Report on the research project
Implication of self-induced confinement of Ultra-High Energy Cosmic Rays

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Gran Sasso Science Institute 2024, October 10, 2024

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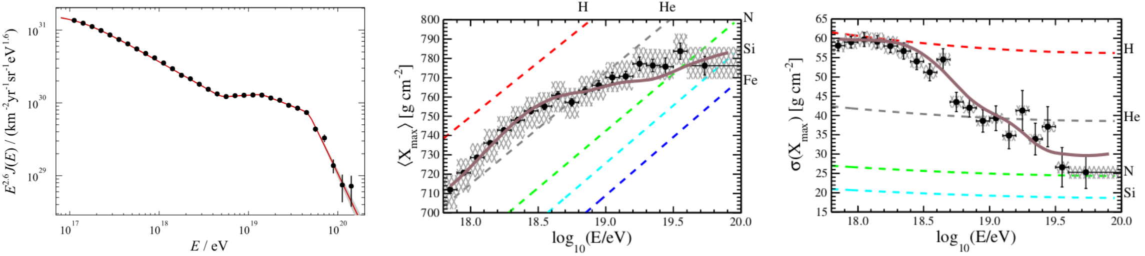
Ultra High-Energy Cosmic Rays

Spectrum and composition beyond the "second knee" (Abreu *et al.* (2021); Aab *et al.* (2016)):

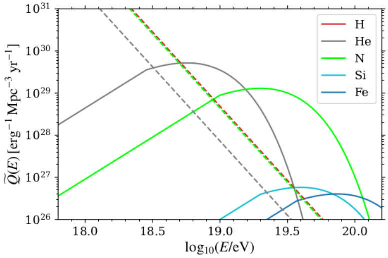
- spectral breaks most likely determined by the composition:
  - Ankle: $\approx$ end of the proton contribution;
  - Instep: Subsequent cutoff of different nuclear species;
- Predominantly mixed mass composition:
  - 100 PeV - 3 EeV: increasingly lighter with the energy;
  - $\gtrsim$ 3 EeV: increasingly heavier, compatible with Peter's cycle.

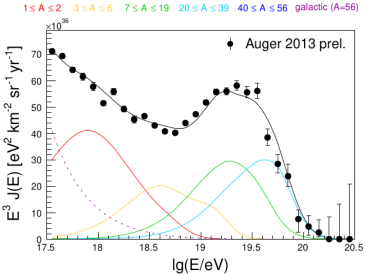


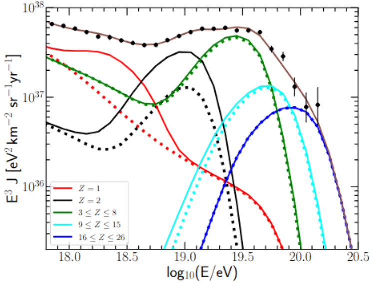
Source characterization

The current interpretation requires two different populations of sources:

- First population: soft injection, $\gamma \approx 3, 3.5$; mainly protons (Halim *et al.* (2023)).
- Second population: very hard injection, $\gamma \lesssim 1$ (also negative values); mainly nuclei
  - Transport mechanism:
    $\rightarrow$ Magnetic horizon: B $\approx 50 - 100$ nG in between the Earth and the closest sources (Halim *et al.* (2024)).
    $\rightarrow$ Photodisintegration of heavy nuclei "in-source" (Unger *et al.* (2015)).
  - Acceleration mechanism:
    $\rightarrow$ unipolar induction, stochastic acceleration in GRB, magnetic reconnections.







Interpretation of the ”High-Energy” population

At energies above the *ankle* ($\approx 10^{18.5}$ eV):

- The spectral features are compatible with subsequent rigidity cutoff of different nuclear species.
- The $X_{\rm max}$ and $\sigma(X_{\rm max})$ behaviors indicate a continuous increase of the mass composition.

In terms of sources' characterization, the population accelerating cosmic rays at Ultra-High Energies is required to:

- Accelerate mainly nuclei.
- Have a relatively low maximum rigidity, $\mathrm{R_{max}} \approx 10^{18.2}$ V.
- Produce a negative spectral index, $\gamma \approx -2$.

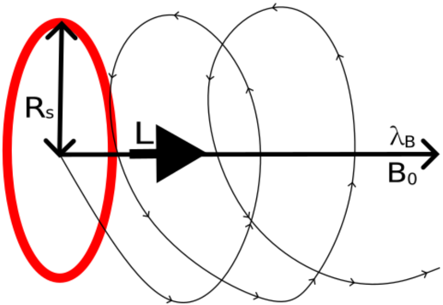
The latter condition is better interpreted in terms of transport, instead of acceleration:

- Large magnetic field ($\approx 50 - 100$ nG) in between the Earth and the closest sources.
- Magnetic confinement within the source environment.

Can the excitation of the Non-Resonant Streaming Instability by UHE Cosmic Rays help to explain the magnetic confinement within, or closeby, the source environment?

Self-induced confinement: source and IGM model

Source		Environment (IGM)	
Luminosity (in CRs)	$L \approx 10^{45}$ erg/s	Magnetic field	$B_0 \approx 1$ nG
Radial Size	$R_s \approx 1$ Mpc	Correlation length	$\lambda_B \approx 10$ Mpc
Energy range	$E_{\rm min} \approx$ GeV, $E_{\rm max} \approx 3$ EeV	Gas density	$\rho_b \approx \delta 4 \cdot 10^{-31}$ g/cm^3
Lasting of the injection	$T_{\rm age} \approx 10$ Gyr	Temperature	$T \approx 10^4$ K



Following the same description as Blasi *et al.* (2015), we consider as "source" any object which accelerates UHECRs or embed an accelerator of UHECRs:

- Injection spectrum $q_s(E) \propto L \times E^{-2} \times f(E_{\rm cut})$.
- Characteristic energy-scale: $R_L(E) = R_s \to E \approx$ EeV.
- Particles with $R_L(E) \leq \lambda_B \to E_{\rm magn} \lesssim 10$ EeV follow the magnetic field lines.
- The current induced by UHECRs leaving the source is

$$J(>E) = e\frac{c}{2}\int_E^{E_{\rm magn}} dEn(E) \approx \frac{eEq(E)}{\pi(R_s + R_L(E))^2}$$

Non Resonant Streaming Instability

- The non-resonant branch of the streaming instability develops if the energy density carried by the UHECR current is larger than the magnetic energy density (Bell (2004)):

$$\frac{EJ(>E)}{ec} > \frac{B_0^2}{4\pi} \quad \Rightarrow \quad L \gtrsim 10^{42}\ \mathrm{erg/s}\, B_{\mathrm{nG}}^2 R_{\mathrm{Mpc}}^2$$

- Differently from the gyroresonant instability, magnetic perturbations are excited at wavelengths smaller than the Larmor radius of the particles, and have a faster growth rate:

$$k_{\max}(E) = \frac{4\pi}{cB_0} J(>E) >> 1/R_L(E) \quad \Longrightarrow \quad \gamma_{\max}(E) = V_A k_{\max}(E) = \frac{B_0}{\sqrt{4\pi\rho}} k_{\max}(E)$$

- In order to develop the instability, the Larmor radius of the thermal protons must be smaller than the growing wavelengths, $k_{\max} R_{L,th} \lesssim 1$ (Zweibel and Everett (2010)). This translates into a lower limit on the original magnetic field to develop the effect:

$$B_0 > \left(\frac{16 L^2 m_p k_B T_{\mathrm{IGM}}}{\Lambda^2 E_{\min}^2 R^4} \right)^{1/4} \approx 10^{-4}\ \mathrm{nG} \left(\frac{L}{10^{45}\ \mathrm{erg/s}} \right)^{1/2} \left(\frac{T_{\mathrm{IGM}}}{10^4\ \mathrm{K}} \right)^{1/4} \left(\frac{R}{\mathrm{Mpc}} \right)^{-1} \left(\frac{E_{\min}}{\mathrm{PeV}} \right)^{-1/2}.$$

Non Resonant Streaming Instability II

- Initially, the magnetic field perturbations grow on a scale $k_{\rm max}^{-1}$ up to values $\delta B/B_0 > 1$. The saturation is achieved through the Lorentz force $J \times B$, which stretches the perturbations on larger scales, matching the Larmor radius of the particles and strongly impacting the CR current:

$$\frac{\delta B_{\rm sat}^2}{4\pi} \approx \frac{EJ(>E)}{ec} \quad \Longrightarrow \quad \delta B_{\rm sat} \approx \sqrt{\frac{4L}{\Lambda c R_s^2}} \sim 25\ {\rm nG} \left(\frac{L}{10^{45}\ {\rm erg/s}}\right)^{1/2} \left(\frac{R_s}{\rm Mpc}\right)^{-1}$$

- On a timescale of a few (5-10) gyration periods ($\gamma_{\rm max}^{-1}$), the excited turbulences can resonantly scatter and diffuse cosmic rays up to a critical energy scale E_c:

$$\tau_{\rm sat}(E_c) = \frac{5}{\gamma_{\rm max}(E_c)} = T_{\rm age} \Rightarrow D(E) = \frac{c}{3}\frac{E_{\rm c}}{e\delta B_{\rm sat}}\left[\frac{E}{E_{\rm c}} + \left(\frac{E}{E_{\rm c}}\right)^2\right] \approx 4\ \frac{{\rm Mpc}^2}{\rm Gyr}\left(\frac{L}{10^{45}\ {\rm erg/s}}\right)^{-\frac{1}{2}}\left(\frac{R}{\rm Mpc}\right)\left(\frac{E}{\rm EeV}\right)$$

- In addition, the isotropization of the CR density within the flux tube leads to a pressure gradient that acts on the plasma, setting it into motion at the Alfven speed (Blasi and Amato (2019))

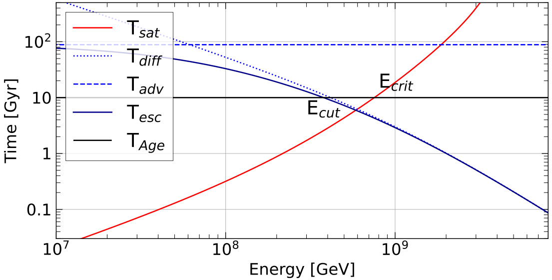
$$V_A = \frac{\delta B_{\rm sat}}{\sqrt{4\pi\rho}} \sim 0.1\ {\rm Mpc/Gyr} \left(\frac{L}{10^{45}{\rm erg/s}}\right)^{1/2}\left(\frac{R}{\rm Mpc}\right)^{-1}\delta^{1/2}$$

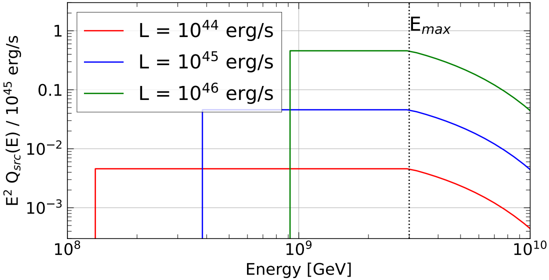
Low energy suppression

A low-energy suppression of the escaping flux appears as a result of diffusion on the self-generated magnetic perturbations:

$$T_{\rm esc}^{-1}(E) = \frac{V_A}{\lambda_B} + \frac{D(E)}{\lambda_B^2} \qquad Q_{\rm scr}(E) \approx q_s(E) \times \mathcal{H}(T_{\rm age} - T_{\rm esc}(E))$$

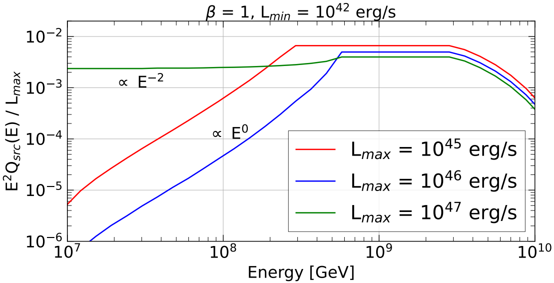
$$T_{\rm esc}(E) = T_{\rm age} \quad \Rightarrow \quad E_{\rm cut} \approx 0.4\,\mathrm{EeV} \left(\frac{L}{10^{45}\,\mathrm{erg/s}}\right)^{1/2} \left(\frac{R}{\mathrm{Mpc}}\right)^{-1} \left(\frac{\lambda_B}{10\,\mathrm{Mpc}}\right)^{2}$$

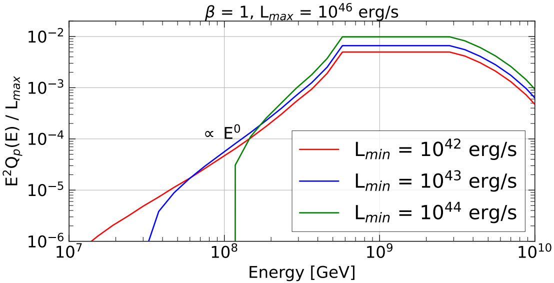




Emissivity of different sources

- Advection implies a maximum luminosity for the confinement to be effective: for too high current intensity L/R^2, the Alfvén speed becomes too high and particles are evacuated from the magnetized bubble: $T_{\rm age} < \lambda_B/V_A \Rightarrow L_{\rm max} \approx 10^{47}$ erg/s $\lambda^2_{\rm 10Mpc} R^2_{\rm Mpc}$.
- The overall emissivity computed for a population of sources distributed as a power-law, $\Phi(L) \propto L^{-\beta}$, results in an injection spectral index unrelated to the acceleration process $Q_{\rm src}(E) \propto E^{2(1-\beta)}$





Production of neutrinos

VHE neutrinos, produced through the photopion interaction, can be produced on the EBL:

- by protons confined within the magnetized cocoons:

$$Q_\nu^{\text{bubbles}}(E_\nu, z) \propto \Phi(L, z) \times q_s(E_p) \times \tau_{\text{esc}}(E_p) \times \mathcal{R}(E_\nu, E_p, n_\gamma(\epsilon)),$$

  with production rate $\mathcal{R}(E_\nu, E_p, n_\gamma(\epsilon)) \propto n_\gamma(\epsilon, z)\frac{d\sigma}{dx}(\epsilon, E_p, E_\nu)$ defined in Kelner and Aharonian (2010a).

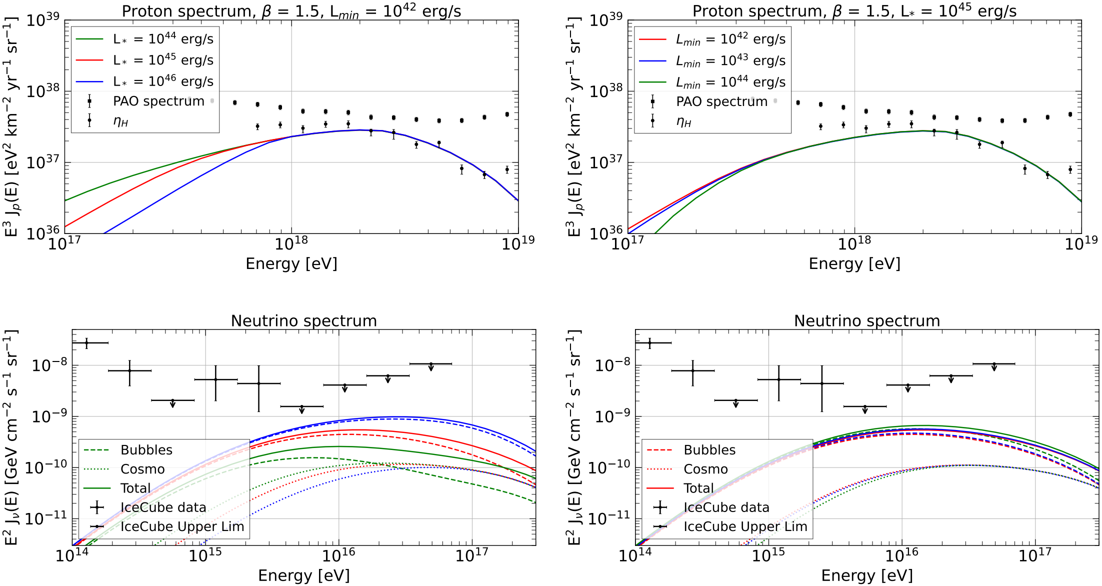
- by released protons that can reach the Earth (cosmogenic neutrinos):

$$Q_\nu^{\text{cosmo}}(E_\nu, z) \propto n_p(E_p) \times \mathcal{R}(E_\nu, E_p, n_\gamma(\epsilon)),$$

  with $n_p(E_p, z)$ being the equilibrium density of protons released from the sources into the Universe Berezinsky *et al.* (2006).

- The first one results larger than the latter for reasonable assumptions on the source's population:
  - Various shapes of the $\Phi(L)$, resembling the luminosity distribution of AGN's / Galaxies.
  - Up to $z_{\text{max}} = 3$, with no redshift evolution of the sources.
  - Normalized to match the proton spectrum as observed by PAO (Abreu *et al.* (2021); Aab *et al.* (2016)).
  - Both confined and released protons interact with the CMB and the EBL (Saldana-Lopez *et al.* (2021)).

Production of neutrinos



First results

- The excitation of the NRSI when the UHECR current leaves the source can help the interpretation of the UHECR spectrum and mass composition without invoking any exotic acceleration mechanism:
  - It naturally induces magnetic confinement close to the sources.
  - It needs an original magnetic field of order B $\approx 0.1 - 1$ nG $\lambda_{10\mathrm{Mpc}}$, in better agreement with Faraday rotation measures than the classical view of the magnetic horizon.
    The turbulent amplified field only exists in the presence of UHECR sources.
  - The shape of the spectrum below the suppression is unrelated to the acceleration mechanism.
  - Confined protons produce more neutrinos than the released ones.
  - The cosmogenic neutrino flux does not overshoot the upper limits posed by Ice Cube (Aartsen *et al.* (2013)).
- To reach a suppression of the flux at the EeV energy scale, some requirements must be fulfilled:
  - The current intensity should be high enough to produce the NRSI, but not too high to evacuate the magnetized cocoons:

$$L_{\mathrm{min}} \approx 10^{42}\ \mathrm{erg/s}\, R^2_{\mathrm{Mpc}}\, B_{\mathrm{nG}} < L < L_{\mathrm{max}} \approx 10^{47}\ \mathrm{erg/s}\, \lambda^2_{10\mathrm{Mpc}} R^2_{\mathrm{Mpc}}$$

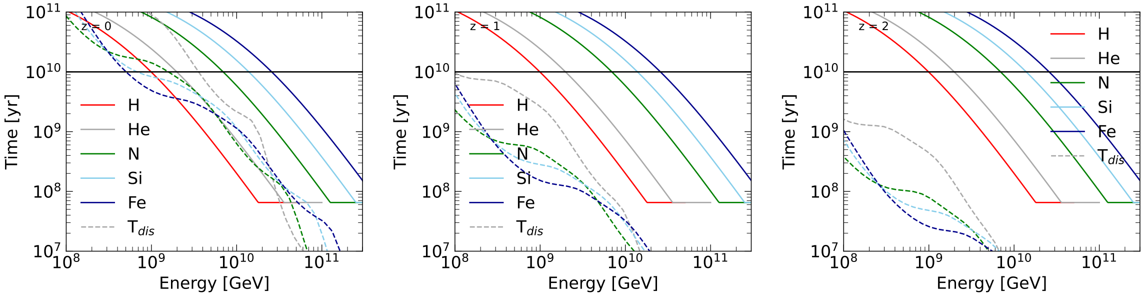
  - A too-high original magnetic field will prevent the instability from developing, but if it's too low, the thermal plasma cannot respond to the perturbations:

$$B_{\mathrm{low}} \approx 10^{-4}\mathrm{nG}\, L_{45}^{1/2} R_{\mathrm{Mpc}}^{-1} E_{\mathrm{PeV}}^{-1/2} < B_0 < \delta B \approx 25\,\mathrm{nG}\, L_{45}^{1/2} R_{\mathrm{Mpc}}^{-1}$$

- The requirements in terms of power and magnetic field suggest that Galaxy clusters and filaments are the best candidates for the NRSI to impact the UHECRs transport in the Universe up to the EeV energy scale.

Next step: nuclei

Competition between the escape time $\propto E/Z$ and the photodisintegration $\propto E/A$



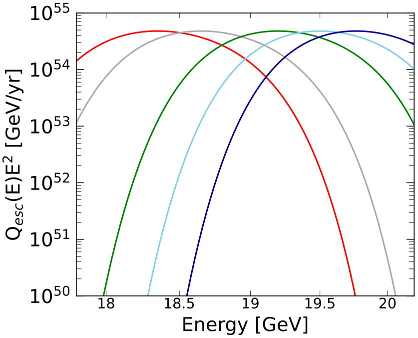
$$N_{\mathrm{CMB}}(\epsilon, z) \approx (1+z)^3\, N_{\mathrm{CMB}}(\epsilon \times (1+z), z=0) \qquad \Rightarrow \qquad \tau^{A}_{\mathrm{dis}}(E, z) \approx (1+z)^3\, \tau^{A}_{\mathrm{dis}}(E/(1+z), z=0)$$

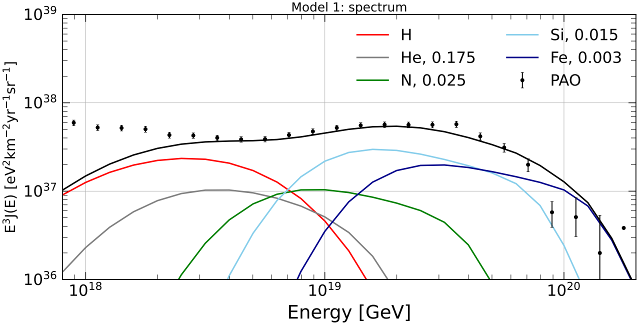
High-redshift sources seem to photodisintegrate easily all the nuclei

Next step: what if we neglect energy losses

Connecting the transport in the magnetized cocoons and outside is in principle non-trivial:

$$\frac{\partial n}{\partial t} + V_A \frac{\partial n}{\partial x} - D(E)\frac{\partial^2 n}{\partial x^2} + \frac{n}{\tau_A} = Q(E)\delta(x) \quad \Rightarrow \quad \widetilde{G} \approx \exp\left(-\frac{(\lambda - V_A T))^2}{4D(E)T}\right)$$





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Analytic transport of cosmogenic particles

Cosmological transport equation:

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

- $b(E,t) = -\frac{dE}{dt}$: energy losses equation (adiabatic + interactions).
- $\widetilde{Q} \propto \widetilde{\mathcal{L}} \times q(E)$: injection term per unit comoving volume from astrophysical CR accelerators.
- $\widetilde{Q} \propto \widetilde{n}_p \times R_{p\gamma_t}$: injection term for secondaries from proton interactions with background photons

From protons to secondary products

$$\widetilde{Q}^{\text{astro}}_{\text{proton}}(E_p, z) \to \widetilde{n}_p(E_p, z) \to \begin{cases} \widetilde{Q}_{\gamma\text{-rays}}(E_\gamma^{\text{VHE}}, z) \to \phi_\gamma^{\text{diff}}(E_\gamma) & E_\gamma \approx 0.1\text{-}100\ \text{GeV} \\ \widetilde{Q}_\nu(E_\nu(1+z), z) \to \phi_\nu(E_\nu) & E_\nu \gtrsim 100\text{TeV} \end{cases}$$

Why it can be important?

- Understanding differences between Monte Carlo propagation codes.
- With the AugerPrime upgrade, PAO is going to be a multimessenger observatory facility
  $\Rightarrow$ Building a comprehensive description of UHE Cosmic Rays - Photons - Neutrinos.

Proton interactions

$$\beta(E,z) = \frac{1}{E}\frac{dE}{dt} = \int d\epsilon' \, \epsilon' \eta(\epsilon') \sigma(\epsilon') \int d\epsilon \frac{n_\gamma(\epsilon, z)}{\epsilon^2}$$

Pair production:

$$E_{\rm th} = \frac{M_e}{2E_\gamma}(M_p + M_e) \approx 2 \cdot 10^{18} \text{ eV}$$

$$p_{\rm CR} + \gamma_t \rightarrow p'_{\rm CR} + e^- + e^+$$

Photo-pion production:

$$E_{\rm th} = \frac{M_\Delta^2 - M_p^2}{2E_\gamma(1-cos\theta)} \approx 2 \cdot 10^{20} \text{ eV} \quad \text{on CMB}$$

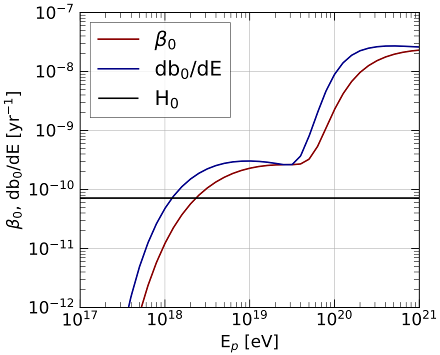
$$p_{\rm CR} + \gamma_{\rm t} \rightarrow \Delta^+ \rightarrow \pi_0 + p'_{\rm CR}$$

$$p_{\rm CR} + \gamma_{\rm t} \rightarrow \Delta^+ \rightarrow \pi_+ + n_{\rm CR}$$

$$p_{\rm CR} + \gamma_{\rm t} \rightarrow \Delta^+_* \rightarrow p'_{\rm CR} + \pi_+ + \pi_-$$

ONLY CMB APPROXIMATION (Berezinsky *et al.* (2006)):

- $\beta(E,z) = (1+z)^3 \, \beta(E(1+z), z=0)$
- $b(E,z) = (1+z)^2 \, b(E(1+z), z=0)$
- $\frac{db(E,z)}{dE} = (1+z)^3 \frac{db(E(1+z),z=0)}{dE}$



Production of secondary particles

$$p_{\mathrm{CR}} + \gamma_{\mathrm{t}} \rightarrow \Delta^{+} \rightarrow \pi_0 + p'_{\mathrm{CR}} \Rightarrow \pi_0 \rightarrow \gamma + \gamma$$

$$p_{\mathrm{CR}} + \gamma_{\mathrm{t}} \rightarrow \Delta^{+} \rightarrow \pi_{+} + n_{\mathrm{CR}} \Rightarrow \begin{cases} n_{\mathrm{CR}} \rightarrow p'_{\mathrm{CR}} + e^{-} + \bar{\nu}_e \\ \pi_{+} \rightarrow \mu^{+} + \nu_\mu \Rightarrow \mu^{+} \rightarrow e^{+} + \bar{\nu}_\mu + \nu_e \end{cases}$$

$$p_{\mathrm{CR}} + \gamma_{\mathrm{t}} \rightarrow \Delta^{+}_{*} \rightarrow p'_{\mathrm{CR}} + \pi_{+} + \pi_{-} \Rightarrow \begin{cases} \pi_{+} \rightarrow \mu^{+} + \nu_\mu \Rightarrow \mu^{+} \rightarrow e^{+} + \bar{\nu}_\mu + \mu_e \\ \pi_{-} \rightarrow \mu^{-} + \bar{\nu}_\mu \Rightarrow \mu^{-} \rightarrow e^{-} + \bar{\nu}_e + \nu_\mu \end{cases}$$

$$p_{\mathrm{CR}} + \gamma_t \rightarrow p'_{\mathrm{CR}} + e^{-} + e^{+}$$

- VHE neutrinos and γ-rays are produced through pions decay.
- Electron / Positron pairs are produced mainly through the pair production, but also from the charged pions decay.
- Leptons and γ-rays produce EM cascades through multiple pair production & Inverse Compton interactions on CMB and EBL target photons $\rightarrow$ Calorimetric estimate of the total energy injected in EM cascade with universal shape fixed by the target fields.
- Neutrinos suffer only adiabatic energy losses (at least for z $\lesssim$ 10)

Photopion Cross Section: differences between MC propagation codes

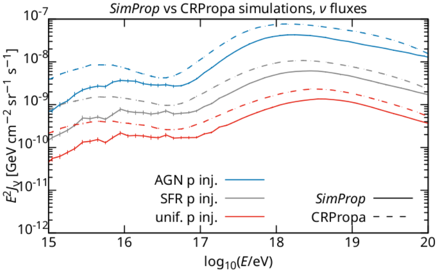
Distribution of final products:

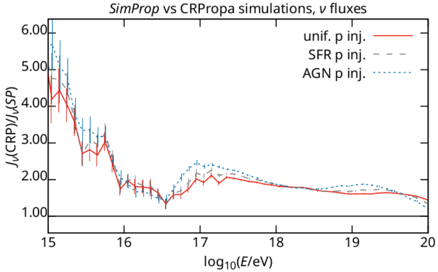
- We rely on parametrized function Φ_i fitted from Monte Carlo simulation of proton - photon interaction performed by SOPHIA (Mücke *et al.* (2000)), the same used in CRPropa.
- Describe the energy distribution of the secondary products (Kelner and Aharonian (2010b)).

$$\frac{dN}{dE_i} = \int d\epsilon \frac{dE_p}{E_p} n_p(E_p) n_\gamma(\epsilon) \Phi_i(\eta, x)$$

$$\Phi_i(\eta, x) = c\frac{d\sigma(\eta, x)}{dx}, \; x = \frac{E_i}{E_p}, \; \eta = \frac{4\epsilon E_p}{m_p^2 c^4}$$

- SimProp treats all photohadronic interactions as single-pion production, with BR from isospin invariance, and with the angular distribution of the outgoing pion assumed isotropic in the CoM frame (Batista *et al.* (2019))





Solution of transport equations

UHE protons:

$$\widetilde{n}_p(E_p, z) = \int_z^{z_{max}} dz_g \left|\frac{dt}{dz_g}\right| \widetilde{Q}(E_{g,p}(E, z, z_g), z_g) \frac{dE_{g,p}}{dE_p}$$

$$\frac{dE_{g,p}(E_p, z, z_g)}{dE_p} = \frac{1+z_g}{1+z} \exp\left(\int_z^{z_g} ds \left|\frac{dt}{ds}\right| \frac{db(E_{g,p}, s)}{dE_p}\right)$$

$$E_{g,p}(E_p, z, z_g) = \int_z^{z_g} ds \left(\frac{E_p}{1+s} + \left|\frac{dt}{ds}\right| b(E_p, s)\right)$$

$$\widetilde{Q}(E, z) = \widetilde{\mathcal{L}} \times q(E) \times S(z) \times f_{\text{cut}}(E_{\text{max}})$$

$$q(E) \propto \left(\frac{E}{E_0}\right)^{-\gamma}$$

$$S(z) \propto (1+z)^m$$

$$f_{\text{cut}}(E_{\text{max}}) \propto \exp\left(-\frac{E}{E_{\text{max}}}\right)$$

Cosmogenic neutrinos:

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

$$E_{g,\nu}(E_\nu, z_g) = E_\nu(1+z_g)$$

$$\widetilde{Q}(E_\nu, z) = \int_{E_\nu}^{+\infty} \frac{dE_p}{E_p} \widetilde{n}_p(E_p, z) \times R_\nu(E_\nu, E_p, z)$$

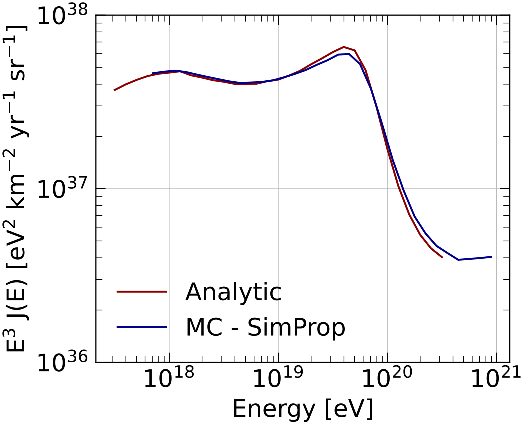
$$R_\nu(E_\nu, E_p, z) = \int_{\epsilon_{th}(E_p)} d\epsilon\, n_\gamma(\epsilon, z) \Sigma_{\nu_i} \Phi_i(E_p, E_\nu, \epsilon)$$

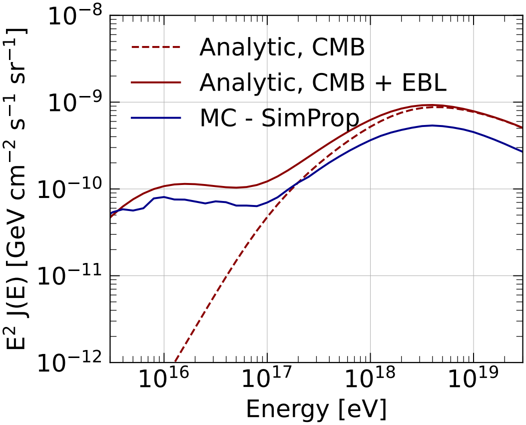
Neutrino Mixing:

$$\phi_{\nu_\mu} \approx \frac{1}{3} \phi_{\nu\text{- all flav.}}$$

Diffuse spectra: protons and neutrinos

Benchmark model: $m = 0, z_{max} = 6, E_0 = 10^{17}$ eV, $E_{max} = 10^{22}$ eV, $\mathcal{L} \approx 4.4 \cdot 10^{45}$ erg Mpc^{-3} yr^{-1}, $\gamma = 2.6$





End of the presentation

Conferences & publications

List of conferences:

- 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, with two contributions, an oral talk and a poster.
- European Cosmic Rays Symposium 2024, in Hvar, Croatia, from 23/09/24 to 27/09/24.
- Conference in memory of V.S. Berezinsky, in L'Aquila (GSSI), Italy, from 01/10/24 to 03/10/24.
- International Symposium on Ultra High Energy Cosmic Rays 2024, in Malargue, Argentina, from 17/11/24 to 21/11/24.

Scientific publications:

- ”Excitation of the non-resonant streaming instability around sources of Ultra-High Energy Cosmic Rays”. *Proceeding of Science 1131*, ICRC2023
- ”Analytic calculations of the spectra of cosmogenic neutrinos”. *Proceeding of Science 1132*, ICRC2023
- ”Implication of UHECR self-induced confinement”. (*work in progress...*)

Other activities

Collaboration activities:

- ”Pierre Auger Observatory International masterclass”, 04/04/23 in L’Aquila (UnivAQ).
- ”Gran Sasso Hands-on 2023, PhD autumn school on experimental astroparticle physics”, from 25/09/23 to 06/10/23, in L’Aquila (LNGS).
- ”SimProp Jamboree”, 13/06/2024, in L’Aquila (GSSI).
- ”Pierre Auger Observatory Collaboration Meeting”, from 10/11/24 to 14/11/24, in Malargue, Argentina.

Phd schools:

- International School of Physics ”Enrico Fermi”, in Varenna, Italy, from 24/06/22 to 29/06/22

GSSI activities:

- Presentation for the Science Fair 2023.
- Presentation for the Science Fair 2024.
- Various presentations at the internal journal club *High-energy AstroParticle Physics Journal, ”HAPPJ”*.

P. Abreu, M. Aglietta, J. M. Albury et al., The European Physical Journal C **81**, 1 (2021).

A. Aab, P. Abreu, M. Aglietta et al., Physics Letters B **762**, 288 (2016).

A. A. Halim, P. Abreu, M. Aglietta et al., Journal of Cosmology and Astroparticle Physics **2023** (05), 024.

A. A. Halim, P. Abreu, M. Aglietta et al., Journal of Cosmology and Astroparticle Physics **2024** (07), 094.

M. Unger, G. R. Farrar and L. A. Anchordoqui, Phys. Rev. D **92**, 123001 (2015).

P. Blasi, E. Amato and M. D'Angelo, Phys. Rev. Lett. **115**, 121101 (2015), arXiv:1508.02866 [astro-ph.HE] .

A. R. Bell, MNRAS **353**, 550 (2004).

E. G. Zweibel and J. E. Everett, The Astrophysical Journal **709**, 1412 (2010).

P. Blasi and E. Amato, Phys. Rev. Lett. **122**, 051101 (2019).

S. R. Kelner and F. A. Aharonian, Phys. Rev. D **82**, 099901 (2010a).

V. Berezinsky, A. Gazizov and S. Grigorieva, Phys. Rev. D **74**, 043005 (2006).

A. Saldana-Lopez, A. Domínguez, P. G. Pérez-González et al., Monthly Notices of the Royal Astronomical Society **507**, 5144 (2021).

M. G. Aartsen, R. Abbasi, Y. Abdou et al., Physical Review Letters **111**, 10.1103/physrevlett.111.021103 (2013).

A. Mücke, R. Engel, J. P. Rachen et al., Computer Physics Communications **124**, 290 (2000), arXiv:astro-ph/9903478 [astro-ph] .

S. R. Kelner and F. A. Aharonian, Phys. Rev. D **82**, 099901 (2010b).

R. A. Batista, D. Boncioli, A. Di Matteo et al., Journal of Cosmology and Astroparticle Physics **2019** (05), 006.