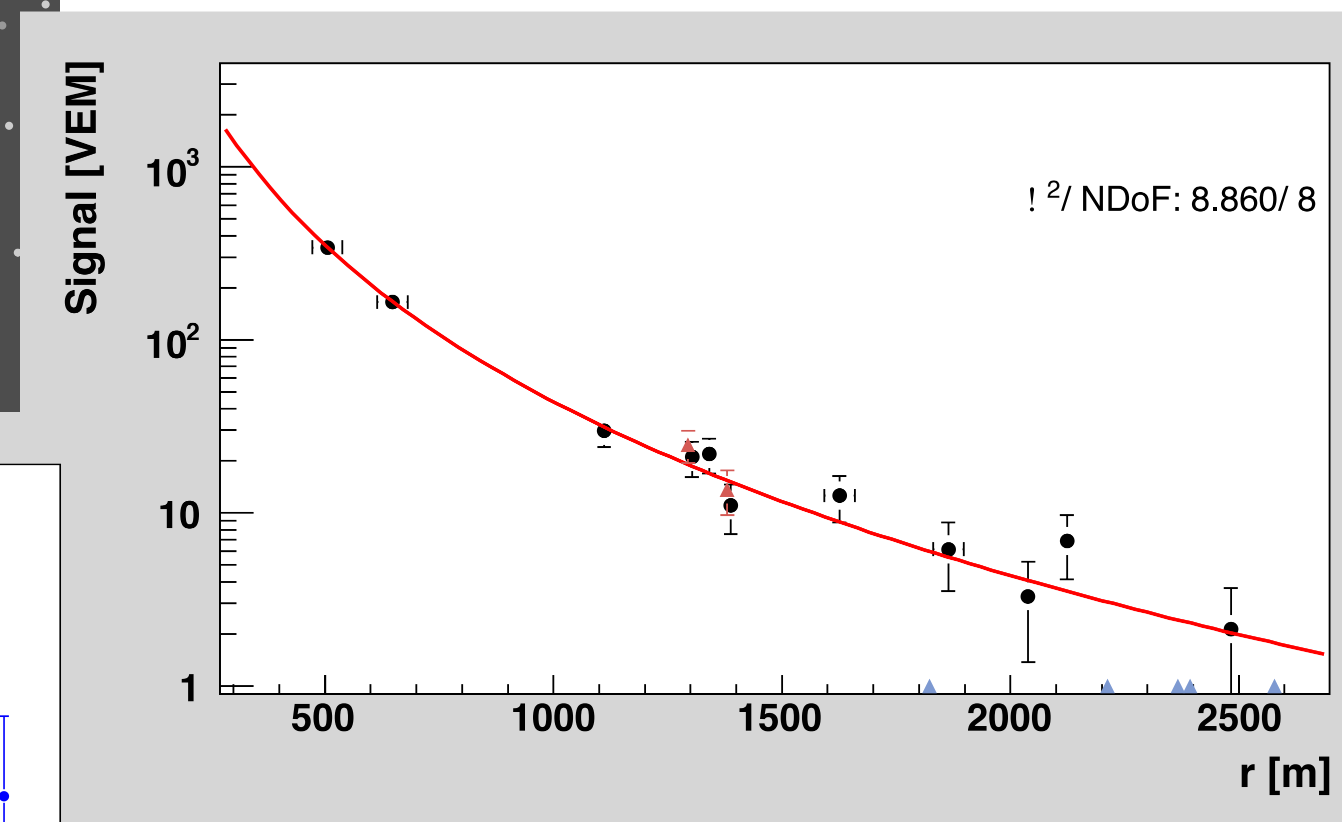


Area ~3000 km^2,
1600 surface detectors,
24 telescopes

Hybrid detection

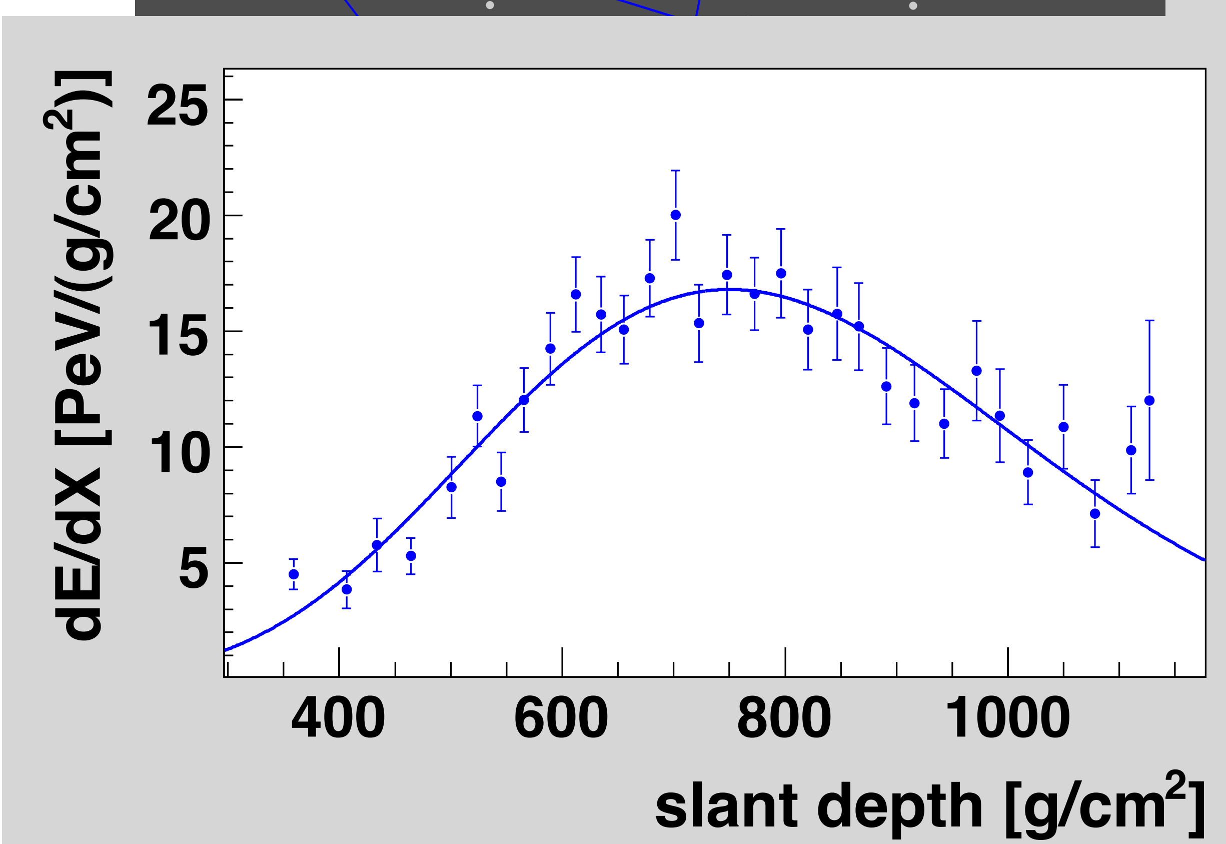


Lateral distribution



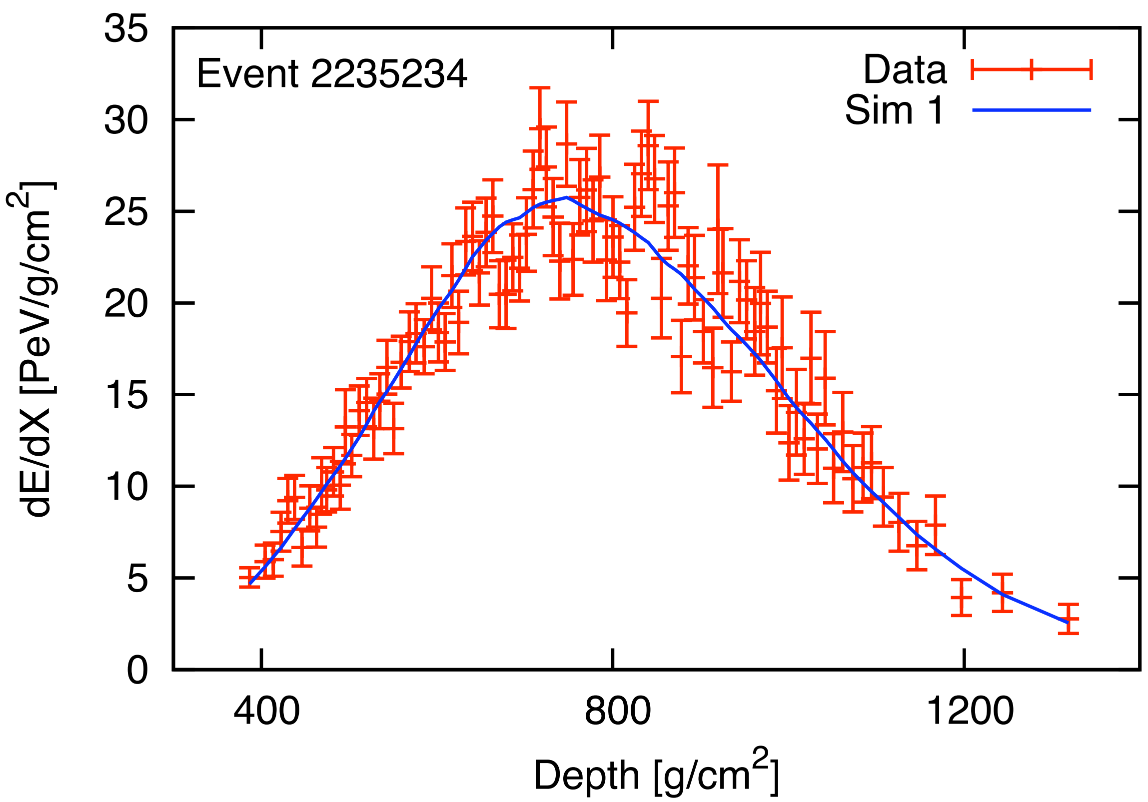
em. particles and muons

electrons



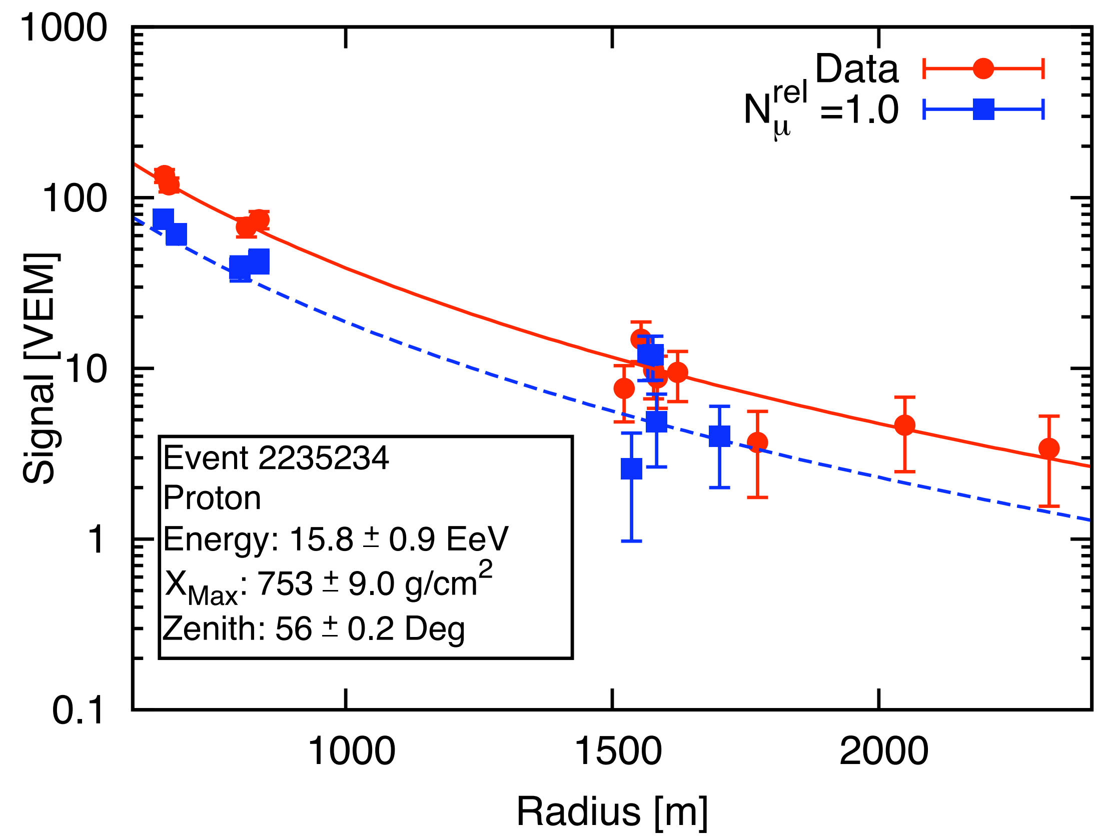
Shower longitudinal profile

Simulation of individual hybrid events



Procedure

- Simulation of 400 showers with reconstructed geometry
- Proton or iron primaries
- SD simulation for best long. profile
- Reconstruction of hybrid event



Results

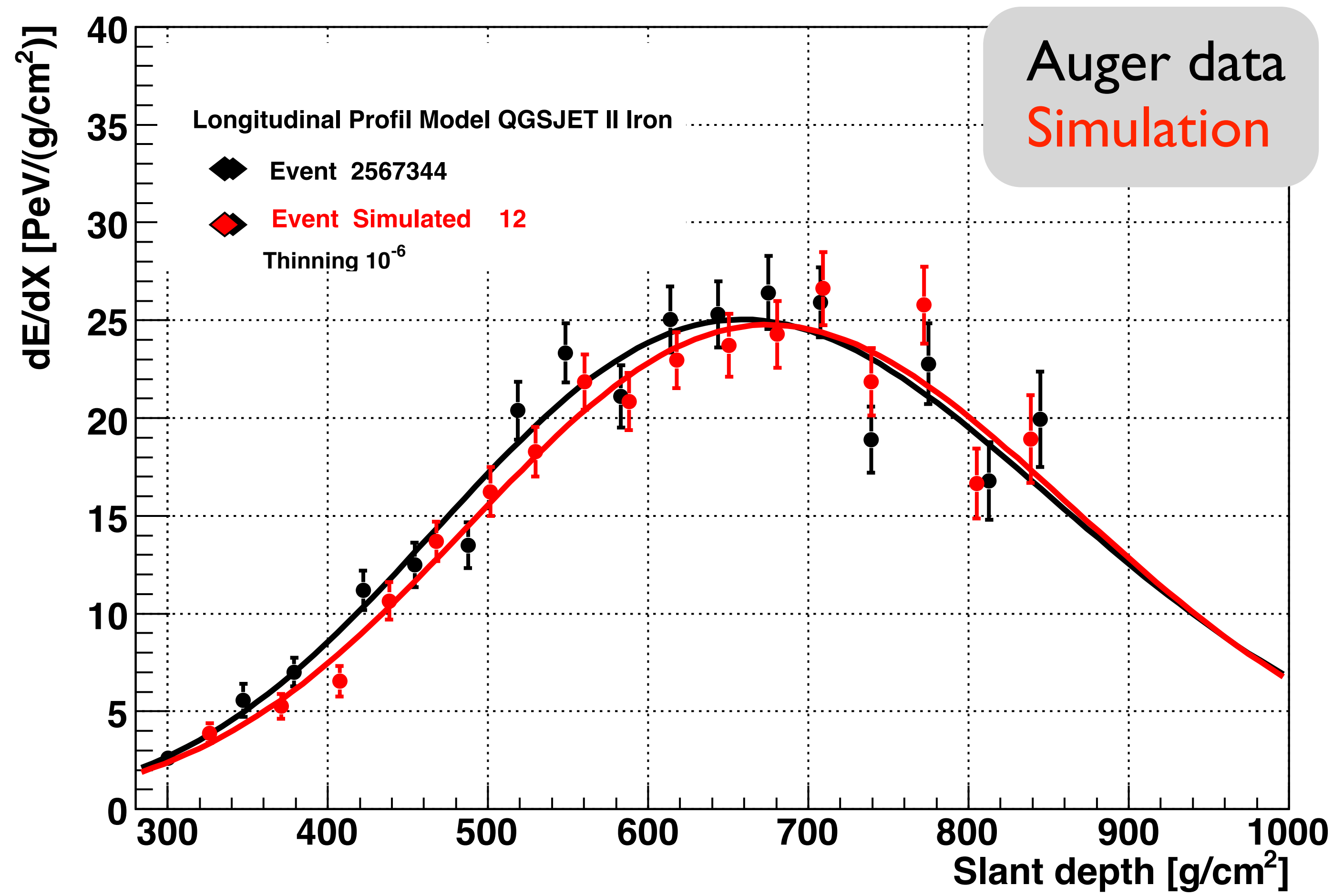
- Muon deficit found in both proton and iron like showers
- Showers with same X_{max} show 10-15% variation of S(1000)

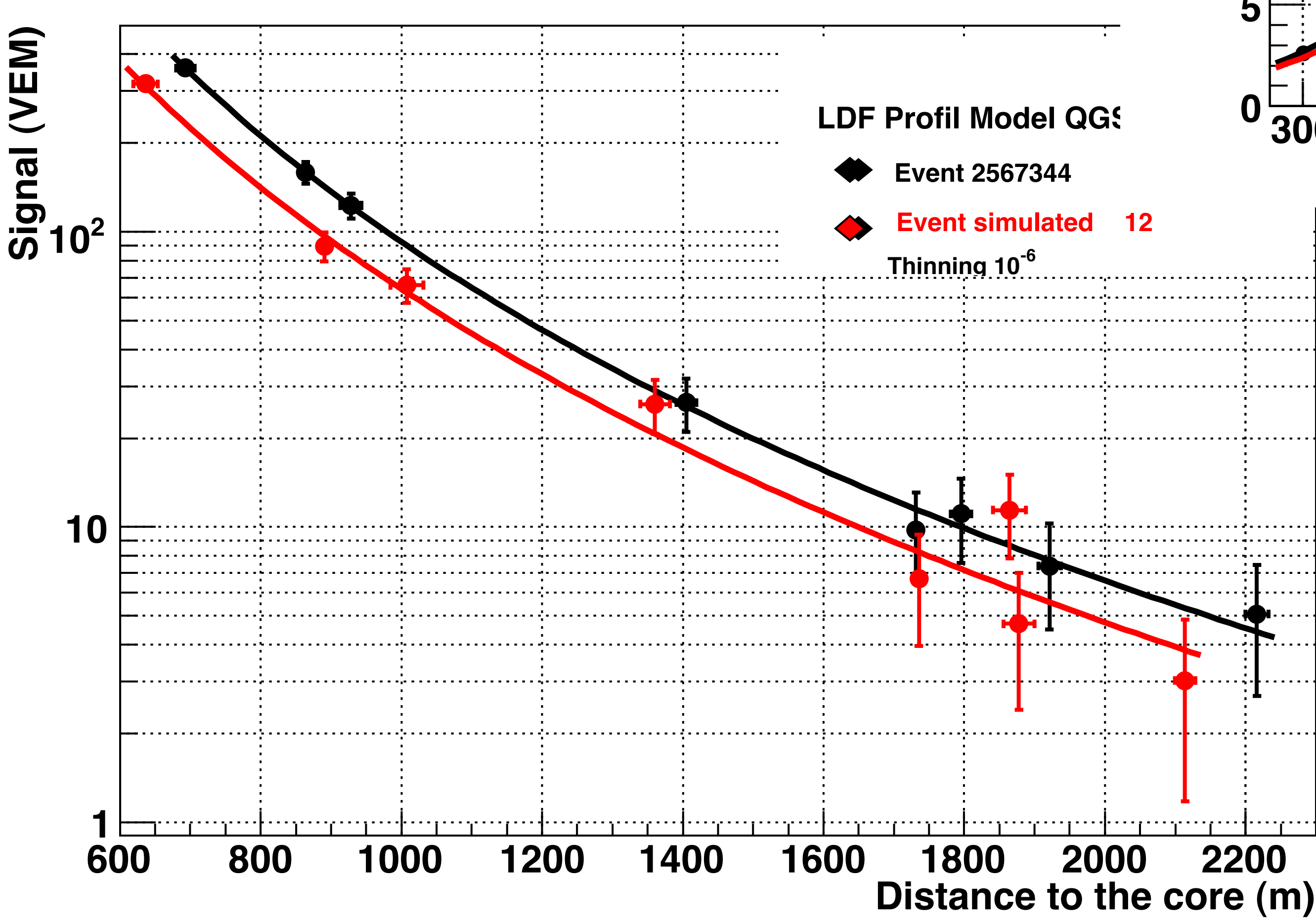
Example: QGSJET II, iron

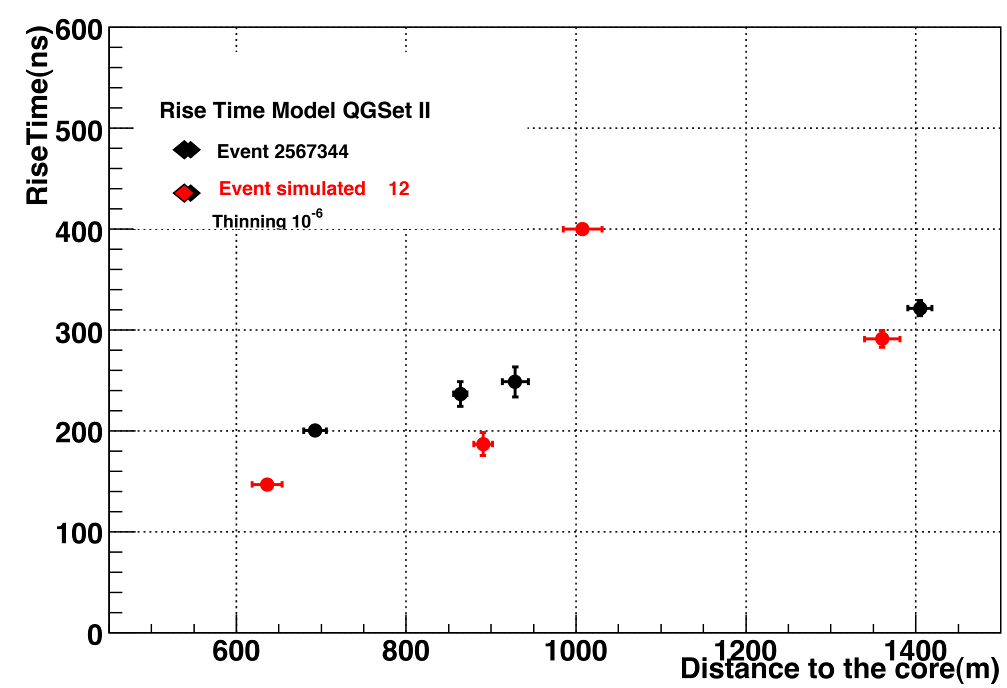
Event 2567344

$\theta = 28°$, E = 1.4×10^{19} eV

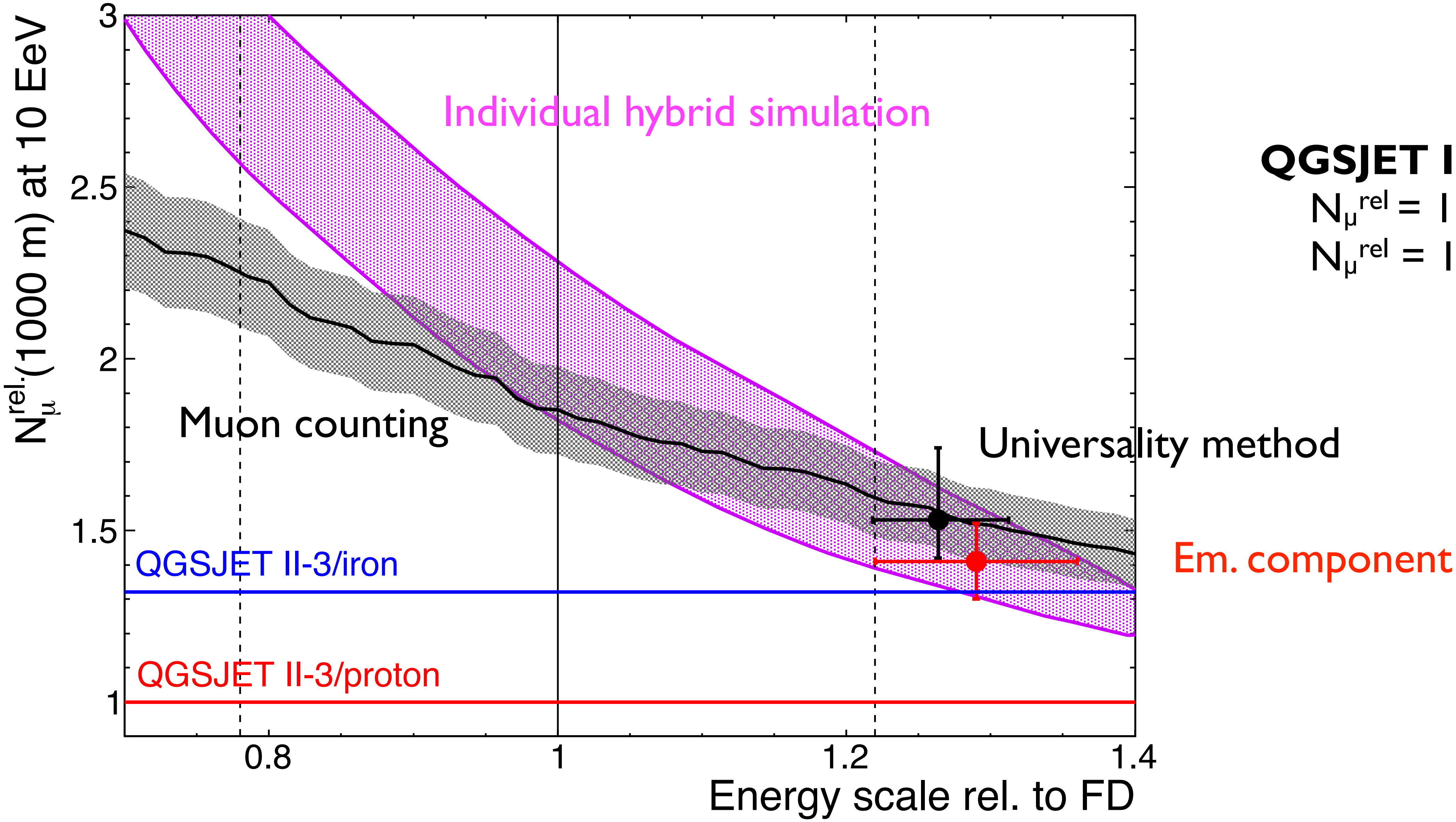
iron-like event







Comparison of results



QGSJET II:

N_μ^{rel} = 1.0 (protons)

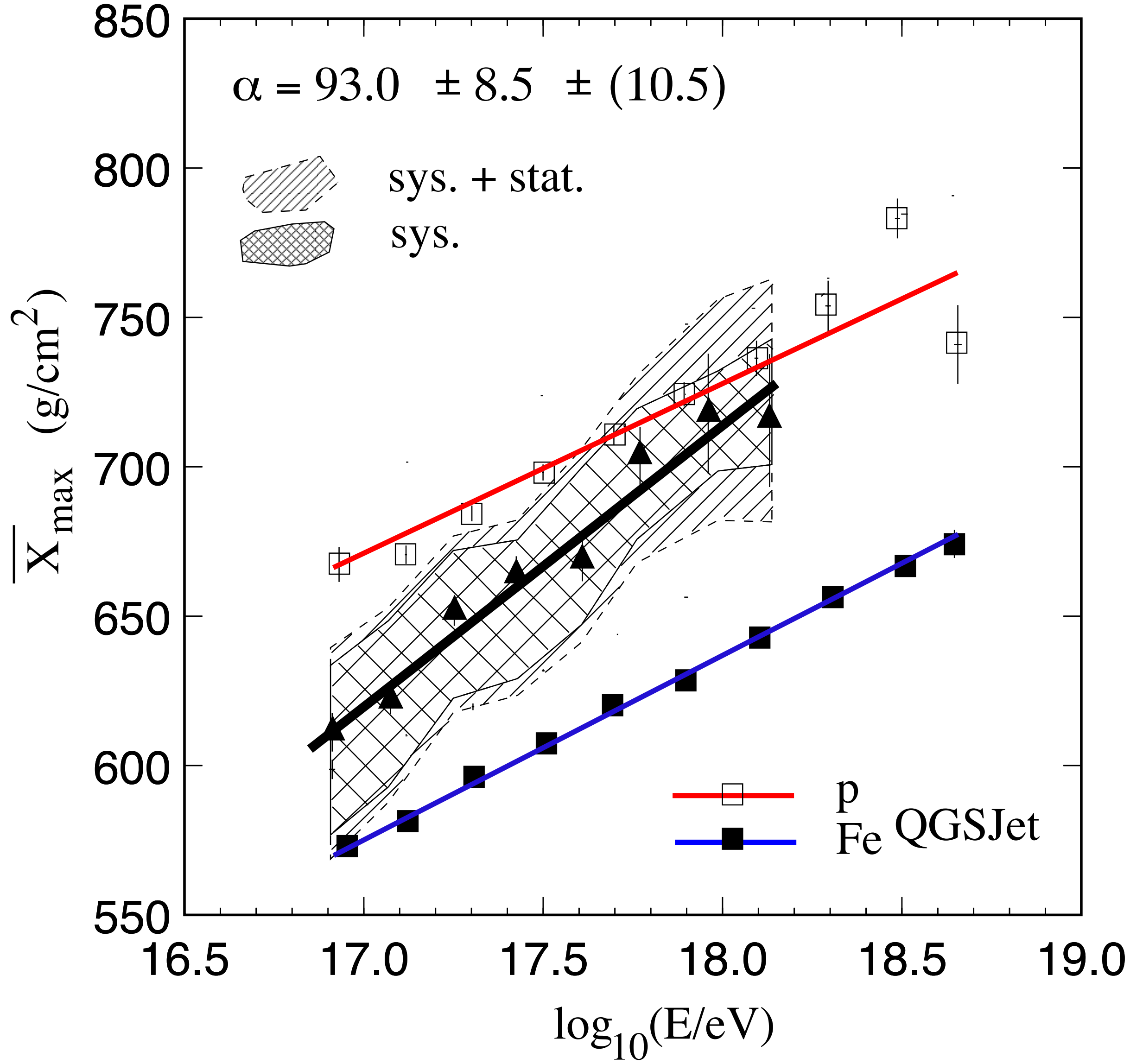
N_μ^{rel} = 1.32 (iron)

Results of different methods consistent

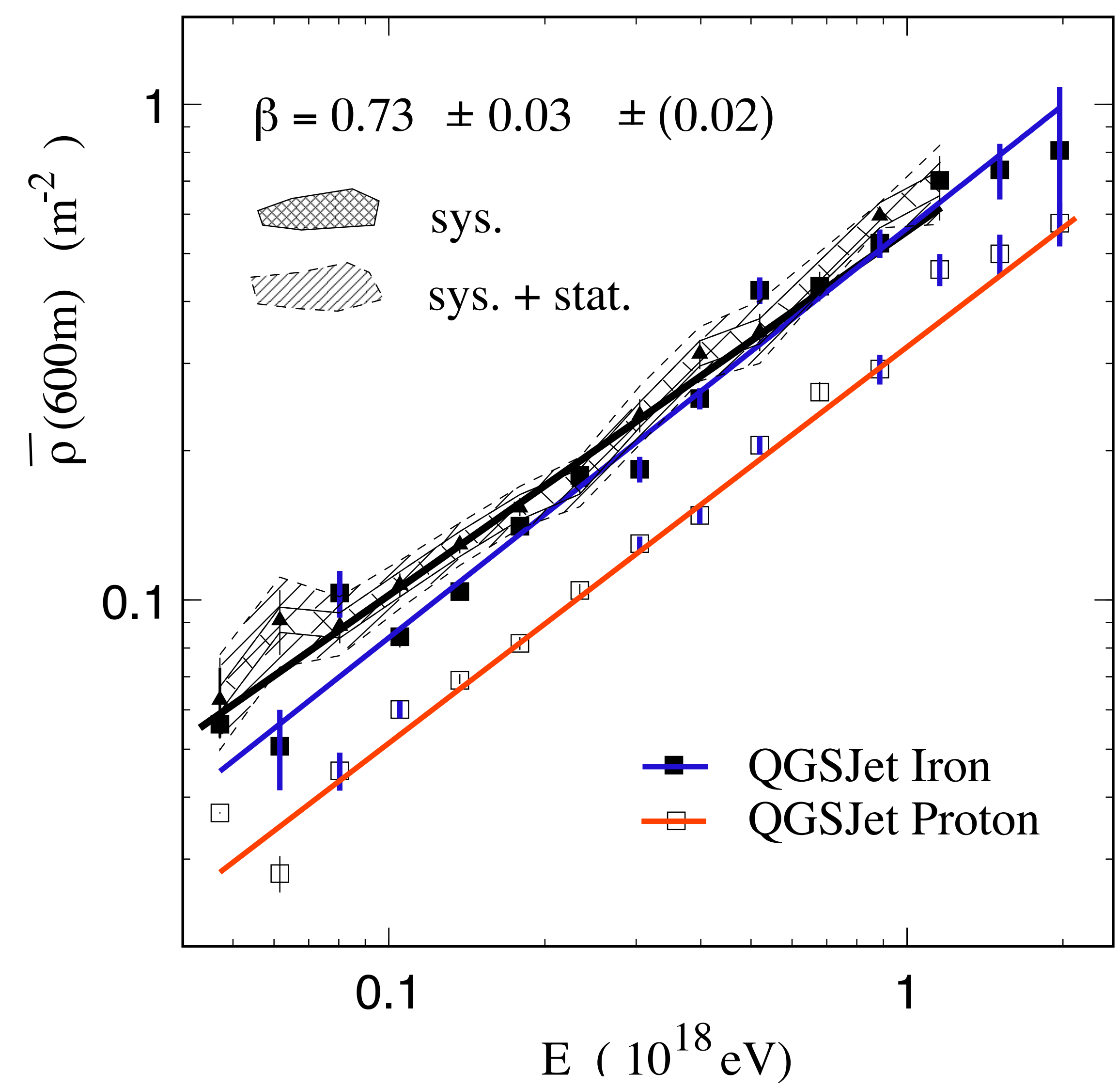
- shift of energy scale expected
- muon deficit in simulation even with shifted energy scale

But: All results depend directly or indirectly on simulation of em. component

HiRes-MIA hybrid measurement



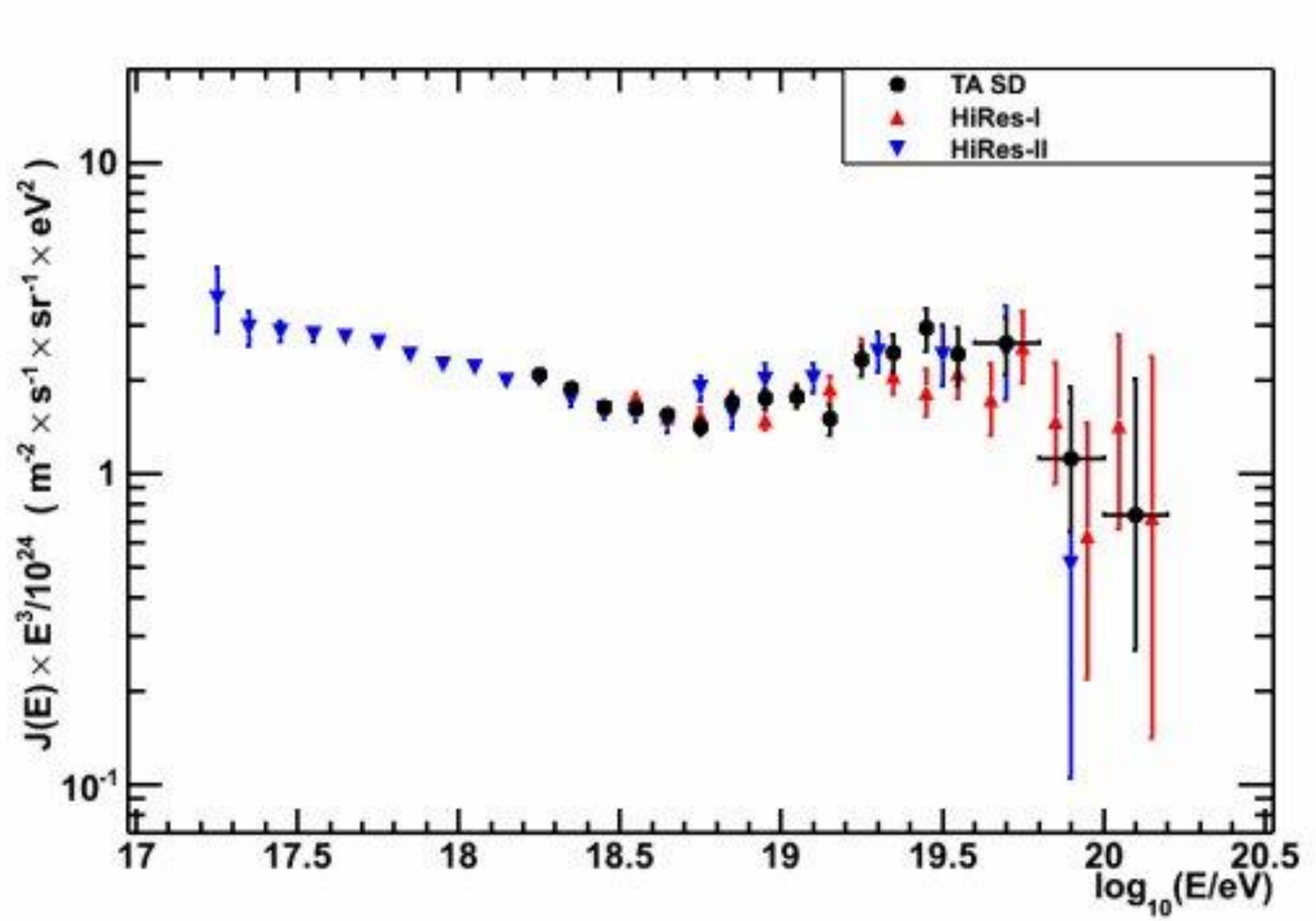
Muon density 600m from core



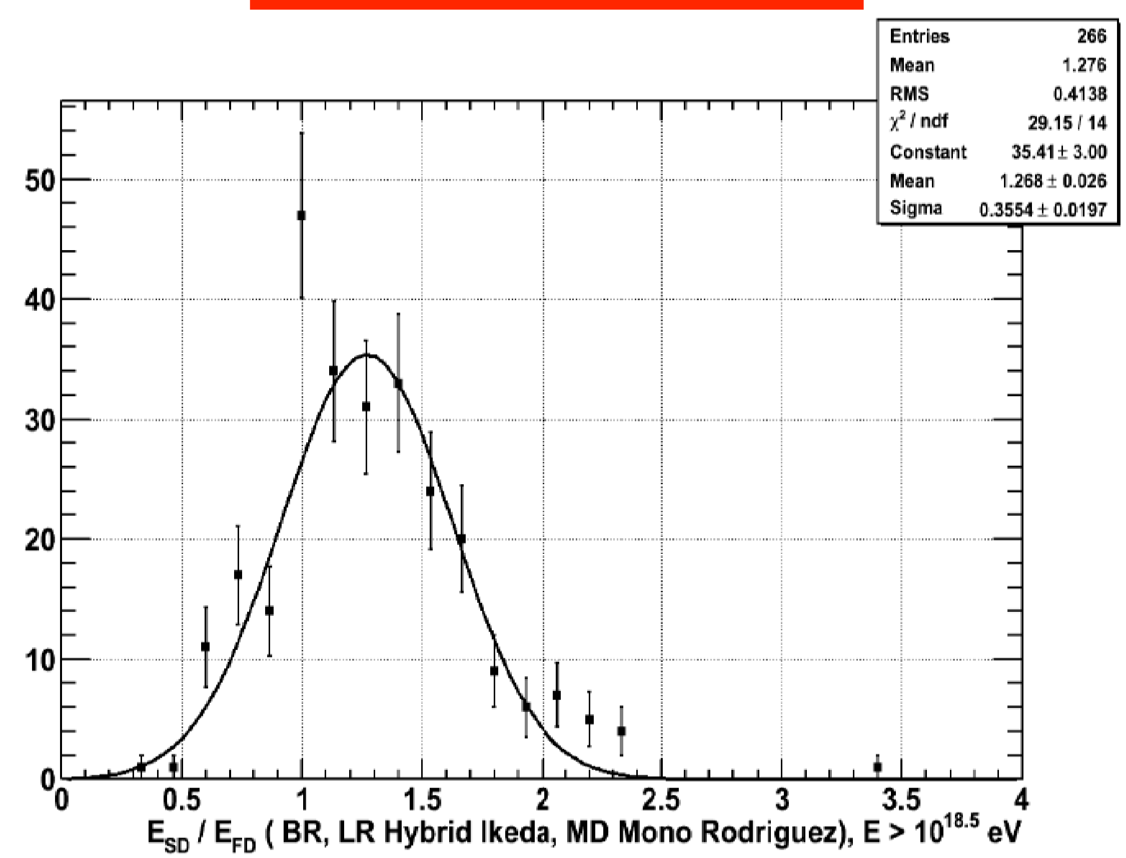
Analysis with QGSJET98 (very similar to QGSJET01)

HiRes Fly's Eye and MIA Collabs., Phys. Rev. Lett. 84 (2000) 4276

Telescope Array: energy scale



- Energy scale is determined more accurately by FD than by CORSIKA QGSJET-II
- Set SD energy scale to FD energy scale using well-reconstructed events seen by both detectors:
- 27% renormalization.



Suppression of flux at ultra-high energy confirmed with scintillator array

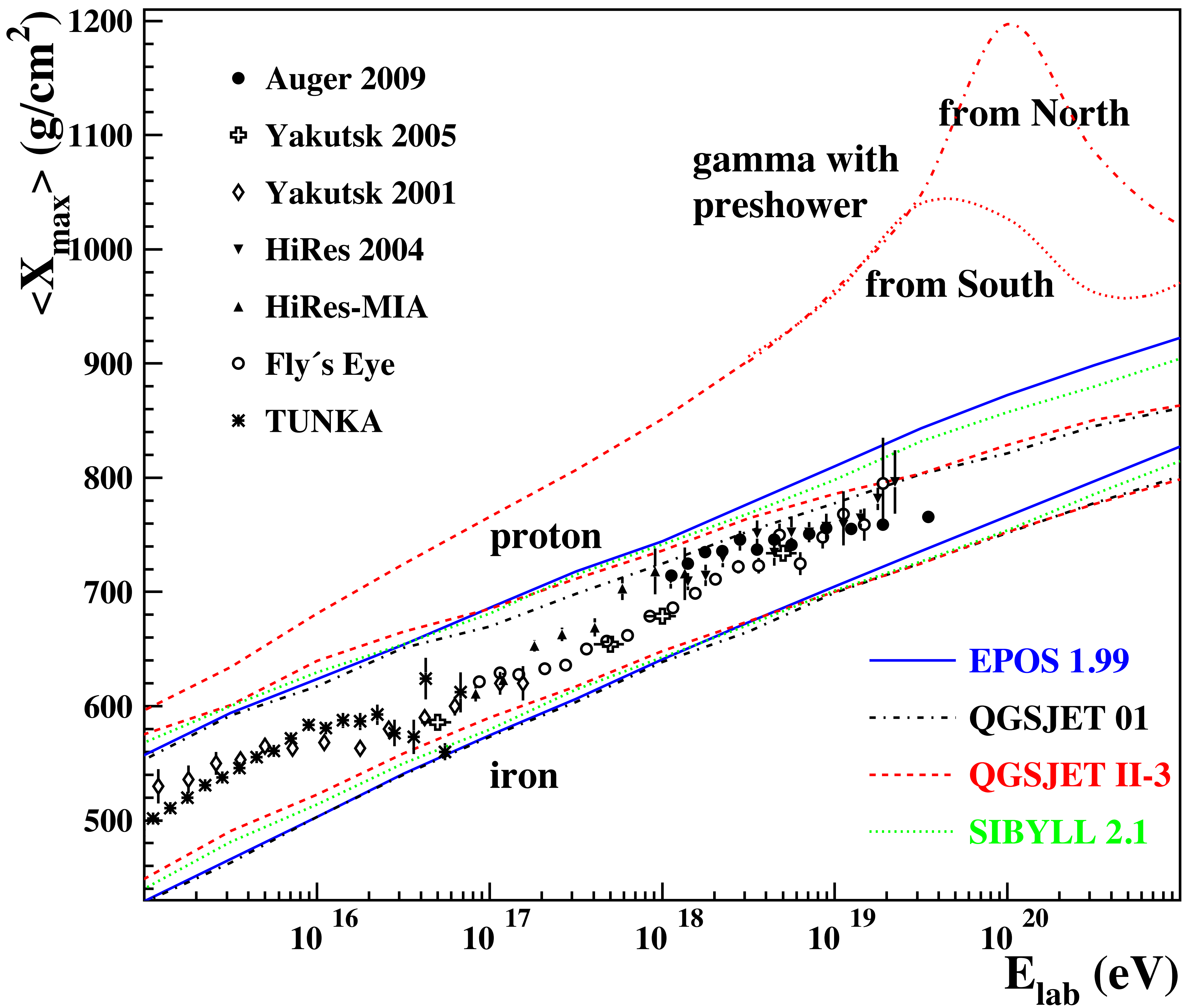
(TA Collab.,Thomson, ICHEP 2010)

Summary

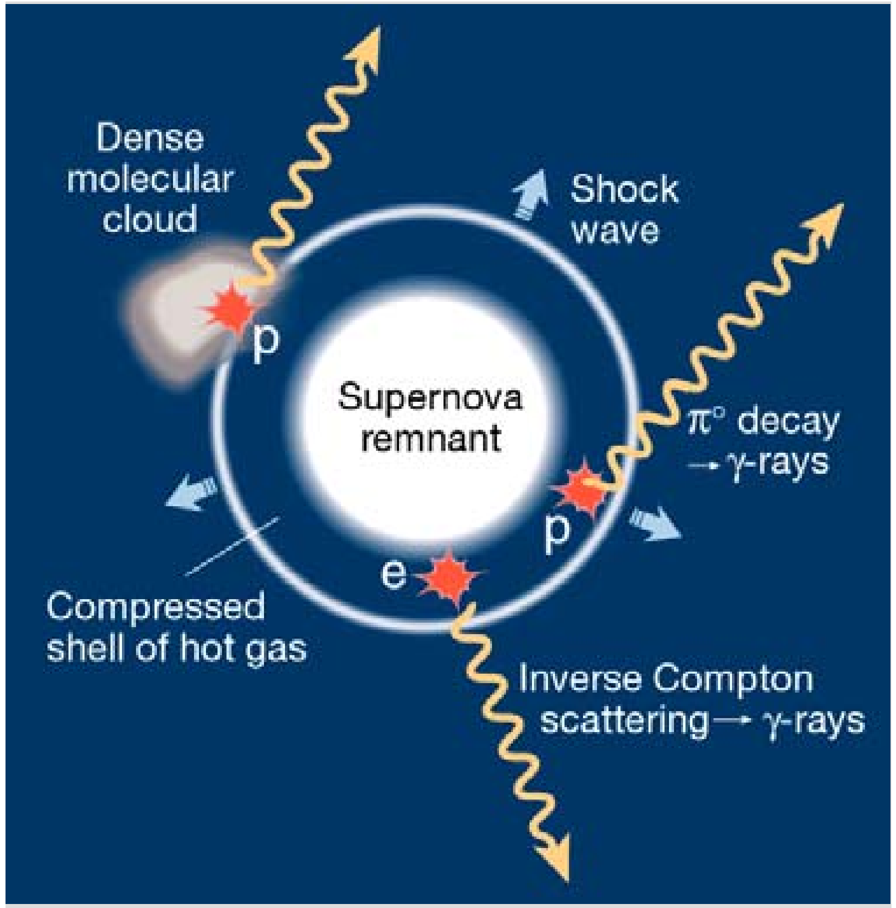
- Many fundamental questions still unsolved in cosmic ray physics
- Composition measurement key ingredient, strong dependence on hadronic interaction models
- Discrepancies indicate shortcomings current models
- Data and input (theory/phenomenology) needed from colliders
- Cosmic ray data allow us to reach to higher energy
- Next talk: what can we learn from cosmic ray observations?

Composition based on mean Xmax

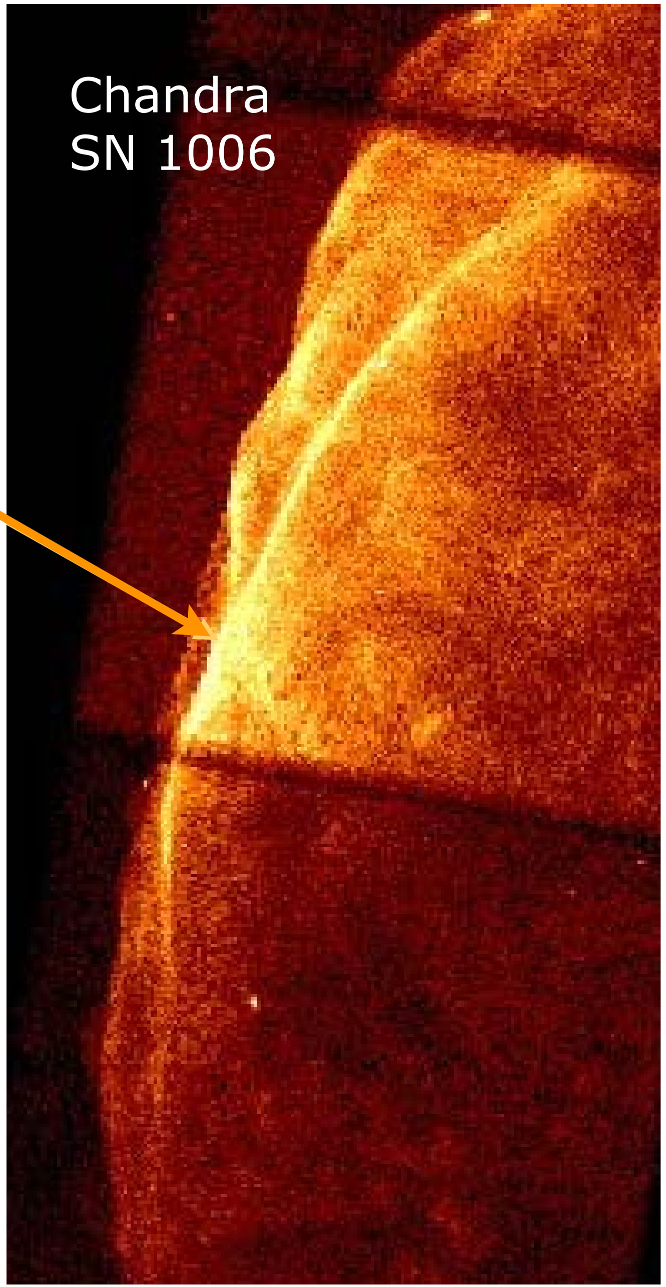
(Heck, 2010)

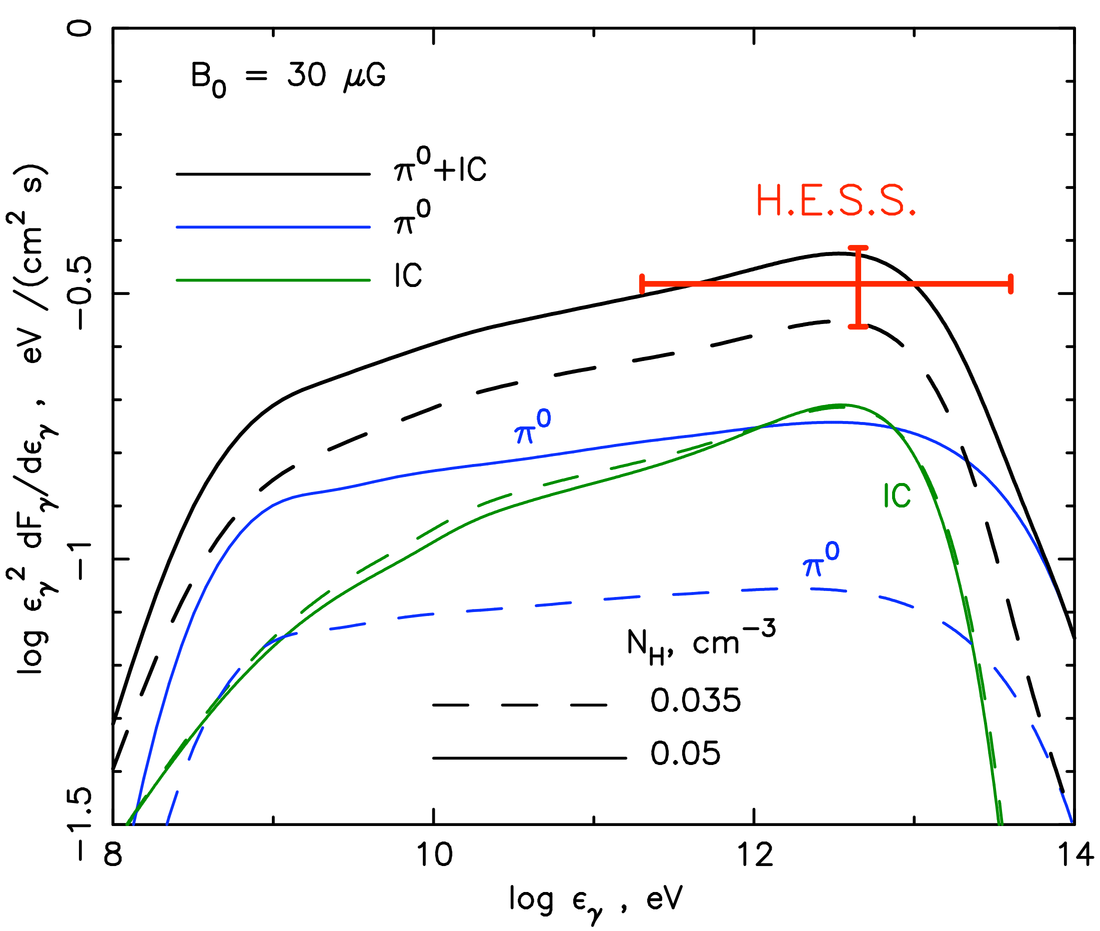


Verification with multi-messenger data



Example: gamma-rays
(neutrinos would be conclusive!)



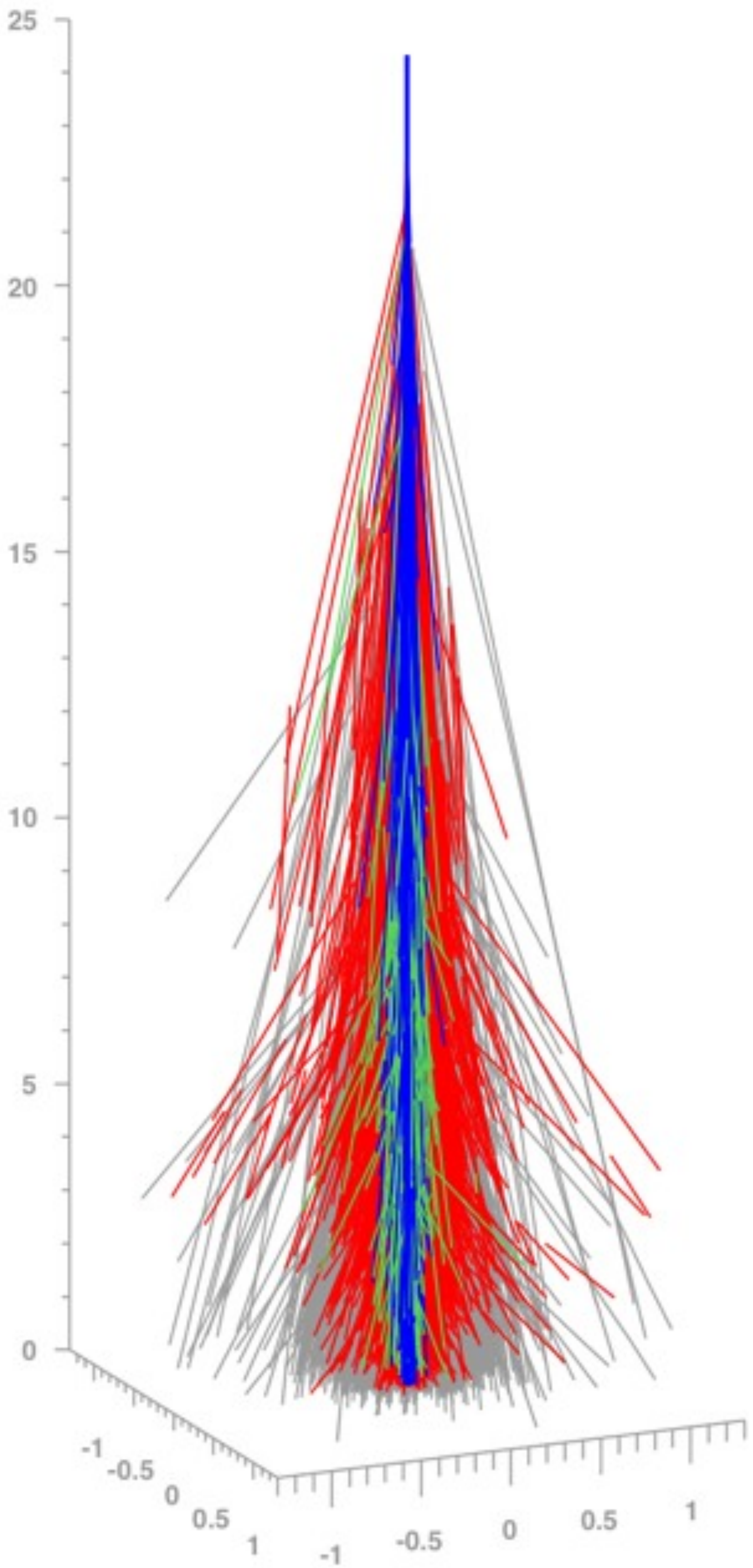


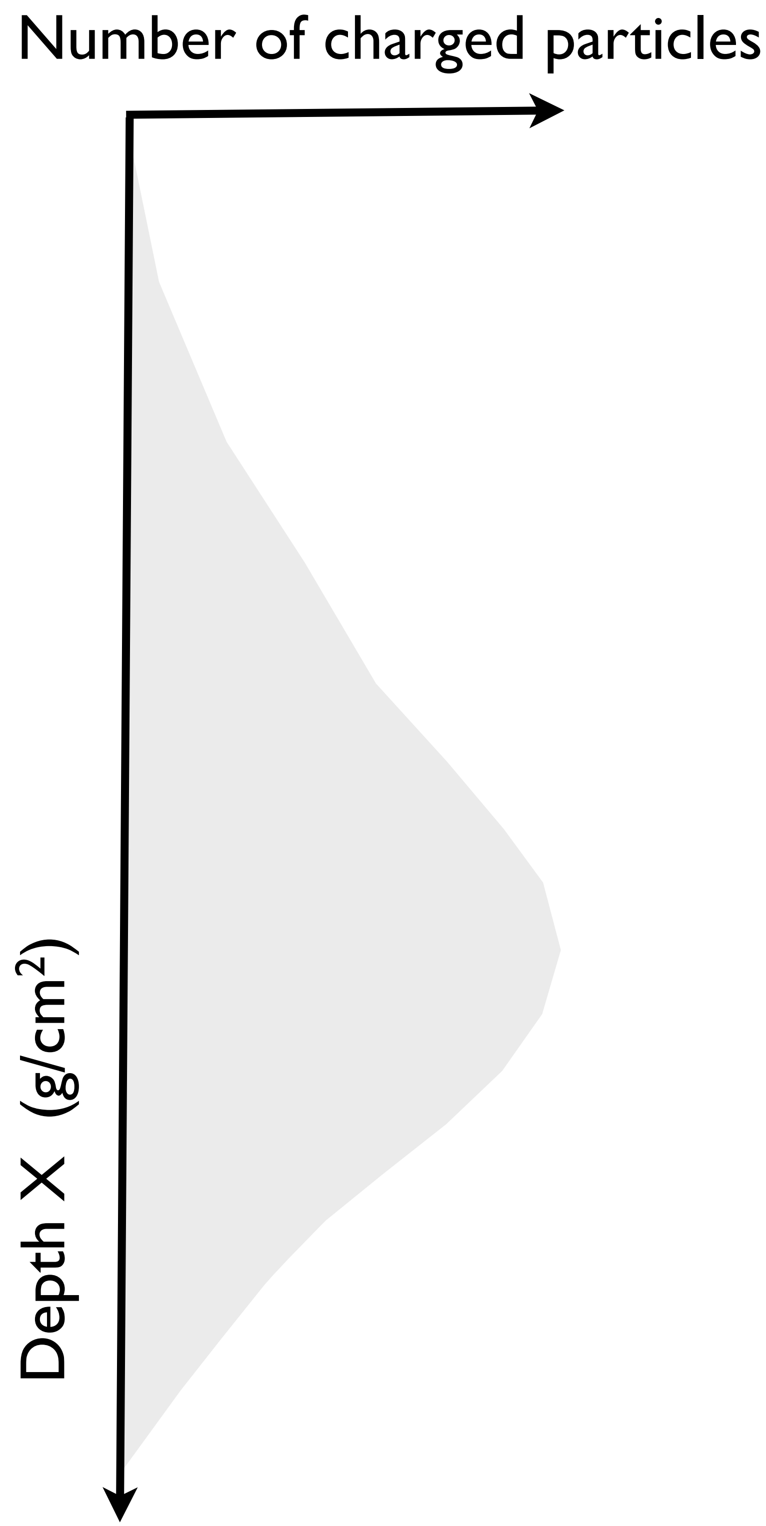
Filaments with high mag. field (100 μG): indirect proof of hadronic particles?

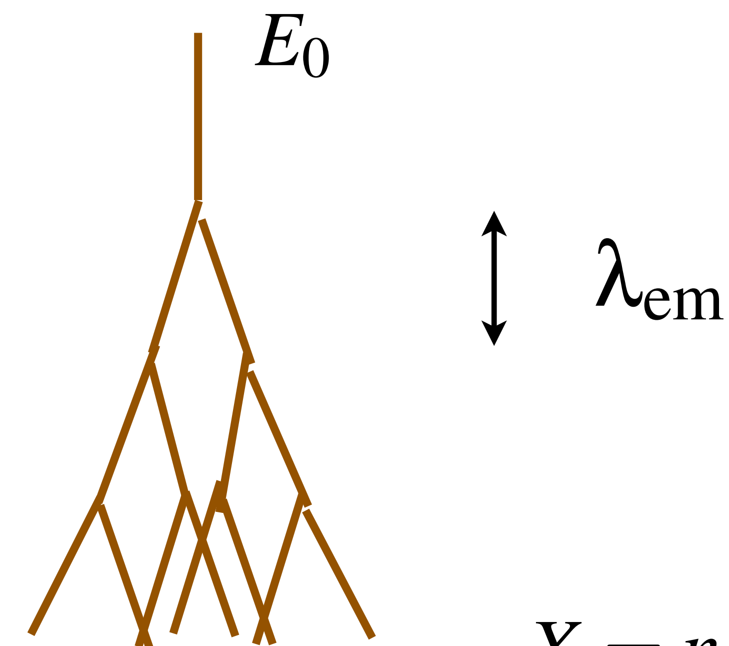
IC contribution derived from X-ray data

(Berezhko et al., astro-ph/0906.3944)

Heitler model of em. shower







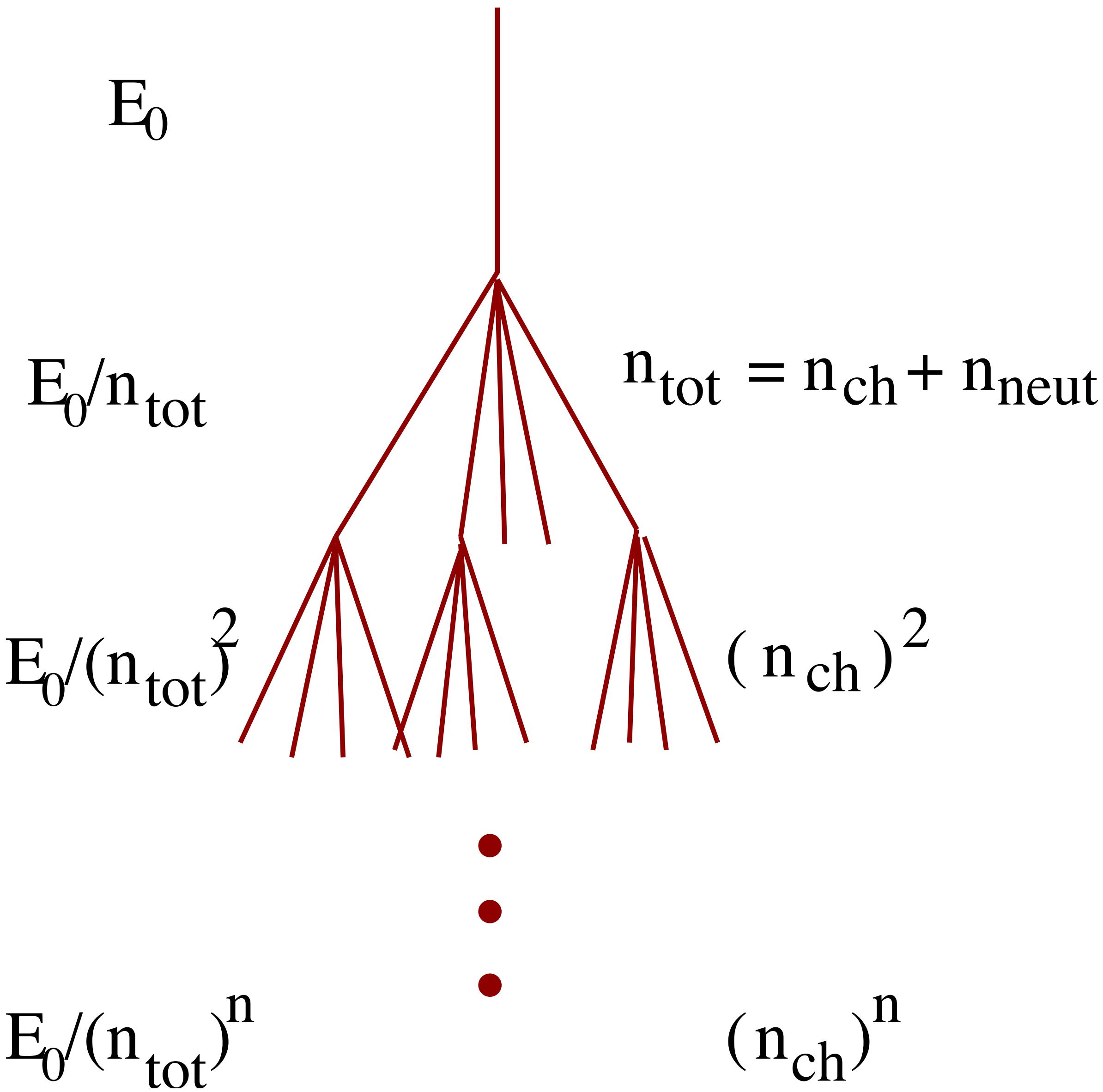
$X = n\,\lambda_{\mathrm{em}}$

$E = E_0/2^n$

Shower maximum: $E = E_c$

$$N_{\max} = E_0/E_c$$
$$X_{\max} \sim \lambda_{\mathrm{em}} \ln(E_0/E_c)$$

Muon production in hadronic showers



Primary particle proton

π^0 decay immediately

$\pi^\pm$ initiate new cascades

$$N_\mu = \left(\frac{E_0}{E_{dec}}\right)^\alpha$$

$$\alpha = \frac{\ln n_{ch}}{\ln n_{tot}} \approx 0.82 \ldots 0.95$$

Assumptions:

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

(Matthews, Astropart.Phys. 22, 2005)

Superposition model

Proton-induced shower

$$N_{\max} = E_0 / E_c$$

$$X_{\max} \sim \lambda_{\text{eff}} \ln(E_0)$$

$$N_\mu = \left(\frac{E_0}{E_{\text{dec}}} \right)^\alpha \qquad \alpha \approx 0.9$$

Assumption: nucleus of mass *A* and energy E_0 corresponds to *A* nucleons (protons) of energy $E_n = E_0/A$

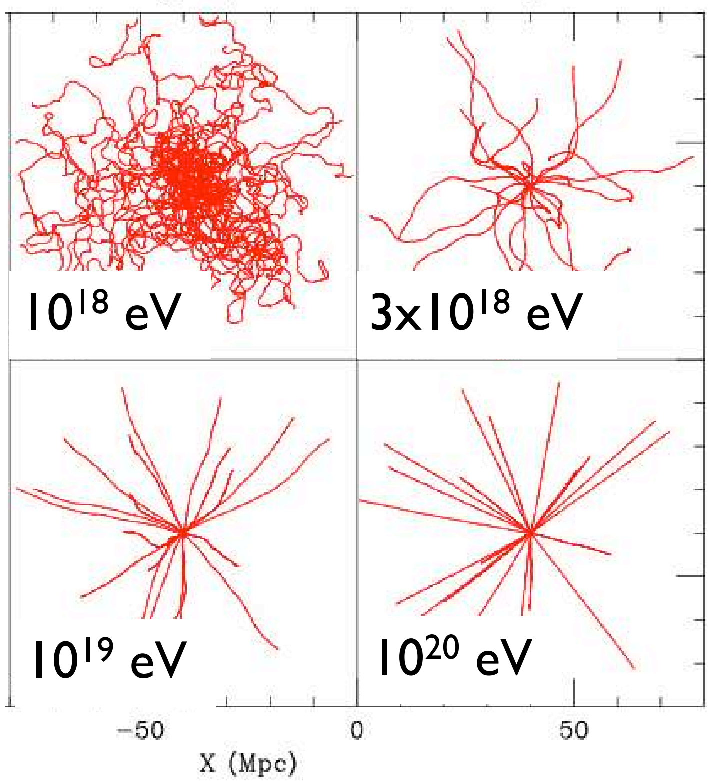
$$N^A_{\max} = A \left(\frac{E_0}{A E_c} \right) = N_{\max}$$

$$X^A_{\max} \sim \lambda_{\text{eff}} \ln(E_0/A)$$

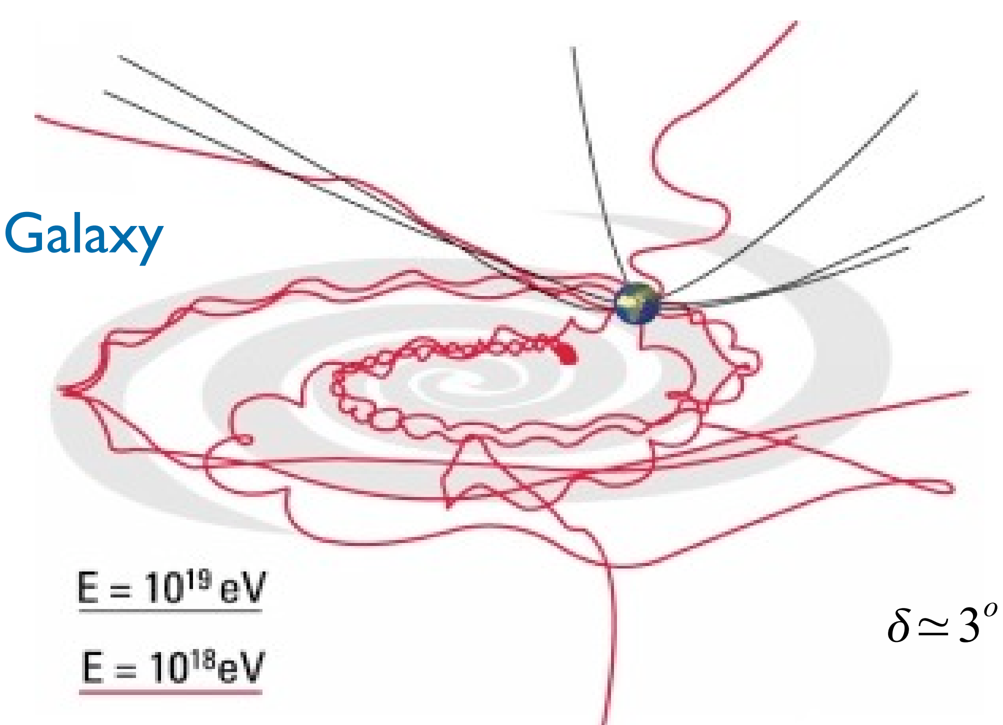
$$N^A_\mu = A \left(\frac{E_0}{A E_{\text{dec}}} \right)^\alpha = A^{1-\alpha} N_\mu$$

GZK horizon and magnetic field deflection

Extragalactic magnetic field

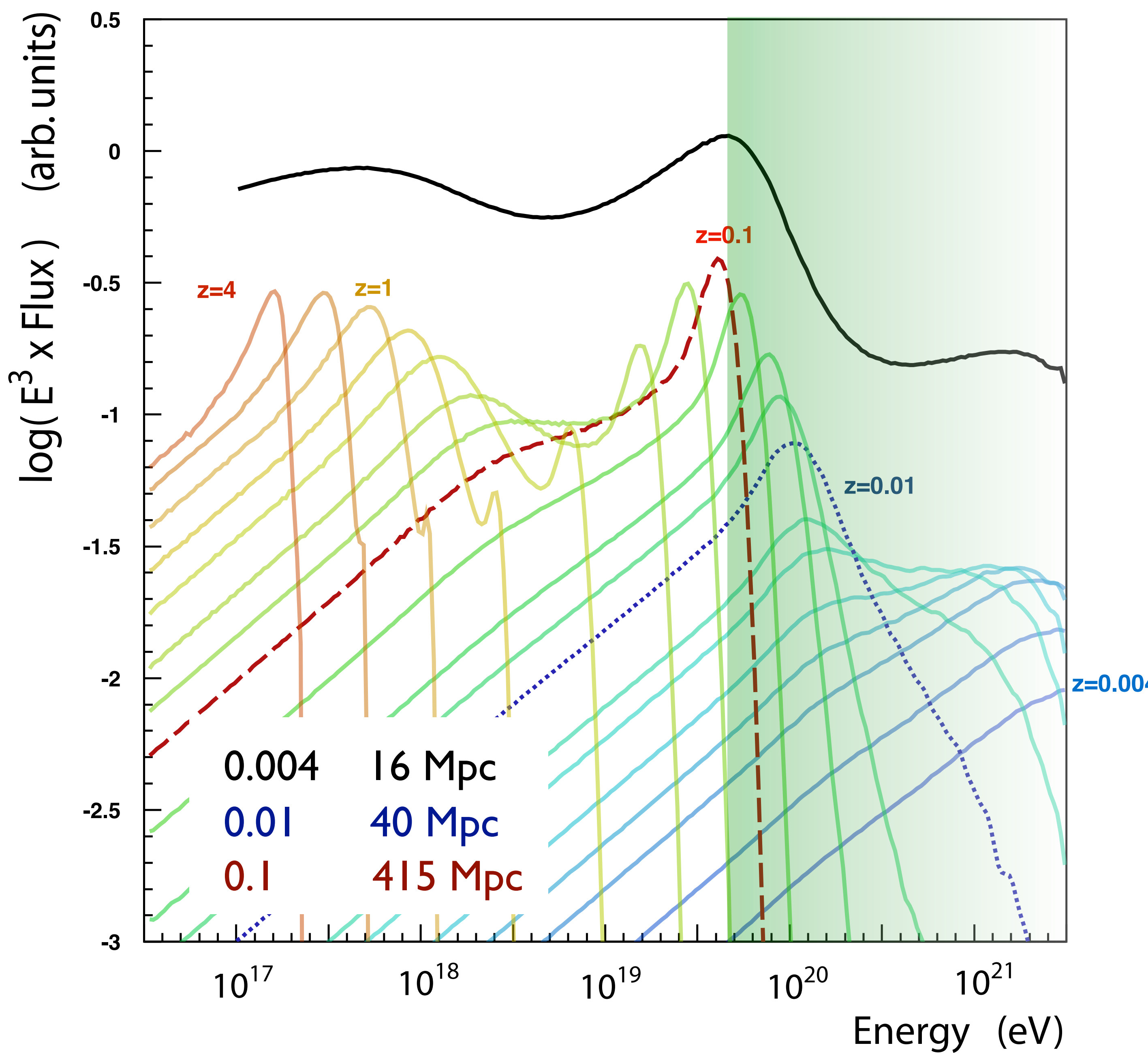


Galaxy



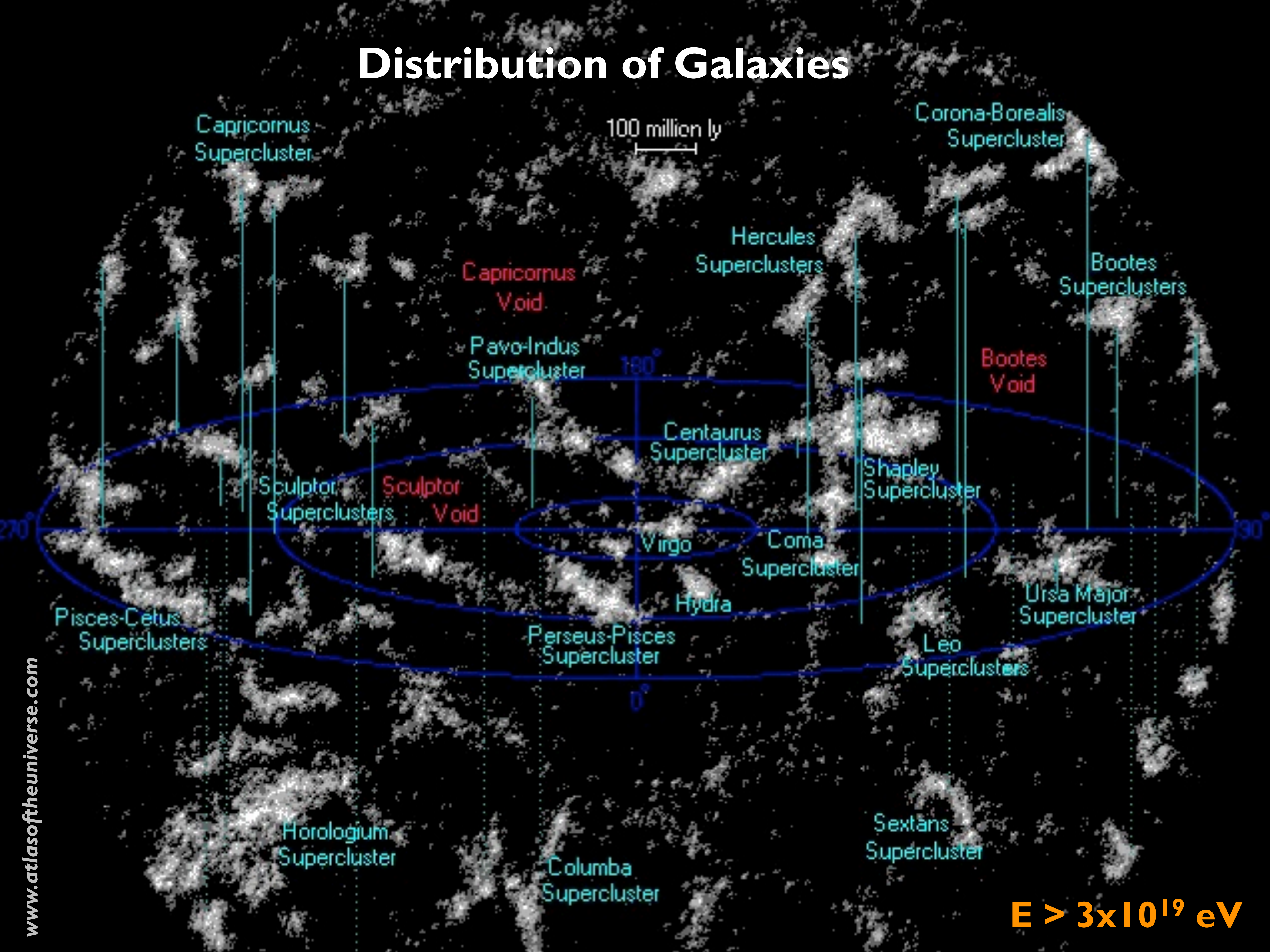
$$\delta \simeq 3^o \frac{B}{3\,\mu G}\frac{L}{kpc}\frac{6\times 10^{19} eV}{E/Z}$$

GZK horizon: energy-source relation



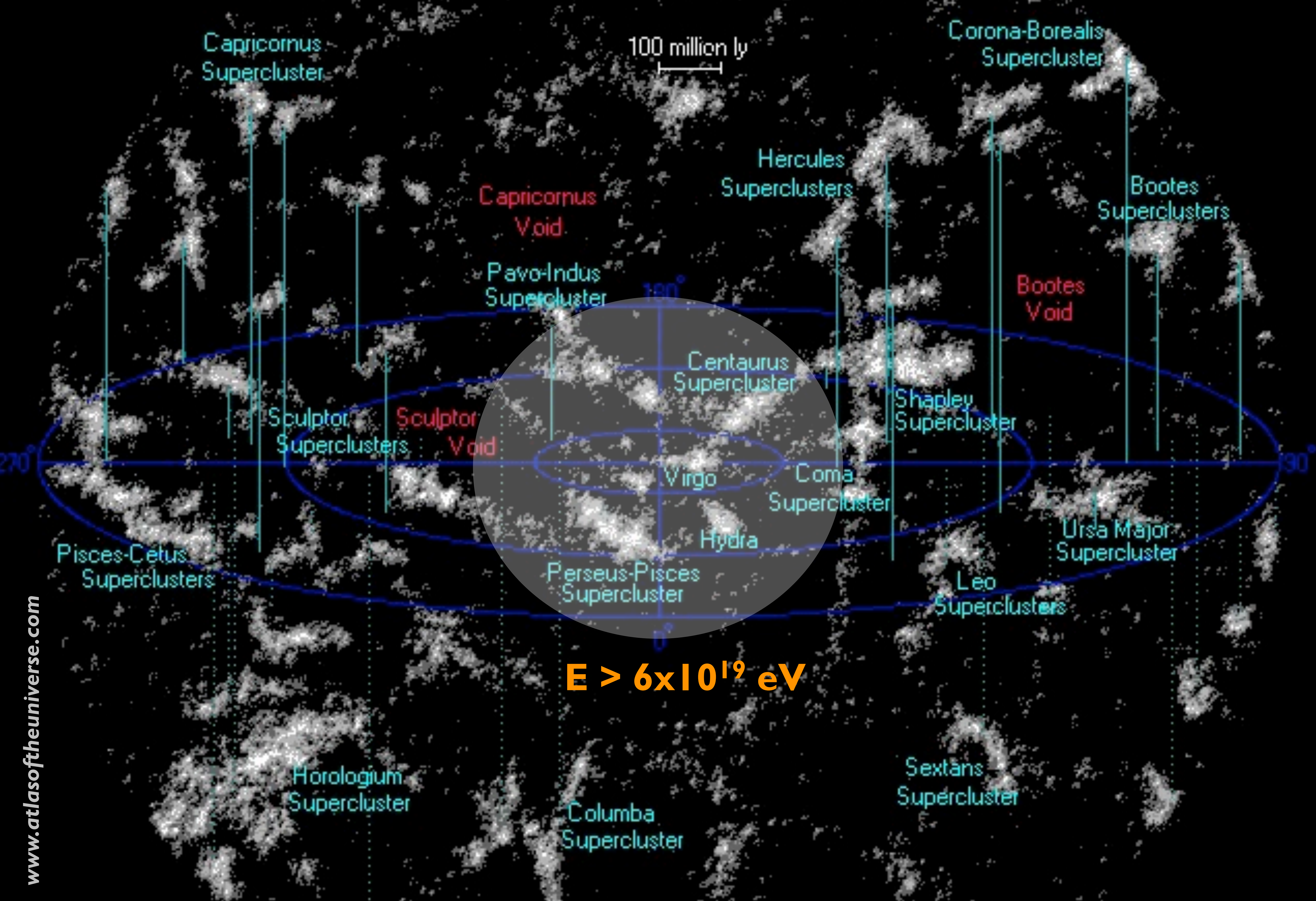
(Bergmann et al., PLB 2006)

Distribution of Galaxies



E > $3x10^{19}$ eV

Distribution of Galaxies



Example: EPOS 1.62, iron

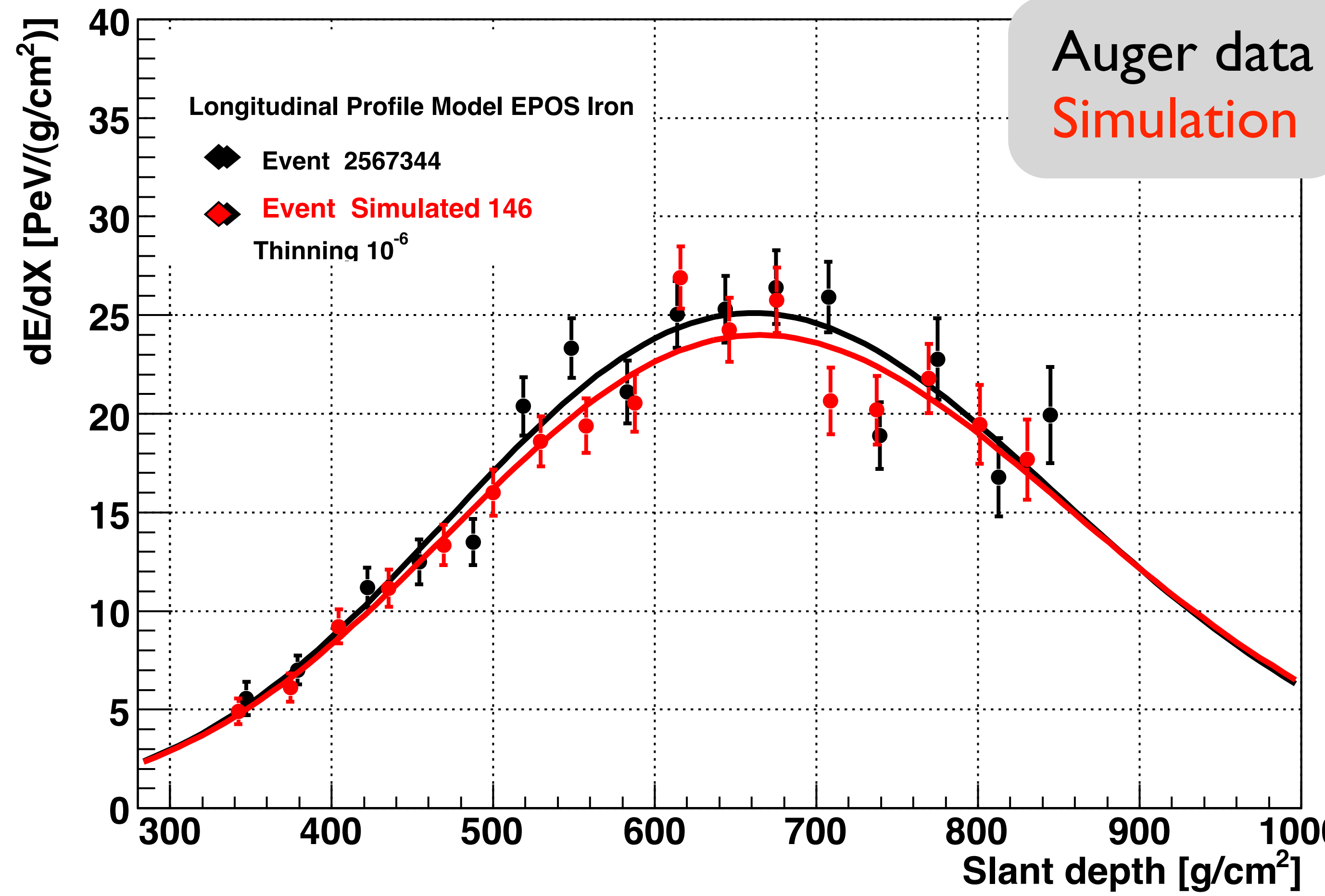
Event 2567344

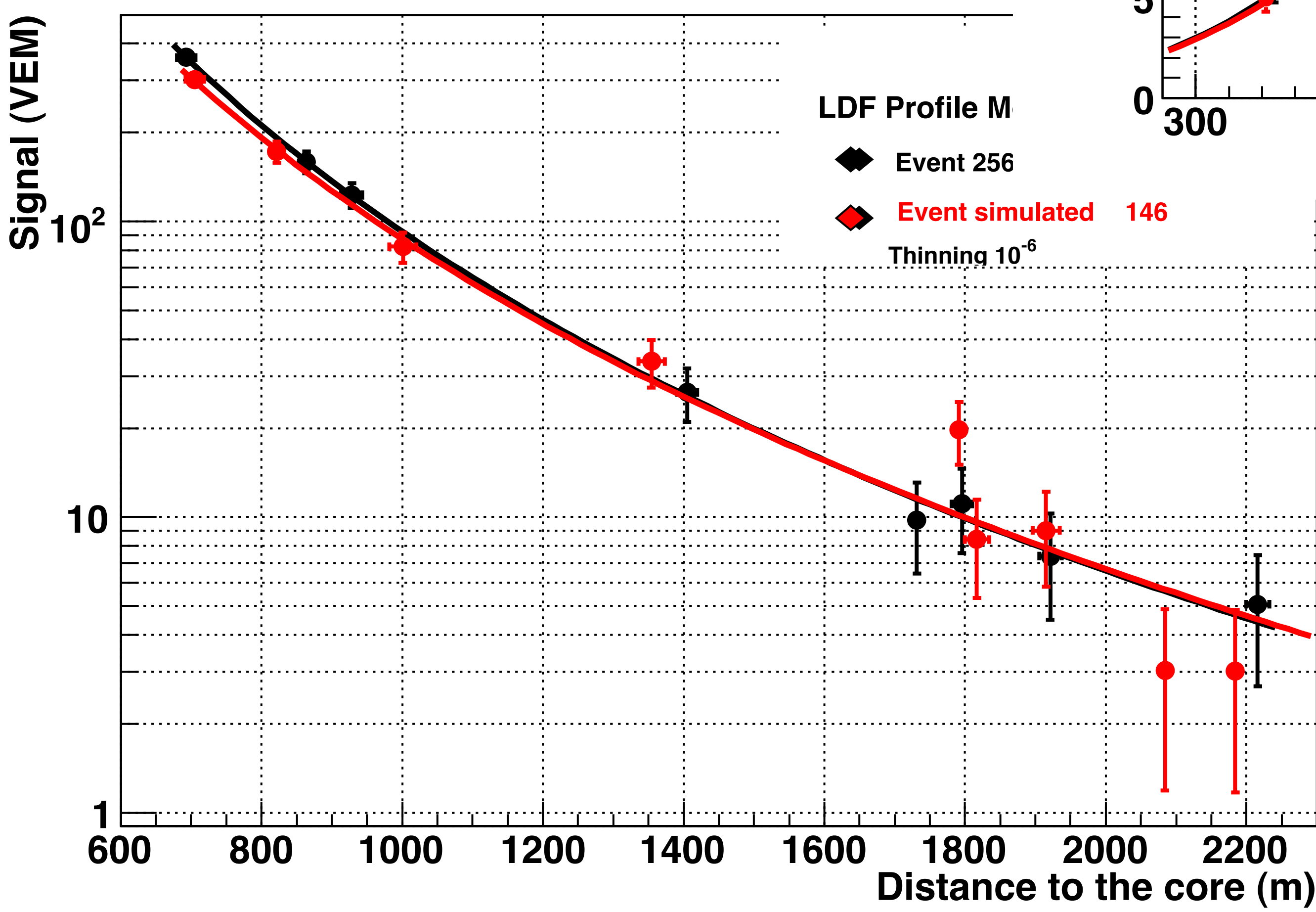
$\theta = 28°$, $E = 1.4 \times 10^{19}$ eV

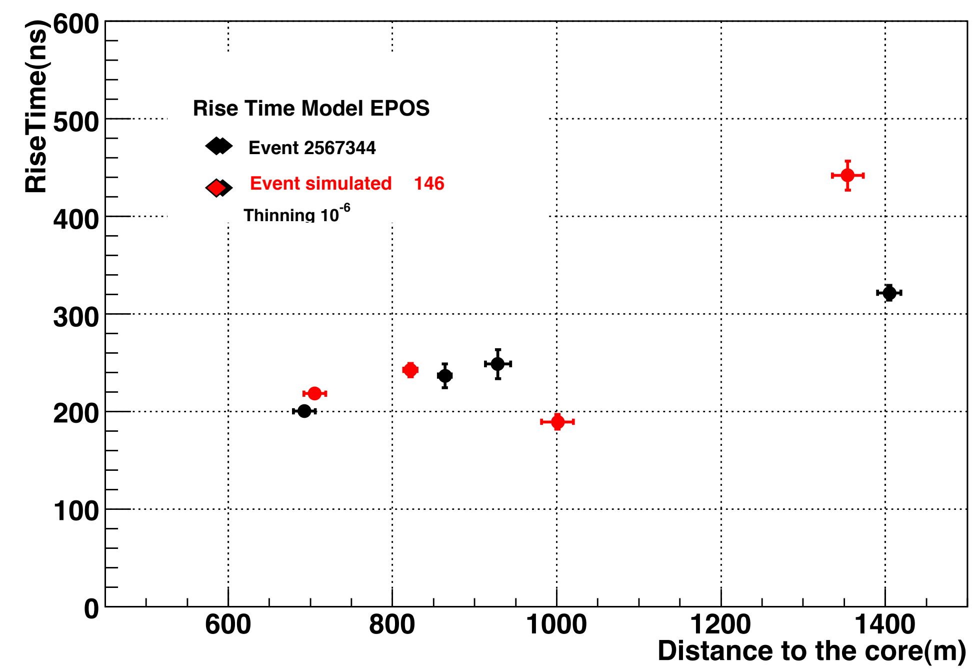
iron-like event

Auger data

Simulation







Importance of fluctuations