

# Coherent Neutrino Scattering for BSM Physics

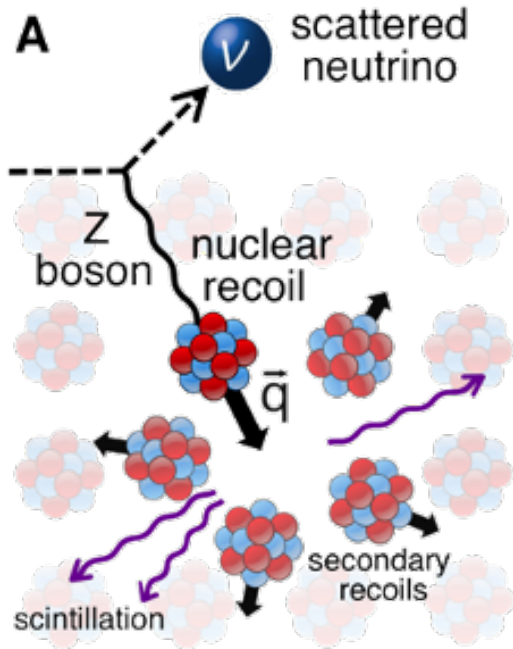


Roger Wendell  
NPN 2026  
2026.05.27



**KYOTO UNIVERSITY**

# Coherent $\nu$ -Nucleus Scattering (CE $\nu$ NS)



## SM Calculation

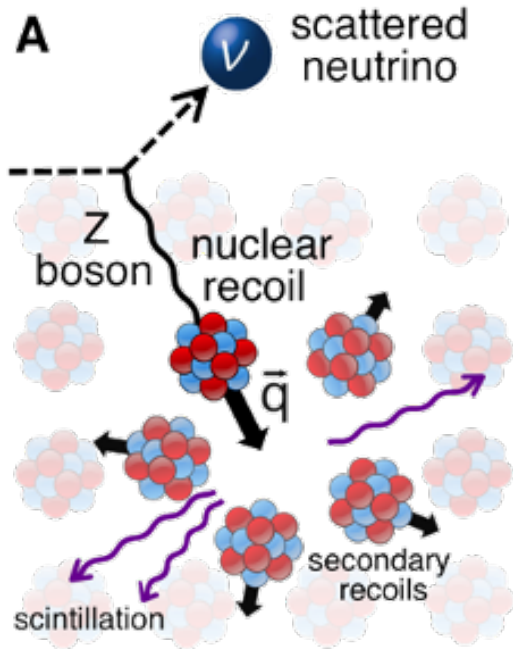
$$\frac{d\sigma}{dT_{coh}} = \frac{G_F^2 M}{2\pi} \left[ (G_V + G_A)^2 + (G_V - G_A)^2 \left(1 - \frac{T}{E_\nu}\right)^2 - (G_V^2 - G_A^2) \frac{MT}{E_\nu^2} \right]$$

$$G_V = (g_V^p Z + g_V^n N) F_{nucl}^V(Q^2)$$

$$G_A = (g_A^p (Z_+ - Z_-) + g_A^n (N_+ - N_-)) F_{nucl}^A(Q^2)$$

- Low  $Q$  NC elastic scattering,  $QR_{nuc} \ll 1$ 
  - $\nu$  interacts coherently with entire nucleus
  - $E_\nu < \sim 50$  MeV
- Clean theoretical prediction within the SM, small uncertainties

# Coherent $\nu$ -Nucleus Scattering (CE $\nu$ NS)



## SM Calculation

$$\frac{d\sigma}{dT} \sim Q_W^2 F^2(Q) M \left( 2 - \frac{MT}{E_\nu^2} \right) \quad \text{For } T \ll E_\nu$$

$$Q_W = N - Z (1 - 4 \sin^2 \theta_W)$$

$$T_{\max} \sim 2 \frac{E_\nu^2}{M}$$

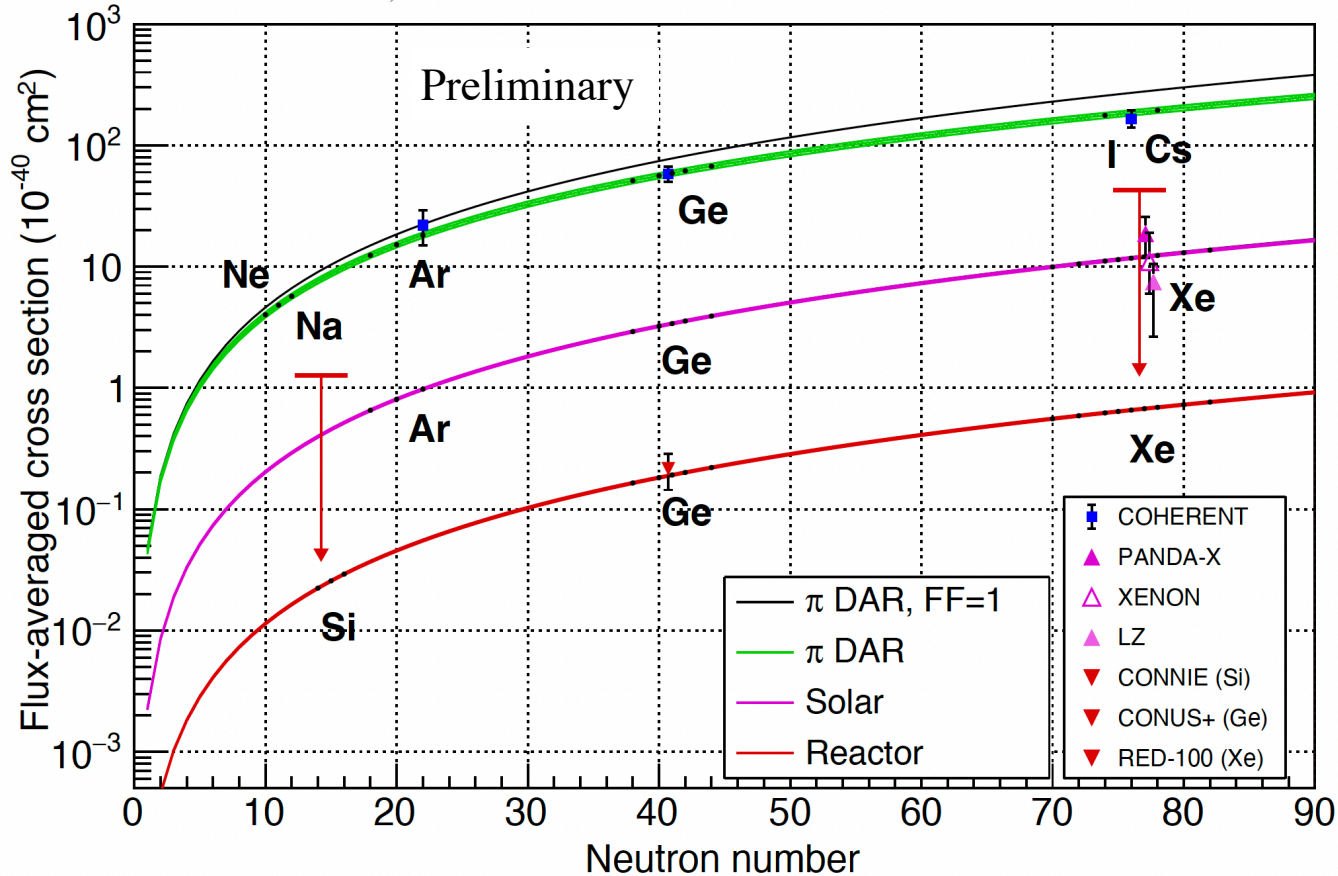
$\sim 18.4 \text{ keV}$ for $^{74}\text{Ge}$ $\sim 10.1 \text{ keV}$ for $^{133}\text{Cs}$
---

$$E_\nu = 25 \text{ MeV}$$

- Contributions from new physics via altered
  - $Q_W$ , Kinematics, or form factors
- Challenge: small recoil energies, directional information?

# Coherent $\nu$ -Nucleus Scattering (CE $\nu$ NS)

COHERENT, arXiv:2602.15652



- $\sin^2 \theta_W = 0.231 \Rightarrow d\sigma/dT \propto N^2$
- First observed in 2017 (CsI, stopped pion source)
  - Recent observations with solar and reactor neutrinos

# The Coherent Experiment At ORNL



Knoxville, TN USA

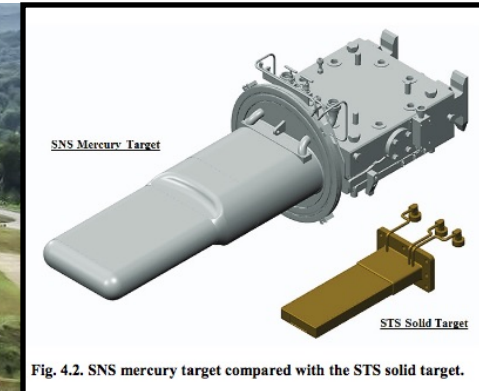


Fig. 4.2. SNS mercury target compared with the STS solid target.

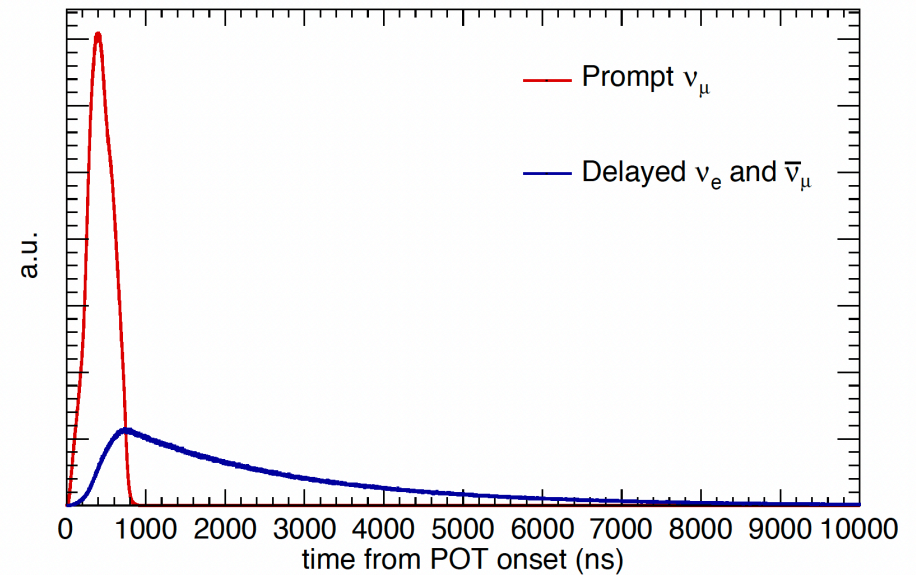
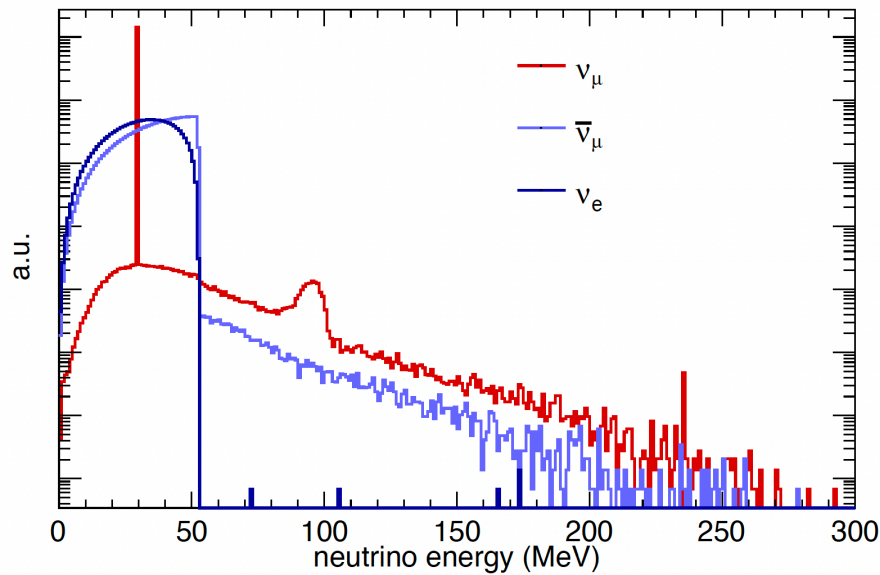
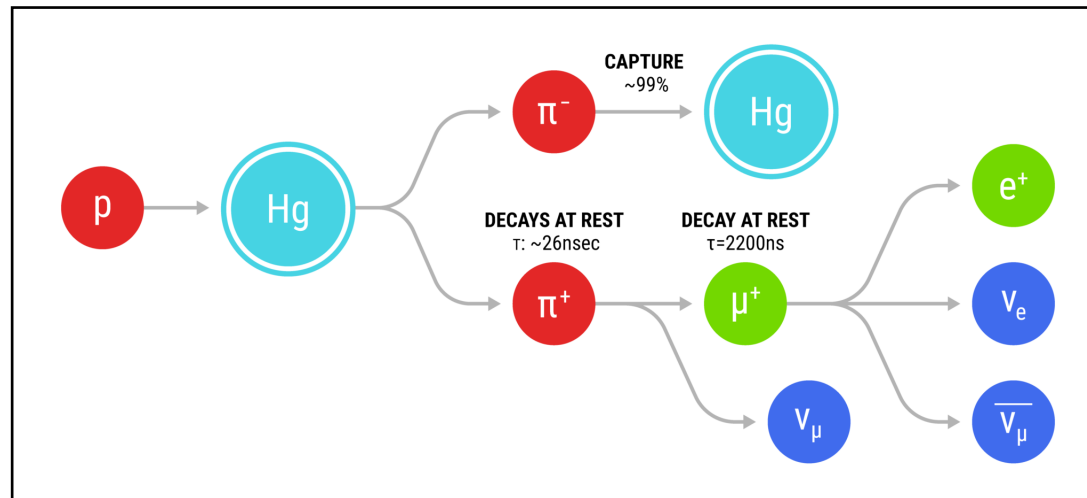
- Spallation neutron source - copious neutrinos as by product
- 1.8 MW  $\rightarrow$  2.0 MW Protons
  - more in future
- Hg target, with pulsed beam

1.3 GeV  $p + \text{Hg} \rightarrow \nu$  from  $\pi^+$  decay at rest

1.9 MW, at 60 Hz, 350ns FWHM

$\phi_\nu \sim 4.7 \times 10^7 \text{ cm}^2 \text{ s}^{-1}$  at 20m

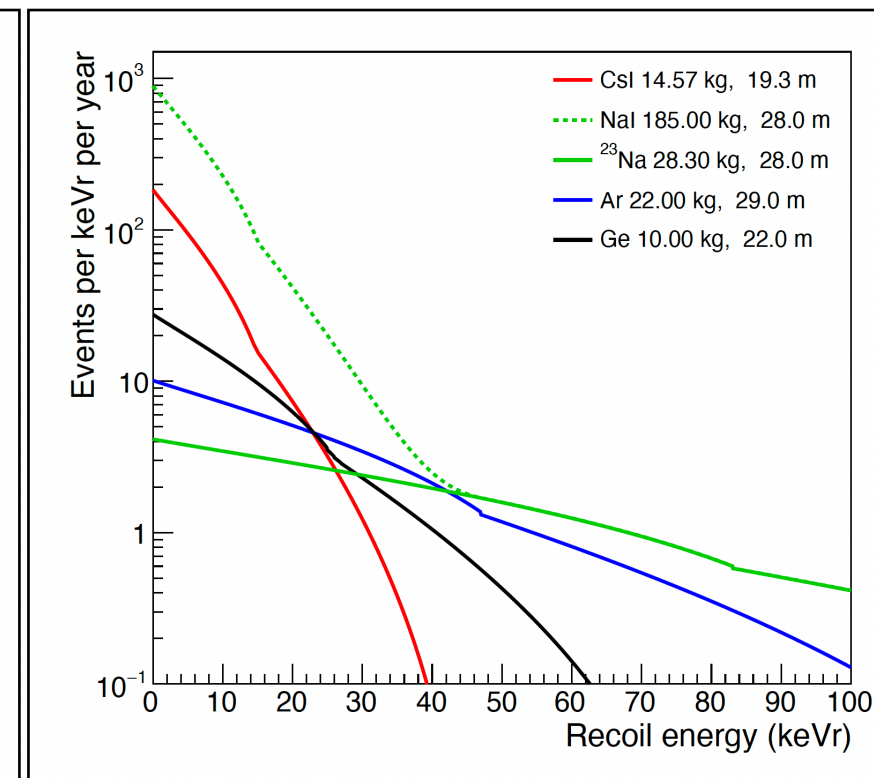
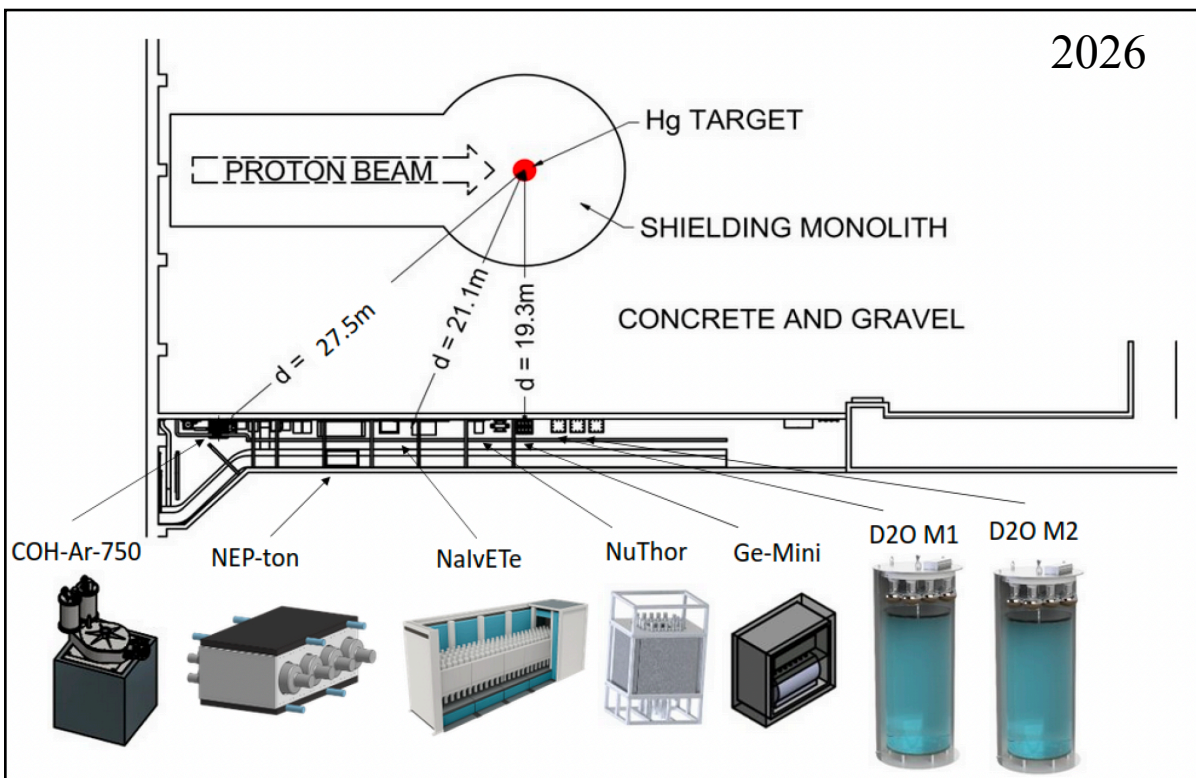
# SNS: Neutrinos from Pion Decay at Rest (DAR)



- Beam timing powerful for signal identification
  - → Measure **backgrounds during off timing** (duty factor  $\sim 10^{-4}$ )

# COHERENT Experiment Overview

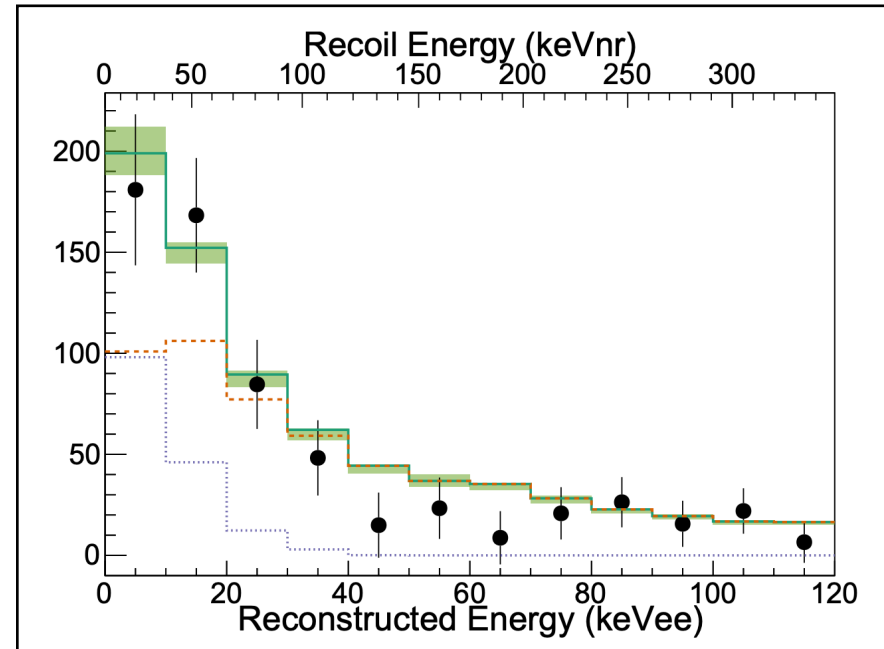
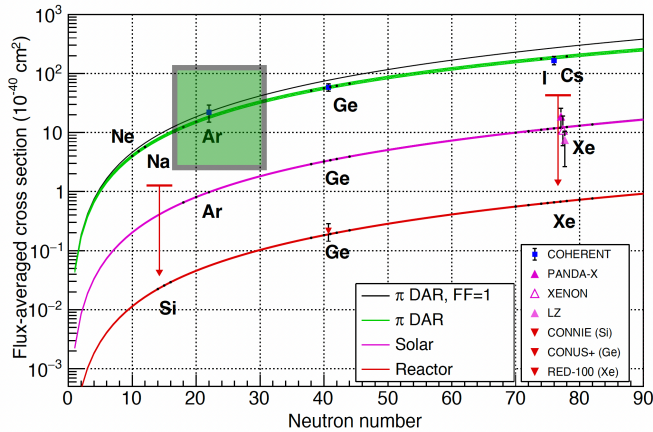
- Neutrino Alley:
  - Several targets for: CEvNS targets ,  $\nu$ -Nucleus inelastic scattering
  - Detectors for flux, background (n) measurements
- Ranging from 19~27m from target
- (Not Shown) Previously: CsI[Na], CENNS-10 single-phase LAr, 185kg NaI, NIN



# COHERENT Results: Ar

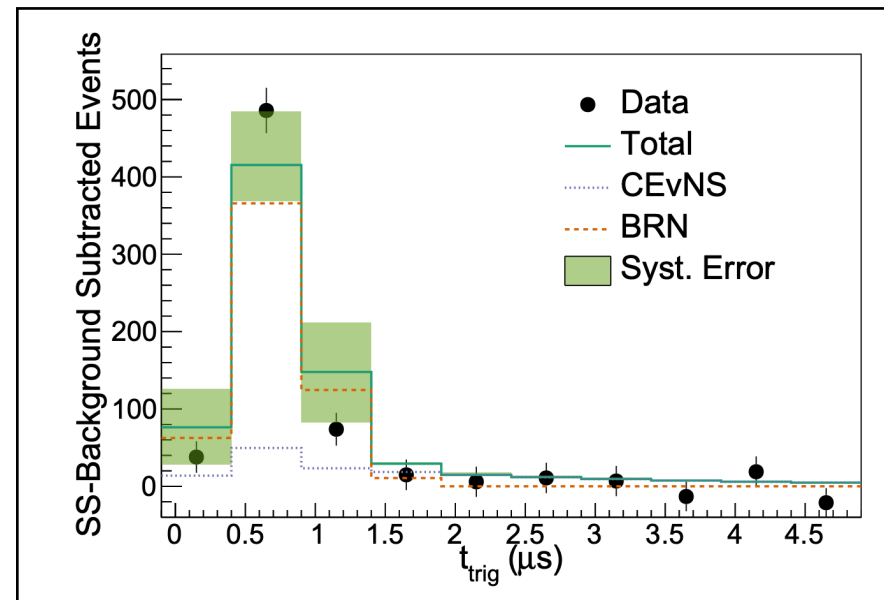
Phys. Rev.Lett. 126 (2021) 1

COHERENT, arXiv:2602.15652



## CENNS-10

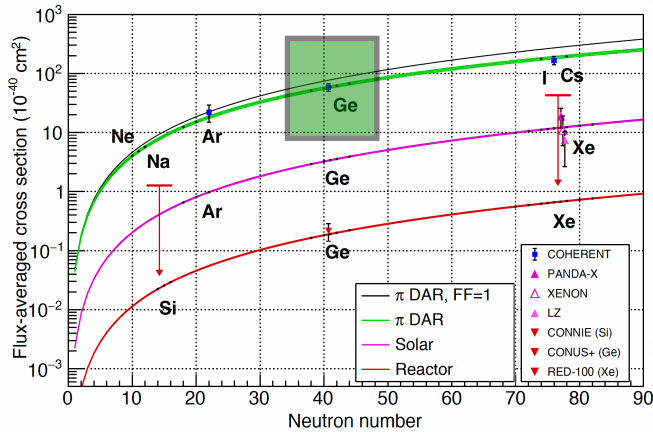
- 24kg  $^{40}\text{Ar}$ (single-phase)
- 27.5 m from source
- $E_{thr} \sim 20\text{keVnr}$
- 146.8 GWhr  $\cdot$  kg
- Observation:  $159 \pm 43$  Events
  
- $\sigma_{sys} \sim 13\%$  (flux dom.)



# COHERENT Results: Ge

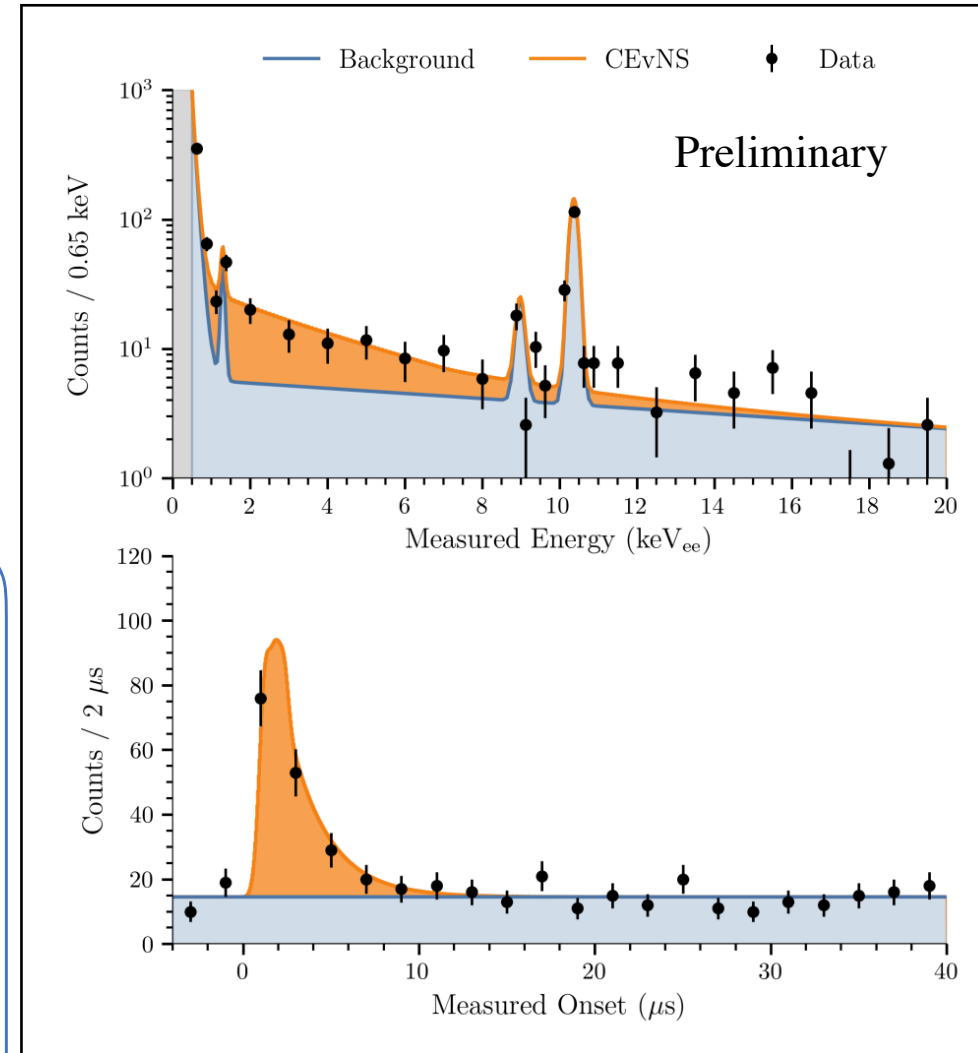
[COHERENT 2603.17951](#)

COHERENT, arXiv:2602.15652



## Ge-Mini

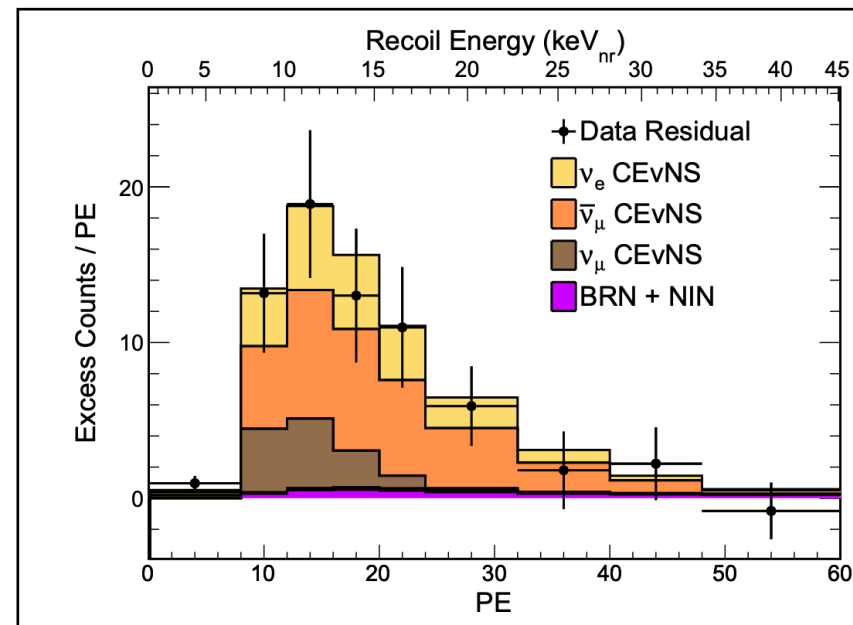
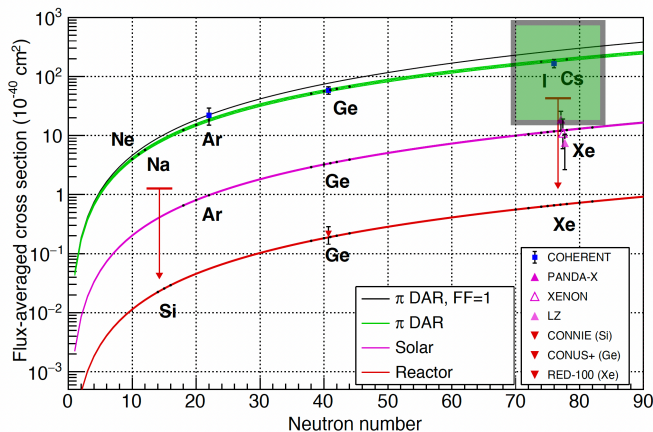
- 18kg HPE Ge (p-type point contact)
- 19.2m from source
- $E_{thr} \sim 2.5 \text{ keVnr}$
- 23.65 GWhr  $\cdot$  kg
- Observation:  $124^{+14}_{-12}$  Events
- SM Prediction:  $124 \pm 13$
- $\sigma_{sys} \sim 10.3\%$  (flux dom.)



# COHERENT Results: CsI

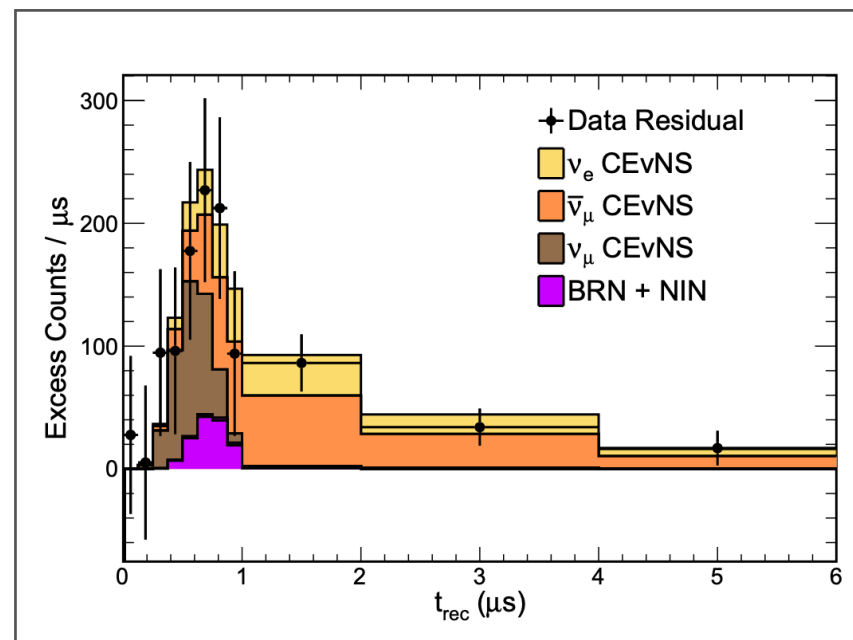
Phys. Rev.Lett. 129 (2022)

COHERENT, arXiv:2602.15652



## CsI

- 14.6 kg CsI[Na]
- 20m from source
- Single PMT Hamamatsu R877-100
- $E_{thr} = 7 \text{ PE}$  ( $\sim 5 \text{ keV}_{nr}$ )
- Observation:  $306 \pm 20$  Events
- SM Prediction:  $341 \pm 11(\text{th.}) \pm 42(\text{exp})$
- $\sin^2 \theta_W = 0.220^{+0.028}_{-0.026}$   $\{Q^2 \approx (50 \text{ MeV})^2\}$



BSM

# Non-Standard Neutrino Interactions (NSI)

- Additional coupling between neutrinos and fermions impact the hamiltonian

$$\mathcal{L}_{\text{vNSI}} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \epsilon_{\alpha,\beta}^{f,P} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta) (\bar{f} \gamma_\mu P f)$$

$$H \rightarrow H + H', \quad H' = \sqrt{8}G_F N_e E_\nu \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{\mu e} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{\tau e} & \epsilon_{\tau\mu} & \epsilon_{\tau\tau} \end{pmatrix}$$

- For  $\epsilon_{ee} = -2 + x$ ,  $x = \epsilon_{\mu\mu} = \epsilon_{\tau\tau}$ ,  $H \rightarrow -H^*$ 
  - Oscillation experiments are not sensitive to the change but
  - $\Delta m^2 \rightarrow -\Delta m^2$ ,  $\delta_{cp} \rightarrow \pi - \delta_{cp}$
  - “LMA-Dark”

## CEvNs

Giunti PRD **101**, 035039 (2020)

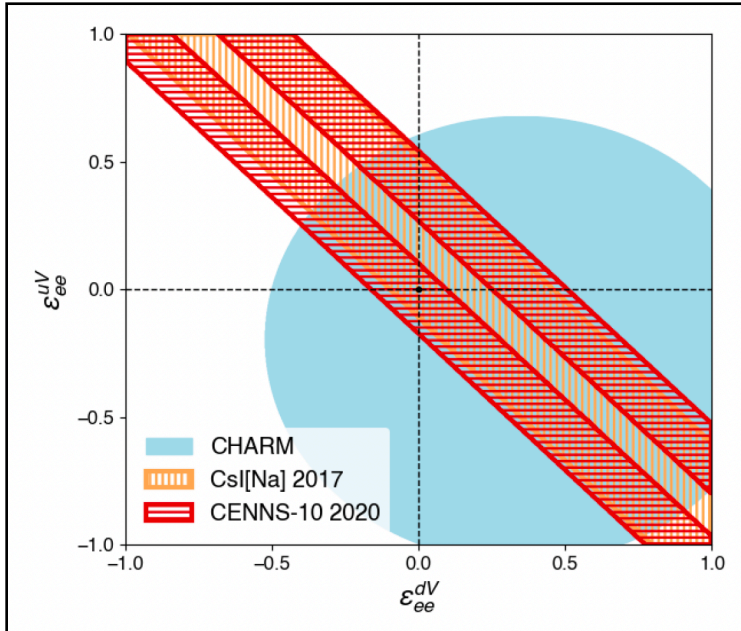
$$Q_{\text{W,NSI}}^2 = \left[ (g_V^p + 2\epsilon_{ee}^{uV} + \epsilon_{ee}^{dV})ZF_Z(q^2) + (g_V^n + \epsilon_{ee}^{uV} + 2\epsilon_{ee}^{dV})NF_Z(q^2) \right]^2 + \sum_{\alpha \neq e} \left[ (2\epsilon_{e\alpha}^{uV} + \epsilon_{e\alpha}^{dV})ZF_Z(q^2) + (\epsilon_{e\alpha}^{uV} + 2\epsilon_{e\alpha}^{dV})NF_N(q^2) \right]^2$$

- CEvNs sensitive to diagonal elements  $\epsilon_{ll}$

# Non-Standard Neutrino Interactions (NSI)

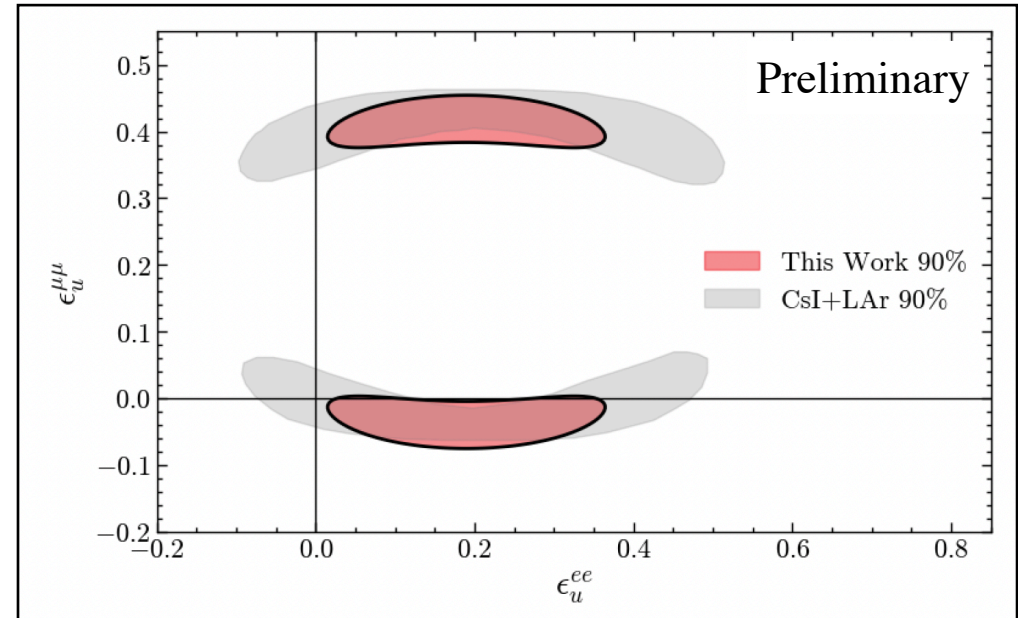
$$Q_{W,NSI}^2 = \left[ (g_V^p + 2\epsilon_{ee}^{uV} + \epsilon_{ee}^{dV})ZF_Z(q^2) + (g_V^n + \epsilon_{ee}^{uV} + 2\epsilon_{ee}^{dV})NF_Z(q^2) \right]^2$$

COHERENT Phys. Rev.Lett. 126 (2021) 1



Ar: 146.8 GWhr · kg  
CsI: 109.2 GWhr · kg

[COHERENT 2603.17951](#)

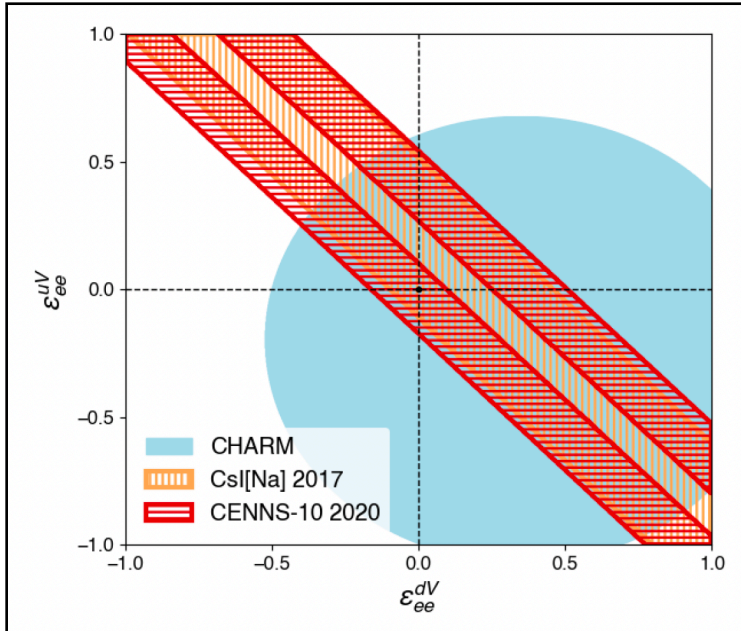


Ge: 23.65 GWhr · kg  
Ar: 146.8 GWhr · kg  
CsI: 204.2 GWhr · kg

# Non-Standard Neutrino Interactions (NSI)

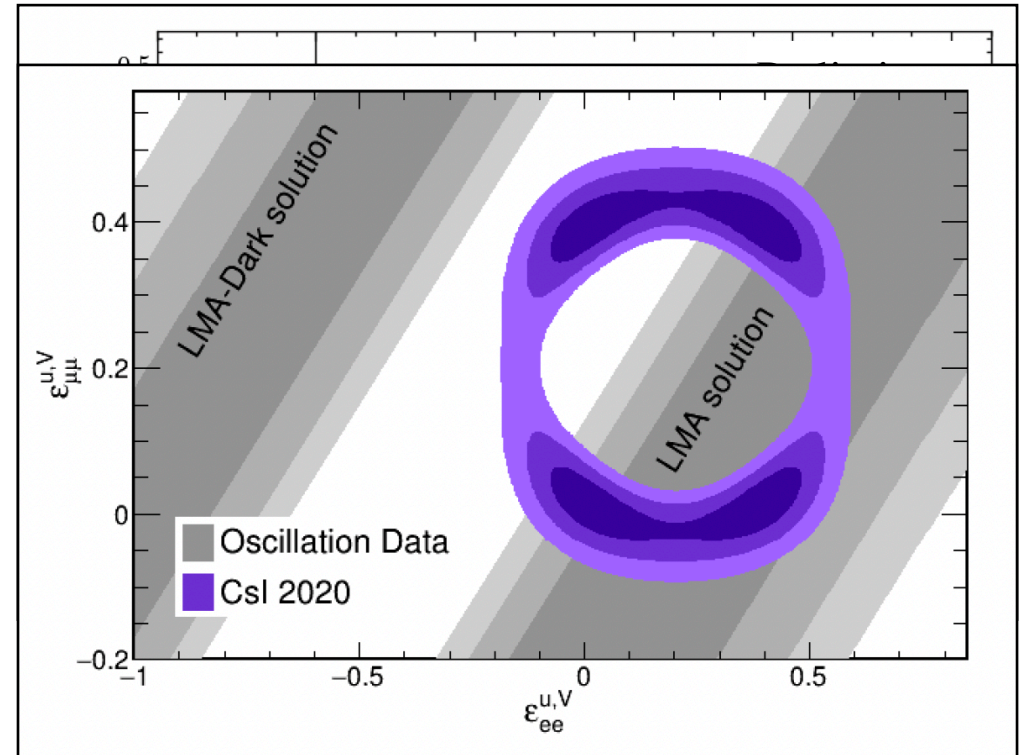
$$Q_{W,NSI}^2 = \left[ (g_V^p + 2\epsilon_{ee}^{uV} + \epsilon_{ee}^{dV})ZF_Z(q^2) + (g_V^n + \epsilon_{ee}^{uV} + 2\epsilon_{ee}^{dV})NF_Z(q^2) \right]^2$$

COHERENT Phys. Rev.Lett. 126 (2021) 1



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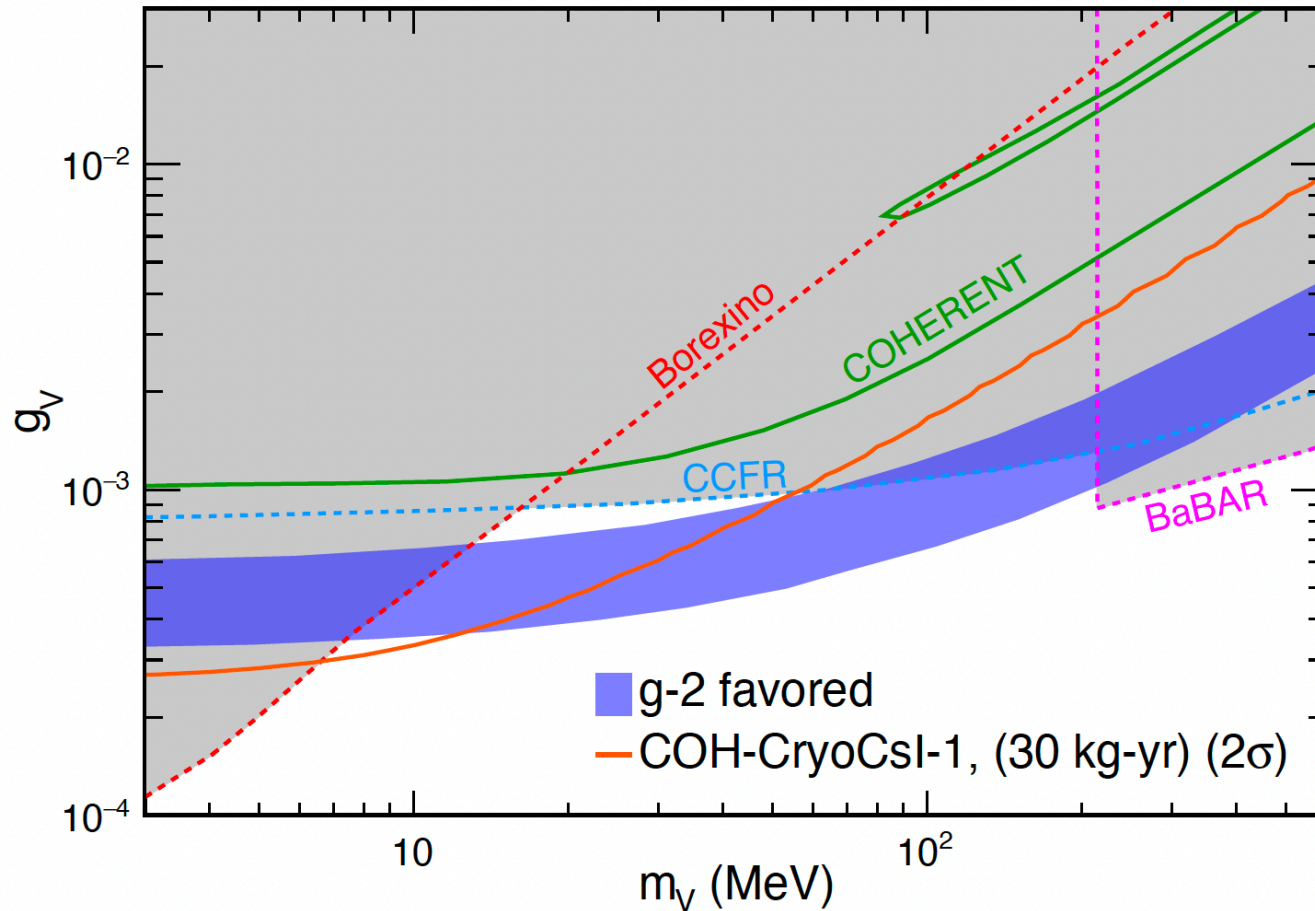
# New Mediators

JHEP 05 (2022) 109

$$Q_{\ell, \text{SM}+\nu}^V = Q_{\ell, \text{SM}}^V + \frac{g_{Z'}^2 Q'_\ell}{\sqrt{2} G_F (|\vec{q}|^2 + M_{Z'}^2)} \left[ (2Q'_u + Q'_d) ZF_Z(|\vec{q}|^2) + (Q'_u + 2Q'_d) NF_N(|\vec{q}|^2) \right]$$

$$|\vec{q}|^2 \simeq 2MT_{\text{nr}}$$

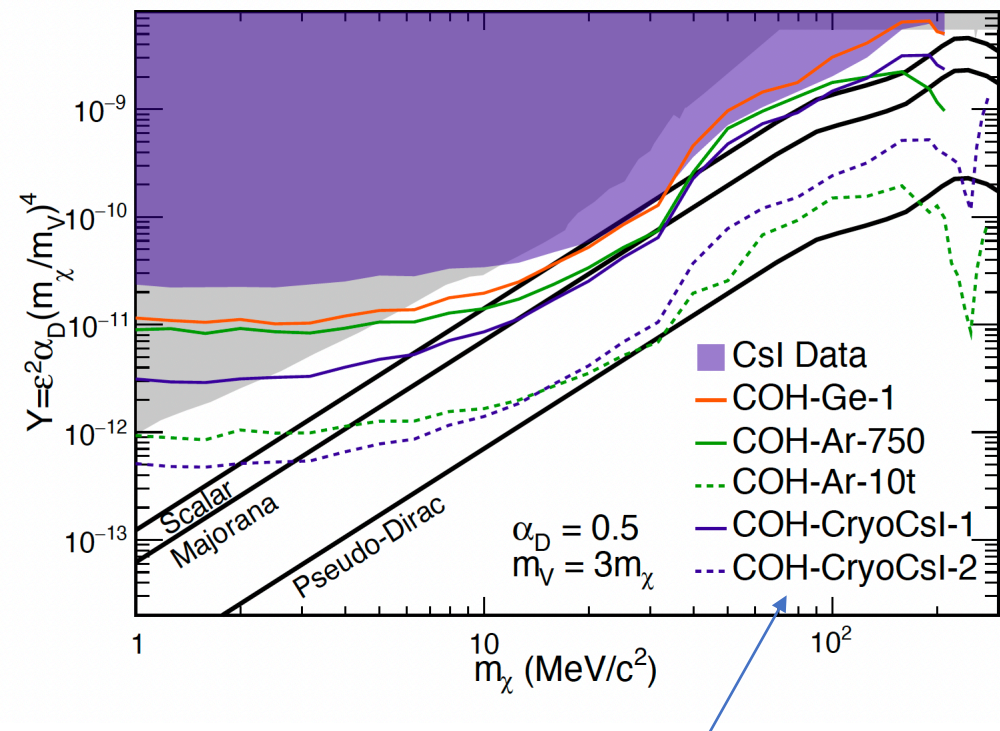
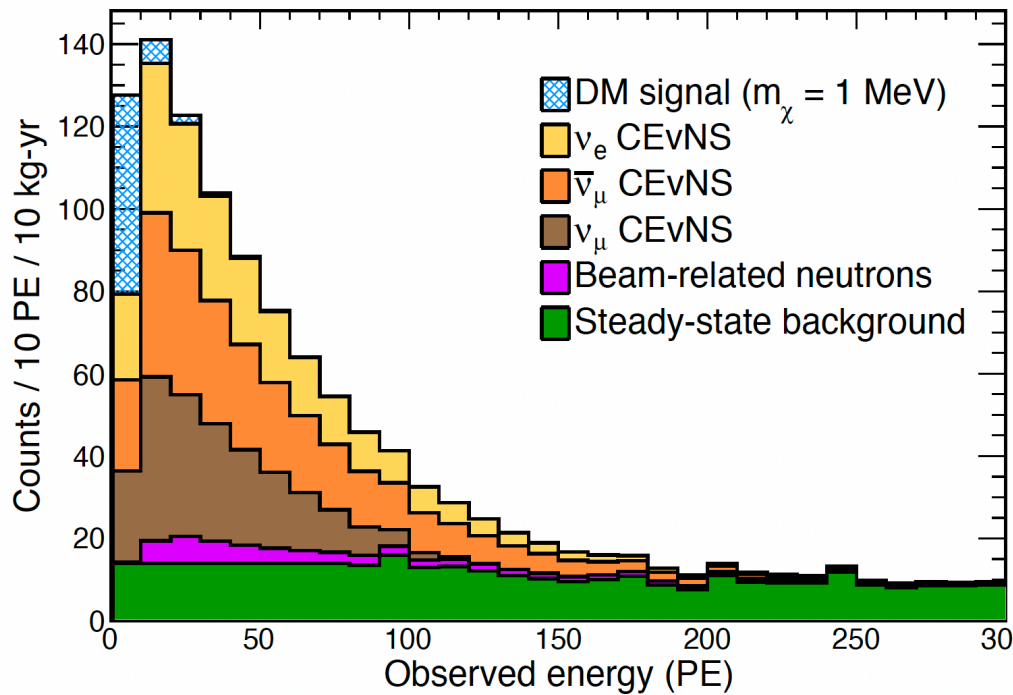
COHERENT Phys.Rev.D 109 (2024) 9



\*g-2 no longer anomalous?

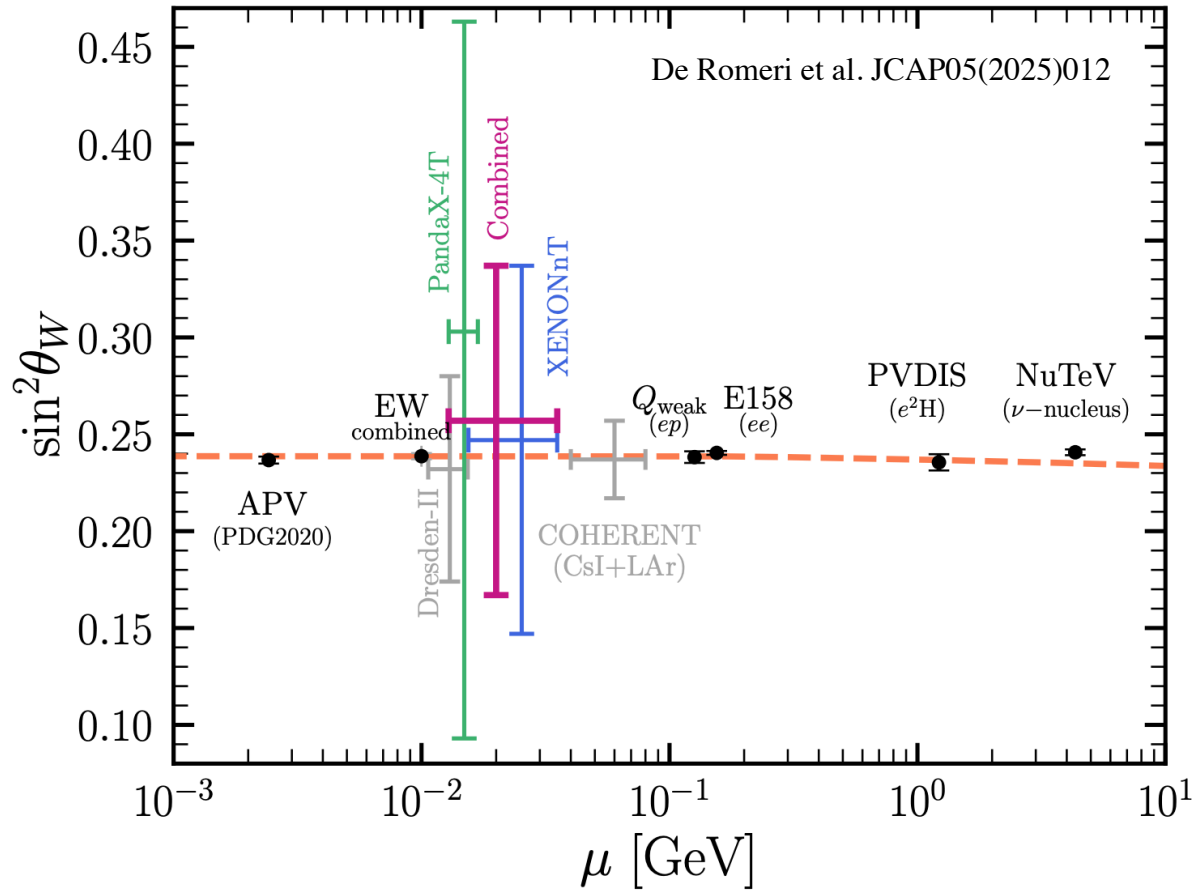
# Dark Matter

- CEvNS detectors naturally sensitive to WIMP-Nucleus scattering
  - Appears as an additional signal on top

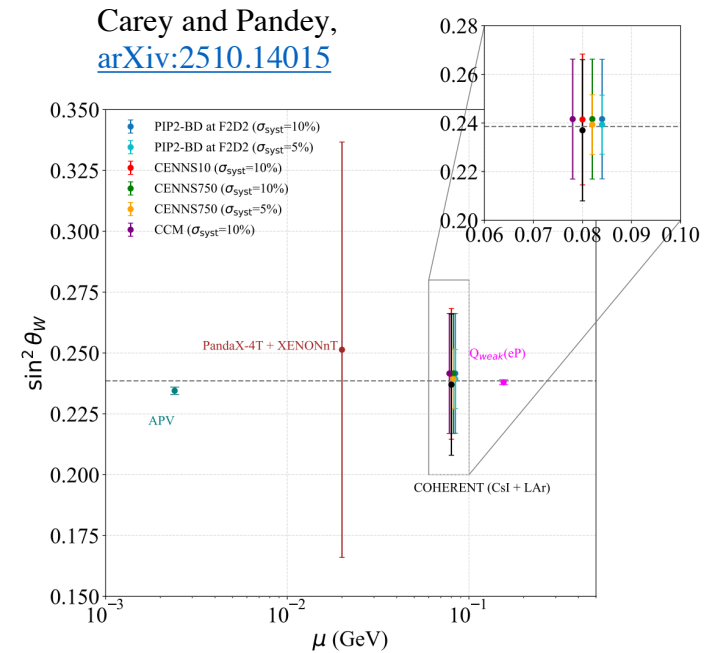


700kg upgraded CsI (undoped)

# Weak Mixing Angle Deviations?



$$Q_W^{SM} = N - Z(1 - 4 \sin^2 \theta_W)$$



- Cross section sensitive to  $\sin^2 \theta_W$  - deviation
- More precise measurements essential

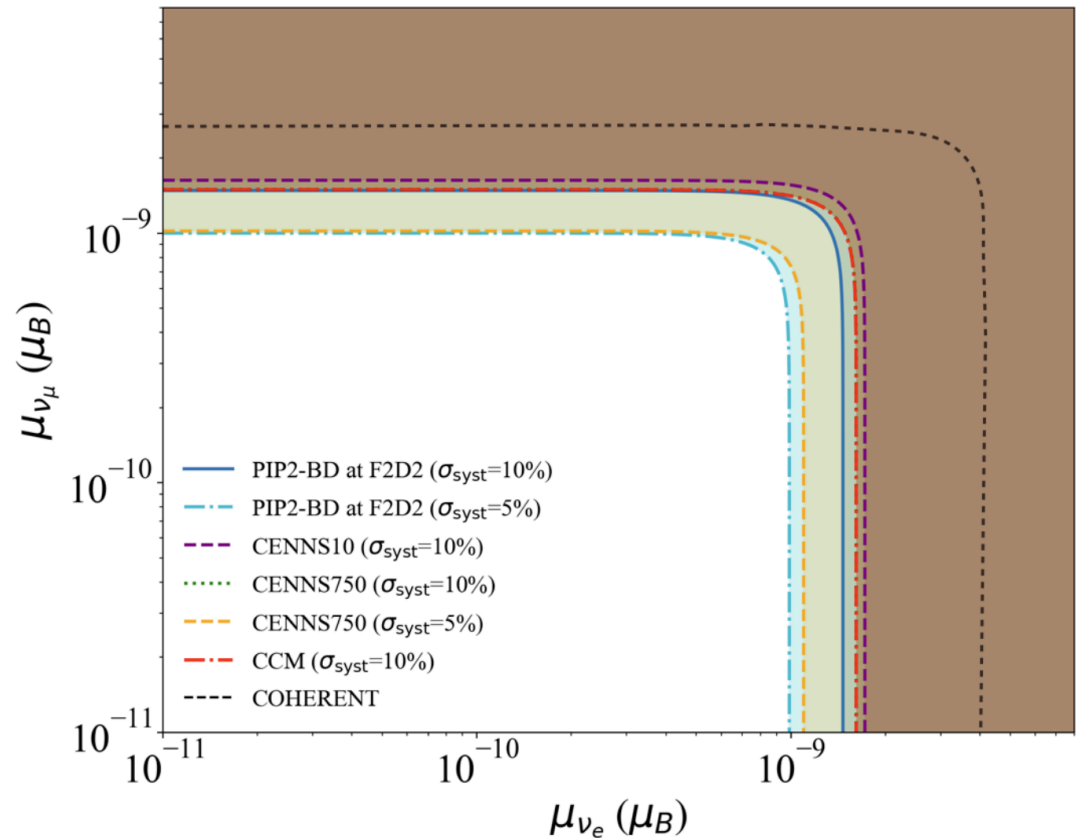
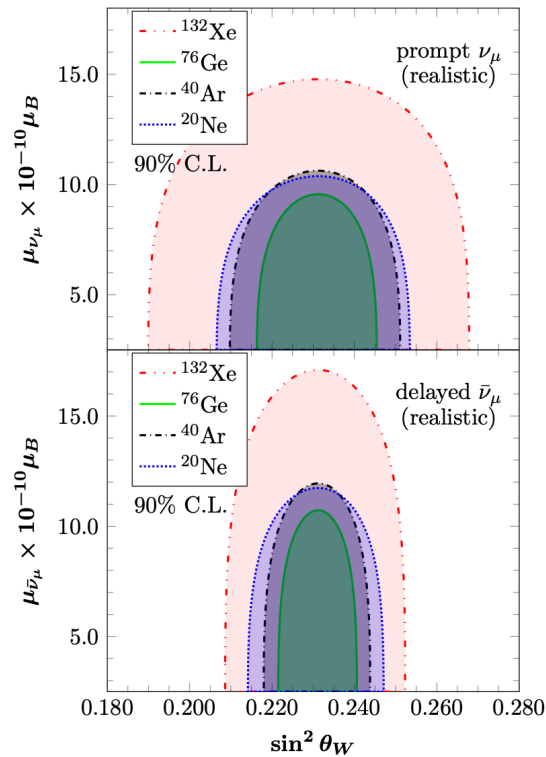
# Neutrino Anomalous Magnetic Moment

Phys. Rev. D 92, 013011 (2015)

$$\left(\frac{d\sigma}{dT}\right)_{\text{EM}} = \frac{\pi\alpha_{\text{em}}^2\mu_{\text{eff}}^2 Z^2}{m_e^2} \left(\frac{1 - T/E_\nu}{T}\right) F_Z^2(q^2)$$

Kosmas et al. Phys. Rev. D 92, 013011

Carey and Pandey arXiv:2510.14015

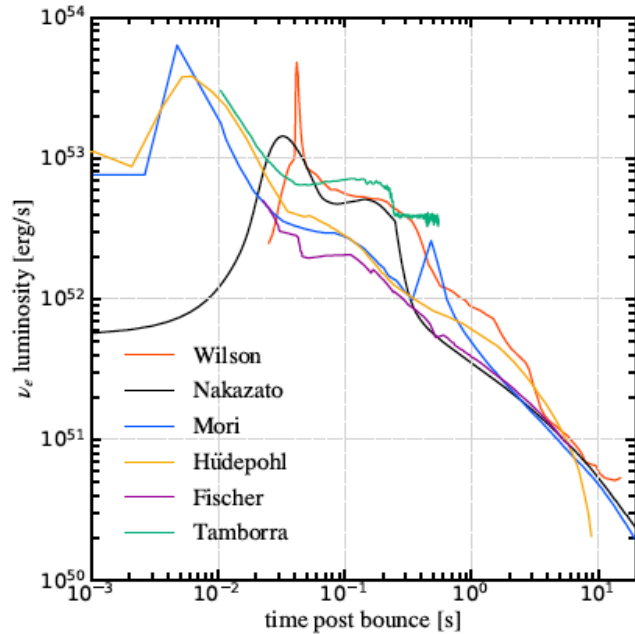


- Characteristic enhancement of cross section at very low recoils
  - Low thresholds required

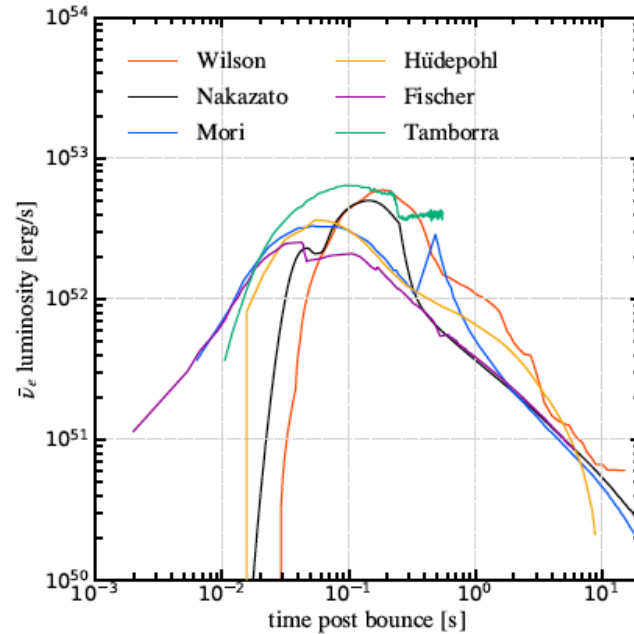
# Supernovae and BSM

# Supernovae

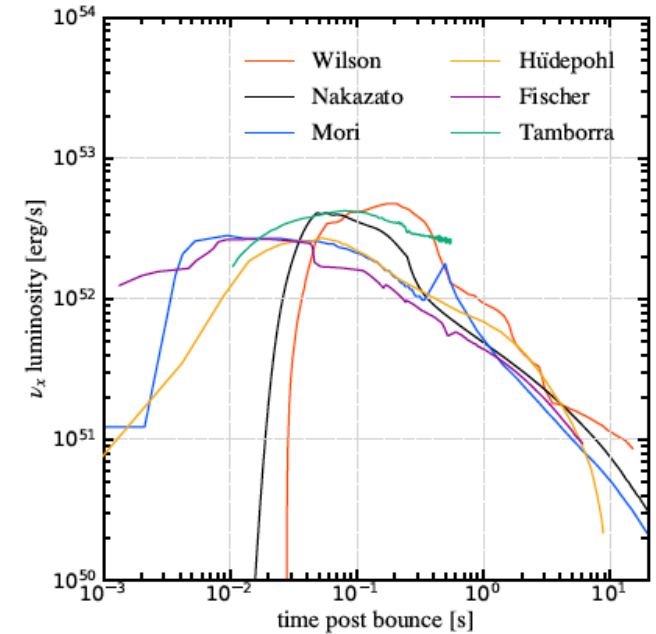
Astrophys. J. 970 (2024) 1, 93.



(a)  $\nu_e$  luminosity

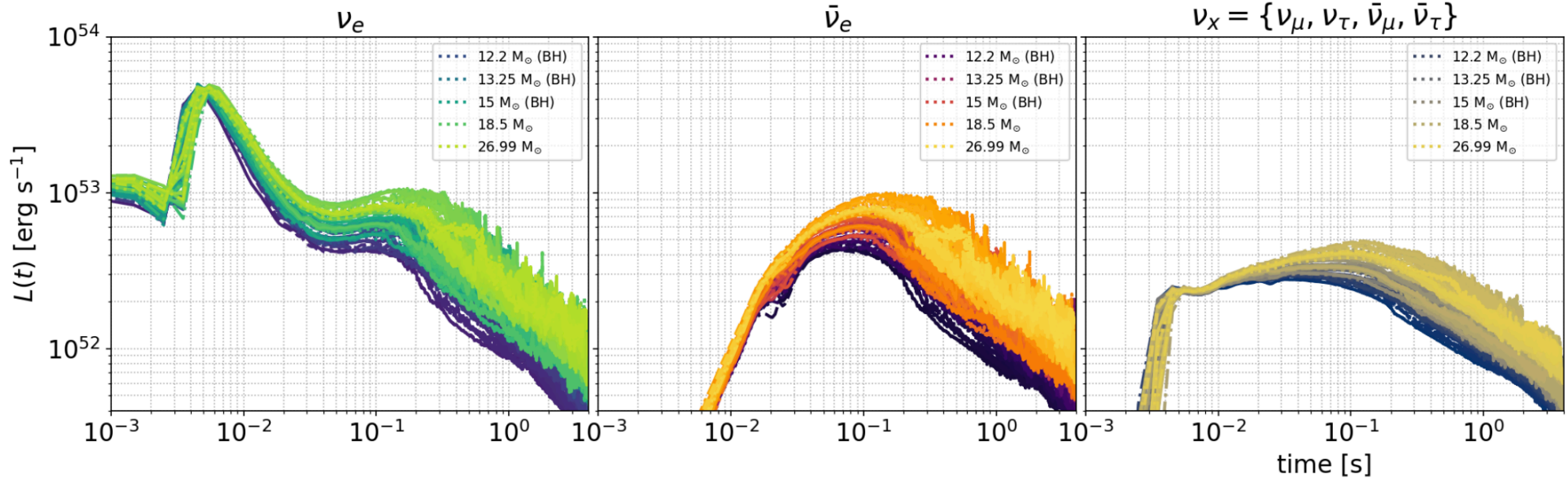


(b)  $\bar{\nu}_e$  luminosity

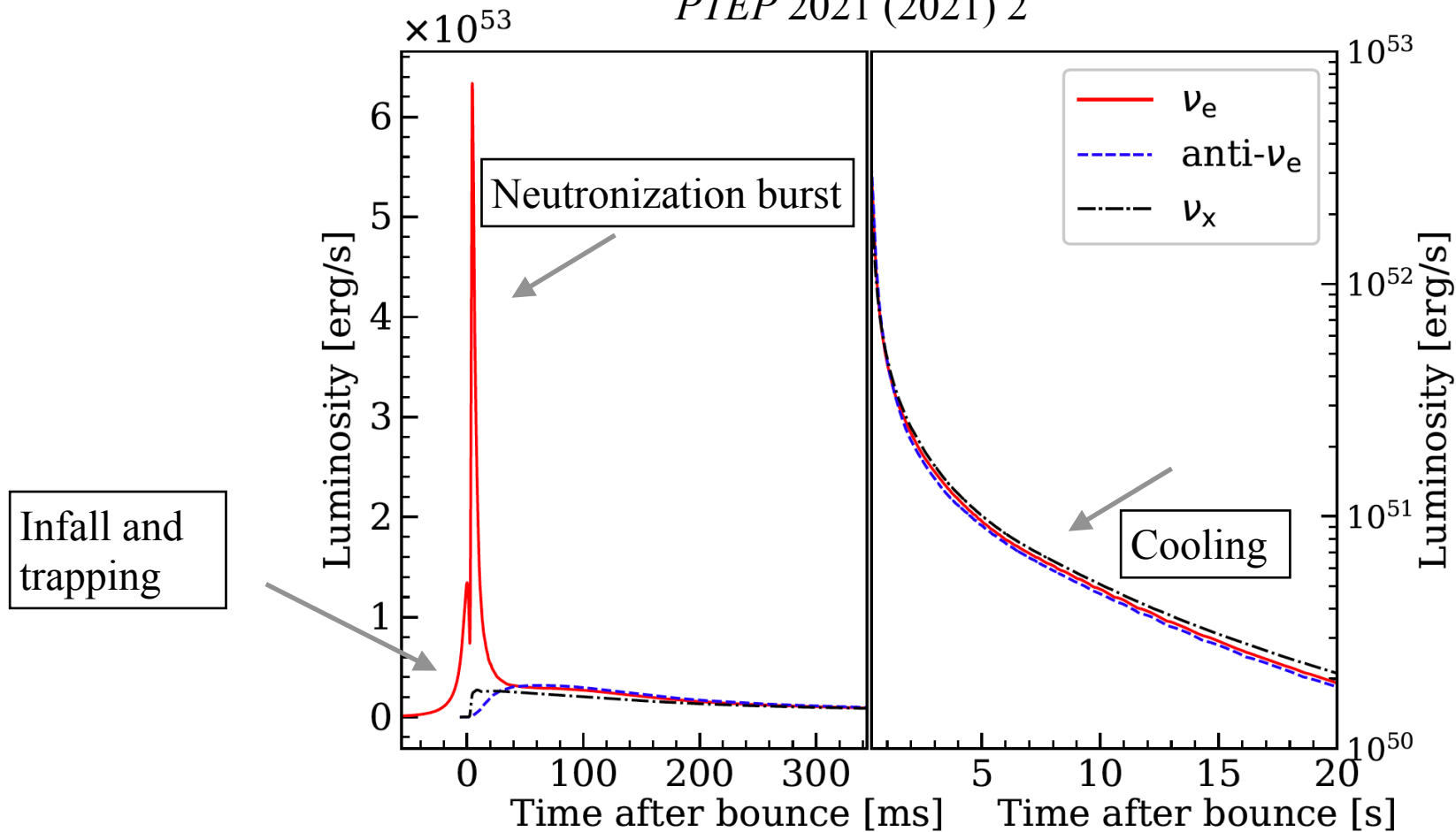


(c)  $\nu_x$  luminosity

- Basic mechanism of core-collapse supernovae explosions established by  $\nu$  from SN1987A observation ( $\sim 24$  events total)
- Details are largely unknown...many models
  - Shock revival mechanism, equation of state, PNS formation
- Must make the most of next observation



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  - Shock revival mechanism, equation of state, PNS formation
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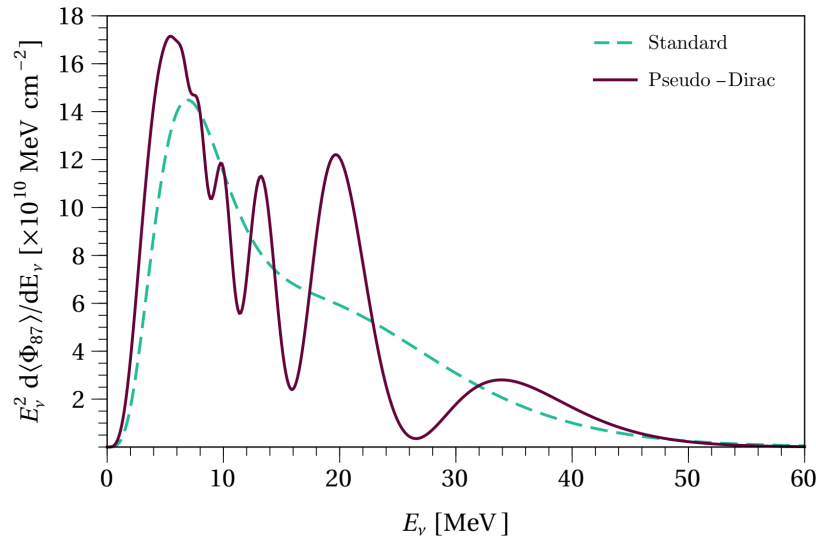
- Different flavors probe different parts of the explosion
- Canonical  $\nu$  luminosity expected to last  $O(10)$ s or longer

A precise understanding of all relevant neutrino cross sections, **including particles in the final state**, is essential for extracting the most information from the next supernova observation

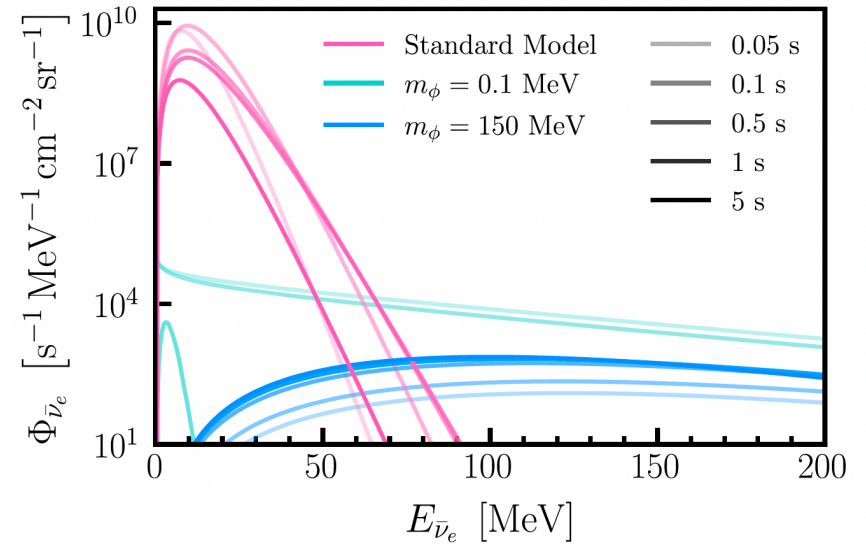
# BSM in Supernovae

- New physics can impact the luminosity, duration, average energy, and spectral shape of neutrino burst

Martinez-solar et al. PRD **105** (2022) 095019

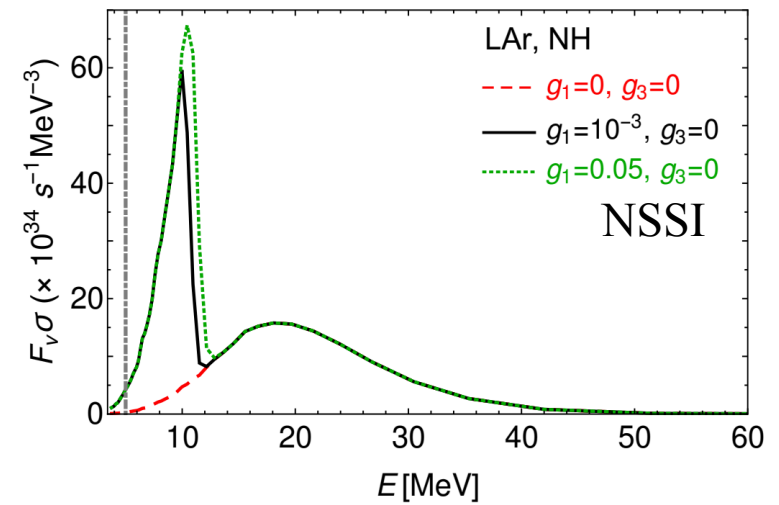


Arguelles et al. PRL **134**, 221002

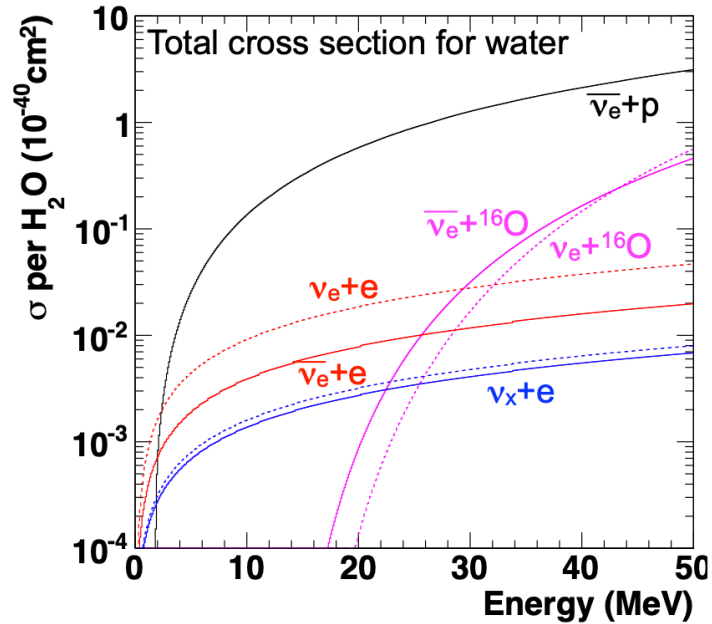


- All manner of new physics can be probed
  - Axions, neutrino magnetic moment, millicharge, majorons, non-standard  $\nu$  self interactions, NSI, etc..
- Not a complete list...
- Precise knowledge of  $\nu - N$  interactions vital!

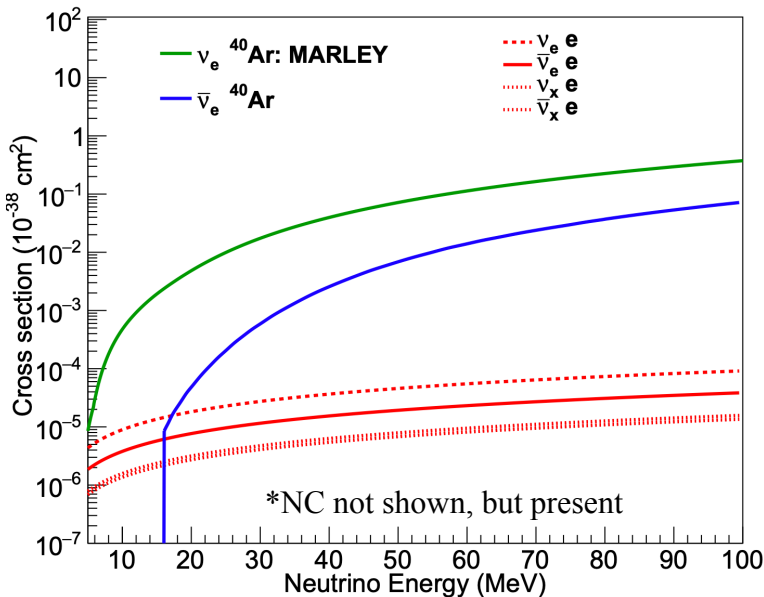
Das et al. JCAP **05** (2017) 051



# Prospects and Limitations for SN Observations

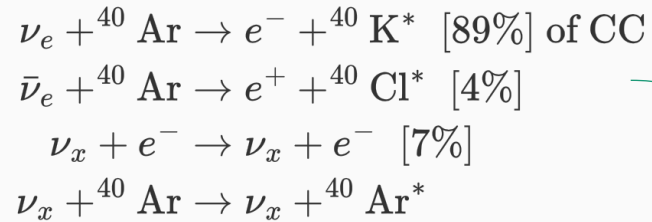


> Error O(10)%



- Expect orders of magnitude more  $\nu$  events for next CCSN observation [10 kpc]
- SK  $\sim O(1k)$  events
- HK  $\sim O(10k)$  events
- DUNE  $\sim O(1k)$  events

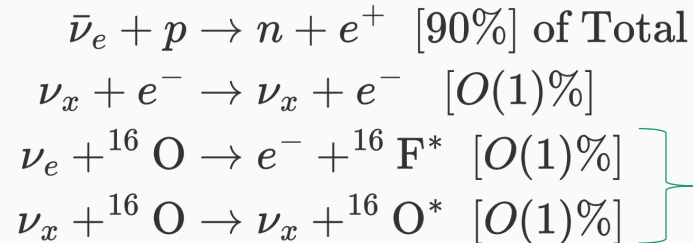
- LAr detectors primarily sensitive to



Only DEAP(2026)  
O(50%)

Unmeasured

- Water Cherenkov detectors sensitive to

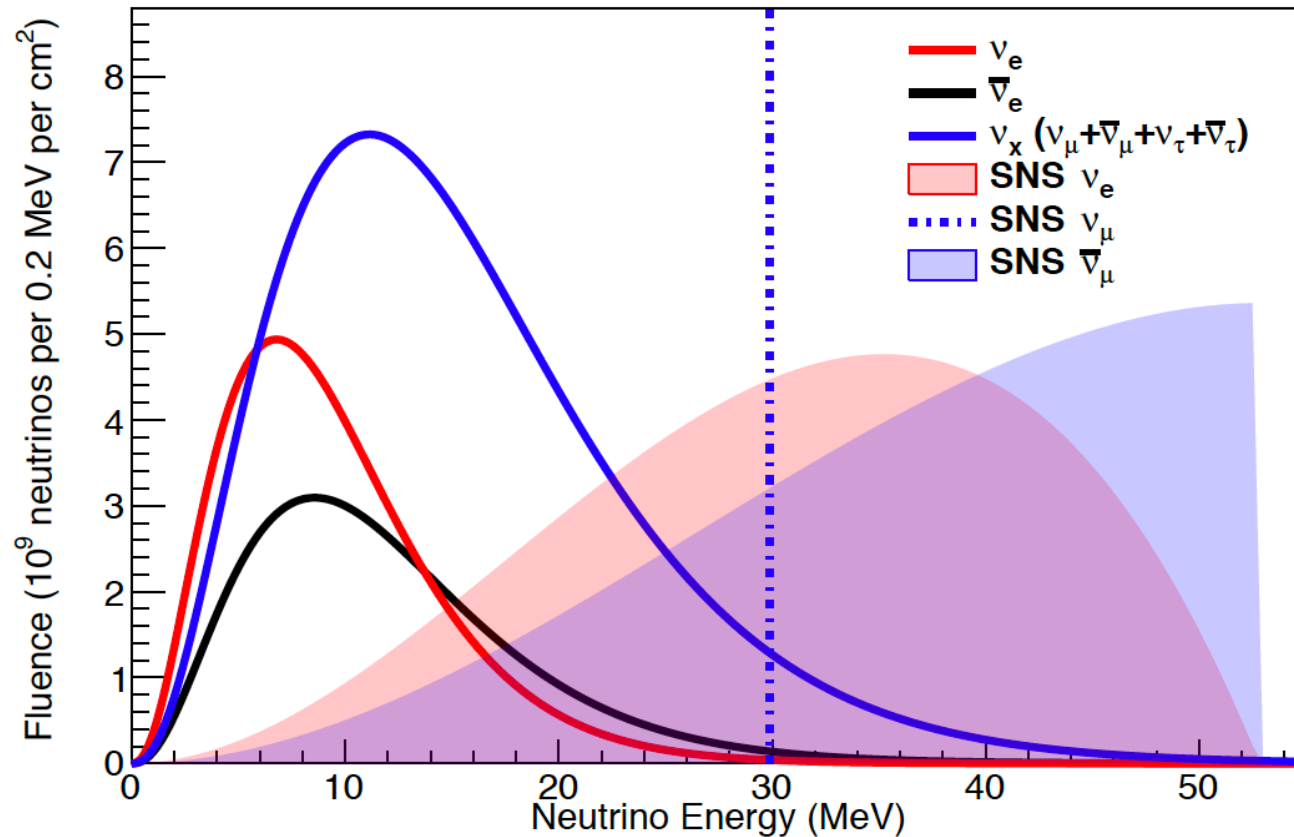


Unmeasured

- However, only IBD and ES reactions are known well...others are essentially unmeasured!

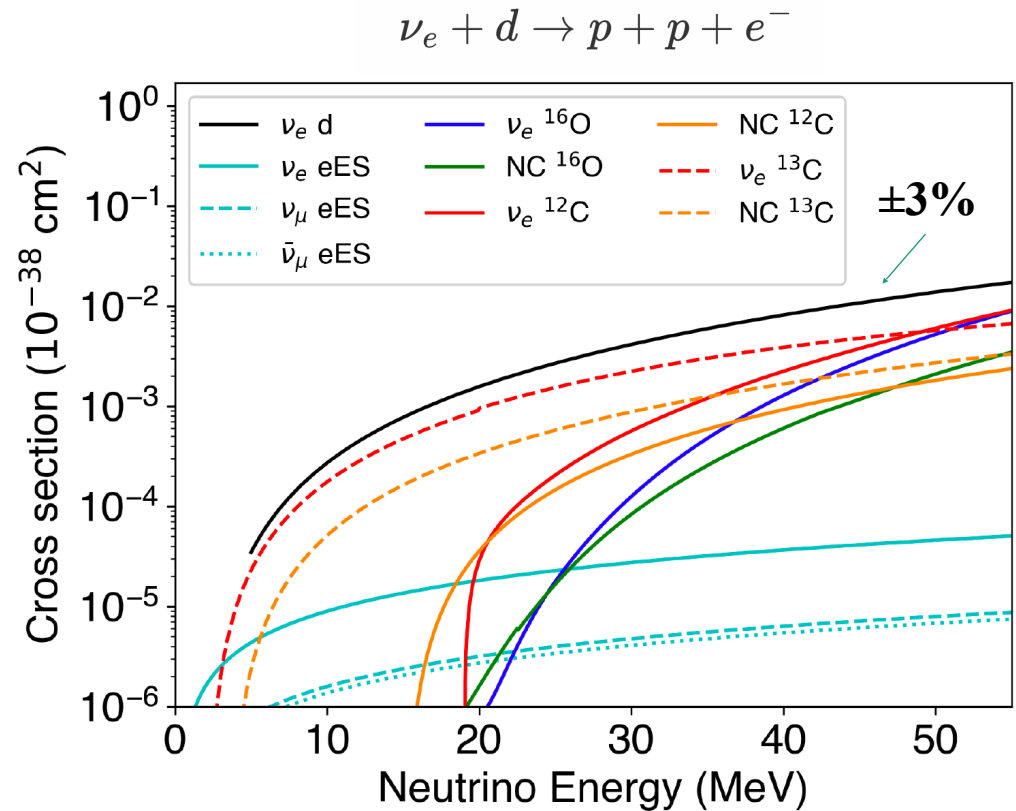
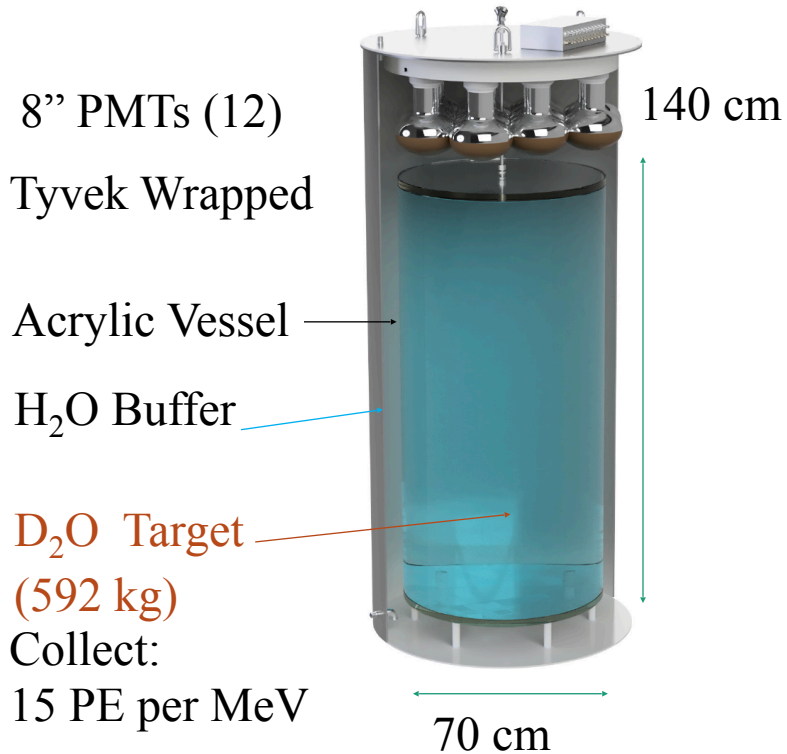
What's in the final state?

# SNS Beam Structure: Ideal for Cross Sections at $\text{SN}\nu$ Energies



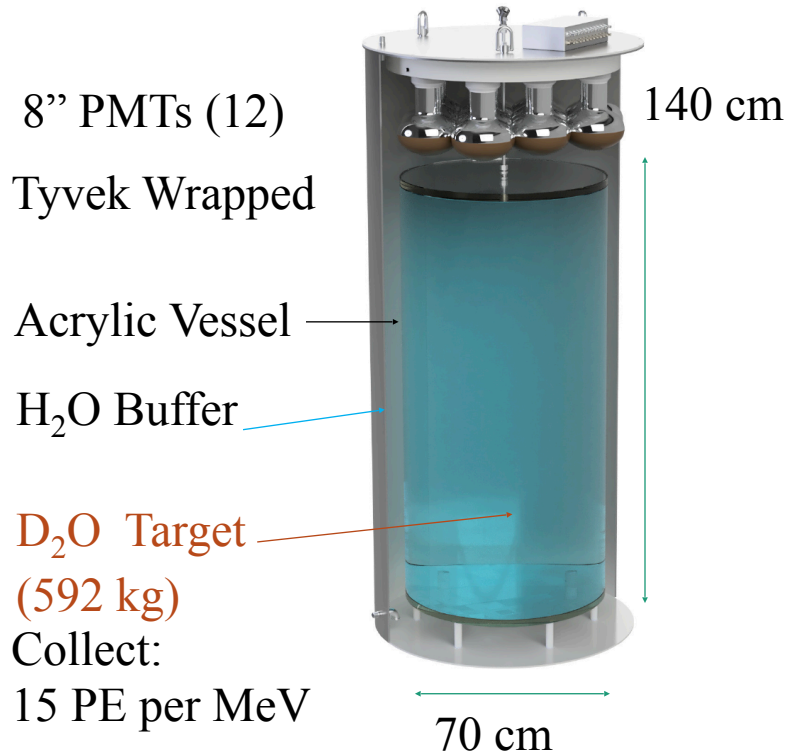
- Delayed Michel decay produces anti- $\nu_\mu$  and  $\nu_e < 52$  MeV
- Spectrum of  $\nu_e$  well known  $\rightarrow$  CC  $\nu_e + ^{16}\text{O}$ , Flux normalization
- Overlaps well with expectation from Supernova

# COHERENT D<sub>2</sub>O

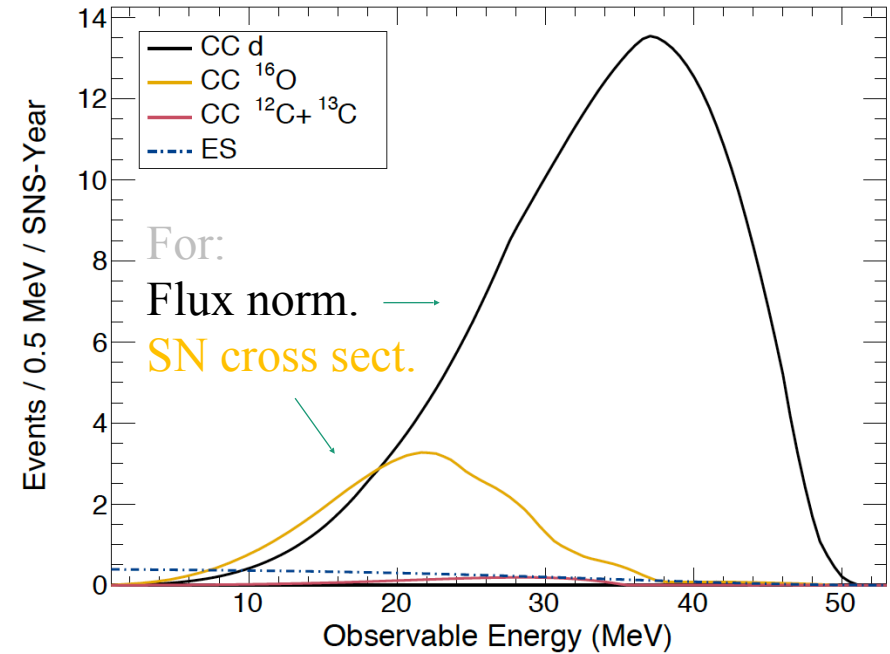


- COHERENT plans on operating *two* D<sub>2</sub>O-based detectors to understand the normalization of the SNS flux
  - 5% flux normalization uncertainty in  $\sim 2$  years
  - Second module entering commissioning now (light water)
- Neutrino-induced deuteron break up cross section known to **better than 3%**

# COHERENT D<sub>2</sub>O

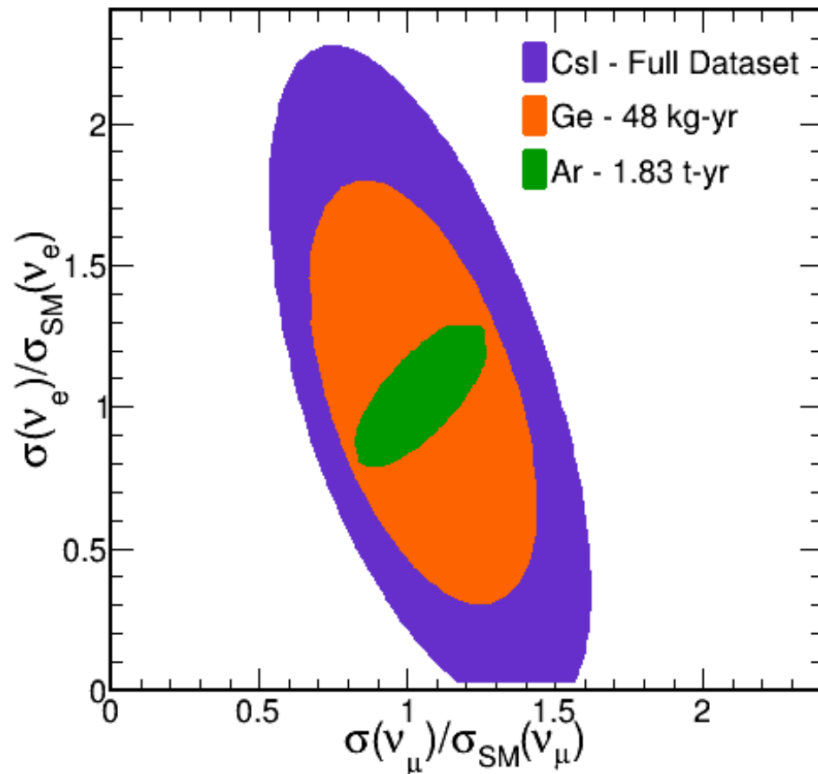


COHERENT JINST 16 (2021) 08

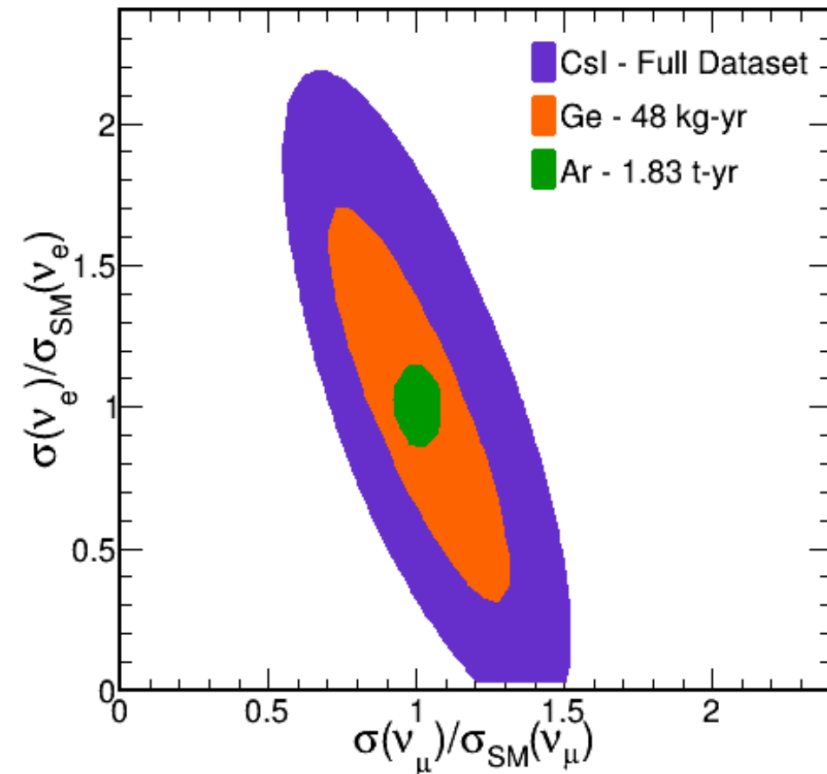


- COHERENT plans on operating *two* D<sub>2</sub>O-based detectors to understand the normalization of the SNS flux
  - 5% flux normalization uncertainty in ~2 years
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10% Flux Uncertainty



3% Flux Uncertainty

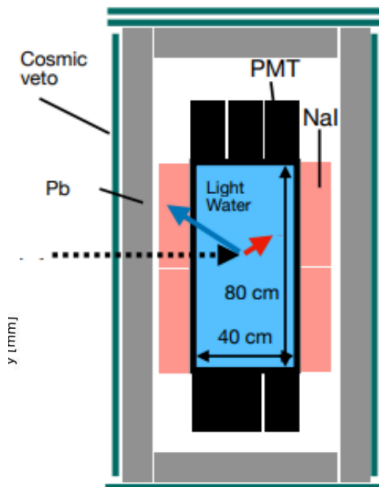


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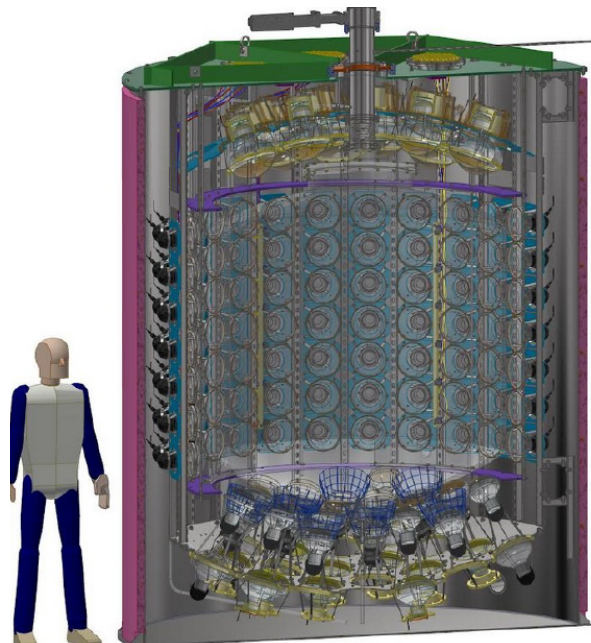
# Future Electron Neutrino-Oxygen Scattering at ORNL

- Unmeasured channel, important for current and future Cherenkov detectors
  - Super-K (1996~) 32 kton
  - Hyper-K (2028~) 186 kton
  - THEIA (203X~) 50 kton
- Precision measurements will open  $\nu_e, \nu_x$  channels in these IBD-dominated detectors
  - → More events, more BSM

100L



EOS (4kton)



Expect  $\sim 10\%$  measurement  
on CC  $\nu_e - {}^{16}\text{O}$  cross section  
in 2 SNS-years

# Summary

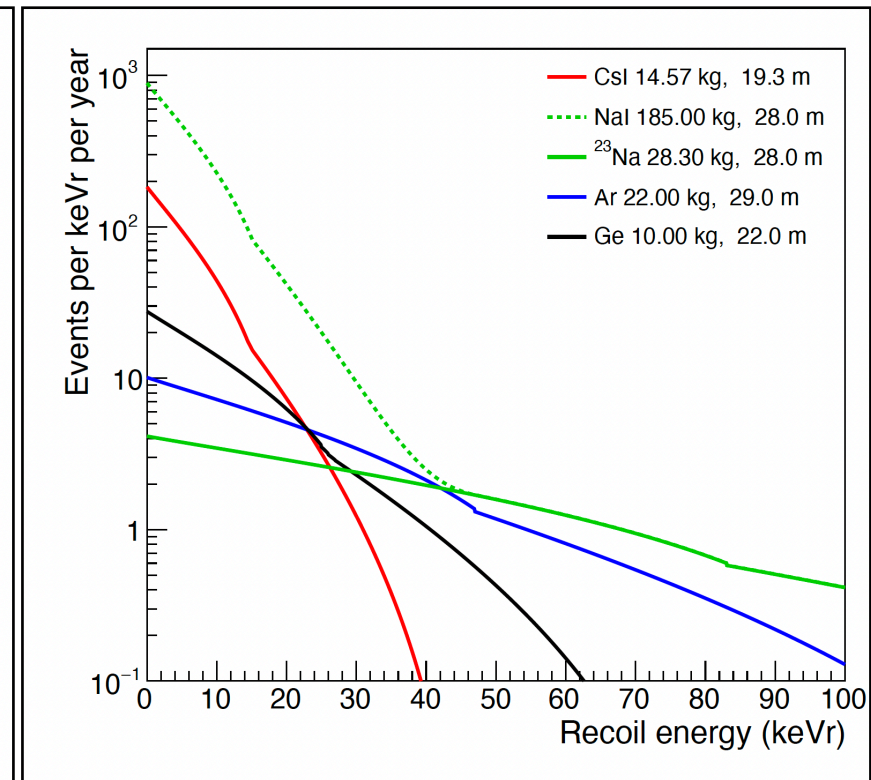
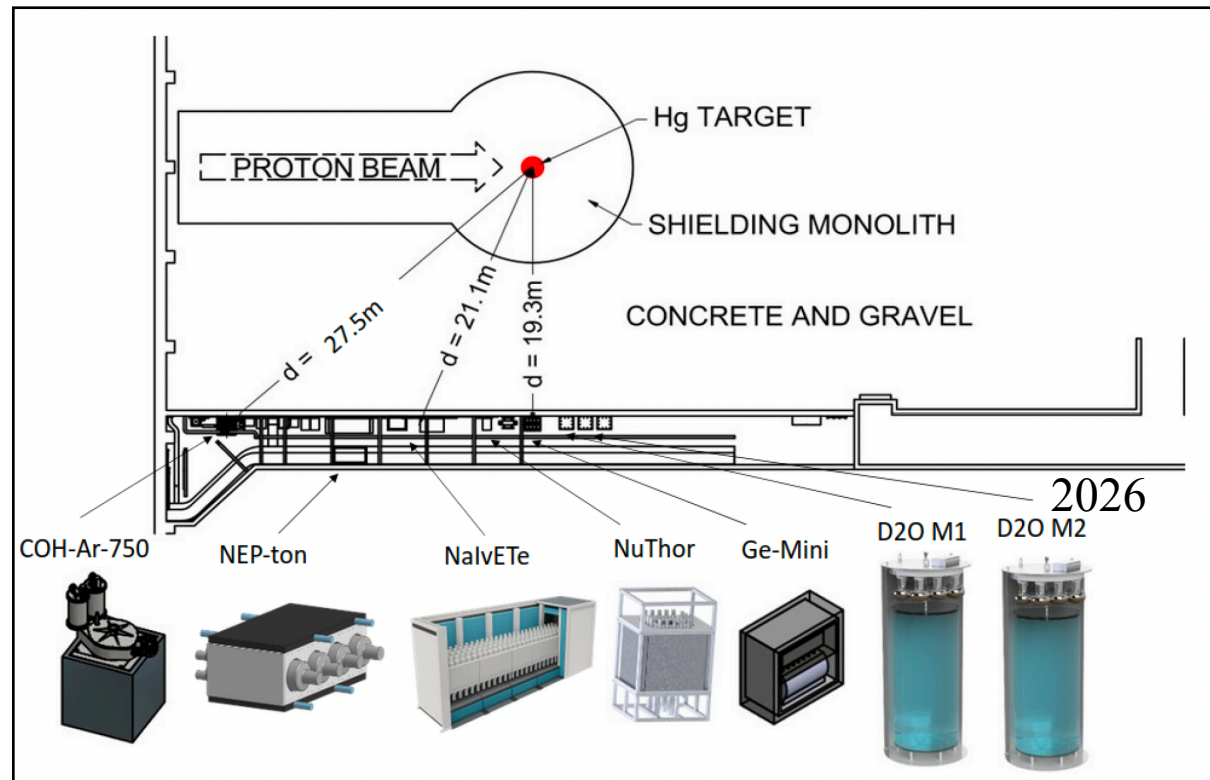
- CEvNs is a well-understood process in the SM, which means measured deviations (of many types) from that prediction could indicate new physics
- Since the first observation in 2017, several improved measurements by COHERENT and others (many not presented here) as well as new constraints on BSM processes
- Still, CEvNs is a burgeoning industry with many groups working toward lower thresholds and higher statistics
- Flux uncertainties are a dominant systematic that will be addressed as part of the COHERENT inelastic program → Boost BSM sensitivity
- Future supernova neutrino observations will provide another playground for tests of both conventional and BSM physics
  - To make the most of those observations, precision inelastic  $\nu - N$  measurements are vital

Thank you!



# Backups

# COHERENT Experiment Overview



20keVnr	13 keVnr	2.5 keVnr
476kg	3.5t	17.6kg
1Ar, 1phase	63, 7.7kg Nal[Tl]	8 HPGe (2.2kg)
122 PMTs		