Impact of coherent scattering on relic neutrinos boosted by cosmic rays

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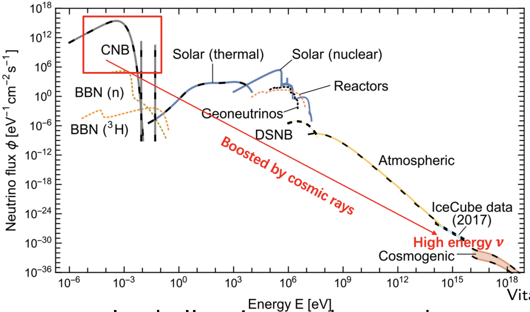
Research background and motivation



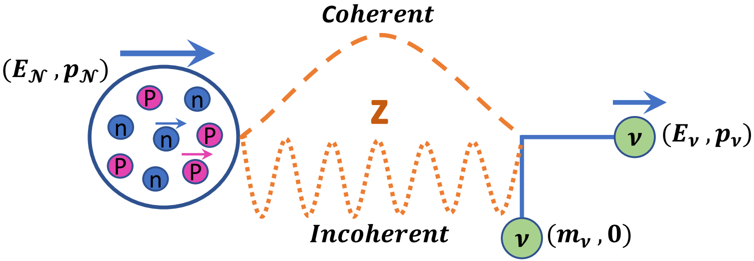
Vitagliano *et al.* [1910.11878]

- The CνB is extremely challenging to detect; the strongest current constraint on the local overdensity is $\eta < 9.7 \times 10^{10}$ (90% CL) from relic-neutrino capture at KATRIN. KATRIN [2202.04587]
- Ultra-high-energy cosmic rays (UHECR) can up-scatter the CνB to very high energies — first proposed by Hara & Sato in the 1980s and revisited by Herrera *et al.* in 2024. Hara & Sato [PTP.62.969; PTP.65.477], Herrera *et al.* [2402.00985]

Earlier works all neglected the contribution from coherent elastic neutrino–nucleus scattering (CEνNS).

Cosmic rays and relic neutrinos

- CEνNS: neutrinos scatter off the whole nucleus, with the cross section coherently enhanced by $\propto N^2$ (valid for $E_\nu \lesssim \mathcal{O}(10)$ MeV).
- Pierre Auger Observatory (PAO) shows that for $E_{\rm CR} > 10$ EeV, the proton fraction is $< 10\%$, i.e. heavy nuclei dominate. Pierre Auger [2211.02857]
- For iron with $E_{\mathcal{N}_i} \sim 10$ EeV scattering on a relic neutrino of $m_\nu = 0.1$ eV, in the rest frame of the nucleus, CνB energy is about ~ 20 MeV — exactly the CEνNS regime.



Scattering cross sections

The total differential cross section of UHECR–CνB scattering includes both coherent and incoherent contributions:

$$\frac{d\sigma^{\nu\mathcal{N}_i}}{dE_\nu} = \frac{d\sigma_{\text{coh}}^{\nu\mathcal{N}_i}}{dE_\nu} + \frac{d\sigma_{\text{incoh}}^{\nu\mathcal{N}_i}}{dE_\nu} \,. \tag{1}$$

Coherence differential cross section:

$$\frac{d\sigma_{\text{coh}}^{\nu\mathcal{N}_i}}{dE_\nu} = \frac{2G_F^2 m_\nu}{\pi} Q_{W,i}^2 \left(1 - \frac{E_\nu}{E_{\mathcal{N}_i}} - \frac{m_{\mathcal{N}_i}^2 E_\nu}{2m_\nu E_{\mathcal{N}_i}^2}\right) F^2(q^2) \,, \tag{2}$$

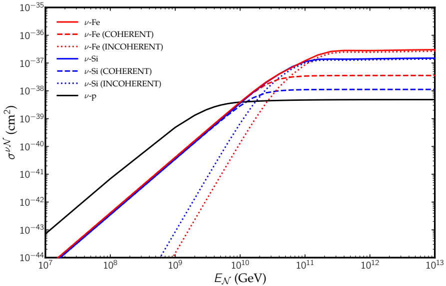
Incoherence differential cross section:

$$\frac{d\sigma_{\text{incoh}}^{\nu\mathcal{N}_i}}{dE_\nu} = \left[Z_i \frac{d\sigma_{\text{ES}}^{\nu p}}{dE_\nu} + N_i \frac{d\sigma_{\text{ES}}^{\nu n}}{dE_\nu}\right] \left(1 - F^2(q^2)\right) . \tag{3}$$

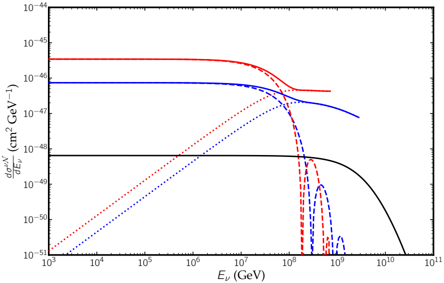
- Coherent $\propto Q_W^2$ and $\propto F^2(q^2)$, corresponding to scattering on the whole nucleus.
- Incoherent $\propto$ nucleon number and $\propto \left(1 - F^2(q^2)\right)$, corresponding to scattering on individual nucleons.

Scattering cross sections

Total cross section



Differential cross section ($E_N = 100$ EeV)



- For $E_N > 10$ EeV, heavy nuclei dominate the cross section.
- For $E_N < 10$ EeV, proton ES dominates.
- At higher energies, heavier nuclei have larger $\sigma_{\nu\mathcal{N}}$.

- For $E_\nu < 10^8$ GeV, heavy nuclei have cross sections $\mathcal{O}(10^2)$ larger than protons.
- Kinematic cutoff

$$E_\nu^{\max} = \frac{E_{N_i}^2}{E_{N_i} + m_{N_i}^2/(2m_\nu)}.$$

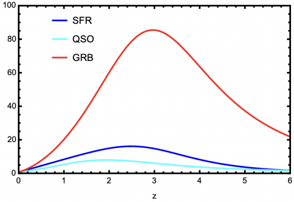
As momentum transfer $q = \sqrt{2m_\nu E_\nu}$ increases, the dominant contribution changes from coherent to incoherent: when q is small, $F^2(q^2) \simeq 1 \Rightarrow$ coherent dominates; when q is large, $1 - F^2(q^2) \simeq 1 \Rightarrow$ incoherent dominates.

Flux of boosted CνB at Earth

UHECR propagate long distances from their sources to the Earth, during which the CνB can be boosted. The boosted CνB flux at Earth is:

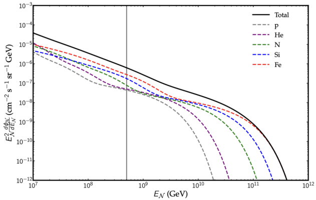
$$\frac{d\phi_\nu}{dE_\nu} = \sum_{i,j} \int_{z_{\rm min}}^{z_{\rm max}} dz \, \frac{c}{H(z)} \, f(z) \, \eta \, n_{\nu_j} (1+z)^3 \int_0^\infty dE_{\mathcal{N}_i} \, \frac{d\sigma^{\nu \mathcal{N}_i}}{dE'_\nu} \, \frac{d\phi_{\mathcal{N}_i}}{dE_{\mathcal{N}_i}} \, \Theta\left[E_\nu^{\rm max} - E'_\nu\right] \tag{4}$$

$f(z)$: CR source distribution



Star Formation Rate (SFR)
Quasi-Stellar Object (QSO)
Gamma-Ray Burst (GRB)
(In my talk we use SFR)

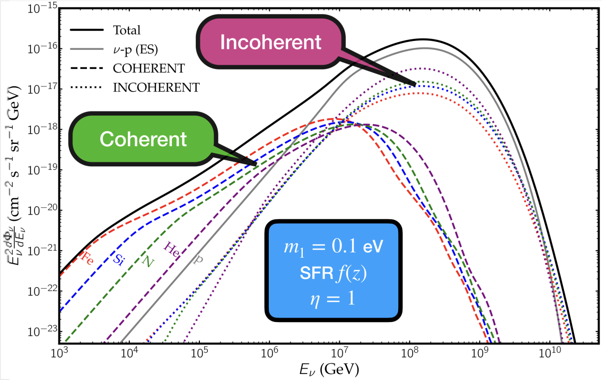
$d\phi_{\mathcal{N}_i}/dE_{\mathcal{N}_i}$: CR flux



We take $E_{\mathcal{N}_i} > 5 \times 10^8$ GeV as UHECR, since only such high-energy particles can escape from their host galaxies.

Flux of boosted CνB at Earth

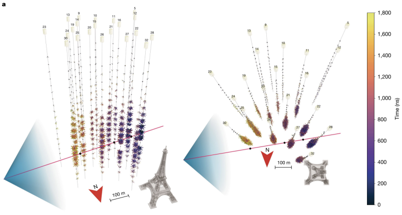
$$m_1 = 0.1 \text{ eV}, \ \eta = 1$$



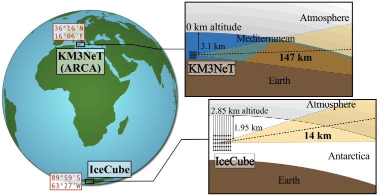
- Coherent scattering dominates for $E_\nu \lesssim 10^7$ GeV, with heavier nuclei showing stronger enhancement.
- For $E_\nu \gtrsim 10^7$ GeV, proton elastic scattering dominates, with significant incoherent contribution from heavy nuclei.

KM3NeT and the KM3-230213A event

- **KM3NeT**: a deep-sea neutrino telescope in the Mediterranean Sea.
- **Detection principle**: multi-PMT optical modules detect Cherenkov light from μ tracks.
- **KM3-230213A**: The highest neutrino energy detected so far is 220 PeV.
- **Tension between KM3NeT and IceCube**: Some new physics models alleviate their tension.



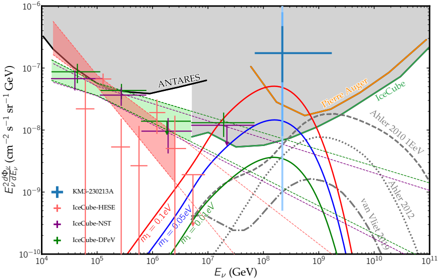
KM3NeT Collaboration [Nature 638, 376 (2025)]



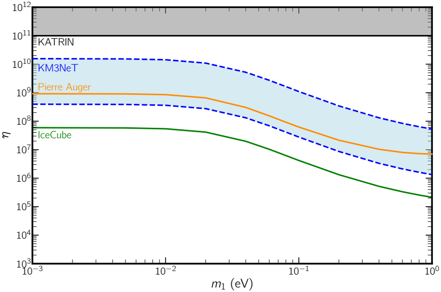
Brdar & Chattopadhyay [arXiv:2502.21299]

Constraints on CνB overdensity

SFR, $\eta = 10^8$



SFR



- At $m_1 = 0.01$ eV, IceCube (PAO) sets $\eta < 5.4 \times 10^7$ (8.5×10^8) at 90% CL.
- For $m_1 < 0.01$ eV, the bounds become flat as the flux is dominated by the heavier eigenstates m_2 and m_3.
- Explaining KM3-230213A requires $\eta \in [\,3.7 \times 10^8,\, 1.5 \times 10^{10}\,]$ for $m_1 = 0.01$ eV.
- Different peak energies and multimessenger observations can distinguish boosted CνB from cosmogenic neutrinos.

Summary

- UHECR boosting the CvB may be a possible source of ultra-high-energy neutrinos.
- The CνB can be boosted to the UHE domain via both coherent and incoherent scattering with UHECR.
- Coherent scattering and incoherent scattering dominate the low- and high-energy regimes, respectively.
- The explanation of the KM3-230213A event can be achieved with $\eta \sim 10^8$ for $m_1 = 0.1$ eV.
- For $m_1 = 0.01$ eV, the 90% CL upper limits are $\eta < 5.4 \times 10^7$ (IceCube) and $\eta < 8.5 \times 10^8$ (PAO).

Thank you!