New approaches in galactic cosmic-ray propagation

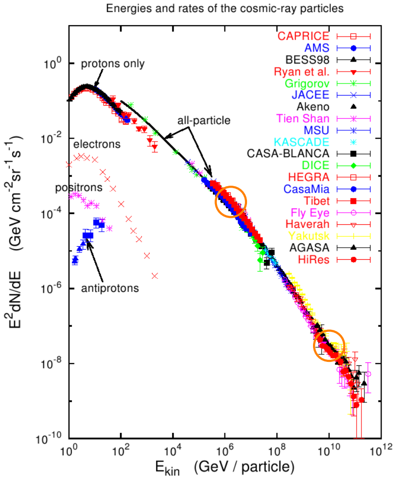
Carmelo Evoli

Gran Sasso Science Institute - L'Aquila

4th Cosmic Ray Anisotropy Workshop @Guadalajara

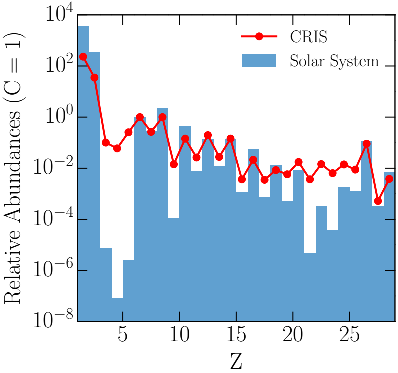
The cosmic-ray spectrum

Credit: Hillas+06



- Almost a perfect power-law over 12 energy decades.
- 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:

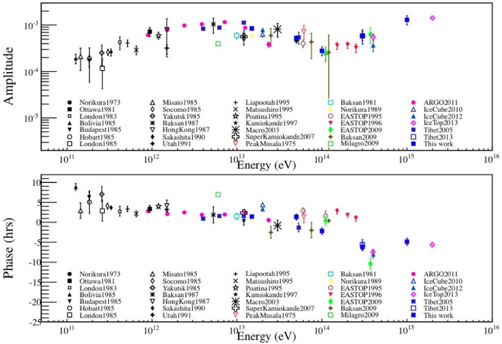
$$c\tau_{\rm esc} = \frac{X(E)}{\bar{n}_{\rm ISM}\mu} \sim 10^3 \text{ kpc} \gg \text{Galaxy size}$$

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

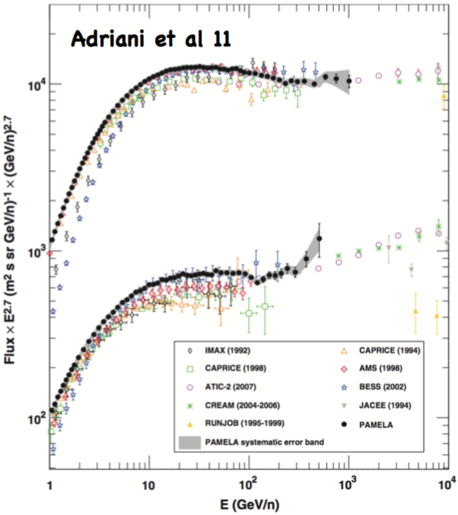
Di Sciascio & Iuppa, 2014

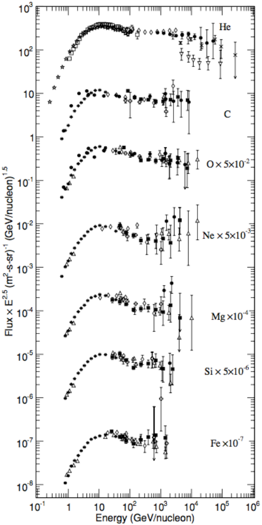


- dipole amplitude increases up to ∼10 TeV and then it decreases
- phase of dipole steadily migrates and suddenly flips

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

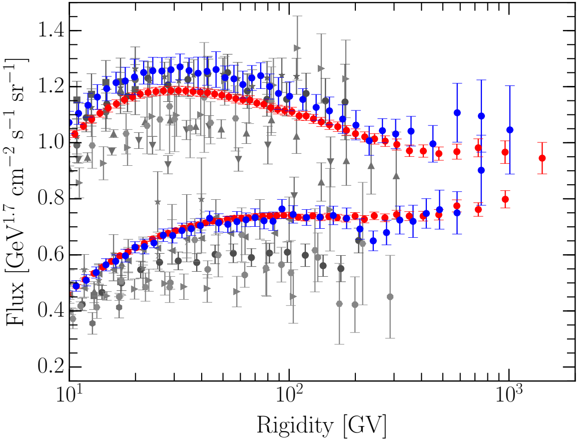
Elemental spectra





AMS-02: The precision era

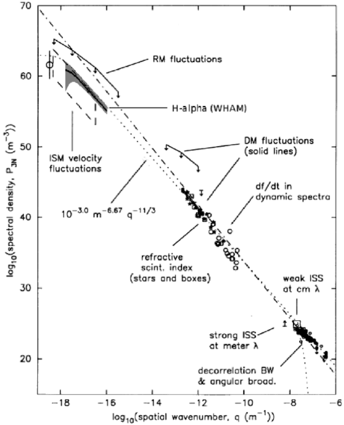
Adriani et al., Science, 2011; Aguilar et al., PRL, 2015



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

The standard picture - I

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



Electron-density fluctuations in the ISM

[Armstrong et al. 1995, ApJ 443, 209]

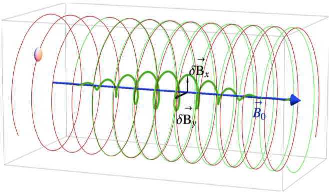
- Turbulence is stirred by Supernovae at a typical scale $L \sim 100$ pc
- Fluctuations of velocity and magnetic field are Alfvénic
- They have a Kolmogorov $k^{-5/3}$ spectrum (density is a passive tracer so it has the same spectrum: $\delta n_e \sim \delta B$):

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

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

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

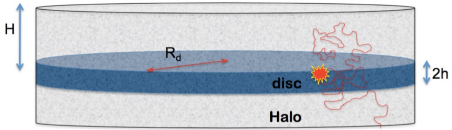
The standard picture - II



- 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 standard picture - III



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

- 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., protons, C, O) at high energy we can ignore energy gain/losses, and the transport equation can be simplified as:

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

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:

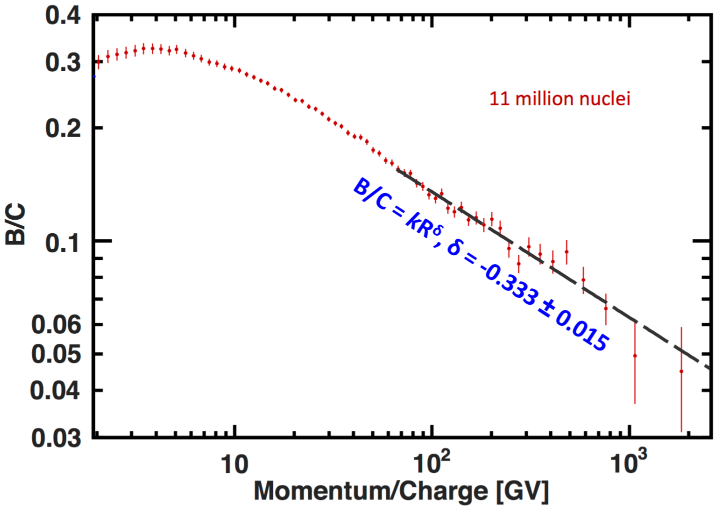
$$N_0(p) = \frac{Q_0(p)}{2A_\mathrm{d}}\frac{H}{D(p)} \sim p^{-\gamma-\delta}$$

For a secondary (e.g., 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



Predictions of the standard picture

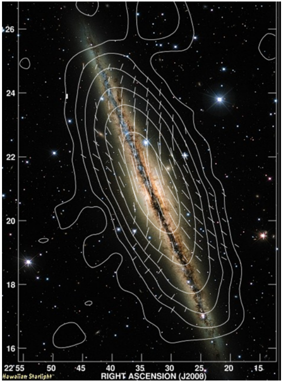
- By solving the transport equation we obtain a featureless (at least up to the knee) propagated spectrum for each primary species, at the odds with observations.
- This result remains true even in more sophisticated approach as GALPROP or DRAGON
- **What is missing in our physical picture?**

The halo size H

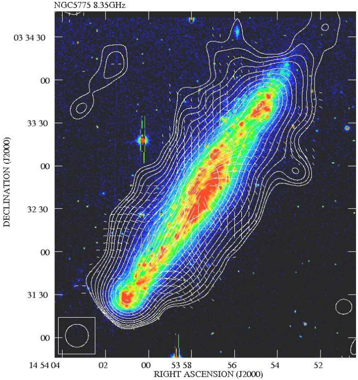
- Assuming $N(z = H) = 0$ reflects the requirement of lack of diffusion (infinite diffusion coefficient)
- May be because $B \to 0$, or because turbulence vanishes (in both cases D cannot be spatially constant!)
- Vanishing turbulence may reflect the lack of sources
- Can be H dependent on p?
- **What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

The radio halo in external galaxies

Credit: MPIfR Bonn



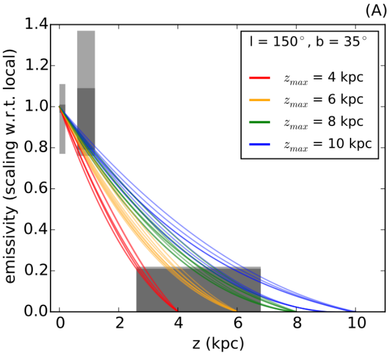
Total radio emission and B-vectors of edge-on galaxy NGC891, observed at 3.6 cm wavelength with the Effelsberg telescope



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

Blasi, Amato & Serpico, PRL, 2012

- 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 (e.g., Wentzel+74)
- 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

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

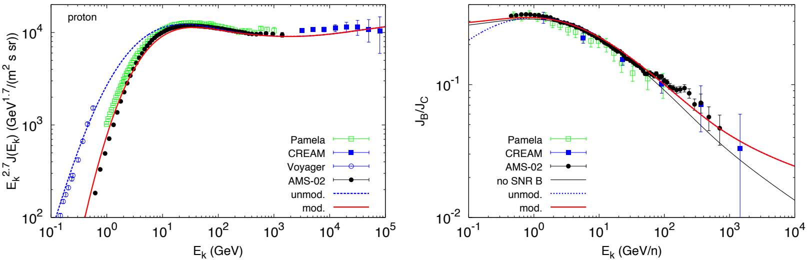
where $W_{\rm CR}$ corresponds to $\Gamma_{\rm CR} = \Gamma_{\rm NLLD}$
Assumptions:

- 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 $\epsilon \sim 10\%$

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

Non-linear cosmic ray transport: main results

Aloisio, Blasi & Serpico, A&A, 2015



- The spectral break as a combination of self-generated and pre-existing waves.
- Voyager data are automatically fitted with no additional breaks, but due to advection with self-generated waves

Non-linear cosmic ray transport: a global picture

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: $D_{kk} = c_k |v_A| k^{7/2} W^{1/2}$

Non-linear cosmic ray transport: a global picture

The turbulence evolution equation

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

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

Non-linear cosmic ray transport: a global picture

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: $D_{kk} = c_k |v_A| k^{7/2} W^{1/2}$
- Advection of the Alfvén waves
- Waves' growth due to cosmic-ray streaming: $\Gamma_{\rm CR} \propto \partial N/\partial z$

Non-linear cosmic ray transport: a global picture

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: $D_{kk} = c_k |v_A| k^{7/2} W^{1/2}$
- Advection of the Alfvén waves
- Waves' growth due to cosmic-ray streaming: $\Gamma_{\rm CR} \propto \partial N/\partial z$
- External (e.g., SNe) source term $Q \sim \delta(z)\delta(k - k_0)$

Non-linear cosmic ray transport: a global picture

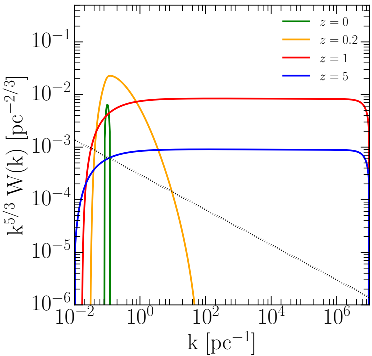
The turbulence evolution equation

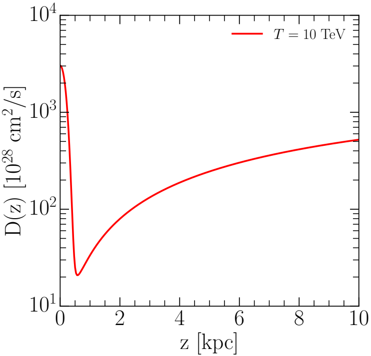
$$\frac{\partial W}{\partial t} = \frac{\partial}{\partial k}\left[D_{kk}\frac{\partial W}{\partial k}\right] + \frac{\partial}{\partial z}\left(v_A W\right) + \Gamma_{\rm CR} W + Q(k)$$

- Diffusion in k-space damping: $D_{kk} = c_k |v_A| k^{7/2} W^{1/2}$
- Advection of the Alfvén waves
- Waves' growth due to cosmic-ray streaming: $\Gamma_{\rm CR} \propto \partial N/\partial z$
- External (e.g., SNe) source term $Q \sim \delta(z)\delta(k - k_0)$
- It enters in the transport equation since $D_{\rm xx} \sim W(k)^1$

Non-linear cosmic ray transport: the turbulent halo

Evoli+2017, in preparation

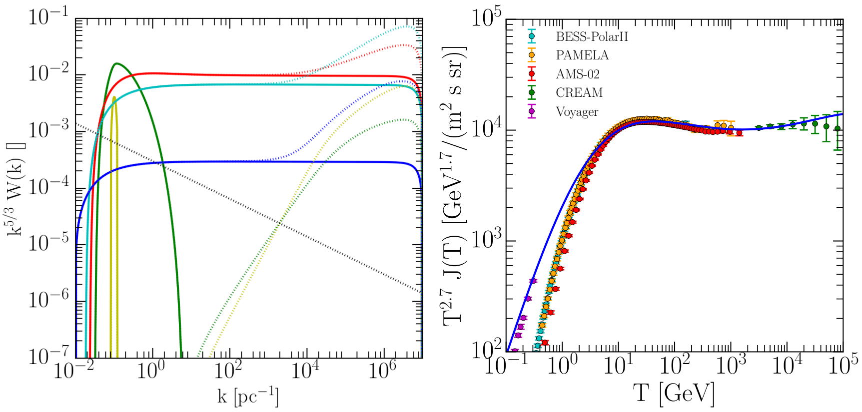




$$\tau_{\rm cascade} = \tau_{\rm adv} \rightarrow \frac{k_0^2}{D_{kk}} = \frac{z_{\rm peak}}{v_A} \rightarrow z_{\rm peak} \sim \mathcal{O}(\rm kpc)$$

Non-linear cosmic ray transport: a global picture

Evoli+2017, in preparation



Turbulence spectrum without (solid) and with (dotted) CR self-generated waves at different distance from the galactic plane: $z = 0$, $z = 0.1$ kpc, $z = 1$ kpc, $z = 5$ kpc

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)
- As a bonus, these models enable us a deeper understanding of the interplay between CR, magnetic turbulence and ISM in our Galaxy