CEvNS observation at the SNS with the COHERENT experiment

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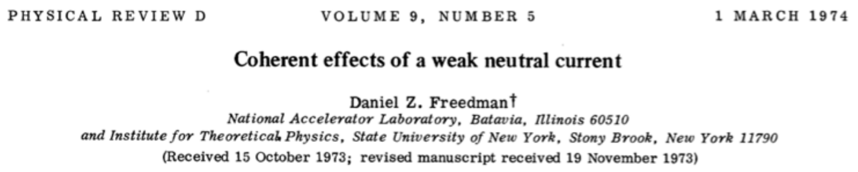
For the COHERENT collaboration

Coherent Elastic Neutrino-Nucleus Scattering - CEvNS

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

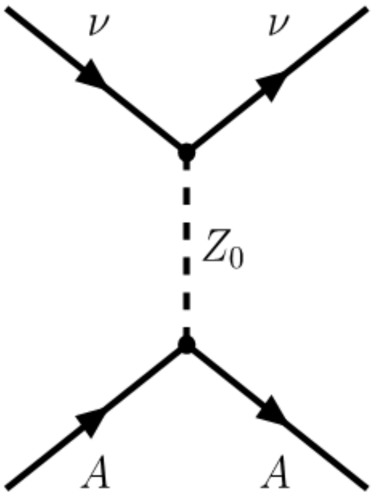
- Neutrino scatters off via exchange a Z-boson (νA → νA)
    - Nucleus recoils as a whole
    - Low momentum transfer, $\lambda_z=1/q<R_N$
    - Identical initial and final states
    - Coherent up to E_ν ~ 50 MeV

- Enhanced cross-section for heavy nuclei!


PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

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)



[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

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

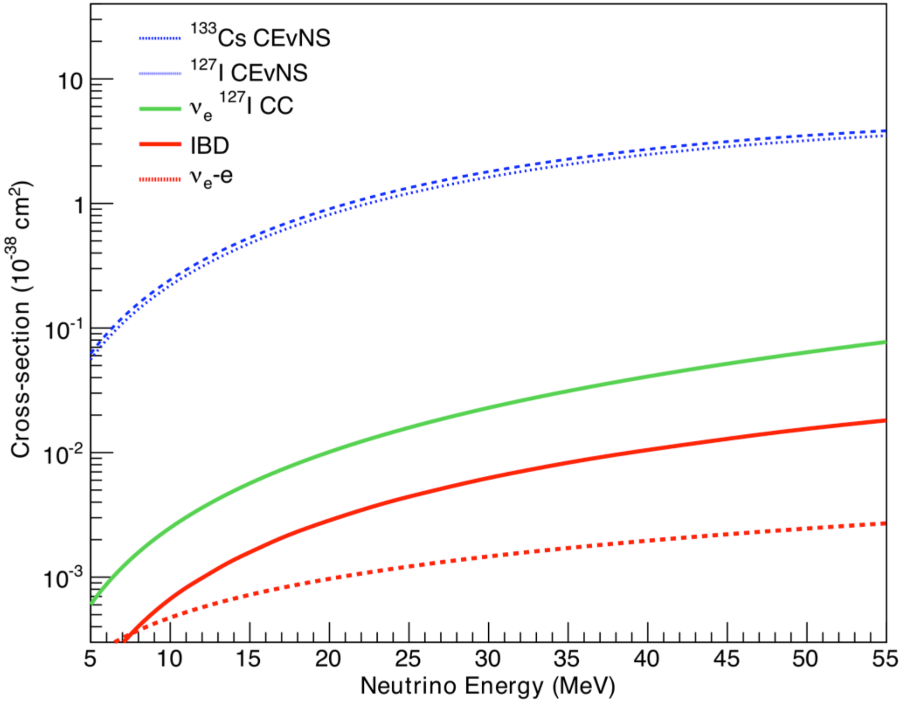
- Standard Model calculation
  - Dependence on neutron number

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

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

- Experimental signature – nuclear recoil
  - Low energy signals

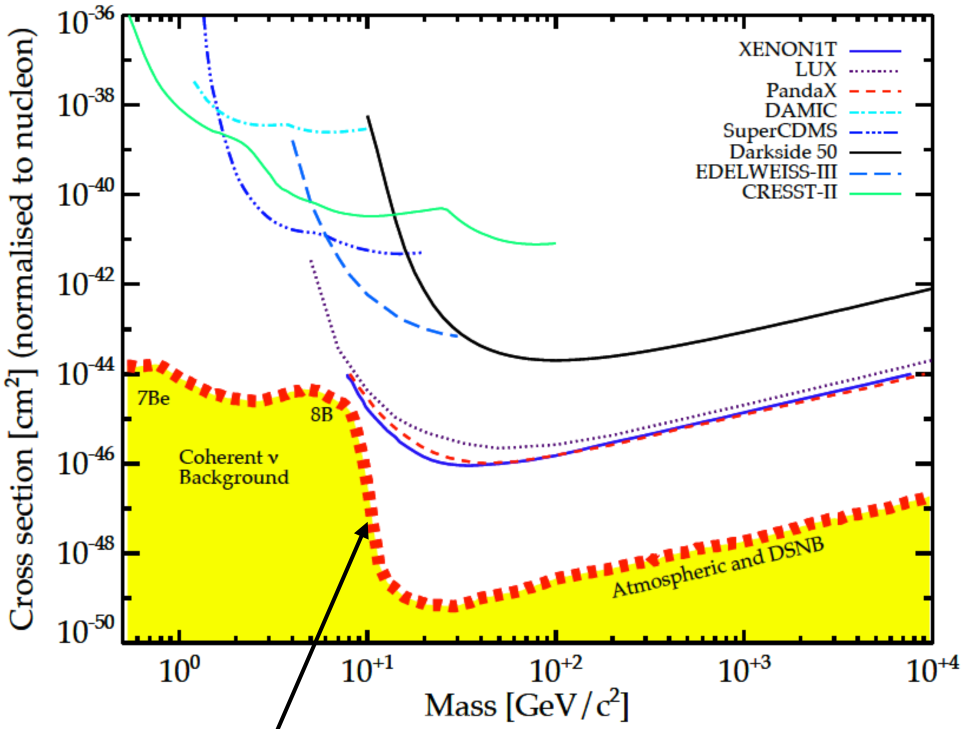
$$E_r^{\max} \simeq \frac{2E_\nu^2}{M} \simeq 50\ \mathrm{keV}$$



[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 ^8B solar neutrino flux



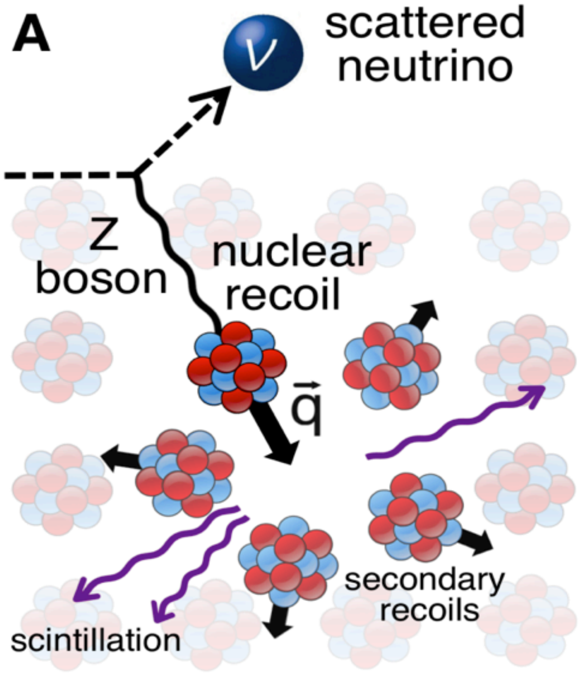
Coherent neutrino background

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

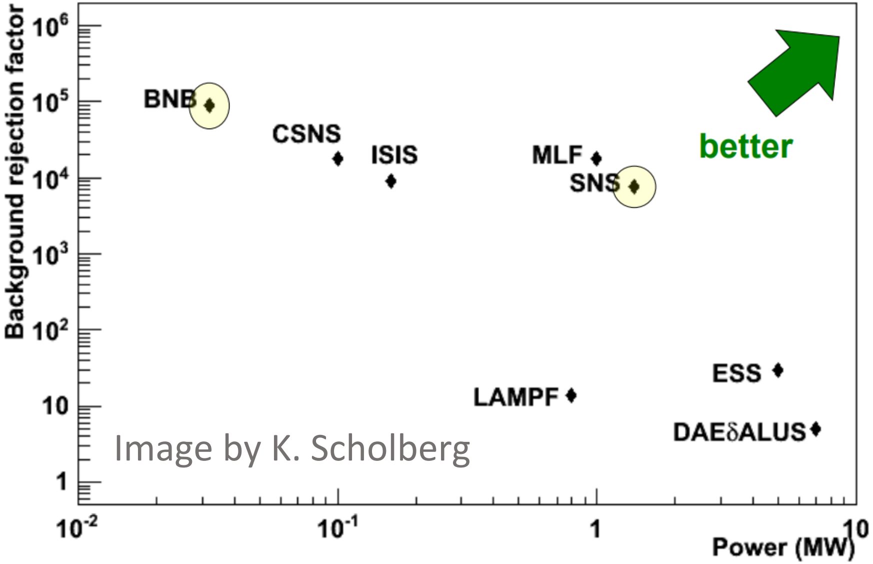
- Very sensitive detectors are very sensitive to backgrounds
  - Low energy neutrons in the detectors can produce similar recoil spectra as neutrino scattering signal

- Need an appropriate source of neutrinos



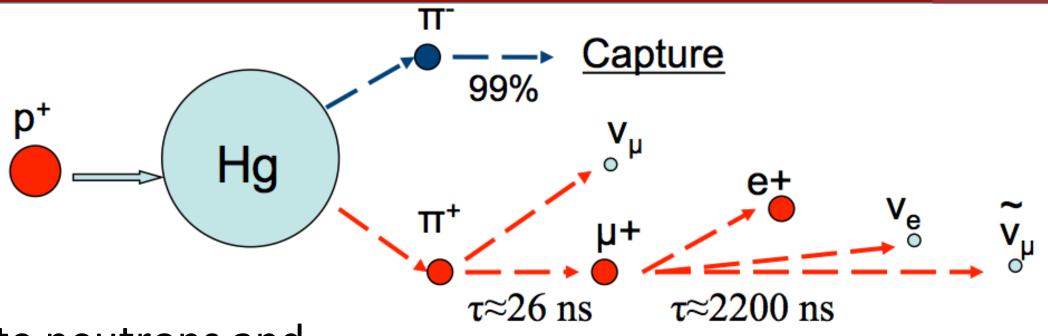
COHERENT program

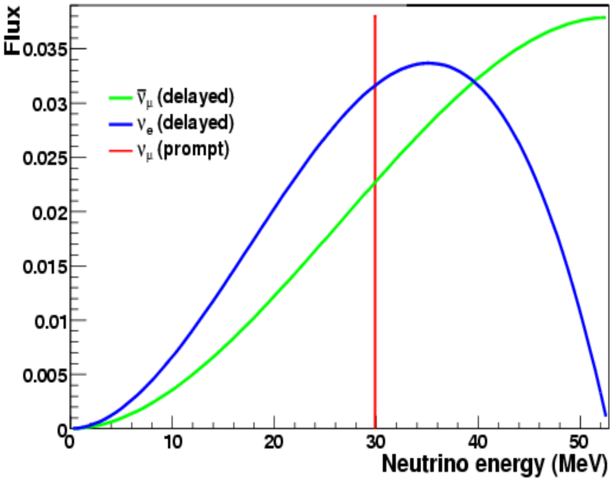
- Goal: unambiguous observation of CEvNS
- Neutrino source
  - pulsed proton beam on a mercury target at the ORNL Spallation Neutron Source (SNS)
- Several nuclear targets / detector technologies for N^2 dependence
  - low threshold detectors
- Well characterized and reduced background
- Pioneering CEvNS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

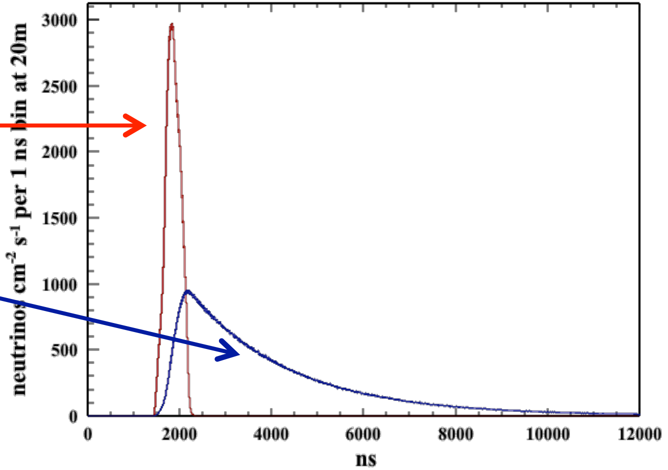




Prompt monochromatic
29.2 MeV

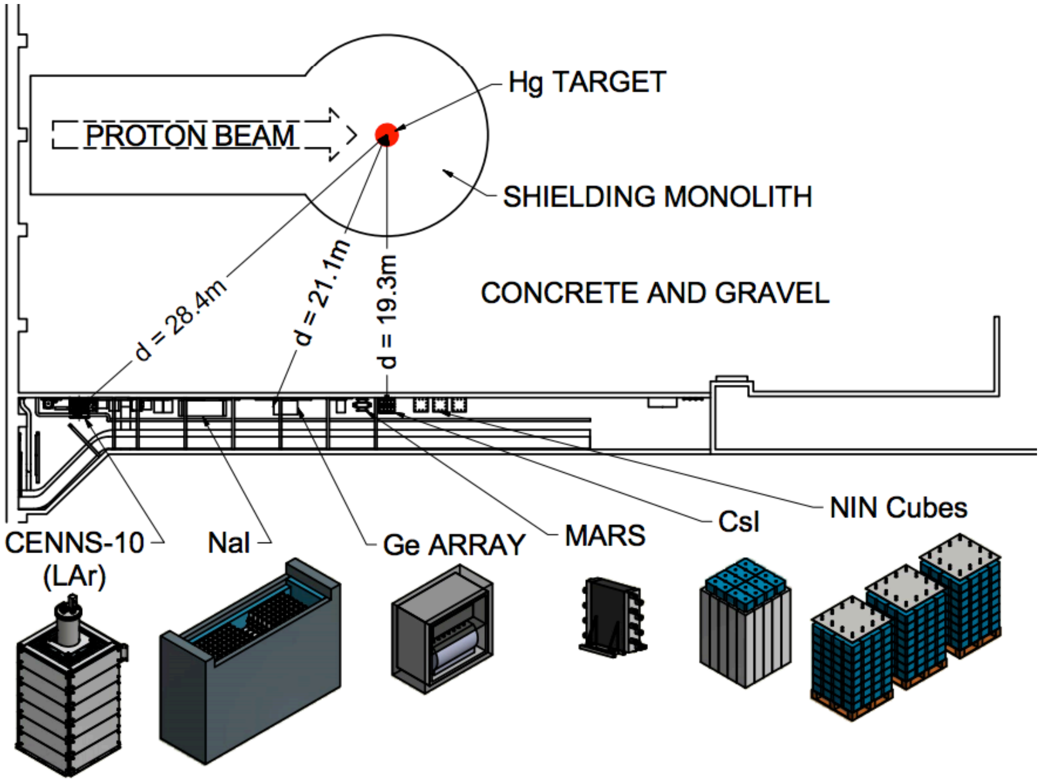
$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$
$$\downarrow$$
$$\mu^+ \longrightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

$0 < E < m_\mu/2$
2.2 μs delayed



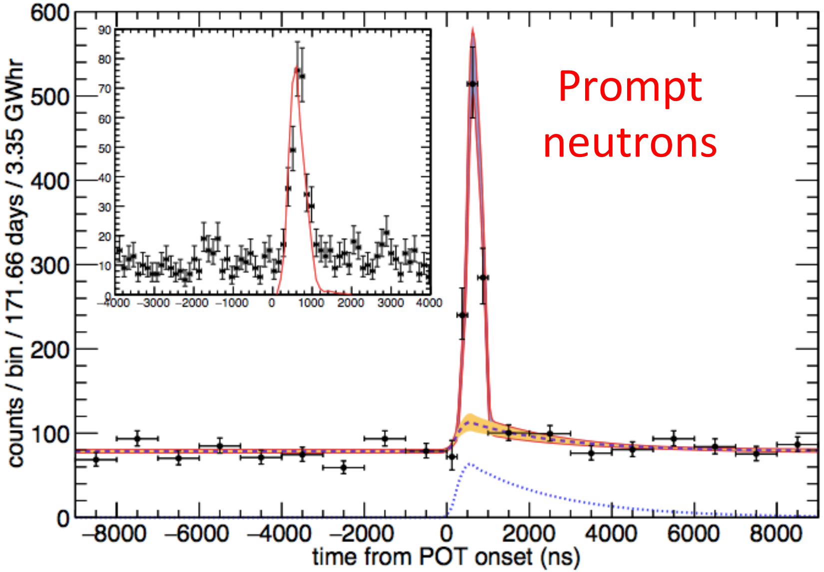
COHERENT Detectors siting and Backgrounds

- 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 -30 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

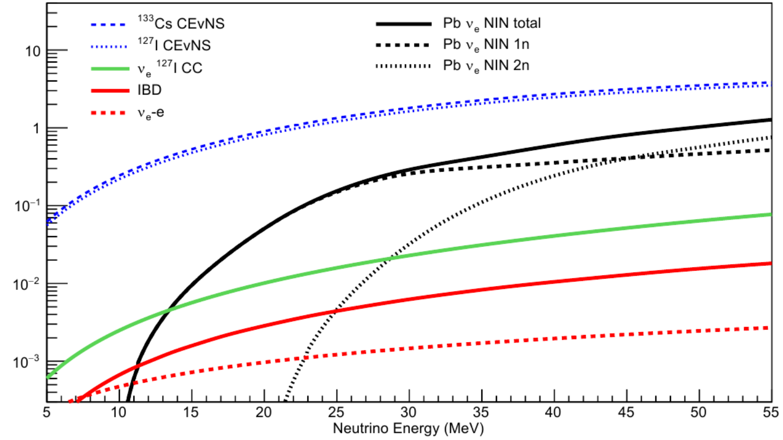
- 100 keV – 1 MeV neutrons can produce similar signal
- Neuron flux measured at different positions with multiple detector technologies w/o shielding:
    - Sandia Scatter Camera – multiplane liquid scintillator
    - SciBath - WLS fiber + liquid scintillator
    - MARS – sandwiched plastic scintillator/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

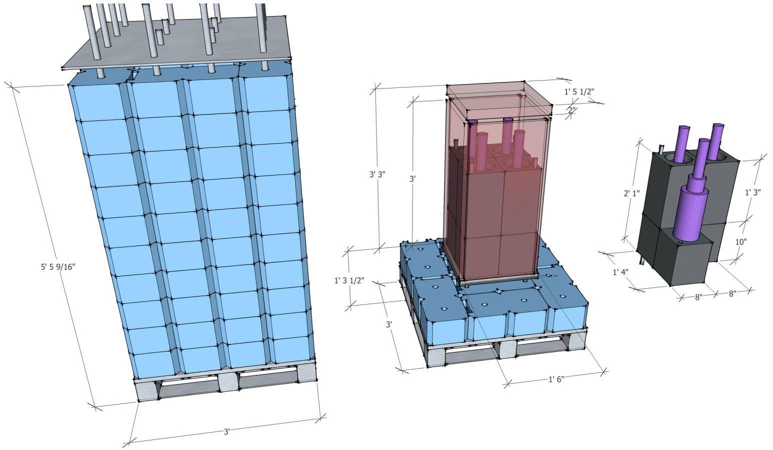


Background - Neutrino induced neutrons

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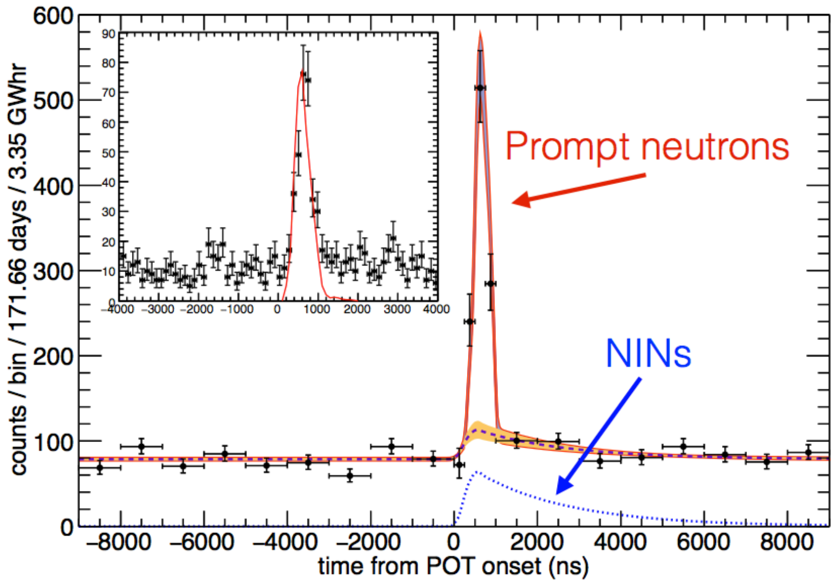
- Never been observed
- Produced by neutrinos in Pb shield [1]
    - requires careful shielding design.
- Cross section is poorly known. A signal in itself in the HALO experiment to detect Supernovae neutrinos [2].
- COHERENT program with Lead (1 ton) and Iron (700 kg) and Cu targets to measure NINs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

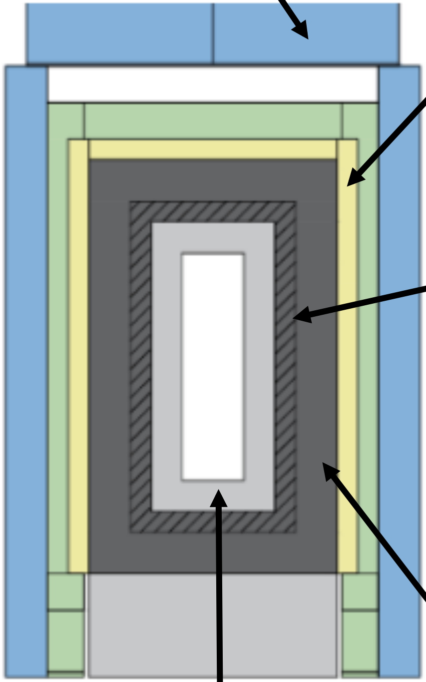
[1] - E. Kolbe, E. Langanke, Phys. Rev. C63 (2001)
[2] - C.A. Duba et al. J. Phys. Conf. Series 136 (2008)



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

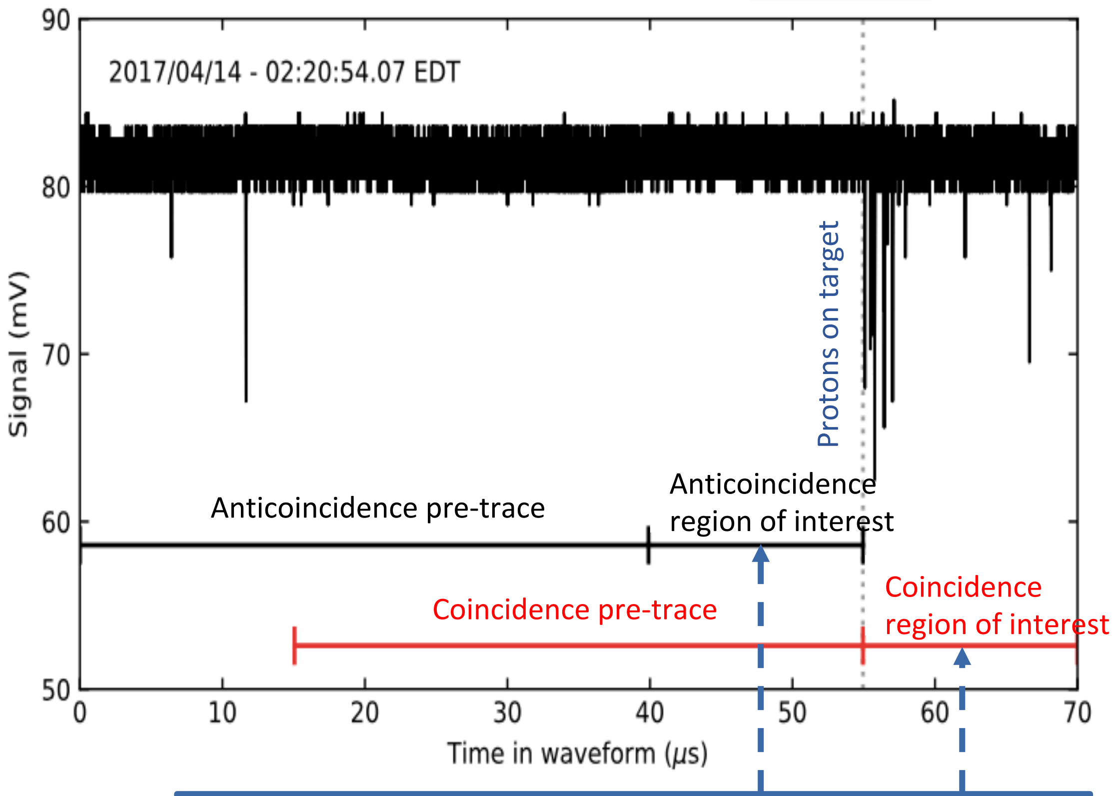
Detector Subsystem – CsI[Na]

- 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



Detector Subsystem - CsI

- 14.6 kg sodium doped CsI inorganic crystal
- Deployed at the SNS “neutrino-alley” in 2015
- ~ 8 GWhr integrated beam power
- Super-bialkali PMT with ~30% QE
- Recording of 70 μs waveforms with 500 MHz sampling of CsI and veto channels
- ~ 2×10^{9} waveforms were recorded



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

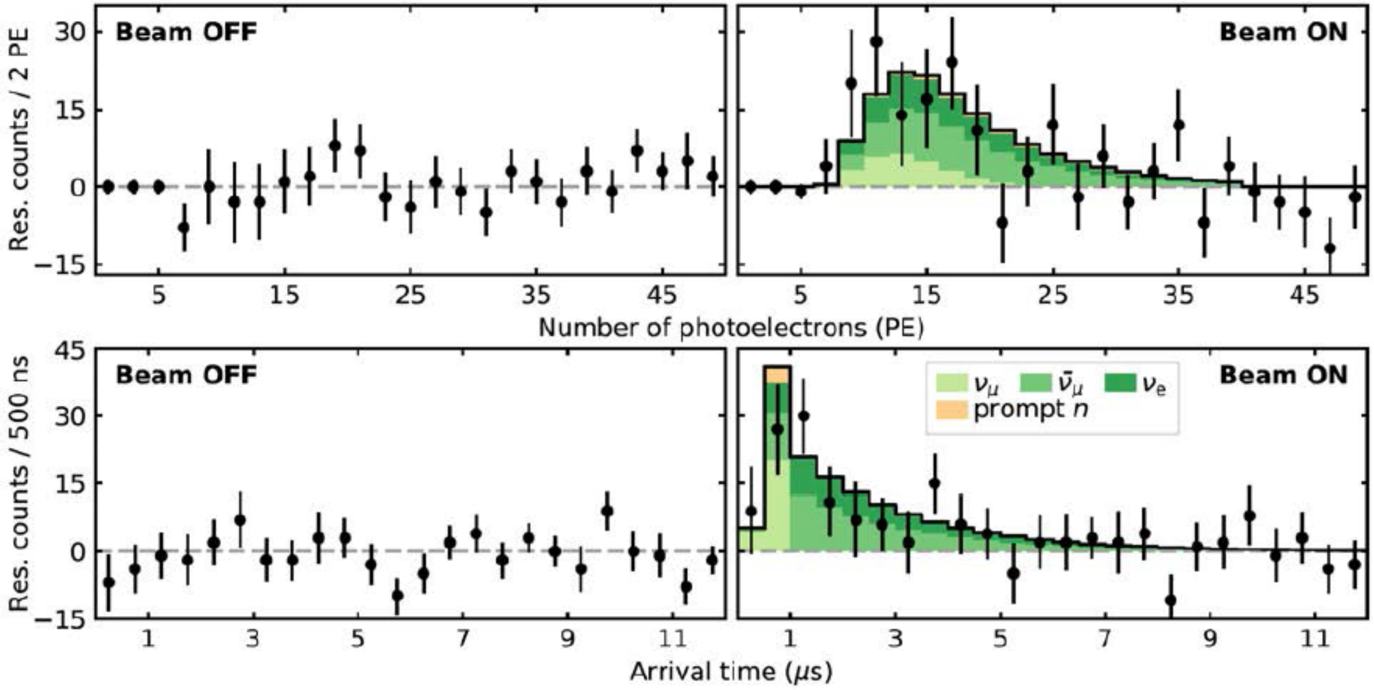
First CEvNS observation

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

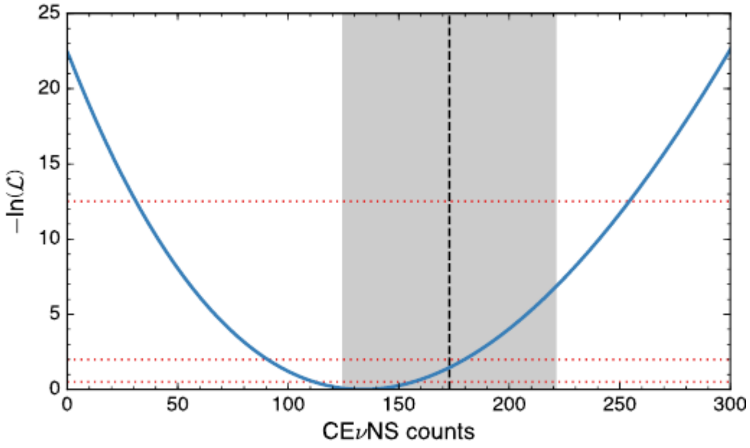
Charge

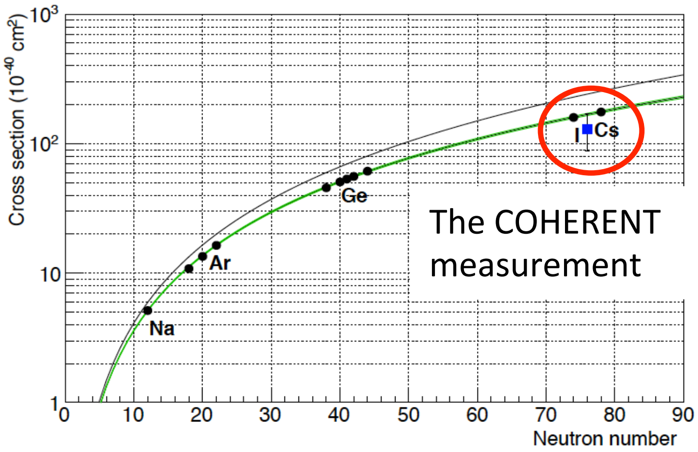
Time



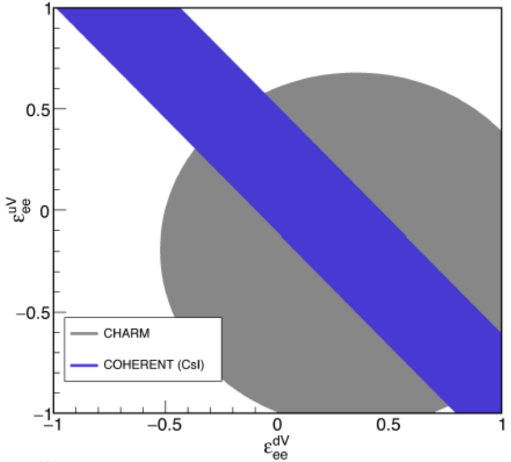
First CEvNS results

- 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





- new constraints on NSIs for M≳10 MeV

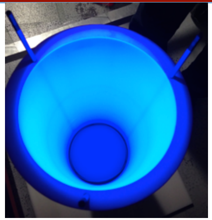


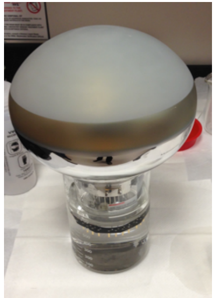
- Data package that constituted CEvNS observation is publicly available: https://zenodo.org/record/1228631

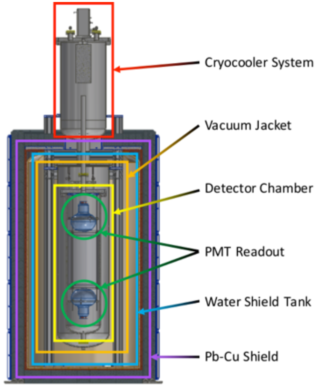
[1] D. Akimov et al., Science (2017)

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)
- Next to provide CEvNS cross-section





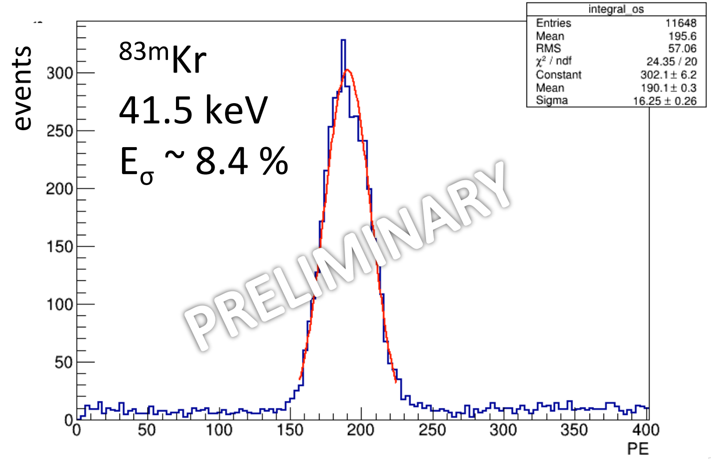


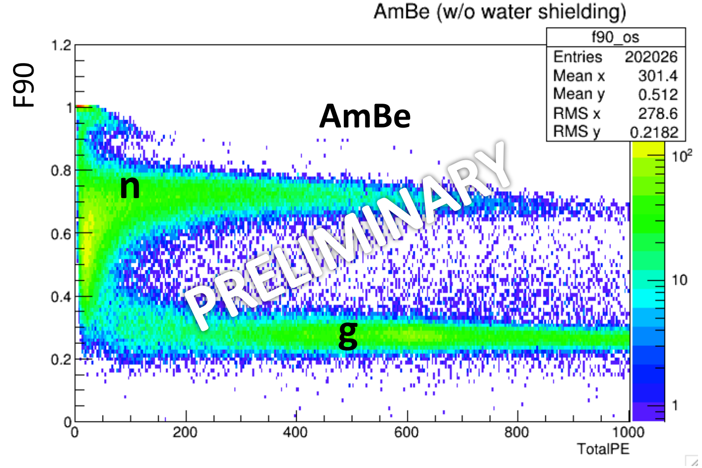
- Full shielding since August 2017
  - Lead 4’’
  - Copper 0.5’’
  - Water 9’’

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

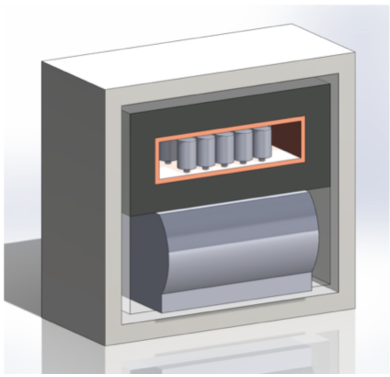
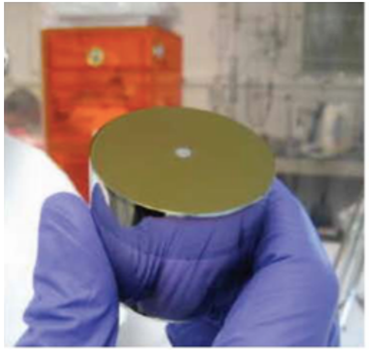
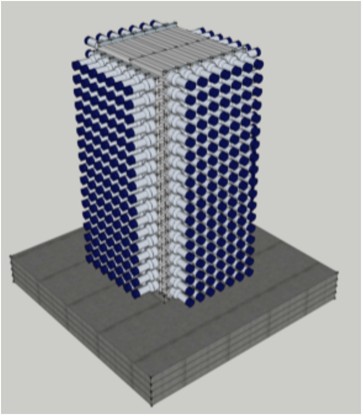
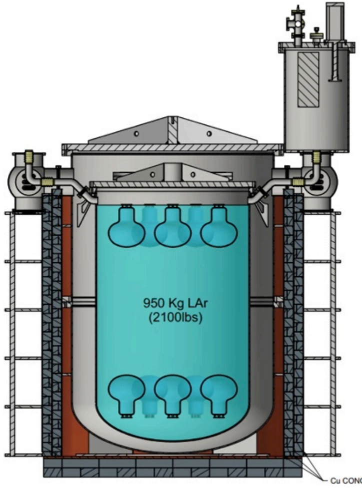
- ~4 pe/keV light yield
- Low-energy ^{83m}Kr source calibration
- Expect ~ 50 CEvNS from Run1 data set
- Triple the data set by the end of the year (Run2)





Future COHERENT

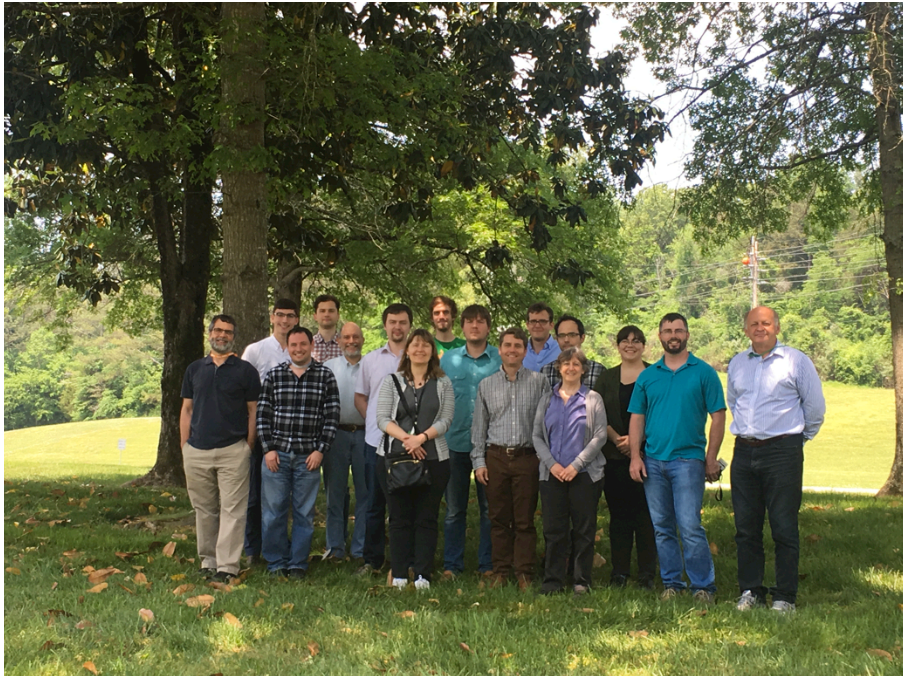
- Improved background studies
- 10 kg Ge, with future upgrade to state-of-the-art tech → study e.m. properties
- NaI[Tl]: 2-ton CEvNS sensitive upgrade → have multiple tons in hand and available for a multi-ton deployment
- Further neutrino induced neutron studies
- LAr: expansion to ~ 1 tonne scale
- Several prospects for additional target nuclei

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

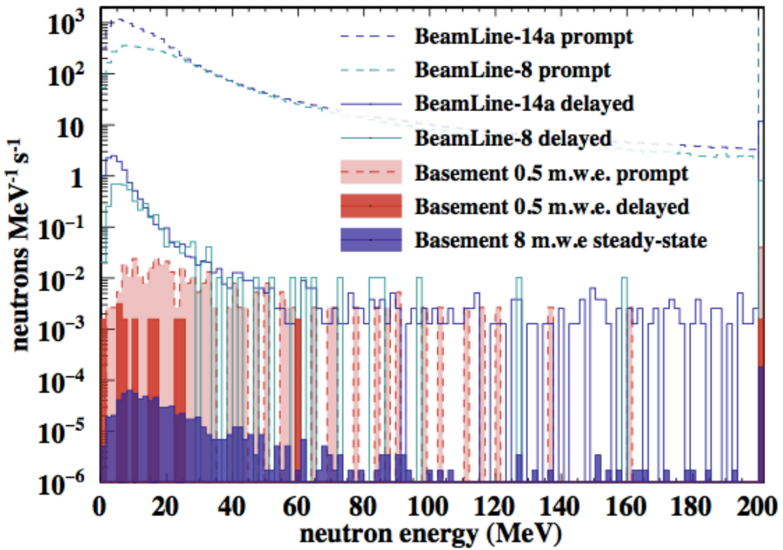


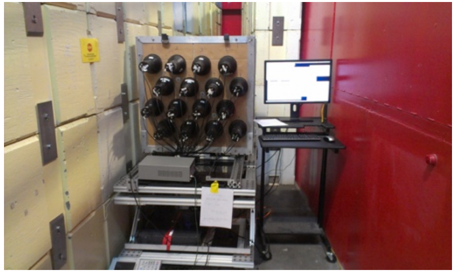
~80 members, 18 institutions 4 countries

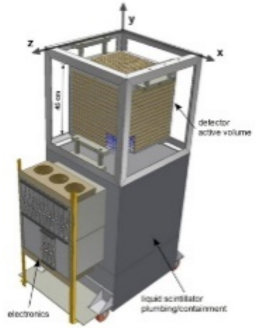
Backup

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

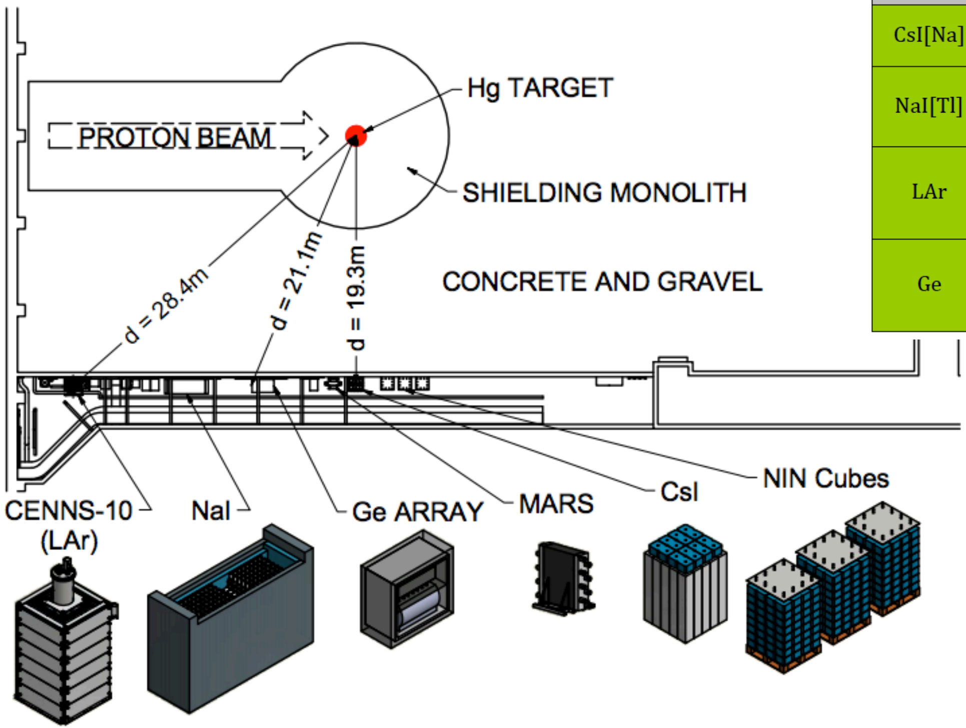






COHERENT Detectors siting

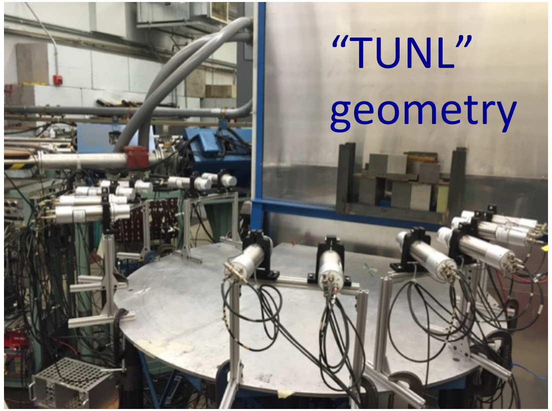
SNS "Neutrino-alley"



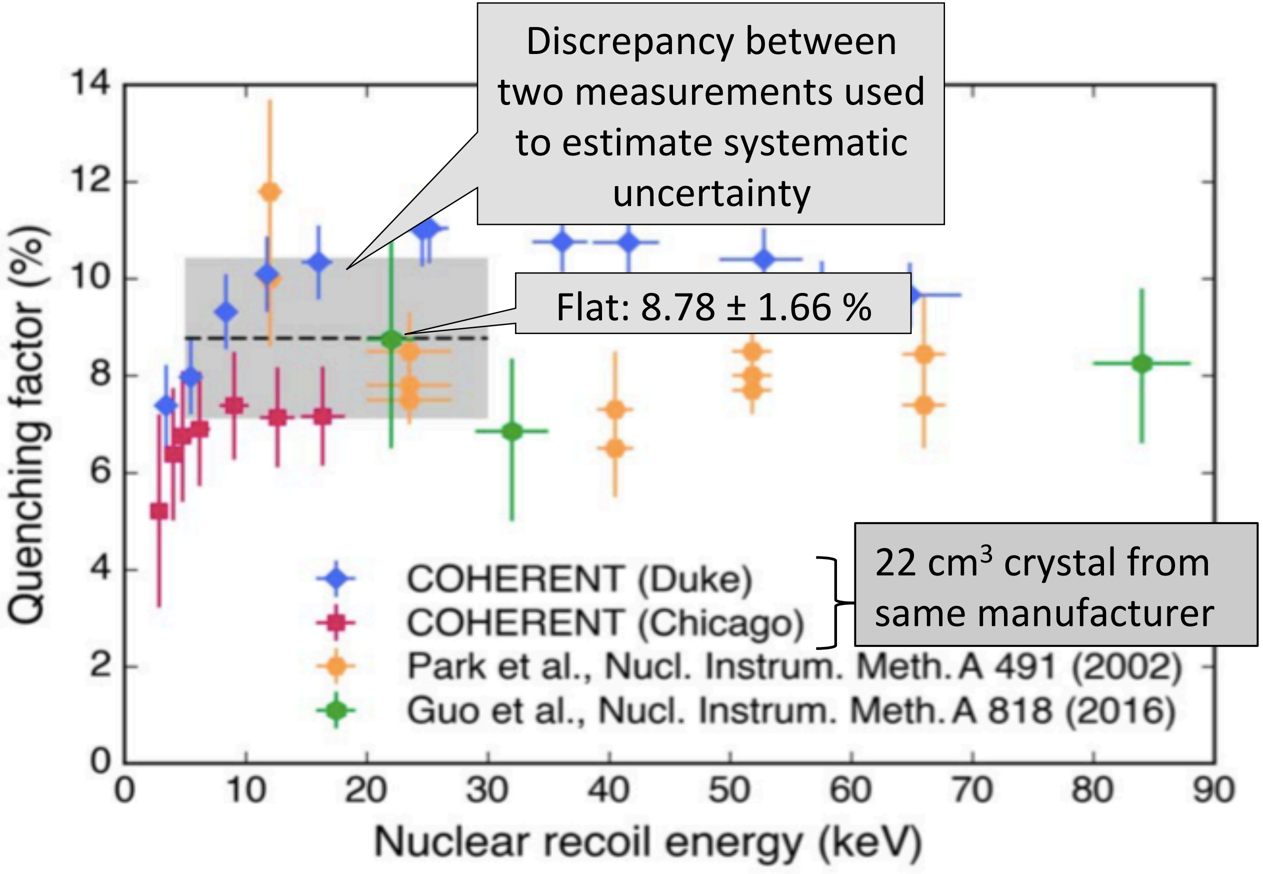
Nuclear Target	Technology	Mass (kg)	Distance from source (m)	Recoil threshold (keVr)	Start data-taking	Possible Future
CsI[Na]	Scintillating crystal	14.6	20	6.5	09/2015	Continue data-taking
NaI[Tl]	Scintillating crystal	185* /2000	28	13	*high-threshold deployment summer 2016	Expansion to 2 tonne
LAr	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



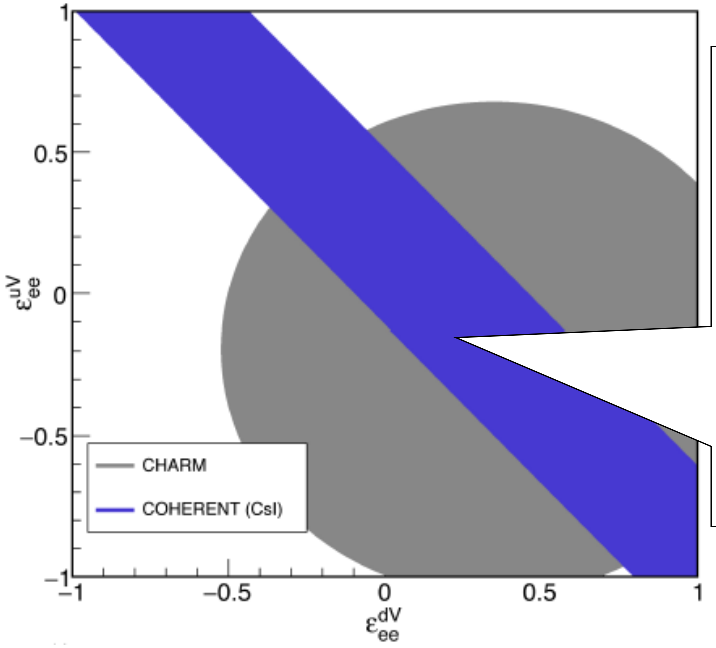
CEvNS and NSI

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