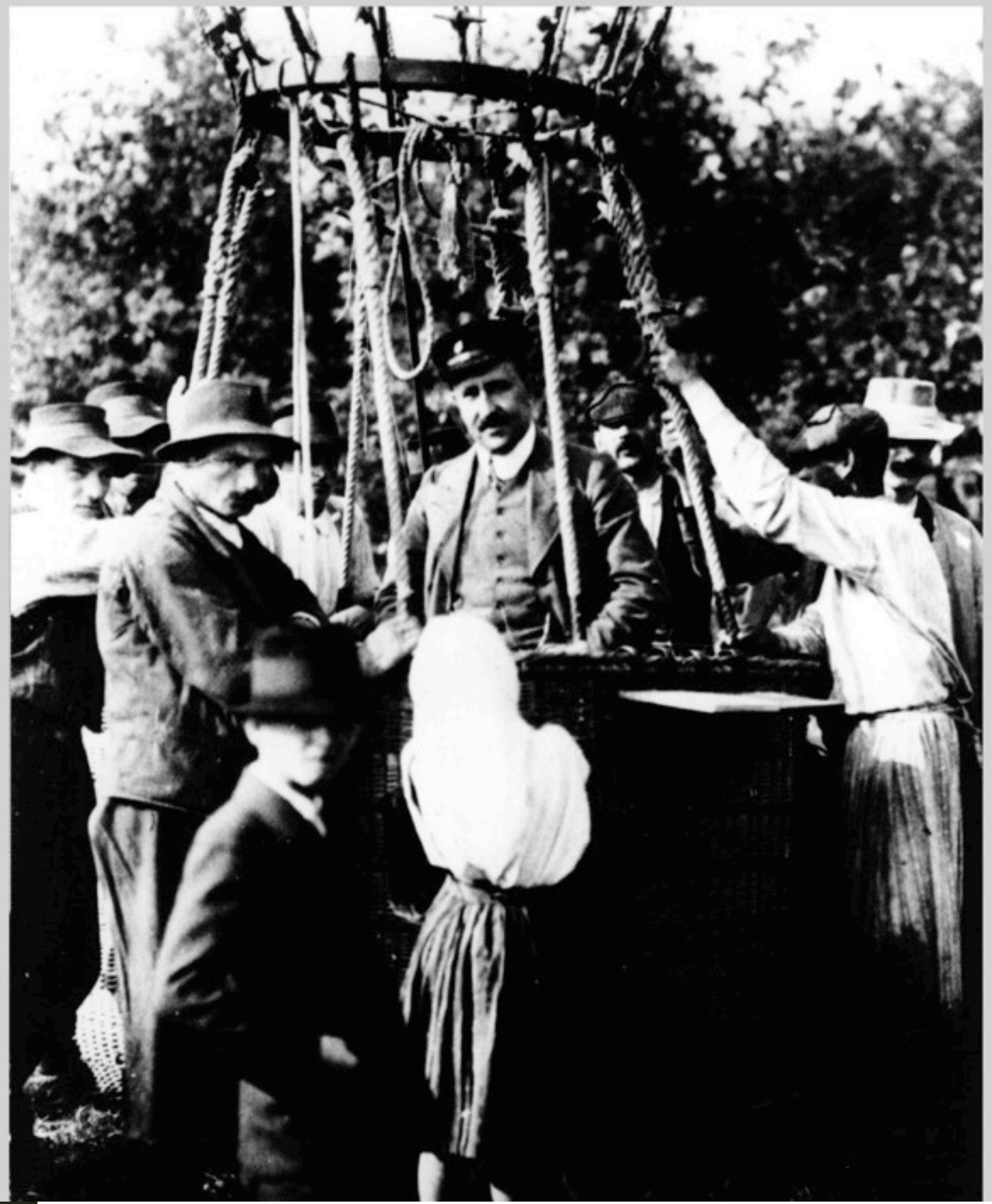
Cosmic rays and air shower physics I

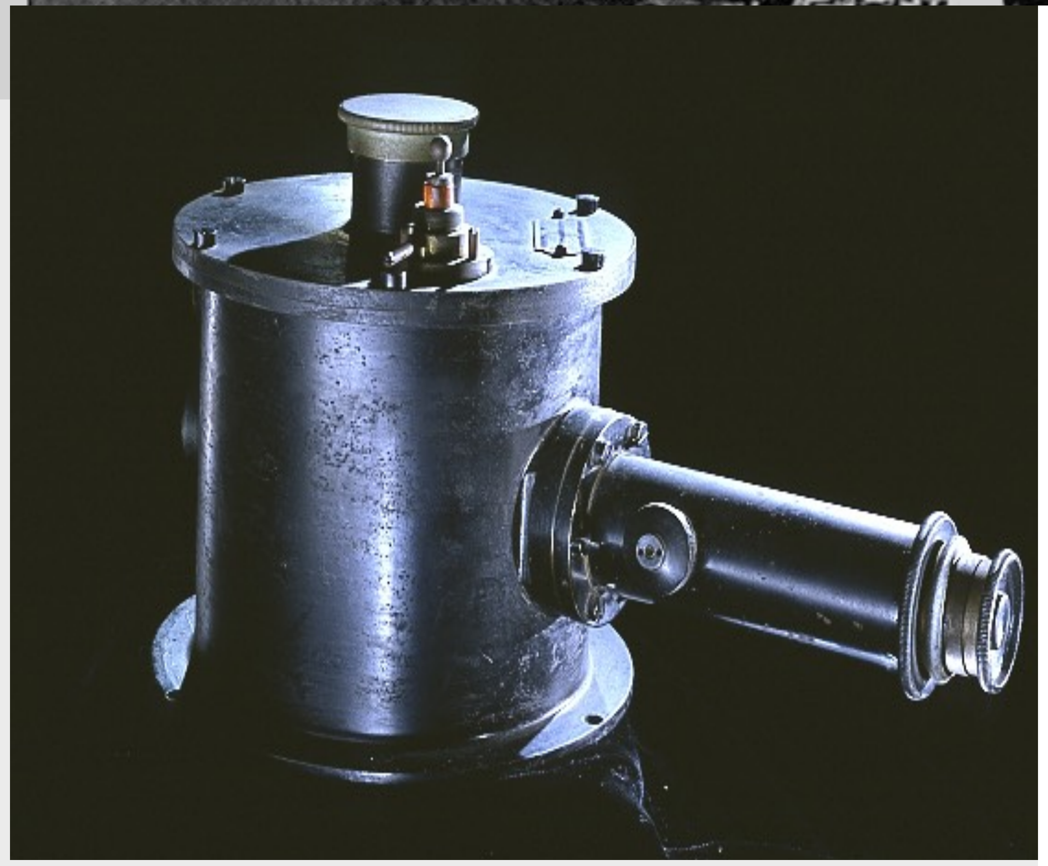
Ralph Engel

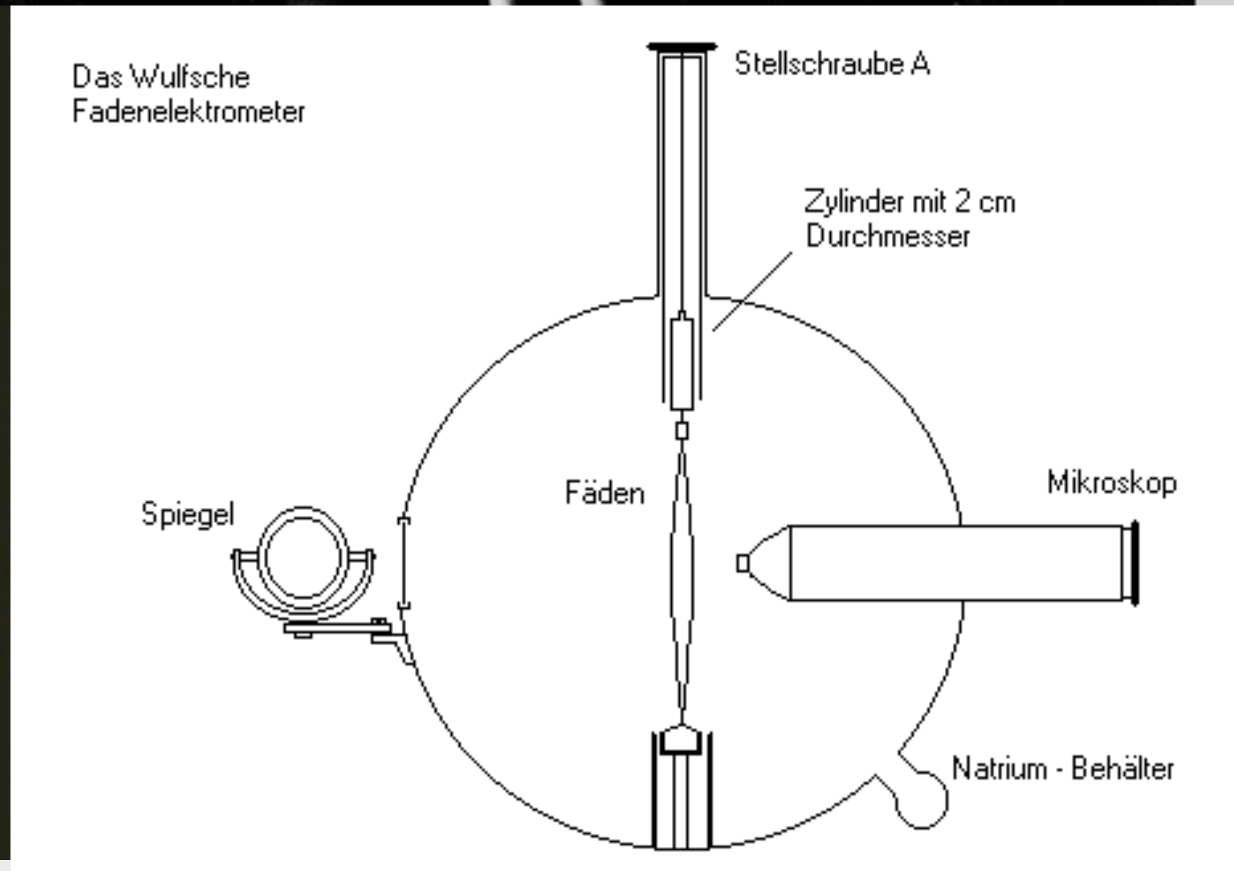
Karlsruhe Institute of Technology (KIT)

(photograph by S. Saffi)

Discovery of cosmic rays (Pacini, Hess, Kolhörster)



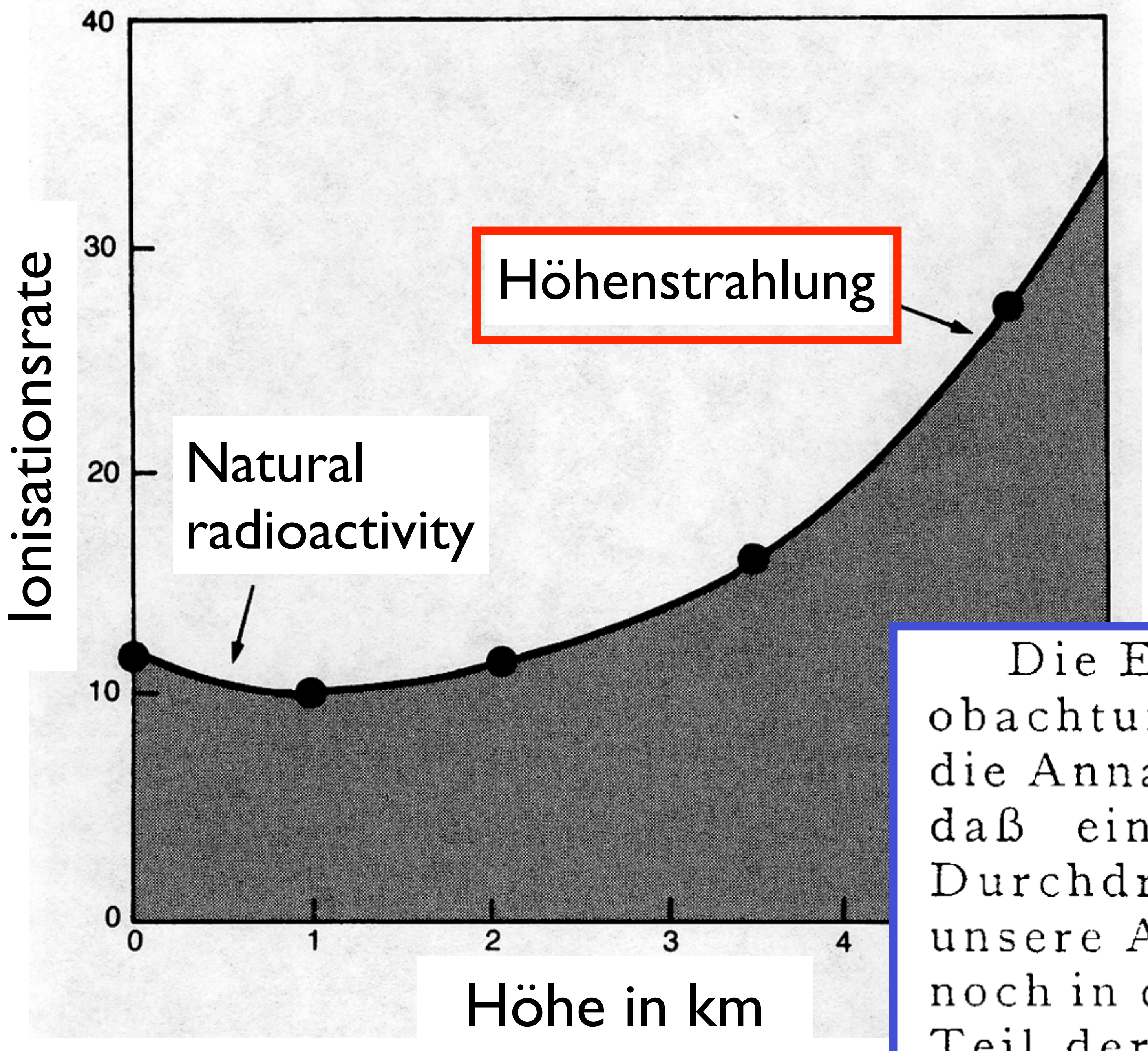




(1911 – 1913)

Viktor F. Hess (Wien), Über Beobachtungen der durchdringenden Strahlung bei sieben Freiballonfahrten.

Im Vorjahre habe ich bereits Gelegenheit gehabt, zwei Ballonfahrten zur Erforschung der durchdringenden Strahlung zu unternehmen; über die erste Fahrt wurde schon auf der Naturforscherversammlung in Karlsruhe von mir berichtet[1]). Bei beiden Fahrten ergab sich keine wesentliche Änderung der Strahlung gegenüber der am Erdboden beobach-



Nobel Prize 1936

Die Ergebnisse der vorliegenden Beobachtungen scheinen am ehesten durch die Annahme erklärt werden zu können, daß eine Strahlung von sehr hoher Durchdringungskraft von oben her in unsere Atmosphäre eindringt, und auch noch in deren untersten Schichten einen Teil der in geschlossenen Gefäßen beobachteten Ionisation hervorruft. Die

Cosmic rays as new energy frontier

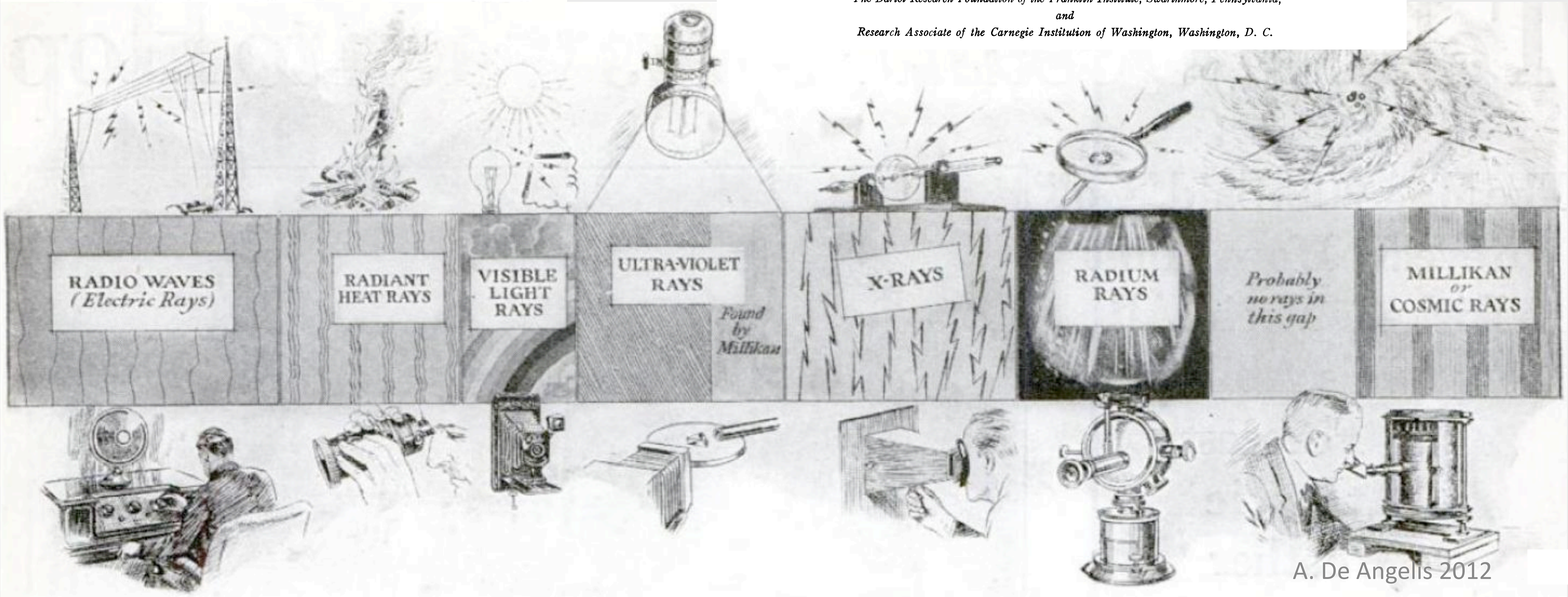
(1928)

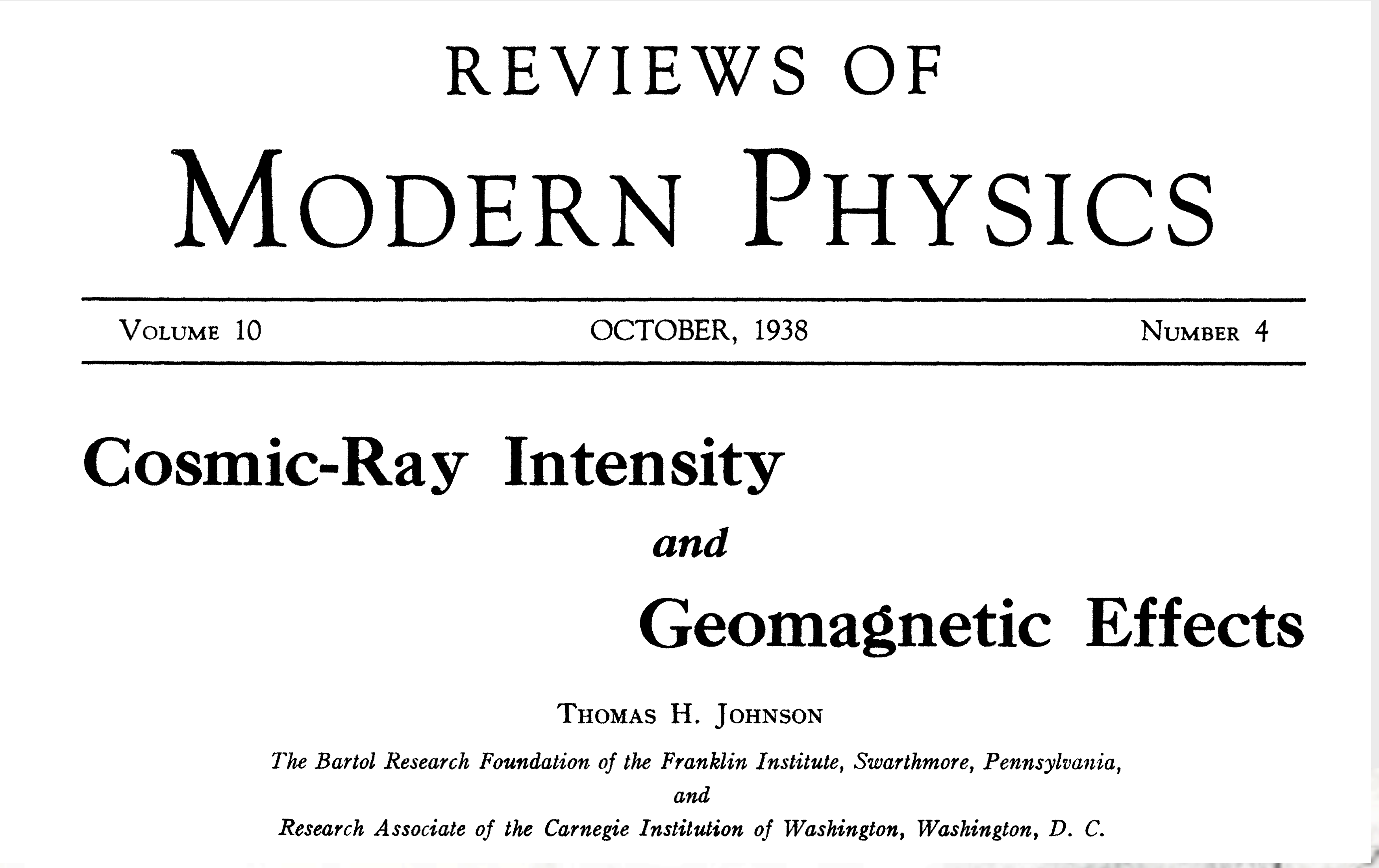
Popular Science MONTHLY

FOUNDED 1872 — FIFTY SEVENTH YEAR

JULY, 1928 — SUMNER BLOSSOM Editor — VOL. 113, NO. 1

Super-Rays Reveal Secret of Creation




REVIEWS OF MODERN PHYSICS

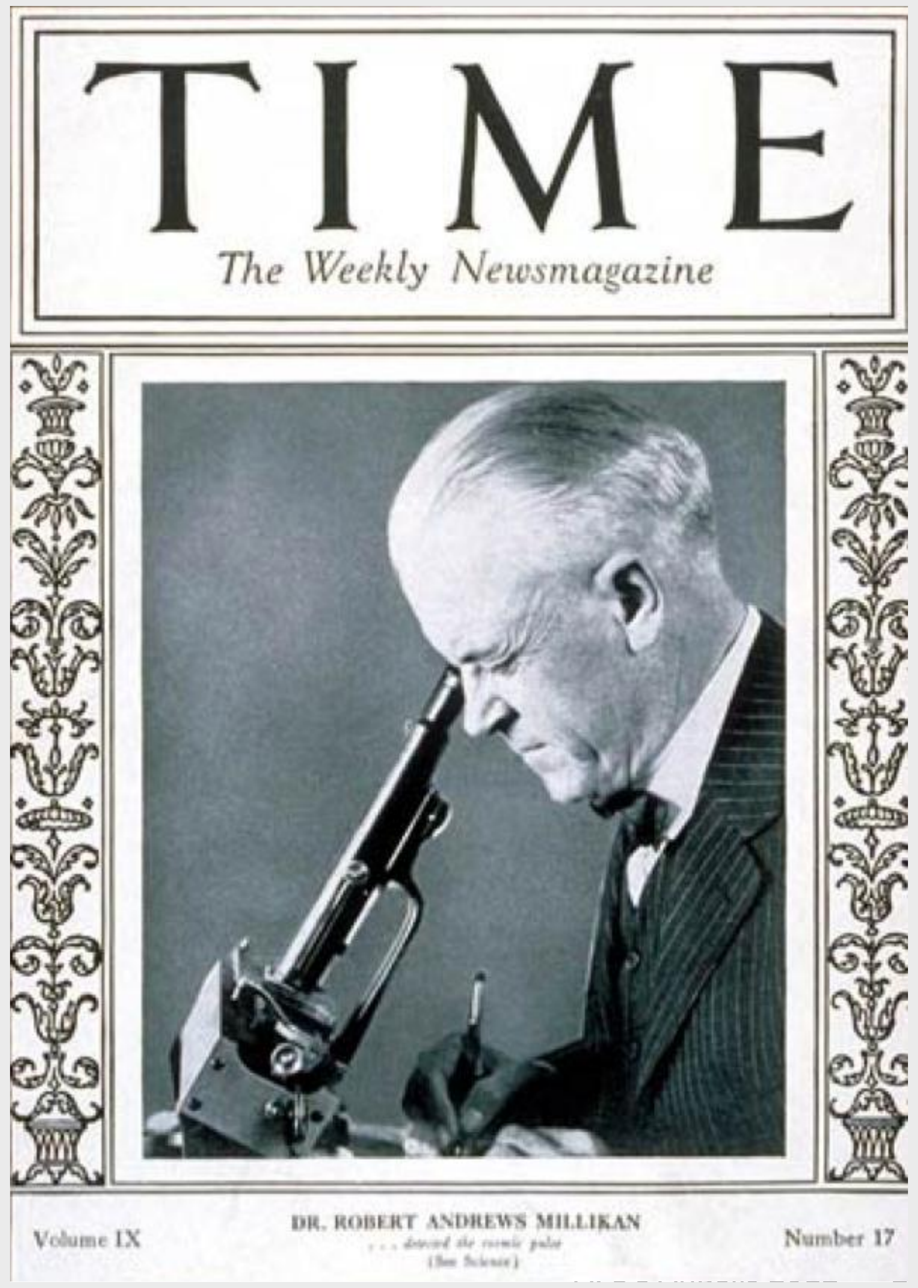
VOLUME 10 — OCTOBER, 1938 — NUMBER 4

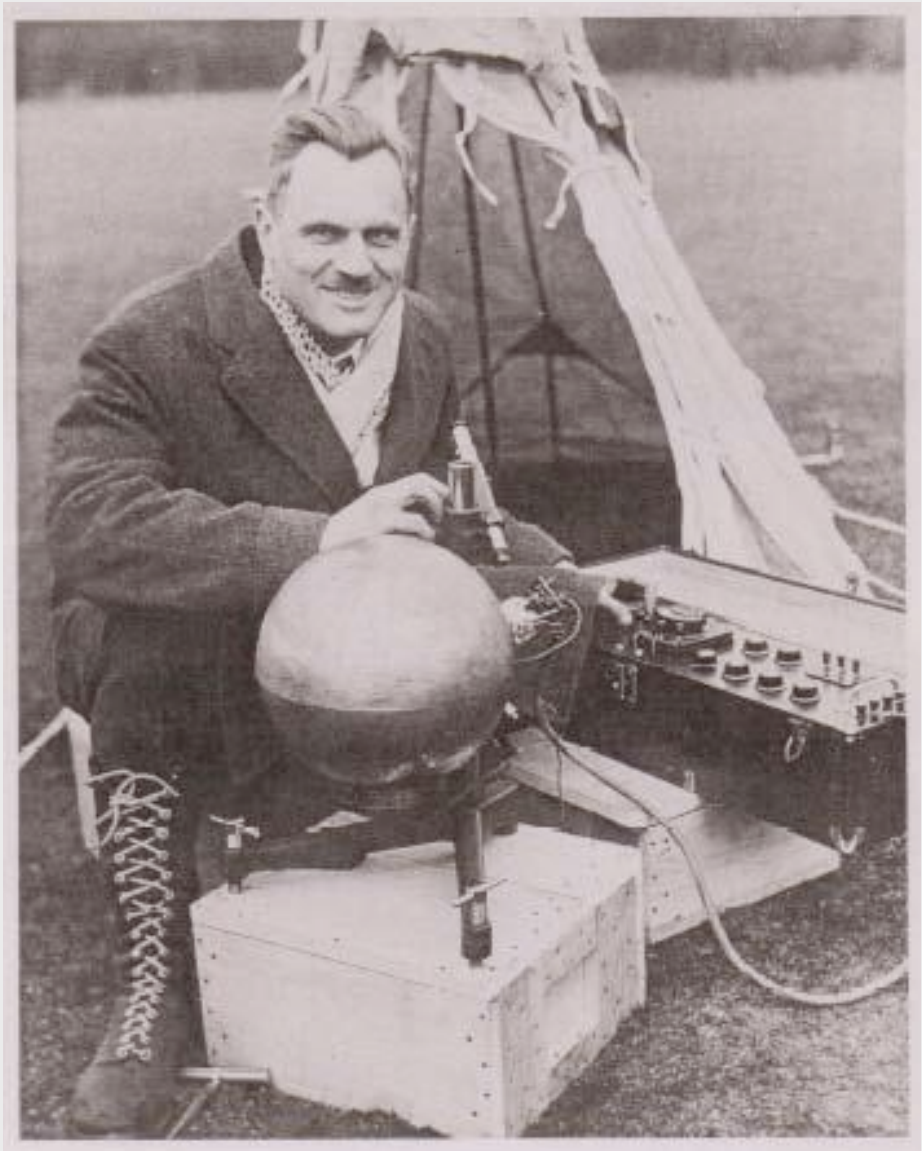
Cosmic-Ray Intensity *and* Geomagnetic Effects

THOMAS H. JOHNSON

The Bartol Research Foundation of the Franklin Institute, Swarthmore, Pennsylvania, and Research Associate of the Carnegie Institution of Washington, Washington, D. C.

Robert Millikan

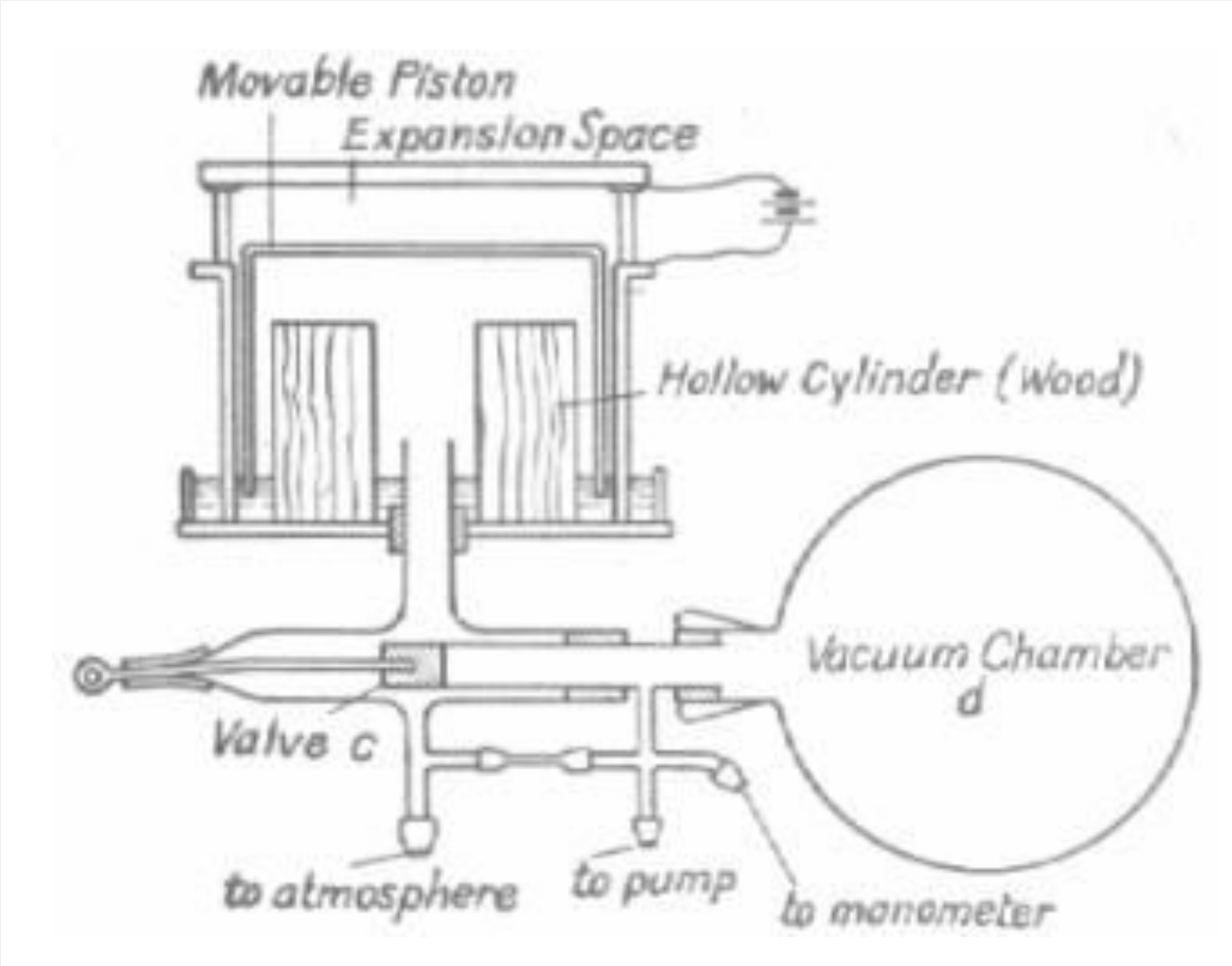




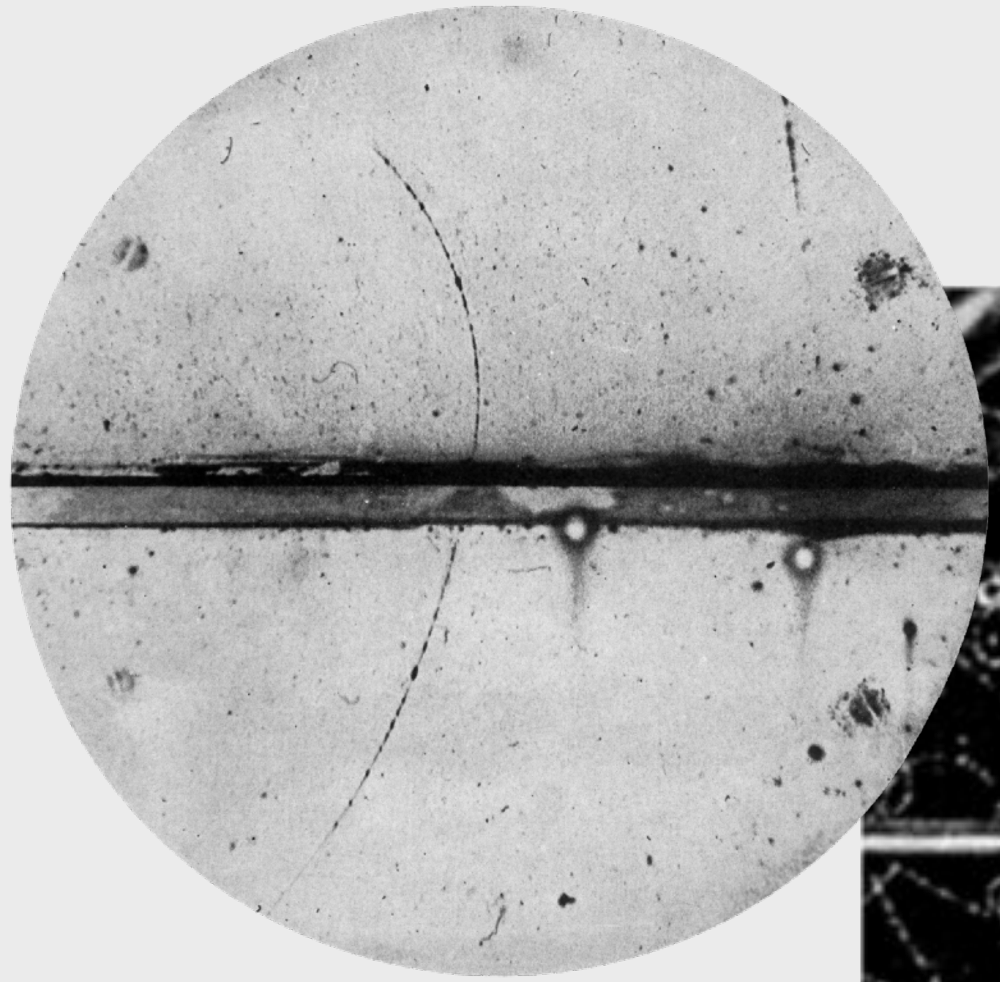
Arthur Compton

A. De Angelis 2012

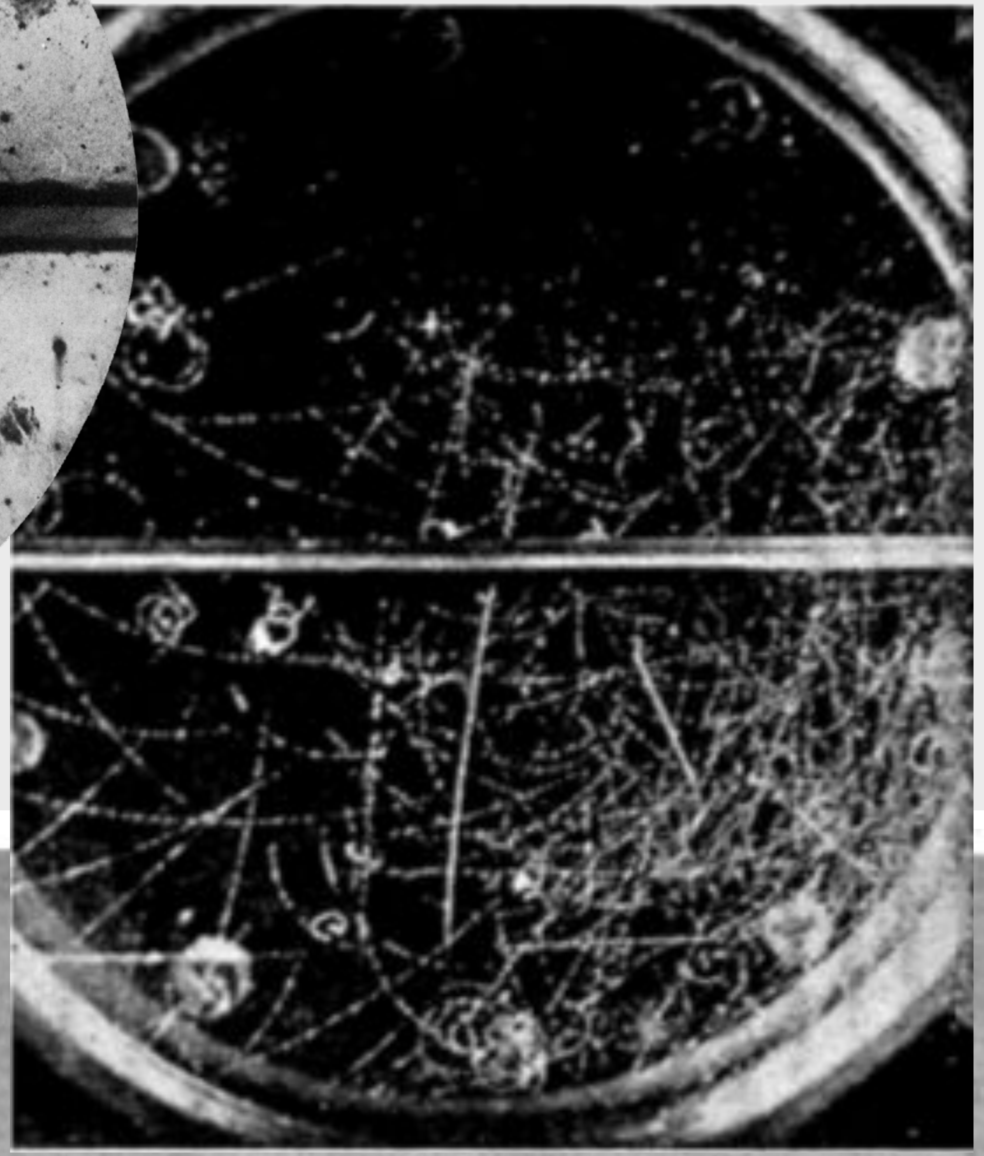
The birth of high-energy particle physics



1911: cloud chamber by Wilson



1932: discovery of positron by Anderson



1936: discovery of muon
(initially mistaken as pion)
by Anderson and Neddermeyer

1947: discovery of pion by
Lattes, Murihead, Occhialini
and Powell

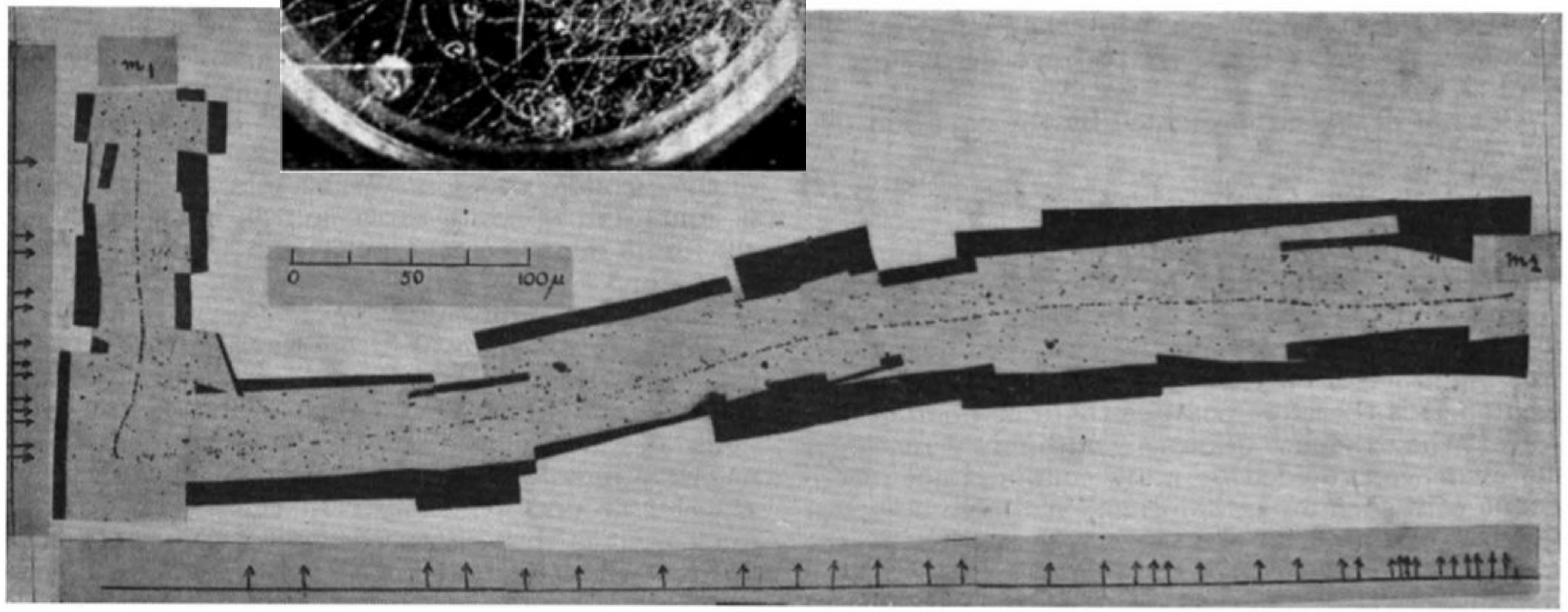
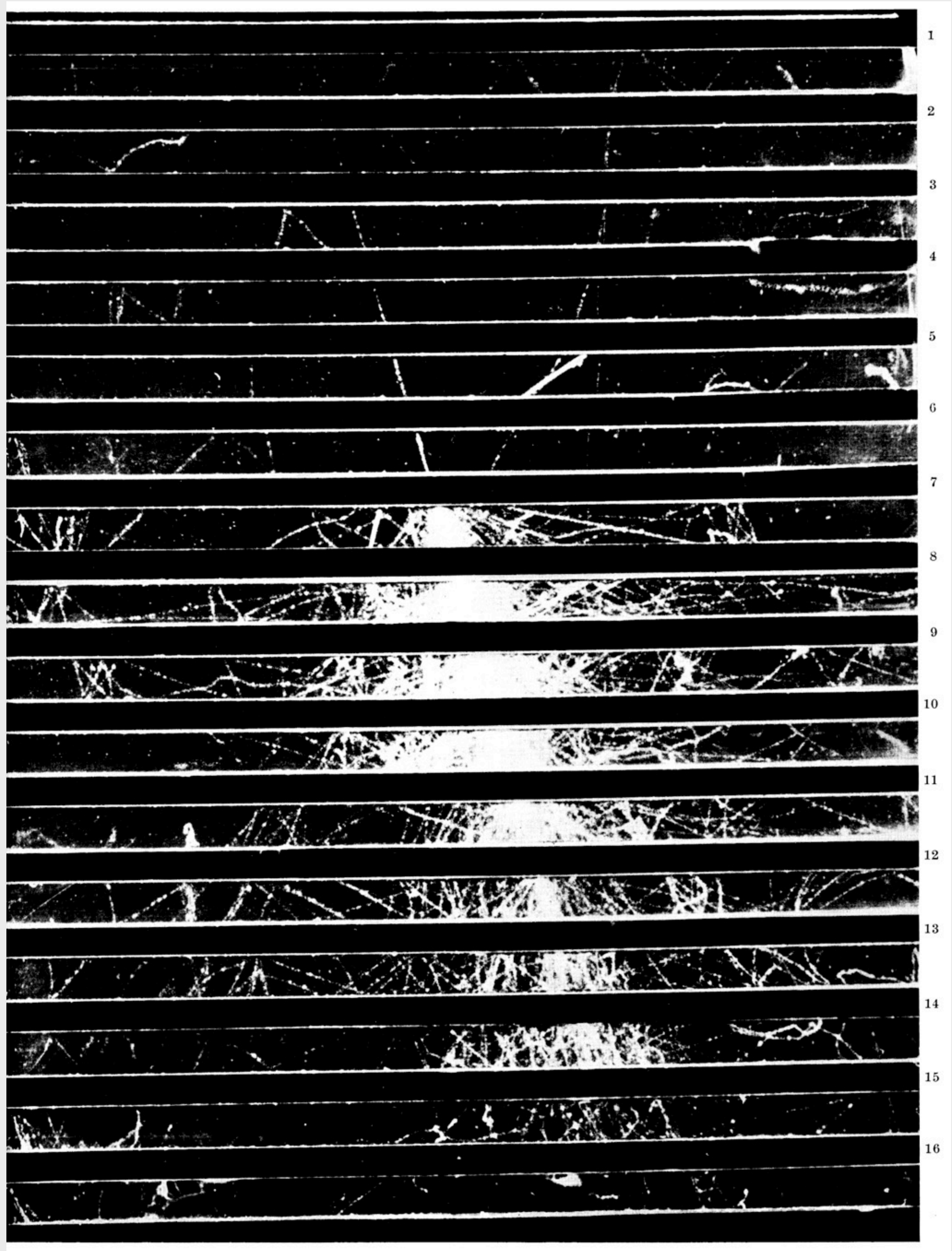


Fig. 1. Observation by Mrs. I. Roberts. Photomicrograph with Cooke × 45 'Fluorite' objective. Ilford 'Nuclear Research', boron-loaded C2 emulsion. m_1 is the primary and m_2 the secondary meson. The arrows, in this and the following photographs, indicate points where changes in direction greater than 2° occur, as observed under the microscope. All the photographs are completely unretouched

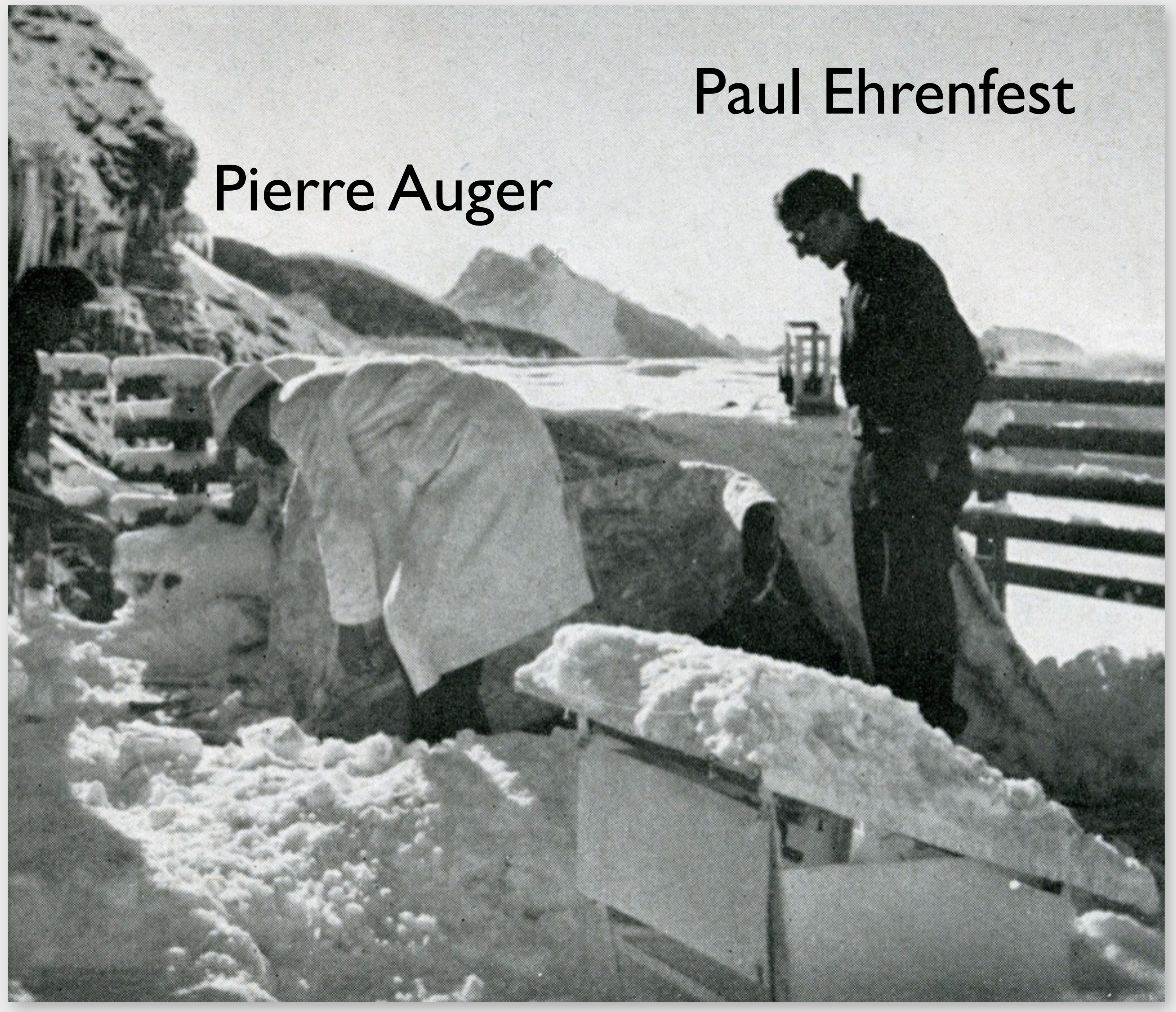
1947: discovery of kaon,
the first strange particle, by Rochester & Butler

1951: discovery of Λ,
the first strange baryon, by Armenteros et al.

Extensive cosmic ray showers (Auger et al. 1936)



Cascade in a cloud chamber at 3027 m altitude (~10 GeV)



Primary particle energies exceeding 10^6 GeV = 10^{15} eV

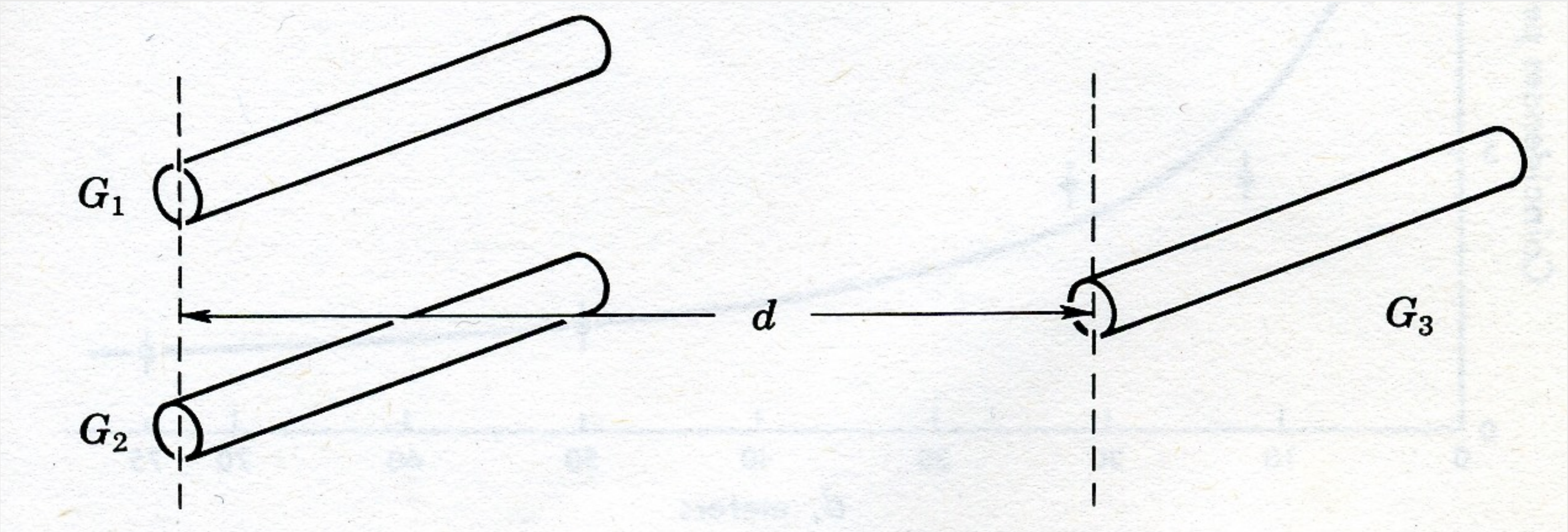


Fig. 12-1 Air-shower experiments by Auger and his collaborators in 1938 were made with the counter arrangement shown here. Counters G_1 and G_2 were placed one above the other, with their axes 22 cm apart. The third counter G_3 was moved horizontally to various distances d ranging from 15 centimeters to 75 meters.

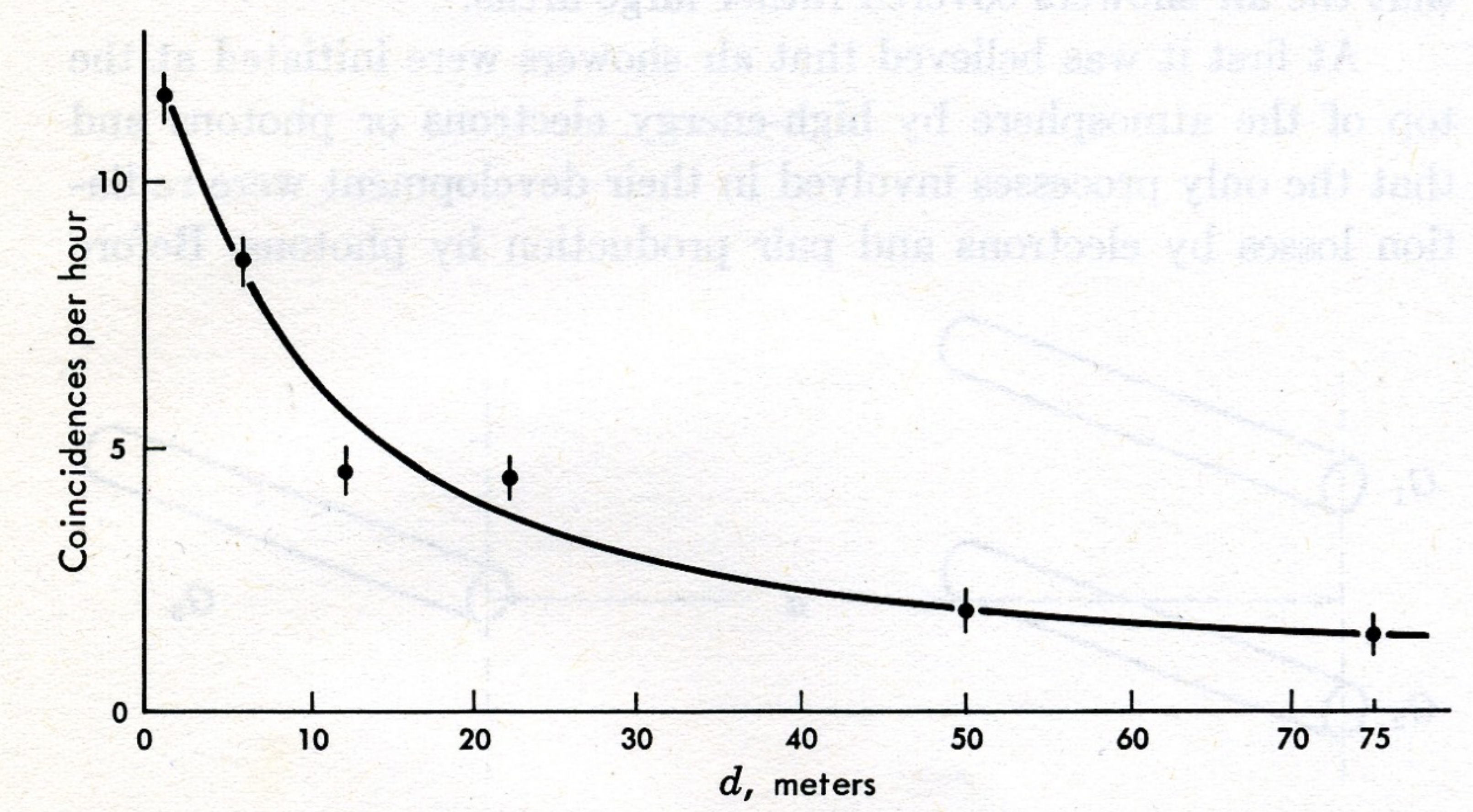
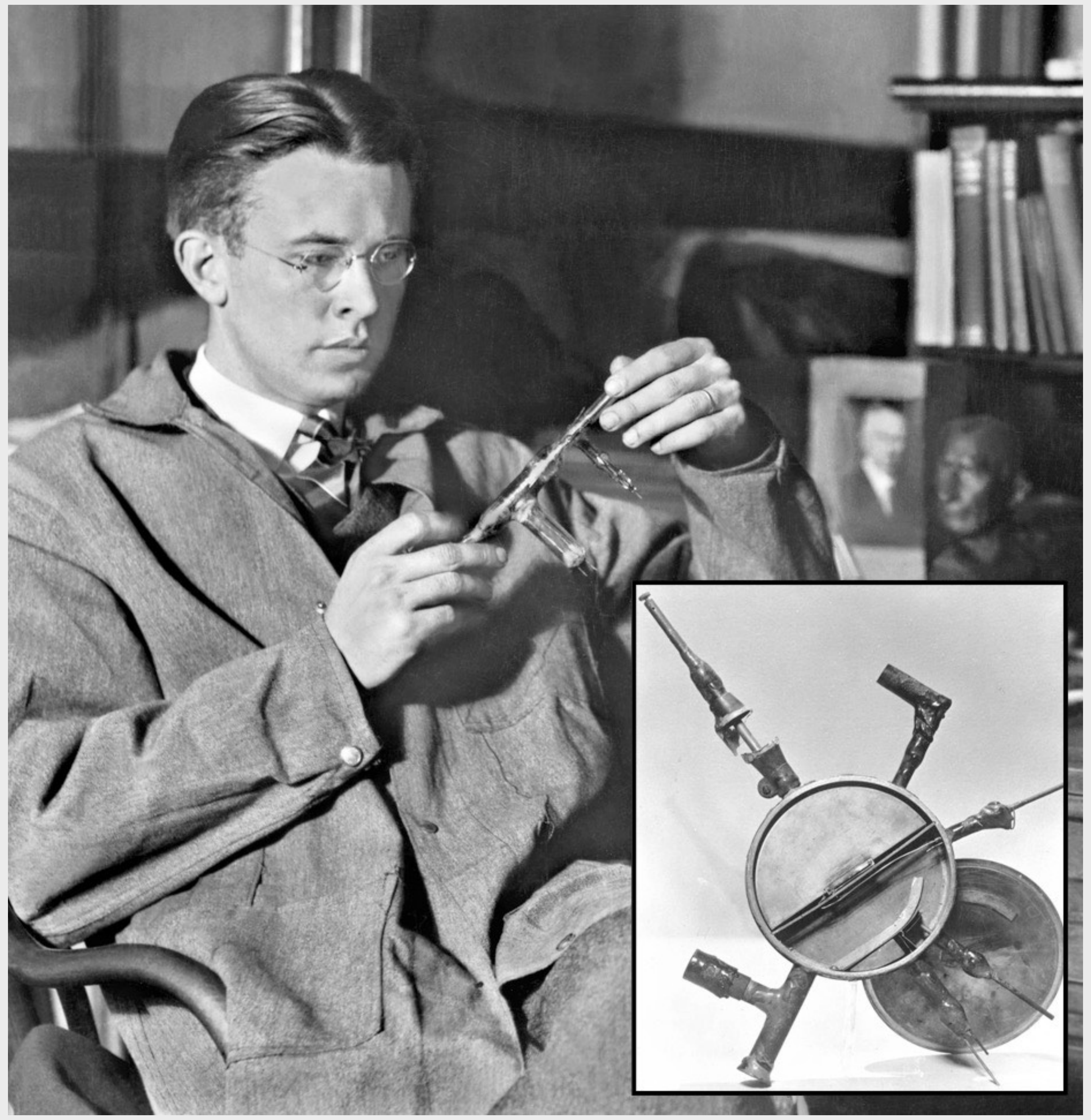
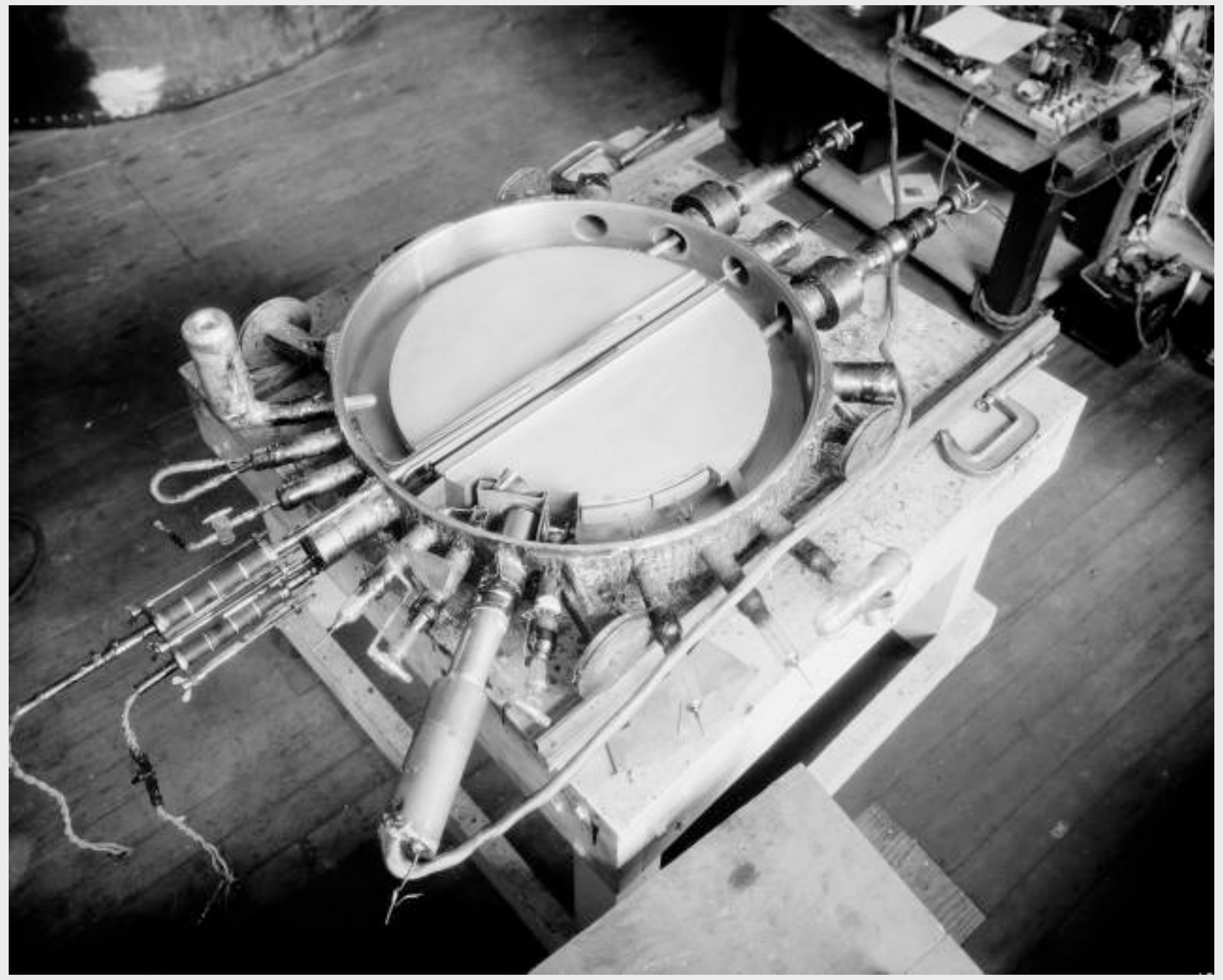


Fig. 12-2 Air-shower data obtained by Auger with the counter arrangement shown in Fig. 12-1. The horizontal scale gives the horizontal distance d between counter G_3 and the pair of counters G_1 and G_2; the vertical scale, the number of coincidences per hour. (From a paper in *Le Journal de Physique et Le Radium*, vol. 10, p. 39, 1939.)

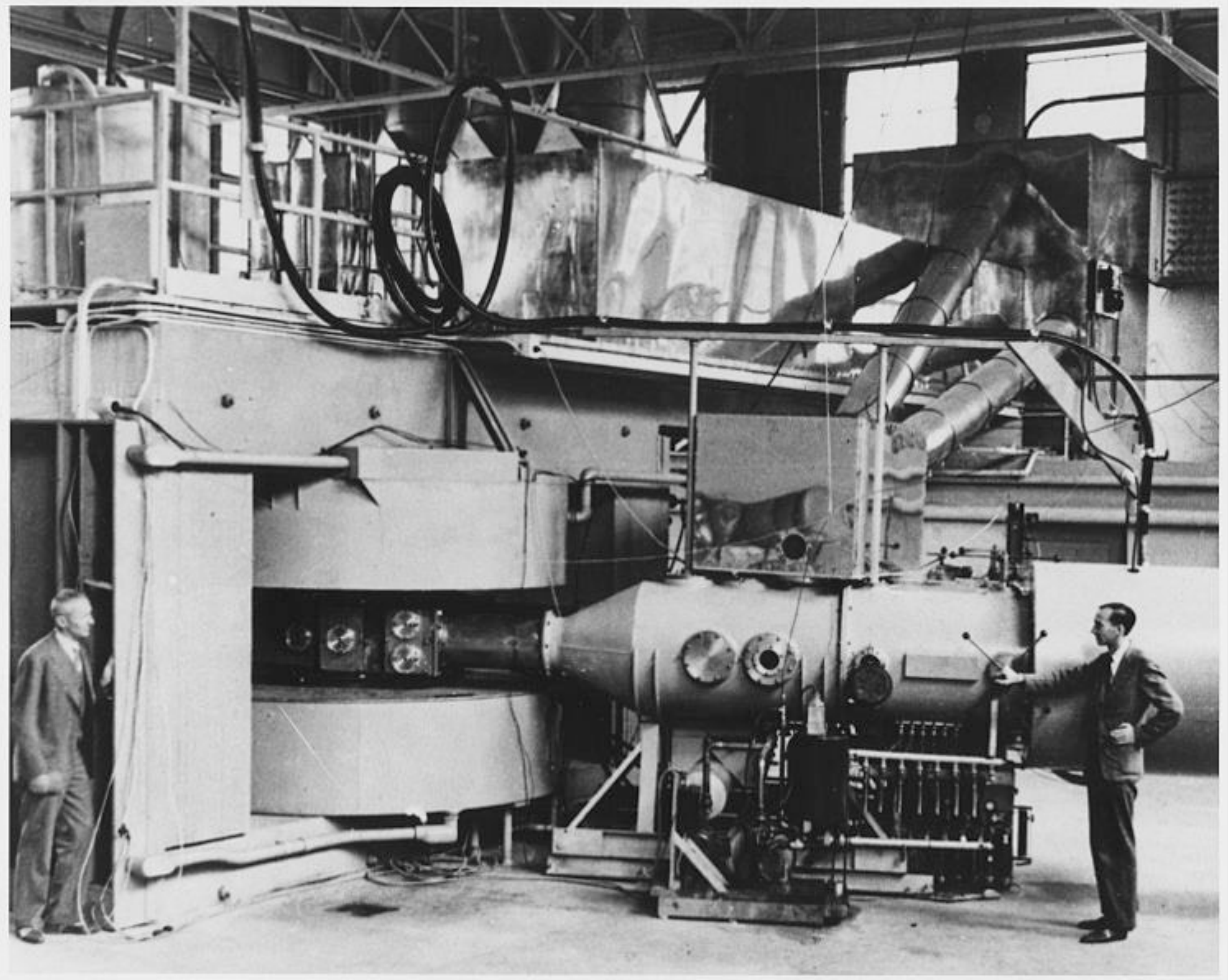
Particle accelerator development

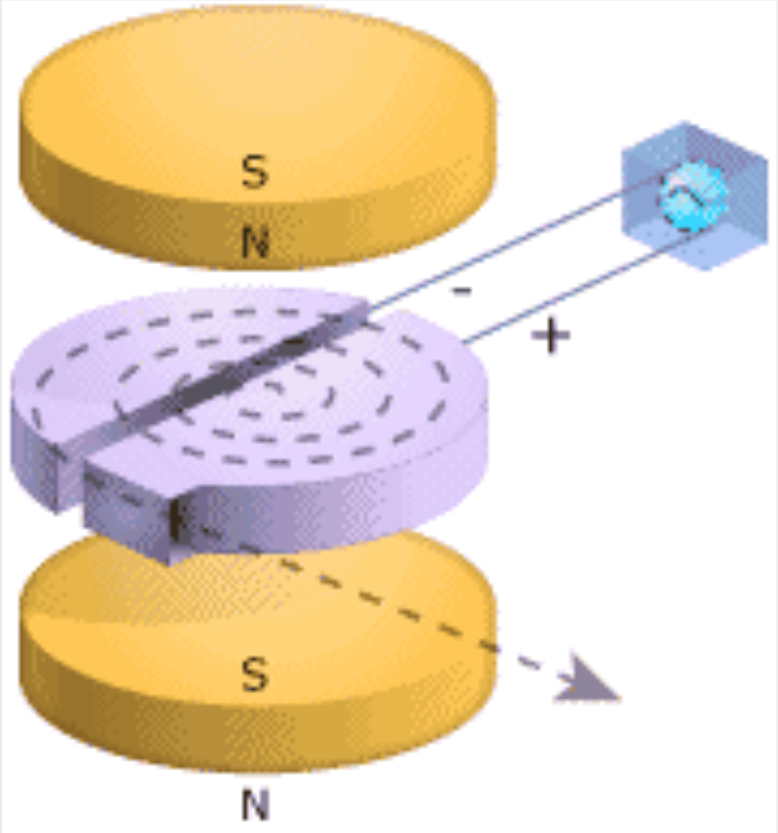




1932: 27-inch cyclotron: 3 MeV protons

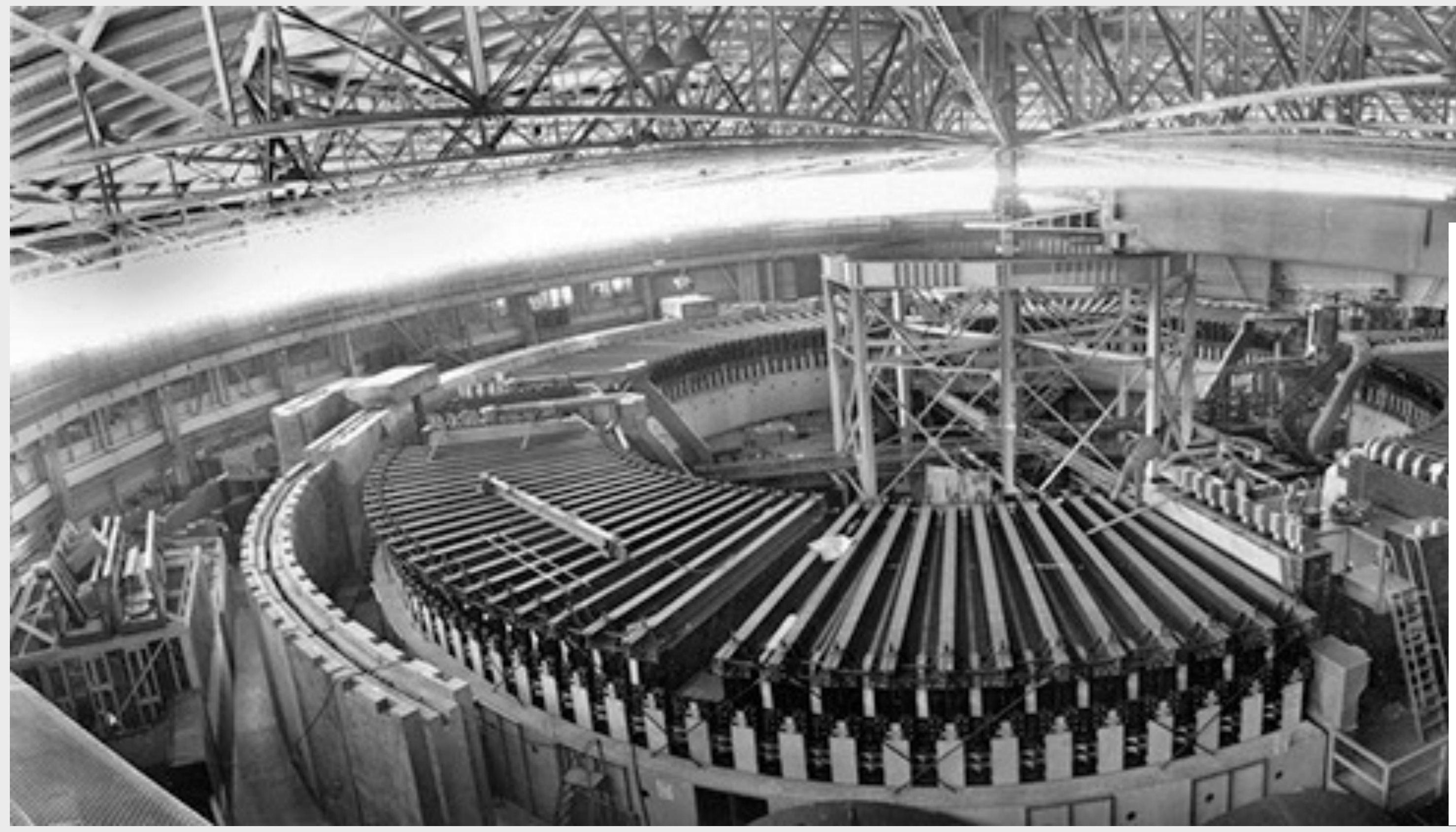
1939: 60-inch cyclotron: 20 MeV protons





Cyclotron (1931)
Ernest Orlando Lawrence
(Nobel prize 1939)

Acceleration by 2kV
max. energy 80 keV



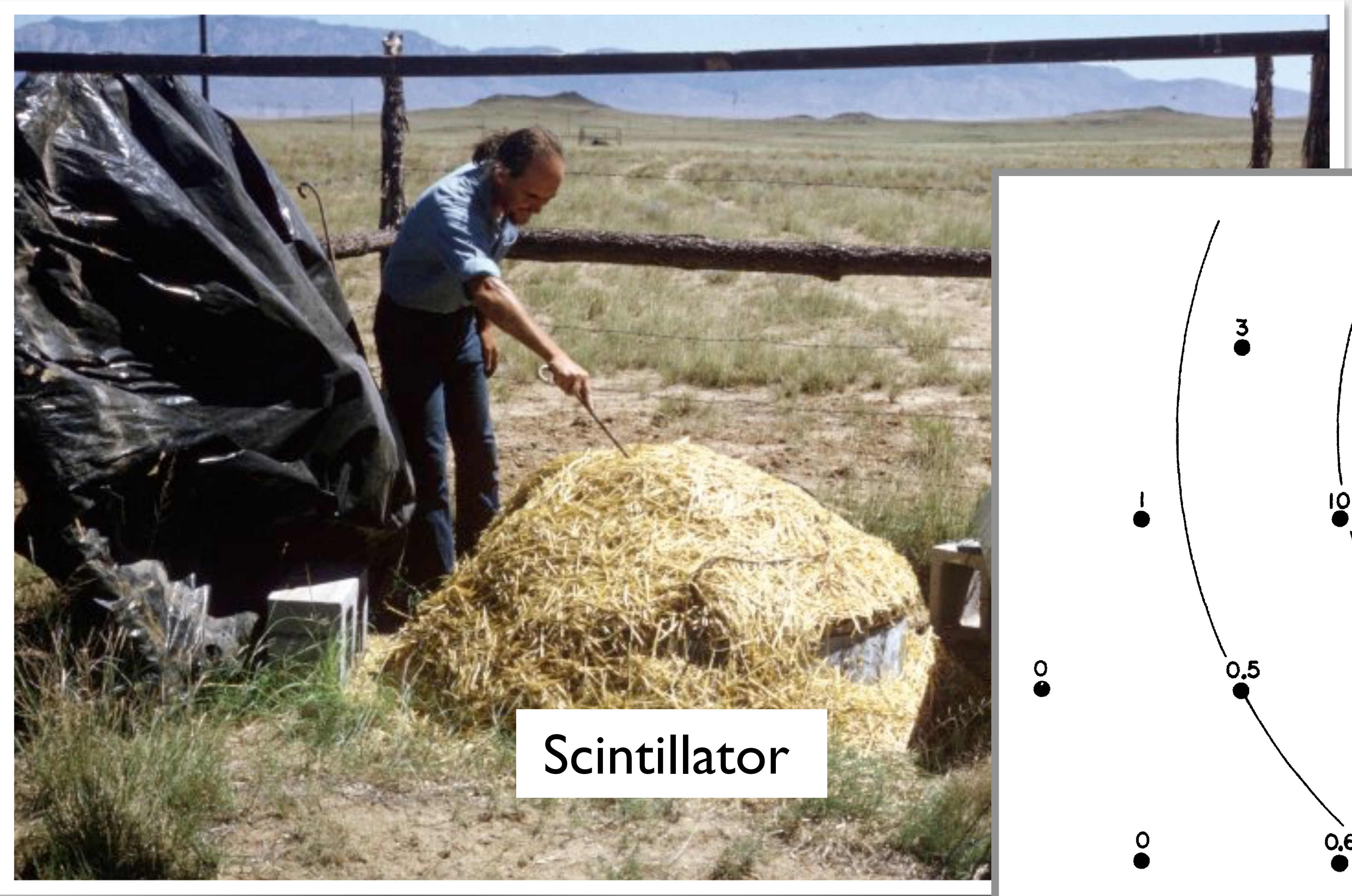
1952: Cosmotron: 3 GeV (Brookhaven)
1954: Bevatron: 6 GeV (Berkeley)
1957: Synchrophasotron: 10 GeV (Dubna)
1960: Brookhaven AGS: 33 GeV
1967: U-70: 70 GeV (Serpukhov)

Cosmic rays of ultra-high energy – 10^{20} eV

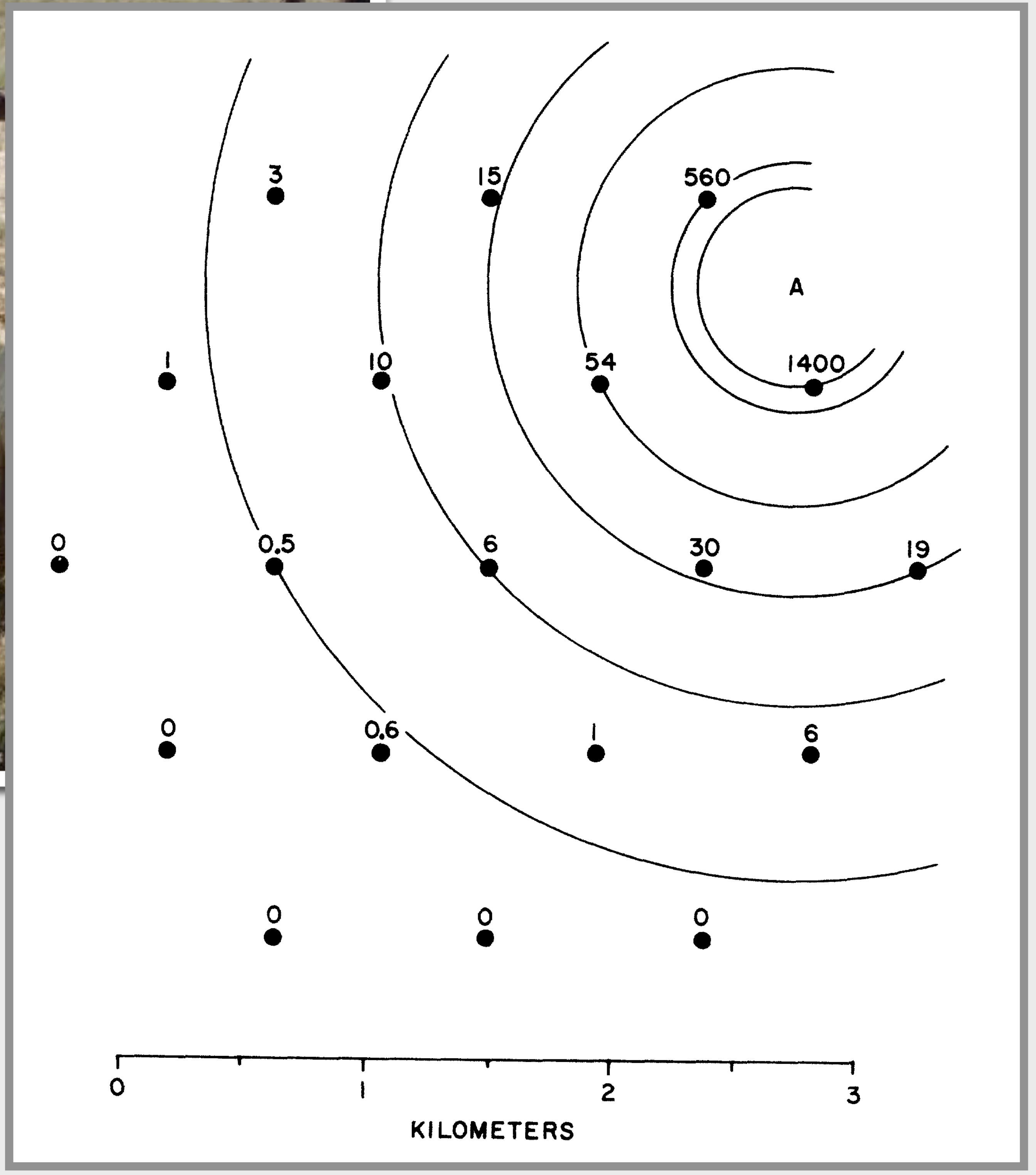
VOLUME 10, NUMBER 4 PHYSICAL REVIEW LETTERS 15 FEBRUARY 1963

EVIDENCE FOR A PRIMARY COSMIC-RAY PARTICLE WITH ENERGY 10^{20} eV†

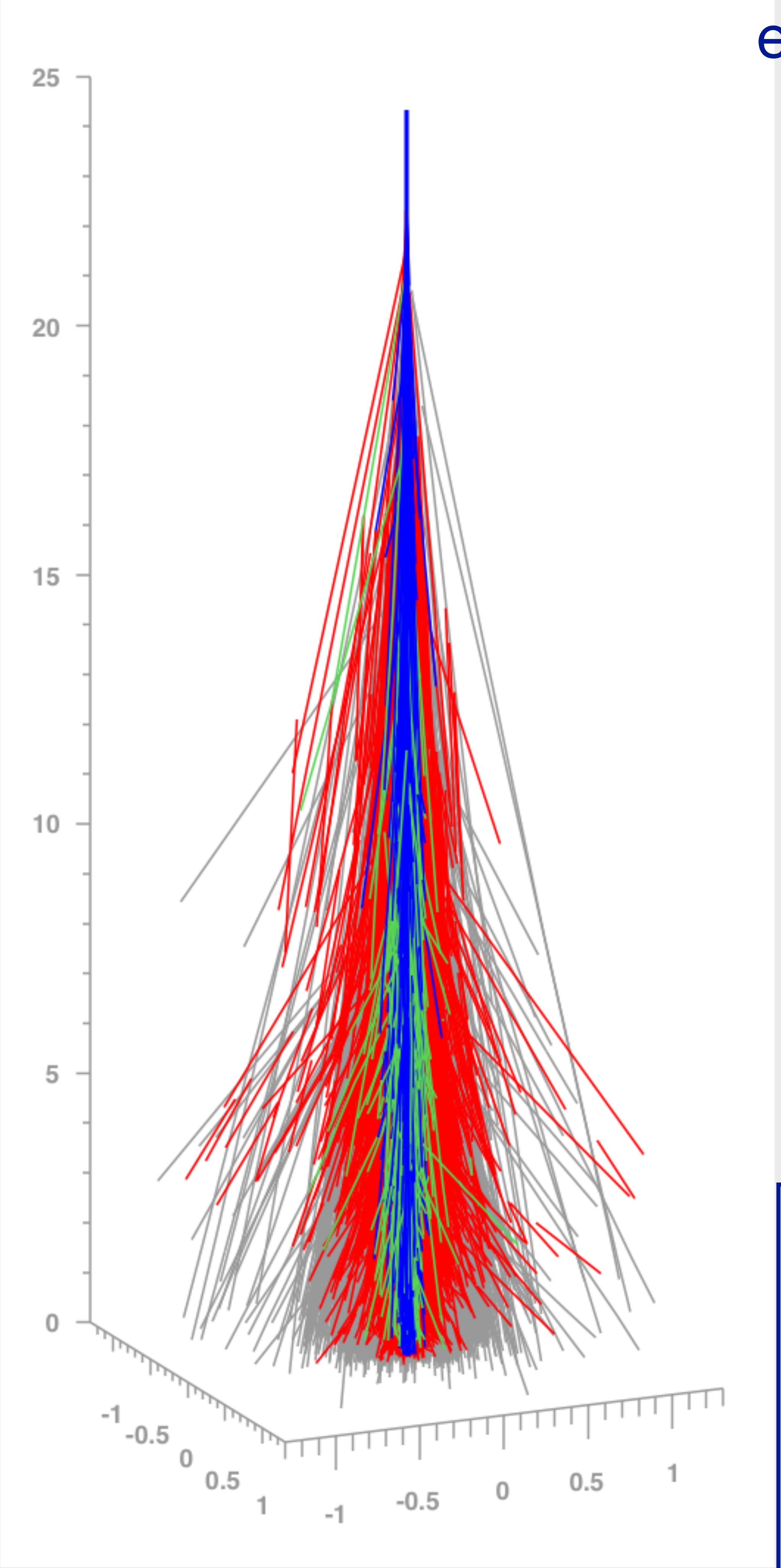
John Linsley
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 10 January 1963)

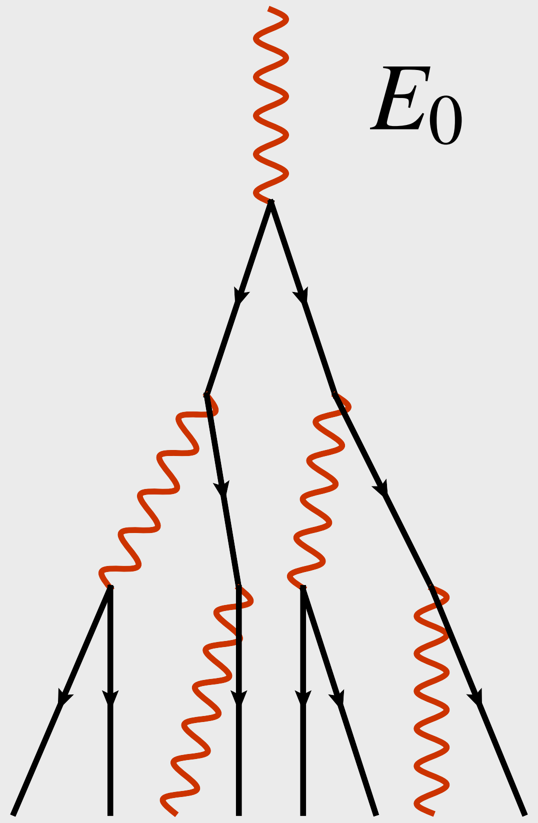


E = 10^{20} eV



Cascade of secondary particles: extensive air shower





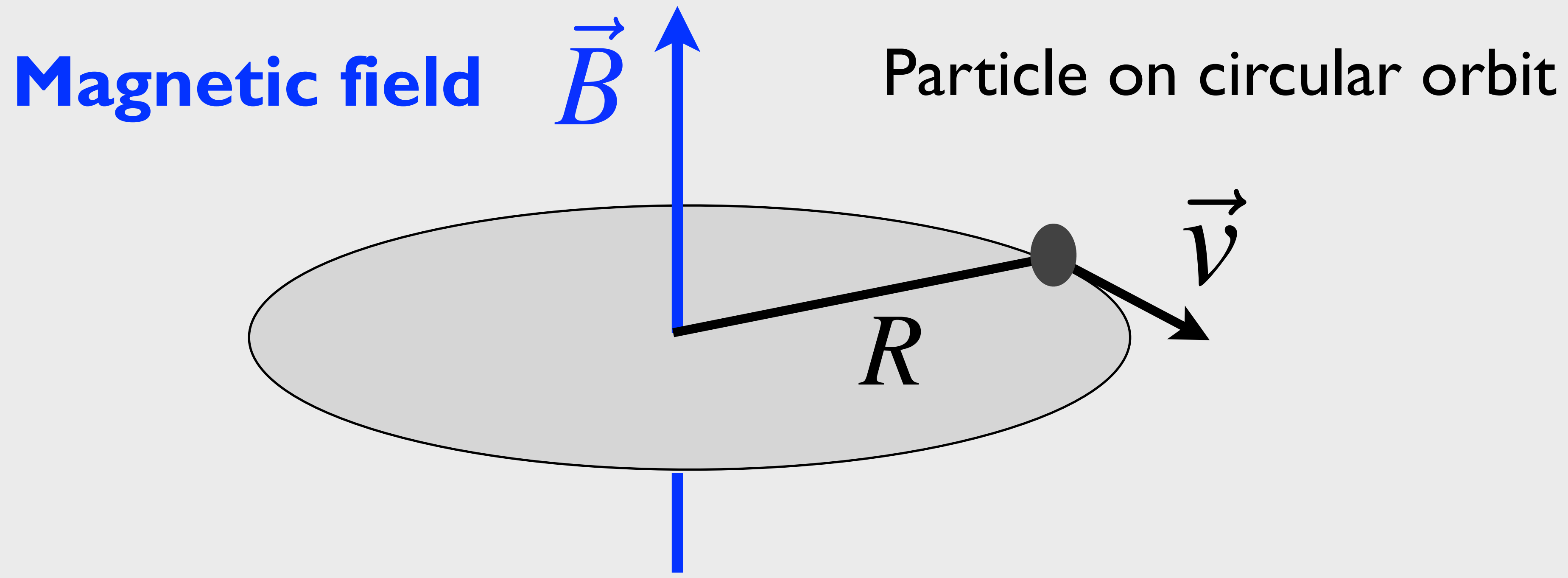
Energy conservation:
1.6 GeV / charged particle,
overall estimate robust

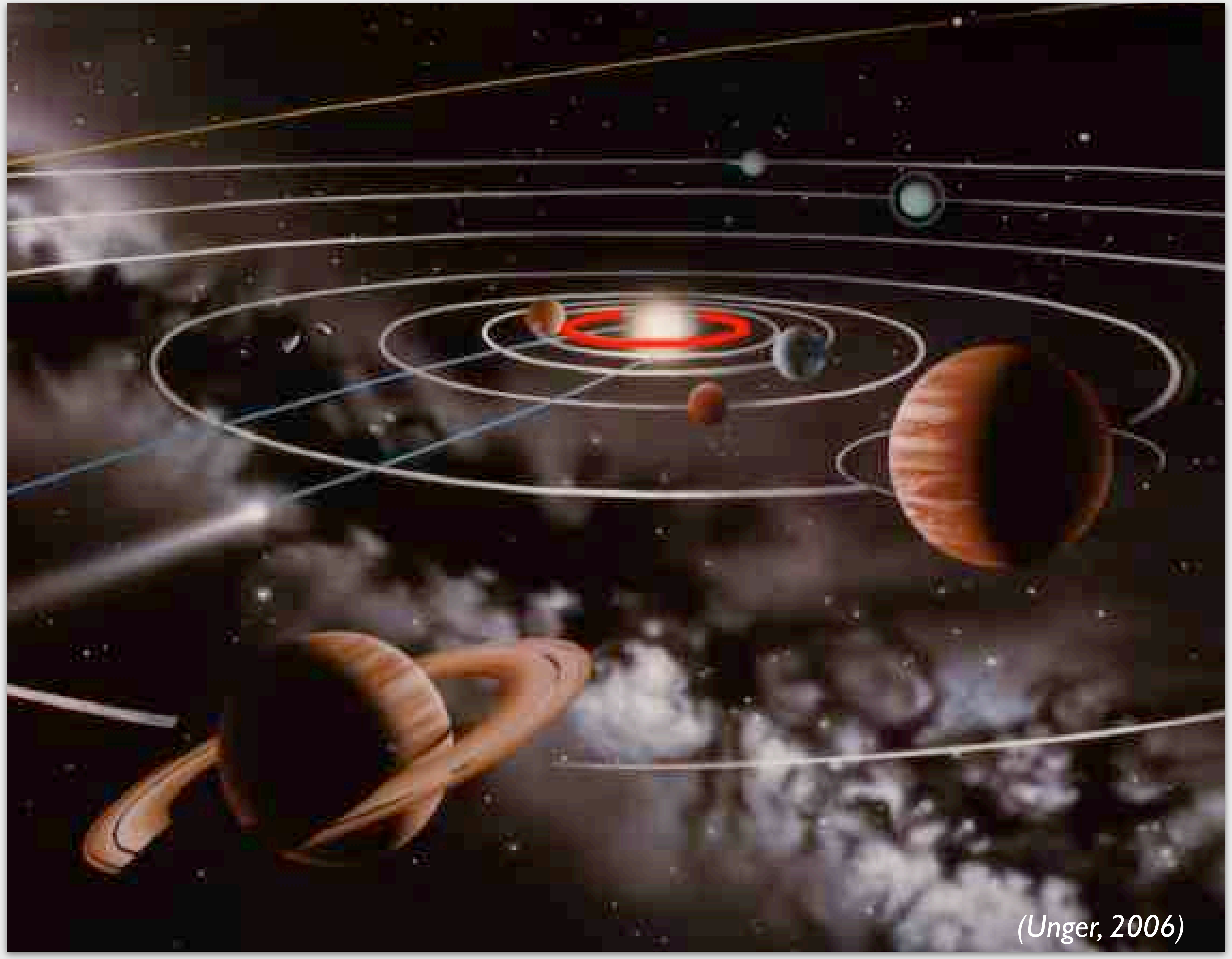
AGASA event, *E* ~1.7 – 2.6 10^{20} eV
(AGASA, PRL 73 (1994) 3491)

OMG event, *E* ~3.2 10^{20} eV
(Fly's Eye, ApJ 441 (1995) 144)

Amaterasu event, *E* ~2.4 10^{20} eV
(TA, Science 382 (2023) 903)

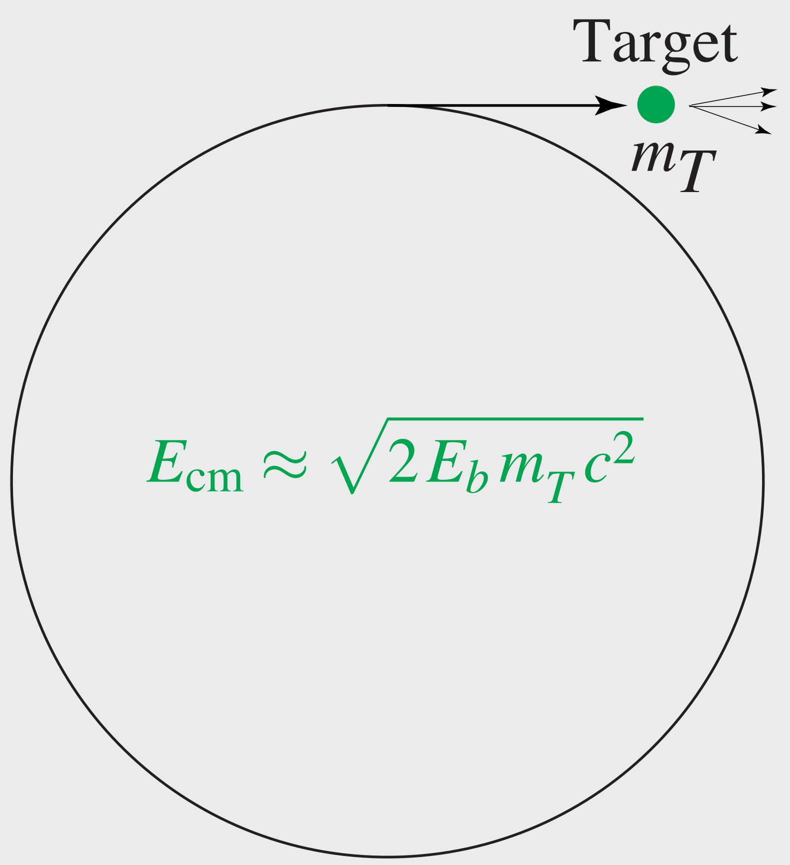
Ultra-high-energy cosmic rays – 10^{20} eV

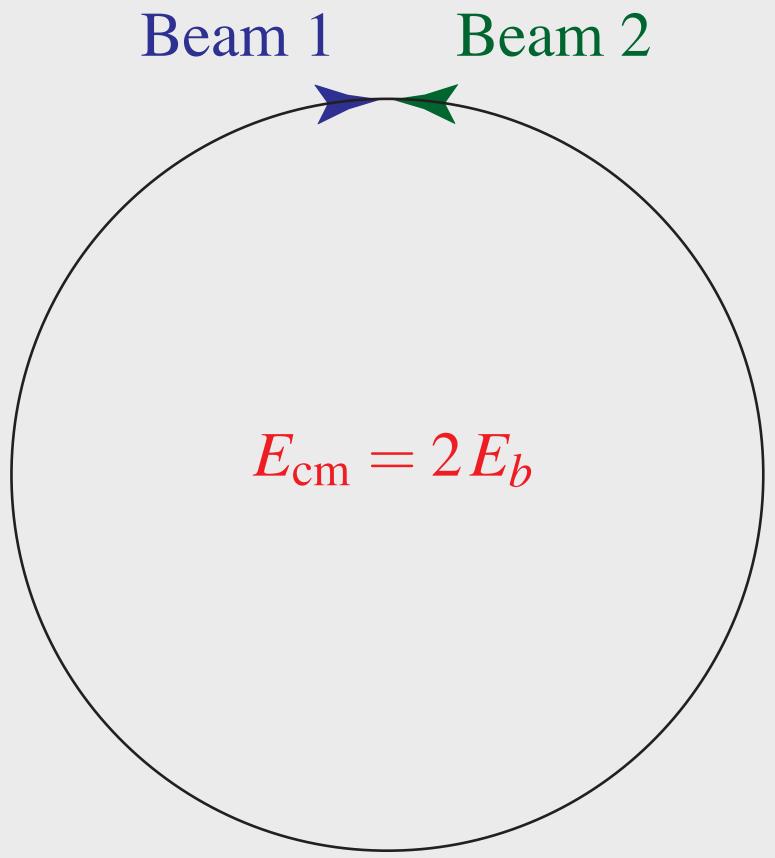




Need accelerator of size of the orbit of the planet Mercury to reach 10^{20} eV with LHC technology

Fixed target vs. collider setup





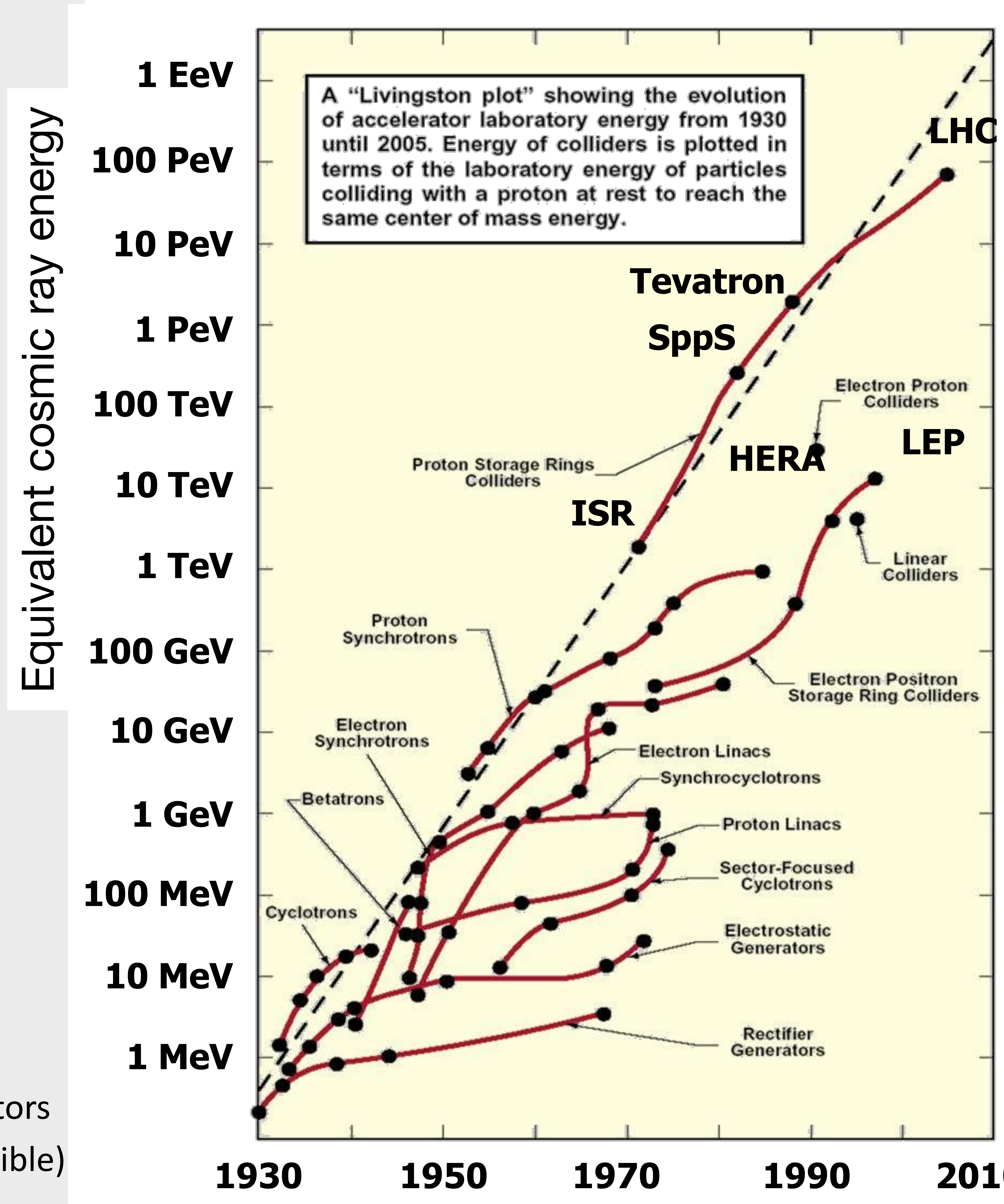
$$E_{\rm lab} \approx \frac{E^2_{\rm c.m.}}{2 m_p}$$

Synchrotron energy loss

$$U_0 = \frac{e^2}{3\epsilon_0} \frac{\beta^3 \gamma^4}{\rho} \propto \frac{1}{\rho} \frac{E^4}{m^4}$$

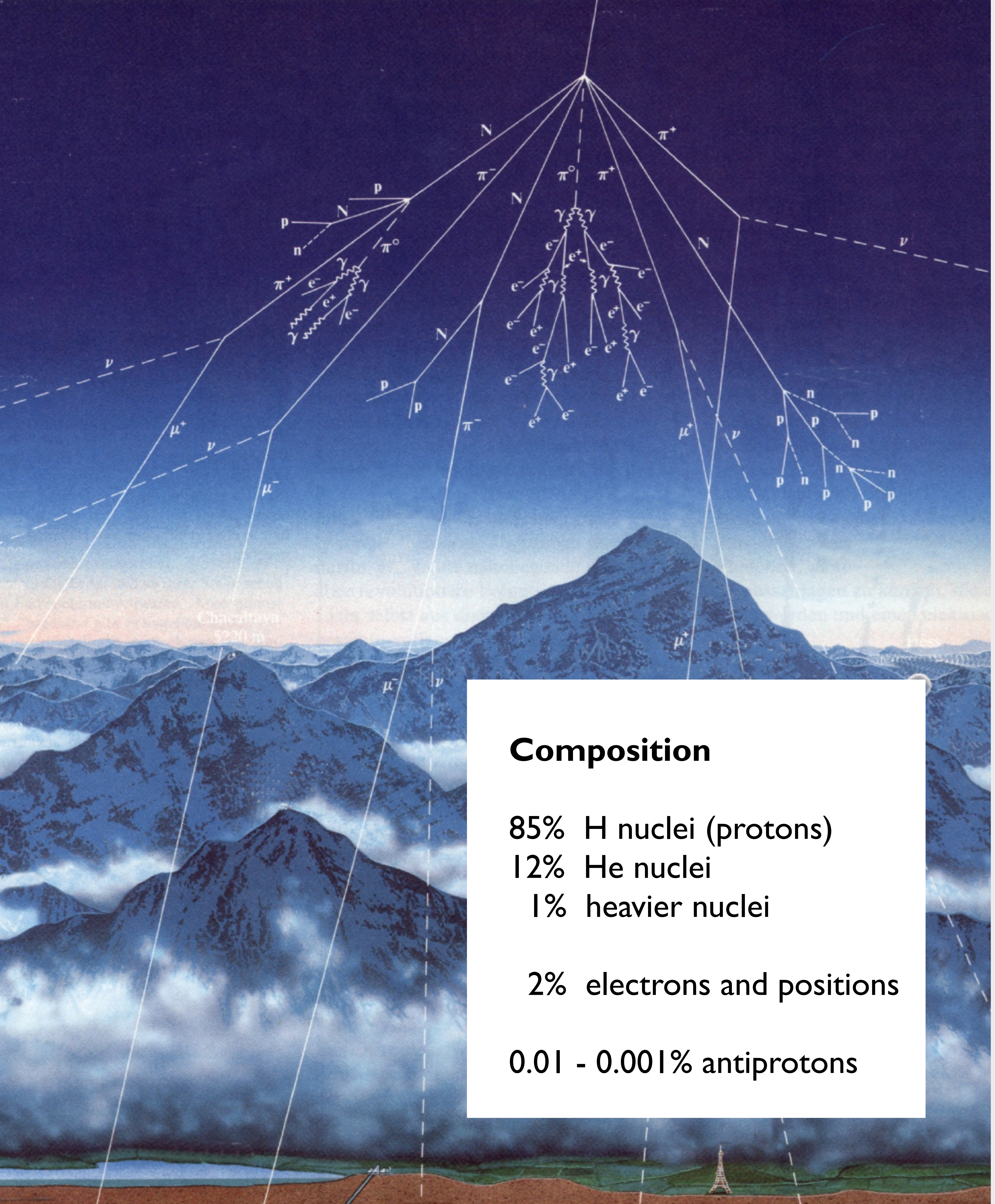
Fixed target: Forward direction (beam fragmentation) covered by detectors

Colliders: Beam direction measurements very challenging (if not impossible)



(Hans Peter Beck, 2007)

Flux of cosmic rays



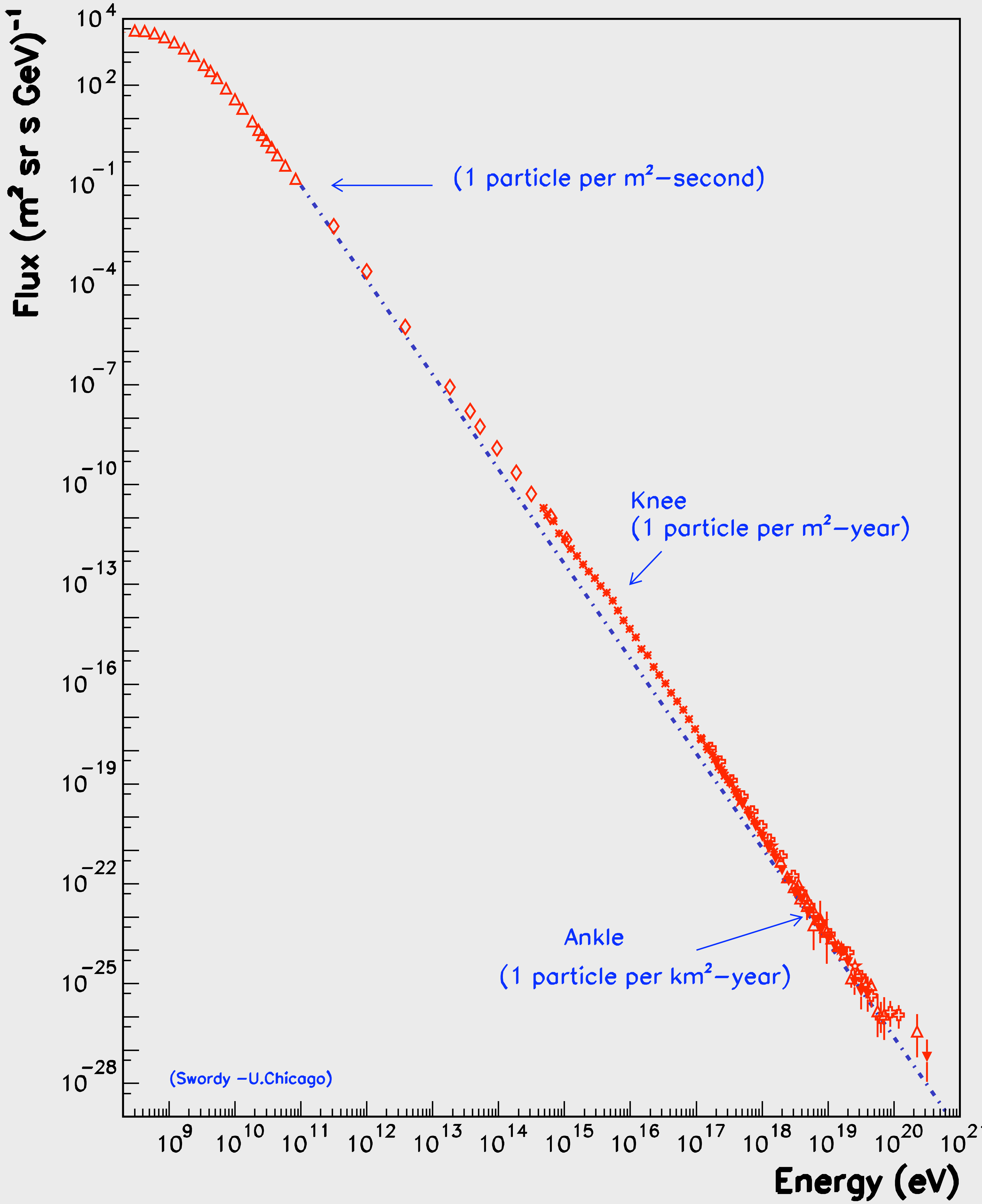
Composition

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

2% electrons and positions

0.01 - 0.001% antiprotons

~ 30 - 40 km



Flux of cosmic rays

Flux approximately power law

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

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

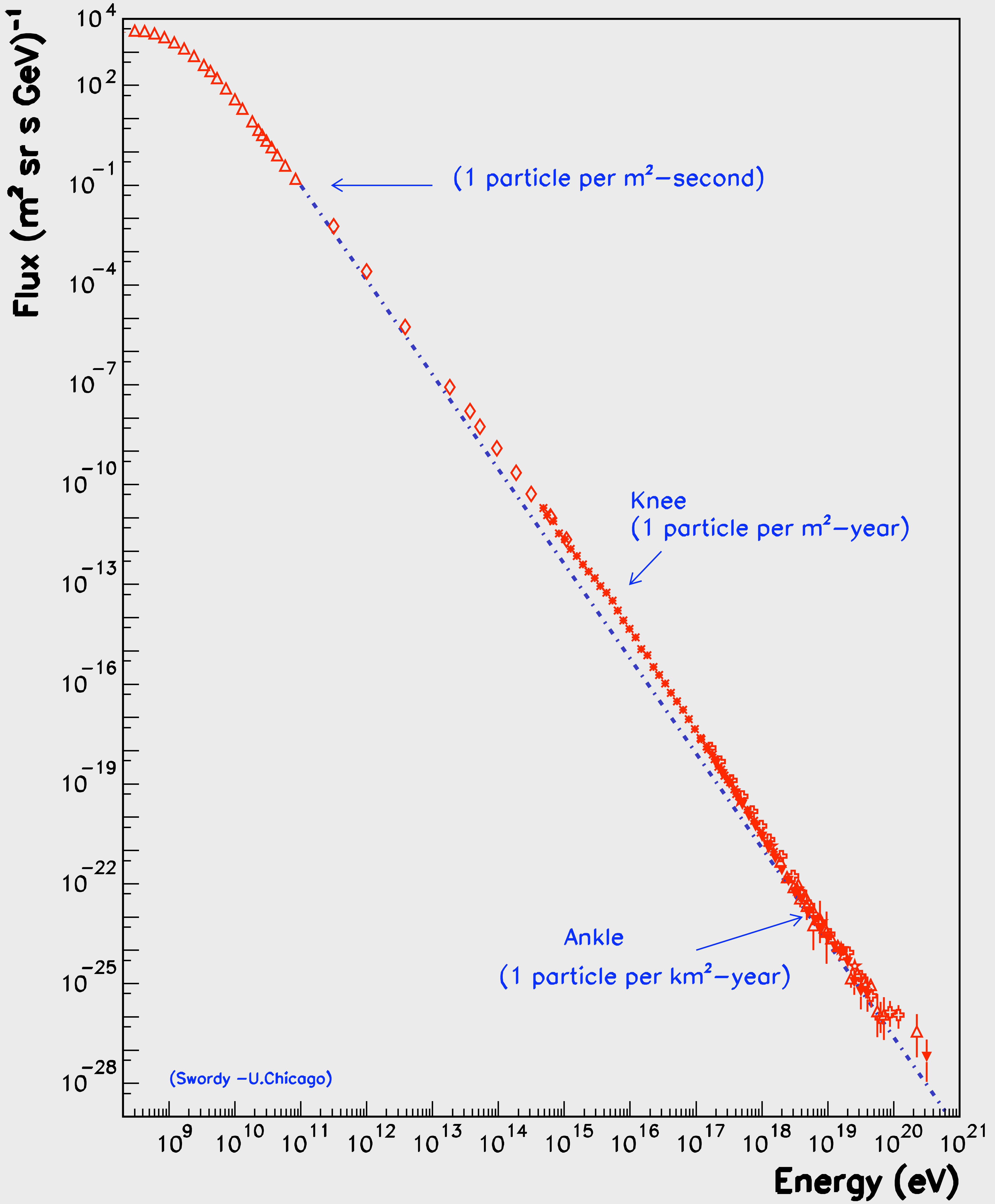
Energy spectrum of all-particle flux (energy per particle)

Composition

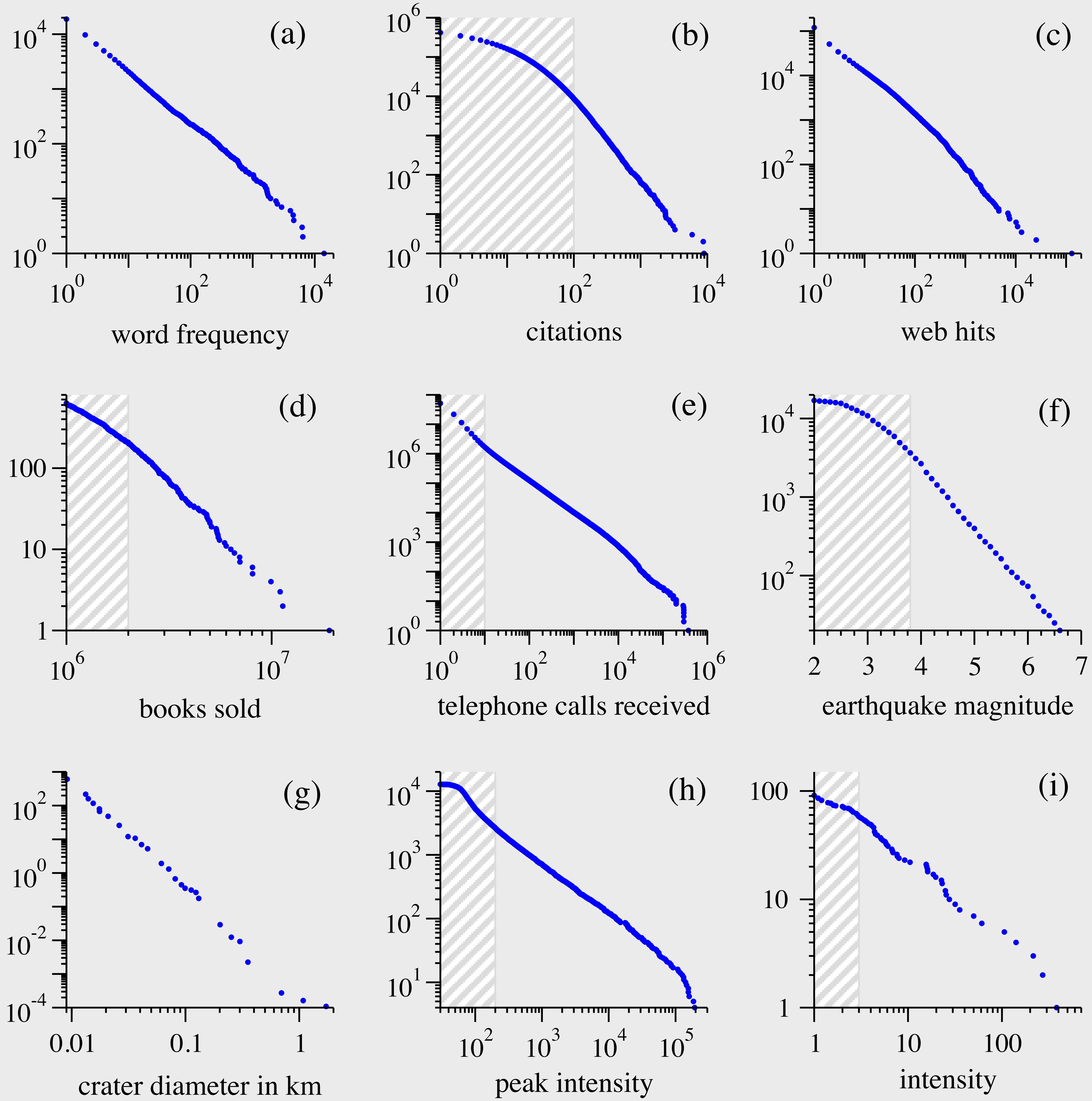
85% H nuclei (protons)
12% He nuclei
1% heavier nuclei

2% electrons and positions

0.01 - 0.001% antiprotons



Power laws are common in nature (i)



Power laws, Pareto distributions and Zipf's law

M. E. J. Newman

Department of Physics and Center for the Study of Complex Systems, University of Michigan, MI 48109. U.S.A.

When the probability of measuring a particular value of some quantity varies inversely as a power of that value, the quantity is said to follow a power law, also known variously as Zipf's law or the Pareto distribution. Power laws appear widely in physics, biology, earth and planetary sciences, economics and finance, computer science, demography and the social sciences. For instance, the distributions of the sizes of cities, earthquakes, solar flares, moon craters, wars and people's personal fortunes all appear to follow power laws. The origin of power-law behaviour has been a topic of debate in the scientific community for more than a century. Here we review some of the empirical evidence for the existence of power-law forms and the theories proposed to explain them.

(M. Newman cond-mat/0412004)

Power laws are common in nature (ii)

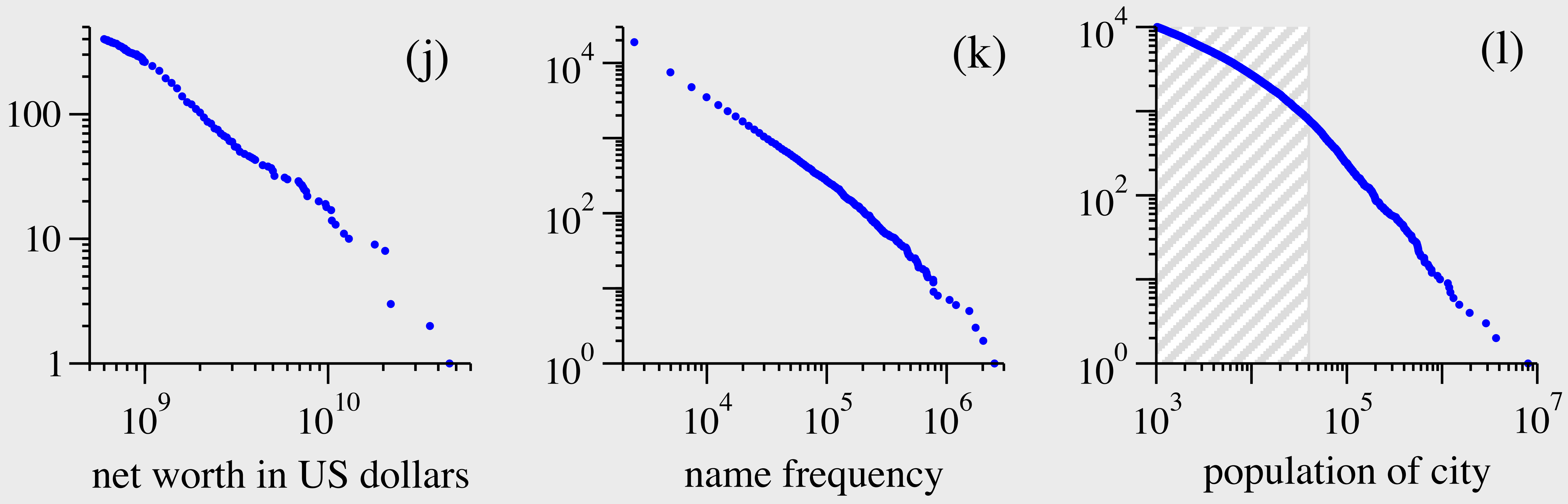
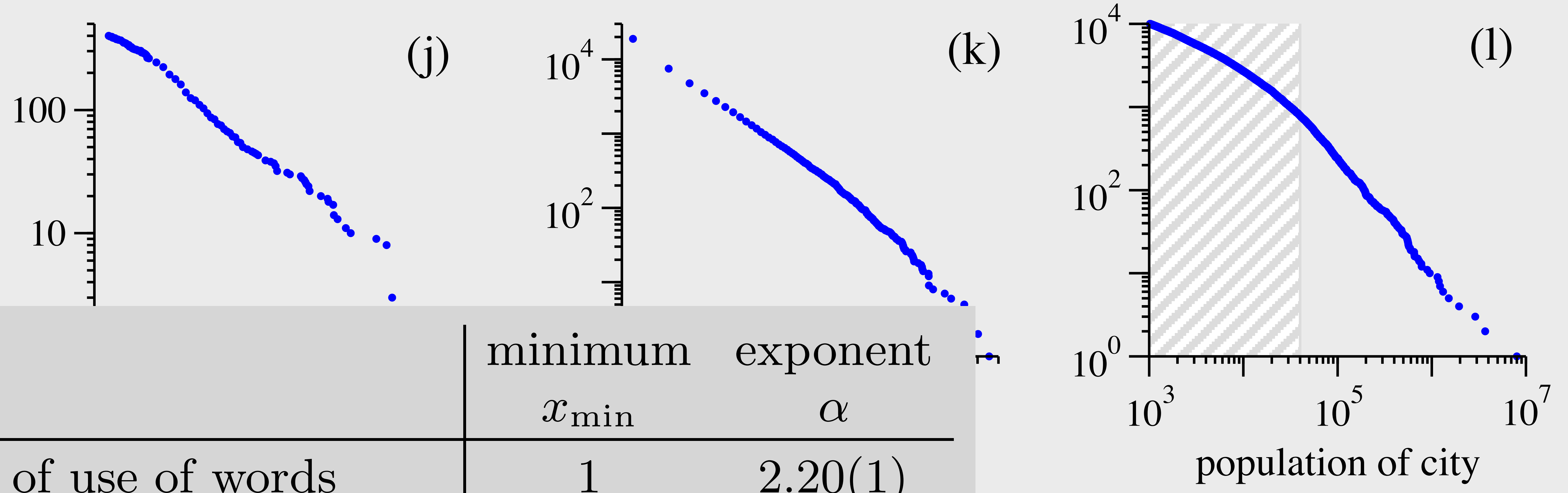


FIG. 4 Cumulative distributions or "rank/frequency plots" of twelve quantities reputed to follow power laws. The distributions were computed as described in Appendix A. Data in the shaded regions were excluded from the calculations of the exponents in Table I. Source references for the data are given 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)



	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)

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ond, measured from Earth orbit between February
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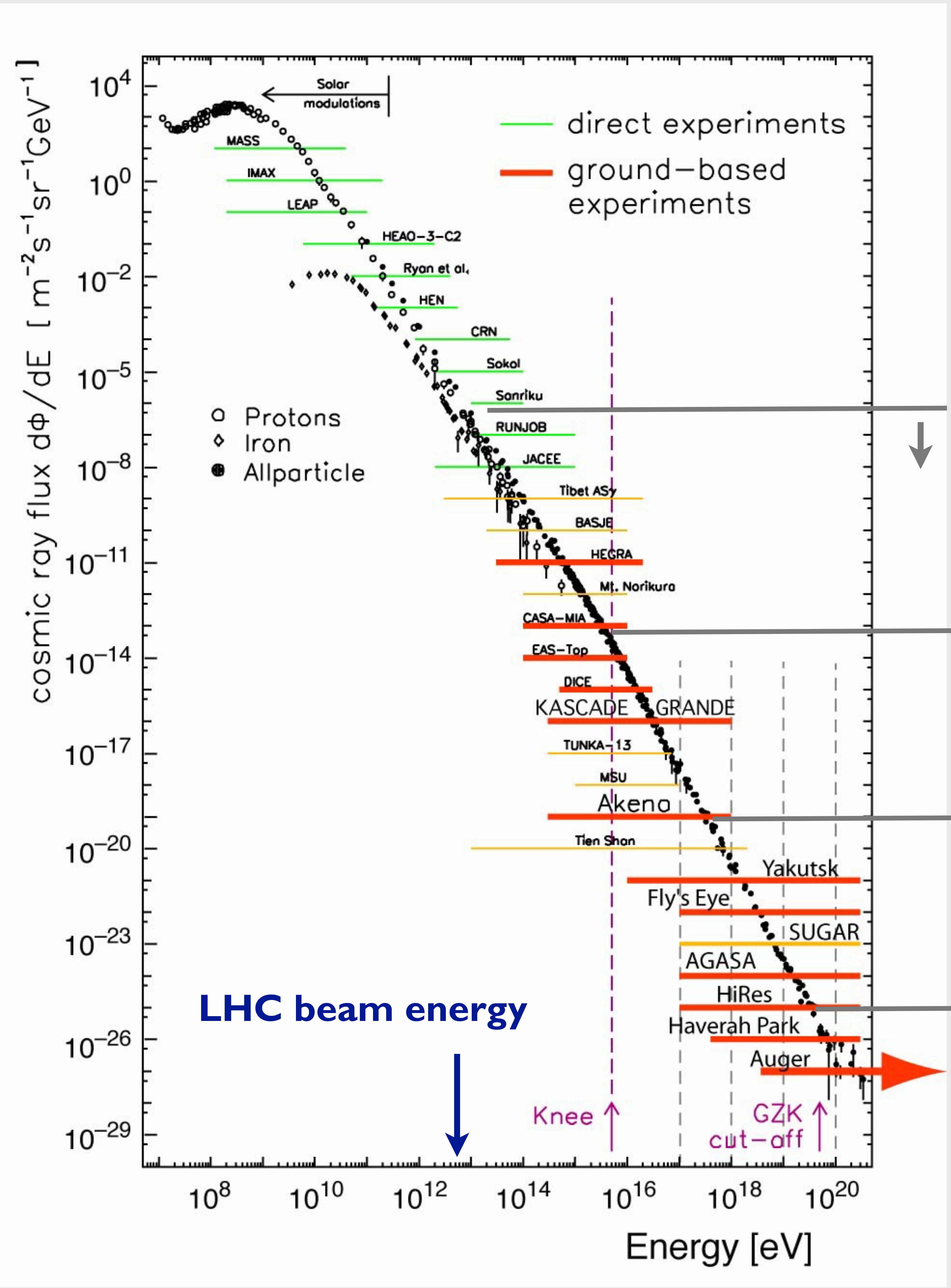
dividuals in the US in October 2003. (k) Frequency
of US cities in the year 2000.

(M. Newman cond-mat/0412004)

Rate of particles



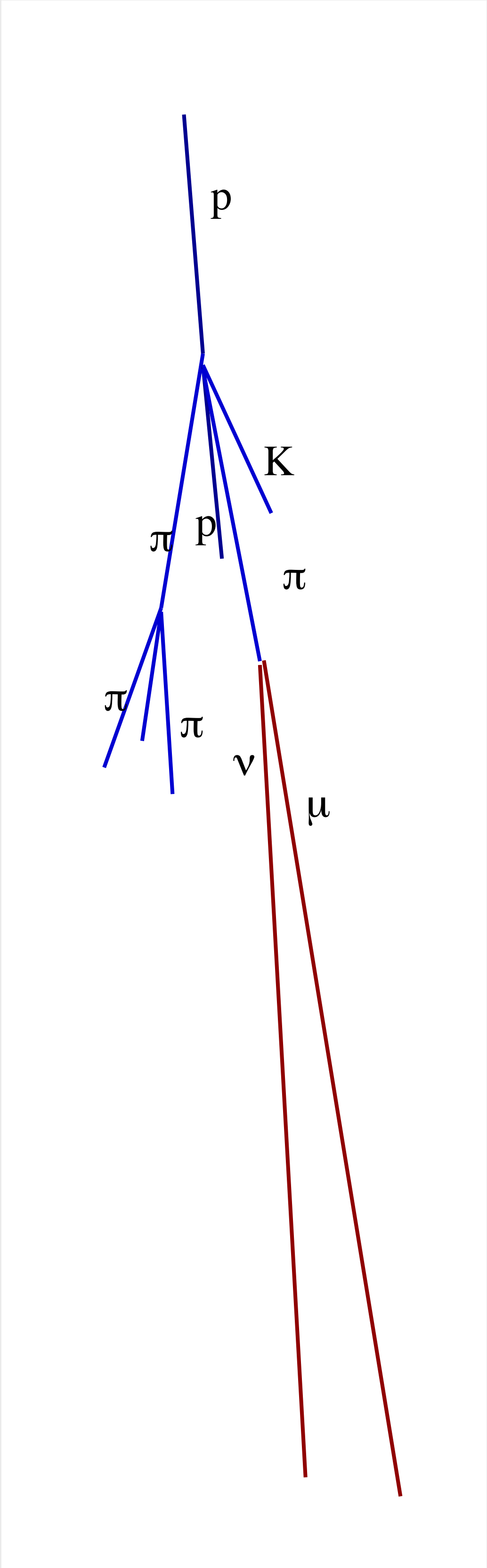
0.1 particles / m^2 min.

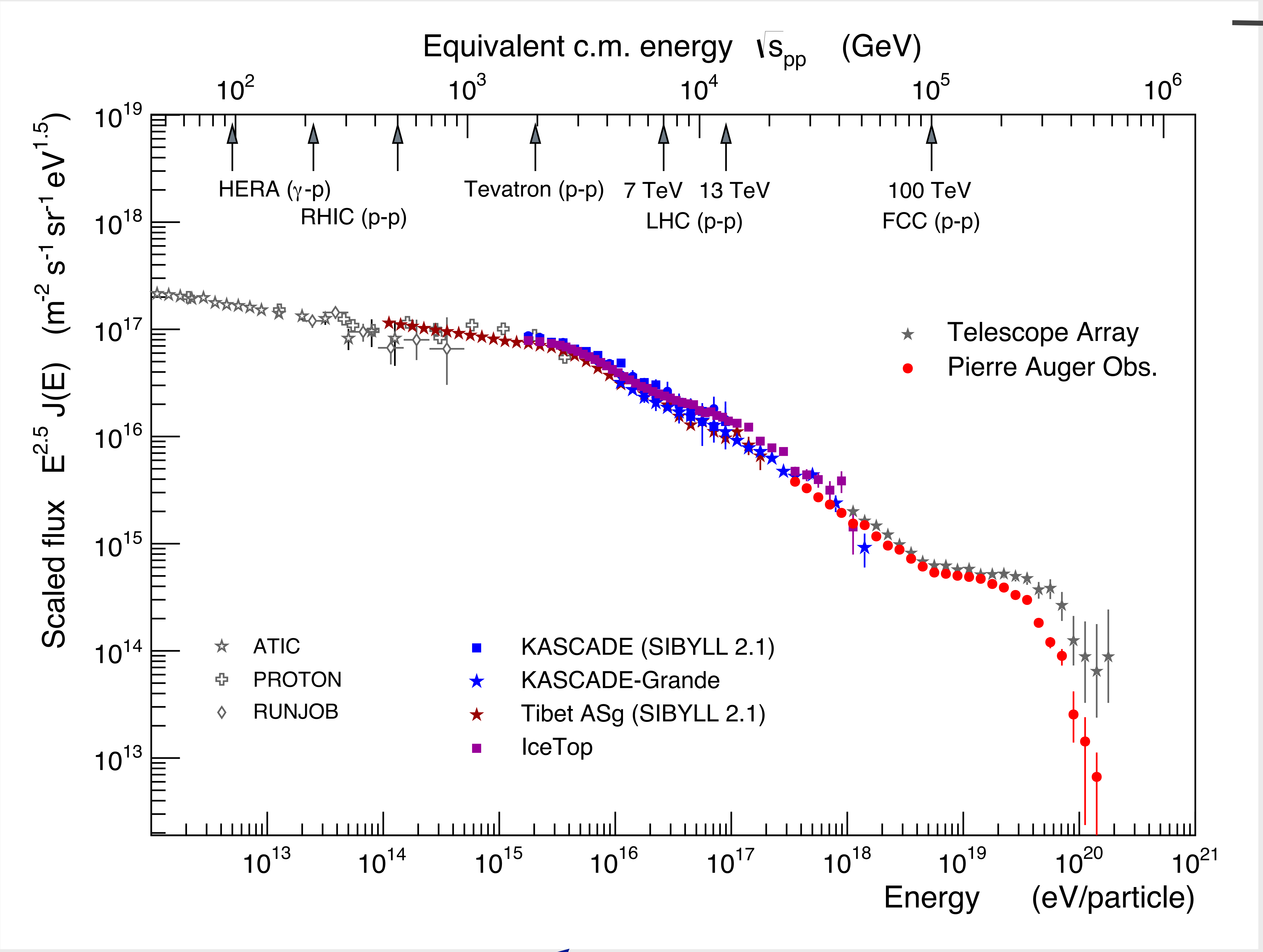
10 particles / km^2 min.

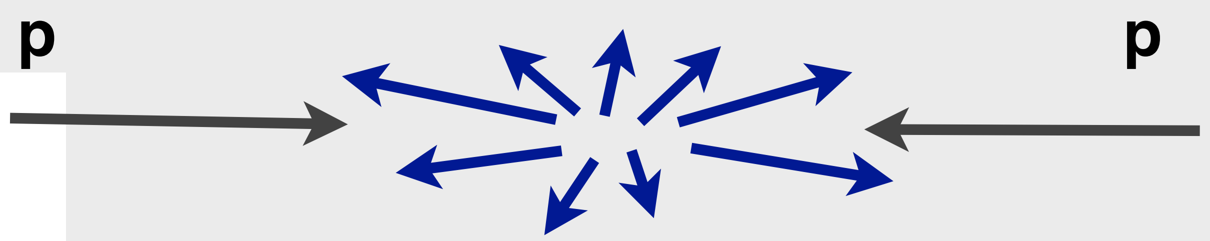
10 particles / km^2 day

10 particles / km^2 century

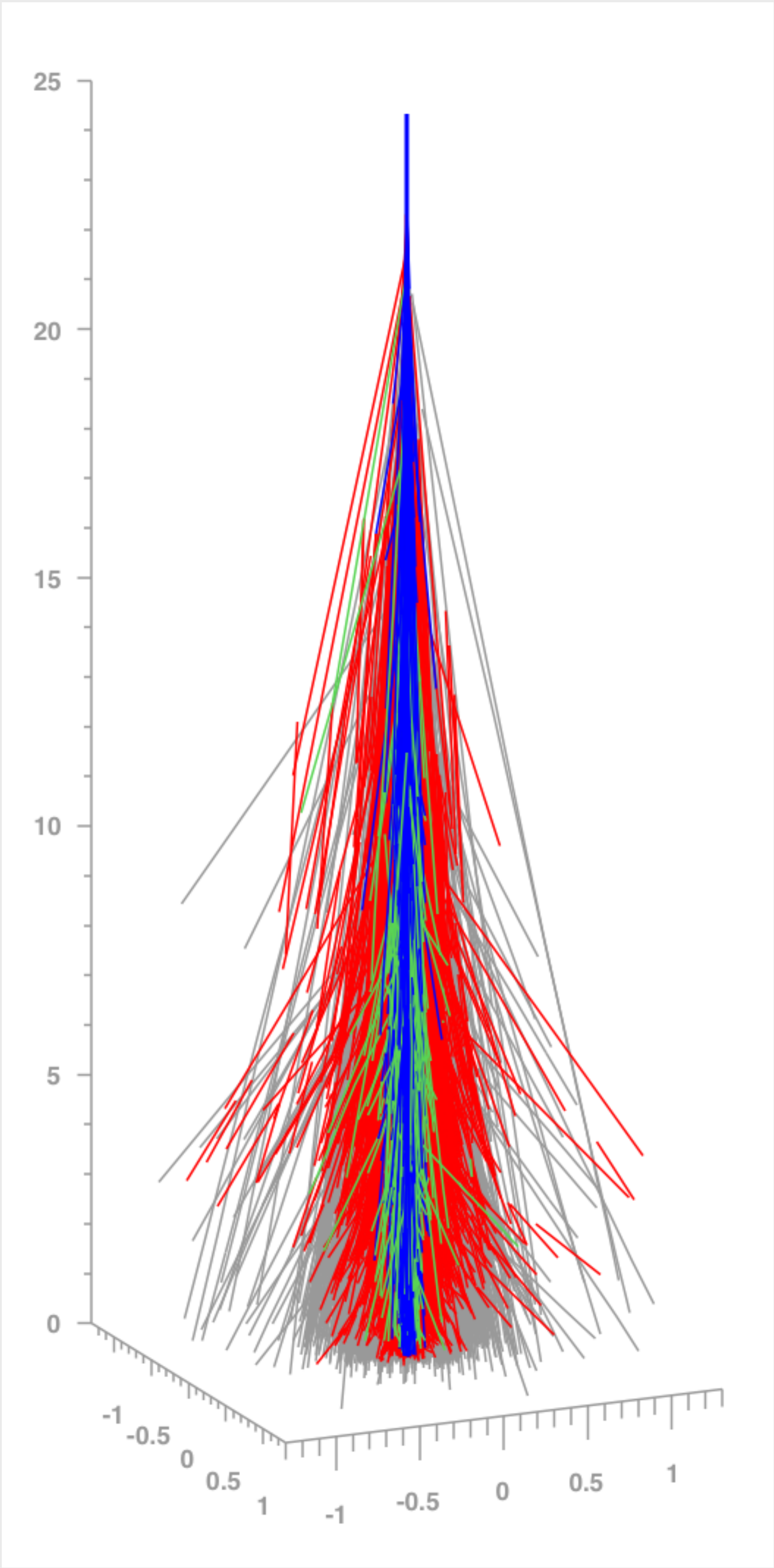
Cosmic ray flux and interaction energies



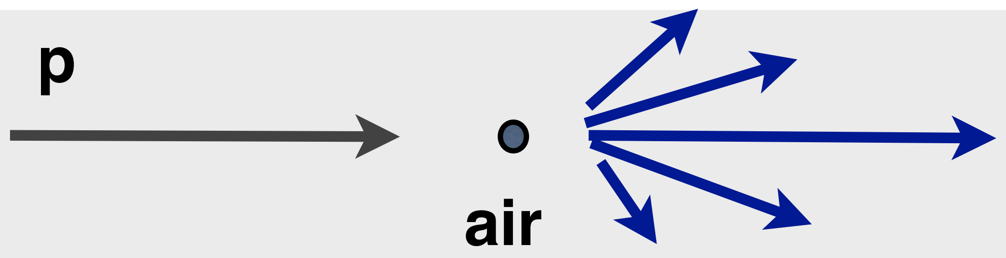




Center-of-mass energy



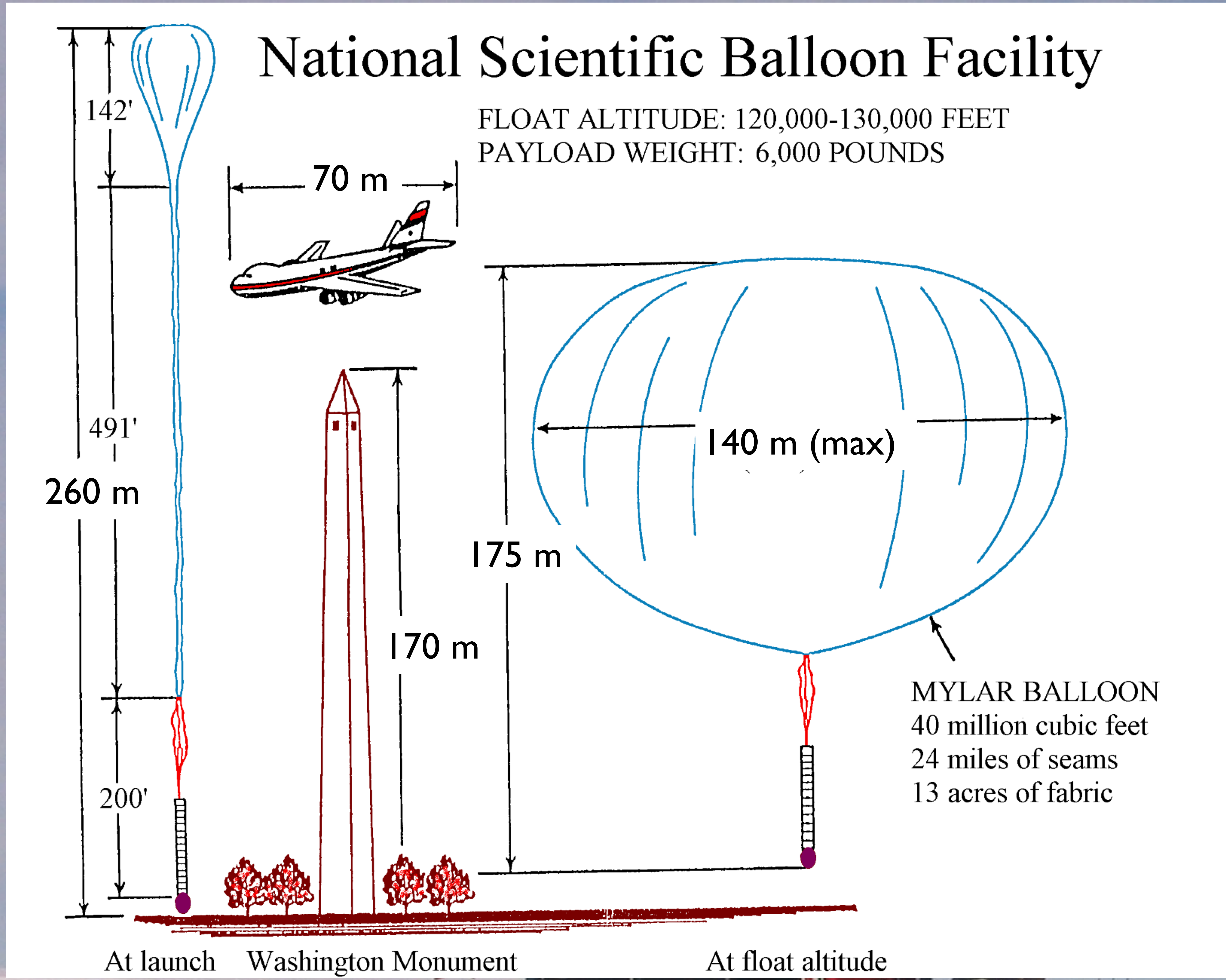
Laboratory energy



Outline of lectures

- Cosmic rays below the knee – direct measurements
- Physics of extensive air showers
- Discussion and exercises *(topics to be decided)*
- Cosmic rays of very high energy – indirect measurements

Long-duration balloon flights

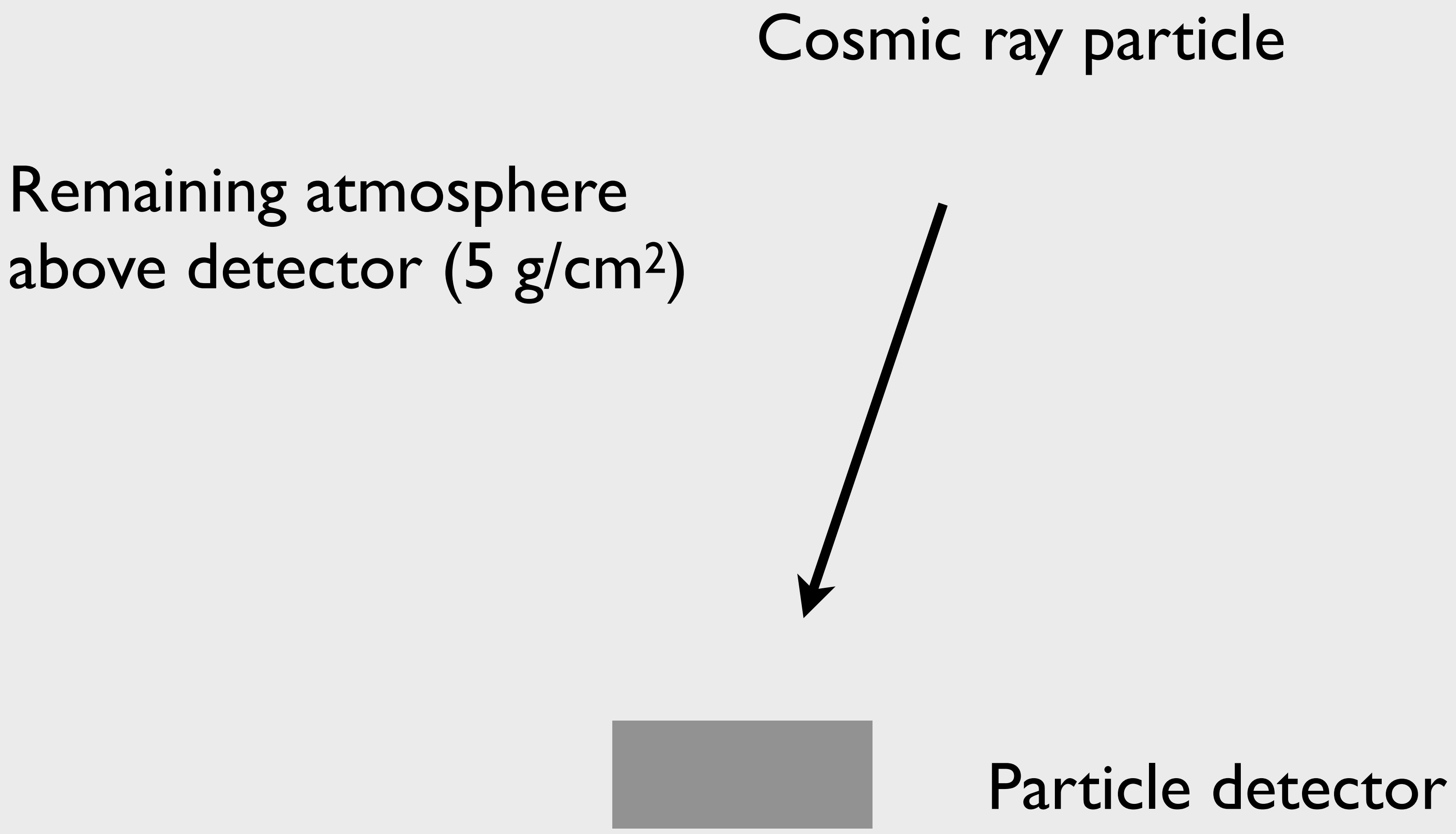


Flight altitude 30-35 km

r weight

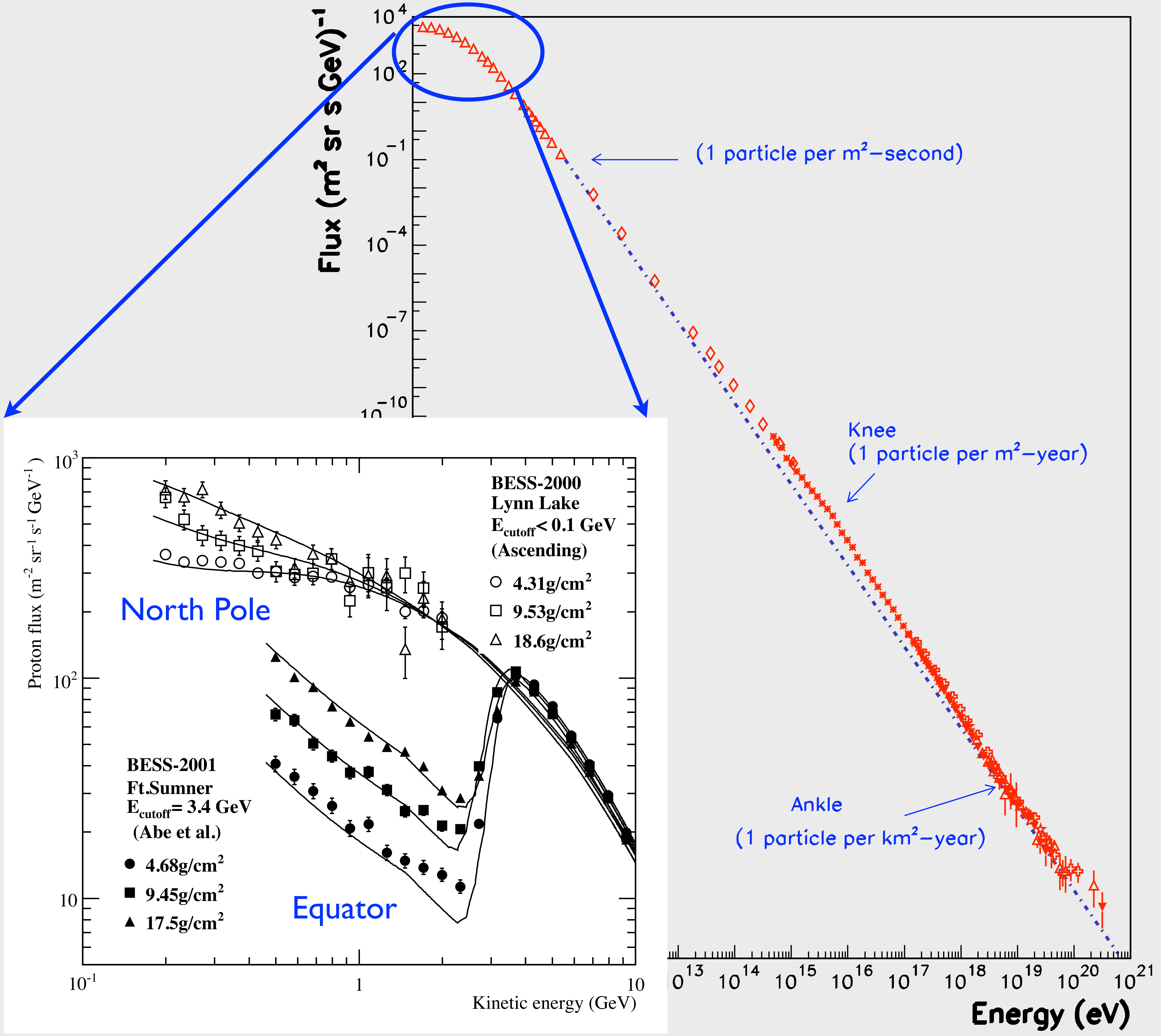
o < 3 tons

Flux at low energy



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

Total atmosphere (vertical) $X_{atm} \approx 1030$ g/cm²



Geomagnetic cutoff and East-West effect

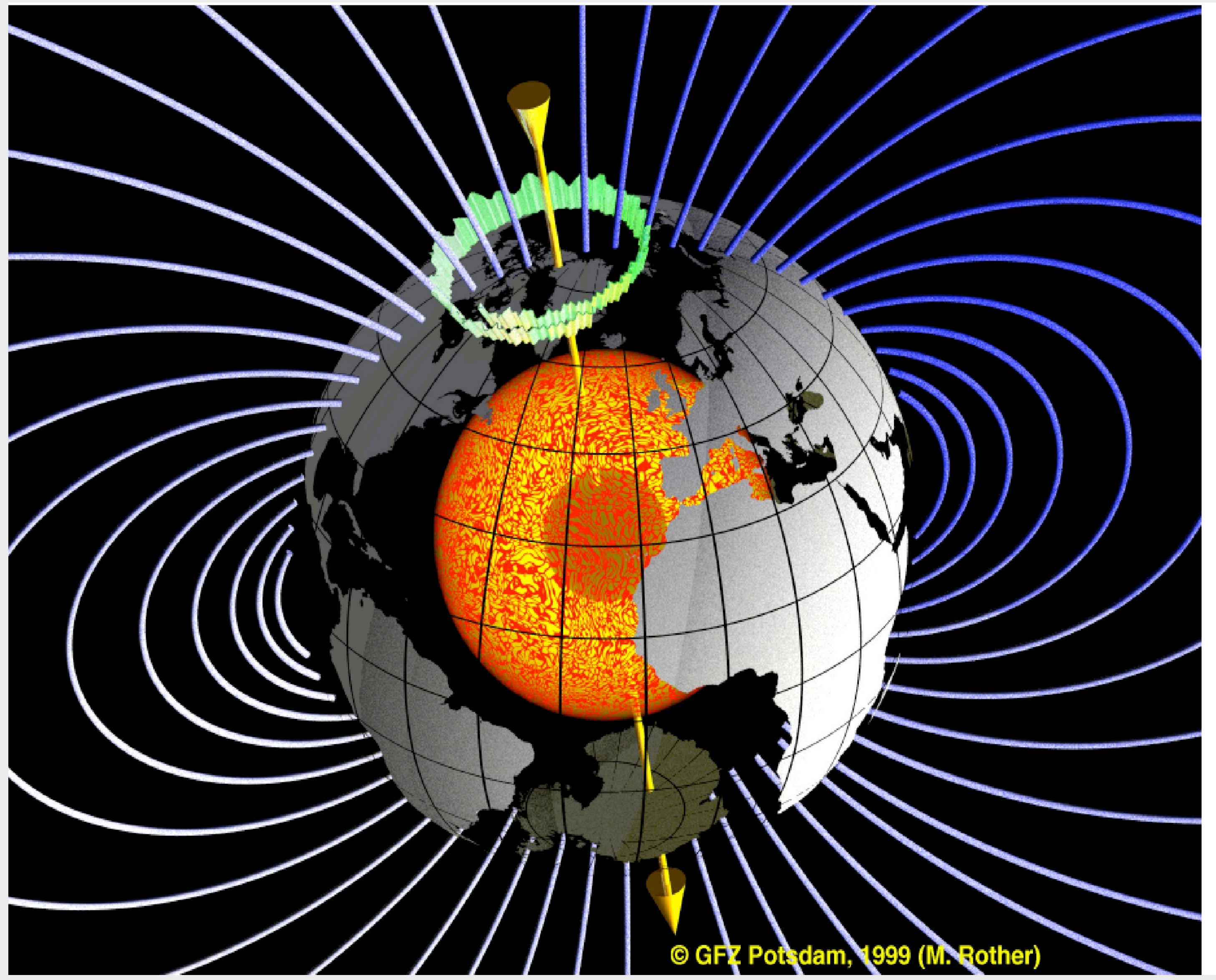
Lorentz force $F_L = qvB$

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

Charge $q = Ze$

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

Rigidity $R = \frac{p}{Ze} \approx \frac{E}{Ze}$

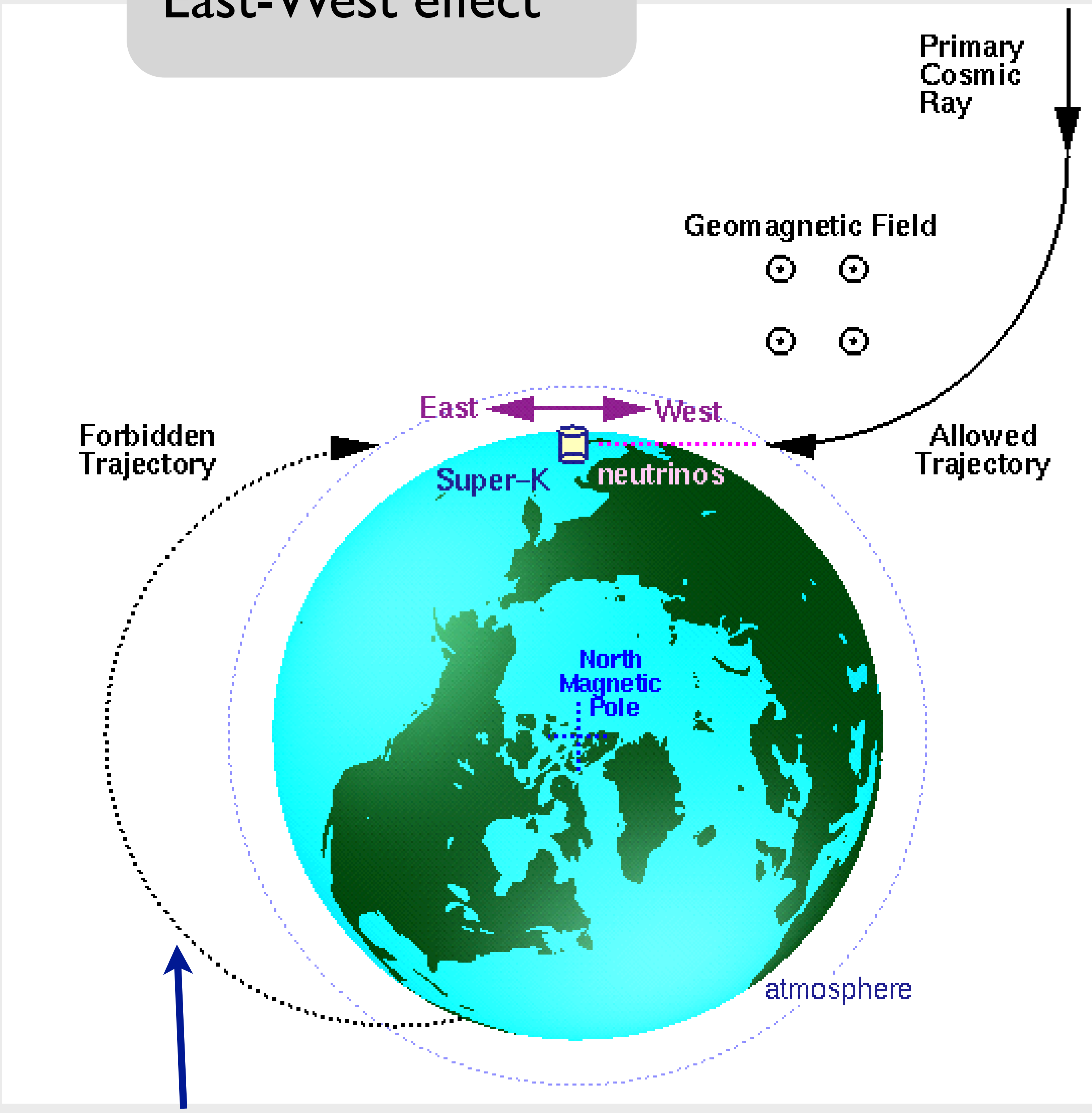


Earth's magnetic field

Vicinity 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

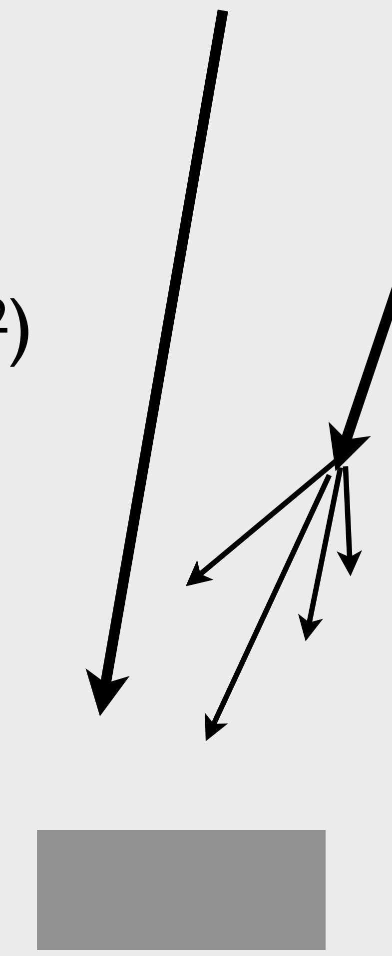


Radius of curvature smaller than radius of Earth

Flux at low energy

Particles with energy greater than cutoff energy

Remaining atmosphere above detector (5 g/cm²)



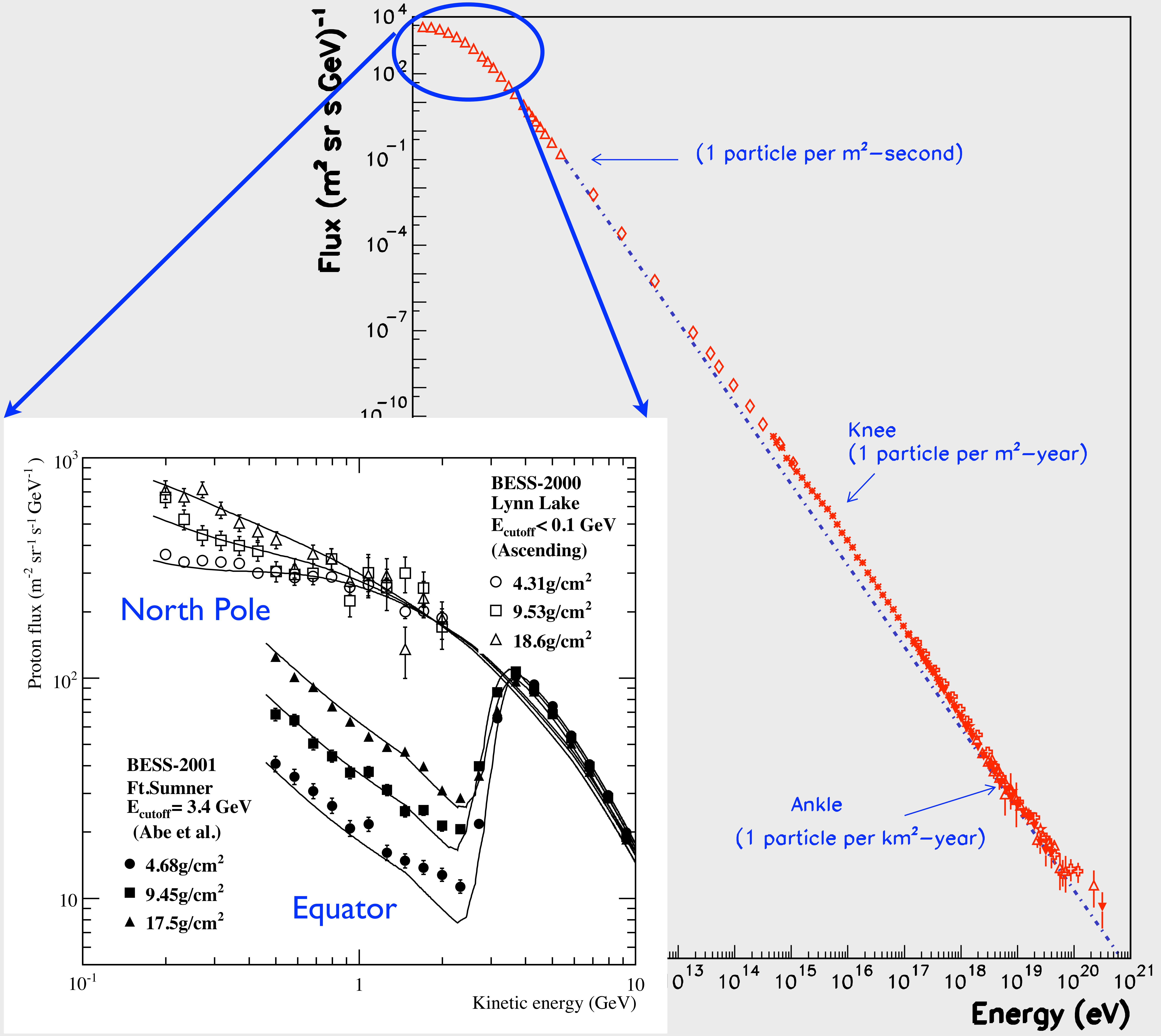
Secondaries

Particle detector

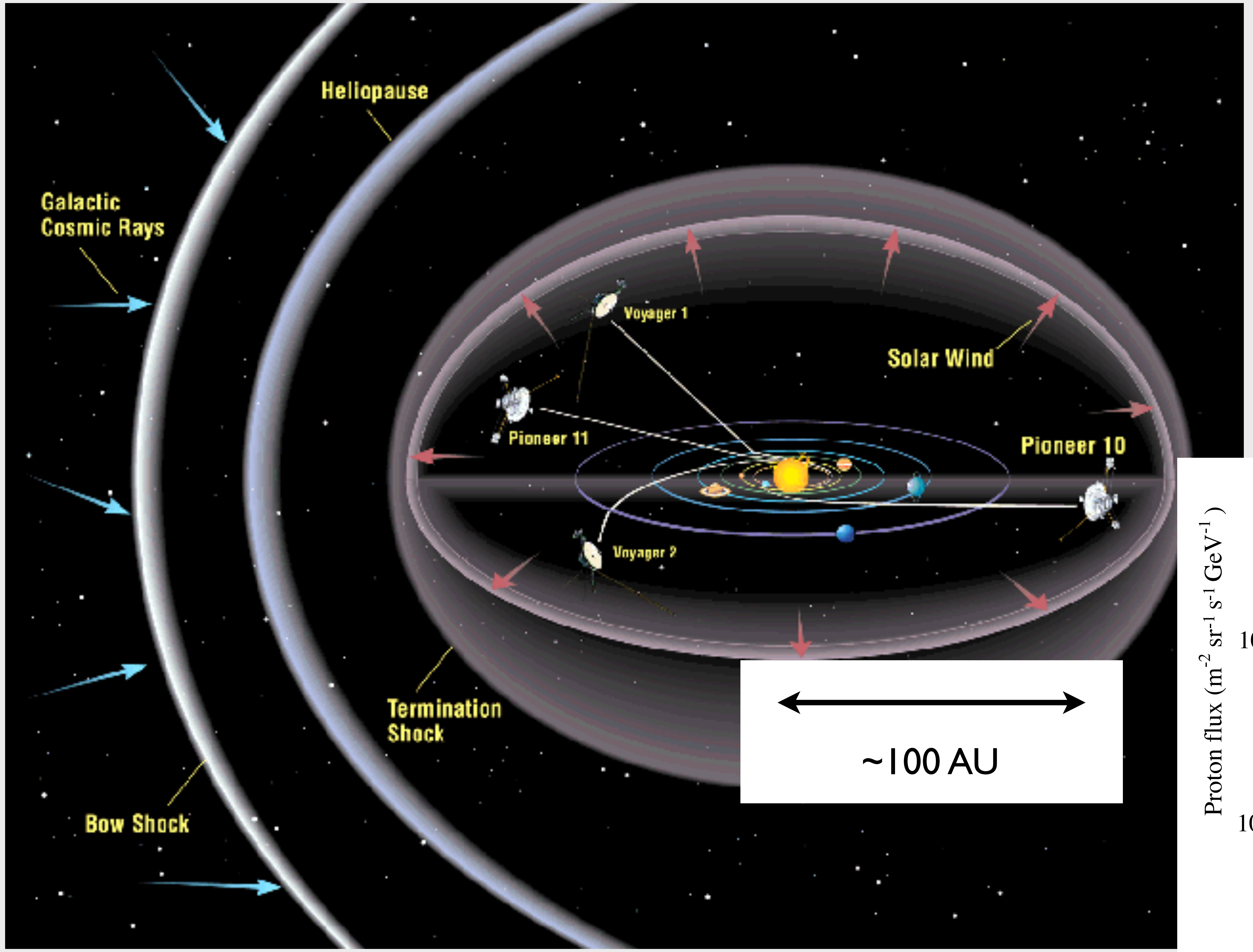
Traversed column depth

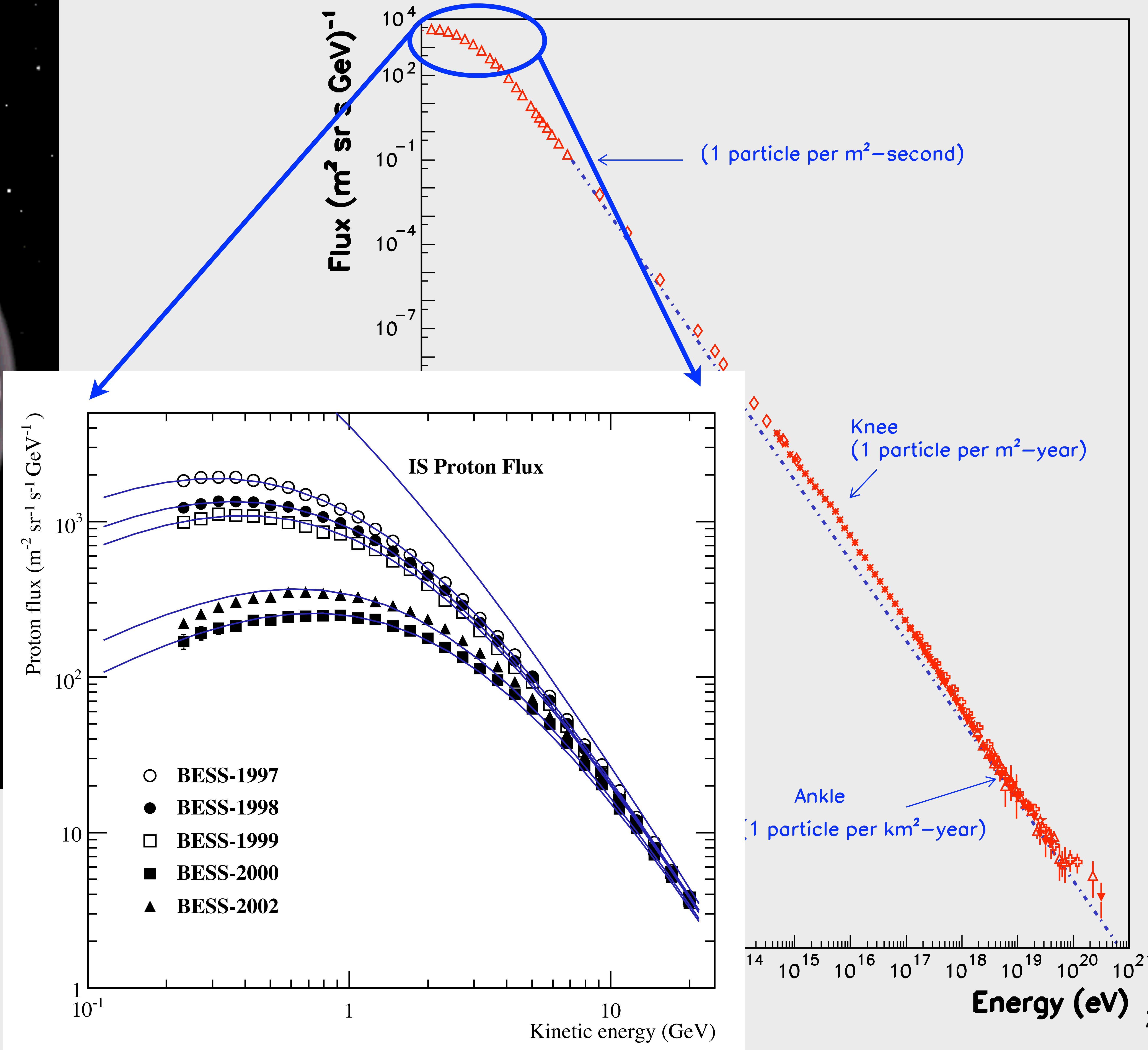
$$X = \int_h^\infty \rho(h)\,dl$$

Total atmosphere (vertical) $X_{atm} \approx 1030$ g/cm²



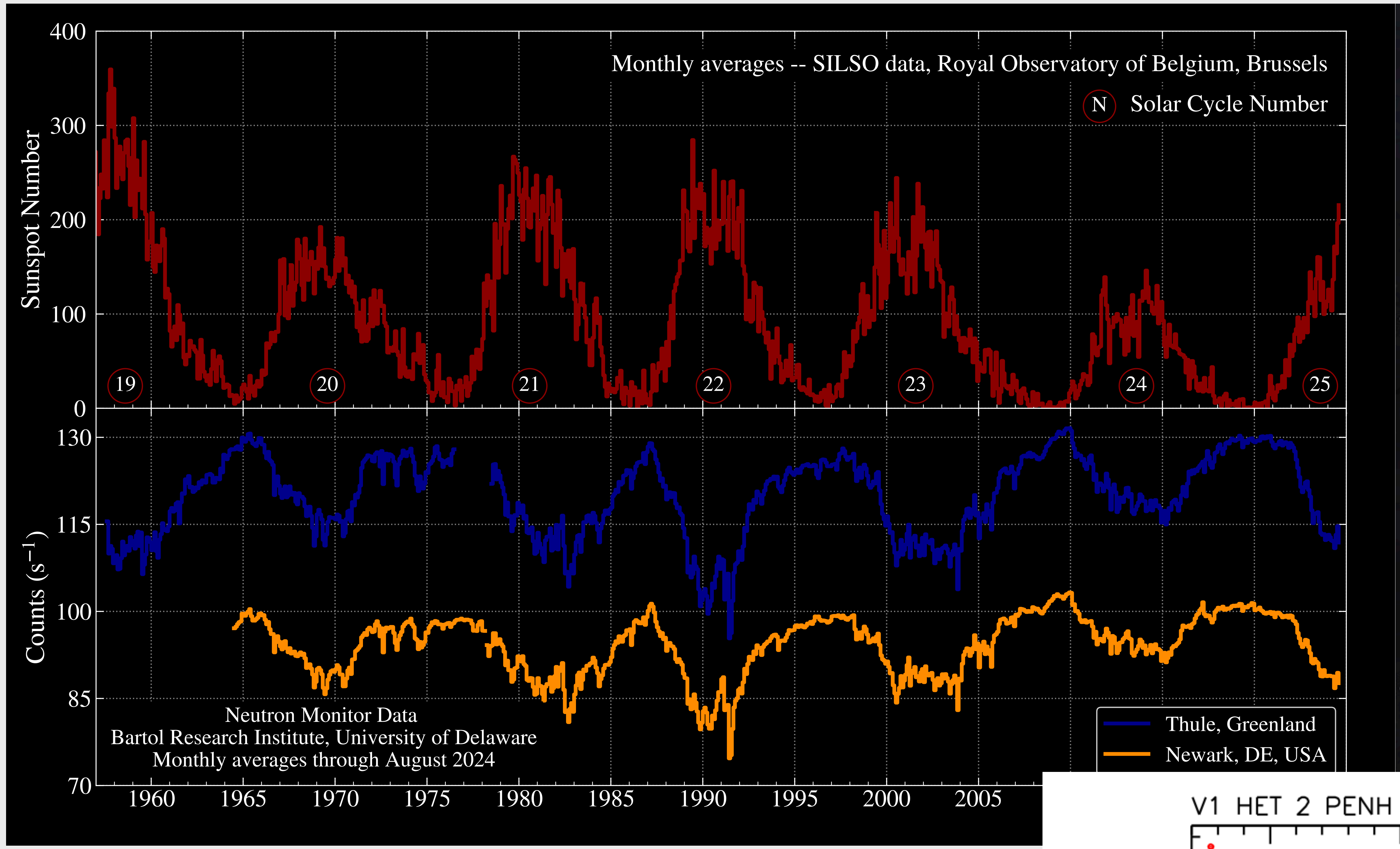
Solar modulation of cosmic flux

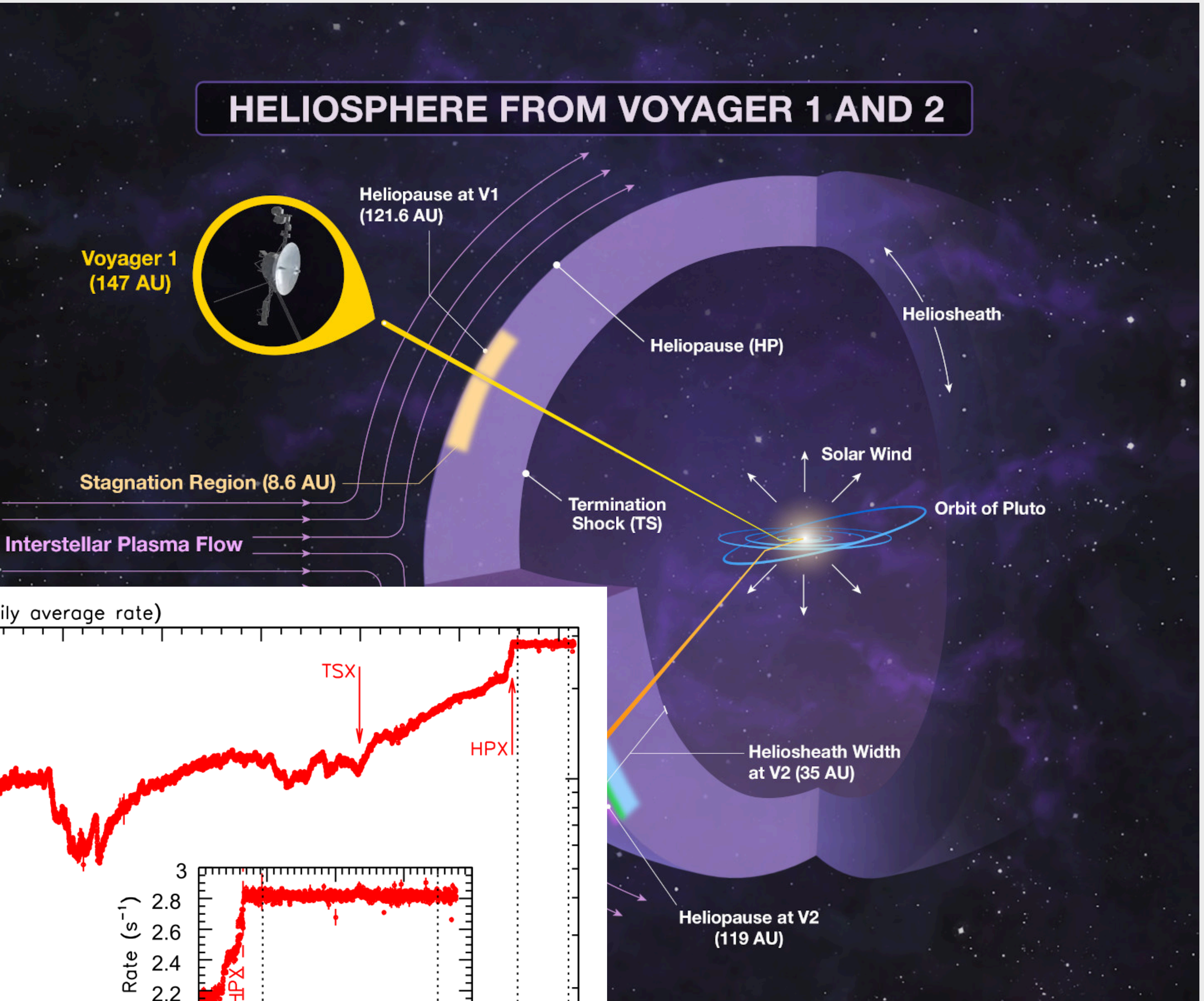




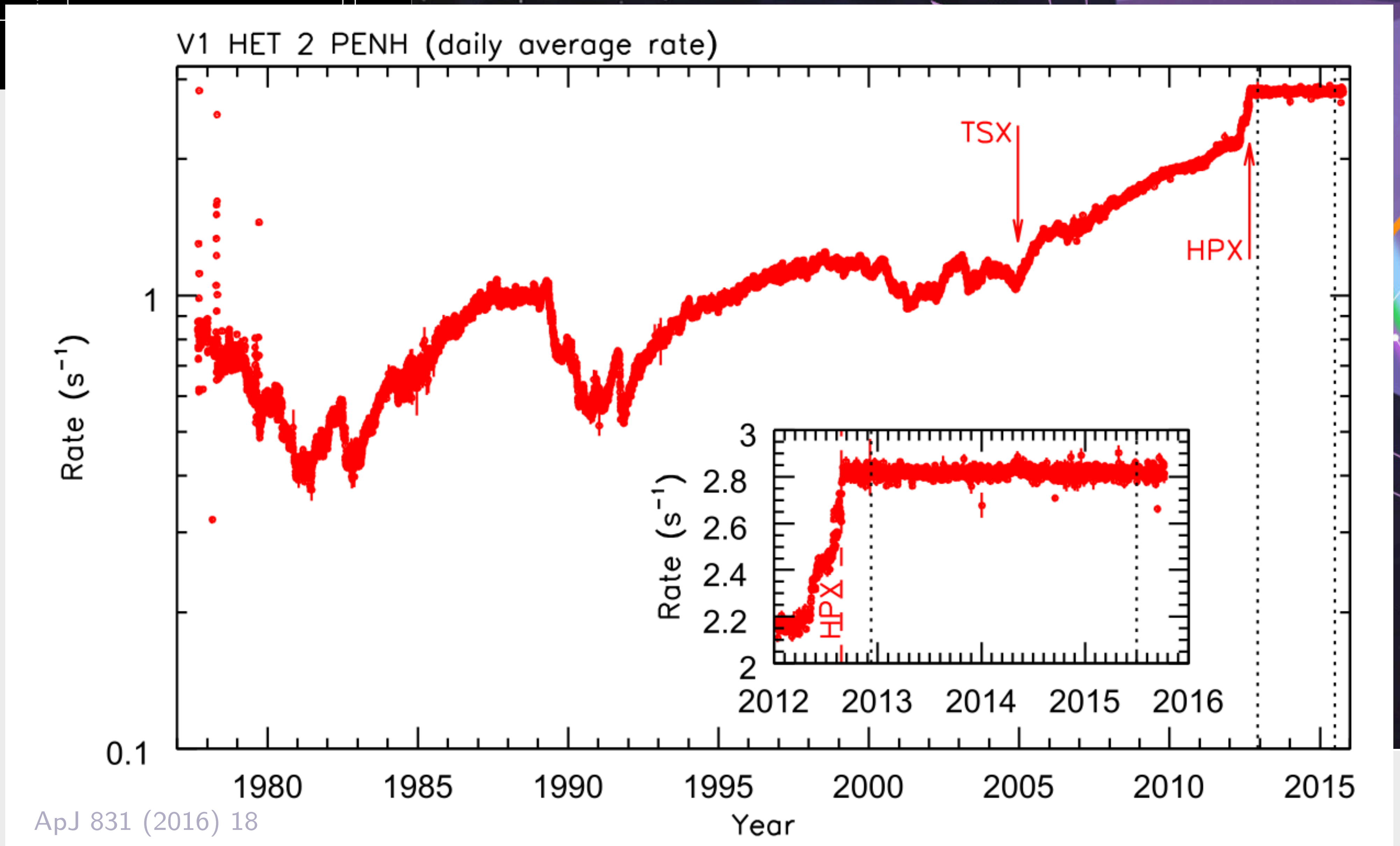
$$\Phi_{\text{Earth}}(E) = \frac{E^2 - m^2}{(E + Z \cdot V_{\text{pot}})^2 - m^2} \Phi_{\text{ISM}}(E + Z \cdot V_{\text{pot}})$$

Solar modulation – observations





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



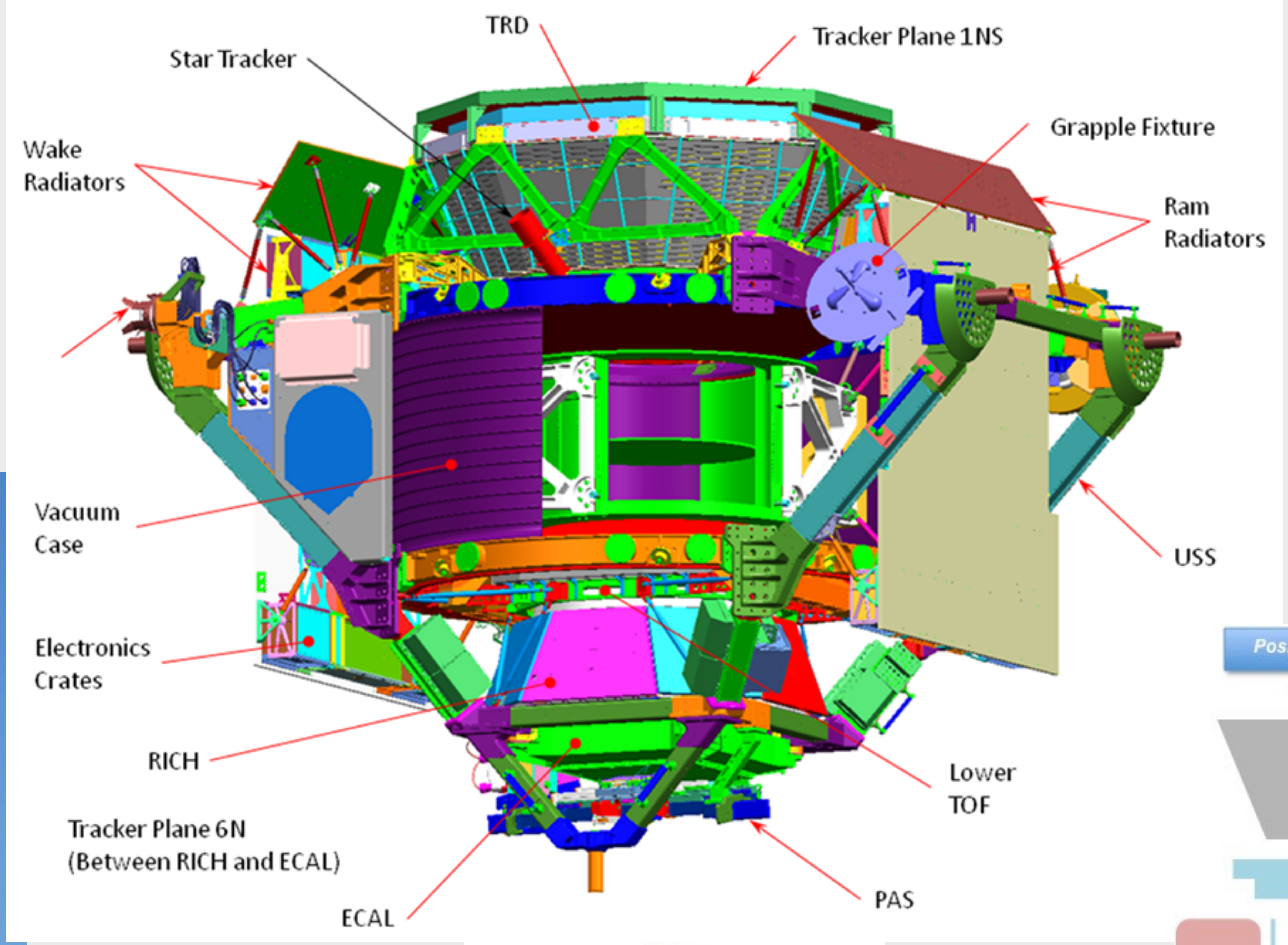
ApJ 831 (2016) 18

Interstellar flux observed by Voyager 1 satellite

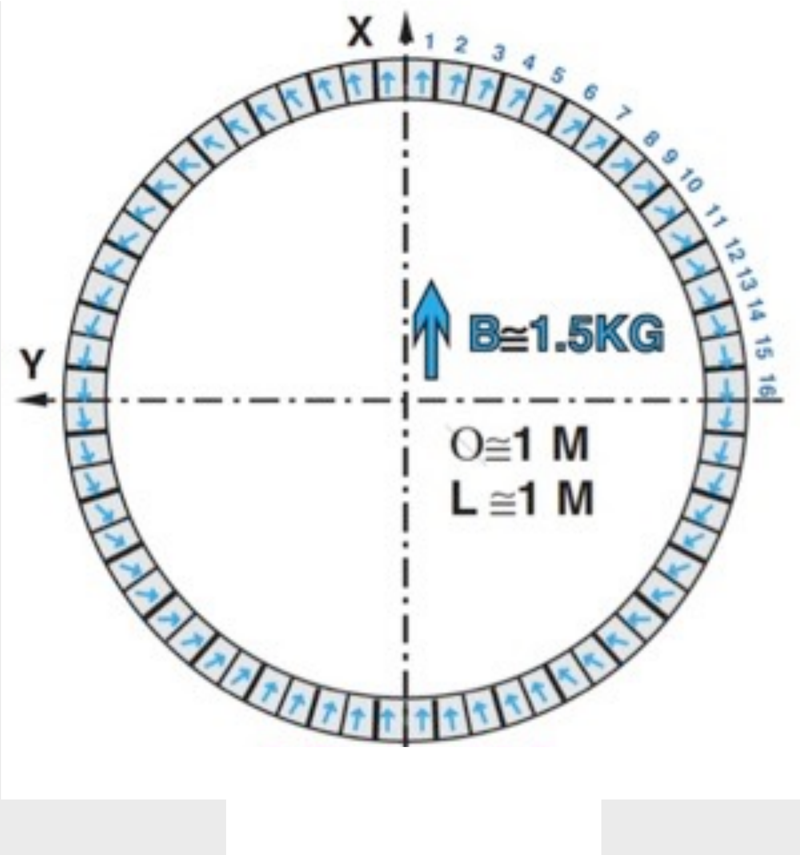
AMS 02

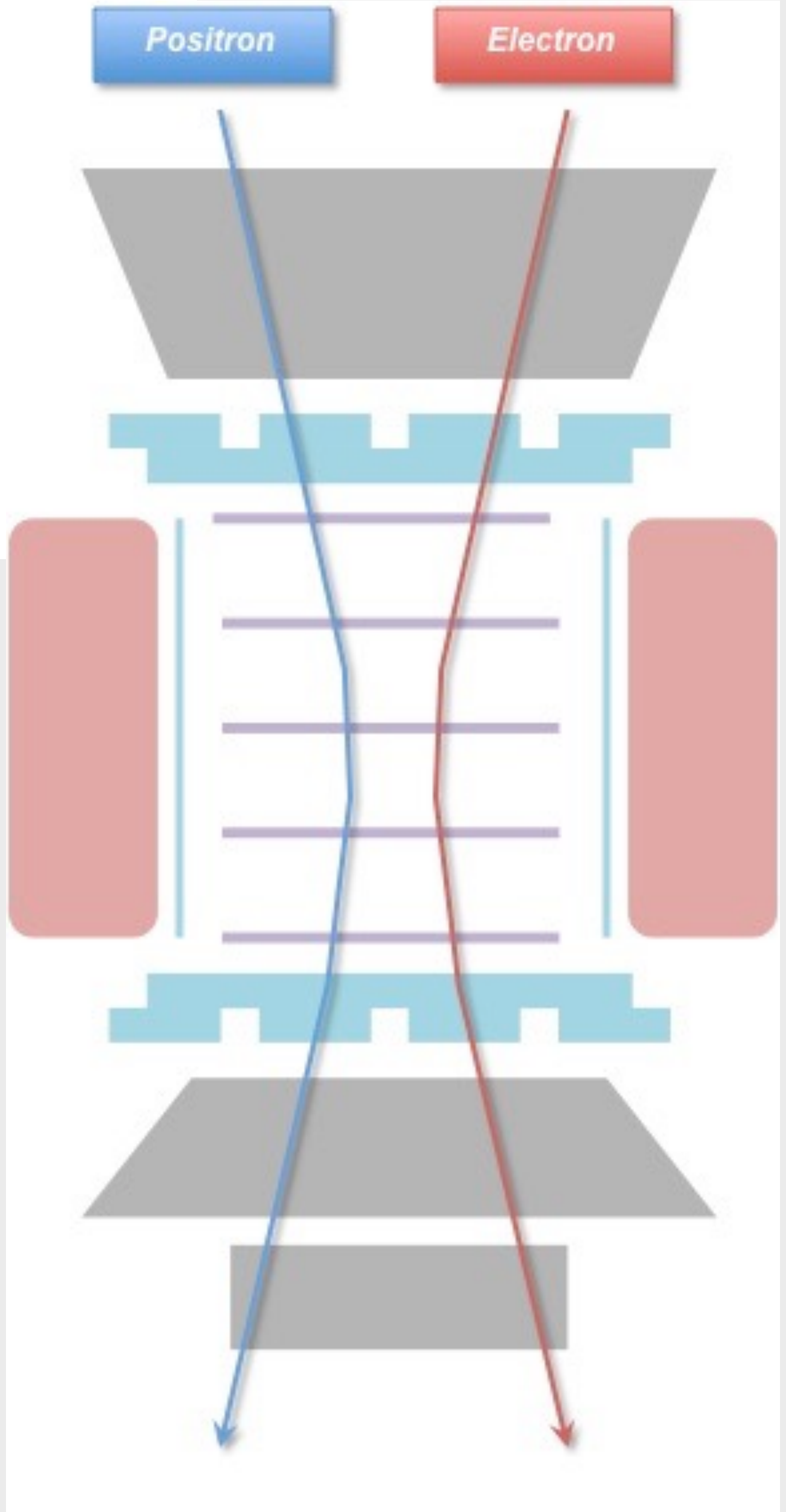
Launch: May 16, 2011

Payload Commander Andreas Sabellek (KIT)



Permanent magnet spectrometer



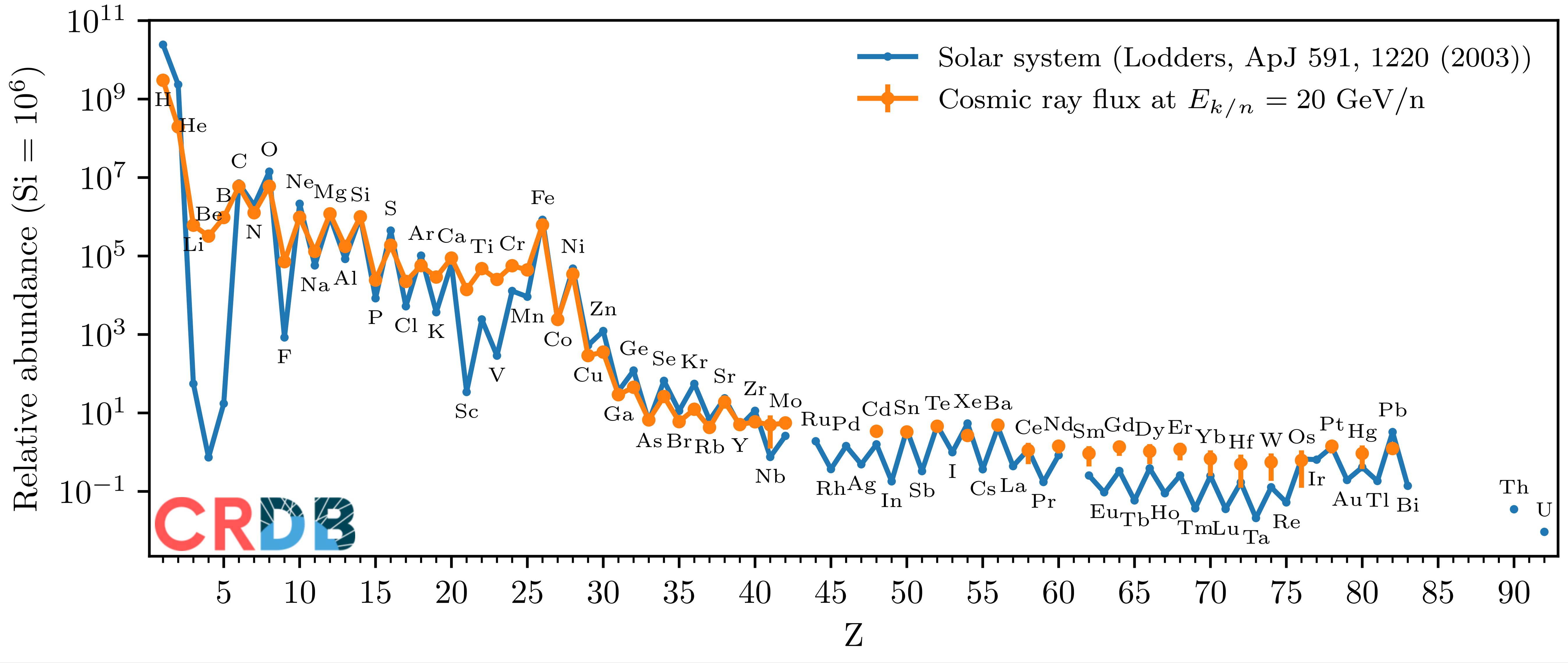


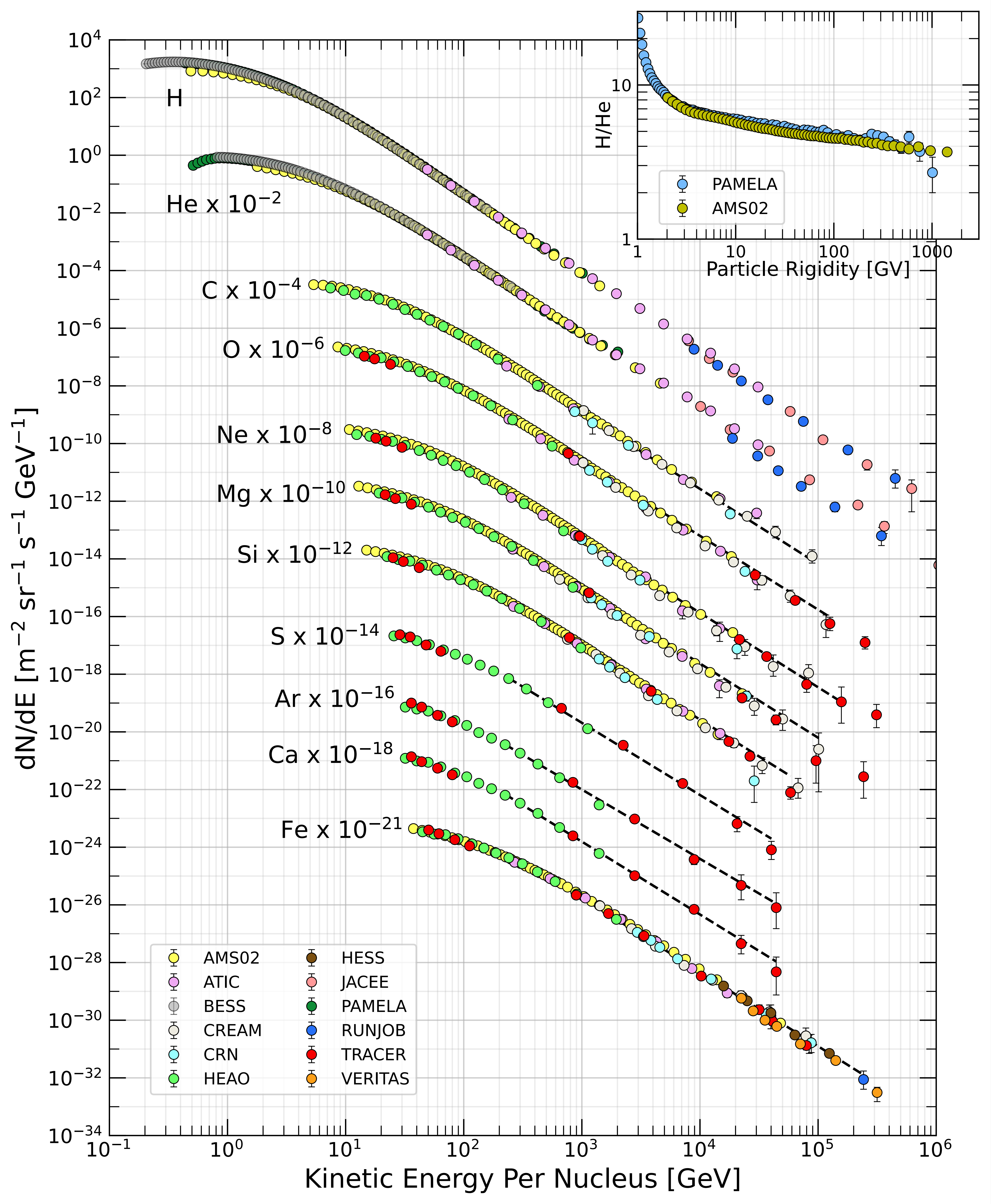
Fluxes of individual elements

Direct measurement of cosmic rays
by balloon-borne detectors or satellites

Power law also found for individual elements,
index of power law almost identical
(but important differences like p/He)

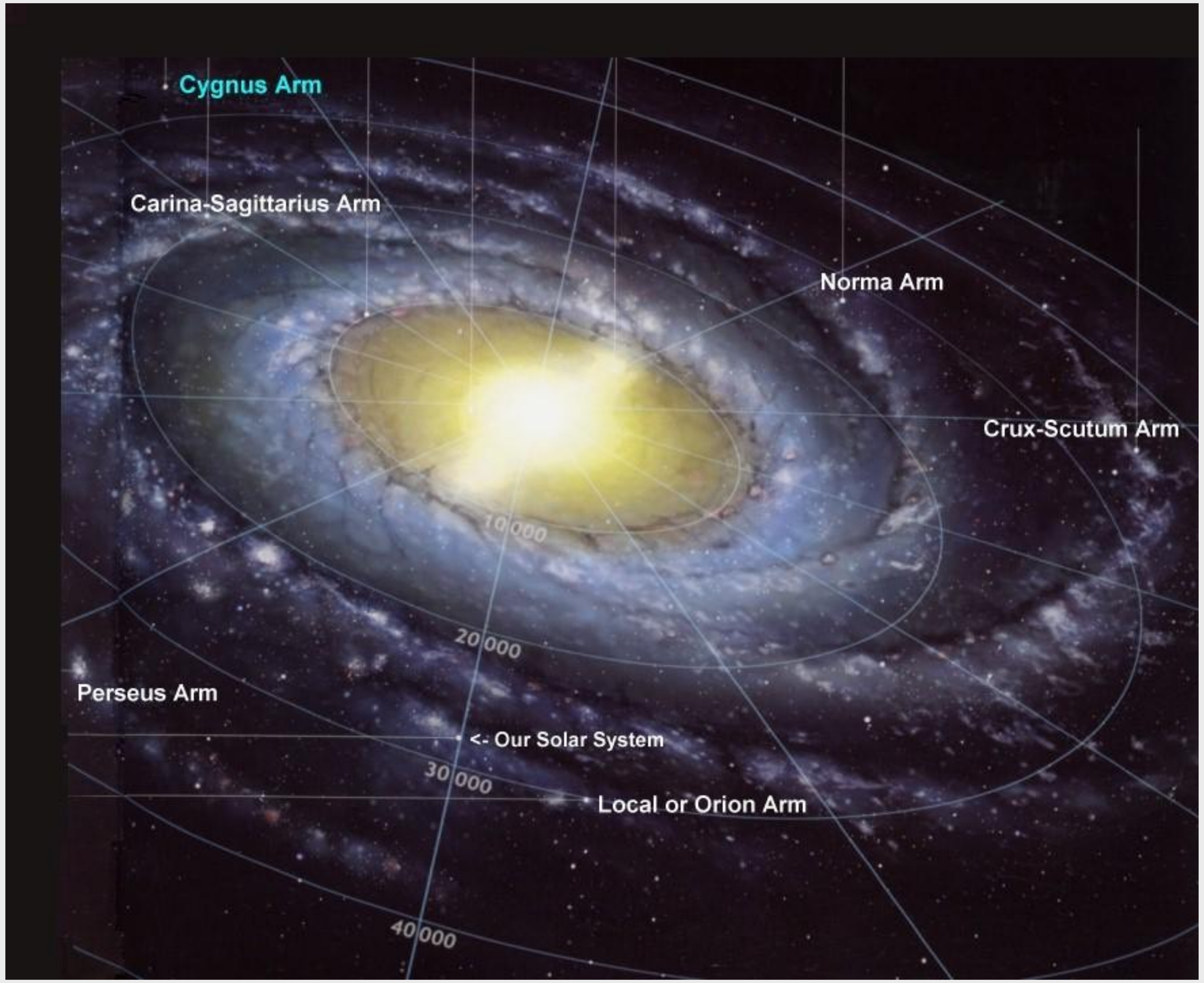
Similar to solar element abundance, but important differences





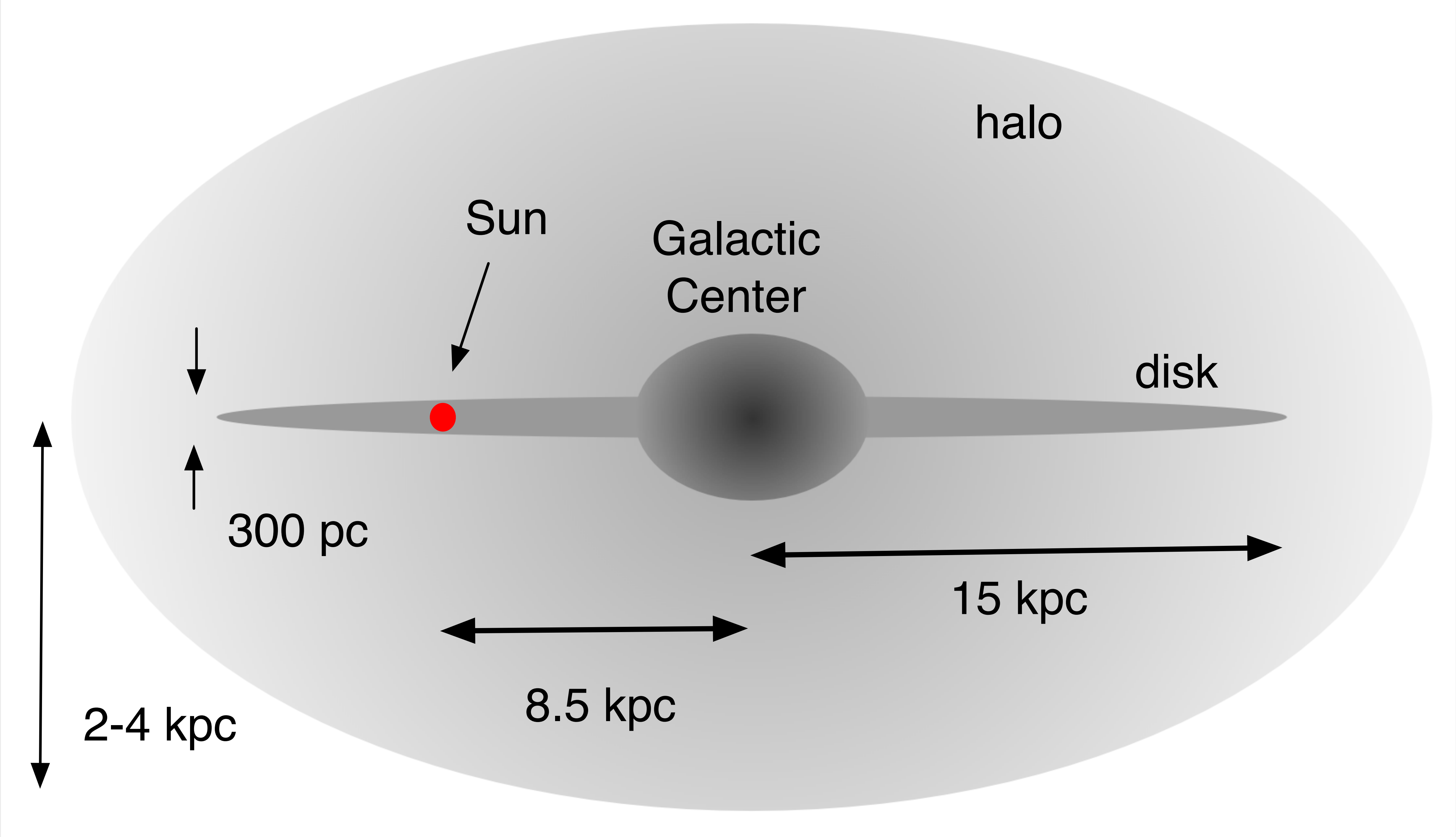
(Review of PDG, 2022 & 2023)

Galaxy and galactic magnetic fields



(astronomy.stackexchange.com)

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

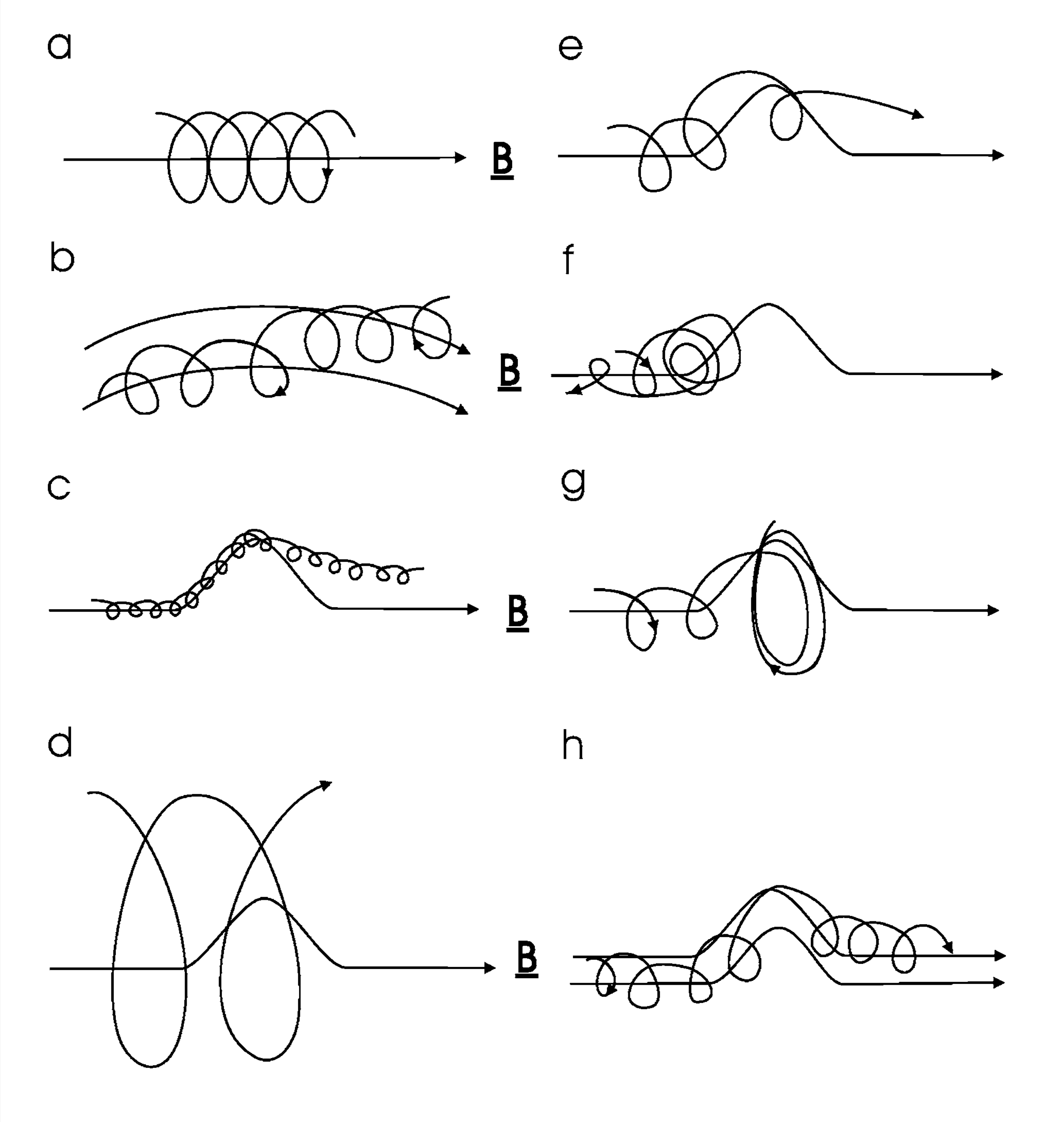


Coherent and turbulent magnetic fields
(of similar strength)

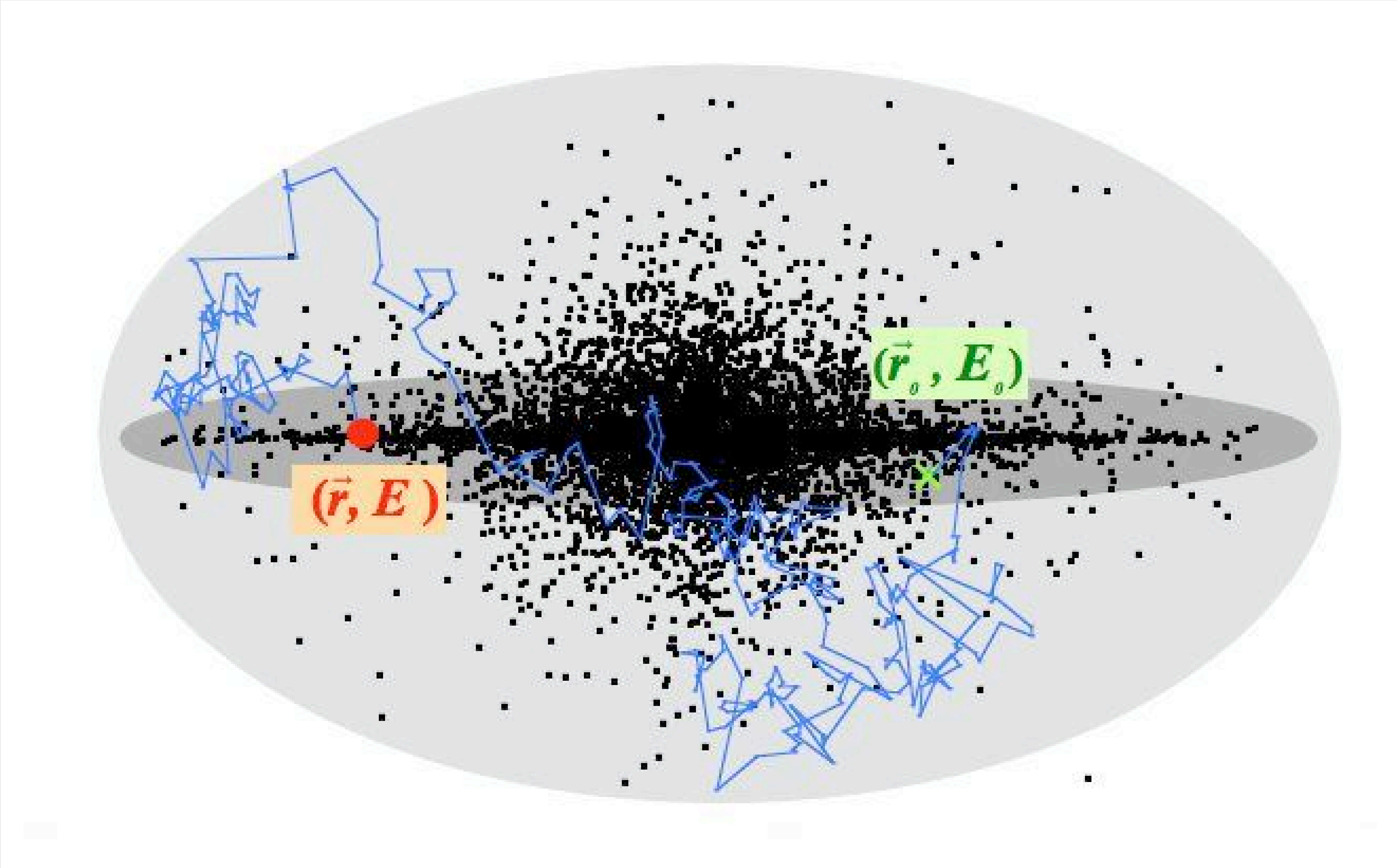
Magnetic field not well known,
B = 3 μG = 30 nT close to Solar System

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

Galaxy and galactic magnetic fields



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



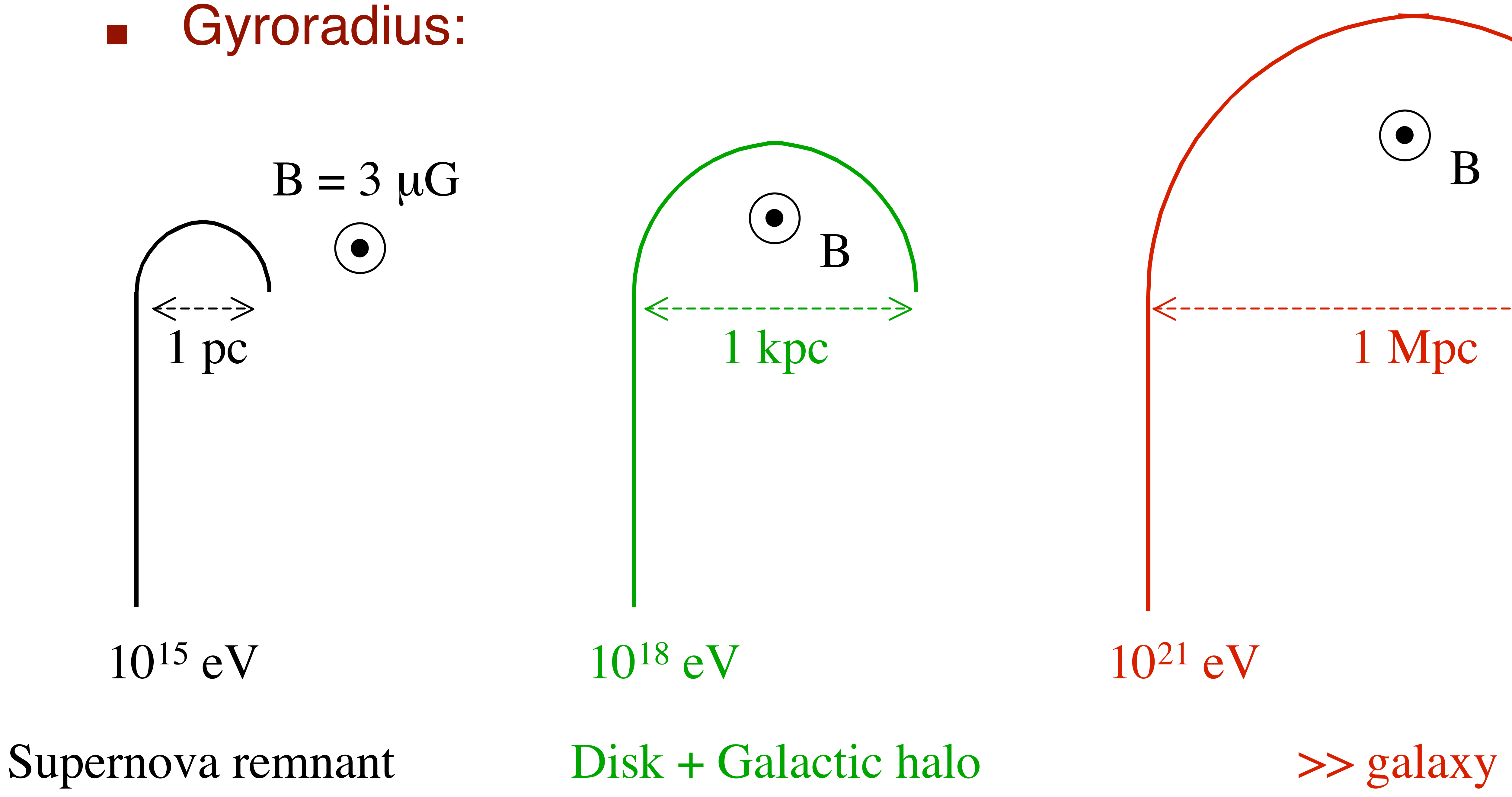
Coherent and turbulent magnetic fields
(of similar strength)

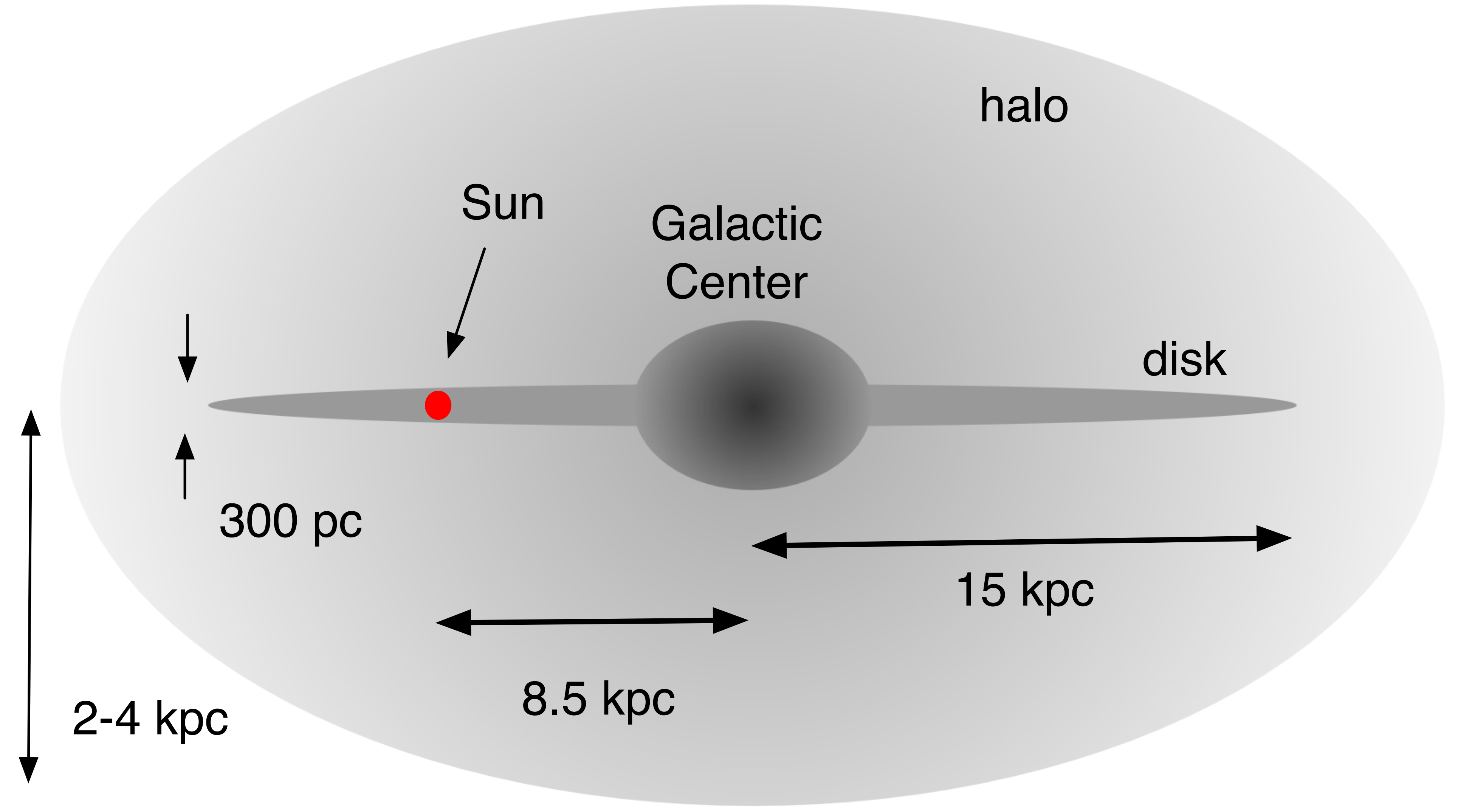
Magnetic field not well known,
B = 3 μG = 30 nT close to Solar System

Diffusion: random walk,
distance scales ~ (time)²

Galactic and extragalactic sources

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





No diffusion in Galactic mag. field at very high energy

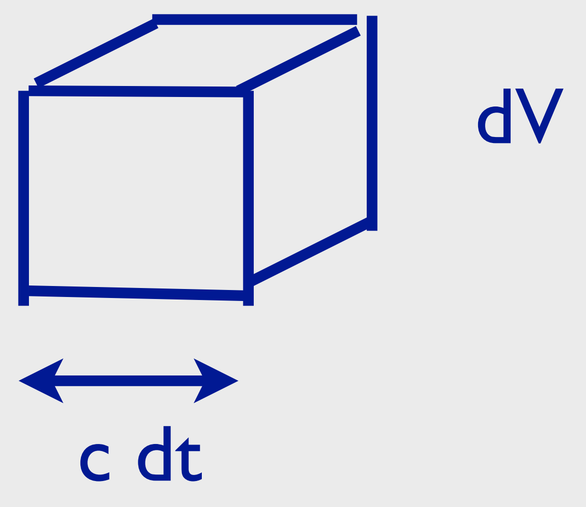
Power needed to maintain cosmic ray flux

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

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

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

Kinetic energy released in SN expl

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

Required power of cosmic ray sources $P_{\text{src}} = E_{\text{tot}}/\tau_{\text{esc}} \approx 10^{41}\,\text{erg/s}$

(1 erg = 0.1 μJ)

Cosmic rays from supernova remnants

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.

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)

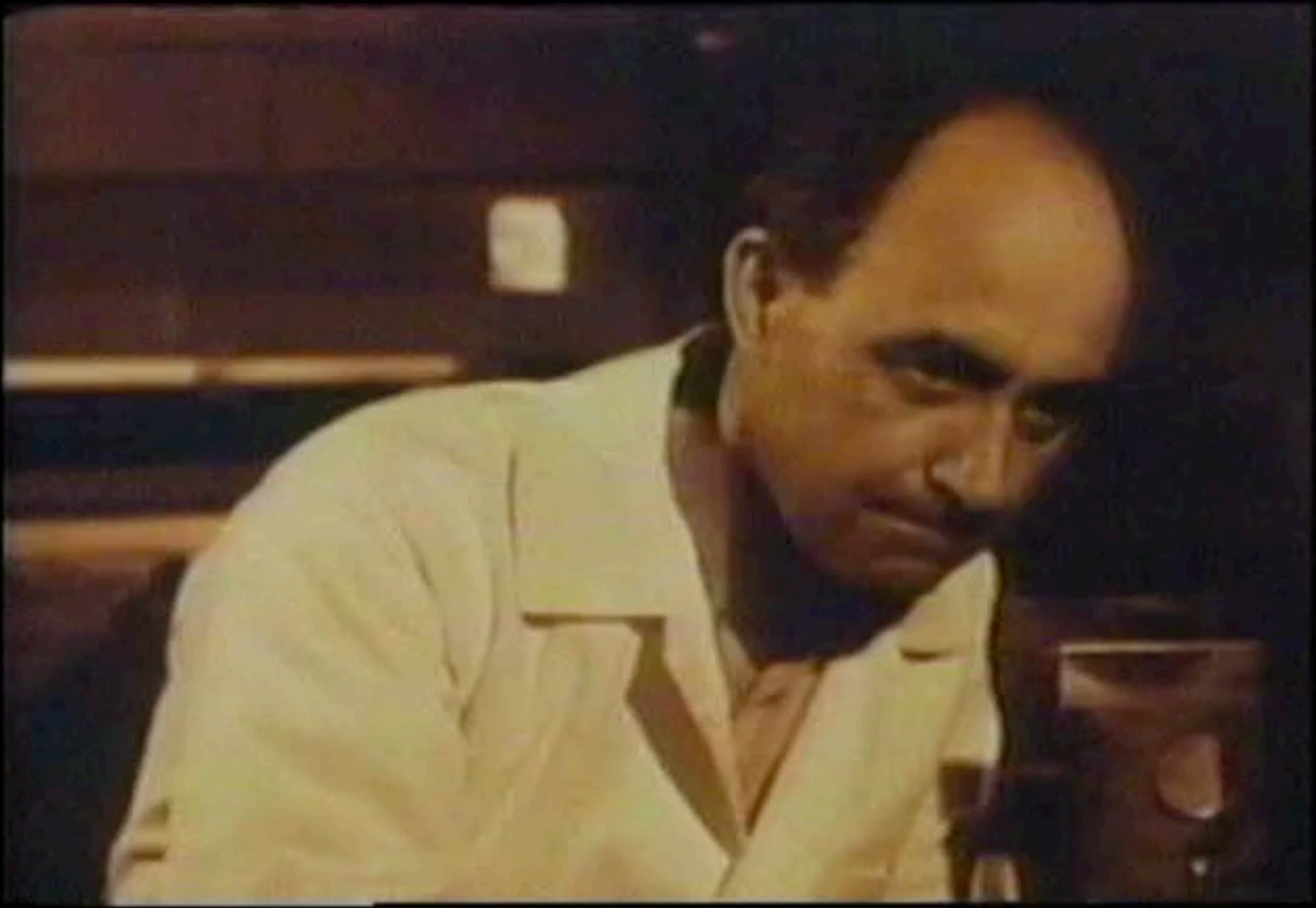
Estimates:

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

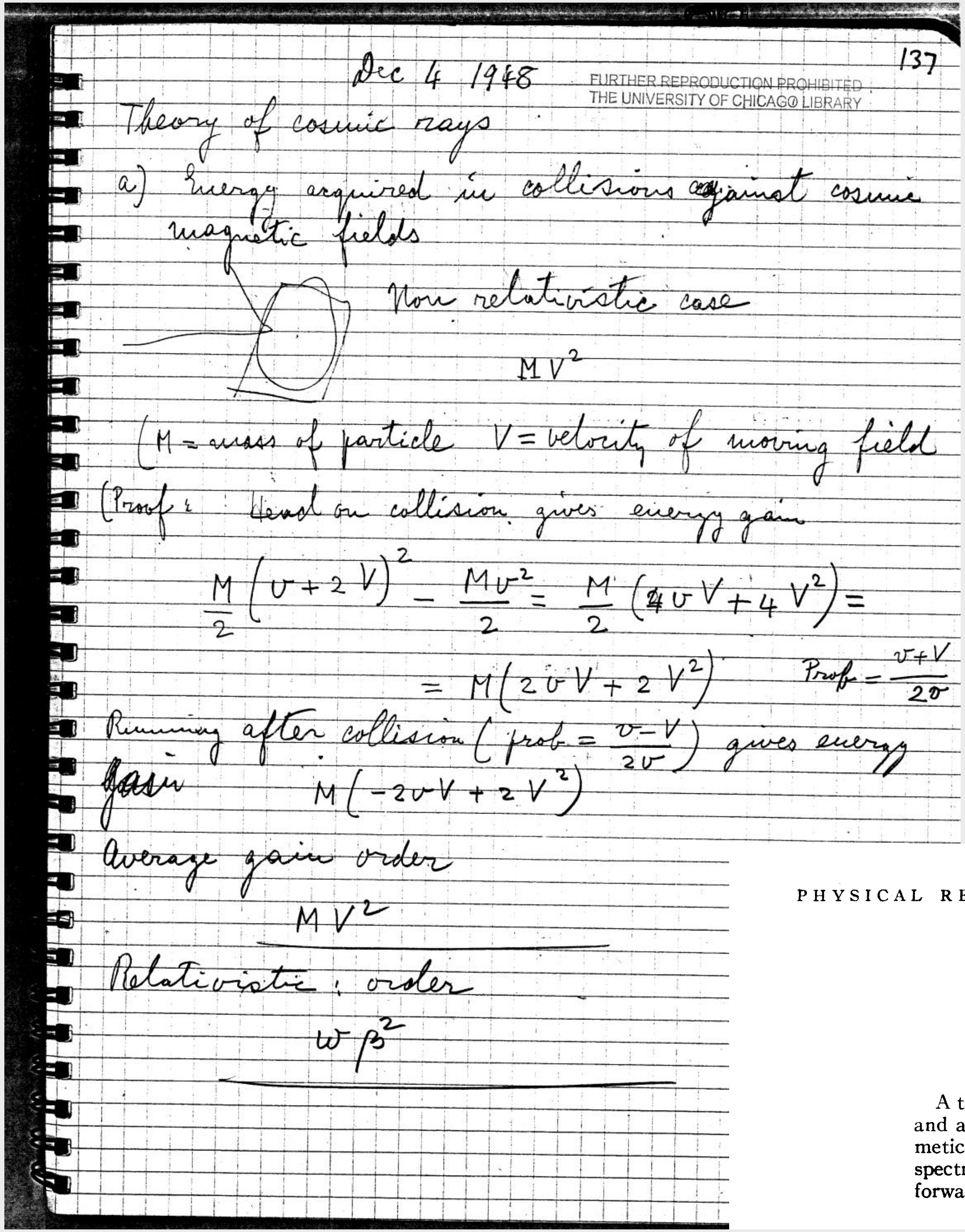
$$P_{\mathrm{SNR}} \approx 10^{42} \mathrm{erg/s}$$

Kinetic energy released in SN explosions

Diffusive shock (Fermi) acceleration



Fermi's original work: second order acceleration


Dec 4 1948 137

Theory of cosmic rays

a) Energy acquired in collisions against cosmic magnetic fields

Non relativistic case

MV^2

(M = mass of particle V = velocity of moving field

(Prob: Head on collision gives energy gain

$$\frac{M}{2}(v+2V)^2 - \frac{Mv^2}{2} = \frac{M}{2}(4vV + 4V^2) =$$

$$= M(2vV + 2V^2) \qquad \text{Prob} = \frac{v+V}{2v}$$

Running after collision ($\text{prob} = \frac{v-V}{2v}$) gives energy gain

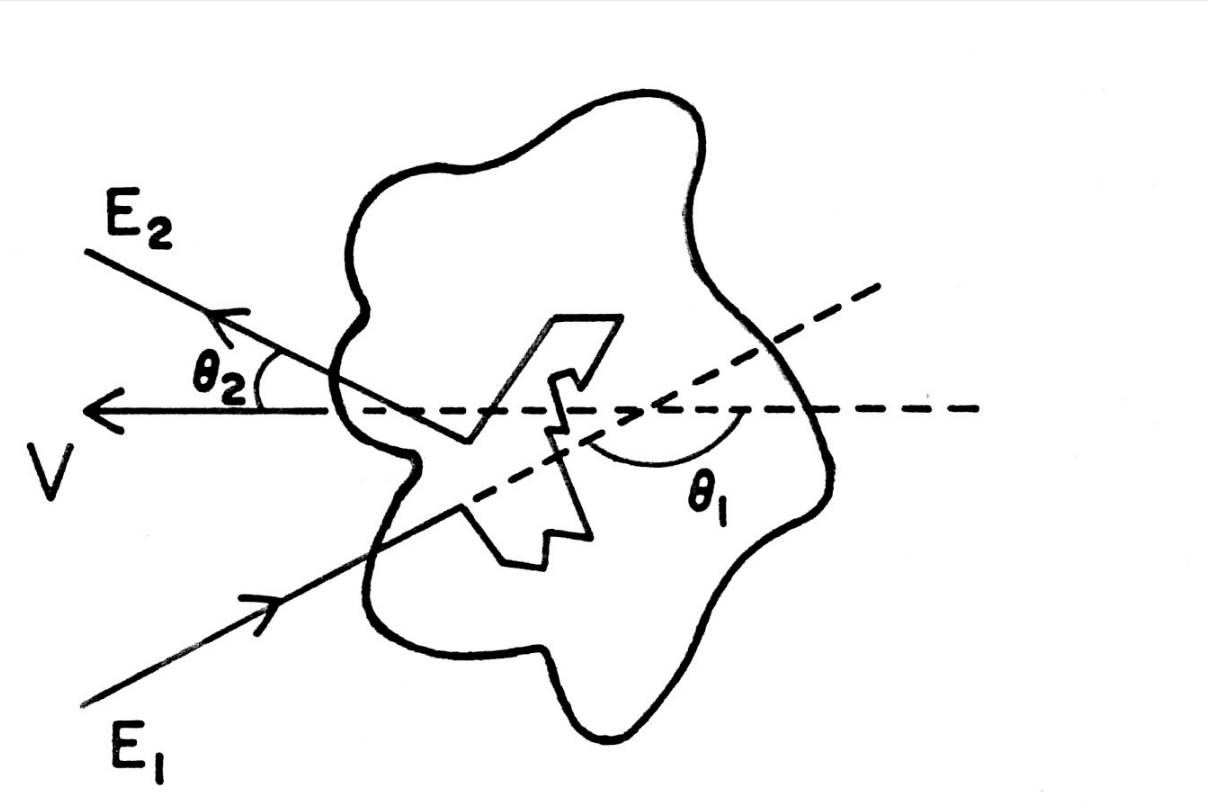
$$M(-2vV + 2V^2)$$

Average gain order

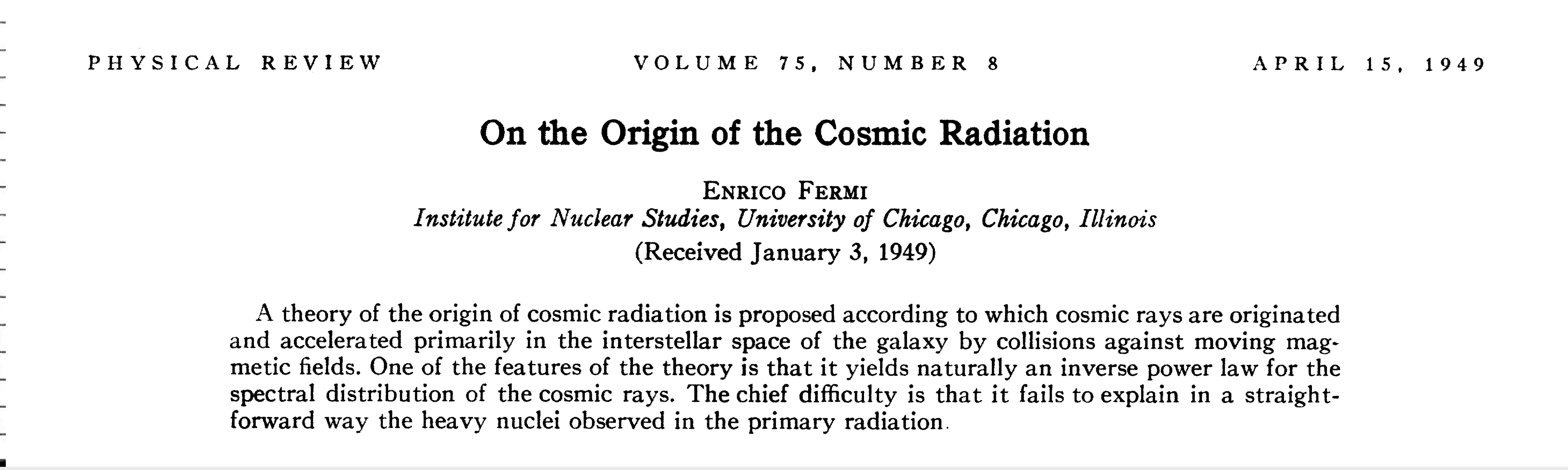
MV^2

Relativistic: order

$w\beta^2$



Particles scatter on moving magnetic clouds


PHYSICAL REVIEW VOLUME 75, NUMBER 8 APRIL 15, 1949

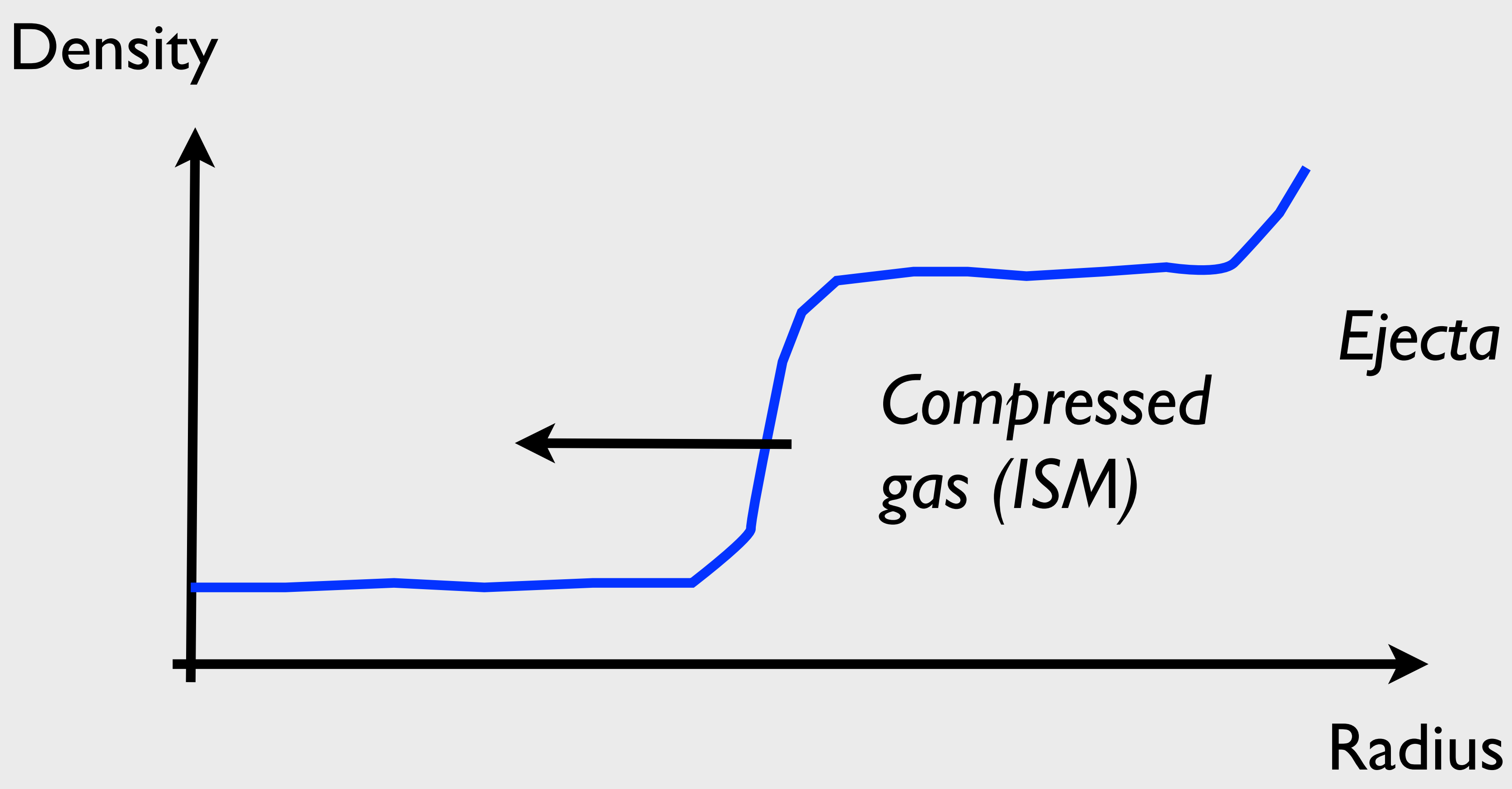
On the Origin of the Cosmic Radiation

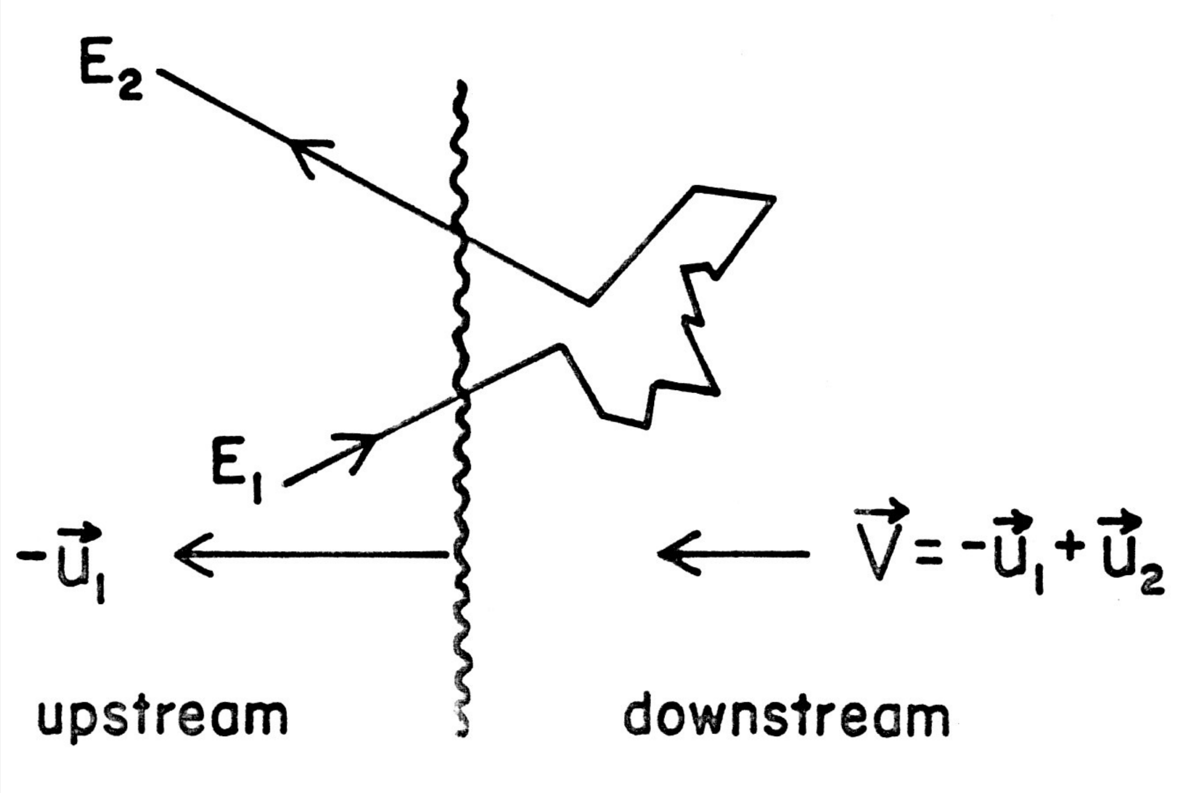
ENRICO FERMI
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois

(Received January 3, 1949)

A theory of the origin of cosmic radiation is proposed according to which cosmic rays are originated and accelerated primarily in the interstellar space of the galaxy by collisions against moving magmetic fields. One of the features of the theory is that it yields naturally an inverse power law for the spectral distribution of the cosmic rays. The chief difficulty is that it fails to explain in a straightforward way the heavy nuclei observed in the primary radiation.

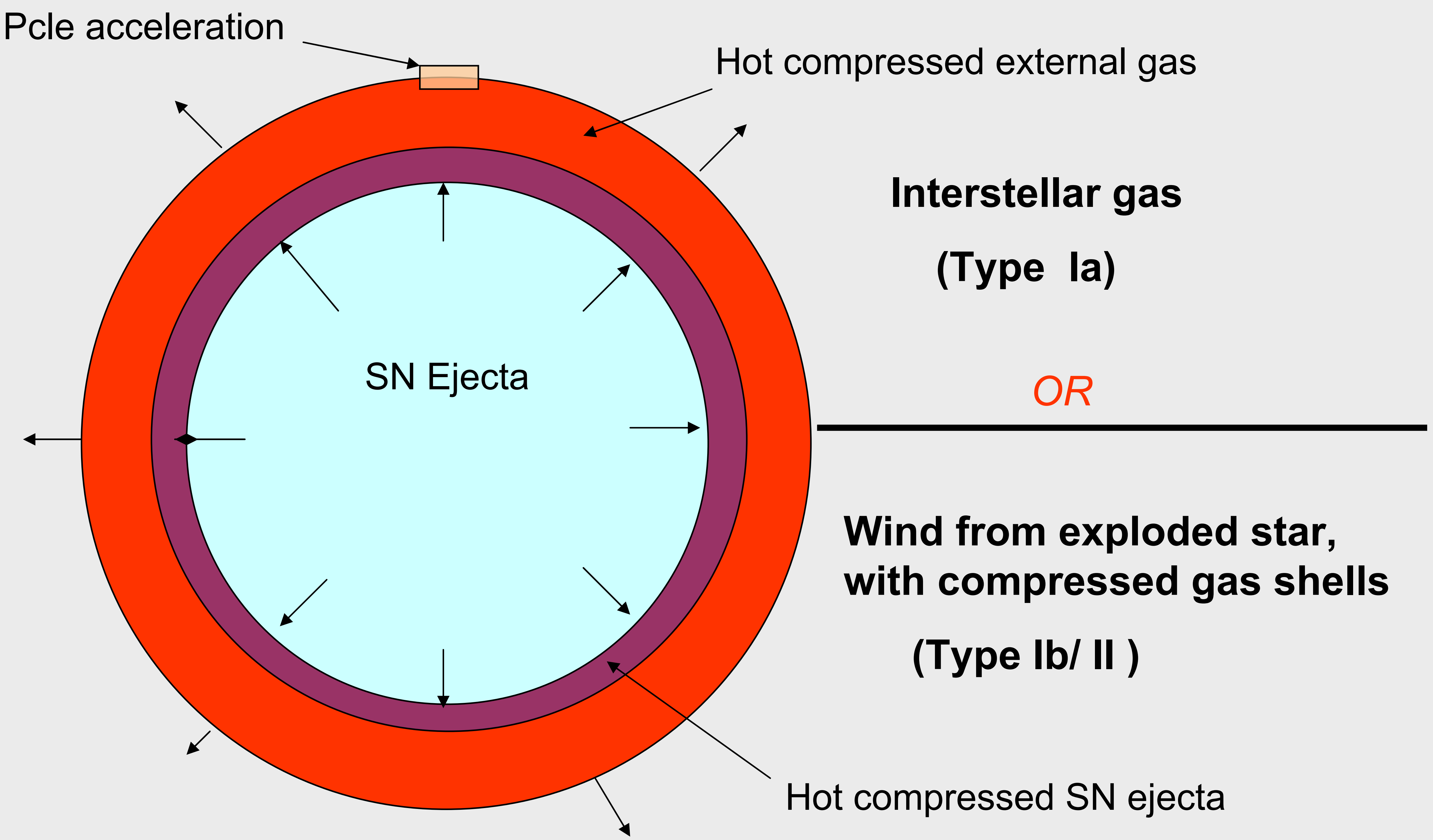
Stochastic acceleration on SN shock fronts





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

Compression ratio follows from physics of ideal gases



(Hillas, 2008)

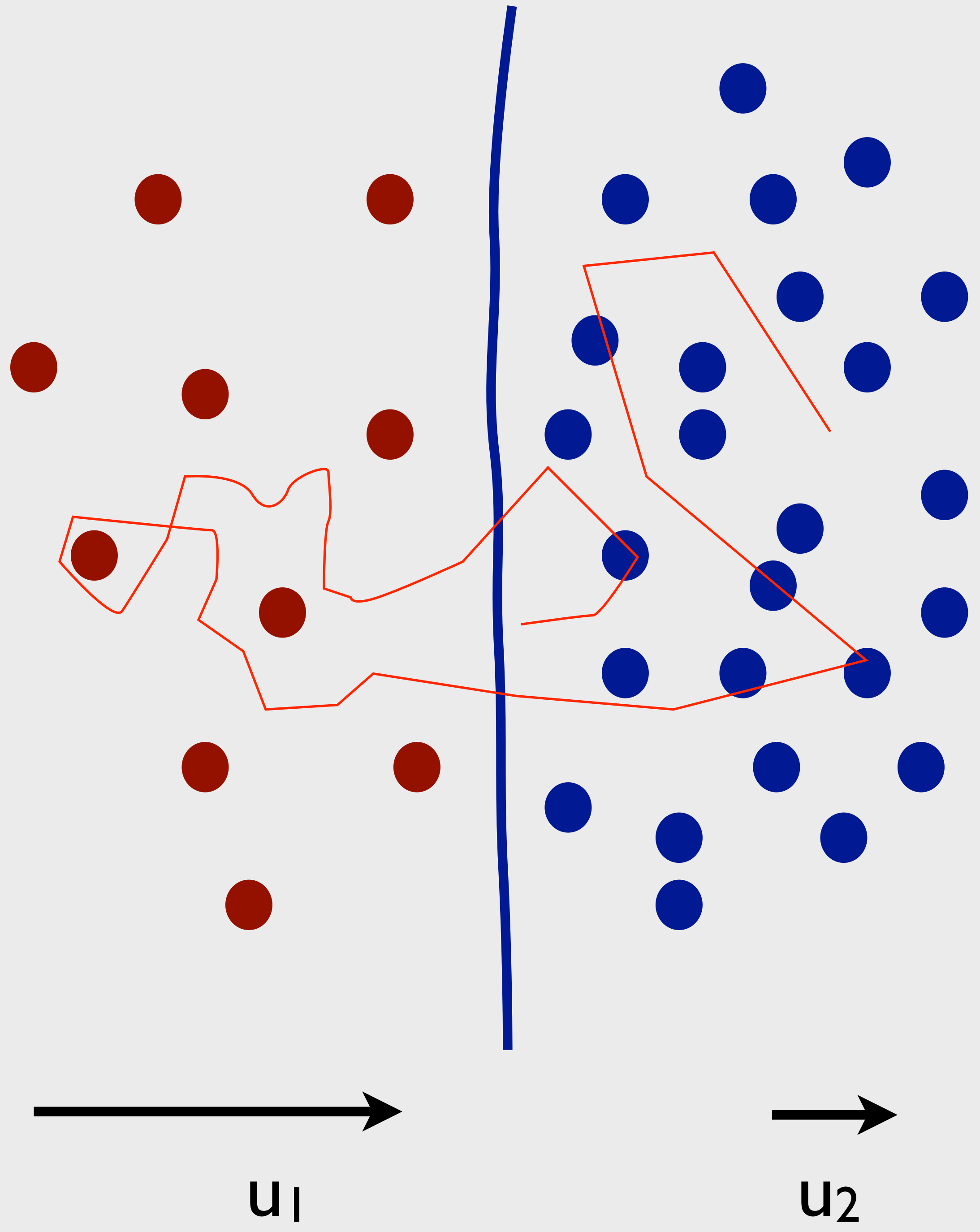
First order Fermi acceleration

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



(in rest frame of shock front)

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

Energy-independent relative energy gain

Factor from averaging over all angles

Expected energy distribution

Assumption: energy-independent escape probability P_{esc} per cycle

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

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

Flux of particles

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

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

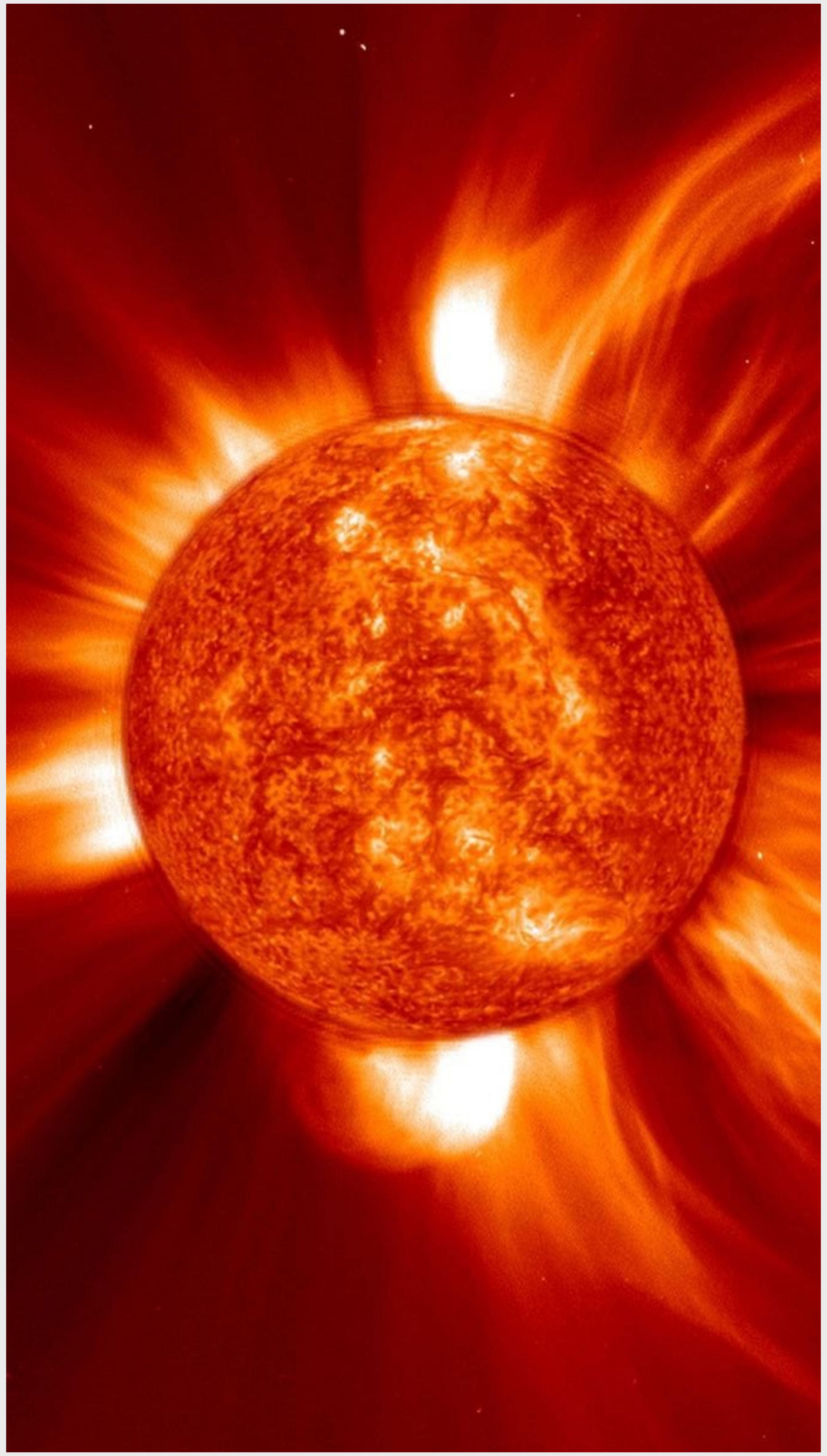
Numerical values depend on many details

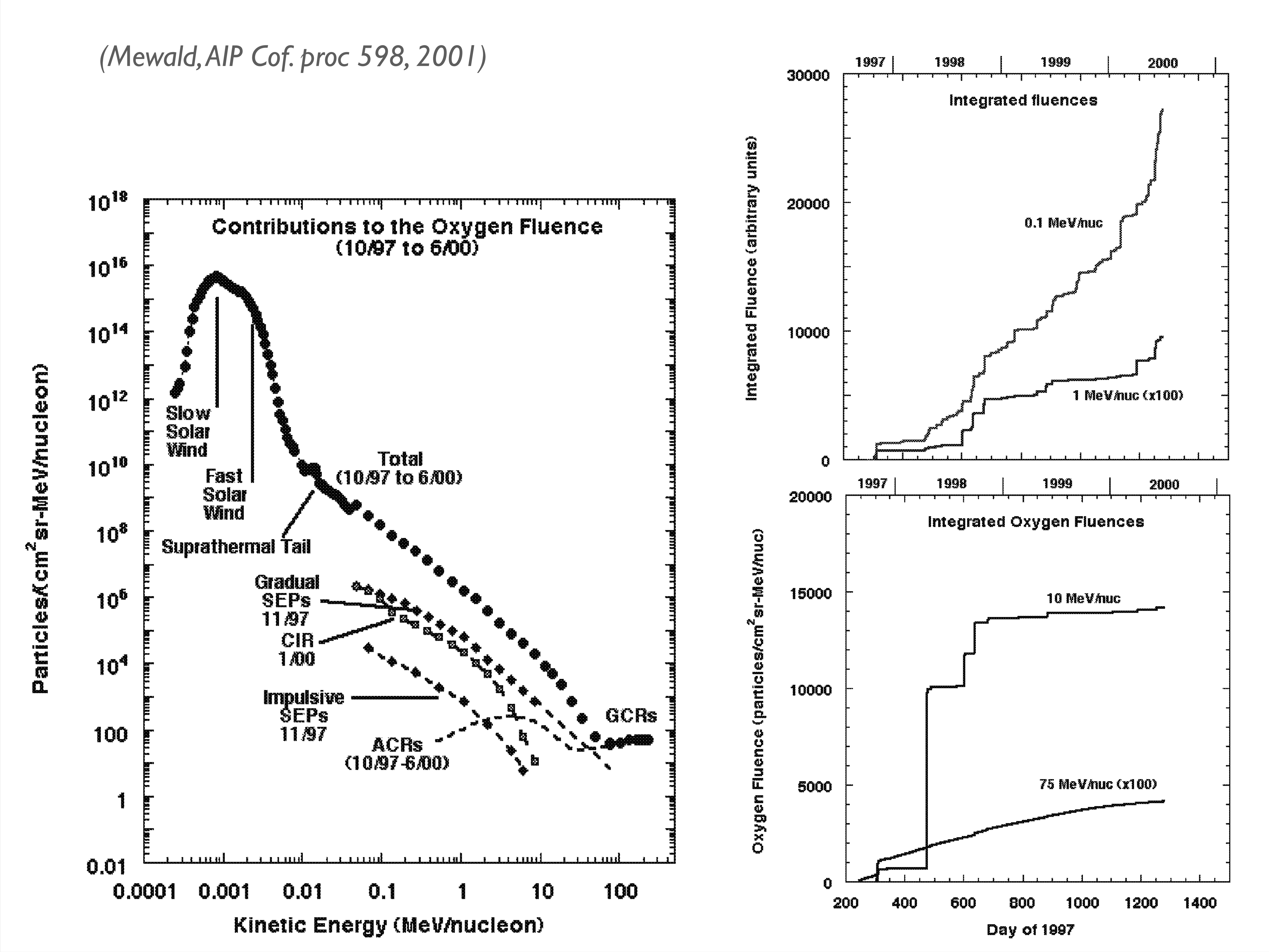
$$\alpha \approx 1$$

(see Longair's textbook)

Ideal diffusive shock acceleration yields dN/dE ~ E^{-2}

Comparison to particle acceleration in heliosphere

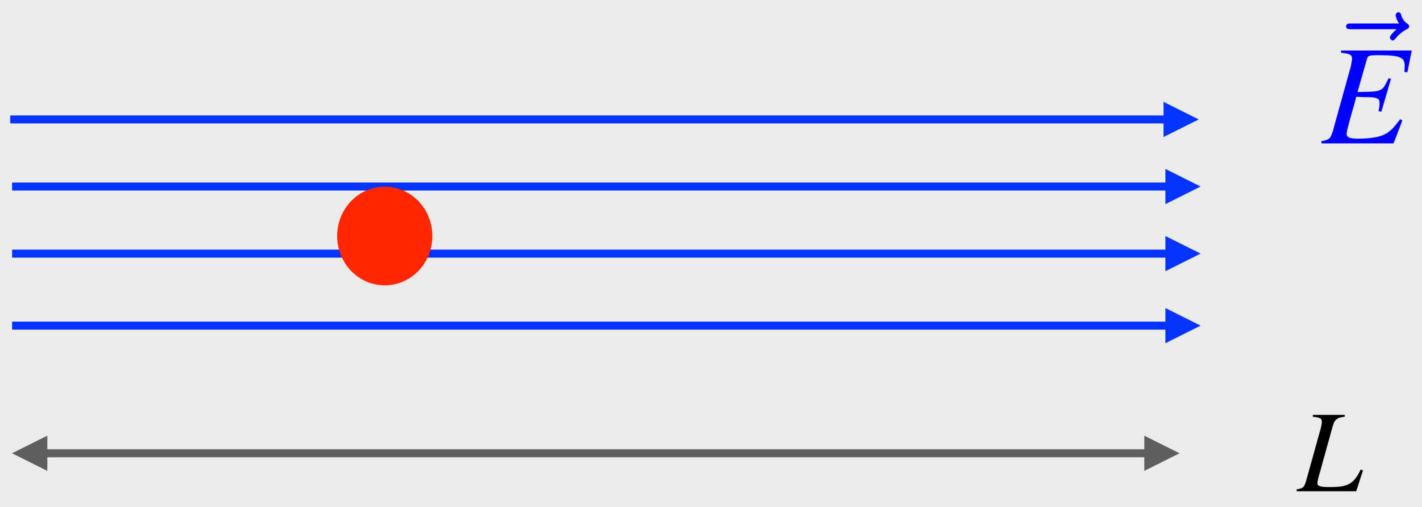




Maximum particle energy

(after S. Gabici, KSETA 2024)

Classic acceleration by electric field



$$E_{p,\max} = qL|\vec{E}|$$

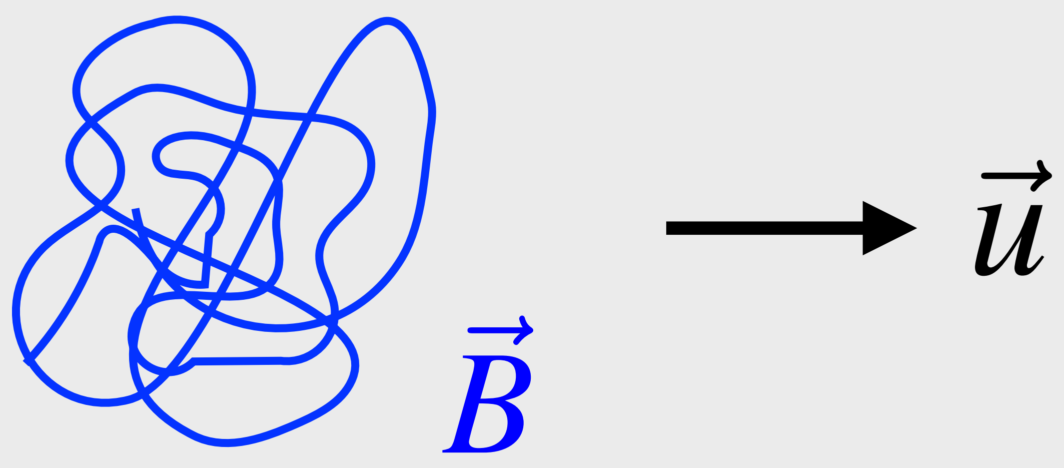
Astrophysical plasmas: no static electric fields (charges are free to travel)

$$\vec{\nabla} \cdot \vec{E} = 4\pi\,\rho = 0$$

Faraday's law: changing magnetic fields produce electric field

$$\vec{\nabla} \times \vec{E} = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t}$$

Lorentz transformation



$$\vec{E} = -\frac{\vec{u}}{c} \times \vec{B}$$

Electric field in lab. frame

Hillas criterion

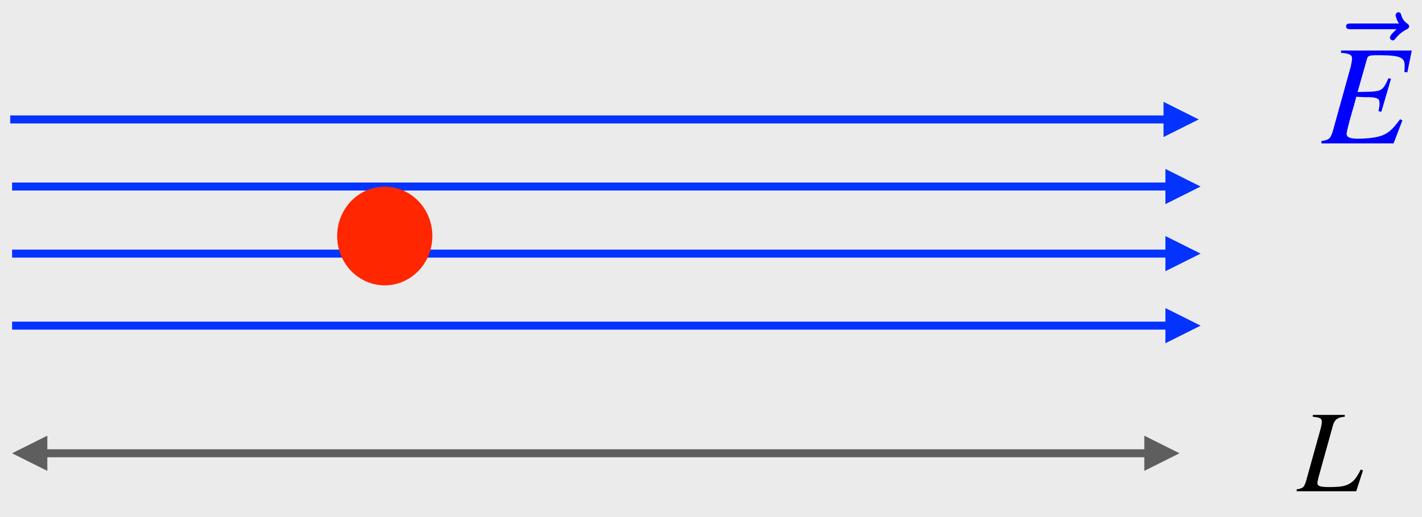
$$E_{p,\max} = qL\frac{u}{c}B = \beta_s qLB$$

$$E_{p,\max} = 3 \times 10^{12} Z \left(\frac{B}{\mu\mathrm{G}}\right)\left(\frac{u}{1000\,\mathrm{km/s}}\right)\left(\frac{L}{\mathrm{pc}}\right)\,\mathrm{eV}$$

Maximum particle energy

(after S. Gabici, KSETA 2024)

Classic acceleration by electric field



Astrophysical plasmas: no static electric fields (charges are free to travel)

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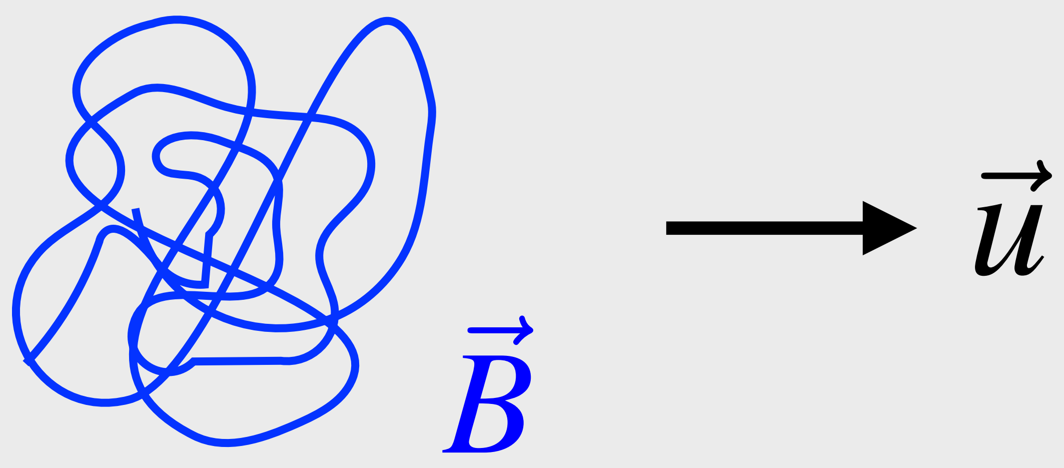
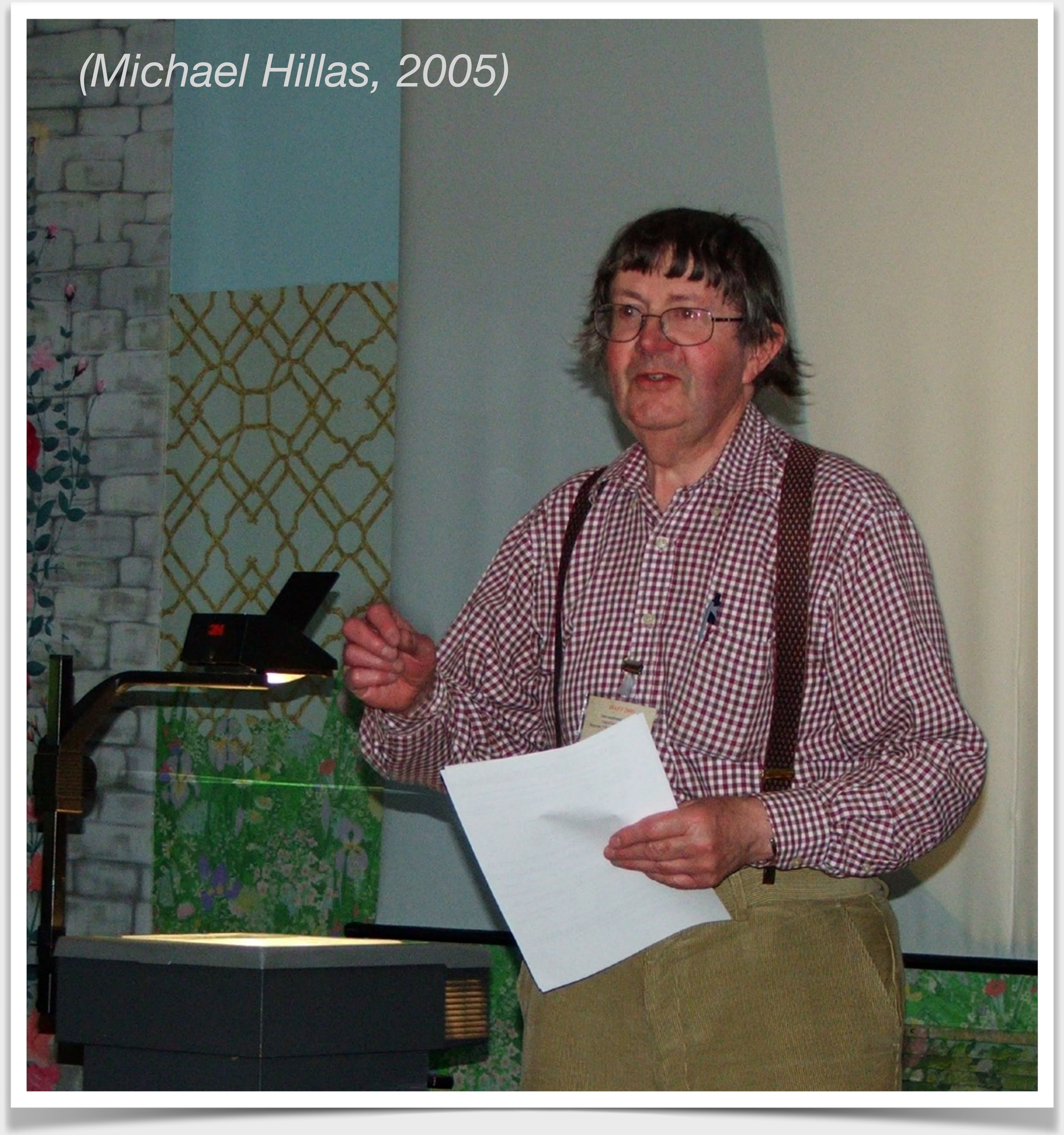
Lorentz transformation





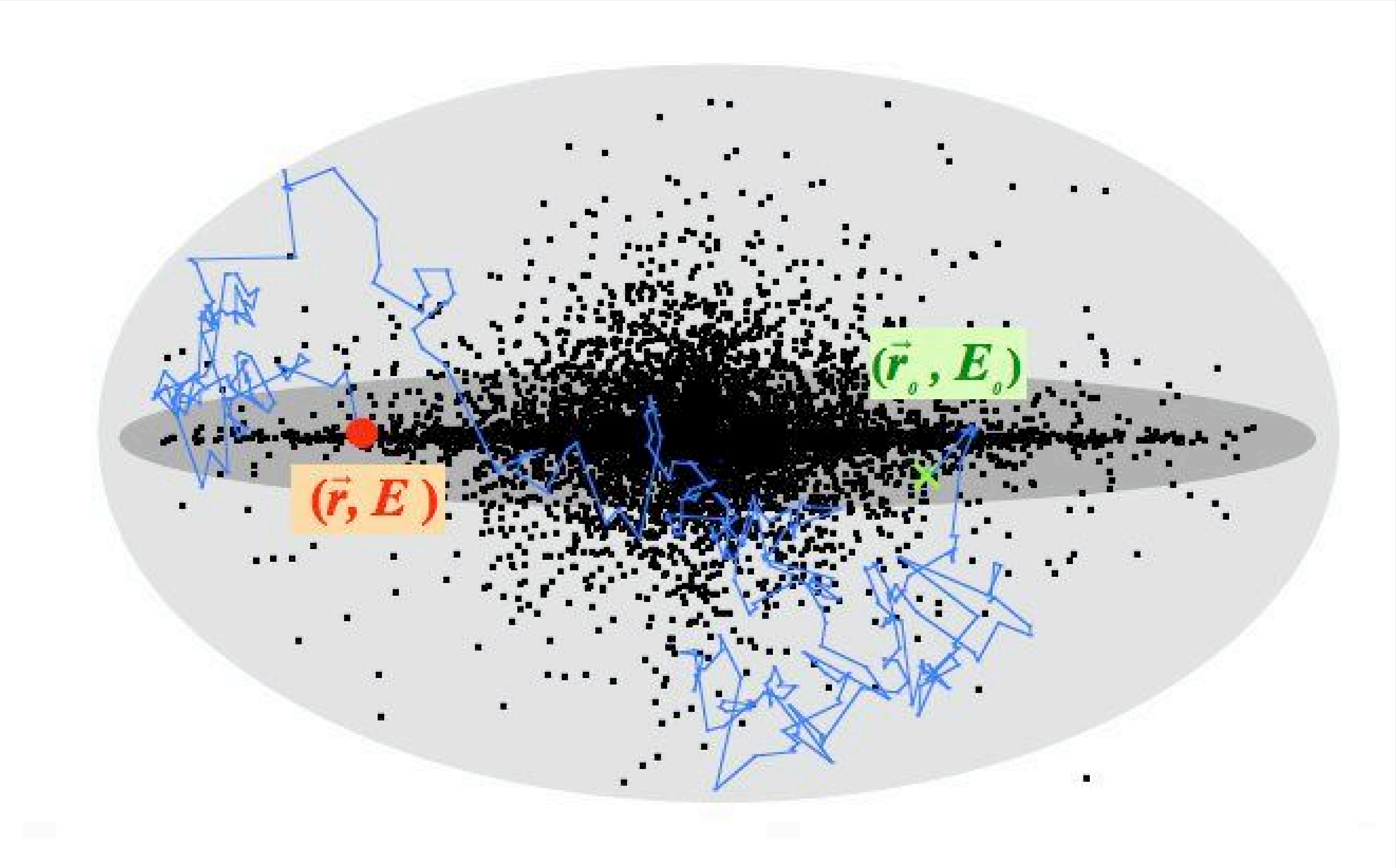
(Hillas, Ann. Rev. Astron. Astrophys. 1984)

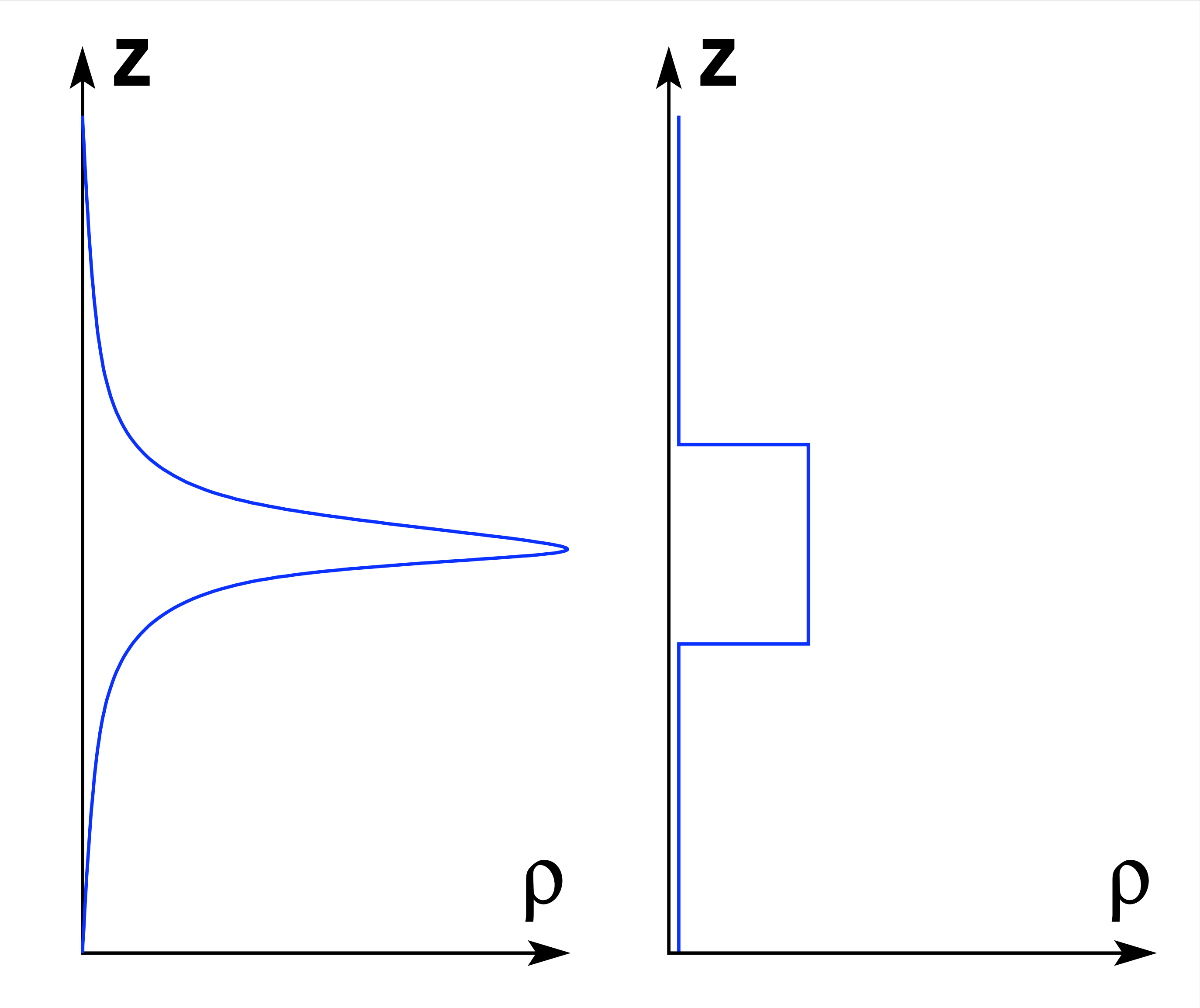
Hillas criterion

$$E_{p,\max} = qL\frac{u}{c}B = \beta_s qLB$$

Very general result, broad application, further restrictions apply (energy losses)

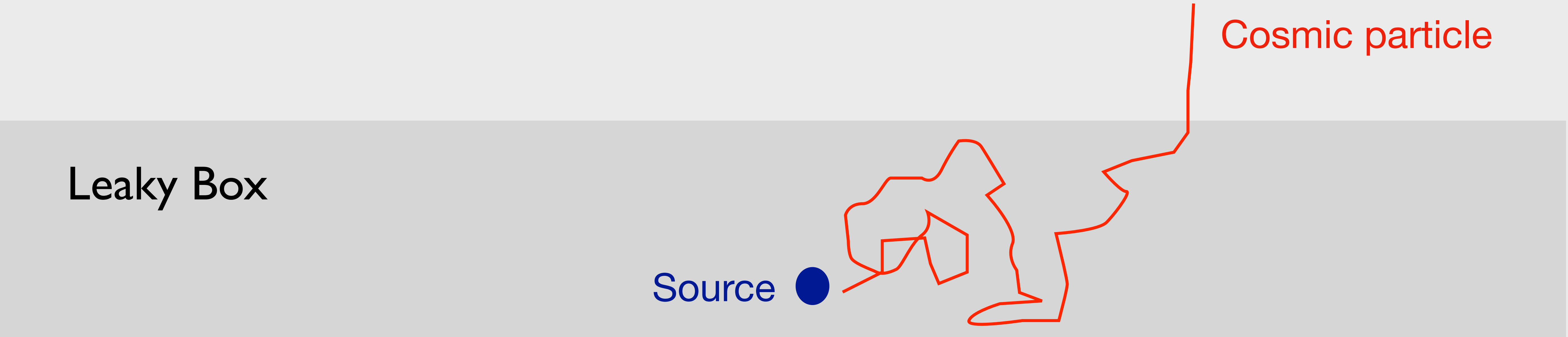
Leaky Box model





realistic density distribution

Leaky Box model



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

Sources uniformly distributed

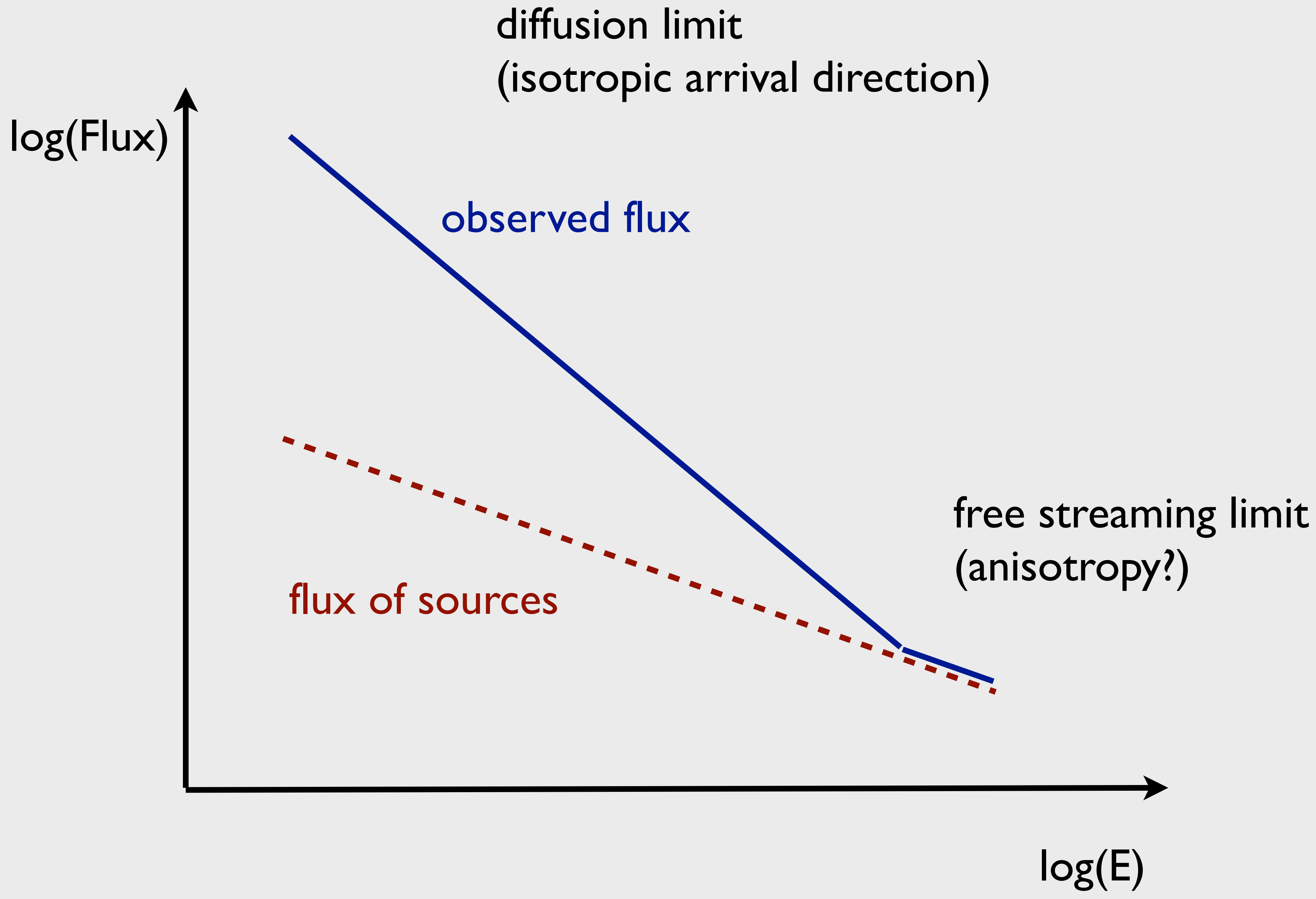
Effect of cosmic ray confinement in galaxy

Simplification: only one particle type considered, no energy losses

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

Assumption: equilibrium reached, flux independent of time

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



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

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

Has to be energy-dependent!

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

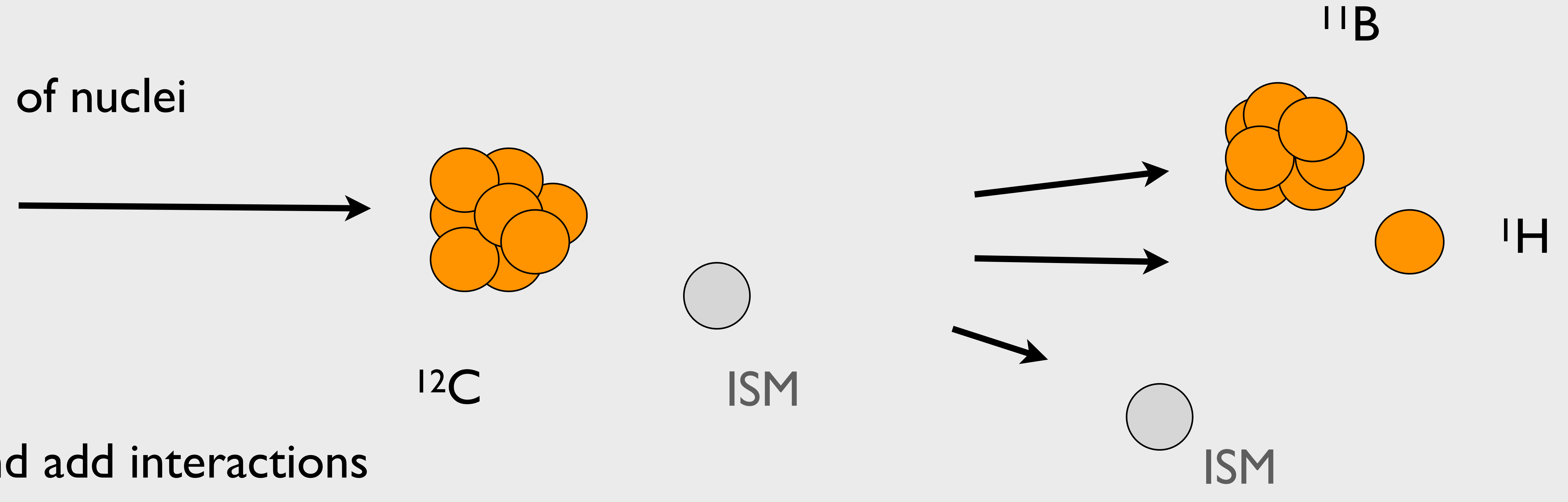
$$\tau_{\mathrm{esc}} \sim E^{-\delta}$$

$$\delta \sim 0.6 \ldots 0.7$$

Cross check of model with secondary elements

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

Spallation of nuclei



Re-write in terms of grammage and add interactions

$$0 = -\frac{1}{\lambda_{B,esc}(E)} N_B - \frac{1}{\lambda_{B,int}} N_B + Q_{C \to B}(E)$$

$$\lambda_{esc}(E) = \beta c \, \rho_{ISM} \, \tau_{esc}(E)$$

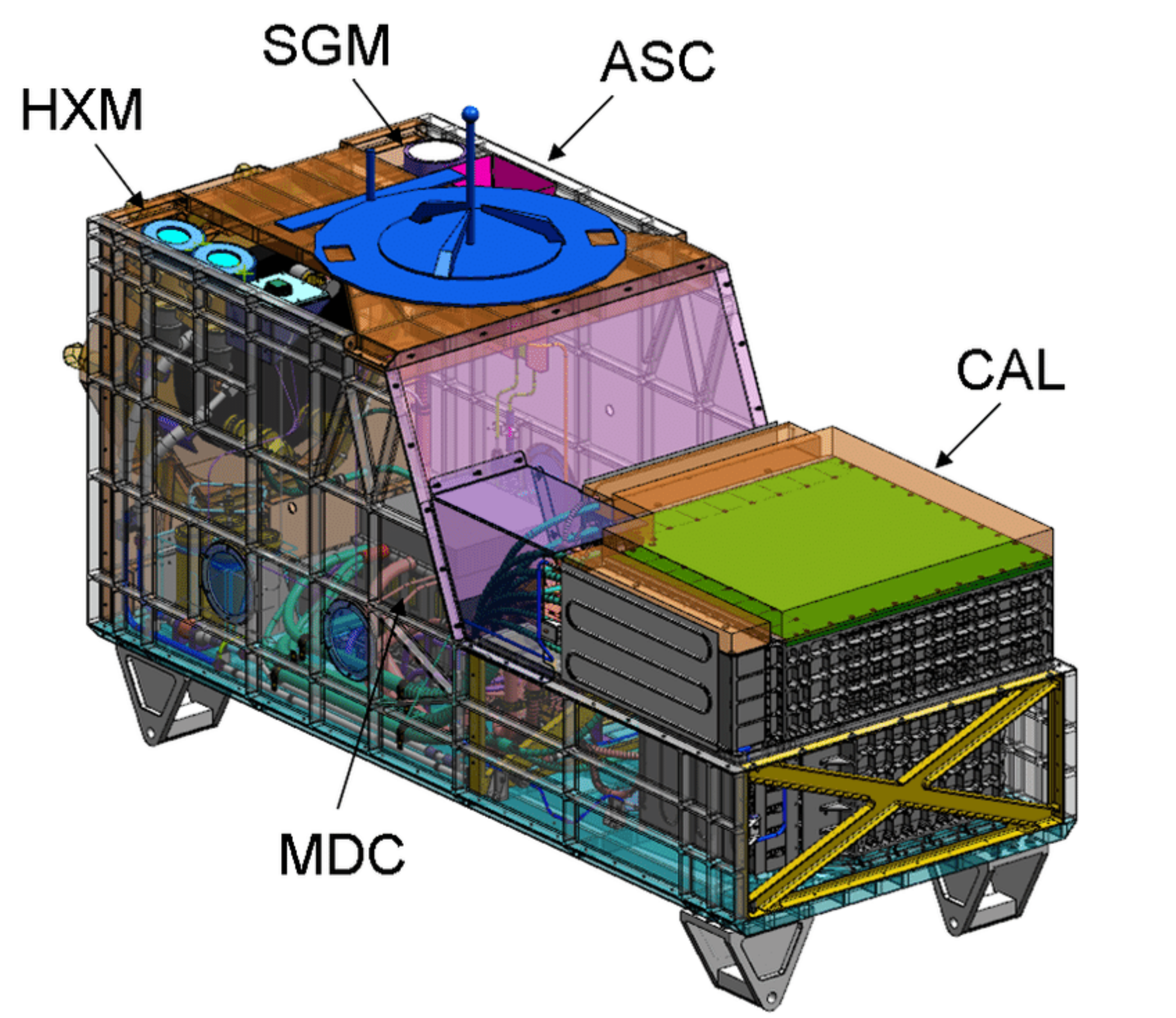
$$Q_{C \to B}(E) = f_{C \to B} \times \frac{1}{\lambda_{C,int}} N_C(E)$$

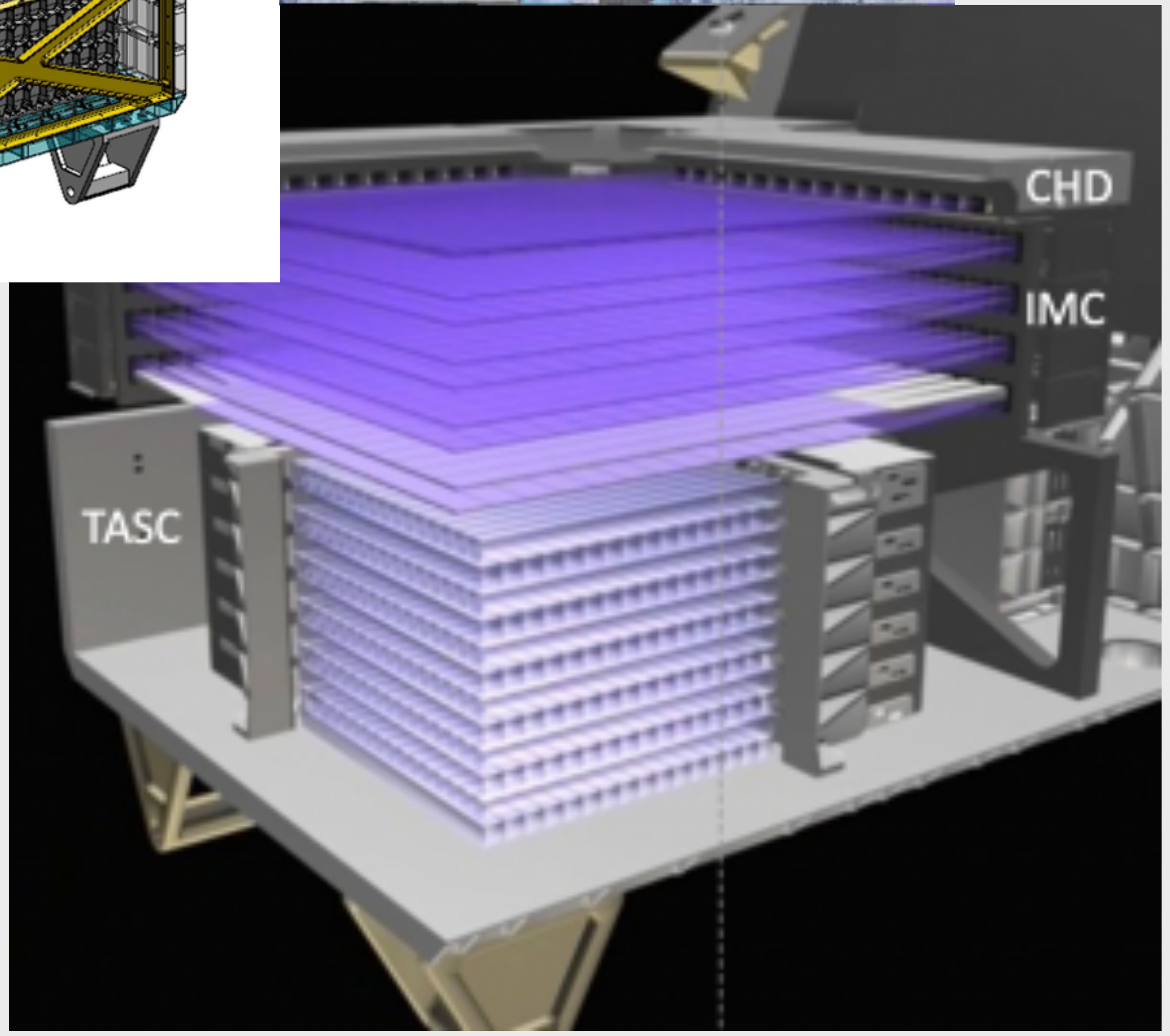
$$\frac{N_B}{N_C} = \frac{f_{C \to B}}{\lambda_{C,int}} \frac{\lambda_{B,esc}(E)}{1 + \lambda_{B,esc}(E)/\lambda_{B,int}}$$

Caution: here always energy per nucleon used

New detectors – CALET and DAMPE

CALET – Calorimetric Electron Telescope

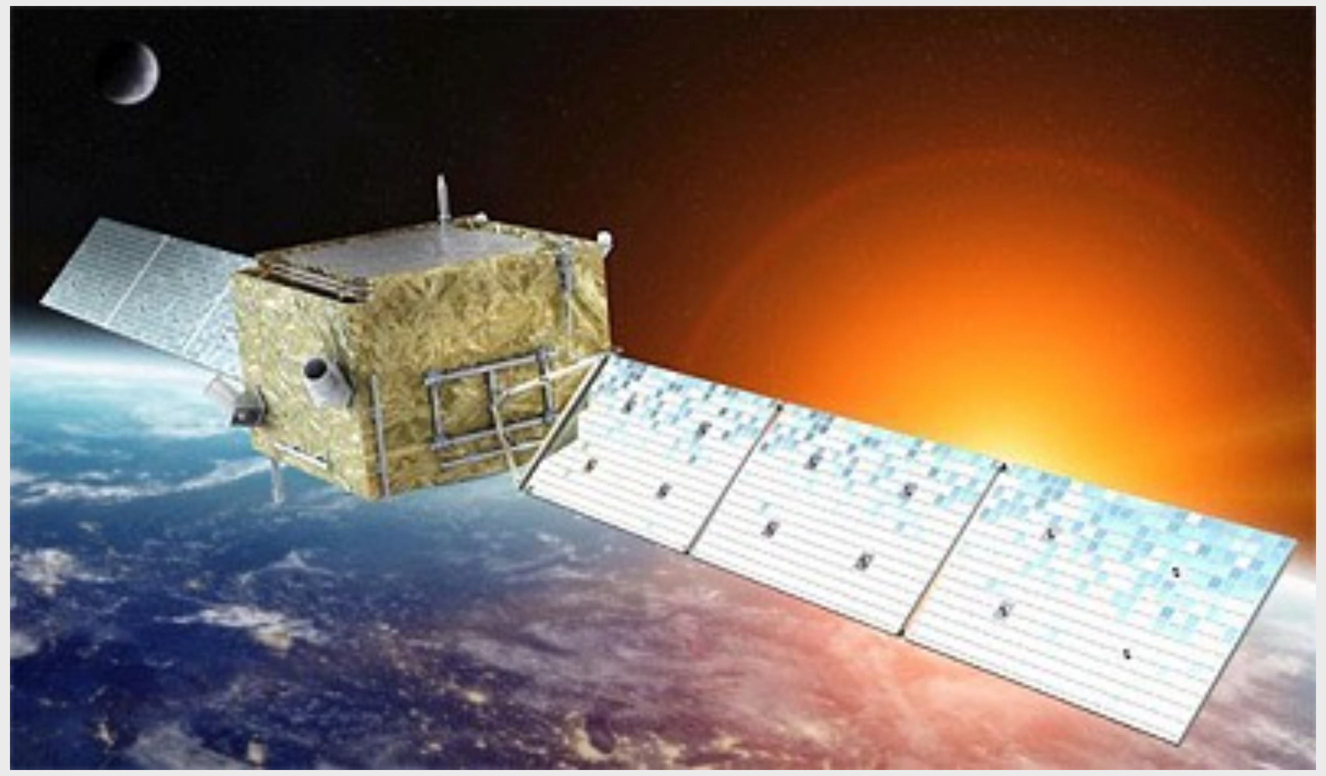


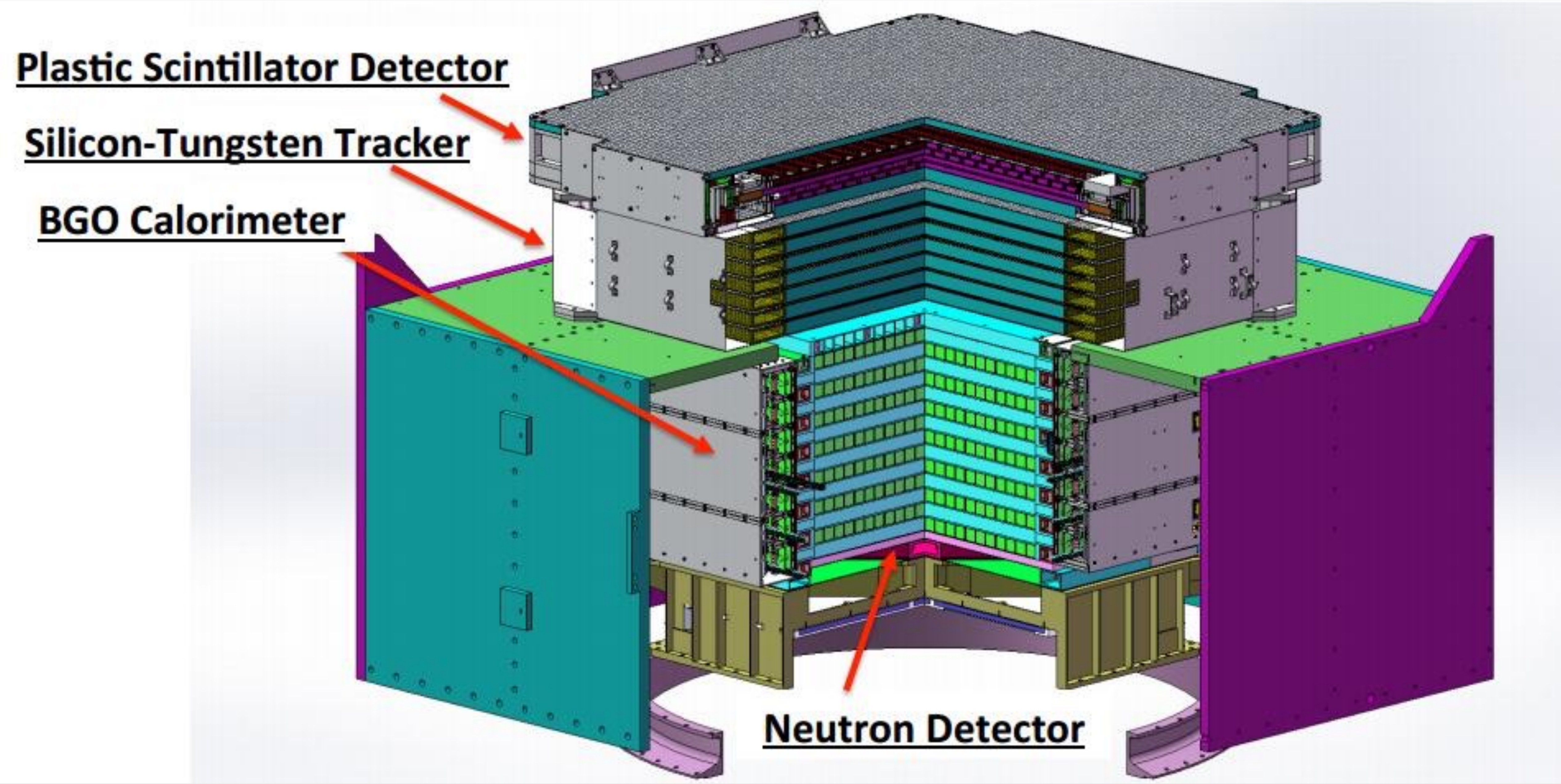


Launched Aug. 19, 2015
Mounted at ISS
Aperture ~ 0.1 m^2 sr

DAMPE – Dark Matter Particle Explorer

Launched Dec. 17, 2015
Orbit at about 500 km
Aperture ~ 0.3 m^2 sr





Cross check of model with secondary elements

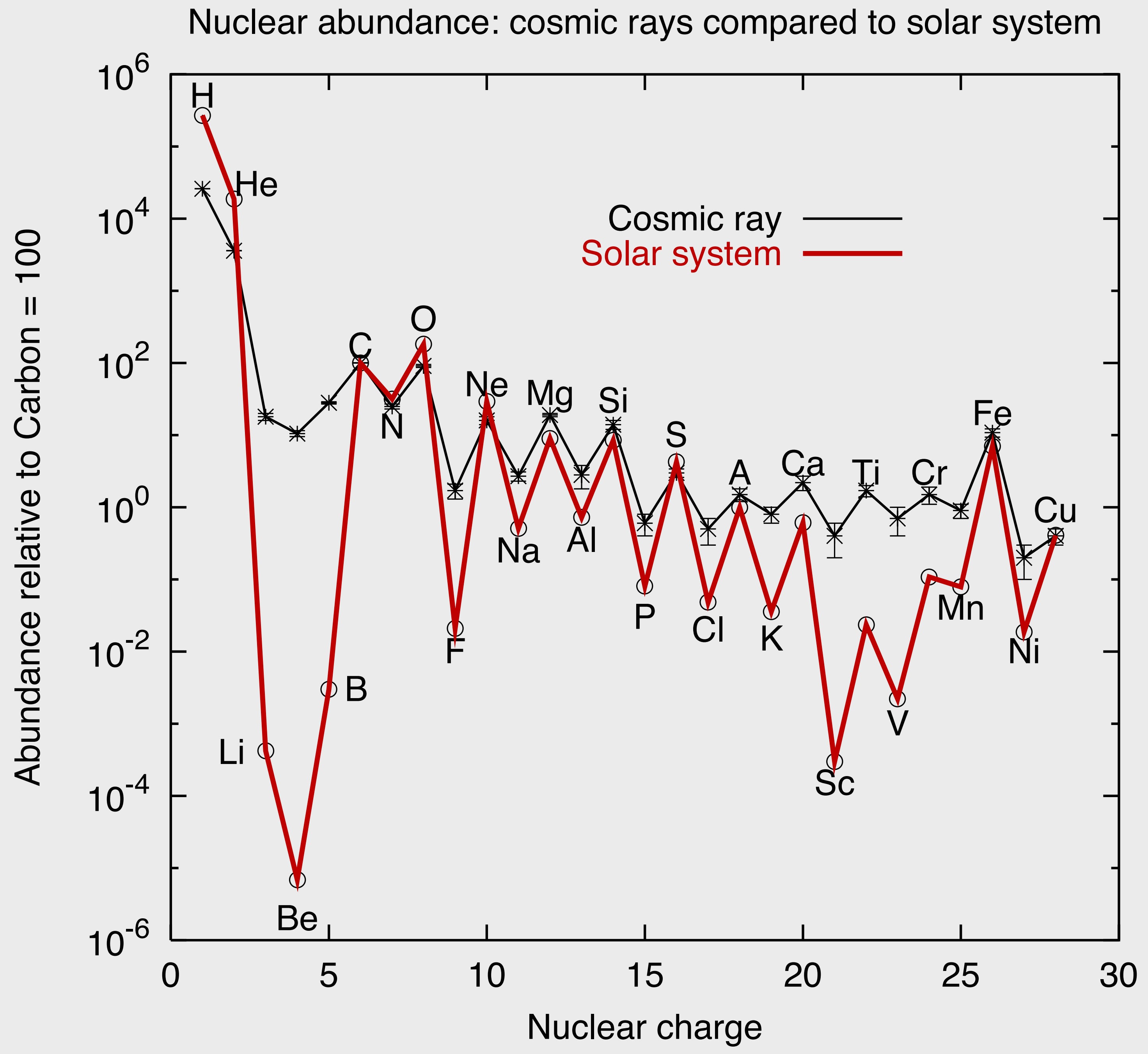
$$\frac{N_B}{N_C} = \frac{f_{C\to B}}{\lambda_{C,int}} \frac{\lambda_{B,esc}(E)}{1+\lambda_{B,esc}(E)/\lambda_{B,int}}$$

$$\lambda_{esc}(E) \sim E^{-\delta}$$

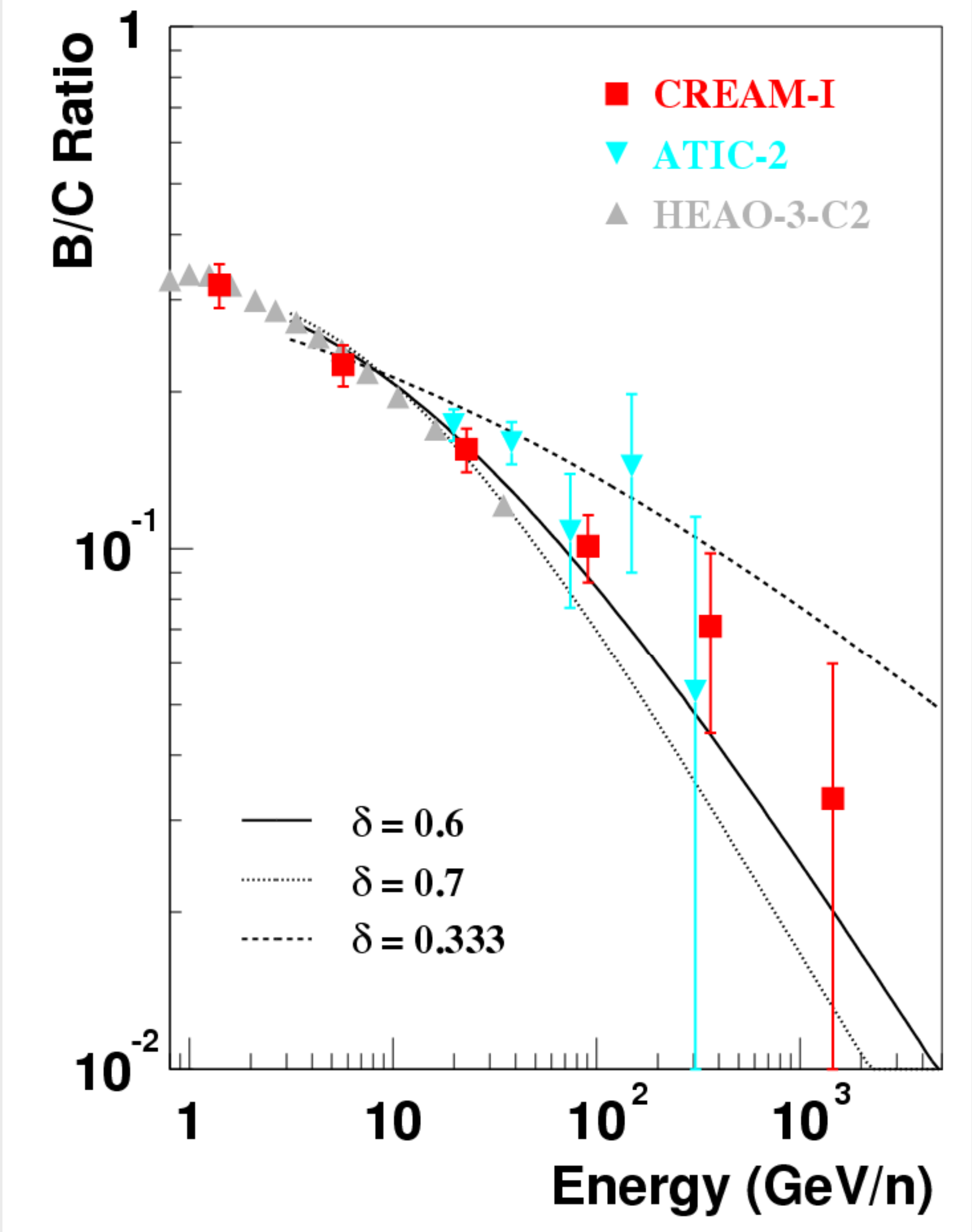
Total column depth traversed ~10 GeV

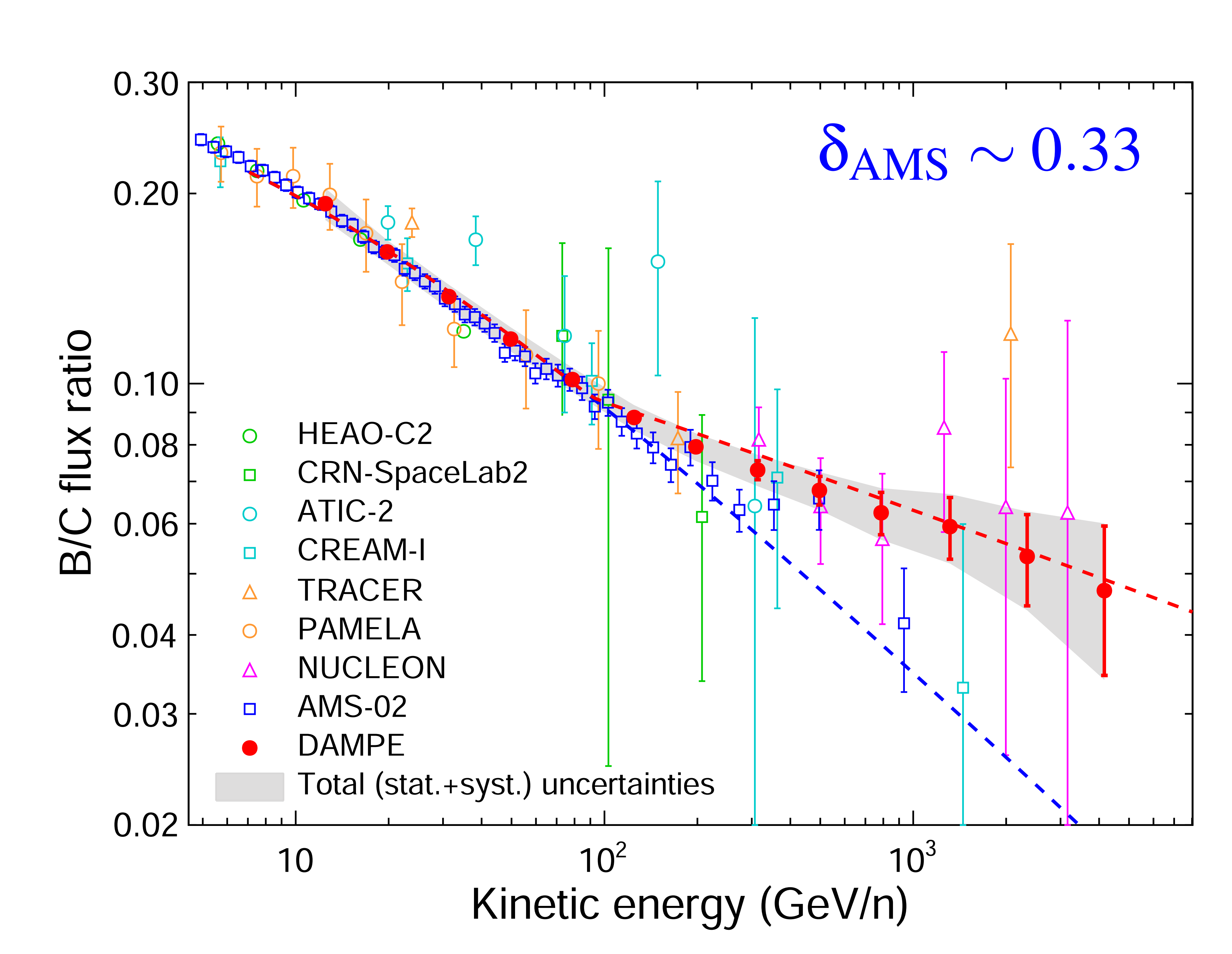
$$X \sim 5\,\mathrm{g/cm^2}$$

$$\lambda_0 \sim 1\,\mathrm{g/cm^2}$$



Old data inconclusive





(DAMPE, Science Bulletin 67 (2022) 2162)

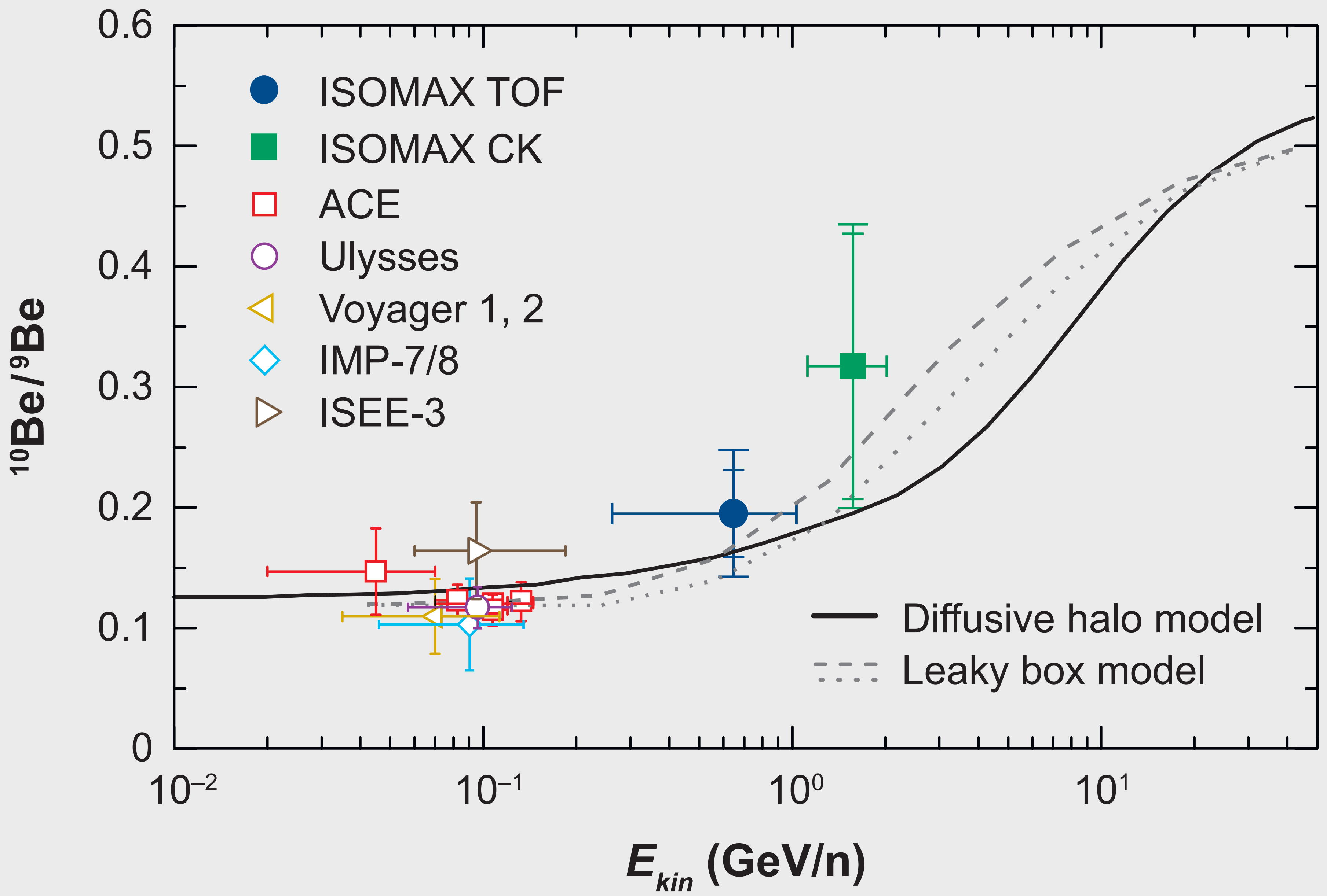
Cosmic ray clocks – energy-dependent escape time

$$\tau_{^{10}\mathrm{Be}} = 2.0 \times 10^6 \mathrm{yr}$$

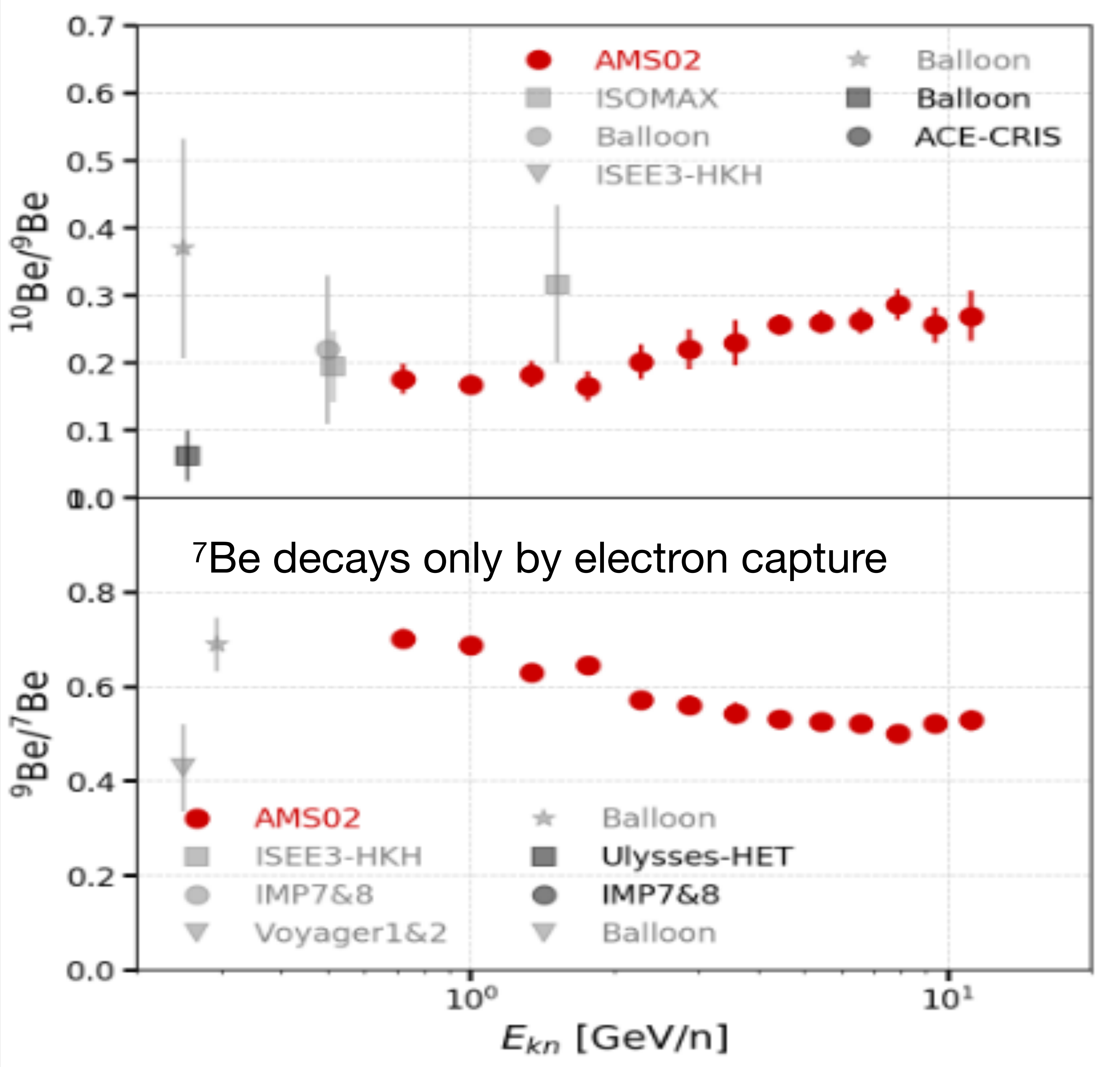
Required by observations

Only rigidity, i.e.
energy/charge important

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



$$\delta_{\mathrm{AMS}} \sim 0.33$$



$$\tau_{\mathrm{esc}} \sim 2 \times 10^7 \,\mathrm{yr}$$

Energy dependence not confirmed by new AMS data

Non-linear diffusive shock acceleration

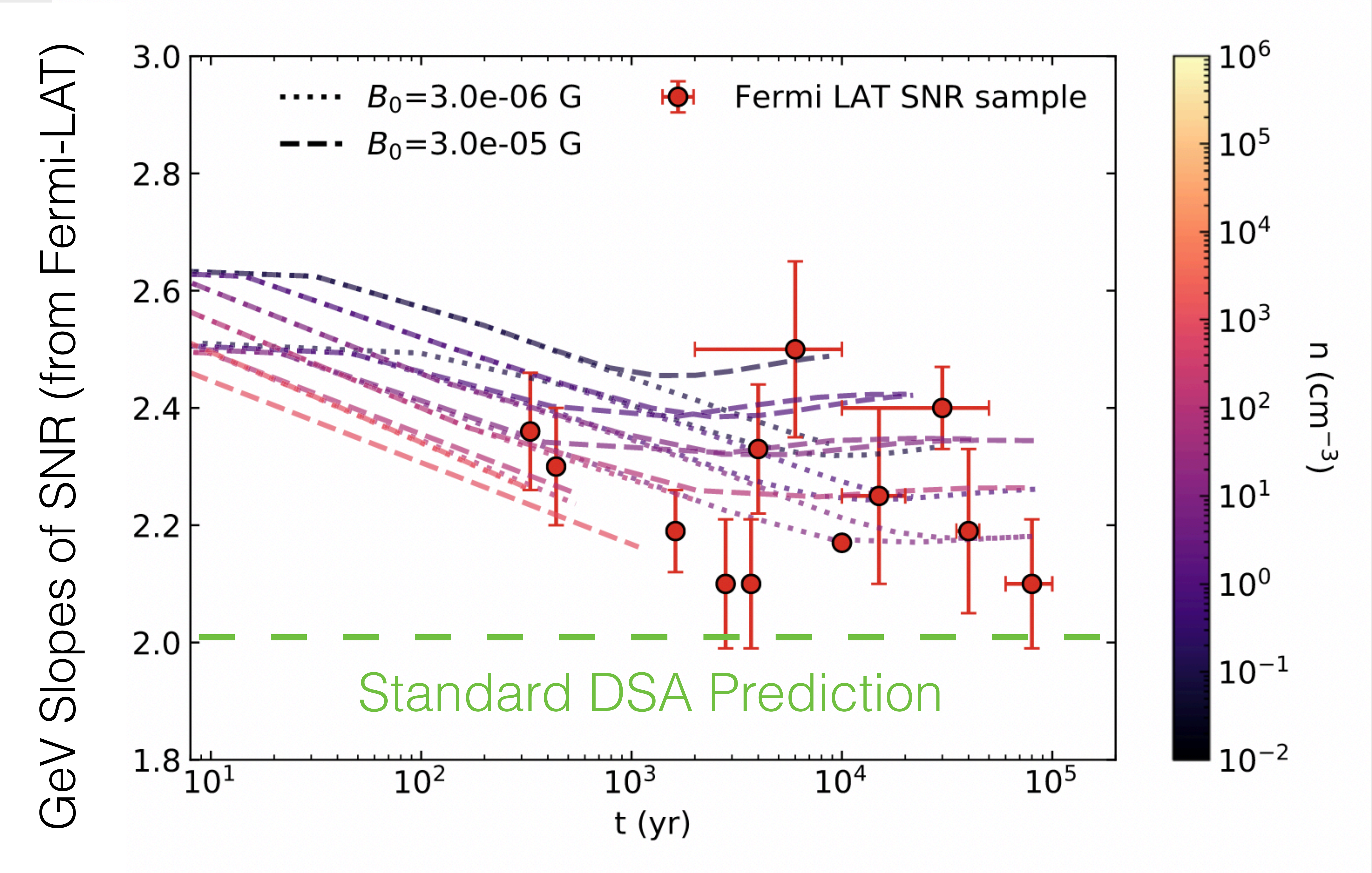
Ideal diffusive shock acceleration $r = \frac{v_1}{v_2} = \frac{\rho_2}{\rho_1}$

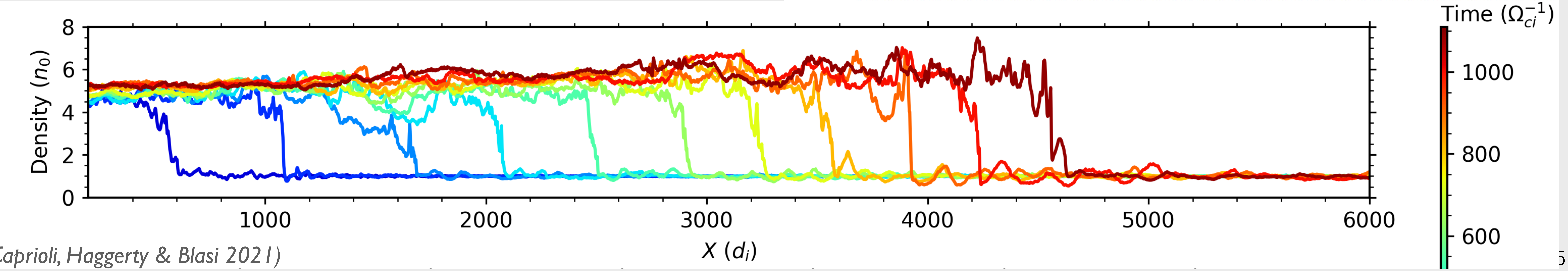
$$f(p) \sim p^{-q}; \;\; q \approx \frac{3r}{r-1}$$

Non-linear diffusive shock acceleration

$$q = \frac{3r}{r - 1 - v_A/u_2}$$

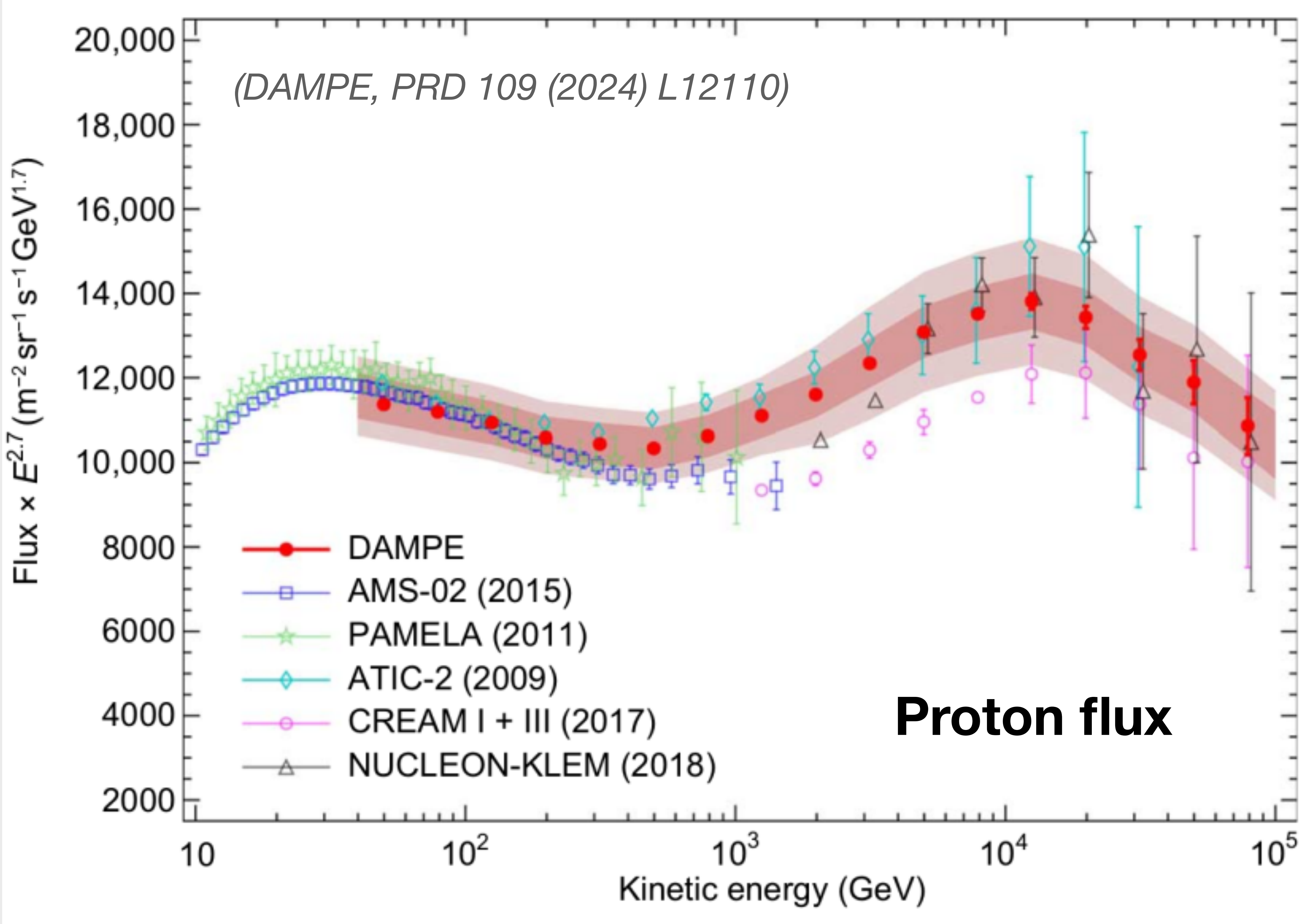
Correction term, larger slopes

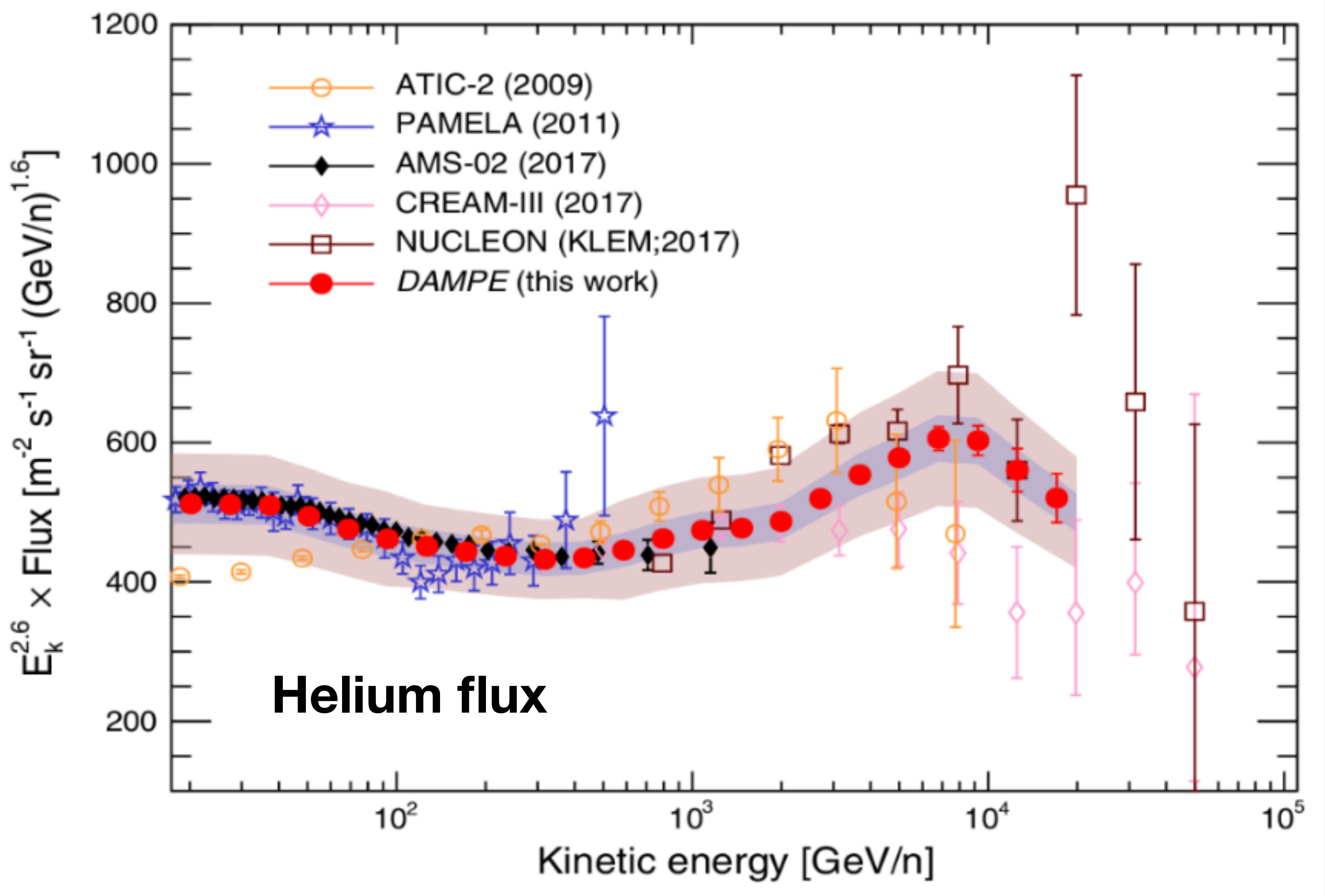




(Caprioli, Haggerty & Blasi 2021)

Unexpected structure of energy spectrum



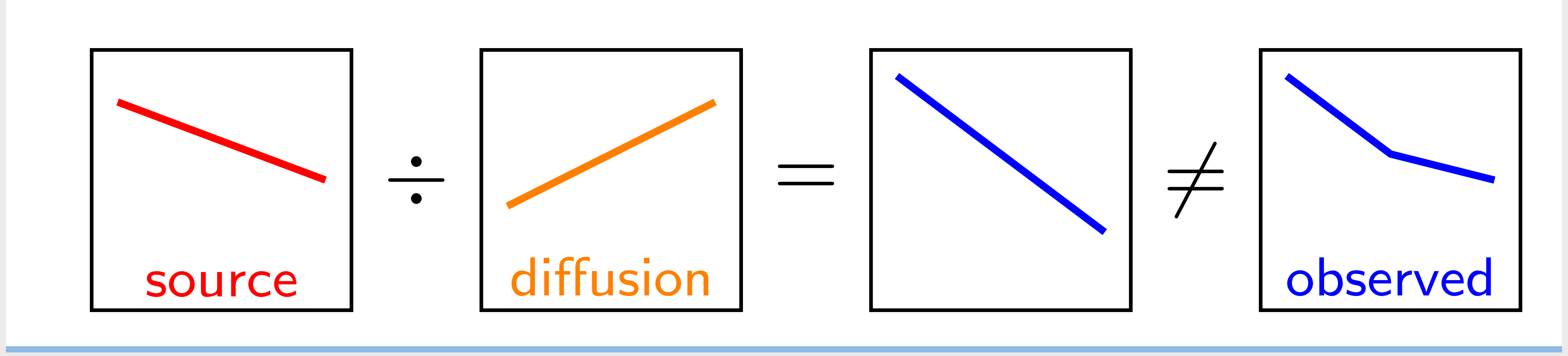


Spectral hardening first found by PAMELA

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

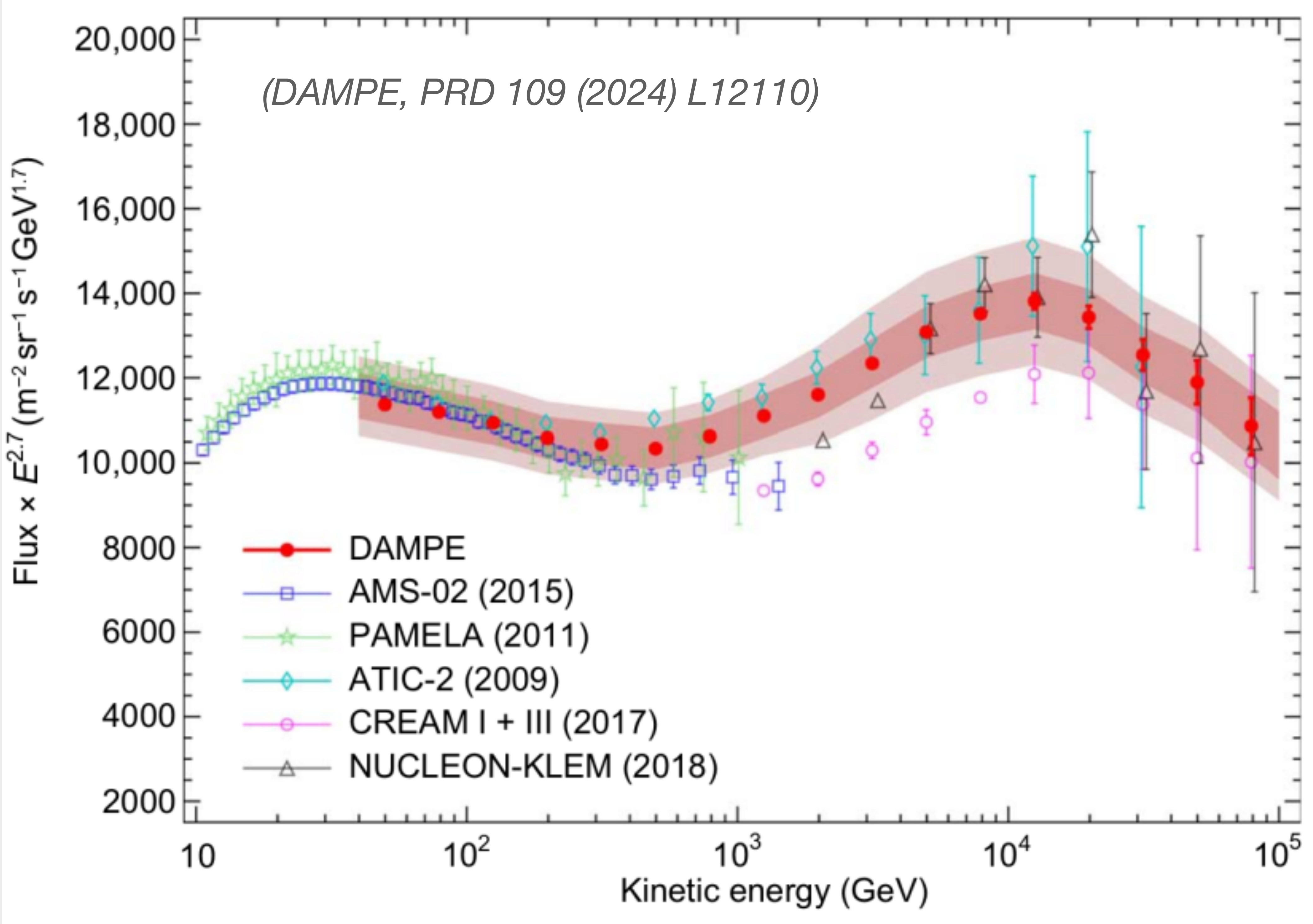
Escape time:
diffusion coefficient

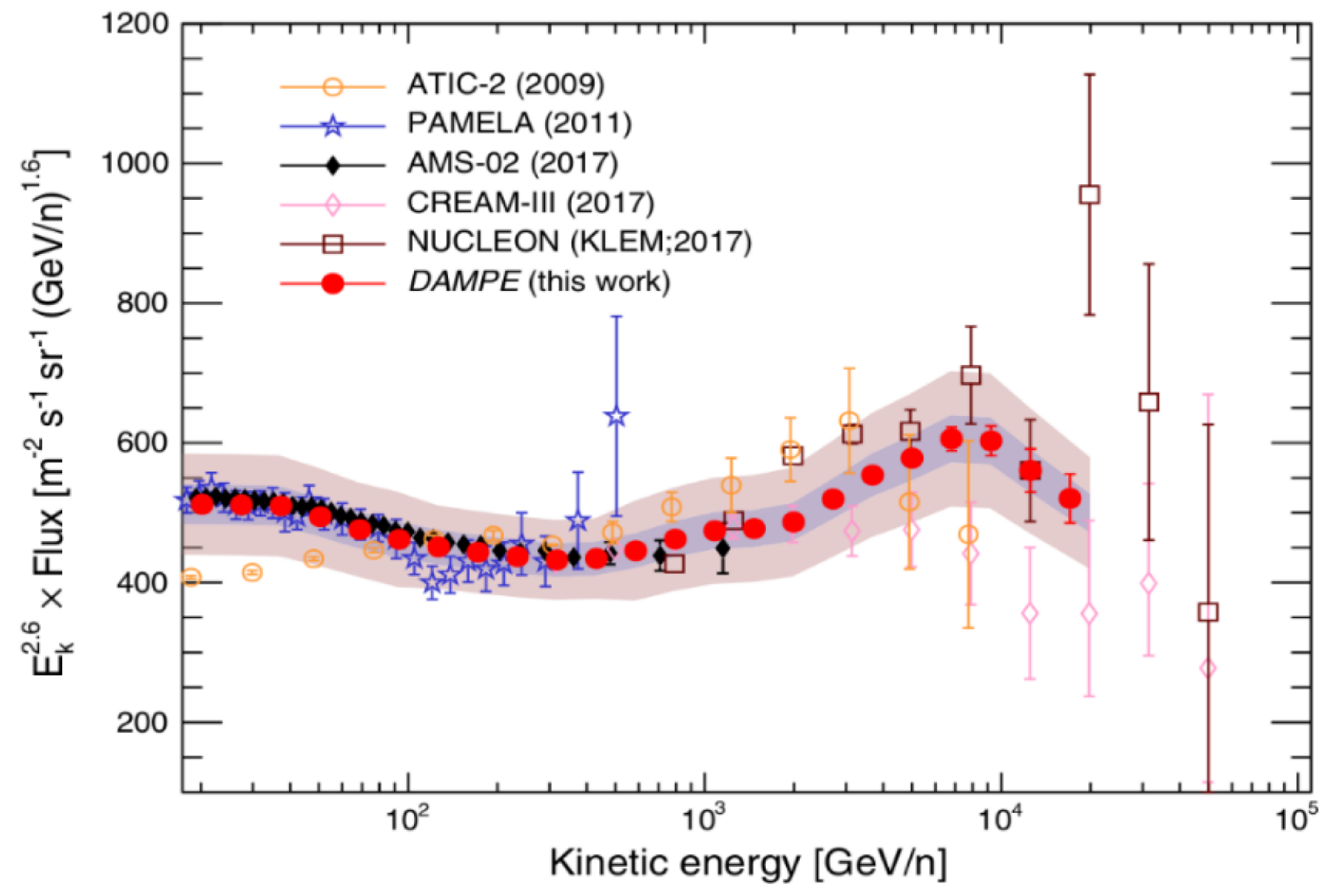
Source



(P. Mertsch, DPG 2023)

Unexpected structure of energy spectrum





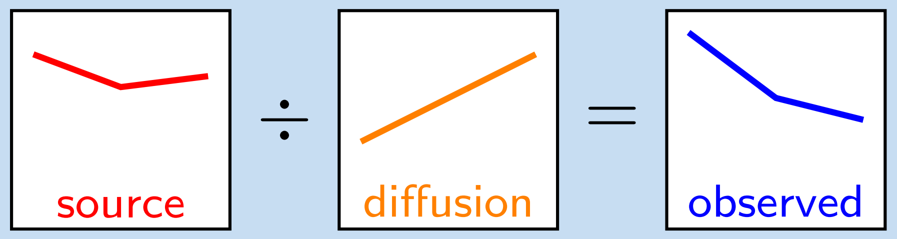
$$N(E) = \tau_{\rm esc}(E)\; Q(E)$$

Escape time: diffusion coefficient

Source

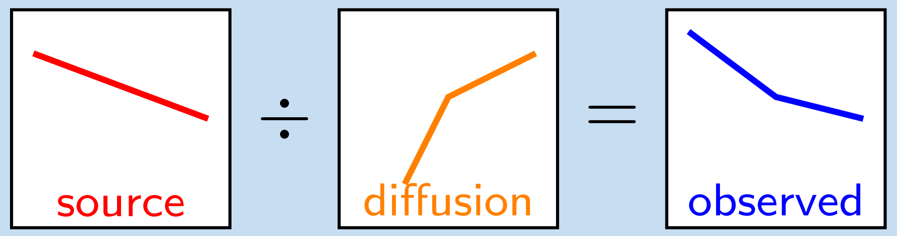
Source effect

- Break in source spectrum
  Stanev, Biermann and Gaisser (1993)
  Parizot (2004)
  Ptuskin, Zirakashvili and Seo (2013)



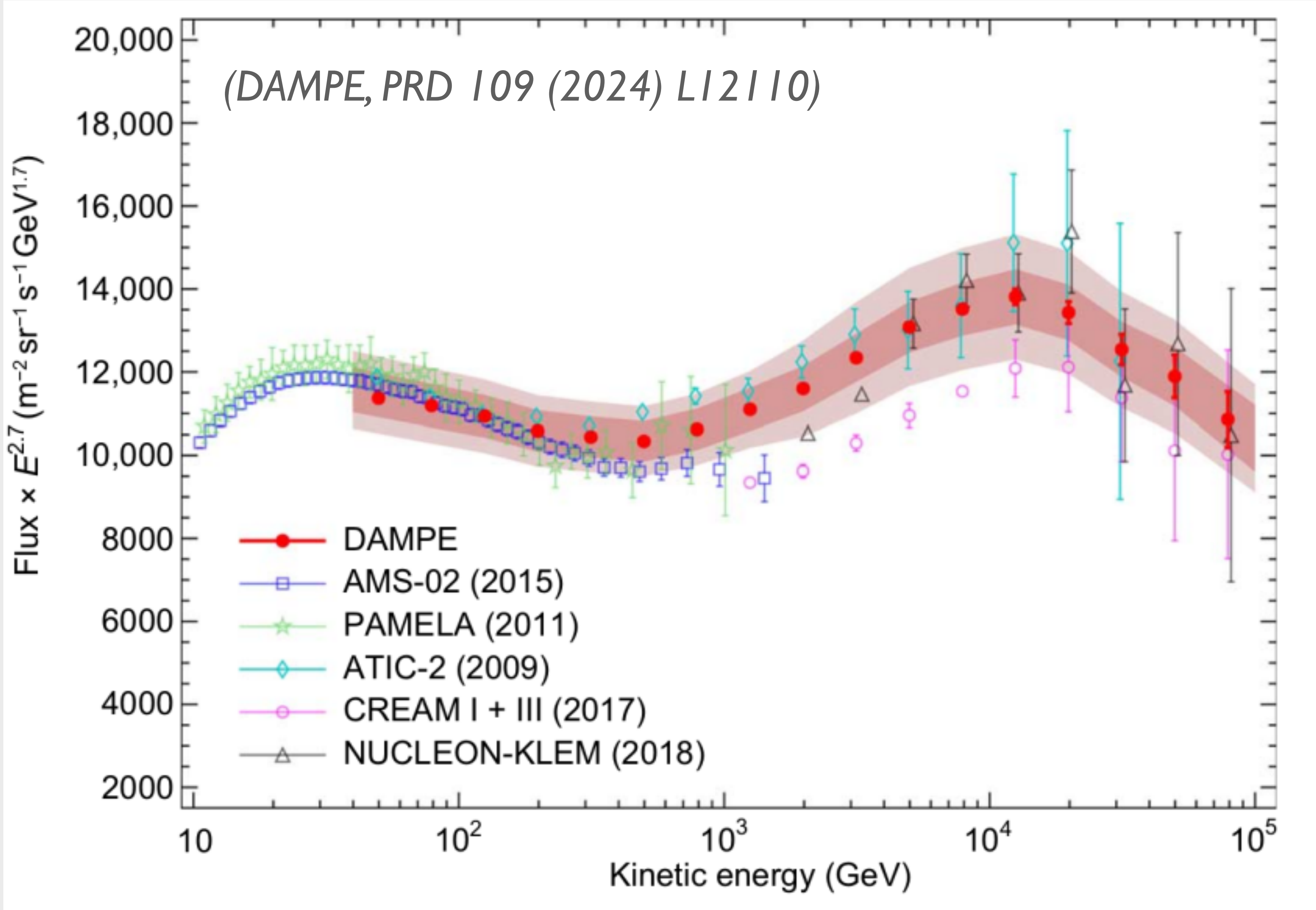
Transport effect

- Break in diffusion coefficient
  Blasi, Amato & Serpico, PRL 109 (2012) 061101
  Tomassetti, ApJL 752 (2012) 13

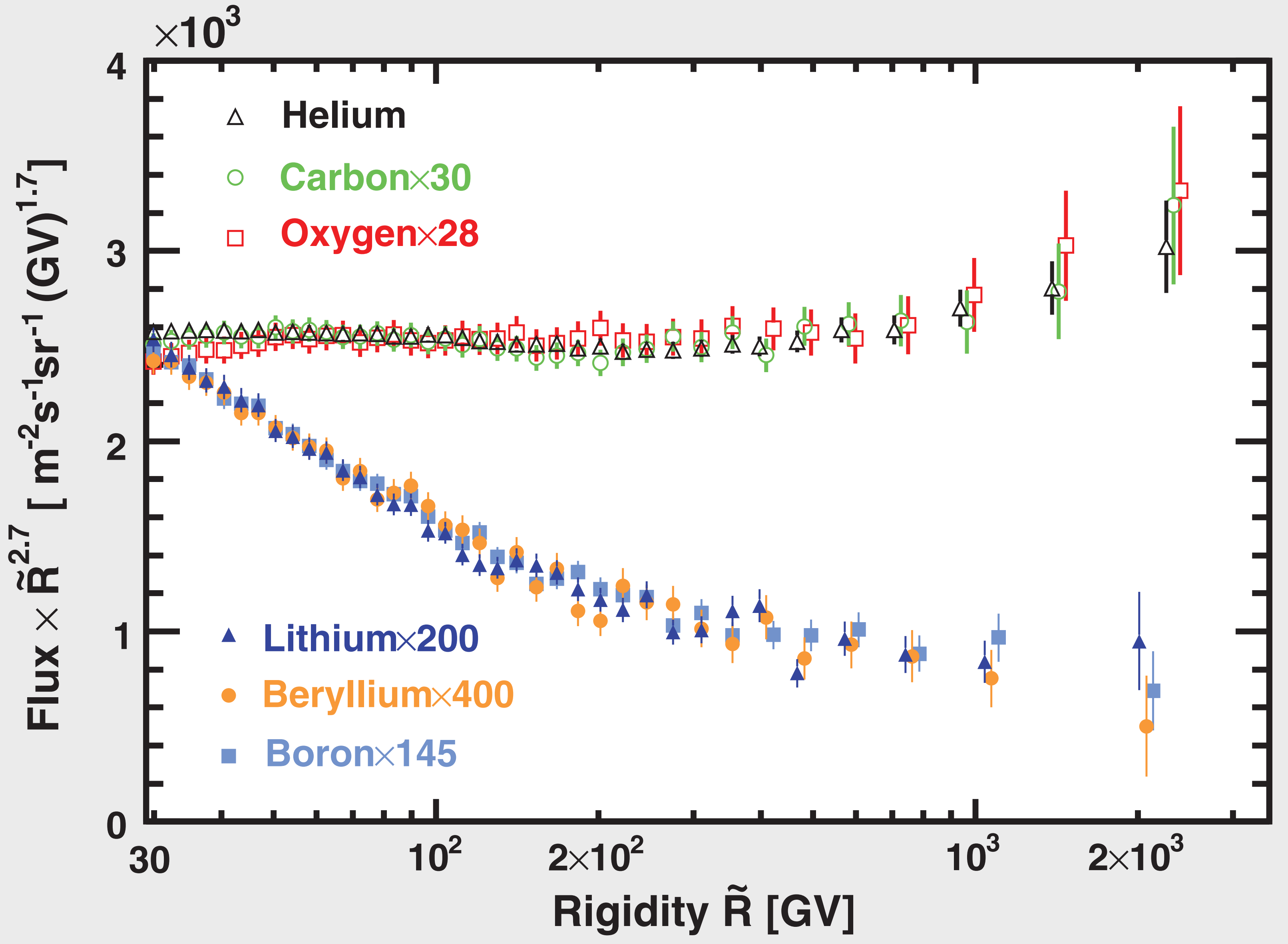


(P. Mertsch, DPG 2023)

Unexpected structure – check with secondaries



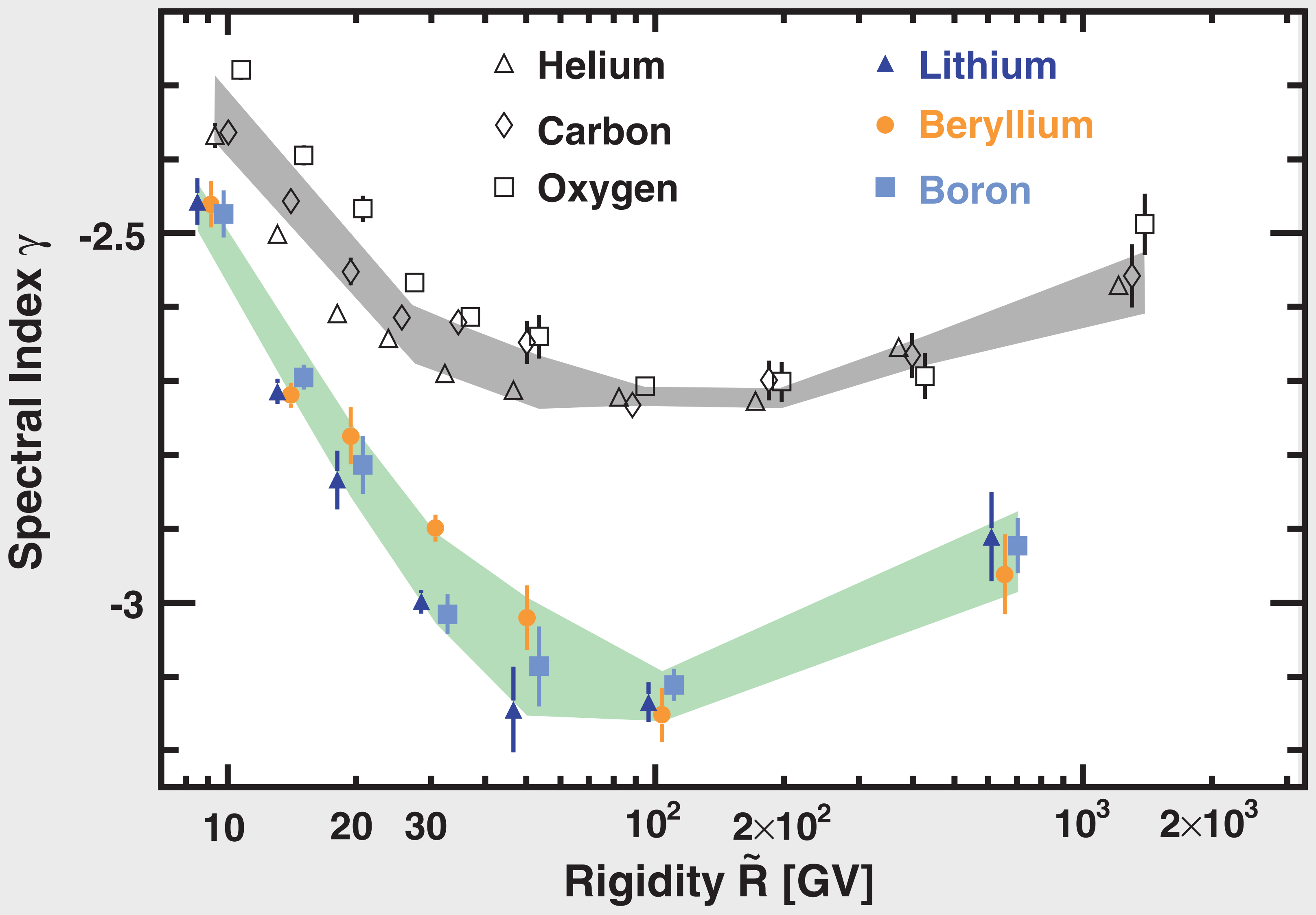
(AMS, PRL 120 (2018) 021101)



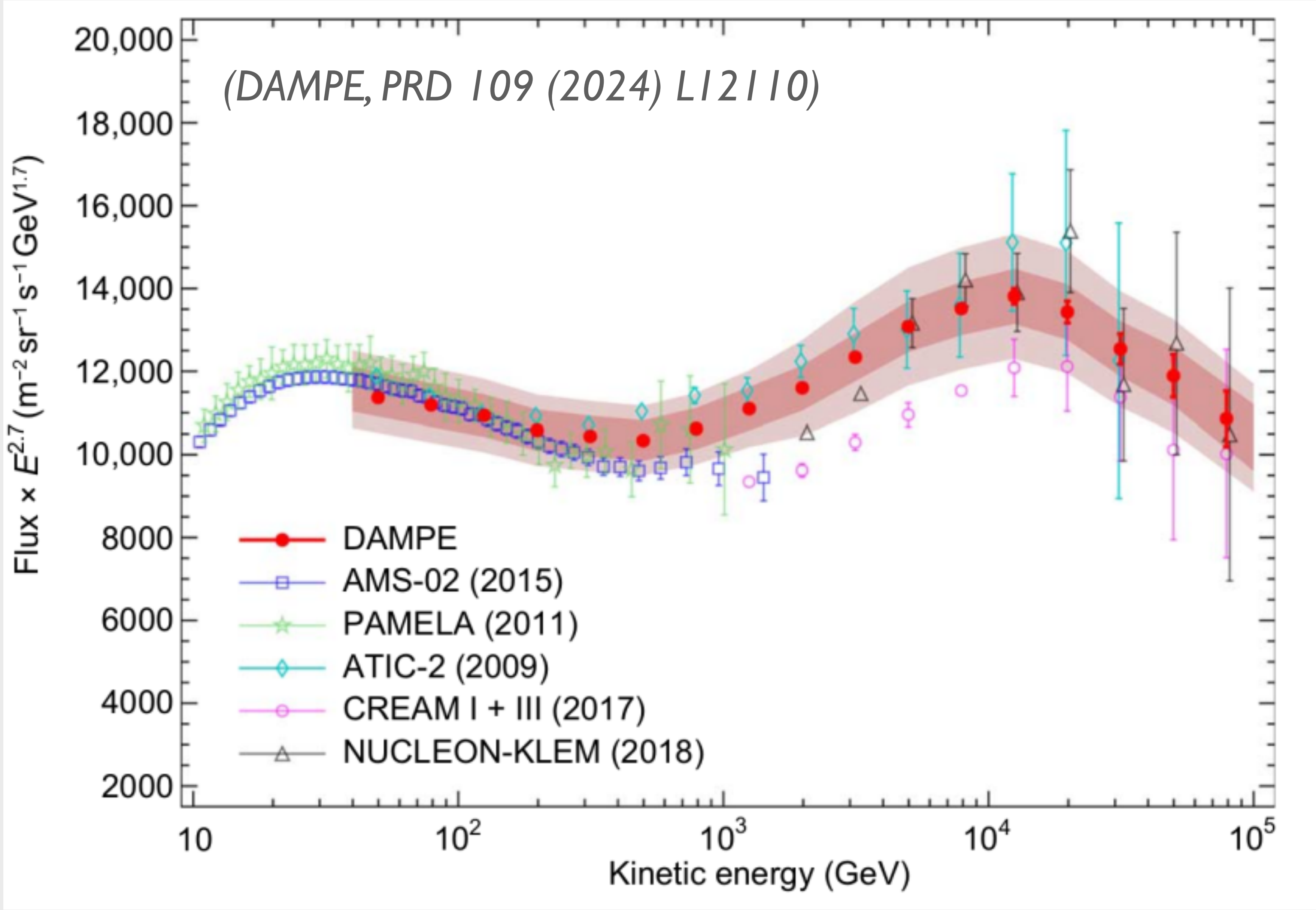
(P. Mertsch, DPG 2023)

- Can be distinguished by secondaries Vladimirov *et al.* (2012)
- break in source spectrum: break in secondaries similar

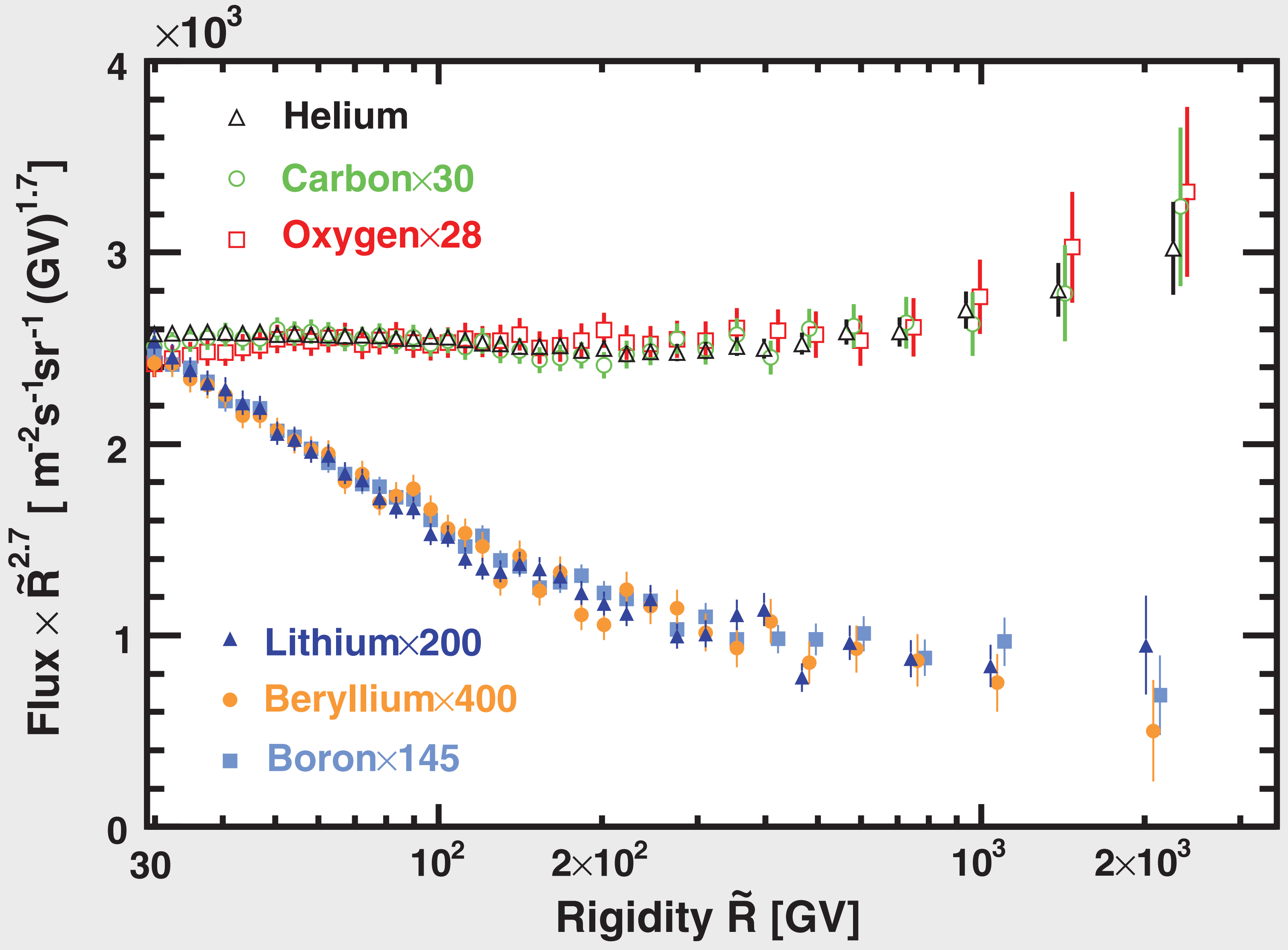
- break in diffusion coefficient: break in secondaries $\sim 2\times$ as strong



Unexpected structure – check with secondaries

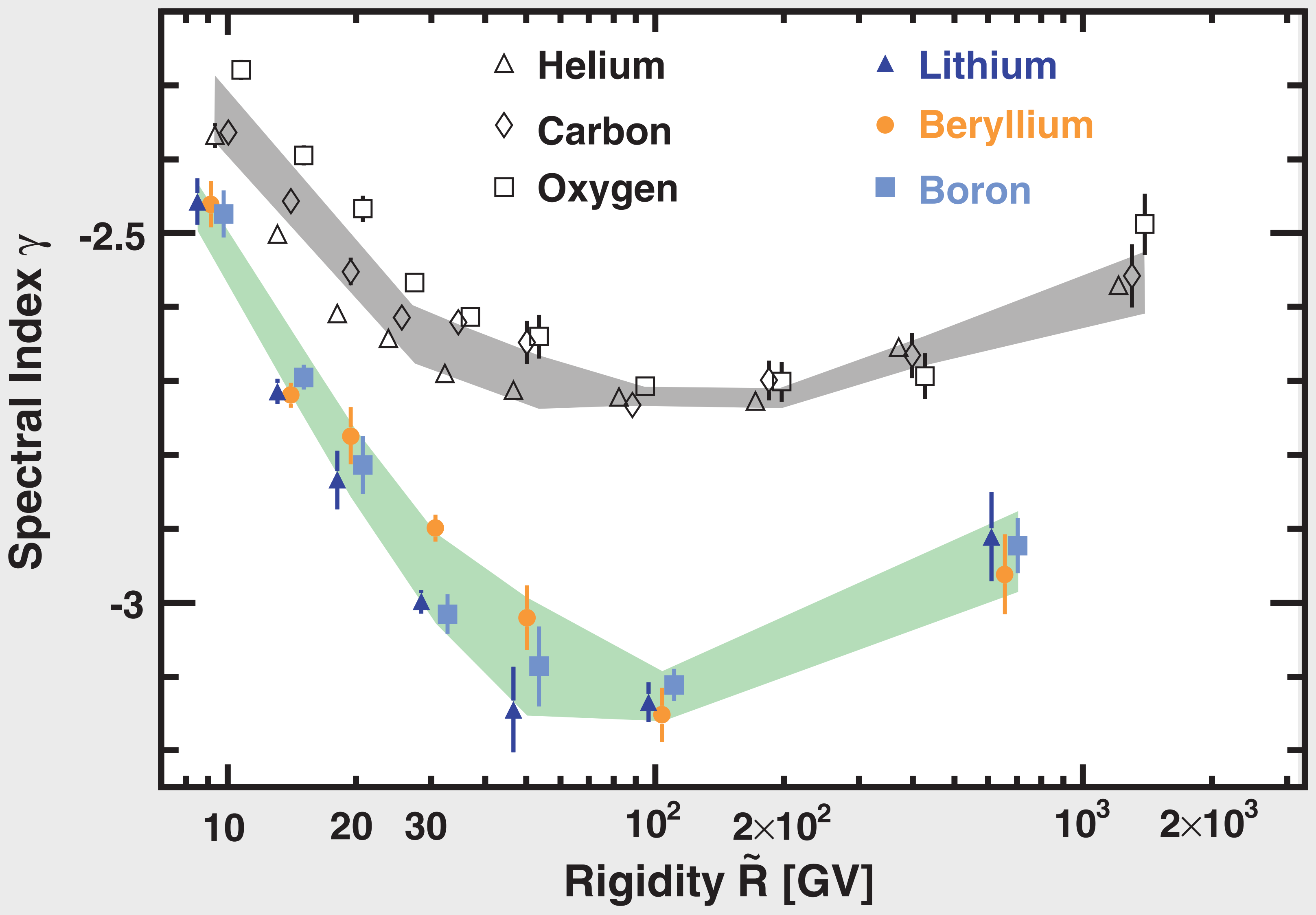


(AMS, PRL 120 (2018) 021101)



Data indicate propagation effect causing hardening

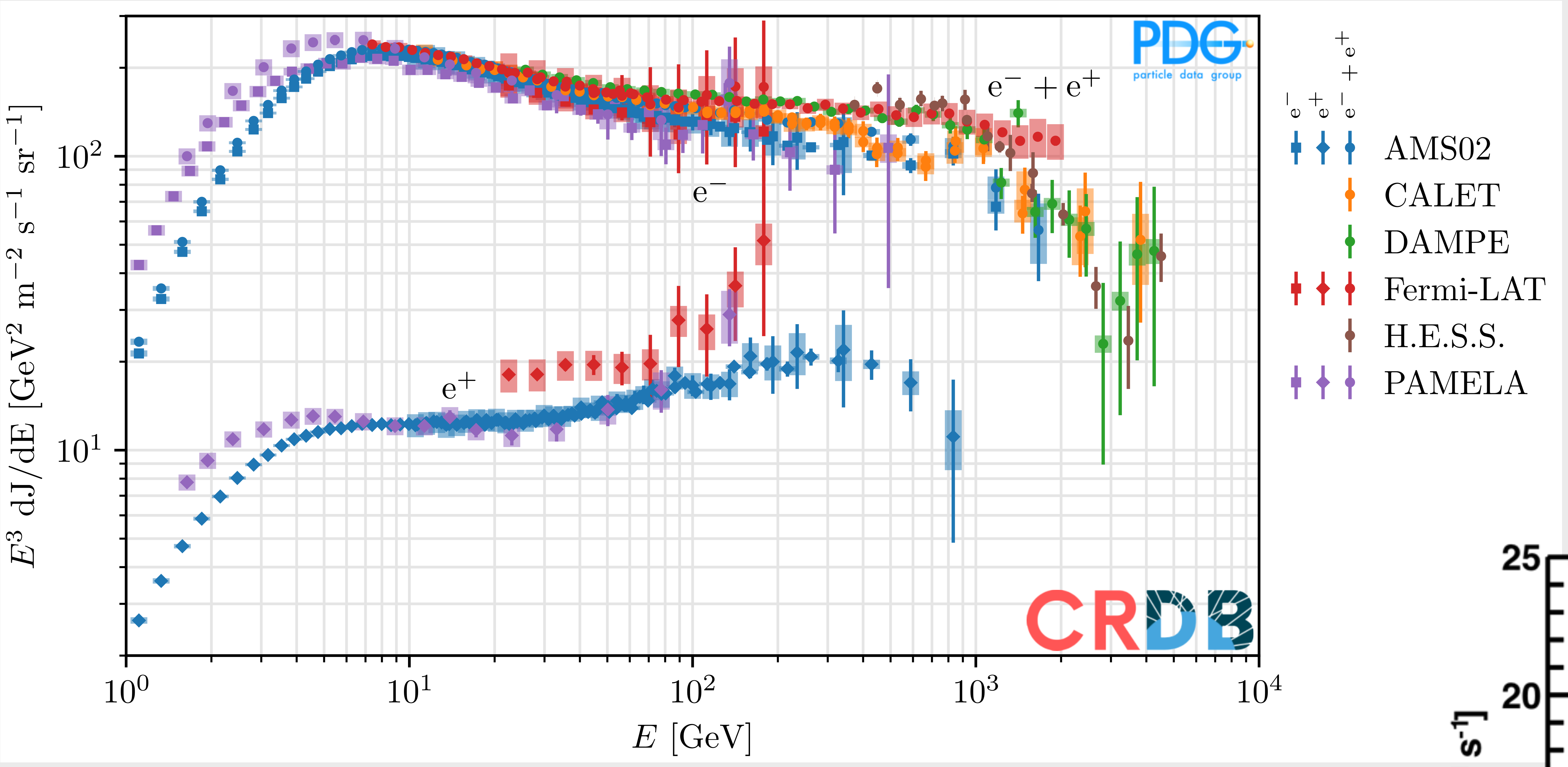
(P. Mertsch, DPG 2023)



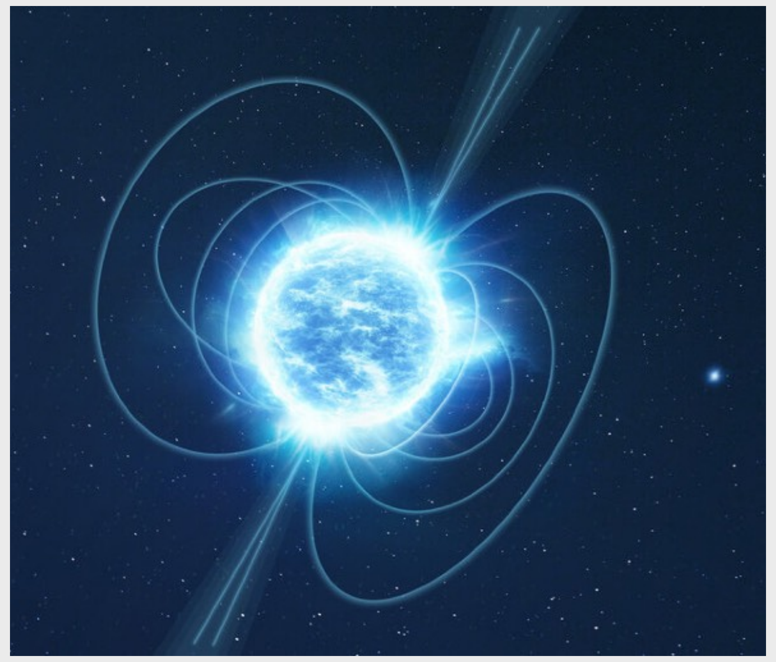
- Can be distinguished by secondaries Vladimirov *et al.* (2012)
- break in source spectrum: break in secondaries similar

- break in diffusion coefficient: break in secondaries ∼ 2× as strong

Electron and positron spectra

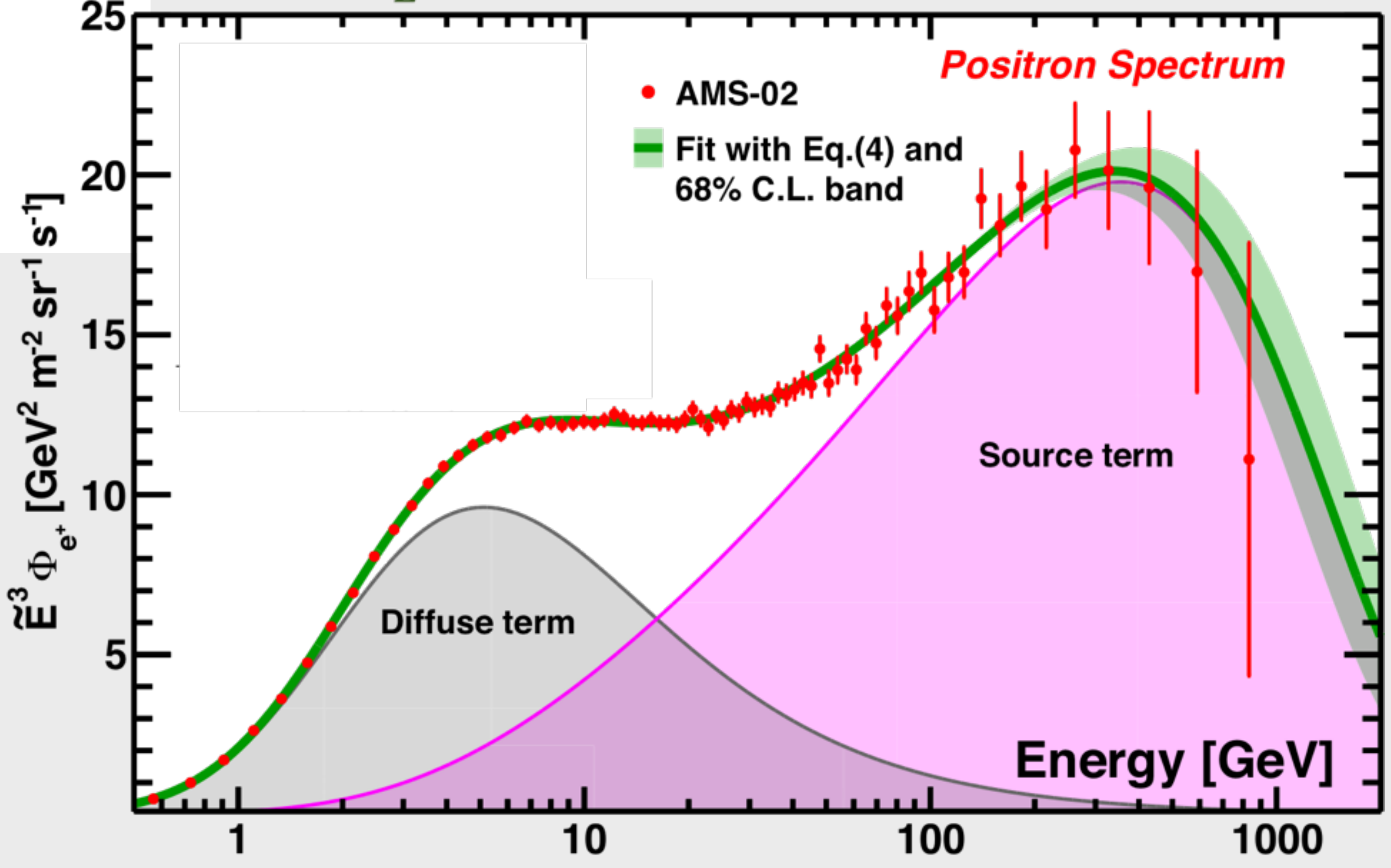


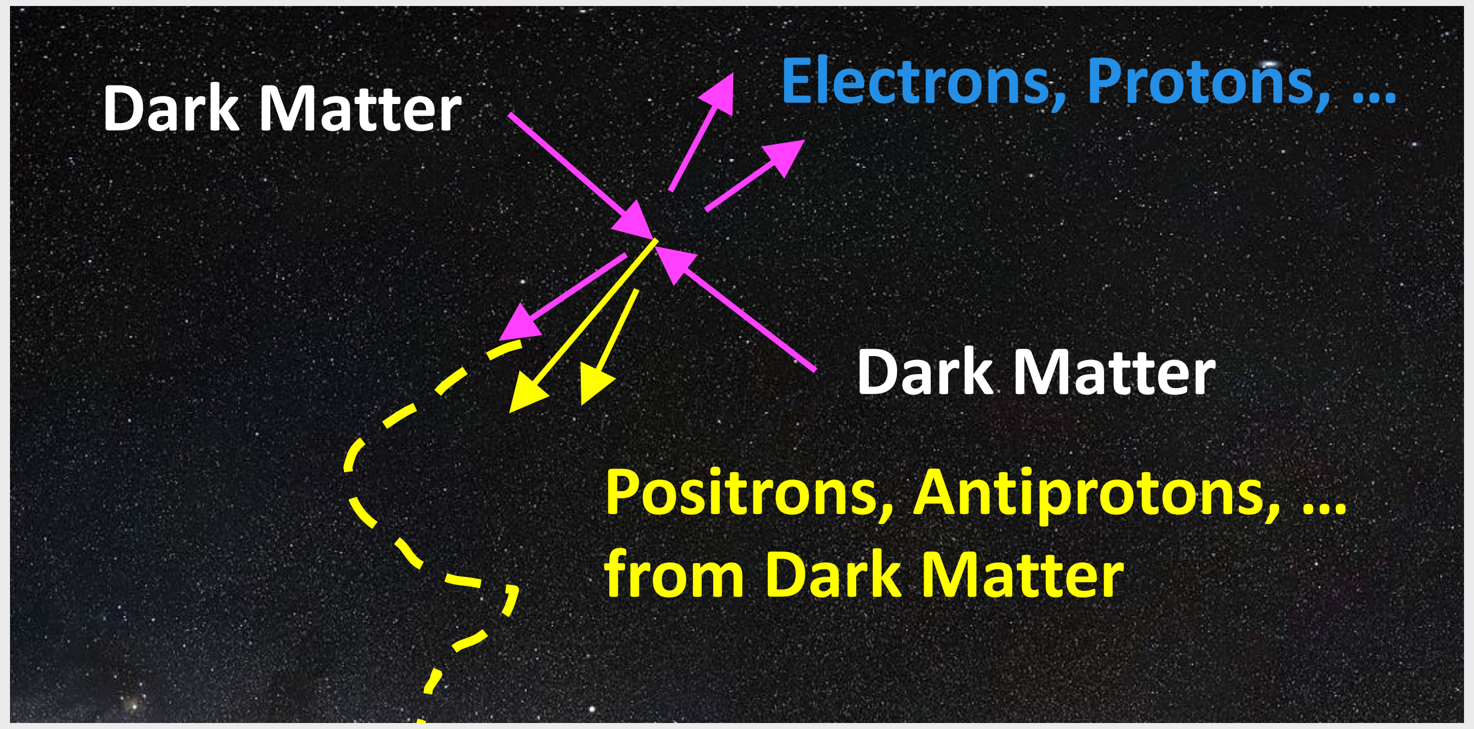
(Blasi, PRL 103 (2009) 051104,
Metrsch et al., PRD 104 (2021) 10, 103029)



Diffuse term **Source term**

$$\Phi_{e^+}(E) = \frac{E^2}{\hat{E}^2}\left[C_d(\hat{E}/E_1)^{\gamma_d} + C_s(\hat{E}/E_2)^{\gamma_s}\exp(-\hat{E}/E_s)\right]$$

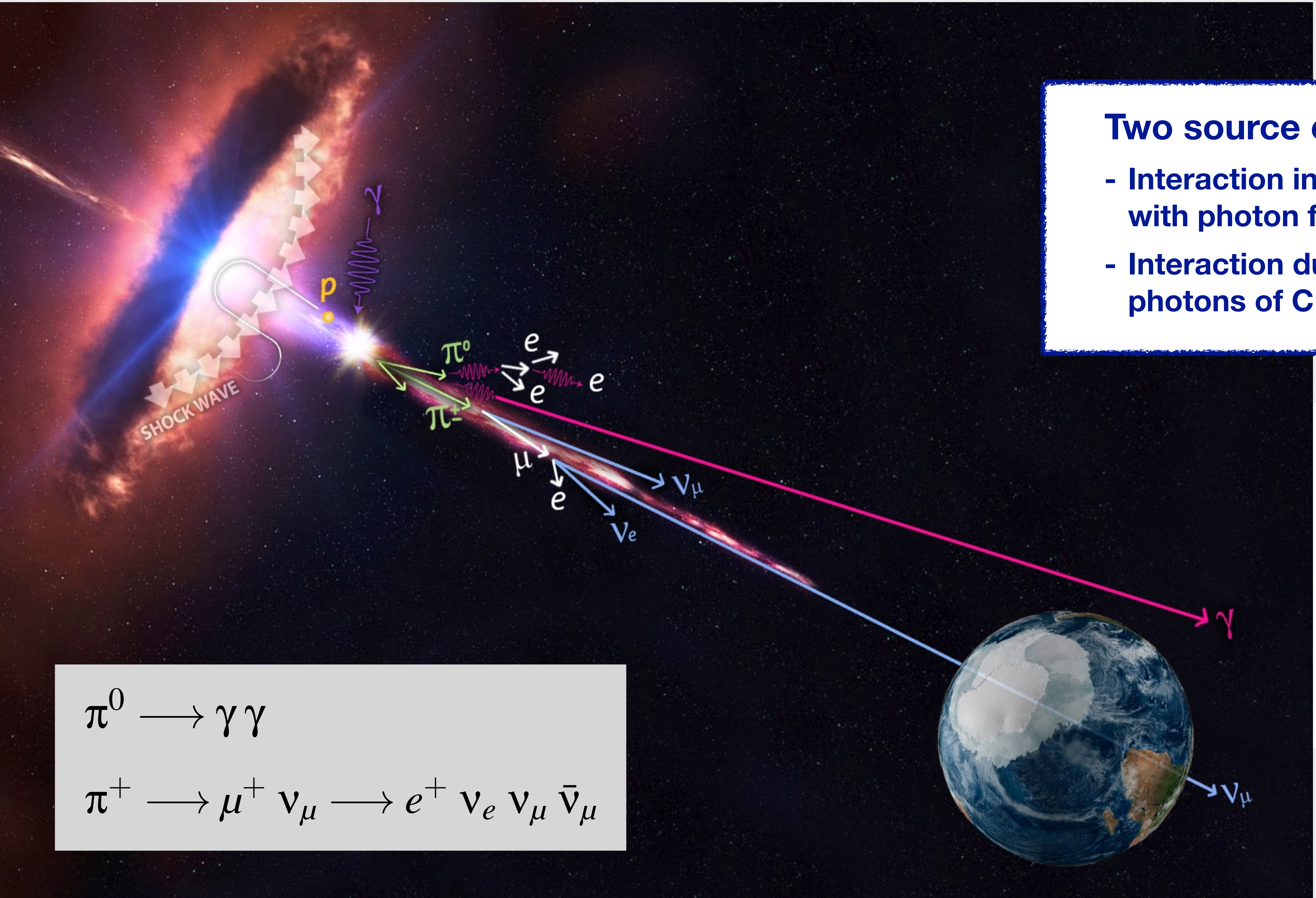




(Bergstrom et al., PRL 103 (2009) 031103,
Chilis & Hooper, PRD 88 (2013) 023013)

Backup slides

Neutral (secondary) particles as messengers

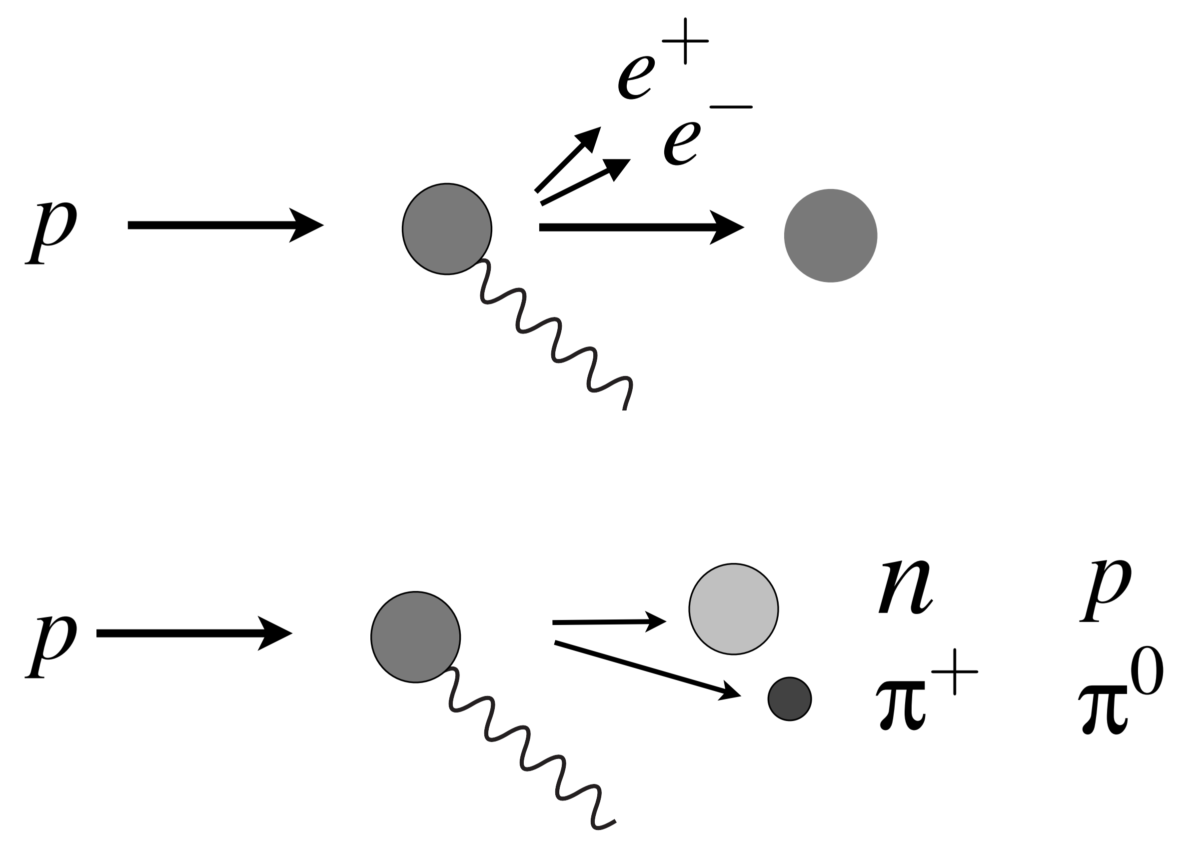


Two source classes

- Interaction in dense source regions with photon field or gas
- Interaction during propagation with photons of CMB and other backgrounds

$$\pi^0 \longrightarrow \gamma\gamma$$

$$\pi^+ \longrightarrow \mu^+ \nu_\mu \longrightarrow e^+ \nu_e \nu_\mu \bar{\nu}_\mu$$



and similar interactions of nuclei, as well as dissociation of nuclei