COHERENT elastic neutrino-nucleus scattering

Pablo Muñoz Candela
IFIC (CSIC - UV), Valencia (Spain)

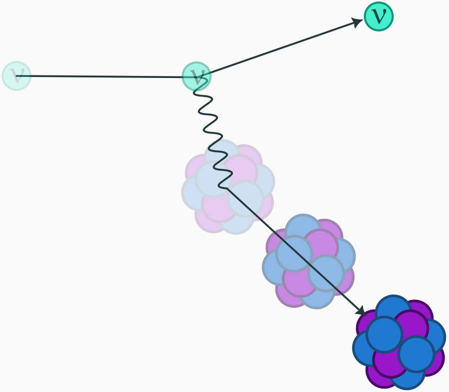
November 22, 2024

IPPP seminar

Durham, United Kingdom

Introduction

What is CEνNS?



Coherent

Elastic

ν (neutrino)

Nucleus

Scattering

A journey of 43 years

Predicted

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)

First detected

RESEARCH

NEUTRINO PHYSICS

Observation of coherent elastic neutrino-nucleus scattering

[...]

Akimov *et al.*, *Science* **357**, 1123–1126 (2017) 15 September 2017

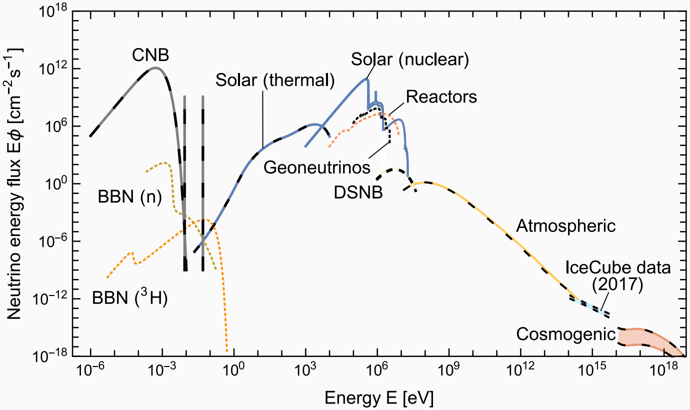
Why did it take so long?

Why did it take so long?

Because the recoil of the nucleus is very small.

Neutrino sources

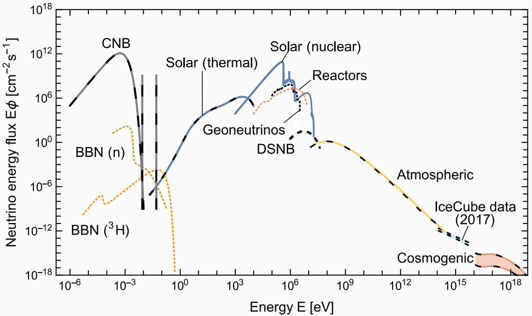
There are several neutrino sources in the Universe



E. Vitagliano, I. Tamborra and G. Raffelt, Rev. Mod. Phys. 92, 45006

There are several neutrino sources in the Universe

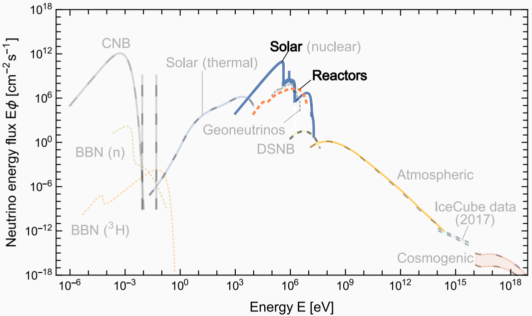
- Cosmic neutrino background (CNB)
- Big Bang Nucleosynthesis (BBN) neutrinos
- Solar neutrinos
- Geoneutrinos
- Supernova neutrinos
- Reactor neutrinos
- Atmospheric neutrinos
- Very high energy neutrinos



E. Vitagliano, I. Tamborra and G. Raffelt, Rev. Mod. Phys. 92, 45006

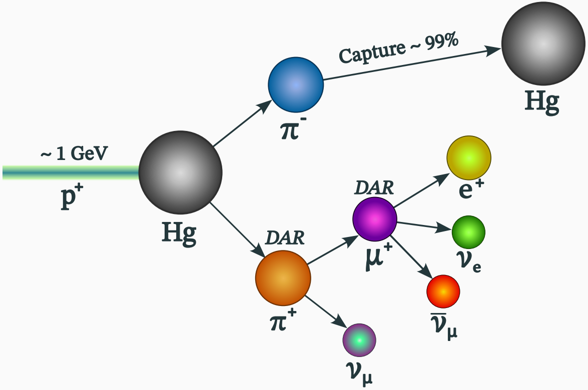
There are several neutrino sources used for CEvNS

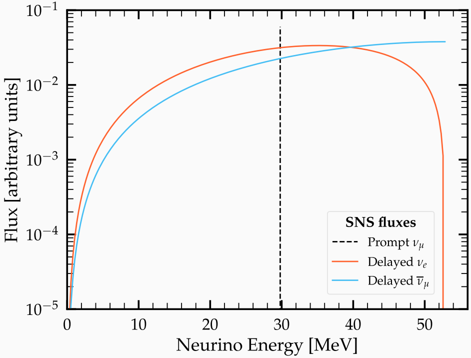
- Cosmic neutrino background (CNB)
- Big Bang Nucleosynthesis (BBN) neutrinos
- Solar neutrinos
- Geoneutrinos
- Supernova neutrinos
- Reactor neutrinos
- Neutrinos from spallation sources
- Atmospheric neutrinos
- Very high energy neutrinos



E. Vitagliano, I. Tamborra and G. Raffelt, Rev. Mod. Phys. 92, 45006

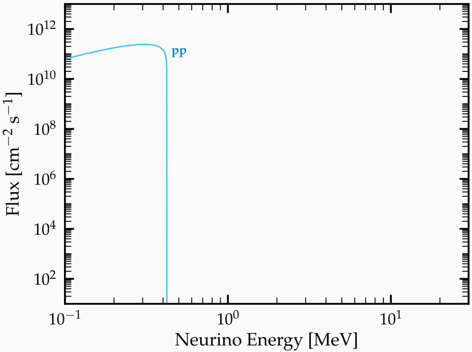
Neutrinos produced at the spallation neutron source (SNS)





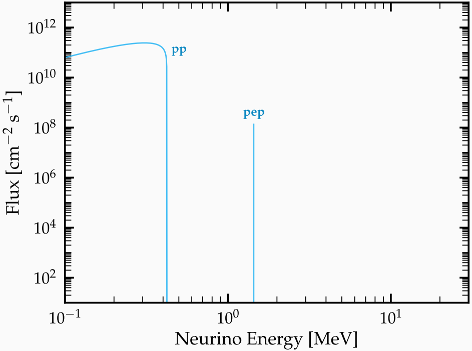
Solar neutrinos are produced in the proton-proton chains inside the Sun

- *pp* component: $p + p \to {}^2\mathrm{H} + e^+ + \boldsymbol{\nu_e}$



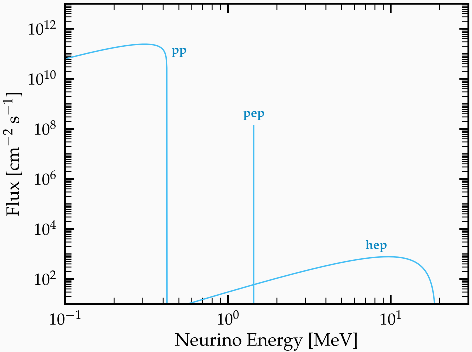
Solar neutrinos are produced in the proton-proton chains inside the Sun

- *pp* component: $p + p \rightarrow {}^{2}\mathrm{H} + e^{+} + \nu_{\mathrm{e}}$
- *pep* component: $p + e^{-} + p \rightarrow {}^{2}\mathrm{H} + \nu_{\mathrm{e}}$



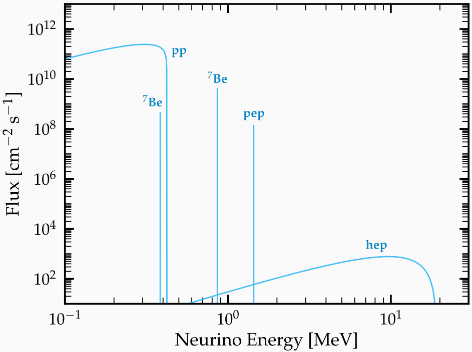
Solar neutrinos are produced in the proton-proton chains inside the Sun

- *pp* component: $p + p \rightarrow {}^2\mathrm{H} + e^+ + \boldsymbol{\nu}_\mathbf{e}$
- *pep* component: $p + e^- + p \rightarrow {}^2\mathrm{H} + \boldsymbol{\nu}_\mathbf{e}$
- *hep* component: ${}^3\mathrm{He} + p \rightarrow {}^4\mathrm{He} + e^+ + \boldsymbol{\nu}_\mathbf{e}$



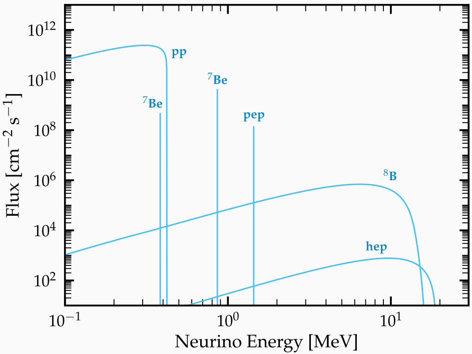
Solar neutrinos are produced in the proton-proton chains inside the Sun

- *pp* component: $p + p \to {}^{2}\mathrm{H} + e^{+} + \nu_{\mathrm{e}}$
- *pep* component: $p + e^{-} + p \to {}^{2}\mathrm{H} + \nu_{\mathrm{e}}$
- *hep* component: ${}^{3}\mathrm{He} + p \to {}^{4}\mathrm{He} + e^{+} + \nu_{\mathrm{e}}$
- ^{7}Be component: ${}^{7}\mathrm{Be} + e^{-} \to {}^{7}\mathrm{Li} + \nu_{\mathrm{e}}$



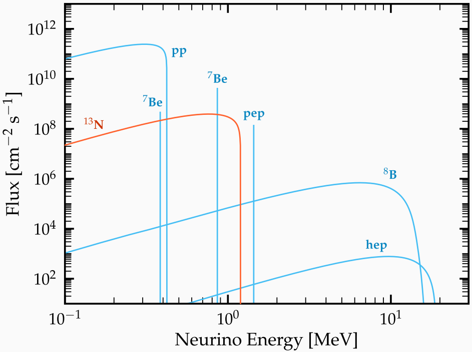
Solar neutrinos are produced in the proton-proton chains inside the Sun

- *pp* component: $p + p \rightarrow {}^2\mathrm{H} + e^+ + \nu_\mathrm{e}$
- *pep* component: $p + e^- + p \rightarrow {}^2\mathrm{H} + \nu_\mathrm{e}$
- *hep* component: ${}^3\mathrm{He} + p \rightarrow {}^4\mathrm{He} + e^+ + \nu_\mathrm{e}$
- ${}^7\mathrm{Be}$ component: ${}^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu_\mathrm{e}$
- ${}^8\mathrm{B}$ component: ${}^8\mathrm{B} \rightarrow {}^8\mathrm{Be}^* + e^- + \nu_\mathrm{e}$



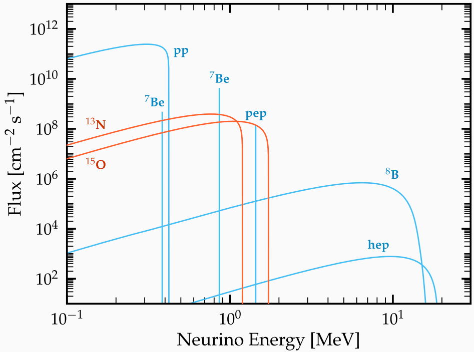
But also in the CNO cycle:

- ^{13}N component: $^{13}\mathrm{N} \rightarrow {}^{13}\mathrm{C} + e^{+} + \nu_{\mathbf{e}}$



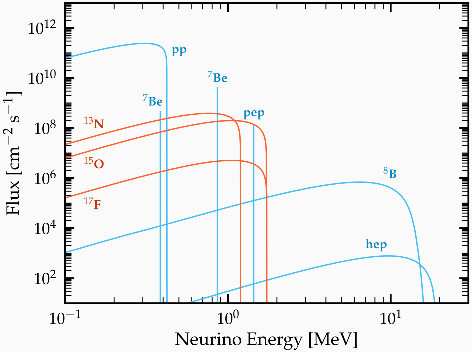
But also in the CNO cycle:

- ^{13}N component: $^{13}\mathrm{N} \to {}^{13}\mathrm{C} + e^{+} + \nu_{e}$
- ^{15}O component: $^{15}\mathrm{O} \to {}^{15}\mathrm{N} + e^{+} + \nu_{e}$



But also in the CNO cycle:

- ^{13}N component: $^{13}\mathrm{N} \to {}^{13}\mathrm{C} + e^{+} + \nu_{\mathbf{e}}$
- ^{15}O component: $^{15}\mathrm{O} \to {}^{15}\mathrm{N} + e^{+} + \nu_{\mathbf{e}}$
- ^{17}F component: $^{17}\mathrm{F} \to {}^{17}\mathrm{O} + e^{+} + \nu_{\mathbf{e}}$



Reactor neutrinos

Electron antineutrinos are produced by the chain of β-decays from neutron-rich isotopes:

Reactor neutrinos

Electron antineutrinos are produced by the chain of β-decays from neutron-rich isotopes:

- $^{235}\mathrm{U}$ (56 %)
- $^{238}\mathrm{U}$ (8 %)
- $^{239}\mathrm{Pu}$ (30 %)
- $^{241}\mathrm{Pu}$ (6 %)

Reactor neutrinos

Electron antineutrinos are produced by the chain of β-decays from neutron-rich isotopes:

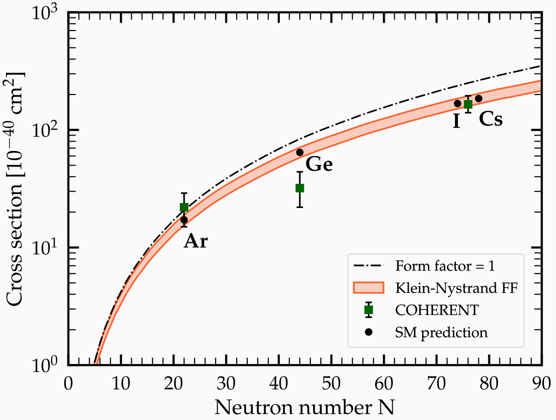
- $^{235}\mathrm{U}$ (56 %)
- $^{238}\mathrm{U}$ (8 %)
- $^{239}\mathrm{Pu}$ (30 %)
- $^{241}\mathrm{Pu}$ (6 %)

Recall that the β-decay changes an isotope following the reaction

$$^{A}_{Z}X \rightarrow {}^{A+1}_{Z}X' + e^{-} + \bar{\boldsymbol{\nu}}_{\mathbf{e}}$$

The CEνNS cross section in the SM

The CEvNS cross section is enhanced by the number of neutrons



$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{4\pi} Q_W^2 F^2(|\mathbf{q}|^2)\left(1 - \frac{MT}{2E_\nu^2}\right).$$

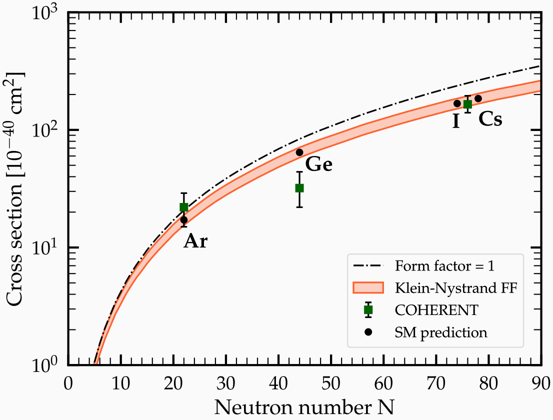
References:

CsI 2021 measurement: D. Akimov *et al.* (COHERENT collaboration) Phys. Rev. Lett. 129, 081801

LAr 2020 measurement: D. Akimov *et al.* (COHERENT collaboration) Phys. Rev. Lett. 126, 012002

Ge 2024 measurement: S. Adamski *et al.* (COHERENT collaboration) arXiv:2406.13806 [hep-ex]

The CEvNS cross section is enhanced by the number of neutrons



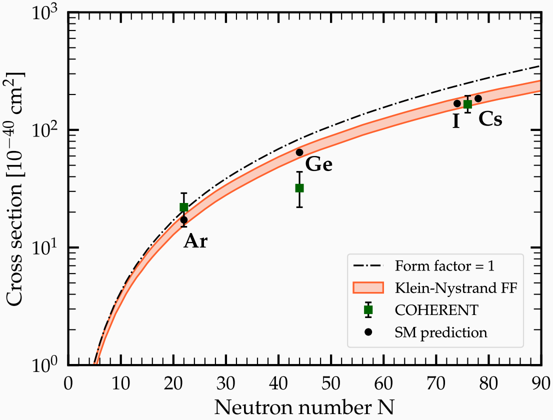
$$\frac{\mathrm{d}\sigma}{\mathrm{d}T} = \frac{G_F^2 M}{4\pi} Q_W^2 F^2(|\mathbf{q}|^2)\left(1 - \frac{MT}{2E_\nu^2}\right).$$

Nuclear recoil energy $T \sim 10$ keV

References:

CsI 2021 measurement: D. Akimov *et al.* (COHERENT collaboration) Phys. Rev. Lett. 129, 081801
LAr 2020 measurement: D. Akimov *et al.* (COHERENT collaboration) Phys. Rev. Lett. 126, 012002
Ge 2024 measurement: S. Adamski *et al.* (COHERENT collaboration) arXiv:2406.13806 [hep-ex]

The CEvNS cross section is enhanced by the number of neutrons



$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{4\pi} Q_W^2 F^2(|\mathbf{q}|^2)\left(1 - \frac{MT}{2E_\nu^2}\right).$$

Incoming neutrino energy

$E_\nu \sim 10$ MeV

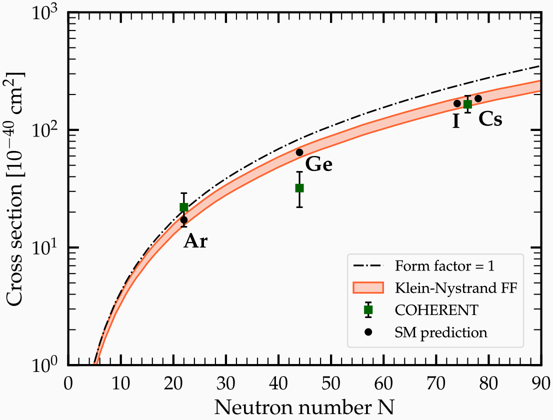
References:

CsI 2021 measurement: D. Akimov *et al.* (COHERENT collaboration) Phys. Rev. Lett. 129, 081801

LAr 2020 measurement: D. Akimov *et al.* (COHERENT collaboration) Phys. Rev. Lett. 126, 012002

Ge 2024 measurement: S. Adamski *et al.* (COHERENT collaboration) arXiv:2406.13806 [hep-ex]

The CEvNS cross section is enhanced by the number of neutrons



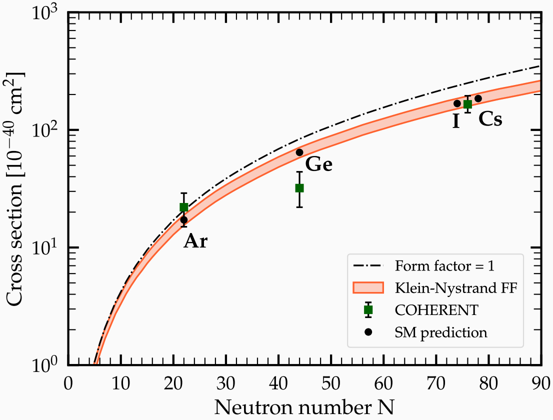
$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{4\pi} Q_W^2 F^2(|\mathbf{q}|^2)\left(1 - \frac{MT}{2E_\nu^2}\right).$$

Fermi coupling constant G_F^2

References:

CsI 2021 measurement: D. Akimov *et al.* (COHERENT collaboration) Phys. Rev. Lett. 129, 081801
LAr 2020 measurement: D. Akimov *et al.* (COHERENT collaboration) Phys. Rev. Lett. 126, 012002
Ge 2024 measurement: S. Adamski *et al.* (COHERENT collaboration) arXiv:2406.13806 [hep-ex]

The CEvNS cross section is enhanced by the number of neutrons



$$\frac{\mathrm{d}\sigma}{\mathrm{d}T} = \frac{\mathrm{G}_\mathrm{F}^2 M}{4\pi} Q_W^2 F^2(|\mathbf{q}|^2)\left(1 - \frac{MT}{2E_\nu^2}\right).$$

Atomic mass of the target M

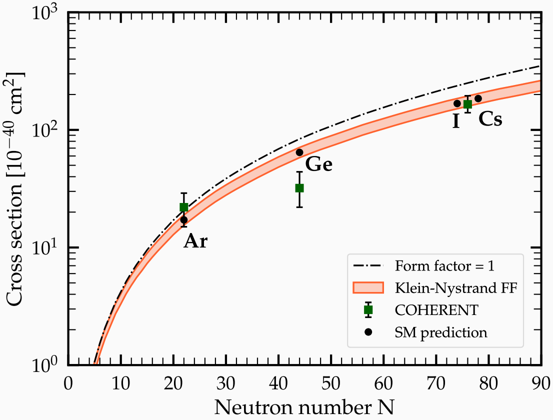
References:

CsI 2021 measurement: D. Akimov *et al.* (COHERENT collaboration) Phys. Rev. Lett. 129, 081801

LAr 2020 measurement: D. Akimov *et al.* (COHERENT collaboration) Phys. Rev. Lett. 126, 012002

Ge 2024 measurement: S. Adamski *et al.* (COHERENT collaboration) arXiv:2406.13806 [hep-ex]

The CEvNS cross section is enhanced by the number of neutrons



$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{4\pi} Q_W^2 F^2(|\mathbf{q}|^2) \left(1 - \frac{MT}{2E_\nu^2}\right) .$$

Form factor $F(|\mathbf{q}|)$

Momentum transfer $\mathbf{q} \approx \sqrt{2MT}$

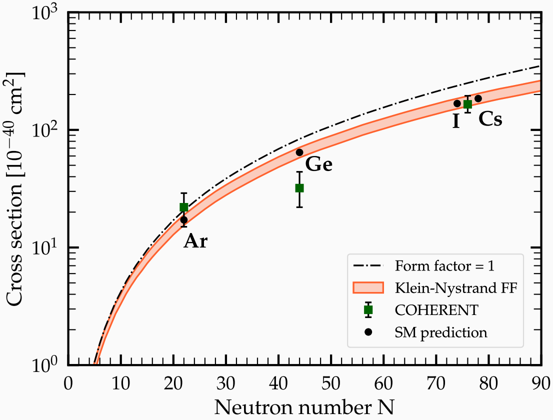
References:

CsI 2021 measurement: D. Akimov *et al.* (COHERENT collaboration) Phys. Rev. Lett. 129, 081801

LAr 2020 measurement: D. Akimov *et al.* (COHERENT collaboration) Phys. Rev. Lett. 126, 012002

Ge 2024 measurement: S. Adamski *et al.* (COHERENT collaboration) arXiv:2406.13806 [hep-ex]

The CEvNS cross section is enhanced by the number of neutrons



$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{4\pi} Q_W^2 F^2(|\mathbf{q}|^2)\left(1 - \frac{MT}{2E_\nu^2}\right).$$

Weak charge

$$Q_W^2 = \left[Z(1 - 4\sin^2\theta_W) - N\right]^2 \approx N^2$$

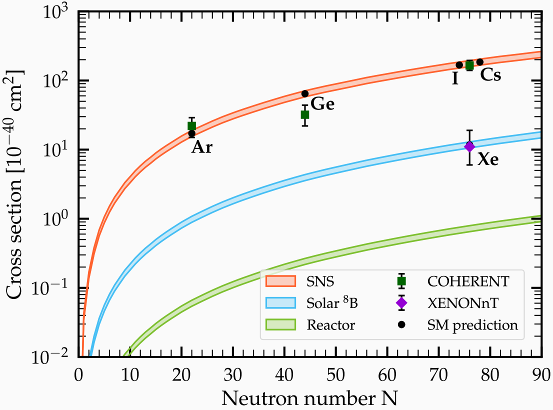
References:

CsI 2021 measurement: D. Akimov *et al.* (COHERENT collaboration) Phys. Rev. Lett. 129, 081801

LAr 2020 measurement: D. Akimov *et al.* (COHERENT collaboration) Phys. Rev. Lett. 126, 012002

Ge 2024 measurement: S. Adamski *et al.* (COHERENT collaboration) arXiv:2406.13806 [hep-ex]

Different neutrino sources produce different values



$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{4\pi} Q_W^2 F^2(|\mathbf{q}|^2) \left(1 - \frac{MT}{2E_\nu^2}\right) .$$

References:

CsI 2021 measurement: D. Akimov *et al.* (COHERENT collaboration) Phys. Rev. Lett. 129, 081801

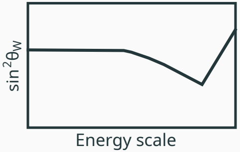
LAr 2020 measurement: D. Akimov *et al.* (COHERENT collaboration) Phys. Rev. Lett. 126, 012002

Ge 2024 measurement: S. Adamski *et al.* (COHERENT collaboration) arXiv:2406.13806 [hep-ex]

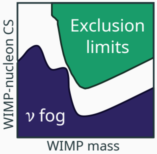
Xe 2024 measurement: E. Aprile *et al.* (XENON collaboration) Phys. Rev. Lett. 133, 191002

CEvNS has applications in the SM and beyond it

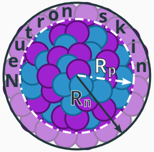
Weak mixing angle



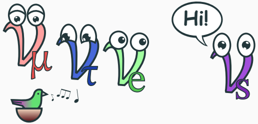
Neutrino fog



Nuclear properties



Sterile neutrinos



and many more

(e.g. new dark sector particles)

Experiments

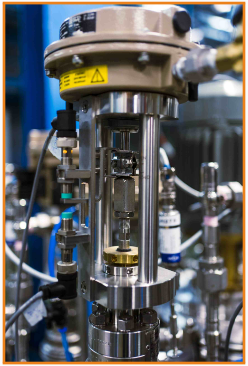
COHERENT detectors were the first ones...

LAr detector
(COHERENT collaboration)

CsI detector
(COHERENT collaboration)

...and a new era began

LZ detector
(LZ collaboration)



XENONnT detector
(XENON collaboration)

The are many more!

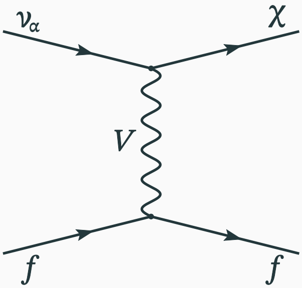
- CONUS
- NUCLEUS
- RICOCHET
- MINER
- RED-100
- νGEN
- TEXONO
- CONNIE
- NEON
- DRESDEN-II
- JUNO
- DARKSIDE
- PandaX
- CHILLAX

Some have already detected CEvNS

- CONUS
- NUCLEUS
- RICOCHET
- MINER
- RED-100
- νGEN
- TEXONO
- CONNIE
- NEON
- DRESDEN-II*
- JUNO
- DARKSIDE
- PandaX
- CHILLAX

Our phenomenological scenario

We propose a new vector mediator. The sterile fermion is produced via up-scattering



$$\mathcal{L}_{\mathrm{SF}}^{\mathrm{V}} \supseteq V_\mu \overline{\chi}\gamma^\mu \left(g_{\chi_L} P_L + g_{\chi_R} P_R\right) \nu_\alpha + V_\mu \sum_f \overline{f}\gamma^\mu \left(g_{f_L} P_L + g_{f_R} P_R\right) f + \mathrm{H.c.}$$

References:
V. Brdar, W. Rodejohann, and X.-J. Xu, JHEP 12 (2018) 024
W.-F. Chang and J. Liao, Phys. Rev. D 102, 075004
W. Chao, T. Li, J. Liao, and M. Su, Phys. Rev. D 104 095017
Z. Chen, T. Li, and J. Liao, JHEP 05 131
T. Li and J. Liao, JHEP 02 (2021) 099

Let us simplify the analysis with some assumptions

$$\mathcal{L}_{\mathrm{SF}}^{\mathrm{V}} \supseteq V_\mu \, \overline{\chi} \gamma^\mu \left(g_{\chi_L} P_L + g_{\chi_R} P_R \right) \nu_\alpha + V_\mu \sum_f \overline{f} \gamma^\mu \left(g_{f_L} P_L + g_{f_R} P_R \right) f + \mathrm{H.c.}$$

Let us simplify the analysis with some assumptions

$$\mathcal{L}_{\mathrm{SF}}^{\mathrm{V}} \supseteq V_\mu \, \overline{\chi}\gamma^\mu \left(g_{\chi_L} P_L + g_{\chi_R} P_R\right) \nu_\alpha + V_\mu \sum_f \overline{f}\gamma^\mu \left(g_{f_L} P_L + g_{f_R} P_R\right) f + \mathrm{H.c.}$$

- Standard model neutrinos: $g_{\chi_R} = 0$

Let us simplify the analysis with some assumptions

$$\mathcal{L}_{\mathrm{SF}}^{\mathrm{V}} \supseteq V_\mu \, \overline{\chi} \gamma^\mu \left(g_{\chi_L} P_L + g_{\chi_R} P_R \right) \nu_\alpha + V_\mu \sum_f \overline{f} \gamma^\mu \left(g_{f_L} P_L + g_{f_R} P_R \right) f + \mathrm{H.c.}$$

- Standard model neutrinos: $g_{\chi_R} = 0$
- Left-right fermion couplings equal: $g_{f_L} = g_{f_R} \equiv g_f$

Let us simplify the analysis with some assumptions

$$\mathcal{L}_{\rm SF}^{\rm V} \supseteq V_\mu \, \overline{\chi}\gamma^\mu \left(g_{\chi_L} P_L + g_{\chi_R} P_R\right) \nu_\alpha + V_\mu \sum_f \overline{f}\gamma^\mu \left(g_{f_L} P_L + g_{f_R} P_R\right) f + \text{H.c.}$$

- Standard model neutrinos: $g_{\chi_R} = 0$
- Left-right fermion couplings equal: $g_{f_L} = g_{f_R} \equiv g_f$
- Universal couplings to u, d and e^-: $g_u = g_d = g_{e^-} \equiv g_f$

Let us simplify the analysis with some assumptions

$$\mathcal{L}_{\mathrm{SF}}^{\mathrm{V}} \supseteq V_\mu \overline{\chi}\gamma^\mu \left(g_{\chi_L} P_L + g_{\chi_R} P_R\right) \nu_\alpha + V_\mu \sum_f \overline{f}\gamma^\mu \left(g_{f_L} P_L + g_{f_R} P_R\right) f + \mathrm{H.c.}$$

- Standard model neutrinos: $g_{\chi_R} = 0$
- Left-right fermion couplings equal: $g_{f_L} = g_{f_R} \equiv g_f$
- Universal couplings to u, d and e^-: $g_u = g_d = g_{e^-} \equiv g_f$
- Same with antiparticles.

Let us simplify the analysis with some assumptions

$$\mathcal{L}_{\mathrm{SF}}^{\mathrm{V}} \supseteq V_\mu\, \overline{\chi}\gamma^\mu \left(g_{\chi_L} P_L + g_{\chi_R} P_R\right) \nu_\alpha + V_\mu \sum_f \overline{f}\gamma^\mu \left(g_{f_L} P_L + g_{f_R} P_R\right) f + \mathrm{H.c.}$$

- Standard model neutrinos: $g_{\chi_R} = 0$
- Left-right fermion couplings equal: $g_{f_L} = g_{f_R} \equiv g_f$
- Universal couplings to u, d and e^-: $g_u = g_d = g_{e^-} \equiv g_f$
- Same with antiparticles.

$$g_V \equiv \sqrt{g_{\chi_L} g_f}$$

A brief aside: elastic neutrino-electron scattering (EνES)

A brief aside: elastic neutrino-electron scattering (EνES)

- In a EνES process, a neutrino scatters off an electron ($\nu + e^- \to \nu + e^-$).

A brief aside: elastic neutrino-electron scattering (EνES)

- In a EνES process, a neutrino scatters off an electron ($\nu + e^- \to \nu + e^-$).
- Recall that the detector is made of atoms.

A brief aside: elastic neutrino-electron scattering (EνES)

- In a EνES process, a neutrino scatters off an electron ($\nu + e^- \rightarrow \nu + e^-$).
- Recall that the detector is made of atoms.
- Therefore, the incoming neutrino will scatter off:
    - an electron of the atom (EνES).

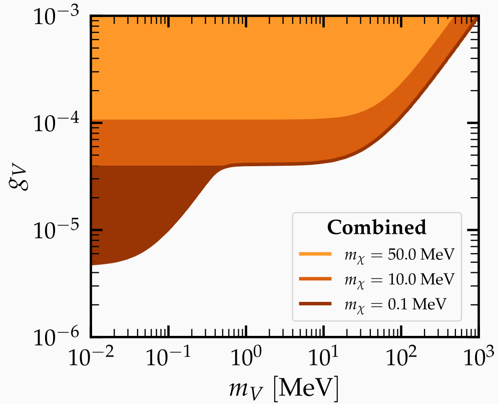
A brief aside: elastic neutrino-electron scattering (EνES)

- In a EνES process, a neutrino scatters off an electron ($\nu + e^- \rightarrow \nu + e^-$).
- Recall that the detector is made of atoms.
- Therefore, the incoming neutrino will scatter off:
    - an electron of the atom (EνES).
    - the nucleus of the atom (CEνNS).

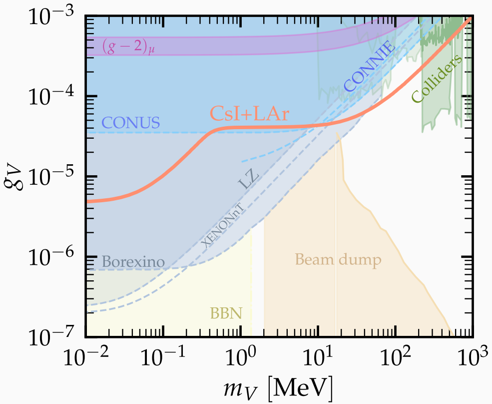
- In a EvES process, a neutrino scatters off an electron ($\nu + e^- \to \nu + e^-$).
- Recall that the detector is made of atoms.
- Therefore, the incoming neutrino will scatter off:
  - an electron of the atom (EvES).
  - the nucleus of the atom (CEvNS).
- We study both processes at the same time in our analysis!

Results

Exclusion regions at 90% C.L. (in colour) change with different sterile fermion masses (m_χ)

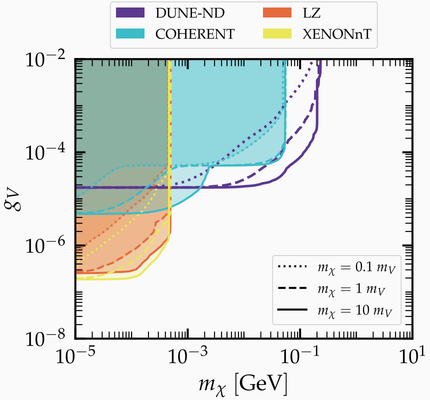


PMC, De Romeri, and Papoulias. *PRD* **108**, 055001



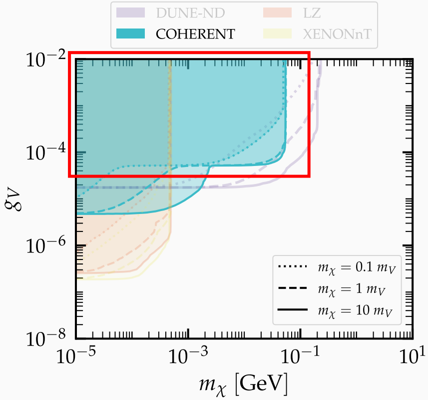
PMC, De Romeri, and Papoulias. *PRD* **108**, 055001

Exclusion regions at 90% C.L. (in colour) change with different sterile fermion masses (m_χ)

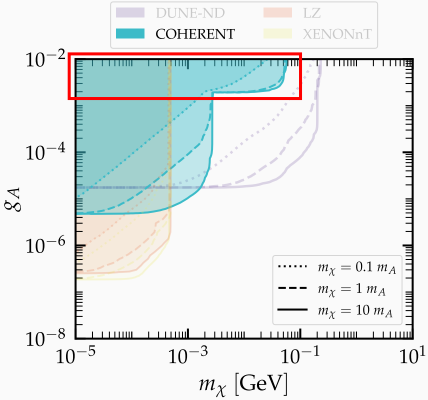


PMC et al. *JHEP* **10** (2024) 032

The axial contribution to the CEvNS is suppressed in comparison to the vector one



PMC et al. *JHEP* **10** (2024) 032



PMC et al. *JHEP* **10** (2024) 032

The future

What lies ahead for CEvNS

- COHERENT will take new measurements using new detectors of different materials.

What lies ahead for CEvNS

- COHERENT will take new measurements using new detectors of different materials.
- As we saw, several experiments are looking for CEvNS using reactor neutrinos: CONNIE, CONUS, Dresden-II, nuGEN, NUCLEUS, TEXONO, among others.

What lies ahead for CEvNS

- COHERENT will take new measurements using new detectors of different materials.
- As we saw, several experiments are looking for CEvNS using reactor neutrinos: CONNIE, CONUS, Dresden-II, nuGEN, NUCLEUS, TEXONO, among others.
- In addition, solar neutrinos are being measured in dark matter experiments.

What lies ahead for CEvNS

- COHERENT will take new measurements using new detectors of different materials.
- As we saw, several experiments are looking for CEvNS using reactor neutrinos: CONNIE, CONUS, Dresden-II, nuGEN, NUCLEUS, TEXONO, among others.
- In addition, solar neutrinos are being measured in dark matter experiments.
- LZ is also looking for CEvNS using supernova neutrinos.

What lies ahead for CEvNS

- COHERENT will take new measurements using new detectors of different materials.
- As we saw, several experiments are looking for CEvNS using reactor neutrinos: CONNIE, CONUS, Dresden-II, nuGEN, NUCLEUS, TEXONO, among others.
- In addition, solar neutrinos are being measured in dark matter experiments.
- LZ is also looking for CEvNS using supernova neutrinos.
- The European Spallation Source (ESS) will be finished in some years. Providing new experiments with a powerful spallation neutrino source.

Conclusions

Conclusions

- CEνNS is a versatile process, characterised by its cross section enhancement.

Conclusions

- CEνNS is a versatile process, characterised by its cross section enhancement.
- It has been measured within different materials (CsI, Ar, Ge, Xe) and with neutrino sources (spallation, solar).

Conclusions

- CEvNS is a versatile process, characterised by its cross section enhancement.
- It has been measured within different materials (CsI, Ar, Ge, Xe) and with neutrino sources (spallation, solar).
- A lot of experiments are looking for it using new sources (reactor, supernova).

Conclusions

- CEvNS is a versatile process, characterised by its cross section enhancement.
- It has been measured within different materials (CsI, Ar, Ge, Xe) and with neutrino sources (spallation, solar).
- A lot of experiments are looking for it using new sources (reactor, supernova).
- We have analyzed existing data from different experiments in order to study a phenomenological scenario of a sterile fermion, providing competitive bounds in the intermediate MeV region.

Conclusions

- CEvNS is a versatile process, characterised by its cross section enhancement.
- It has been measured within different materials (CsI, Ar, Ge, Xe) and with neutrino sources (spallation, solar).
- A lot of experiments are looking for it using new sources (reactor, supernova).
- We have analyzed existing data from different experiments in order to study a phenomenological scenario of a sterile fermion, providing competitive bounds in the intermediate MeV region.
- All future experiments and improvements in the sensitivity give room to a plethora of applications for both precision tests of the Standard Model and for new physics in the neutrino sector.

Thank you!

PMC, De Romeri, and Papoulias. *Phys. Rev. D* 108, 055001

PMC, De Romeri, Melas, Papoulias, and Saoulidou, *JHEP* 10 (2024) 032

We add new effective interactions. All possible Lorentz invariants

$$\mathcal{L}^{a}_{\mathrm{SF}} \supseteq \frac{G_F}{\sqrt{2}}\, \varepsilon^{a}_{\ell} \left(\overline{\chi}\, \Gamma^{a} P_L \nu_{\ell}\right)\left(\overline{f}\, \Gamma_{a} f\right) + \mathrm{H.c.}\,,$$

$$\Gamma^{a} = \{I,\, i\gamma^{5},\, \gamma^{\mu},\, \gamma^{\mu}\gamma^{5},\, \sigma^{\mu\nu}\}$$

- Mediator mass m_a comparable to momentum transfer $|\mathbf{q}|$

$$G_F^2 |\varepsilon^{a}_{\ell}|^2 \longrightarrow \frac{2 g_a^4}{\left(m_a^2 + |\mathbf{q}|^2\right)^2}$$

- Recover previous vector and scalar cross sections of *Phys. Rev. D* **108**, 055001

CsI statistical analysis

$$\chi^2_{\rm CsI}\Big|_{\rm CE\nu NS+ES} = 2\sum_{i=1}^{9}\sum_{j=1}^{11}\left[N_{ij}^{\rm th} - N_{ij}^{\rm exp} + N_{ij}^{\rm exp}\ln\left(\frac{N_{ij}^{\rm exp}}{N_{ij}^{\rm th}}\right)\right] + \sum_{k=0}^{5}\left(\frac{\alpha_k}{\sigma_k}\right)^2,$$

$$N_{ij}^{\rm th} = (1+\alpha_0+\alpha_5)N_{ij}^{\rm CE\nu NS}(\alpha_4,\alpha_6,\alpha_7) + (1+\alpha_0)N_{ij}^{\rm ES}(\alpha_6,\alpha_7) + (1+\alpha_1)N_{ij}^{\rm BRN}(\alpha_6) + (1+\alpha_2)N_{ij}^{\rm NIN}(\alpha_6) + (1+\alpha_3)N_{ij}^{\rm SSB}\,.$$

- $\sigma_0 = 11\%$ efficiency + flux
- $\sigma_1 = 25\%$ BRN
- $\sigma_2 = 35\%$ NIN
- $\sigma_3 = 2.1\%$ SSB
- $\sigma_4 = 5\%$ nuclear radius $R_A = 1.23A^{1/3}(1+\alpha_4)$
- $\sigma_5 = 3.8\%$ QF
- α_6 beam timing no prior
- α_7 CEvNS efficiency

LAr statistical analysis

$$\chi^2_{\mathrm{LAr}} = \sum_{i=1}^{12}\sum_{j=1}^{10}\left(\frac{N_{ij}^{\mathrm{th}} - N_{ij}^{\mathrm{exp}}}{\sigma_{ij}}\right)^2 + \sum_{k=0,3,4,8}\left(\frac{\beta_k}{\sigma_k}\right)^2 + \sum_{k=1,2,5,6,7}(\beta_k)^2 \,,$$

$$N_{ij}^{\mathrm{th}} = \left(1 + \beta_0 + \beta_1\Delta_{\mathrm{CE\nu NS}}^{F_{90+}} + \beta_1\Delta_{\mathrm{CE\nu NS}}^{F_{90-}} + \beta_2\Delta_{\mathrm{CE\nu NS}}^{t_{\mathrm{trig}}}\right)N_{ij}^{\mathrm{CE\nu NS}} + (1+\beta_3)\,N_{ij}^{\mathrm{SSB}} + (1+\beta_8)\,N_{ij}^{\mathrm{dBRN}} + \left(1 + \beta_4 + \beta_5\Delta_{\mathrm{pBRN}}^{E_+} + \beta_5\Delta_{\mathrm{pBRN}}^{E_-} + \beta_6\Delta_{\mathrm{pBRN}}^{t_{\mathrm{trig}}^{+}} + \beta_6\Delta_{\mathrm{pBRN}}^{t_{\mathrm{trig}}^{-}} + \beta_7\Delta_{\mathrm{pBRN}}^{t_{\mathrm{trig}}^{\mathrm{w}}}\right)N_{ij}^{\mathrm{pBRN}} \,.$$

Normalization uncertainties:

- $\sigma_0 = 13\%$ CEvNS
- $\sigma_3 = 0.79\%$ SS
- $\sigma_4 = 32\%$ prompt BRN
- $\sigma_8 = 100\%$ delayed BRN

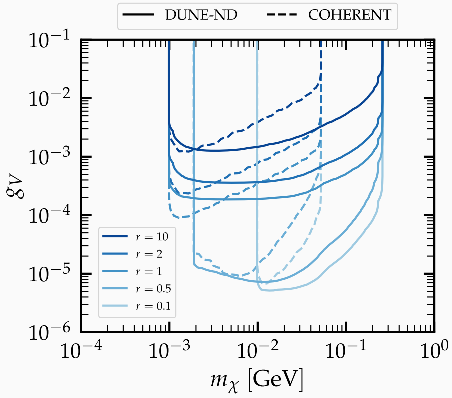
Shape uncertainties:

- β_1 and β_2 CEvNS
- β_5, β_6 and β_7 prompt BRN

Possible decay channels

Tree-level decays:

- If $m_\chi > m_V$, then $m_\chi \to V\nu_\ell$
- If $m_\chi < m_V$, then $m_\chi \to \nu_\ell f\bar{f}$



PMC et al. *JHEP* **10** (2024) 032