Neutrino 2022, Virtual Seoul

New results from COHERENT

Dan Pershey, Duke University
for the COHERENT collaboration

Jun 4, 2022

Spallation Neutron Source (SNS) at Oak Ridge National Lab (ORNL)

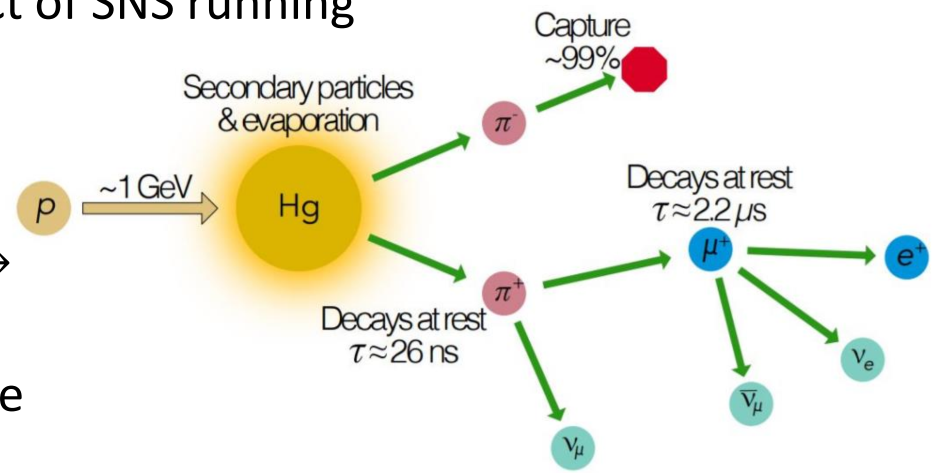
- A premier neutron accelerator complex which produces an incredibly intense flux of low-energy neutrinos with exciting physics agenda complementary to its neutron studies
- In early stages of upgrade to double accelerator power and increase beam energy
- The Proton Power Upgrade (coming few years):
  - Beam energy: 1.0 GeV → 1.3 GeV
  - Beam power: 1.4 MW → 2.8 MW
  - Pulse duration (FWHM): 350 ns
- Construction of a second target station extending neutrino research at the lab (≈2030)

Neutrino Flux at the SNS

- Low energy pions are a natural by-product of SNS running
  - π^+ will stop and decay at rest

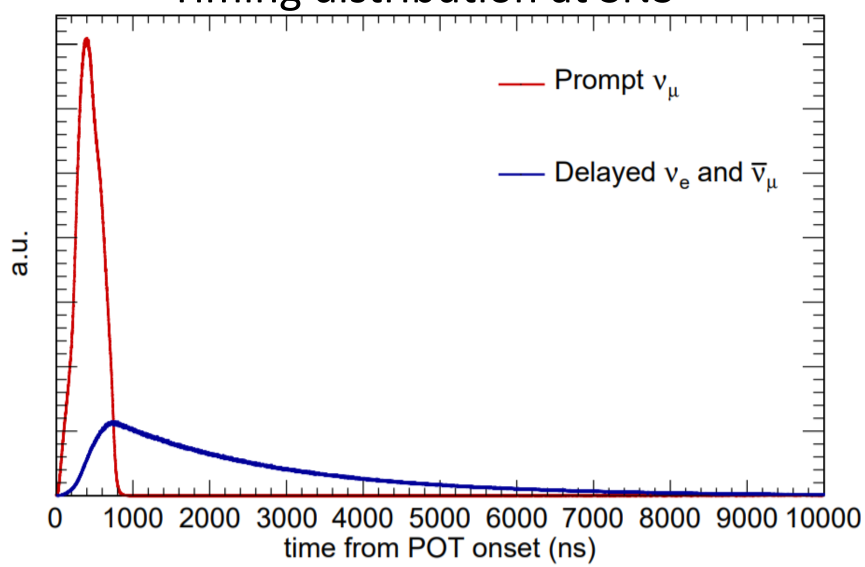
$$\pi^+ \rightarrow \mu^+ + \nu_\mu \quad : \tau = 26 \text{ ns}$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \quad : \tau = 2200 \text{ ns}$$

  - Flux includes three flavors of neutrinos → can test lepton flavor universality

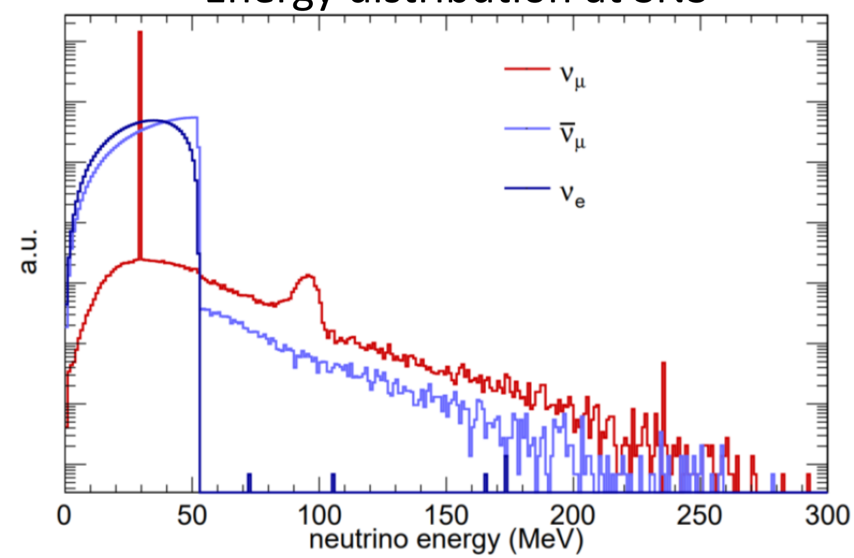


- Flux shape is very well known in both time and energy with very small contribution from decay in flight

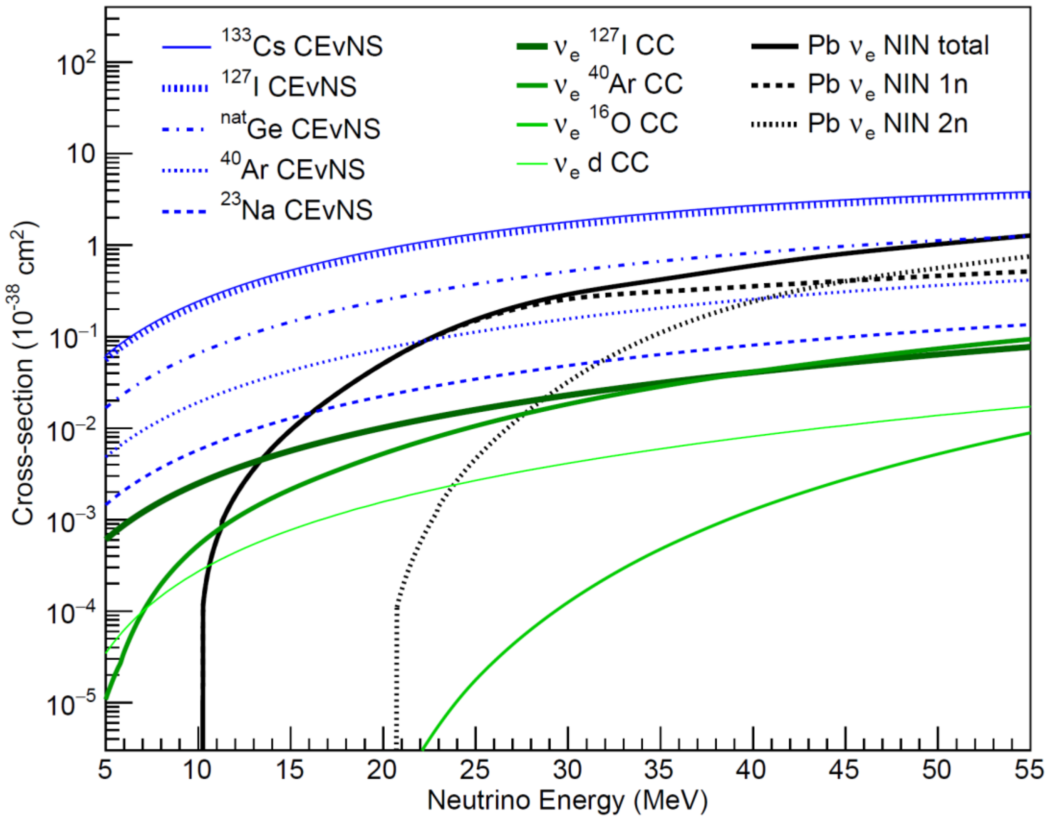
Timing distribution at SNS



Energy distribution at SNS

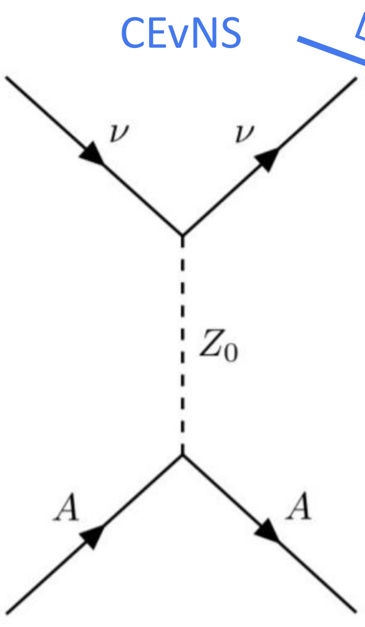


Low-energy neutrino scattering at the SNS

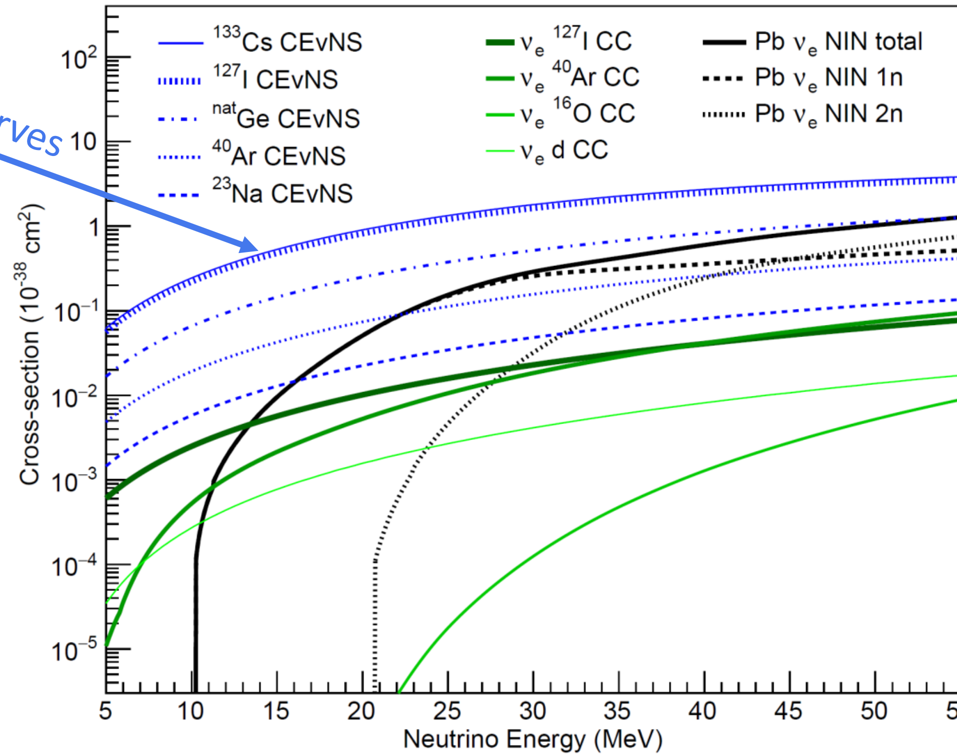


Several scattering processes contribute in the SNS flux region of interest, all of which have not been measured or are poorly measured outside the SNS

Coherent Elastic Neutrino Nucleus Scattering (CEvNS)



Large blue curves

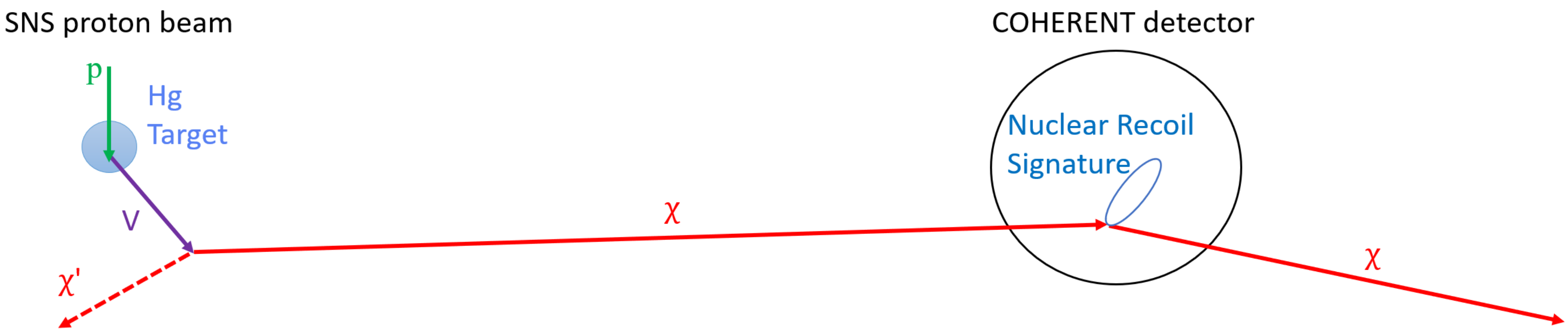


- The process is coherent, which gives a large cross section, roughly scaling with the square of the number of neutrons

$$\sigma \approx \frac{G_F^2}{4\pi}(N-(1-4\sin^2\theta_W)Z)^2E_\nu^2$$

- Very large cross section, compared to low-energy neutrino processes
  - Measurements within reach of kg-scale detectors with 10t-scale detectors capable of precision BSM tests

Searching for dark matter with CEvNS detectors



- A CEvNS detector at the SNS operates like a standard beam dump experiment
- Any hidden sector particles with masses below ≈ 220 MeV/c^2 could be produced in the many proton-Hg interactions within the SNS target
- May include mediators between SM and dark matter particles – probe vector portal to DM

- Simplest scenario postulates a vector mediator that kinetically mixes with SM photon: $\mathcal{L} \sim \frac{1}{2}\varepsilon^2 F_{\mu\upsilon}V^{\mu\upsilon}$
- Model parameters
  - DM and mediator masses: m_χ and m_V
  - SM-mediator and DM-mediator couplings: ε and α_D
- Relic abundance given in terms of $Y = \varepsilon^2\alpha_D\left(m_\chi/m_V\right)^4$

Classical WIMP mass regime:
  Lee and Weinberg, Phys. Rev. Lett. **39** 165 (1977)
Early sub-GeV DM phenomenology:
  Fayet, Phys. Rev. **D70**, 023514 (2004)
  Boehm and Fayet, Nuc. Phys. **B683**, 219 (2004)
  Pospelov et al., Phys. Lett. **B662**, 53 (2008)
Coherent DM scattering / DM at the SNS:
  deNiverville et al., Phys. Rev. **D84**, 075020 (2015)
  Dutta et al., Phys. Rev. Lett. **123**, 061801 (2019)

Searching for BSM Interactions with CEvNS

- CEvNS is sensitive to non-standard interactions (NSI) between neutrinos and quarks mediated by some heavy (> 50 MeV/c^2), undiscovered particle
- Generally parameterized by coupling constants: $\varepsilon^{N}_{\alpha\beta}$ $(\alpha, \beta \in e, \mu, \tau)$

$$\mathcal{L}^{NSI}_{\nu Hadron} = -\frac{G_F}{\sqrt{2}} \sum_{\substack{q=u,d \\ \alpha,\beta=e,\mu,\tau}} \left[\bar{\nu}_\alpha \gamma^\mu (1-\gamma^5)\nu_\beta\right] \left(\varepsilon^{qL}_{\alpha\beta}\left[\bar{q}\gamma_\mu(1-\gamma^5)q\right] + \varepsilon^{qR}_{\alpha\beta}\left[\bar{q}\gamma_\mu(1+\gamma^5)q\right]\right)$$

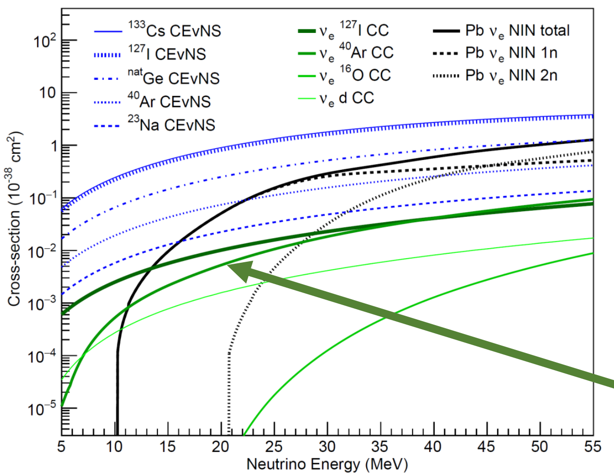
Barranco et al., JHEP **12** 021 (2005)

- NSI scenarios would scale the observed CEvNS rate and several ε parameters are only constrained at ∼ unity
  - ε_{ee} / $\varepsilon_{\mu\mu}$ / $\varepsilon_{\tau\tau}$ break flavor universality predicted by the standard model (at tree level)
  - $\varepsilon_{e\mu}$ / $\varepsilon_{e\tau}$ / $\varepsilon_{\mu\tau}$ change neutrino flavors
- NSI would affect our interpretation of neutrino oscillation data from long-baseline neutrino oscillation results from experiments like NOvA and DUNE which CEvNS data can resolve
  - CEvNS can resolve these measurements of the CP violating angle and neutrino mass ordering

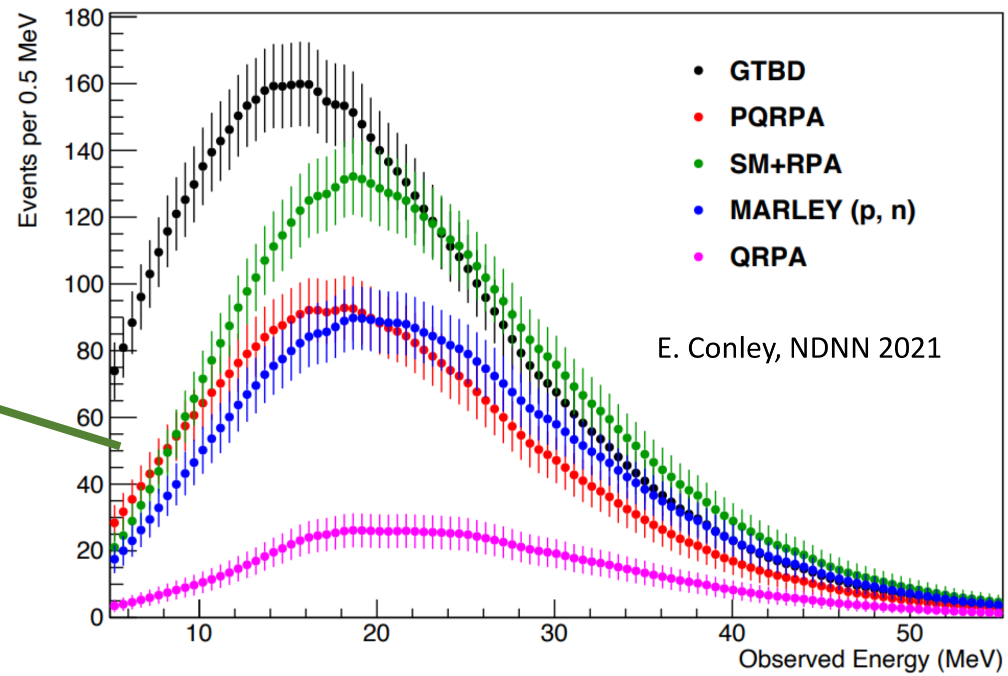
Δm^2_{32}: Coloma et al., PRD **94** 055005 (2017)
δ_{CP}: Denton et al., PRL **126** 051801 (2020)
θ_{12}: Coloma et al., PRD **96** 115007 (2017)

Inelastic charged current interactions on argon

Interactions accessible at the SNS



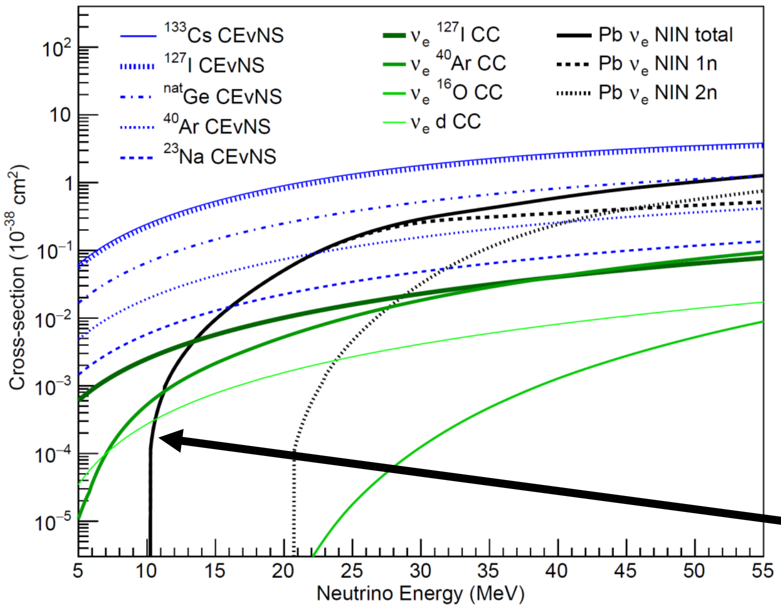
Interactions in DUNE from core-collapse supernova – 10 kpc

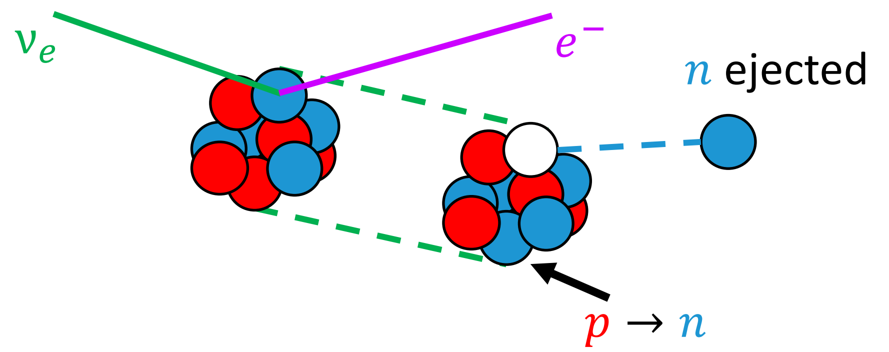


- ❑ Next generation argon scintillation detector will have the dynamic range to study both CEvNS and high-energy inelastic interactions
  - Next generation CENNS750 detector will observe ≈ 340 ν_e CC events / year
- ❑ Theoretical predictions for these cross sections span > 1 order of magnitude – SNS data critical for ensuring success of DUNE low-energy physics goals
- ❑ Will also measure ^{127}I CC and ^{16}O CC cross sectoins

Neutron production in neutrino interactions

Interactions accessible at the SNS





$$\nu_e + (N, Z) \rightarrow e^- + (N-2, Z+1) + n$$

- In neutrino interactions at SNS energies, inelastic interactions that free a nucleon from the struck nucleus are possible
  - For heavy, neutron-rich nuclei, neutron emission is likely
  - A beam-related neutron background for CEvNS that can't be shielded
- Neutrino-induced neutron (NIN) an efficient signal channel for detecting ν_e flux from a burst of neutrinos released in a core-collapse supernova
  - HALO experiment: Nucl. And Part. Phys. Proc. 265-266, 233-235 (2015)

COHERENT efforts at the SNS

- Measure CEvNS with multiple nuclear targets test the standard-model cross section and search for BSM physics
- Utilize detectors to studying low-energy inelastic scattering processes
- Additional programs to evaluate backgrounds and reduce systematic uncertainty

COHERENT CEvNS detectors

Target	Technology	Fid. Mass	Threshold	Deployment
CsI[Na]	Scintillation	14.6	6.5 keV_{nr}	2015
Liquid Ar	Scintillation	24.4/610 kg	20 keV_{nr}	2017/≈2023
Ge	Ionization	18 kg	0.4 keV_{ee}	2022
NaI[Tl]	Scintillation	3500 kg	13 keV_{nr}	2022

Additional programs

Dedicated neutron detectors:
MARS and neutron timing cells (ongoing)
NUBEs – measure neutrino-induced neutrons (ongoing)
NaIvE – measuring CC neutrino interactions (ongoing)
nuThor – measure neutrino-induced fission on Th (2022)
Heavy water detector to normalize ν flux (2022)

COHERENT results

CsI – CEvNS discovery (Science **357** 6356 1123-6, 2017)
LAr – CEvNS measurement (PRL **126** 012002, 2021)
LAr – Argon calibration (JINST **16** P04002, 2021)
CsI – Full-dataset CEvNS (arXiv:2110.07730, 2021)
CsI – Search for dark matter (arXiv:2110.11453, 2021)
CsI – Quenching factor (arXiv:2111.02477, 2021)
MARS – SNS neutron bkg (JINST **17** P03021, 2022)
CsI – Leptophobic DM (arXiv:2205.12414, 2022)

+ more sensitivity and future design publications
New results for Neutrino 2022!

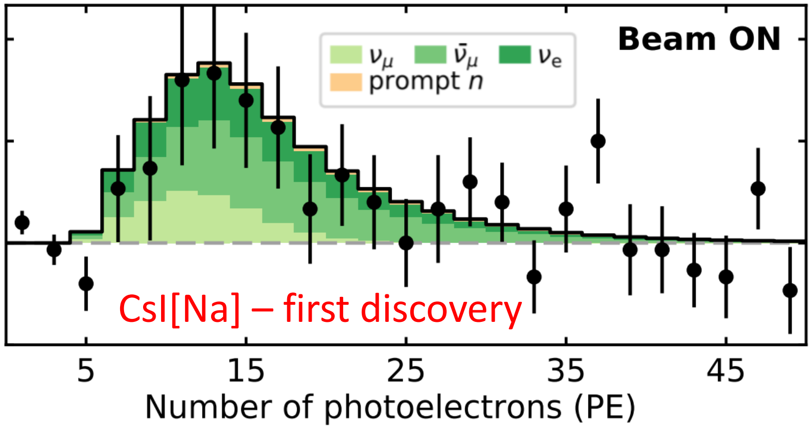
COHERENT posters at Neutrino-2022

Ben Suh – CEvNS on LAr from the COHERENT collaboration
Max Hughes – COH-Ar-750: A future ton-scale LAr detector for CEvNS
Erin Conley – Prospects for measurement of neutrino-argon charged-current interactions with the COHERENT liquid argon detector
Adryanna Major – Deployment of COHERENT multi-tonne NaI[Tl] detector: NaIvETe
Sam Hedges – Results from COHERENT's neutrino-induced neutron detectors
Conan Bock – Monte Carlo simulation of a dedicated neutron detector for the COHERENT experiment at the SNS, ORNL
Karla Tellez-Giron-Flores – A heavy water detector for flux normalization at COHERENT
Eli Ward – Measuring charged-current neutrino-nucleus cross section on Oxygen
Diana Parno – Neutrino-flux model for COHERENT
Keyu Ding – Cryogenic inorganic scintillator detectors for COHERENT

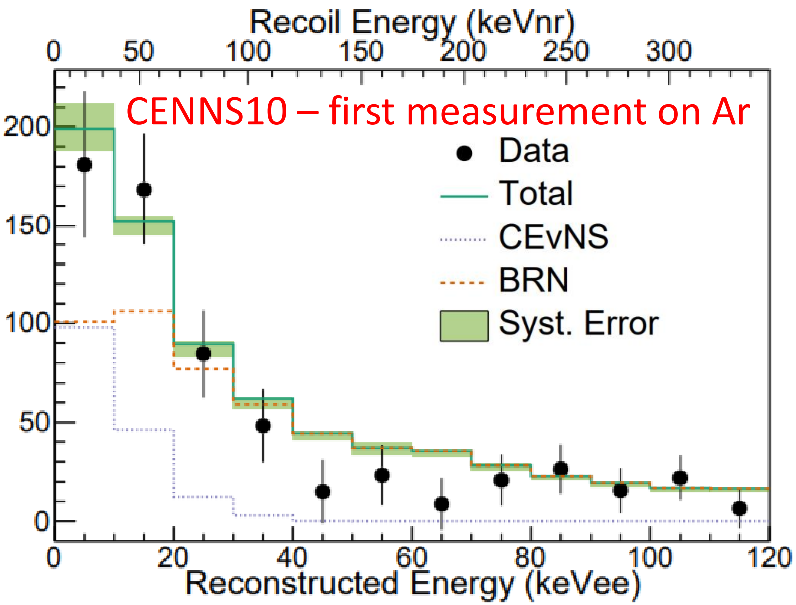
Full-dataset CEvNS and dark matter results from CsI[Na] detector

First-light CEvNS measurements from COHERENT

- COHERENT discovered CEvNS in 2017 using the a low-background CsI[Na] scintillator
  - 13 PE/keV$_{ee}$ light yield with threshold ≈ 1 keV$_{nr}$
  - Principal uncertainty: quenching of nuclear recoils
  - 6.7σ evidence for CEvNS with rate consistent with standard model expectations



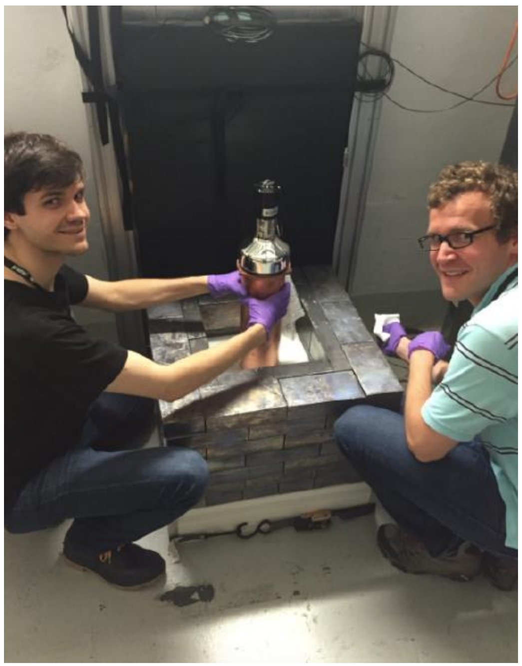
- Also made first measurement of CEvNS in argon in 2021 with CENNS10 detector
  - 4.2 PE/keV$_{ee}$ light yield with threshold ≈ 20 keV$_{nr}$
  - Principal uncertainty: modeling of beam-related neutron background studied with neutron calibrations
  - 3.4σ evidence for CEvNS again consistent with standard model

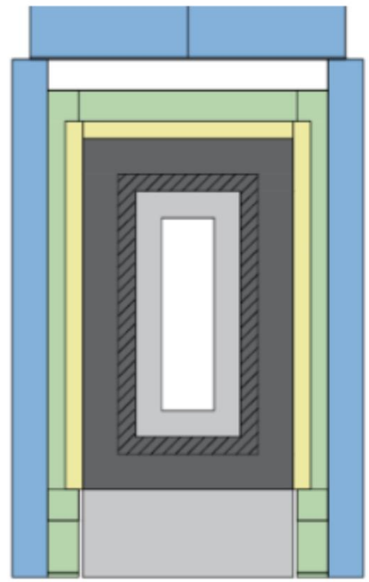


CsI: COHERENT, Science **357** 6356 1123-1126 (2017)
Ar: COHERENT, PRL **126** 012002 (2021)

The COHERENT CsI[Na] detector

A hand-held neutrino detector
– 14.6-kg CsI[Na] crystal
– Manufactured by Amcrys-H
– Single R877-100 PMT



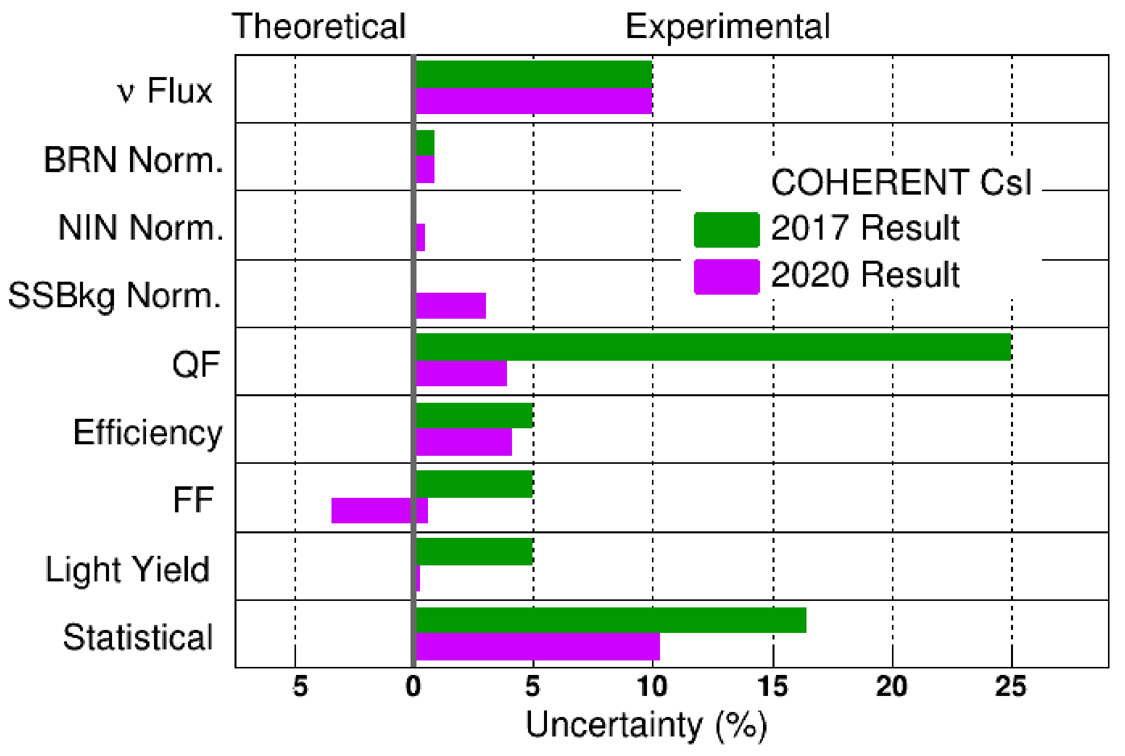


Shielding design

– Veto to tag cosmic events
– Lead to shield from gammas
– Water and plastic to moderate neutrons

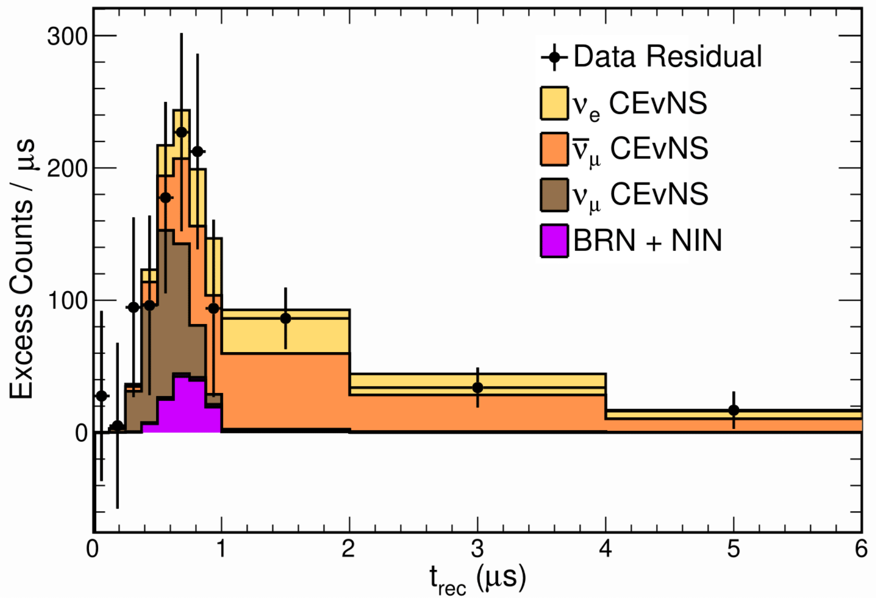
Layer	HDPE*	Low backg. lead	Lead	Muon veto	Water
Thickness	3"	2"	4"	2"	4"
Colour					

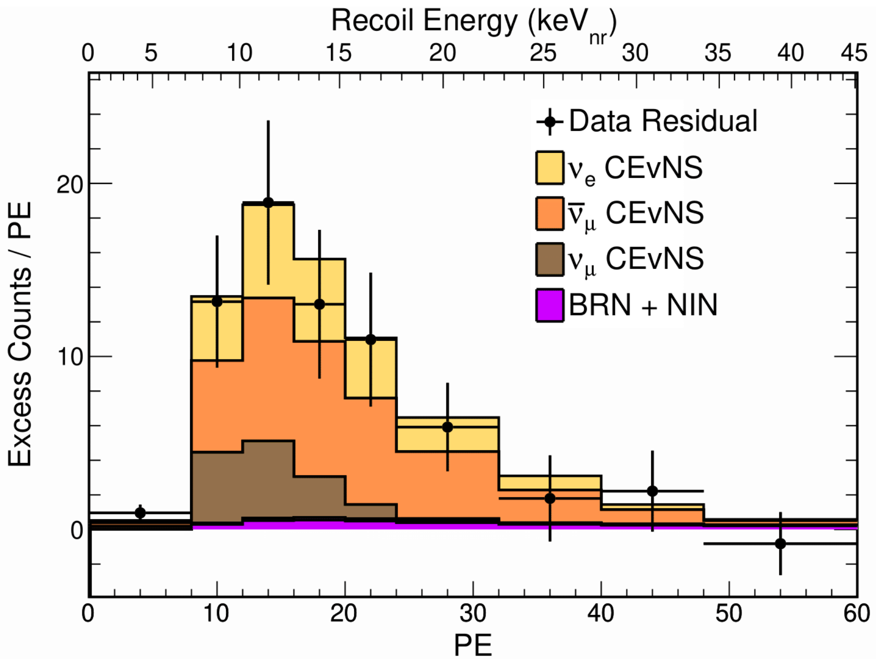
Towards precision measurements with CsI[Na]



- ❑ Doubled dataset from first observation will allow precise tests of CEvNS shape
- ❑ Quenching error improved 25% → 4% by studying newly available data with a better model and fit strategy
- ❑ Overall precision improves 33% → 16%

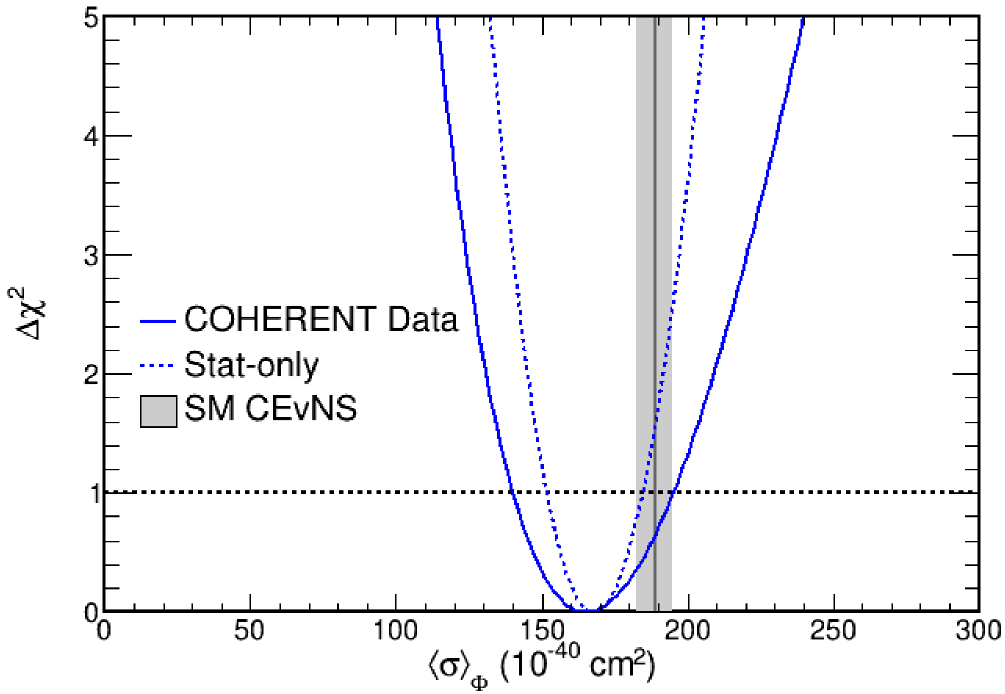
Full-exposure CsI[Na] data





- CEvNS agrees well with standard model prediction in both shape and rate
- At the SNS, CEvNS from ν_μ occur earlier than CEvNS from $\nu_e/\bar{\nu}_\mu$
- This is a lever arm for constraining CEvNS cross sections for different flavors separately
  - Now have collected enough exposure and understand our sample well enough to exploit this information, allowing precision measurements that exploit the SNS flux shape
- Allows independent measurement of CEvNS cross section for different flavors

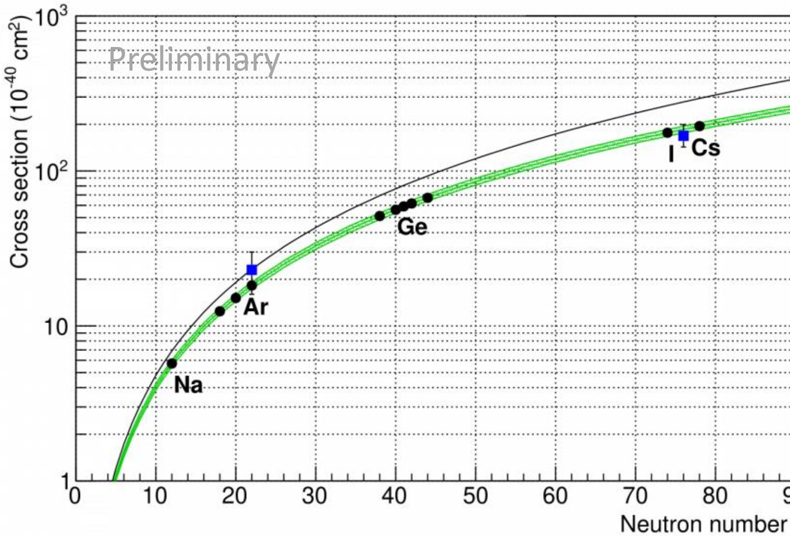
Determining the CEvNS Cross Section



COHERENT, arXiv:2110.07730 (2021), submitted to PRL

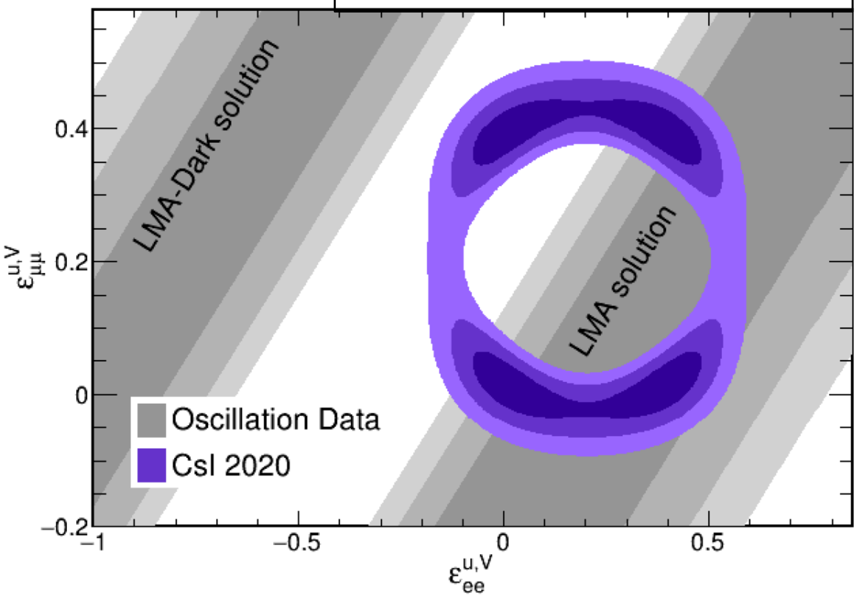
No-CEvNS rejection	11.6 σ
SM CEvNS prediction	341 ± 11(th) ± 42(ex)
Fit CEvNS events	306 ± 20
Fit χ^2/dof	82.4/98
CEvNS cross section	$165^{+30}_{-25} \times 10^{-40}$ cm^2
SM cross section	$189 \pm 6 \times 10^{-40}$ cm^2

- From the observed CEvNS rate, we calculate the flux-averaged cross section
  - Result is consistent with the standard model prediction to 1 σ
- Observed cross section consistent with COHERENT argon result and expected N^2 scaling of cross section



NSI: clarifying solar neutrino oscillation data

Coloma et al., PRD **96** 115007 (2017)



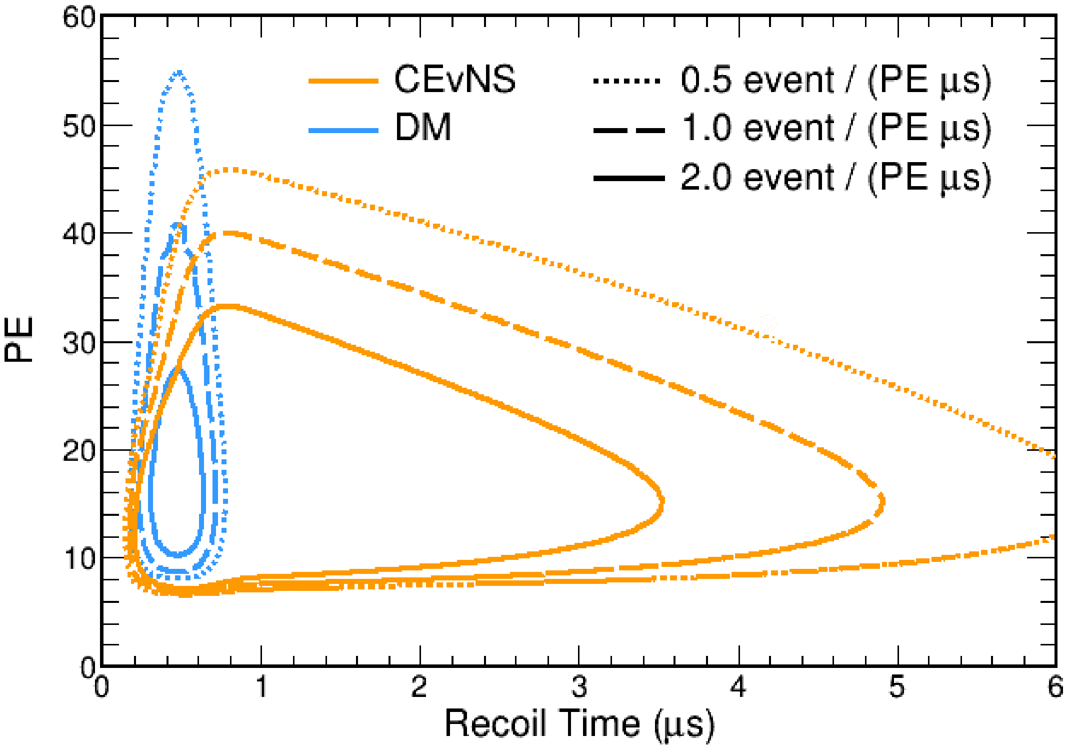
2D Gaussian 1/2/3σ critical up-values

- We can test the LMA-dark neutrino oscillation scenario with CEvNS data
- Ambiguity predicted for
  - Would flip the θ_{12} octant: $\theta_{12} \rightarrow \pi/2 - \theta_{12}$
- LMA-dark would require non-zero $\varepsilon_{ee}^{u,V}$ and $\varepsilon_{\mu\mu}^{u,V}$, which adjust the CEvNS cross section for ν_e and ν_μ flavors differently – tests our sensitivity to CEvNS shape

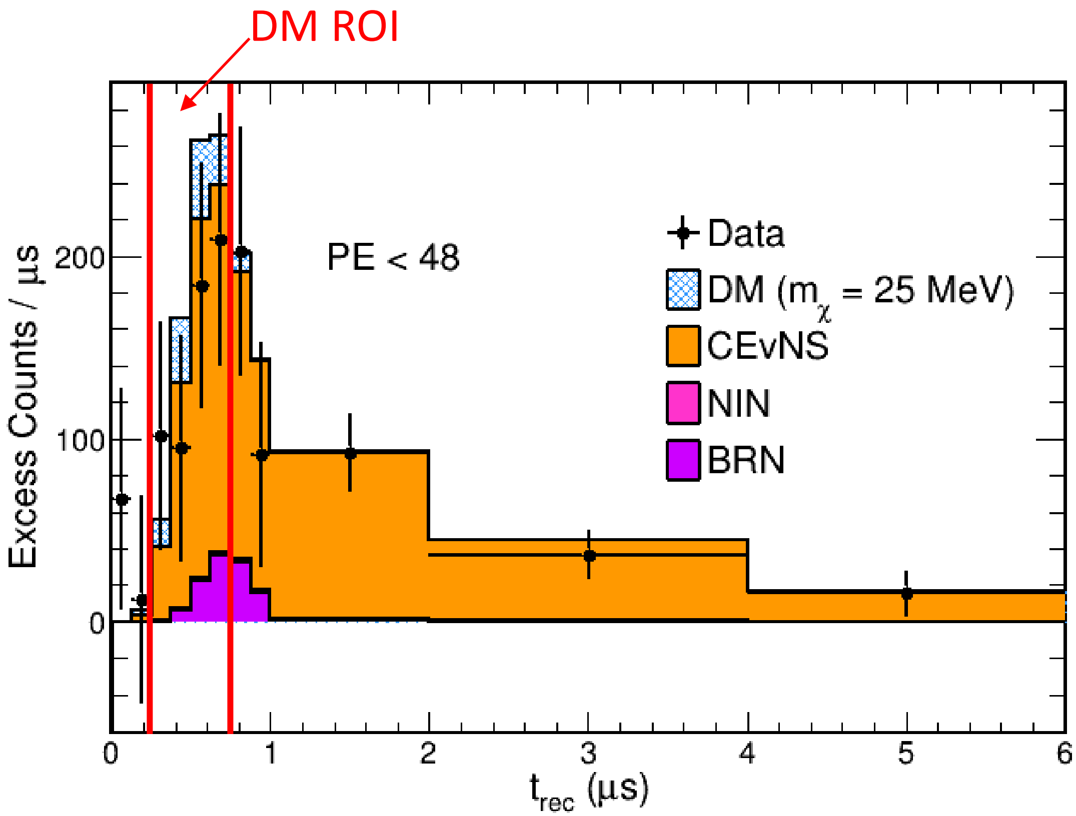
Predicting dark matter events in our sample

DM produced at SNS would give an additional population of nuclear recoils coincident with the arrival of the beam

CEvNS expected in both prompt and delayed regions – 2D fit to data can constrain CEvNS signal for precise DM search



Searching for dark matter in CsI[Na] data



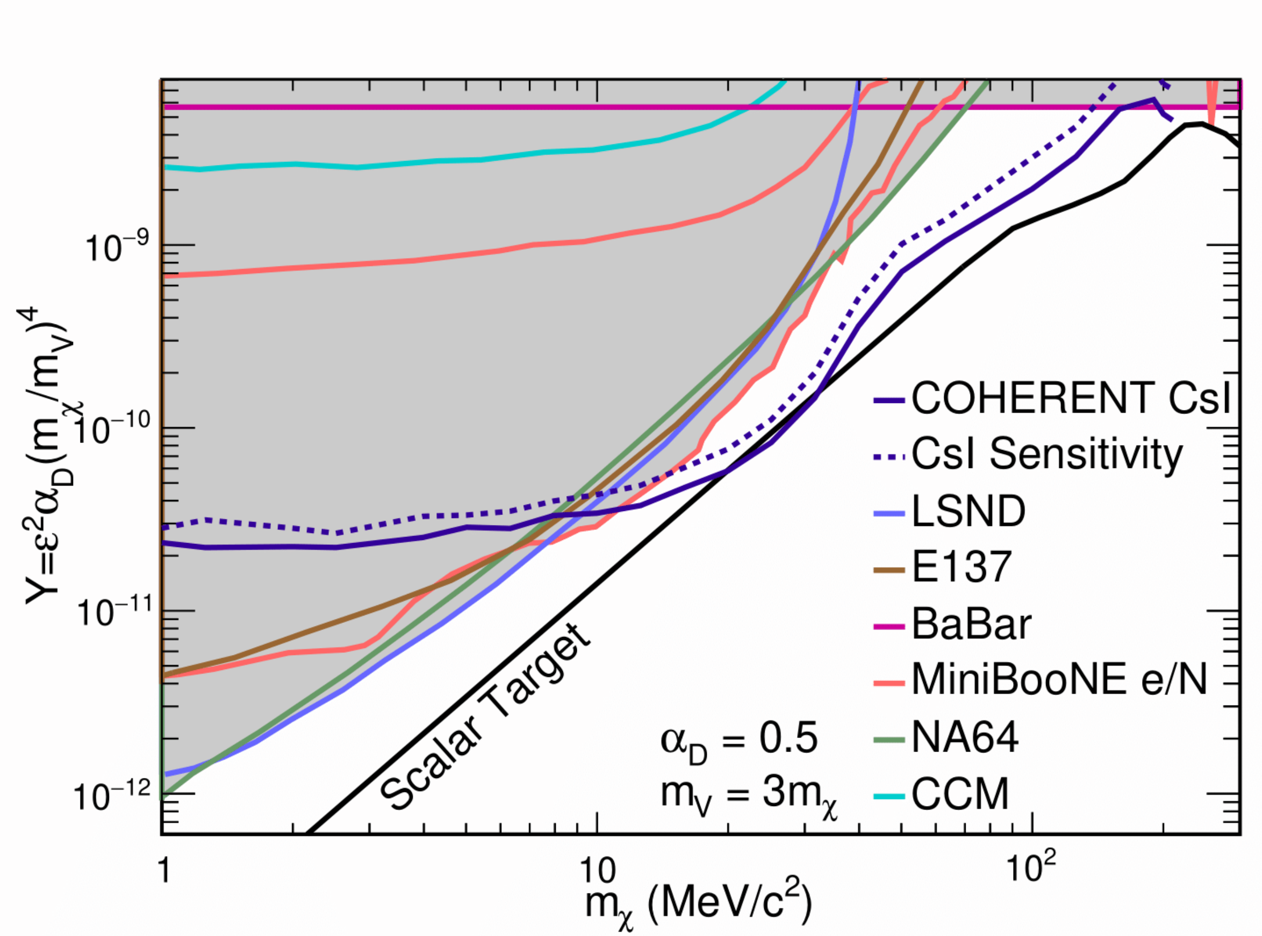
	Prediction	Data
DM		0^{+15}
CEvNS	341 ± 43	320 ± 33
BRN	27.6 ± 6.9	25.8 ± 6.6
NIN	7.6 ± 2.7	7.4 ± 2.7

COHERENT, arXiv:2110.11453 (2021)

- Our data is consistent with predictions for the standard-model backgrounds within expected errors
- In DM signal region, we see a slight deficit relative to the standard-model prediction
  - Doesn't look like a dark matter signal – best we can do is set a limit
  - DM normalization in plot set to 90% limit from our data

COHERENT constraint on sub-GeV dark matter

CsI data significantly improves on constraints for masses 11 - 165 MeV/c^2 and first accelerator search to probe beyond the scalar target for the DM relic abundance

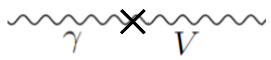


Searching for leptophobic dark matter

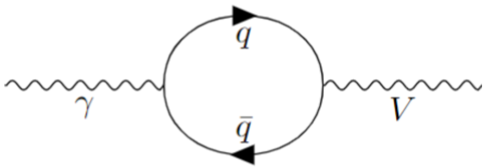
- Above model assumes a general BSM kinetic mixing between photon and portal particle

- Leptophobic dark matter: a specific case of general model – portal couples directly to quarks
  - Interaction Lagrangian: $\mathcal{L} \sim \sqrt{4\pi\alpha_B} V^{\mu} \sum_q \bar{q}\gamma_\mu q$

General kinetic mixing:



Leptophobic dark matter:

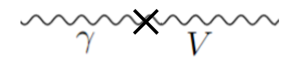


Searching for leptophobic dark matter

New result!

- Above model assumes a general BSM kinetic mixing between photon and portal particle

General kinetic mixing:



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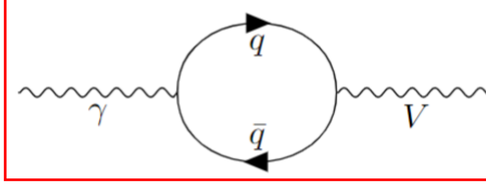
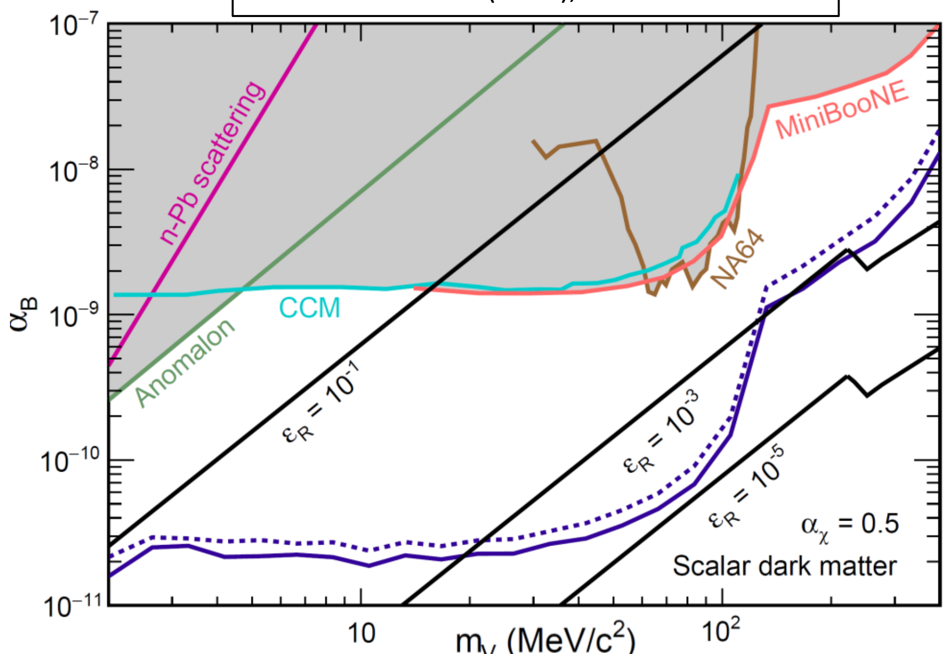
Leptophobic dark matter:



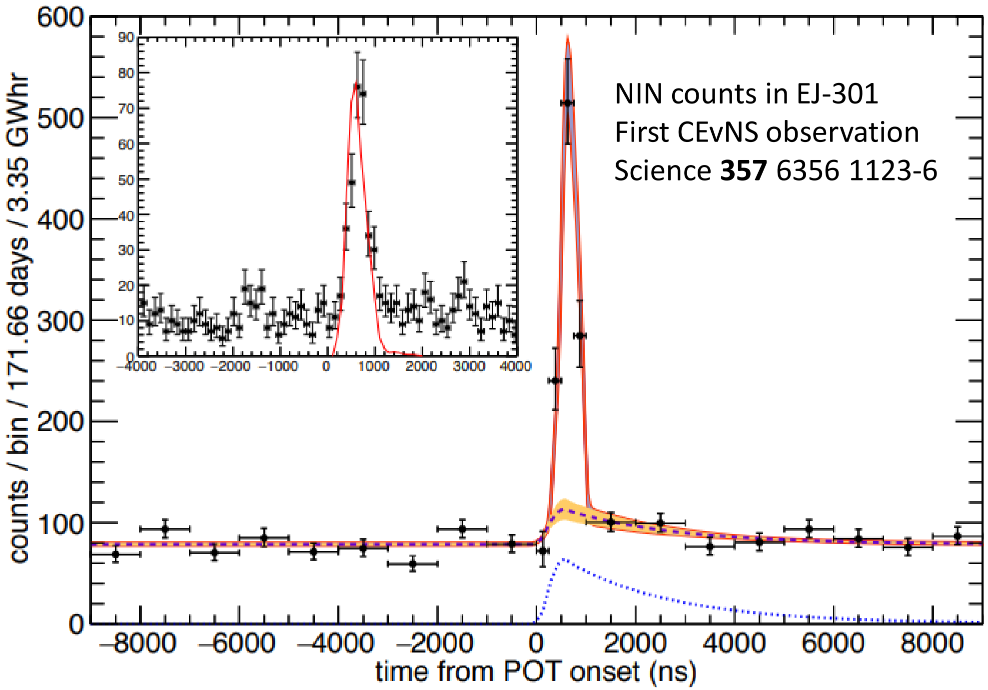
- COHERENT constraint two orders of magnitude stronger than past results
  - Experiments studying electron scattering are not sensitive to this channel
- Possible to probe relic abundance for $m_V/m_\chi \approx 2$ parameterized in terms of $\varepsilon_R \equiv \left(m_V/2m_\chi\right)^2 - 1$
- COHERENT data will soon completely rule out scalar model for $m_V/m_\chi > 2$

New constraint for NDM (May 2022)
arXiv 2205.12414 (2022), submitted to PRD



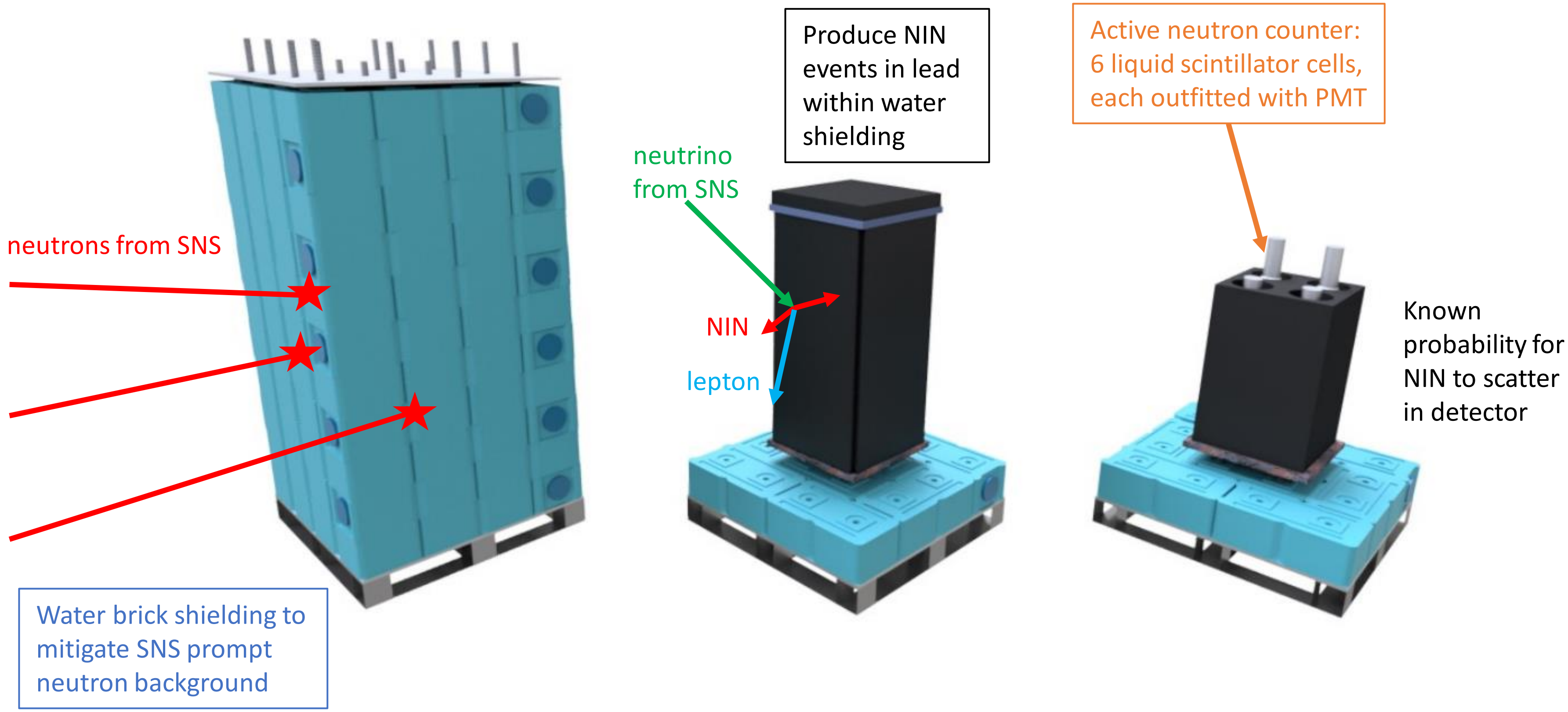
New search for neutrino-induced neutron (NIN) events with COHERENT

First attempt to observe NIN events



- ❑ Two neutron backgrounds for COHERENT: beam-related neutrons (BRN) and neutrino-induced neutrons (NIN)
- ❑ COHERENT deployed an EJ-301 detector in the CsI[Na] shielding to study these
  - Timing fit gives 2.9σ evidence of NIN contribution, with best fit 35% lower than prediction
  - Want to build a detector specifically to study NIN rate to improve understanding

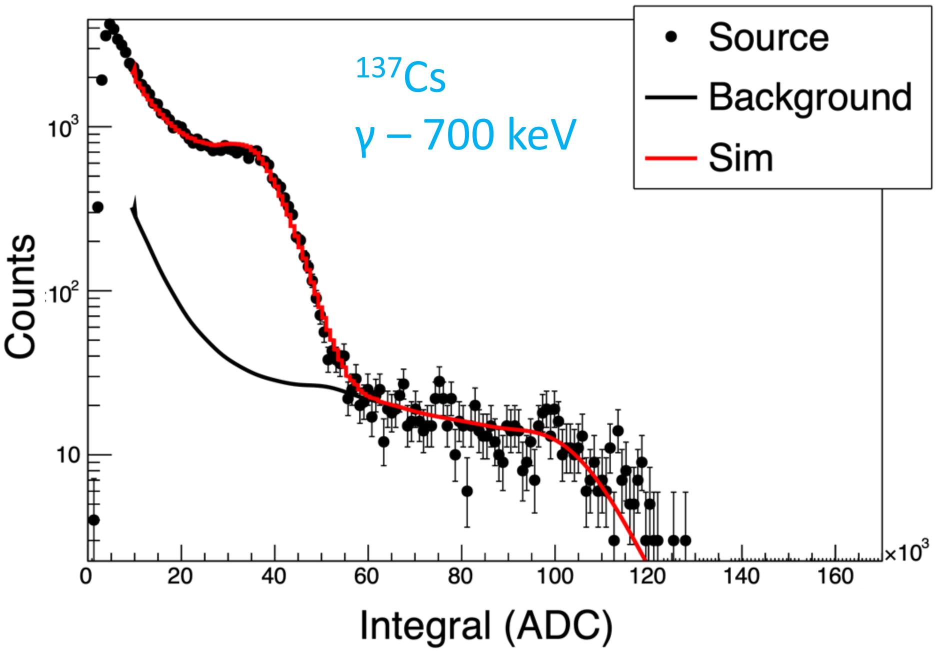
Neutrino cubes (NUBEs) detectors



Dedicated liquid scintillator detectors designed to observe NIN events

Calibrating NUBEs detector

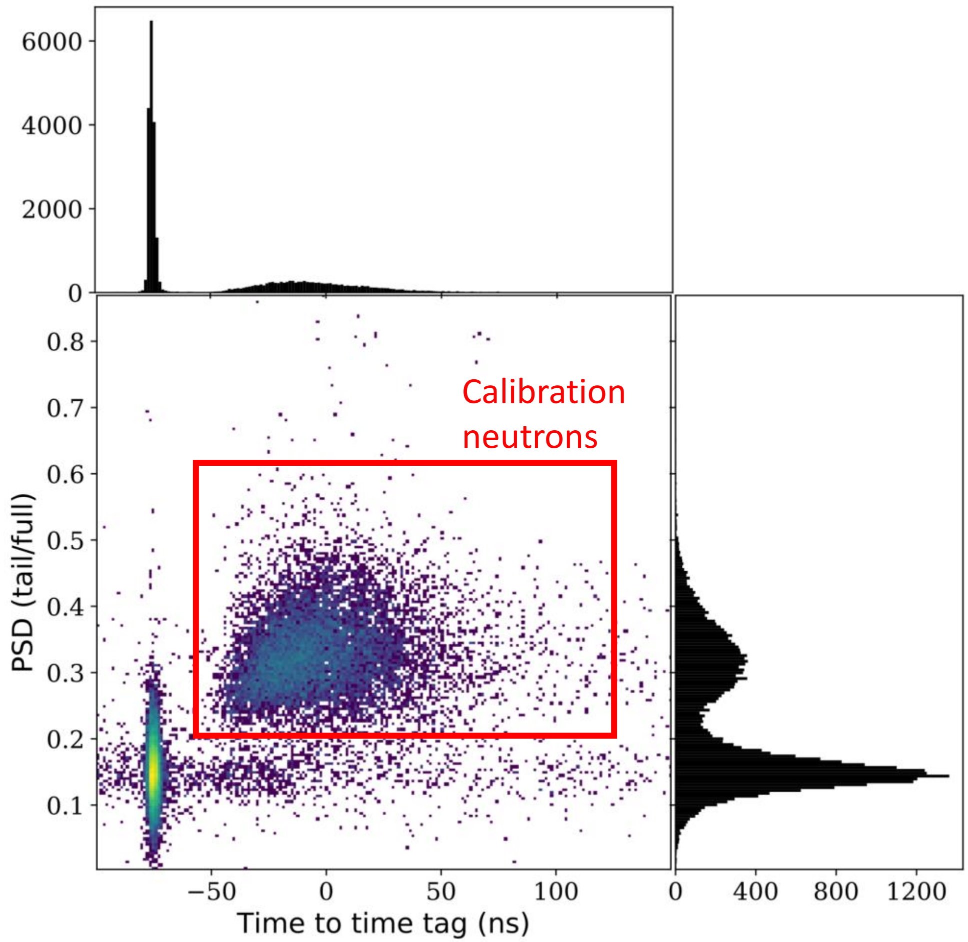
- Light yield determined by source calibration data: ^{133}Ba, ^{137}Cs, ^{22}Na
- Excellent agreement between data and simulation



- Pulse shape discrimination (PSD) between neutron and electron recoils possible in liquid scintillators
- PSD response is calibrated with a time-tagged ^{252}Cf source
  - Populations of neutrons and gammas separable by time-of-flight afford

Calibrating neutron response in NUBEs

- Light yield determined by source calibration data: ^{133}Ba, ^{137}Cs, ^{22}Na
- Excellent agreement between data and simulation



- Pulse shape discrimination (PSD) between neutron and electron recoils possible in liquid scintillators
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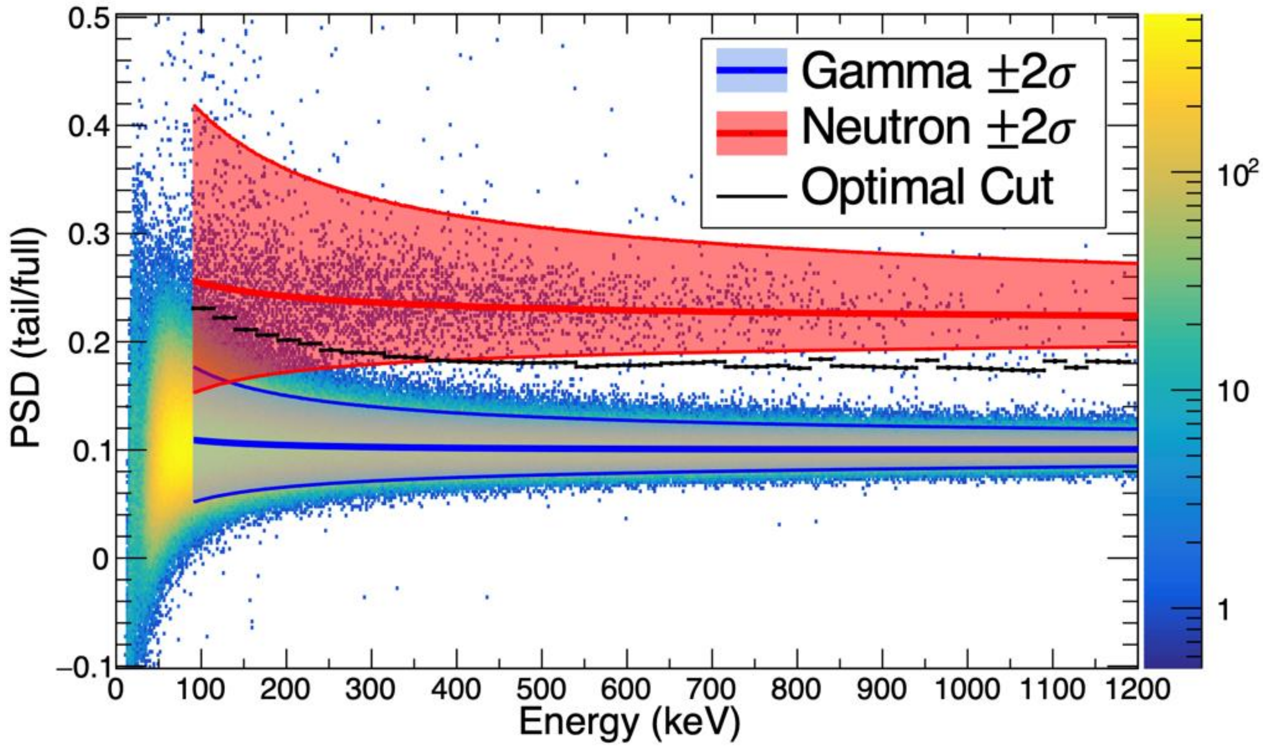
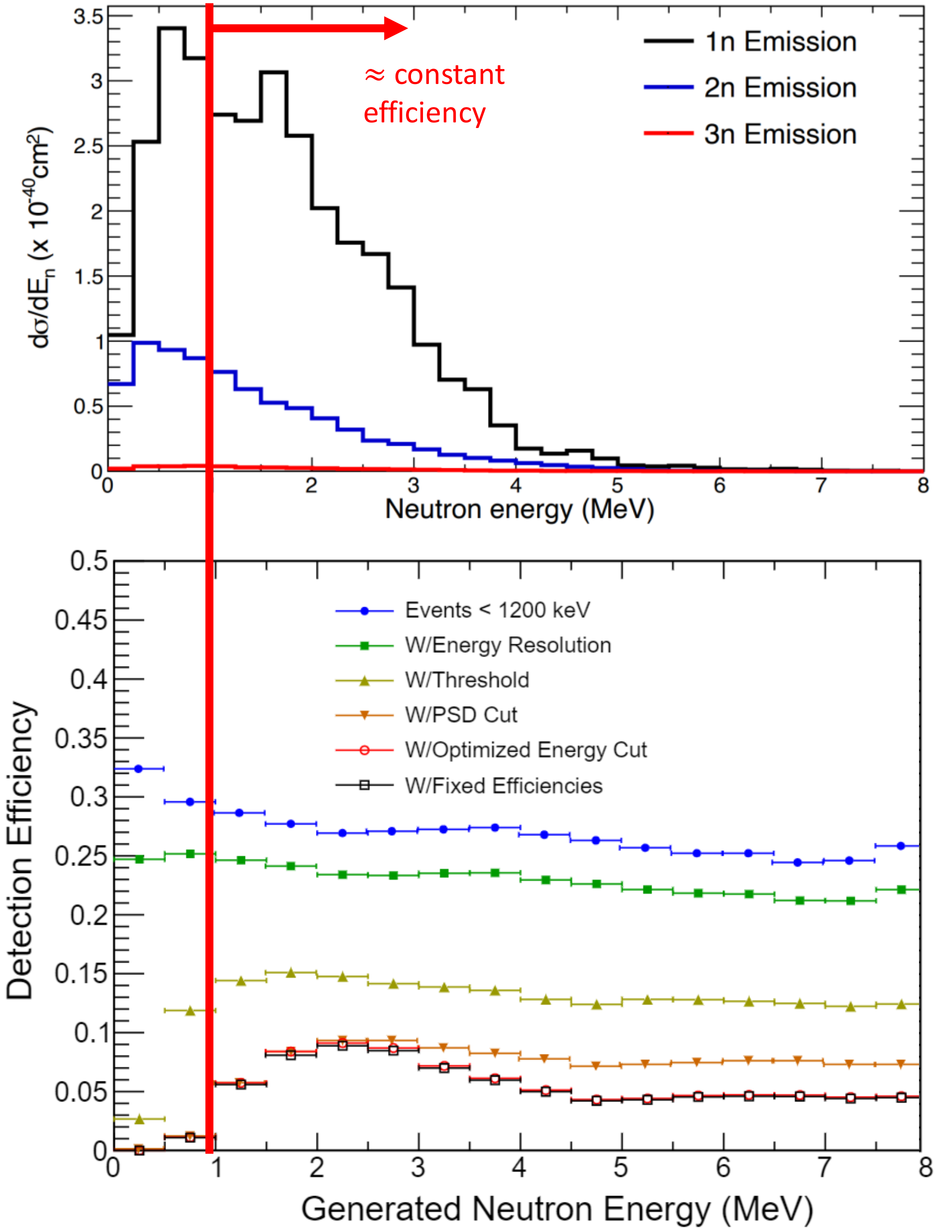
Separating NR/ER recoils with PSD



- Recoil type discernable above ≈ 100 keV_{ee}, set as analysis threshold
- PSD model determined by fitting calibration data in bins of observed energy for signal and background
- Apply an energy-dependent PSD cut determined by optimizing neutron identification over steady-state background

Predicted NIN energy spectrum



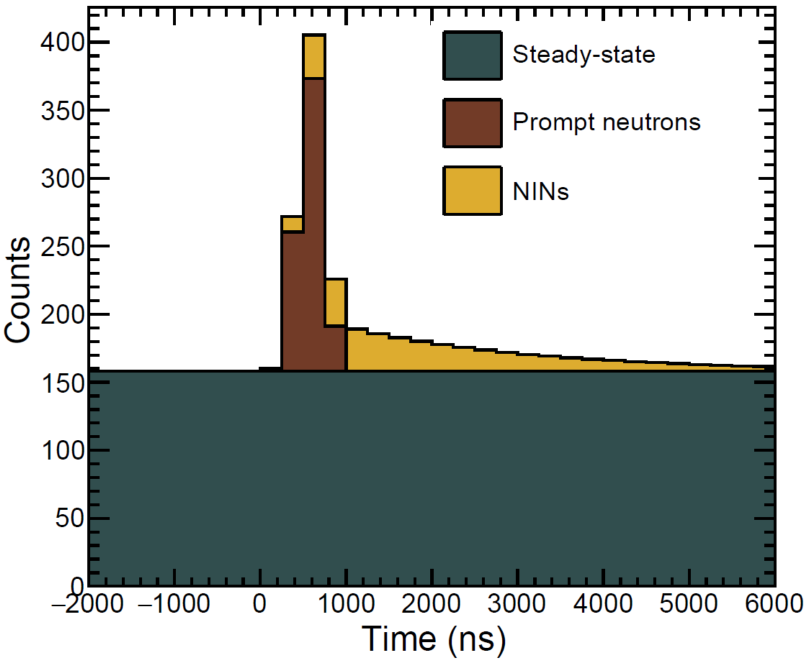
Neutrino interactions simulated with MARLEY offering detailed information about final state particles

MARLEY:
S. Gardiner, Comput. Phys. Commun. **269** 108123 (2021)

Select ≈ 5-10% of produced NIN events, relatively independent of neutron kinetic energy > 1 MeV

Determining NIN normalization from timing

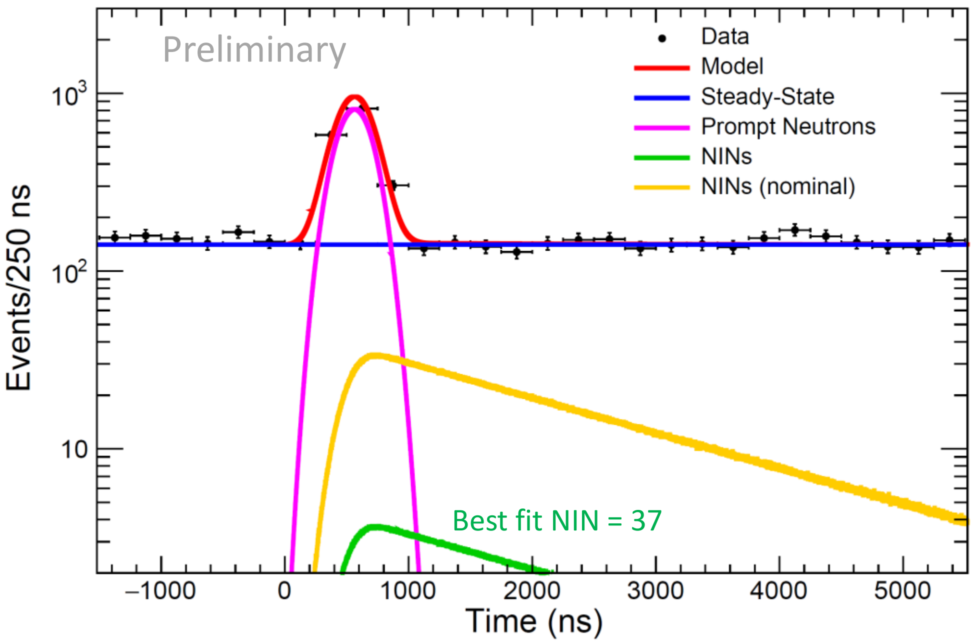
- Expect 346 NIN events in analysis sample
- Main backgrounds:
  - Steady-state – measured from out of time data
  - Prompt neutrons from SNS – normalization not well known, but timing is understood
- NIN and prompt neutron normalizations can be determined with a timing fit
  - Two independent fitters developed to cross-check each other

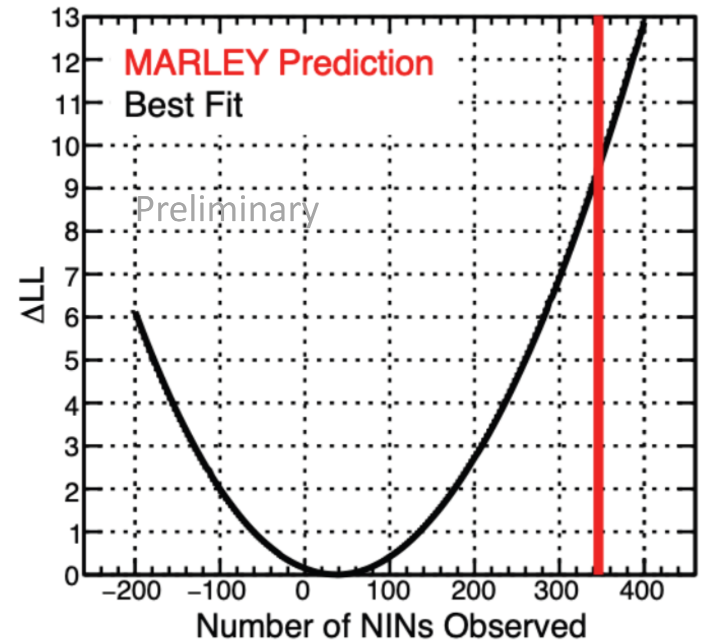


Systematic uncertainties

Neutrino flux normalization (10%)
Prompt neutron arrival time – constrained by neutron timing cells
Prompt neutron timing width due to differences in neutron time of flight

Observed NIN rate





Observed number of NIN events: 37^{+69}_{-37}, inconsistent with MARLEY at > 4σ

Result cross checks

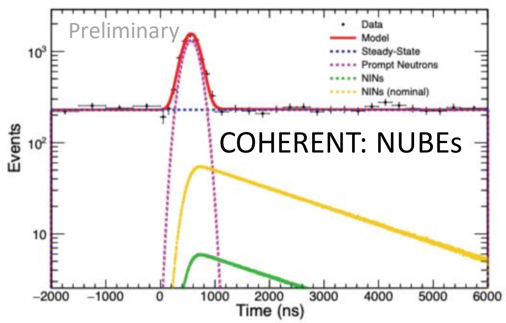
Possible detector simulation underestimates the neutron opacity of our lead -> but lead spec'd at 99.99% pure, consistent with our density measurement of lead used in experiment

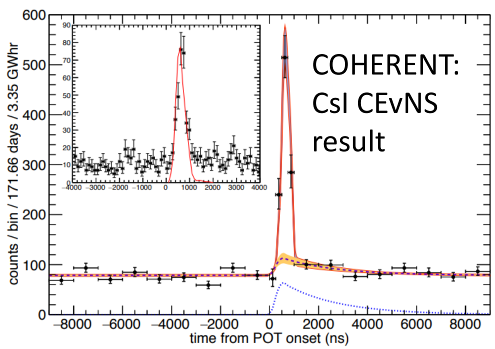
Possible neutron energies much lower than predicted -> additional fit of low recoil energy neutrons that was not included in analysis due to increased uncertainty on PSD behavior. Fit consistent with above rate and was sensitive to all neutron energies > 0.5 MeV

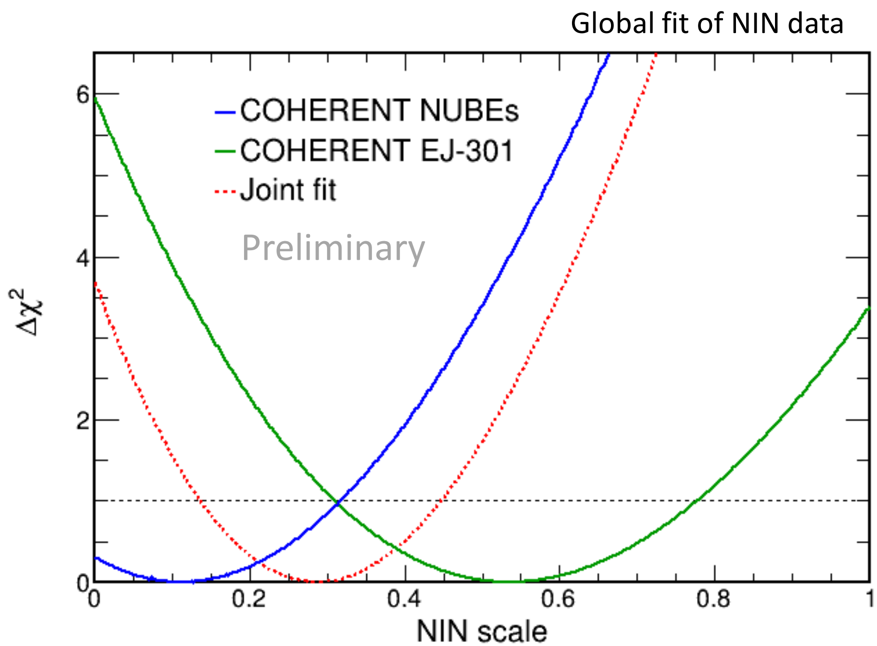
Possible changes in neutron efficiencies with time -> prompt neutrons track with beam exposure

Global NIN data from COHERENT

New result!





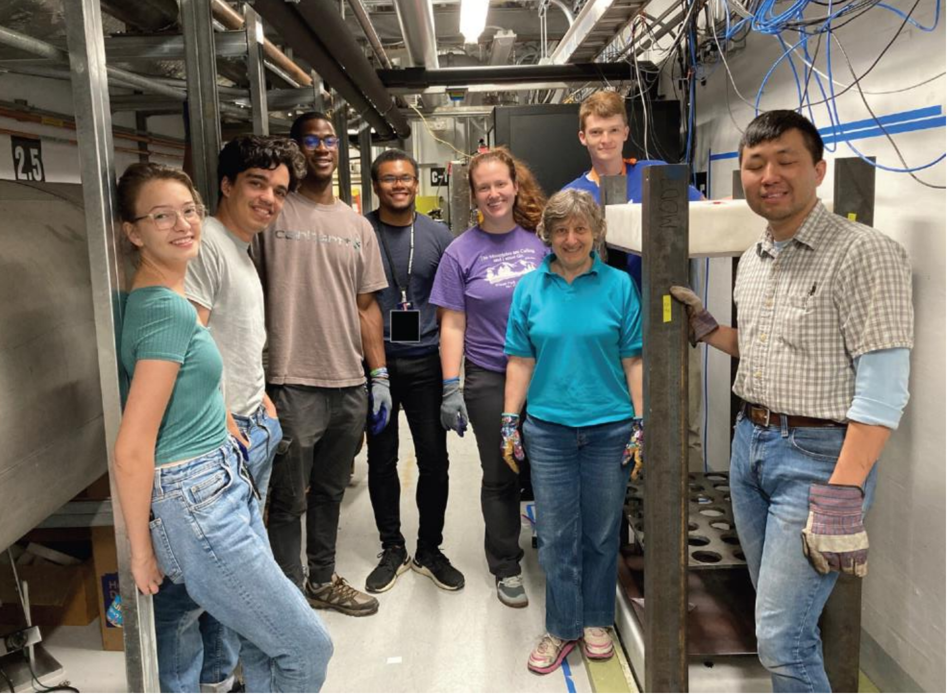


- Perform a joint fit of COHERENT NIN data from NUBEs and EJ-301 scintillator cells
  - Before box-opening, EJ-301 data reassessed with updated uncertainties on prompt neutrons timing profile -> significance of NIN observation dropped 2.9σ to 2.3σ
- Best fit NIN rate is $0.29^{+0.16}_{-0.15}$ × the MARLEY prediction and consistent with both NUBEs and EJ-301 datasets at about 1σ

Future measurement form DaRveX – arXiv:2205.11769
COHERENT working on next-stage NIN detector

Future for COHERENT at the SNS

The future is happening: commissioning at the SNS summer 2022



E. Nieuwenhuizen, R. Bouabid, E. Ujah, T. Johnson, A. Major, D. Markoff, J. Runge, B. Suh

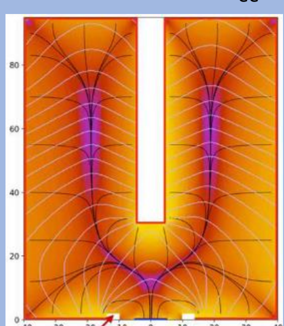
nuThor installed at SNS

COH-Th-1 (nuThor)

18-kg Th with neutron counters
Neutrino-induced fission – high neutron multiplicity events

COH-Ge-1 (GeMini)

18-kg Ge PPC detector
Precision CEvNS measurements
Low-threshold (0.4 keV_{ee})

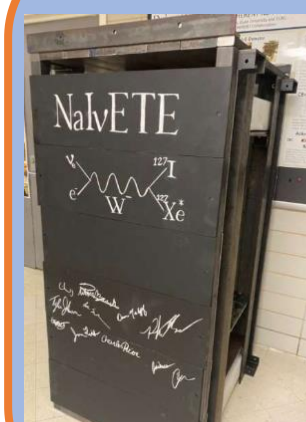


E-field for e⁻ drift charge

Cryo test for Canberra PPC

COH-NaI-2 (NaIvETe)

3.5-t scintillation detector
CEvNS search and CC
High/low gain digitization



500 kg test assembly

Crystal characterization

COH-D2O-1 (R2D2O)

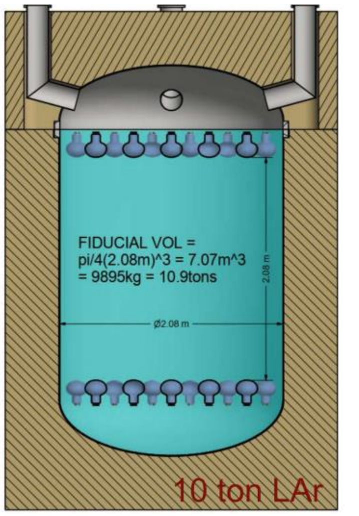
600-kg heavy water detector
Normalize SNS neutrino flux from d(υ,e) rate

PMT tests in water

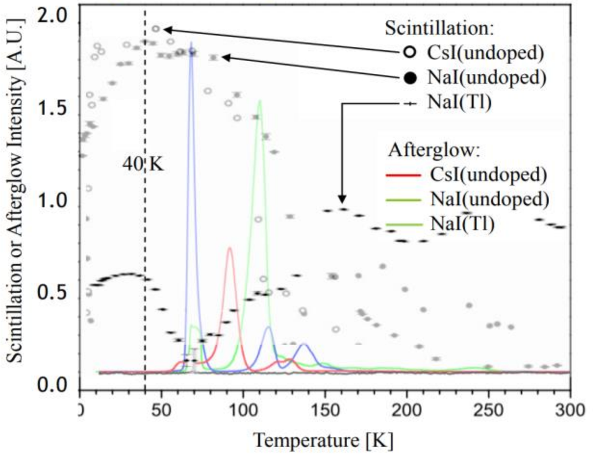
+ I. Bernardi, M. Hughes, E. Ward

Future COHERENT CEvNS detectors

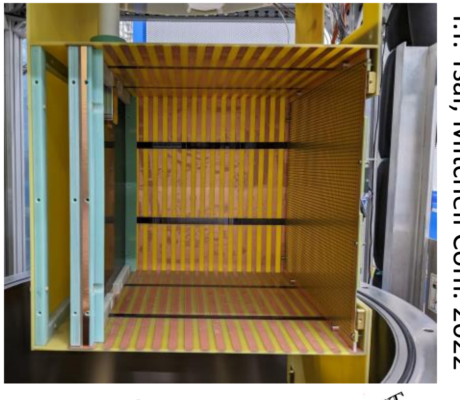
- Upgrades of 24-kg argon scintillation calorimeter, but larger!:
  - COH-Ar-750: 610-kg fiducial volume
    Recent funding from Korea National Research Foundation (Jun 1, 2022)
  - COH-Ar-10t: 10-t fiducial volume
- Both designs will measure CEvNS, search for DM / other BSM signatures, and study ν_e CC inelastic interactions



D. Chernyak et al., Eur. Phys. **C80** 547 (2020)



- Upgrade of COHERENT CsI[Na] detector: array of cryogenic, undoped CsI scintillating detectors
  - Cooling undoped CsI to 40 K increases the crystal light yield while also eliminating background scintillation within the crystal (afterglow light)
- Can deploy 10(700) kg of crystal with a threshold of ≈ 0.1 keV_{ee} at the first(second) target station

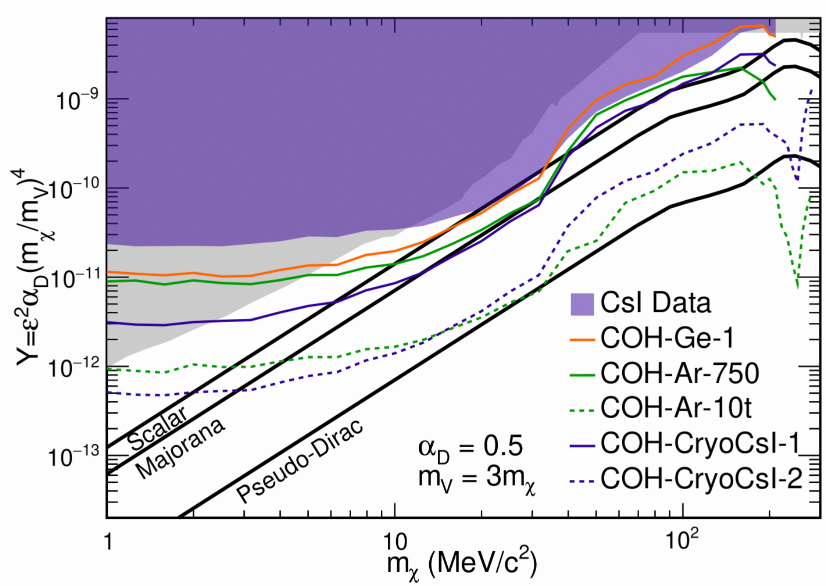


Y.T. Tsai, Mitchell Conf. 2022

- Deployment of first argon TPC in neutrino alley
- Precise reconstruction, particle identification, and channel tagging of 10-50 MeV neutrino interactions on argon

Physics goals for CEvNS at the SNS

- Search for dark matter with strong sensitivity
  - Larger exposure
  - On-axis detector to increase DM/CEvNS ratio
- Can explore expected relic abundance of DM for scalar and fermionic scenarios
- Test of lepton-flavor universality of CEvNS
- Timing differences in ν_e/ν_μ fluxes allow 1% test of difference in flavored cross sections
- Explore exotic oscillation phenomena
- Will cover parameter space favored by LSND / MiniBooNE and other short-baseline oscillation searches
- Unique opportunity at SNS – measure oscillations on two baselines using data from first and second target stations



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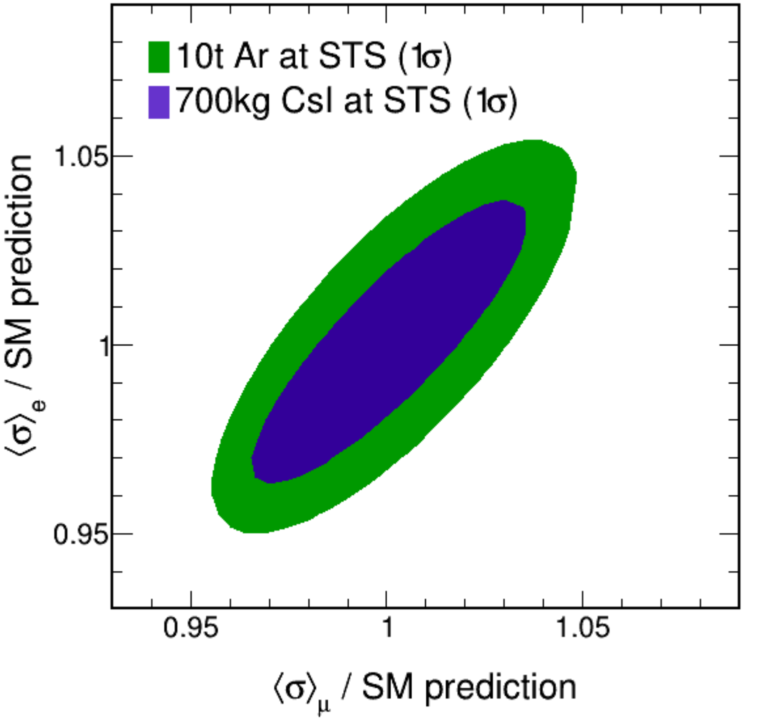

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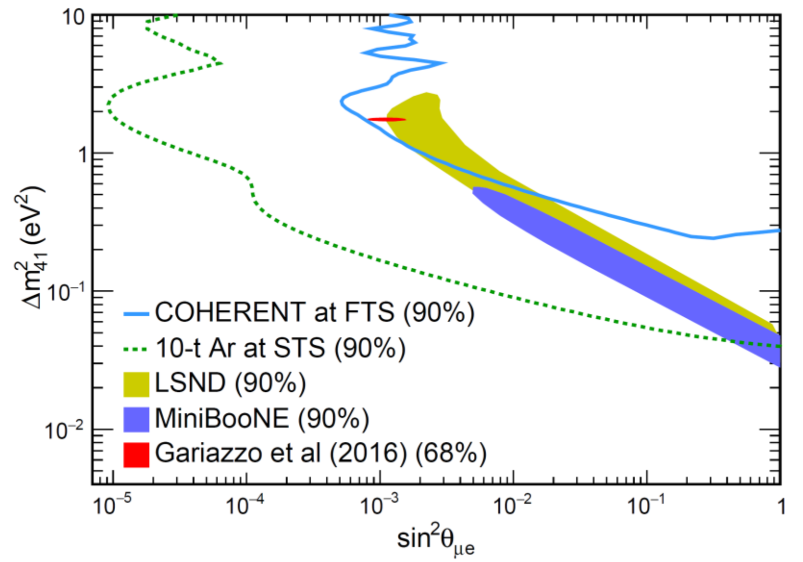


Summary

- COHERENT continues its campaign to measure CEvNS, search for new physics, and other low-energy neutrino scattering processes
- First measurement from NUBEs detectors to measure NIN cross section
- Currently deploying four detectors at the SNS
- New detectors to design and implement over coming decade/


COHERENT
SNS

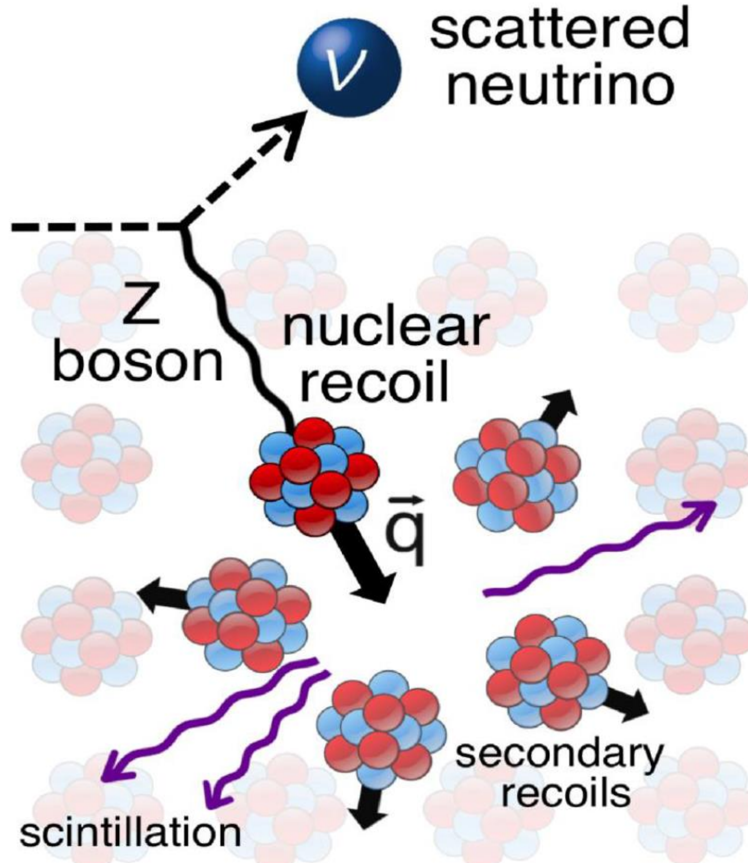
Backup

Nuclear recoil signature

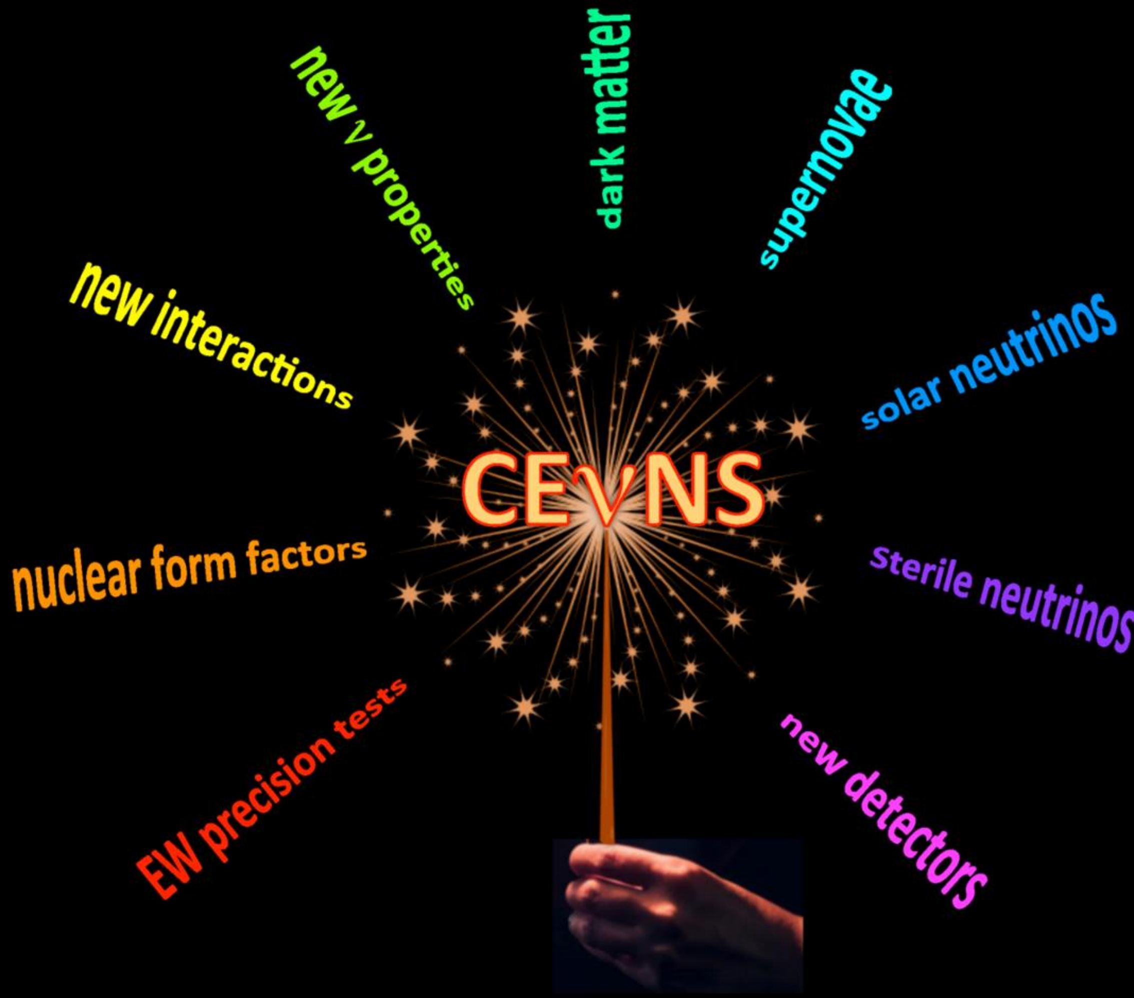
- The struck nucleus acquires a small recoil energy
  - Max recoil energy is $2E_\nu^2/M$
  - For a 30 MeV neutrino, this gives a max recoil of 15 keV (CsI) and 48 keV (Ar)

1: Need a detector with a very low threshold
  - Recent advances in dark matter detection has made keV-scale thresholds possible

2: Will need to place detector in a large neutrino flux – SNS!



Why measure CEvNS?



E Lisi, Neutrino 2018

CEvNS disambiguates neutrino oscillation data

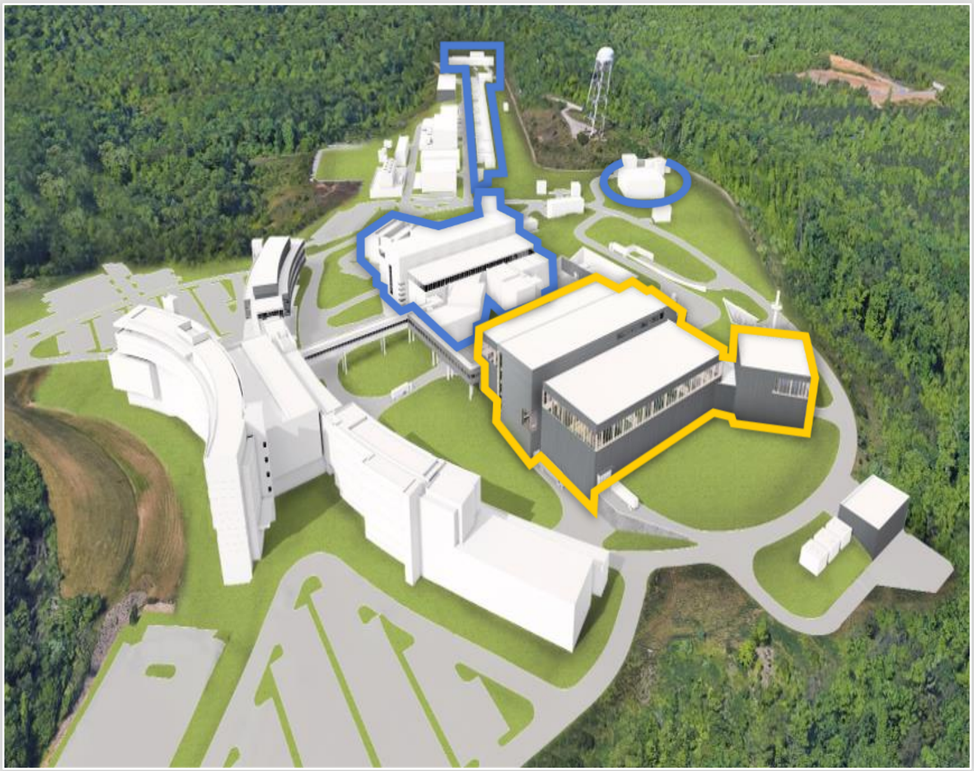
$$\Delta m^2_{31} \to -\Delta m^2_{31} + \Delta m^2_{21} = -\Delta m^2_{32}\,,$$
$$\sin\theta_{12} \leftrightarrow \cos\theta_{12}\,,$$
$$\delta \to \pi - \delta\,,$$
$$(\epsilon_{ee} - \epsilon_{\mu\mu}) \to -(\epsilon_{ee} - \epsilon_{\mu\mu}) - 2\,,$$
$$(\epsilon_{\tau\tau} - \epsilon_{\mu\mu}) \to -(\epsilon_{\tau\tau} - \epsilon_{\mu\mu})\,,$$
$$\epsilon_{\alpha\beta} \to -\epsilon^*_{\alpha\beta} \qquad (\alpha \neq \beta)\,.$$

Coloma et al., Phys. Rev. **D96** 115007

- NSI affects neutrino oscillation probabilities – in the existence of NSI scenarios,
- In fact, a complete degeneracy exists with a properly chosen $\varepsilon^q_{\alpha\beta}$ matrix and neutrino mixing parameters that would transform $H \to -H^*$ and thus be completely indistinguishable from a scenario with no NSI assumed

- To make matters worse, this transformation would suggest that oscillation data would prefer the opposite **neutrino mass ordering** and a different value of $\boldsymbol{\delta_{CP}}$
  - Normal MO without NSI and Inverted MO with NSI give equally good fits!

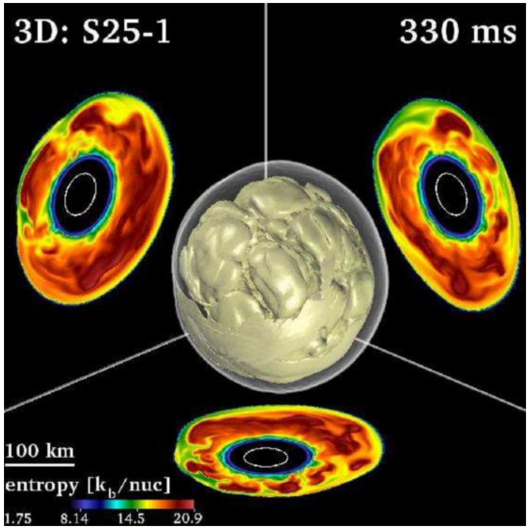
Construction of the Second Target Station (STS)



- Second target station expands the neutrino program at SNS ≈ 2030 offering simultaneous operation of both targets
- Collaborating with lab to design specialized detector halls for large CEvNS detectors

Detecting supernovae with NIN interactions

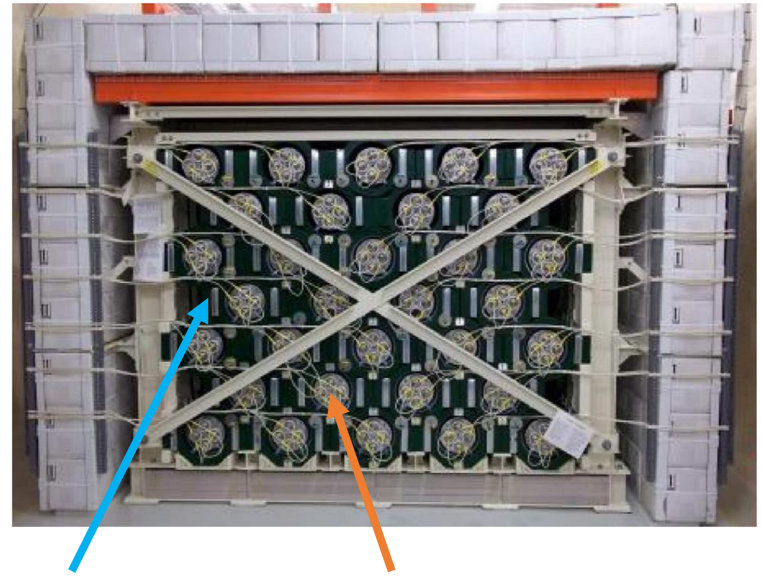
F. Hanke et al., ApJ 770 66



Dying massive star releases > 99% of gravitational binding energy as a burst of neutrinos, detectable on Earth from across the galaxy

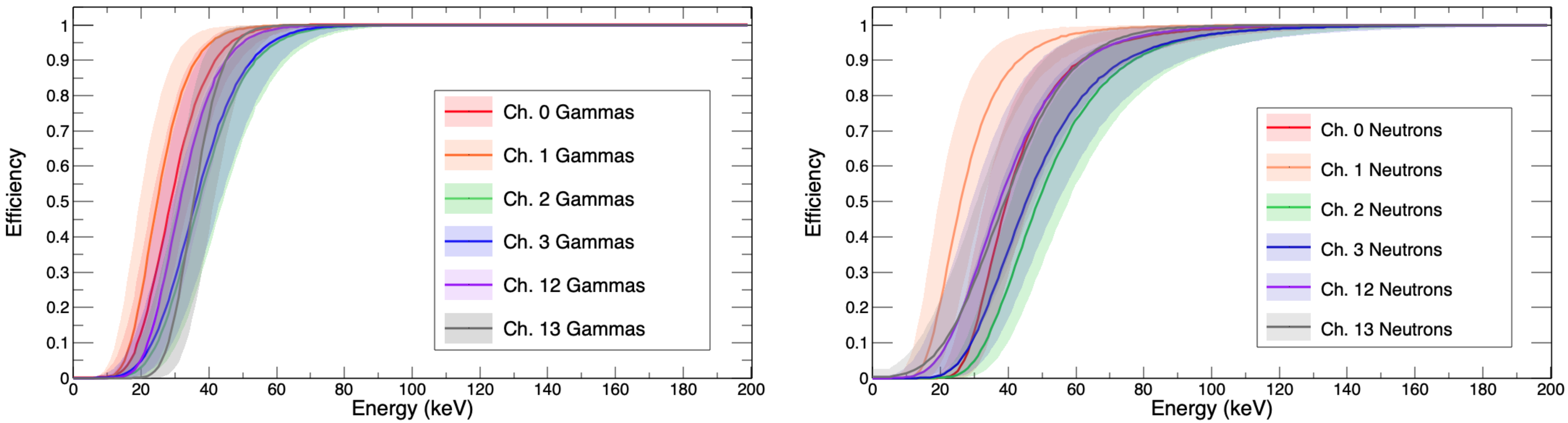
ν_x flux travels ≈ 10 kpc

HALO observatory, SNOLAB



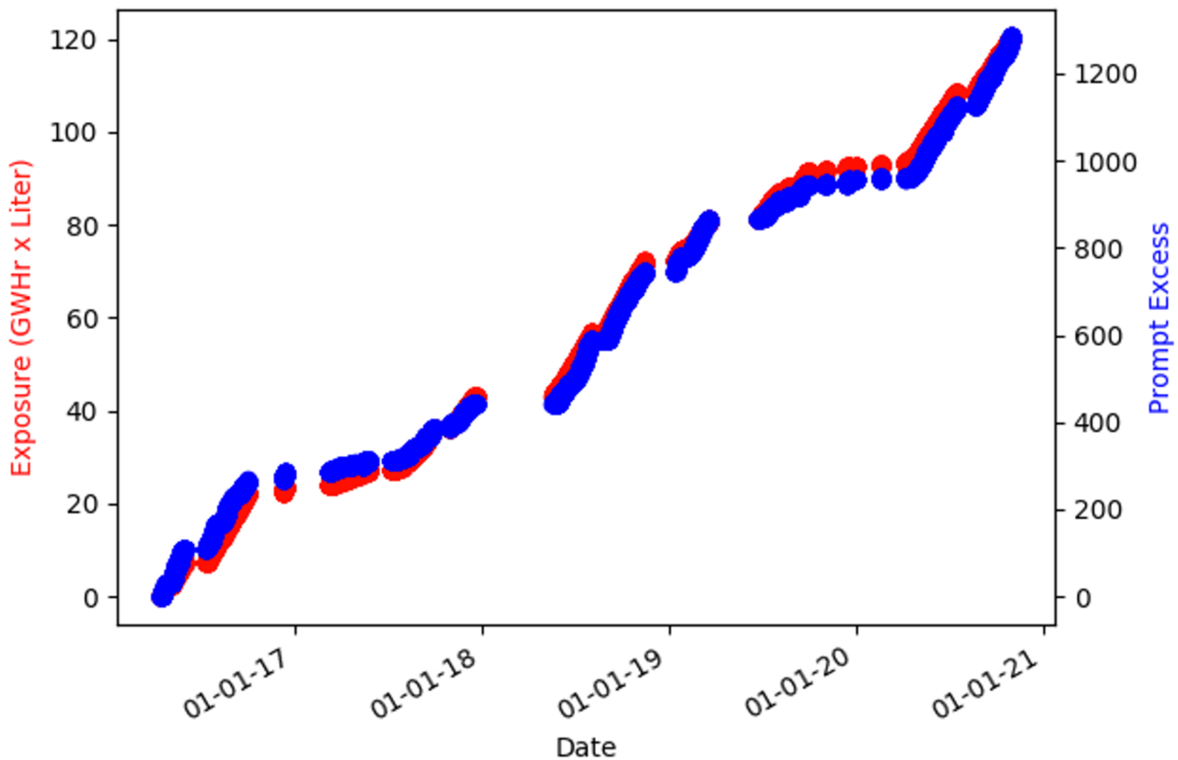
- NIN channel used to detect neutrinos from a core-collapse supernova
- HALO detector will see about 40 ν_e events from a supernova at 10kpc
  - 80t lead target volume
  - Detection with ^{3}He counters achieving 28% neutron efficiency
- Plans for upgrade to HALO-1kt detector which could see > 1000 ν_e events

Selecting recoil events in NUBEs



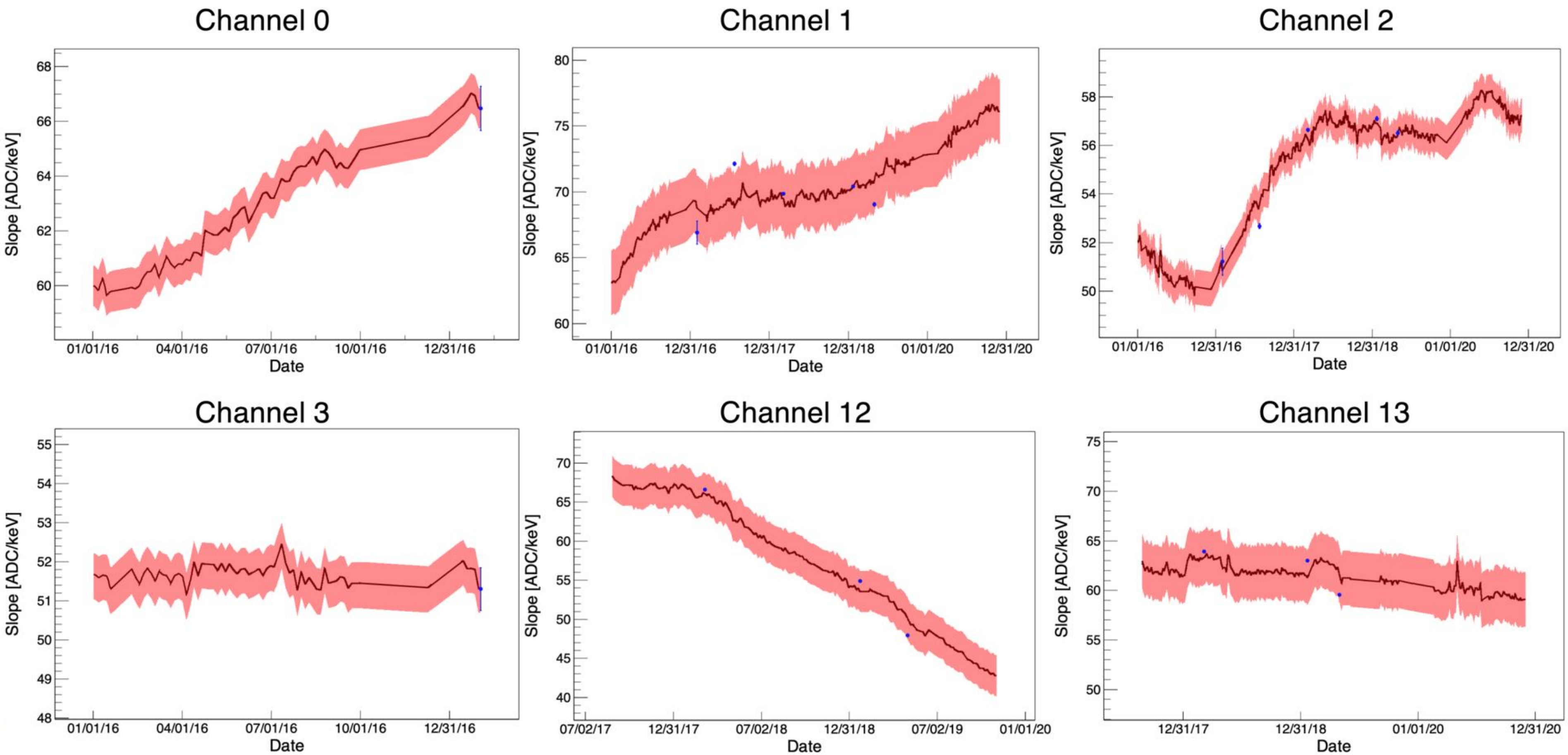
- PSD fit performed for each scintillator cell separately, yielding separate efficiency curves
- Threshold set to ≈ 100 keV where uncertainty on neutron efficiency is low
  - Threshold determined for each detector channel separately
- Curves calibrated with ^{252}Cf data – no reliance on simulation

Monitoring neutrons during data collection



- Prompt neutrons from SNS give convenient check of neutron selection efficiency during beam operations
- Rate of prompt neutrons consistent with accrual of beam exposure

Monitoring NUBEs detector response stability



❑ Calibration of each channel run over course of detector running to track changes in response which are incorporated into analysis