The COHERENT Experiment

Charlie Prior

On behalf of the COHERENT Collaboration

Duke

COHERENT Collaboration

- ~80 Members over 20 Institutions
- Formed to search for coherent elastic neutrino-nucleus scattering (CEvNS)
- Based at Oak Ridge National Laboratory's Spallation Neutron Source
- Complementary searches for inelastic neutrino-nucleus interactions (INCOHERENT)

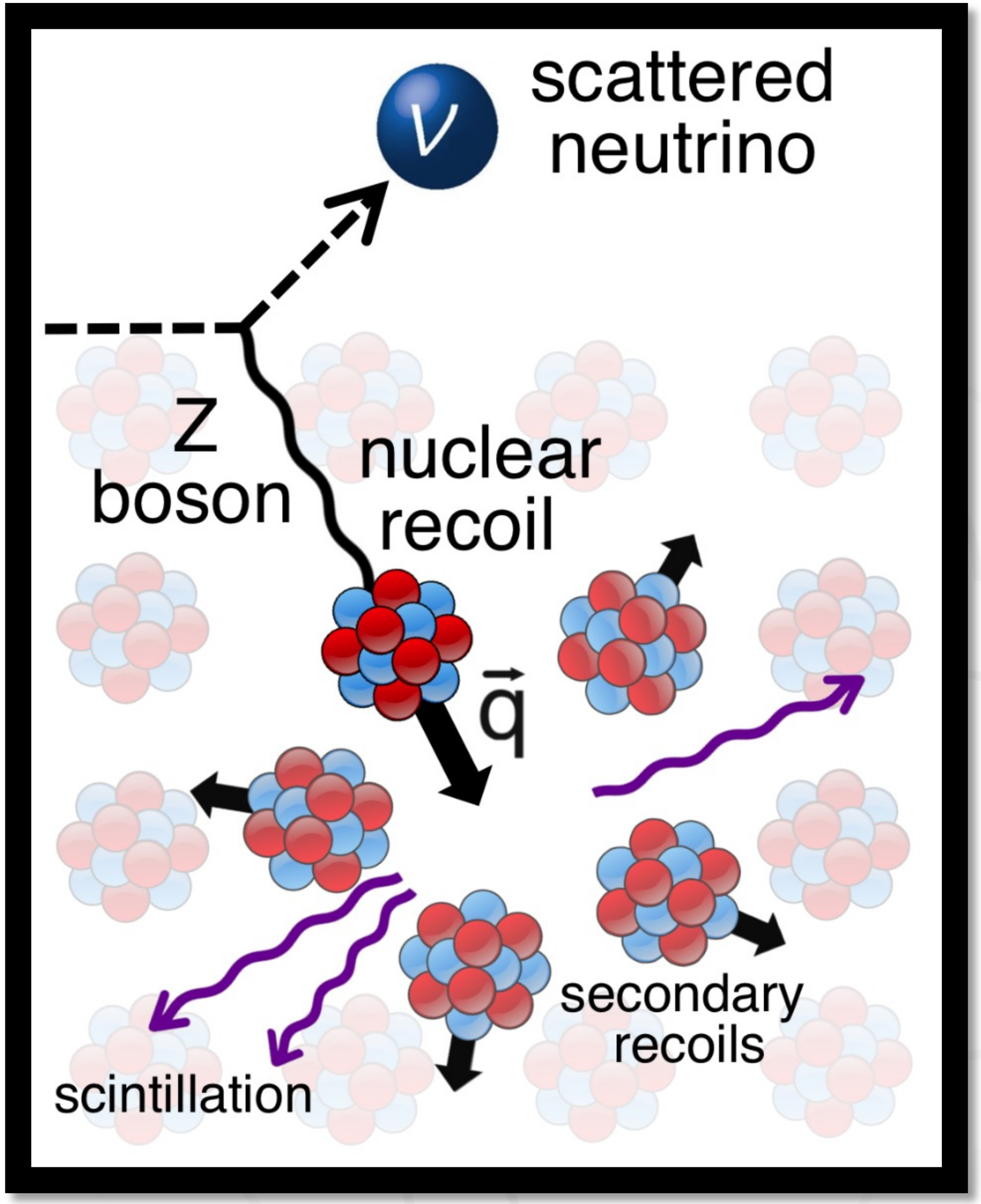
Oak Ridge National Laboratory · Duke University · TUNL Triangle Universities Nuclear Laboratory · KAIST · Laurentian University Université Laurentienne · Los Alamos National Laboratory EST. 1943 · NC State University · University of Washington · University of South Dakota · The University of Tennessee Knoxville · Sandia National Laboratories · The University of Chicago · MEPhI · Carnegie Mellon University · University of Florida · NC Central University · Tufts University


IRAN L. THOMAS AUDITORIUM

CEvNS Motivations

CEvNS

- Weak neutral process
- Neutrino interacts with the nucleus as a whole via Z-boson exchange
- Wavefunctions of the recoiling nucleons are in phase with each other
- Hard to detect! (Like hitting a ~~bowling ball~~ **Great Pyramid of Giza** with a ping pong ball)



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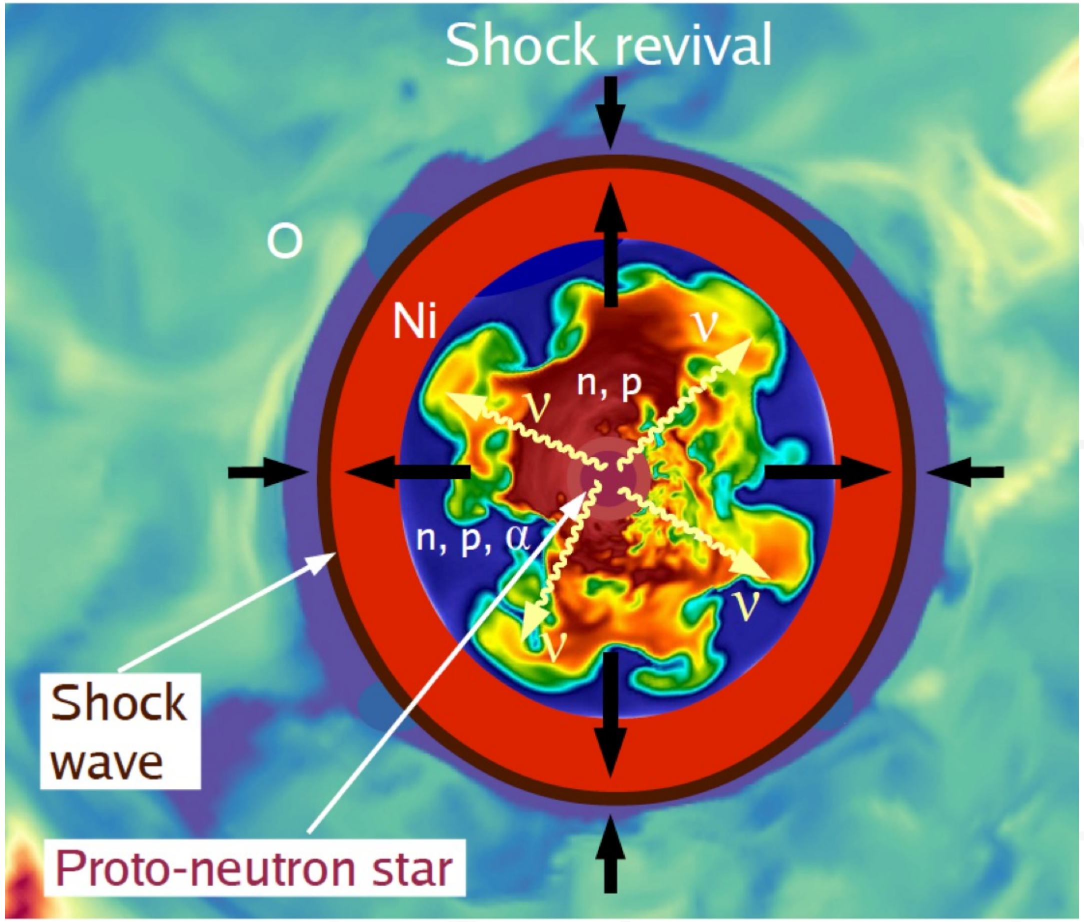
Motivations: Core-Collapse Supernovae

- Neutrinos carry 99% of the energy out of a core-collapse supernova
- CEvNS provides the pressure needed to accelerate the outer iron layer to escape velocity
- J.R. Wilson, PRL 32 (74) 849



Irene Tabor, NuEclipse 2017

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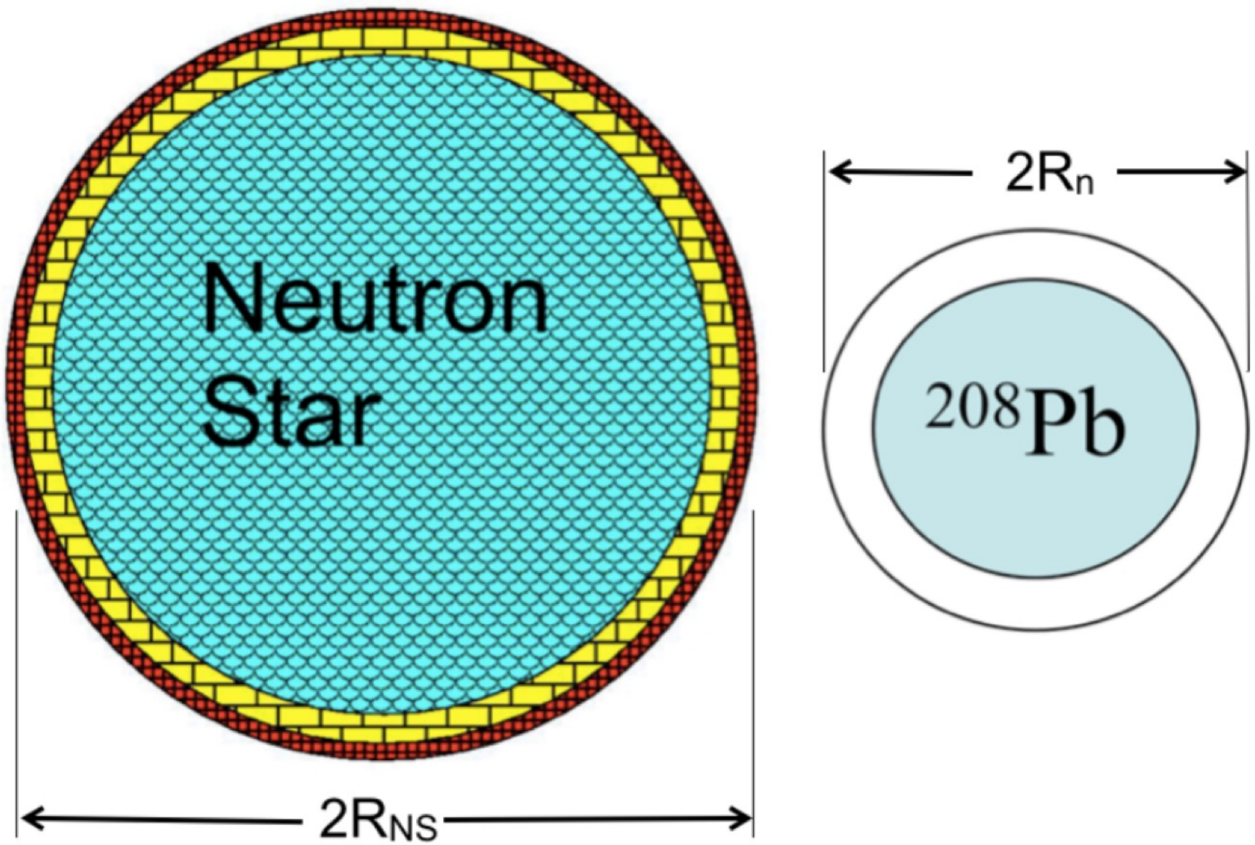
Motivations: Neutron Skin Depth

- Neutrons in nuclei are pushed out past the radius of protons
- Loss of coherence places constraint on neutron distribution
- Implications for neutron star structure and equation of state



Chuck Horowitz, NuEclipse 2017

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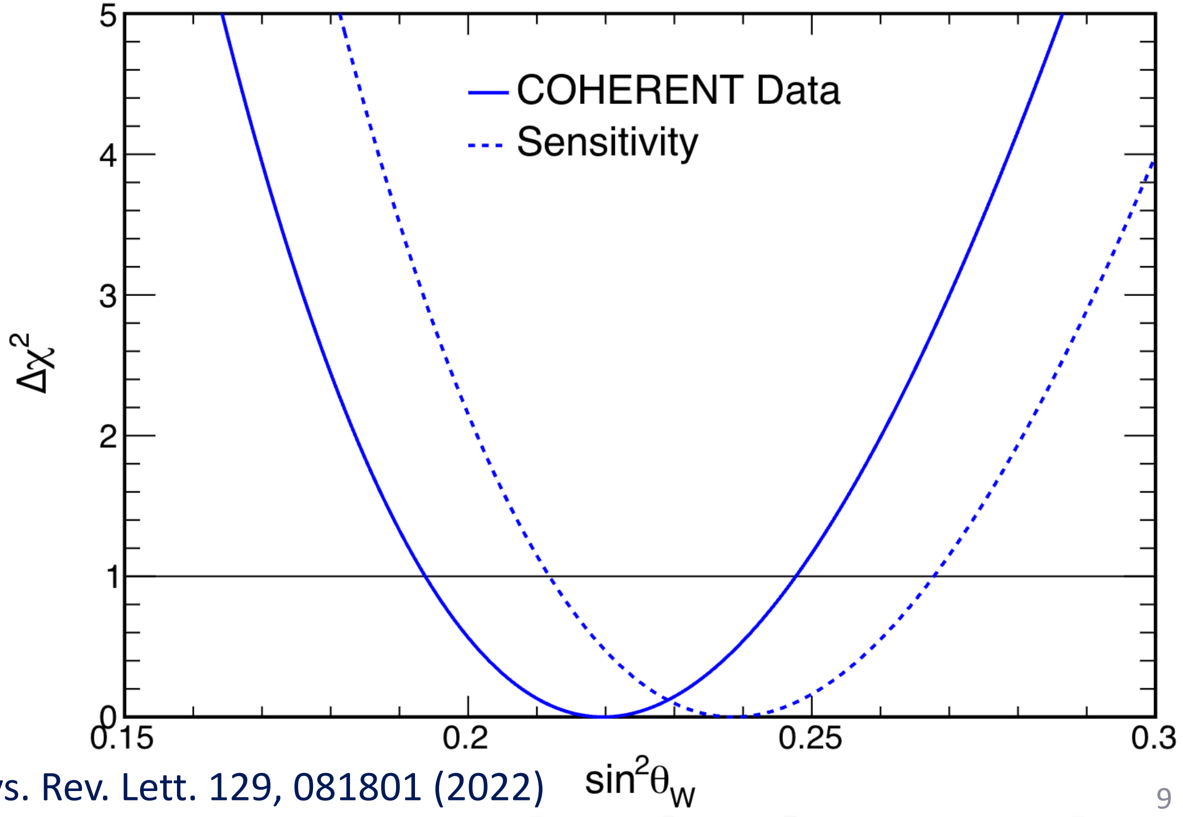
Motivations: Weak Mixing Angle

- Few measurements at low Q^2
- Testing the standard model in a new kinematic region (around 50 MeV)

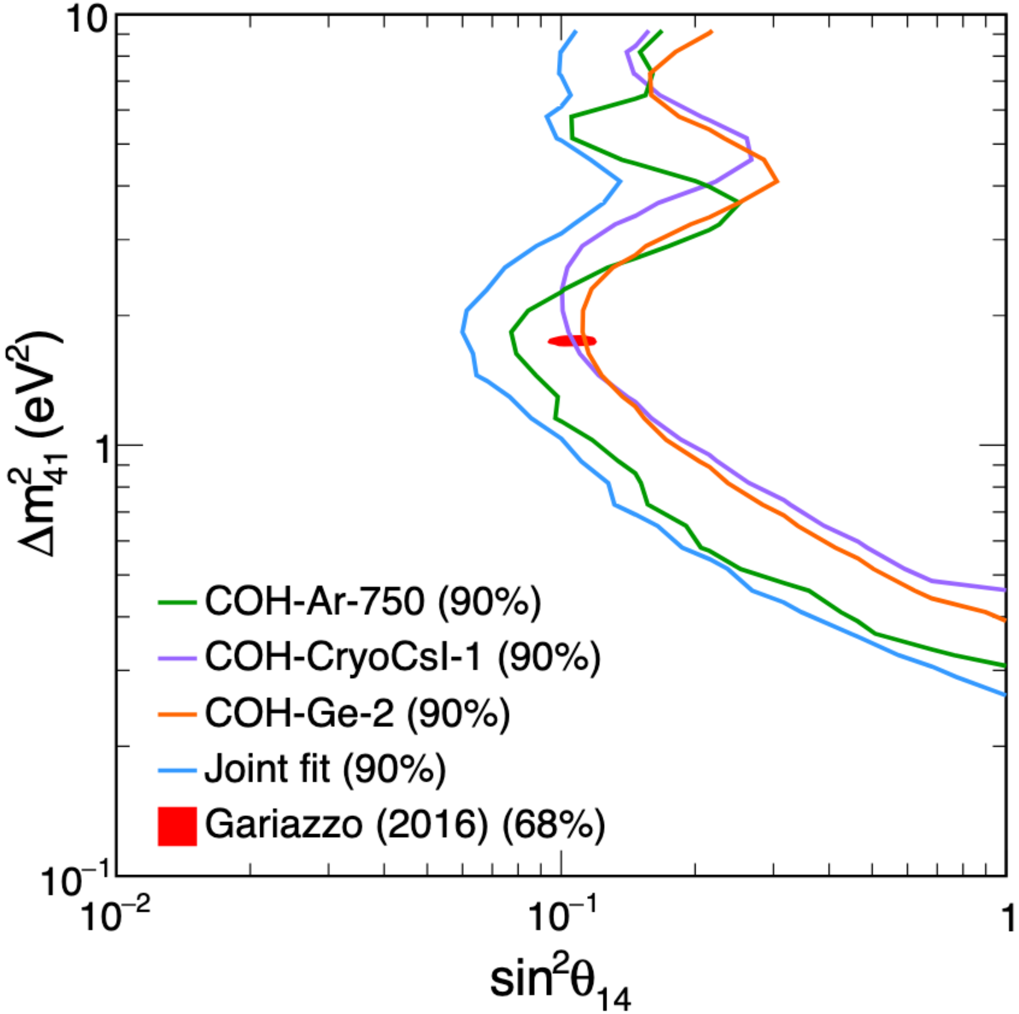
$$\sigma_{coh} \sim \frac{G_f^2 E^2}{4\pi}(Z(4\ sin^2\theta_w - 1) + N)^2$$



COHERENT. Phys. Rev. Lett. 129, 081801 (2022)

Motivations: Sterile Neutrinos

- Recoils ~ 10 – 53 MeV
- Detectors 19.3 – 28m from target
- Δm_{41}^2 = 0.4 – 3.4 eV^2, near the global best fit of 1.7 eV^2
- Can measure neutral-current disappearance with only COHERENT data with inclusion of INCOHERENT ν_e measurements



COHERENT. The COHERENT Experimental Program, Snowmass contribution arxiv:2204.04575 (2022)

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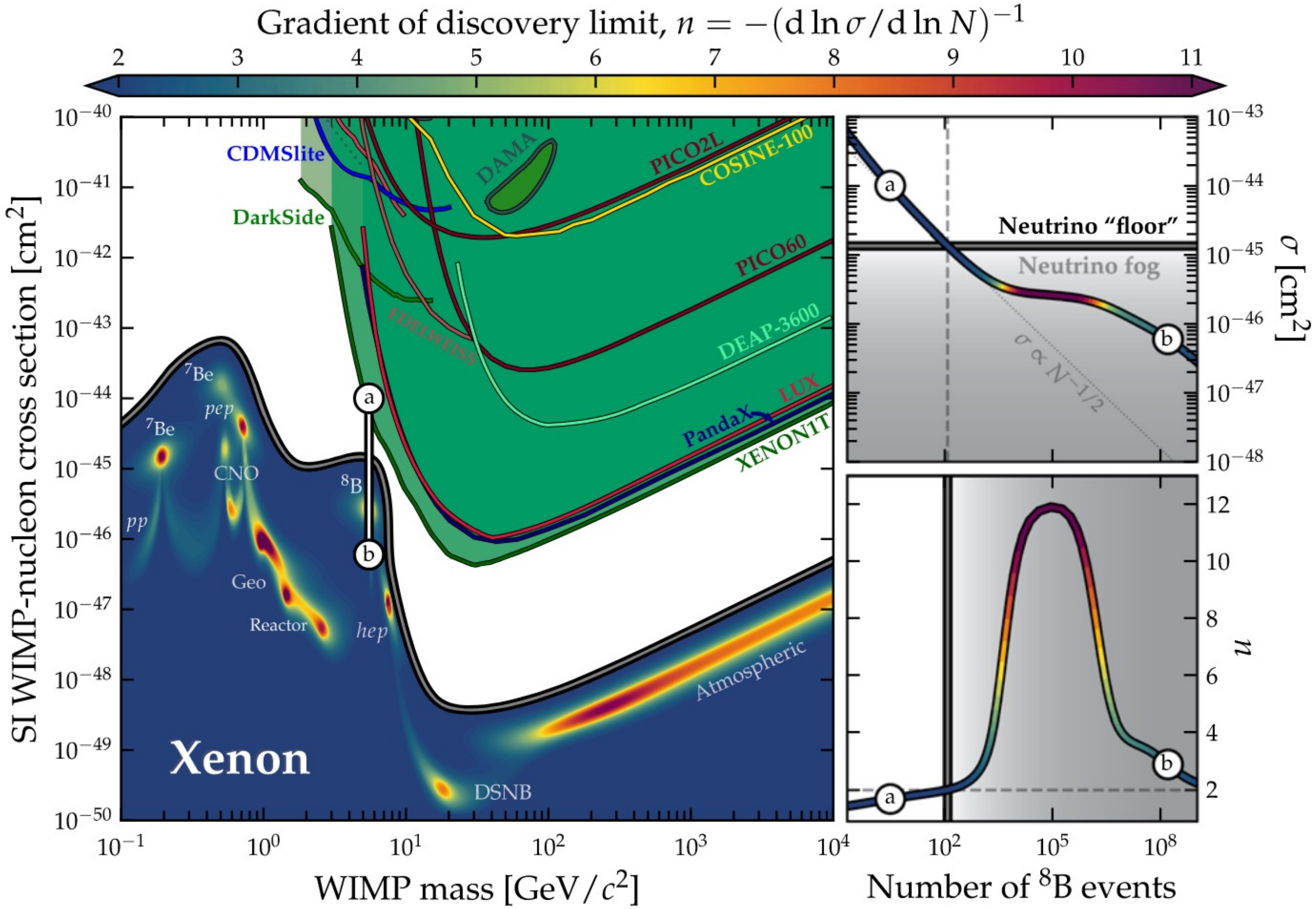
Motivations: Neutrino Fog

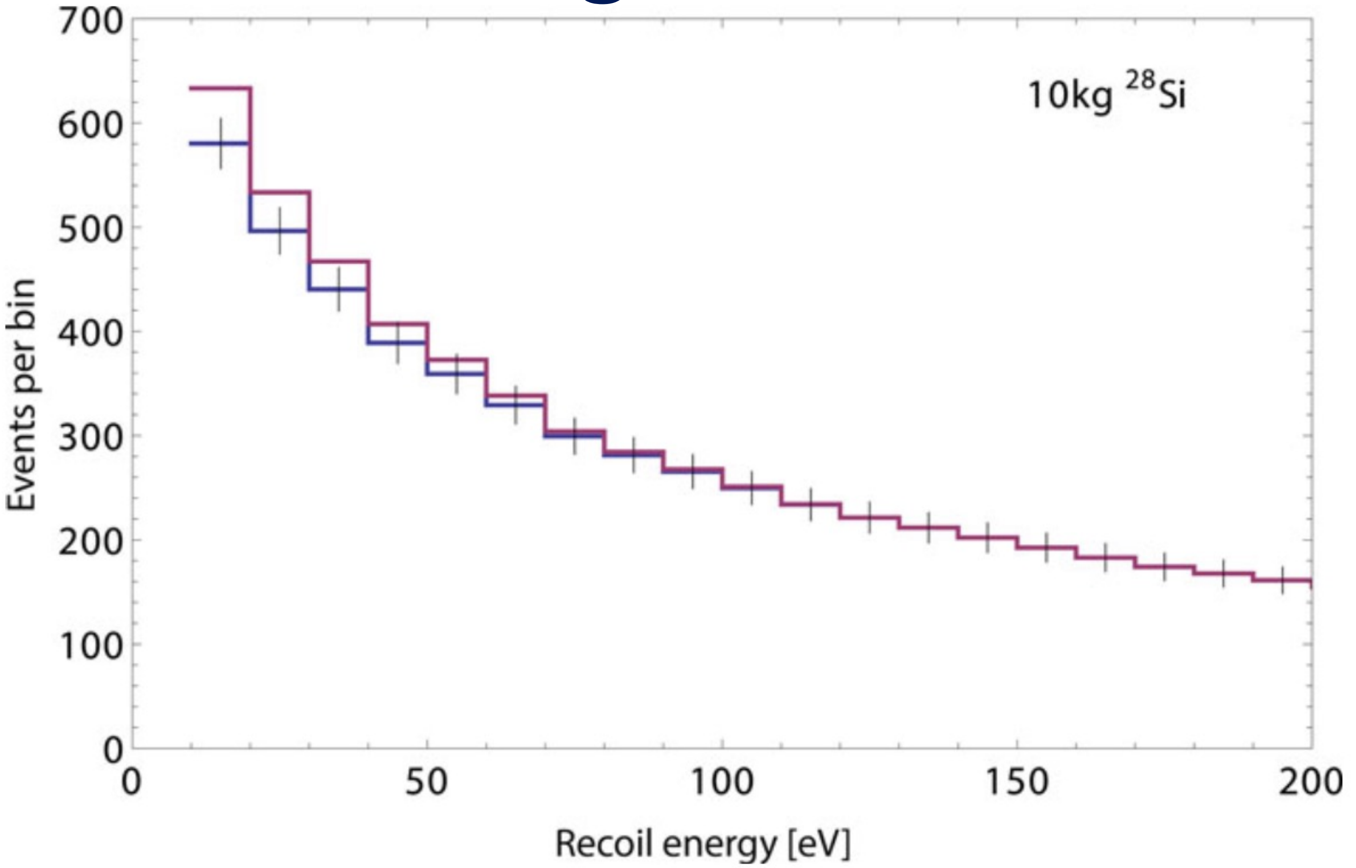
- Understanding the CEvNS cross-section is critical to breaking through the neutrino fog.



C. A. J. O'Hare Phys. Rev. Lett. 127, 251802 (2021)

Motivations: Reactor Monitoring

- Plutonium breeding at a reactor emits a telltale neutrino spectrum
- Antineutrinos have a maximum energy of 1.26 MeV (below IBD threshold)
- Important to understand CEvNS and low-energy recoils



Nuclear recoil counts for core only (blue line) and core+blanket (red line) for a 10 kg silicon-28 CEvNS detector at 25 m standoff for 90 days. Black lines indicate statistical errors.

B.K. Cogswell and P. Huber, Sci. Glob. Secur. **24**, 114 (2016).

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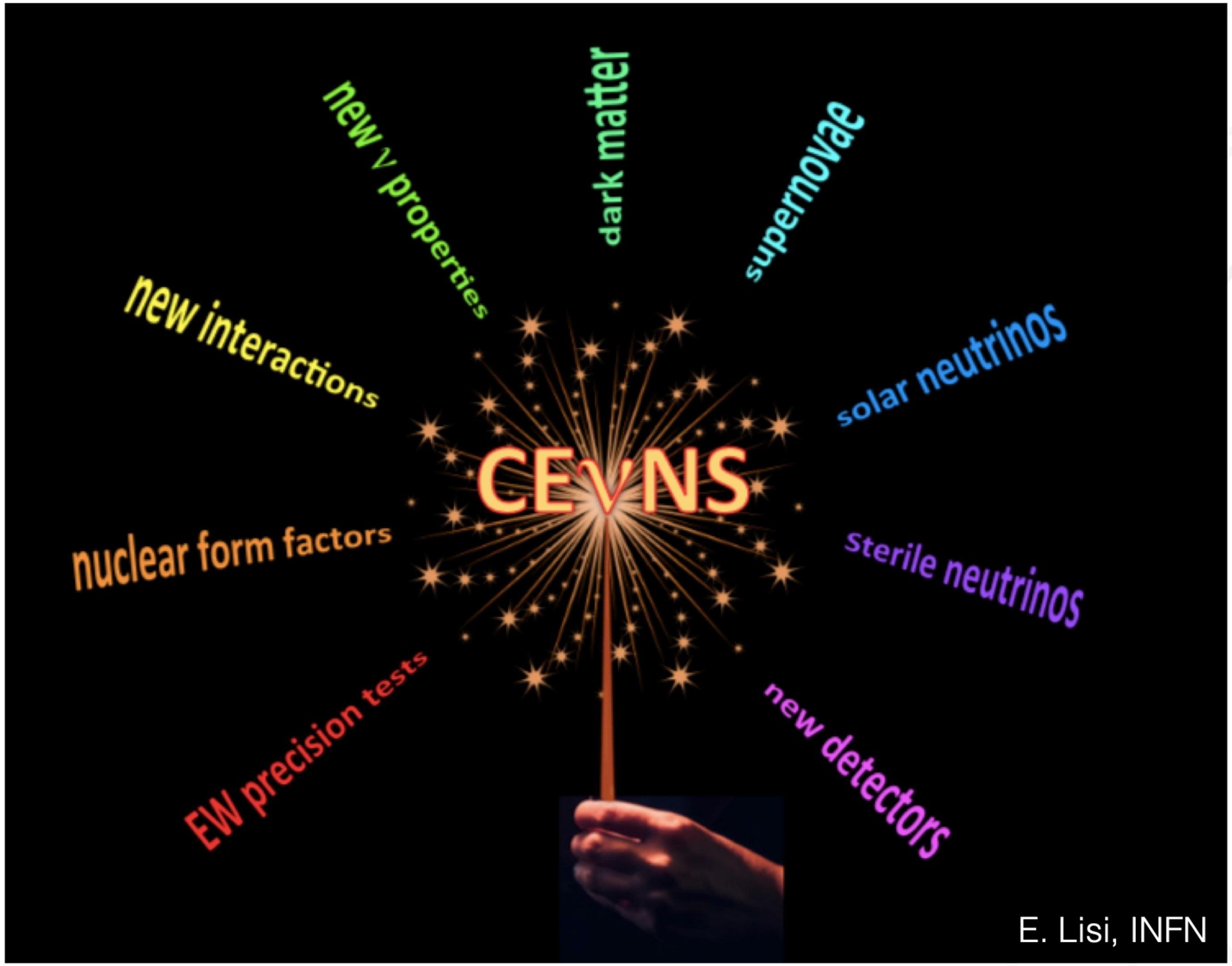
The Global CEvNS Research Program



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The Spallation Neutron Source & Neutrino Alley

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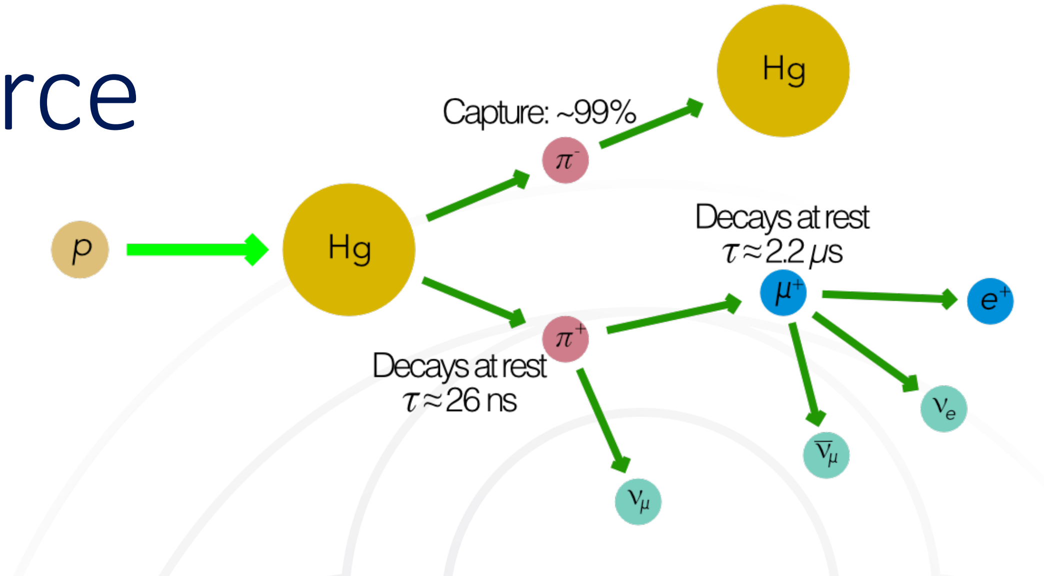
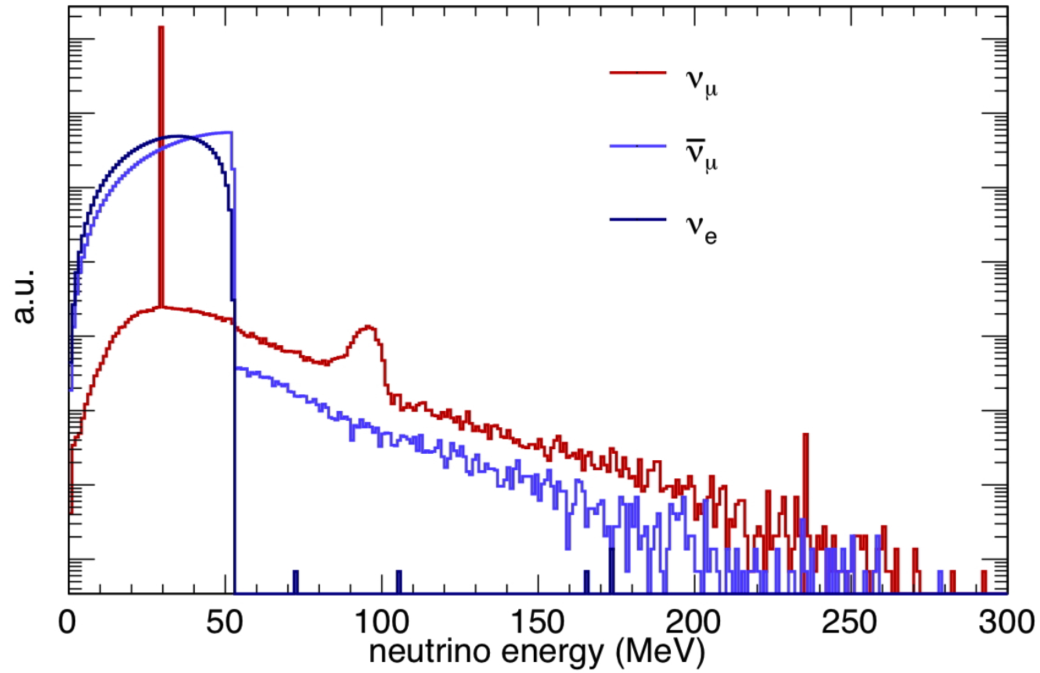
The Spallation Neutron Source

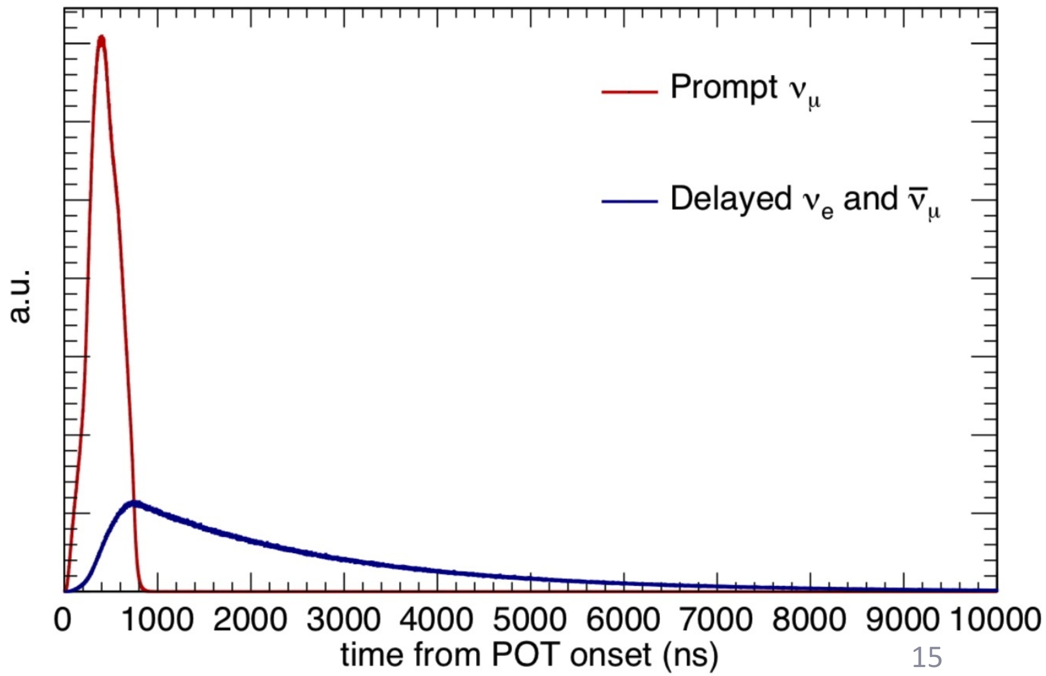


Pion Decay-at-Rest Neutrino Source

ν flux: $4.3\text{x}10^7$ **ν** $cm^{-2}\ s^{-1}$ at 20 m

Pulsed: 800 ns full-width at 60 Hz





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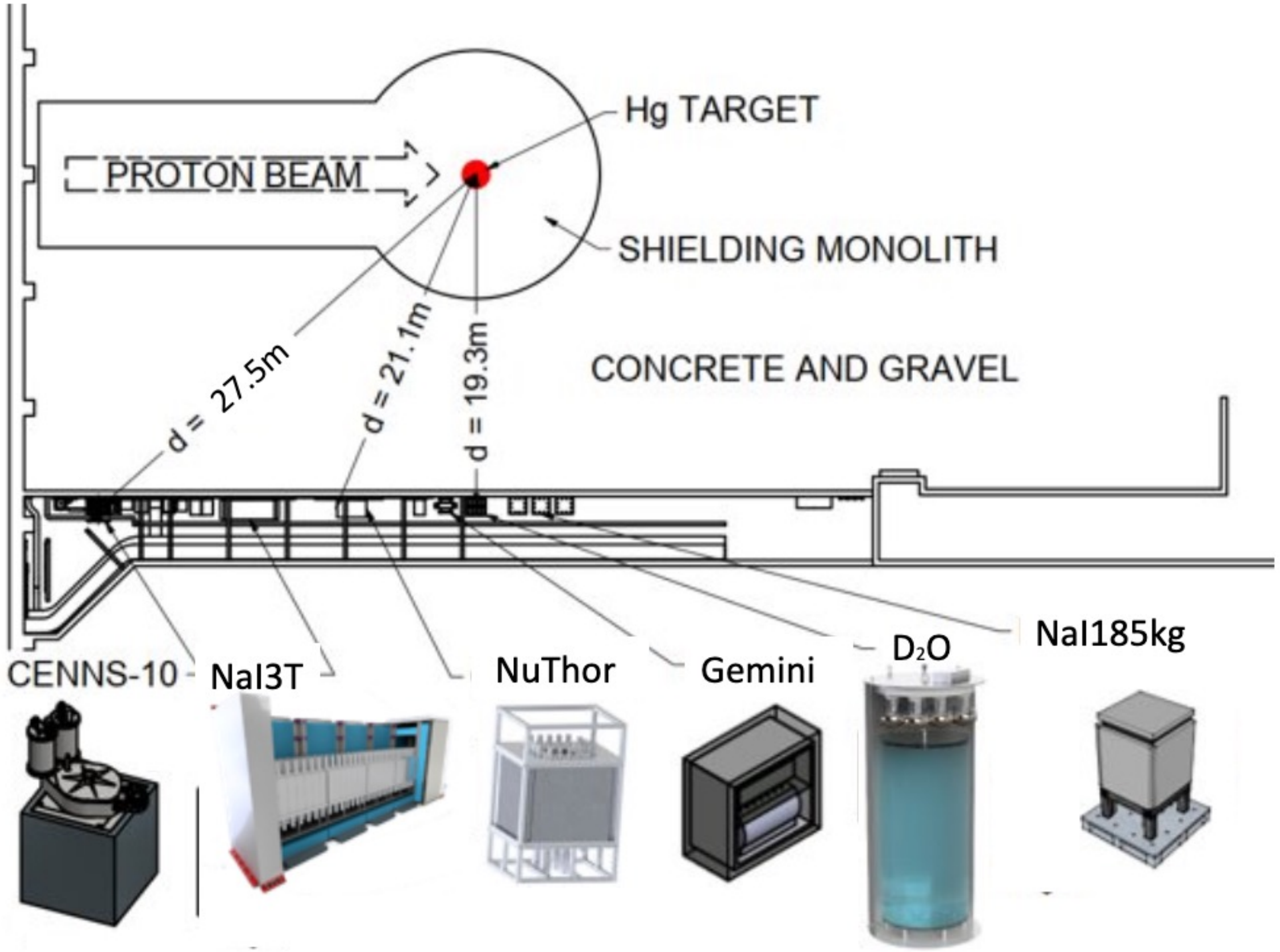
Neutrino Alley

- Basement corridor beneath the SNS target
- Large reduction in neutron flux while still high in neutrino flux
- Suite of 10 Detectors:
  - 4 CEvNS Detectors
  - 4 Inelastic ν-Nucleus Detector
  - 2 Neutron Background Detectors



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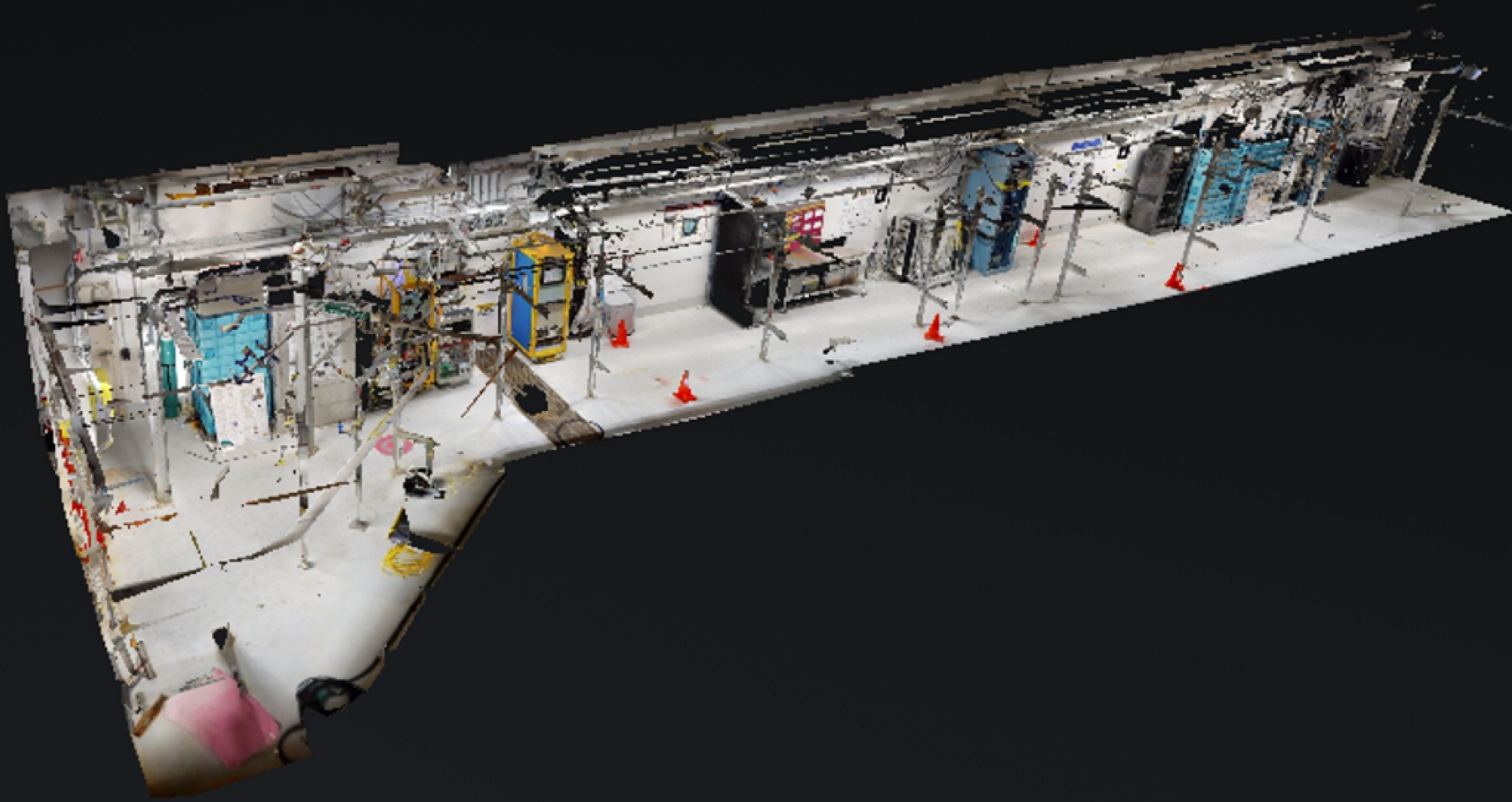

Other Potential Locations

- COHERENT is exploring taking more space around the SNS
- For example, Nube (neutrino cube) deployed to the water room
- Plenty of space for new experiments!

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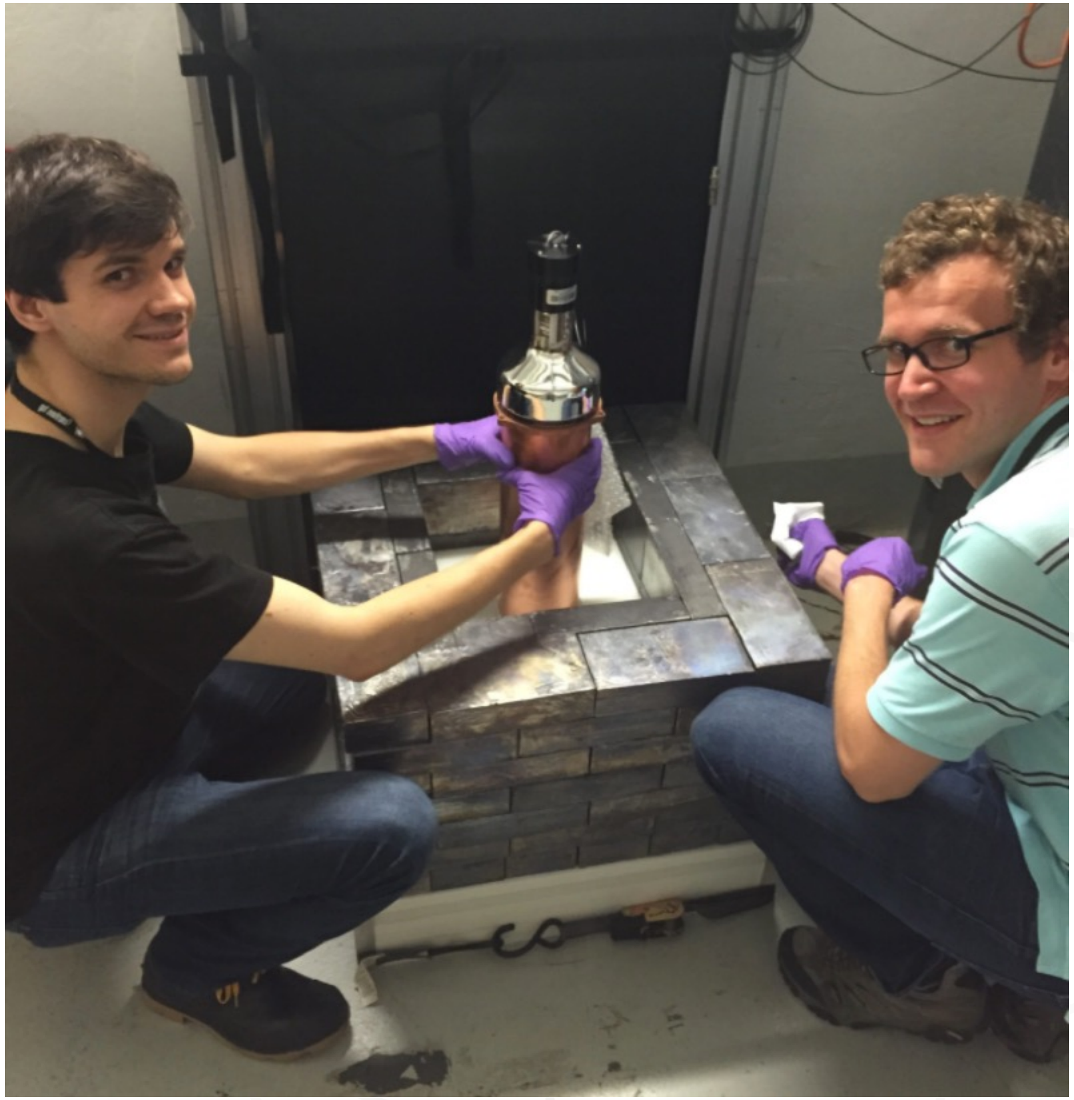
First CsI Deployment

- 14.6 kg low-background CsI[Na] detector deployed neutrino alley in the summer of 2015



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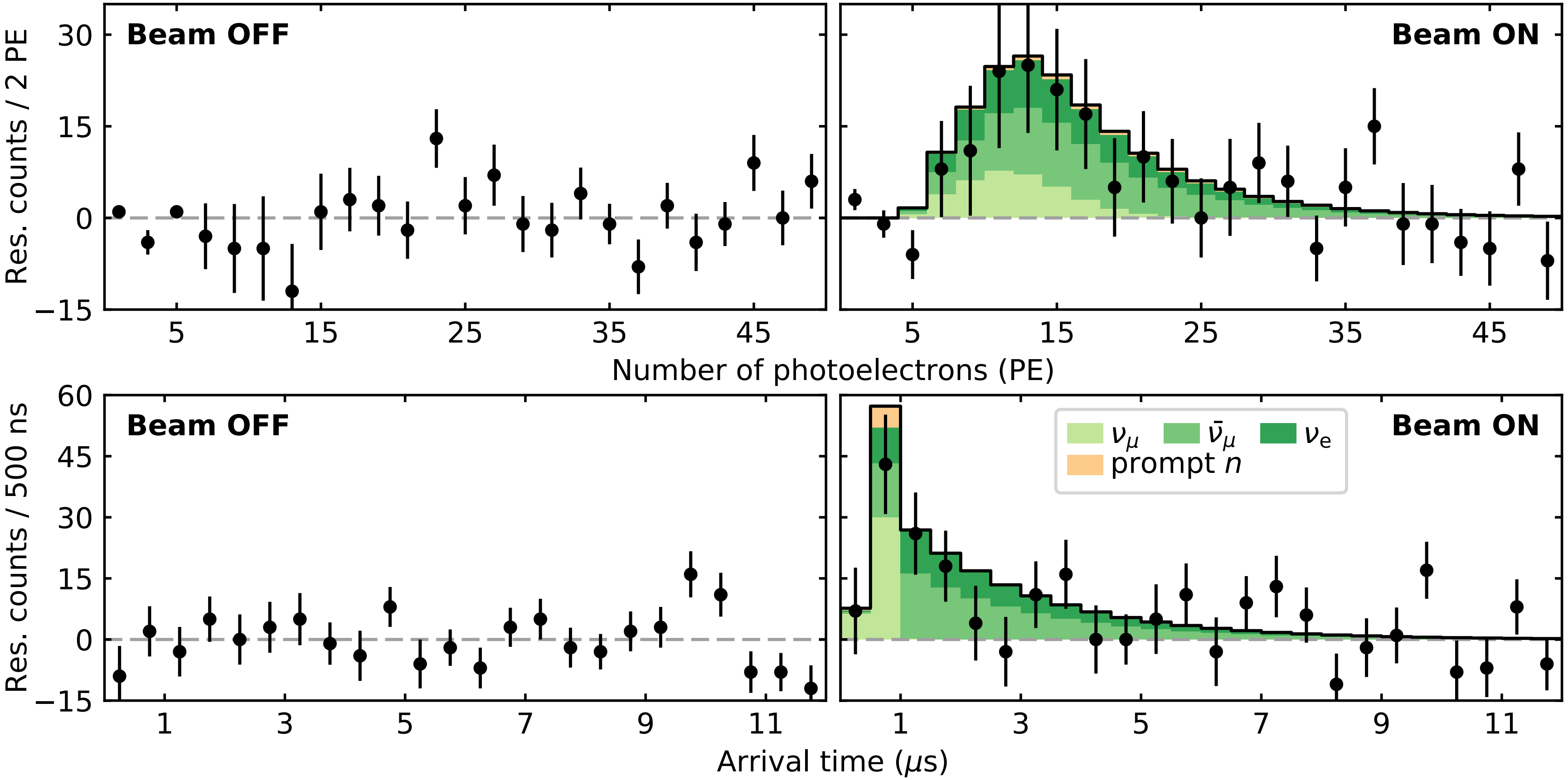
The First Result

Observation of coherent elastic neutrino-nucleus scattering

6.7σ



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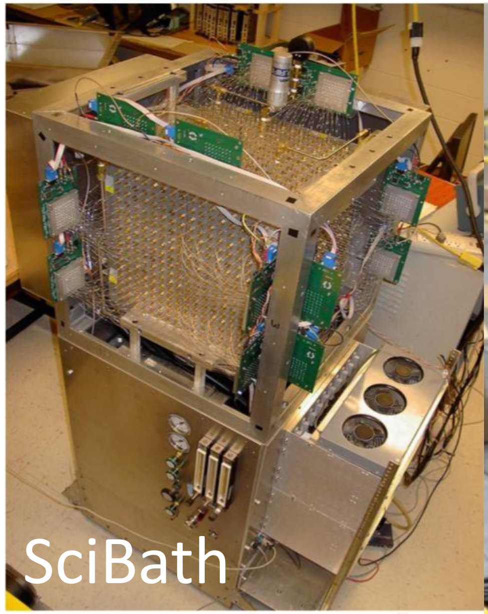
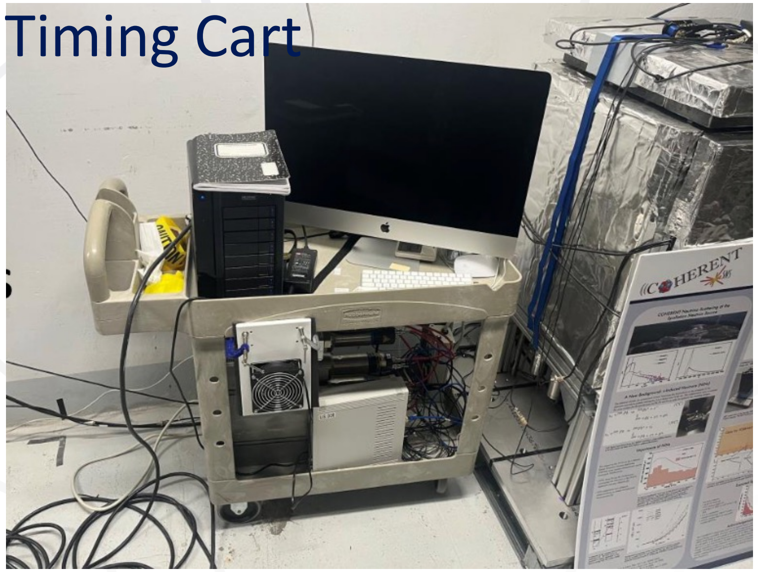
COHERENT. Science 357, 1123 (2017).

How can we improve?

Background Detectors

- Beam-Related Neutrons (BRNs): The neutrons produced by the accelerator
- Neutrino-Induced Neutrons (NINs): the neutrons produced by CC interactions on shielding (iron and lead)





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Lead Nube

- 900kg cast lead target
- 127 GWhr*liter exposure
- Looking for NINs on Lead

$$\nu_e + {}^{208}\mathrm{Pb} \rightarrow e^- + {}^{208}\mathrm{Bi}^*$$

$$ {}^{208}\mathrm{Bi}^* \rightarrow {}^{208-\mathrm{X}}\mathrm{Bi} + \mathrm{X}n + \mathrm{Y}\gamma$$

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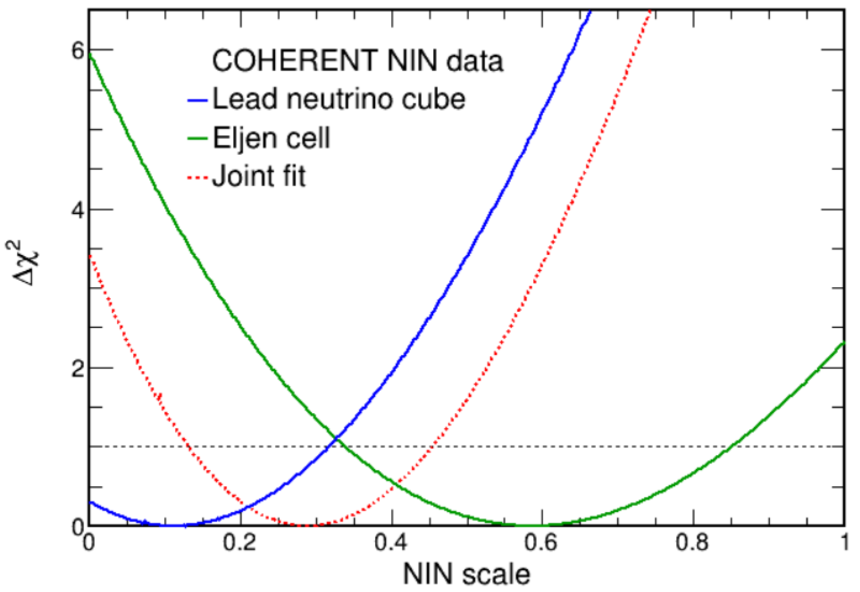
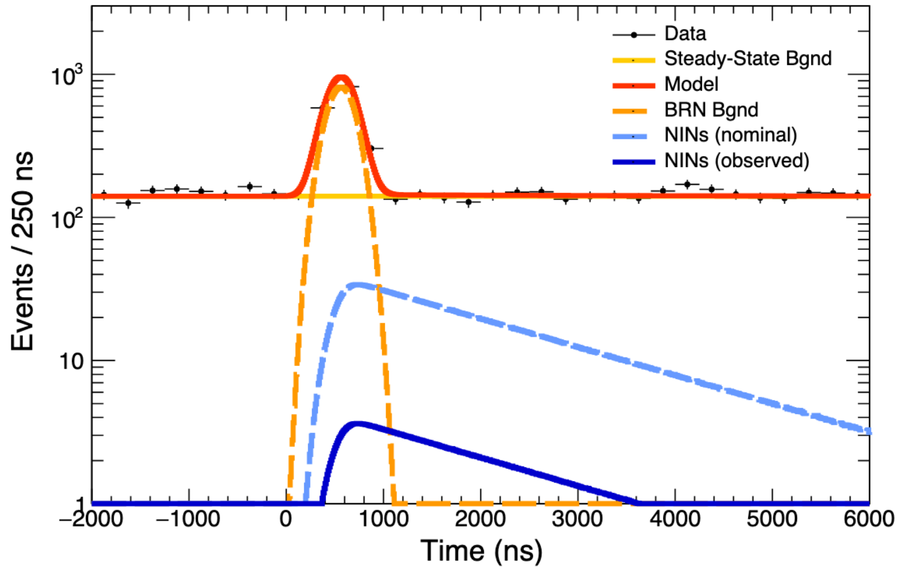
Lead Nube

- 36 (+72, -36) events observed
- >4σ lower than expectations
- Parts of the theoretical cross-section not well understood: could be lower than expected
- Data analyzed from 2016 to 2021





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

Neutrino Flux: D_2O

- Heavy water Cherenkov detector
- Designed to measure neutrino flux in neutrino alley
- Charge-current cross-section on deuterium is well-understood
- Will measure the flux within 5% uncertainty in two years (down from 10%)
- Will reduce a dominant systematic uncertainty in cross-section measurements

COHERENT. JINST 16 P08048 (2021)

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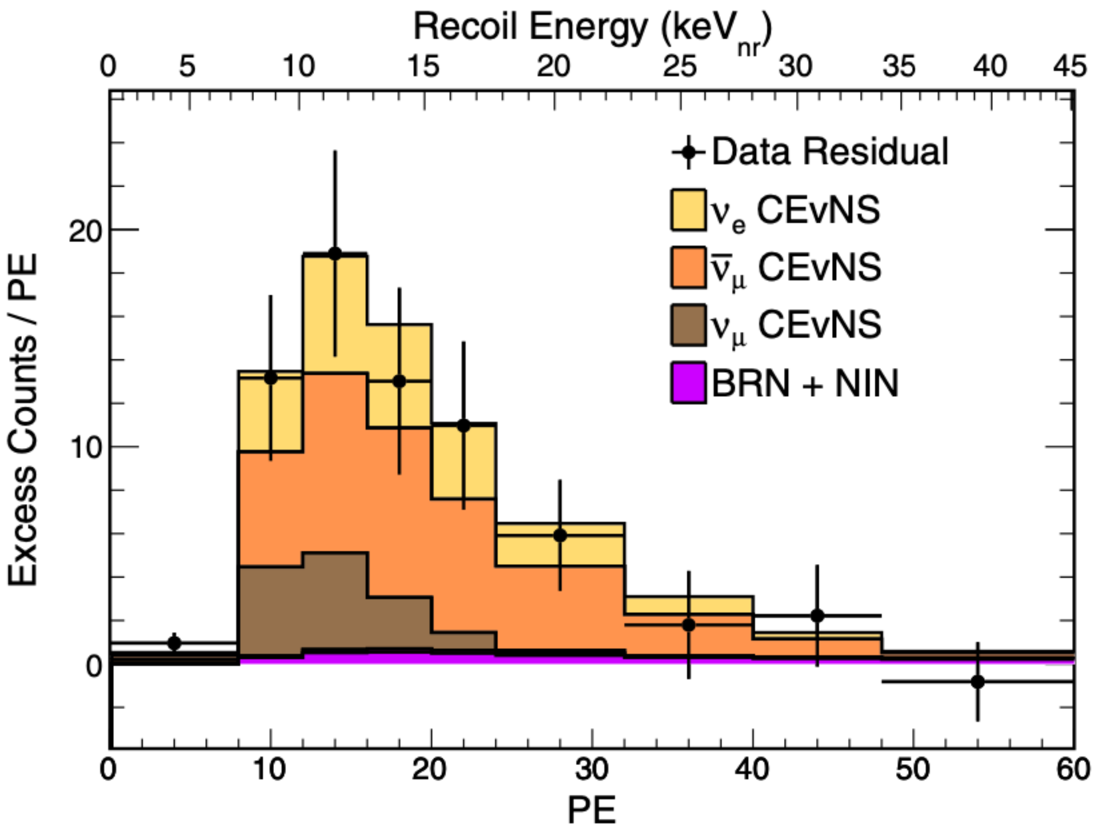
Quenching Factors

- Photons and neutron/inos produce different amounts of visible energy:
  - Photons primarily interact with atomic **electrons**
  - Neutrons/low energy neutrinos on the other hand primarily interact with the atomic **nucleus**.
- This results in different signals for the same energy deposition.

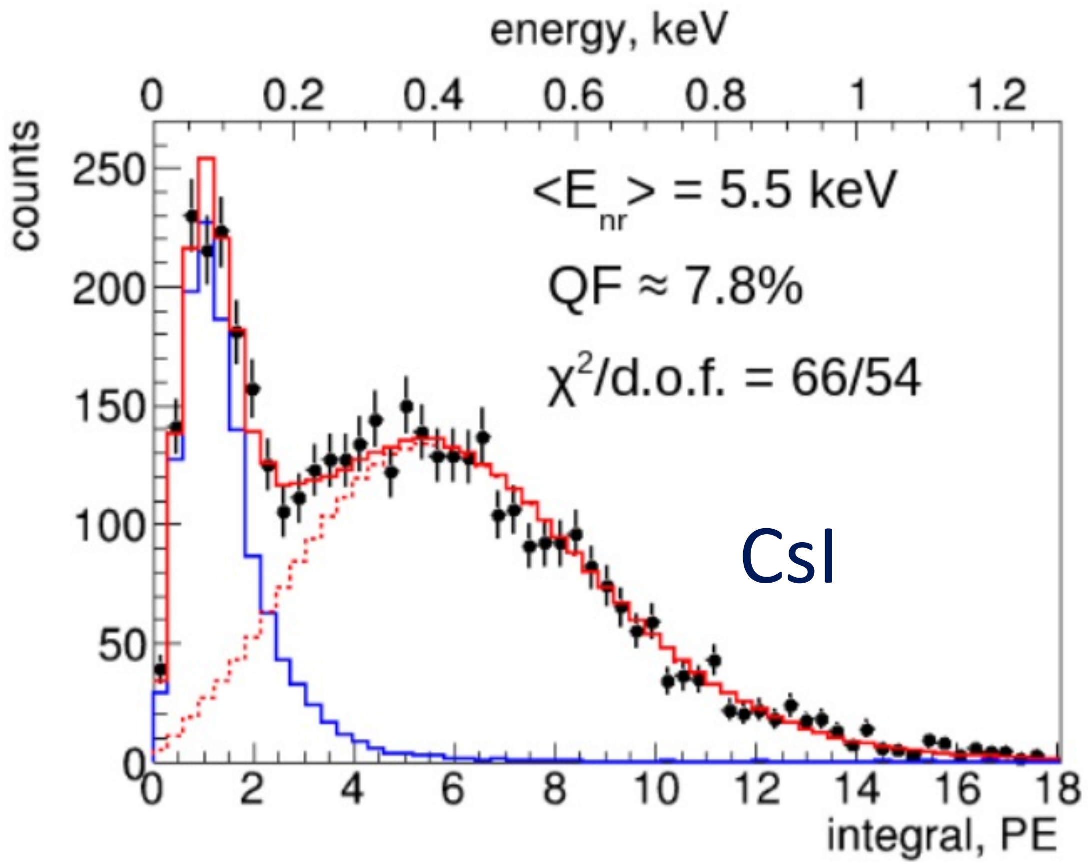
Where does this scale come from?

What is keV_{nr}?

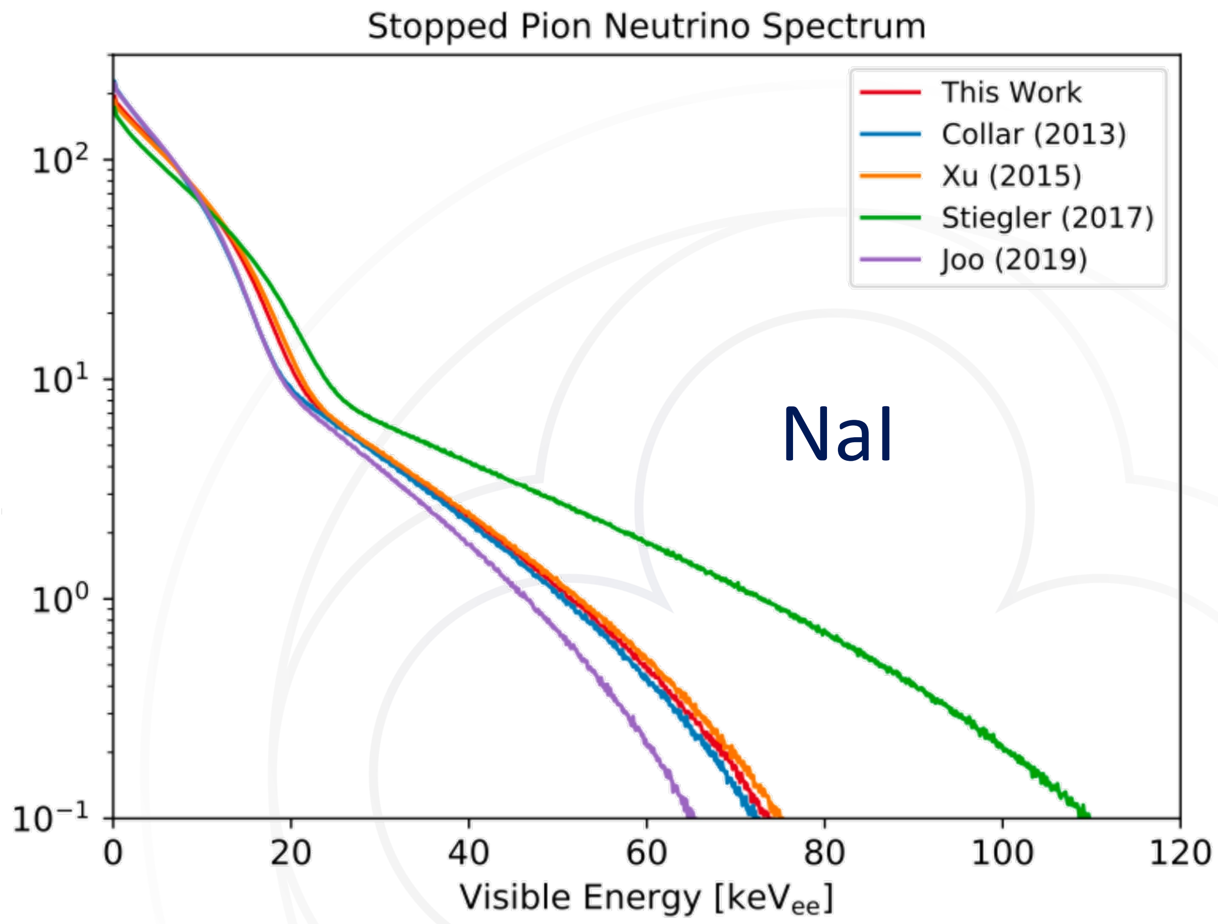


COHERENT. Phys. Rev. Lett. 129, 081801 (2022)

Quenching Factors



COHERENT. JINST 17 P10034 (2022)



S. Hedges, *Low Energy Neutrino-Nucleus Interactions at the Spallation Neutron Source*, PhD Thesis. (Duke University, Durham, 2021).

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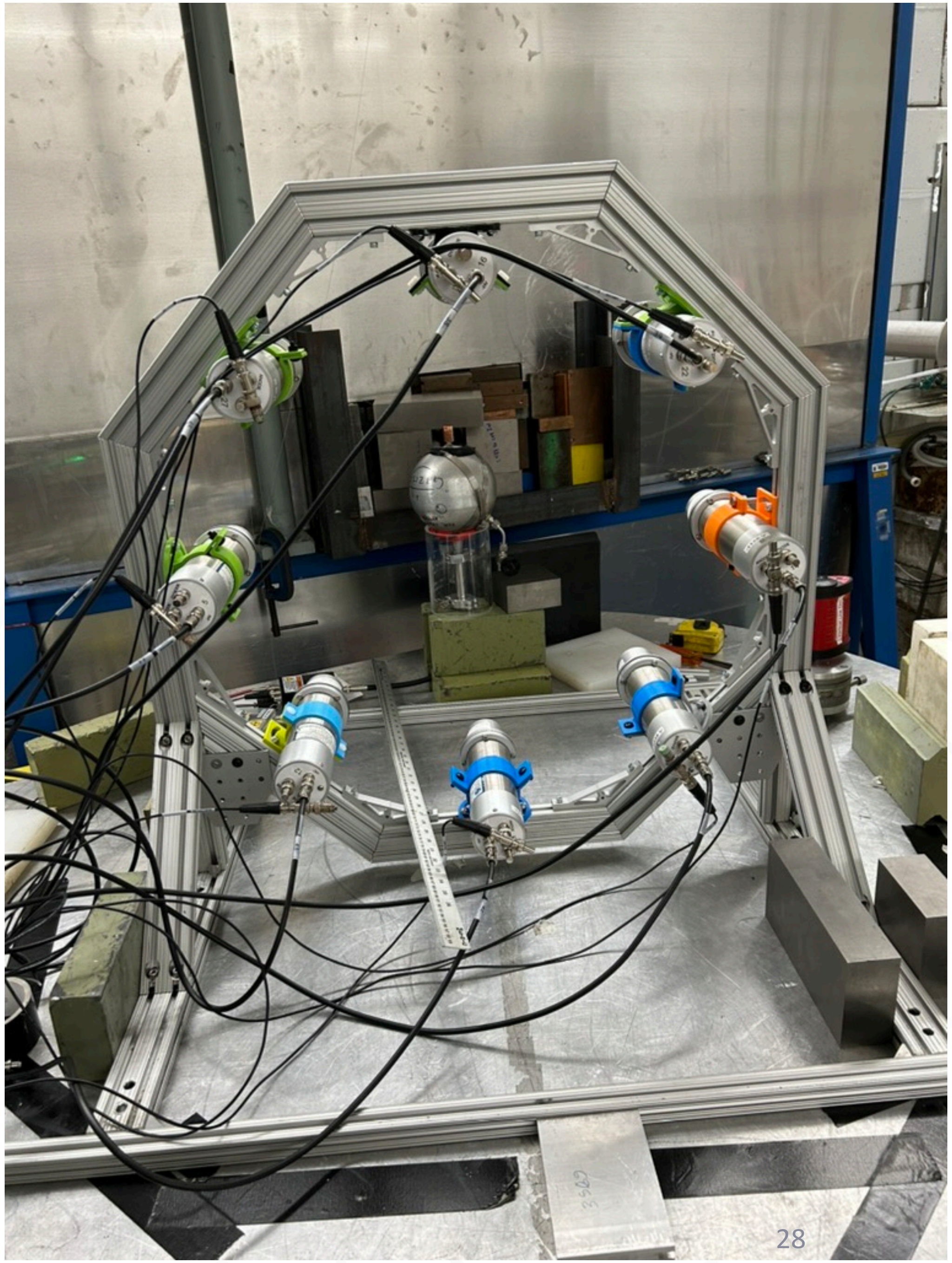
Quenching Factors

Facility at TUNL

- Neutron beam from $^7Li(p,n)^7Be$ or $D(d,n)^3He$ reactions
- 2.5MHz pulsed beam
- Experience measuring many materials: CsI[Na], CsI, NaI[Tl], BGO, Ge, CeBr, Neon…



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Quenching Factors

Facility at TUNL

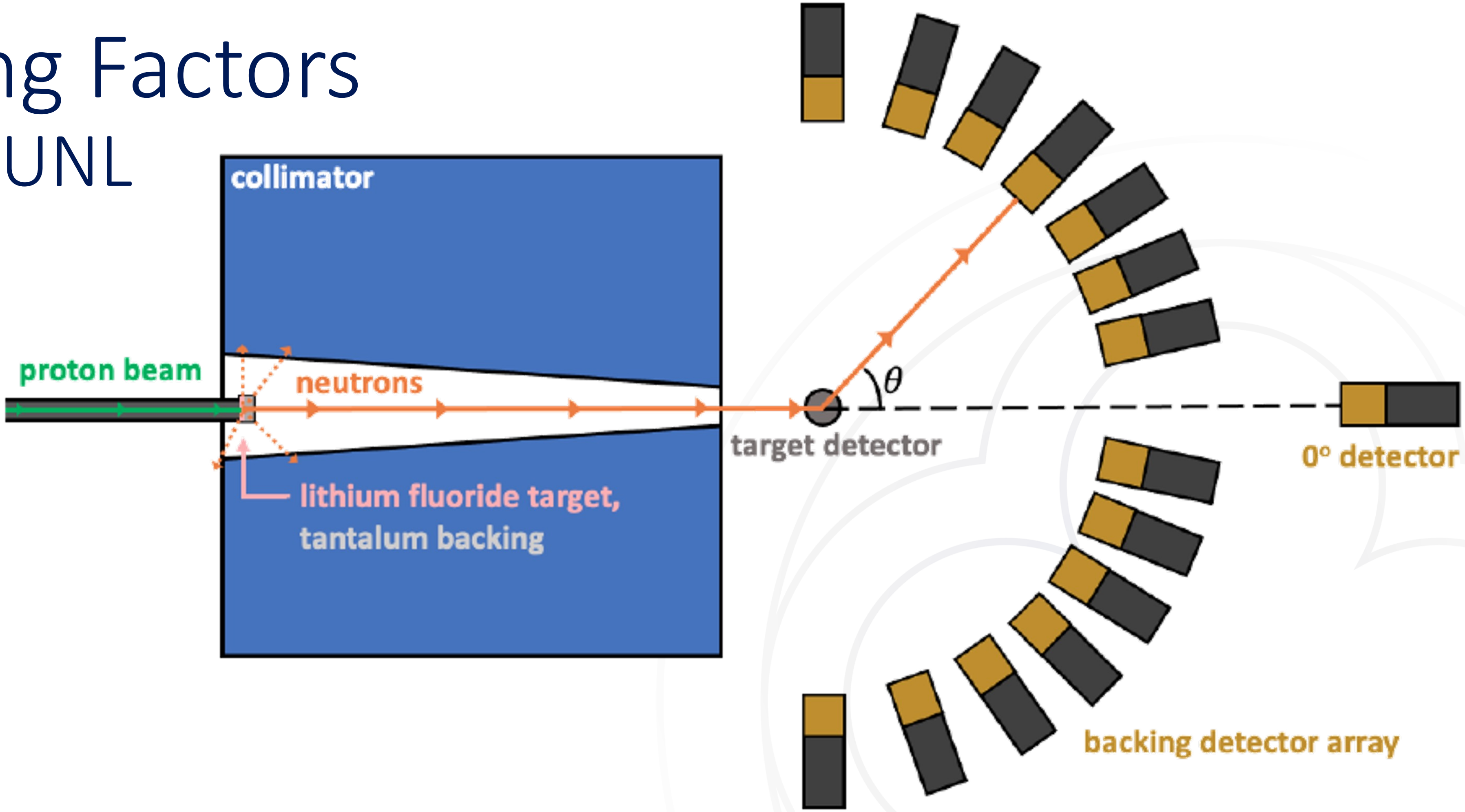

Diagram of a typical nuclear recoil light yield measurement at TUNL.

S. Hedges, *Low Energy Neutrino-Nucleus Interactions at the Spallation Neutron Source*, PhD Thesis. (Duke University, Durham, 2021).

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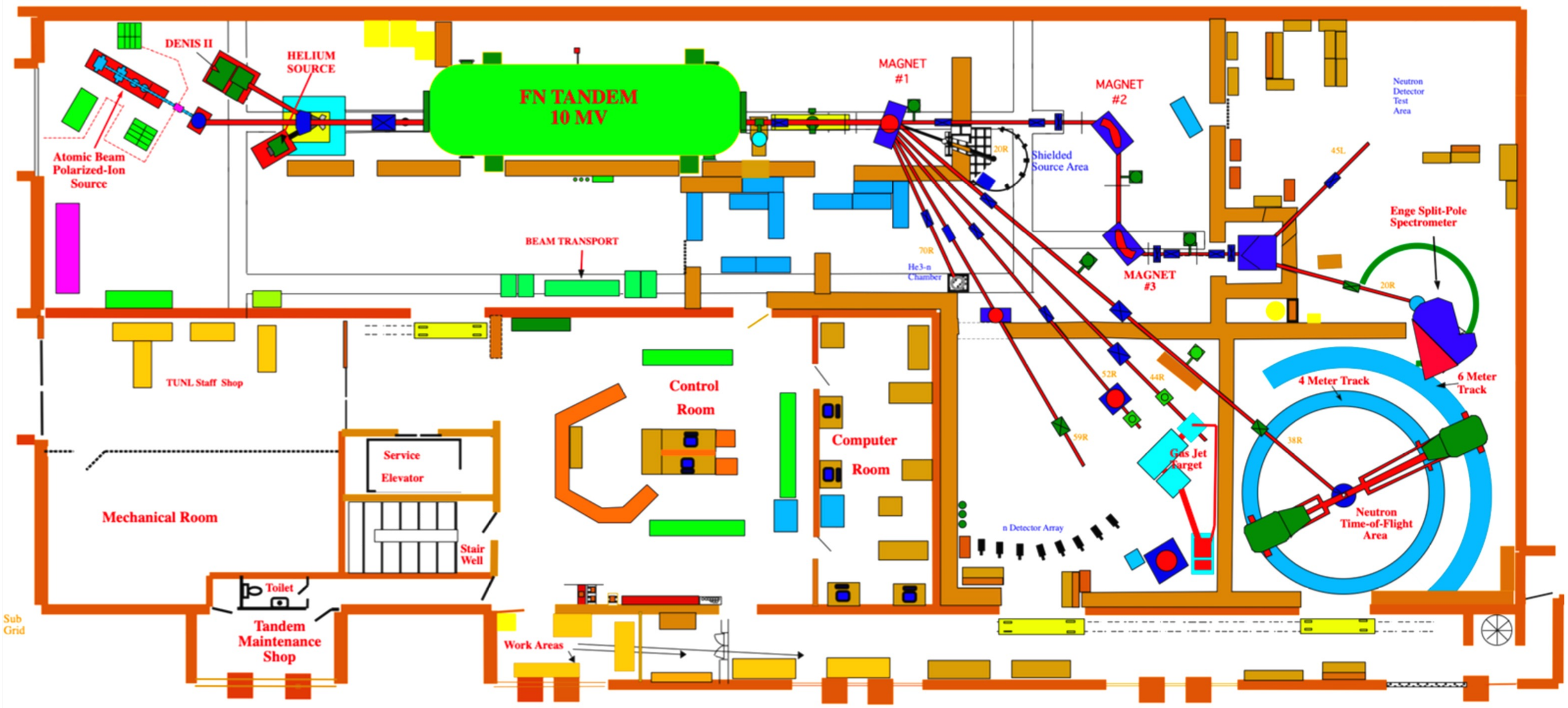
Quenching Factors

Facility at TUNL

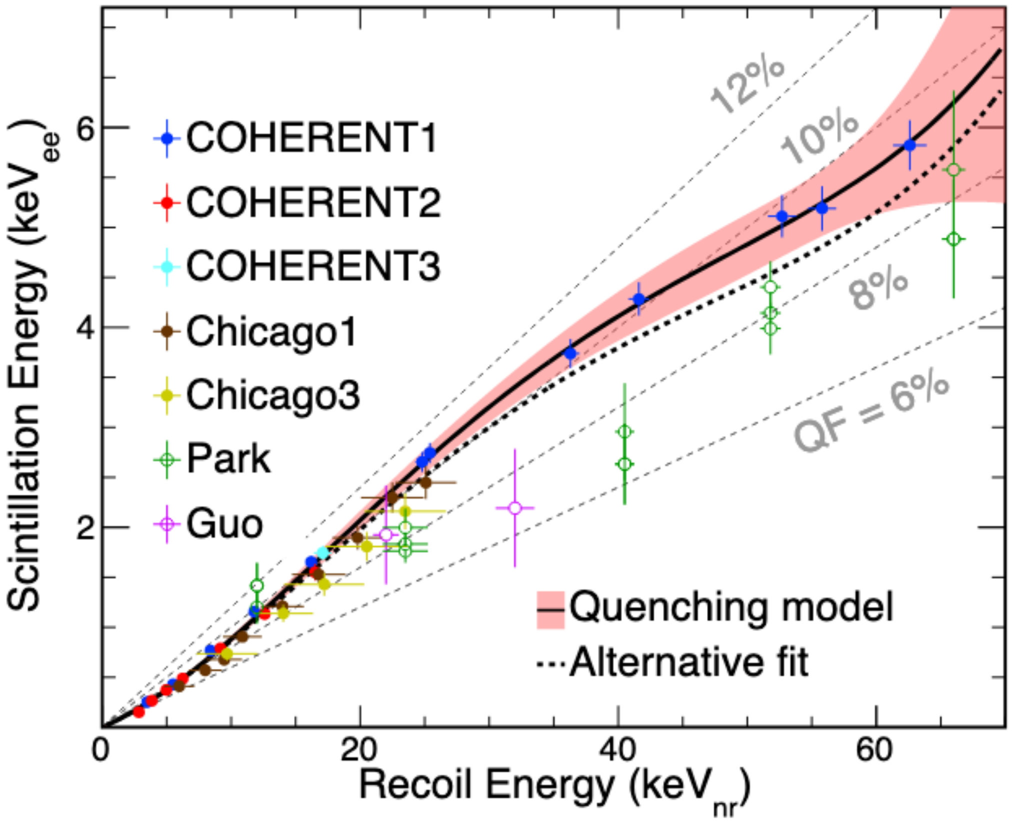


Quenching Factors

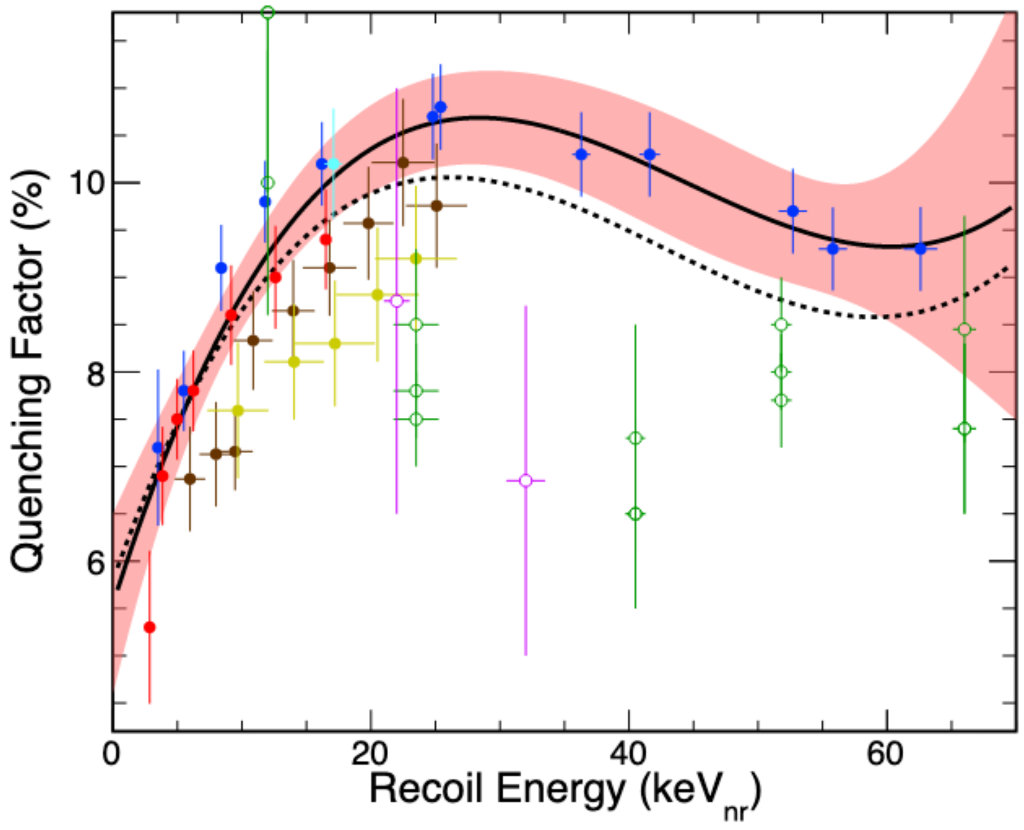
Second CsI[Na] Result

Reduced QF uncertainty to 3.8%!

COHERENT. Phys. Rev. Lett. 129, 081801 (2022)

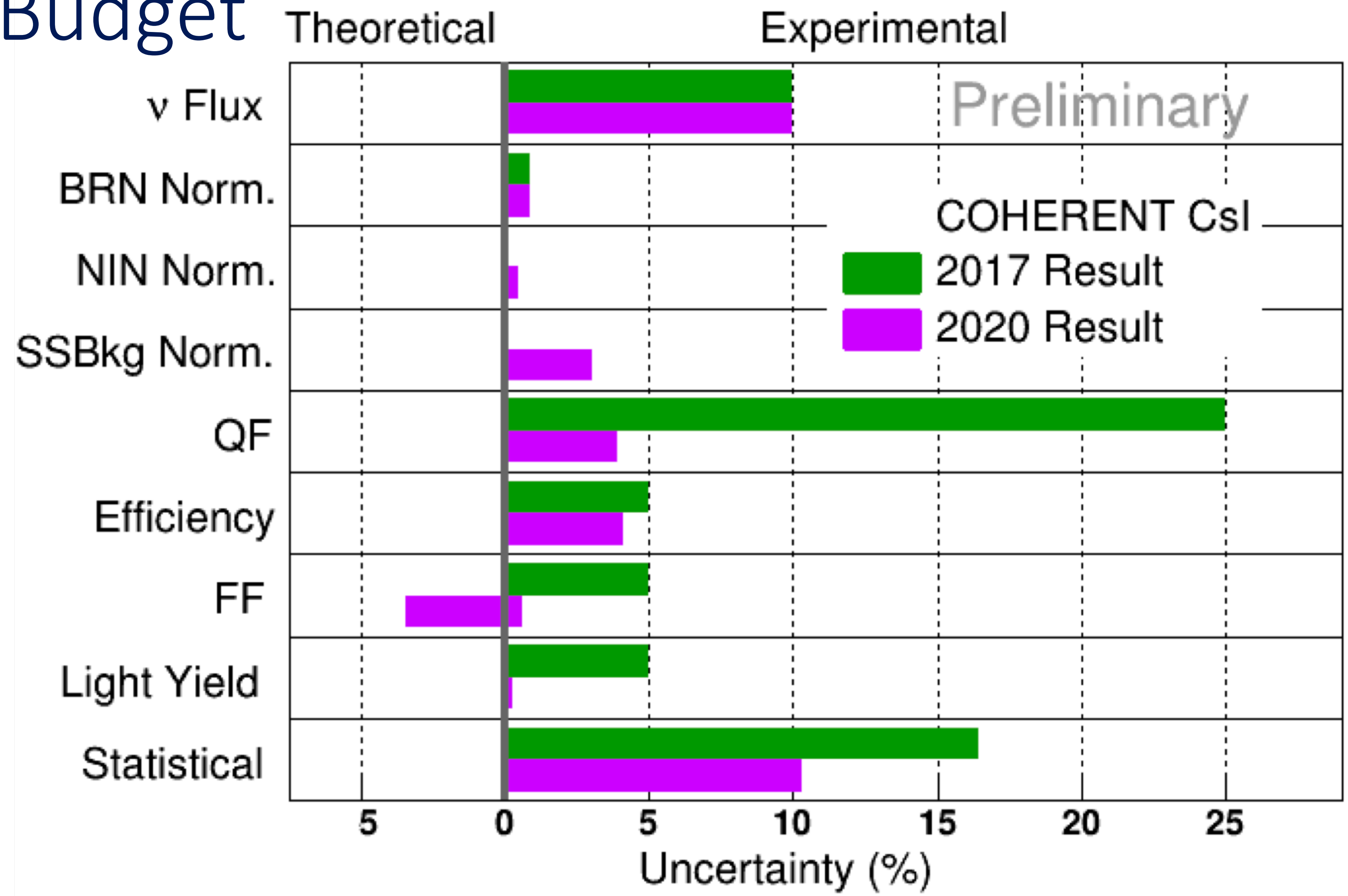


5 measurements included in fit (filled circles)



COHERENT. JINST 17 P10034 (2022)

Error Budget



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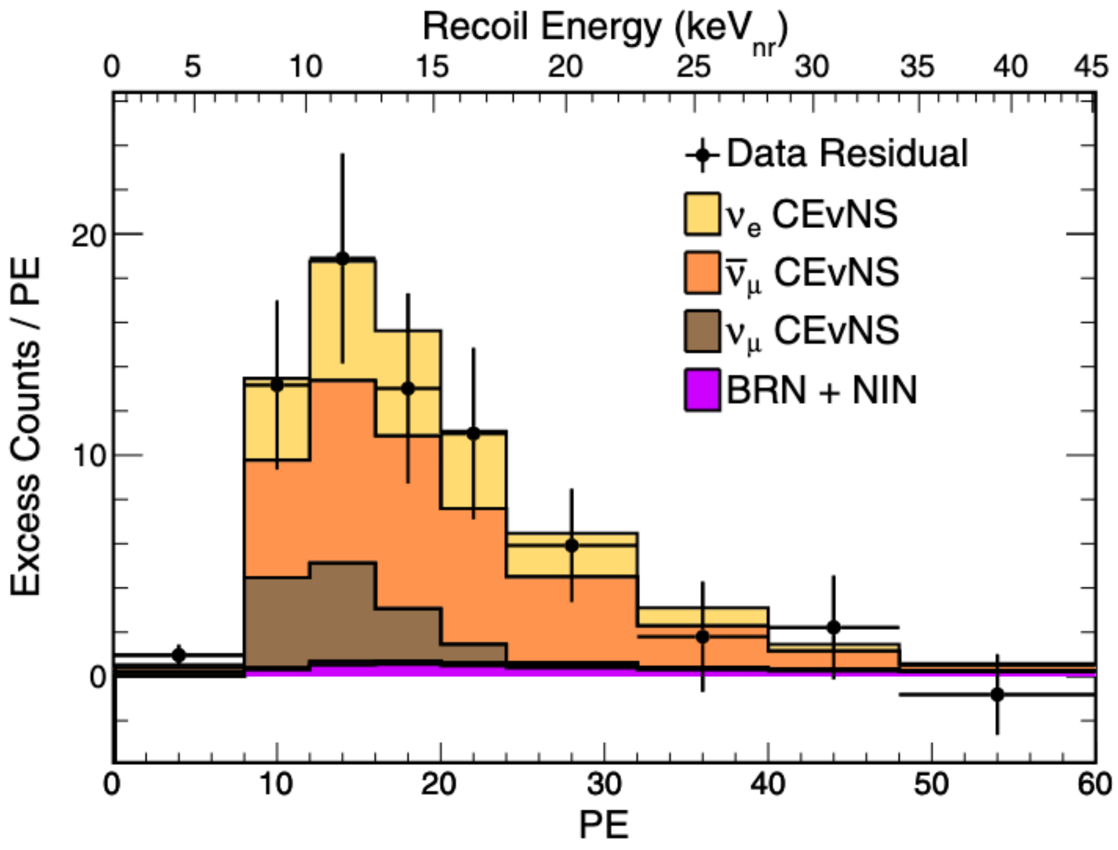
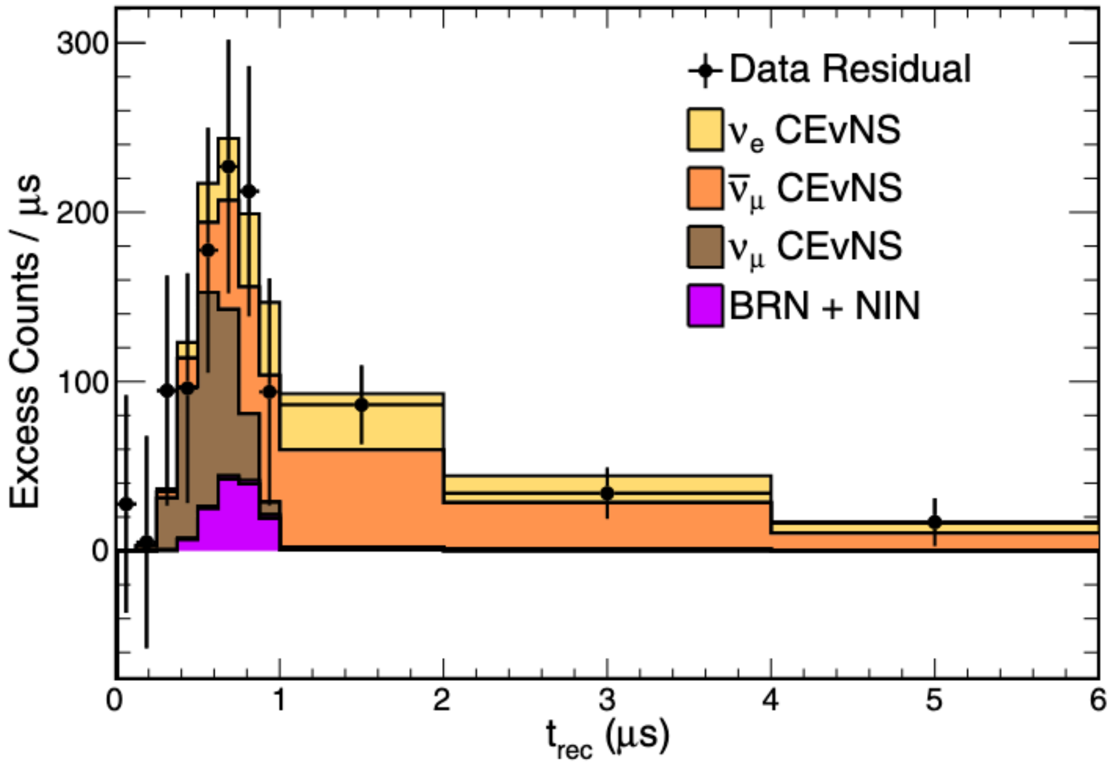
Second CsI[Na] Result

11.6σ





COHERENT. Phys. Rev. Lett. 129, 081801 (2022)

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Lighter Nuclei

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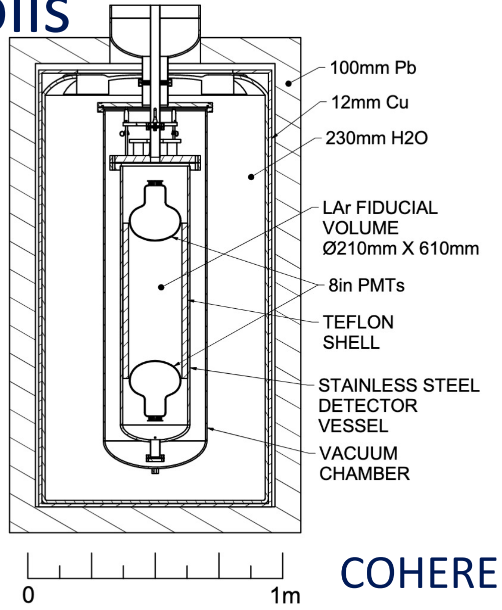
Lighter Nuclei: Liquid Argon

- CENNS-10 detector consisting of 24kg of atmospheric argon
- Pulse shape discrimination possible to differentiate electronic and nuclear recoils
- First results in 2021



COHERENT. Phys. Rev. Lett. 126, 012002 (2021)

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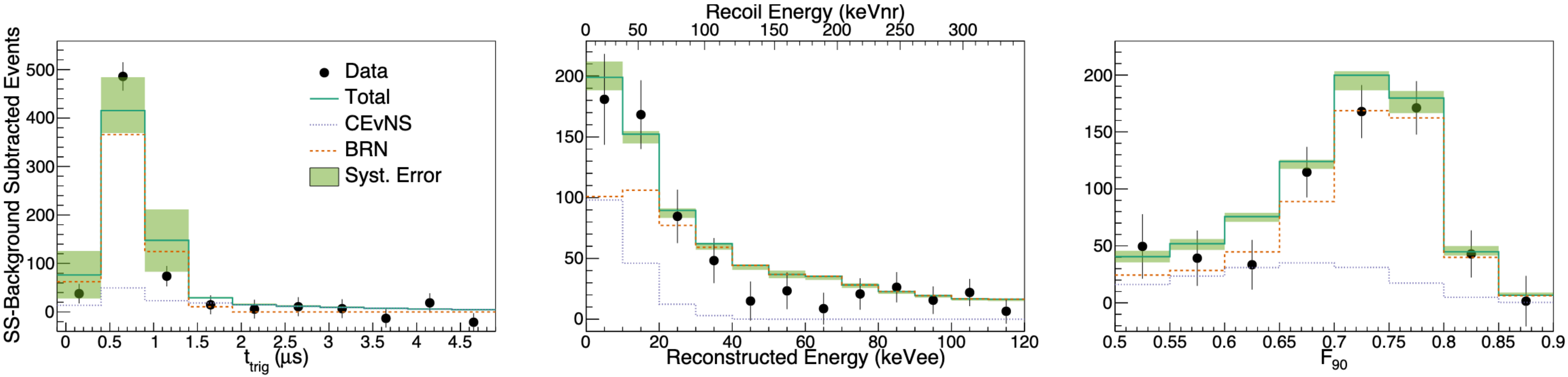
Lighter Nuclei: Liquid Argon

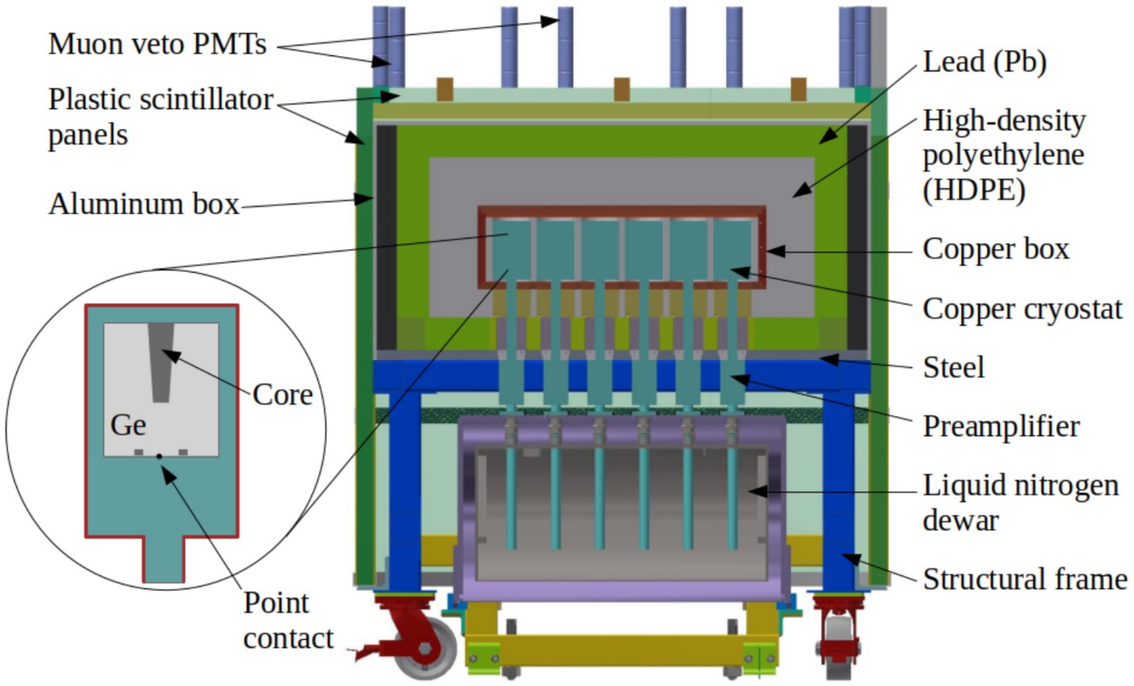
3.5σ



COHERENT. Phys. Rev. Lett. 126, 012002 (2021)

Lighter Nuclei: Germanium

- 8 high-purity germanium diodes ~2.2kg each
- Low threshold, high resolution
- Gemini detector was commissioned from May 2022 – June 2023
- Results analyzed from June – August 2023



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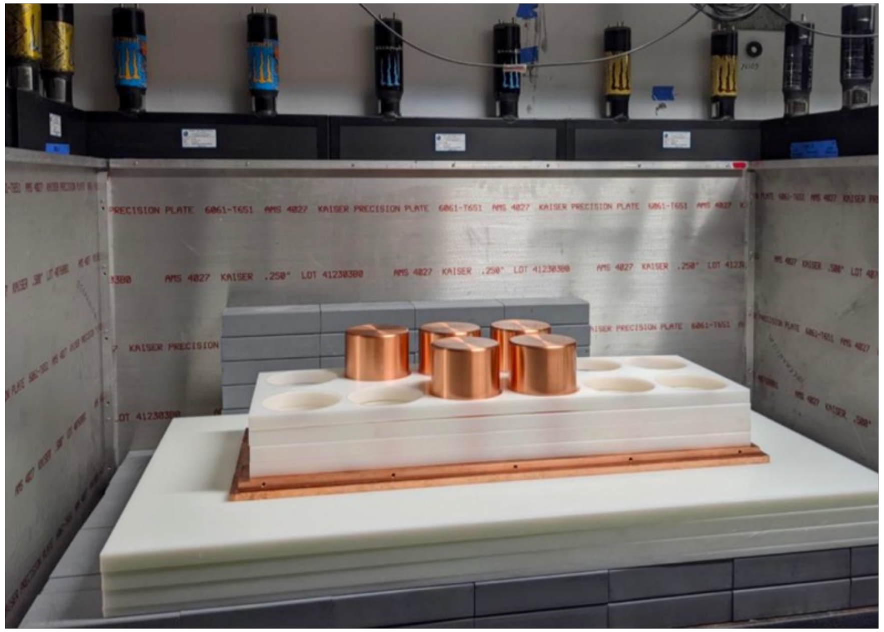
COHERENT SNS



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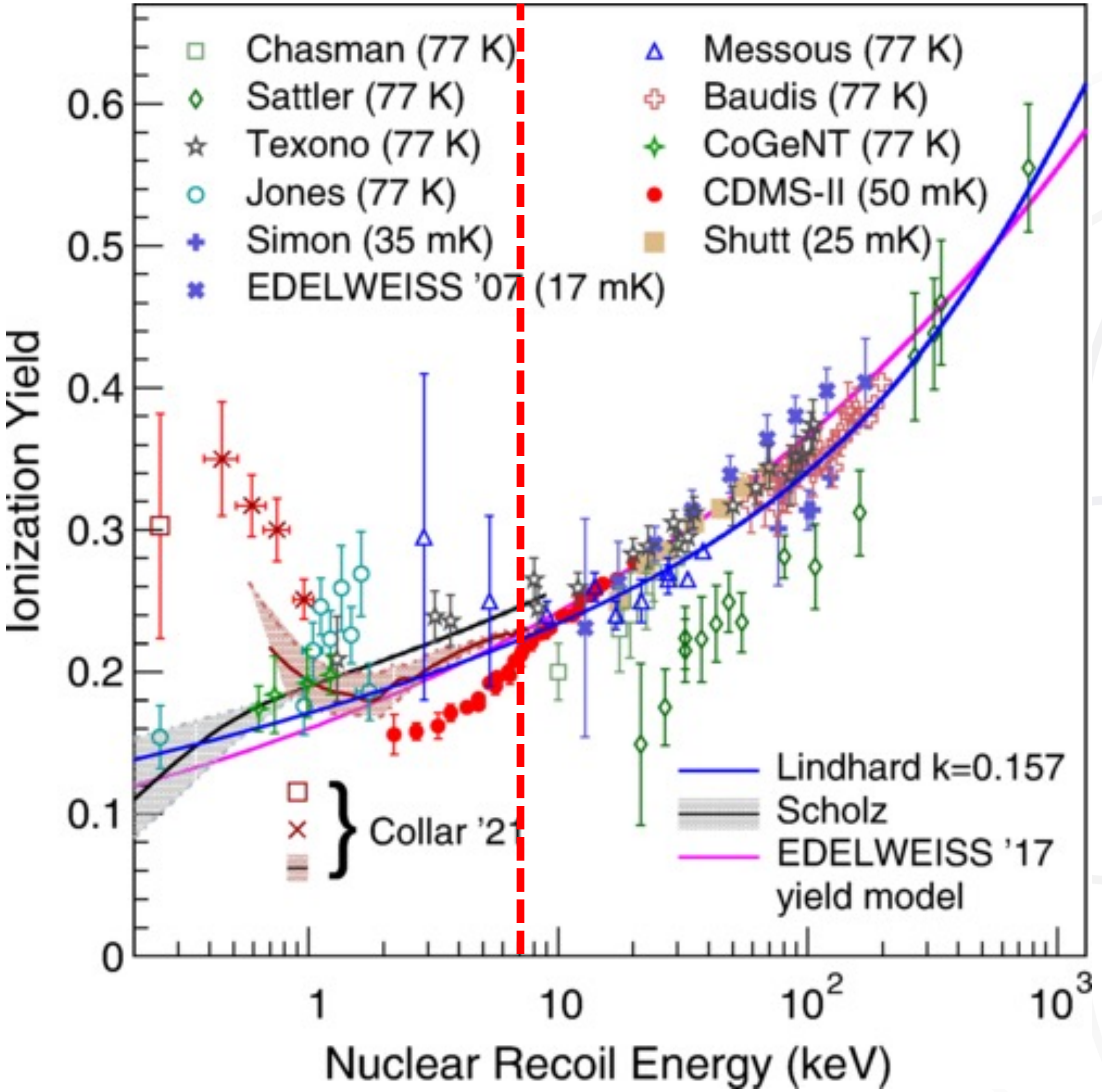
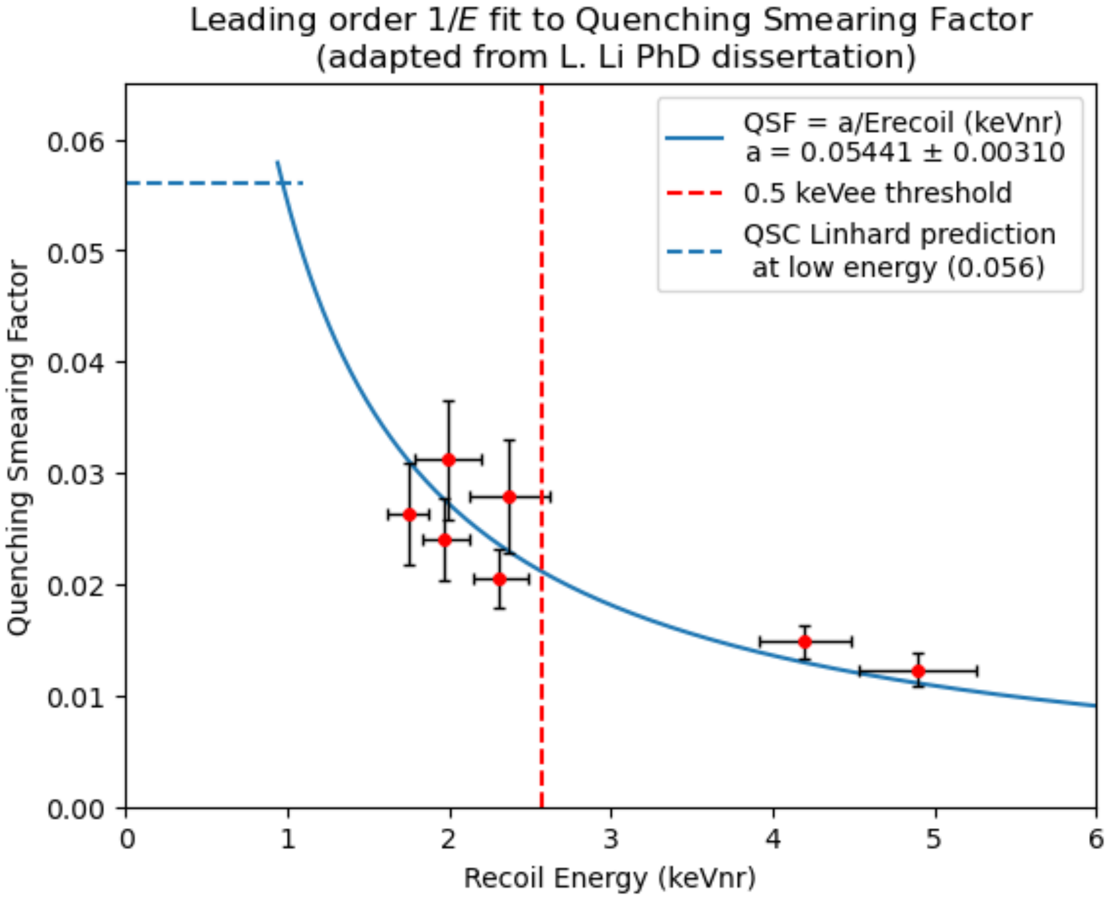
Lighter Nuclei: Germanium



M. F. Albakry et al.
Phys. Rev. D 105, 122002 (2022)

Lighter Nuclei: Germanium



E_{nr}/keVnr	1.75	1.97	2.31	1.99	4.20	2.37	4.89
E_{nr}/eVee	292±21	332±20	403±20	350±20	827±28	425±28	999±35
σ^2_{nr}/eV^2	458±66	595±86	882±128	1310±190	3422±496	1980±287	5402±783
σ^2_{noise}/eV^2	1038±15	1050±17	1071±21	1692±28	1816±70	1715±27	1871±69
σ^2_E/eV^2	3739±216	4290±231	5282±256	6820±439	15372±600	8730±579	19552±924

E. van Nieuwenhuizen

L. Li, *A Measurement of The Response of A High Purity Germanium Detector to Low-Energy Nuclear Recoils*, PhD Thesis. (Duke University, Durham, 2022).

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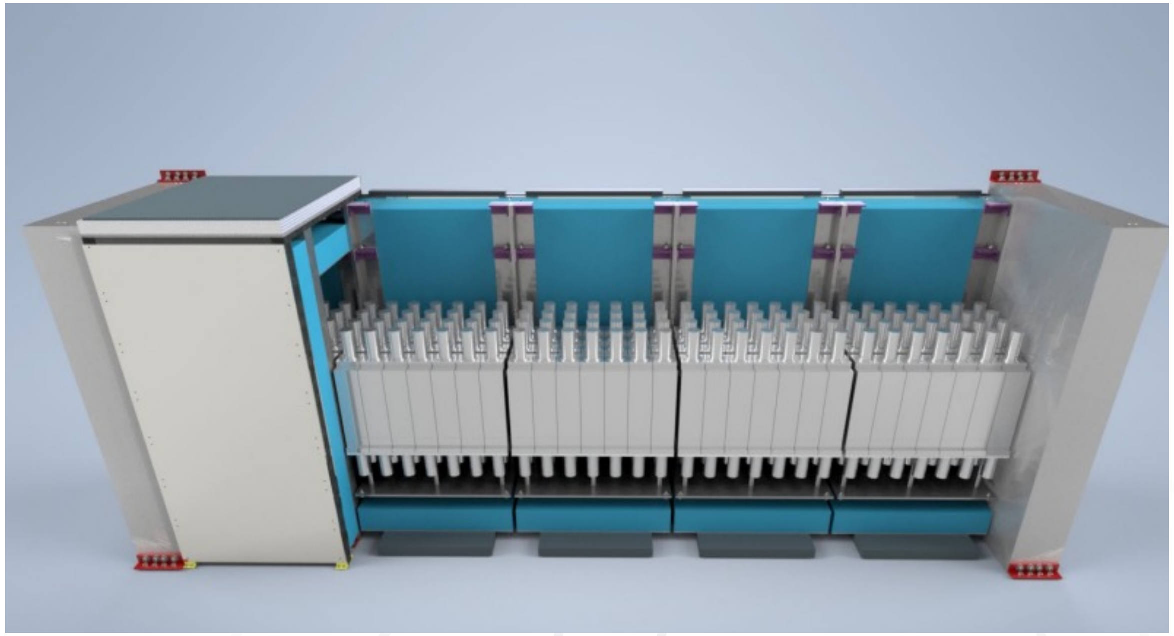
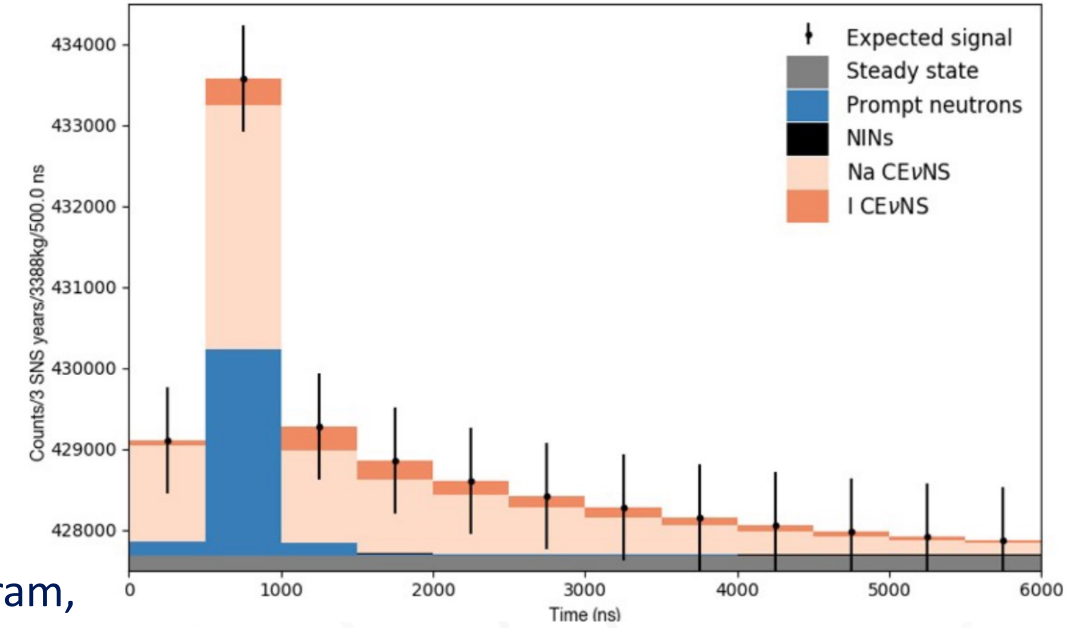
Nu Bigger

NaIvETe

- Multi-tonne modular array
- Each module of 63 7.7kg crystals provides 485 kg of detector mass
- High and low gain channels for CEvNS and CC interactions respectively
- First data expected imminently





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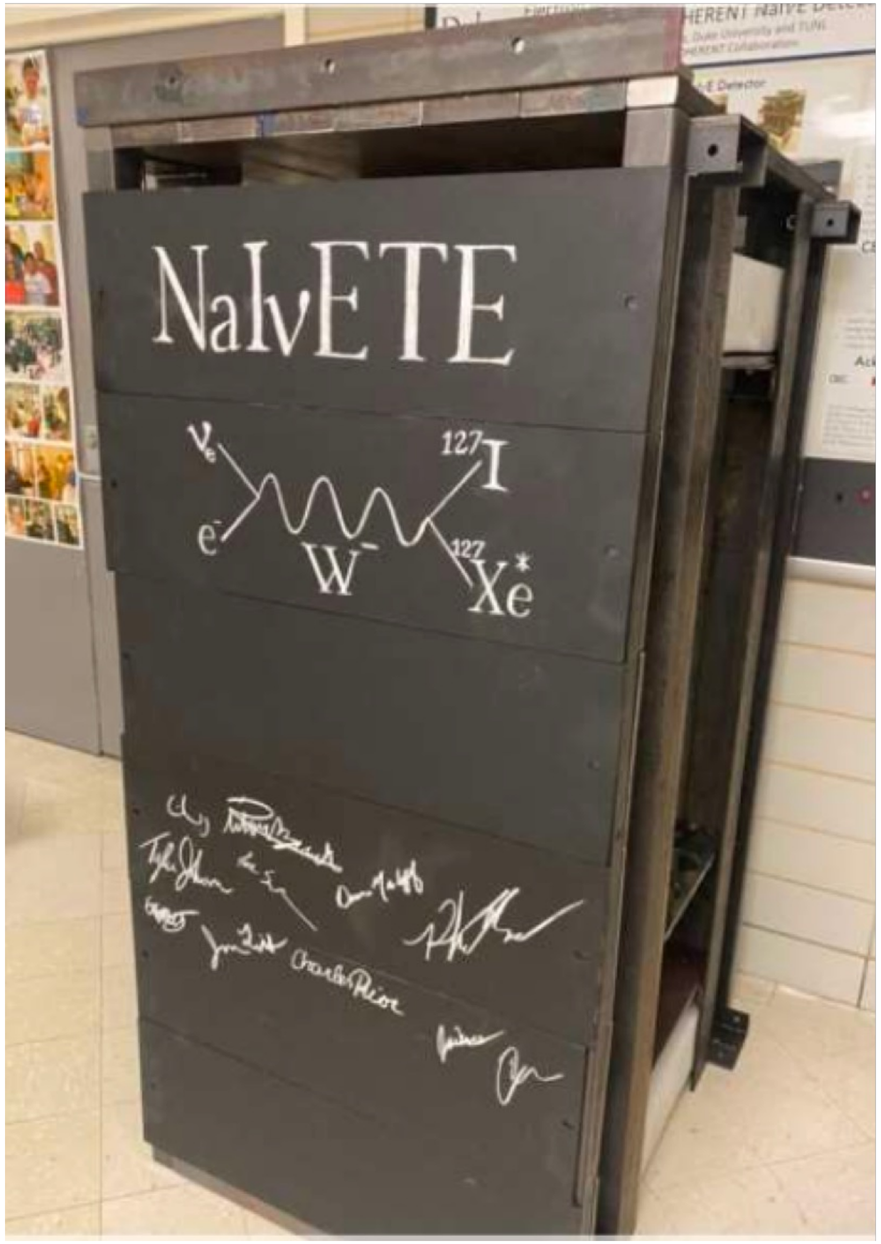
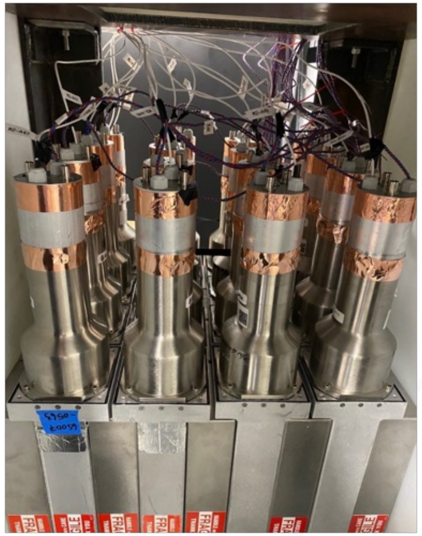
COHERENT. The COHERENT Experimental Program, Snowmass contribution arxiv:2204.04575 (2022)





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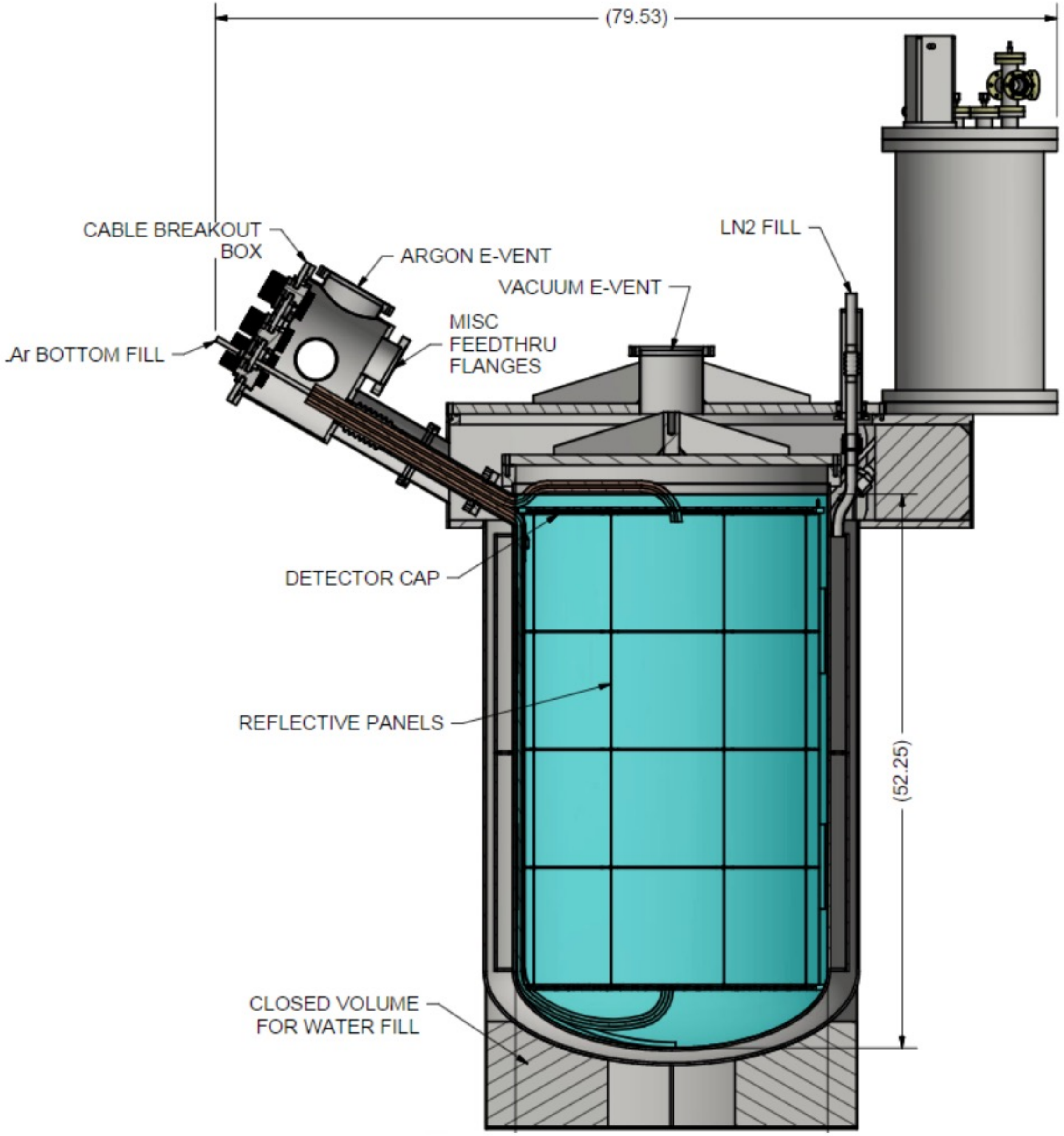
CENNS-750

- 750kg volume, 610kg active volume
- 2×58 array of 3-inch Hamamatsu PMTs



COHERENT. The COHERENT Experimental Program, Snowmass contribution arxiv:2204.04575 (2022)

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INCOHERENT

NuThor

- Hunting for neutrino-induced fission ("NuFission")
- Target: 52 kg of ^{232}Th metal

$$\nu_e + {}^{232}Th \rightarrow e^- + {}^{232}Pa^*$$

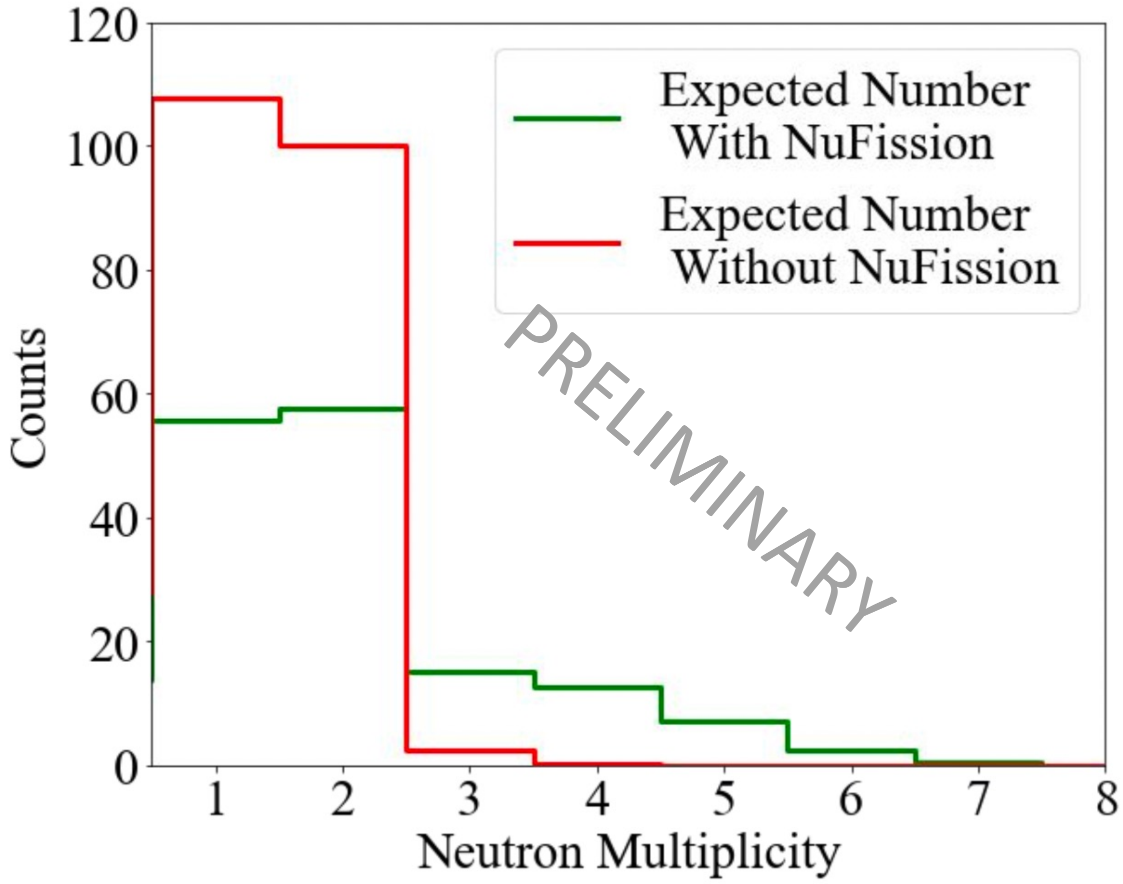
- ^{232}Th has the lowest spontaneous fission rate of any actinide

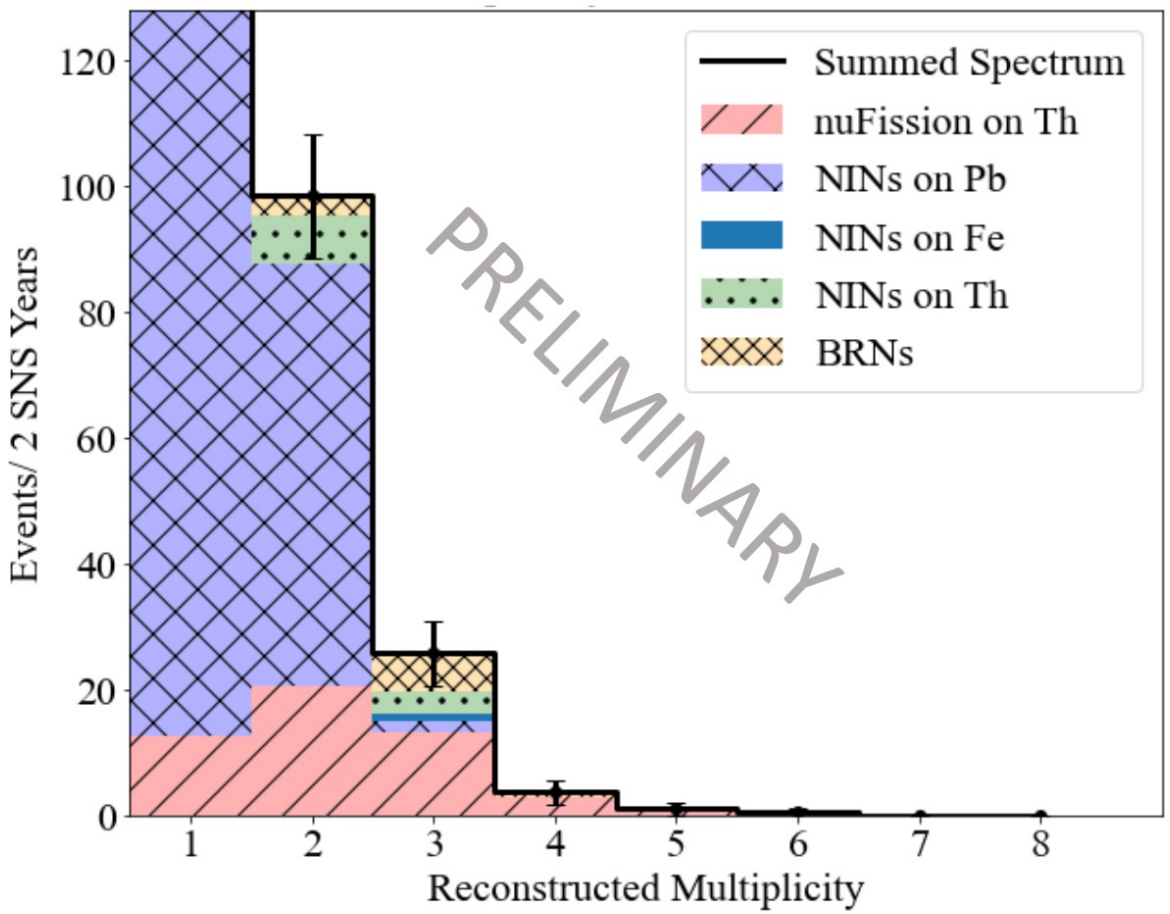
Tyler Johnson

Duke

NuThor

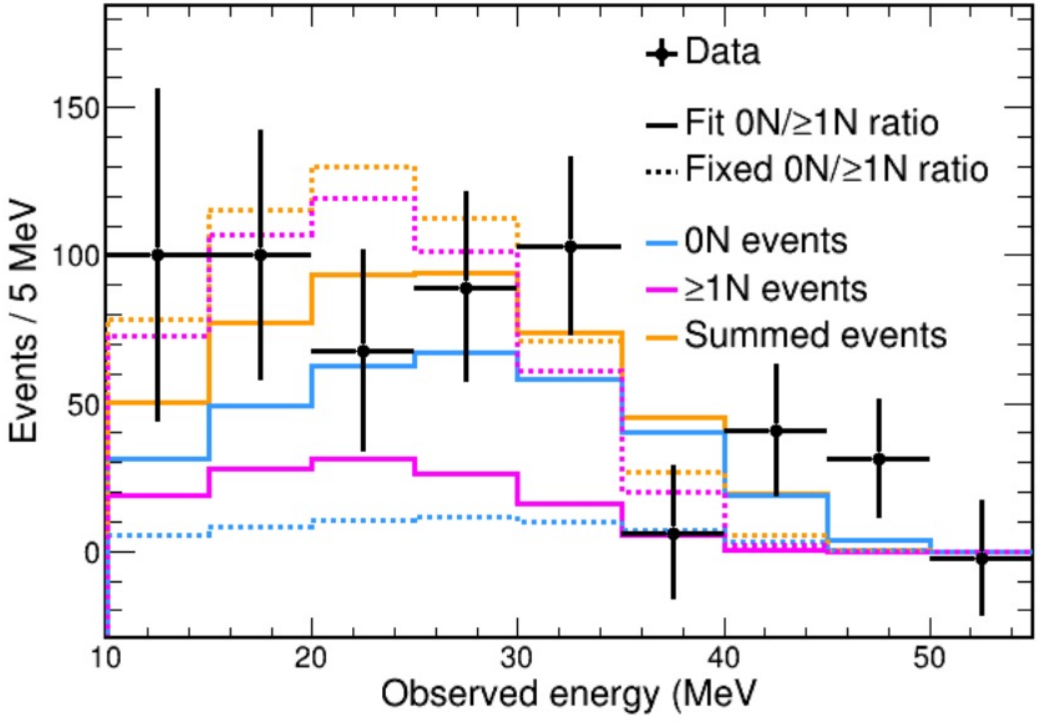
Find through neutron multiplicity numbers

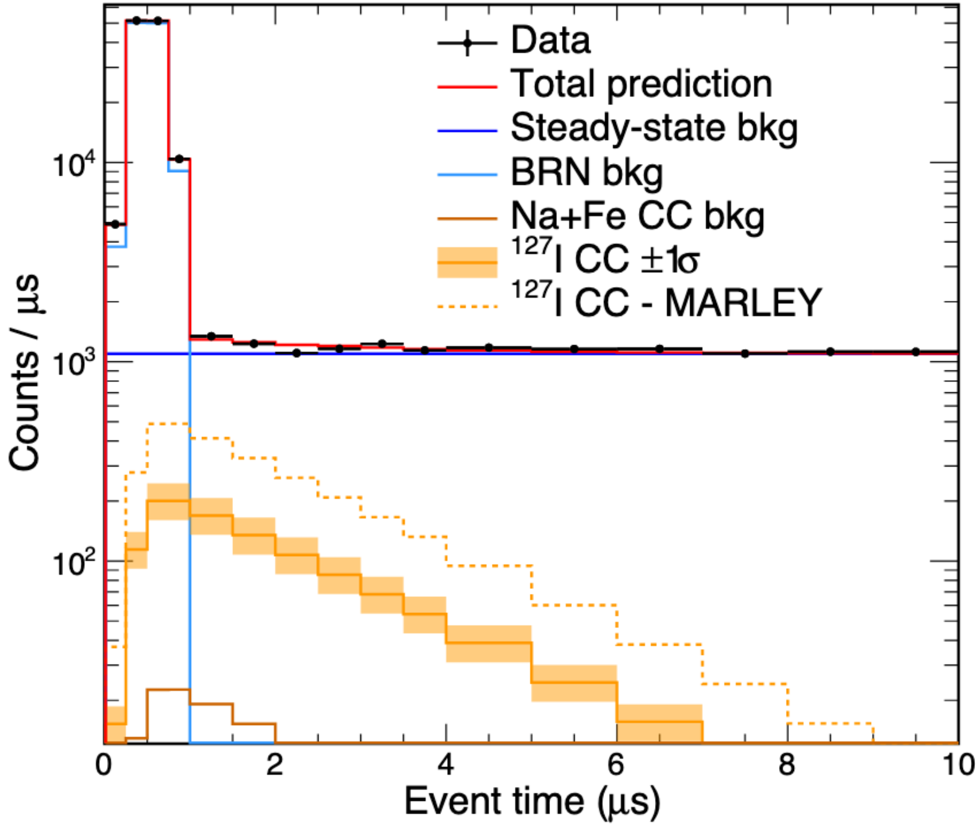


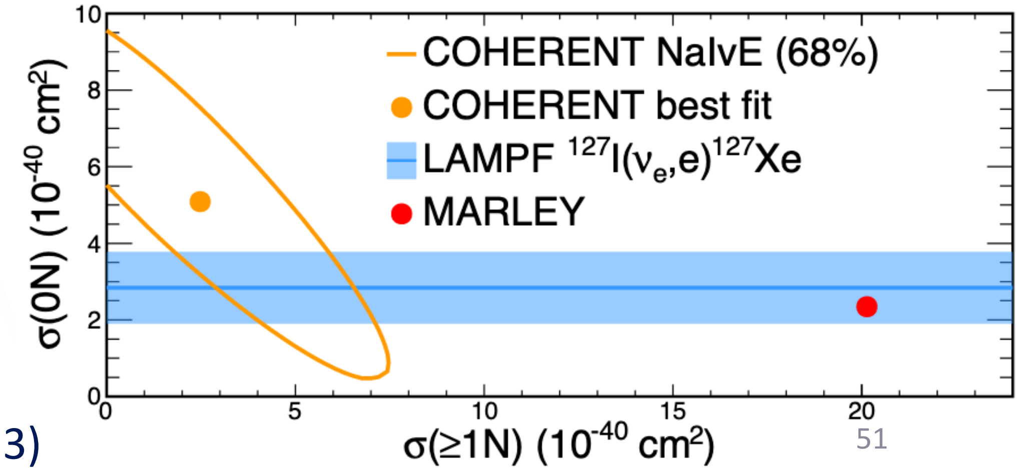


NaIvE/NaIvETe

- NaIvE measured the inclusive electron-neutrino charged-current cross-section on ^{127}I in 2023







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

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Lead Glass

- Cherenkov detector
- Deployed in Summer 2023
- Will investigate the CC cross-section on lead

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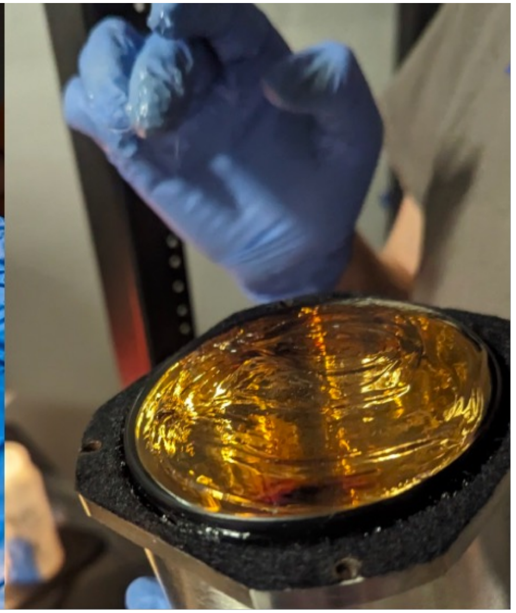

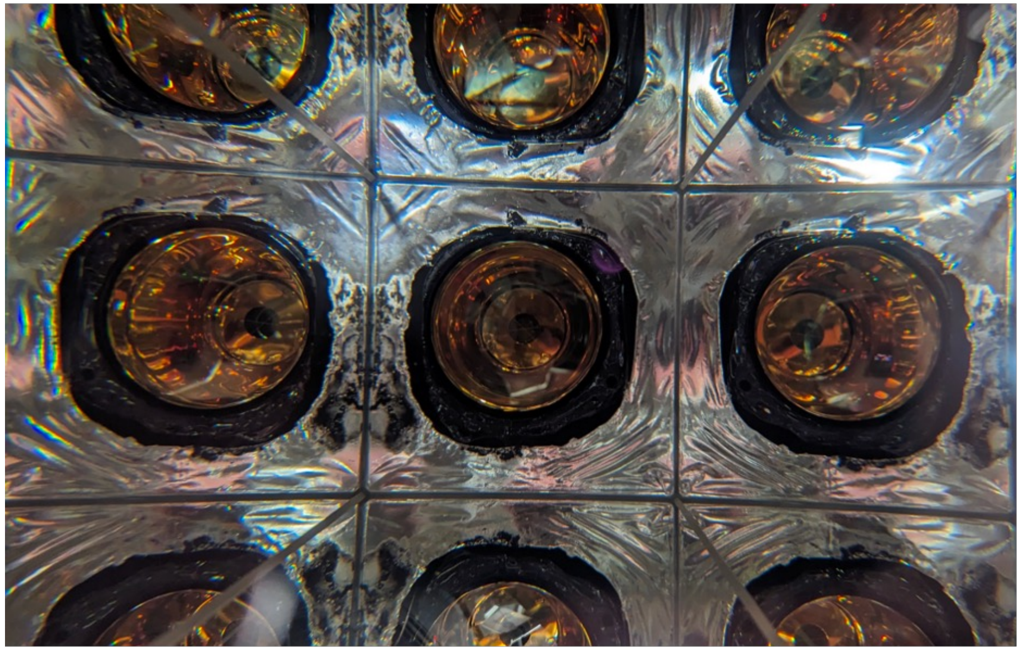

What’s Next?

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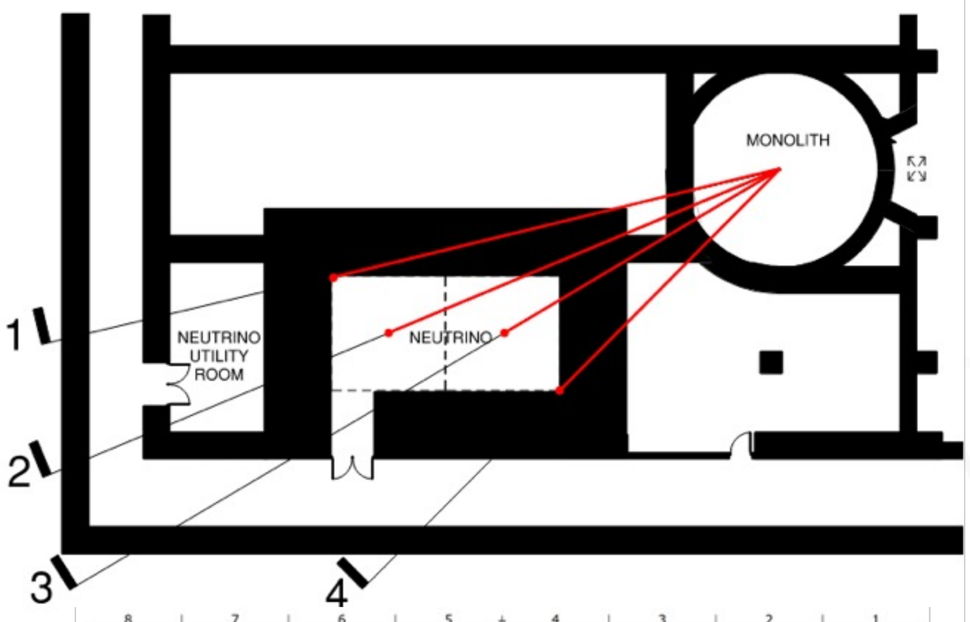
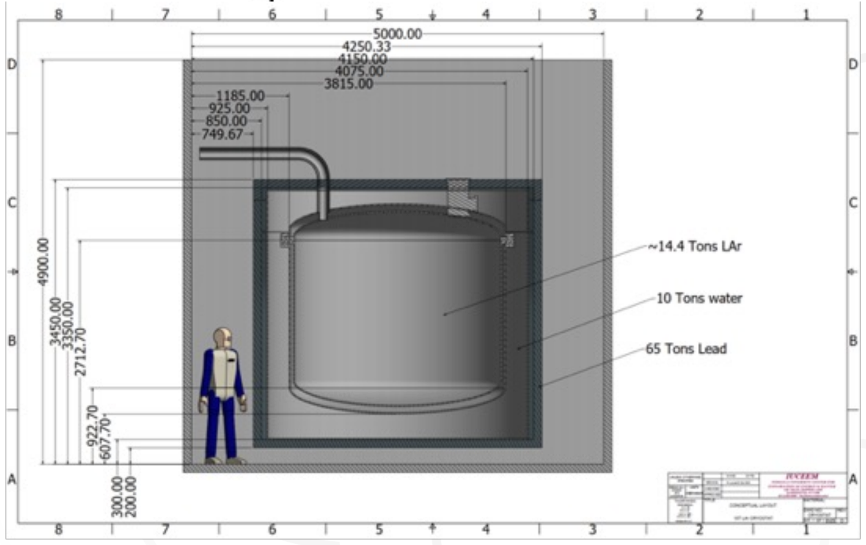
STS Upgrade

- Future upgrade to the SNS, a new target station
- Will receive ¼ of the proton beam (15Hz)
- Better backgrounds
- Proposed dedicated space for a neutrino laboratory (more space for new experiments!)
- Second location provides opportunity for multi-baseline experiments

STS Basement Concept for Neutrinos





10-ton Argon Cryostat Concept, IU

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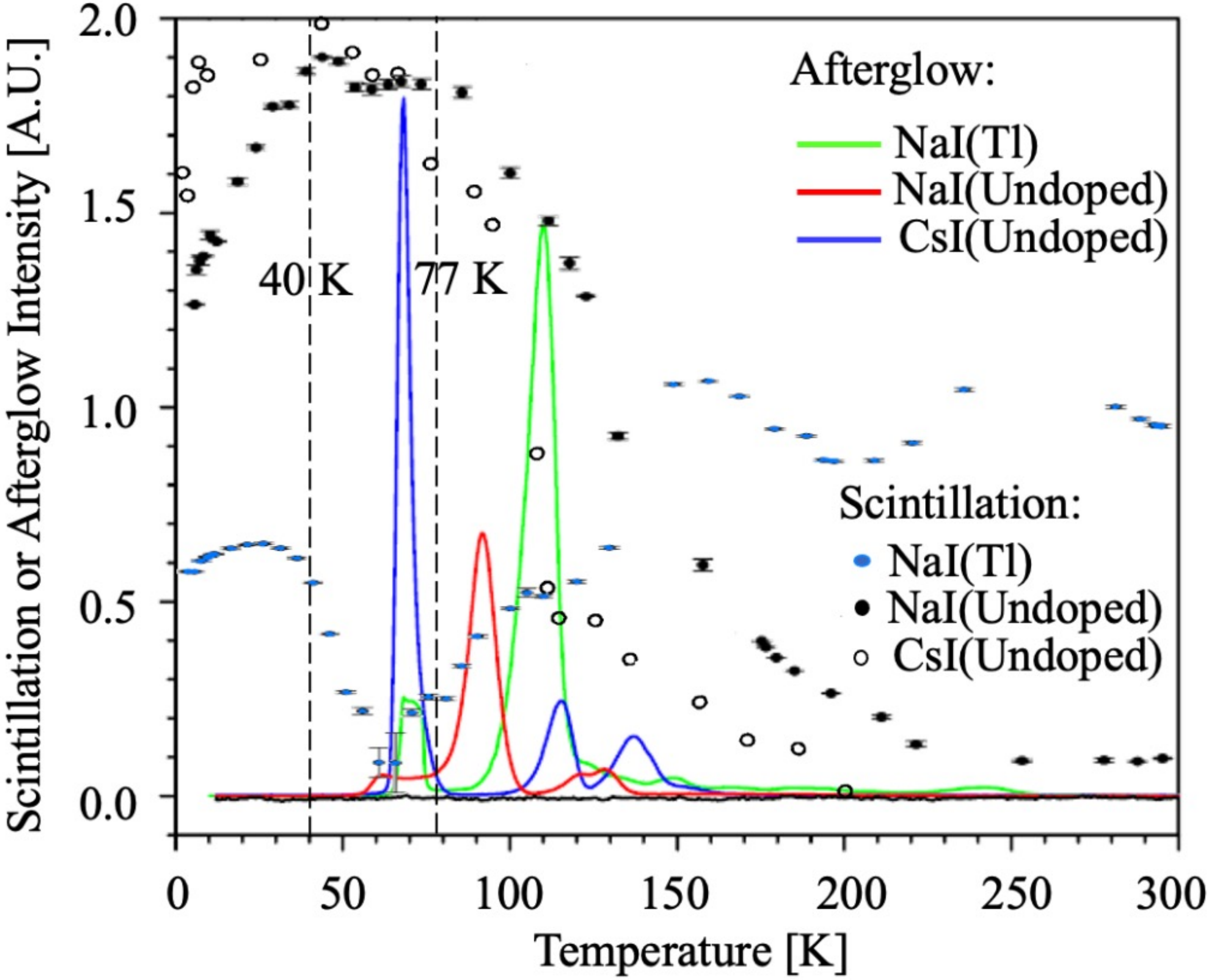
Directional Detection?

- Because of the point-source nature of the mercury target, the SNS provides an ideal source of isotropic neutrinos – perfect for directional detection experiments
- The SNS is a prime facility for testing neutrino and accelerator-produced dark matter interactions

Cryogenic CsI

- When cooled to cryogenic temperatures (40K-77K), undoped CsI offers unparalleled light yield
- 0.5 keV_{nr} threshold (down from ~8 keV_{nr} from original experiment)
- Revisit the CsI experiment with higher sensitivity, lower threshold



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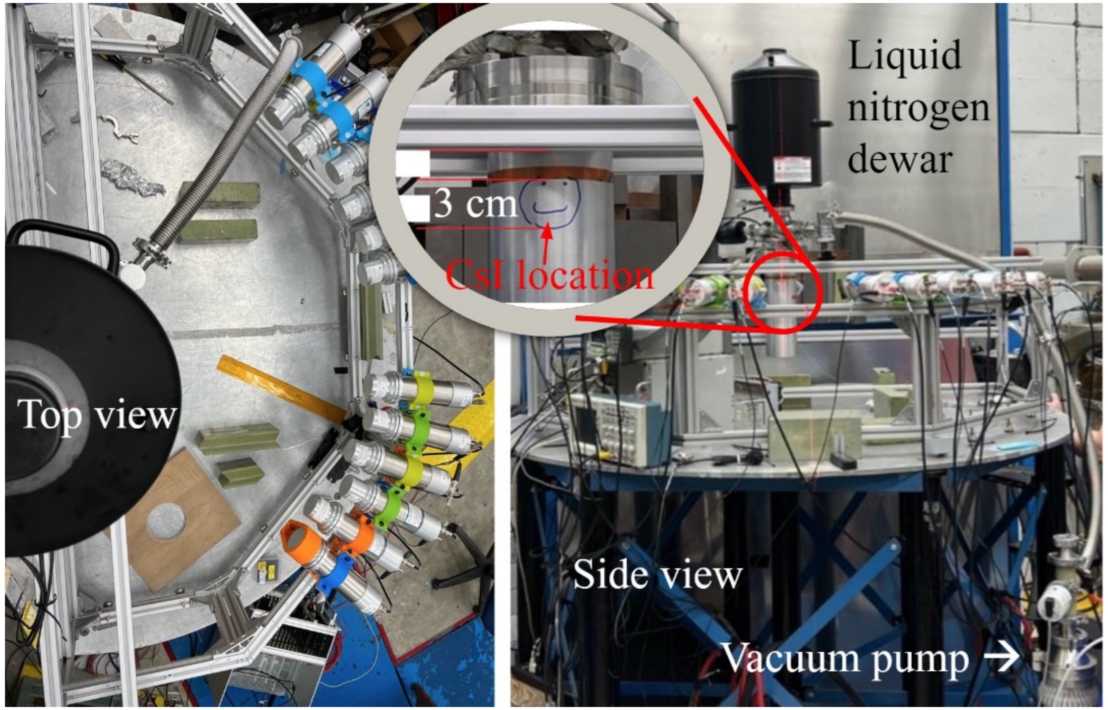
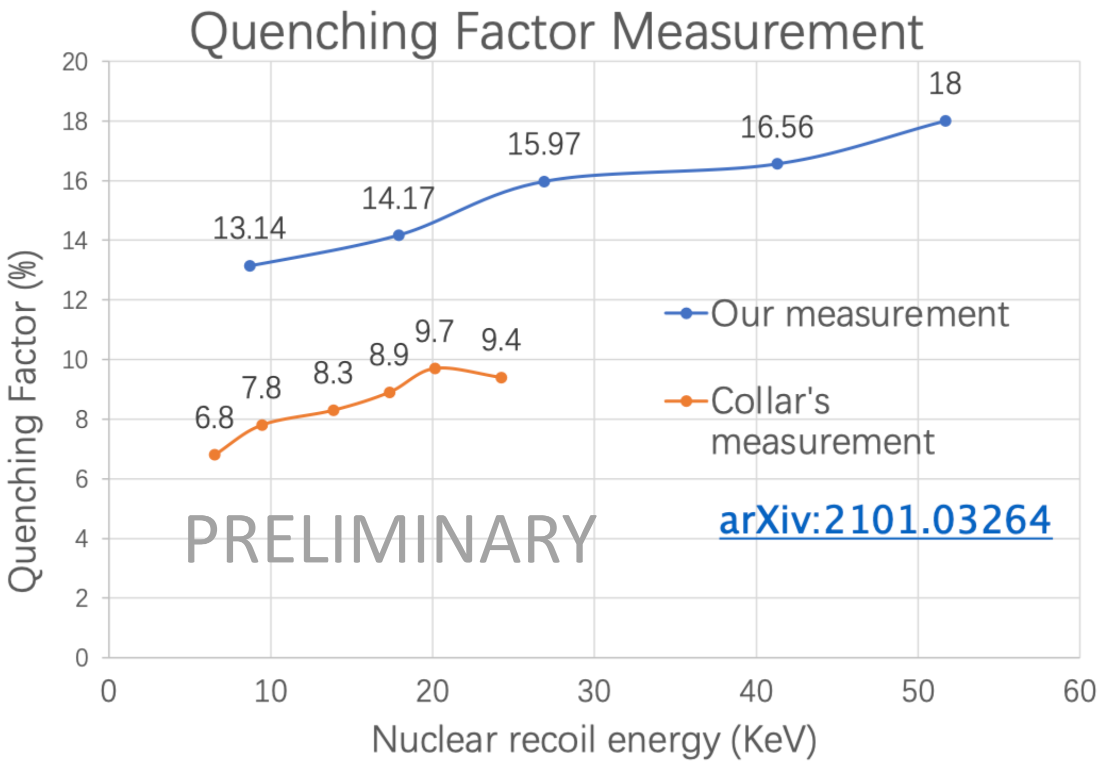
Cryogenic CsI Quenching Factors

- Measured the cryogenic undoped CsI QF at TUNL in Summer 2022





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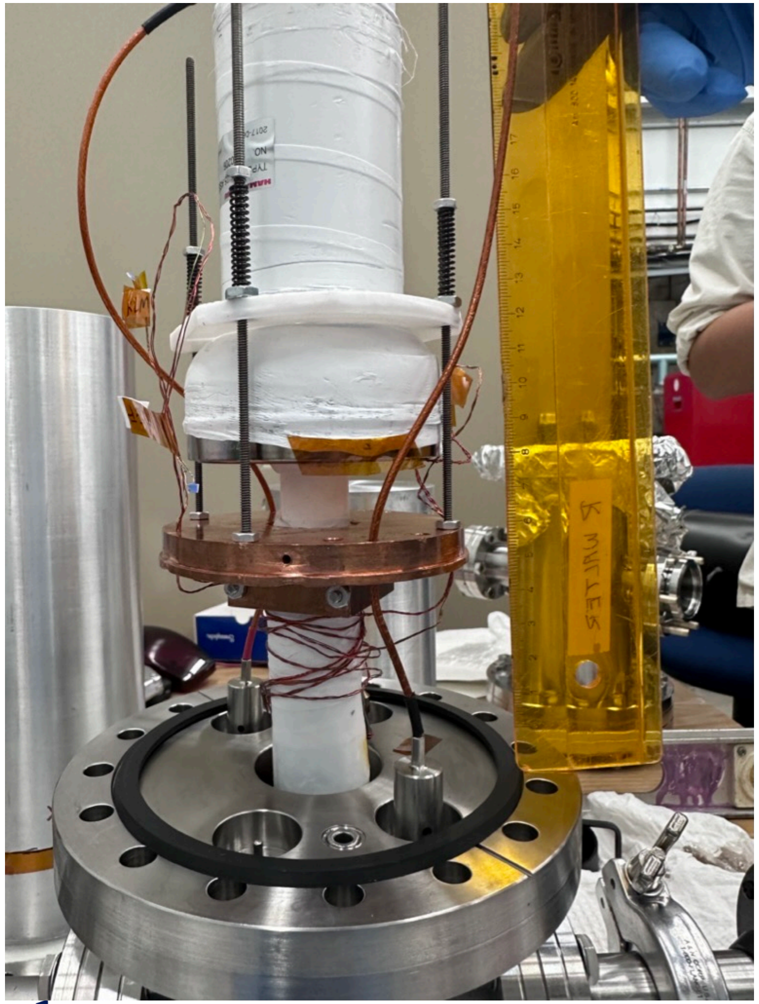
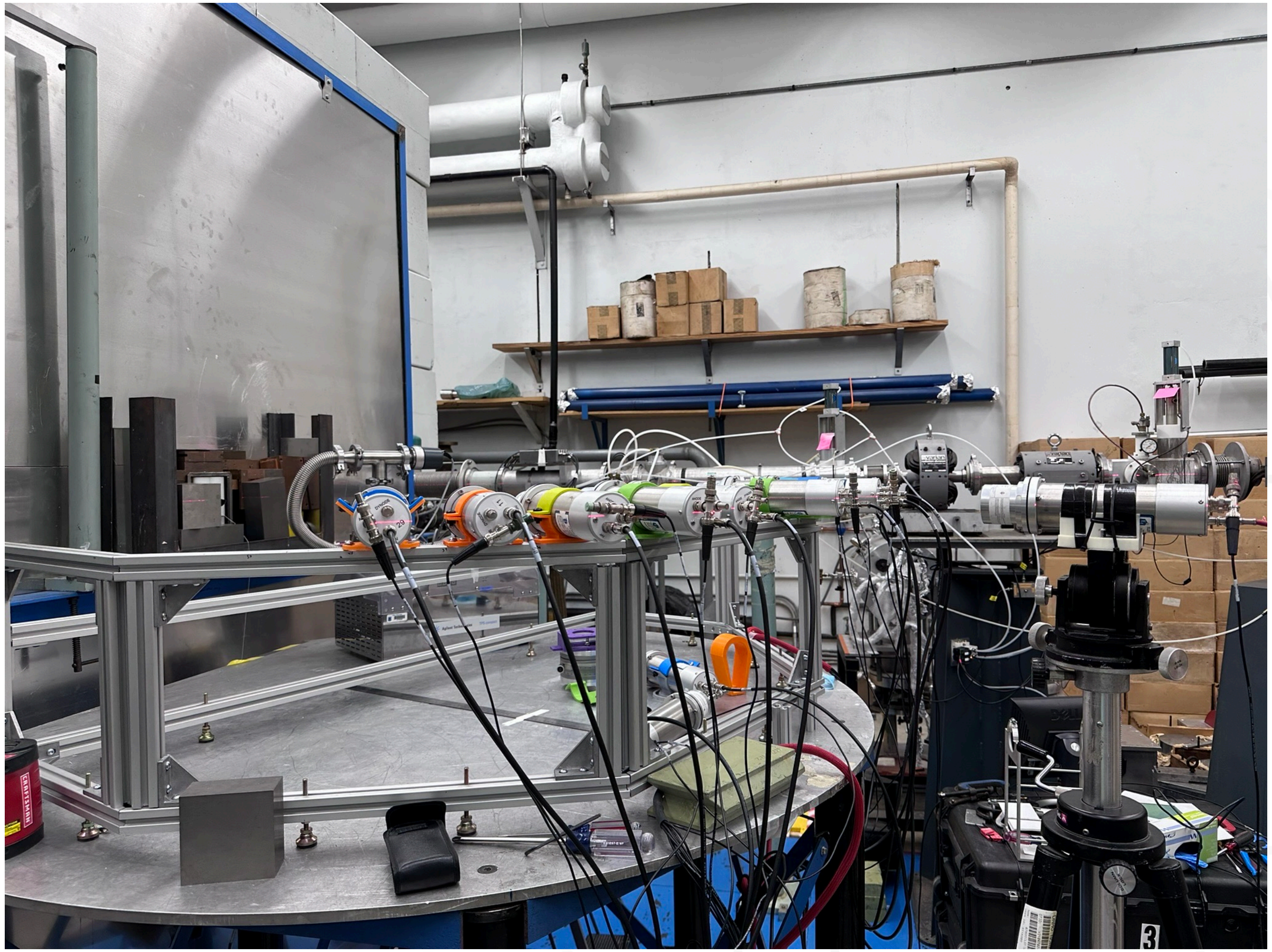
BGO Quenching Factors



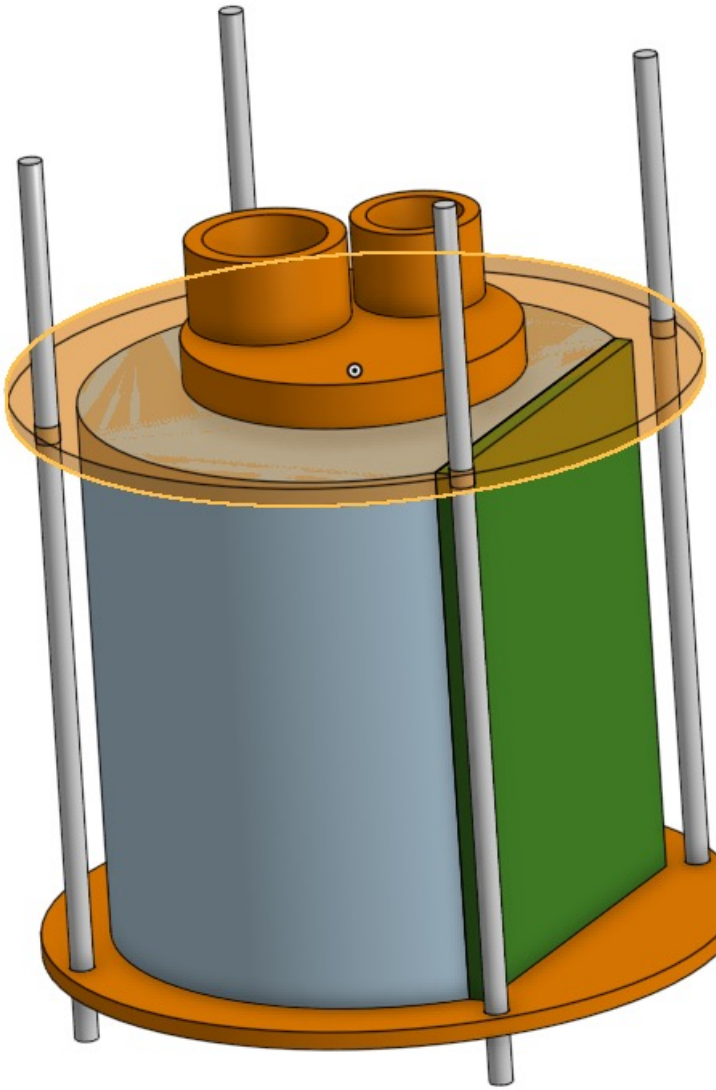


Discussion

Backup Slides

Cryogenic CsI

- 6” x 6” crystal (approx. 12 kg)



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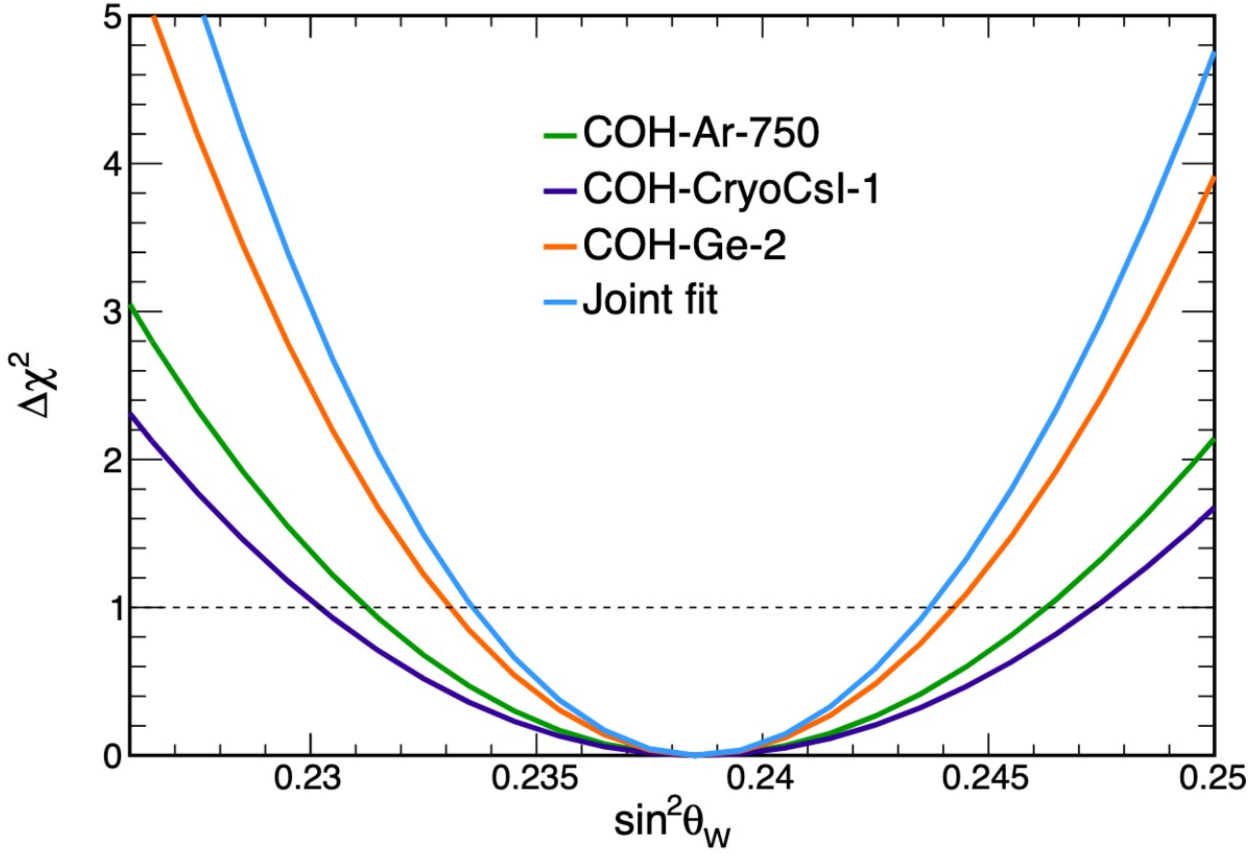
Weak Mixing Angle Future Sensitivity



COHERENT. The COHERENT Experimental Program, Snowmass contribution arxiv:2204.04575 (2022)

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COHERENT Physics Reach

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

The term quenching factor refers to the requirement to understand detector response for nuclear recoils. Abbreviations: CC, charged current; NC, neutral current; SM, Standard Model.

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Barbeau et al. Annual Review of Nuclear and Particle Science 73:1, 41-68 (2023)

CEvNS Differential Cross Section

For $T \ll E_\upsilon$,

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

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

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

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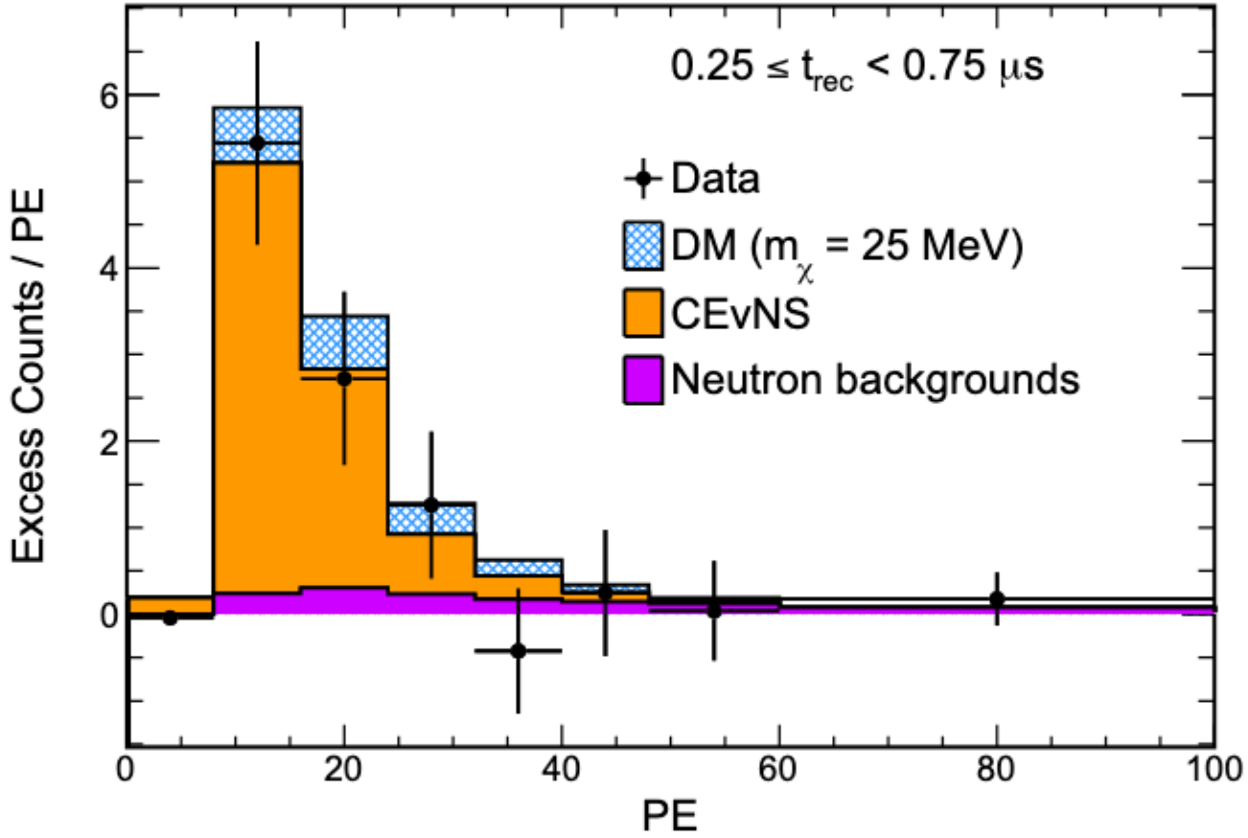
Accelerator Produced DM

- Sub-GeV DM would be produced by accelerators.
- Light scalar DM can be observed via a vector mediator V which decays $V \to \bar{\chi}\chi$
- No evidence of DM with masses 1-220 MeV from COHERENT

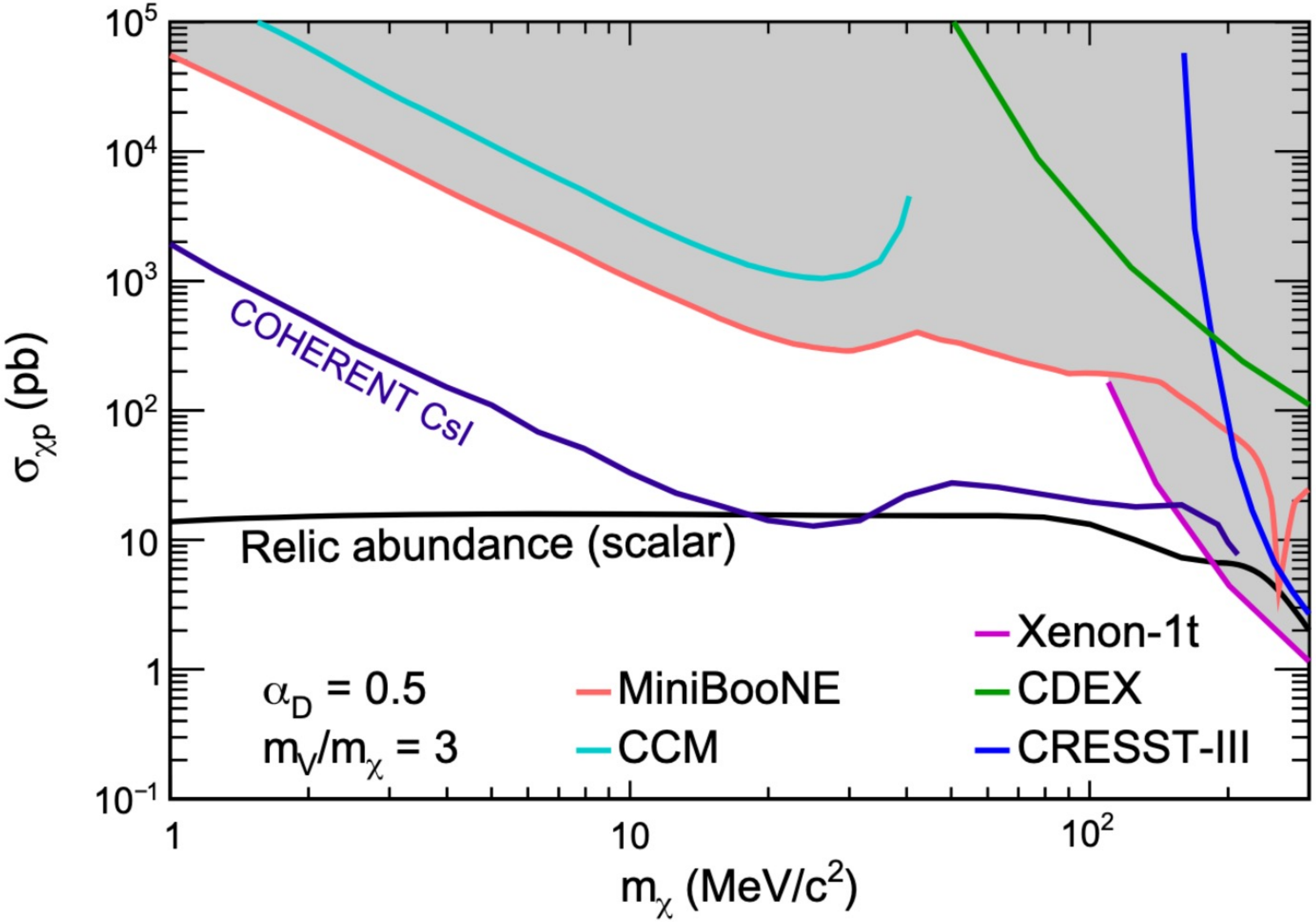


The expected DM distribution at the 90% limit is stacked on top of the SM background.

Best Fit: 0 events

COHERENT. Phys. Rev. Lett. 130, 051803 (2023)

Dark Matter Exclusion Region



COHERENT. Phys. Rev. Lett. 130, 051803 (2023)