Transport des rayons cosmiques

I - composante Galactique

Principle of CR transport

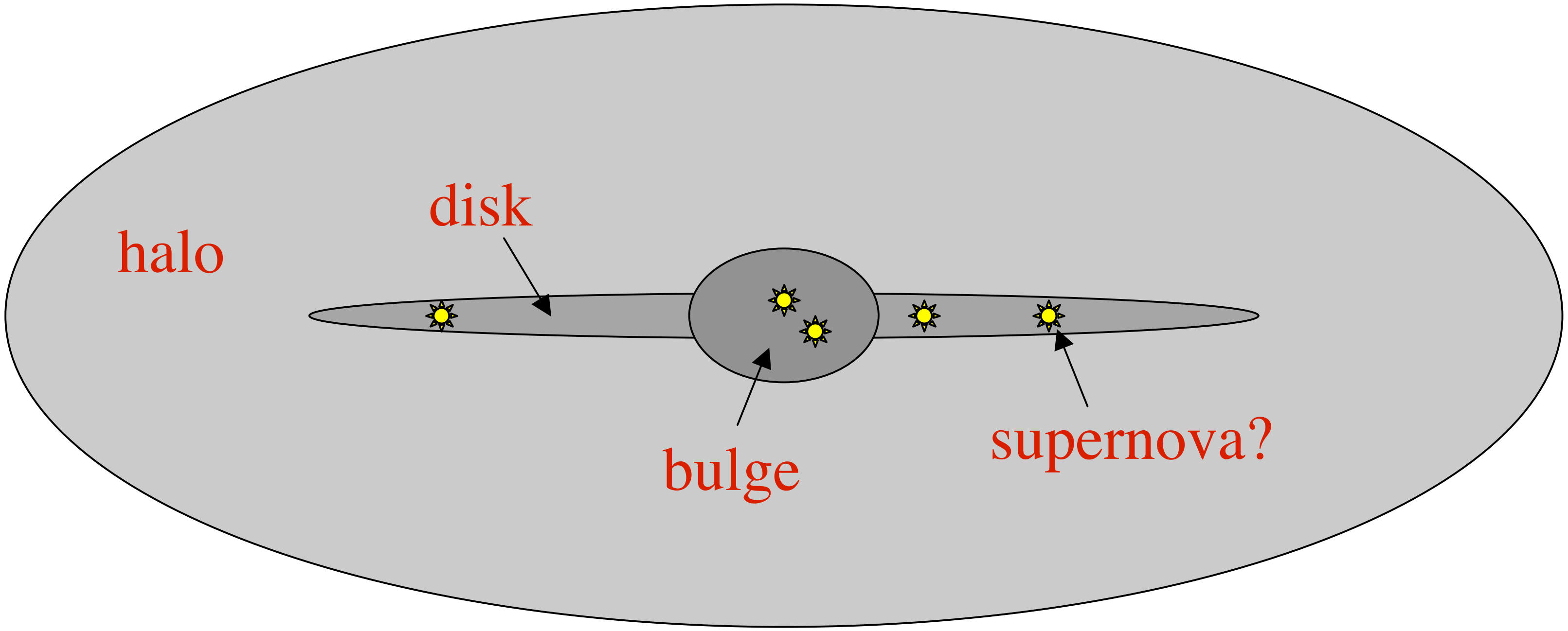
- Link the **observed** CR characteristics to the CR characteristics **at the source**

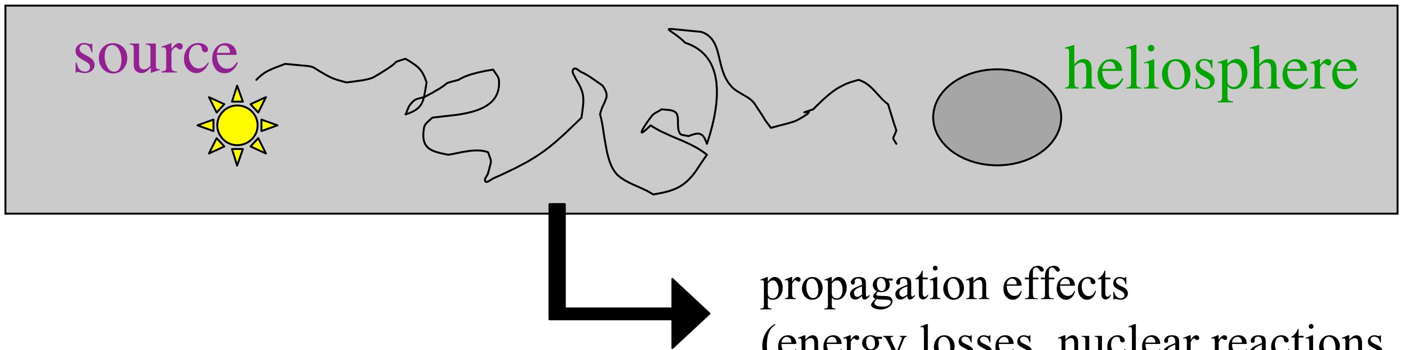
- The CRs are affected while they propagate in the interstellar medium

  - arrival directions
  - composition
  - energy spectrum

  } all combined…

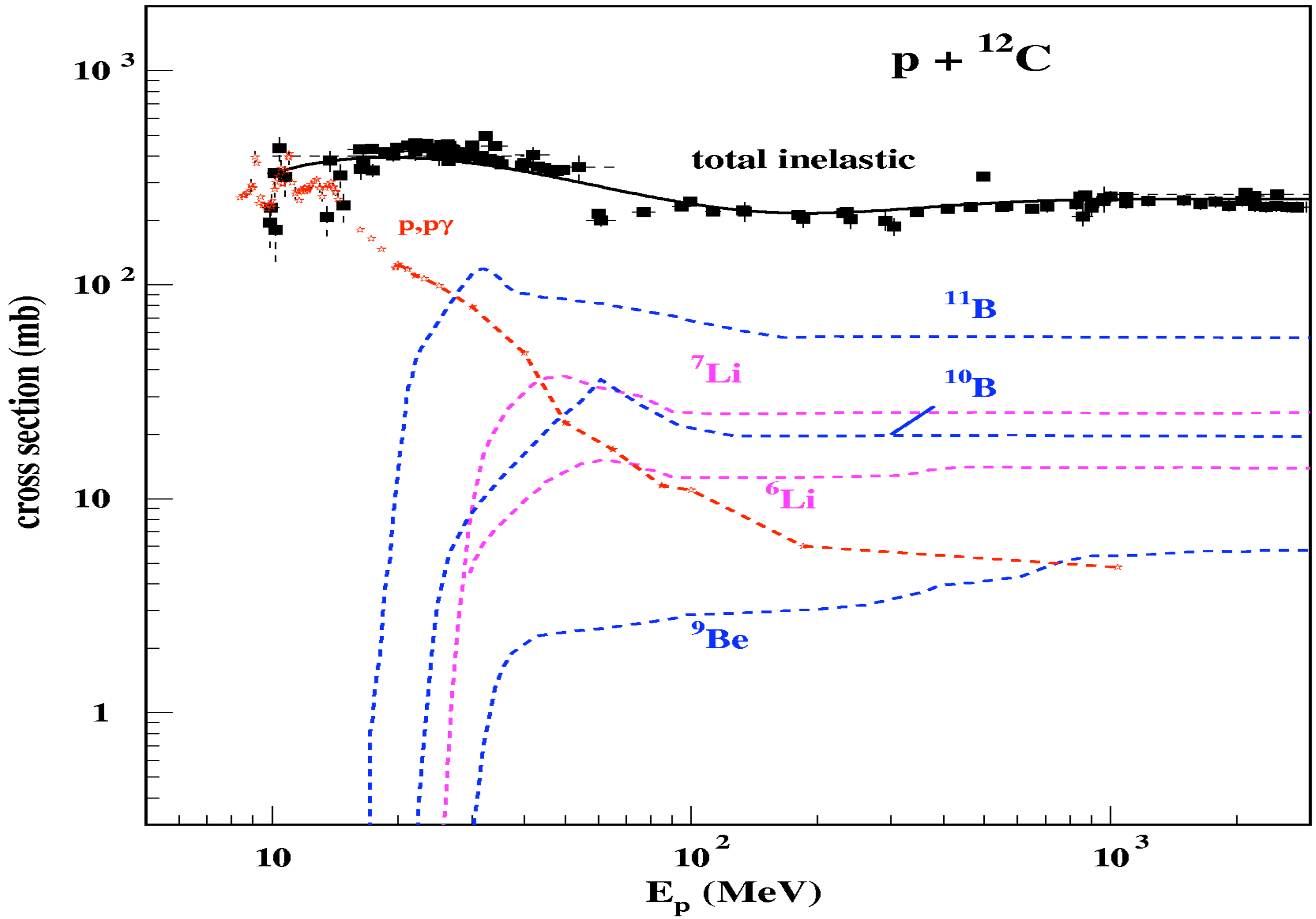
Sketch of the Galaxy and halo





propagation effects
(energy losses, nuclear reactions…)

Nuclear interactions



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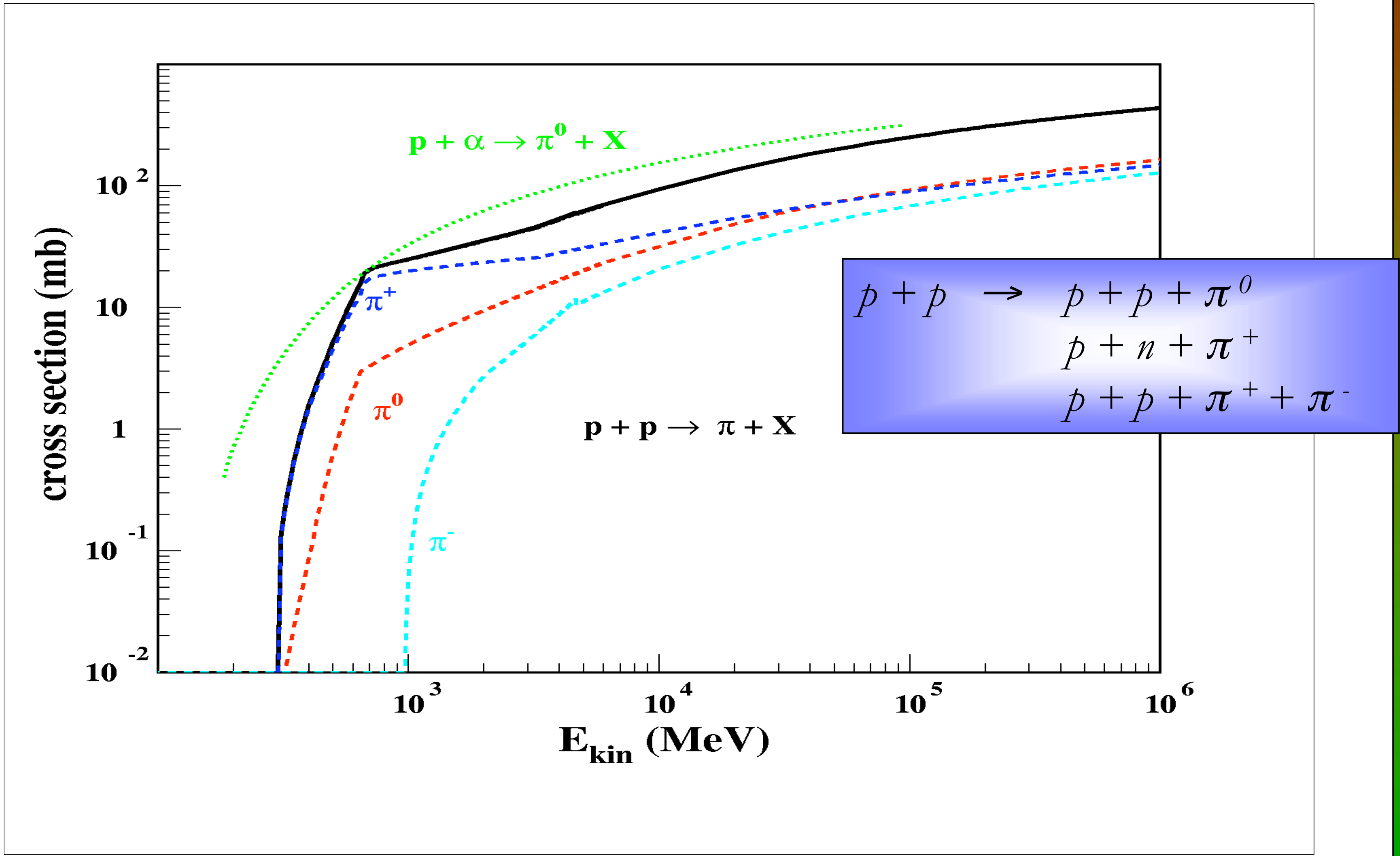
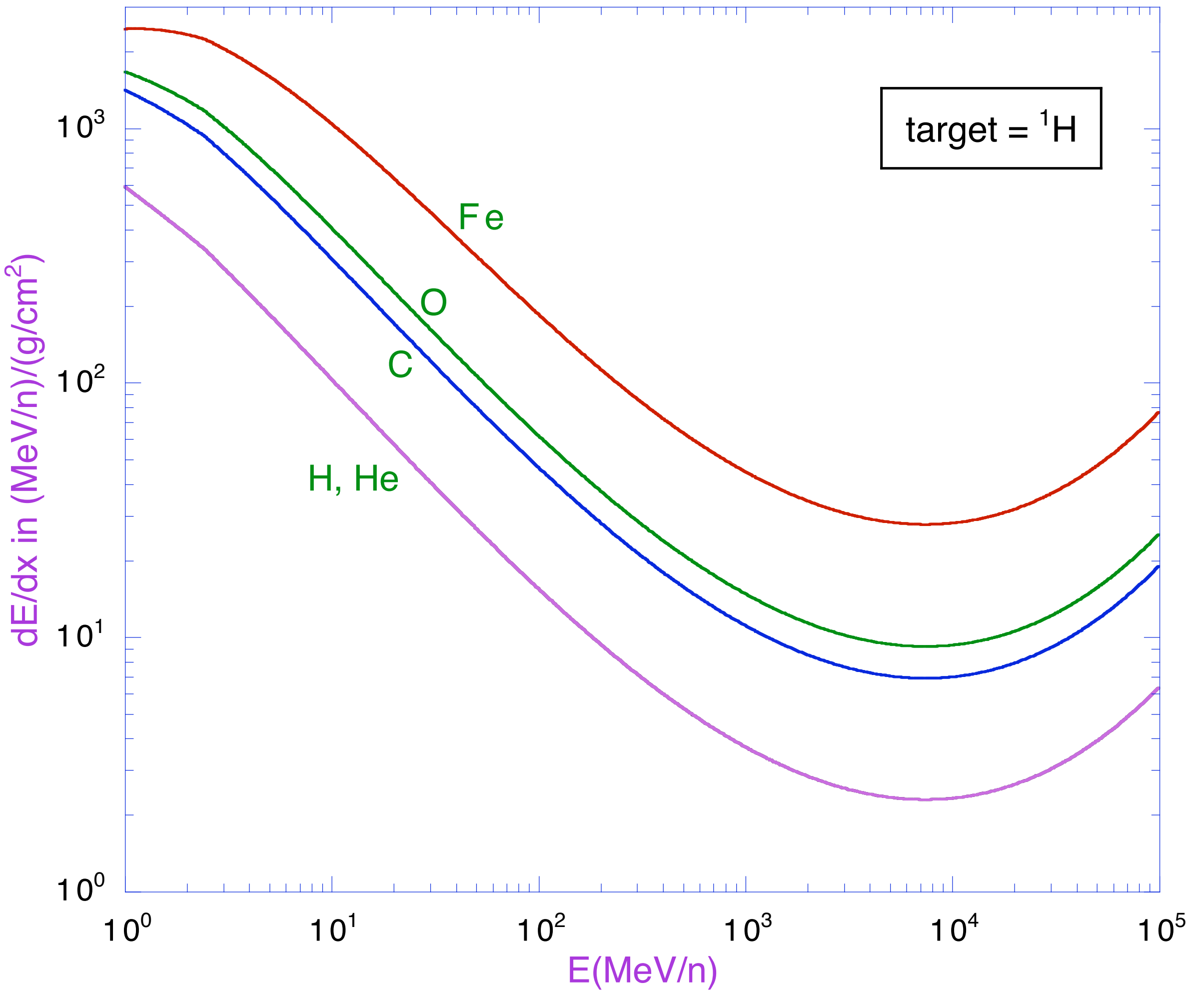
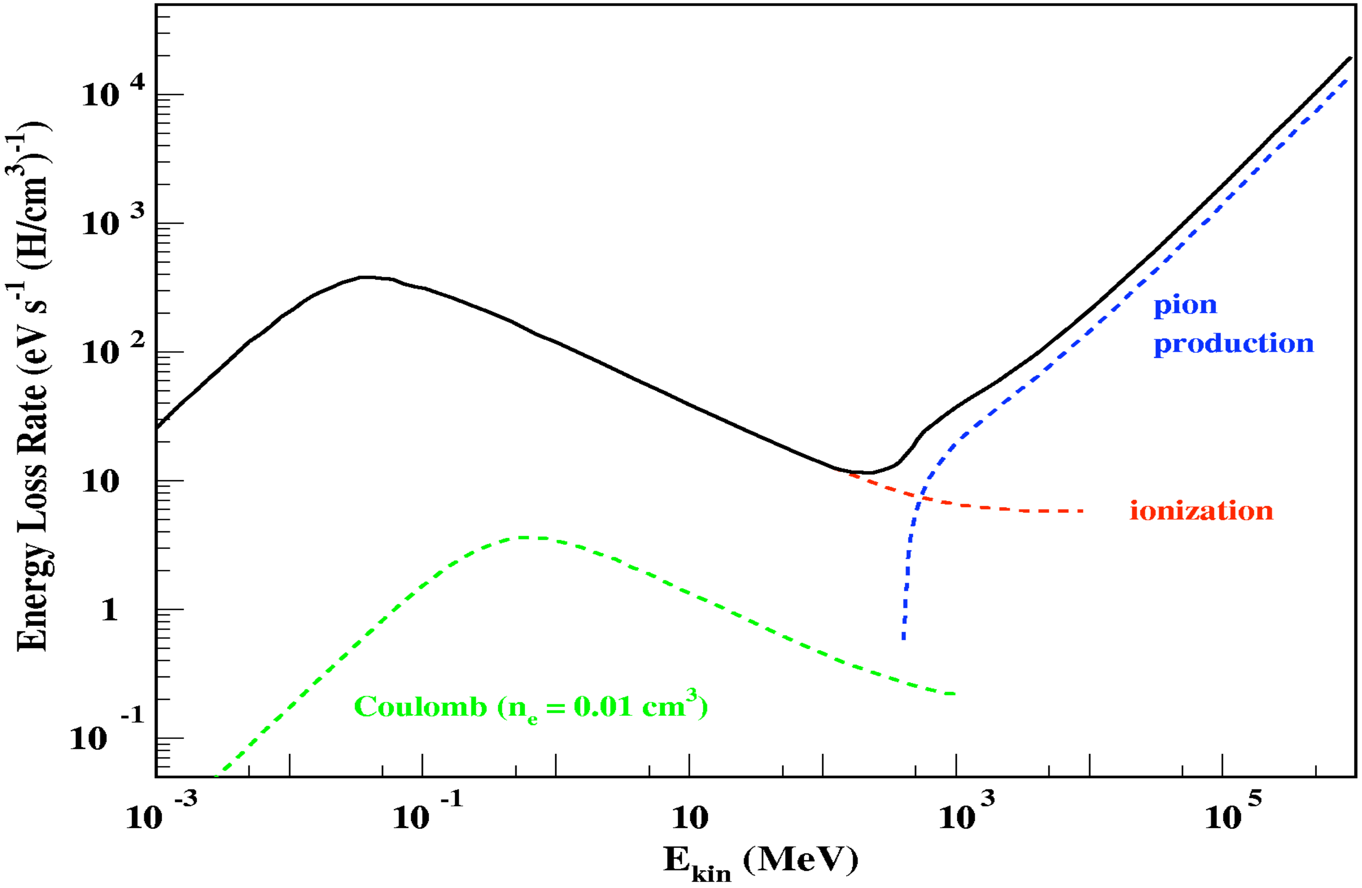


Coulombian energy losses



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

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

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

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

Steady state

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

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3D transport equation

- Diffusive approximation...

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

flux in energy space (losses + acc.)

injection, « in flight » production

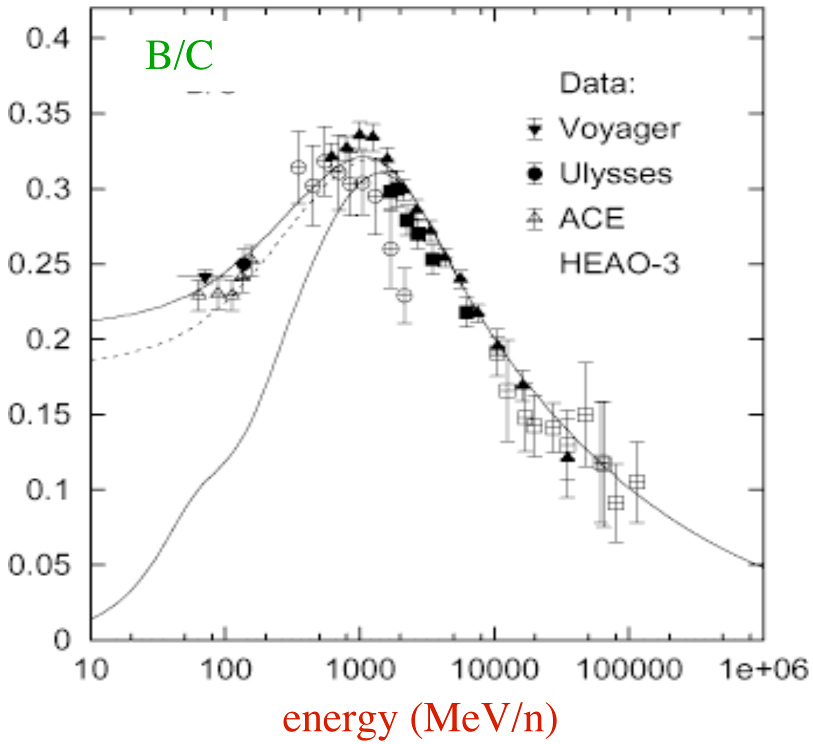
destruction, decay, escape

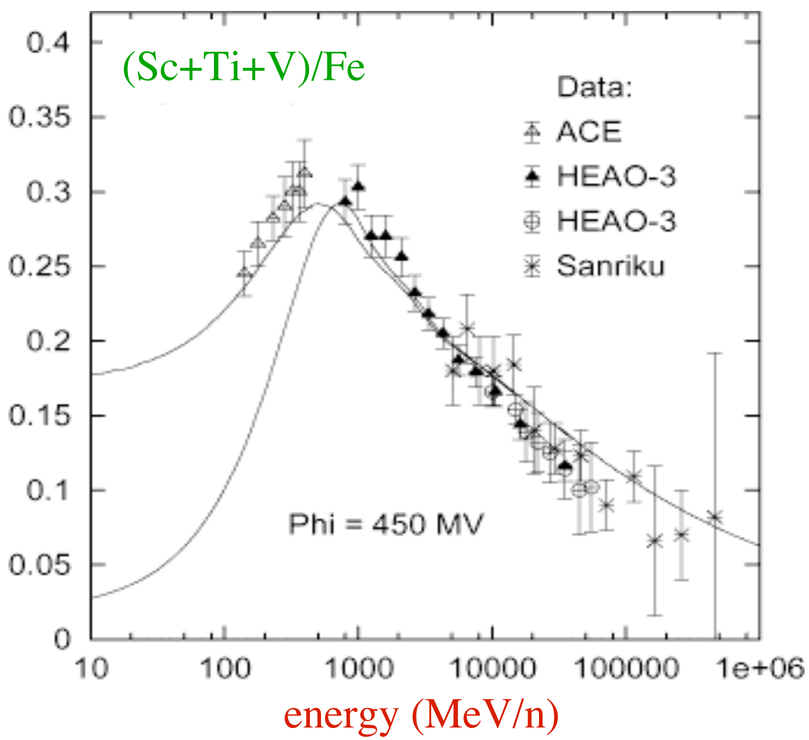
diffusion

- 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

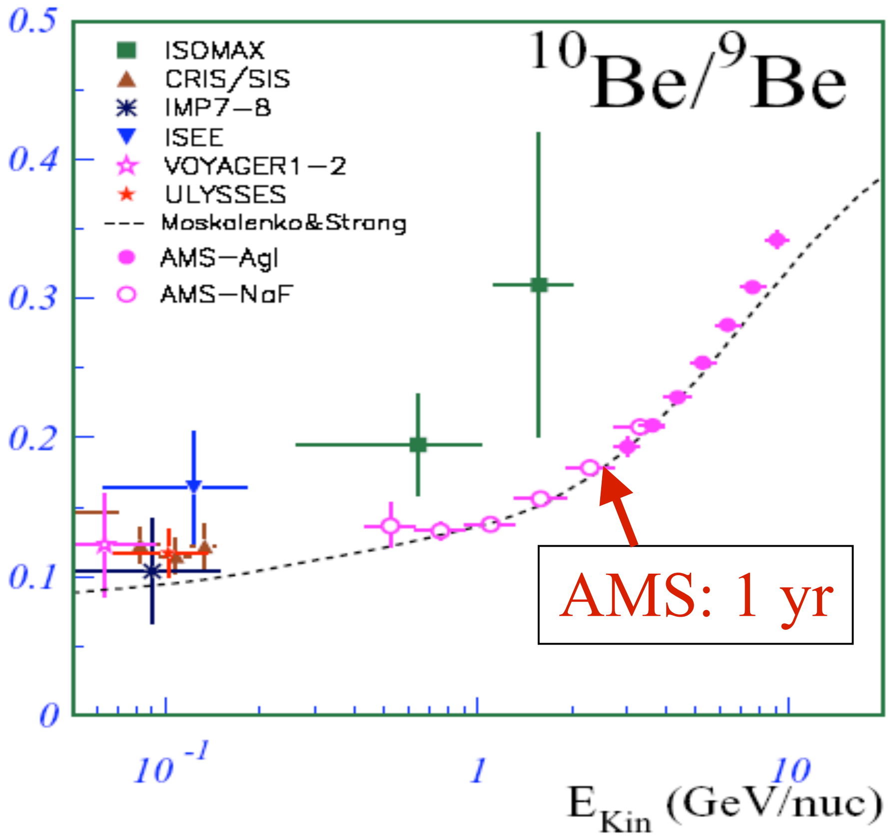




[Strong & Moskalenko (2001)]

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

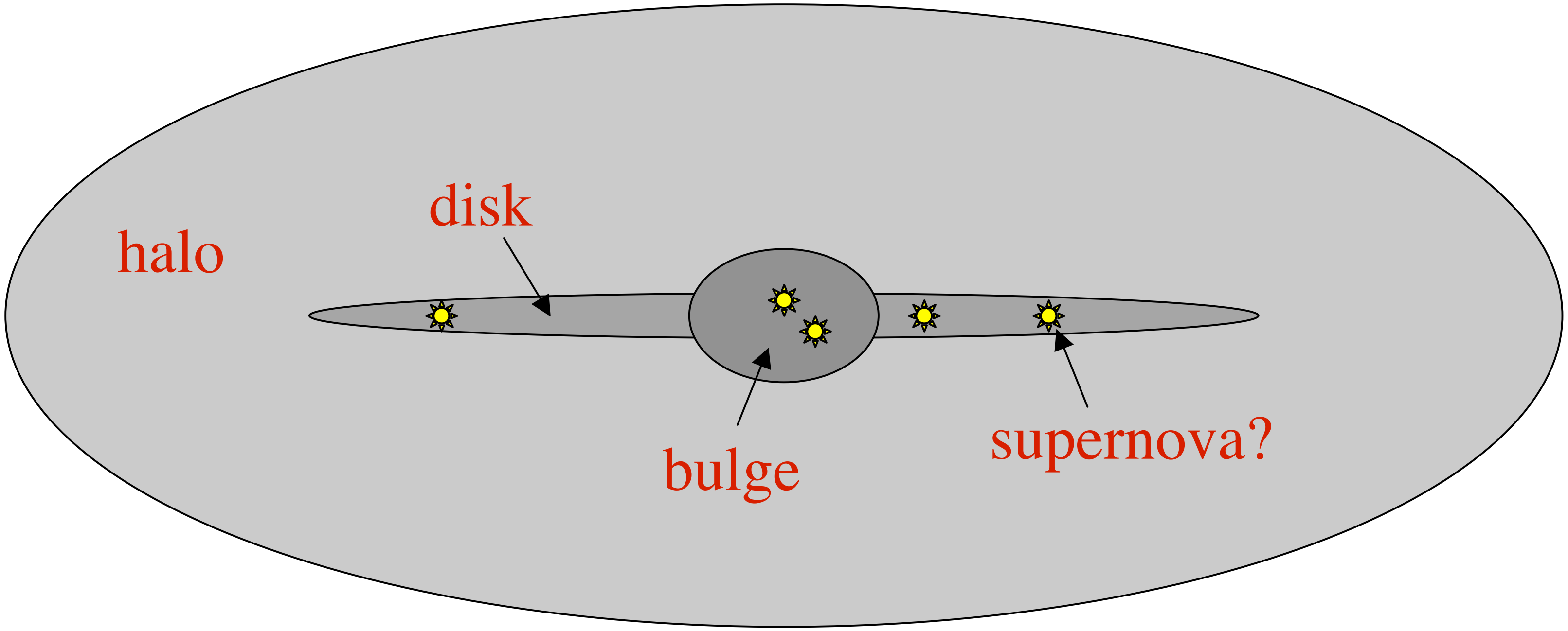
- Cosmic-ray clocks

  ⇒ CRs have spent typically **$\tau_{RC} \sim 2\ 10^7$ years** on their way

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

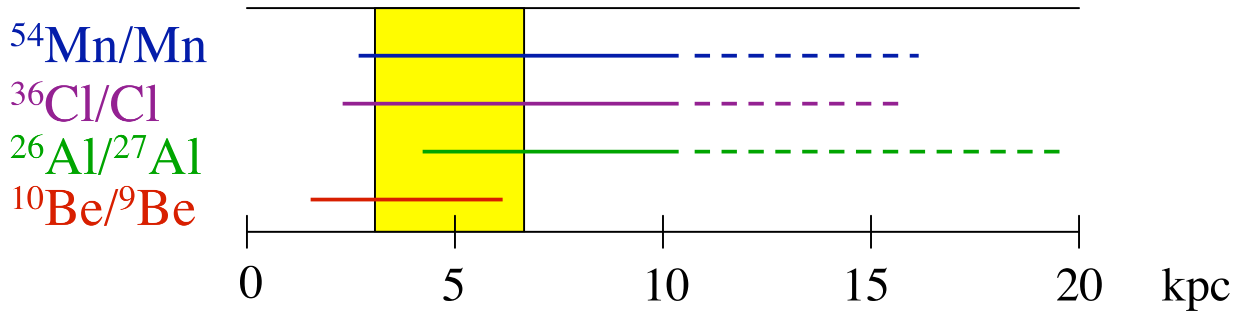
- Thus, they must have spent quite some time in the halo! (H_{halo} ~ 3–7 kpc)

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

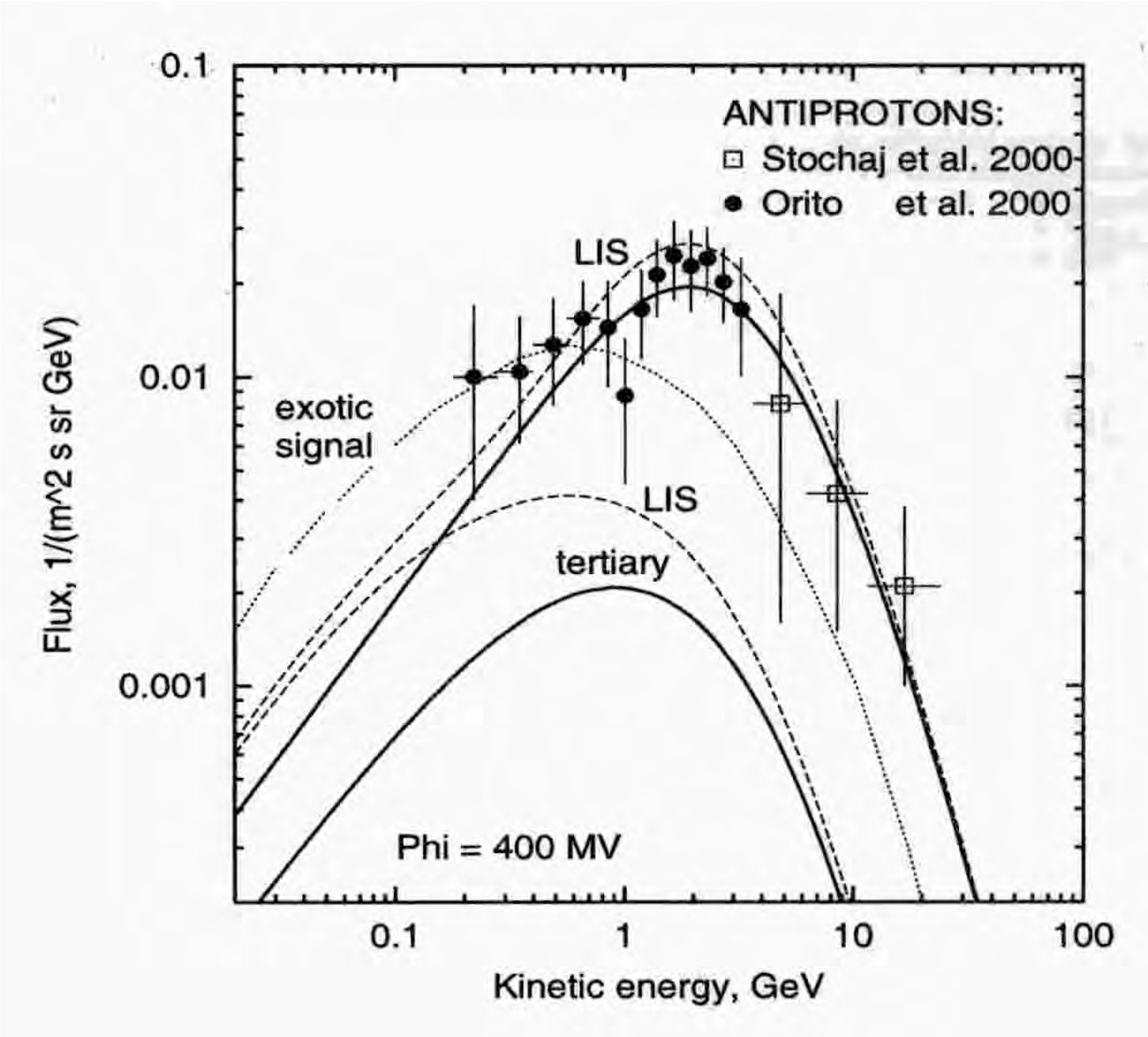
Summary

- 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?**

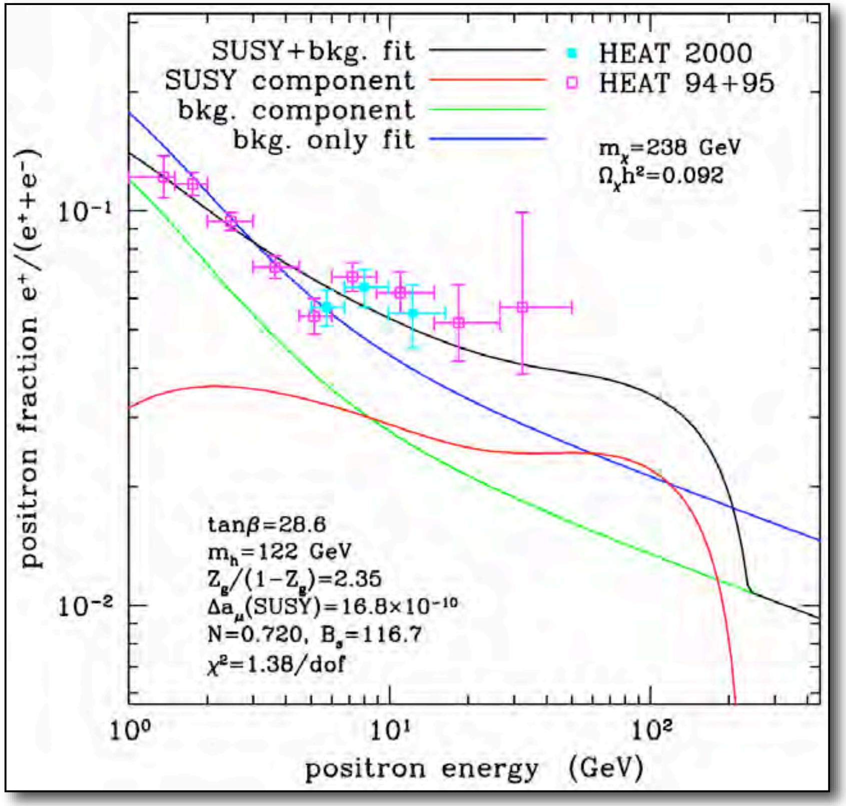
Antiprotons

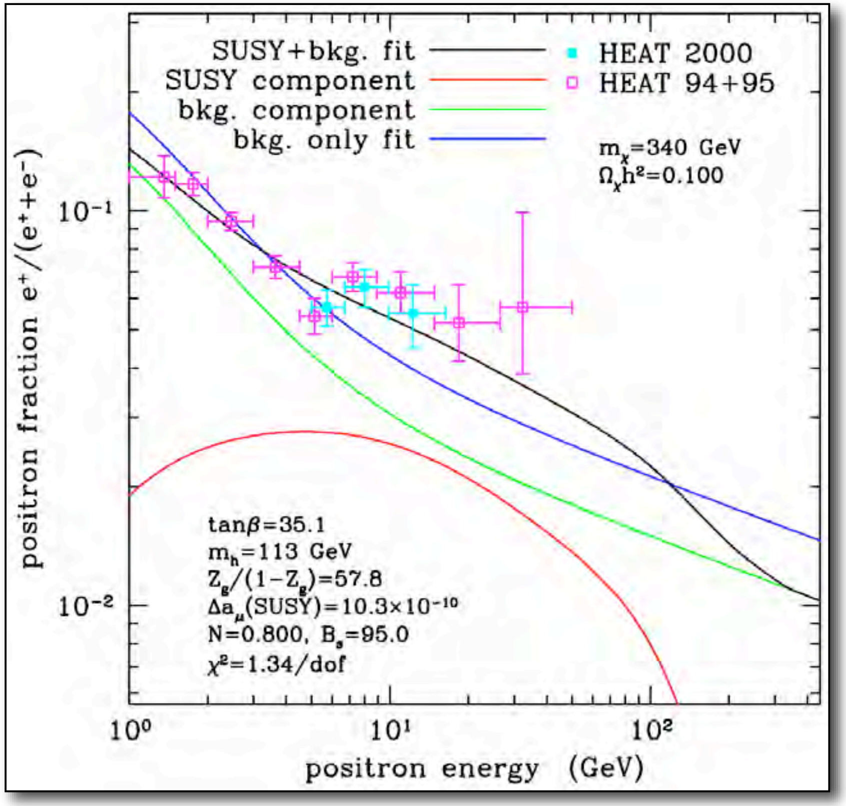


Strong & Moskalenko (2001)

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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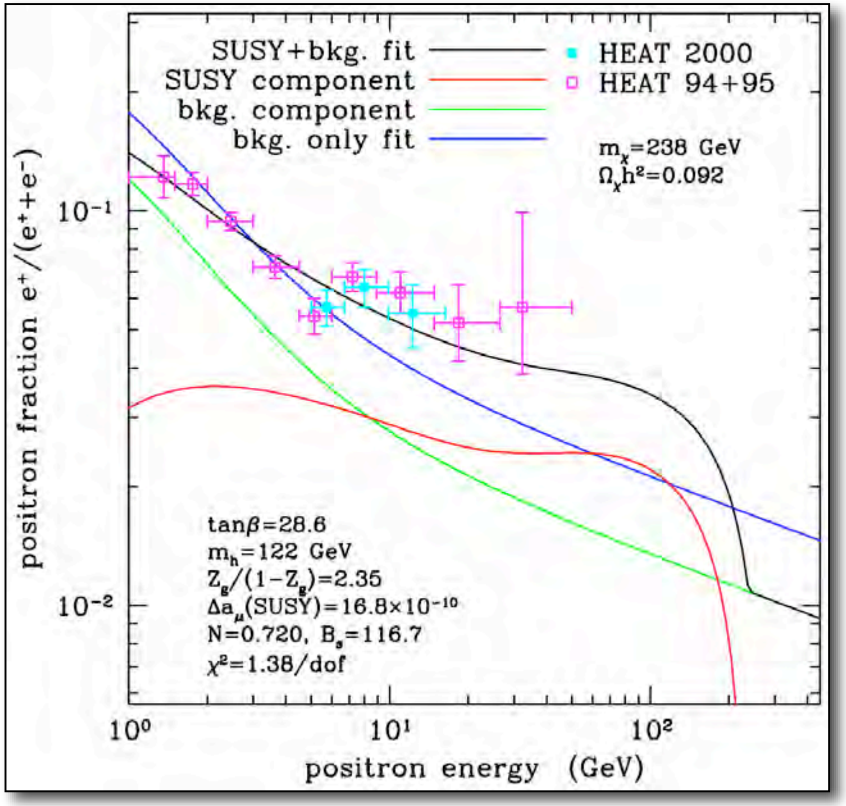

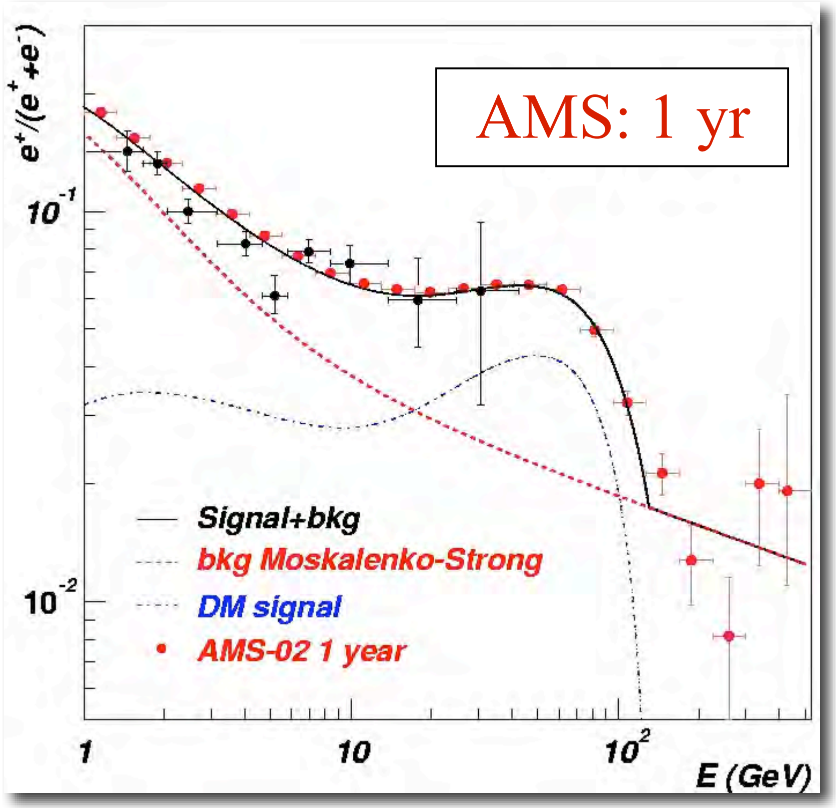

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CR transport and Galactic confinement

Steady state

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

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

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"i" represents a given nuclear type

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

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

"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!)

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

Simple model: slope steepening

- Confinement time of cosmic rays of energy E:

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

- Injection rate in the whole Galaxy:

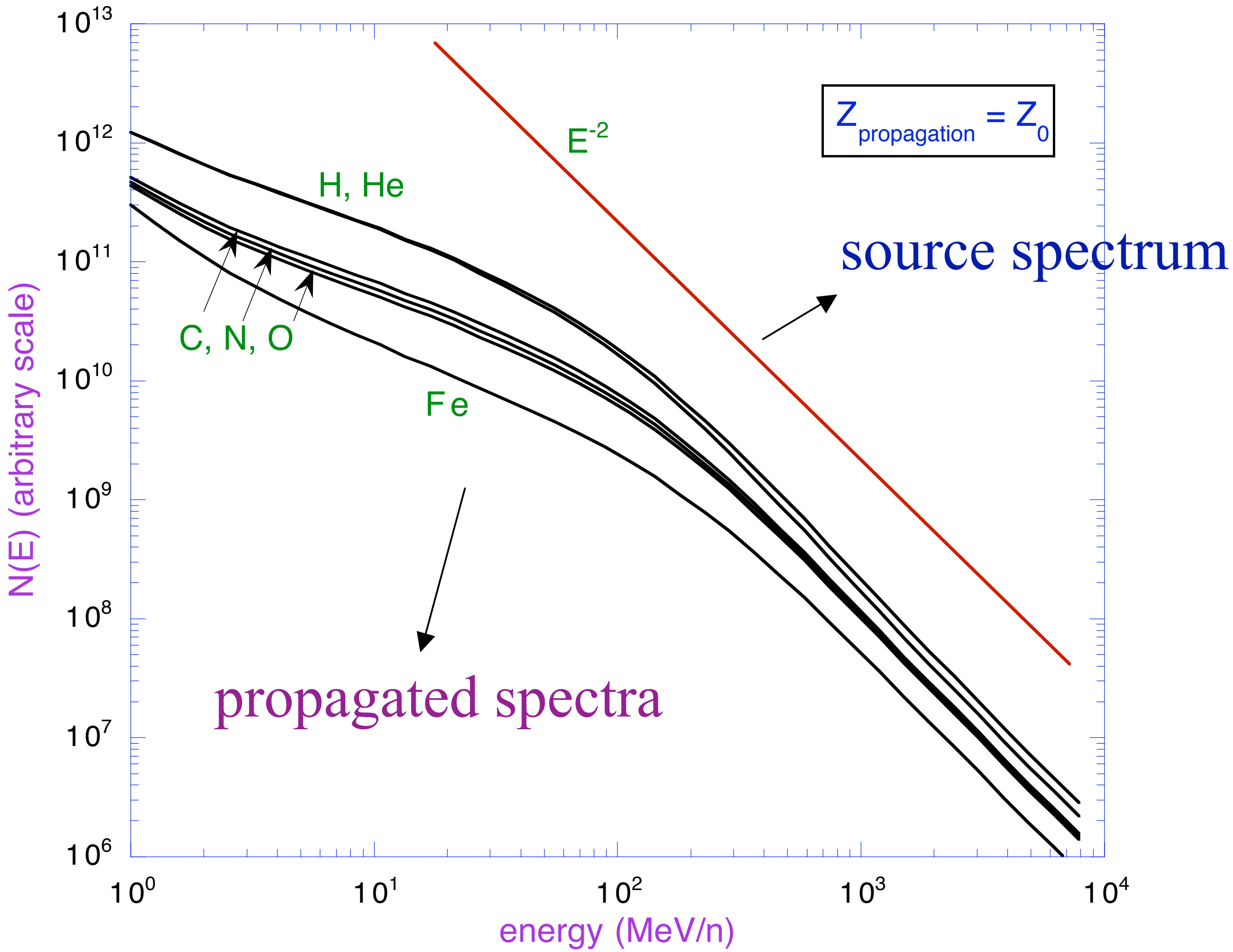
$$Q(E) \propto E^{-x}$$

- Resulting number in the Galaxy (steady-state)

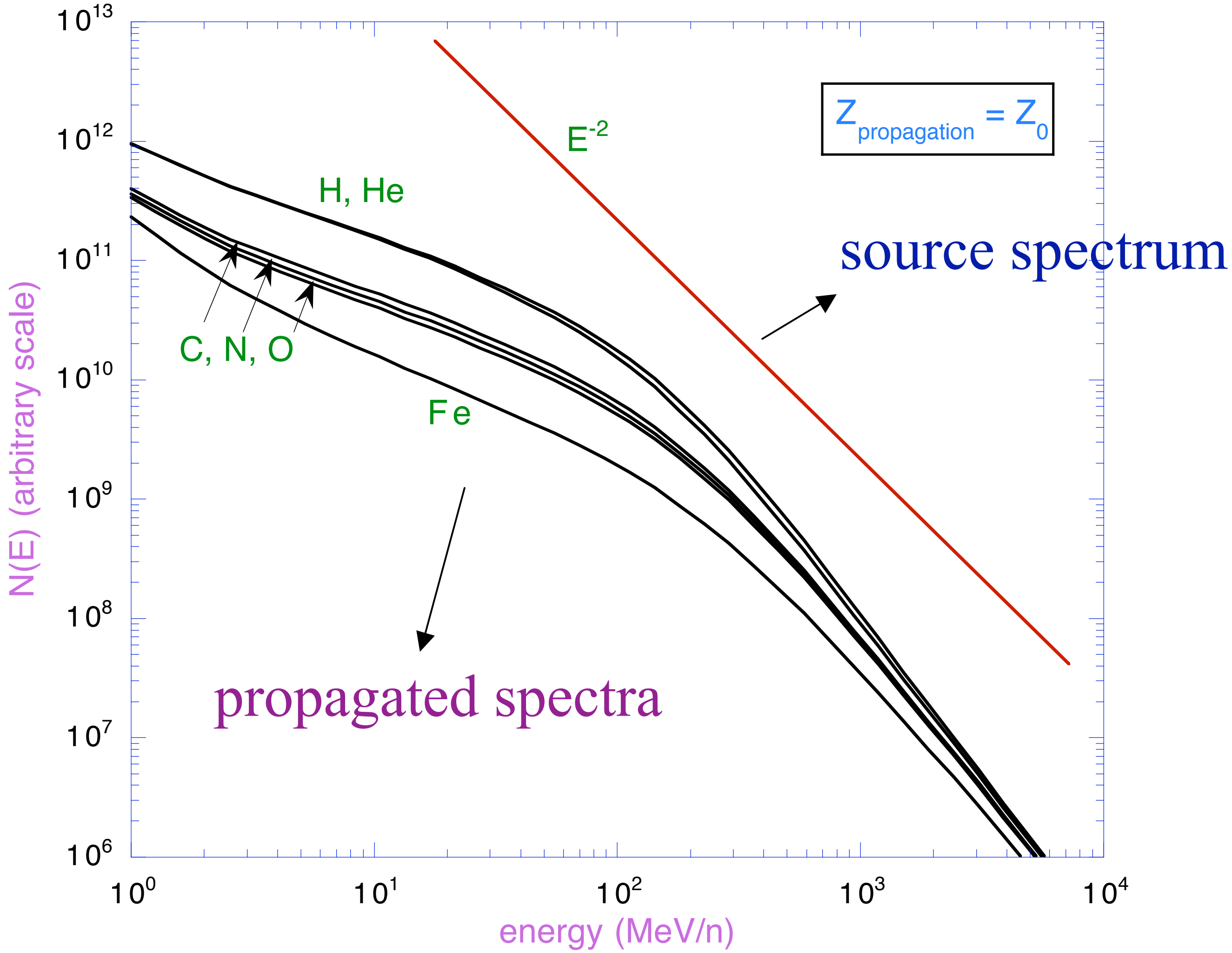
$$N(E) = Q(E) \times \tau_{\text{conf}}(E) \propto E^{-(x+\alpha)}$$

slope steepening

Energy losses



Energy losses + escape



Source spectrum and CR diffusion

- CR confinement time: $\tau_{\text{conf}}(E) \propto E^{-\alpha}$
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- "propagated spectrum": $N(E) \propto E^{-(x+\alpha)}$

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- Naive box model: $\tau_{\rm conf}(E) \simeq \frac{H^2}{D(E)}$ → $D(E) \propto E^{\alpha}$

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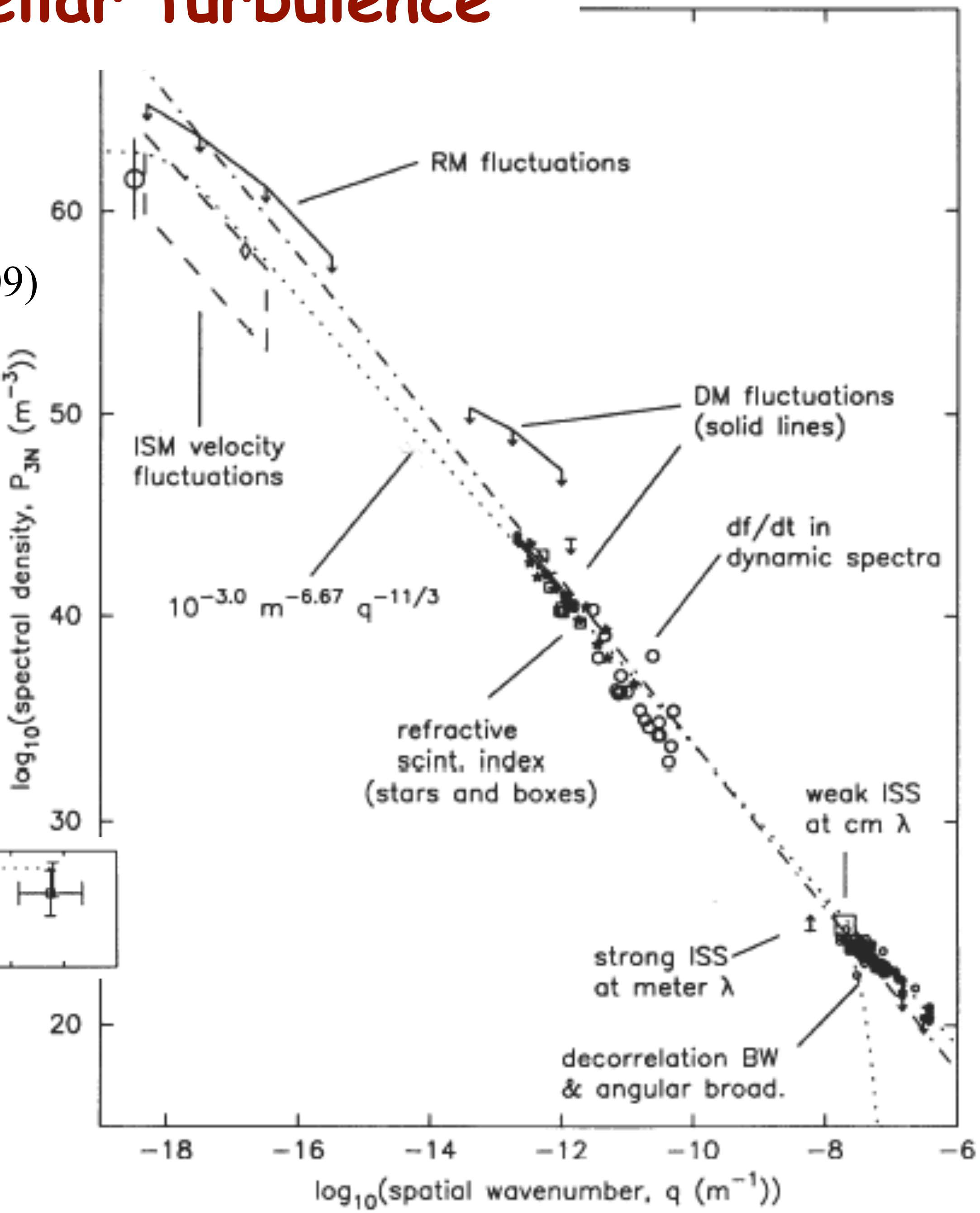
- We need to have: $\boxed{x+\alpha \simeq 2.7}$
- Naive box model: $\tau_{\mathrm{conf}}(E) \simeq \frac{H^2}{D(E)} \Rightarrow D(E) \propto E^{\alpha}$

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

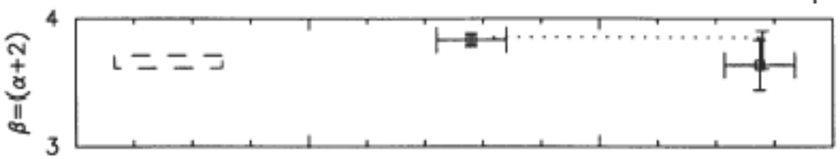
"Interstellar turbulence"

- 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!