Impact of coherent scattering on relic neutrinos boosted by cosmic rays

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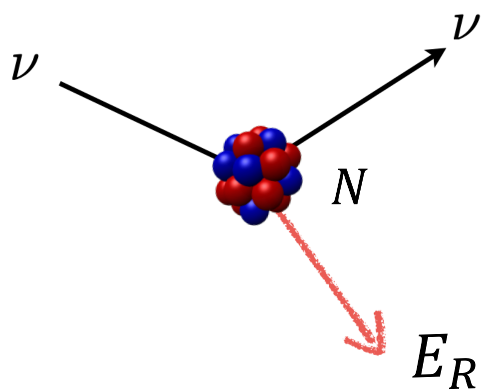
新物理前沿与交叉科学研讨会

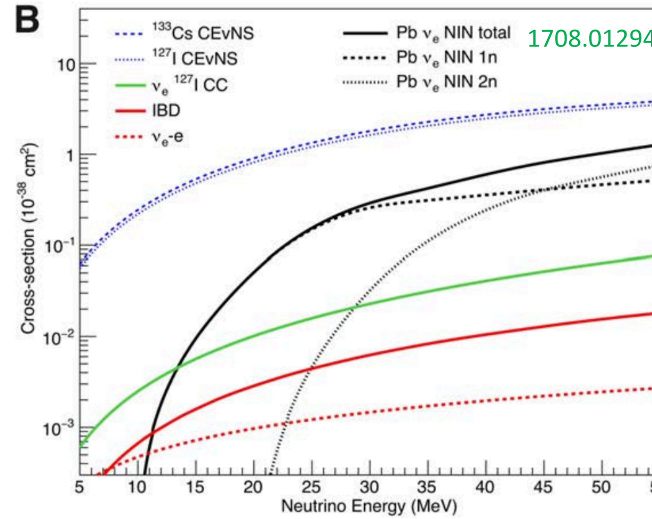
南京师范大学，南京，05/17/2026

Outline

- Introduction to CEvNS
- Impact of coherent scattering
  - CEvNS as a probe of new interactions
  - Coherent scattering on relic neutrinos
- Summary

Coherent Elastic ν-Nucleus Scattering





- Coherence condition $qR \lesssim 1$ ⇒ $\mathcal{A} = \sum_{i=1}^{A} \mathcal{A}_i \; , \quad \sigma \propto \mathcal{A}\mathcal{A}^{+}$

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

Nuclear form factor

$$\begin{cases} g_p^V = \frac{1}{2} - 2\sin^2\theta_W \sim 0.03 \\ g_n^V = -0.5 \end{cases}$$

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

- Satisfied for $E_\nu < 50$ MeV, Nuclear recoil energy $E_r \leq \frac{2E_\nu^2}{M+2E_\nu} \sim O(10)$ keV

En route to CEνNS

PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

Coherent effects of a weak neutral current

Daniel Z. Freedman†
National Accelerator Laboratory, Batavia, Illinois 60510
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790
(Received 15 October 1973; revised manuscript received 19 November 1973)

If there is a weak neutral current, then the elastic scattering process $\nu + A \to \nu + A$ should have a sharp coherent forward peak just as $e + A \to e + A$ does. Experiments to observe this peak can give important information on the isospin structure of the neutral current. The experiments are very difficult, although the estimated cross sections (about 10^{-38} cm^2 on carbon) are favorable. The coherent cross sections (in contrast to incoherent) are almost energy-independent. Therefore, energies as low as 100 MeV may be suitable. Quasi-coherent nuclear excitation processes $\nu + A \to \nu + A^*$ provide possible tests of the conservation of the weak neutral current. Because of strong coherent effects at very low energies, the nuclear elastic scattering process may be important in inhibiting cooling by neutrino emission in stellar collapse and neutron stars.

PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1984

Principles and applications of a neutral-current detector for neutrino physics and astronomy

A. Drukier and L. Stodolsky
Max-Planck-Institut für Physik und Astrophysik, Werner-Heisenberg-Institut für Physik, Munich, Federal Republic of Germany
(Received 21 November 1983)

We study detection of MeV-range neutrinos through elastic scattering on nuclei and identification of the recoil energy. The very large value of the neutral-current cross section due to coherence indicates a detector would be relatively light and suggests the possibility of a true "neutrino observatory." The recoil energy which must be detected is very small (10–10^3 eV), however. We examine a

PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses 1–10^6 GeV; particles with spin-dependent interactions of typical weak strength and masses 1–10^2 GeV; or strongly interacting particles of masses 1–10^{13} GeV.

PRL **100,** 021303 (2008) PHYSICAL REVIEW LETTERS week ending 18 JANUARY 2008

First Results from the XENON10 Dark Matter Experiment at the Gran Sasso National Laboratory

PRL **117,** 121303 (2016) PHYSICAL REVIEW LETTERS week ending 16 SEPTEMBER 2016

Dark Matter Results from First 98.7 Days of Data from the PandaX-II Experiment

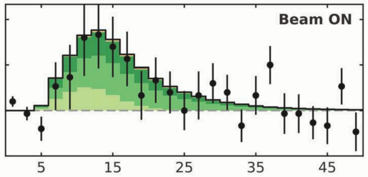
PHYSICAL REVIEW LETTERS **120,** 241301 (2018)

Limits on Light Weakly Interacting Massive Particles from the First 102.8 kg × day Data of the CDEX-10 Experiment

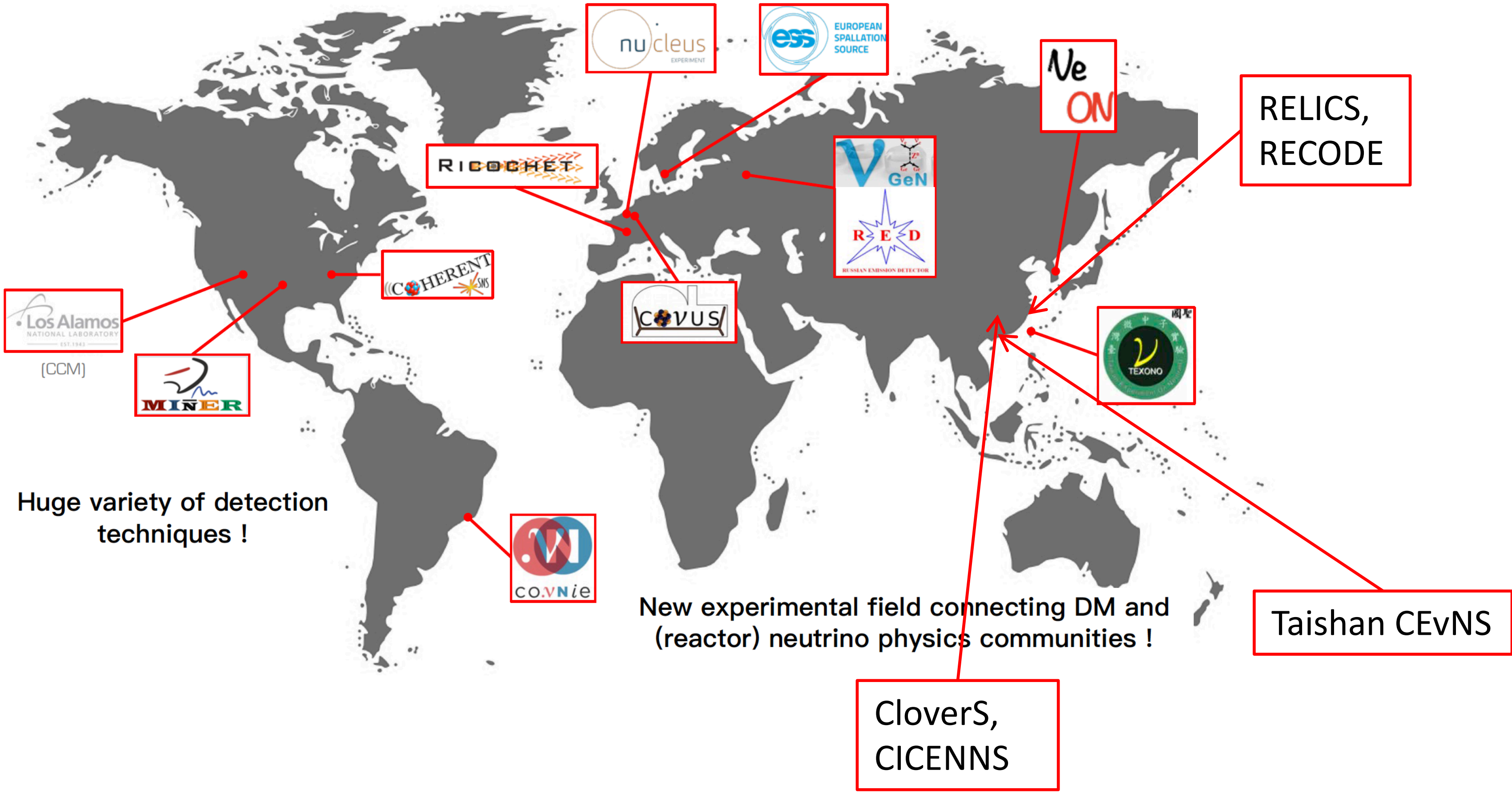
RESEARCH

NEUTRINO PHYSICS

Observation of coherent elastic neutrino-nucleus scattering



Global experimental efforts

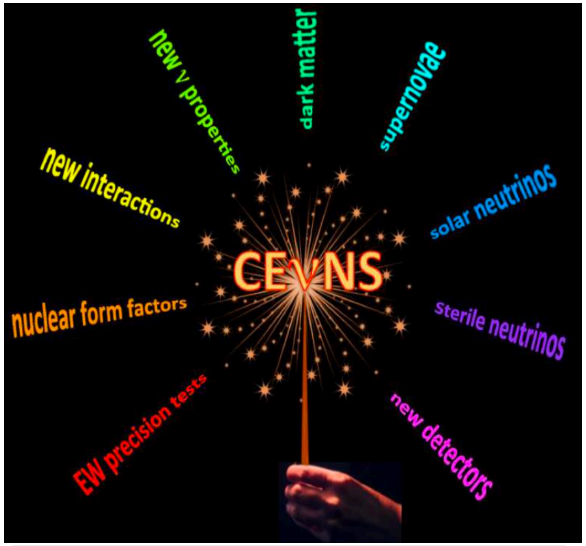


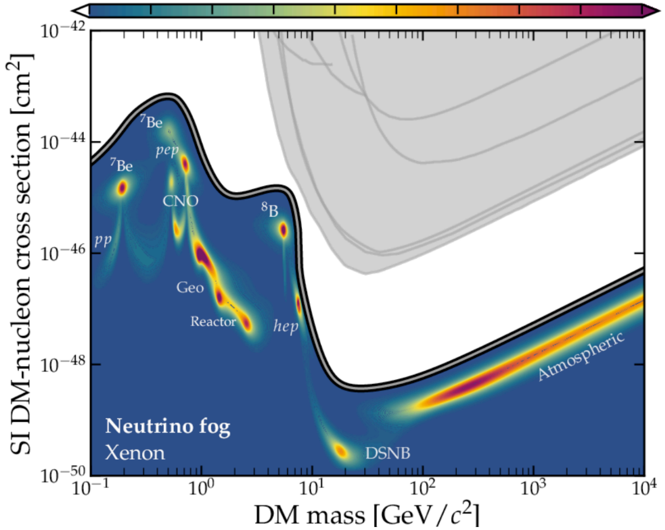
Adapted from M. VIVIER@Magnificent CEvNS 2020

Physics potential

- **SM tests:** weak mixing angle, electroweak charges;
- **Neutrino properties:** neutrino magnetic moment, neutrino charge radius, radiative corrections;
- **New physics:** nonstandard interactions, generalized interactions, light mediators, light dark matter, sterile neutrinos;
- **Nuclear physics:** neutron radius, quenching factor, reactor neutrino flux;
- **Astrophysics:** supernova, DSNB, solar, atmospheric neutrinos, …

E. Lisi, Neutrino 2018





O'Hare, PRL [2109.03116]

Current data

- πDAR source @ SNS

COHERENT first observed in 2017 at 6.7σ, improved in 2022 at 11.6σ with a CsI detector

COHERENT, Science 357,1123 (2017)

COHERENT, PRL 129 081801 (2022)

Later confirmed in 2021 with LAr detector and in 2025 with Ge detector

COHERENT, PRL 126, 012002 (2021)

COHERENT, PRL 134, 231801 (2025)

- Reactor neutrino source

Dresden-II see a strong preference in a Ge detector

Colaresi at al. , PRL 129, 211802 (2022)

CONUS+ first observed at 3.7σ in a Ge detector

CONUS+, Nature 643, 8074 (2025)

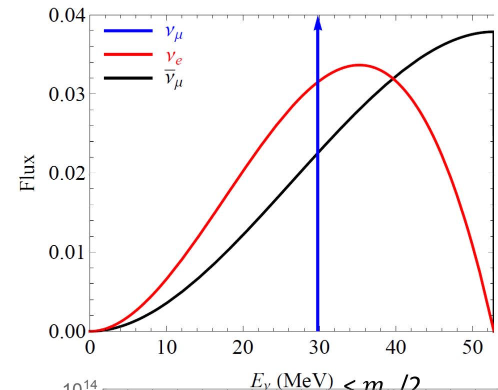
- Solar ^{8}B neutrino source

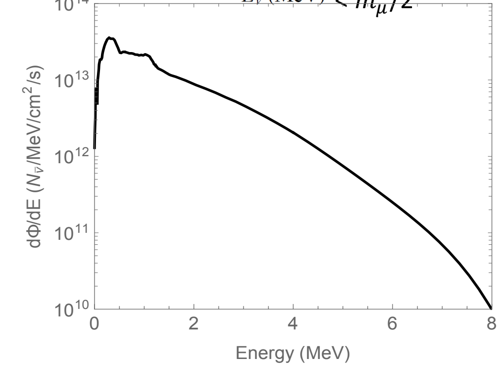
PandaX-4T detected at 2.64σ in a LXe detector

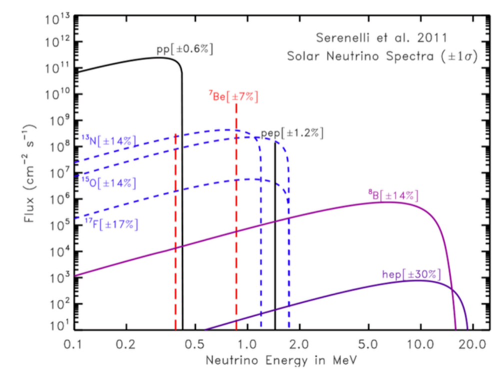
PandaX, PRL 133, 191001 (2024)

XENONnT detected at 2.73σ in a LXe detector

XENON, PRL 133, 191002 (2024)





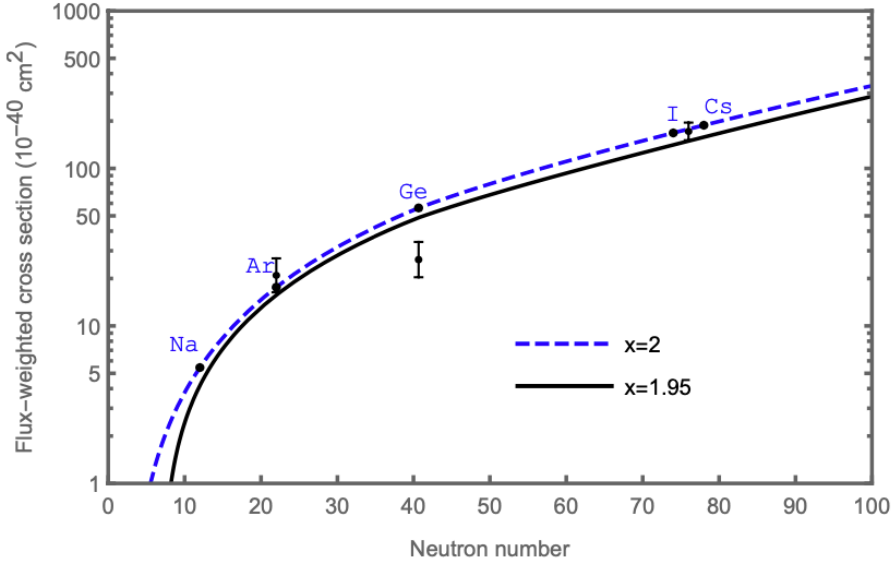


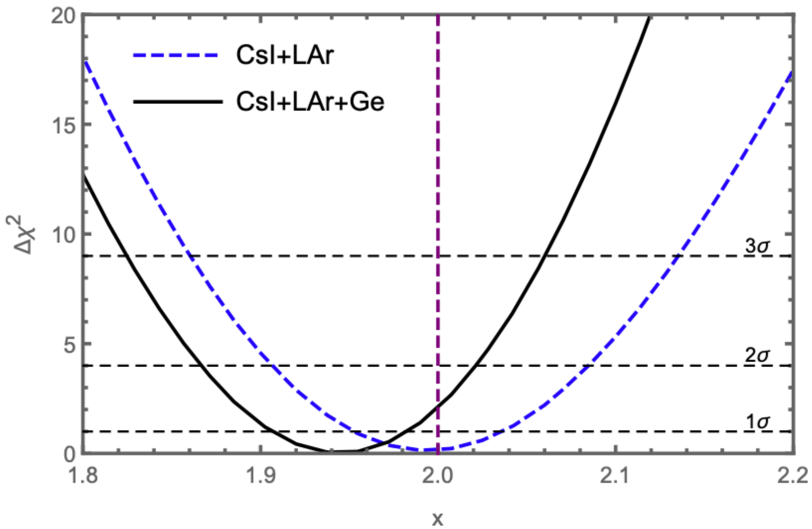
SM tests: N^2 dependence

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

$$Q_{\rm SM}^2 = \left[N g_V^n F_N(q^2) + Z g_V^p F_Z(q^2)\right]^2 \Longrightarrow Q_{\rm SM}^x = \left[N g_V^n F_N(q^2) + Z g_V^p F_Z(q^2)\right]^x$$

- Introduced parameter x: $x = 2 \rightarrow$ full coherence; $x = 1 \rightarrow$ total decoherence.





JL, Marfatia, Zhang, PRD [2408.06255]

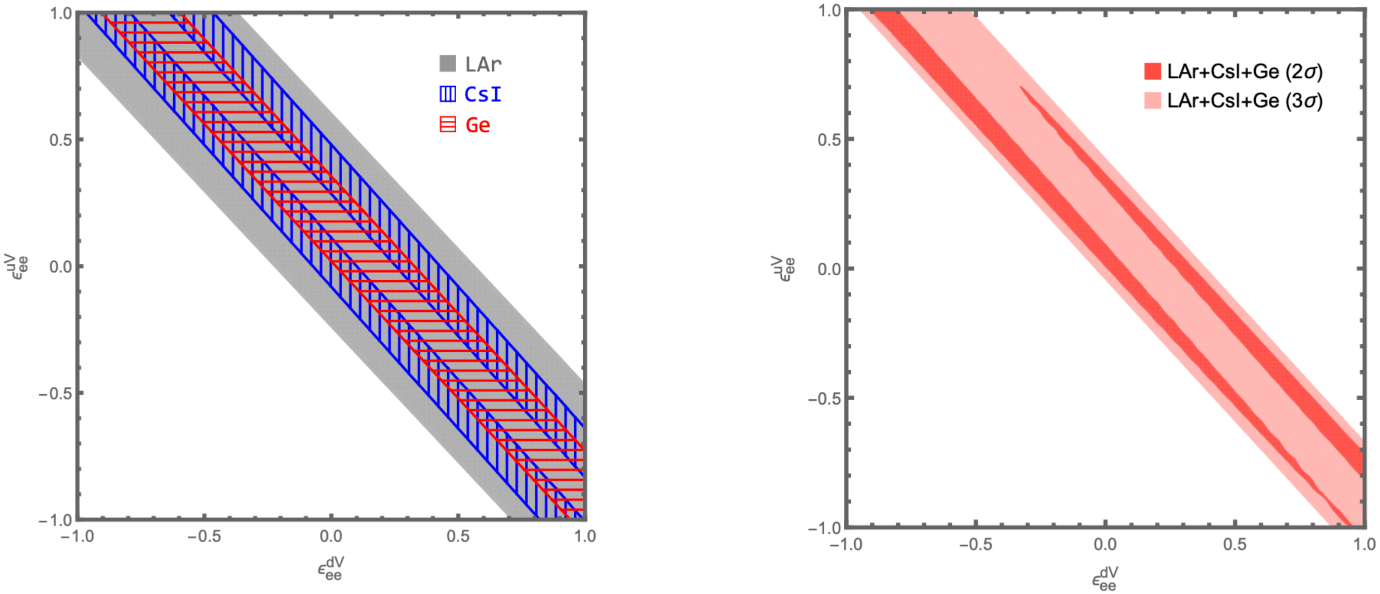
BSM constraints: Nonstandard interactions

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_F \sum_{q,\ell,\ell'} \varepsilon_{\ell\ell'}^{qV,C} (\bar{\nu}_\ell \gamma^\mu P_L \nu_{\ell'})(\bar{q}\gamma_\mu P_C q) \,,$$

$$Q^2_{{\rm NSI},\ell} = \left[\left(g_V^p + 2\varepsilon_{\ell\ell}^{uV} + \varepsilon_{\ell\ell}^{dV}\right) Z + \left(g_V^n + \varepsilon_{\ell\ell}^{uV} + 2\varepsilon_{\ell\ell}^{dV}\right) N\right]^2 + \sum_{\ell,\ell'} \left[\left(2\varepsilon_{\ell\ell'}^{uV} + \varepsilon_{\ell\ell'}^{dV}\right) Z + \left(\varepsilon_{\ell\ell'}^{uV} + 2\varepsilon_{\ell\ell'}^{dV}\right) N\right]^2$$

$$[(g_V^p + \epsilon_{ee}^{dV} + 2\epsilon_{ee}^{uV})Z + (g_V^n + 2\epsilon_{ee}^{dV} + \epsilon_{ee}^{uV})N] = \pm[(g_V^p + \hat{\epsilon}_{ee}^{dV} + 2\hat{\epsilon}_{ee}^{uV})Z + (g_V^n + 2\hat{\epsilon}_{ee}^{dV} + \hat{\epsilon}_{ee}^{uV})N]$$

- different materials have different slopes, combination will break degeneracies



JL, Marfatia, Zhang, PRD [2408.06255]

BSM constraints: Generalized interactions

$$\mathcal{L}_{\rm NGI} = \frac{G_F}{\sqrt{2}} \sum_{\substack{a=S,P,V,A,T \\ q=u,d}} [\bar{\nu}\Gamma^a \nu]\, [\bar{q}\Gamma_a (C_a^q + i\gamma_5 D_a^q)\, q] \ , \qquad \Gamma_a = \{\mathbb{I}, i\gamma_5, \gamma_\mu, \gamma_\mu\gamma_5, \sigma_{\mu\nu}\}$$

$$\mathcal{O}_q \xrightarrow{\text{step (I)}} \mathcal{O}_n \xrightarrow{\text{step (II)}} \mathcal{O}_N \ ,$$

Aristizabal Sierra et.al., JHEP [1806.07424]

- Many previous studies use the same spin-independent (SI) form factor for all GNI.

$$\frac{d\sigma}{dE_{\rm nr}}\bigg|^{\rm NGI}_{{\rm CE}\nu{\rm NS}} = \frac{G_F^2 m_N}{4\pi} F_W^2(|\vec{q}|^2)\Big\{C_S^2 \frac{m_N E_{\rm nr}}{2E_\nu^2} + \left(C_V + 2\,Q_V^{\rm SM}\right)^2 \left(1 - \frac{m_N E_{\rm nr}}{2E_\nu^2} - \frac{E_{\rm nr}}{E_\nu}\right) + 8\,C_T^2 \left(1 - \frac{m_N E_{\rm nr}}{4E_\nu^2} - \frac{E_{\rm nr}}{E_\nu}\right) \pm \mathcal{R}\frac{E_{\rm nr}}{E_\nu}\Big\}\,.$$

Han, et. al., JHEP [2004.13869];
Flores,et.al.,PRD [2112.05103];
Majumda et. al., PRD [2112.03309];
De Romeri, et.al. JHEP [2211.11905], ...

- Tensor interactions induce spin-dependent (SD) nuclear structure effects.
- The standard SI form factor → a set of nuclear response functions

Hoferichter, et.al., JHEP [2007.08529];
Candela, et.al, JHEP [2404.12476];
De Romeri, et.al., JCAP [2411.11749];
Chattaraj, et.al., JHEP [2501.12443];...

$$\frac{{\rm d}\sigma_{\nu\mathcal{N}}}{{\rm d}T_{\mathcal{N}}}\bigg|^{T}(E_\nu, T_{\mathcal{N}}) = \frac{m_{\mathcal{N}}}{2J+1}\frac{g_T^4}{(m_T^2 + 2m_{\mathcal{N}}T_{\mathcal{N}})^2} \times \left[\left(2 - \frac{m_{\mathcal{N}}T_{\mathcal{N}}}{E_\nu^2} - \frac{2T_{\mathcal{N}}}{E_\nu}\right)\tilde{S}^{\mathcal{T}}(|\mathbf{q}|^2) + \left(1 - \frac{T_{\mathcal{N}}}{E_\nu}\right)\tilde{S}^{\mathcal{L}}(|\mathbf{q}|^2)\right]\,.$$

- The LO operator is $\vec{\sigma}_N$ in the momentum expansion, since $q/m_N \sim O(0.01)$.
- There is no coherent enhancement due to opposite spin directions cancel each other.

Tensor interactions: Coherence strikes back

$$\mathcal{L}_{\rm eff}^{T} = \sum_{\mathfrak{q}=u,d} \sum_{\alpha=e,\mu,\tau} G_{T,\alpha}^{q} (\overline{\nu}_\alpha \sigma^{\mu\nu} \nu_\alpha)(\overline{\mathfrak{q}} \sigma_{\mu\nu} \mathfrak{q})$$

$$\langle N_{p'} | \overline{\mathfrak{q}} \sigma^{\mu\nu} \mathfrak{q} | N_p \rangle = \overline{u}_{p'} \left[\sigma^{\mu\nu} F_{1,T}^{\mathfrak{q},N} - \frac{i}{m_N} (\gamma^\mu q^\nu - \gamma^\nu q^\mu) F_{2,T}^{\mathfrak{q},N} \right] u_p$$

tensor charge (→ $F_{1,T}^{\mathfrak{q},N}$)

tensor anomalous magnetic moment (→ $F_{2,T}^{\mathfrak{q},N}$)

NR expansion ⇒

	$\mathcal{L}_{(0)}^{1}$	$\mathcal{L}_{(1)}^{1}$	$\mathcal{L}_{(0)}^{2}$
neutrino	$-2\overline{u}_{k'}\vec{\sigma}_{(0)}u_k$	$2\overline{u}_{k'}\vec{\sigma}_{(1)}u_k$	$-2\overline{u}_{k'}\vec{\sigma}_{(0)}u_k$
nucleon	$\frac{i\vec{q}1_N - \vec{P}\times\vec{\sigma}_N}{2m_N} G_T^{N,1}\rho$	$\vec{\sigma}_N G_T^{N,1}\rho$	$-\frac{i\vec{q}}{m_N} 1_N G_T^{N,2}\rho$
parity	odd	even	odd

JL, Tang, Zhang, PRD [2502.10702]

- Previous EFT results only consider nuclear response functions for P-even operator $\vec{\sigma}_N$, and the momentum suppressed P-odd operators are ignored due to $\frac{|q|}{m_N} \sim O(0.01)$.
- Momentum suppressed P-odd terms can be coherently enhanced.

$$\frac{d\sigma_T}{dE_r} = \frac{d\sigma_T^{\rm O}}{dE_r} + \frac{d\sigma_T^{\rm E}}{dE_r}\,,$$

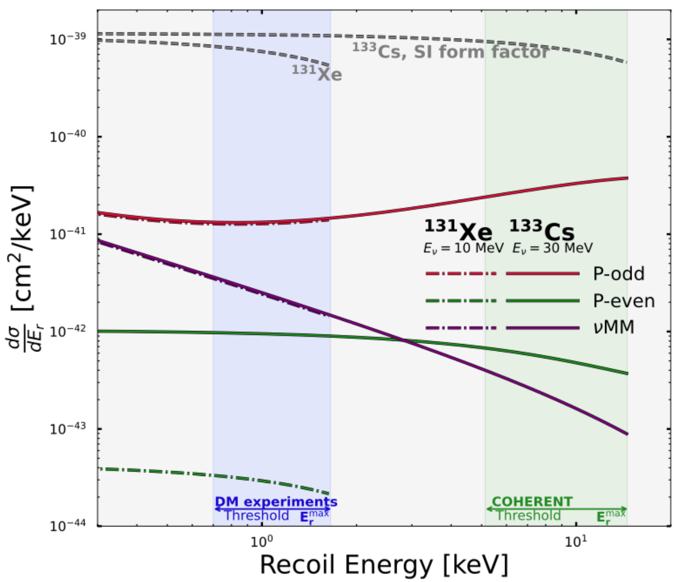
$$\frac{d\sigma_T^{\rm O}}{dE_r} = \frac{M}{2\pi}\frac{|\vec{q}|^2}{m_N^2}\sum_{N,N'=p,n}\left(c_0^N c_0^{N'}\mathcal{F}_N^M\mathcal{F}_{N'}^M + 4c_0^N G_T^{N',1}\mathcal{F}_N^{\Phi''}\mathcal{F}_{N'}^M + 4G_T^{N,1}G_T^{N',1}\mathcal{F}_N^{\Phi''}\mathcal{F}_{N'}^{\Phi''}\right)\left(1-\frac{E_r}{E_\nu}\right)$$

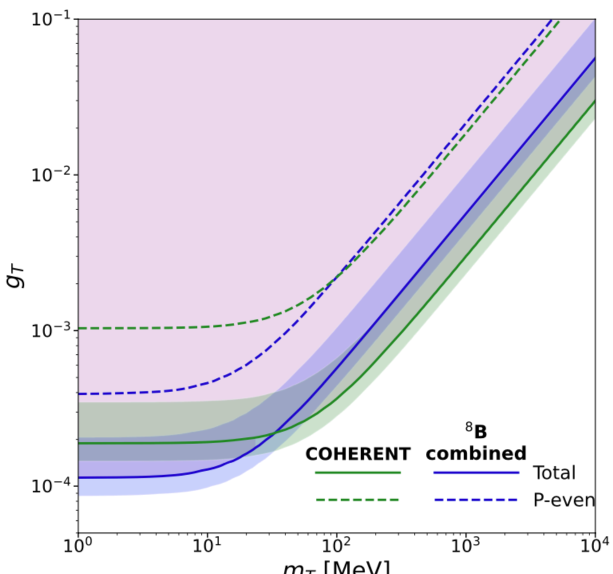
$$\frac{d\sigma_T^{\rm E}}{dE_r} = \frac{M}{\pi}\sum_{N,N'=p,n}\left[2G_T^{N,1}G_T^{N',1}\left(1-\frac{E_r}{E_\nu}\right)\mathcal{F}_N^{\Sigma''}\mathcal{F}_{N'}^{\Sigma''} + G_T^{N,1}G_T^{N',1}\left(1-\frac{ME_r}{2E_\nu^2}-\frac{E_r}{E_\nu}\right)\mathcal{F}_N^{\Sigma'}\mathcal{F}_{N'}^{\Sigma'}\right]$$

In the long-wavelength limit: $\mathcal{F}_p^{M_0}(0) = Z \quad \mathcal{F}_n^{M_0}(0) = N \quad F_{\Sigma'}^N(0) = \sqrt{\frac{8(J_i+1)}{3J_i}}\langle S_N\rangle$

$$\sigma_T^{\rm O}/\sigma_T^{\rm E} \simeq \frac{A^2|\vec{q}|^2}{m_N^2\langle \mathbf{S}_N\rangle^2} \gtrsim \mathcal{O}(10)$$

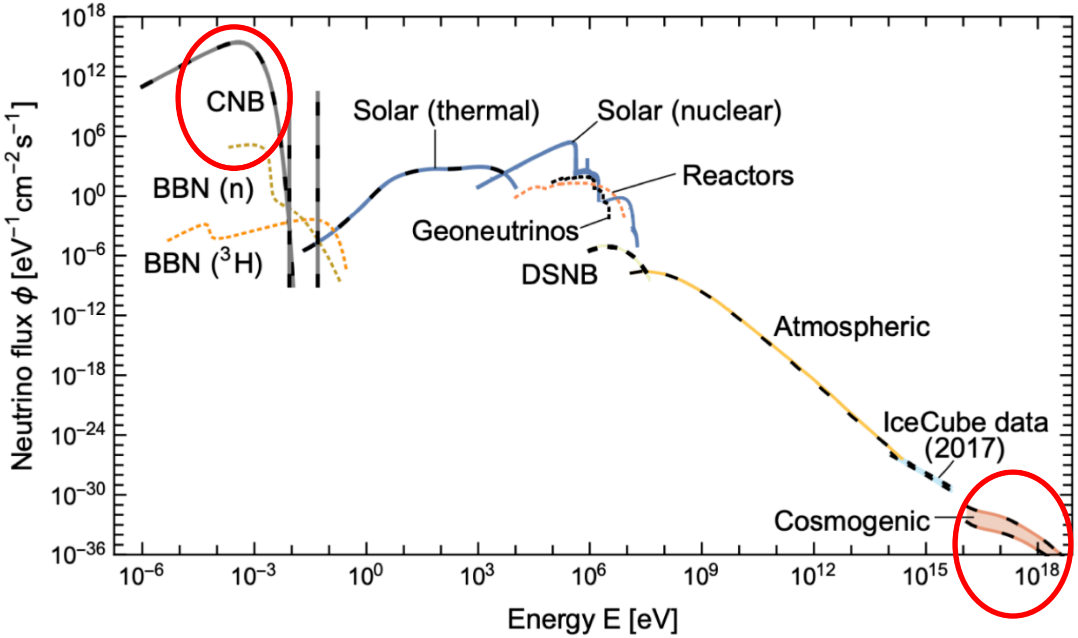
For $A \gtrsim 100 \quad \langle \mathbf{S}_N\rangle^2 \sim \mathcal{O}(0.1)$
$|\vec{q}| \sim 10~\mathrm{MeV},\ m_N \sim 1~\mathrm{GeV}$





JL, Tang, Zhang, PRD [2502.10702]

Unified neutrino spectrum



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).

Measurement of CνB

- PTOLEMY storing tritium atoms on a graphene sheet, but still faces severe technical challenges by the Heisenberg uncertainty principle.

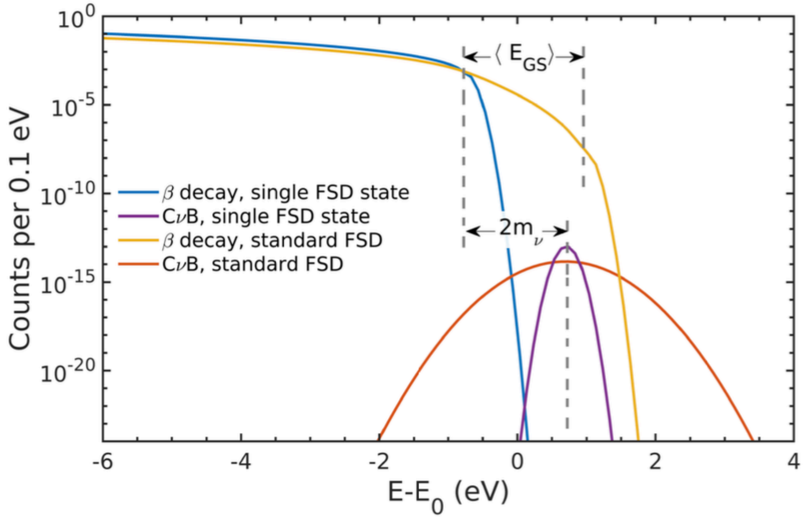
  Cheipesh, Cheianov, Boyarsky [2101.10069]

- Neutrino number overdensity can be greatly enhanced in some non-standard scenarios; a hypothetical local source can reach CνB overdensity $\eta \sim 10^{11}$.

  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]



CR 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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**Department of Physics, Kyoto Sangyo University, Kyoto 603*
Research Institute for Fundamental Physics
Kyoto University, Kyoto 606

(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]

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

Herrera, Horiuchi, Qi [2405.14946]

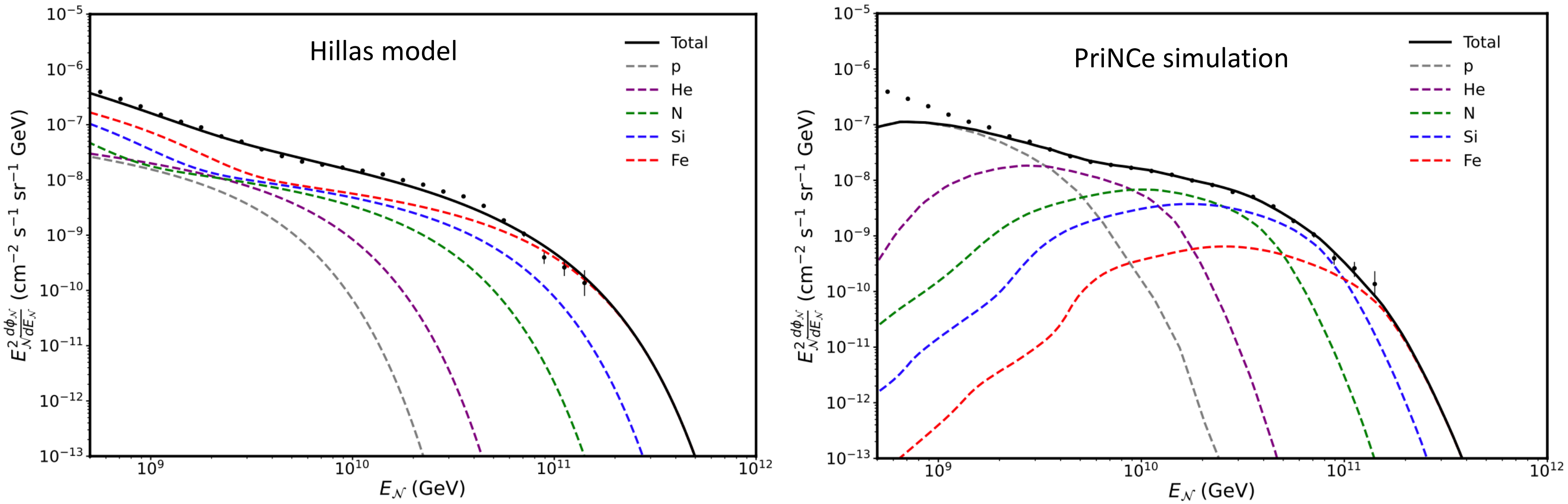
Mass composition of UHECR

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

Pierre Auger [2211.02857]

- 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]

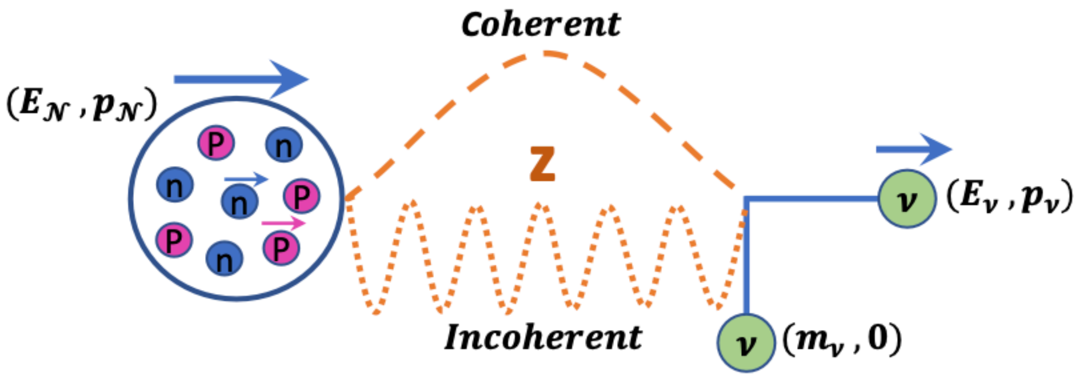


Zhang, Sandrock, **JL**, Yue, PRD [2505.04791]

Coherent Enhancement

- 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 ~ 20 MeV in nucleus rest frame — exactly in the CEνNS regime.

Zhang, Sandrock, **JL**, Yue, PRD [2505.04791]



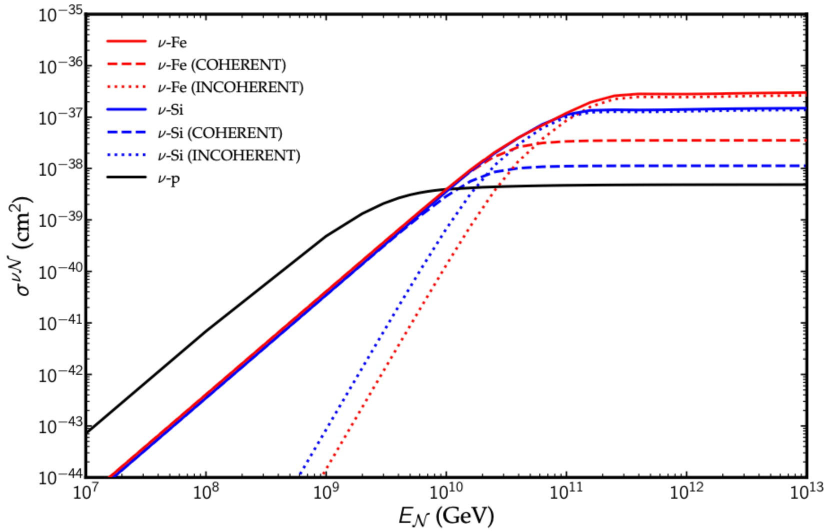
$$\frac{d\sigma^{\nu\mathcal{N}_i}_{\text{coh}}}{dE_\nu} = \frac{2G_F^2 m_\nu}{\pi} Q^2_{W,i} \left(1 - \frac{E_\nu}{E_{\mathcal{N}_i}} - \frac{m^2_{\mathcal{N}_i} E_\nu}{2m_\nu E^2_{\mathcal{N}_i}}\right) F^2(q^2)$$

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

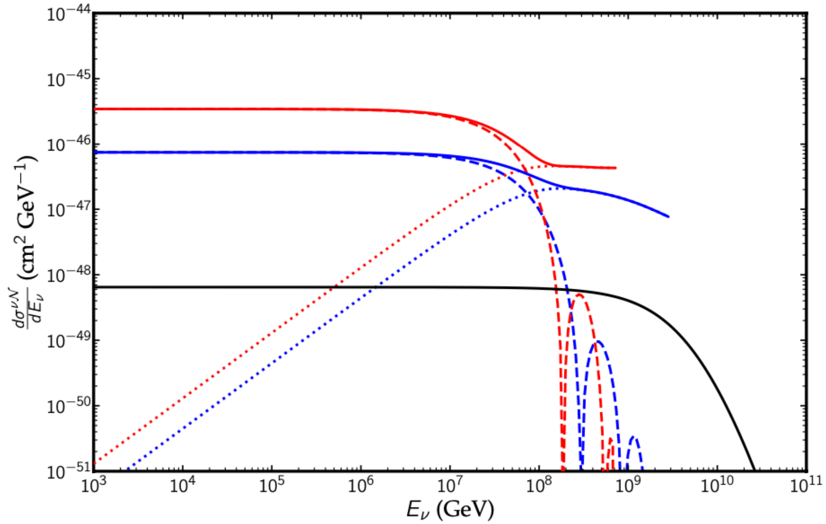
- Coherent $\propto N^2$ and $F^2(q^2)$, corresponding to scattering on the whole nucleus.
- Incoherent $\propto N\ (Z)$ and $\left(1 - F^2(q^2)\right)$, corresponding to scattering on individual nucleons.

Cross sections

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.

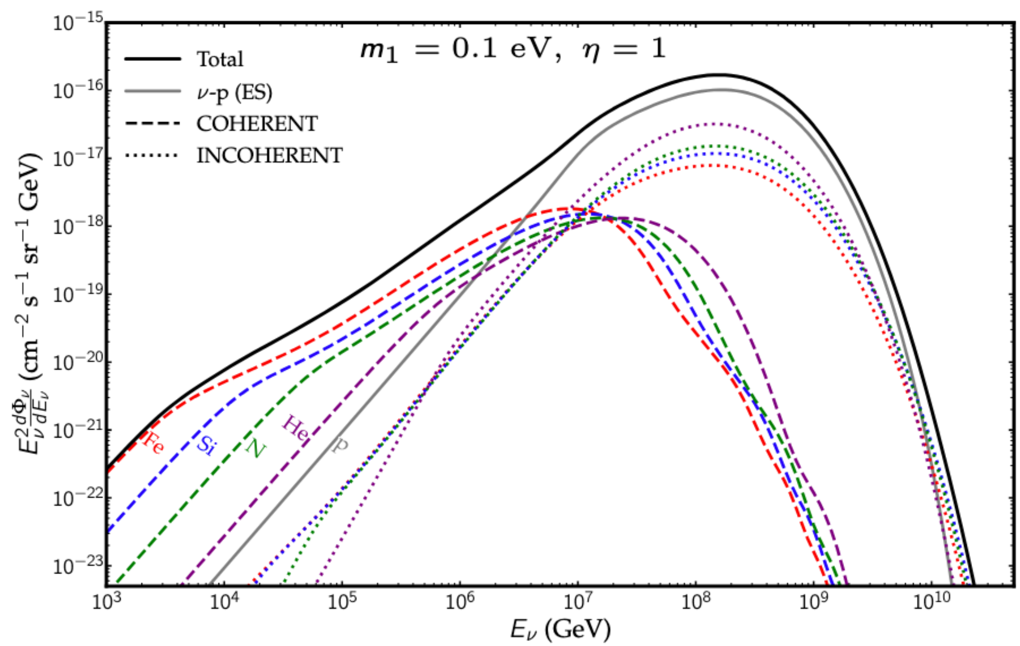
Diffuse flux of Boosted CνB

The diffuse flux of UHECR boosted CνB at Earth is:

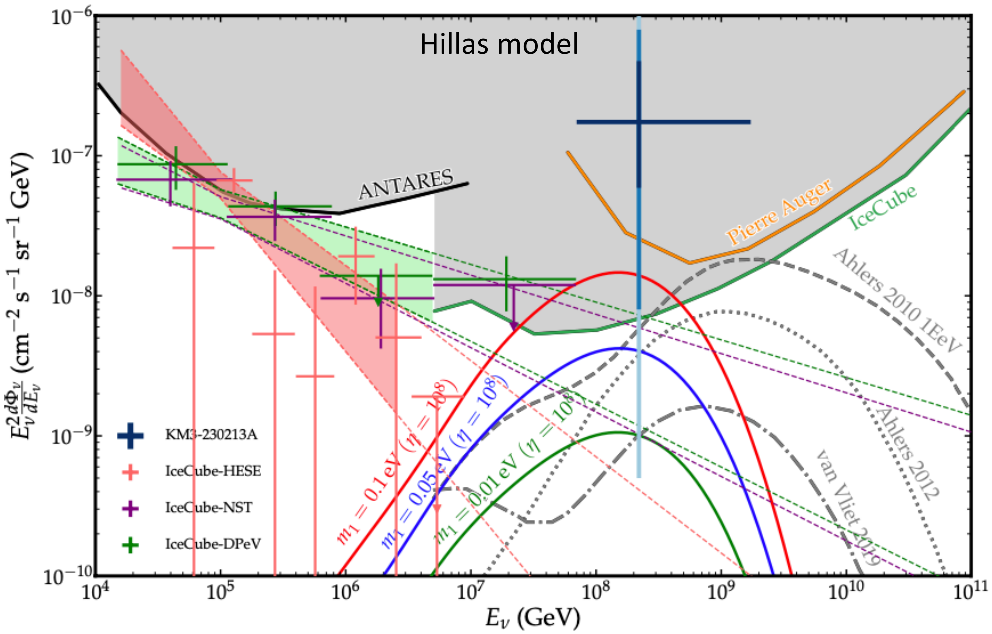
Herrera, Horiuchi, Qi [2405.14946]

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

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.



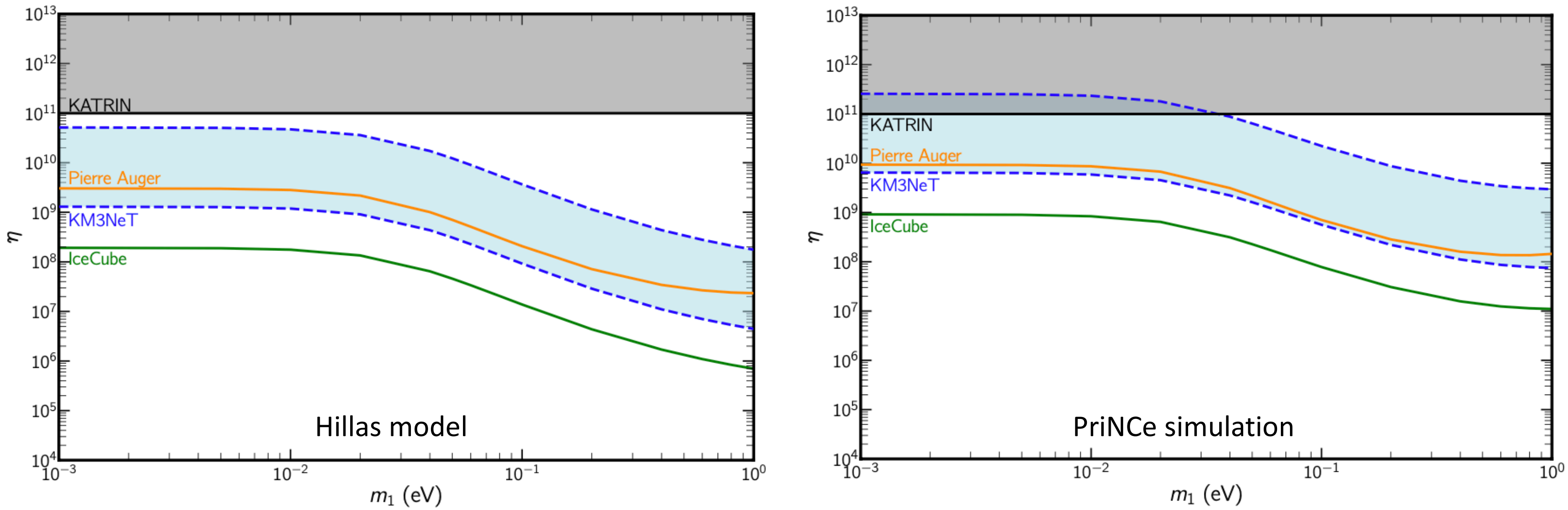
Comparison with experimental data



Zhang, Sandrock, **JL**, Yue, PRD [2505.04791]

- 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



Zhang, Sandrock, **JL**, Yue, PRD [2505.04791]

- At $m_1 = 0.1$ eV, IceCube (PAO) sets $\eta < 7.8 \times 10^7$ (7.0×10^8) at 90% CL; Stronger than KATRIN bound.
- 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 $\eta \in [\,5.9 \times 10^9,\, 2.3 \times 10^{11}\,]$ for $m_1 = 0.01$ eV.

Summary

- CEvNS opens a new window to test the SM and explore new physics.
- Tensor interactions is not entirely spin-suppressed, and NLO terms can be coherently enhanced by a few orders of magnitude.
- The cross section of UHECR boosted CvB can be coherently enhanced; similar to terrestrial CEvNS experiments.
- Both experimental and theoretical studies are still undergoing rapid development in CEvNS, and new ideas are continually emerging.

Thank you!