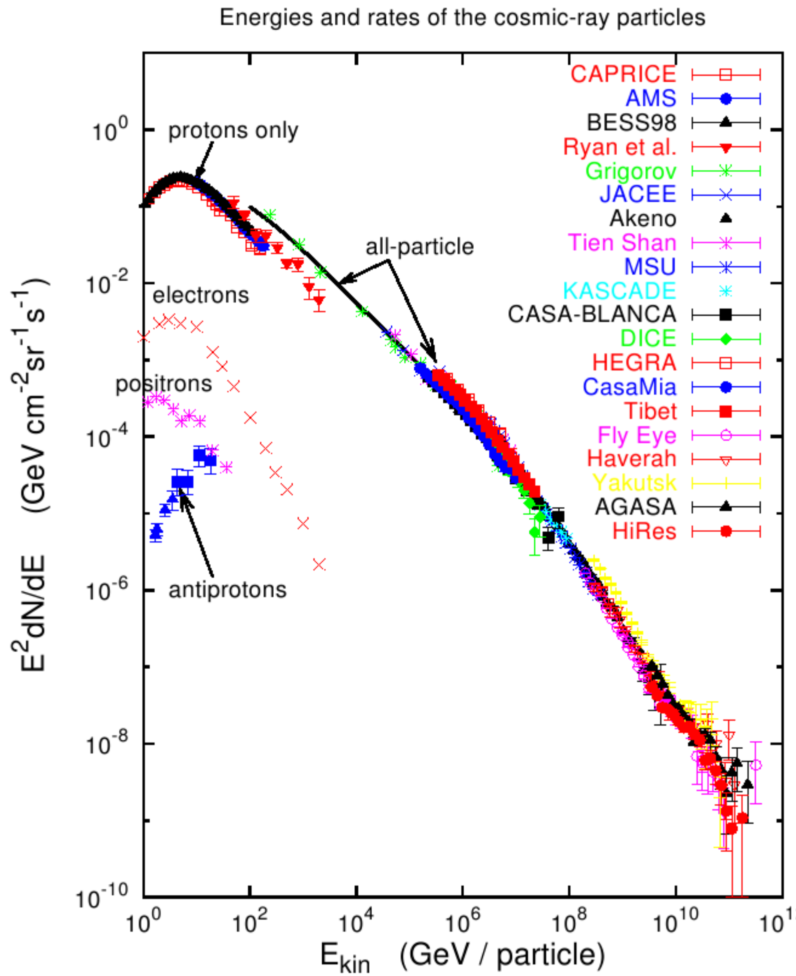
Advances in Particle Astrophysics

Session II-III: Galactic Cosmic Rays

Kfir Blum
Weizmann Institute

CERN academic training 11-15/04/2016

The Galaxy is filled with a gas of high-energy particles, of several types



Hillas, astro-ph/0607109

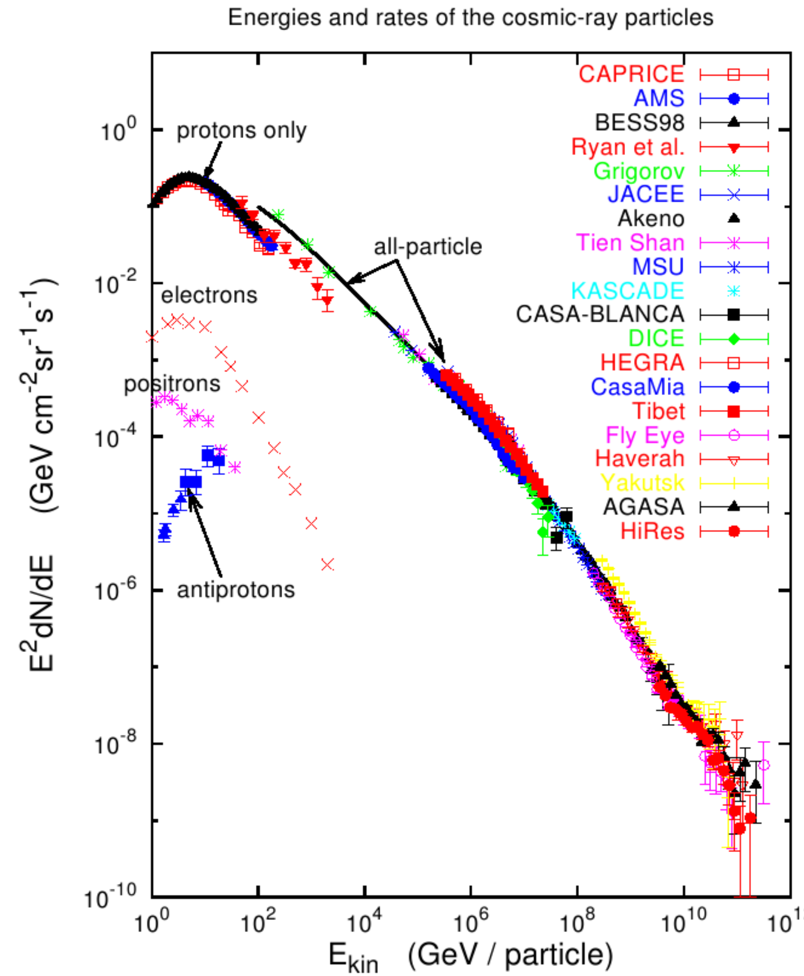
The Galaxy is filled with a gas of high-energy particles, of several types

Magnetic rigidity

$$\mathcal{R} = p/Z$$

Larmor radius

$$L = \mathcal{R}/B \approx 3 \times 10^{-4} \left(\frac{\mathcal{R}}{\mathrm{TV}}\right) \left(\frac{\mathrm{B}}{3\ \mu\mathrm{G}}\right)^{-1}\ \mathrm{pc}$$



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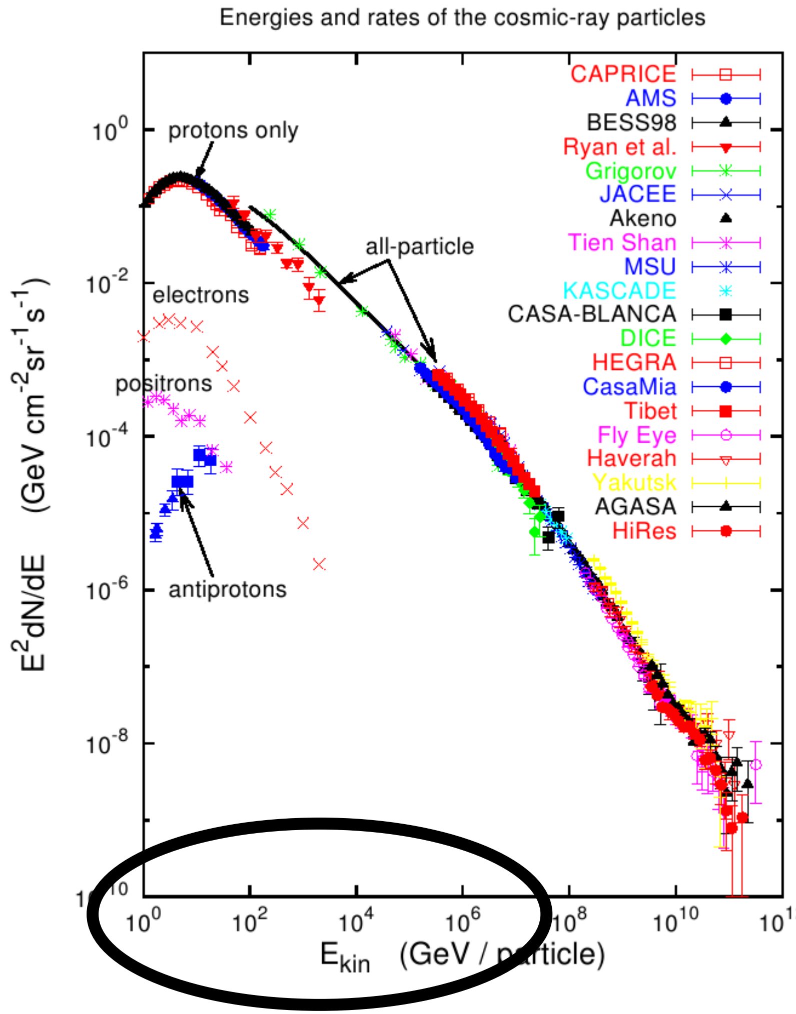
Galactic:



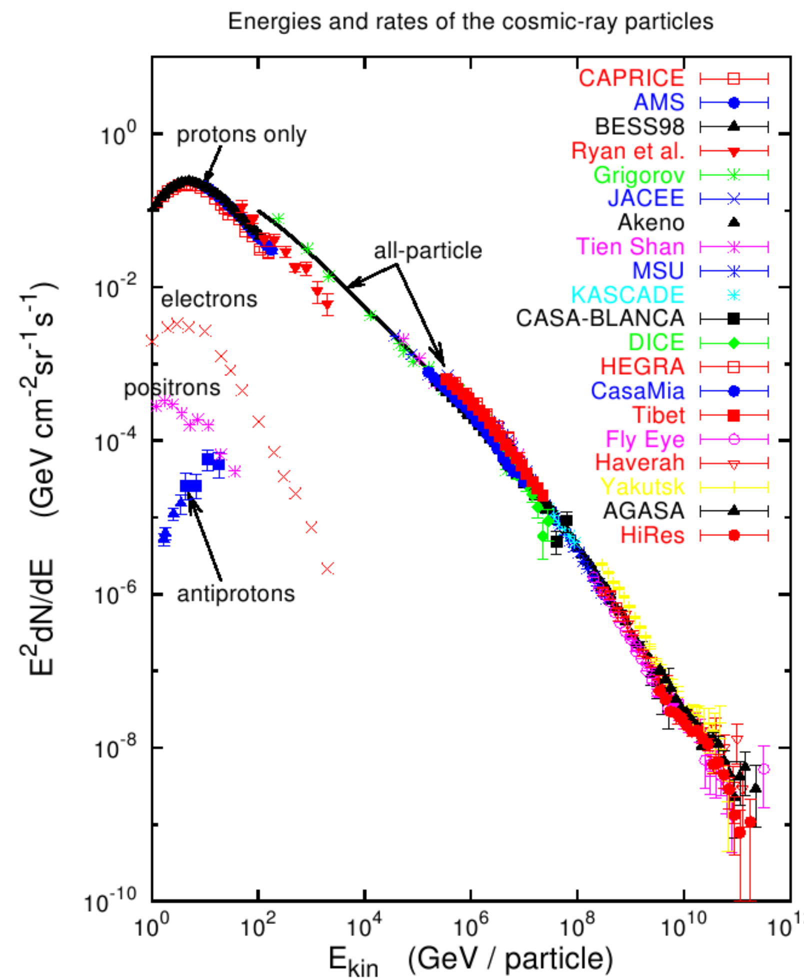
Hillas, astro-ph/0607109

The Galaxy is filled with a gas of high-energy particles, of several types

Two basic populations:

1. **primary** cosmic rays (p, He, C, O, Fe, e-,…), composition consistent with stellar material, accelerated to relativistic energy

2. **secondary** cosmic rays (B, sub-Fe, pbar, e+,…), much higher abundance than in stars, but smaller flux than neighboring (in A) primary CRs (e.g. B/C~0.1). Consistent w/ spallation products of primary component



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Open questions:

What is the source of Galactic cosmic rays?
How do cosmic rays escape from the Galaxy?

Do we see exotic sources like dark matter or pulsars?

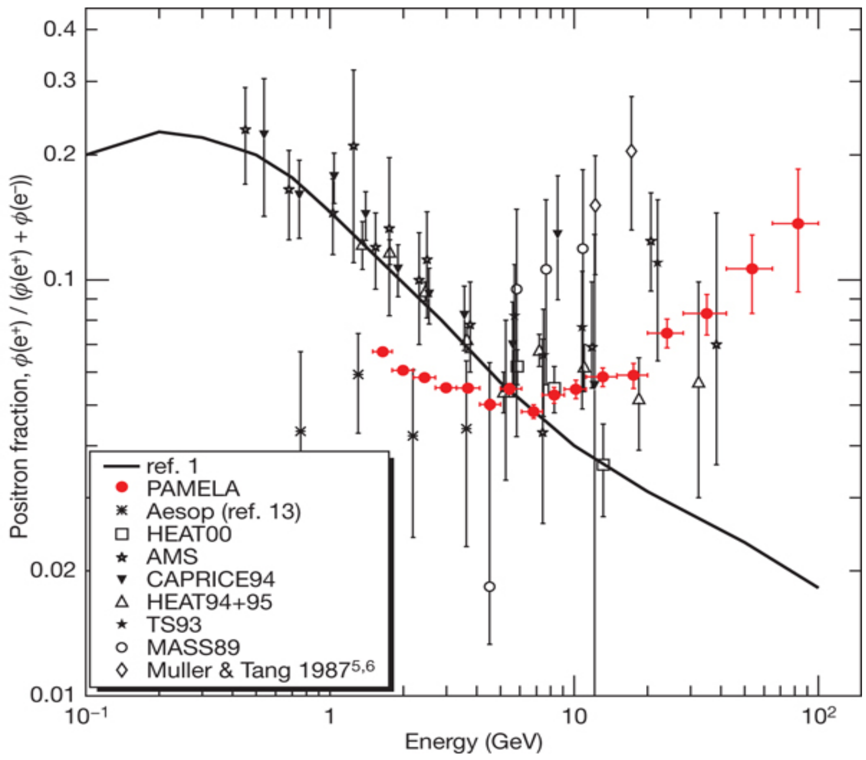
PAMELA + AMS data = major progress.

I will give my take on some of these results, focusing on e+ and pbar.

Aim at what we can calculate and what we can learn, without committing to detailed model assumptions.

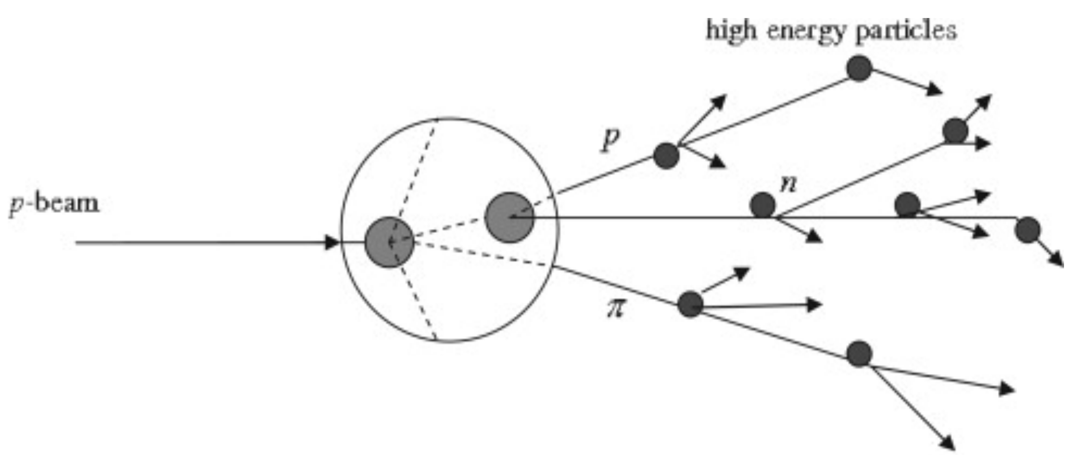
Katz et al; MNRAS 405 (2010) 1458
KB; JCAP 1111 (2011) 037
KB, Katz, Waxman; PRL 111, 211101 (2013)

PAMELA (2009) **positron anomaly?**

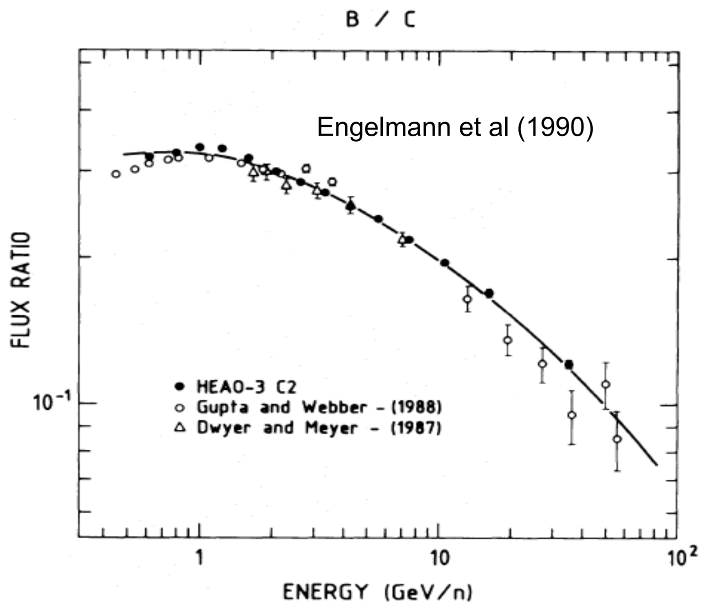


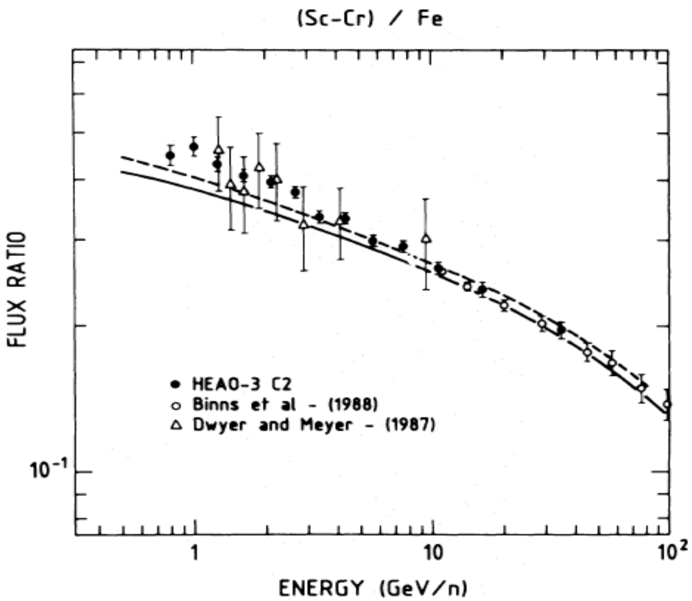
Antimatter occurs as secondary

$$pp \longrightarrow pn\pi^+ \longrightarrow ppe^-e^+\nu_e\bar{\nu}_e\nu_\mu\bar{\nu}_\mu$$



Stable secondaries with no energy loss (B, pbar, sub-Fe,…)

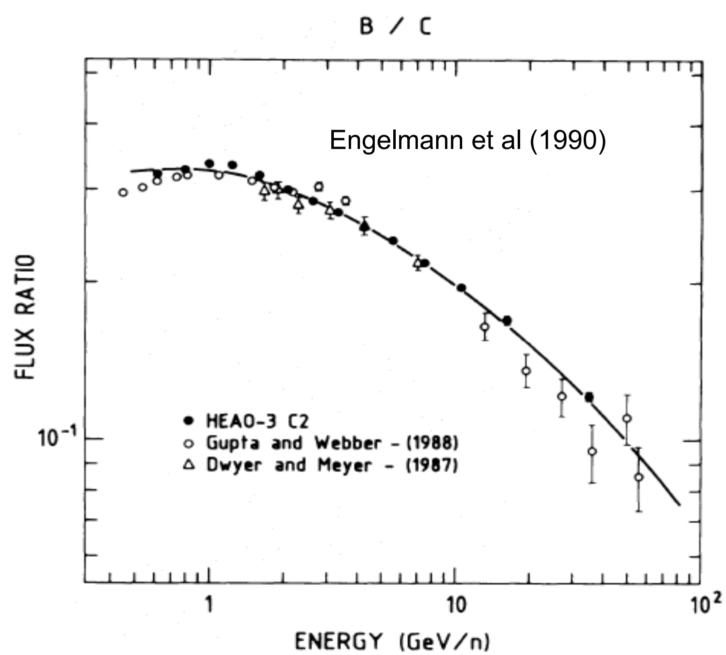


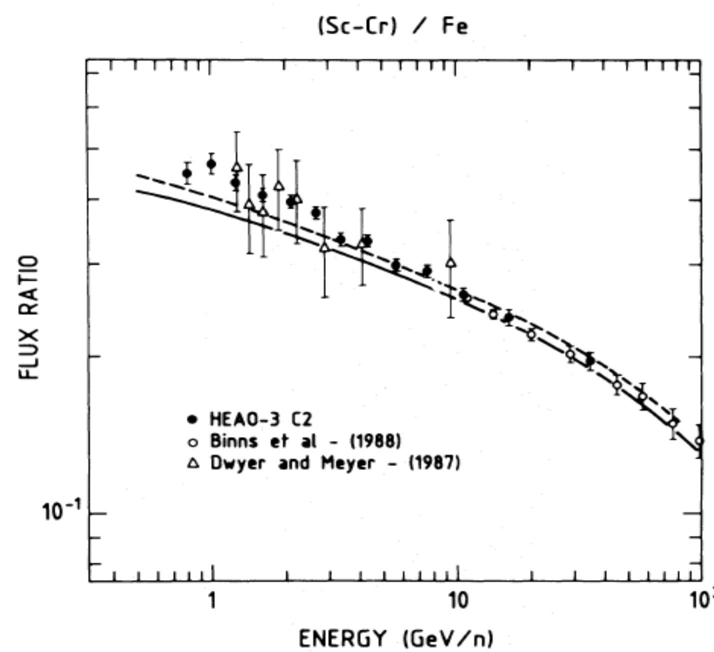


Stable secondaries with no energy loss (B, pbar, sub-Fe,…)

• **Empirical** relation: $$\frac{n_A}{n_B} = \frac{Q_A}{Q_B}$$

• $Q_A(\mathcal{R})$ = Local net production per unit column density of target, for species A





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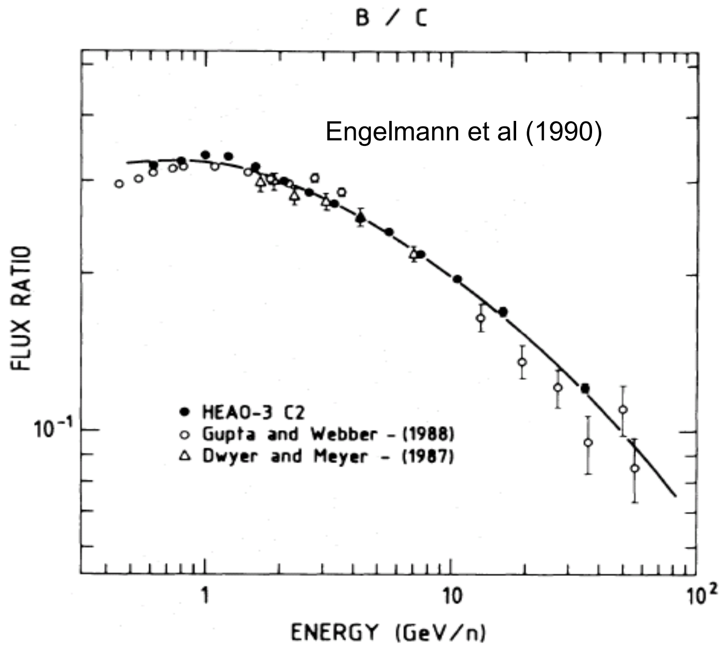
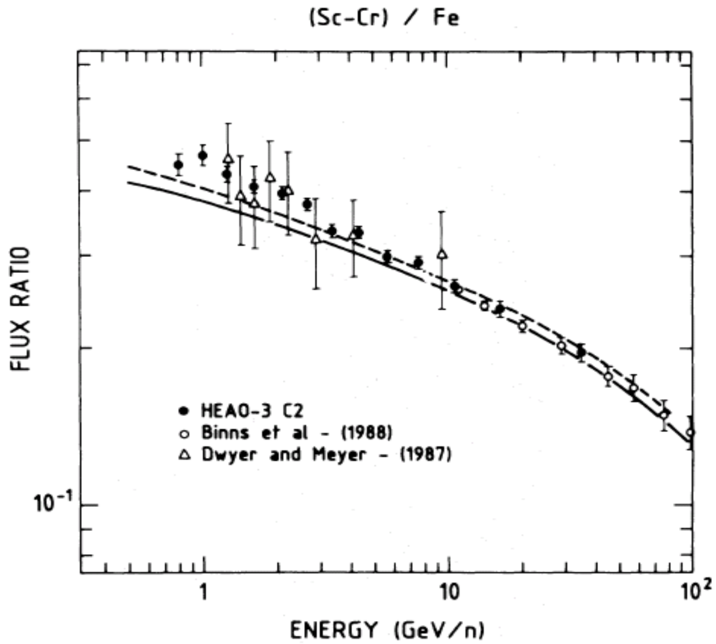
$$\frac{n_A(\mathcal{R})}{n_B(\mathcal{R})} = \frac{Q_A(\mathcal{R})}{Q_B(\mathcal{R})}$$ equivalent to: $$n_A(\mathcal{R}) = Q_A(\mathcal{R}) \times X_{\mathrm{esc}}(\mathcal{R})$$

- X_{esc} = “mean column density” ≈ $8.7(R/10GV)^{-0.4}$ g/cm^2. *No species label*





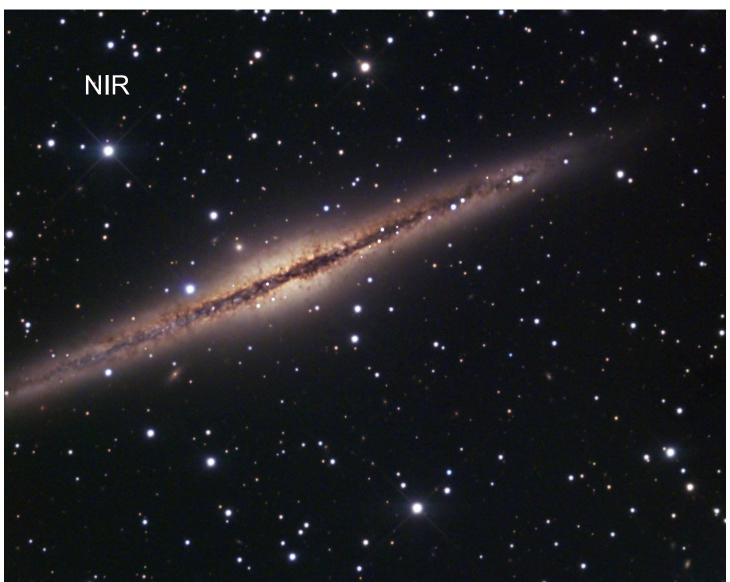
Stable secondaries with no energy loss (B, pbar, sub-Fe,…)

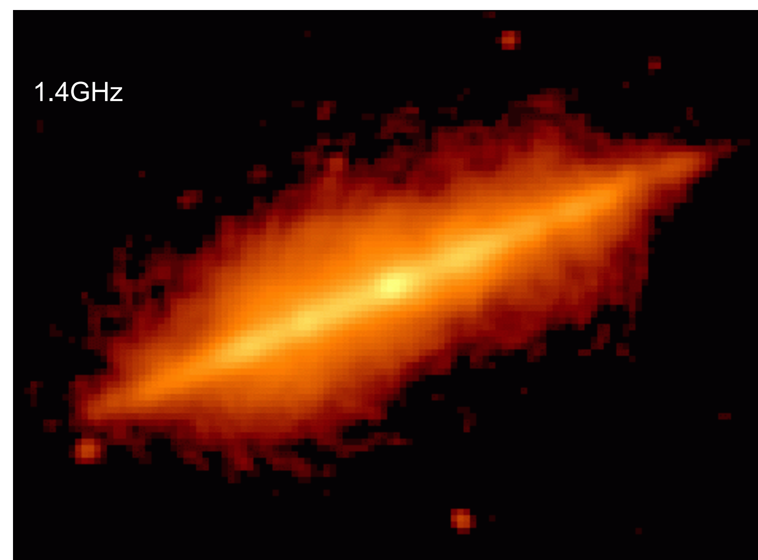
Theoretically, this is a natural relation.

Guaranteed to apply if the *composition* of CRs and ISM is uniform (well mixed) in the region of the Galaxy where spallation happens

$$\frac{n_A(\mathcal{R})}{n_B(\mathcal{R})} = \frac{Q_A(\mathcal{R})}{Q_B(\mathcal{R})} \quad \text{equivalent to:} \quad n_A(\mathcal{R}) = Q_A(\mathcal{R}) \times X_{\rm esc}(\mathcal{R})$$

NGC 891





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equivalent to:

$$n_A(\mathcal{R}) = Q_A(\mathcal{R}) \times X_{\rm esc}(\mathcal{R})$$

$$\nu \approx 0.29 \times \frac{3eB}{4\pi m_e c}\left(\frac{\epsilon}{m_e c^2}\right)^2 \approx 1\ \mathrm{GHz}\left(\frac{B}{1\ \mu\mathrm{G}}\right)\left(\frac{\epsilon}{15\ \mathrm{GeV}}\right)^2$$

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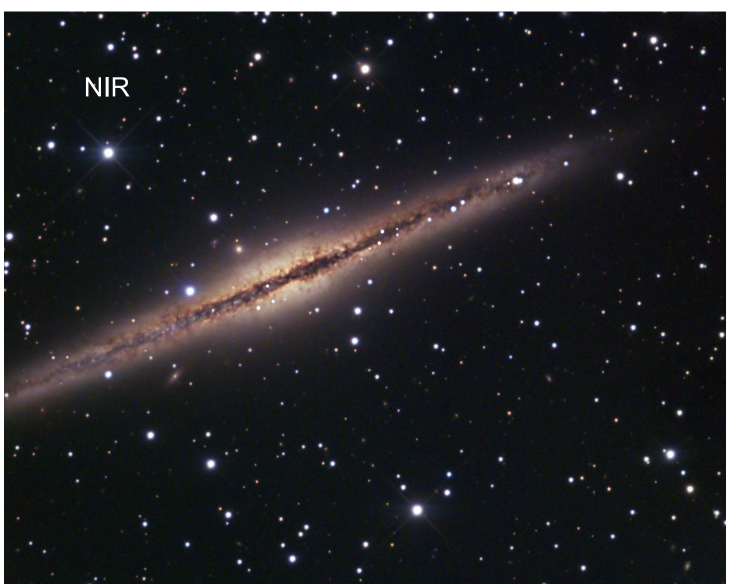

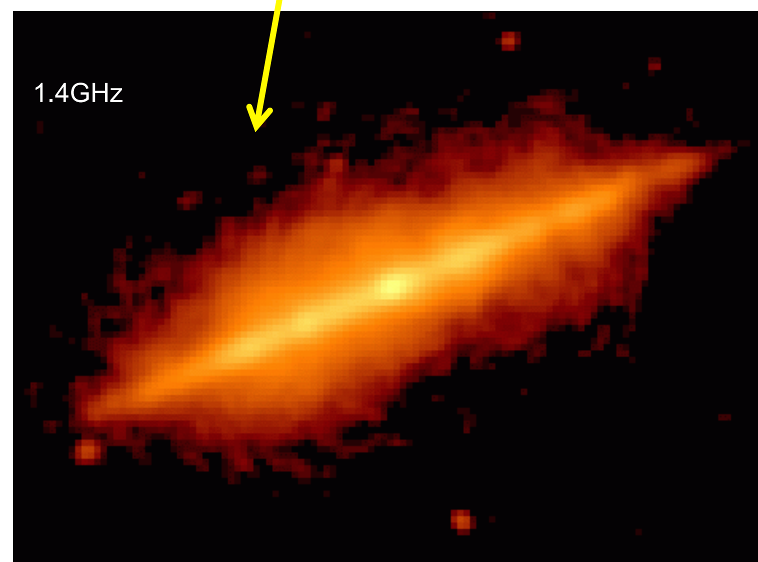

Net source per unit column density traversed: production – loss

$$Q_B(\mathcal{R}, \vec{r}, t) = \sum_{i=C,N,O,\ldots} \left(\frac{\sigma_{i\to B}}{\bar{m}}\right) n_i(\mathcal{R}, \vec{r}, t) - \left(\frac{\sigma_B}{\bar{m}}\right) n_B(\mathcal{R}, \vec{r}, t)$$

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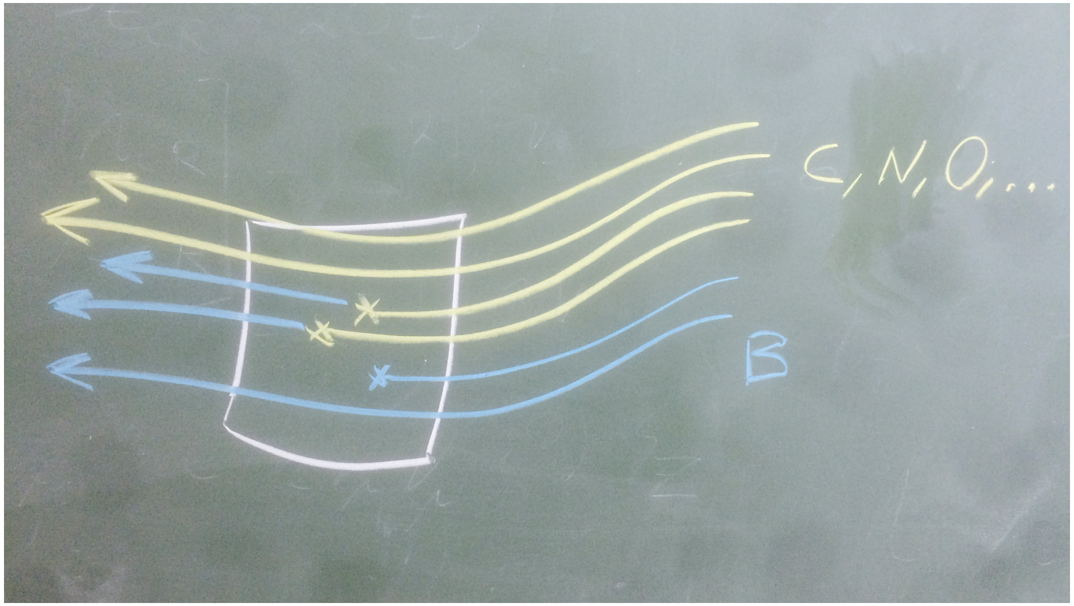

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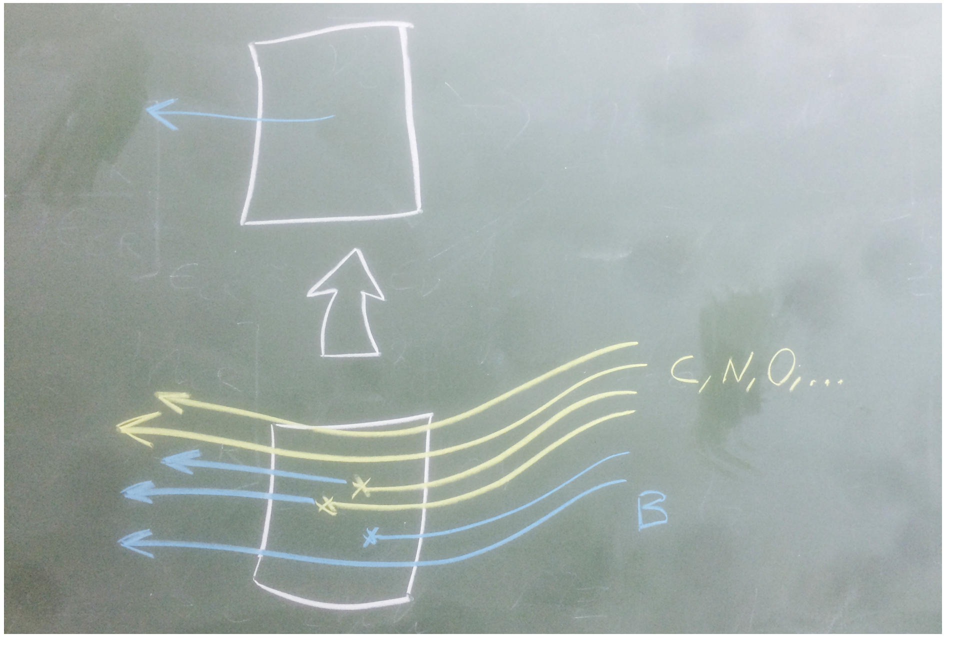

X_{esc}

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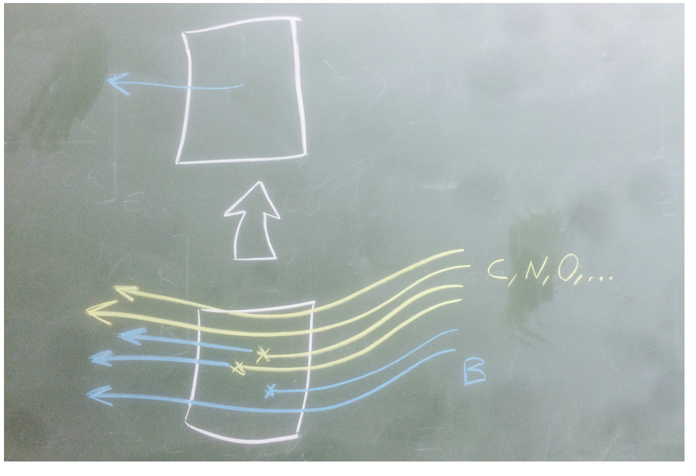
High-energy fragmentation CH → BX: B inherits Lorentz factor Γ of parent C

So B inherits magnetic rigidity, $R_B \approx R_C$

$$R = \frac{p}{Z} = \frac{\Gamma A m_p}{Z} \approx 2\Gamma m_p$$



X_{esc}

Net source per unit column density traversed: production – loss

$$Q_B(\mathcal{R},\vec{r},t) = \sum_{i=C,N,O,\ldots} \left(\frac{\sigma_{i\rightarrow B}}{\bar{m}}\right) n_i(\mathcal{R},\vec{r},t) - \left(\frac{\sigma_B}{\bar{m}}\right) n_B(\mathcal{R},\vec{r},t)$$

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$$R = \frac{p}{Z} = \frac{\Gamma A m_p}{Z} \approx 2\Gamma m_p$$

CNO→B: accurate to O(10%)…

A/Z ≈ 2.2 2 2 2

X_{esc}

Net source per unit column density traversed: production – loss

$$Q_B(\mathcal{R},\vec{r},t) = \sum_{i=C,N,O,\ldots} \left(\frac{\sigma_{i\to B}}{\bar{m}}\right) n_i(\mathcal{R},\vec{r},t) - \left(\frac{\sigma_B}{\bar{m}}\right) n_B(\mathcal{R},\vec{r},t)$$

In general:

$$n_B(\mathcal{R},\vec{r}_\odot,t_\odot) = \int d^3r \int dt\, c\, \rho_{ISM}(\vec{r},t)\, Q_B(\mathcal{R},\vec{r},t)\, P\left(\mathcal{R};\{\vec{r},t\},\{\vec{r}_\odot,t_\odot\}\right)$$

X_{esc}

Net source per unit column density traversed: production – loss

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$$F_B = \frac{\sum_{i=C,N,O,\ldots}\left(\frac{\sigma_{i\to B}}{\bar{m}}\right)\frac{n_i(\mathcal{R},\vec{r},t)}{n_C(\mathcal{R},\vec{r},t)} - \left(\frac{\sigma_B}{\bar{m}}\right)\frac{n_B(\mathcal{R},\vec{r},t)}{n_C(\mathcal{R},\vec{r},t)}}{\sum_{i=C,N,O,\ldots}\left(\frac{\sigma_{i\to B}}{\bar{m}}\right)\frac{n_i(\mathcal{R},\vec{r}_\odot,t_\odot)}{n_C(\mathcal{R},\vec{r}_\odot,t_\odot)} - \left(\frac{\sigma_B}{\bar{m}}\right)\frac{n_B(\mathcal{R},\vec{r}_\odot,t_\odot)}{n_C(\mathcal{R},\vec{r}_\odot,t_\odot)}}$$

X_{esc}

Net source per unit column density traversed: production – loss

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Uniform *composition:* $\quad \dfrac{n_i(\mathcal{R},\vec{r},t)}{n_j(\mathcal{R},\vec{r},t)} = f_{ij}(\mathcal{R})$ independent of r,t

$$\Rightarrow \quad F_B = \frac{\sum_{i=C,N,O,\ldots} \left(\frac{\sigma_{i\to B}}{\bar{m}}\right) \frac{n_i(\mathcal{R},\vec{r},t)}{n_C(\mathcal{R},\vec{r},t)} - \left(\frac{\sigma_B}{\bar{m}}\right) \frac{n_B(\mathcal{R},\vec{r},t)}{n_C(\mathcal{R},\vec{r},t)}}{\sum_{i=C,N,O,\ldots} \left(\frac{\sigma_{i\to B}}{\bar{m}}\right) \frac{n_i(\mathcal{R},\vec{r}_\odot,t_\odot)}{n_C(\mathcal{R},\vec{r}_\odot,t_\odot)} - \left(\frac{\sigma_B}{\bar{m}}\right) \frac{n_B(\mathcal{R},\vec{r}_\odot,t_\odot)}{n_C(\mathcal{R},\vec{r}_\odot,t_\odot)}} \approx 1$$

X_{esc}

Net source per unit column density traversed: production – loss

$$Q_B(\mathcal{R},\vec{r},t) = \sum_{i=C,N,O,\ldots} \left(\frac{\sigma_{i\to B}}{\bar{m}}\right) n_i(\mathcal{R},\vec{r},t) - \left(\frac{\sigma_B}{\bar{m}}\right) n_B(\mathcal{R},\vec{r},t)$$

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Uniform *composition* →

$$n_B(\mathcal{R},\vec{r}_\odot,t_\odot) \approx Q_B(\mathcal{R})\, X_{\rm esc}(\mathcal{R})$$

$$X_{\rm esc} = \int d^3r \int dt\, c\, \rho_{ISM}(\vec{r},t)\, \frac{n_C\left(\mathcal{R},\vec{r},t\right)}{n_C\left(\mathcal{R},\vec{r}_\odot,t_\odot\right)}\, P\left(\mathcal{R};\{\vec{r},t\},\{\vec{r}_\odot,t_\odot\}\right)$$

Stable secondaries with no energy loss

Comment about applicability of the analysis: **high energy (relativistic)**

Below R~10GV, various propagation effects can change energy of particle during trajectory; spallation cross sections are energy dependent; rigidity not transferred in fragmentation;…

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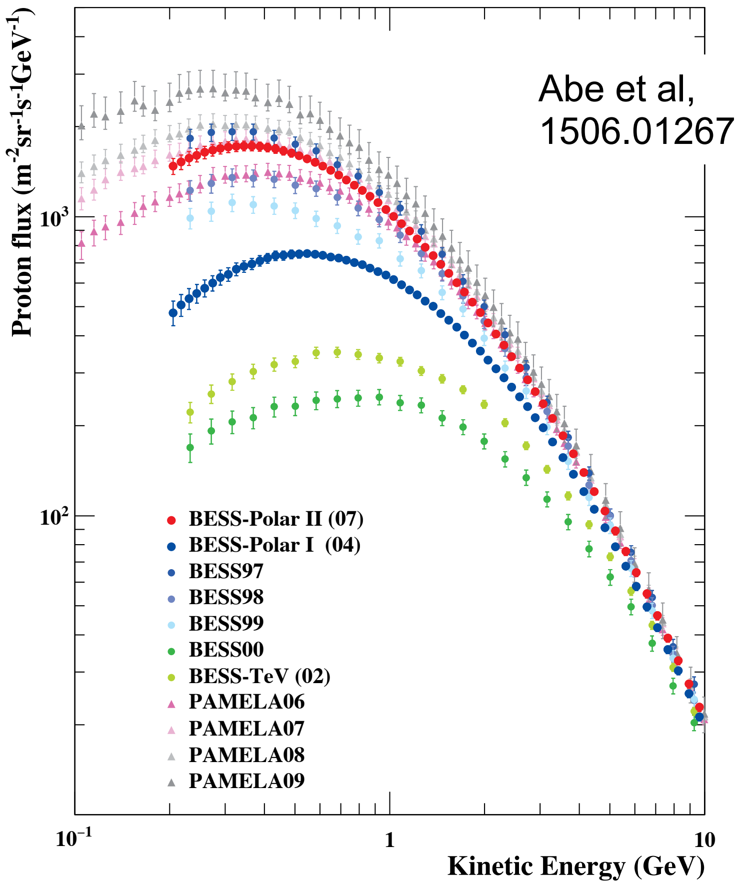
Example: solar modulation

We will keep our

analysis to R > 10GV



Stable secondaries with no energy loss

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Stable secondaries with no energy loss

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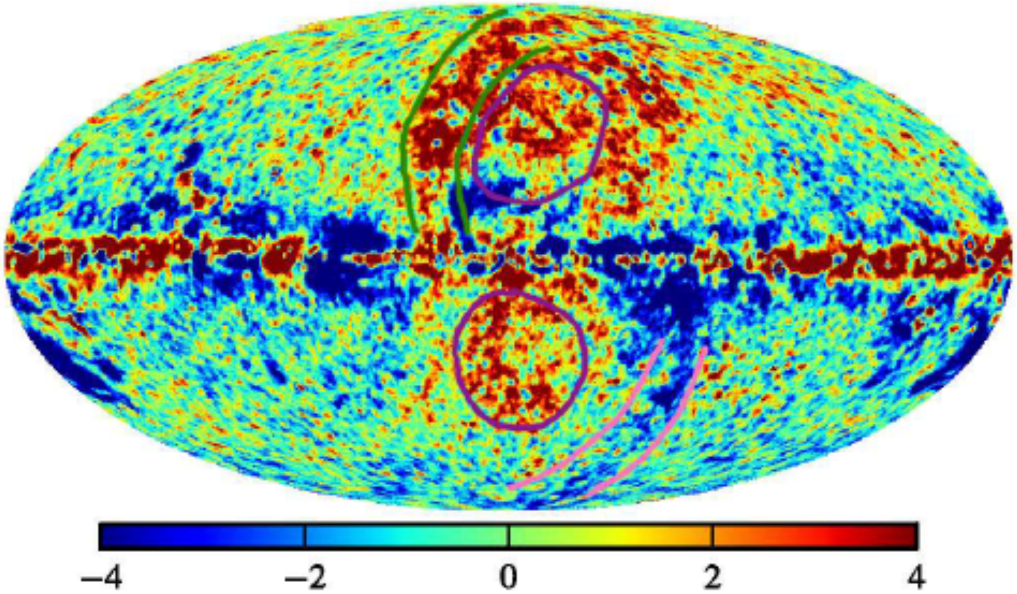
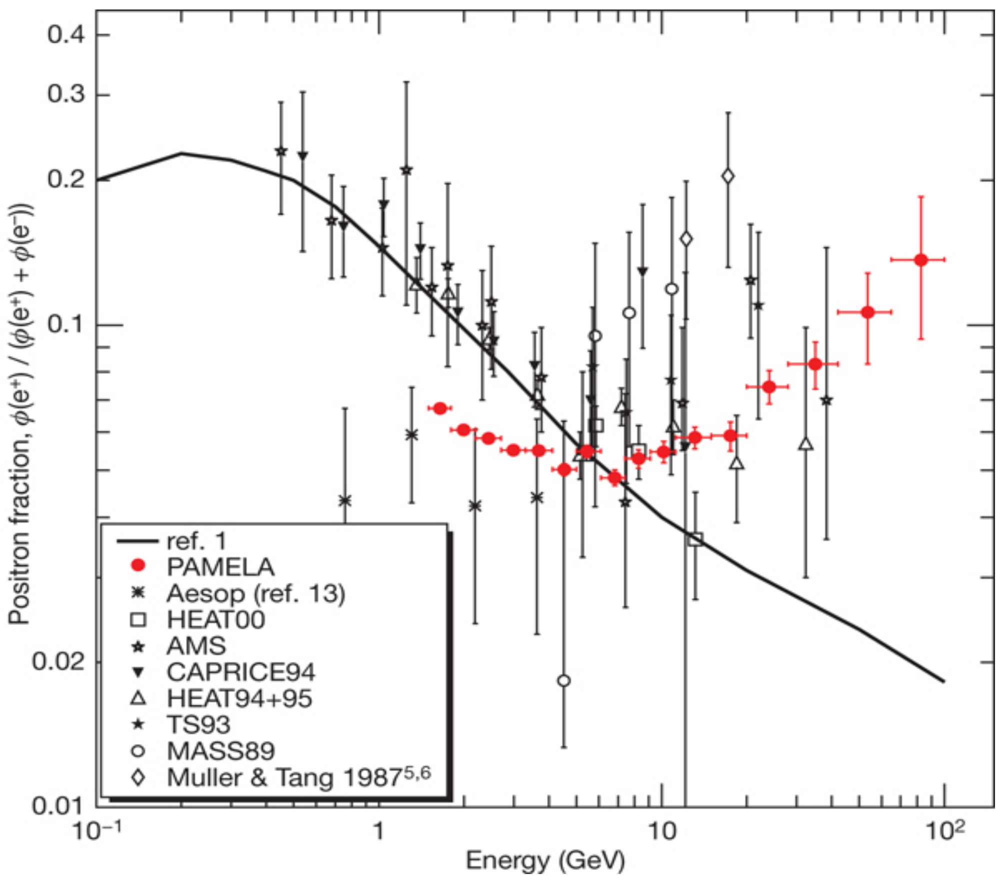
Do not need to assume homogeneous diffusion, boundary conditions, steady state,...



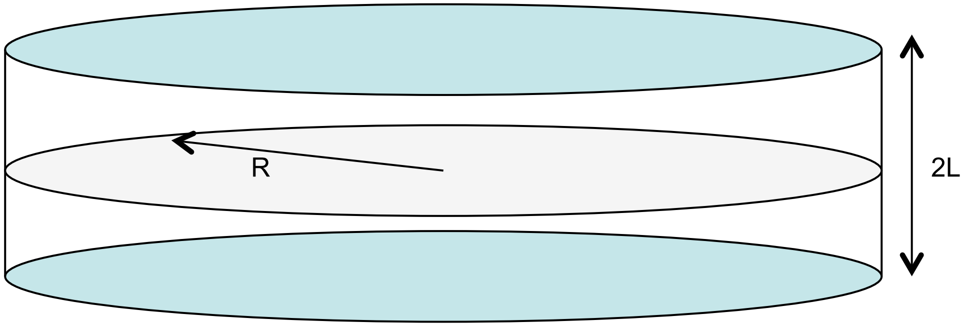
…and verifying this relation does not teach us that these assumptions are correct

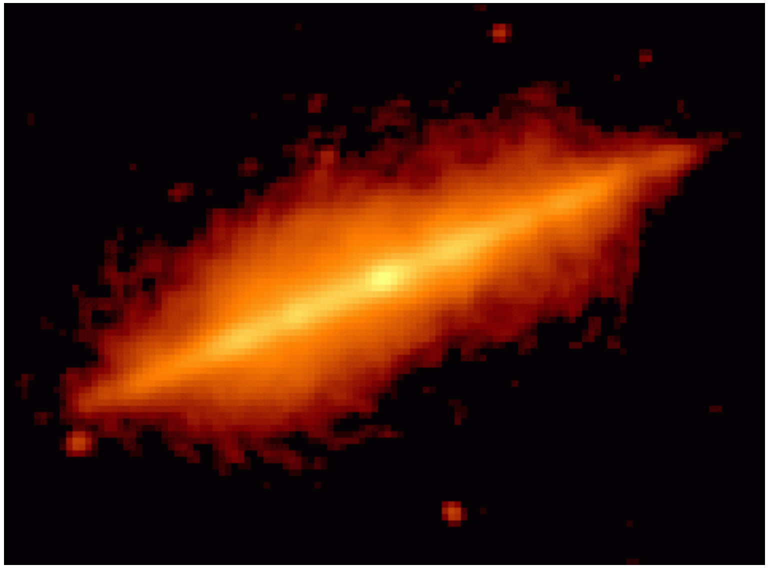
About diffusion models



About diffusion models

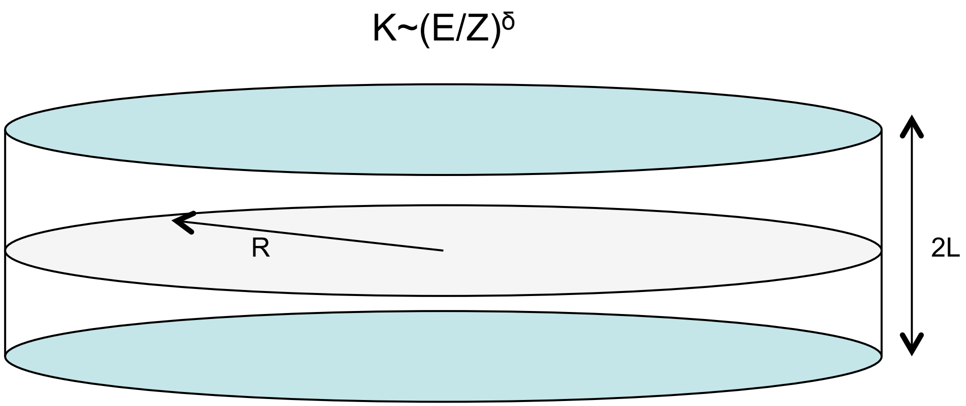
$K \sim (E/Z)^{\delta}$





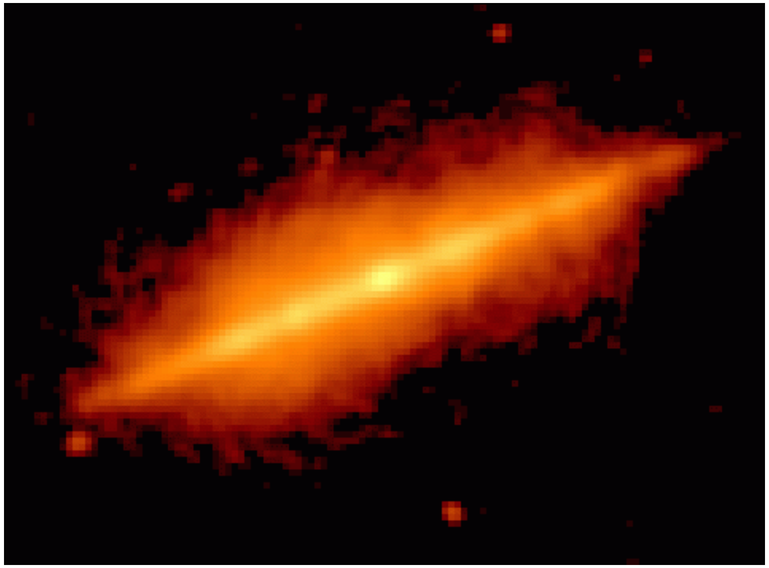
Strong, Moskalenko, Ptuskin, Ann.Rev.Nucl.Part.Sci. 57 (2007) 285-327

About diffusion models

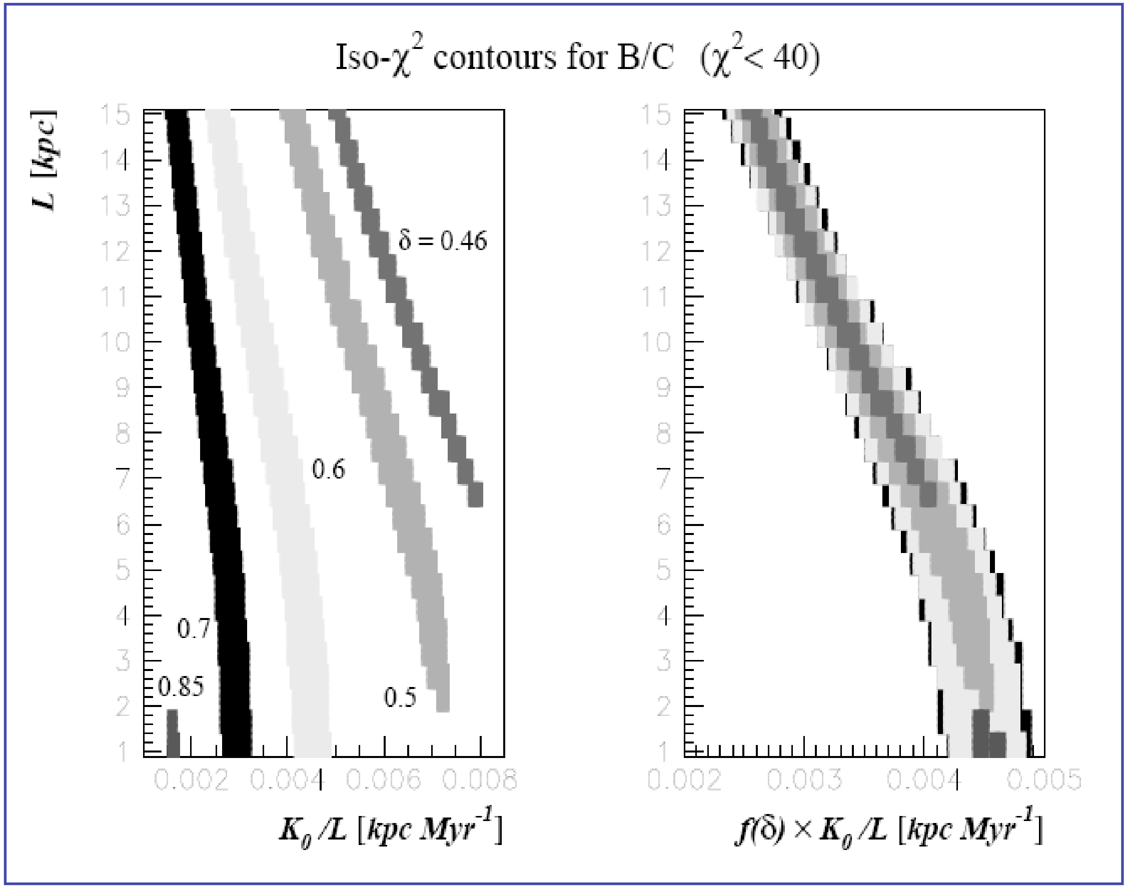


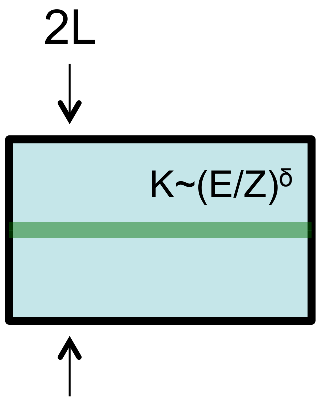
To a good approximation, disc+halo homogeneous diffusion models satisfy the criterion of uniform CR composition *where spallation happens*.

Should satisfy $$\frac{n_A}{n_B} = \frac{Q_A}{Q_B}$$

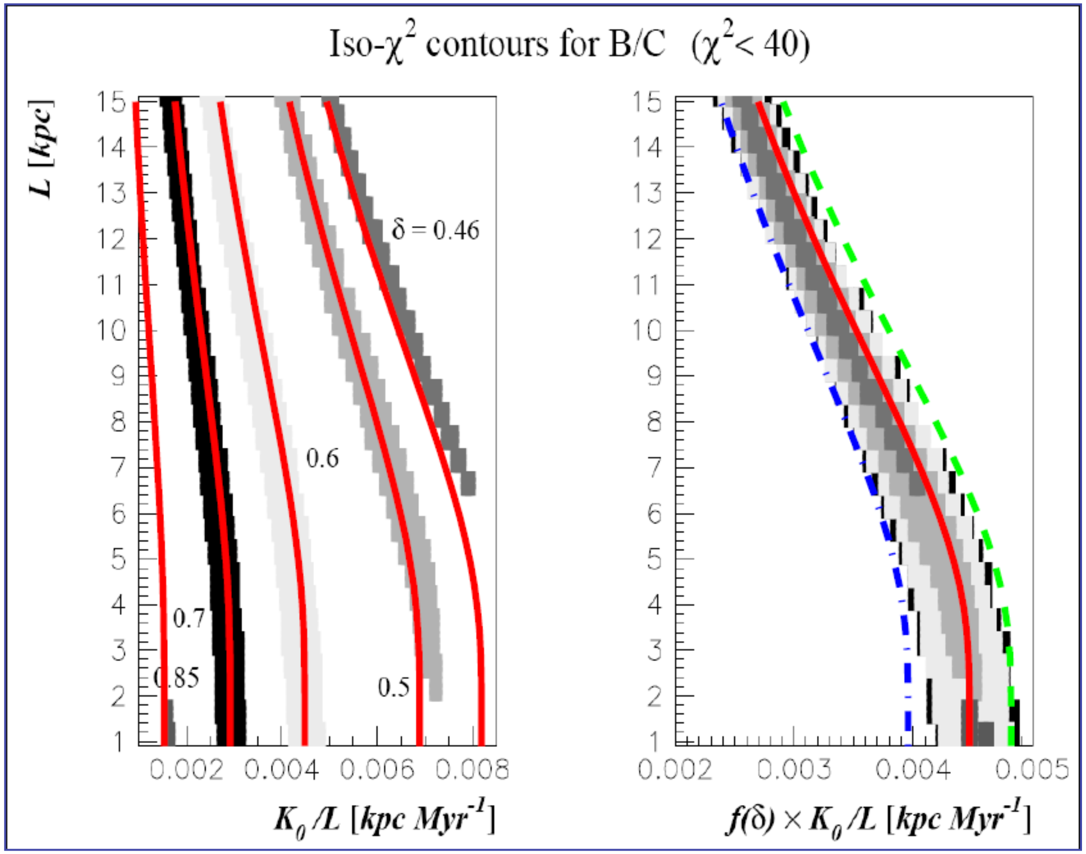


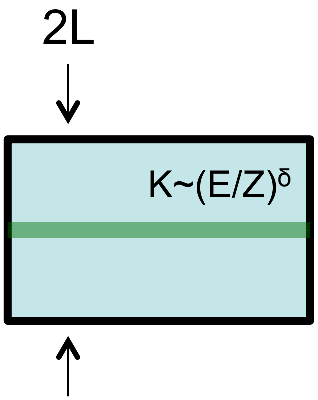
diffusion models fit X_{esc}





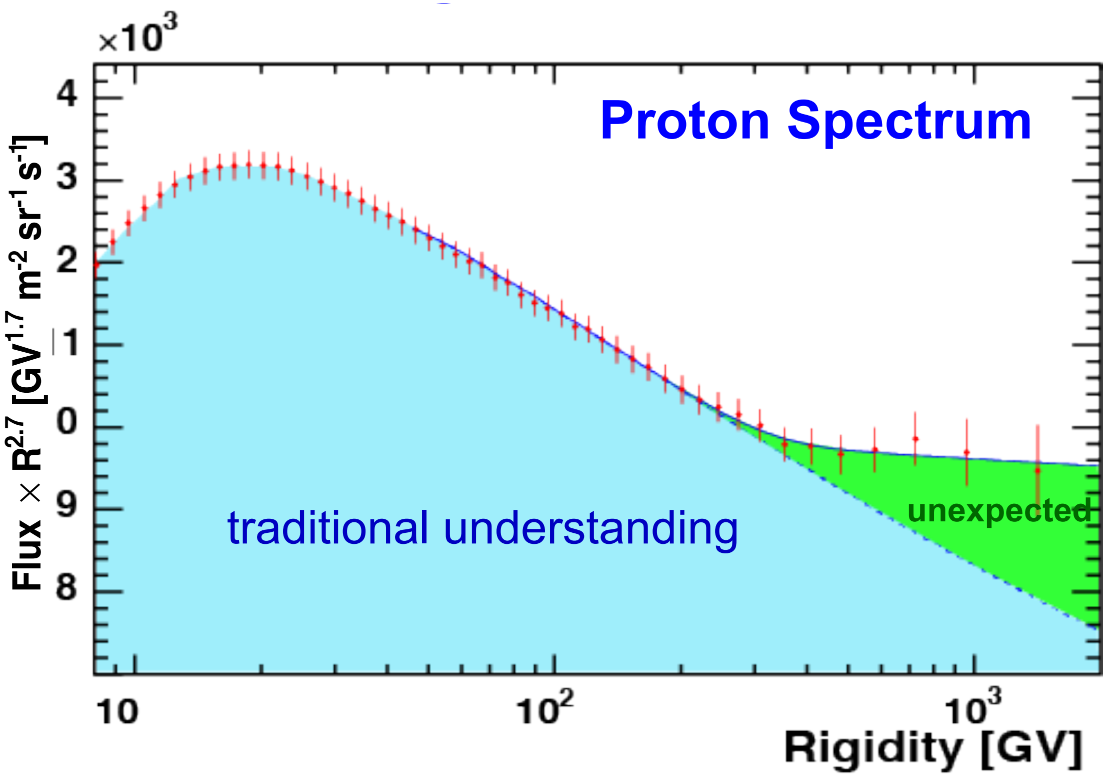
Maurin et al, **Astrophys.J.555:585-596,2001** diffusion models fit X_{esc}





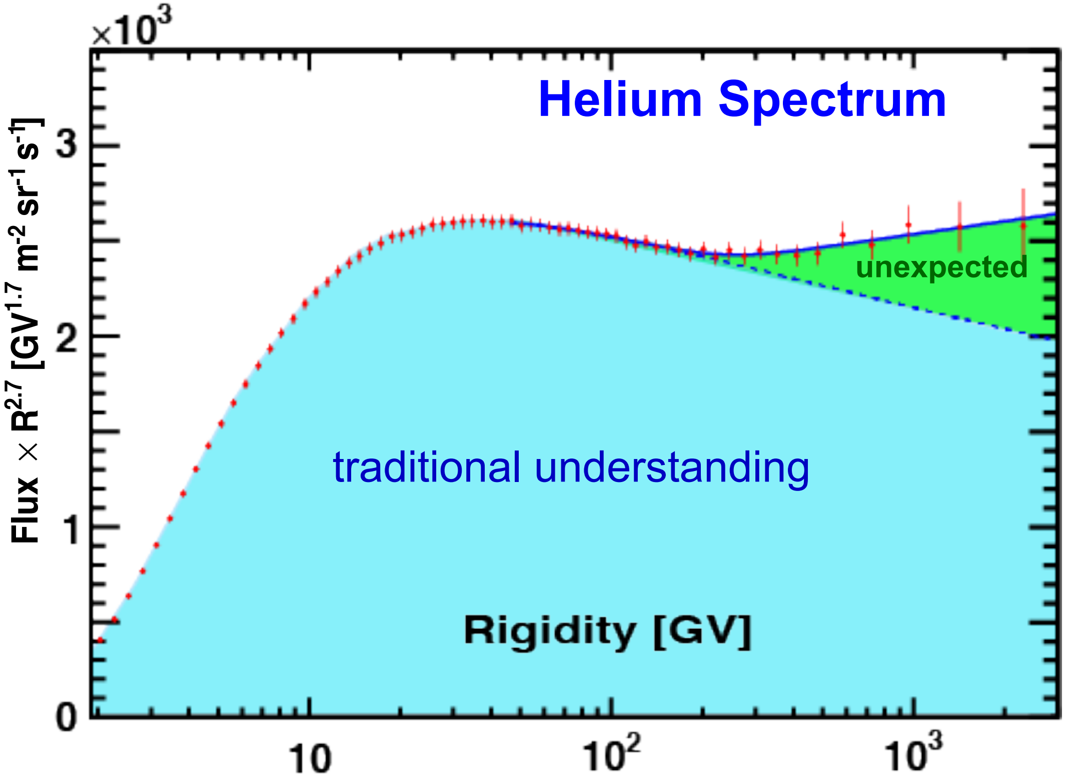
$$X_{\mathrm{esc}} = X_{\mathrm{disc}} \frac{Lc}{2D} \frac{2R}{L} \sum_{k=1}^{\infty} J_0 \left[\nu_k (r_s/R)\right] \frac{\tanh\left[\nu_k (L/R)\right]}{\nu_k^2 J_1(\nu_k)}$$

About diffusion models



S. Schael, Moriond 2016 for AMS02

About diffusion models



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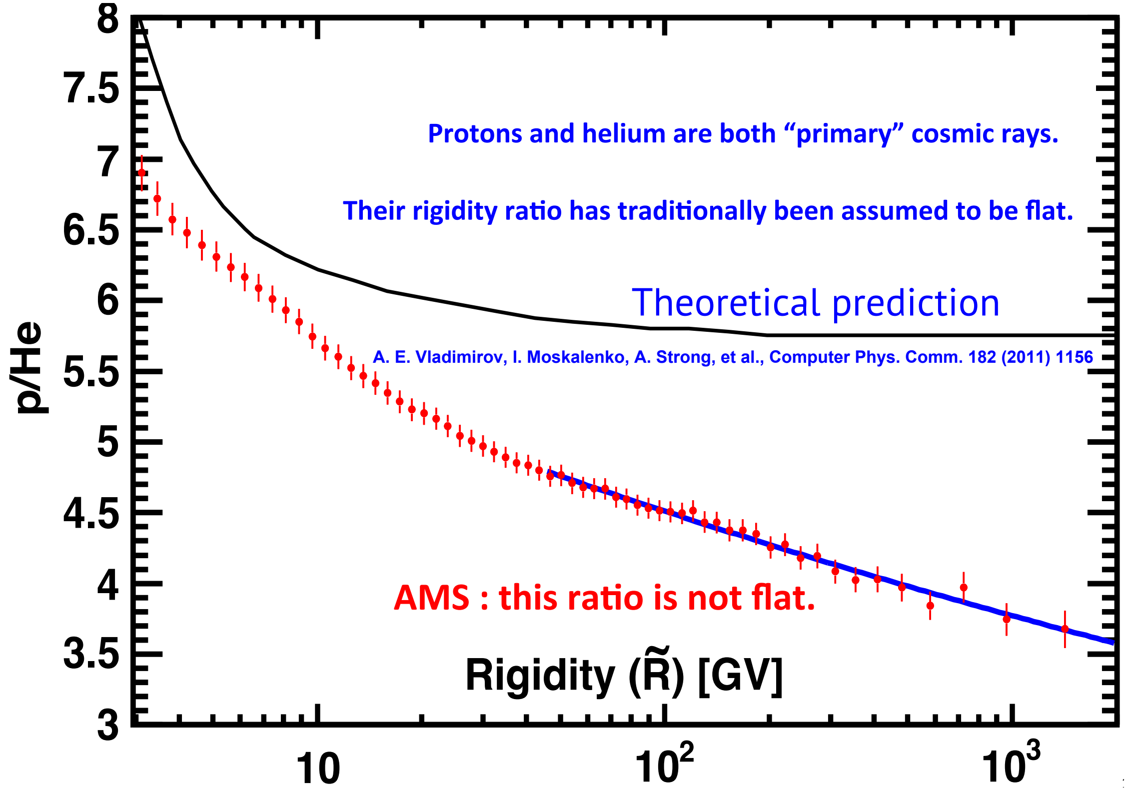

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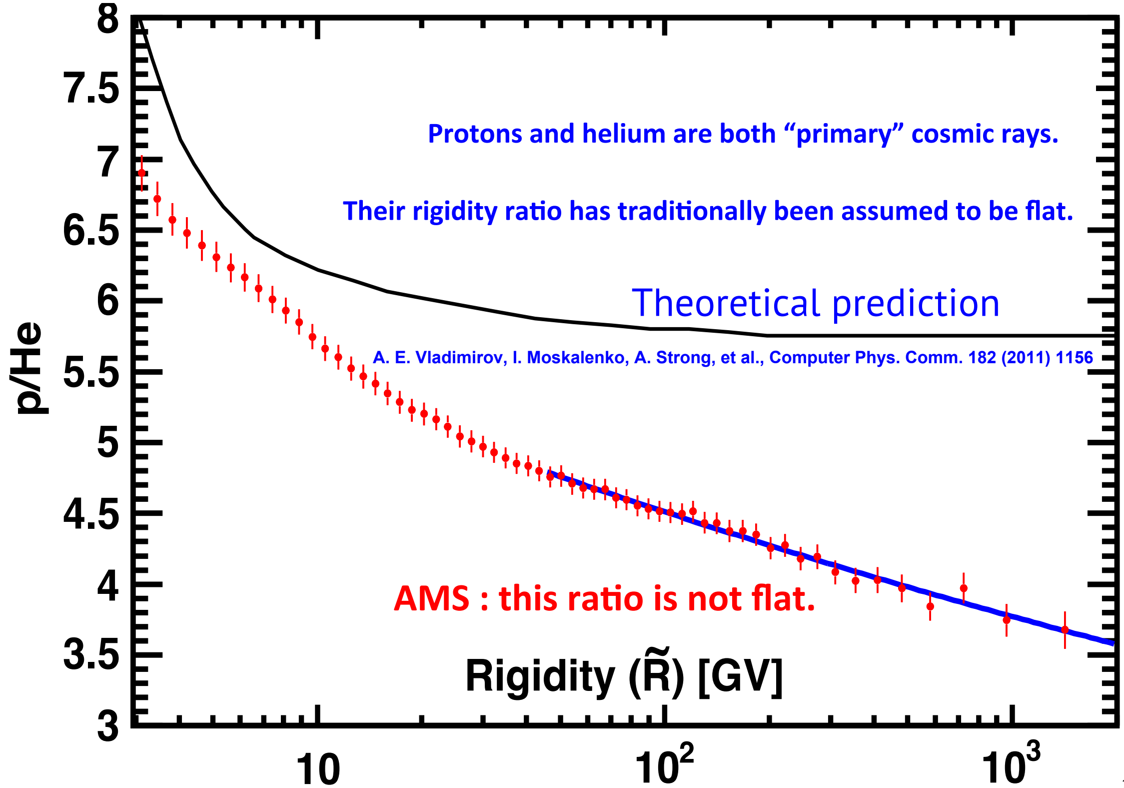
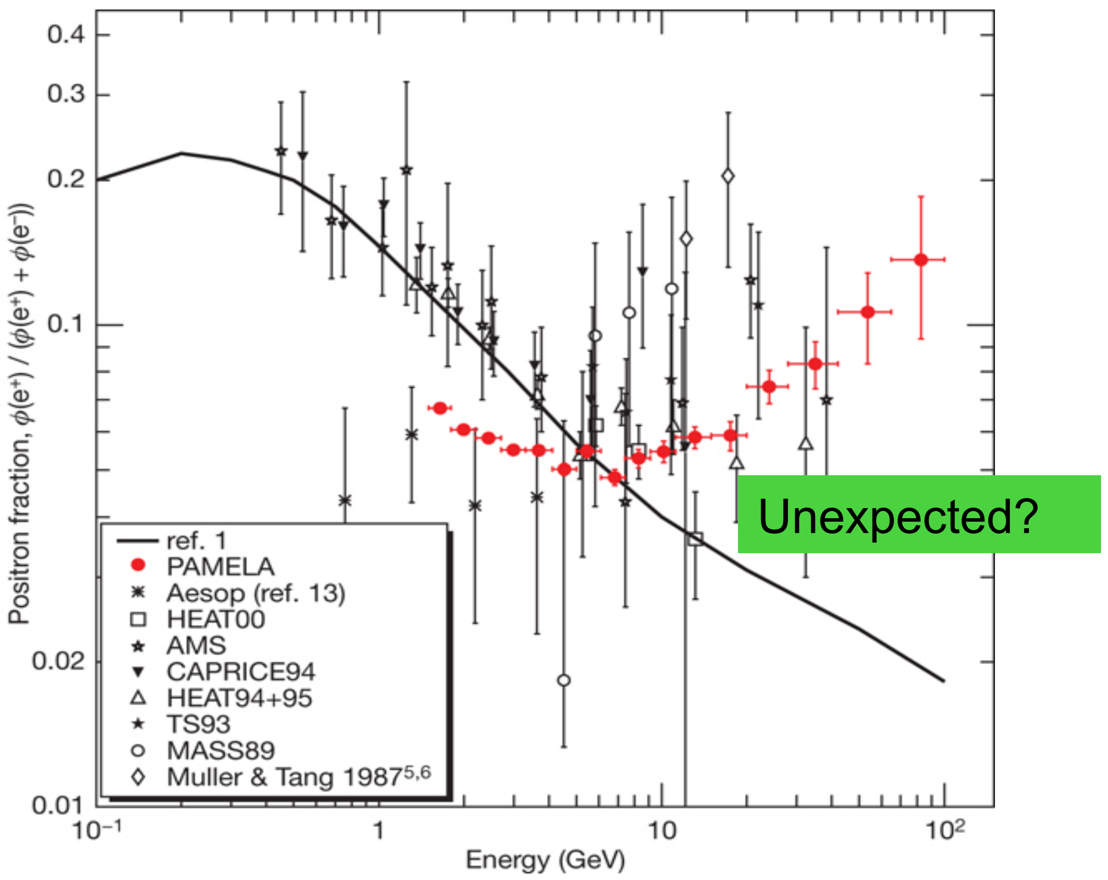


To be clear:
p & He are *primary* CRs: the heart of the beast.

About diffusion models



Ginzburg & Ptuskin, Rev.Mod.Phys. 48 (**1976**) 161-189

On the origin of cosmic rays: Some problems in high-energy astrophysics*

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This paper reviews the present state of the problem of the origin of cosmic rays . Primary attention is paid to galactic diffusion models with a halo, and questions of cosmic-ray chemical composition, electron component, and synchrotron galactic radioemission. The authors' conclusion is that models with a large halo with a characteristic cosmic-ray age $T_{cr} \sim 10^8$ years are confirmed by radio data, and at least do not contradict the information on cosmic-ray chemical composition. The paper also deals with the problems of anisotropy, plasma phenomena in cosmic rays, and the prospects of gamma-ray astronomy.

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C. Fundamental equations describing cosmic-ray propagation in the Galaxy

A high isotropy and a rather large content of secondary nuclei in cosmic rays indicate an effective "mixing" and a long wandering of high-energy particles in the Galaxy. Such a mixing and isotropization can be ascribed to several different causes: a stochastic structure of the galactic magnetic field and its large-scale inhomogeneities (Fermi, 1949; GS §10); an instability of anisotropic distributions of relativistic particles in the interstellar plasma (Ginzburg, 1965; Wentzel, 1974); macro-instability of the system formed by the relativistic gas of cosmic rays, the interstellar magnetic field, the interstellar plasma, and the gravitational field (Parker, 1969); or a strong particle reflection on the Galaxy boundaries. Unfortunately, complete analysis of all the known possibilities and a choice of a concrete physical

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mechanism responsible for cosmic-ray propagation in the Galaxy have not been worked out. This is mainly owing to the absence of complete enough information on the interstellar medium parameters and on the galactic magnetic field structure. It is natural that various approximate models are widely used in a situation where there is no consistent theory which could explain the character of cosmic-ray propagation proceeding from a strict picture of charged relativistic particle interaction with the interstellar plasma. These approximate methods make it possible to systematize and coordinate numerous experimental facts, and to explain characteristic features of the composition, spectra, and anisotropy of different cosmic-ray components. Since within

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Cosmic-ray propagation is most often considered within the diffusion approximation. Moreover (this assumption is in some sense independent), we shall think of cosmic rays as locally isotropic, which means that anisotropy may appear only when account is taken of the spatial inhomogeneity of particle concentration $N_i(\vec{r}, t, E)$.

We should note here that the applicability of the diffusion approximations (2.8)–(2.9) to cosmic-ray propagation in the magnetic fields is not at all obvious. For this approximation to be valid it is not enough that the field have a strongly pronounced irregular random component since in this case there also exists a strong tendency for particle propagation along the lines of force of the magnetic field, even if they are rather tangled. But in the

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Galaxy, for example, differential rotation and the motion of gas clouds and spiral arms cause a constant mixing of the lines of force. At the same time we are usually interested not only in a picture averaged over rather large space regions (say, regions of tens and hundreds of parsecs) but also in a picture which is extended in time. To estimate average cosmic-ray gradients and their lifetime T_{cr} in the Galaxy it is in fact sufficient to know the concentration N_i averaged for the time $t \ll T_{cr} \sim 10^6 - 10^8$ yr, which means that the time of averaging may well be 10^5 yr.

Here we will keep to first principle, approximate, calculations, based on particle physics.

We do not offer cosmic ray propagation models,

but we *can* formulate basic limits (and sometimes accurate predictions).

antiprotons

$$\frac{n_{\bar{p}}}{n_{\text{Boron}}} = \frac{Q_{\bar{p}}}{Q_{\text{Boron}}}$$