The COHERENT collaboration and its first observation of CEvNS

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(Indiana University)

For the COHERENT collaboration

Coherent Elastic Neutrino-Nucleus Scattering - CEvNS

- NC (flavor independent) process predicted in 1974 by D. Freedman and V. Kopeliovich [1, 2]

- Neutrino scatters off via exchange a Z-boson (νA → νA)
  - Nucleus recoils as a whole
  - Low momentum transfer, $\lambda_z = 1/q < R_N$
  - Identical initial and final states
  - Coherent up to E_ν ~ 50 MeV

- Enhanced cross-section for heavy nuclei!

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Coherent effects of a weak neutral current

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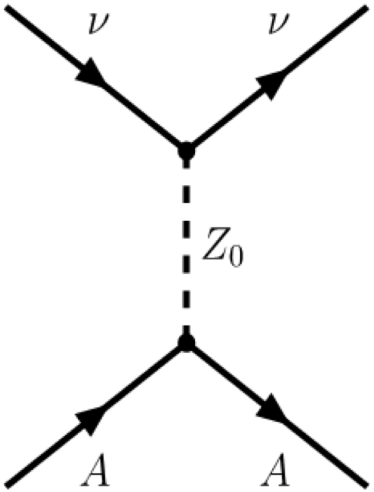
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790
(Received 15 October 1973; revised manuscript received 19 November 1973)



[1] D.Z. Freedman, Phys Rev D 9 (1974)
[2] V.B.Kopeliovich & L.L.Frankfurt JETP Lett. 19 (1974)

Coherent Elastic Neutrino-Nucleus Scattering - CEvNS

$$\frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2} k^2 (1 + \cos\theta) \frac{(N - (1 - 4\sin^2\theta_W)Z)^2}{4} F^2(Q^2)$$

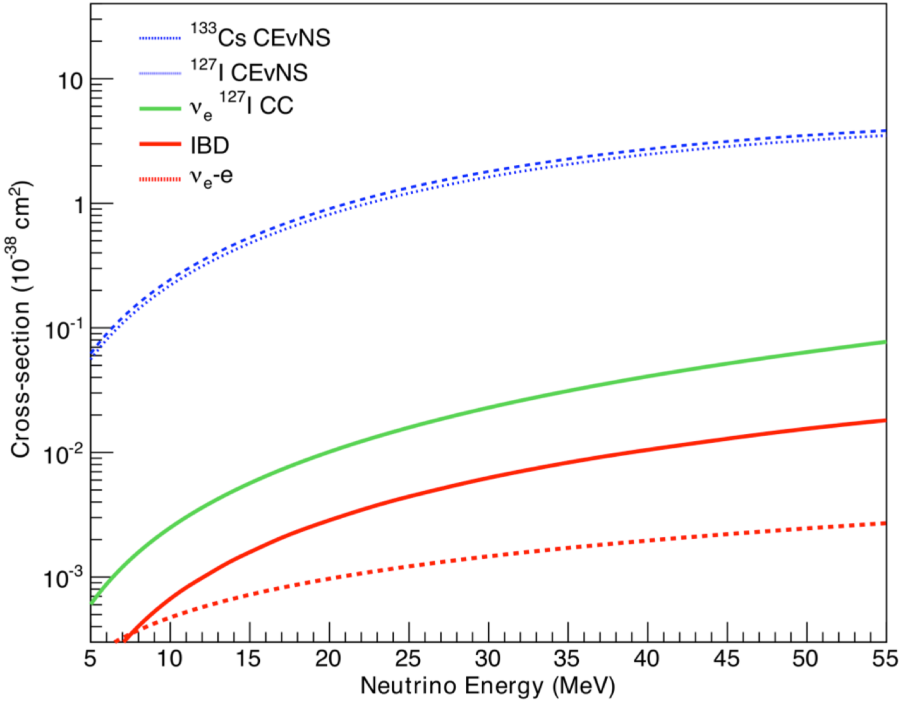
- Standard Model calculation
  - Dependence on neutron number

$$\sigma \approx \frac{G_F^2 N^2}{4\,\pi}$$

  - Largest of all Standard Model low-energy neutrino interaction cross-sections

- Experimental signature – nuclear recoil
  - Low energy signals

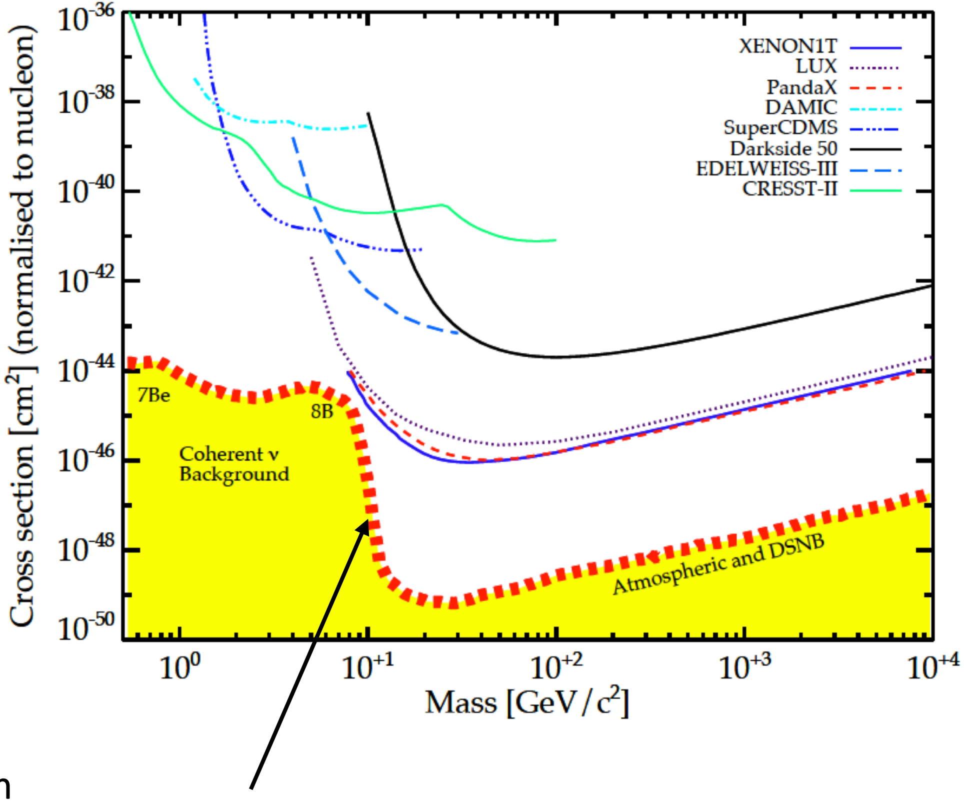
$$E_r^{\max} \simeq \frac{2E_\nu^2}{M} \simeq 50\ \mathrm{keV}$$



[1] D.Z. Freedman, Phys Rev D 9 (1974)

Physics from CEvNS

- Standard model tests
  - Proton weak charge ($\sin^2(\theta_W)$)
  - Nuclear form factors
  - Non-standard interactions of neutrinos
  - Neutrino magnetic moment
- Supernova Neutrino detection channel
- Reactor Monitoring
- Dark Matter (DM)
  - Accelerator DM search with O(1 ton) CEvNS detector
  - CEvNS is important background for next generation of a ton-scale direct searches
    - Will begin to be sensitive CEVNS from ^{8}B solar neutrino flux



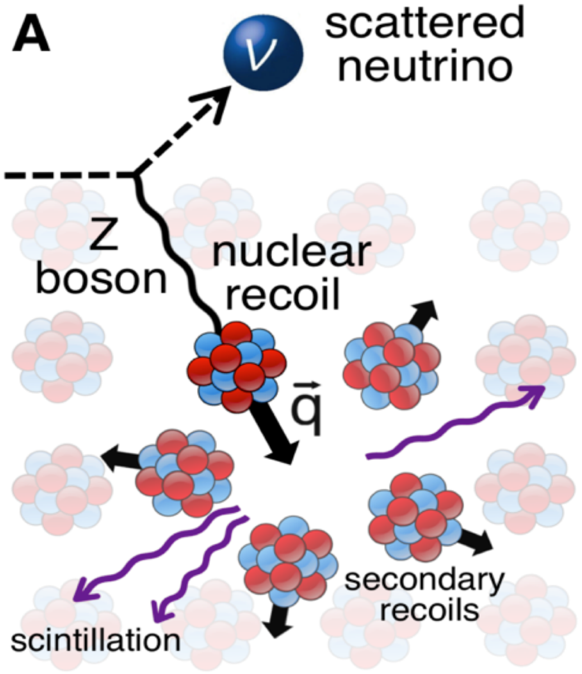
Coherent neutrino background

Experimental challenges and COHERENT program

- Experimental signature is a low-energy recoiling nucleus
  - Heavier nuclei: higher cross section but lower recoil energies
  - Nuclear recoil signal yields are quenched
  - Need to calibrate detector performance at low-energy

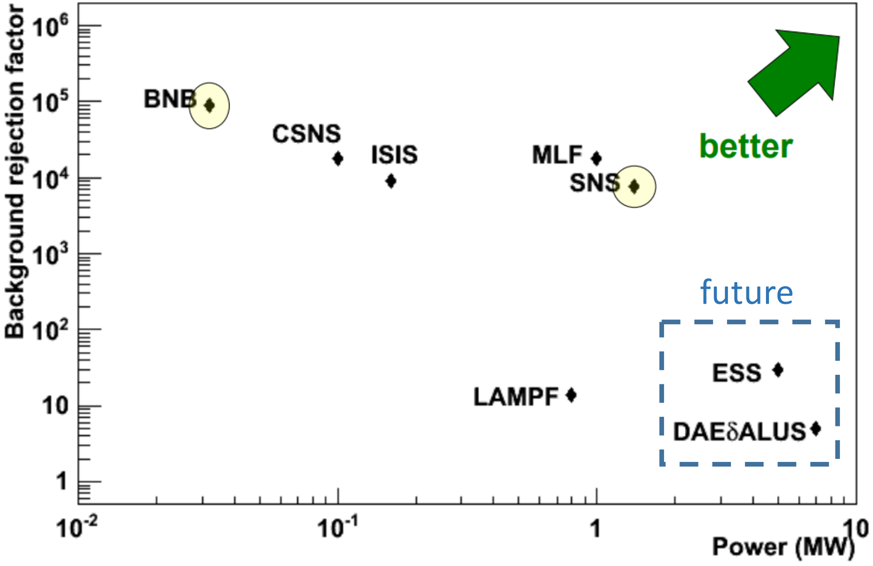
- Very sensitive detectors are very sensitive to backgrounds
  - Low energy neutrons in the detectors can produce similar recoil spectra as neutrino scattering signal

- Need an appropriate source of neutrinos



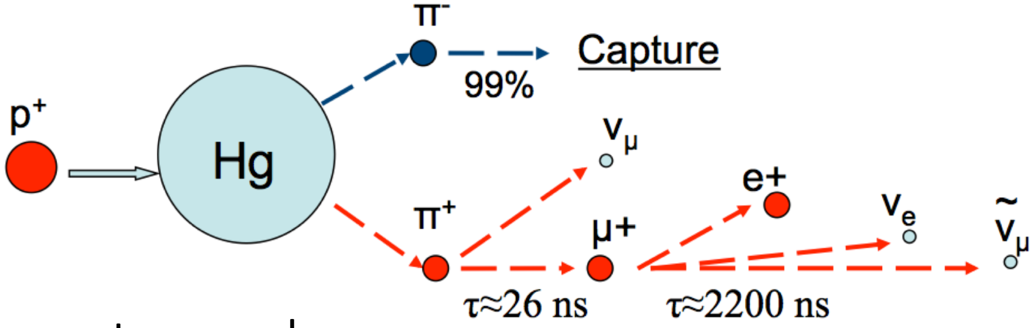
COHERENT program

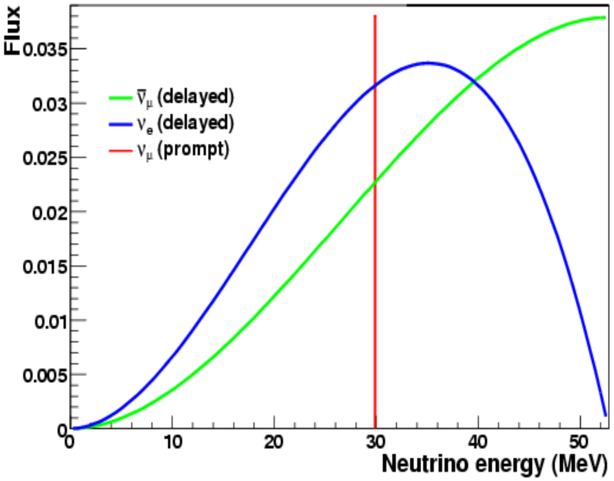
- Goal: unambiguous observation and study of CEvNS
- Neutrino source
  - pulsed proton beam on a mercury target at the ORNL Spallation Neutron Source (SNS)
- Several nuclear targets / detector technologies for N^2 dependence
  - low threshold detectors
- Well characterized and reduced background
- Pioneering CEvNS detector: CsI[Na]
- https://coherent.ornl.gov



Spallation Neutron Source (SNS) at Oak Ridge

- Pulsed Proton Beam
  - ~1 MW power
  - 60 Hz, 600 ns spill
  - Pulsing allows natural background rejection for factor ~ 10^4
  - Proton collisions with mercury create neutrons and neutrinos (~ 10^7 $cm^{-2}s^{-1}$ per flavor at 20 m).





Prompt monochromatic
29.2 MeV

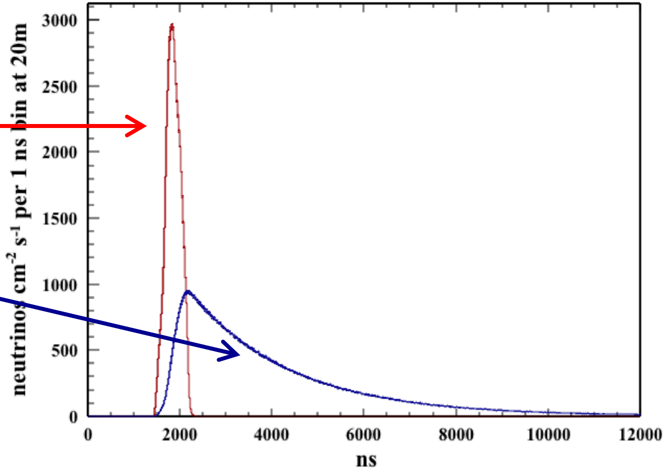
$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$

$$\downarrow$$

$$\mu^+ \longrightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

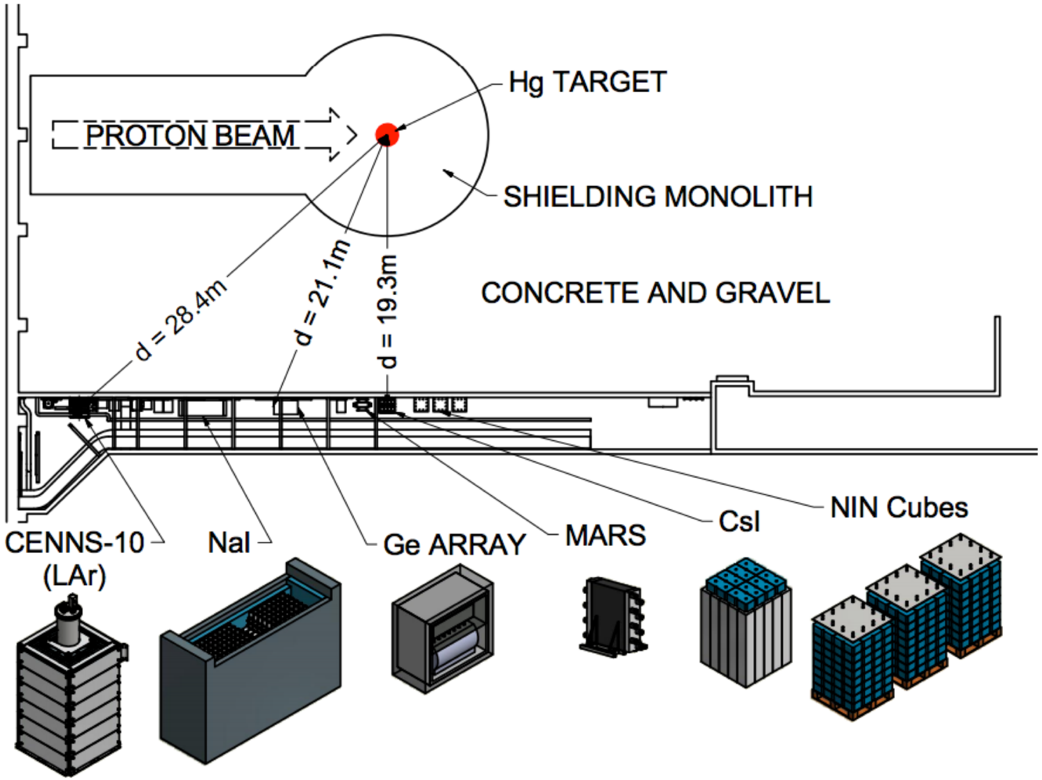
$0 < E < m_\mu/2$

2.2 μs delayed



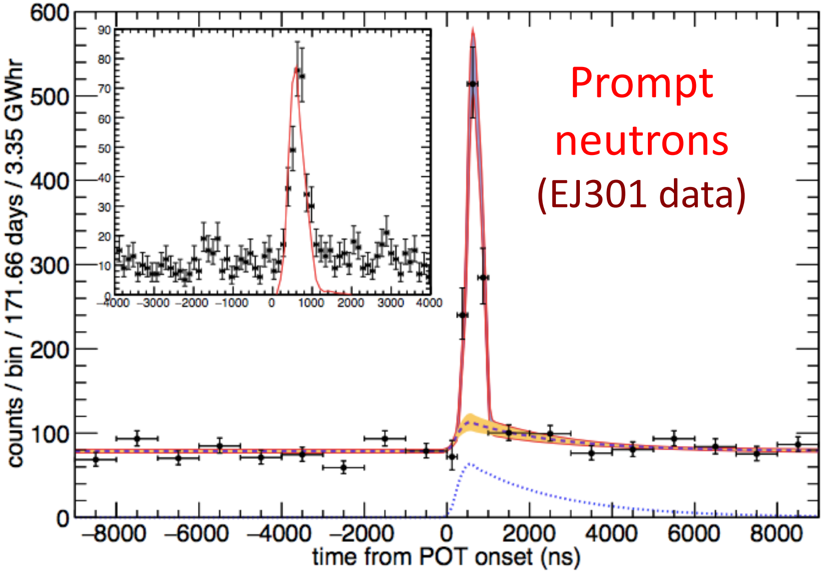
COHERENT Detectors siting and Backgrounds

- Background depends on siting at the SNS target building
  - "Neutrino alley"
    - Detectors located at SNS basement
    - ~ 8 m.w.e. overburden
      - Reduction of the CR backgrounds
    - ~20 – 29 m of gravel and concrete in the direction to target
      - "prompt" neutron flux reduction
  - Background measurements were performed at different locations with different detector technologies



"Prompt" Neutron Background

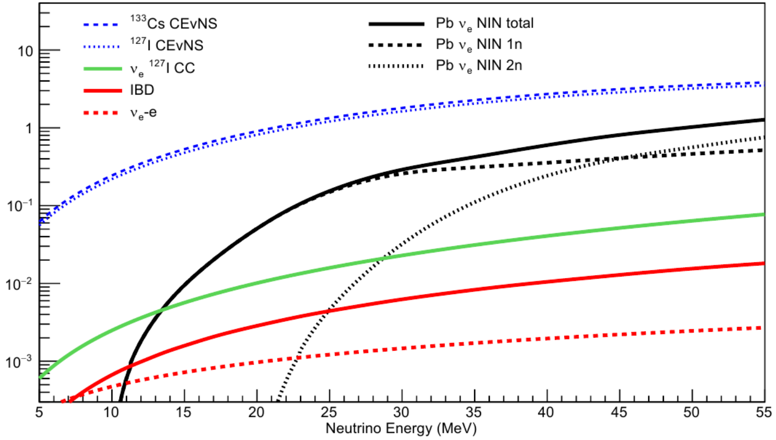
- 100 keV – 1 MeV neutrons can produce similar signal
- Neuron flux measured at different positions with multiple detector technologies w/o shielding:
  - Sandia Scatter Camera – multiplane liquid scintillator
  - SciBath - WLS fiber + liquid scintillator
  - MARS – sandwiched plastic scintillator/Gd sheets
- Prompt neutron flux ~10^{-7} neutrons/cm^2/s
- Expected rates in detector below CEvNS signal

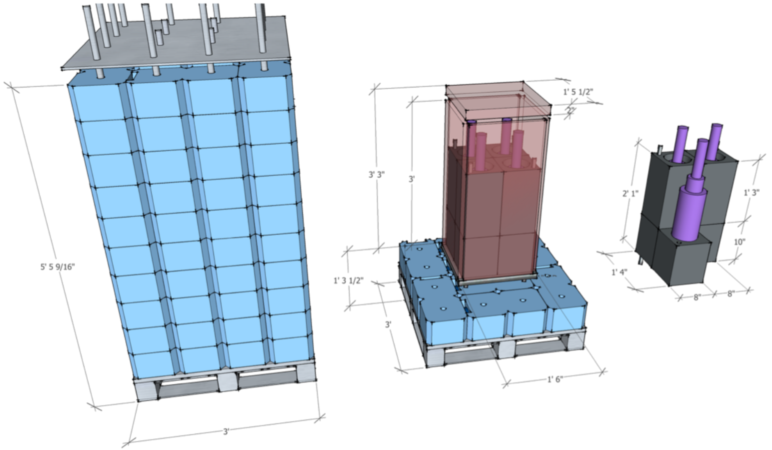


Background - Neutrino induced neutrons

Neutrino induced neutrons (NINs) coincident with the CEnNS signal:

- Never been observed
- Produced by neutrinos in Pb shield [1]
    - requires careful shielding design.
- Cross section is poorly known. NIN is a signal in the HALO experiment to detect Supernovae neutrinos [2].





[1] - E. Kolbe, E. Langanke, Phys. Rev. C63 (2001)

[2] - C.A. Duba et al. J. Phys. Conf. Series 136 (2008)

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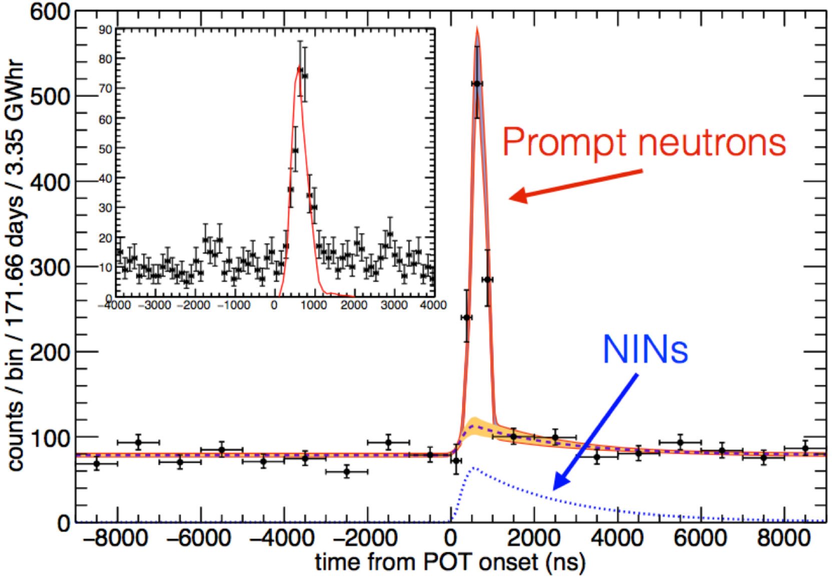
- Never been observed
- Produced by neutrinos in Pb shield [1]
  - requires careful shielding design.
- Cross section is poorly known. NIN is a signal in the HALO experiment to detect Supernovae neutrinos [2].
- COHERENT program with Lead (1 ton) and Iron (700 kg) and Cu targets to measure NINs (for background evaluation) and their production cross section (as a physics measurement).

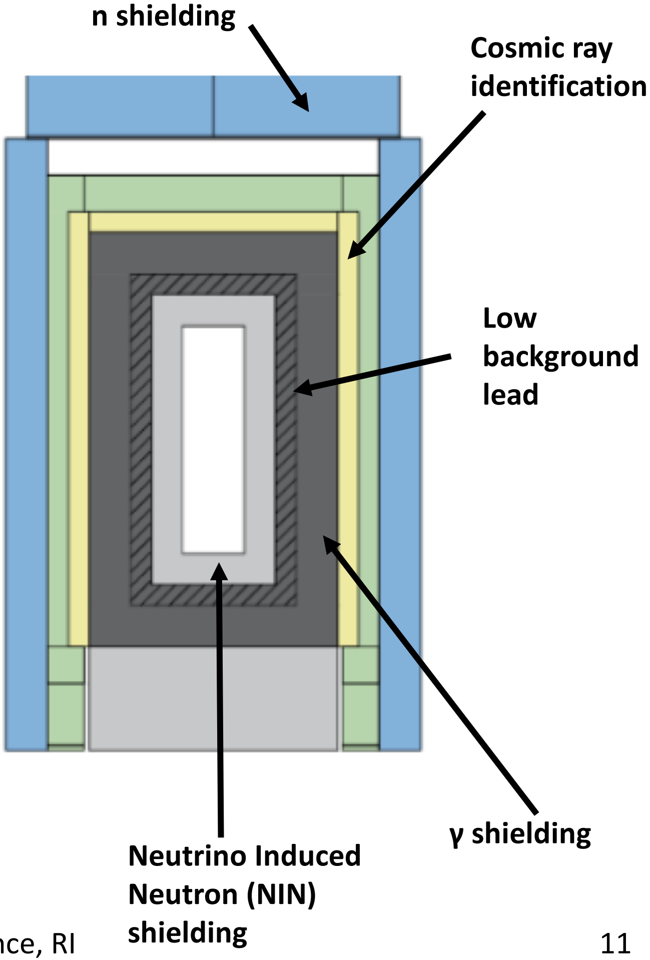


- First indication of NINs detection (1.7 times below theory prediction)

[1] - E. Kolbe, E. Langanke, Phys. Rev. C63 (2001)
[2] - C.A. Duba et al. J. Phys. Conf. Series 136 (2008)

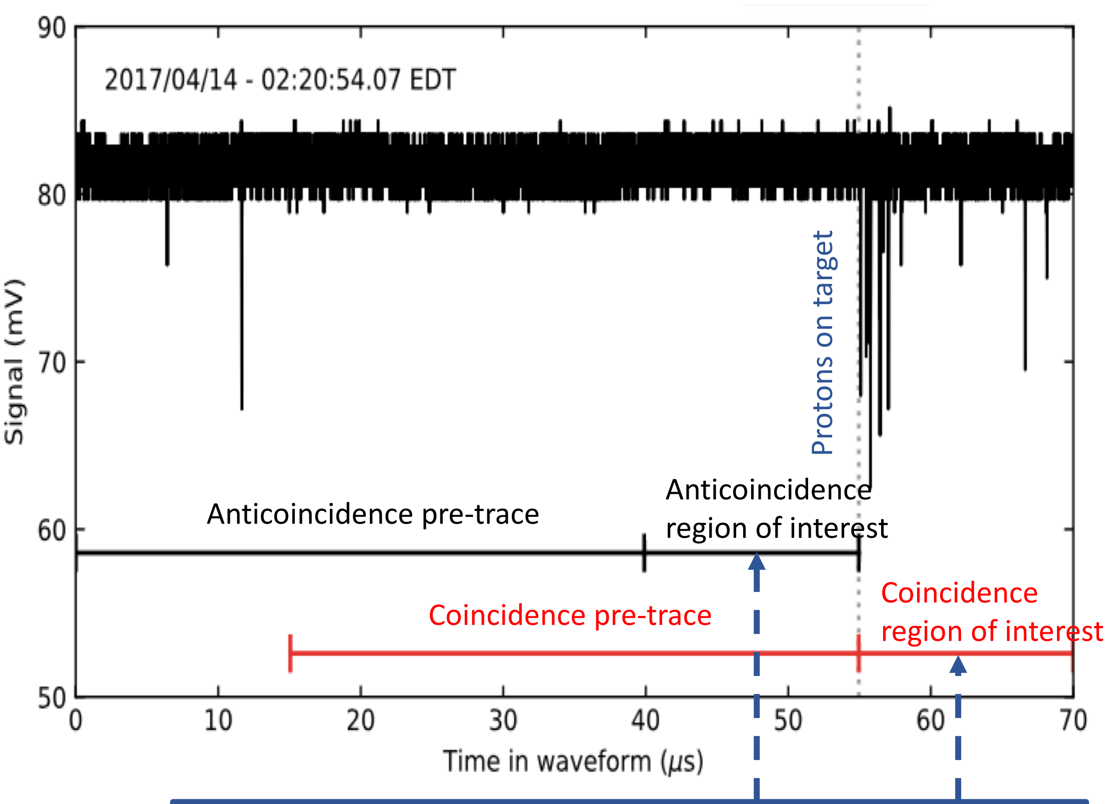
Detector Subsystem – CsI[Na]

- 14.6 kg sodium doped CsI inorganic crystal
    - electroformed-copper can
    - PTFE reflector and synthetic silica window
- High light yield
- Low intrinsic background
- Room temperature operation
- Deployed at the SNS "neutrino-alley" in 2015
    - 1.76x10^{23} POT delivered to CsI (7.48 GWhr)



Detector Subsystem - CsI

- Super-bialkali PMT Hamamatsu R877-100 with ~30% QE
- Recording of 70 µs waveforms with 500 MHz sampling of CsI and veto channels
- ~ 2×10^9 waveforms were recorded
- 2 independent analyses with slightly different cut:
  - count beam-on low-energy events (nuclear recoils)
  - subtract steady state backgrounds from beam-off data
  - measure/subtract beam-related backgrounds (neutrons)



CEnNS + Beam-on Background =
(Event count in C ROI) – (Event count in AC ROI)

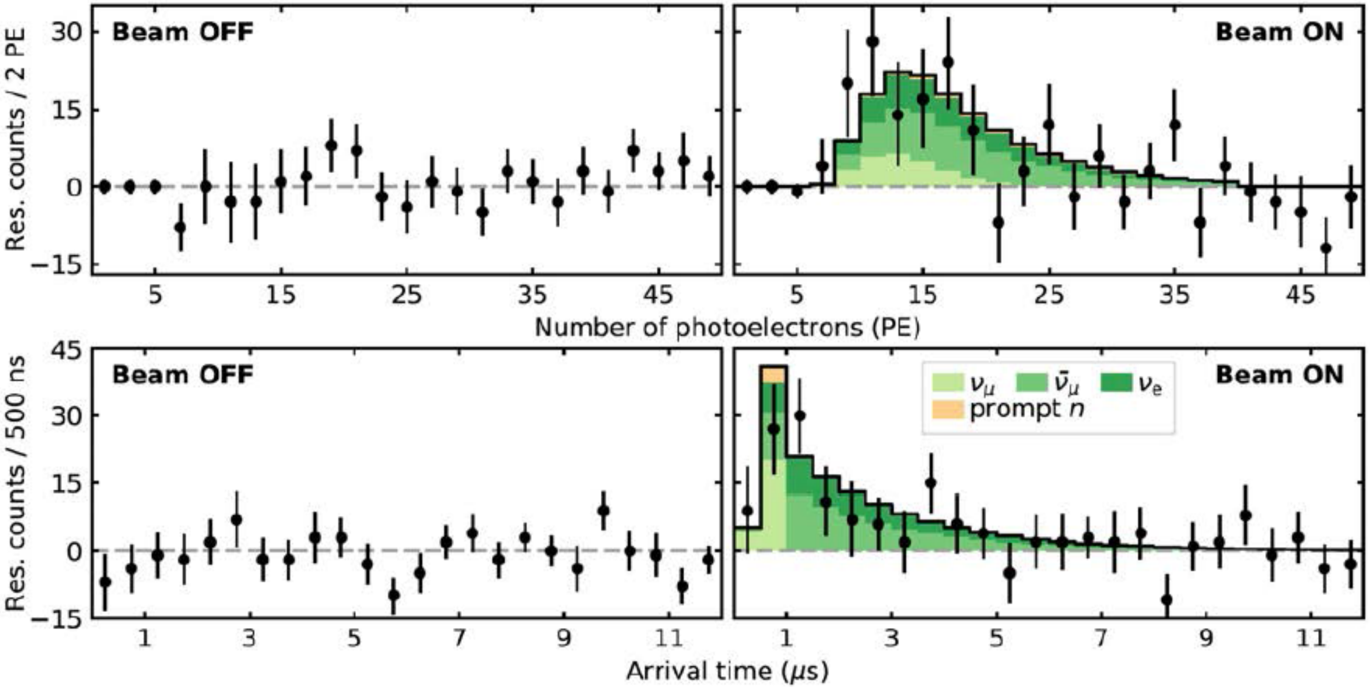
First CEvNS observation

Data points are the **residuals** between CsI[Na] signals in the 12 ms following POT triggers and the 12 ms before:

- Beam OFF: 153.5 live-days
- Beam ON: 308.1 live-days, 7.48 GWhr onto the SNS target

Charge
~ 1.2 PE/keVnr

Time

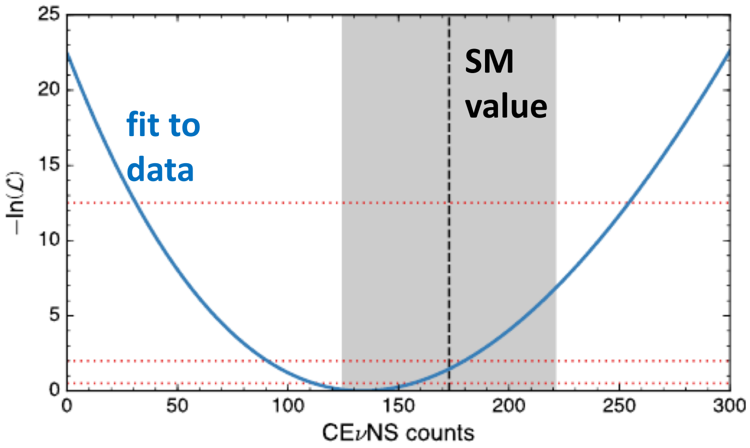


First CEvNS results

- 2D-profile likelihood analysis
  - 134 ± 22 observed events [1]
- Standard model prediction 173 ± 48 events
  - Agreement with the SM prediction to within 1σ
- No CEvNS rejected at 6.7σ

Beam ON coincidence window	547 counts
Anticoincidence window	405 counts
Beam-on bg: prompt beam neutrons	7.0 ± 1.7
Beam-on bg: NINs (neglected)	4.0 ± 1.3
Signal counts, single-bin counting	136 ± 31
Signal counts, 2D likelihood fit	**134 ± 22**
Predicted SM signal counts	**173 ± 48**

6 ≤ PE ≤ 30, 0 ≤ t ≤ 6000 ns



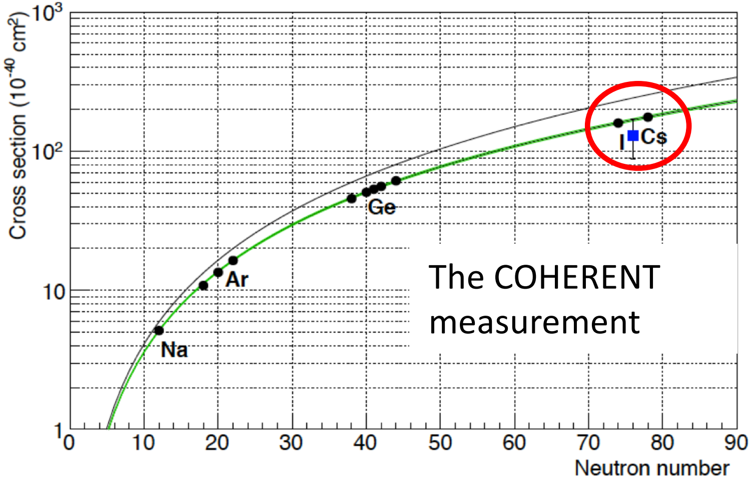
Uncertainties on signal and background predictions	
Event selection	5%
Flux	10%
Quenching factor	25%
Form factor	5%
Total uncertainty on signal	**28%**
Beam-on neutron background	25%

- Data package that constituted CEvNS observation is publicly available: https://zenodo.org/record/1228631

[1] D. Akimov et al., Science (2017)

CsI[Na]results

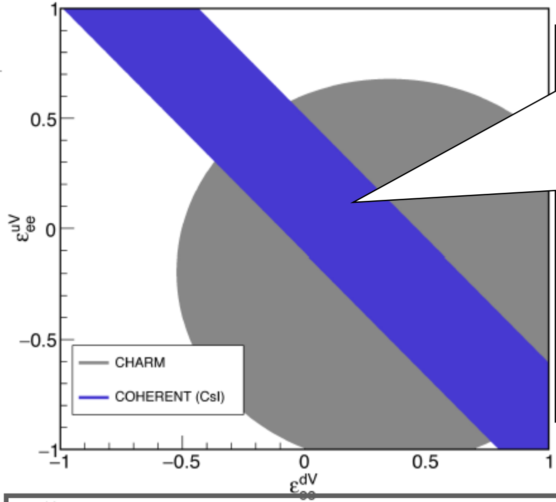
- 2D-profile likelihood analysis
  - 134 ± 22 observed events [1]
- Standard model prediction 173 ± 48 events
  - Agreement with the SM prediction to within 1σ
- No CEvNS rejected at 6.7σ
- consistent w/SM within 1s



$$\mathcal{L}_{\nu H}^{NSI} = -\frac{G_F}{\sqrt{2}} \sum_{\substack{q=u,d \\ f,g=e,\mu,\tau}} [\bar{\nu}_f \gamma^\mu (1-\gamma^5)\nu_g] \times (\varepsilon_{fg}^{qL}[\bar{q}\gamma_\mu(1-\gamma^5)q] + \varepsilon_{fg}^{qR}[\bar{q}\gamma_\mu(1+\gamma^5)q]).$$

New constraints on NSIs for M≳10 MeV

- Simple one-bin analysis
- Considering only $\varepsilon_{ee}^{uV}, \varepsilon_{ee}^{dV}$ to have non-zero values

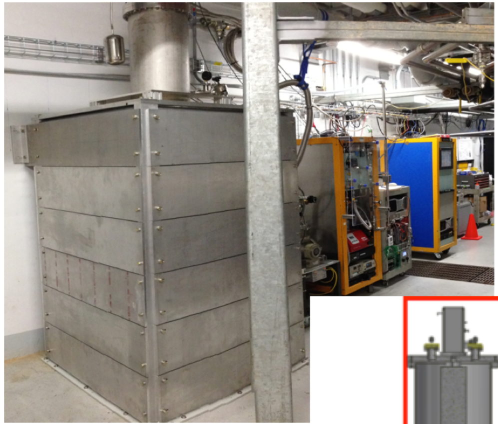


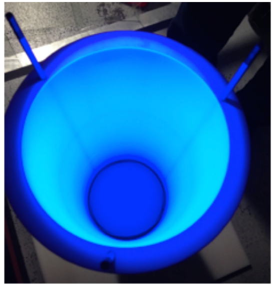
Separate bands not resolved due to current uncertainty (dominated by QF).. will improve, and different N targets will help

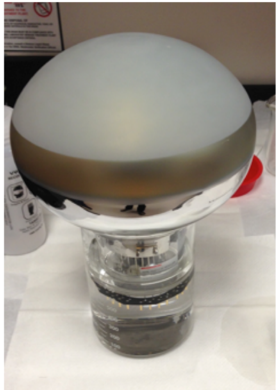
Additional statistics and more complicated analysis to come

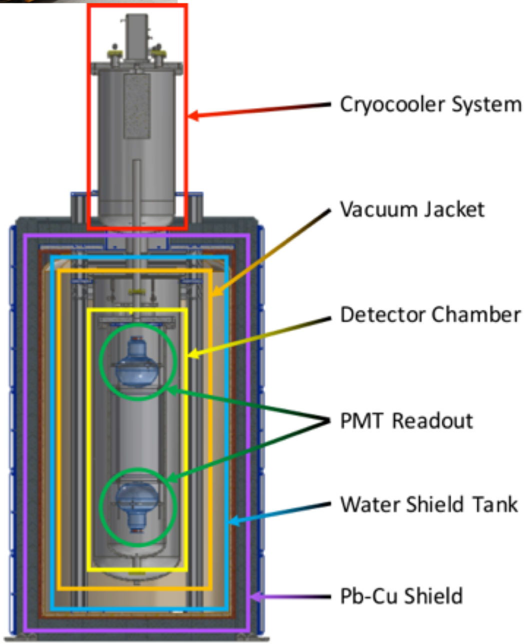
LAr for COHERENT

- CENNS-10 detector
  - Single-phase
  - 2x 8” Hamamatsu R5912-MOD02 PMTs
  - Wavelength shifter tetraphenyl butadiene (TPB) coated Teflon side walls and PMTs
  - ~ 22 kg fiducial volume
  - ~ 20 keVnr energy threshold
- Installed at SNS late 2016 (“Run0”)
- Upgraded in June 2017 to improve light collection capabilities (Run1”, ended May-18)
  - Full shielding operation (8” H_2O, ¼” Cu, 4” Pb)
- Next to provide CEvNS cross-section





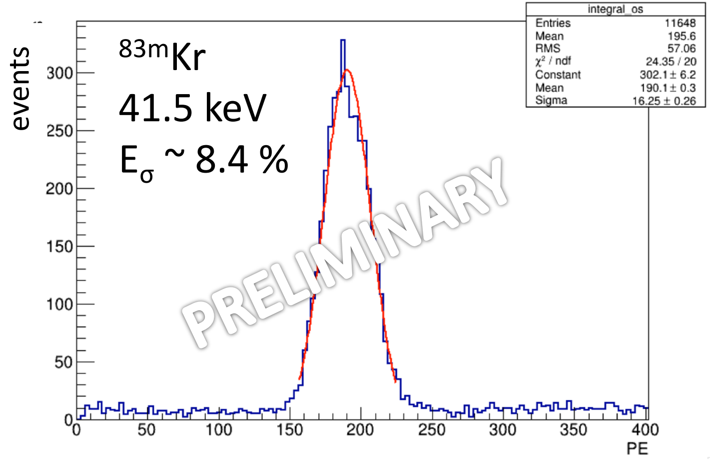




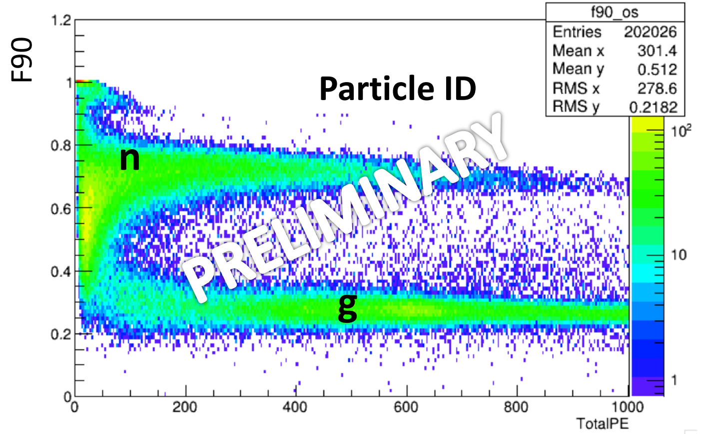
LAr for COHERENT

- CENNS-10 detector
  - 2x Hamamatsu R5912-MOD02 PMTs
  - Wavelength shifter tetraphenyl butadiene (TPB) coated Teflon side walls
  - ~ 22 kg fiducial volume
  - ~ 20 keVnr energy threshold

- ~4.5 pe/keV light yield
- Low-energy ^{83m}Kr source calibration
- Expect ~ 140 CEvNS/SNS-year

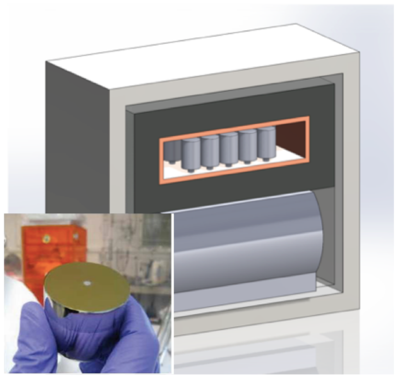


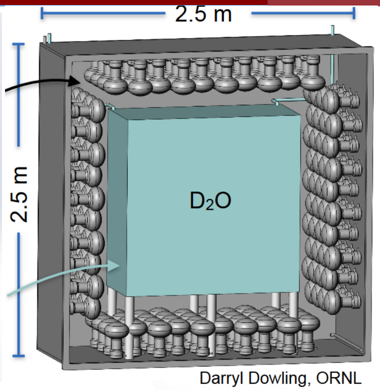
AmBe (w/o water shielding)

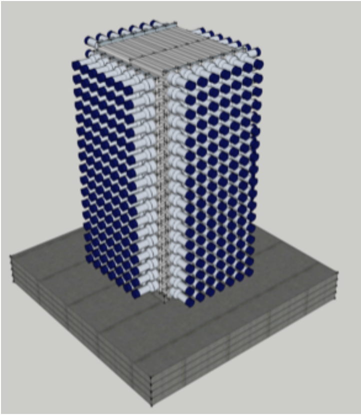


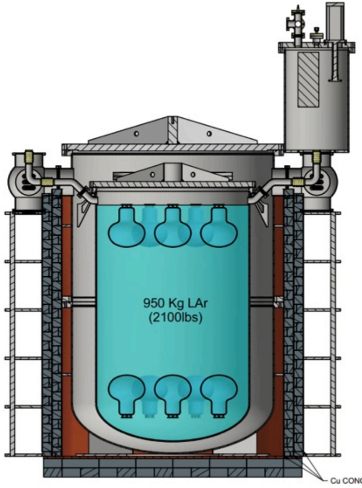
Future COHERENT

- Current data should provide first CEvNS LAr signal
- Double statistics with CsI[Na] by the end of the calendar year
- Improved background, neutrino induced neutron studies
- Future data from Ge and NaI[Tl] 2-ton CEvNS sensitive upgrade
- Precision CEvNS measurement
- Proposal in progress for larger detectors:
  - D_2O for flux normalization
  - O(1 ton) liquid noble gas detector w/underground Ar







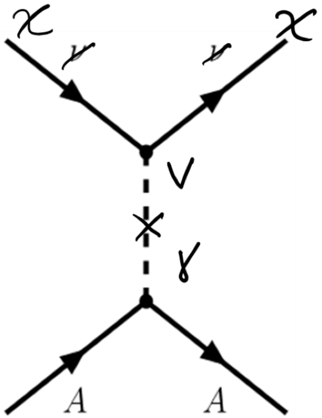


Future COHERENT – Physics

Search for accelerator-produced, low-mass, dark matter

- Via: $p \rightarrow \mathrm{Hg} \rightarrow \pi^{0,\pm}$

$$\pi^0 \longrightarrow \gamma + V^{(*)} \longrightarrow \gamma + \chi^\dagger + \chi$$



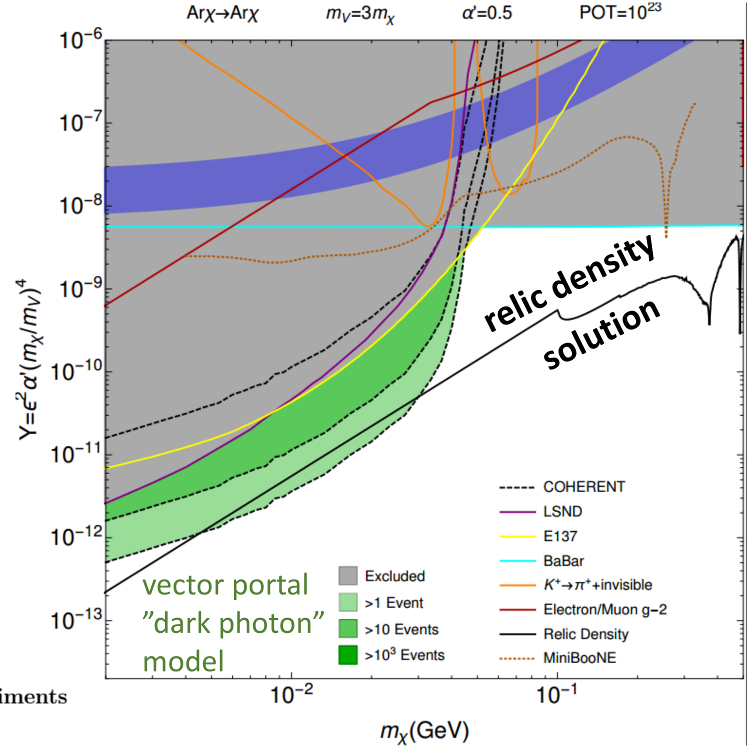
Light new physics in coherent neutrino-nucleus scattering experiments

Patrick deNiverville,[1] Maxim Pospelov,[1,2] and Adam Ritz[1]

[1] *Department of Physics and Astronomy, University of Victoria, Victoria, BC V8P 5C2, Canada*
[2] *Perimeter Institute for Theoretical Physics, Waterloo, ON N2J 2W9, Canada*

(Dated: May 2015)

1 ton-year LAr – SNS DM sensitivity

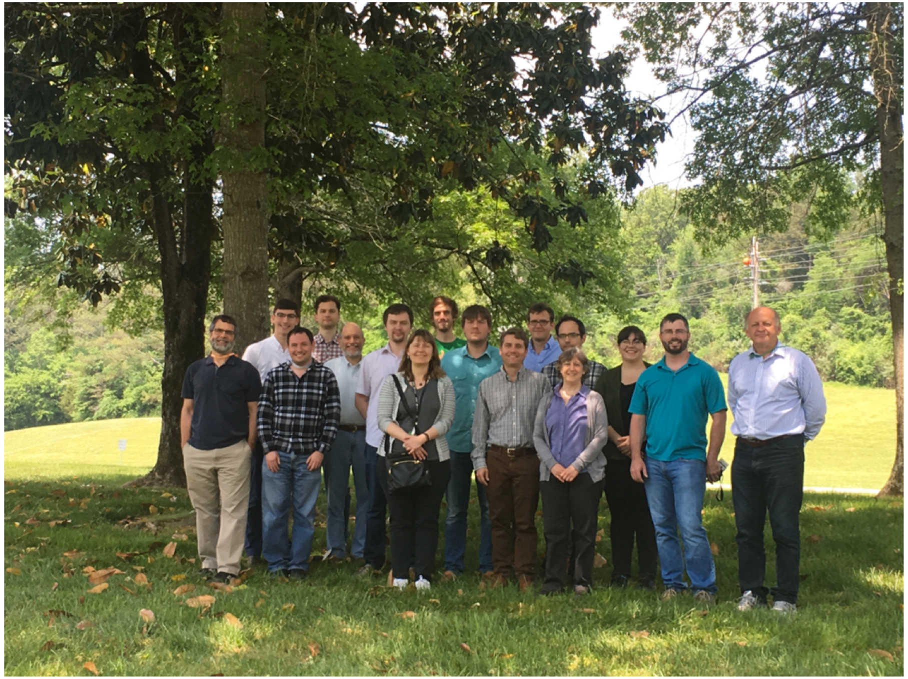


arXiv:1505.07805

Summary

- Search for CEvNS at SNS and measure the coherent neutrino-nucleus cross section in multiple nuclei
- SNS is a great source for a CEvNS measurement due to pulsed beam and beam power
- First CEvNS observation in CsI[Na] (August 2017) made by COHERENT collaboration
- Multiple target material detectors (NaI[Tl], LAr, Ge) taking data and under development to show N^2 dependence. Other target materials under consideration for feasibility.
- Working towards ton-scale detectors for future physics reach

COHERENT collaboration

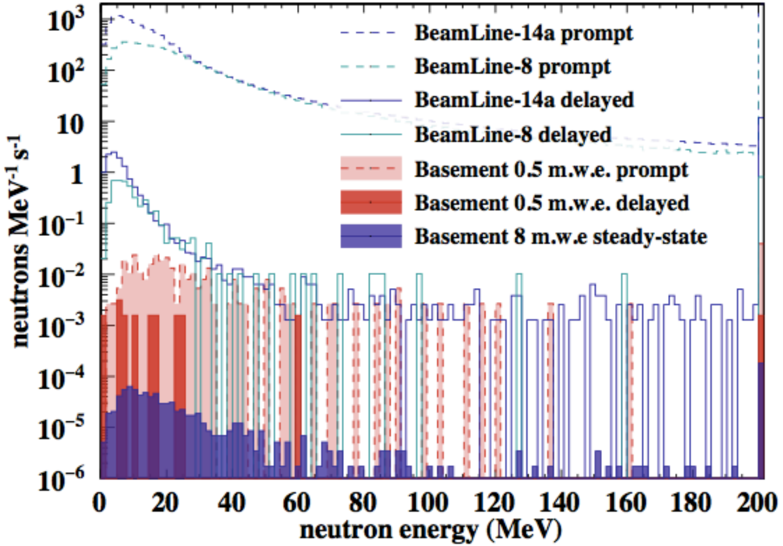


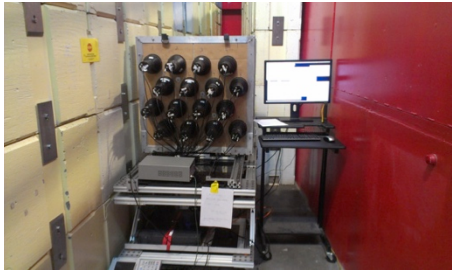
~80 members, 18 institutions 4 countries

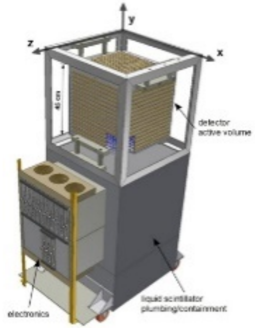
Backup

Neutron Background

- 100 keV – 1 MeV neutrons can produce similar signal
- Neuron flux measured at different positions with multiple detector technologies:
    - Sandia Scatter Camera – multiplane liquid scintillator
    - SciBath - WLS fiber + liquid scintillator
- Low neutron background in the SNS basement
- Prompt neutron flux ~10^{-7} neutrons/cm^2/s
- Expected rates in detector below CEvNS signal

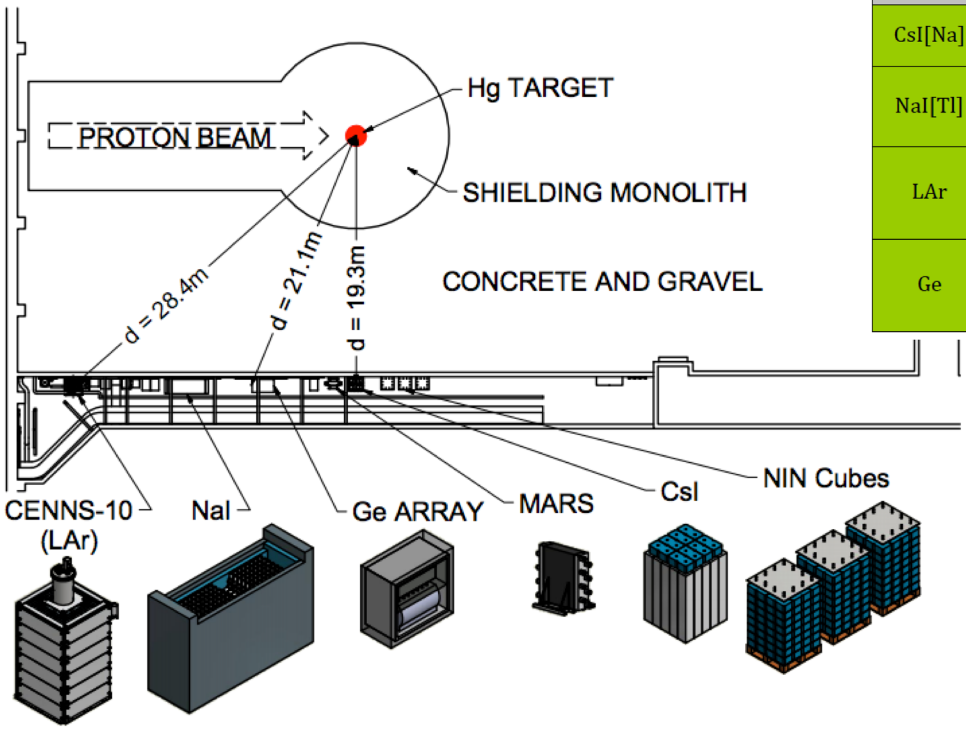






COHERENT Detectors siting

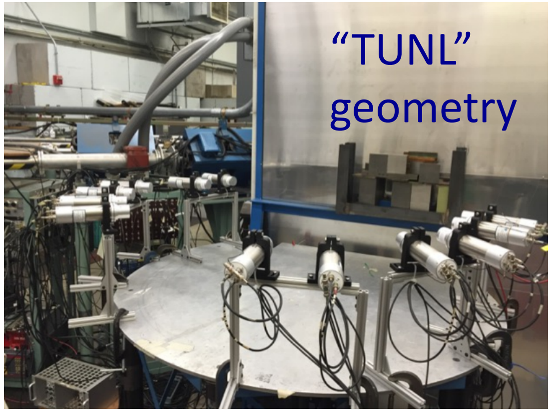
SNS "Neutrino-alley"



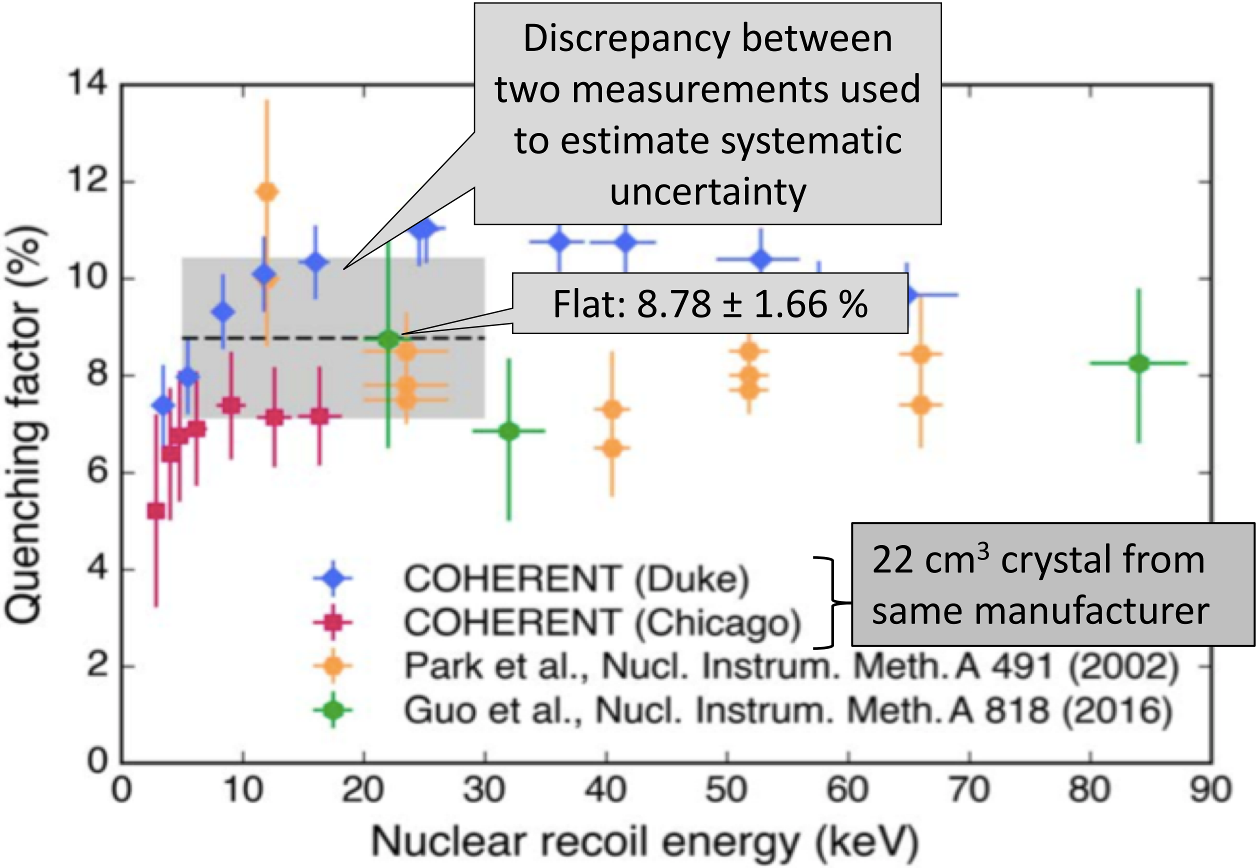
Nuclear Target	Technology	Mass (kg)	Distance from source (m)	Recoil threshold (keVr)	Start data-taking	Possible Future
CsI[Na]	Scintillating crystal	14.6	20	6.5	09/2015	Continue data-taking
NaI[Tl]	Scintillating crystal	185* /2000	28	13	*high-threshold deployment summer 2016	Expansion to 2 tonne
LAr	Single-phase	22	29	20	12/2016, Upgraded 07/2017	Expansion to ~ 1 tonne scale
Ge	HPGe PPC	10	22	5	2018	Ge expansion w/ lower threshold

- COHERENT non-CEvNS detectors
  - Neutron background
    - Sandia Neutron Scatter Camera (deployed 2014-2016)
    - SciBath (deployed 2015)
    - MARS (deployed 2017 – now)
  - Neutrino induced neutron
    - Lead Nube (see G08.08 talk)
    - Iron Nube

CsI[Na] – Quenching factor measurements



- Elastically scatter neutrons into "backing detectors" at known angles, corresponding to well-defined recoil energies
- Disagreement between COHERENT measurements under (re)analysis



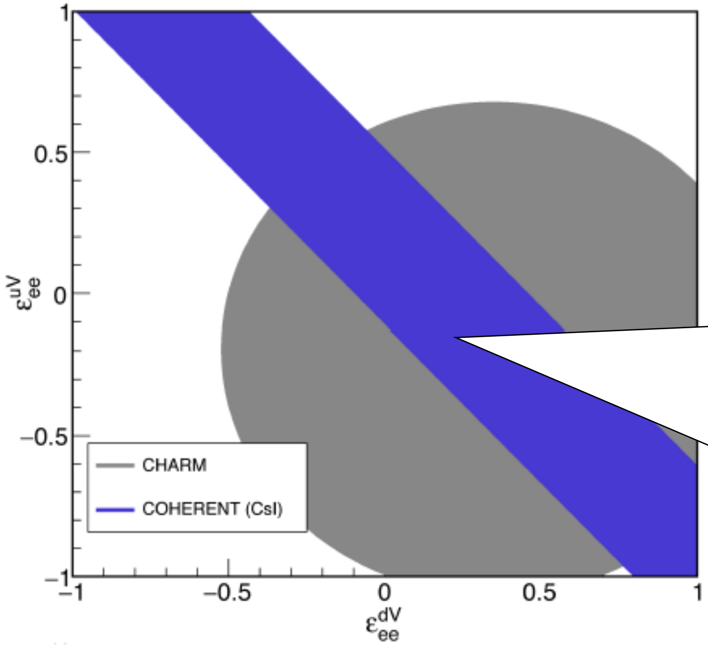
CEvNS and NSI

Model independent parameterization of NS contributions to ν-q interactions

$$\mathcal{L}_{\nu H}^{NSI} = -\frac{G_F}{\sqrt{2}} \sum_{\substack{q=u,d \\ f,g=e,\mu,\tau}} [\bar{\nu}_f \gamma^\mu (1-\gamma^5)\nu_g] \times (\varepsilon_{fg}^{qL}[\bar{q}\gamma_\mu(1-\gamma^5)q] + \varepsilon_{fg}^{qR}[\bar{q}\gamma_\mu(1+\gamma^5)q]).$$

- Considering only $\varepsilon_{ee}^{uV}, \varepsilon_{ee}^{dV}$ to have non-zero values
- First result put constraints on non-universal interactions

Additional statistics and more complicated analysis to come



Separate bands not resolved due to current uncertainty (dominated by QF).. will improve, and different N targets will help

NaI[Tl] for COHERENT

- Thallium doped sodium iodide scintillating inorganic crystal
  - Scintillation process very similar to CsI scintillation
- Currently 185 kg total
  - 24 7.7 kg detectors
- Currently not sensitive to CEvNS
  - Being used for a different neutrino measurement
    - Charged current interaction on ^{127}I
  - Background characterization for ton-scale upgrade