The Physics of Cosmic Rays – An Overview

Ralph Engel

Karlsruhe Institut für Technologie (KIT)

~ 30 - 40 km

Cosmic rays

Composition

85% H nuclei (protons)
12% He nuclei
1% heavier nuclei

2% electrons and positions

0.01 - 0.001% antiprotons

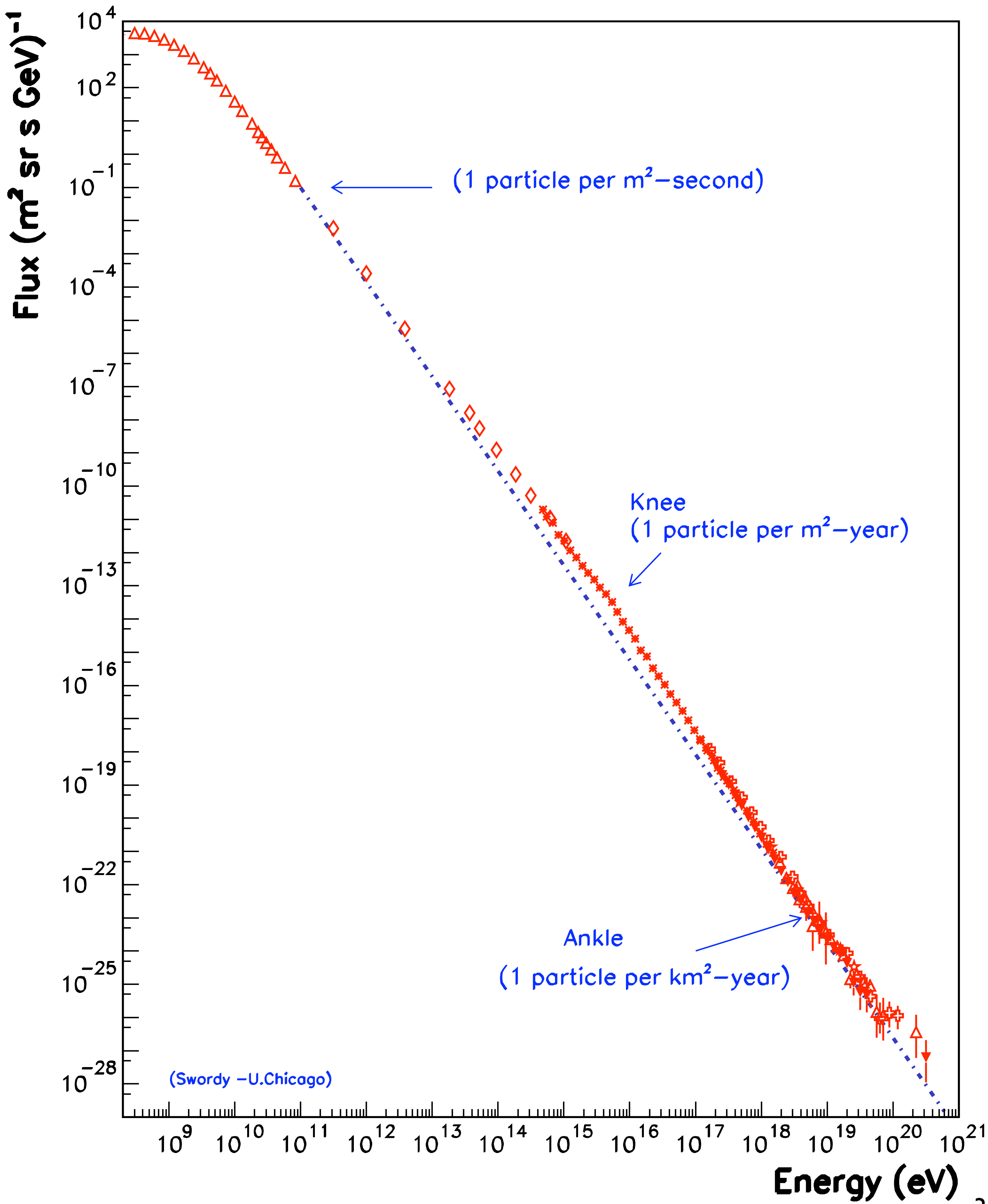
Flux of cosmic rays

Flux follows power law

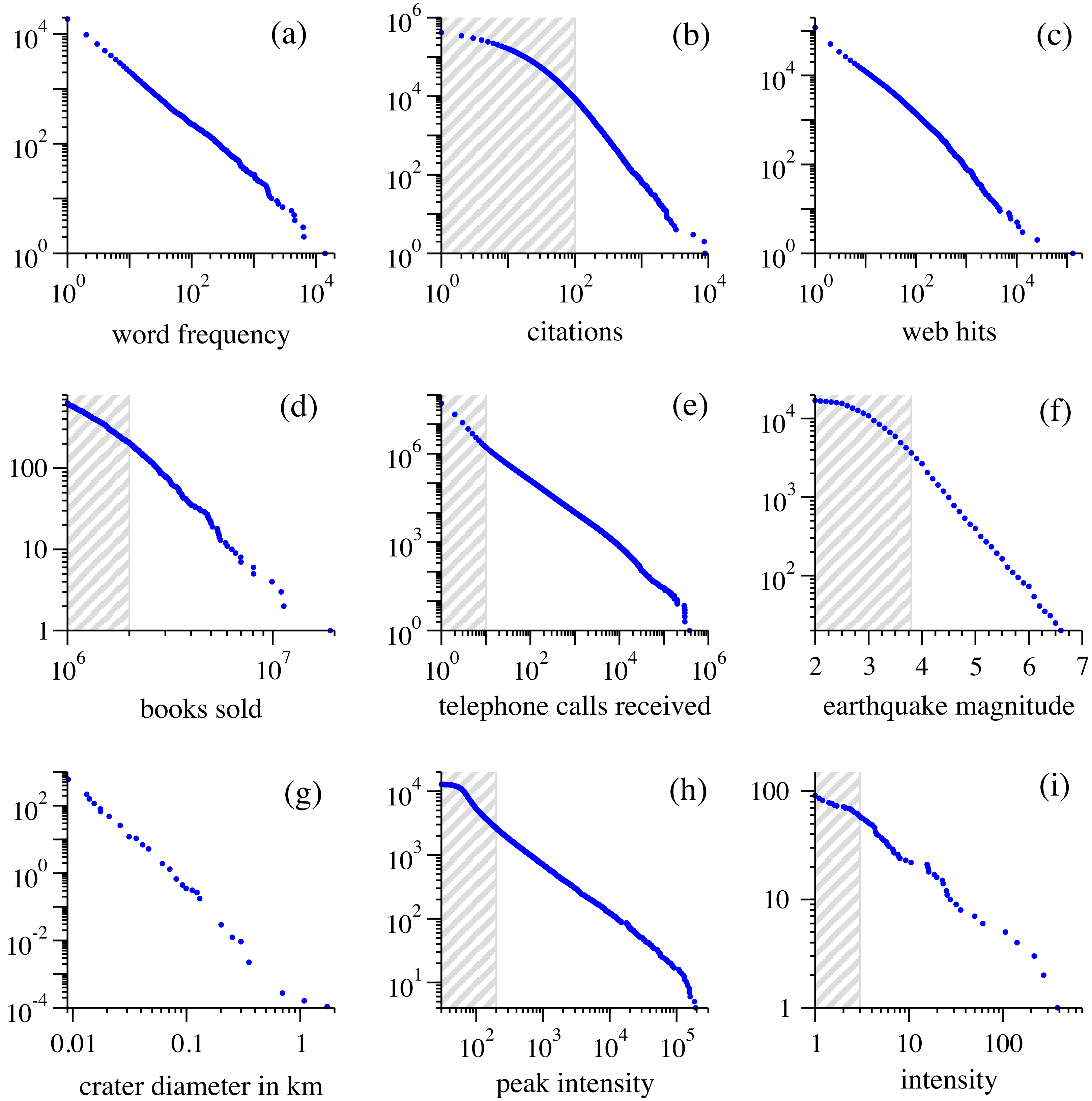
$$\frac{dN}{dE\,d\Omega\,dA\,dt} \propto E^{-\gamma}$$

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

Energy spectrum of all-particle flux



Power laws are common in nature (i)



(M. Newman cond-mat/0412004)

Power laws are common in nature (ii)

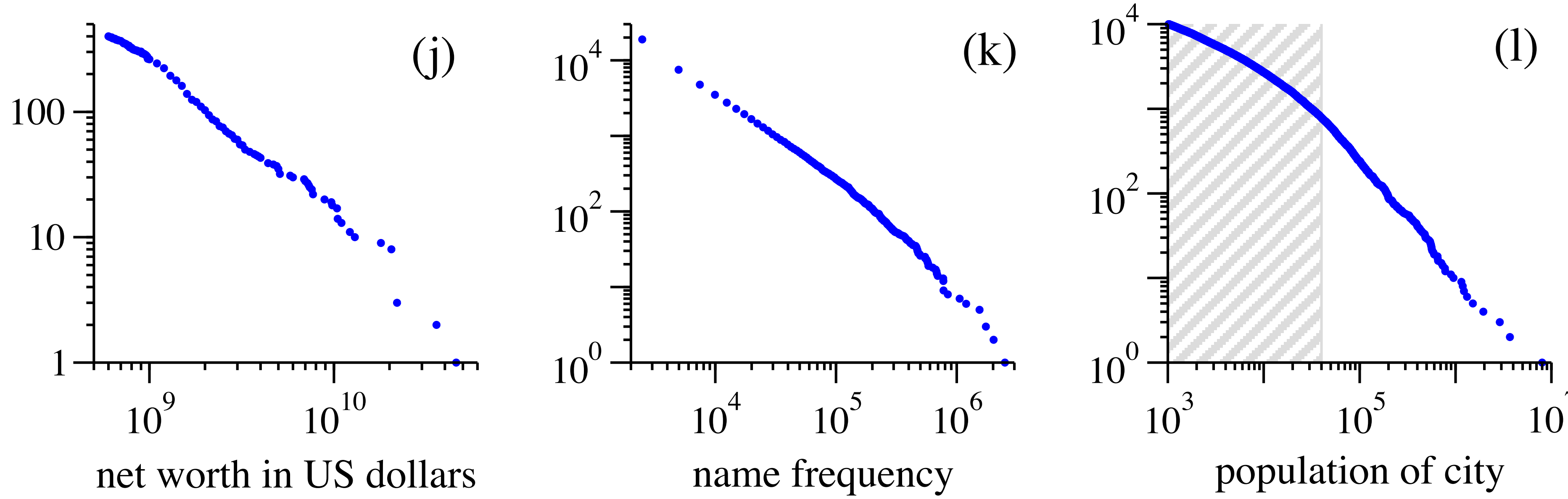
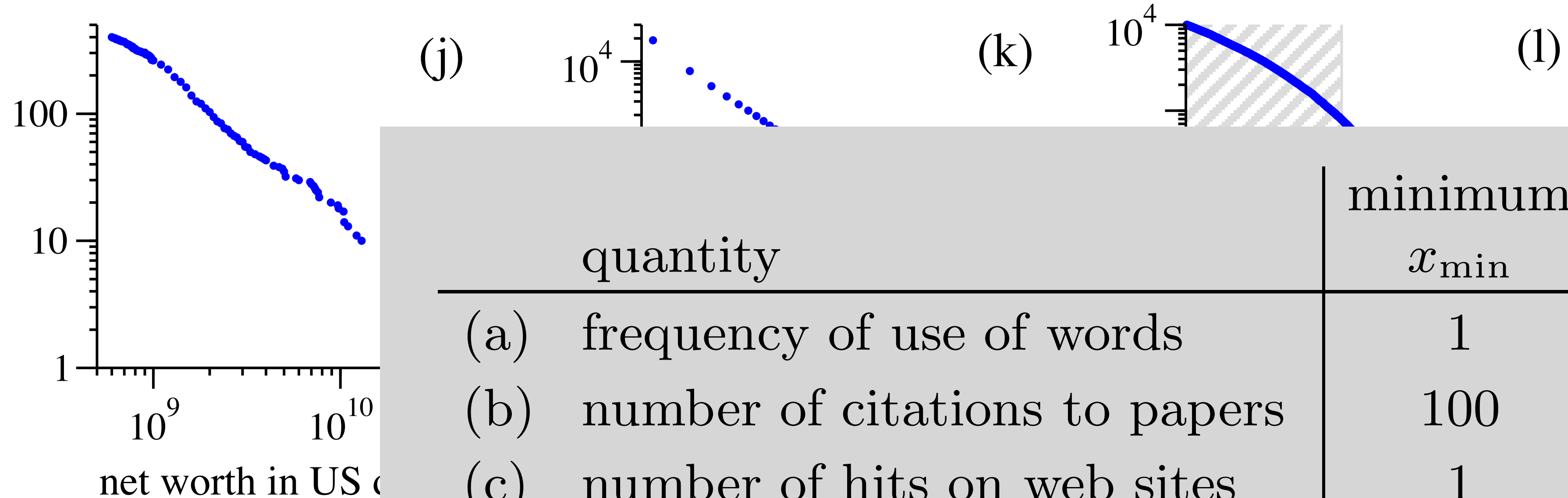


FIG. 4 Cumulative distributions or "rank/frequency plots" of twelve quantities reputed to follow power laws. The distributions were computed as described in Appendix A. Data in the shaded regions were excluded from the calculations of the exponents in Table I. Source references for the data are given in the text. (a) Numbers of occurrences of words in the novel *Moby Dick* by Hermann Melville. (b) Numbers of citations to scientific papers published in 1981, from time of publication until June 1997. (c) Numbers of hits on web sites by 60 000 users of the America Online Internet service for the day of 1 December 1997. (d) Numbers of copies of bestselling books sold in the US between 1895 and 1965. (e) Number of calls received by AT&T telephone customers in the US for a single day. (f) Magnitude of earthquakes in California between January 1910 and May 1992. Magnitude is proportional to the logarithm of the maximum amplitude of the earthquake, and hence the distribution obeys a power law even though the horizontal axis is linear. (g) Diameter of craters on the moon. Vertical axis is measured per square kilometre. (h) Peak gamma-ray intensity of solar flares in counts per second, measured from Earth orbit between February 1980 and November 1989. (i) Intensity of wars from 1816 to 1980, measured as battle deaths per 10 000 of the population of the participating countries. (j) Aggregate net worth in dollars of the richest individuals in the US in October 2003. (k) Frequency of occurrence of family names in the US in the year 1990. (l) Populations of US cities in the year 2000.

(M. Newman cond-mat/0412004)

Power laws are common in nature (ii)



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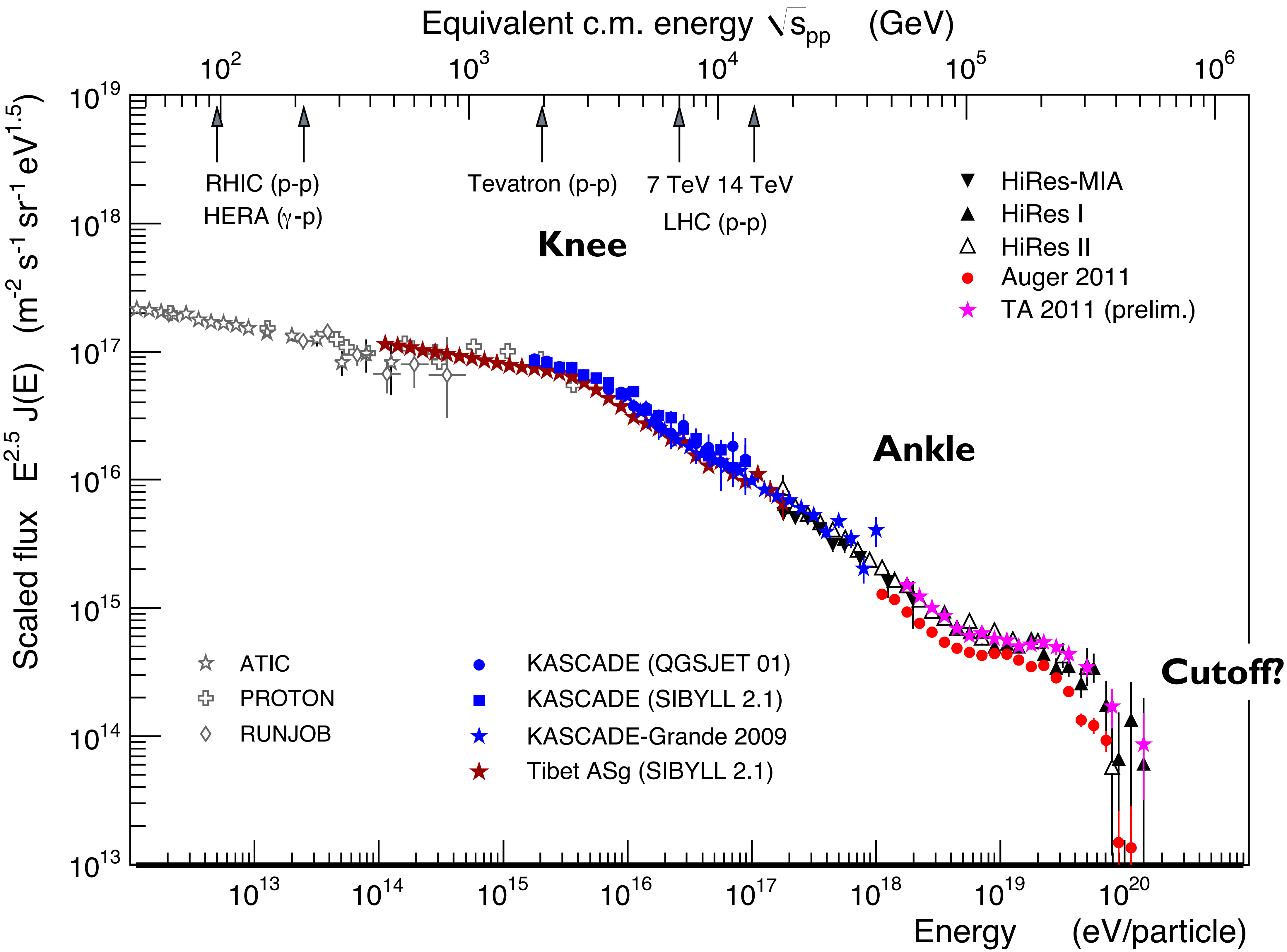
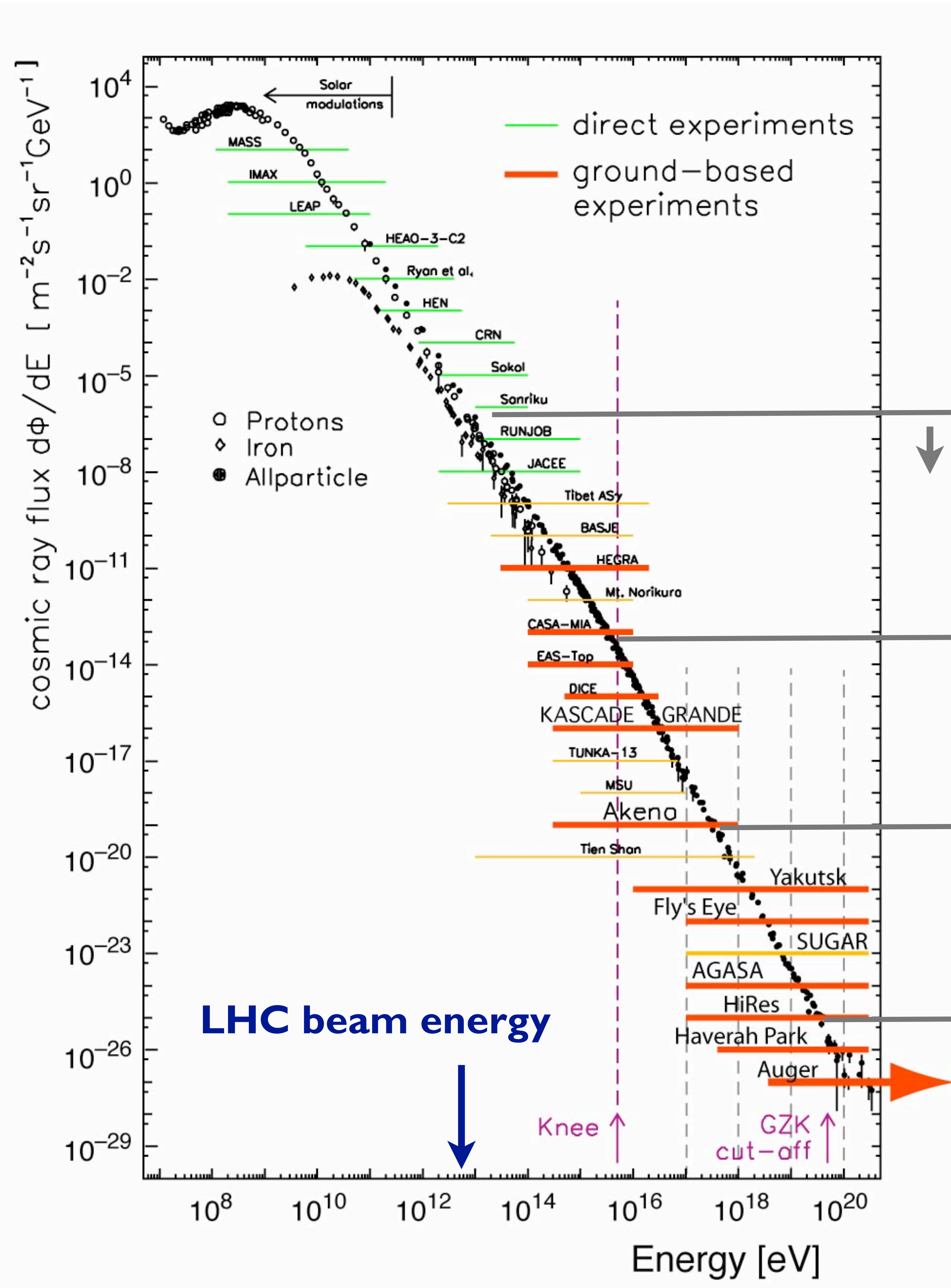
	quantity	minimum $x_{\min}$	exponent α
(a)	frequency of use of words	1	2.20(1)
(b)	number of citations to papers	100	3.04(2)
(c)	number of hits on web sites	1	2.40(1)
(d)	copies of books sold in the US	2 000 000	3.51(16)
(e)	telephone calls received	10	2.22(1)
(f)	magnitude of earthquakes	3.8	3.04(4)
(g)	diameter of moon craters	0.01	3.14(5)
(h)	intensity of solar flares	200	1.83(2)
(i)	intensity of wars	3	1.80(9)
(j)	net worth of Americans	$600m	2.09(4)
(k)	frequency of family names	10 000	1.94(1)
(l)	population of US cities	40 000	2.30(5)

(M. Newman cond-mat/0412004)

Re-scaled flux: several breaks in power law



Rate of particles



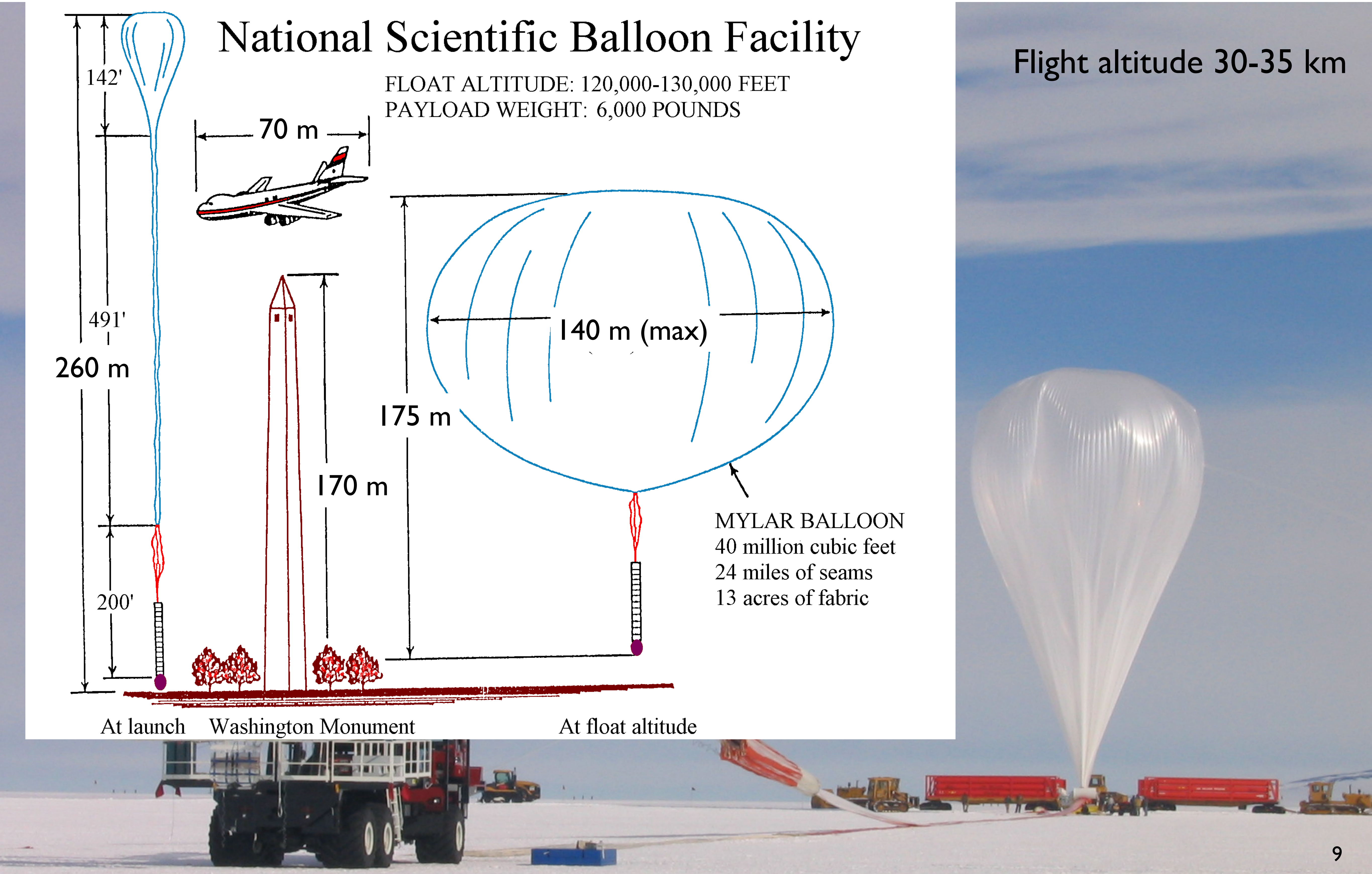
0.1 particles / m² min.

10 particles / km² min.

10 particles / km² day

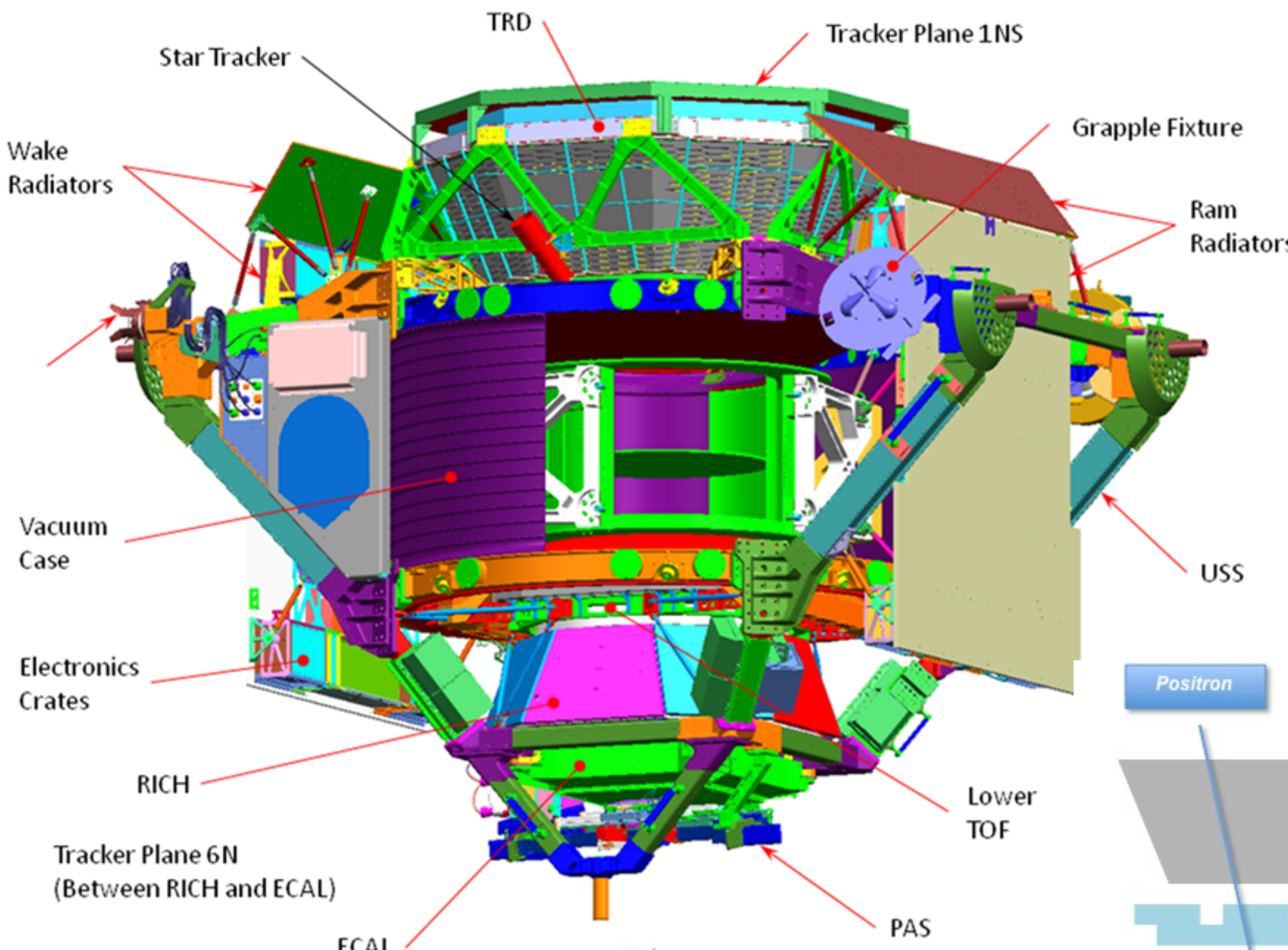
10 particles / km² century

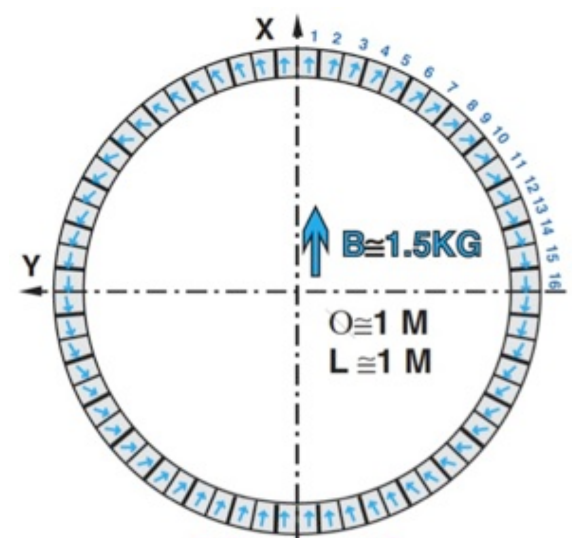
Long-duration balloon flights

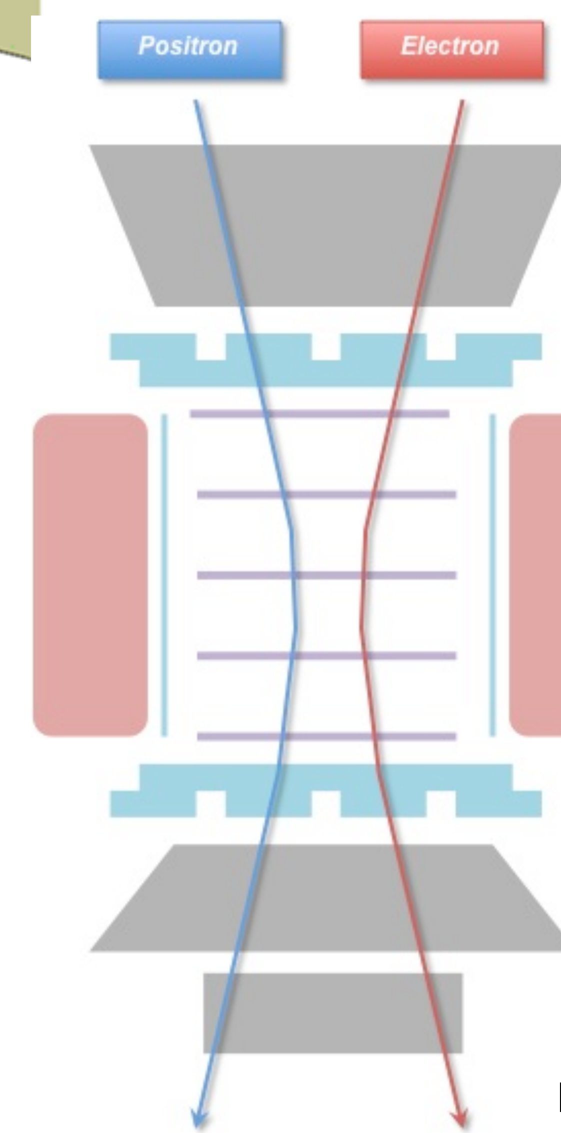


AMS 02

Launch: May 16, 2011

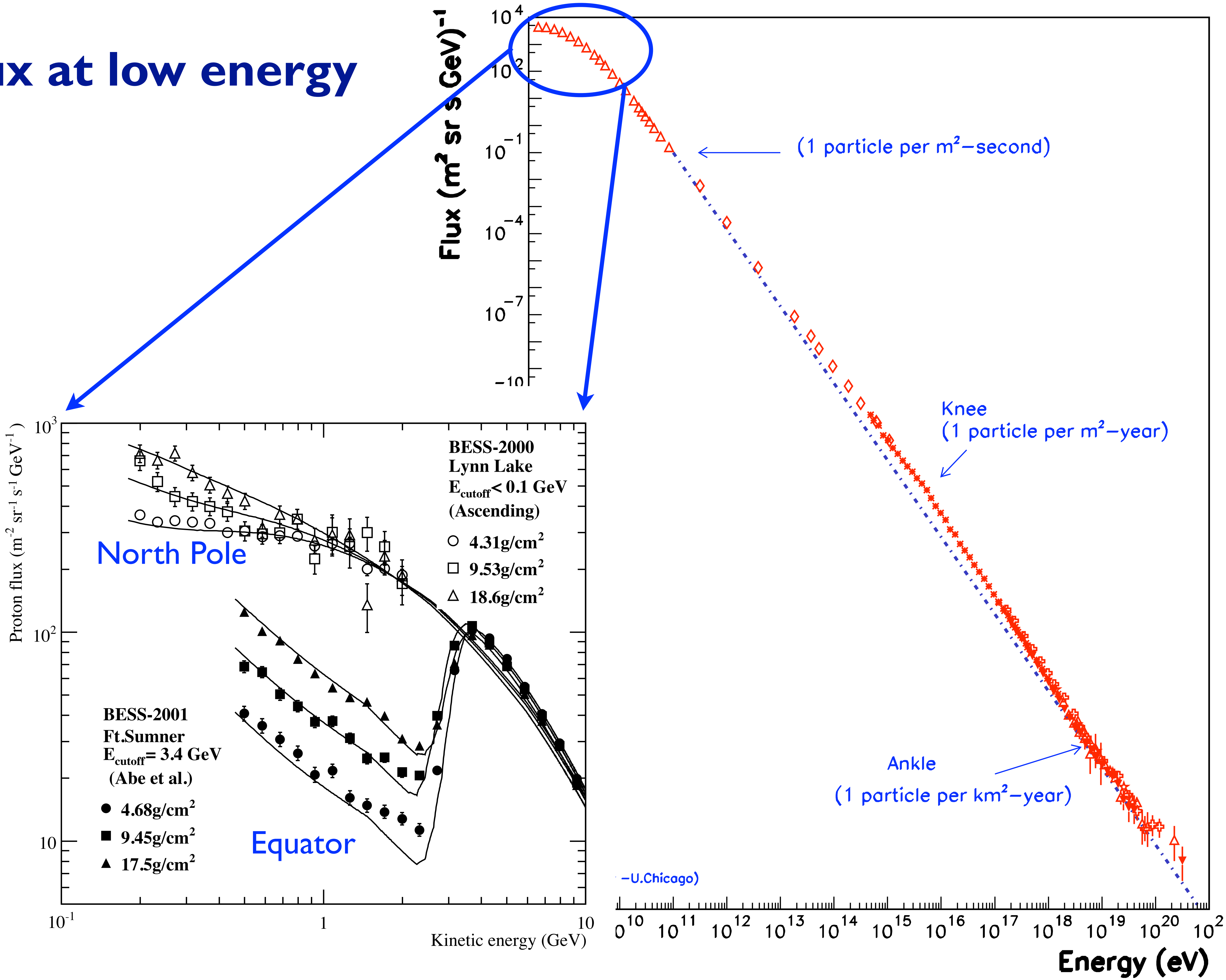




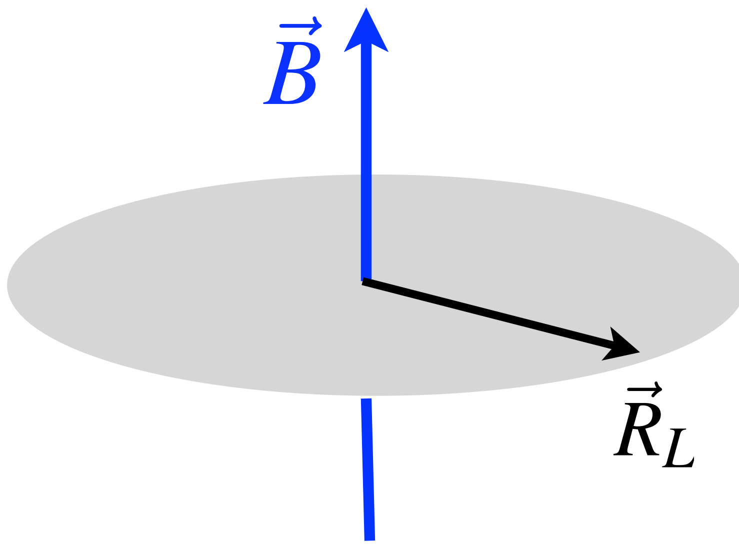


Payload Commander
Andreas Sabellek (KIT)

Flux at low energy



Estimate of radius of curvature of trajectory



Lorentz force $F_L = qvB$

Inertial force $F_F = m\frac{v^2}{R_L}$

Charge $q = Ze$

Momentum $p = mv \longrightarrow E/c$

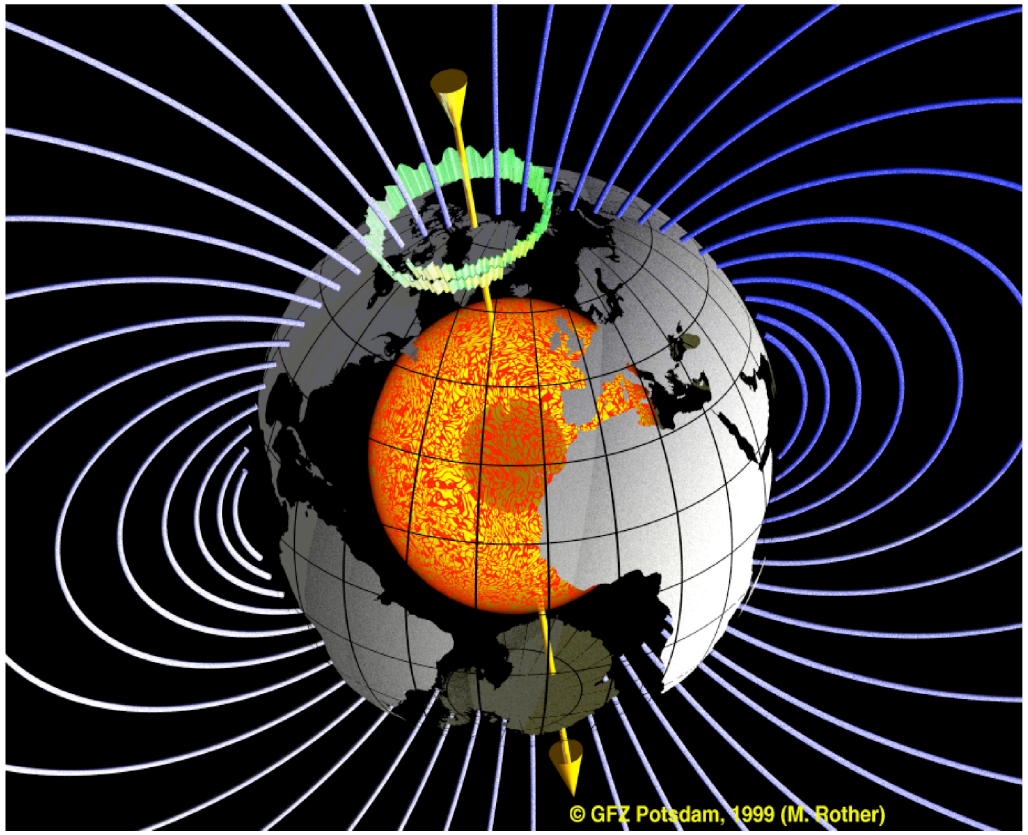
relaticistic limit

$$R_L = \frac{p}{ZeB}$$

Rigidity

$$R = \frac{p}{Ze}$$

Geomagnetic cutoff and East-West effect

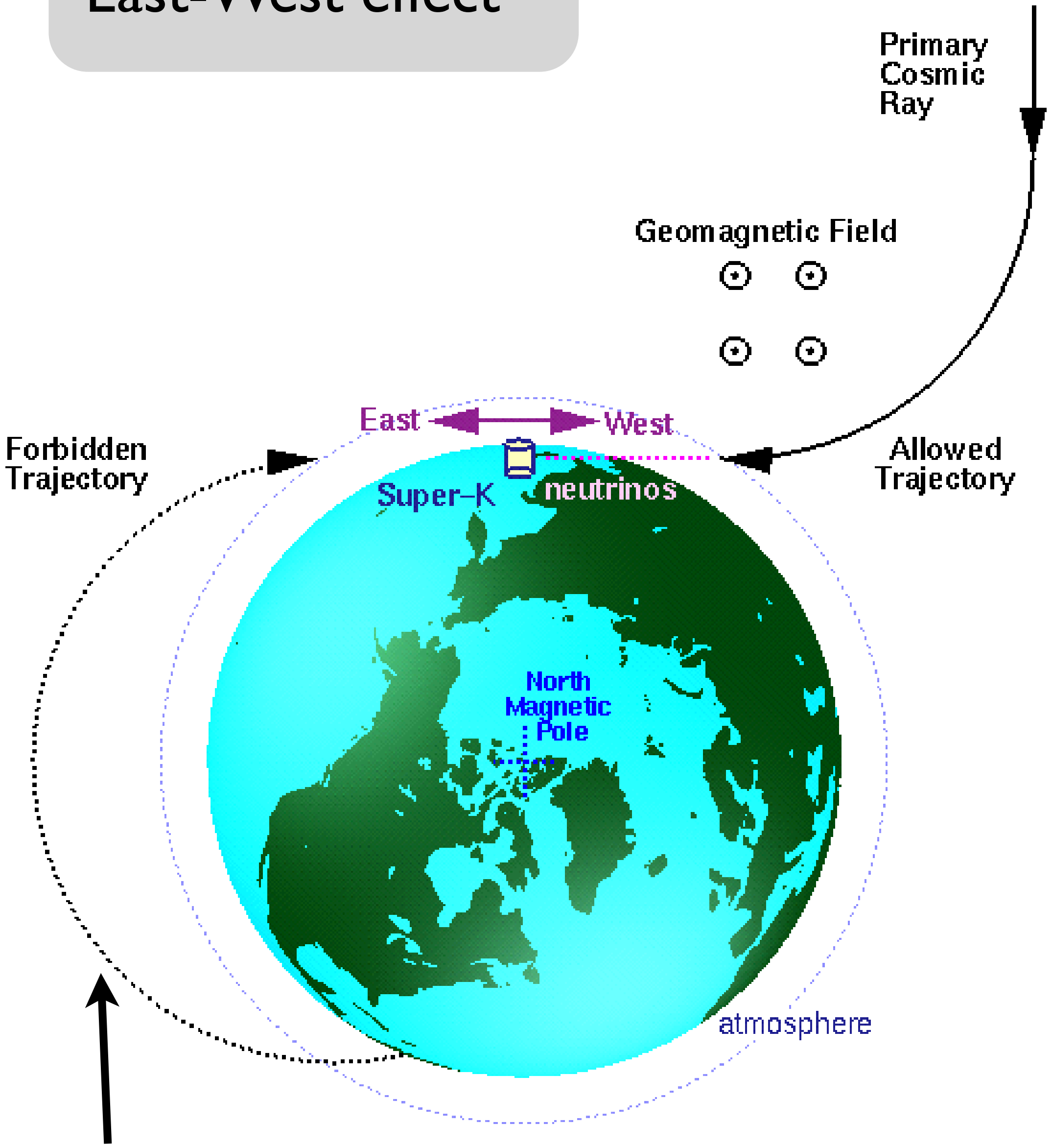


Earth's magnetic field

Vincinity of poles: B ≈ 60 μT
Equator: B ≈ 30 μT

$$R_L = 3 \times 10^3 \left(\frac{E}{\mathrm{GeV}}\right)\left(\frac{\mu\mathrm{T}}{ZB}\right)\ \mathrm{km}$$

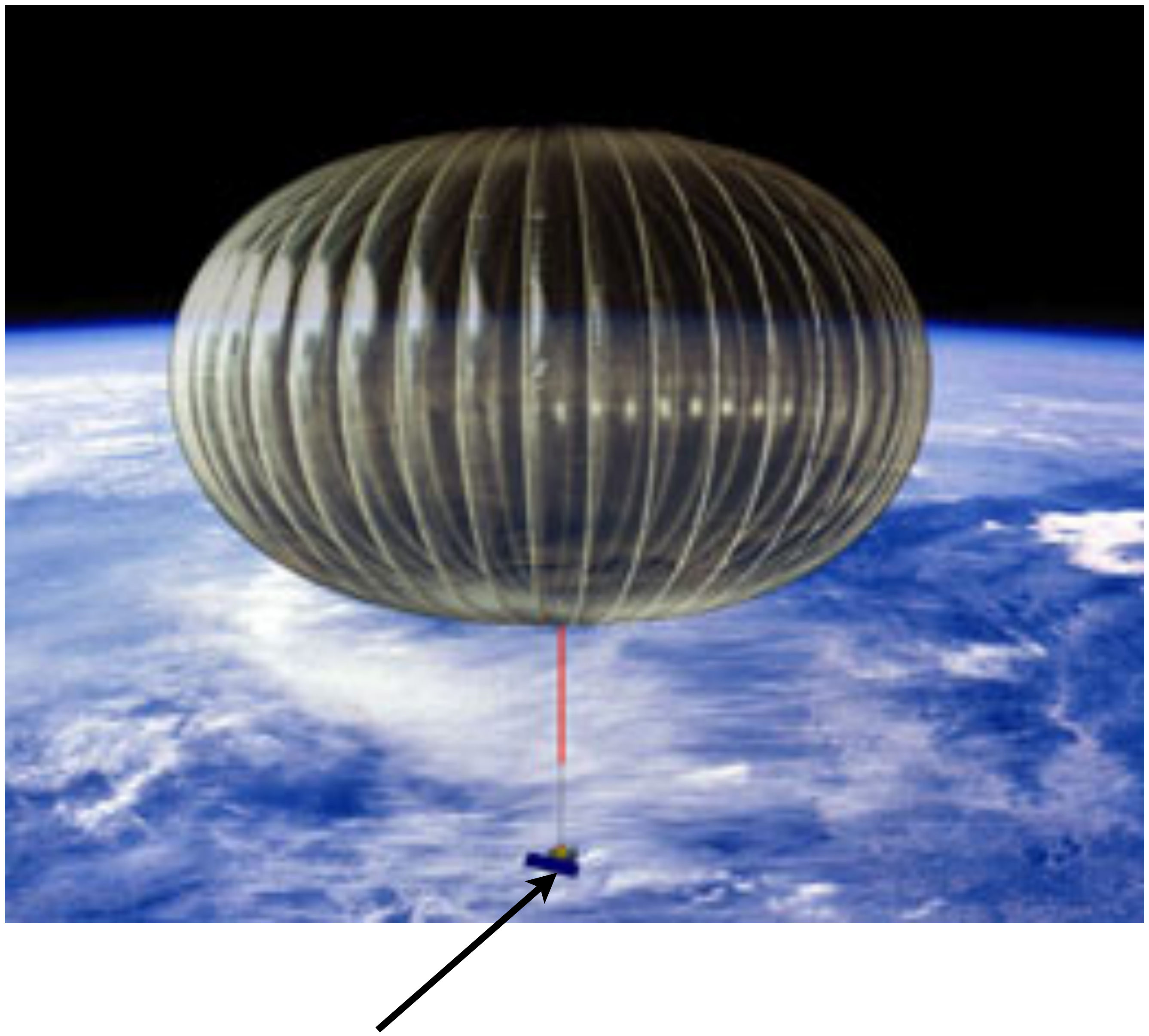
East-West effect



Radius of curvature
smaller than radius of Earth

Particles below geomagnetic cutoff

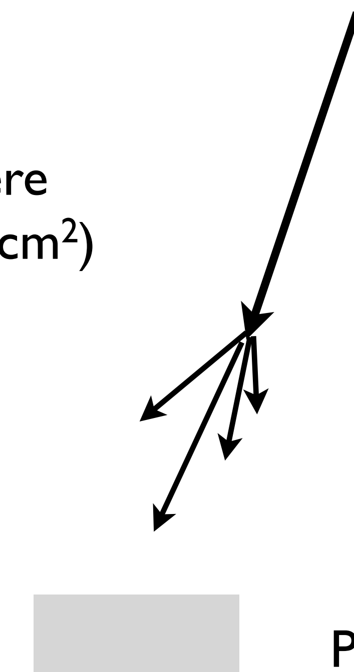
Measurement in upper atmosphere



Particle detector

Particle with energy greater than cutoff

Remaining atmosphere above detector (5 g/cm^2)



Secondaries

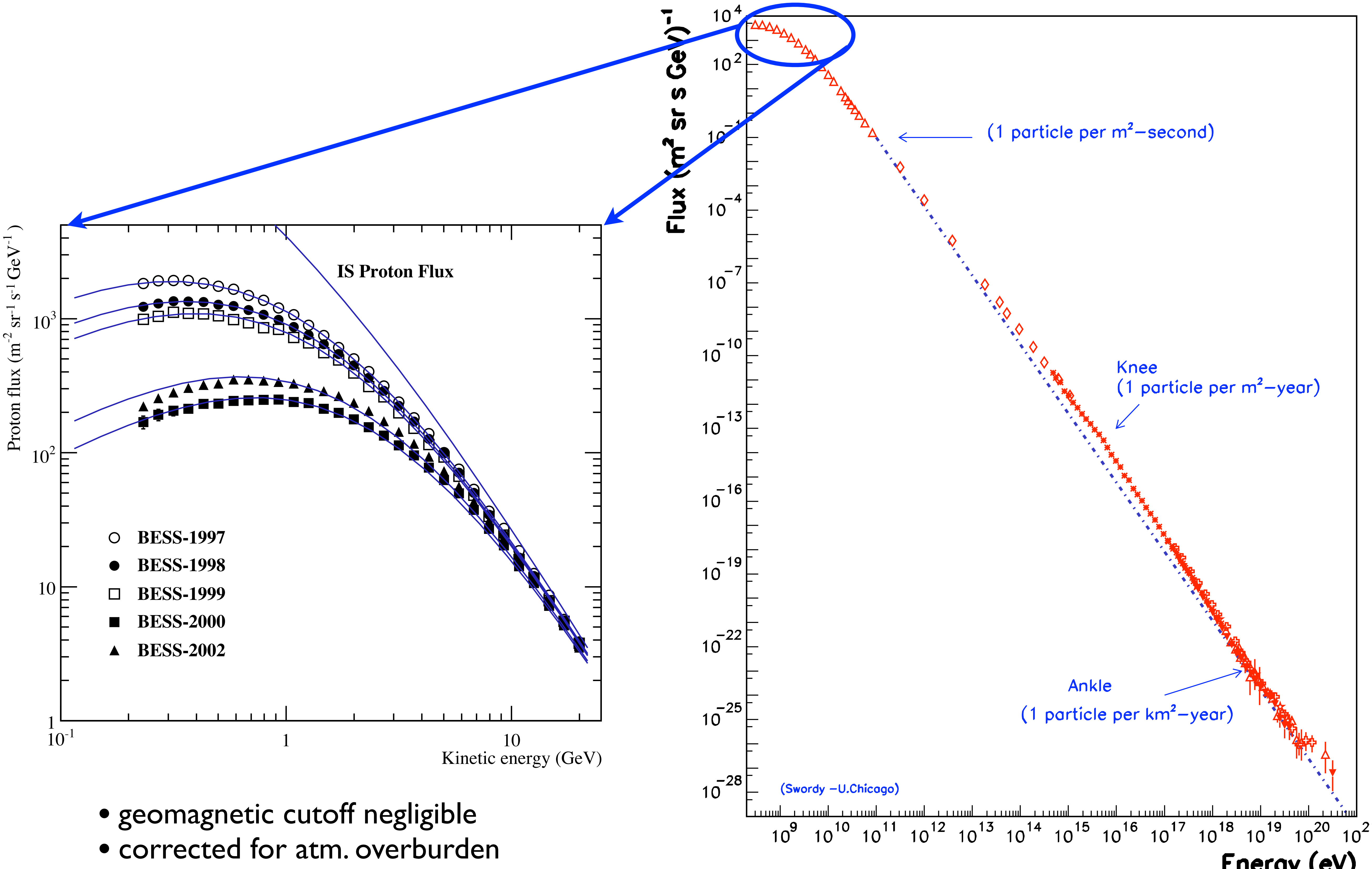
Particle detector

Traversed column depth

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

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

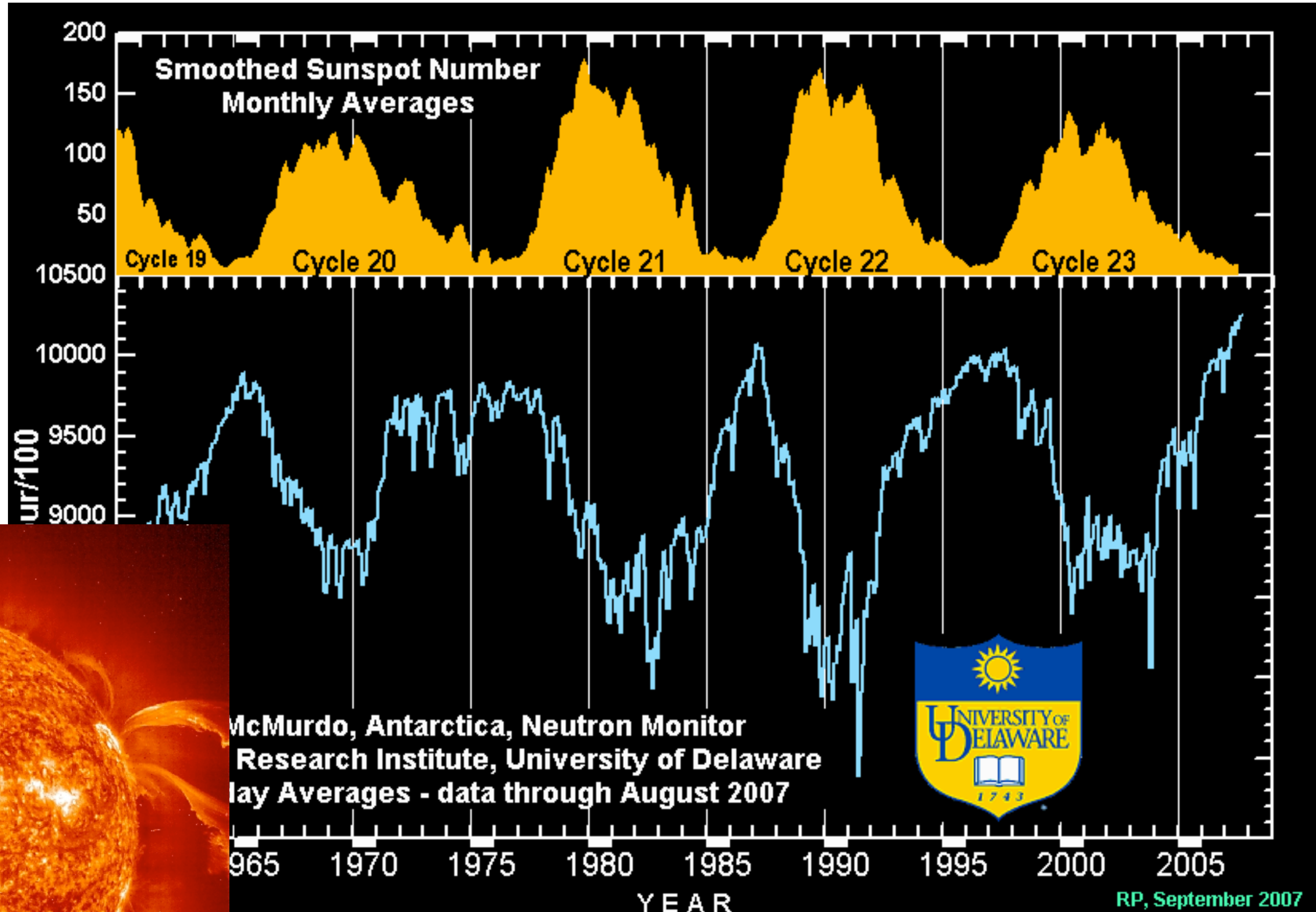
Temporal variation of flux at poles

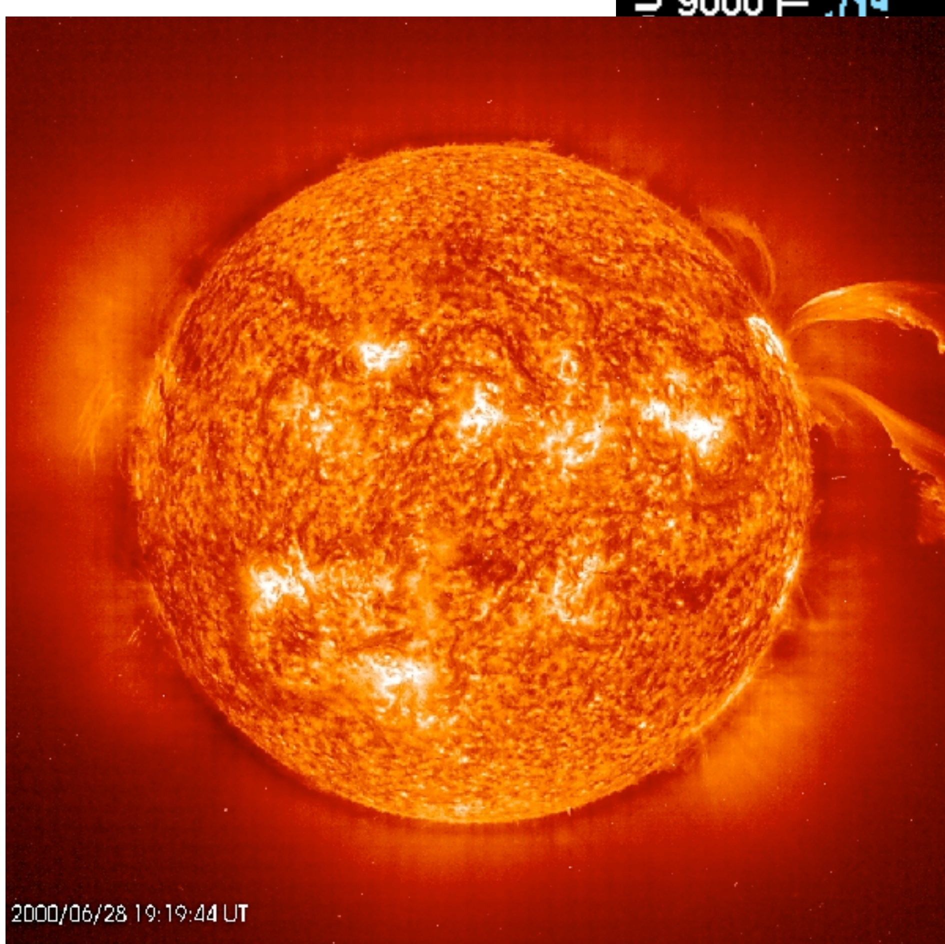


- geomagnetic cutoff negligible
- corrected for atm. overburden

Anti-Correlation with solar activity

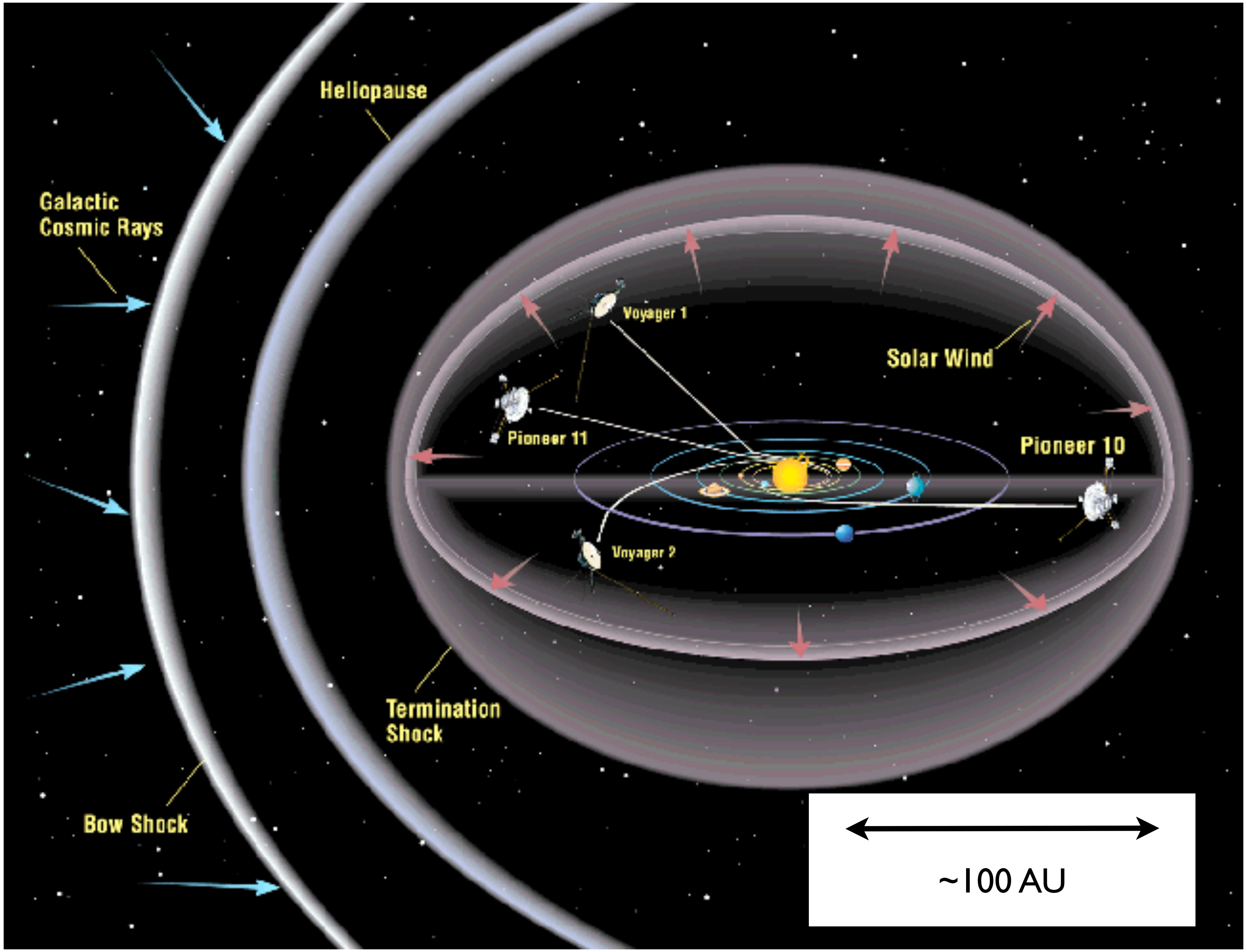
Flux of cosmic rays at poles





Differential rotation of sun: reversal of mag. field every 11 years (full period 22 years)

Solar modulation of cosmic ray flux



Heliosphere

Example:
Proton energy
reduced by
0.5 to 1 GeV after
crossing Solar Wind

Sources not in solar system

$$\Phi_{\text{Earth}}(E) = \frac{E^2 - m^2}{(E + Z \cdot V_{\text{pot}})^2 - m^2} \Phi_{\text{ISM}}(E + Z \cdot V_{\text{pot}})$$

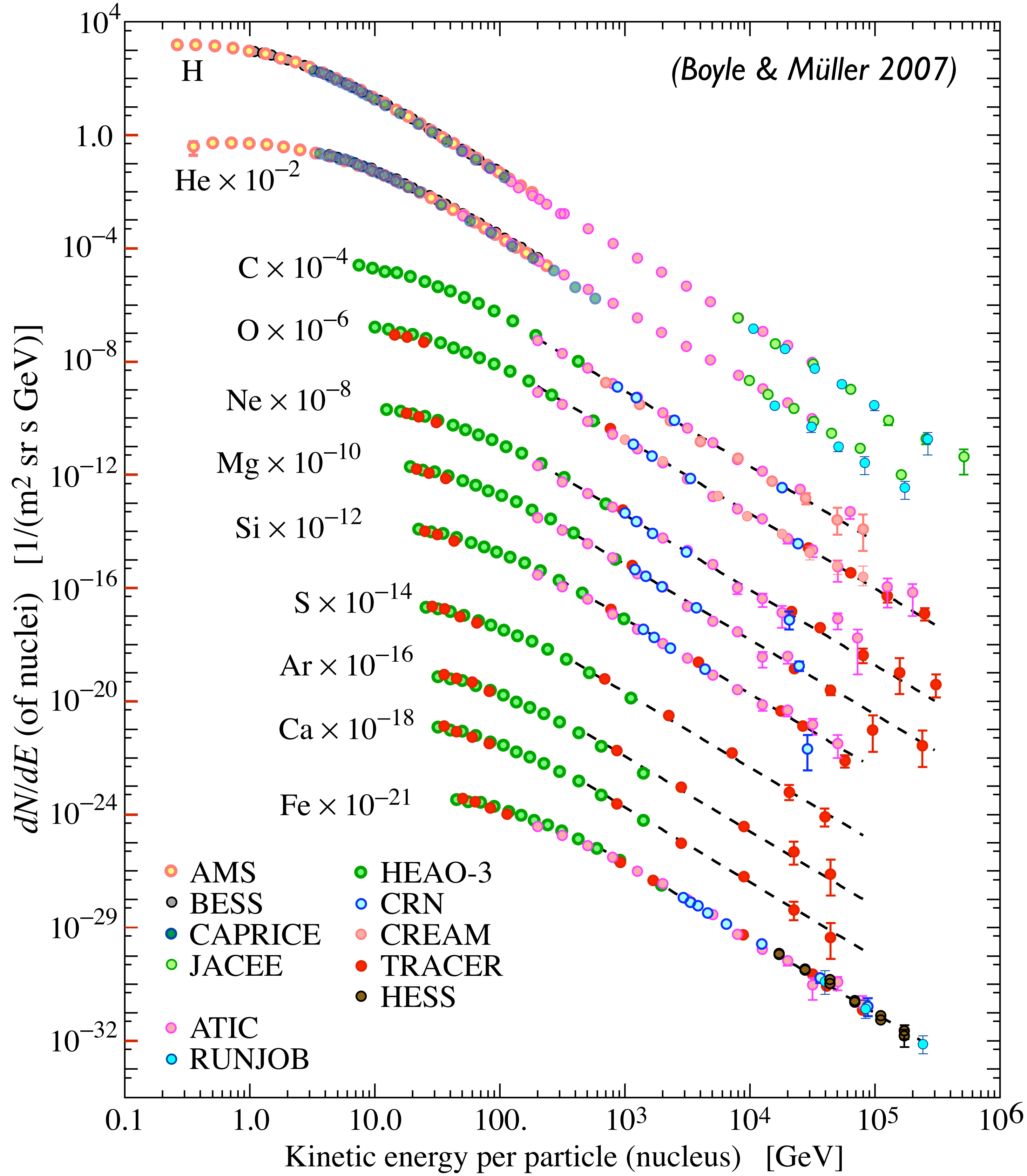
Fluxes of individual elements

Power law also found for individual elements

Index of power law almost identical (heavier elements harder spectra?)

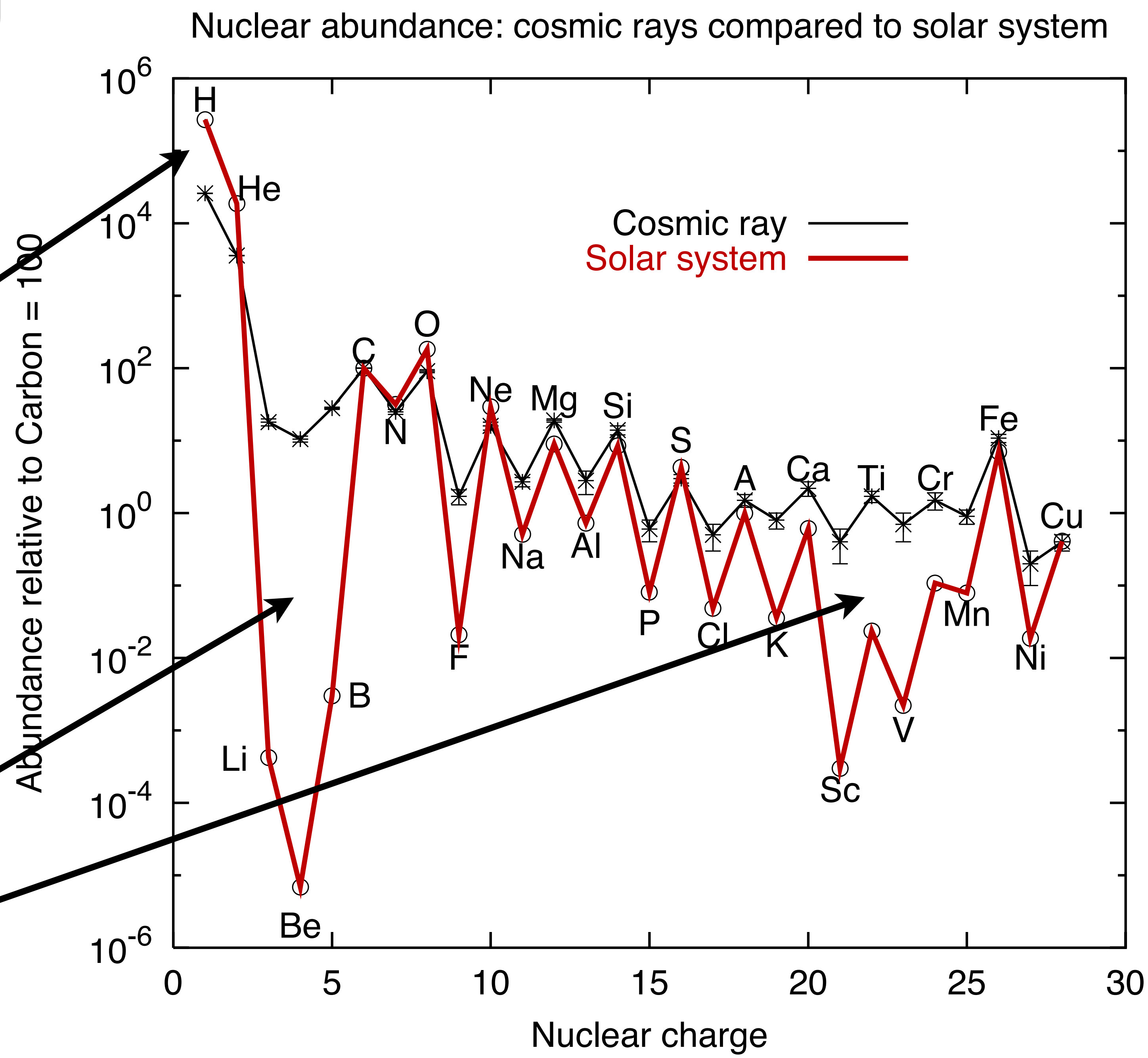
Relative abundance of nuclei

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



Comparison of element abundances

Flux of elements at ~1GeV

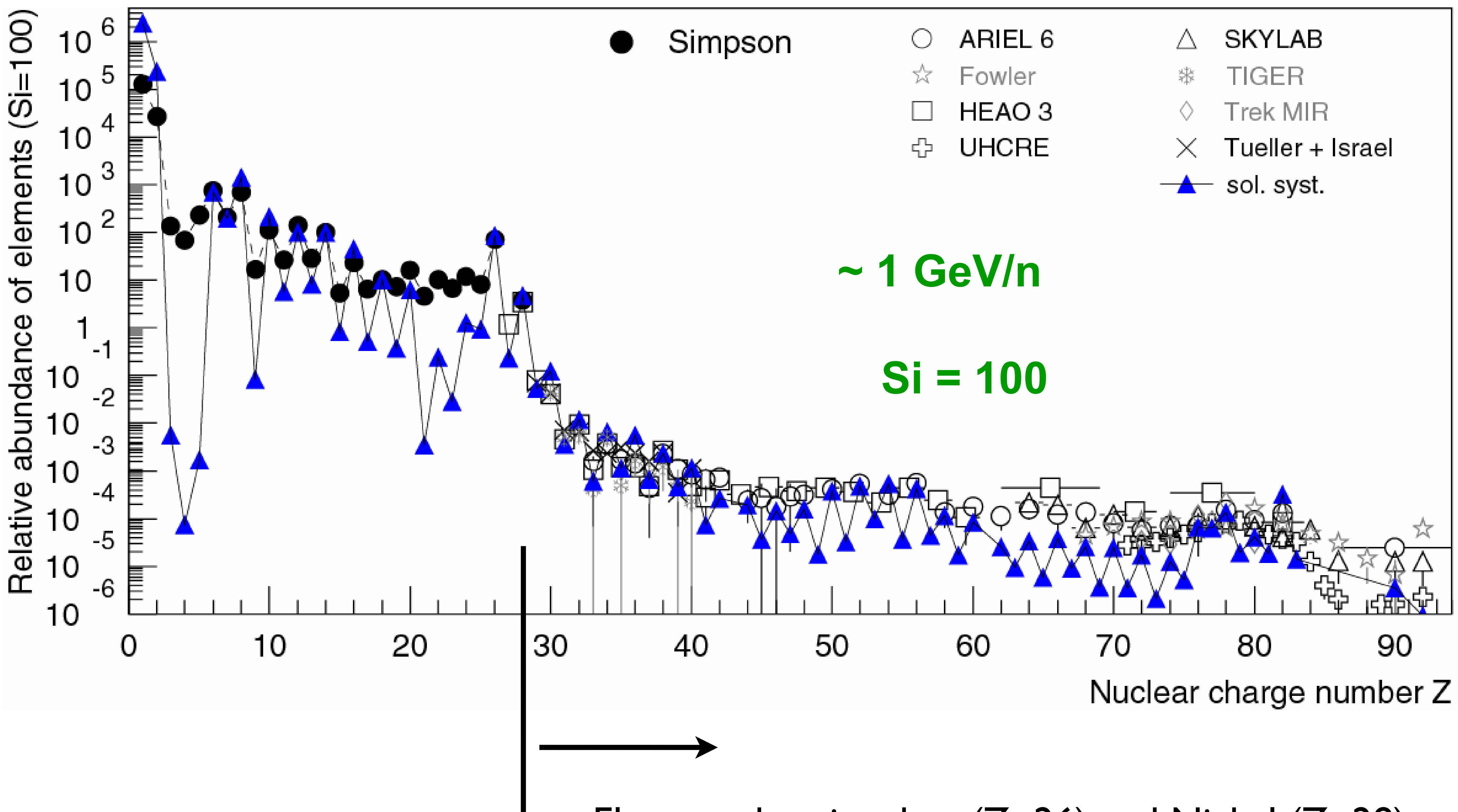


Discrepancy for hydrogen:
first ionization potential (FIP)?

Not typical products of
Supernova explosions

(Gaisser & Stanev, NPA 2006)

What about heavy elements ?

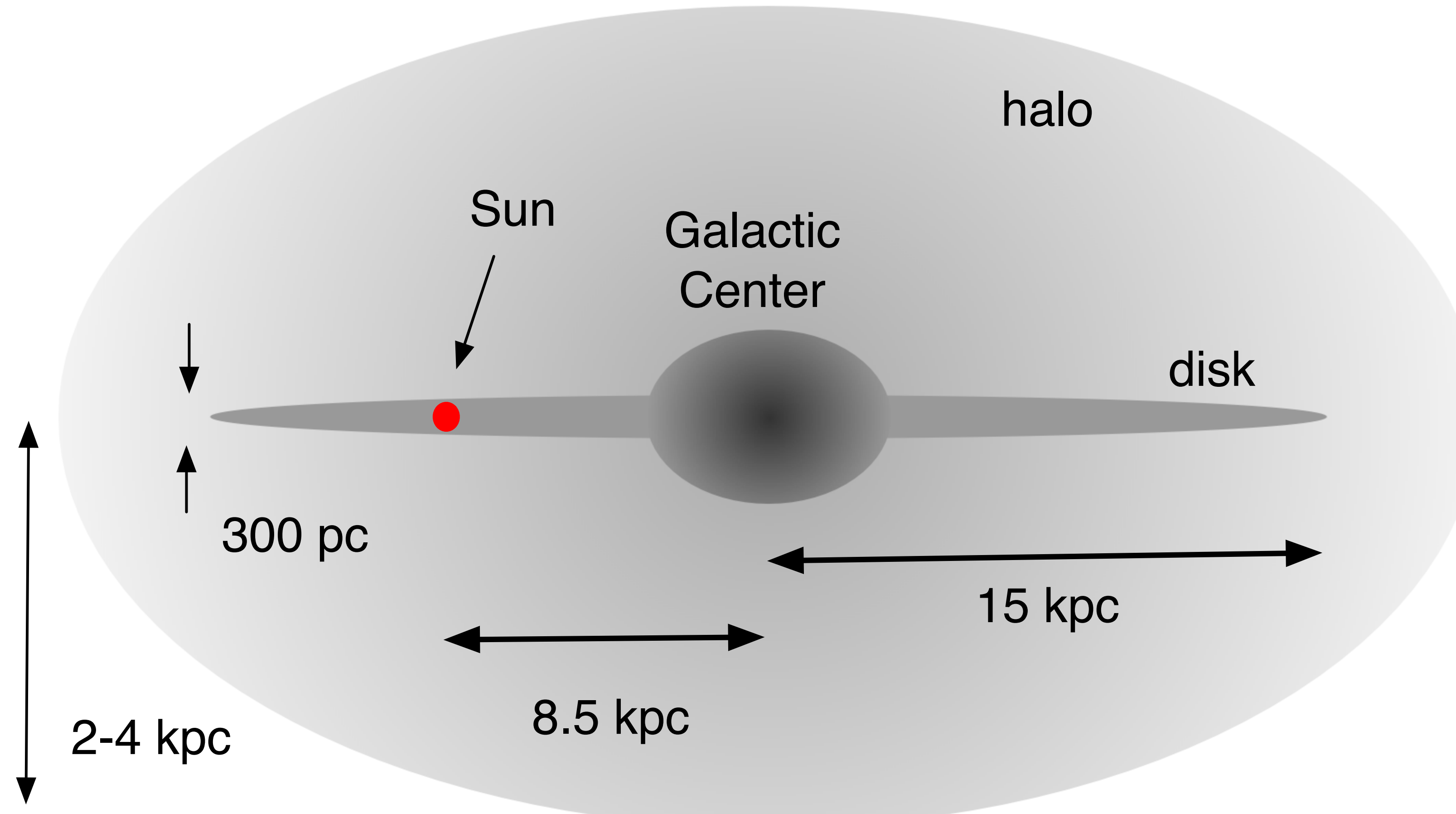


Elements heavier than (Z=26) and Nickel (Z=28)
hardly produced in SN explosions

Galaxy and galactic magnetic fields

(Andromeda, M31)

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



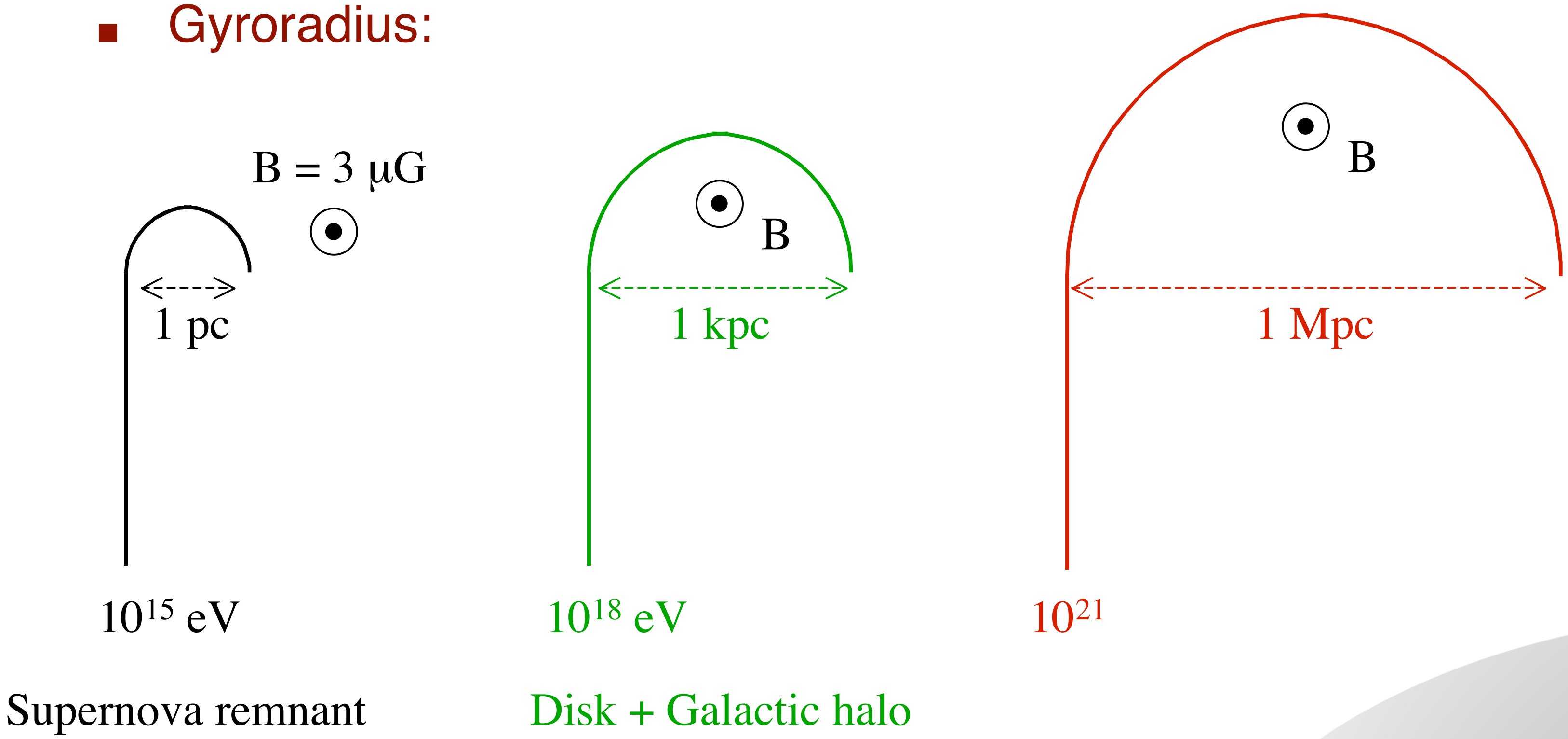
$$R_L \simeq 1\,\mathrm{pc} \times \left(\frac{E}{10^{15}\,\mathrm{eV}}\right)\left(\frac{\mu\mathrm{G}}{ZB}\right)$$

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

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

Galactic and extragalactic sources

- Galactic magnetic field: ~ 3 μG (3.10^{-10} T)
- Gyroradius:



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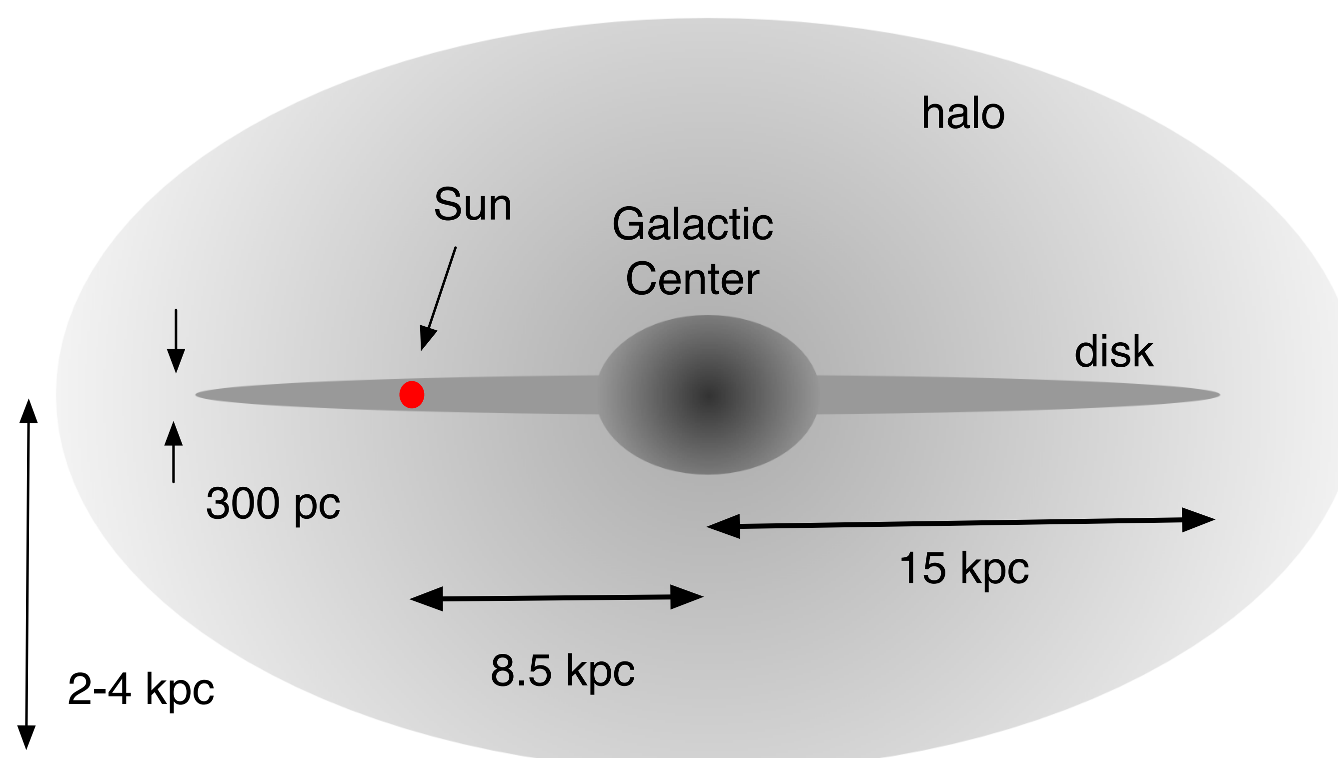
No diffusion in Galactic mag. field at very high energy



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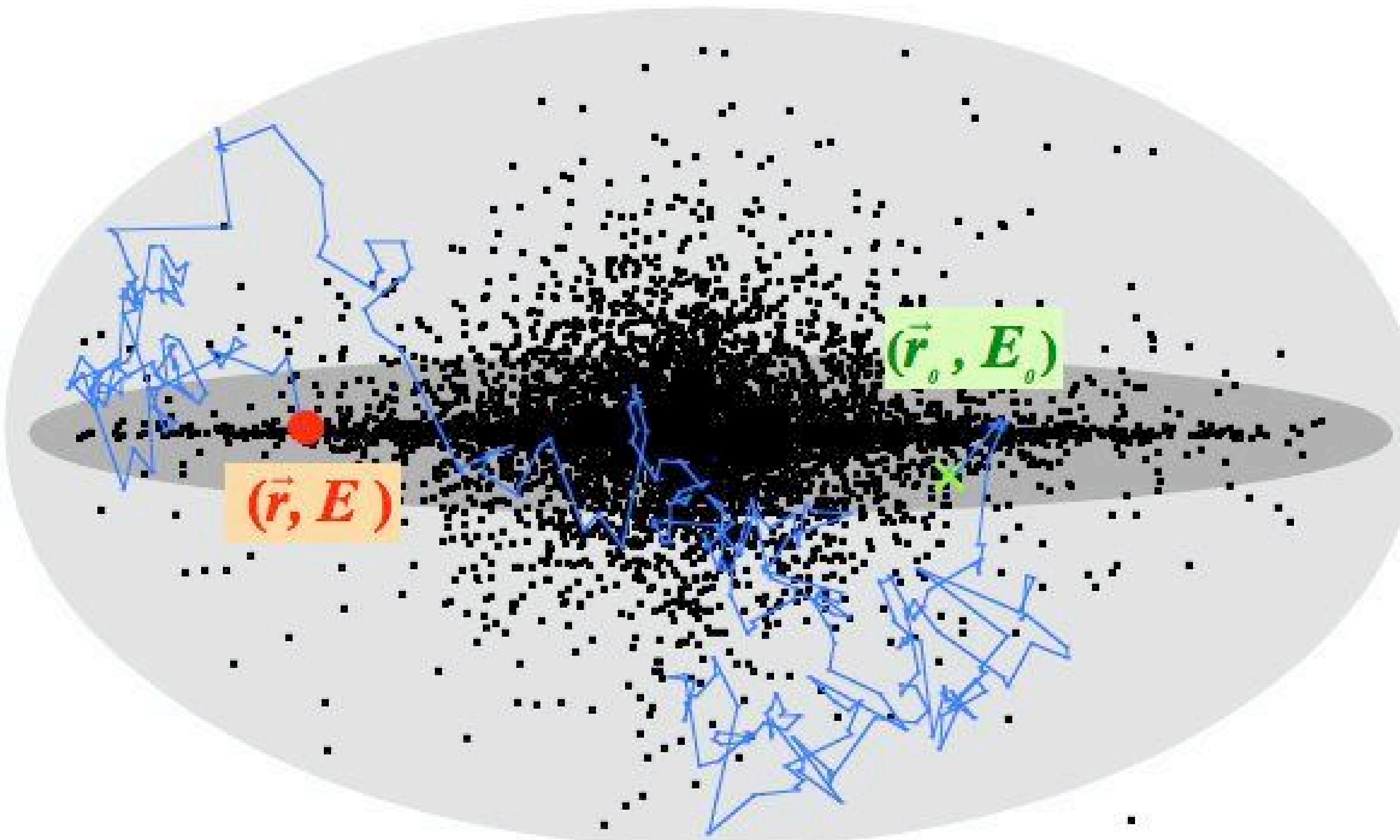

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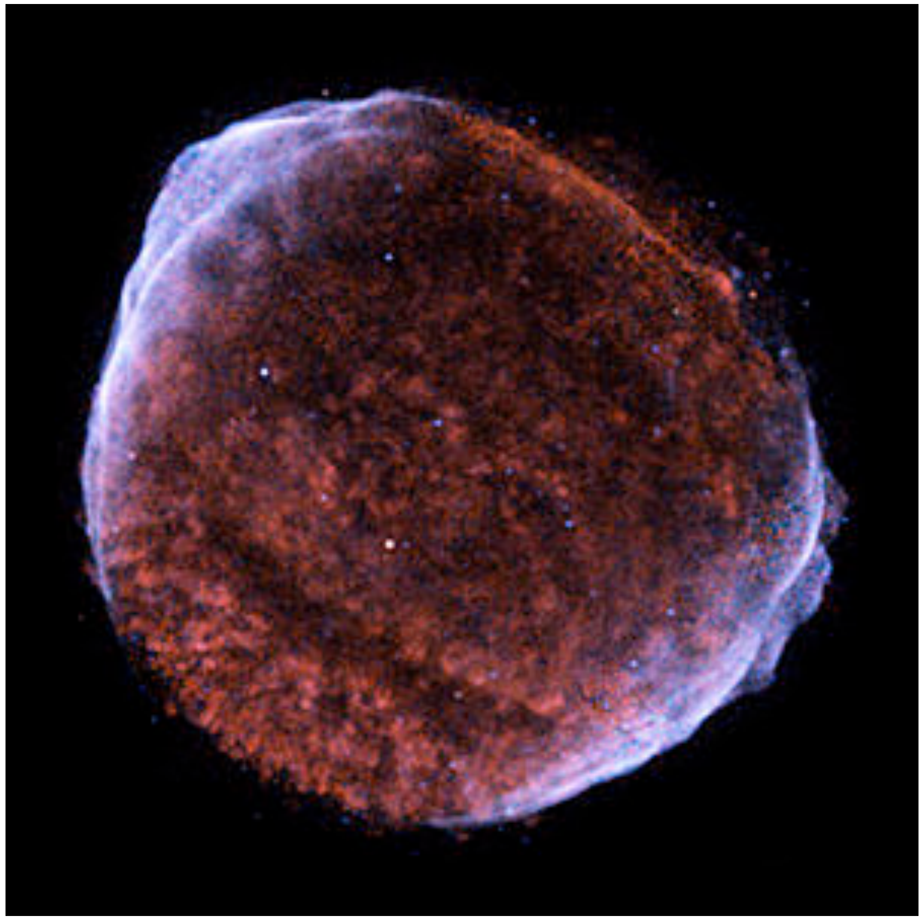
Supernova remnants

SN remnant 1006



20 pc

Distance ~ 2.2 kpc

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: $\sim 10^{51}$ erg

(1 erg = 0.1 μJ)

General arguments:

- Rate and energy budget
- Acceleration theory
- Elemental composition

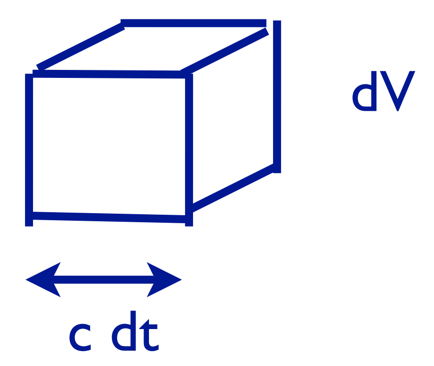
Power needed to maintain cosmic ray flux

Assumption: entire galaxy homogeneously filled with cosmic rays

Density of particles for given flux

Isotropy $\int d\Omega = 4\pi$

$$\frac{dN}{dE\,dV} = \frac{4\pi}{c}\,\frac{dN}{dE\,d\Omega\,dA\,dt}$$



Total cosmic ray energy

$$E_{\text{tot}} = \int dV \int dE\; E \cdot \frac{dN}{dE\,dV}$$

Mean escape time $\tau_{\text{esc}} \approx 10^7 a$

$$P_{\text{src}} = E_{\text{tot}}/\tau_{\text{esc}} \approx 10^{41}\,\text{erg/s}$$

$$P_{\text{SNR}} \approx 10^{42}\,\text{erg/s}$$

Power of cosmic ray sources

Kinetic energy released in SN explosions

COSMIC RAYS FROM SUPER-NOVAE

By W. Baade and F. Zwicky

Mount Wilson Observatory, Carnegie Institution of Washington and California Institute of Technology, Pasadena

Communicated March 19, 1934

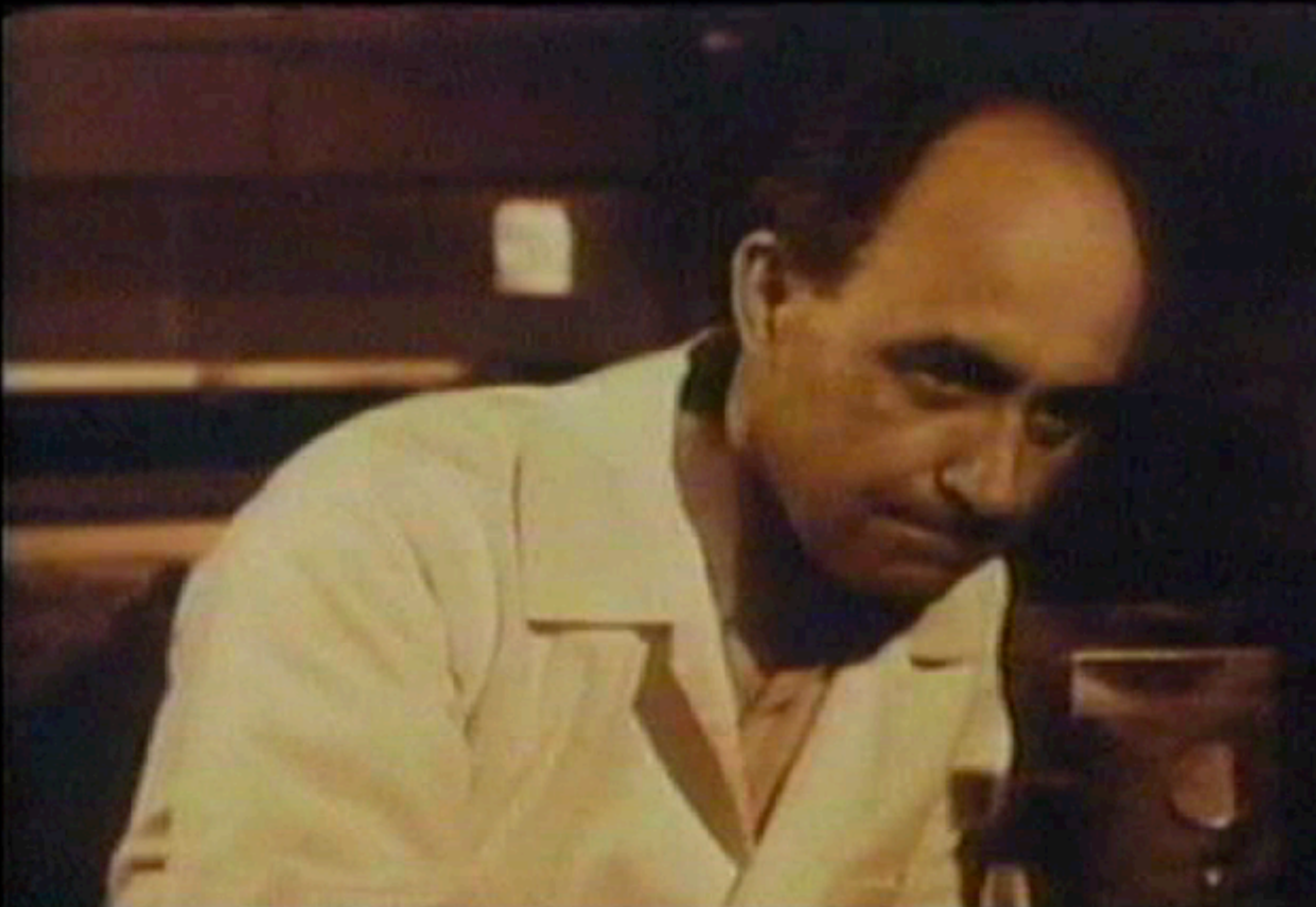
A. Introduction.—Two important facts support the view that cosmic rays are of extragalactic origin, if, for the moment, we disregard the possibility that the earth may possess a very high and self-renewing electrostatic potential with respect to interstellar space.

If interest in these questions still prevails at that future time, science will therefore be able to test the correctness of our hypothesis some time during the next thousand years or so, as the occurrence of a super-nova in our own system would multiply the intensity of the cosmic rays by a factor one thousand or more. It also seems quite possible to observe with cosmic-ray electroscopes the flare-up of a super-nova in one of the nearer extragalactic nebulae, as for them $r = 1000\,n$, and

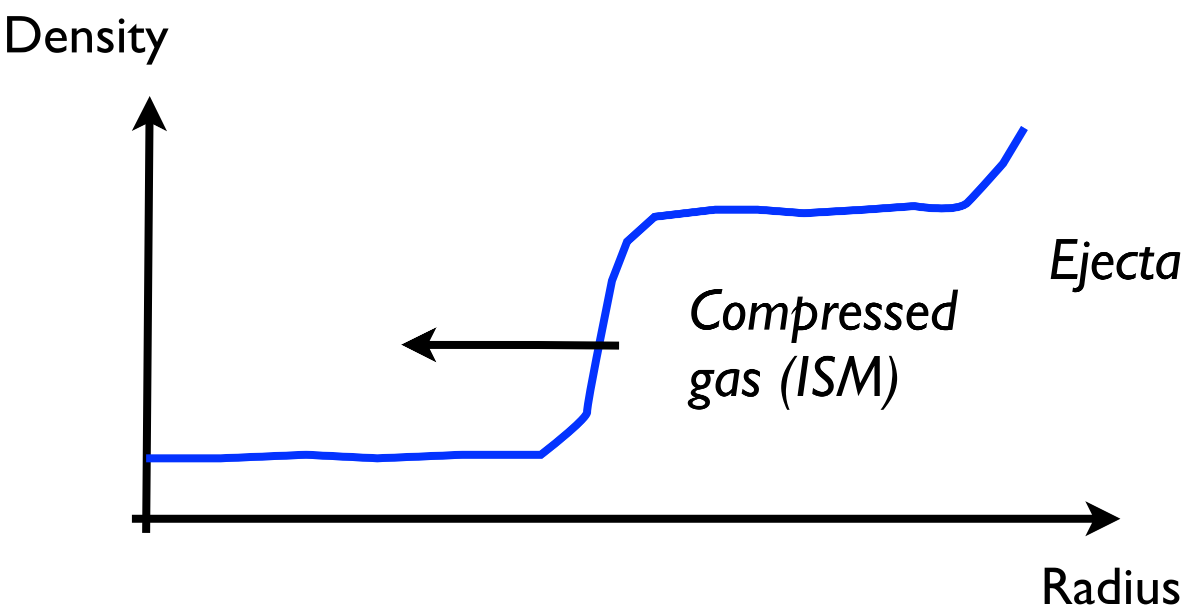
$$\Delta\sigma = 0.01/n^2 \text{ ergs/cm.}^2 \text{ sec.}, \qquad (10)$$

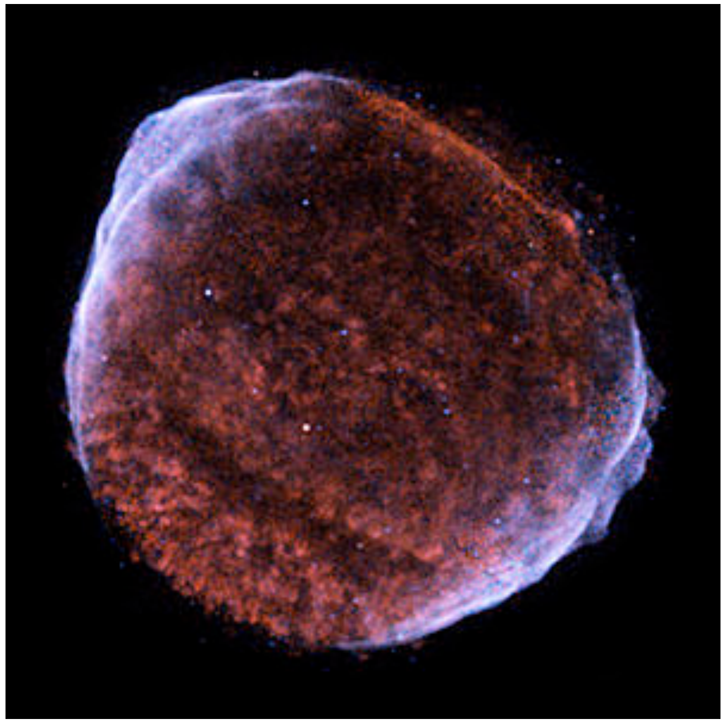
where n is a number of the order one. It might in this connection be of interest to follow up the causes for Regener's[4] curious balloon observation of March 29, 1933.

Stochastic Fermi acceleration

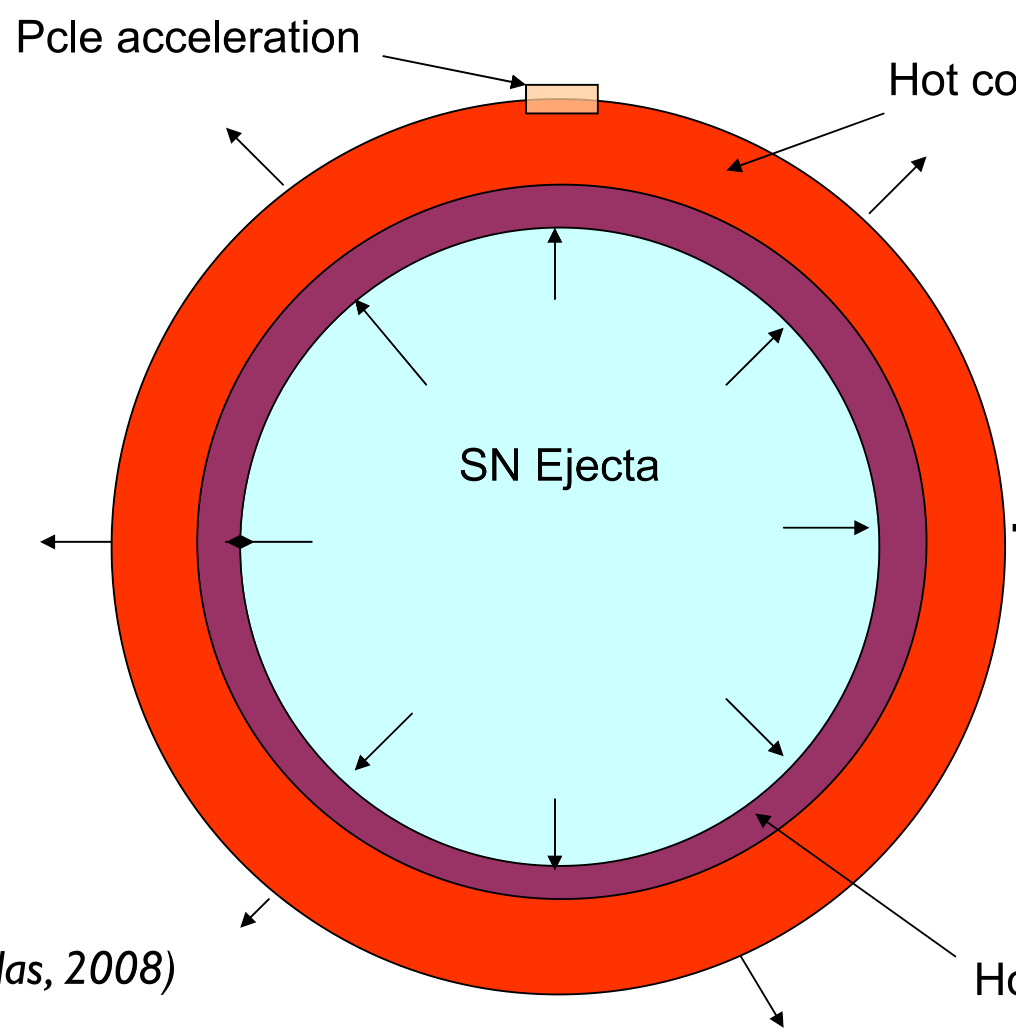


Stochastic acceleration on SN shock fronts





$$4\rho_{\rm ISM} \approx \rho_{\rm shock}$$



Interstellar gas

(Type Ia)

OR

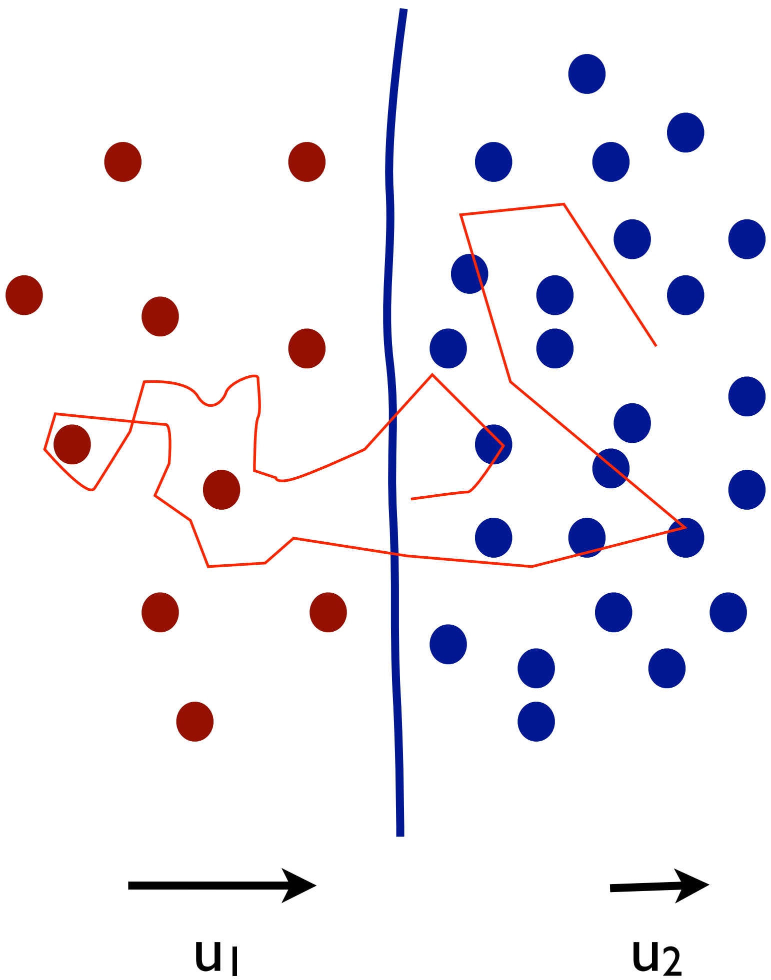
Wind from exploded star, with compressed gas shells

(Type Ib/ II)

(Hillas, 2008)

First order Fermi acceleration

Assumption:
particles scatter elastically on turbulent mag. fields



Rest frame of shock front

$$\Delta E = \frac{1}{2}m\left(v + (u_1 - u_2)\right)^2 - \frac{1}{2}mv^2$$

$$\frac{\Delta E}{E} \approx 2\frac{(u_1 - u_2)}{v}$$

vertical crossing,
non-relativistic shock speed

$$\frac{\Delta E}{E} = \frac{4}{3}\frac{(u_1 - u_2)}{c}$$

Energy-independent relative energy gain

Factor from averaging over all angles

Expected energy distribution

Assumption: energy-independent escape probability P_{esc}

Energy gain per complete cycle of crossings $$\frac{\Delta E}{E} = \xi$$

Energy after *k* cycles $$E = E_0\,\xi^k$$

Number of particles available for further acceleration

$$N = N_0\,(1 - P_{\rm esc})^k$$

Flux of particles

$$N(>E) = {\rm const}\; E^{-\alpha}$$

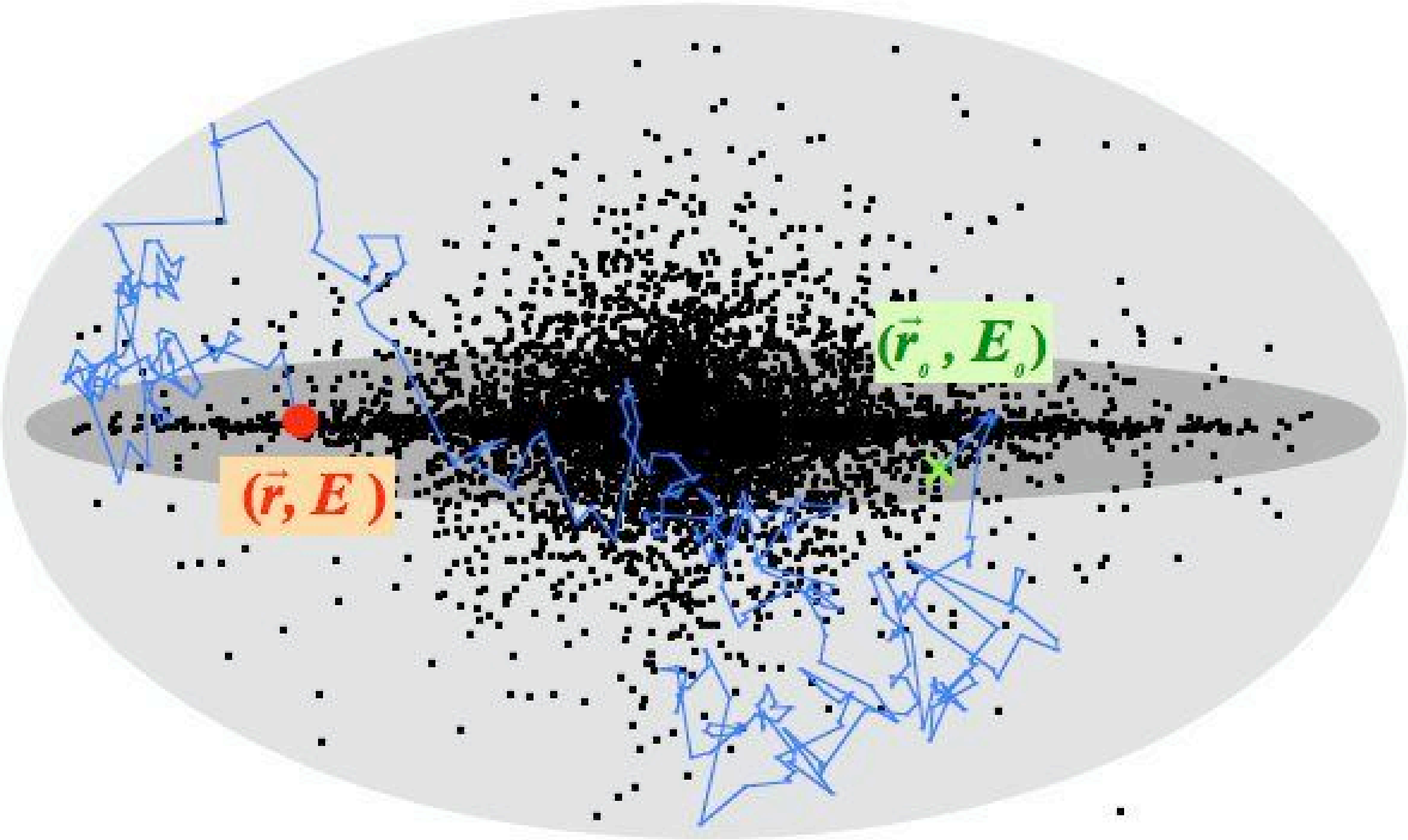
$$\alpha = -\ln(1 - P_{\rm esc})/\ln\xi$$

Numerical values depend on many details

$$\alpha = 1$$

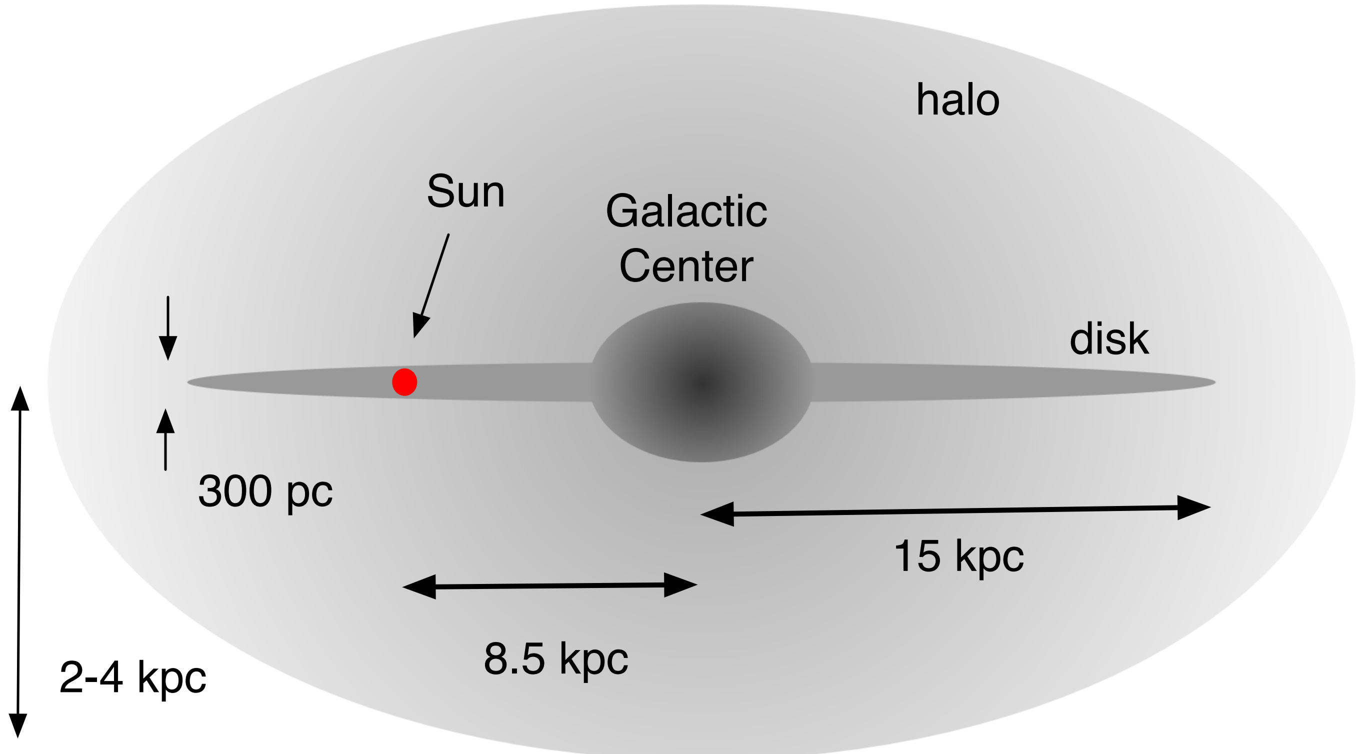
Corresponds to dN/dE ~ E^{-2}

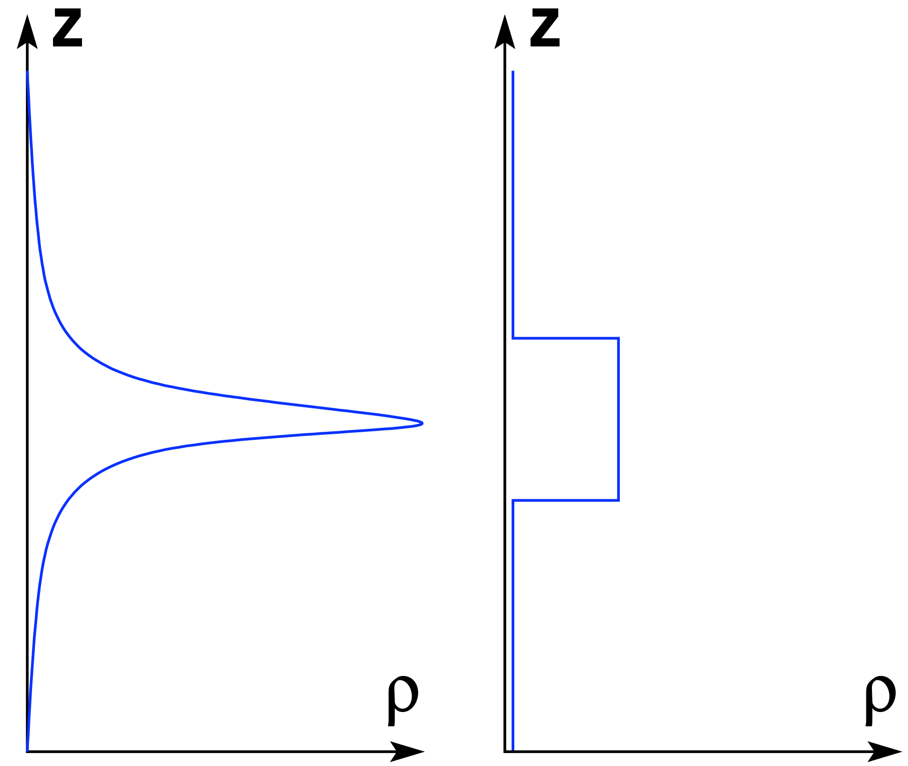
Propagation of cosmic rays in the Galaxy



Diffusion, escape,
interaction with interstellar medium

Leaky Box model

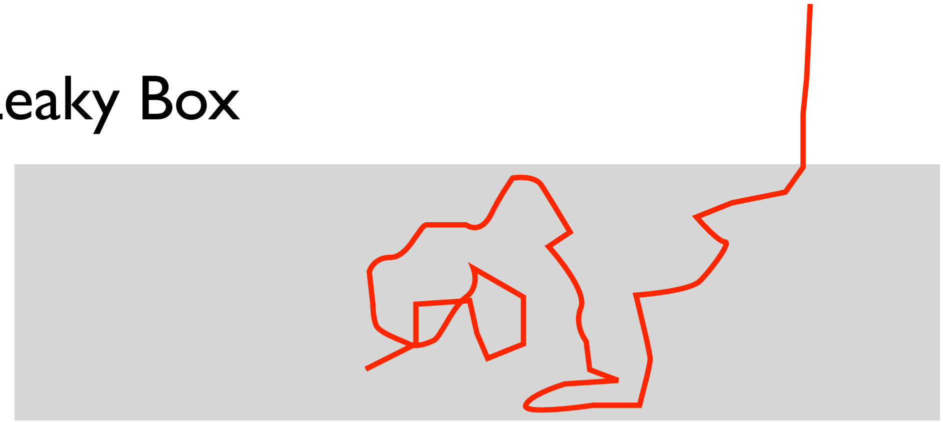




realistic density distribution

Leaky Box model

Leaky Box



Number of particles that escape from box proportional to number of particles in box

Effect of cosmic ray confinement in galaxy

Simplification: only one particle type considered, no energy losses

$$\frac{\partial N(E)}{\partial t} = -\frac{1}{\tau_{\rm esc}} N(E) + Q(E)$$

Flux independent of time

$$0 = -\frac{1}{\tau_{\rm esc}} N(E) + Q(E)$$

$$N(E) = \tau_{\rm esc}\, Q(E)$$

Observation: $\sim E^{-2.7}$

Has to be energy-dependent!

Theory: $\sim E^{-2}$

Energy-dependent escape time

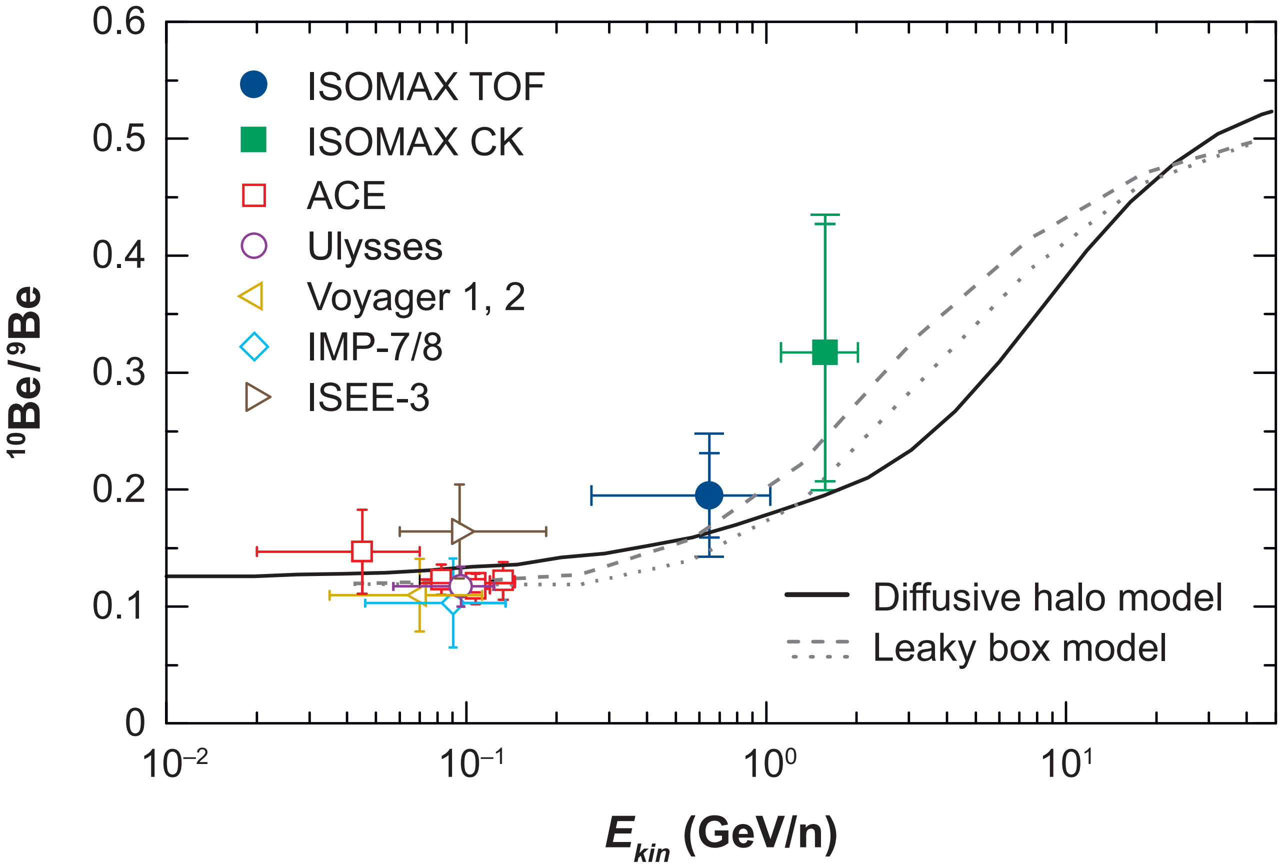
Required by observations $\tau_{\rm esc} \propto E^{-0.7}$

Prediction if diffusion in magnetic field determines escape process

$$\tau_{\rm esc} \propto \left(\frac{E}{Z}\right)^{-0.7}$$

Only energy/charge important

$$\tau_{^{10}{\rm Be}} = 3.9 \times 10^6 {\rm yr}$$



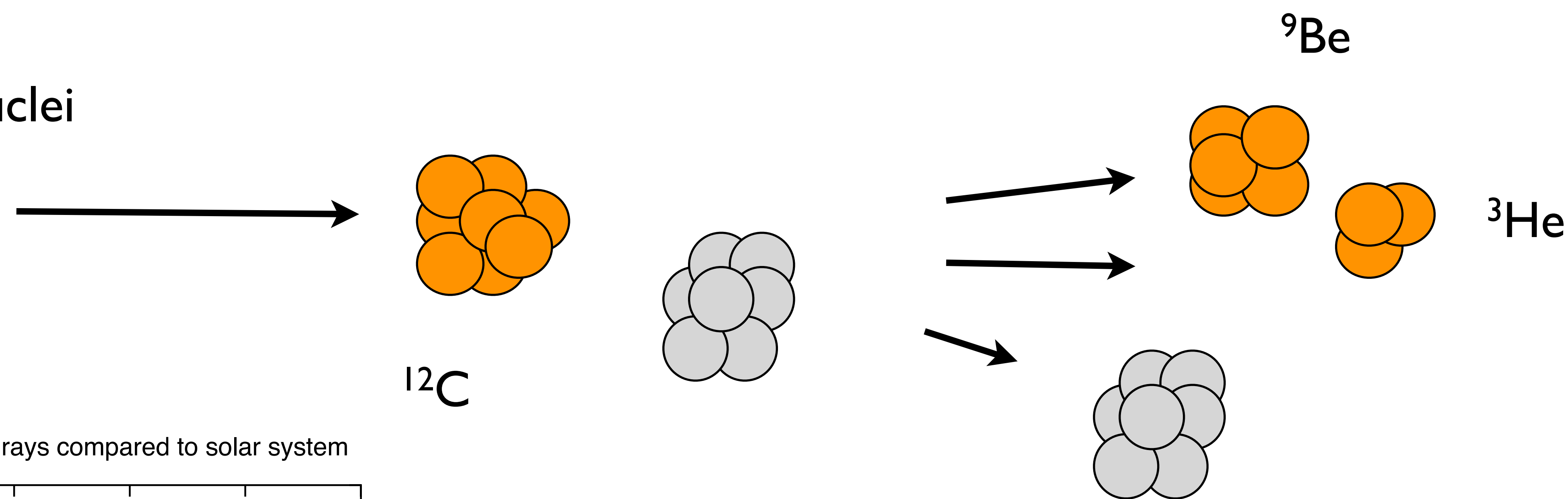
$$N(E) = \tau_{\rm esc}\, Q(E)$$

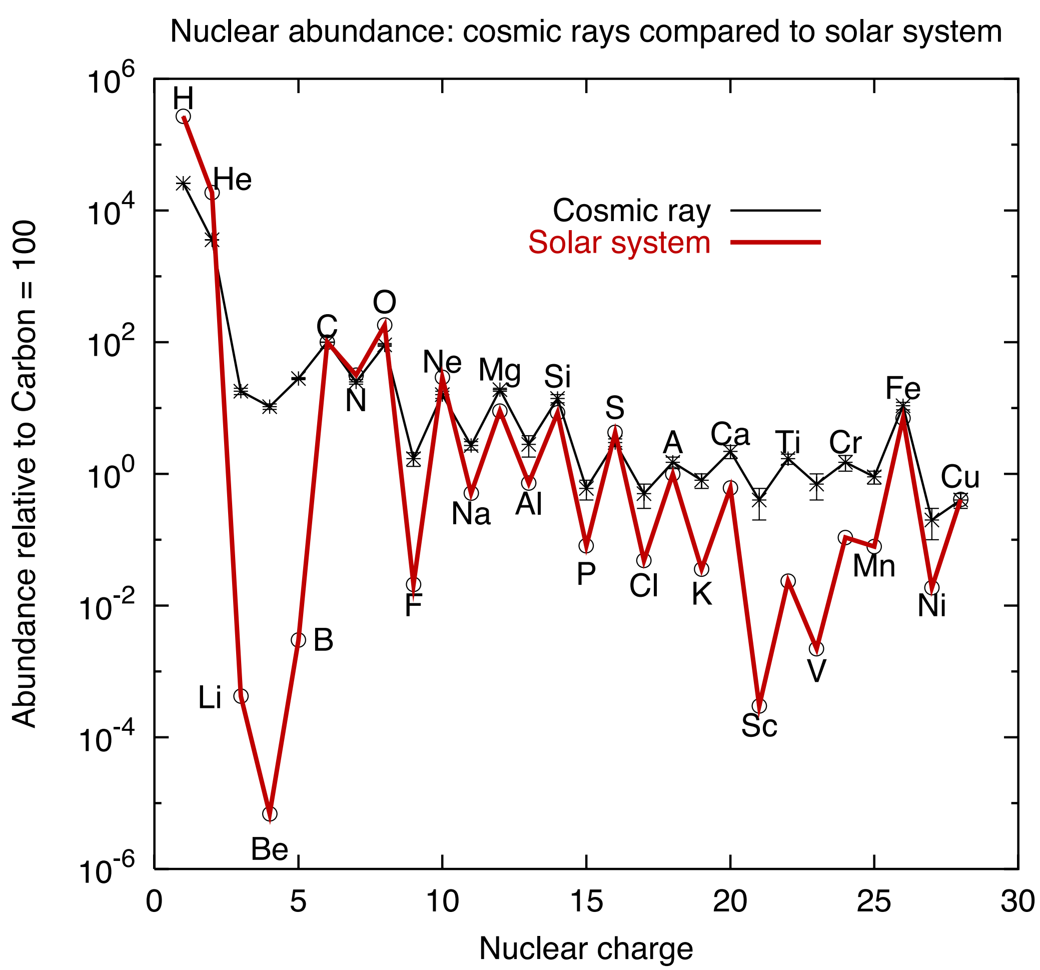
With τ_{esc} ~ 2 x10^7 yr: enhancement of cosmic ray density by factor **10^3 - 10^4** relative to free streaming

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

Particles about only 1/10 of the time in the Galcatic disk, otherweise in magnetic halo

Ratio of secondary to primary elements

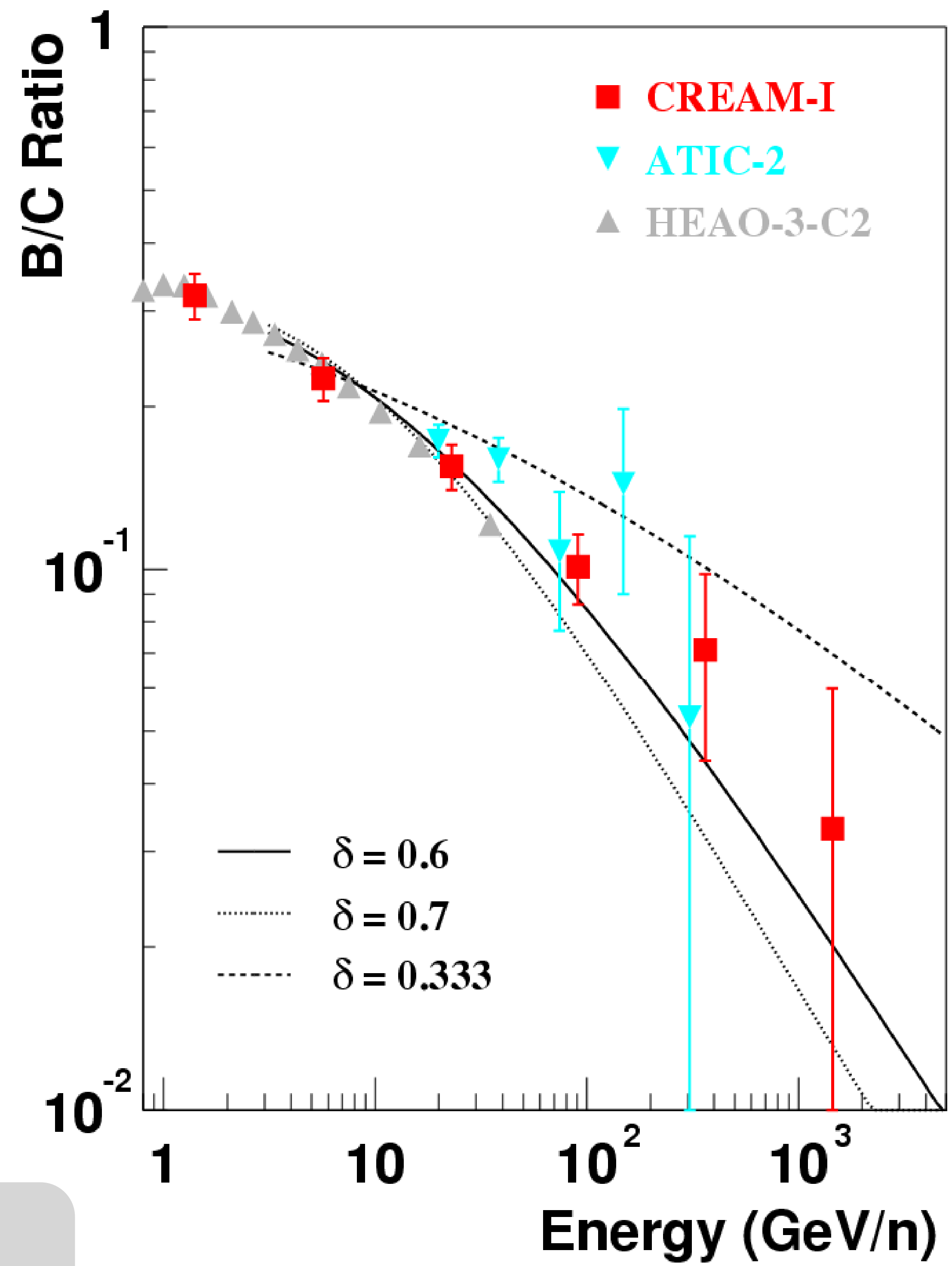
Cosmic rays of higher energy
- escape faster
- have a smaller chance to interact

Total column density traversed ~1 GeV

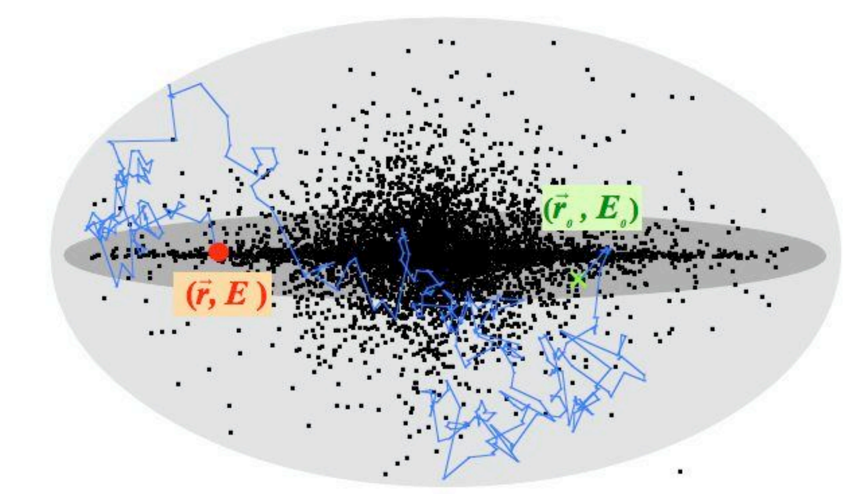
X_p = 5 ... 15 g/cm^2

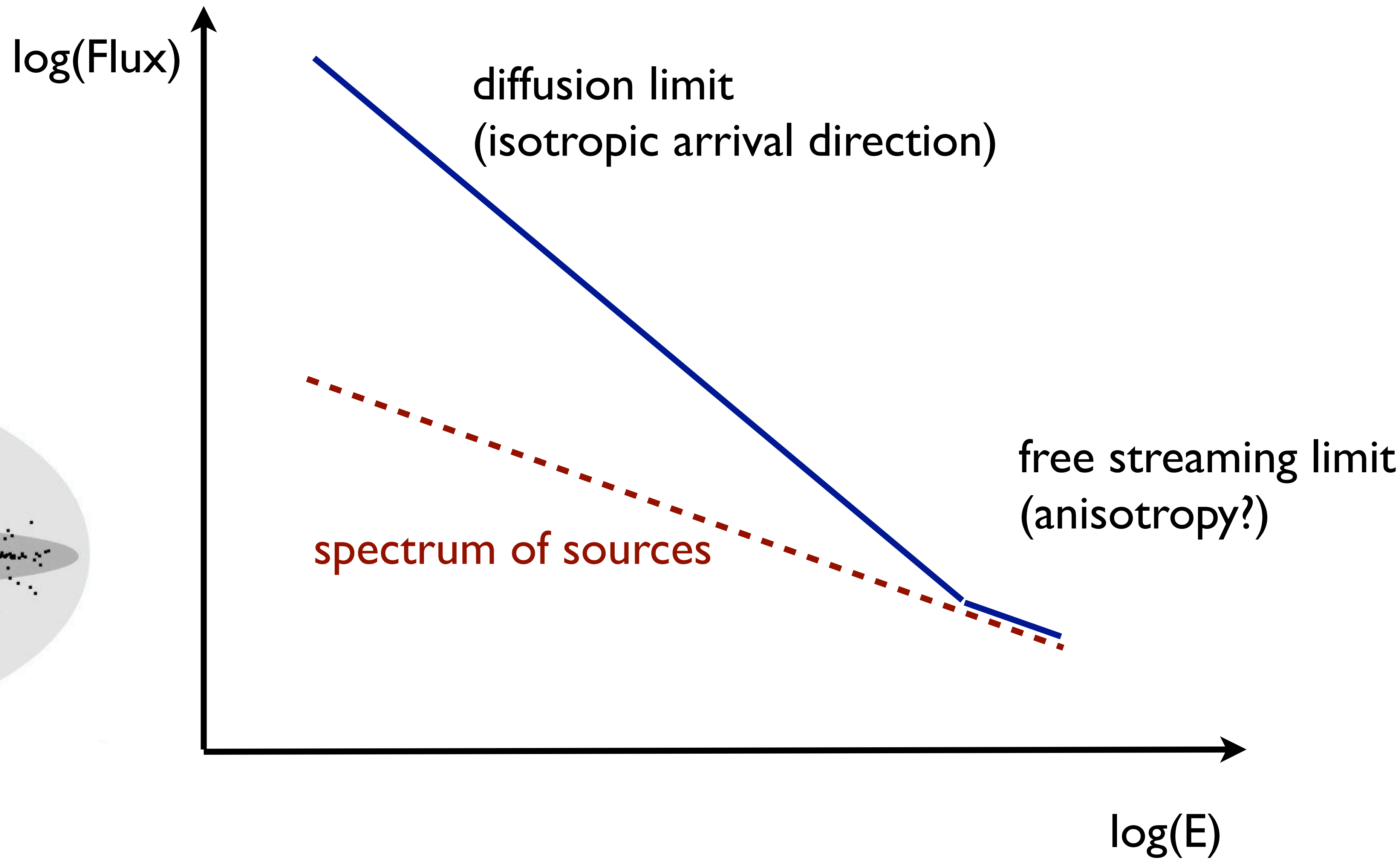
Interaction length of C ~ 70 g/cm^2

If cosmic rays would propagate only in galactic disk this would correspond to τ_{esc} ~ 10^6 yr



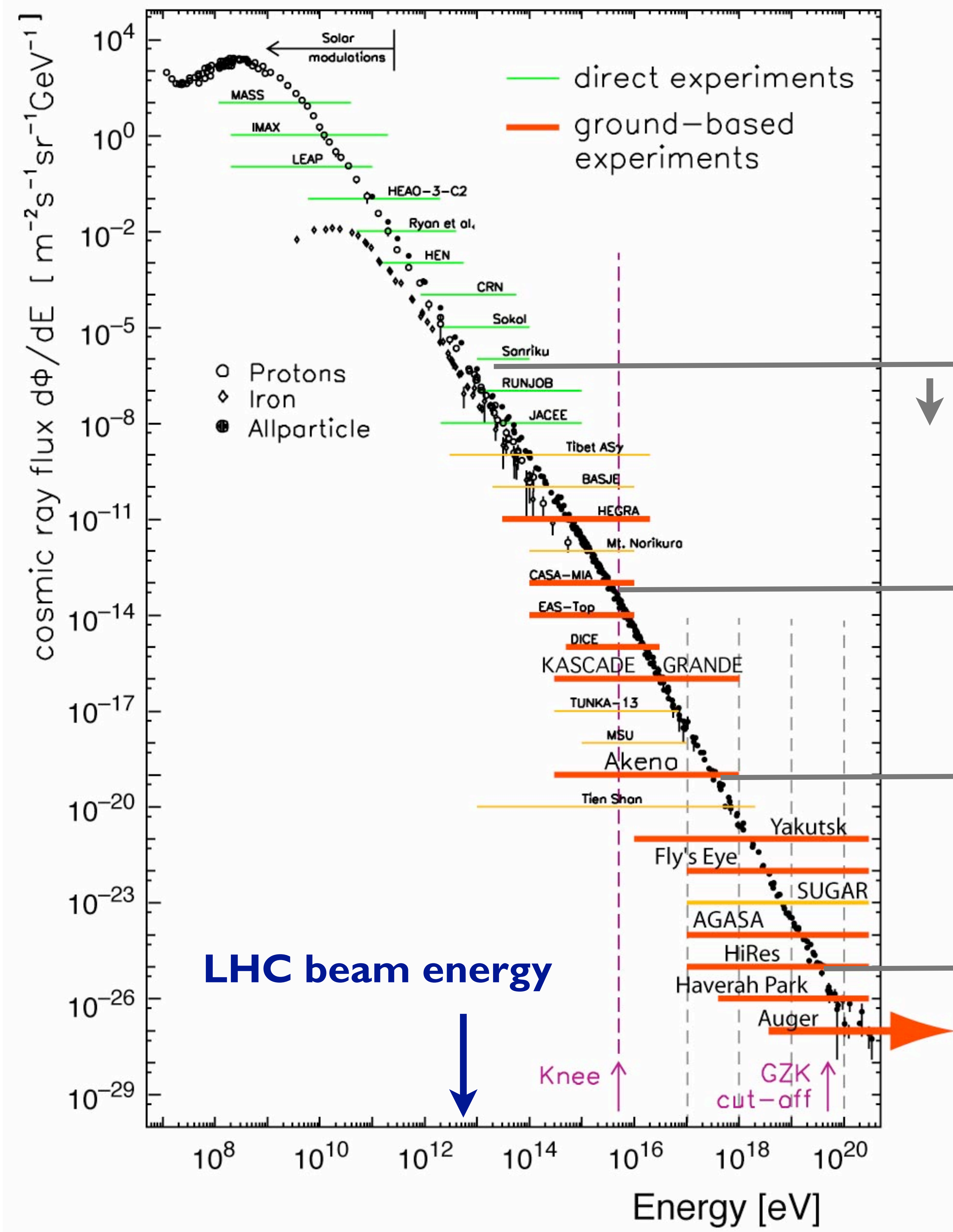
Magnetic fields: Confinement in the Galaxy





Observed spectrum softer than injection spectrum
Density of particles much higher than without mag. fields

Rate of particles



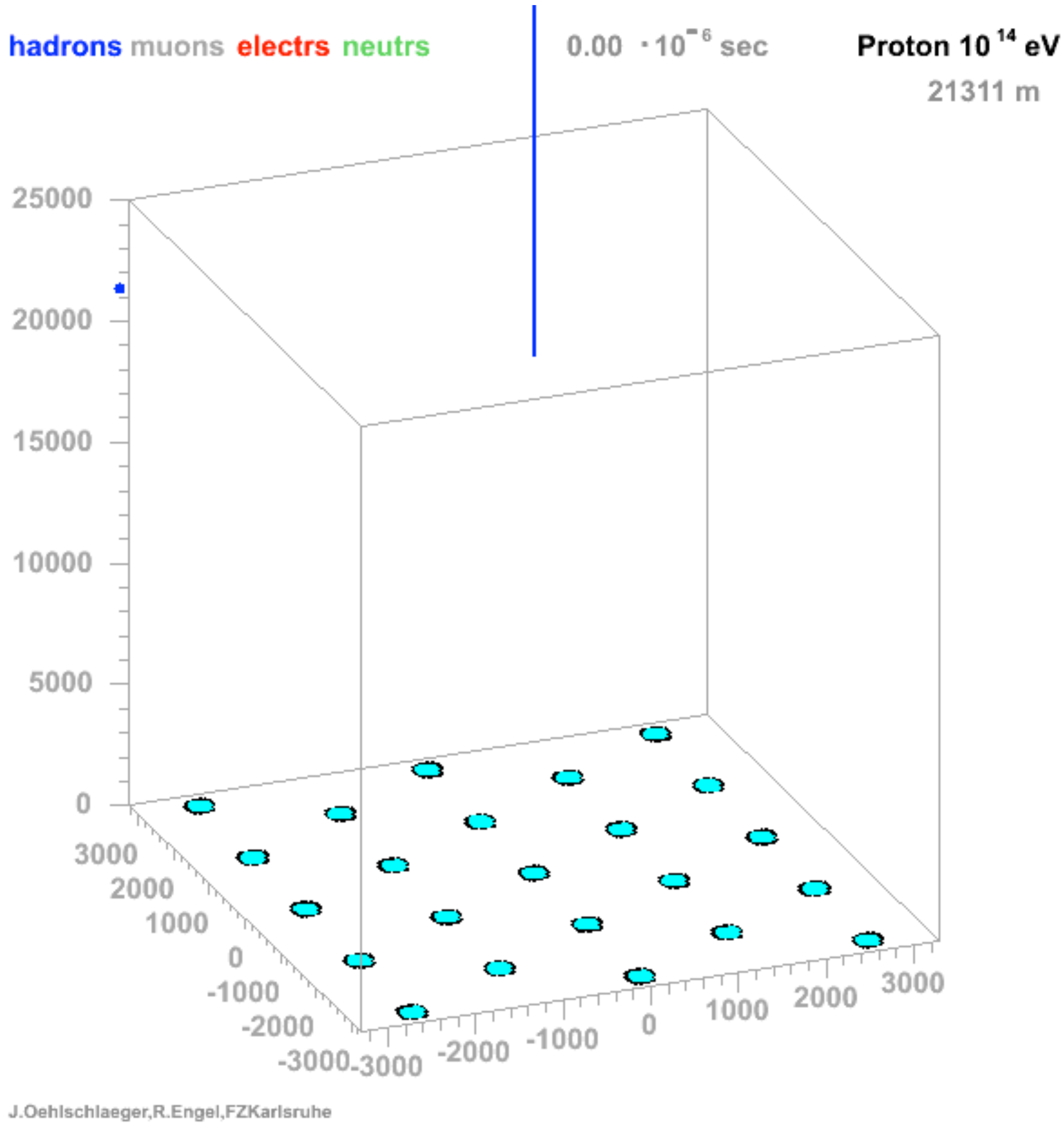
0.1 particles / m^2 min.

10 particles / km^2 min.

10 particles / km^2 day

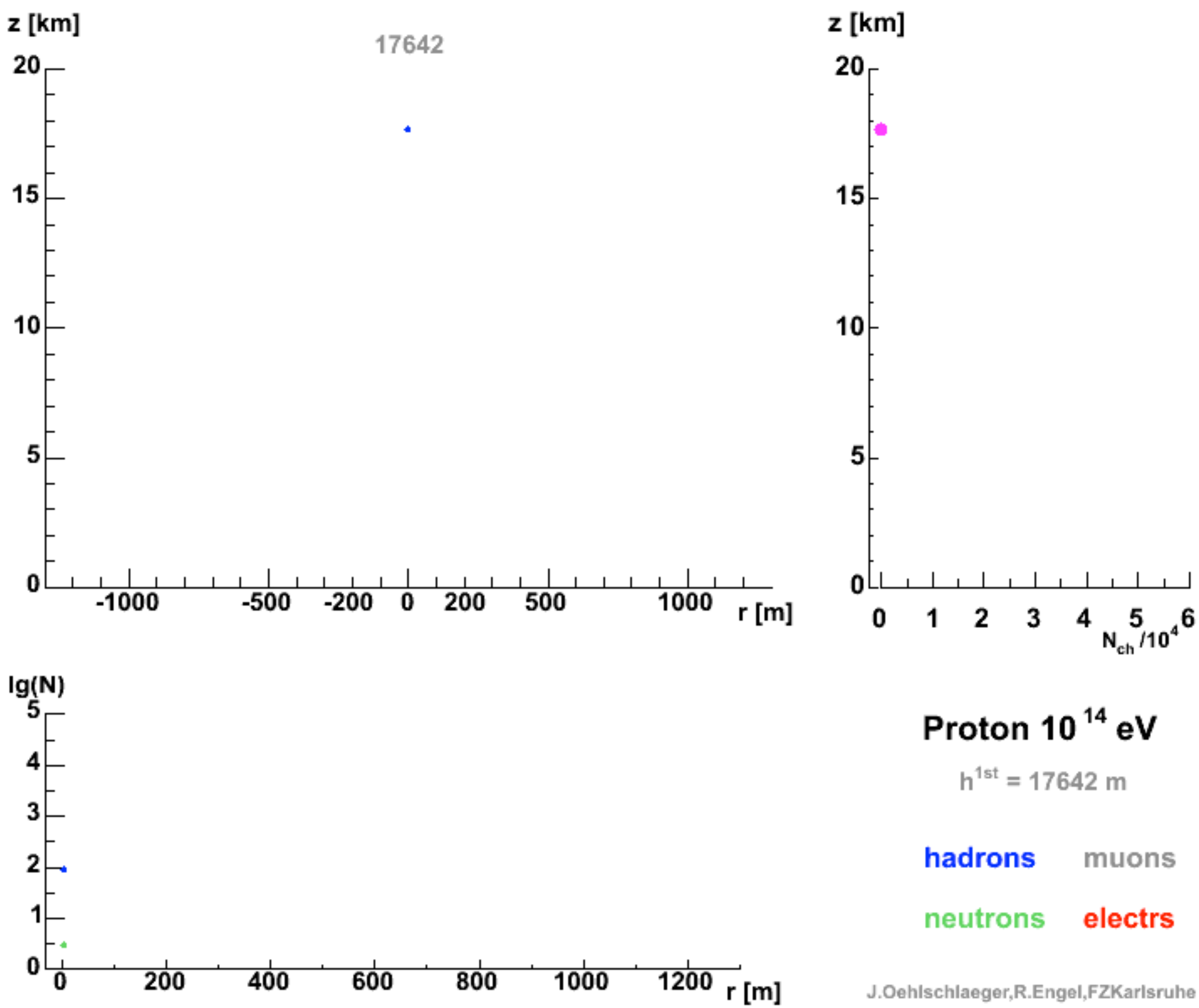
10 particles / km^2 century

Simulation of proton-induced air shower

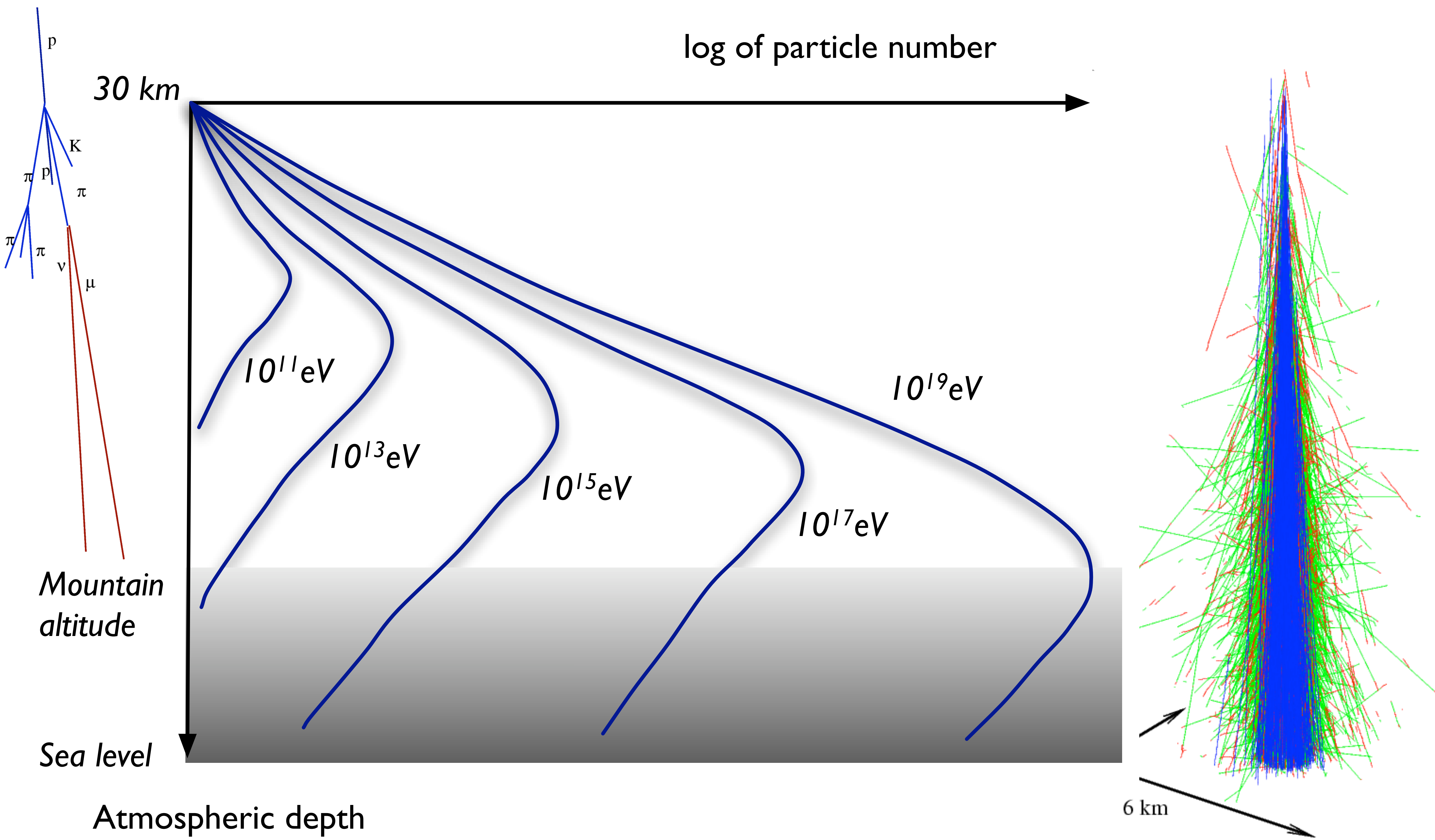


Particles arrive at ground in a disc propagating with speed of light

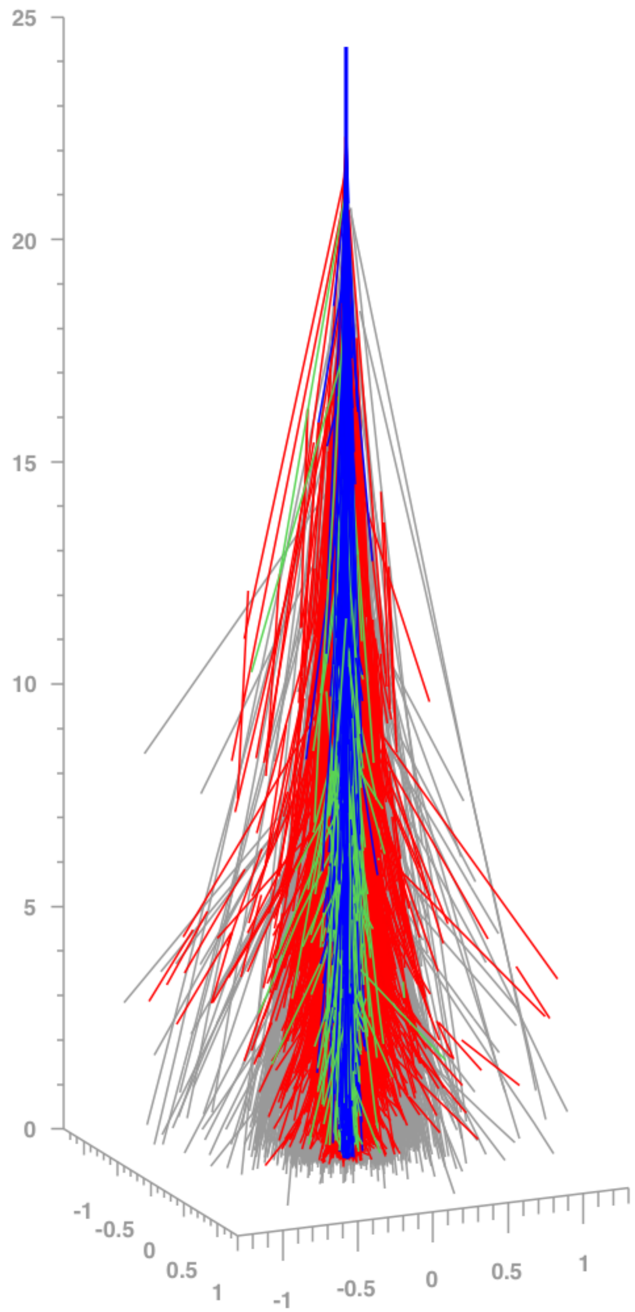
Simulation of shower development (ii)



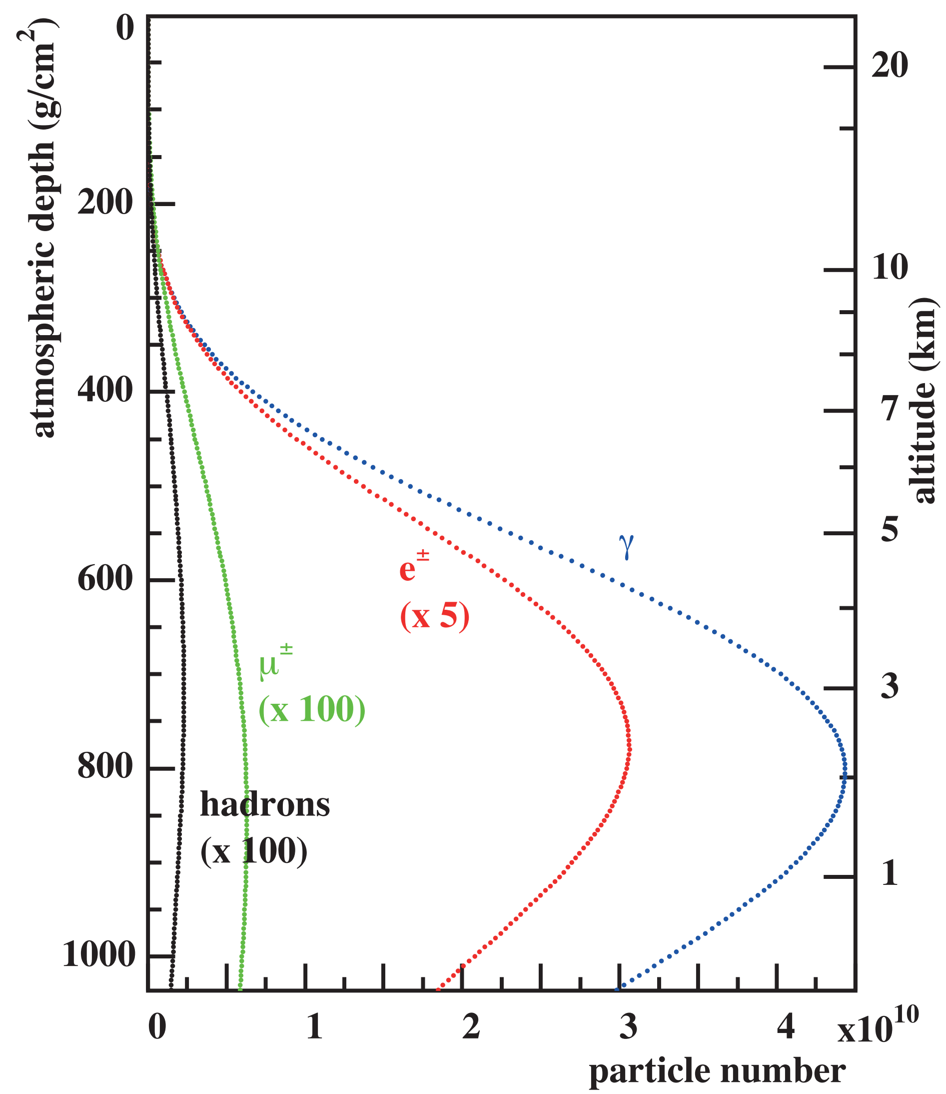
Typical detection techniques



Measurement techniques



Proton-induced shower of 10^{19} eV

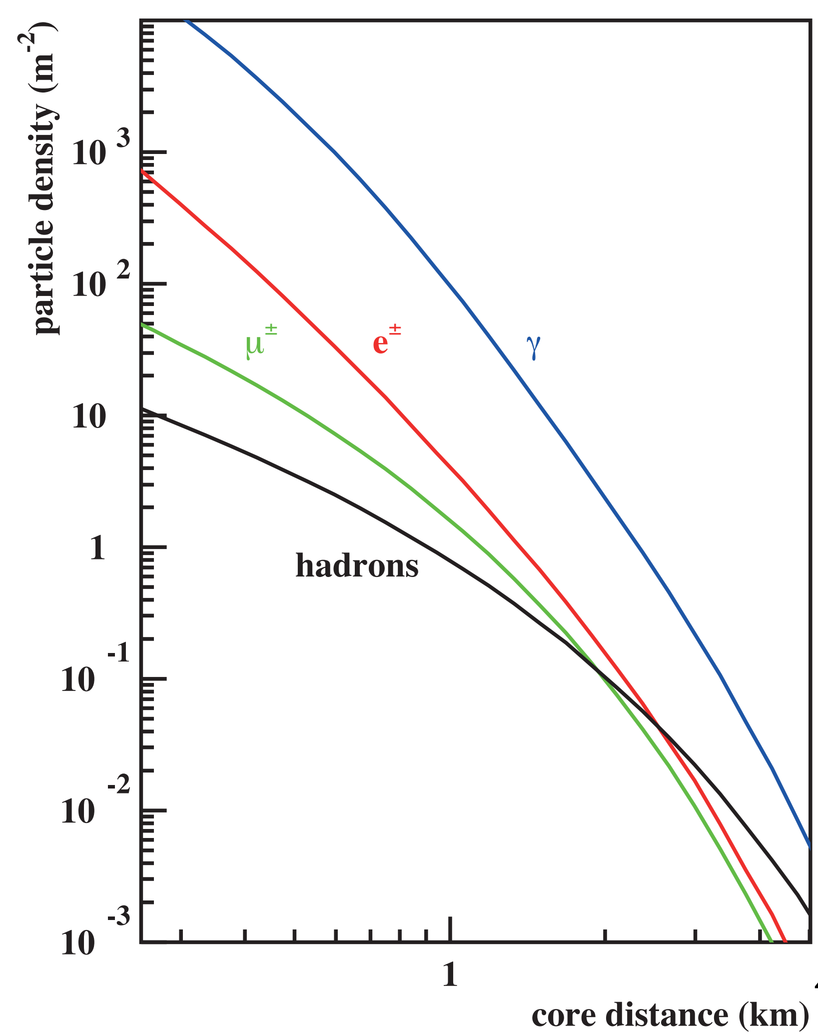


Longitudinal profile:

Cherenkov light

Fluorescence light of N_2

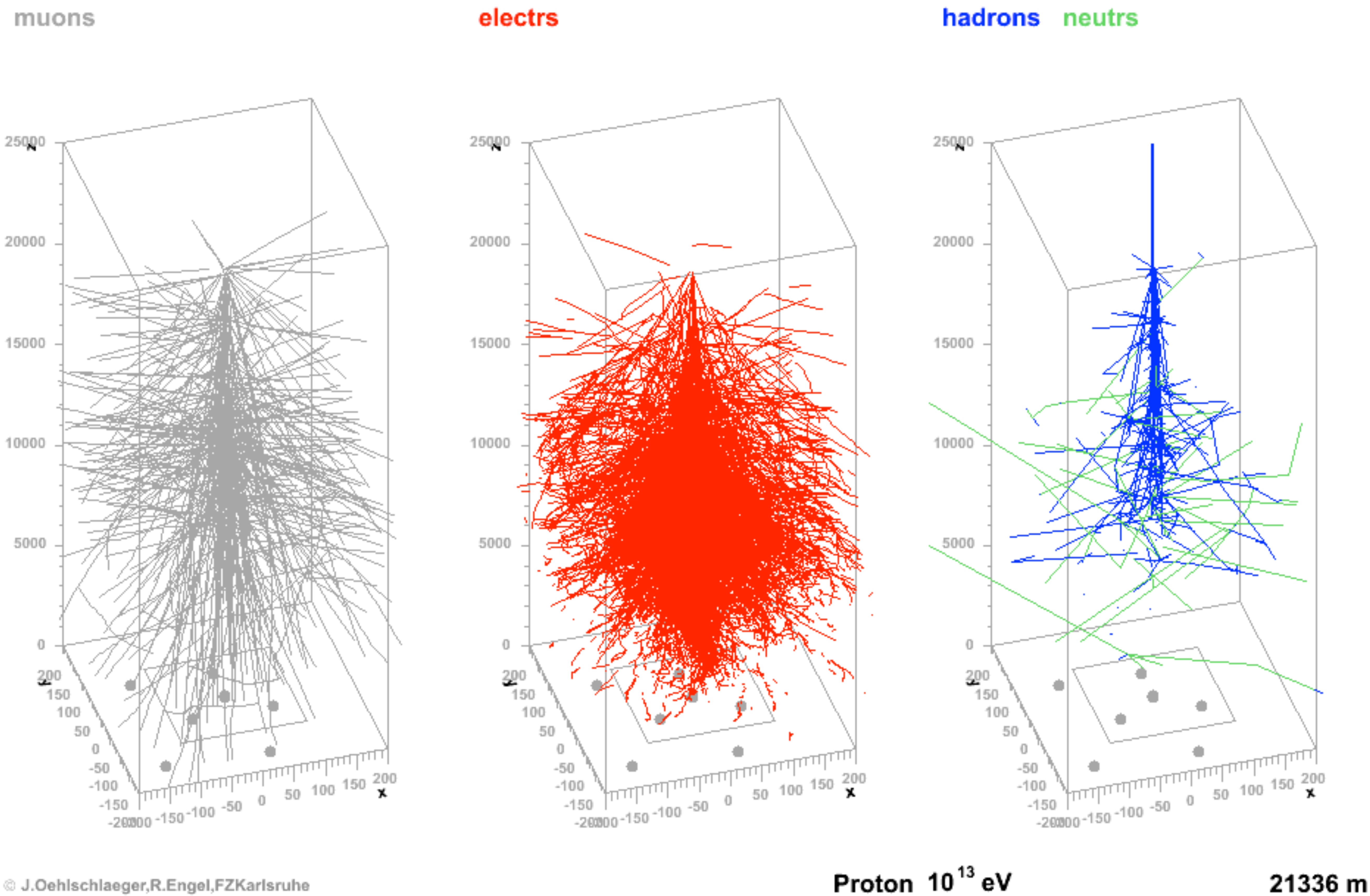
(RE, Pierog, Heck, ARNPS 2011)



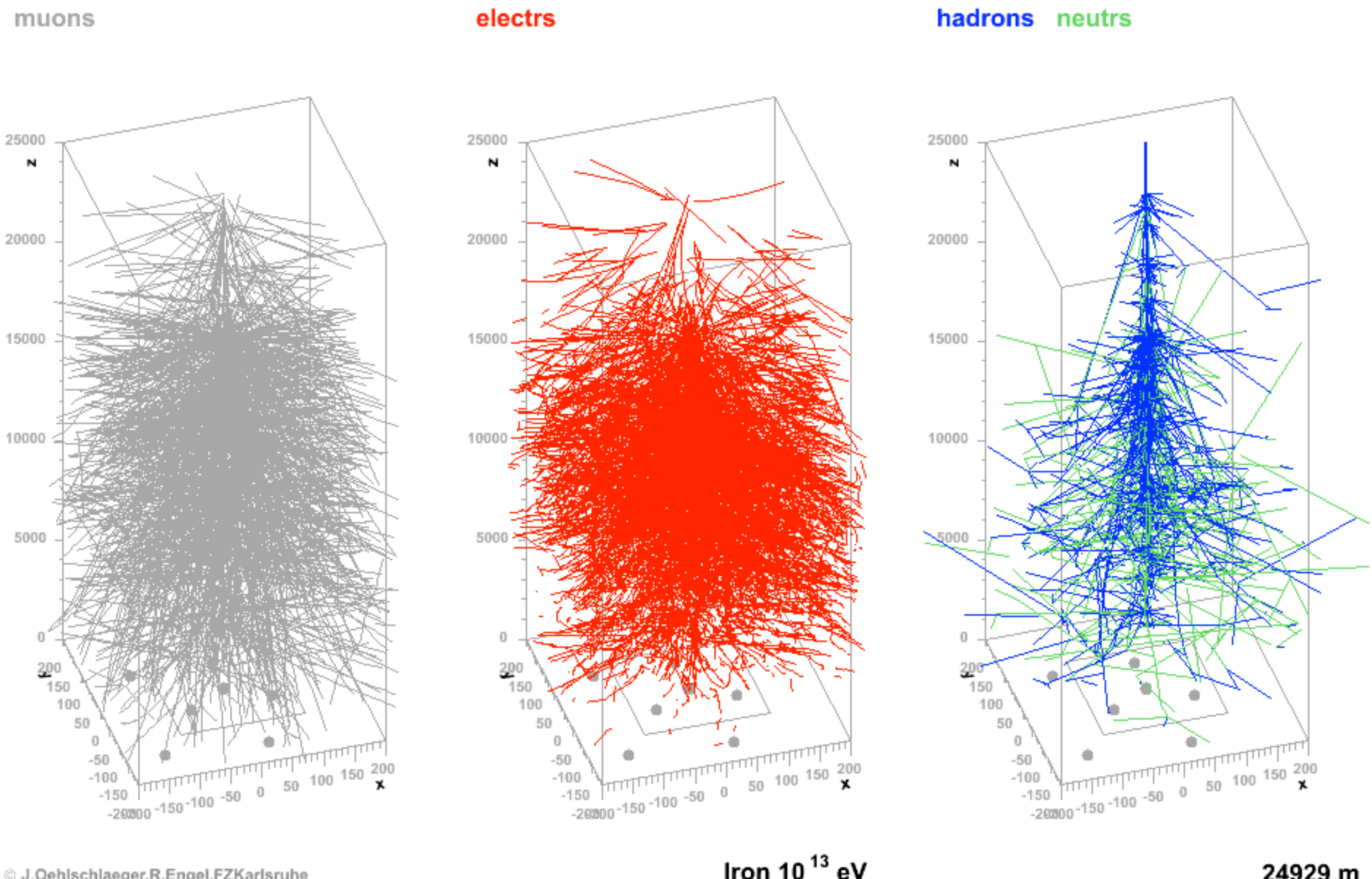
Lateral profiles:

particle detectors at ground

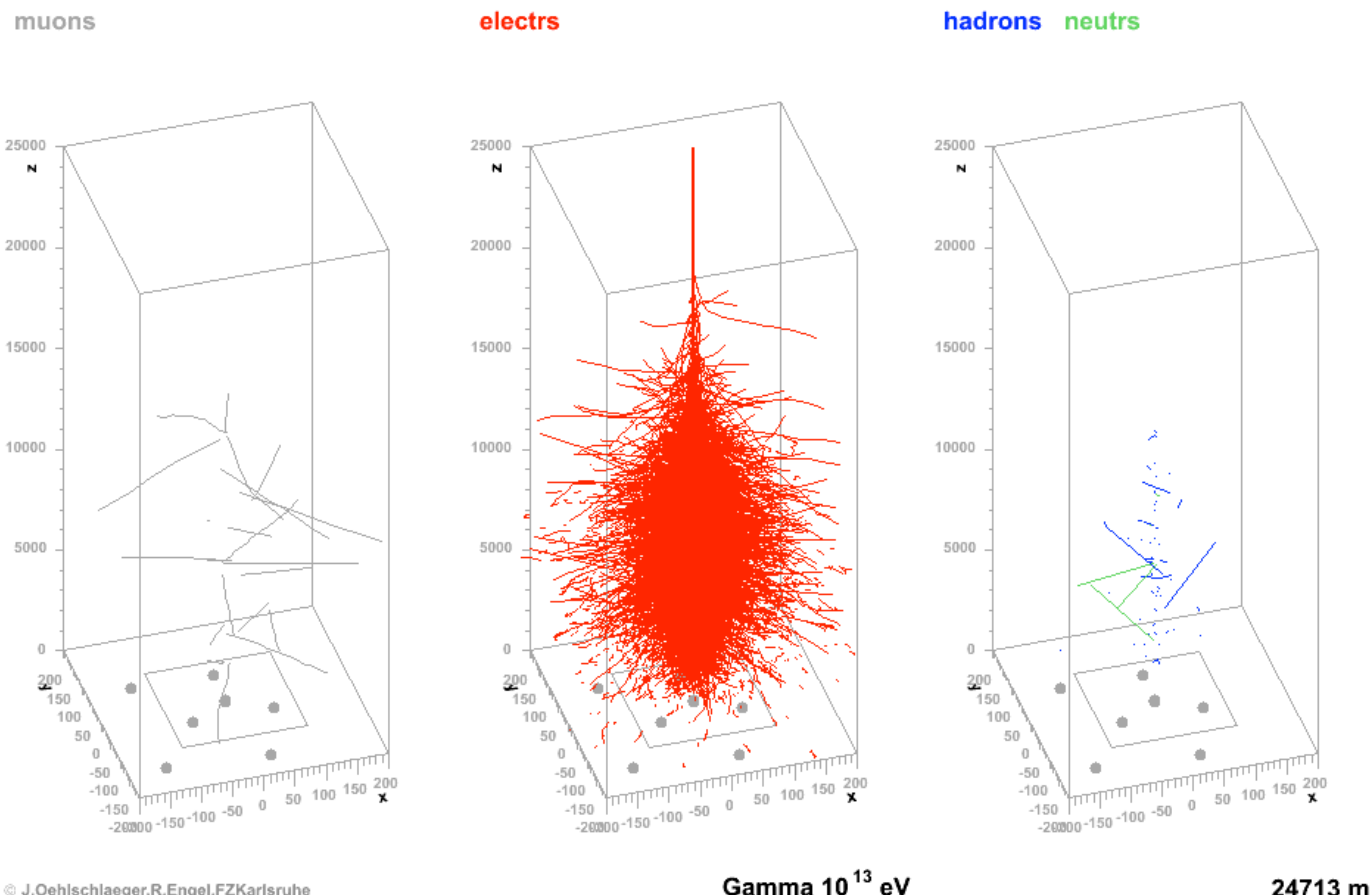
Proton-initiated air shower



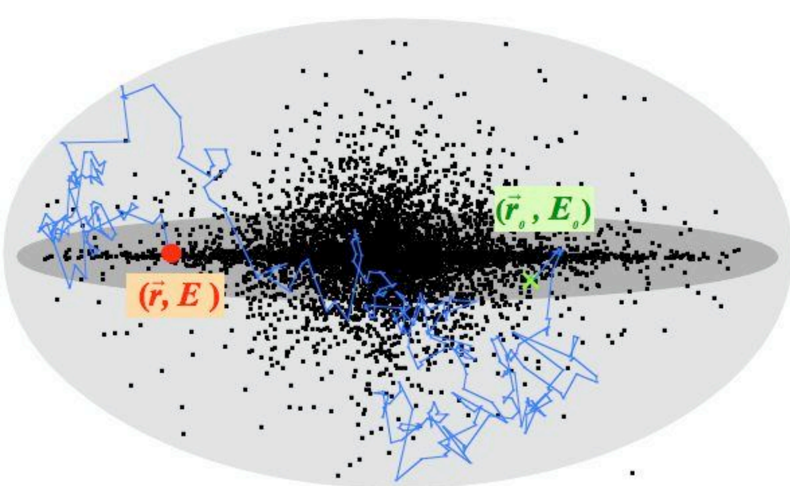
Iron-initiated air shower

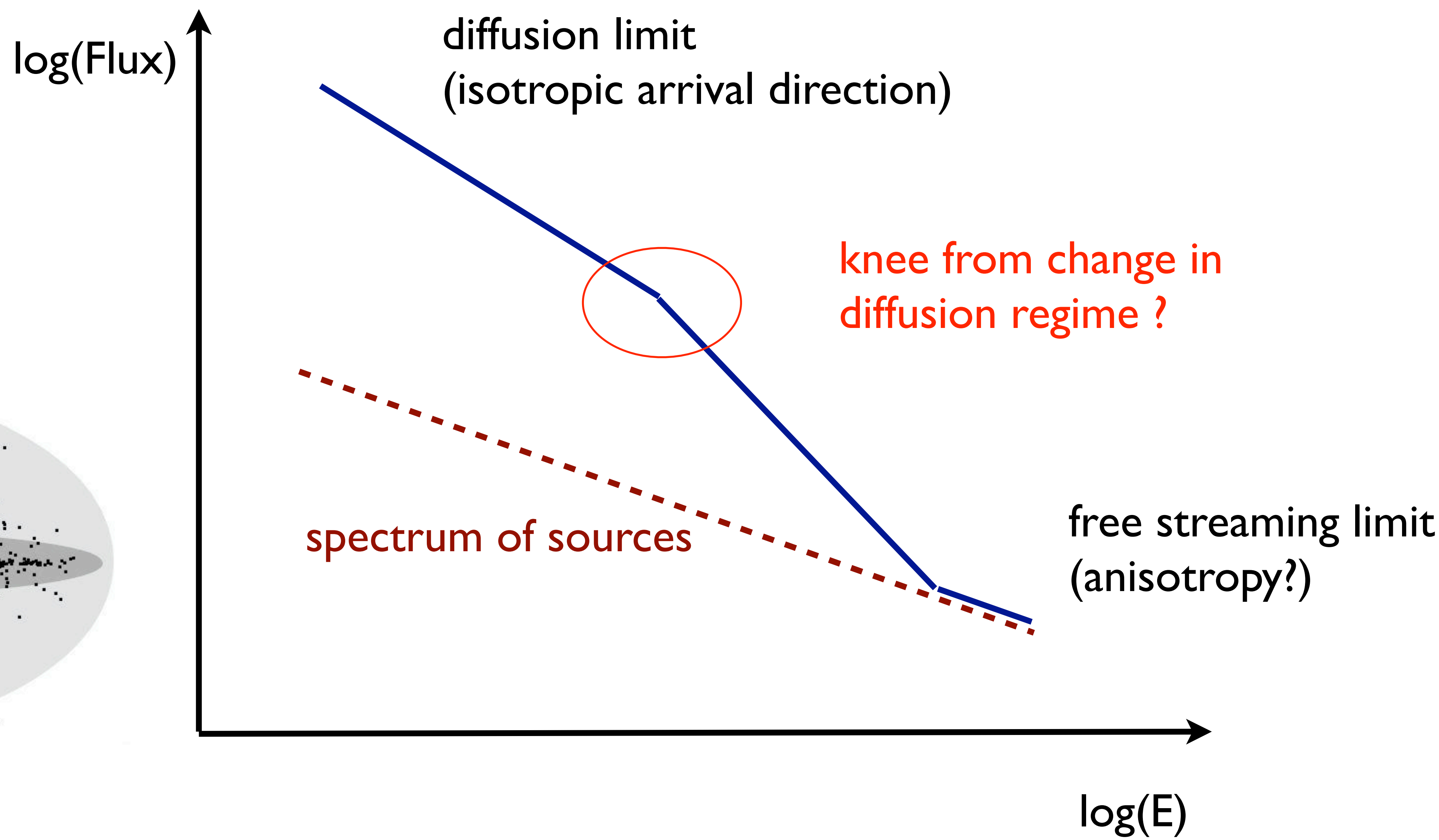


Photon-initiated air shower



Interpretation of the knee (i)



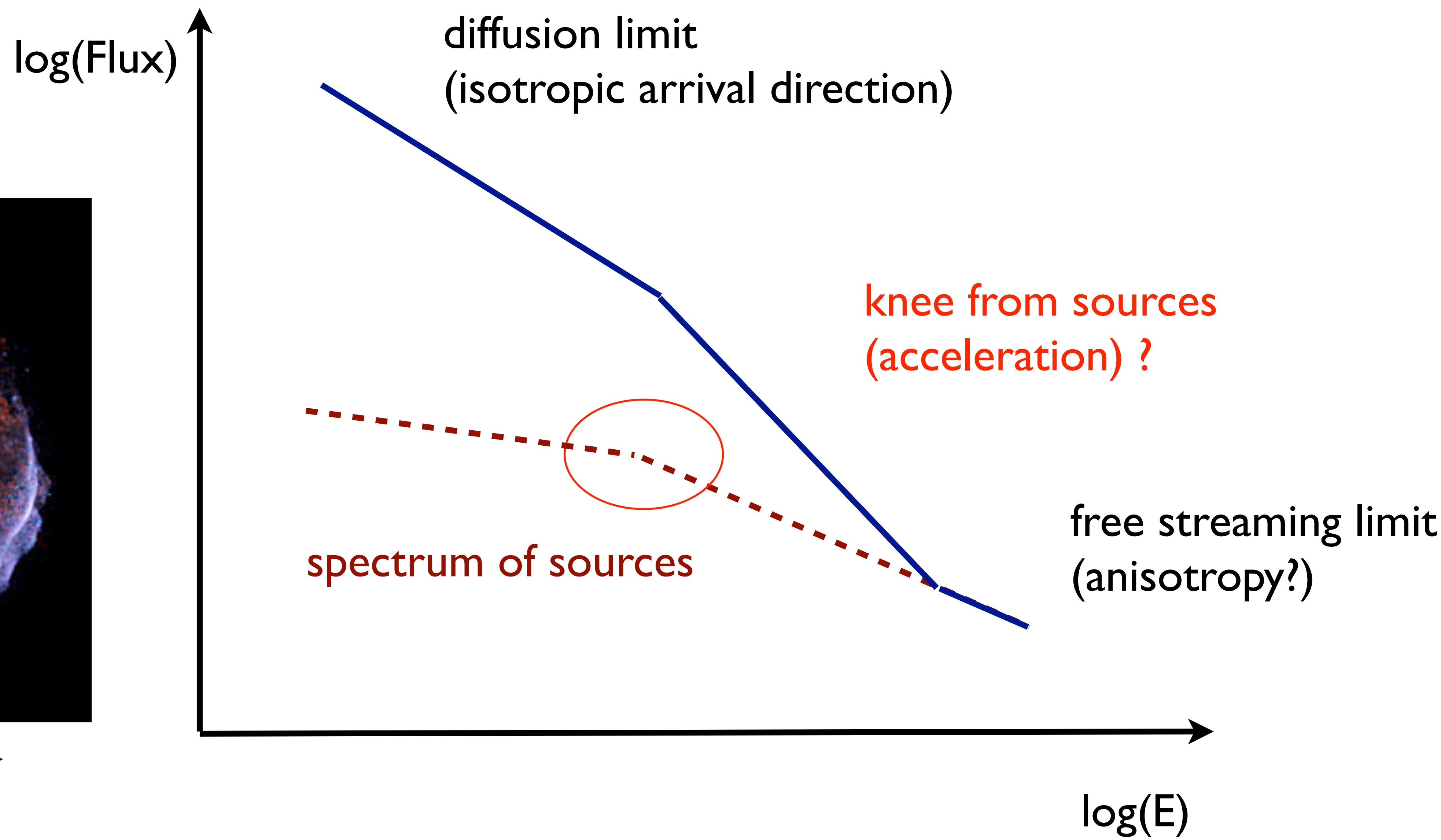


Diffusion: same behaviour for different elements at same rigidity $p/Z \sim E/Z$

Interpretation of the knee (ii)

SN remnant 1006

Distance ~ 2.2 kpc



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

Exotic models for interpretation

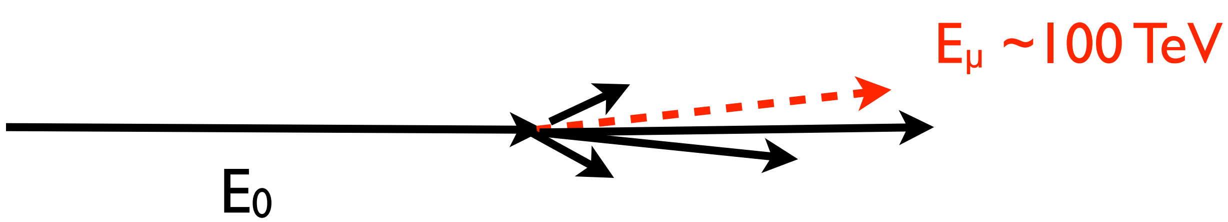
The knee and unusual events at PeV energies

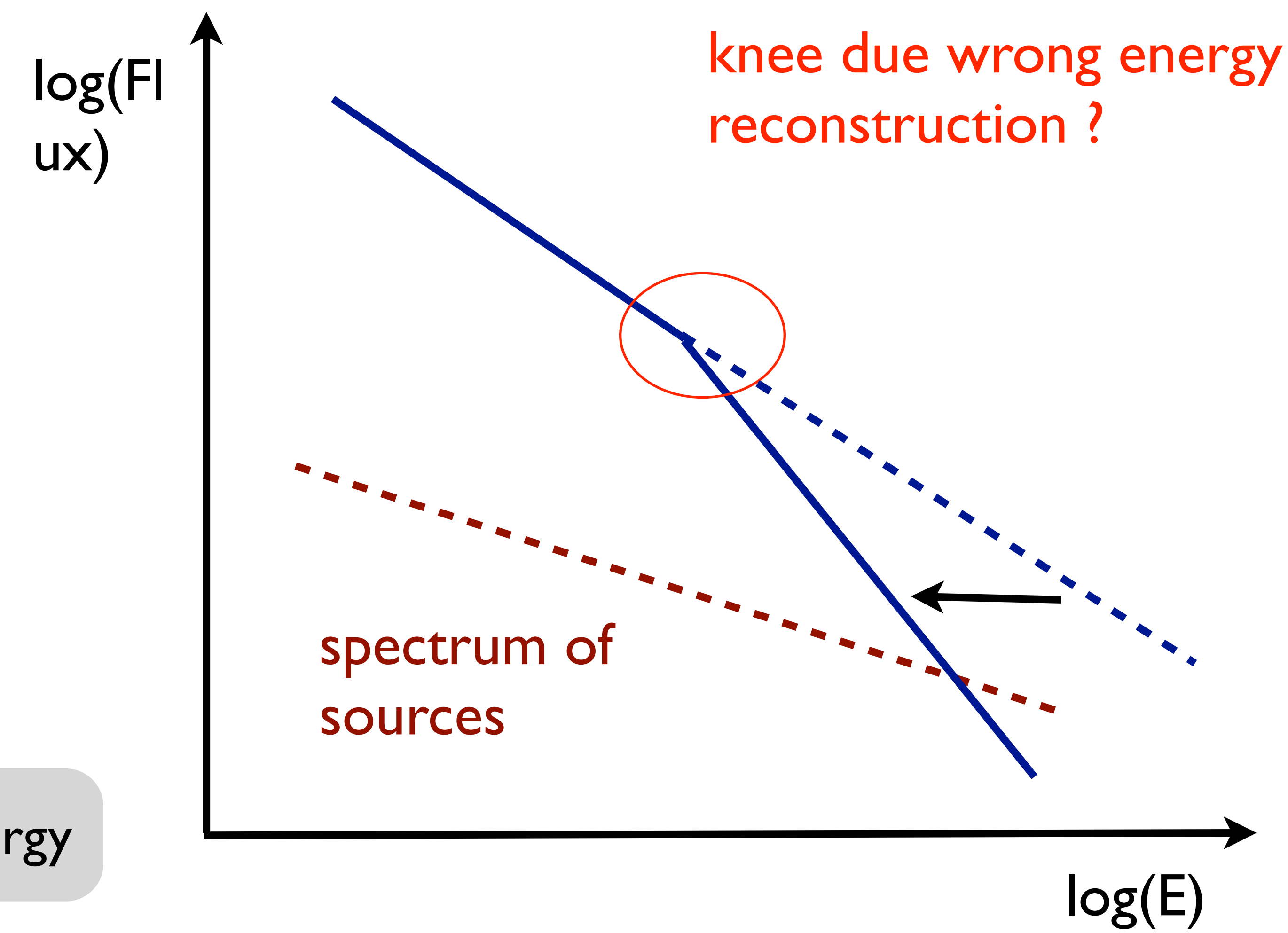
A.A.Petrukhin[a]

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.





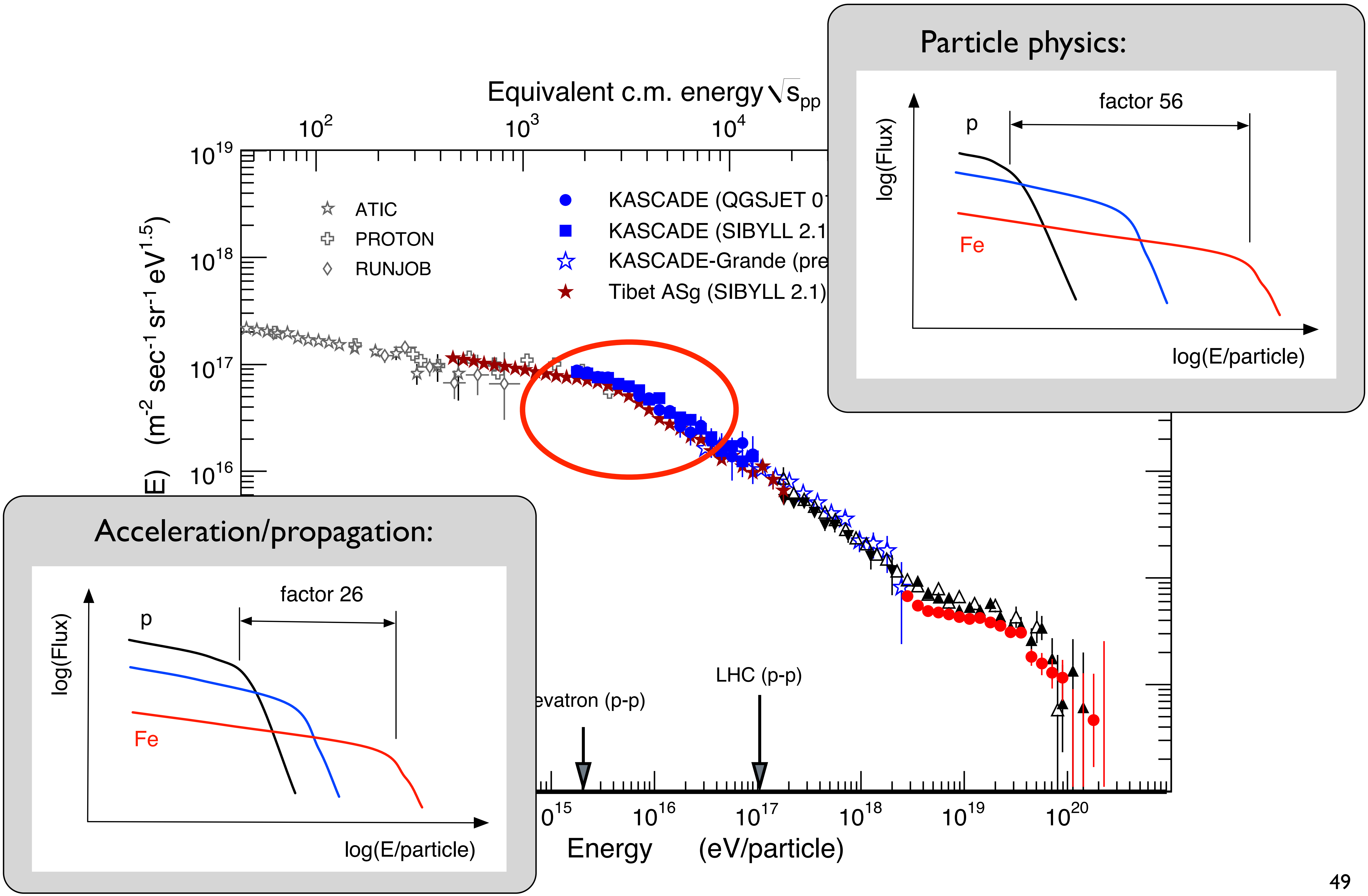
New physics, the cosmic ray spectrum knee, and *pp* cross section measurements

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

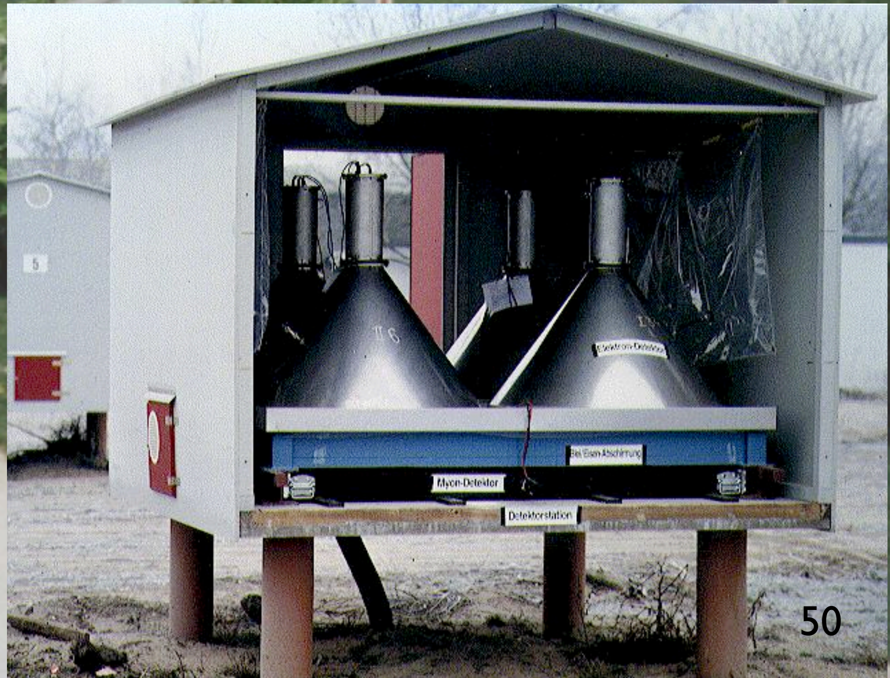
Origin and physics of the knee



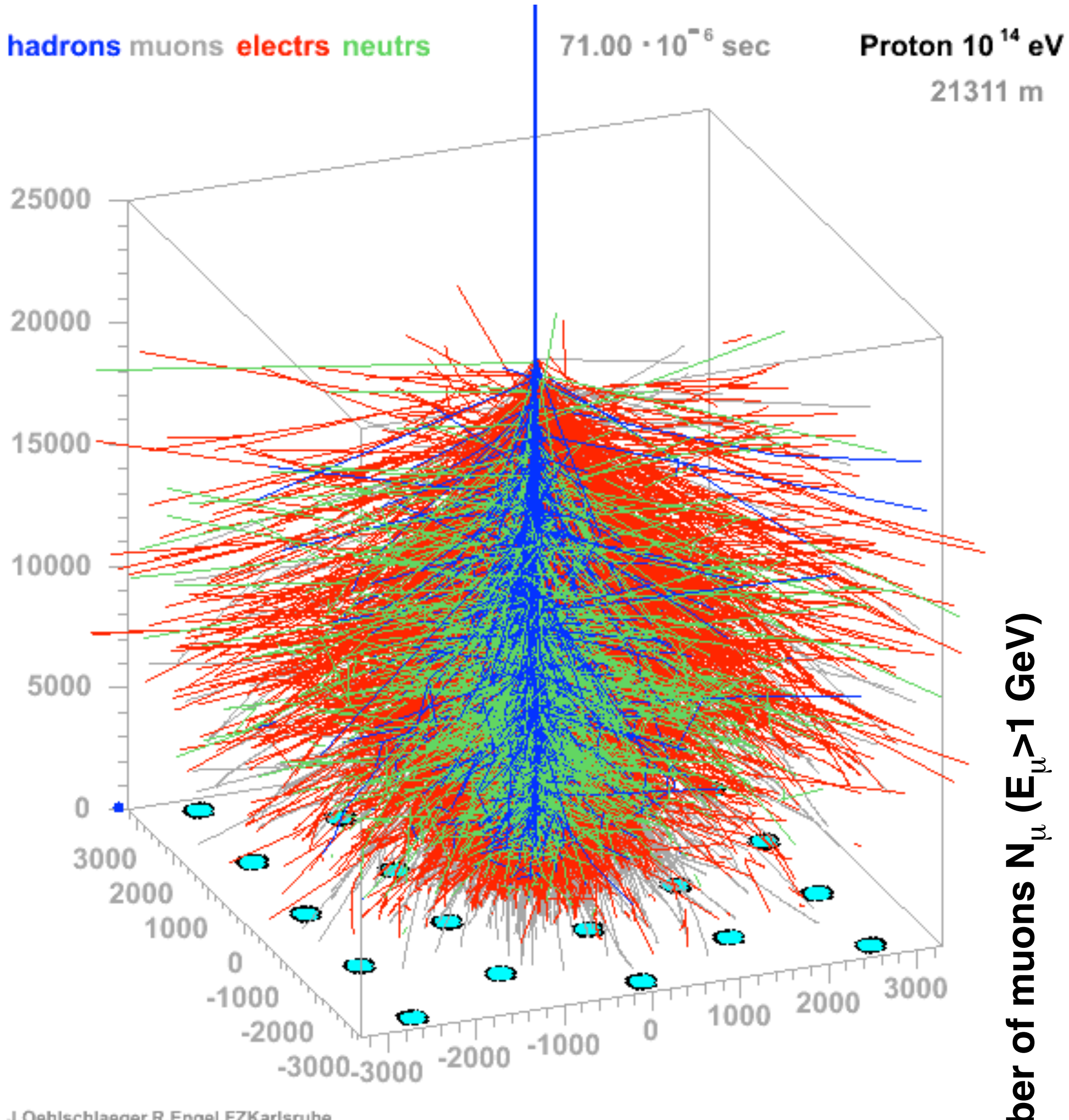
KASCADE

Karlsruhe, Germany

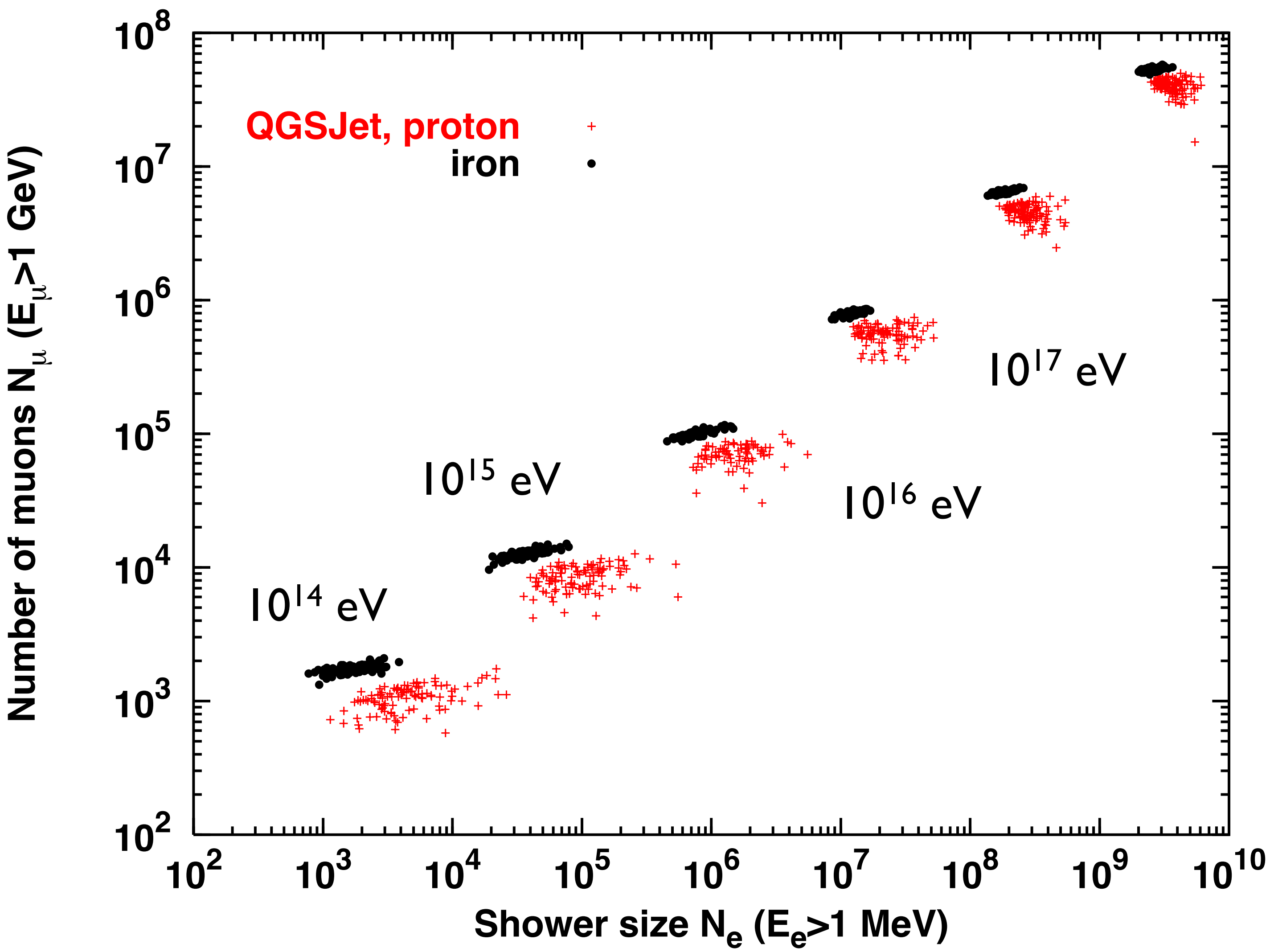
Area ~ 0.04 km^2,
252 surface detectors



Air shower ground arrays

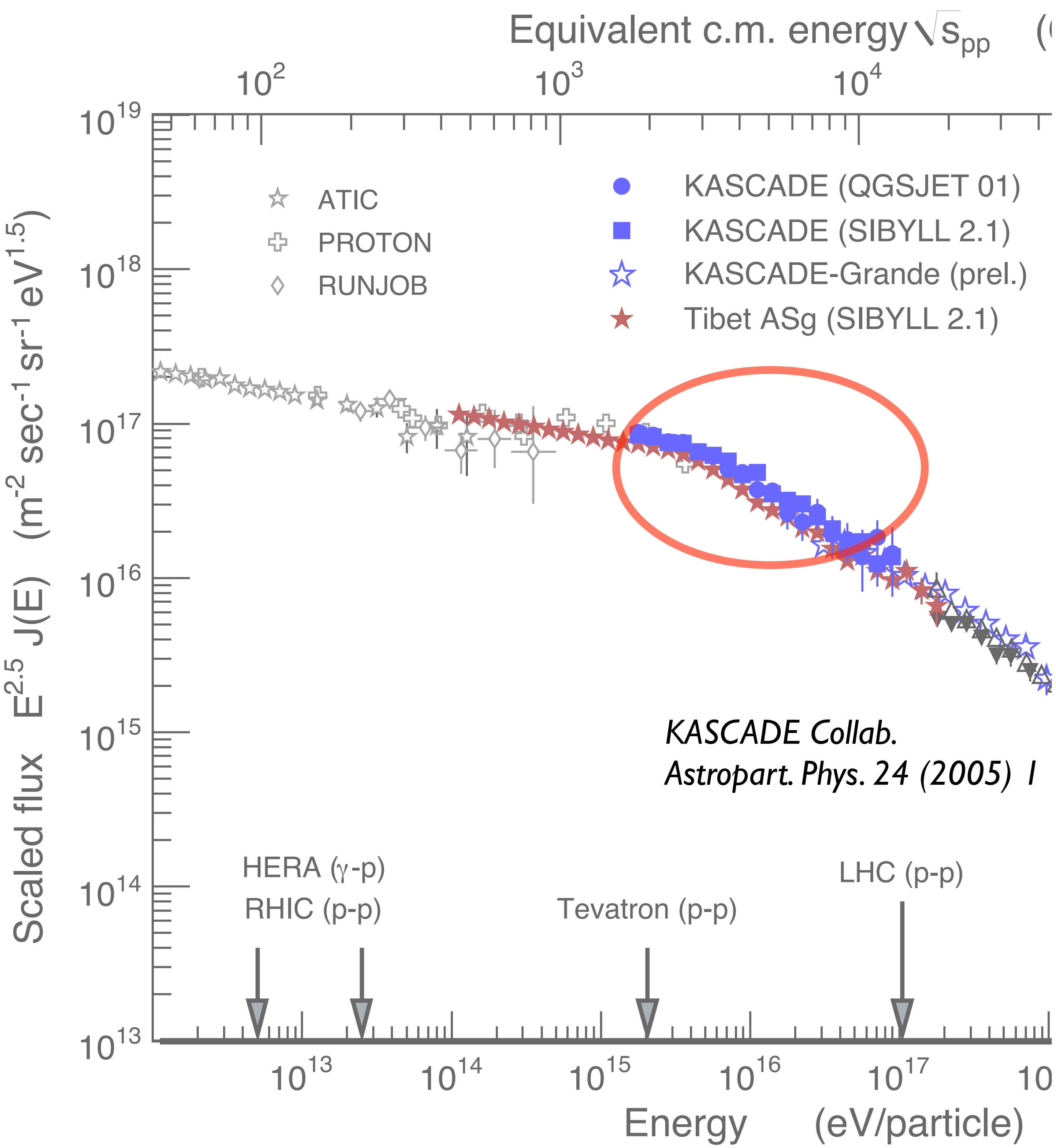


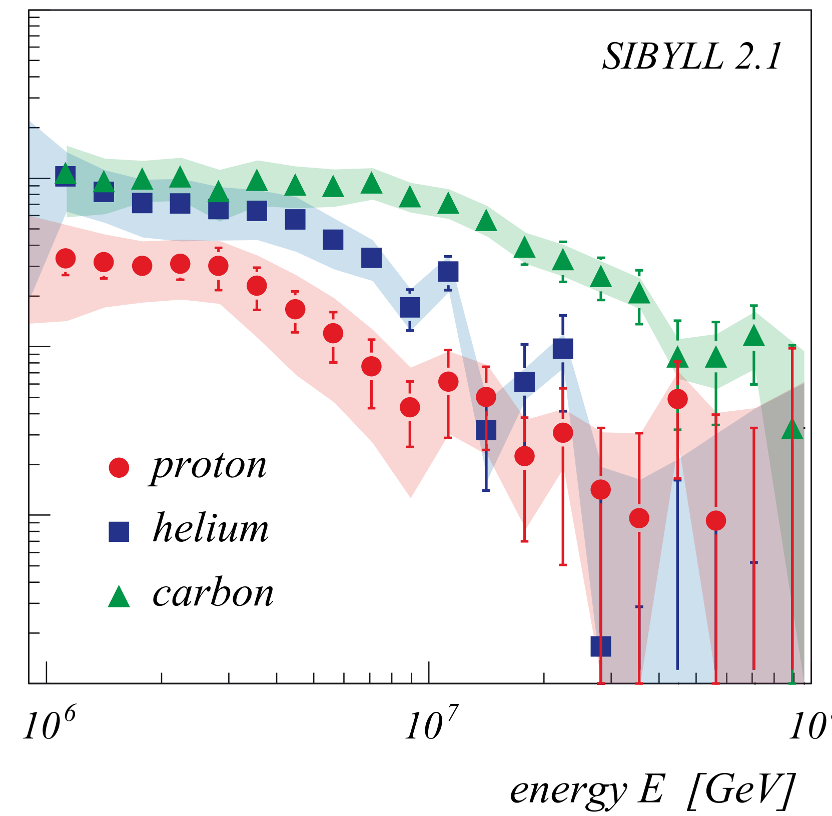
Combined energy-composition analysis

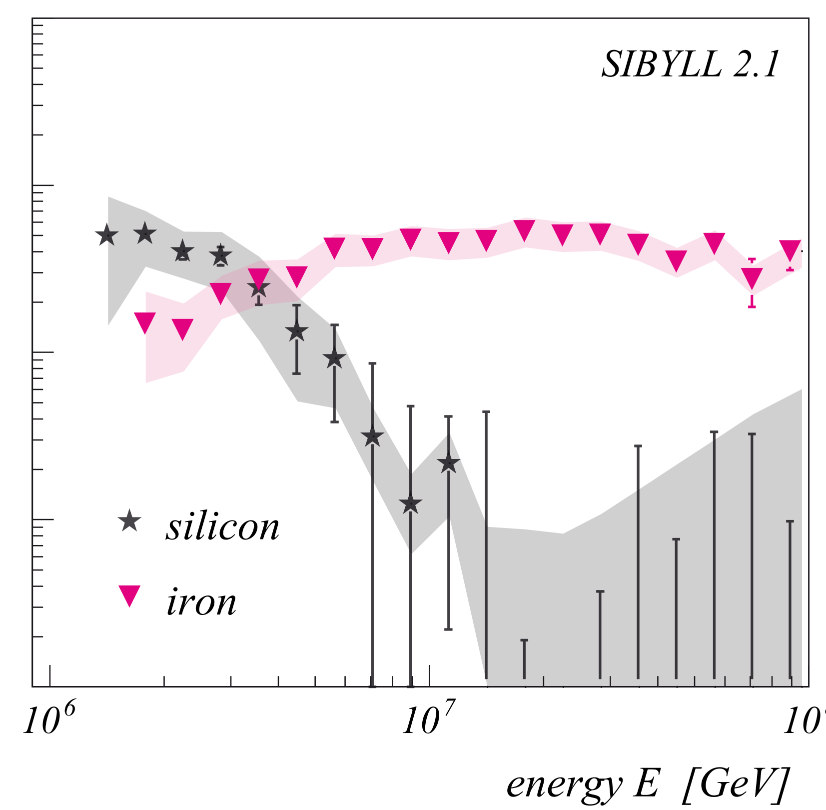


Example:
KASCADE-Grande (Karlsruhe)

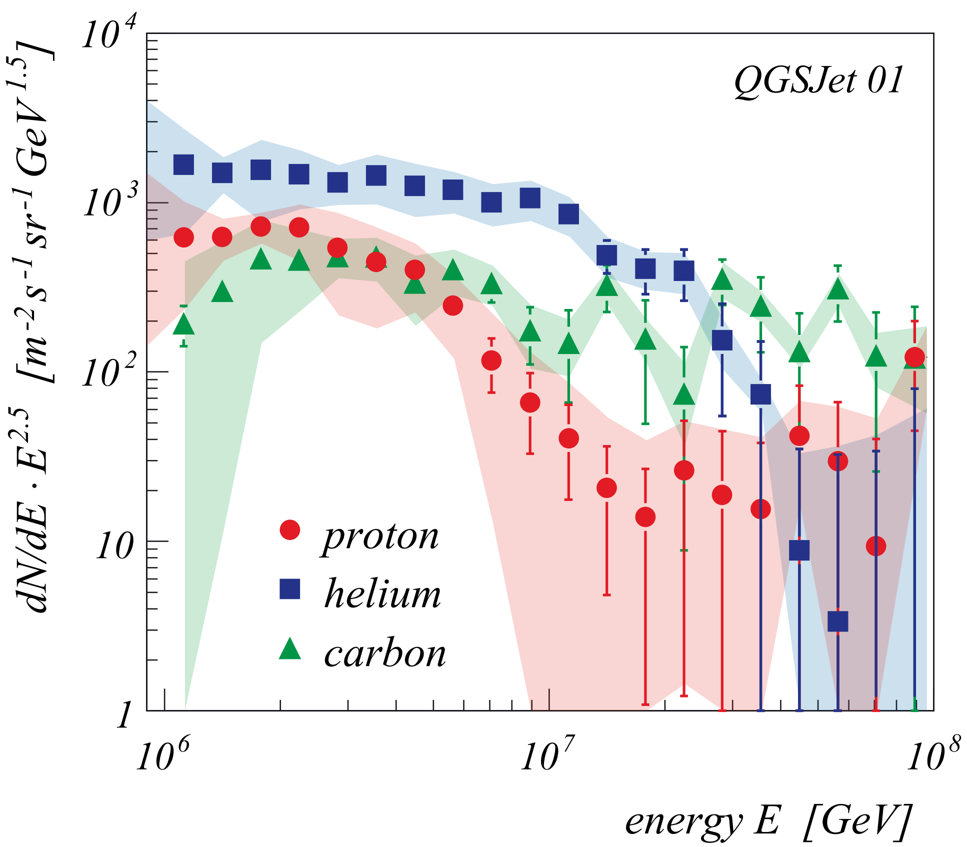
Composition in Knee region (i)

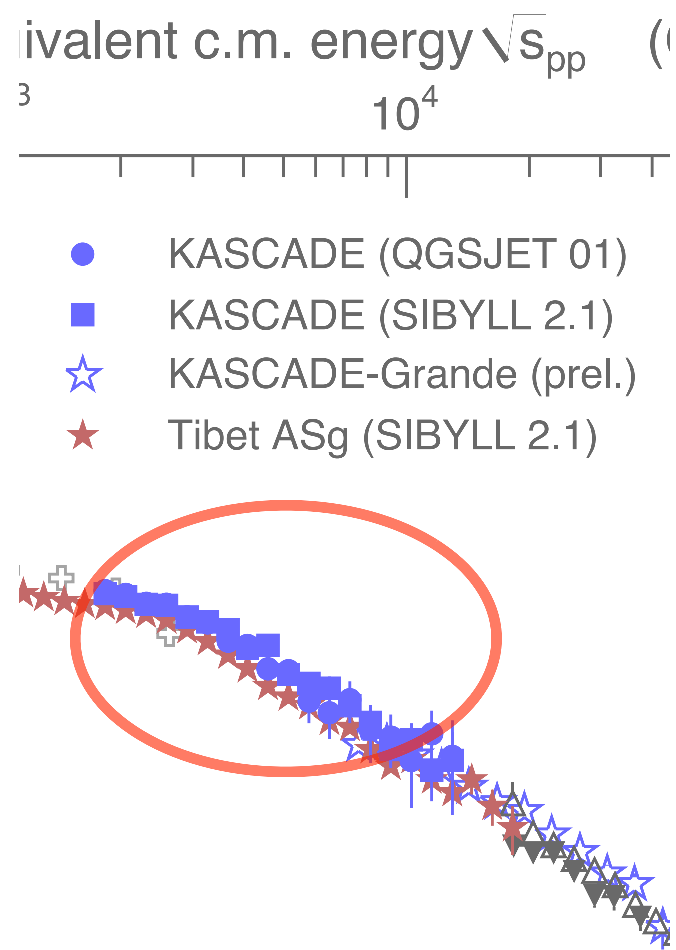


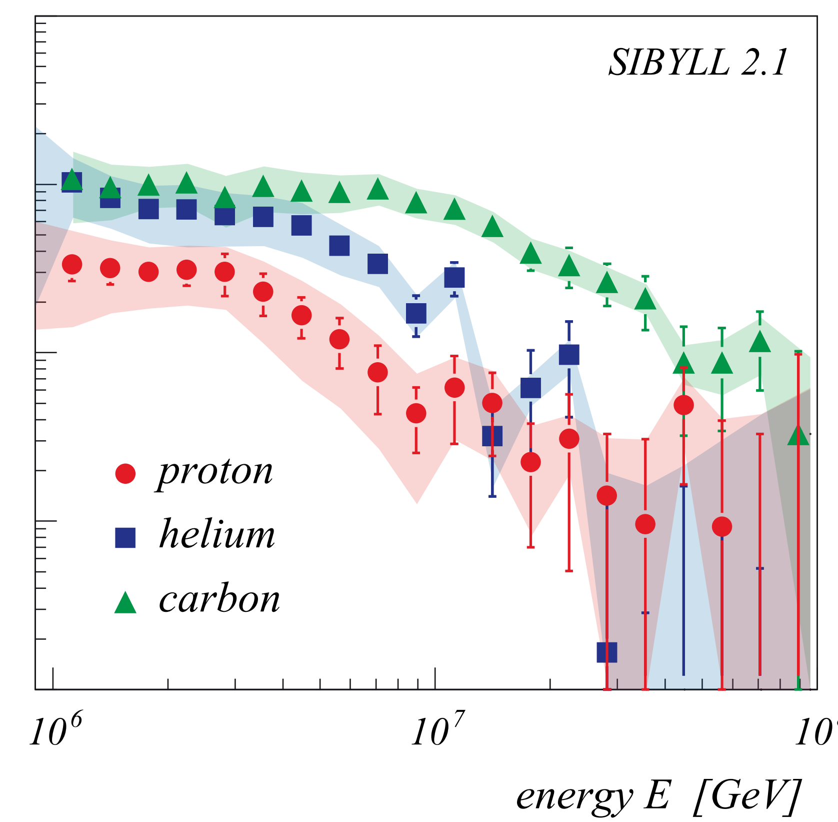


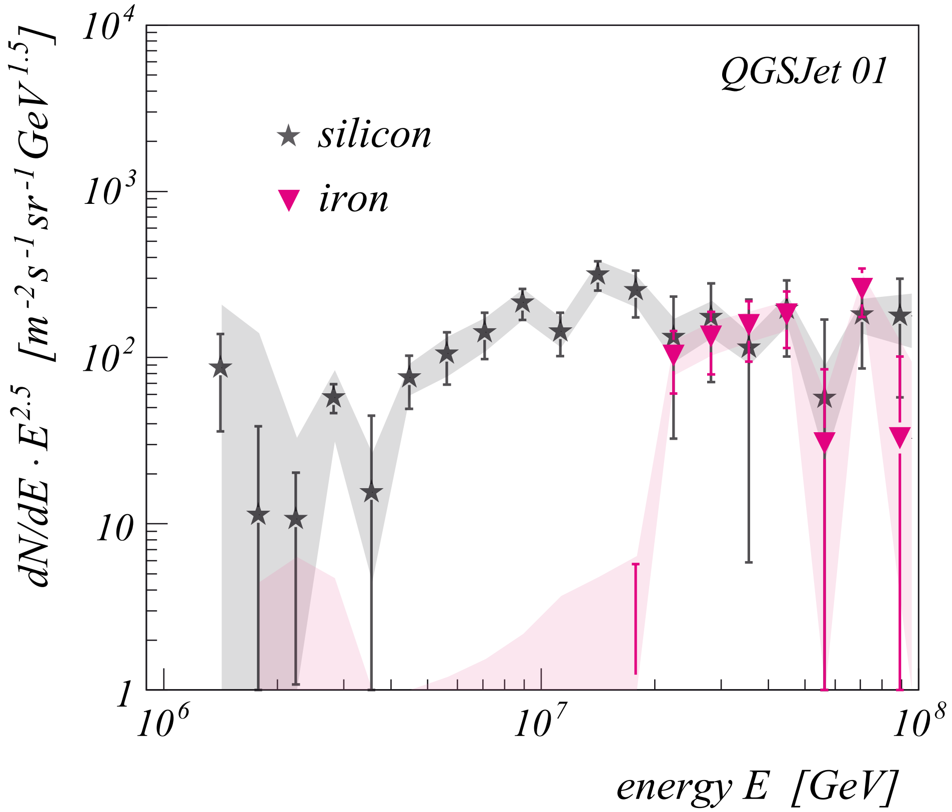


Composition in Knee region (ii)

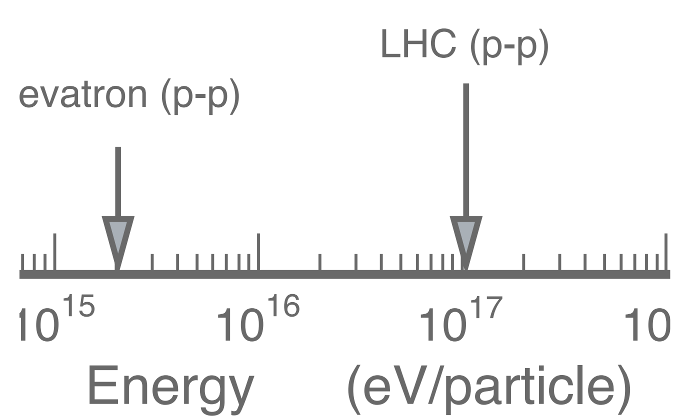


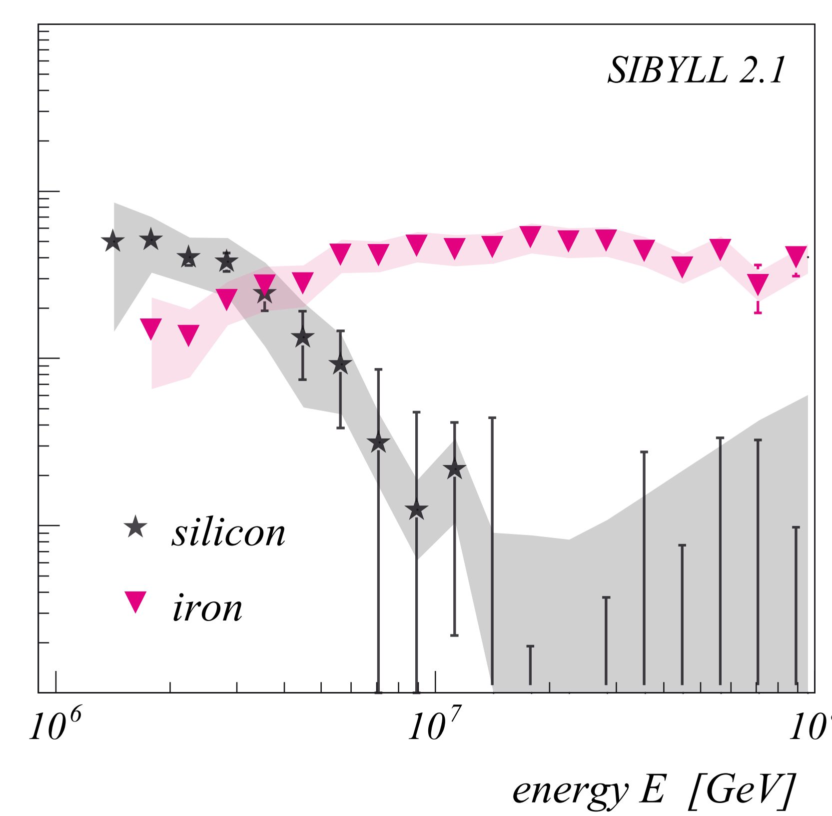




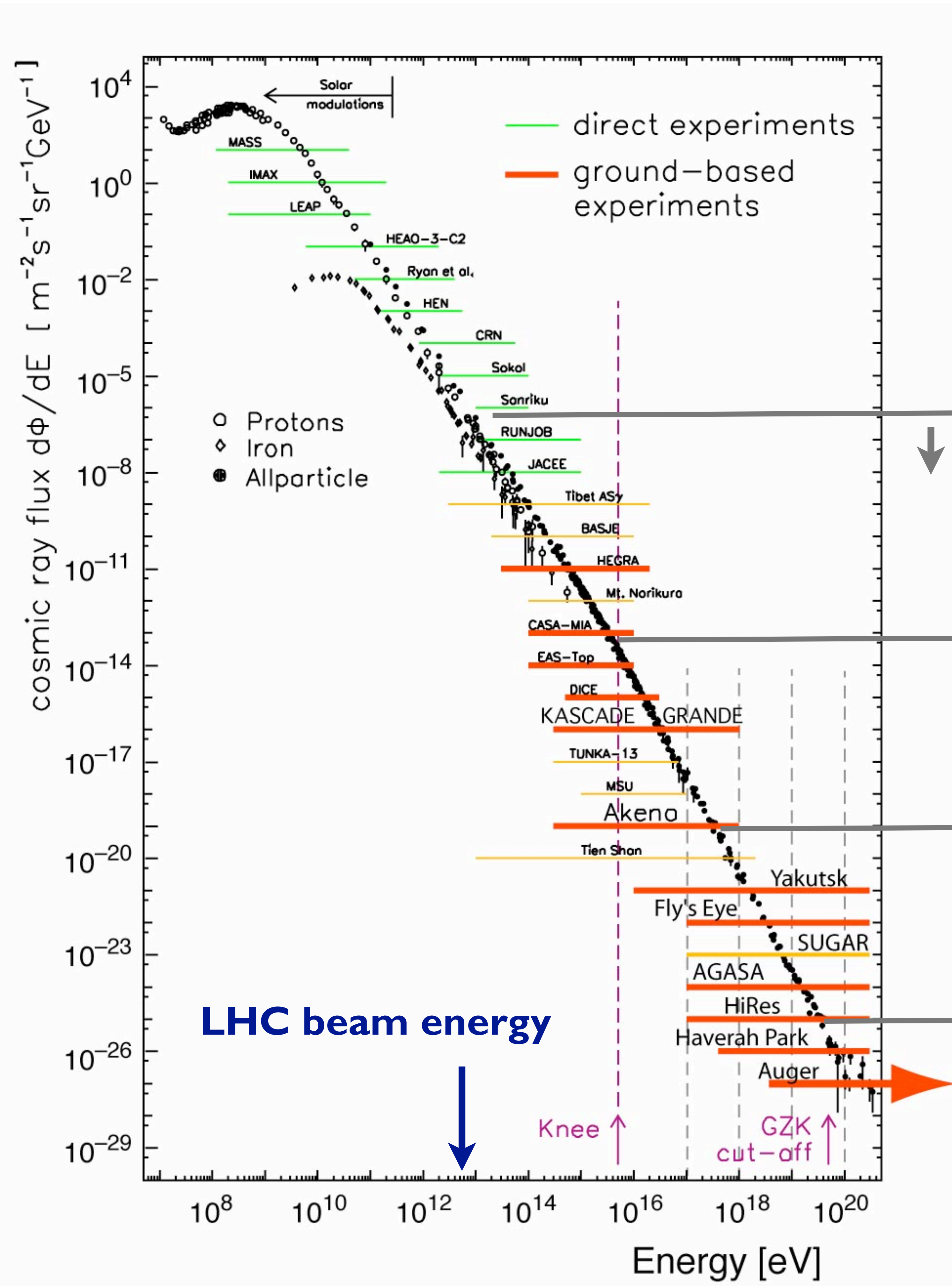


KASCADE Collab.
Astropart. Phys. 24 (2005) 1





Rate of particles



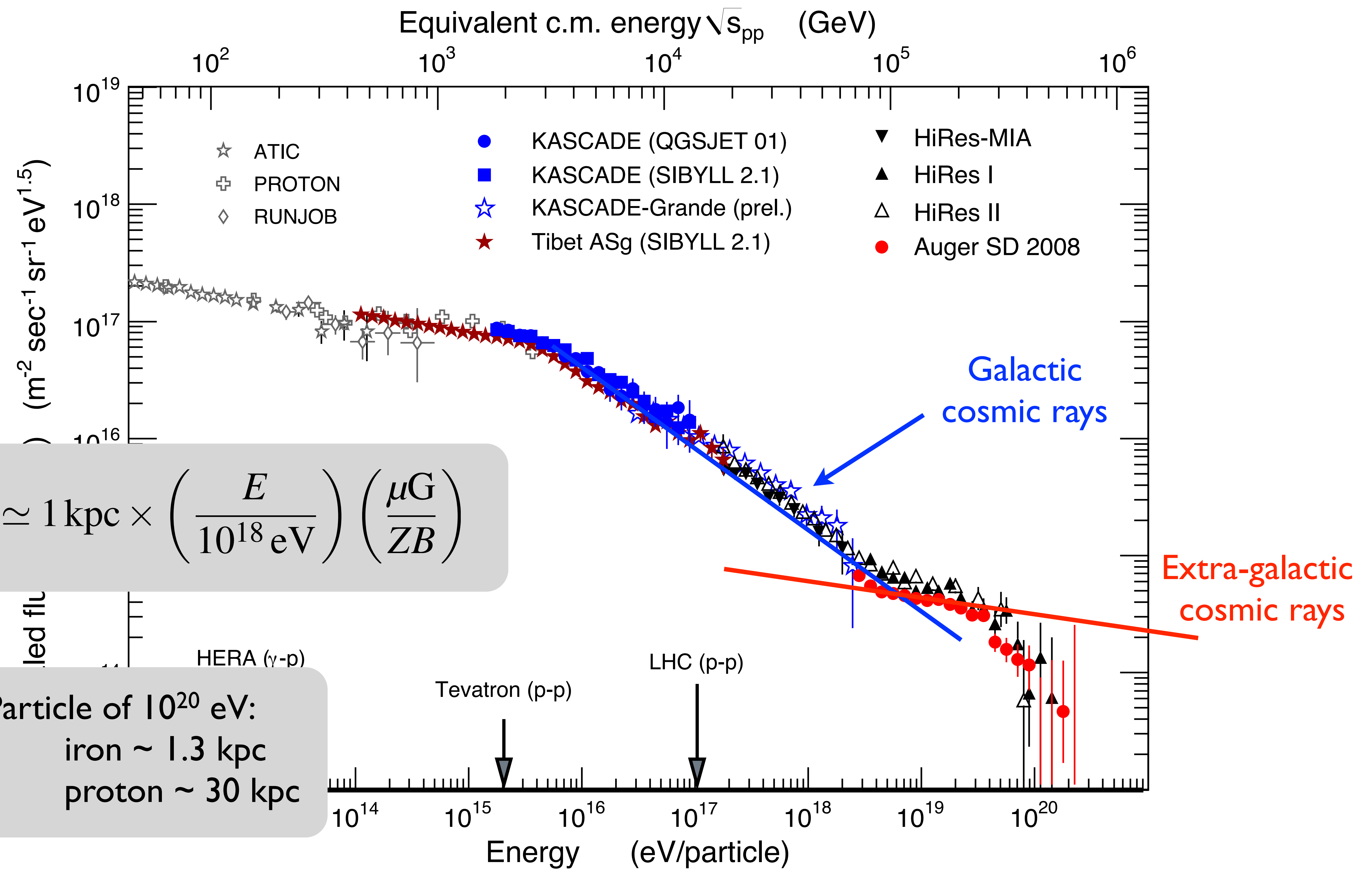
0.1 particles / m² min.

10 particles / km² min.

10 particles / km² day

10 particles / km² century

Origin of the ankle: transition model



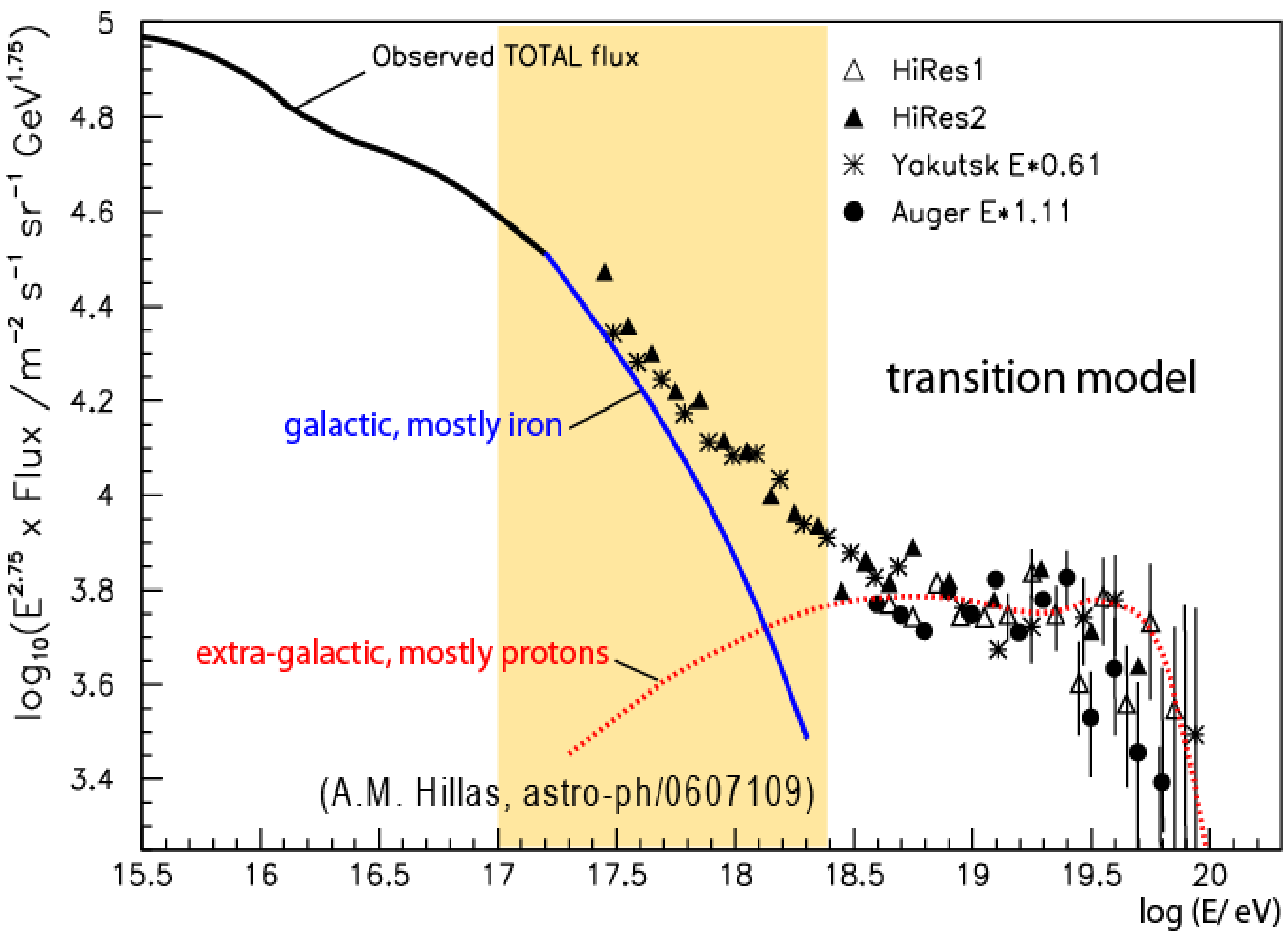
$$r_g \simeq 1\,\text{kpc} \times \left(\frac{E}{10^{18}\,\text{eV}}\right)\left(\frac{\mu\text{G}}{ZB}\right)$$

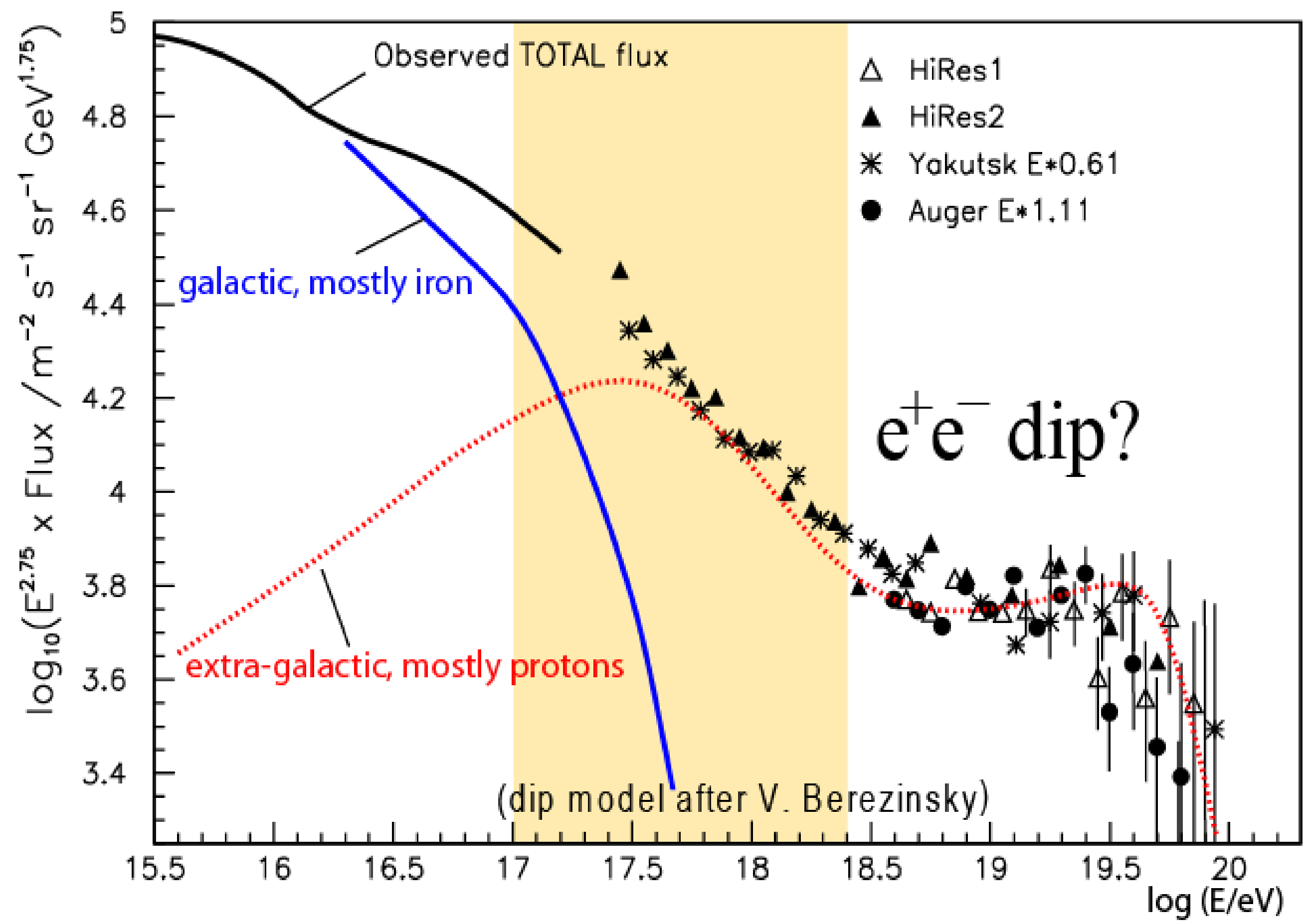
Particle of 10^{20} eV:

iron ~ 1.3 kpc

proton ~ 30 kpc

Transition from galactic to extragalactic sources



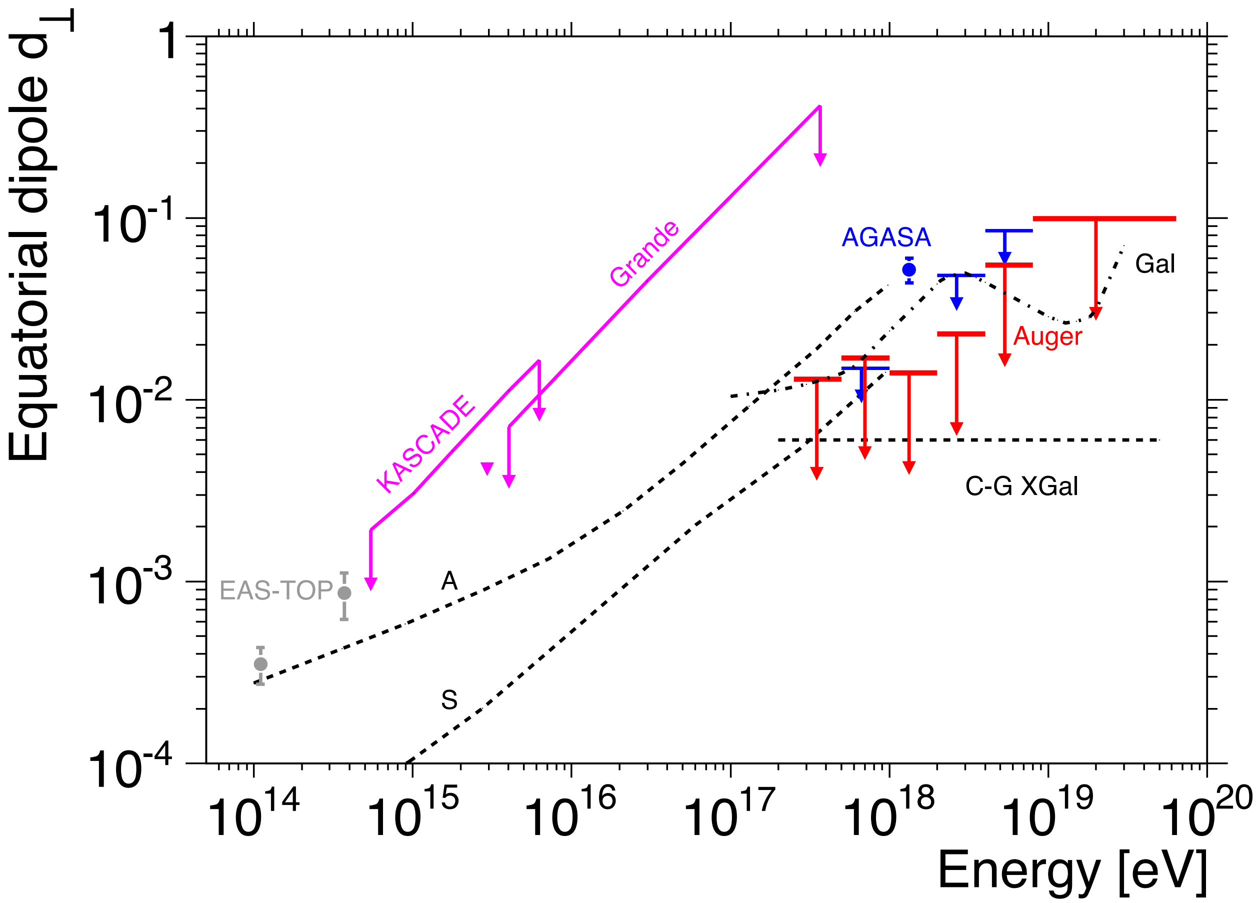


Hillas:
- Ankle is transition galactic to extragalactic cosmic rays
- Injection spectrum $dN/dE \sim E^{-2.3}$

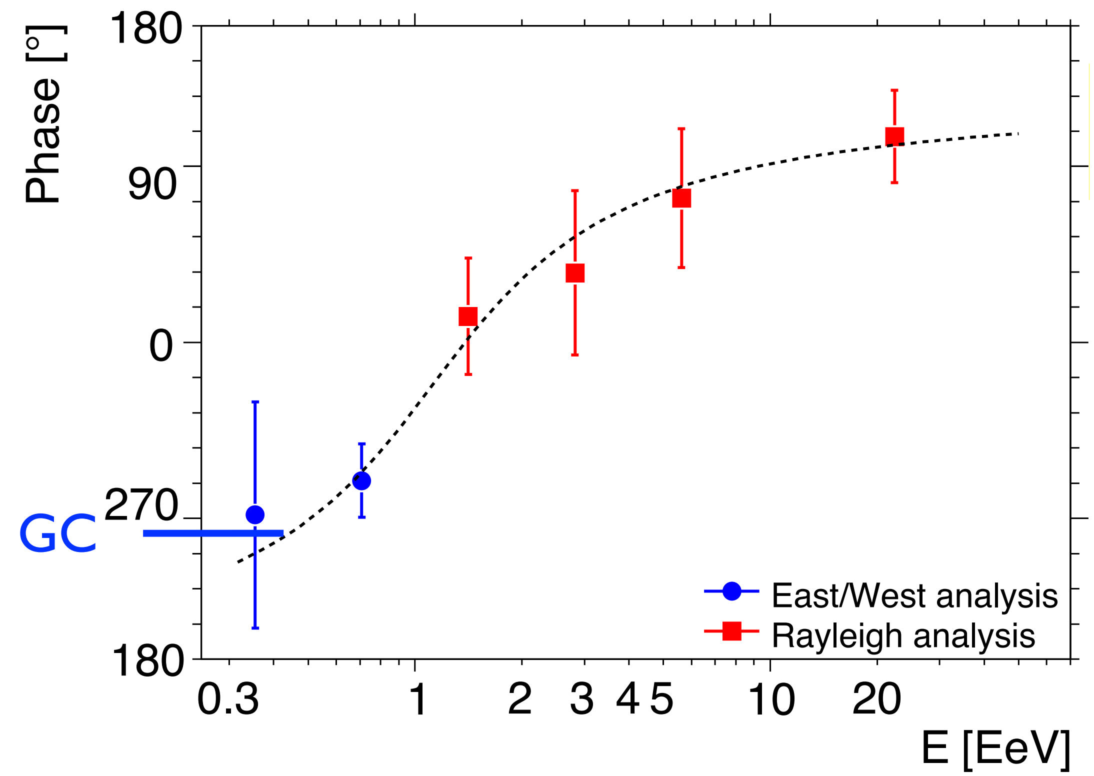
Berezinsky et al.:
- Ankle is feature due to extragalactic proton propagation
- Injection spectrum $dN/dE \sim E^{-2.7}$

Flux very similar, composition different

Large scale anisotropy data



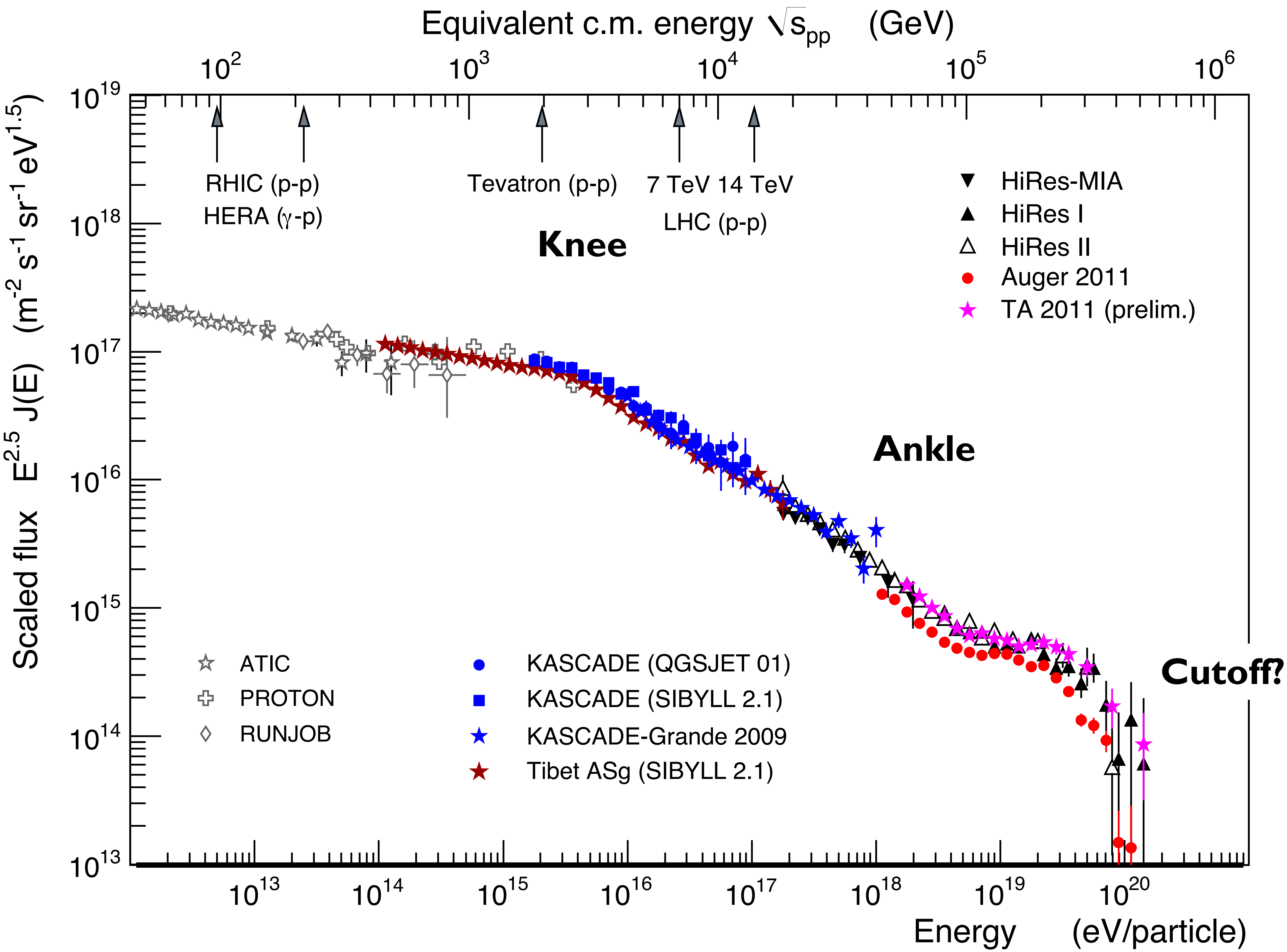
(Auger Collab. Astropart. Phys. 34 (2011) 627)



Typically only search for dipole anisotropy in equatorial coordinates (Rayleigh analysis)
Phase expected to be more sensitive than amplitude

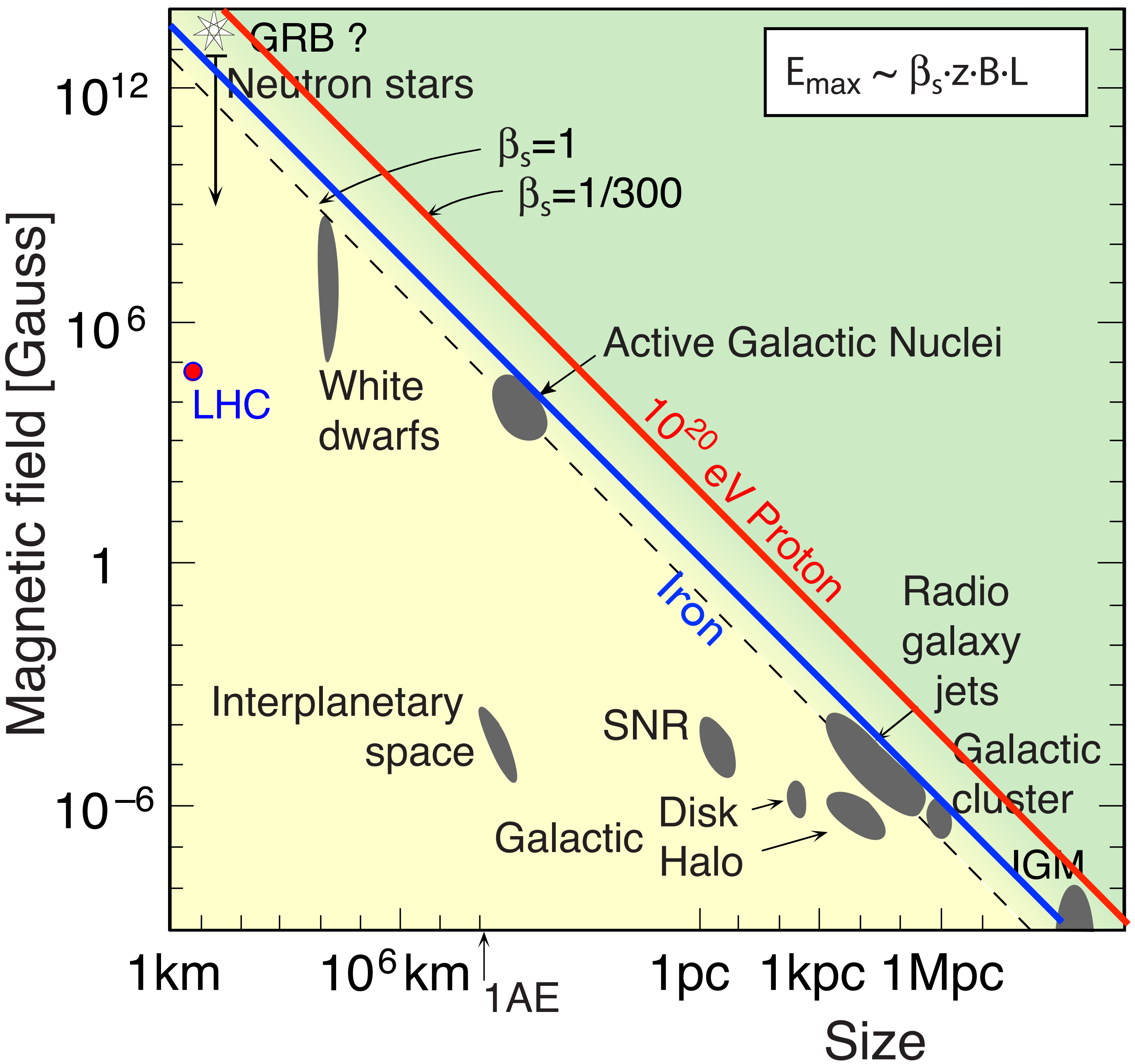
Upper limits: surprisingly small anisotropy of arrival direction distribution

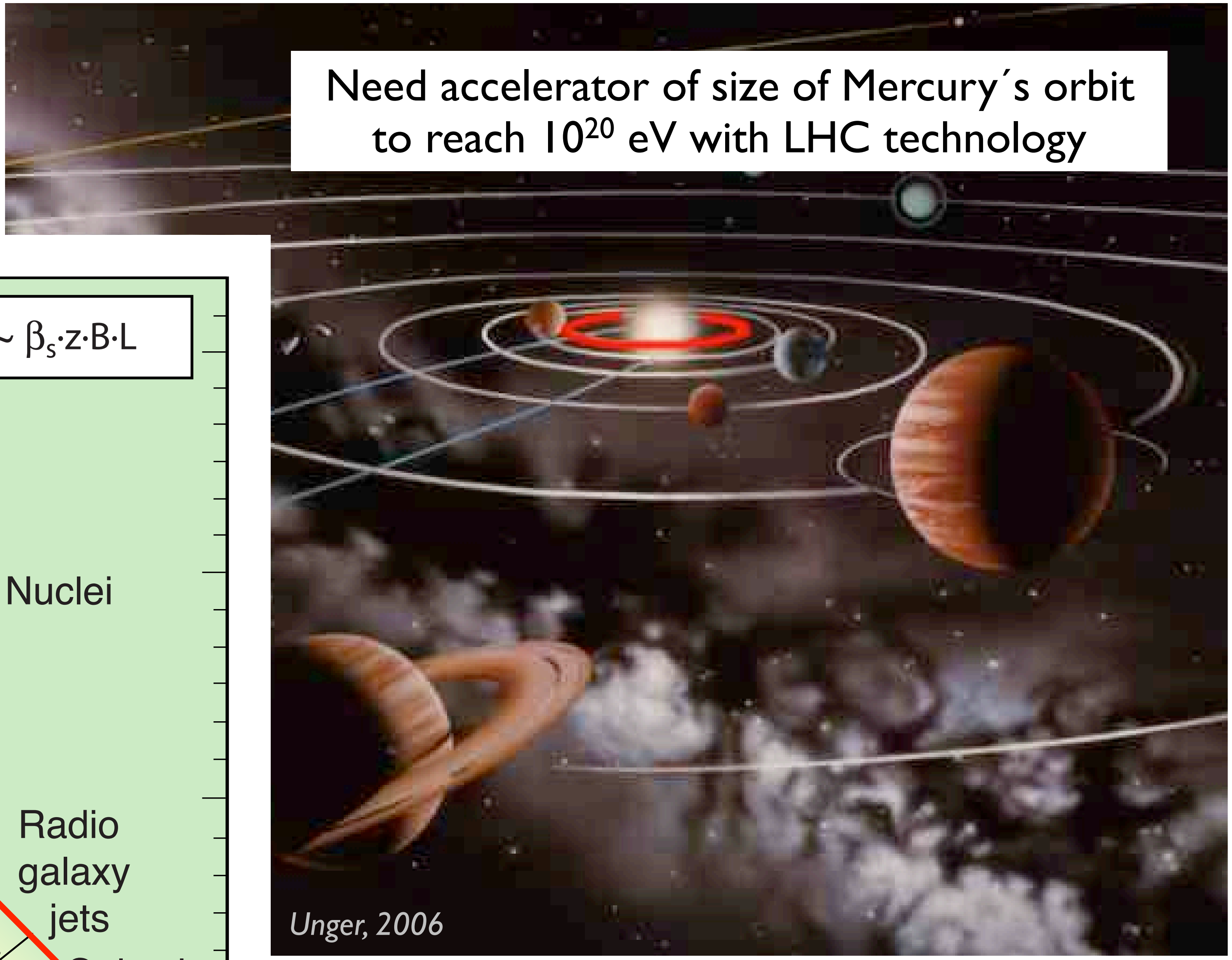
Re-scaled flux: several breaks in power law



Problem 1: Sources of 10^{20} eV particles

Hillas plot (1984)



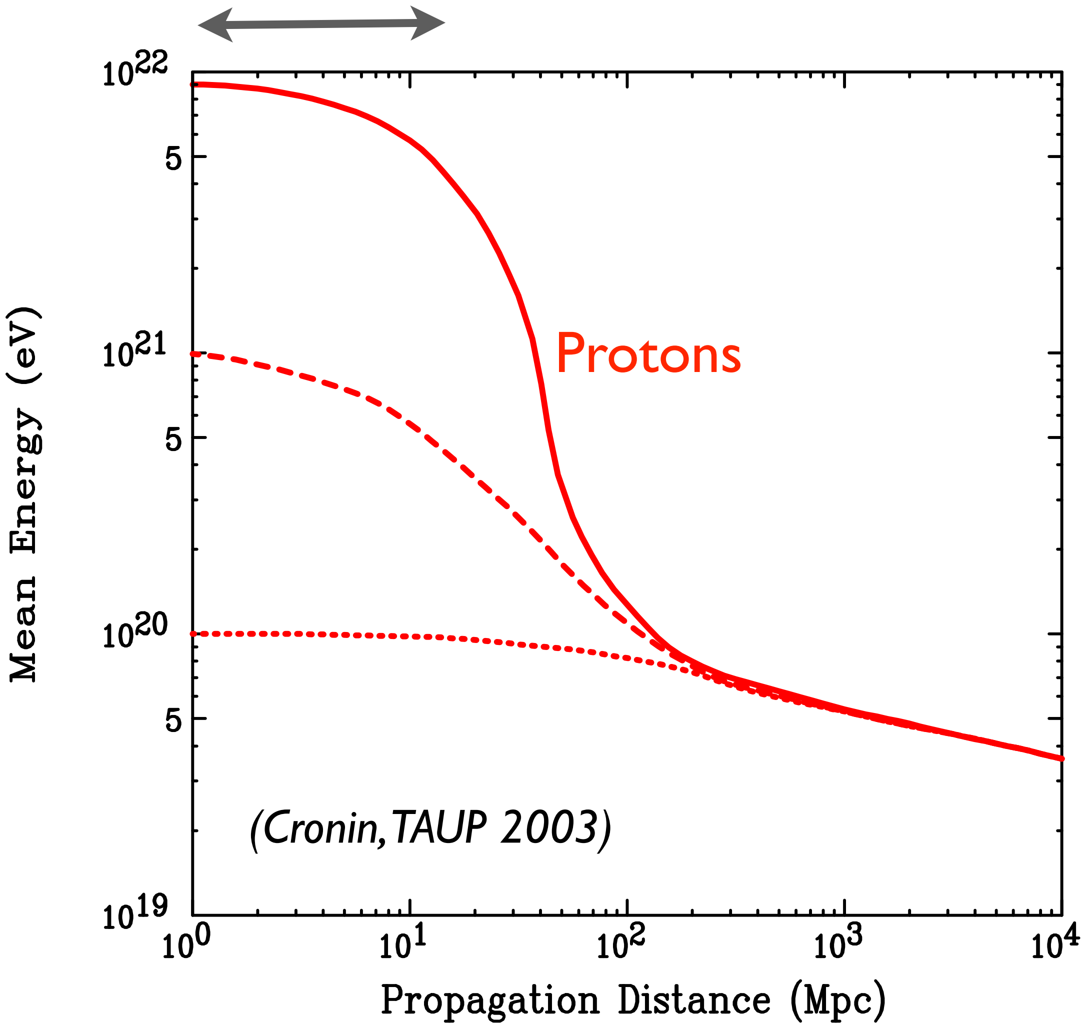


Realistic constraints more severe

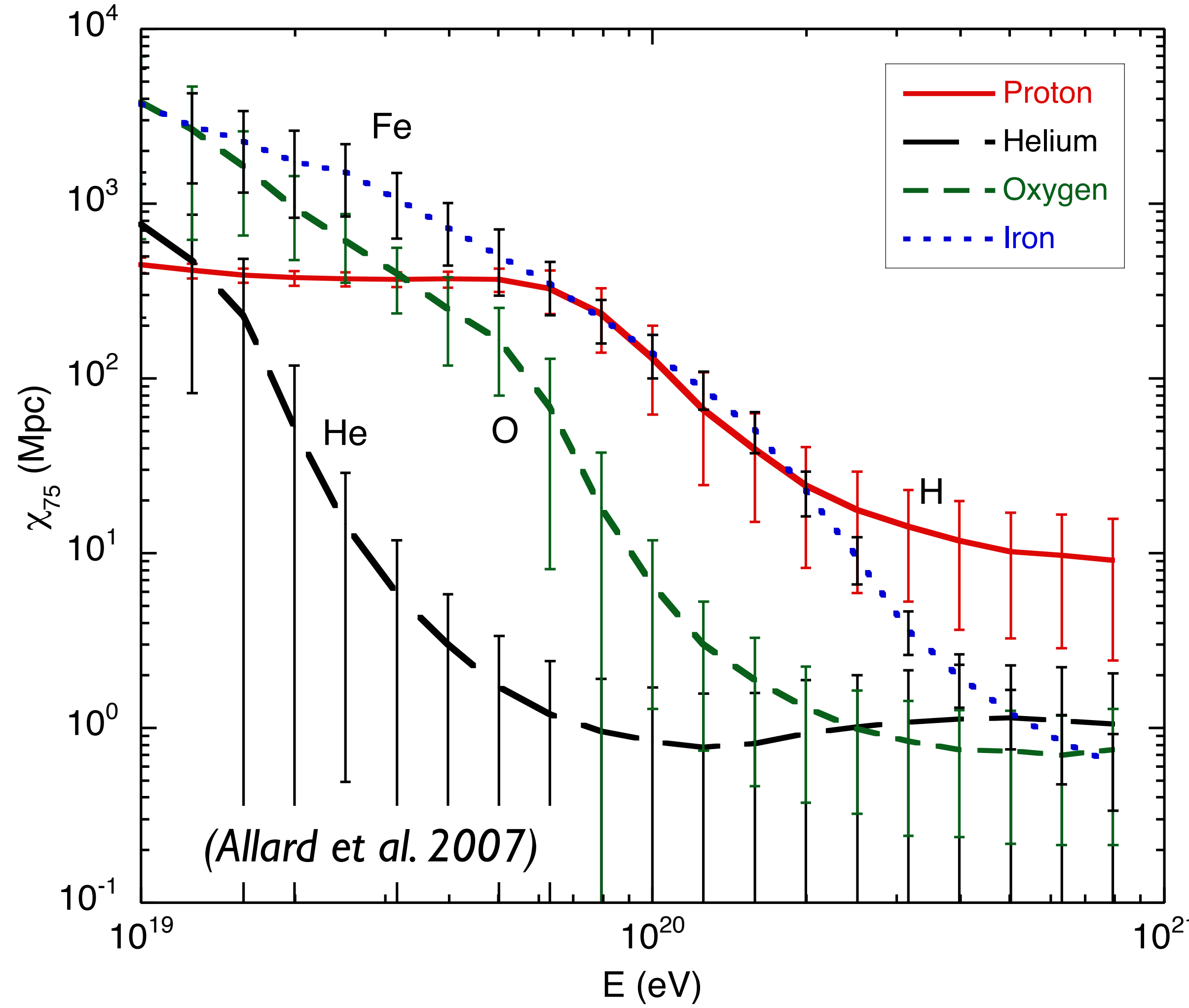
- small acceleration efficiency
- synchrotron & adiabatic losses
- interactions in source region

Problem 2: Flux suppression due to GZK effect

Energy loss length



Energy loss length



Greisen-Zatsepin-Kuzmin effect (1966)

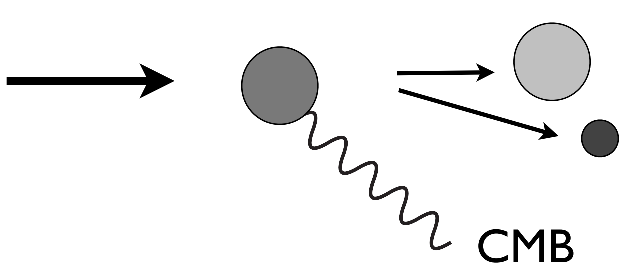
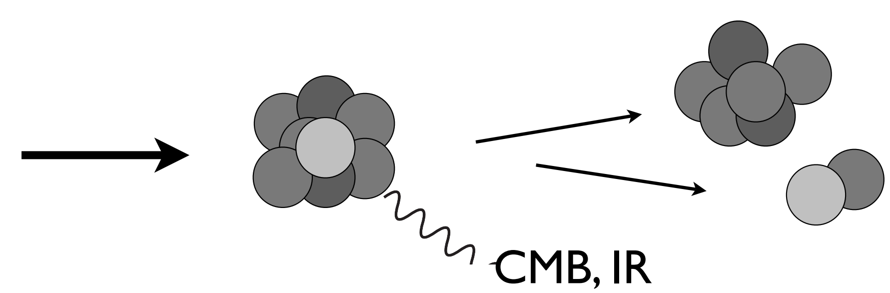
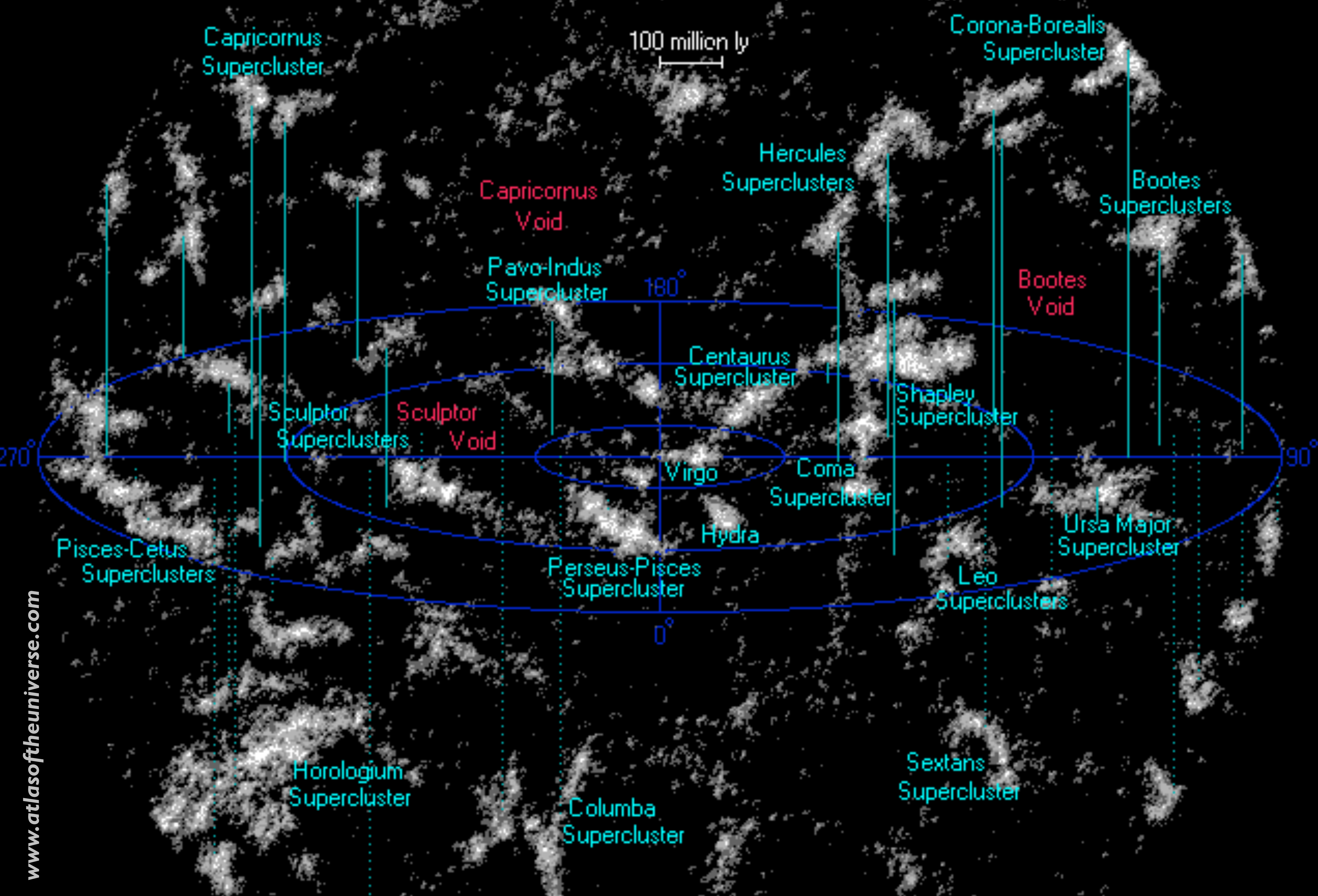


Photo-pion production

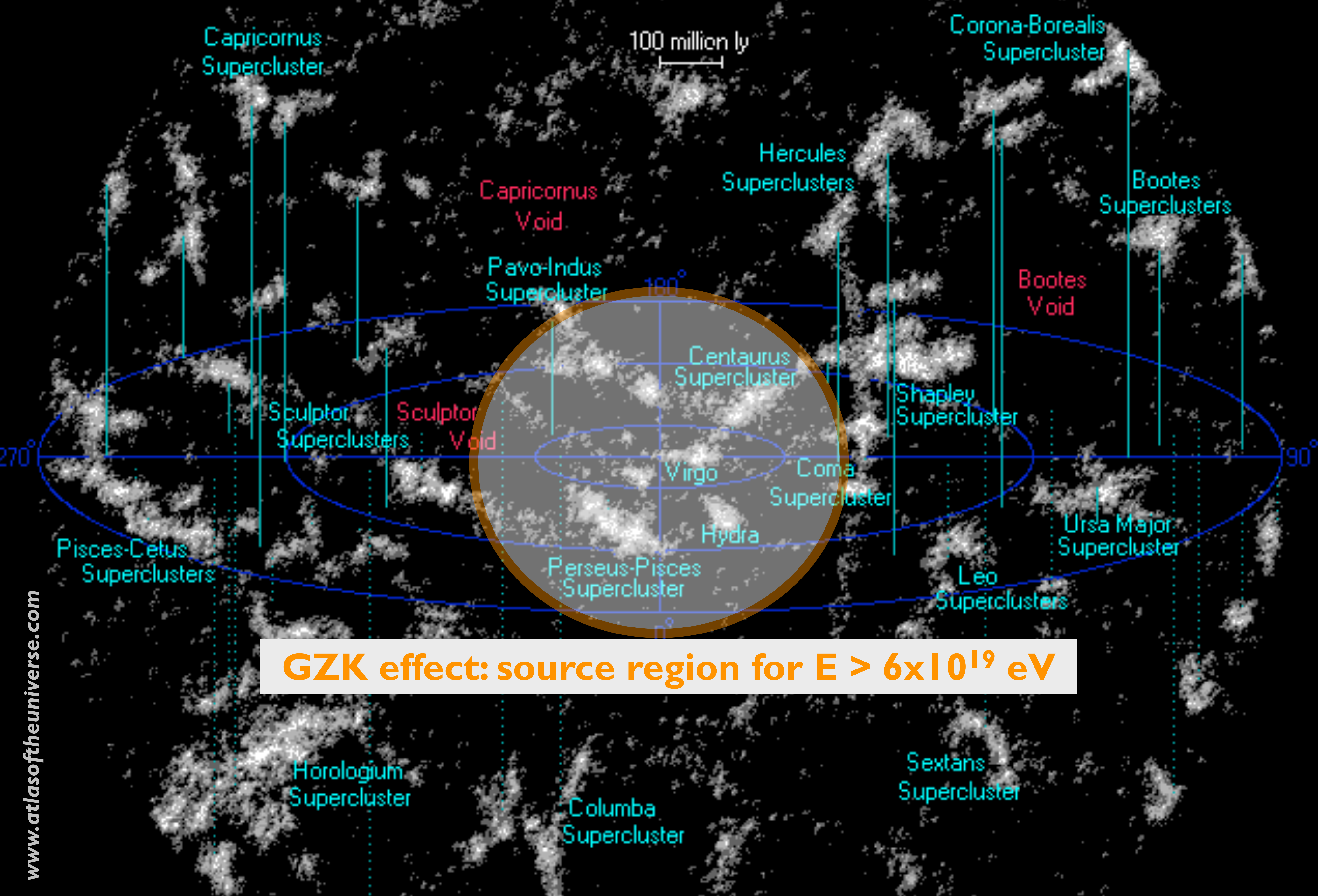
Photo-dissociation (giant dipole resonance)



Problem 3: Arrival direction distribution

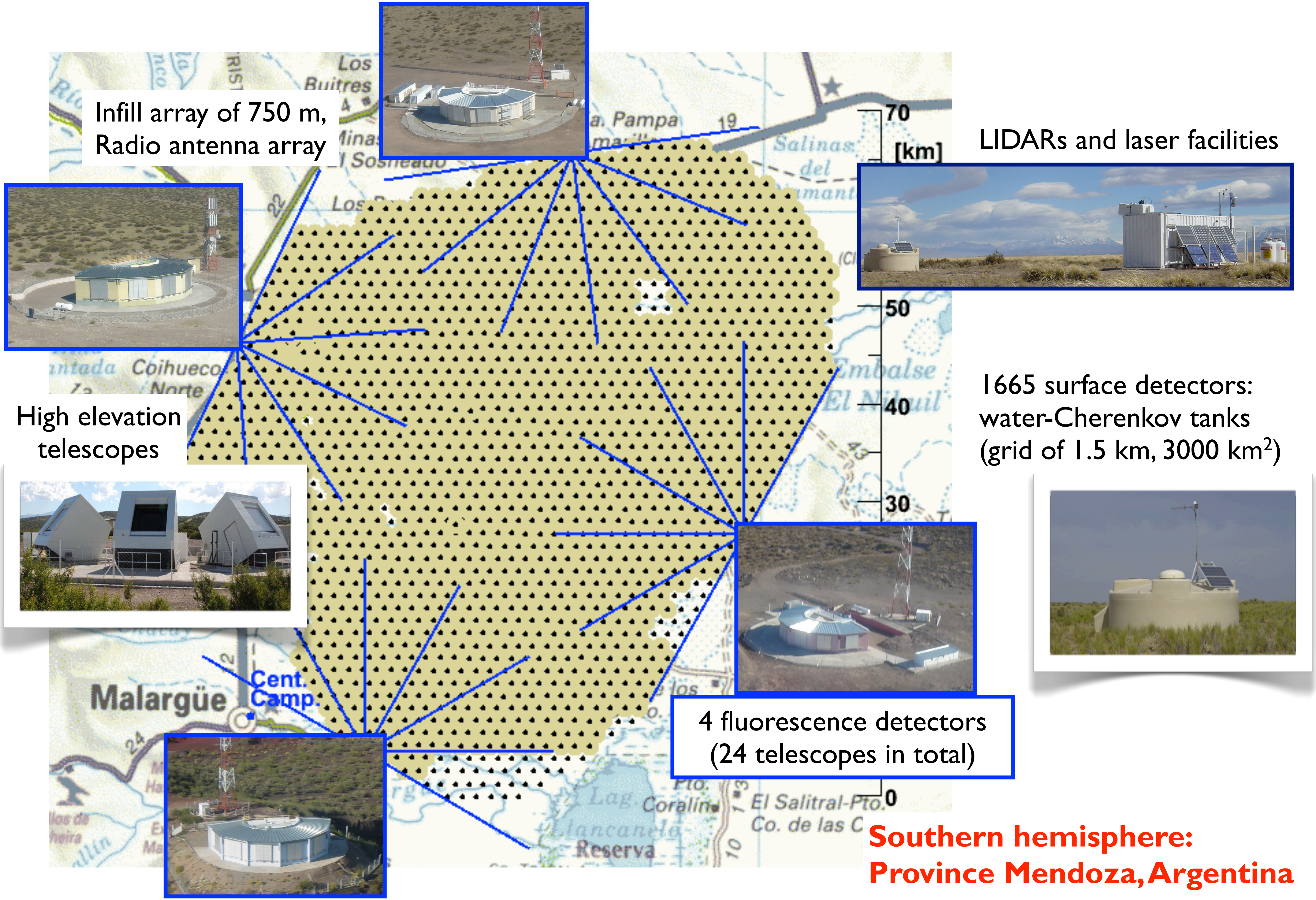


GZK effect: anisotropy expected for light elements



GZK effect: source region for E > $6x10^{19}$ eV

The Pierre Auger Observatory



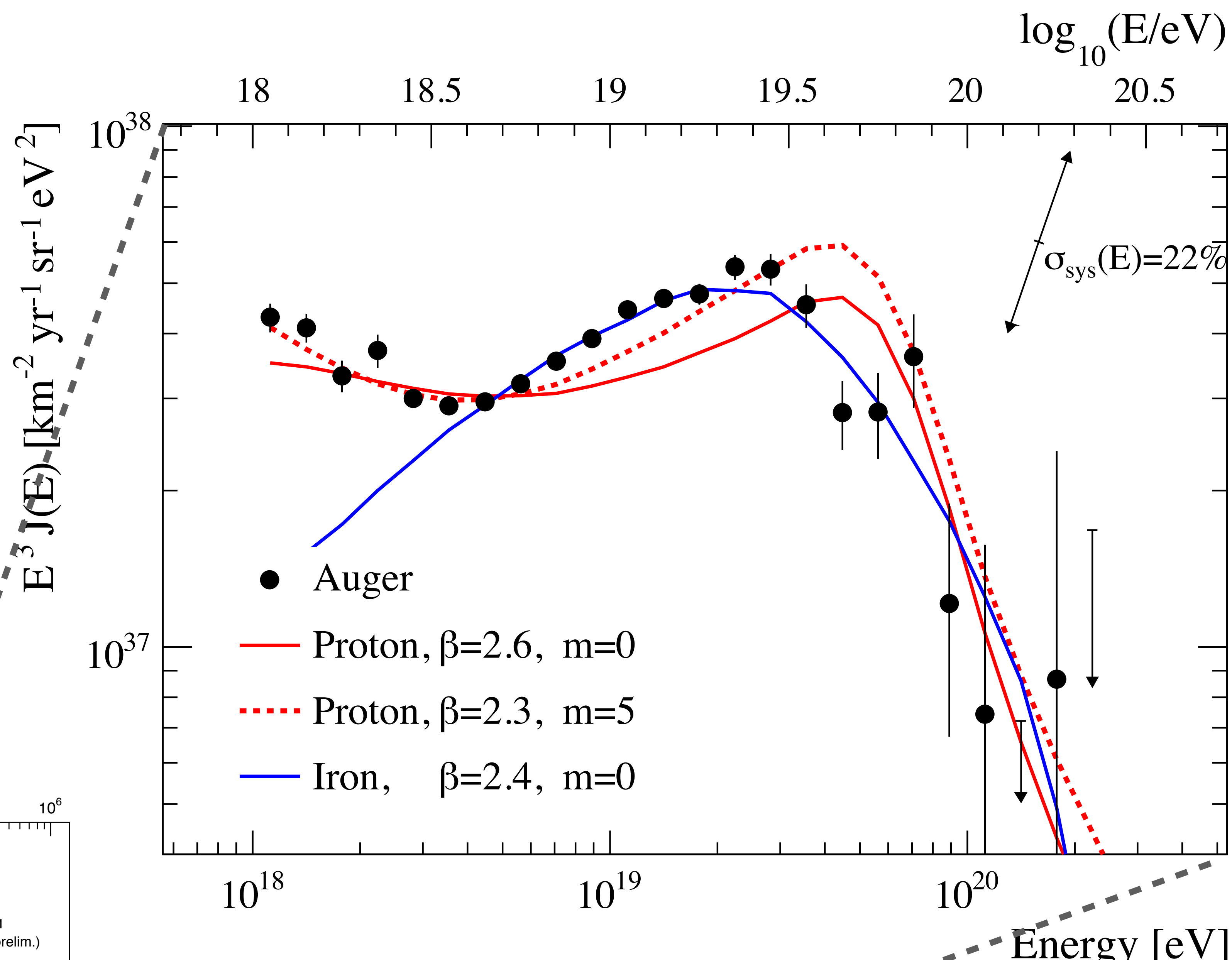
Flux suppression compatible with GZK effect ?

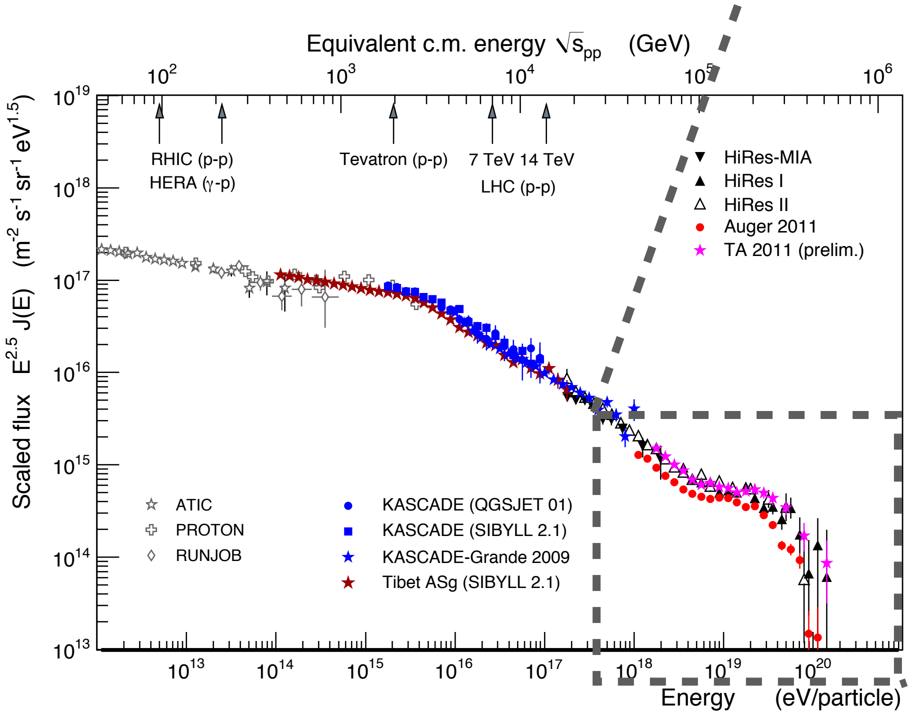
Proton dominated flux

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