Cosmic-ray propagation in self-generated turbulence

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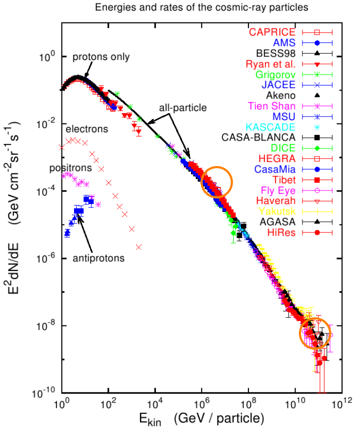
Three-elephants in the gamma-ray sky @Garmisch-Partenkirchen

in collaboration with R. Aloisio, P. Blasi and G. Morlino (GSSI)

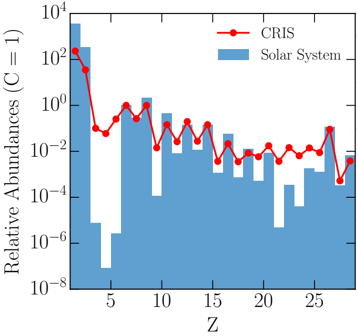
The cosmic-ray spectrum

Credit: Hillas+06



- Almost a perfect power-law over 12 energy decades.
- Evidence of the "knee" and "ankle" features.
- Observed at energy higher than terrestrial laboratories.
- Direct measurements versus air-cascade reconstructions.
- Composition:
  $\sim$ 98% are nuclei
    $\sim$ 87% protons
    $\sim$ 12% He
    $\sim$ 1% heavier nuclei
  $\sim$ 2% are electrons
  $\sim$ 0.1% are anti-matter particles (positrons and antiprotons)

The grammage pillar



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

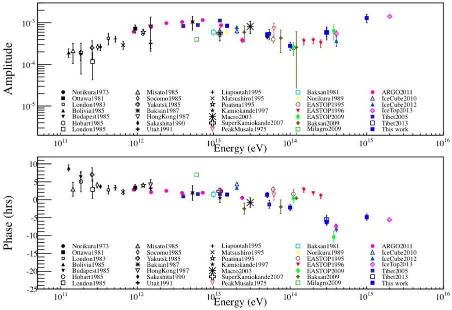
$$c\tau_{\rm esc} = \frac{X(E)}{\bar{n}_{\rm ISM}\mu} \sim 10^3 \text{ kpc} \gg \text{Galaxy size}$$

and it suggests that SN explosions can sustain the galactic CR population:

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

The anisotropy puzzle

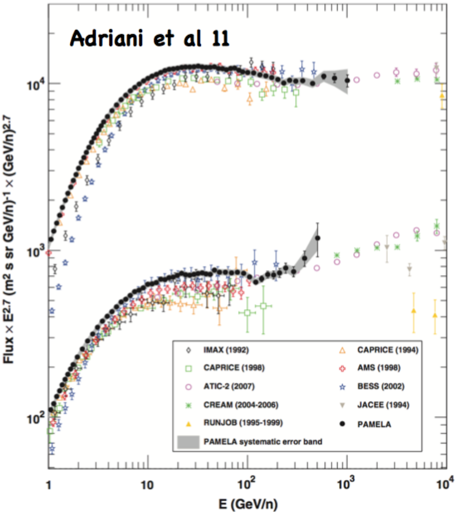
Di Sciascio & Iuppa, 2014

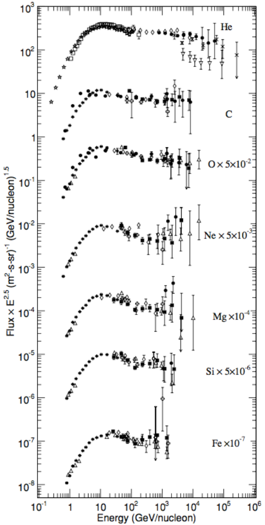


- dipole amplitude increases up to ∼10 TeV and then it decreases
- phase of dipole steadily migrates and suddenly flips

$$A \sim \frac{v_A}{c} \sim 10^{-4} \frac{v_A}{30\,\mathrm{km/s}}$$

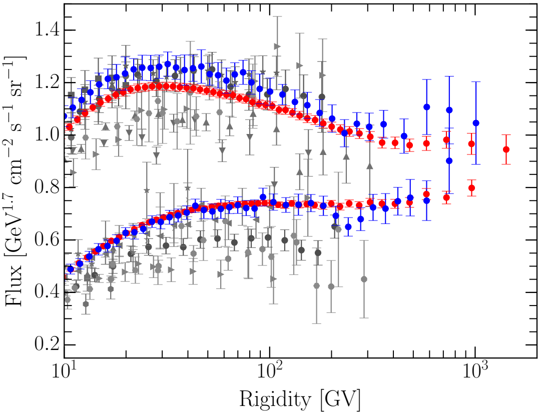
Elemental spectra





PAMELA and AMS-02: The precision era

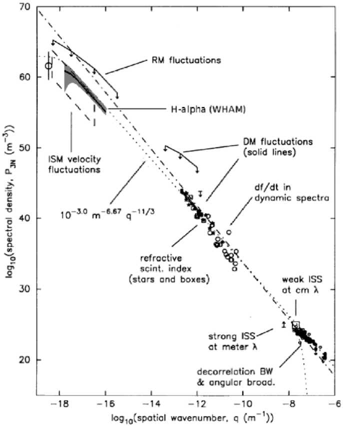
Adriani et al., Science, 2011; Aguilar et al., PRL, 2015



PAMELA and AMS-02 measurements of proton and helium (x10) spectrum.

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]

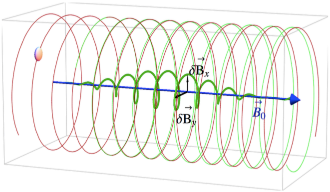
- Turbulence is stirred by Supernovae at a typical scale $L \sim 10 - 100$ pc
- Fluctuations of velocity and magnetic field are Alfvénic
- They have a Kolmogorov $k^{-5/3}$ spectrum (density is a passive tracer so it has the same spectrum: $\delta n_e \sim \delta B$):

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

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

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

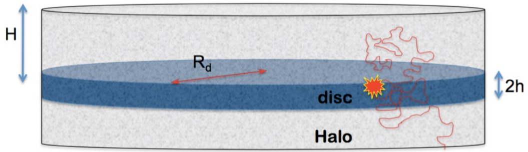
Charged particle in a turbulent field



- 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:

$$D_{\rm xx}(p) = \frac{v r_L}{3} \frac{1}{k_{\rm res} W(k_{\rm res})} \sim \overbrace{3 \times 10^{28}\,\text{cm}^2/\text{s}}^{3\times10^{27}/\eta_B\,\text{cm}^2/\text{s}} \left(\frac{p}{\text{GeV/c}}\right)^{1/3}$$

The transport equation



$$\frac{\partial N_i}{\partial t} - \overbrace{\vec{\nabla} \cdot \left(D_{\rm xx} \cdot \vec{\nabla} N_i - \vec{u} N_i \right)}^{\text{transport}} = \overbrace{Q_{\rm SN} + Q_{\rm losses} + Q_{\rm frag/decay}}^{\text{gain/sinks}}$$

- Spatial diffusion: $\vec{\nabla} \cdot \vec{J} = Q$
- Advection by Galactic winds/outflows: $\vec{u} = u_z^w$
- Source term proportional to Galactic SN profile
- Energy losses: ionization, Bremsstrahlung, IC, Synchrotron, ...
- Production of light nuclei due to the inelastic scattering or the decay of heavier species

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:

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

For $z \neq 0$ one has:

$$D\frac{\partial N}{\partial z} = \text{constant} \rightarrow N(z) = N_0\left(1 - \frac{z}{H}\right)$$

where we used the definition of a *halo*: $N(z = \pm H) = 0$.
The typical solution gives:

$$N_0(p) = \frac{Q_0(p)}{2A_\mathrm{d}}\frac{H}{D(p)} \sim \boxed{p^{-\gamma-\delta}}$$

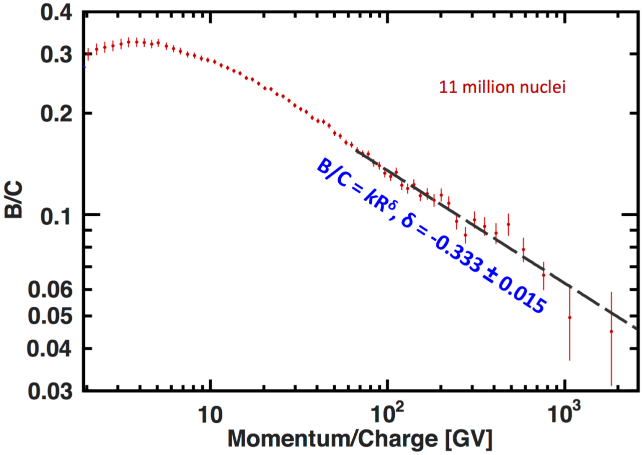
For a secondary (e.g., Li, Be, B) the source term is proportional to the primary density:

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

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

Comparison with B/C as measured by AMS-02

Aguilar et al., PRL, 2016

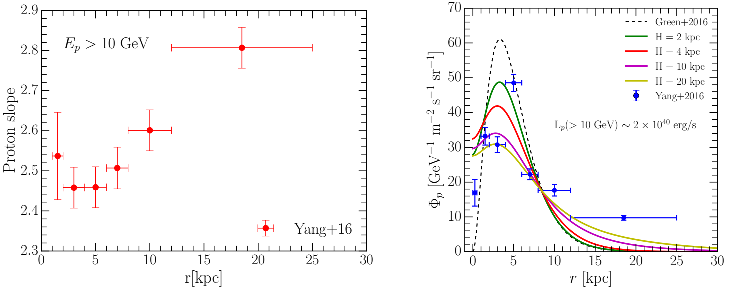


Predictions of the standard picture

- By solving the transport equation we obtain a featureless (at least up to the knee) propagated spectrum for each primary species, at the odds with observations.
- This result remains true even in more sophisticated approach as GALPROP or USINE or DRAGON or PICARD (in order of appearance)
- **What is missing in our physical picture?**

Limits of standard approach: not-local observations

Yang, Aharonian, Evoli, PRD, 2016



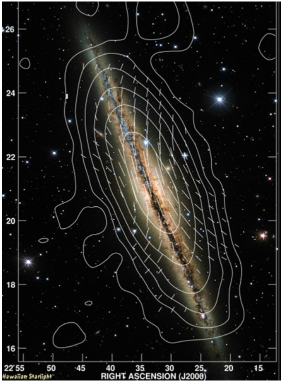
The one-zone model for transport implemented in most of the numerical approaches fails in reproducing not-local observation as γ-ray diffuse and anisotropy.

The halo size H

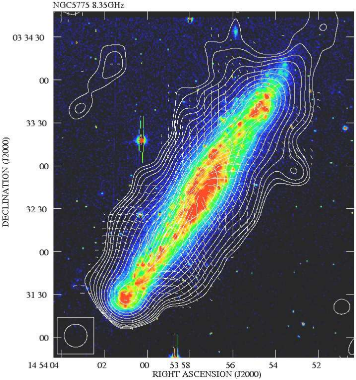
- Assuming $N(z = H) = 0$ reflects the requirement of lack of diffusion (infinite diffusion coefficient)
- May be because $B \to 0$, or because turbulence vanishes (in both cases D cannot be spatially constant!)
- Vanishing turbulence may reflect the lack of sources
- Can be H dependent on p?
- **What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

The radio halo in external galaxies

Credit: MPIfR Bonn



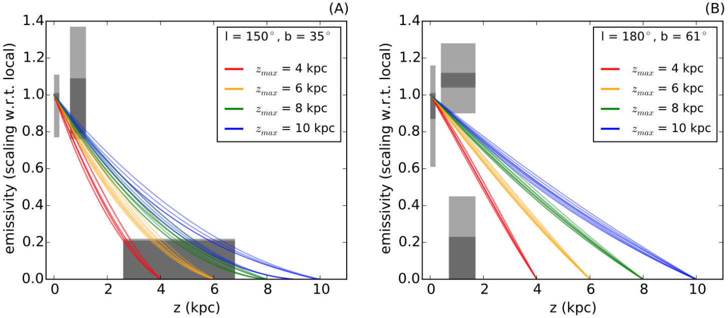
Total radio emission and B-vectors of edge-on galaxy NGC891, observed at 3.6 cm wavelength with the Effelsberg telescope



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 N)
- Indication of a halo with $H \sim$ few kpc

Non-linear cosmic ray transport

Skilling71, Wentzel74

- CR energy density is ~ 1 eV/cm^{-3} in equipartition with: 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 $k \sim r_L$)
- Waves are amplified by CRs through streaming instability:

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

  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 $\epsilon \sim 10\%$

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

The turbulence evolution equation

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

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

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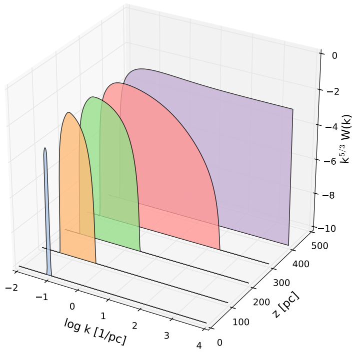
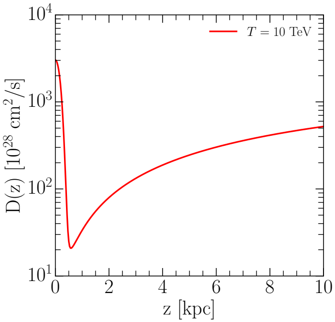
- External (e.g., SNe) source term $Q \sim \delta(z)\delta(k - k_0)$
- In the absence of the instability, it returns a kolmogorov spectrum: $W(k) \sim k^{-5/3}$

Non-linear cosmic ray transport: the turbulent halo

Evoli+2017, in preparation

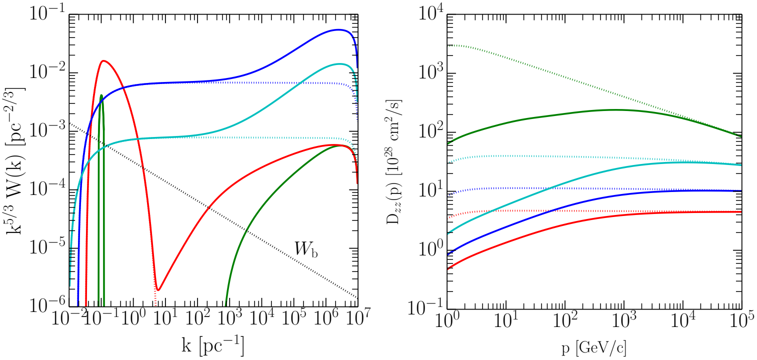




$$\tau_{\rm cascade} = \tau_{\rm adv} \rightarrow \frac{k_0^2}{D_{kk}} = \frac{z_{\rm peak}}{v_A} \rightarrow z_{\rm peak} \sim \mathcal{O}(\rm kpc)$$

Non-linear cosmic ray transport: a global picture

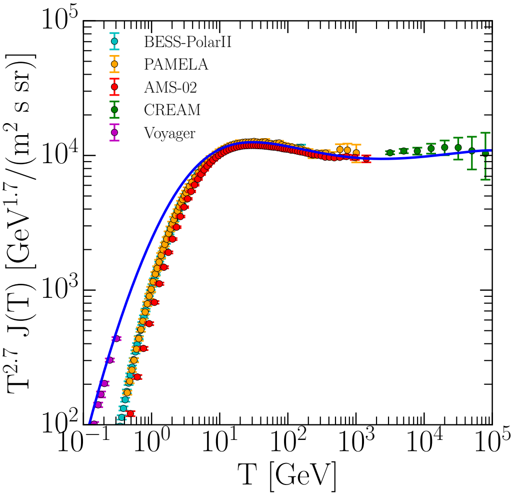
Evoli+2017, in preparation



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+2017, in preparation



- 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

The elephant in the glassware

In Fig: Cosmic rays with $\sim$GeV energy propagating in the interstellar turbulence. We assume that nothing is going to happen.

Conclusions

- Recent findings by PAMELA and AMS-02 (breaks in the spectra of primaries, B/C a 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$200 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.