Report on the reseach activity

Excitation of the Non-Resonant Streaming Instability around sources of UHECRs

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Presentation Overview

self confinement of Ultra-High Energy Cosmic Rays

- The excitation of the NRSI in the Intergalactic space was first discussed in [1] (P. Blasi, E. Amato, M. D'angelo, *High energy cosmic ray self-confinement close to extragalactic sources*)
- For the typical luminosity invoked for a source of Ultra-High Energy Cosmic Rays, the current associated with the CRs flux is large enough to excite the streaming instability in the Inter-Galactic Medium.
- The excited plasma waves scatter cosmic rays and force them to diffuse in the source vicinity.
- In the case of the Non-Resonant modes of the instability, the level of the perturbed magnetic field can exceed its original value by orders of magnitude, leading to a very low diffusion coefficient.
- This phenomenon leads to a suppression at ”low” energy of the cosmic ray flux at large distance from the source.
- The density of lower energetic particles is increased in the source vicinity, enhancing also the production of secondary particles.

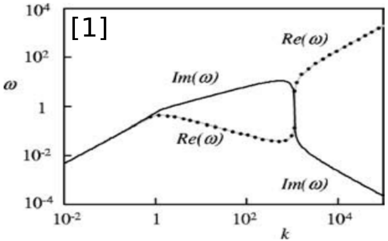
The NRSI appears when the energy flux associated with the CRs current is larger than the original magnetic energy density: $\frac{EJ_{CR}(>E)}{ec} > \frac{B_0^2}{4\pi}$

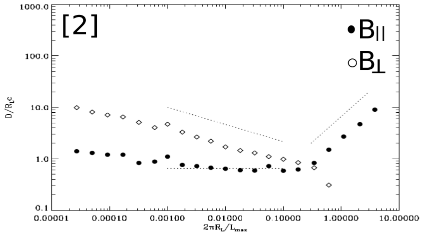
The wavelength with the higher growth rate is much shorter than the Larmor radius of the particles dominating the current:

$$k_{max} = \frac{4\pi}{c}\frac{J_{CR}(>E)}{B_0} \longleftrightarrow k_{max}R_L(E) >> 1$$

Assuming: $q(E) \propto E^{-2} \longrightarrow \gamma_{max} = V_A \cdot k_{max} \propto E^{-1}$

$$D(E) \propto \begin{cases} E & E \leq E_{sat} \\ E^2 & E > E_{sat} \end{cases}$$





[1] A.R. Bell, *Monthly Notices of the Royal Astronomical Society*, 2004 [2]
[2] A. Marcowith, *Astronomy & Astrophysics*, 2006 [3]

Diffusion: $$\tau_D(x) = \frac{x^2}{4D(E)}$$

When the unsteable waves begin to scatter and diffuse the particles, the cosmic ray pressure develops a gradient in the direction parallel to the original magnetic field. This results in a force applied on the background plasma which set it into motion; an equilibrium situation is reached when both the plasma and the bulk of cosmic rays drift at the Alfven speed in the amplified magnetic field

Advection: $$\tau_{Adv}(x) = \frac{x}{V_A}$$

[3] Comparing the transport timescales with the Age of the Universe, cosmic rays with energy below $\sim 10^8$ GeV are not able to leave the source vicinity.

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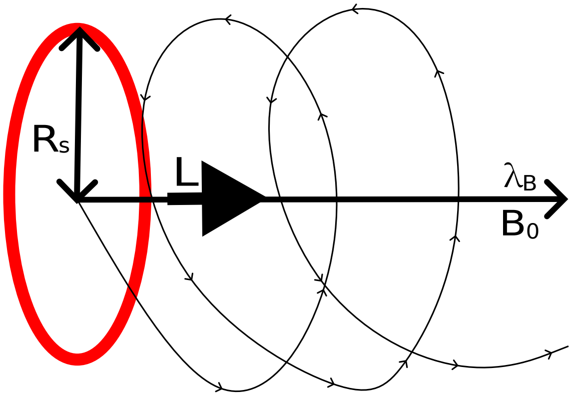
[3] P. Blasi, *Physical Review Letters*, 2015 [1]

Source and IGM



From the continuity equation:

$$n_{CR}(E) = \frac{2q(E)}{\pi R^2(E)c} \qquad R(E) = max[R_s, R_L(E)]$$

We consider a source injecting continuously a spectrum of cosmic rays:

$$q(E) = \frac{L}{\Lambda} E^{-2}$$

in the Inter-Galactic Space, permeated by a magnetic field B_0 correlated on a length scale λ_B

Cosmic rays with energy:

$$E < eB_0\lambda_B \sim 9 \times 10^8 \text{ GeV } B_{-10}\lambda_{10}$$

are forced to move spiraling along the field lines.

Magnetic field limits

[4] UPPER LIMIT:

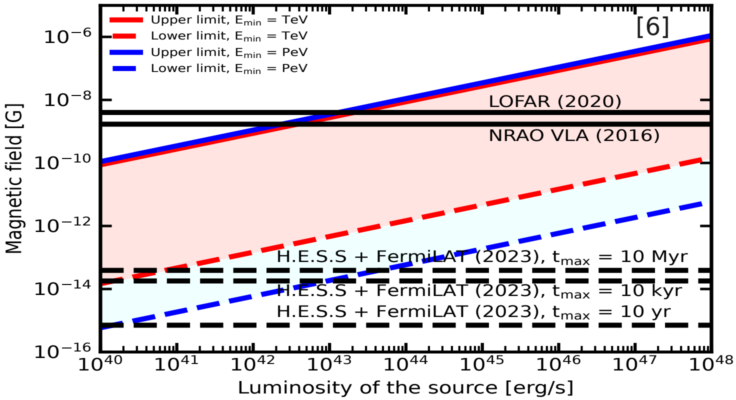
$$\frac{EJ_{CR}(>E)}{ec} > \frac{B_0^2}{4\pi},$$

$$B_0 < B_{sat} \approx 8.4 \times 10^{-9}\ \mathrm{G}\ \frac{L_{44}^{1/2}}{\Lambda_{20} R_{s,Mpc}}.$$

[5] LOWER LIMIT:

$$k_{max} \frac{\sqrt{2 m_p c^2 k_B T}}{e B_0} < 1,$$

$$B_0 > 5.5 \times 10^{-14}\ \mathrm{G}\ \frac{L_{44}^{1/2} T_4^{1/4}}{\Lambda_{20}^{1/2} R_{s,Mpc} E_{min,PeV}^{1/2}}.$$



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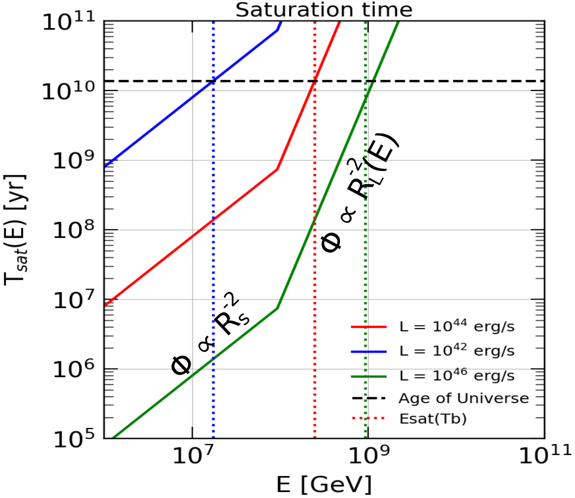
[4] Bell, *Monthly Notices of the Royal Astronomical Society 353 (2004) 550* [4].

[5] Zweibel +, *The Astrophysical Journal 709 (2010) 1412* [5].

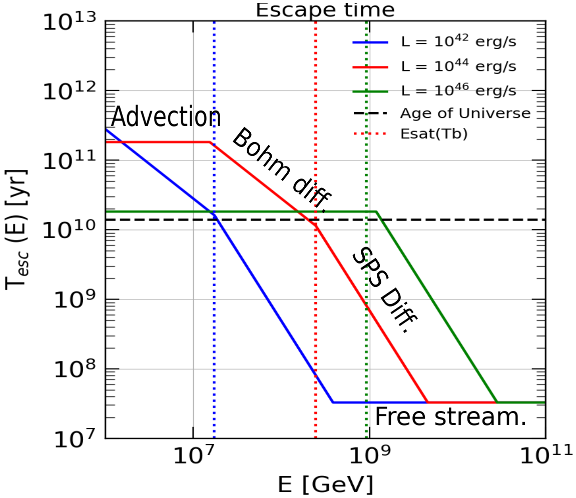
[6] Upper limits: Pshirkov + 2016, *Physical review letters* (NRAO VLA) [6], and O'Sullivan + 2020, *Monthly Notices of the Royal Astronomical Society* (LOFAR) [7] Lower limits: Aharonian + 2023, *arXiv e-prints* (H.E.S.S. and Fermi-LAT collaborations) [8].

Saturation of the instability

$$\tau_{sat}(E) = \frac{5}{\gamma_{max}} \sim 10\ \mathrm{Myr}\ \frac{\rho_b^{1/2} R^2_{s,Mpc} E_{PeV}}{L_{44}}$$



$$E_{cut} \sim 2 \times 10^8\ \mathrm{GeV}\ \frac{L_{44}^{5/12} \lambda_{10} B_{-10}^{1/3}}{R_{s,Mpc}^{1/2} \rho_b^{1/12}}$$



Confinement

$$\frac{\partial n(E,x,t)}{\partial t} + V_d(E,t)\frac{\partial n(E,x,t)}{\partial x} = Q(E)\delta(x)$$

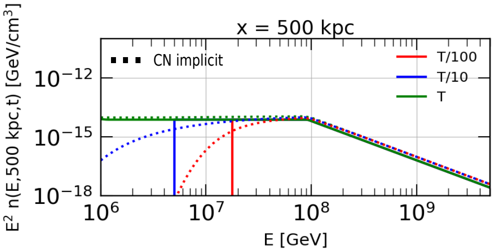
$$n(E,x,t) \sim \int_{T_{min}}^{t} dt' \cdot \frac{Q_0(E)}{V_d(E,t)} \cdot \delta\left(t - t' - \tau_p(E,x,t,t')\right)$$

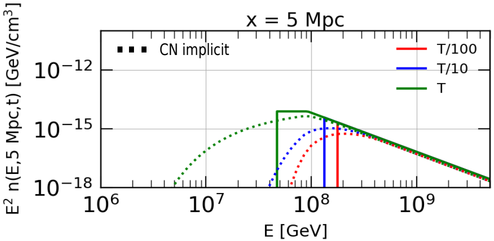
$$V_d = V_A, \quad \sqrt{\frac{4D(E,t)}{t - T_{min}}}, \quad c$$

We compare this approximated solution with the one obtained integrating numerically the advection/ diffusion equation:

$$\frac{\partial n(E,x,t)}{\partial t} + V_A(E,t)\frac{\partial n(E,x,t)}{\partial x} = D(E,t)\frac{\partial^2 n(E,x,t)}{\partial x^2} + Q(E)\delta(x)$$

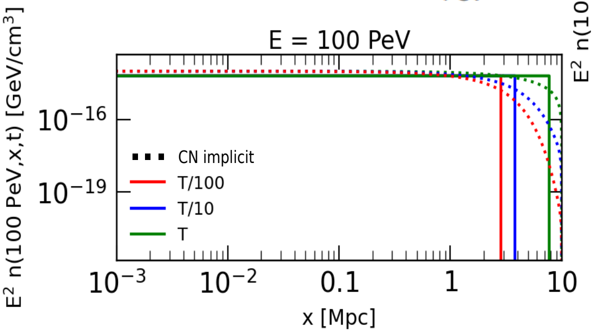
with boundary conditions: $\begin{cases} n(E, x=0, t) = Q_0/c \\ n(E, x=\lambda_B, t) = 0 \end{cases}$

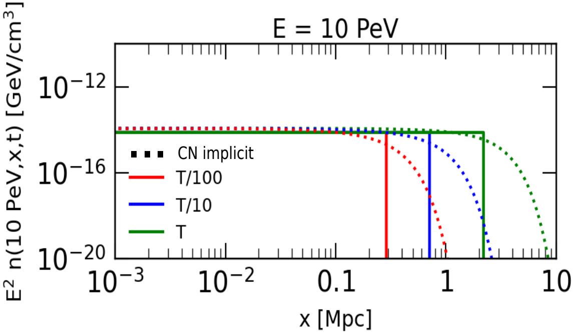




$$D^B(E) \sim 3 \cdot 10^{30} \, \frac{E_{\rm PeV}}{L_{44}^{1/2}} \, \frac{\rm cm^2}{\rm s}$$

$$\Rightarrow \tau_D(E,x) \sim 0.75 \cdot 10^{18} \, \frac{L_{44}^{1/2} x_{\rm Mpc}^2}{E_{\rm PeV}} \, \rm s$$

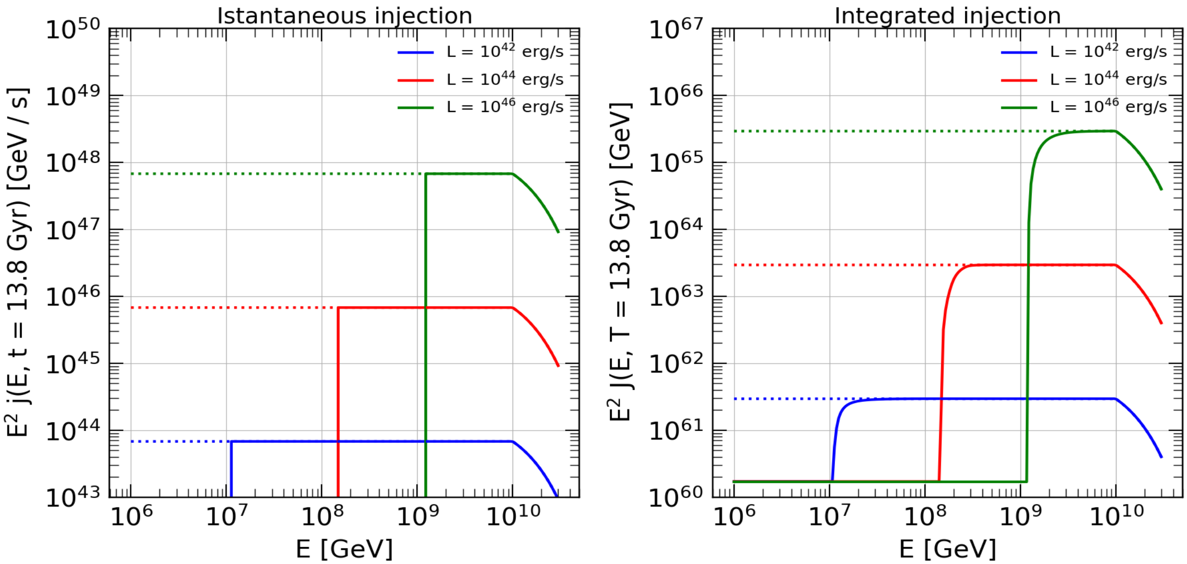




$$\tau_D(E,x) = T \;\Rightarrow$$

$$x \sim 0.75 \, \frac{E_{\rm PeV}^{1/2} T_{\rm AoU}^{1/2}}{L_{44}^{1/4}} \, \rm Mpc$$

Suppression of the injection



Production of neutrinos

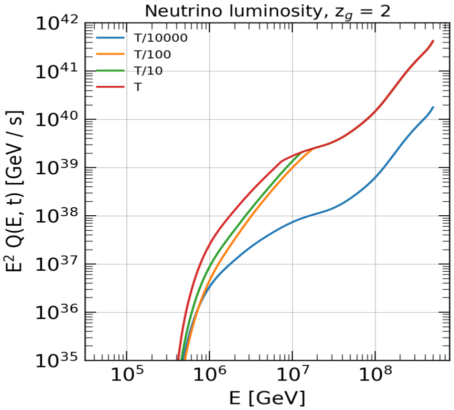
Fixing the inelasticity of the process: $E_p/E_\nu = \eta_0 = 0.05$

$$\Rightarrow Q_\nu(E_\nu, z_g, T) =$$

$$\int_0^{\lambda_B} dx \cdot \pi R^2 \left(\frac{E_\nu}{\eta_0}\right) \cdot n\left(\frac{E_\nu}{\eta_0}, x, T\right) \otimes$$

$$\int_{\epsilon_{th}(\frac{E_\nu}{\eta_0})}^{\epsilon_{max}} d\epsilon \cdot \eta_0 \cdot n_\gamma(\epsilon, z_g) \cdot [c \cdot \sigma(\eta_0, \epsilon)]$$

Cross sections for the production of each neutrino flavour are taken by a parametrization of the results of SOPHIA [7], the EBL model from [8].



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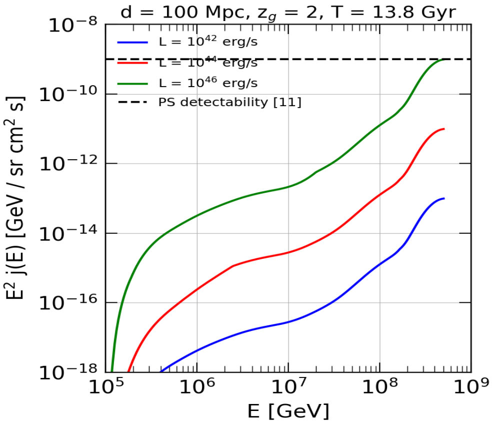
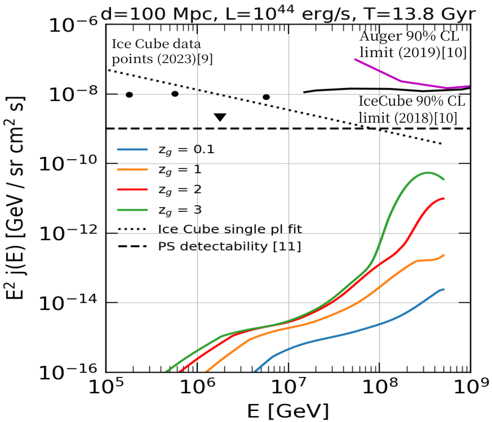
[7] S. R. Kelner, *Physical Review D.*, 2008 [9]

[8] A. Saldana, *Monthly Notices of the Royal Astronomical Society*, 2021

Flux of neutrinos from a point source





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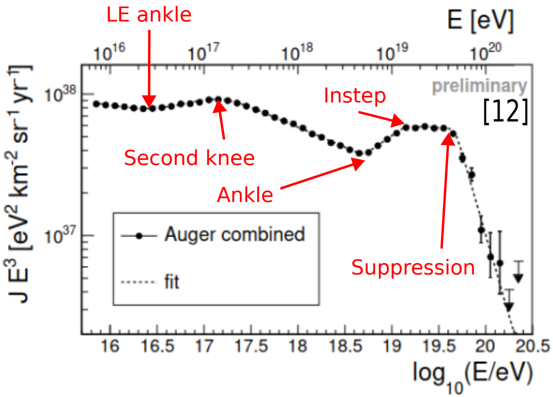
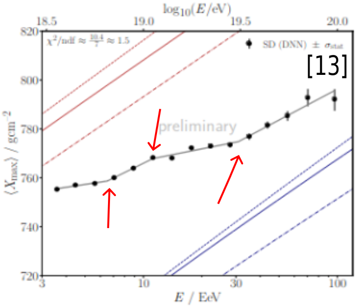
[9] Ice Cube collaboration, *Proceedings of Science, ICRC 2023* [10]
[10] L. Perrone, *EPJ Web of Conferences*, 2023 [11]
[11] F. Capel, *Physical Review D*, 2020

Composition and spectral feature



Many spectral feature, not only at the UHE but also in the region of transition between galactic and extragalactic cosmic rays.



Mixed composition, with the fraction of heavy nuclei increasing with the energy

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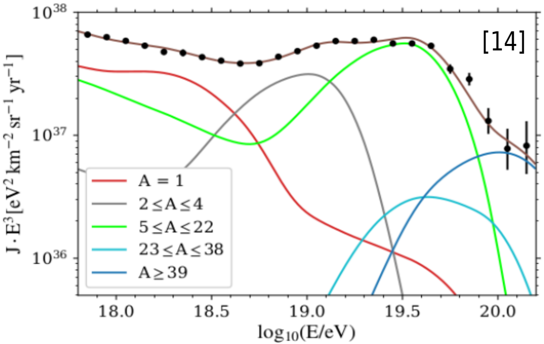
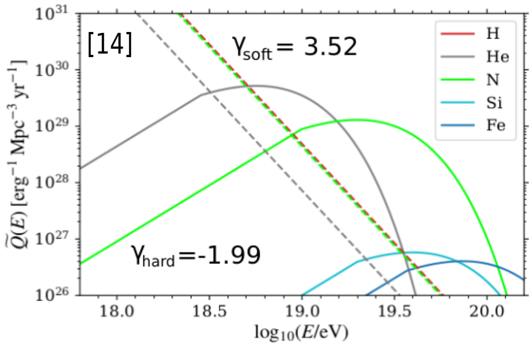
[12] V. Novotny, *Proceedings of Science*, 2021 [12]
[13] J. Glombitza, *Proceedings of Science*, 2023 [13]

Best Fit (top of the atmosphere)



Spectrum at the escape from the sources



In order to reproduce the observed spectral features and the X_{max} distribution, two different class of sources are needed!

The spectral index for the "hard" population is negative!

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[14] A. A. Halim, *Journal of Cosmology and Astroparticle Physics*, 2023 [14]

Better measurements, more questions

- Any hypothetical acceleration mechanism proposed to take place in UHECR sources leads to a positive spectral index.
- A strong suppression of the injection at low energy, convoluted with a distribution of sources with different properties, can appear as a negative spectral index.
- The two components, hard and soft, can be related to each other through the photodisintegration processes or being accelerated by (at least 2) different class of sources.
- The proton fraction injected with the hard spectral index is negligible.
- Whether or not the light nuclei fraction of the soft component could be of Galactic origin is part of the question, but the isotropy in the arrival direction measured at the ankle and below disfavor the galactic origin.

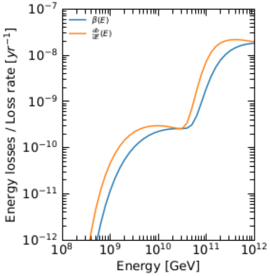
Analytic calculation of cosmogenic neutrinos

$$\frac{\partial n(E,t)}{\partial t} + 3H(t)n(E,t) - \frac{\partial}{\partial E}\left[b(E,t)n(E,t)\right] = \frac{\mathbf{Q}(E,t)}{a^3(t)},$$

$$\frac{dn(E_g,z)}{dz} + \left[3H(z) - \frac{\partial b(E_g,z)}{\partial E_g}\right]\left|\frac{dt}{dz}\right| n(E_g,z) = \left|\frac{dt}{dz}\right|\frac{\mathbf{Q}(E_g,z)}{(1+z)^{-3}}$$

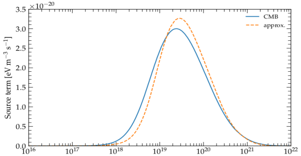
$$n(E,z) = (1+z)^3 \int_z^\infty dz_g \frac{\mathbf{Q}\left[E_g(E,z,z_g),z_g\right]}{(1+z_g)H(z_g)}\frac{dE_g(E,z,z_g)}{dE},$$

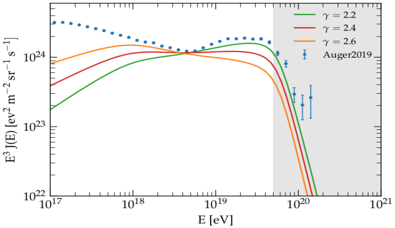
$$\frac{dE_g(E,z,z_g)}{dE} = \frac{1+z_g}{1+z}\exp\left(\int_z^{z_g} ds \left|\frac{dt}{ds}\right| \frac{db_{\rm int}(E',s)}{dE'}\Bigg|_{E'=E_g(E,z,s)}\right)$$

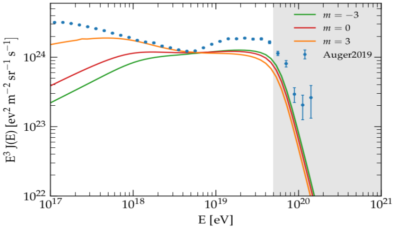


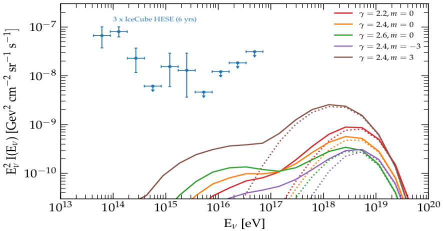
$$n_\nu(E_\nu) = \int_0^{z_{\rm max}} dz_g \left|\frac{dt}{dz_g}\right| \frac{\mathbf{Q}_\nu(E_g,z_g)}{(1+z_g)^2},$$

$$\mathbf{Q}_\nu(E_\nu,z) = \frac{c}{(1+z)^3}\int_{E_\nu}^\infty \frac{dE_p}{E_p} n_p(E_p,z) \times \int_0^\infty d\epsilon\, n_\gamma(\epsilon,z)\frac{d\sigma_\nu}{dx}(x,\rho)$$









List of activities

- Publications:
  - ”Excitation of the non-resonant streaming instability around sources of Ultra-High Energy Cosmic Rays”. *Proceeding of Science 1131*, ICRC2023 [15]
  - ”Analytic calculations of the spectra of cosmogenic neutrinos”. *Proceeding of Science 1132*, ICRC2023 [16]
- Conferences & schools :
  - International School of Physics ”Enrico Fermi”, in Varenna, Italy, from 24/06/22 to 29/06/22.
  - International Symposium on Ultra High Energy Cosmic Rays 2022, in L'Aquila, Italy, from 03/10/23 to 07/10/22.
  - International Cosmic Rays Conference (ICRC) 2023, in Nagoya, Japan, from 26/07/23 to 4/08/23.
- Research group activities:
  - ”Pierre Auger Observatory International masterclass”, 04/04/23.
  - ”Gran Sasso Hands-on 2023, PhD autumn school on experimental astroparticle physics”, from 25/09/23 to 06/10/23.

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