Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

Karlsruhe Institute of Technology

The Physics of Cosmic Rays – An Overview

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Outline

Review of important measurements and observations
(flux, temporal variation, anisotropy, elemental composition)

Supernova remnants as galactic sources
(galaxy, magnetic fields, energy budget, stochastic acceleration)

Propagation of cosmic rays in the galaxy
(diffusion, leaky box model, primary vs. secondary elements, lifetime)

Open problems and new puzzles
(flux features, knee, ankle, isotropy, transition from galactic to extragalactic sources, extragalactic sources, ...)

Separate lectures
Electron and positron fluxes *(Wolfgang Menn)*
Cosmic rays at the highest energies *(Markus Roth)*

Review of known properties of cosmic rays

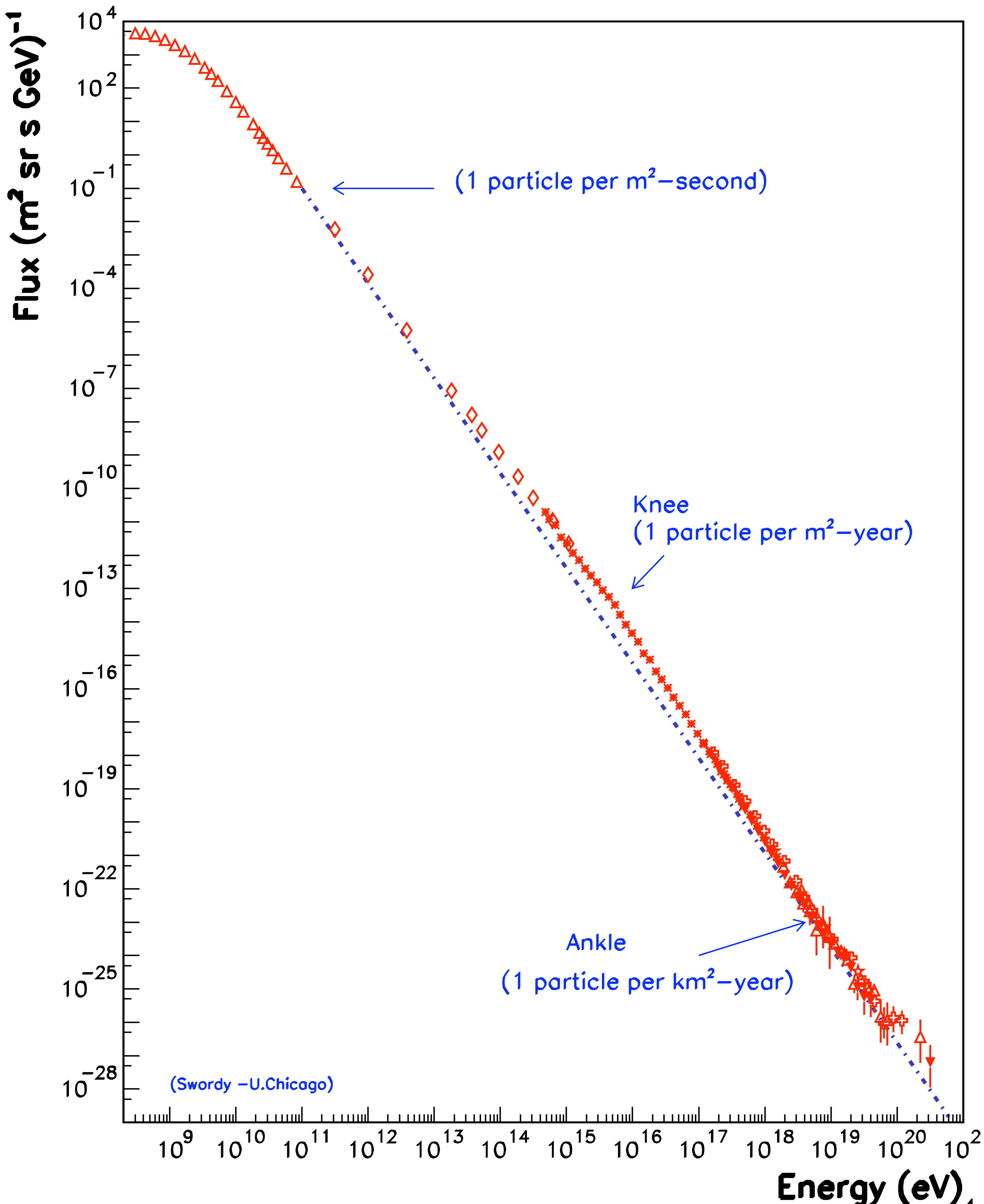
Flux of cosmic rays

Flux follows power law

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

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

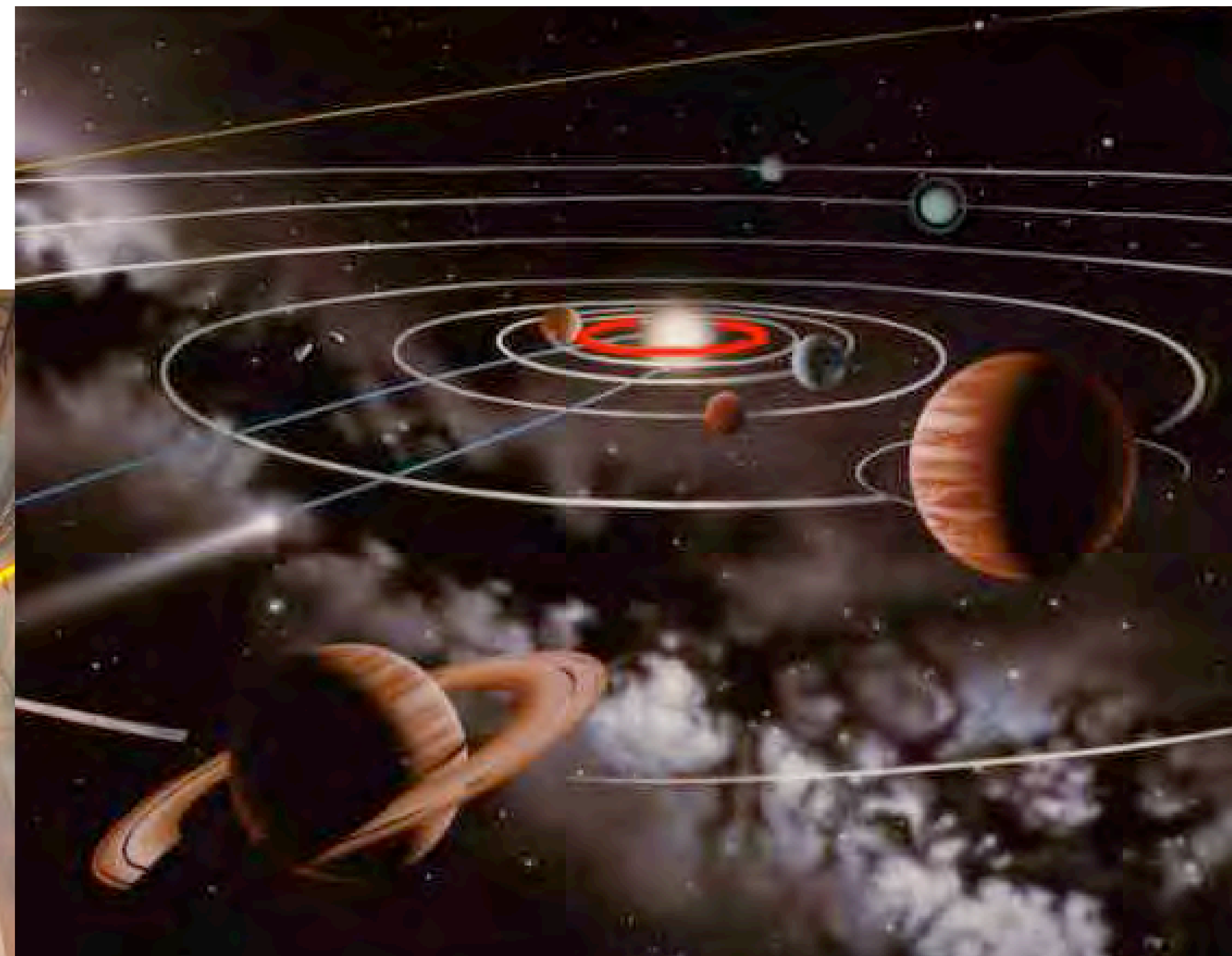
Energy spectrum of all-particle flux



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

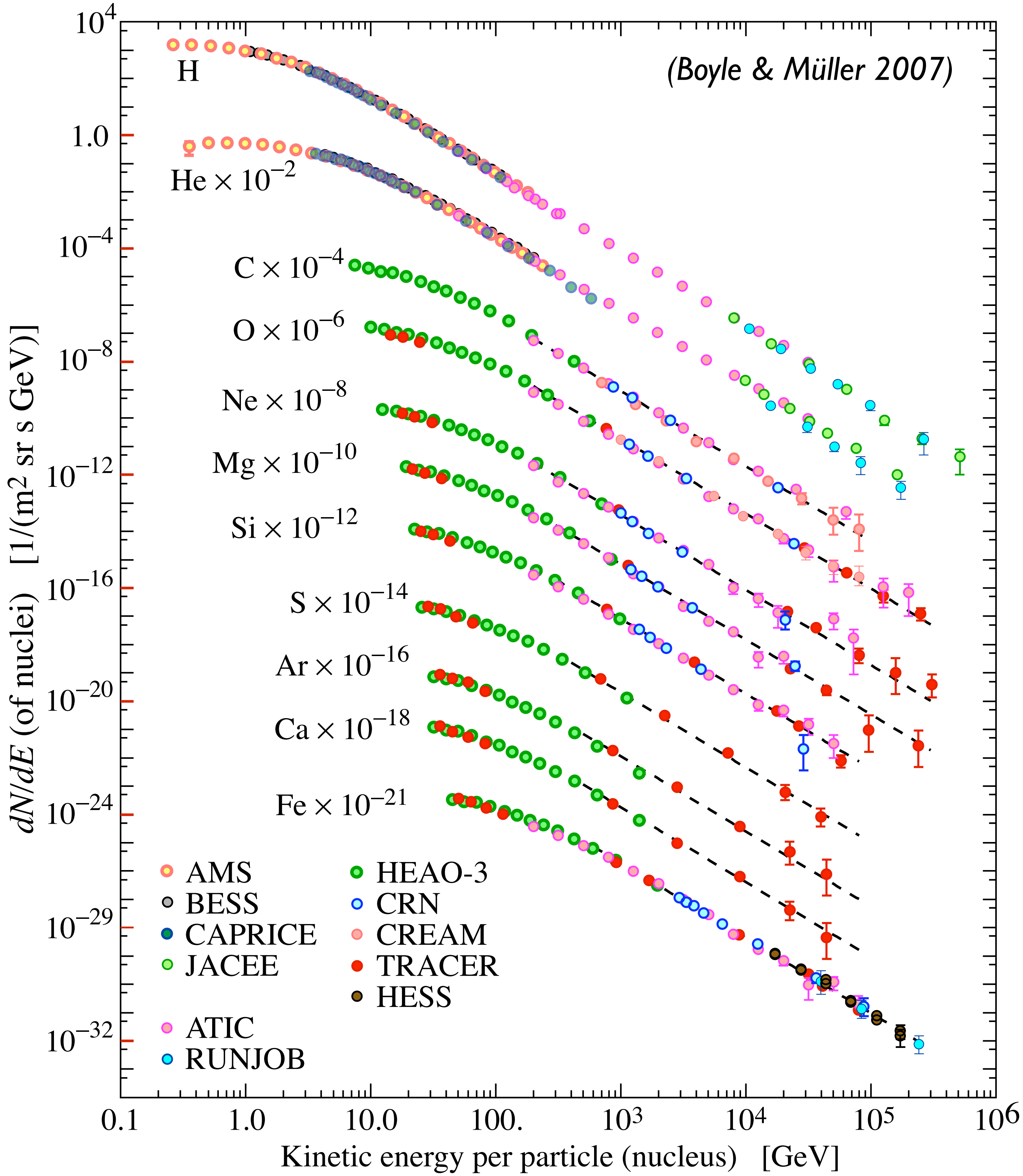
Fluxes of individual elements

Power law also found for individual elements

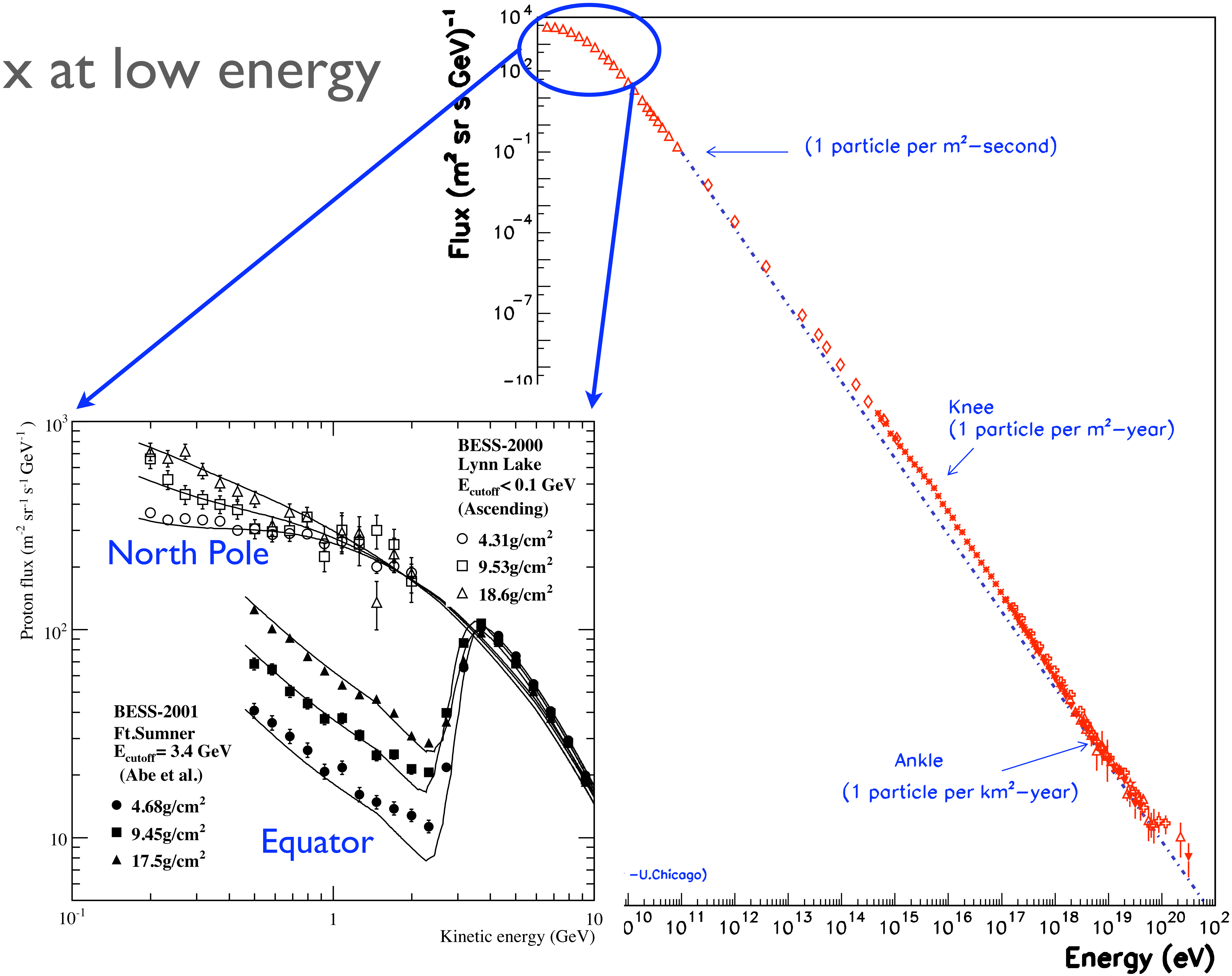
Index of power law almost identical (heavier elements have slightly harder spectra)

Relative abundance of nuclei

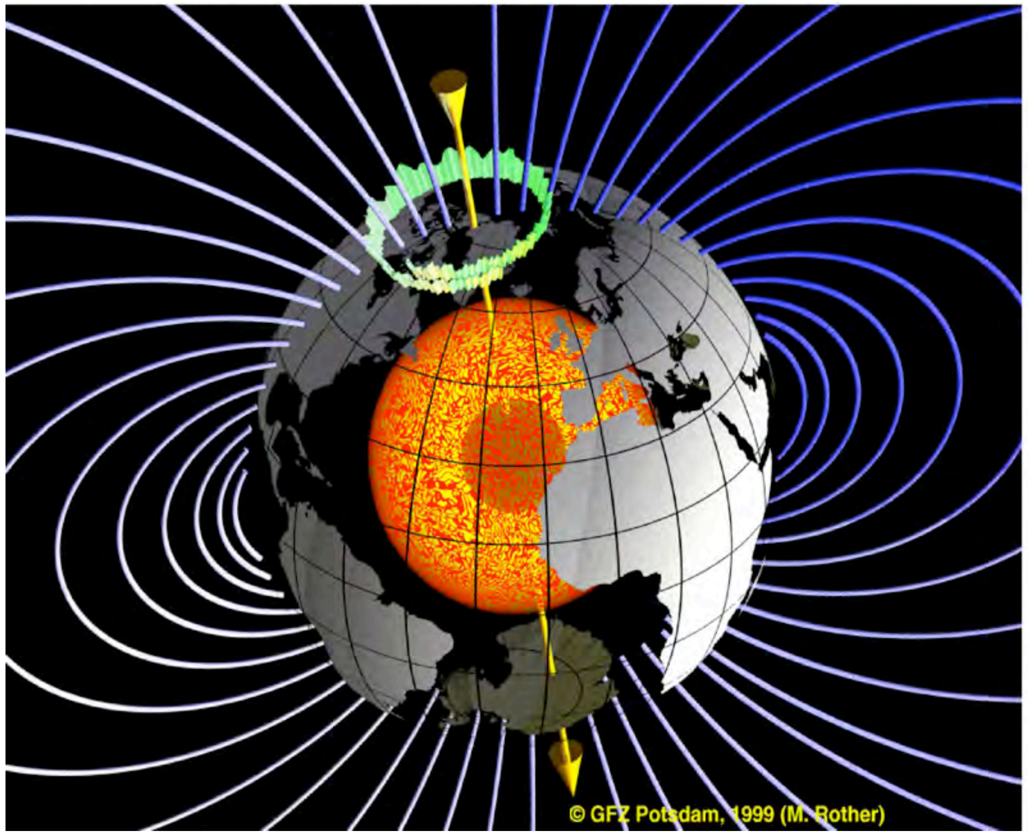
H	: He	: Z= 6-9	: 10-20	: 21-30
1	: 0.38	: 0.22	: 0.15	: 0.4



Flux at low energy



Geomagnetic cutoff and East-West effect

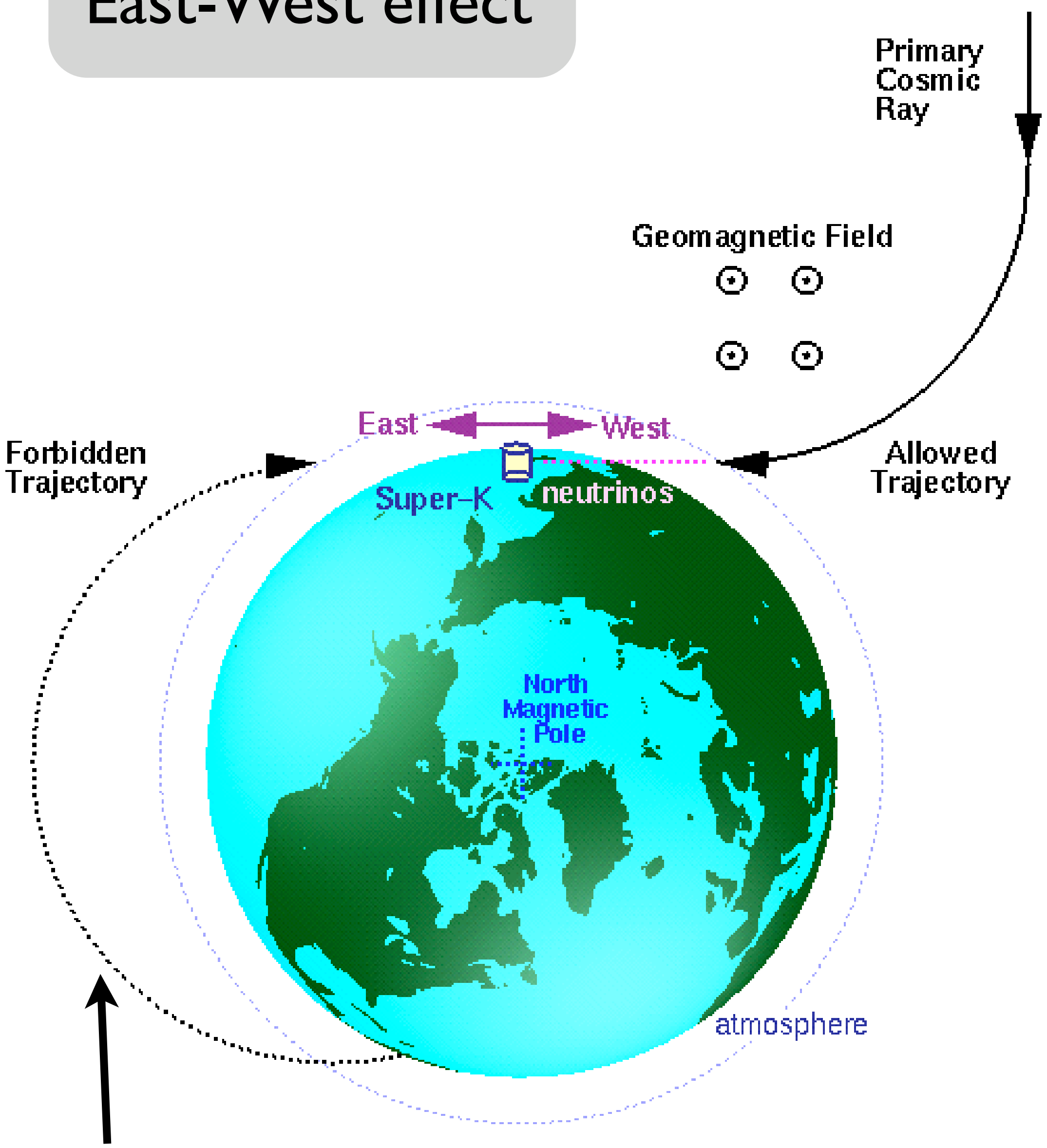


Earth's magnetic field

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

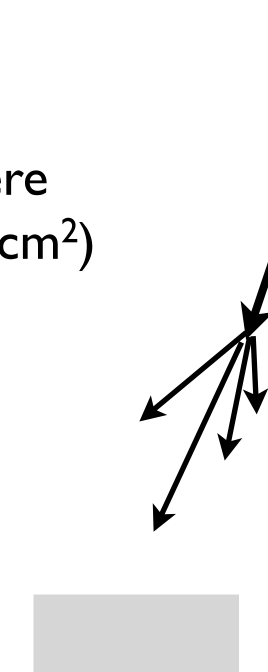


Radius of curvature
smaller than radius of Earth

Particles below geomagnetic cutoff

Measurement in upper atmosphere

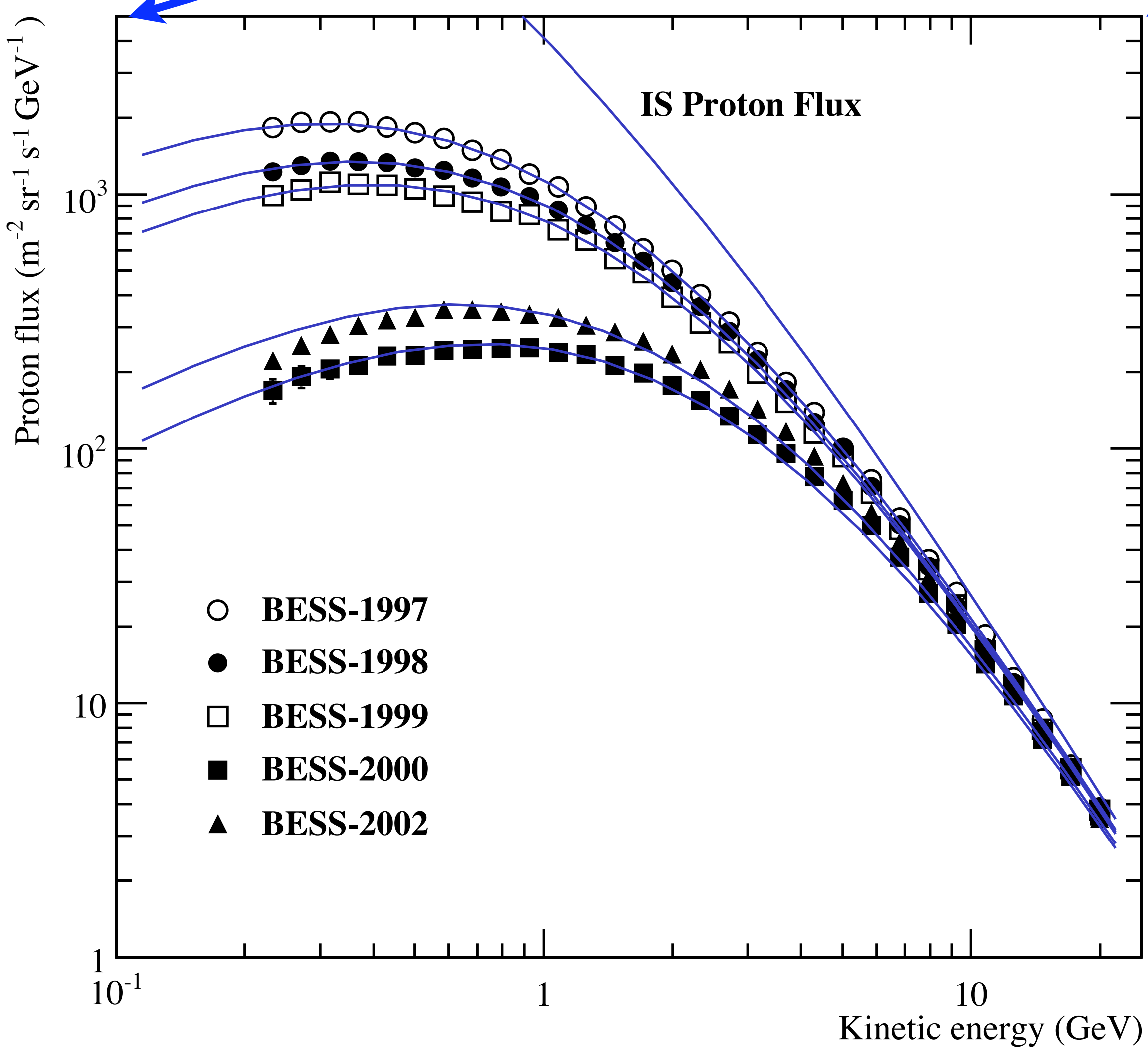
Particle detector

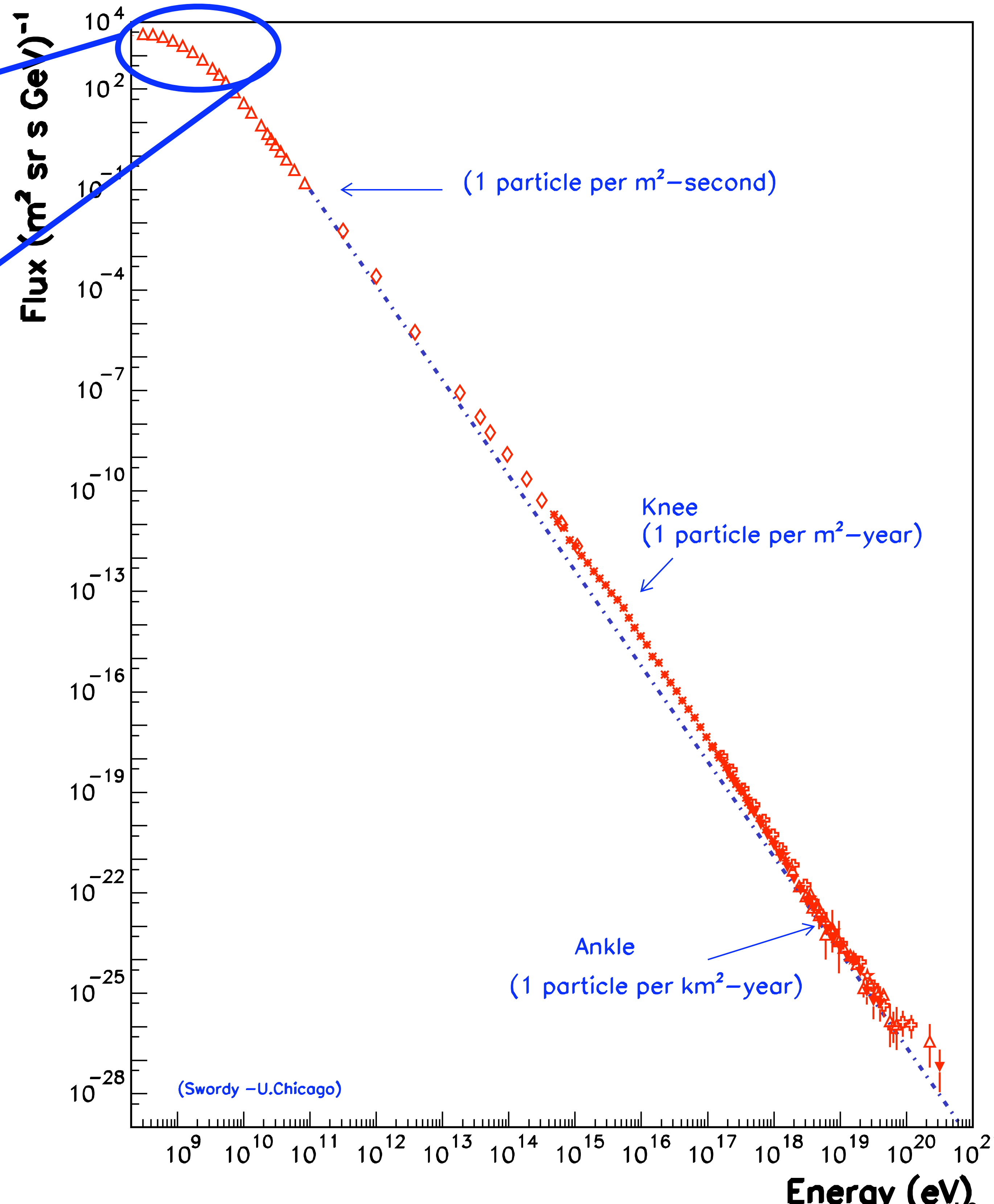


Traversed column depth $$X = \int_h^\infty \rho(h)\,dl$$

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

Temporal variation of flux at poles

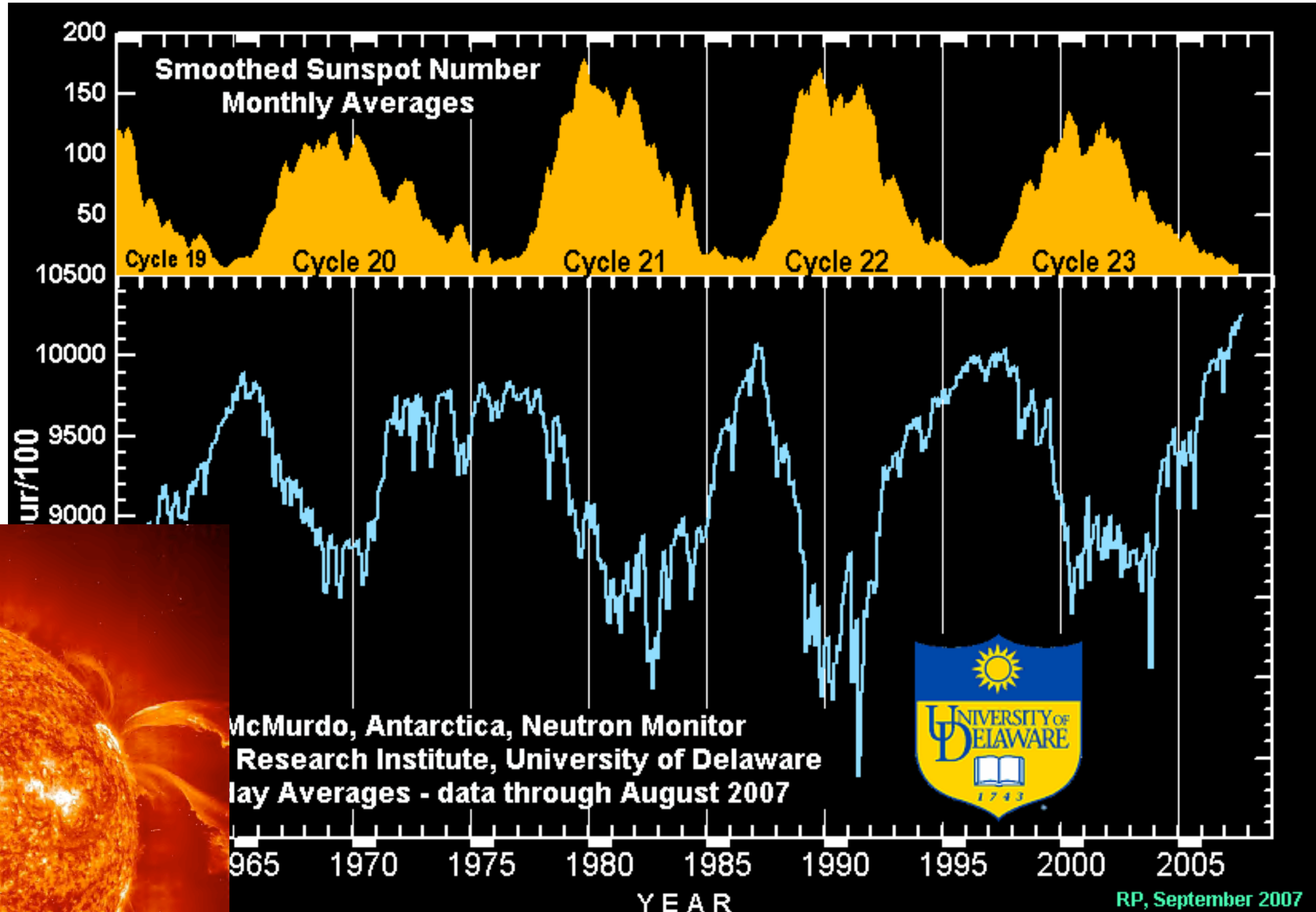




- geomagnetic cutoff negligible
- corrected for atm. overburden

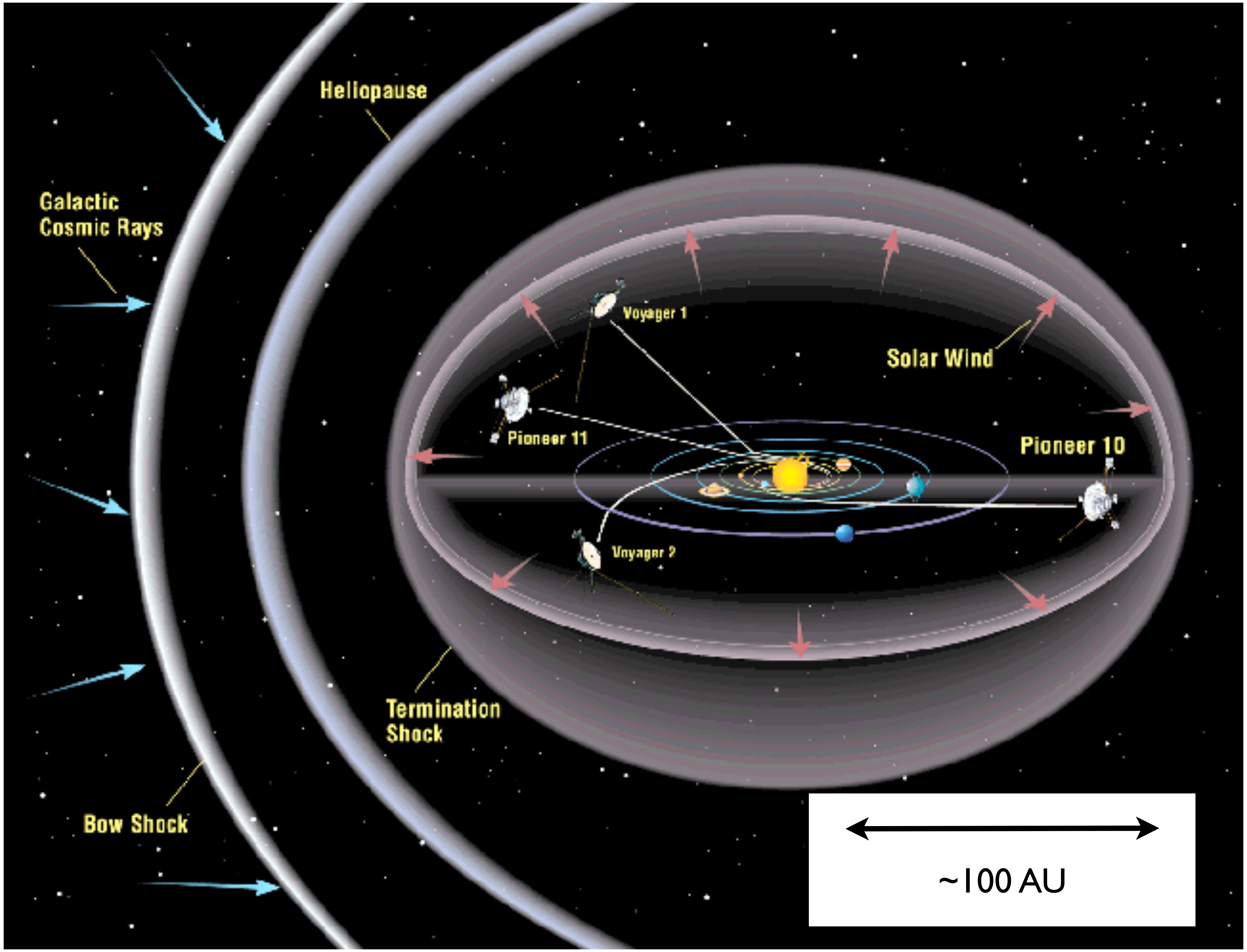
Anti-Correlation with solar activity

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

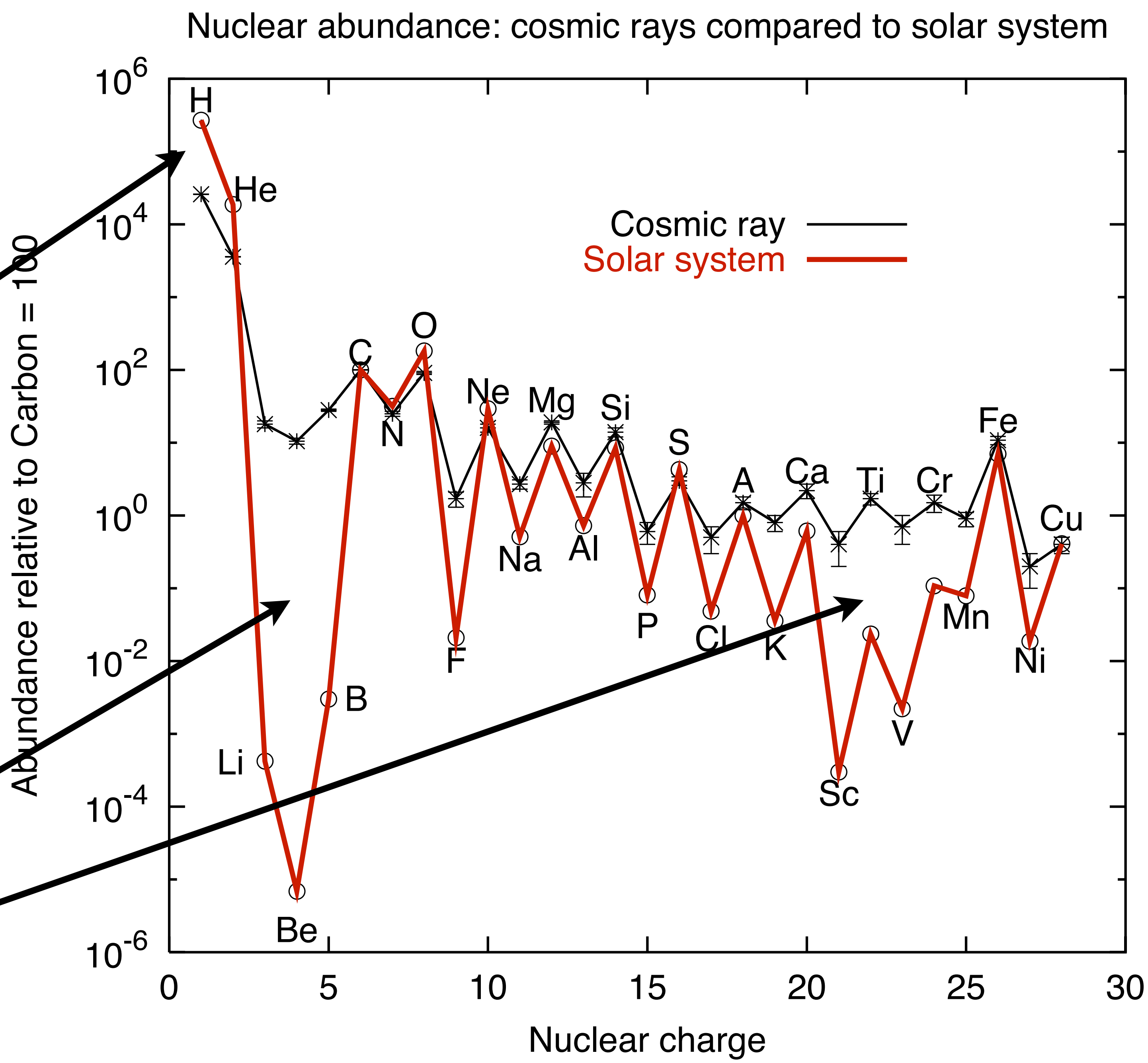
Example:
Proton energy reduced by 0.5 to 1 GeV after crossing Solar Wind

Sources not in solar system

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

Comparison of element abundances

Flux of elements at ~1GeV

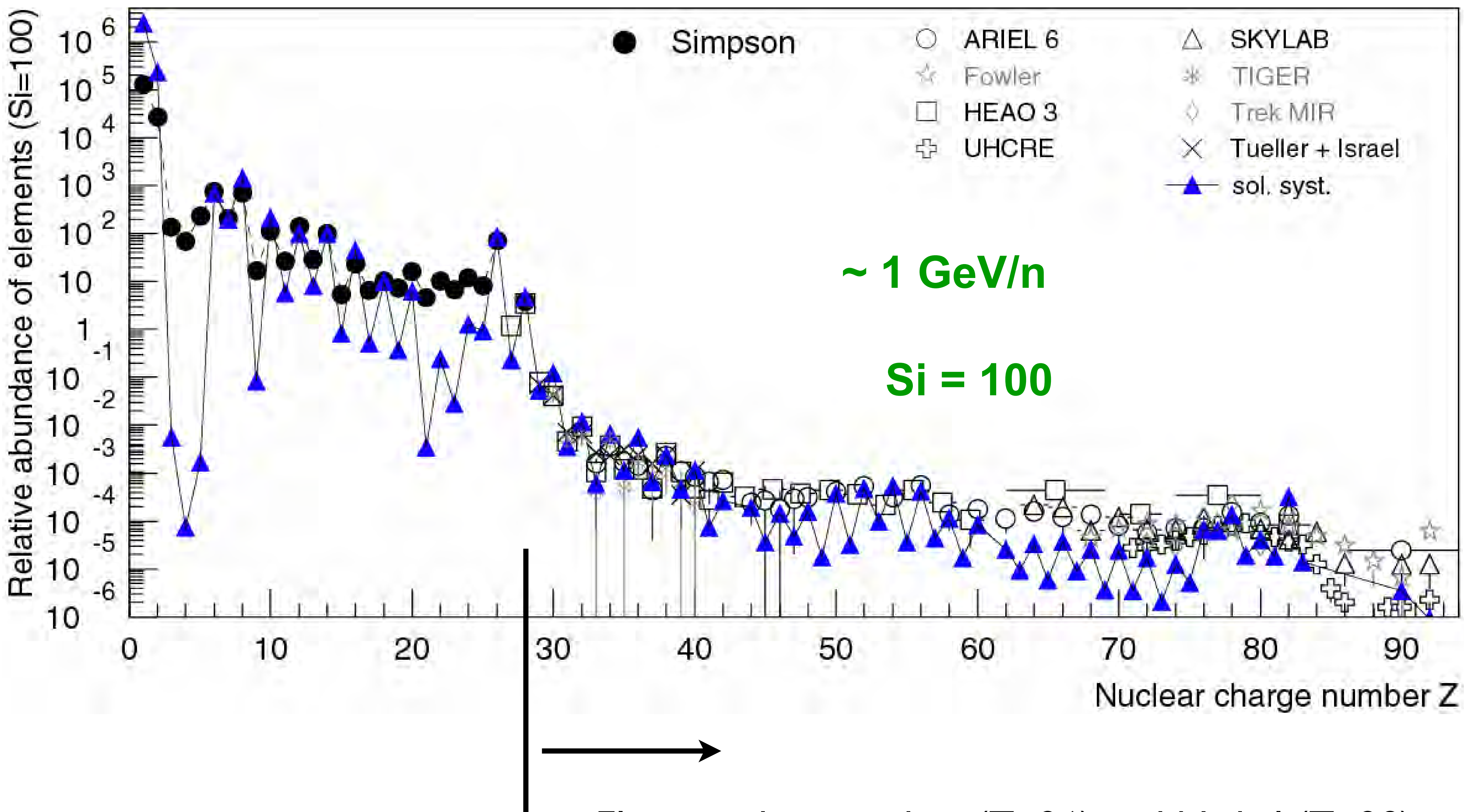


Discrepancy for hydrogen:
first ionization potential (FIP)?

Not typical products of
Supernova explosions

(Gaisser & Stanev, NPA 2006)

What about heavy elements ?



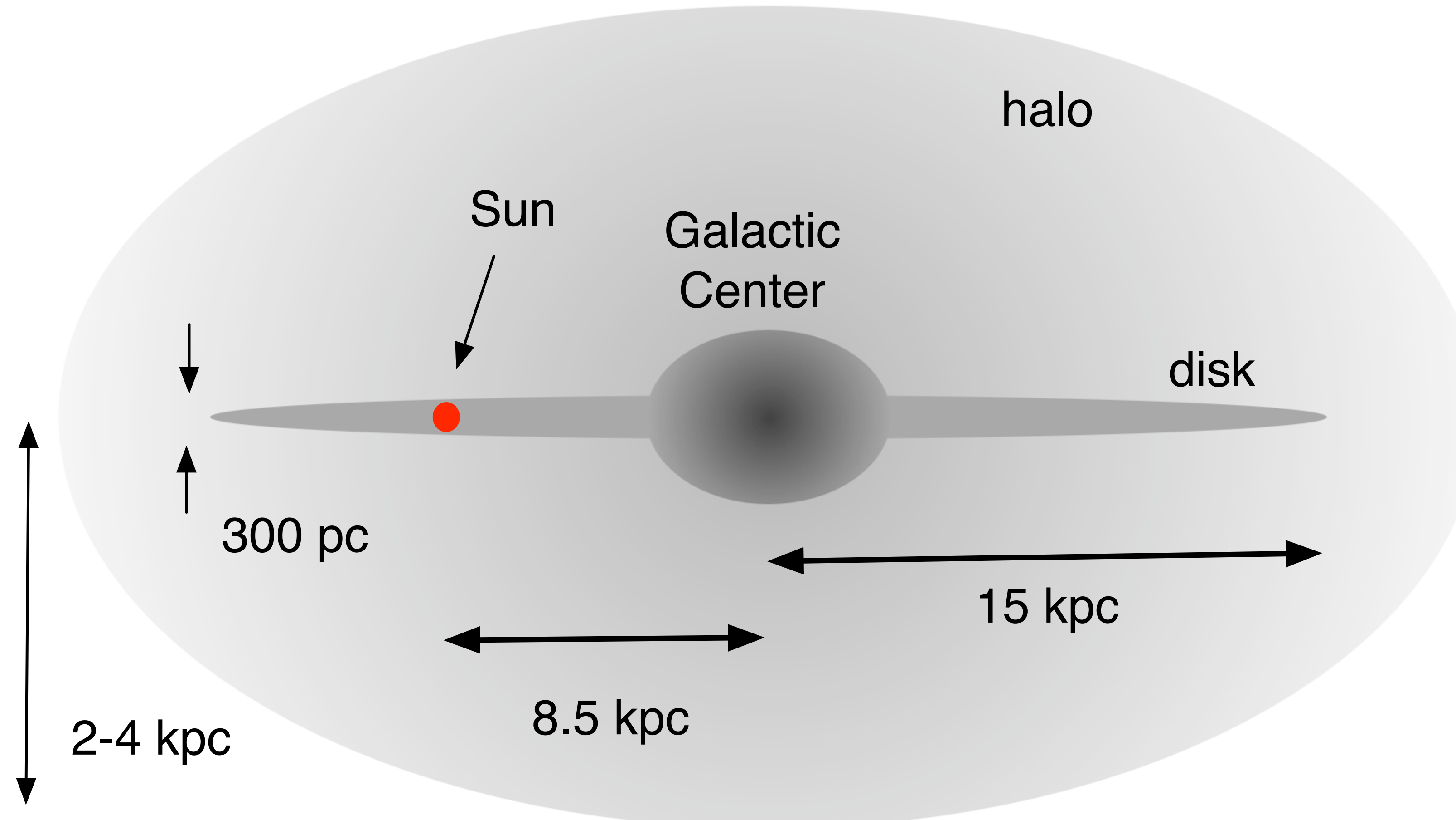
Elements heavier than (Z=26) and Nickel (Z=28)
hardly produced in SN explosions

Supernova remnants as galactic sources

Galaxy and galactic magnetic fields

(Andromeda, M31)

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



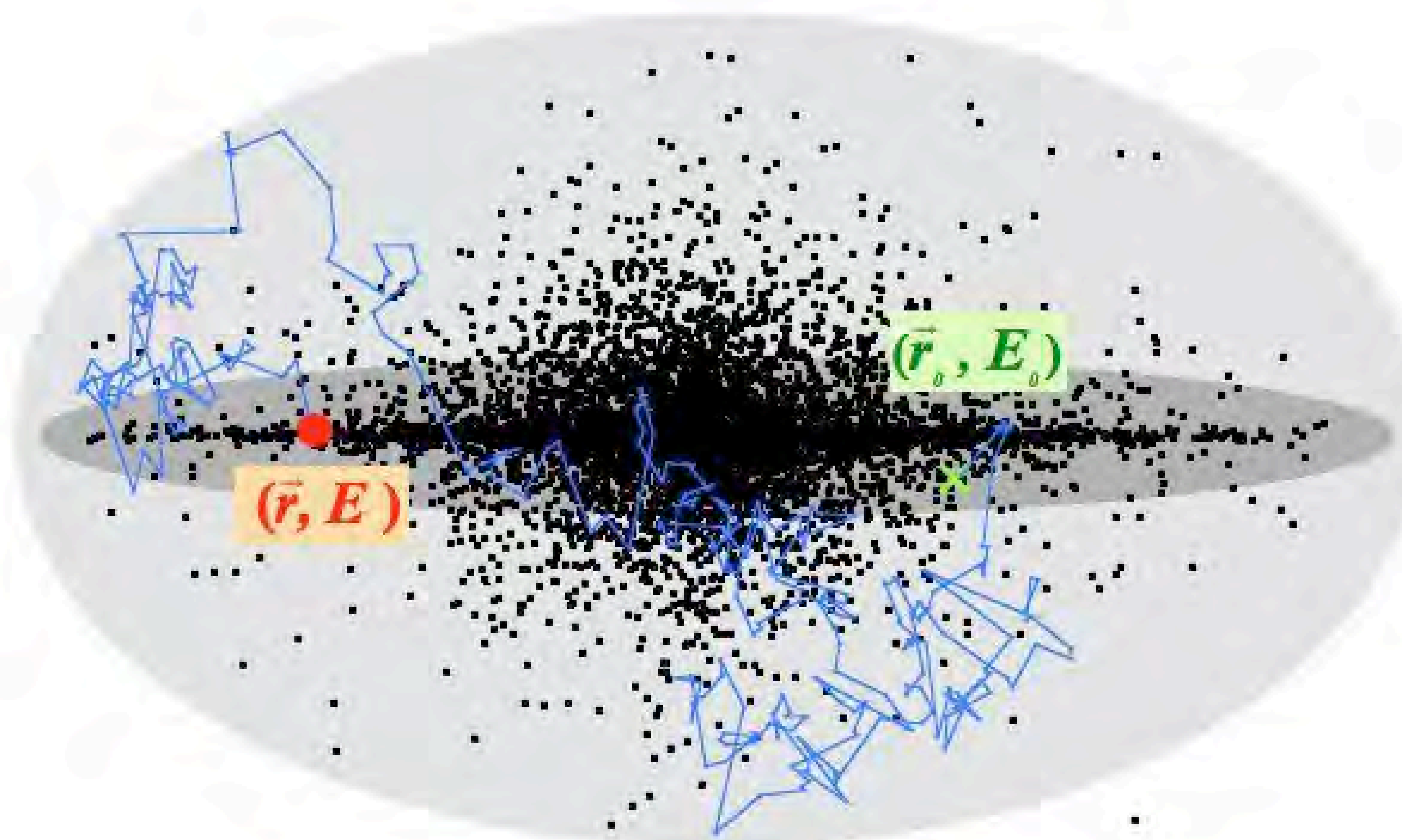
Magnetic field not well known,
B = 3 μG = 30 nT close to Solar System

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

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

Galaxy and galactic magnetic fields

(Andromeda, M31)



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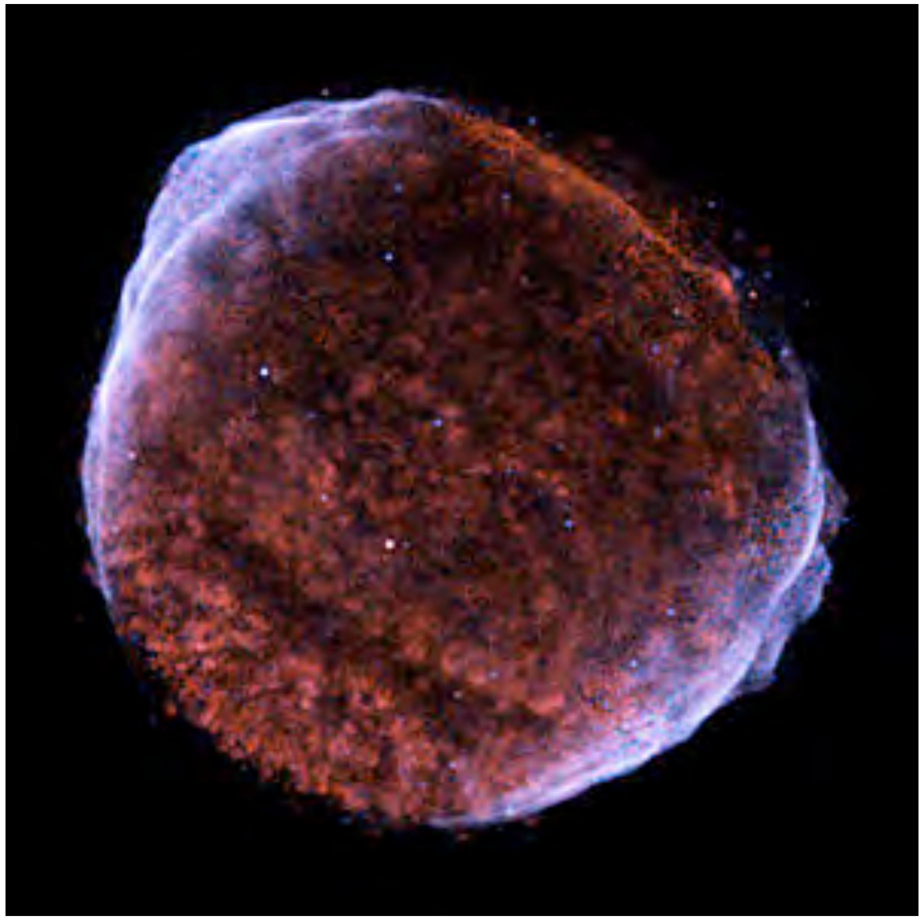
Diffusion: distance scales ~ $(\text{time})^2$ ⟶ Extragalactic sources unlikely

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: ~10^{51} erg

(1 erg = 0.1 μJ)

General arguments:

- Rate and energy budget
- Acceleration theory
- Elemental composition

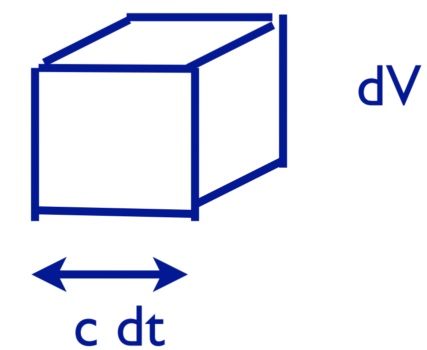
Power needed to maintain cosmic ray flux

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

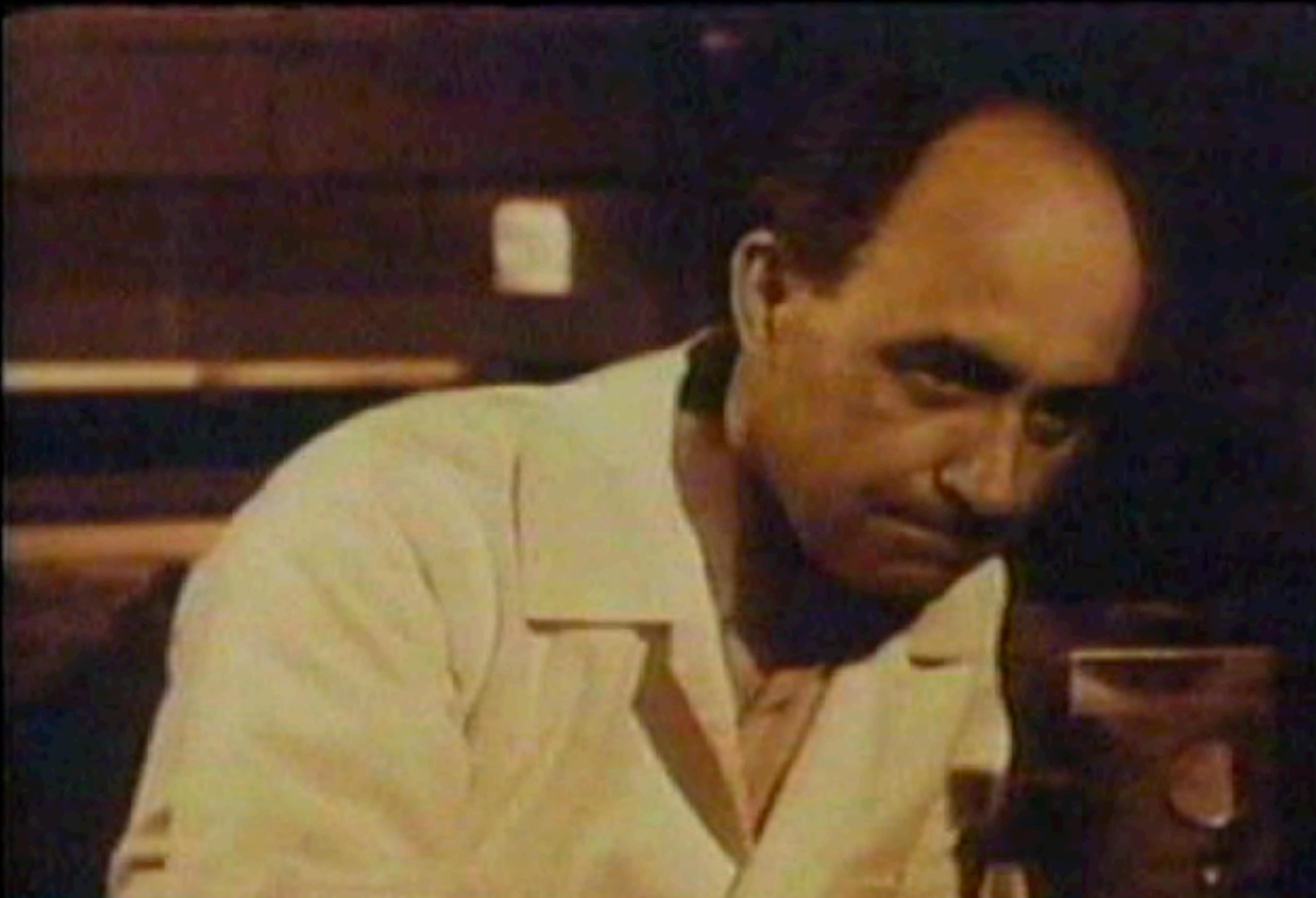
$$P_{\text{src}} = E_{\text{tot}}/\tau_{\text{esc}} \approx 10^{41}\,\text{erg/s}$$

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

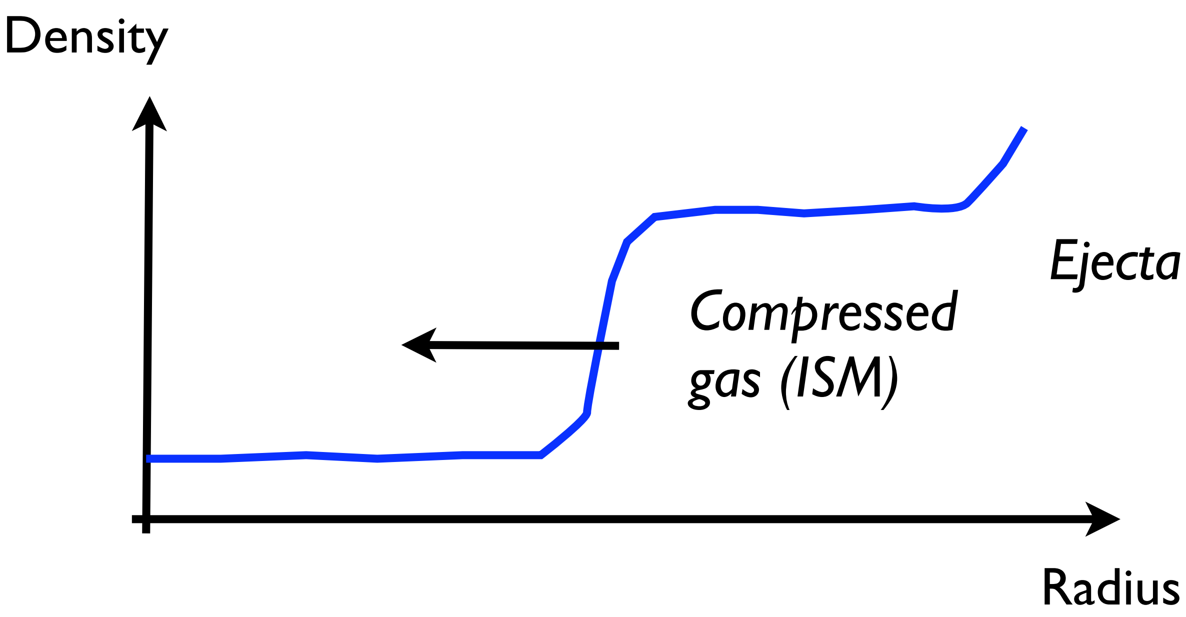
Power of cosmic ray sources

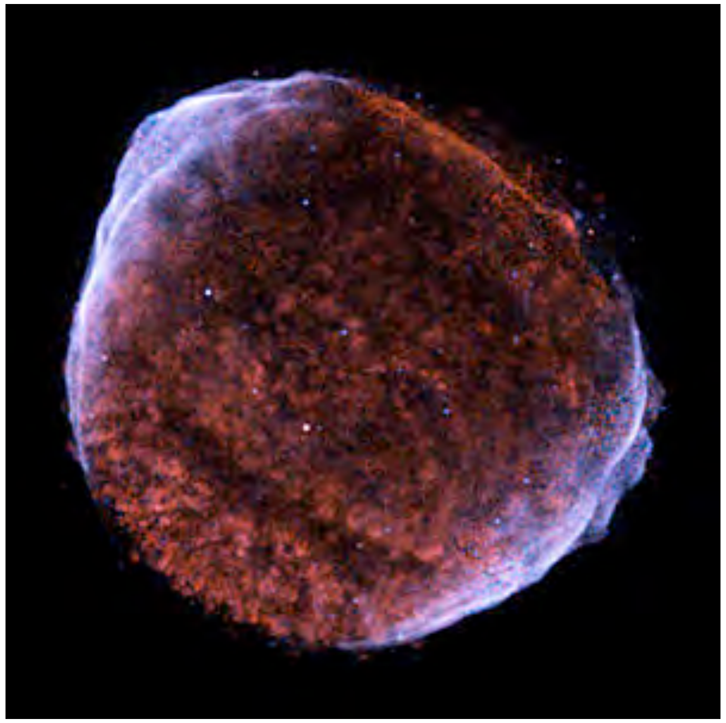
Kinetic energy released in SN explosions

Stochastic Fermi acceleration

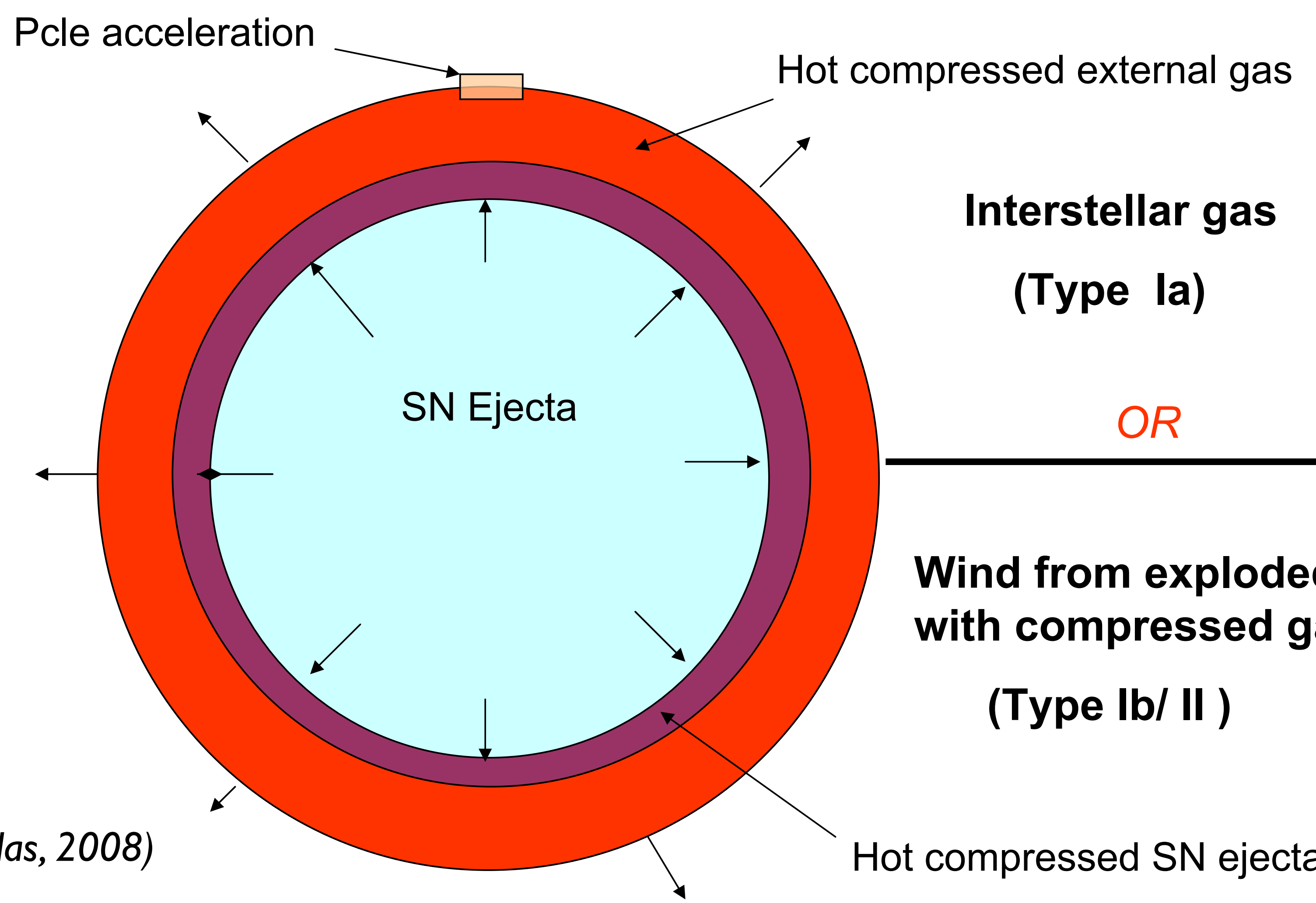


Stochastic acceleration on SN shock fronts





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



Interstellar gas

(Type Ia)

OR

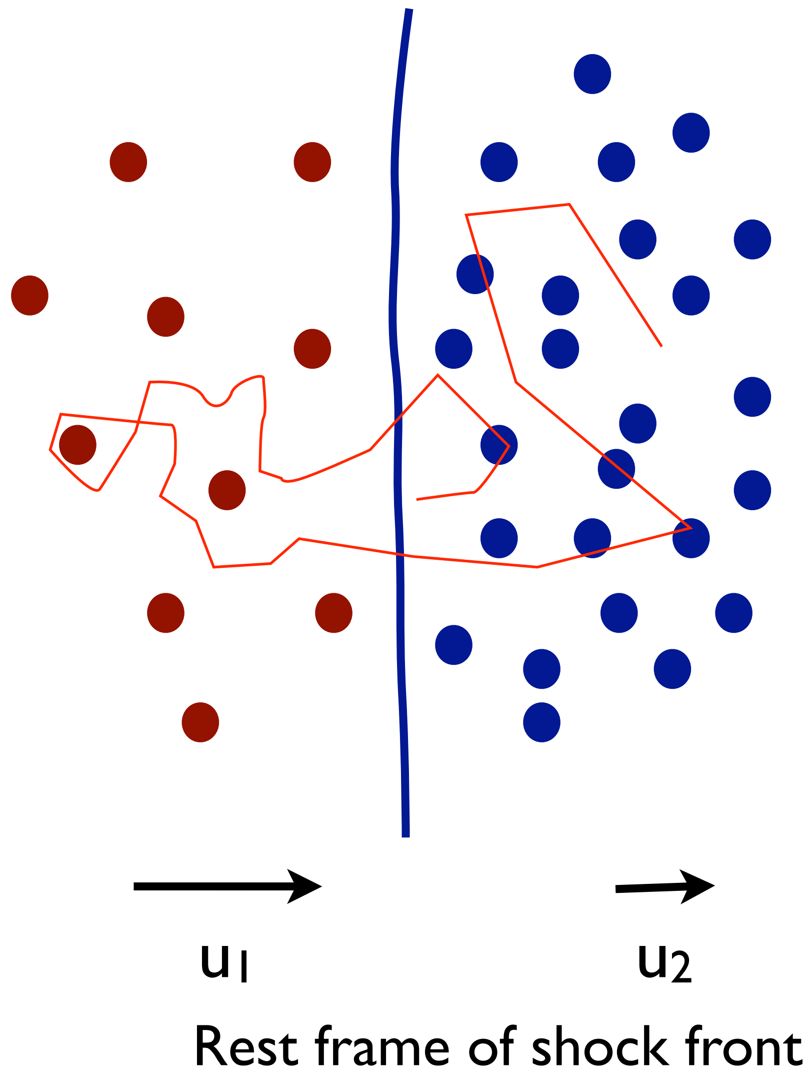
Wind from exploded star, with compressed gas shells

(Type Ib/ II)

(Hillas, 2008)

First order Fermi acceleration

Assumption:
particles scatter elastically on turbulent mag. fields



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

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

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

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

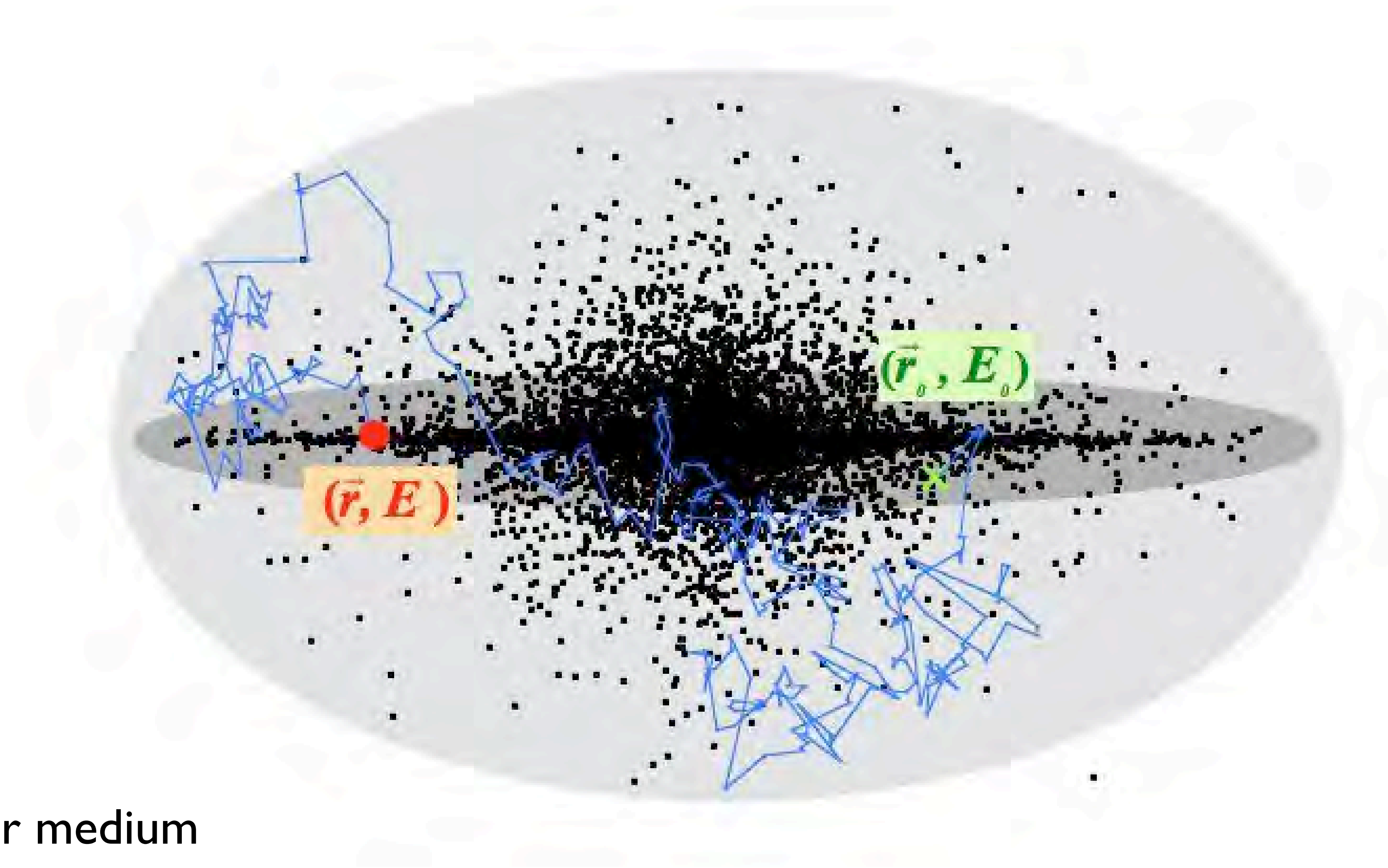
$$\alpha = -\ln(1 - P_{\rm esc}) / \ln \xi$$

Numerical values depend on many details

$$\alpha = 1$$

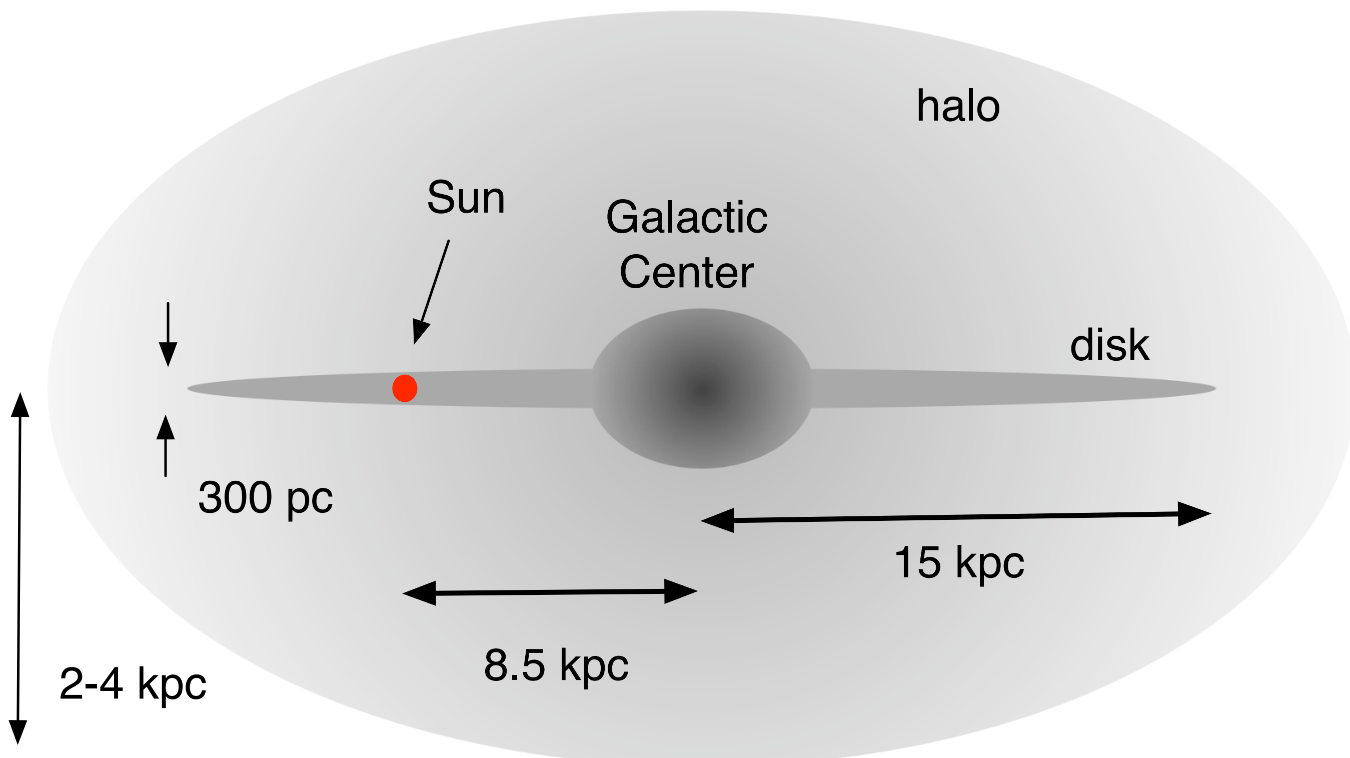
Corresponds to dN/dE ~ E^{-2}

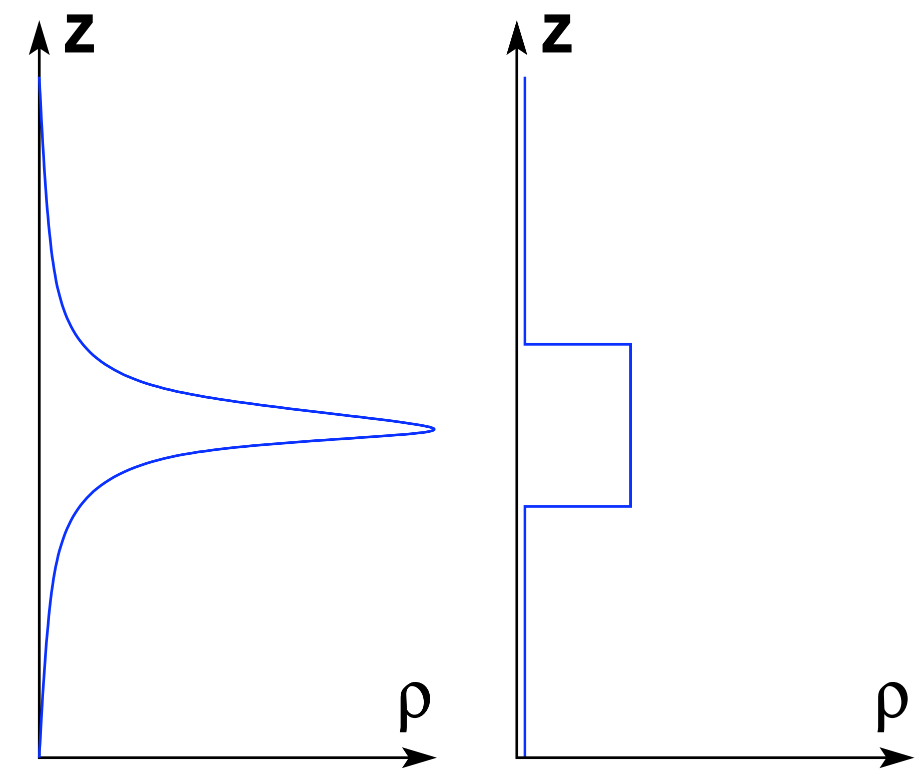
Propagation of cosmic rays in the Galaxy



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: ~$E^{-2.7}$

Has to be energy-dependent!

Theory: ~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

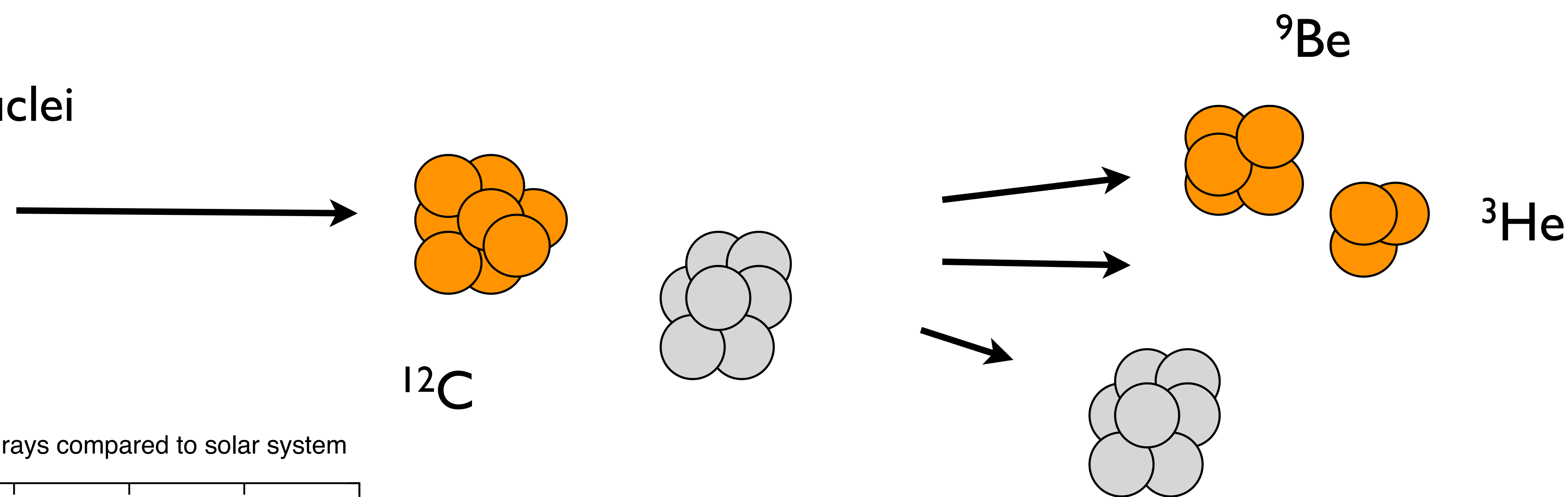
$$N(E) = \tau_{\rm esc}\, Q(E)$$

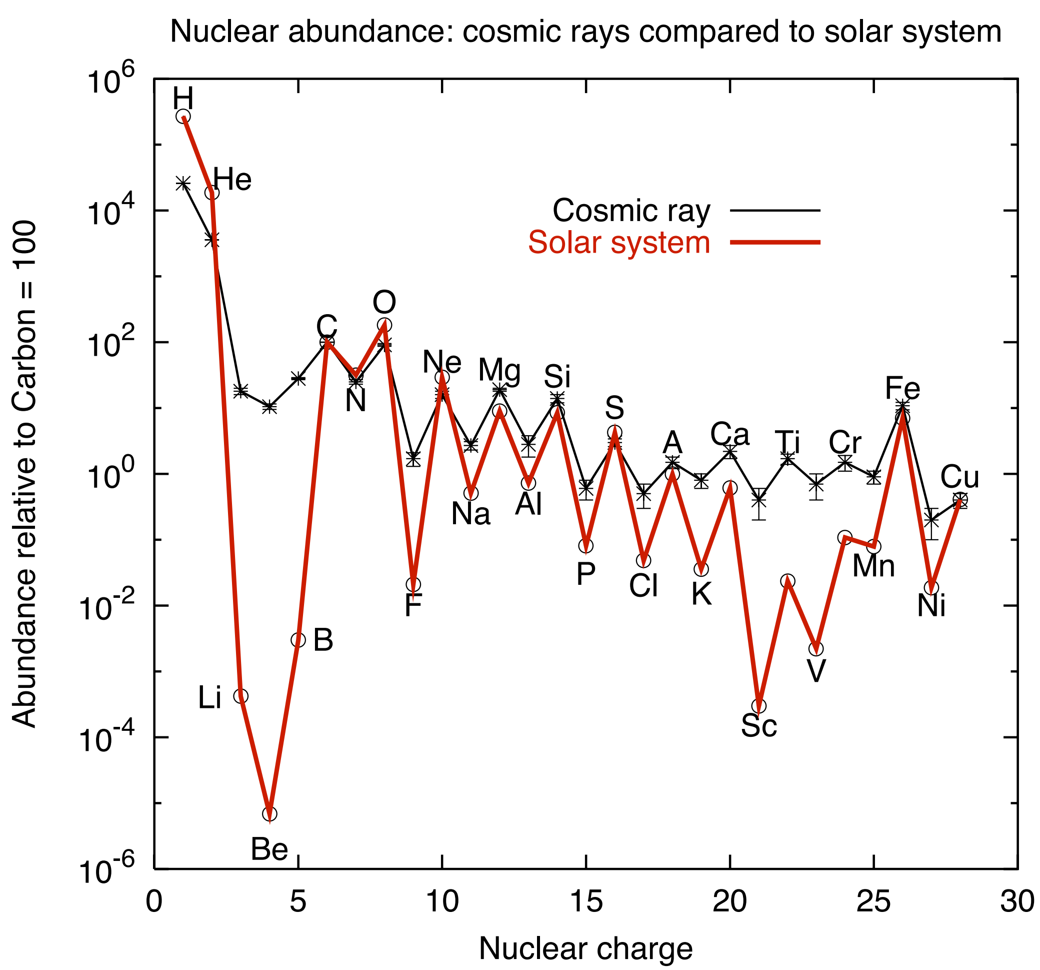
With τ_{esc} ~ 10^7 yr: enhancement of cosmic ray density by **10^3 - 10^4** relative to free streaming

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

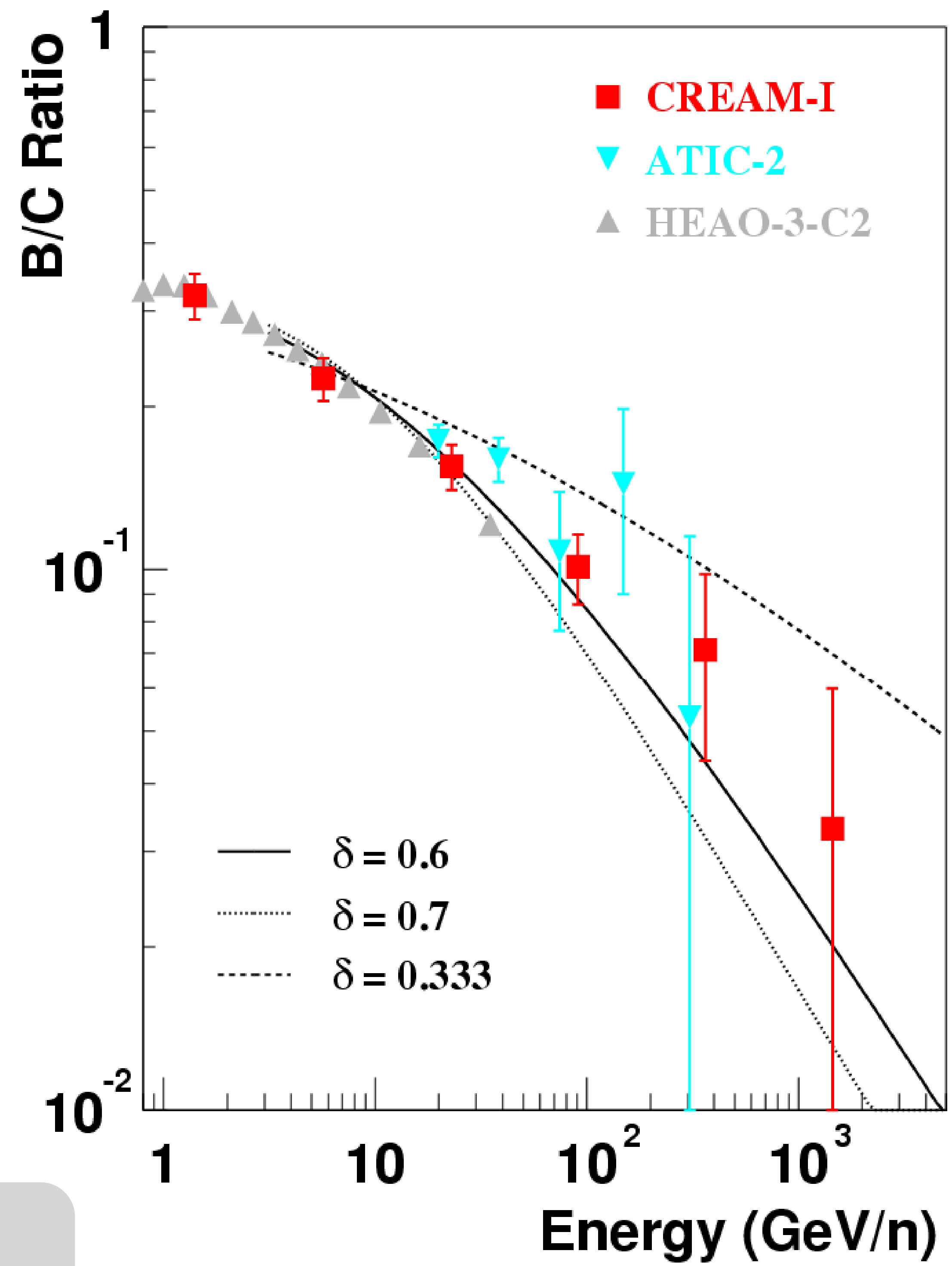
Ratio of secondary to primary elements

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

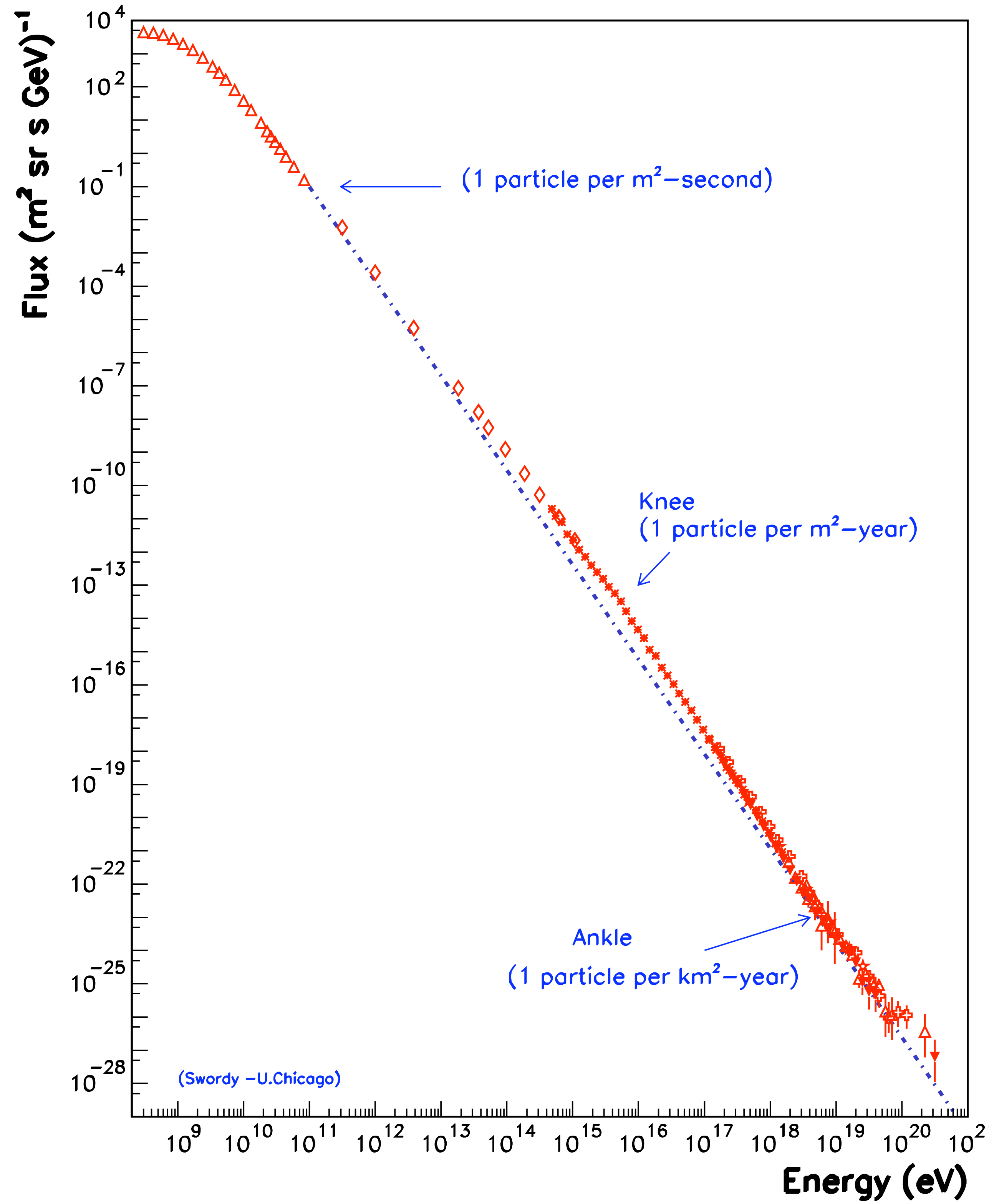
Summary (I)

Theory of galactic cosmic rays

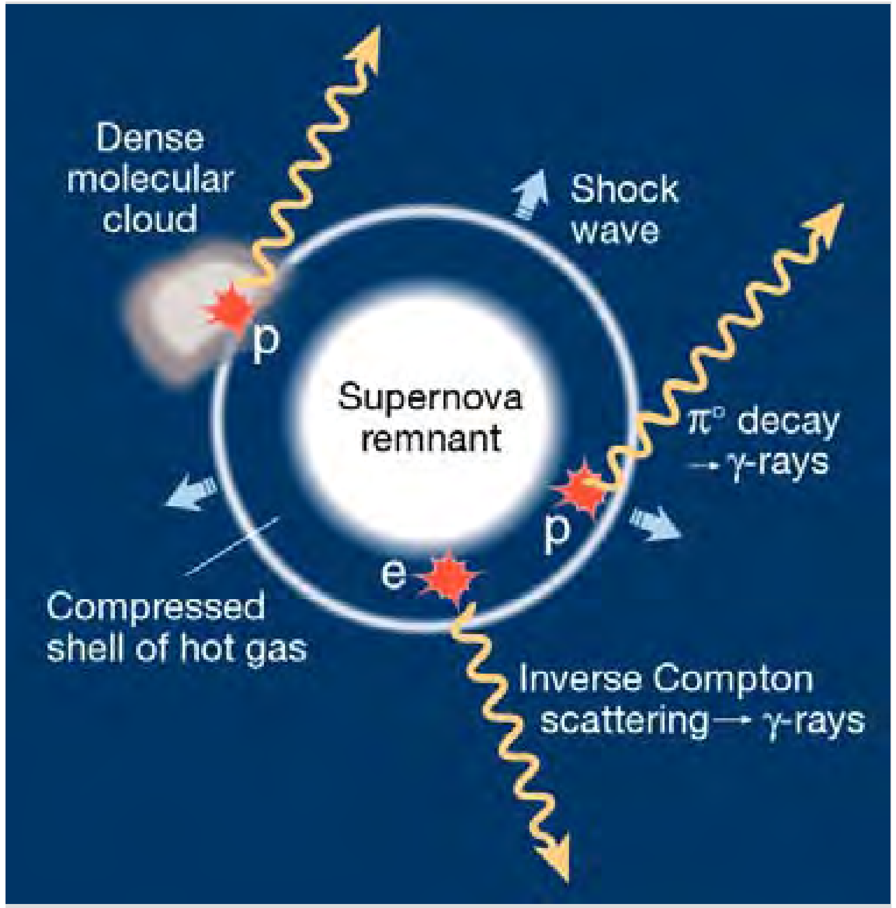
- solar modulation
- geomagnetic cutoff
- SNR most likely sources
- injected flux follows approx. power law
- elemental abundance similar to local matter
- diffusion in gal. magnetic fields
- ratio of secondary to primary elements
- lifetime of cosmic rays

Open questions

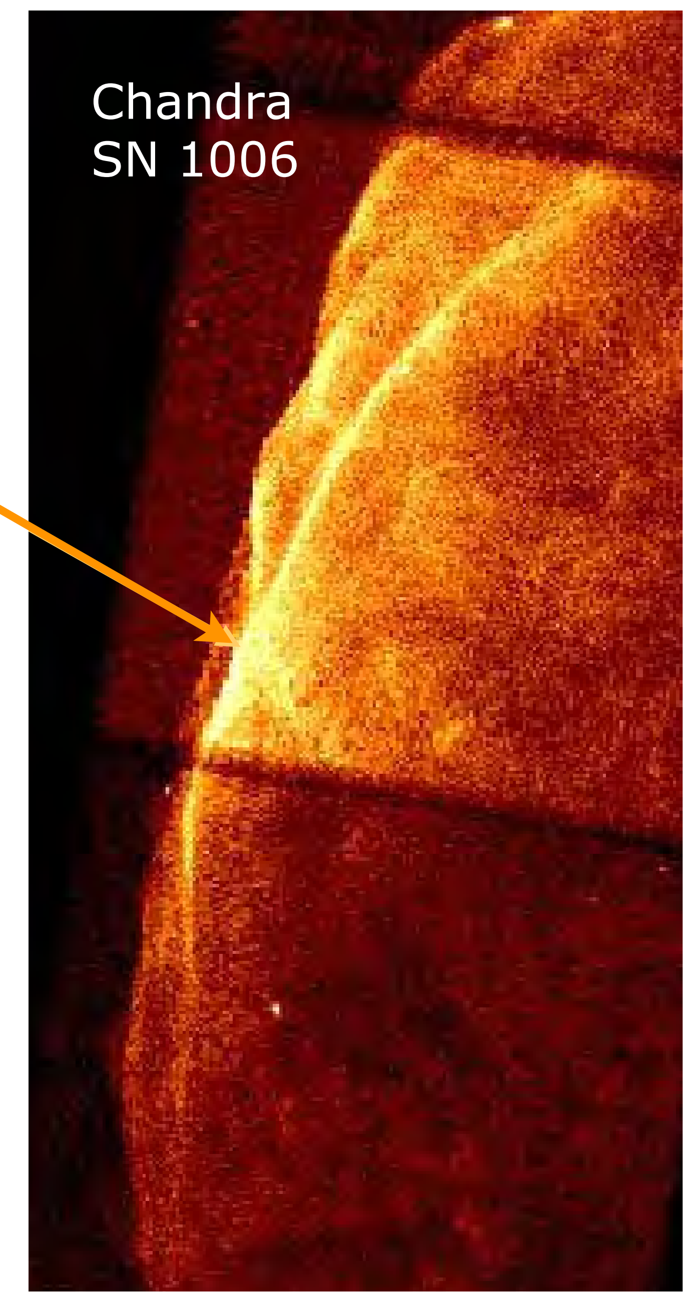
- confirmation of SNR as sources
- maximum energy of galactic sources
- origin of the knee
- origin of the ankle
- transition from galactic to extragalactic cosmic rays
- isotropy vs. anisotropy of arrival directions
- extragalactic sources



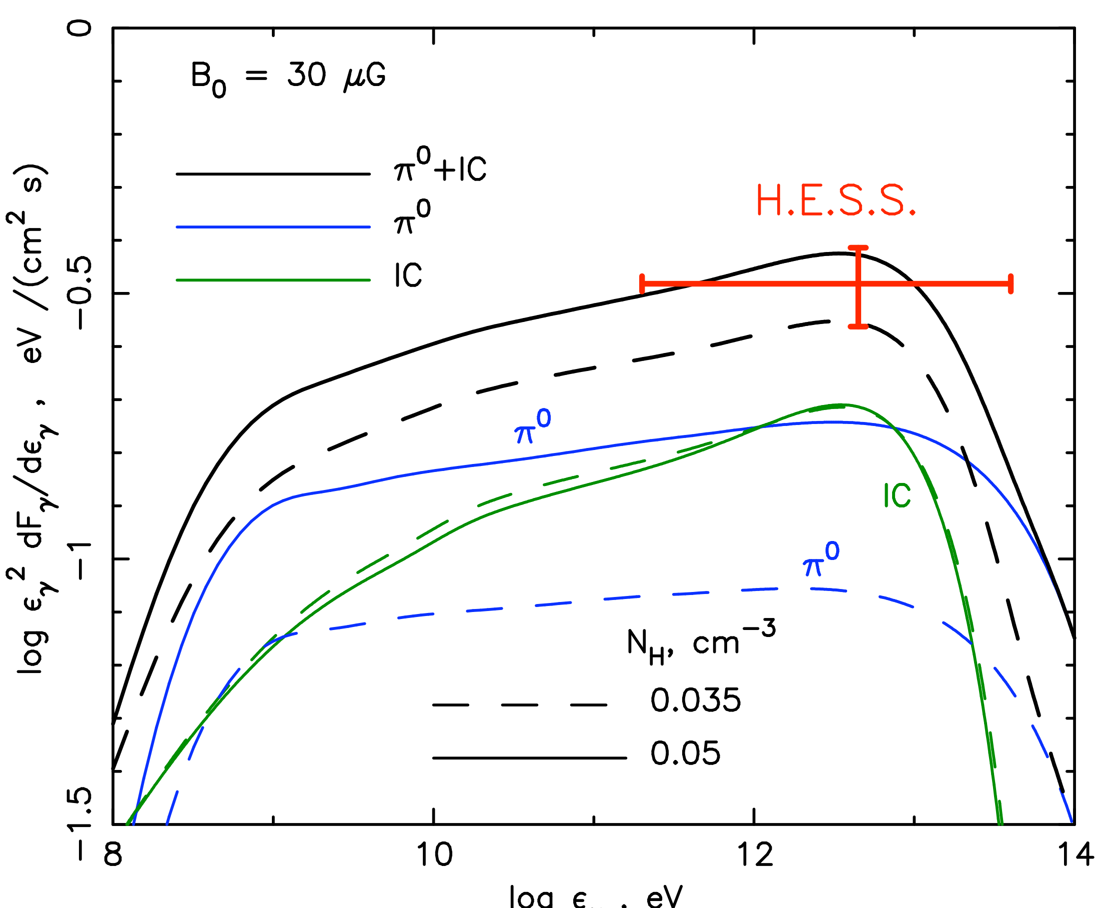
Verification with multi-messenger data



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



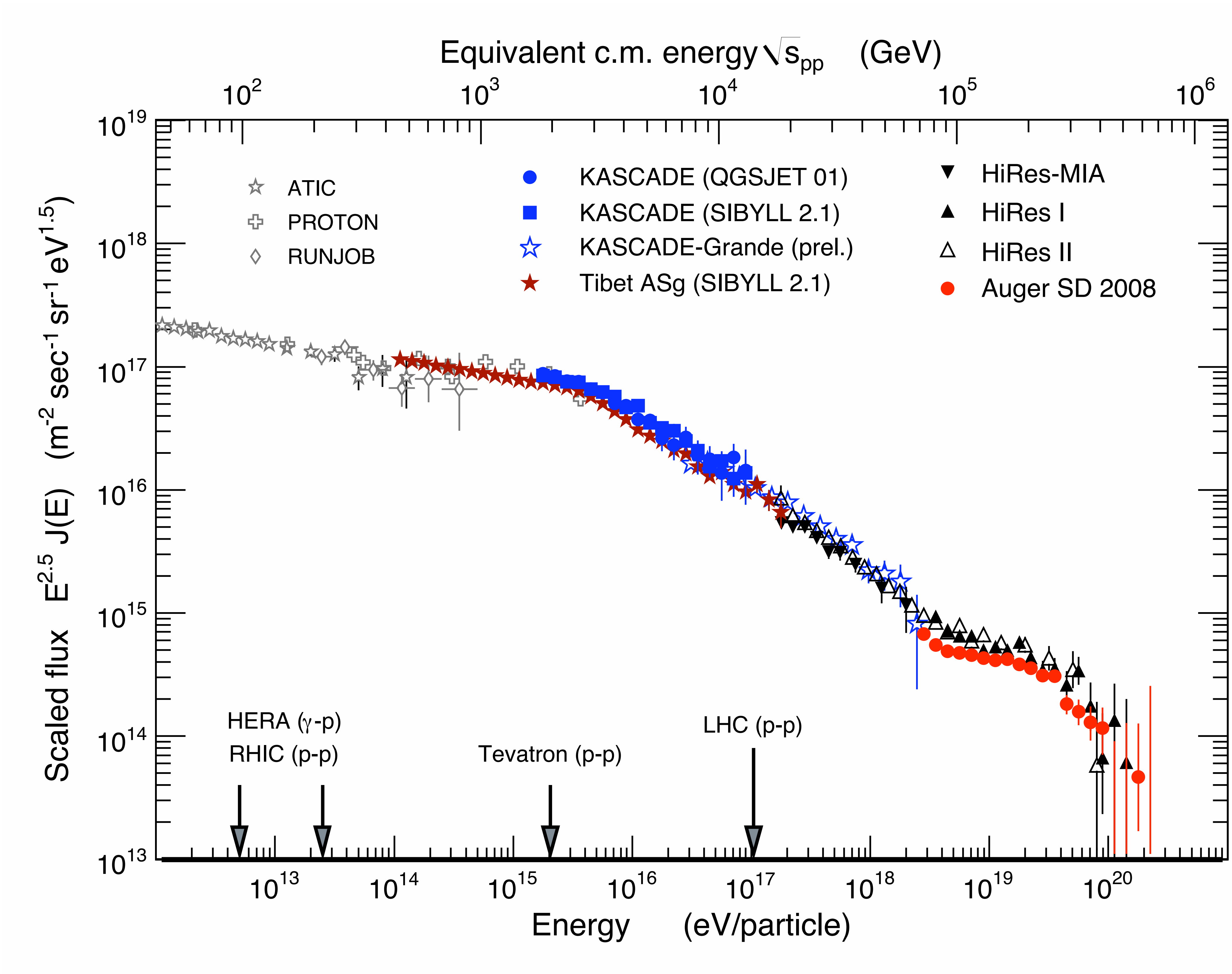
Filaments with high mag. field (100 μG): indirect proof of hadronic particles?



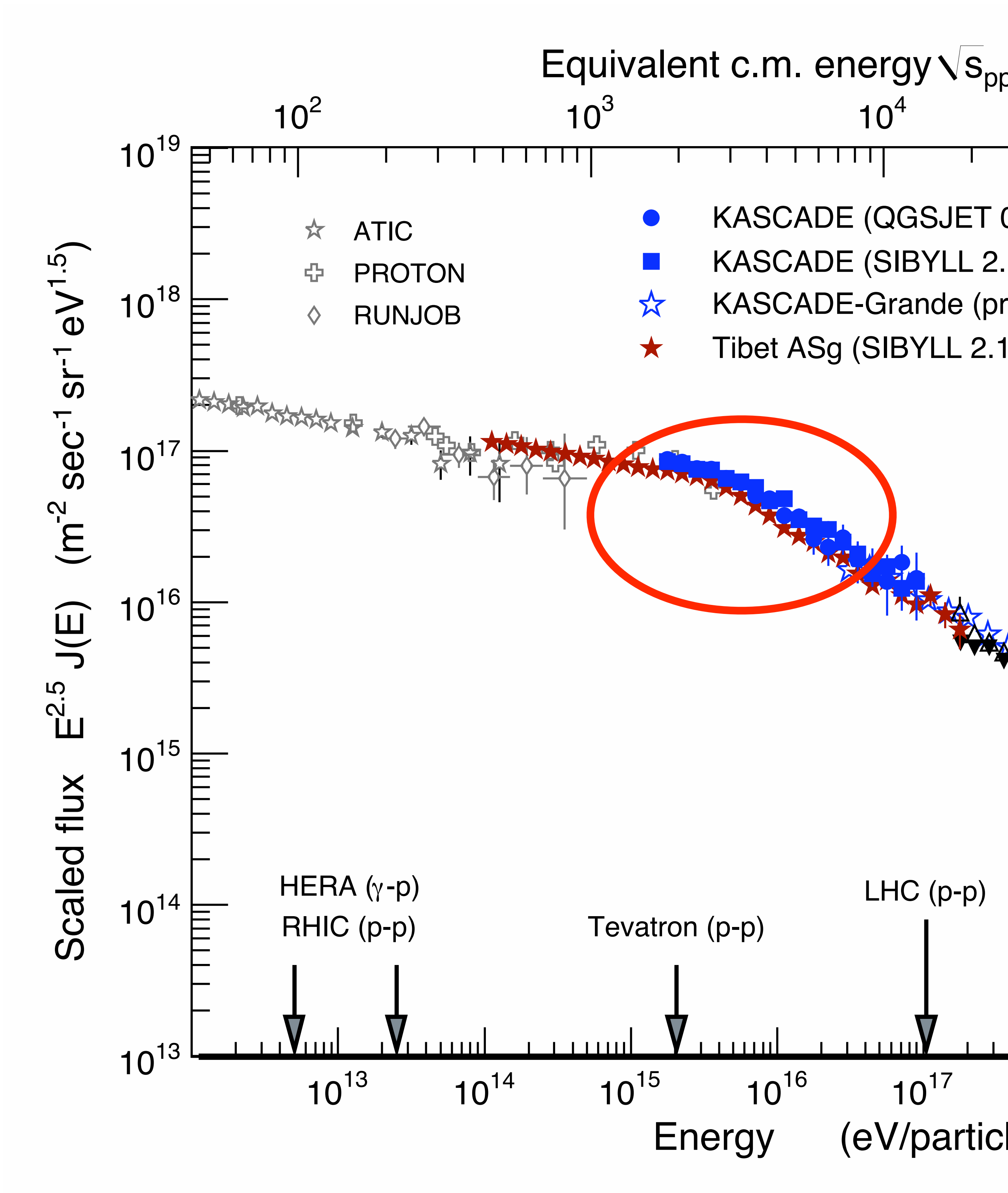
IC contribution
derived from X-ray data

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

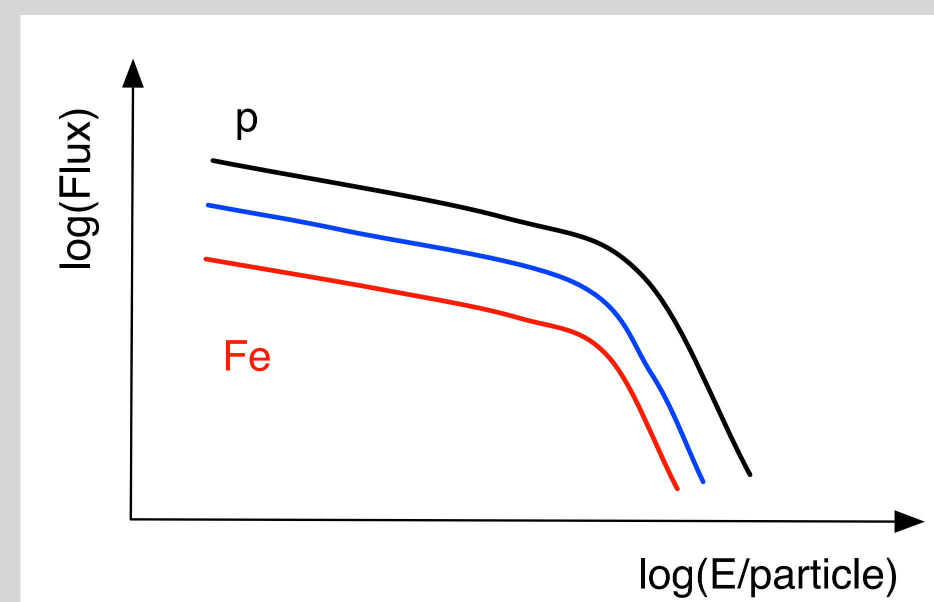
Origin of the knee and the ankle



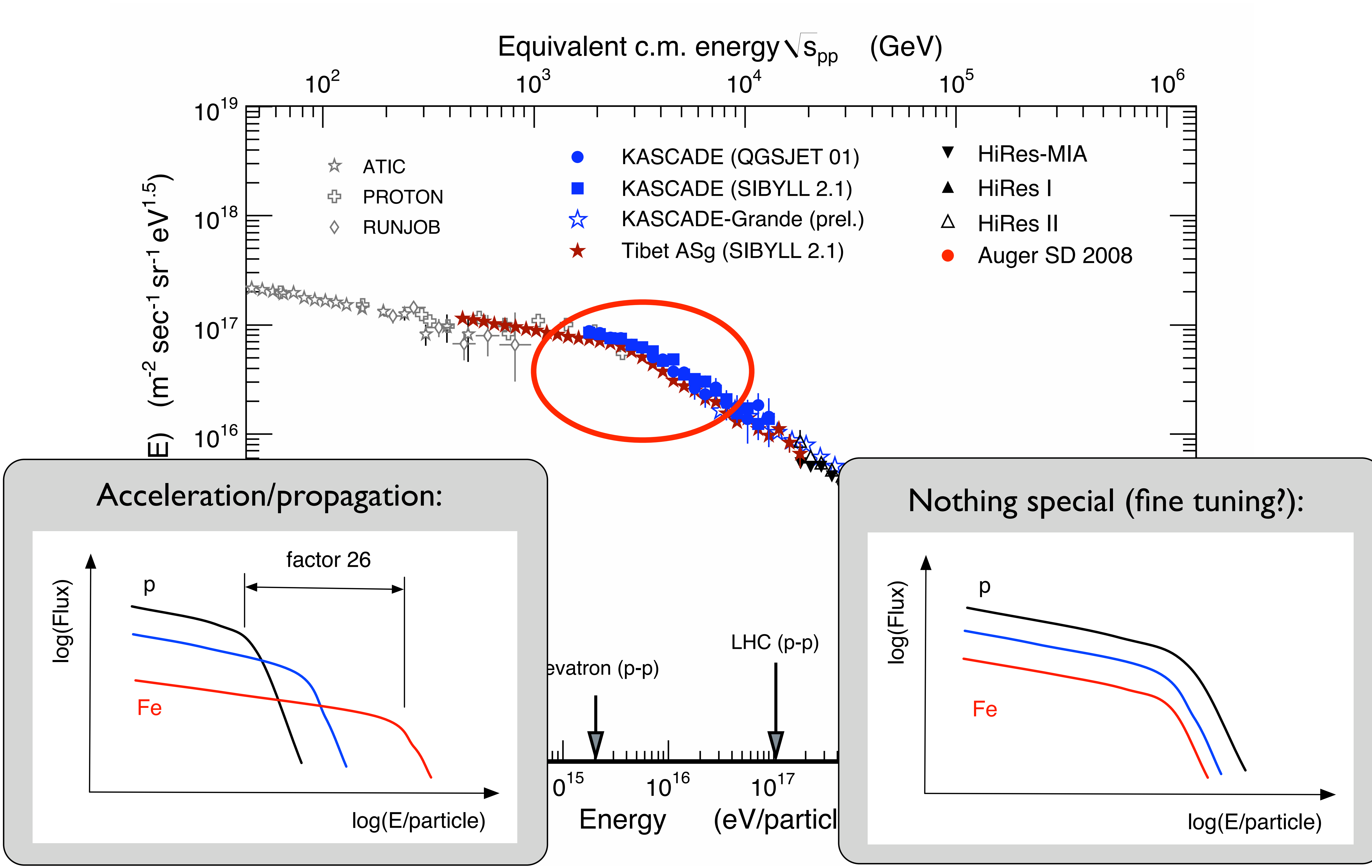
Origin of the knee and the ankle



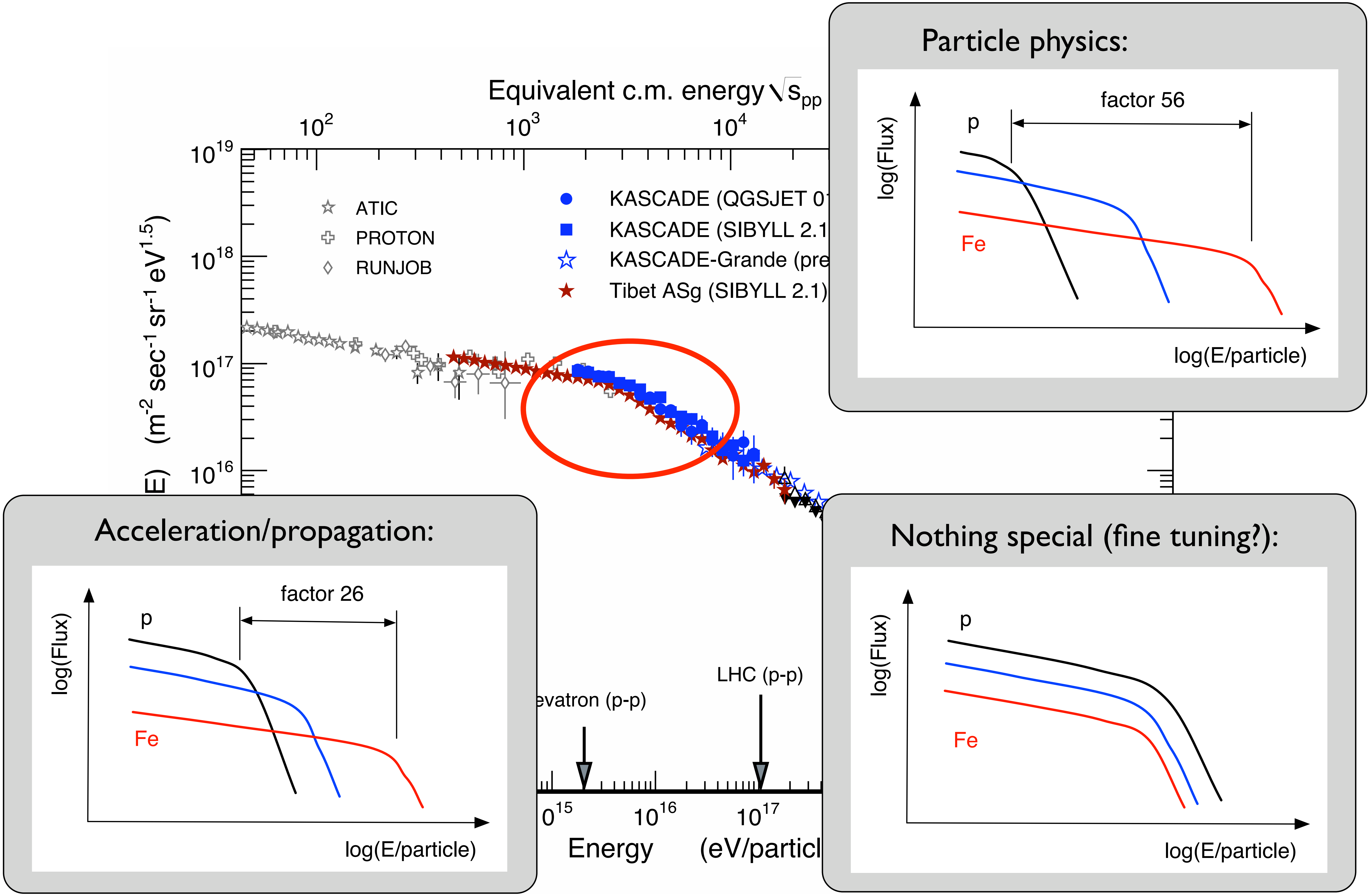
Nothing special (fine tuning?):



Origin of the knee and the ankle



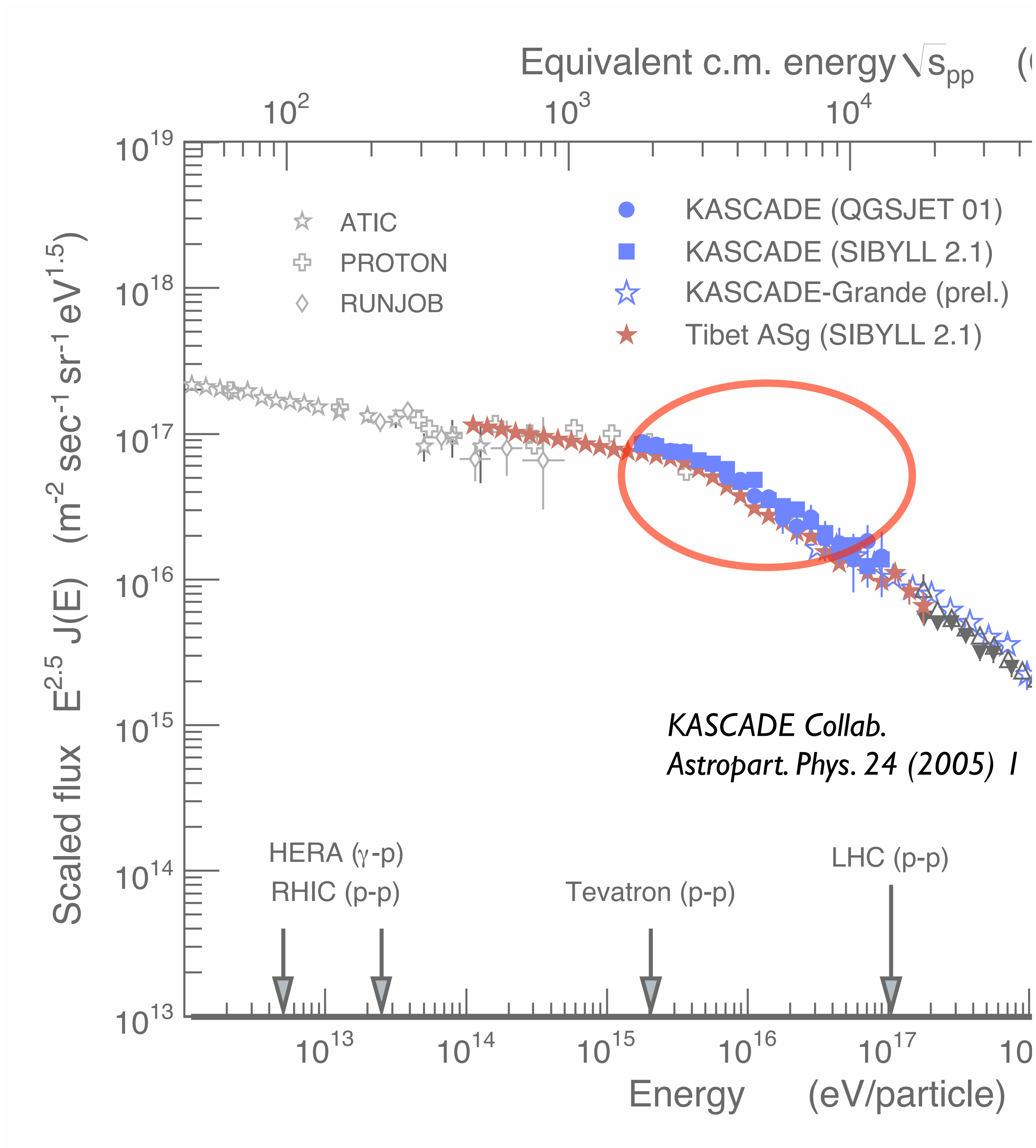
Origin of the knee

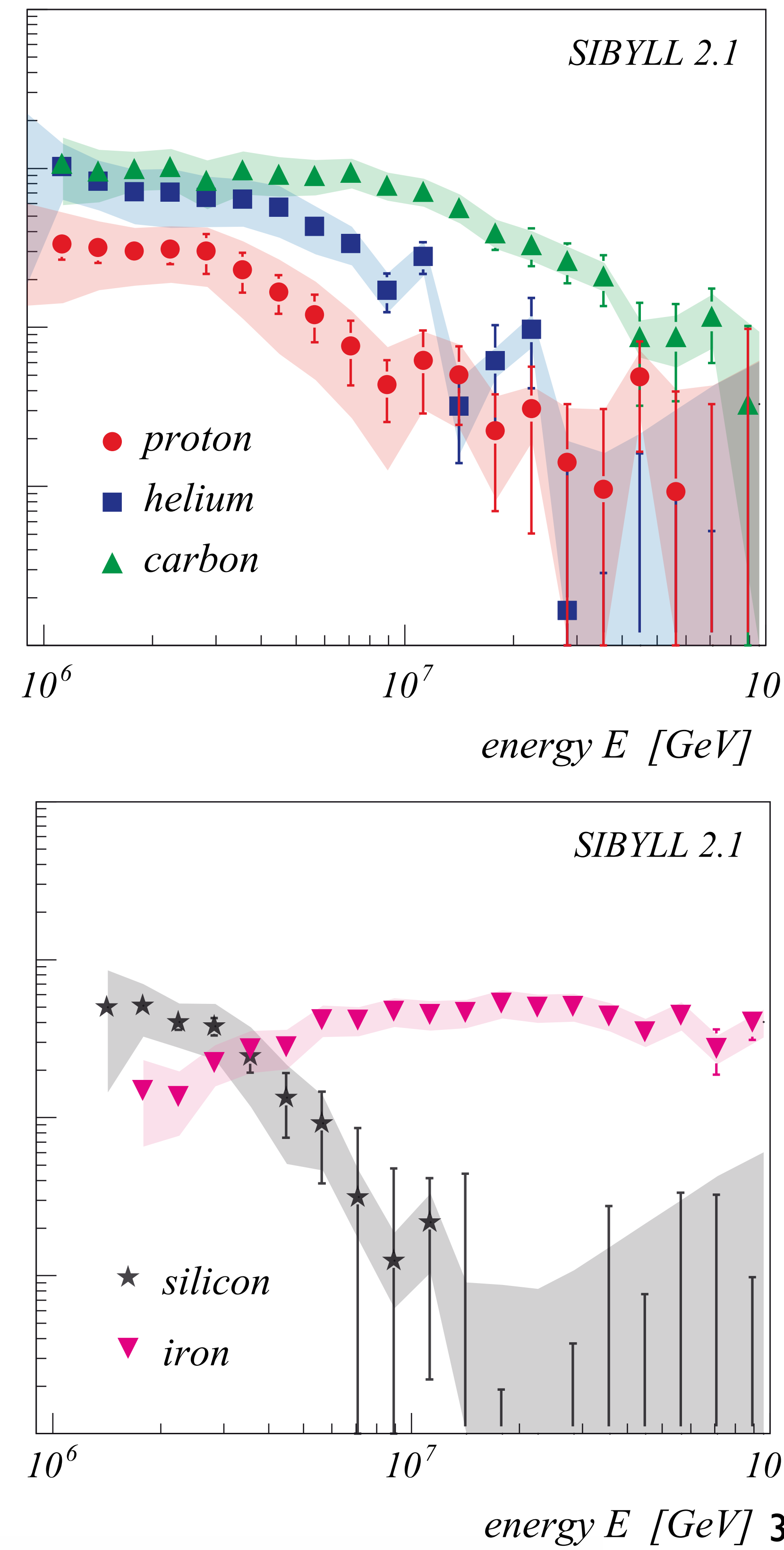


KASCADE

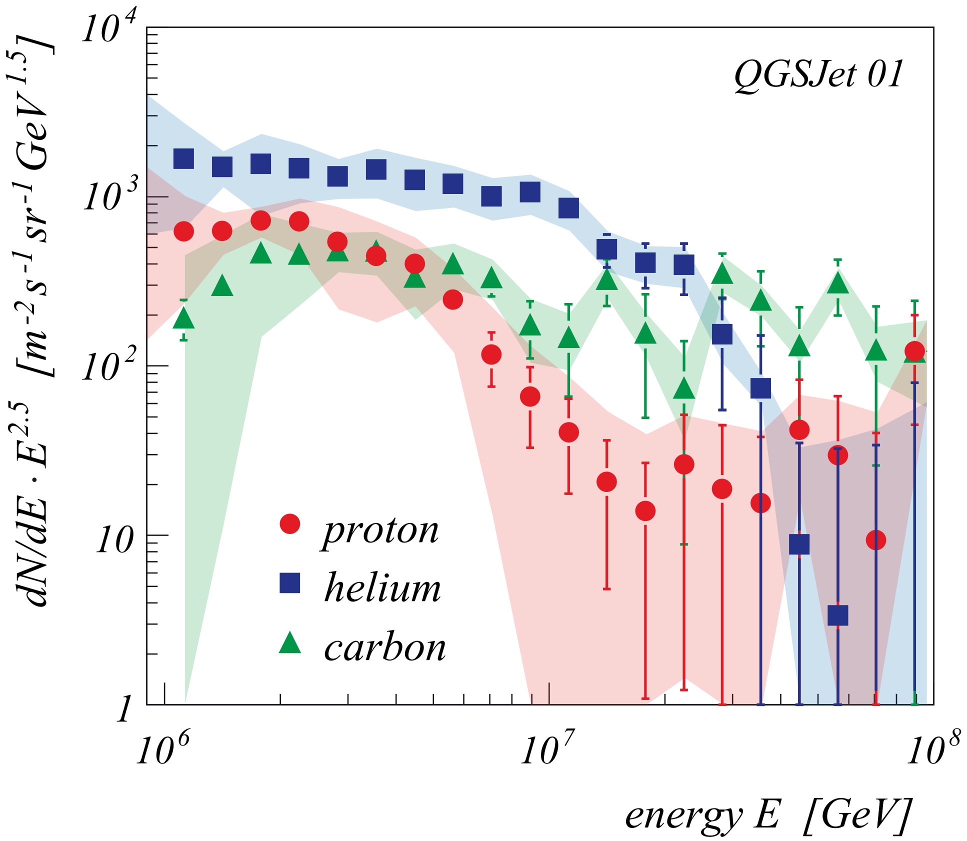
Area ~ 0.04 km^2,
252 surface detectors

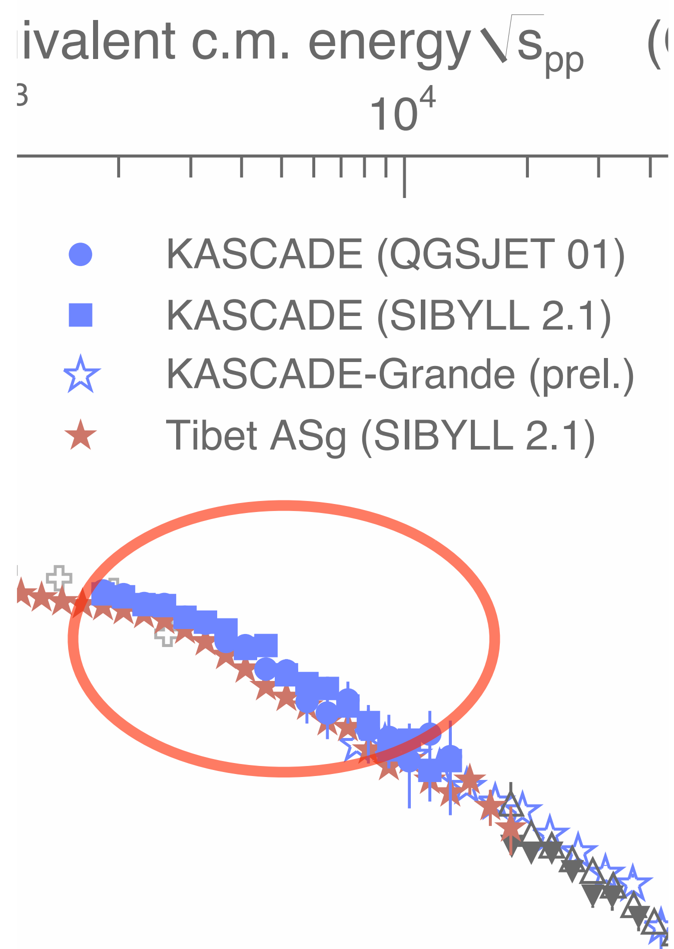
Composition in Knee region (i)



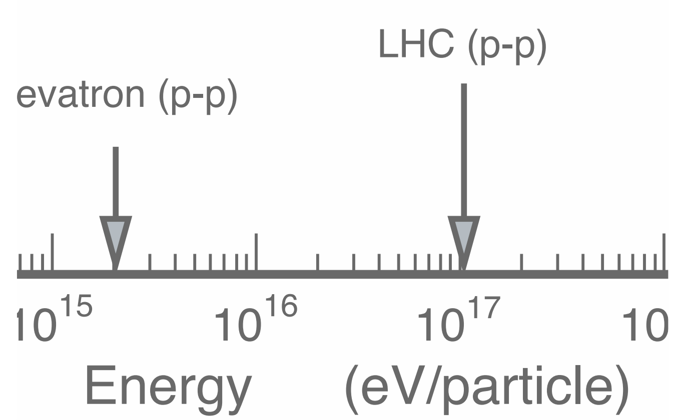


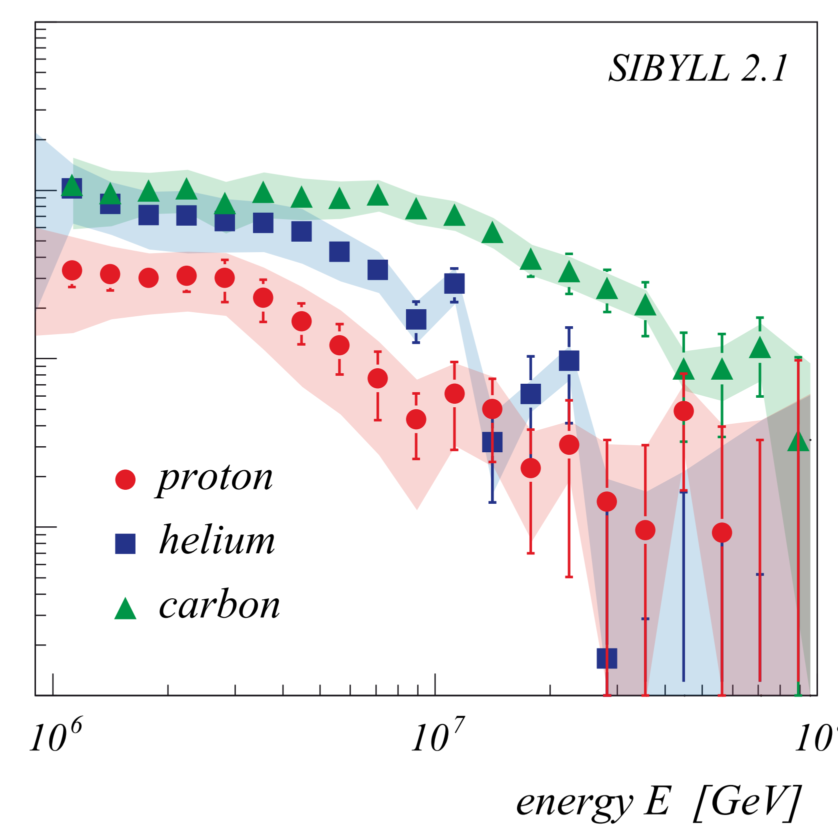
Composition in Knee region (ii)

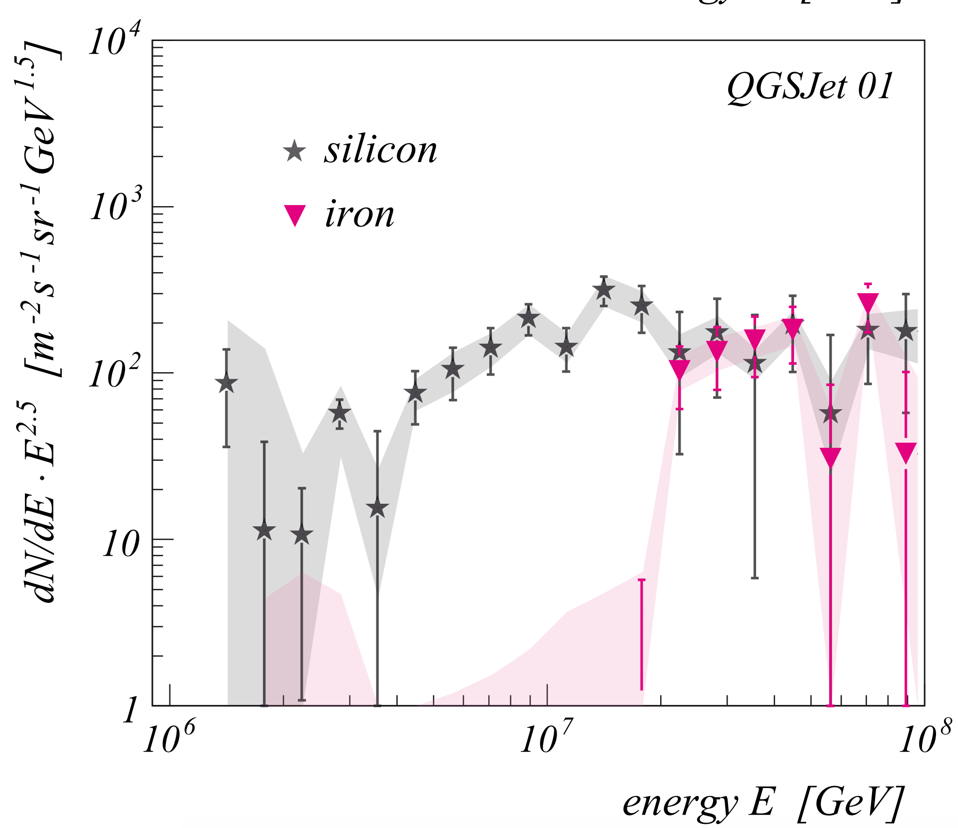


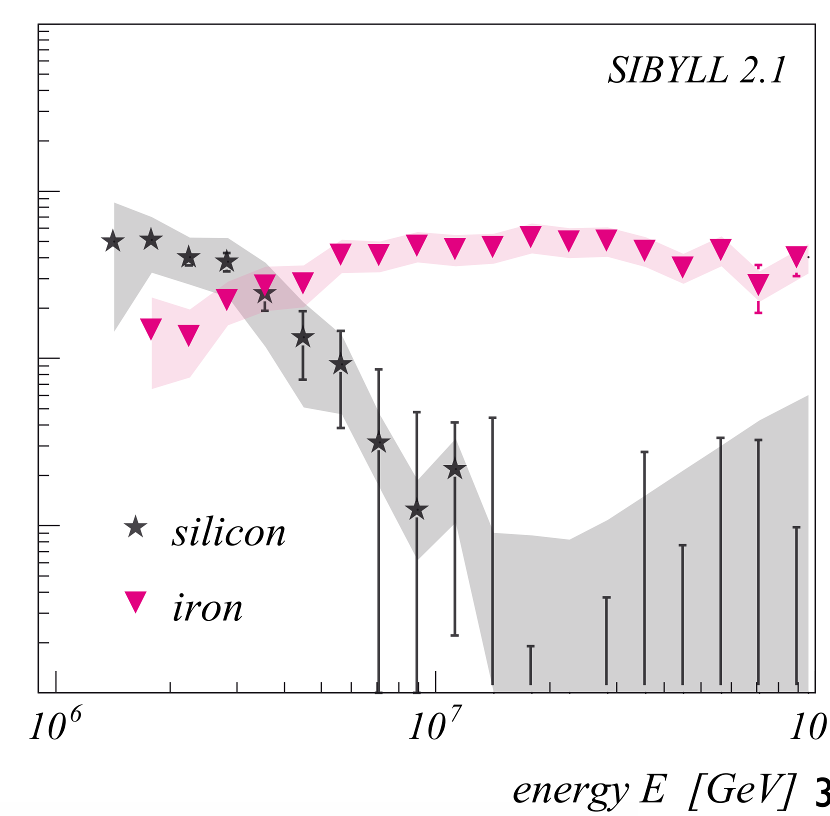


KASCADE Collab.
Astropart. Phys. 24 (2005) 1

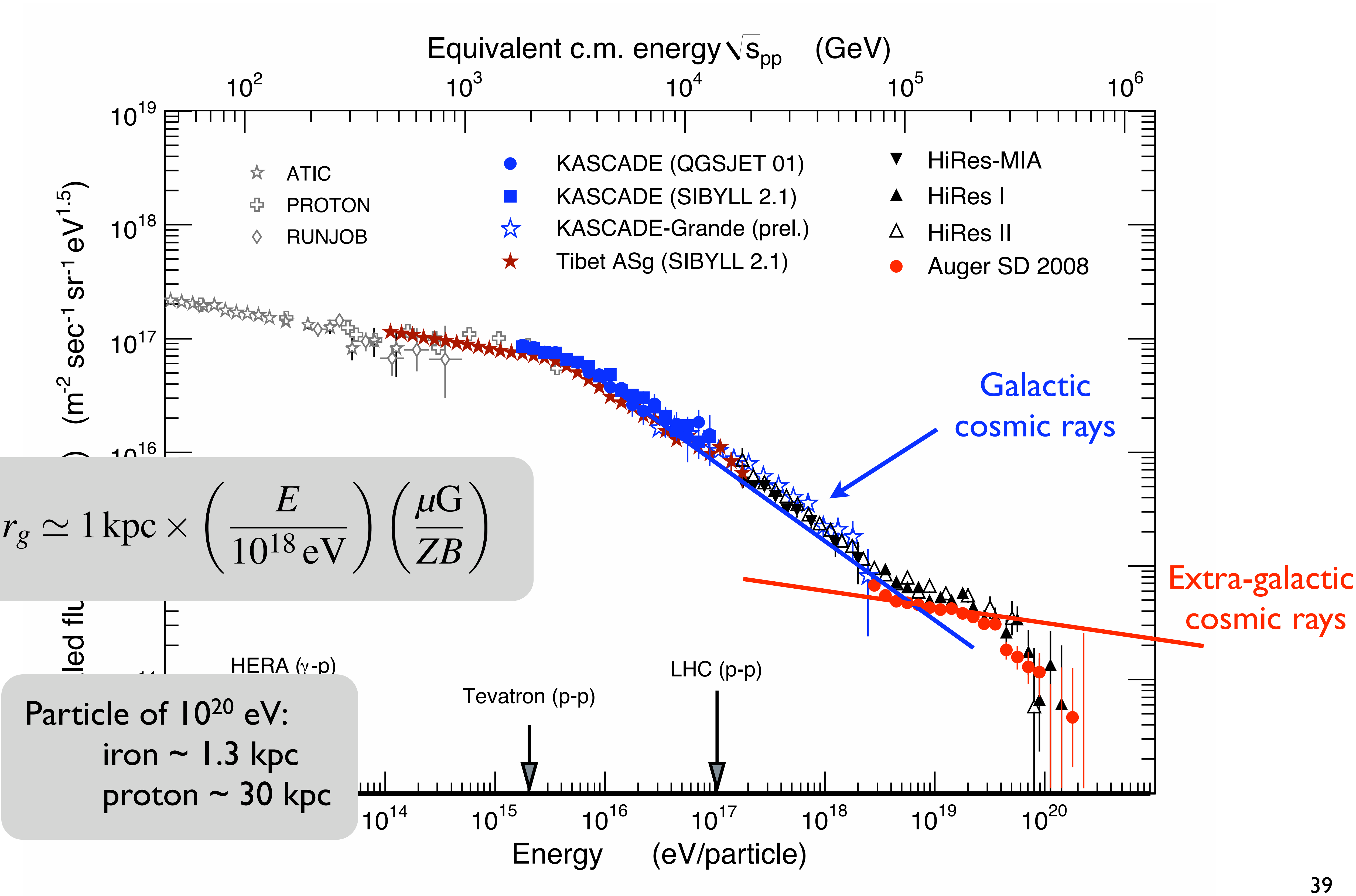








Origin of the ankle: transition model

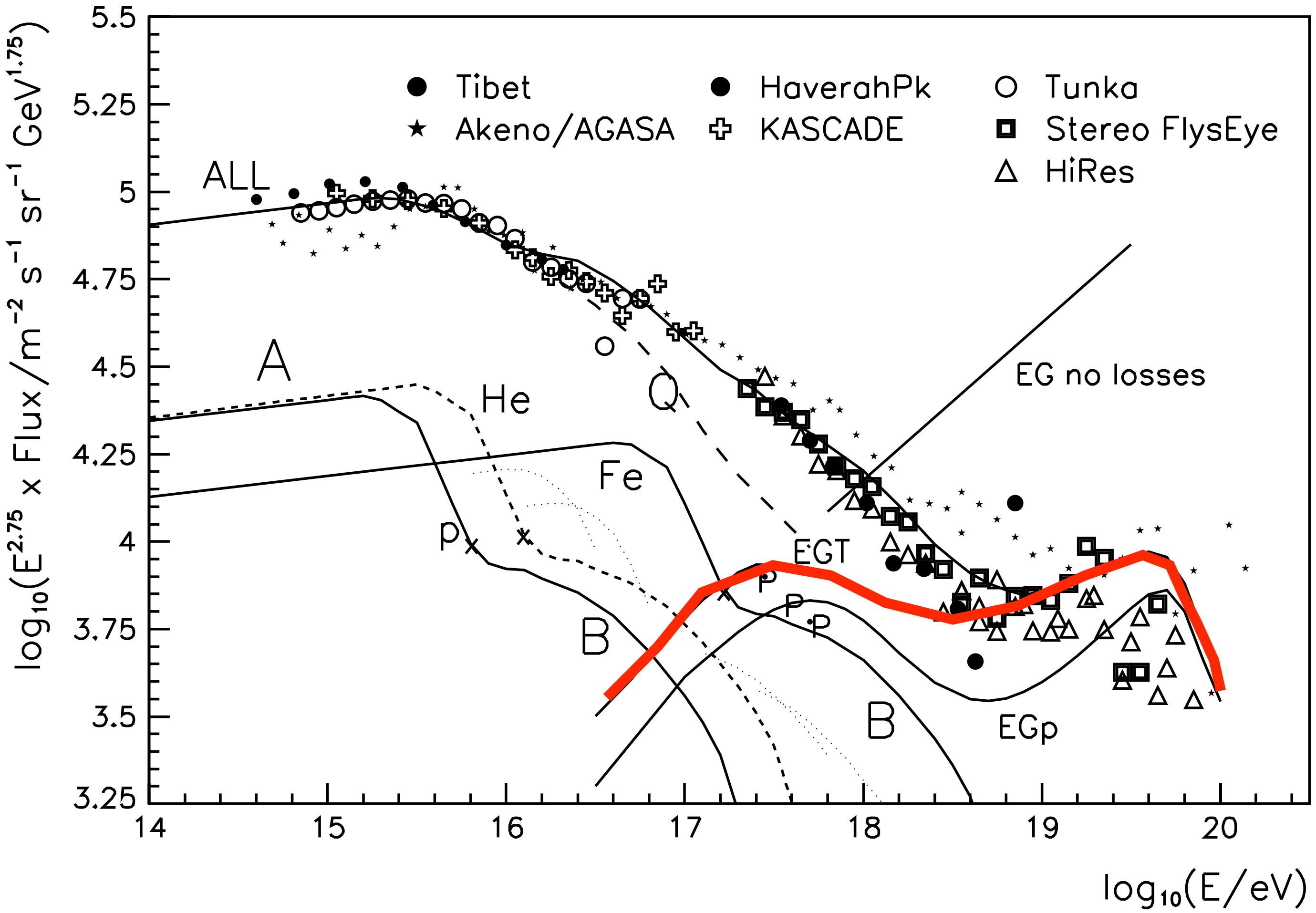


$$r_g \simeq 1\,\mathrm{kpc} \times \left(\frac{E}{10^{18}\,\mathrm{eV}}\right)\left(\frac{\mu\mathrm{G}}{ZB}\right)$$

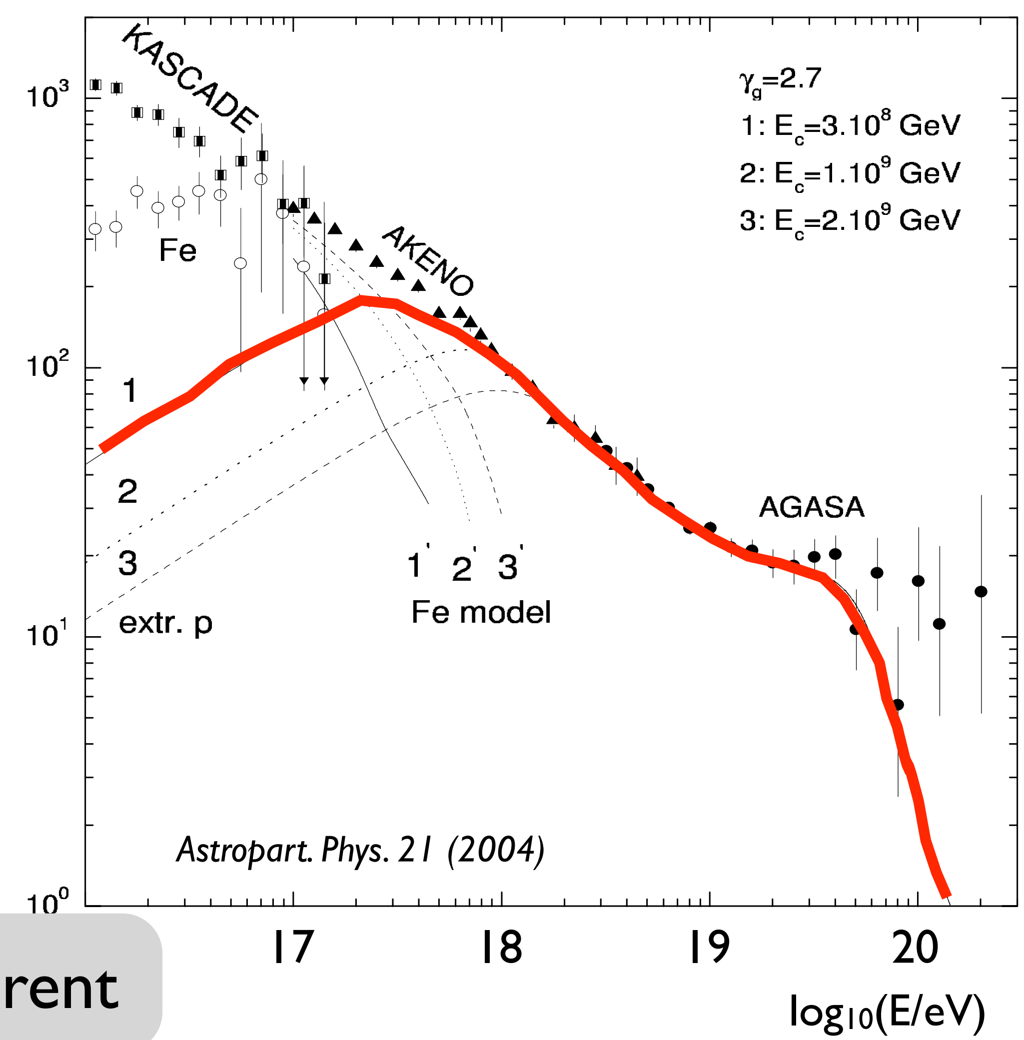
Particle of 10^{20} eV:
iron ~ 1.3 kpc
proton ~ 30 kpc

Origin of the ankle: pair production (dip) model

J. Phys. G31 (2005)



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



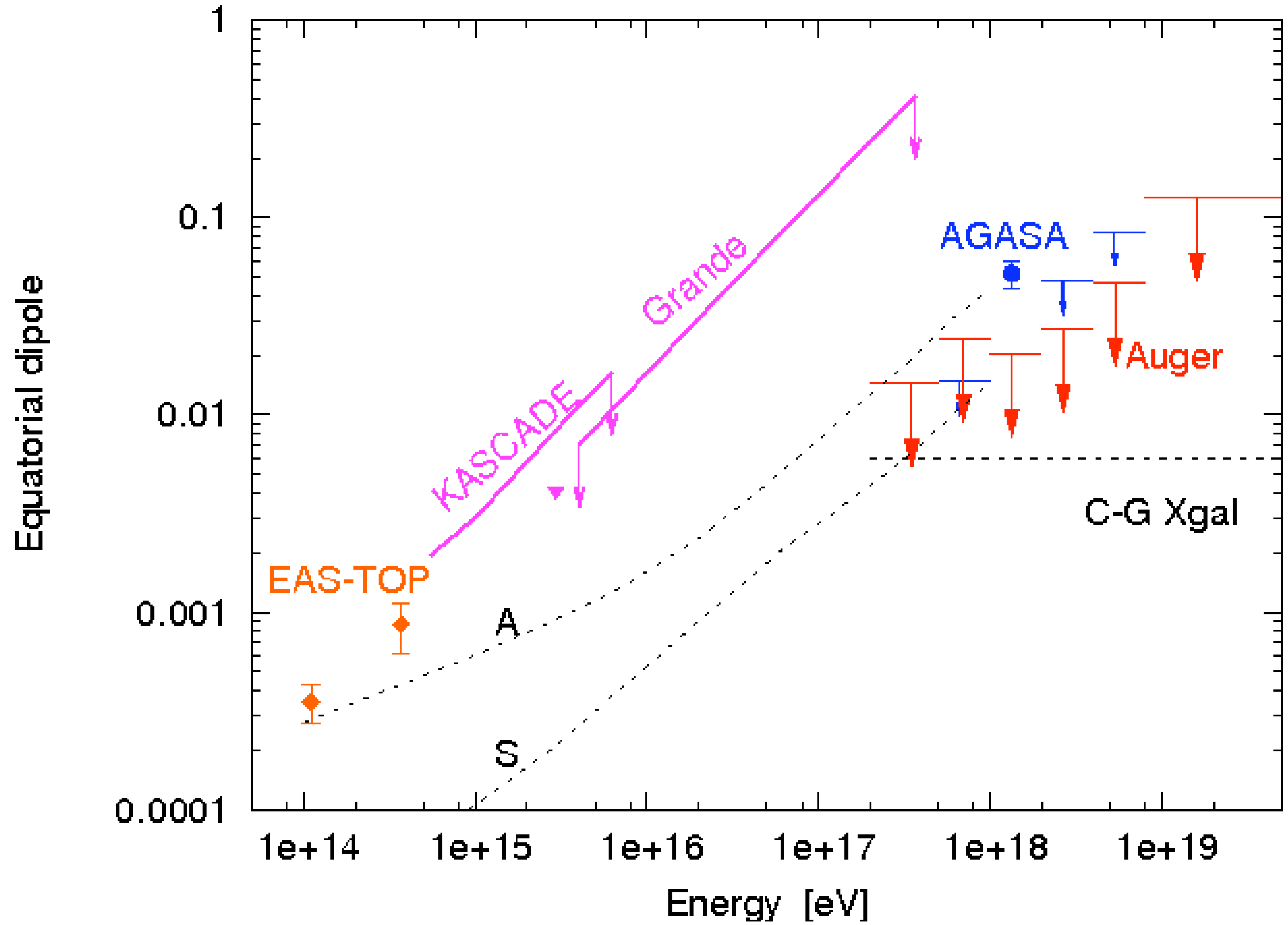
Hillas, Wibig & Wolfendale et al.:
- Ankle is transition galactic to extragalactic cosmic rays
- Injection spectrum ***dN/dE ~ E$^{-2.3}$***

Flux very similar, composition & anisotropy different

Arrival direction distribution of cosmic rays

A Galactic sources reach energies of 10^{19} eV
- only heavy elements confined to galaxy
- global dipole anisotropy
- source regions (light elements)
- no large scale anisotropy found so far

(Auger ICRC 2009)



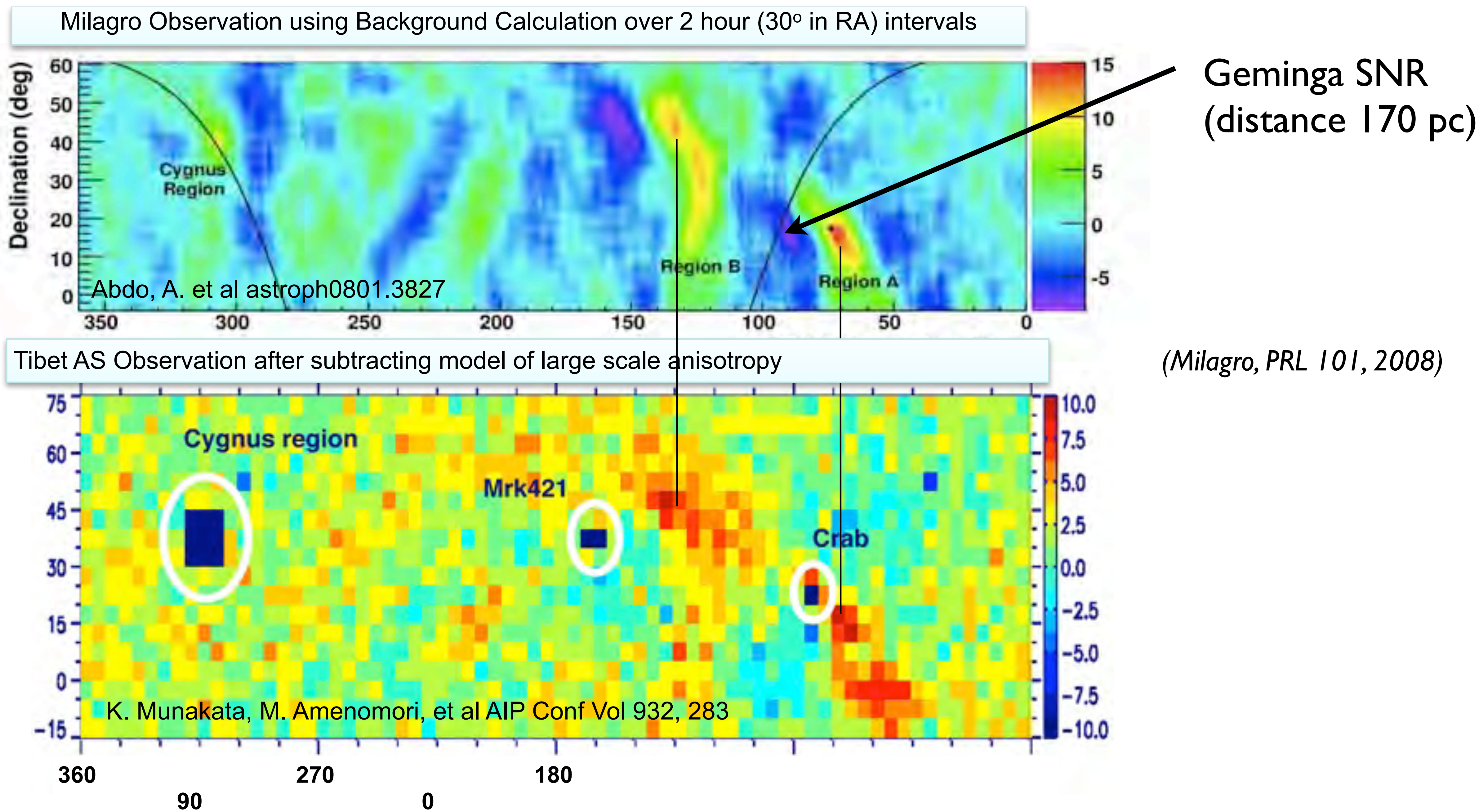
Leaky box model predicts
rapid rise of anisotropy

B Transition to extragalactic sources at lower energy (~10^{17} eV)
- pair-production model
- isotropy ($10^{17} < E < 10^{19.7}$ eV)
- composition 80% protons
- in contradiction to composition data from Auger

New puzzle at low energy –

Signatures of a local source?

Anisotropy at "too low" an energy

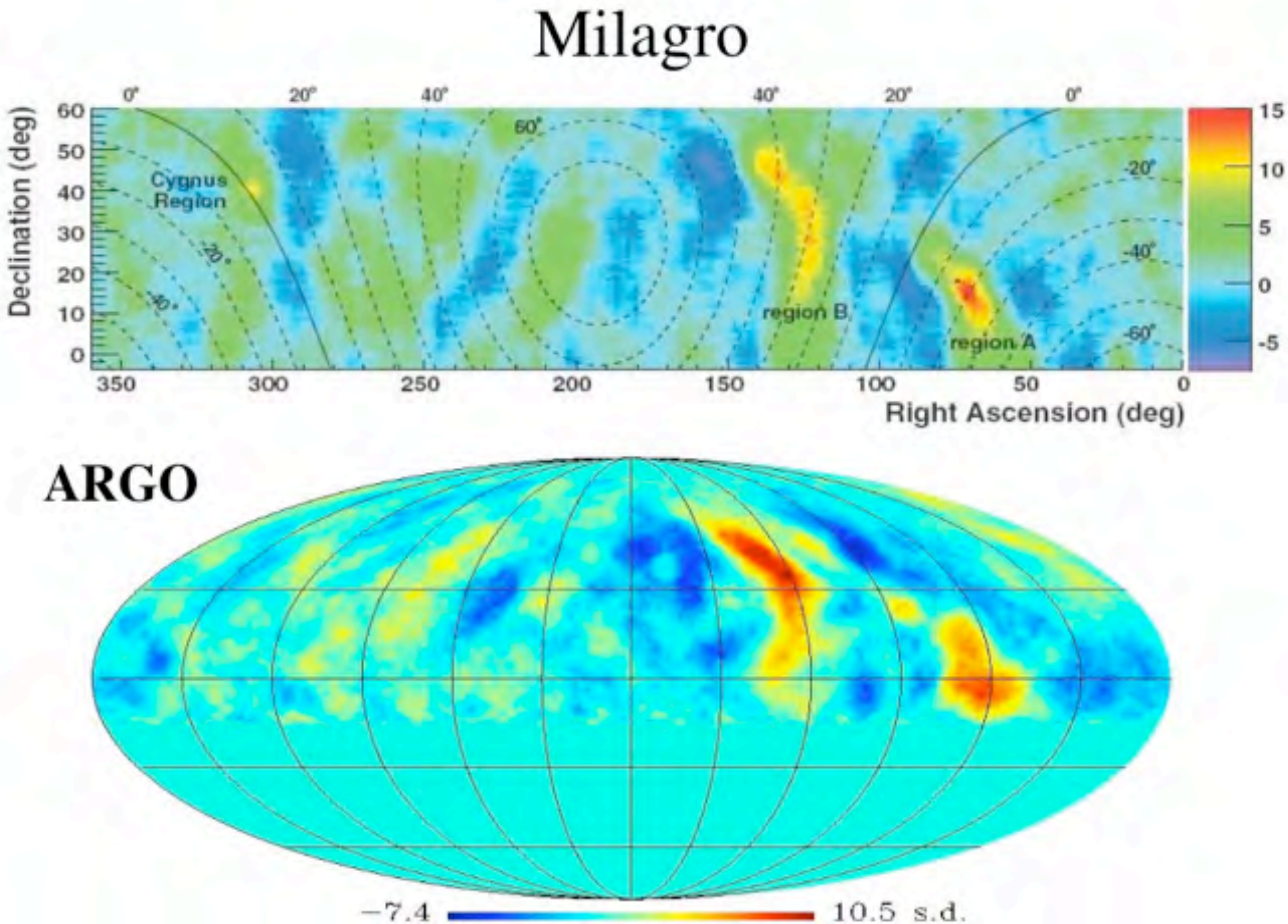


(Milagro, PRL 101, 2008)

Milagro: Relative excess of 4-6 10^{-4}, more than 10 sigma significance
Energy of cosmic rays ~10^{13} eV = 10 TeV (Lamor radius < 10^{-2} pc)

(Goodman, ICRC 2009)

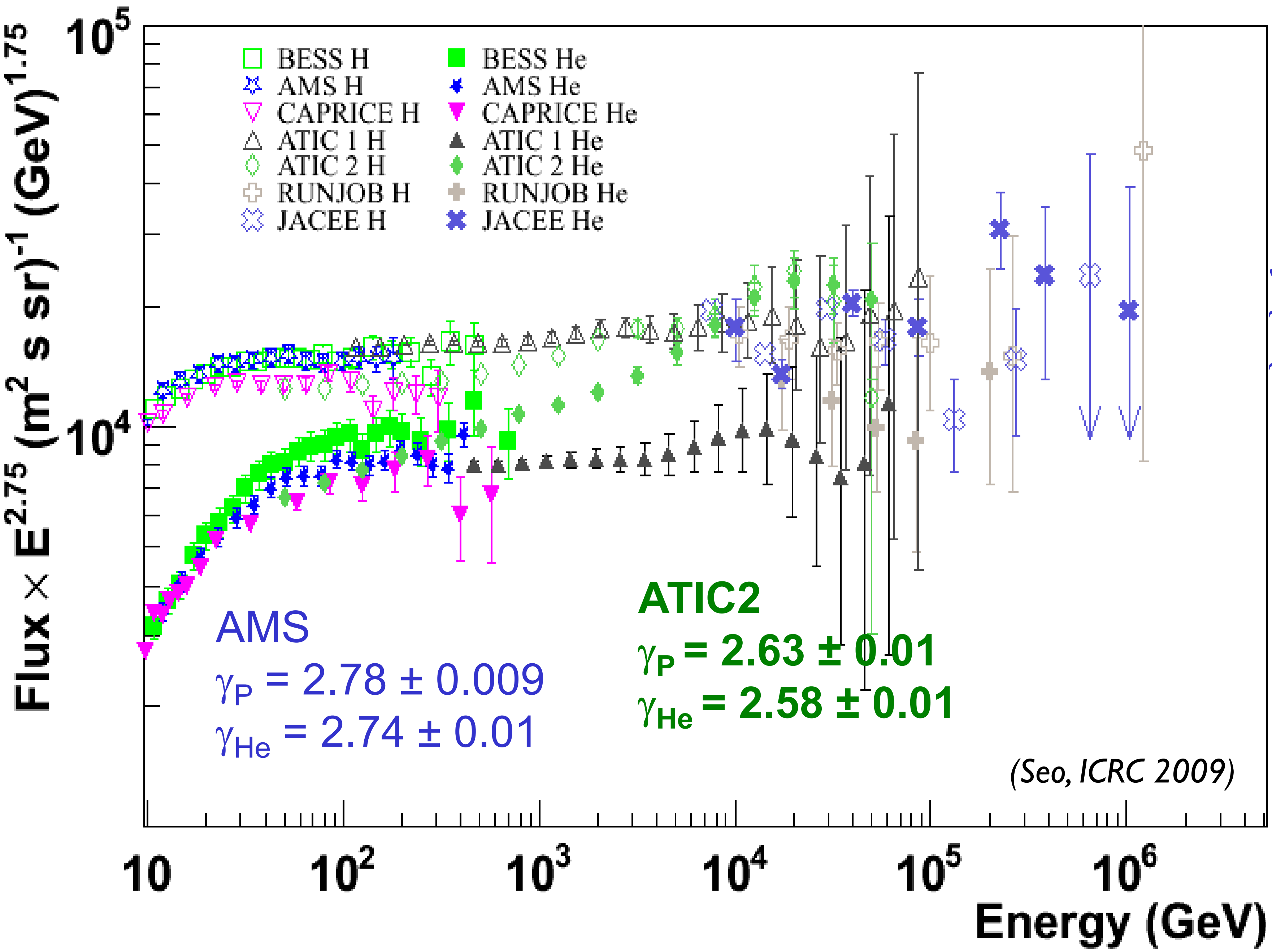
Milagro anisotropy confirmed by several observations



http://people.roma2.infn.it/~aldo/RICAP09_trasp_Web/Vernetto_ARGO_RICAP09ar.pdf

(Goodman, ICRC 2009)

Update of direct flux measurements



$$I_j \propto E^{-\gamma}$$

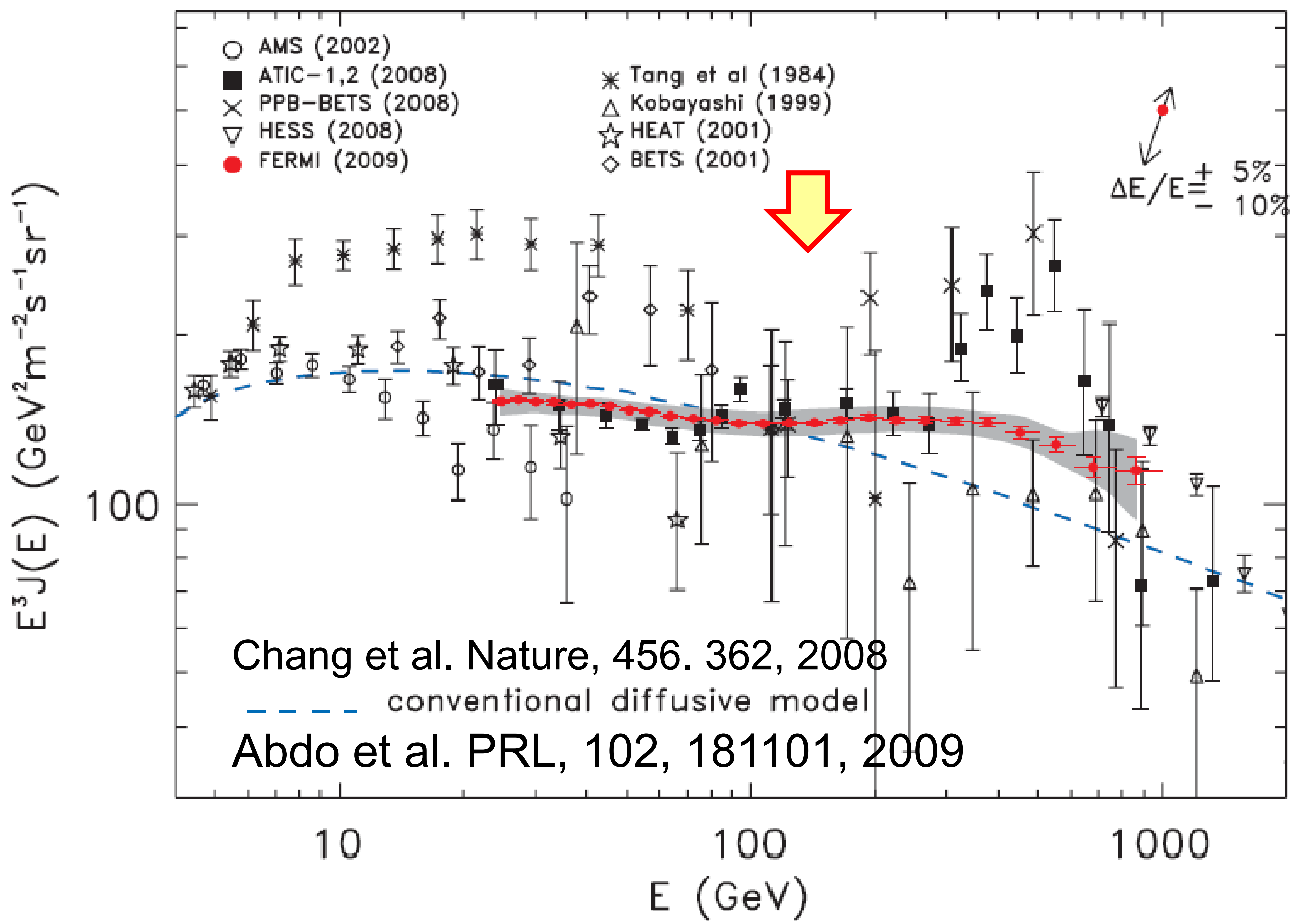
JACEE
$\gamma_P = 2.80 \pm 0.04$
$\gamma_{He} = 2.68{+0.04}{-0.06}$

RUNJOB
$\gamma_P = 2.78 \pm 0.05$
(2.74 ± 0.08)
$\gamma_{He} = 2.81 \pm 0.06$
(2.78 ± 0.2)

New CREAM data confirm ATIC2
Crossing of helium and proton fluxes observed

(Seo et al, ICRC 2009)

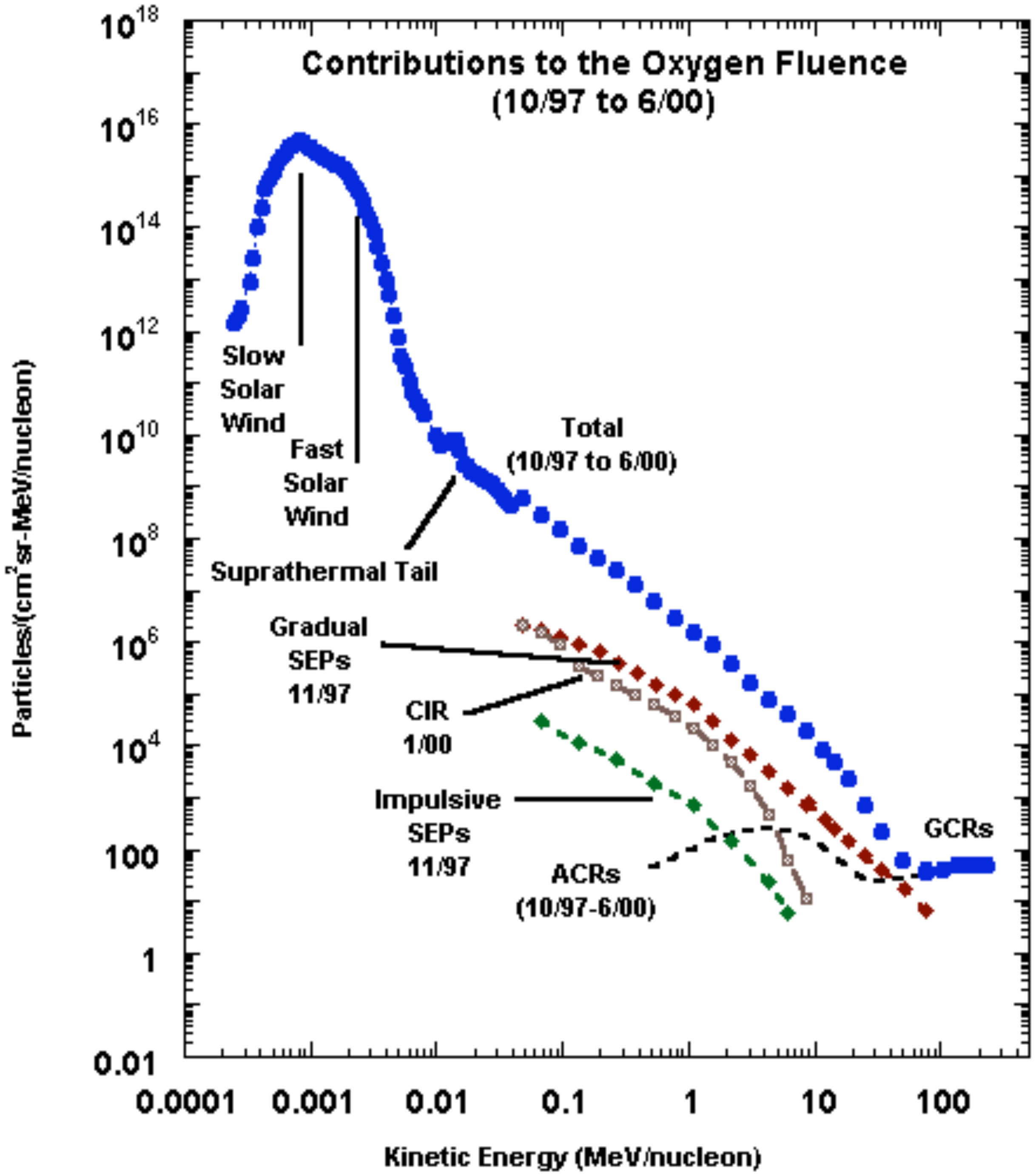
Similar feature in electron spectrum – a coincidence ?

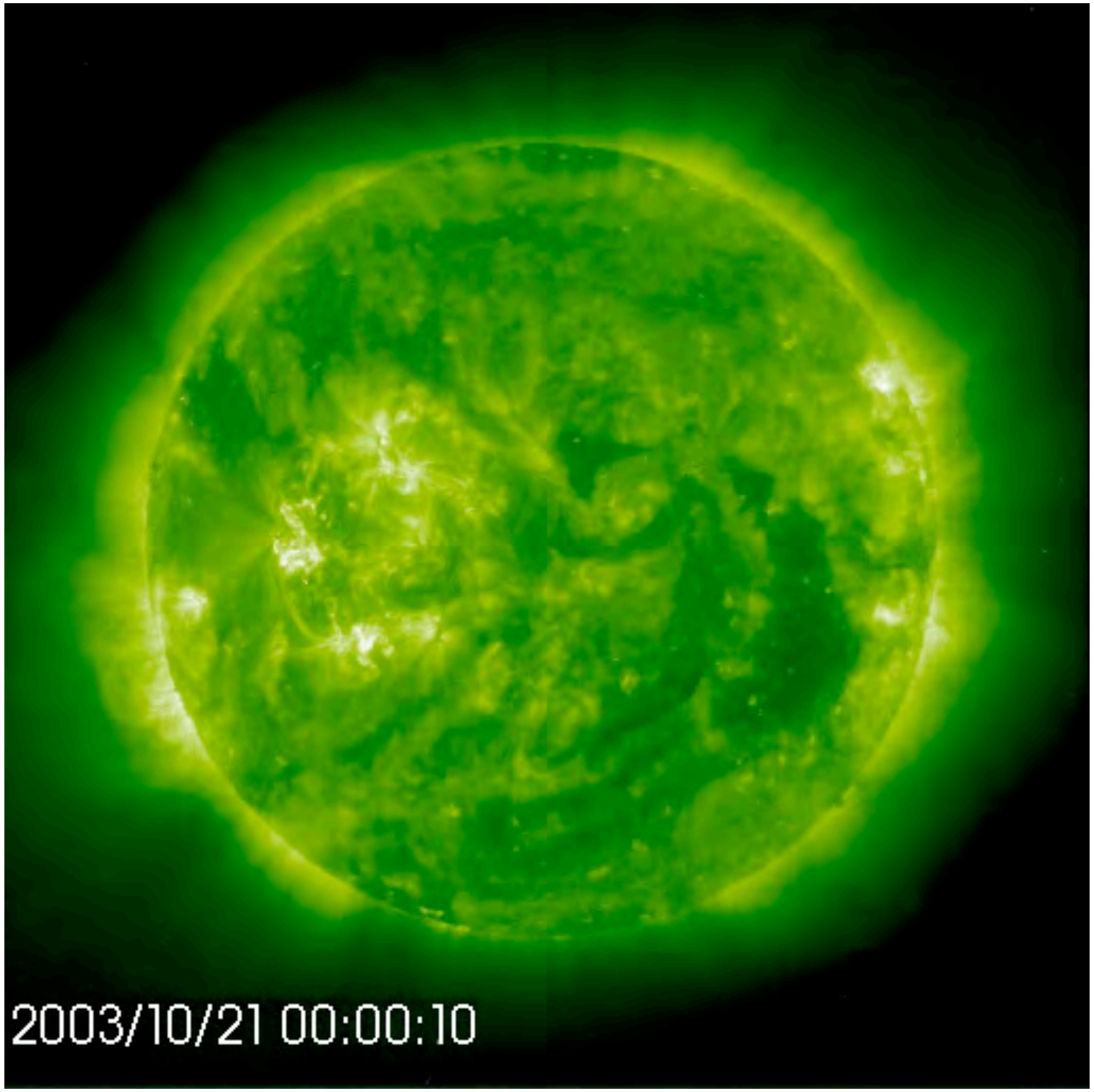


(For a discussion see lecture by Manfred Menn)

Acceleration of particles at the sun

Direct detection of particles
from shock acceleration





Aufnahme mit LASCO (SOHO)

(Mewaldt et al., A.I.P. Conf. Proc. 598 (2001) 165)