

Coherence in Neutrino Scattering: From New Physics to Relic Neutrinos

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Based on: 2502.10702 , 2505.04791 , 2606.18088

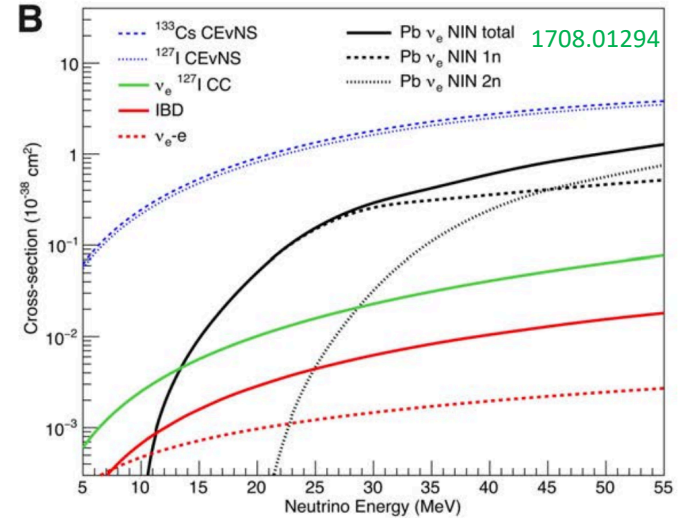
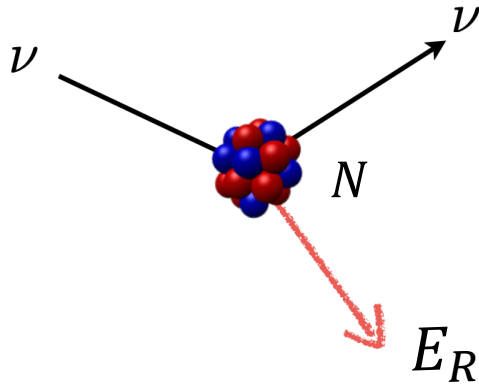
中国物理学会高能物理分会

广州, 07/15/2026

Outline

- Introduction to CEvNS
- Impact of coherent scattering
 - Coherent scattering with tensor interactions
 - Coherent scattering on relic neutrinos
- Summary

Coherent Elastic ν -Nucleus Scattering



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

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

Nuclear form factor

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

$$Q_{\text{SM}}^2 = (Zg_p^V + Ng_n^V)^2$$

$$\sigma_{\text{SM}} \propto N^2$$

➤ 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 $\nu + A \rightarrow \nu + A$ should have a sharp coherent forward peak just as $e + A \rightarrow e + A$ 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} cm² 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 $\nu + A \rightarrow \nu + A^*$ 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} 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 $1-10^{10}$ 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

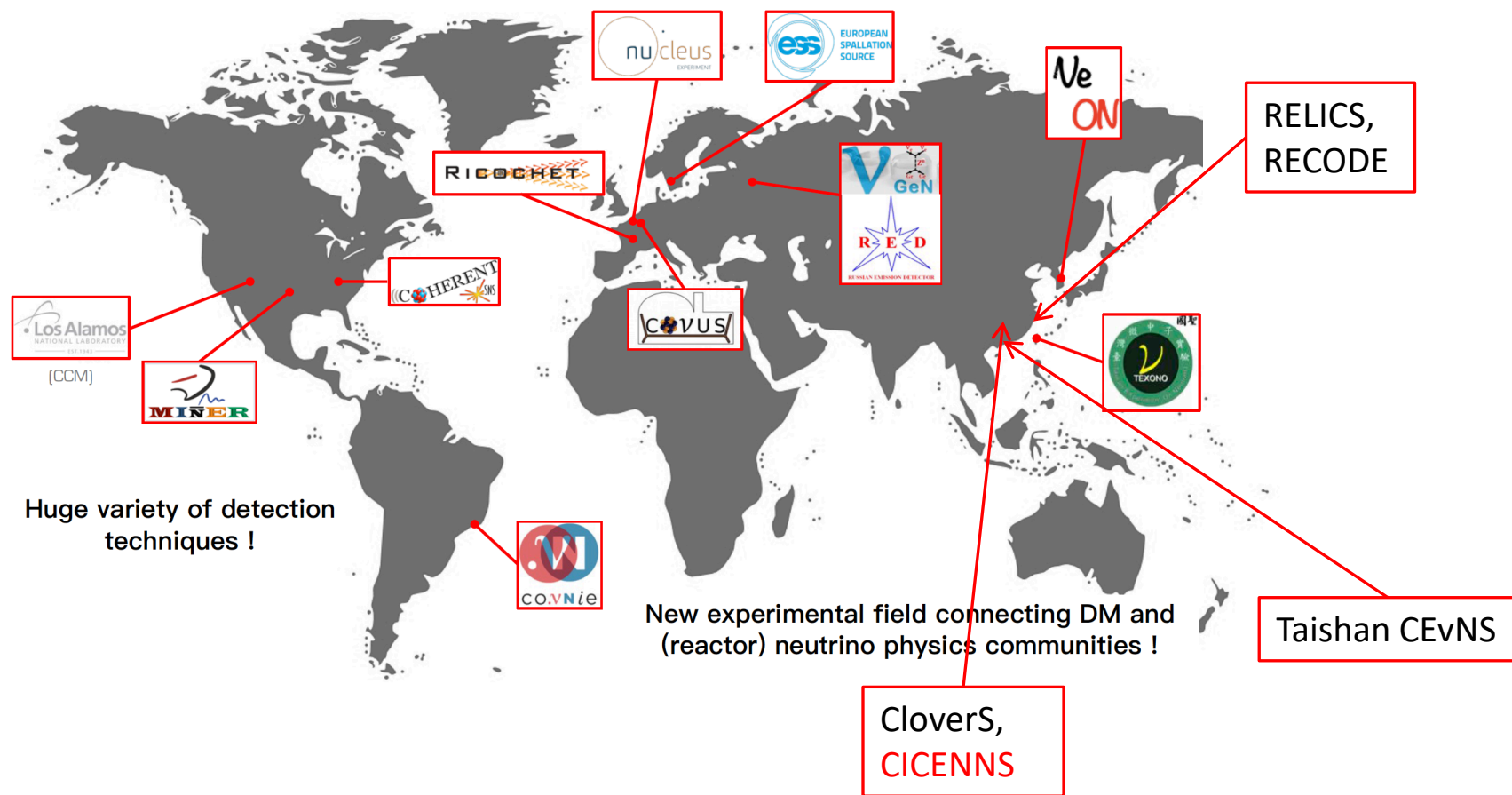
NEUTRINO PHYSICS

Observation of coherent elastic neutrino-nucleus scattering

Science

Beam ON

Global experimental efforts

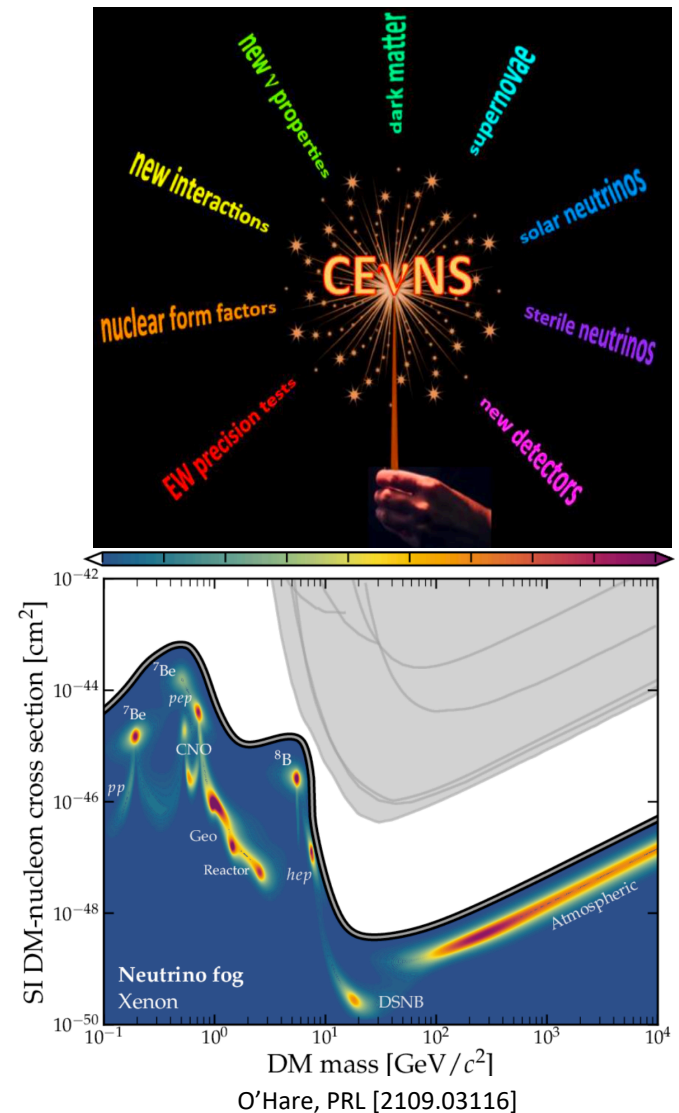


Adapted from M. VIVIER@Magnificent CEvNS 2020

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



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Generalized neutrino interactions

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

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

Aristizabal Sierra et.al., JHEP [1806.07424]

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

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

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.
- EFT framework → a set of **nuclear response functions**

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

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];...

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

NLO: Coherence strikes back

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

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

NR expansion

tensor charge

tensor anomalous magnetic moment

	$\mathcal{L}_{(0)}^1$	$\mathcal{L}_{(1)}^1$	$\mathcal{L}_{(0)}^2$
neutrino	$-2\bar{u}_{k'} \vec{\sigma}_{(0)} u_k$	$2\bar{u}_{k'} \vec{\sigma}_{(1)} u_k$	$-2\bar{u}_{k'} \vec{\sigma}_{(0)} u_k$
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 $\frac{|q|}{m_N} \sim \mathcal{O}(0.01)$.
- However, momentum suppressed **P-odd** terms can be **coherently enhanced**.

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

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

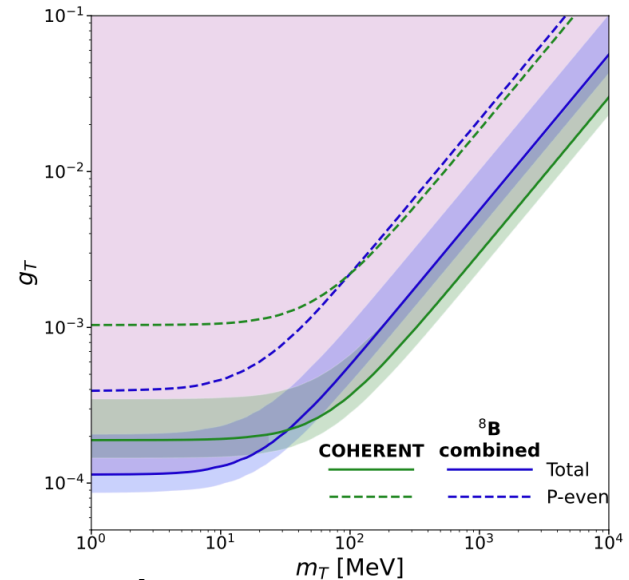
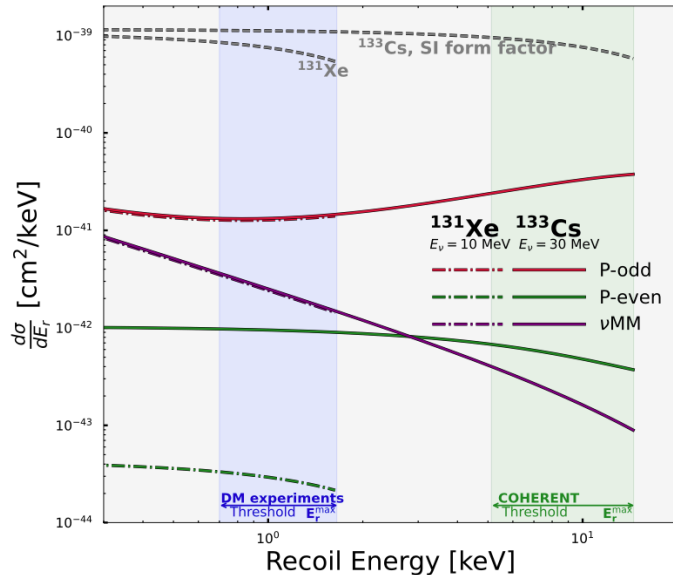
$$\frac{d\sigma_T^E}{dE_r} = \frac{M}{\pi} \sum_{N,N'=p,n} \left[2G_T^{N,1} G_T^{N',1} \left(1 - \frac{E_r}{E_\nu} \right) \mathcal{F}_N^{\Sigma''} \mathcal{F}_{N'}^{\Sigma''} + G_T^{N,1} G_T^{N',1} \left(1 - \frac{ME_r}{2E_\nu^2} - \frac{E_r}{E_\nu} \right) \mathcal{F}_N^{\Sigma'} \mathcal{F}_{N'}^{\Sigma'}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

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

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

For

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

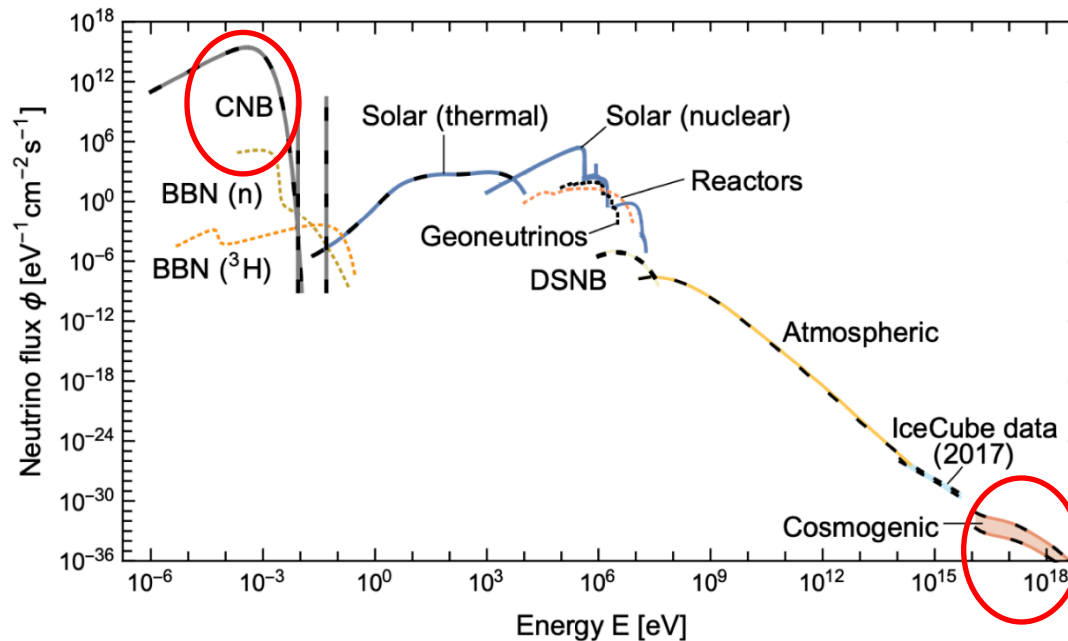


JL, Tang, Zhang, PRD [2502.10702]

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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 ($T \simeq 1.95 \text{ K}$).

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

Tetsuya HARA* and Humitaka SATO

**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 [\[2405.14946\]](#)

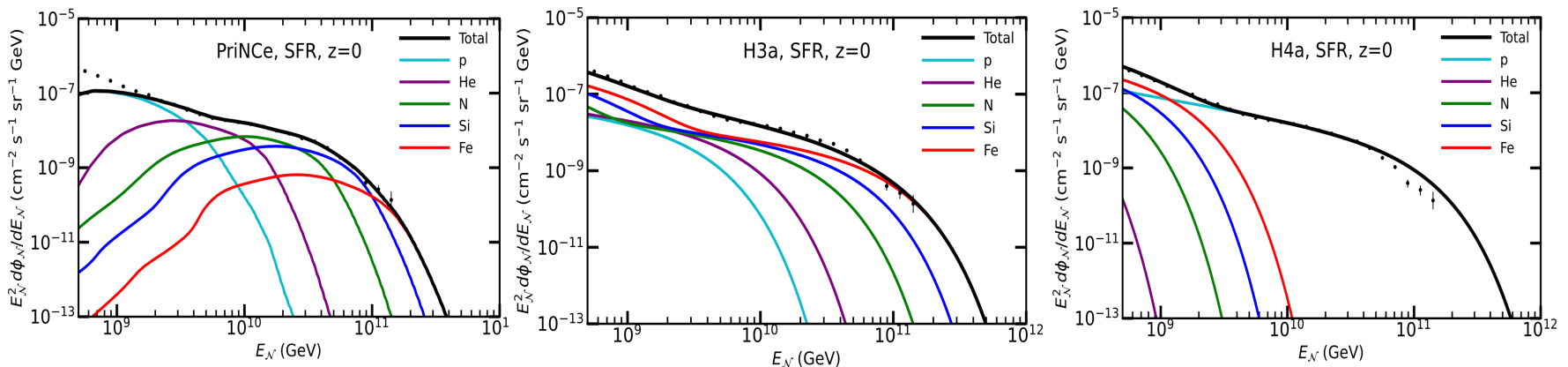
Composition of UHECR

- 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.

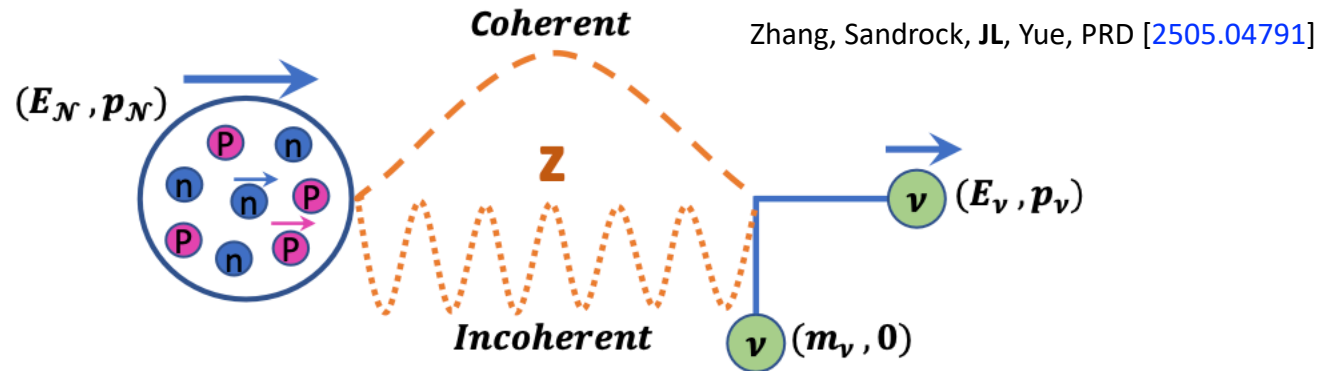
Kachelriess, Semikoz [1904.08160]



- Propagation of UHECR spectra can be simulated by the **PriNce** code.
- Hillas models: Pop. 1, Pop. 2, and Pop. 3 define **H3a**; Pop. 3* replaces Pop. 3 in **H4a**.

Coherent Enhancement

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

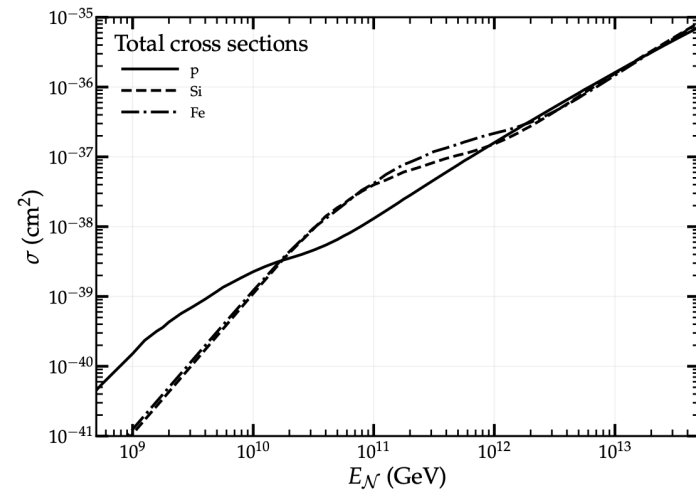
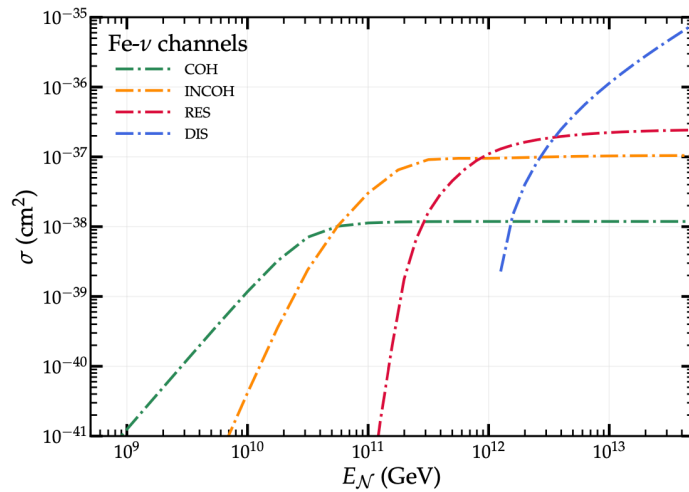
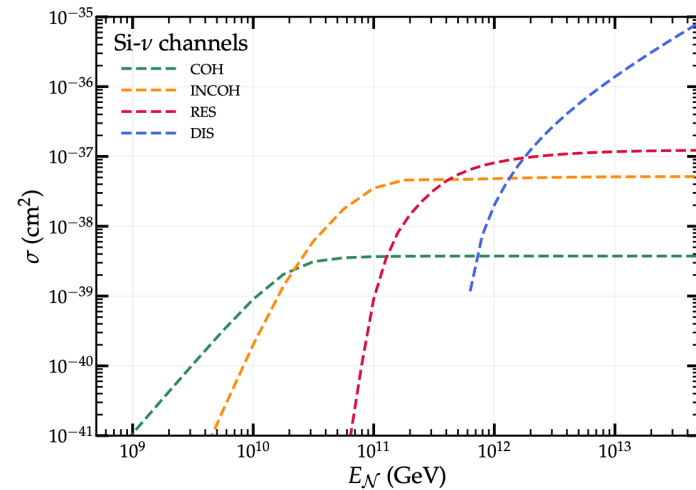
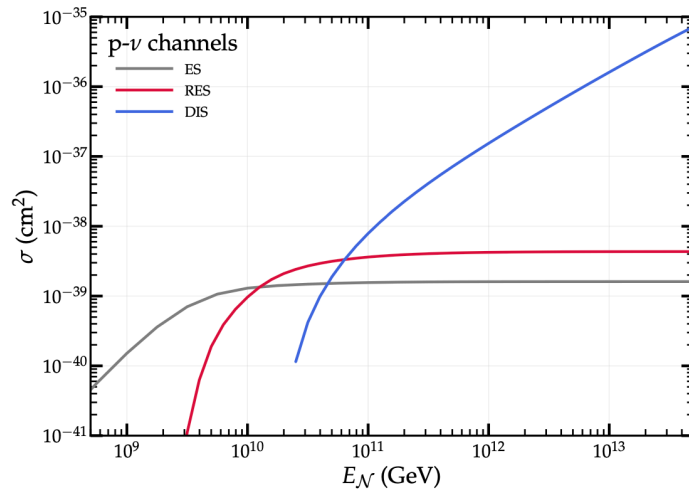


$$\frac{d\sigma_{\text{coh}}^{\nu\mathcal{N}_i}}{dE_\nu} = \frac{2G_F^2 m_\nu}{\pi} Q_{W,i}^2 \left(1 - \frac{E_\nu}{E_{\mathcal{N}_i}} - \frac{m_{\mathcal{N}_i}^2 E_\nu}{2m_\nu E_{\mathcal{N}_i}^2} \right) F^2(q^2)$$

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

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

Cross sections



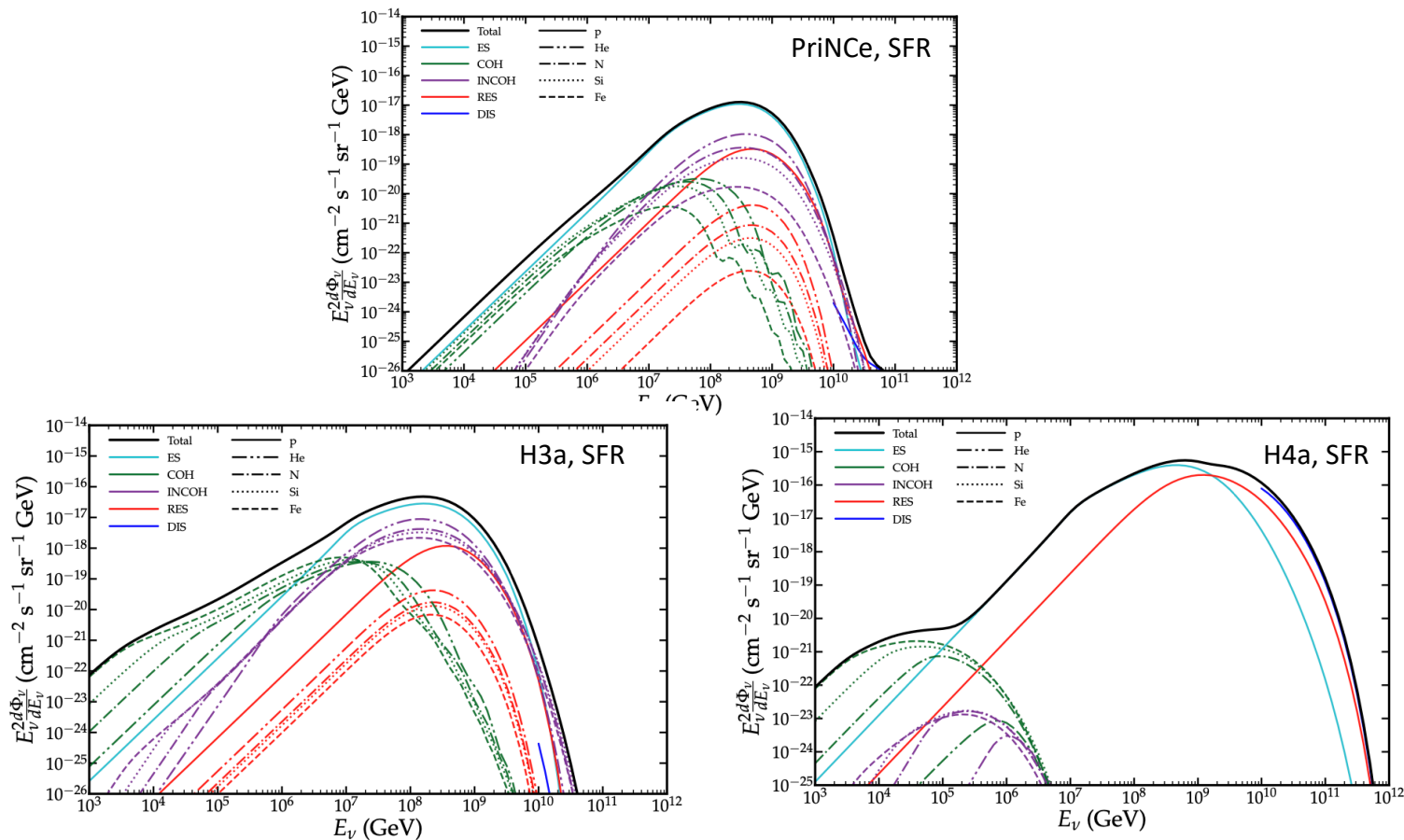
Zhang, JL [[2606.18088](#)]

Diffuse flux of Boosted CνB

- The diffuse flux of UHECR boosted CνB at Earth is:

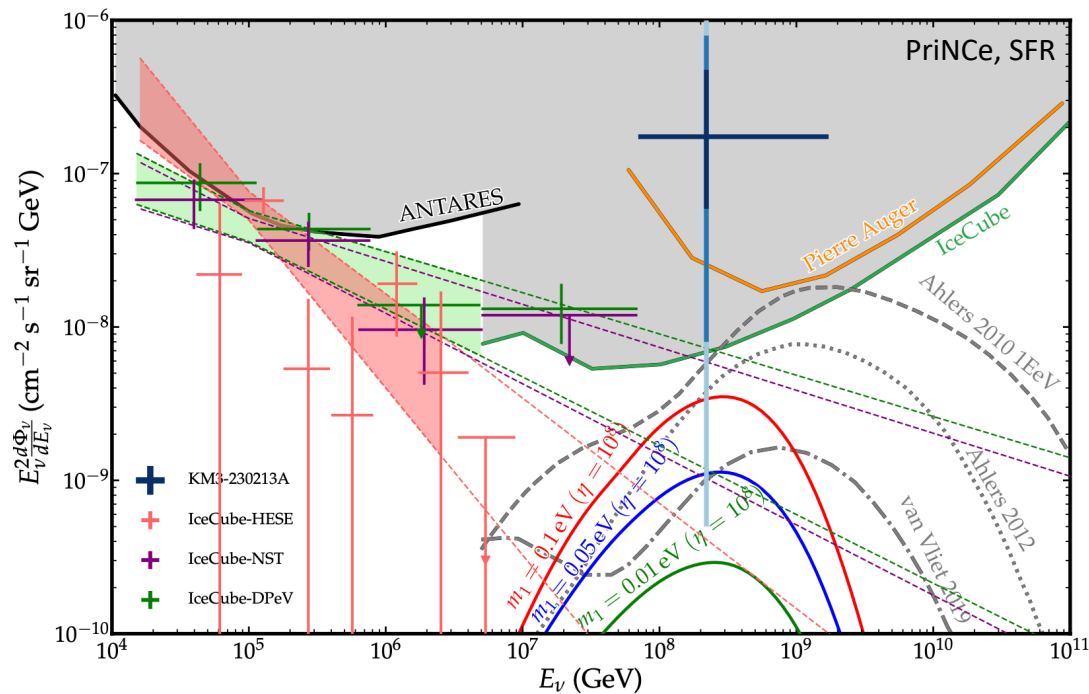
Herrera, Horiuchi, Qi [2405.14946]

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



Zhang, JL [2606.18088]

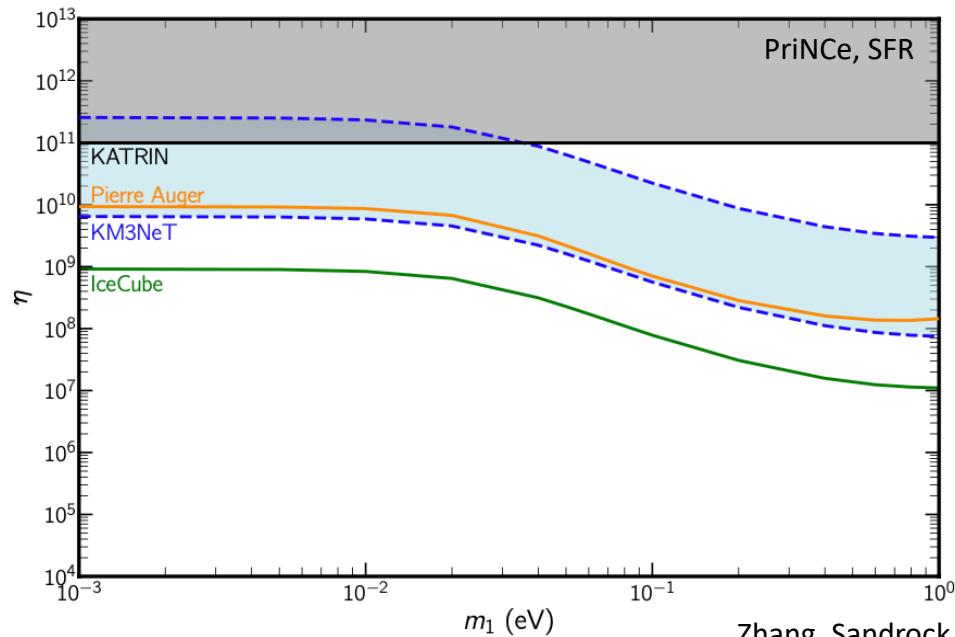
Comparison with experimental data



Zhang, Sandrock, JL, Yue, PRD [[2505.04791](#)]

- The boosted CνB flux decreases as m_{lightest} becomes smaller.
- The peak of the boosted CνB flux coincides with KM3-230213A event.
- Boosted flux has different energy spectrum than cosmogenic neutrinos.

Constraints on CνB overdensity



- 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

- Observation of 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!

Backup slides

Current data

❖ π DAR 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 et al., PRL 129, 211802 (2022)

CONUS+ first observed at 3.7σ in a Ge detector

CONUS+, Nature 643, 8074 (2025)

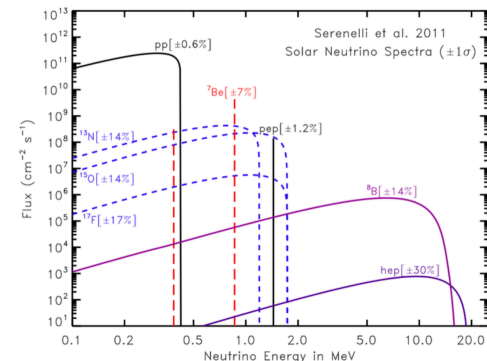
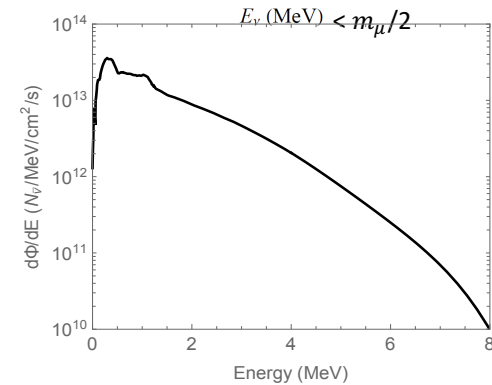
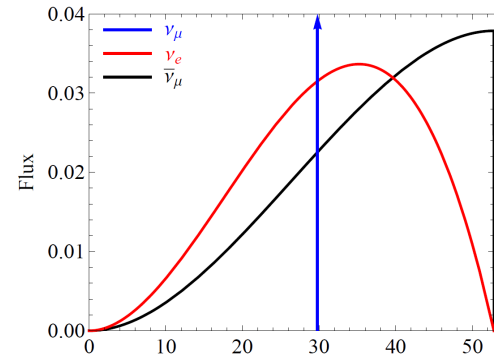
❖ Solar ^8B neutrino source

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)



Hillas model

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

➤ Pop. 1, Pop. 2, and Pop. 3 define H3a, while Pop. 3* replaces Pop. 3 in H4a.

