On the origin of the cosmic-ray halo

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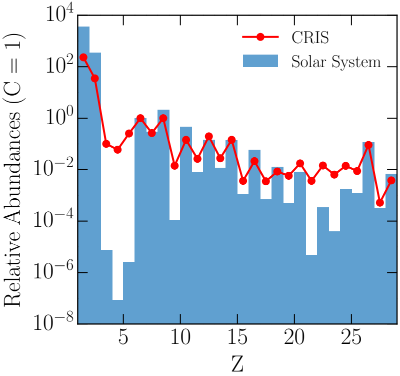
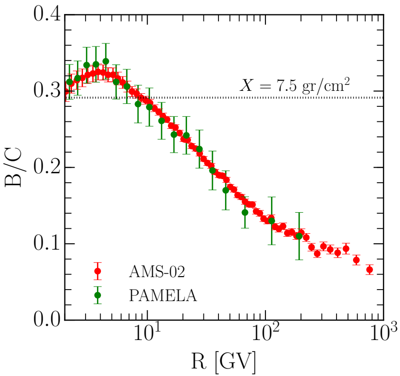
CRISM @ Grenoble

based on: C. Evoli, R. Aloisio, P. Blasi and G. Morlino, 2018, PRL arXiv:1806.04153

The diffusive paradigm of galactic CRs





The ratio of boron and carbon fluxes provides us with the best estimates of the time spent by CRs in the Galaxy before escaping.

The diffusive paradigm of galactic CRs

- The grammage traversed by CRs is related to the escape time:

$$X(E) = \bar{n}\mu v \tau_{\rm esc}(E)$$

- if we assume that the gas is concentrated in a thin disc, h, and the diffusive halo extends to a height H, the mean density

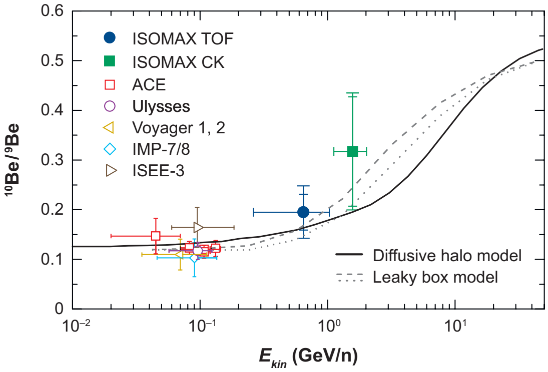
$$\bar{n} = n_d \frac{h}{H} \sim 0.1 \left(\frac{H}{2\,\rm kpc} \right)^{-1} \rm cm^{-3}$$

- the typical escape time is

$$\boxed{\tau_{\rm esc} \sim 50 \left(\frac{H}{2\,\rm kpc} \right) \rm Myr}$$

The diffusive paradigm of galactic CRs

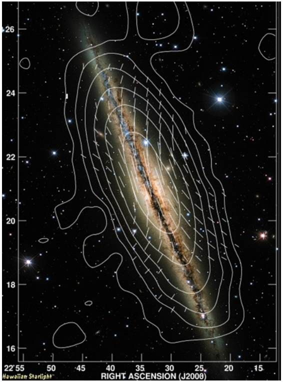
Strong et al., 2007, Annu. Rev. Nucl. Part. Sci.



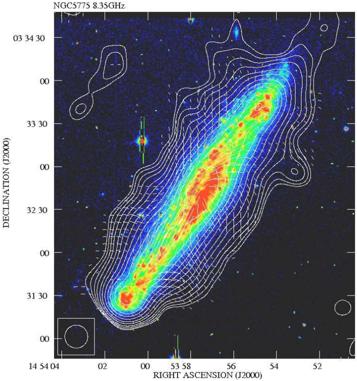
The observed fraction of unstable isotopes which live long enough, e.g. Be^{10} ($\tau \sim 1.4$ Myr), can be used to derive $H \gtrsim 2\ \mathrm{kpc}$

The radio halo in external galaxies

Credit: MPIfR Bonn



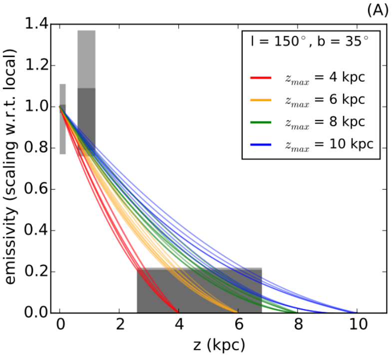
Total radio emission of edge-on galaxy NGC891, observed at 3.6 cm wavelength with the Effelsberg telescope



Total radio intensity 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

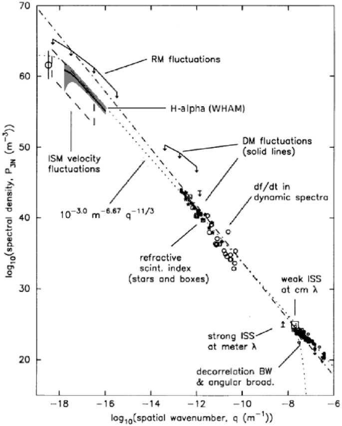
Tibaldo et al., 2015, ApJ



- Using high-velocity clouds to measure the emissivity per atom as a function of z (proportional to CR density)
- Indication of a halo with $H \gtrsim$ few kpc

The interstellar turbulence

"The (second) Great Power-Law in the Sky" (Jokipii)



Electron-density fluctuations in the ISM
[Armstrong et al. 1995, ApJ 443, 209]

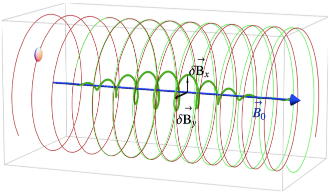
- Turbulence is stirred by Supernovae at a typical scale $L \sim 10 - 100$ pc
- Fluctuations of velocity and magnetic field are Alfvénic (moving at v_A)
- They have a Kolmogorov $k^{-5/3}$ spectrum (density is a passive tracer so it has the same spectrum: $\delta n_e \sim \delta B^2$):

$$W(k)dk \equiv \frac{\langle \delta B \rangle^2(k)}{B_0^2} = \frac{2}{3}\frac{\eta_B}{k_0}\left(\frac{k}{k_0}\right)^{-5/3}$$

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

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

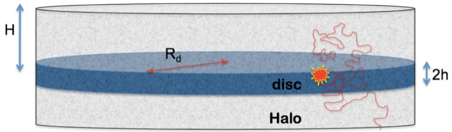
Charged particle in a turbulent field: QLT



- The turbulent field amplitude is a small fluctuation with respect to the regular component
- Resonant interaction wave-particle: $k_{\rm res}^{-1} \sim r_L(p)$
- It follows:

$$D_{zz}(p) = \frac{v r_L}{3} \frac{1}{k_{\rm res} W(k_{\rm res})} \sim \overbrace{3 \times 10^{28}\,\mathrm{cm}^2/\mathrm{s}}^{3\times 10^{27}/\eta_B\,\mathrm{cm}^2/\mathrm{s}} \left(\frac{p}{\mathrm{GeV/c}} \right)^{1/3}$$

The CR transport equation in the halo model



$$-\frac{\partial}{\partial z}\left(D_{\rm zz}\frac{\partial f_i}{\partial z}\right) + u\frac{\partial f_i}{\partial z} - \frac{du}{dz}\frac{p}{3}\frac{\partial f_i}{\partial p} = Q_{\rm SN} - \frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2\frac{dp}{dt}f_i\right] + Q_{\rm frag/decay}$$

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

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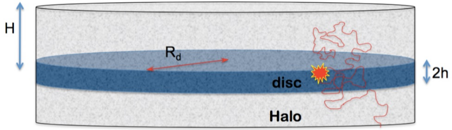

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- Advection by Galactic winds/outflows: $u = u_w + v_A \sim v_A$

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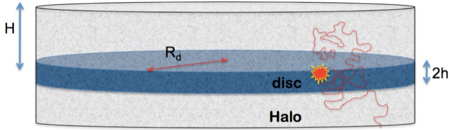

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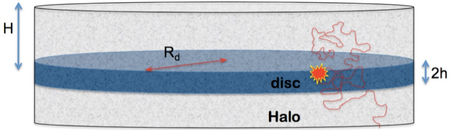

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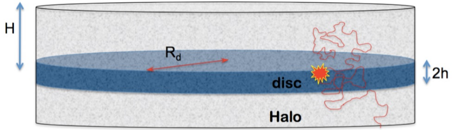

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- Advection by Galactic winds/outflows: $u = u_w + v_A \sim v_A$
- Source term proportional to Galactic SN profile
- Energy losses: ionization, Bremsstrahlung, IC, Synchrotron, ...
- Production/destruction of nuclei due to inelastic scattering or decay

Predictions of the halo model

- For a primary CR species (e.g., H, C, O) at energies where I can ignore losses and advection, the transport equation can be simplified as:

$$-\frac{\partial}{\partial z}\left[D\frac{\partial f}{\partial z}\right] = Q_0(p)\delta(z)$$

- For $z \neq 0$ one has:

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

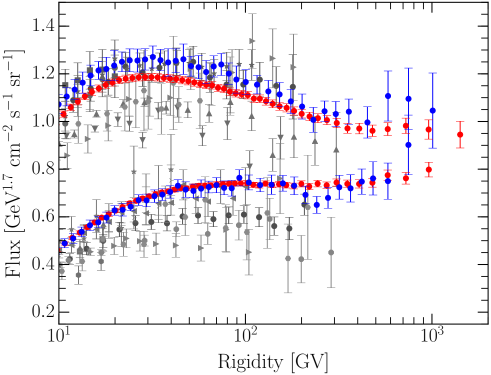
where I used the definition of a *halo*: $f(z = \pm H) = 0$.

- The typical solution on the plane gives:

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

The H and He hardening

Adriani et al., Science, 2011; Aguilar et al., PRL, 2015



- By solving the transport equation we obtain a featureless (up to the knee) propagated spectrum for primaries, at the odds with observations.
- **What is missing in our physical picture?**

The halo size H

- Assuming $f(z = \pm H) = 0$ 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?
- **What is the physical meaning of H?**

The turbulence evolution equation

Jones, ApJ 413, 619 (1993)

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

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

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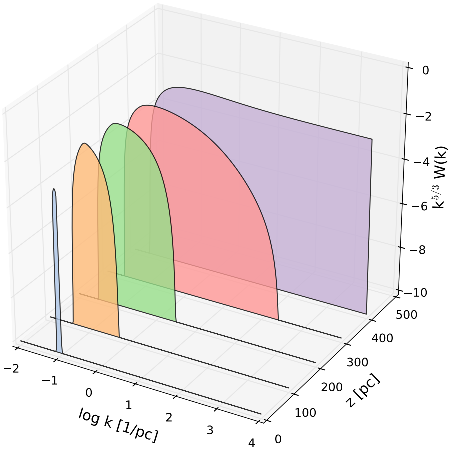
- Waves growth due to cosmic-ray streaming: $\Gamma_{\rm CR} \propto \partial f / \partial z$
- External (e.g., SNe) source term $Q \sim \delta(z)\delta(k - k_0)$
- In the absence of CRs ($\Gamma_{\rm CR} \to 0$), it returns a kolmogorov spectrum: $W(k) \sim k^{-5/3}$

The turbulent halo

Evoli et al., 2018, PRL



$$\tau_{\rm cascade} = \tau_{\rm adv} \rightarrow \frac{k_0^2}{D_{kk}} = \frac{z_c}{v_A}$$

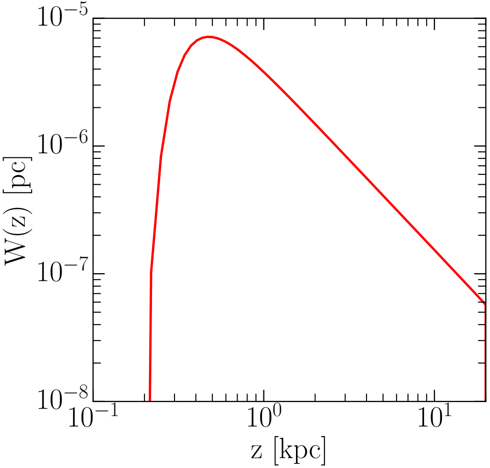
$$\Downarrow$$

$$\boxed{z_c \sim \mathcal{O}(\mathrm{kpc})}$$

- z_c set the distance at which turbulence start cascading.

The turbulent halo

Evoli et al., 2018, PRL



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- z_c set the distance at which turbulence start cascading.

The turbulent halo

- Assuming now a power-law diffusion coefficient $D(z) = D_0(z/z_c)^\alpha$ for $z > z_c$:

$$-\frac{\partial}{\partial z}\left[D_0\left(\frac{z}{z_c}\right)^\alpha \frac{\partial f}{\partial z}\right] = Q_0(p)\delta(z)$$

- it implies that the density on the disk is:

$$f_0 \propto 1 - \left(\frac{H}{z_c}\right)^{-\alpha+1}$$

- which shows that $f(z=0)$ is weakly dependent on H as long as $\alpha > 1$

Non-linear cosmic ray transport

Skilling71, Wentzel74

- CR energy density is ~ 1 eV/cm^{-3} is comparable to starlight, turbulent gas motions and magnetic fields.
- In these conditions, low energy can self-generate the turbulence for their scattering (notice that self-generated waves are with $k \sim r_L$)
- Waves are amplified by CRs through streaming instability:

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

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

$$\Gamma_{\rm d} = \frac{D_{\rm kk}}{k^2} = (2c_k)^{-3/2} k v_A (kW)^{1/2}$$

- 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 $\Gamma_{\rm CR} = \Gamma_{\rm d}$

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 $\epsilon \sim 10\%$

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

Non-linear cosmic ray transport: a global picture

Evoli et al., 2018, PRL

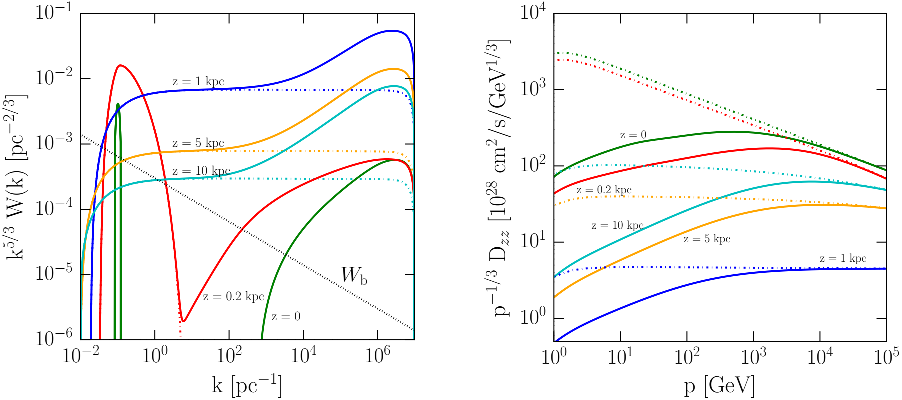


Figure: Turbulence spectrum without (dotted) and with (solid) CR self-generated waves at different distance from the galactic plane.

Non-linear cosmic ray transport: a global picture

Evoli et al., 2018, PRL

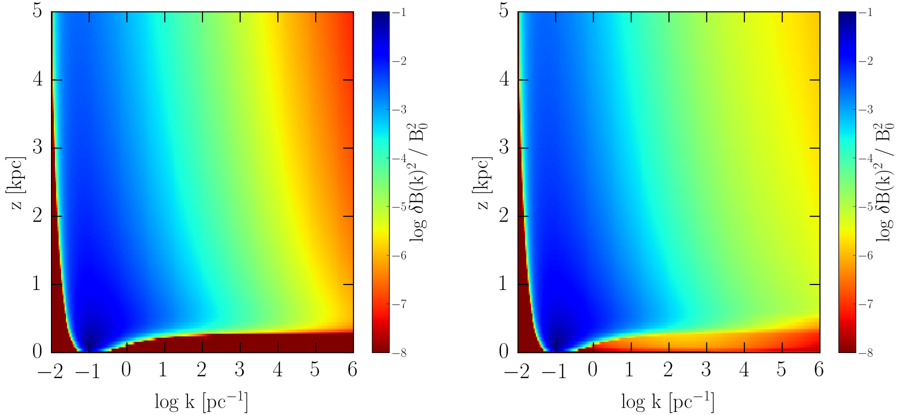
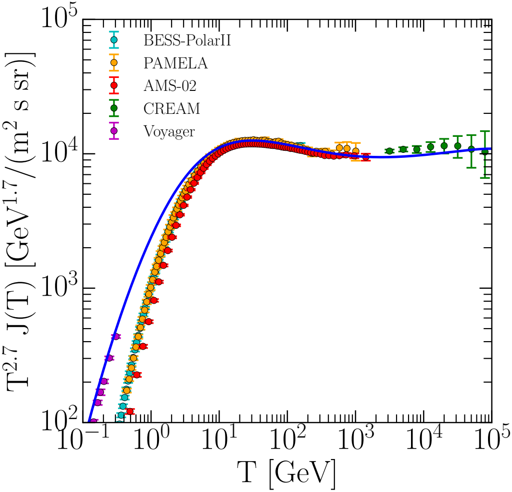


Figure: The normalized turbulent magnetic field $kW(k)$ in the halo without (left) and with (right) CR self-generation.

Non-linear cosmic ray transport: a global picture

Evoli et al., 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
- No *H* is assumed here

Conclusions

- Recent findings by PAMELA and AMS-02 (breaks in the spectra of primaries, high-energy B/C, flat anti-protons, rising positron fraction) are challenging the standard scenario of CR propagation ($\rightarrow$ Philipp's talk).
- I present a 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.
- At some level, non-linearities should play a role for propagation (as they do for acceleration). In our model, they allow to reproduce local observables (primary spectra) without ad hoc breaks.
- These models enable us a deeper understanding of the interplay between CR, magnetic turbulence and ISM in our Galaxy.