Ultra-High-Energy Cosmic-Ray Boosted Relic Neutrinos

Jiajun Liao

Sun Yat-Sen University

In collaboration with Jiajie Zhang,
Alexander Sandrock and Baobiao Yue

Zhang, Sandrock, JL, Yue [2505.04791]

Zhang, JL [2606.18088]

NEXUS 2026, September 11, 2026, TDLI, Shanghai

Outline

1. **Introduction**

   Motivation and recent progress

2. **SM scattering channels**

   ES, COH, INCOH, RES and DIS

3. **Cosmic-ray models**

   PriNCe and Hillas H3a/H4a

4. **Boosted relic neutrinos**

   Energy spectra and relic-density constraints

Cosmic neutrino background

The most abundant neutrinos in the Universe, yet no direct detection.

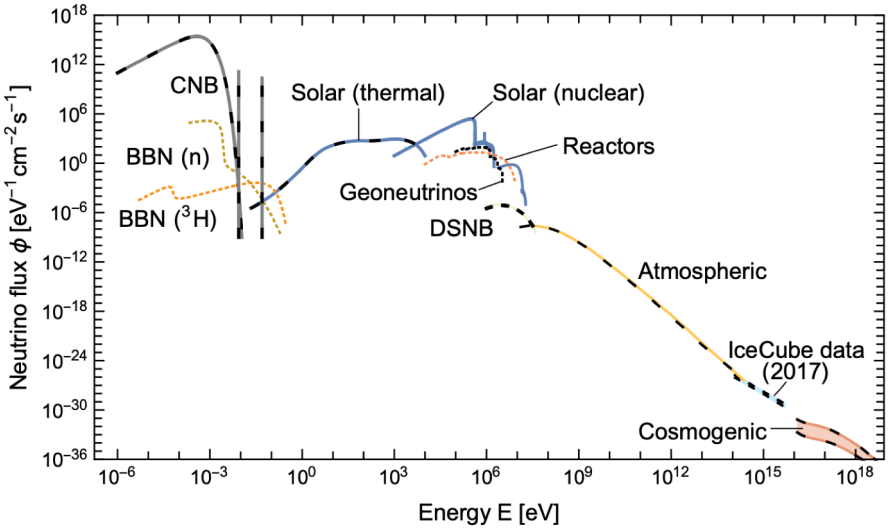
Detecting the CνB remains a **holy grail of neutrino physics**.

Direct capture: $\nu_e + {}^3\mathrm{H} \to {}^3\mathrm{He} + e^-$.

KATRIN only excludes enormous local overdensities:

$\eta < 9.7 \times 10^{10}$ (90% CL, Majorana).

KATRIN [2202.04587]



Vitagliano, Tamborra, Raffelt [1910.11878]

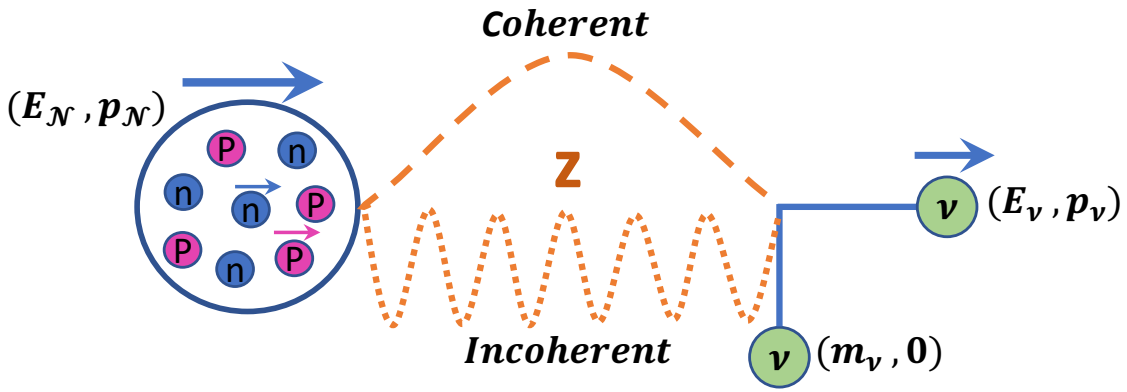
Cosmogenic neutrinos: UHECRs collide with CMB photons (GZK process).

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

Could UHECRs instead boost the abundant relic neutrinos?

Cosmic-ray boosted CνB

$$A_{\rm UHECR} + \nu_{\rm relic} \longrightarrow X + \nu_{\rm boosted}$$



- Hara and Sato studied elastic and inelastic scattering of relic neutrinos by high-energy cosmic rays.

  Hara and Sato, Prog. Theor. Phys. 64, 3 (1980); 65, 2(1981)

- Non-observation of boosted flux in the Galactic and blazar TXS 0506+056 constrain η at roughly 10^{13} and 10^{11}, respectively.

  Císcar-Monsalvatje, Herrera, Shoemaker [2402.00985]

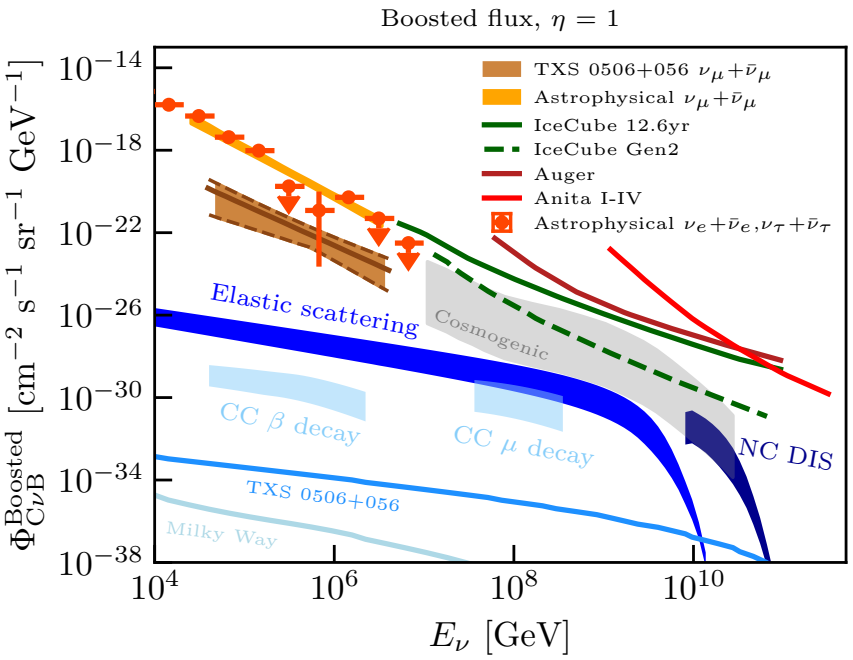
- Cosmic-ray reservoir (e.g. galaxy clusters with long UHECR trapping) enhances the signal, giving limits down to $\eta \sim 10^{10}$.

  De Marchi, Granelli, Nava, Sala [2405.04568]

Diffuse boosted relic neutrinos

Cosmological accumulation enhances the diffuse signal in the adopted CR model.

Herrera, Horiuchi, Qi [2405.14946]



2026: additional channels

NC DIS adds a hard UHE component.

CC: $p + \bar{\nu}_\ell \to n + \ell^+$.

Decays yield **secondary neutrinos**, subdominant here.

Adopted CR population

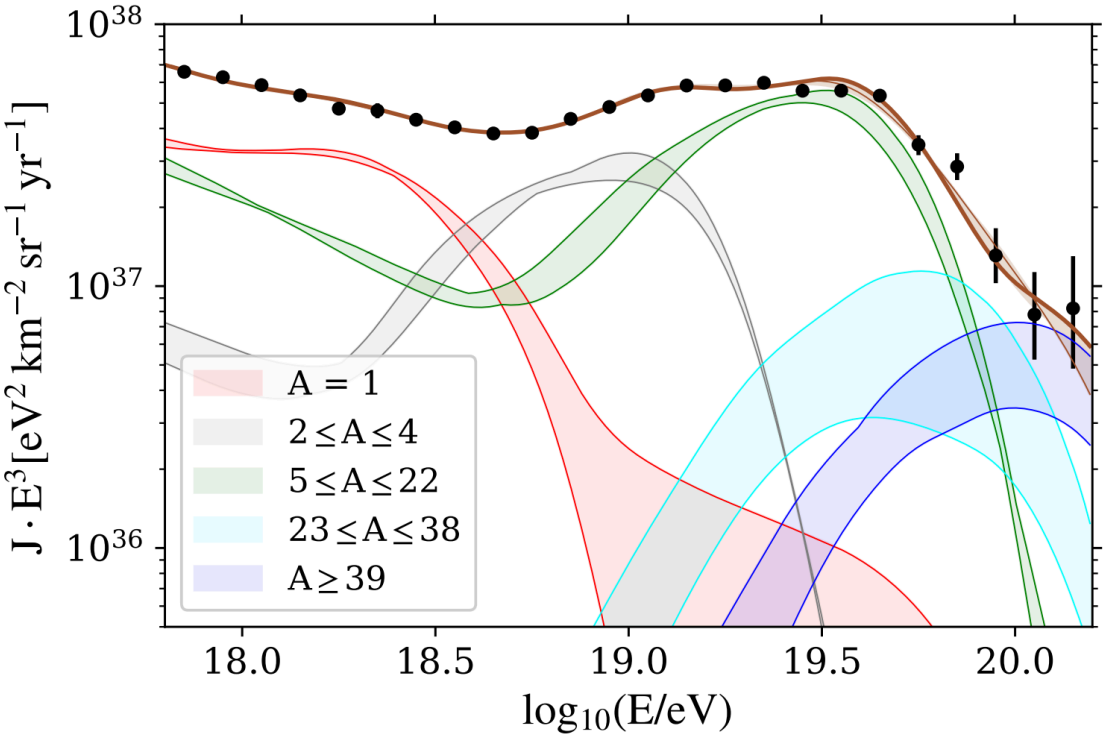
Pure protons; broken power law

Herrera, Horiuchi, Qi, Shoemaker [2601.09790]

Reported sensitivity: IceCube $\eta \sim 10^2 - 10^3$; Gen2 $\eta \sim 1 - 10$,

The boosted neutrino signals are strongly depend on the CR models.

UHECR composition



Pierre Auger [2211.02857]

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

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

$$E_N \simeq E_A/A.$$

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

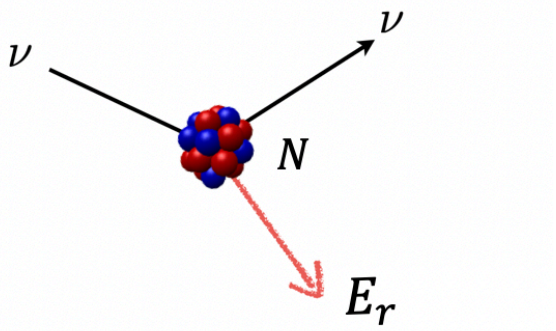
Arisaka et al. [0709.3390] Allard et al. [0805.4779]

Nuclear coherence

Incoming relic-neutrino energy in the Iron nuclear rest frame:

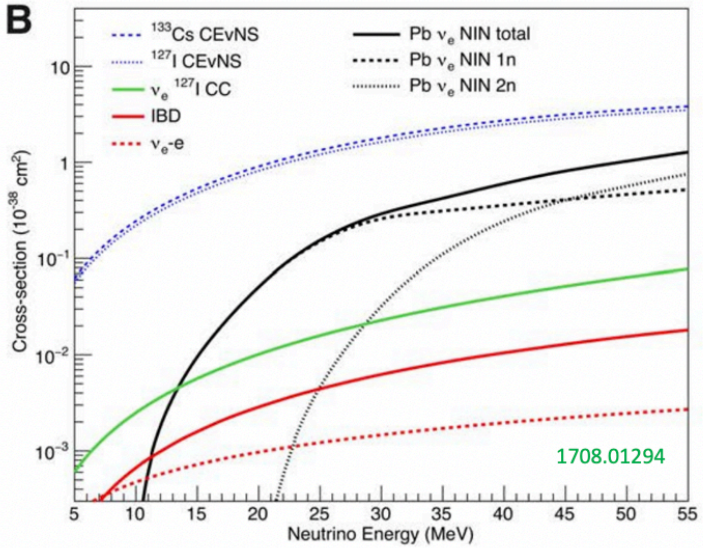
$$E_\nu^\star \simeq \frac{E_A}{m_A} m_\nu \simeq 20\ \mathrm{MeV} \left(\frac{E_A}{10\ \mathrm{EeV}}\right)\left(\frac{m_\nu}{0.1\ \mathrm{eV}}\right)$$

Coherent elastic neutrino-nucleus scattering (CEνNS)



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

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



- 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 scattering

Coherent: the nuclear weak charge

$$\frac{d\sigma_{\rm COH}}{dE'_\nu} = \frac{G_F^2 m_\nu}{\pi} Q_W^2 \left(1 - \frac{E'_\nu}{E_A} - \frac{m_A^2 E'_\nu}{2 m_\nu E_A^2}\right) F_A^2(Q^2)$$

$$Q_W = Z(\tfrac{1}{2} - 2\sin^2\theta_W) - \tfrac{N}{2}, \qquad Q^2 \simeq 2 m_\nu E'_\nu.$$

Incoherent: resolved nucleons

$$\frac{d\sigma_{\rm INCOH}}{dE'_\nu} = \left[Z\frac{d\sigma^{\rm ES}_{\nu p}}{dE'_\nu} + N\frac{d\sigma^{\rm ES}_{\nu n}}{dE'_\nu}\right]\left[1 - F_A^2(Q^2)\right]$$

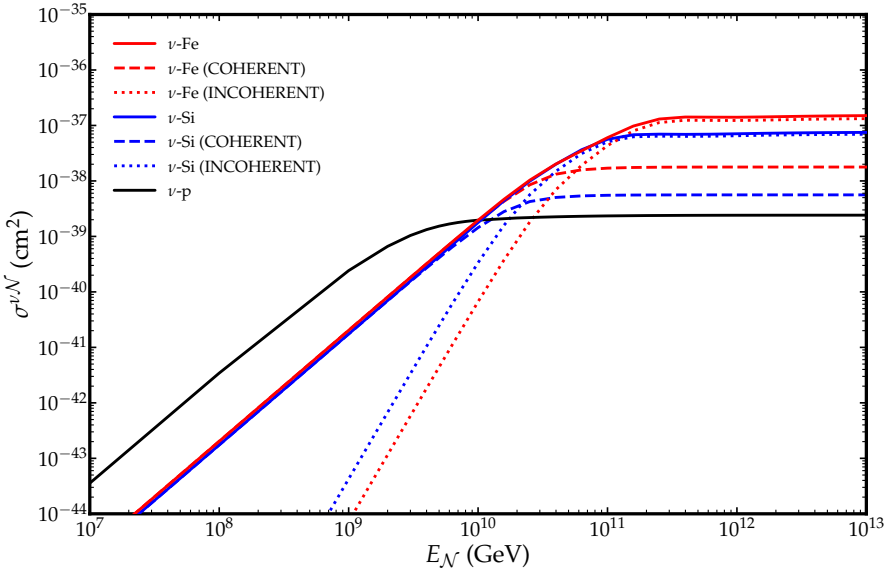
Bednyakov, Naumov [1806.08768]

- 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.

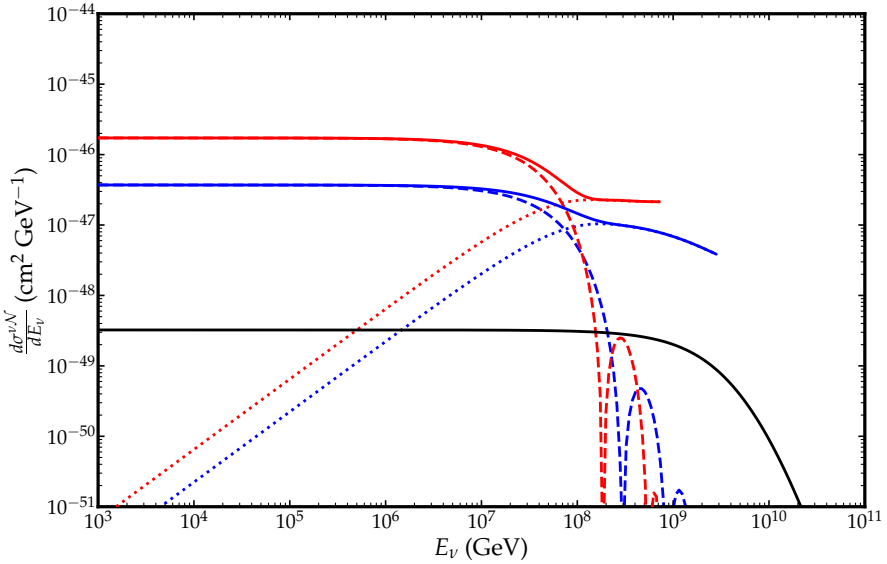
$$q \to 0: \ F(q^2) \to 1, \qquad q \to \infty: \ F(q^2) \to 0.$$

Elastic cross sections

Total cross section



Neutrino energy transfer



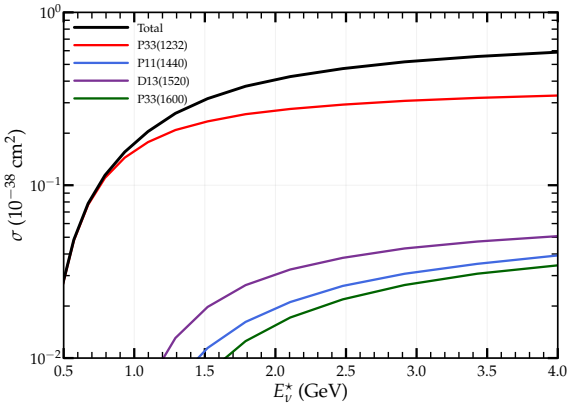
- At $E_A = 100$ EeV, Fe gives about **two orders of magnitude** larger differential cross section than a proton.
- Form factors suppress large-Q scattering, $Q^2 \simeq 2m_\nu E_\nu$.
- There is a cutoff for E_ν for a given E_N.

$$E_\nu^{\max} \simeq \frac{E_A^2}{E_A + m_A^2/(2m_\nu)}$$

Resonance production

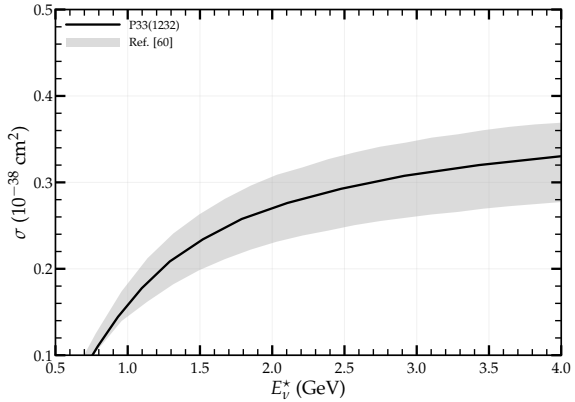
$$N + \nu \longrightarrow N^* + \nu, \qquad N^* \longrightarrow N\pi, \ldots$$

Resonance spectrum



Berger, Sehgal [0709.4378]; GENIE [2106.09381]

$\Delta(1232)$

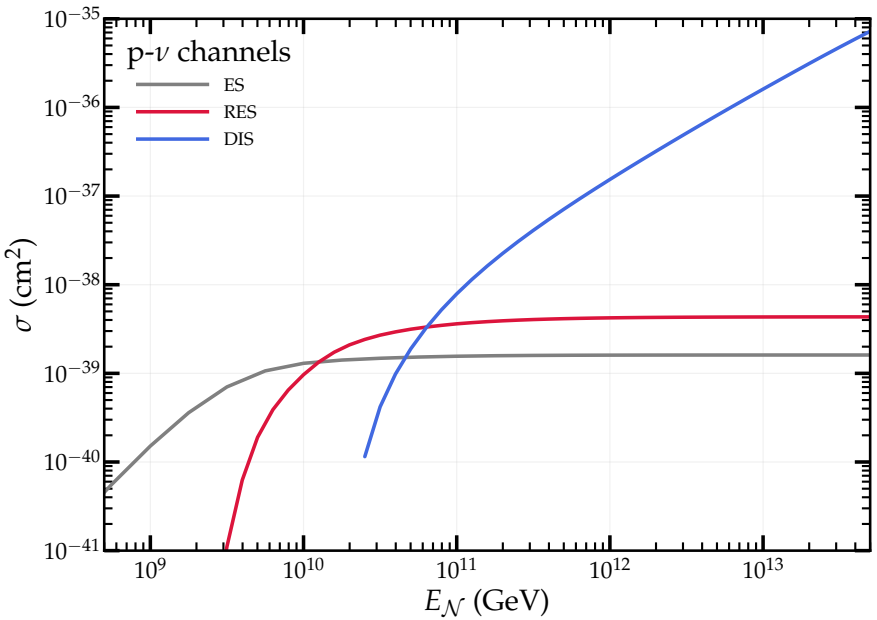


Comparison: Abbaslu et al. [2412.13349]

- 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.
- The plotted $E_\nu^\star$ is in the nucleon rest frame: $E_\nu^\star \simeq m_\nu E_N / m_N$. For $m_\nu = 0.1$ eV, a GeV-scale collision requires $E_N \sim 10$ EeV.

Deep-inelastic scattering

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



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]

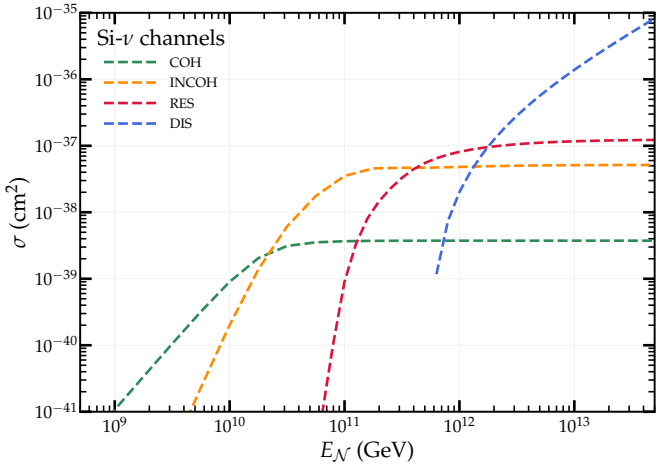
$$E'_\nu \simeq xyE_N.$$

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

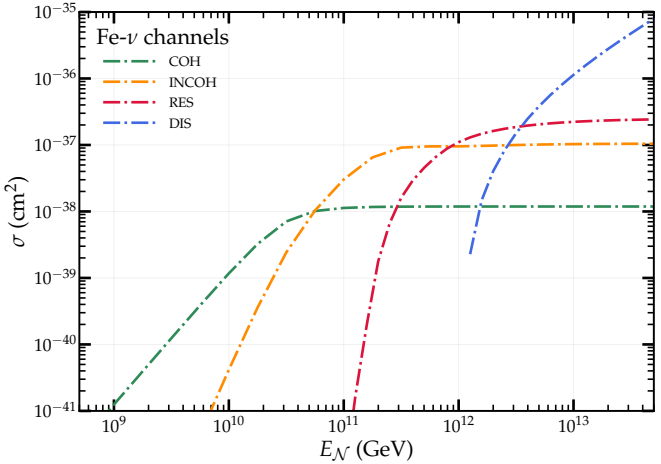
- DIS overtakes ES and RES for $E_N \gtrsim 60$ **EeV** and continues to grow over the plotted range.
- Producing UHE neutrinos requires energetic partons. The signal probes the **high-energy CR tail and its composition**.

Nuclear cross sections

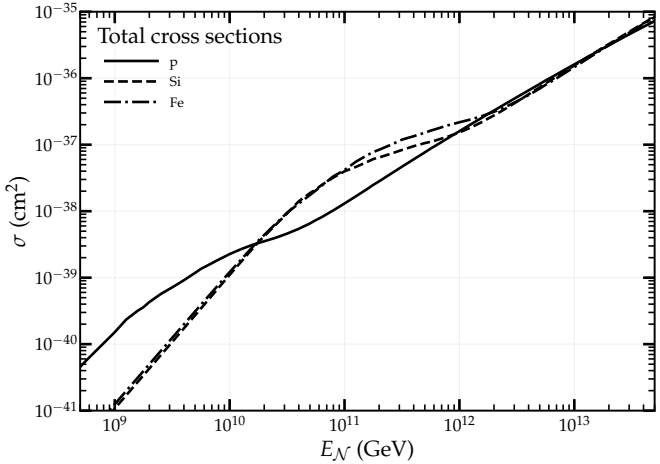
Silicon



Iron



Total cross sections



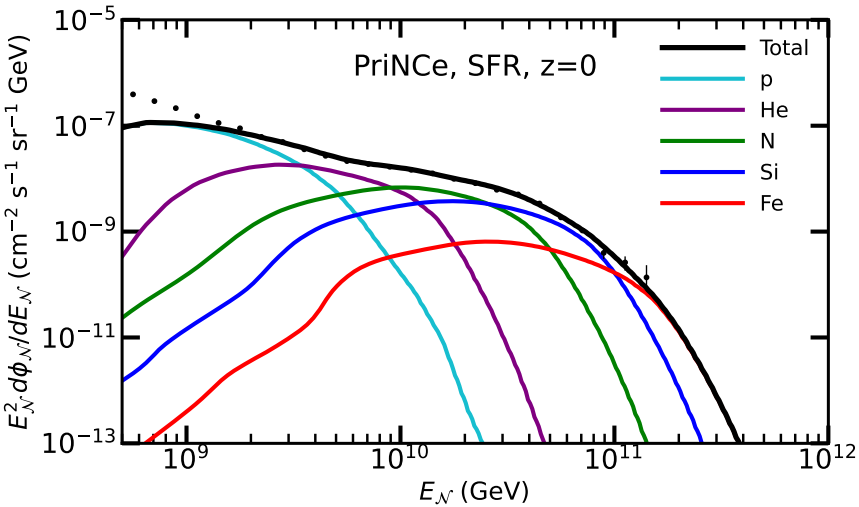
- The proton cross section is largest at lower energy.
- $E_N \simeq E_A/A$ delays RES/DIS for heavy nuclei.
- **The flux also depends on the CR composition**.

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

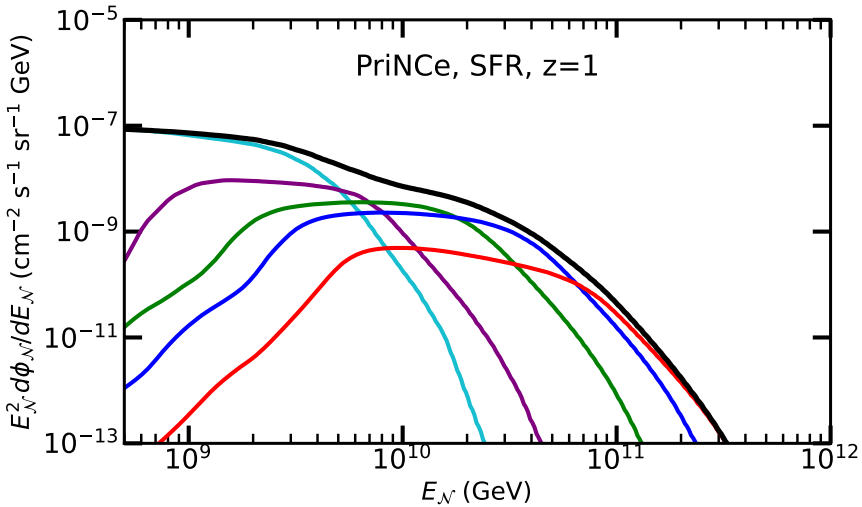
Heinze et al. [1901.03338]

- 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.

Hillas H3a and H4a

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

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

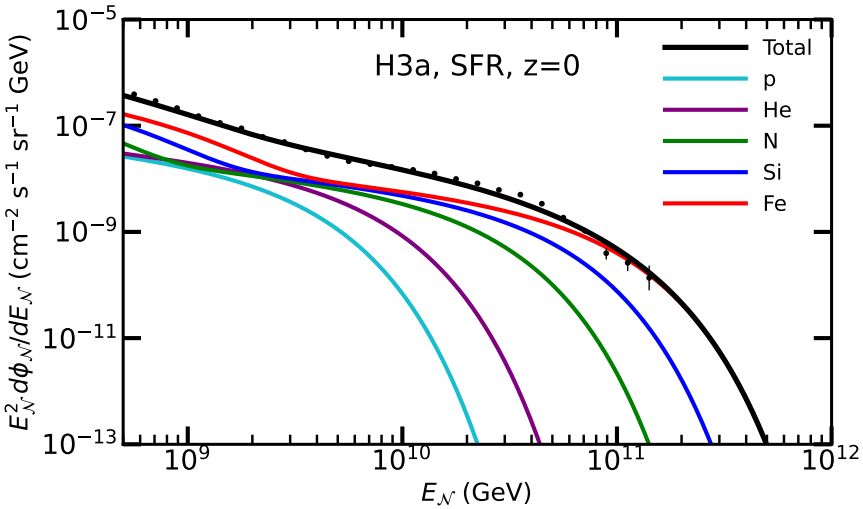
Population (R_c)	Parameter	p	He	N	Si	Fe
1 (4 PV)	$a_{i,j}$	7860	3550	2200	1430	2120
	$\gamma_{i,j}$	1.66	1.58	1.63	1.67	1.63
2 (30 PV)	$a_{i,j}$	20	20	13.4	13.4	13.4
	$\gamma_{i,j}$	1.4	1.4	1.4	1.4	1.4
3 (2 EV)	$a_{i,j}$	1.7	1.7	1.14	1.14	1.14
	$\gamma_{i,j}$	1.4	1.4	1.4	1.4	1.4
3^* (60 EV)	$a_{i,j}$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

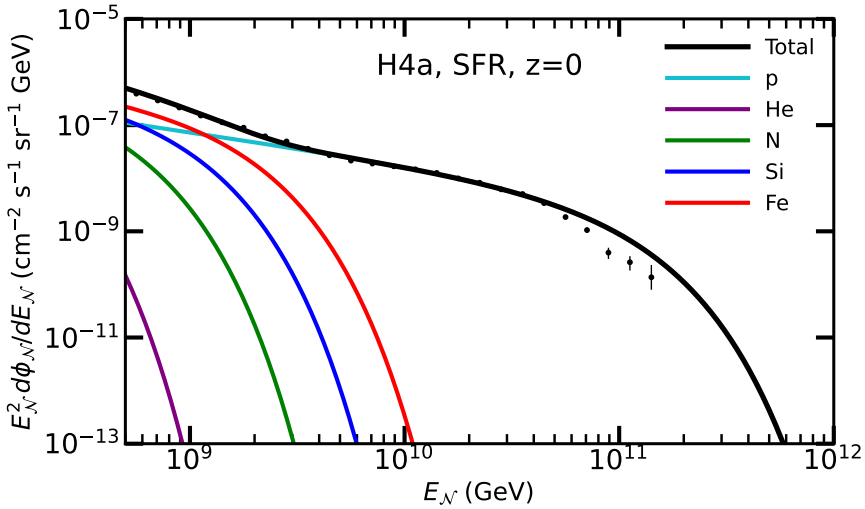
Gaisser [1111.6675]; Gaisser, Stanev, Tilav [1303.3565]

H3a and H4a cosmic-ray spectra

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

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

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

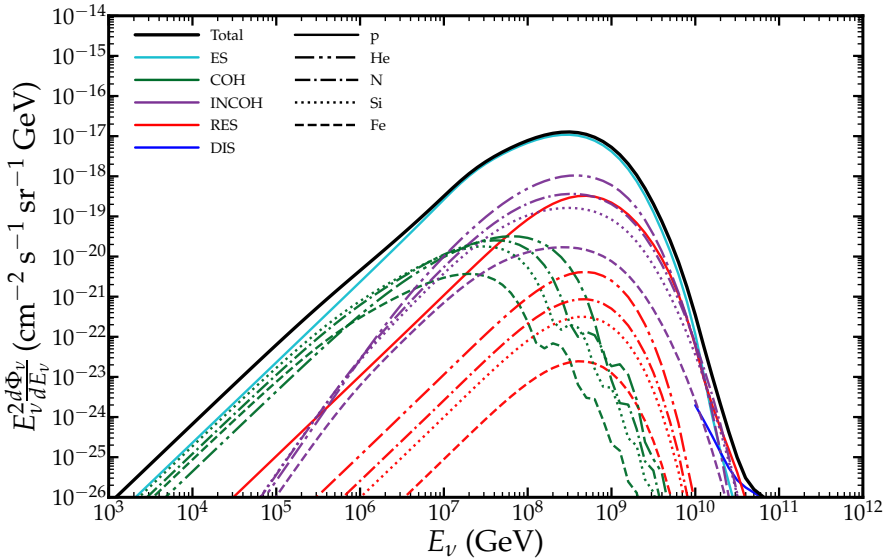
Herrera, Horiuchi, Qi [2405.14946]

- 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, QSR, GRB).
- The signal depends on the **relic-neutrino density**, the available **CR flux**, and the differential **cross section**.
- For a fixed CR population, the flux scales with $\eta = n_\nu / n_{\nu,\mathrm{standard}}$.

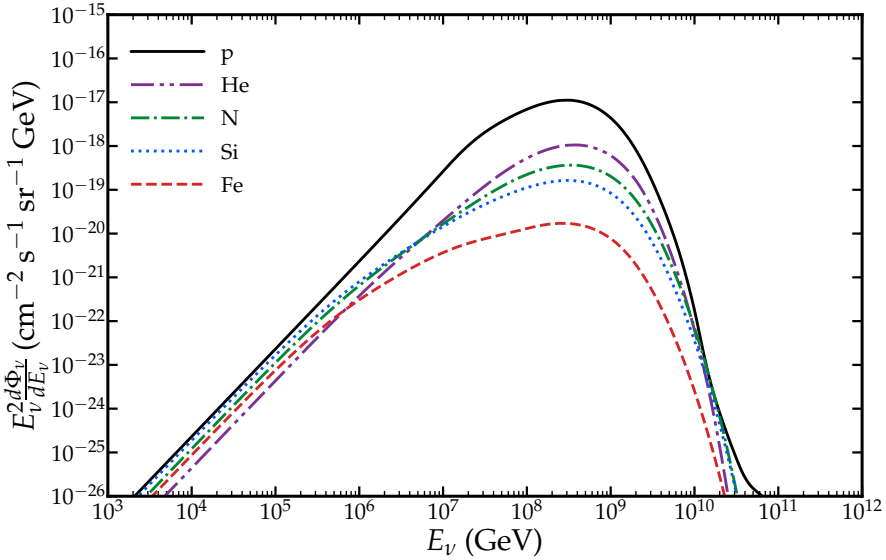
PriNCe neutrino spectrum

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

Scattering channels



CR composition

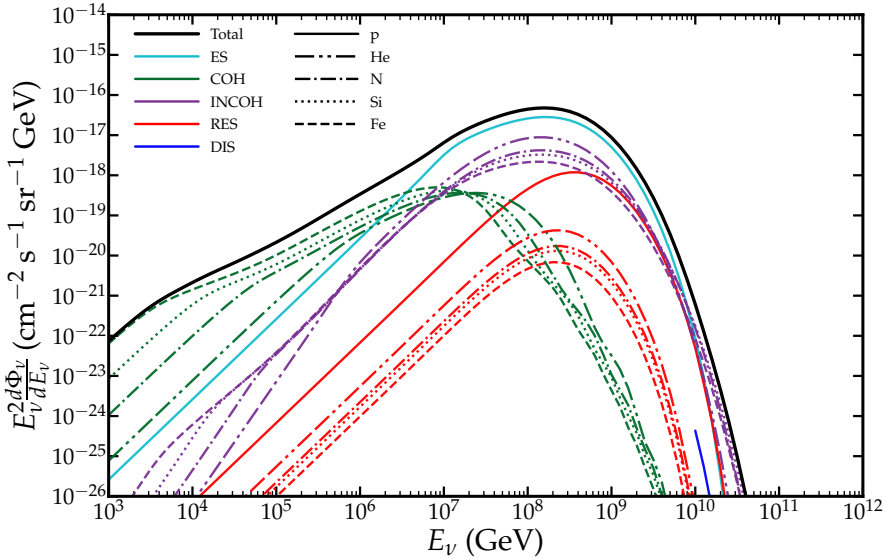


- **Proton ES dominates**: protons are most abundant in the 0.5–3 EeV CR range that supplies most of the signal.
- Coherent scattering enhances the **low-energy nuclear contribution**.
- The injection cutoff rigidity ($R_{\max} \simeq 1.8$ EV) and propagation suppress high-energy nucleons, leaving **RES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

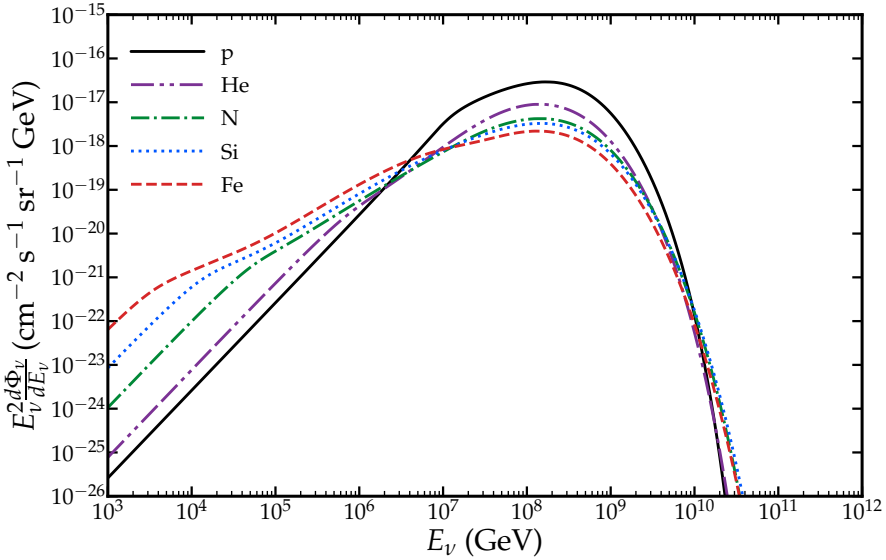
H3a neutrino spectrum

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

Scattering channels



CR composition

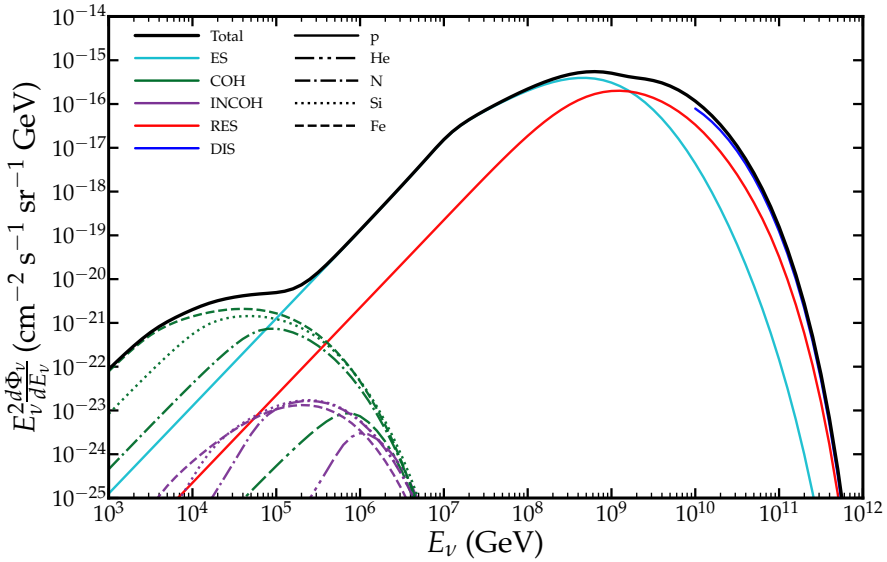


- Below about 5 PeV, **Si and Fe dominate due to coherent scattering**.
- At higher energies, coherence is lost and lighter CR become more important.
- RES dominate above $E_\nu \sim 10$ EeV. The cutoff rigidity $R_c = 2$ EV suppresses high-energy nucleons, keeping DIS small.

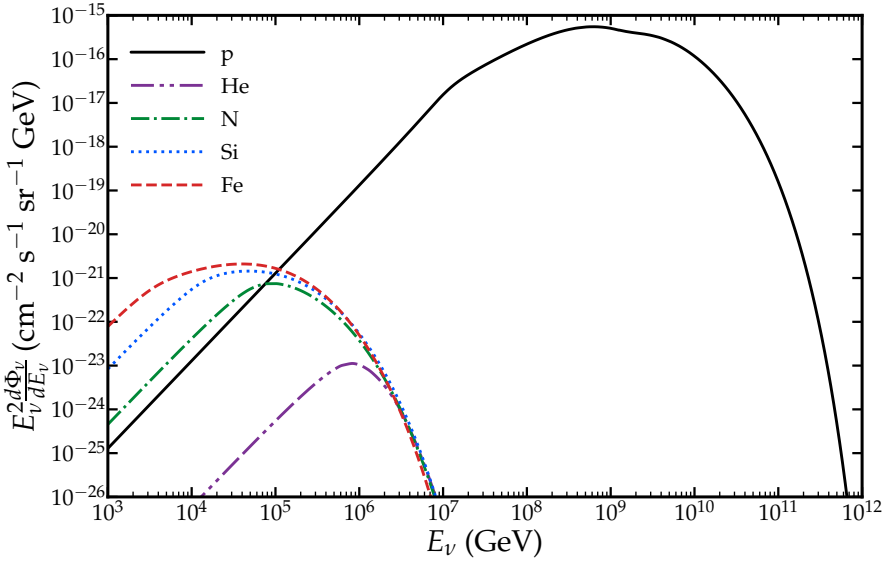
H4a neutrino spectrum

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

Scattering channels



CR composition

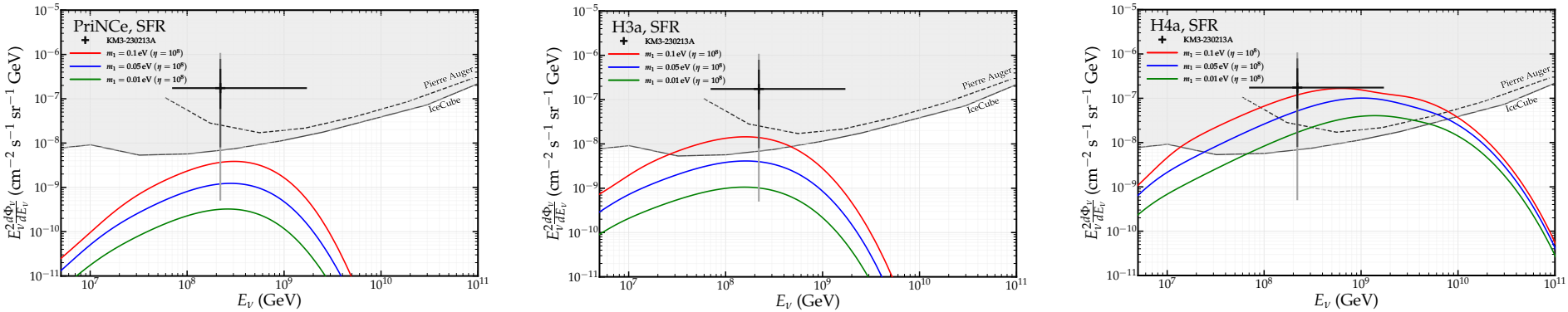


- The high-rigidity proton population gives a **larger flux extending to higher neutrino energies**.
- ES, RES and DIS contribute at successively higher energies. **DIS is most visible in H4a**.

Neutrino mass and detectability

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

PriNCe **H3a** **H4a**

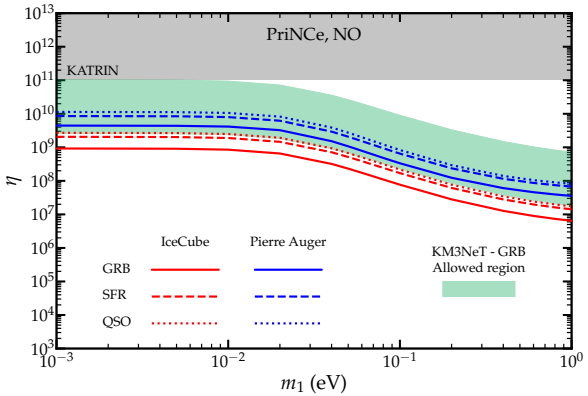


IceCube [2502.01963]; Auger [1906.07422]; KM3NeT Nature 638, 376 (2025)

- 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 the hundreds-of-PeV region, with a higher-energy tail in H4a.
- Standard density, $\eta = 1$, is far below current sensitivity. An **enhanced relic density** is required for detection.

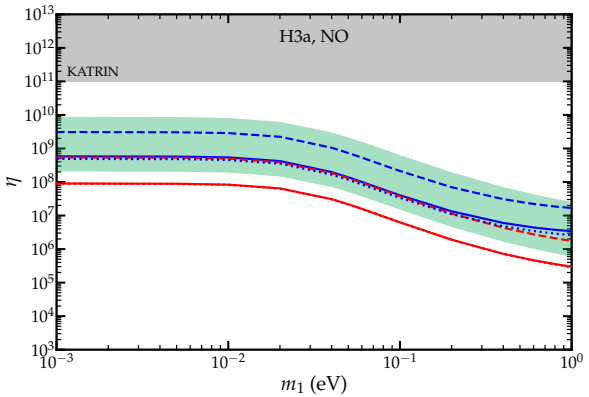
Relic-density constraints

PriNCe



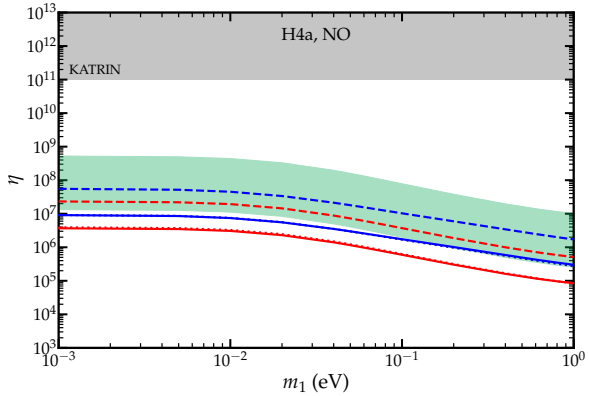
$\eta \lesssim 8 \times 10^7$

H3a



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

H4a



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

Bounds below the plots: IceCube, $m_1 = 0.1$ eV, GRB source evolution.

- **GRB evolution gives the strongest bounds**. H4a improves on PriNCe by **about two orders of magnitude** through its high-energy protons.
- Caveats: current limits remain above the cosmological bound $\eta \lesssim 2 \times 10^4$.

Bondarenko et al. [2306.12366]

- Future experiments like GRAND, IceCube-Gen2 and TRIDENT could improve the reach.

Summary

- UHECR scattering offers a **SM probe of relic neutrinos** at high-energy telescopes.
- **Nuclear coherence enhances the low-energy flux**. RES and DIS become relevant for sufficiently energetic CRs.
- The CR model determines the signal: proton ES in PriNCe, nuclear coherence in H3a, and a stronger inelastic tail in H4a.
- IceCube probes enhanced relic densities, with **strong dependence on CR composition and rigidity**. The standard CνB remains beyond current reach.

Thank you!

Cosmic-ray source evolution

- **Star formation rate (SFR)**: the baseline history of stellar activity.

Hopkins, Beacom [astro-ph/0601463]

- **Quasi-stellar objects (QSO)**: rapid growth toward peak quasar activity at $z \sim 2$.

Wall et al. [astro-ph/0408122]

- **Gamma-ray bursts (GRB)**: enhanced high-redshift activity relative to SFR,

$$f_{\rm GRB}(z) = f_{\rm SFR}(z)(1+z)^{1.26}.$$

Lan et al. [2109.00766]

- PriNCe follows the evolving spectrum and composition. For H3a/H4a, we use $J_i(E,z) = f(z)J_i(E,0)$.

Event rates

$$N_{\rm ev} = 4\pi T \int dE_\nu \, \frac{d\phi_\nu}{dE_\nu} \, A_{\rm eff}(E_\nu).$$

Experiment	Exposure	Events	90% count
IceCube	12.6 yr	0	2.44
Pierre Auger	14.7 yr	0	2.39
KM3NeT	335 days	1	$[0.11, 4.36]$

IceCube [2502.01963]; Auger [1906.07422]

KM3NeT Nature 638, 376 (2025); Feldman, Cousins [physics/9711021]

- Fold each predicted spectrum with the corresponding detector response. Auger's published exposure includes time and solid angle.
- The upper event count sets the upper limit on η for each CR model and neutrino mass.