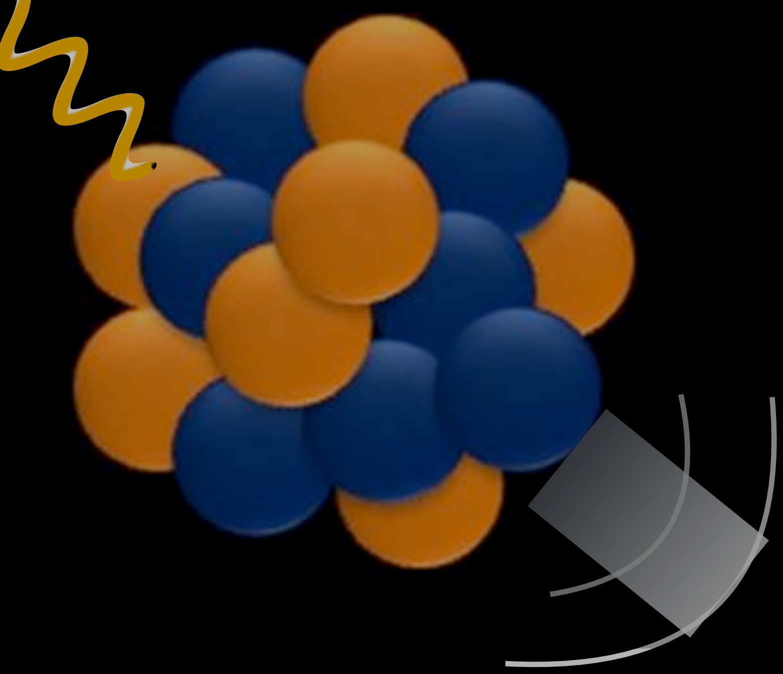
Valentina De Romeri
(IFIC Valencia - UV/CSIC)

Coherent elastic neutrino-nucleus scattering in the Standard Model and beyond

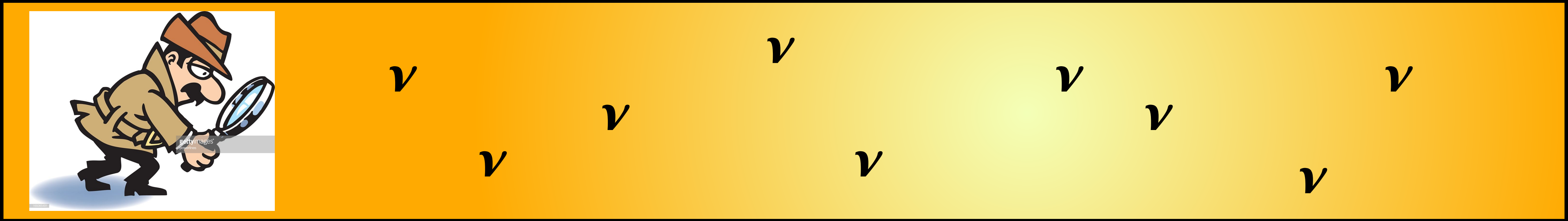

The Dark Side of the Universe DSU2022



7 December 2022
University of New South Wales (UNSW) Sydney, Australia

Outline

- Introduction and motivations
  - Coherent elastic neutrino nucleus scattering (CEνNS)
  - Observation of CEνNS at COHERENT
  - Evidence of CEνNS at Dresden-II
- Physics potential of CEνNS
  - SM physics (weak mixing angle)
  - New interactions: NSI
  - New interactions: NGI
  - New interactions: Light mediators
  - New electromagnetic properties
- Impact on the neutrino floor
- Summary



Coherent Elastic Neutrino-Nucleus Scattering

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

- CEνNS occurs when the neutrino energy E_ν is such that nucleon amplitudes sum up coherently ($|\vec{q}| \leq 1/R_{\text{nucleus}}$):
  => cross section enhancement $\sigma \sim (\#\text{scatter targets})^2$
  => upper limit on neutrino energy (up to $E_\nu \sim 100$ MeV)

- Total cross section scales approximately like N^2

$$\frac{d\sigma}{dE_R} \propto N^2$$

- Can be few orders of magnitude larger than inverse beta decay process used to first observe neutrinos

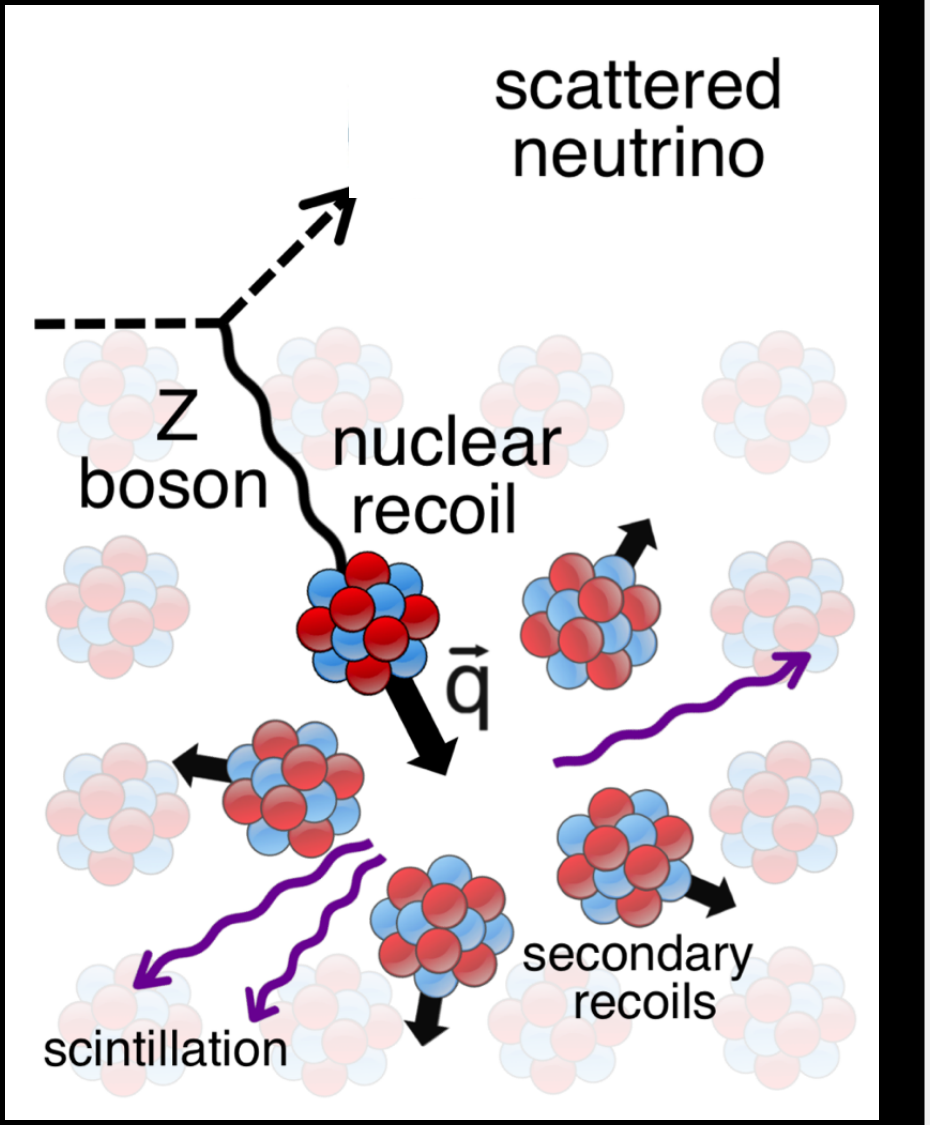


Image adapted from COHERENT exp.

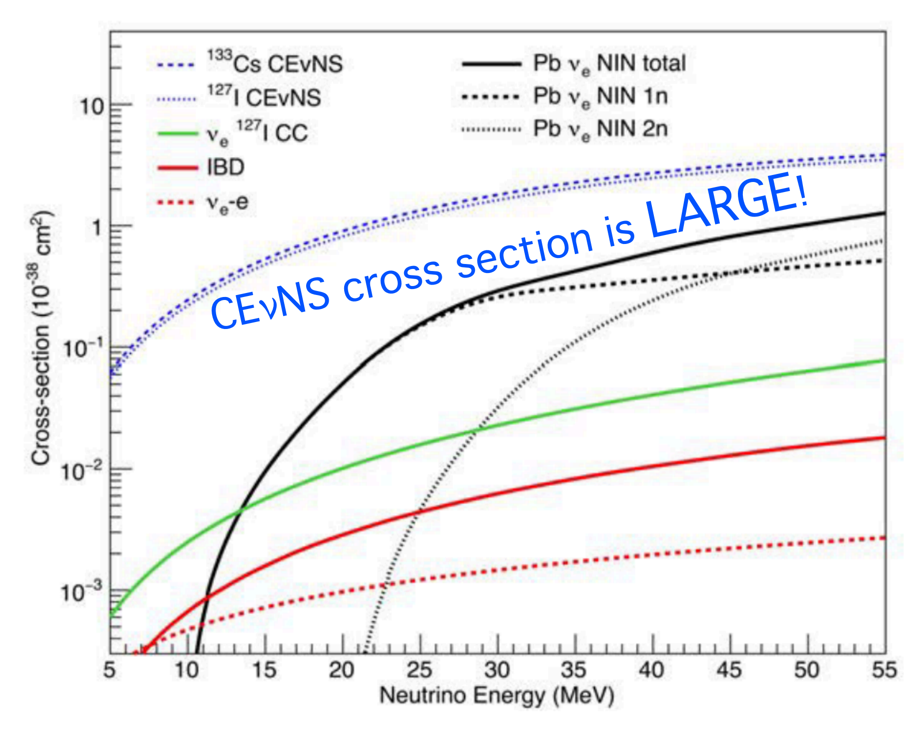
D.Z. Freedman, Phys. Rev. D 9 (1974)
V.B. Kopeliovich and L.L. Frankfurt, ZhETF Pis. Red. 19 (1974)

Coherent Elastic Neutrino-Nucleus Scattering

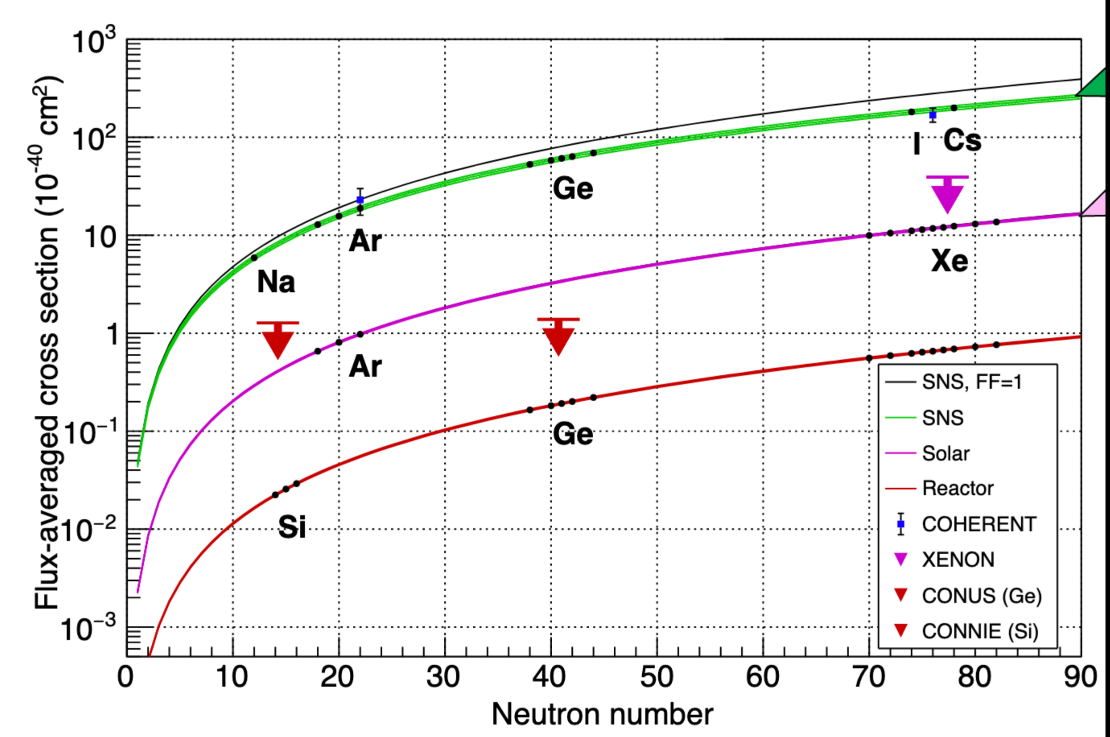
- First theoretically predicted in 1974

D.Z. Freedman, Phys. Rev. D 9 (1974)
V.B. Kopeliovich and L.L. Frankfurt, ZhETF Pis. Red. 19 (1974)

- CEνNS is an exceptionally challenging process to observe
- Despite its large cross section, not observed for years due to tiny nuclear recoil energies
  - Heavier nuclei: higher cross section but lower recoil
  - Both cross-section and maximum recoil energy increase with neutrino energy
  - Max recoil energy: $E_R^{\max} = \dfrac{2E_\nu^2}{m_N}$

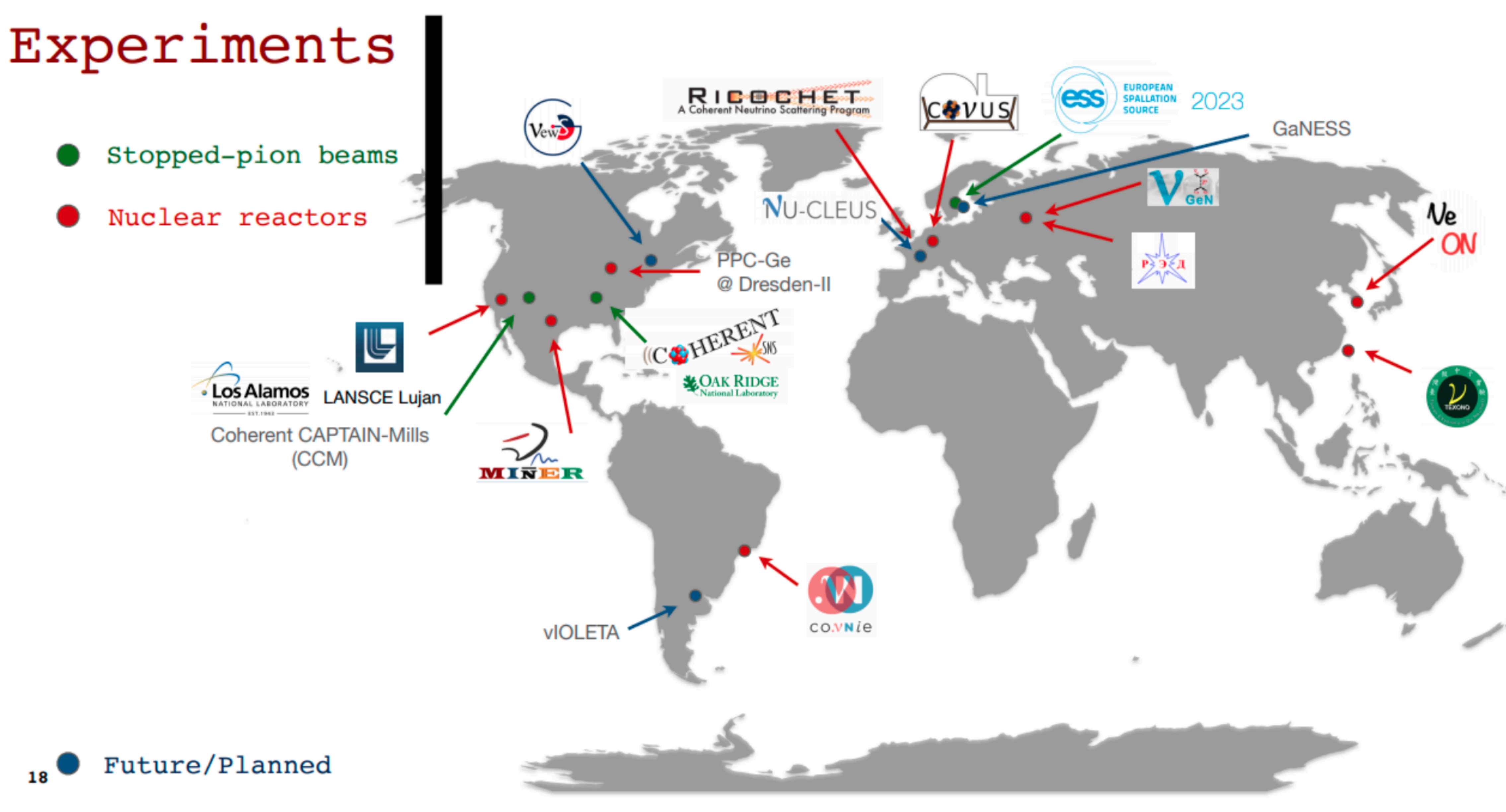

CEνNS cross section is LARGE!

D. Akimov et al. (COHERENT). Science 357, 1123–1126 (2017)



Credit to K. Scholberg @ISAPP 2021

CEvNS experiments worldwide



Credit to M. Green @Aspen 2019 Winter Conference

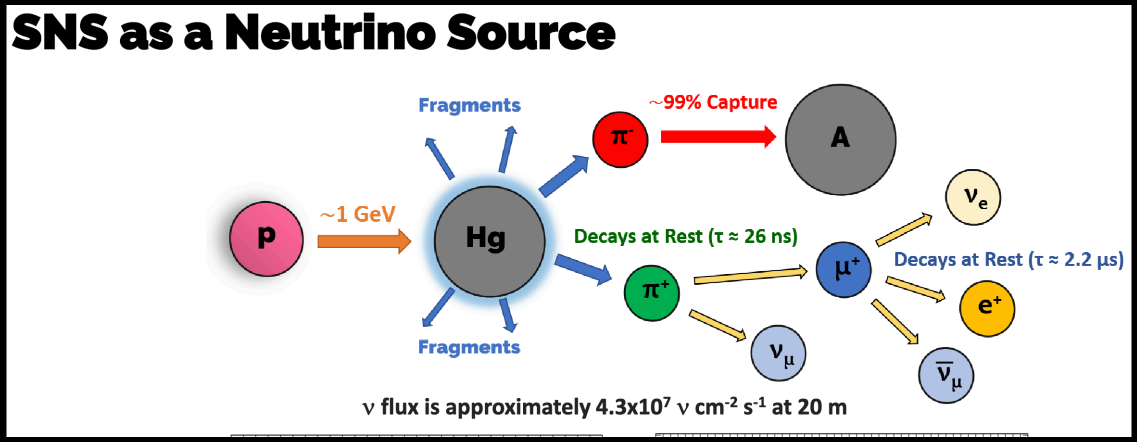
+ SBC (Mexico), JSNS^2 (Japan) …

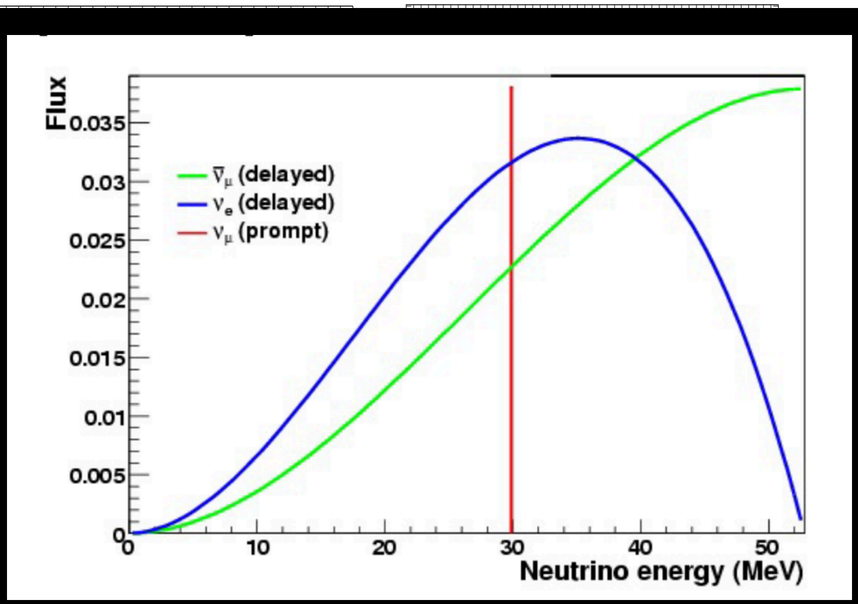
Neutrino sources

Preferable requisites:

- High flux
- Well understood spectrum
- Multiple flavours
- Possibility of locating the detector close
- Background rejection

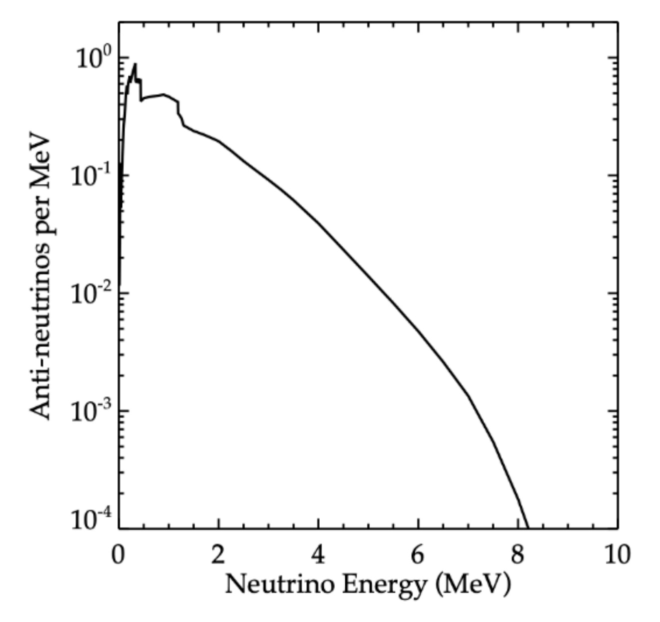
Stopped-Pion (π-DAR) Neutrinos





D. Akimov et al. (COHERENT). 2110.07730

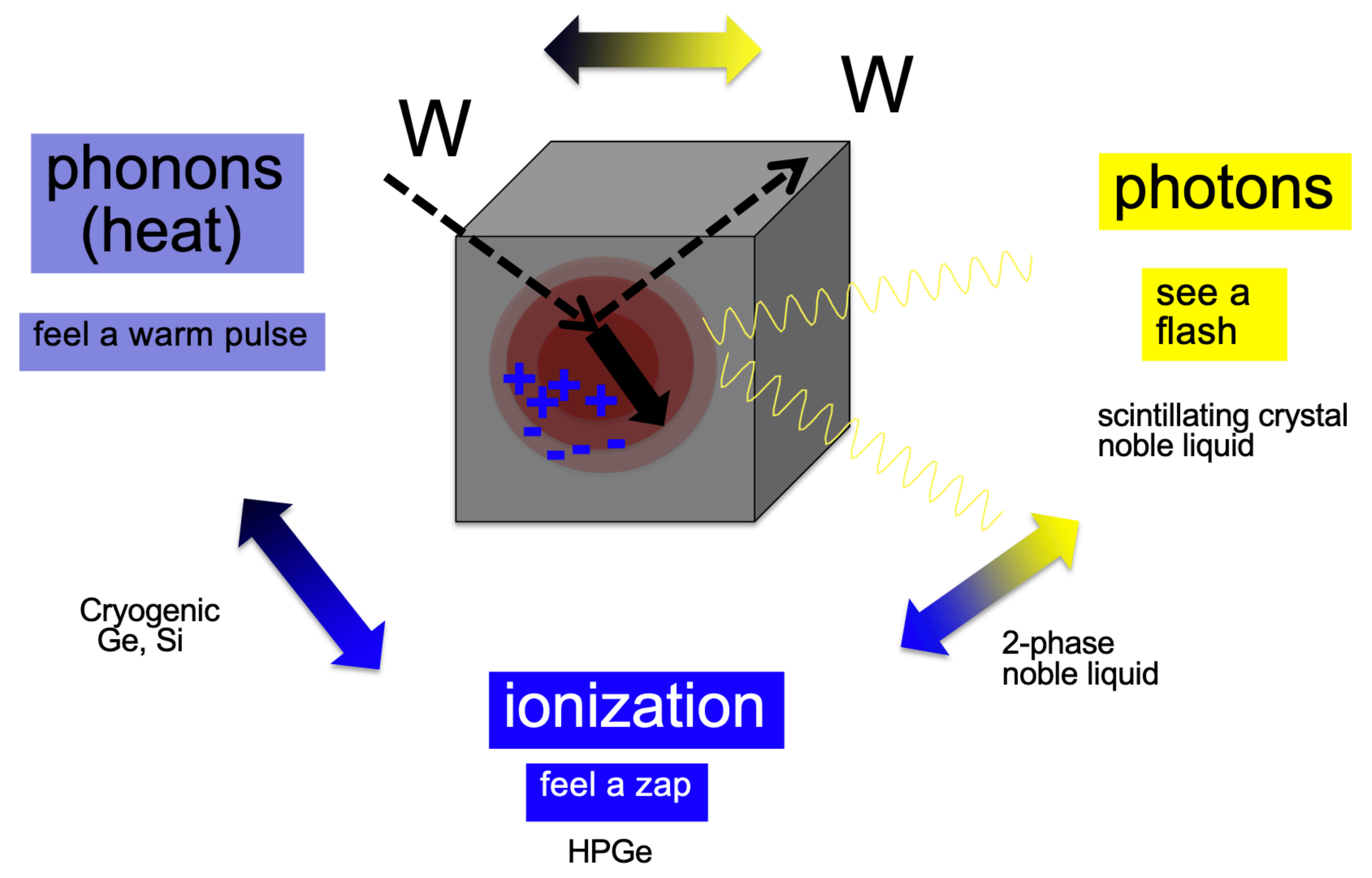
Neutrinos from nuclear reactors



Snowmass 2021 2203.07361

- ^{51}Cr, an electron-capture decaying isotope (four monochromatic lines)
- Geo-neutrinos
- Next-generation neutrino beams (more energetic)

Low-energy nuclear recoil detection strategies



phonons (heat)

feel a warm pulse

photons

see a flash

scintillating crystal
noble liquid

Cryogenic
Ge, Si

2-phase
noble liquid

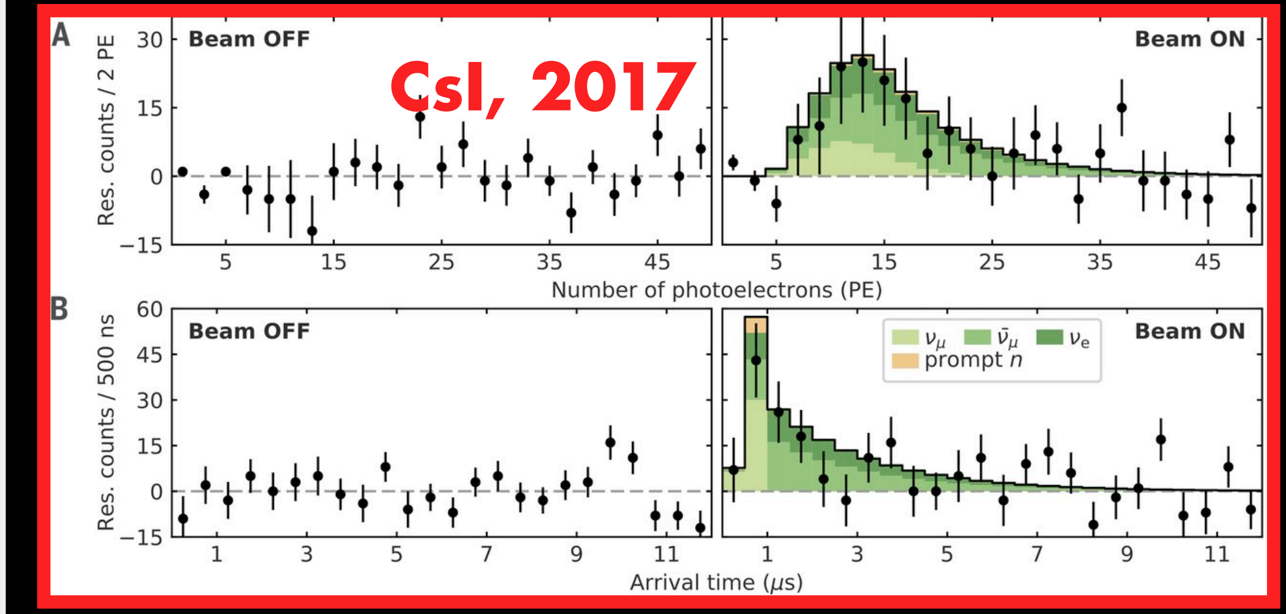
ionization

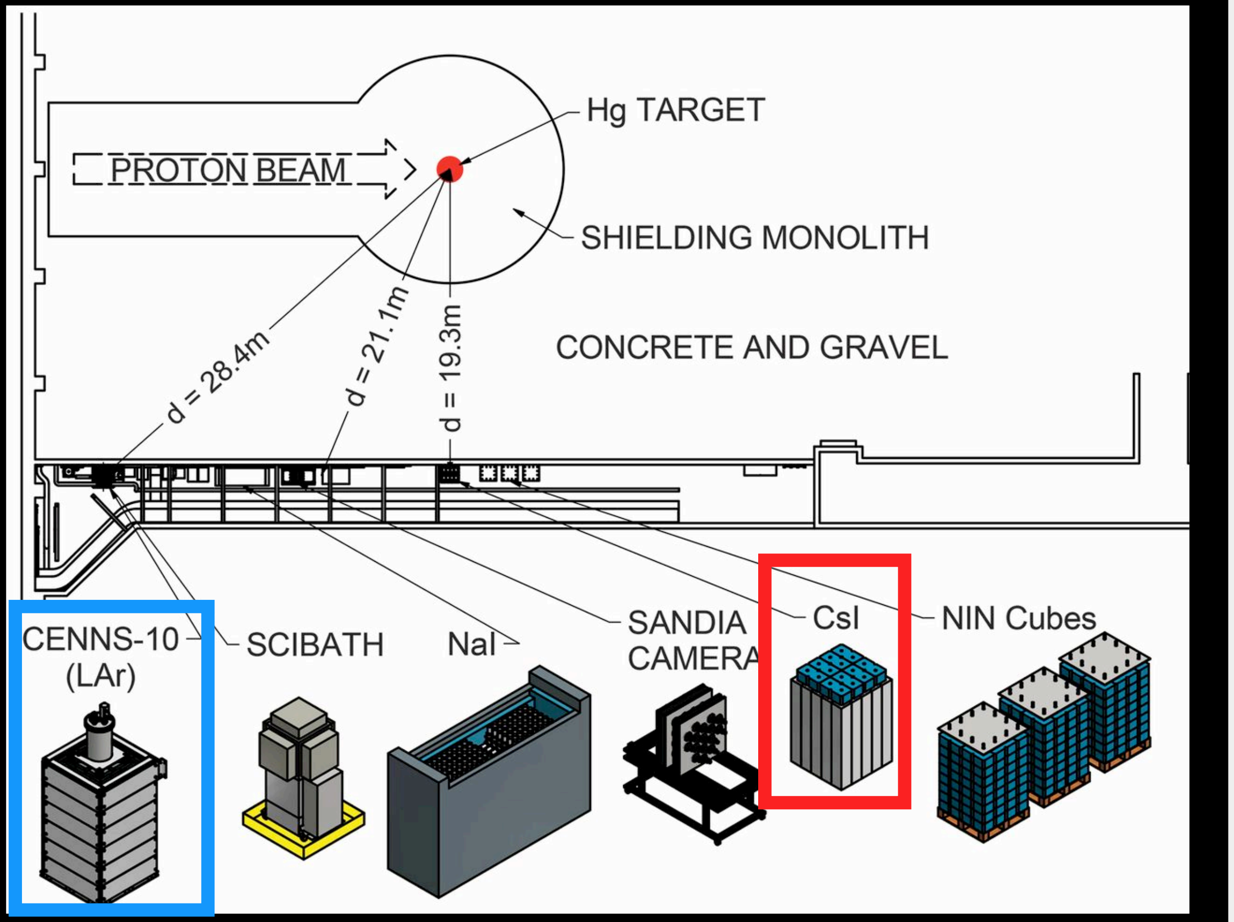
feel a zap

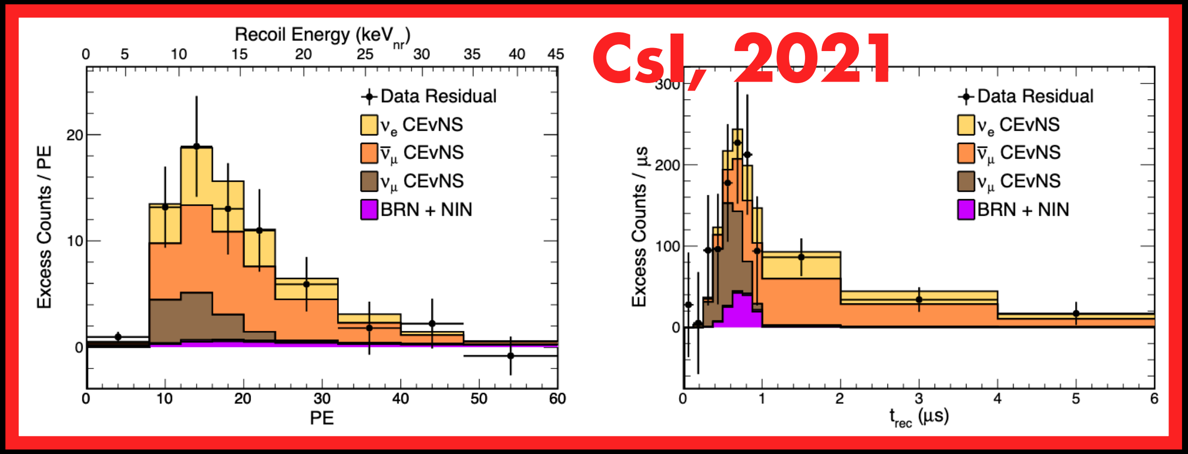
HPGe

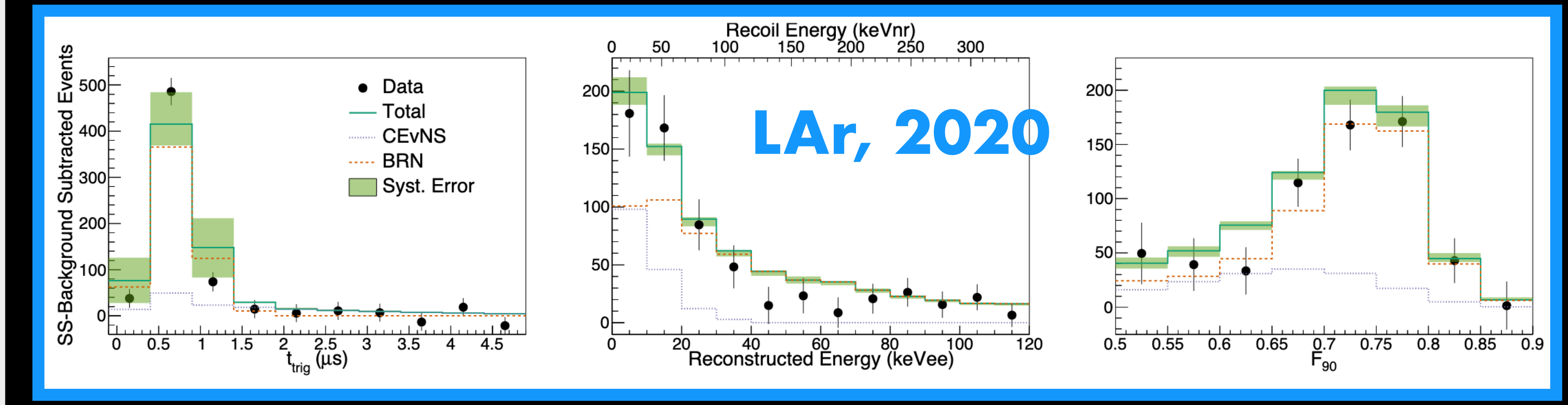
Credit to K. Scholberg @INSS 2021

Observation of CEνNS by COHERENT









D. Akimov et al. (COHERENT). Science 357, 1123–1126 (2017)
D. Akimov et al. (COHERENT). 2110.07730
D. Akimov et al. (COHERENT). Phys. Rev. Lett. 126, 012002 (2021)
Daughhetee, BNL Physics Seminar 2020

Evidence of CEνNS at CC-1701 (Dresden-II reactor)

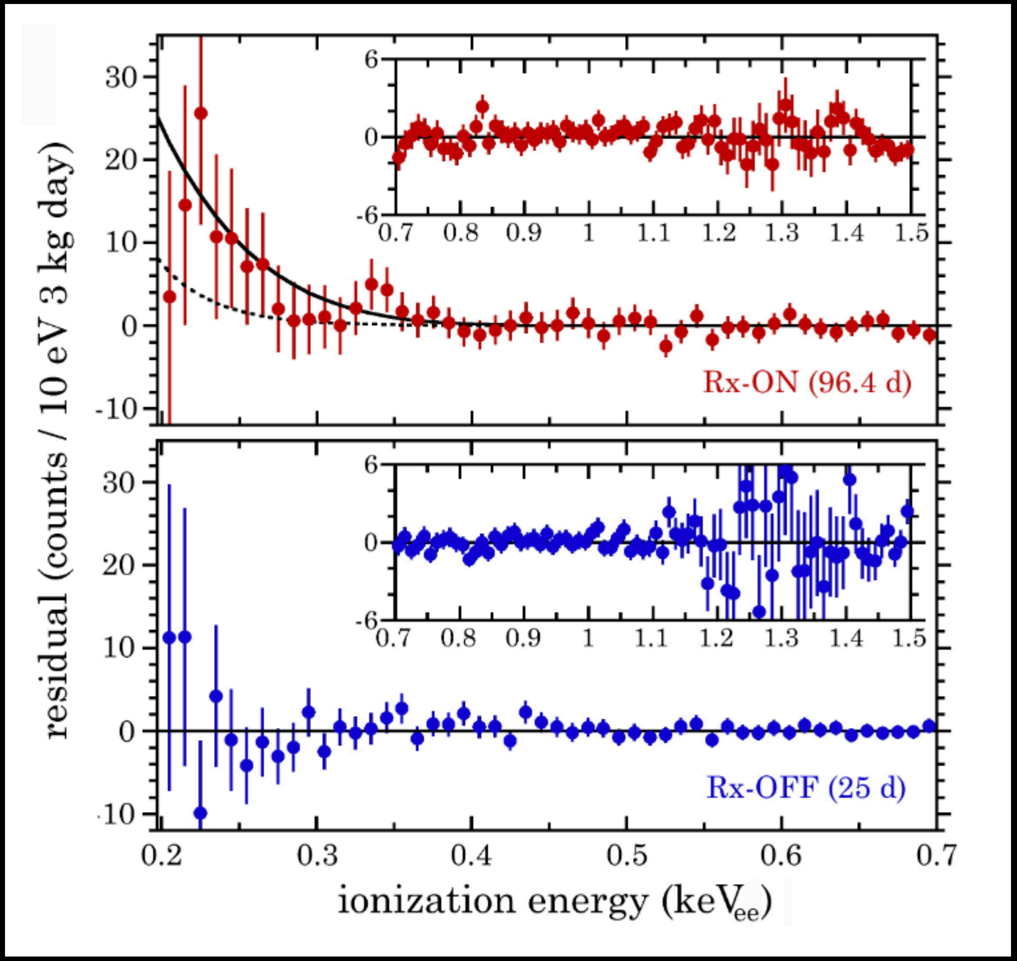
Neutrino source: Dresden-II boiling water reactor (USA) 2.96GW → 4.8 x10^{13} neutrinos/sec/cm^2

Detector: NCC-1701, a 2.924 kg ultra-low noise p-type point contact (PPC) Germanium detector

- low energy threshold (0.2 keV$_{ee}$)
- distance to core: 10.39m
- 96.4-day exposure

CEνNS results: suggestive evidence of CEνNS is reported with strong preference (with respect to the background-only hypothesis)

- strongly dependent on quenching factor model

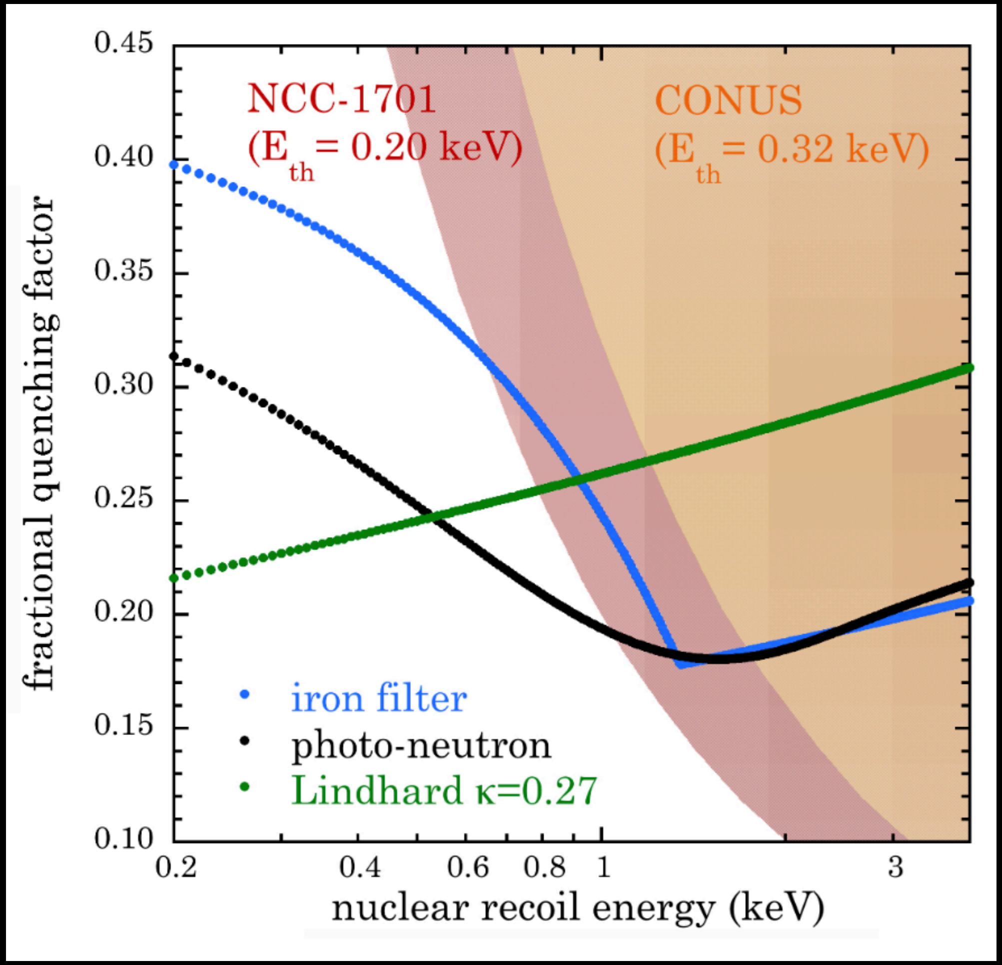


Colaresi, Collar, Hossbach, Lewis, Yocum, Phys.Rev.Lett. 129 (2022) 21, 211802

Evidence of CEνNS ? at CC-1701 (Dresden-II reactor)

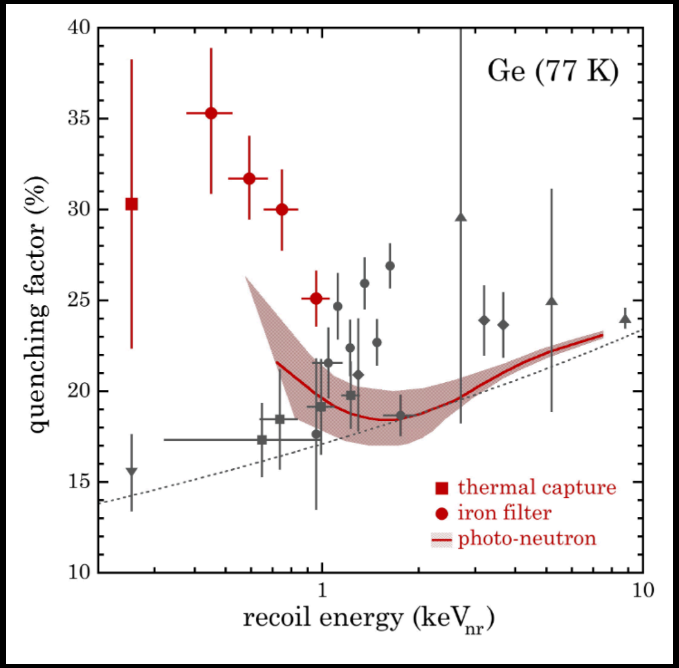
The quenching factor (QF) describes the observed reduction in ionization yield produced by a nuclear recoil when compared to an electron recoil of same energy

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



Colaresi et al., Phys. Rev. D 104, 072003 (2021)
Colaresi et al., Phys.Rev.Lett. 129 (2022) 21, 211802

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



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

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

CONUS Phys. Rev. Lett. 126, 041804

Coherent Elastic Neutrino-Nucleus Scattering

CEνNS has a well-calculable 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

$$\frac{d\sigma}{dT} = \frac{\boxed{G_F^2}M}{4\pi}\boxed{\left(1-\frac{MT}{2E_\nu^2}-\frac{T}{E_\nu}\right)}\boxed{Q_\mathrm{W}^2}\boxed{[F_\mathrm{W}(q^2)]^2} + \cancel{\frac{G_F^2 M}{4\pi}\left(1+\frac{MT}{2E_\nu^2}-\frac{T}{E_\nu}\right)F_A(q^2)}$$

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 $q^2 = 2MT$

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

- EW precision tests:
  - Weak mixing angle
- Nuclear physics
  - Nuclear form factors
  - Neutron radius and “skin”
- Supernovae
- Solar neutrinos

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

- New neutrino interactions
  - Non-standard interactions
  - Generalised interactions
  - New mediators
- Neutrino properties
  - Neutrino charge radius
  - Magnetic moments
- Sterile neutrinos
- Dark matter

Cerdeño et al, arXiv:1604.01025; Farzan et al, arXiv:1802.05171; Aristizabal Sierra et al, arXiv:1806.07424; Khan and Rodejohann, arXiv:1907.12444; Aristizabal Sierra et al, arXiv:1910.12437; Miranda et al, arXiv:2003.12050; Aristizabal Sierra et al, JHEP 09 (2019) 069; Suliga and Tamborra, arXiv:2010.14545; CONUS, arXiv:2110.02174; Li and Xia, arXiv:2201.05015; Atzori Corona et al, arXiv:2202.11002; Liao et al, arXiv:2202.10622; Coloma et al, arXiv:2202.10829; Lindner et al, arXiv:1612.04150; Aristizabal Sierra et al, arXiv:1806.07424; Aristizabal Sierra et al, JCAP 01 (2022) 01, 055, …………

Physics potential of CEνNS

- SM precision tests:
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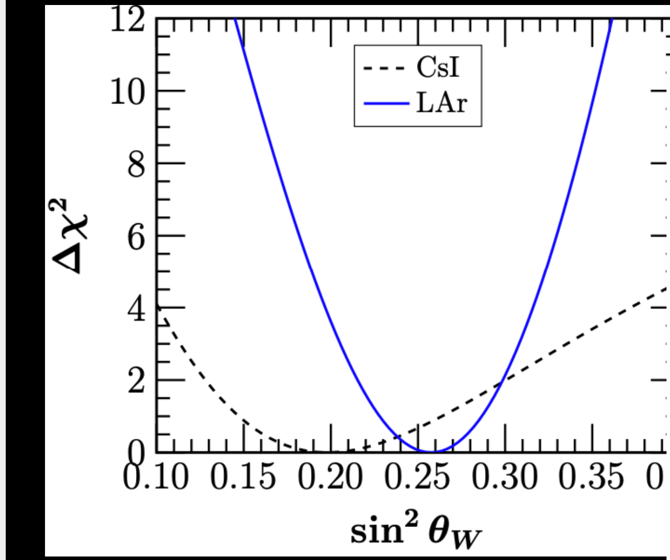
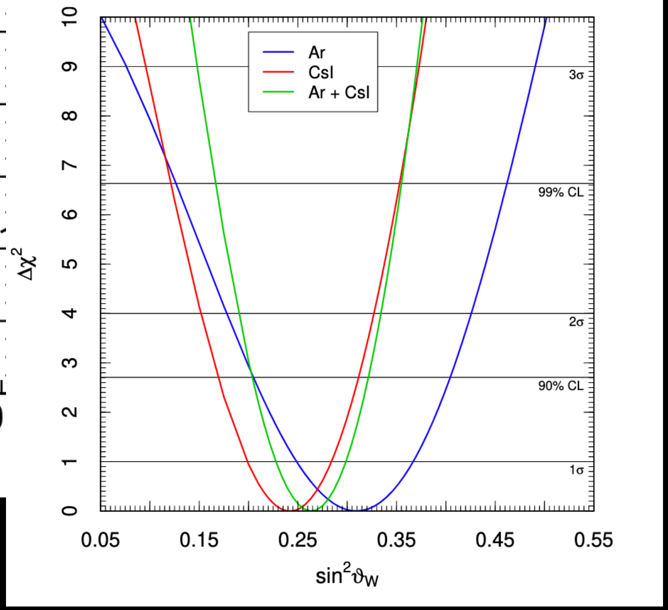
SM precision tests: weak mixing angle

COHERENT CsI (2017) + LAr

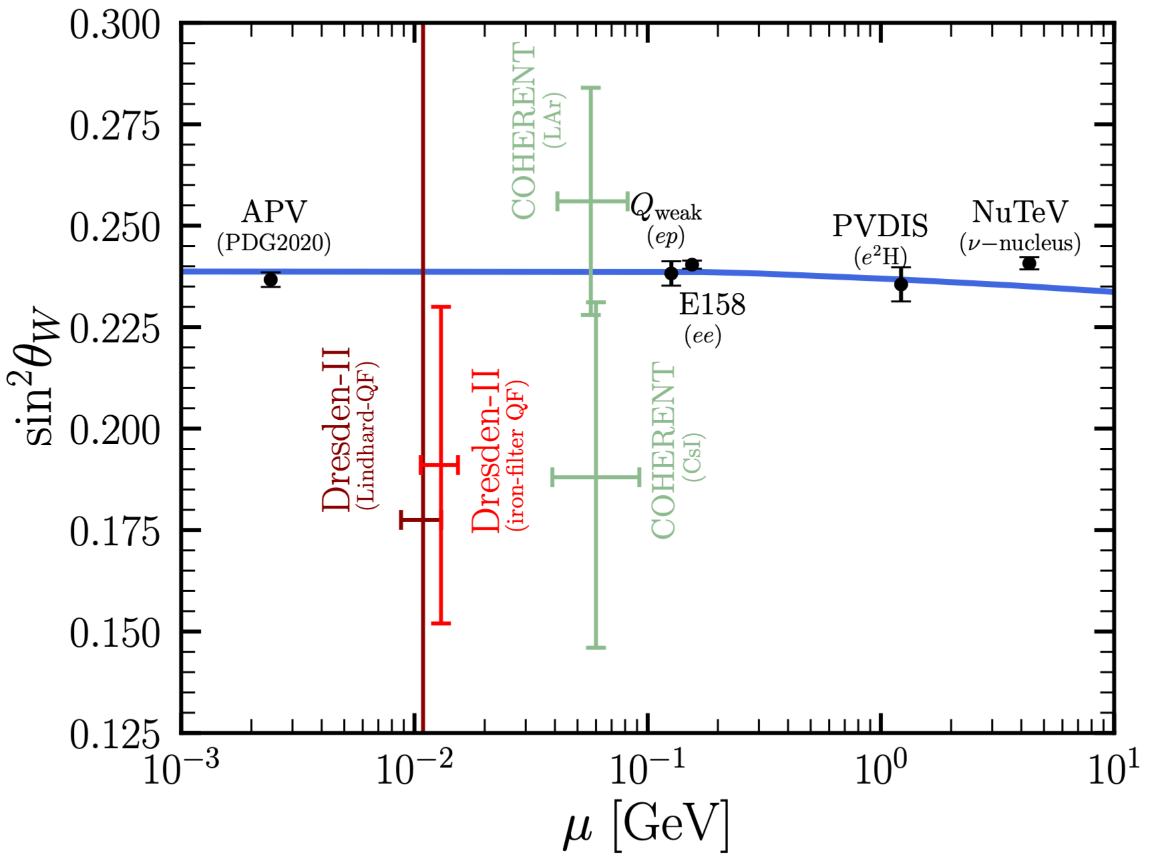


Miranda et al. JHEP 05 (2020) 130

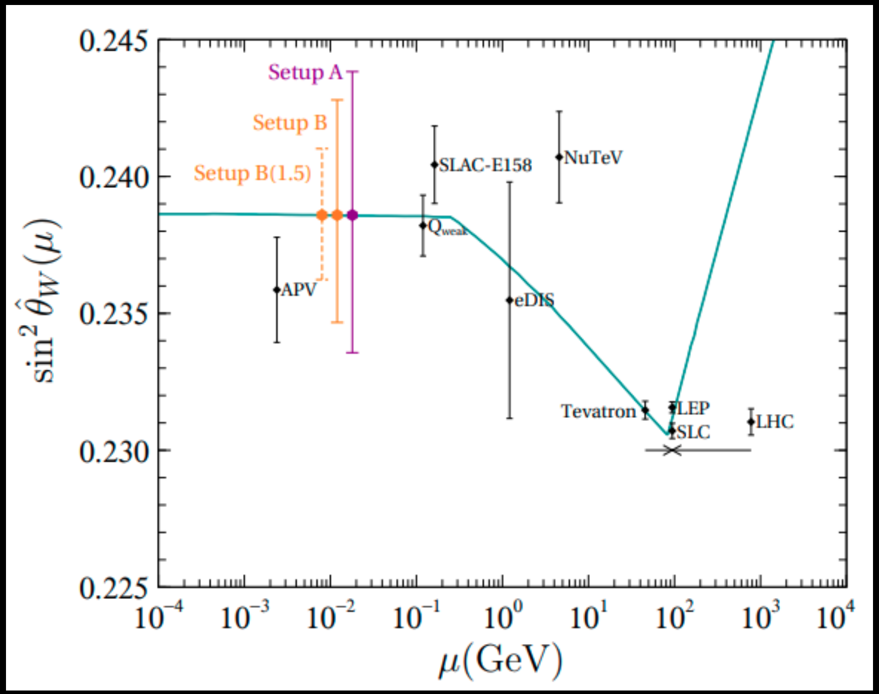


Cadeddu et al. Phys.Rev.D 102 (2020) 1, 015030

Dresden-II Ge



Aristizabal, VDR, Papoulias JHEP 09 (2022) 076
See also Majumdar+ 2208.13262 [hep-ph]

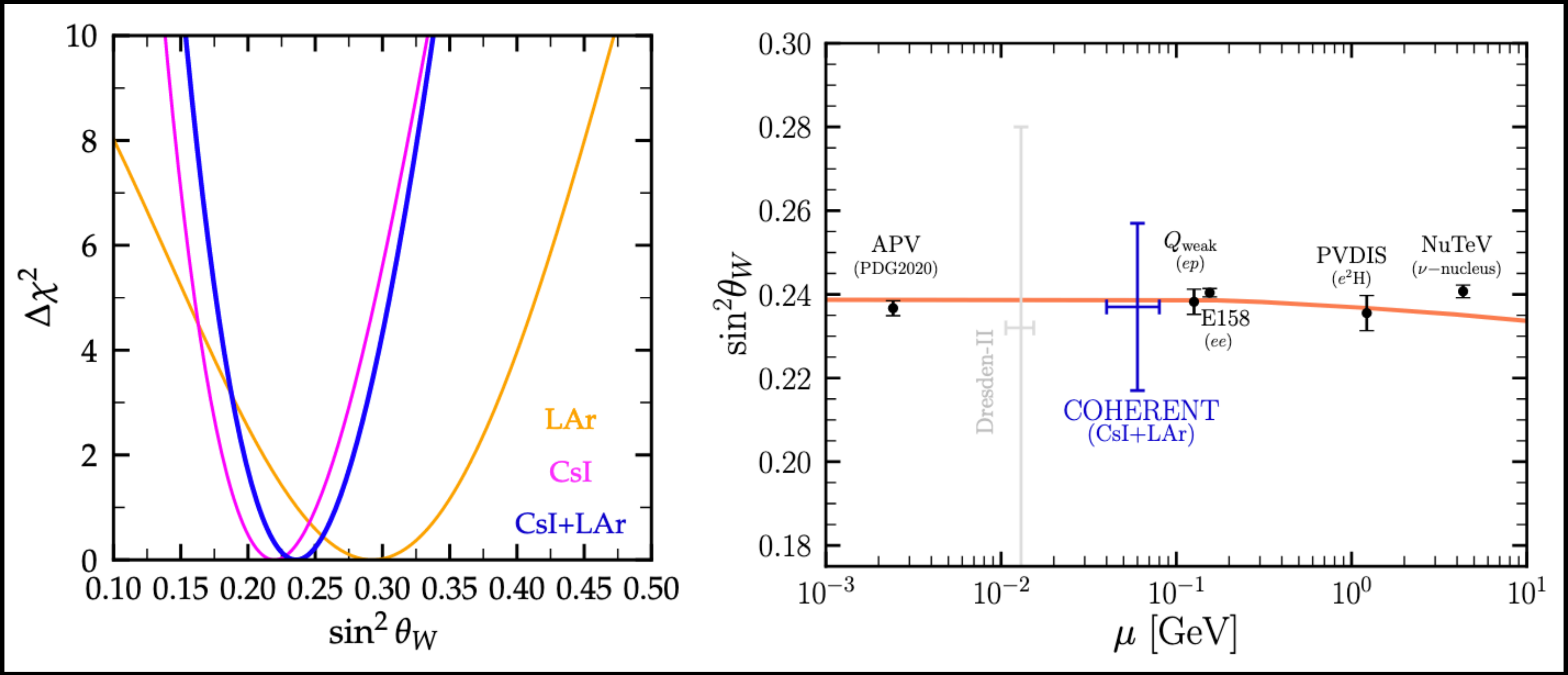


SBC LAr

[SBC Collaboration] L. J. Flores et al. Phys.Rev.D 103 (2021) 9, L091301

SM precision tests: weak mixing angle

COHERENT CsI (2021) + LAr



VDR, Miranda, Papoulias, Sanchez-García,Tórtola and Valle, 2211.11905 [hep-ph]
Majumdar+ 2208.13262 [hep-ph]

$$\boxed{\sin^2\theta_{\mathrm{W}} = 0.237 \pm 0.029} \quad (1\sigma)$$

See also: Cadeddu+ Phys. Rev. C 104 no. 6, (2021) 065502, Atzori-Corona+ JHEP 09 (2022) 164

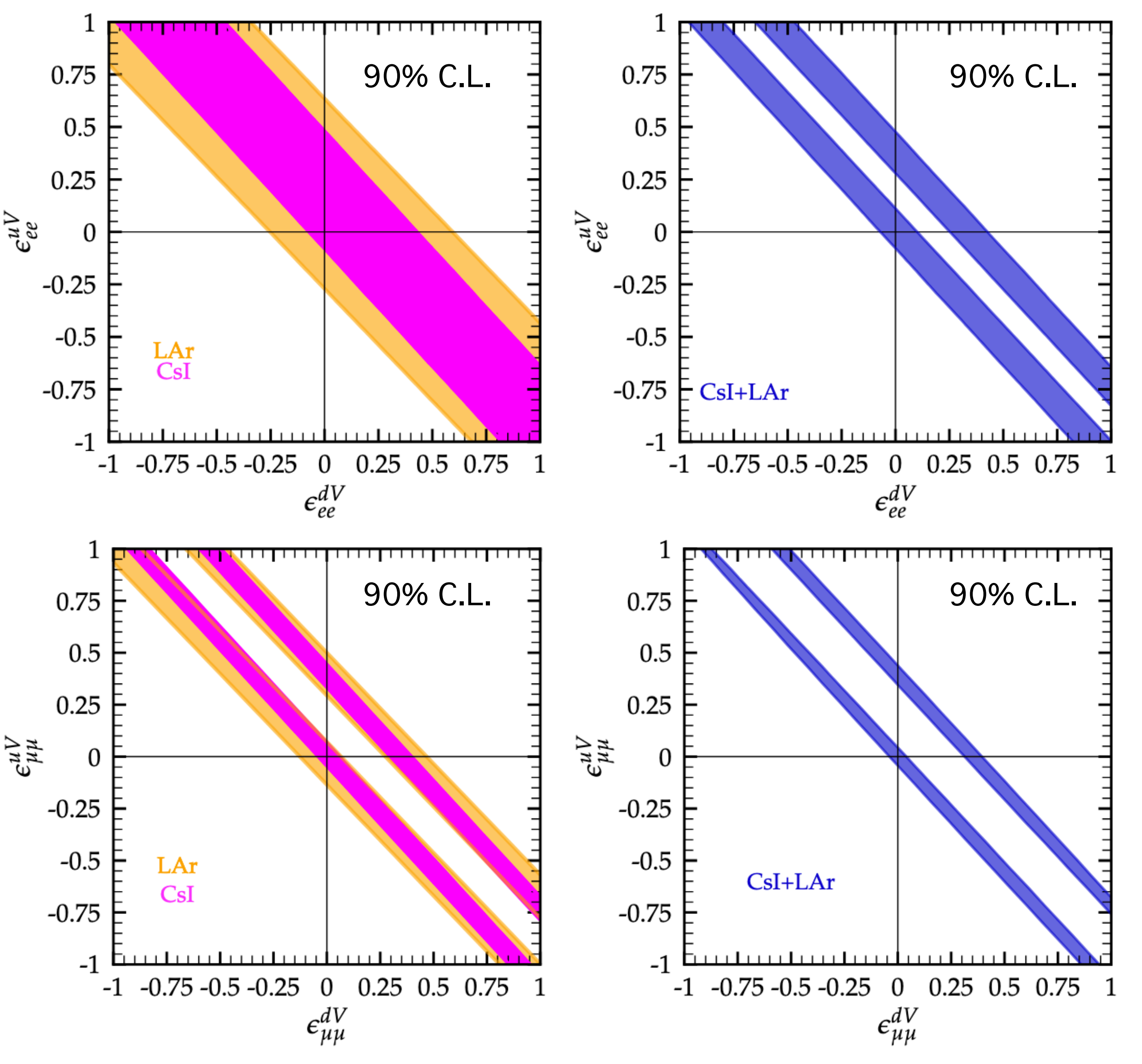
New neutrino interactions: NSI

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

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

$$\begin{aligned} Q_V^{\rm NSI} &= \left[\left(g_V^p + 2\varepsilon_{\alpha\alpha}^{uV} + \varepsilon_{\alpha\alpha}^{dV}\right) Z + \left(g_V^n + \varepsilon_{\alpha\alpha}^{uV} + 2\varepsilon_{\alpha\alpha}^{dV}\right) N\right] \\ &+ \sum_{\alpha} \left[\left(2\varepsilon_{\alpha\beta}^{uV} + \varepsilon_{\alpha\beta}^{dV}\right) Z + \left(\varepsilon_{\alpha\beta}^{uV} + 2\varepsilon_{\alpha\beta}^{dV}\right) N\right] . \end{aligned}$$

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



COHERENT CsI (2021) + LAr

VDR, Miranda, Papoulias, Sanchez-García, Tórtola and Valle, 2211.11905 [hep-ph]

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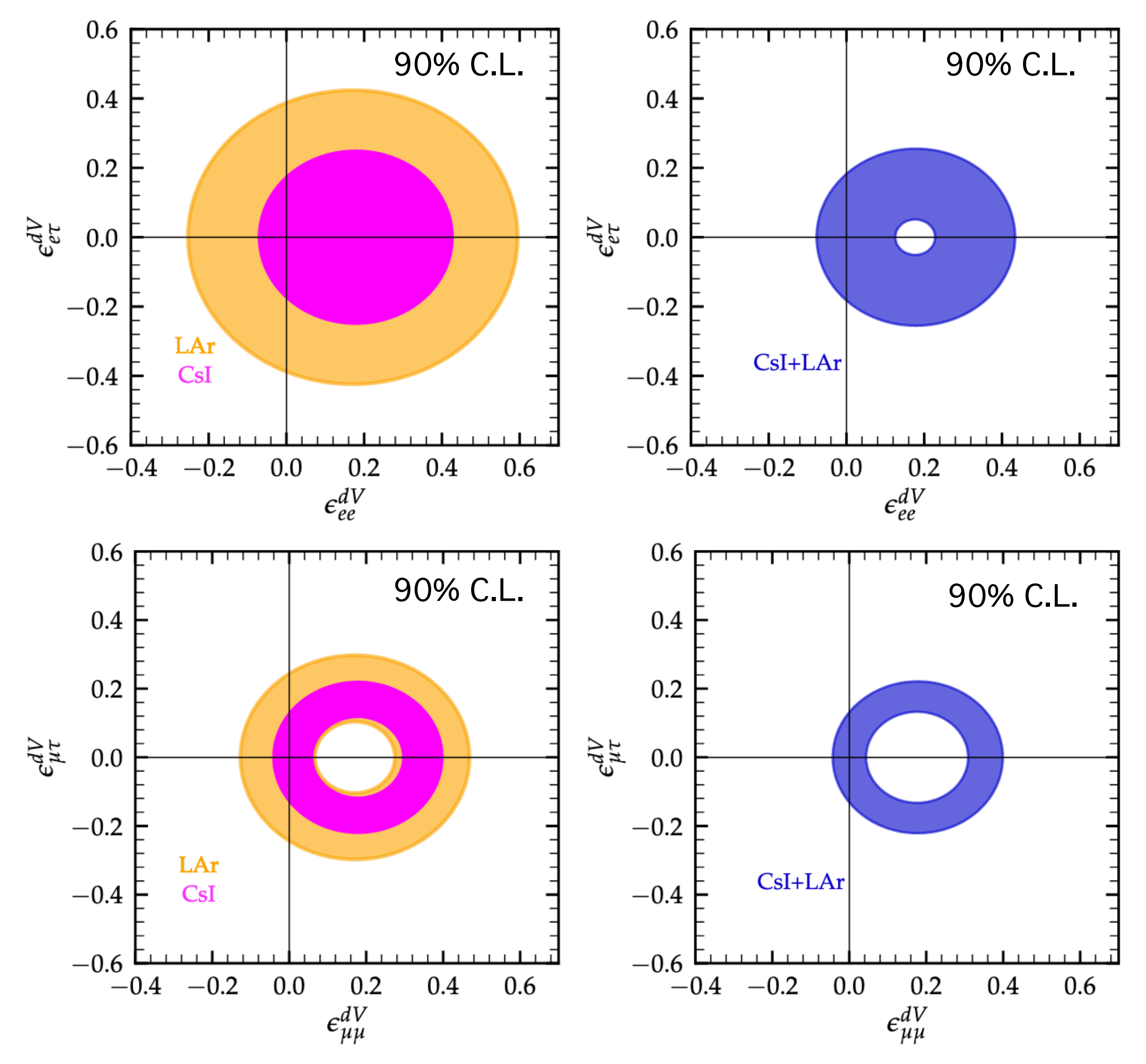
The NSI couplings quantify the relative strength of the NSI in terms of G_F and can be either flavour preserving (non-universal, $\alpha = \beta$) or flavor changing ($\alpha \neq \beta$).



COHERENT CsI (2021) + LAr

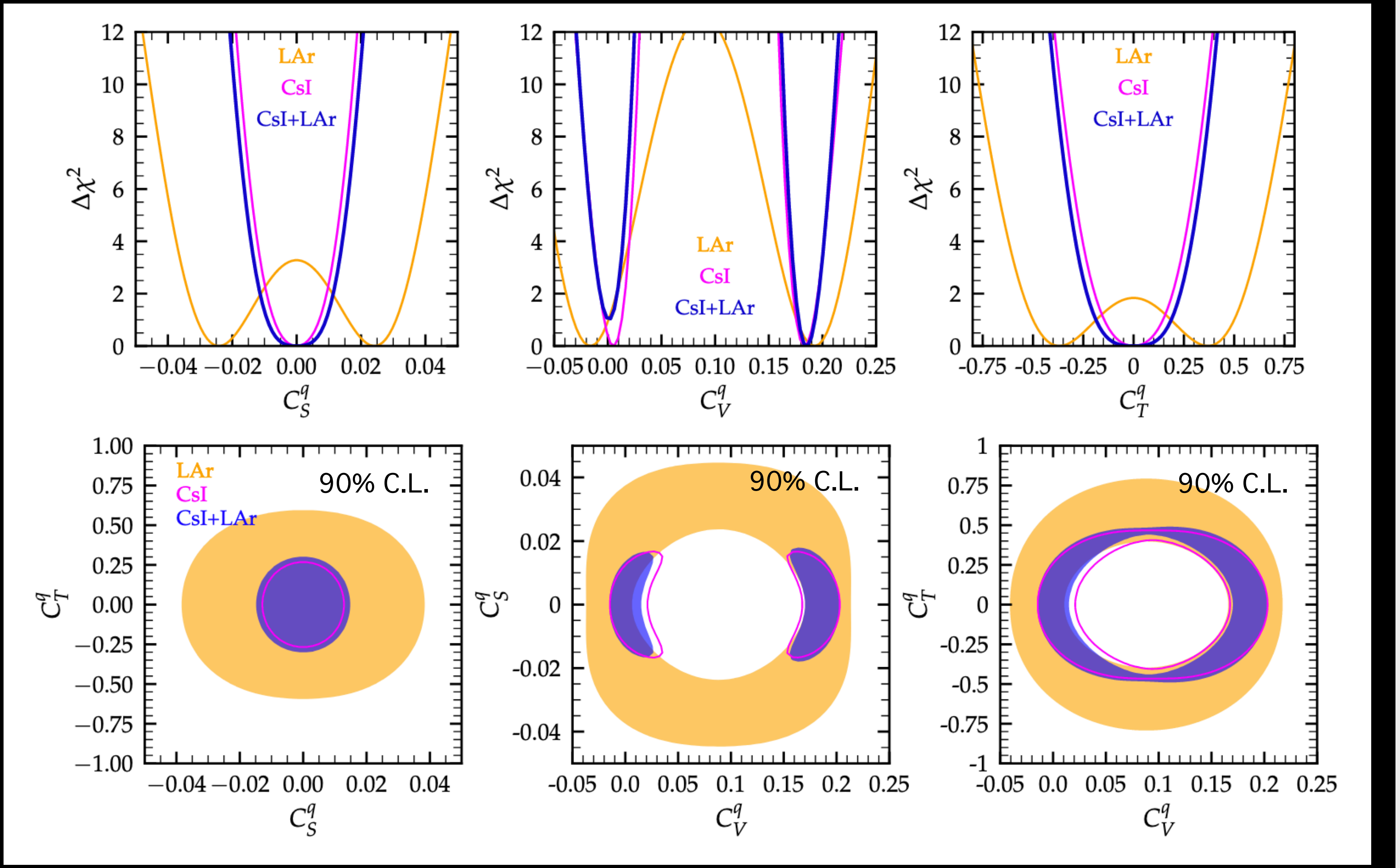
VDR, Miranda, Papoulias, Sanchez-García, Tórtola and Valle, 2211.11905 [hep-ph]

New neutrino interactions: NGI

Additional types of Lorentz-invariant interactions involving also scalar and tensor terms

$$\mathscr{L}_{\text{eff}}^{\text{NGI}} = \frac{G_F}{\sqrt{2}} \sum_{X=S,P,V,A,T} \left[\bar{\nu}\Gamma^X \nu\right] \left[\bar{q}\Gamma_X \left(C_X^q + i\gamma_5 D_X^q\right) q\right]$$

COHERENT CsI (2021) + LAr



Lee & Yang, Phys. Rev. 104 (1956) 254–258
Lindner et al., JHEP 03 (2017) 097
Aristizabal, VDR, Rojas Phys. Rev. D 98 (2018) 075018
Flores et al. Phys. Rev. D 105 no. 5, (2022) 05501

VDR, Miranda, Papoulias, Sanchez-García,Tórtola and Valle, 2211.11905 [hep-ph]

New neutrino interactions: LV

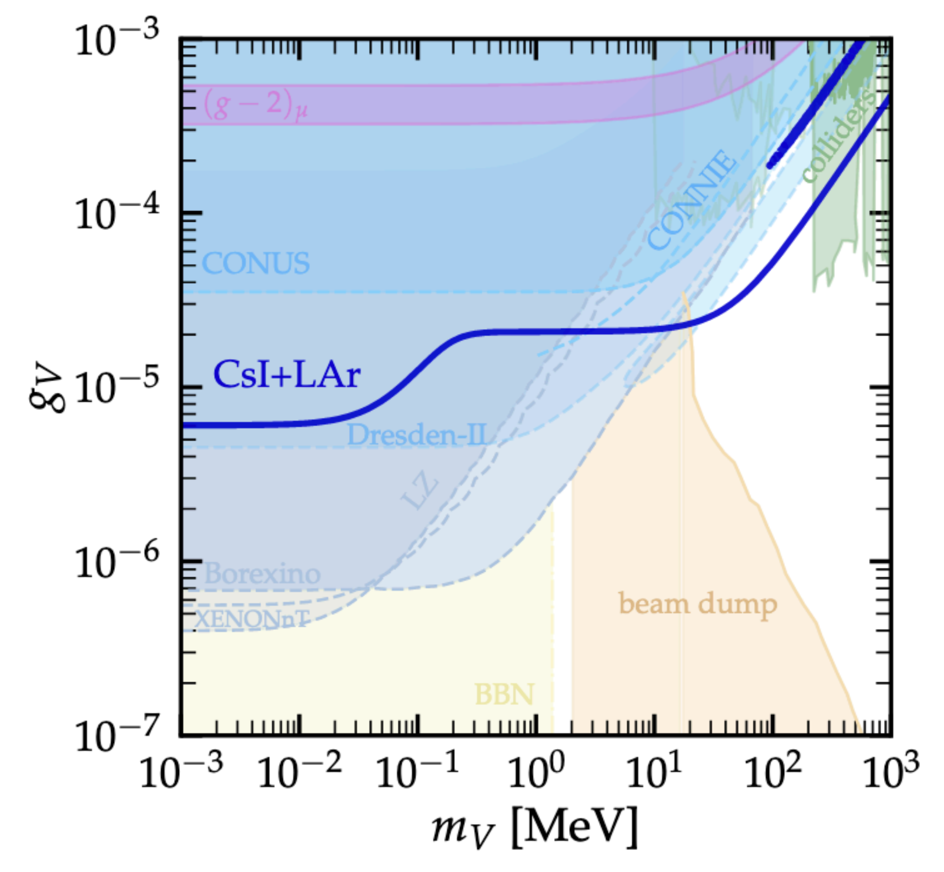
$$\left.\frac{d\sigma_{\nu_\ell\mathcal{N}}}{dE_{\rm nr}}\right|^{\rm LV}_{\rm CE\nu NS} = \left(1+\kappa\frac{C_V}{\sqrt{2}G_F Q_V^{\rm SM}\left(2m_\mathcal{N}E_{\rm nr}+m_V^2\right)}\right)^2 \left.\frac{d\sigma_{\nu_\ell\mathcal{N}}}{dE_{\rm nr}}\right|^{\rm SM}_{\rm CE\nu NS}$$

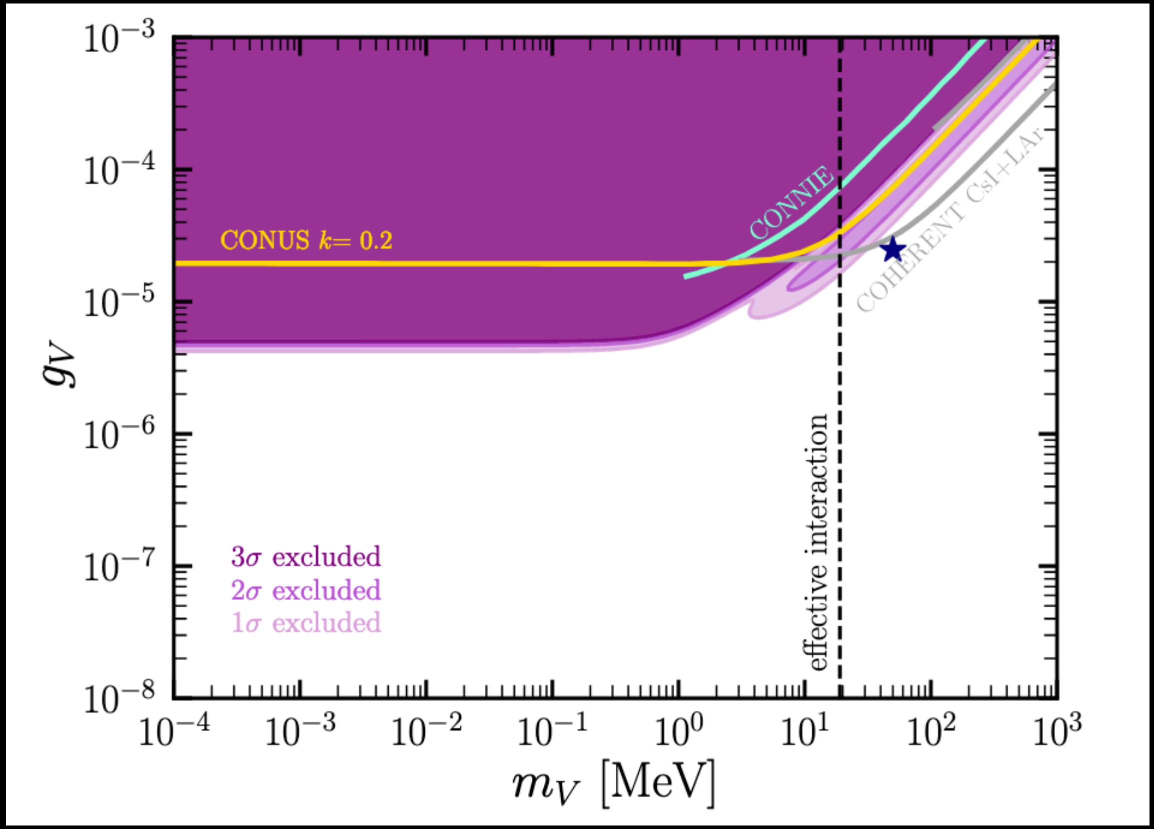
$$C_V = g_{\nu V}\left[\left(2g_{uV}+g_{dV}\right)Z+\left(g_{uV}+2g_{dV}\right)N\right]$$

$$g_X = \sqrt{g_{\nu X}g_{fX}};\ f=\{u,d\}$$

COHERENT CsI (2021) + LAr

Dresden-II (Ge) - iron filter





Aristizabal, VDR, Papoulias JHEP 09 (2022) 076

VDR, Miranda, Papoulias, Sanchez-García,Tórtola and Valle, 2211.11905 [hep-ph]

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

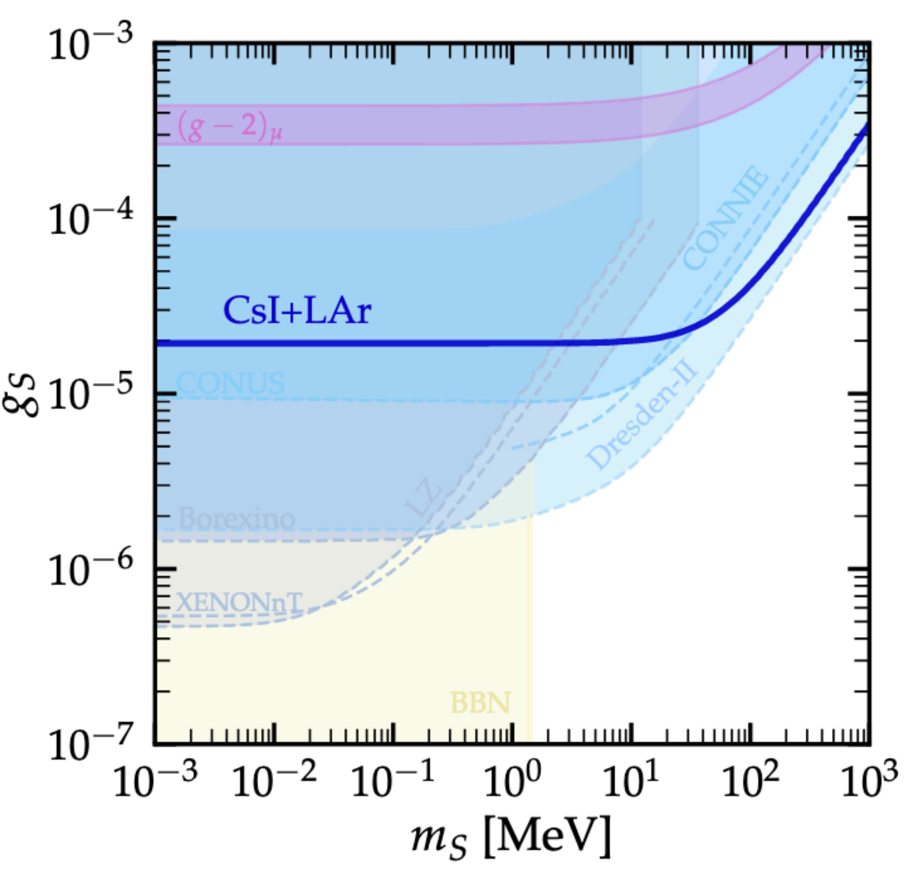
New neutrino interactions: LS

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

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

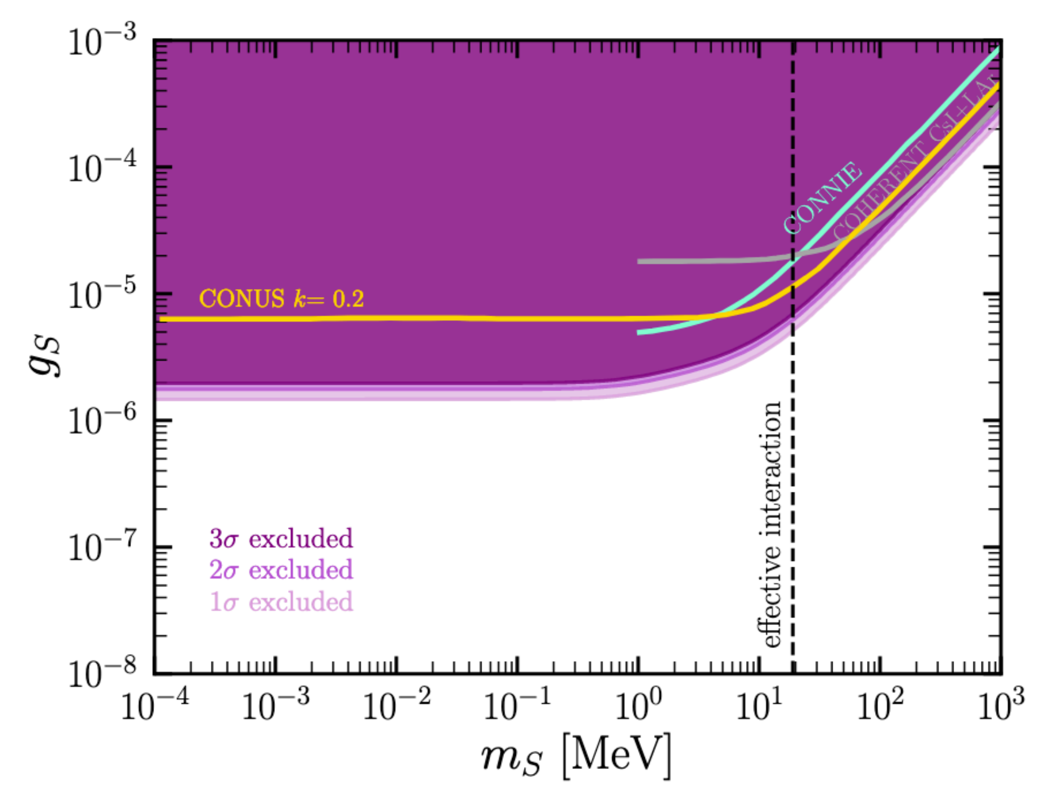
$$g_X = \sqrt{g_{\nu X}g_{fX}};\ f = \{u,d\}$$

COHERENT CsI (2021) + LAr



VDR, Miranda, Papoulias, Sanchez-García,Tórtola and Valle, 2211.11905 [hep-ph]

Dresden-II (Ge) - iron filter



Aristizabal, VDR, Papoulias JHEP 09 (2022) 076

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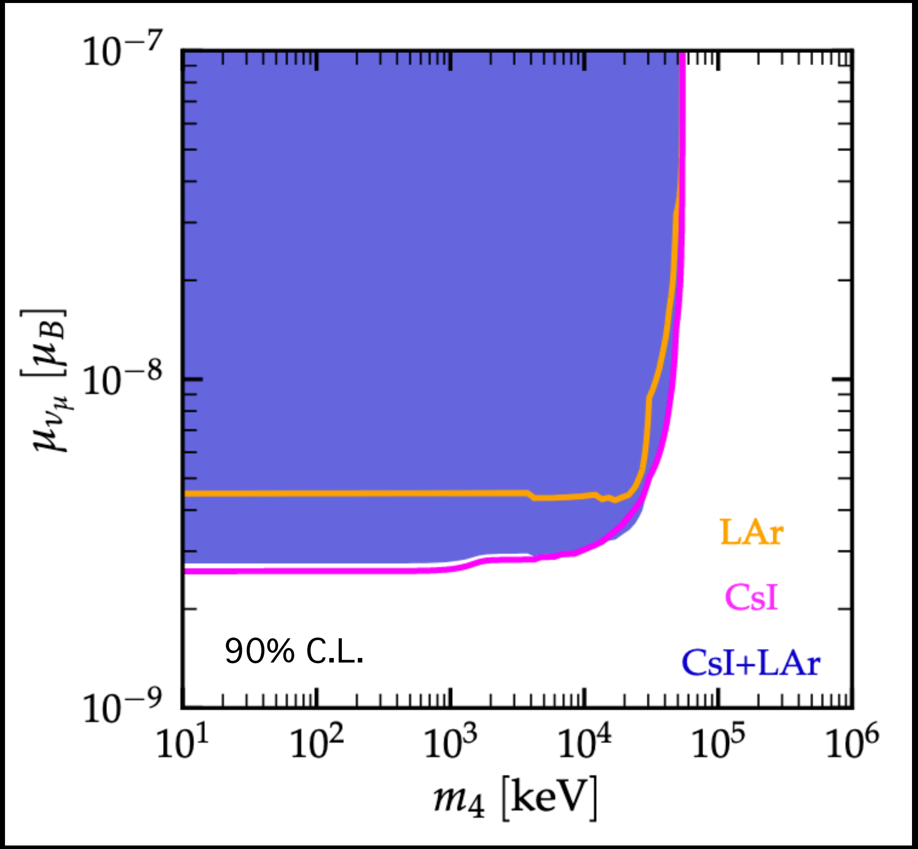
Sterile neutrino dipole portal

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

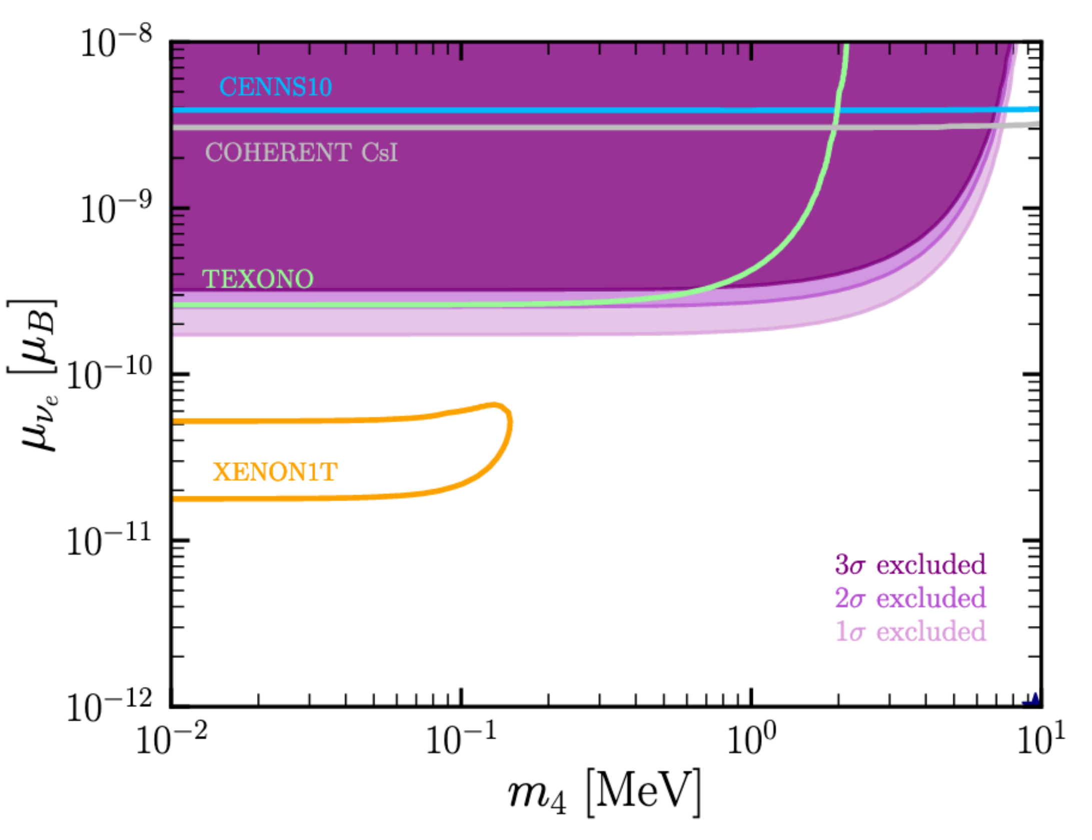
$$\mathcal{L} = \bar{\nu}\sigma_{\mu\nu}\lambda\nu_R F^{\mu\nu} + \text{H.c.}$$

$$\left.\frac{d\sigma_{\nu_\ell \mathcal{N}}}{dE_{\text{nr}}}\right|_{\text{CE}\nu\text{NS}}^{\text{DP}} = \frac{\pi\alpha_{\text{EM}}^2}{m_e^2} Z^2 F_W^2(|\vec{q}|^2)\left|\frac{\mu_{\nu_\ell}}{\mu_{\text{B}}}\right|^2 \times\left[\frac{1}{E_{\text{nr}}} - \frac{1}{E_\nu} - \frac{m_4^2}{2E_\nu E_{\text{nr}} m_N}\left(1 - \frac{E_{\text{nr}}}{2E_\nu} + \frac{m_N}{2E_\nu}\right) + \frac{m_4^4(E_{\text{nr}} - m_N)}{8E_\nu^2 E_{\text{nr}}^2 m_N^2}\right]$$

COHERENT CsI (2021) + LAr



Dresden-II (Ge) - iron filter



VDR, Miranda, Papoulias, Sanchez-García,Tórtola and Valle, 2211.11905 [hep-ph]

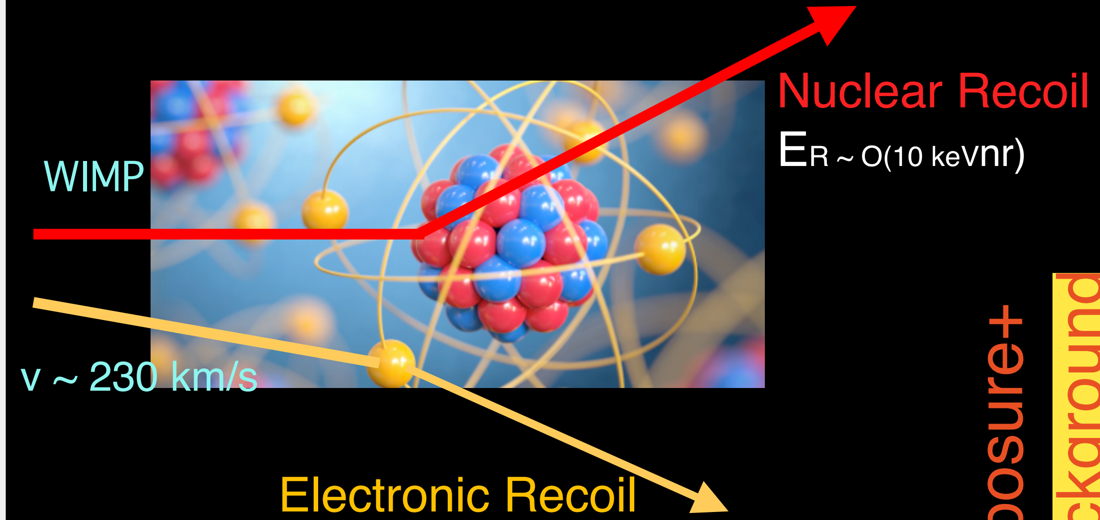
Aristizabal, VDR, Papoulias JHEP 09 (2022) 076

Direct WIMP Searches

If DM is made of particles that interact among themselves and with SM particles (e.g. WIMPs) we may hope to detect it. One strategy:

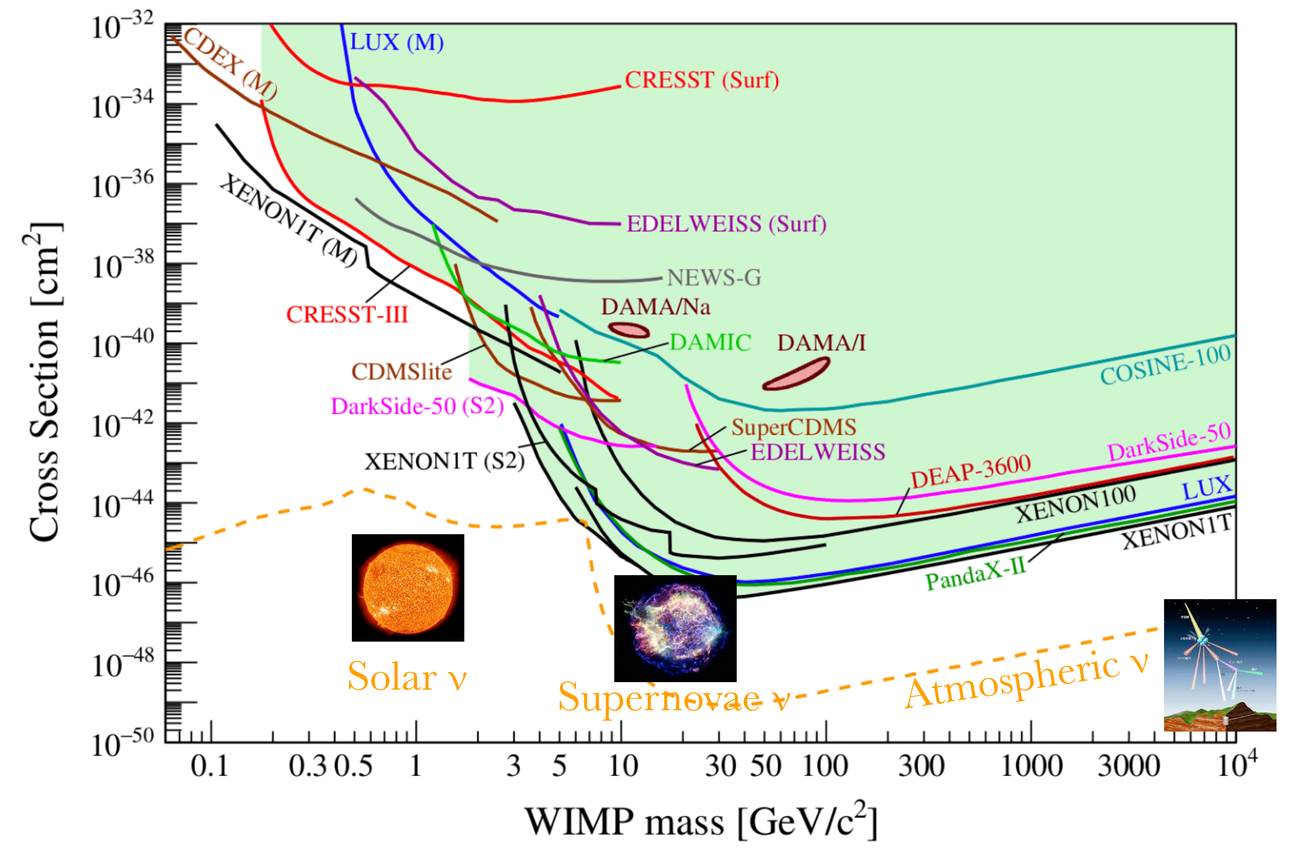
DIRECT DETECTION

Which looks for energy deposited within a detector by the DM-nuclei scattering



Exposure+ Background

spin-independent WIMP-nucleon interactions

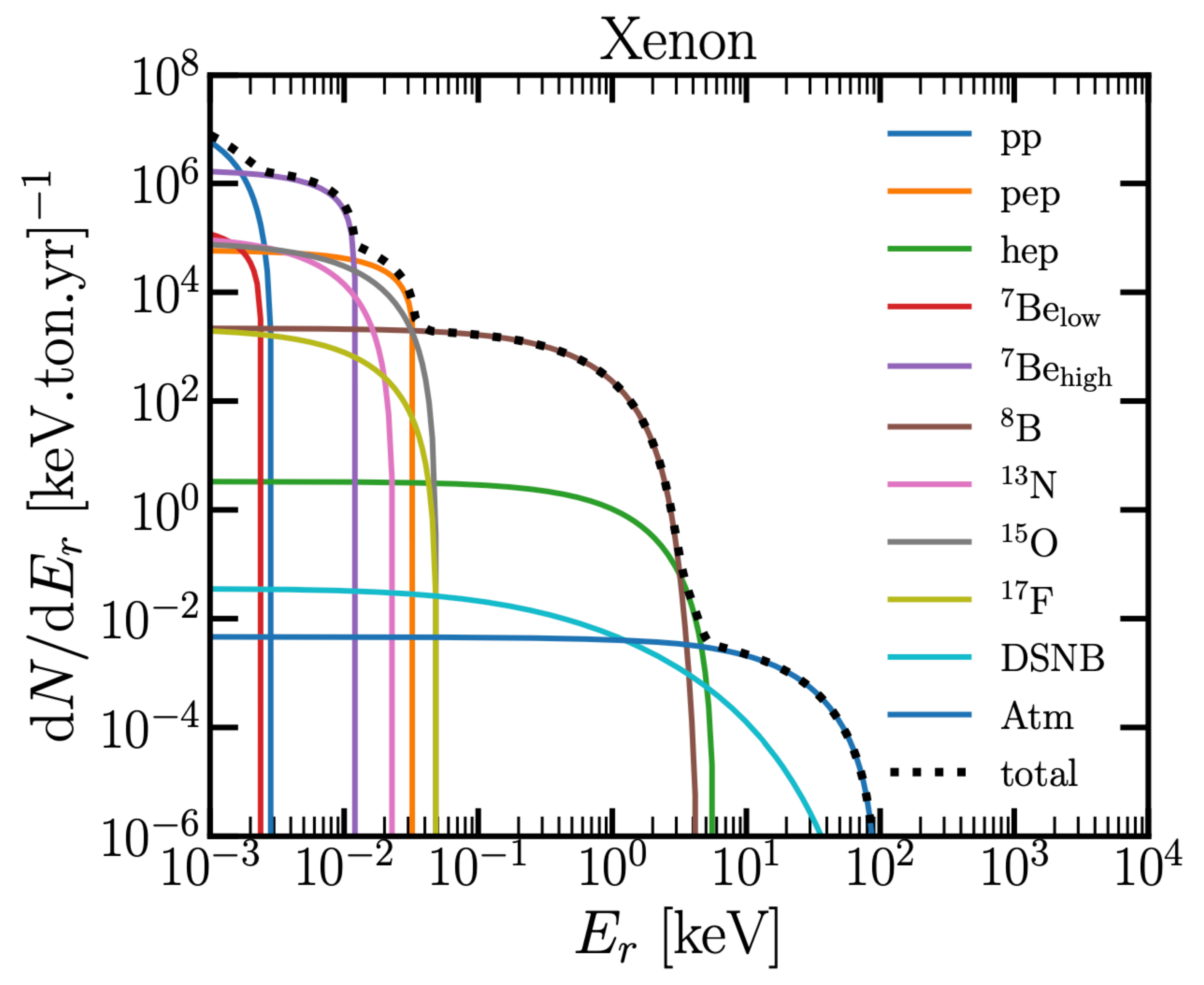


Threshold

Direct Detection of Dark Matter – APPEC Committee Report 2021

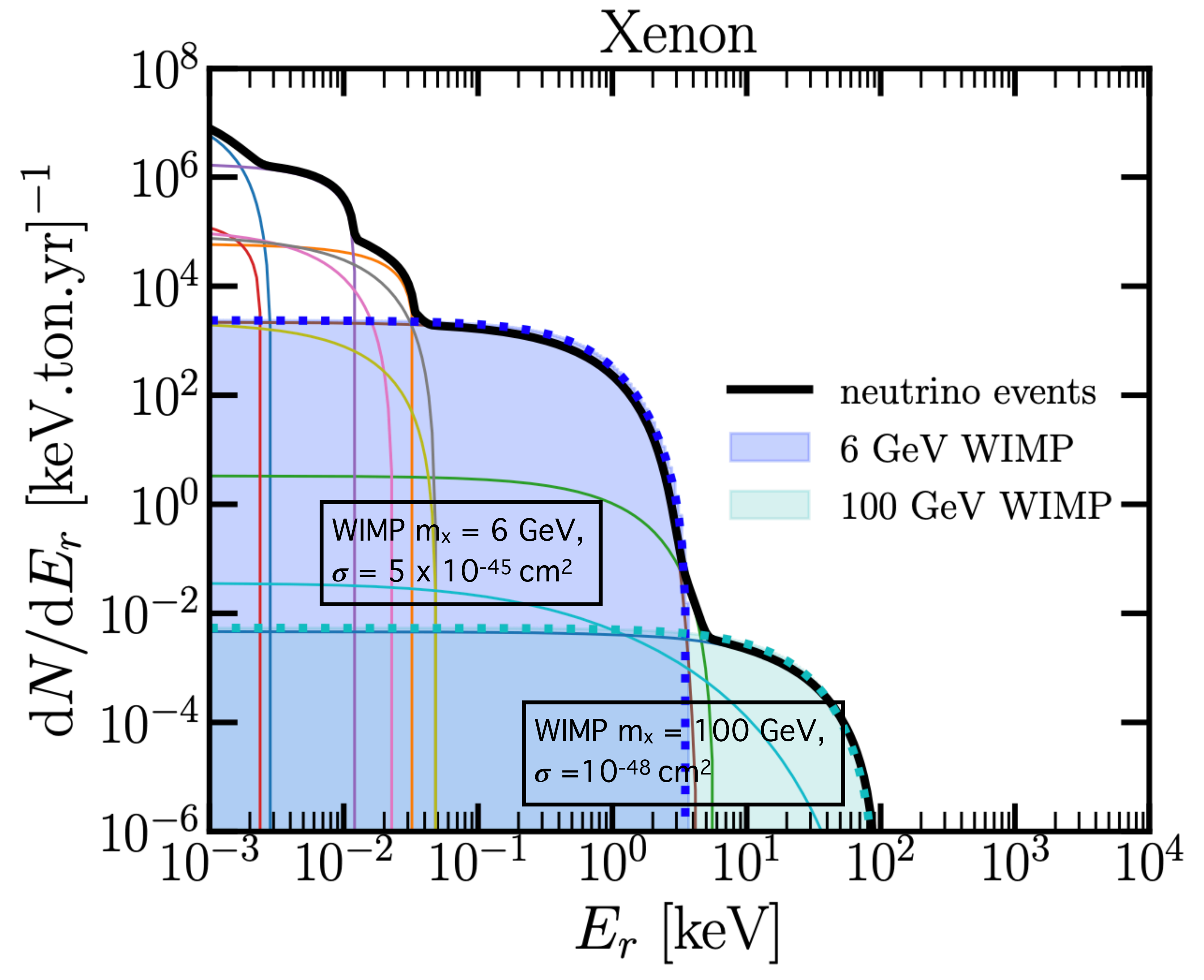
Astrophysical neutrinos

Expected recoil rates from coherent neutrino-nucleus scattering on Xenon:



Astrophysical neutrinos

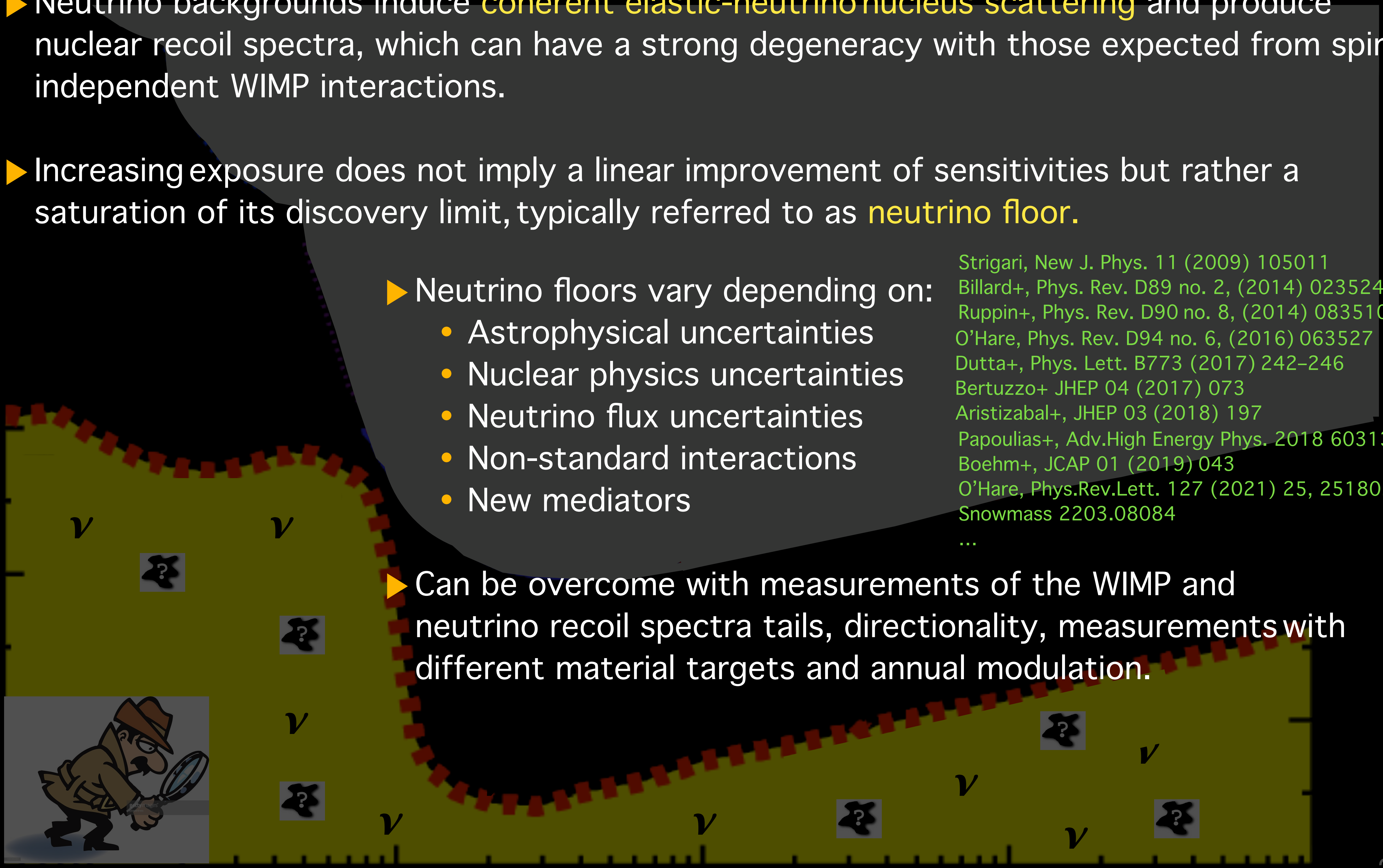
Expected recoil rates from coherent neutrino-nucleus scattering on Xenon:



Neutrino floors (or fog)

- Neutrino backgrounds induce coherent elastic-neutrino nucleus scattering and produce nuclear recoil spectra, which can have a strong degeneracy with those expected from spin-independent WIMP interactions.

- Increasing exposure does not imply a linear improvement of sensitivities but rather a saturation of its discovery limit, typically referred to as neutrino floor.



- Neutrino floors vary depending on:
  - Astrophysical uncertainties
  - Nuclear physics uncertainties
  - Neutrino flux uncertainties
  - Non-standard interactions
  - New mediators

Strigari, New J. Phys. 11 (2009) 105011
Billard+, Phys. Rev. D89 no. 2, (2014) 023524
Ruppin+, Phys. Rev. D90 no. 8, (2014) 083510
O'Hare, Phys. Rev. D94 no. 6, (2016) 063527
Dutta+, Phys. Lett. B773 (2017) 242–246
Bertuzzo+ JHEP 04 (2017) 073
Aristizabal+, JHEP 03 (2018) 197
Papoulias+, Adv.High Energy Phys. 2018 6031362
Boehm+, JCAP 01 (2019) 043
O'Hare, Phys.Rev.Lett. 127 (2021) 25, 251802
Snowmass 2203.08084
...

- Can be overcome with measurements of the WIMP and neutrino recoil spectra tails, directionality, measurements with different material targets and annual modulation.

WIMP discovery limits

Discovery limit: smallest WIMP cross section for which a given experiment has a 90% probability of detecting a WIMP signal at ≥ 3σ.

$$\mathcal{L}(m_\chi, \sigma_{\chi-n}, \Phi, \mathcal{P}) = \prod_{i=1}^{n_{\mathrm{bins}}} P(N^i_{\mathrm{Exp}}, N^i_{\mathrm{Obs}}) \times \boxed{G(\mathcal{P}_i, \mu_{\mathcal{P}_i}, \sigma_{\mathcal{P}_i})} \times \prod_{\alpha=1}^{n_\nu} G(\phi_\alpha, \mu_\alpha, \sigma_\alpha)$$

Billard, Strigari, Figueroa-Feliciano PRD 89(2014)
Aristizabal, VDR, Flores, Papoulias JCAP 01 (2022) 01, 055

The profile likelihood ratio corresponds to a test against the null hypothesis H_0 (CEνNS background only) vs the alternative hypothesis H_1 (WIMP signal + CEνNS background).

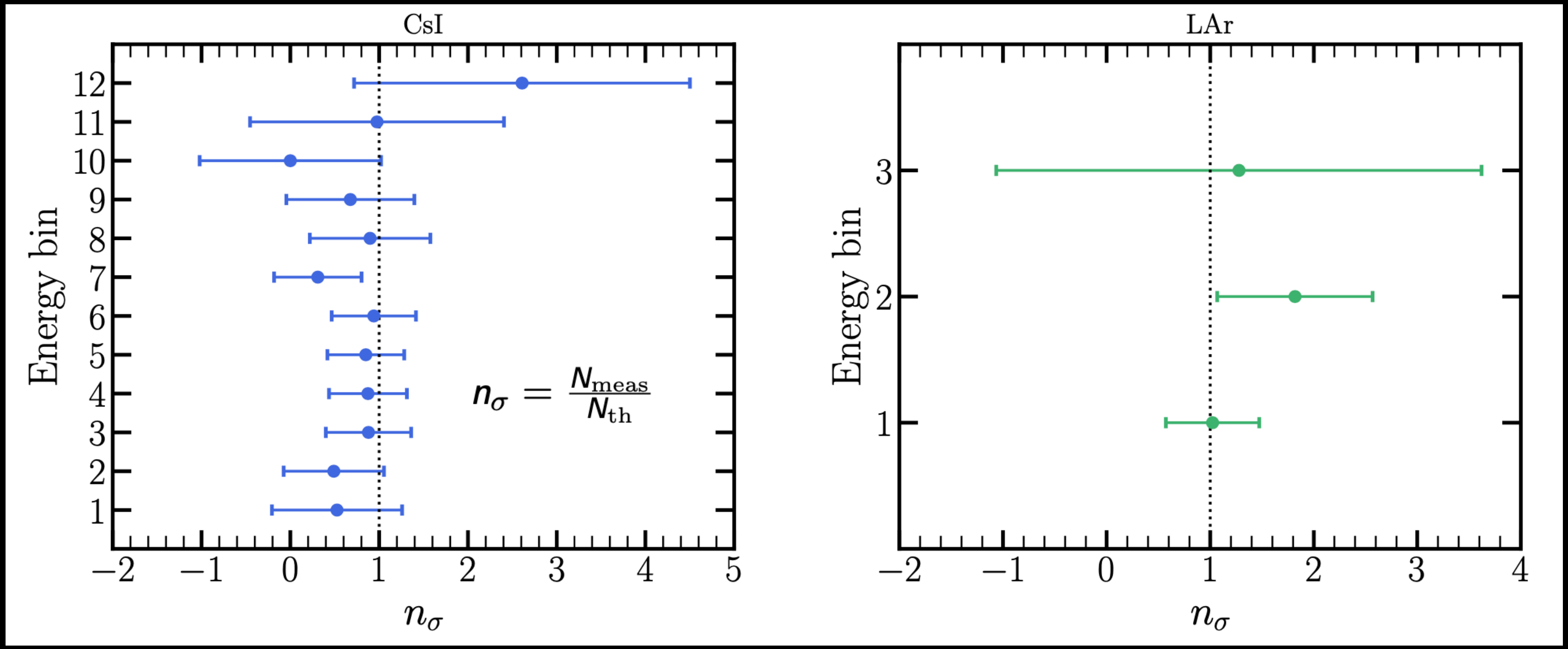
- Poisson distribution $P(k,\lambda) = \frac{\lambda^k e^{-\lambda}}{k!}$
- Gauss distribution $G(x,\mu,\sigma^2) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}$
- $N^i_{\mathrm{Exp}} = N^i_\nu(\Phi_\alpha)$
- $N^i_{\mathrm{Obs}} = \sum_\alpha N^i_\nu(\Phi_\alpha) + N^i_W$
- $\lambda(0) = \frac{\mathcal{L}_0}{\mathcal{L}_1}$ where $\mathcal{L}_0$ is the minimized function
- statistical significance: $\mathcal{Z} = \sqrt{-2\ln\lambda(0)}$.
  e.g. $\mathcal{Z} = 3$ corresponds to 90% C.L.

Parameter ($\mathcal{P}$)	Normalization (μ)	Uncertainty
R_n	4.78 fm	10%
$\sin^2\theta_W$	0.2387	10%

Billard+,PRD 89 n2 (2014) 023524
Ruppin+, Phys. Rev. D90 no. 8, (2014) 083510
O'Hare+, PRD 92 (2015) 063518
O'Hare, Phys. Rev. D94 no. 6, (2016) 063527
Gonzalez-Carcía+, JHEP 07 (2018) 019
....

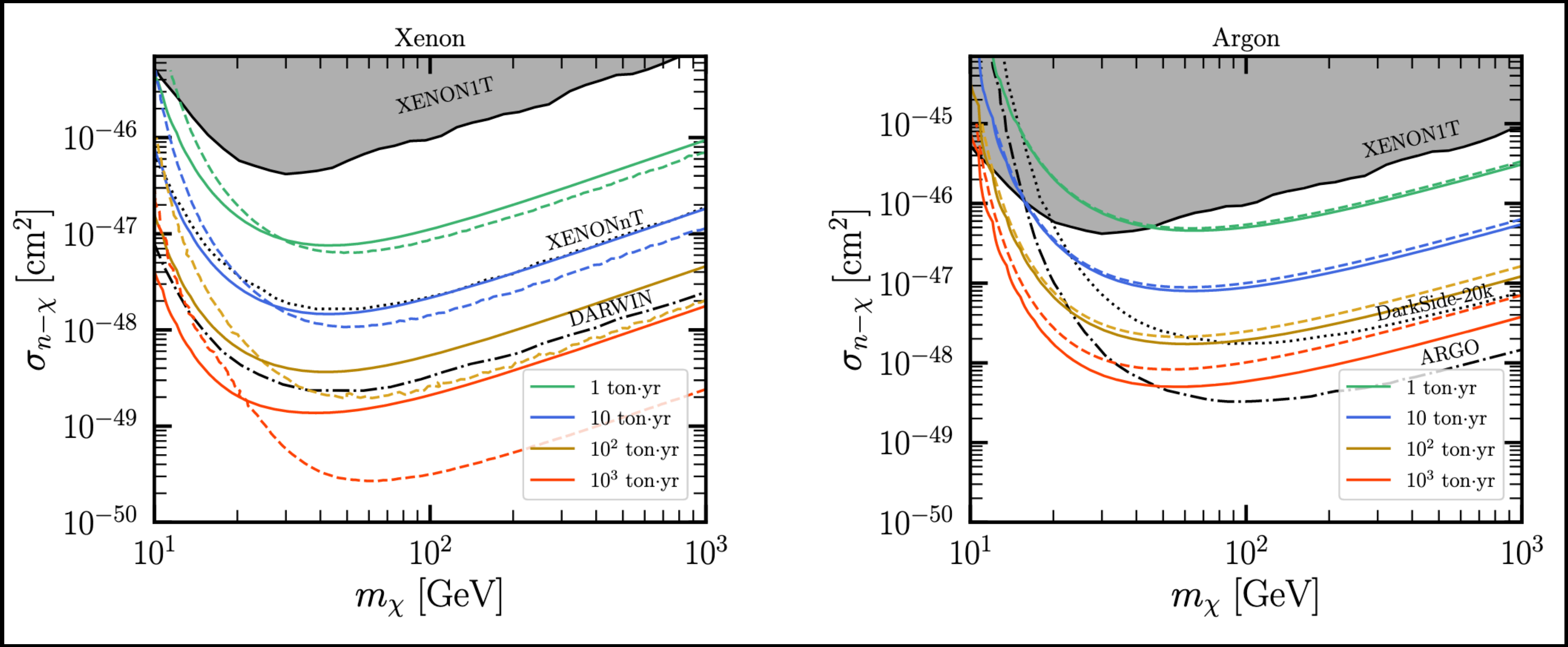
Data-driven analysis

- Use the measured CEνNS cross section with its uncertainty. This approach encodes all possible uncertainties that the cross section can involve, independently of assumptions.
- We extract from the COHERENT CsI (2017) and LAr data the CEνNS cross section central values together with their standard deviations.
- We weigh the theoretical SM value of the CEνNS differential cross section with a multiplicative factor n_σ and use a spectral χ^2 test to fit n_σ in each recoil energy bin.



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

Data-driven analysis



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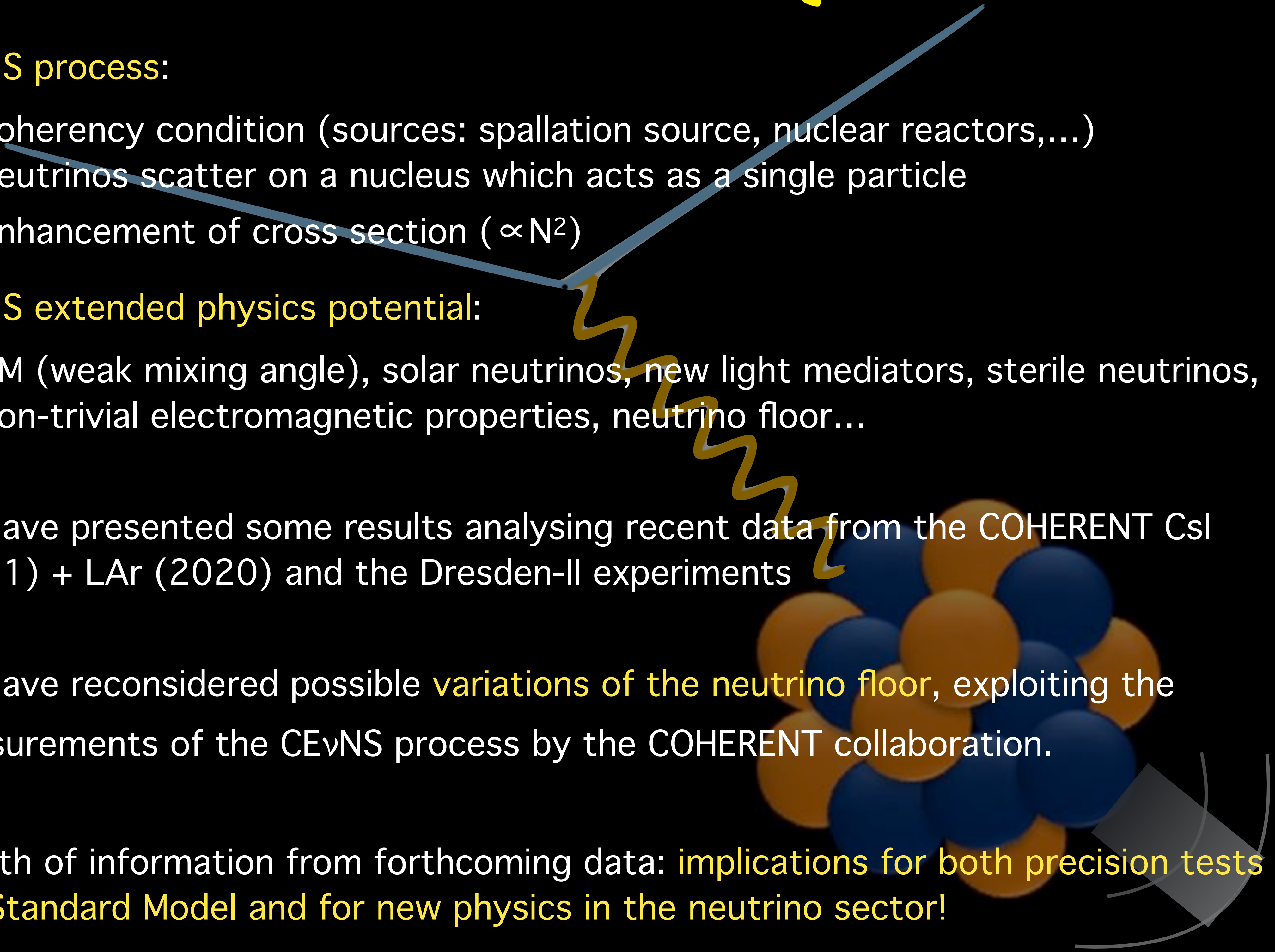
- In the analysis with CsI data, compared with the SM expectation (solid curves), WIMP discovery limits improve. The measured CEνNS cross section (central values) is smaller than the SM expectation, thus resulting in a background depletion.
- Results derived using the LAr data behave differently.

Summary



- CEνNS process:
  - coherency condition (sources: spallation source, nuclear reactors,...)
  - neutrinos scatter on a nucleus which acts as a single particle
  - enhancement of cross section ($\propto N^2$)
- CEνNS extended physics potential:
  - SM (weak mixing angle), solar neutrinos, new light mediators, sterile neutrinos, non-trivial electromagnetic properties, neutrino floor…
- We have presented some results analysing recent data from the COHERENT CsI (2021) + LAr (2020) and the Dresden-II experiments
- We have reconsidered possible variations of the neutrino floor, exploiting the measurements of the CEνNS process by the COHERENT collaboration.
- Wealth of information from forthcoming data: implications for both precision tests of the Standard Model and for new physics in the neutrino sector!


Thank you!