Phenomenology and Theory of Cosmic Particles in the Galaxy

Carmelo Evoli

Gran Sasso Science Institute, L'Aquila (Italy)

New Perspectives on Galactic Magnetism
Newcastle University

The beginning of Cosmic Ray Astrophysics

PHYSICAL REVIEW VOLUME 75, NUMBER 8 APRIL 15, 1949

On the Origin of the Cosmic Radiation

Enrico Fermi
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received January 3, 1949)

A theory of the origin of cosmic radiation is proposed according to which cosmic rays are originated and accelerated primarily in the interstellar space of the galaxy by collisions against moving magmetic fields. One of the features of the theory is that it yields naturally an inverse power law for the spectral distribution of the cosmic rays. The chief difficulty is that it fails to explain in a straightforward way the heavy nuclei observed in the primary radiation.

predicted a galactic magnetic field of $\sim 5\mu G$

Enrico Fermi

Astronomicheskii Zhurnal, Vol. 36, p.17 (1959)

THE DISTRIBUTION OF RELATIVISTIC ELECTRONS IN THE GALAXY AND THE SPECTRUM OF SYNCHROTRON RADIO EMISSION

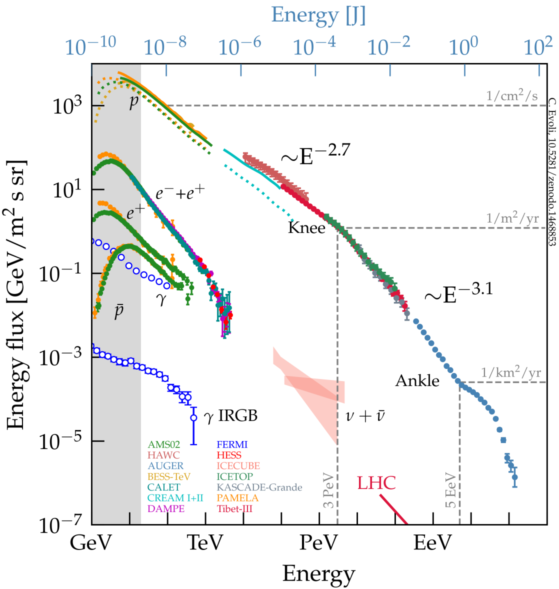
S. I. Syrovat-skii
P. N. Lebedev Physical Institute, Academy of Sciences, USSR

The problem of the diffusion of particles is solved, taking into account the regular changes of the particle energy during this process. The spatial distribution and the energy spectrum of electrons, whose energy changes because of radiation emission in the magnetic field, were found on the assumption that the sources occupy an ellipsoidal volume and inject into interstellar space relativistic electrons with an energy spectrum $QE^{-\gamma_0}$. The case when the distribution of the sources coincides with the flat subsystem of the galaxy and $\gamma_0 = 2$ is considered in detail. The energy spectra of electrons along the line of sight in different directions and the corresponding intensities of synchrotron radiation were calculated. It is shown that the energy spectrum of electrons along the line of sight can be represented in a limited energy region by the expression $KE^{-\gamma}$, where γ varies within the limits $2 < \gamma < 3$, depending on the choice of the diffusion coefficient. The choice of the diffusion coefficient of relativistic particles in interstellar space equal to $D = 10^{29}$ cm/sec and the intensity of the

More accurate data on the radio radiation observed in different directions will make it possible to increase the accuracy of the determinations of the various parameters and also to determine the value of q which lies within the limits 0.6–0.8. The numerical estimates made must be regarded as preliminary, particularly since it is possible that the source-spectrum exponent is slightly different from that adopted by us (35).

Sergei Ivanovich Syrovatskii

The cosmic-ray spectrum 70 years later...



The cosmic-ray spectrum 70 years later...

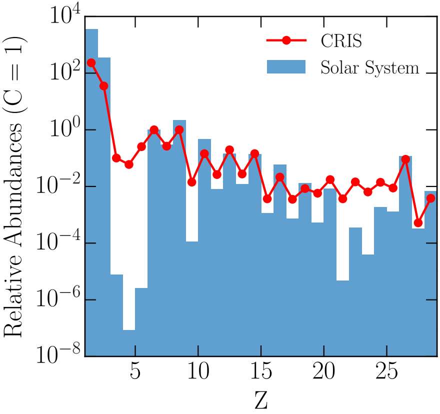
- **Non-thermal:** Almost a perfect power-law over more than 11 energy decades.
- Evidence of departures from a perfect power-law: the **knee** and the **ankle** features.
- Spectrum cut-off at $\gtrsim 10^{20}$ eV, **GZK or cosmic-ray sources out of steam?**.
- Particles observed at energy higher than any terrestrial laboratory $\times 10^3$.
- Direct measurements (at low-E) versus air-cascade reconstructions (at high-E).
- **Composition** at R $\sim$ 10 GV:
  - $\sim$ 99.2% are nuclei
  - $\sim$ 84% protons and $\sim$ 15% He
  - $\sim$ 1% heavier nuclei
  - $\sim$ 0.7% are electrons
  - $\sim$ 0.1% are **anti-matter** particles (positrons and antiprotons)

The classical questions in CR physics

Gabici, Evoli+, arXiv:1903.11584

- 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)
- Where is the transition between galactic and extra-galactic CRs? (the knee being the first suspect!)
- What is their contribution to high-energy diffuse emissions (γ and ν's) and low-frequency radio emissions?

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**).
- From this plot it follows the more robust evidence of **diffusive** transport so far!

The grammage pillar

- The **grammage**, χ, is the amount of material that the particle go trough along propagation (a sort of "column density"):

$$\chi = \int dl \rho(l)$$

- and can be measured by the secondary-over-primary ratio, e.g.:

$$\frac{\mathrm{B}}{\mathrm{C}} \sim \frac{\chi}{\bar{m}_{\rm ISM}/\sigma_{C\to B}} \sim 0.3 \to \chi \sim 5 \ \mathrm{g/cm^2}$$

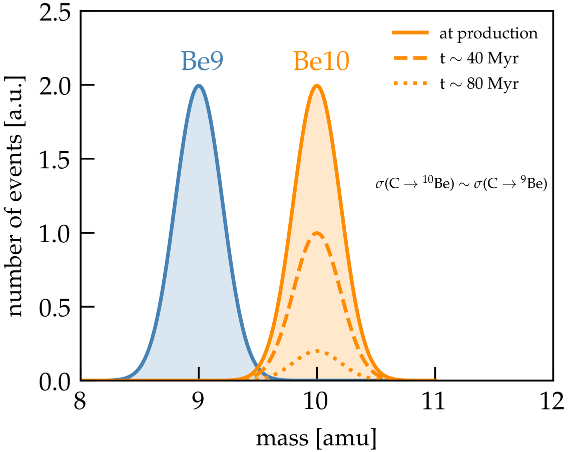
- Let me assume that the grammage is accumulated in the disk (more than a working hypothesis!)
- At each crossing of the disk ($h \sim 200$ pc):

$$\chi_d \sim m_p n_{\rm gas} h \sim 10^{-3} \ \mathrm{g/cm^2} \ll \chi_{\rm BC}$$

- Therefore the particles have to cross the disk many times. I can estimate what is the **minimum** time spent in the gas region as:

$$t_{\rm prop} \sim \frac{\chi_{\rm B/C}}{\chi_{\rm d}} \frac{h}{v} \sim 5 \times 10^6 \, \text{years} \ll \frac{R_G}{c}$$

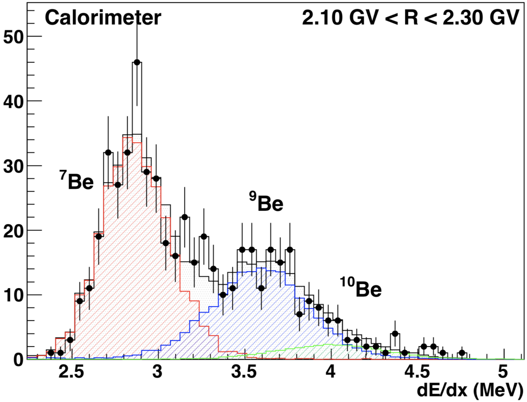
The escape timescale



- ^{10}Be has a decay timescale of $\sim$ 1.39 Myr
- the isotopic ratio points toward an escape timescale of $O(100)$ Myr
- the presence of a low-density **halo**

The escape timescale

PAMELA Collaboration, ApJ, Vol. 862, 141 (2018)



- ^{10}Be has a decay timescale of ~ 1.39 Myr
- the isotopic ratio points toward an escape timescale of $O(100)$ Myr
- the presence of a low-density **halo**

Cosmic ray escape time and sources

D. Ter Haar, Reviews of Modern Physics, 1950

- The escape time is crucial to identify CR source suspects.
- The luminosity required to sustain the galactic CR population:

$$L_{\rm CR} = \frac{\epsilon_{\rm CR} V_{\rm MW}}{\tau_{\rm esc}} \sim 10^{41}\,\text{erg/s}$$

where

  - $\epsilon_{\rm CR} \sim 1$ eV/cm^3 is the local CR energy density
  - $V_{\rm MW} = \pi R_d^2 2H \sim 2 \times 10^{68}$ cm^{-3} is the Milky Way Volume
  - $\tau_{\rm esc} \sim 100$ Myr is the "escape" time

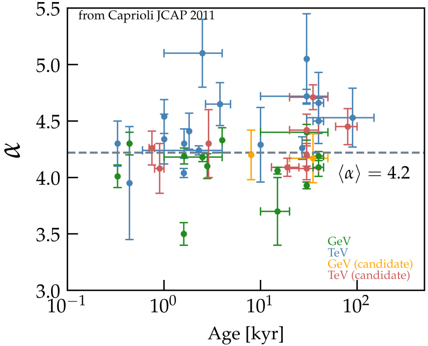
- SNe energy rate in our Galaxy:

$$L_{\rm SN} = E_{\rm SN} R_{\rm SN} \sim 10^{42}\,\text{erg/s}$$

- Galactic SNe provide the right energetics if $\sim 10\%$ efficiency in CR acceleration is achieved.

Galactic cosmic-ray factories

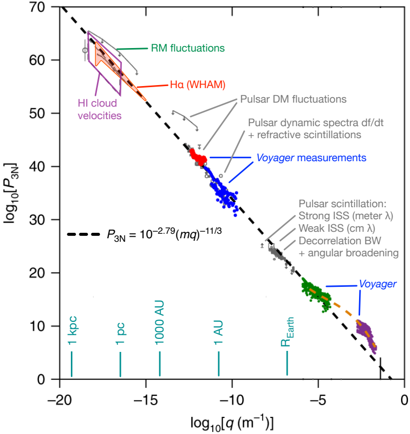
A.R. Bell, Astroparticle Physics, 43, 56 (2013)



- Diffusive shock acceleration (DSA) predicts $q \equiv \frac{dn}{dt\, d^3p} \propto p^{-4}$ for strong shocks, indipendent on microphysics
- maybe **softer** because of non-linear effects
- Pure rigidity dependent acceleration (**universality**) with a unique power-law in momentum (**scale-free**).

The interstellar turbulence

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



Electron-density fluctuations in the ISM
[Armstrong+, ApJ 1995 - Chepurnov & Lazarian, ApJ 2010 - Lee & Lee, Nature Astr. 2019]

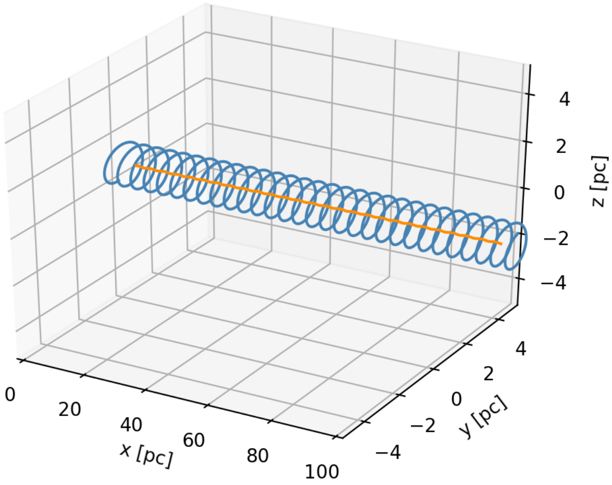
- Turbulence is stirred by Supernovae at a typical scale $L \sim 10 - 100$ pc
- Fluctuations of velocity and magnetic field are Alfvénic
- They have a Kolmogorov $\alpha \sim -5/3$ spectrum (density is a passive tracer so it has the same spectrum: $\delta n_e \sim \delta B^2$):

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

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

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

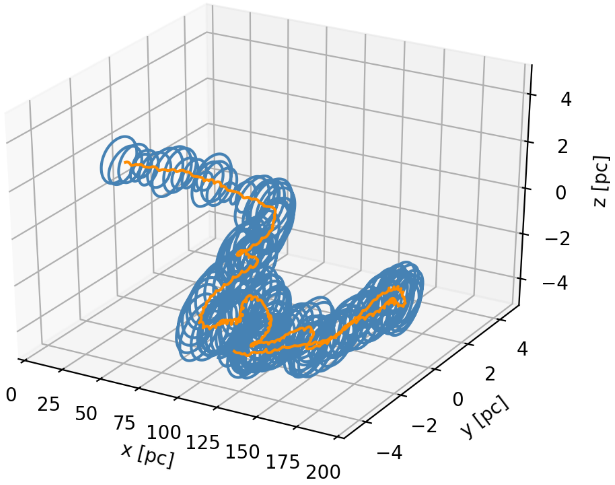
Charged particle in a turbulent field
Jokipii, ApJ 1966



- $R \equiv p/Z = 0.1$ PV
- $B_0 = B_x = 1\mu$G $\rightarrow r_L \sim 0.1$pc
- $\delta B / B_0 = 0$

Charged particle in a turbulent field

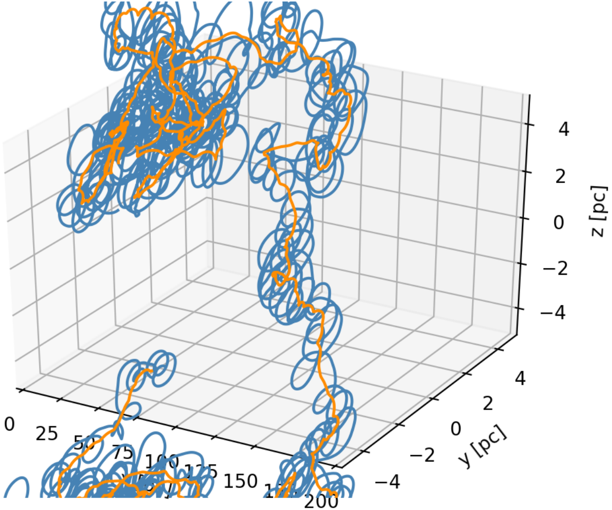
Jokipii, ApJ 1966



- $R \equiv p/Z = 0.1$ PV
- $B_0 = B_x = 1\mu$G $\rightarrow r_L \sim 0.1$pc
- $\delta B / B_0 = 0.1$
- $\lambda \sim O(100)$ pc
- $D_\parallel \gg D_\perp$

Charged particle in a turbulent field

Jokipii, ApJ 1966

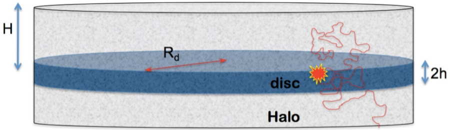


- $R \equiv p/Z = 0.1$ PV
- $B_0 = B_x = 1\mu$G
  $\rightarrow r_L \sim 0.1$pc
- $\delta B/B_0 = 1$
- $D_\parallel \gtrsim D_\perp$

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**

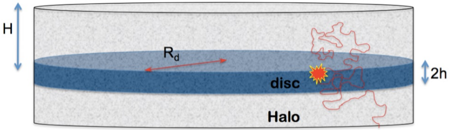
The CR transport equation in the halo model



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

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

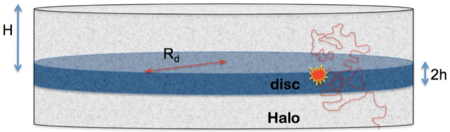
The CR transport equation in the halo model



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

- Spatial diffusion: $\vec{\nabla} \cdot \vec{J}$
- Advection by Galactic winds/outflows: $u = u_w + v_A \sim v_A$

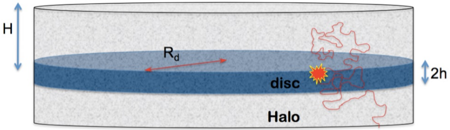
The CR transport equation in the halo model



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

- Spatial diffusion: $\vec{\nabla} \cdot \vec{J}$
- Advection by Galactic winds/outflows: $u = u_w + v_A \sim v_A$
- Source term proportional to Galactic SN profile

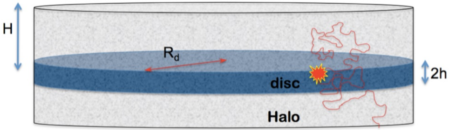
The CR transport equation in the halo model



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

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

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

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

For $z \neq 0$ one has:

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

where we used the definition of a *halo*: $f(z = \pm H) = 0$.
The typical solution for a **primary** species, e.g., C, gives (assuming injection $Q_{\rm SNR} \propto p^{-\gamma}$):

$$f_C(p) = \frac{Q_{\rm SNR}(p)}{2\pi R_d^2}\frac{H}{D(p)} \sim p^{-\gamma-\delta}$$

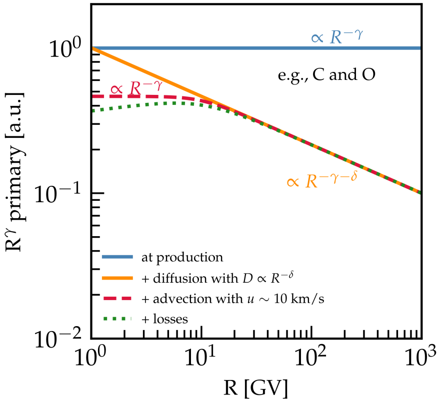
For a *secondary*, e.g., B, species the source term is proportional to the primary density:

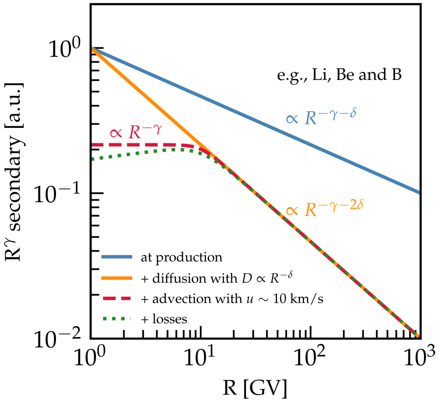
$$Q_B \sim \bar{n}_{\rm ISM} c\sigma_{C\to B} f_C \;\to\; f_{\rm B}(p) \propto \frac{f_C(p)}{D(p)}$$

and finally

$$\frac{\rm B}{\rm C} \propto p^{-\delta}$$

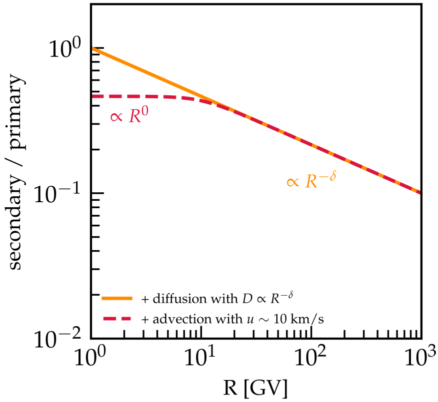
Phenomenology of cosmic-ray transport

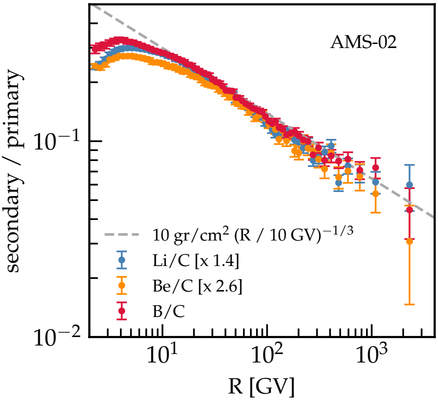




- Diffusion is a rigidity dependent escape mechanism
- Advection could be relevant at low rigidities for reasonable values of u

Phenomenology of cosmic-ray transport

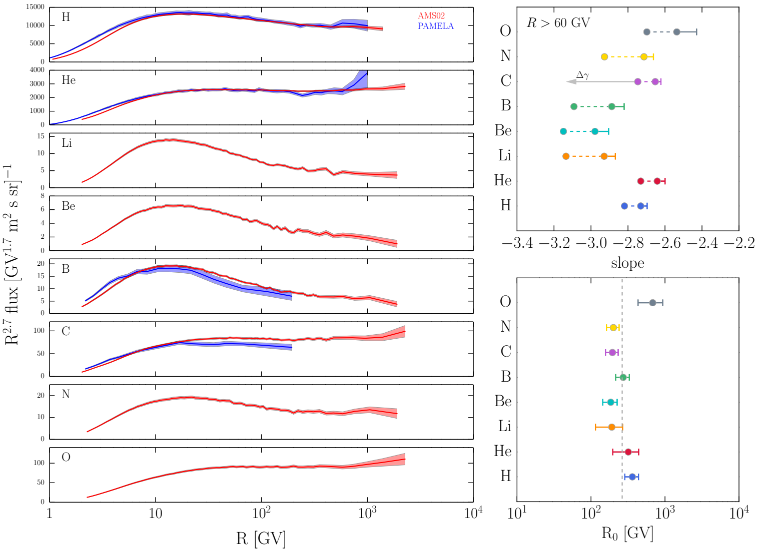




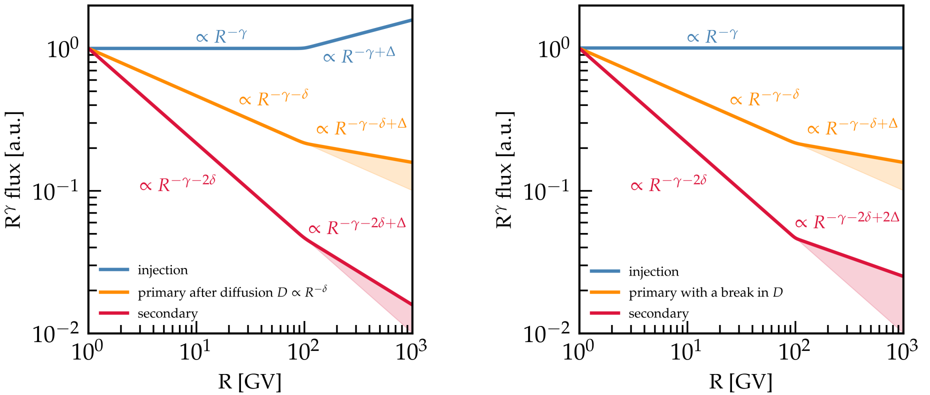
- Evidence of energy dependent **grammage**
- diffusive transport at least for $R \gtrsim 10$ GV

Unprecedented data precision: The rigidity break

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

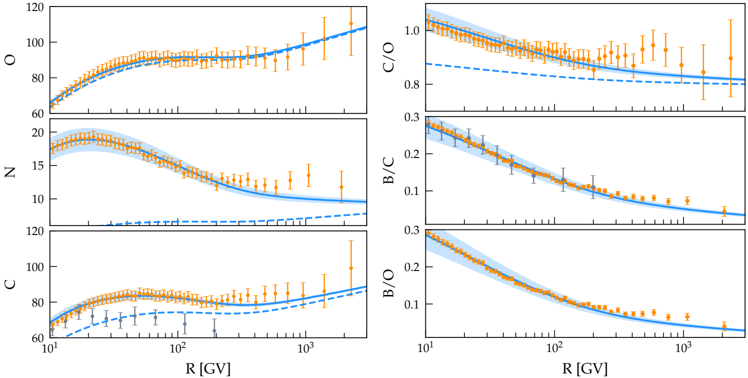


About the origin of the break: injection or diffusion?



- The observed spectral hardening at ~ 300 GV is likely 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]**

Phenomenology of galactic cosmic-rays

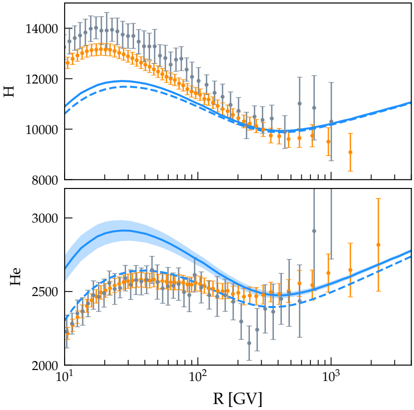


- Let me model D as a smoothly-broken power-law:

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

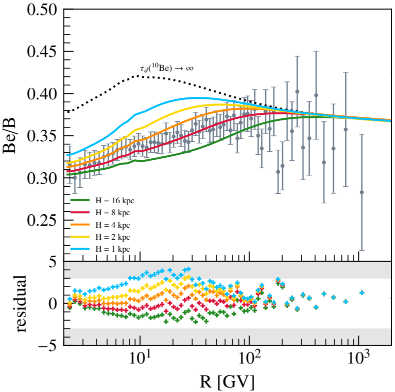
- by fitting primary and secondary/primary measurements we find: $\delta \sim 0.64$, $D_0/H \sim 0.25 \times 10^{28}$ **cm/s^2/kpc**, $\Delta\delta \sim 0.2$, $u \sim 7$ km/s and $\gamma \sim 4.26$
- **B/C and C/O as grammage indicators are severely limited by our knowledge of cross-sections.**

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]**.

The Beryllium over Boron ratio as cosmic-ray clock



- Only total Beryllium has been measured, with high precision altough
- In diffusive models:

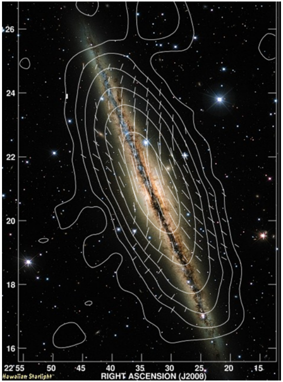
$$t_{\rm esc} \sim \frac{H^2}{2D} \sim 60\,\text{Myr} \left(\frac{H}{\text{kpc}}\right) \left(\frac{0.25 \times 10^{28}\,\text{cm}^2/\text{s}/\text{kpc}}{D_0/H}\right)$$

- By solving the transport equation with standard assumptions 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

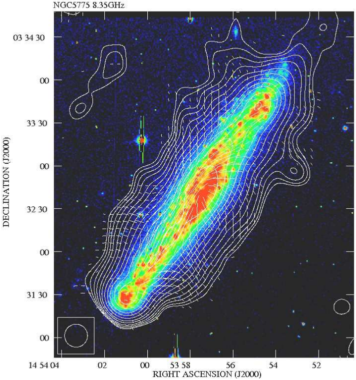
- Assuming $f(z = H) = 0$ reflects the requirement of lack of diffusion (infinite diffusion coefficient)
- May be because $B \to 0$, or because turbulence vanishes (in both cases D cannot be spatially constant!)
- Vanishing turbulence may reflect the lack of sources
- Can be H dependent on p? (remember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



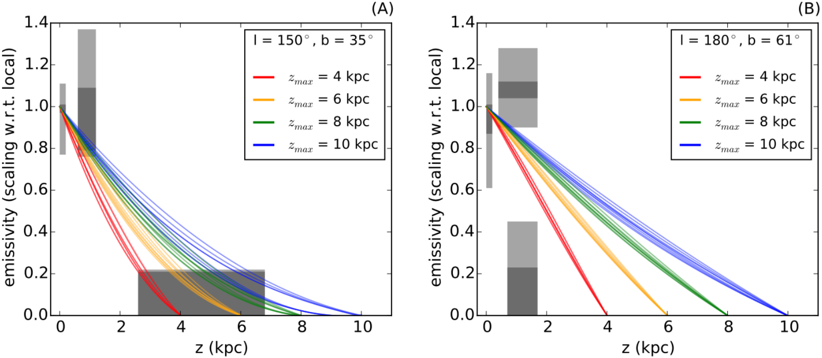
Total radio intensity and B-vectors of edge-on galaxy NGC 5775,

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 $\epsilon \sim 10\%$

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

The turbulence evolution equation

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

The turbulence evolution equation

Eilek, ApJ 1979

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

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

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

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: $D_{kk} = c_k |v_A| k^{7/2} W^{1/2}$
- 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 $Q \sim \delta(z)\delta(k - k_0)$

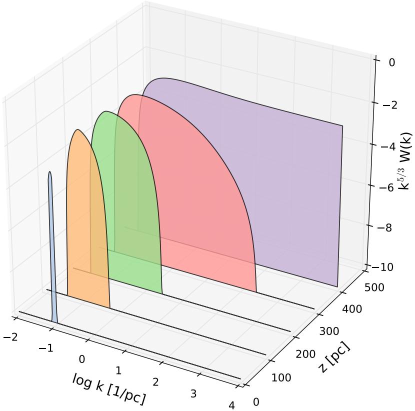
The turbulence evolution equation
Eilek, ApJ 1979

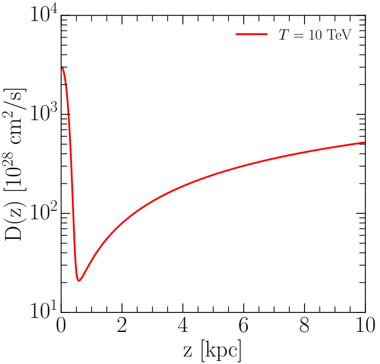
$$\frac{\partial W}{\partial t} = \frac{\partial}{\partial k}\left[D_{kk}\frac{\partial W}{\partial k}\right] + \frac{\partial}{\partial z}(v_A W) + \Gamma_{\rm CR} W + Q(k)$$

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

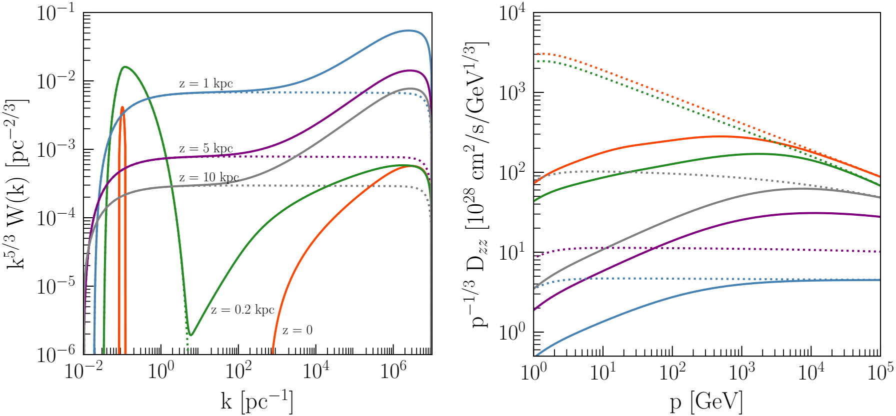
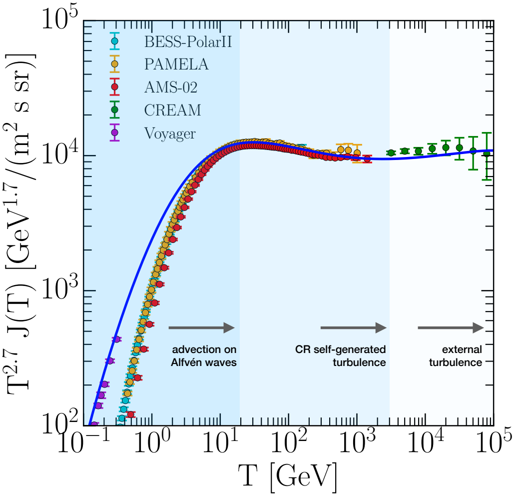


Figure: Turbulence spectrum without (dotted) and with (solid) CR self-generated waves at different distance from the galactic plane.

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. **Exciting news from gamma-ray observations as well!**
- 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 ∼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. **A more fundamental description of CR propagation is hoped for.**

Thank you!

Carmelo Evoli

GRAN SASSO SCIENCE INSTITUTE
Viale Francesco Crispi, 7, L'Aquila (Italy)
mailto: carmelo.evoli@gssi.it
@carmeloevoli
carmeloevoli
e.carmelo
0000-0002-6023-5253
slides available at:
https://zenodo.org/communities/carmeloevoli_talks