The COHERENT Experiment: A Walk Down Neutrino Alley

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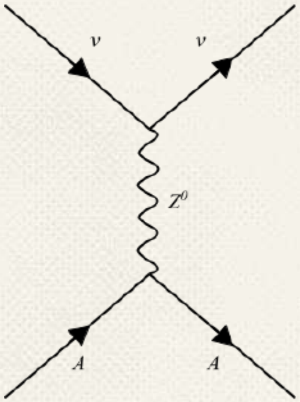
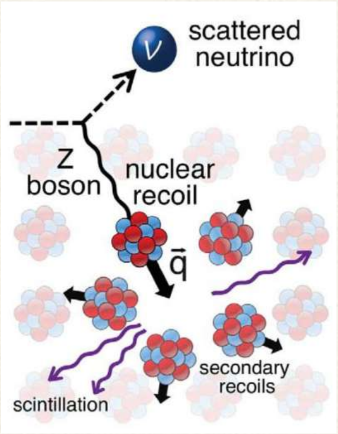
UGent Seminar

May 13, 2025

What is CEvNS?

Coherent **E**lastic **N**eutrino-**N**ucleus **S**cattering

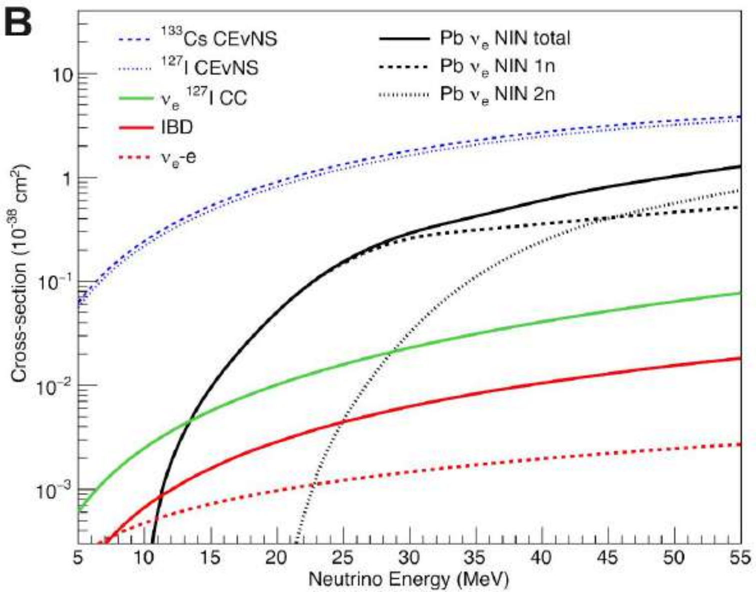


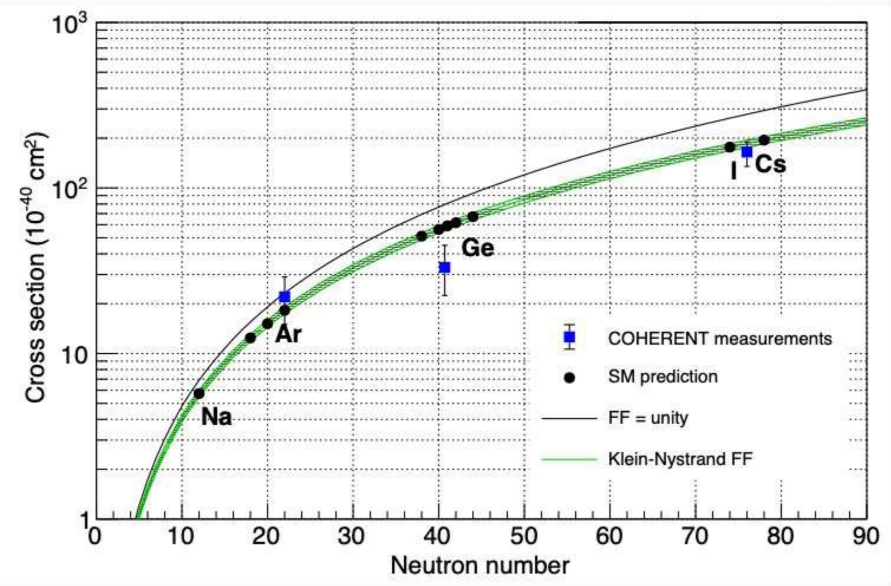


Predicted by Daniel Freedman in 1974, as a Standard-Model process.

Coherence condition met at neutrino energies of $\lesssim$ 50 MeV

Coherent Elastic Neutrino-Nucleus Scattering

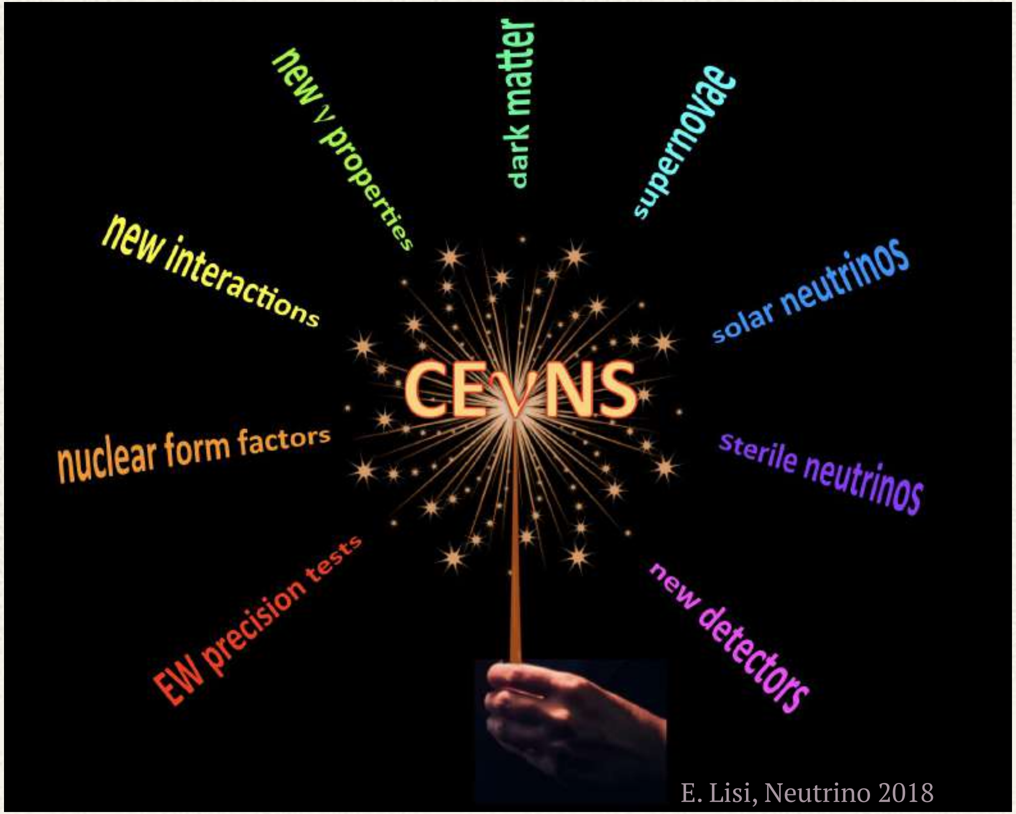




The heavier the target nucleus, the higher the cross section

"Enhanced" cross section, increases $\propto$ **N²** !

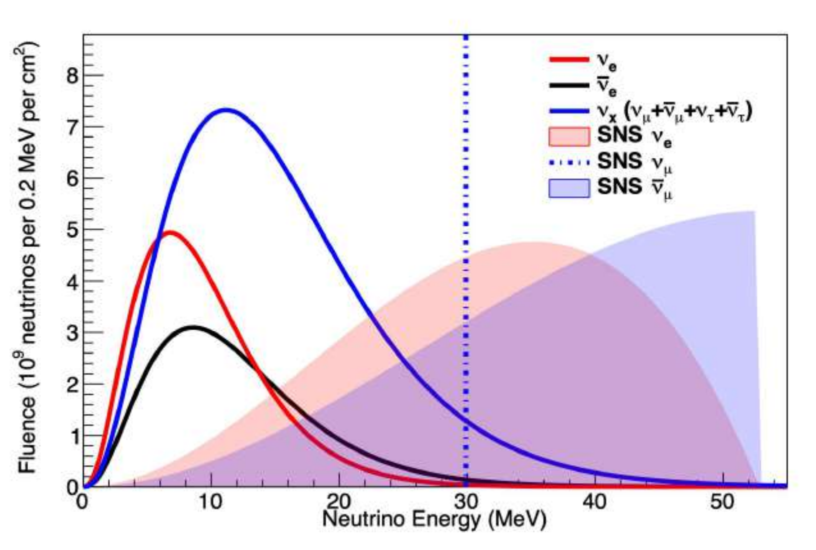
Why Does CEvNS Matter?



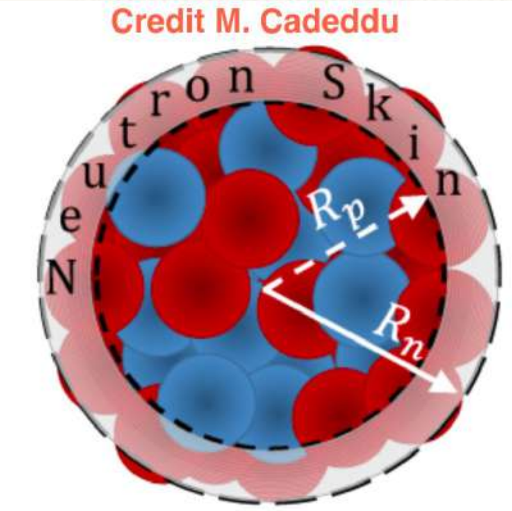
CEvNS matters for: Supernovae

Neutrinos carry most of the energy from supernovae

Neutrino interactions (like at the Spallation Neutron Source) help us understand cross sections: neutrino energies at the SNS are supernova-esque!

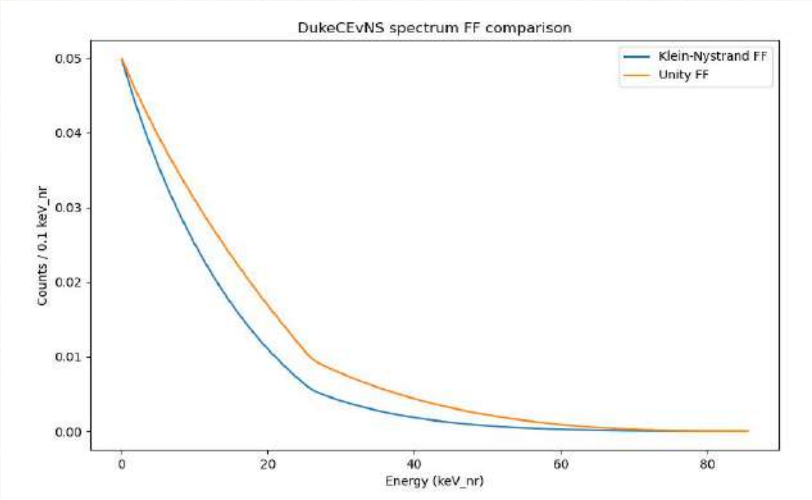


CEvNS matters for: Neutron Skin Depth



Larger radius of neutrons give a neutron"skin" around nucleus

Neutron form factor contributes to decoherence in neutrino interactions - suppression of rate

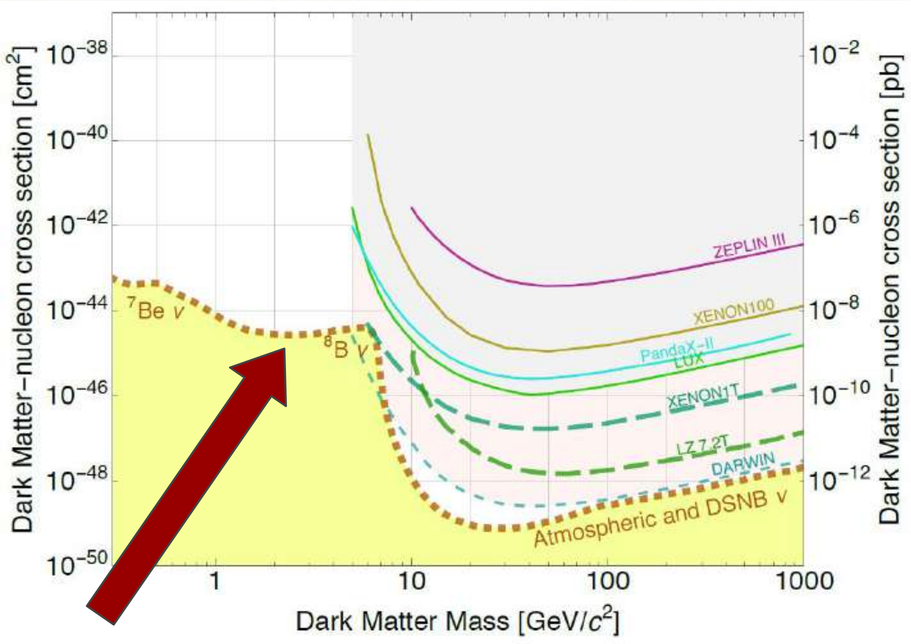


Implications for neutron star structure and equation of state

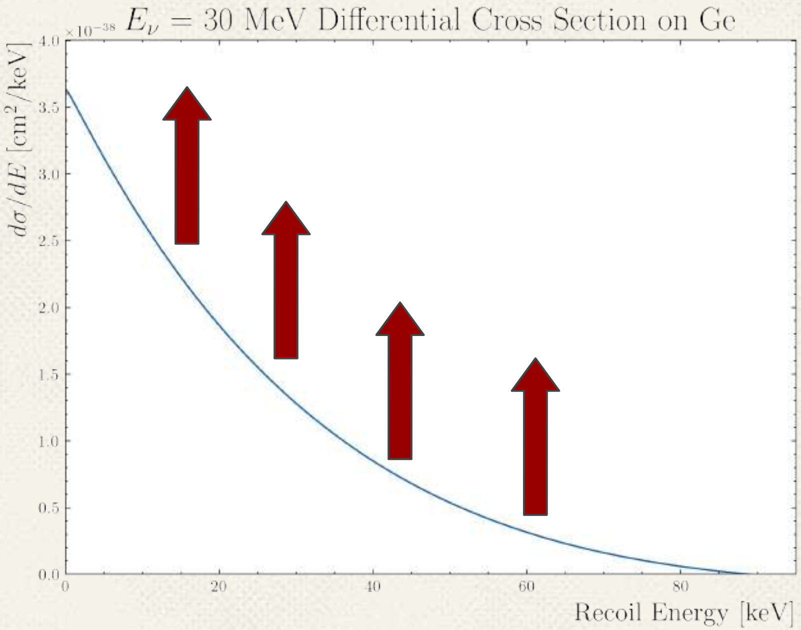
CEvNS matters for: Dark Matter

CEvNS is an irreducible background for weakly interacting massive particle (WIMP) dark matter searches: "neutrino fog"

WIMPs, if detected, have the same interaction signature as CEvNS



CEvNS matters for: “Extra” Z Bosons



An example CEvNS recoil energy spectrum on germanium, for a 30 MeV neutrino

CEvNS interacts with weak neutral current and is **flavor blind**

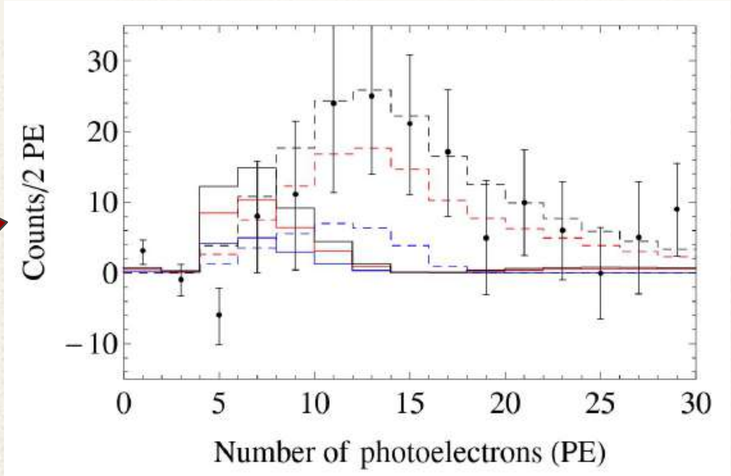
CEvNS is **well-predicted** by standard model, to the percent-level

If we see CEvNS rate changes, a new Z’ mediator could be the culprit

CEvNS matters for: NSI's

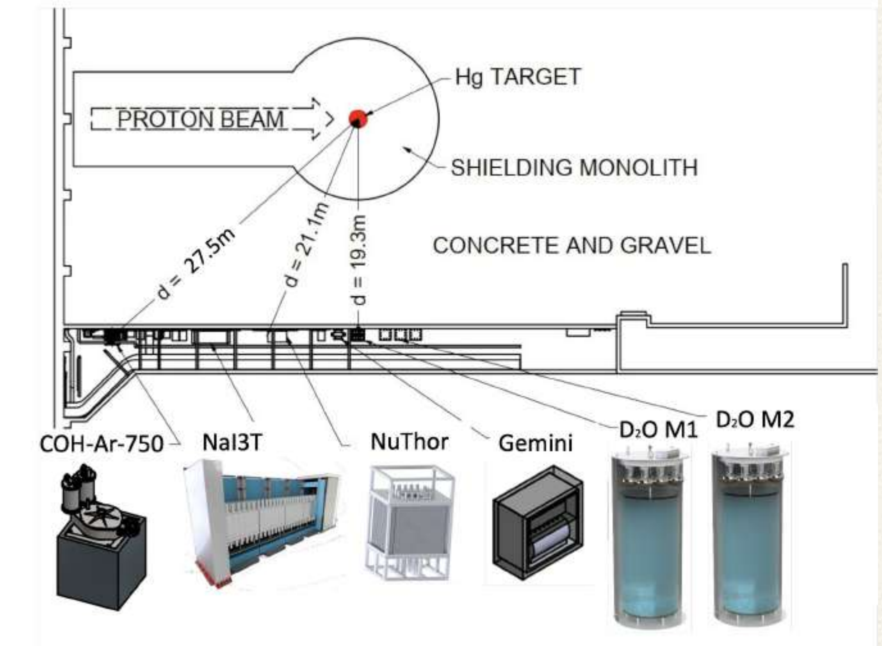
Heavy mediators (like new Z' boson) cause full CEvNS rate change

Light mediators would causes a shape distortion in the energy spectrum



How can we search for non-standard interactions? Multiple targets, low thresholds, and great energy resolution!

CEvNS matters for: Sterile Neutrinos

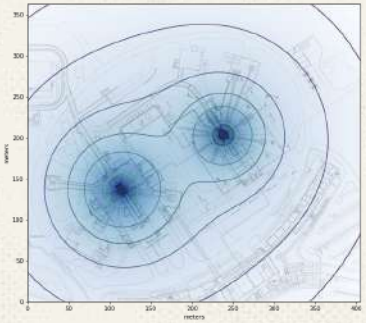


Multiple short baselines at the SNS!

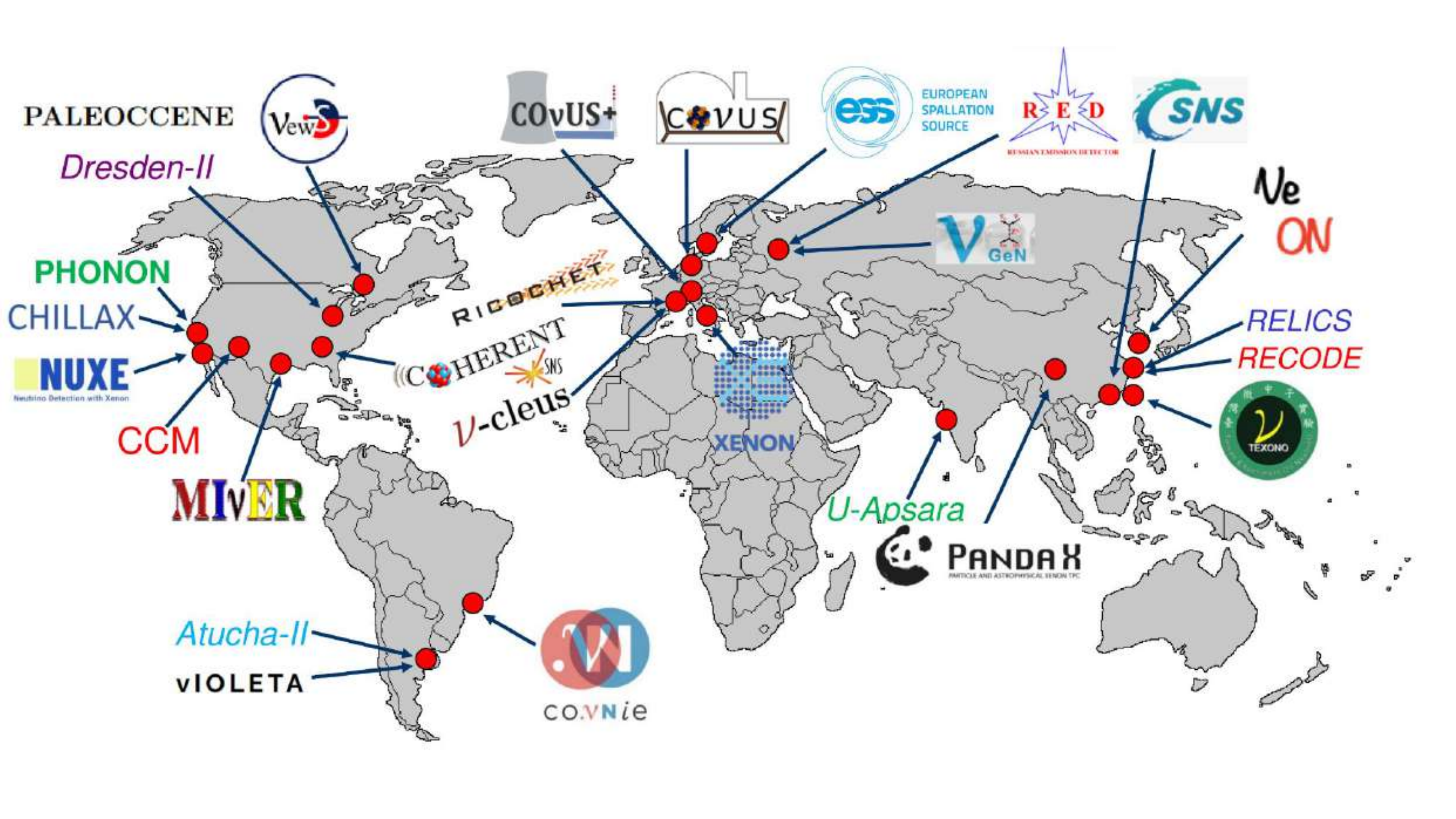
CEvNS is flavor-blind, so we don't care to disambiguate: a loss in rate of any flavor to a sterile would be interesting!

Need many baselines, lots of detectors, and different XC's, both CEvNS and CC

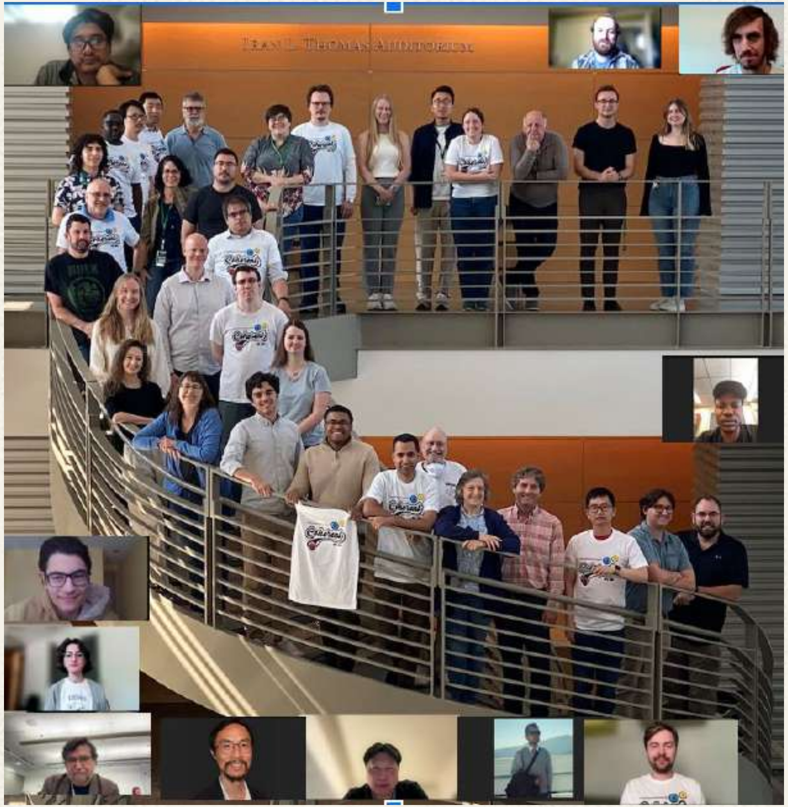
Future facility upgrade will give two "deuling" neutrino sources



A Vibrant New Field



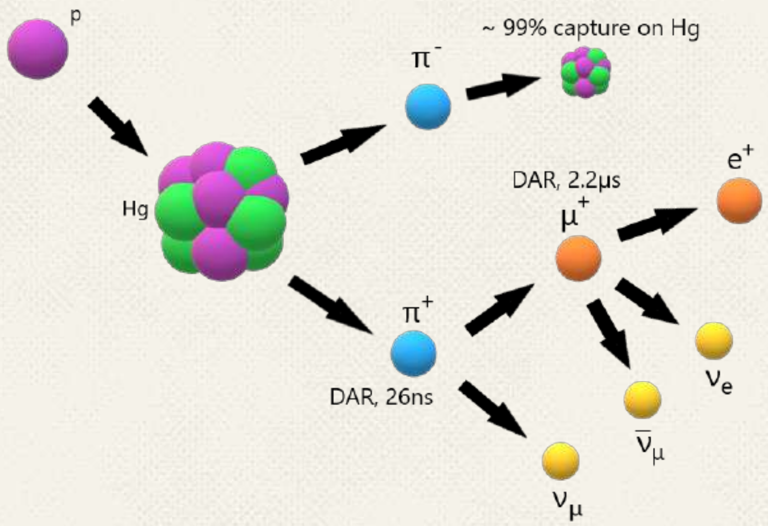
The COHERENT Collaboration

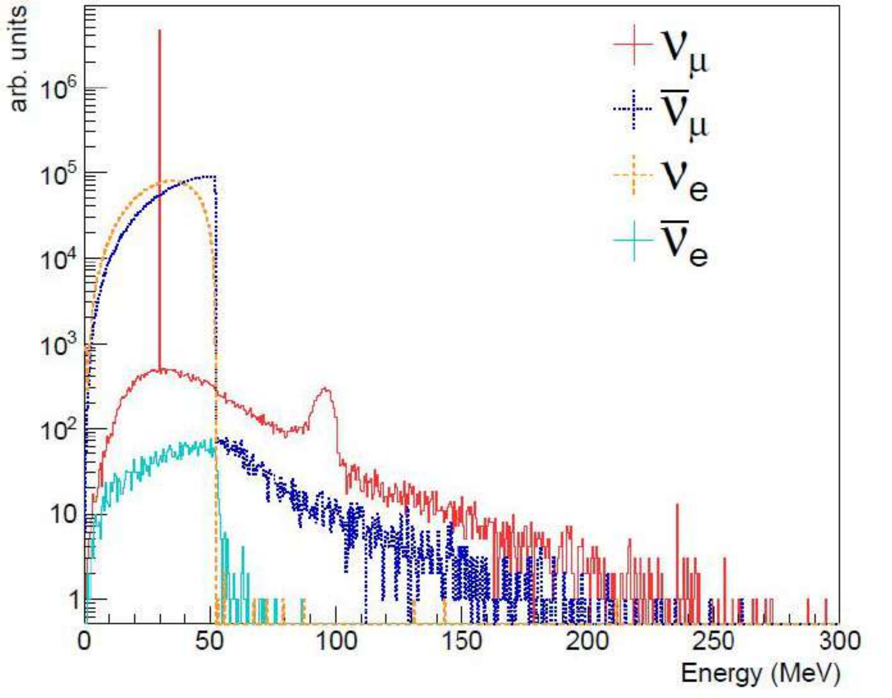


28 institutions, 6 countries, and >100 collaborators

What is the SNS?

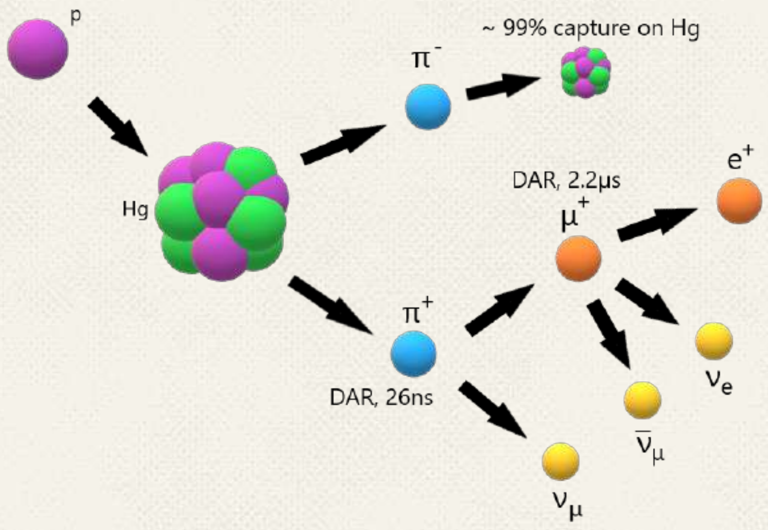
SNS Neutrinos: πDAR

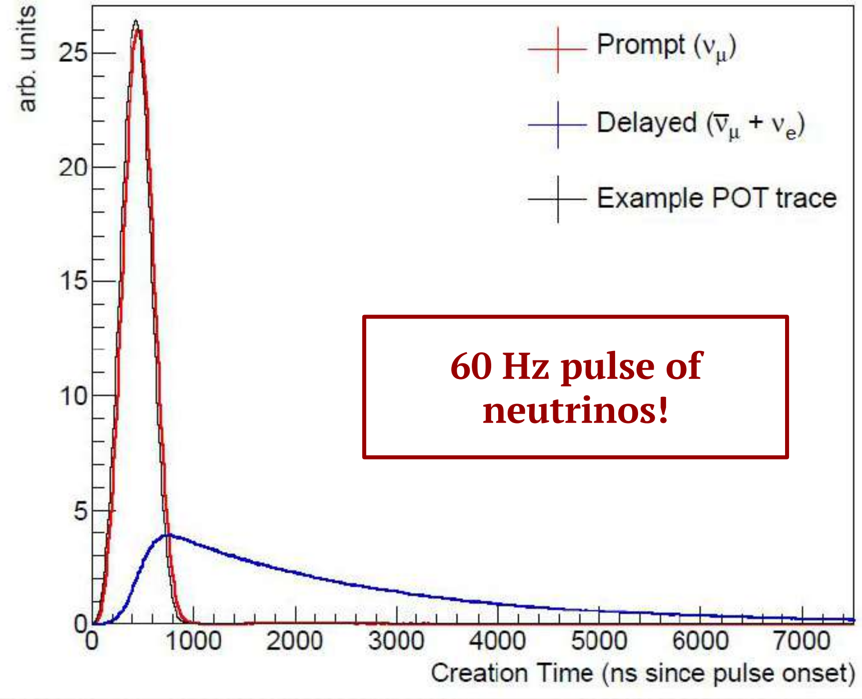




ν flux of ~10^7 ν's cm^{-2} s^{-1}

SNS Neutrinos: πDAR

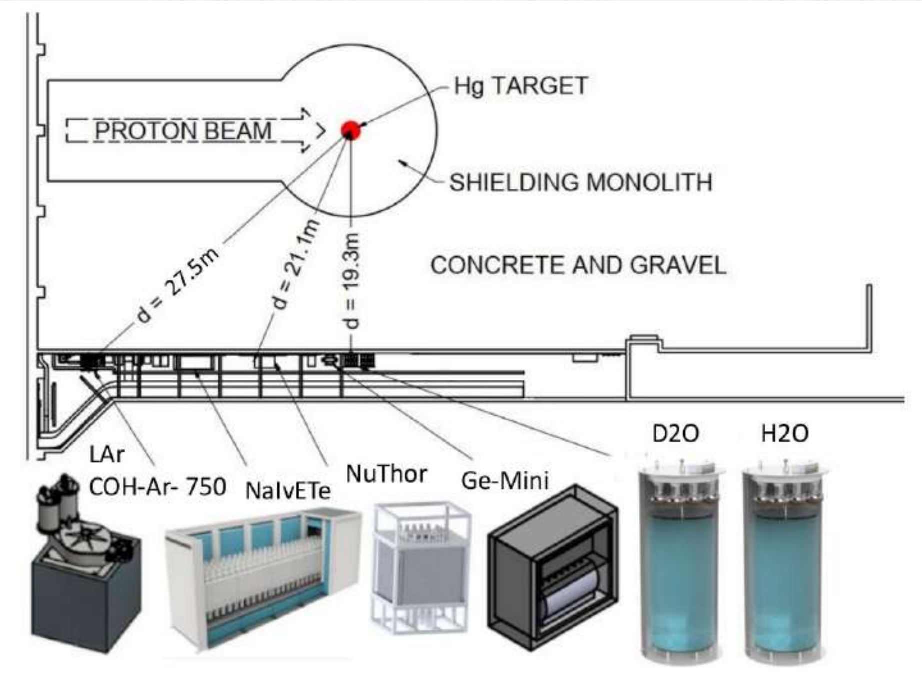


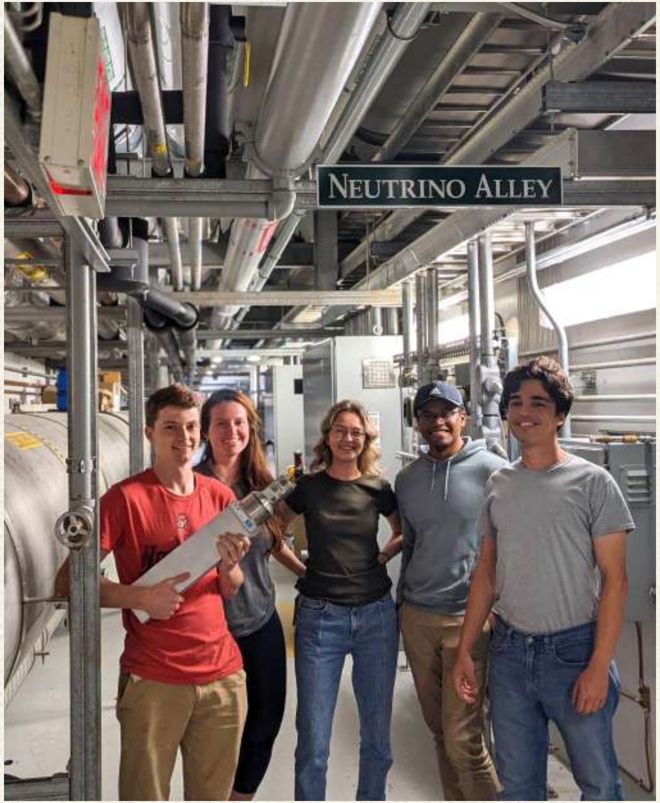


60 Hz pulse of neutrinos!

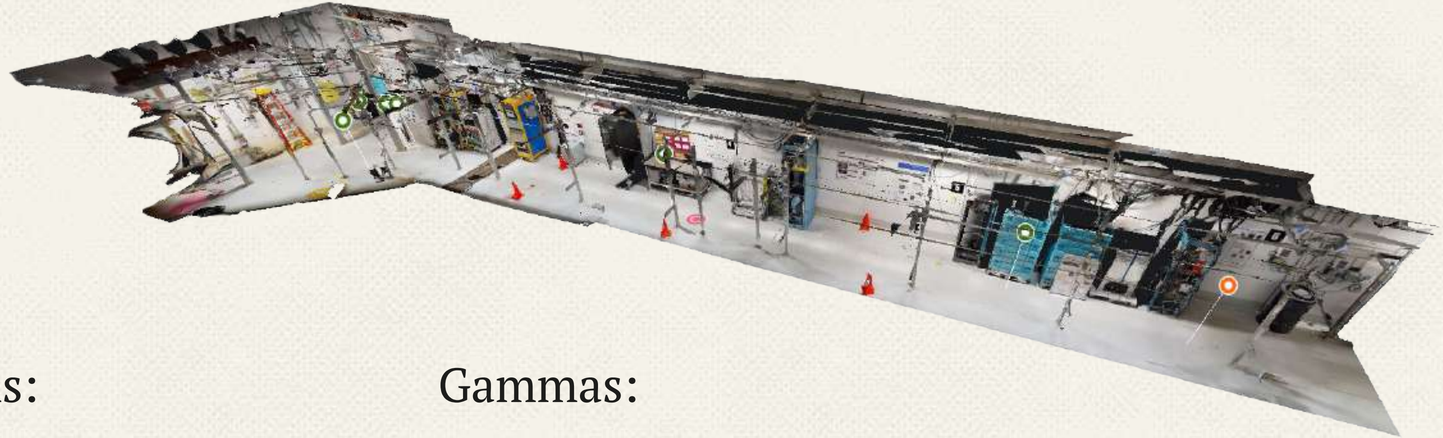
SNS is a PULSED source ---> ~10^4 - scale reduction in backgrounds

Neutrino Alley





SNS Backgrounds



Neutrons:

- Beam-related neutrons
- Neutrino-induced neutrons
- Muon-induced neutrons

Gammas:

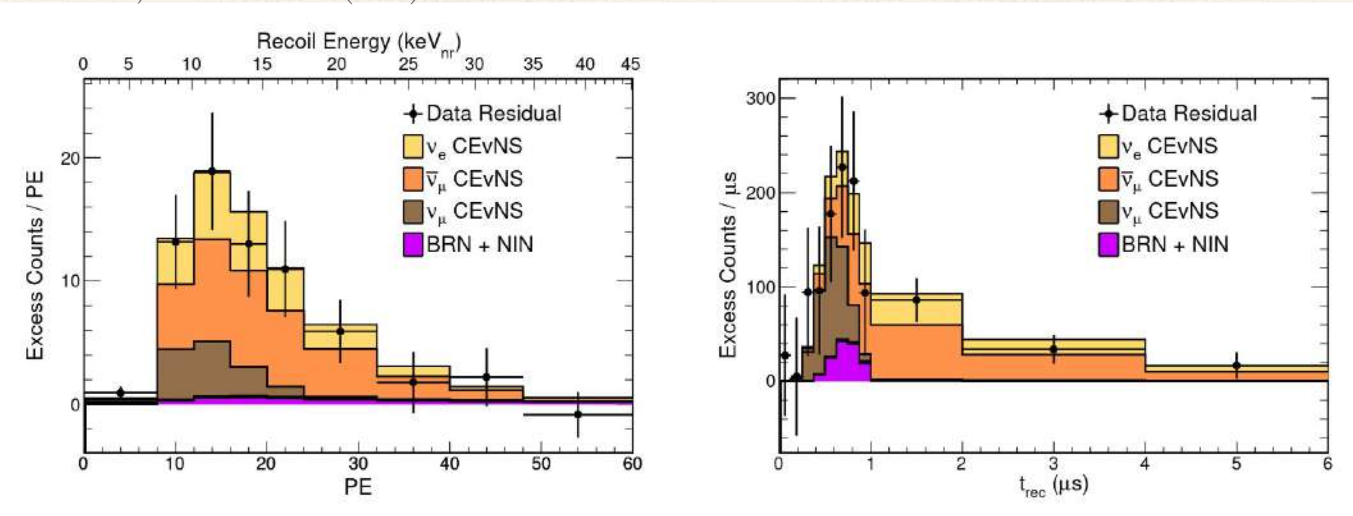
- 511 keV from $e^+ e^-$ annihilation in Hot Off-Gas pipe
- Radioactive decay of Uranium and Thorium (concrete)
- Betas from Pb-210, bremsstrahlung off shielding

Cosmics:

- Muons
- Particle showers due to muon interaction in shielding

2017: CEvNS no longer eludes us!

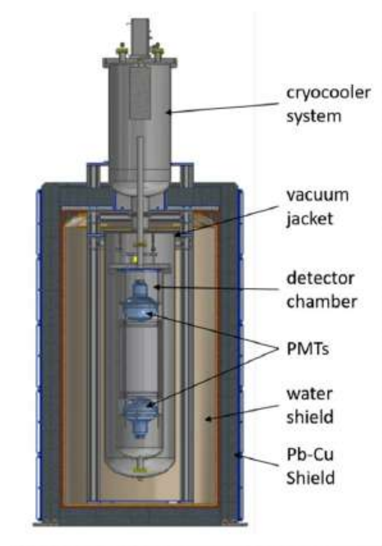
COHERENT, PRL 126 012002 (2021)

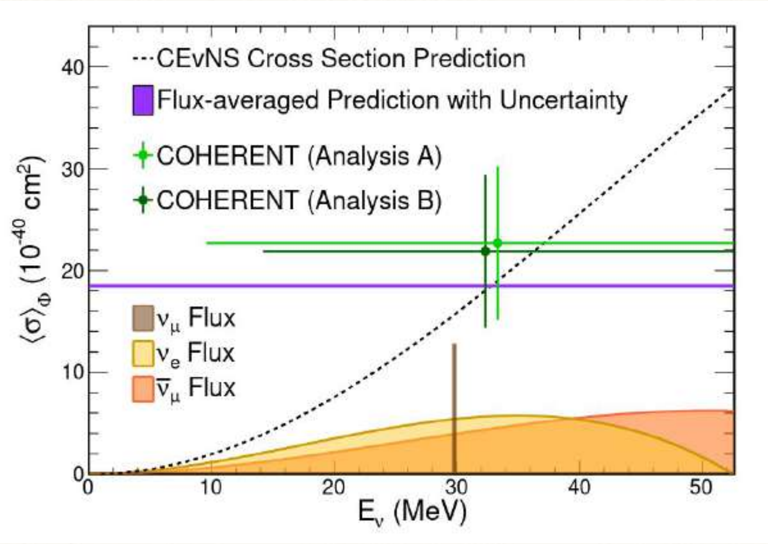


Akimov et al. Science Vol 357, Issue 6356 15 September 2017

First detection of CEvNS on CsI at 6.7 σ confidence (11.6 σ after combined dataset)

> 3σ detection of CEvNS on argon

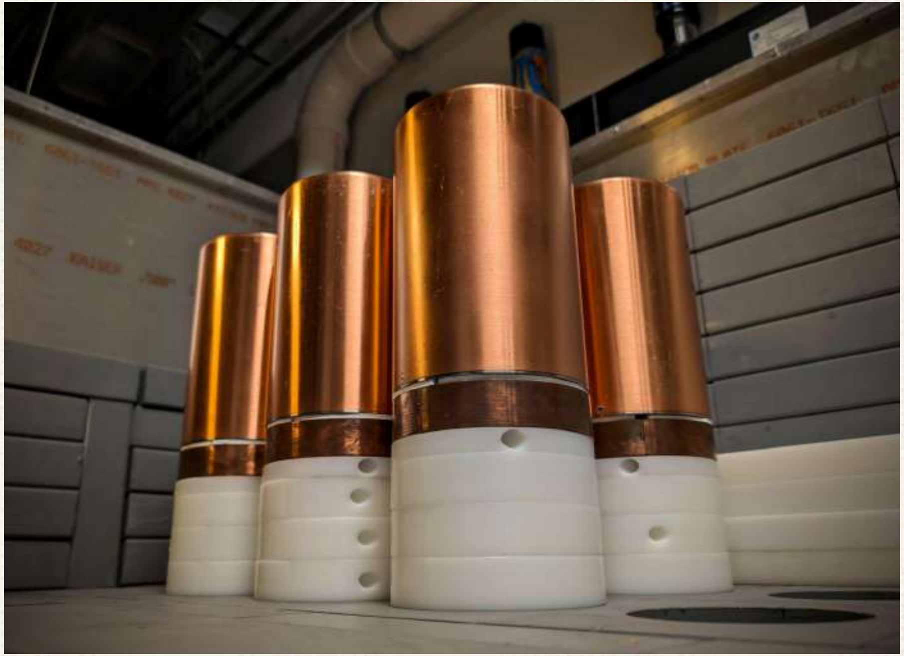


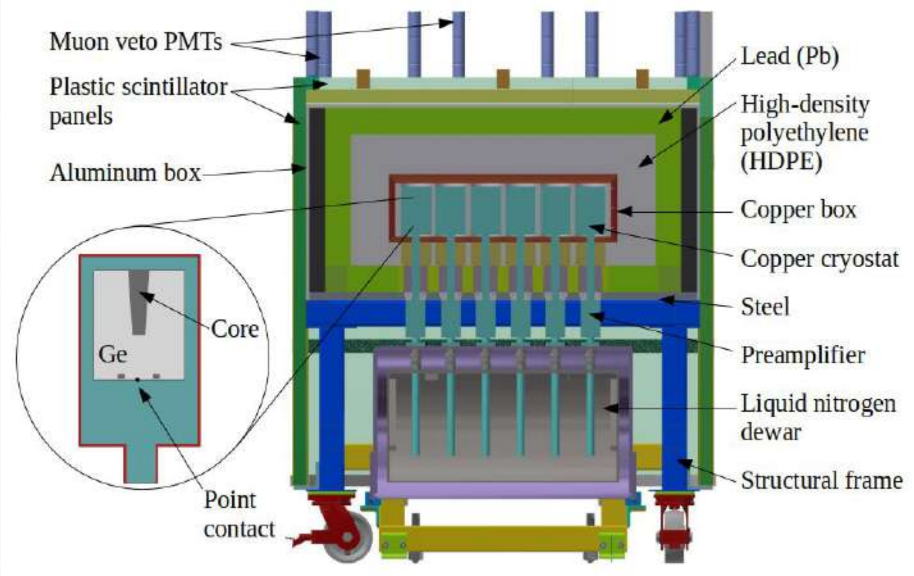


24 kg of single phase liquid argon

Data collected from July 2017 - September 2018

Ge-mini





18 kg of high purity germanium semiconductor detectors

Ge-mini

Commissioning start: Spring 2022

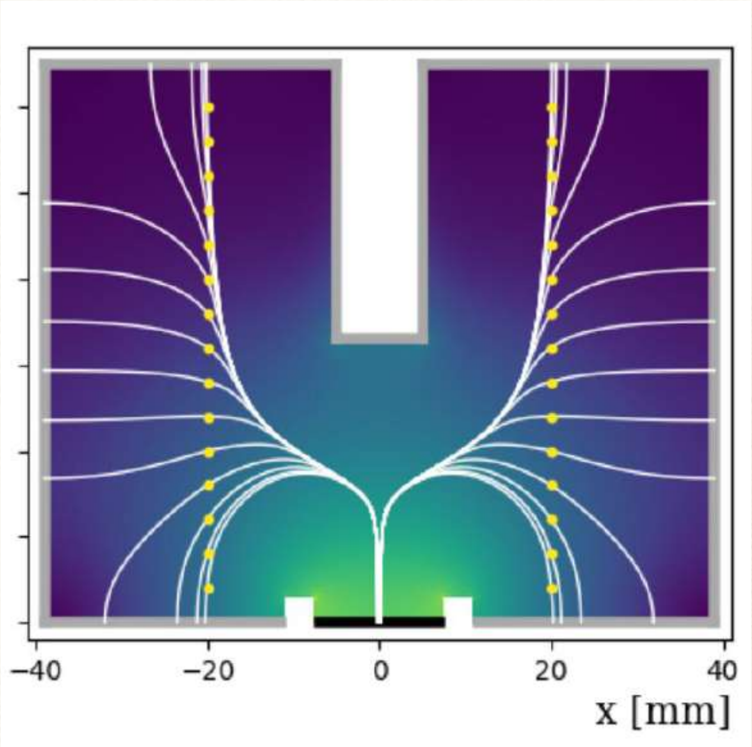
Excellent energy resolution: FWHM pulser peak ~135 eV

Low thresholds: unoptimized 1.5 keV, can go lower

Low intrinsic backgrounds

Cooled to 77 K in LN_2

Ge-mini



T. Comellato, M. Agostini, S. Schonert, Eur.Phys.J.C 81 (2021) 1, 76

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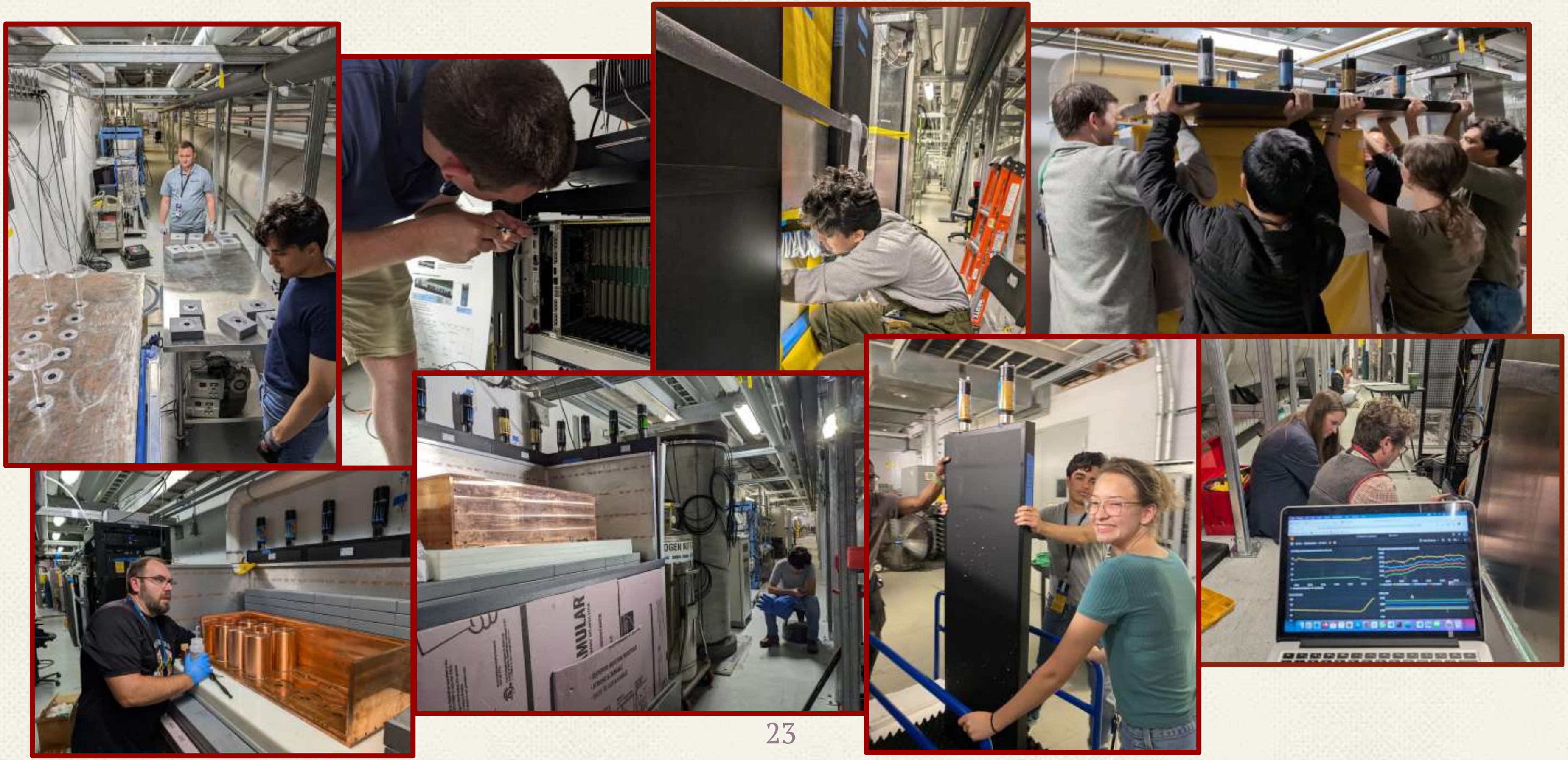
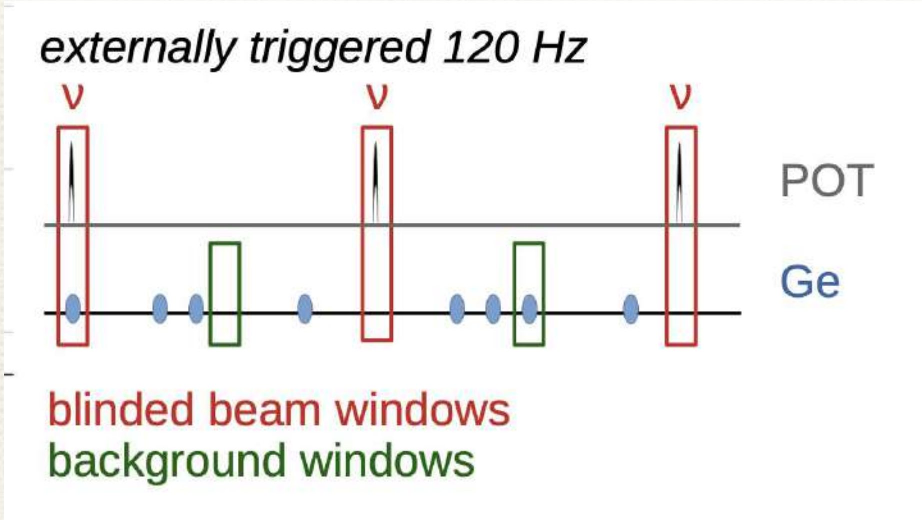
Ge-mini: Commissioning

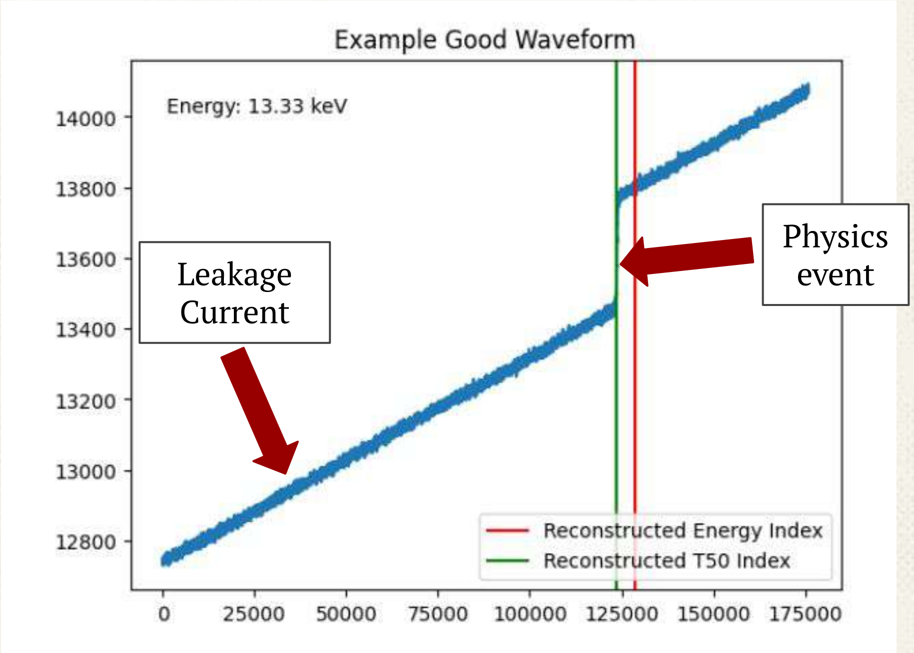


How does Ge-mini collect data?

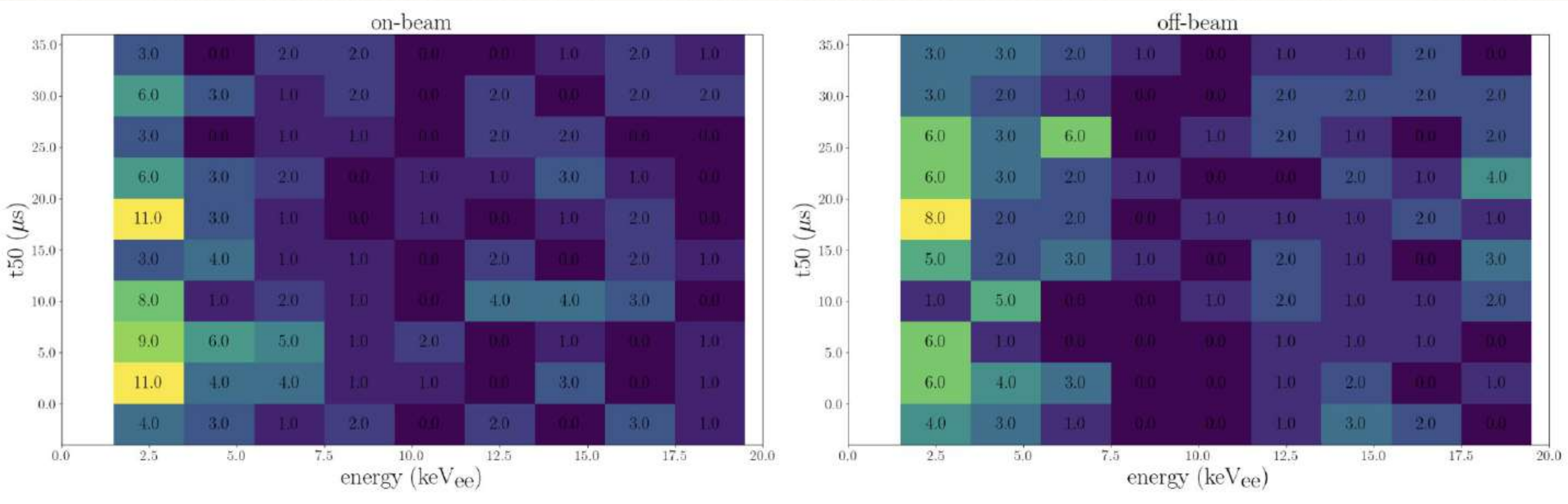


← 120Hz trigger for signal & background windows

~100μs baseline, externally triggered by SNS beam →



2024: First-Light CEvNS Measurement on Ge



3.9σ significance measurement of CEvNS on germanium

A counting analysis: 21.0 ± 7.8 CEvNS events in region [1.5, 8.5] keV and [0,8] μs

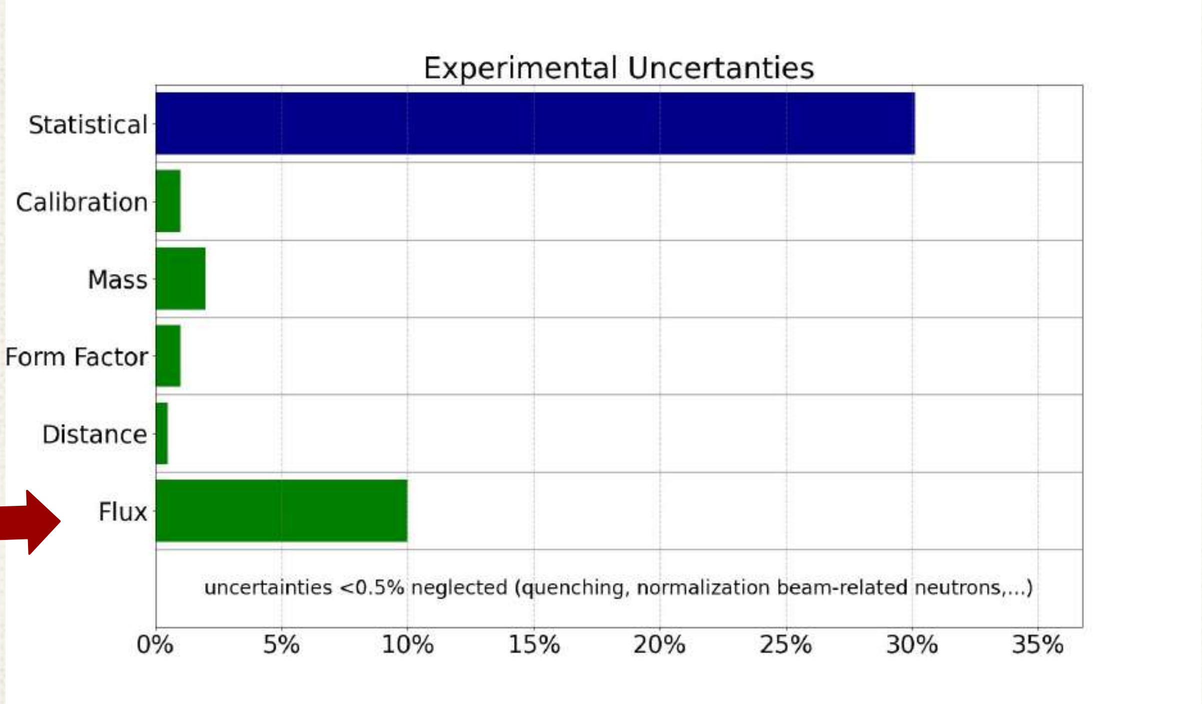
1.9σ from Standard-Model Prediction

COHERENT, preprint 2406.13806

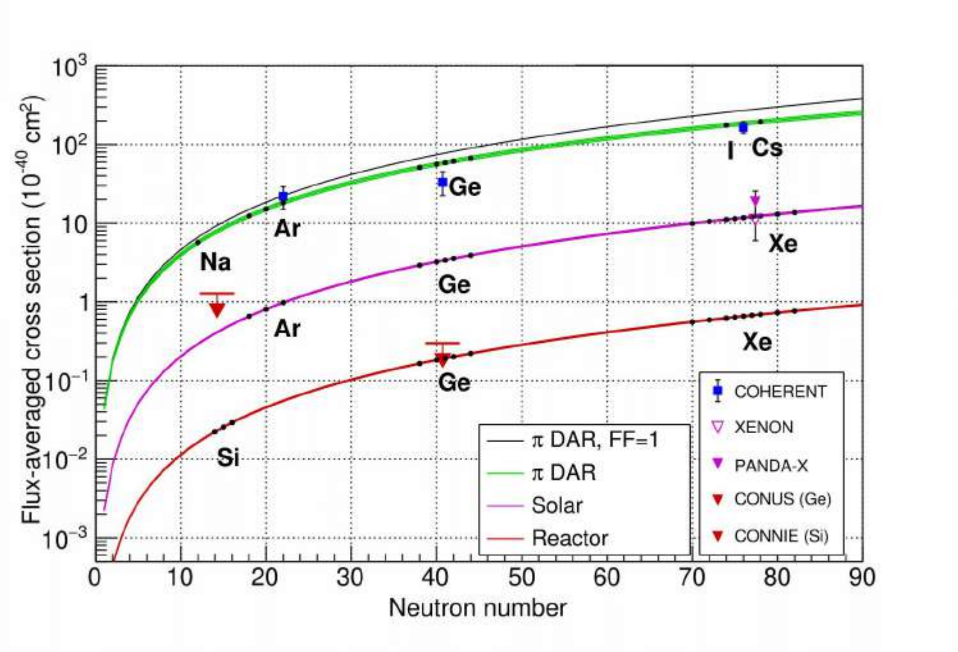
More left to do for germanium...

Still statistically limited: currently taking more data

Supporting experiment (D_2O) to reduce flux uncertainty… more on this later



Many CEvNS Results: what's next?



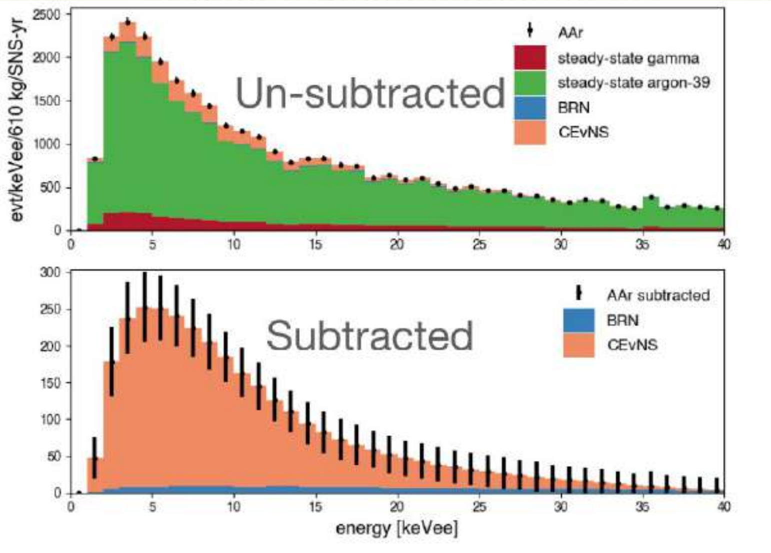
Entering a period of "precision CEvNS" measurements

For NSI's, constraints on weak mixing angle, neutrino magnetic moment, steriles, neutron form factor....

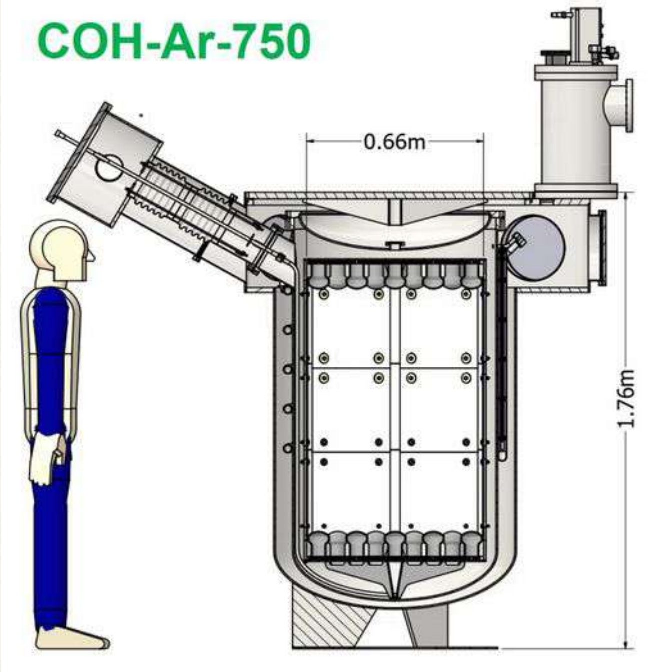
We need incredibly low systematic and statistical uncertainties, in the percent level!

Solution: scale up in mass, increase exposure, and reduce uncertainties

Going bigger: COH-Ar-750



Upgrade from 24 kg to 475 kg of liquid argon

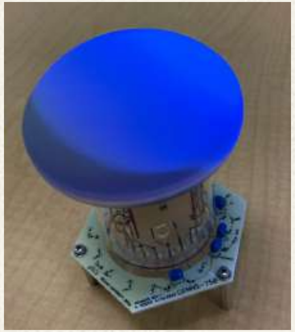


Expected events per SNS year:

CEvNS: ~ 5000 events

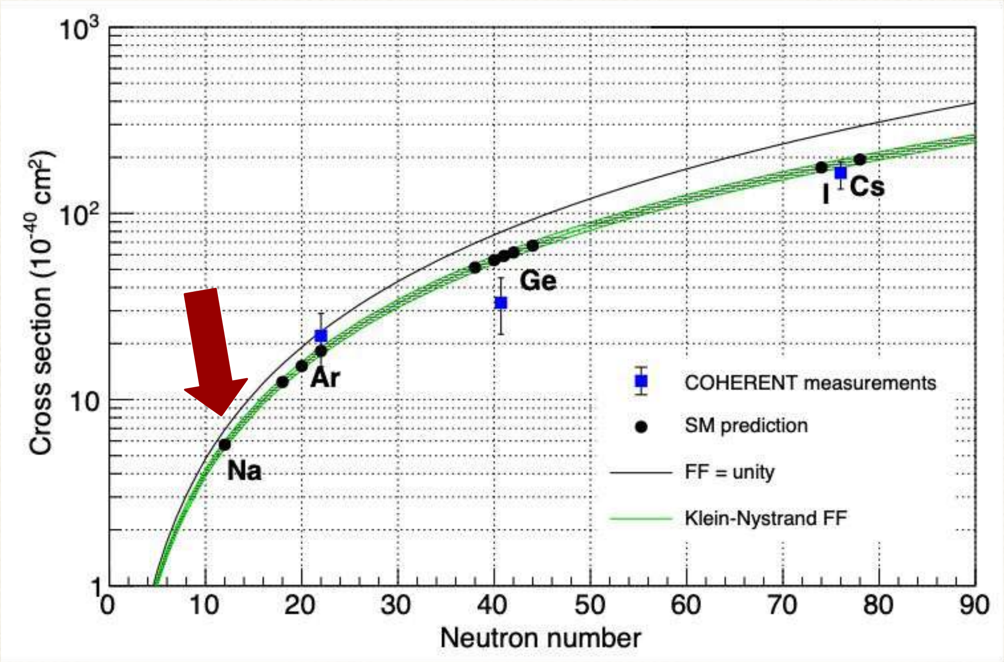
Inelastic CC: > 500 events

Going bigger: COH-Ar-750



Vessel delivered from SNU Korea, commissioning currently underway at Oak Ridge National Lab!

Bigger, and more targets



CEvNS measurements on CsI, Ar, and Ge, but what about lower neutron number?

Na a great candidate, and luckily, we have a ton… 2.4 tonnes!

NaIvETe

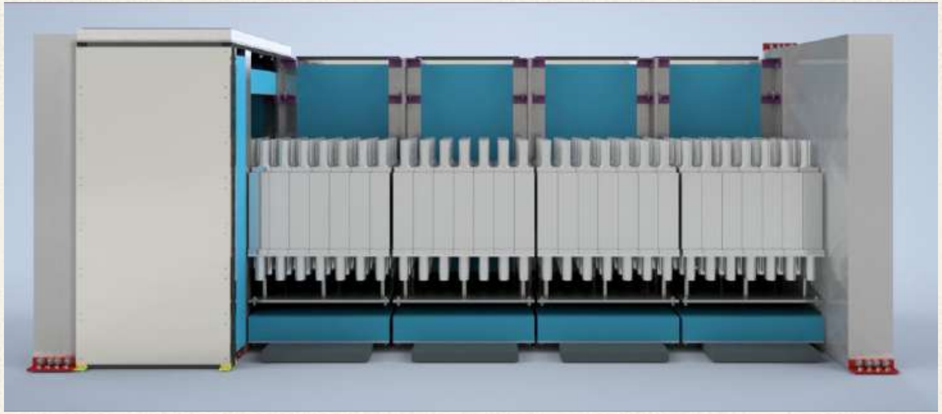
“Sodium-Iodide Neutrino Experiment at the TonnE scale”

2.4 kg of NaI, 315 crystals, 3/5 modules currently deployed

Can measure:

- CEvNS on Na
- Charge Current on Iodine

Dual-gain bases can do keV and MeV scale light detection

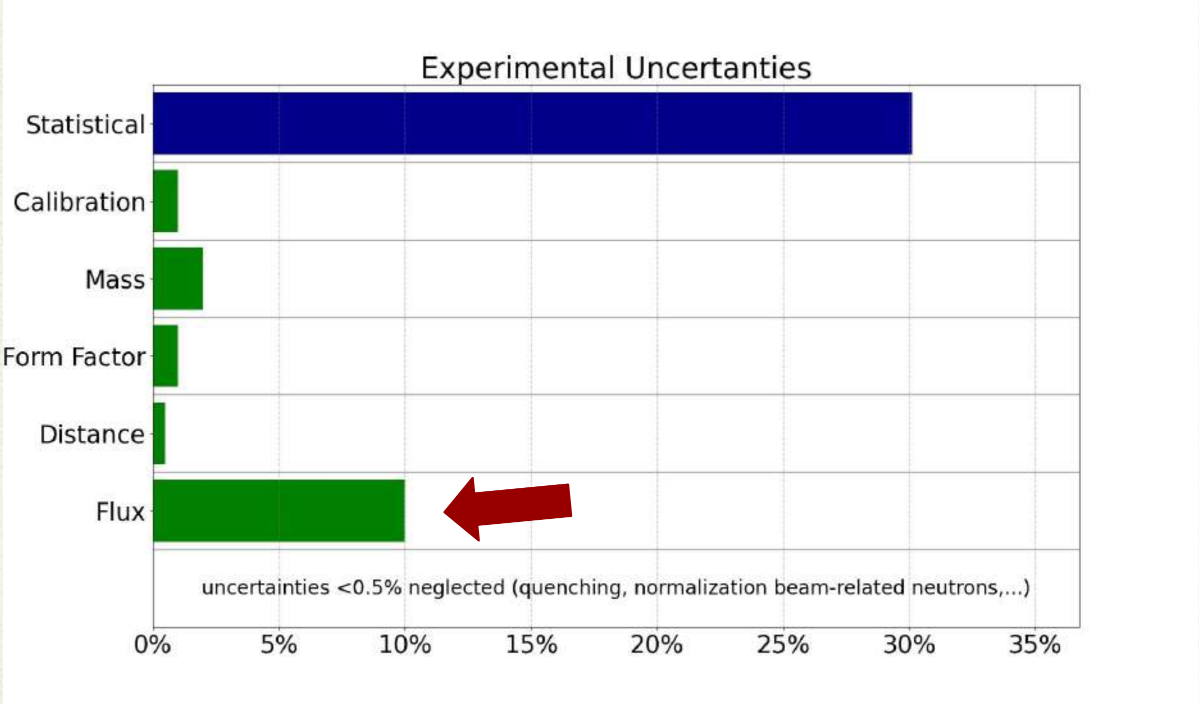


Neutrino flux uncertainty

Neutrino flux determined from simulations, but still a 10% systematic uncertainty

Impacts all experiments in Neutrino Alley

Flux uncertainty needs to decrease as we drop in statistical uncertainty



Solution: (A lot of) D2O

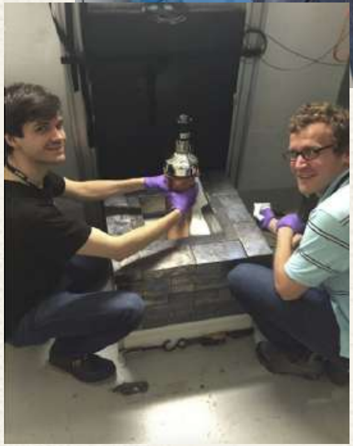
Well-understood reaction:

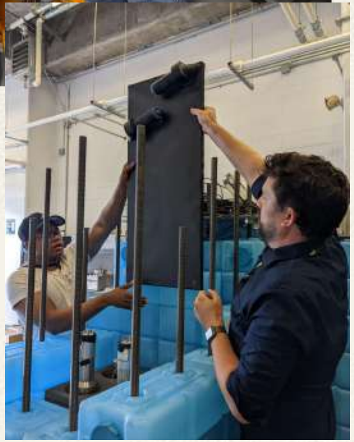
$$\nu_e + d \rightarrow p + p + e^-$$

Will reduce flux uncertainty down from 10% → 3%

Modularity: one identical module with H_2O will allow subtraction of the CC interaction on ^{16}O

inCOHERENT at COHERENT: Pb NINs





A background for COHERENT:
Neutrino-Induced Neutrons

Charge current neutrino interaction on lead shielding yields beam-correlated backgrounds

Nubes (pictured) yielded CC xsec result 0.29 times expected → suspiciously low

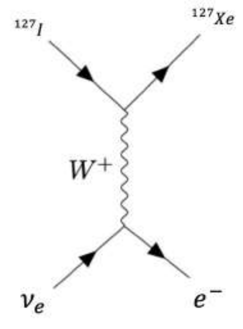
Phys. Rev. D **108**, 072001 (2023)

NaIvE-185

Deployment of a tonne-scale NaI experiment is a lot, start with prototype

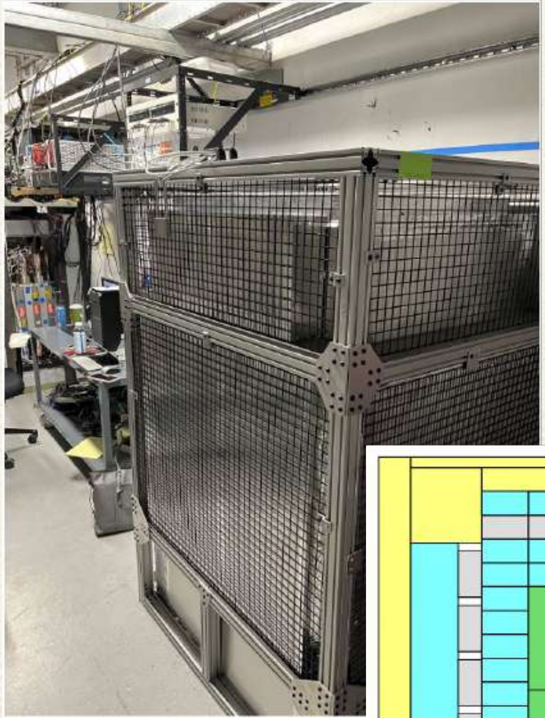
185 kg of NaI, with a measured charged current result of 5.8σ, but 40% of the theorized value

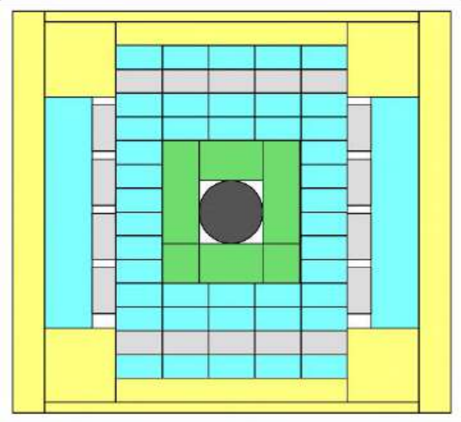
Solution: bigger, and more experiments to investigate CC low cross sections!



Phys. Rev. Lett. 131, 221801 (2023)

Neutrino-Induced Fission: NuThor





Neutrino-induced fission first theorized in 1971

52kg of Thorium, surrounded by NaI scintillator, Gd-water, lead, borated polyethylene

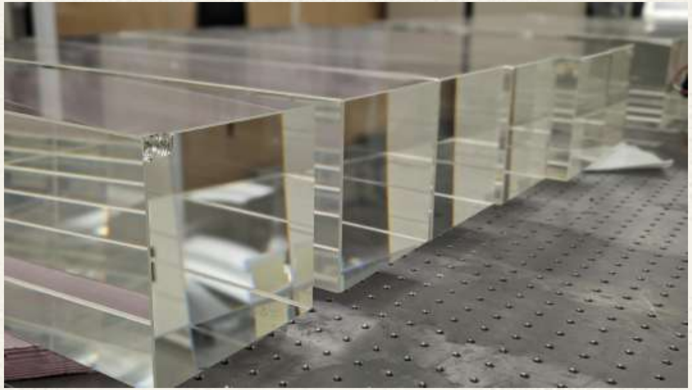
First detection of ν-fission at 2.4 σ significance

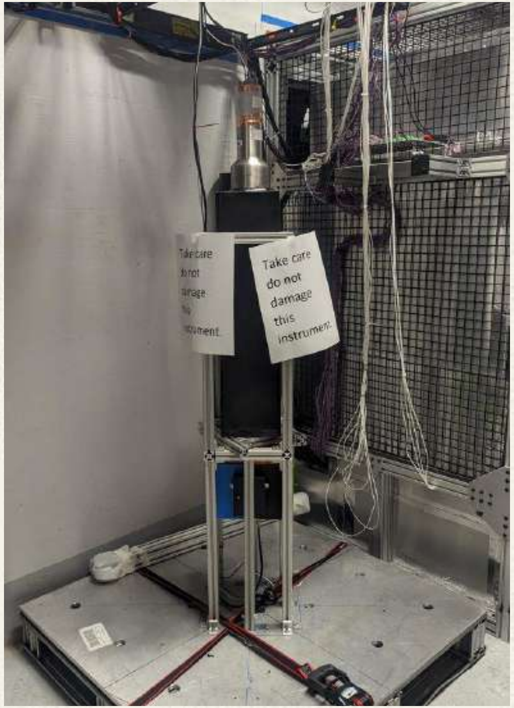
Coming up soon: Pb Glass

COHERENT reuses & recycles:

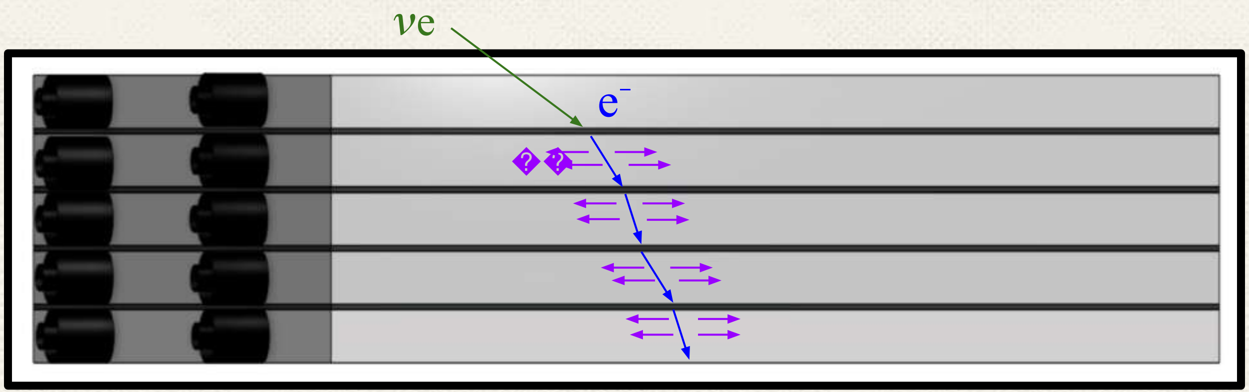
Decommissioned Pb glass usable for a large-scale Pb charged-current study

More mass to help solve mystery of low CC results



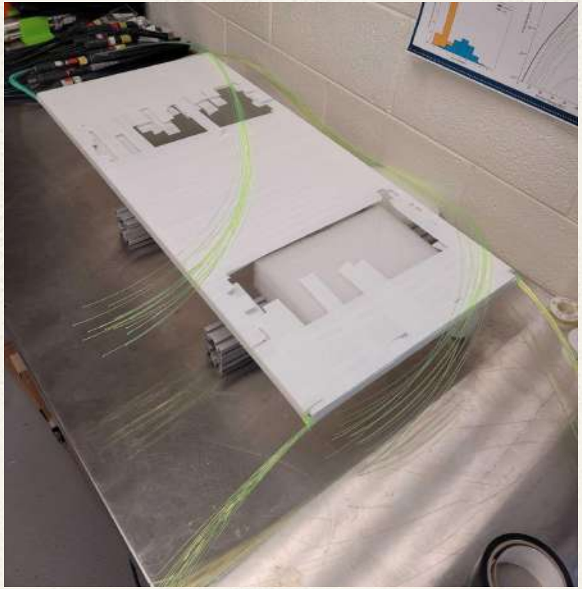


Coming up soon: Metal Sandwich



Physicists love modularity: alternating scintillator and swappable metal sheet (target)

More inelastic charged-current, with potential for directionality



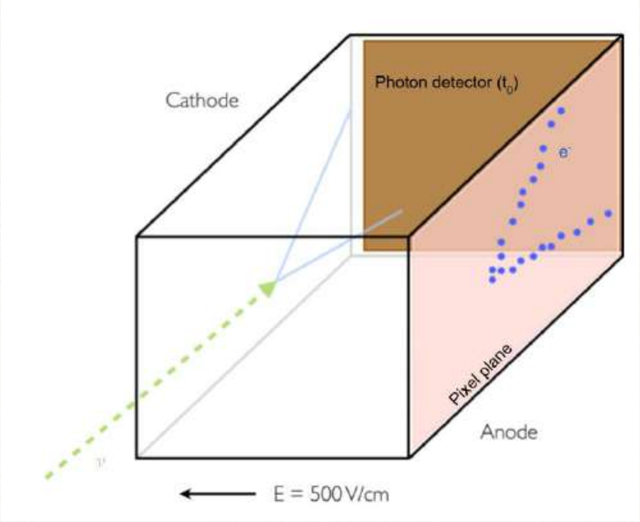
Scintillator prototype with λ-shifting fibers

Coming up soon: LAr TPC

More incoherent: a liquid argon time-projection chamber

Allows for a full 3D reconstruction of neutrino interactions

Additional benefit: small-scale prototype of DUNE near detector



Prototype at SLAC. Courtesy of Yun-Tse Tsai

SNS Upgrades

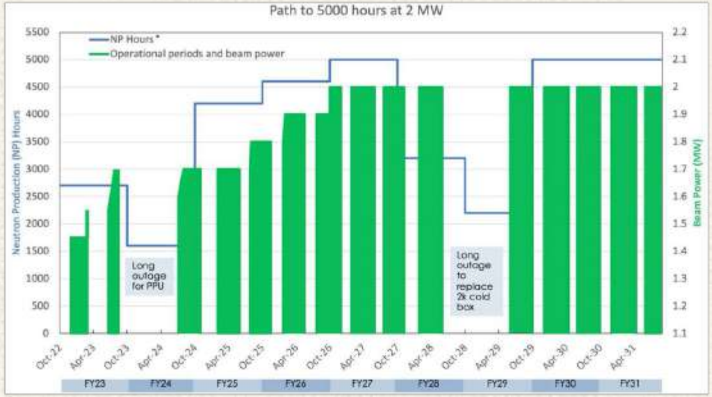


Figure 1. The path to 5,000 h of neutron production at 2 MW of beam power. The green blocks represent beam time to users. *These are the planned neutron production hours for each FY.

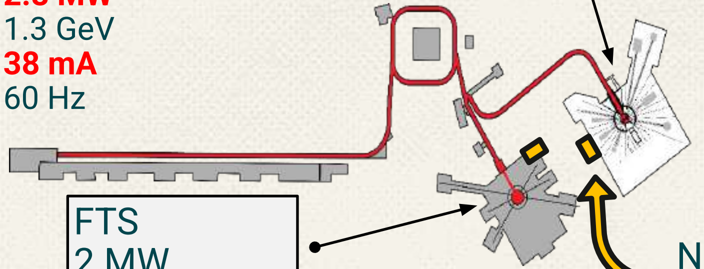
SNS is growing:

Power increase to 2 MW for First Target Station by 2026

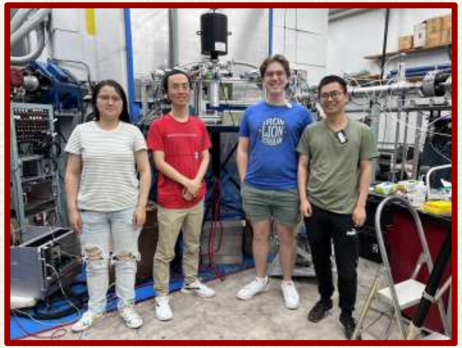
Construction of Second Target Station to follow

Potentially space for more multi-ton neutrino experiments!

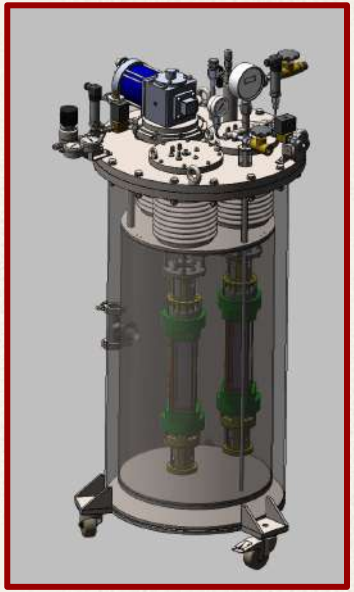
SNS Site with Second Target Station



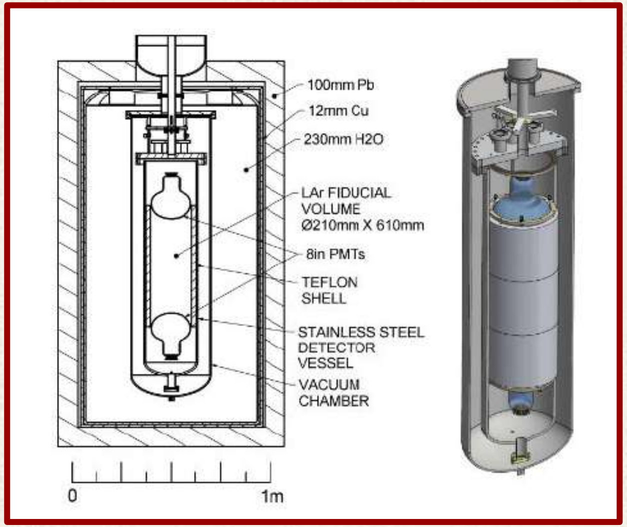
Other notable COHERENT Efforts:



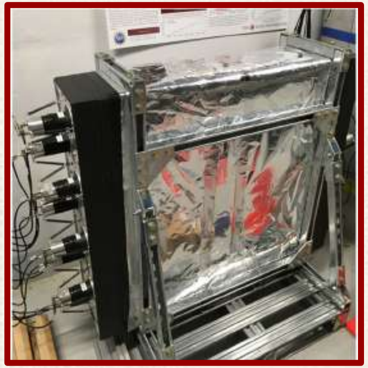
Detector Calibration facility
(Tandem van de Graaff @ TUNL)



Cryogenic CsI



Liquid Neon in CENNS-10



MARS detector

And many, many more...

The full lifecycle of an experiment:

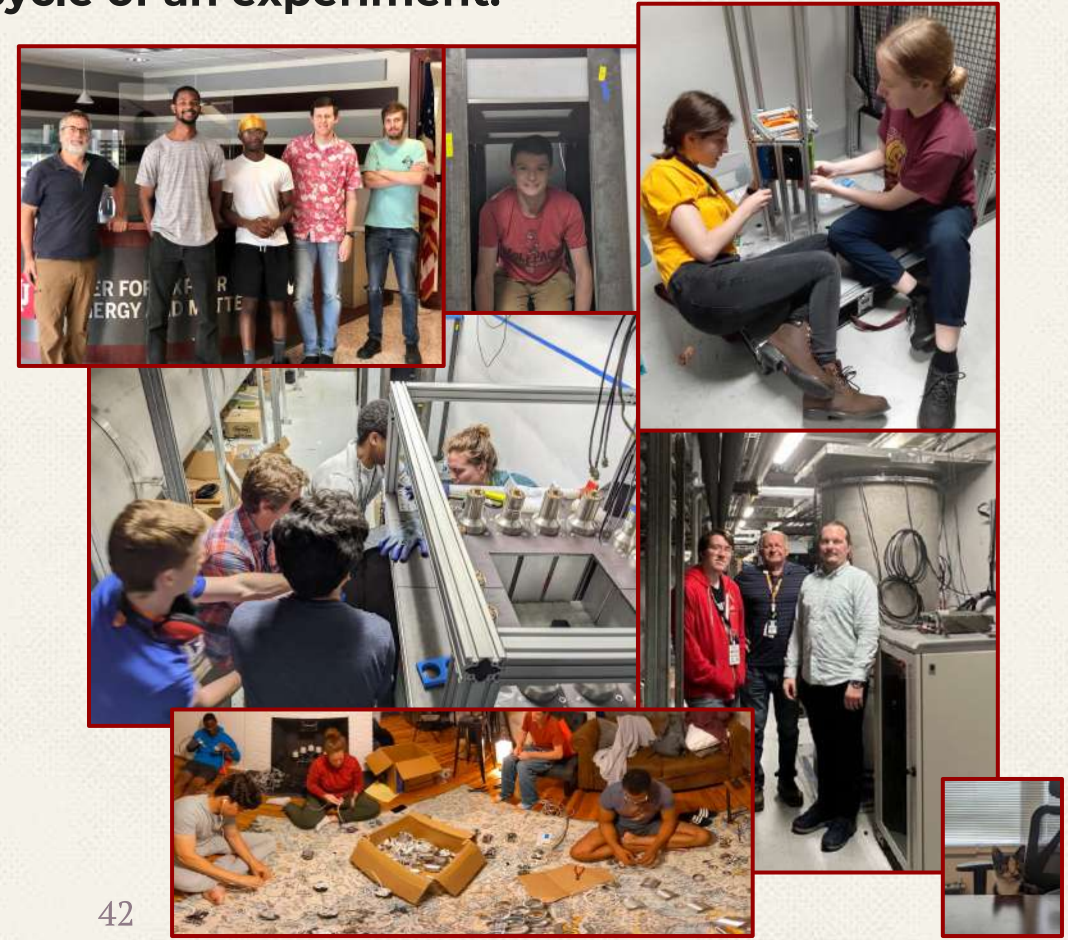
In numbers, COHERENT has:

Theses: **17**

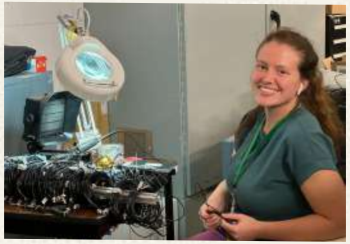
Thesis prizes: **5**

Publications: **15**

COHERENT is an excellent training grounds for students!



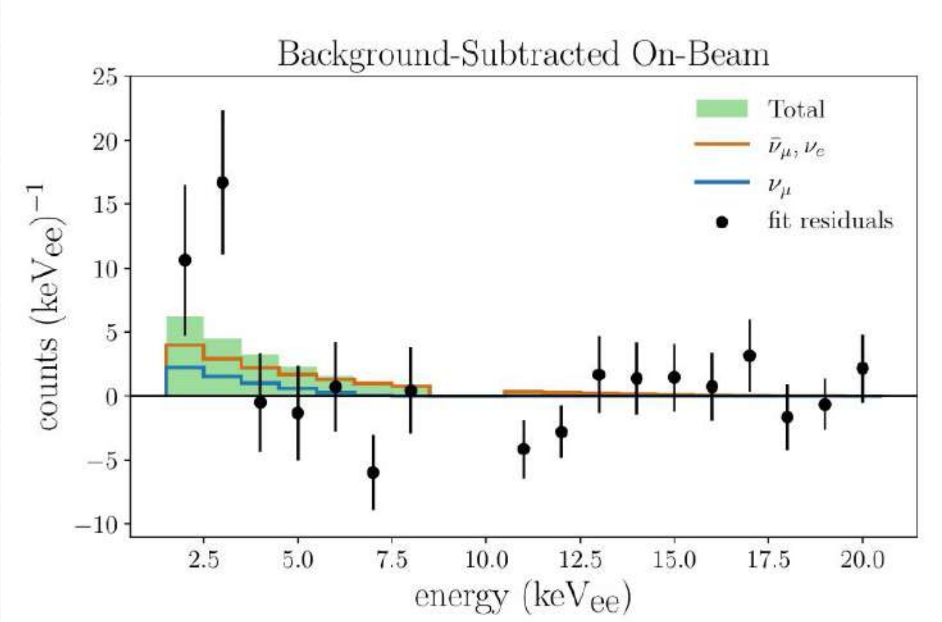
Thank you! Questions?

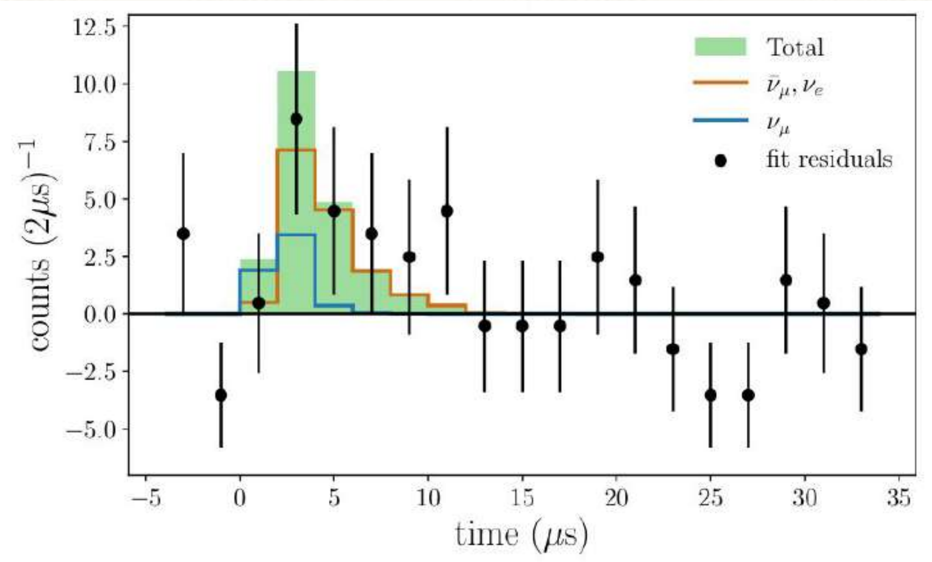


COHERENT SNS

Backup slides

CEvNS Ge result: energy and time

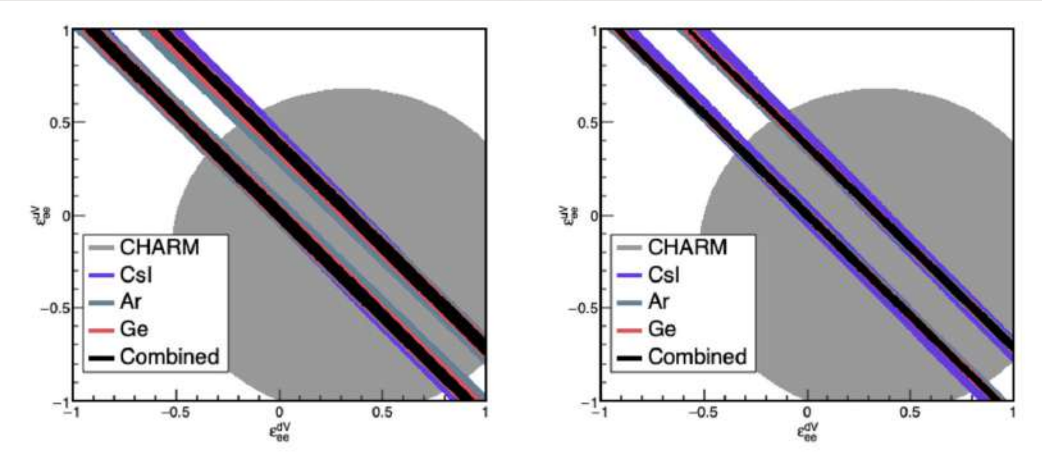




Ge-mini Experimental Reach: Non-Standard Interactions

16 kg Ge, 3 SNS years

16 kg Ge, 6 SNS years

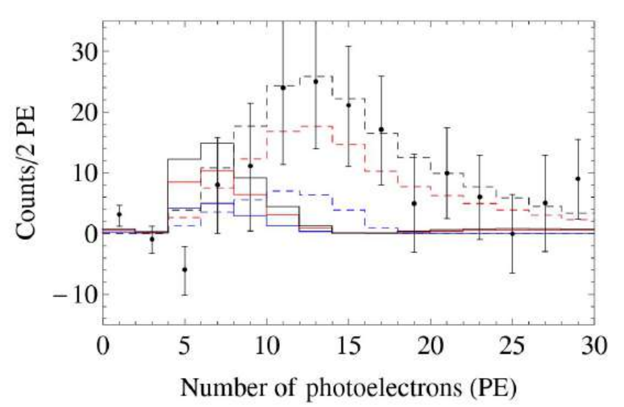


COHERENT Collaboration

Heavy mediators

Enhancement or reduction on the CEvNS rate

14.6 kg CsI



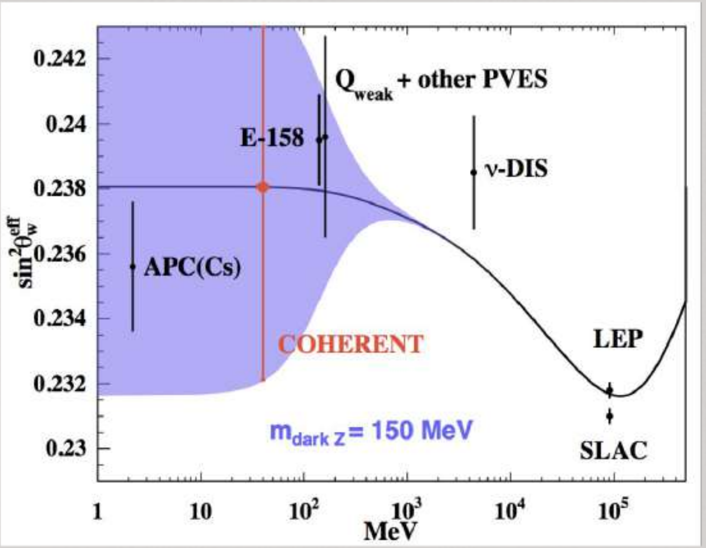
J. Liao, D. Marfatia, Phys Let. B, 775 (2017), p.54
https://doi.org/10.1016/j.physletb.2017.10.046

Light mediators

Effect on CEvNS recoil spectral shape

Ge has lower thresholds, and better energy resolution

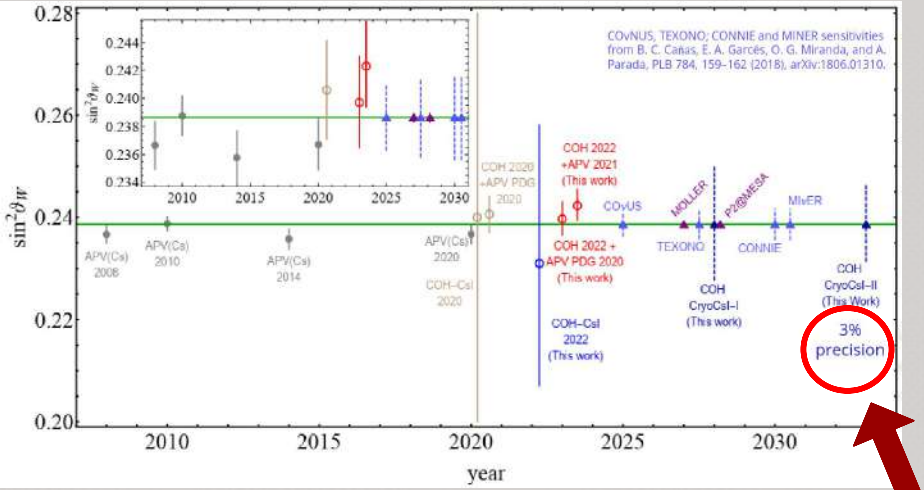
Ge-mini Experimental Reach: Weak Mixing Angle



P.S. Barbeau

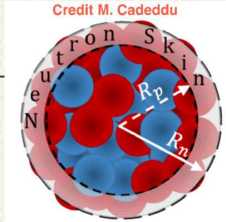
Weak mixing angle, assuming 5% uncertainty on CEvNS rate

$$\sigma_{CE\nu NS} \sim \frac{G_f^2 E^2}{4\pi} \left(Z\left(4\sin^2\theta_w - 1\right) + N\right)^2$$

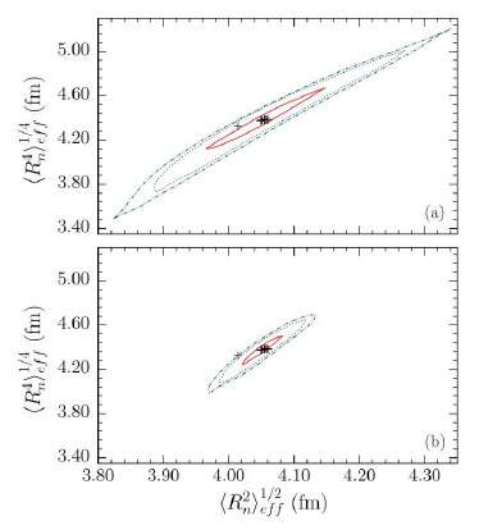


M. Cadeddu, Magnificent CEvNS 2023, Munich

Future Ge Experimental Reach: Neutron Form Factor

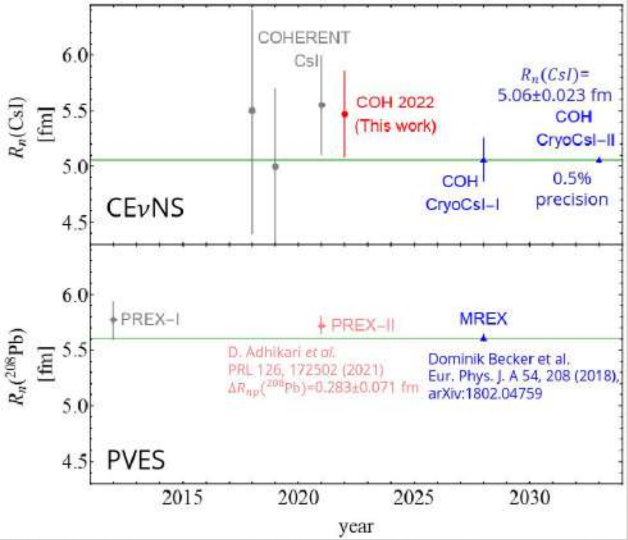


Neutron Form Factor



[1]

- Model-independent measure of neutron radius
- Patton et al. (2012) study indicates possibility of measuring FF to a few % if shape uncertainty can sink to 1%
- Study underway, including Campaign 2 backgrounds



[2]

$$F_n(Q^2) \approx \left(1 - \frac{Q^2}{3!}\langle R_n^2\rangle + \frac{Q^4}{5!}\langle R_n^4\rangle + \ldots\right)$$

[1] K. Patton, J. Engel, G.C. McLaughlin, N. Schunck, PHYSICAL REVIEW C 86, 024612 (2012) (DOI: 10.1103/PhysRevC.86.024612)
[2] M. Cadeddu, Magnificent CEvNS 2023, Munich

COHERENT Physics Goals

Table 1 COHERENT physics topics and corresponding experimental requirements

Topic	Experimental signature	Detector requirements
Nonstandard neutrino interactions, new mediators	Deviation from N^2, deviation from SM recoil shape, event rate scaling	Multiple targets, energy resolution, quenching factor
Weak mixing angle	Event rate scaling	Multiple targets, quenching factor
Neutrino magnetic moment	Low-recoil-energy excess	Low-energy threshold, energy resolution, quenching factor
Inelastic CC/NC cross section for supernova	High-energy (MeV) electrons, gammas	Large mass, dynamic range
Inelastic CC/NC cross section for weak coupling parameters	High-energy (MeV) electrons, gammas	Large mass, dynamic range
Nuclear form factors	Recoil spectrum shape	Energy resolution, multiple targets, quenching factor
Accelerator-produced dark matter	Event rate scaling, recoil spectrum shape, timing, direction with respect to source	Energy resolution, quenching factor
Sterile oscillations	Event rate and spectrum at multiple baselines	Similar or movable detectors at different baselines

COHERENT at the Spallation Neutron Source
P.S. Barbeau, Yu. Efremenko, K. Scholberg
Annual Review of Nuclear and Particle Science 2023 73:1, 41-68
https://doi.org/10.1146/annurev-nucl-101918-023518

Non-Standard Interactions (NSIs)

Beyond-Standard Model test: probe for heavy mediator **vector couplings** between neutrino and quarks

Vector couplings may **increase** or **decrease** CEvNS cross section: measurements on many Z/N targets can **break degeneracies**

BSM test: light mediators (Z’) may distort CEvNS recoil energy spectrum, detectors with great energy resolution may be sensitive to distortions

Neutrino Magnetic Moment

SM states small μ_ν , contributes towards **uptick** of CEvNS events at low recoil energy T

Larger than expected μ_ν may indicate BSM physics

How can we measure CEvNS?

Core-collapse supernovae:

- ~ 10^{12} ν's cm^{-2} s^{-1}
- MeV - 10's of MeV
- Rare

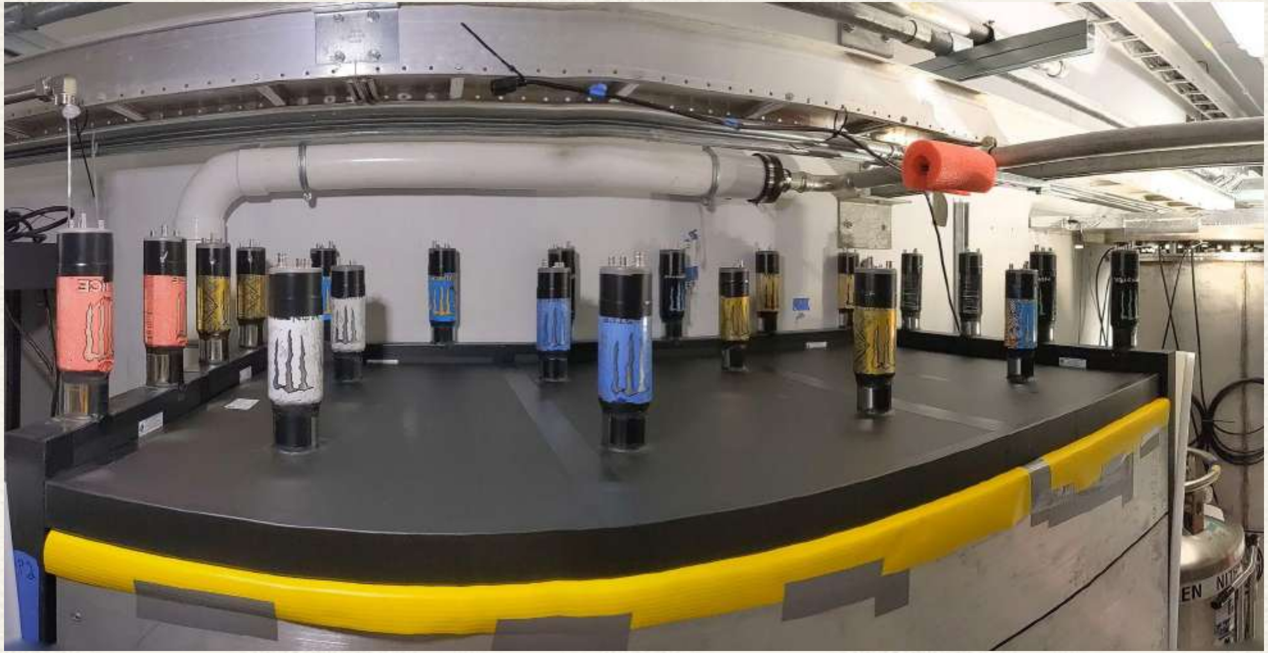
Nuclear reactors:

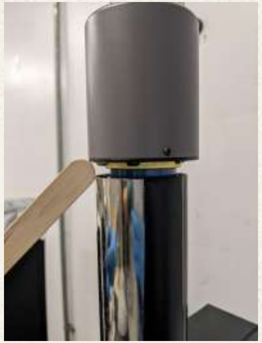
- ~ 10^{12} ν's cm^{-2} s^{-1} flux
- ~ 1000's of keV (low recoil E)
- Background rejection challenges

Stopped-pion Sources:

- 10^{7} ν's cm^{-2} s^{-1} flux
- 1-50 MeV
- Pulsed neutrino source

Ge-mini Muon Veto





Top scintillator panel

CEvNS Cross Section with Vector and Axial-Vector Contributions

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

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

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

D. Akimov et al. (COHERENT Collaboration), The COHERENT experimental program (2022), arXiv:2204.04575v1 [hep-ex].

CEvNS Cross Section - Weak Mixing Angle

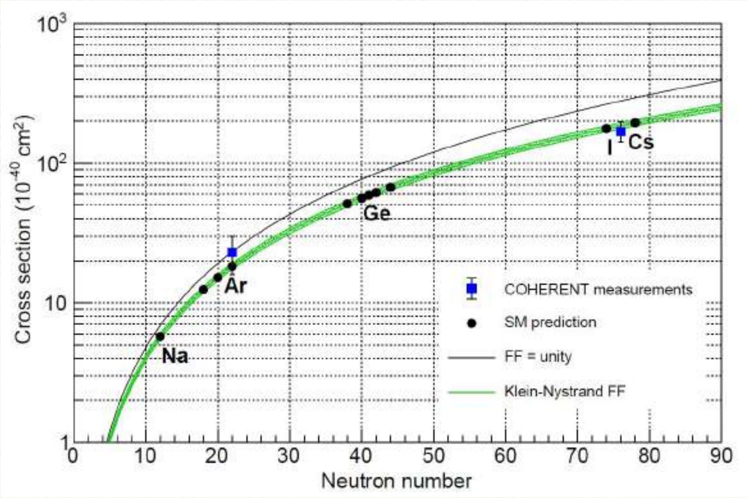
CEvNS cross section:

$$\frac{d\sigma}{d\cos(\theta)} = \frac{G^2}{8\pi}[Z(4\underline{\sin^2\theta_W} - 1) + N]^2 E^2 (1+\cos\theta)$$

$$\underline{\sin^2\theta_W} \simeq 0.22 \text{ or } \sim \frac{1}{4}$$

$$= \frac{G^2}{8\pi} N^2 E^2 (1+\cos\theta)$$

"Enhanced" cross section, increases $\propto$ N^2 !



P. S. Barbeau, Y. Efremenko, and K. Scholberg, COHERENT at the Spallation Neutron Source (2021), arXiv:2111.07033v1 [hep-ex].

CEvNS Cross Section - Momentum Transfer and Recoil Energy

CEvNS cross section in terms of:

Momentum transfer to the target nucleus:

$$\frac{d\sigma}{d\Delta^2} = \frac{G^2}{8\pi} N^2 \left(1 - \frac{\Delta^2}{\Delta^2_{\mathrm{max}}}\right)$$

$$\Delta^2 = 2E^2(1 - \cos\theta)$$

Recoil energy of target nucleus:

$$\frac{d\sigma}{dT} = \frac{G^2}{4\pi} N^2 M \left(1 - \frac{MT}{2E^2}\right)$$

Coherence condition met at neutrino energies of $\lesssim$ 50 MeV where Q*R $\lesssim$ 1

NSI Heavy Mediator Vector Coupling Cross Section

$$\left(\frac{d\sigma}{dT}\right)_{\nu_\alpha A} = \frac{G_F^2 M}{\pi} F^2(2MT)\left[1 - \frac{MT}{2E_\nu^2}\right] \times$$
$$\{[Z(g_V^p + 2\varepsilon_{\alpha\alpha}^{uV} + \varepsilon_{\alpha\alpha}^{dV}) + N(g_V^n + \varepsilon_{\alpha\alpha}^{uV} + 2\varepsilon_{\alpha\alpha}^{dV})]^2$$
$$+ \sum_{\alpha\neq\beta}[Z(2\varepsilon_{\alpha\beta}^{uV} + \varepsilon_{\alpha\beta}^{dV}) + N(\varepsilon_{\alpha\beta}^{uV} + 2\varepsilon_{\alpha\beta}^{dV})]^2\}.$$

P. S. Barbeau, Y. Efremenko, and K. Scholberg, COHERENT at the Spallation Neutron Source (2021), arXiv:2111.07033v1 [hep-ex].

Measuring Form Factors

$$\frac{d\sigma}{dT} = \frac{G^2}{4\pi} N^2 M \underline{\mathbf{F^2(\Delta)}} \left(1 - \frac{MT}{2E^2}\right)$$

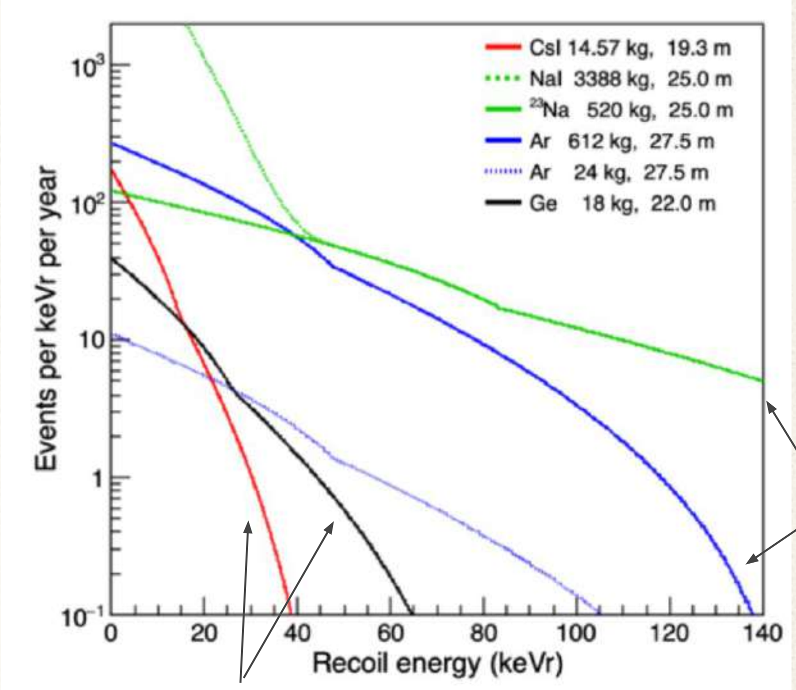
Form factor suppresses the cross section, but $F^2(\Delta) \approx 1$ at low momentum transfer

Higher momentum transfer = decreased CEvNS rate (xsec suppression **~ < 5%**)

With superior energy resolution, Germanium detectors may see **reduced counts at higher T**

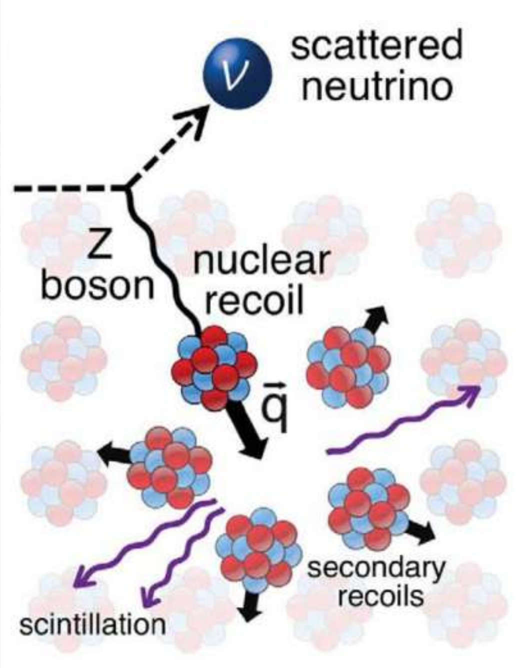
Can measure form factor contribution to CEvNS rate, important for neutron radius and neutron skin depth.

CEvNS Recoil Spectra on Different Nuclei



Lighter nuclei ≈ higher energy nuclear recoil

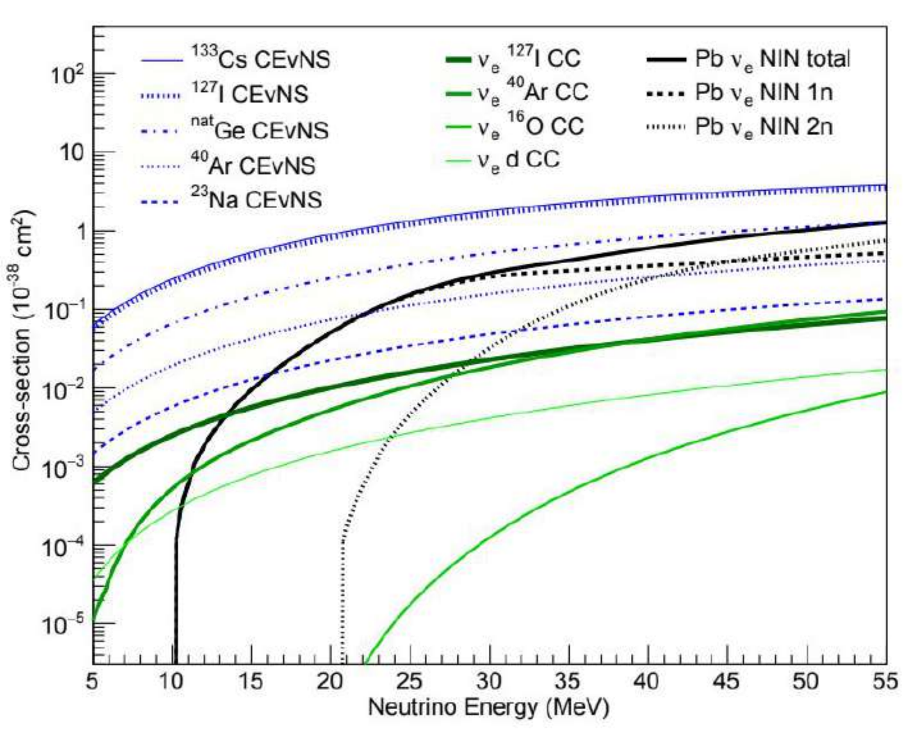
Heavier nuclei ≈ lower energy nuclear recoil



P. S. Barbeau, Y. Efremenko, and K. Scholberg, COHERENT at the Spallation Neutron Source (2021), arXiv:2111.07033v1 [hep-ex].

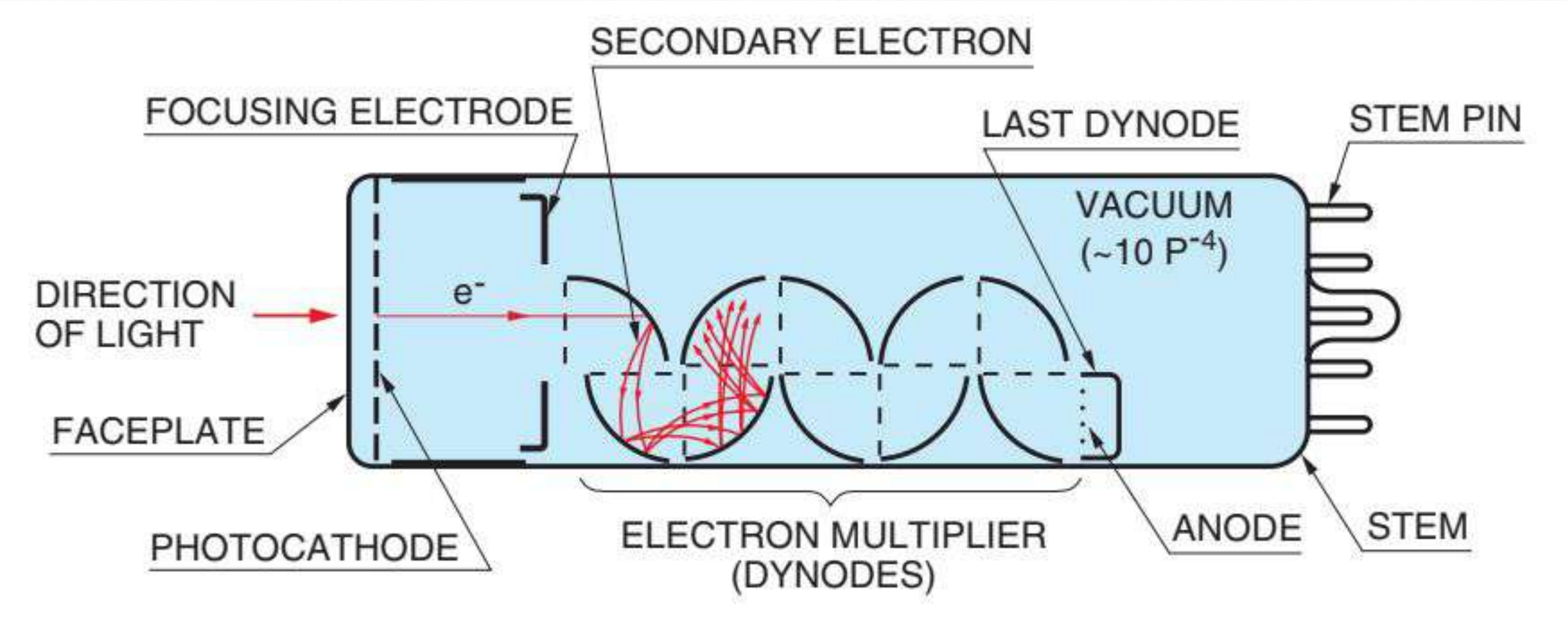
D. Akimov et al. (COHERENT Collaboration), Observation of coherent elastic neutrino-nucleus scattering, Science **357**, 1123 (2017).

Plot of CEvNS, CC, and NINs Cross Sections



P. S. Barbeau, Y. Efremenko, and K. Scholberg, COHERENT at the Spall
Neutron Source (2021), arXiv:2111.07033v1 [hep-ex].

How does a PMT work?



Hamamatsu Photonics, *Photomultiplier Tubes: Basics and Applications* (2017), 4th edition.