Excitation of non-resonant streaming instabilities around sources of Ultra-High Energy Cosmic Rays

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NRSI around sources of Cosmic Rays

Each source of Cosmic Rays in the Universe (SNRs, Our Galaxy, sources of UHECRs...) has an escaping flux through the ISM/IGM, that can excite perturbations of the magnetic field.

Observations in the last years show a reduced diffusion coefficient around Galactic Cosmic Ray sources (PWN Halos, SNRs..) wrt. the mean Galactic diffusion coefficient inferred from the secondary to primary ratio.

Instabilities are triggered by the condition than the local energy flux associated to the current is bigger than the local magnetic energy density times the speed of light.

$$\frac{1}{e}\int_{E_{min}}^{E_{max}} dE \cdot E j_{cr}(E) > c \cdot \frac{B_0}{4\pi}$$

Self-induced diffusion

The strong current of CRs that flows out from the source can excite the non resonant modes of the plasma in various astrophysical environments, enhancing the power in perturbation of the magnetic field.

$$D(E) = \frac{c}{3} \frac{R_L}{k_{res} F(k_{res})}$$

The instabilities are excited at wavelenghts shorter than the Larmor radius of the low-energetic particles in the currents, so the cosmic rays transport is unaffected by the perturbations till they reach the saturation.

As a result, low energetic particles cannot leave the circumsource environment, but diffuse close to the source.

Advection of the plasma

Diffusion of Cosmic Rays creates a strong gradient of pressure along the direction of the ordered magnetic field which results in a force applied on the plasma.

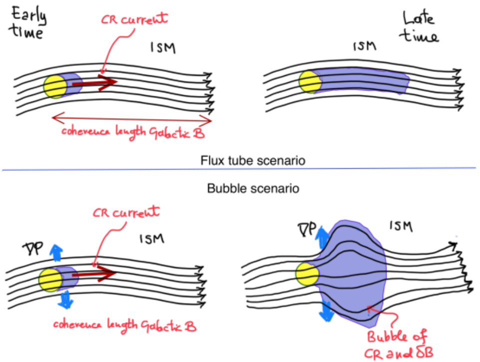
Due to the excited waves, low energetic particles are tied to plasma and their transport is dominated by the advection of the plasma.

$$\frac{\partial n_{CR}}{\partial t} + V_A(\delta B) \cdot \frac{\partial n_{CR}}{\partial z} - \frac{\partial}{\partial z}\left(D(E, \delta B)\frac{\partial n_{CR}}{\partial z}\right) = Q_0(E)\delta(z)$$

Blasi and Amato (2019)

Bubble scenario

The isotropization of diffusive particles builds up a strong pressure gradient even in the perpendicular direction. The flux tube approximation can easily fall at later time, when the energy density in CRs accumulated in the tube exceeds the thermal pressure of the plasma. Schroer et al. (2021)



MHD approach

The capability of a strong current of cosmic rays to excite unstable modes in the plasma has a central role in many phenomena concerning cosmic ray's acceleration and propagation.
Streaming instability was first discovered by Bell (2004) Bell (2004) , adding to the standard MHD equations the force exerted on the plasma by the cosmic ray's current.

$$\rho \frac{\mathrm{d}\boldsymbol{u}}{\mathrm{d}t} = -\nabla P - \frac{1}{\mu_0}\boldsymbol{B} \wedge (\nabla \wedge \boldsymbol{B}) - \boldsymbol{j}_{\mathrm{cr}} \wedge \boldsymbol{B} + n_{\mathrm{cr}} e\boldsymbol{u} \wedge \boldsymbol{B},$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \wedge (\boldsymbol{u} \wedge \boldsymbol{B}); \qquad \frac{\mathrm{d}\rho}{\mathrm{d}t} = -\nabla \cdot (\rho \boldsymbol{u}).$$

The last term is the force exerted by the magnetic field on the background moving plasma, which for quasineutrality carries a net (negative) charge.

Kinetic approach

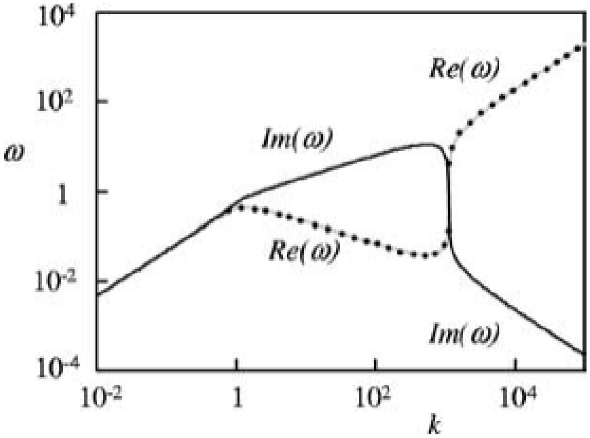
The same result can be obtained with a purely kinetic approach

$$\frac{c^2k^2}{\omega^2} = 1 + \sum_\alpha \frac{4\pi^2 q_\alpha^2}{\omega} \int_0^\infty \mathrm{d}p \int_{-1}^{+1} \mathrm{d}\mu \frac{p^2 v(p)(1-\mu^2)}{\omega + kv(p)\mu \pm \Omega_\alpha} \times \left[\frac{\partial f_\alpha}{\partial p} + \left(\frac{kv}{\omega} + \mu\right) \frac{1}{p}\frac{\partial f_\alpha}{\partial \mu}\right],$$

Including, a part the two thermal populations of protons and electrons, the cosmic rays distribution function and:

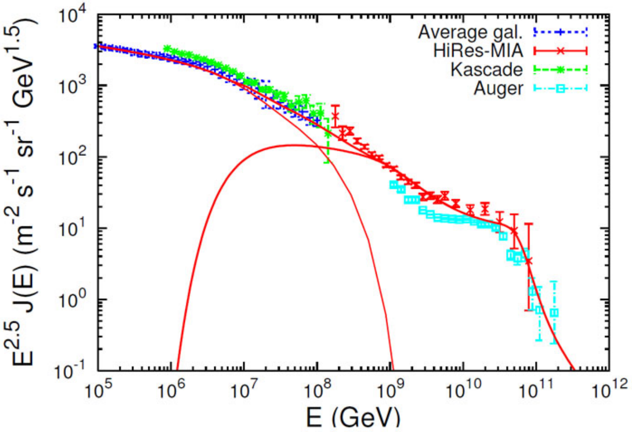
- another population of cold electrons.
- a small drift between protons and electrons.

Dispersion relation



Low-energy cutoff

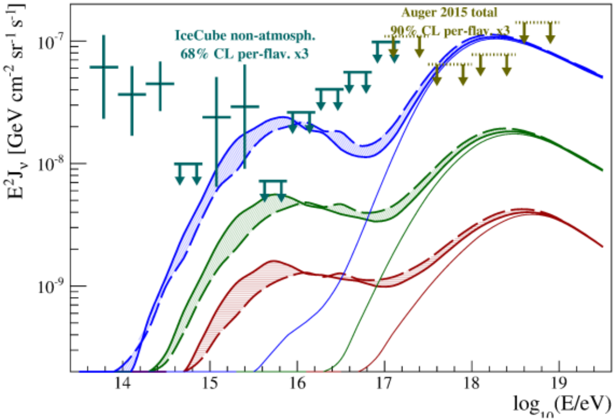
At which energy we start to observe extragalactic cosmic rays?



Aloisio (2012)

Production of neutrinos

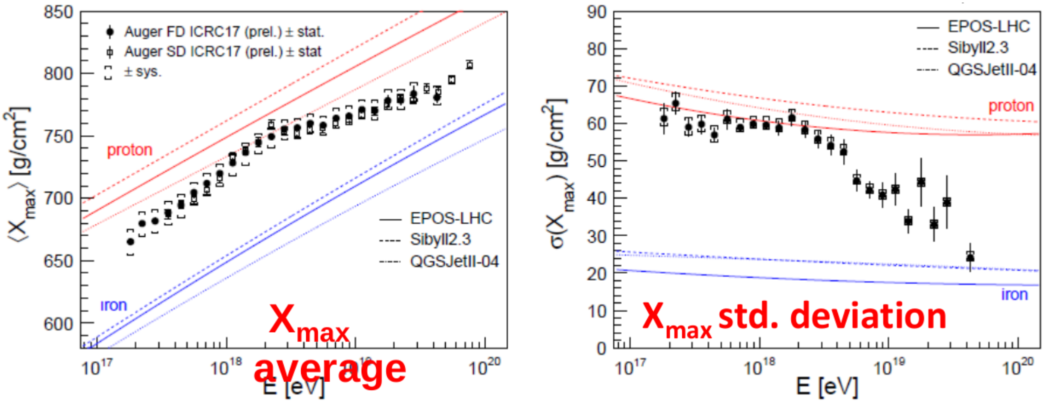
The production of neutrinos in the PeV range is enhanced closed to the source?



Aloisio et al. (2015)

Mass composition

How the time Cosmic Rays spend closeby their source impact the mass composition at Ultra High Energy?



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