The COHERENT experimental program at the SNS

Keyu Ding

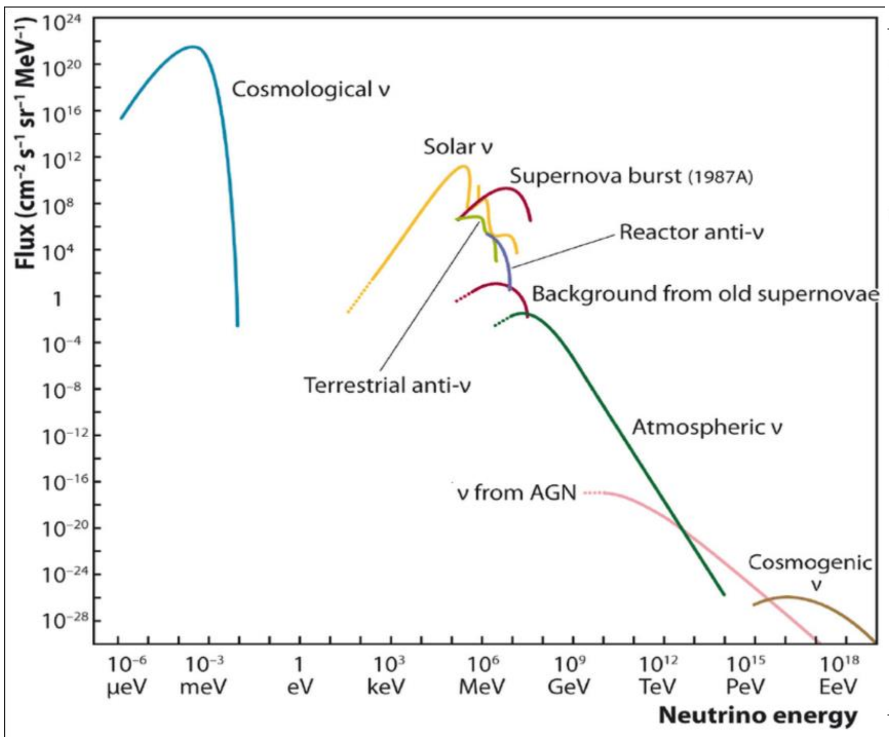
July 5, 2023

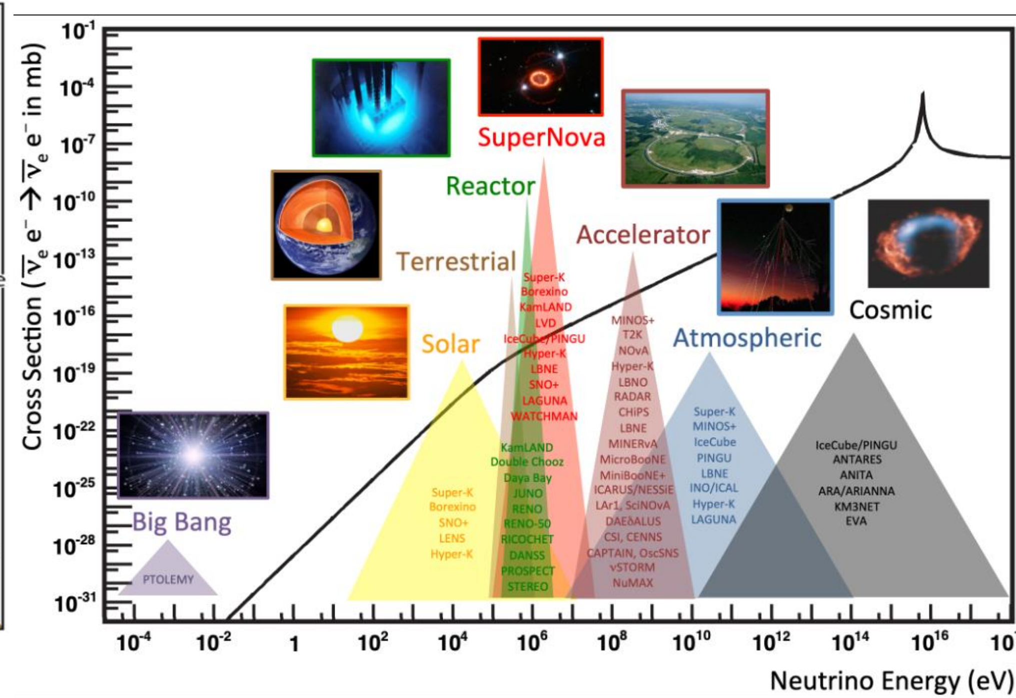
Neutrino sources

Grand Unified Neutrino Spectrum at Earth
Edoardo Vitagliano, Irene Tamborra, Georg Raffelt. Oct 25, 2019. 54 pp.
MPP-2019-205
e-Print: arXiv:1910.11878 [astro-ph.HE] | PDF

Flux — **Cross section** — **Number of targets** /money

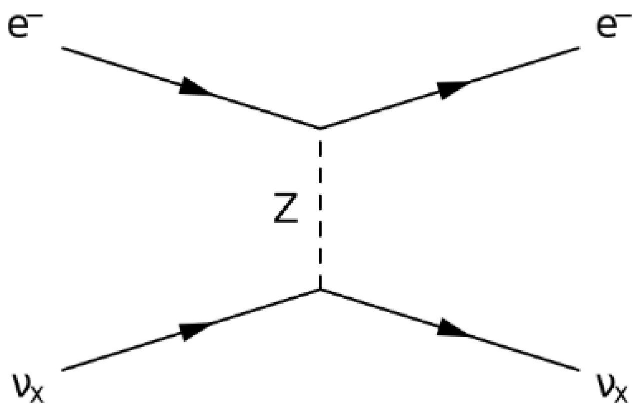
Event rate $R = \Phi \, \sigma \, N_t$

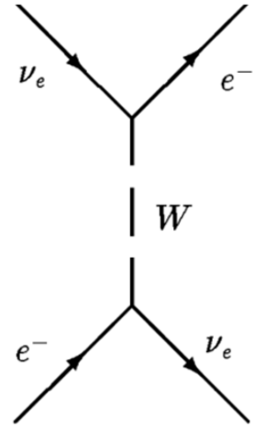


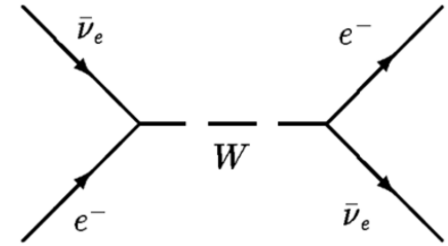


Neutrino interactions with matter

- Electron



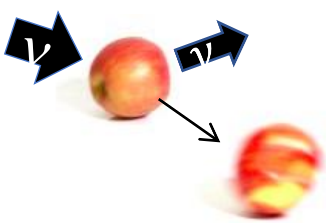


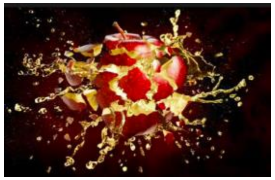


- Nucleus, however, complicated

Energies deposited

keV MeV GeV TeV PeV

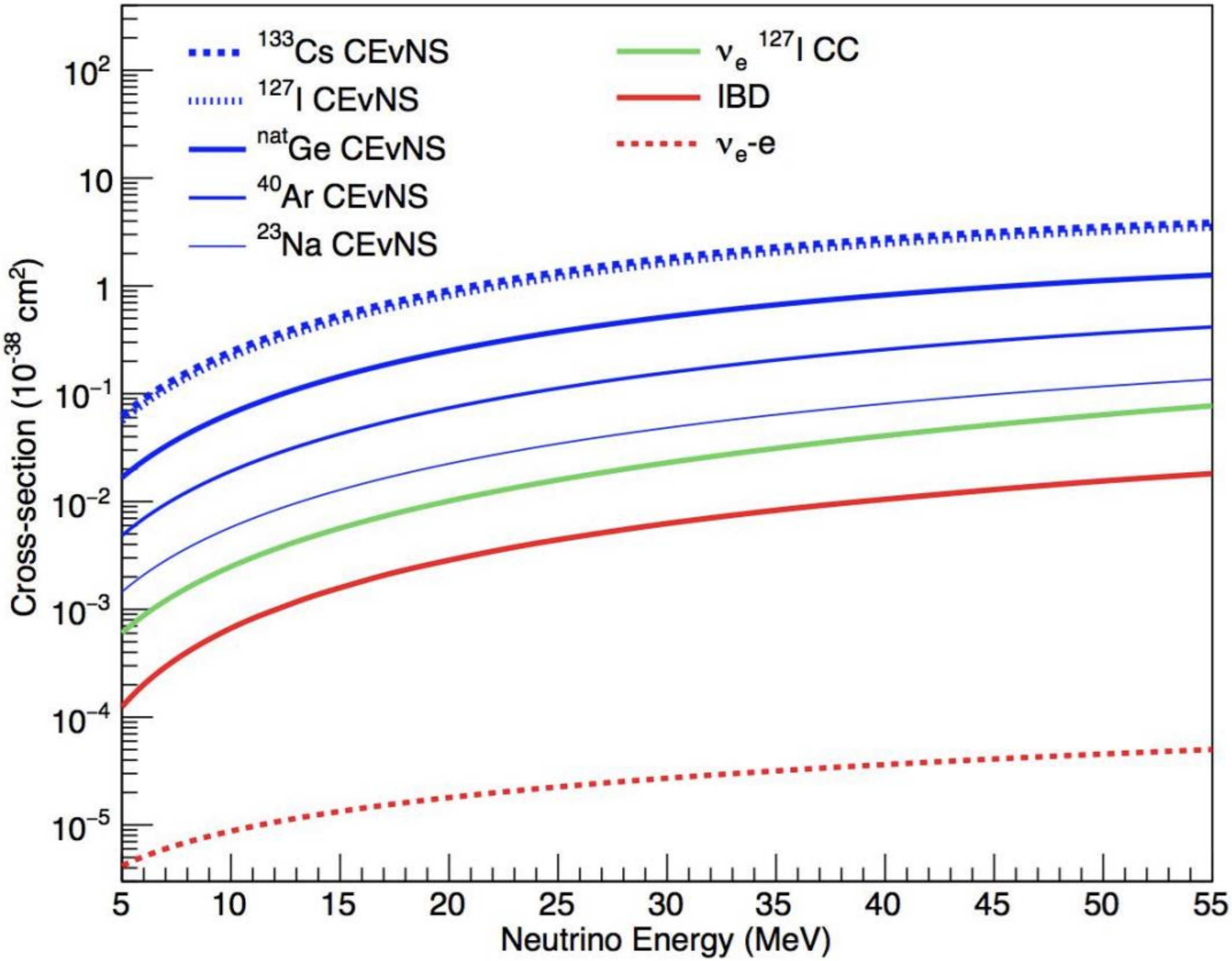




Coherent elastic neutrino-nucleus scattering (CEvNS)

This is the *gentlest* interaction of a neutrino with a nucleus

Why CEvNS: high cross-section



Cross section

$$\frac{d\sigma}{dT} \simeq \frac{G_F^2 M}{2\pi} \frac{Q_W^2}{4} F^2(Q) \left(2 - \frac{MT}{E_\nu^2}\right)$$

E_ν: neutrino energy
T: nuclear recoil energy
M: nuclear mass
Q = √ (2 M T): momentum transfer

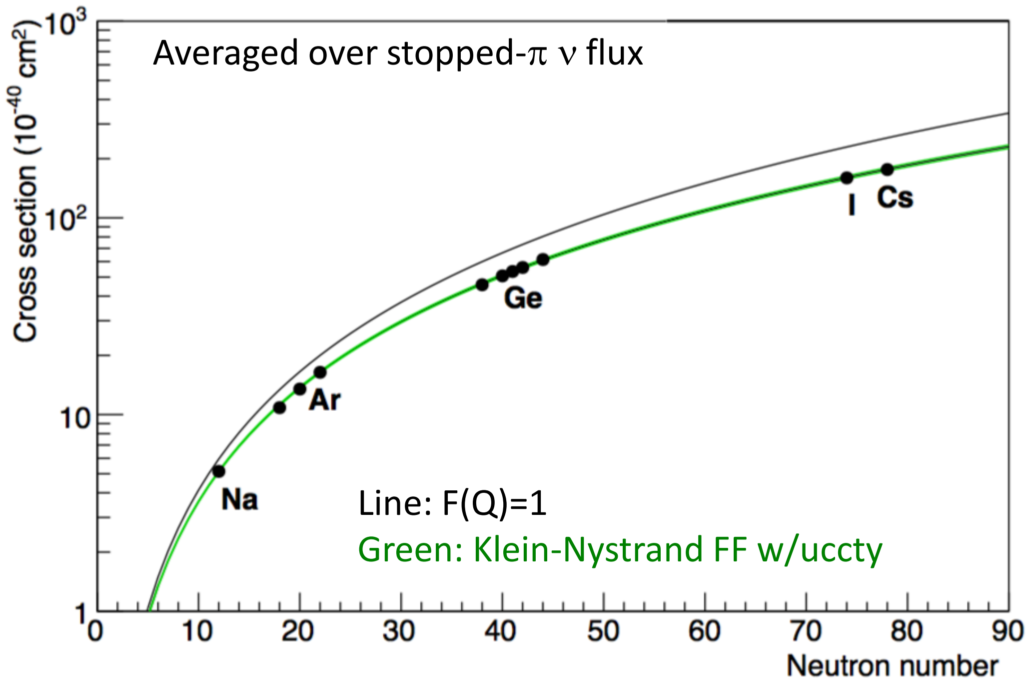
weak nuclear charge

Form factor: F=1 ➔ full coherence

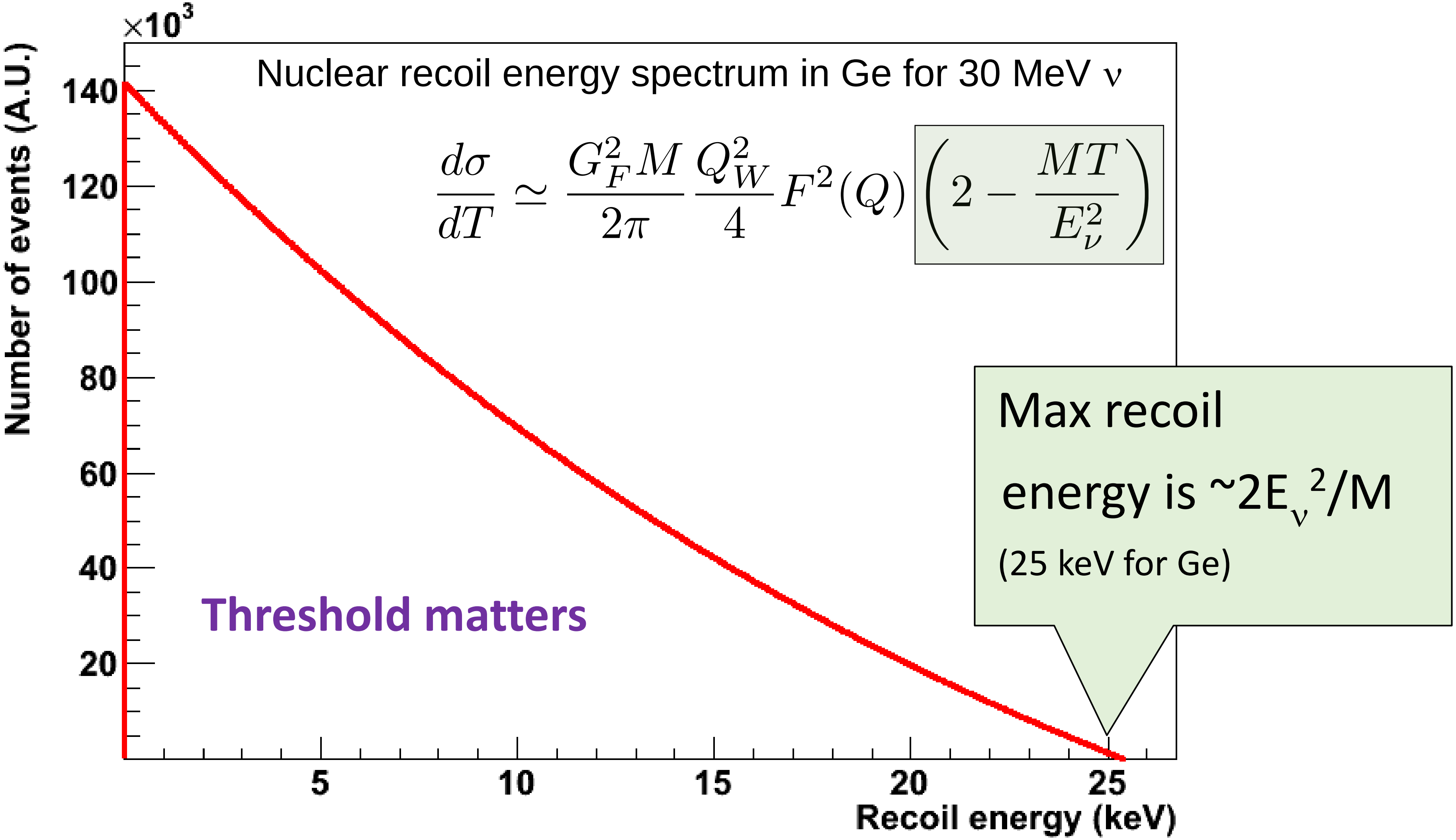
$$Q_W = N - (1 - 4\sin^2\theta_W)Z$$

$$\Rightarrow \frac{d\sigma}{dT} \propto N^2$$

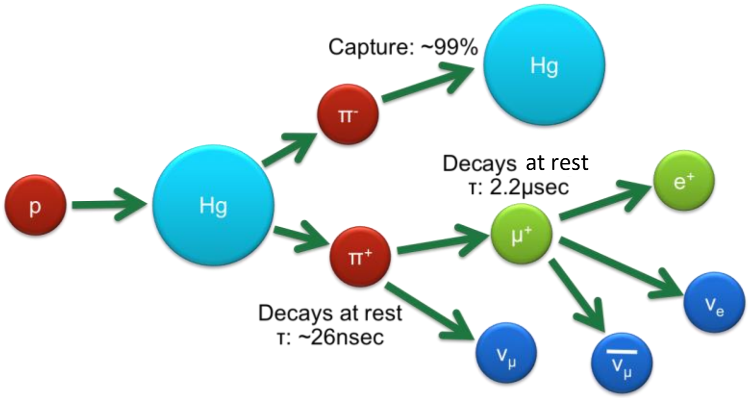
Different target matters



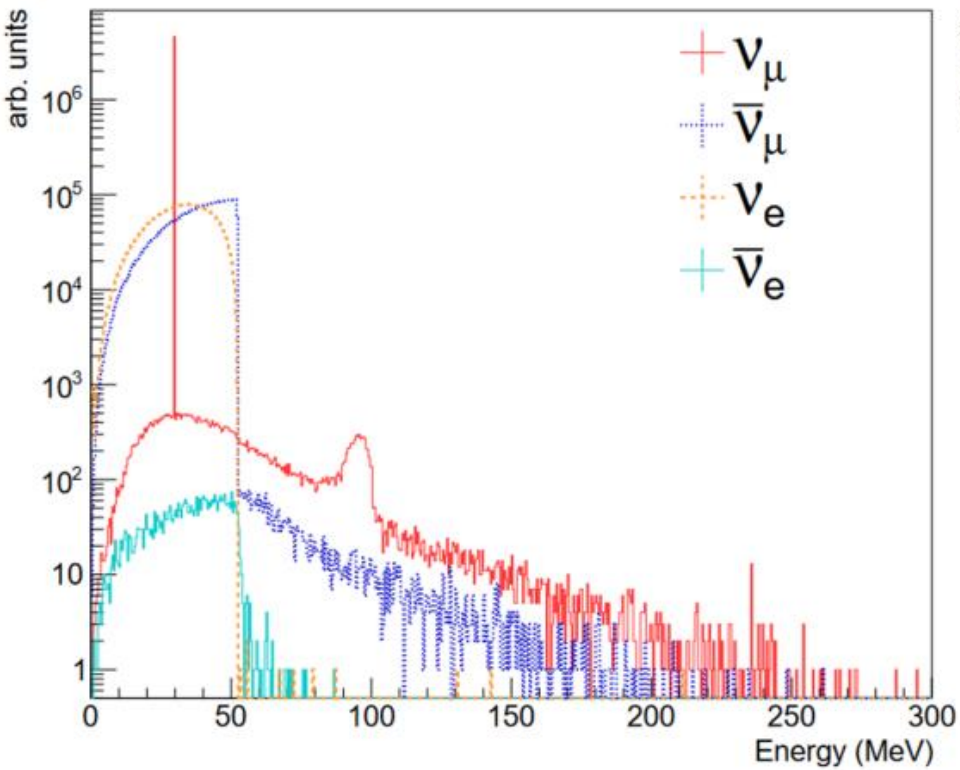
Large cross section (by neutrino standards) but hard to observe due to tiny nuclear recoil energies:

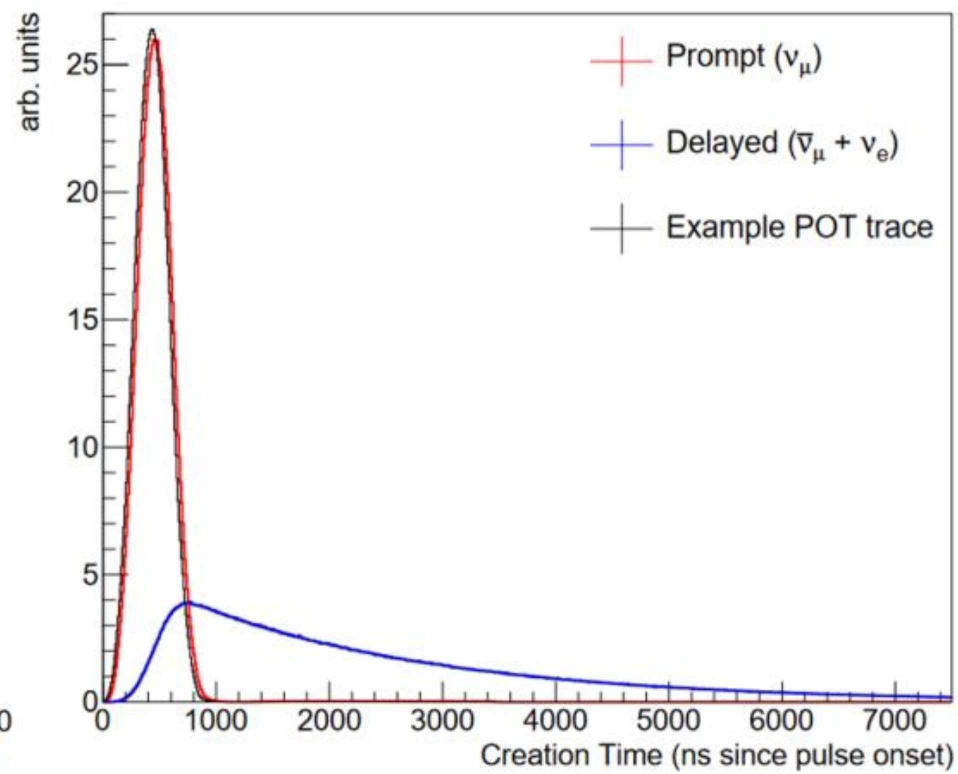


Stopped-Pion (pDAR) Neutrinos



Distributions of neutrino energy (left) and creation time (right) produced at the SNS predicted by our Geant4 simulation

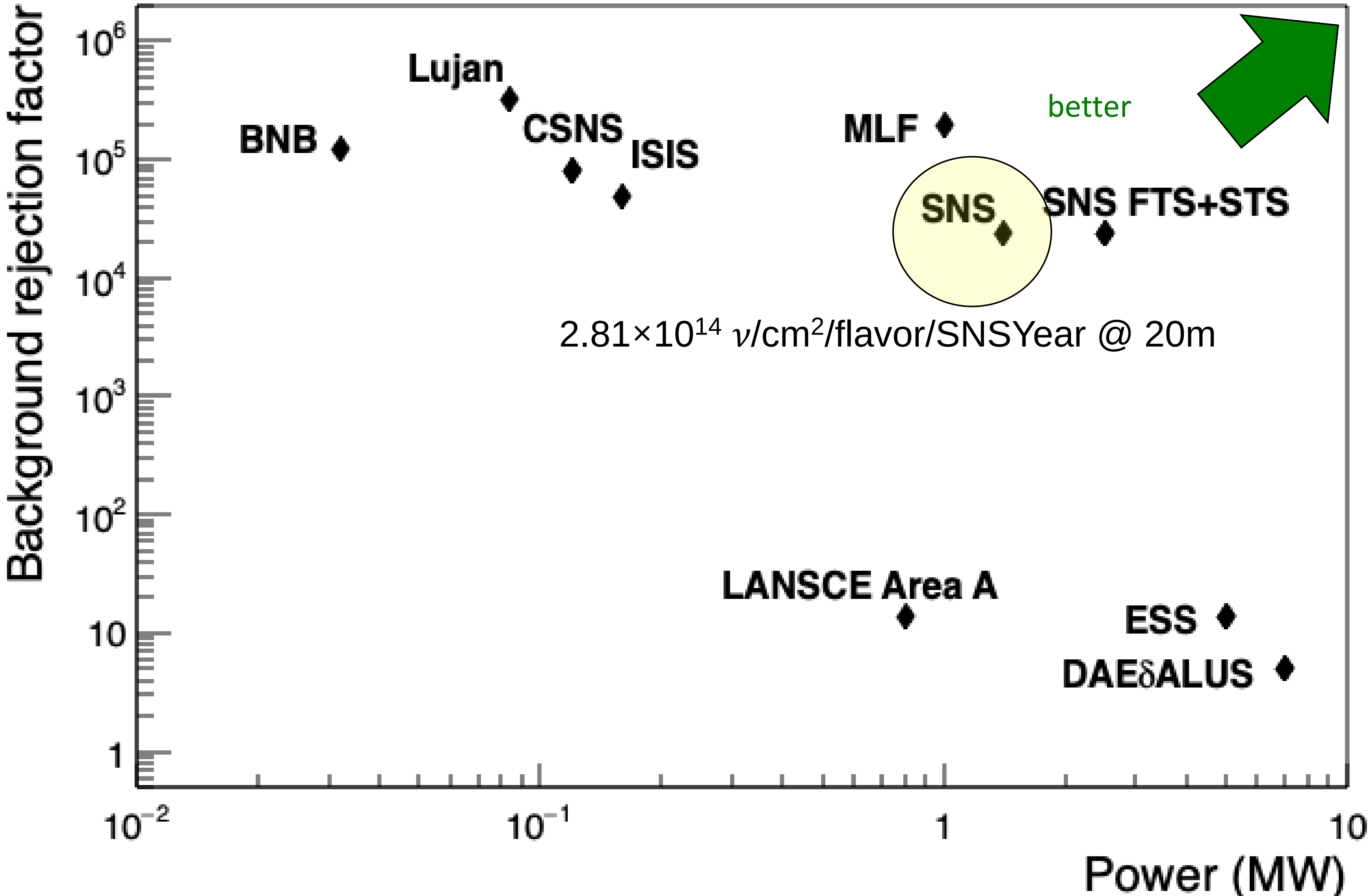




from duty cycle

Comparison of πDAR ν sources

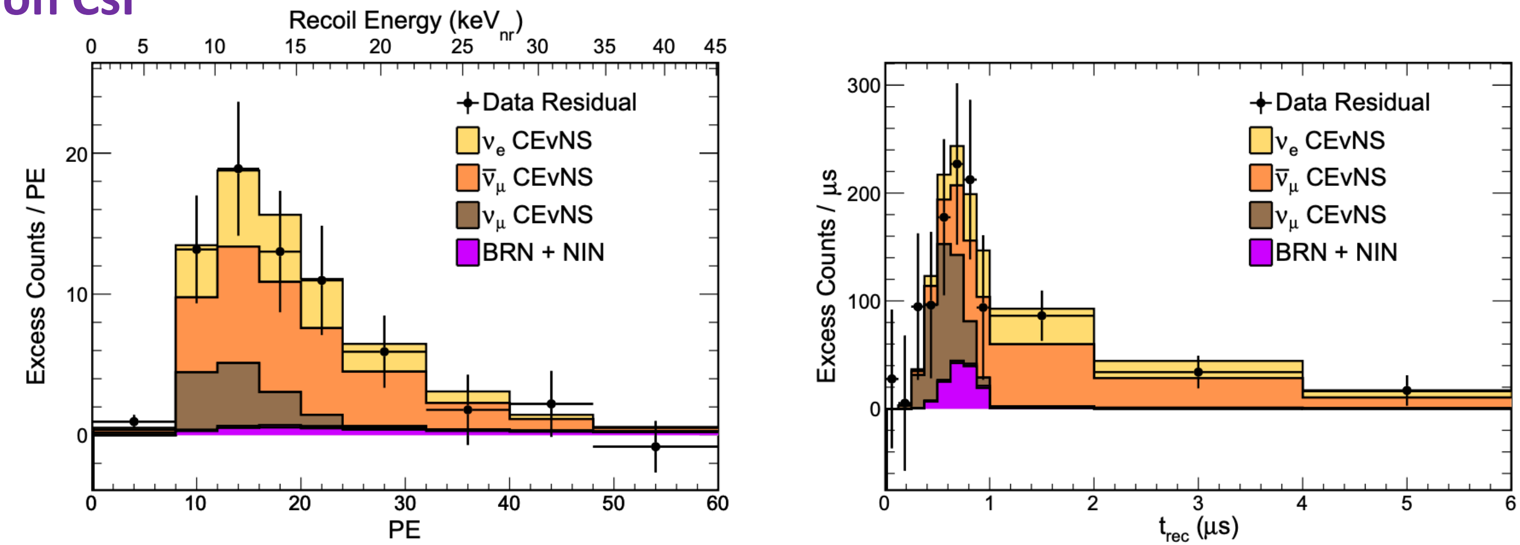
Fun fact, free neutrinos



$\propto \nu$ flux

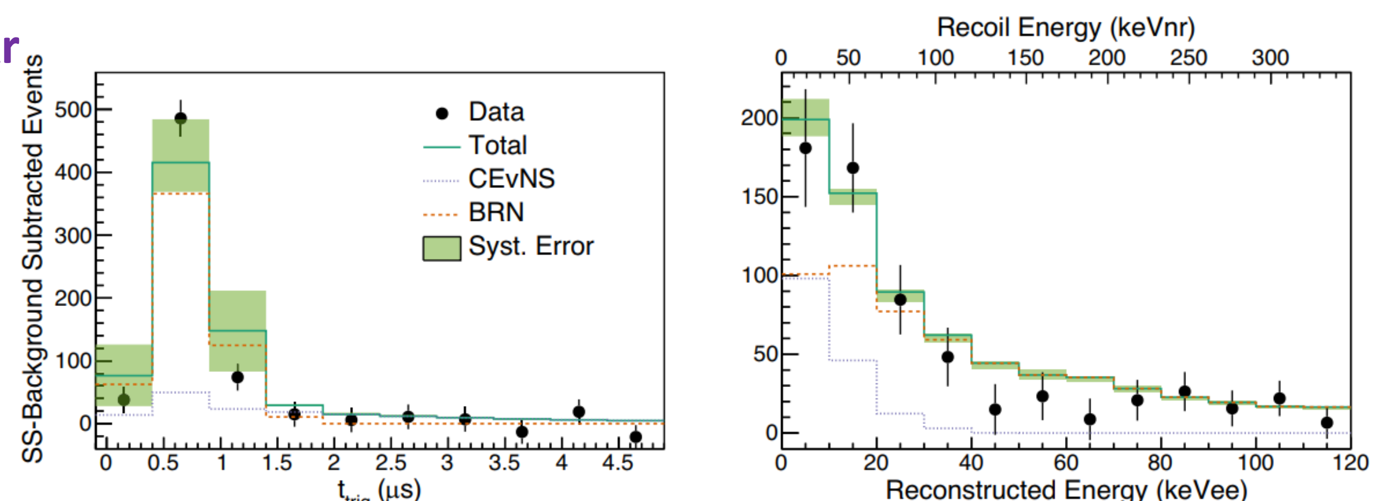
A fistful of CEvNS, all from COHERENT

CEvNS on CsI



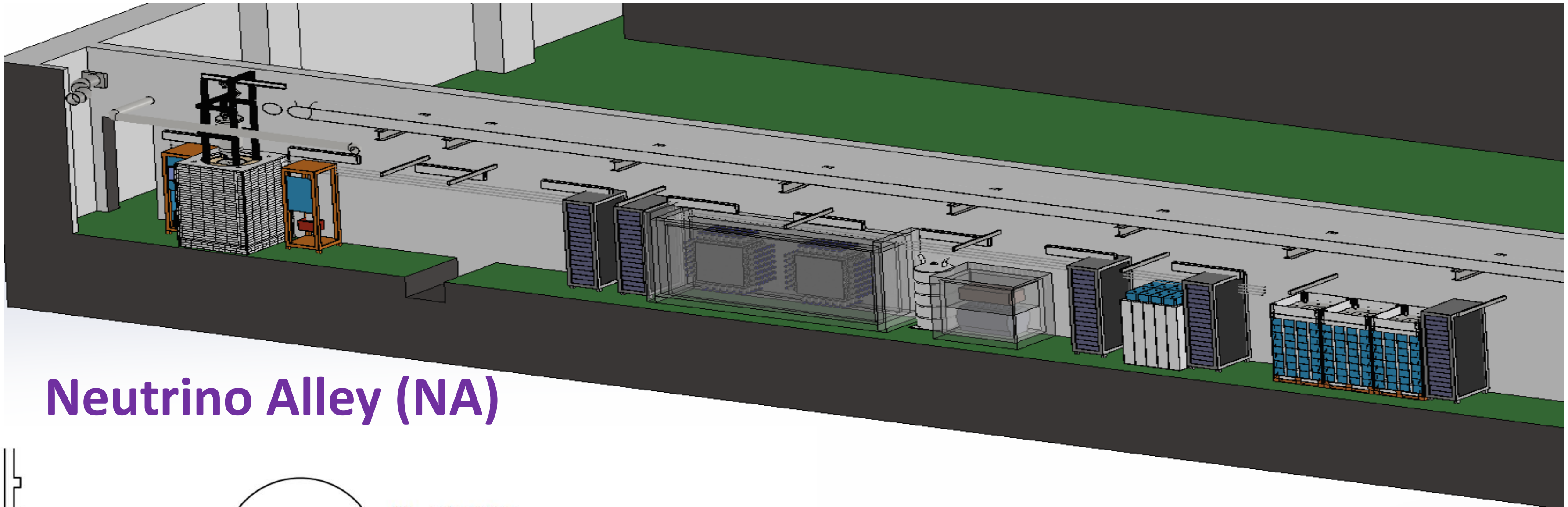
*COHERENT, PRL **129** (2022) 081801*

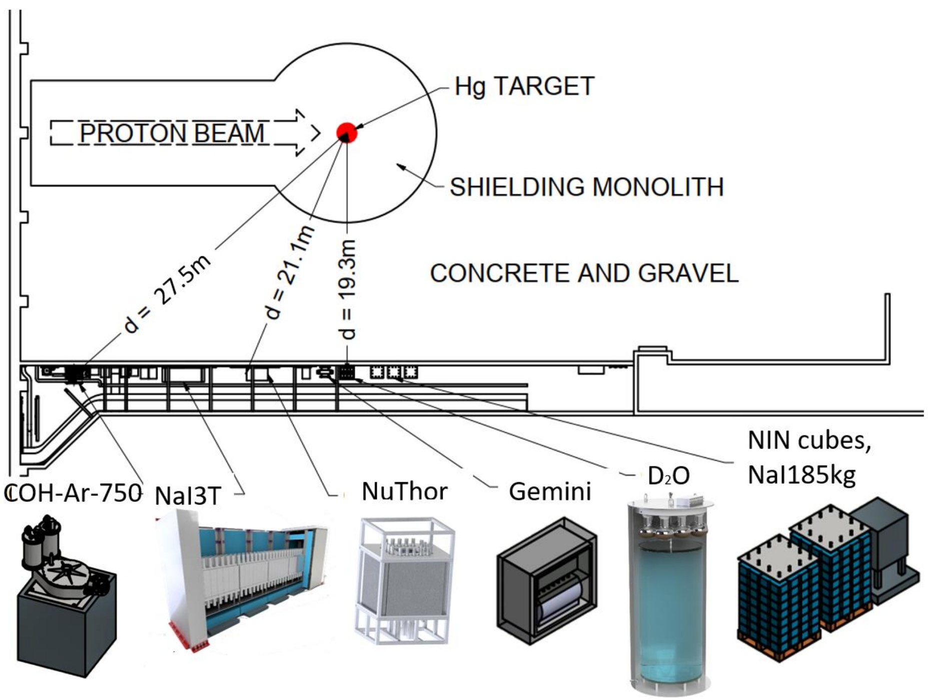
CEvNS on Ar



*COHERENT, PRL **126** 012002 (2021)*

COHERENT "First Light" CEvNS Program





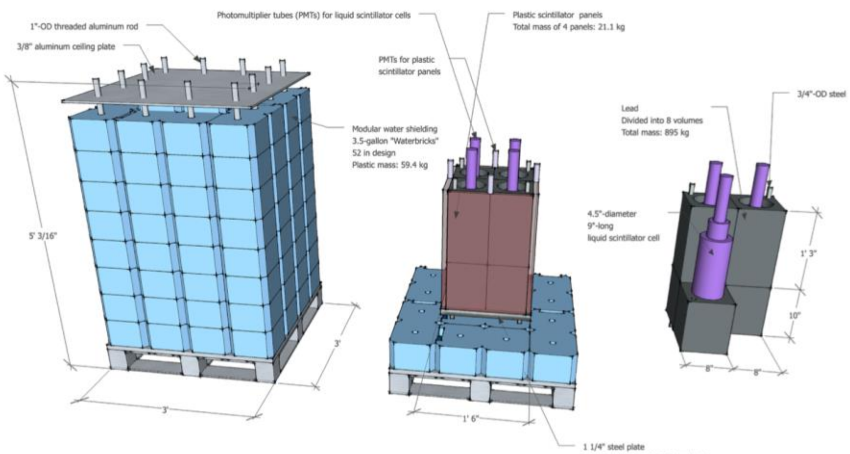
- Complete the mapping of N^2 Dependence
- Multiple Targets key feature of COHERENT Experiment
- NA virtual tour at https://my.matterport.com/show/?m=XYA19MBVdQS&nozoom=1&help=1&hl=1&lp=1

Physics Background Detectors

Neutrino Induced Neutron Detectors
Pb & Fe Nubes

$$\nu_e + {}^{208}Pb \rightarrow {}^{208}Bi^* + e^- \quad \text{(CC)}$$
$$\hookrightarrow {}^{208-y}Bi + x\gamma + \boxed{yn}$$

$$\nu_x + {}^{208}Pb \rightarrow {}^{208}Pb^* + \nu'_x \quad \text{(NC)}$$
$$\hookrightarrow {}^{208-y}Pb + x\gamma + \boxed{yn}$$



- ➢ $0.29^{+0.17}_{-0.16}$ times MARLEY prediction
- ➢ No NIN events at 1.8 σ -> good for background, bad for supernova detection (HALO)

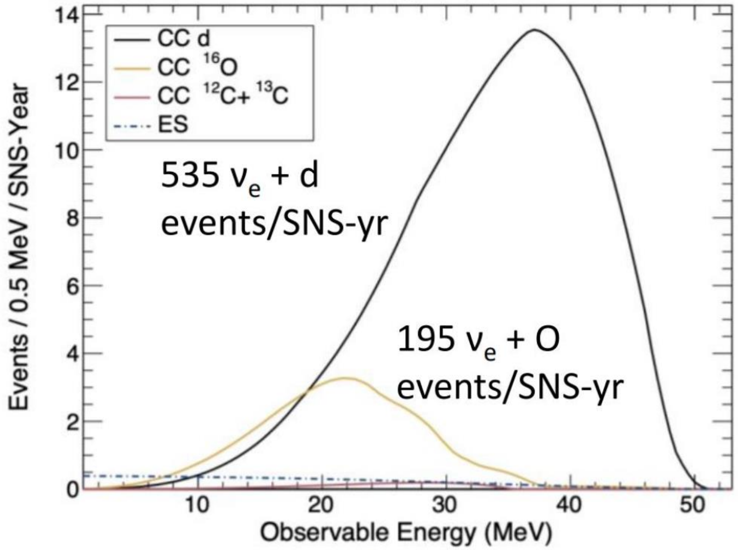
Designed by TUNL/Duke University
Installed in Neutrino Alley in 2014
Fermilab W&C Sam Hedges https://arxiv.org/pdf/2212.11295

MARS
Fast Neutron Backgrounds

Mobile device
Assembled at Sandia
Installed in Neutrino Alley in 2017
COHERENT, 2022 JINST 17 P03021

COHERENT Precision Program now underway

Precise Flux Normalization

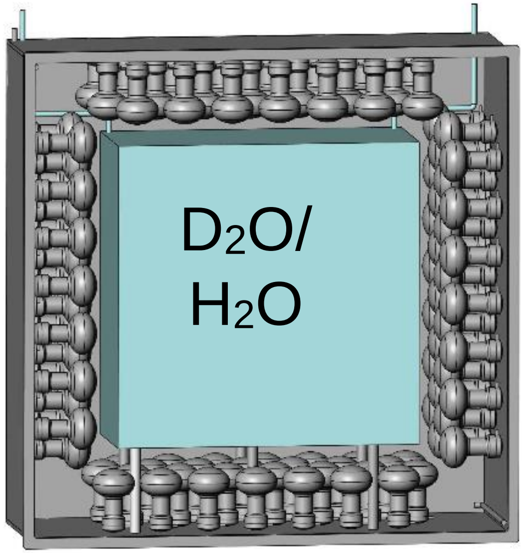


UTK/CMU/VT/ORNL

- Two modules
- Calorimetry: no Ring Imaging
- Pin down 10% to 3% Statistical in 2 yrs
- Now operating

COHERENT 2021 JINST 16 P08048

Fully Instrumented Water Cherenkov



Performance Optimized Detector

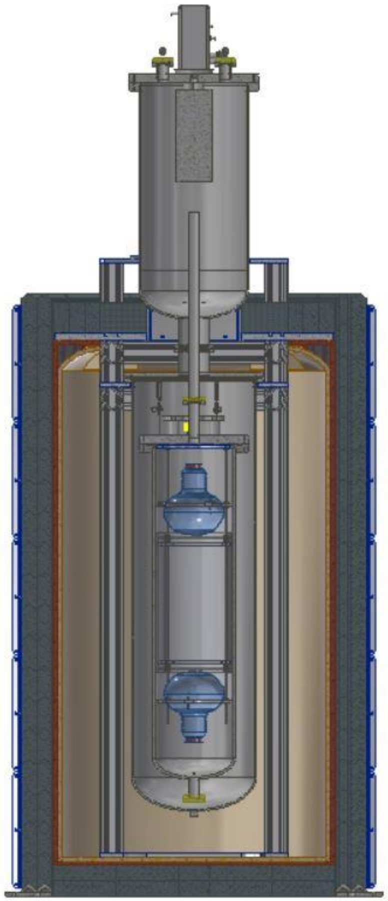
- High Light Collection
- Ring Reconstruction
- Directional Information
- CC differential cross section
- Fully characterize interaction response for supernova detection

US-Japan Workshop on Measurements for Supernova Neutrino Detection, ORNL Mar 2023

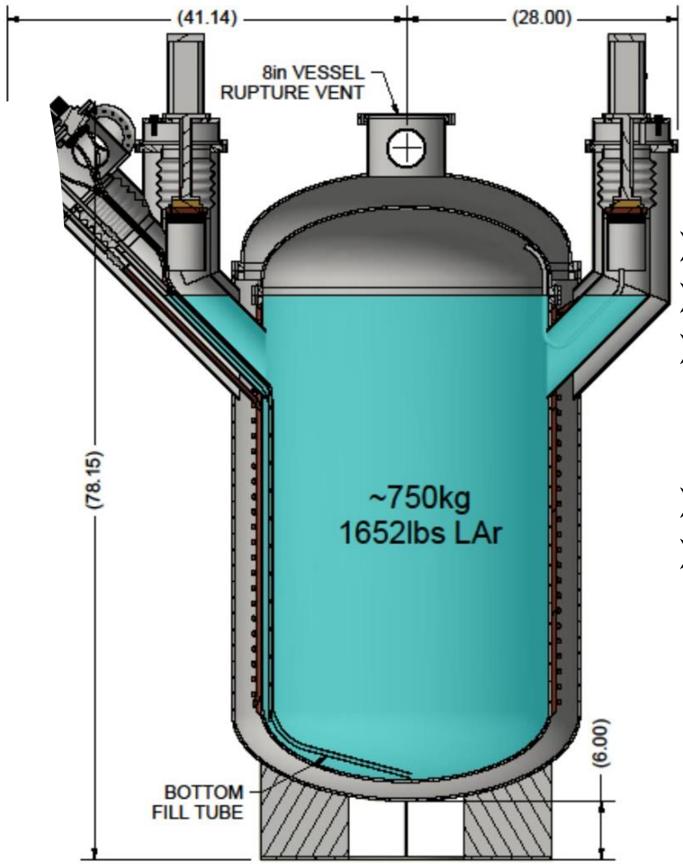
*S.Nakamura et. al. Nucl.Phys. A721(2003) 549

Ongoing detectors

Liquid Argon detectors



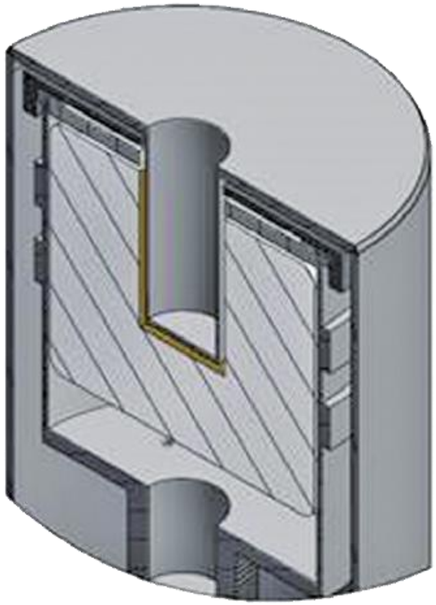
- 24 kg Fiducial Mass
- Single Phase
- Kr^{83m} Calibrations
- 4.5 p.e. per keVee
- 20 keVnr threshold
- ~5σ data in-hand
- Final analysis underway



Walt Fox, IU

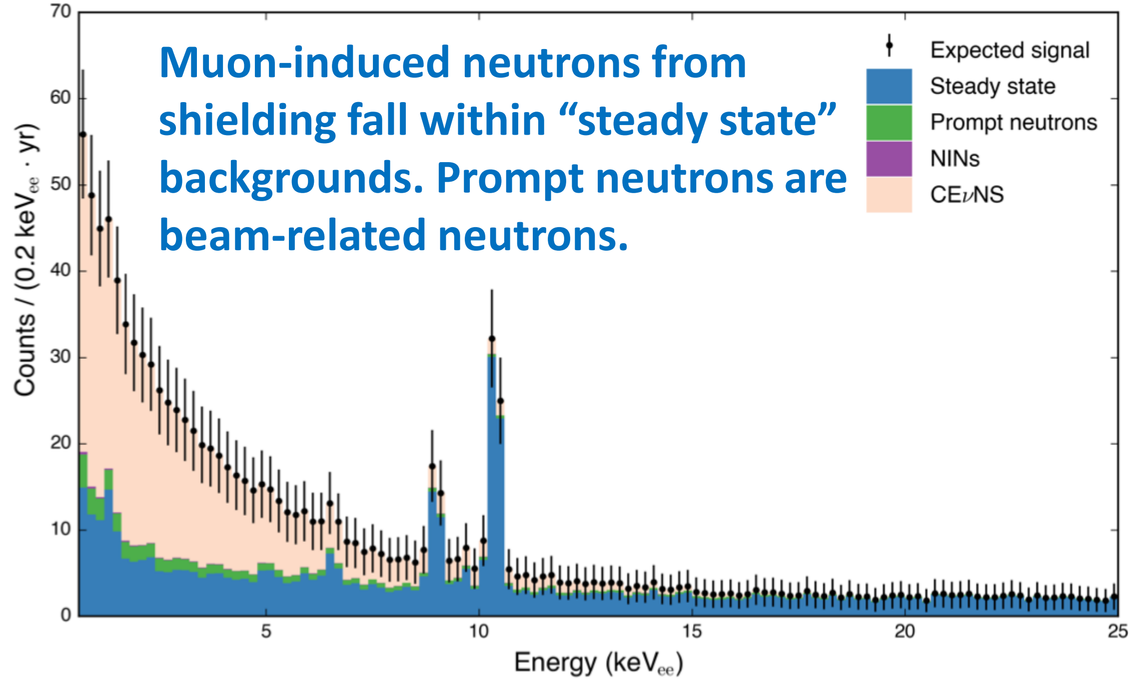
- Future design: 750kg LAr
- Single phase
- Light Collection Options
  - 3" PMT TPB
  - SiPM, Xenon Doping, …
- ~3000 CEvNS/yr
- Fabrication underway @ Seoul and IU

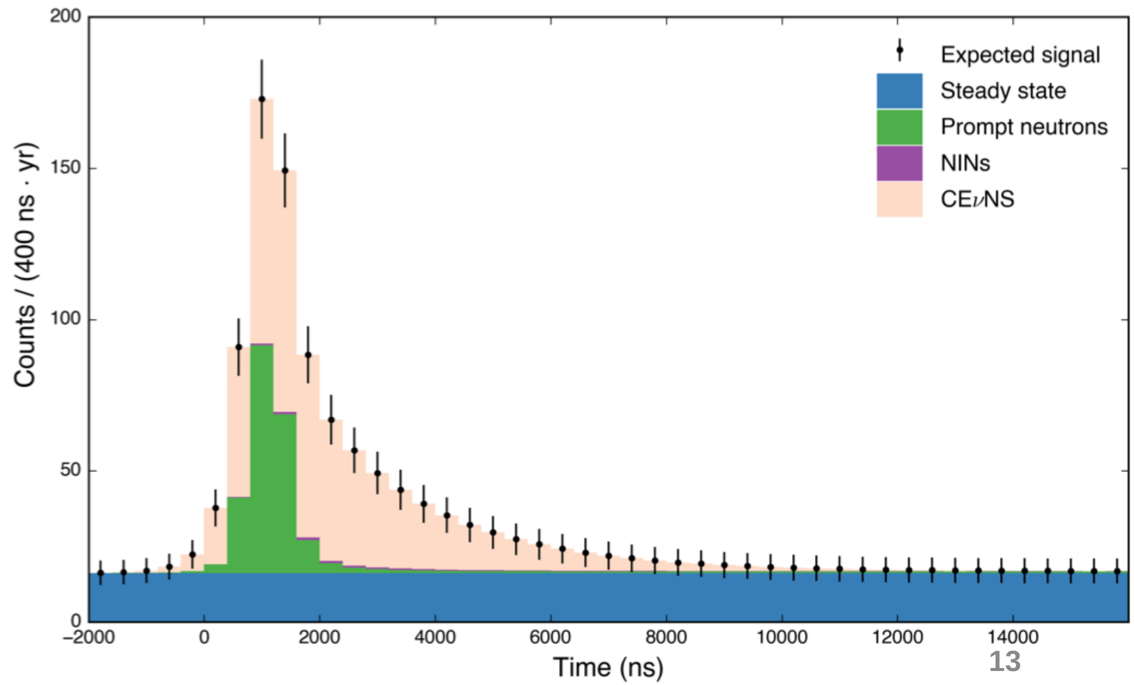
Ge-mini



- Lowest Threshold -> 0.4 keVee, ~2-2.5 keVnr
- Electronic noise<150 eV FWHM
- 16 kg HPGe Array
- 500-600 CEvNS/yr
- Installation 2022

Designed by TUNL/Duke
Installed in Neutrino Alley



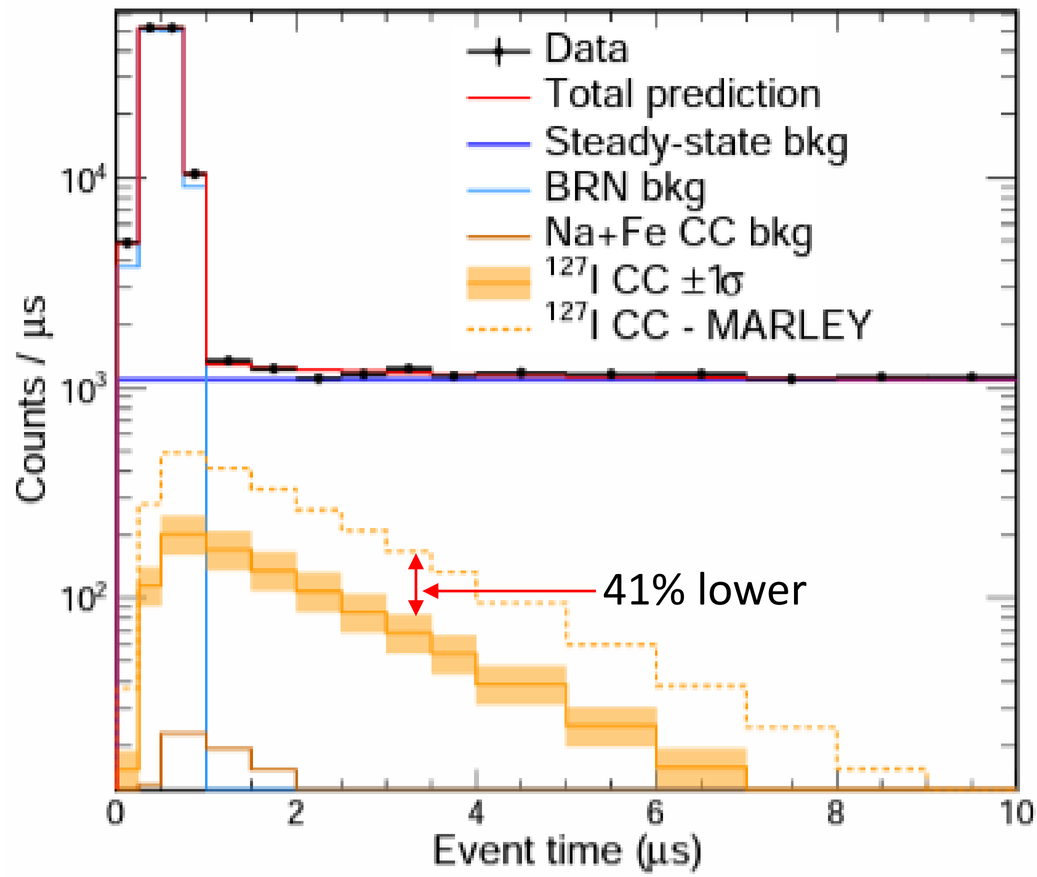


NaIvETe: Inelastic Interactions

$$\nu_e + ^{127}\mathrm{I} \rightarrow ^{127}\mathrm{Xe} + \mathrm{e}^-$$

- Lightest-Nucleus
- 3.4 ton NaI Array
- 3σ CEvNS/yr
- Installation 2022

The observed NaIvE (185 kgs) timing spectrum



- Energy of ν_e: 10-55 MeV
- Measured cross section: $9.2^{+2.1}_{-1.8} \times 10^{-40}\ cm^2$

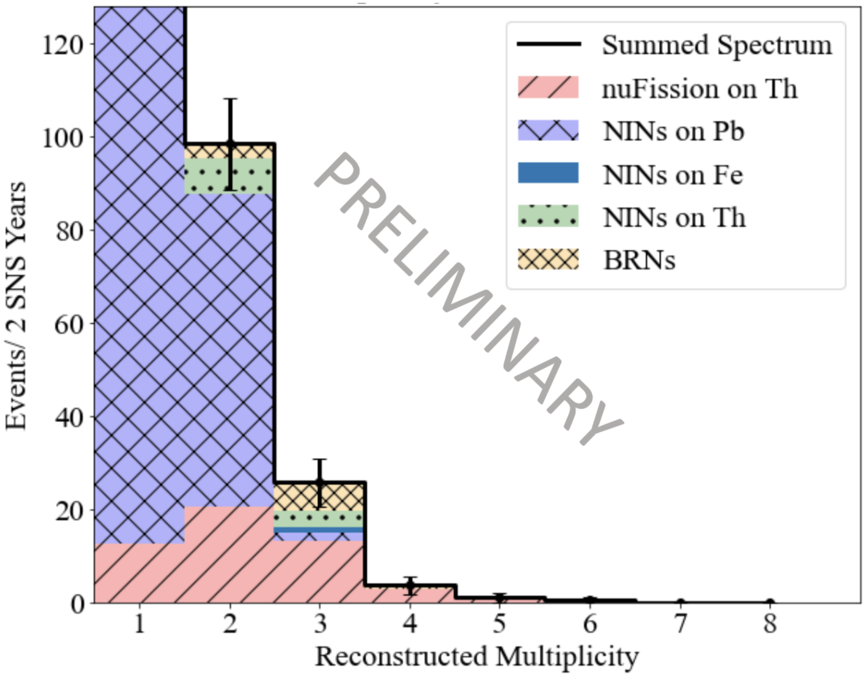
Designed by TUNL/Duke
Installed in Neutrino Alley

https://arxiv.org/abs/2305.19594

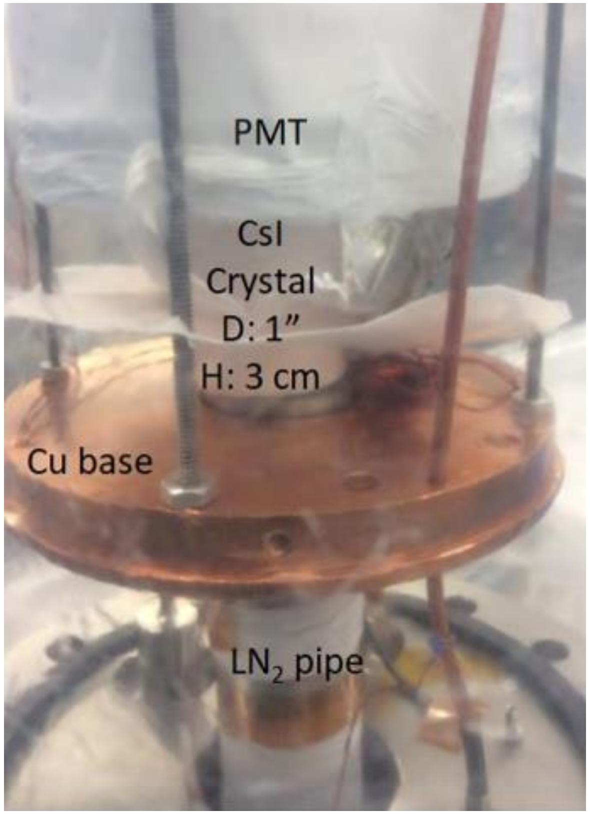
NuThor: Neutrino Induced Fissions

60 kgs thorium metal

Designed by TUNL/Duke
Installed in Neutrino Alley



Cryogenic Scintillating Crystals



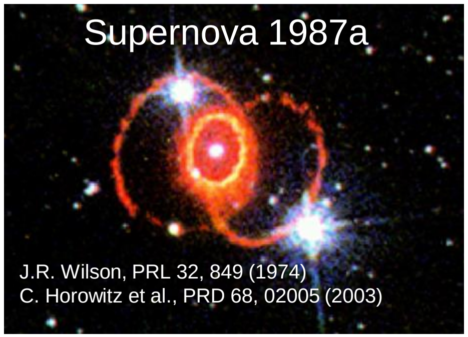
COH-CryoCsI

- Undoped CsI
- Maximal Light Yield, Minimal Afterglow at 40K
- Well matched for SiPM readout
- QF ~ 17%, analysis on the way
- ~0.4 keVnr thresholds possible
- 10kg and 750kg concepts

	Experiments	Type of crystals	Light yield [PE/keVee]	
	COHERENT 2017	CsI[Na]	13.5 ± 0.1	**Science p. eaao0990 (2017)**
	PMT+small crystal	undoped CsI	20.4 ± 0.8	**J. Inst. 11(10), P10003 (2016)**
higher quantum efficiency	PMTs+large crystal	undoped CsI	26.0 ± 0.4	**Eur. Phys. J. C 80, 547 (2020)**
	Improved light collection	undoped CsI	33.5 ± 0.7	**Eur. Phys. J. C 80(12), 1146 (2020)**
	PMT $\rightarrow$ SiPMs	undoped CsI	43.0 ± 1.1	**Eur. Phys. J. C 82, 344 (2022)**
	WLS coating on SiPMs	undoped CsI	50.0 ± 1.0	
	$77 \rightarrow 40$ K, & SiPMs* with 50% PDE	undoped CsI	60 (final goal)	

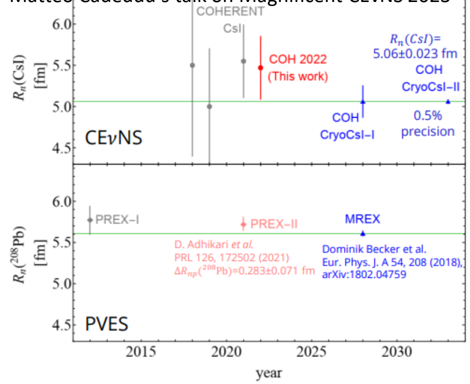
Broad Impact of πDAR CEvNS Studies

Largest σ in Supernovae dynamics

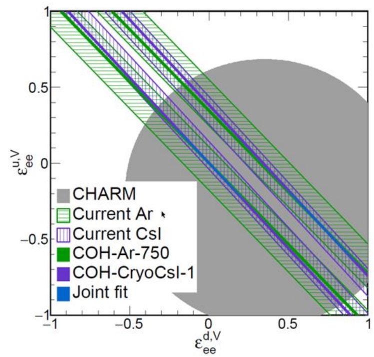


Nuclear Form Factors

Matteo Cadeddu's talk on Magnificent CEvNS 2023

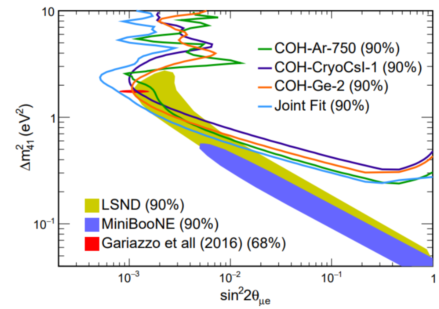


Non-Standard Interactions



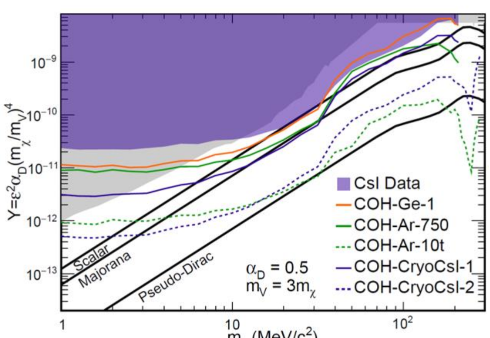
COHERENT Snowmass whitepaper 2022

Sterile Searches



COHERENT Snowmass whitepaper 2022

Accelerator DM searches



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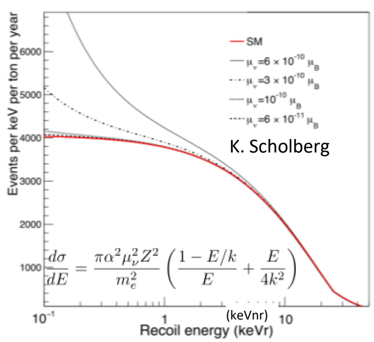
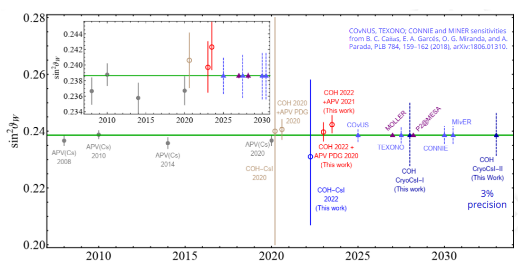
Neutrino Magnetic Moment



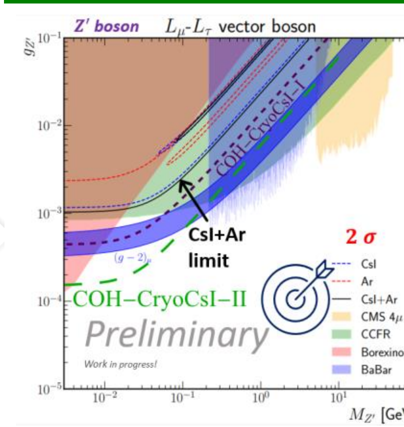
See also Kosmas et al., arXiv:1505.03202

Weak Mixing Angle



Matteo Cadeddu's talk on Magnificent CEvNS 2023

BSM light mediator searches



Mattia Atzori Corona's talk on Magnificent CEvNS 2023

Phase 1: 3 years exposure
Phase 2: 5 years exposure

COHERENT Collaboration

- ~100 members, 21 institutions
- Formed in 2013 to observe CEvNS in multiple nuclear targets to measure N^2-scaling of cross section
- Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (ORNL) is also a perfect source of neutrinos.
- Intense flux of low-energy pulsed neutrinos also useful for studying supernova neutrinos, neutron radius, inelastic neutrino-nucleus interactions, sterile neutrinos, dark matter, neutrino magnetic moment, weak mixing angle and BSM light mediator

https://sites.duke.edu/coherent/

Take away

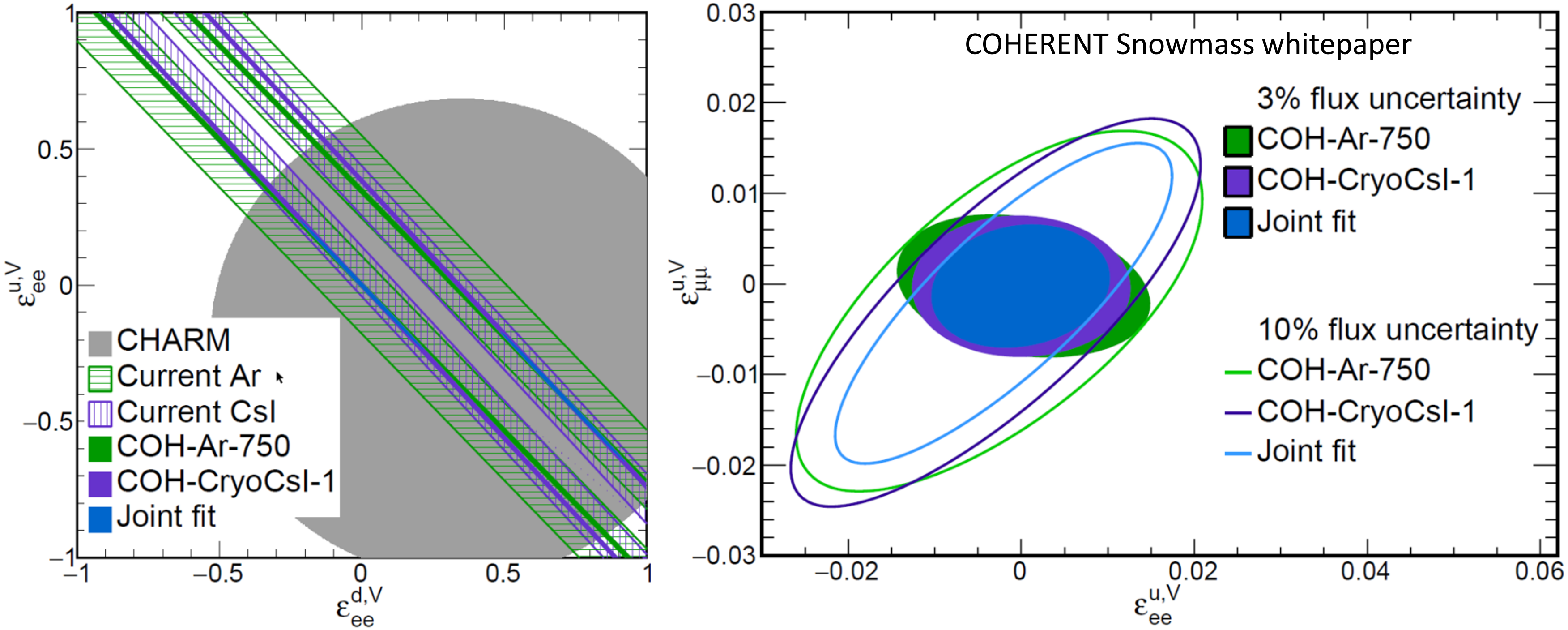
CEvNS are money saver!

- High cross-section, require low energy threshold detectors
- Well predicted in the standard model
- Precision measurements can be a great tool to probe physics in the standard model and beyond

Thank you!
Questions?

Back up

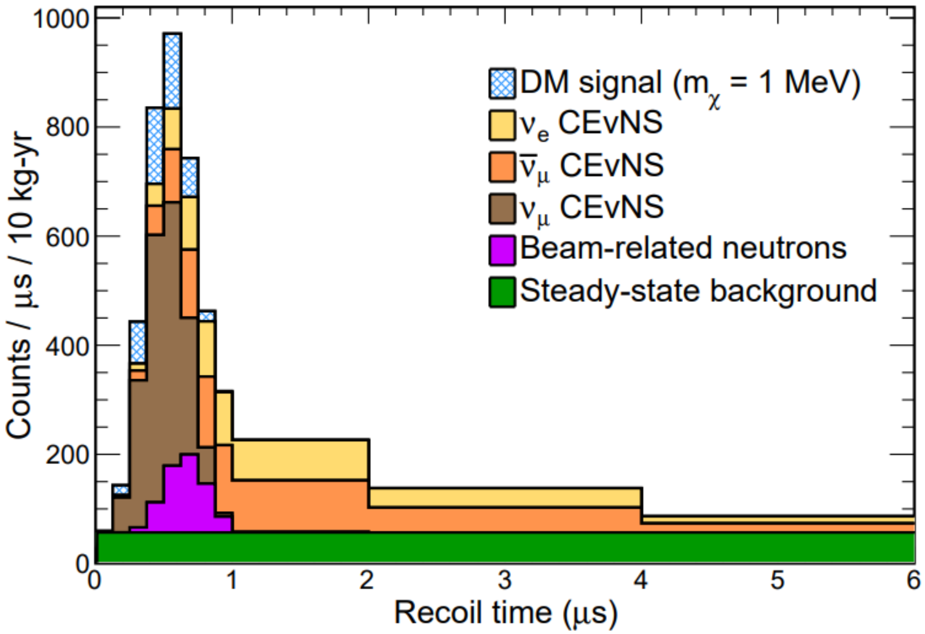
Sensitivities on Non-standard neutrino Interactions

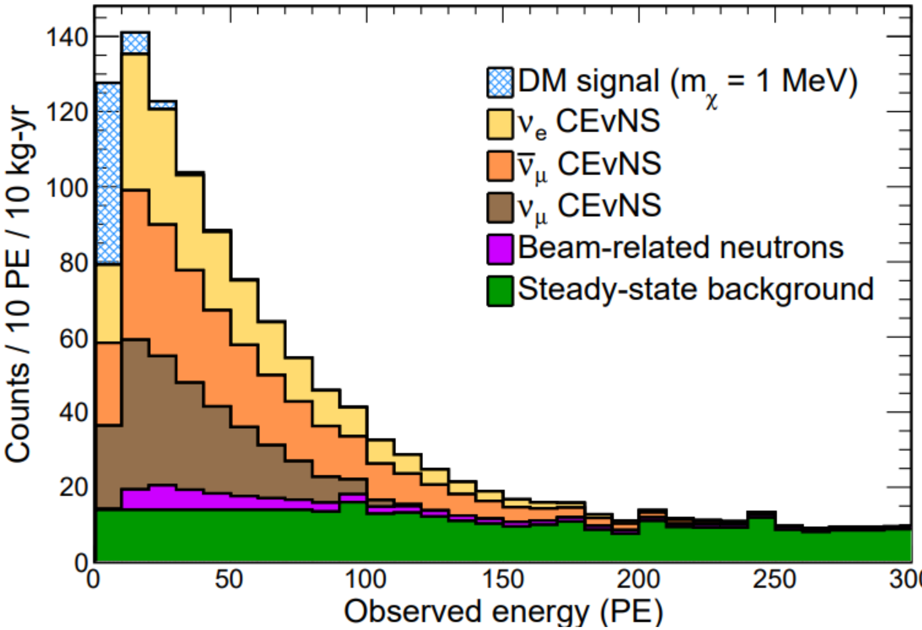


- $\epsilon_{\alpha\beta}^{q}$ would change the CEvNS cross section by modifying the weak charge, Q_{α}^{2} ~ N/Z (joint fit)
- Assuming no contributions from other parameters, observable: flux (# of events)
- BSM evidence: non-zero values of coupling parameters

From Daniel Pershey

Observable on low-mass dark matter (LDM)

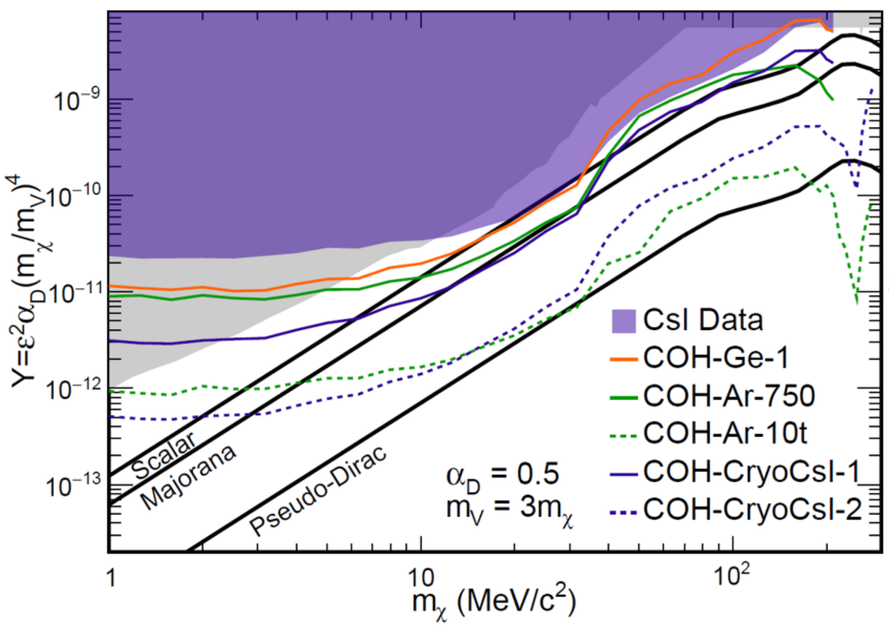


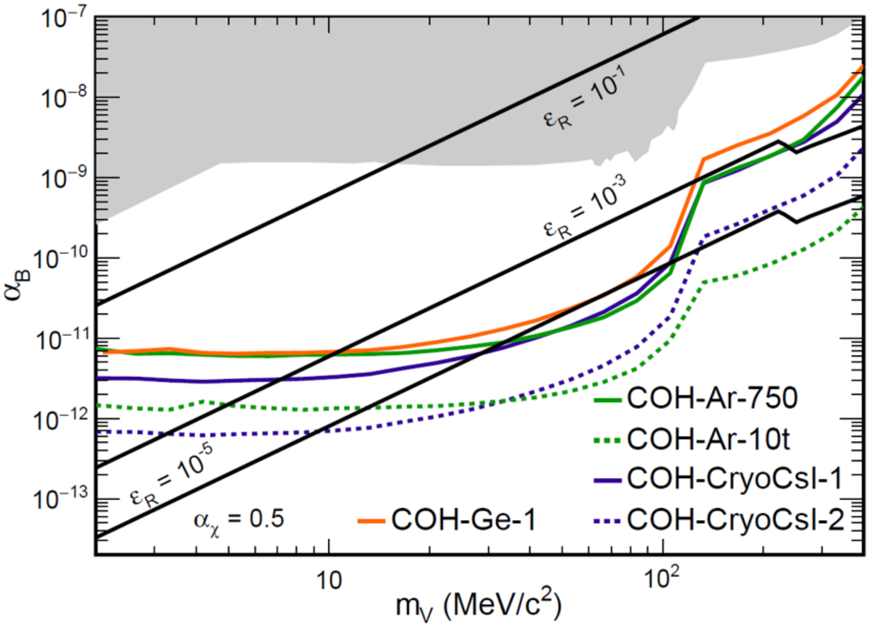


Time (left) and energy (right) distributions of CEvNS and DM signals

Sensitivities on LDM

COHERENT Snowmass whitepaper





$$\pi^0 \to \gamma + V^* \to \gamma + \chi^\dagger + \chi$$

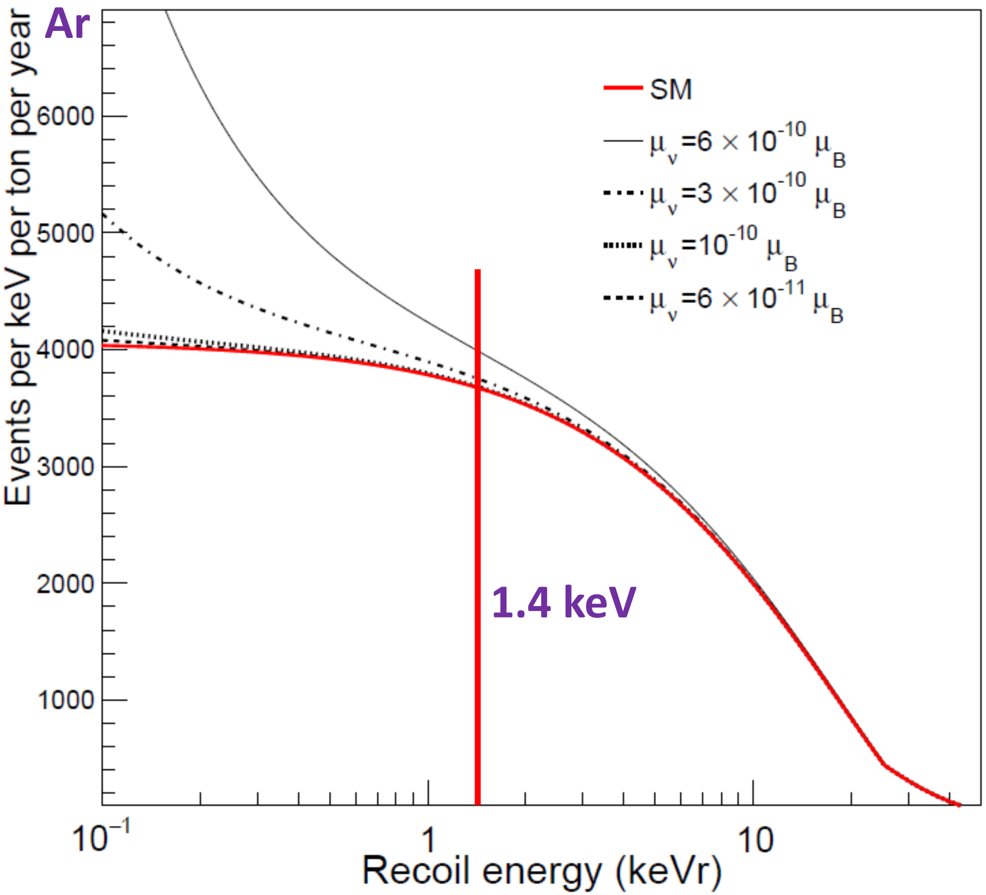
$$\pi^- + p \to n + V^* \to n + \chi^\dagger + \chi$$

Kinetic mixing (left) and leptophobic (right) dark-matter models

Assuming dark matter is scalar

Observable on magnetic moment

e.g. arXiv:1505.03202, 1711.09773, 2207.05036



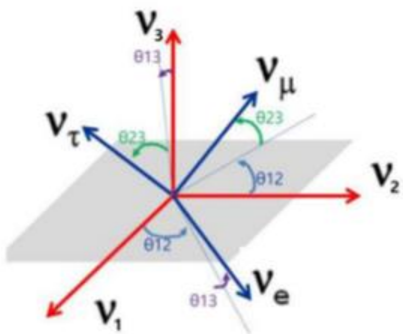
- Non-zero neutrino magnetic moment modifies CEvNS event rate at low energies
- Current limit: LZ and XENONnT
- All assuming the same amount of signal detected, nu_eff means three flavors contribution, nu_e means only nu_e contributes

$$\mu_\nu = \frac{3e_0 G_F}{8\sqrt{2}\pi^2} m_\nu \simeq 3.2 \times 10^{-19} \left(\frac{m_\nu}{\text{eV}}\right) \mu_B,$$

	$\lvert\mu_\nu\rvert [\times 10^{-11} \mu_B]$	$q_\nu\ [\times 10^{-13} e_0]$ FEA	$q_\nu\ [\times 10^{-13} e_0]$ EPA
ν_{eff}	< 1.1	[-3.0, 4.7]	[-1.5, 1.5]
ν_e	< 1.5	[-3.6, 6.5]	[-2.1, 2.0]
ν_μ	< 2.3	[-8.9, 8.8]	[-3.1, 3.1]
ν_τ	< 2.1	[-8.1, 8.1]	[-2.8, 2.8]

Expanding model to include four

Dan's talk on Neutrinos at ORNL Workshop

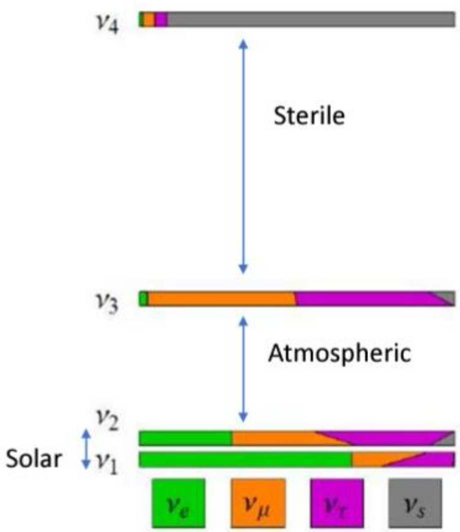


Parameterized by PMNS matrix

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

U_{s1} U_{s2} U_{s3}

$$P(\nu_\alpha \to \nu_\beta) = \left| \sum_{i=1}^{N_\nu} U_{i\alpha}^\dagger U_{\beta i} e^{-im_i^2 L/2E} \right|^2$$

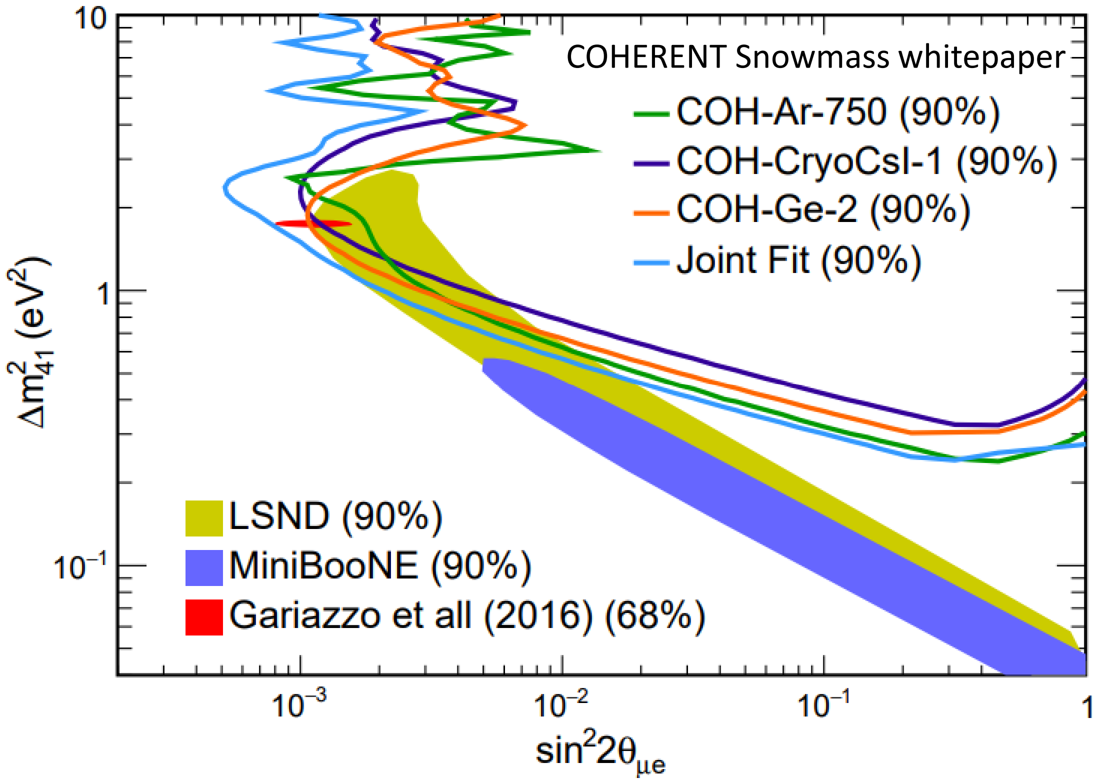


L/E, distance matters

$$1 - P(\nu_e \to \nu_s) = 1 - \sin^2 2\theta_{14} \cos^2 \theta_{24} \cos^2 \theta_{34} \sin^2 \frac{\Delta m_{41}^2 L}{4E}$$

$$1 - P(\nu_\mu \to \nu_s) = 1 - \cos^4 \theta_{14} \sin^2 2\theta_{24} \cos^2 \theta_{34} \sin^2 \frac{\Delta m_{41}^2 L}{4E}$$

Sensitivities on sterile neutrinos

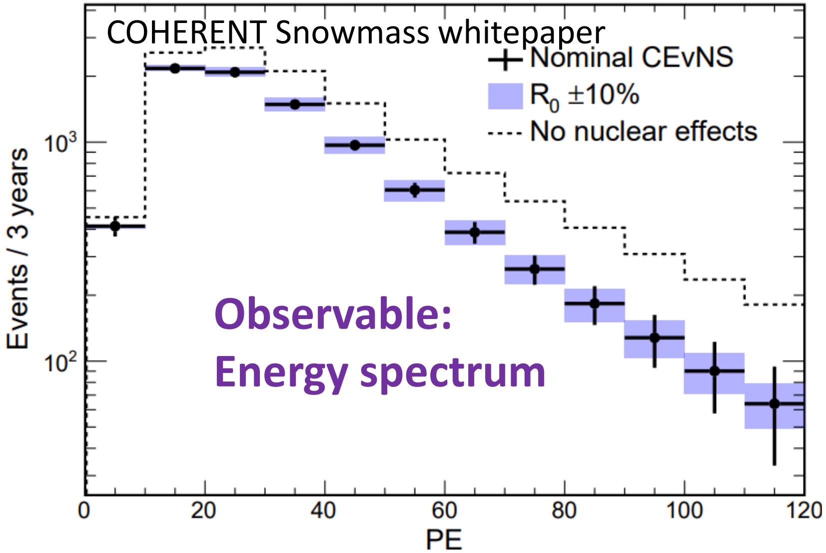


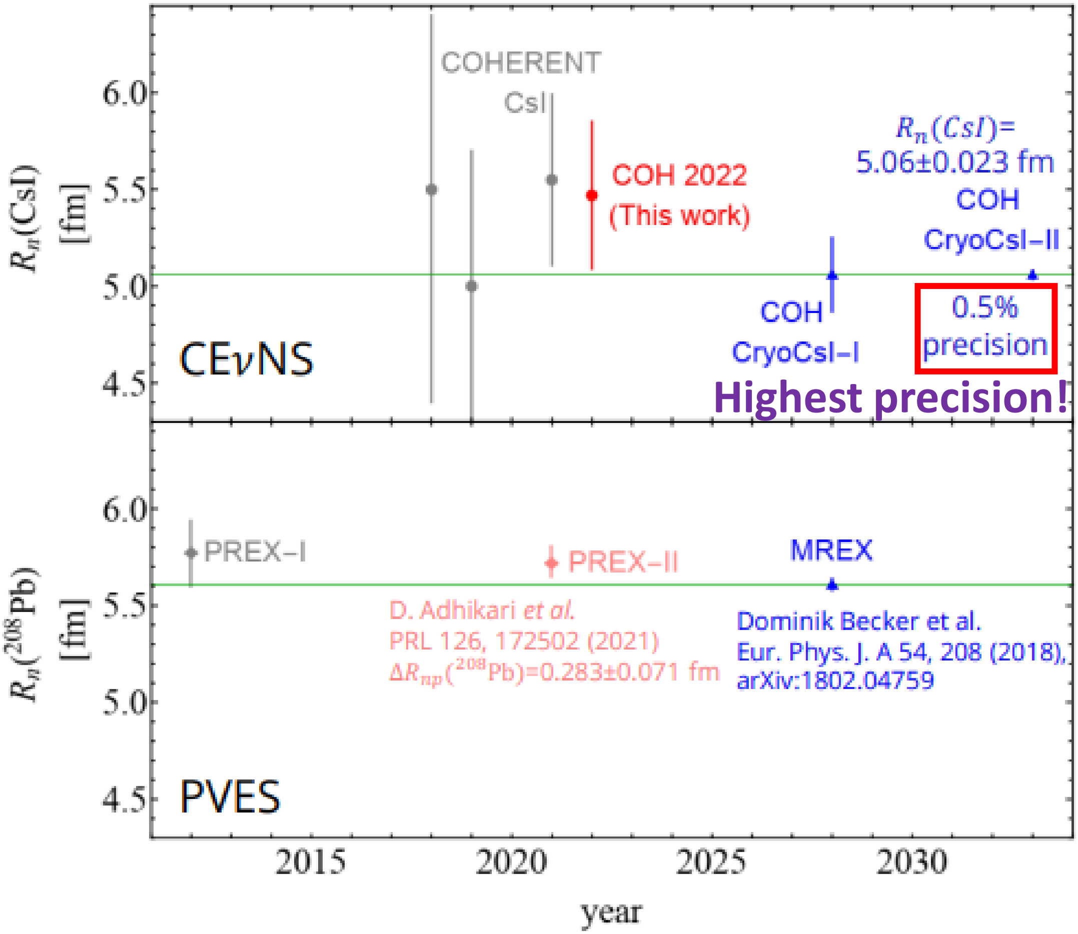
$\text{Sin}^2 2\theta_{\mu e} = \sin^2 2\theta_{14} \sin^2 \theta_{24}$

- 19.3 m for COHCryoCsI-1
  22 m for COH-Ge-2 (50 kg)
  28 m for COH-Ar-750
- Observable: energy spectrum
  Evidence: low energy excess
- Right top, excluded region
- Shadowed region, possible existence of sterile neutrinos

Sensitivities on neutron radius

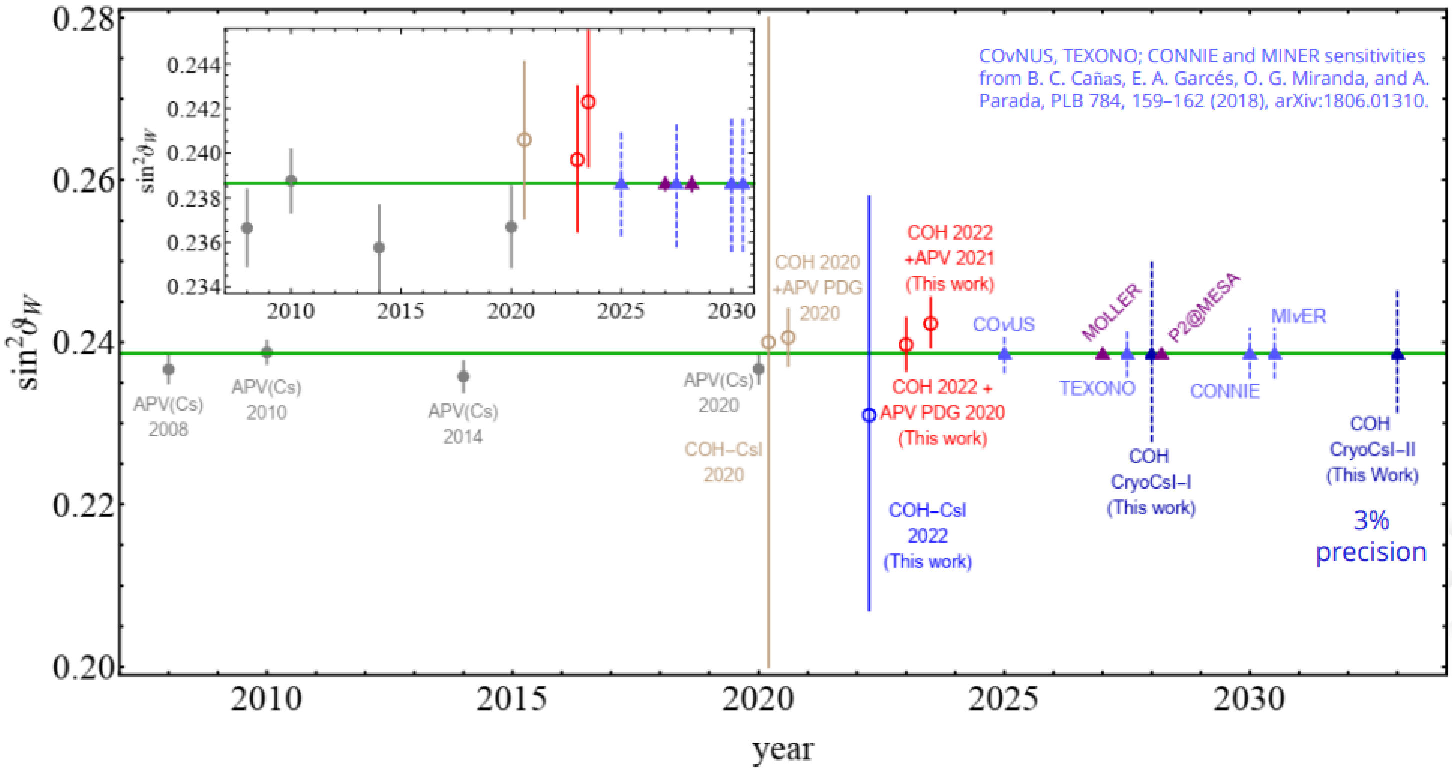
Matteo Cadeddu's talk on Magnificent CEvNS 2023





Sensitivities on weak mixing angle

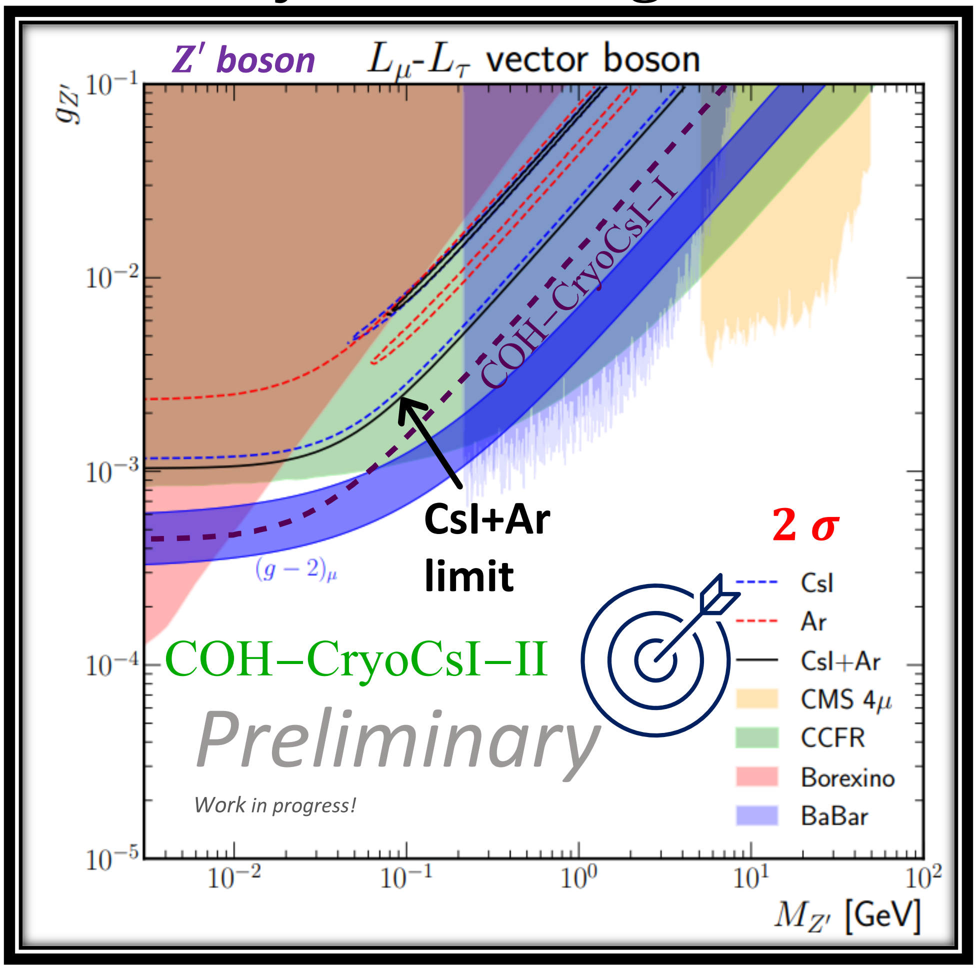
Matteo Cadeddu’s talk on Magnificent CEvNS 2023
COHERENT Snowmass whitepaper



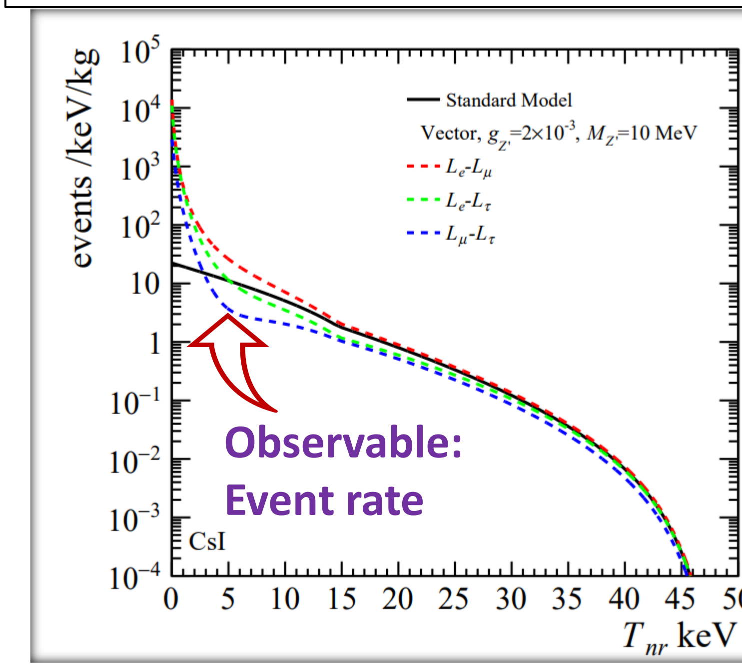
- **Observable: flux**
- **COH-Ge-2 is more sensitive**
- **Joint fit of COH-Ar-750, COH-CryoCsI-1, and COH-Ge-2 give 2.1% precision**

Sensitivity on BSM light mediators

Mattia Atzori Corona's talk on Magnificent CEvNS 2023



- One of the most popular model because $(g-2)_\mu$ band **is not excluded** and for its connection with Cosmology and other anomalies.
- **COH-Cryo-CsI-II** detector **will almost completely exclude or confirm $L_\mu - L_\tau$!**

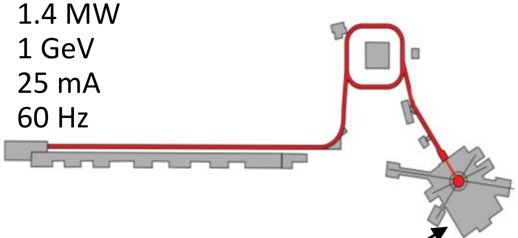


PPU and STS upgrades will ensure SNS remains the world's brightest accelerator-based neutron source

Today

- 900 users
- Materials at atomic resolution and fast dynamics

1.4 MW
1 GeV
25 mA
60 Hz

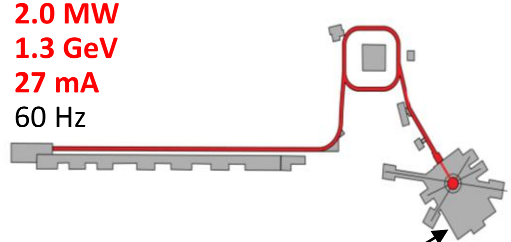


FTS
1.4 MW
60 Hz

2024 after PPU

- **1000+** users
- Enhanced capabilities

2.0 MW
1.3 GeV
27 mA
60 Hz



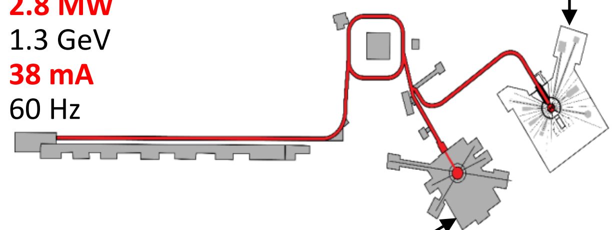
FTS
2 MW
60 Hz

2032 after STS

- **2000+** users
- Hierarchical materials, time-resolution and small samples

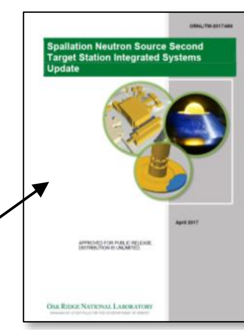
STS
0.7 MW
15 Hz

2.8 MW
1.3 GeV
38 mA
60 Hz

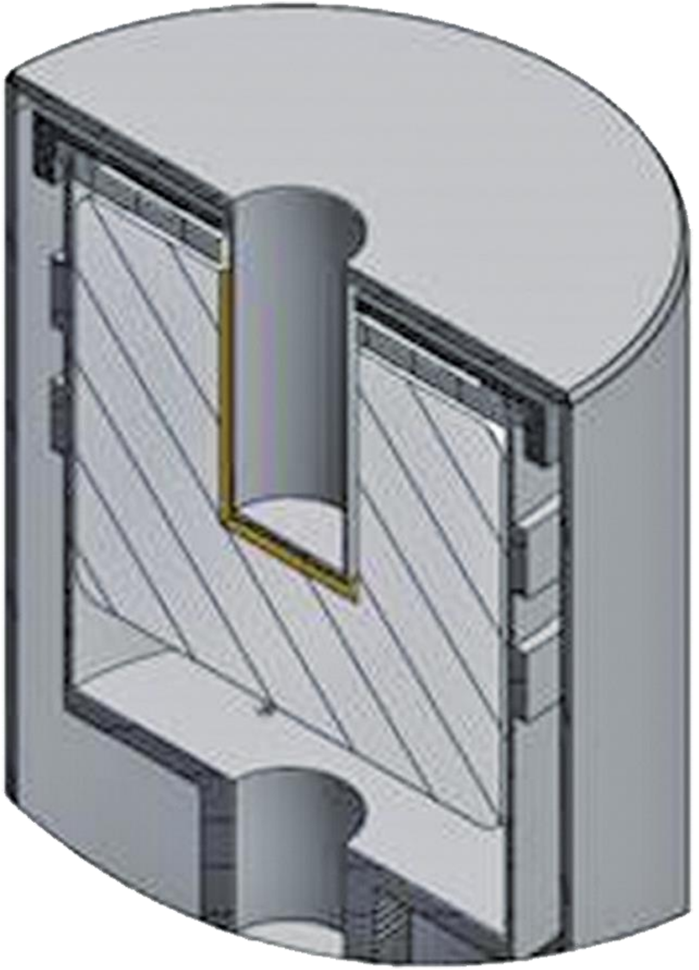


FTS
2 MW
45 pulses/sec

The choice of 15 Hz and 0.7 MW resulted from a detailed analysis of STS design (reviewed by a panel of experts in 2017) and optimizes performance of STS without impacting performance of FTS



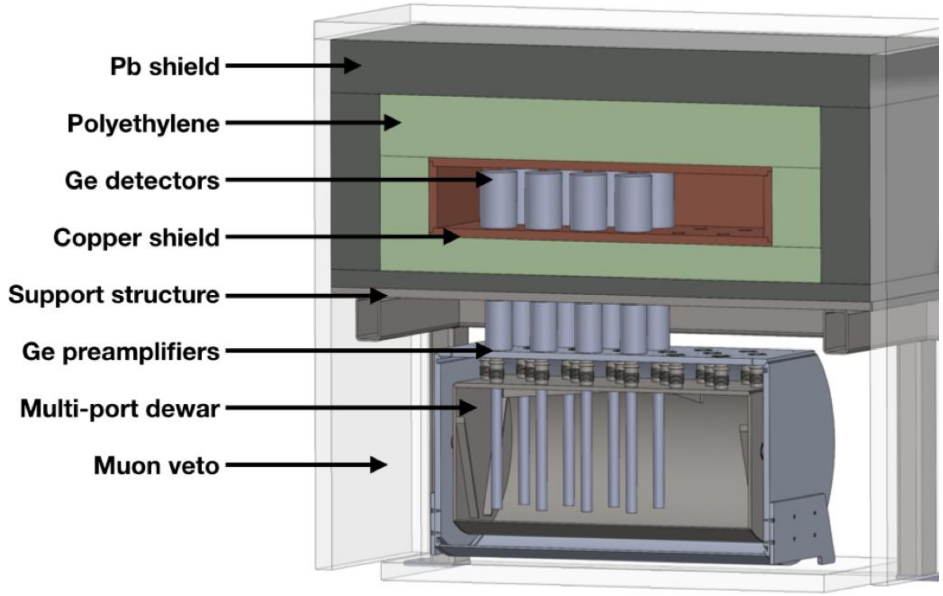
Why Ge-mini?

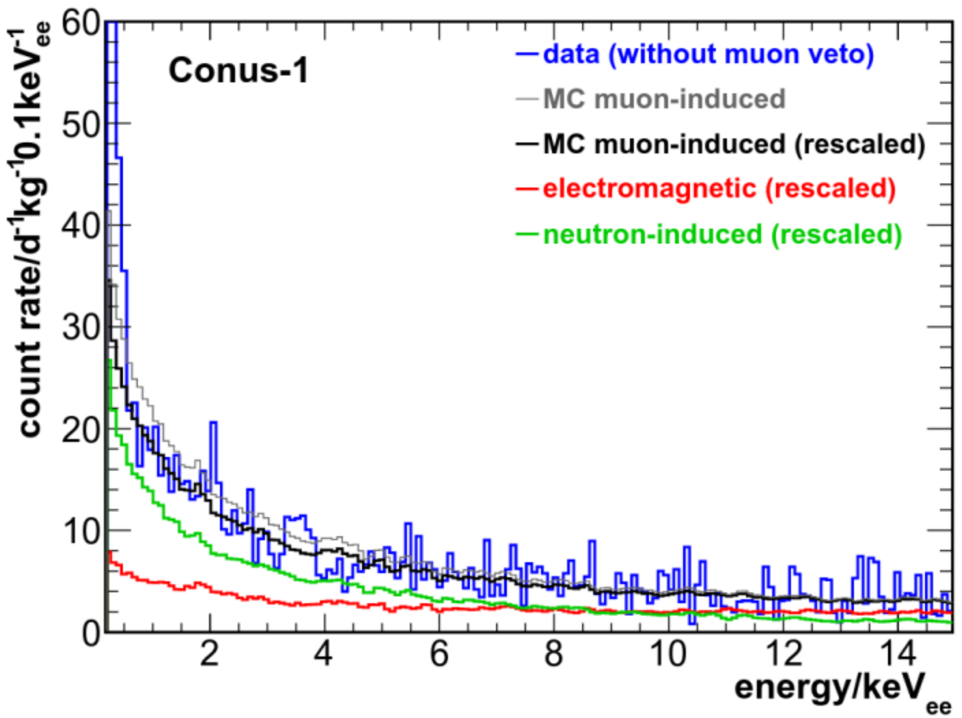


Ge-mini: inverted coaxial point-contact Ge detector

- Inverted coaxial -> large mass
- point-contact -> low threshold
- Electronic noise<150 eV FWHM
- Threshold -> 0.4 keVee, ~2-2.5 keVnr

Shielding structure

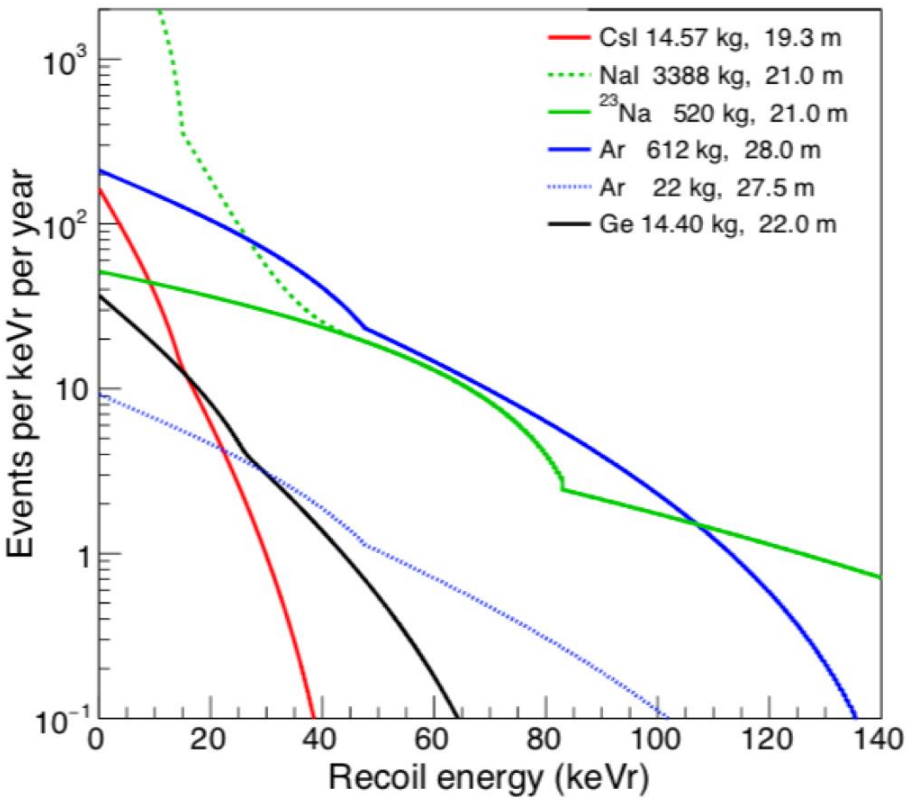




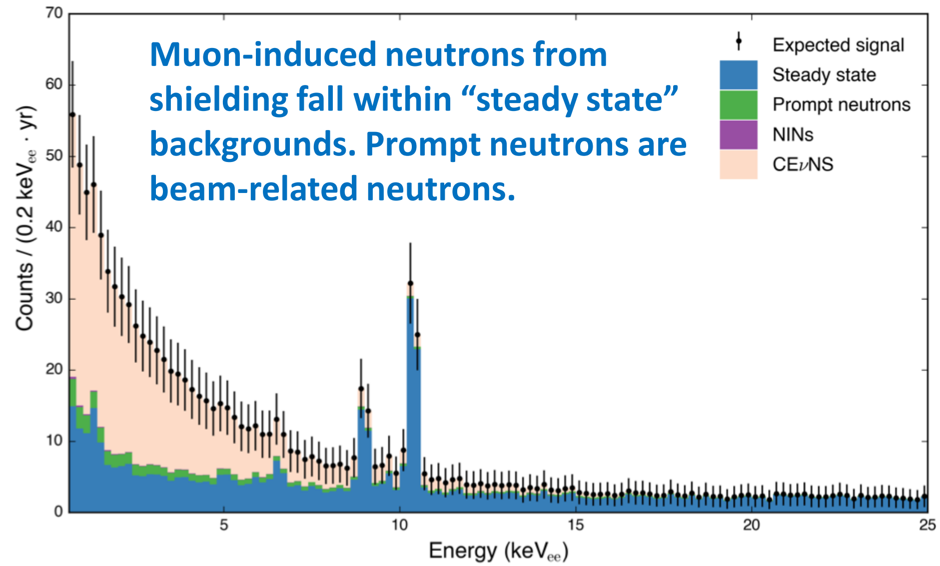
- Pb and Copper (heavy nucleus) shields from gamma-rays
- Polyethylene capture neutron
- Muon veto

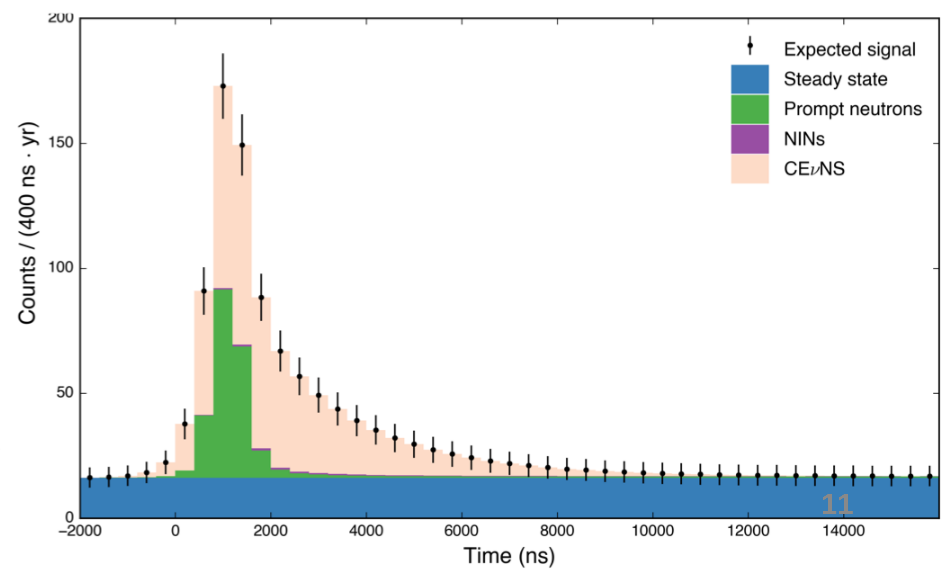
Data from similar shallow-depth Ge CEvNS experiments (such as CONUS) help guide Ge-mini background considerations

Ge-mini expected CEvNS events



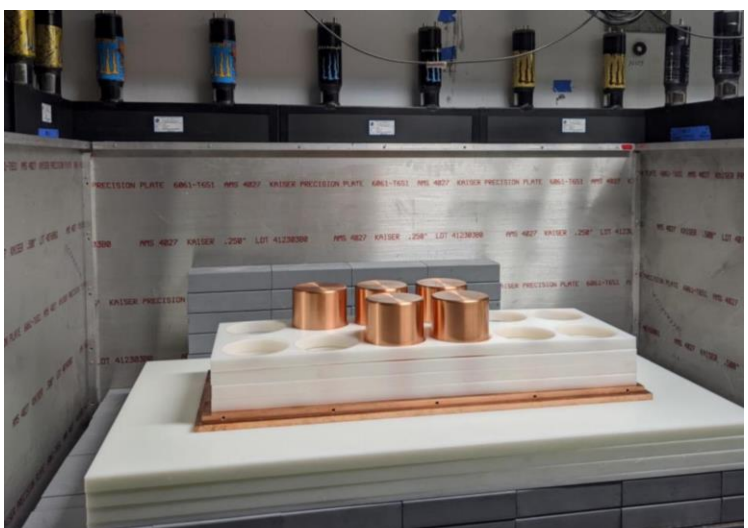
Muon-induced neutrons from shielding fall within "steady state" backgrounds. Prompt neutrons are beam-related neutrons.



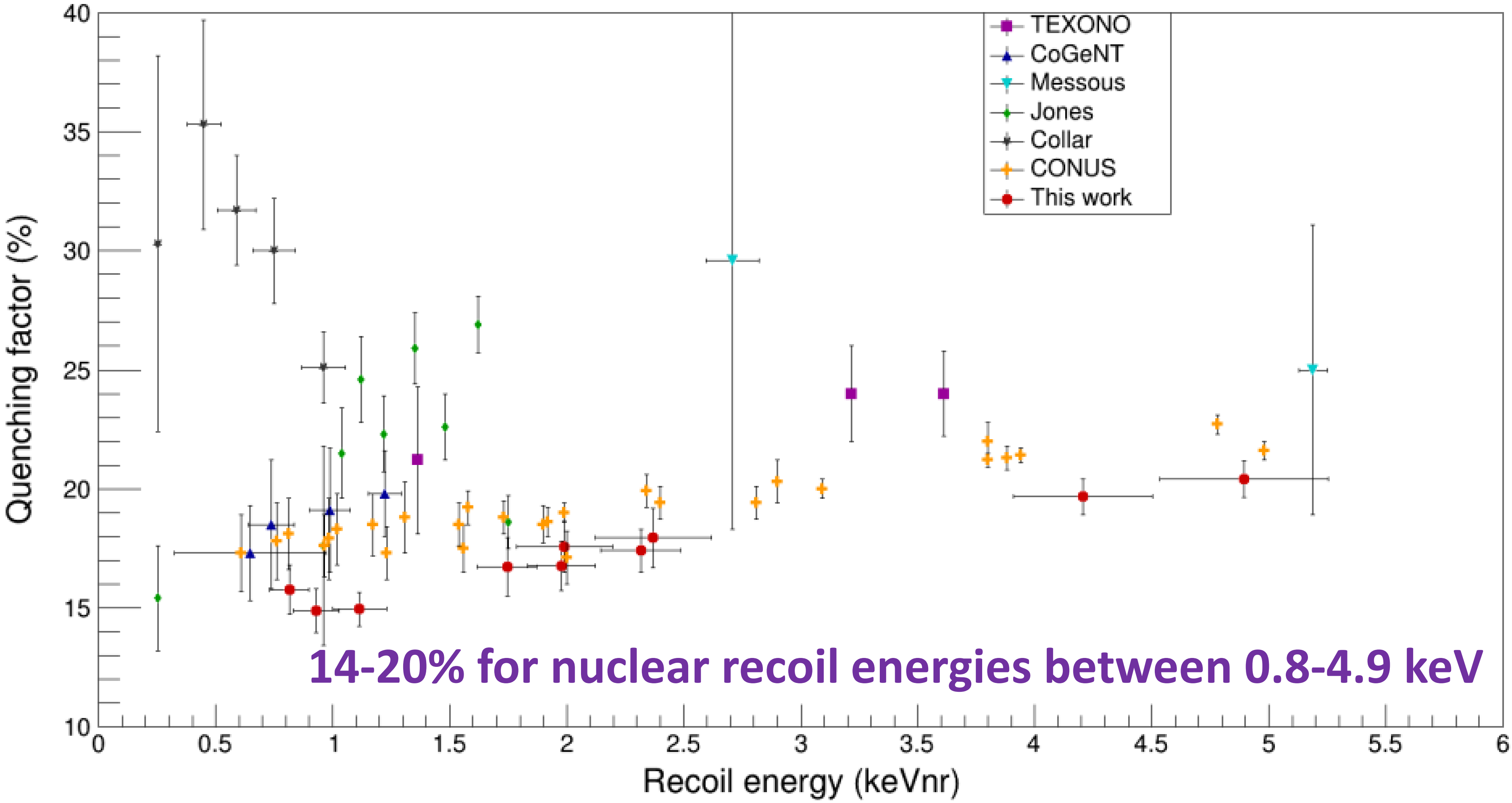


Current status: Ge-mini

- 10 kg worth has been deployed
- The rest 8 kg will be deployed this summer



QF



Long Li's dissertation