IFIC INSTITUT DE FÍSICA CORPUSCULAR
CSIC
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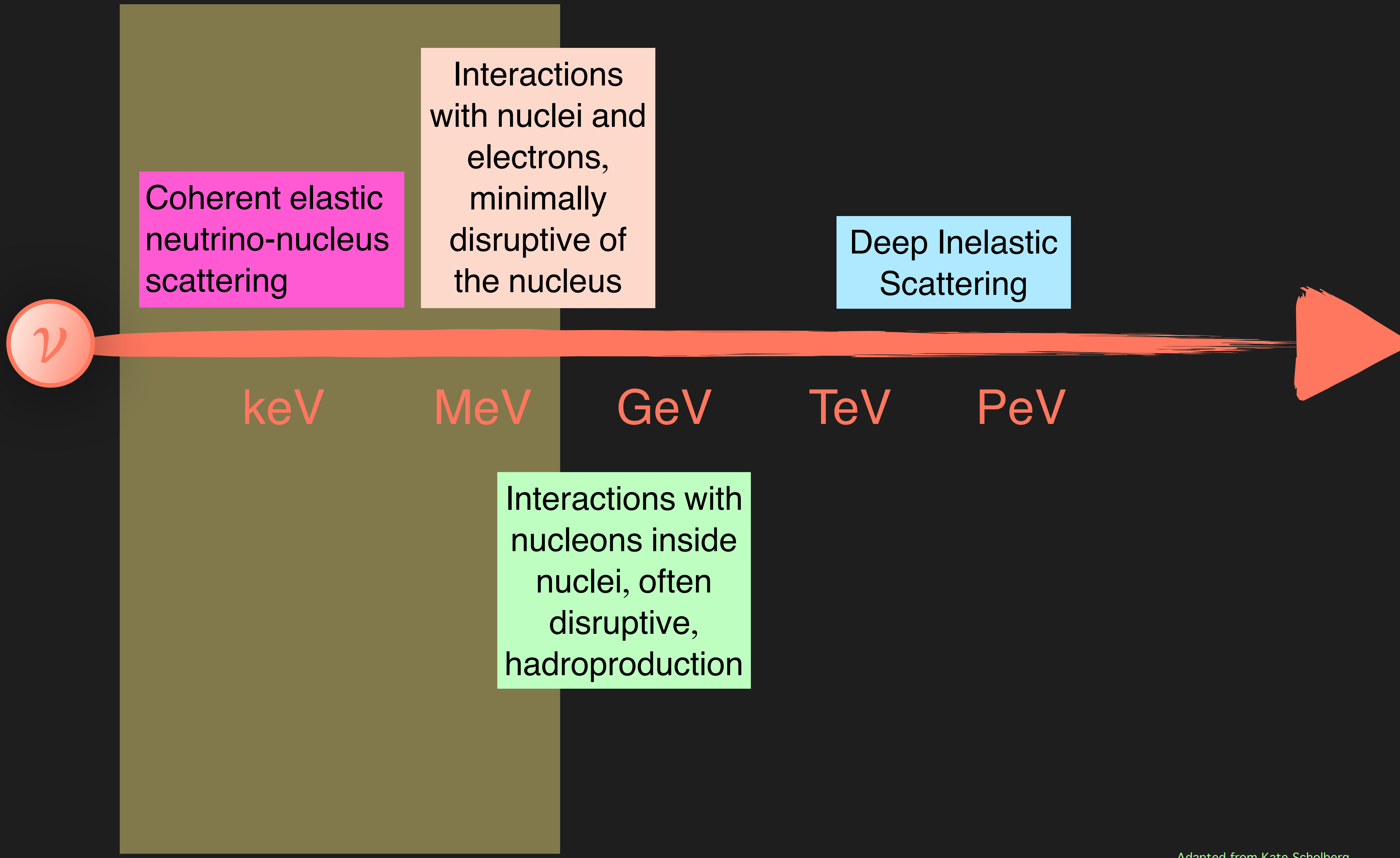
ASTROPARTICLES Astroparticles and High Energy Physics Group
VNIVERSITAT DE VALÈNCIA
EXCELENCIA SEVERO OCHOA
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
Financiado por la Unión Europea NextGenerationEU
Plan de Recuperación, Transformación y Resiliencia
AGENCIA ESTATAL DE INVESTIGACIÓN

Valentina De Romeri
(IFIC Valencia - UV/CSIC)

NEW PHYSICS SEARCHES WITH COHERENT ELASTIC NEUTRINO-NUCLEUS SCATTERING

PASCOS 2025
Durham, UK
24 July 2025

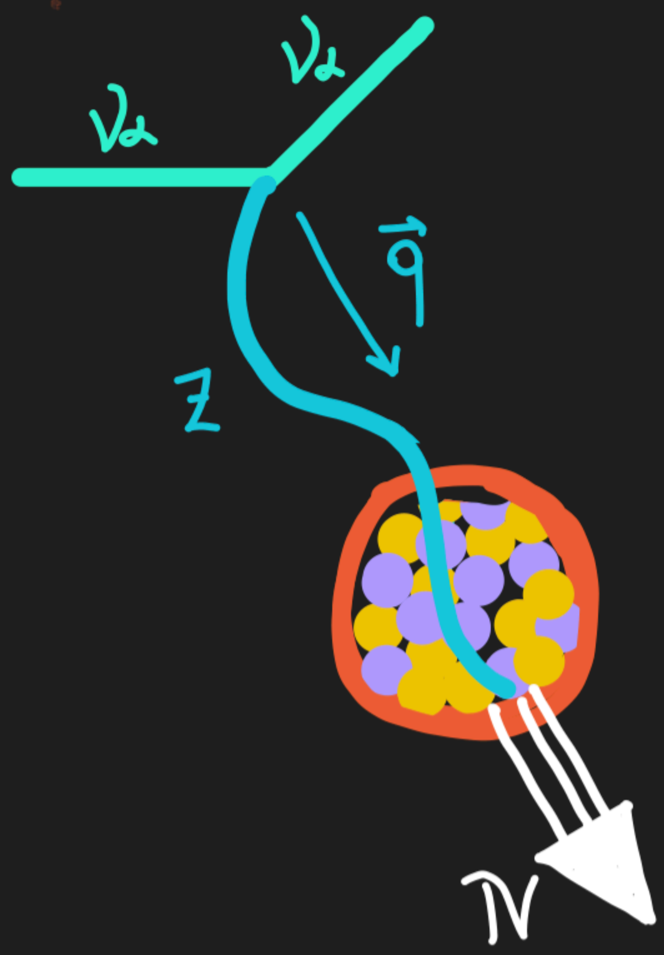
NEUTRINO INTERACTIONS WITH NUCLEI



Adapted from Kate Scholberg

COHERENT ELASTIC νEUTRINO-NUCLEUS SCATTERING (CEνNS)

Neutral-current process: $\nu + N(A,Z) \rightarrow \nu + N(A,Z)$



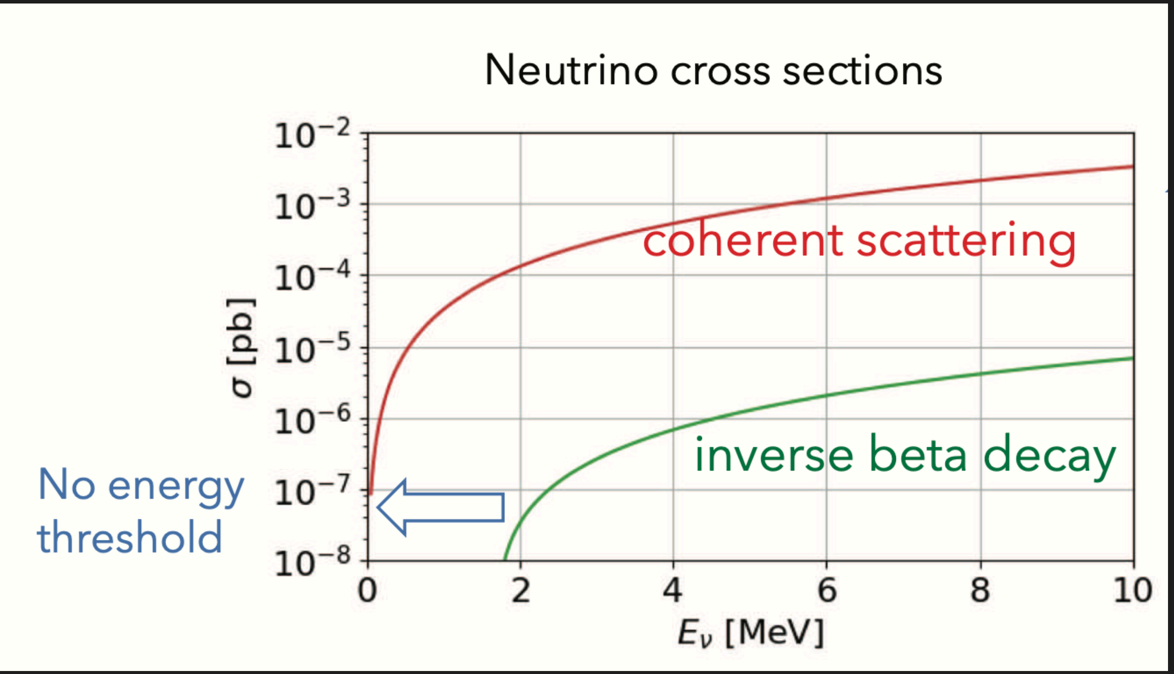
- The neutrino sees the nucleus as a whole
- CEνNS occurs when:
  - Wavelength of the mediator > nuclear radius

  or
  - $|\vec{q}| \lesssim 1/R_{nucleus}$

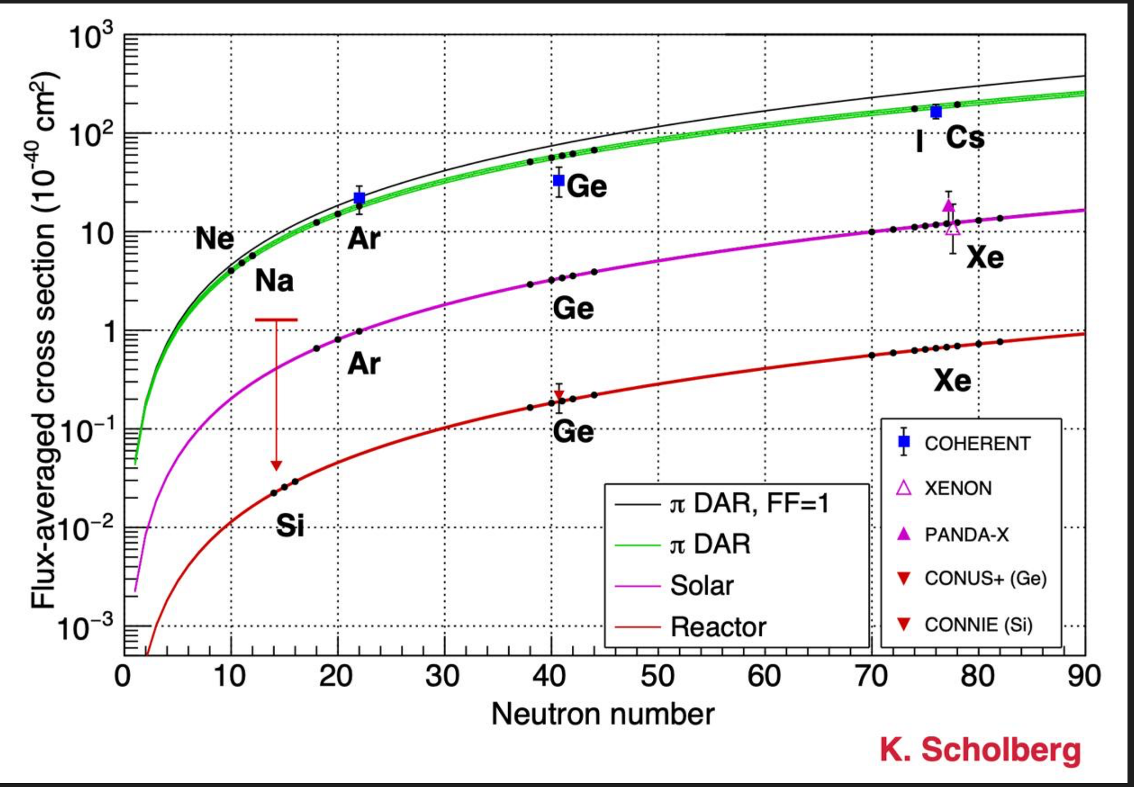
- Coherent: target nucleon wave functions remain in phase with each other before and after the collision. Amplitudes of scattering on individual nucleons add.
- Elastic: no new particles are created and nuclear target remains in the same energy state.

COHERENT ELASTIC νEUTRINO-NUCLEUS SCATTERING (CEνNS)

- Total cross section scales approximately like N^2 $$\frac{d\sigma}{dE_R} \propto N^2$$
- CEvNS cross section is large!
- Despite its large cross section, not observed for years due to tiny nuclear recoil energies.



Credit: R. Strauss @ Magnificent CEvNS



AN ACT OF HUBRIS

First theoretically predicted in 1974

D.Z. Freedman, Phys. Rev. D 9 (1974)
V.B. Kopeliovich and L.L. Frankfurt, JETP Lett. 19 4 236 (1974)

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)

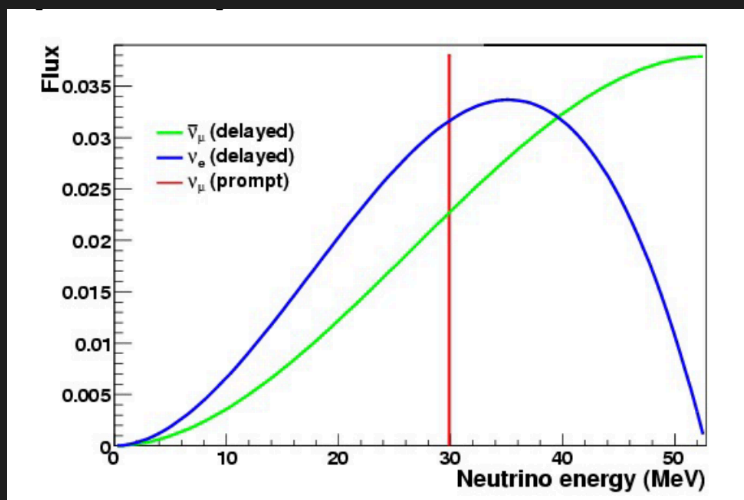
If there is a weak neutral current, then the elastic scattering process $\nu + A \to \nu + A$ should have a sharp coherent forward peak just as $e + A \to e + A$ does. Experiments to observe this peak can give important information on the isospin structure of the neutral current. The experiments are 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.

Our suggestion may be an act of hubris, because the inevitable constraints of interaction rate, resolution, and background pose grave experimental difficulties for elastic neutrino-nucleus scattering. We will discuss these problems at the end of this note, but first we wish to present the theoretical ideas relevant to the experiments.

Experimentally the most conspicuous and most difficult feature of our process is that the only detectable reaction product is a recoil nucleus of low momentum. Ideally the apparatus should have sufficient resolution to identify and determine the momentum of the recoil nucleus and sufficient mass to achieve a reasonable interaction rate. Neutron background is a serious problem

CEνNS was observed for the first time ~40 years later,
in 2017 by the COHERENT experiment at the Oak Ridge Spallation Neutron Source.

LOW-ENERGY NEUTRINO SOURCES



D. Akimov et al. (COHERENT). 2110.07730

ARTIFICIAL SOURCES

Stopped pions (Decay at rest)

Reactors

Radioactive source ^{51}Cr

Beam induced radioactive sources (IsoDAR)

Next-generation neutrino beams

NATURAL SOURCES

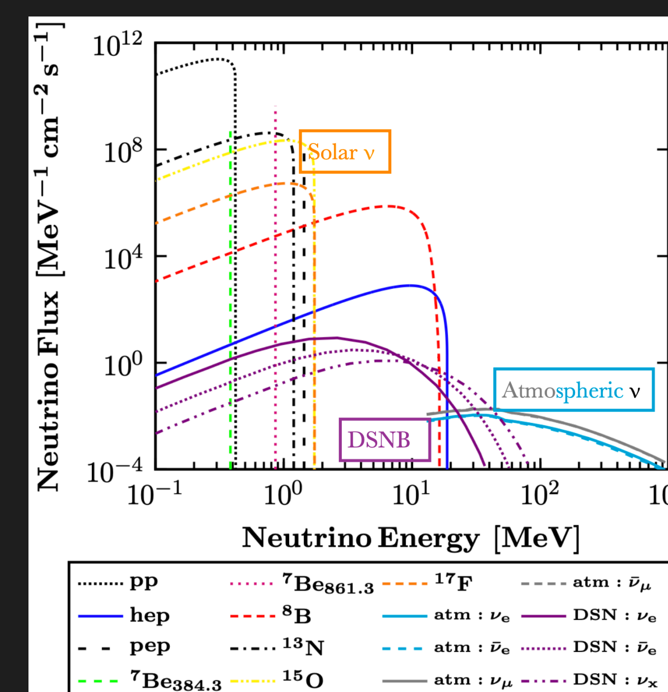
Geoneutrinos

DSNB

Atmospheric neutrinos

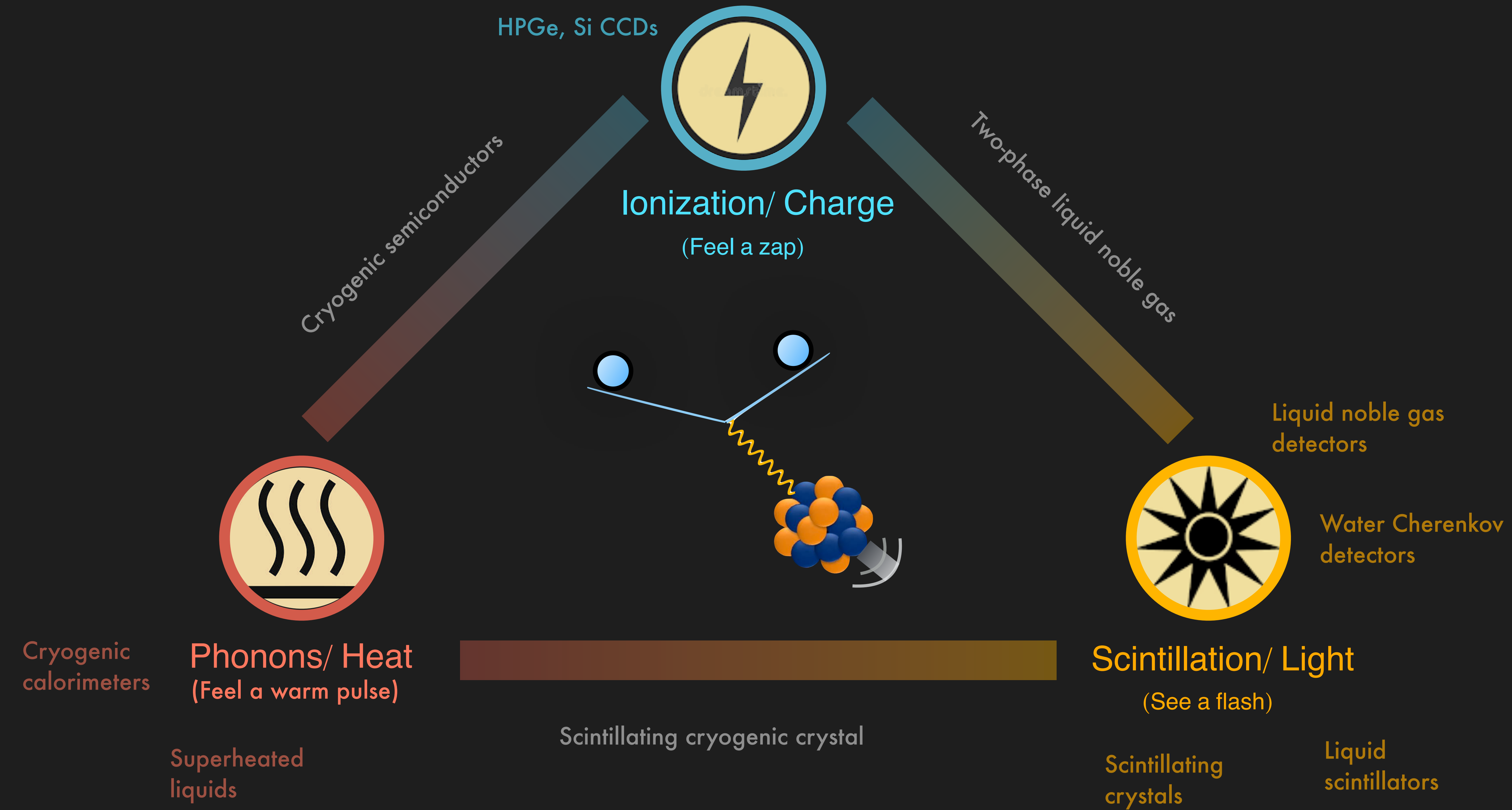
Supernova bursts neutrinos

Solar neutrinos



Aristizabal, VDR, Flores, Papoulias JCAP 01 (2022) 01, 055

LOW-ENERGY NUCLEAR RECOIL DETECTION STRATEGIES



Adapted from V. Wagner M7s school 2023

CEvNS EXPERIMENTS WORLDWIDE

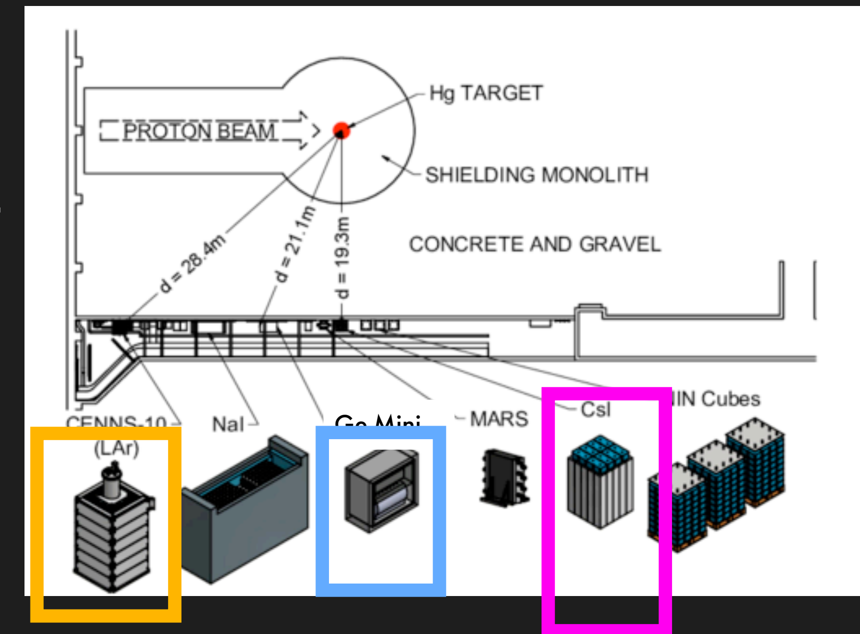
Updated from I. Nasteva @NEUTRINO 2024

LIST OF CEvNS OBSERVATIONS

Stopped pions
(Decay at rest)

- 2017(->2021): COHERENT-CsI[Na], 11.6σ CL
- 2020: COHERENT-LAr, 3.9σ CL
- 2024: COHERENT-Ge, 3.9σ CL

D. Akimov et al. (COHERENT) Science 357, 1123–1126 (2017)
D. Akimov et al. (COHERENT) Phys. Rev. Lett. 129, 081801
D. Akimov et al. (COHERENT) Phys. Rev. Lett. 126, 012002 (2021)
S. Adamski et al. (COHERENT) Phys. Rev. Lett. **134**, 231801 (2025)



24 kg
10 kg
14 kg

LIST OF CEνNS OBSERVATIONS

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D. Akimov et al. (COHERENT) Phys. Rev. Lett. 126, 012002 (2021)
S. Adamski et al. (COHERENT) Phys. Rev. Lett. **134**, 231801 (2025)

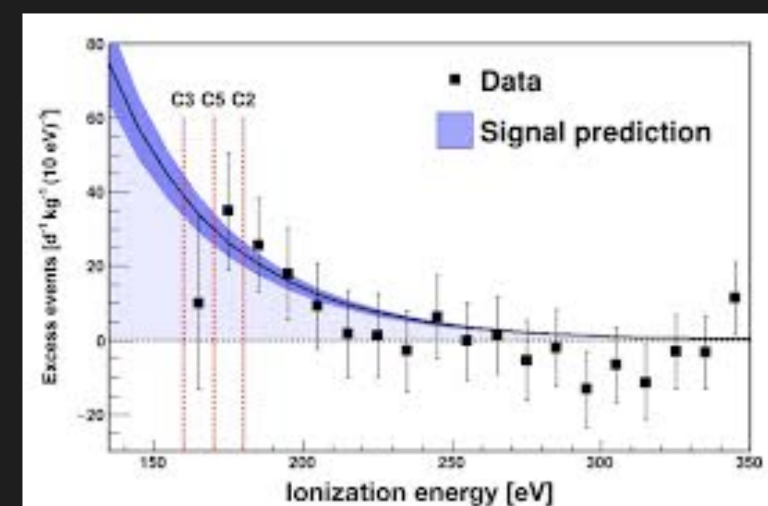
Reactors

- 2022: Dresden-II, Ge

Colaresi, Collar et al. Phys. Rev. Lett. 129 (2022) 211802

- 2025: CONUS+, Ge, 3.7σ CL

Ackermann+ 2501.05206



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D. Akimov et al. (COHERENT) Phys. Rev. Lett. 129, 081801
D. Akimov et al. (COHERENT) Phys. Rev. Lett. 126, 012002 (2021)
S. Adamski et al. (COHERENT) Phys. Rev. Lett. **134**, 231801 (2025)

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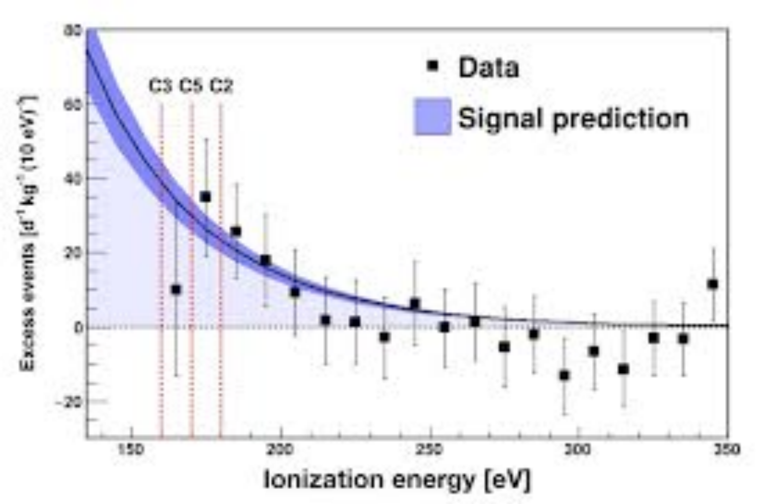
- 2022: Dresden-II, Ge

Colaresi, Collar et al. Phys. Rev. Lett. 129 (2022) 211802

- 2025: CONUS+, Ge, 3.7σ CL

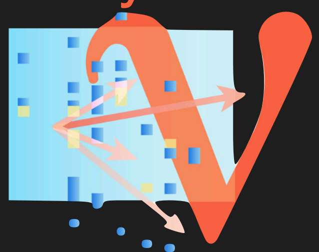
Ackermann+ 2501.05206

Quenching factor dependence!



LIST OF CEνNS OBSERVATIONS

Stopped pions (Decay at rest)



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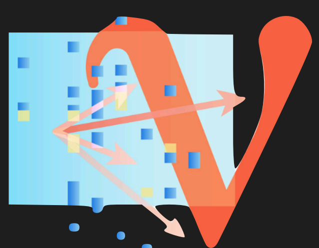
Reactors



- 2022: Dresden-II, Ge

Colaresi, Collar et al. Phys. Rev. Lett. 129 (2022) 211802

- 2025: CONUS+, Ge, 3.7σ CL

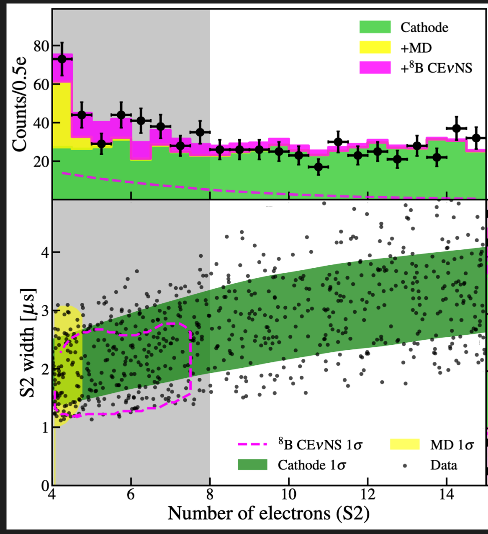
Ackermann+ 2501.05206

^{8}B Solar neutrinos

- 2024: XENONnT-Xe, 2.73σ CL
- 2024: PandaX-4T-Xe, 2.64σ CL

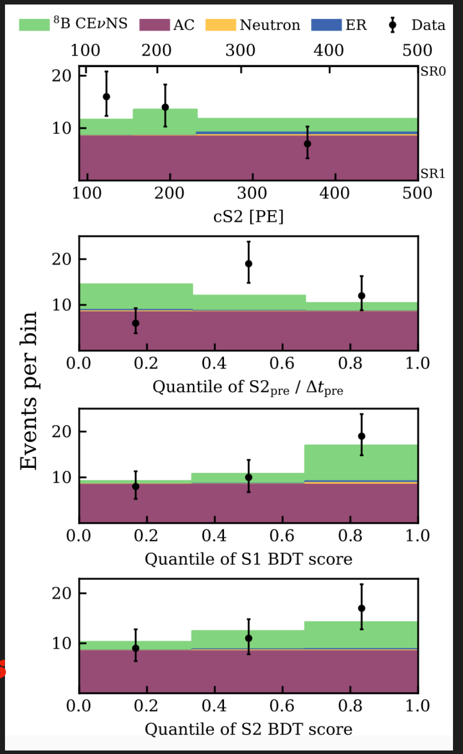
E. Aprile et al. (XENONnT) PRL 133, 191002 (2024)
Z. Bo et al. (PandaX) PRL **133**, 191001

PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC



XENON

LXe: 2024
3.5 ton years
2.7σ
37 events



CEνNS CROSS SECTION IN THE SM

CEνNS cross-section in the SM:

(probability of kicking a nucleus with nuclear recoil energy T)

Fermi constant (SM parameter)

Kinematics

Nuclear Form Factor: F=1 full coherence

$$\frac{d\sigma}{dT_{\mathcal{N}}} = \frac{G_F^2 m_{\mathcal{N}}}{4\pi}\left(1 - \frac{m_{\mathcal{N}} T_{\mathcal{N}}}{2E_\nu^2} - \frac{T_{\mathcal{N}}}{E_\nu}\right) Q_W^2 F_W^2(|\mathbf{q}|^2) + \frac{G_F^2 m_{\mathcal{N}}}{4\pi}\left(1 + \frac{m_{\mathcal{N}} T_{\mathcal{N}}}{2E_\nu^2} - \frac{T_{\mathcal{N}}}{E_\nu}\right) F_A(|\mathbf{q}|^2)$$

Weak nuclear charge

$$Q_{\mathrm{W}} = [Z(1 - 4\sin^2\theta_{\mathrm{W}}) - N]$$

$s_W^2 = 0.23$ → protons unimportant

Neutron contribution dominates

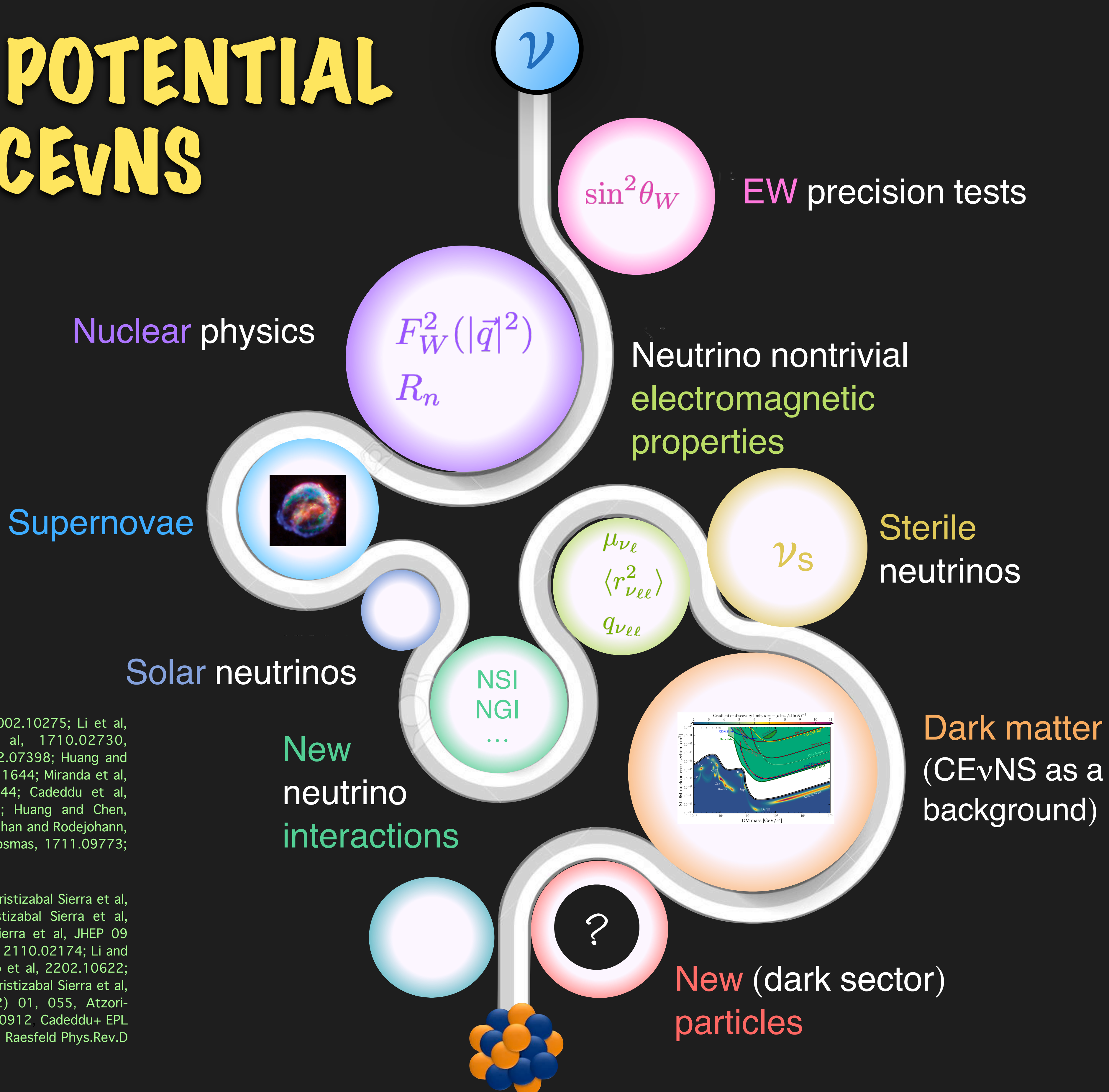
- E_ν: is the incident neutrino energy
- M : the nuclear mass of the detector material
- 3-momentum transfer $|\vec{q}|^2 = 2MT$
- (Q_A included in F_A)

Axial contribution is small for most nuclei, spin-dependent.

It vanishes for nuclei with even number of protons and neutrons

Freedman, PRD 9 (1974) 1389; Drukier, Stodolsky, PRD 30 (1984) 2295; Barranco, Miranda, Rashba, hep-ph/0508299

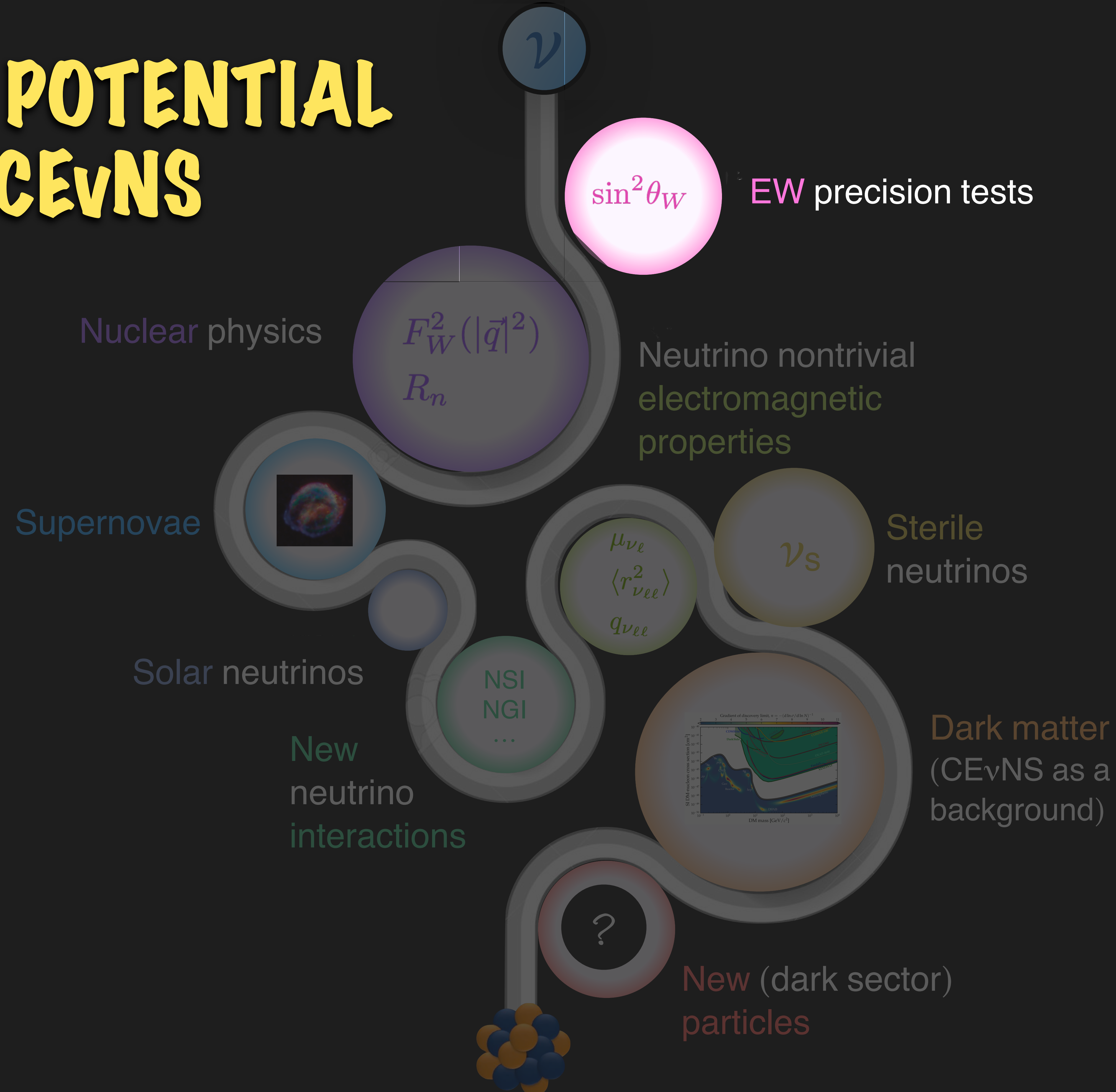
PHYSICS POTENTIAL OF CEνNS



Brdar and Rodejohann, 1810.03626; Chang and Liao, 2002.10275; Li et al, 2005.01543; CONUS, 2110.02174; Cadeddu et al, 1710.02730, 2005.01645, 1908.06045; Aristizabal Sierra et al, 1902.07398; Huang and Chen, 1902.07625; Papoulias et al, 1903.03722, 1907.11644; Miranda et al, 2003.12050; Papoulias et al, 1711.09773, 1907.11644; Cadeddu et al, 1808.10202, 2005.01645, 1908.06045, 2205.09484; Huang and Chen, 1902.07625; Miranda et al, 1902.09036, 2003.12050; Khan and Rodejohann, 1907.12444; COHERENT, 2110.07730; Papoulias and Kosmas, 1711.09773; Blanco et al, 1901.08094; Miranda et al, 1902.09036

Cerdeño et al, 1604.01025; Farzan et al, 1802.05171; Aristizabal Sierra et al, 1806.07424; Khan and Rodejohann, 1907.12444; Aristizabal Sierra et al, 1910.12437; Miranda et al, 2003.12050; Aristizabal Sierra et al, JHEP 09 (2019) 069; Suliga and Tamborra, 2010.14545; CONUS, 2110.02174; Li and Xia, 2201.05015; Atzori Corona et al, 2202.11002; Liao et al, 2202.10622; Coloma et al, 2202.10829; Lindner et al, 1612.04150; Aristizabal Sierra et al, 1806.07424; Aristizabal Sierra et al, JCAP 01 (2022) 01, 055, Atzori-Corona+ Eur.Phys.J.C 83 (2023) 7, 683, Behera+ 2304.00912, Cadeddu+ EPL 143 (2023) 3, 34001, Atzori-Corona+ 2307.12911, Von Raesfeld Phys.Rev.D 105 (2022) 5, 056002, Bresó-Pla JHEP05(2023)074
…………

PHYSICS POTENTIAL OF CEνNS



STANDARD MODEL PHYSICS

$$\left.\frac{d\sigma_{\nu\mathcal{N}}}{dE_{\rm nr}}\right|^{\rm SM}_{\rm CE\nu NS} = \frac{G_F^2 m_N}{\pi} F_W^2(\mathbf{q}^2) Q_{\rm w}^2 \left(1 - \frac{m_N E_{\rm nr}}{2E_\nu^2} - \frac{E_{\rm nr}}{E_\nu} + \frac{E_{\rm nr}^2}{2E_\nu^2}\right)$$

$$Q_{\rm W} = -N/2 + (1/2 - 2\sin^2\theta_{\rm w})Z$$

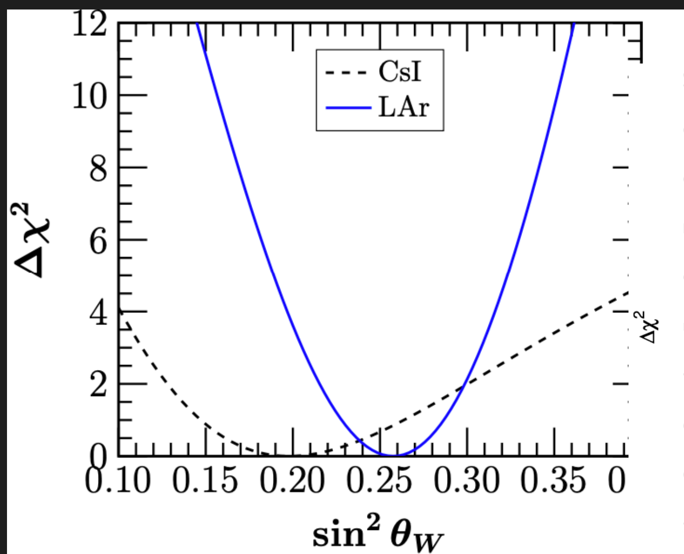
$s_W^2 = 0.23$ → protons unimportant
Neutron contribution dominates

Information on the value of the neutrino neutral-current interaction at low energy:

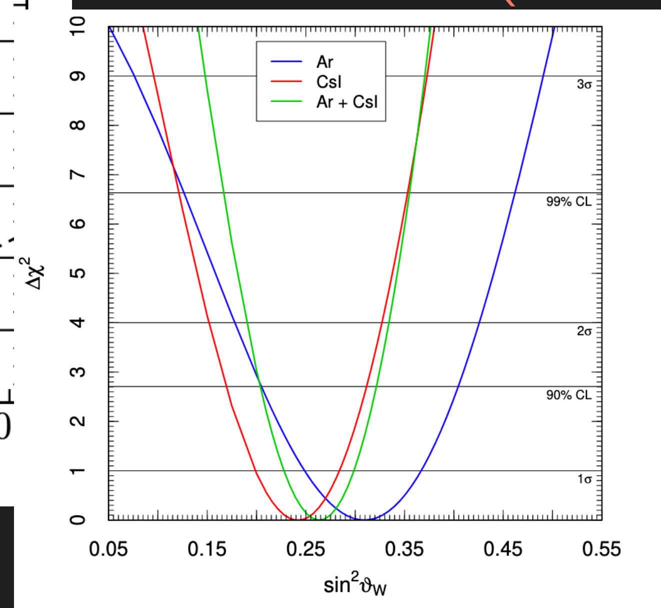
- Observable: $\sin^2\theta_w$
- poorly measured at low energies
- Affects the normalization of CEvNS spectra

EW PRECISION TESTS: WEAK MIXING ANGLE

COHERENT CsI (2017) + LAr (2020)

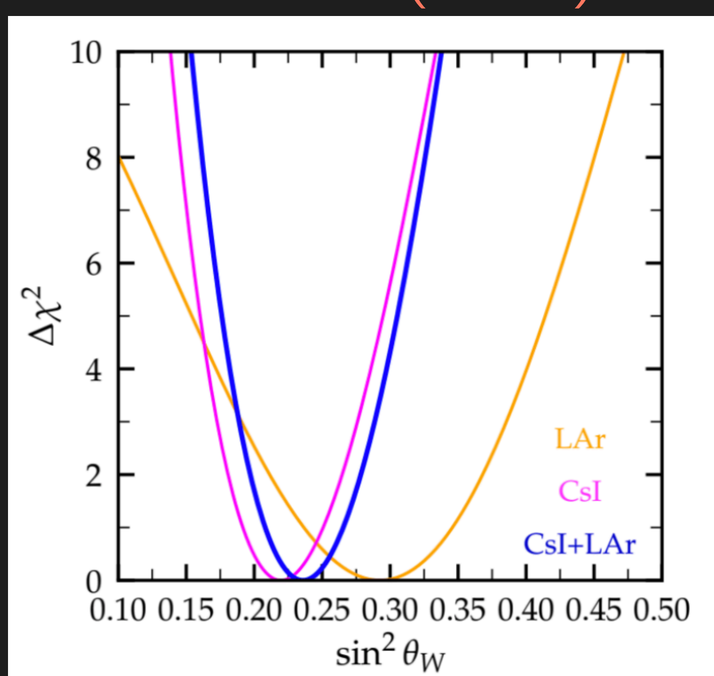


Miranda et al. JHEP 05 (2020) 130



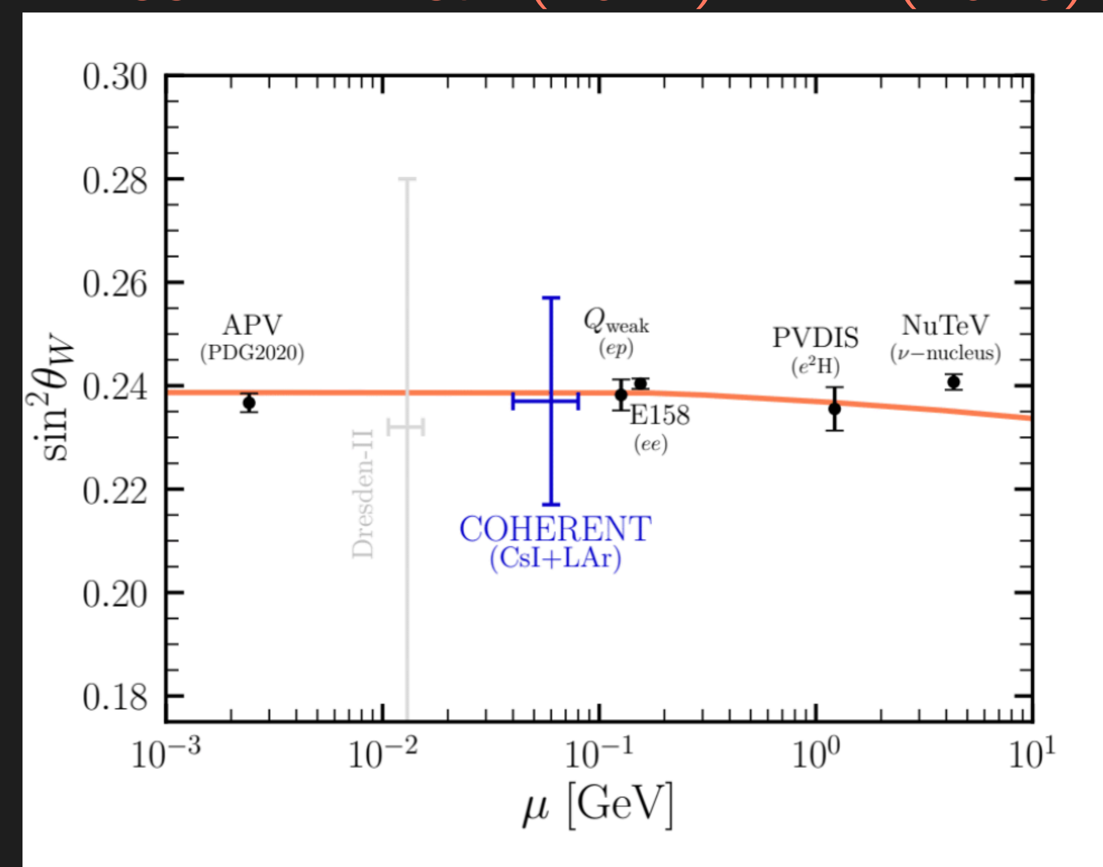
Cadeddu et al. Phys. Rev. D 102, 015030 (2020)

COHERENT CsI (2021) + LAr (2020)



VDR, Miranda, Papoulias+ JHEP 04 (2023) 035

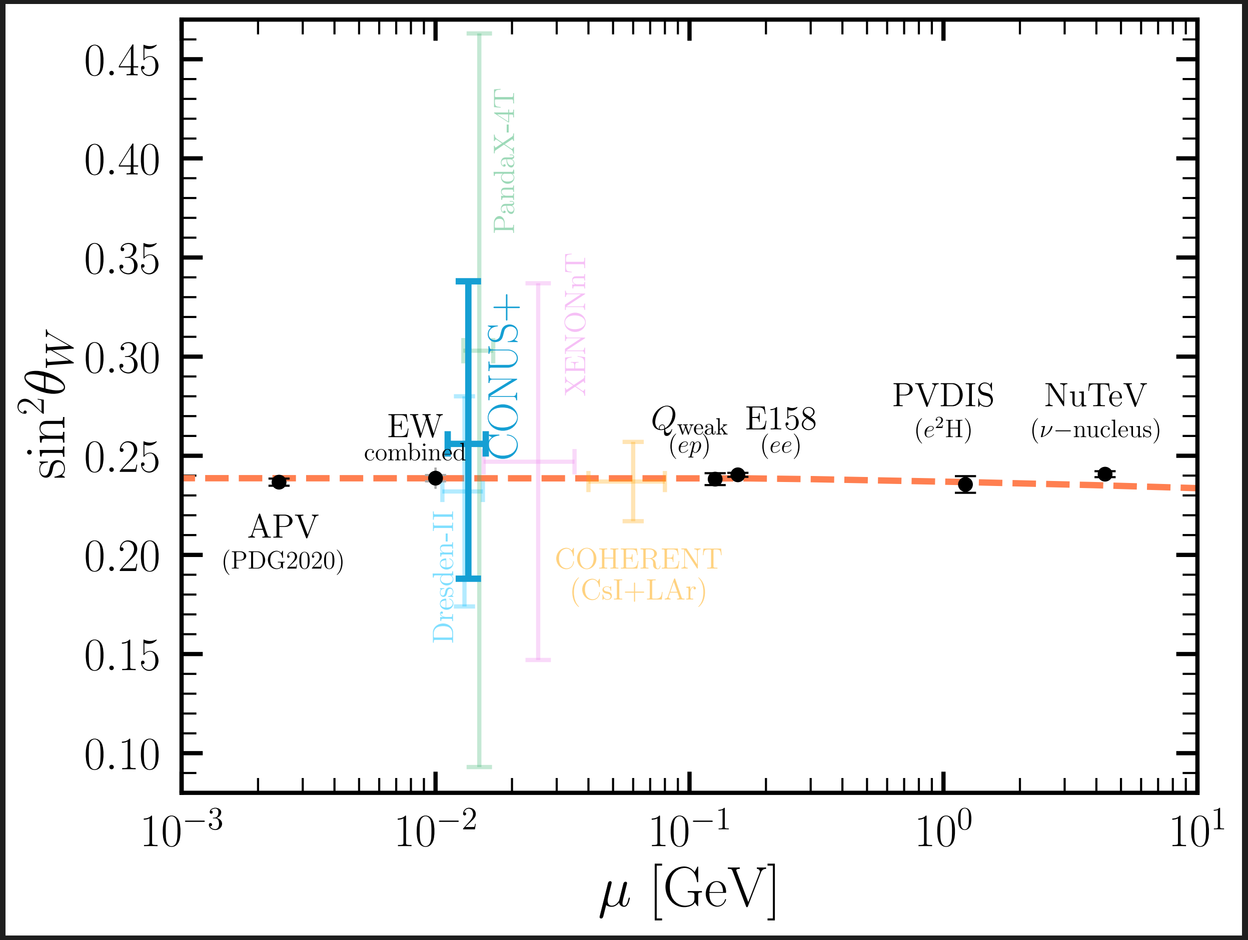
COHERENT CsI (2021) + LAr (2020)



VDR, Miranda, Papoulias+ JHEP 04 (2023) 035
See also Cadeddu et al. ’20,’21,’22,’23,’24
(Also combination with APV data)

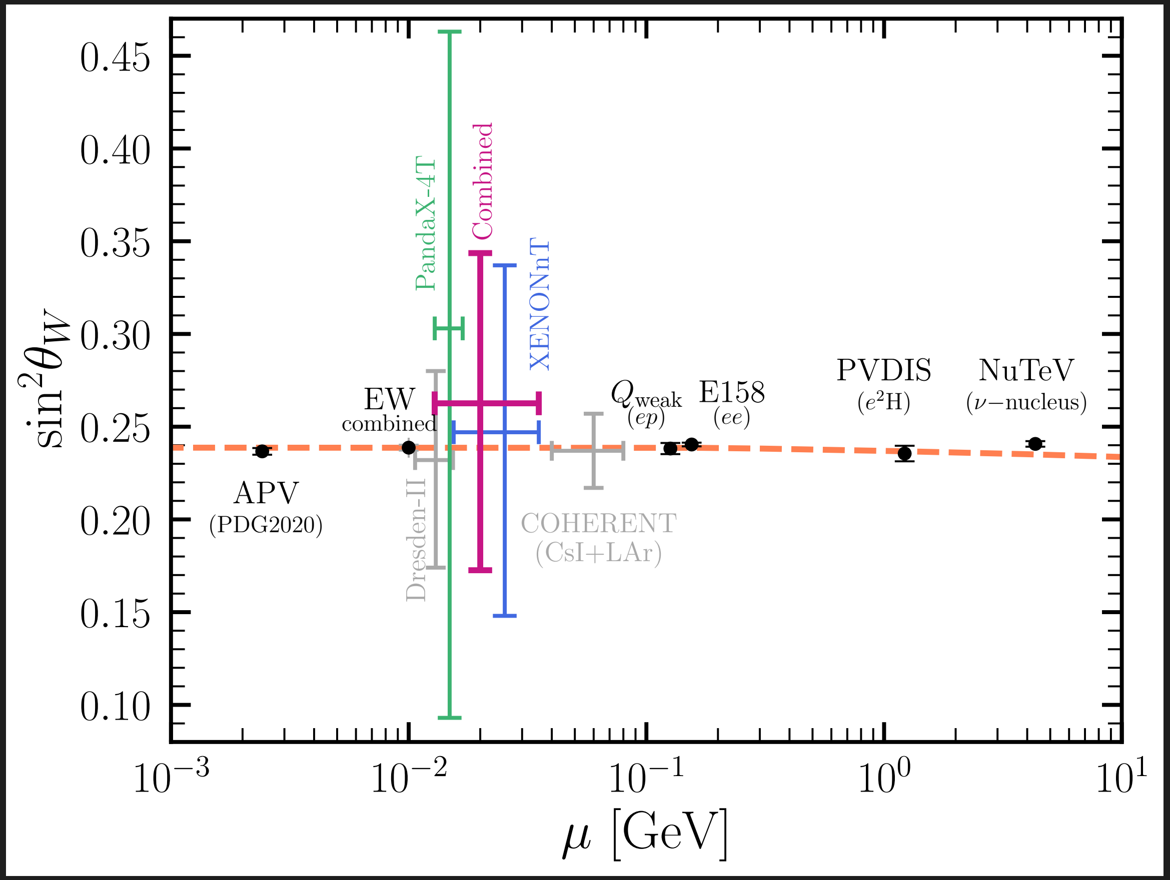
EW PRECISION TESTS: WEAK MIXING ANGLE

CONUS+ (2025)



VDR, Papoulias, Sanchez Garcia PRD 111, 075025 (2025)

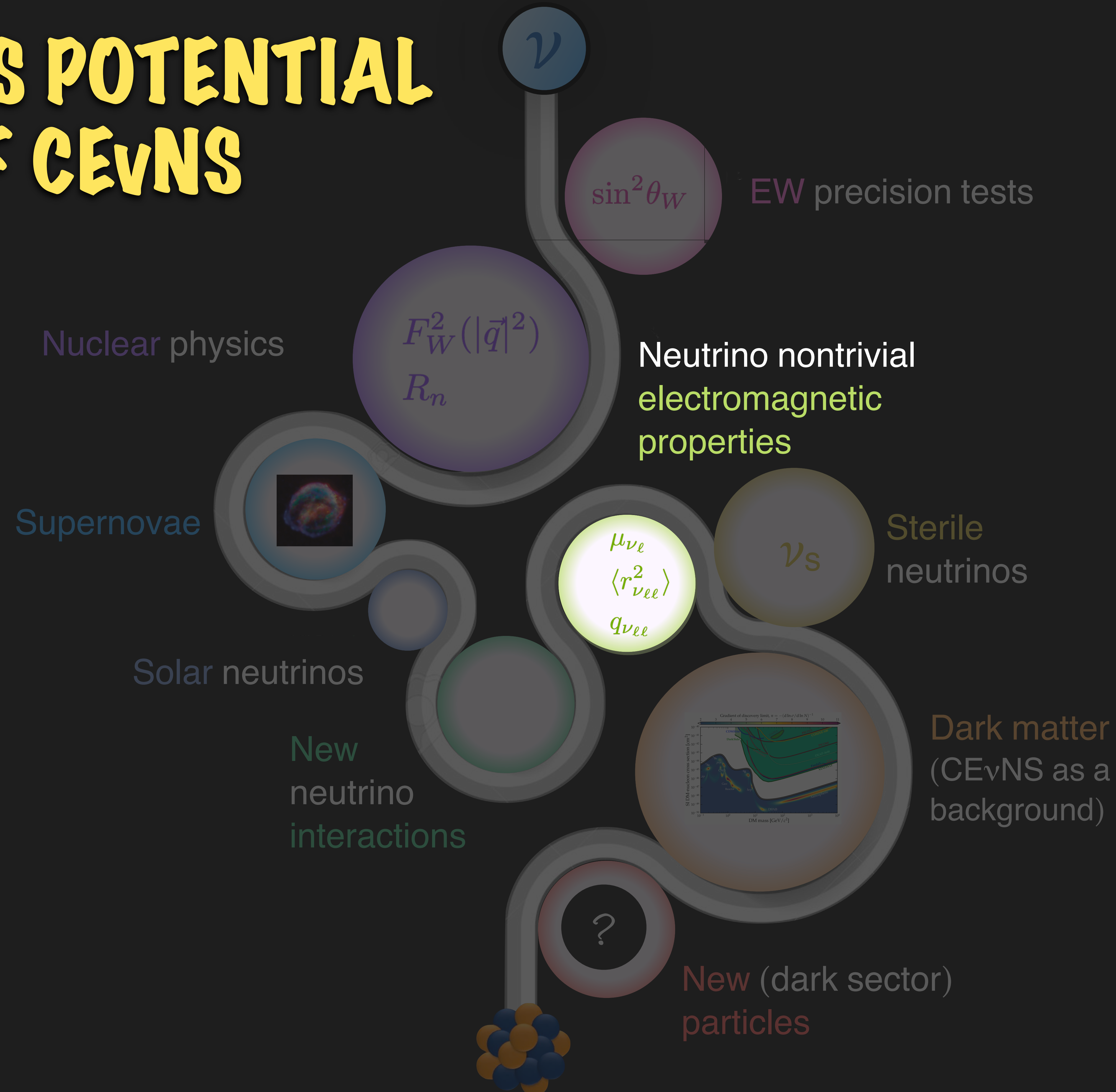
PandaX-4T (2024), XENONnT (2024)



Aristizabal, VDR, Papoulias JHEP 09 (2022) 076
Majumdar+ Phys.Rev.D 106 (2022) 9, 093010
Boehm, Maity arXiv:2409.0438
VDR, Papoulias, Ternes JCAP 05 (2025) 012

See also Alpízar-Vanegas+ 2501.10355, Chattaraj+ 2501.12441

PHYSICS POTENTIAL OF CEνNS



NEUTRINO MAGNETIC MOMENT

Predicted to be zero for massless neutrinos. It can arise in BSM extensions for massive neutrinos. Neutrino magnetic moment interactions flip chirality and do not interfere with the SM terms.

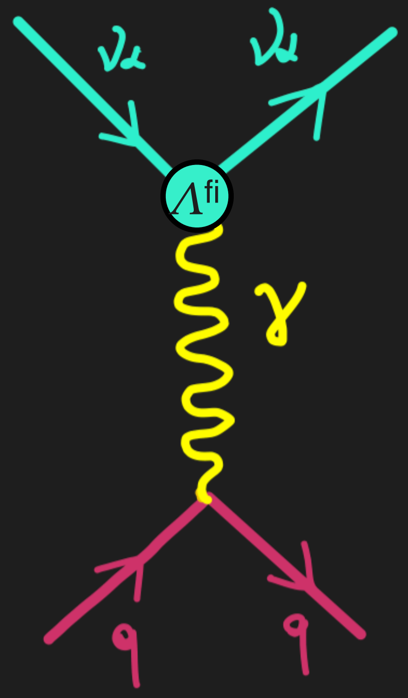
$$\frac{d\sigma_{\nu_\ell \mathcal{N}}}{dE_{\rm nr}}\Bigg|^{\rm MM}_{{\rm CE}\nu{\rm NS}} = \frac{\pi \alpha^2_{\rm EM}}{m_e^2}\left(\frac{1}{E_{\rm nr}} - \frac{1}{E_\nu}\right) Z^2 F_W^2(|\vec{q}|^2)\left|\frac{\mu_{\nu_\ell}}{\mu_{\rm B}}\right|^2$$

Vogel, Engel. PRD 39 [1989] 3378

Careful with comparisons!

$\mu_\nu{}^2$ is an effective neutrino magnetic moment dependent on a given neutrino beam.

- can be dominant for sub-keV threshold experiments
- may lead to detectable distortions of the recoil spectrum



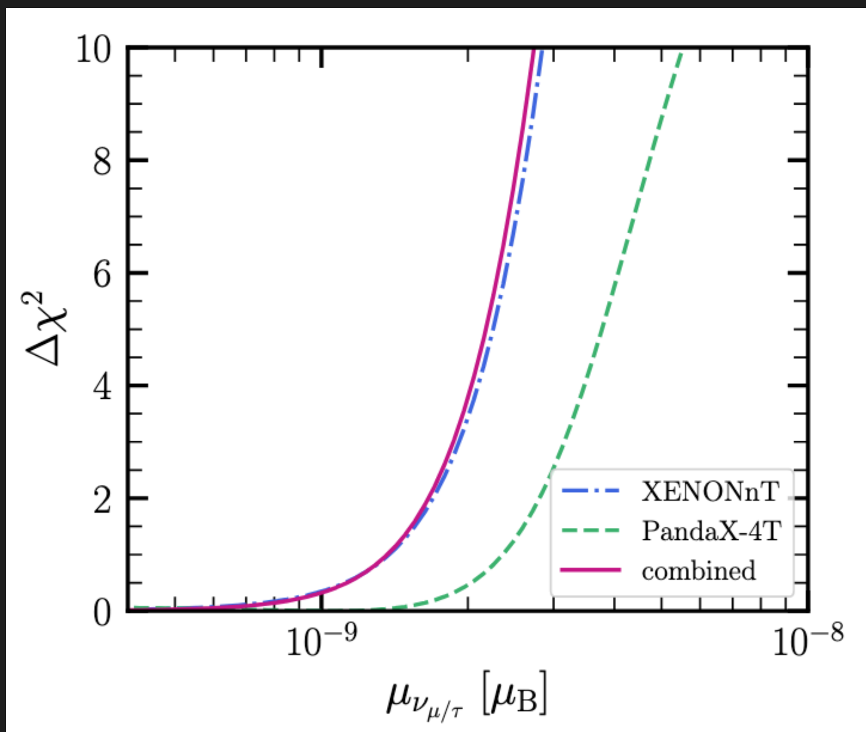
Schechter Valle, PhysRevD.24.1883
Canas+ Phys.Lett. B753 (2016) 191–198
Miranda+ JHEP 1907 (2019) 103,

Aristizabal-Sierra+ Phys.Rev.D 105 (2022) 035027
Ternes, Tortola, 2505.02633

C. Giunti, A. Studenikin, Rev Mod Phys, 87, 531 (2015)

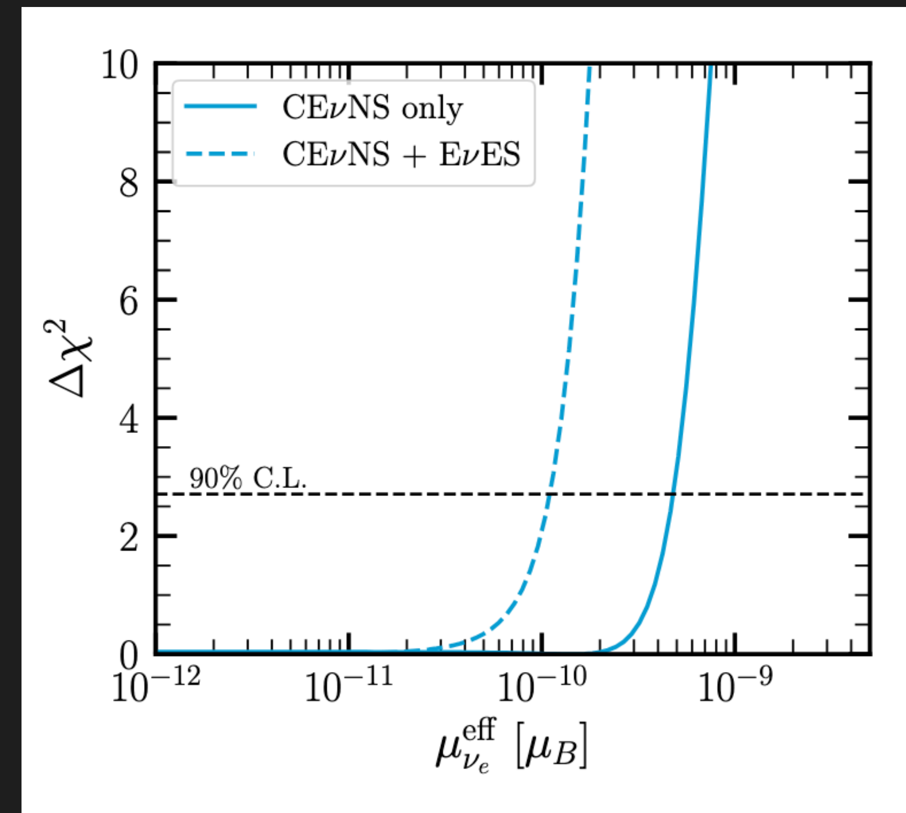
NEUTRINO MAGNETIC MOMENT

CEvNS data at PandaX-4T (2024), XENONnT (2024)



VDR, Papoulias, Sanchez Garcia, Ternes, Tortola *JCAP* 05 (2025) 080

CONUS+ (2025)



VDR, Papoulias, Sanchez Garcia PRD 111, 075025 (2025)

Experiment	$\mu^{\rm eff}_{\nu_e}$ (10^{-11} μ_B)	**Process**	**Reference**
CONUS+	≤ 11	CEνNS+EνES	this work
COHERENT (CsI+LAr)	≤ 360	CEνNS+EνES	[89]
DRESDEN-II	≤ 19	CEνNS+EνES	[35]
XENONnT + PandaX-4T (combined)	≤ 190	CEνNS	[20]
CONUS	≤ 7.5	EνES	[42]
Borexino	≤ 3.7	EνES	[96]
TEXONO	≤ 7.4	EνES	[97]
GEMMA	≤ 2.9	EνES	[98]
LZ	≤ 1.4	EνES	[99]
XENONnT	≤ 0.9	EνES	[99]
XENONnT+PandaX-4T+LZ (combined)	≤ 1.03	EνES	[100]

VDR, Papoulias, Sanchez Garcia PRD 111, 075025 (2025)

VDR, Papoulias, Sanchez Garcia, Ternes, Tortola *JCAP* 05 (2025) 080

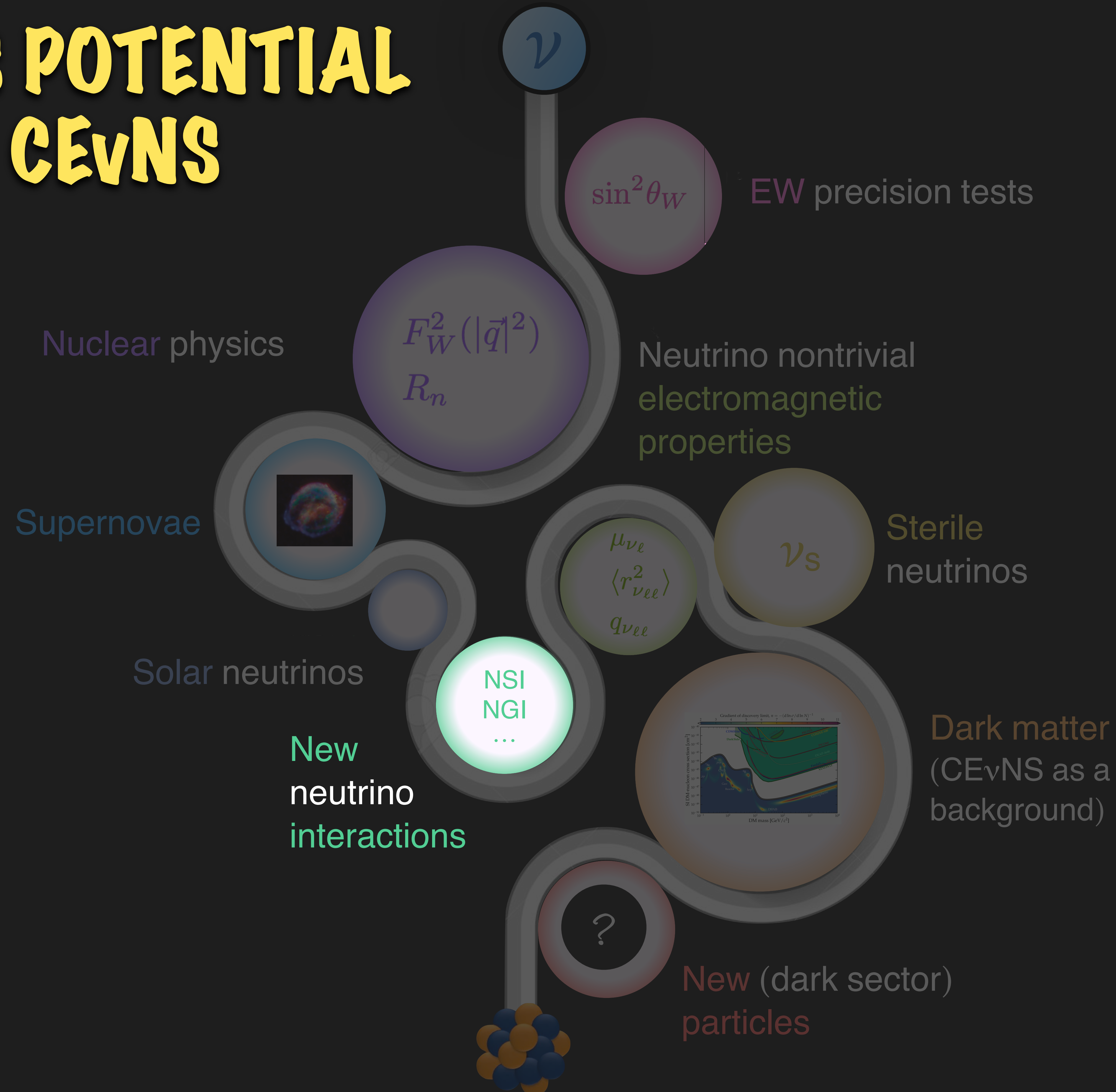
New best limits using solar EνES in LZ and XENONnT

XENONnT Collab. PRL 129, 161805 (2022)

Giunti, Ternes, PRD 108 (2023) 9, 095044

See also: Atzori-Corona+ PRD 107 (2023) 5, 053001; ShivaSankar K. A.+, *Phys.Lett.B* 839 (2023) 137742; Khan, Phys. Lett. B 837 (2023) 137650 and Phys. Lett. B 839 (2023) 137742

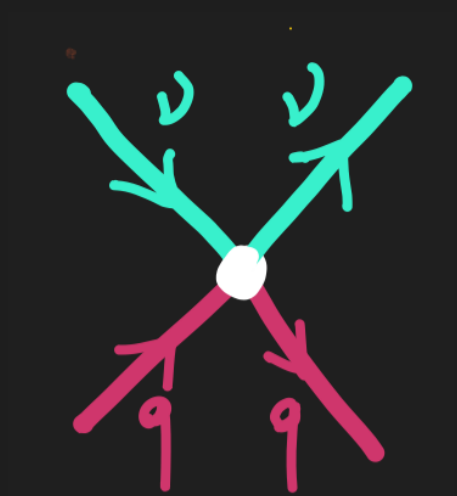
PHYSICS POTENTIAL OF CEνNS



NEW NEUTRINO INTERACTIONS: NSI

Neutrino NSI can be formulated in terms of the effective (dimension-6) four-fermion Lagrangian:

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



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

The NSI couplings quantify the relative strength of the NSI in terms of G_F and can be either flavour preserving (non-universal) or flavor changing.

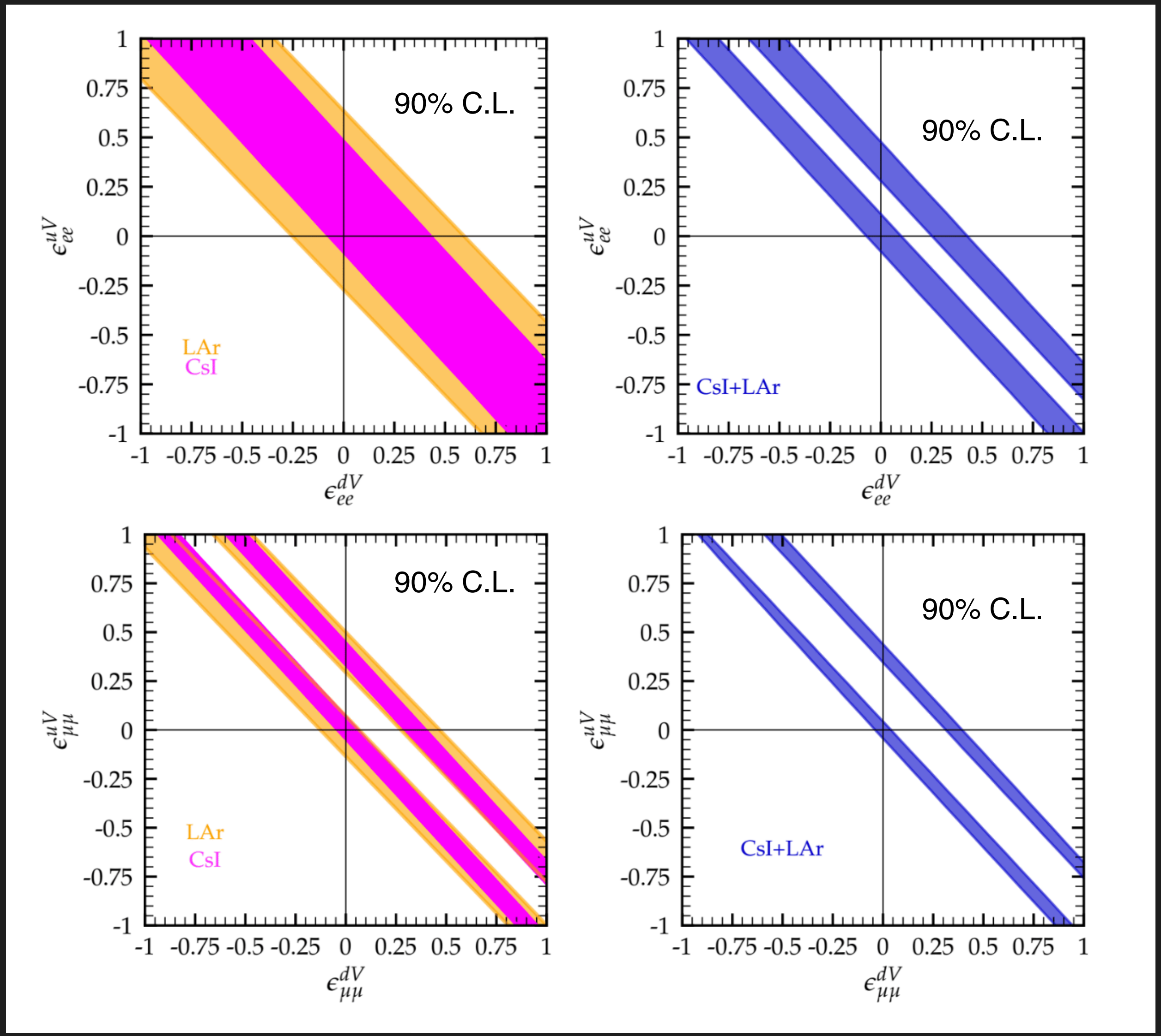
See also: S. Davidson et. al., JHEP 03 (2003) 011 J. Barranco, O.G. Miranda and T.I. Rashba, JHEP 0512 (2005) 021, K. Scholberg, PRD 73 (2006) 033005, Coloma+ Phys. Rev. D 96, 115007 (2017), JHEP 02, 023 (2020), JHEP 05 (2022) 037, Papoulias+ Phys. Rev. D 97, 033003 (2018), Giunti PRD 101, 035039 (2020), Denton+ JHEP 04, 266 (2021), Esteban+ JHEP 08, 180 (2018), COHERENT Colab. arXiv:2110.07730, Coloma+ JHEP 05 (2022) 037, Bresó-Pla+ JHEP 05 (2023) 074, Coloma+ JHEP 08 (2023) 03, Liao+ arXiv:2408.06255, Alpízar-Vanegas+ 2501.10355, Chattaraj+ 2501.12441...

NEW NEUTRINO INTERACTIONS: NSI

Neutrino NSI can be formulated in terms of the effective four-fermion Lagrangian:

$$\mathcal{L}_{\mathrm{NC}}^{\mathrm{NSI}} = -2\sqrt{2}G_F \sum_{q,\ell,\ell'} \varepsilon_{\ell\ell'}^{qX} (\bar{\nu}_\ell \gamma^\mu P_L \nu_{\ell'})(\bar{f}\gamma_\mu P_X f)$$

COHERENT CsI (2021) + LAr



VDR, Miranda, Papoulias, Sanchez-García, Tórtola and Valle, JHEP 04 (2023) 035

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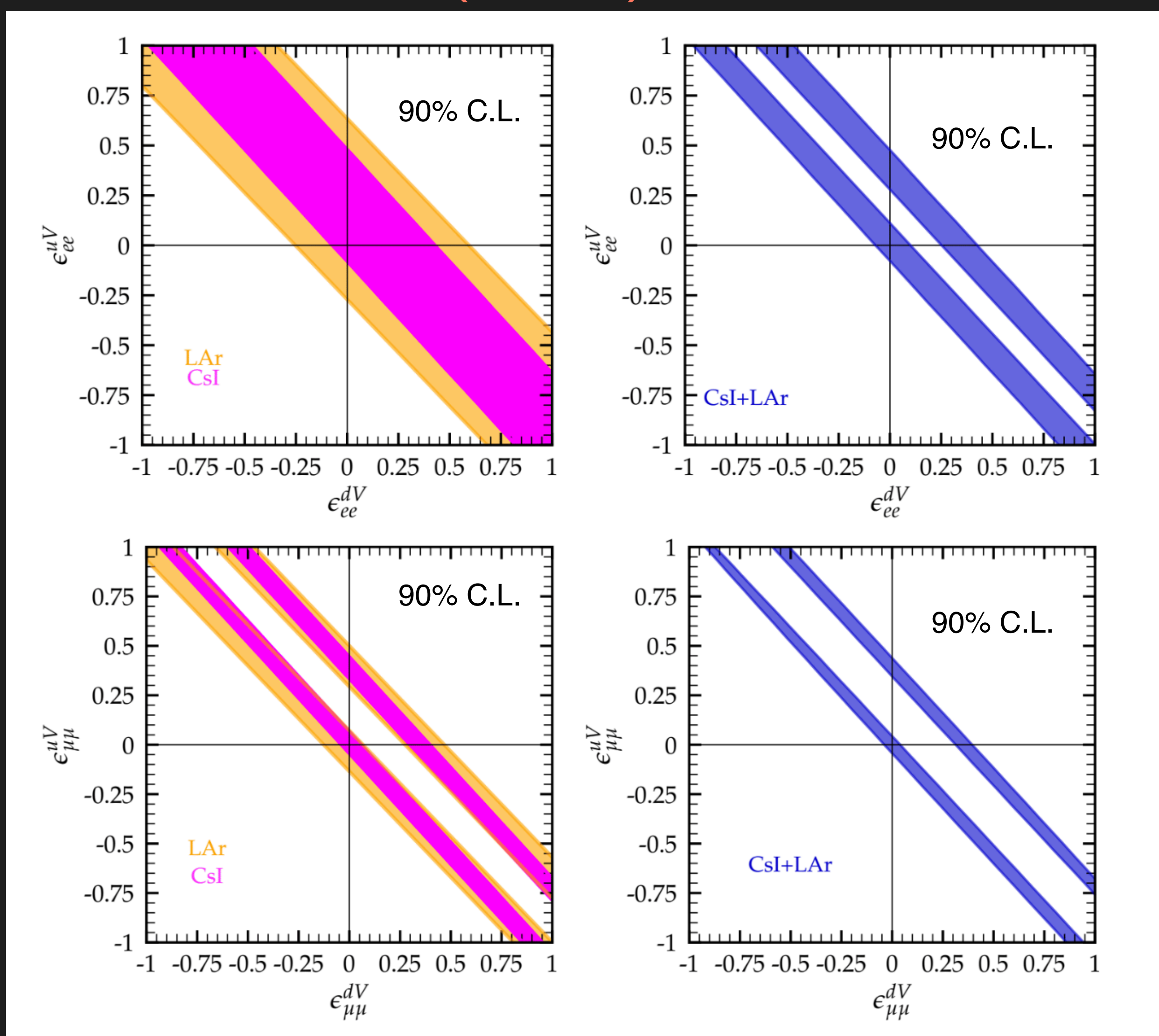
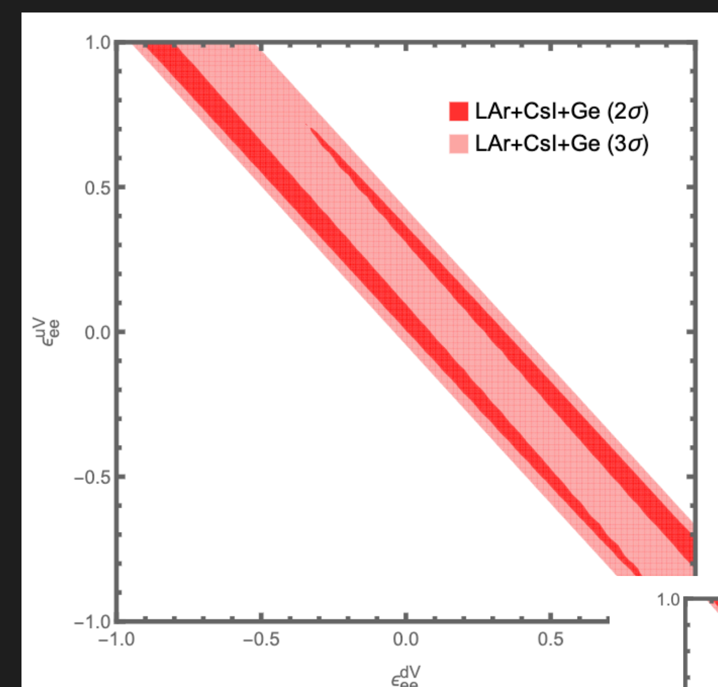
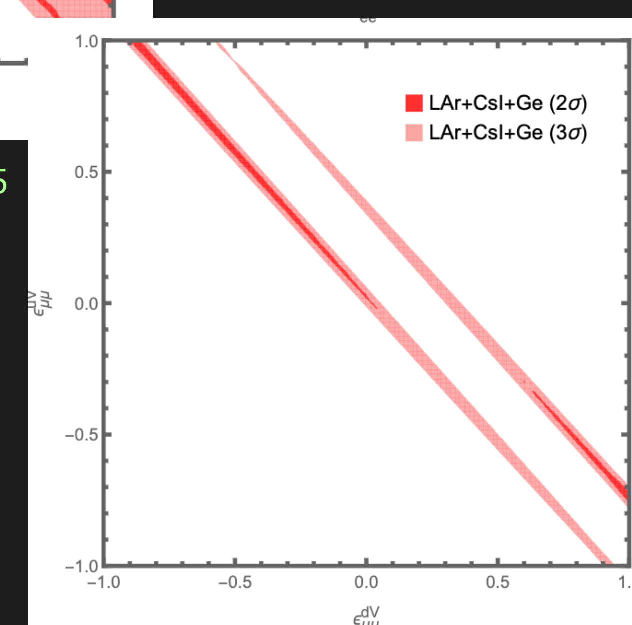


VDR, Miranda, Papoulias, Sanchez-García,Tórtola and Valle, JHEP 04 (2023) 035



Liao+ arXiv:2408.06255

COHERENT CsI (2021) + LAr + Ge



NEW NEUTRINO INTERACTIONS: NSI

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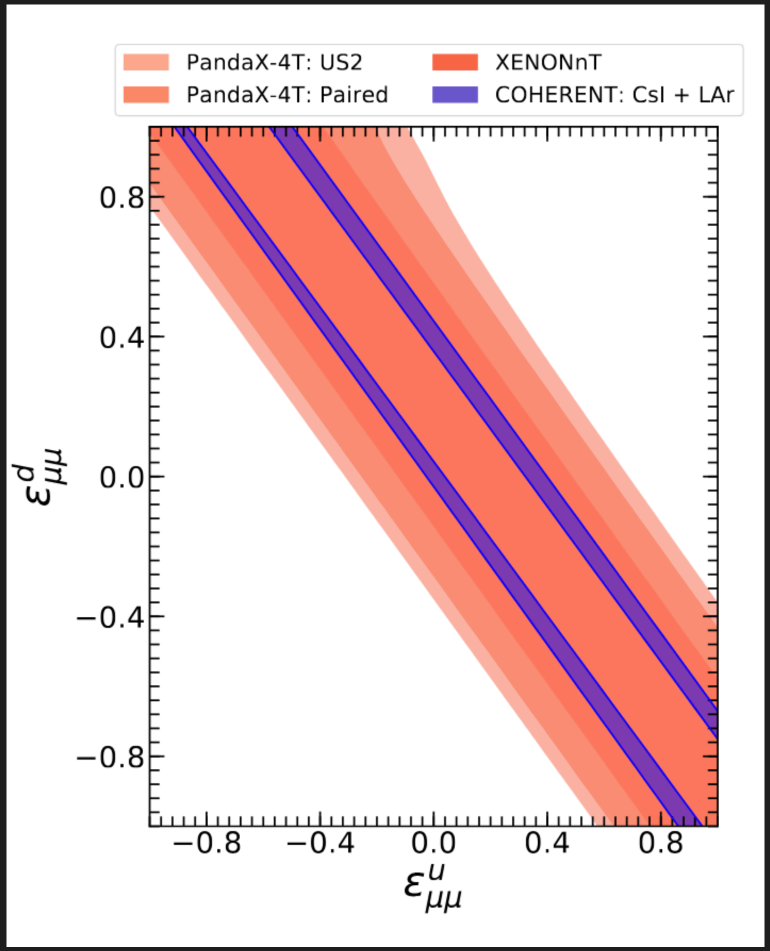
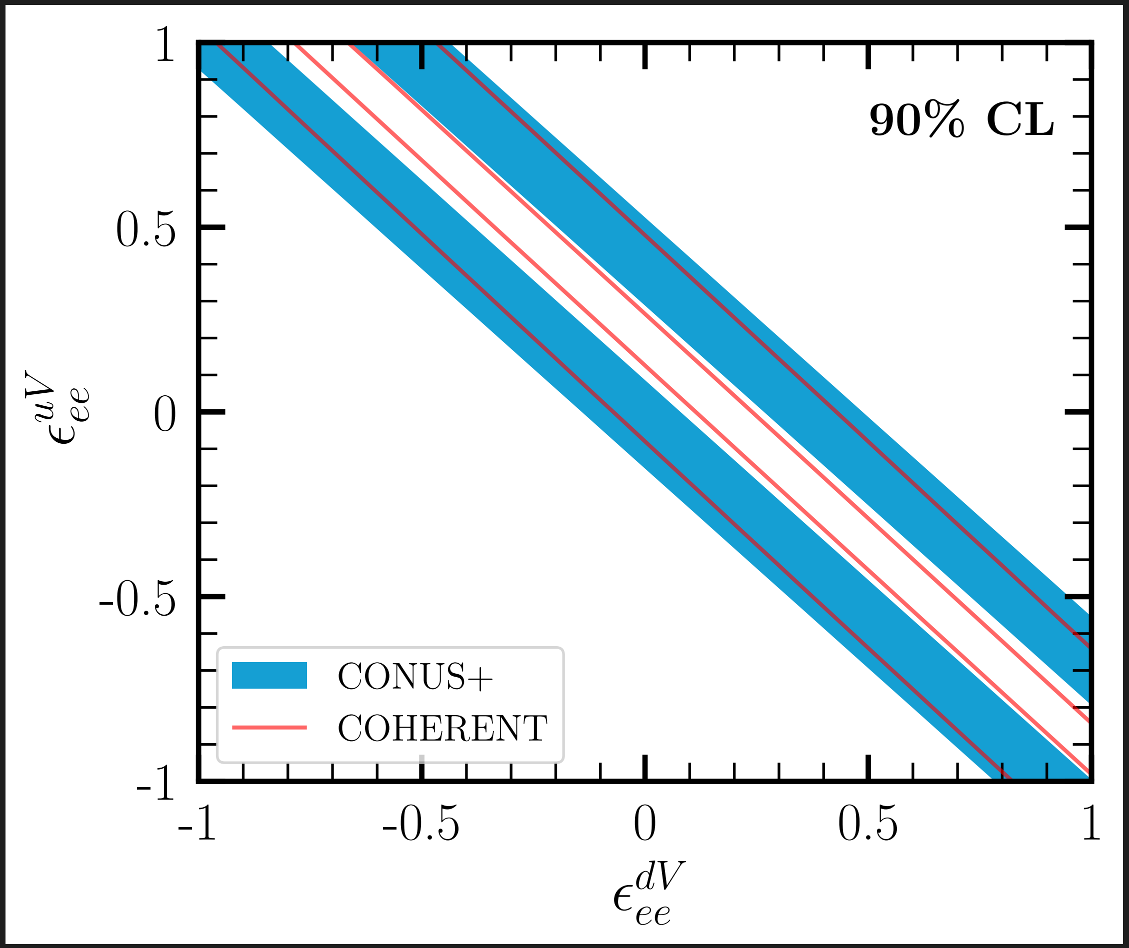
COHERENT CsI (2021) + LAr vs XENONnT and PANDAX-4T



Aristizabal+ arXiV: 2409.02003
See also Li+ 2409.04703

CONUS+ (2025)



VDR, Papoulias, Sanchez Garcia PRD 111, 075025 (2025)

See also Alpízar-Vanegas+ 2501.10355, Chattaraj+ 2501.12441

NEW NEUTRINO INTERACTIONS: LIGHT MEDIATORS

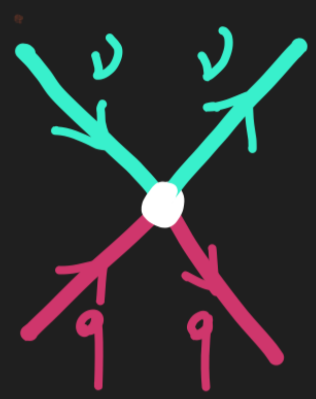
New BSM scenarios might be associated with different types of interactions and mediators. These mediators would contribute to CEνNS leading to detectable distortions of the event rates, especially at low-energy recoils.

Cerdeño+ JHEP 1605 (2016) 118
Bertuzzo+ JHEP 1704 (2017) 073
Farzan+ JHEP 1805 (2018) 066
Denton+ PRD 106 (2022) 015022

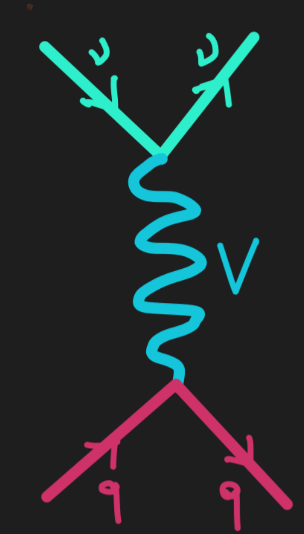
Low-energy neutrino experiments are sensitive to interactions involving light mediators, inducing spectral distortions at low recoil energies.

We may consider light mediators with a mass comparable to the typical momentum transfer

$$|\mathbf{q}| \approx \sqrt{2 m_{\mathcal{N}} E_{\mathrm{nr}}}$$



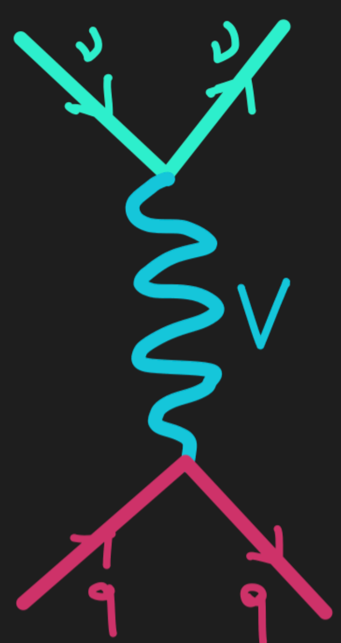
$$G_F^2 |\varepsilon_\ell^X|^2 \to \frac{2 g_X^4}{(m_X^2 + |\mathbf{q}|^2)^2}$$



NEW NEUTRINO INTERACTIONS: LV

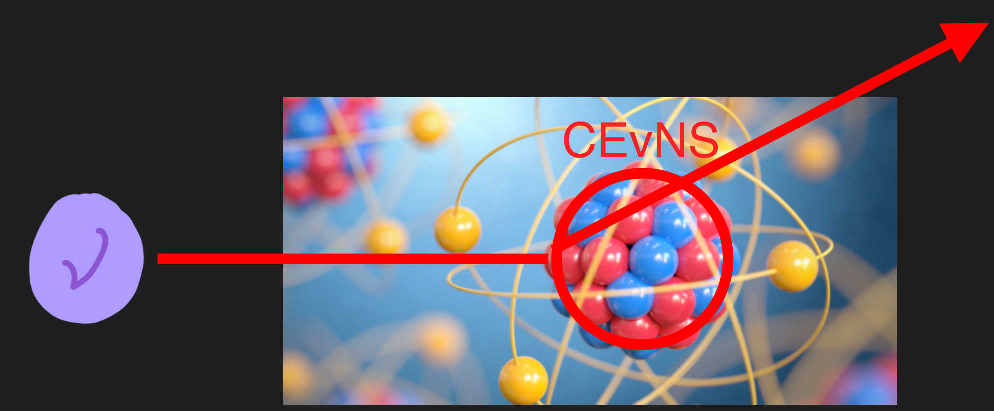
$$\left.\frac{d\sigma}{dE_{\rm nr}}\right|^{\rm LV}_{\rm CE\nu NS} = \left(1 + \kappa \frac{C_V}{\sqrt{2} G_F Q_W^{\rm SM} \left(2 m_N E_{\rm nr} + m_V^2\right)}\right)^2 \left.\frac{d\sigma}{dE_{\rm nr}}\right|^{\rm SM}_{\rm CE\nu NS}$$

$$C_V = g_{\nu V}\left[\left(2 g_{uV} + g_{dV}\right) Z + \left(g_{uV} + 2 g_{dV}\right) N\right]$$



$\kappa = 1$ for universal couplings
$\kappa = -1/3$ in the B – L model

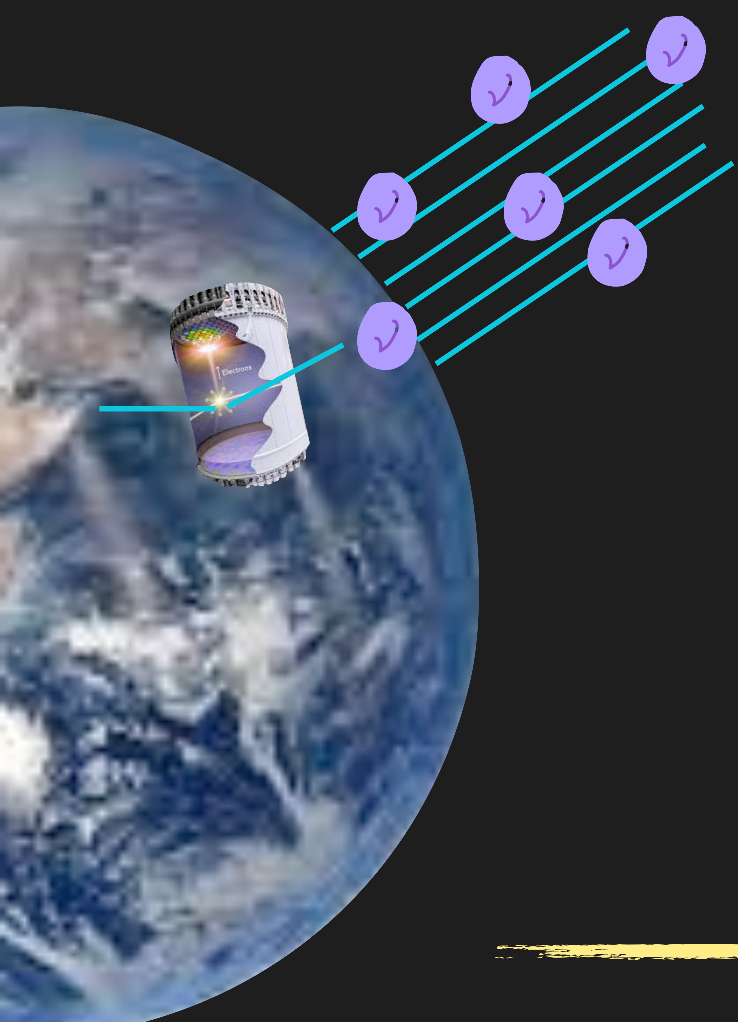
$$g_V = \sqrt{g_{\nu V} g_{qV}}$$

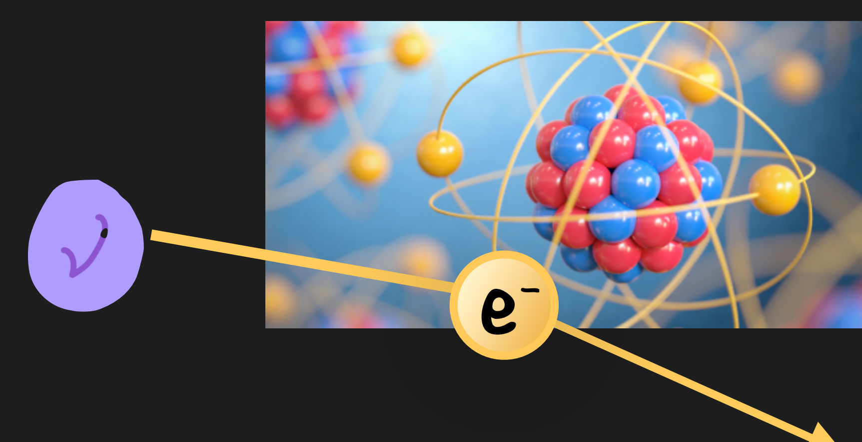


ELASTIC νEUTRINO-ELECTRON SCATTERING (EνES)

$$\left.\frac{d\sigma_{\nu_\ell \mathscr{A}}}{dE_{\text{er}}}\right|^{\text{SM}}_{\text{E}\nu\text{ES}} = Z^{\mathscr{A}}_{\text{eff}}(E_{\text{er}}) \frac{G_F^2 m_e}{2\pi}\left[(g_V^{\nu_\ell}+g_A^{\nu_\ell})^2 + (g_V^{\nu_\ell}-g_A^{\nu_\ell})^2\left(1-\frac{E_{\text{er}}}{E_\nu}\right)^2 - \left((g_V^{\nu_\ell})^2-(g_A^{\nu_\ell})^2\right)\frac{m_e E_{\text{er}}}{E_\nu^2}\right]$$

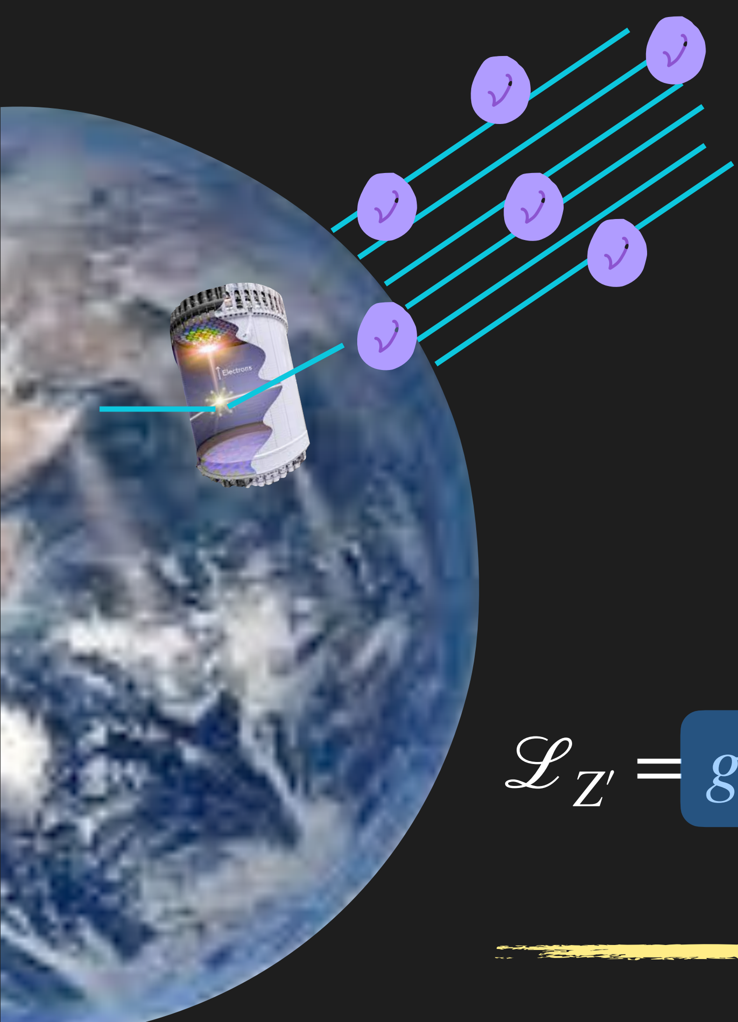
effective number of electrons
that can be ionized
with an energy deposition Eer



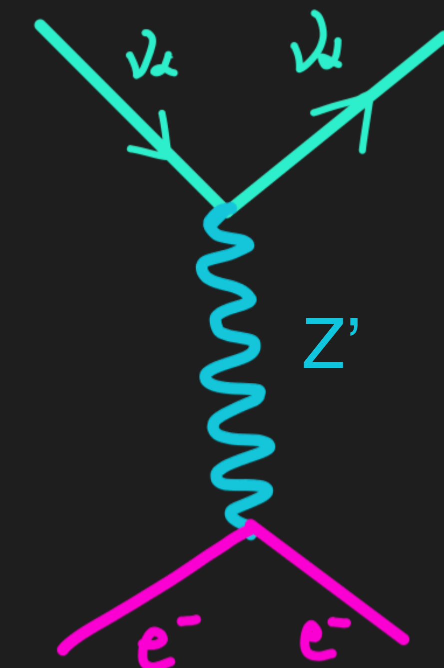


ELASTIC νEUTRINO-ELECTRON SCATTERING (EνES)

$$\left.\frac{d\sigma_{\nu_\ell \mathscr{A}}}{dE_{\rm er}}\right|^{\rm SM}_{\rm E\nu ES} = Z^{\mathscr{A}}_{\rm eff}(E_{\rm er})\frac{G_F^2 m_e}{2\pi}\left[(g_V^{\nu_\ell}+g_A^{\nu_\ell})^2 + (g_V^{\nu_\ell}-g_A^{\nu_\ell})^2\left(1-\frac{E_{\rm er}}{E_\nu}\right)^2 - \left((g_V^{\nu_\ell})^2-(g_A^{\nu_\ell})^2\right)\frac{m_e E_{\rm er}}{E_\nu^2}\right]$$

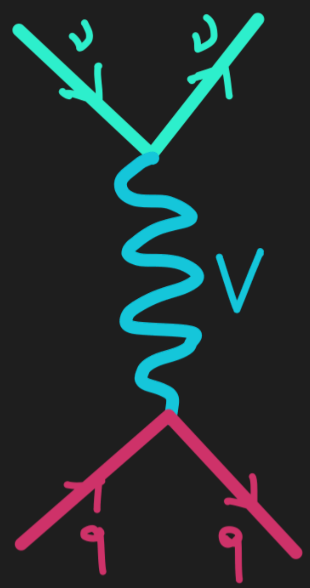


$$g_V \to g_V^{\rm SM} + \frac{(g_{Z'})^2 Q^e_{Z'} Q^{\nu_\alpha}_{Z'}}{\sqrt{2}G_F(2m_e T_e + m_{Z'}^2)}$$

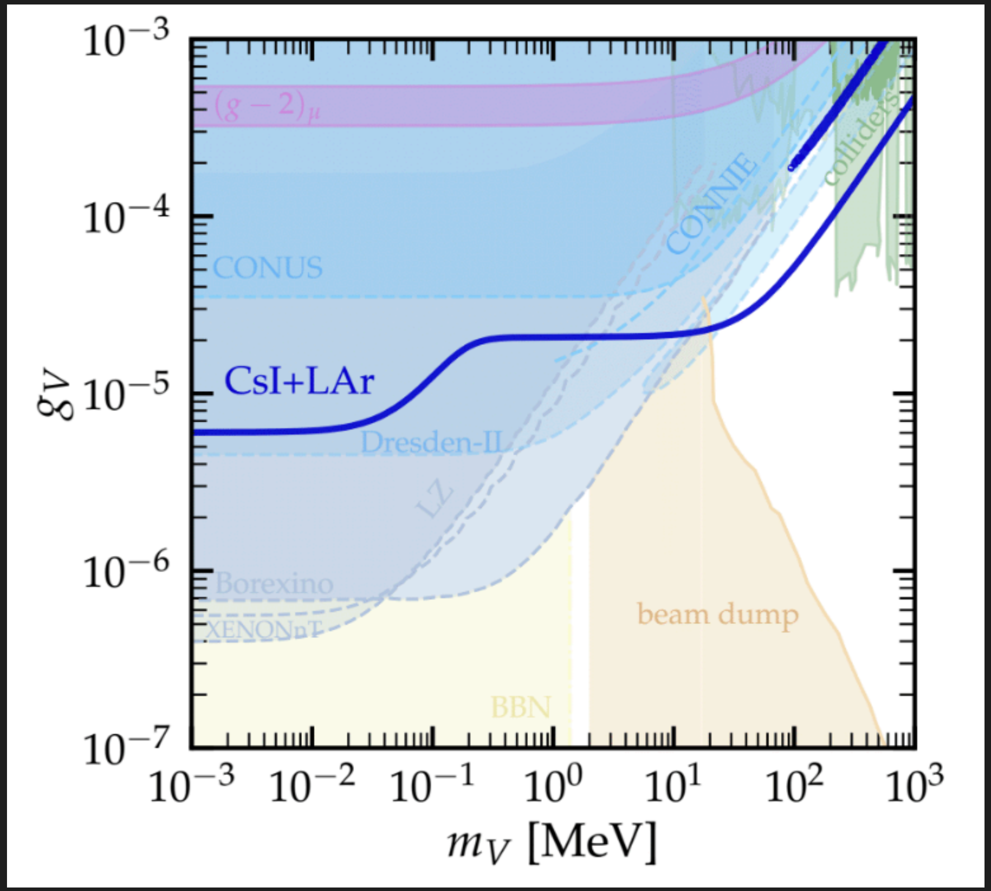


$$\mathscr{L}_{Z'} = g_{Z'} Z'_\mu \left(Q^f_{Z'} \bar{f}\gamma^\mu f + \sum_\alpha Q^{\nu_\alpha}_{Z'} \bar{\nu}_{\alpha,L}\gamma^\mu \nu_{\alpha,L}\right) + \frac{1}{2} m_{Z'}^2 Z'^\mu Z'_\mu$$

NEW NEUTRINO INTERACTIONS: LV

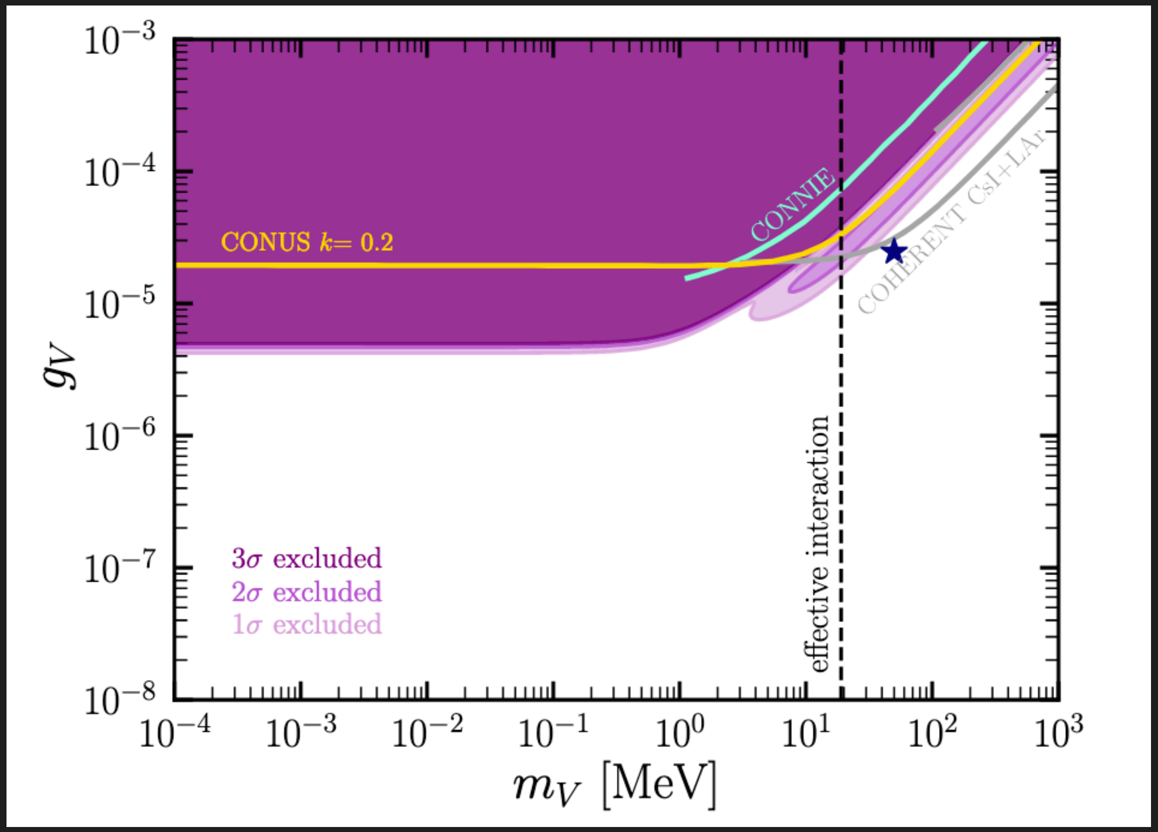


COHERENT CsI (2021) + LAr



VDR, Miranda, Papoulias, Sanchez-García,Tórtola and Valle, JHEP 04 (2023) 035

Dresden-II (Ge) - iron filter

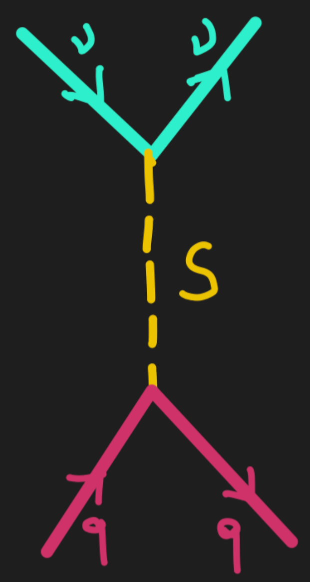


Aristizabal, VDR, Papoulias JHEP 09 (2022) 076

- Complementary analyses in: J. Liao, H. Liu, and D. Marfatia, 2202.10622, Coloma et al. 2202.10829, Atzori-Corona et al. 2205.09484, A. Khan 2203.08892, Majumdar+ 2208.13262

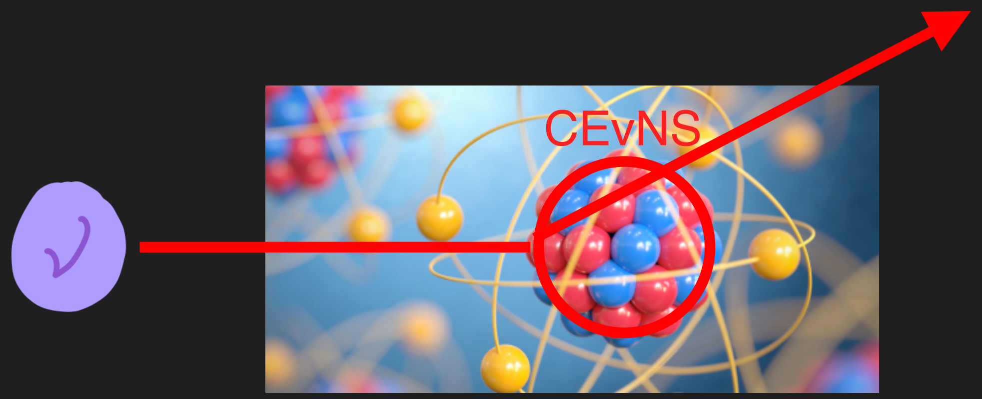
NEW NEUTRINO INTERACTIONS: LS

$$\left.\frac{d\sigma_{\nu_\ell \mathcal{N}}}{dE_{\rm nr}}\right|^{\rm LS}_{\rm CE\nu NS} = \frac{m_N^2 E_{\rm nr}\, C_S^2}{4\pi E_\nu^2 \left(2 m_N E_{\rm nr} + m_S^2\right)^2} F_W^2(|\vec{q}\,|^2)$$



$$C_S = g_{\nu S}\left(Z \sum_q g_{qS} \frac{m_p}{m_q} f_q^p + N \sum_q g_{qS} \frac{m_n}{m_q} f_q^n\right)$$

$$g_S = \sqrt{g_{\nu S}\, g_{qS}}$$



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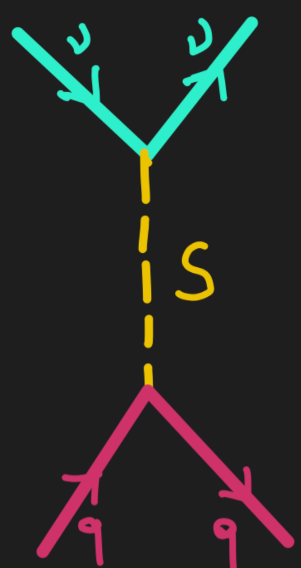
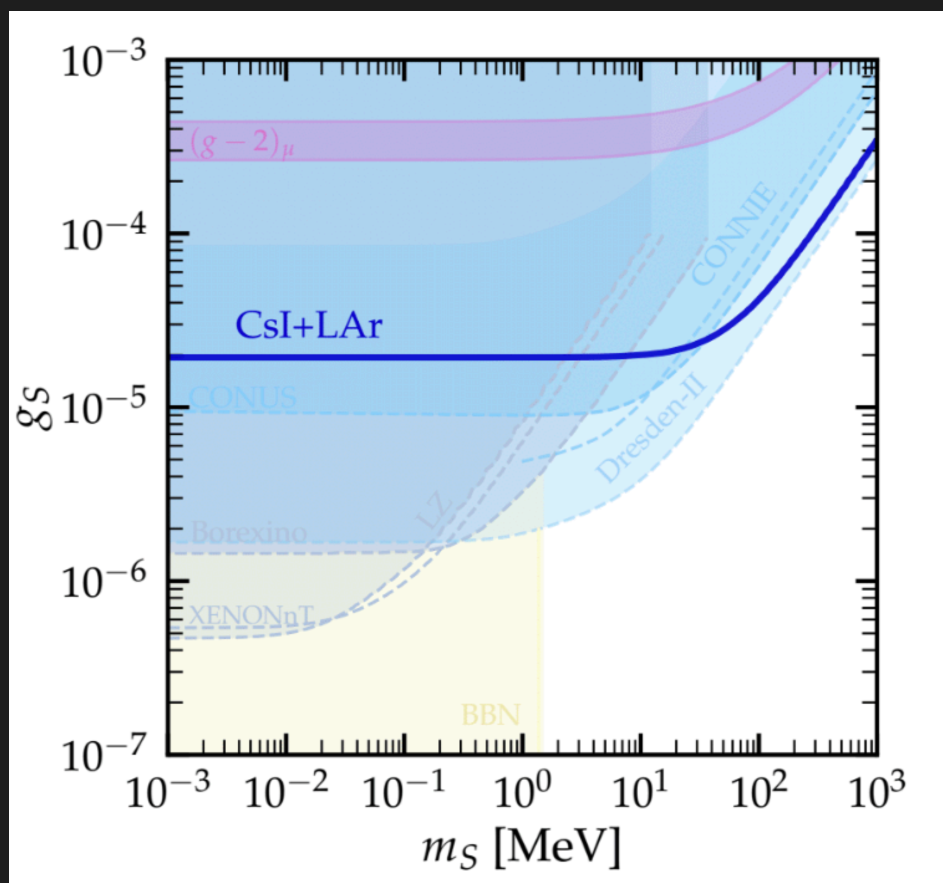


COHERENT CsI (2021) + LAr



VDR, Miranda, Papoulias, Sanchez-García,Tórtola and Valle, JHEP 04 (2023) 035

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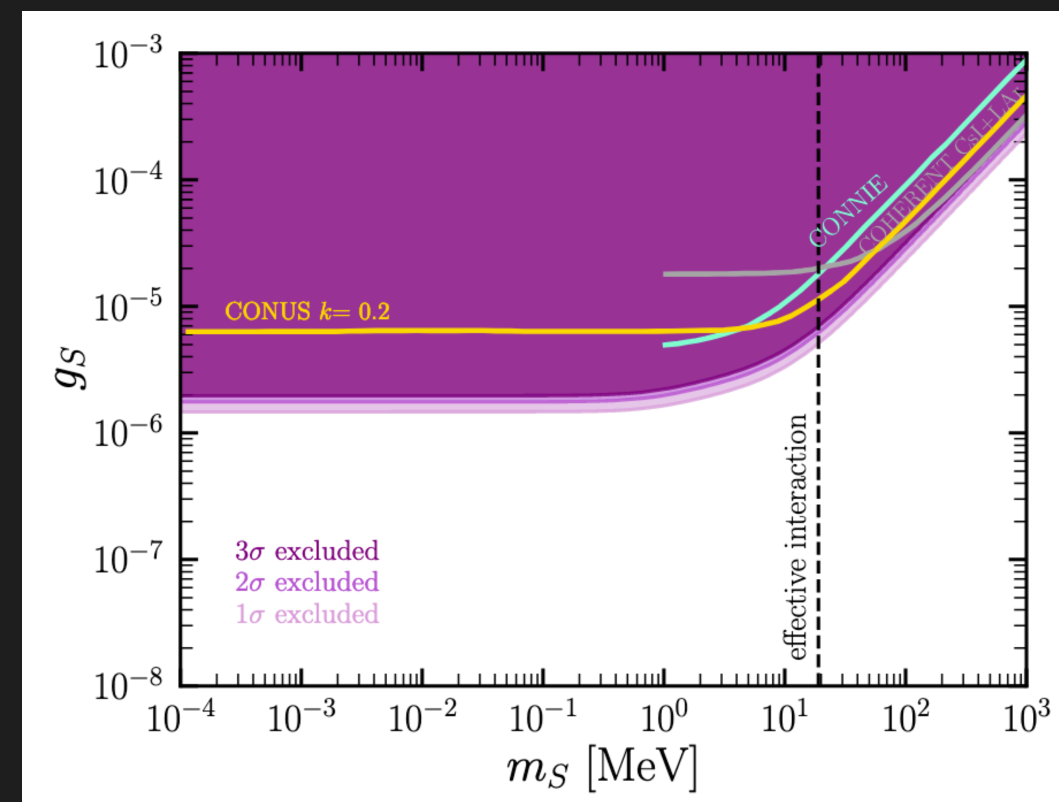

Aristizabal, VDR, Papoulias JHEP 09 (2022) 076

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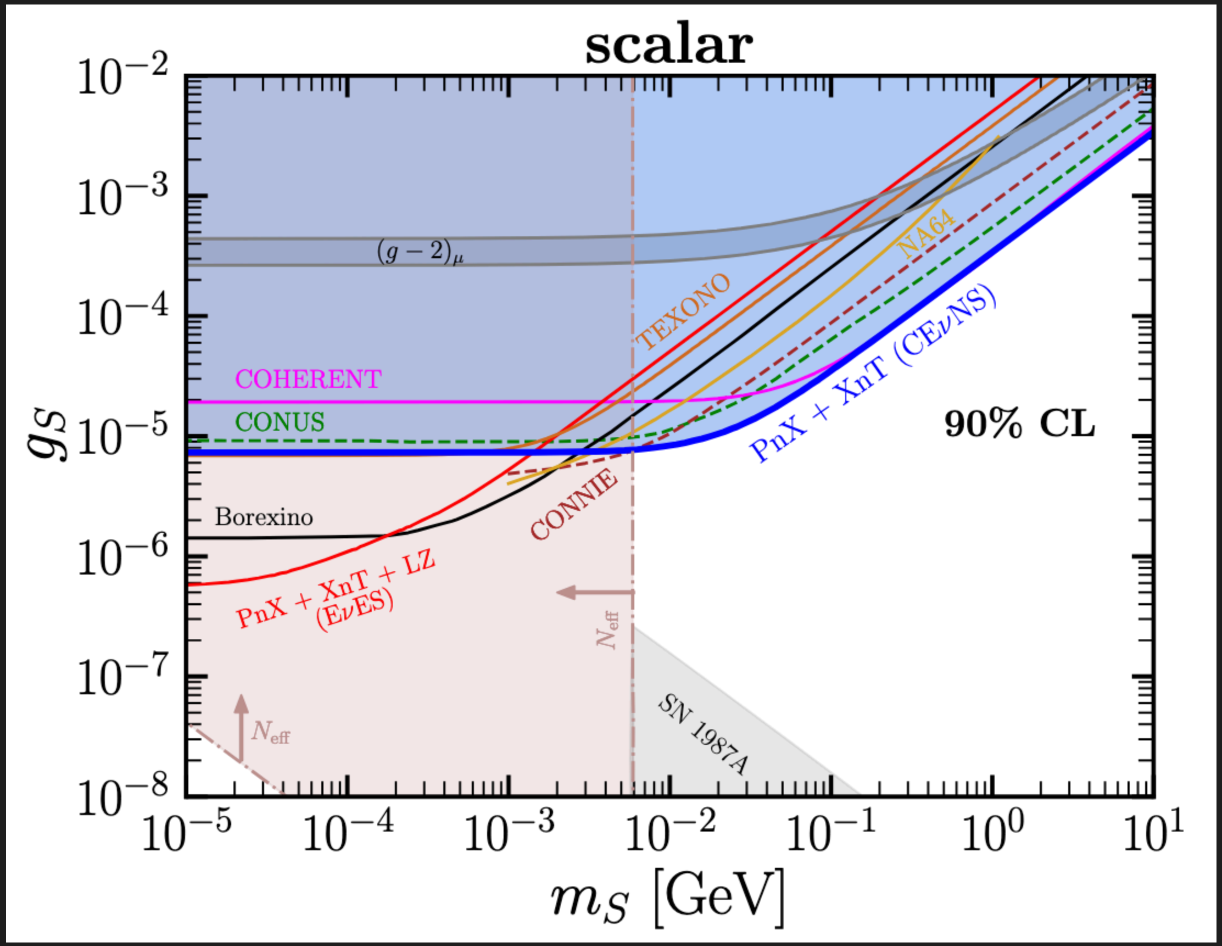
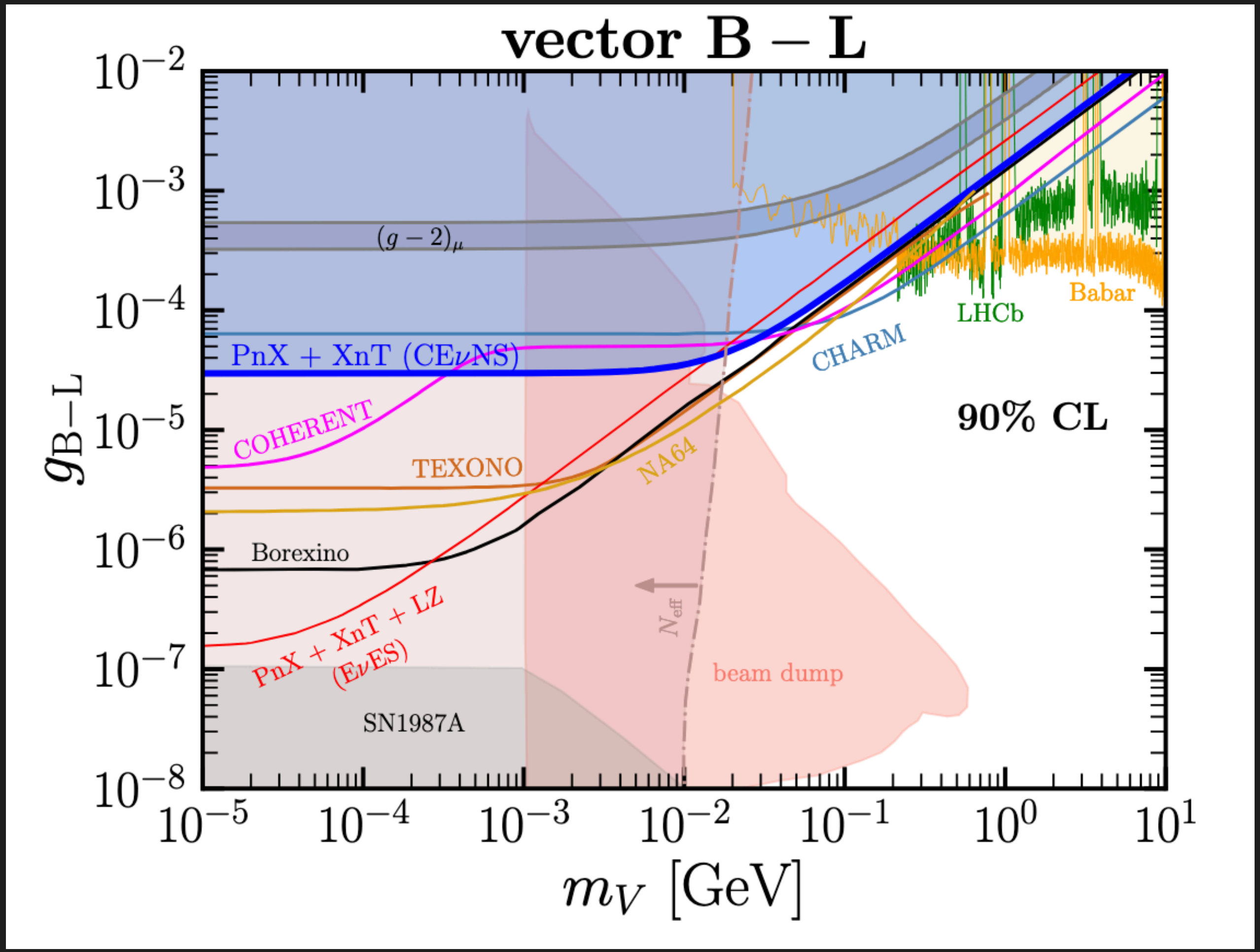
NEW NEUTRINO INTERACTIONS: LIGHT MEDIATORS

XENONnT + PandaX-4T (2024)



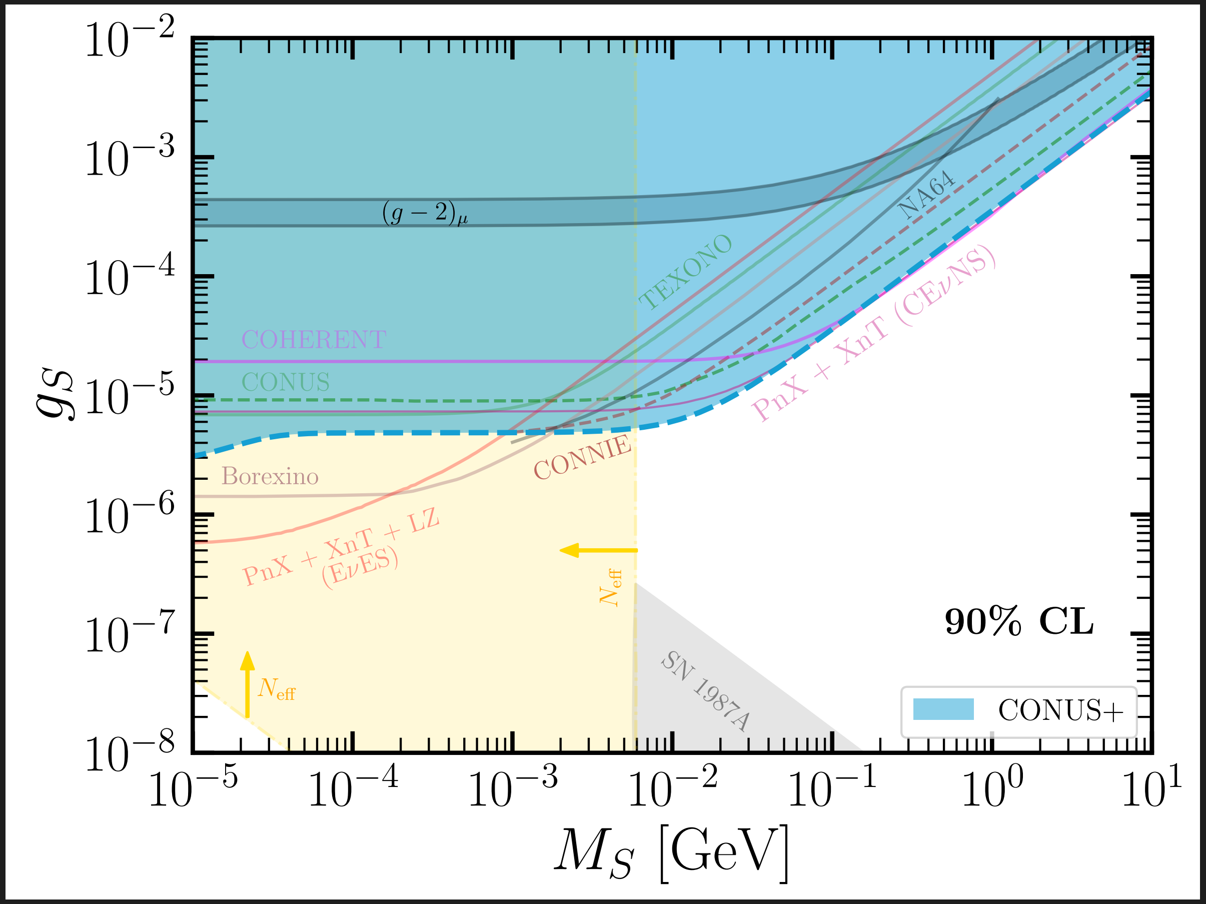


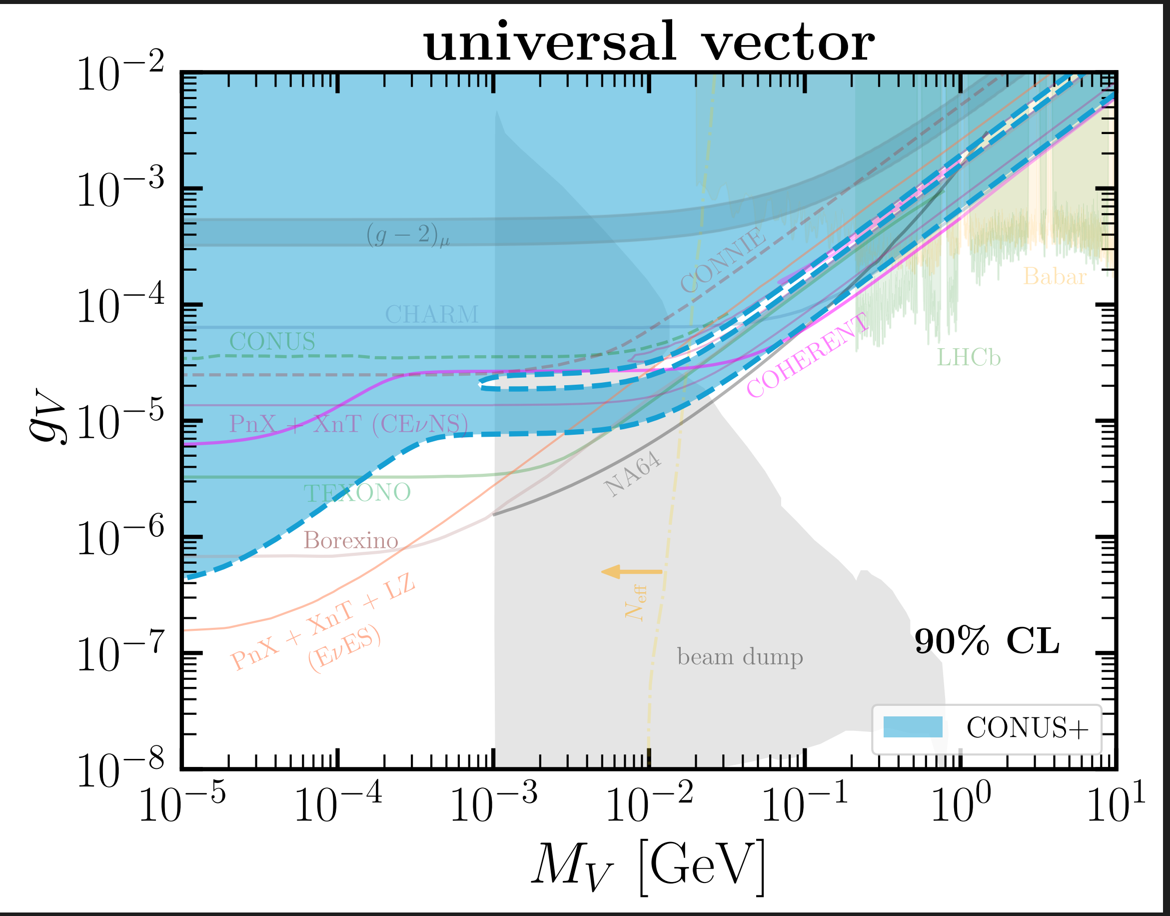
VDR, Papoulias, Ternes JCAP 05 (2025) 012

See also Blanco-Mas+ 2411.14206

NEW NEUTRINO INTERACTIONS: LIGHT MEDIATORS

CONUS+ (2025)

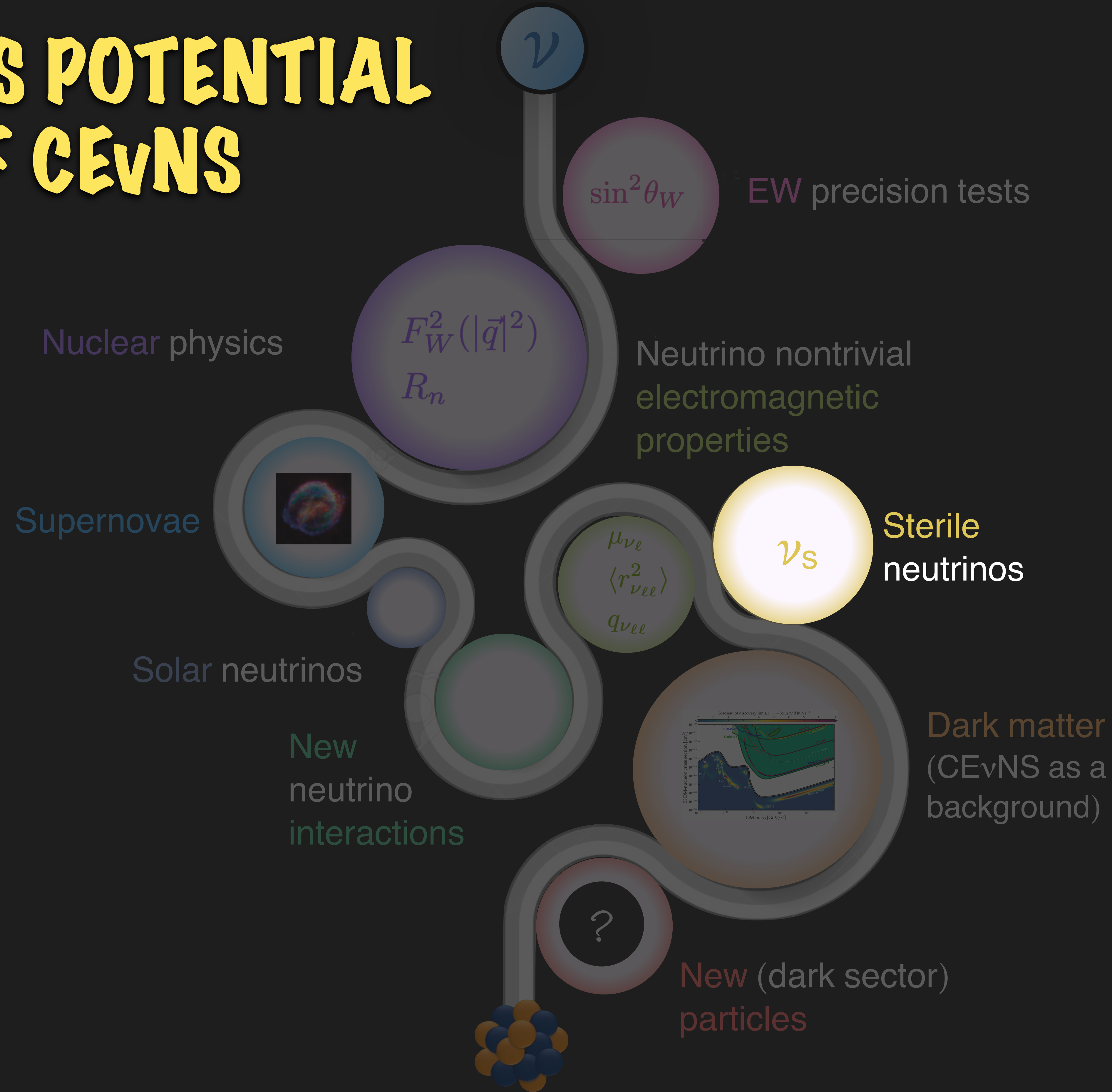




VDR, Papoulias, Sanchez Garcia PRD 111, 075025 (2025)

See also Chattaraj+ 2501.12441

PHYSICS POTENTIAL OF CEvNS

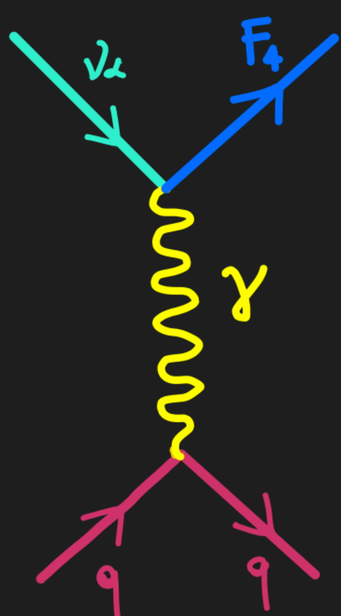


STERILE NEUTRINO DIPOLE PORTAL

Transition of an active neutrino to a massive sterile state, induced by a magnetic coupling: $\nu_L + N \rightarrow F_4 + N$

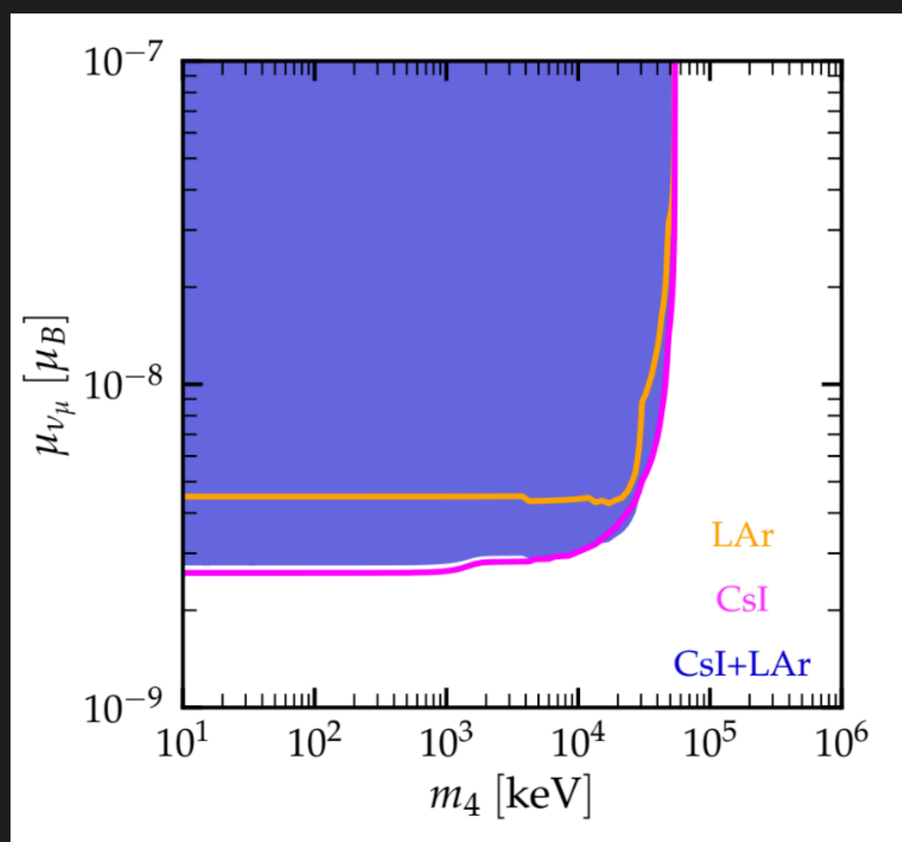
McKeen, Pospelov PRD 82 (2010)

$$\mathscr{L}_{\mathrm{DP}} = \bar{\nu}_4 (i\gamma^\mu \partial_\mu - m_4)\nu_4 + \frac{\sqrt{\pi\alpha_{\mathrm{EM}}}}{2m_e}\left|\frac{\mu^{\mathrm{eff}}_{\nu_\ell}}{\mu_{\mathrm{B}}}\right|^2 \bar{\nu}_4 \sigma_{\mu\nu}\nu_\ell F^{\mu\nu}$$



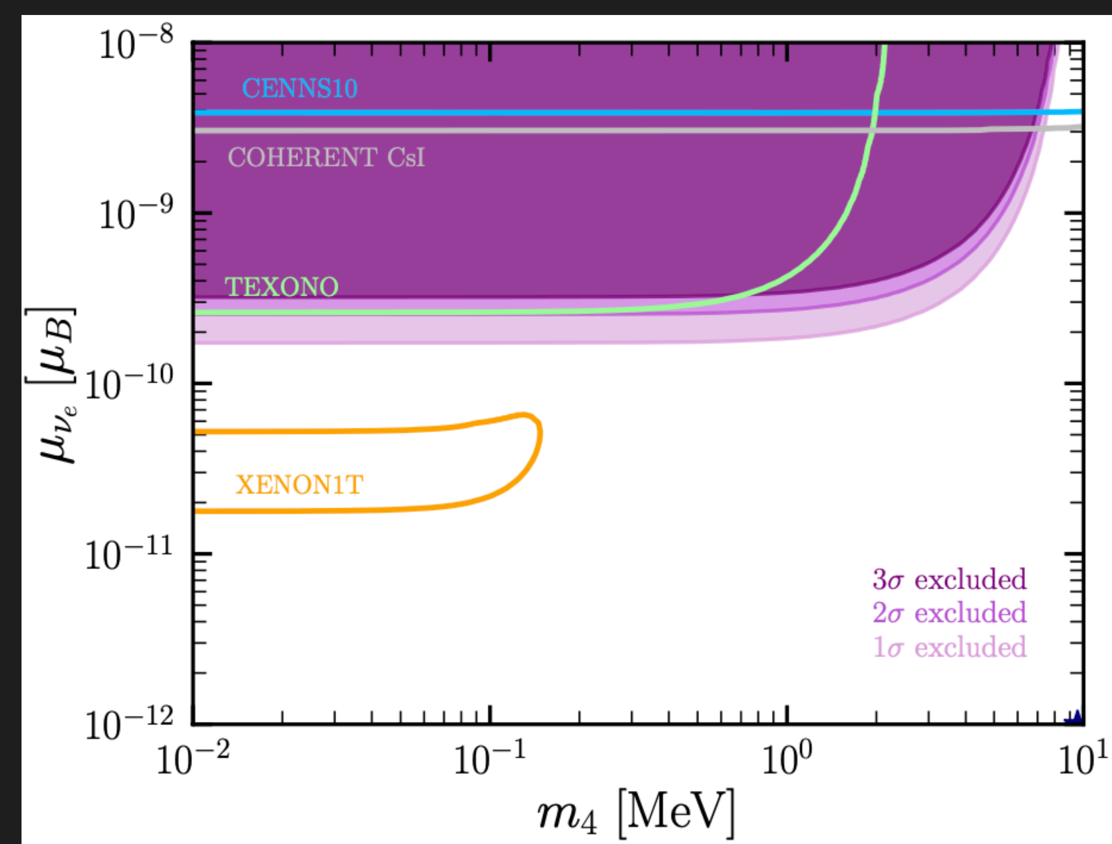
$$\frac{d\sigma_{\nu\mathcal{N}}}{dT_\mathcal{N}}\bigg|^{\mathrm{DP}}_{\mathrm{CE}\nu\mathrm{NS}} = \frac{\pi\alpha^2_{\mathrm{EM}}}{m_e^2} Z^2 F_W^2(|\vec{q}|^2)\left|\frac{\mu^{\mathrm{eff}}_{\nu_\ell}}{\mu_{\mathrm{B}}}\right|^2 \left[\frac{1}{T_\mathcal{N}} - \frac{1}{E_\nu} - \frac{m_4^2}{2E_\nu T_\mathcal{N} m_\mathcal{N}}\left(1 - \frac{T_\mathcal{N}}{2E_\nu} + \frac{m_\mathcal{N}}{2E_\nu}\right) + \frac{m_4^4(T_\mathcal{N} - m_\mathcal{N})}{8E_\nu^2 T_\mathcal{N}^2 m_\mathcal{N}^2}\right]$$

COHERENT CsI (2021) + LAr



VDR, Miranda, Papoulias, Sanchez-García,Tórtola and Valle, JHEP 04 (2023) 035

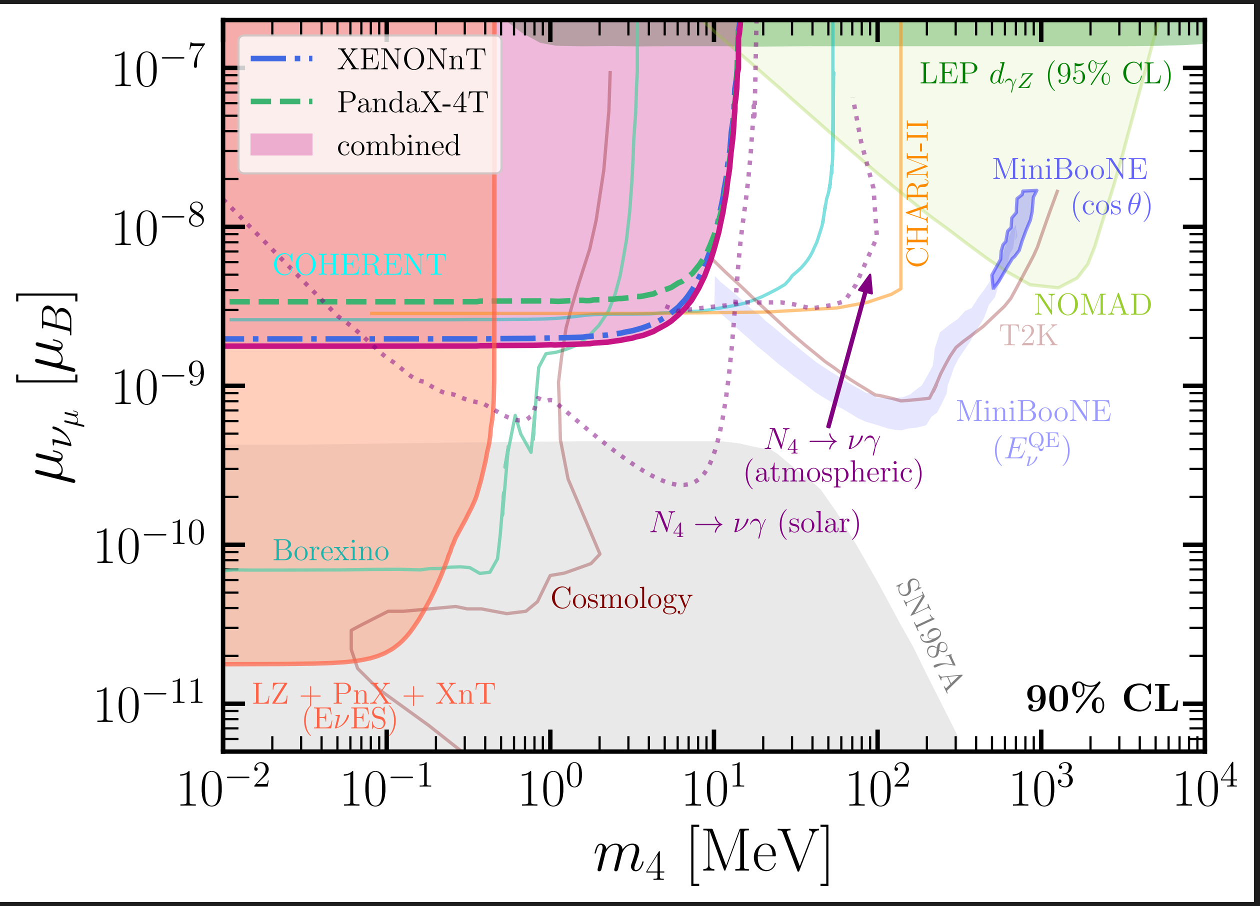
Dresden-II (Ge) - iron filter

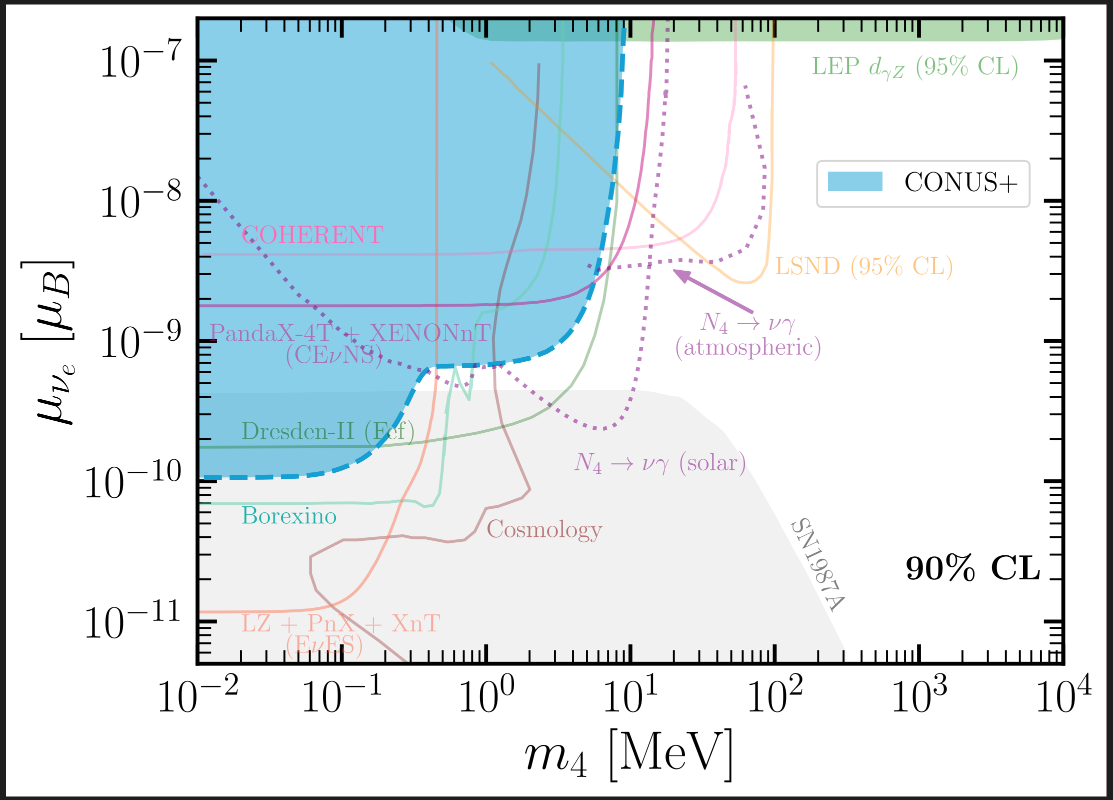


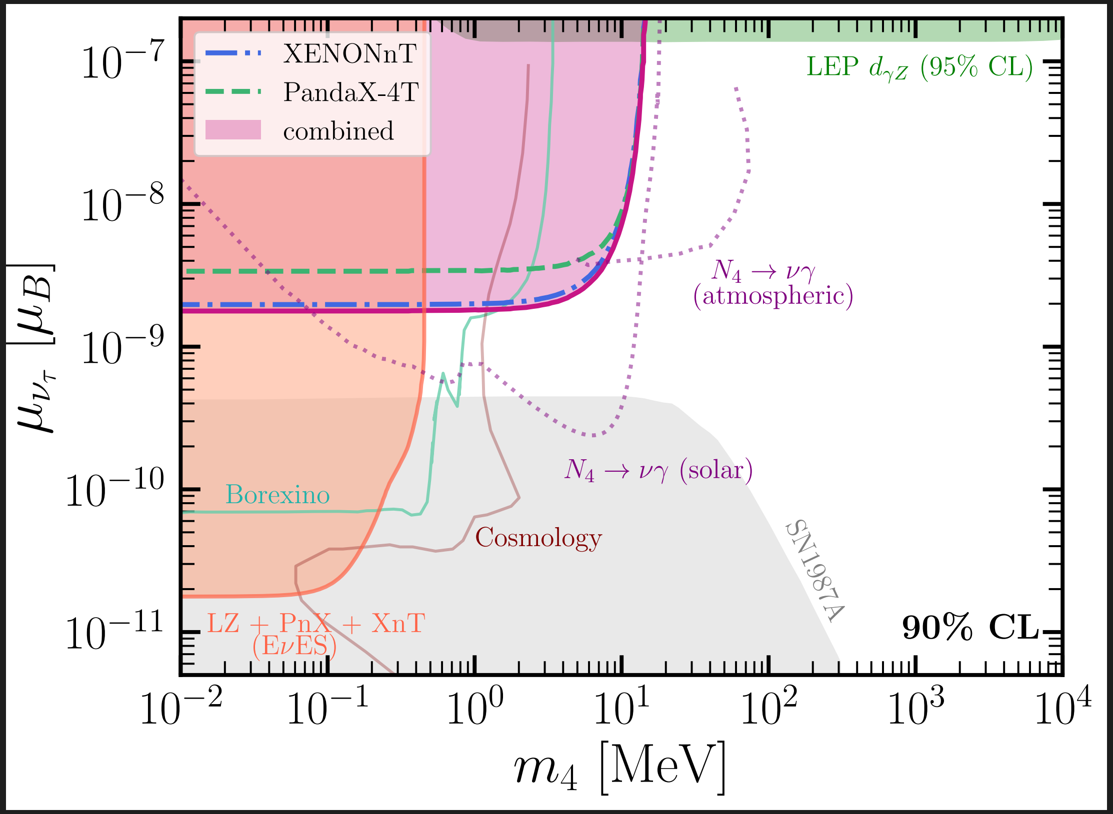
Aristizabal, VDR, Papoulias JHEP 09 (2022) 076

STERILE NEUTRINO DIPOLE PORTAL

XENONnT + PandaX-4T (2024)
CONUS+ (2025)

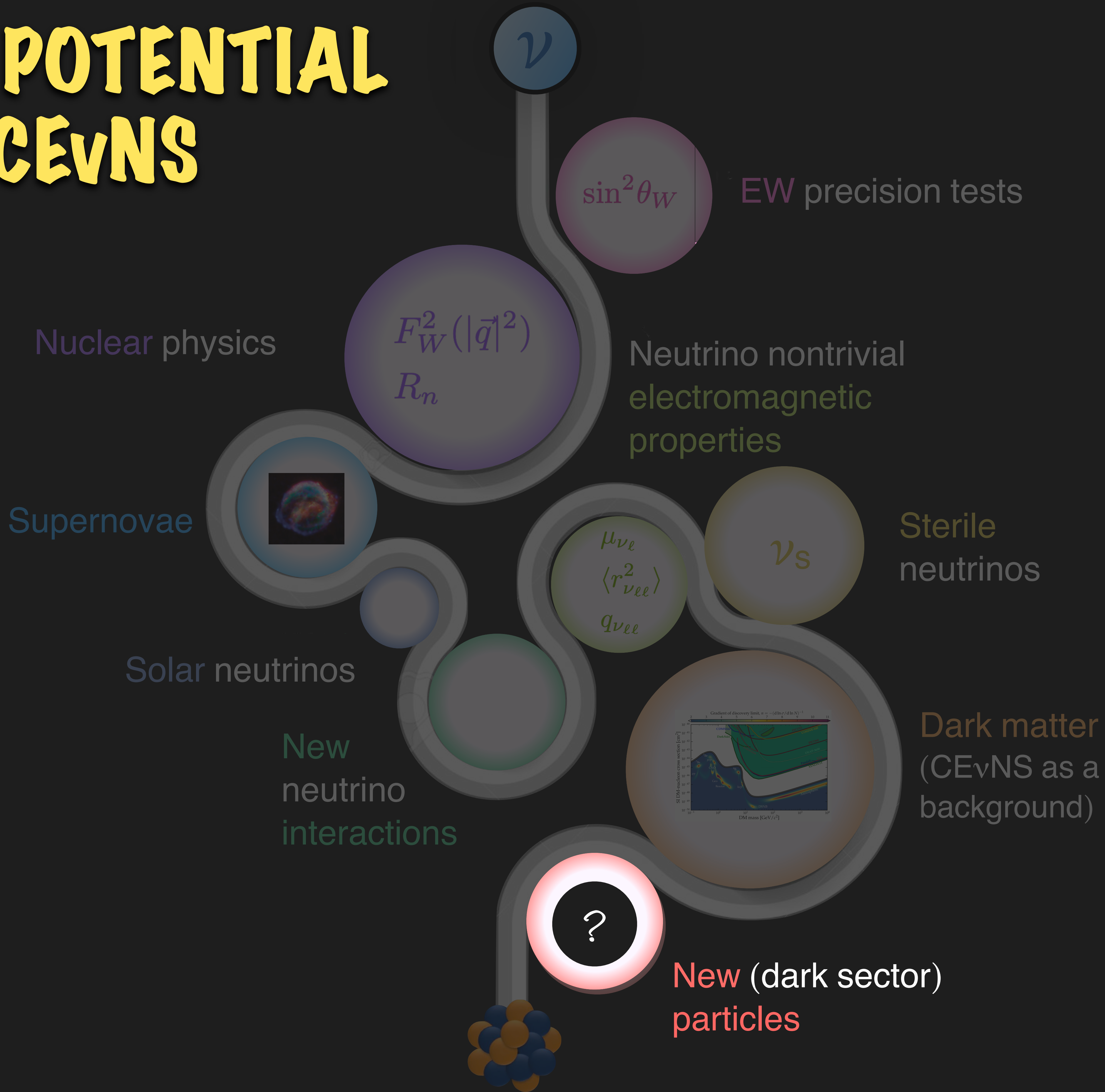






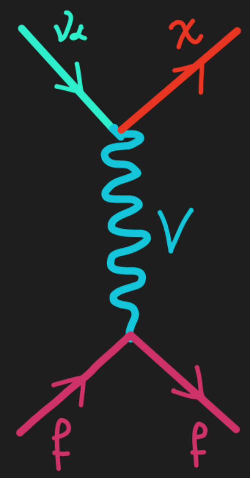
VDR, Papoulias, Sanchez Garcia, Ternes, Tortola JCAP 05 (2025) 080
VDR, Papoulias, Sanchez Garcia PRD 111, 075025 (2025)

PHYSICS POTENTIAL OF CEνNS



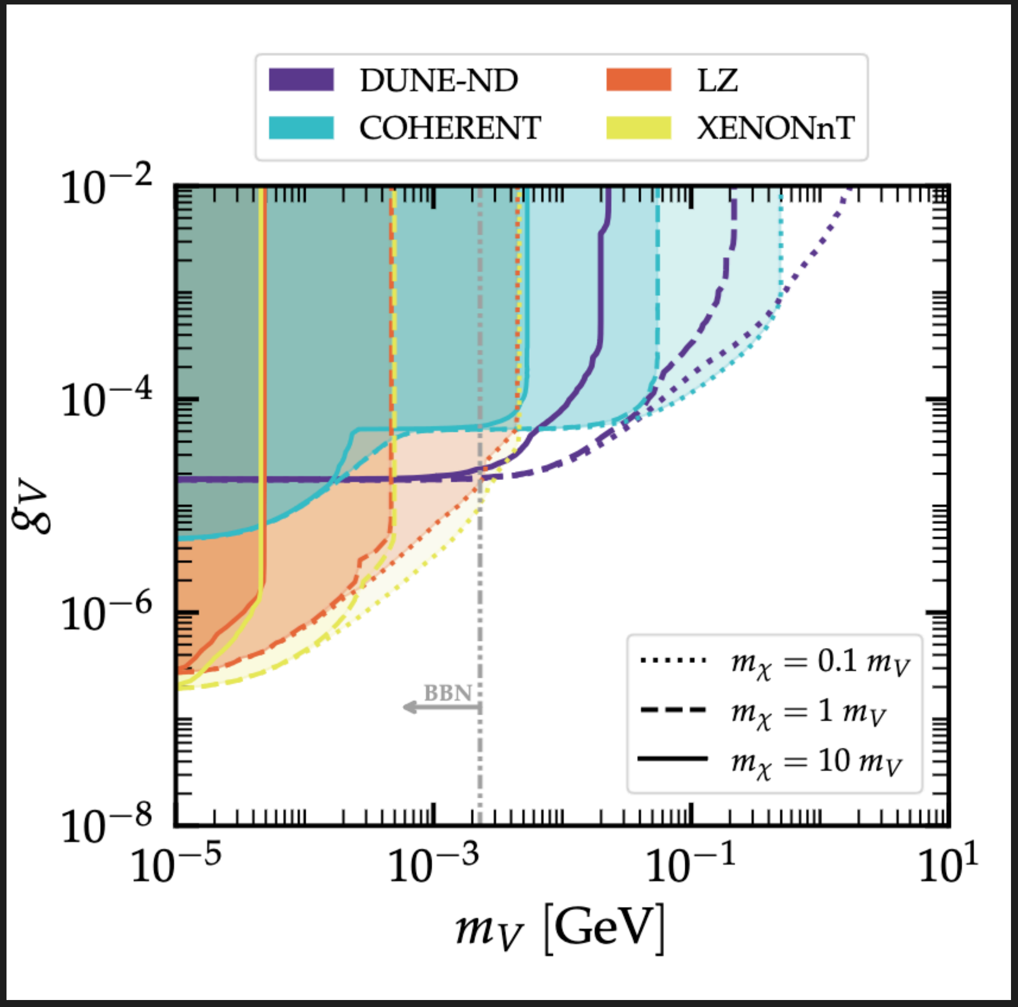
UPSCATTERING INTO A STERILE FERMION

Possible production of a new MeV-scale fermion through the up-scattering process of neutrinos off the nuclei and the electrons of the detector material through some new.
Complementarity with COHERENT and DUNE experiments.



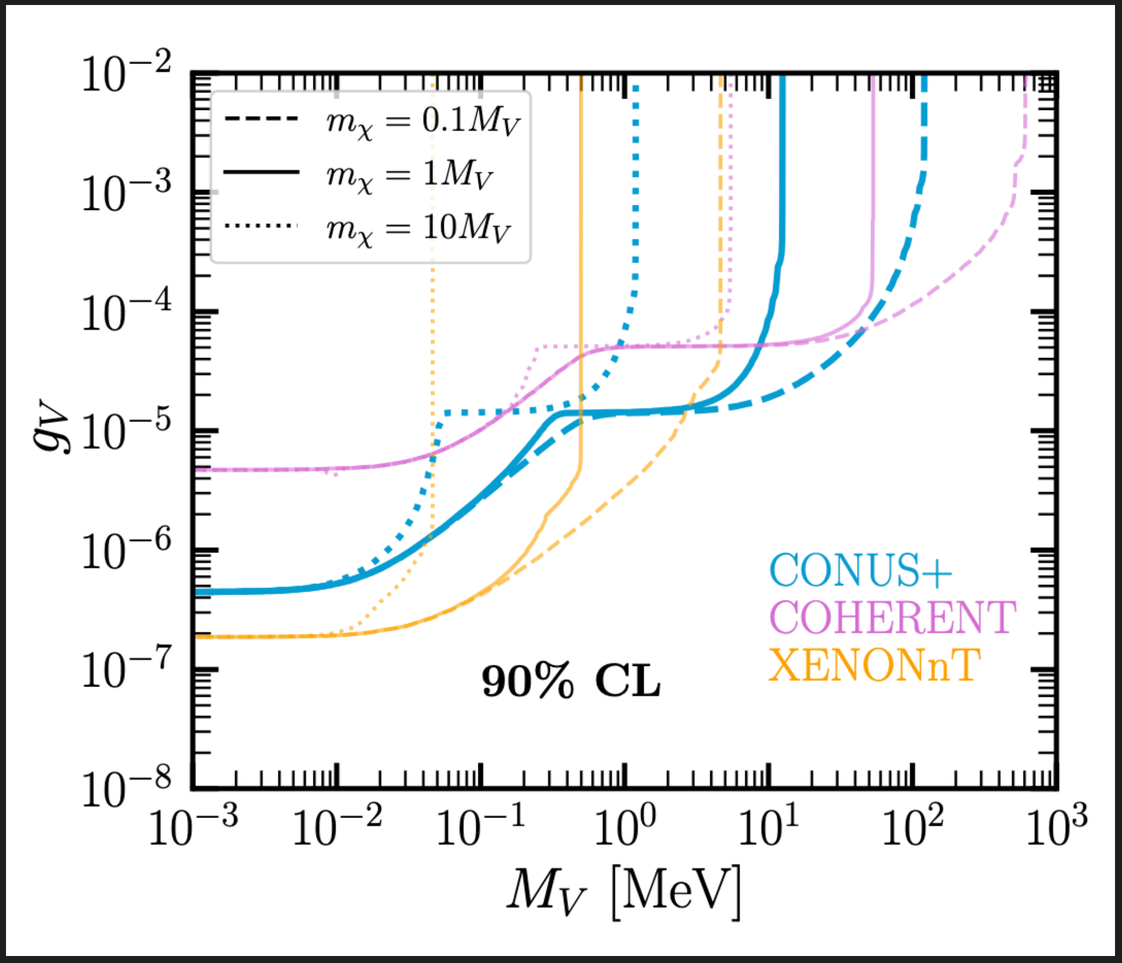
See also: Brdar+ JHEP 12 (2018) 024, Chao+ PRD 104 (2021) 095017, Chen+ JHEP 05 (2021) 131, LI & Liao JHEP 02 (2021) 099, Chang & Liao PRD 102 no. 7, (2020) 075004, VDR, Candela, Papoulias Phys.Rev.D 108 (2023) 5, 055001

COHERENT CsI (2021) + LAr
EvES data at XENONnT and LZ



Candela, VDR+ JHEP 10 (2024) 032

CONUS+ (2025)



VDR, Papoulias, Sanchez Garcia PRD 111, 075025 (2025)

WHAT'S NEXT?

CEvNS measurements are growing fast, heading to high statistics and precision.

- Global fits with diverse neutrino probes including DM DD data are gaining importance.
  Atzori-Corona+, arXiv: 2504.05272
- Dark matter detectors are becoming complementary to terrestrial experiments in detecting ~MeV neutrinos.
- Careful treatment of backgrounds and uncertainties (e.g. quenching factors). Billard+ JCAP 11 (2018) 016; Baxter+ JHEP 02 (2020) 123; Galindo+ PRD 105 (2022) 3, 033001
- Exploit the complementarity of various experimental targets and sources to maximise the physics potential.
  Tomalak, 2506.03255 (2025)
  Hellgren+, PLB 868 (2025) 139624
- Increased statistics will require to account for small terms in theoretical predictions: (flavor-dependent) radiative corrections, nuclear form factors, axial terms, inelastic contributions…

Summary

- CEνNS process:
  - coherency condition (sources: spallation source, nuclear reactors,…)
  - neutrinos scatter on a nucleus which act as a single particle
  - enhancement of the cross section ($\propto N^2$)
- CEνNS experiments and data:
  - COHERENT (CsI, LAr, Ge…)
  - Reactor experiments (Dresden-II and CONUS+)
  - Now also DM DD experiments!
- CEνNS extended physics potential:
  - SM physics (weak mixing angle, nuclear physics)
  - Electromagnetic properties
  - BSM scenarios: NSI, NGI, new light mediators, production of a dark fermion, ALPs, sterile neutrinos…
  - Impact on the neutrino floor/fog
- Wealth of information from forthcoming data: implications for both precision tests of the Standard Model and for new physics in the neutrino sector!

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Thank you!

- Acknowledgments:
  - CIDEXG/2022/20 (Generalitat Valenciana)
  - CNS2023-144124 (MCIN/AEI/ 10.13039/501100011033 and “Next Generation EU”/PRTR)
  - PID2023-147306NB-I00 (MCIN/AEI/ 10.13039/501100011033)
  - Severo Ochoa (CEX2023-001292-S)

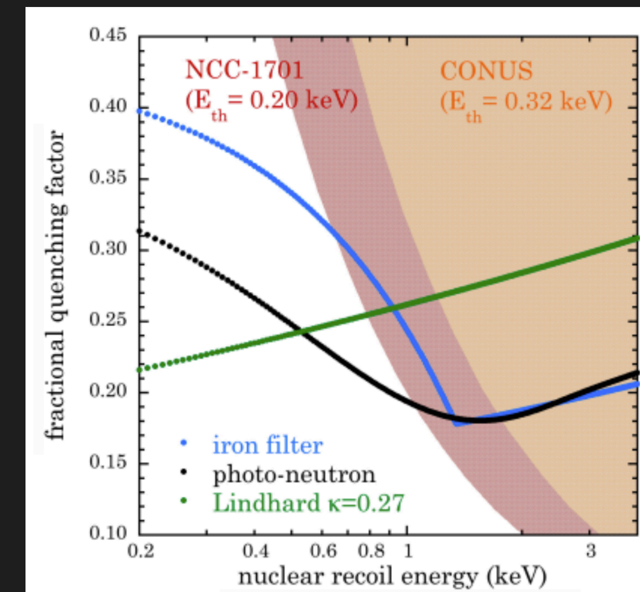
LIST OF CEvNS OBSERVATIONS

Hard to reconcile different measurements with the same choice of quenching factor.

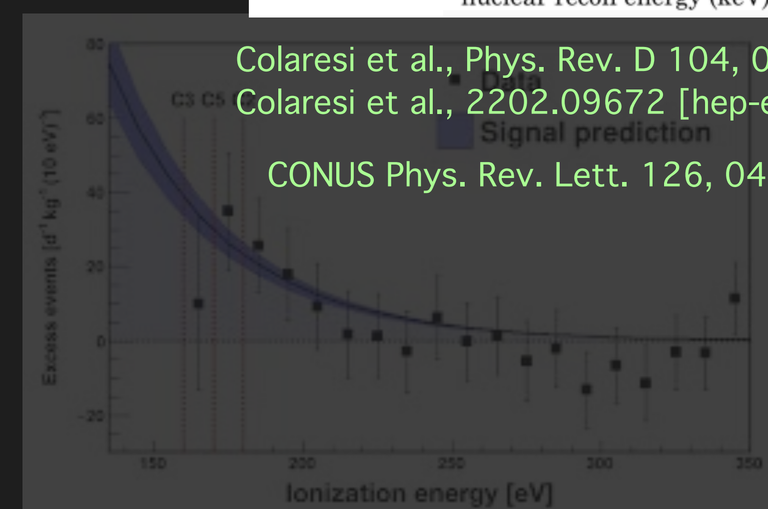
New results from vGEN and more (e.g., Ricochet) expected soon.

Y. Li+, 2502.12308

Ch. Phys. C 49 053004 (2025)



Quenching factor dependence!



Colaresi et al., Phys. Rev. D 104, 072003 (2021)
Colaresi et al., 2202.09672 [hep-ex]

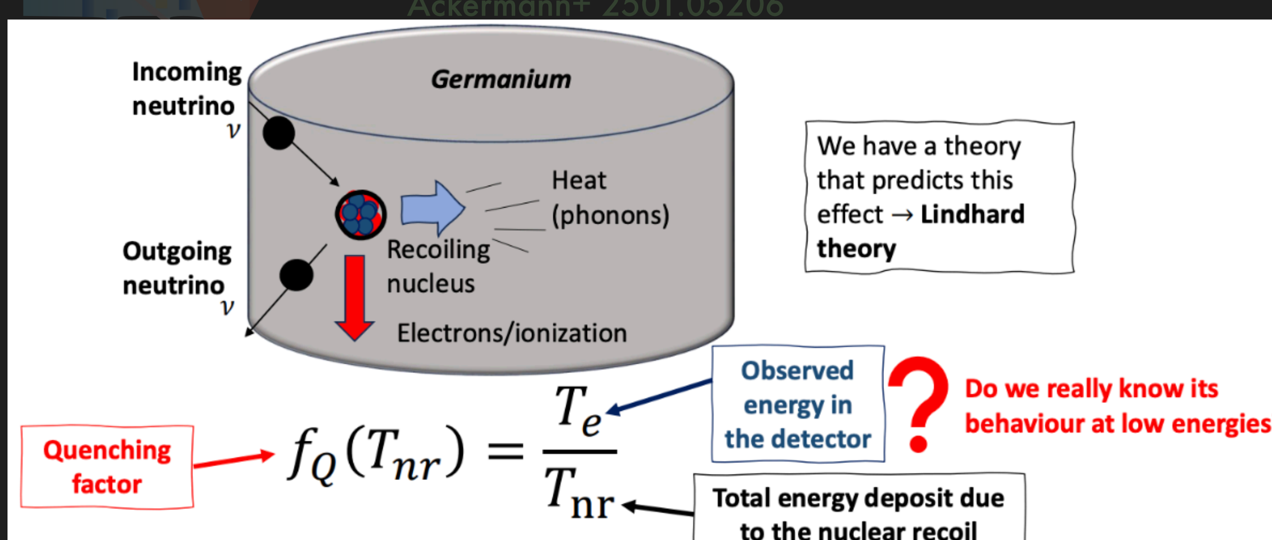
CONUS Phys. Rev. Lett. 126, 041804

- 2022: Dresden-II, Ge

Colaresi, Collar et al. Phys. Rev. Lett. 129 (2022) 211802

- 2025: CONUS+, Ge, 3.7σ CL

Ackermann+ 2501.05206

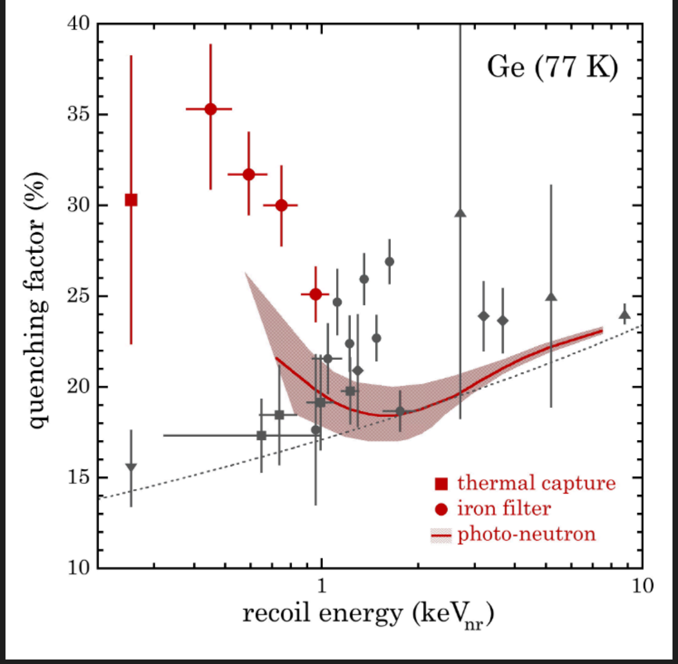


Credit: Atzori Corona Magnificent CEvNS 2024

EVIDENCE OF CEνNS ? AT NCC-1701 (DRESDEN-II REACTOR)

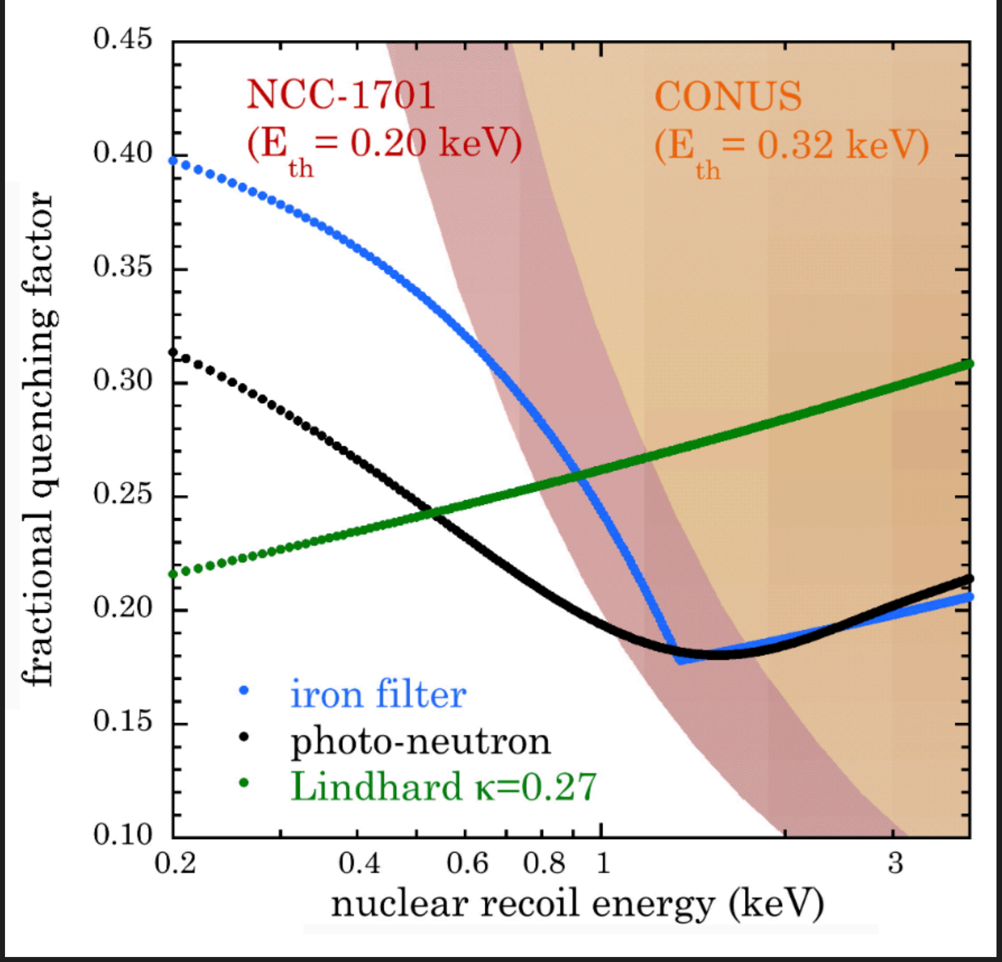
The quenching factor (QF) describes the observed reduction in ionization yield produced by a nuclear recoil when compared to an electron recoil of same energy

- often not (yet) well known at low recoil energies for CEνNS
- major uncertainty!



J.I. Collar et al, Phys. Rev. D 103, 122003

$$QF = E_{meas}/E_{nuclear\ recoil}$$



Colaresi et al., Phys. Rev. D 104, 072003 (2021)
Colaresi et al., 2202.09672 [hep-ex]

CONUS: Direct measurement of ionization quenching factor: k=0.162+-0.004 (compatible with Lindhard)

CONUS Phys. Rev. Lett. 126, 041804

Statistical analysis

CsI

$$\chi^2_{\rm CsI}\Big|_{\rm CE\nu NS(+ES)} = 2\sum_{i=1}^{9}\sum_{j=1}^{11}\left[N_{\rm th}^{\rm CsI} - N_{ij}^{\rm exp} + N_{ij}^{\rm exp}\ln\left(\frac{N_{ij}^{\rm exp}}{N_{\rm th}^{\rm CsI}}\right)\right] + \sum_{k=0}^{4(5)}\left(\frac{\alpha_k}{\sigma_k}\right)^2 .$$

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

- COHERENT Collaboration Phys.Rev.Lett. 129 no. 8, (2022) 081801

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

LAr

- $\sigma_0 = 13\%$ normal. CEνNS
- $\sigma_3 = 0.79\%$ SS
- $\sigma_8 = 100\%$ delayed BRN
- $\sigma_4 = 32\%$ prompt BRN
- β_1, β_2, β_5, β_6 and β_7 shape uncertainties

$$\begin{aligned} \chi^2_{\rm LAr} = \sum_{i=1}^{12}\sum_{j=1}^{10}\frac{1}{\sigma_{ij}^2}\Big[&(1+\beta_0+\beta_1\Delta_{\rm CE\nu NS}^{F_{90+}}+\beta_1\Delta_{\rm CE\nu NS}^{F_{90-}}+\beta_2\Delta_{\rm CE\nu NS}^{t_{\rm trig}})N_{ij}^{\rm CE\nu NS} \\ &+(1+\beta_3)N_{ij}^{\rm SSB} \\ &+(1+\beta_4+\beta_5\Delta_{\rm pBRN}^{E_+}+\beta_5\Delta_{\rm pBRN}^{E_-}+\beta_6\Delta_{\rm pBRN}^{t_{\rm trig}^+}+\beta_6\Delta_{\rm pBRN}^{t_{\rm trig}^-}+\beta_7\Delta_{\rm pBRN}^{t_{\rm trig}^{\rm w}})N_{ij}^{\rm pBRN} \\ &+(1+\beta_8)N_{ij}^{\rm dBRN}-N_{ij}^{\rm exp}\Big]^2 \\ &+\sum_{k=0,3,4,8}\left(\frac{\beta_k}{\sigma_k}\right)^2+\sum_{k=1,2,5,6,7}(\beta_k)^2 , \end{aligned}$$

- Atzori-Corona et al. 2205.09484, COHERENT Collaboration 2006.12659

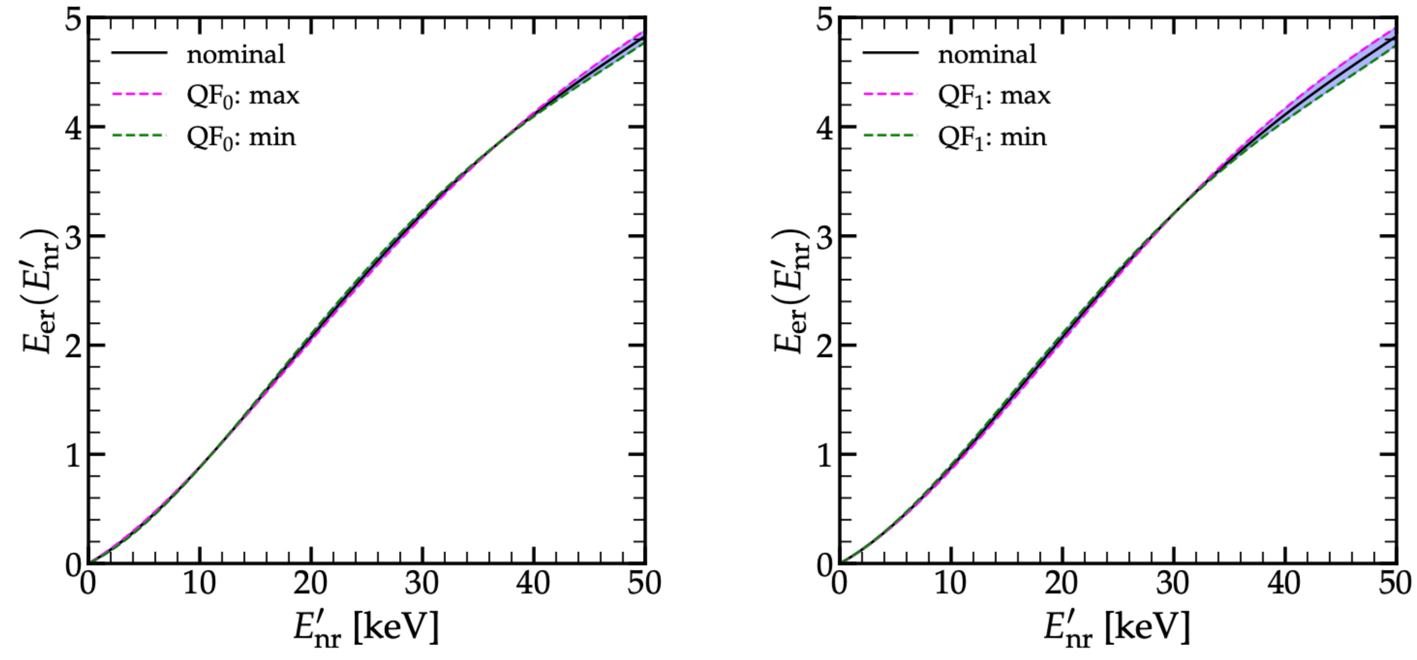
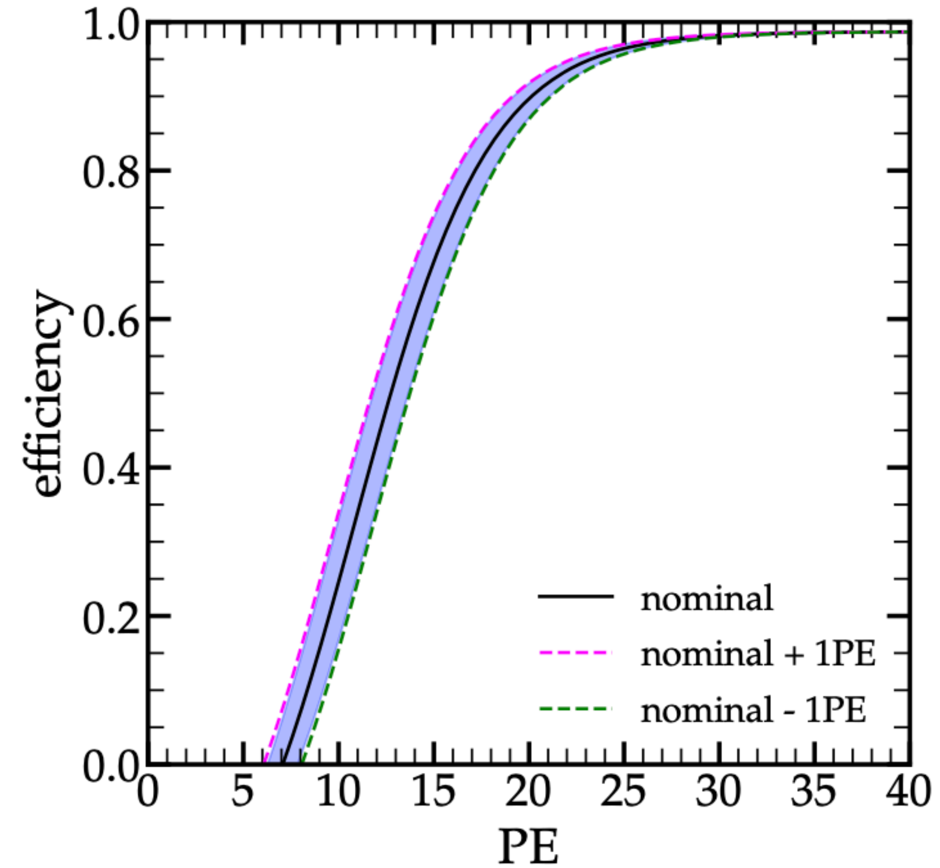


FIG. 17: COHERENT-CsI scintillation curve as function of the true nuclear recoil energy for the two QF models reported by COHERENT [8].



$$\chi^2_{\rm LAr} = \sum_{i=1}^{12}\sum_{j=1}^{10}\frac{1}{\sigma_{ij}^2}\Big[(1+\beta_0+\beta_1\Delta^{F_{90+}}_{{\rm CE}\nu{\rm NS}}+\beta_1\Delta^{F_{90-}}_{{\rm CE}\nu{\rm NS}}+\beta_2\Delta^{\rm t_{trig}}_{{\rm CE}\nu{\rm NS}})N_{ij}^{{\rm CE}\nu{\rm NS}}$$
$$+(1+\beta_3)N_{ij}^{\rm SSB}$$
$$+(1+\beta_4+\beta_5\Delta^{E_+}_{\rm pBRN}+\beta_5\Delta^{E_-}_{\rm pBRN}+\beta_6\Delta^{t^+_{\rm trig}}_{\rm pBRN}+\beta_6\Delta^{t^-_{\rm trig}}_{\rm pBRN}+\beta_7\Delta^{t^{\rm w}_{\rm trig}}_{\rm pBRN})N_{ij}^{\rm pBRN}$$
$$+(1+\beta_8)N_{ij}^{\rm dBRN}-N_{ij}^{\rm exp}\Big]^2$$
$$+\sum_{k=0,3,4,8}\left(\frac{\beta_k}{\sigma_k}\right)^2+\sum_{k=1,2,5,6,7}(\beta_k)^2\,, \tag{39}$$

where $\sigma_{ij}^2 = N_{ij}^{\rm exp} + N_{ij}^{\rm SSB}/5$. The nuisance parameters β_0, β_3, β_4 and β_8 are introduced to account for the normalization of CEνNS [10], SS, prompt BRN and delayed BRN, respectively, with the corresponding uncertainties being $\{\sigma_0,\ \sigma_3,\ \sigma_4,\ \sigma_8\}=\{0.13,\ 0.0079,\ 0.32,\ 1.0\}$ [9]. The shape uncertainties are taken into account by introducing the nuisance parameters $\beta_1, \beta_2, \beta_5, \beta_6$ and β_7. The first two parameters modify the shape of the CEνNS prediction, while the last three affect the shape of the prompt BRN background. In particular, for the case of CEνNS, the relevant sources of systematic uncertainty are the $\pm 1\sigma$ energy distributions of the F_{90} parameter, given by $\Delta^{F_{90+}}_{{\rm CE}\nu{\rm NS}}$ and $\Delta^{F_{90-}}_{{\rm CE}\nu{\rm NS}}$, and the mean time to trigger distribution, $\Delta^{\rm t_{trig}}_{{\rm CE}\nu{\rm NS}}$. Similarly, for the shape of the prompt BRN background, the relevant distributions are the $\pm 1\sigma$ energy distributions ($\Delta^{E_+}_{\rm pBRN}$ and $\Delta^{E_-}_{\rm pBRN}$), the $\pm 1\sigma$ mean time to trigger distributions ($\Delta^{t^+_{\rm trig}}_{\rm pBRN}$ and $\Delta^{t^-_{\rm trig}}_{\rm pBRN}$) and the trigger width distribution ($\Delta^{t^{\rm w}_{\rm trig}}_{\rm pBRN}$). These distributions, introduced in Eq. (39), are defined as

$$\Delta_\lambda^{\xi_\lambda} = \frac{N_{ij}^{\lambda,\xi_\lambda} - N_{ij}^{\lambda,{\rm CV}}}{N_{ij}^{\lambda,{\rm CV}}}\,, \tag{40}$$

where λ = {CEνNS, pBRN, ξ_λ is any of the sources relevant to the given λ as described above, while CV denotes the central values of the CEνNS or prompt BRN distributions, all taken from

Coherent Elastic νeutrino-Nucleus Scattering (CEνNS)

Heavy target nucleus:

A = 133, M ~ 133 GeV
R = 1.2 $A^{1/3}$ ~ 6 fm

CEνNS occurs for $|\vec{q}| \lesssim 35$ MeV

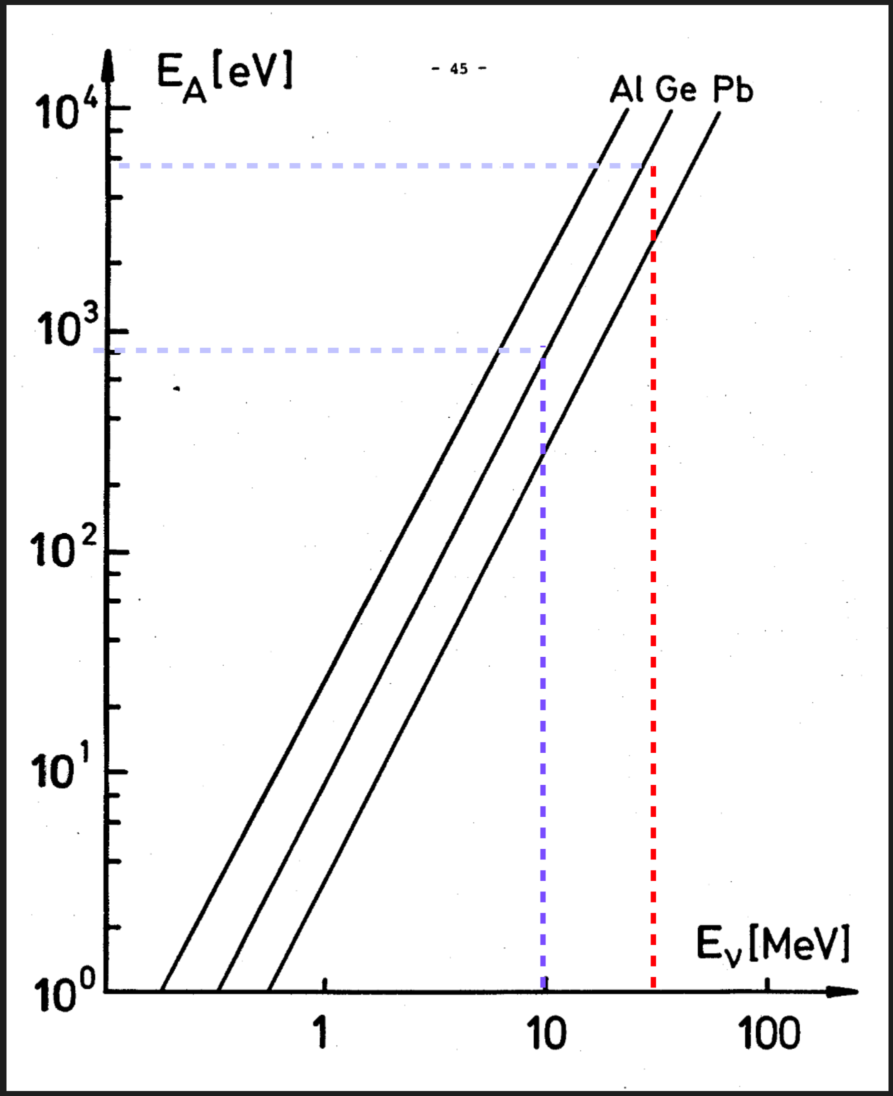
Maximum nuclear recoil is $E_R^{\max} = \dfrac{2E_\nu^2}{m_N}$

Accelerator neutrinos: $E_\nu \lesssim 50\ \mathrm{MeV}$ $E_R \lesssim \mathcal{O}(10)\ \mathrm{keV}$

Close to decoherence

Reactor neutrinos: $E_\nu \lesssim 10\ \mathrm{MeV}$ $E_R \lesssim \mathcal{O}(100)\ \mathrm{eV}$

Full coherence



Drukier, Stodolsky, PRD 30 (1984) 2295

- No threshold
- Heavier nuclei: higher cross section but lower recoil
- Both cross-section and maximum recoil energy increase with neutrino energy