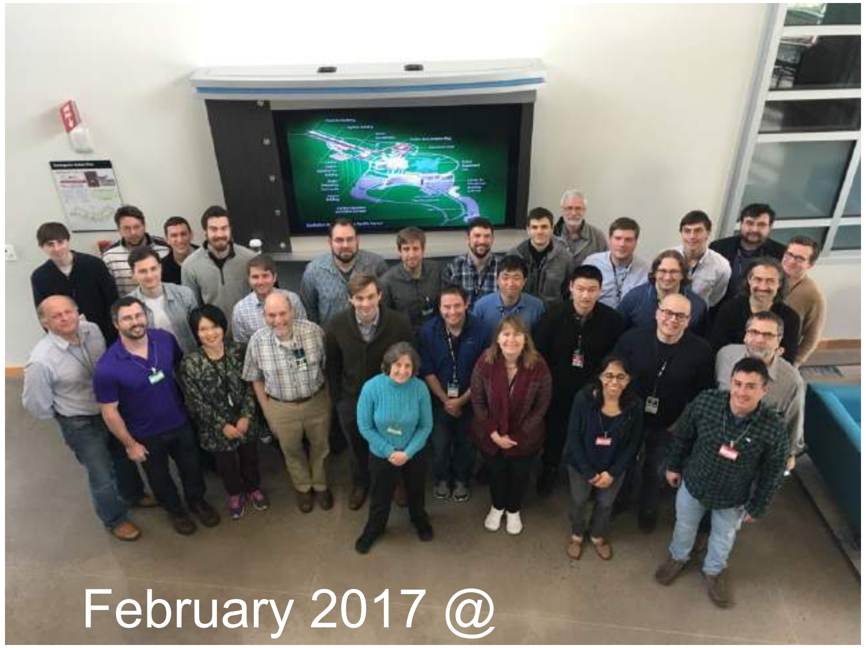
Study of CEvNS by the COHERENT collaboration

Yu. Efremenko

New trends in Hight-Energy Physics
Montenegro, September 24, 2018

On Behalf of COHERENT collaboration

Prime goal of the collaboration is to detect and study
Coherent Elastic neutrino Nucleus Scattering → CEvNS

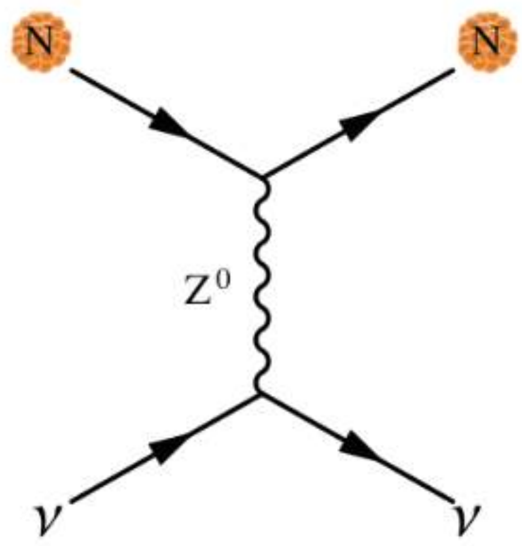


18 Institutions (USA, Russia, Canada, Korea)

Coherent Elastic neutrino-Nucleus Scattering (CEvNS)

A neutrino scatters on a nucleus via exchange of a Z, and the nucleus recoils as a whole;

coherent up to E_ν~ 50 MeV



D.Z. Freedman PRD 9 (1974)

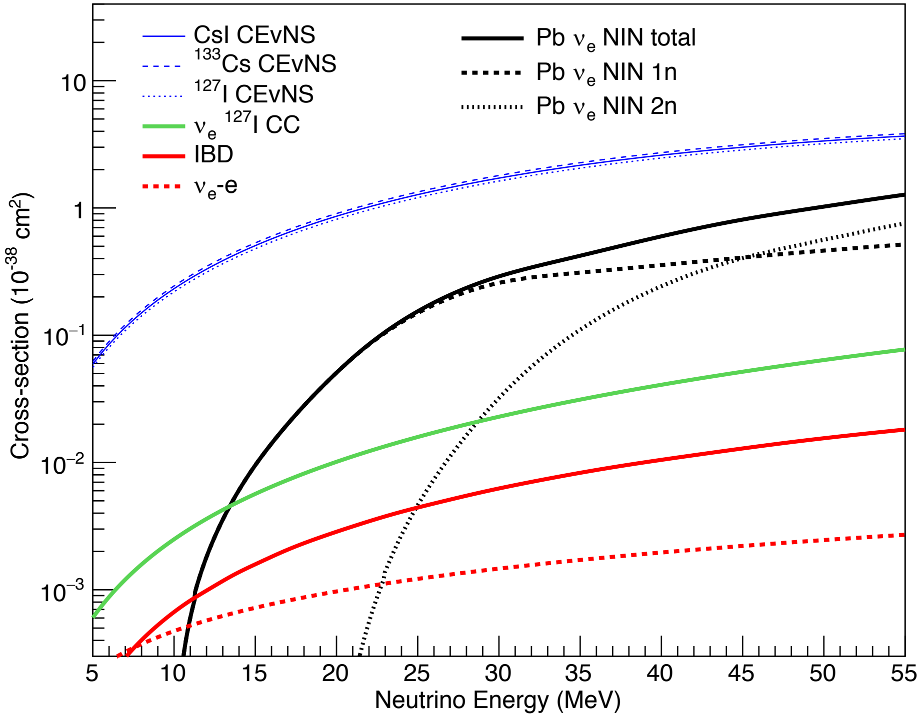
Submitted Oct 15, 1973

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.

V.B.Kopeliovich & L.L.Frankfurt

JETP Lett. 19 (1974)

Submitted Jan 7, 1974



CEvNS cross-section is large!

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

CEvNS cross section is well calculated in the Standard Model

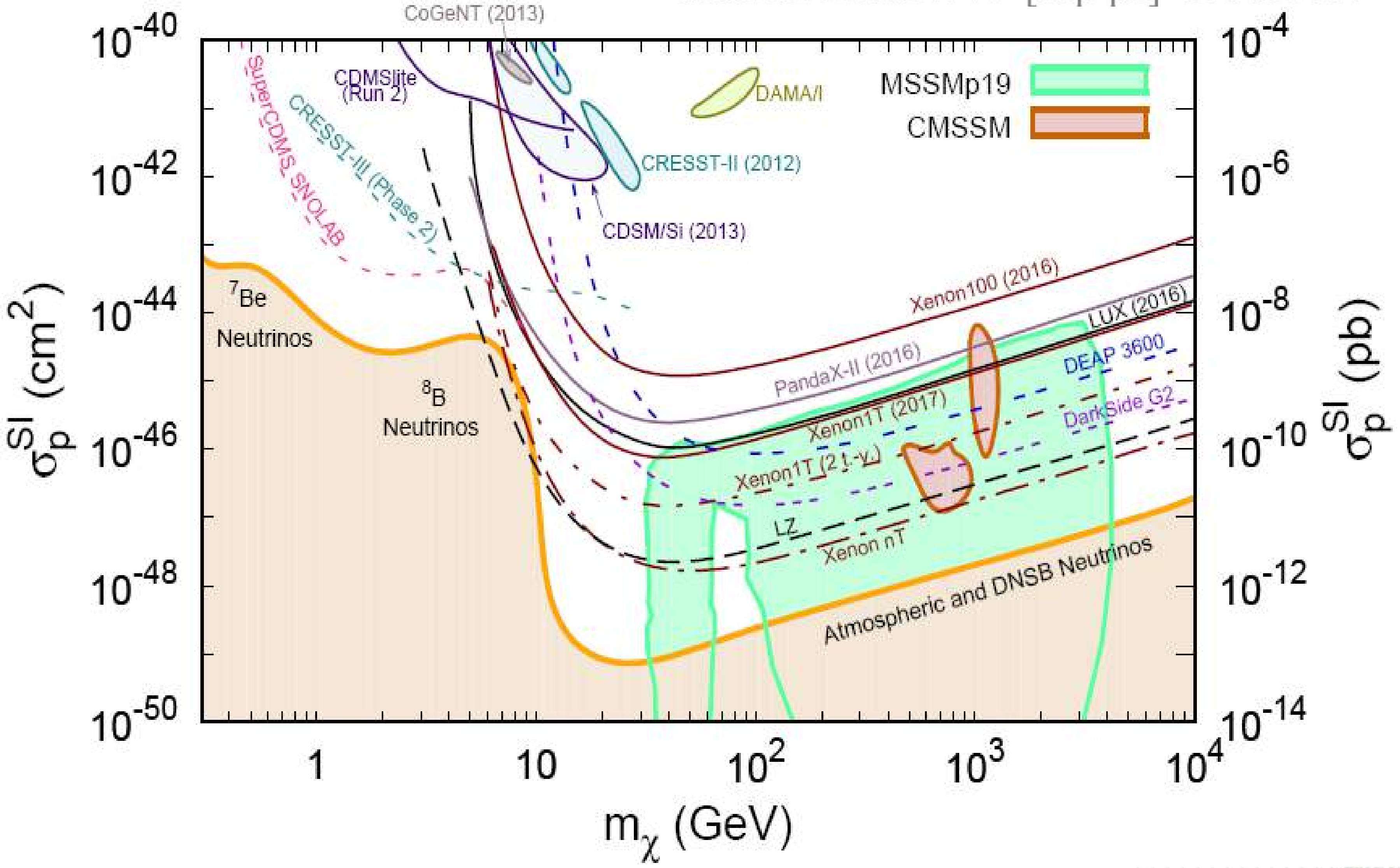
CEvNS is Very Hard to Detect

		Nuclear Reactors	DAR
Target	Atomic weight, u	Max E_{nr} (5 MeV ν)	Max E_{nr} (30 MeV ν)
C	12.0	4.5 keV	161.0 keV
Na	23.0	2.3 keV	84.0 keV
Ar	39.9	1.3 keV	48.4 keV
Ge	72.6	0.74 keV	26.6 keV
Cs	132.9	0.40 keV	14.5 keV

Nuclear recoils have very low energy (max. $E_{nr} = 2E^2/M$)

CEνNS is irreducible background floor for DM experiments

arXiv:1707.06277v1 [hep-ph] 19 Jul 2017



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Why CEvNS are interesting?
Non-Standard Interactions of Neutrinos

new interaction specific to ν's

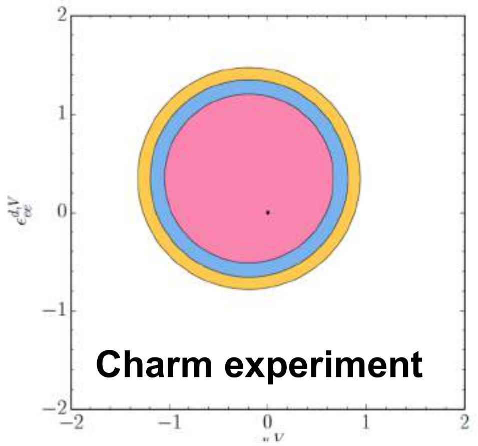
$$\mathcal{L}_{\nu H}^{NSI} = -\frac{G_F}{\sqrt{2}} \sum_{\substack{q=u,d \\ \alpha,\beta=e,\mu,\tau}} [\bar{\nu}_\alpha \gamma^\mu (1-\gamma^5)\nu_\beta] \times (\varepsilon_{\alpha\beta}^{qL}[\bar{q}\gamma_\mu(1-\gamma^5)q] + \varepsilon_{\alpha\beta}^{qR}[\bar{q}\gamma_\mu(1+\gamma^5)q])$$

J. H J. High Energy Phys. 03(2003) 011

TABLE I. Constraints on NSI parameters, from Ref. [35].

NSI parameter limit	Source
$-1 < \varepsilon_{ee}^{uL} < 0.3$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$-0.4 < \varepsilon_{ee}^{uR} < 0.7$	
$-0.3 < \varepsilon_{ee}^{dL} < 0.3$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$-0.6 < \varepsilon_{ee}^{dR} < 0.5$	
$\lvert\varepsilon_{\mu\mu}^{uL}\rvert < 0.003$	NuTeV νN, $\bar{\nu} N$ scattering
$-0.008 < \varepsilon_{\mu\mu}^{uR} < 0.003$	
$\lvert\varepsilon_{\mu\mu}^{dL}\rvert < 0.003$	NuTeV νN, $\bar{\nu} N$ scattering
$-0.008 < \varepsilon_{\mu\mu}^{dR} < 0.015$	
$\lvert\varepsilon_{e\mu}^{uP}\rvert < 7.7 \times 10^{-4}$	$\mu \to e$ conversion on nuclei
$\lvert\varepsilon_{e\mu}^{dP}\rvert < 7.7 \times 10^{-4}$	$\mu \to e$ conversion on nuclei
$\lvert\varepsilon_{e\tau}^{uP}\rvert < 0.5$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$\lvert\varepsilon_{e\tau}^{dP}\rvert < 0.5$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$\lvert\varepsilon_{\mu\tau}^{uP}\rvert < 0.05$	NuTeV νN, $\bar{\nu} N$ scattering
$\lvert\varepsilon_{\mu\tau}^{dP}\rvert < 0.05$	NuTeV νN, $\bar{\nu} N$ scattering

Non-Standard ν Interactions (Supersummetry, neutrino mass models) can impact the cross-section differently for different nuclei

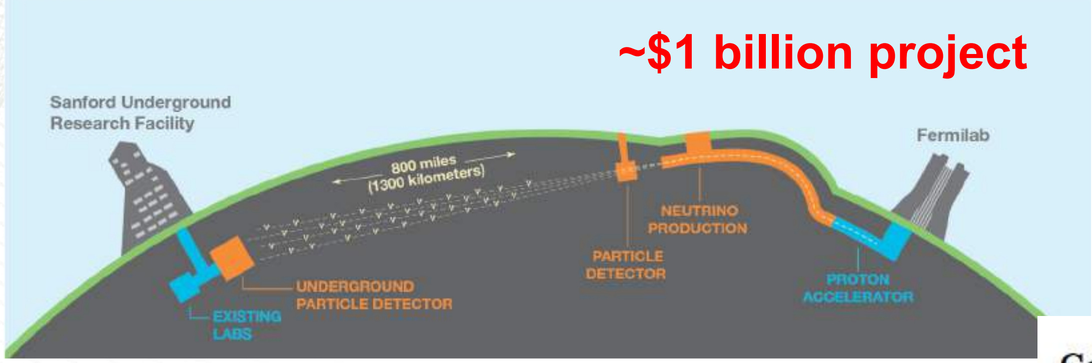


Curtailing the Dark Side in Non-Standard Neutrino Interactions

Pilar Coloma[a] Peter B. Denton,[a,b,1] M. C. Gonzalez-Garcia,[c,d,e] Michele Maltoni,[f] Thomas Schwetz[g]

arXiv:1701.04828v2 [hep-ph] 20 Apr 2017

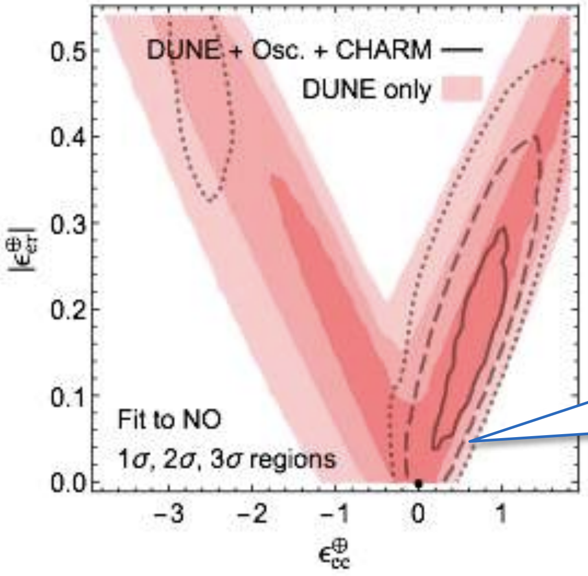
Why CEvNS are interesting? Oscillation degeneracy



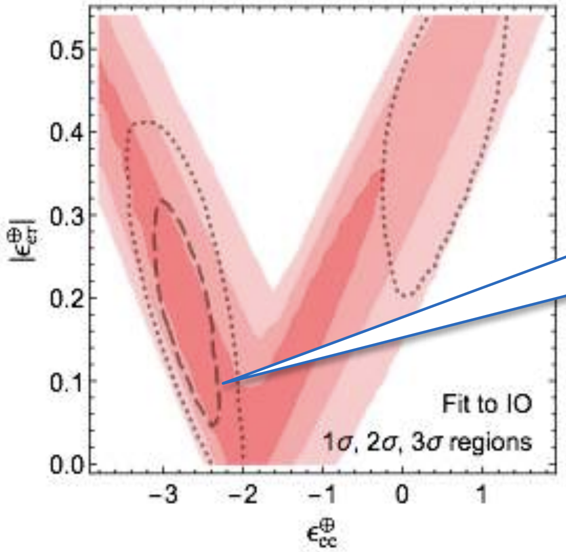
– measuring the charge-parity (CP) violating phase CP,
– determining the neutrino mass ordering (the sign of Δm^2_{12})
– precision tests of the three-flavor neutrino oscillation paradigm

Generalized mass ordering degeneracy in neutrino oscillation experiments

Pilar Coloma[1] and Thomas Schwetz[2] arXiv:1604.05772v1



NO w/no NSI...



...looks just like IO w/NSI

If you allow for NSI to exist, Degeneracy appears.

We can not tell the neutrino mass ordering without constrains on NSI

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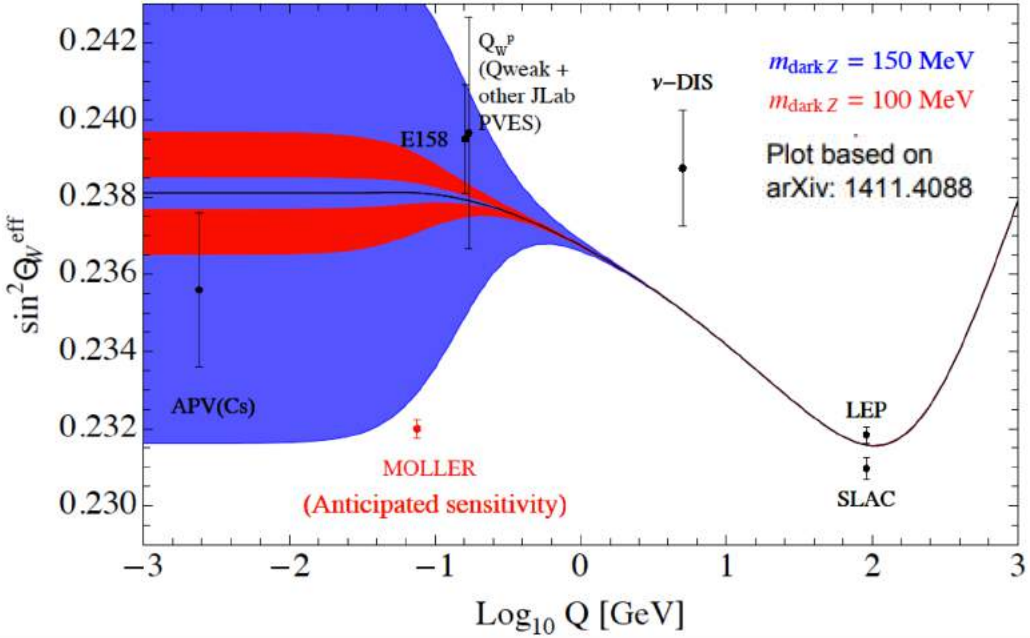
Why CEvNS is interesting?
It is sensitive to the Electro week angle

$$\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B^0 \\ W^0 \end{pmatrix}$$

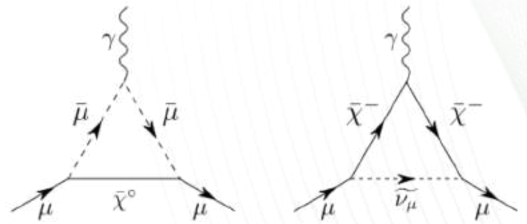
$$\sigma_{tot} = \frac{G_F^2 E_\nu^2}{4\pi}\left[Z\left(1-4\sin^2\theta_W\right)-N\right]^2 F^2(Q^2)$$

Measurements with targets having different Z/N ratio are required.

$Sun^2\theta_w$ is a free parameter in the Standard Model
There is no fundamental theory which explain its value
It is "running" constant, its value depends on the momentum transfer.



Proposed correction to g-2 for muon magnetic moment due to a light mediator

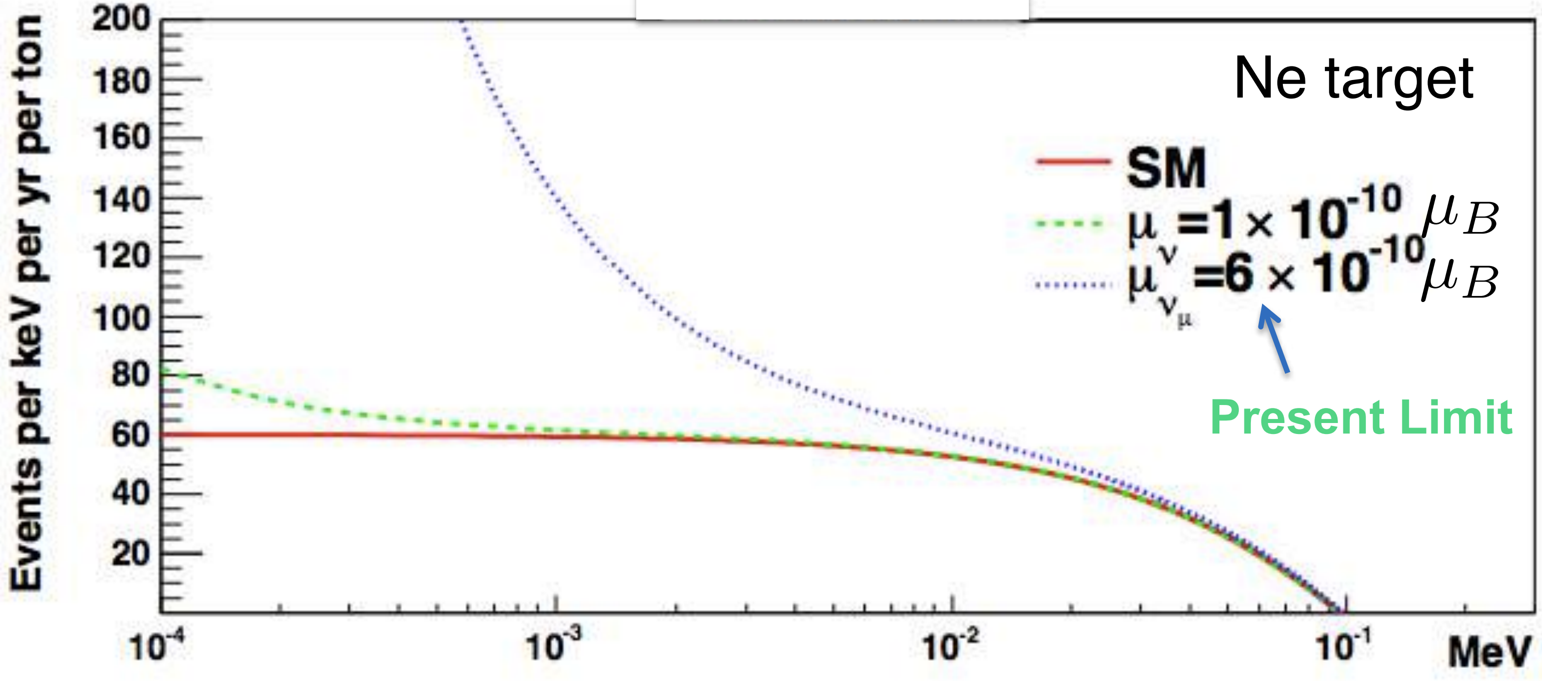


If this is correct it can manifest itself in θ_W value at low Q^2

Why CEvNS are interesting?
Search for neutrino magnetic moment

Signature is distortion at low recoil energy E

$$\frac{d\sigma}{dE} = \frac{\pi \alpha^2 \mu_\nu^2 Z^2}{m_e^2} \left(\frac{1 - E/k}{E} + \frac{E}{4k^2} \right)$$



➔requires detector with very low energy threshold

See also Kosmas et al., arXiv:1505.03202

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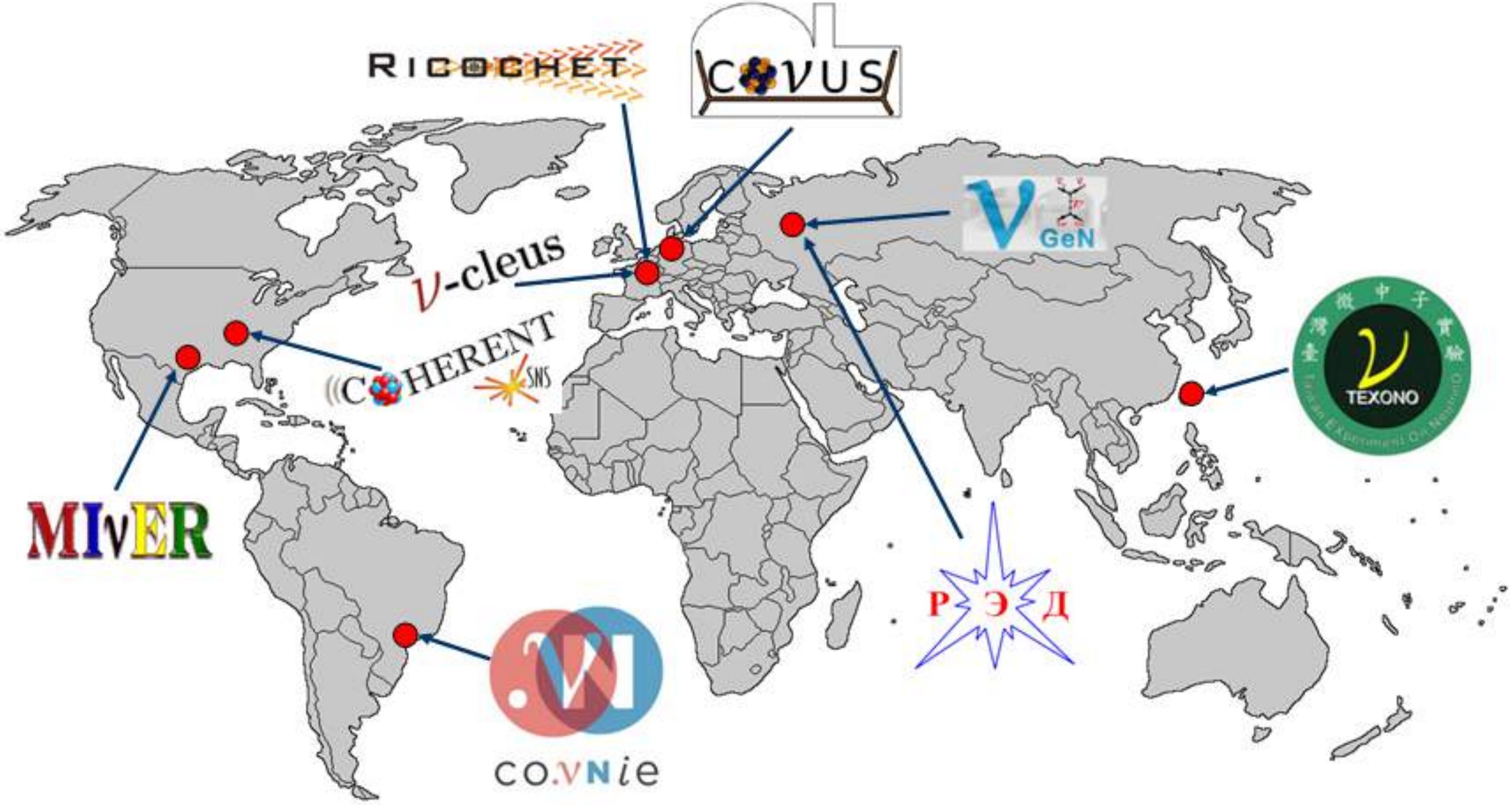
Why to Search for CEvNS

Large effect on Supernovae dynamics. J.R. Wilson, PRL 32 (74) 849
We should measure it to validate the models

World Wide Efforts to Detect CEvNS



Except COHERENT, all other collaboration attempt to use nuclear reactors as a neutrino source

Nuclear reactors give large flux, but low energy neutrinos with a constant flux

Why SNS?

- It is world most powerful pulsed neutrino source. Presently it delivers $7 \cdot 10^{20}$ POT daily
  ~9% of protons produce 3 neutrinos

- Neutrino energies at SNS are ideal to study CEvNS and Supernovae related neutrino cross sections.
  For most of neutrinos E_ν < 53 MeV

- Decay At Rest from pions and muons (DAR) gives very well defined neutrino spectra

- Fine duty factor let suppression of steady background by a factor of 2000.
  It is like being at the 1000 m.w.e underground

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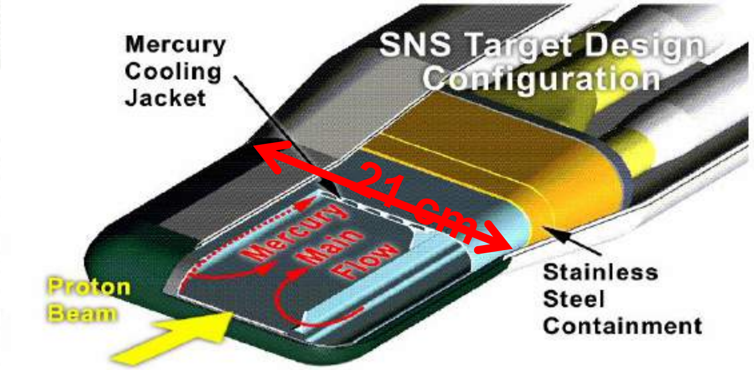
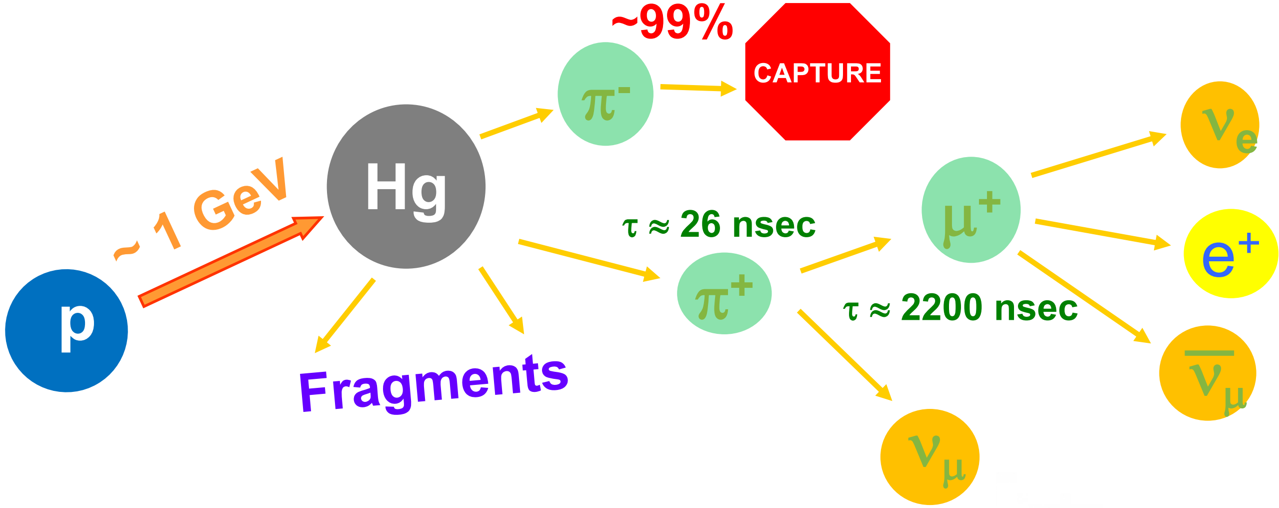
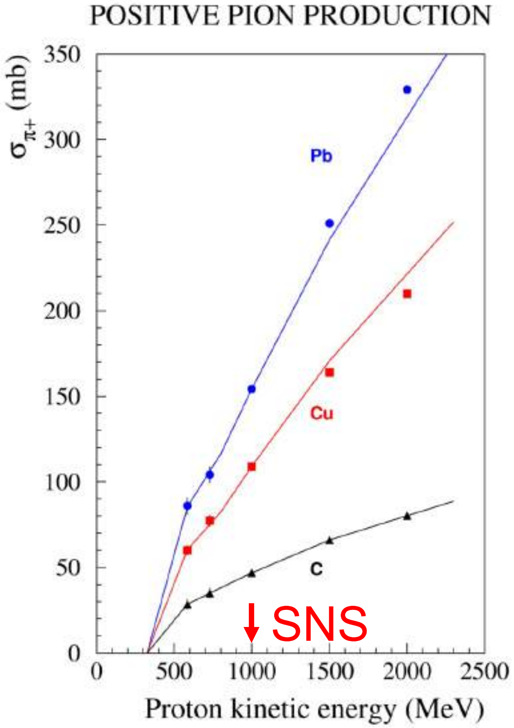
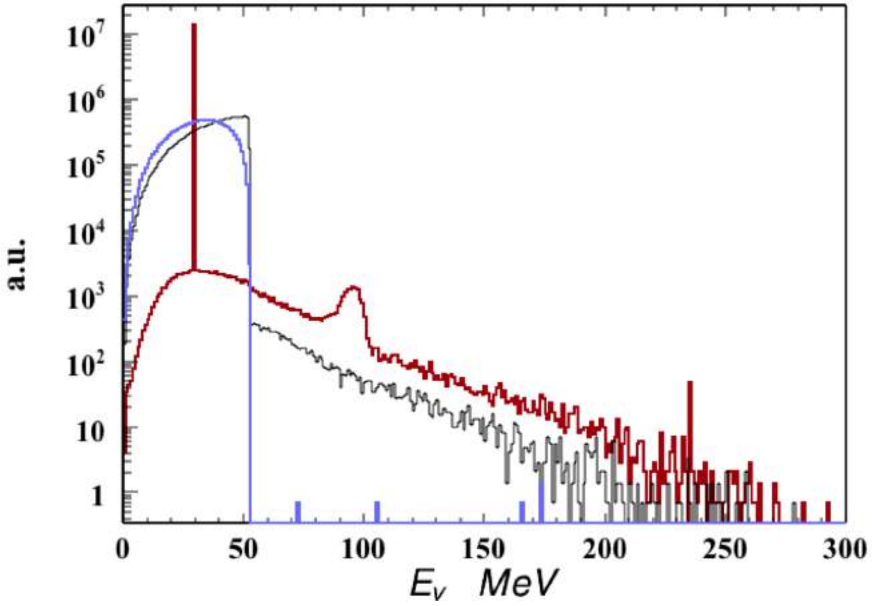
Neutrino Production at the SNS



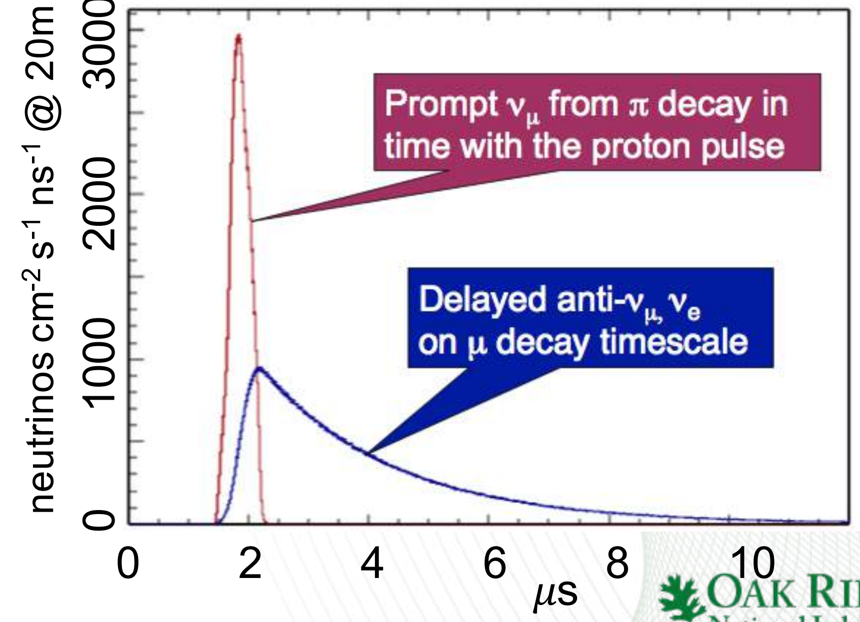




Neutrino Energy



Neutrino Timing



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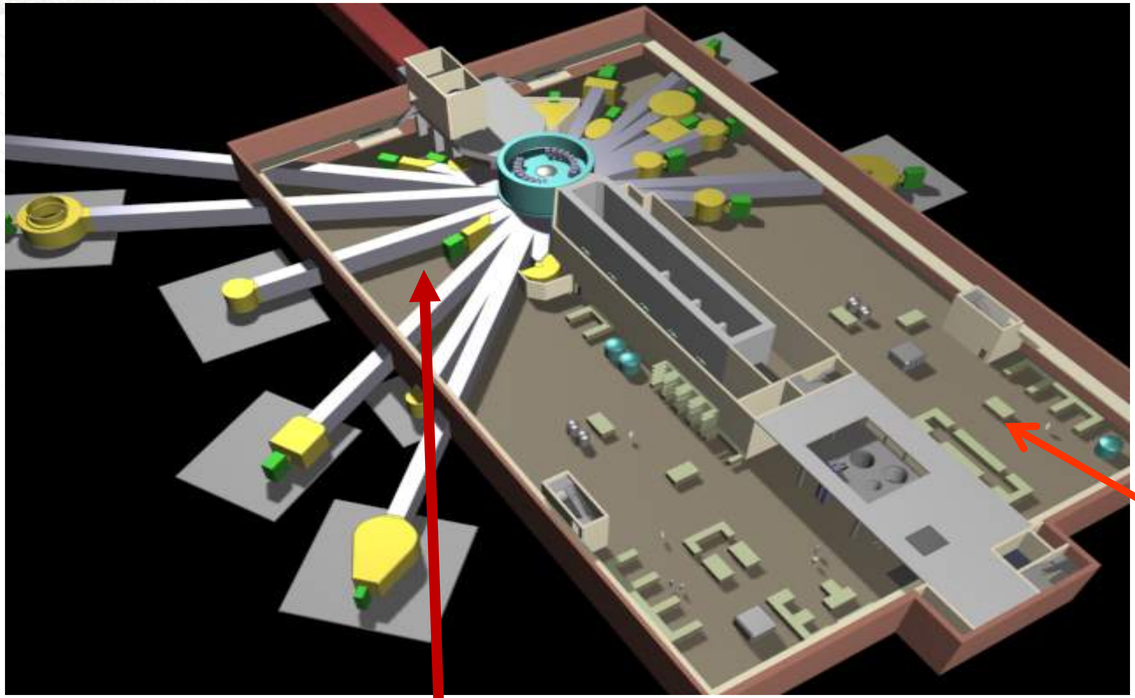
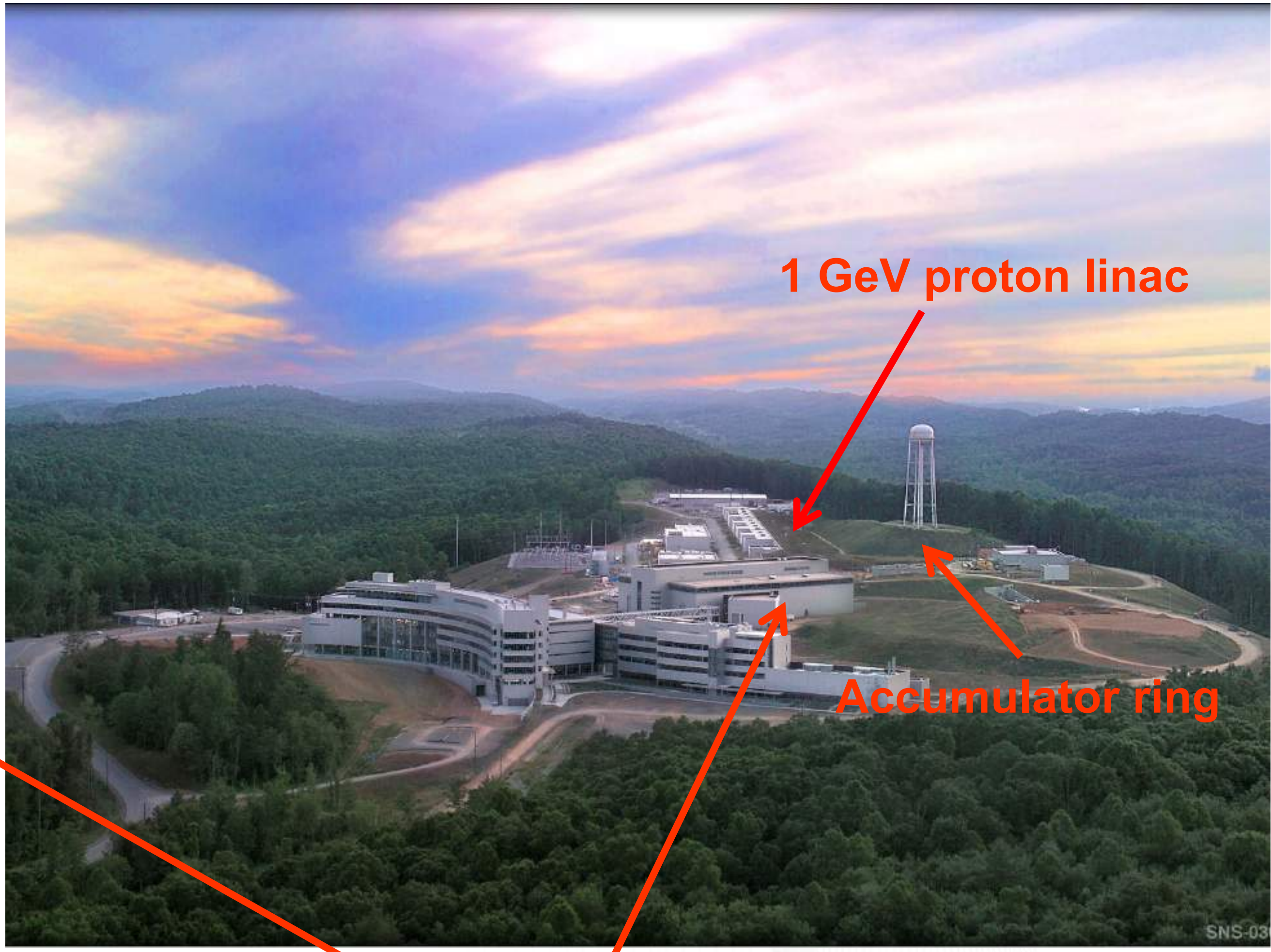
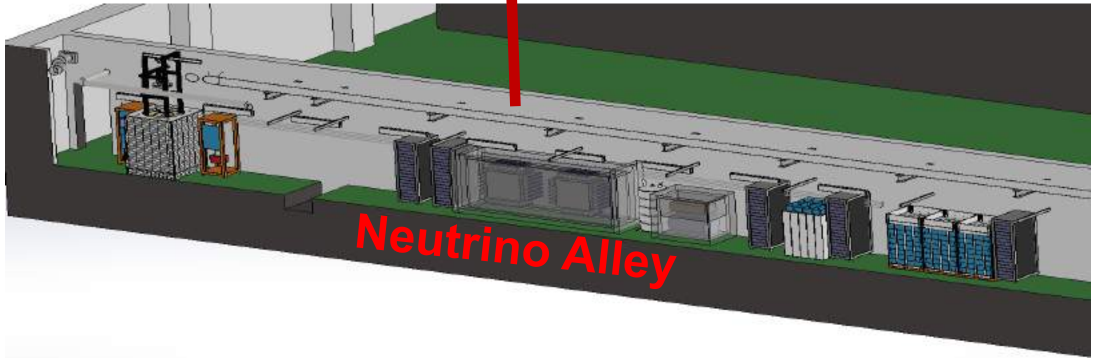
Neutrino Alley Location

After extensive BG program study we find a well protected location







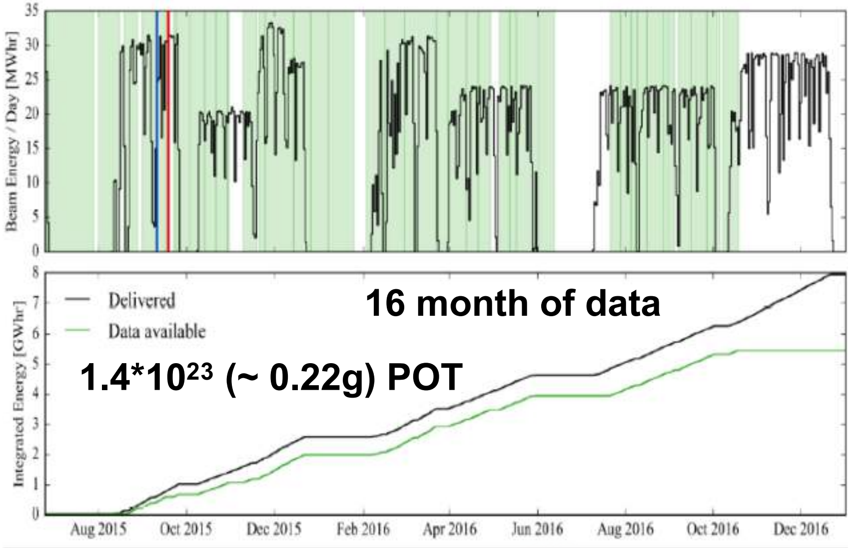
Target Building

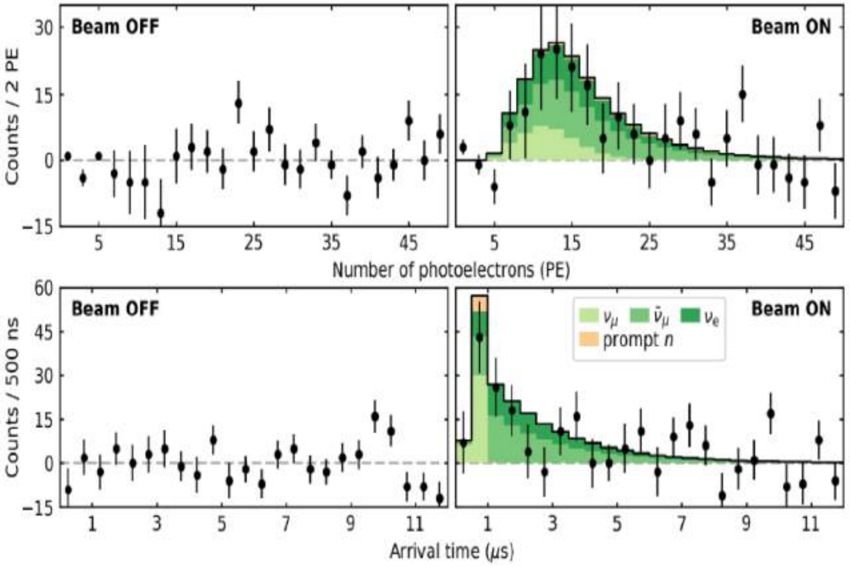
Alley is 20-30 meters from the target. Space between target and alley is filled with steel, gravel and concrete

There are extra 10 MWE from above

First Detection of CEvNS with CsI detector

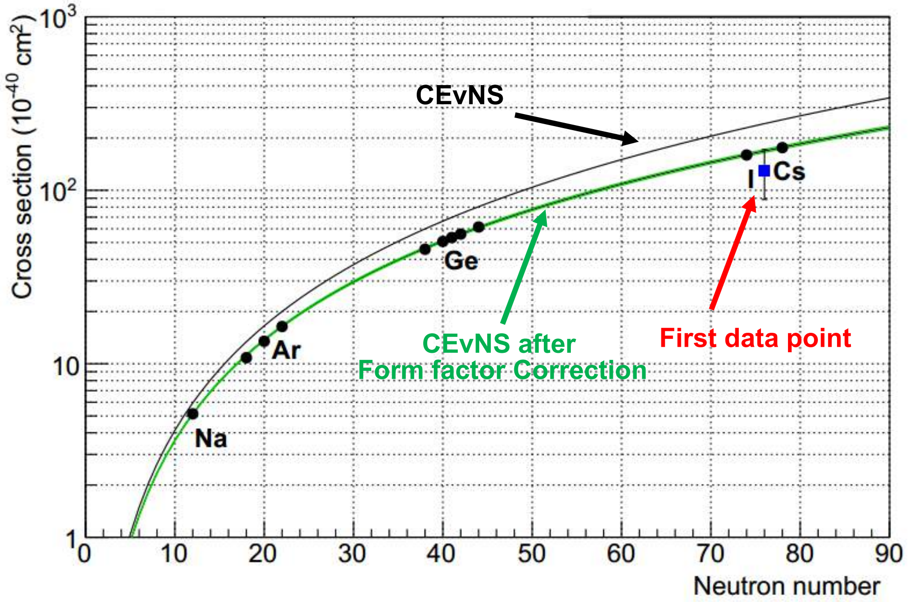
First working hand held neutrino detector -14kg!!!





We continue to take data with CsI detector

Now it is twice more statistics compare to the first publication

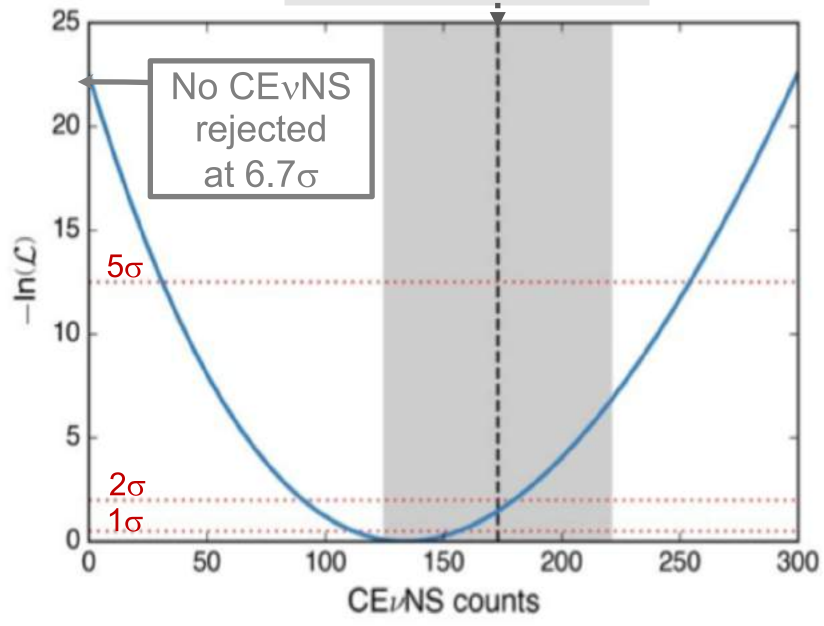


Some Details About the First CEvNS Detection

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, 2D likelihood fit	134 ± 22 (16%)
Predicted SM signal counts	173 ± 48 (28%)

Uncertainties on signal and background predictions	
Event selection (signal acceptance)	5%
Form Factor	5%
Neutrino Flux	10%
CsI Quenching Factor (QF)	25%
Total uncertainty on signal	28%

SM prediction: 173 events



All uncertainties except neutrino flux are detector specific and could be much less for other technologies

To unlock high precision CEvNS program we need to calibrate SNS neutrino flux and measure QF well

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What Did We Learn So far?

CEvNS does exists
However, nobody doubt that !!!

"It's a real thrill that something that I predicted 43 years ago has been realized experimentally,"

Daniel Freedman

SNS is beautiful low energy pulsed neutrino source with "Neutrino Alley"

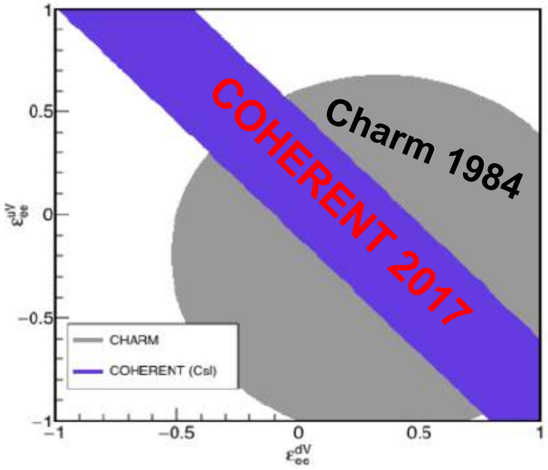
We know how to detect CEvNS

So far we have a binary answers "*YES*"

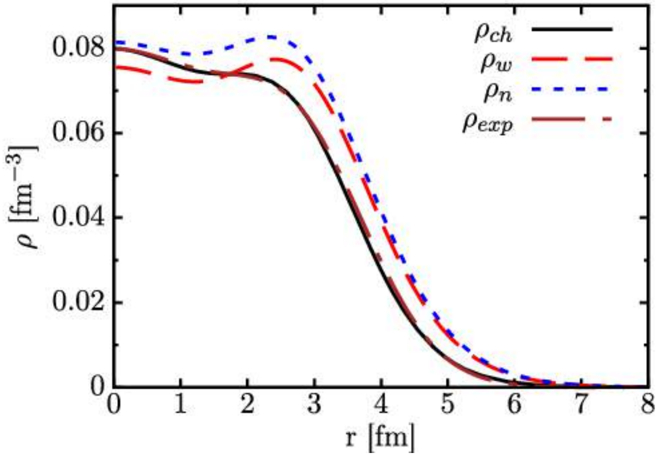
Next step is precision measurements of CEvNS cross sections to search for anomalies

Future Physics for COHERENT

Non-Standard ν Interactions: Test of the SM, DM



Nuclear Physics Form Factors, Axial Currents, Incoherent processes

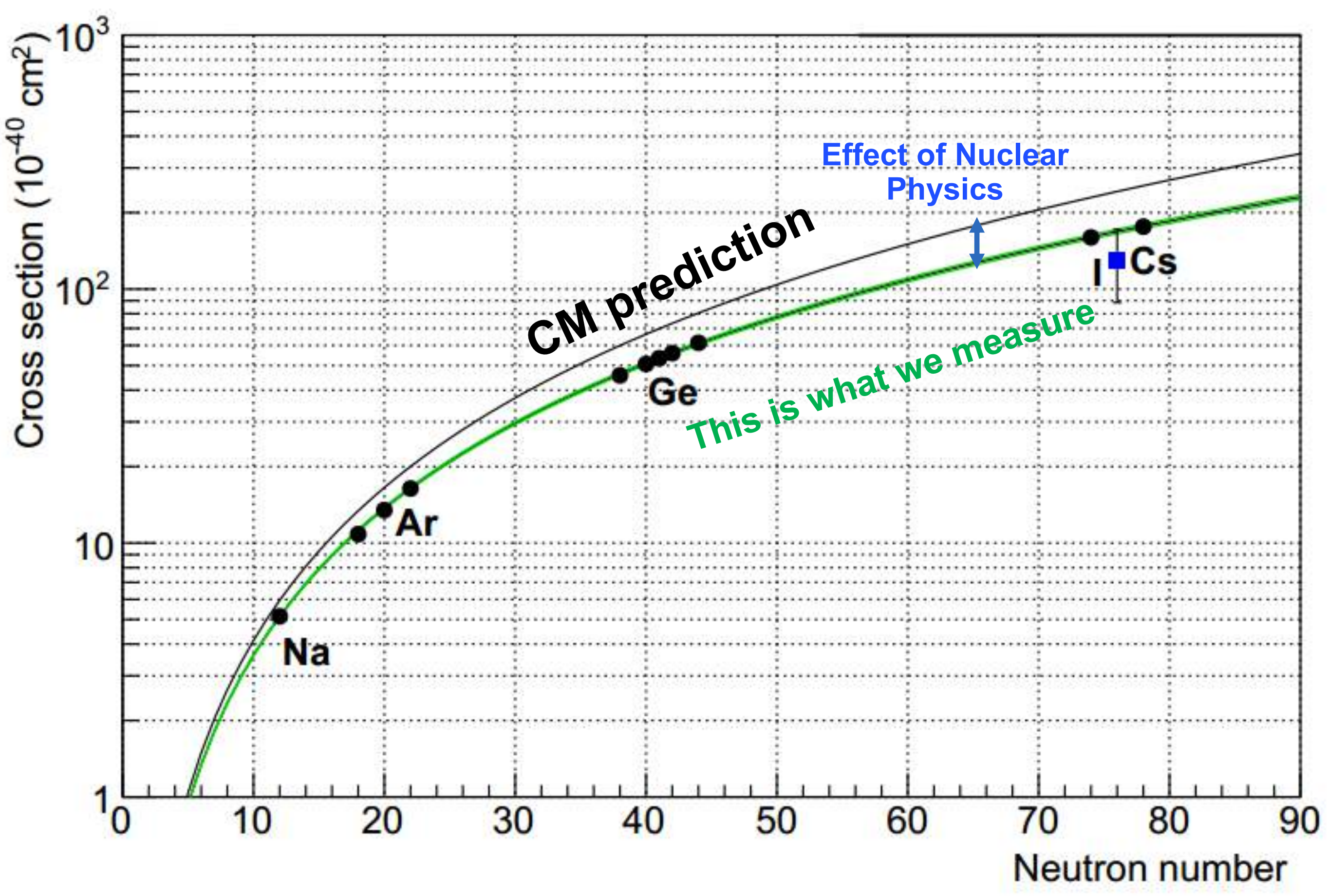


Supernovae Cross Sections and E_W Measurements

Those studies become important if we do measurements with a very good accuracy

To do so we need multiple detectors able to accumulate large statistics with accurate measurements of recoil spectra

We Need Large Detectors With Various Targets



To untangle effects of nuclear form factors we need measurements at the wide range of target masses: Light, Middle, and Heavy

To have handle on axial current it is interesting to have close targets with different spins.
Example ^{40}Ar s=0 and ^{23}Na s=3/2

Targets near neutrino less double beta decay isotopes (e.g. Ge) are of special interest.

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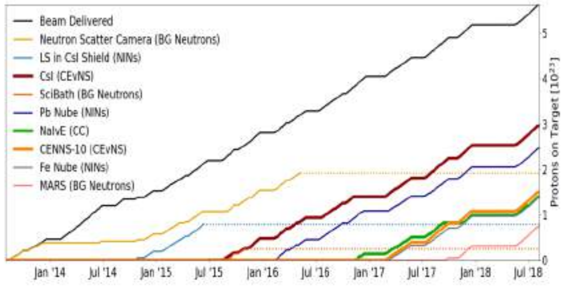
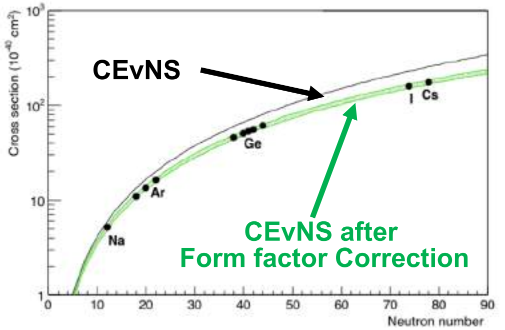
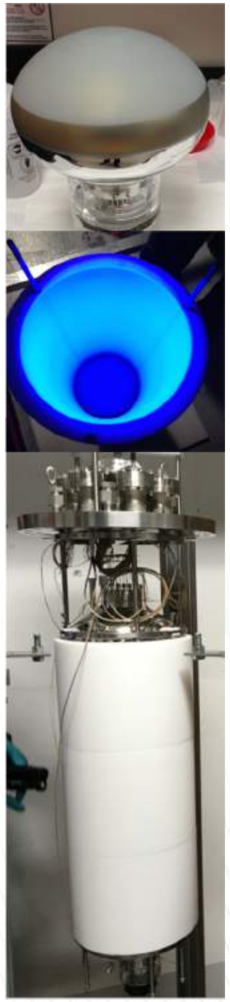


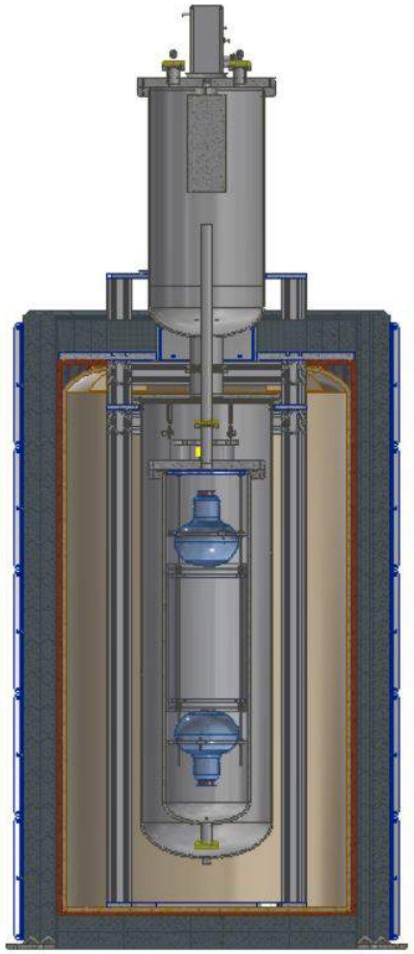
Next step is Detection CEvNC with LAr detector



Single Phase Liquid Argon Detector CENNS-10

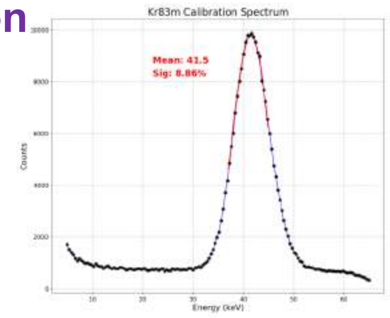
Aim is to detect CEvNS for very different target

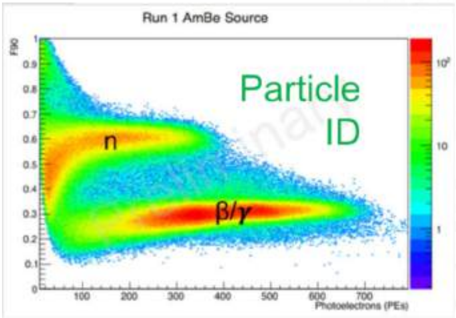




CENNS-10 SNS timeline:

- 10-12/2016: commission and deployed detector at SNS
- 12/16 - 5/17: "Run -0". Poor light collection, E_{thresh}~100keVnr
  Test of hardware.
- 7/17- now: "Run 1" Rebuild detector. Light collection increase by a factor of 10! It should be enough to see CEvNS. E_{thresh}~20keVnr
  Presently accumulated statistics is ~5 GWhr (~$1.2*10^{23}$ POT)
  SNS is running at 1.4 MW with a good lifetime.
- We implemented blind analysis by looking on the data between beam spills only.
  Planning to open box soon!!!!





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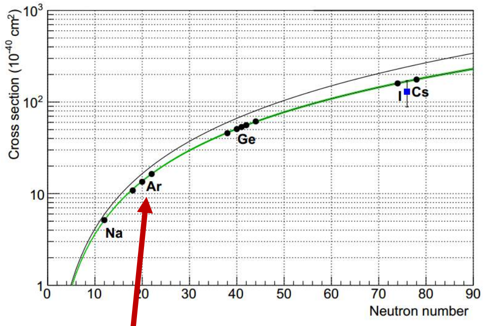
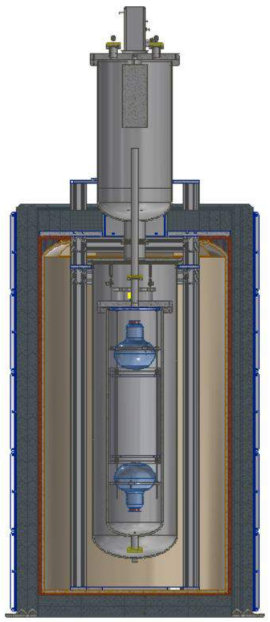
Future Activities - 1 ton LAr detector



Need high statistics low background measurements of CEvNS



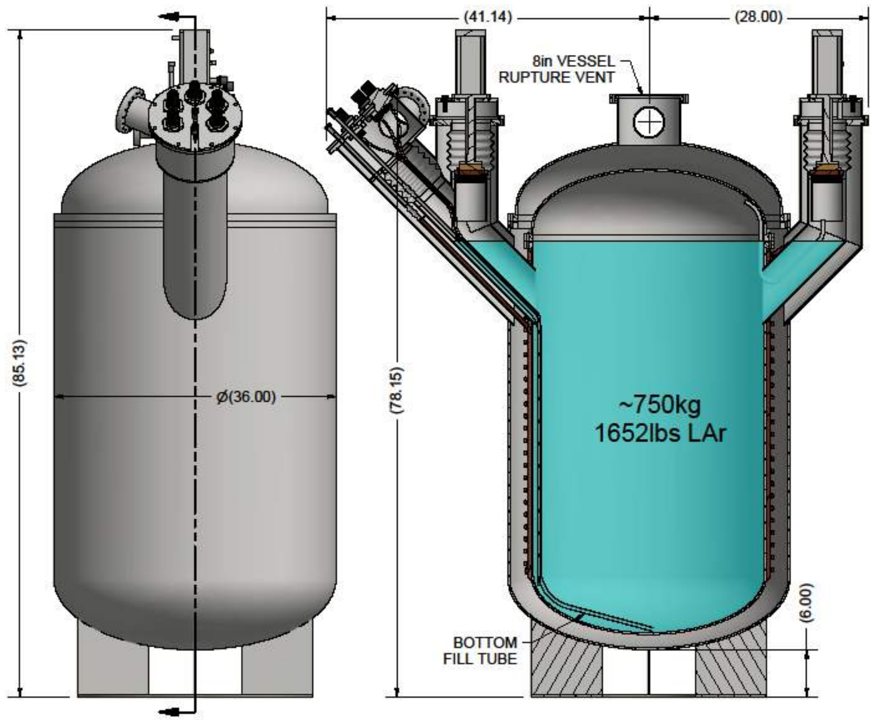
Transition from 22 kg to 1 ton LAr detector.

Can fit at the same place where presently 22 kg detector is sitting

Potentially use depleted Argon to reduce background from ^{39}Ar

Will see thousands of CEvNS events per year + CC

Can later replace Ar to Xe



Future Activities – SNS Neutrino Flux calibration

Presently we assume that neutrino flux at SNS is known within 10%

Cross sections of neutrino interaction with Deuterium are known with 2-3% accuracy

S.Nakamura et. al. Nucl.Phys. A721(2003) 549

Prompt NC ν_μ +d → $1.8*10^{-41}$ cm^2
Delayed NC $\nu_{e\mu\text{-}bar}$+ d → $6.0*10^{-41}$ cm^2
Delayed CC ν_e + d → $5.5*10^{-41}$ cm^2

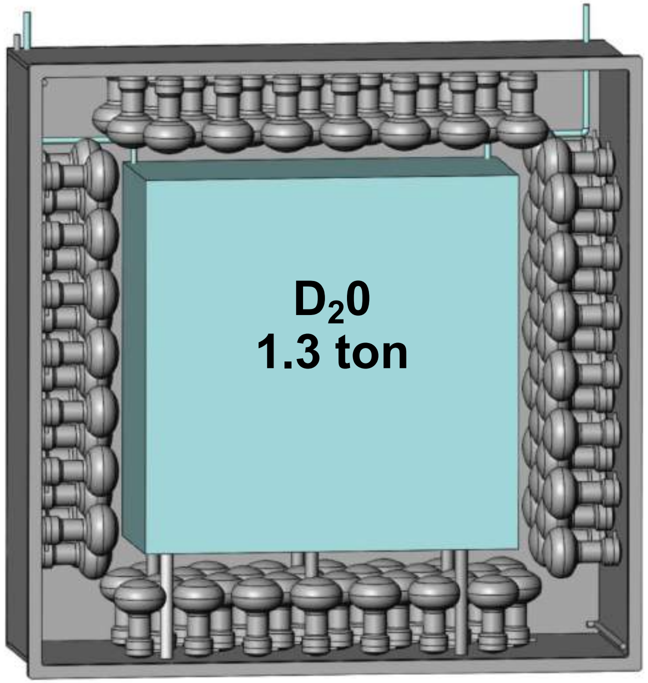
For 1 t fiducial mass detector ~ thousand interactions per year

Detector calibration with Michel Electrons (same energy range)

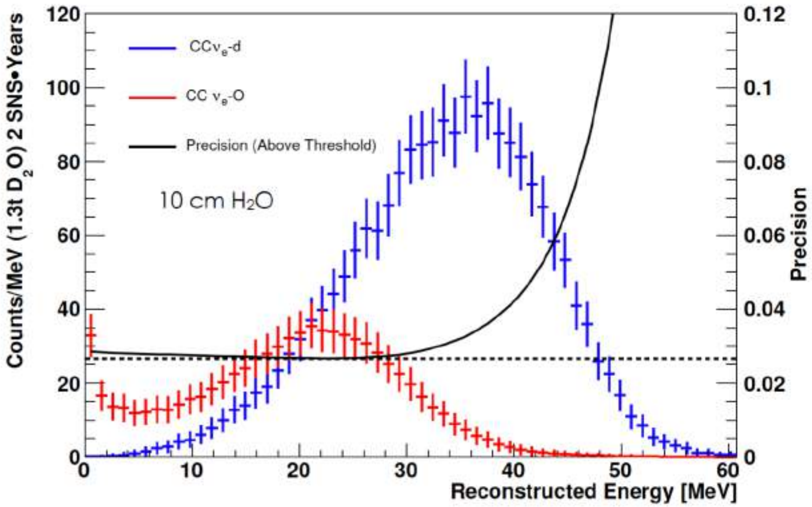
Well defined D_2O mass constrained by acrylic tank

10 cm of light water tail catcher

Outer dimensions 2.3 * 2.3 * 1.0 m^3



See Jason's Talk



SNS calibration and CC measurements on Oxygen

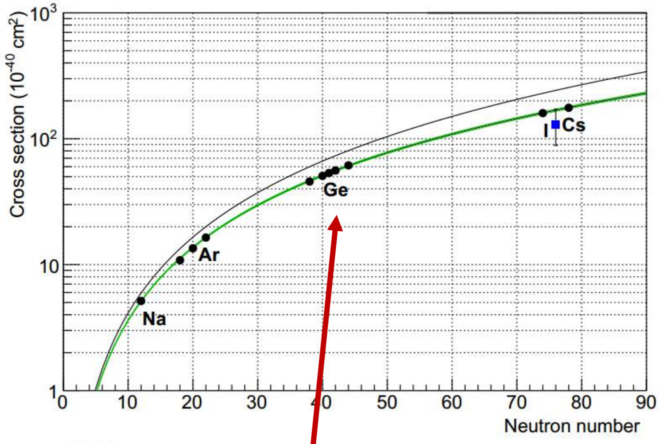
New Germanium Target for COHERENT

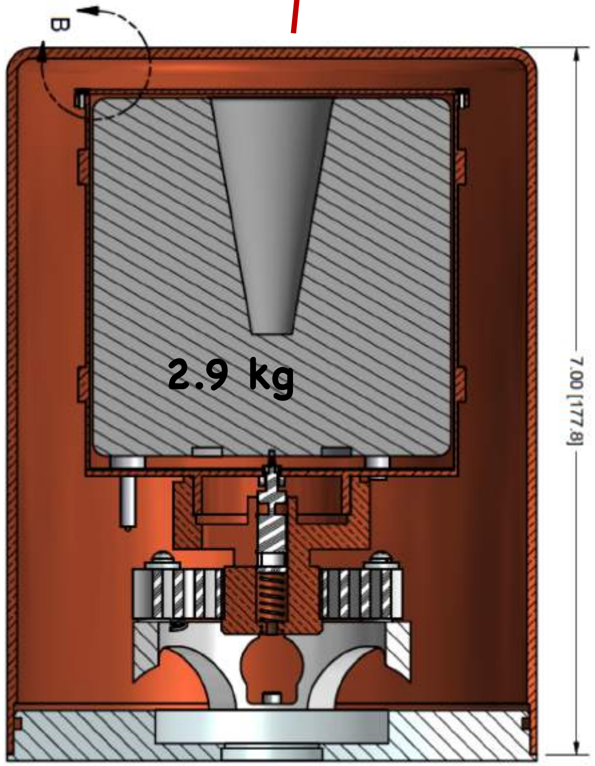
- Use state-of-the-art PPC Ge technology to perform a *precision* measurement of CEνNS. **>800 events/yr from 10 kg** array, with signal/background of ~15 (this was ~1/4 for CsI[Na] first COHERENT result).

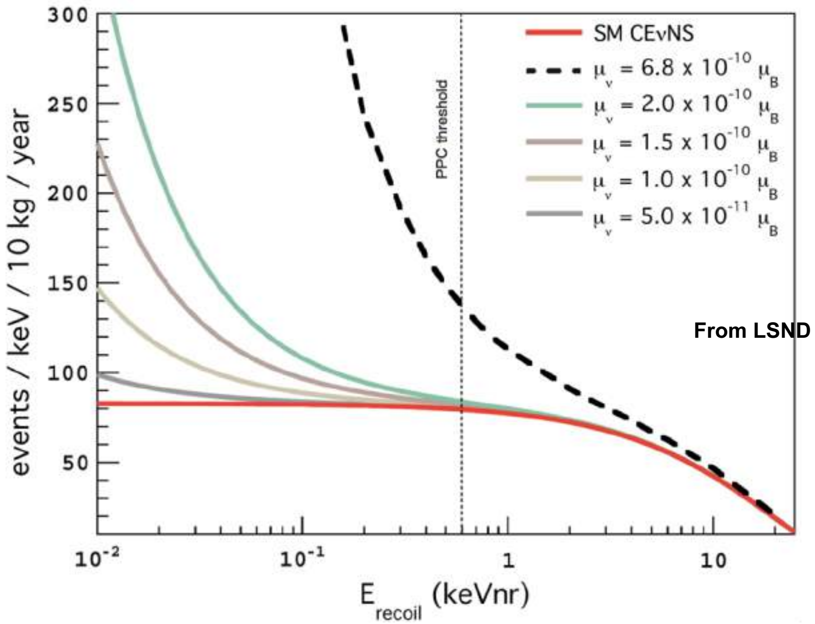
- Demonstrated analysis **threshold of 120eVee/600eVnr** (>70% SA, no false positives) allows measurement of full CEνNS recoil spectrum. Accompanying ongoing effort in quenching factor characterization.

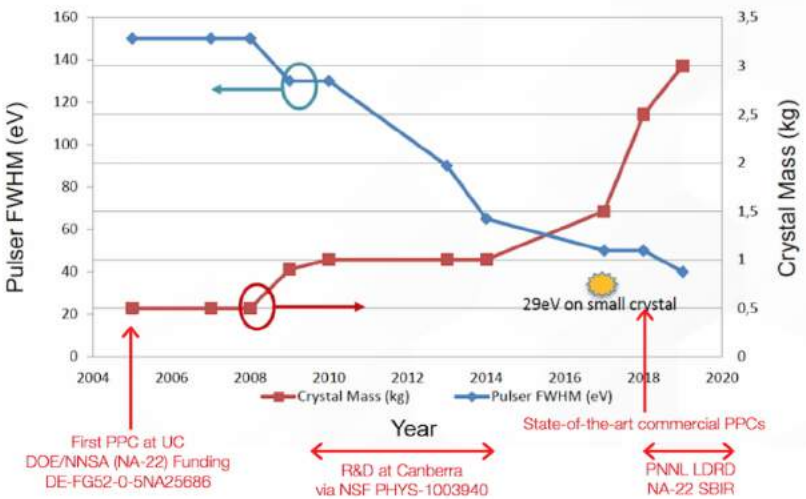
- Improved sensitivity to ν electromagnetic properties, non-standard ν interactions, MiniBooNE/LSND anomaly (steriles), DM models…

- **Two first detectors (6 kg) funded at University of Chicago through DARPA and NSF**. Shield will be designed to accommodate additional two units. **Support from ORNL/NSCU on shield design and installation is necessary**. Demonstration of threshold and background in 2018. **Planning to start of data-taking at SNS at 2019.**

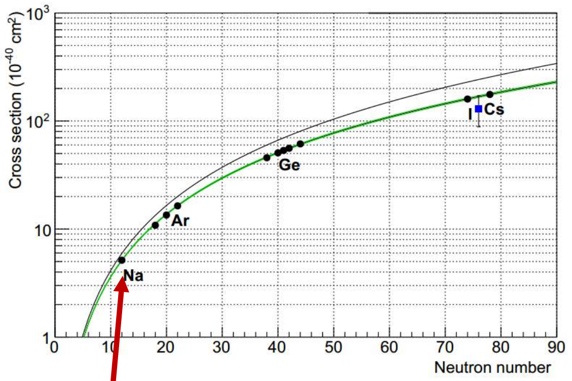








2t NaI detectors array

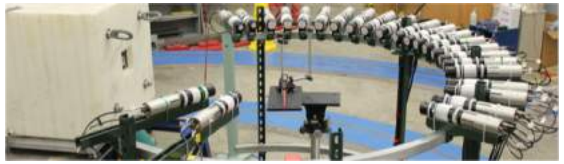


Transition from now deployed 185 kg to 2 ton array of NaI detectors

Detectors are available

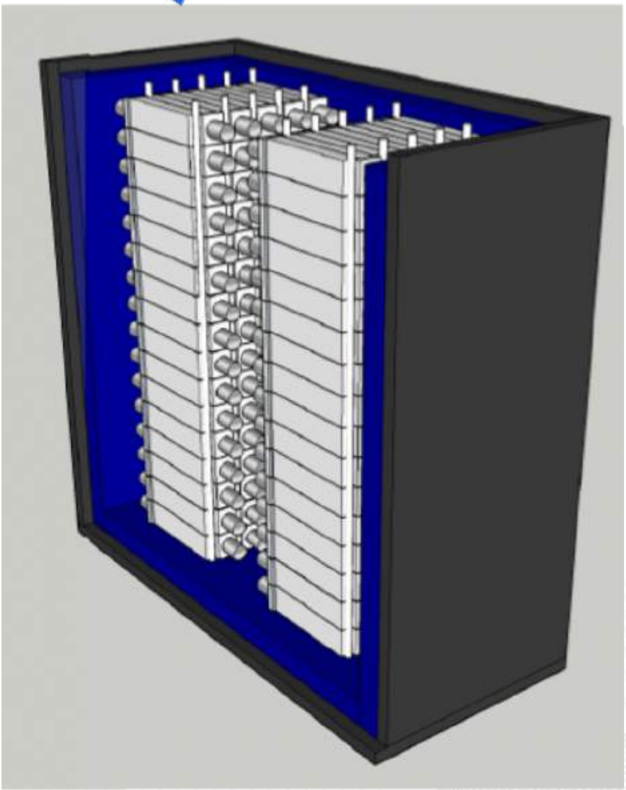
Need dual gain bases (prototypes has been build)

Program to measure Quenching Factors is ongoing at TUNL



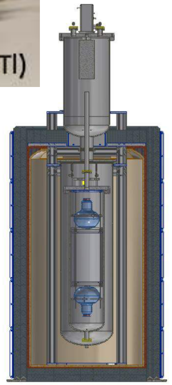
Need electronics and HV; some funds are secure

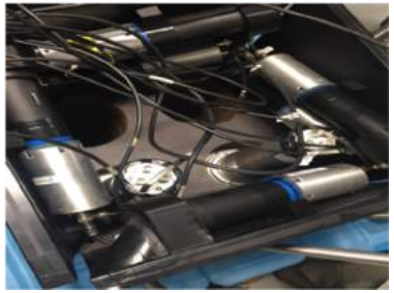
Potential to detect both CEvNS and CC reactions

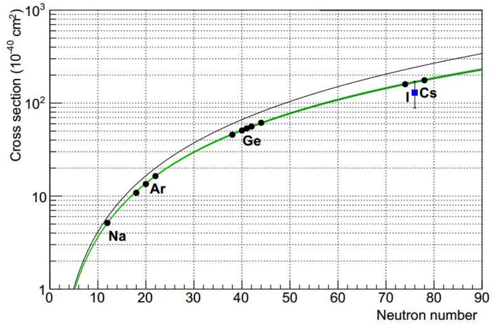


COHERENT Collaboration Steps

Present: First Light

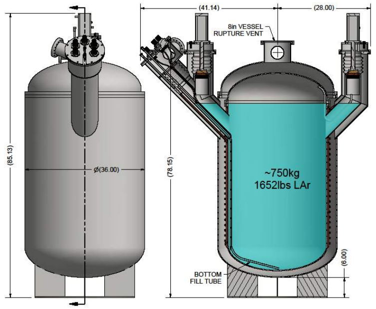


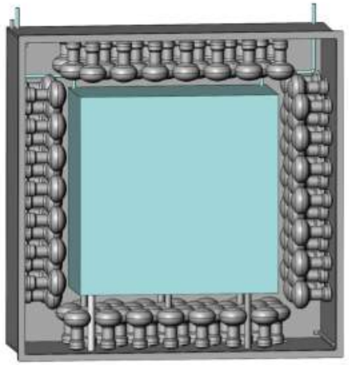


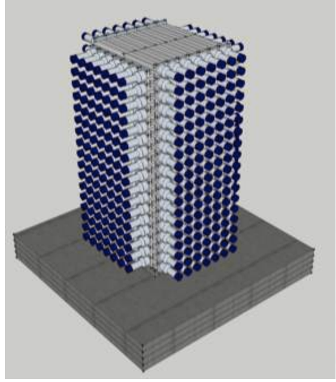


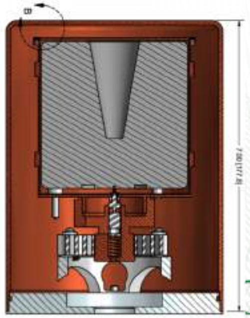
- **Detect CEvNS**
- **Measure CEvNS for heavy and light nuclei**
- **Detect NINs**

Next Step: New Deployments









- **Deploy low threshold Ge detectors**
- **Calibrate SNS neutrino flux**
- **High precision CEvNS studies. Look for physics beyond SM. Eliminate Dark Sector as a degeneracy for DUNE**
- **By product Measure neutrino CC to support Supernovae physics, and Weak interaction physics (Lead, Argon, Oxygen, Iodine)**

Young COHERENT members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Summary

Detection of CEvNS opened new portal to look for physics beyond the SM

First set of experiments have been deployed, we have first positive result, and continue to take data

Preparation are on the way to build and deploy ~6 kg Ge detectors and 2t NaI detectors

Collaboration is planning to build and deploy for 1t LAr(Xe) and 1t D_2O detectors in near future

Our major goals are:

- Collect data for precision tests of SM in new channel
- Make inputs into nuclear physics theory
- Provide CC and NC measurement for O, Ar, I, and Pb for E_ν relevant for SN