Phenomenology and theory of Galactic cosmic-ray propagation

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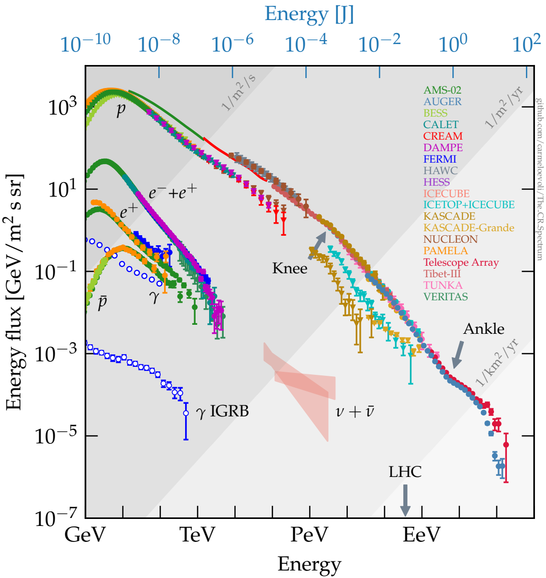
September 19, 2022

The cosmic-ray spectrum in 2022

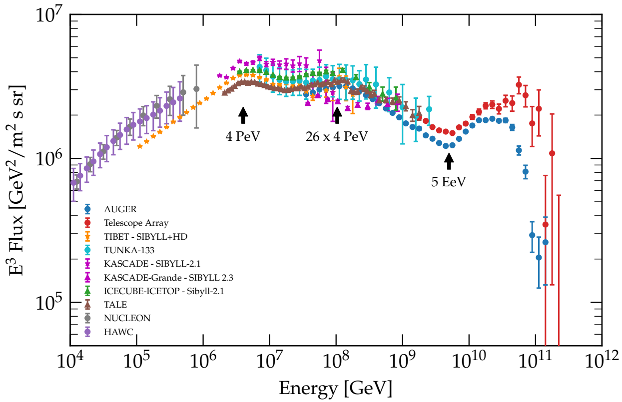


The cosmic-ray spectrum in 2022

- CRs are a non-thermal population of relativistic particles that pervade the solar system, galaxies, clusters and intergalactic space
- Almost a perfect power law over more than 11 energy decades!
- At low energy $dN/dE \propto E^{-2.7} \to E^2 dN/dE \propto E^{-0.7}$
  $\longrightarrow$ most of the energy is in $\sim$ GeV CR protons
- energy density near Earth $\sim 2 \times 10^{-12}$ erg cm^{-3} $\sim$ eV cm^{-3}
  $\longrightarrow$ close to equipartition, important agent for ISM ionization, driving Galactic outflows, ...
- Evidence of departures from a perfect power law: most spectacular are the knee and the ankle
- Spectrum cut-off at $\gtrsim 10^{20}$ eV $\longrightarrow$ GZK or cosmic-ray sources out of steam?
- Particles observed at energy higher than any terrestrial laboratory $\sqrt{s_{\rm LHC}} \sim 2 \times 10^{17}$ eV
- Composition at 10 GeV: ~ 99.2% are nuclei, ~ 0.7% are electrons, ~ 0.1% are anti-matter particles (positrons and antiprotons)

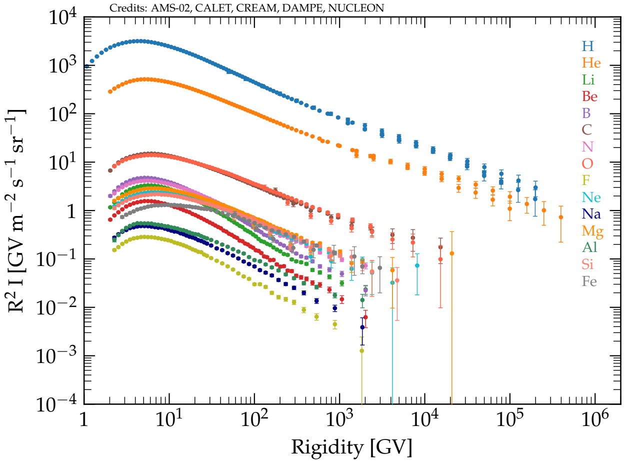
The end of the Galactic spectrum

Aloisio+, JCAP 2014; Globus+, PRD 2015; Thoudam+, A&A 2016; Evoli & Boncioli, in prep.



- If (first) knee is made by H $\longrightarrow$ Galactic CRs end with heavy elements at ~ 100 PeV (second) knee
- Maximum energy of Galactic accelerators OR a change in the transport regime (diffusive $\longrightarrow$ ballistic)?
- The Larmor radius of these particles in the Galactic B-field $r_L = \frac{p}{ZeB} \sim 100\,\text{pc} \left(\frac{E}{\text{PeV}}\right)\left(\frac{\mu\text{G}}{ZB}\right)$
- Direct measurements at ~PeV will be crucial to our understanding

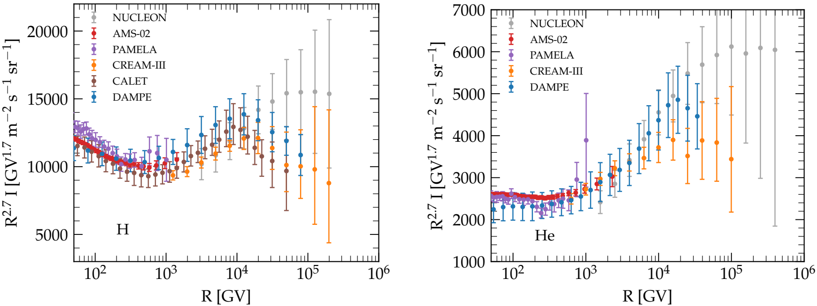
Galactic Cosmic Rays: unprecedented measurements



- The spectrum of each isotope includes contributions from many different parents (both in terms of fragmentation and decays) giving to each observed isotope a potentially very complex history

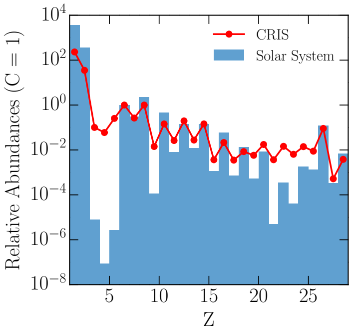
Galactic Cosmic Rays: a decade of surprises!

PAMELA Coll., Science 2011; AMS-02 Coll., PRL 2015; CREAM Coll., ApJ 2017; NUCLEON Coll., JETP 2018; DAMPE Coll., Science 2019



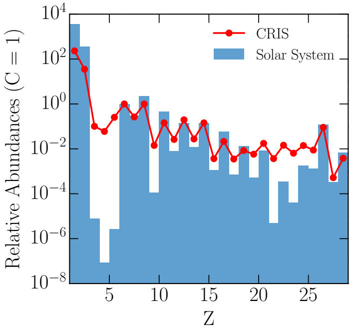
- ▷ Spectra of protons and helium are not a single power law below the knee $\longrightarrow$ some physics kicking in?
- ▷ The hardening at $R = p/Z \sim 300 - 400$ GV is well established since first observation by PAMELA
- ▷ AMS-02 confirmed the same break for almost all nuclei
- ▷ The softening at $R = p/Z \sim 10$ TV is observed by different experiments, first strong evidence in DAMPE
- ▷ The He spectrum (at Earth!) is slightly harder than that of protons

The cosmic-ray composition at $E \sim$ GeV



- Thermal particles in the average interstellar medium are somehow accelerated to relativistic energies becoming CRs $\longrightarrow$ primary CRs
- It must exist also a second population which is produced during propagation by primary spallation $\longrightarrow$ secondary CRs

The cosmic-ray composition at $E \sim$ GeV



- The average galactic grammage $\chi_{\rm gal}$ can be directly inferred from this plot:

$$\frac{\rm B}{\rm C} \sim \chi_{\rm gal} \frac{\sigma_{C \to B}}{\langle m \rangle_{\rm ISM}} \sim 0.3 \to \chi_{\rm gal} \sim 5 \ {\rm g\,cm}^{-2}$$

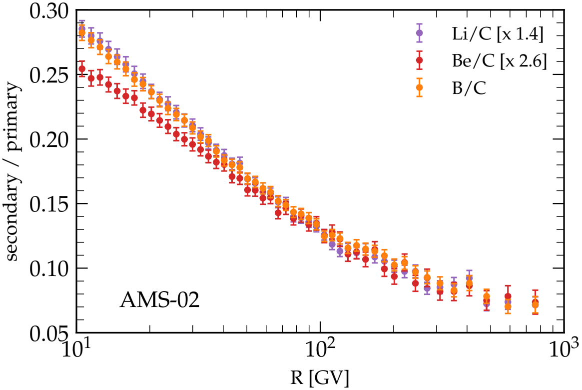
- To be compared with the grammage X_d accumulated at each crossing of the gas disk $h \sim 100$ pc:

$$X_d \sim m_p n_{\rm gas} h \sim 10^{-3}\,{\rm g\,cm}^{-2} \ll X_{\rm gal}$$

- Robust evidence of diffusive transport!

Measurements of the B-Li-Be in CRs up to $\sim$ TeV

AMS-02 Coll., PRL 120, 021101 (2018)

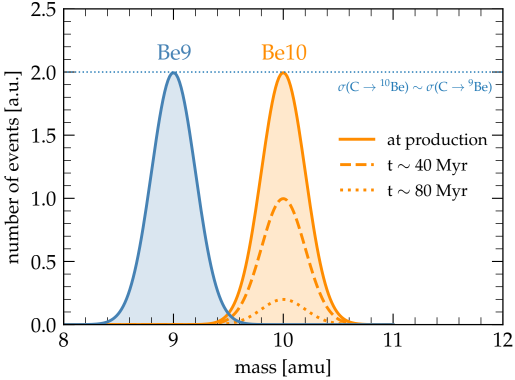


Key points

Evidence of rigidity dependent grammage $\longrightarrow$ high-energy particles spend less time in our Galaxy than low-energy ones

Cosmic-ray lifetime

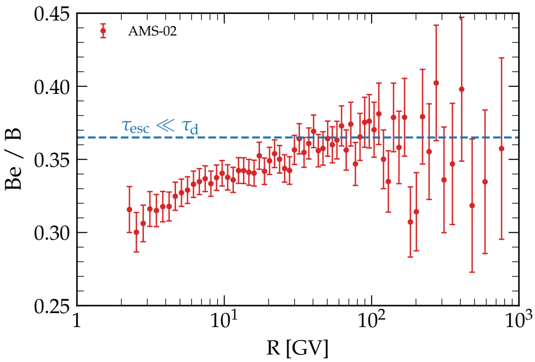
Garcia-Munoz et al., ApJ (1977); PAMELA Collaboration, ApJ, Vol. 862, 141 (2018)



- ^{10}Be is a β^- unstable isotope decaying in ^{10}B with an half-life of ~ 1.5 Myr
- Similar production rates than other (stable) isotopes $\sigma_{\rm Be9} \sim \sigma_{\rm Be10}$
- Traditionally the ratio ^{9}Be/^{10}Be has been used as CR clock $\to$ however no measurements of this ratio at $E \gtrsim 1$ GeV/n

Cosmic-ray lifetime

AMS-02 Coll., PRL 120, 021101 (2018); Evoli et al., PRD 101, 023013 (2020); Weinrich+, A&A 639, A74 (2020)

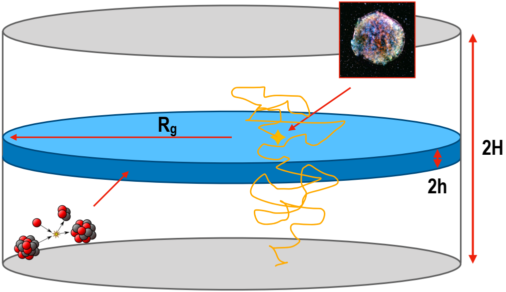


- Since ^{10}Be decays to ^{10}B the ratio **Be/B** is affected twice (excellent recent AMS-02 data!)
- The observed ratio hints to a **CR lifetime** ($\equiv$ from production to escape) of

$$t_{\rm esc} \sim \mathcal{O}(100)\,\text{Myr} \gg \frac{R_{\rm G}}{c}$$

The Galactic halo model

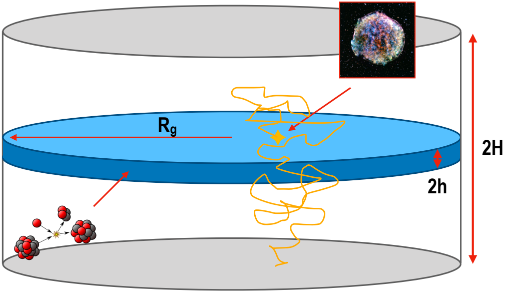
Morrison, Olbert and Rossi, Phys. Rev (1954); Ginzburg and Syrovatskii (1964)



- Galactic CRs are accelerated in the disc h by SNRs and hence are injected with a spectrum $Q_s \propto p^{-\alpha}$ where $\alpha \gtrsim 4$
- after injection, CRs propagate diffusively throughout the Galactic halo ($\sim 1D$) with a diffusion coefficient $D \propto p^{\delta}$ where $\delta \sim 1/3 - 1/2$
- Secondary production, e.g. LiBeB, takes place predominantly in the disc h where all the gas is confined.
- H is the diffusive halo size (free escape boundary) and R_d is the radius of the Galactic disc.
- Simplifying assumptions: symmetry, homogeneity, isotropy, stationarity, linearity, ...

The Galactic halo model

Morrison, Olbert and Rossi, Phys. Rev (1954); Ginzburg and Syrovatskii (1964)



- Based on a great legacy of the past.
- Few main assumptions!
- Key points: The model had cracked under the blows of accurate measurements!

Galactic halo model predictions

- The intensity of a primary nucleus, e.g. Carbon:

$$I_{\rm C}(R) = \overset{\text{injection}}{Q_{\rm C} \left(\frac{R}{R_0}\right)^{-\alpha}} \overset{\text{transport}}{\frac{X(R)}{1 + \frac{X(R)}{\hat{X}_{\rm C}}}}$$

- Where X is the grammage traversed by nuclei:

$$X(R) = n_d \left(\frac{h}{H}\right) m_p v \frac{H^2}{D(R)} = \bar{n} m_p v \tau_{\rm esc}(R) \propto R^{-\delta}$$

- and the critical grammage (energy independent) is:

$$\hat{X}_{\rm C} = \frac{m_p}{\sigma_{\rm C}}$$

- Relevant limits:

diffusion dominated: for $X \ll \hat{X}$ the equilibrium spectrum is $I_{\rm C} \propto R^{-\gamma-\delta}$

spallation dominated: for $X \gg \hat{X}$ the equilibrium spectrum is $I_{\rm C} \propto R^{-\gamma}$

Galactic halo model predictions

- For a pure secondary species, e.g. Boron:

$$I_{\rm B}(R) = \overset{\text{injection}}{I_{\rm C}(R)} \frac{\chi(R)}{\hat{\chi}_{\rm C\to B}} \overset{\text{transport}}{\left(1 + \frac{\chi(R)}{\hat{\chi}_{\rm B}}\right)^{-1}}$$

- which reflects in the following B/C ratio:

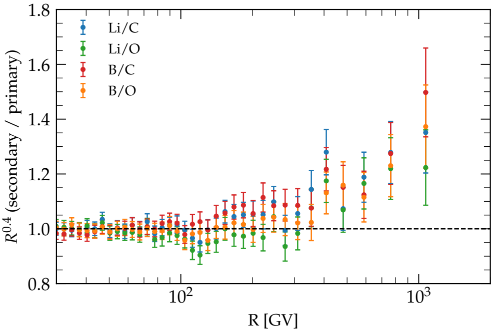
$$\frac{\rm B}{\rm C} = \frac{\frac{\chi(T)}{\hat{\chi}_{\rm C\to B}}}{1 + \frac{\chi(T)}{\hat{\chi}_{\rm B}}}$$

- Relevant limits:

diffusion dominated: for $\chi \ll \hat{\chi}$ the ratio is B/C $\propto \chi(R) \propto 1/D(R)$

spallation dominated: for $\chi \gg \hat{\chi}$ the ratio is B/C $\sim$ constant

Galactic halo model predictions



▷ Stable secondary over primary ratio:

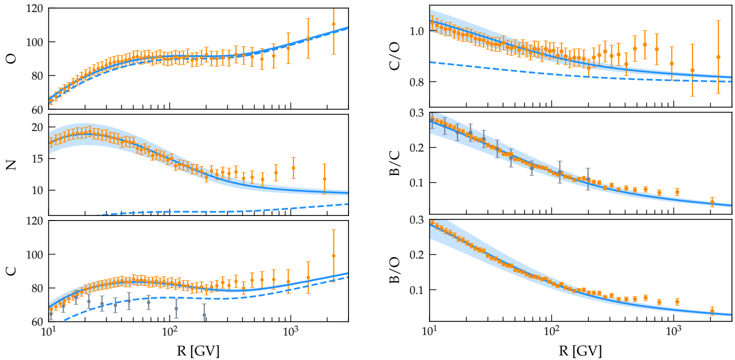
$$\frac{I_s(T)}{I_p(T)} \propto \chi(T) \propto \frac{H}{D(T)} \quad \leftarrow \text{degeneracy!}$$

▷ Unstable secondary over stable secondary ratio:

$$\frac{I_s^*(T)}{I_s(T)} \propto \frac{\sqrt{D(T)}}{H^2} \quad \leftarrow \text{break the degeneracy!}$$

CR phenomenology: secondary-over-primary ratios

Evoli et al., PRD 99 (2019); Weinrich et al., A&A 639 (2020)



- Driven by theoretical arguments, we model $D(R)$ as a smoothly-broken power-law [Evoli et al., PRL 2018]:

$$D(R) = \boxed{2 v_A H} + \frac{\boxed{\beta D_0 (R/\mathrm{GV})^{\delta}}}{\boxed{[1 + (R/R_b)^{\Delta\delta/s}]^s}}$$

CR phenomenology: secondary-over-primary ratios

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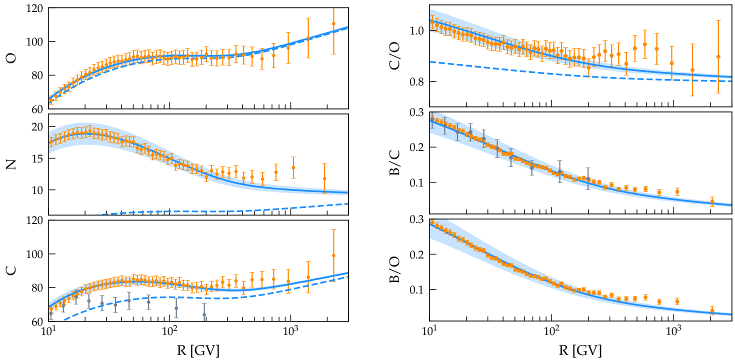


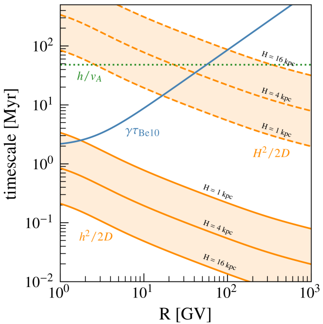
- by fitting primary and secondary/primary measurements we infer the properties of galactic transport:

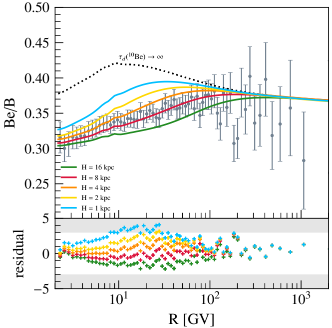
$$\delta \sim 0.54\,,\; D_0/H \sim 0.5 \times 10^{28}\ \text{cm/s}^2\text{/kpc}\,,\; \Delta\delta \sim 0.2\,,\; v_A \sim 5\ \text{km/s}$$

- All nuclei injected with $\gamma \sim 4.3$
- All species are a mixture of a primary and a secondary component (look at C)!
- Shaded areas show uncertainty from fragmentation cross sections [Genolini et al., PRC 2018]

The Beryllium-over-Boron ratio and the escape time

Evoli et al., PRD 101 (2020)



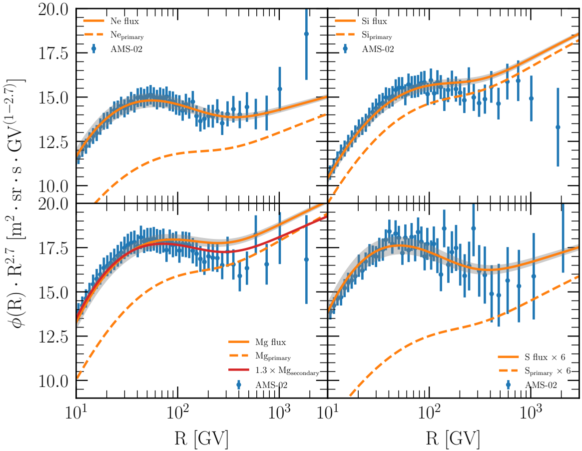


- Traditionally the ratio ^{9}Be/^{10}Be has been used as CR clock $\longrightarrow$ however no measurements of this ratio at $E \gtrsim 1$ GeV/n
- Make sure that ^{10}Be decays outside the disc (hostile to CR transport) $\longrightarrow$ at $\gtrsim$ few GeV this is certainly the case
- Preference for large halos $H \gtrsim 5$ kpc [Weinrich et al., A&A (2020), Maurin et al., arXiv:2203.07265]
- Notice that H and $\tau_{\rm esc}$ are mutual corresponding

$$\tau_{\rm esc}(10\,{\rm GV}) \sim \frac{H^2}{2D} \sim 50\,{\rm Myr} \left(\frac{H}{5\,{\rm kpc}}\right) \left(\frac{1.5 \times 10^{28}\,{\rm cm}^2/{\rm s}/{\rm kpc}}{D_0/H}\right)$$

Intermediate mass nuclei: Ne, Mg, Si, S

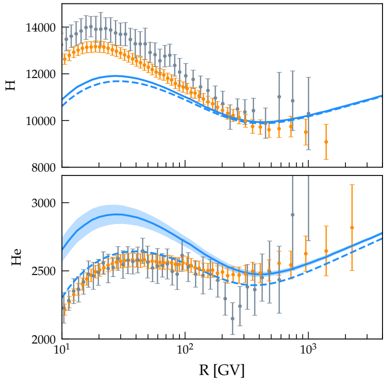
Schroer, CE, and Blasi, PRD 2021



- Well compatible as a combination of a primary (dashed line) and a secondary contribution and an universal injection slope $\gamma \simeq 4.3$

The injection of light nuclei: proton and helium

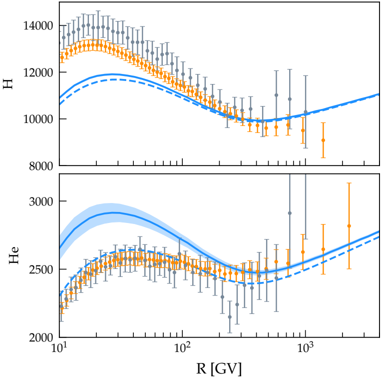
Evoli et al., PRD 99 (2019)



- H is softer than nuclei, while He is harder: $\Delta\gamma \sim \pm 0.05$
- At odds with what one would expect in the case of pure rigidity dependent acceleration [Serpico, ICRC 2015]
- Problematic even for models of the difference between H and He injection based on the different A/Z at shocks [Hanusch+, Apj 2019]
- For He the problem arises from secondary production of ^{3}He that populates the low-energy spectrum

The injection of light nuclei: proton and helium

Evoli et al., PRD 99 (2019)

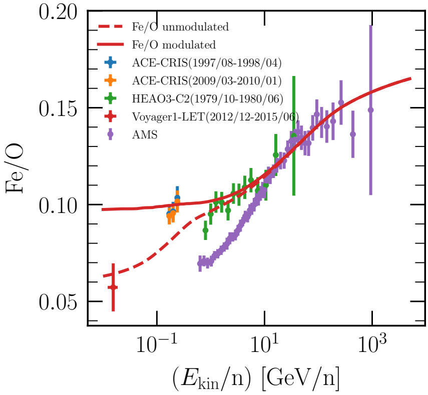


Key points

It will be crucial to measure the p/He ratio at energies above TeV!

The strange case of the Iron spectrum

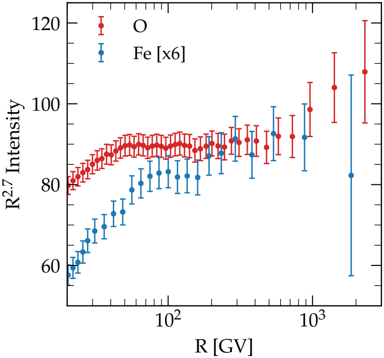
Schroer, CE, and Blasi, PRD 2021

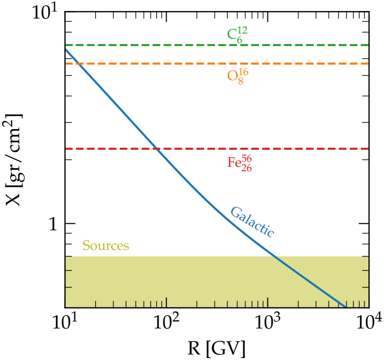


We found that AMS-02 data on Fe/O flux are hard to reconcile not only with the results of existing calculations of CR transport on Galactic scales, but also with the results of previous measurements.

The strange case of the Iron spectrum

Schroer, CE, and Blasi, PRD 2021

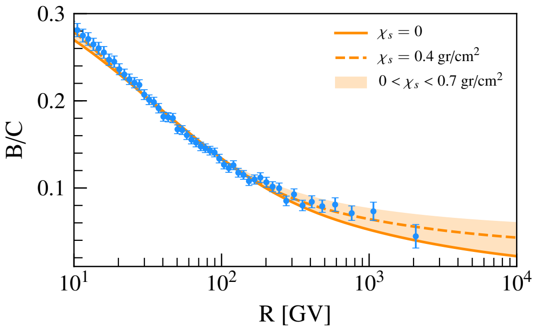




- Notice that two pure primary species injected with the same slope do not manifest the same spectrum after propagation!
- No need of additional populations.

Additional effects not included in this picture

Evoli et al., PRD 99 (2019)



- ▷ Second-order Fermi acceleration in the ISM [Ptuskin et al., 2006, ApJ 642; Drury & Strong, 2017, A&A 597]
- ▷ Shock re-acceleration of secondary nuclei [Blasi, 2017, MNRAS 471; Bresci et al., 2019, MNRAS 488]
- ▷ Grammage at the sources [D'Angelo et al., 2016, PRD 94; Nava et al., 2016, MNRAS 461; Jacobs et al., 2022, JCAP 05]
- ▷ Secondary production at the sources [Blasi, 2009, PRL 103; Mertsch & Sarkar, 2014, PRD 90]
- ▷ ...

Hints on a flattering of the B/C have been whispered by DAMPE, NUCLEON...

What B/C does imply on scattering micro-physics?

- By reproducing local measurements we obtained:

from B/C: $D(\mathrm{GV})/H \simeq 0.35 \times 10^{28}\ \mathrm{cm}^2/\mathrm{s}$ + from Be/B: $H \simeq 5\ \mathrm{kpc}$ $\rightarrow$ $D(\mathrm{GV}) \simeq 1.8 \times 10^{28}\ \mathrm{cm}^2/\mathrm{s}$

- In terms of a diffusion coefficient:

$$D(E) = \frac{1}{3} r_{\mathrm{L}}(E) v \frac{1}{\mathcal{F}(k_{\mathrm{res}})} = \frac{1}{3} v \lambda_{\mathrm{diff}}(E) \quad \text{where} \quad k_{\mathrm{res}} = \frac{1}{r_{\mathrm{L}}(E)}$$

- implying that at $\sim$ GV:

$$\lambda_{\mathrm{diff}} \simeq \mathrm{pc}$$

this is (on average) how much a GV particle has to travel before to deflect by 90°

- the turbulence level required to do so

$$r_{\mathrm{L}}(\mathrm{GV}) \simeq 10^{12}\ \mathrm{cm} \rightarrow \mathcal{F}(k) \simeq \frac{r_{\mathrm{L}} c}{3 D_0} \simeq 6 \times 10^{-7} = \left(\frac{\delta B}{B_0}\right)^2_{k_{\mathrm{res}}}$$

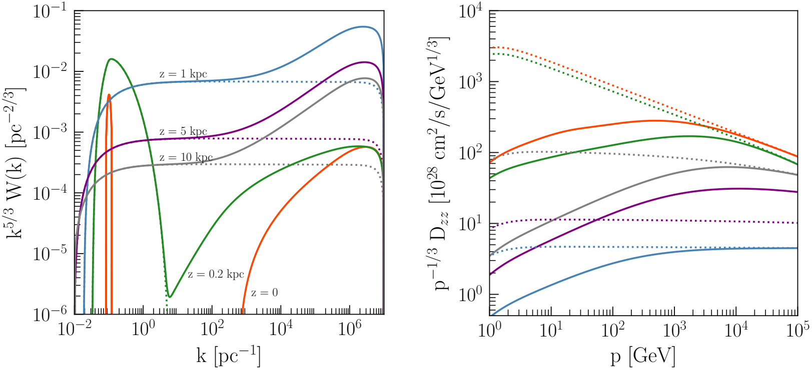
Another example of “Little things affect Big things”

Transport ($\sim 10^{22}$ cm) $\longrightarrow$ mean free path ($\sim 10^{18}$ cm) $\longrightarrow$ waves lenght ($\sim 10^{13}$ cm)

Such a tiny perturbation at the scale of the Solar System stretches the transport time in the Galaxy from kyrs’ to 100 Million of years!

Understanding the origin of waves: non-linear cosmic ray transport

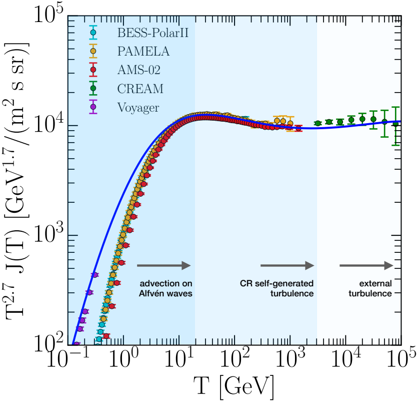
Evoli, Blasi, Morlino & Aloisio, PRL 2018



- Turbulence spectrum (left) and diffusion coefficient (right) without (dotted) and with (solid) CR self-generated waves at different distances from Galactic plane
- The wave advection originates the turbulent halo at a distance $\tau_{\rm cascade} = \tau_{\rm adv} \rightarrow z_{\rm H} \sim \mathcal{O}(\rm kpc)$
- In these approaches $D(p, z)$ is an output of the model

Understanding the origin of waves: a global picture

Evoli, Blasi, Morlino & Aloisio, PRL 2018



Main remarks:

- Pre-existing waves (Kolmogorov) dominates above the break.
- Self-generated turbulence between 1-100 GeV.
- Voyager data are reproduced with no additional breaks (single injection slope), but due to advection with self-generated waves (+ ionization losses).
- H is not predetermined here.
- None of these effects were included in the numerical simulations of CR transport before.

From phenomenology to a more fundamental theory

Phenomenology accomplishments

- Very remarkable that such a simple approach provides explanation of data at few % level! [Schroer+, PRD 2021]
- Nuclei $Z \geq 6$ share the same source spectrum but different from H and He: critical issue for the SN paradigm? [see also Weinrich et al., A&A 2020]
- The (sharp!) break at $\sim$300 GV is due to transport [Genolini+, PRL 119, 24 (2017)]
- Transport at 10-100 GeV is diffusive with $\langle D \rangle \propto E^{-0.5}$ (and Kolmogorov-ish at higher energies)
- CRs fill a magnetized halo above and below the disk of size $H \gtrsim 5$ kpc

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Theoretical issues

- Clear separation between acceleration and transport?
- Physicality of halo boundaries at H? [Dogiel+, ApJ 2020]
- Role of anisotropic diffusion? $\longrightarrow$ maybe relevant for γ's [Cerri+, JCAP 2017]
- What is the origin of the scattering centres? External turbulent cascade or self-generated? What is the role of ion-neutral damping? [Zirakashvili, NPB 2014; Evoli+, PRL 2018]
- Is it the grammage accumulated close to the sources relevant at high-energy? [Bykov+, SSRv 2020]