OAK RIDGE National Laboratory

New Results from COHERENT

M. R. Heath
ORNL
Mar. 18, 2021

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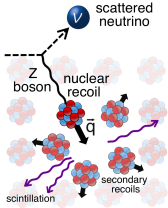
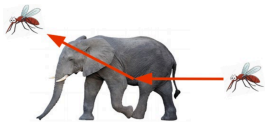
U.S. DEPARTMENT OF ENERGY

Coherent Elastic Neutrino-Nucleus Scattering

CEvNS

- Neutrino interacts with nucleus which recoils coherently
  - $E_\nu \lesssim \frac{hc}{R_N} \approx 50\,\text{MeV}$
- **LARGE** cross section
  - $\sigma \approx 0.4 \times 10^{-44} N^2 E_\nu^2 \text{cm}^2$
  - N^2 dependence is tell-tale signature
- **SMALL** recoil energy
  - $E_r^{max} \lesssim \frac{2E_\nu^2}{M_N} \simeq 50\,\text{keV}$

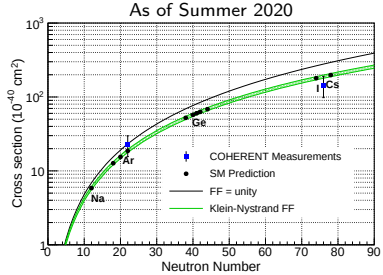




Coherent effects of a weak neutral current

Daniel Z. Freedman†
National Accelerator Laboratory, Batavia, Illinois 60510
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790
(Received 15 October 1973; revised manuscript received 19 November 1973)

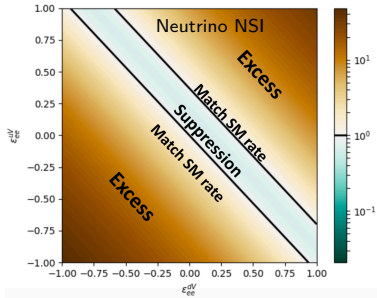
Our suggestion may be an act of hubris, because the inevitable constraints of interaction rate, resolution, and background pose grave experimental difficulties for elastic neutrino-nucleus scattering.

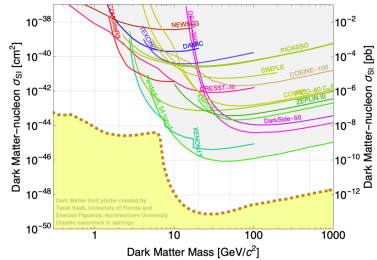


Coherent Elastic Neutrino-Nucleus Scattering

Why CEvNS

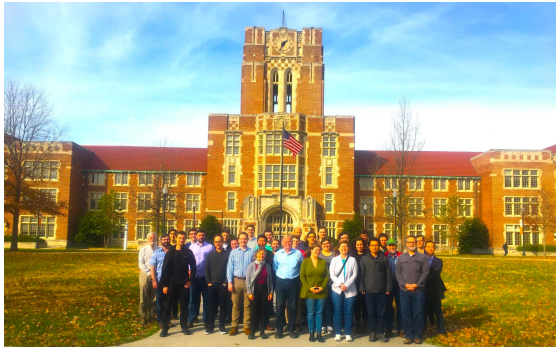
- Well-understood cross section allows for beyond-SM checks
  - $\sigma_{Tot} = \frac{G_F^2 E_\nu^2}{4\pi}\left[Z\left(1-4\sin^2\theta_W\right)-N\right]^2 F^2\left(Q^2\right)$
  - Neutrino electromagnetic properties
  - Non-Standard Interactions
- Important bkg for next-gen DM experiments
- Dominant neutrino interaction in supernovae
  - And detection channel!
- Applications to reactor monitoring





http://cdms.berkeley.edu/limitplots

COHERENT



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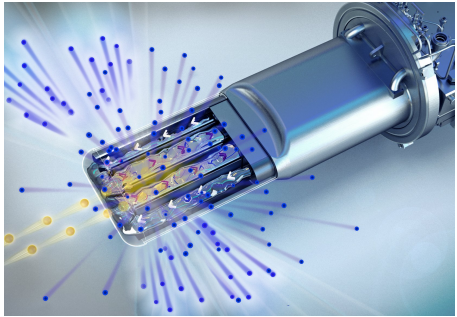
CNEC Consortium for Nonproliferation Enabling Capabilities · KICP · NNSA National Nuclear Security Administration · NSF · U.S. Department of Energy

COHERENT at the Spallation Neutron Source

The Spallation Neutron Source

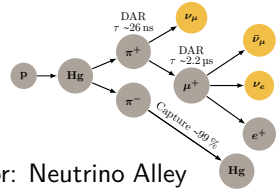
- 1 GeV protons hit liquid-Hg target
- Recently reached 1.4 MW
- **Pulsed** at 60 Hz
  - Pulse duration: 350 ns FWHM
  - Measure steady-state bkg out of beam!
- Neutrinos come along for free!

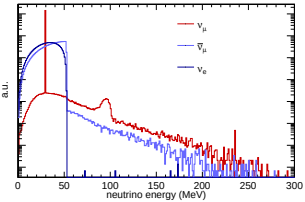
Credit: ORNL/Jill Hemman

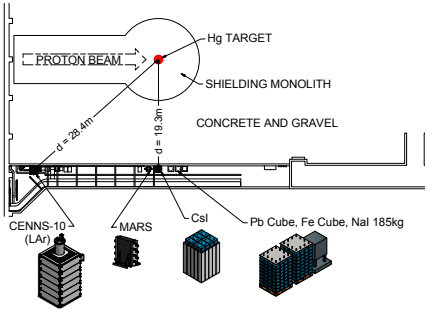


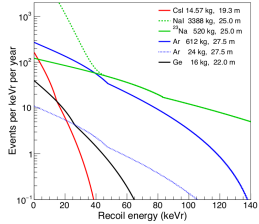
COHERENT at the SNS

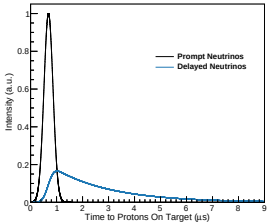
- Pion-decay-at-rest neutrino source
  - $0.09\,\pi/\,\mathrm{POT}$
- **EXTREMELY** neutron quiet corridor: Neutrino Alley
- Multi-target program to measure N^2 dependence







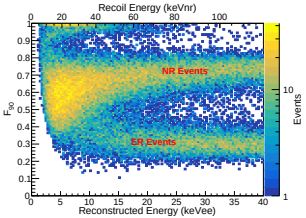


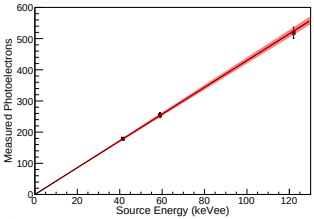


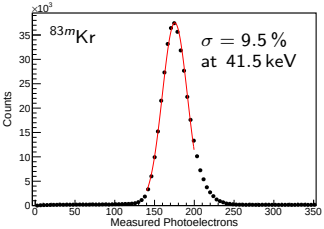
COHERENT at the SNS: CEvNS On Ar

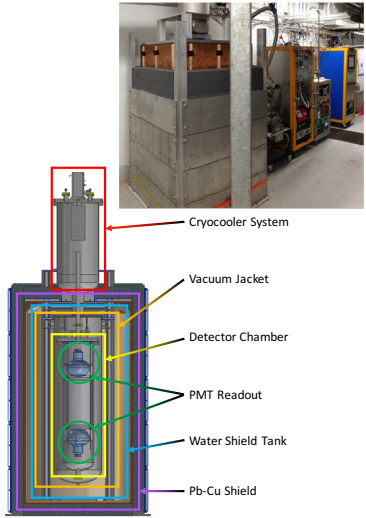
COH-Ar-10

- Aka CENNS-10
- 24 kg fiducial mass
- Single-phase scintillation-only
- 4.5 PE/keVee
  - 20 keVnr threshold
- 6.12 GWhr





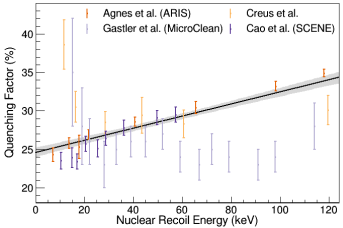




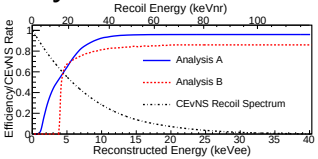
Phys. Rev. D 100 (2019) 11, 115020
Phys. Rev. Lett. 126, 012002

COHERENT at the SNS: First Observation of Ar!

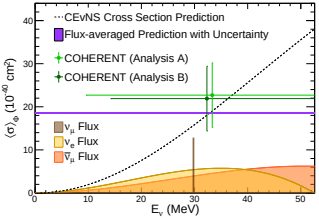
Global Fit to Quenching Factor Data



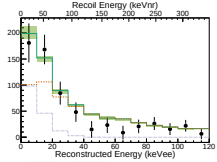
2 Independent Blind Analyses



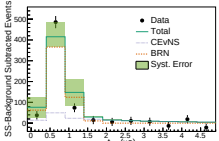
CEvNS Cross Section



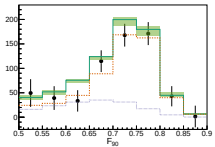
Energy



Time



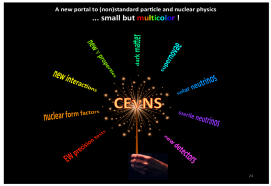
PSD



- Combine best-fit CEvNS counts with flux, fid. volume, efficiency uncertainties: $\frac{N_{meas}}{N_{SM}} = 1.2 \pm 0.4$
- Flux-averaged cross section: $\sigma_{meas} = (2.3 \pm 0.7) \times 10^{-39}$ cm^2

COHERENT at the SNS: First Light Results

CEvNS as Probe of New Physics



Slide by Eligio Lisi at NuInt 2018
https://indico.cern.ch/event/703880/

The COHERENT experiment has demonstrated the scientific potential of a CEvNS program using the intensity, timing structure, and hermetic shielding at the Spallation Neutron Source.

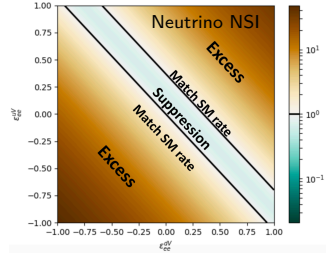
Community Workshops

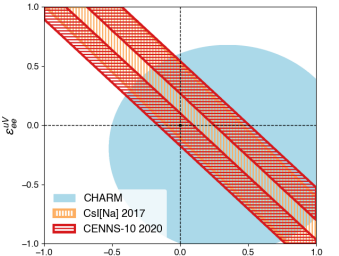
- nuEclipse 2017
- Magnificent CEvNS Workshops, 2018 Chicago, 2019 Chapel Hill
- Second Target Station Science Workshops, July 2019, Dec 2019

From "Can we see it?"
to "What can we do with it?"

Neutrino 2020 Virtual Meeting

Courtesy of J. Newby ORNL





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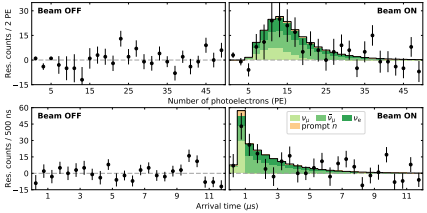
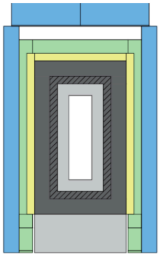
COHERENT at the SNS: CsI

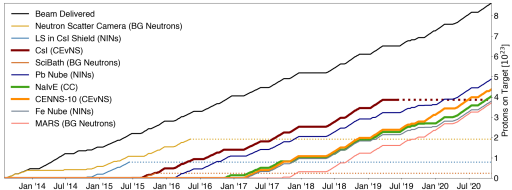
First CsI Result 2017!

- Everything came together in 2017
  - Intense neutrino source
  - Sensitive detector
  - Low backgrounds
- First CEvNS detection with 14.6 kg CsI detector
- 6.7 σ significance
- Now new results with increased statistics, better understanding of systematics!





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



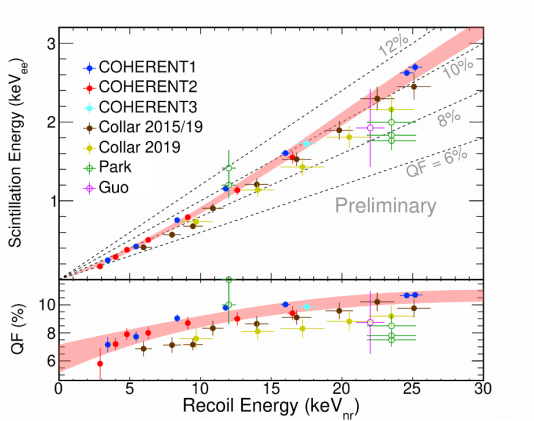
Now 2.2x statistics!

Science 357 (2017) 6356, 1123-1126

COHERENT at the SNS: CsI

Scintillation Response to Nuclear Recoils

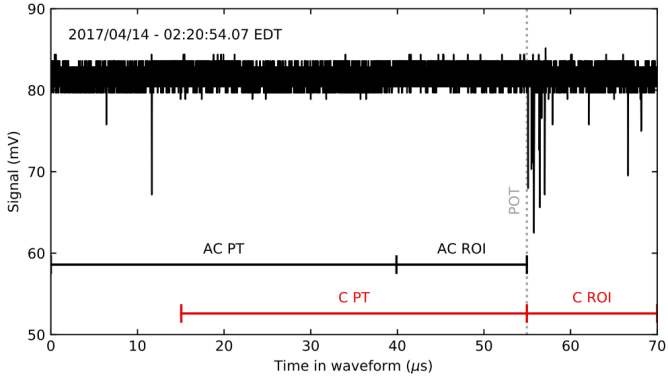
- Nuclear recoil light output 'quenched' relative to similar energy electronic recoil
- Update quenching factor fit:
- Include 5 datasets using CsI[Na] crystal from same manufacturer as COHERENT crystal
- 4th-degree polynomial global fit



COHERENT at the SNS: CsI

Waveform Reconstruction

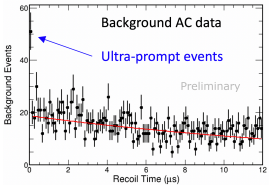
- Each waveform has a coincidence window (C) in time with the beam and an anticoincidence window (AC) preceding the beam
- AC events give unbiased *in situ* estimate of steady-state backgrounds in neutrino alley

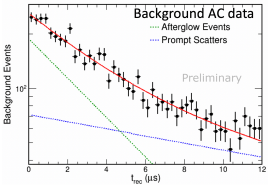


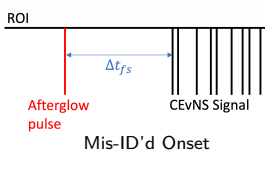
COHERENT at the SNS: CsI Full Dataset

Event Selection

	Data Cut	Purpose	
Quality	Muon veto, PMT saturation, digitizer overflow	Reject cosmic-induced events, require energy consistent with low-energy recoil	Reduce detector livetime. No cut on ROI and effect measured *in situ*
Scintillation Activity	< 6 PE pulses in pretrace	Reject events occurring when detector is bright	
Ultra-prompt	No PE in final 0.2 µs of pretrace	Reject events from tail-end of pretrace sneaking into ROI	
Afterglow	$\Delta t_{fs} < 0.52$ µs	Reject events with mis-ID'd onset	Efficiency calculated with simulation. 5x reduction of mis-ID'd onset events, negligible effect on signal
Δt between first and second PE peaks	≥ 9 pulses in ROI	Reject accidental coincidence from afterglow	Efficiency determined from ^{133}Ba calibration.



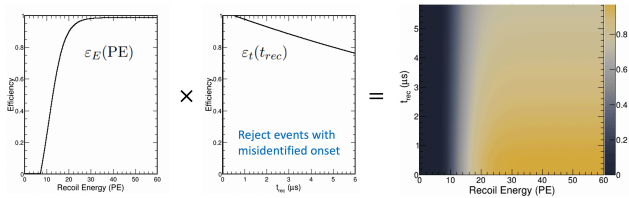




COHERENT at the SNS: CsI Full Dataset

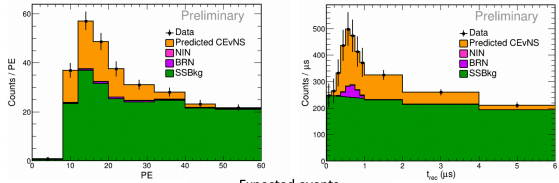
CEvNS Selection Efficiency

- Efficiency depends on energy AND time
- Dependence is **uncorrelated**



Expected Rates

- 2D likelihood fit in *PE* and t_{rec}
- Beam-unrelated steady-state background measured *in situ* with out-of-time data
- Beam-related neutron background small



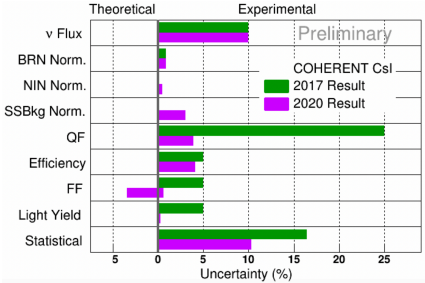
Expected events

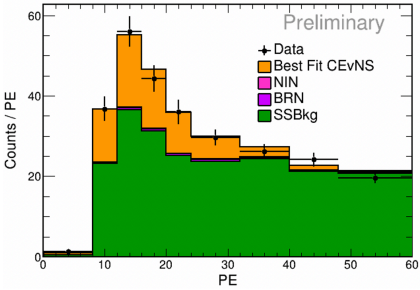
Steady-state background	1286
Beam-related neutrons	18
Neutrino-induced neutrons	6
CEvNS	333

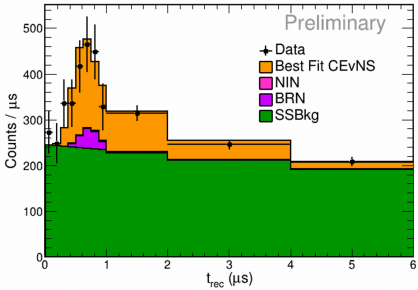
COHERENT at the SNS: CsI Full Dataset

Best-Fit Results

- Data match best-fit spectra very well
- Best-fit CEvNS slightly low, consistent within error
- Uncertainty now dominated by flux normalization
- Overall prediction improved from 2017:
  33 % → 16 %





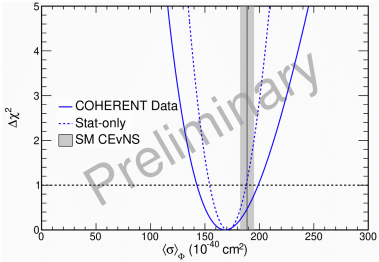


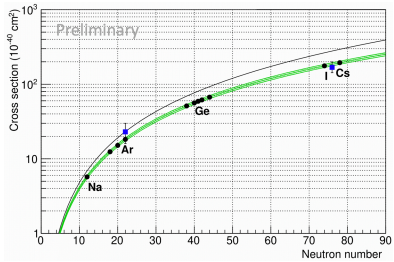
COHERENT at the SNS: CsI Full Dataset

Best-Fit Results

- No-CEvNS hypothesis rejected at $11.6\,\sigma$
- Consistent with Standard Model prediction to $1\,\sigma$

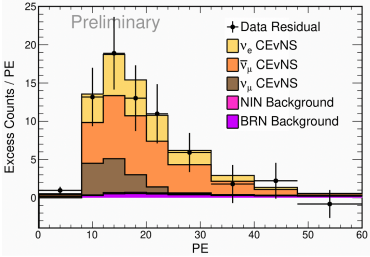
No-CEvNS Rejection	$11.6\,\sigma$
SM CEvNS Prediction	$333 \pm 11(\text{th}) \pm 43(\text{ex})$
Fit CEvNS Events	306 ± 20
Fit χ^2/dof	$82.4/98$
CEvNS cross section	$169^{+30}_{-26} \times 10^{-40}\,\text{cm}^2$
SM cross section	$(189 \pm 6) \times 10^{-40}\,\text{cm}^2$

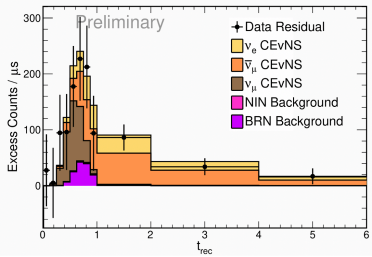


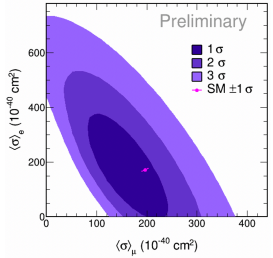


COHERENT at the SNS: CsI Full Dataset

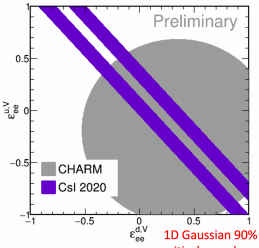
Ex. New Physics Study: Flavor-Dependent X-Sec.







- Short SNS pulses allow neutrino flavor separation
- Allows for measurement of flavored CEvNS cross sections (σ_μ and σ_e) to constrain NSI



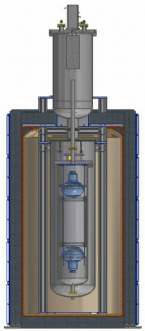
1D Gaussian 90% critical up-values

*Additional Physics Studies in D. Pershey Mag7s and FNAL JETP Seminar talks

COHERENT at the SNS

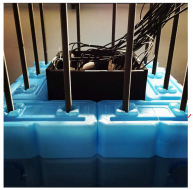
Ongoing COHERENT Activities

Argon



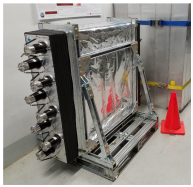
- COH-Ar-10 continues running
- Accumulated 2x statistics

NUBES



- Measure neutrino-induced neutrons on Pb and Fe

MARS



- Mobile neutron-flux monitor

NaIνE

- Background measurements for tonne-scale NaI
- Charged-current cross sections on ^{127}I

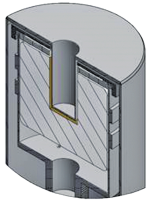
Supporting Work

- Absolute timing measurement of SNS beam
- Map neutron timing/flux throughout hallway

COHERENT at the SNS

Commissioning 2 new detectors in 2021

- 16 kg of low-threshold Ge PPC detectors "COH-Ge-1"
- Expect $>$ 500 CEvNS evts/yr at $E_{rec} > 0.3$ keVee
- Good energy resolution
- 7/8 detectors in hand. Finalizing shielding design



- Multi-ton array of NaI crystals "COH-NaI-2"
- 13 keVnr threshold for CEvNS on Na from NaIνE background measurements
- Lightest COHERENT nucleus
- ^{23}Na sensitive to axial currents

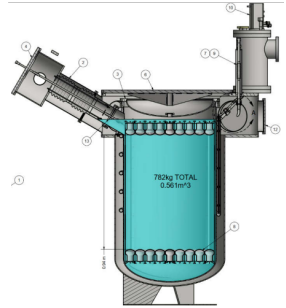
Future Precision-Measurement Plans at the SNS

Flux Normalization

- Charged-current cross section with deuterium known to $\approx 3\,\%$
- Heavy-water Cherenkov detector planned to measure neutrino flux directly
- D_2O on hand!

Tonne-Scale Ar

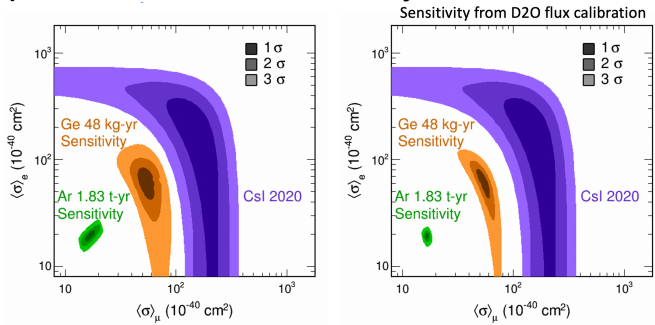
- Ton-scale LAr detector COH-Ar-750
- Single phase, scintillation only
- Expect 3000 CEvNS evts/yr
- Sensitive to accelerator-produced dark matter and charged-current Ar events!



Future Precision-Measurement Plans at the SNS: SNS Upgrades

- Proton Power Upgrade (2024)
  - Increase power of proton beam
  - $1.4 \rightarrow 2.0\,\text{MW}$
- Second Target Station (≈ 2028)
  - Total SNS power: 2.8 MW
  - Interest from the lab to include neutrino detector hall for $\approx 10\,\text{t}$ detector in STS hall design

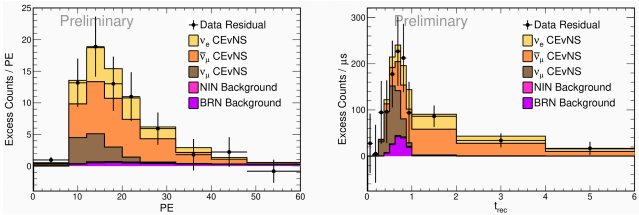
Future Flavor-Dependent Cross Section Sensitivity



- Future COH-Ge-1 and COH-Ar-750 will be capable of precision CEvNS measurements, increasing sensitivity to flavored CEvNS cross sections
- Limited by current 10 % uncertainty on neutrino flux
  - Will greatly benefit from D_2O flux normalization measurement!

Conclusions / Summary

- CEvNS measurements at the SNS offer opportunities for sensitive BSM, nuclear, and neutrino studies
- COHERENT has successfully measured CEvNS on multiple targets at the SNS
- COHERENT is pursuing several nuclear targets and is entering a phase of precision measurements

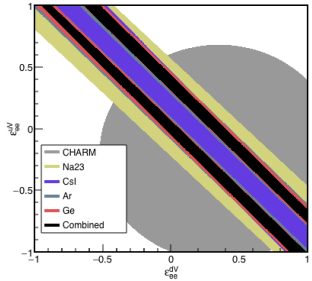


Acknowledgements:
We are grateful for logistical support and advice from SNS (a DOE Office of Science facility). Much of the background measurement work was done using ORNL SEED funds, as well as Sandia Laboratories Directed Research and Development (LDRD) and NA-22 support. LAr detector deployment is supported by ORNL LDRD funds and the CENNS-10 detector is on loan from Fermilab. We thank Pacific Northwest National Laboratory colleagues and Triangle Universities Nuclear Laboratory for making resources for various detector components available. COHERENT collaborators are supported by the U.S. Department of Energy Office of Science, the National Science Foundation, NASA, and the Sloan Foundation.

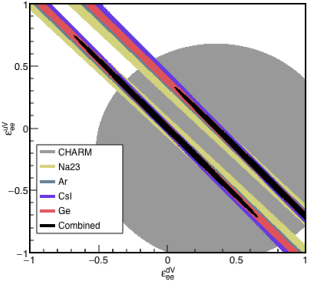
Backups

Beyond First-Light Measurements

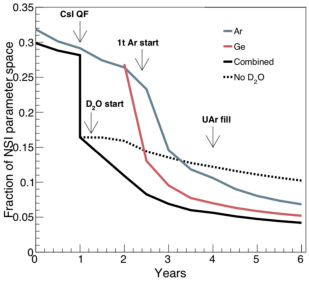
Eg: Neutrino NSI



Near-Future/First light



Precision Measurements

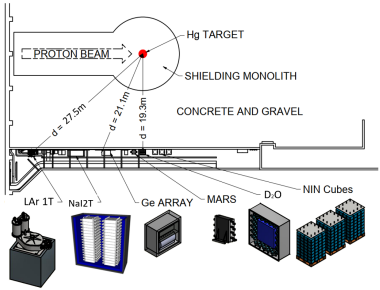


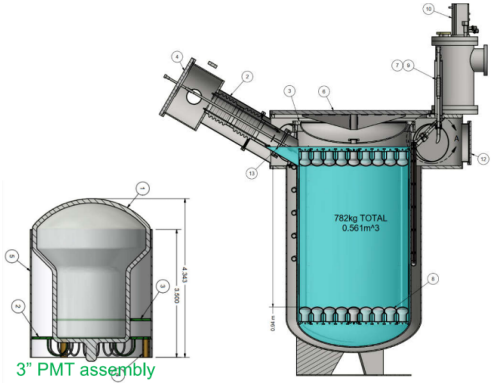
Allowed NSI Parameter Space

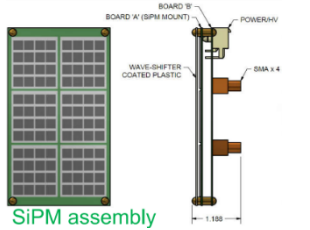
- Multiple targets with different N/Z constrain parameter space
- Sensitivity studies incorporating recoil/time spectra underway
- Flux normalization via D_2O CC detector greatly improves 10 % uncertainty on neutrino flux

Enter CENNS-750

- Single-phase liquid argon calorimeter
- 610 kg fiducial mass
- Designed to meet/exceed 20 keVnr threshold
- Extensive photodetector R&D/Simulation underway
- Designed for future use of underground Ar

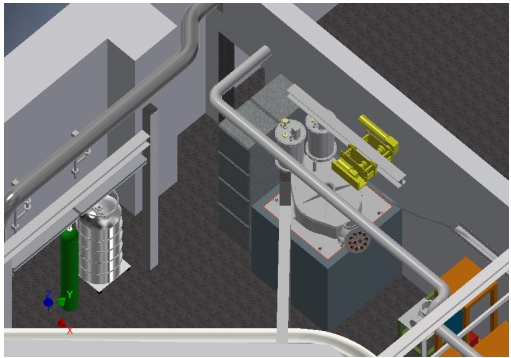


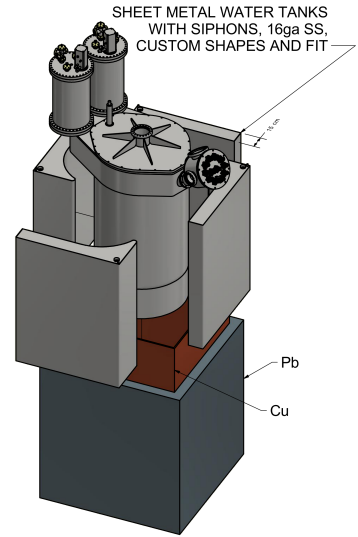




CENNS-750 in Neutrino Alley

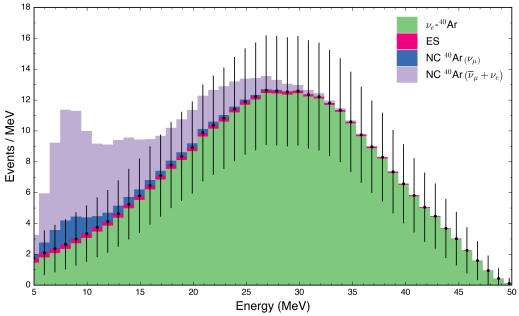
- It fits!
- Designed to occupy current CENNS-10 footprint

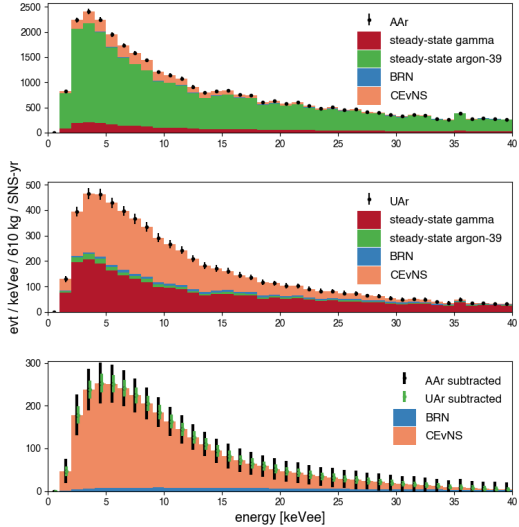




Precision Physics

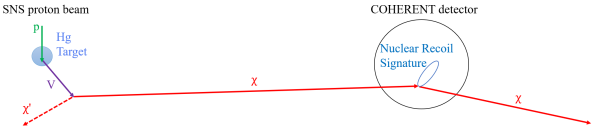
- 3000 CEvNS events/SNS year
- Expect 400 CC and NC inelastic events/SNS year
  - Cross sections important for understanding DUNE SN signature

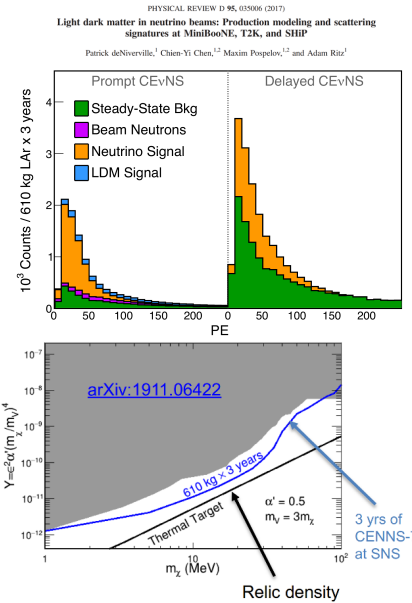




Vector Portal DM

- Potential vector portal dark matter produced by pions in SNS target
- Signal:
  - Nuclear recoils following beam time profile
  - Spectrum dependent on mediator and DM mass
  - Sensitivity improved via better understanding/mitigation of beam-related neutrons

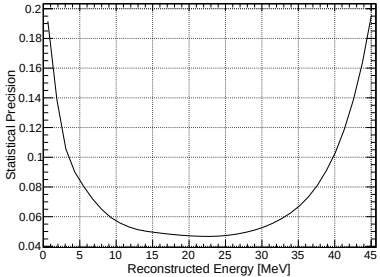




D_2O Expected Signal/Bkg Rates

Expected Precision

- Expected 4.7 % precision in 2 SNS-years
- Single 592 kg detector module



	Total Events	Events Above Threshold
$\nu_e + D$	1040	912
$\nu_e + O$	390	159
Cosmics	20200	293