Cosmic-ray propagation

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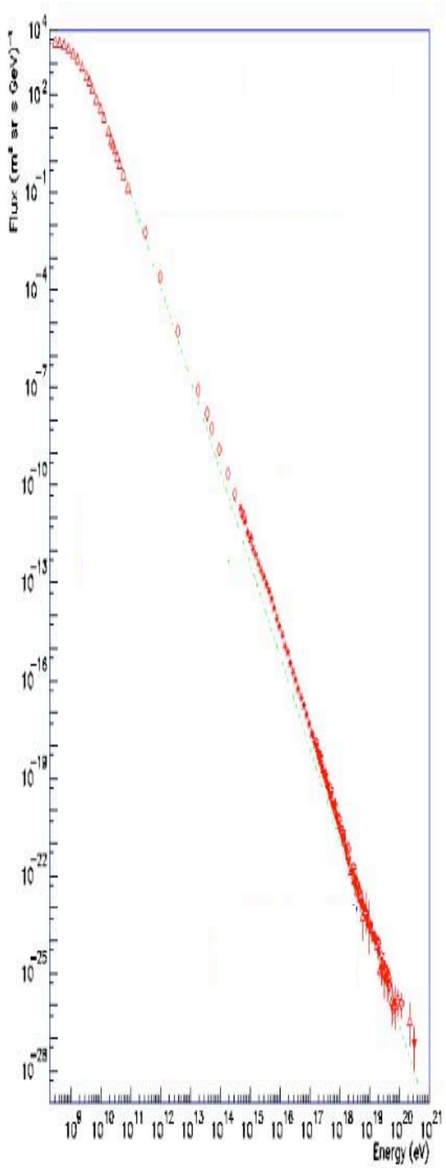
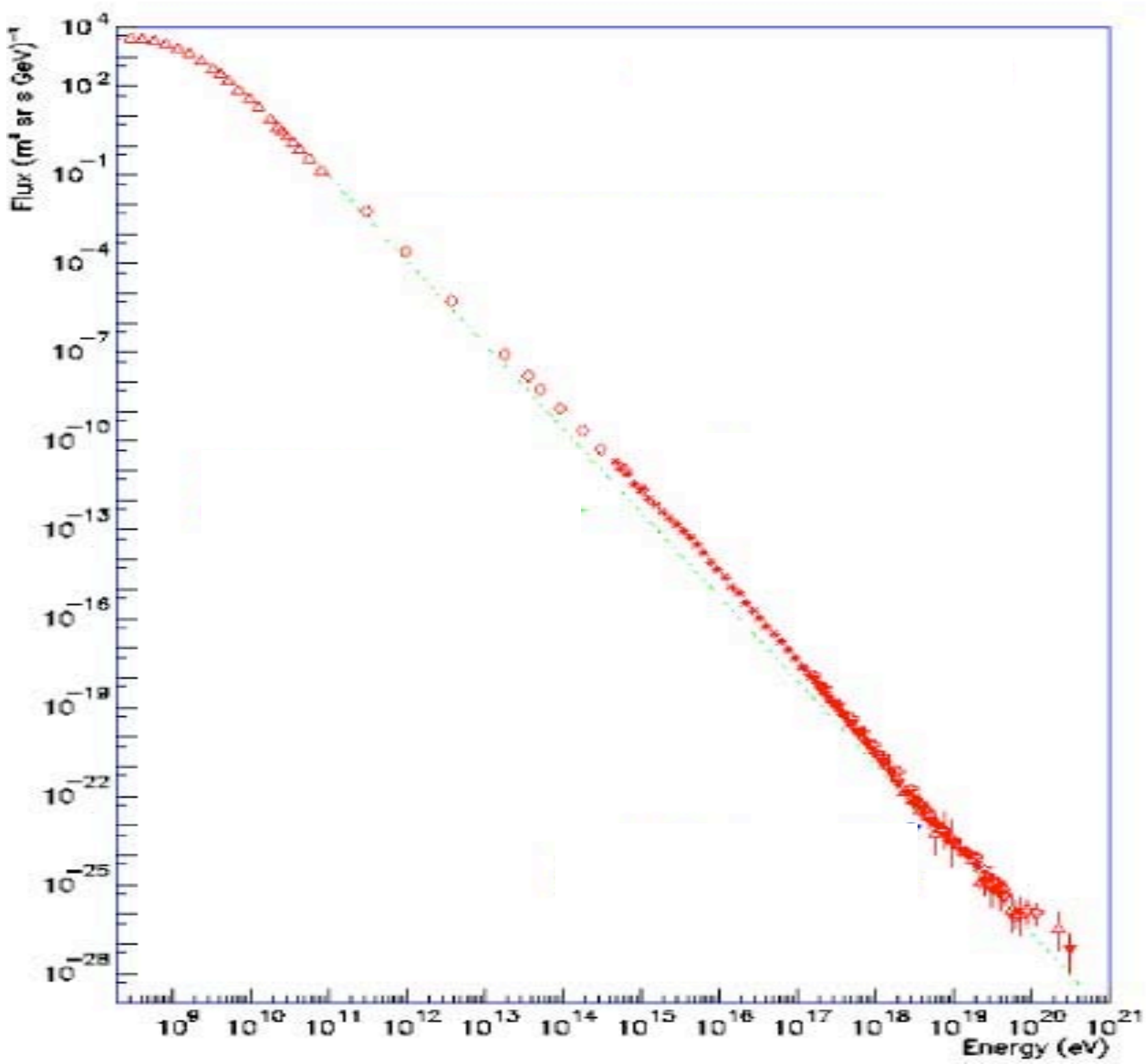
Avertissement !

- Les particules énergétiques sont omniprésentes en astrophysique et en astroparticules.
- La compréhension des mécanismes d'accélération et d'interaction de ces particules est donc capitale, et l'étude des sources non-thermiques en est la clé.
- Les rayons cosmiques sont des particules énergétiques, mais toute particule énergétique n'est pas un rayon cosmique.
- Les rayons cosmiques, c'est ça :

(Une des 7 merveilles du monde physique)



Spectre magnifique… mais un peu monotone !

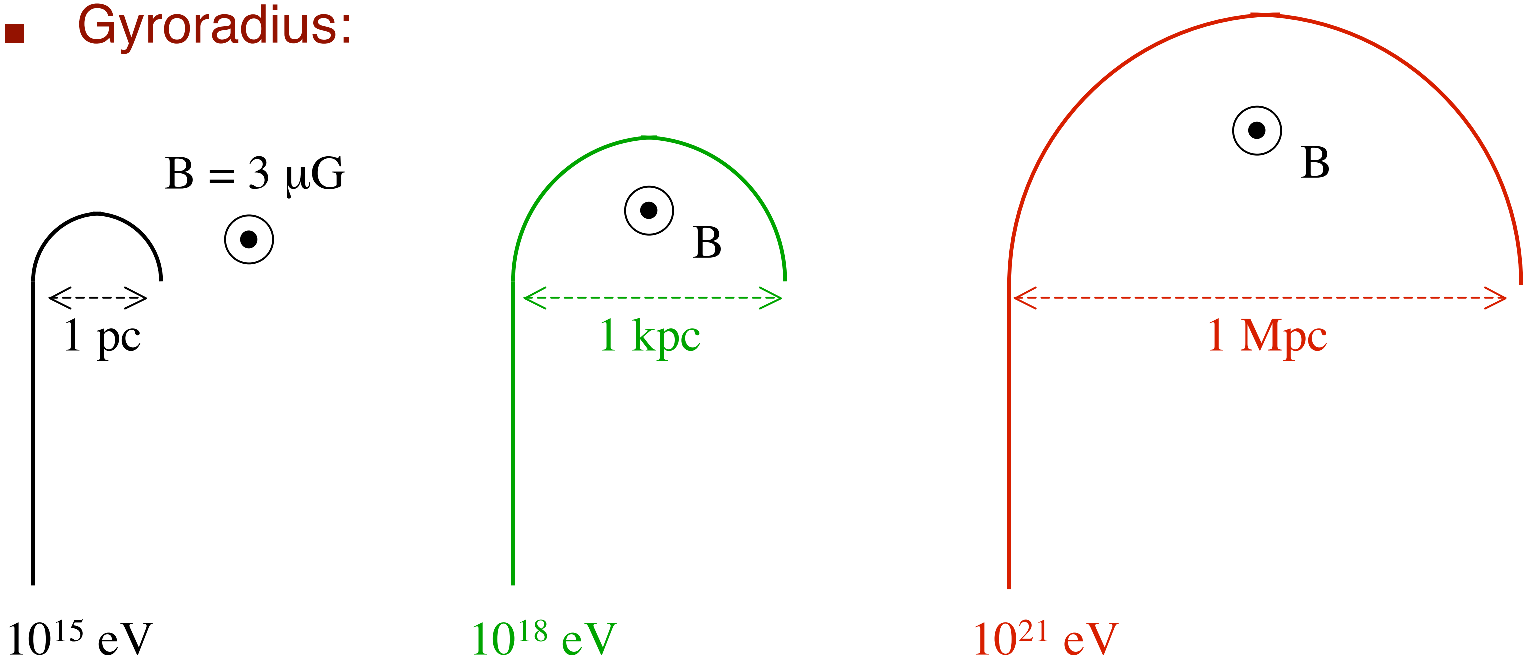


Observables fondamentales
du rayonnement cosmique

- Direction d'arrivée
- Énergie
- Masse (i.e. quel type de noyau)

Non rectilinear propagation!

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



Supernova remnant

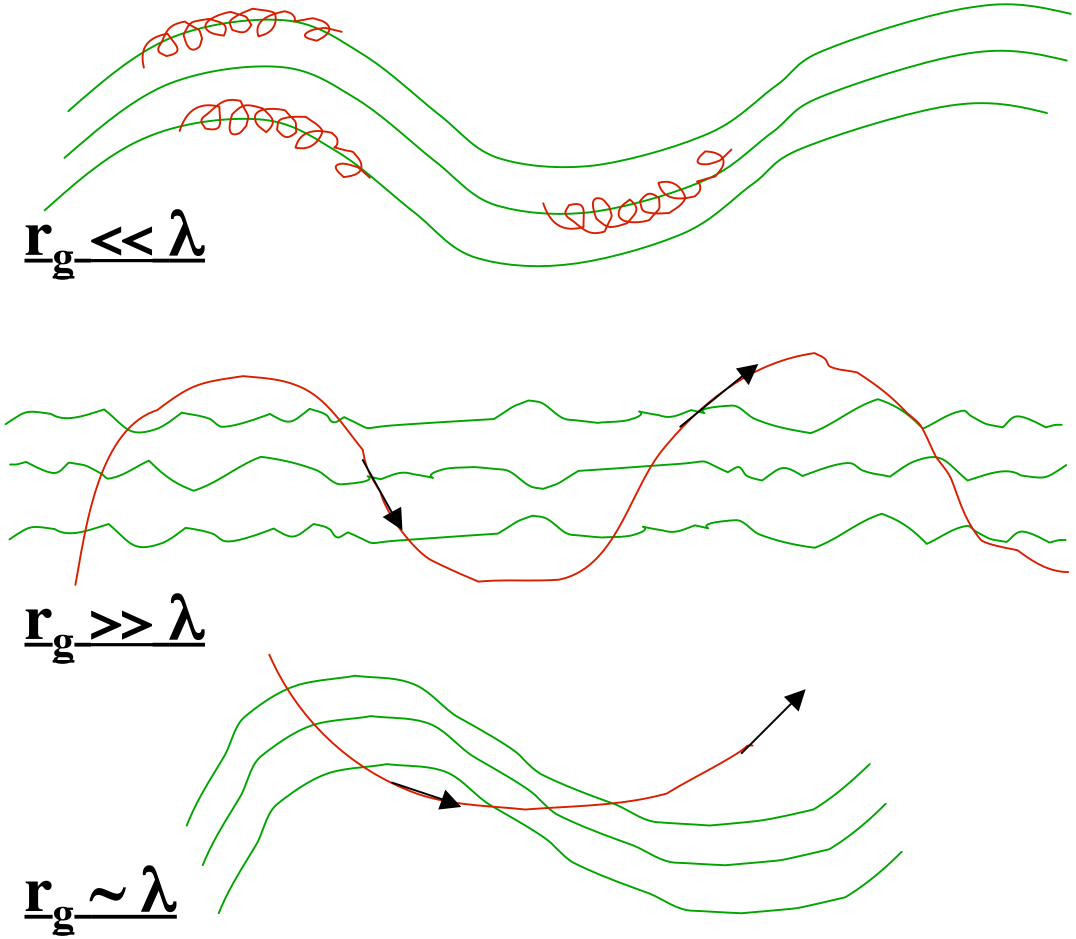
Disk + Galactic halo

>> galaxy

→ proton astronomy?

Interaction with B inhomogeneities

- Magnetic inhomogeneities ≈ perturbed field lines



Adjustment of the pitch angle to conserve the first adiabatic invariant:

$p_\perp^2 / B \sim \text{cst}$

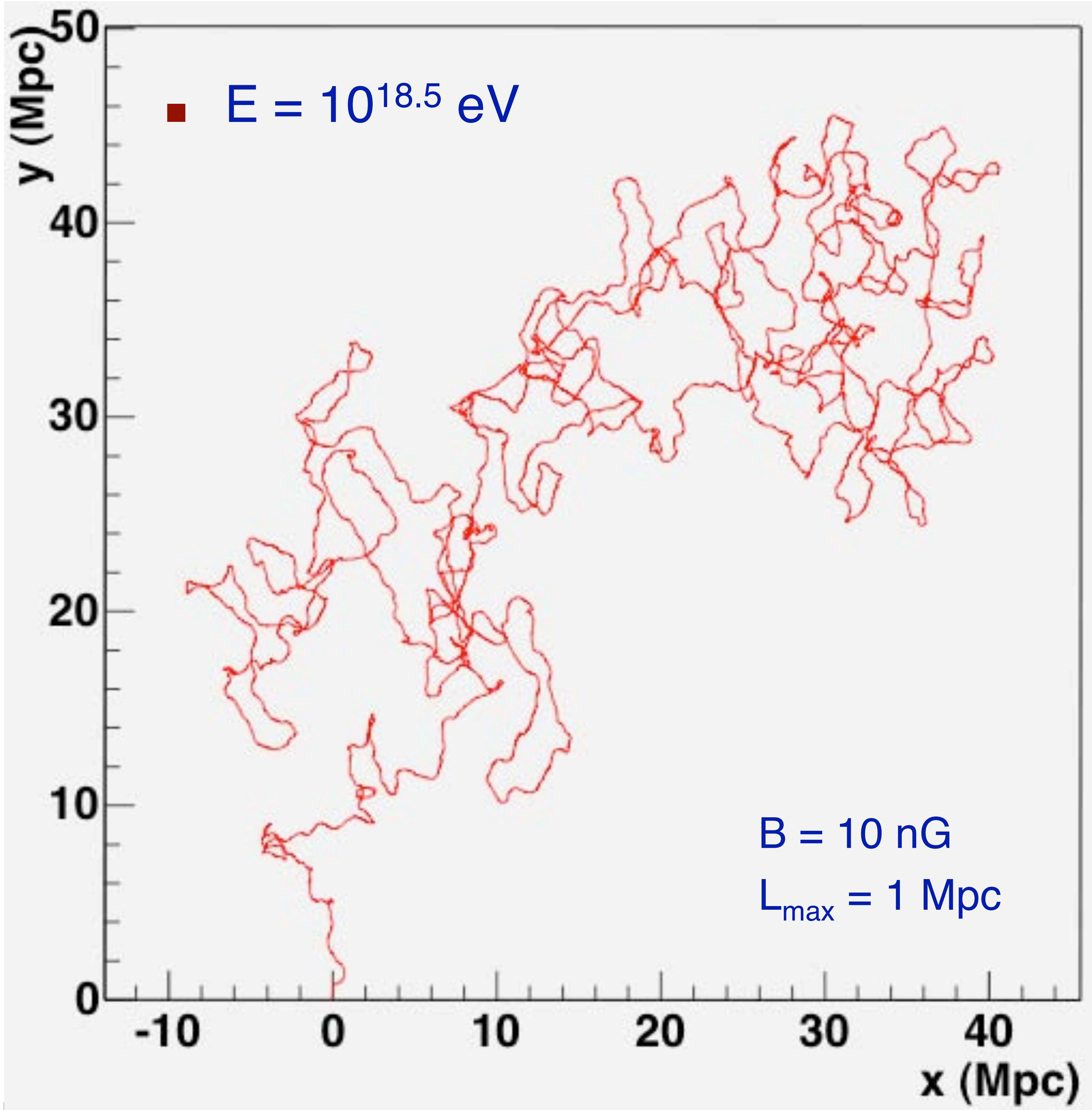
Nothing special...

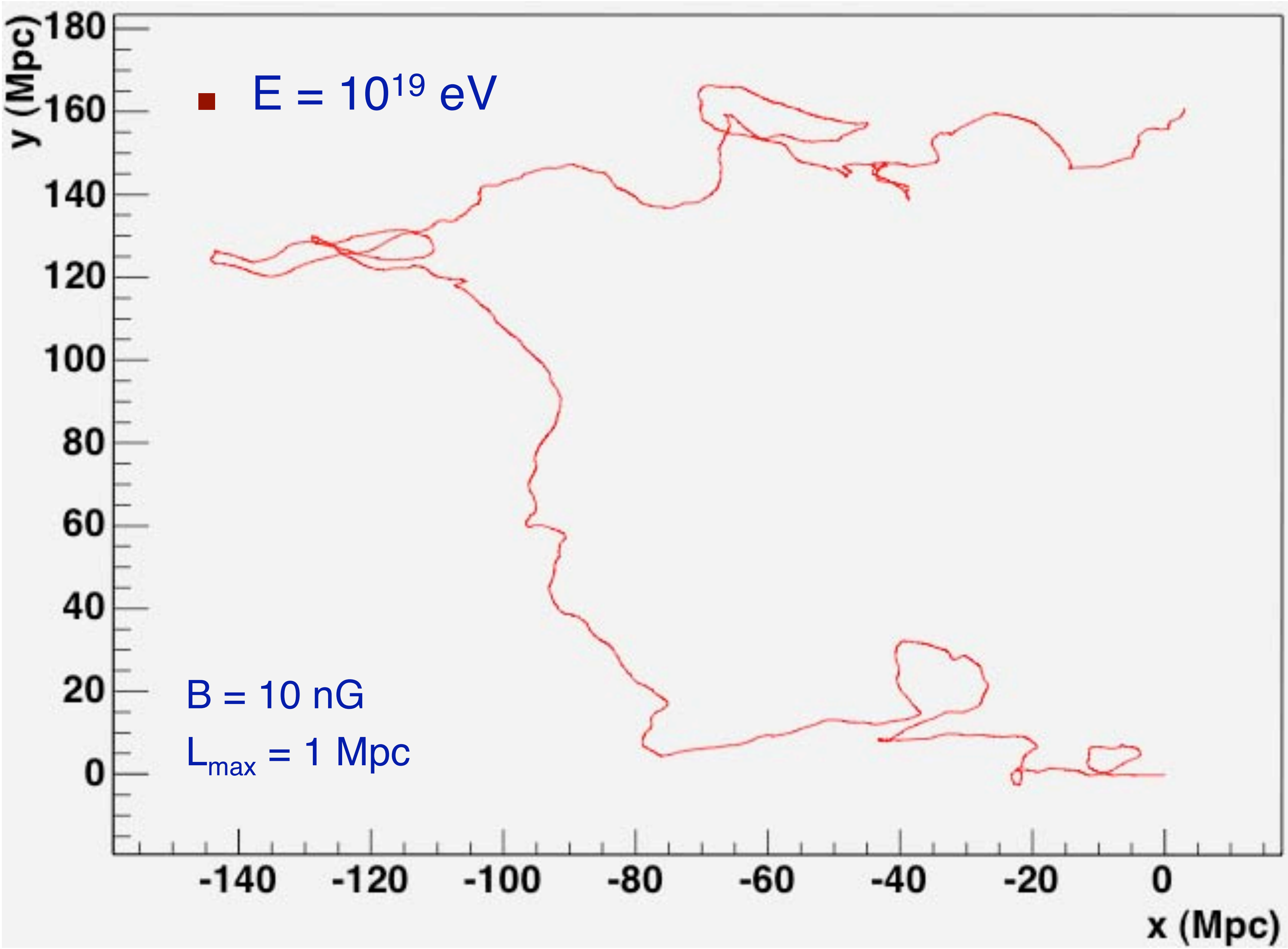
Pitch-angle scattering:

$\Delta\alpha \sim B_1/B_0$

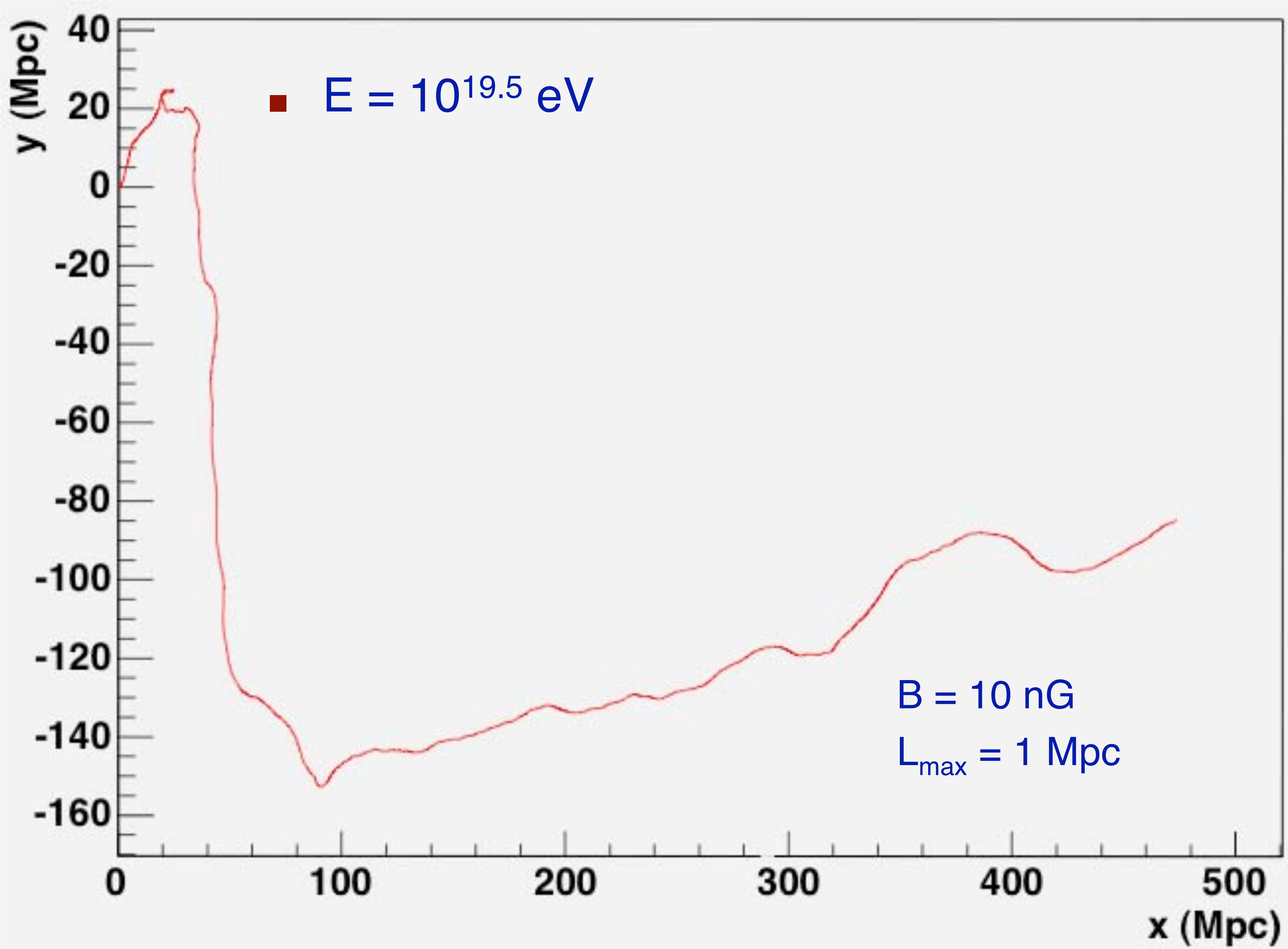
Guiding centre drift:

$r \sim r_g \, \Delta\alpha$

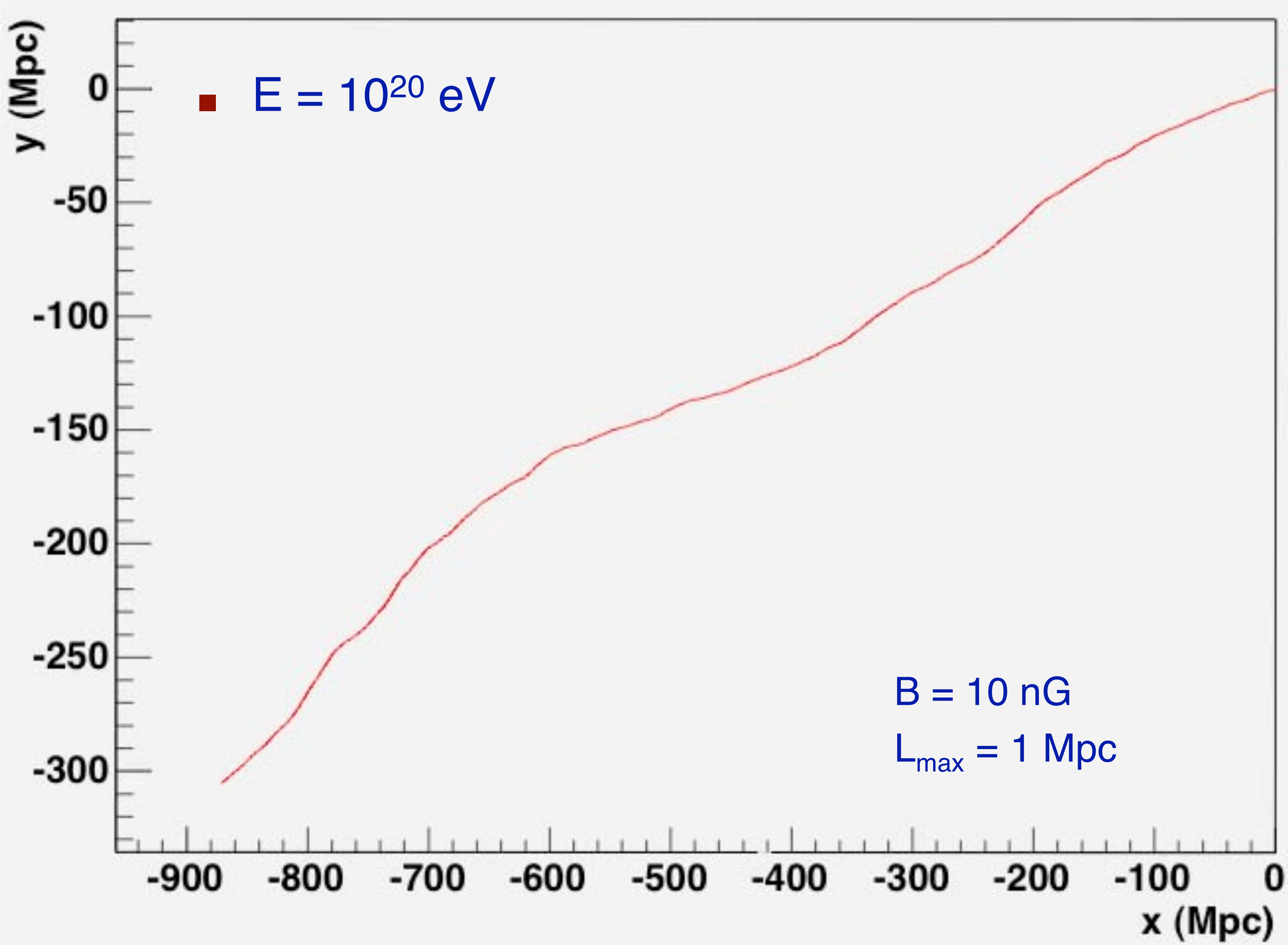

y (Mpc)
50
40
30
20
10
0
-10
0
10
20
30
40
x (Mpc)
E = $10^{18.5}$ eV
B = 10 nG
L_{max} = 1 Mpc



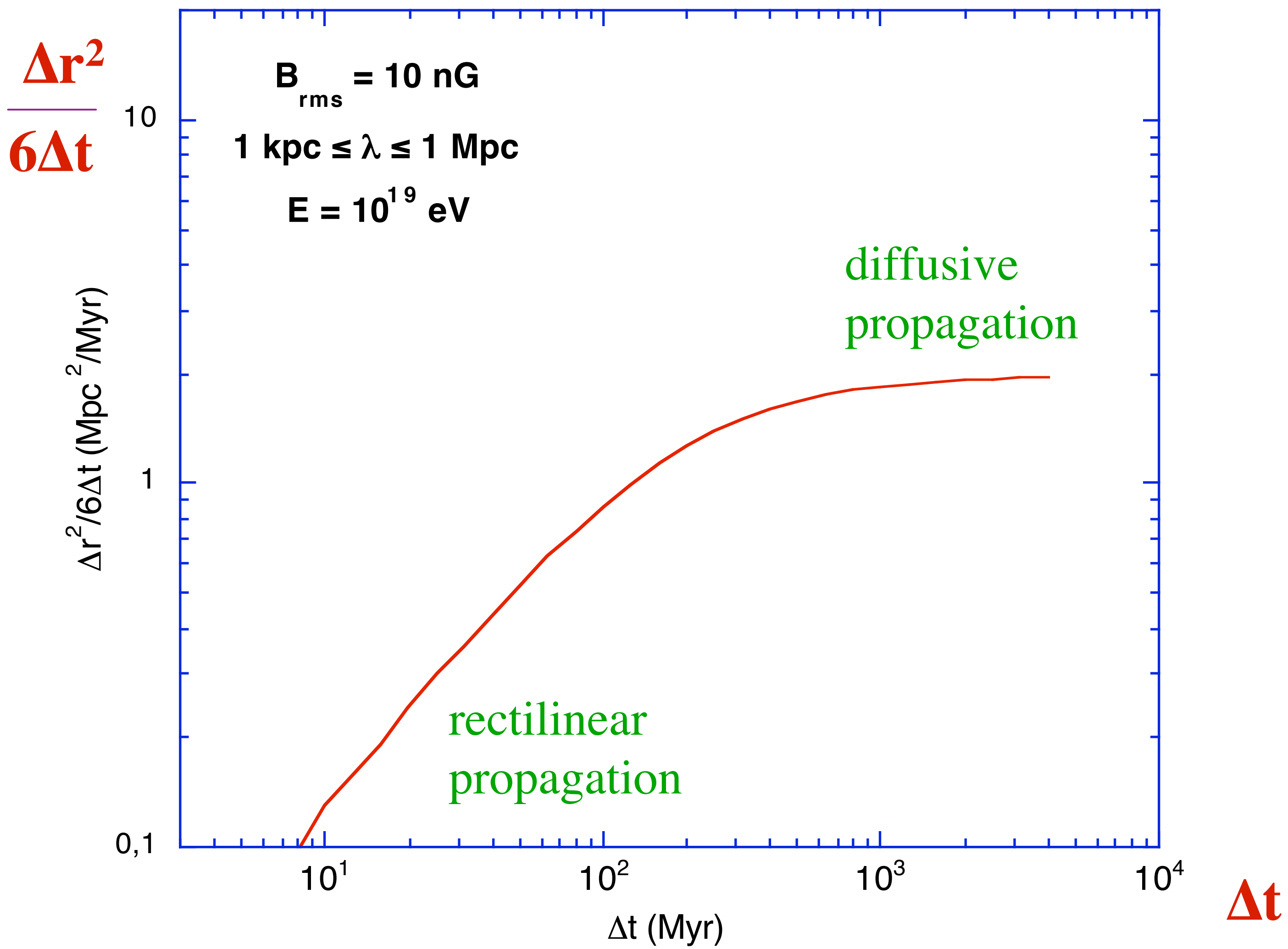
E = 10^{19} eV
B = 10 nG
L_{max} = 1 Mpc
y (Mpc)
180
160
140
120
100
80
60
40
20
0
-140
-120
-100
-80
-60
-40
-20
0
x (Mpc)



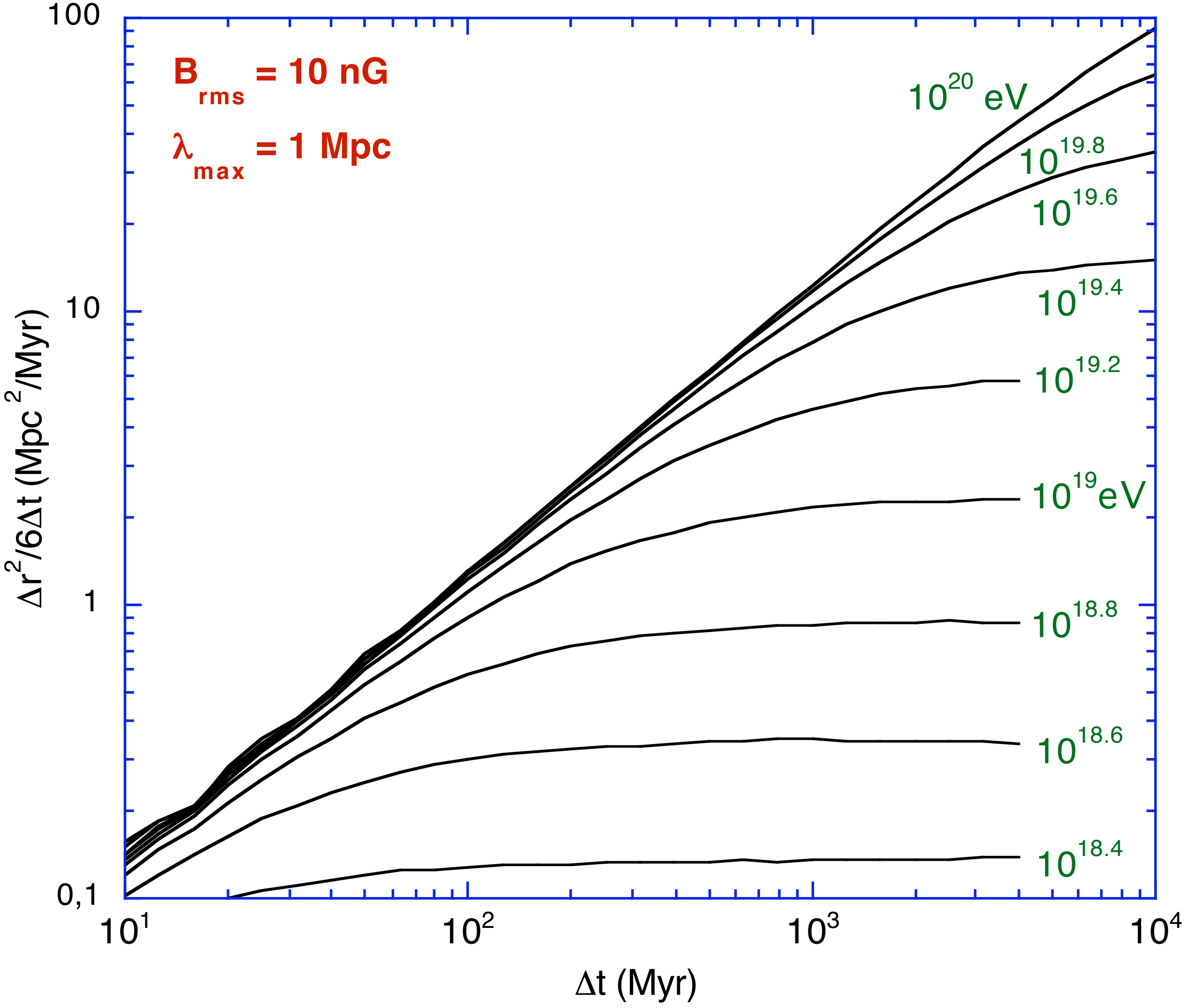
E = $10^{19.5}$ eV
B = 10 nG
L_{max} = 1 Mpc
y (Mpc)
40
20
0
-20
-40
-60
-80
-100
-120
-140
-160
0
100
200
300
400
500
x (Mpc)


E = 10^20 eV
B = 10 nG
L_max = 1 Mpc
y (Mpc)
x (Mpc)
0
-50
-100
-150
-200
-250
-300
-900
-800
-700
-600
-500
-400
-300
-200
-100
0

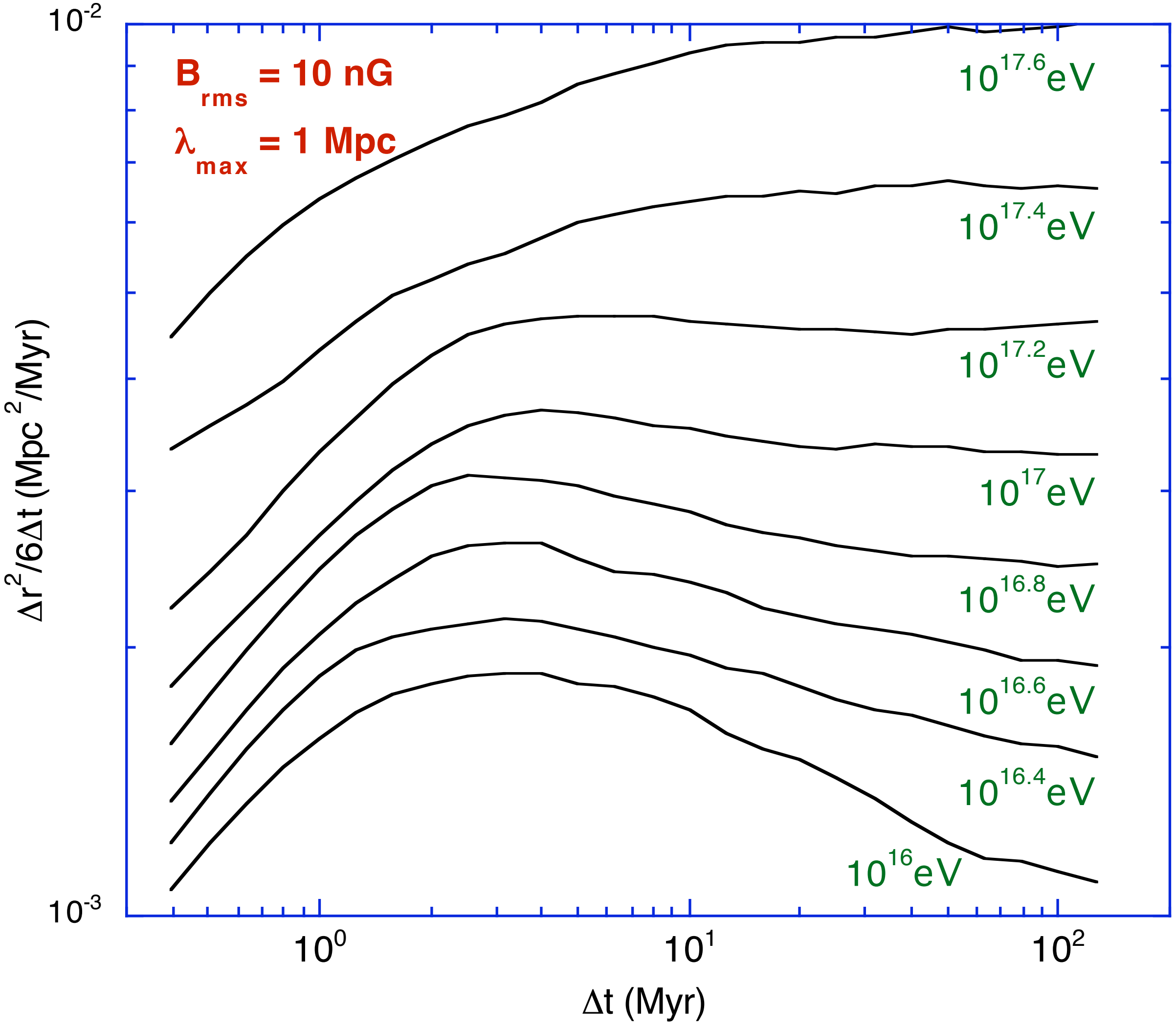
Reaching the diffusion regime



Reaching the diffusion regime



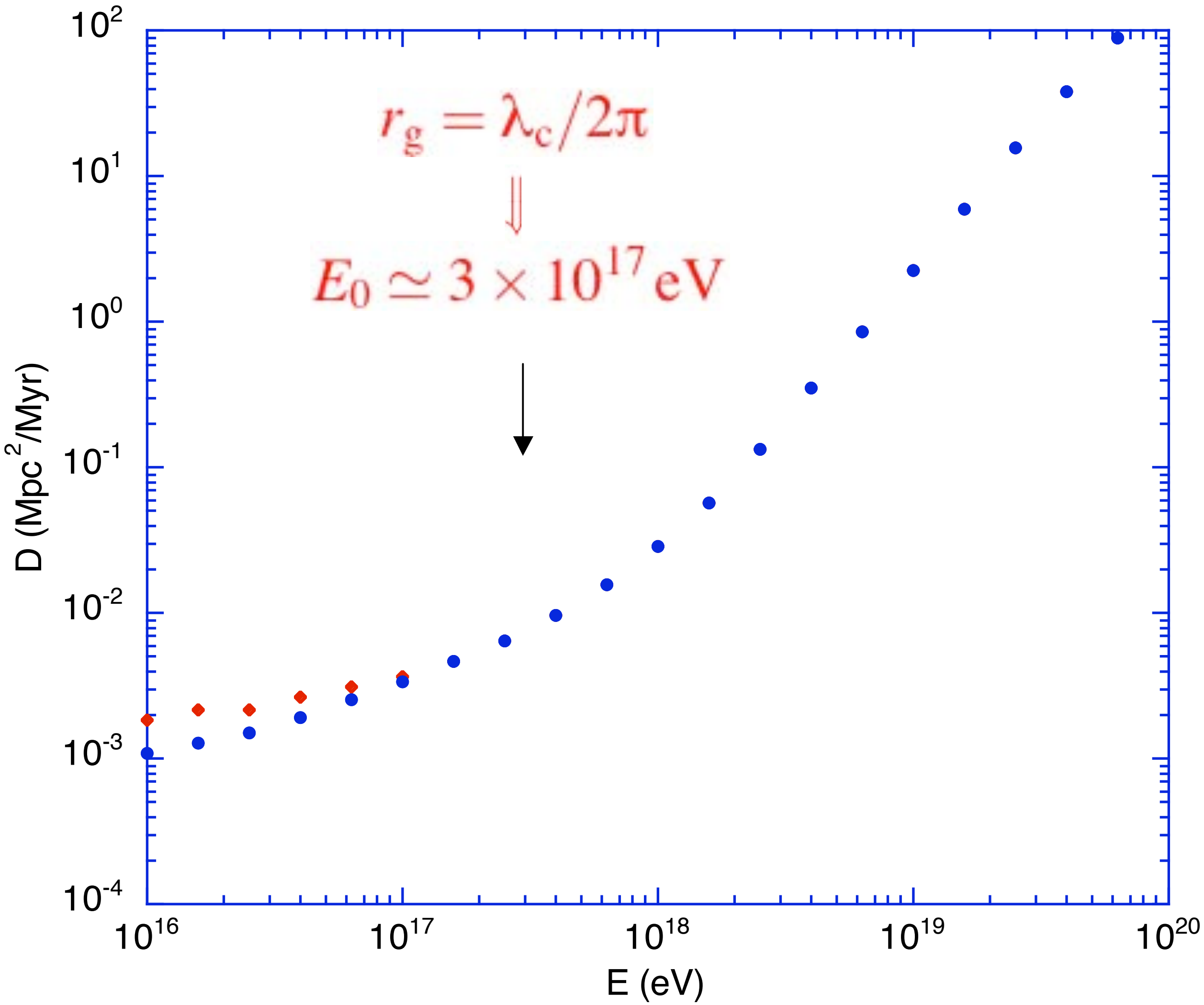
Reaching the diffusion regime



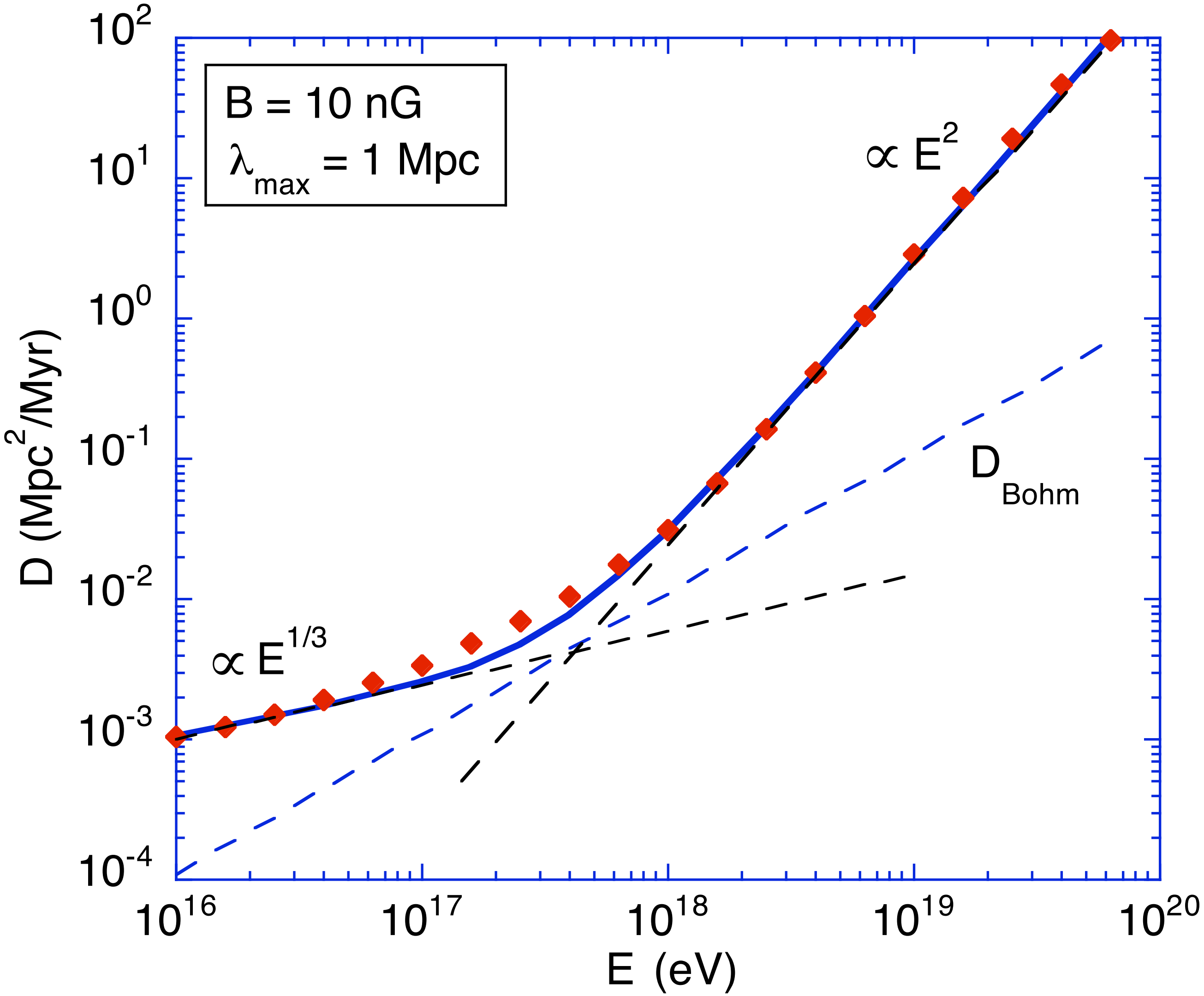
B = 10 nG

L_{max} = 1 Mpc

D(E)

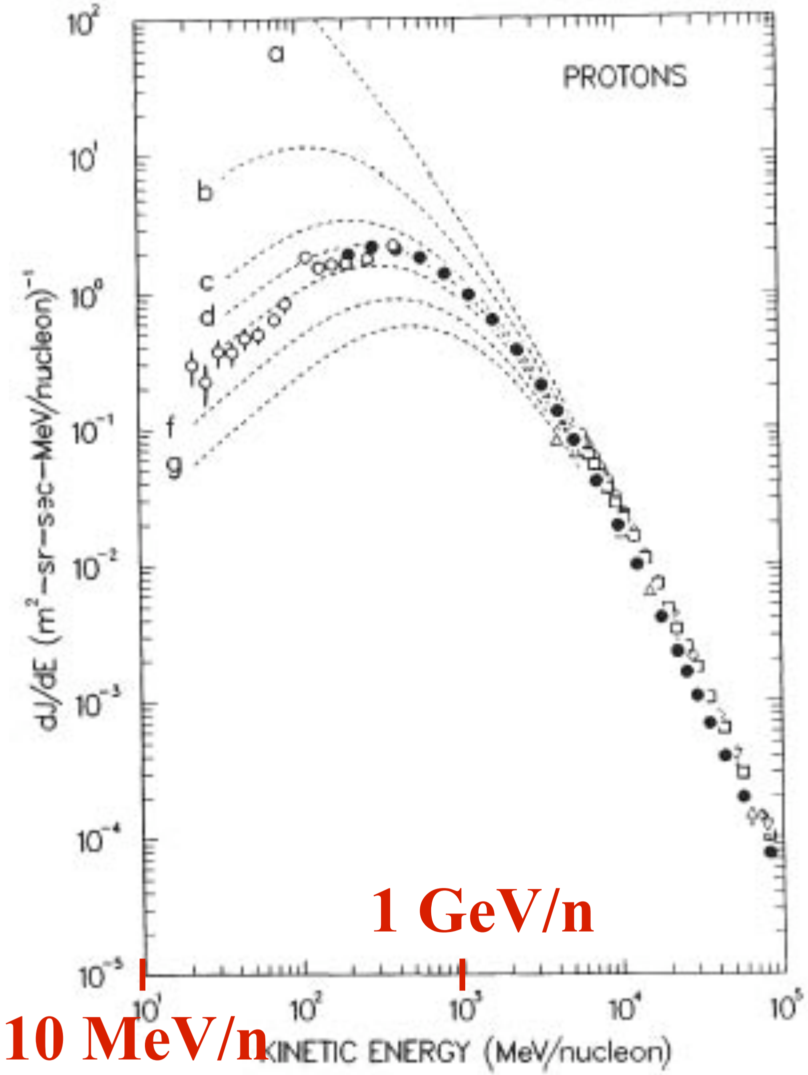


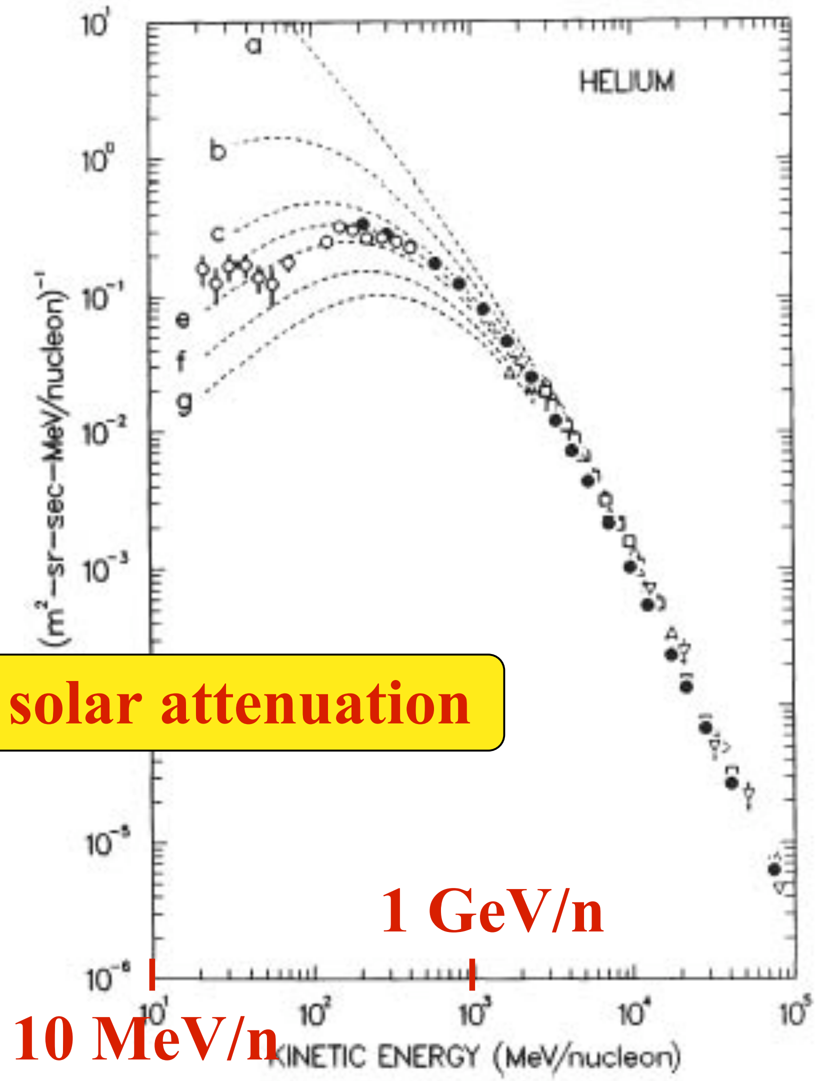
D(E)



B = 10 nG
λ_max = 1 Mpc
∝ E^2
∝ E^1/3
D_Bohm
D (Mpc^2/Myr)
E (eV)
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^16
10^17
10^18
10^19
10^20

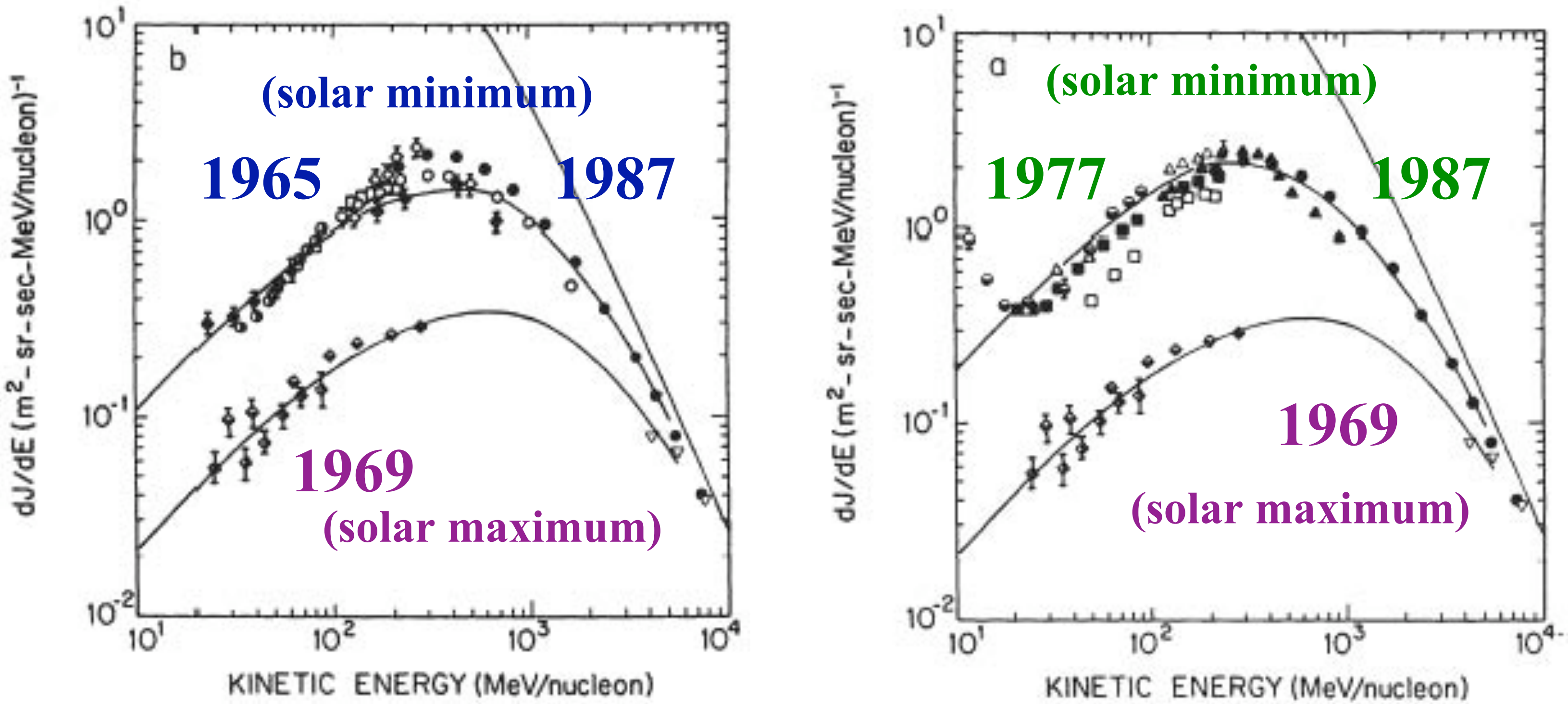
Low-energy cosmic-rays…





solar attenuation

Solar modulation

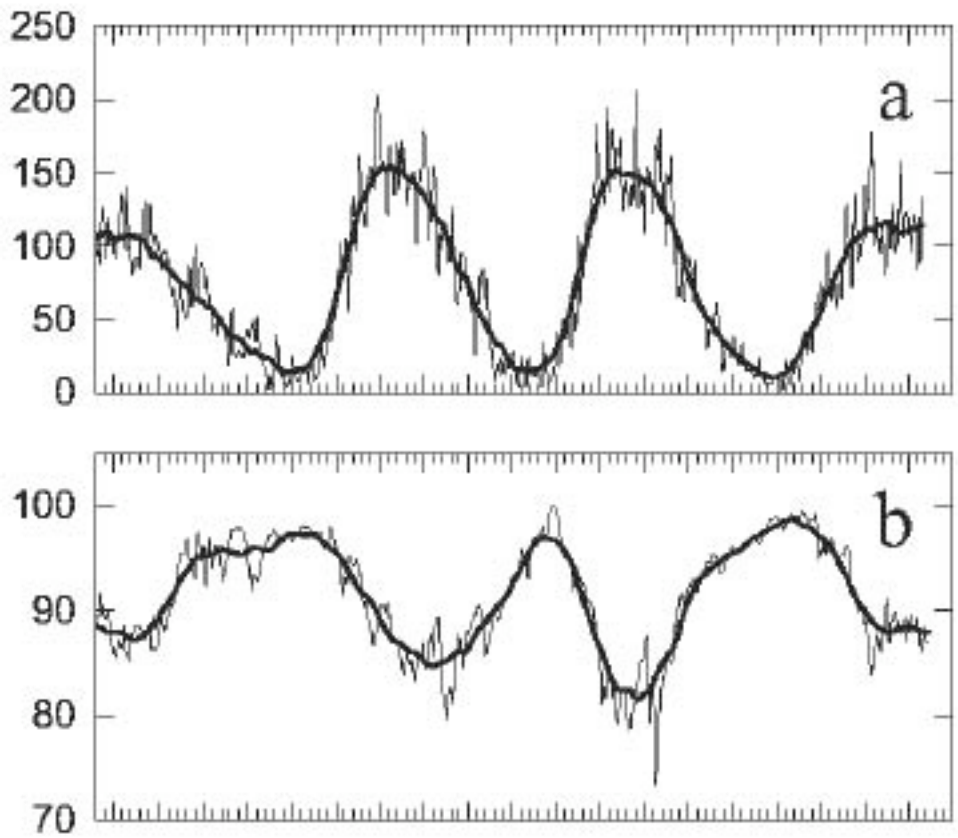


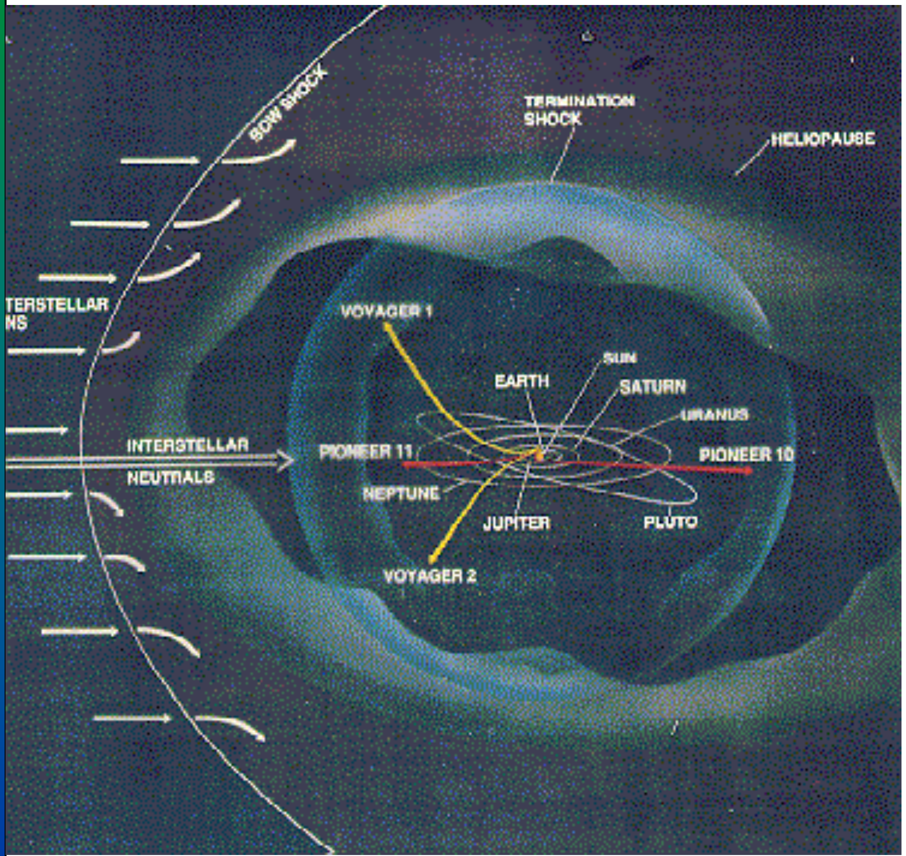
Solar modulation

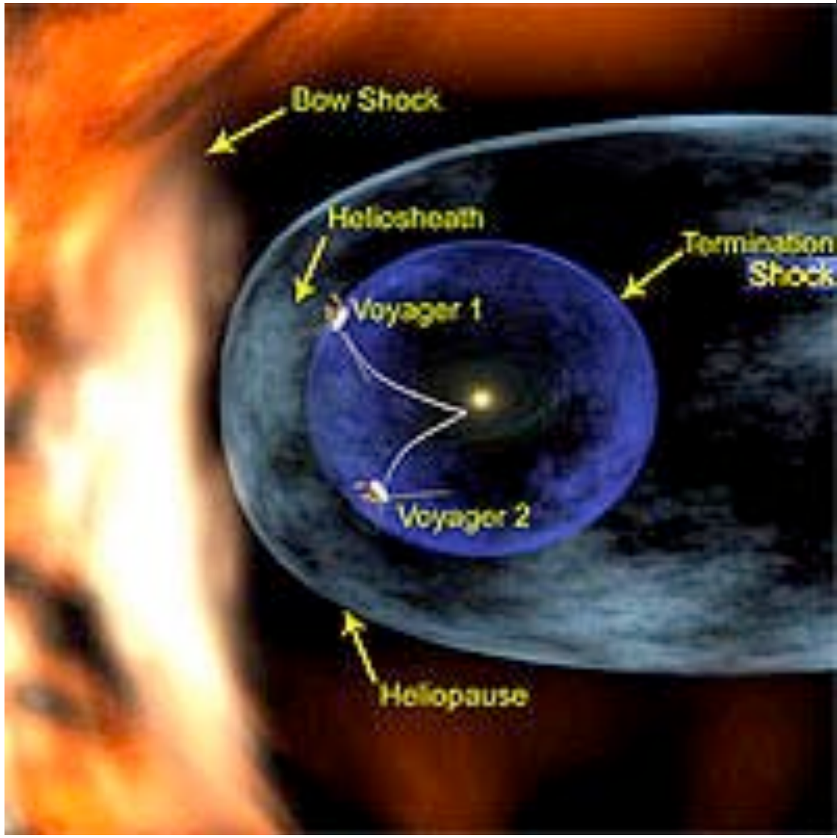
- Flux variation in coincidence with solar cycles

Sun spot activity

CR intensity




BOW SHOCK
TERMINATION SHOCK
HELIOPAUSE
TERSTELLAR
NS
VOYAGER 1
SUN
EARTH
SATURN
URANUS
INTERSTELLAR
NEUTRALS
PIONEER 11
PIONEER 10
NEPTUNE
JUPITER
PLUTO
VOYAGER 2


Bow Shock
Heliosheath
Termination Shock
Voyager 1
Voyager 2
Heliopause

Solar modulation: voyager and Pioneer data

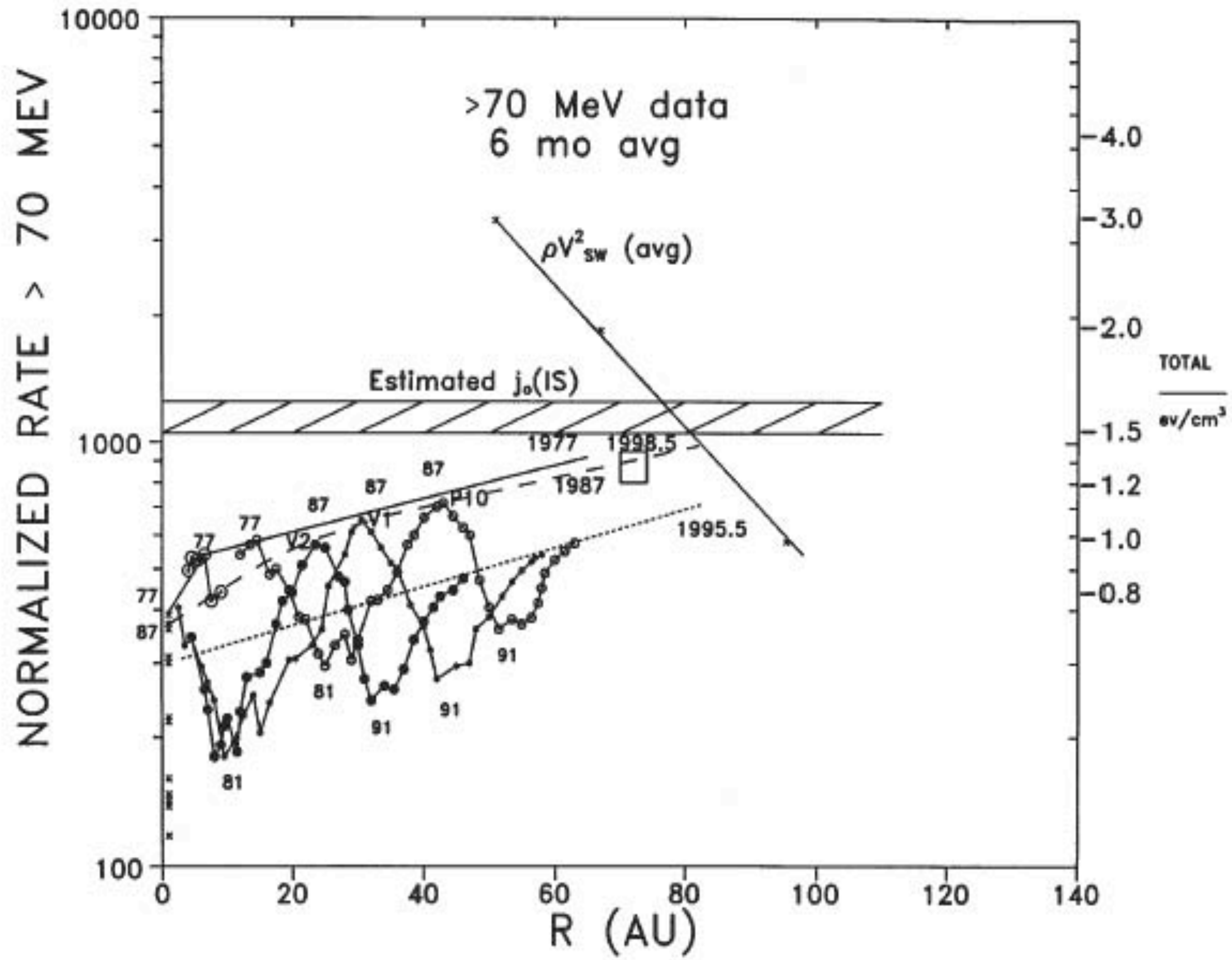
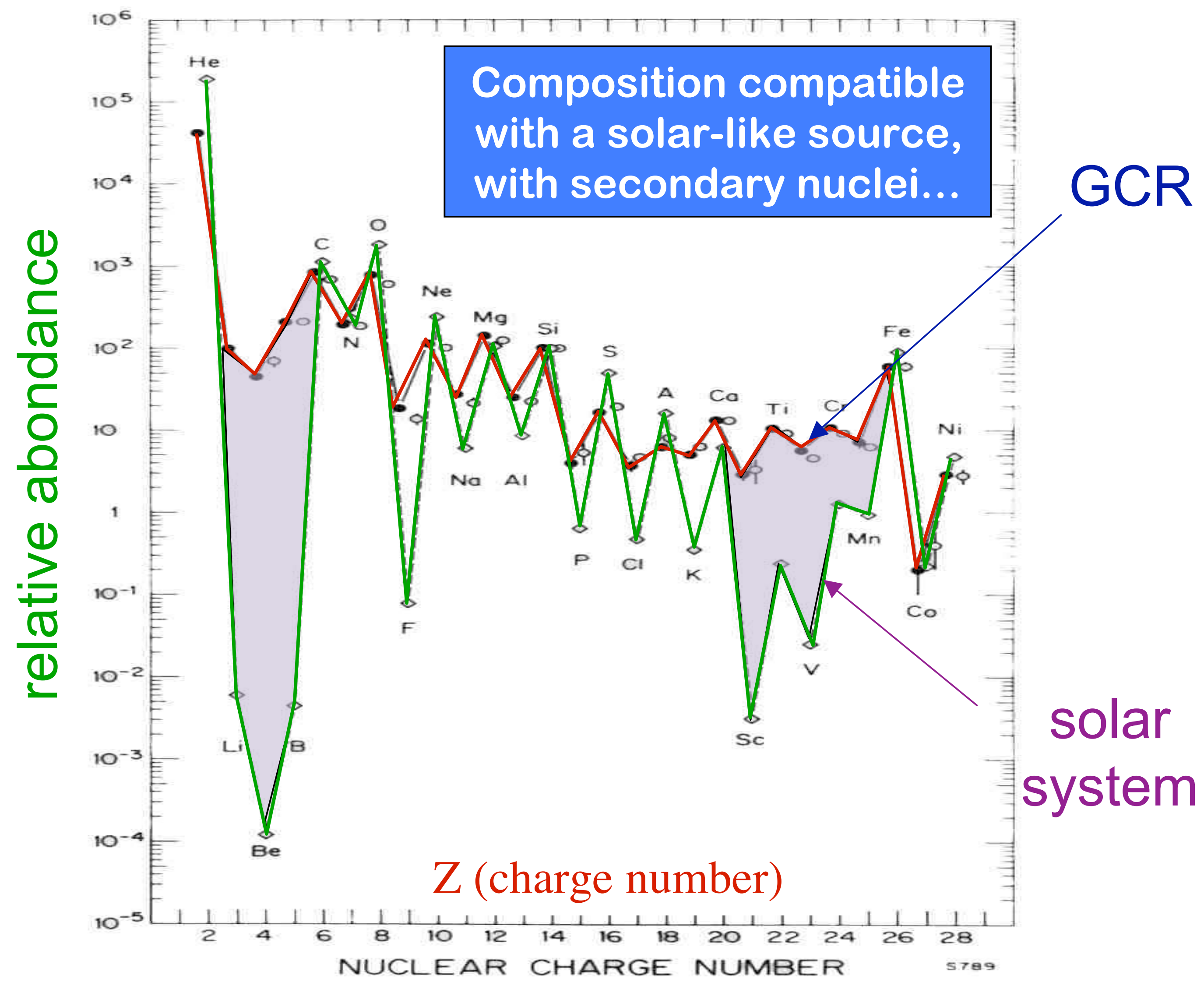


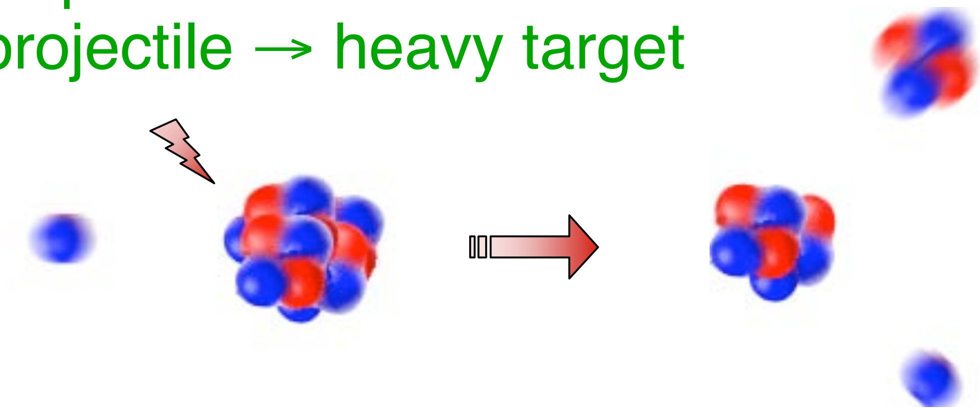
FIG. 1.—Counting rates of greater than 70 MeV cosmic rays vs. distance measured on *Voyager* and Pioneer spacecraft from 1977 to 1995. These integral rates, converted to energy densities are shown on the right-hand axis. The estimated interstellar counting rate is shown as a hatched region. The average energy density contained in the solar wind is also shown.

CR composition vs. solar system



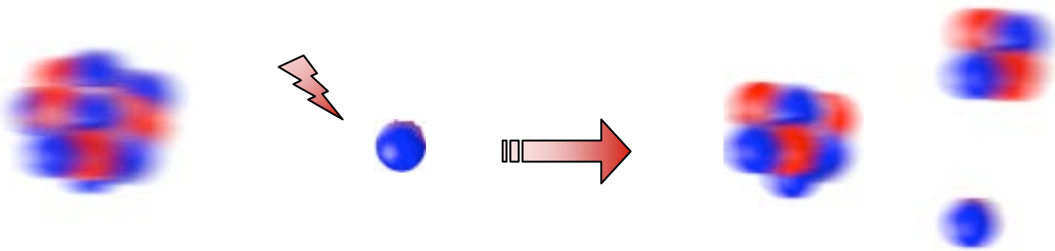
CR-induced spallation

- Direct spallation:
  light projectile → heavy target



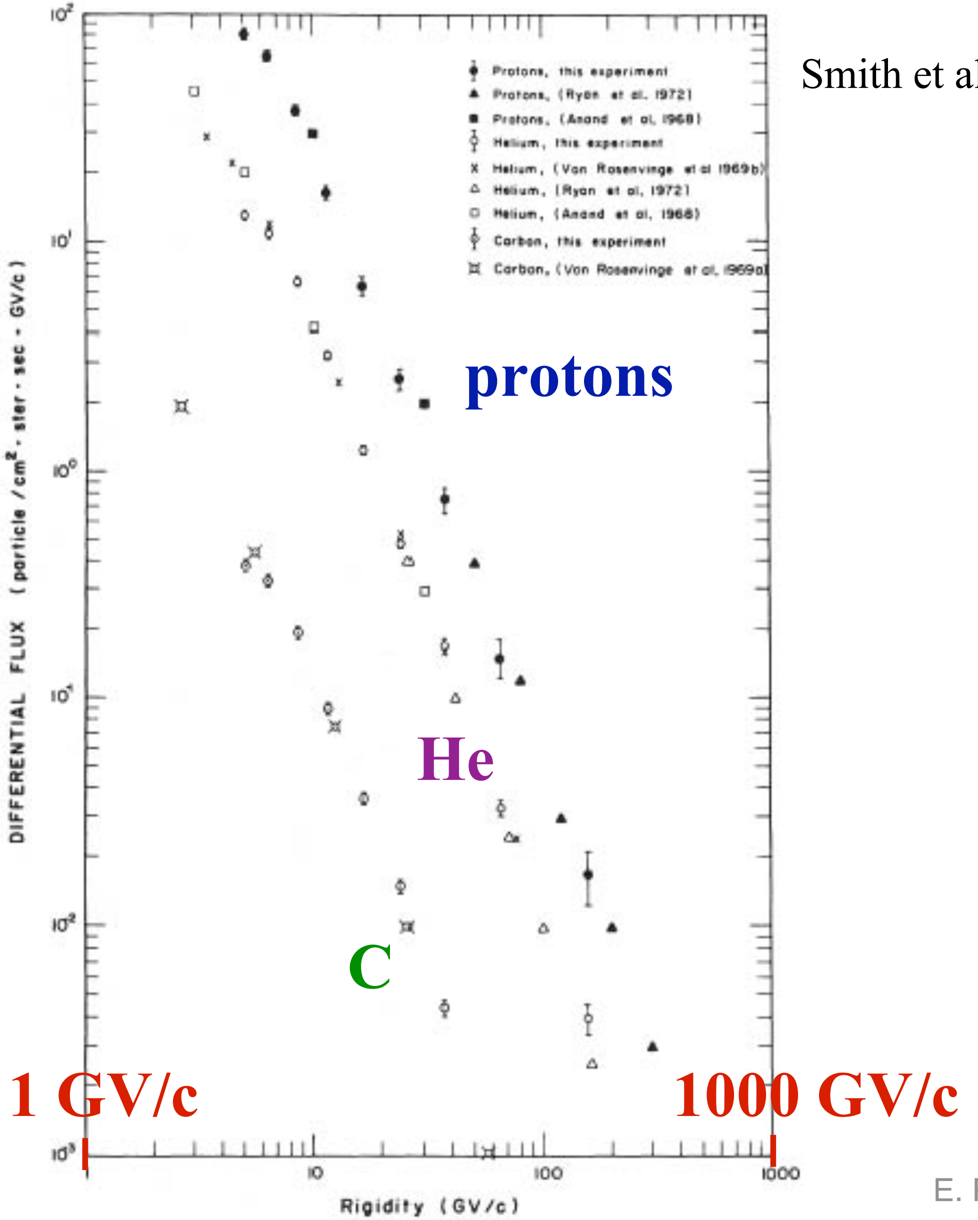
LiBeB nucleo-synthesis

- Inverse spallation:
  heavy projectile → light target



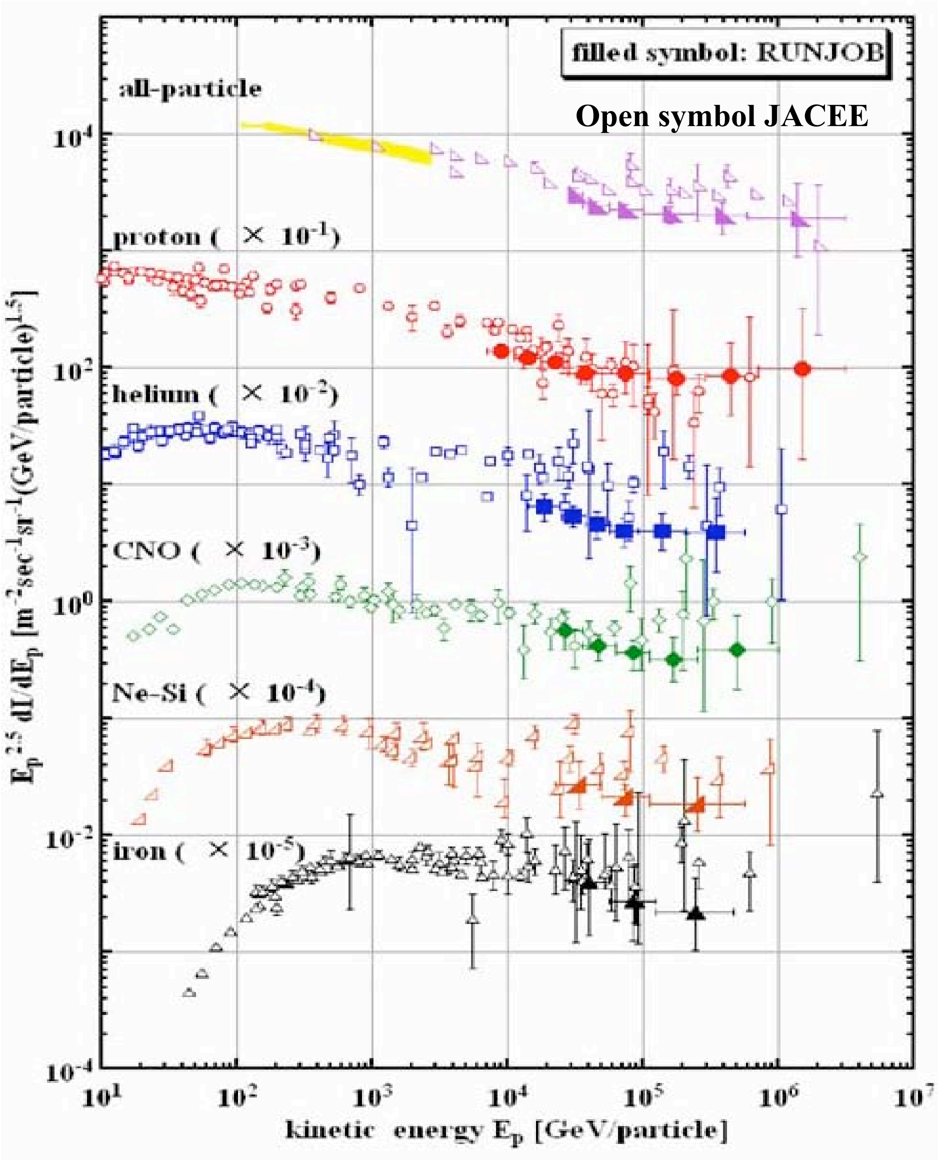
CR transport

Spectra of different nuclei



Smith et al. (1973)

Spectra of different nuclei

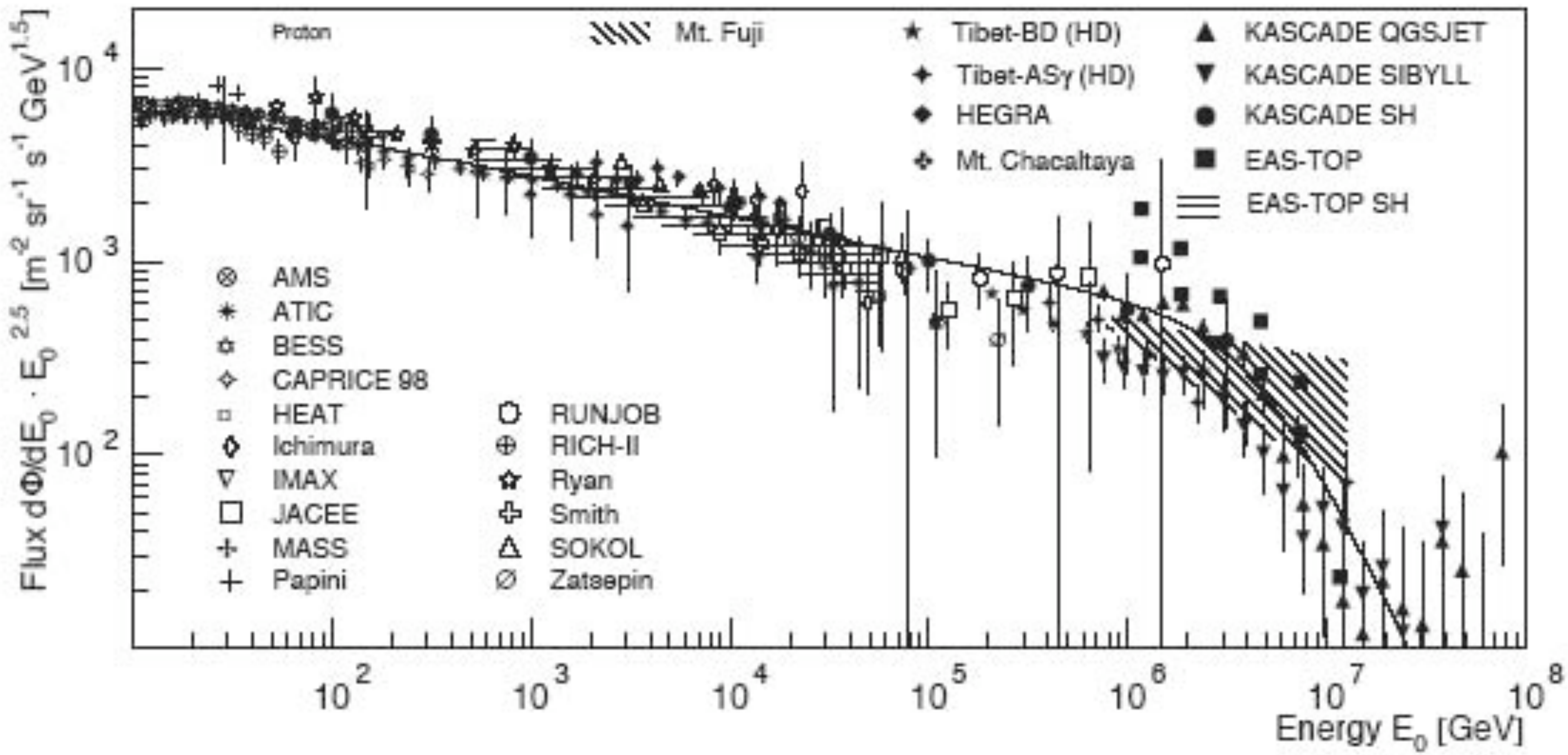


Nota Bene…

1) Apart from nuclear interactions and energy losses, it should only depend on the CR rigidity (Larmor radius)

2) Beware of how you define composition: at a given energy, at a given rigidity, or at a given energy per nucleon?

[CR flux] x $E^{2.5}$


Proton
Mt. Fuji
Tibet-BD (HD)
Tibet-ASγ (HD)
HEGRA
Mt. Chacaltaya
KASCADE QGSJET
KASCADE SIBYLL
KASCADE SH
EAS-TOP
EAS-TOP SH
AMS
ATIC
BESS
CAPRICE 98
HEAT
Ichimura
IMAX
JACEE
MASS
Papini
RUNJOB
RICH-II
Ryan
Smith
SOKOL
Zatsepin
Flux dΦ/dE0 · E0^2.5 [m^-2 sr^-1 s^-1 GeV^1.5]
Energy E0 [GeV]

Elemental knees

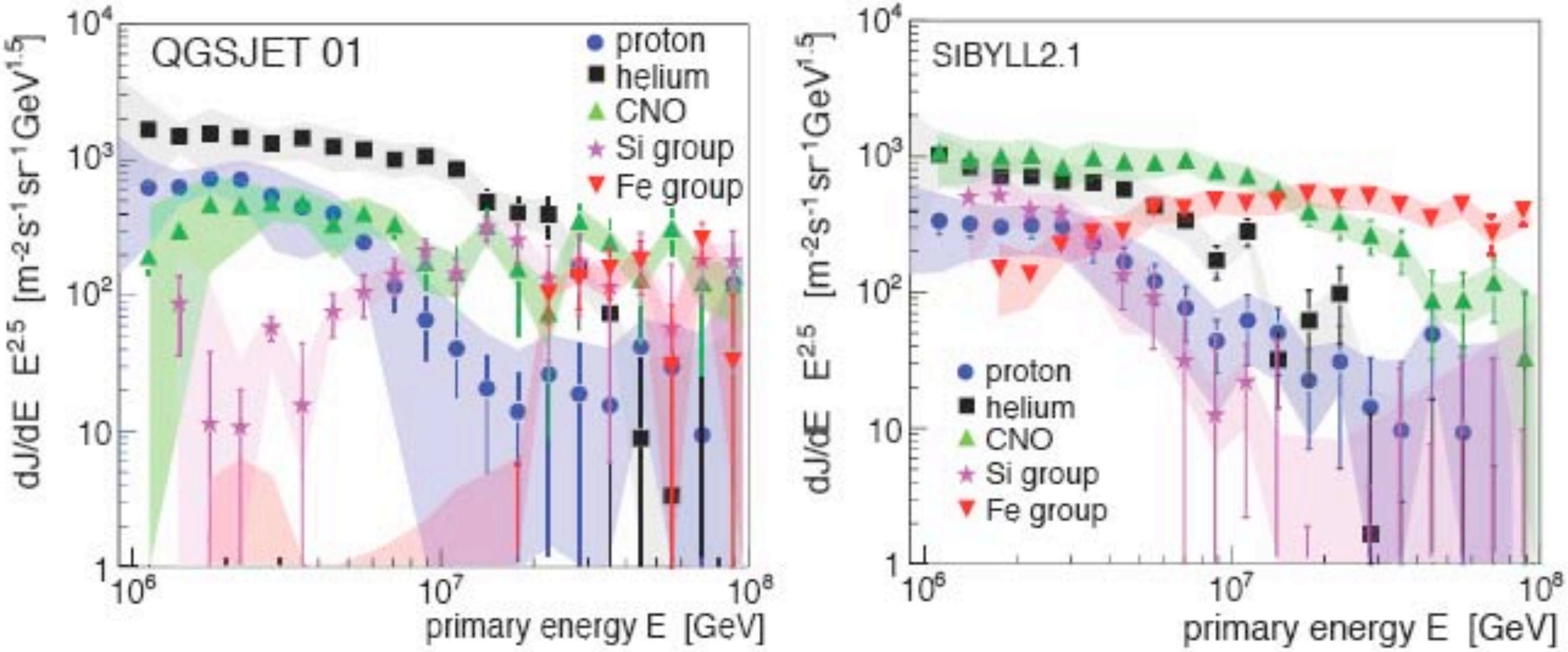
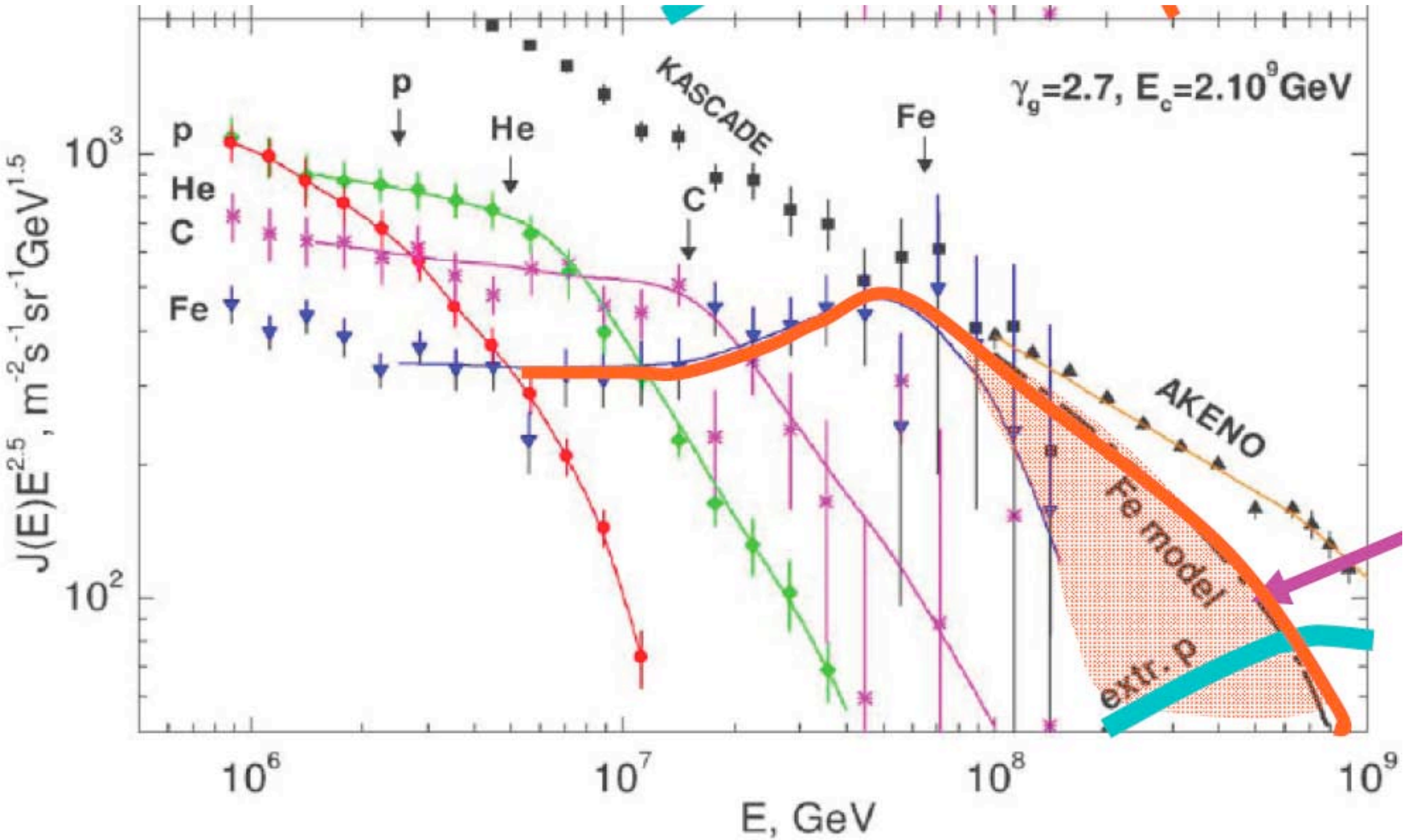


Fig. 7. Energy spectra for elemental groups as obtained by the KASCADE experiment, using two different models (QGSJET 01 and SIBYLL 2.1) to interpret hadronic interactions in the atmosphere [54].

from Hörandel (astro-ph/0611387)

Elemental knees



Berezinsky, et al. (2004)

CR transport in the universe

Principle of CR transport

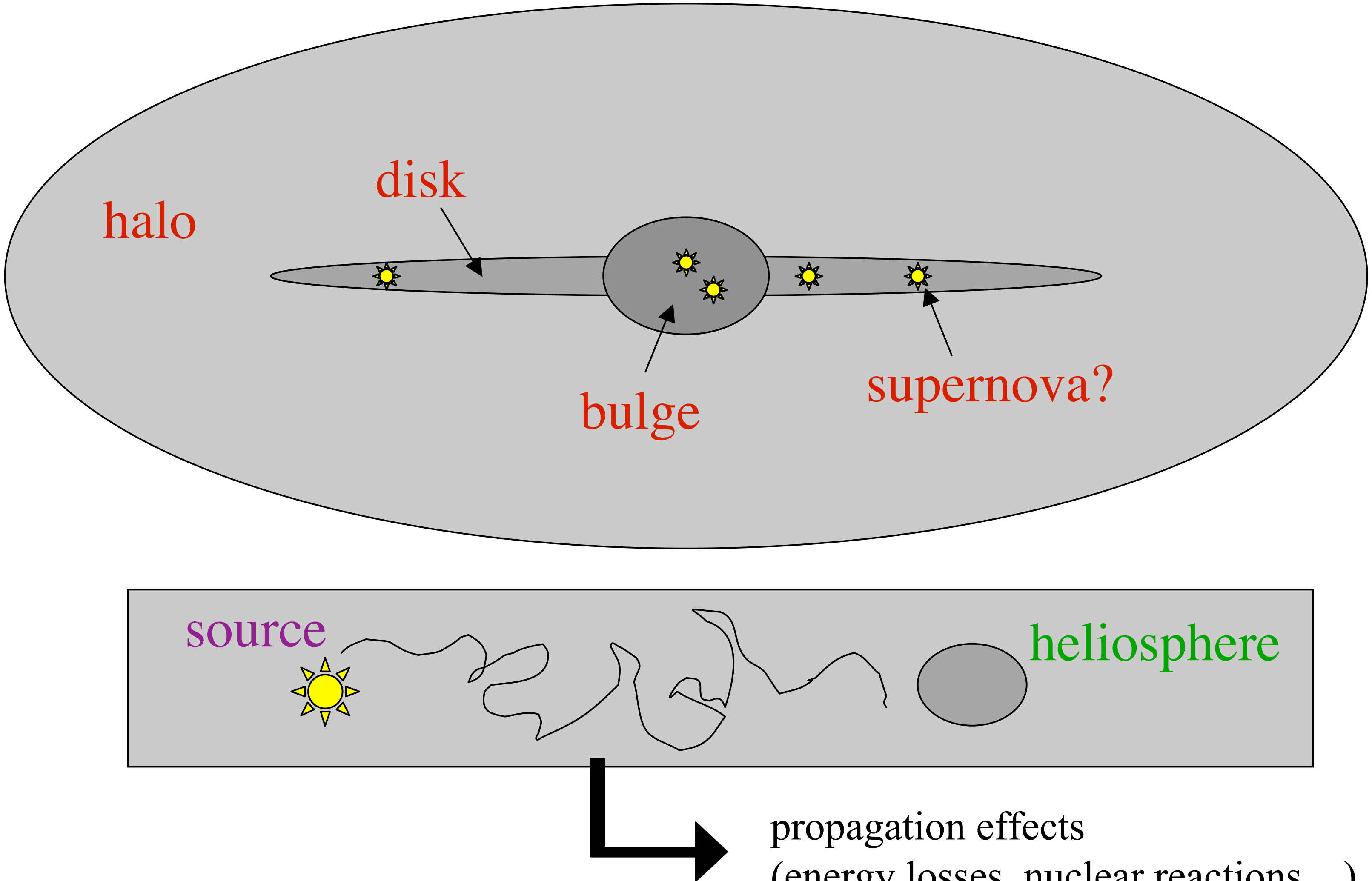
- Link the **observed** CR characteristics to the CR characteristics **at the source**

- The CRs are affected while they propagate in the interstellar medium

  - arrival directions
  - composition
  - energy spectrum

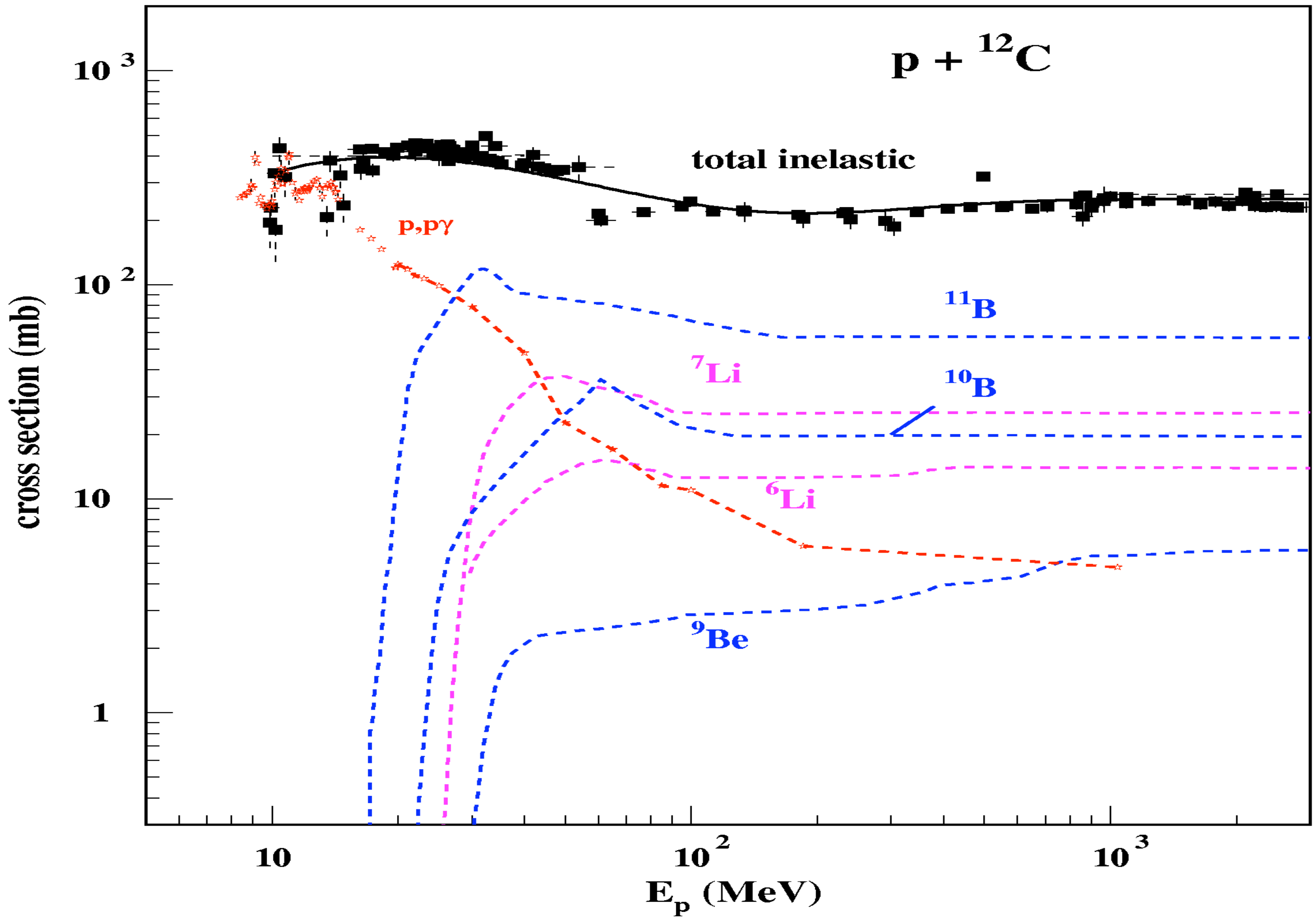
  } all combined…

Sketch of the Galaxy and halo

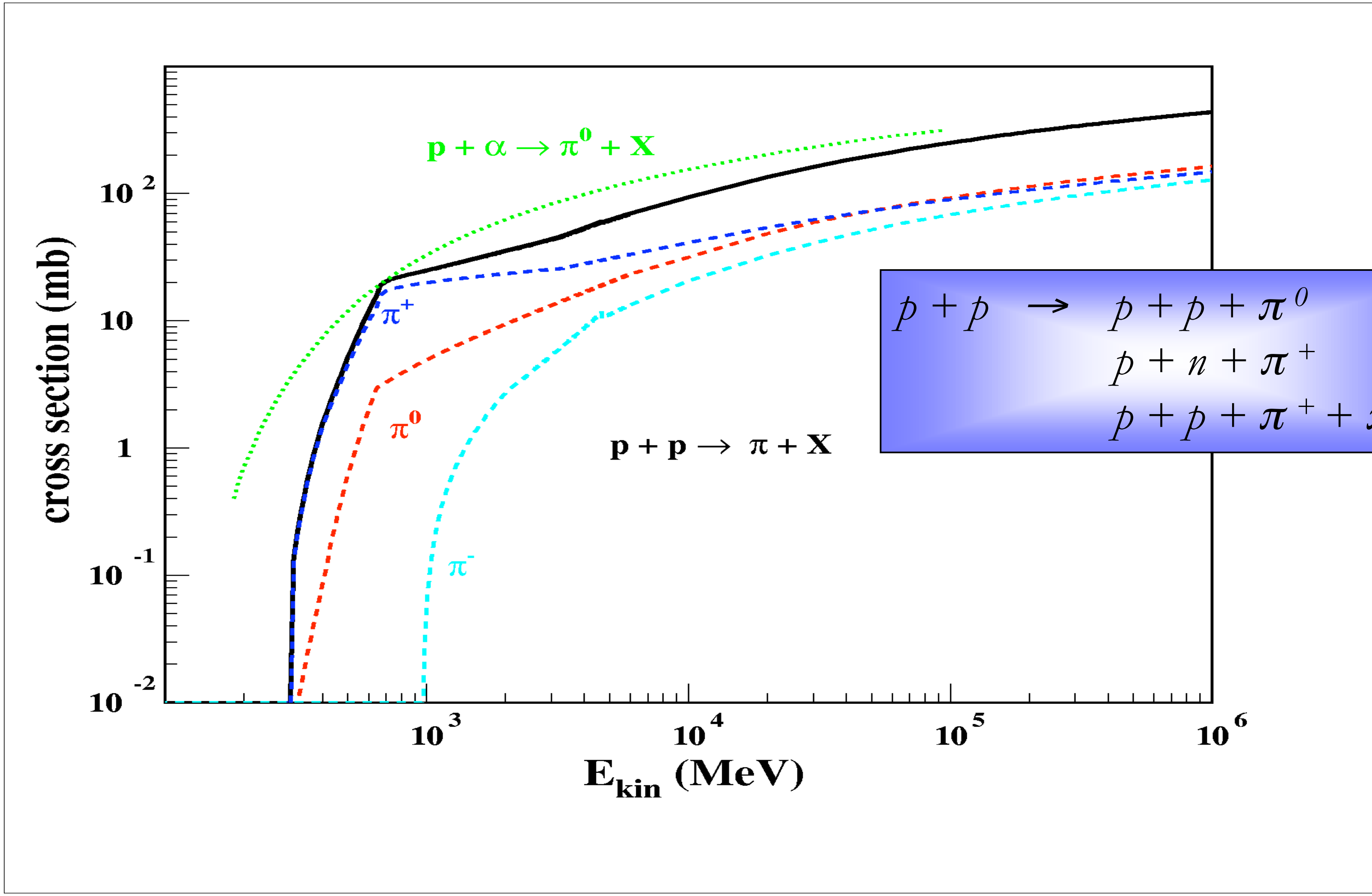


propagation effects
(energy losses, nuclear reactions…)

Nuclear interactions

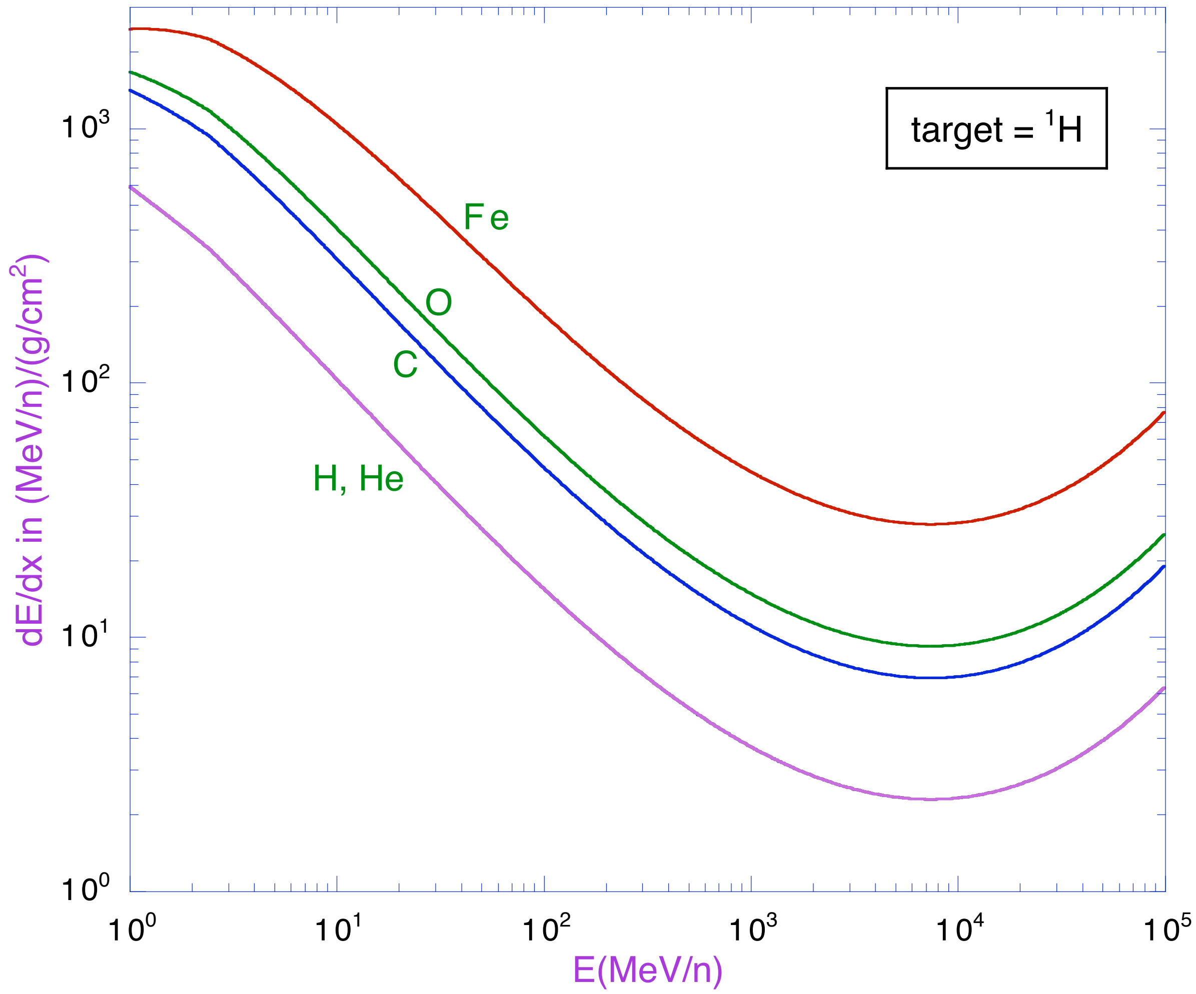


Nuclear interactions

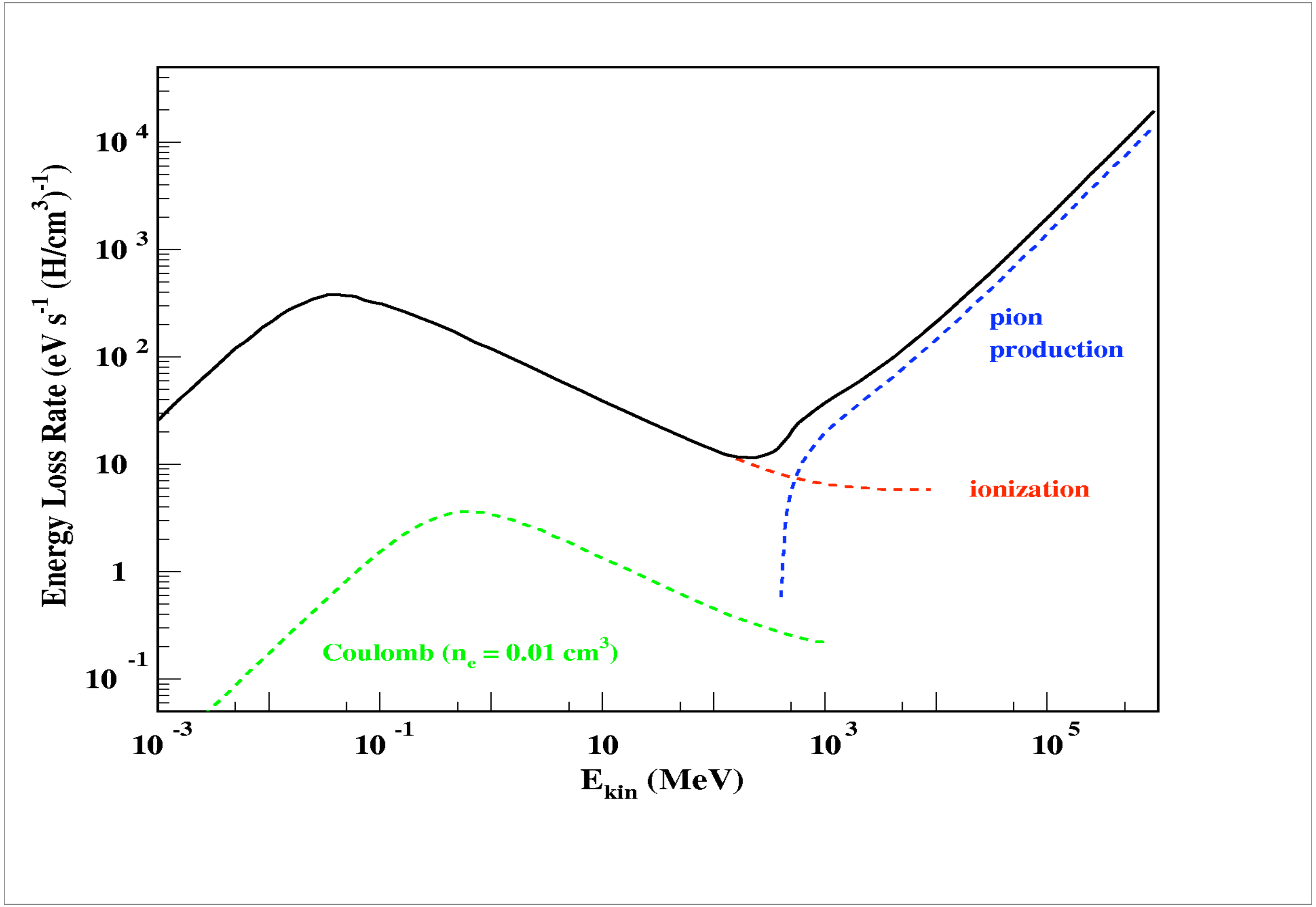


$$p + p \;\longrightarrow\; p + p + \pi^0$$
$$p + n + \pi^+$$
$$p + p + \pi^+ + \pi^-$$

Coulombian energy losses



Energy losses



CR transport in the Galactic box

GCR transport equation

$$\frac{\partial}{\partial t}N_i(E,t)+\frac{\partial}{\partial E}(\dot{E}_i(E)N_i(E,t))=Q_i(E,t)$$

"i" represents a given nuclear type

GCR transport equation

$$\frac{\partial}{\partial t}N_i(E,t) + \frac{\partial}{\partial E}(\dot{E}_i(E)N_i(E,t)) = Q_i(E,t)$$

$$- \frac{N_i(E,t)}{\tau_{esc}(E)}$$

"i" represents a given nuclear type

GCR transport equation

$$\frac{\partial}{\partial t}N_i(E,t) + \frac{\partial}{\partial E}(\dot{E}_i(E)N_i(E,t)) = Q_i(E,t)$$

$$-\frac{N_i(E,t)}{\tau_{\mathrm{esc}}(E)}$$

$$-\frac{N_i(E,t)}{\tau_{\mathrm{dec}}\sqrt{1-\frac{v_i^2(E)}{c^2}}}$$

"i" represents a given nuclear type

GCR transport equation

$$\frac{\partial}{\partial t} N_i(E,t) + \frac{\partial}{\partial E}(\dot{E}_i(E) N_i(E,t)) = Q_i(E,t)$$

$$- \frac{N_i(E,t)}{\tau_{\rm esc}(E)}$$

$$- \frac{N_i(E,t)}{\tau_{\rm dec}\sqrt{1 - \frac{v_i^2(E)}{c^2}}}$$

$$- N_i(E,t) v_i(E) \times [\sigma_{\rm p\it i}(E) n_{\rm H} + \sigma_{\alpha i}(E) n_{\rm He}]$$

"i" represents a given nuclear type

GCR transport equation

$$\frac{\partial}{\partial t}N_i(E,t)+\frac{\partial}{\partial E}(\dot{E}_i(E)N_i(E,t))=Q_i(E,t)$$

$$-\frac{N_i(E,t)}{\tau_{\mathrm{esc}}(E)}$$

"i" represents a given nuclear type

$$-\frac{N_i(E,t)}{\tau_{\mathrm{dec}}\sqrt{1-\frac{v_i^2(E)}{c^2}}}$$

$$-N_i(E,t)v_i(E)\times[\sigma_{\mathrm{p}i}(E)n_{\mathrm{H}}+\sigma_{\alpha i}(E)n_{\mathrm{He}}]$$

$$+\sum_j\int_0^\infty \mathrm{d}E'v_j(E')N_j(E',t)[\sigma_{\mathrm{p}ji}(E,E')n_{\mathrm{H}}+\sigma_{\alpha ji}(E,E')n_{\mathrm{He}}]$$

GCR transport equation

$$\frac{\partial}{\partial t} N_i(E,t) + \frac{\partial}{\partial E}(\dot{E}_i(E) N_i(E,t)) = Q_i(E,t)$$

$$- \frac{N_i(E,t)}{\tau_{\rm esc}(E)}$$

$$- \frac{N_i(E,t)}{\tau_{\rm dec}\sqrt{1 - \frac{v_i^2(E)}{c^2}}}$$

$$- N_i(E,t) v_i(E) \times [\sigma_{{\rm p}i}(E) n_{\rm H} + \sigma_{\alpha i}(E) n_{\rm He}]$$

$$+ \sum_j \int_0^\infty {\rm d}E' v_j(E') N_j(E',t) [\sigma_{{\rm p}ji}(E,E') n_{\rm H} + \sigma_{\alpha ji}(E,E') n_{\rm He}]$$

$$+ \frac{1}{2} \frac{\partial^2}{\partial E^2} [K(E) N_i(E,t)]$$

"i" represents a given nuclear type

Steady state

$$\cancel{\frac{\partial}{\partial t} N_i(E,t)} + \frac{\partial}{\partial E}\left(\dot{E}_i(E) N_i(E,\cancel{t})\right) = Q_i(E,\cancel{t})$$

$$- \frac{N_i(E,\cancel{t})}{\tau_{\rm esc}(E)}$$

$$- \frac{N_i(E,\cancel{t})}{\tau_{\rm dec}\sqrt{1 - \frac{v_i^2(E)}{c^2}}}$$

$$- N_i(E,t) v_i(E) \times [\sigma_{{\rm p}i}(E) n_{\rm H} + \sigma_{\alpha i}(E) n_{\rm He}]$$

$$+ \sum_j \int_0^\infty {\rm d}E' v_j(E') N_j(E',t) [\sigma_{{\rm p}ji}(E,E') n_{\rm H} + \sigma_{\alpha ji}(E,E') n_{\rm He}]$$

$$+ \frac{1}{2}\frac{\partial^2}{\partial E^2}[K(E) N_i(E,t)]$$

"i" represents a given nuclear type

Steady state

$$\frac{\partial}{\partial t} N_i(E,t) + \frac{\partial}{\partial E}(\dot{E}_i(E) N_i(E,t)) = Q_i(E,t)$$

$$- \frac{N_i(E,t)}{\tau_{esc}(E)}$$

$$- \frac{N_i(E,t)}{\tau_{dec}\sqrt{1 - \frac{v_i^2(E)}{c^2}}}$$

$$- N_i(E,t) v_i(E) \times [\sigma_{pi}(E) n_H + \sigma_{\alpha i}(E) n_{He}]$$

$$+ \sum_j \int_0^\infty dE' v_j(E') N_j(E',t) [\sigma_{pji}(E,E') n_H + \sigma_{\alpha ji}(E,E') n_{He}]$$

$$+ \frac{1}{2} \frac{\partial^2}{\partial E^2}[K(E) N_i(E,t)]$$

"i" represents a given nuclear type

3D transport equation

- Diffusive approximation...

$$\frac{\partial N_i}{\partial t} + \frac{\partial}{\partial E}\left[b(\mathbf{r}, E) N_i(\mathbf{r}, E, t)\right] = Q_i(\mathbf{r}, E) - \frac{N_i}{\tau_{\mathrm{tot}}(\mathbf{r}, E)} + D(\mathbf{r}, E)\nabla^2 N_i$$

flux in energy space (losses + acc.)

injection, « in flight » production

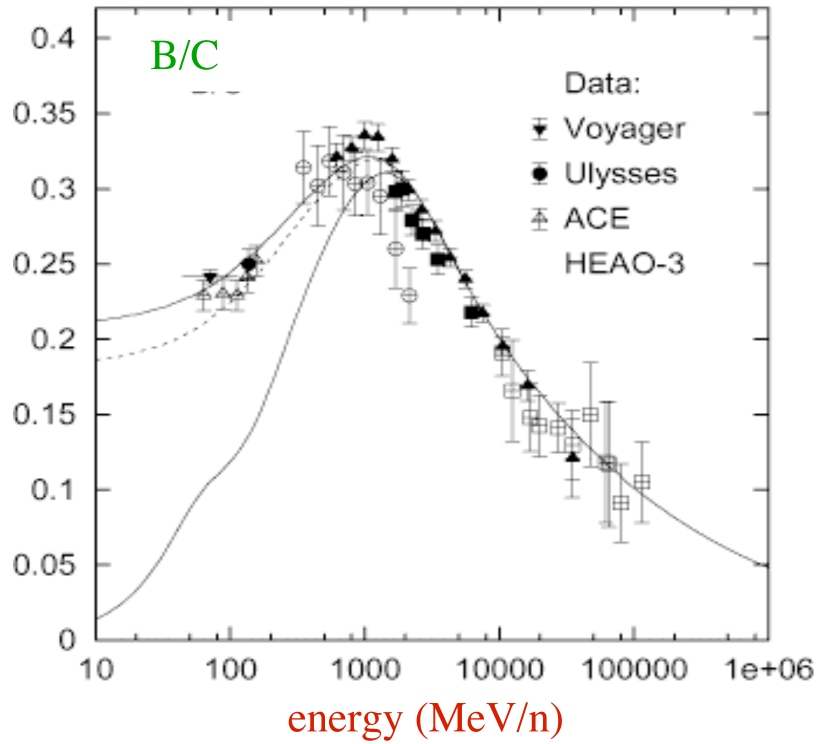
destruction, decay, escape

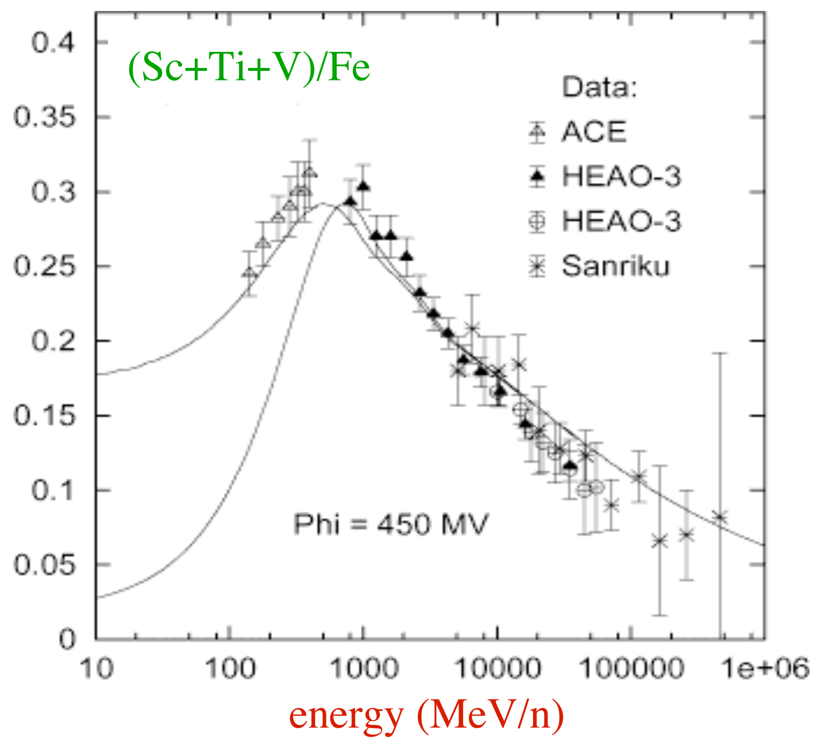
diffusion

- Re-acceleration...

$$+\frac{1}{2}\frac{\partial^2}{\partial E^2}\left[c(\mathbf{r},E)N_i(\mathbf{r},E,t)\right]$$

secondary/primary ratios

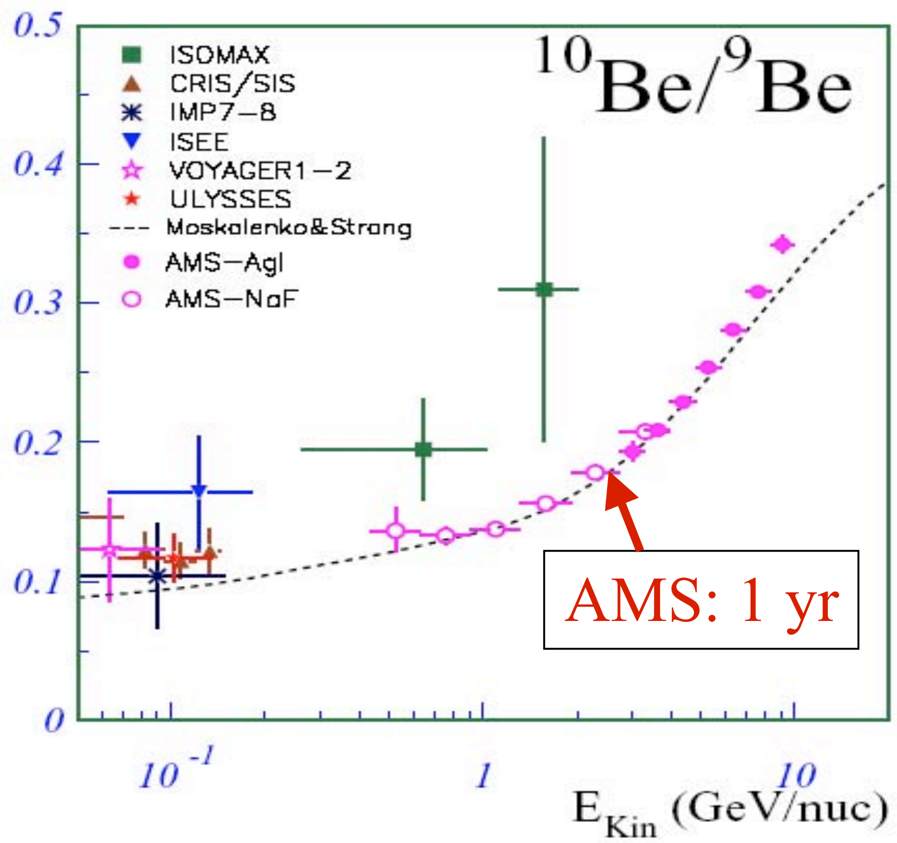




[Strong & Moskalenko (2001)]

Cosmic-ray clocks

- $^{12}C + H \rightarrow\ ^{9}Be$ (stable secondary nucleus)
  $^{12}C + H \rightarrow\ ^{10}Be$ (unstable secondary nucleus: ~ 4 Myr)



- The $^{10}Be/^{9}Be$ ratio depends on the history of secondary nuclei production (on cross sections)
- Link between time and the quantity of matter gone through

[+ ^{26}Al, ^{36}Cl, ^{53}Mn, ^{54}Mn, ^{59}N]

Result of propagation studies

- **All** observations can be reproduced!
- With very few parameters:
  - Energy losses given by physics
  - Measured cross sections
  - Escape depends on diffusion coefficient D(E)
  - Self-consistent re-acceleration
- Best fit : $D(E) \propto E^{0.36} \sim E^{1/3}$ (Kolmogorov) ?
- Source spectrum in $p^{-2.35}$

Result of propagation studies

- Secondary/primary ratios

  ⇒ on average, CRs have gone through a grammage of **X_{RC} = 6—10 g/cm^2** from their sources to the Earth

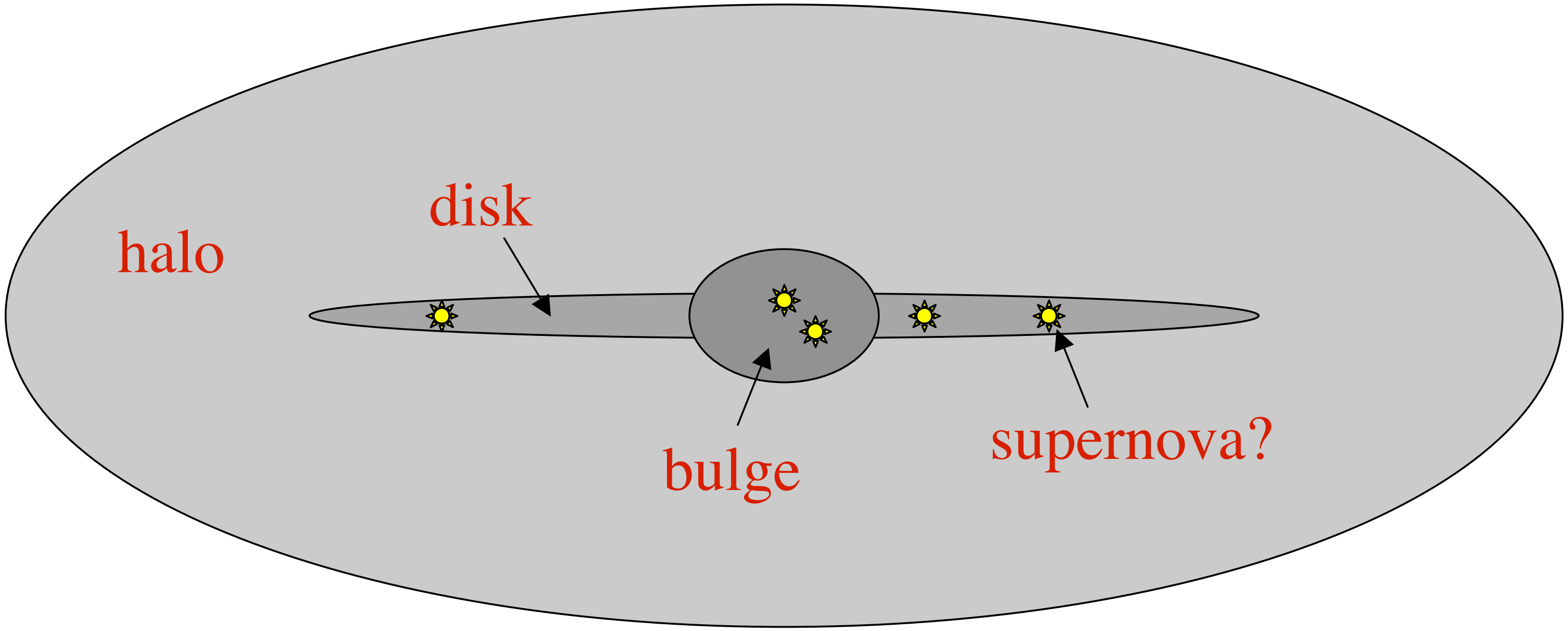
- Cosmic-ray clocks

  ⇒ CRs have spent typically **τ_{RC} ~ 2 10^7 years** on their way

- Thus, they propagated in a medium of average density **n** = $X_{RC}/c\tau_{RC}$ **~ 0.2 part. cm^{-3}**

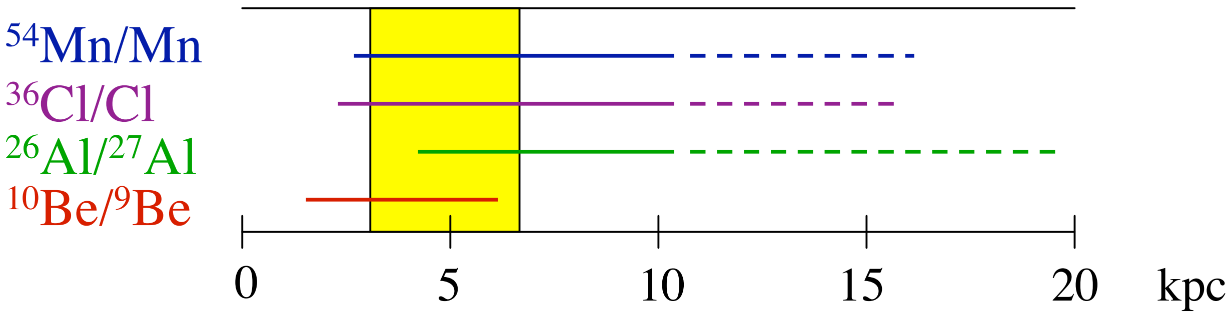
- Thus, they must have spent quite some time in the halo! (H_{halo} ~ 3–7 kpc)

Galactic cosmic-ray confinement



- Magnetic confinement of cosmic rays in a much larger volume than the usual Galactic gas

Cosmic-ray clocks



halo height

Cosmic-ray energetics

- 1.8 eV/cm^3 in (15 kpc × 15 kpc × 10 kpc), renewed every 2 10^7 years

$$\Rightarrow 2.8 \times 10^{41} \text{ erg/s}$$

- 1 SN of 10^{51} erg every 30 years

$$\Rightarrow 10^{42} \text{ erg/s}$$

⇒ 25–30% of the SN energy goes to cosmic-rays

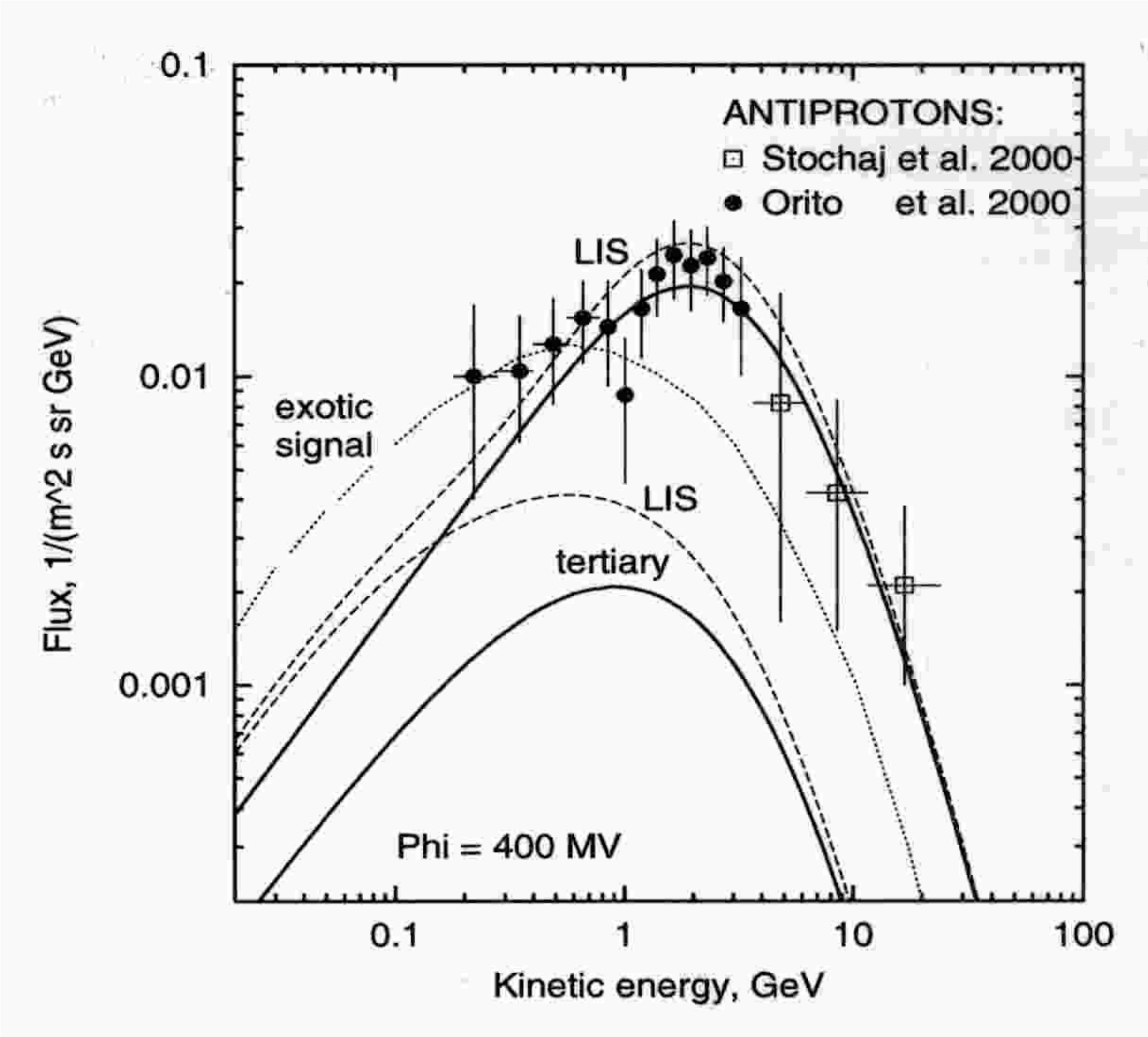
Summary

- Cosmic-rays **transport** must be understood to relate "source CRs" to "propagated CRs"
- Transport in all 3 "spectral dimensions"
- Trajectories, composition and energies are entangled: $\Rightarrow$ treat them all in the same model
- There are **many observables**… and they can be accounted for within simple models
- $\Rightarrow$ **low-energy CR** phenomenology is rather successful

↓

Can we do better? **Should we?**

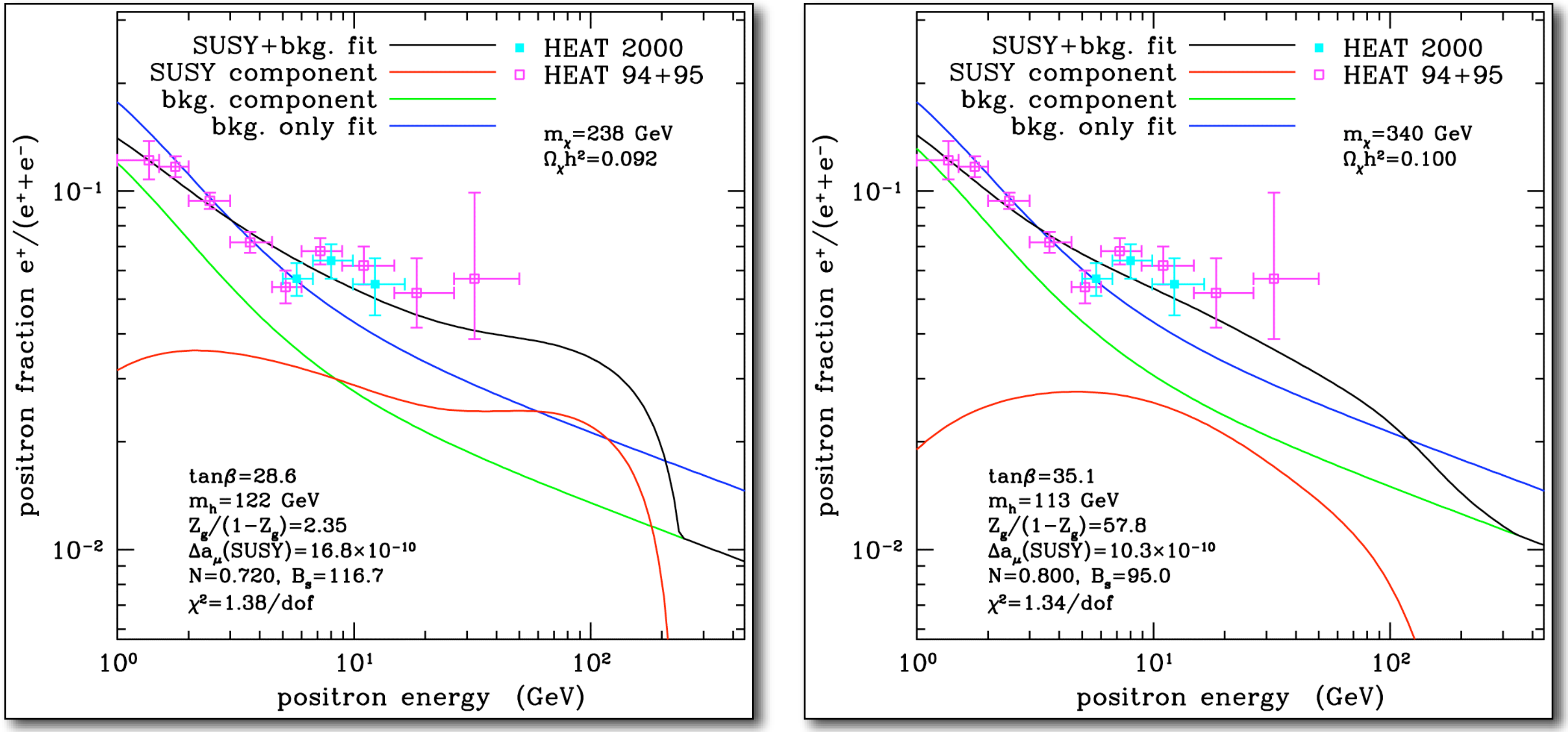
Antiprotons



Strong & Moskalenko (2001)

Search for dark matter: anti-p, anti-D, e+, γ

positron fraction: $e^+/(e^- + e^+)$



better fits with a SUSY signal

(χ^2/d.o.f. = 1.34 and 1.38 instead of 2.33 with the background CRs alone)

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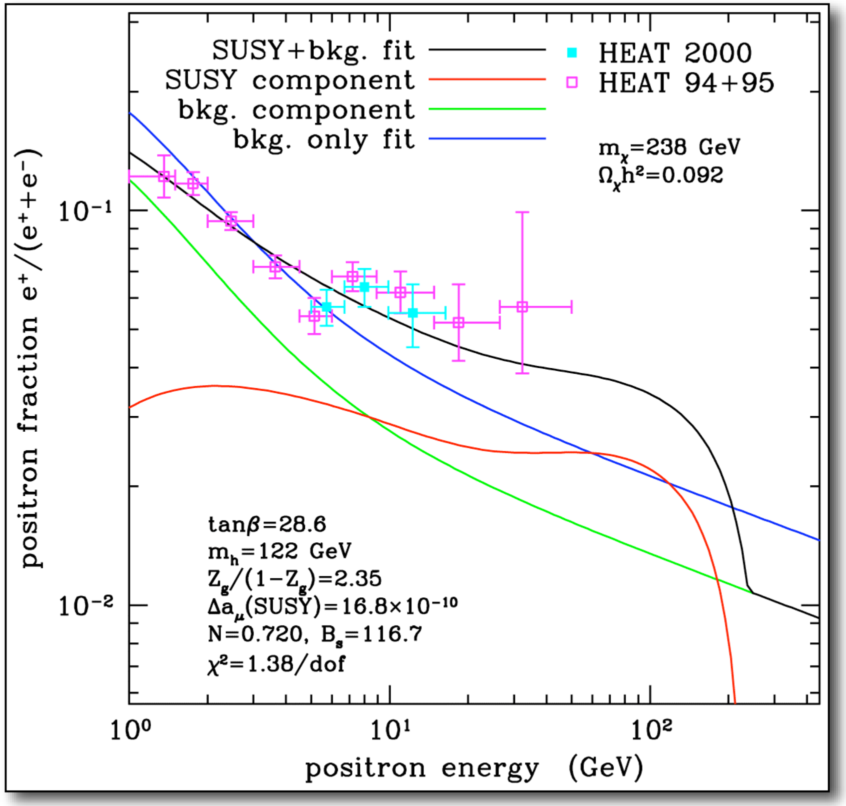

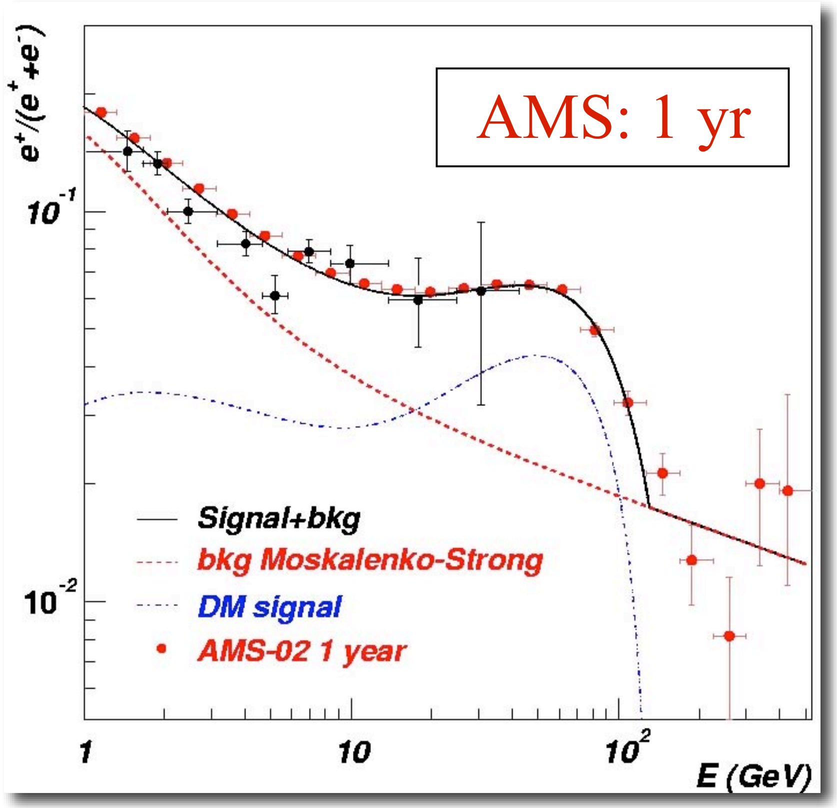

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CR transport and Galactic confinement

Steady state

$$\frac{\partial}{\partial t}N_i(E,t)+\frac{\partial}{\partial E}(\dot{E}_i(E)N_i(E,t))=Q_i(E,t)$$

$$-\frac{N_i(E,t)}{\tau_{\mathrm{esc}}(E)}$$

$$-\frac{N_i(E,t)}{\tau_{\mathrm{dec}}\sqrt{1-\frac{v_i^2(E)}{c^2}}}$$

$$-N_i(E,t)v_i(E)\times[\sigma_{\mathrm{p}i}(E)n_{\mathrm{H}}+\sigma_{\alpha i}(E)n_{\mathrm{He}}]$$

$$+\sum_j\int_0^\infty \mathrm{d}E' v_j(E')N_j(E',t)[\sigma_{\mathrm{p}ji}(E,E')n_{\mathrm{H}}+\sigma_{\alpha ji}(E,E')n_{\mathrm{He}}]$$

$$+\frac{1}{2}\frac{\partial^2}{\partial E^2}[K(E)N_i(E,t)]$$

"i" represents a given nuclear type

Steady state + high energy (> 10 GeV/n)

$$\frac{\partial}{\partial t}N_i(E,t) + \frac{\partial}{\partial E}(\dot{E}_i(E)N_i(E,t)) = Q_i(E,t)$$

$$-\frac{N_i(E,t)}{\tau_{\rm esc}(E)}$$

$$-\frac{N_i(E,t)}{\tau_{\rm dec}\sqrt{1-\frac{v_i^2(E)}{c^2}}}$$

$$-N_i(E,t)v_i(E)\times[\sigma_{pi}(E)n_{\rm H}+\sigma_{\alpha i}(E)n_{\rm He}]$$

$$+\sum_j\int_0^\infty {\rm d}E'v_j(E')N_j(E',t)[\sigma_{pji}(E,E')n_{\rm H}+\sigma_{\alpha ji}(E,E')n_{\rm He}]$$

$$+\frac{1}{2}\frac{\partial^2}{\partial E^2}[K(E)N_i(E,t)]$$

"i" represents a given nuclear type

Steady state + high energy

$$Q_i(E) - \frac{N_i(E)}{\tau_{\mathrm{esc},i}(E)} = 0$$

Solution (sic!)

$$N_i(E) = Q_i(E) \times \tau_{\mathrm{esc},i}(E)$$

Simple model: slope steepening

- Confinement time of cosmic rays of energy E:

$$\tau_{\mathrm{conf}}(E) \propto E^{-\alpha}$$

- Injection rate in the whole Galaxy:

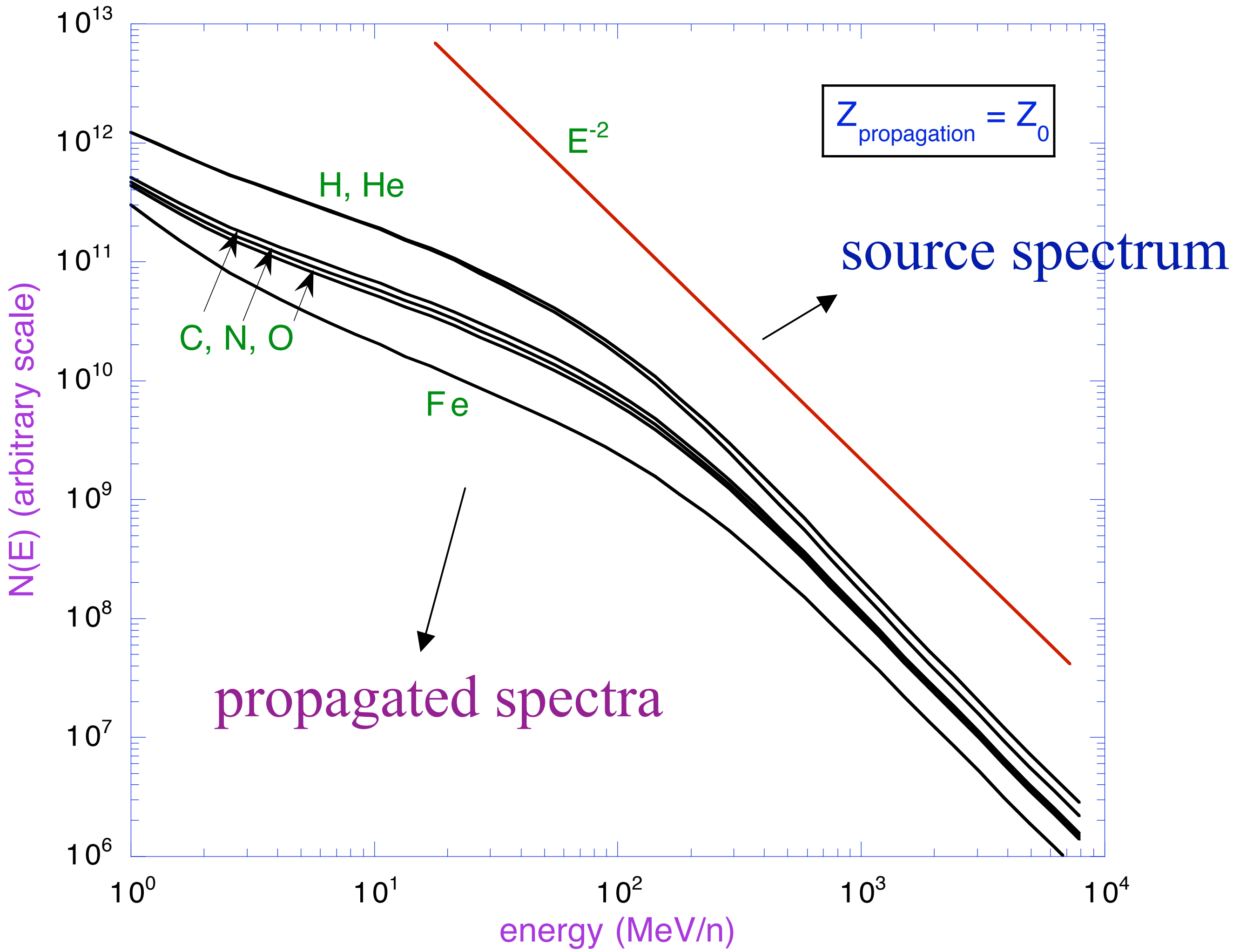
$$Q(E) \propto E^{-x}$$

- Resulting number in the Galaxy (steady-state)

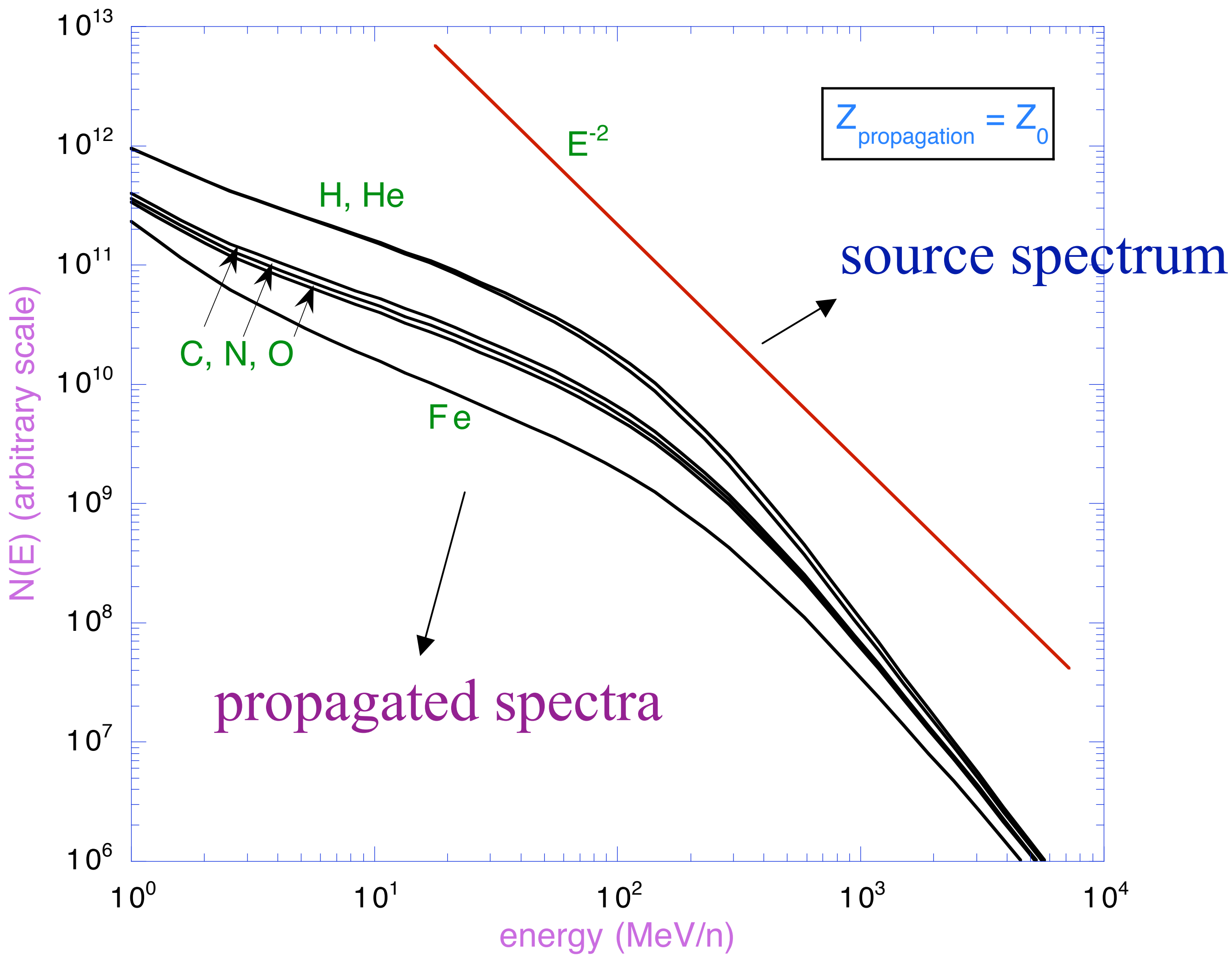
$$N(E) = Q(E) \times \tau_{\mathrm{conf}}(E) \propto E^{-(x+\alpha)}$$

slope steepening

Energy losses



Energy losses + escape



Source spectrum and CR diffusion

- CR confinement time: $\tau_{\rm conf}(E) \propto E^{-\alpha}$
- Injection rate in the whole Galaxy: $Q(E) \propto E^{-x}$
- "propagated spectrum": $N(E) \propto E^{-(x+\alpha)}$
- We need to have: $\boxed{x+\alpha \simeq 2.7}$
- Naive box model: $\tau_{\rm conf}(E) \simeq \dfrac{H^2}{D(E)}$ → $D(E) \propto E^{\alpha}$

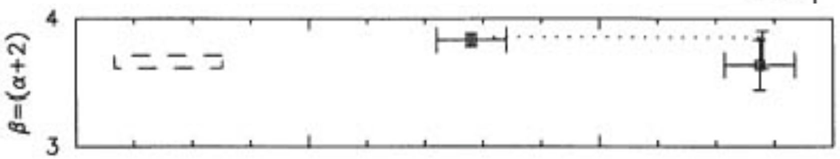
NB: "Best fit" from secondary/primary studies: $x \simeq 2.35$ $\alpha \simeq 0.36$

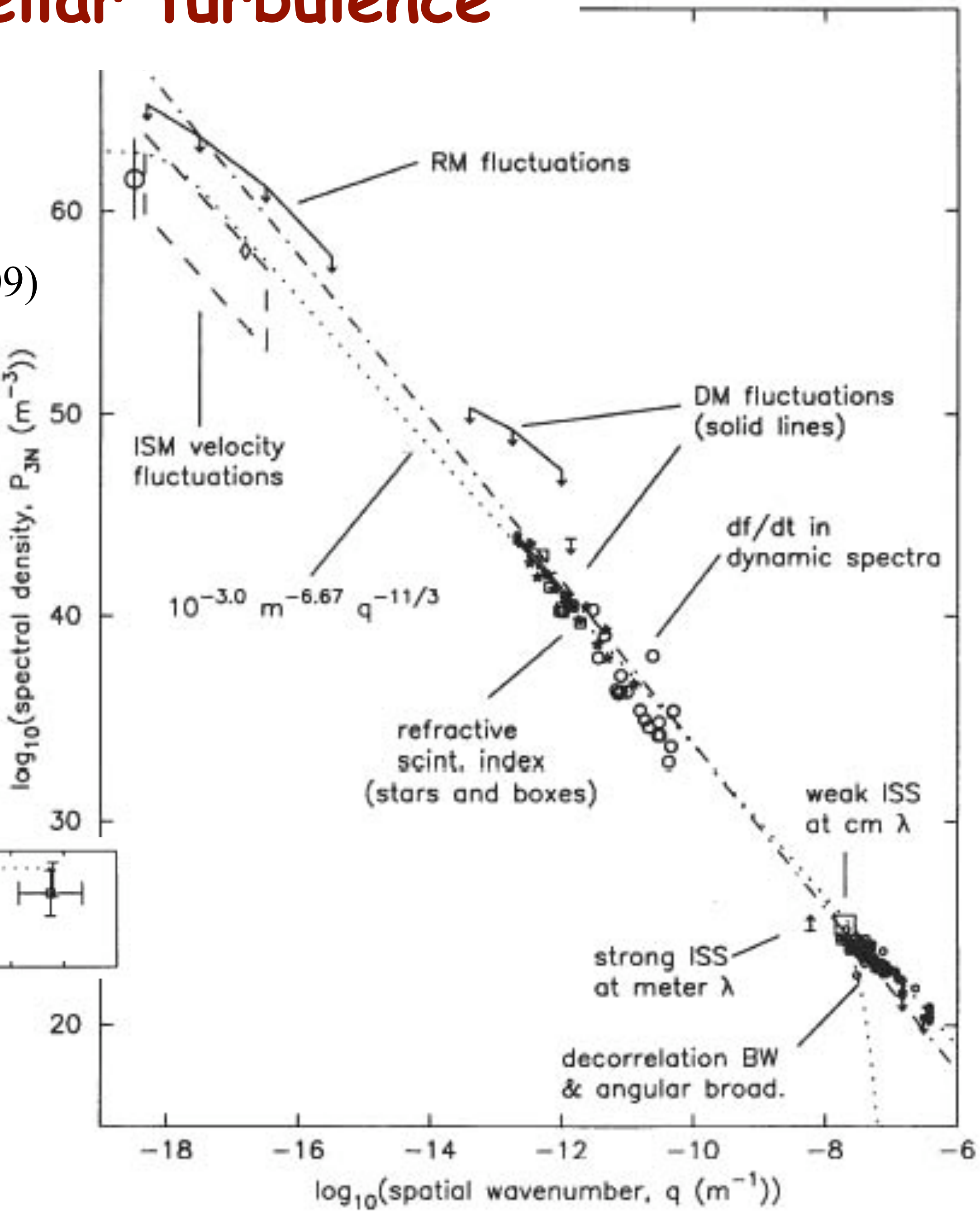
"Interstellar turbulence"

- e⁻ density fluctuations

(Armstrong, et al., 1995, ApJ 443, 209)

- "spectral index"





Final notes

- Beware: all energetic particles (EPs) are not CRs…
- EP sources are known, but their phenomenology is often uncertain: more work is needed, obs. and theory, multi-messenger approach…
- Global CR phenomenology is not particularly problematic, but the sources are unknown (100 years after their discovery!)
- Secondary particles are extremely important: photons (non-thermal astronomy! + diffuse backgrounds!), nuclei (LiBeB nucleosynthesis!), neutrinos, etc.
- Magnetic fields isotropize the CRs, and mix all sources… except at very high E!
- CRs at low E are Galactic (GCRs), while CRs at high E are extragalactic (EGCRs): the GCR/EGCR transition is a key!