Impact of Coherent Scattering on Cosmic-Ray Boosted Relic Neutrinos

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Based on arXiv:2505.04791

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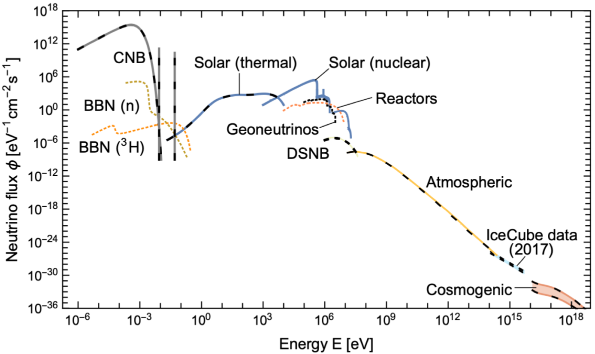
Neutrino Spectrum at Earth

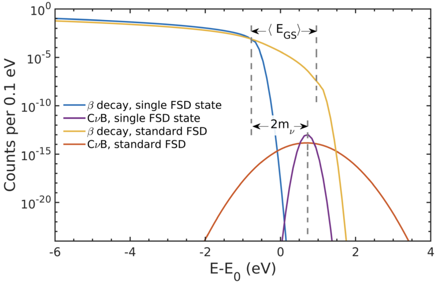


Vitagliano, Tamborra, Raffelt1 [1910.11878]

- Two key targets remain undetected:
  - **Cosmogenic neutrinos** – produced by UHECR scattering on the CMB (GZK process).
  - **Relic neutrinos** – predicted by ΛCDM, but extremely challenging to detect directly ($T \simeq 1.95$ K).

Tritium Capture of Relic Neutrinos

- PTOLEMY storing tritium atoms on a graphene sheet, but still faces severe technical challenges by the Heisenberg uncertainty principle.
  Cheipesh, Cheianov, Boyarsky [2101.10069]
- Neutrino number overdensity can be greatly enhanced in some non-standard scenarios; a hypothetical local source can reach $\eta \sim 10^{11}$.
  Bondarenko, Boyarsky, Pradler, Sokolenko [2306.12366]
- The strongest experimental constraint on the local overdensity is $\eta < 9.7 \times 10^{10}$ at KATRIN.
  KATRIN [2202.04587]



Cosmic-Ray Boosted CνB

Prog. Theor. Phys. Vol. 64, No. 3, September 1980, Progress Letters

Scattering of the Cosmic Neutrinos by High Energy Cosmic Rays

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(Received June 23, 1980)

- Non-observation of boosted flux in the Milky Way and at blazar TXS 0506+056 set upper limits on local CνB overdensity $\sim 10^{13}$ and $\sim 10^{11}$ at the blazar.

Císcar-Monsalvatje, Herrera, Shoemaker [2402.00985]

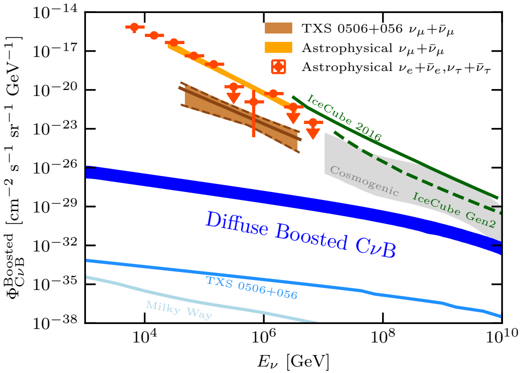
- Considered cosmic-ray reservoirs (e.g. galaxy clusters with long UHECR trapping), and set the limit on overdensity in clusters down to $\eta \sim 10^{10}$.

De Marchi, Granelli, Nava, Sala [2405.04568]

Diffuse Boosted CνB

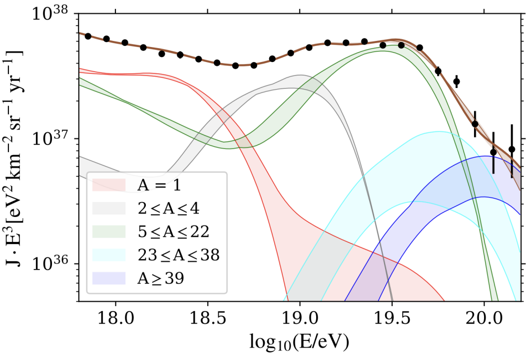
- Calculated the diffuse boosted CνB assuming pure-proton cosmic rays across cosmic history.

Herrera, Horiuchi, Qi [2405.14946]



- Recent Pierre Auger Observatory (PAO) data shows that there are $<10\%$ protons above 10 EeV, i.e. heavy nuclei dominate.

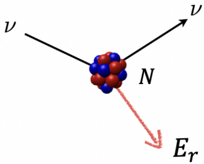
Pierre Auger [2211.02857]



Coherent Elastic Neutrino-nucleus Scattering (CEνNS)

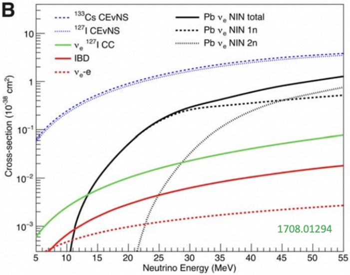
- For $E_\nu \lesssim \mathcal{O}(10)$ MeV, neutrinos scatter off the nucleus as a whole since the momentum transfer is smaller than the inverse of the nuclear radius, and the cross section can be coherently enhanced.

Freedman Phys. Rev. D 9, 1389 (1974)



$$\frac{d\sigma}{dE_r} = \frac{G_F^2 m_N}{4\pi}\left(1 - \frac{E_r m_N}{2E_\nu^2}\right) Q_{\rm SM}^2 F(q^2)^2$$

$$Q_{\rm SM}^2 = \left(Z g_p^V + N g_n^V\right)^2 \propto N^2$$



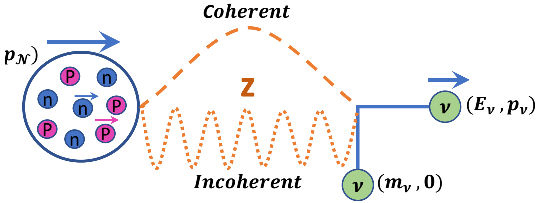
- 2017 — first observed by COHERENT in stopped π beams.
- 2024 — solar ^8B neutrinos by PandaX and XENONnT.
- 2025 — reactor neutrinos by CONUS+. [See Manfred Lindner's talk]

Coherent Enhancement for Boosted CνB

- Observations from the PAO, KASCADE-Grande, and TA show an increasing prevalence of heavy nuclei at ultra-high-energies. Some studies even adopt a pure iron model for UHECR composition.

Kachelriess, Semikoz [1904.08160]

- For iron CR with $E_{\mathcal{N}_i} \sim 10$ EeV scattering on a relic neutrino of $m_\nu = 0.1$ eV, CνB energy is $\sim$ 20 MeV in nucleus rest frame — exactly in the CEνNS regime.



Scattering Cross Sections

The total differential cross section of neutrino-nucleus scattering includes both coherent and incoherent contributions:

Bednyakov, Naumov [1806.08768]

$$\frac{d\sigma^{\nu\mathcal{N}_i}}{dE_\nu} = \frac{d\sigma^{\nu\mathcal{N}_i}_{\text{coh}}}{dE_\nu} + \frac{d\sigma^{\nu\mathcal{N}_i}_{\text{incoh}}}{dE_\nu}$$

- Coherent differential cross section:

$$\frac{d\sigma^{\nu\mathcal{N}_i}_{\text{coh}}}{dE_\nu} = \frac{2G_F^2 m_\nu}{\pi} Q^2_{W,i} \left(1 - \frac{E_\nu}{E_{\mathcal{N}_i}} - \frac{m^2_{\mathcal{N}_i} E_\nu}{2m_\nu E^2_{\mathcal{N}_i}}\right) F^2(q^2)$$

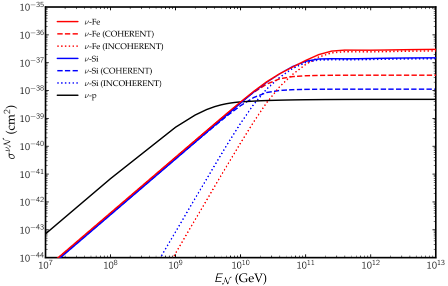
- Incoherent differential cross section:

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

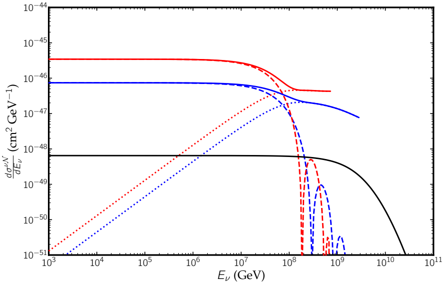
- Coherent $\propto N^2$ and $F^2(q^2)$, corresponding to scattering on the whole nucleus.
- Incoherent $\propto N$ (Z) and $\left(1 - F^2(q^2)\right)$, corresponding to scattering on individual nucleons.

Numerical results

Total cross section



Differential cross section ($E_N = 100$ EeV)



- For $E_N > 10$ EeV, heavier nuclei have larger cross sections.
- For $E_N < 10$ EeV, proton elastic scattering dominates.

- 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 part: when q is small, $F^2(q^2) \simeq 1 \Rightarrow$ coherent part dominates; when q is large, $1 - F^2(q^2) \simeq 1 \Rightarrow$ incoherent part dominates.

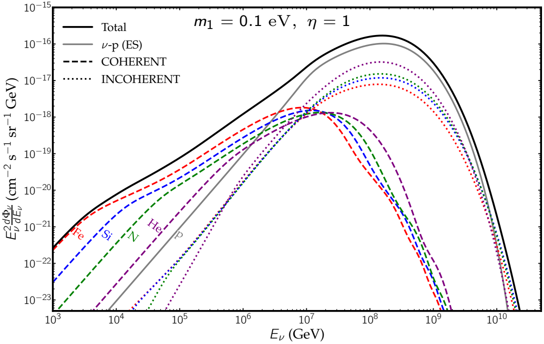
Diffuse Flux of Boosted CνB at Earth

The diffuse flux of UHECR boosted CνB at Earth is:

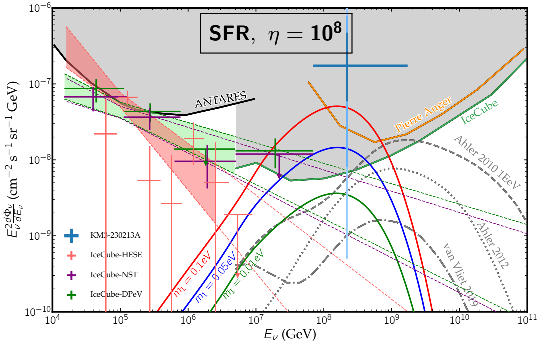
Herrera, Horiuchi, Qi [2405.14946]

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

where $f(z)$ is CR source distribution from star formation rate (SFR) model, and $\frac{d\phi_{\mathcal{N}_i}}{dE_{\mathcal{N}_i}}$ is all-particle CR energy spectrum adopt from the Hillas model.

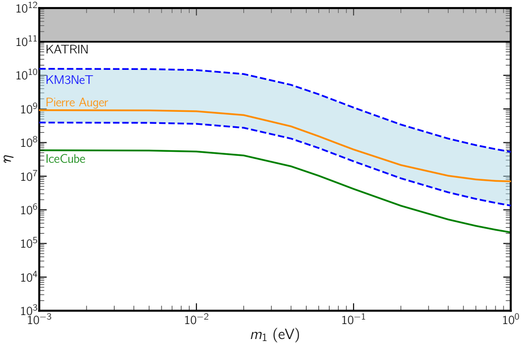


Compare with Experimental Data



- The boosted CνB flux decreases as the lightest neutrino mass becomes smaller.
- Boosted flux peaks at different energies than cosmogenic neutrinos.
- The peak of the boosted CνB flux coincides with KM3-230213A event.

Constraints on CνB Overdensity



- At $m_1 = 0.1\ \mathrm{eV}$, IceCube (PAO) sets $\eta < 4.2 \times 10^6$ (6.2×10^7) at 90% CL; Stronger than KATRIN bound.
- For $m_1 < 0.01\ \mathrm{eV}$, 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 $m_1 = 0.01\ \mathrm{eV}$.

Summary

- Comic-ray boosted CνB provides a new source of ultra-high-energy neutrinos.
- The cross section of UHECR scattering off CνB can be coherently enhanced; similar to terrestrial CEνNS experiments.
- Non-observation of boosted flux at IC and PAO set a stronger bound on CνB overdensity than current experimental limit at KATRIN.
- The explanation of the KM3-230213A event requires an overdensity of $\eta \sim 10^8$.

Thanks for your attention!