# Recent results on Galactic Cosmic Rays

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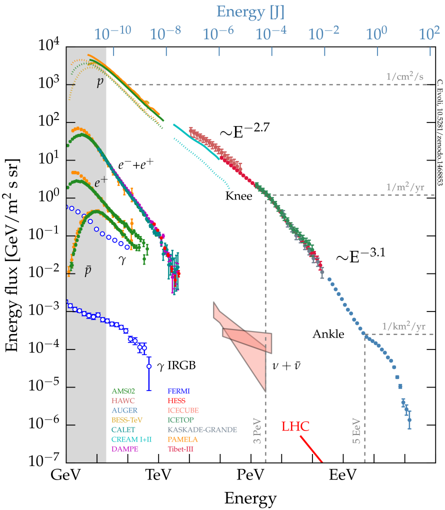
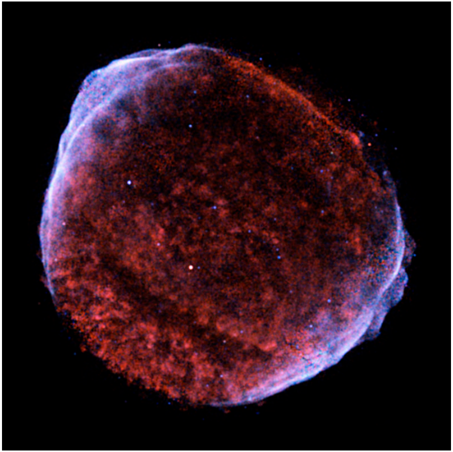
# The cosmic-ray “multi-messenger” spectrum




- Non-thermal: Almost a perfect power-law over 11 energy decades.
- Evidence of departures from a perfect power-law: the knee and ankle features.
- Spectrum cut-off at $\gtrsim 10^{20}$ eV.
- Particles observed at energy higher than any terrestrial laboratory.
- Direct measurements (at low-E) versus air-cascade reconstructions (at high-E).
- Composition at R∼10 GV:
  - ∼ 99.2% are nuclei
    - ∼ 84% protons
    - ∼ 15% He
    - ∼ 1% heavier nuclei
  - ∼ 0.7% are electrons
  - ∼ 0.1% are anti-matter particles
- None of them can be unambiguously explained as secondary Dark Matter product! (as far as we know)

# Cosmic Ray factories in our Galaxy: SNR



Chandra's image of SN 1006. In blue high-energy electrons emission.

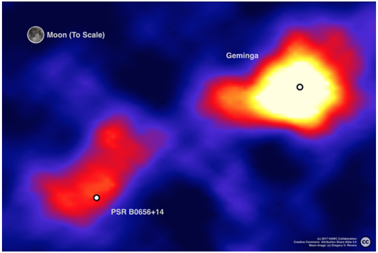
- Energetically dominant component of the CRs at about a GeV/nucleon are certainly Galactic (Fermi, 1949)
- With an energy density of $\epsilon_{\rm CR} \sim 1$ eV/cm$^3$, CRs are in rough equipartition with magnetic fields, gas, photon fields.
- SN explosions can sustain the galactic CR population:

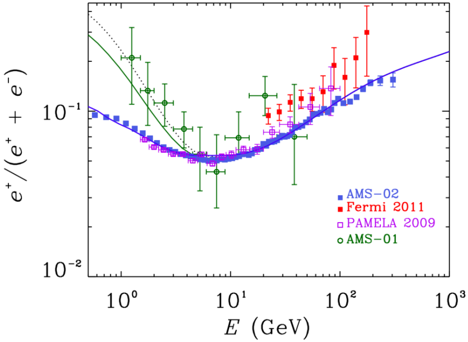
$$L_{\rm CR} = \frac{\epsilon_{\rm CR} V_{\rm MW}}{\tau_{\rm esc}} \sim 0.1 \div 0.5\, L_{\rm SN}$$

- DSA mechanism predicts a power-law injection spectrum $\propto p^{-2}$

# Cosmic Ray factories in our Galaxy: sources

Gaggero+2013, PRL; Cholis+2018, PRD

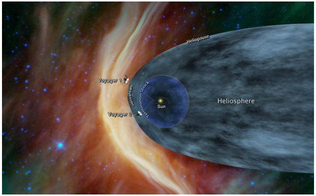


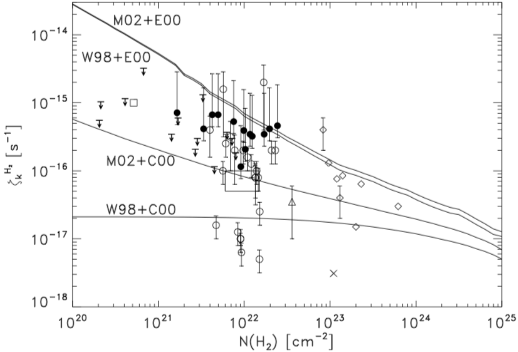




- Particle acceleration at the highest speed shocks in nature ($10^4 < \Gamma < 10^7$)
- Cosmic Rays: only sources showing direct evidence for PeV particles
- Anti-matter storage rooms: as many positrons as electrons

# Cosmic Rays in our Galaxy: star formation and ionization

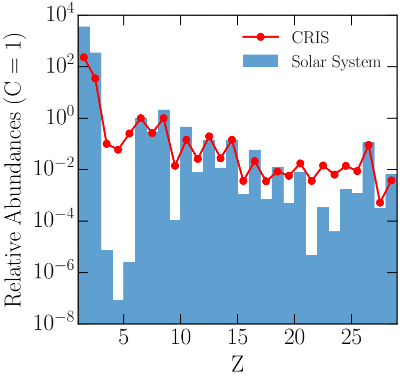
Padovani+2009 (A&A), Gabici+2010 (A&A), Ivlev+2018 (ApJ)

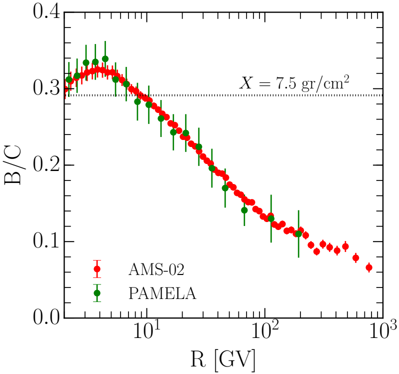



- Voyager's launched in 1977 has been measuring the CRs outside the heliosphere
- These sub-GeV particles drives star-formation being able to penetrate molecular clouds.

# 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

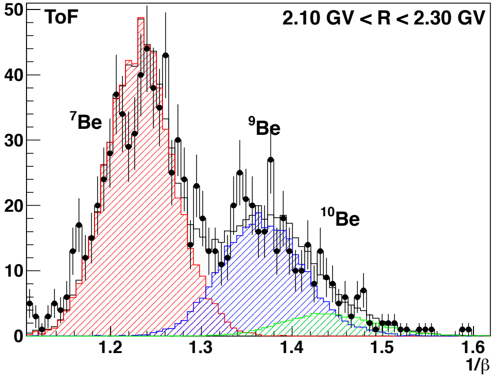
$$\bar{n} = n_d \frac{h}{H} \sim 0.1 \left( \frac{H}{4\,{\rm kpc}} \right)^{-1} {\rm cm}^{-3}$$

- the typical escape time is

$$\tau_{\rm esc} \sim 100 \left( \frac{H}{4\,{\rm kpc}} \right) {\rm Myr}$$

# Cosmic-ray clocks

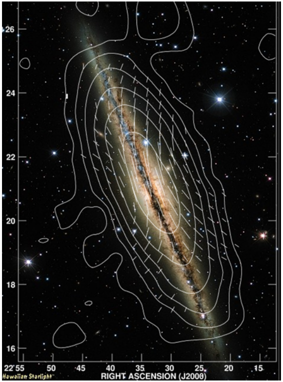
PAMELA Collaboration, 2018, ApJ, 862, 2



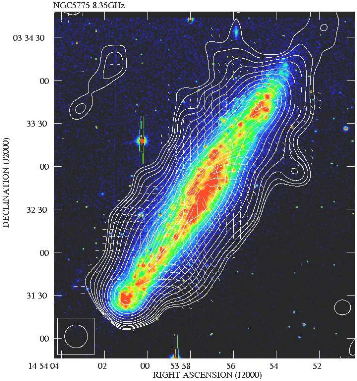

The observed fraction of unstable isotopes which live long enough, e.g. $\mathrm{Be}^{10}$ ($\tau \sim 1.4$ Myr), can be used to derive $H \gtrsim 2$ kpc

# The radio halo in external galaxies

Credit: MPIfR Bonn



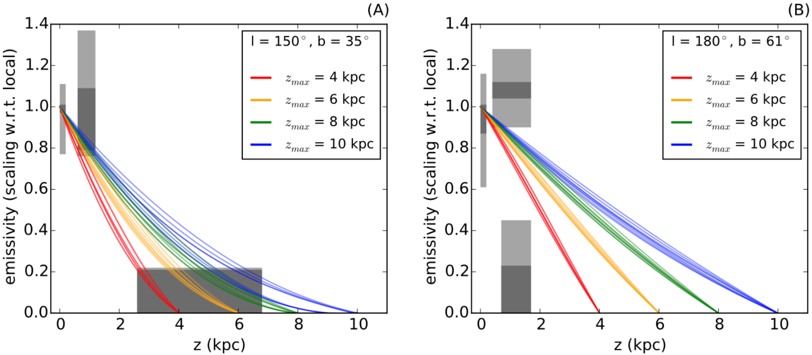

Total radio emission of edge-on galaxy NGC891, observed at 3.6 cm wavelength with the Effelsberg telescope




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

# The $\gamma$-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

# Charged particle transport in turbulent magnetic fields

- A charged particle moving in a field $\vec{B}_0 + \delta\vec{B}$, with $\delta B \ll B_0$ and $\delta\vec{B} \perp \vec{B}_0$:

$$\frac{d\vec{p}}{dt} = q\frac{\vec{v}}{c} \times (\vec{B}_0 + \delta\vec{B})$$

- The perturbation acts on the particle pitch angle only:

$$\frac{d\mu}{dt} = \frac{qv}{pc}(1-\mu^2)^{1/2}\delta B \cos(\Omega t - kz + \psi) \qquad \Omega \equiv \frac{qB_0}{mc\gamma}$$

- It follows:

$$\langle \delta\mu \rangle_{\psi,t} = 0$$

$$\langle \delta\mu^2 \rangle_{\psi,t} = \frac{q^2 v^2 (1-\mu^2)\delta B^2}{c^2 p^2 \mu}\delta(k - \Omega/v\mu)\delta t \propto \delta t$$

- If there are many such waves with a power spectrum $W(k)$:

$$D_{\mu\mu} = \left\langle \frac{\delta\mu^2}{\Delta t} \right\rangle = \frac{\pi}{2}\Omega(1-\mu^2)k_{\rm res}W(k_{\rm res}) \qquad k_{\rm res} \equiv \frac{\Omega}{v\mu} \sim \frac{1}{r_L \mu}$$

# Charged particle transport in turbulent magnetic fields

- The particles deflect by 90 degrees in a timescale

$$\tau_{90} \sim \frac{1}{\Omega k_{\rm res} W(k_{\rm res})}$$

- Therefore, the diffusion in pitch angle also implies their scattering in space

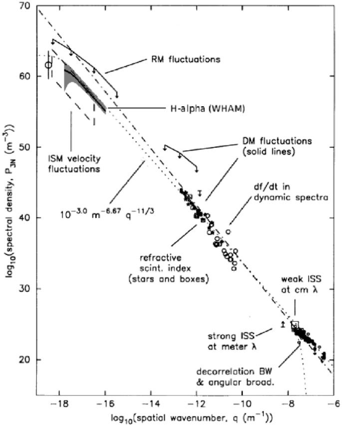
$$D_{\rm zz} = \left\langle \frac{\Delta z^2}{\Delta t} \right\rangle \sim \frac{v^2}{\Omega k_{\rm res} W(k_{\rm res})} \sim \frac{1}{3} r_L v \frac{1}{k_{\rm res} W(k_{\rm res})}$$

$$W(k) \propto k^{-\beta} \;\; \Rightarrow \;\; D_{\rm zz}(p) \sim 10^{27} \left(\frac{\delta B}{B_0}\right)^{-1} \left(\frac{p}{\rm GeV/c}\right)^{2-\beta} \; {\rm cm^2/s}$$

- What are the waves the CRs scatter off?

# 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]

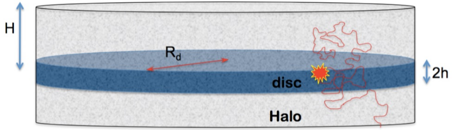
- Turbulence is stirred by Supernovae at a typical scale $L \sim 10 - 100$ pc
- Fluctuations of velocity and magnetic field are Alfvénic (moving at $v_A$)
- They have a Kolmogorov $k^{-5/3}$ spectrum (density is a passive tracer so it has the same spectrum: $\delta n_e \sim \delta B^2$):

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

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

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

# 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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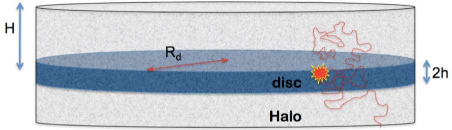


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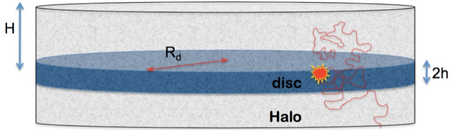


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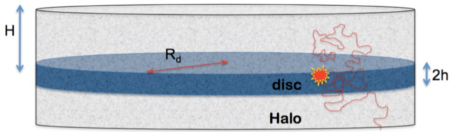


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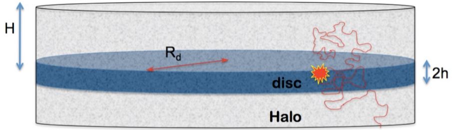


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- Advection by Galactic winds/outflows: $u = u_w + v_A \sim v_A$
- Source term proportional to Galactic SN profile
- Energy losses: ionization, Bremsstrahlung, IC, Synchrotron, ...
- Production/destruction of nuclei due to inelastic scattering or decay

# 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:

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

# Predictions of the halo model

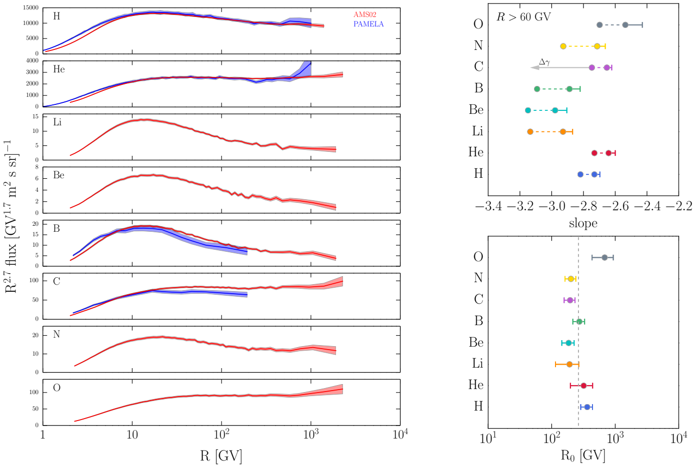
- For a secondary (e.g., Li, Be, B) the source term is proportional to the primary density $Q_B \sim \bar{n}_{\rm ISM} c \sigma_{C \to B} N_C$:

$$\frac{N_B}{N_C} \sim \frac{H}{D_0} p^{-\delta} \quad (1)$$

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

- By solving the transport equation we obtain a featureless (up to the knee) propagated spectrum for primaries, and steepened by energy-dependent diffusion for secondary species.

# Individual spectra after PAMELA and AMS02




- New and exciting discoveries!
- Secondary spectra unambiguously requires a change of slope in transport.
- 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 $H$?

# Non-linear cosmic ray transport

Skilling71, Wentzel74

- CR energy density is $\sim 1$ 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 $\epsilon \sim 10\%$

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

# 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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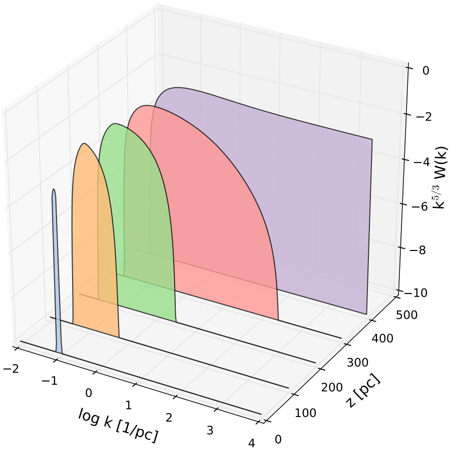
- Diffusion in $k$-space (non-linear): $D_{kk} = c_k |v_A| k^{7/2} W^{1/2}$
- Advection of the Alfvén waves
- Waves growth due to cosmic-ray streaming: $\Gamma_{\rm CR} \propto \partial f / \partial z$
- External (e.g., SNe) source term $Q \sim \delta(z)\delta(k - k_0)$
- In the absence of CRs ($\Gamma_{\rm CR} \to 0$), it returns a kolmogorov spectrum: $W(k) \sim k^{-5/3}$

# The turbulent halo

Evoli et al., 2018, PRL




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

$$\Downarrow$$

$$z_c \sim \mathcal{O}(\rm kpc)$$

- $z_c$ set the distance at which turbulence start cascading.

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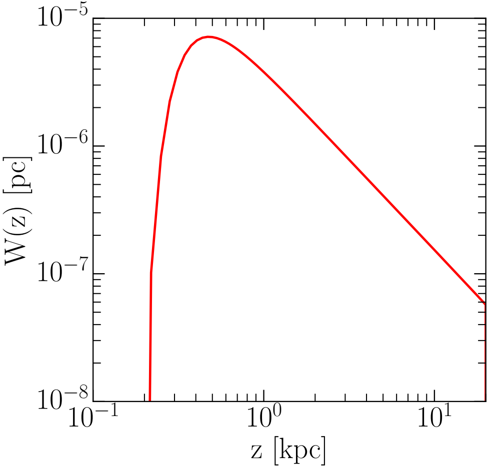


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# Non-linear cosmic ray transport: a global picture

Evoli et al., 2018, PRL

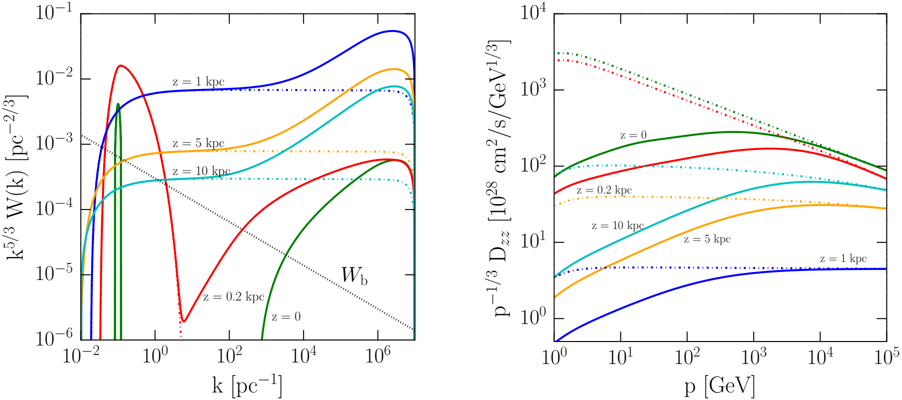
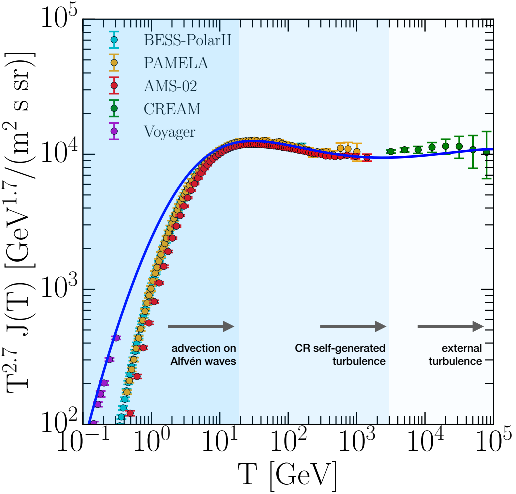



Figure: Turbulence spectrum without (dotted) and with (solid) CR self-generated waves at different distance from the galactic plane.

# Non-linear cosmic ray transport: a global picture

Evoli et al., 2018, PRL




- Pre-existing waves (Kolmogorov) dominates above the break
- Self-generated turbulence between ∼10-300 GeV
- Voyager data are reproduced with no additional breaks, but due to advection with self-generated waves
- No Halo is assumed a-priori here

# Quick implication #1: Seeding for the magnetic field?

- The magnetic field of a $10^8$ $M_\odot$ virialized object at $z = 30$:

$$B_h = B_{\rm IGM,0}(1+z)^2 \left( \frac{\bar{\rho}}{\rho_{\rm IGM}} \right)^{2/3}$$

$$U_B = \frac{B_h^2}{8\pi} \sim 4 \times 10^{-17}\,{\rm erg\,cm^{-3}} \left( \frac{B_{\rm IGM,0}}{10^{-12}{\rm G}} \right)^2 \left( \frac{1+z}{30} \right)^4$$

- The SFR for this halo is linked to the halo mass:

$$\rho_* = f_* \frac{\Omega_b}{\Omega_m} \frac{M_h}{t_{\rm ff}(z)} \to N_{\rm SN} = f_{\rm SN} \rho_* t_{\rm H}(z) \sim {\rm few} \times 10^3$$

  where $N_{\rm SN}$ is the number of SNe exploded at that time.

- Therefore a very rough estimate of the *average* CR energy density in the galaxy:

$$U_{\rm CR} = \frac{\eta N_{\rm SN} E_{\rm SN}}{(4\pi/3) r_v^3} \sim 7 \times 10^{-12}\,{\rm erg\,cm^{-3}} \gg U_B$$

# Quick implication #2: Heating and ionization on ISM?

- I can rewrite the growth rate as

$$\Gamma_{\rm CR} \sim \frac{P_{\rm CR}(> p)}{P_B} \frac{v_A}{H} \frac{1}{kW}$$

- By equating with $\Gamma_D$ I can derive $kW$ and finally:

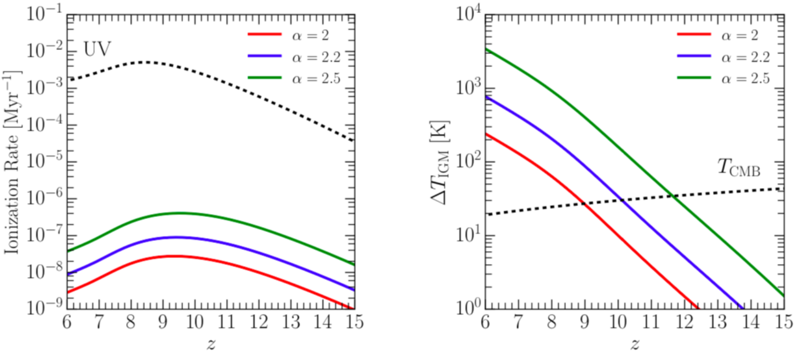
$$D_{\rm s-g} \propto \left( \frac{P_{\rm CR}(> p)}{P_B} \right)^{-1} \gg D_{\rm MW}$$

- Energy losses in the halo are extremely more relevant than in the Galaxy:

$$\frac{t_l}{t_d} \propto \frac{D_{\rm s-g}}{n_{\rm gas}}$$

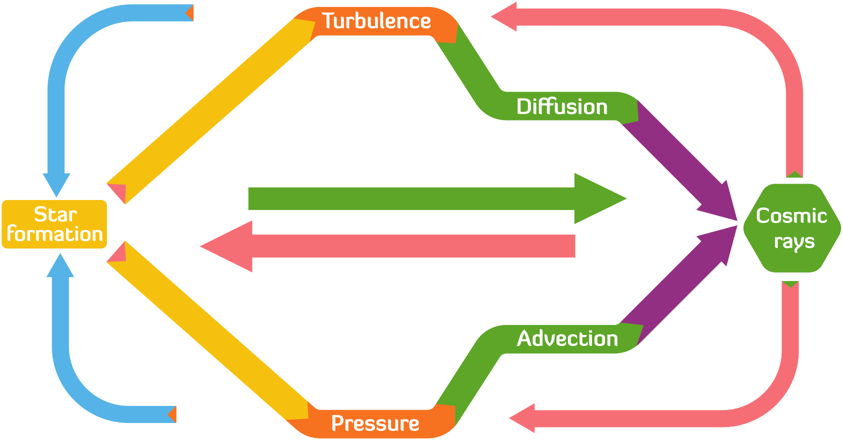
# Quick implication #3: 21cm signal

Leite+, MNRAS, 2017




- Increment of the average IGM temperature by CRs as a function of redshift for three values of the CR injection slope $\alpha$.

# Take home message



# 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.
- 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.
- These models enable us a deeper understanding of the interplay between CR, magnetic turbulence and ISM in our (and possibly other) Galaxy.