NuInt 2022, Seoul National University

Review of the COHERENT Experiment

Dan Pershey – Duke University
Oct 27, 2022

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

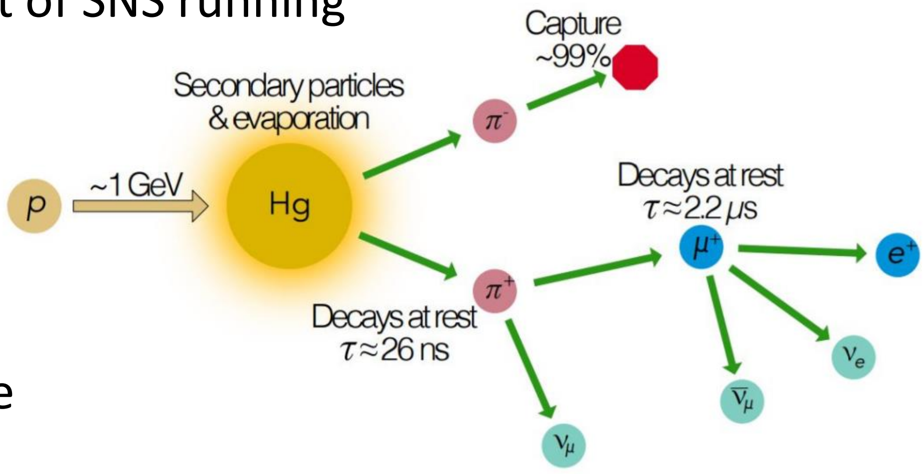
- ❑ A premier neutron accelerator complex which produces an incredibly intense flux of low-energy neutrinos with exciting physics agenda complementary to its neutron studies
- ❑ In early stages of upgrade to double accelerator power and increase beam energy
- ❑ The Proton Power Upgrade (coming few years):
  - 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

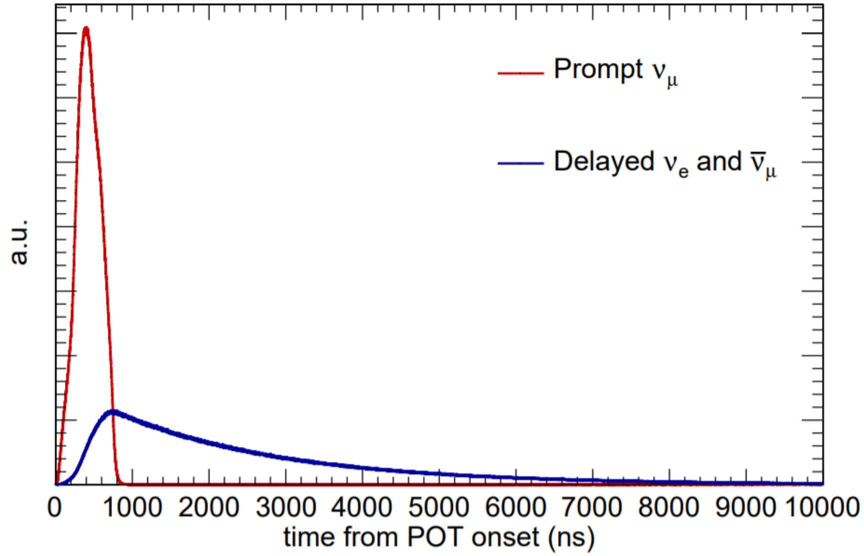
$$\pi^+ \rightarrow \mu^+ + \nu_\mu \quad : \ \tau = 26 \text{ ns}$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \quad : \ \tau = 2200 \text{ ns}$$

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

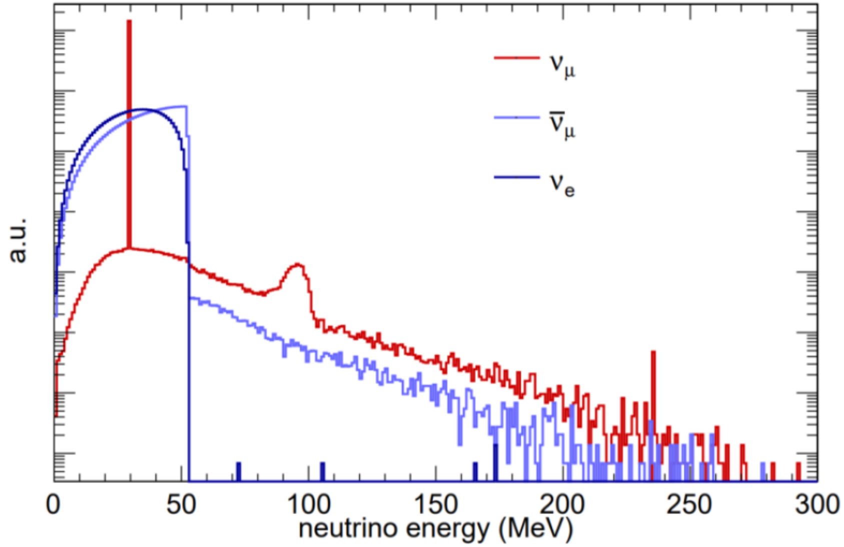


- Flux shape is very well known in both time and energy with very small contribution from decay in flight

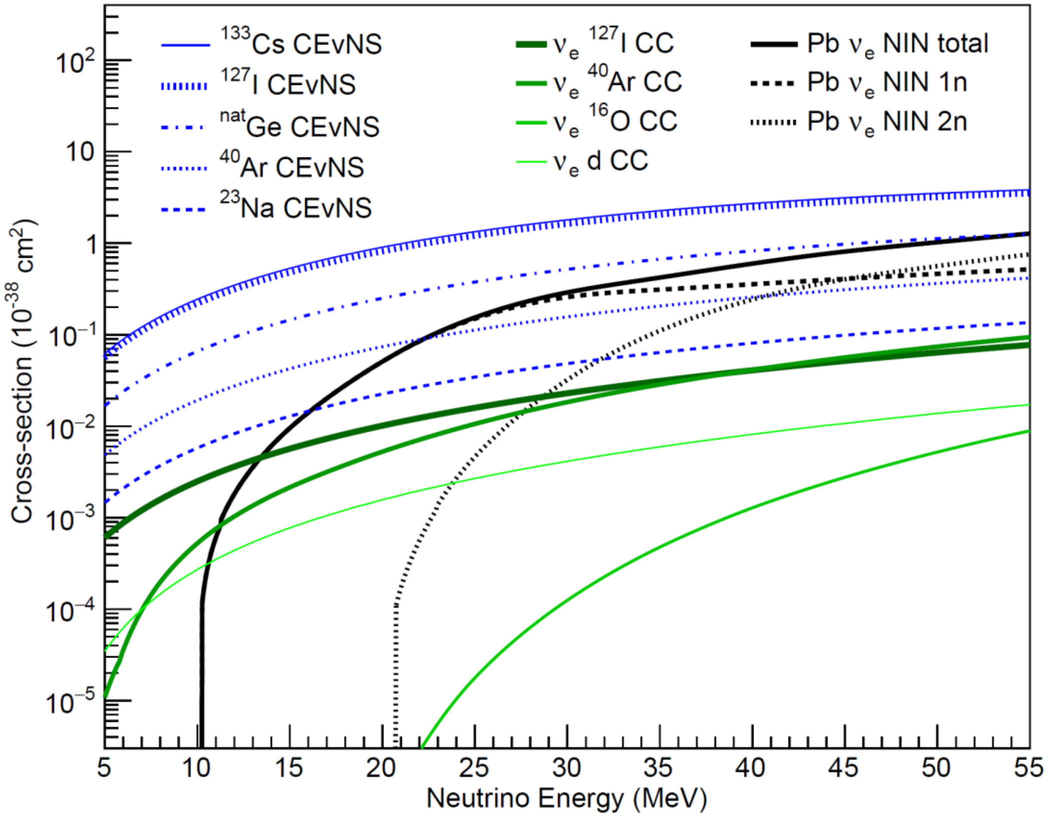
Timing distribution at SNS



Energy distribution at SNS



Low-energy neutrino scattering at the SNS

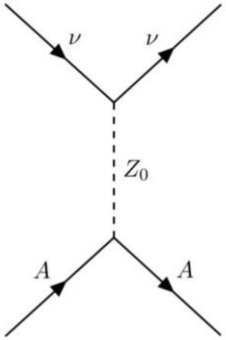


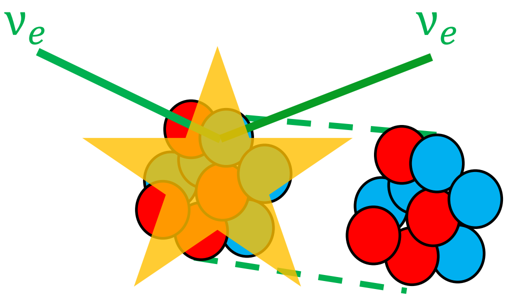
Several scattering processes contribute in the SNS flux region of interest, all of which have not been measured or are poorly measured outside the SNS

Coherent Elastic Neutrino Nucleus Scattering (CEvNS)

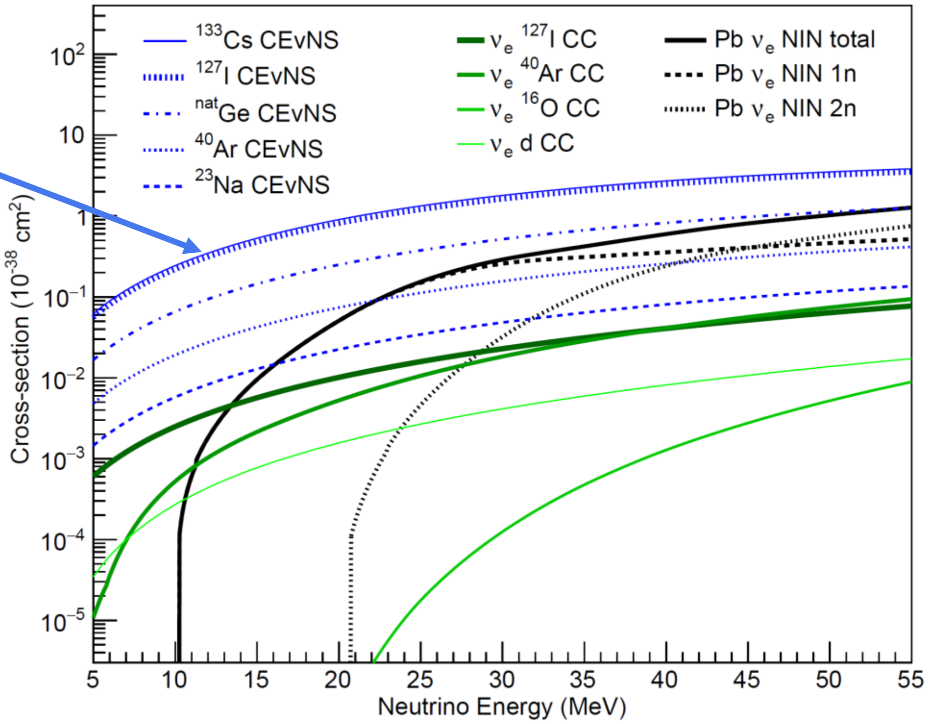
CEvNS

Large blue curves





$$\lambda = h/\sqrt{Q^2} \gg R_p$$



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

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

- ☐ Very large cross section, compared to low-energy neutrino processes
- ☐ Cross section also precisely predicted by standard model
  - Measurements within reach of kg-scale detectors with 10t-scale detectors capable of precision BSM tests

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: $\varepsilon^{N}_{\alpha\beta}$ $(\alpha, \beta \in e, \mu, \tau)$

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

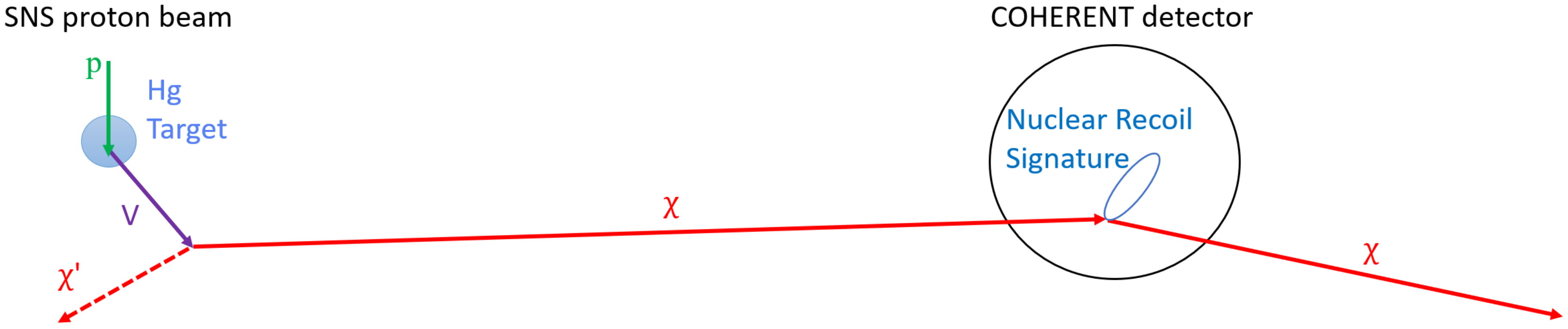
Barranco et al., JHEP **12** 021 (2005)

- 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)

Searching for dark matter with CEvNS detectors

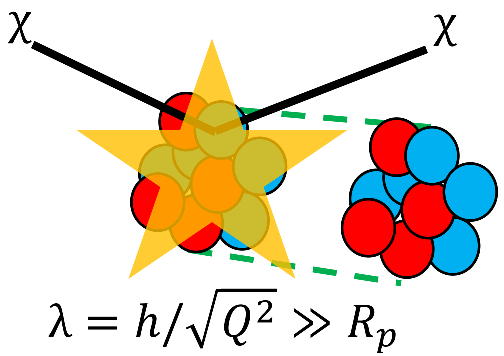


- A CEvNS detector at the SNS operates like a standard beam dump experiment
- Any hidden sector particles with masses below ≈ 220 MeV/c^2 could be produced in the many proton-Hg interactions within the SNS target
- May include mediators between SM and dark matter particles – probe vector portal to DM

- 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)

Advantages of low-recoil detectors: cross section



- ❑ COHERNET studies low enough Q^2 that the deBroglie wavelength is large compared to nuclear radius
- ❑ All nucleons within nucleus recoil coherently from neutrino or DM scattering
- ❑ Astroparticle direct-detection experiments have exploited this for years – now accelerator experiments can too with CEvNS detectors

- ❑ This coherency gives a Z^2 enhancement in the cross section → big effect for CsI (Z of 53/55)
- ❑ Game-changing – investing in a small 14-kg detector can compete with multi-ton detectors

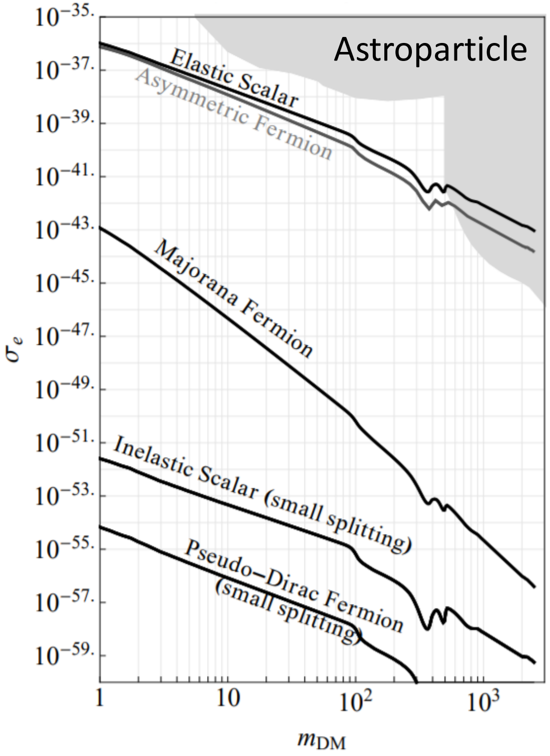
Direct-detection experiments searching for light dark matter

	Mass (t)
LSND	167
MiniBooNE	450
COHERENT CsI	0.0146

Advantages of accelerator: less model dependent

- ❑ Astroparticle experiments are within grasp of the expected dark matter concentration for scalar DM
- ❑ But if DM is a fermion, the scattering cross section is heavily suppressed by DM speed $v/c < 0.001$
- ❑ Predictions span 20 orders of magnitude

arXiv 1707.04591



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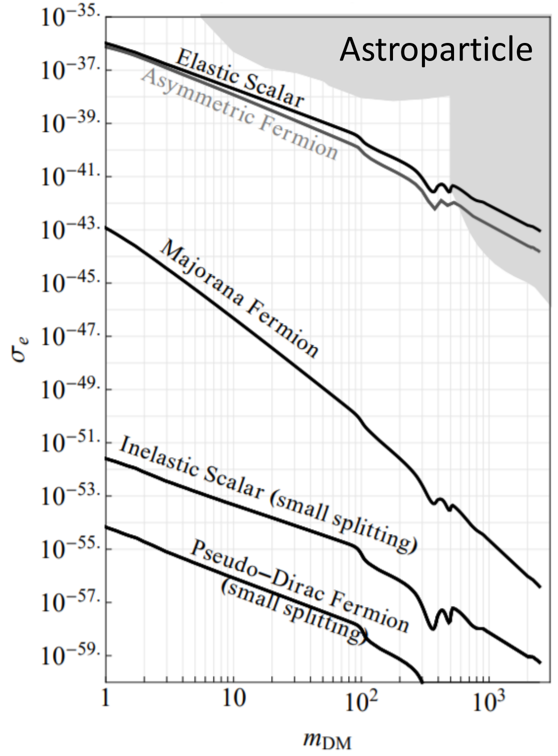
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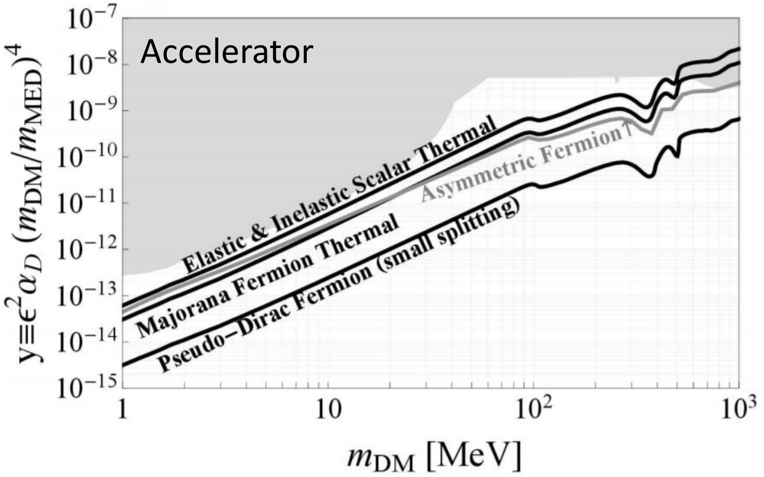
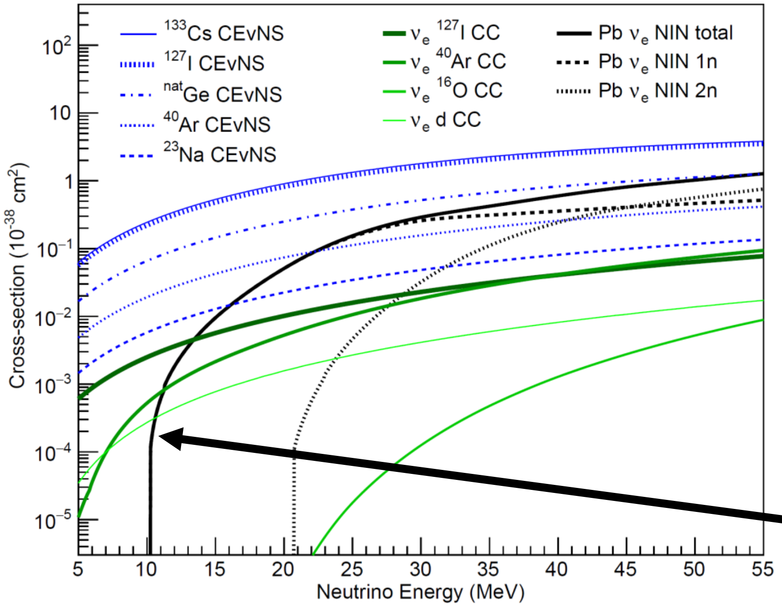
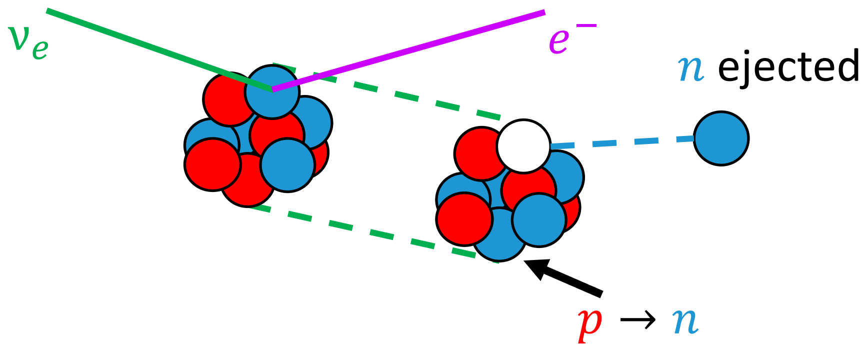


- At accelerators, DM is relativistic with only a factor of 20 between different expectations
  - Accelerator searches only viable options to test fermionic DM
- COHERENT gets the best of both worlds
  - Independent of DM particle spin like accelerator methods
  - Large coherent cross section like astroparticle methods

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)

See Rex Tayloe's in this session for more on inelastic interactions (green curves)

Current 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
- ☐ Already testing interactions on several nuclei with many subsystems coming online this year

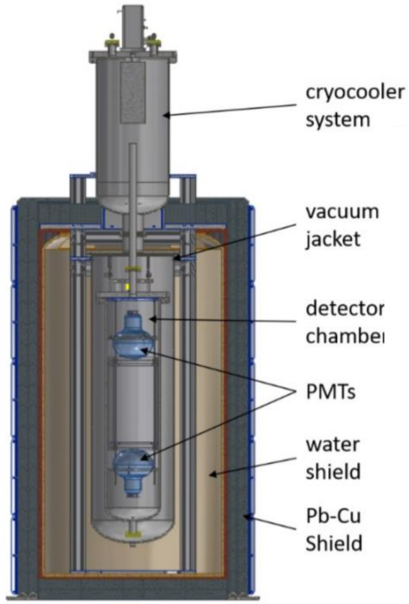
COHERENT CEvNS detectors

Target	Technology	Fid. Mass	Threshold	CEvNS?	Inelastics	First result
CsI[Na]	Scintillation	14.6	$6.5\ \mathrm{keV}_{nr}$	Yes		2017
Liquid Ar	Scintillation	24.4/610 kg	$20\ \mathrm{keV}_{nr}$	Yes	Yes	2020
Ge	Ionization	18 kg	$0.4\ \mathrm{keV}_{ee}$	Yes		
NaI[Tl]	Scintillation	3500 kg	$13\ \mathrm{keV}_{nr}$	Yes	Yes	
Pb	Scintillation	≈ 10 kg	$100\ \mathrm{keV}_{ee}$		Yes	2022
Th	Scintillation	TBD	TBD		Yes	
D2O	Chernkov	600 kg	TBD		Yes	

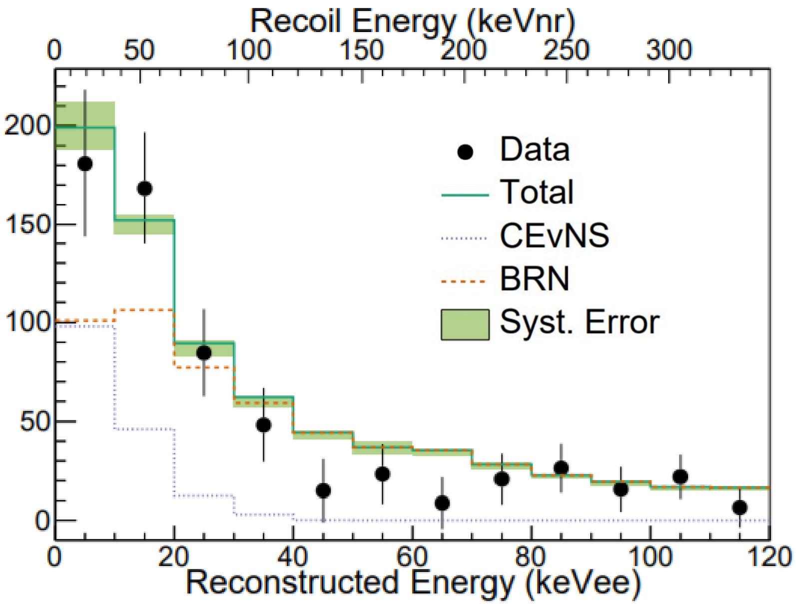
New for 2022!

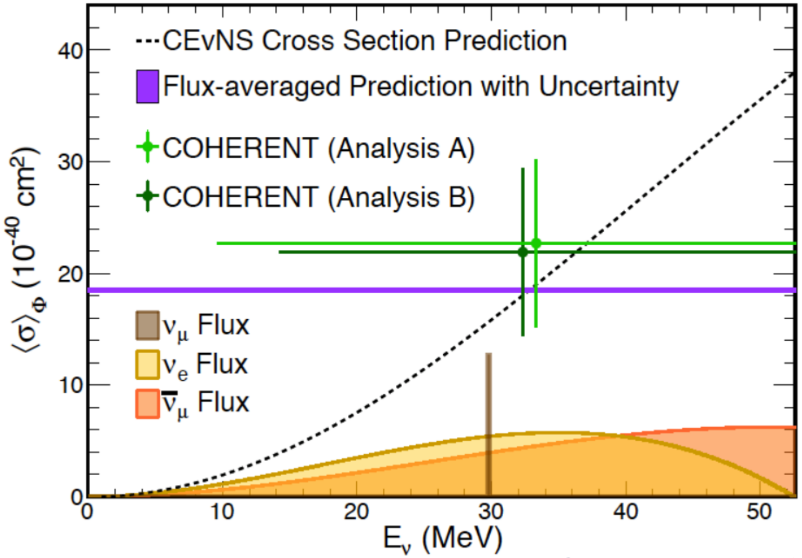
Current CEvNS data

COHERENT CEvNS Detection on ^{40}Ar



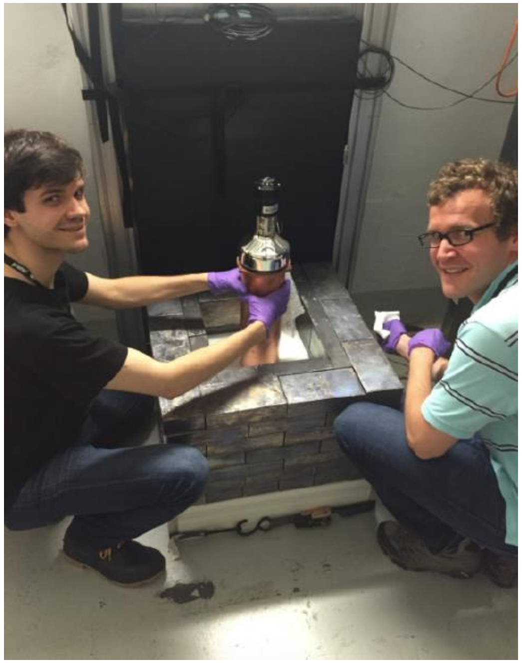
- CENNS-10 (aka. COH-Ar-10): 24.4-kg liquid argon scintillation calorimeter with a 20 keVnr threshold
  - Originally built by J. Yoo et al. at Fermilab
  - Upgraded in 2017 with TPB-coated PMT's and Teflon walls to increase light yield for CEvNS detection in neutrino alley
- CEvNS excess observed with 3.5σ evidence on argon
  - Second detection of CEvNS after COHERENT CsI[Na] detector
  - Result: PRL **126** 012002 (2021)
- Much recent progress with our argon program – see Rex Tayloe's talk for more

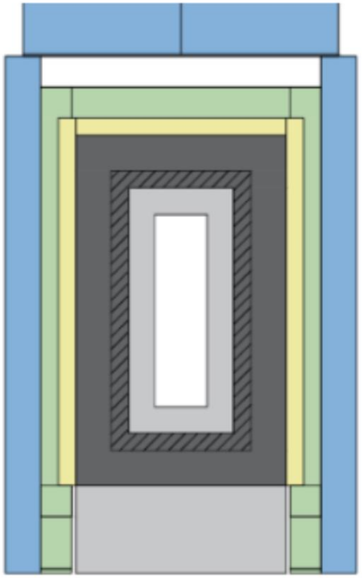




The COHERENT CsI[Na] detector

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



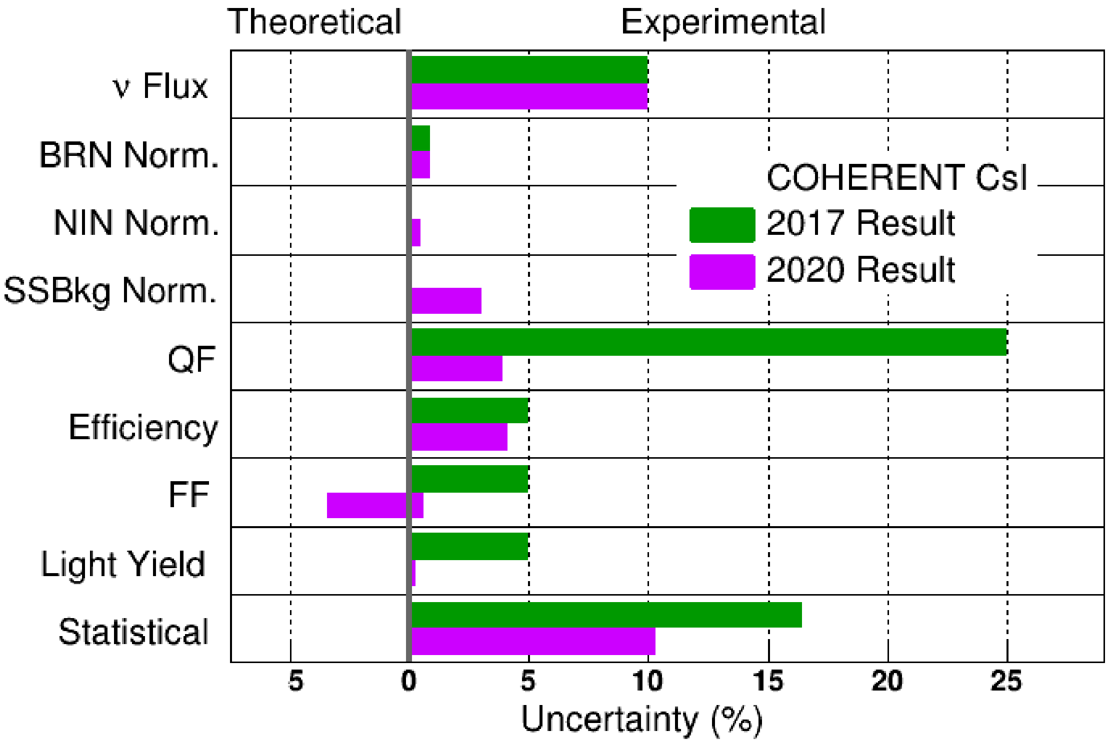


Shielding design

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

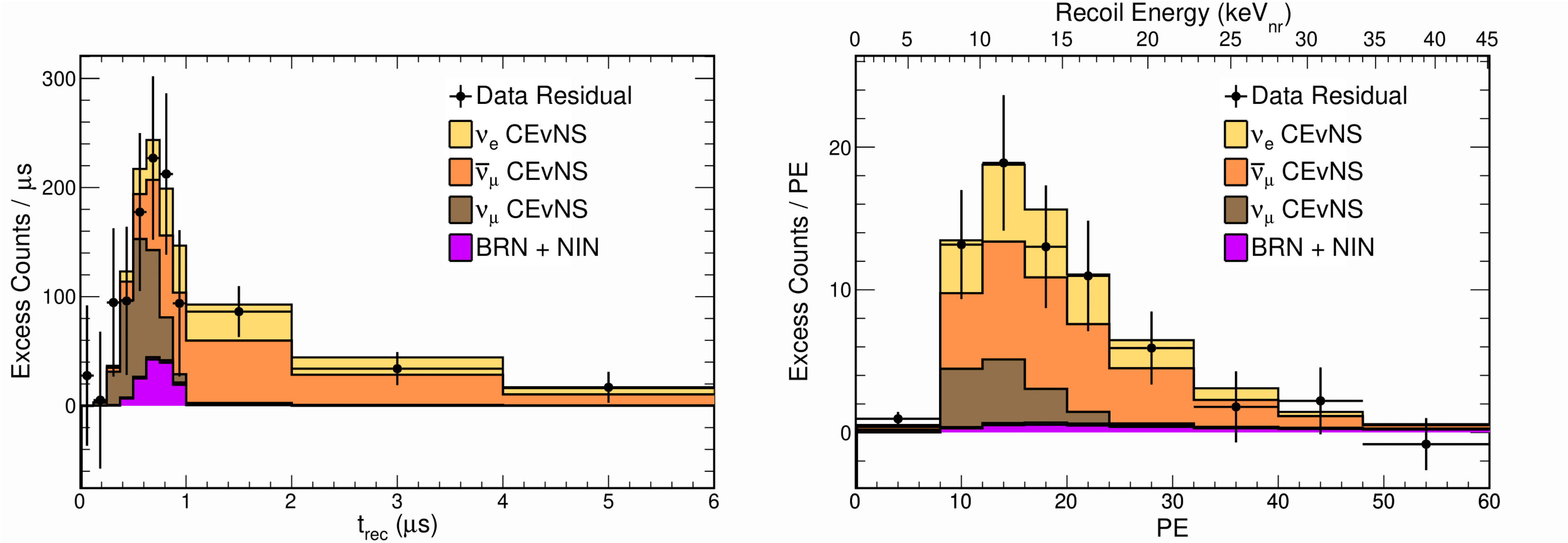
Layer	HDPE*	Low backg. lead	Lead	Muon veto	Water
Thickness	3"	2"	4"	2"	4"
Colour	⬜	▨	⬛	🟨	🟦

Towards precision measurements with CsI[Na]



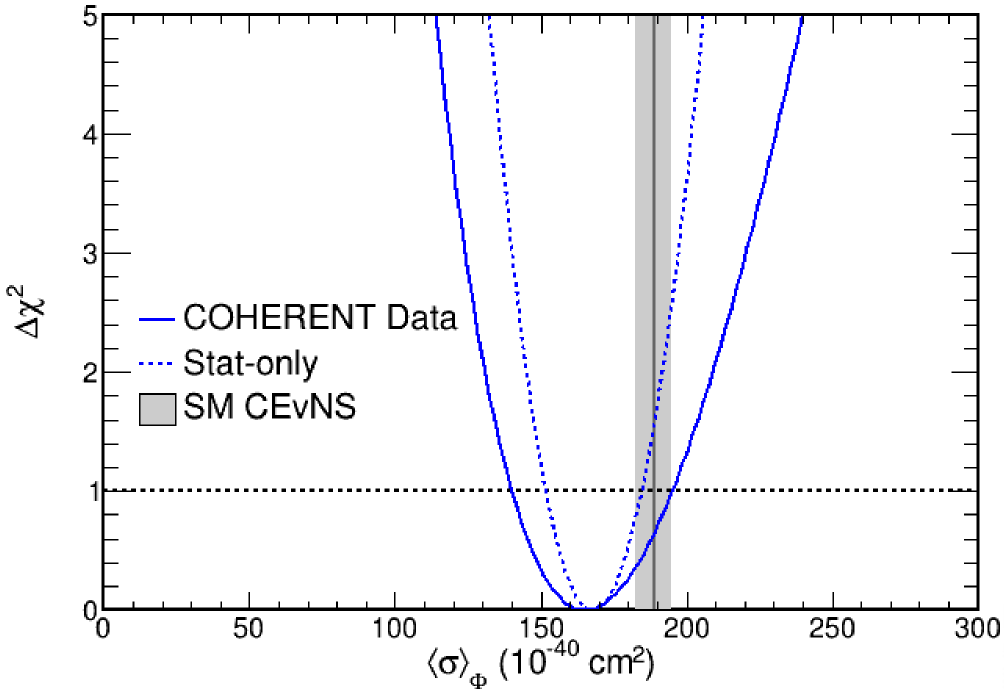
- ❑ Doubled dataset from first observation will allow precise tests of CEvNS shape
- ❑ Quenching error improved 25% → 4% by studying newly available data with a better model and fit strategy
- ❑ Overall precision improves 33% → 16%

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

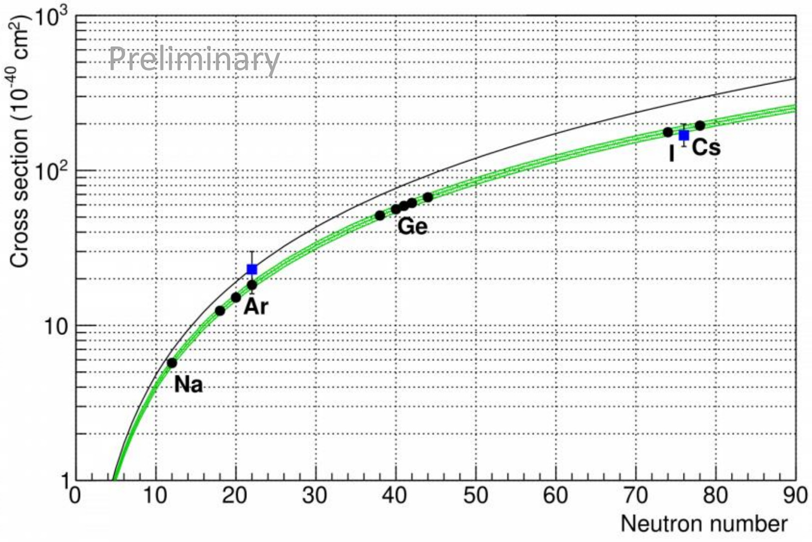
Determining the CEvNS Cross Section



COHERENT, PRL **129** 081801

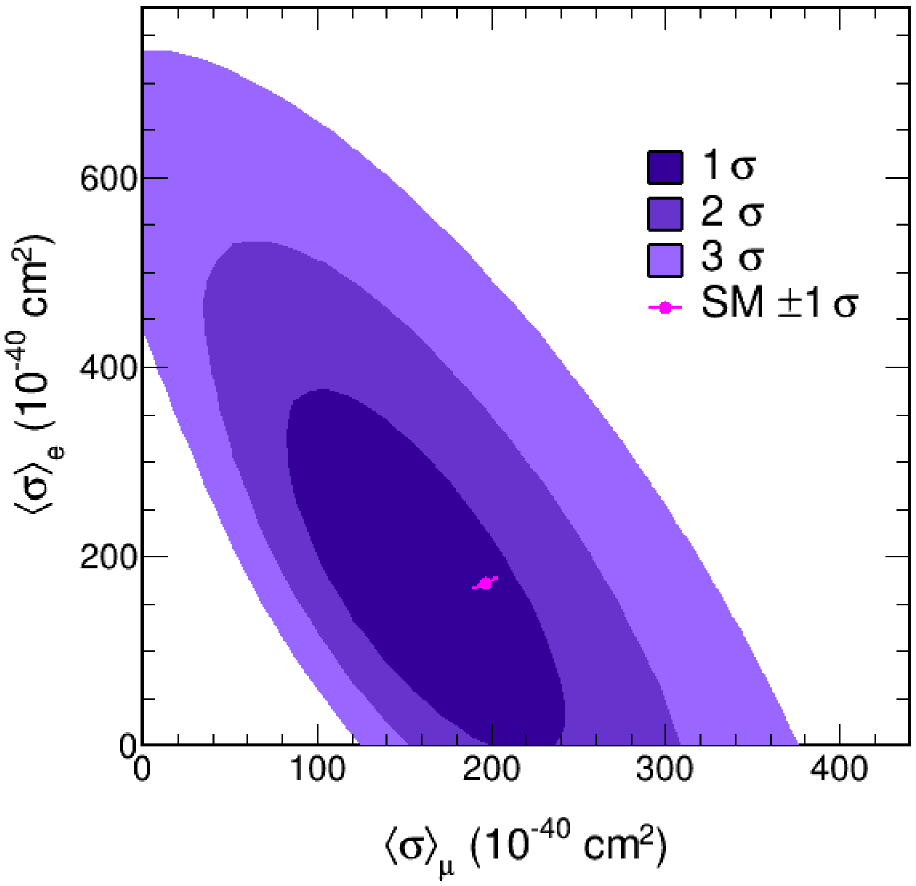
No-CEvNS rejection	11.6 σ
SM CEvNS prediction	341 ± 11(th) ± 42(ex)
Fit CEvNS events	306 ± 20
Fit χ^2/dof	82.4/98
CEvNS cross section	$165^{+30}_{-25} \times 10^{-40}$ cm^2
SM cross section	$189 \pm 6 \times 10^{-40}$ cm^2

- ❑ 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

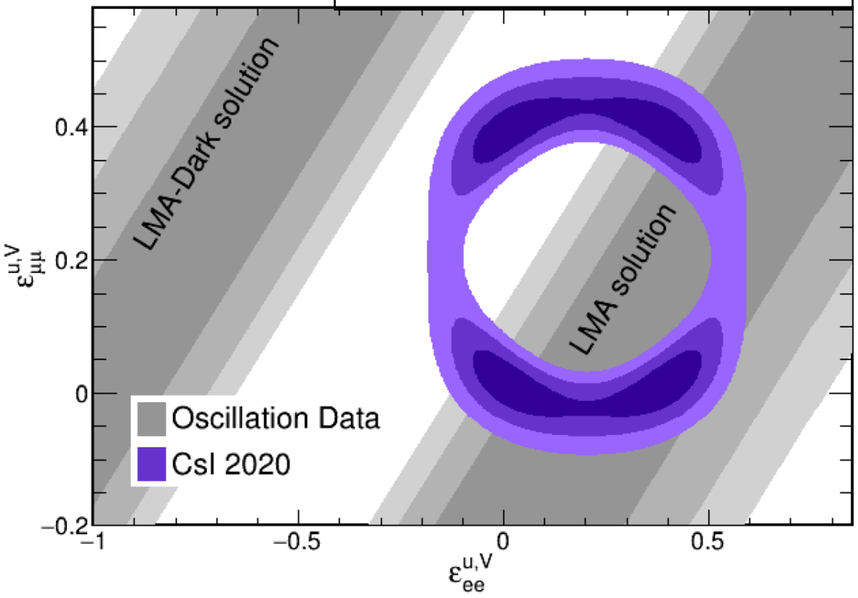


Flavored CEvNS Cross Section

- ❑ Allow for completely different $\langle\sigma\rangle_\mu$ and $\langle\sigma\rangle_e$ as would be allowed in NSI scenarios
- ❑ ν_μ timing sheds light on the fraction of observed CEvNS that are from each flavor
- ❑ As in 1D CEvNS fit, the SM prediction is included within the 1 σ contour



NSI: clarifying solar neutrino oscillation data



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

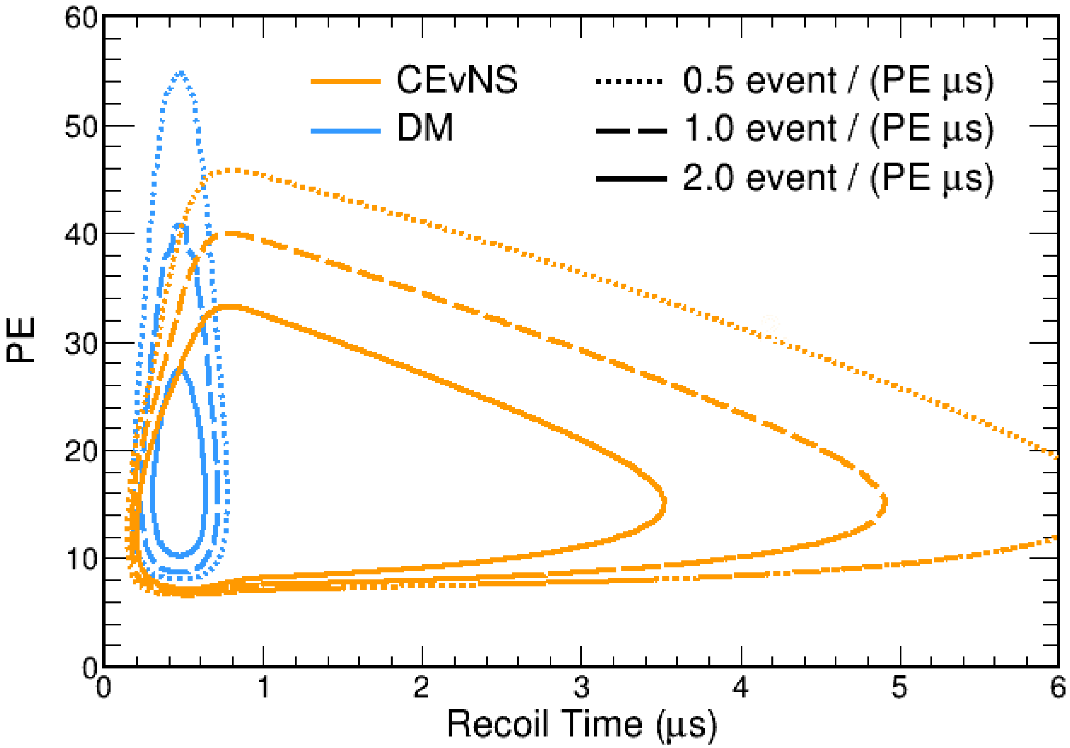
2D Gaussian 1/2/3σ critical up-values

- 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

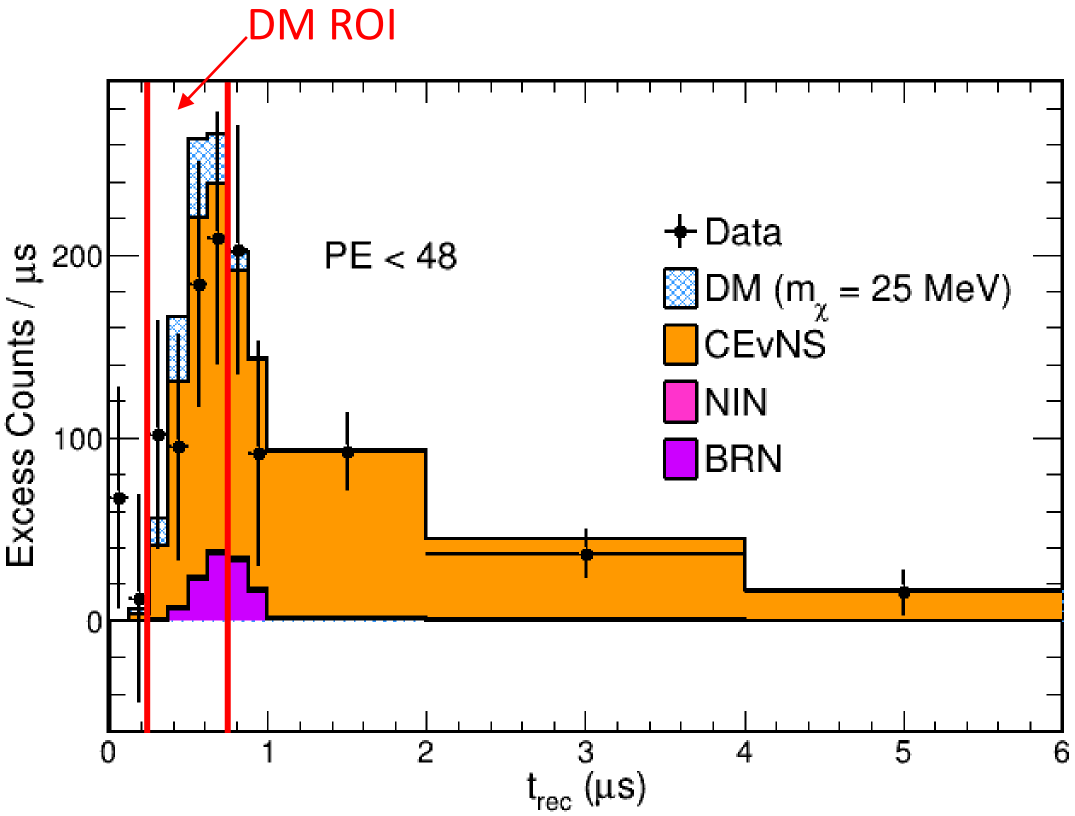
Predicting dark matter events in our sample

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



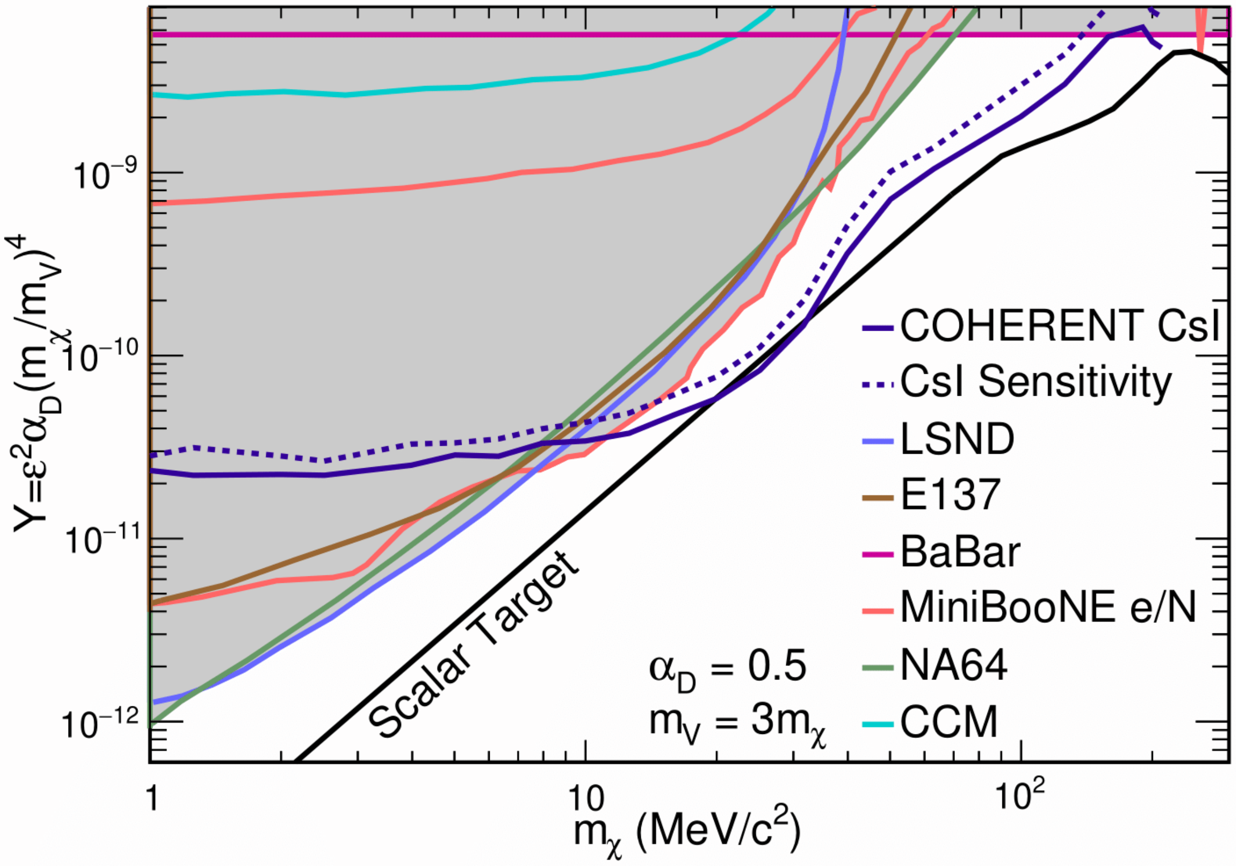
	Prediction	Data
DM		0^{+15}
CEvNS	341 ± 43	320 ± 33
BRN	27.6 ± 6.9	25.8 ± 6.6
NIN	7.6 ± 2.7	7.4 ± 2.7

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

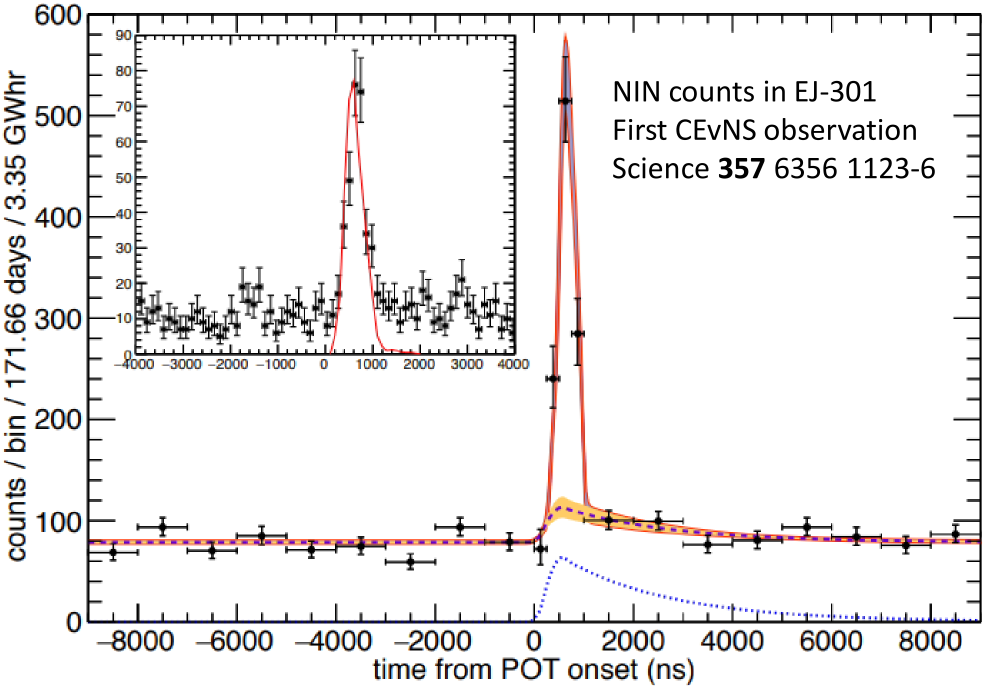
COHERENT constraint on sub-GeV dark matter

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



Current inelastic scattering data

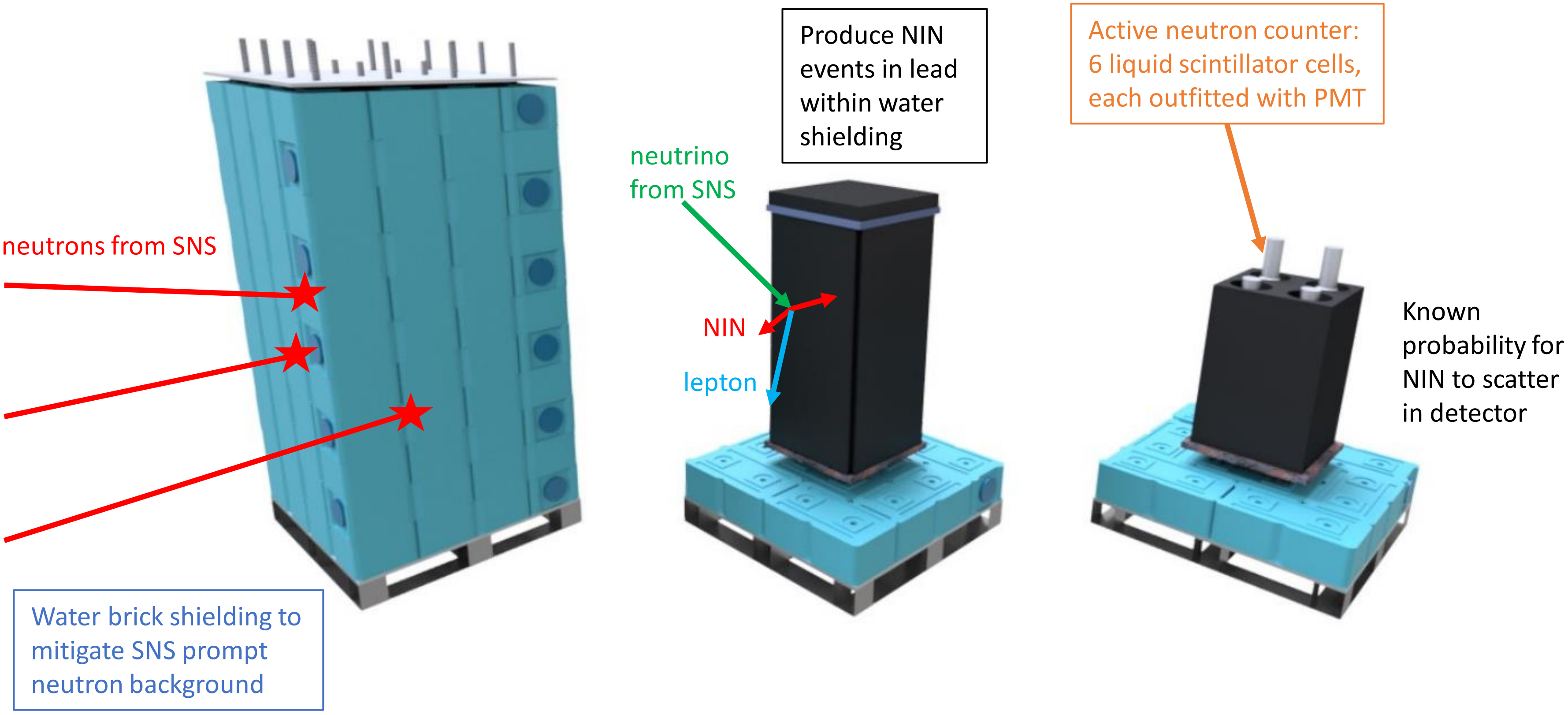
First attempt to observe NIN events



NIN counts in EJ-301
First CEvNS observation
Science **357** 6356 1123-6

- ❑ 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



neutrons from SNS

Water brick shielding to mitigate SNS prompt neutron background

neutrino from SNS

NIN

lepton

Produce NIN events in lead within water shielding

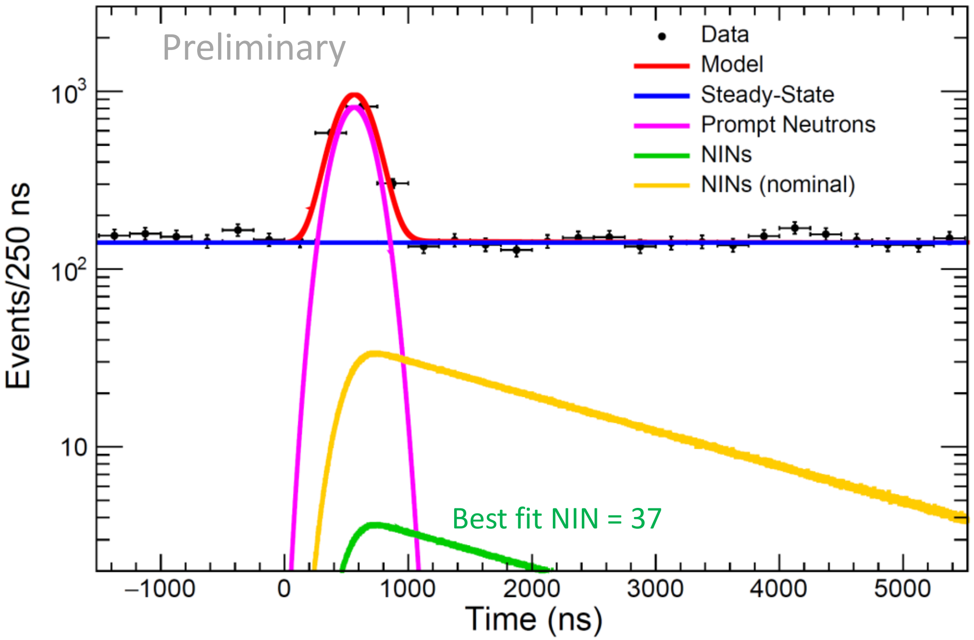
Active neutron counter: 6 liquid scintillator cells, each outfitted with PMT

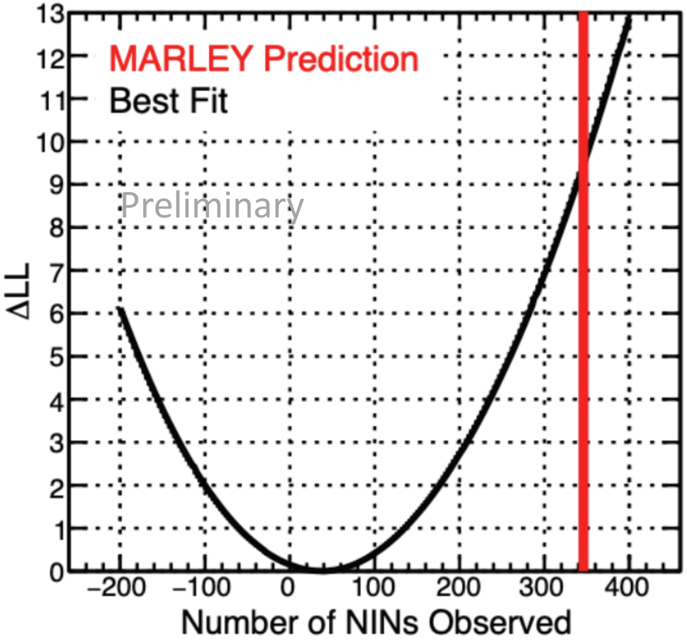
Known probability for NIN to scatter in detector

Dedicated liquid scintillator detectors designed to observe NIN events

Observed NIN rate

New result!





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

Result cross checks

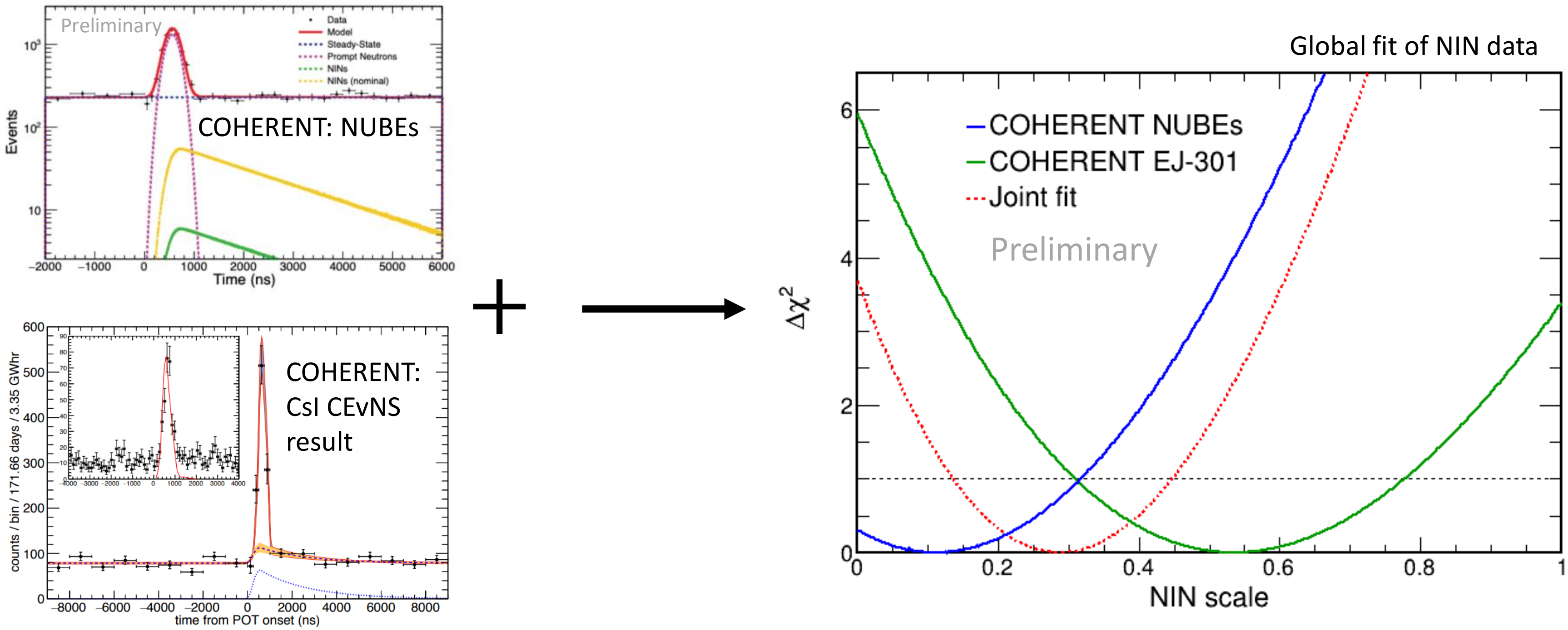
Possible detector simulation underestimates the neutron opacity of our lead -> but lead spec'd at 99.99% pure, consistent with our density measurement of lead used in experiment

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

New result!

Global NIN data from COHERENT



- ❑ 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 work

Measuring scattering on NaI

- We have two generations of detectors for studying neutrino interactions on NaI
- NaIvE – 185 kg of NaI crystals with 900 keV threshold and a muon veto to reject cosmics

First COHERENT data for inelastic scattering off ^{127}I coming soon!

- Upgraded NaIvETe – seven 500-kg modules of NaI digitized at two gains allowing simultaneously measurement of CEvNS and ^{127}I CC
- First module deployed at Oak Ridge with second coming this year

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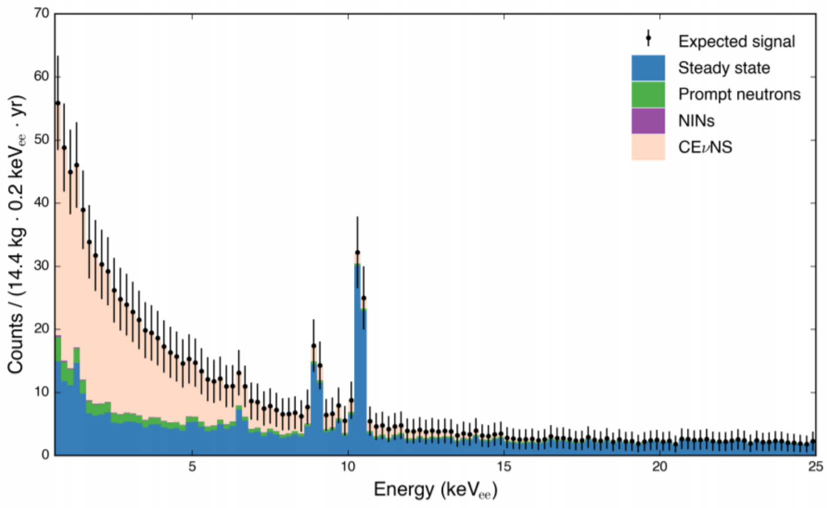
- Also introducing the NuThor detector now in Neutrino Alley – first measurement of neutrino-induced fission. Uses a Th fissile target

GeMini – a germanium CEvNS detector

- ❑ Array of 18 kg of high-purity germanium PPC detectors for CEvNS detector
- ❑ Each of eight detectors constructed by Mirion Tech.
- ❑ Detector characterization and deployment of first detectors into shielding assembly recently completed, transitioning to commissioning

- ❑ Assembly will reach a low threshold, 0.2-0.4 keVnr
- ❑ Low intrinsic backgrounds and excellent energy resolution allows for precise CEvNS measurement and search for energy-dependent BSM effects



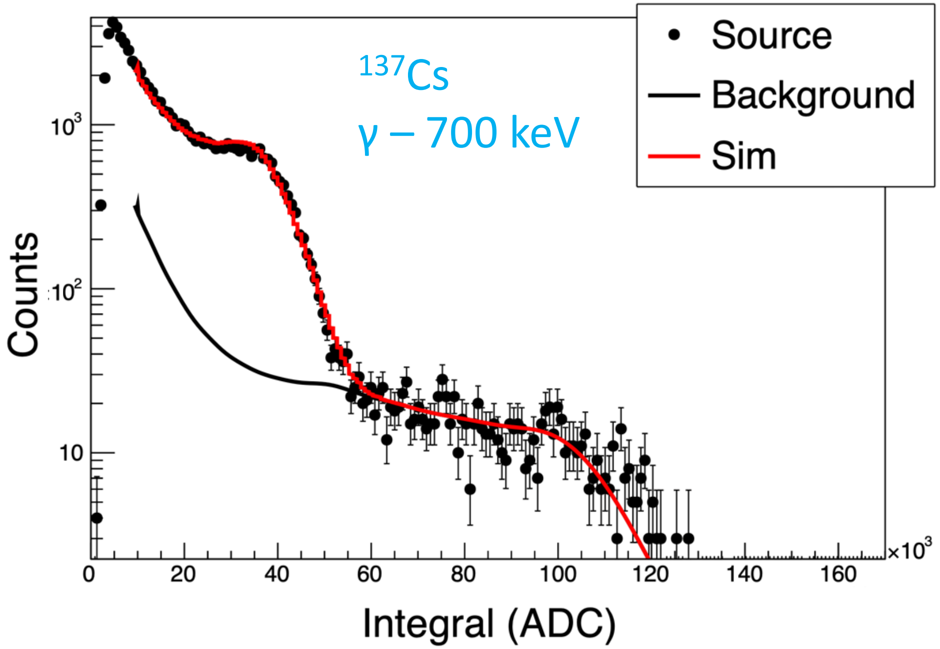
Summary

- ❑ COHERENT continues its campaign to measure CEvNS, search for new physics, and other low-energy neutrino scattering processes
- ❑ First inelastic measurement on Pb – paper coming soon – with more data upcoming
- ❑ Currently deploying several detectors at the SNS


COHERENT
SNS

Calibrating NUBEs detector

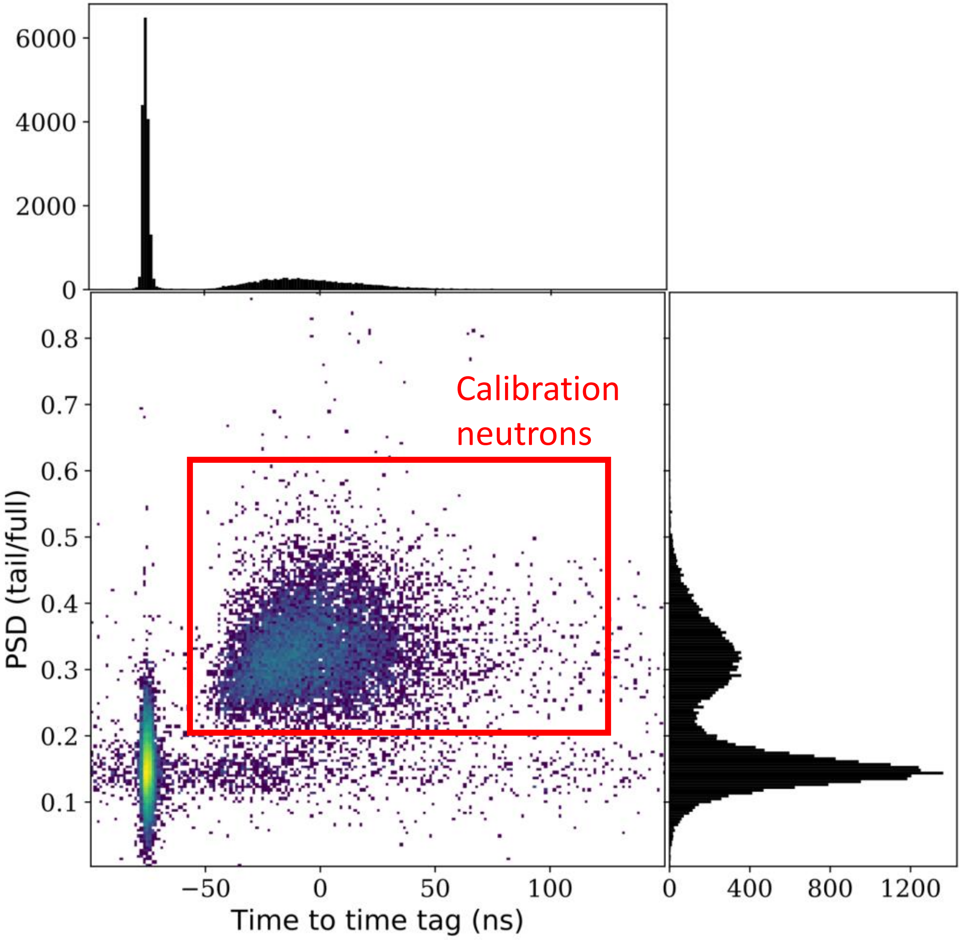
- ❑ Light yield determined by source calibration data: ^{133}Ba, ^{137}Cs, ^{22}Na
- ❑ Excellent agreement between data and simulation



- ❑ 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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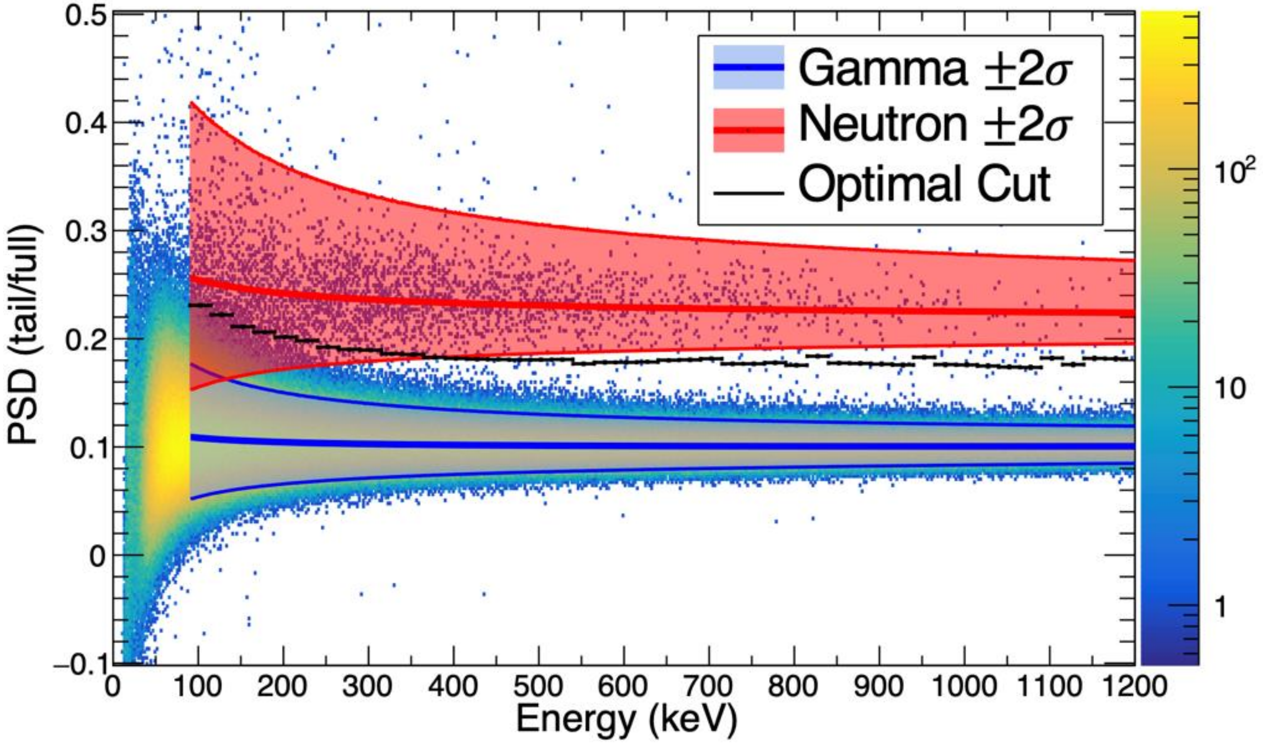
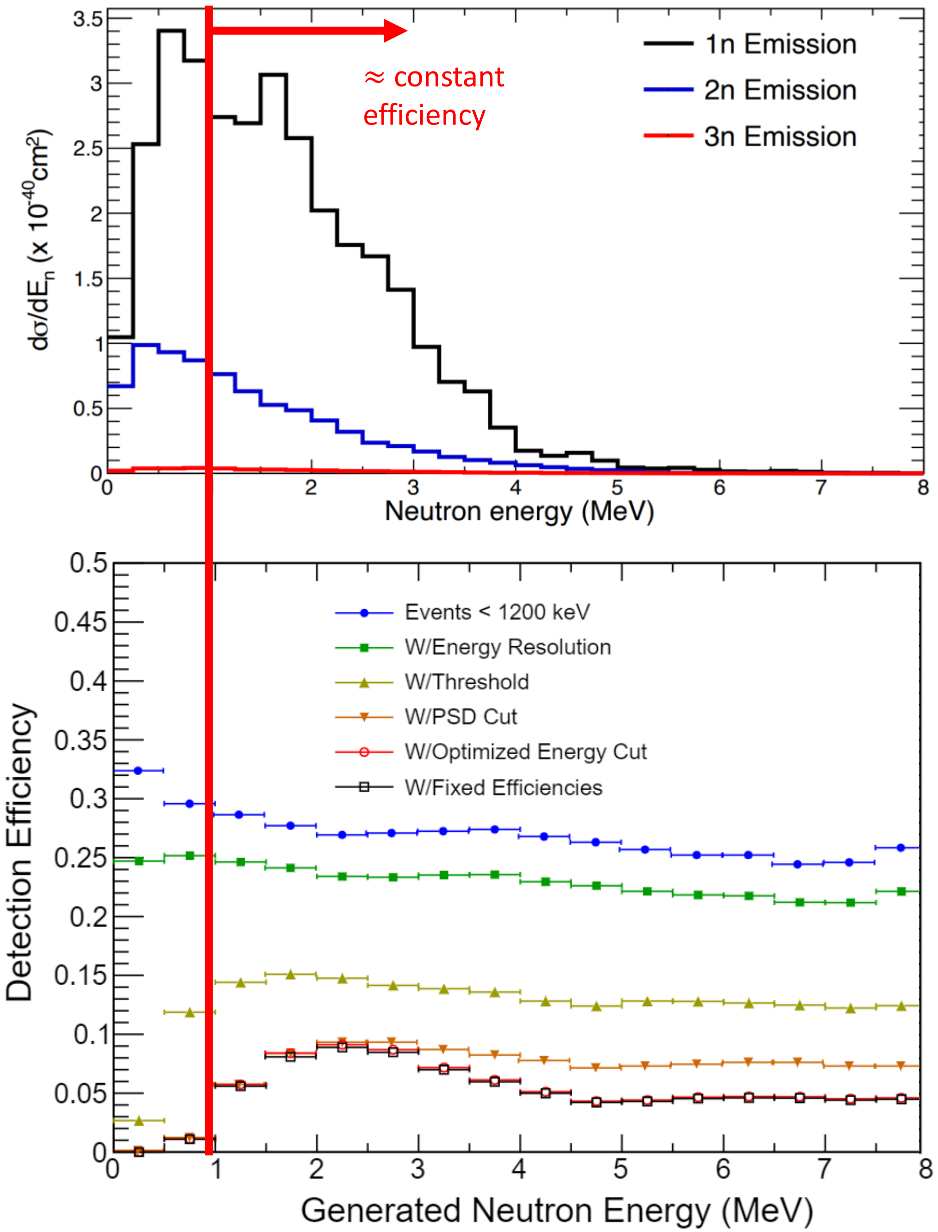
Separating NR/ER recoils with PSD



- ☐ 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



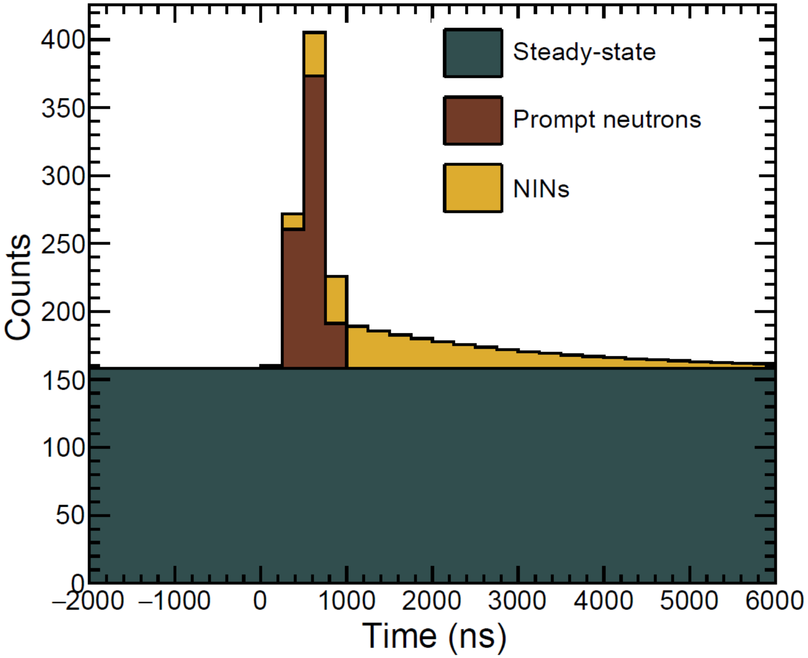
Neutrino interactions simulated with MARLEY offering detailed information about final state particles

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