Probing Cosmic Neutrino Background Boosted by Ultra-High-Energy Cosmic Rays

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Zhang, Sandrock, JL, Yue [2505.04791] Zhang, JL [2606.18088]

宇宙背景中微子与暗物质探测研讨会，中国高等科学技术中心，北京，10/30/2026

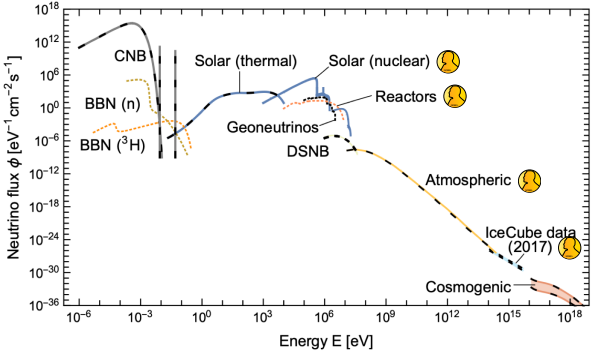
Outline

1. **Introduction**
   Cosmic rays boosted CνB, recent progresses
2. **SM scattering channels**
   From coherent nuclear scattering to deep-inelastic scattering
3. **Ultra-high-energy cosmic rays**
   Composition and CR models
4. **Boosted relic neutrinos**
   Boosted neutrino spectra, constraints on the overdensity

Cosmic neutrino background

- **The most abundant neutrinos in the Universe**, yet no direct detection.
- Detecting the CνB remains a **holy grail of neutrino physics**.
- **Direct capture**: $\nu_e + {}^3\mathrm{H} \to {}^3\mathrm{He} + e^-$, but meV resolution needed (PTOLEMY)
- KATRIN only excludes enormous local overdensity ($\eta \equiv n_\nu / n_{\nu,\mathrm{standard}}$):
  $\eta < 9.7 \times 10^{10}$ (90% CL, Majorana).

KATRIN [2202.04587]



Vitagliano, Tamborra, Raffelt [1910.11878]

Cosmogenic neutrinos: UHECRs cross the CMB ($n_\gamma \simeq 411\ \mathrm{cm}^{-3}$) (GZK process).

$$p_{\mathrm{UHE}} + \gamma_{\mathrm{CMB}} \to \Delta^+ \to n + \pi^+, \qquad \pi^+ \to \mu^+ + \nu_\mu, \quad \mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu.$$

Could UHECRs cross CνB ($n_\nu \simeq 336\ \mathrm{cm}^{-3}$) produces **boosted high energy neutrinos?**



Francis Halzen

Nobel Prize in Physics 2026

"for decisive contributions to the IceCube Neutrino Observatory and the discovery of high-energy neutrinos of astrophysical origin"

IceCube milestones

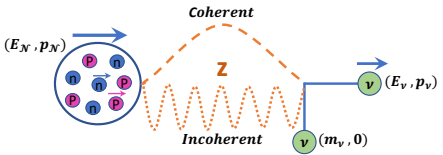
2013 astrophysical neutrinos [Science 342, 1242856]
2018 TXS 0506+056 [Science 361, eaat1378]
2021 Glashow resonance at 6 PeV [Nature 591, 220]
2022 NGC 1068 [Science 378, 538]
2023 Galactic plane [Science 380, 1338]

IceCube opened a new window: high-energy neutrino astronomy

Relic neutrinos boosted by UHECRs would appear in exactly this window: **the boosted CνB becomes a target that real data can test.**

$$A_{\rm UHECR} + \nu_{\rm relic} \xrightarrow{Z} A + \nu_{\rm boosted}$$

Hara, Sato [PTP 64, 1089 (1980); 65, 477 (1981)]



Zhang, Sandrock, JL, Yue [2505.04791]

Maximal energy transfer

$$E_\nu^{\rm max} = \frac{E_A^2}{E_A + m_A^2/2m_\nu}, \qquad \frac{m_A^2}{2m_\nu} \simeq \begin{cases} 4.4\ \text{EeV} & (p) \\ 1.4\times10^4\ \text{EeV} & (\text{Fe}) \end{cases}$$

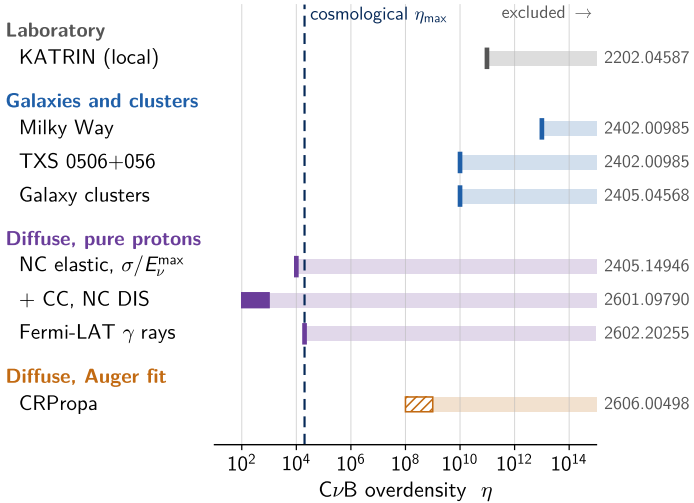
- a nucleon above a few EeV transfers most of its energy
- coherent scattering on Fe at 10 EeV gives $E_\nu \lesssim 7$ PeV
- PeV–EeV neutrinos: **IceCube, Auger, KM3NeT**

Relic neutrino in the cosmic-ray rest frame:
$E_\nu^\star \simeq (E_A/m_A)\, m_\nu$

- p at 10 EeV: $E_\nu^\star \simeq 1$ GeV, the RES and DIS regime
- Fe at 10 EeV: $E_\nu^\star \simeq 20$ MeV, the CEνNS regime

One process covers the whole range of neutrino–nucleus scattering.

Recent progress



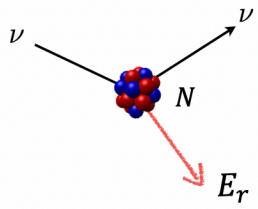
Different regions

- local: KATRIN, Milky Way
- sources: TXS 0506+056; clusters confining UHECRs for ~ 2 Gyr
- cosmological average: UHECRs at $z \lesssim 6$

Diffuse limits differ by $\sim 10^7$

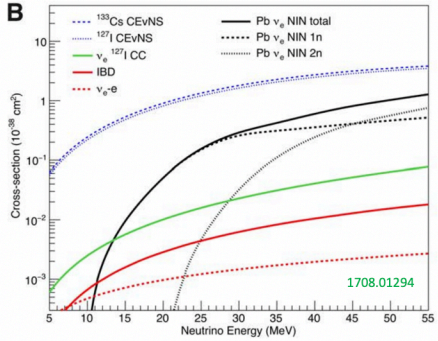
- cosmic rays: pure protons up to 10^{11} GeV, or Auger-fitted mixed composition
- cross section: $\sigma/E_\nu^{\max}$; form factors; RES, DIS
- observable: boosted ν or secondary γ

Coherent elastic neutrino-nucleus scattering (CEνNS)



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

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

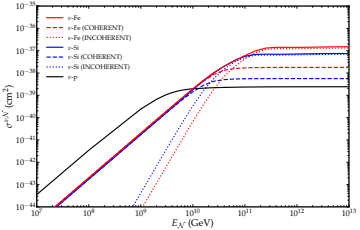


- 2017 – first observed by COHERENT in stopped π beams. [Science 357,1123 (2017)]
- 2024 – solar ^8B neutrinos by PandaX and XENONnT. [PRL 133, 191001 & 191002 (2024)]
- 2025 – reactor neutrinos by CONUS+. [Nature 643, 8074 (2025)]

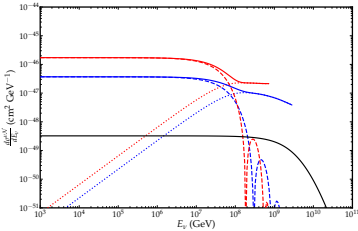
Coherent and incoherent elastic scattering

$$\frac{d\sigma_{\rm COH}}{dE_\nu} = \frac{G_F^2 m_\nu}{\pi} Q_W^2 \left(1 - \frac{E_\nu}{E_A} - \frac{m_A^2 E_\nu}{2 m_\nu E_A^2}\right) F_A^2, \qquad \frac{d\sigma_{\rm INCOH}}{dE_\nu} = \left[Z \frac{d\sigma_{\nu p}}{dE_\nu} + N \frac{d\sigma_{\nu n}}{dE_\nu}\right] (1 - F_A^2)$$

Total cross section



Differential, $E_A = 100$ EeV

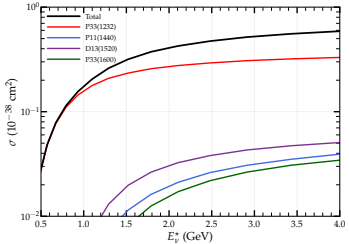


$m_\nu = 0.1$ eV. Fe (red), Si (blue), p (grey); dashed: coherent, dotted: incoherent.

- COH $\propto N^2$ and $F^2(q^2)$, corresponds to scattering on the whole nucleus.
- INCOH $\propto N\,(Z)$ and $\left(1 - F^2(q^2)\right)$, scattering on individual nucleons.
- **Coherent enhancement**: iron exceeds the proton by two orders of magnitude for $E_\nu \lesssim 10^8$ GeV.

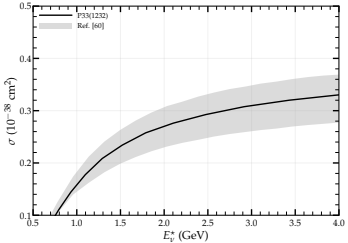
$$N + \nu \longrightarrow N^* + \nu, \qquad N^* \longrightarrow N\pi, \ldots$$

Resonance spectrum



Berger, Sehgal [0709.4378]; GENIE [2106.09381]

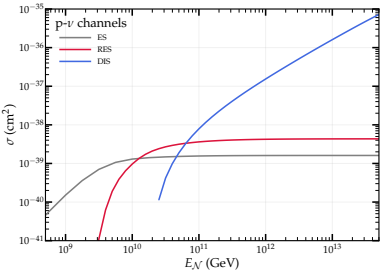
$\Delta(1232)$



Comparison: Abbaslu et al. [2412.13349]

- RES covers the **intermediate region between ES and DIS**; Our treatment includes 17 GENIE resonance states.
- $\Delta(1232)$ **is the largest resonance contribution**; higher states account for the gap to the total curve.

$$\nu + q(\bar{q}) \longrightarrow \nu + q(\bar{q}), \qquad \nu + N \longrightarrow \nu + X$$



Proton CR, $m_\nu = 0.1$ eV

At large Q^2, neutrino resolves **quarks and antiquarks**.

Parton distributions determine the inclusive scattering rate.

Kovarik et al. [1509.00792]

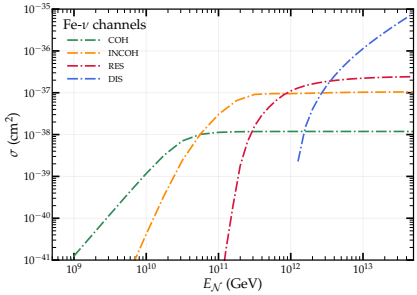
$$E'_\nu \simeq xyE_N.$$

x: parton momentum fraction
y: fraction of parton energy transferred to the neutrino

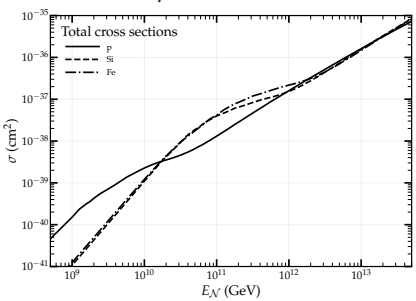
- DIS overtakes ES and RES for $E_N \gtrsim 60$ **EeV** and continues to grow over the plotted range.
- Producing UHE neutrinos requires energetic partons. The signal probes the **high-energy CR tail and its composition**.

Nuclear cross sections

Iron



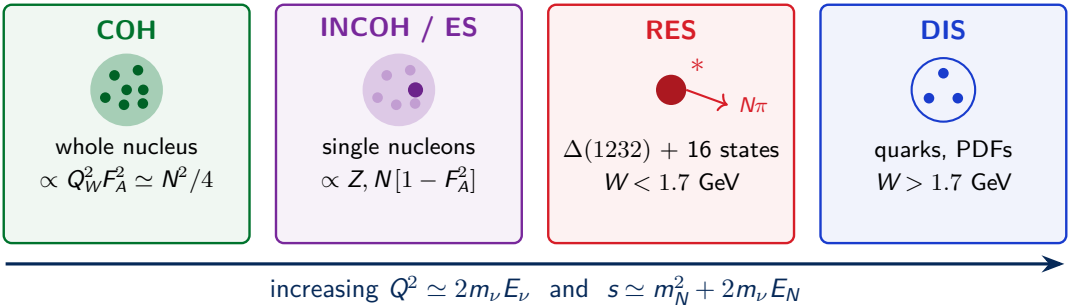
***p*, Si, Fe**



Nuclei show the same sequence, **COH** $\rightarrow$ **INCOH** $\rightarrow$ **RES** $\rightarrow$ **DIS**, at A times higher energy, because each nucleon carries only E_A/A.

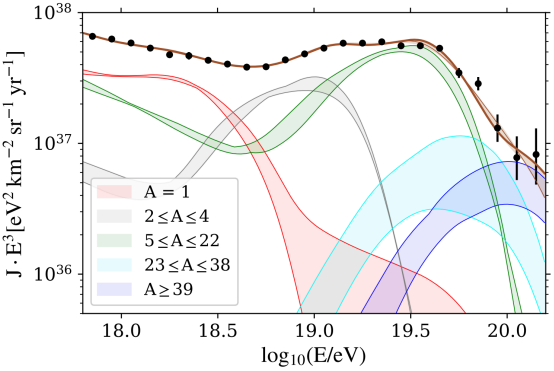
Which channel operates depends on the energy per nucleon.

Scattering regimes



$m_\nu = 0.1$ eV	**COH** edge	**ES** plateau	**RES** threshold	**DIS** dominant
scale	$\frac{1}{2m_\nu R_A^2}$	$\frac{M_A^2}{2m_\nu}$	$\frac{m_N m_\pi}{m_\nu}$	
value	$E_\nu \simeq 10$ PeV (Fe)	$E_\nu \simeq 5$ EeV	$E_N \simeq 1.4$ EeV	$E_N \gtrsim 60$ EeV

UHECR composition



Auger composition analyses favor an increasingly heavy component at high energy.

A nucleus carries a larger weak charge, but each nucleon has only

$$E_N \simeq E_A/A.$$

Pierre Auger [2211.02857]

- The Auger fits shown favor a proton fraction $\lesssim 10\%$ above 10 EeV.
- Pure-iron source scenarios have also been used in some phenomenlogical studies.

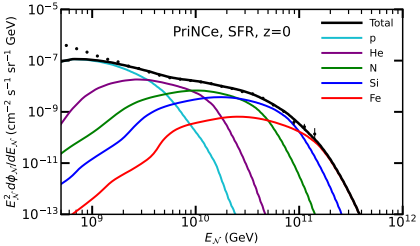
Arisaka et al. [0709.3390] Allard et al. [0805.4779]

- **PriNCe**: a simulation code solving UHECR transport in the CMB/EBL.

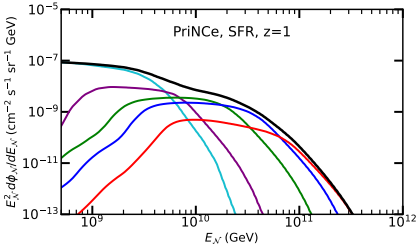
Heinze et al. [1901.03338]

- Inject p, He, N, Si and Fe, and fit the **propagated spectrum and composition** to Auger data.

$z = 0$



$z = 1$



- **Energy losses and nuclear fragmentation** reshape the CR spectrum and composition during propagation.

Phenomenological models of the observed CR spectrum, built from rigidity-limited populations:

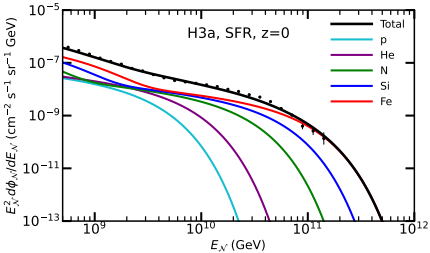
$$J_i(E,0) = k_{\rm H} \sum_j a_{i,j} E^{-\gamma_{i,j}-1} \exp\left[-\frac{E}{Z_i R_{c,j}}\right].$$

Population (R_c)	Parameter	p	He	N	Si	Fe
1 (4 PV)	$a_{i,j}$	7860	3550	2200	1430	2120
	$\gamma_{i,j}$	1.66	1.58	1.63	1.67	1.63
2 (30 PV)	$a_{i,j}$	20	20	13.4	13.4	13.4
	$\gamma_{i,j}$	1.4	1.4	1.4	1.4	1.4
3 (2 EV)	$a_{i,j}$	1.7	1.7	1.14	1.14	1.14
	$\gamma_{i,j}$	1.4	1.4	1.4	1.4	1.4
3^* (60 EV)	$a_{i,j}$	200	0	0	0	0
	$\gamma_{i,j}$	1.6	–	–	–	–

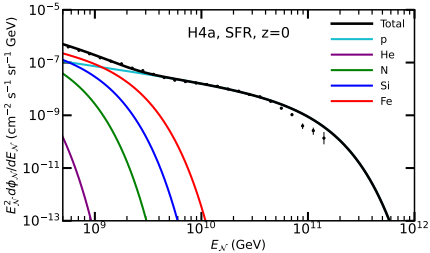
- **H3a**: $1+2+3$ (mixed). **H4a**: $1+2+3^*$ (protons).
- Pop. 1: Galactic knee. Pop. 2: transition region of uncertain origin.
- Pop. 3: extragalactic, **mixed in H3a and proton-only in H4a**.

Gaisser [1111.6675]; Gaisser, Stanev, Tilav [1303.3565]

H3a: mixed composition



H4a: high-energy protons



- H3a: $R_c = 2$ EV. H4a: $R_c = 60$ EV and a longer high-energy nucleon tail.
- Here Auger fixes the **overall flux normalization** only. H4a's proton dominance is **disfavored by Auger composition data**.
- H4a's higher nucleon energies enhance the **RES and DIS signal**.

Boosted-neutrino flux

$$\frac{d\phi_\nu}{dE_\nu} = \sum_{A,j} \int_0^6 dz \, \frac{c}{H(z)} \, n_{\nu_j}(z) \int_{E_{A,\min}}^{\infty} dE_A \, J_A(E_A, z) \, \frac{d\sigma_{Aj}}{dE'_\nu}$$

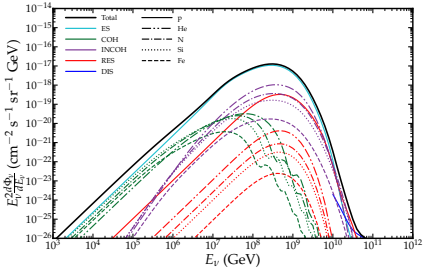
$$E'_\nu = (1+z)E_\nu, \qquad n_{\nu_j}(z) = \eta \, n_{\nu_j,0}(1+z)^3.$$

Herrera, Horiuchi, Qi [2405.14946]

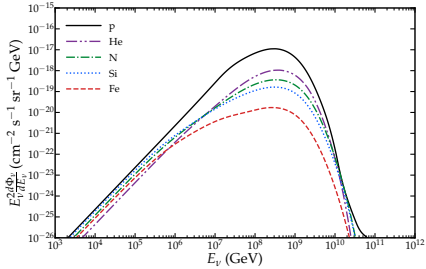
- PriNCe follows the evolving spectrum and composition. For H3a/H4a, we use $J_i(E,z) = f(z) J_i(E,0)$.
- $f(z)$ is a normalized source evolution function (SFR, QSO, GRB).
- The signal depends on the **relic-neutrino density**, the available **CR flux**, and the differential **cross section**.

SFR, NO, $m_1 = 0.1$ eV, $\eta = 1$.

Scattering channels



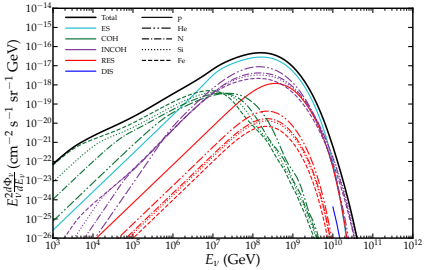
CR composition



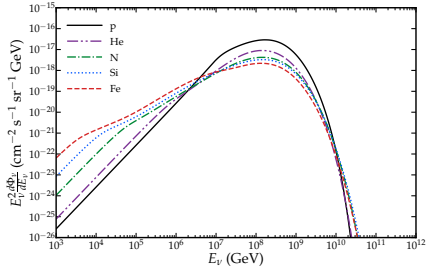
- **Proton ES dominates**: protons are most abundant in the 0.5–3 EeV CR range that supplies most of the signal.
- Coherent scattering enhances the **low-energy nuclear contribution**.
- The injection cutoff rigidity ($R_{\max} \simeq 1.8$ EV) and propagation suppress high-energy nucleons, leaving **RES and DIS subdominant**.

SFR, NO, $m_1 = 0.1$ eV, $\eta = 1$.

Scattering channels



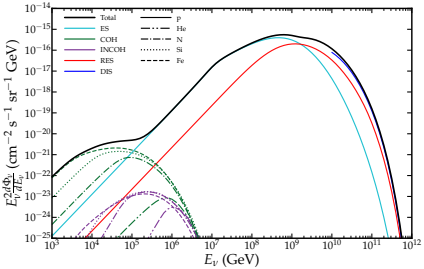
CR composition



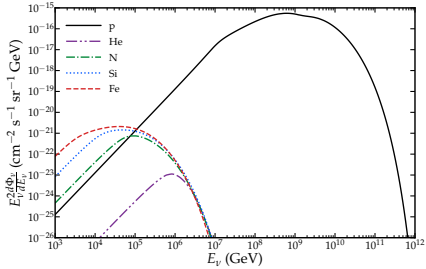
- Below about 5 PeV, **Si and Fe dominate due to coherent scattering**.
- At higher energies, coherence is lost and lighter CR become more important.
- RES dominate above $E_\nu \sim 10$ EeV. The cutoff rigidity $R_c = 2$ EV suppresses high-energy nucleons, keeping DIS small.

SFR, NO, $m_1 = 0.1$ eV, $\eta = 1$.

Scattering channels



CR composition

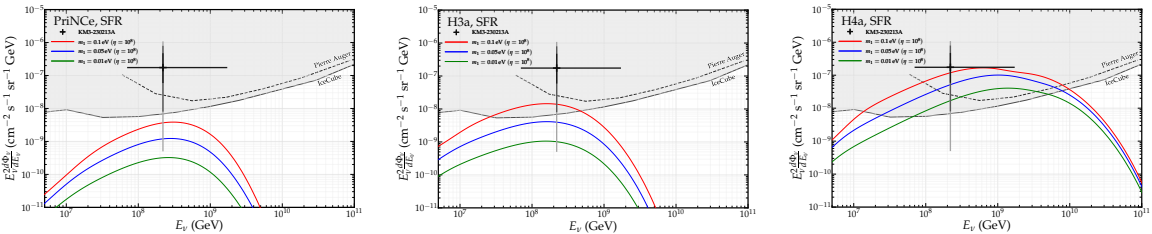


- The high-rigidity proton population gives a **larger flux extending to higher neutrino energies**.
- ES, RES and DIS contribute at successively higher energies. **DIS is most visible in H4a**.

Neutrino mass and detectability

SFR, NO, $\eta = 10^8$; $m_1 = 0.1,\ 0.05,\ 0.01$ eV (red, blue, green).

PriNCe **H3a** **H4a**

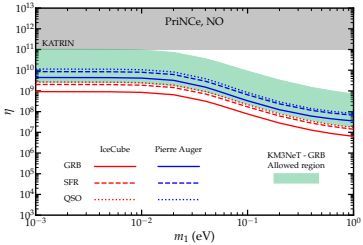


IceCube [2502.01963]; Auger [1906.07422]; KM3NeT Nature 638, 376 (2025)

- A larger m_ν raises the collision energy, $s_{\nu N} \simeq m_N^2 + 2 m_\nu E_N$, giving **more energetic boosted neutrinos**.
- The signal reaches hundreds-of-PeV region, **KM3-230213A** (220 PeV) lies right at the peak.
- Standard density, $\eta = 1$, is far below current sensitivity. An **enhanced relic density** is required for detection.

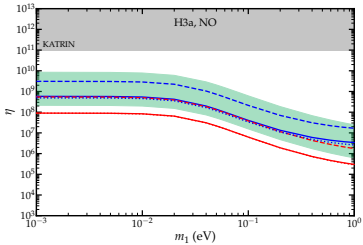
Relic-density constraints

PriNCe



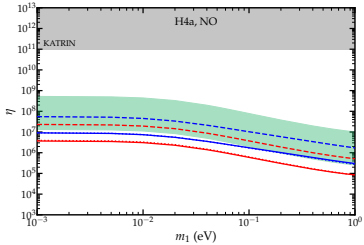
$\eta \lesssim 8 \times 10^7$

H3a



$\eta \lesssim 6 \times 10^6$

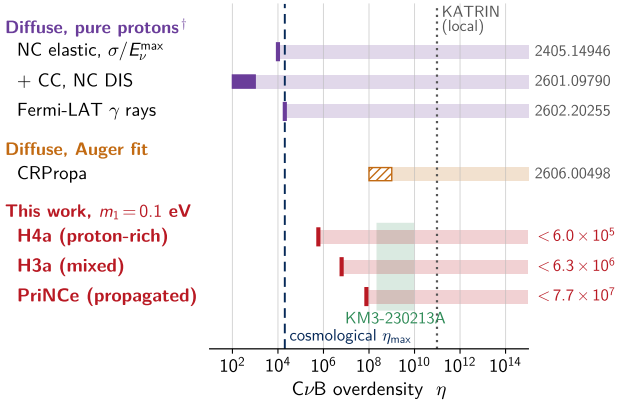
H4a



$\eta \lesssim 6 \times 10^5$

- **GRB evolution gives the strongest bounds**. H4a improves on PriNCe by **about two orders of magnitude** through its high-energy protons.
- Explaining KM3-230213A needs $\eta \sim 10^8$–10^{10}: **in tension with IceCube**, similar to other diffuse sources.
- Future experiments like GRAND, IceCube-Gen2 and TRIDENT could improve the reach.

Comparison with other studies



†assumed proton flux: 7–70× the measured flux of all nuclei at 10 EeV

Our limits are 10^2–10^6 weaker than the pure-proton ones:

- **Cosmic-ray flux**: their proton flux is 17–68 times the measured flux of all nuclei at 10 EeV.
- **Maximum rigidity**: protons up to 10^{11} GeV switch on resonances and DIS.
- **Cross section**: $\sigma/E_\nu^{\max}$ without form factors.

A limit on η is only as good as the cosmic-ray model behind it.

Summary

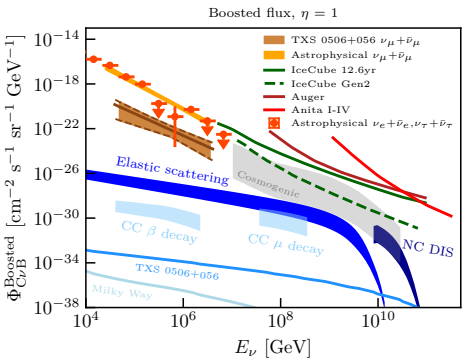
- IceCube has opened the high-energy neutrino window; cosmic rays can boost the relic neutrinos into its detection.
- Heavy nuclei scatter relic neutrinos **coherently**, as in CEνNS; this shapes the flux below 10^7 GeV.
- RES and DIS become relevant for sufficiently energetic CRs. The channel follows the energy per nucleon; the high-energy tail traces the **maximum rigidity**.
- The CR model determines the signal: proton ES in PriNCe, nuclear coherence in H3a, and a stronger inelastic tail in H4a. **CR model is the key input**.
- The standard CνB remains beyond current reach. Next: IceCube-Gen2, GRAND, TRIDENT...

Thank you!

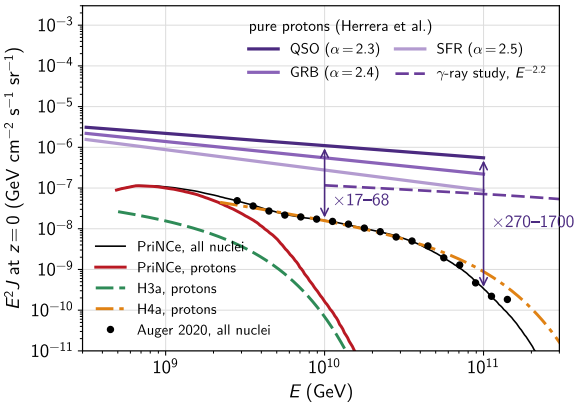
Backup: charged currents and DIS

Herrera, Horiuchi, Qi, Shoemaker [2601.09790]

- Same proton spectra as 2405.14946; NC elastic now with nucleon form factors.
- CC quasi-elastic $p + \bar{\nu}_\ell \to n + \ell^+$: secondary neutrinos from n and ℓ decays, subdominant.
- NC DIS above $E_p \simeq 2$ GeV $m_p/m_\nu \simeq 2 \times 10^{10}$ GeV dominates at $E_\nu \simeq 10^{10}$ GeV.
- The boosted flux must stay below the published flux limits: IceCube $\eta \sim 10^2$–10^3, Gen2 $\sim$ 1–10 ($m_\nu \gtrsim 0.1$ eV).



Backup: cosmic-ray flux in the pure-proton studies



Herrera et al. [2405.14946, 2601.09790]

- Pure protons, $E^{-2.7}$ below 10^7 GeV, $E^{-\alpha}$ above ($\alpha = 2.5$, 2.4, 2.3) up to 10^{11} GeV; no ankle, no GZK suppression.
- $z = 0$: **17–68 times** the measured flux of all nuclei at 10 EeV, **270–1700 times** at 100 EeV.
- $z = 1$–3: times $f(z) \simeq 10$ (SFR), 7–17 (GRB), 50–130 (QSO), no energy losses.
- Their DIS limit $\eta \sim 10^2$–10^3 comes from $E_p = 10^{10}$–10^{11} GeV.

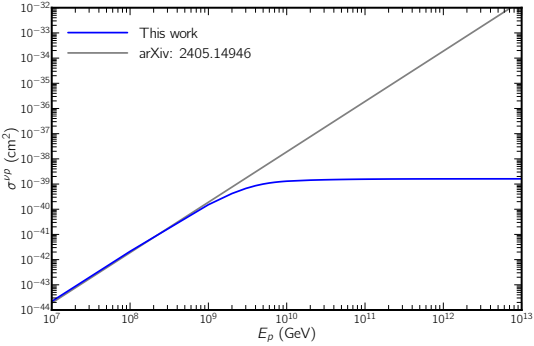
Herrera, Loeb [2602.20255]: $u_{\rm CR} = \dot{\varepsilon}/H_0$, $E^{-2.2}$: 7 times the measured flux at 10 EeV, 220 times at 100 EeV.

Herrera, Horiuchi, Qi [2405.14946]

- First diffuse calculation: cosmic rays at $z \leq 6$ with SFR, GRB, QSO evolution.
- Pure protons; $E^{-2.7}$ below 10^7 GeV, $E^{-\alpha}$ above ($\alpha = 2.5$, 2.4, 2.3), $E_p^{\max} = 10^{11}$ GeV; no propagation losses.
- $d\sigma/dT_\nu \to \sigma_{p\nu}(T_p)/T_\nu^{\max}$; IceCube gives $\eta \lesssim 10^4$.

Cross section [2505.04791, App. C]: their $\sigma_{p\nu} \propto E_p^2$ continues the low-energy elastic form; nucleon form factors make the elastic σ saturate above 10^{10} GeV. At 10^{11} GeV the difference is $\sim 10^3$; even ES + RES + DIS stays $\sim 10^2$ below.

NC νp cross section



Backup: maximal cosmological overdensity

How $\eta_{\max}$ arises (Bondarenko, Boyarsky, Pradler, Sokolenko [2306.12366])

- $N_{\rm eff}$: $\eta \gg 1$ must be produced after CMB decoupling.
- Energy budget: $\langle E_\nu \rangle \, \eta \, n_0 \lesssim \rho_c \Rightarrow$ $\eta \lesssim 10^2$ eV$/\langle E_\nu \rangle$.
- Pauli: $n \leq p_{\max}^3 / 6\pi^2$ per degree of freedom. Most ν at fixed ρ: a degenerate massless gas, $k_F \lesssim (8\pi^2 \rho_c)^{1/4} \simeq 7.5$ meV $\Rightarrow \eta \lesssim 2 \times 10^4$.
- $m_\nu = 0.1$ eV: $\langle E_\nu \rangle \geq m_\nu \Rightarrow \eta \lesssim 10^3$ ($\simeq 140$ if all $\nu_i, \bar{\nu}_i$ are overdense).
- Galaxy: $\eta \leq 240 \, (m_\nu / \text{eV})^3$ for bound ν, $\eta \lesssim 5 \times 10^3$ for escaping ν.

Beyond $\eta_{\max}$: new physics needed

- **Local sources**: ν escaping from the Sun ($\eta \lesssim 4 \times 10^9$) or the Earth ($\eta \lesssim 10^{12}$); requires converting a sizeable fraction of their mass.
- **Clusters** bound by a new Yukawa force: $\eta \lesssim 10^7 (m_\nu / 0.1 \text{ eV})^3$, from C$\nu$B fragmentation at $z_f \lesssim 200$ [2201.00939].
- **Late production** (DM decay, dark energy): still within the energy budget.
- UHECR scattering weights η along the cosmic-ray path: overdensities where cosmic rays are confined in reservoirs. [2405.04568].