Galactic Cosmic-Rays after AMS02

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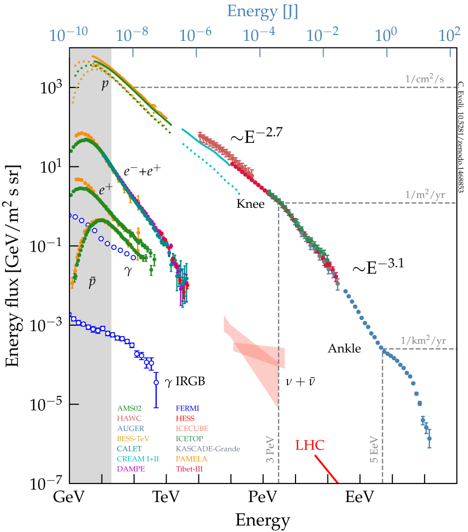
2nd Cosmic-ray Antideuteron Workshop @ UCLA
March 27, 2019

The cosmic-ray spectrum



- **Non-thermal:** Almost a perfect power-law over more than 11 energy decades.
- Evidence of departures from a perfect power-law: the **knee** and the **ankle** features.
- Spectrum cut-off at $\gtrsim 10^{20}$ eV.
- Particles observed at energy higher than any terrestrial laboratory.
- Composition at R∼10 GV:
  ∼ 99.2% are nuclei
    ∼ 84% protons
    ∼ 15% He
    ∼ 1% heavier nuclei
  ∼ 0.7% are electrons

The classical questions in CR physics

Gabici+, arXiv tomorrow(?)

- Which classes of sources contribute to the CR flux in different energy ranges?
- **Which are the relevant processes responsible for CR confinement in the Galaxy?**
- Are CR nuclei and electrons accelerated by the same sources?
- What is the origin of CR anti-matter?
- What is the role of CRs in the ISM? (e.g., for star formation)

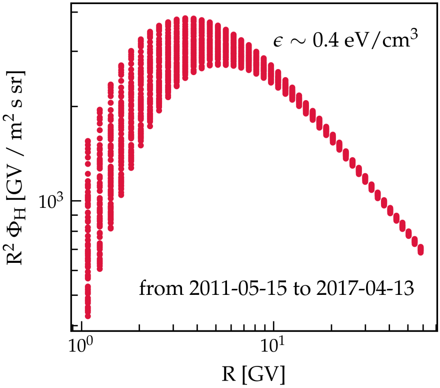
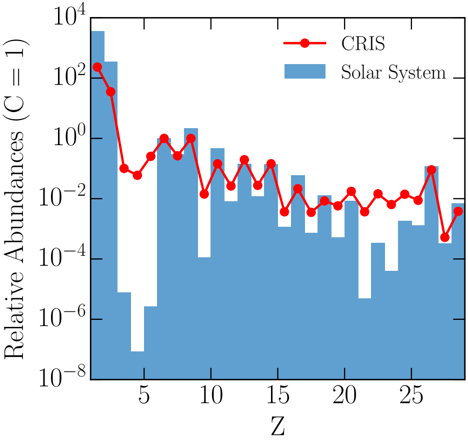


Figure: The TOA proton flux as measured by AMS02 at different times.

LiBeB as cosmic-ray clocks



- If we assume that acceleration takes place in the average interstellar medium then this component must be produced during propagation (from that the term **secondary**).

The grammage pillar

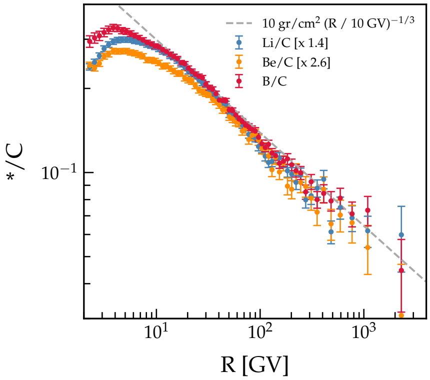


Figure: Secondary-over-primary ratios from AMS02.

- From this plot it follows the more robust evidence of **diffusion** so far:

$$\mathrm{B/C} \sim \frac{X}{\bar{m}_{\mathrm{ISM}}/\sigma_{C\to B}}$$

- following:

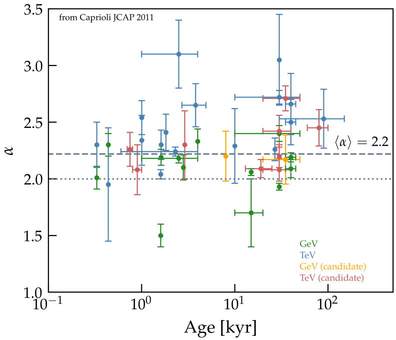
$$\tau_{\mathrm{esc}}(10\,\mathrm{GV}) \sim \frac{X(R)}{\bar{n}_{\mathrm{ISM}}\mu v} \sim 90\,\mathrm{Myr}$$

- while

$$\tau_{\mathrm{ball}} \sim R_G/v \sim 3\times 10^4\ \mathrm{yr}$$

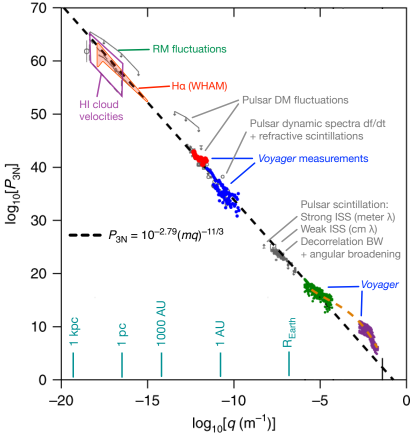
- **The escape time is energy dependent and (roughly) scales like $R^{-1/3}$**

Galactic cosmic-ray factories



- Galactic SN Remnants provide the right energetics ($\sim 10\%$ efficiency)
- Diffusive shock acceleration (DSA) predicts $q \propto E^{-2}$ for strong shocks, indipendent on microphysics
- maybe **softer** because of non-linear effects
- Pure rigidity dependent acceleration (**universality**) with a single power-law in momentum.

The interstellar turbulence



Electron-density fluctuations in the ISM

[Armstrong+, ApJ 1995 - Chepurnov & Lazarian, ApJ 2010 - Lee & Lee, Nature Astr. 2019]

- Turbulence is stirred by Supernovae at a typical scale $L \sim 10 - 100$ pc
- Fluctuations of velocity and magnetic field are Alfvénic
- They have a Kolmogorov $\alpha \sim -5/3$ spectrum (density is a passive tracer so it has the same spectrum: $\delta n_e \sim \delta B^2$):

$$W(k)dk \equiv \frac{\langle \delta B \rangle^2(k)}{B_0^2} = \frac{2}{3}\frac{\eta_B}{k_0}\left(\frac{k}{k_0}\right)^{-\alpha}$$

- where $k_0 = L^{-1}$ and the level of turbulence is

$$\eta_B = \int_{k_0}^{\infty} dk\, W(k) \sim 0.1 \div 0.01$$

Charged particle in a turbulent field

Jokipii, ApJ 1966

- The turbulent field produces a **small fluctuation** with respect to the regular component

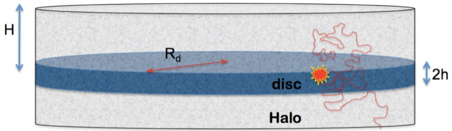
$$\langle \delta B^2 \rangle (k) \ll B_0^2 \text{ for } k \gg k_0$$

- The particle interacts resonantly with the waves, when the condition $k_{\rm res}^{-1} \sim r_L(p)$ is met
- The diffusion coefficient becomes:

$$D_{\rm QLT}(p) = \frac{v r_L}{3} \frac{1}{k_{\rm res} W(k_{\rm res})} \sim \frac{3 \times 10^{27}}{\eta_B} \left(\frac{p}{\rm GeV/c} \right)^{2-\alpha}$$

- $\lambda \sim$ kpc for $k_{\rm res} W(k_{\rm res}) \sim 10^{-6}$ at scales $\sim$ A.U.
- that is just another example of the problem: **little things affect big things**

The CR transport equation in the halo model



$$-\frac{\partial}{\partial z}\left(D_z \frac{\partial f_\alpha}{\partial z}\right) + u\frac{\partial f_\alpha}{\partial z} - \frac{du}{dz}\frac{p}{3}\frac{\partial f_\alpha}{\partial p} = q_{\rm SN} - \frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2 \dot{p} f_\alpha\right] - \frac{f_\alpha}{\tau_\alpha^{\rm in}} + \sum_{\alpha'>\alpha} b_{\alpha'\alpha}\frac{f_{\alpha'}}{\tau_{\alpha'}^{\rm in}}$$

- Spatial diffusion: $\vec{\nabla} \cdot \vec{J}$

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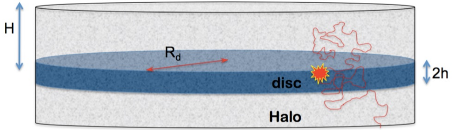

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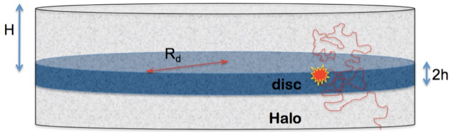

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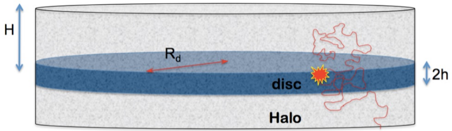

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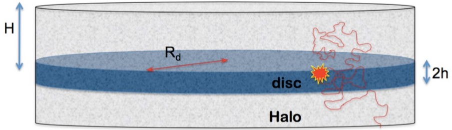

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- Spatial diffusion: $\vec{\nabla} \cdot \vec{J}$
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- Source term proportional to Galactic SN profile
- Energy losses: ionization, Bremsstrahlung, IC, Synchrotron, . . .
- Production/destruction of nuclei due to inelastic scattering (or decay)

Predictions of the standard picture

For a primary CR species (e.g., H, C, O) at **high energy** we can ignore energy gain/losses, and the transport equation can be simplified as:

$$\cancelto{0}{\frac{\partial f}{\partial t}} = Q_0(p)\delta(z) + \frac{\partial}{\partial z}\left[D\frac{\partial f}{\partial z}\right]$$

For $z \neq 0$ one has:

$$D\frac{\partial f}{\partial z} = \text{constant} \rightarrow f(z) = f_0\left(1 - \frac{z}{H}\right)$$

where we used the definition of a halo: $f(z = \pm H) = 0$.

The typical solution gives (assuming injection $Q \propto p^{-\gamma}$):

$$f_0(p) = \frac{Q_0(p)}{2A_{\mathrm{d}}}\frac{H}{D(p)} \sim p^{-\gamma-\delta}$$

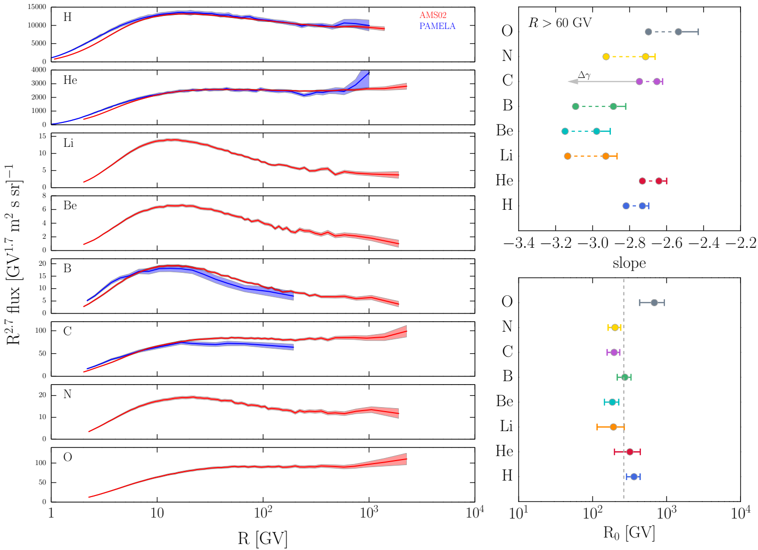
For a secondary (e.g., Li, Be, B) the source term is proportional to the primary density:

$$Q_B \sim \bar{n}_{\mathrm{ISM}} c\sigma_{C\to B} N_C \rightarrow \frac{\mathrm{B}}{\mathrm{C}} \sim \frac{H}{D_0} p^{-\delta}$$

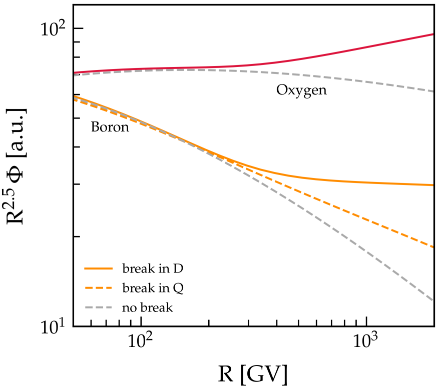
where we use $\bar{n}_{\mathrm{ISM}} = n_{\mathrm{disk}} h/H$.

Unprecedented data precision: The rigidity break

Adriani+, Science 2011 - Aguilar+, PRLs 2013 and so on

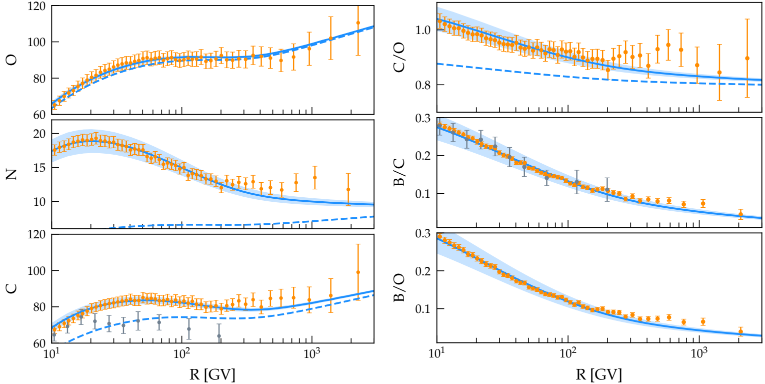


The break is a propagation matter



- We conlude from the data that the observed spectral hardening at ~ 300 GV is due to a change of regime in particle **diffusion**
- Similar conclusion from a Bayesian analysis in **[Genolini+, PRL 2018]**
- Physical mechanisms able to explain the break are presented in **[Blasi, Amato & Serpico, PRL 2012 - Tomassetti, ApJL 752 (2012) 13]**

Fitting the nuclei heavier than He



- Modelling D with a smooth break:

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

- we find $\delta = 0.64$, $D_0/H = 0.25 \times 10^{28}$ cm/s^2, $\Delta\delta = 0.2$, $u = 7$ km/s and $\gamma = 4.26$
- **B/C and C/O as grammage indicators are severely limited by our knowledge of cross-sections.**

The problem with cross-sections: need for new measurements

Genolini+, PRC 2018 - Reinert & Winkler, JCAP 2018 - Evoli+, JCAP 2018

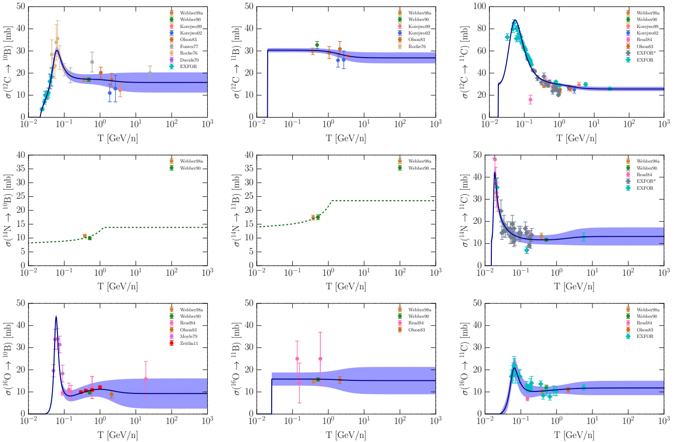
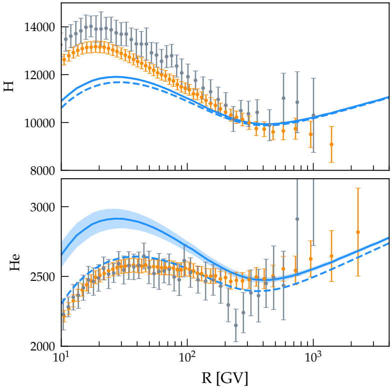


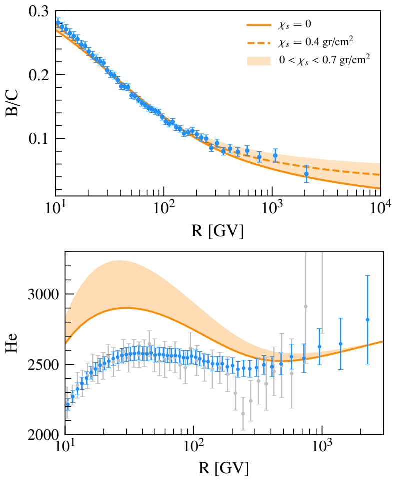
Figure: Cross-sections for Boron prodution by **CNO** spallation on **Hydrogen** target as a function of kinetic energy per nucleon. Data are taken from GALPROP and from EXFOR database.

The injection drama



- H is **softer** than nuclei, while He is **harder**
- 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]**.

Grammage at the source



- To provide a better fit of high-energy B/C we account for an additional contribution to the grammage traversed by CRs
- The grammage due to confinement inside a SNR can be easily estimated as **[Aloisio, Blasi & Serpico, A&A 2015]**

$$X_{\rm SNR} \sim 0.2\,{\rm g/cm}^{-2}$$

- It is important at high-energy since the harder spectrum
- B/C can constrain $X_s \lesssim 0.7$ gr/cm^2
- However the injection problem for He gets worse!

A new scenario for cosmic-ray propagation in the halo

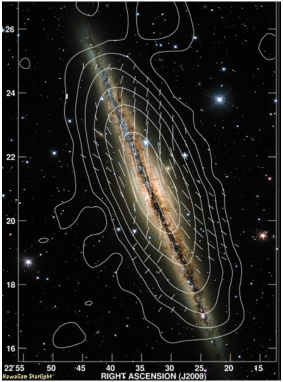
- By solving the transport equation we obtain a featureless (at least up to the knee) propagated spectrum for each primary species, differently thant wath is observed.
- This result remains true even in more sophisticated approach as GALPROP or DRAGON
- **What is missing in our physical picture?**

The halo size H

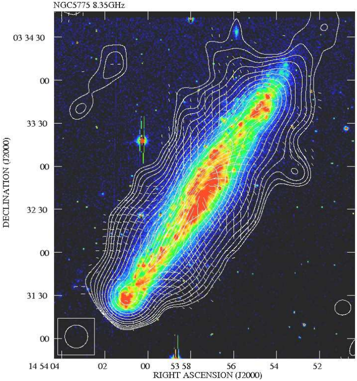
- Assuming $f(z = H) = 0$ reflects the requirement of lack of diffusion (infinite diffusion coefficient)
- May be because $B \to 0$, or because turbulence vanishes (in both cases D cannot be spatially constant!)
- Vanishing turbulence may reflect the lack of sources
- Can be H dependent on p? (remember **B/C** $\sim D/H$!)
- **What is the physical meaning of H?**

The radio halo in external galaxies

Credit: MPIfR Bonn



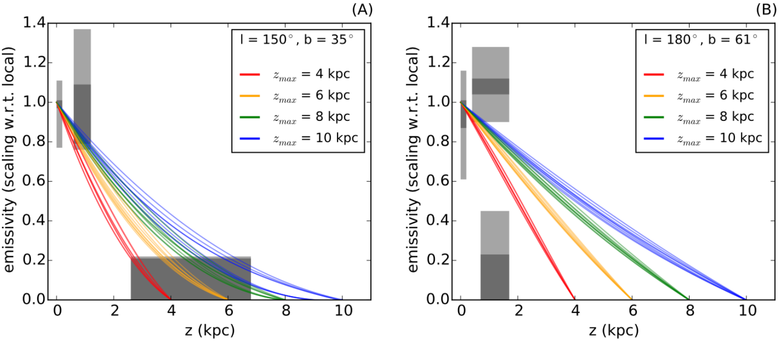
Total radio emission and B-vectors of edge-on galaxy NGC891, observed at 3.6 cm wavelength with the Effelsberg telescope



Total radio intensity and B-vectors of edge-on galaxy NGC 5775, combined from observations at 3.6 cm wavelength with the VLA and Effelsberg telescopes

The γ-halo in our Galaxy

Tibaldo et al., 2015, ApJ



- Using high-velocity clouds one can measure the emissivity per atom as a function of z (proportional to f)
- Indication of a halo with $H \sim$ few kpc

Non-linear cosmic ray transport

Skilling71, Wentzel74

- The net effect of spatial diffusion is to reduce the momentum of the particles forcing them, eventually, to move at the same speed as the waves $\sim v_A$
- If CR stream faster than the waves, the net effect of diffusion is to make waves grow and make CR diffusive motion slow down: this process is known as **self-generation of waves** (notice that self-generated waves are $k \sim r_L$)
- Waves are amplified by CRs through streaming instability:

$$\Gamma_{\rm CR} = \frac{16\pi^2}{3} \frac{v_A}{kW(k)B_0^2} \left[v(p) p^4 \frac{\partial f}{\partial z} \right]$$

and are damped by wave-wave interactions that lead the development of a turbulent cascade (NLLD):

$$\Gamma_{\rm NLLD} = (2c_k)^{-3/2} k v_A (kW)^{1/2}$$

- What is the typical scale/energy up to which self-generated turbulence is dominant?

Non-linear cosmic ray transport

Blasi, Amato & Serpico, PRL, 2012

Transition occurs at scale where external turbulence (e.g., from SNe) equals in energy density the self-generated turbulence

$$W_{\rm ext}(k_{\rm tr}) = W_{\rm CR}(k_{\rm tr})$$

where $W_{\rm CR}$ corresponds to $\Gamma_{\rm CR} = \Gamma_{\rm NLLD}$

Assumptions:

- Quasi-linear theory applies
- The external turbulence has a Kolmogorov spectrum
- Main source of damping is non-linear damping
- Diffusion in external turbulence explains high-energy flux with SNR efficiency of $\epsilon \sim 10\%$

$$E_{\rm tr} = 228\,\mathrm{GeV} \left(\frac{R_{d,10}^2 H_3^{-1/3}}{\epsilon_{0.1} E_{51} \mathcal{R}_{30}} \right)^{3/2(\gamma_p - 4)} B_{0,\mu}^{(2\gamma_p - 5)/2(\gamma_p - 4)}$$

The turbulence evolution equation

Eilek, ApJ 1979

$$\frac{\partial W}{\partial t} = \frac{\partial}{\partial k}\left[D_{kk}\frac{\partial W}{\partial k}\right] + \frac{\partial}{\partial z}(v_A W) + \Gamma_{\rm CR} W + Q(k)$$

- Diffusion in k-space damping: $D_{kk} = c_k |v_A| k^{7/2} W^{1/2}$

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- Waves growth due to cosmic-ray streaming: $\Gamma_{\rm CR} \propto \partial f / \partial z$

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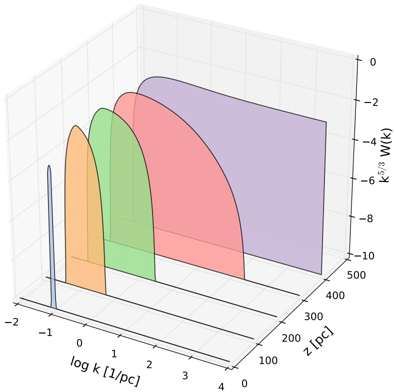
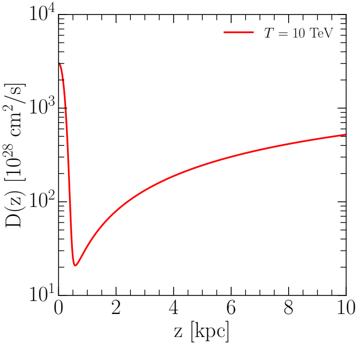
- External (e.g., SNe) source term $Q \sim \delta(z)\delta(k - k_0)$
- In the absence of the instability, it returns a kolmogorov spectrum: $W(k) \sim k^{-5/3}$

Wave advection → the turbulent halo

Evoli, Blasi, Morlino & Aloisio, 2018, PRL

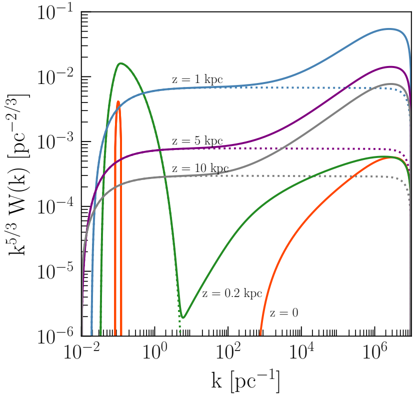




$$\tau_{\rm cascade} = \tau_{\rm adv} \rightarrow \frac{k_0^2}{D_{kk}} = \frac{z_{\rm peak}}{v_A} \rightarrow z_{\rm peak} \sim \mathcal{O}({\rm kpc})$$

Non-linear cosmic ray transport: diffusion coefficient

Evoli, Blasi, Morlino & Aloisio, 2018, PRL



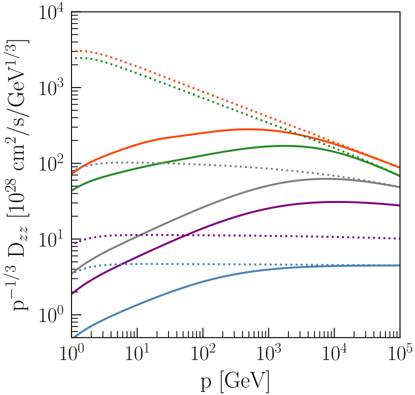
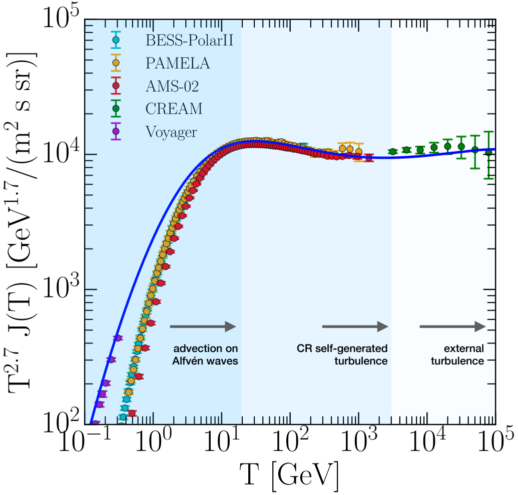


Figure: Turbulence spectrum without (dotted) and with (solid) CR self-generated waves at different distance from the galactic plane.

Non-linear cosmic ray transport: a global picture

Evoli, Blasi, Morlino & Aloisio, 2018, PRL



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

Conclusions

- Recent findings by PAMELA and AMS-02 (breaks in the spectra of primaries, B/C à la Kolmogorov, flat anti-protons, rising positron fraction) are challenging the standard scenario of CR propagation.
- Non-linearities might play an essential role for propagation (as they do for acceleration). They allow to reproduce local observables (primary spectra) without ad hoc breaks.
- We present a non-linear model in which SNRs inject: a) turbulence at a given scale with efficiency $\epsilon_{\rm w} \sim 10^{-4}$ and b) cosmic-rays with a single power-law and $\epsilon_{\rm CR} \sim 10^{-1}$. The turbulent halo and the change of slope at $\sim$300 GV are obtained self-consistently.
- As a bonus, these models enable us a deeper understanding of the interplay between CR, magnetic turbulence and ISM in our Galaxy.

The road ahead..