Cosmic Ray Transport & Self-Generated Turbulence

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MHD & Plasma waves

From the **Liouville theorem** for a **collisionless plasma**, the evolution in the **phase space** of each particle's species is described by the **Vlasov equation**:

$$\frac{\partial f_s}{\partial t} + \vec{v}\cdot\vec{\nabla}_x f_s + \frac{q_s}{m_s}\left(\vec{E} + \frac{\vec{v}}{c}\times\vec{B}\right)\cdot\vec{\nabla}_v f_s = 0$$

Summing the Vlasov equations of **thermal electrons and protons**, the equation for the **mass and momentum conservation**, known as **ideal MHD equations**, are obtained:

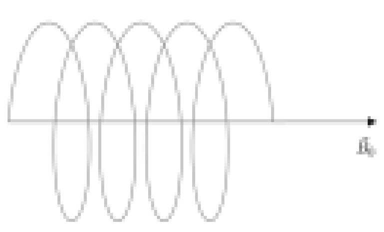
$$\frac{\partial \rho}{\partial t} + \vec{\nabla}\cdot(\rho\vec{v}) = 0$$

$$\rho\left[\frac{\partial \vec{v}}{\partial t} + \vec{v}\cdot\vec{\nabla}\vec{v}\right] = -\vec{\nabla}P + \frac{1}{4\pi}\left(\vec{\nabla}\times\vec{B}\right)\times\vec{B}$$

From perturbative analysis, one can see that waves with **wave-vector** $\vec{k} \parallel B_0$, known as **Alfvèn waves**, travel at the Alfvèn speed:

$$\omega^2 = k^2 v_A^2 \qquad v_A = \frac{B_0}{\sqrt{4\pi\rho}}$$

Cosmic Rays diffusion



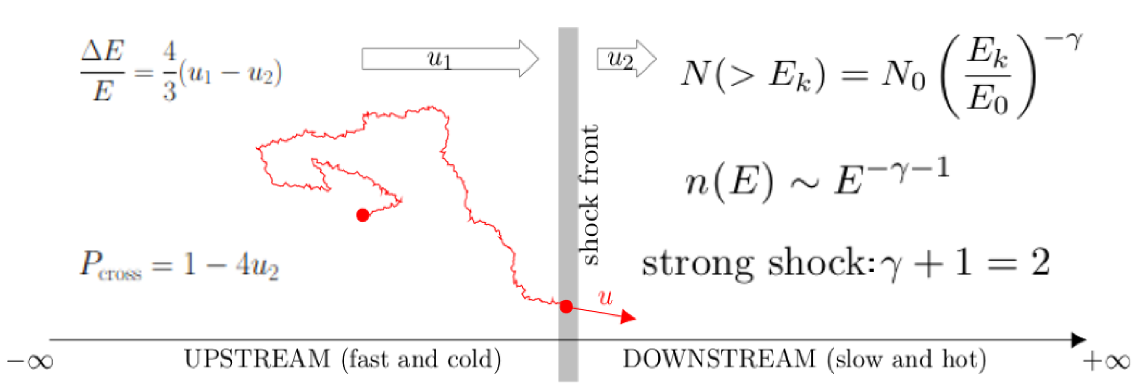
$$m\gamma\frac{d\vec{v}}{dt} = \frac{q}{c}\left[\vec{v}\times\left(\vec{B}_0 + \delta\vec{B}\right)\right]$$

$$\frac{d\mu}{dt} = \frac{q\delta B}{mc\gamma}(1-\mu^2)^{1/2}\cos\left[\Omega t \mp kv\mu t \mp \phi\right]$$

$$\langle\frac{\Delta\mu\Delta\mu}{\Delta t}\rangle = \left(\frac{q\delta B}{mc\gamma}\right)^2(1-\mu^2)\frac{\pi}{\mu v}\delta\left[k \mp \frac{\Omega}{v\mu}\right]$$

The **pitch angle diffusion** on magnetic perturbations has a **resonance condition** that depends on the **test-particle pitch angle** (μ): $k_{\rm wave} = \frac{1}{R_L\mu}$. $\Rightarrow$ A spectrum of turbulence δB(k) is able to diffuse a spectrum of cosmic rays. For a deeper treatment, **see P. Blasi short course**, *HE-1: Particle acceleration in astrophysical plasma.*

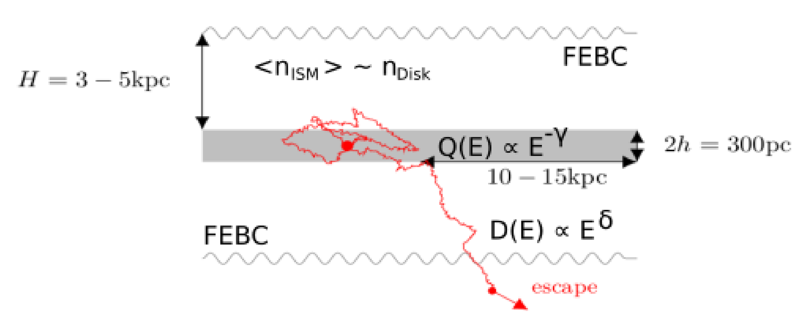
DSA & Supernovae paradigm



To explain how **Galactic sources** can reach the **energy of the CR's knee**, something is needed to **amplify the turbulence in the upstream!**

$$\tau_{\rm acc} = \frac{3}{u_1 - u_2}\left[\frac{D_1}{u_1} + \frac{D_2}{u_2}\right] \sim 1000\ {\rm yr}\ \cdot {\rm E}_{\rm GeV}^{1/2}.$$

Leaky Box model



$$n(E)_{\rm I} \propto \begin{cases} Q(E)H^2/D(E) \propto E^{-\gamma-\delta} & \text{if } \tau_{\rm esc} << \tau_{\rm spall} \\ Q(E)\tau_{\rm spall} \propto E^{-\gamma} & \text{if } \tau_{\rm esc} >> \tau_{\rm spall} \end{cases}$$

$$n(E)_{\rm II} \propto \begin{cases} n(E)_{\rm I}H^2/D(E) \propto E^{-\gamma-2\delta} & \text{if } \tau_{\rm esc} << \tau_{\rm spall} \\ n(E)_{\rm I}\tau_{\rm spall} \propto E^{-\gamma} & \text{if } \tau_{\rm esc} >> \tau_{\rm spall} \end{cases}$$

$$n(E)_{\rm II}^{\rm unst.}/n(E)_{\rm II}^{\rm st.} \propto \sqrt{H^2/D(E)} \propto E^{-\delta/2} \quad \text{if } \tau_{\rm esc} >> \tau_{\rm decay}$$

Credit: *Ulyana Dupletsa, "P. Blasi course notes 2020/2021"*

Streaming instability

When the **plasma-waves dispersion relation** has an **imaginary component**, the magnetic field fluctuations are **exponentially amplified or damped**.
Including Cosmic Rays in the plasma description (**kinetically**, through their Vlasov equation, or in **MHD**, through their energy density and pressure), leads to the excitation of unstable waves **through their current**.

$$EJ(>E) >> cU_{\rm B} \Rightarrow \textbf{Non-resonant modes}$$
$$EJ(>E) << cU_{\rm B} \Rightarrow \textbf{Resonant modes}$$

- The CR's current excites unstable magnetic fluctuations.
- The growth of the waves suppresses the CR's diffusion coefficient and develops a pressure gradient that acts on the plasma.
- Both **advection and diffusion** impact the current.

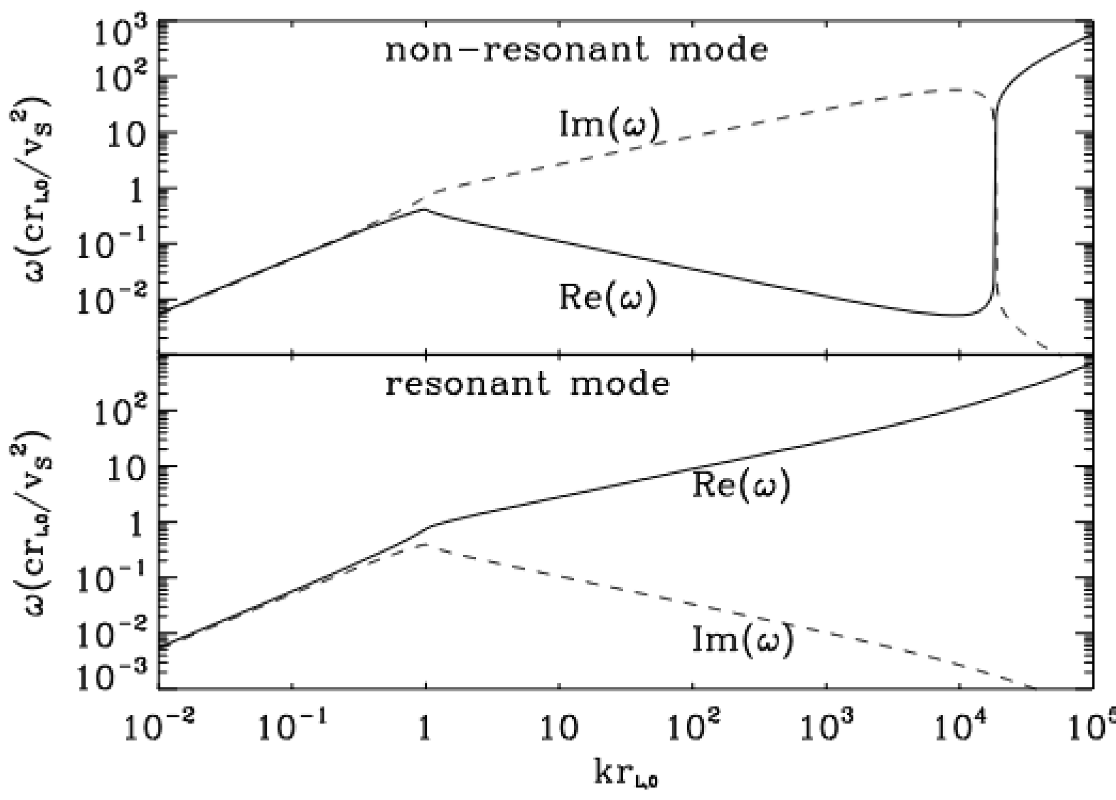


Figure: *Amato, E. and Blasi, P. "A kinetic approach to cosmic-ray-induced streaming instability at supernova shocks" (2009), MNRAS.*
Bell, A. R. "Turbulent amplification of magnetic field and diffusive shock acceleration of cosmic rays" (2004), MNRAS

In general, these are **non-linear effects**, studied **phenomenologically**, **semi-analytically** and through **numerical simulations**:

- **PIC**: Both plasma and CRs are treated as particles (**fully kinetic**).
- **Hybrid**: plasma electrons are treated as a fluid (**MHD**), CRs and ions as particles (**kinetic**)

Why do we need these? What can we measure?

- **Secondary products** (γ, ν).
- **Primary / Secondary nuclei** (H/He, B/C ...).
- **Diffusion** acts in **rigidity** (prop. + acc.), while **spallation** acts in **Energy/nucleon** (prop.).

Non-linear DSA in Supernovae

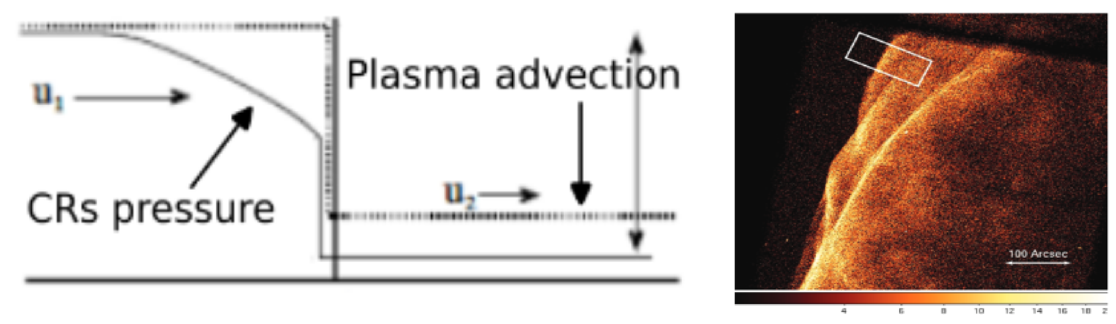


Figure: *Morlino, G. and Amato, E. and Blasi, P. and Caprioli, D. "Spatial structure of X-ray filaments in SN 1006" (2010), MNRAS: Letters.*

Galactic Halo

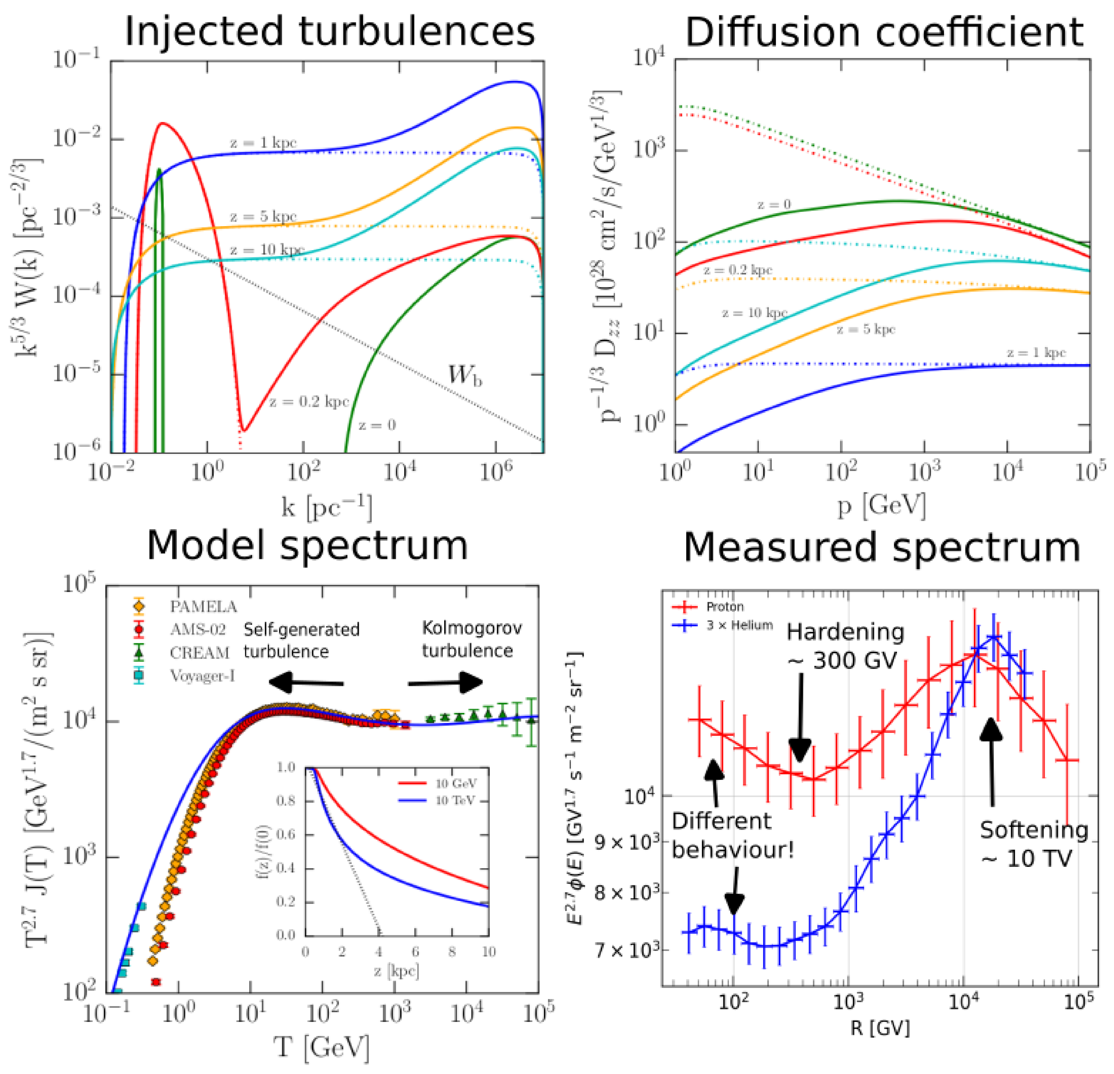


Figure: *Evoli, C. and Blasi, P. and Morlino, G. and Aloisio, R. "Origin of the Cosmic Ray Galactic Halo Driven by Advected Turbulence and Self-Generated Waves" (2018), PRL.*
An, Q. et al. "Measurement of the cosmic ray proton spectrum from 40 GeV to 100 TeV with the DAMPE satellite" (2019), Science Advances.

Low-diffusivity bubbles

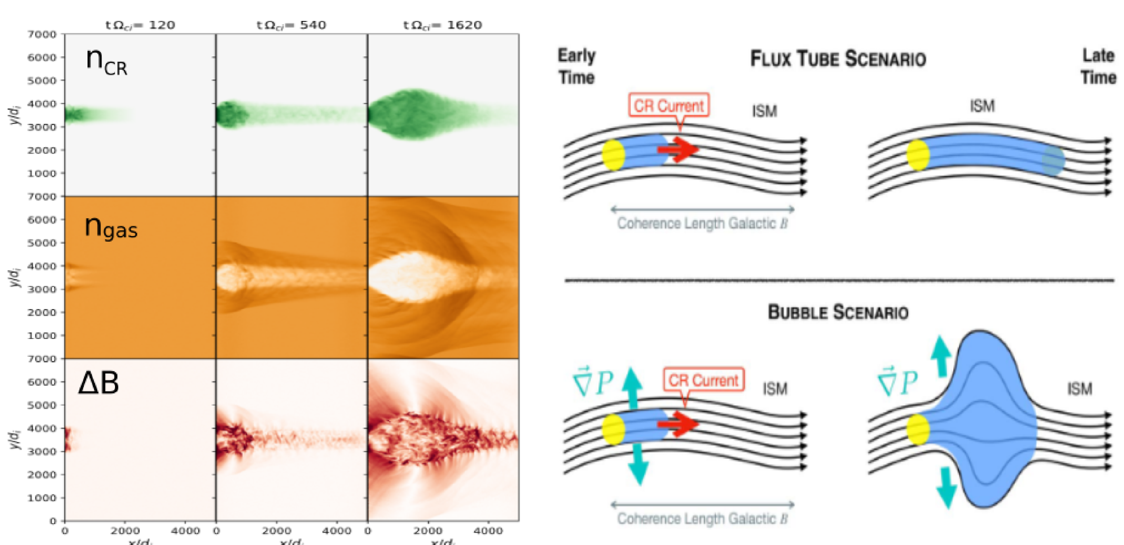


Figure: *Schroer, B. et al. "Dynamical Effects of Cosmic Rays on the Medium Surrounding Their Sources" (2021), AAS.*

Ultra-High Energy Cosmic Rays

For more details, **see R. Aloisio short course**, *HE-7: UHECR theory.*

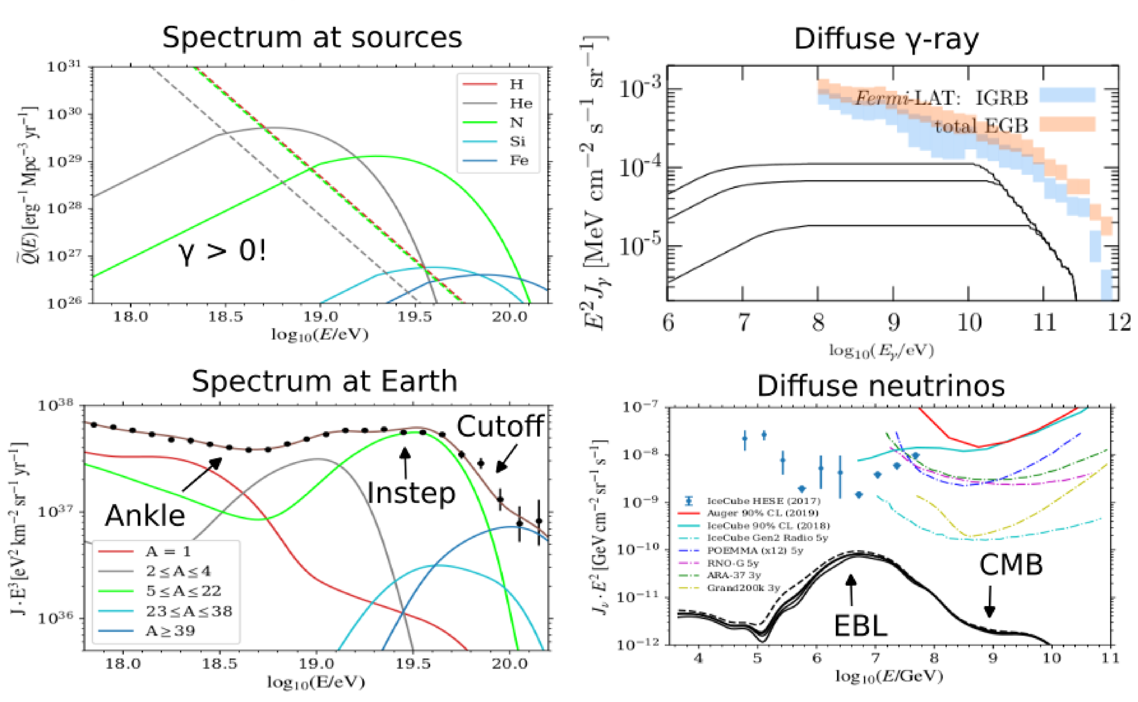


Figure: *Halim, A. et al. "Constraining the sources of ultra-high-energy cosmic rays across and above the ankle with the spectrum and composition data measured at the Pierre Auger Observatory" (2023), JCAP*

What we measure:

- **Anisotropy** due to **local sources distribution**.
- **Energy-spectrum features** due to mixed **mass-composition** and **interactions**.
- **Highest proton-fraction** at the **ankle**.

(some)**Open questions**:

- Which are the **sources**?
- Which is the **acceleration mechanism** at play? (DSA, relativistic shocks, unipolar inductor...)
- **Magnetic horizon**:
  - **Self-induced** or **pre-existing** turbulence? (the **cosmological magnetic field** is poorly known...)
  - Where the **transition between Galactic** and **extra-galactic flux** takes place? How the **mass composition in the transition region** is affected?
- **cosmogenic neutrinos**:
  - ν's produced on the **CMB** still below observational limits.
  - neutral particles produced only by UHE hadrons ⇒ they can **point-back to the sources**!