Physics of High Energy Cosmic Rays

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Cosmic Rays

~ 30 - 40 km

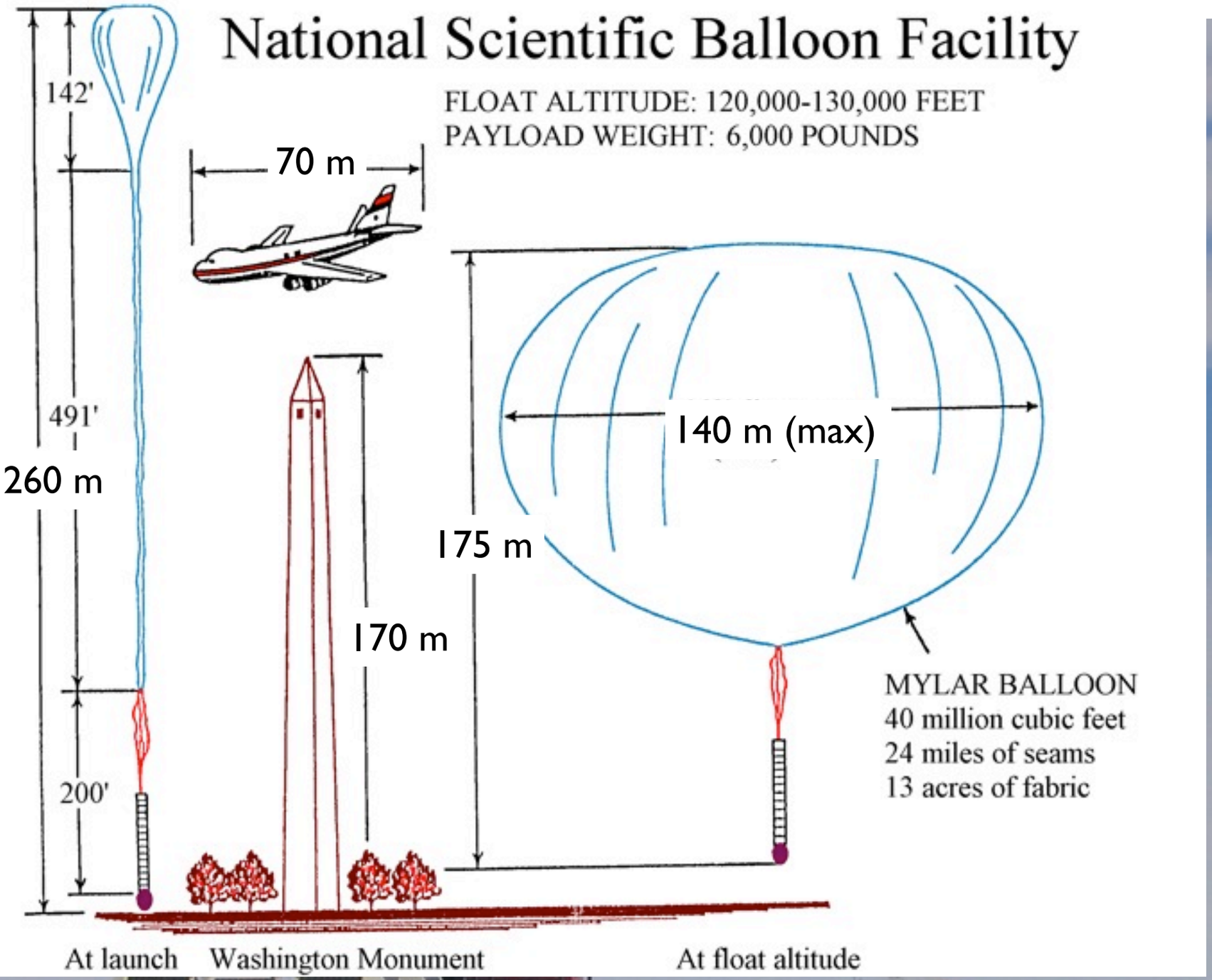
Atmosphere as shield from highly ionizing radiation

At sea level:
mainly muons as secondary particles

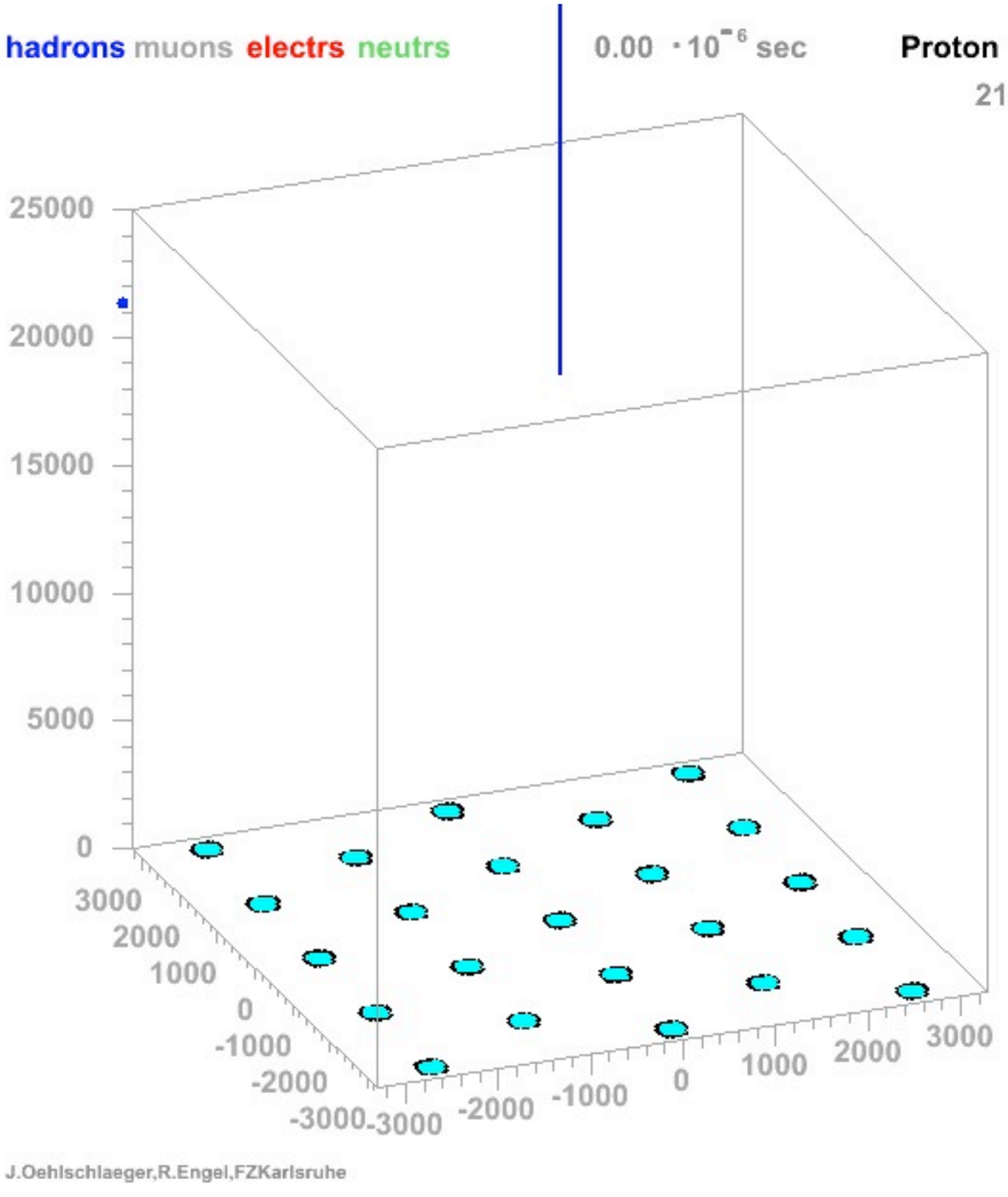
Relative abundance of nuclei

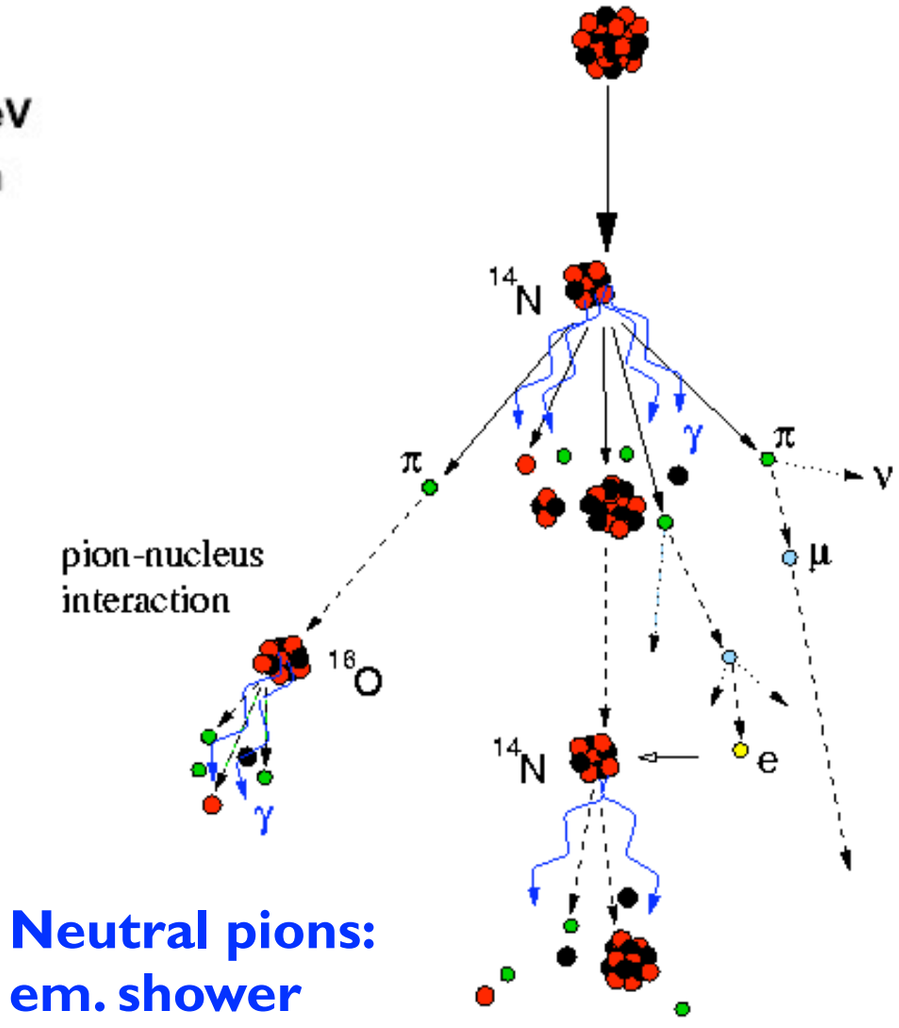
H	He	Z= 6-9	10-20	21-30
1	0.38	0.22	0.15	0.4

High-altitude balloon measurements



Particle cascades: Extensive air shower





Neutral pions: em. shower

Charged pions: muons and neutrinos

Secondary particles arrive at ground at almost the same time

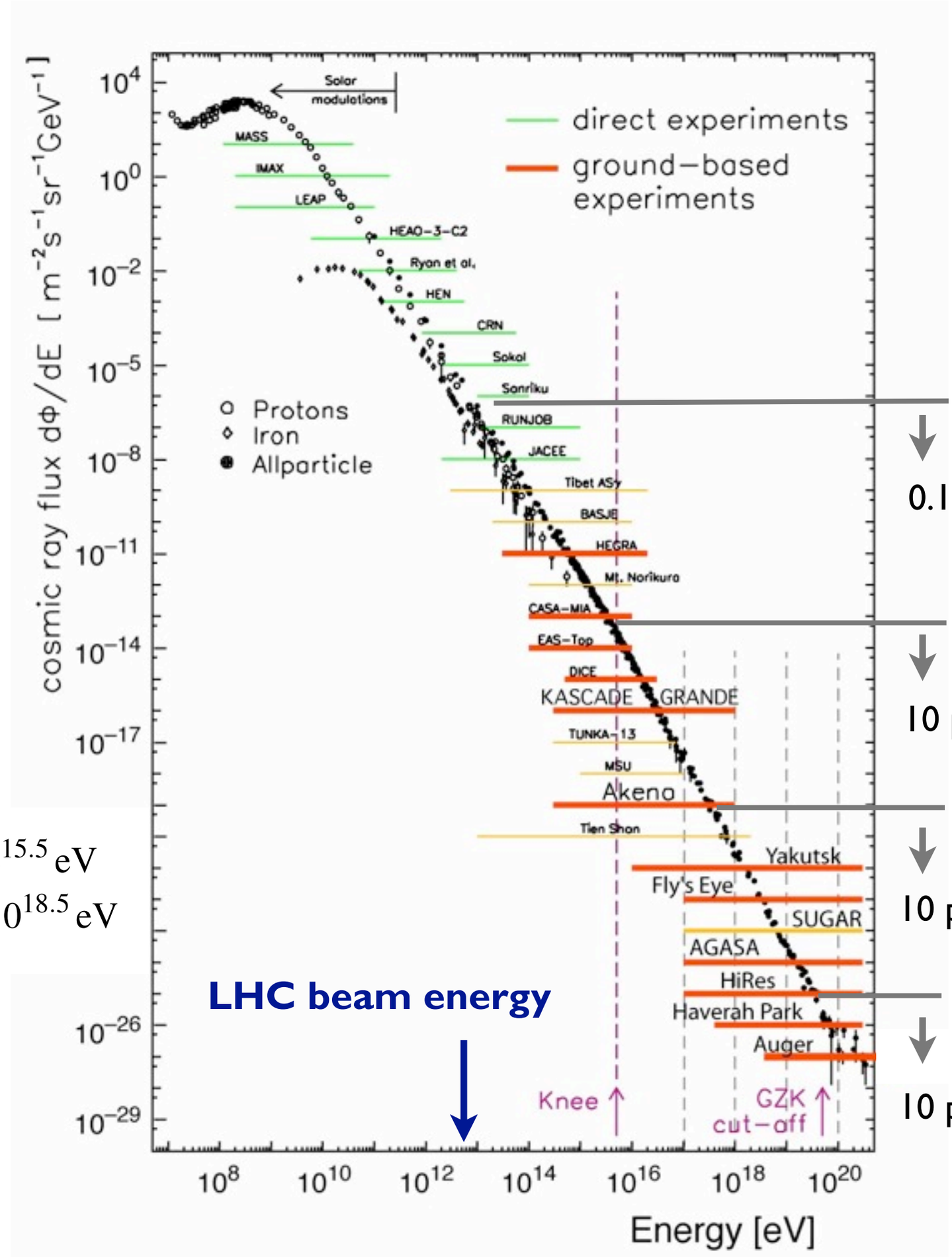
All-particle flux

Power law

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

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

≈ 3.1 $\quad 10^{15.5}\,\text{eV} < E < 10^{18.5}\,\text{eV}$

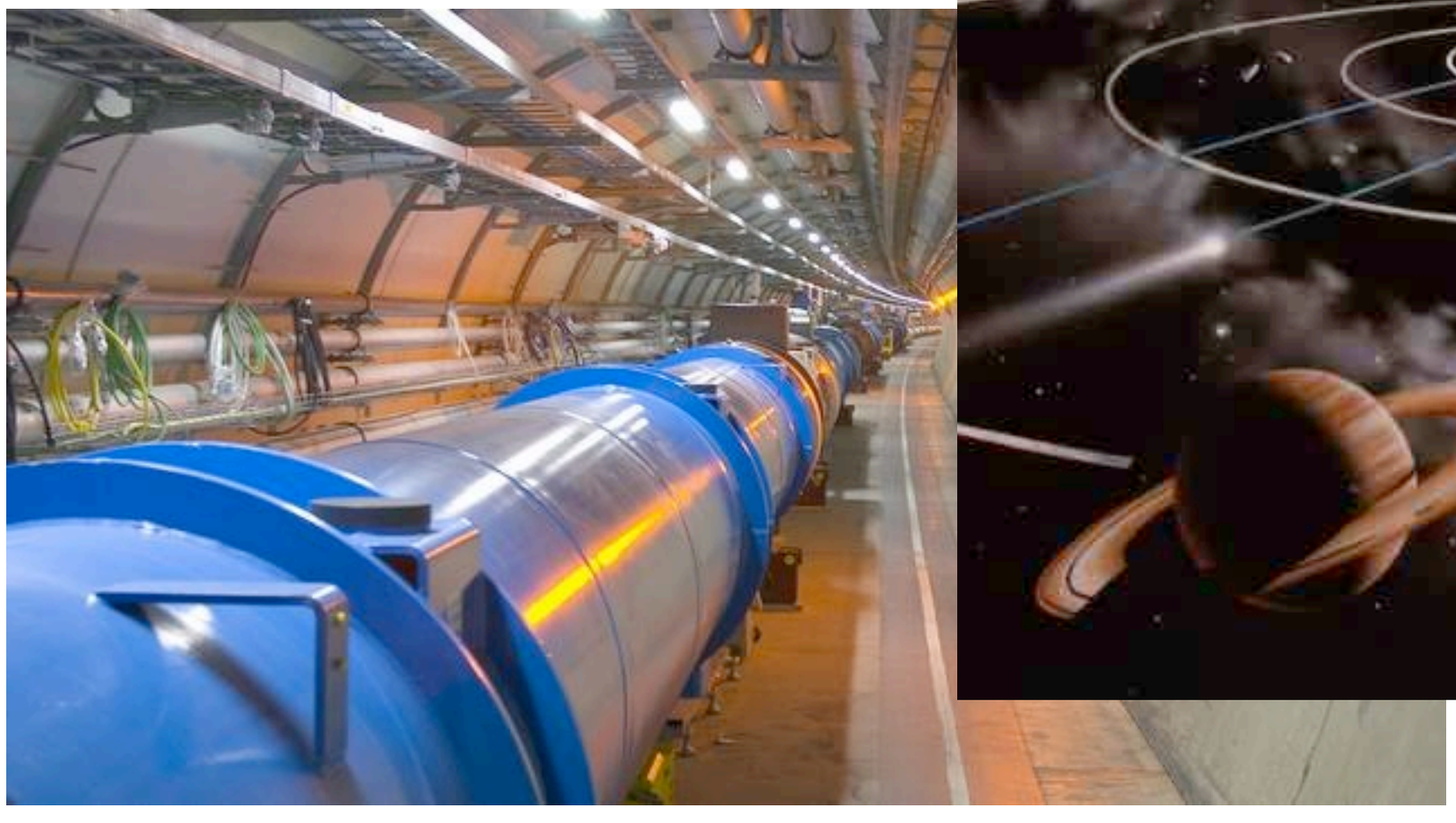


Ultra-high energy: 10^{20} eV

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

(M. Unger, 2006)

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



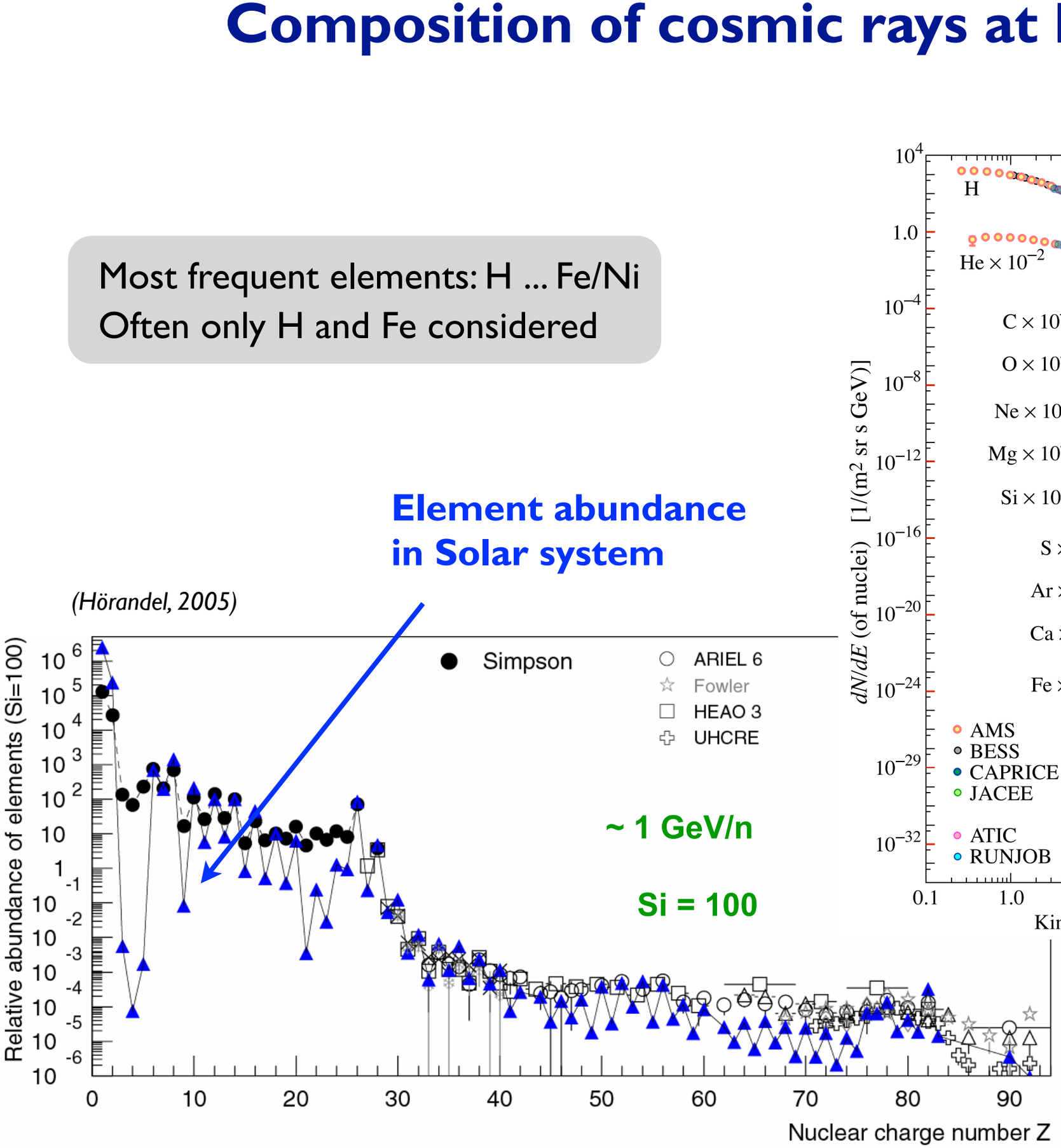
Acceleration time for LHC: 815 years

Composition of cosmic rays at low energy

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

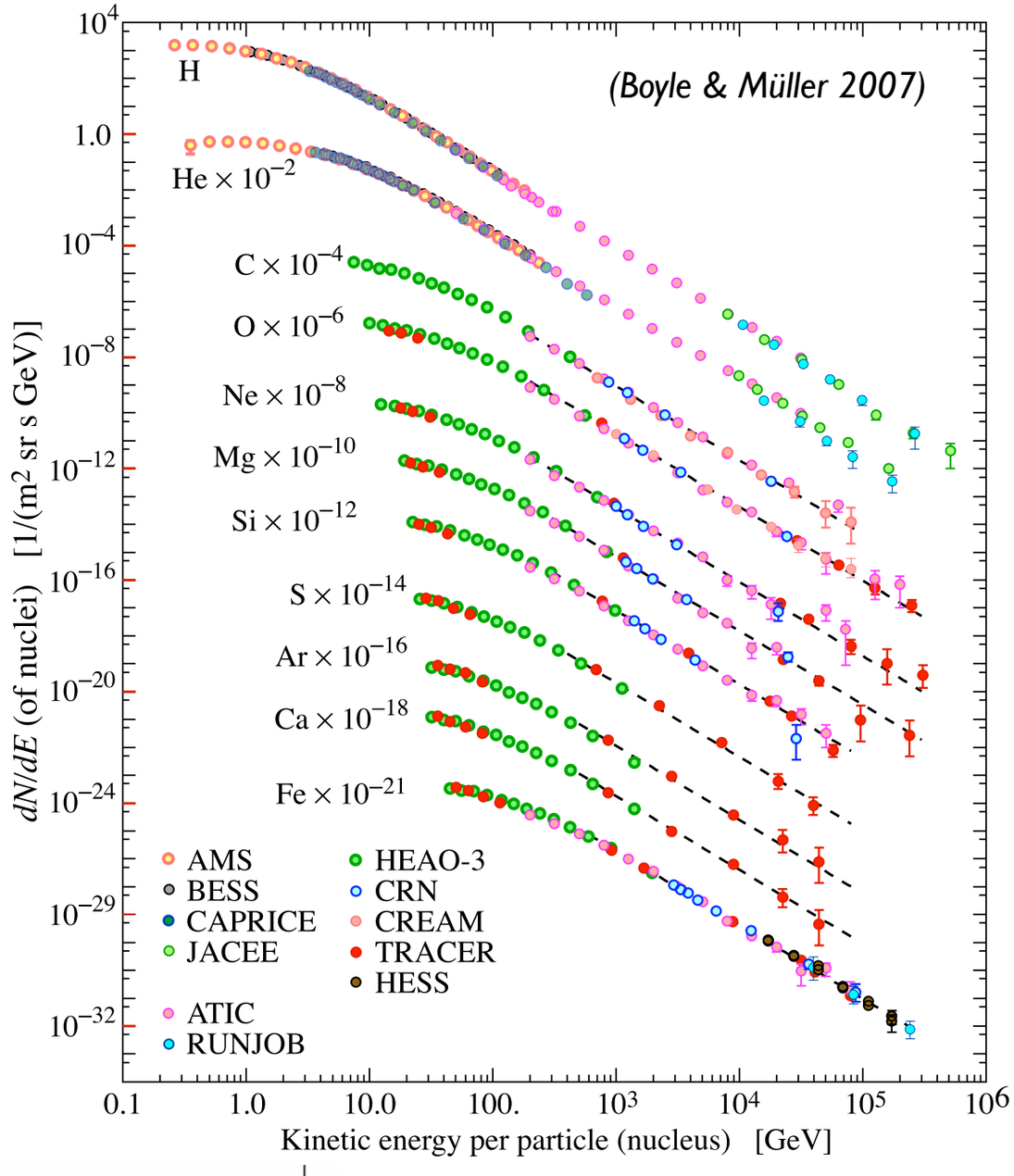
Element abundance in Solar system

(Hörandel, 2005)



~ 1 GeV/n

Si = 100



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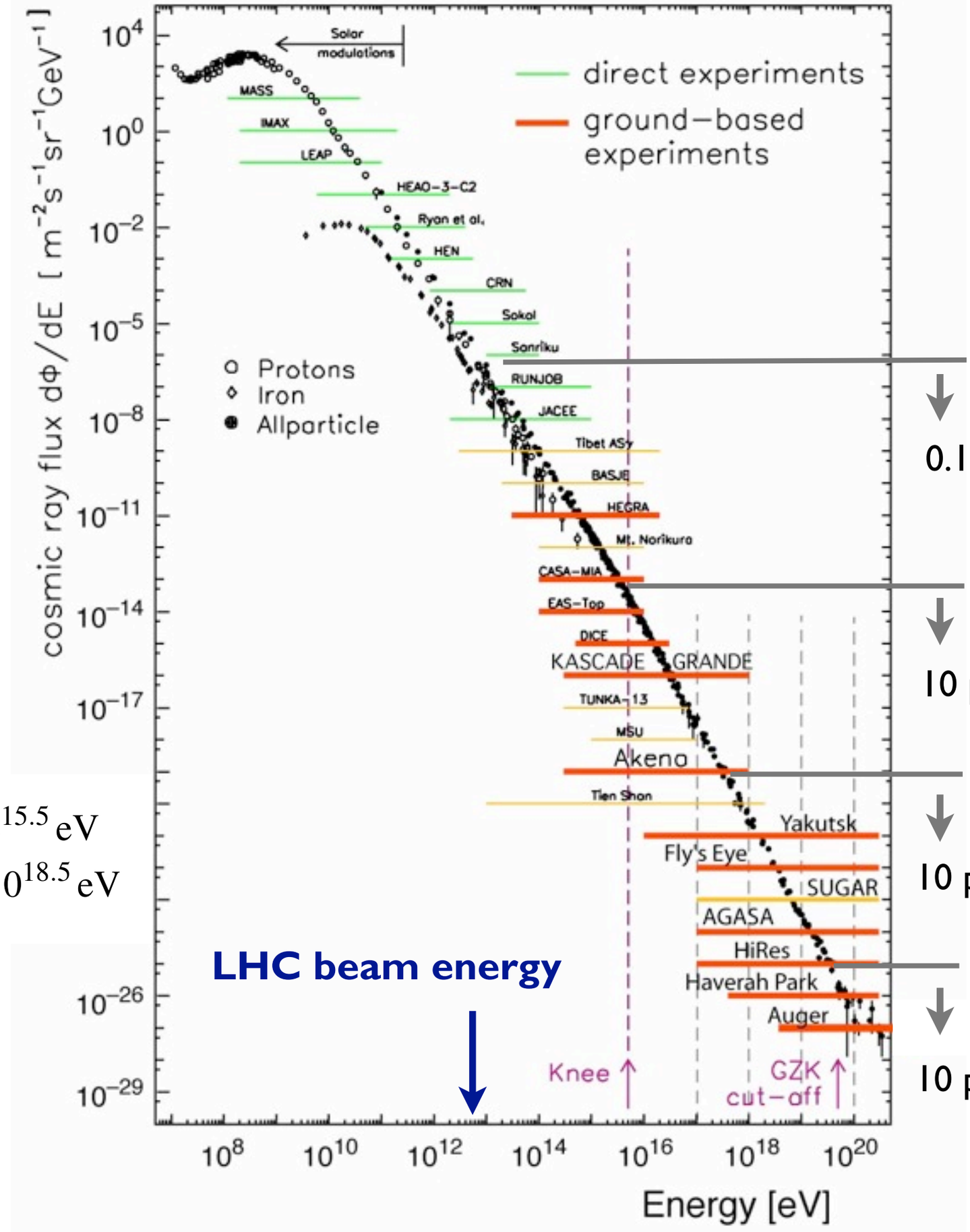
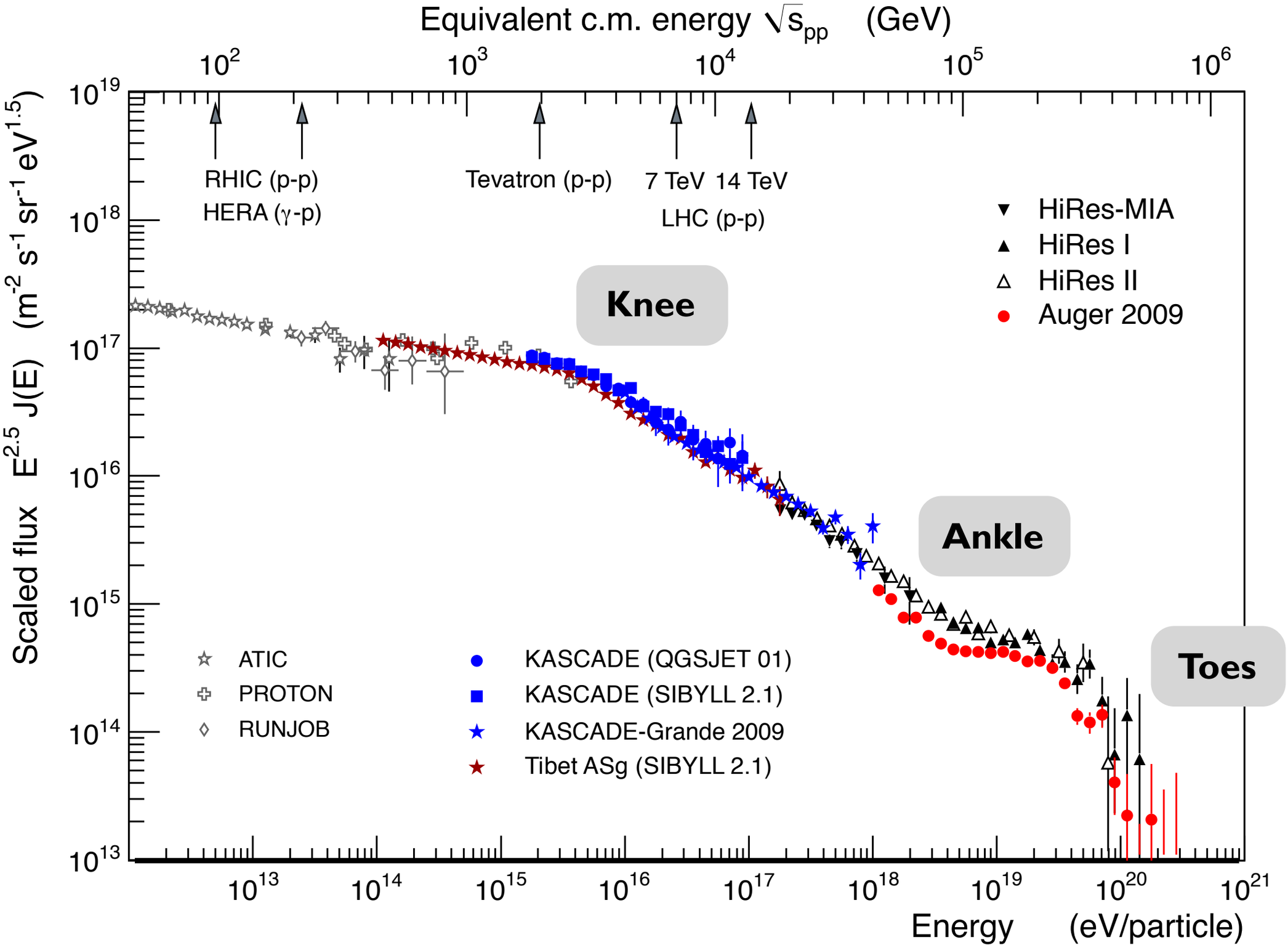
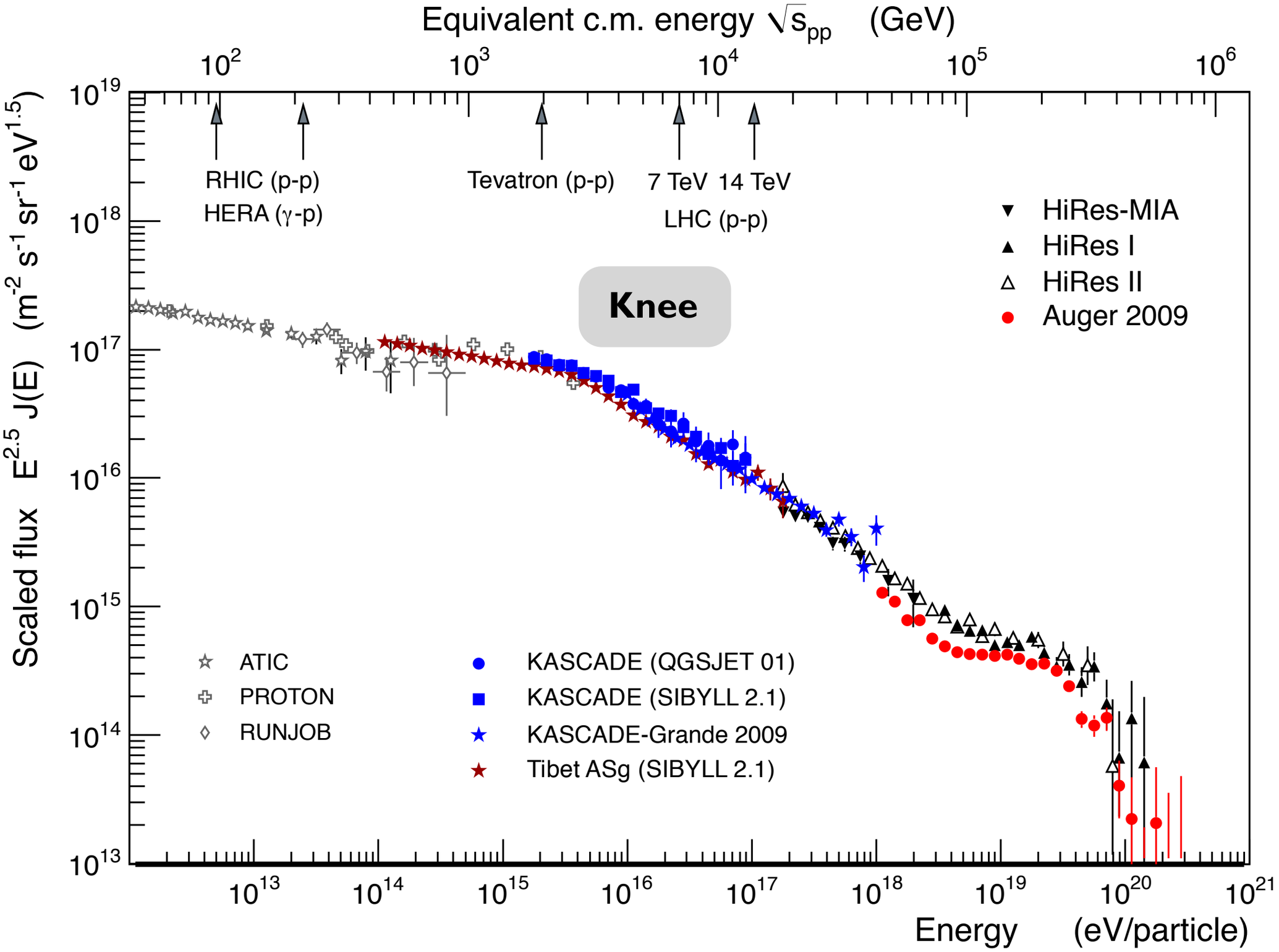


Energy spectrum of particles

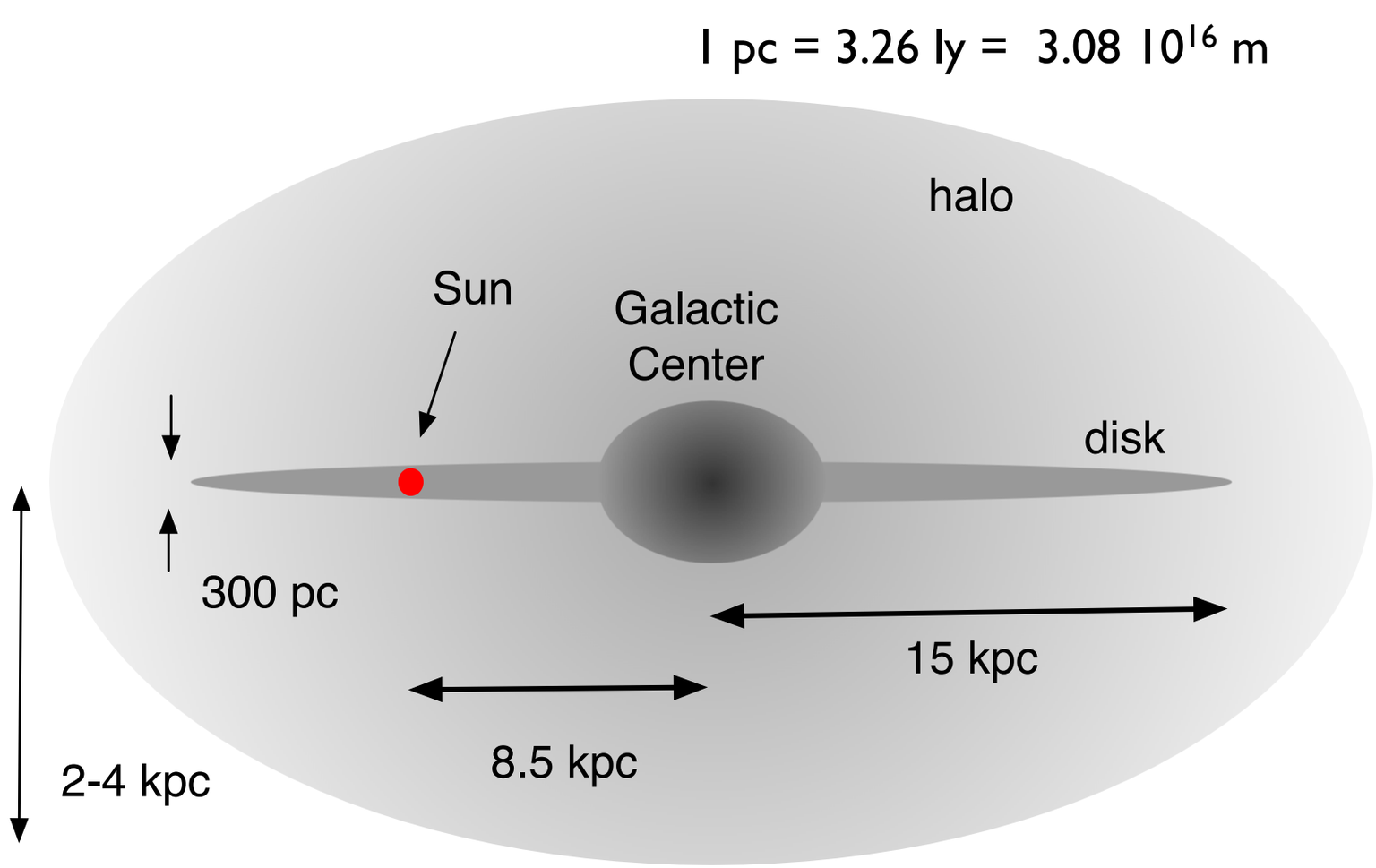


Galactic cosmic rays: the knee



Galaxy and galactic magnetic fields

(Andromeda, M31)



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 ~ (time)^2 → Extragalactic sources unlikely

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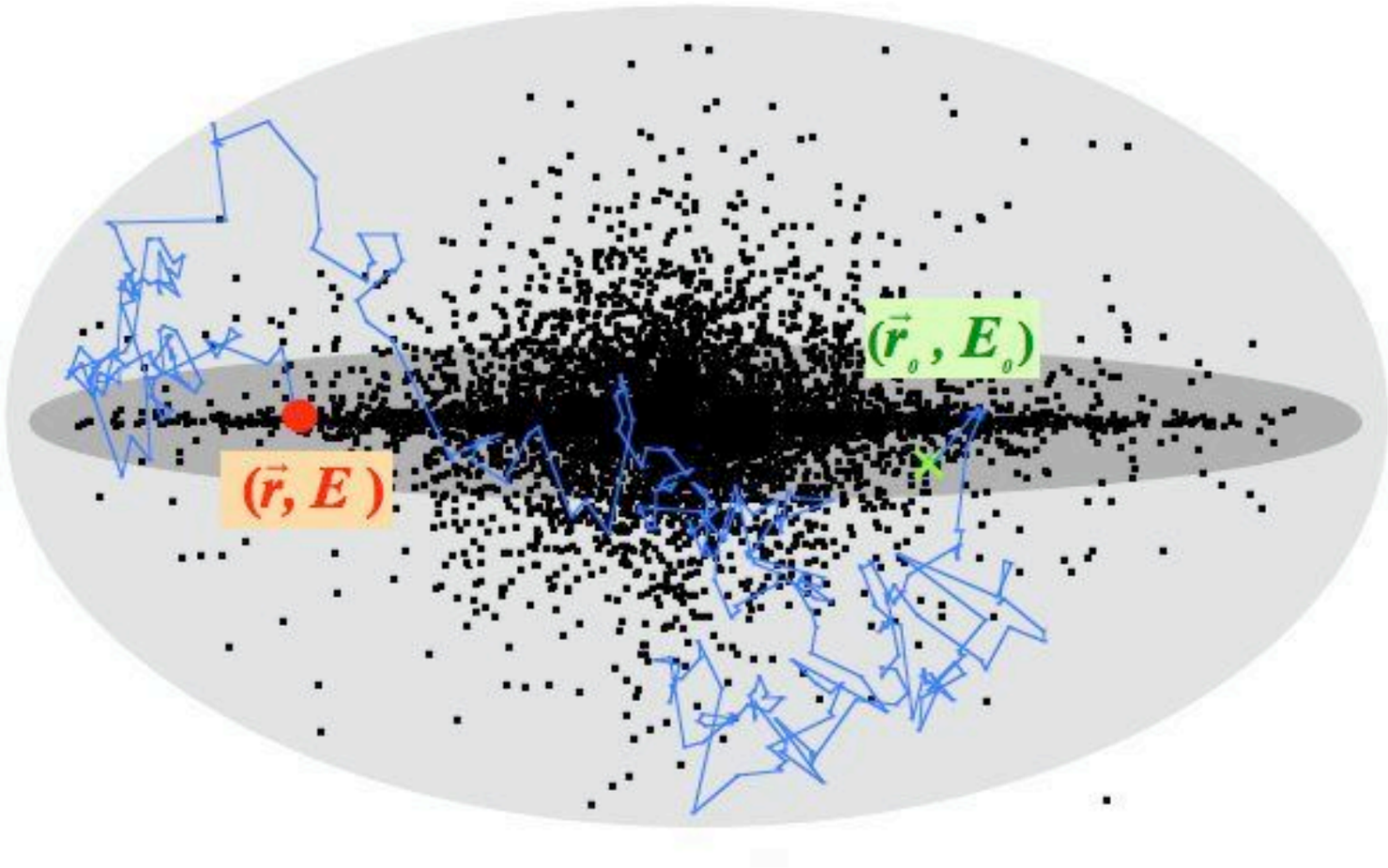

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Source candidates: Supernova remnants

SN remnant 1006 (2.2 kpc distance)

Expansion velocity ~ 7000 km/s

Observed galactic SN explosions:

1604 (Kepler)
1572 (Tycho)
1181 (Chinese astronomers)
1054 (Crab nebula)
1006 (Chinese and Arabian records)

Estimates:

~3 SN explosions / 100 yrs
Kinetic energy of ejecta: ~10^{51} erg

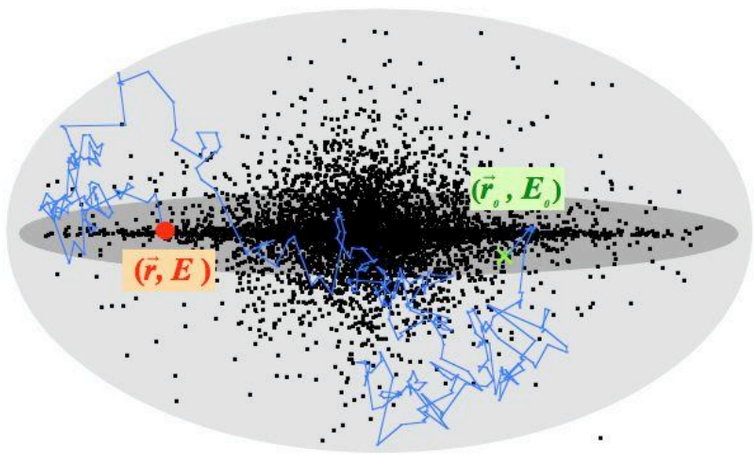
(1 erg = 0.1 μJ)

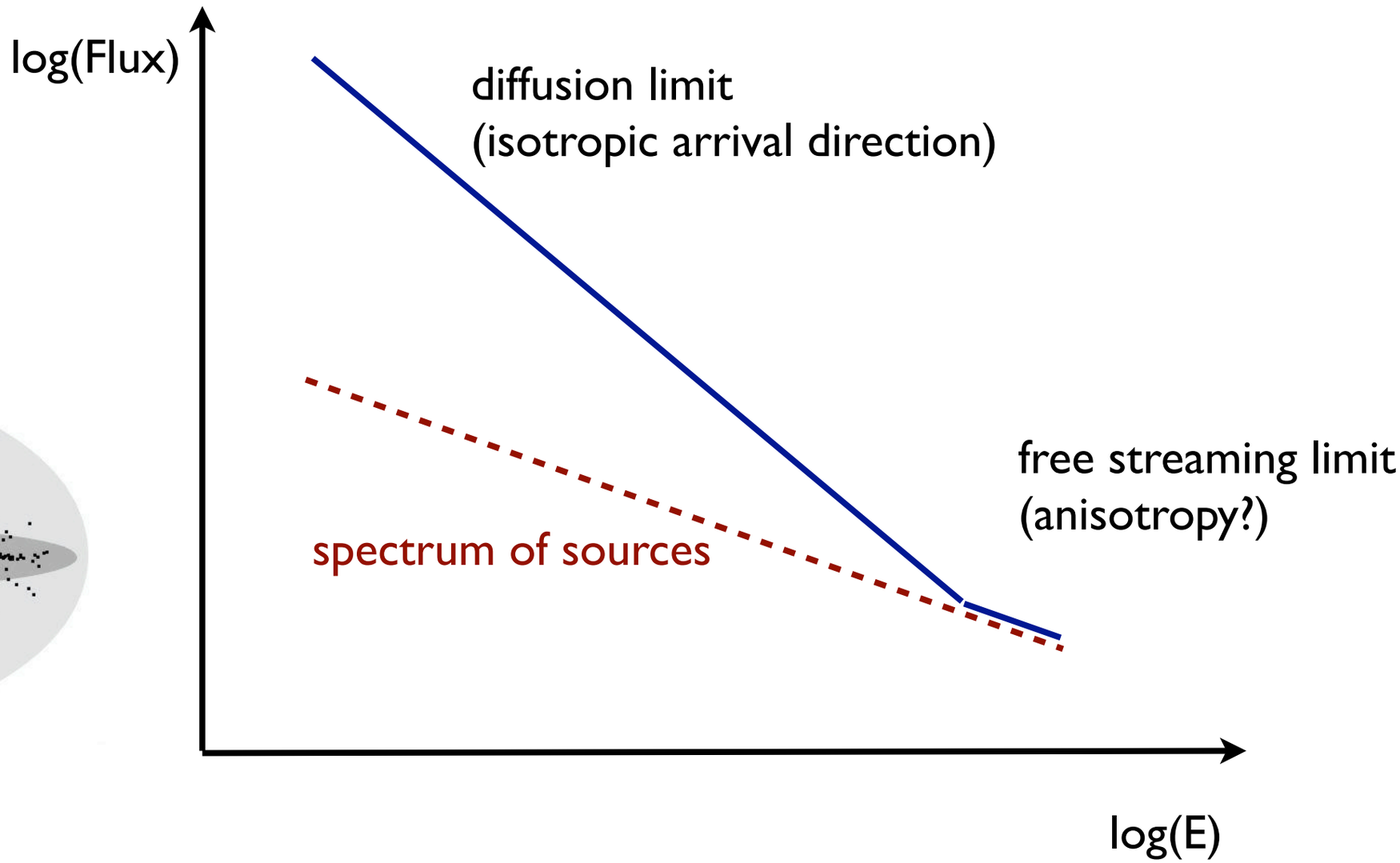
General arguments:

- Rate and energy budget
- Acceleration theory
- Elemental composition

Multi-messenger observations: gamma-rays & neutrinos – confirmation still lacking

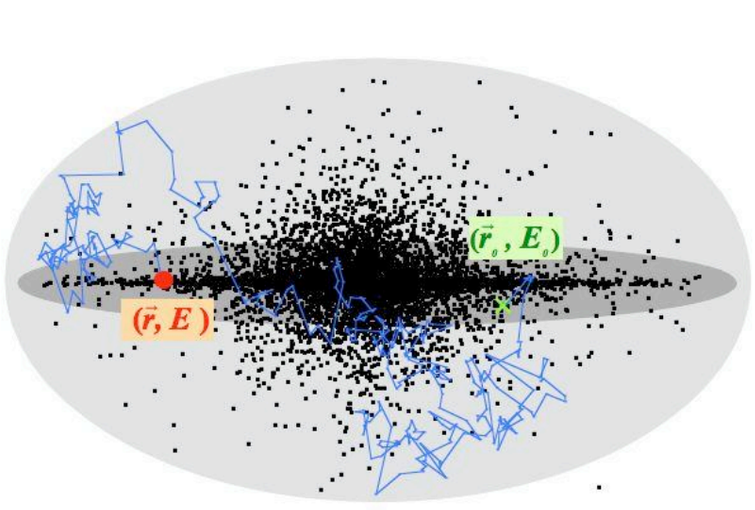
Magnetic fields: Confinement in the Galaxy (i)

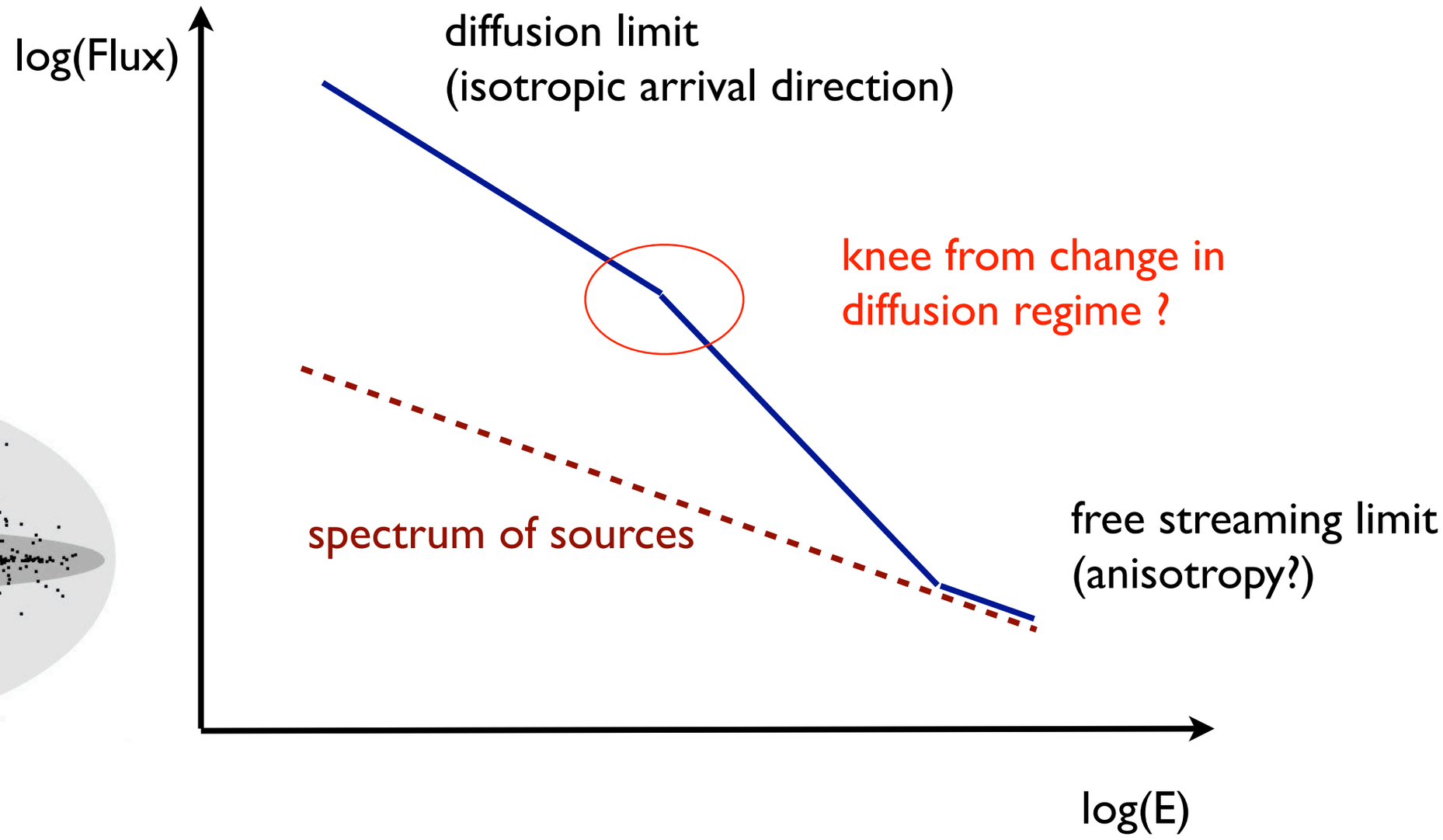




Observed spectrum softer than injection spectrum

Magnetic fields: Confinement in the Galaxy (ii)



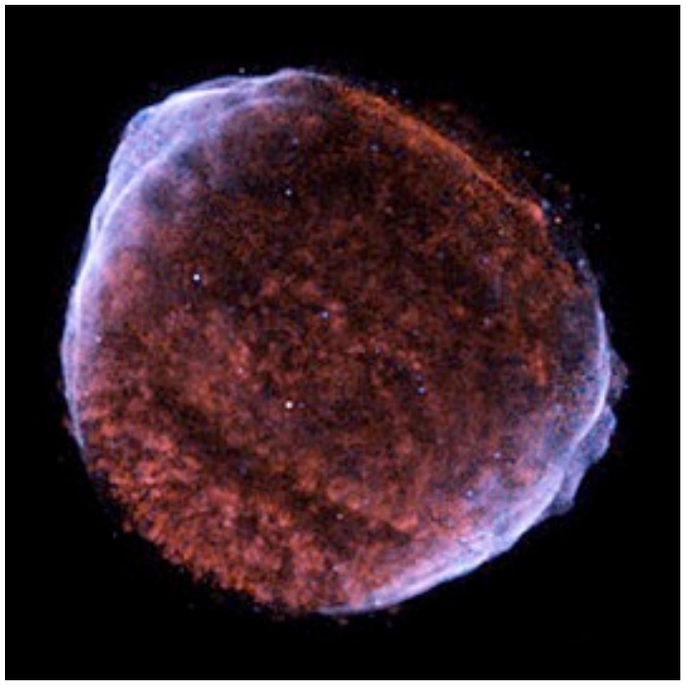


Diffusion: same behaviour for different elements at same rigidity $p/Z \sim E/Z$

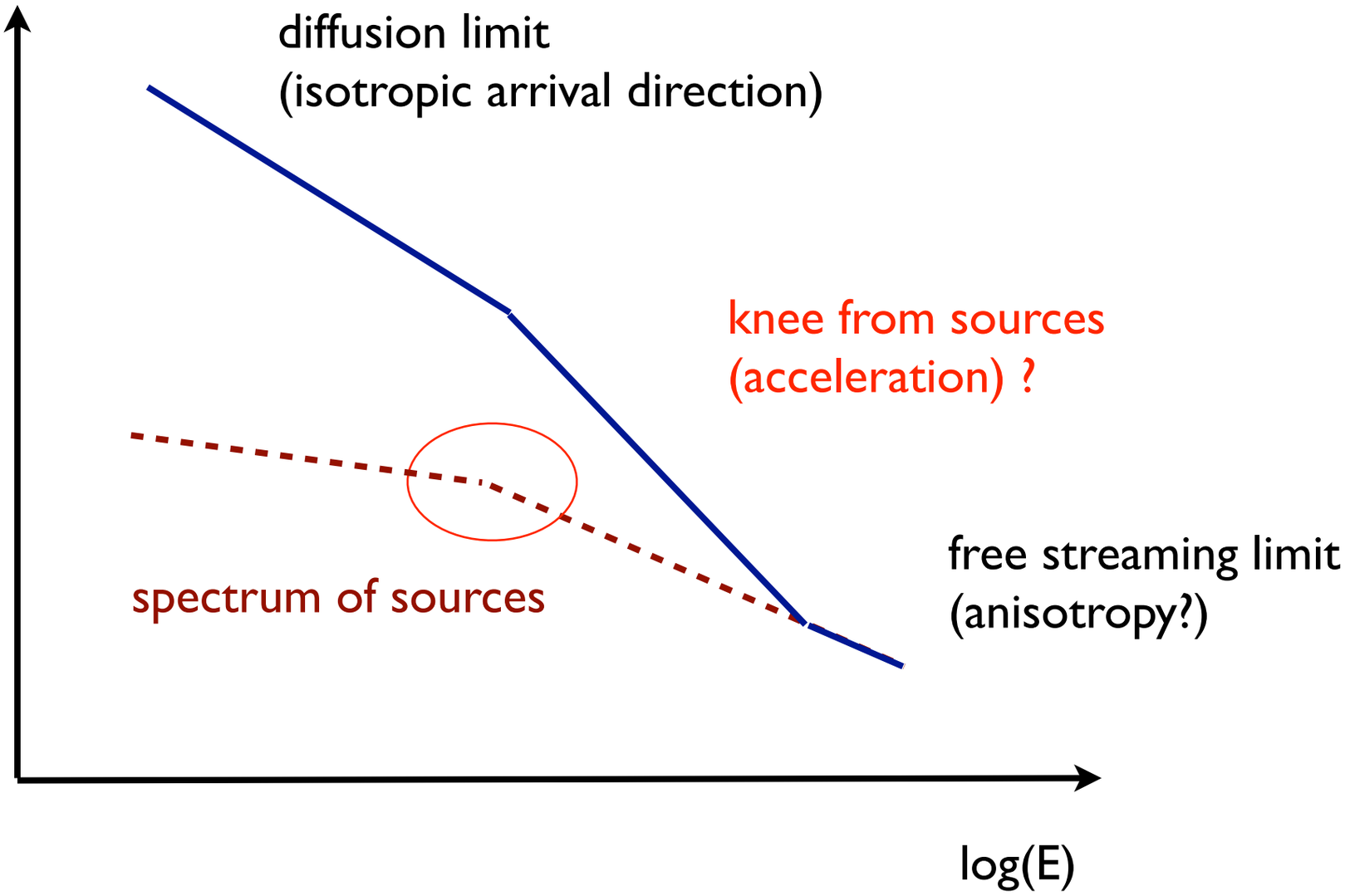
Magnetic fields: Confinement in sources

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

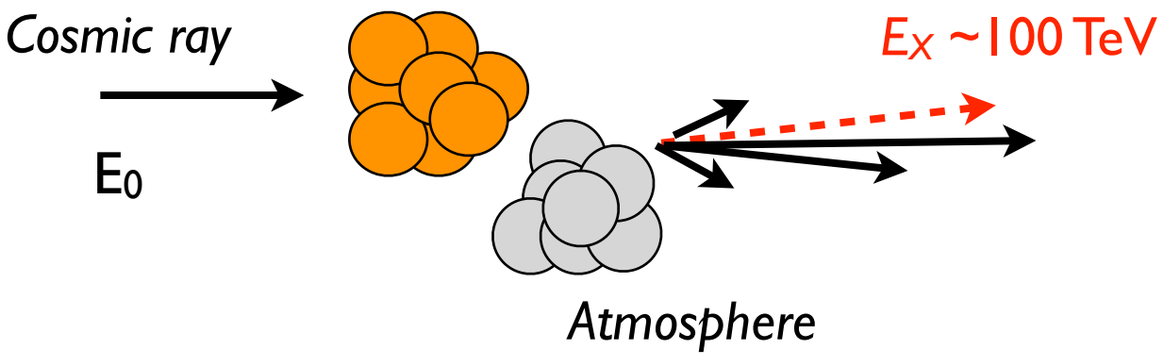
The knee and unusual events at PeV energies

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.

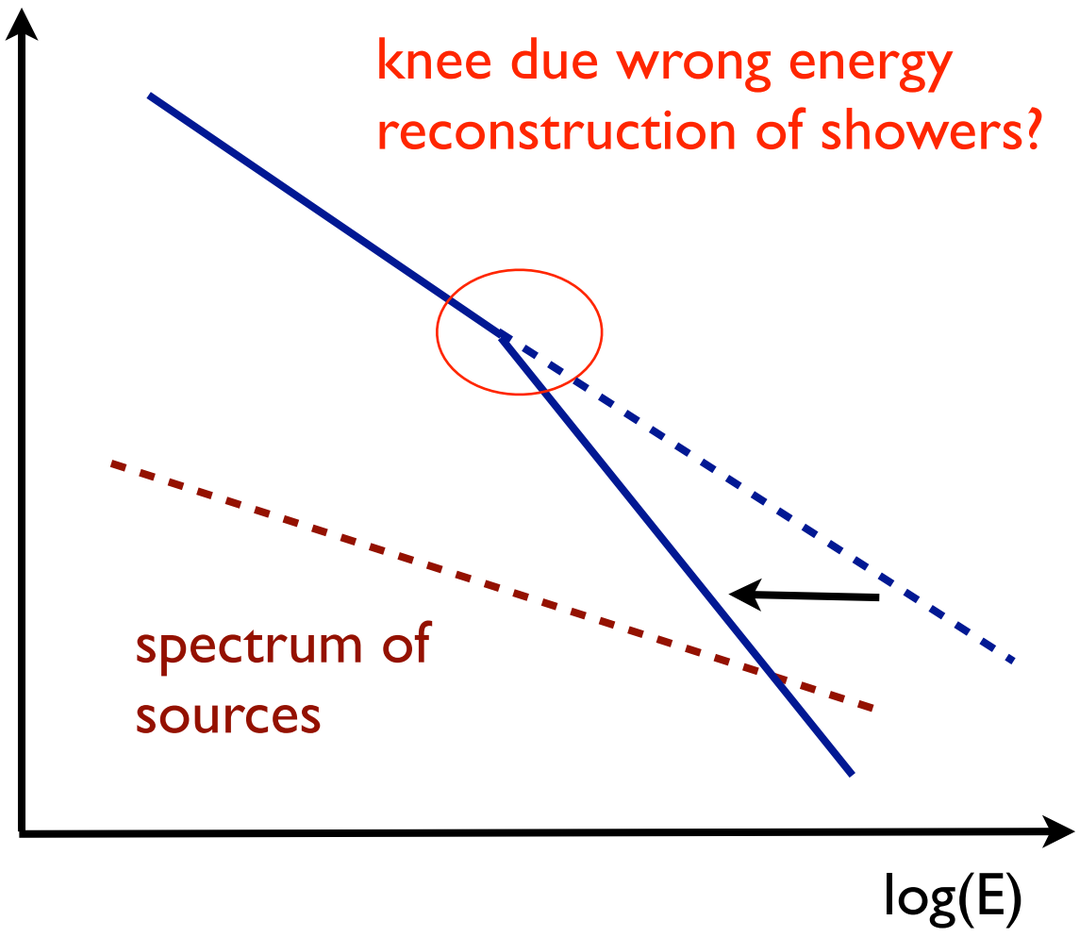


New physics, the cosmic ray spectrum knee, and pp cross section measurements

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

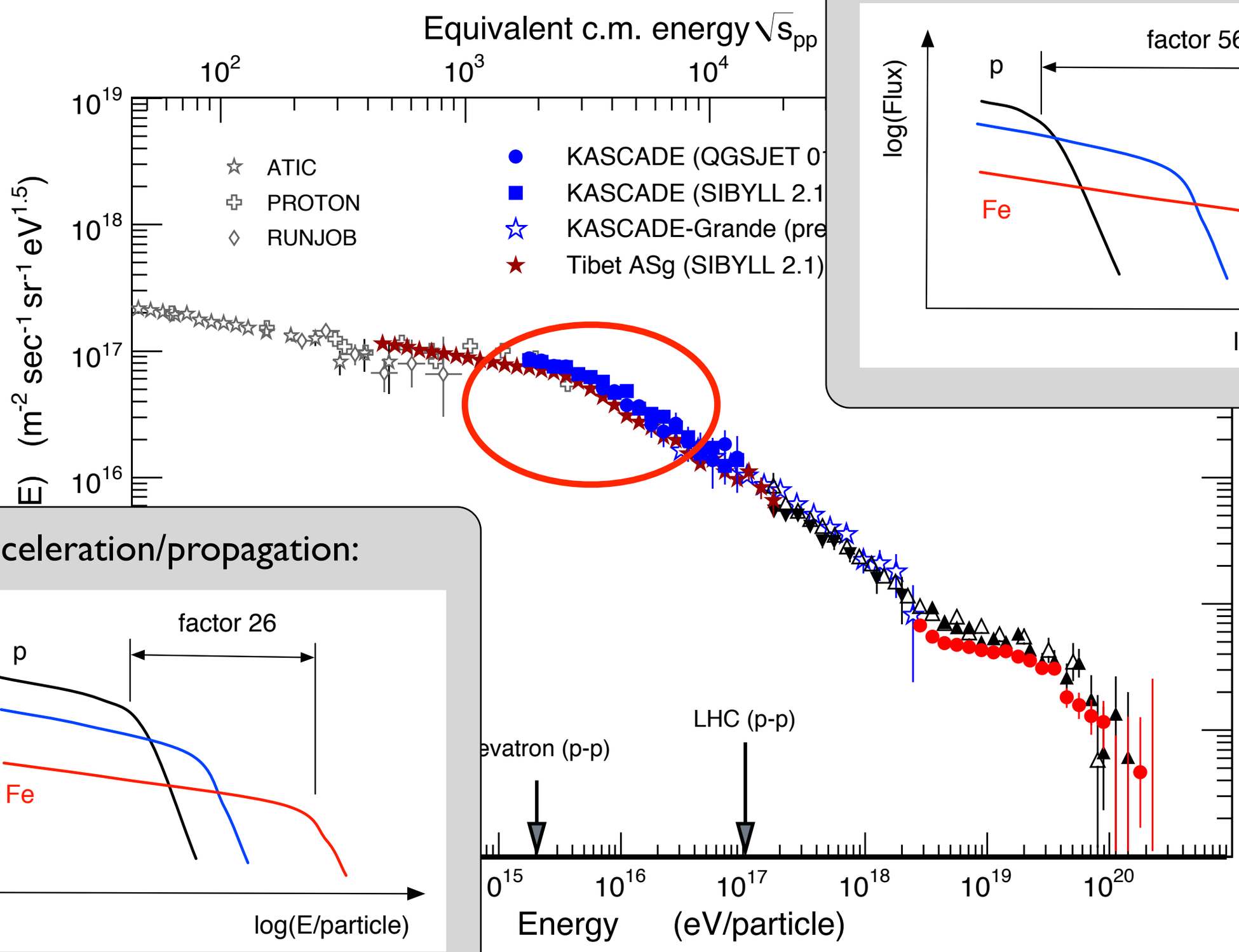
December 7, 2009

New physics: scaling with nucleon-nucleon cms energy



Threshold scales with E/A

Origin and physics of the knee

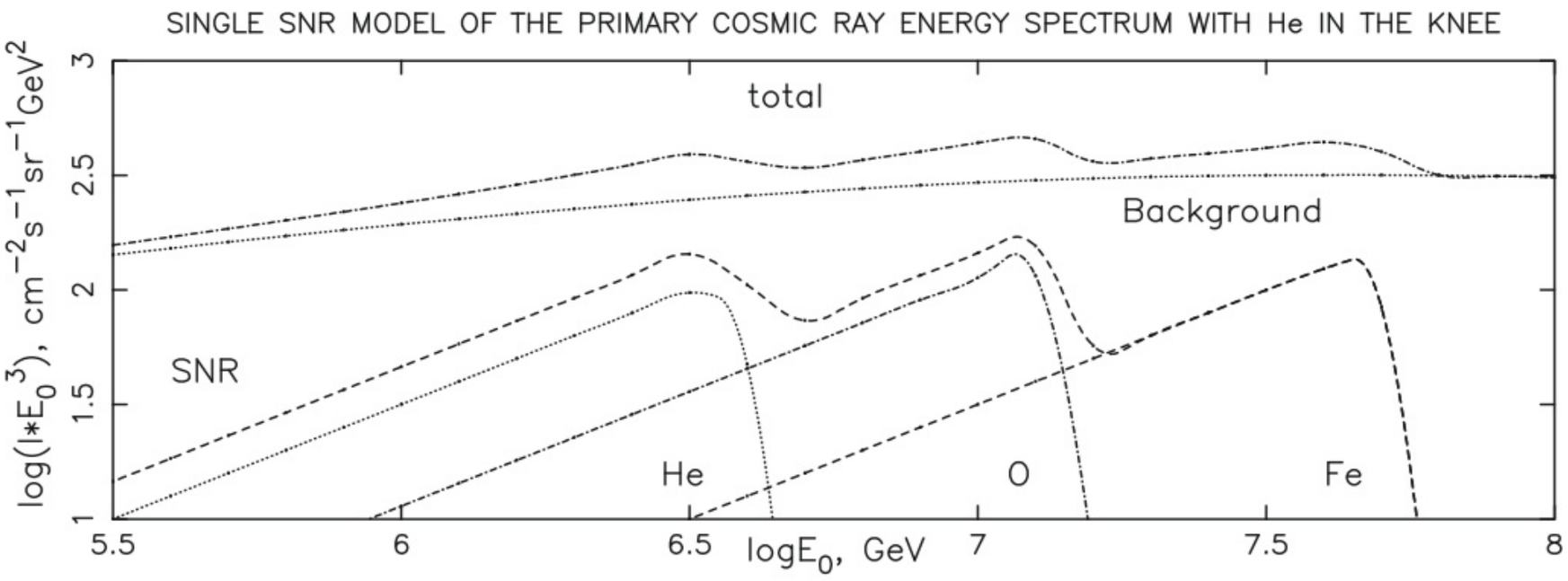


Particle physics:

Acceleration/propagation:

Some other models for the knee ...

Anisotropy likely at some level

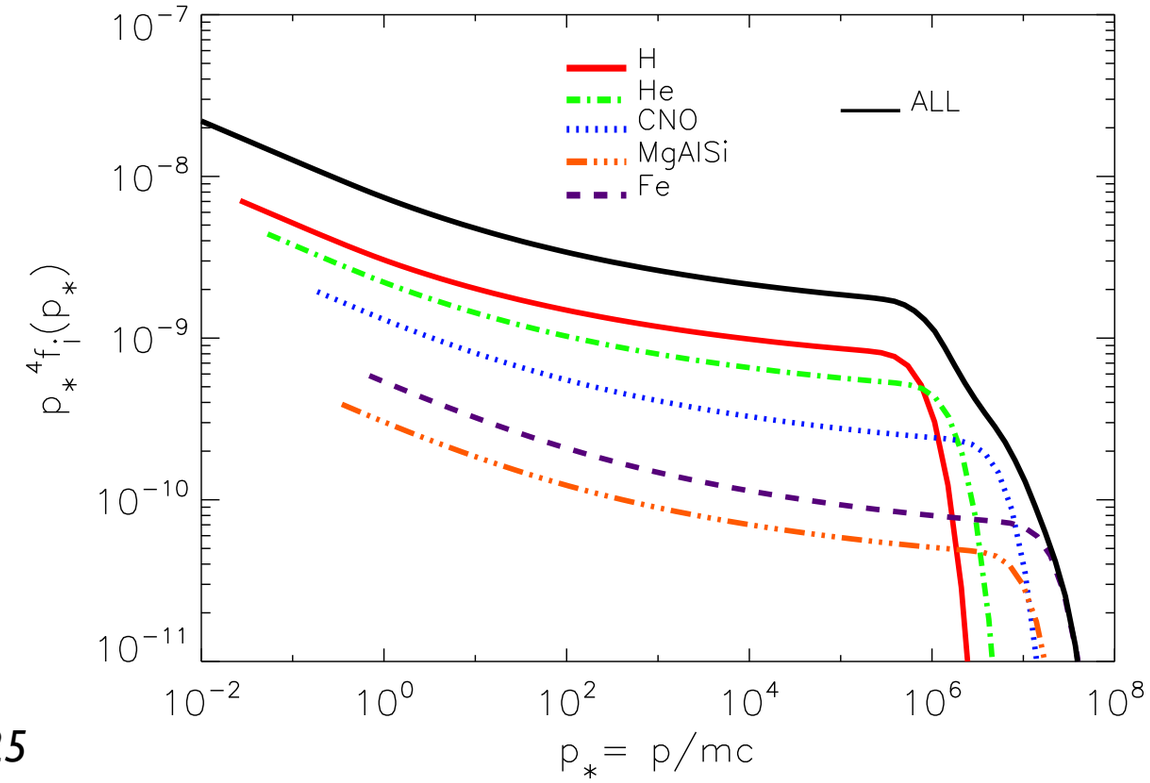


Erlykin & Wolfendale, J.Phys.G32:1-8,2006

Non-linear shock acceleration

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

Magnetic field amplification, similar end values for different environments

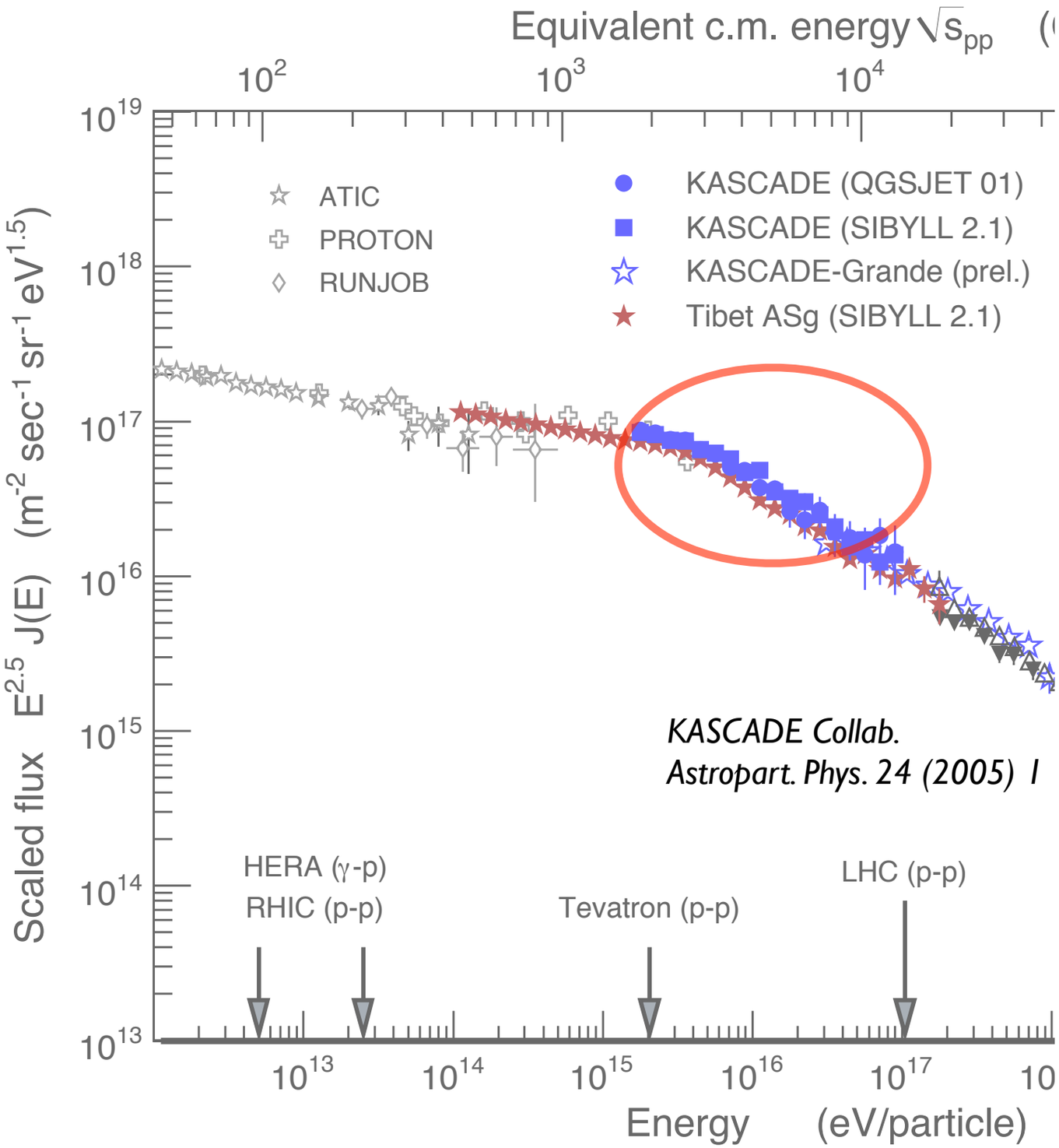


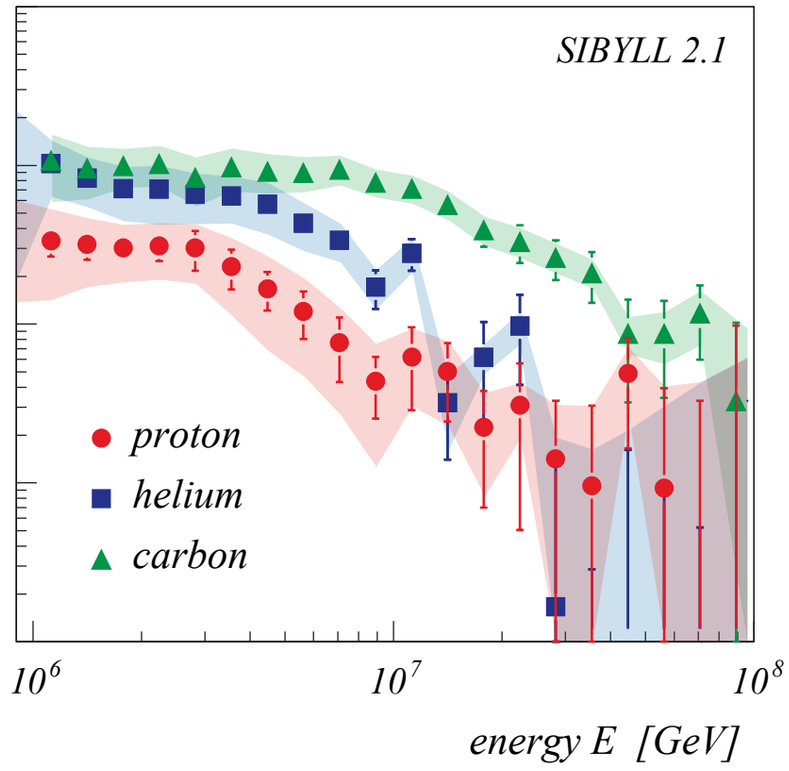
Caprioli, Blasi, Amato, astro-ph/1007.1925

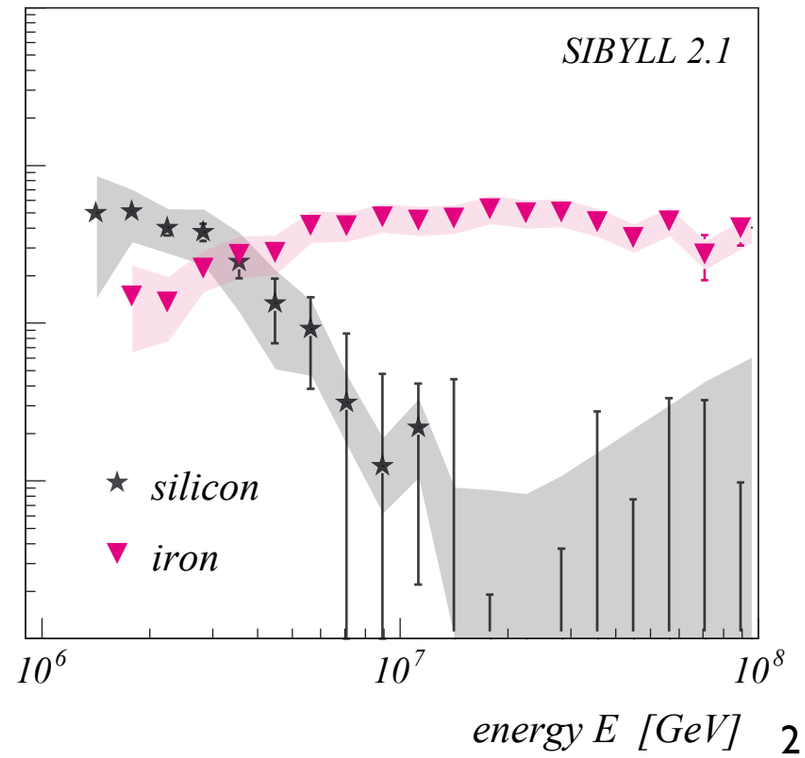
KASCADE

Area ~ 0.04 km^2,
252 surface detectors

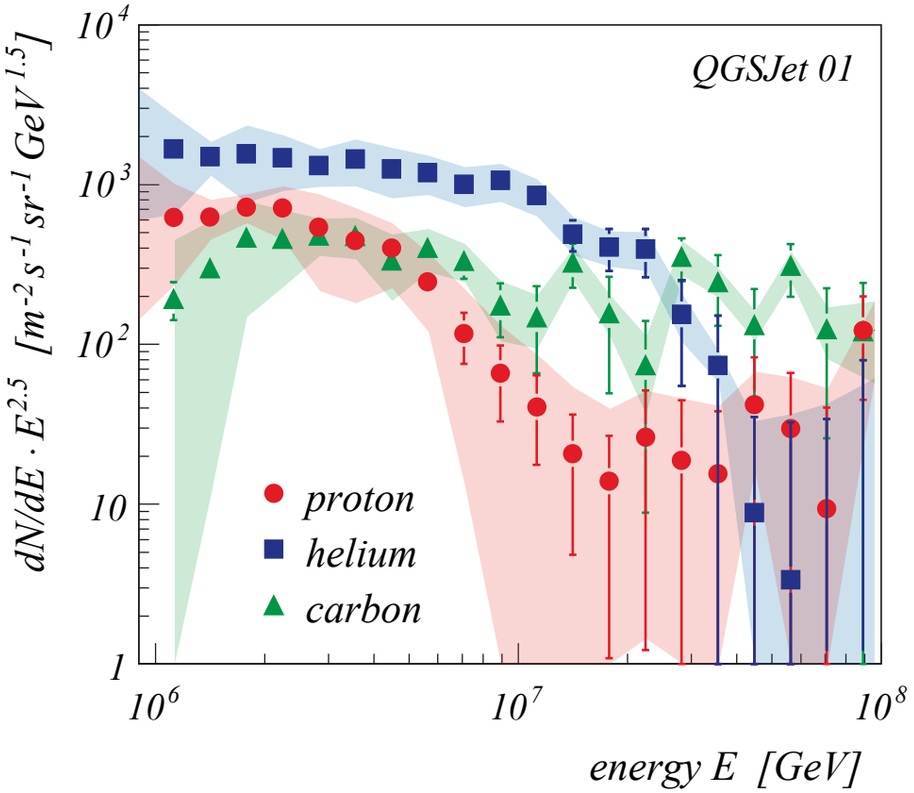
Composition in Knee region (i)

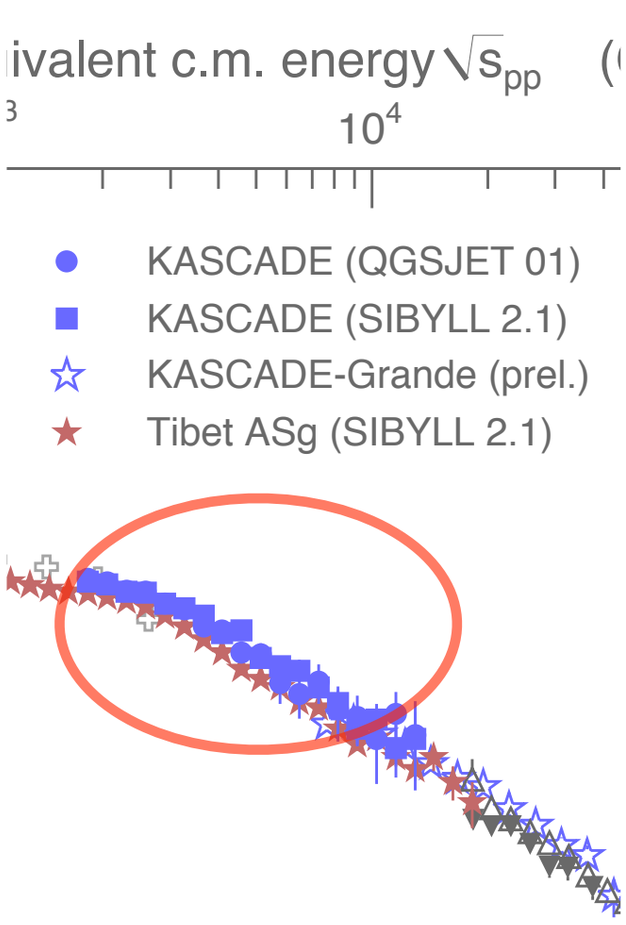


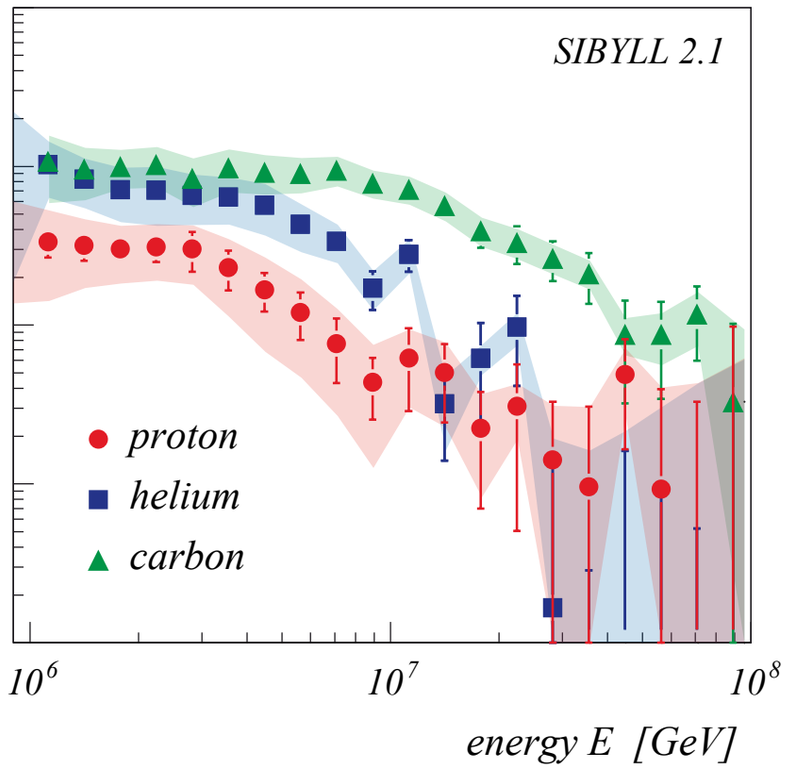


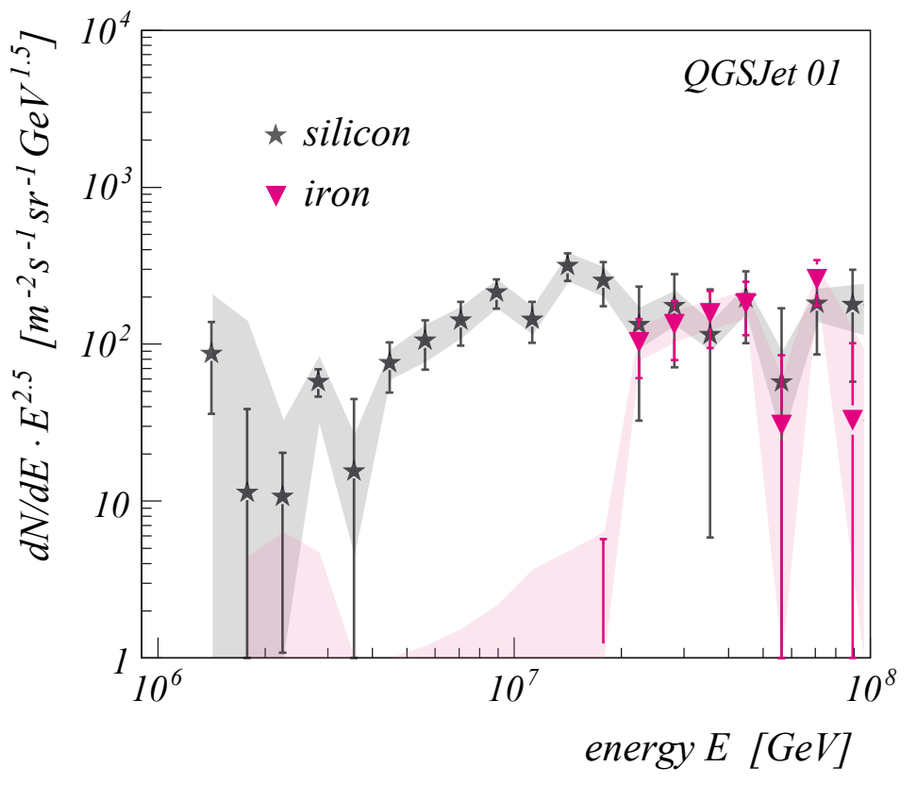


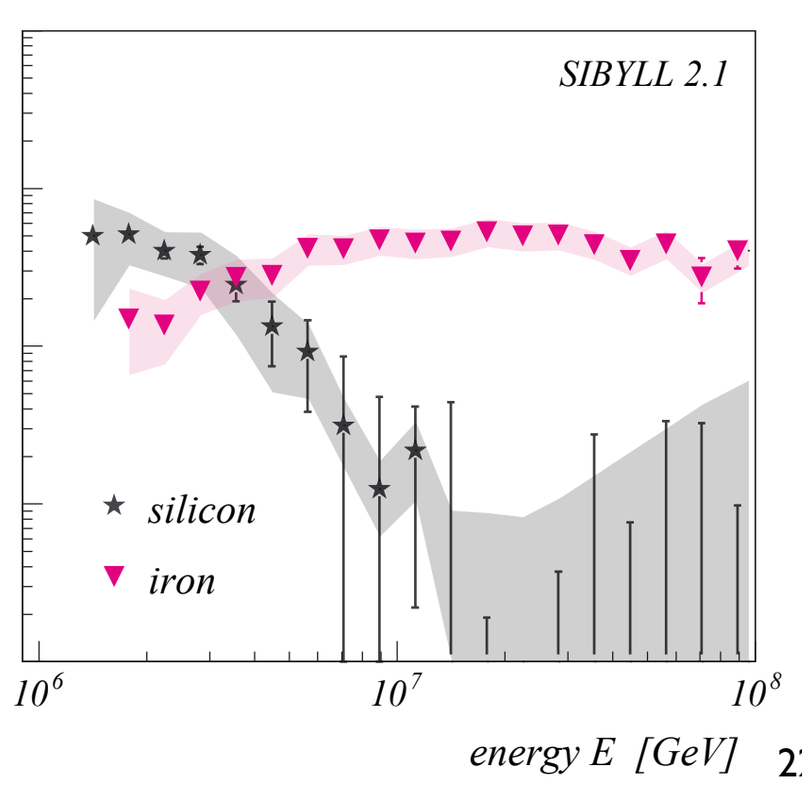
Composition in Knee region (ii)



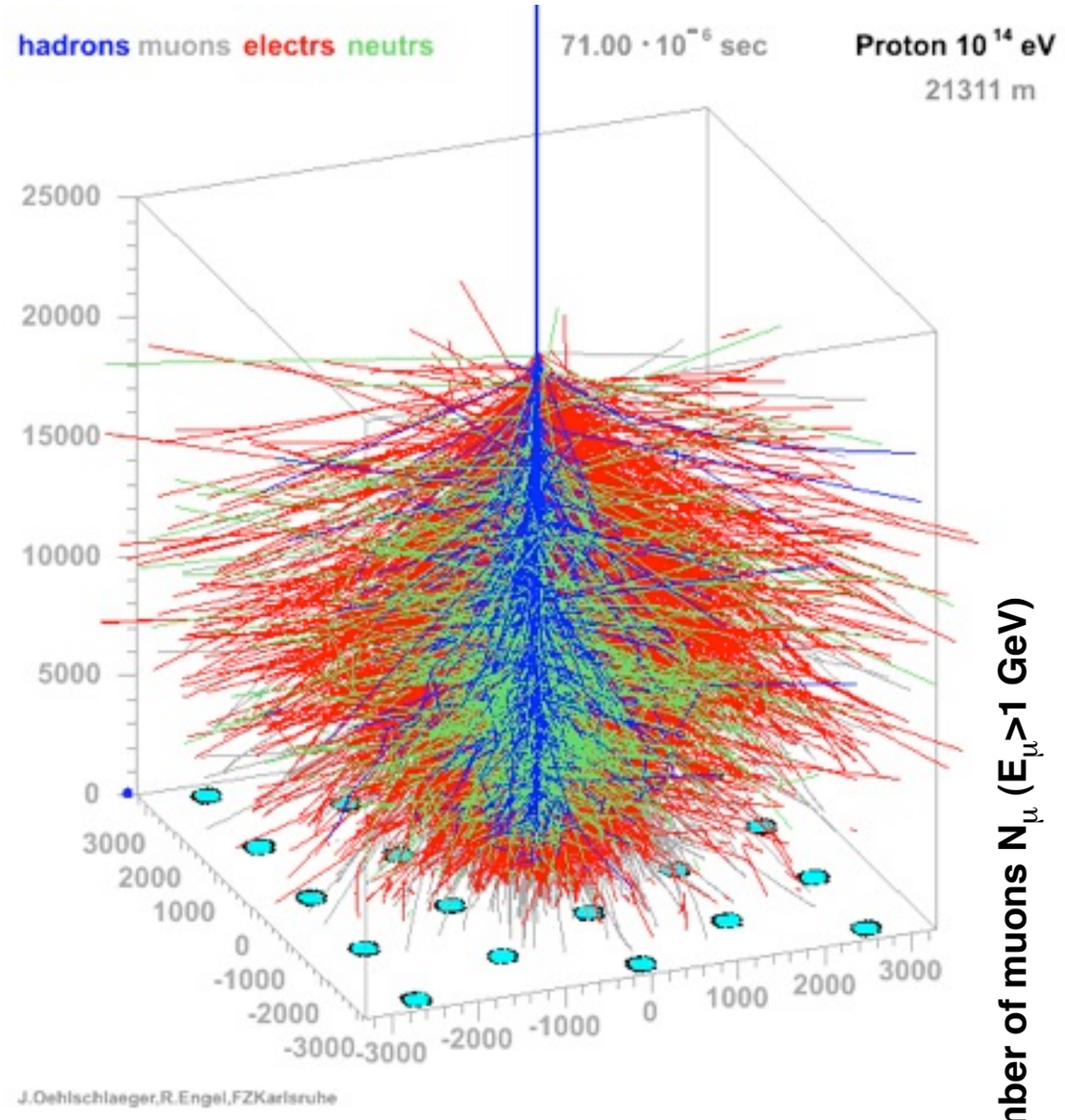






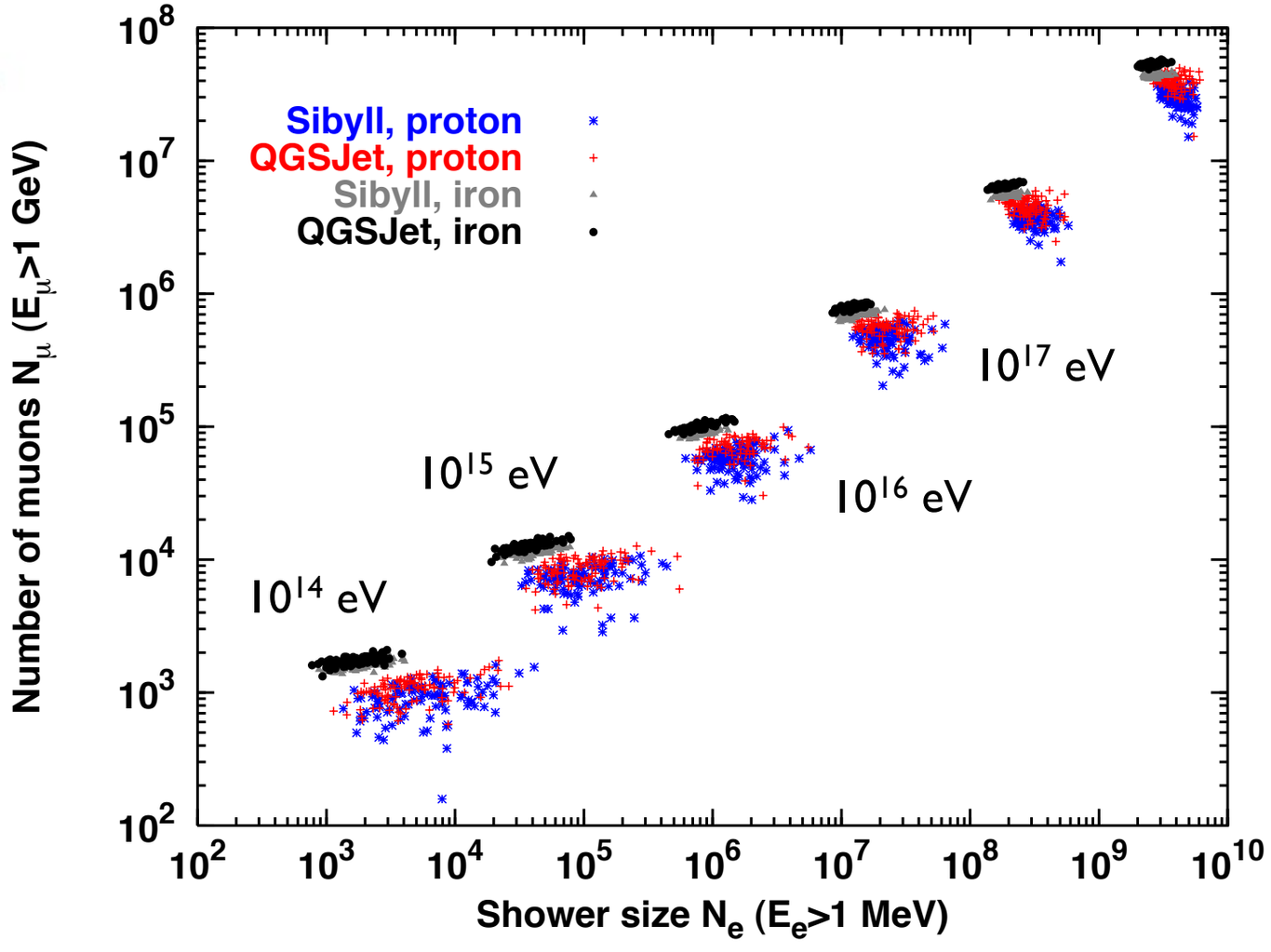


Air shower ground arrays

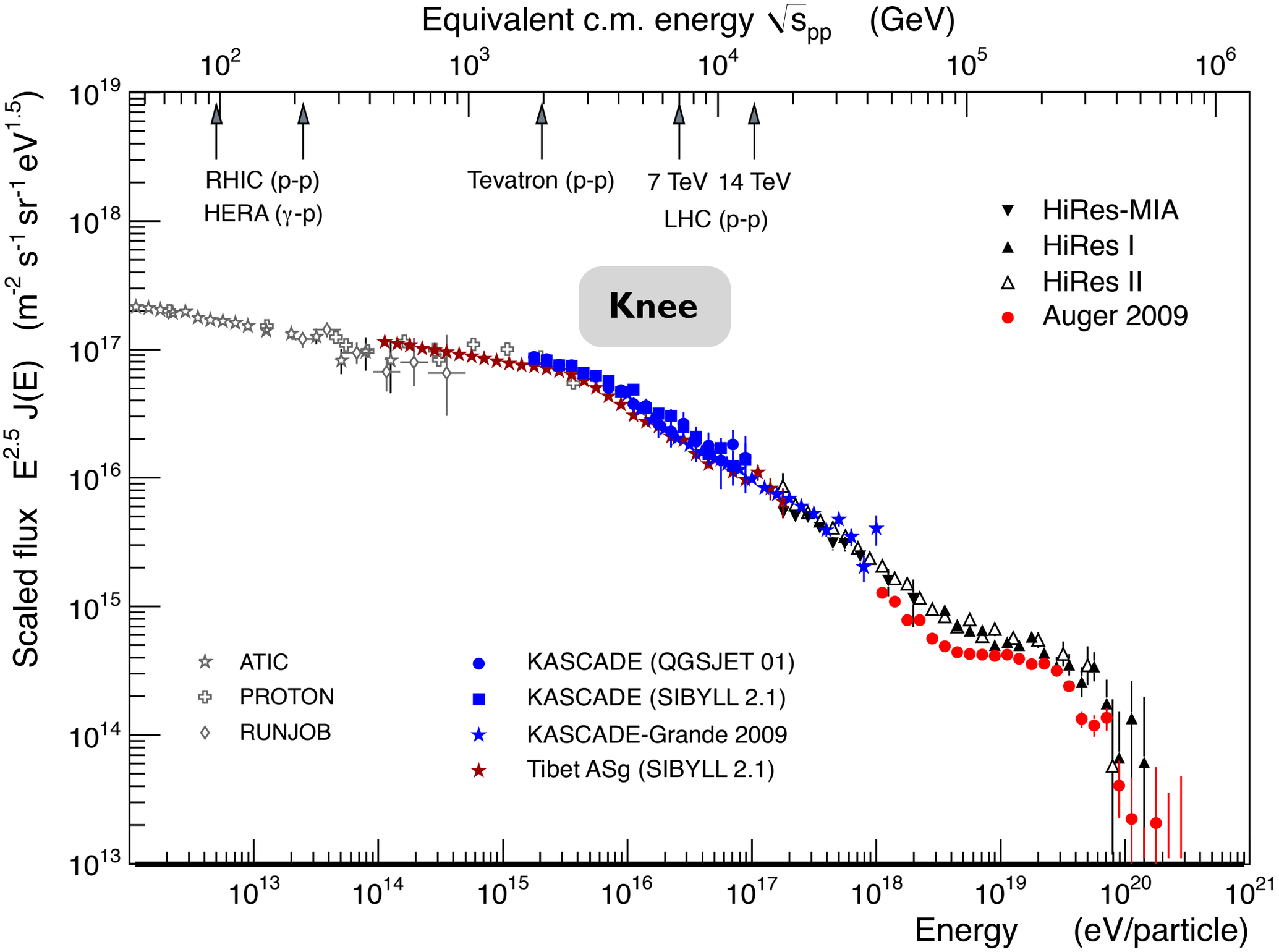


Example:
KASCADE-Grande (Karlsruhe)

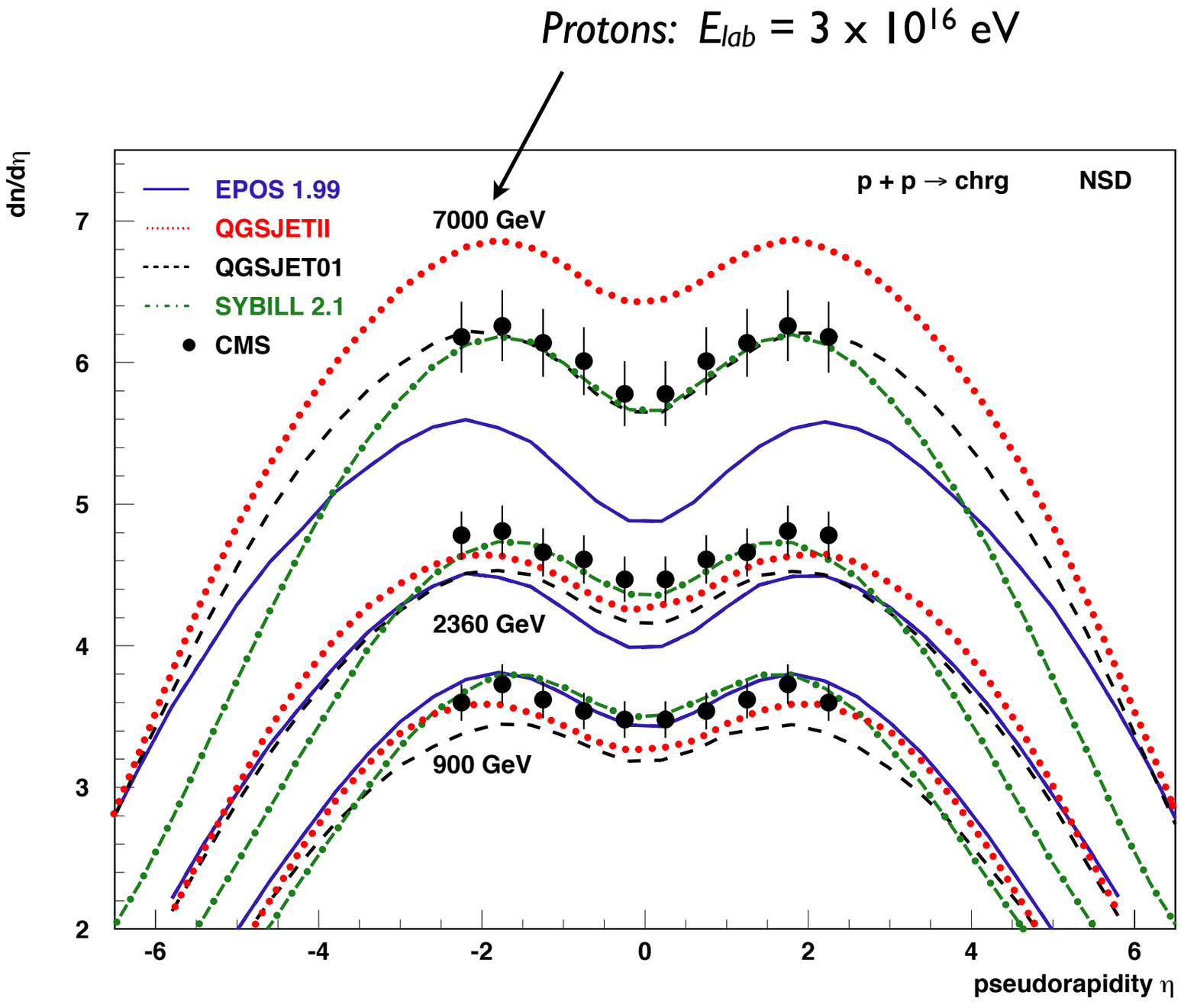
Combined energy-composition analysis



Galactic cosmic rays: the knee



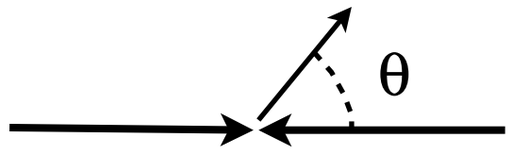
LHC: distribution of charged secondary particles



Detailed LHC comparison

D. D'Enterria, RE, T. Pierog, S. Ostapchenko (astro-ph/1101.5596)

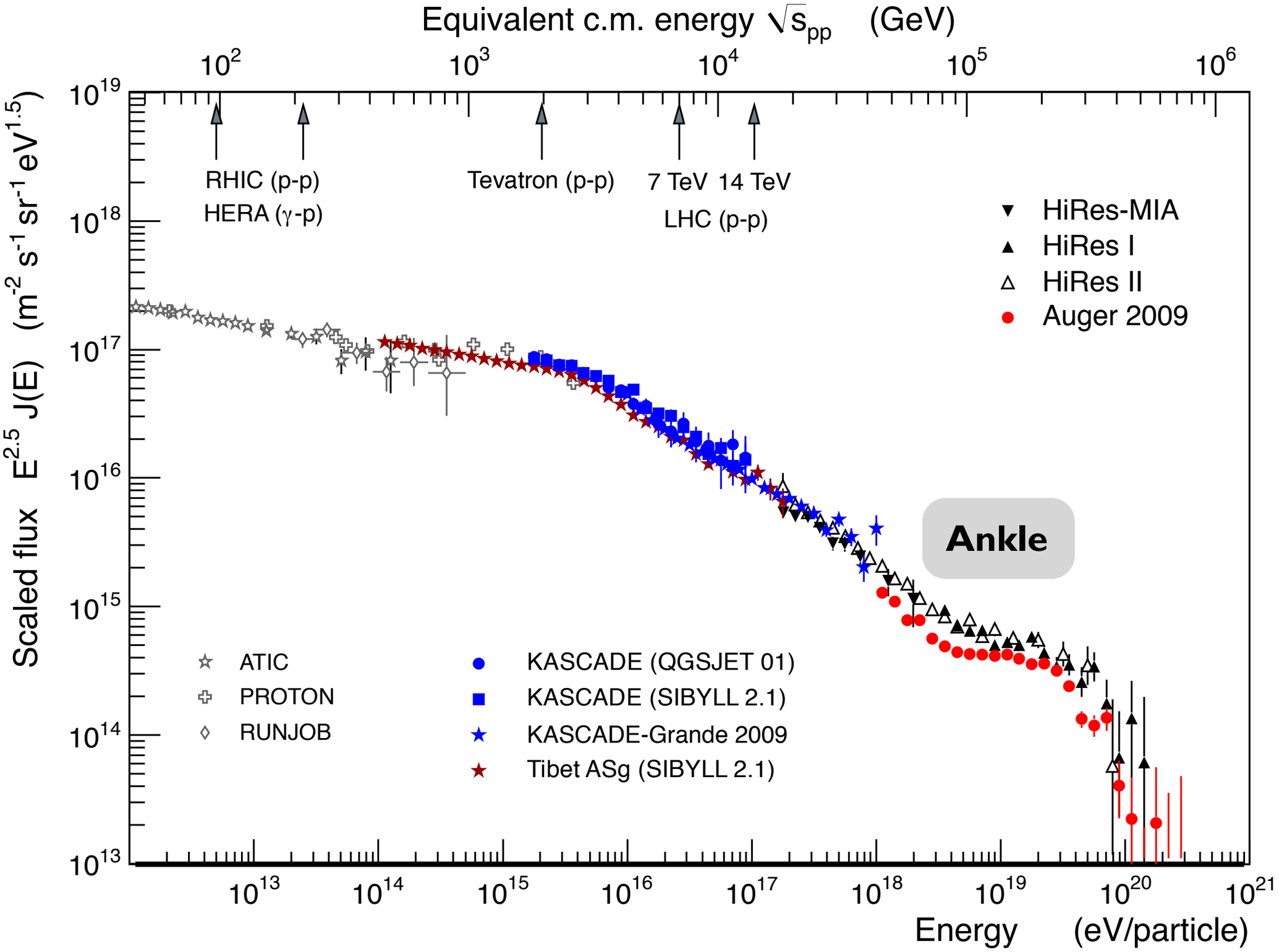
Significant improvement of models expected



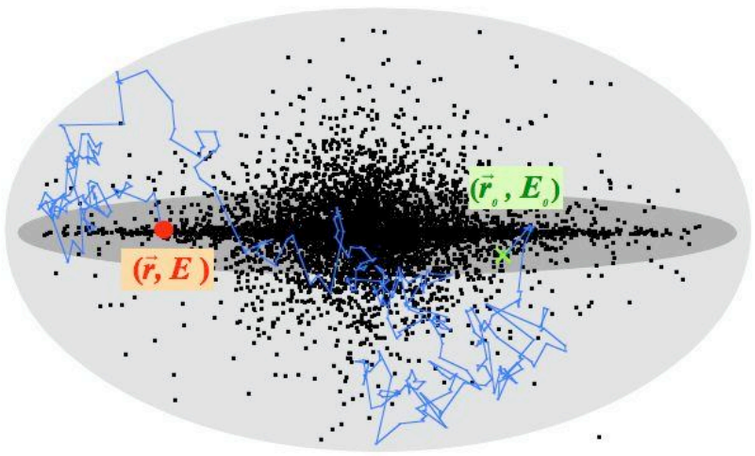
$$\eta = -\ln\tan\frac{\theta}{2}$$

LHC: Exotic scenatios for knee very unlikely
~20% of primary energy should be transferred to invisible particles

Transition to extragalactic sources: the ankle



Ankle as transition to free-streaming limit ?



log(Flux)

diffusion limit
(isotropic arrival direction)

knee from change in
diffusion regime ?

spectrum of sources

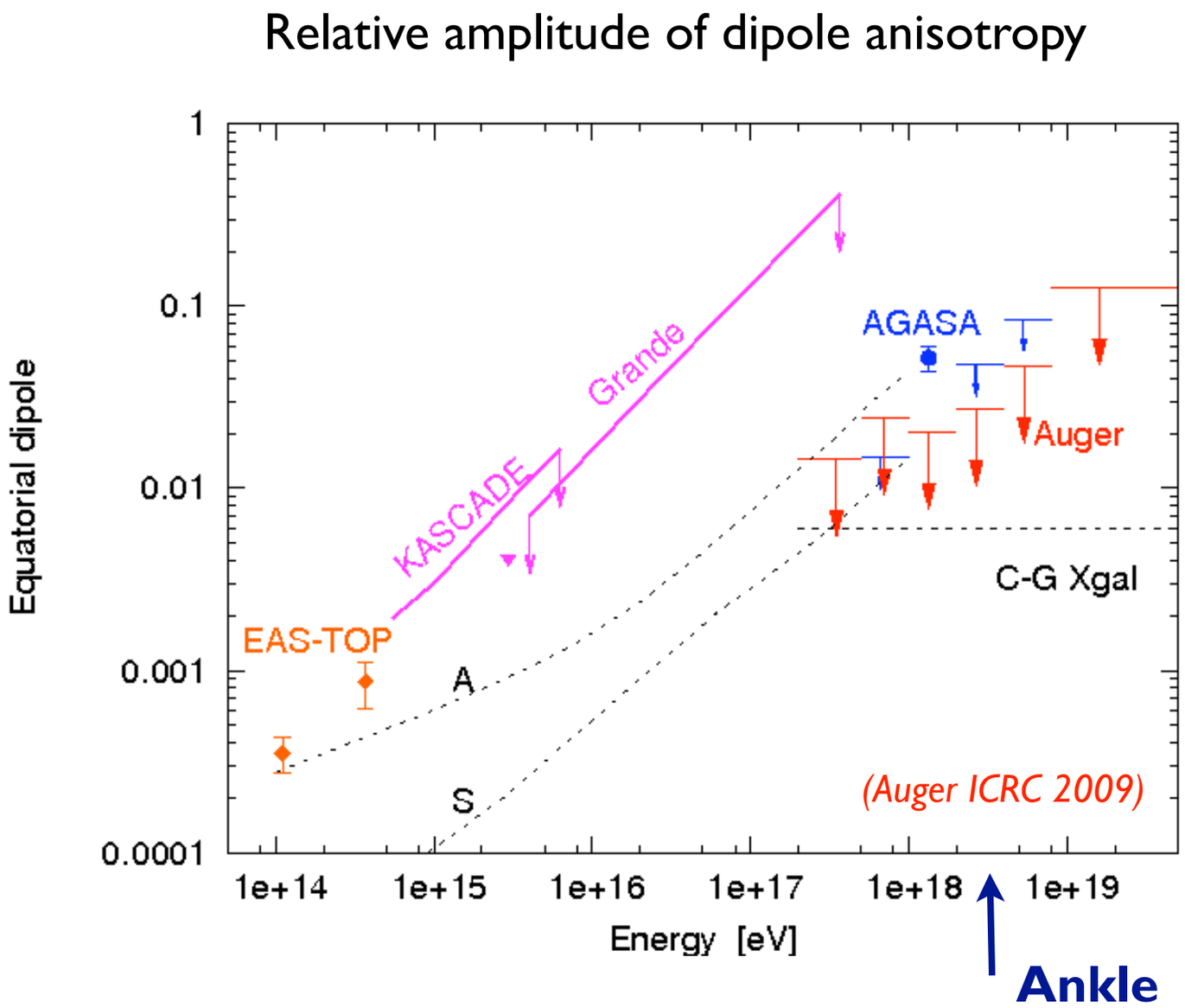
free streaming limit
(anisotropy?)

log(E)

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

Earth not in center of Galaxy: strong anisotropy expected

Arrival direction distribution of cosmic rays



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

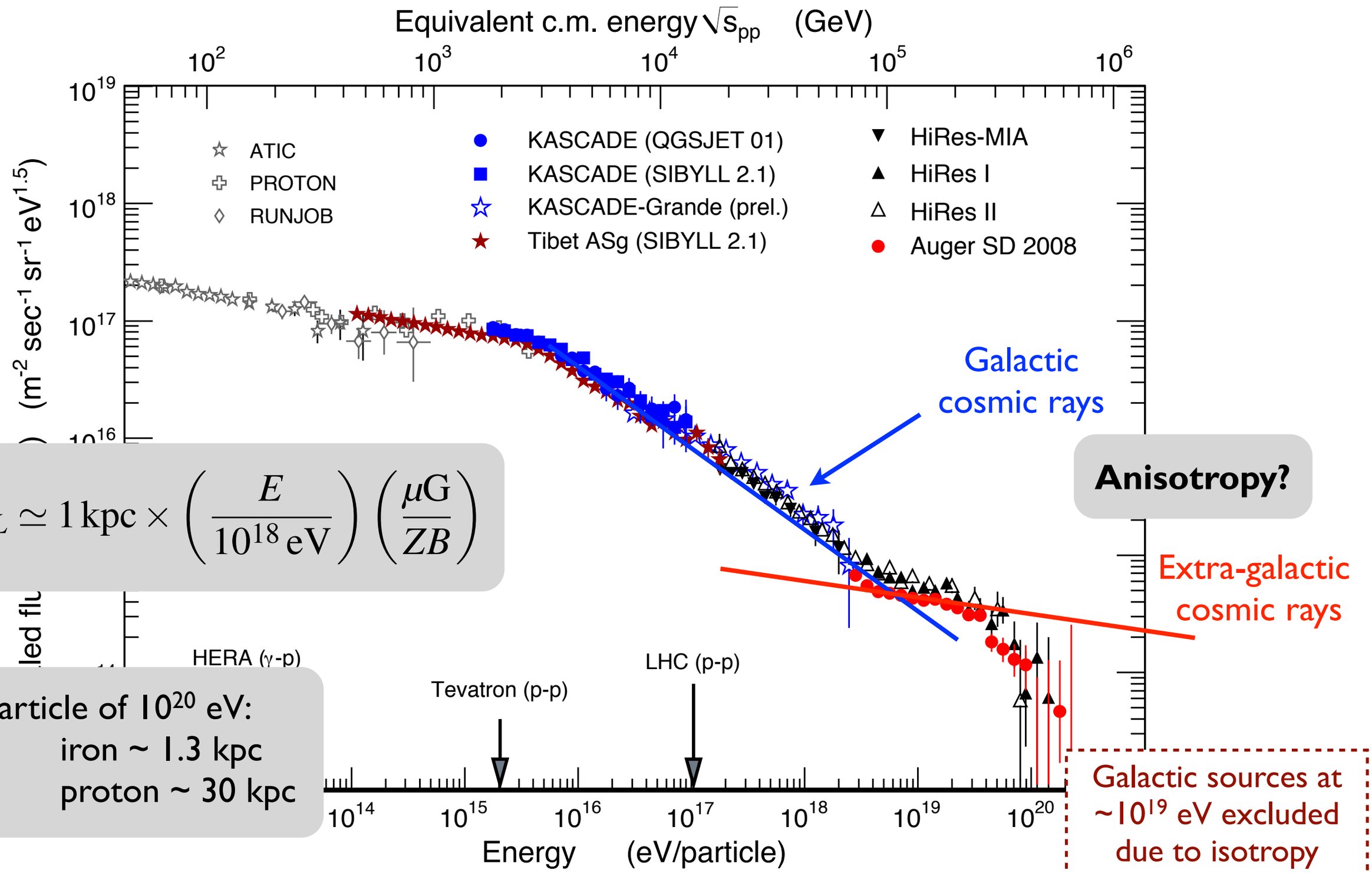
Transition between galactic and extragalactic sources

Dipole anisotropy expected from galactic diffusion (large for protons, small for heavy nuclei)

No anisotropy expected for extragalactic sources (independent of composition)

No anisotropy below 6 x 10^{19} eV found: interpretation of ankle unclear

Transition to extra-galactic sources ?



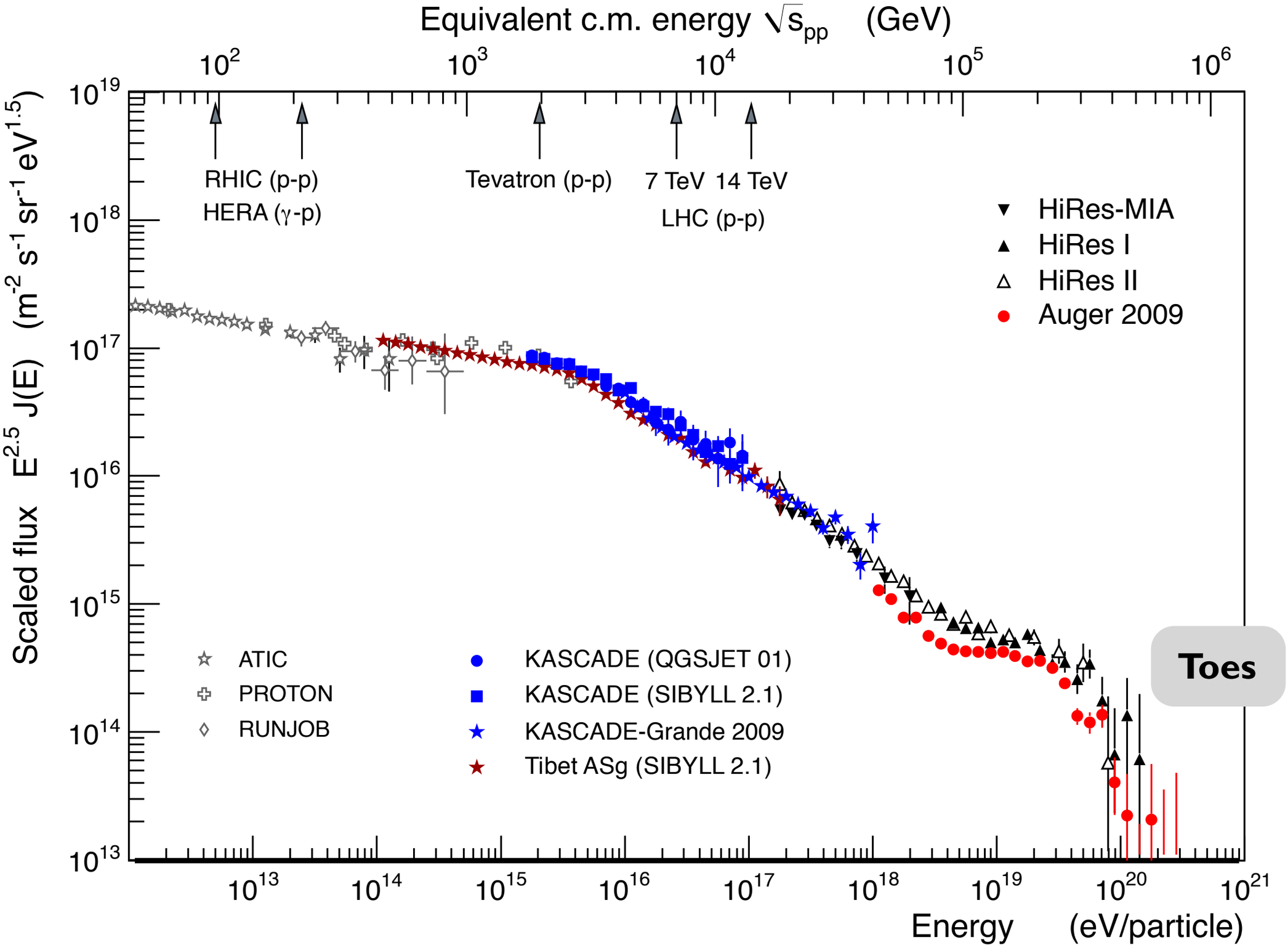
$$R_L \simeq 1\,\mathrm{kpc} \times \left(\frac{E}{10^{18}\,\mathrm{eV}}\right)\left(\frac{\mu\mathrm{G}}{ZB}\right)$$

Anisotropy?

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

Galactic sources at ~10^{19} eV excluded due to isotropy

The upper end of the energy spectrum



Problem 1: Sources must be extreme objects

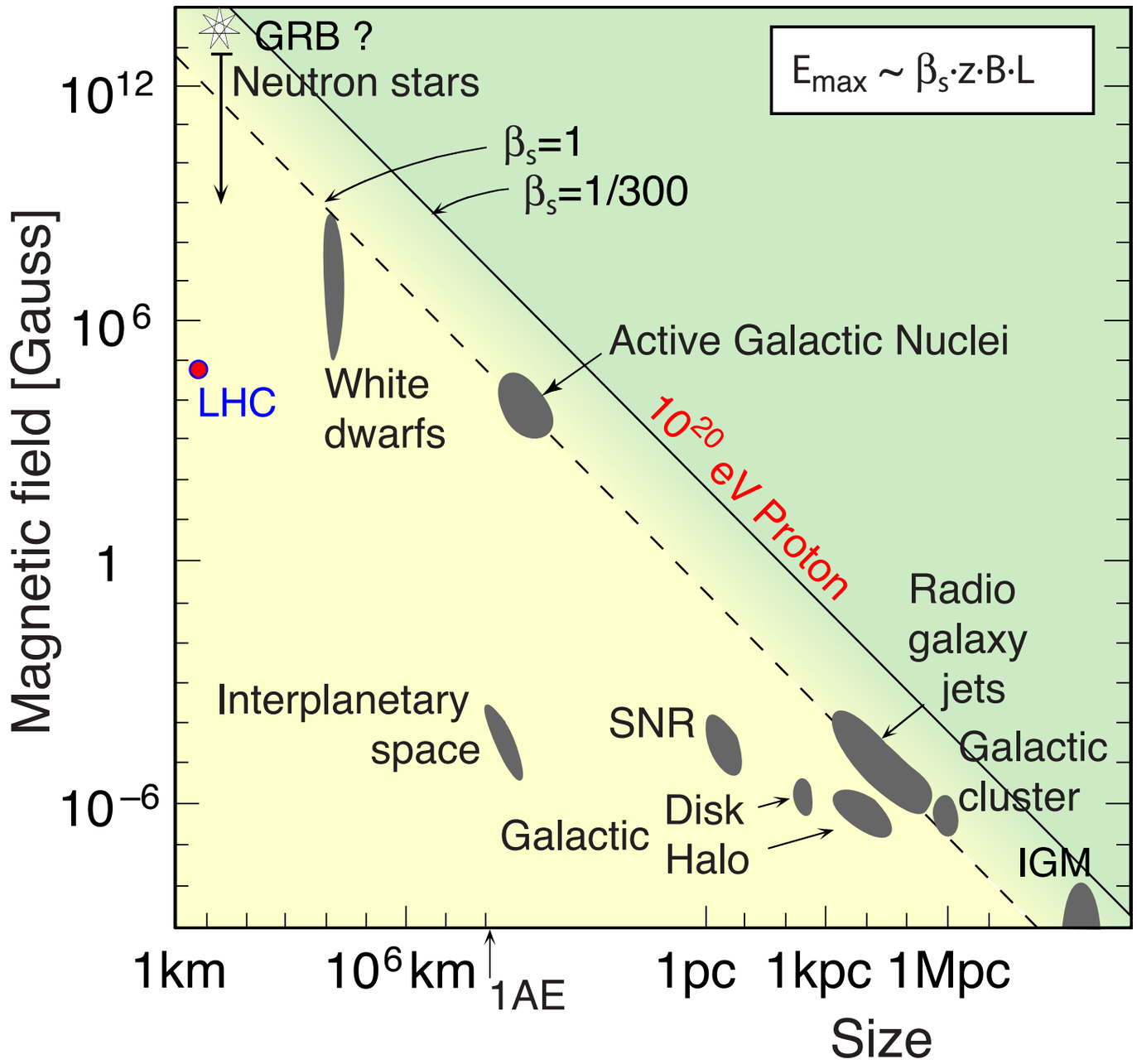
Hillas 1984:

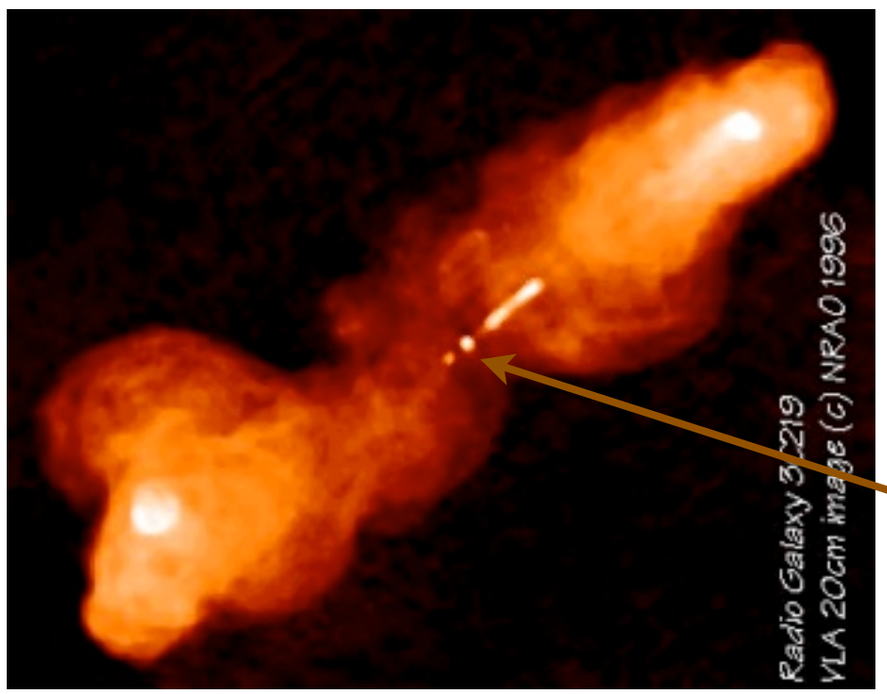
$$E_{\max} \simeq 10^{18}\,\mathrm{eV}\; Z\; \beta\; \left(\frac{R}{\mathrm{kpc}}\right)\left(\frac{B}{\mu\mathrm{G}}\right)$$

shock velocity

size of acc. region

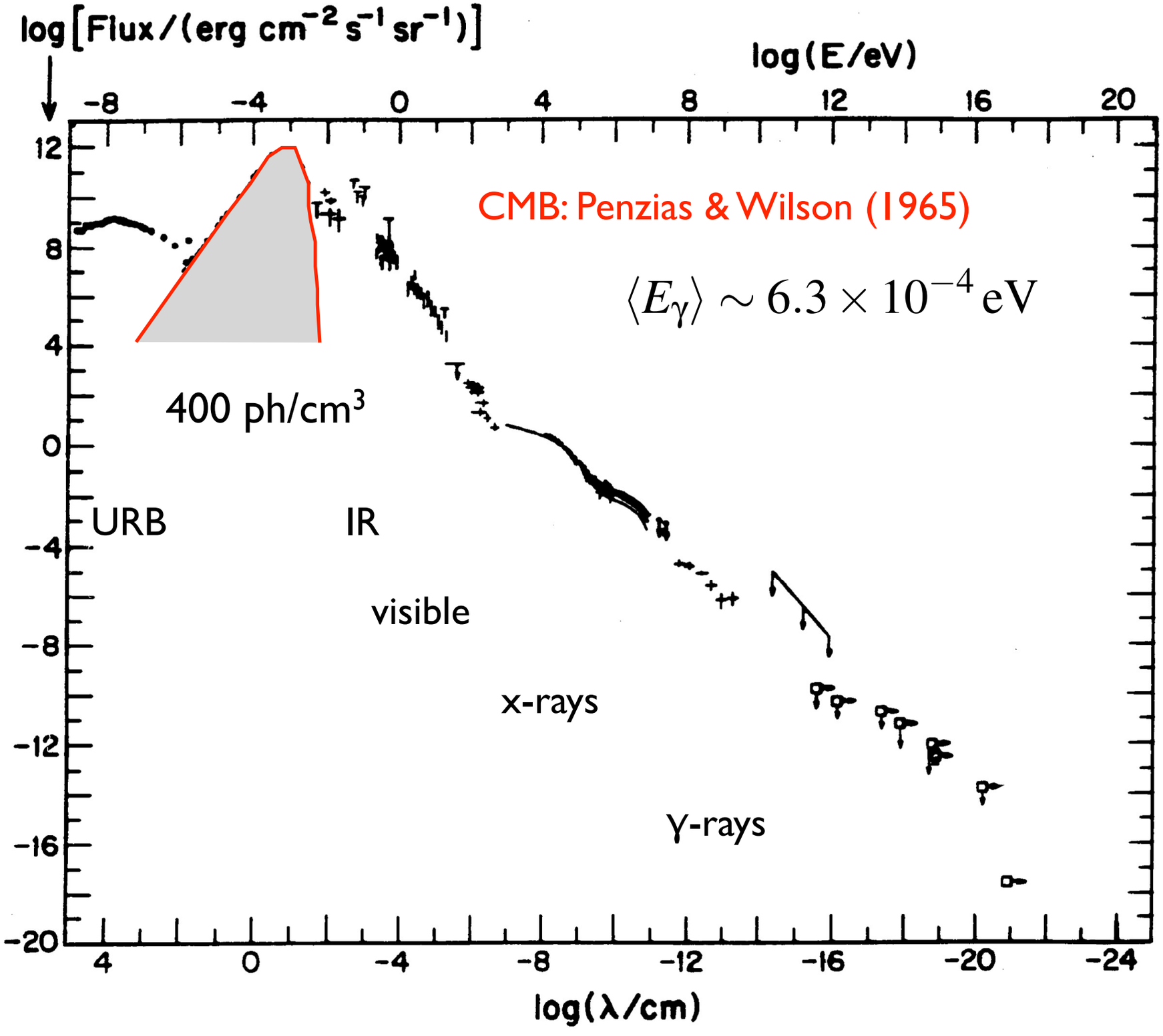
mag. field strength





Black hole of ~10^9 solar masses

Problem 2: Energy loss during propagation



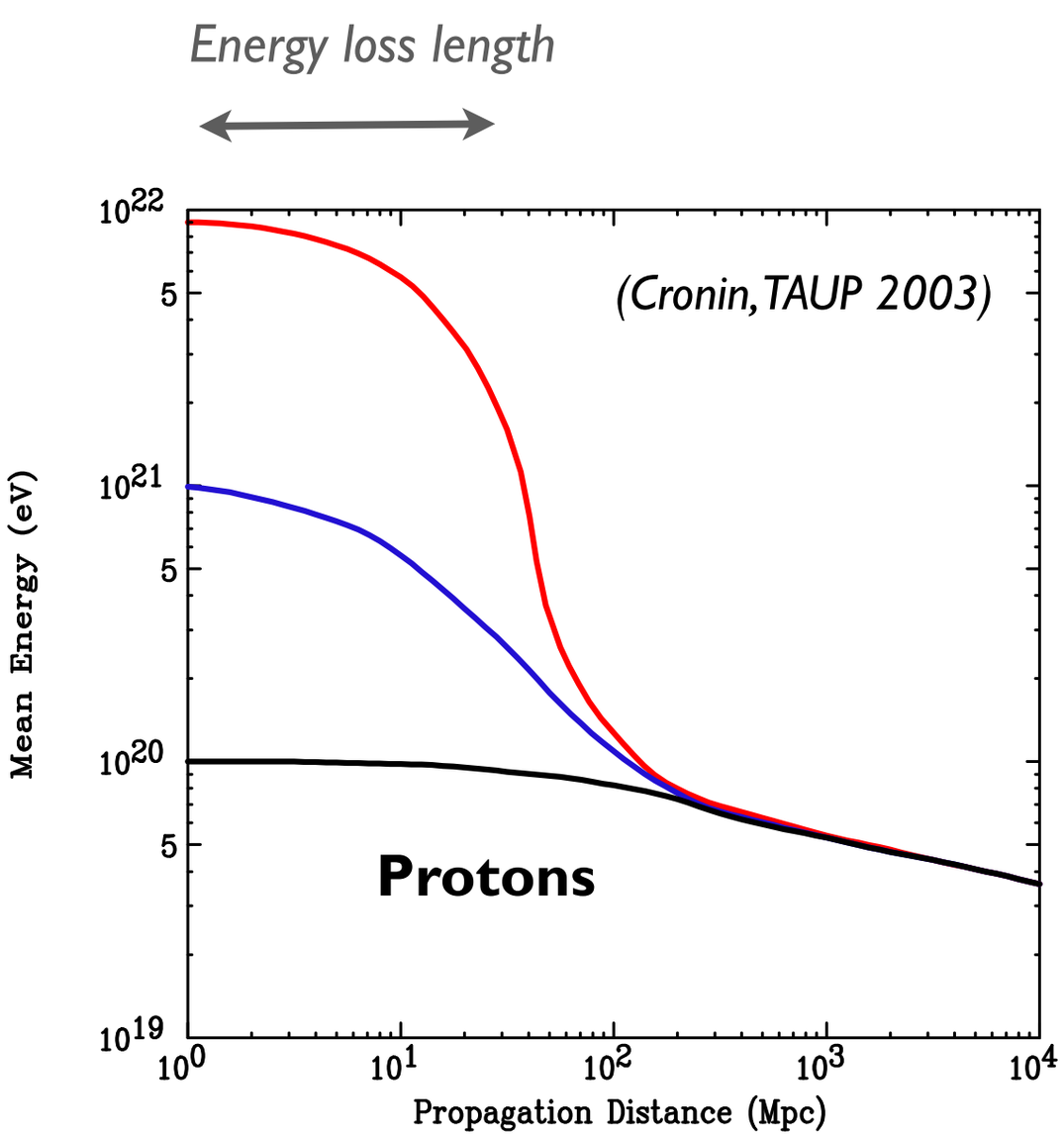
Greisen, Zatsepin & Kuzmin (1966)

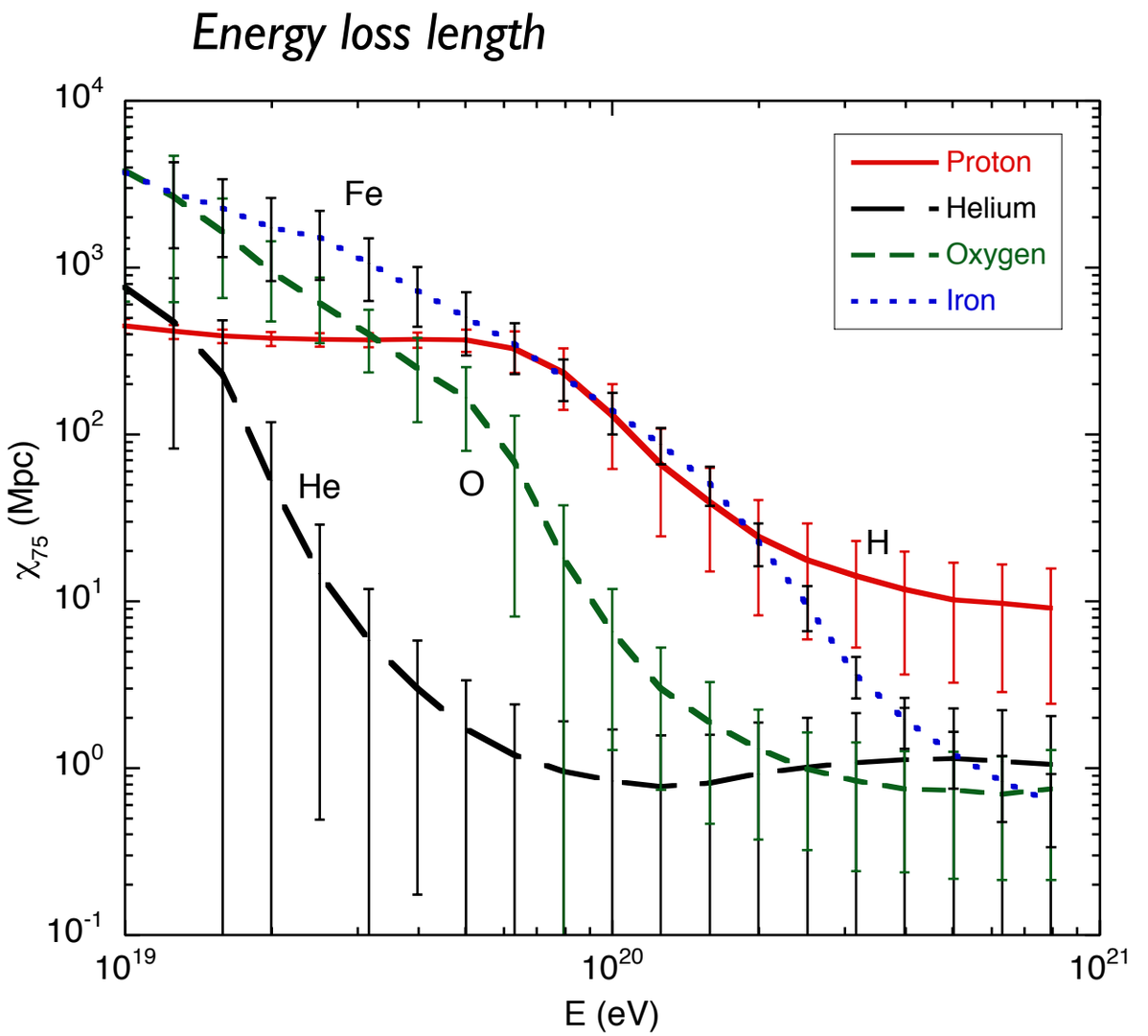
GZK effect

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

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

Energy loss for different particles





(Allard et al. 2007)

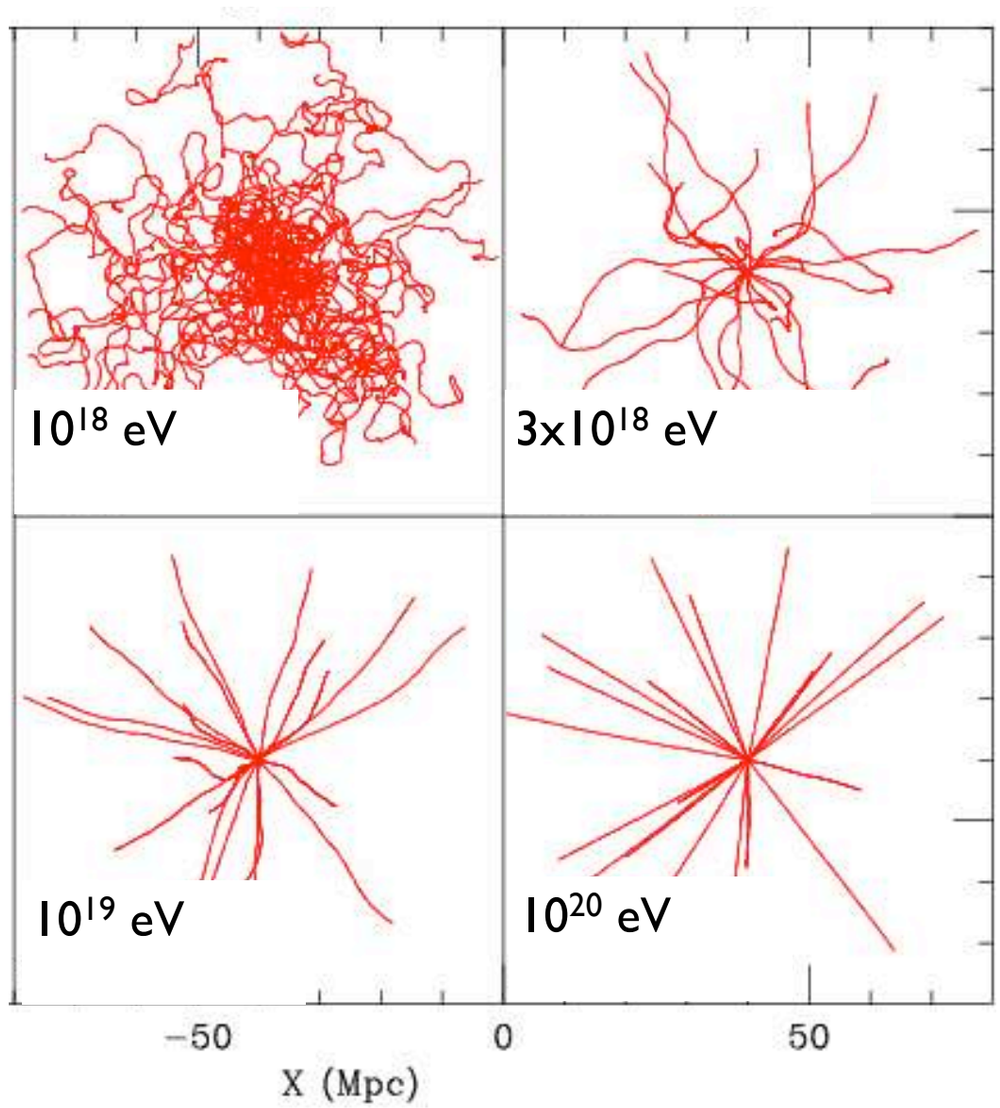
Proton and iron suffer smallest (and almost equal) energy loss

Problem 3: Deflection in magnetic fields

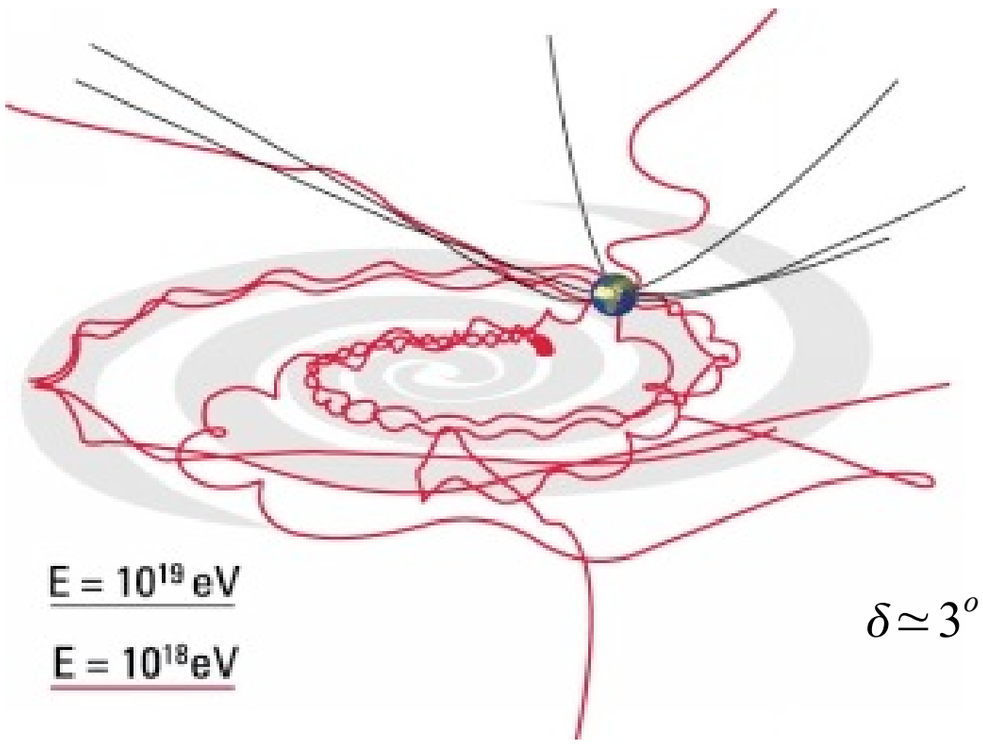
Typical field strengths:

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

Extragalactic magnetic fields

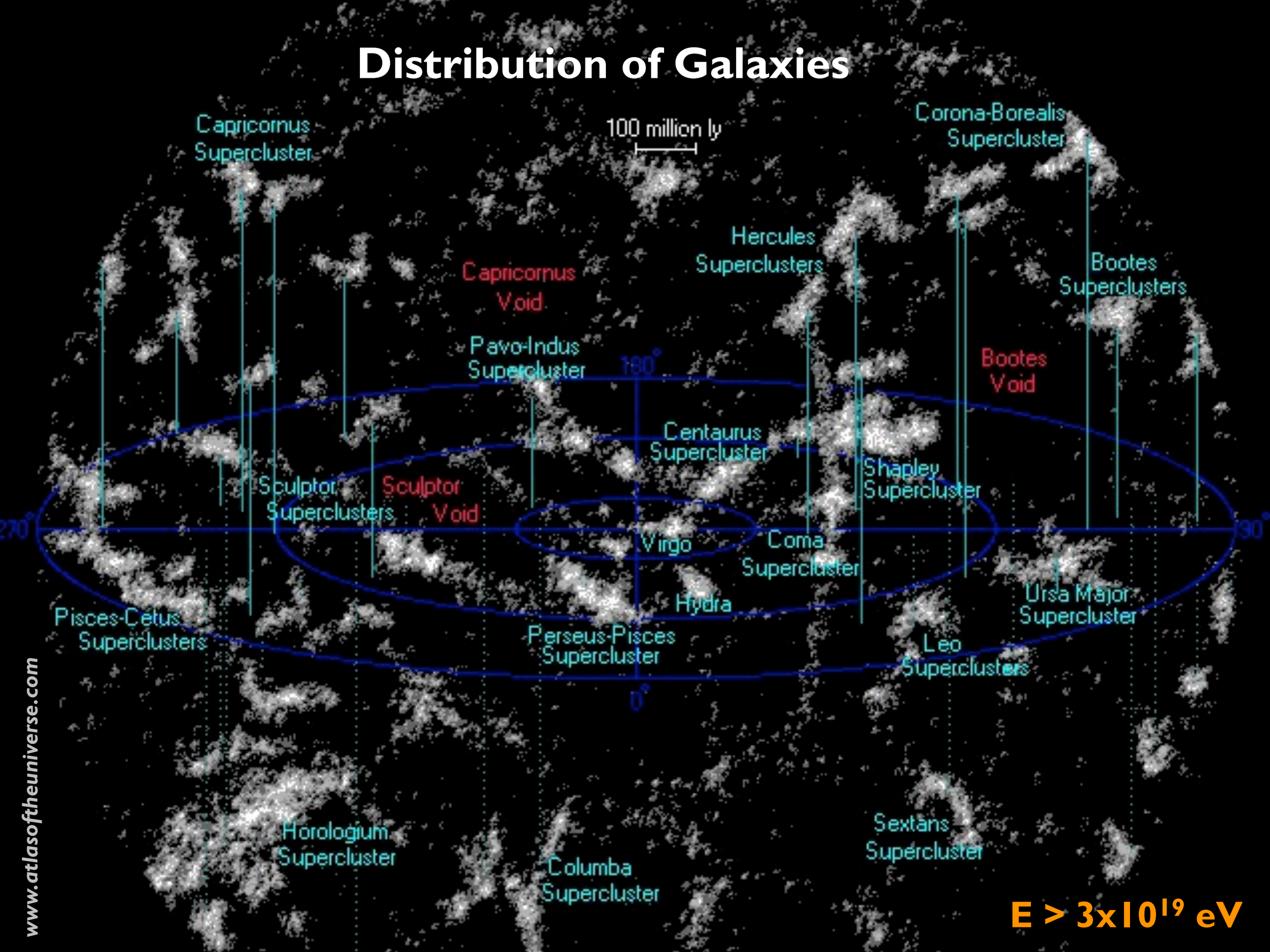


Galactic magnetic fields

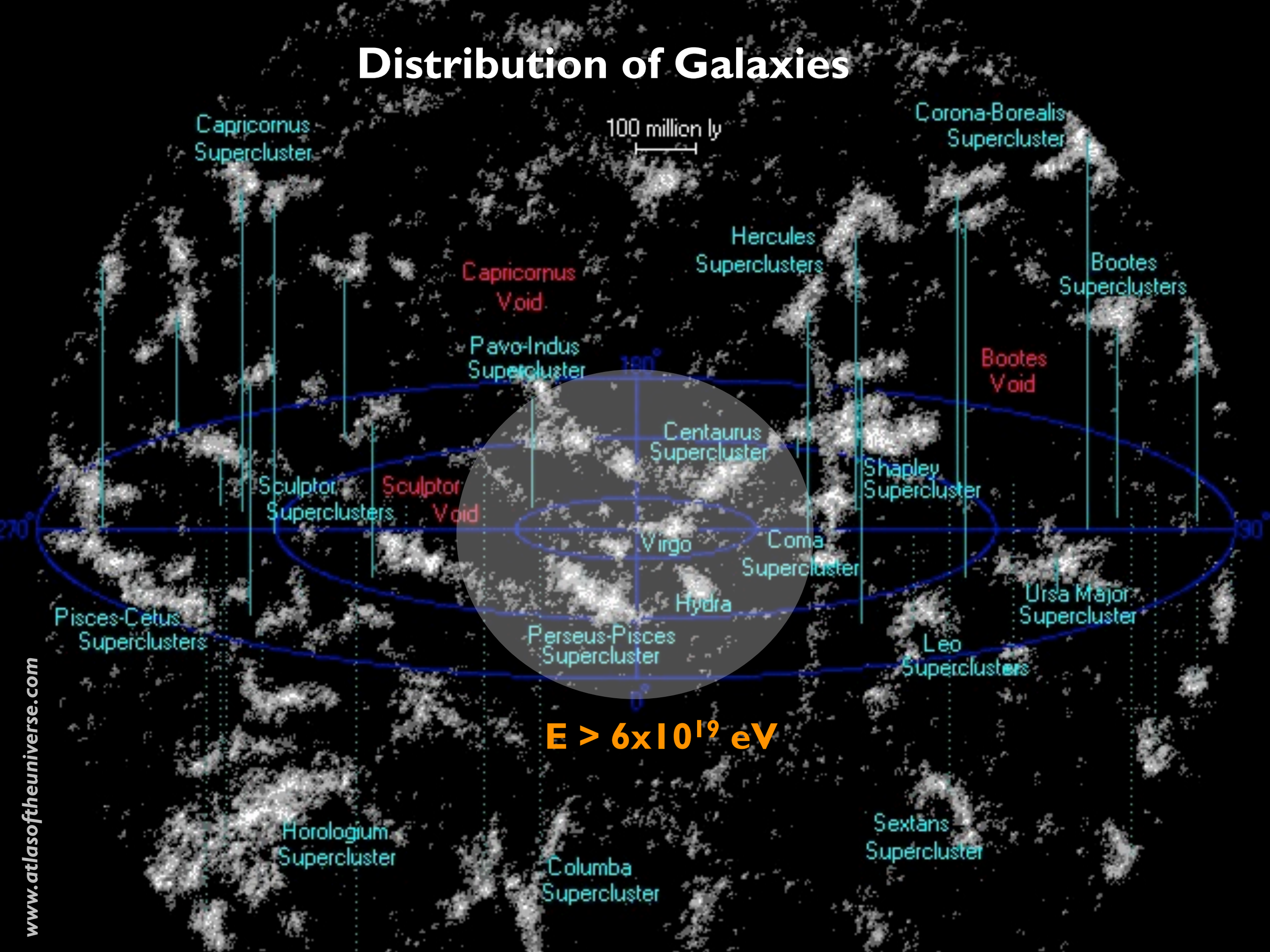


$$\delta \simeq 3^{o} \frac{B}{3\,\mu G} \frac{L}{kpc} \frac{6\times 10^{19} eV}{E/Z}$$

Distribution of Galaxies

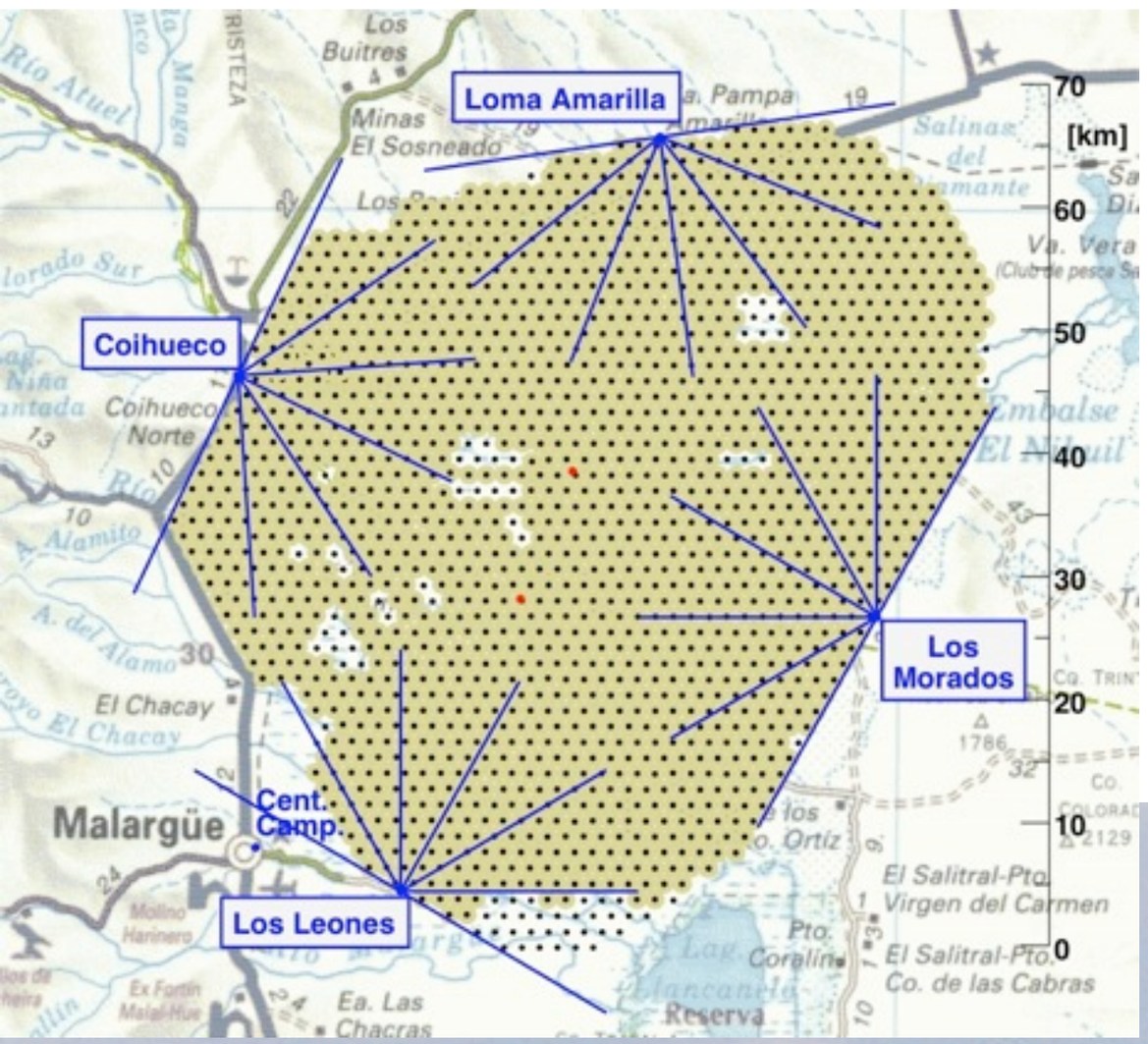


Distribution of Galaxies



Southern Pierre Auger Observatory

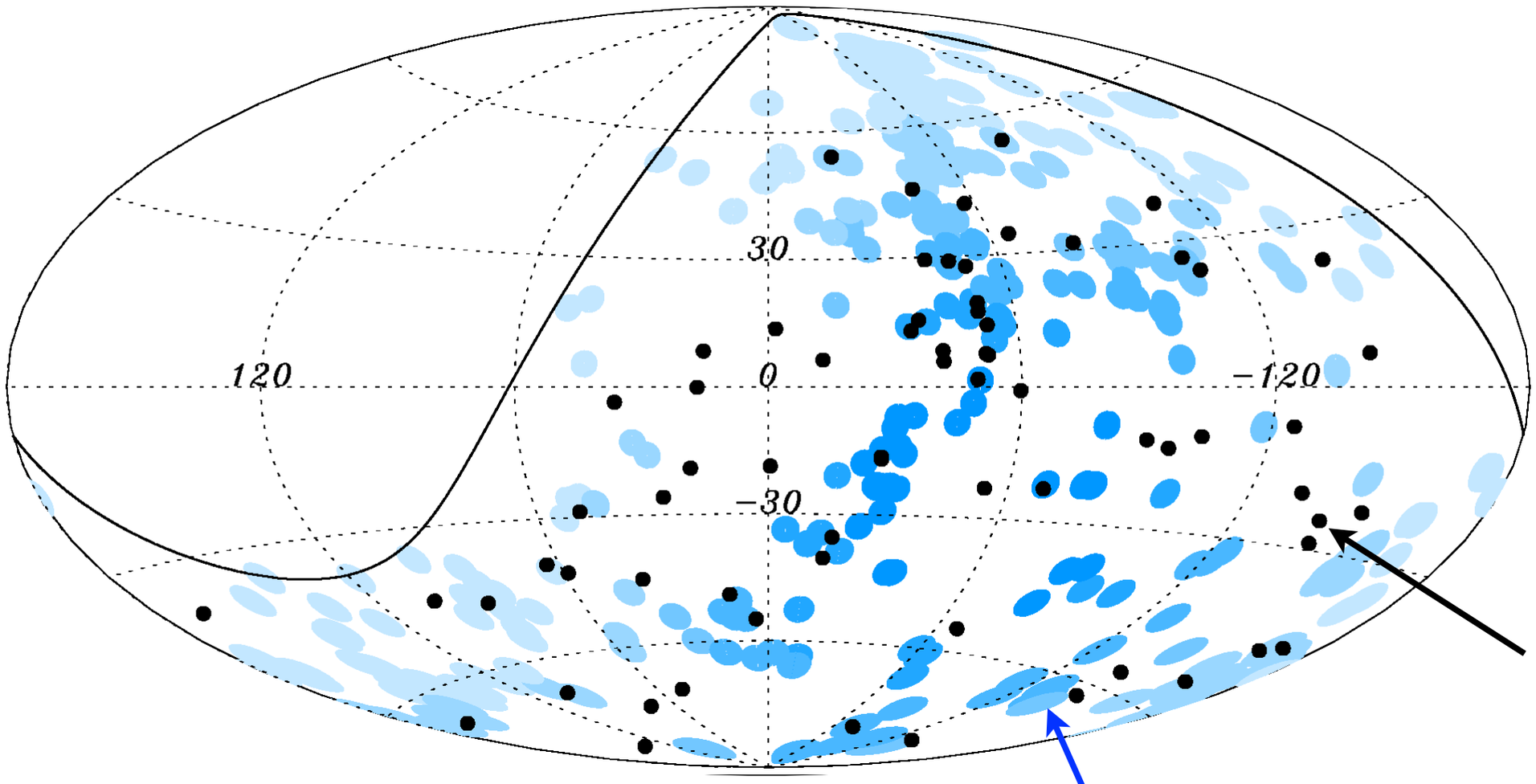
Malargue, Argentina



Area ~3000 km^2,
1660 surface detectors (1.5 km grid)
24+3 fluorescence telescopes

Anisotropy at the highest energies

Discovery in 2007: Science cover article



(Auger, Astropart. Phys. 2010)

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

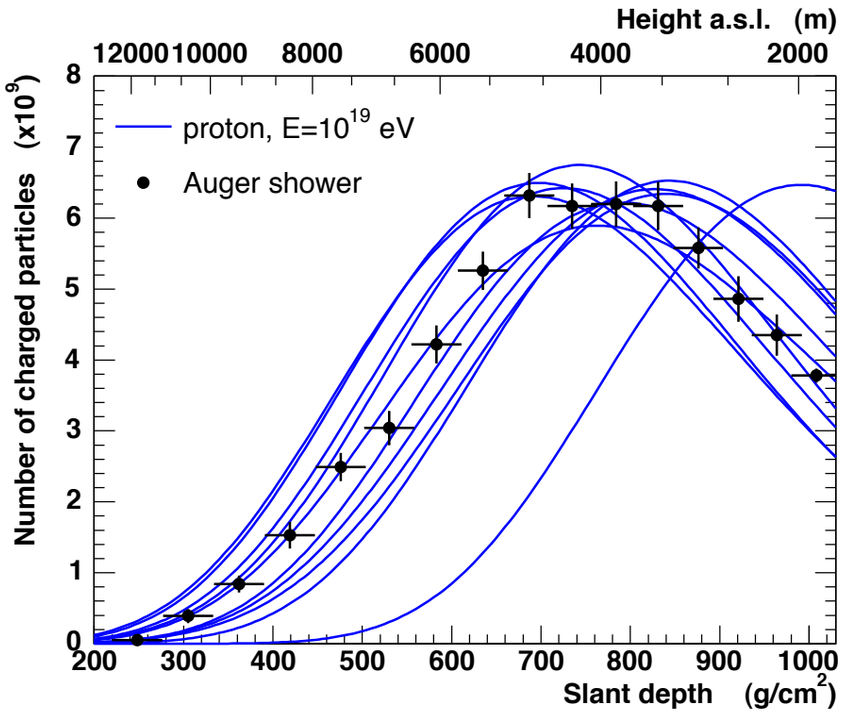
Correlation:
38+0.07-0.06%

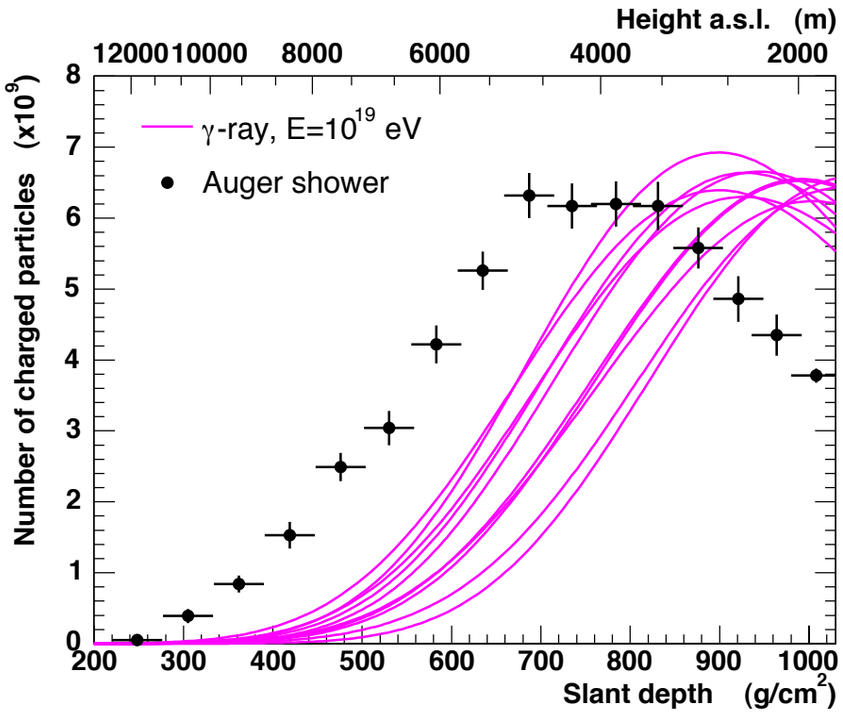
Isotropy: 21%

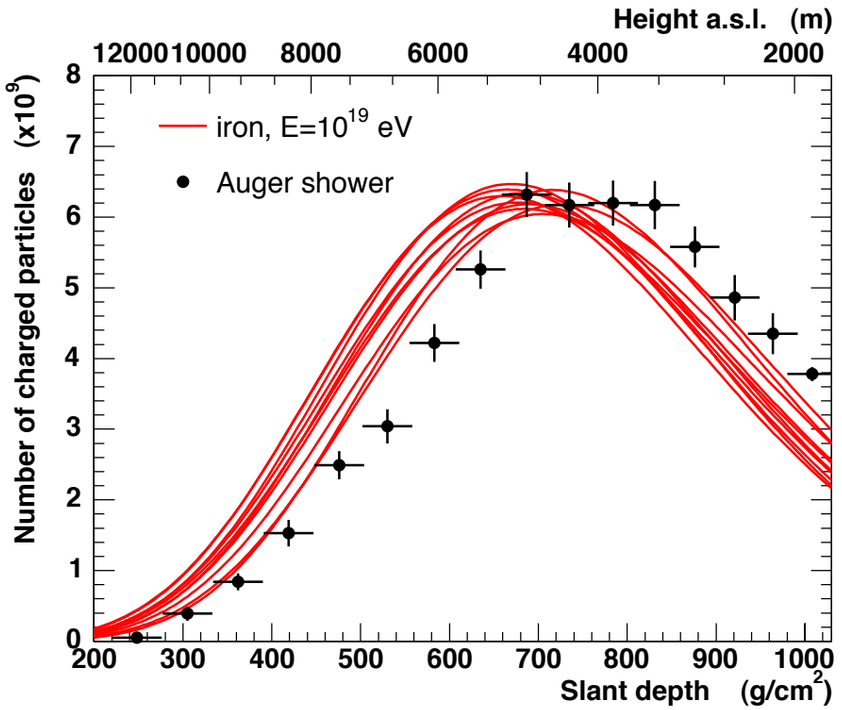
Note:

- anisotropy only for source distances up to GZK sphere (as one would expect)
- no correlation found in HiRes data (smaller statistics, northern hemisphere)

Composition analysis using shower profiles



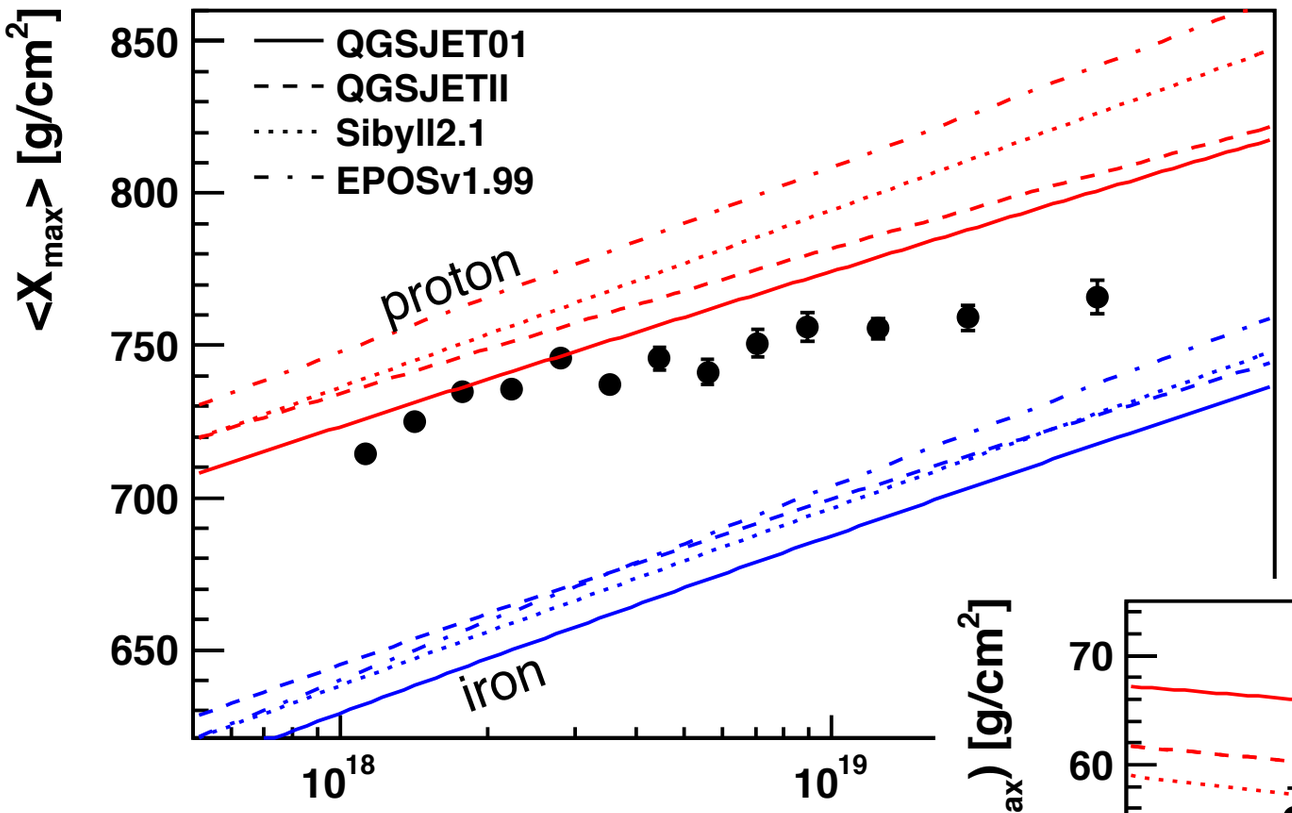




Example: event measured by Auger Collab. (ICRC 2003)

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

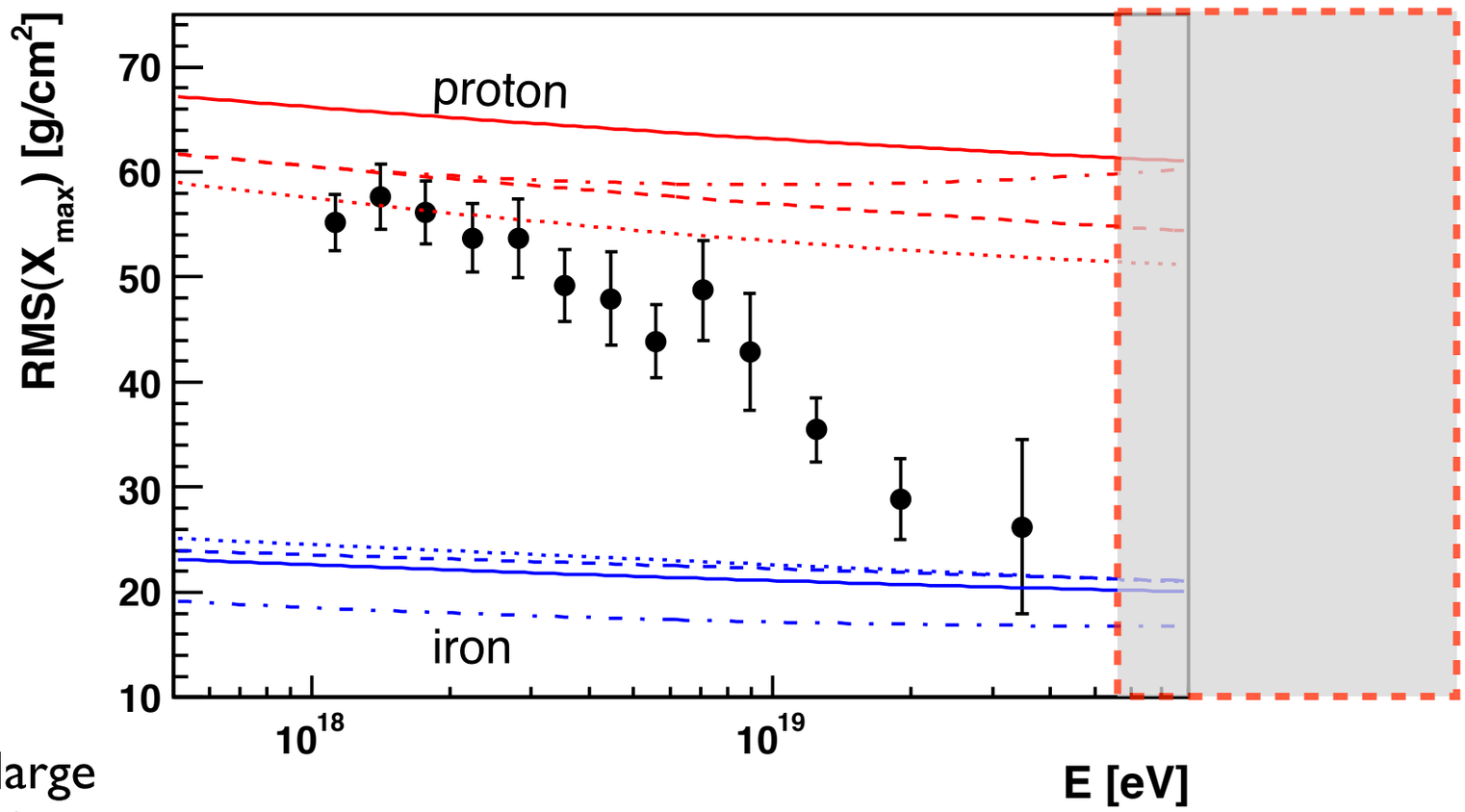
Unexpected change of mass composition !



Change of cosmic ray composition form mixed or light to heavy

(Auger Collab. PRL 104, 2010)

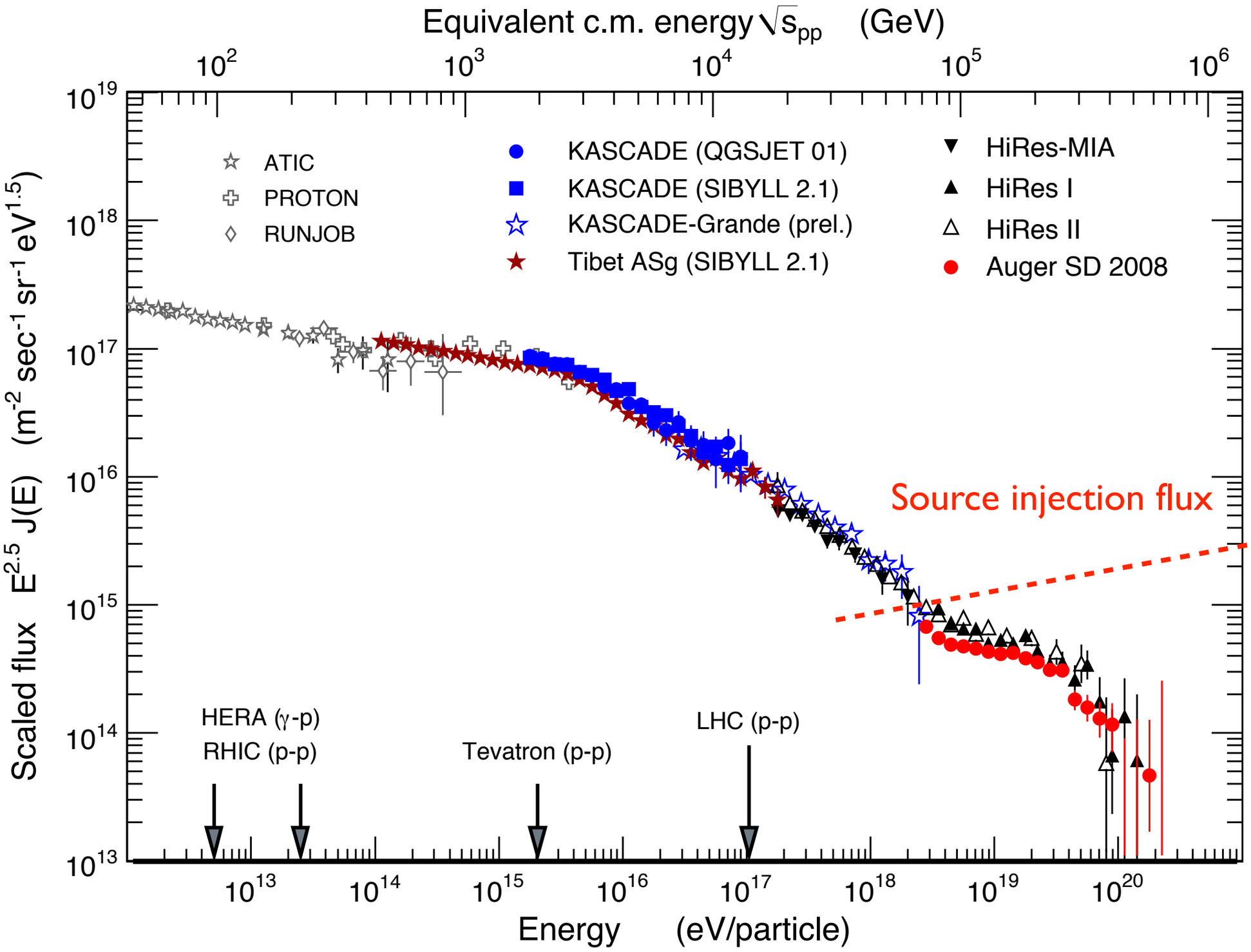
Anisotropy



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

Theoretical uncertainties on mean Xmax large
Uncertainties on prediction of fluctuations?

Upper end: Flux suppression due to GZK effect ?



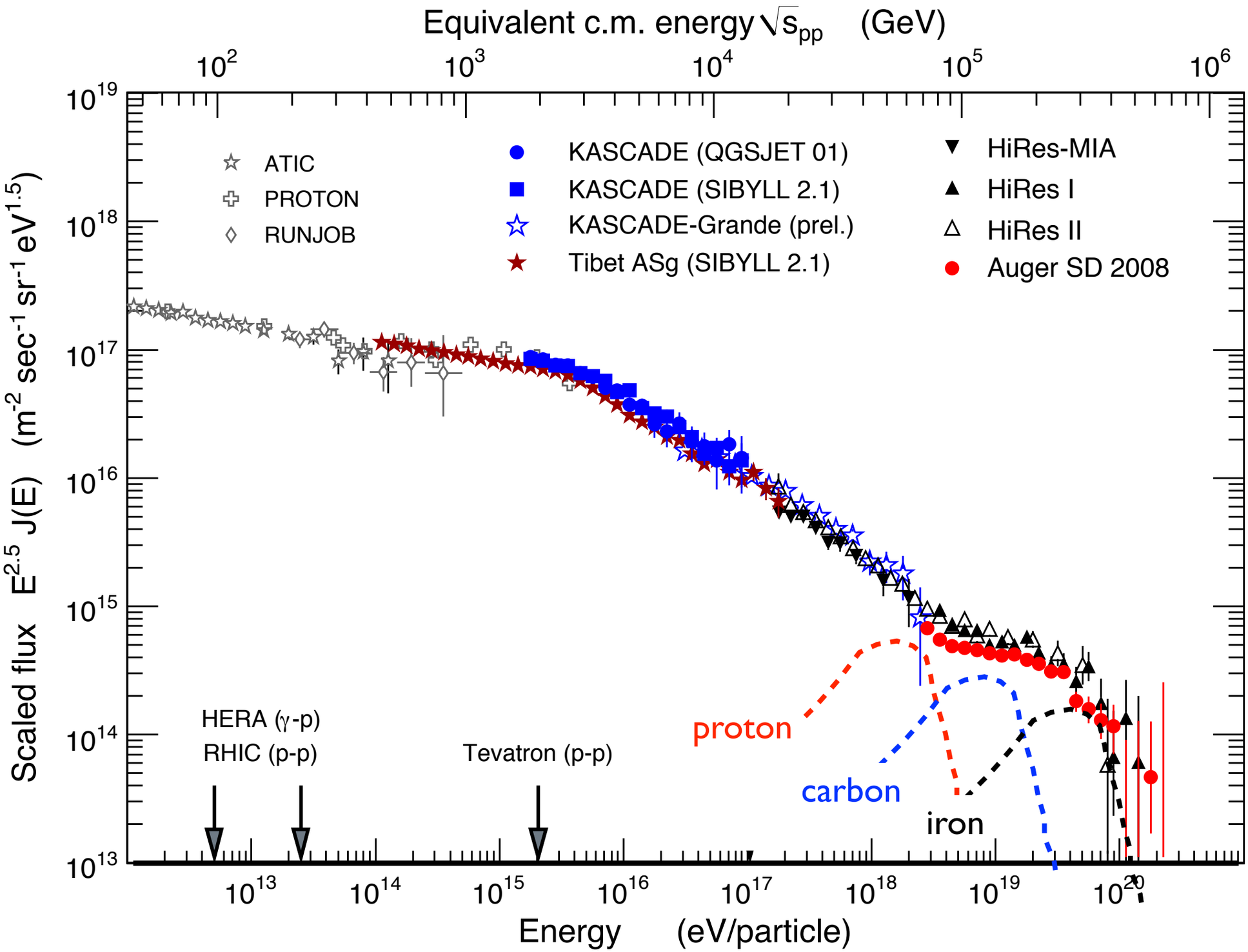
Composition proton and/or iron dominated at upper energy end

Particle physics

Upper end: flux suppression due to GZK effect

Why is there a transition from a light to a heavy composition ?

Upper end: Maximum injection energy of source(s) ?



Extragalactic particles: isotropy in ankle region

Composition related to rigidity at source

Upper end: superposition of max. energy and GZK effect

Why is max. injection energy so similar to GZK threshold ?