Connecting the LHC to ultra-high energy cosmic rays: from 10 to 100 TeV CMS

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Outline

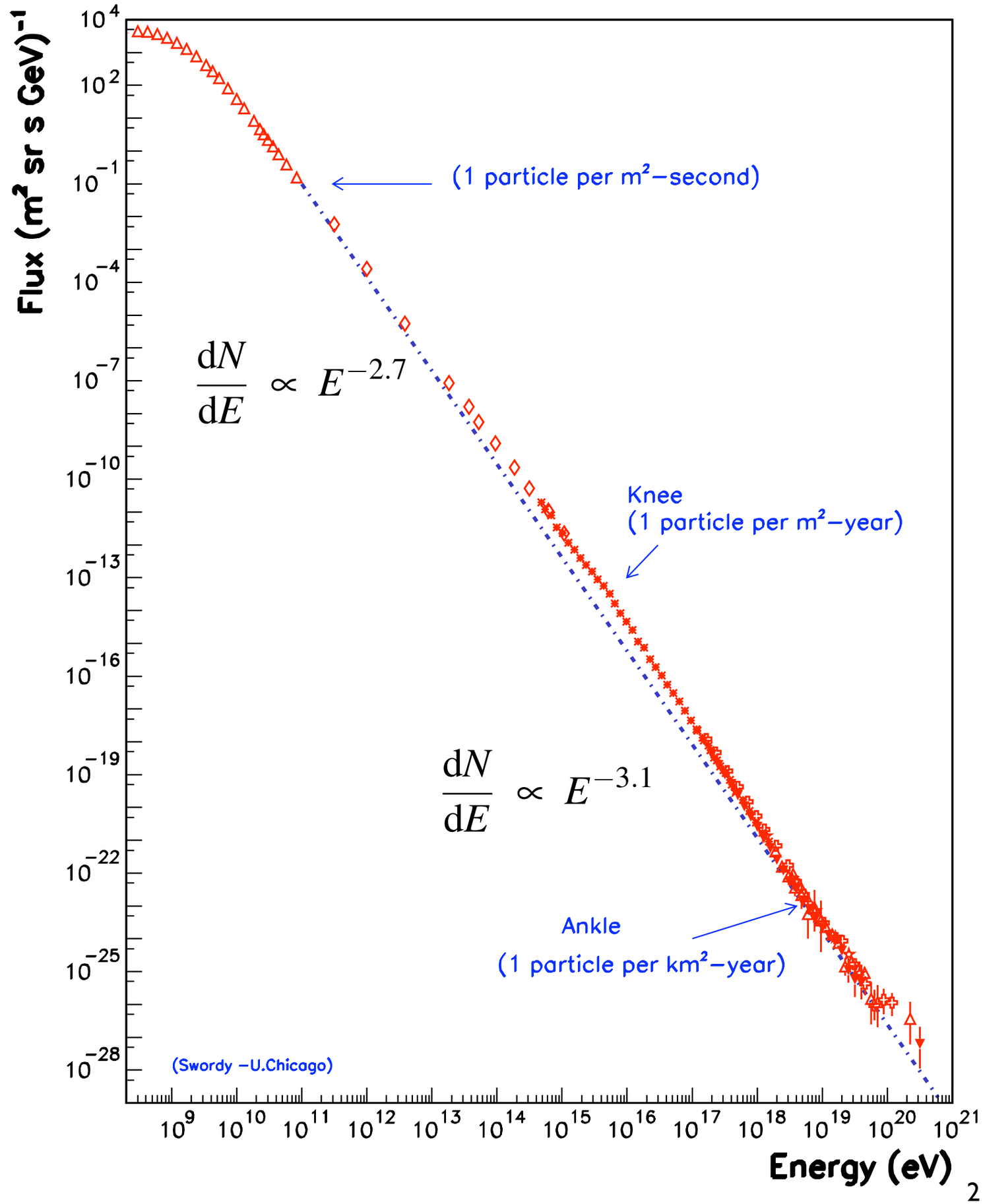
Cosmic rays and air showers

First LHC data and the knee

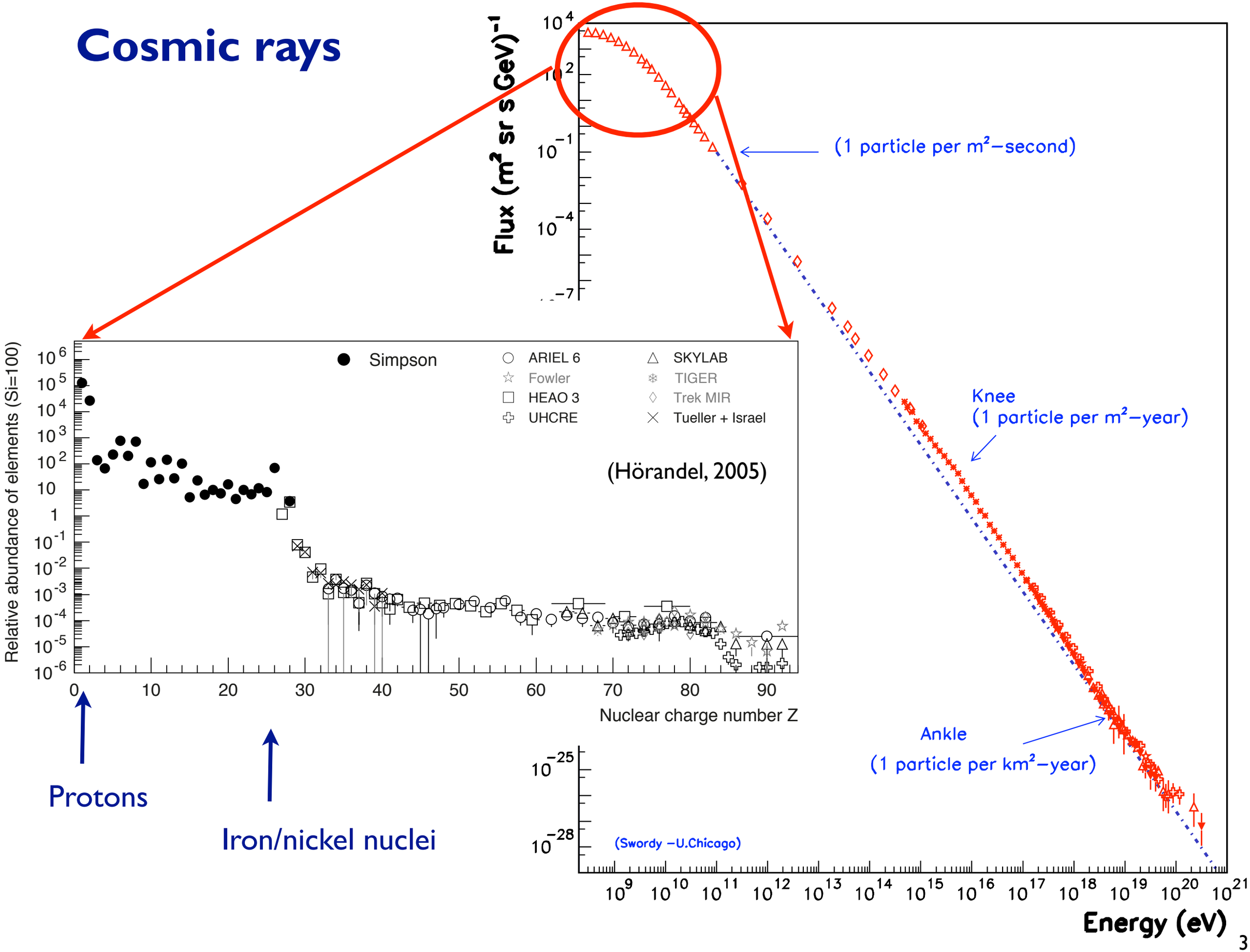
Cross section measurements using air showers

Muons in air showers at 10^{19} eV

Astrophysical constraints at the highest energies



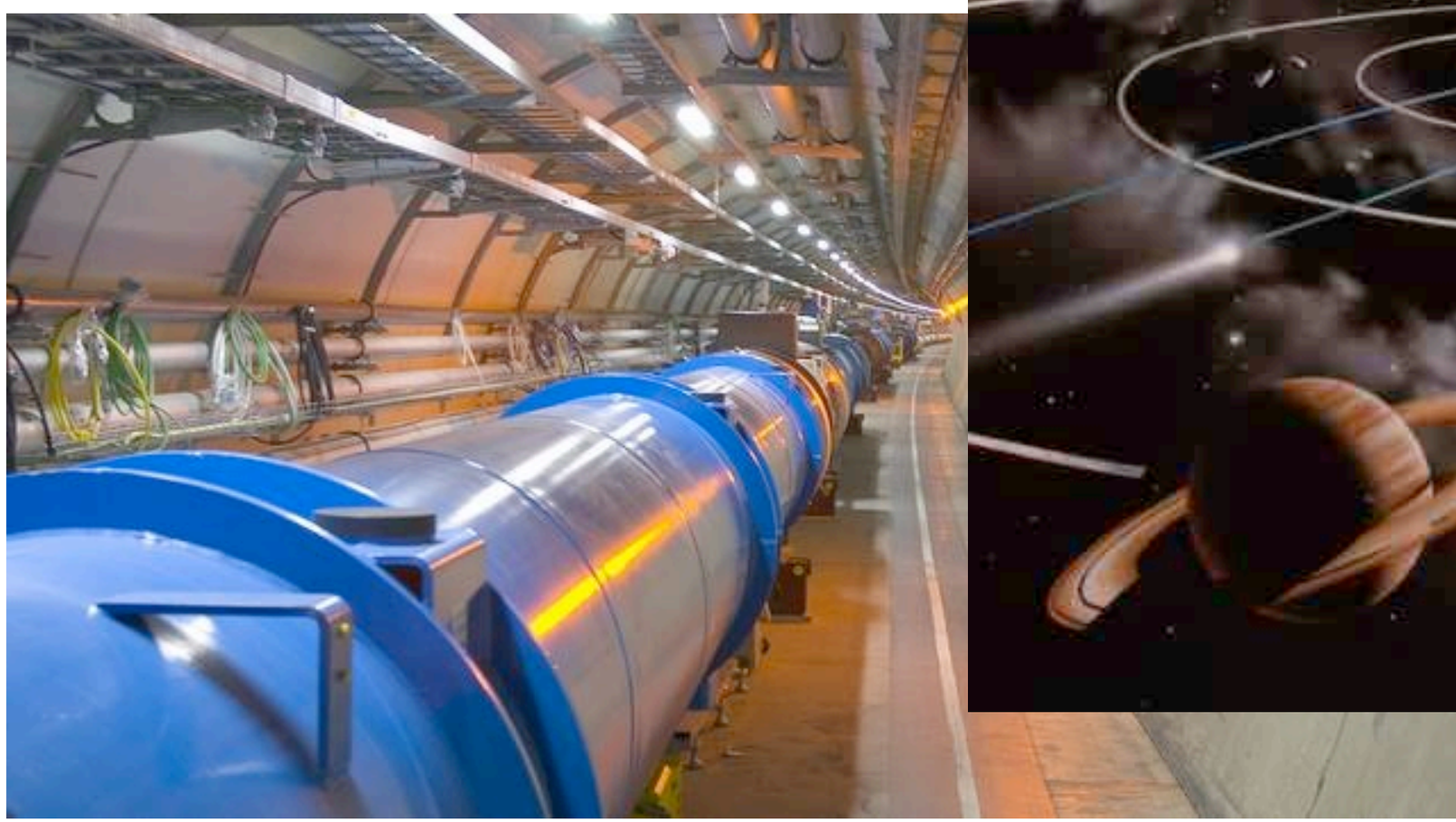
Cosmic rays

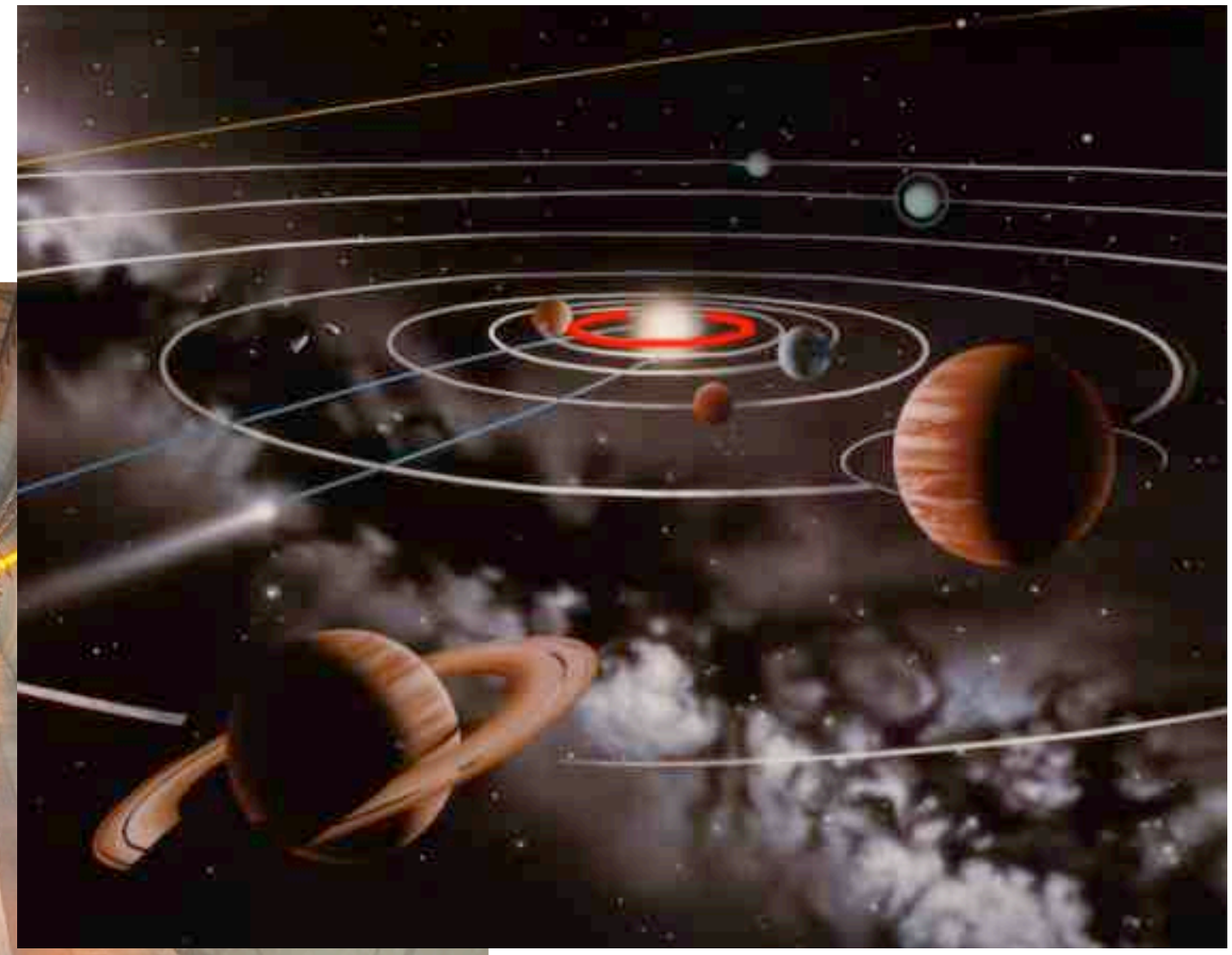

Flux (m² sr s GeV)⁻¹
(1 particle per m²–second)
Knee
(1 particle per m²–year)
Ankle
(1 particle per km²–year)
(Swordy –U.Chicago)
Energy (eV)
Relative abundance of elements (Si=100)
Simpson
ARIEL 6
Fowler
HEAO 3
UHCRE
SKYLAB
TIGER
Trek MIR
Tueller + Israel
(Hörandel, 2005)
Nuclear charge number Z
Protons
Iron/nickel nuclei

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

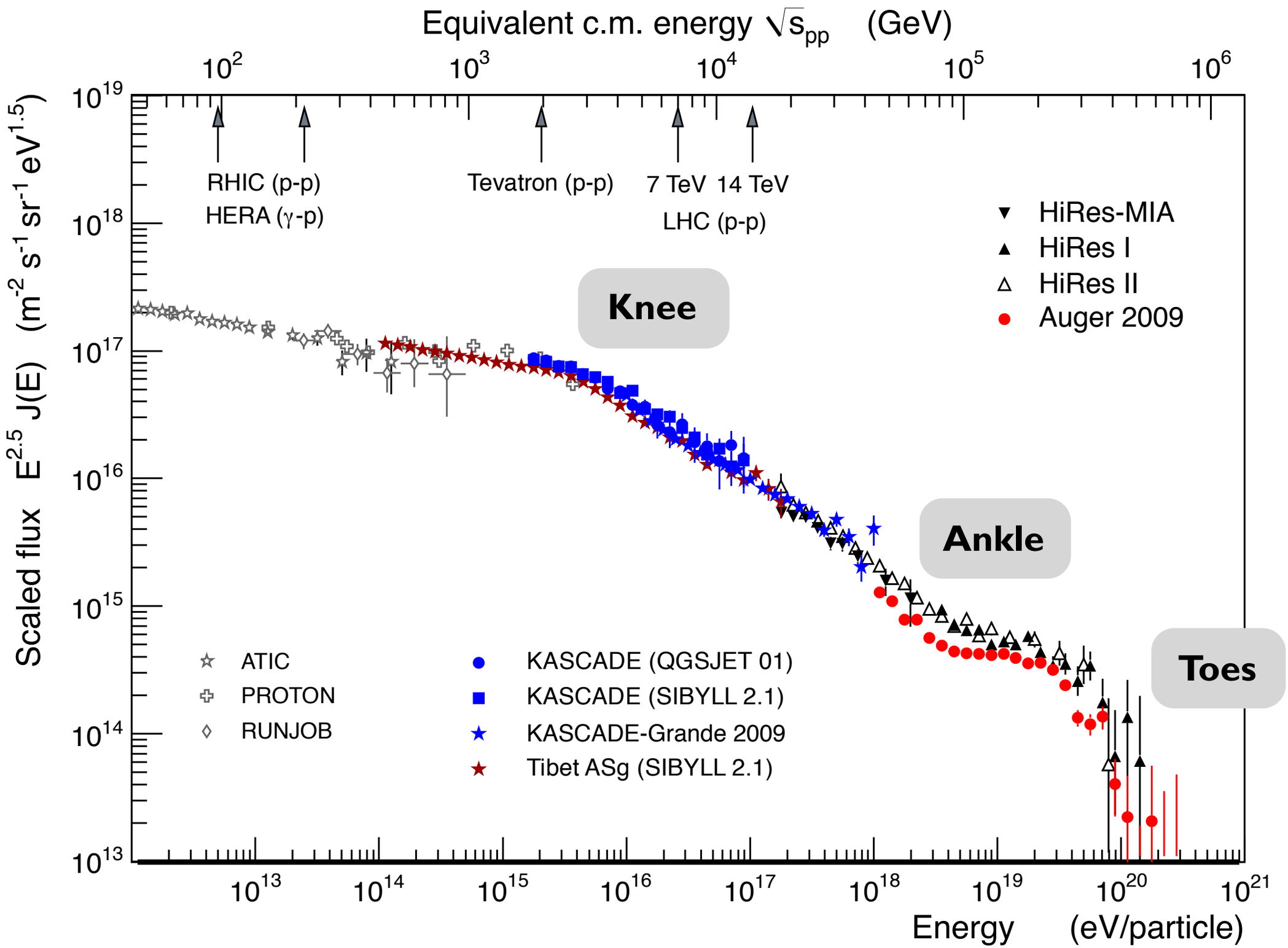




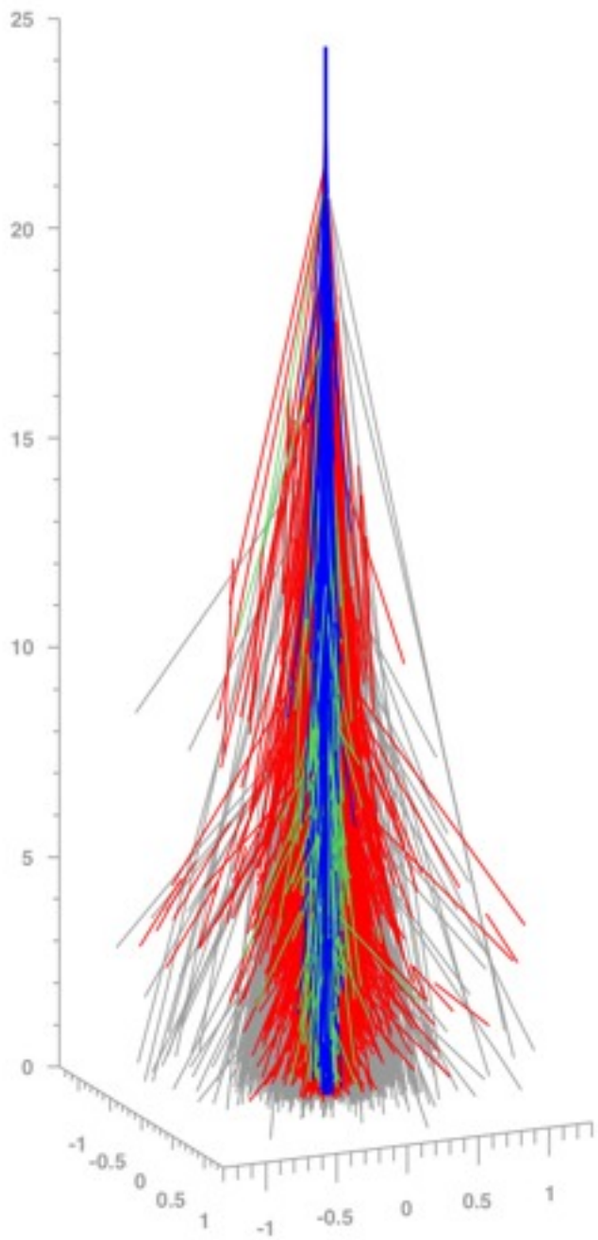
(M. Unger, 2006)

Acceleration time for LHC: 815 years

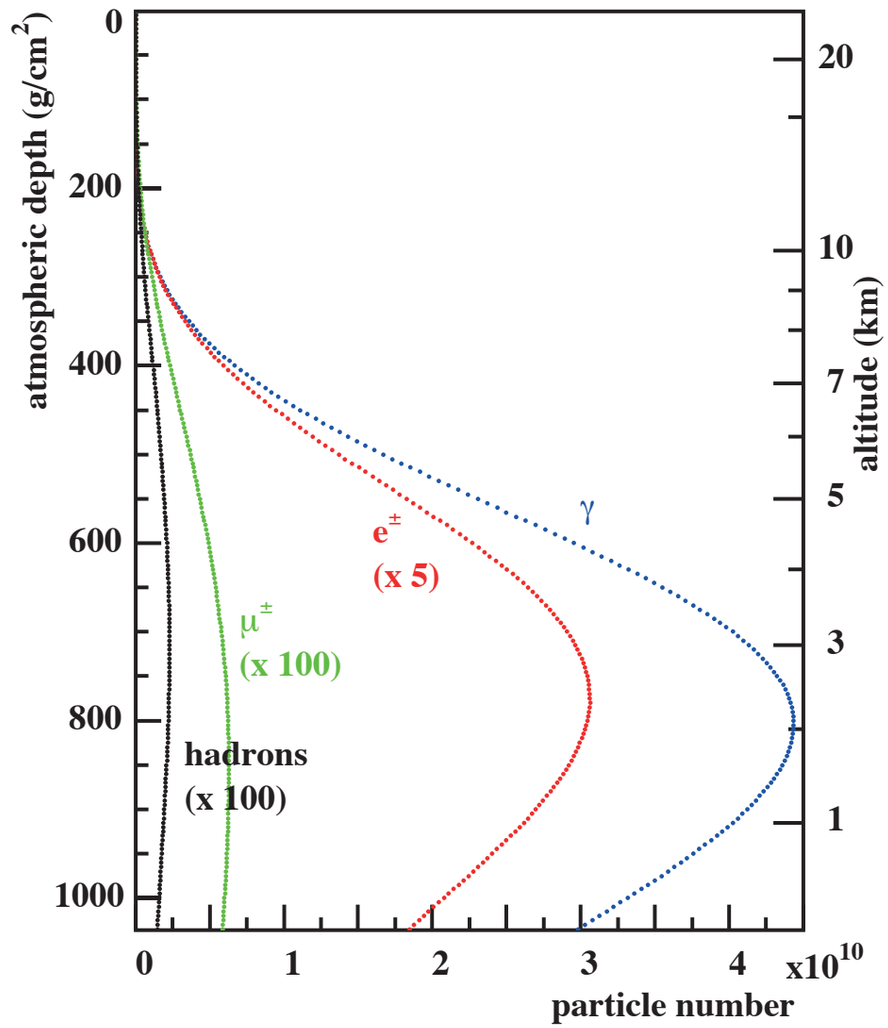
Energy spectrum and collider energies



Extensive air showers

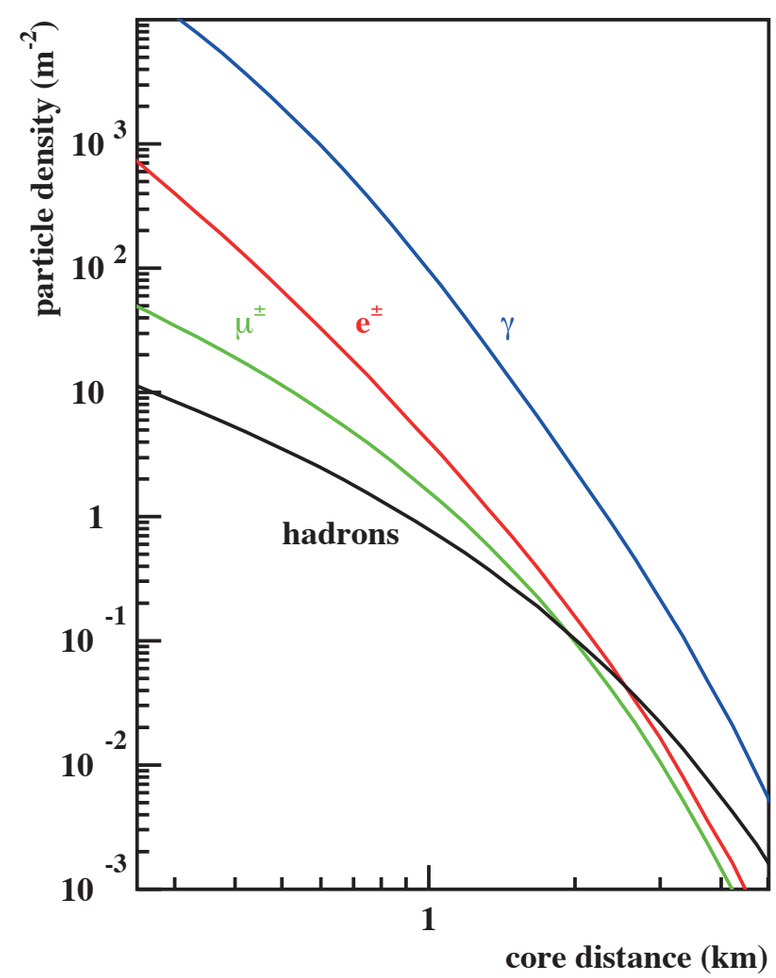


Proton-induced shower of 10^{19} eV



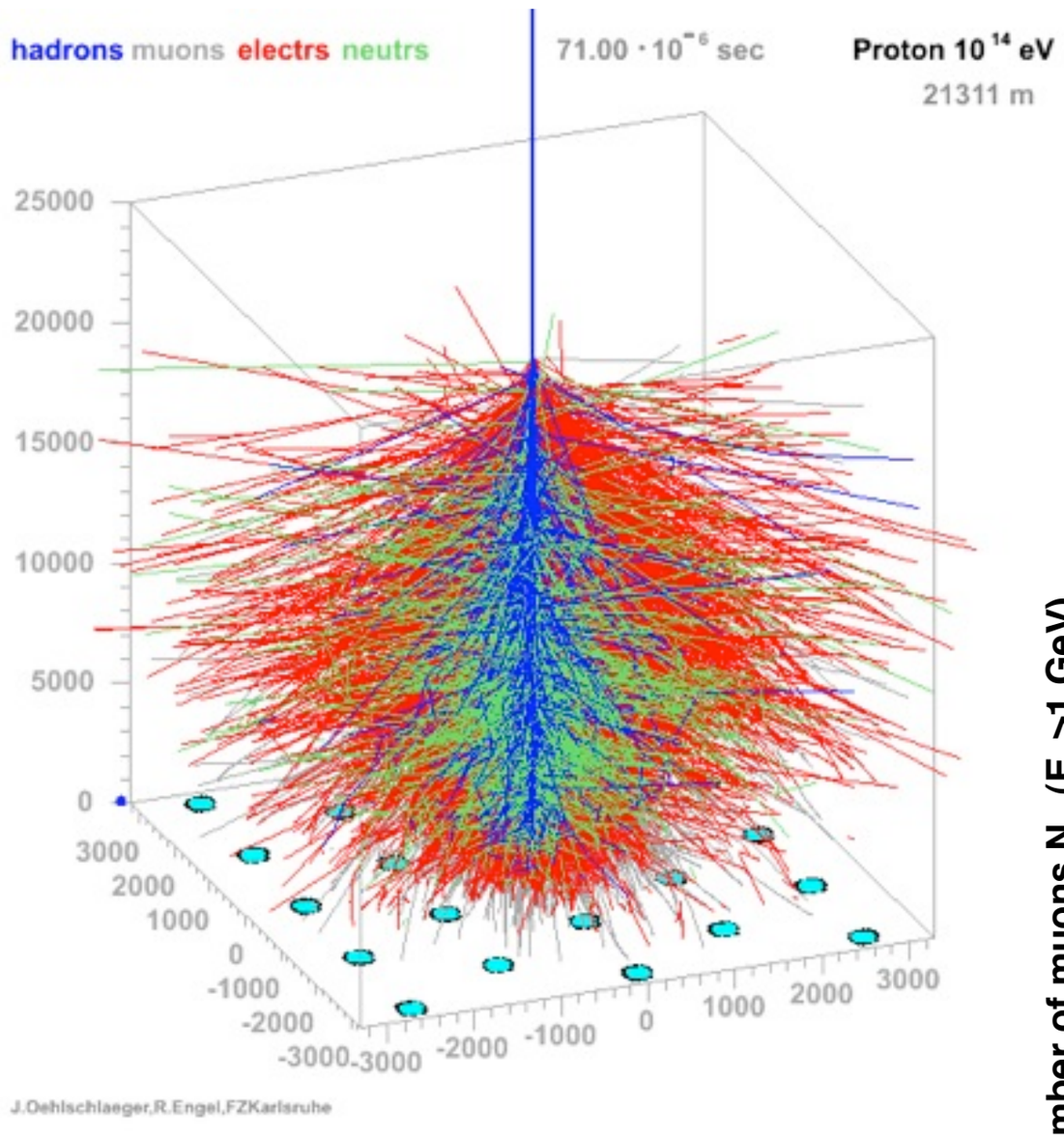
Longitudinal profile:
Cherenkov light
Fluorescence light of N_2

(RE, Pierog, Heck, ARNPS 2011)

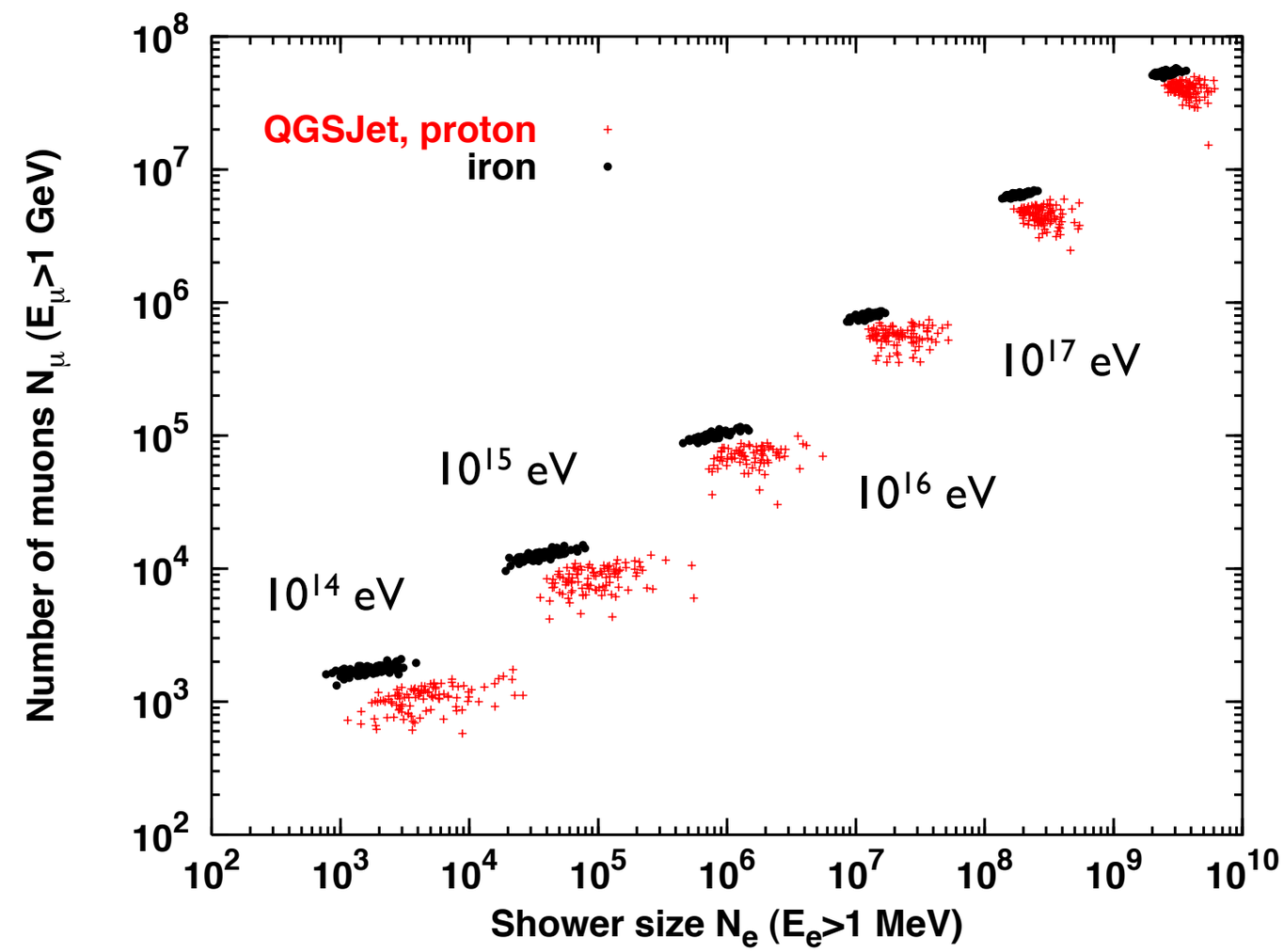


Lateral profiles:
particle detectors at ground

Energy and composition measurement (Ne-Nμ)

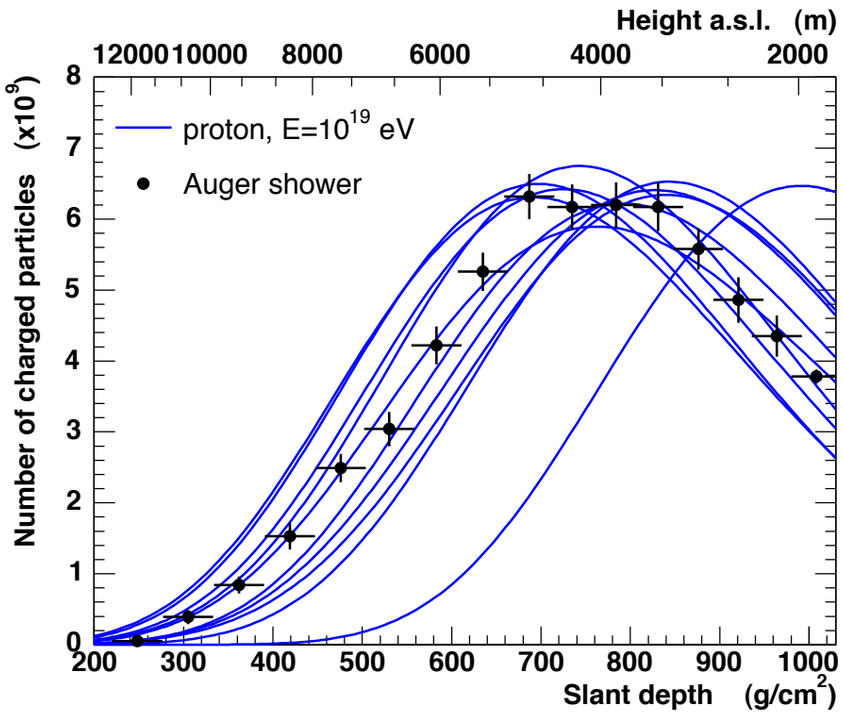


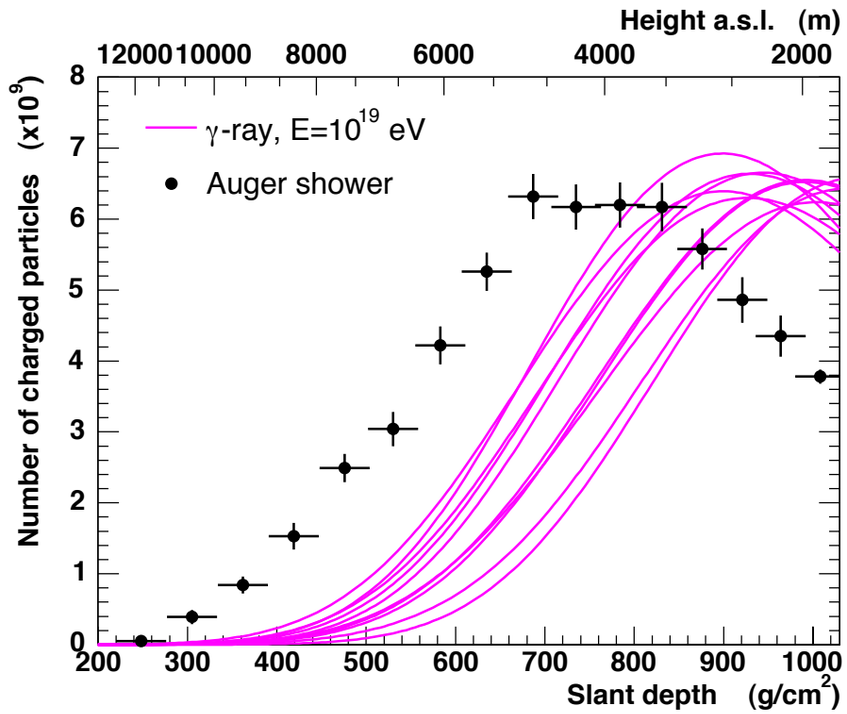
Monte Carlo simulation of showers

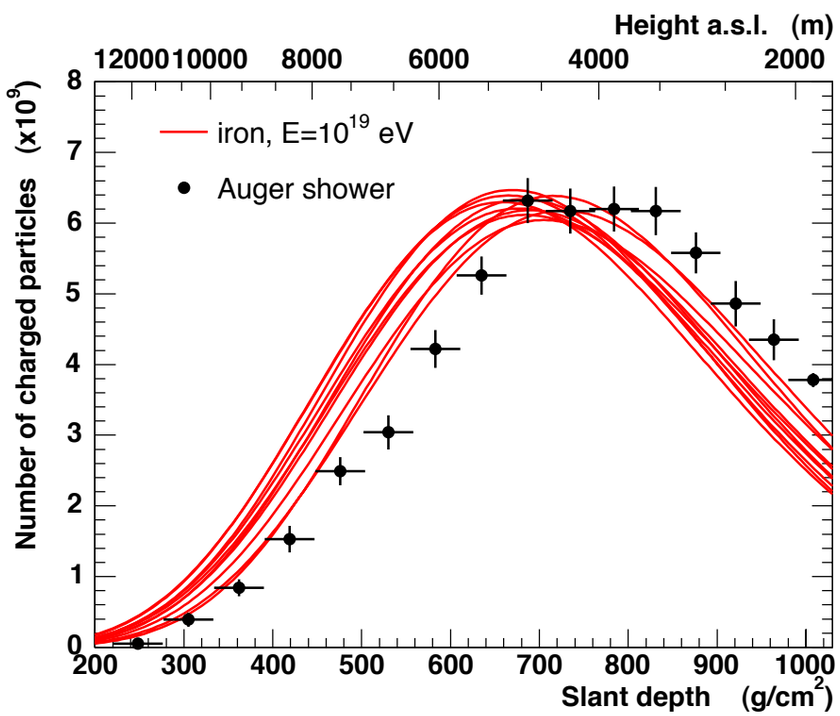


Example:
KASCADE-Grande (Karlsruhe)

Energy and composition measurement: shower profiles



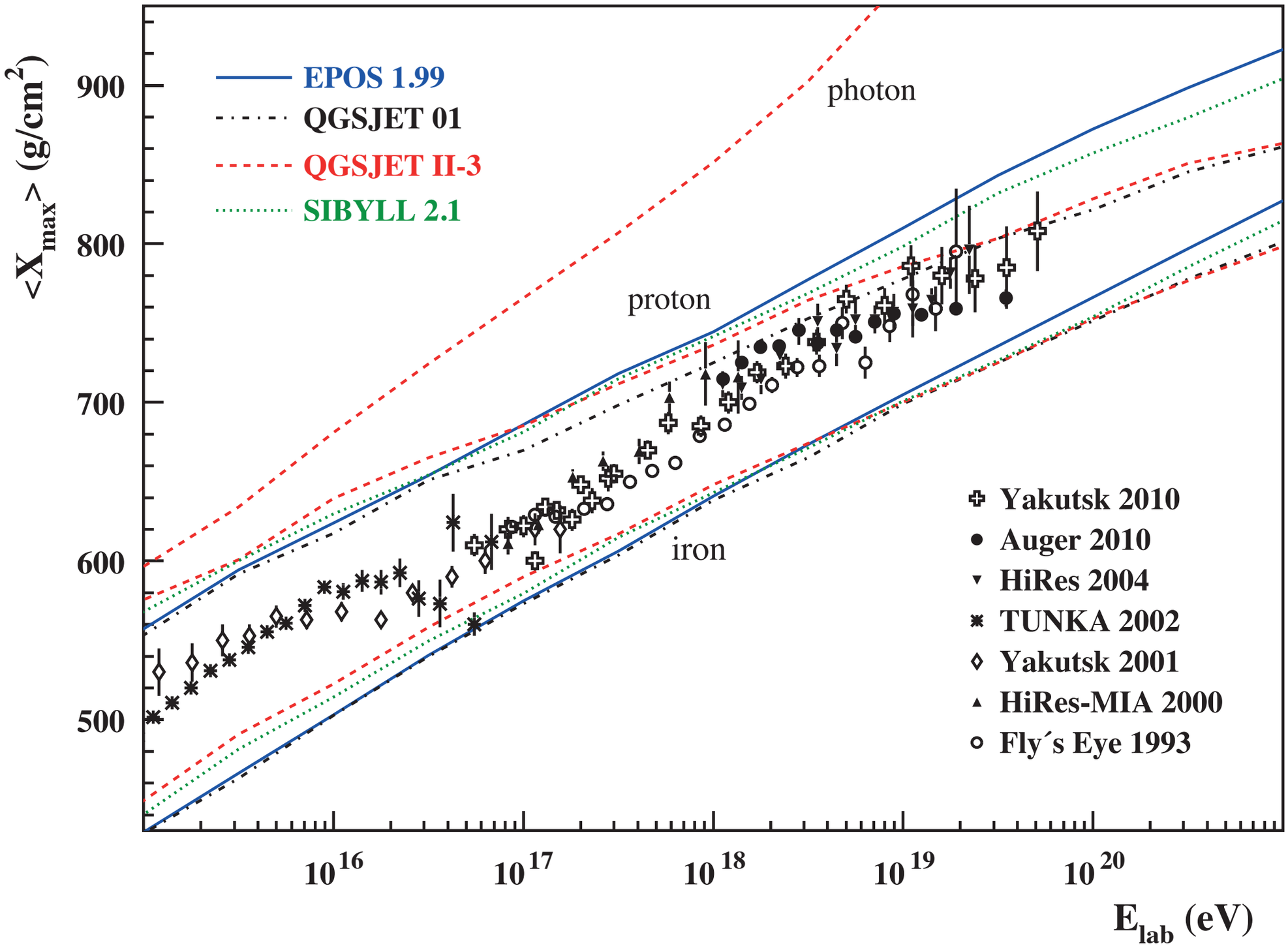




Example: event measured by Auger Collab. (ICRC 2003)

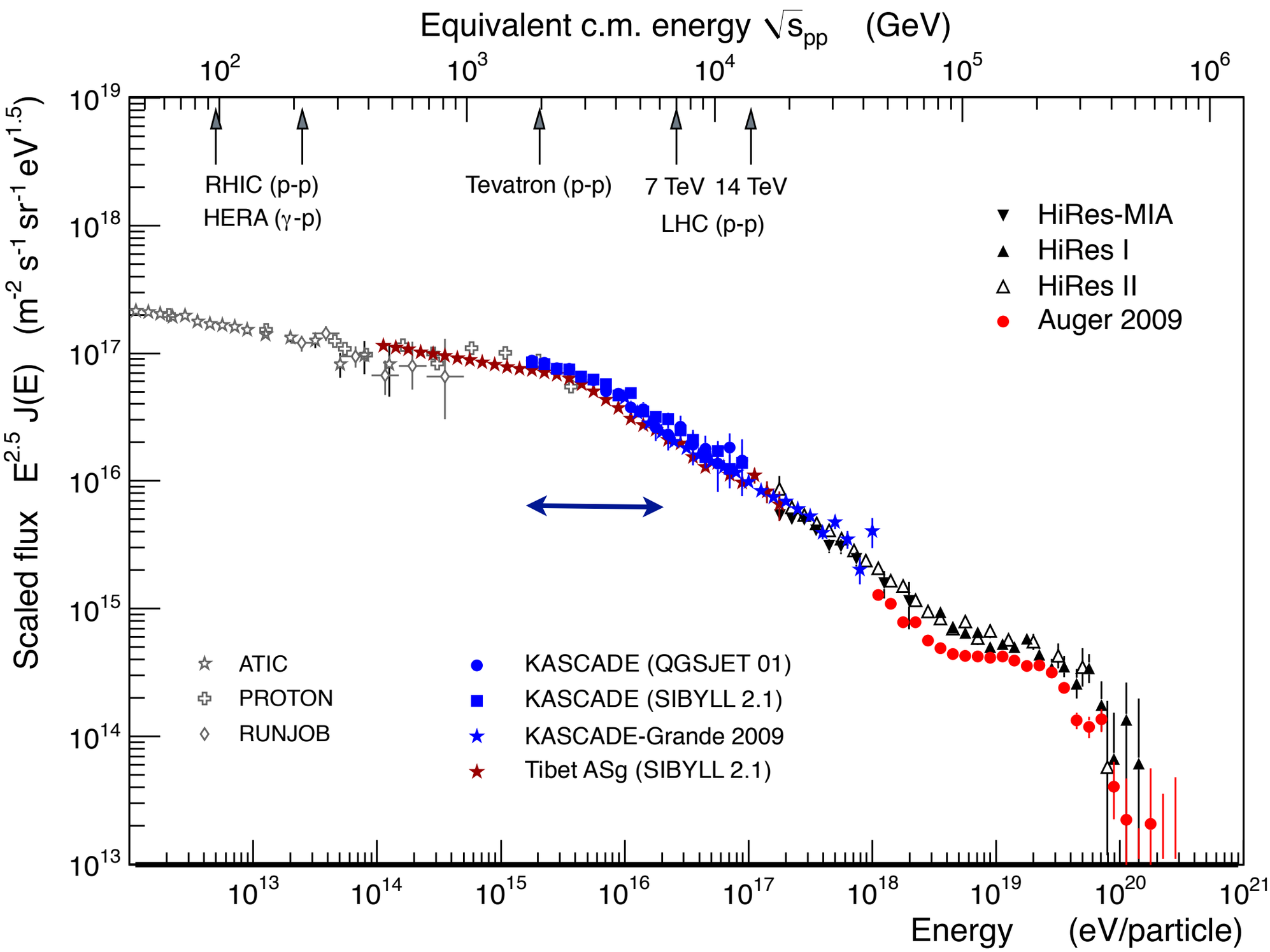
- Energy well determined
- Primary particle type: mean and fluctuations of shower depth of maximum

Mean depth of shower maximum (composition?)



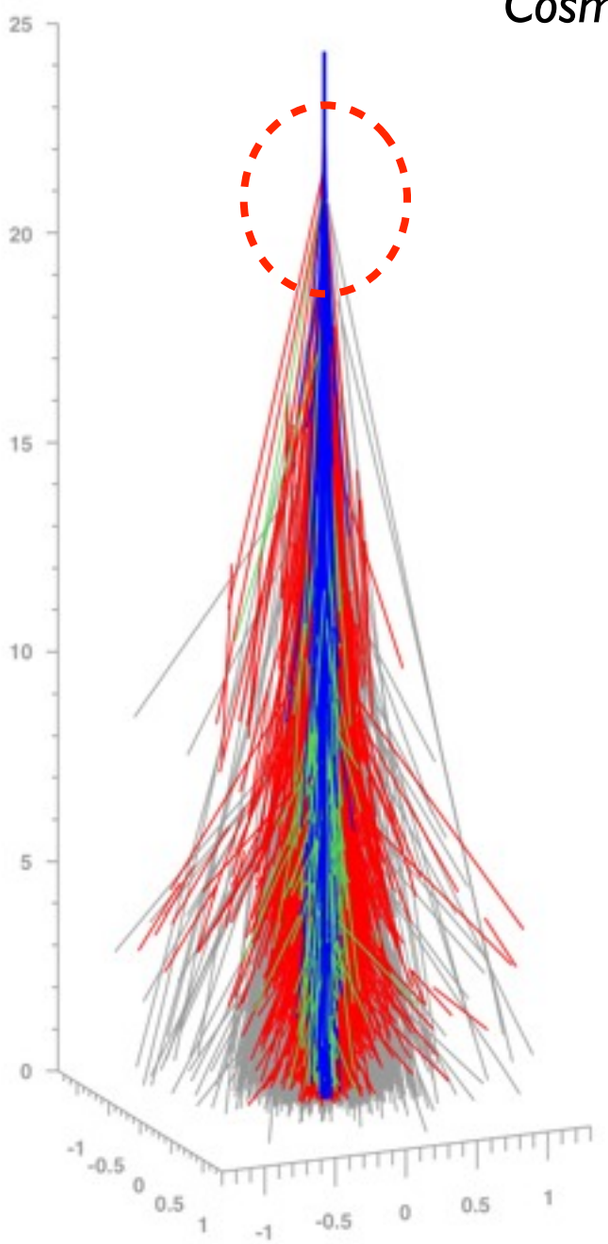
(RE, Pierog, Heck, ARNPS 2011)

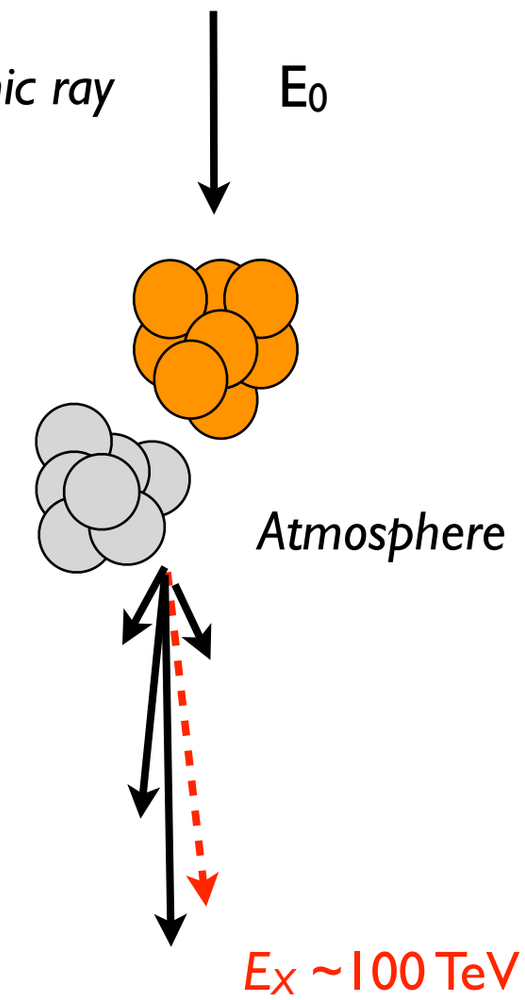
First LHC data and the interpretation of the knee



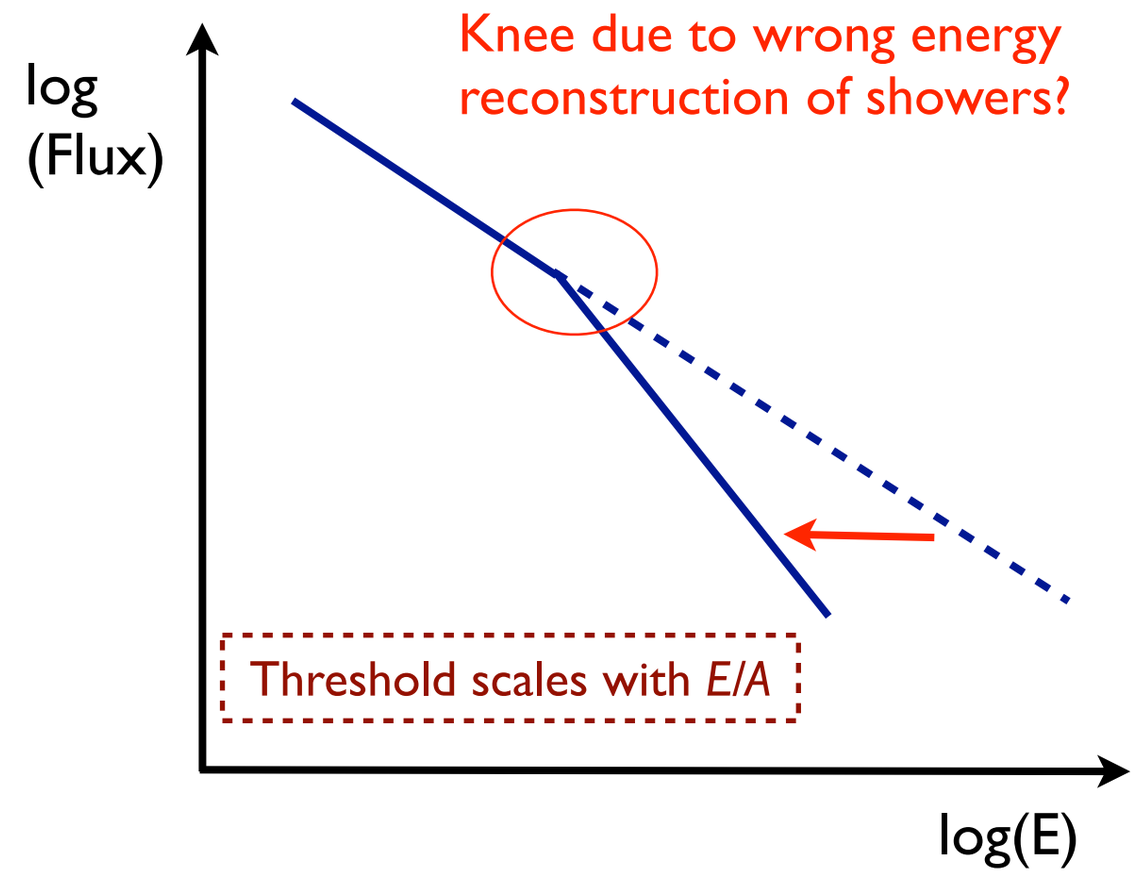
Knee energy range

Exotic models for the knee



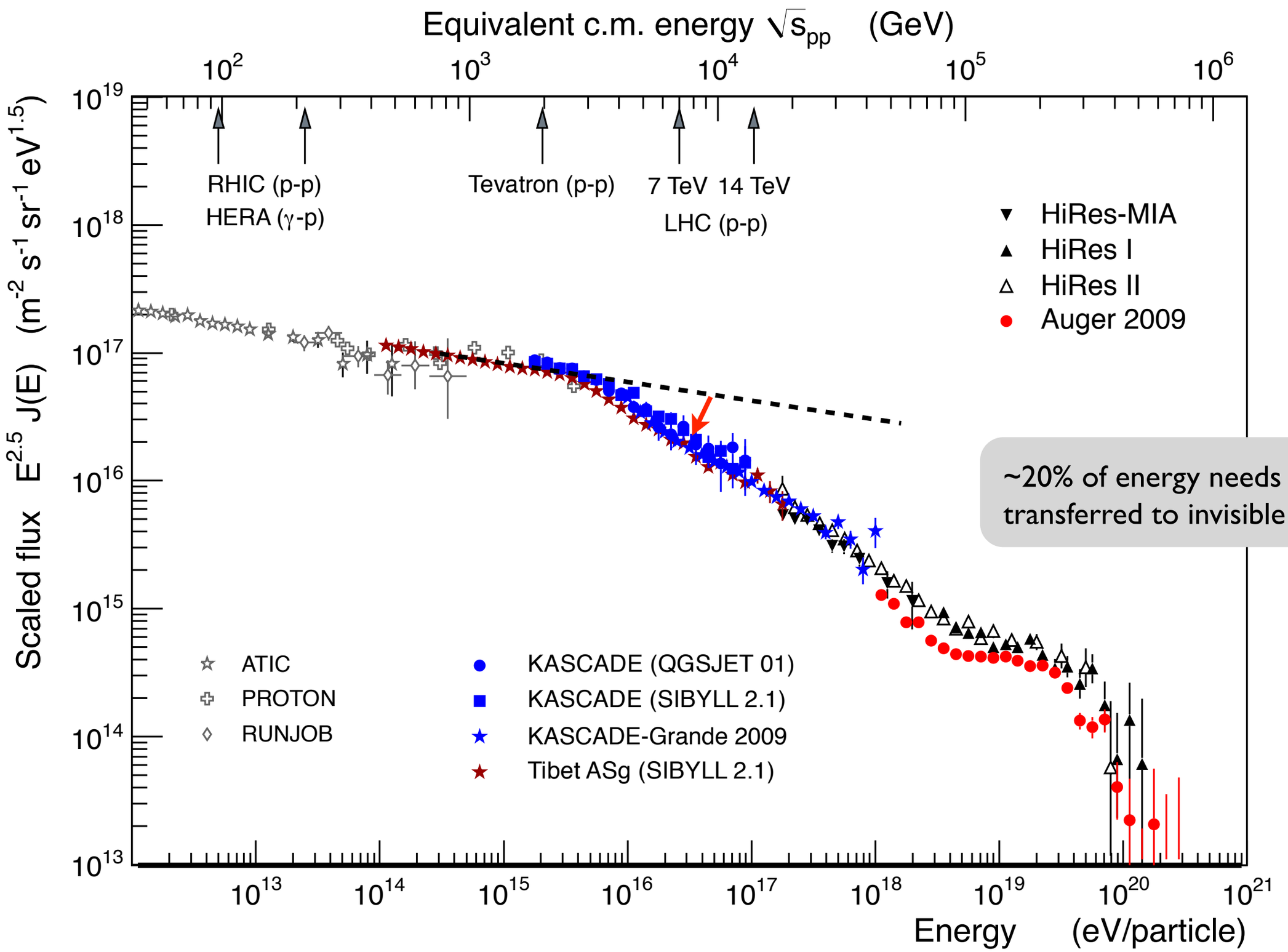


Petrukhin, NPB 151 (2006) 57
Barcelo at al. JACP 06 (2009) 027
Dixit et al. EPJC 68 (2010) 573
Petrukhin NPB 212 (2011) 235



New physics: scaling with nucleon-nucleon cms energy

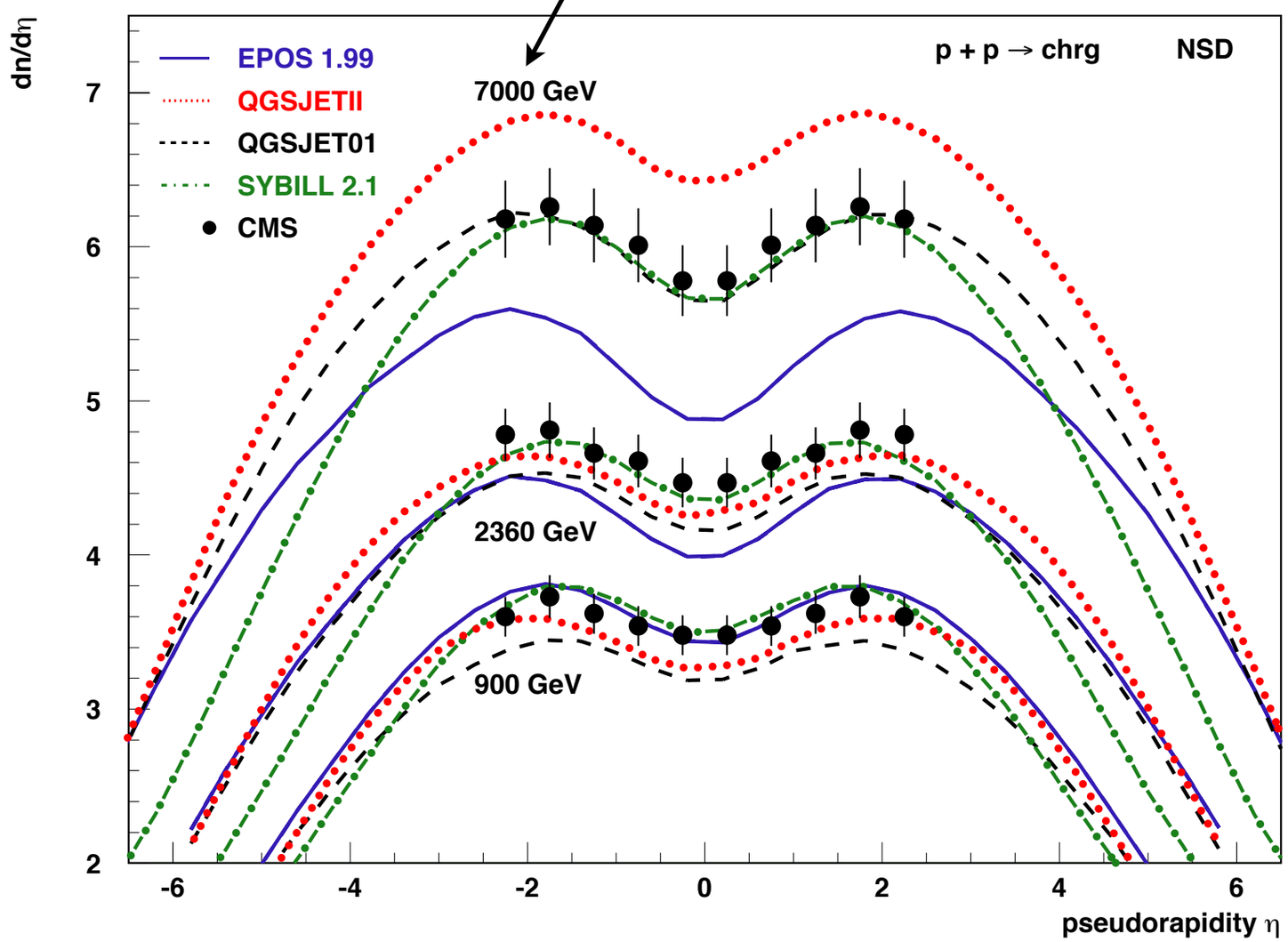
LHC data probe the region beyond the knee



~20% of energy needs to be transferred to invisible channel

LHC: distribution of charged secondary particles

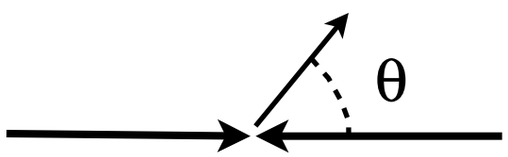
Protons: $E_{lab} = 3 \times 10^{16}$ eV



Detailed LHC comparison

D'Enterria et al. (astro-ph/1101.5596)

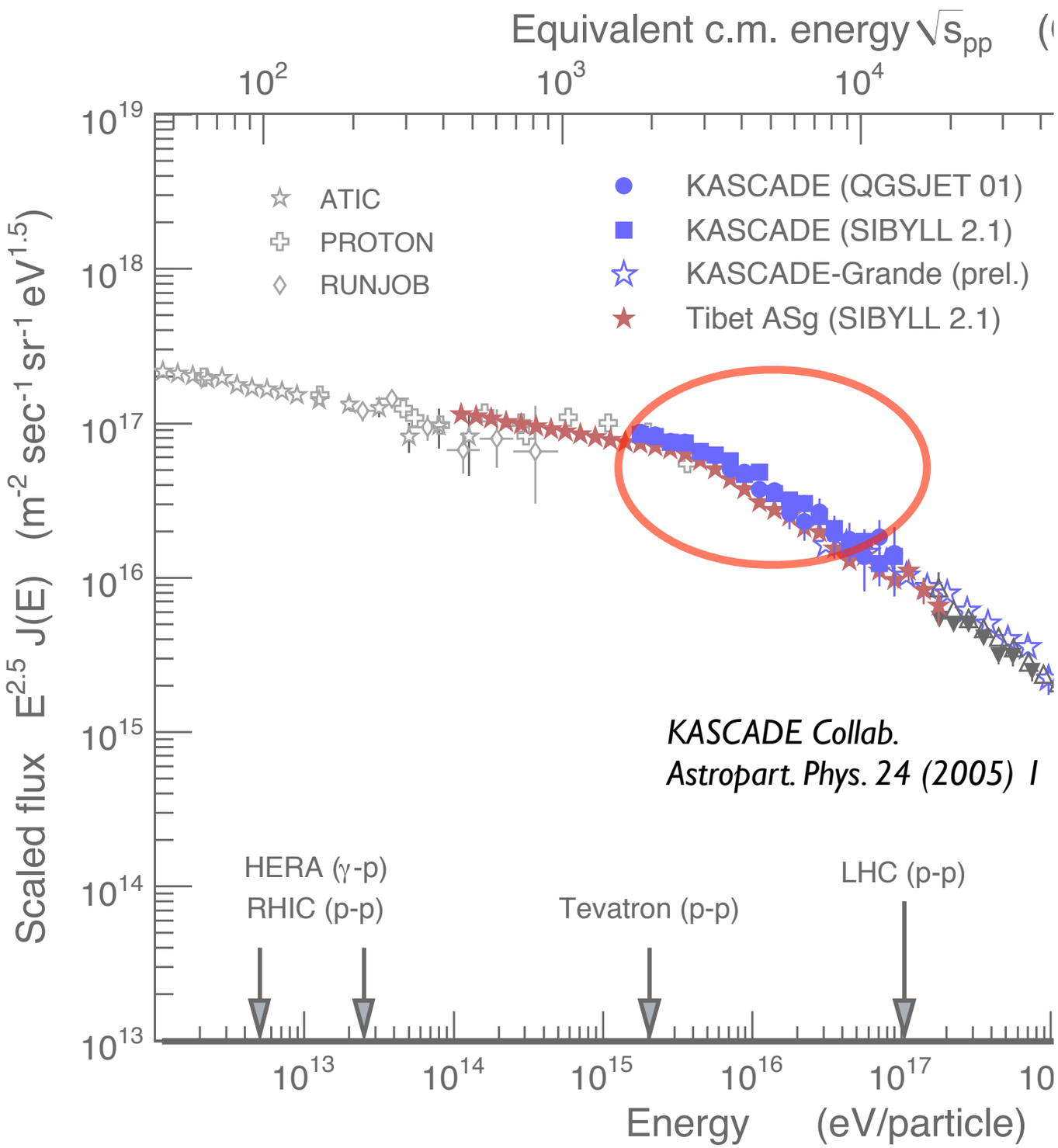
Significant improvement of models expected

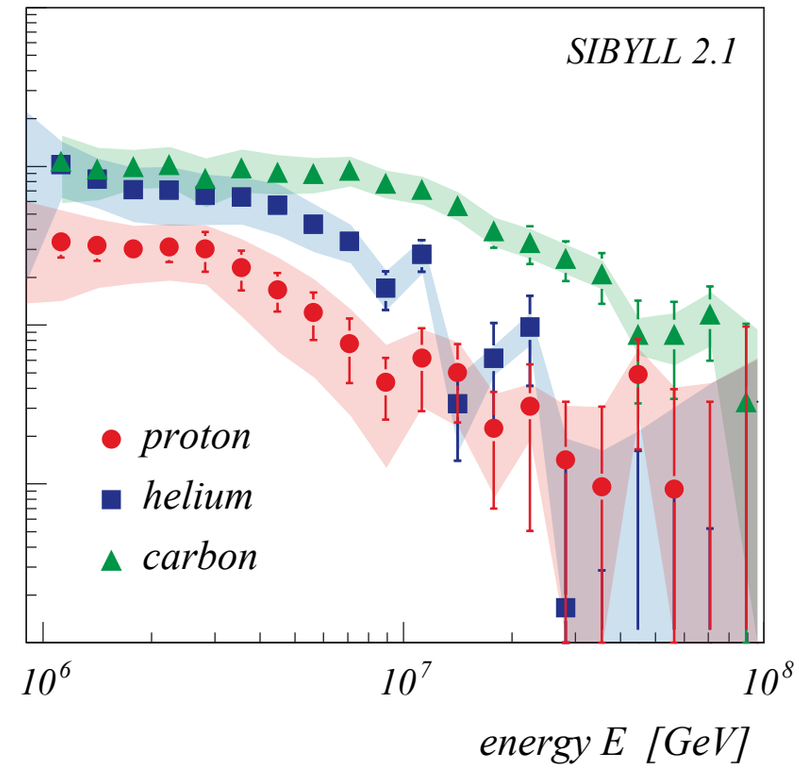


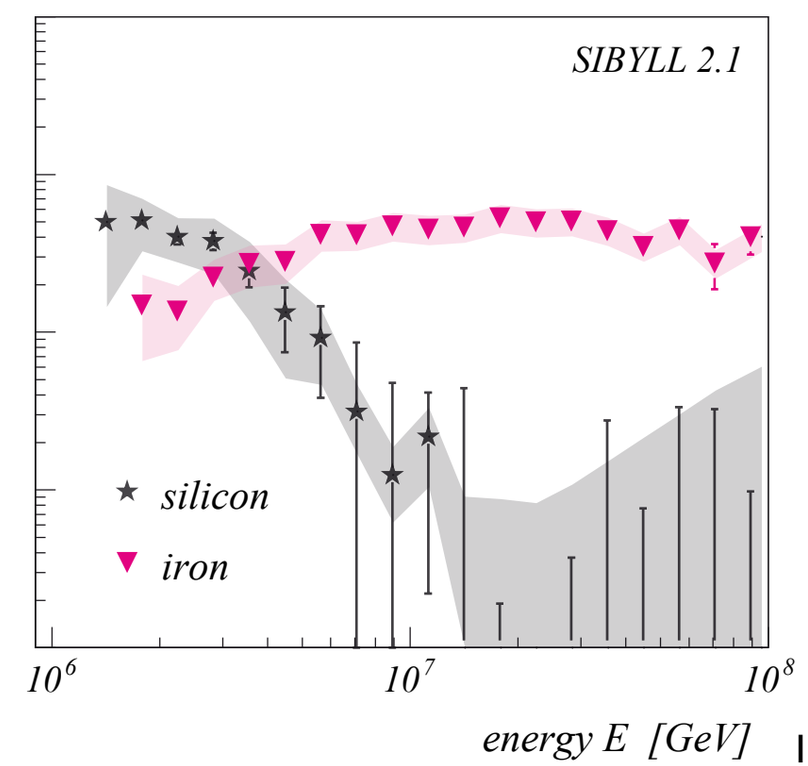
$$\eta = -\ln \tan \frac{\theta}{2}$$

LHC: Exotic scenatios for knee very unlikely, model predictions bracket LHC data on secondary particle multiplicity

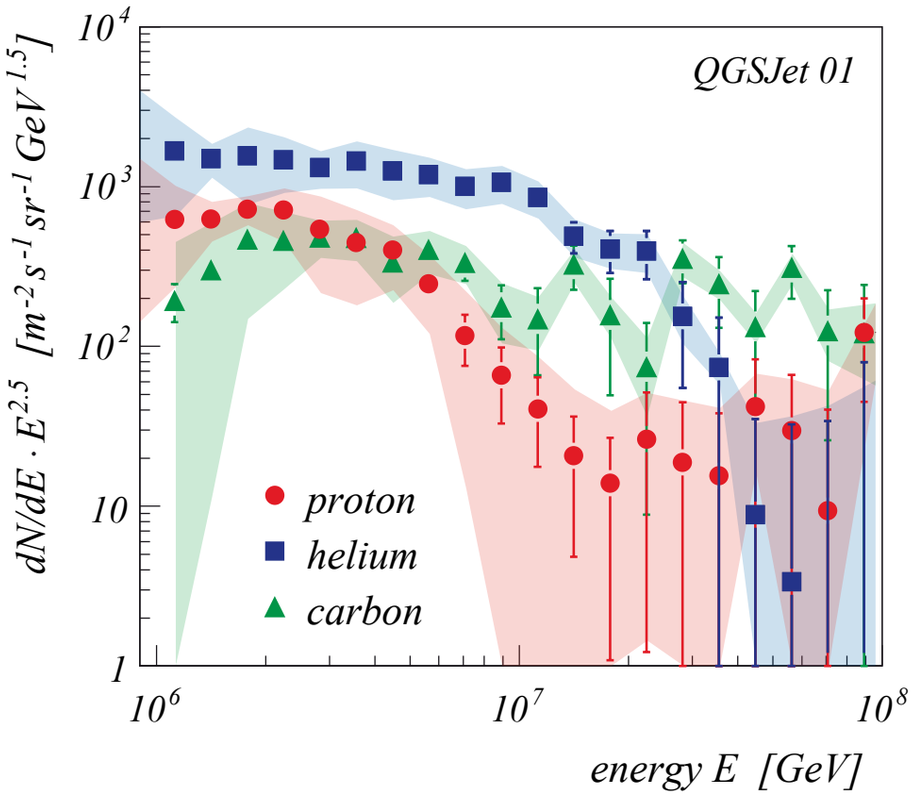
Composition in knee region (i)

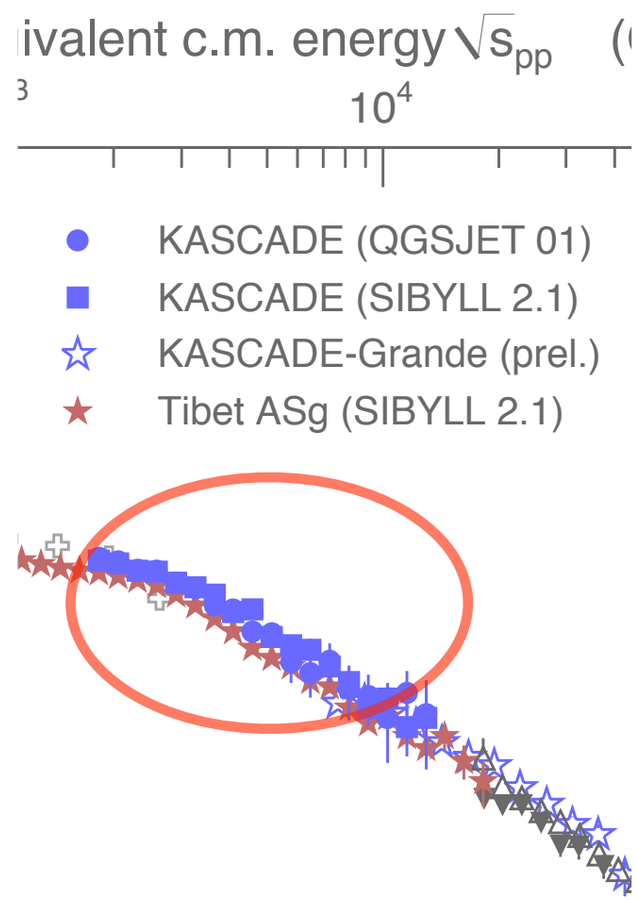


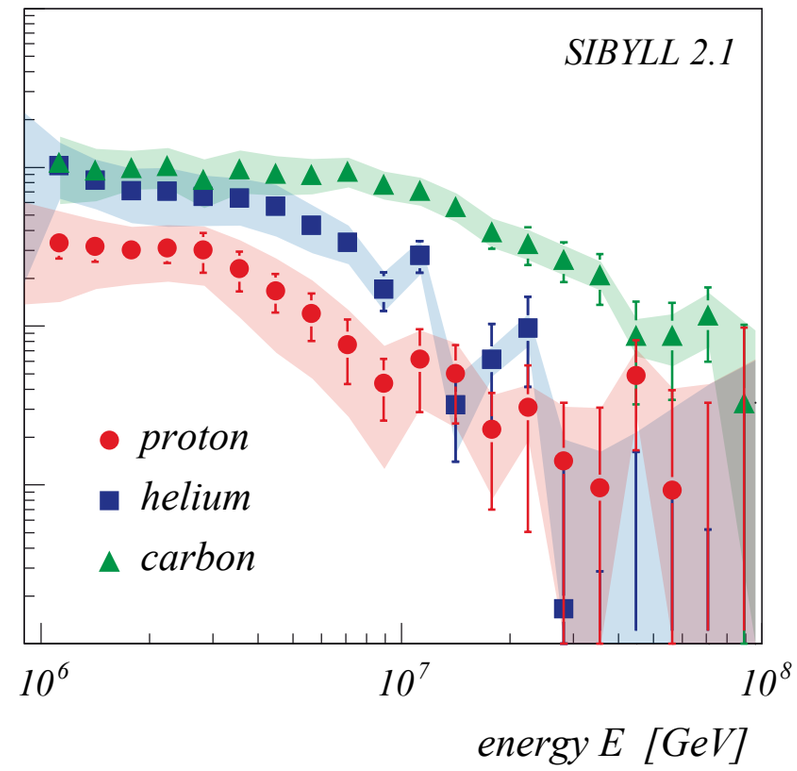


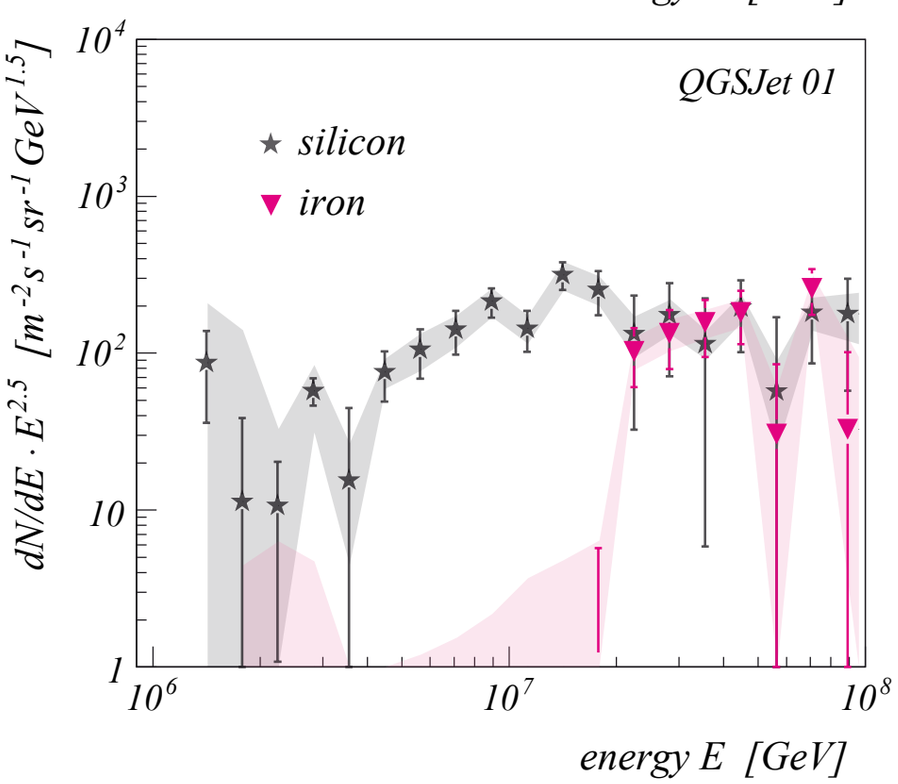


Composition in knee region (ii)

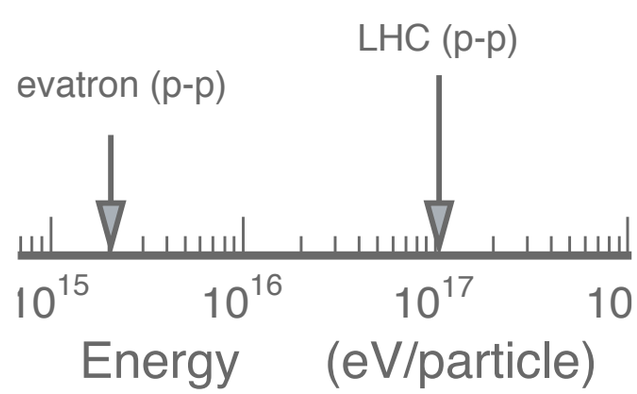


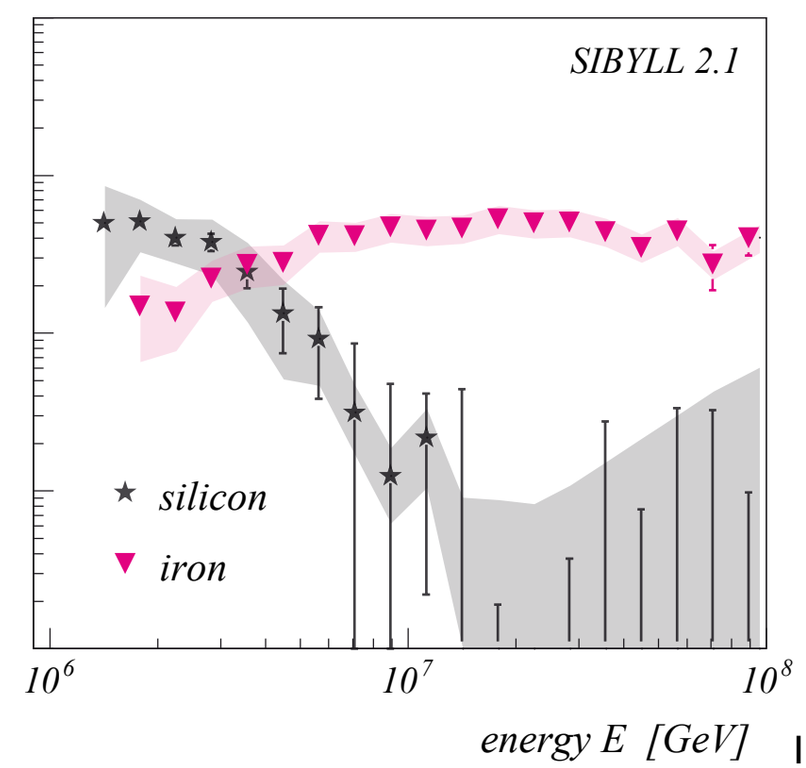




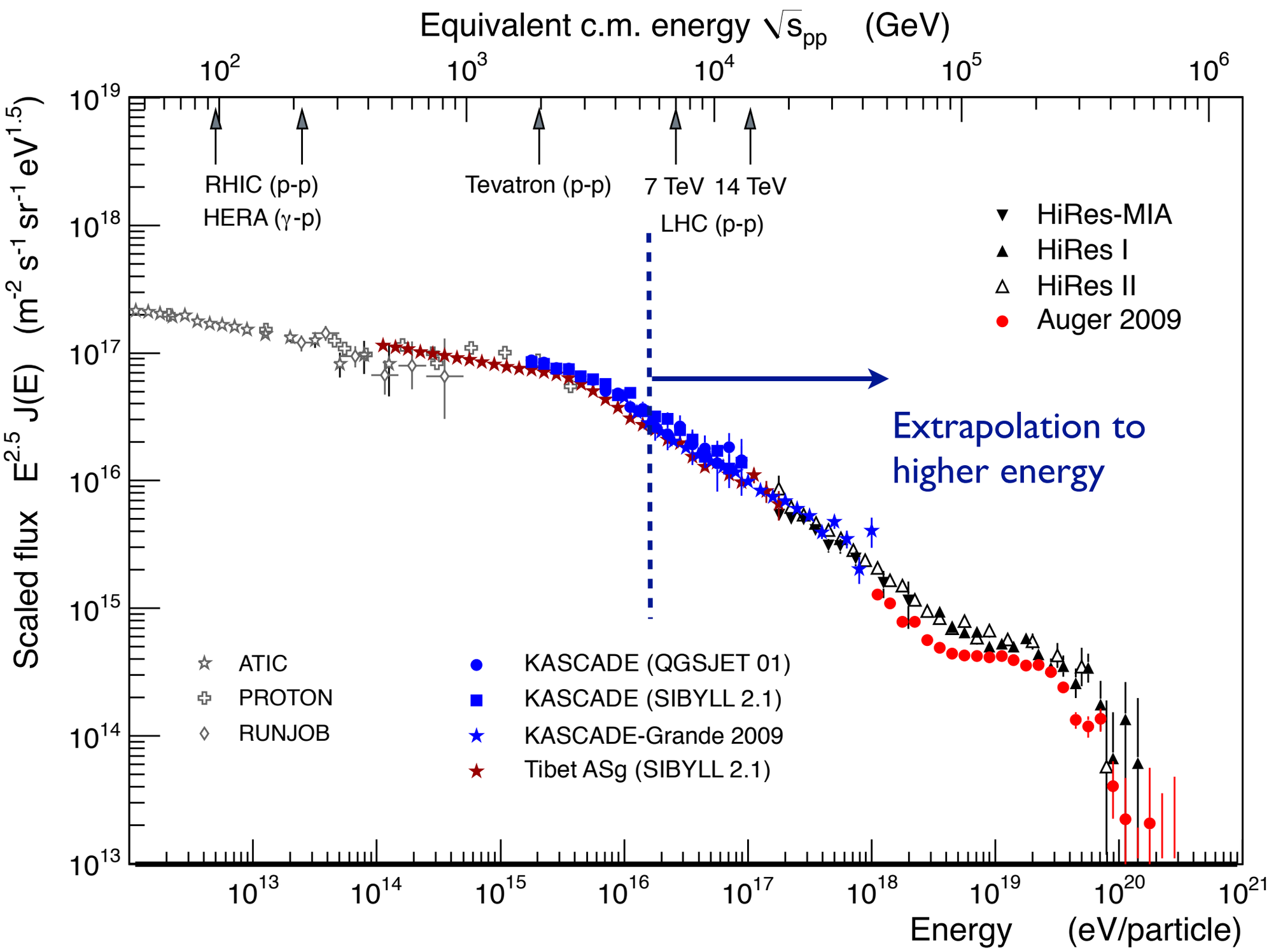


KASCADE Collab.
Astropart. Phys. 24 (2005) 1

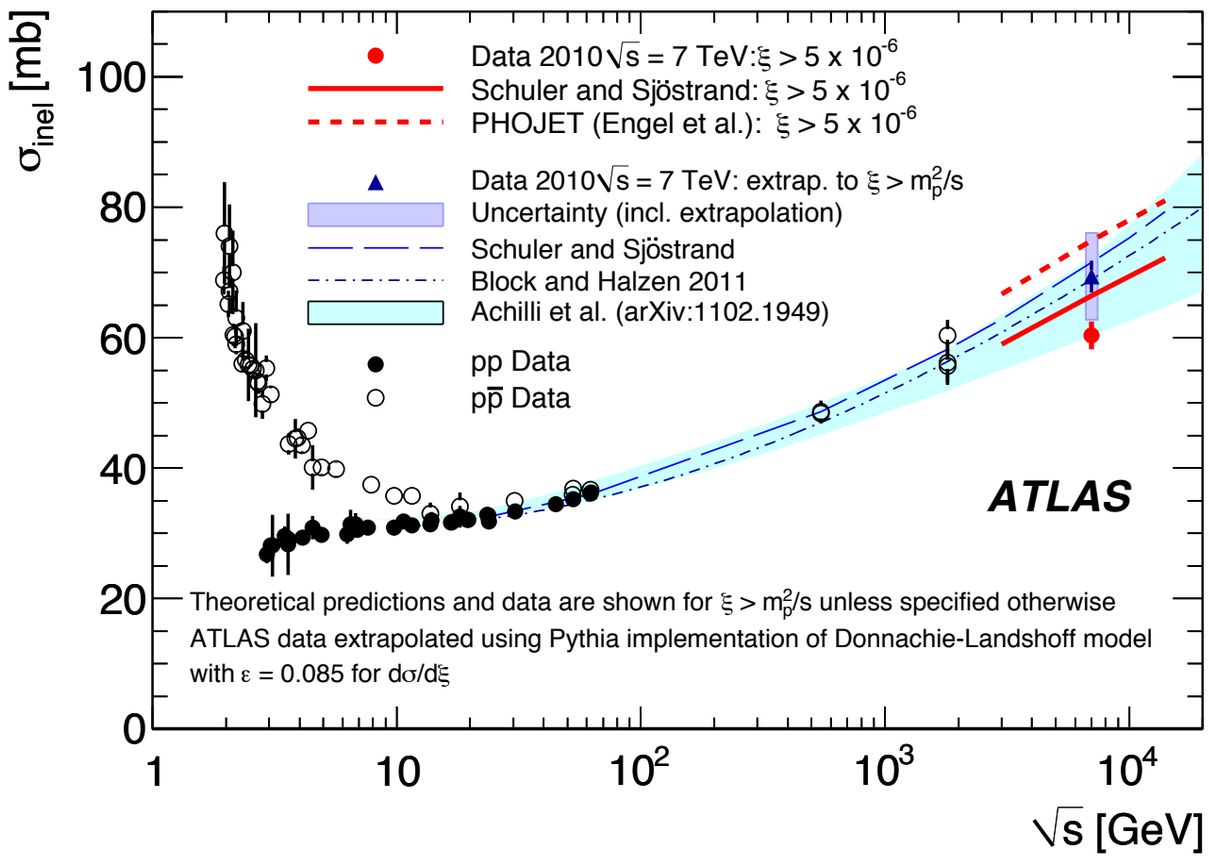




First LHC data and the extrapolation of interaction models



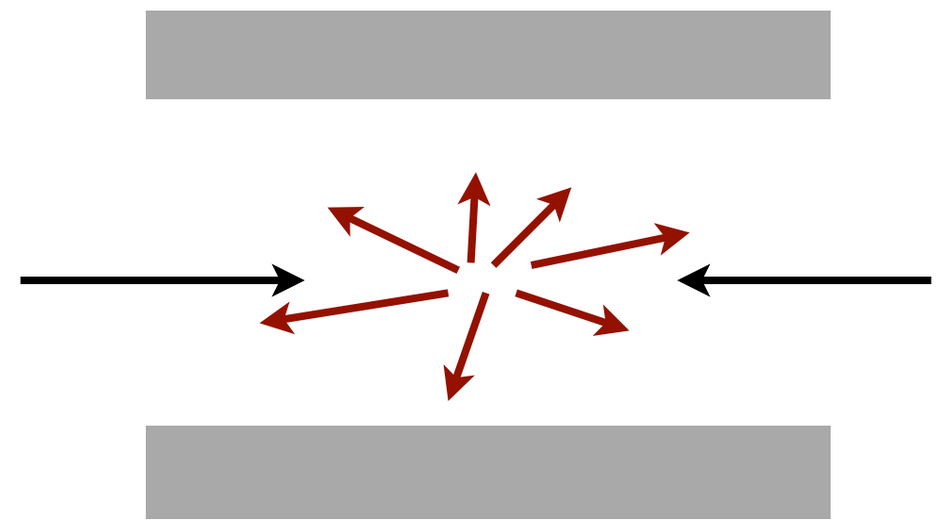
Measurement of pp cross section at LHC



(ATLAS, 1104.0326)

$$\frac{\Delta p}{p} = \xi > 5 \times 10^{-6}$$

$$\sigma_{\mathrm{ATLAS}} = 60.3 \pm 0.05 \pm 0.5 \pm 2.1\mathrm{mb}$$



N_{trk} Pt (MeV)	3 200	4 200	3 250	4 250	σ_{tot}
CMS	59.7	58.6	58.9	57.3	
Q-II-03	65.2	64.6	63.0	62.0	77.5
SYBILL-2.1	71.5	71.0	70.2	69.3	79.6

(CMS, DIS Workshop, Brookhaven)

$$\sigma_{\mathrm{CMS}} = 59.7 \pm 0.1 \pm 1.1 \pm 2.4\mathrm{mb}$$

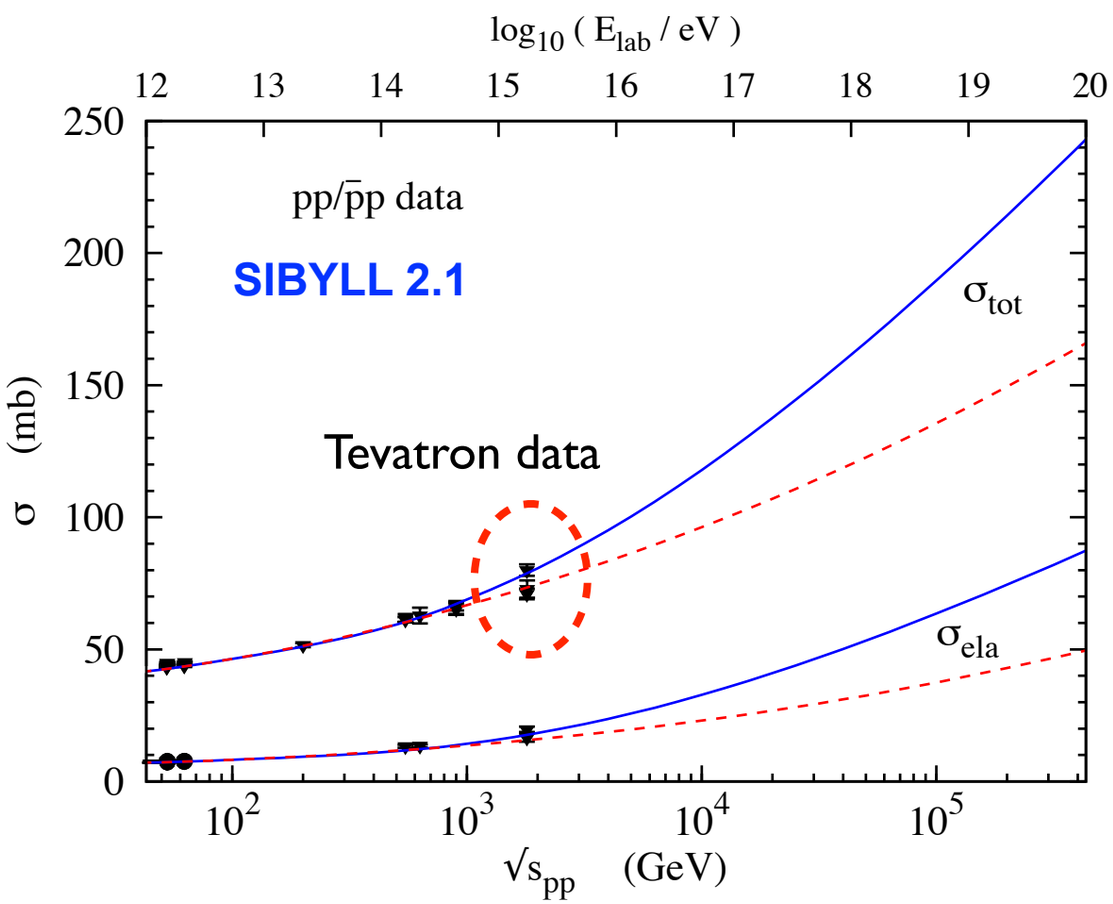
Direct comparison with model predictions (no extrapolation), extrapolation strongly model-dependent

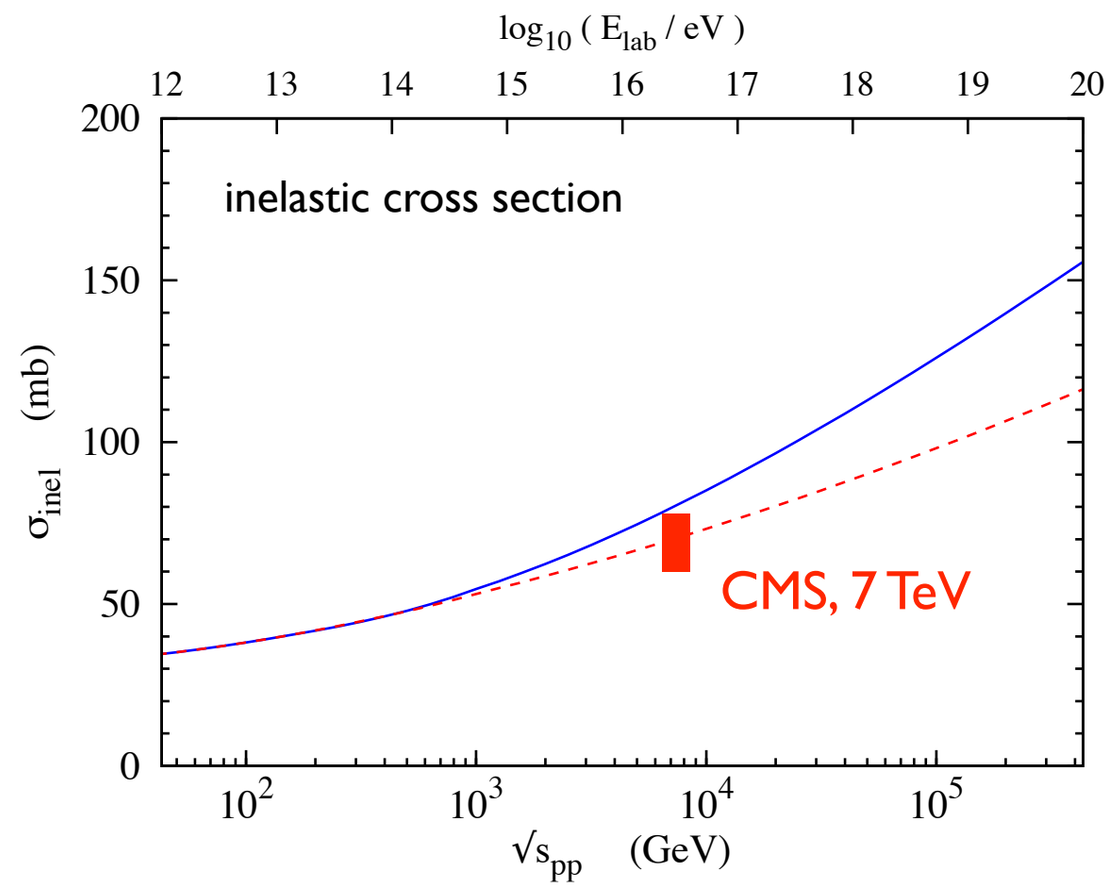
Importance of LHC cross section measurement (i)

LHC: ATLAS $\sigma_{\text{ine}} = (69.4 \pm 2.4 \pm 6.9)$ mb

CMS $\sigma_{\text{ine}} = (70.8 \pm 3.9)$ mb

(extrapolated cross sections compatible)

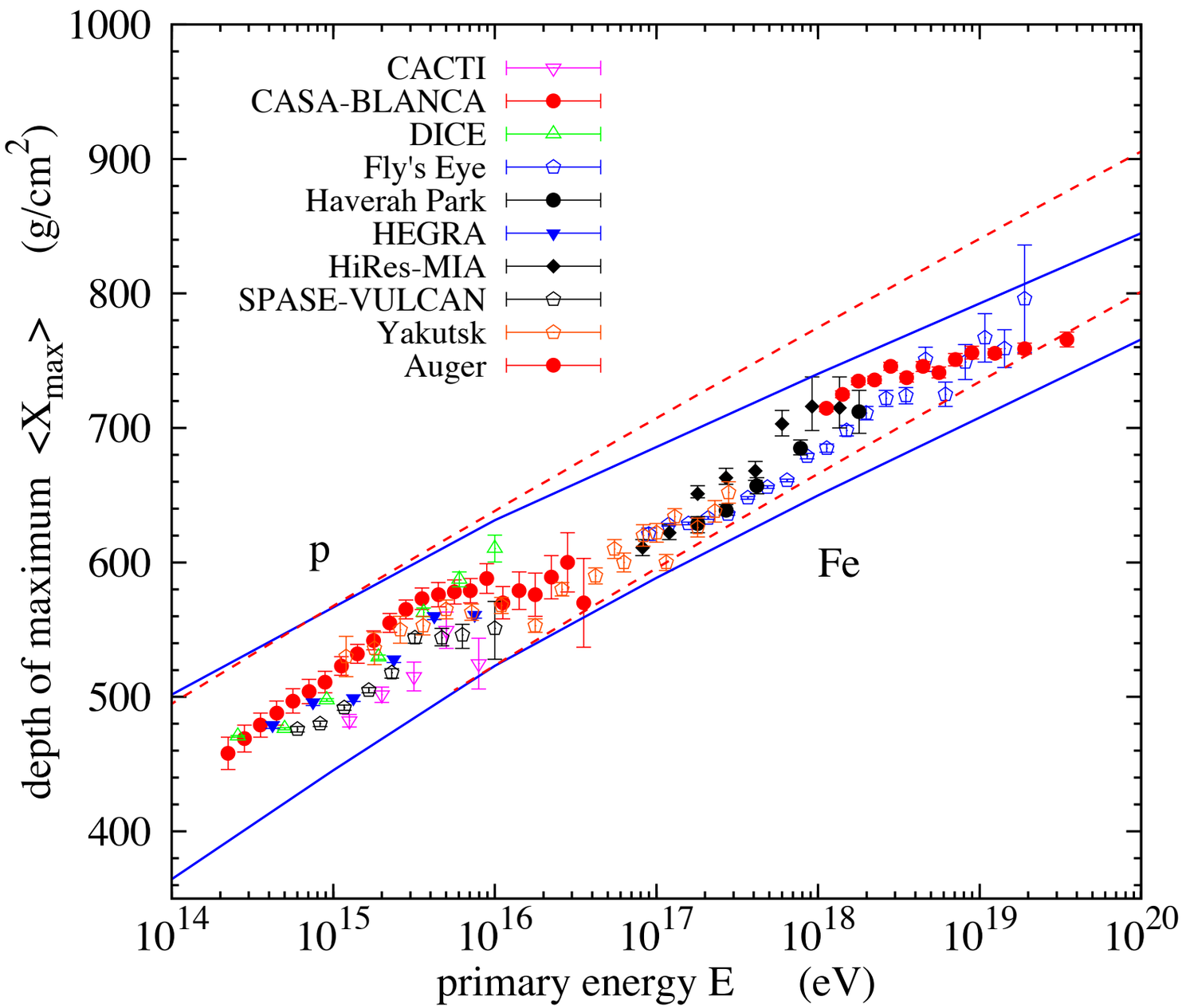




Cross section discrepany resolved in favour of lower measurements

TOTEM: total cross section measurement with much higher precision

Importance of LHC cross section measurement (ii)



Extrapolation with low cross section

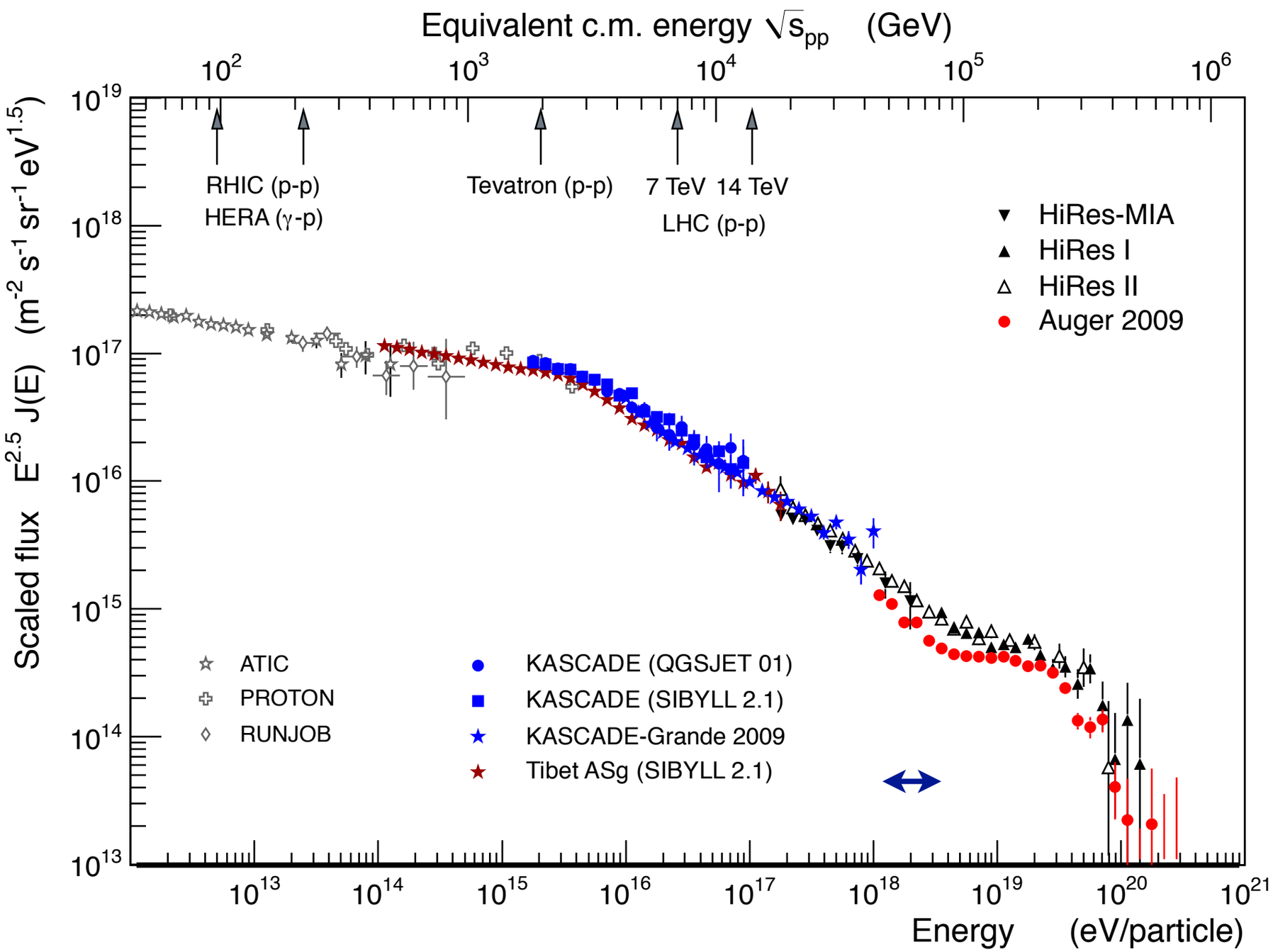
SIBYLL 2.1 (high cross section)

SIBYLL: interpretation would change to heavier elements

QGSJET: same trend, but smaller overall effect

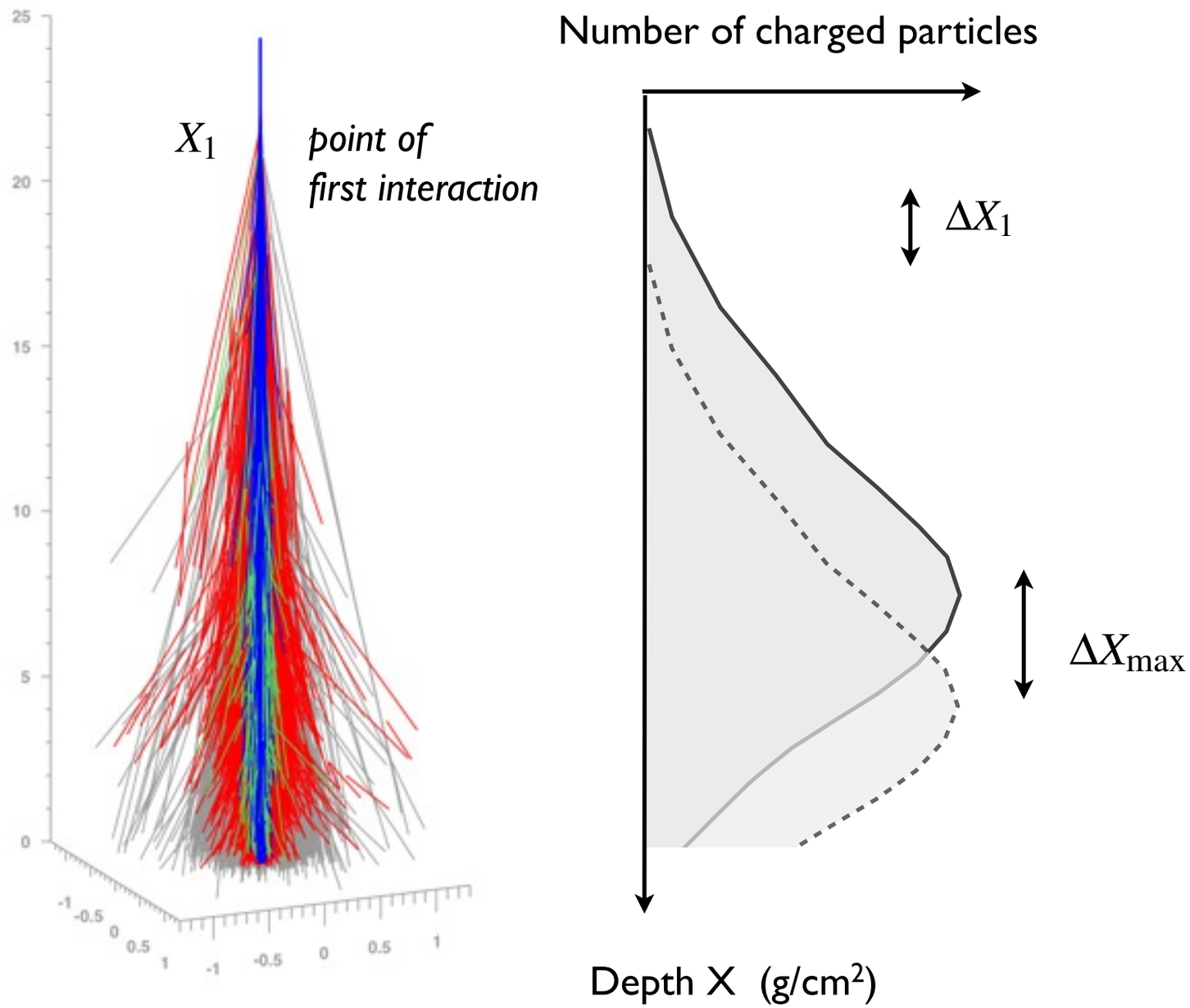
Study only for changed cross section, global tuning to LHC data will be needed

Extending the cross section measurements to higher energy



Maximum statistics for fluorescence observations and indications of mixed/light composition

Cross section measurement with air showers



$$\frac{\mathrm{d}P}{\mathrm{d}X_1} = \frac{1}{\lambda_{\mathrm{int}}} e^{-X_1/\lambda_{\mathrm{int}}}$$

$$\mathrm{RMS}(X_1) = \lambda_{\mathrm{int}}$$

$$\sigma_{\mathrm{p-air}} = \frac{\langle m_{\mathrm{air}} \rangle}{\lambda_{\mathrm{int}}}$$

Difficulties

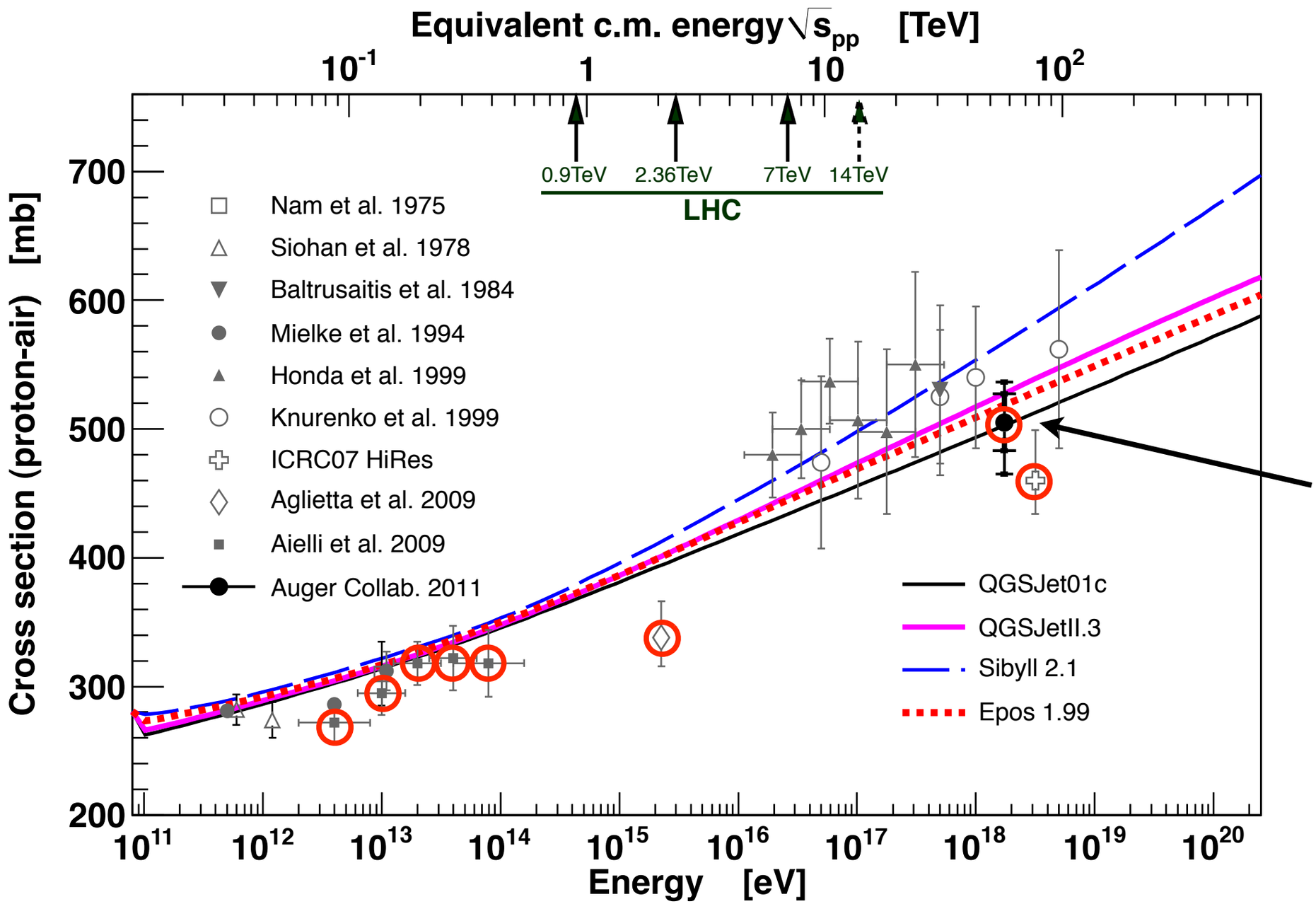
- mass composition
- fluctuations in shower development (model needed for correction)

  $\mathrm{RMS}(X_1) \sim \mathrm{RMS}(X_{\max} - X_1)$

- experimental resolution ~20 g/cm^2

R. Ulrich et al. NJP 11 (2009) 065018

Proton-air cross section for particle production

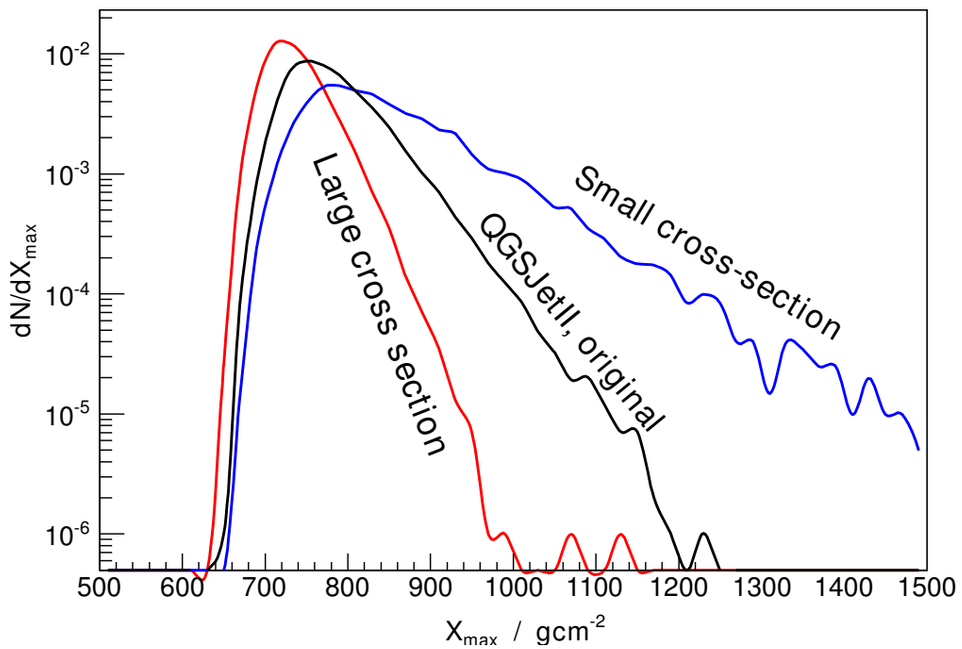


Measurement from Auger Observatory (several models used)

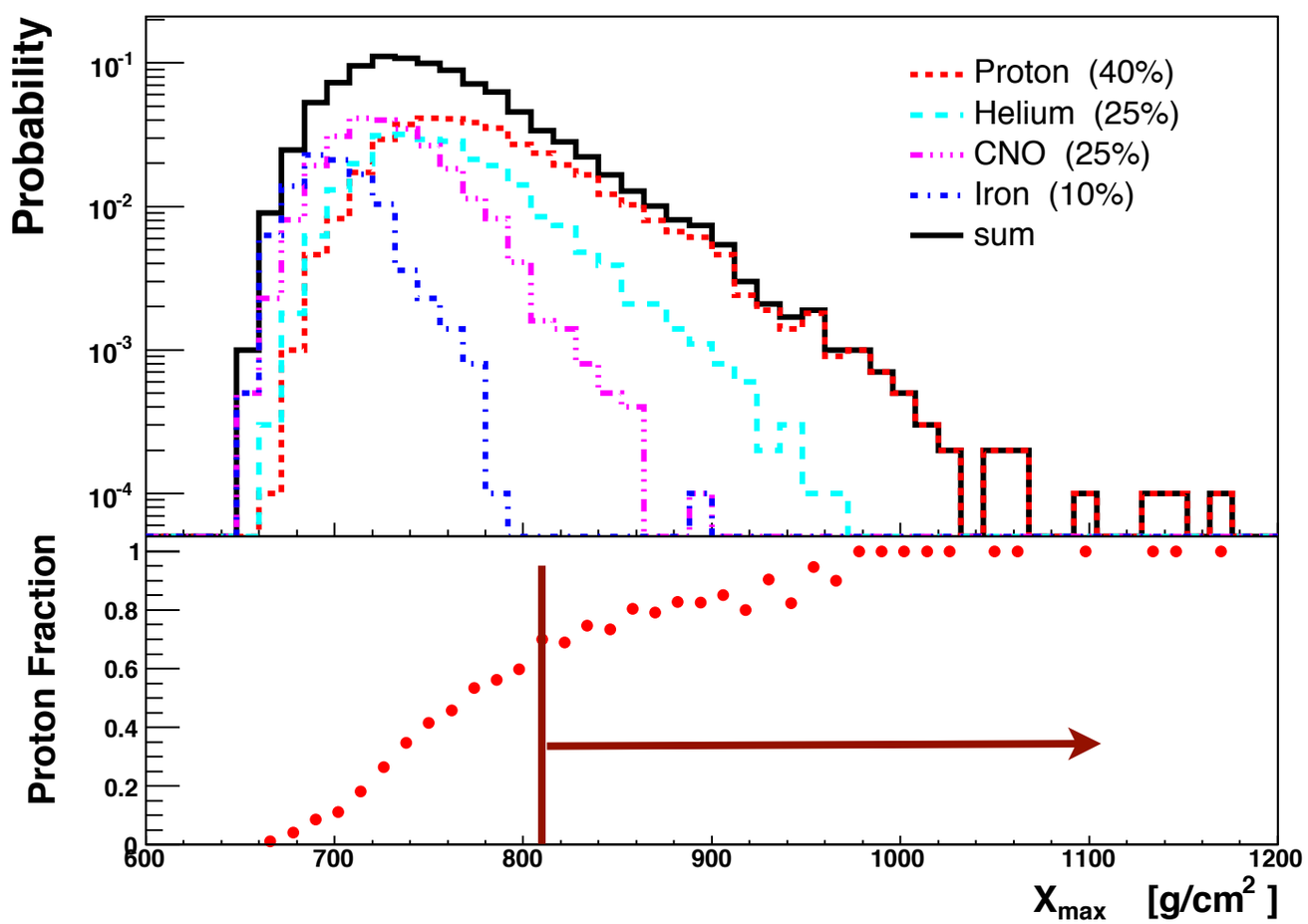
Measurements based on QGSJET interaction model

(Compilation: Pierre Auger Collab. 1107.4804)

Cross section measurement: composition



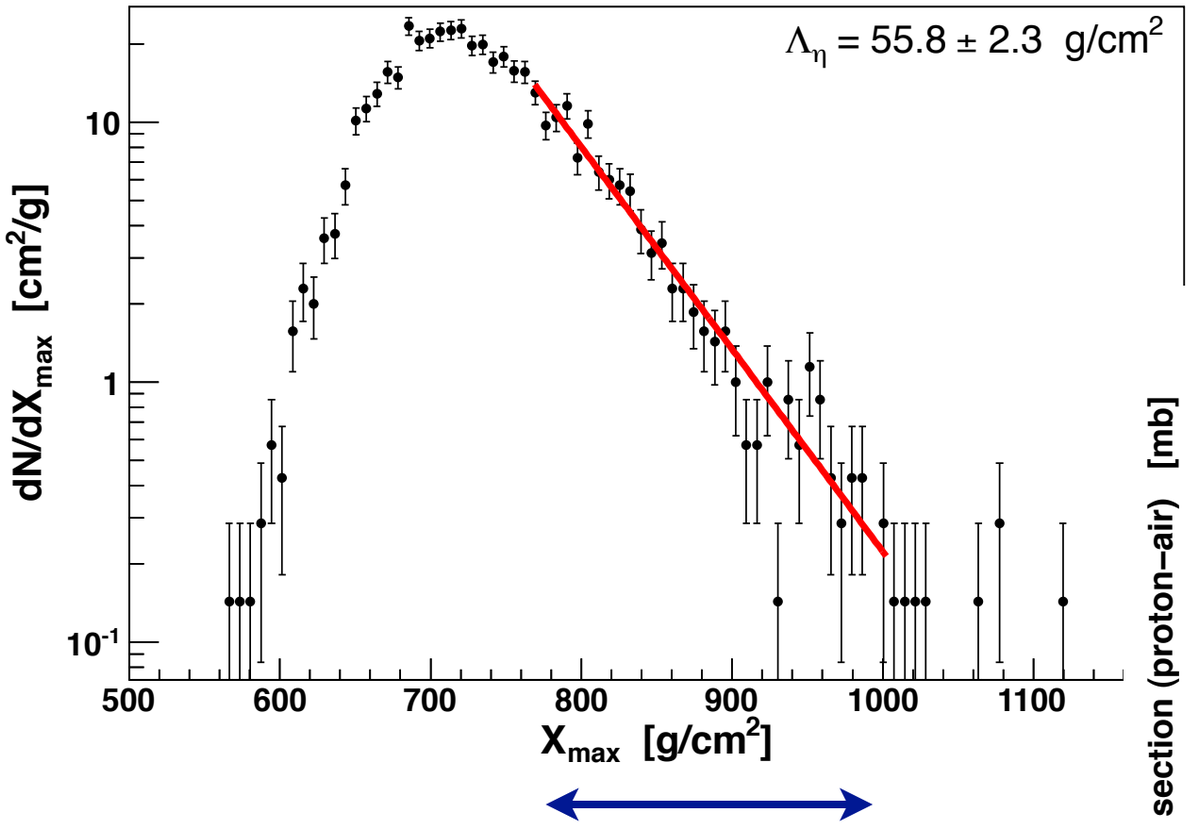
Simulation for proton showers with different cross sections:
very good sensitivity of tail of distribution



Example of distribution of X_{max} for mixed composition

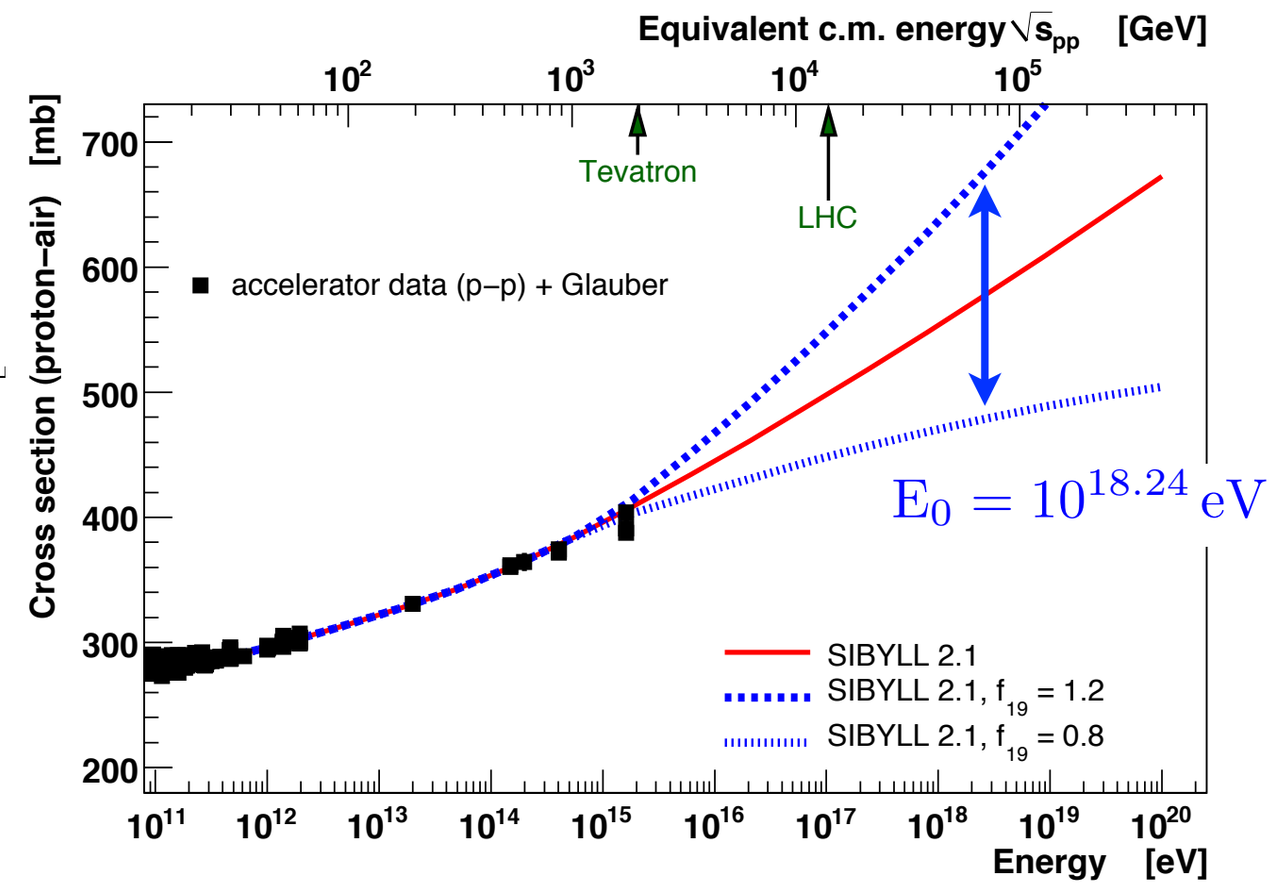
Only deep showers are used in analysis to enhance proton fraction in data sample

Cross section measurement: self-consistency



(Pierre Auger Collab. 1107.4804)

Depth range of analysis

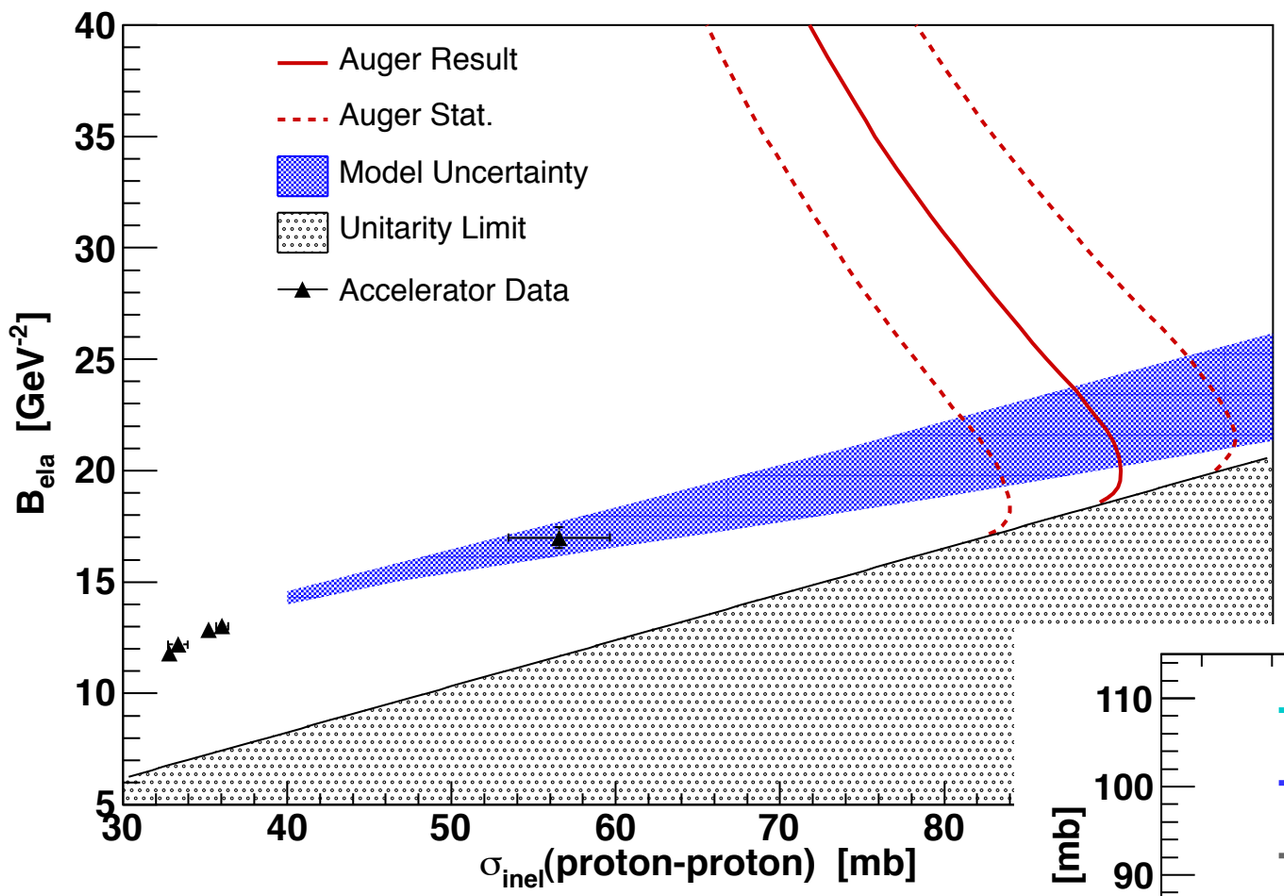


Cross section accepted if simulated slope fits measured slope of Xmax distribution

$$\sigma_{p\text{-air}} = \left(505 \pm 22_{\text{stat}} \left(^{+26}_{-34}\right)_{\text{sys}}\right) \text{ mb}$$

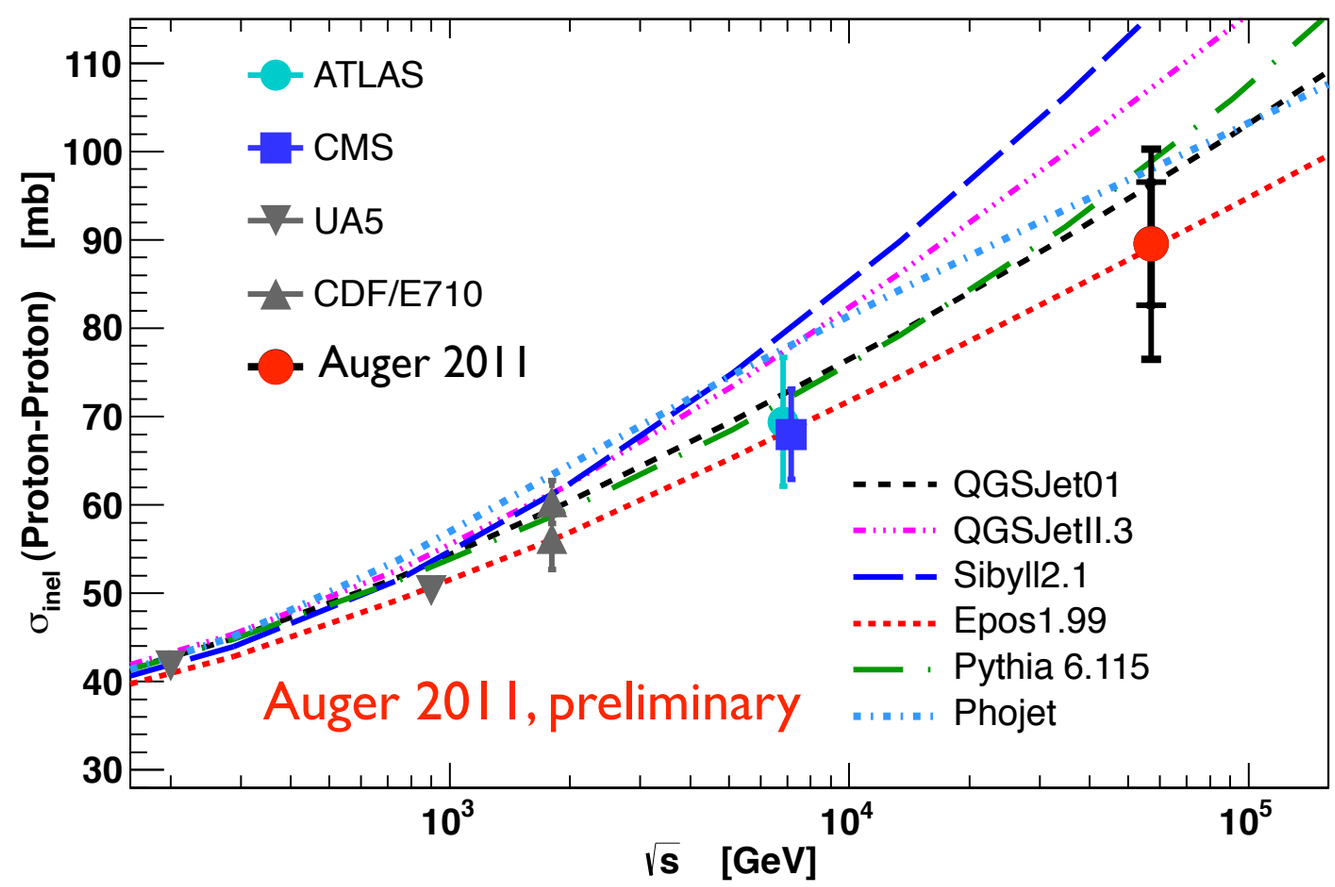
Simulation of data sample with different cross sections, interpolation to measured low-energy values

Conversion to proton-proton cross section



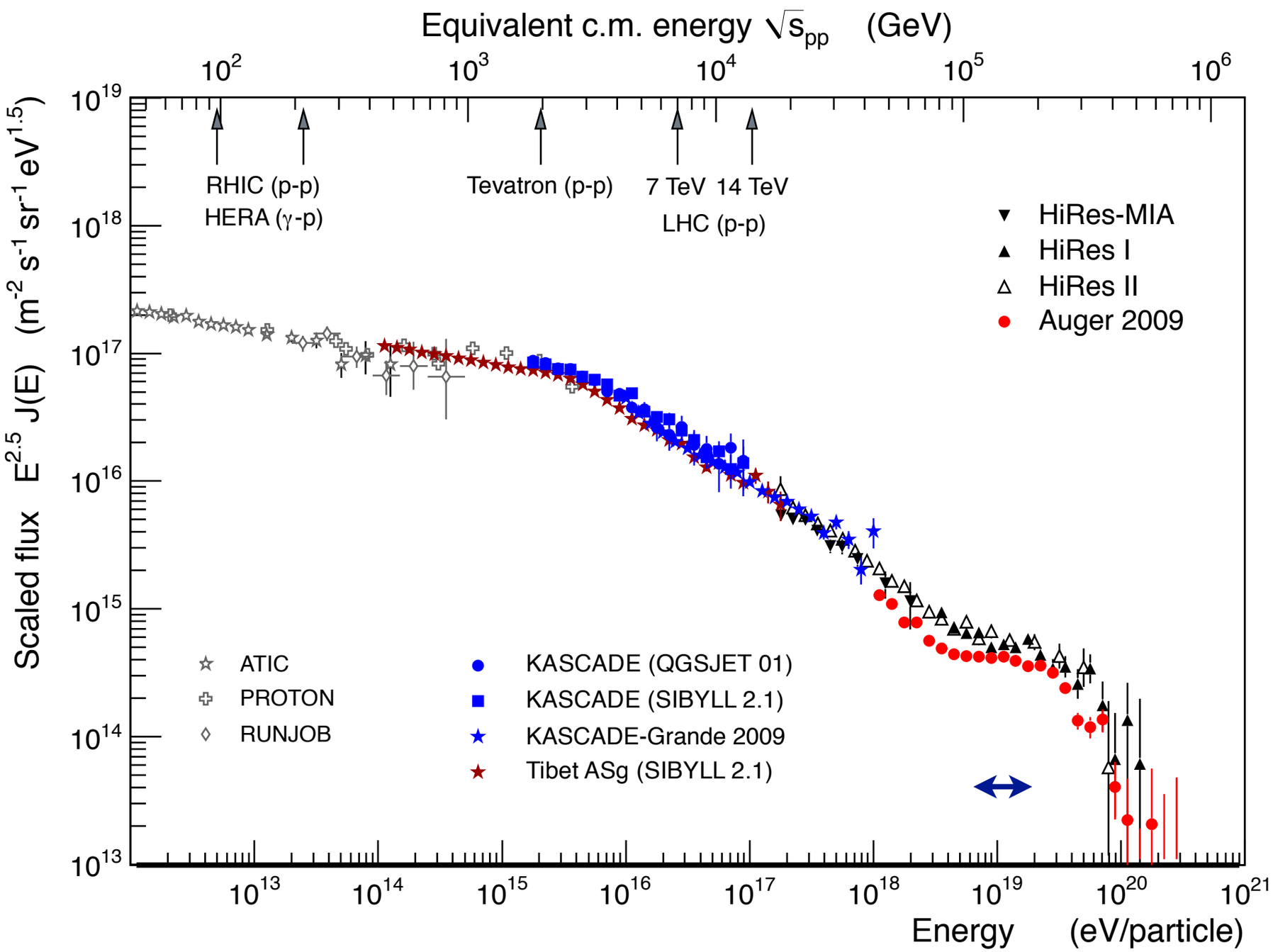
Standard Glauber calculation with harmonic oscillator potential for light nuclei, no inelastic states included

(Pierre Auger Collab. arXiv:1107.4804 & ICRC 2011 Beijing)



Result on p-air cross section to a good approximation model-independent, p-p cross section model-dependent

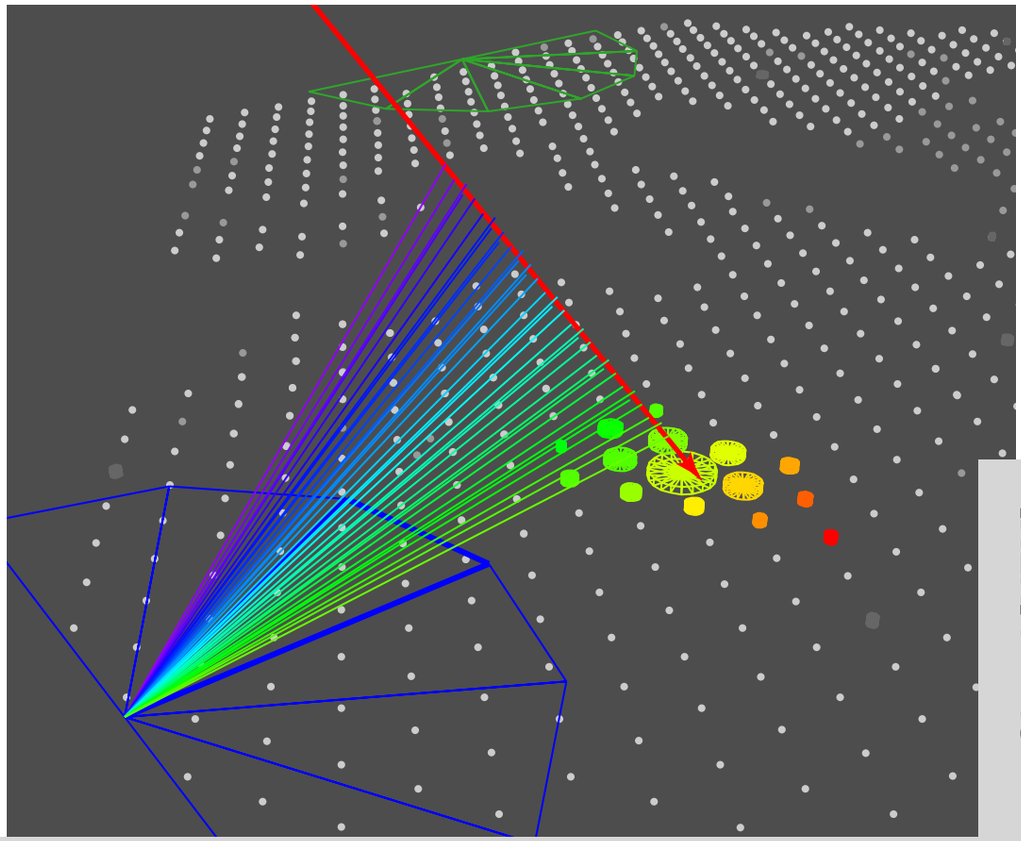
Muon production in air showers at ~10^{19} eV



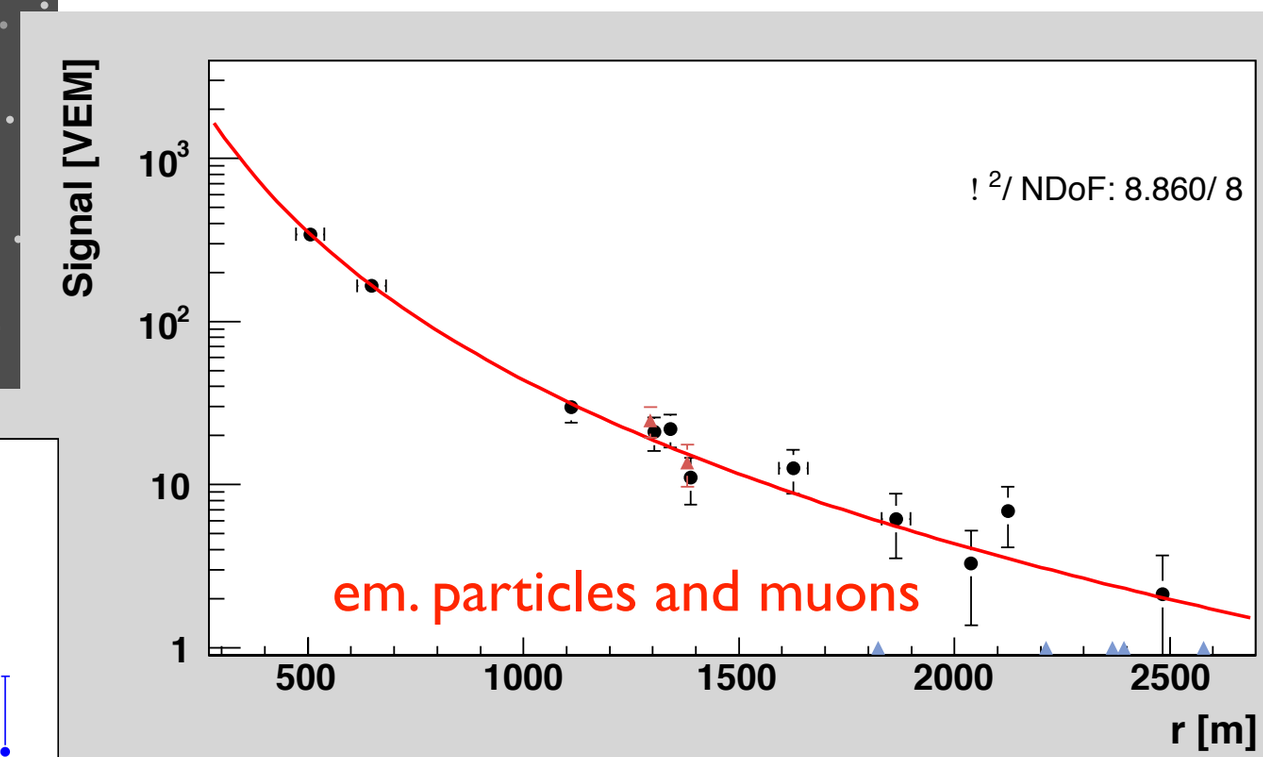
Full efficiency and high statistics range of Pierre Auger Observatory

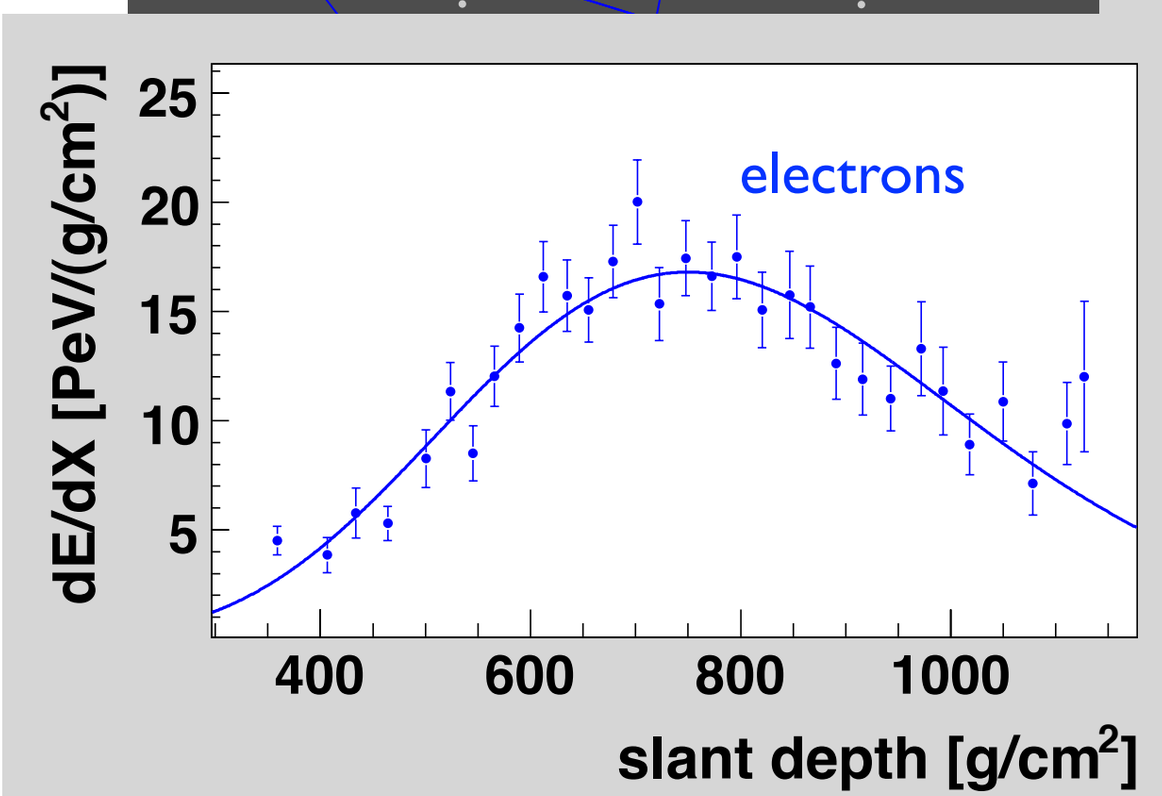
Do shower simulations reproduce the observed shower characteristics ?

Hybrid detection



Lateral distribution





Shower longitudinal profile

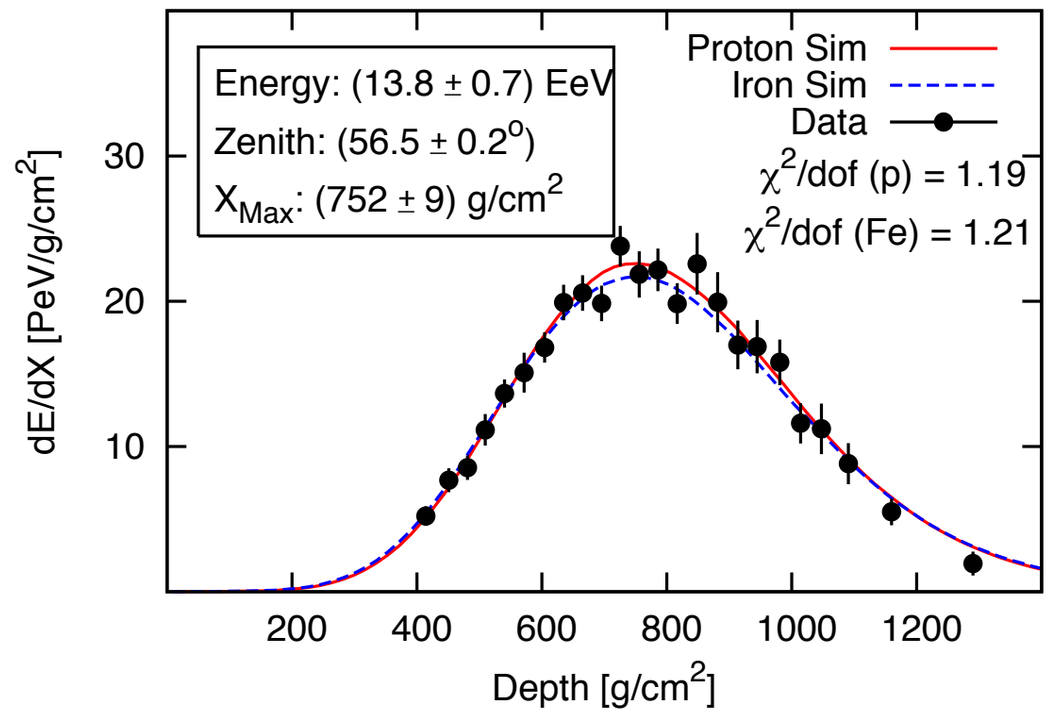
Auger: water-Cherenkov detectors

Telescope Array: Scintillation detectors

Auger Observatory: Study of individual hybrid events

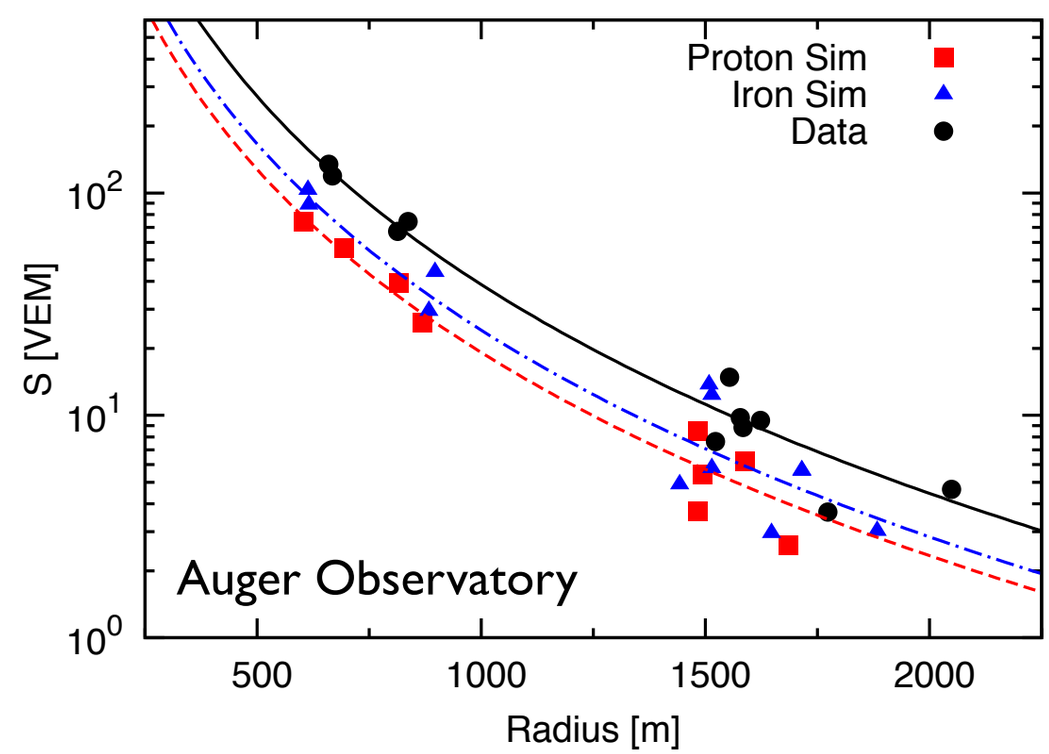
Procedure

- Selection of high-quality showers of ~10^{19} eV
- Simulation of 400 showers for each event with reconstructed geometry
- Proton or iron primaries
- surface detector simulation for best longitudinal profiles



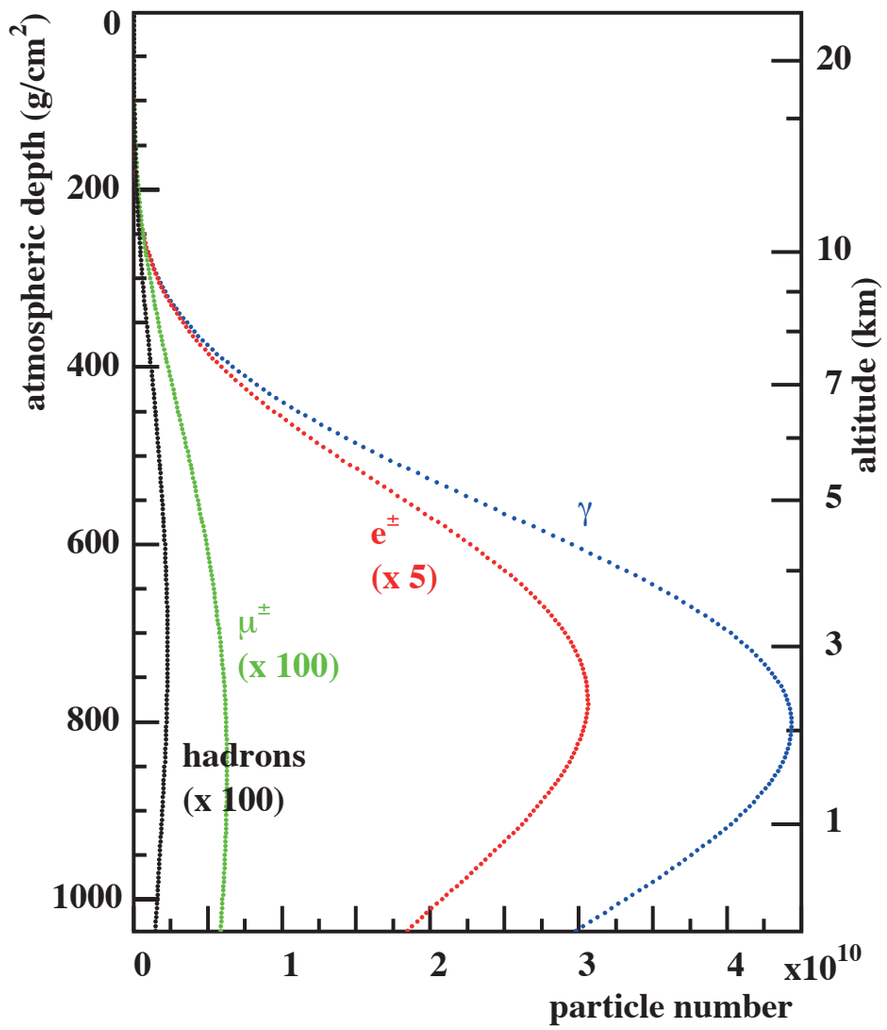
Results

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

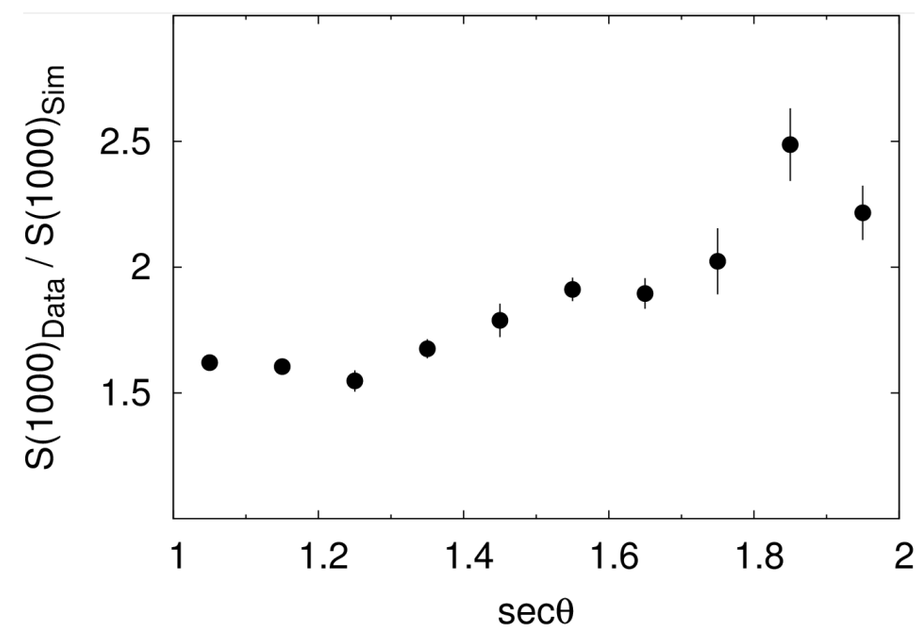


(Pierre Auger Collab. 1107.4804)

Angular dependence of discrepancy: Muon component?



Muon contribution to detected signal increases with increasing zenith angle (em. component absorbed in atmosphere)



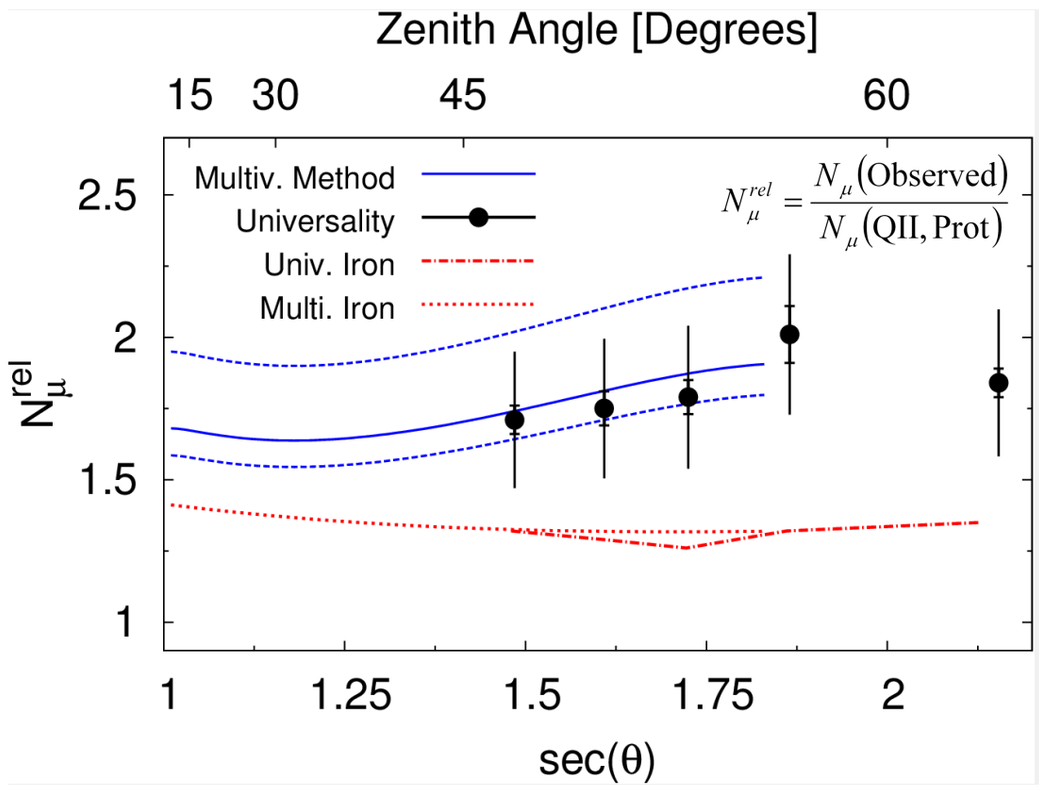
(Auger Collab.1107.4809)

Very inclined showers Θ>60°: $S_{\mathrm{data}}/S_{\mathrm{MC}} = 2.13 \pm 0.04(\mathrm{stat}) \pm 0.11(\mathrm{sys})$

All results given relative to proton-induced showers simulated with QGSJET II.03

Do we have a muon problem?

Muon discrepancy confirmed by independent muon counting methods



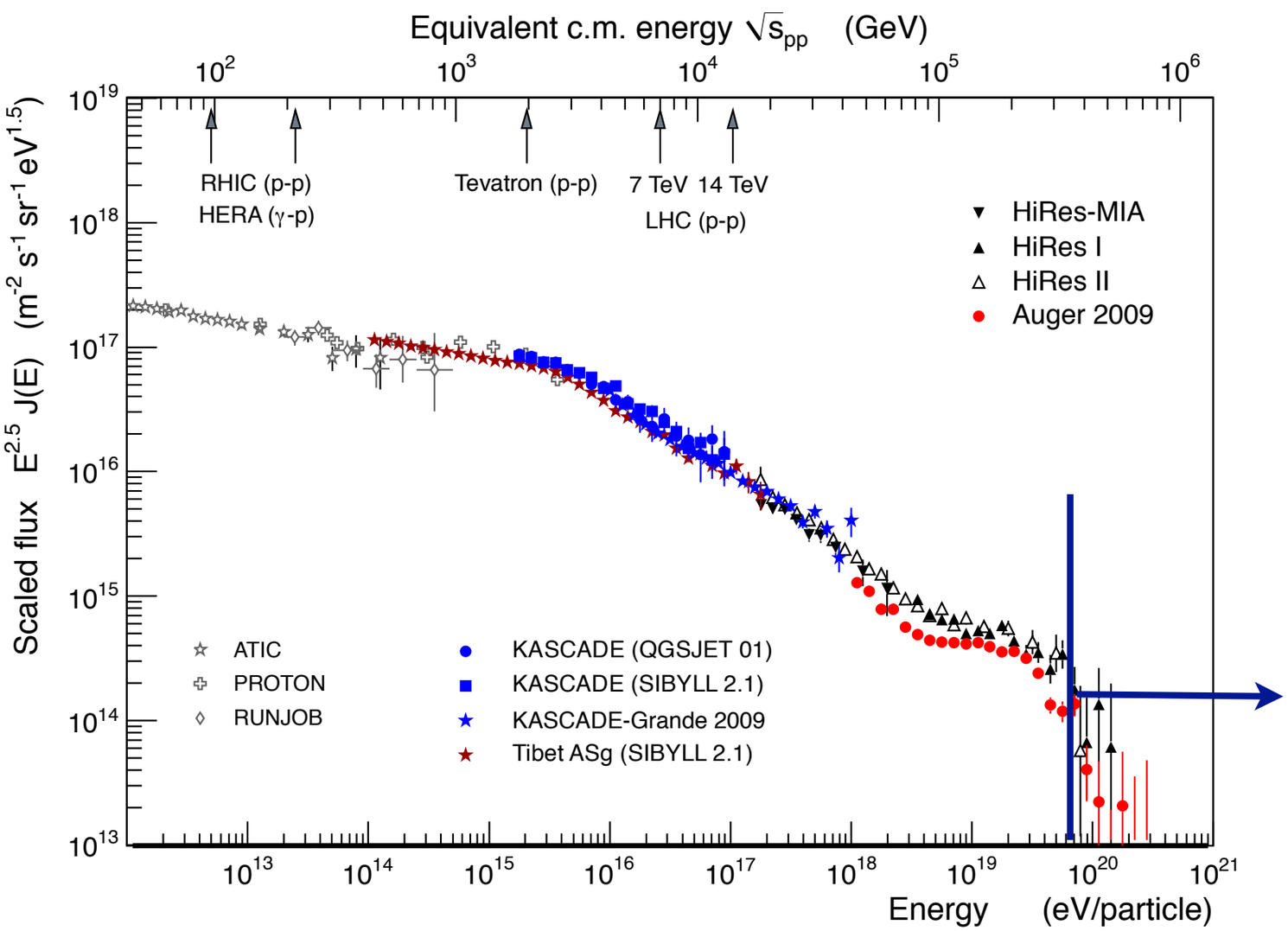
Similar, but smaller discrepancy found by Telescope Array (renormalization of ~27% needed)

- muon signal less important in scintillators
- showers of zenith angle < 45°
- energy scale of TA 20% higher than Auger Observatory

Possible solution: enhanced baryon-antibaryon pair production in nuclear interactions ?

(Pierog & Werner, PRL 101 (2008) 17110)

The upper end of the energy spectrum

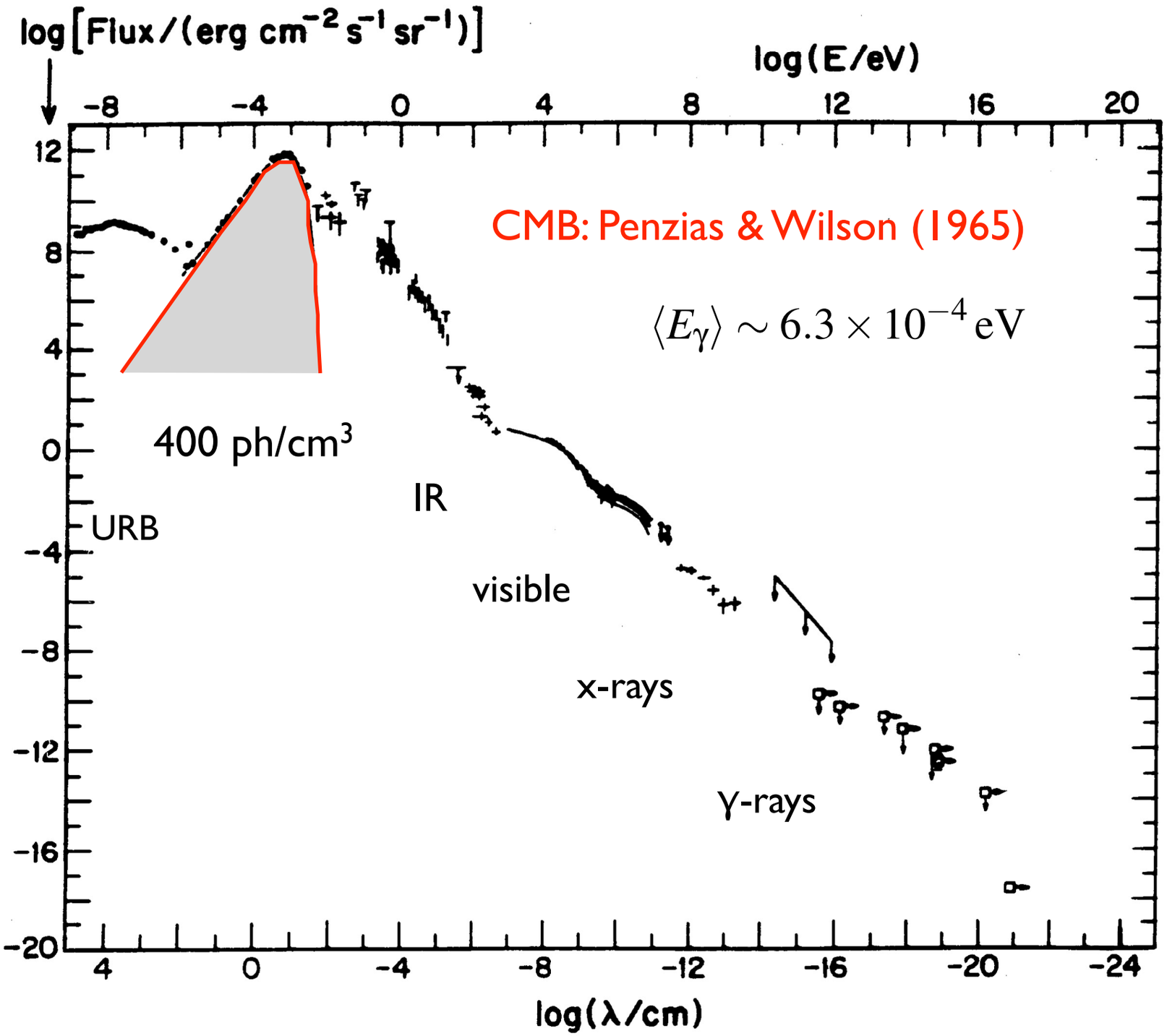


Very limited statistics,
strong flux suppression

Composition from correlations and deflection in galactic magnetic field ?

Composition information from flux suppression ?

Highest energies and GZK energy loss effect



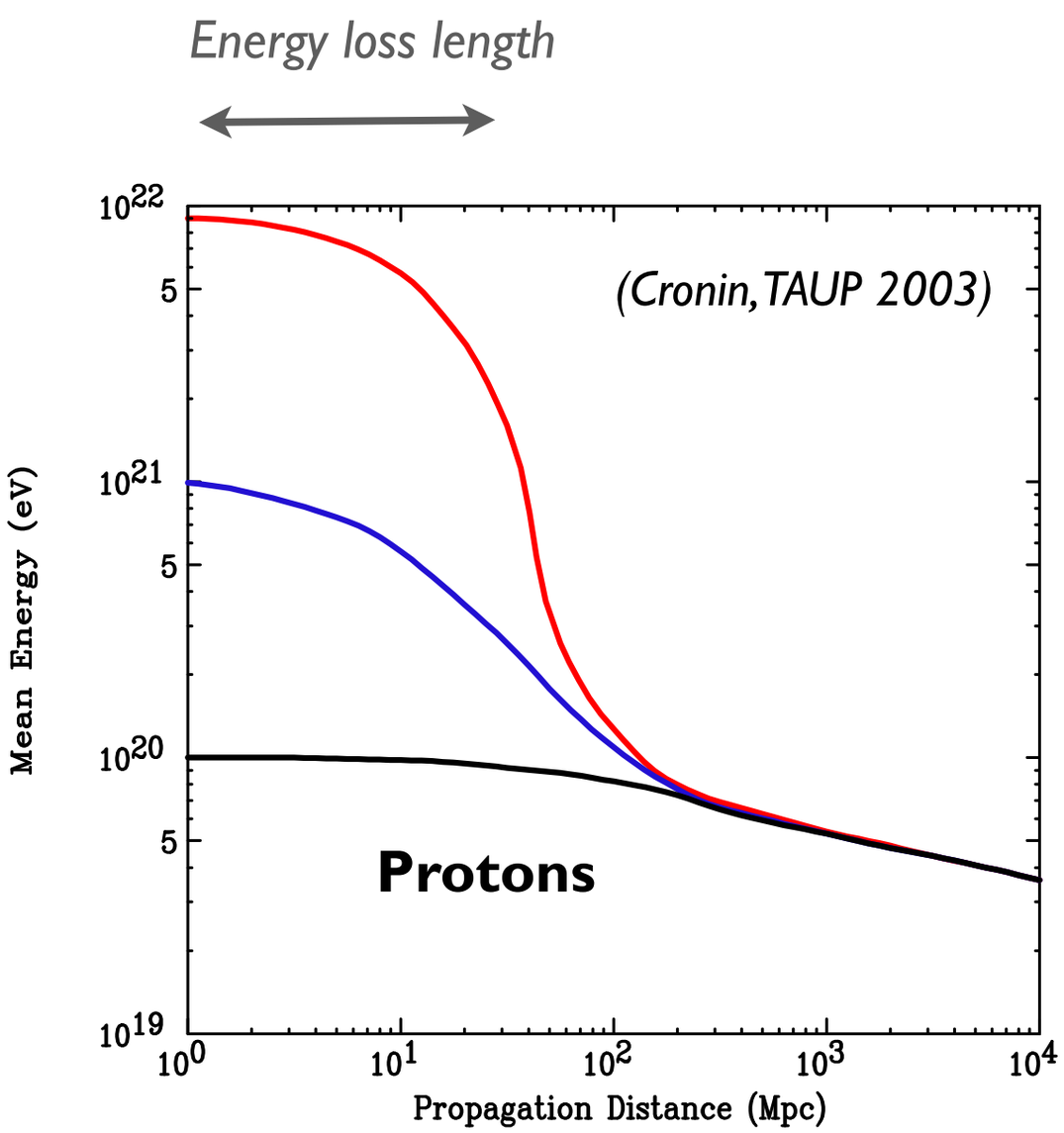
Greisen, Zatsepin & Kuzmin (1966)

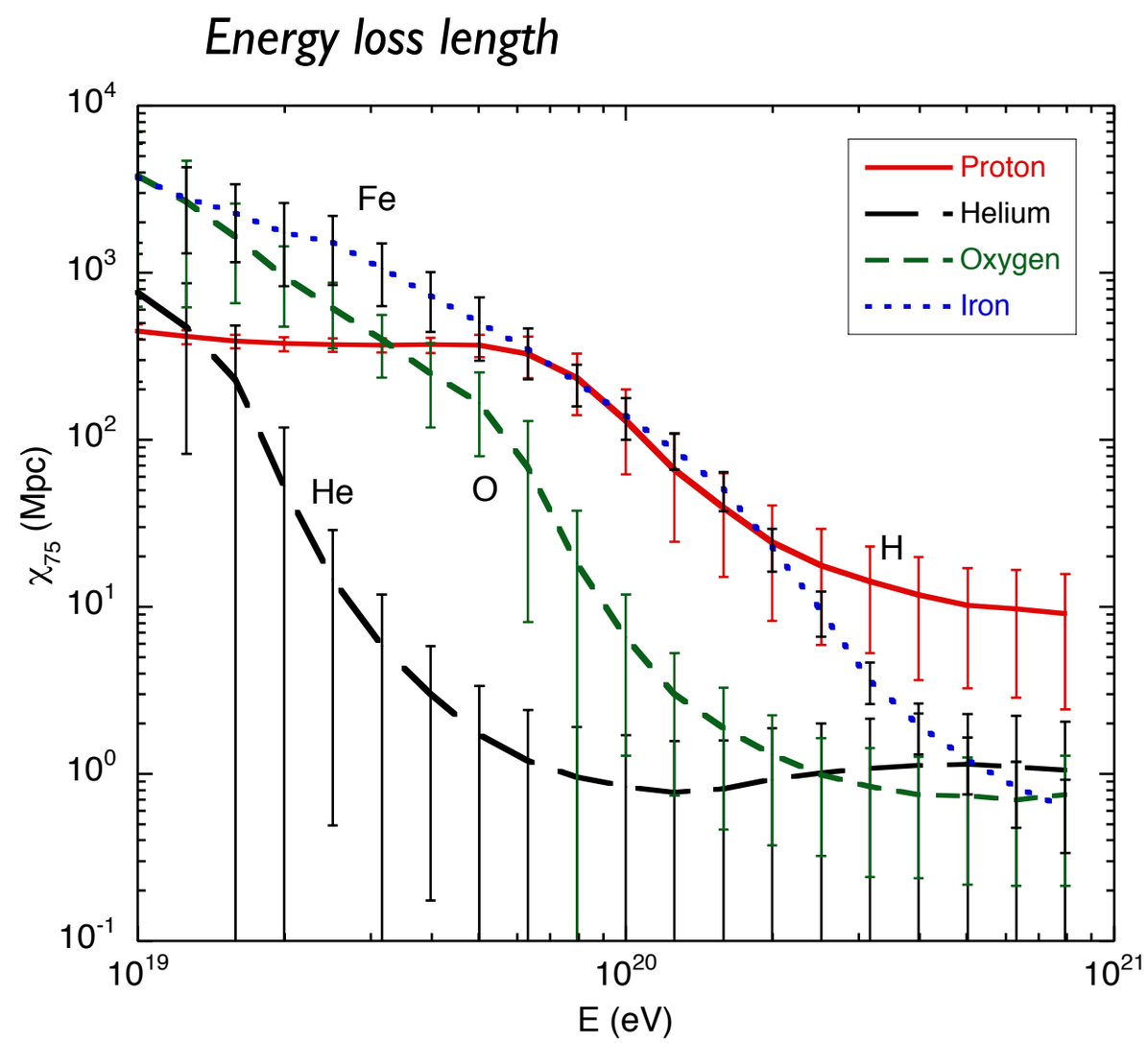
GZK effect

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

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

GZK effect as composition selection mechanism

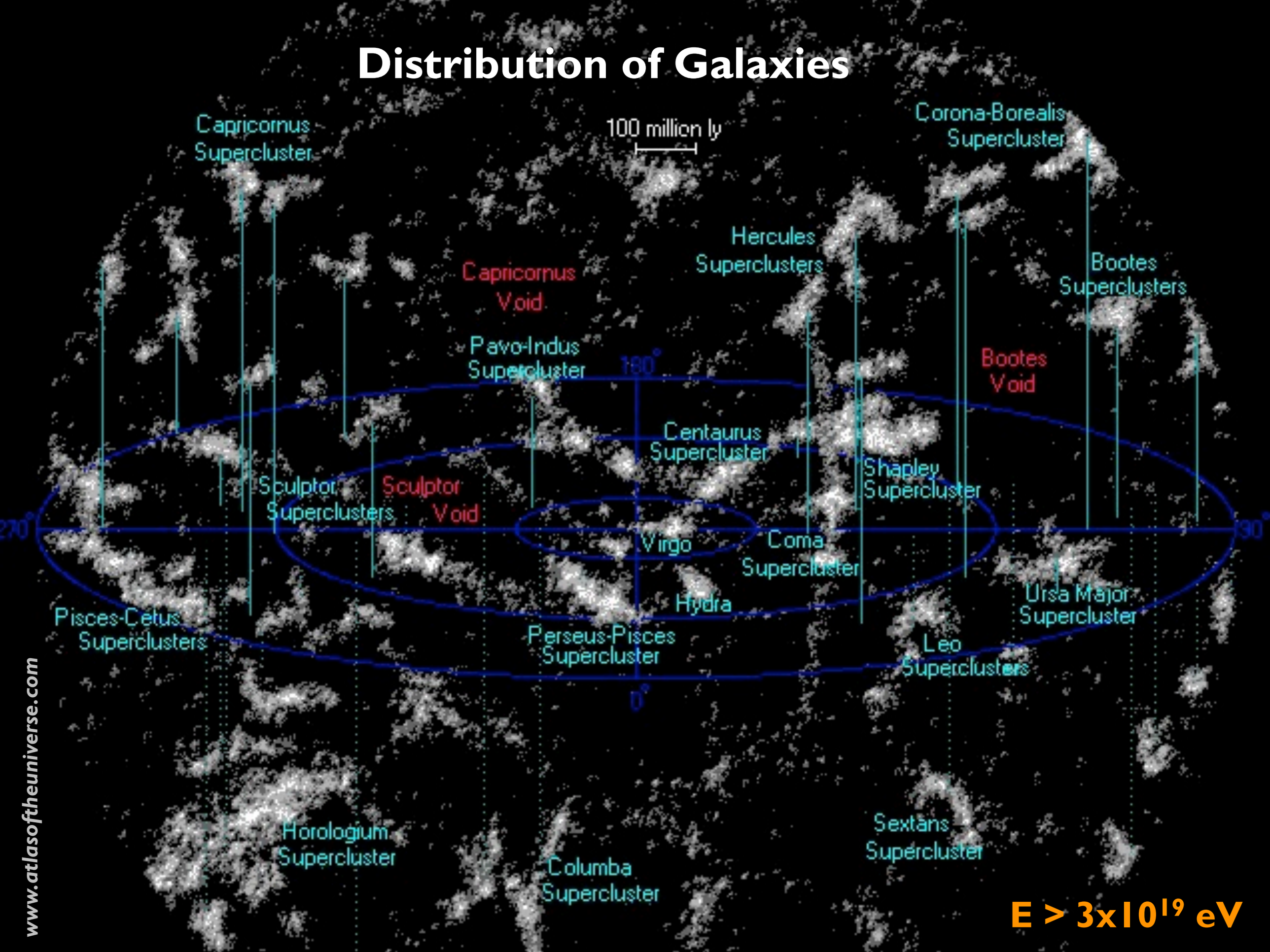




(Allard et al. 2007)

Proton and iron suffer smallest (and almost equal) energy loss

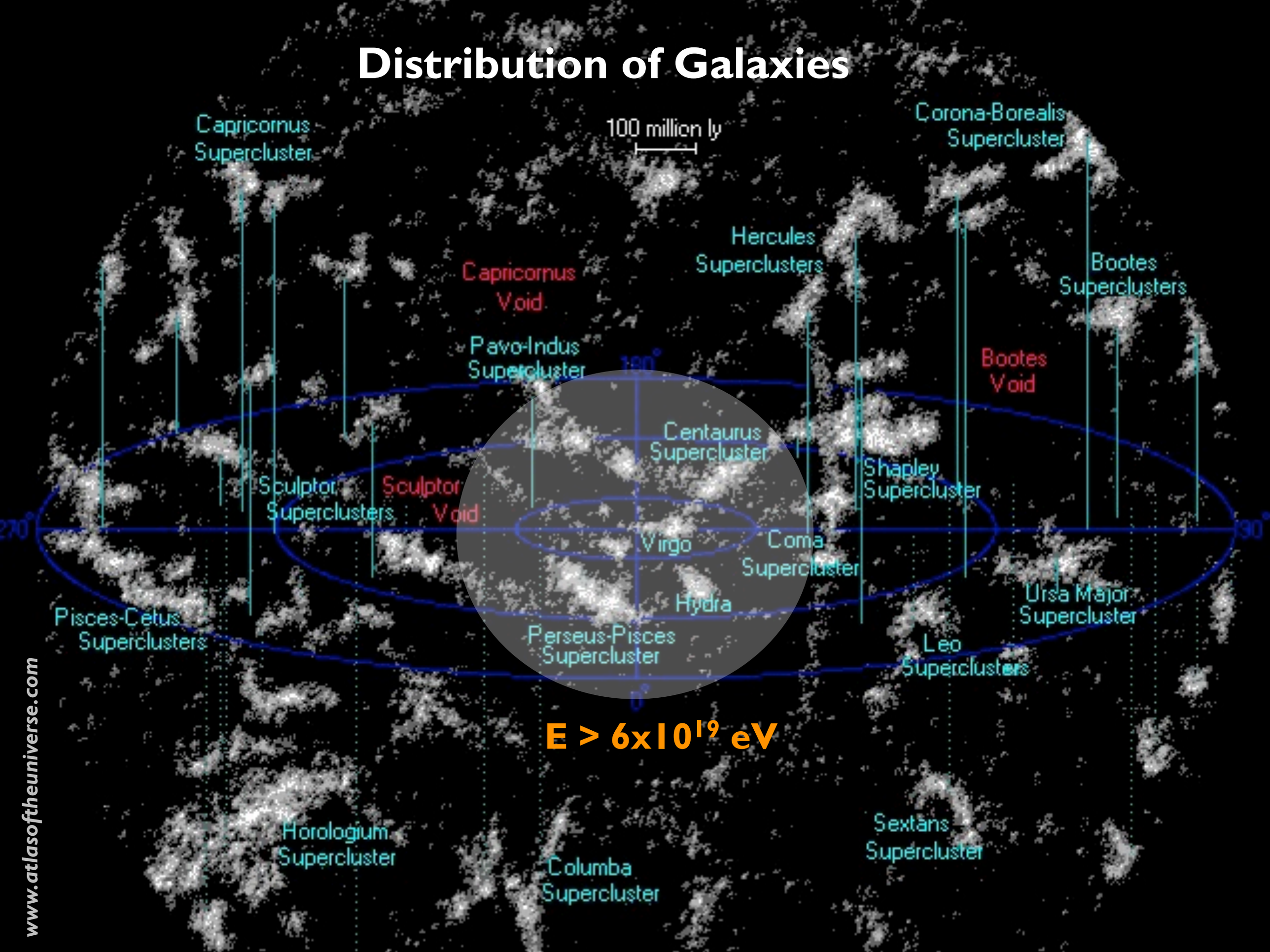
Distribution of Galaxies



$E > 3 \times 10^{19}$ eV

www.atlasoftheuniverse.com

Distribution of Galaxies

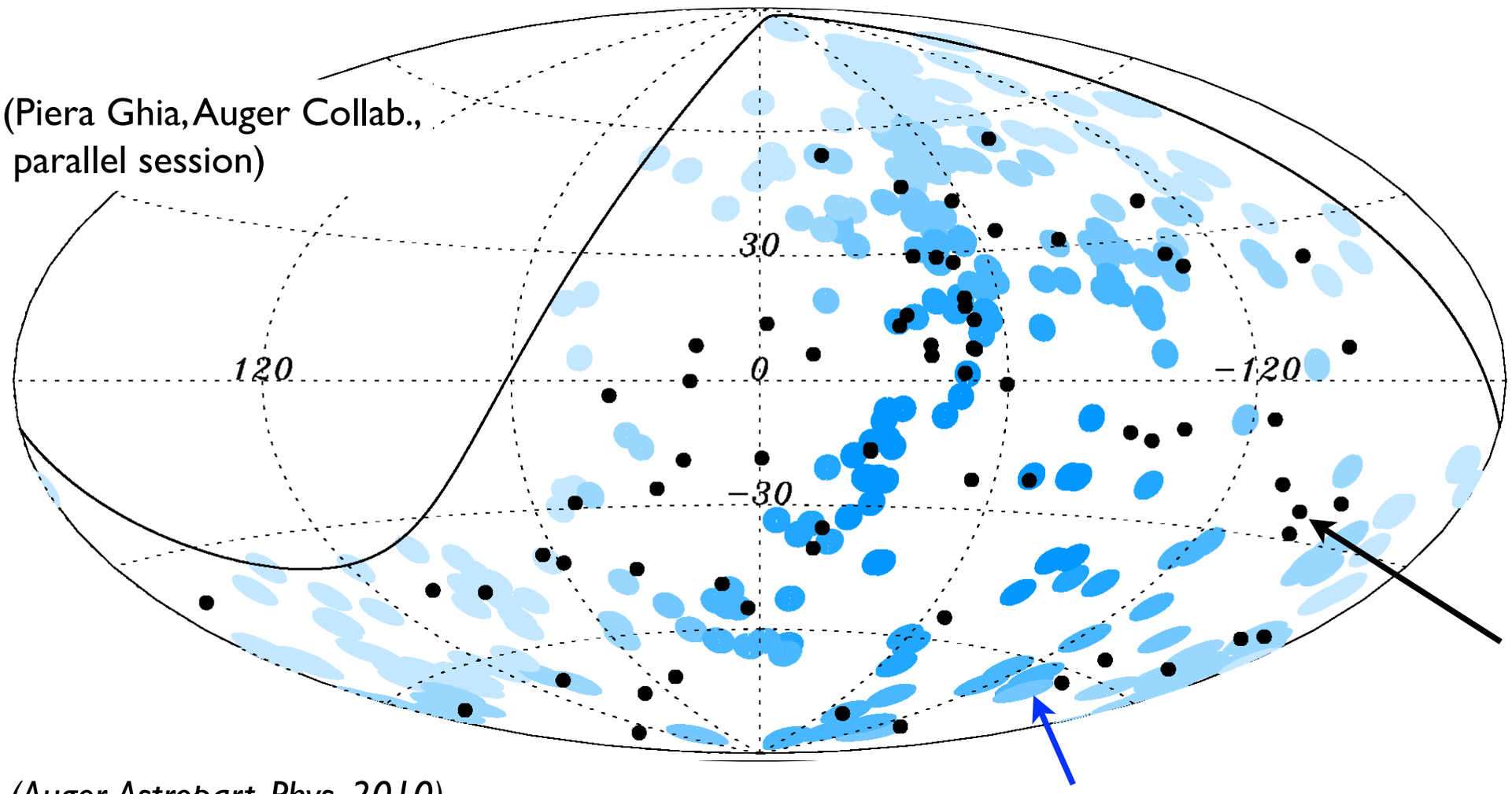


www.atlasoftheuniverse.com

Anisotropy at the highest energies

Auger Observatory: discovery of anisotropy: 70% correlation *(Science 318, 2007)*

(Piera Ghia, Auger Collab., parallel session)



$E > 5.5 \times 10^{19}$ eV

Correlation: 38+0.07-0.06%

Isotropy: 21%

Arrival direction of cosmic ray

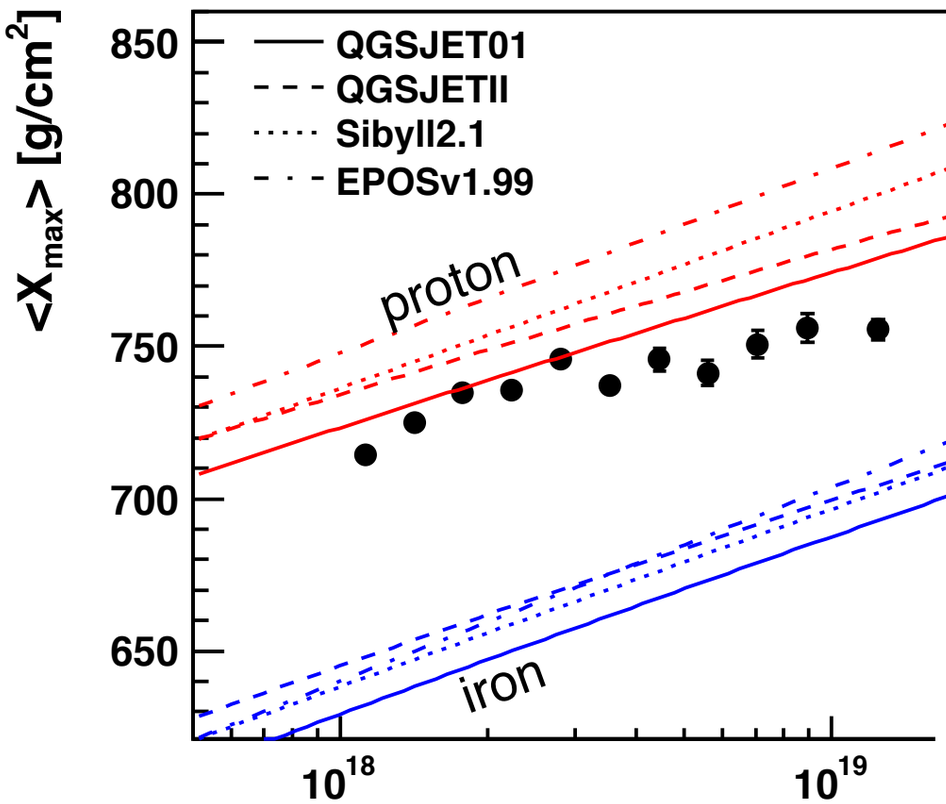
(Auger, Astropart. Phys. 2010)

Active Galactic Nucleus (AGN) smeared by 3.1°

Note:

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

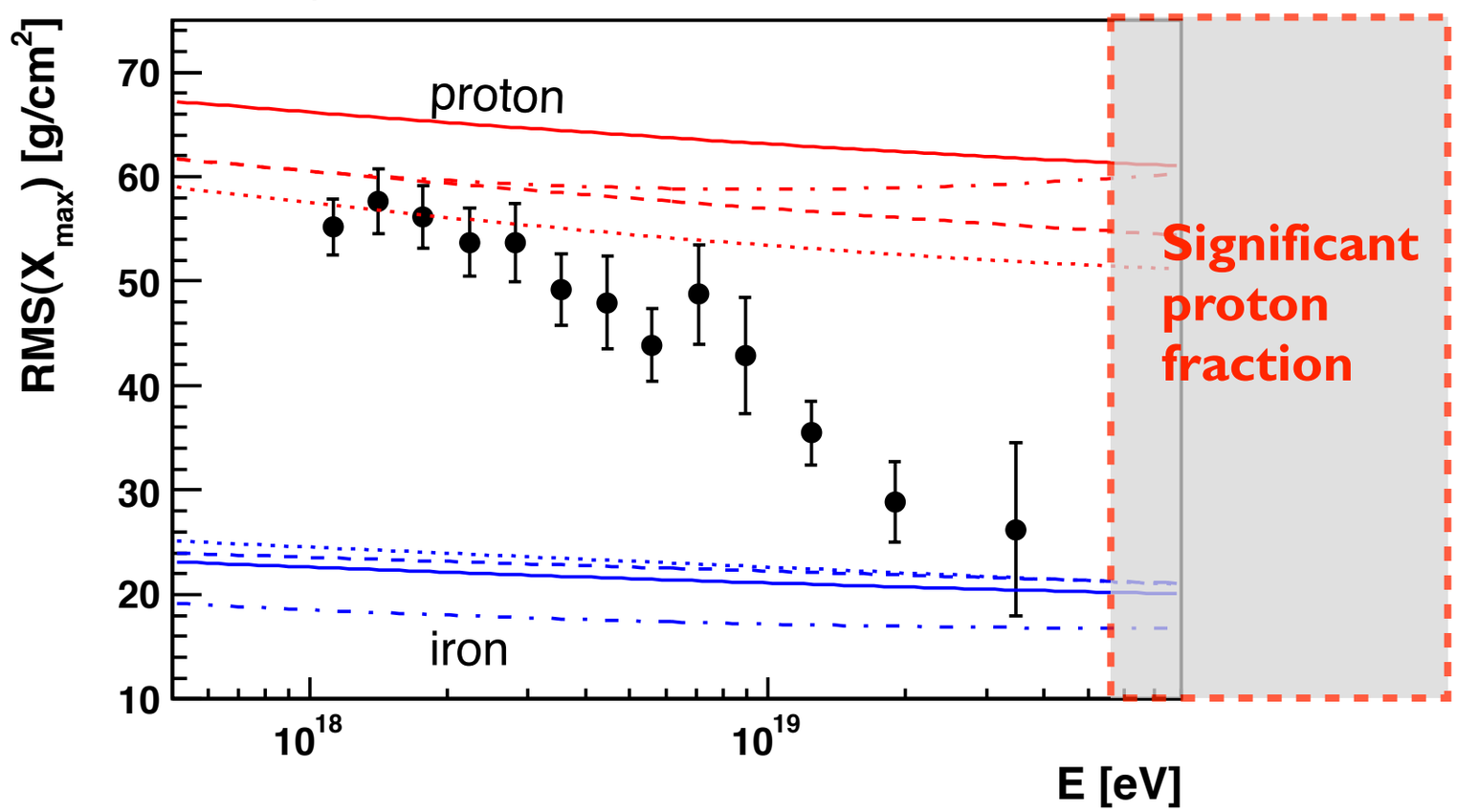
Auger Observatory: Composition data



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

(Auger Collab. PRL 104, 2010)

Anisotropy

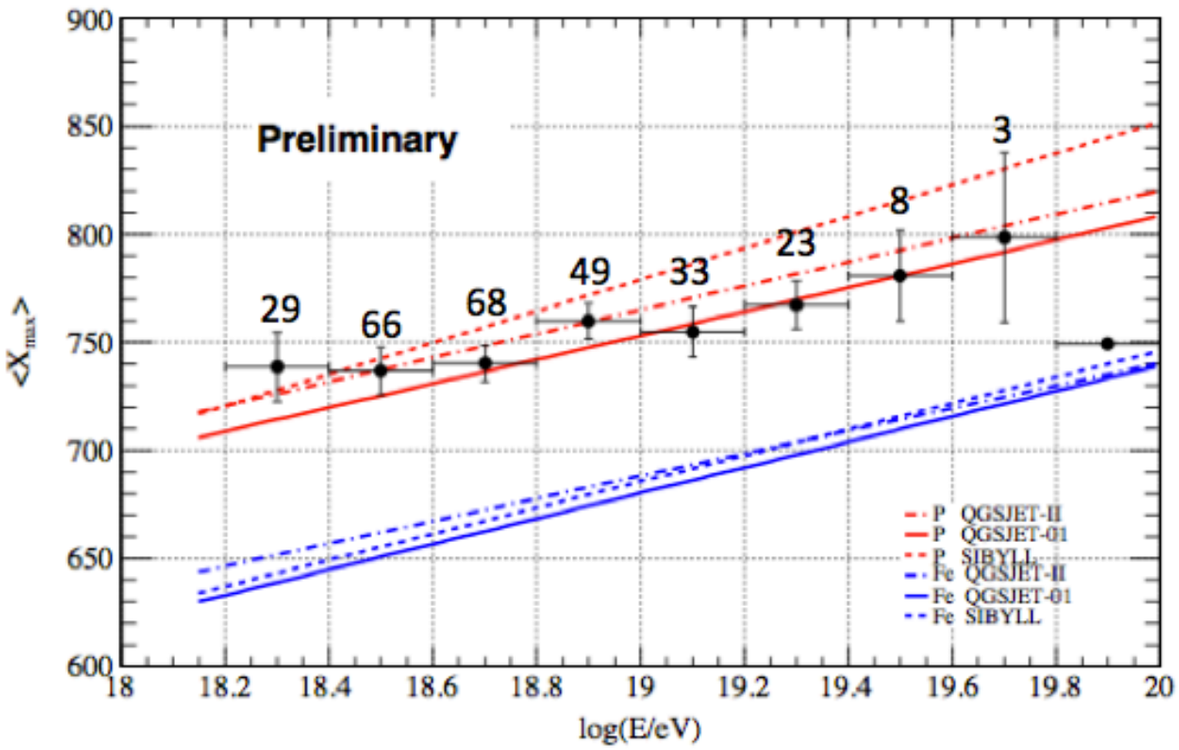


Sys. uncertainty: 13 g/cm^2 (mean)
6 g/cm^2 (RMS)

Independent confirmation from other composition indicators

(Piera Ghia, Auger Collab., parallel session)

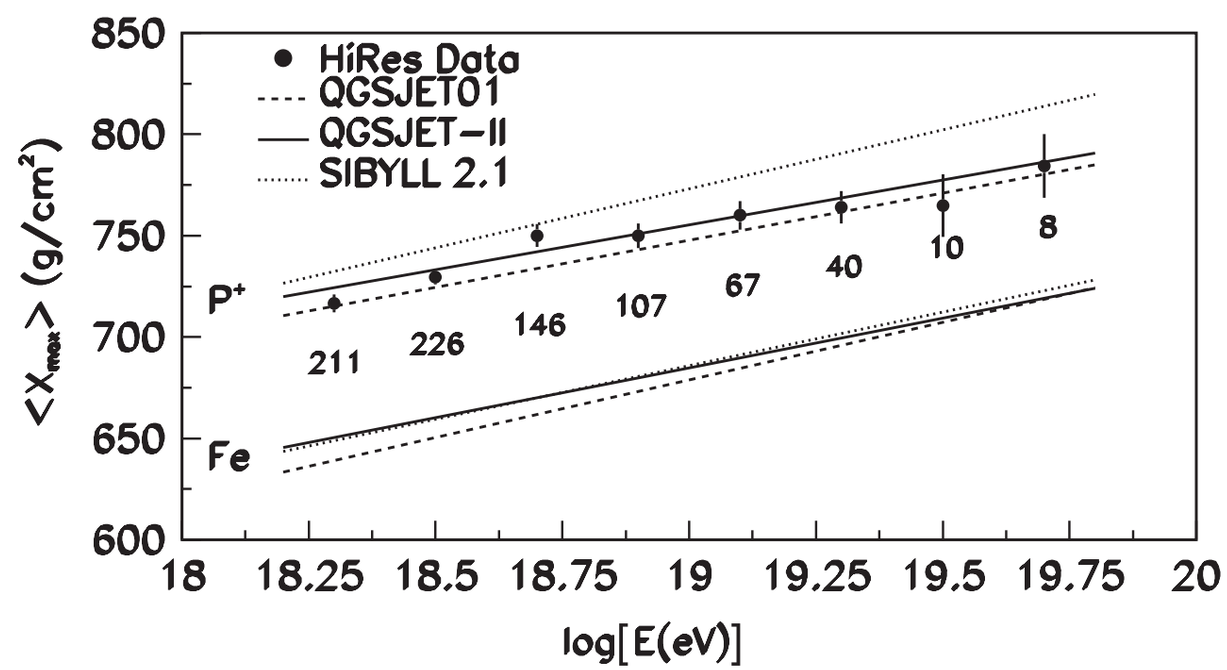
Telescope Array: Composition measurement



(Pierre Sokolsky, TA Collab., parallel session)

TA data compatible with light composition (independent analysis)

HiRes Collab. PRL 104 (2010) 161101



Anisotropy:

- no correlation found in HiRes data (smaller statistics than Auger, northern hemisphere)
- current TA data still inconclusive (limited statistics and sky coverage)

Summary

First LHC data and the knee:

exotic models disfavoured

Cross section measurements:

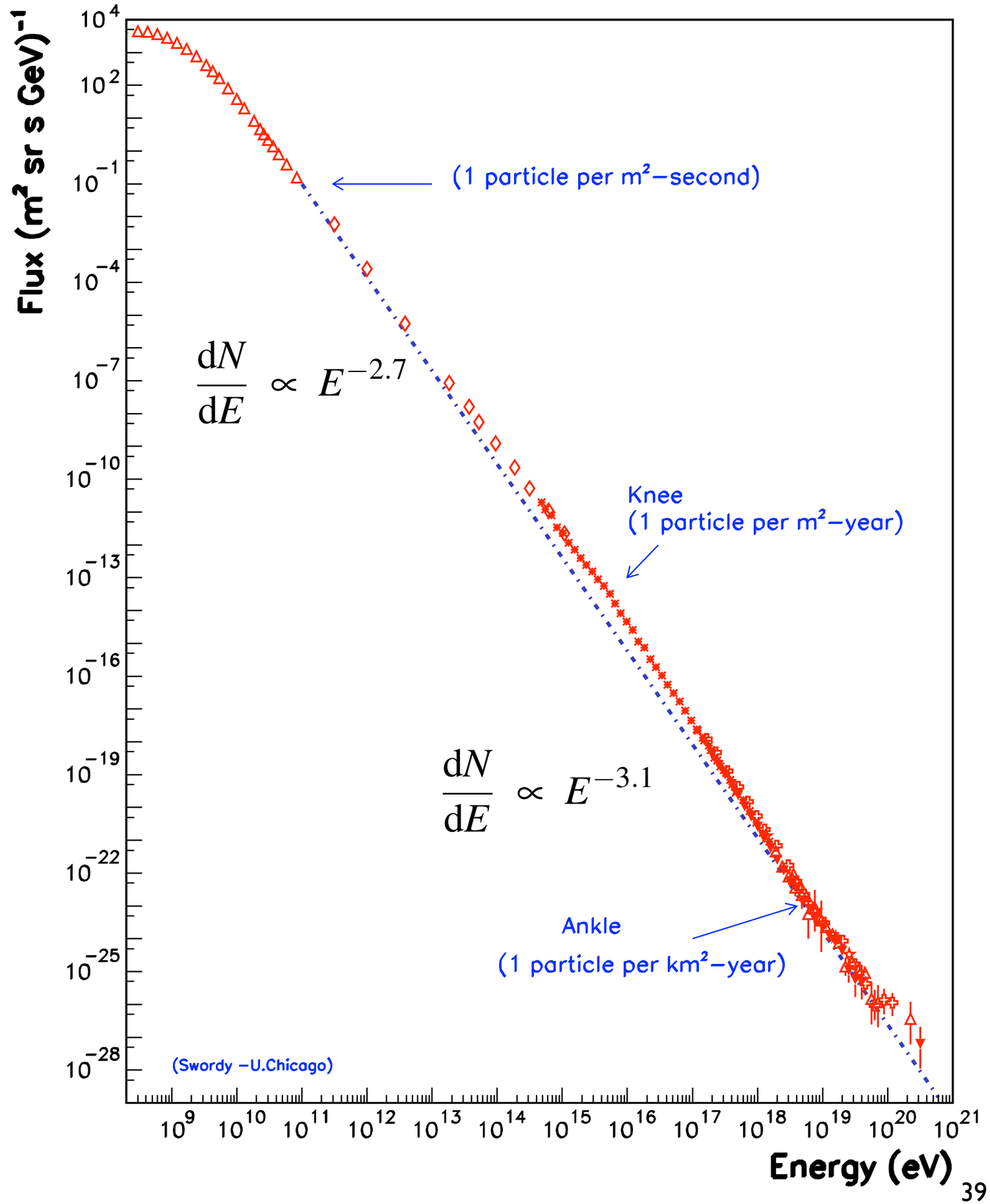
LHC data for extrapolation,
air shower data at higher energy

Muons in air showers at 10^{19} eV:

still a serious probelm

Astrophysical constraints at the highest energies:

very helpful and expected,
but situation unclear right now



Problem 1: Sources must be extreme objects

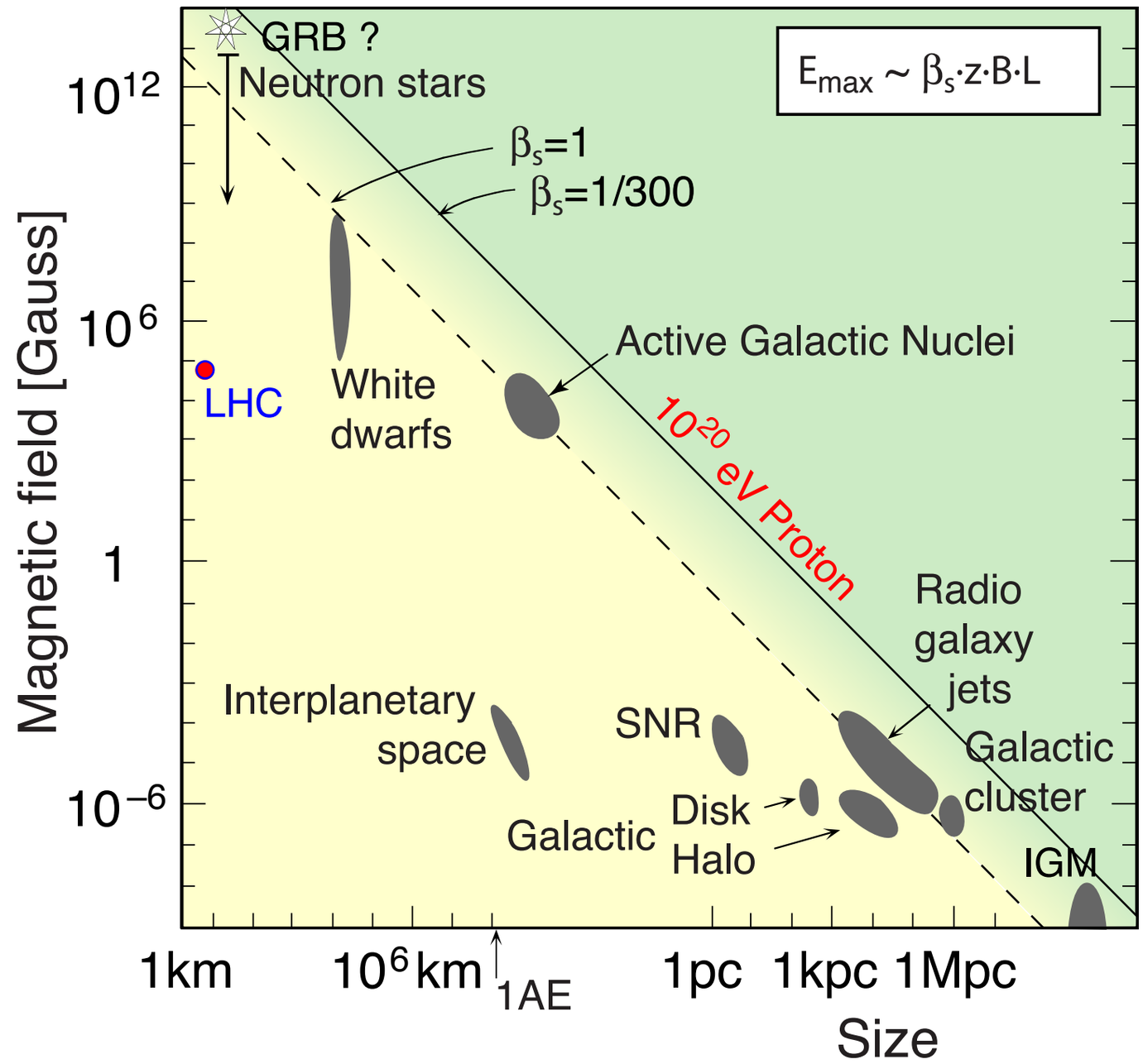
Hillas 1984:

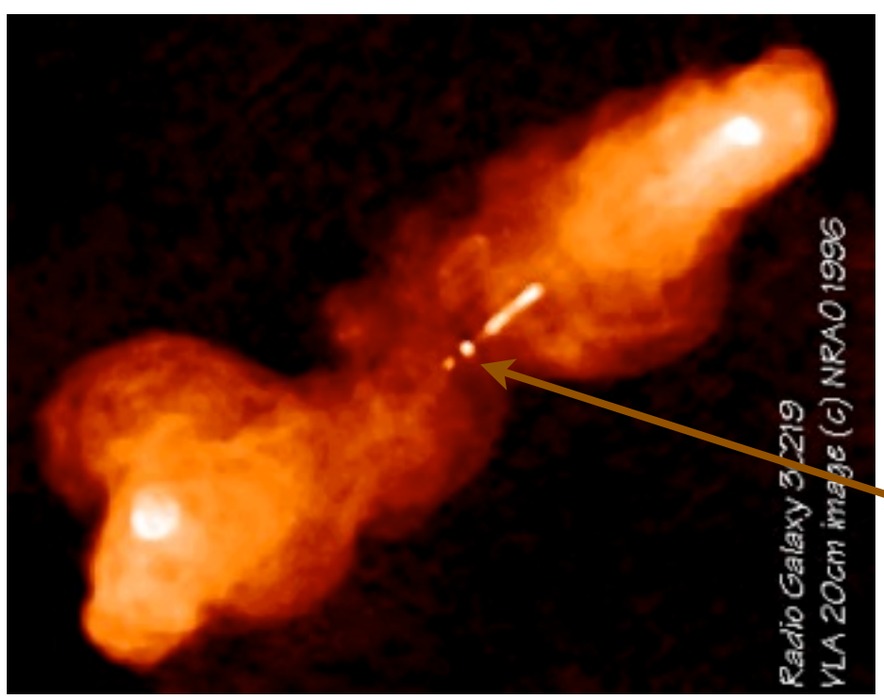
$$E_{\max} \simeq 10^{18}\,\mathrm{eV}\; Z\,\beta \left(\frac{R}{\mathrm{kpc}}\right)\left(\frac{B}{\mu\mathrm{G}}\right)$$

shock velocity

size of acc. region

mag. field strength





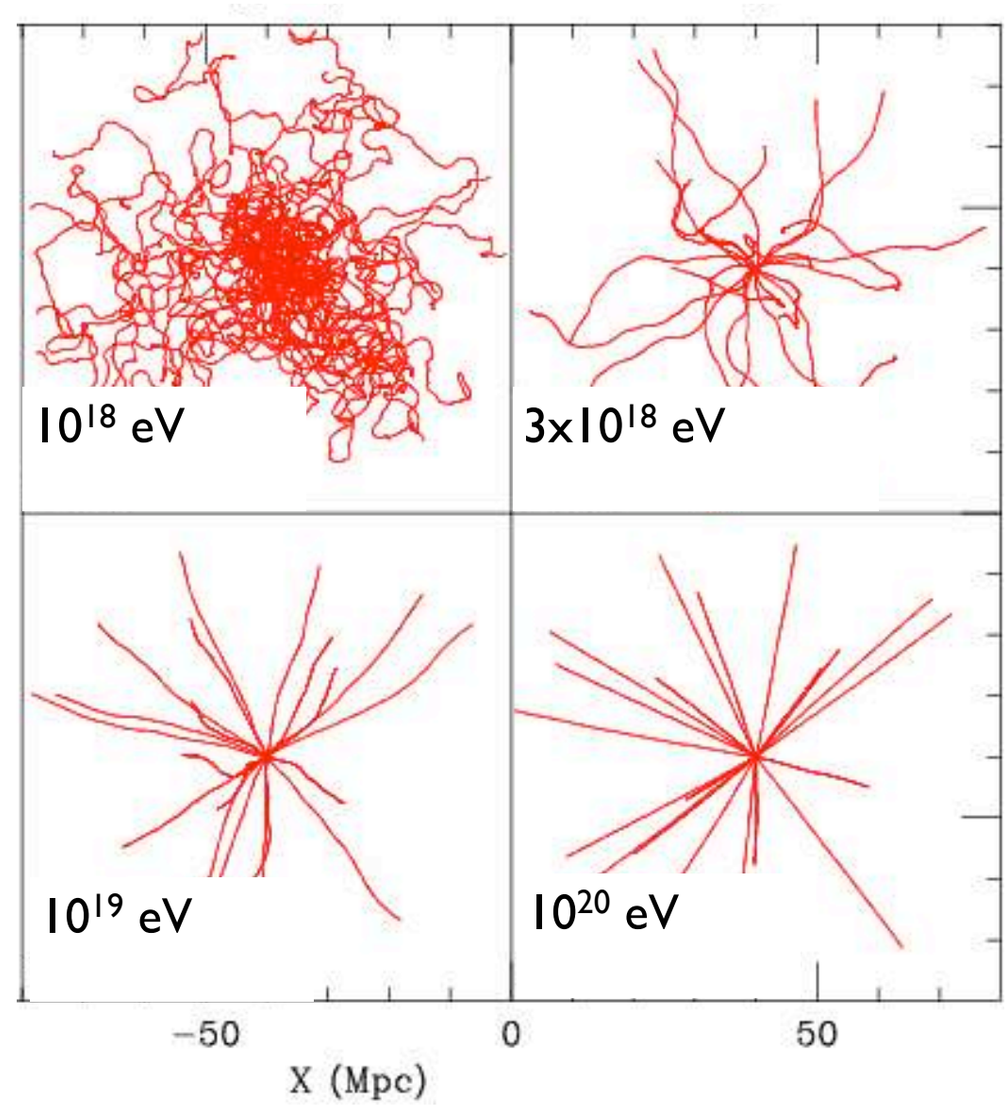
Black hole of ~10^9 solar masses

Problem 3: Deflection in magnetic fields

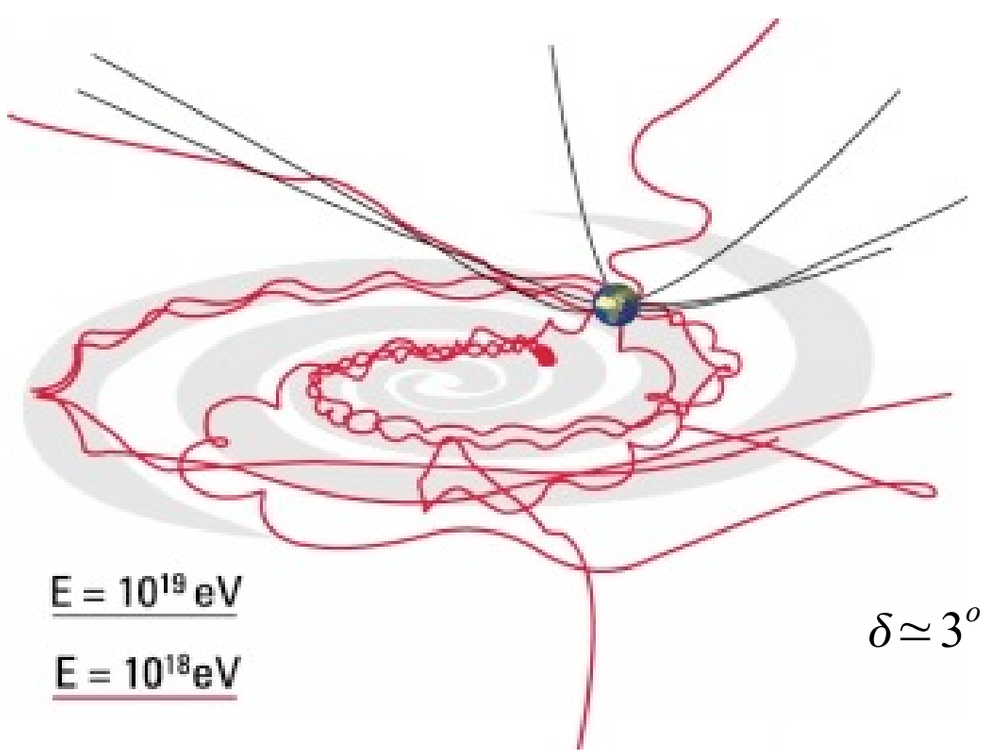
Typical field strengths:

- proton deflection angle ~few degrees
- iron deflection angle large
- proton astronomy ?

Extragalactic magnetic fields

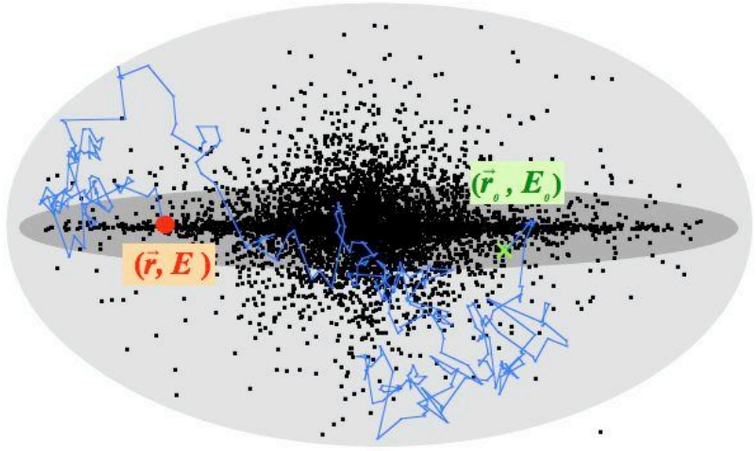


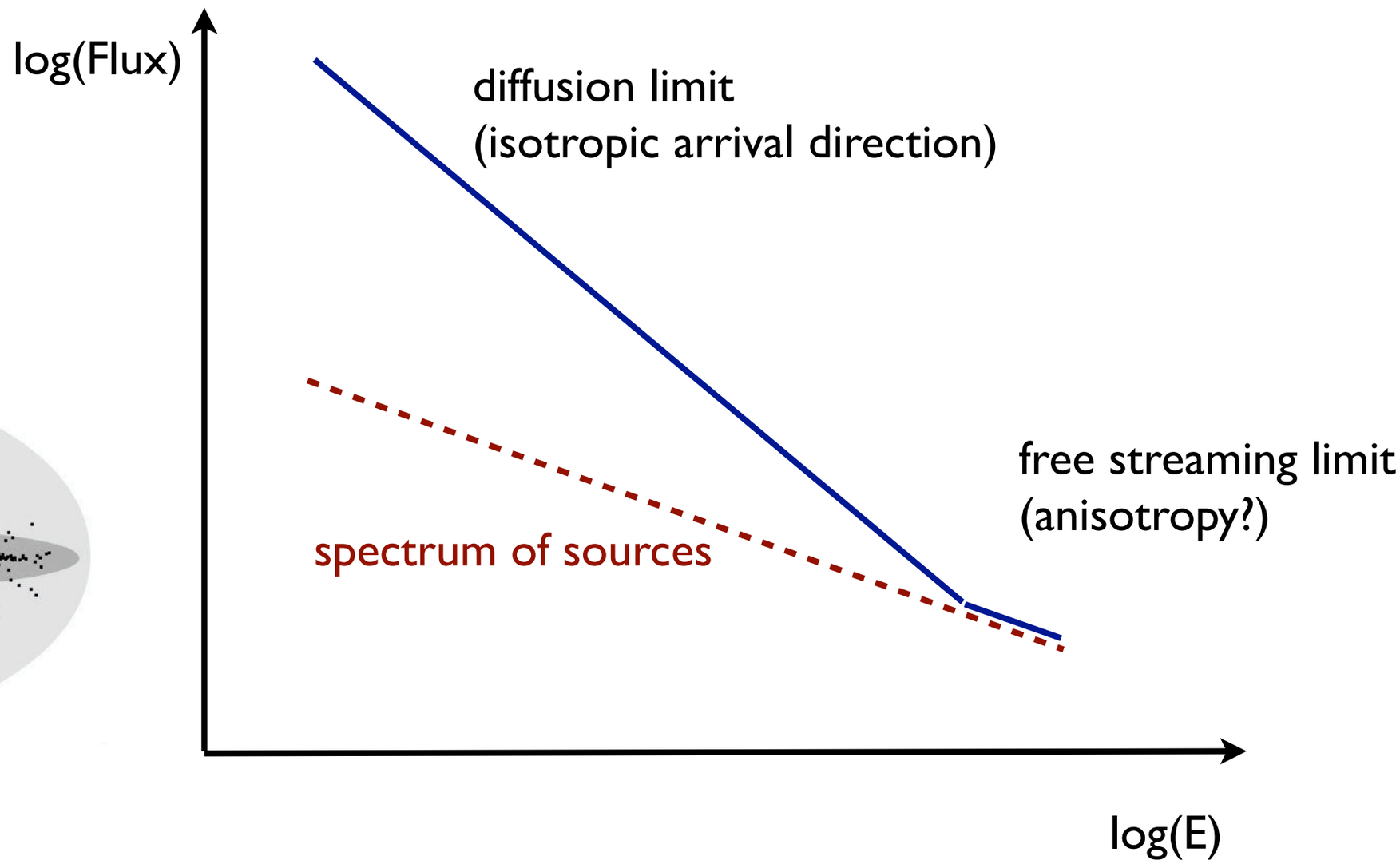
Galactic magnetic fields



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

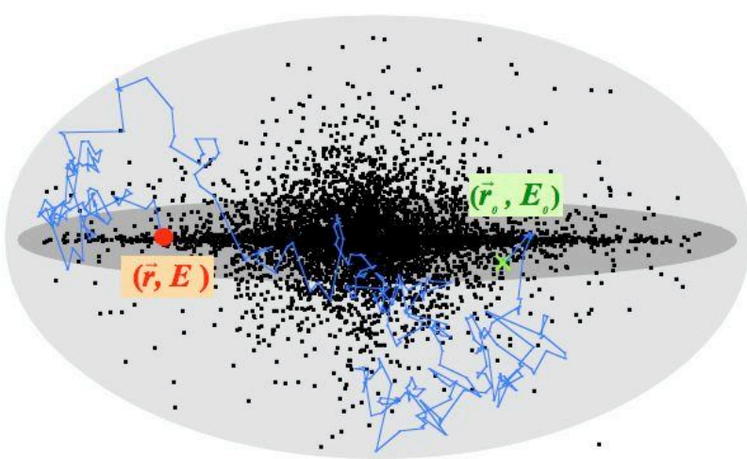
Magnetic fields: Confinement in the Galaxy (i)

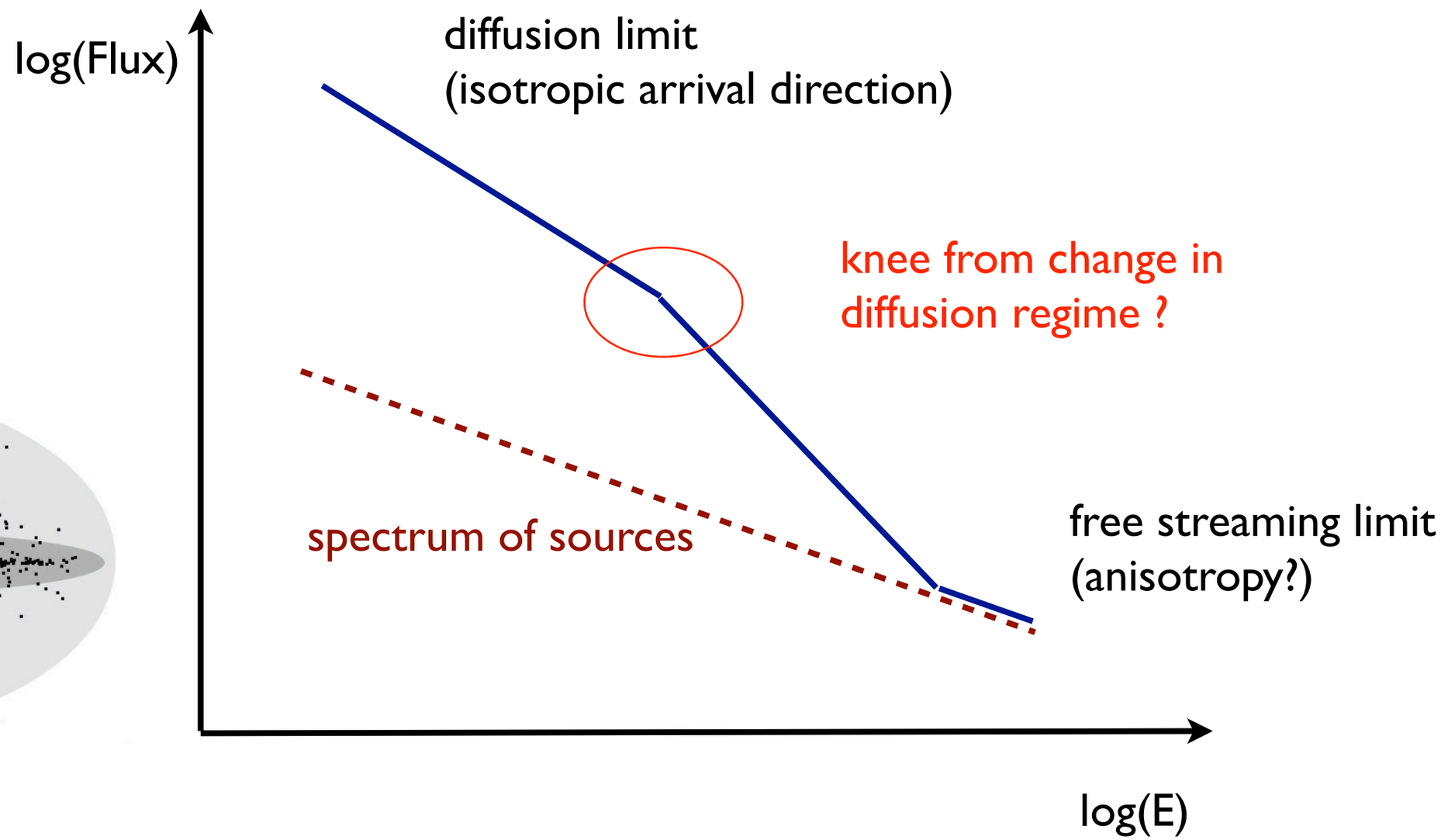




Observed spectrum softer than injection spectrum

Magnetic fields: Confinement in the Galaxy (ii)





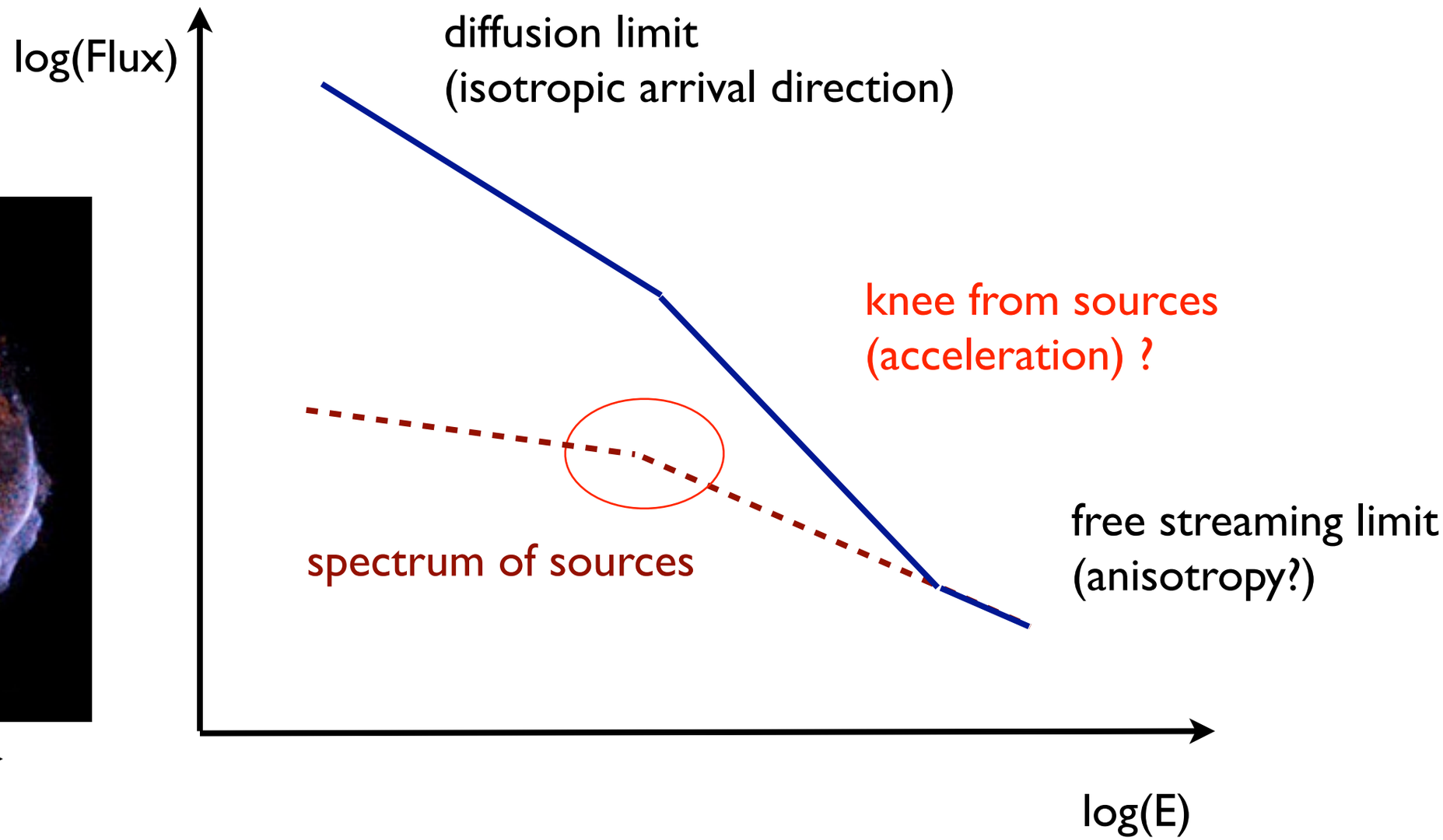
Diffusion: same behaviour for different elements at same rigidity $p/Z \sim E/Z$

Magnetic fields: Confinement in sources

SN remnant 1006

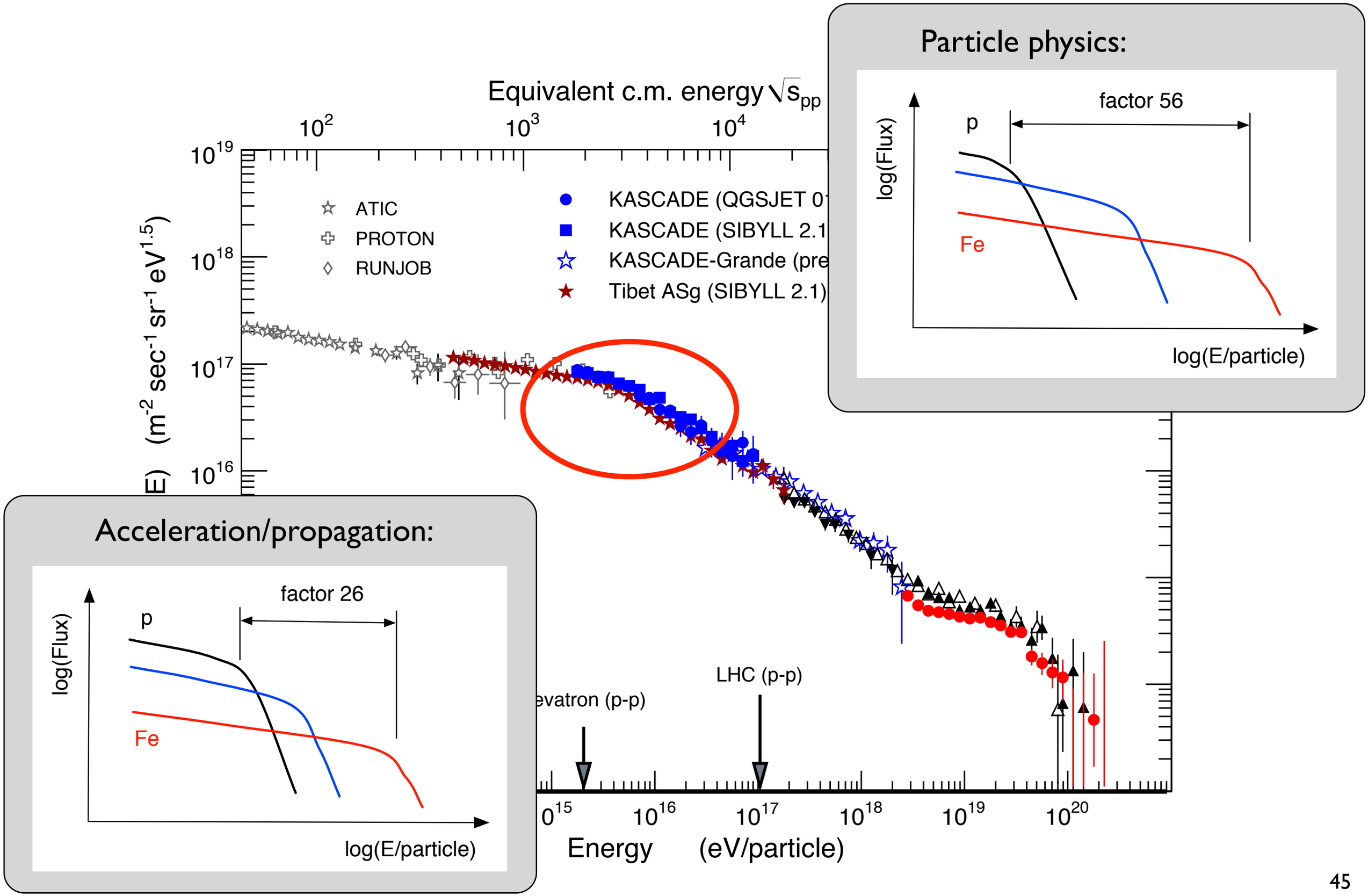
Distance ~ 2.2 kpc

20 pc

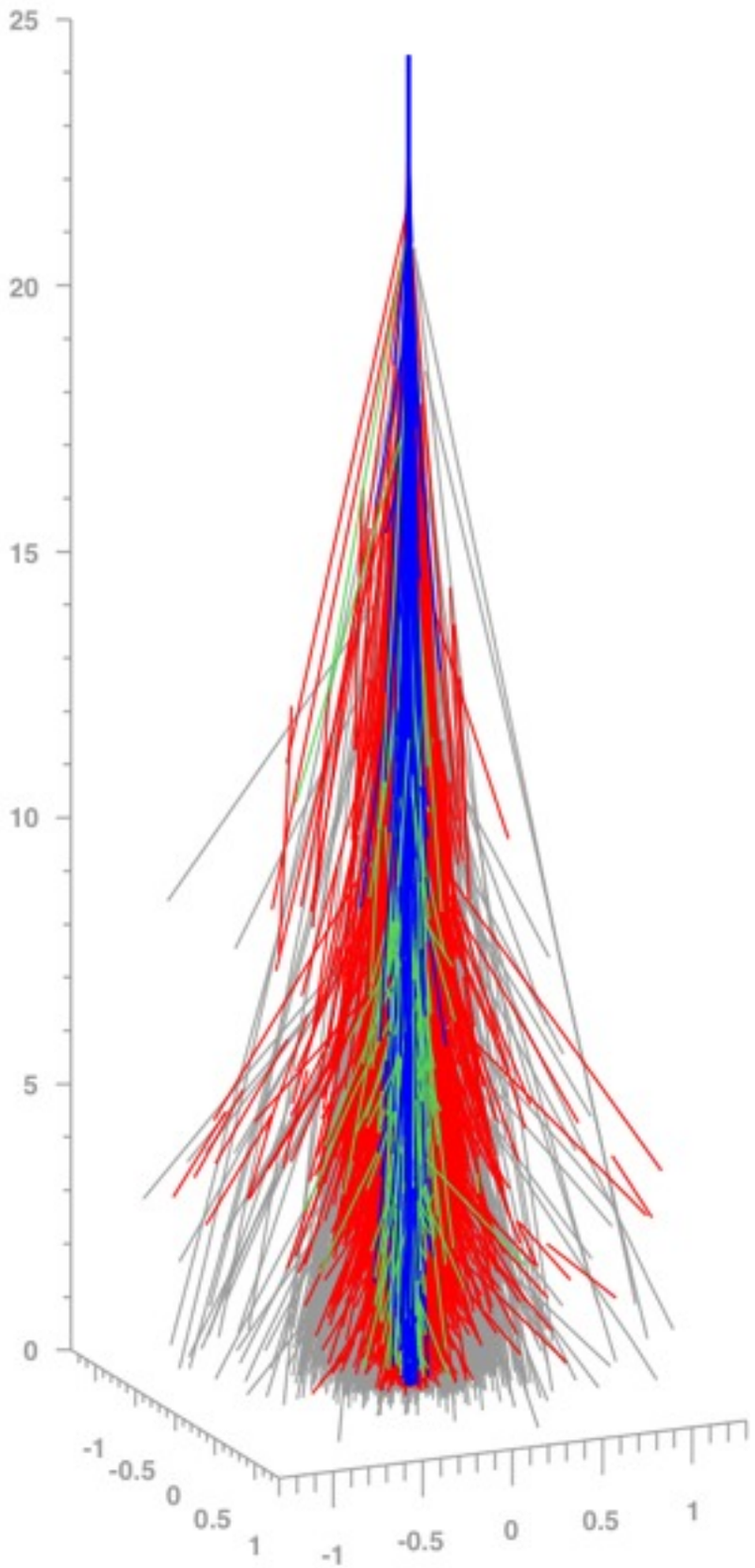


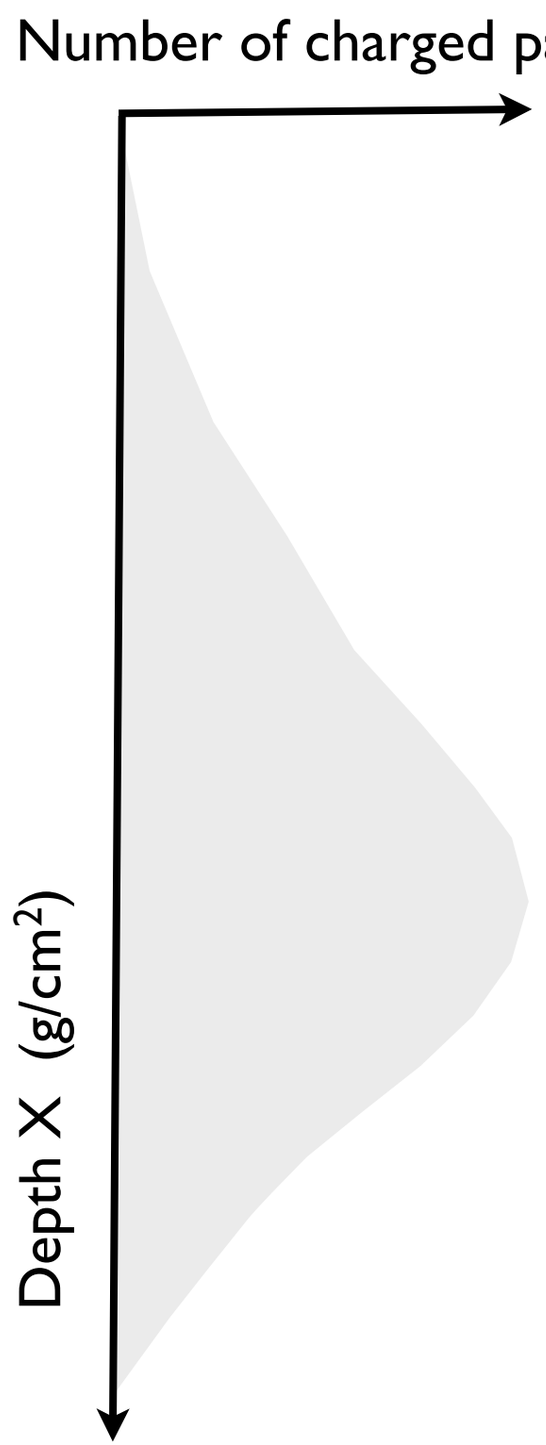
Acceleration: same behaviour for different elements at same rigidity $p/Z \sim E/Z$

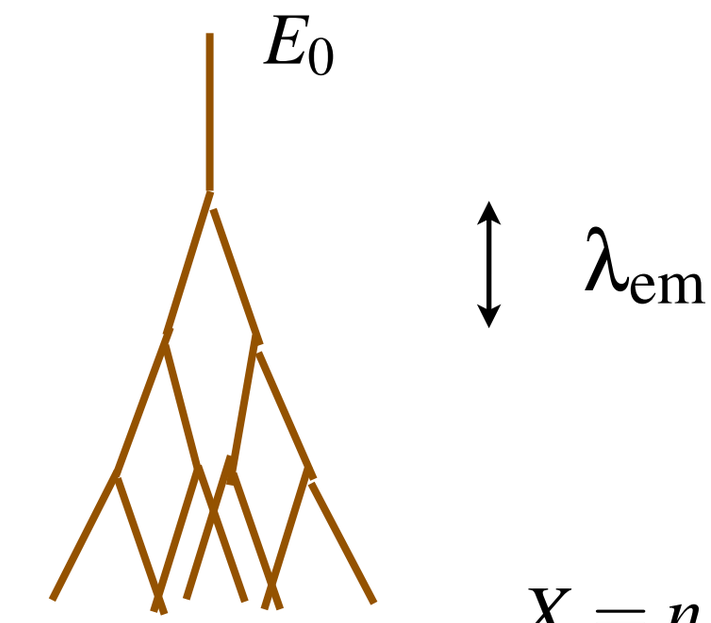
Origin and physics of the knee



Heitler model of em. shower







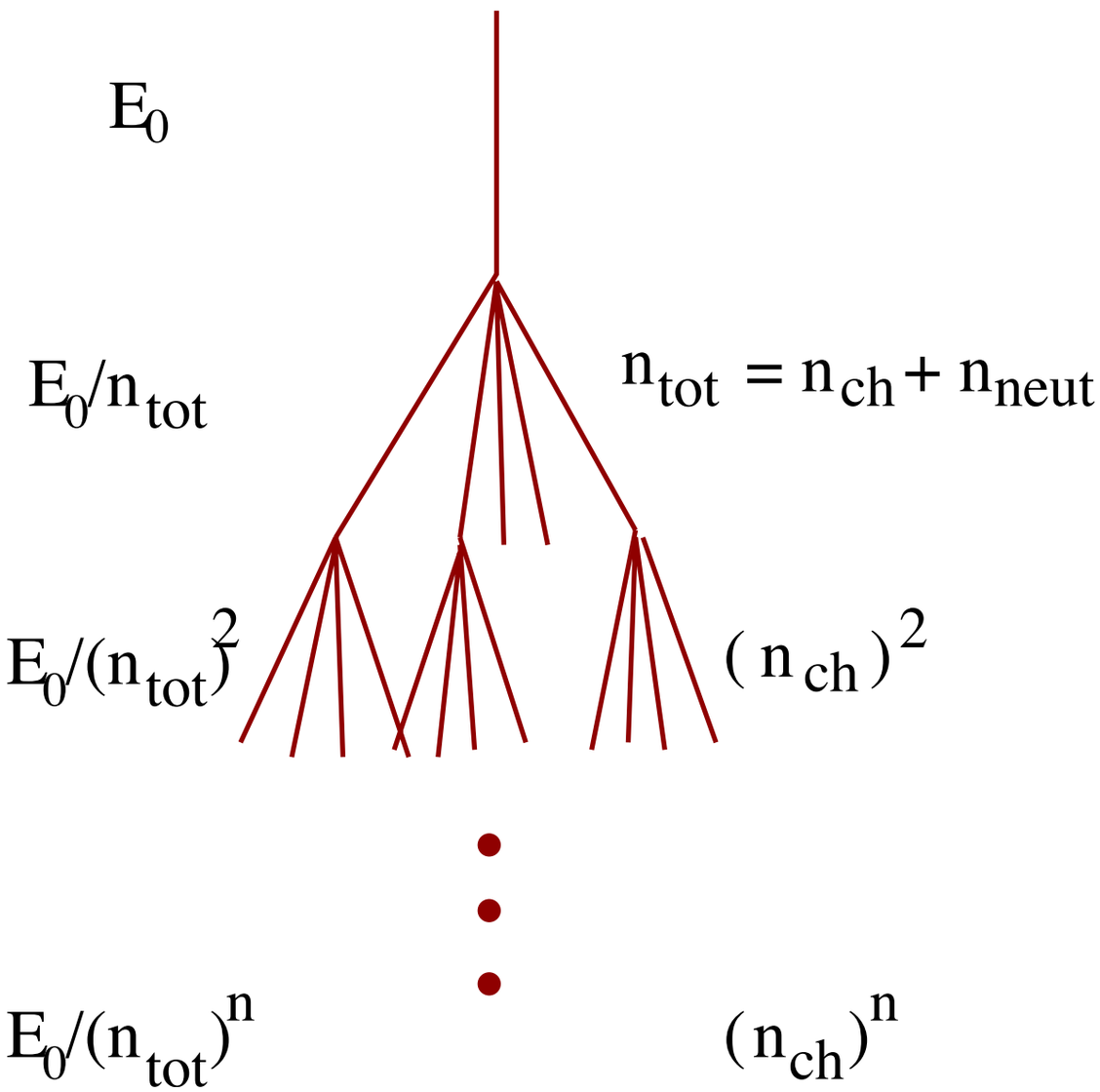
$$X = n\,\lambda_{\mathrm{em}}$$

$$E = E_0/2^n$$

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

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

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

Assumptions:

- cascade stops at $E_{\mathrm{part}} = E_{\mathrm{dec}}$
- 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 $E_n = E_0/A$

$$N_{\max}^A = A\left(\frac{E_0}{AE_c}\right) = N_{\max}$$

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

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