Coherent neutrino scattering status and perspectives

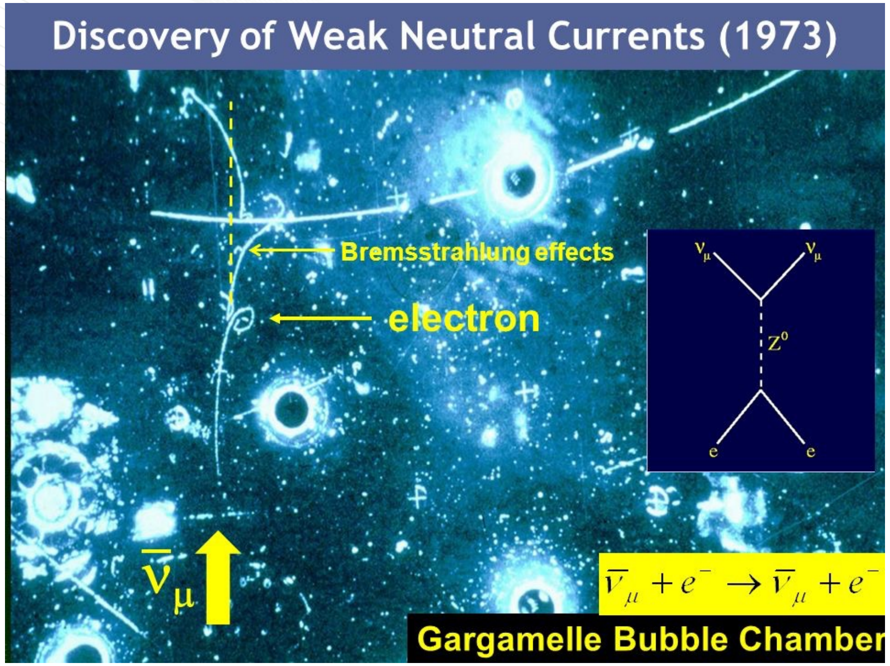
Yu. Efremenko

UTK/ORNL

Lomonosov-2021, August 25

Coherent Elastic Neutrino Nucleus Scattering (CEvNS)

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



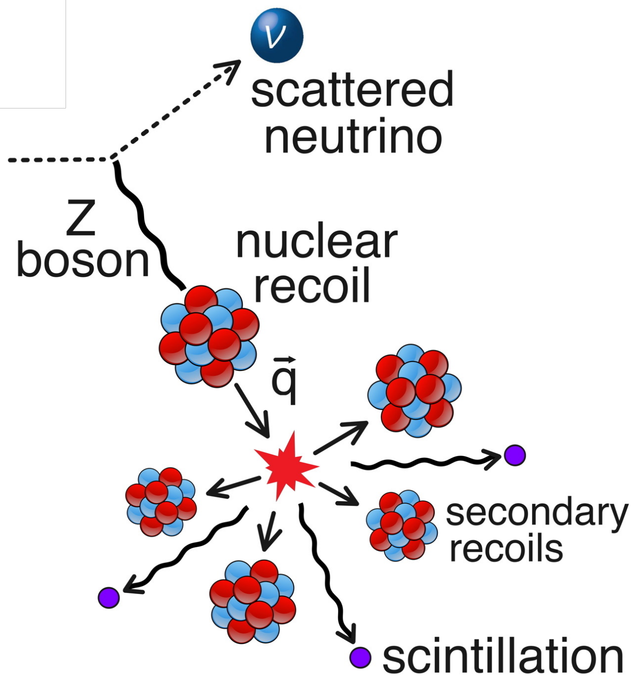
D.Z. Freedman PRD 9 (1974)

Submitted Oct 15, 1973

V.B.Kopeliovich & L.L.Frankfurt

JETP Lett. 19 (1974)

Submitted Jan 7, 1974

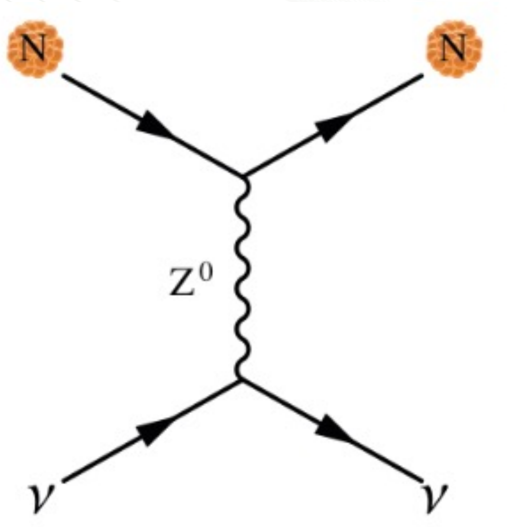


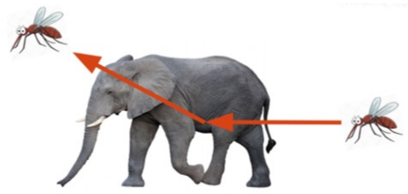
$$\frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2} k^2 (1 + \cos\theta) \frac{(N - (1 - 4\sin^2\theta_W)Z)^2}{4} F^2(Q^2)$$

$$\propto N^2$$

CEvNS cross section is predicted by the Standard Model !!!

Coherent Elastic neutrino-Nucleus Scattering (CEvNS)

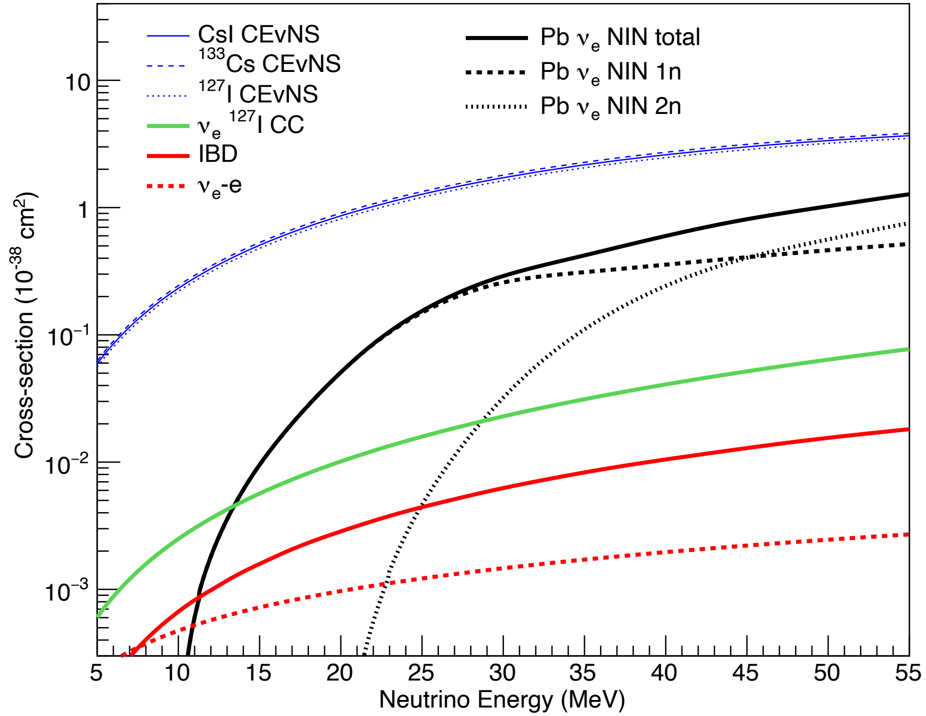




CEvNS cross-section is larger than any other neutrino interaction cross-sections at low energy, but it is hard to detect

D.Z. Freedman PRD 9 (1974)

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.



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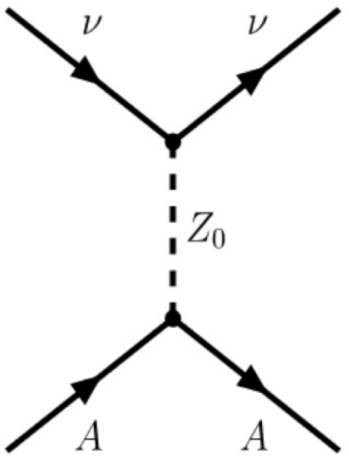
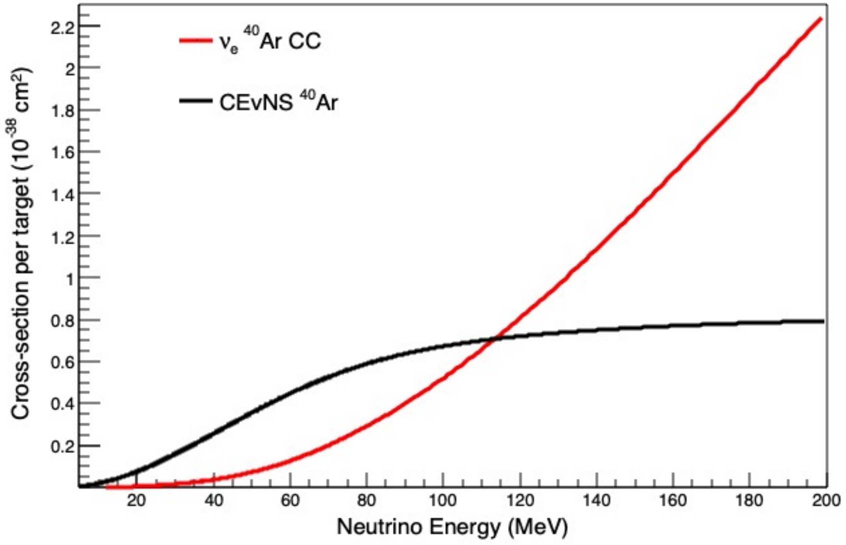
Nuclear Form Factor at CEvNS

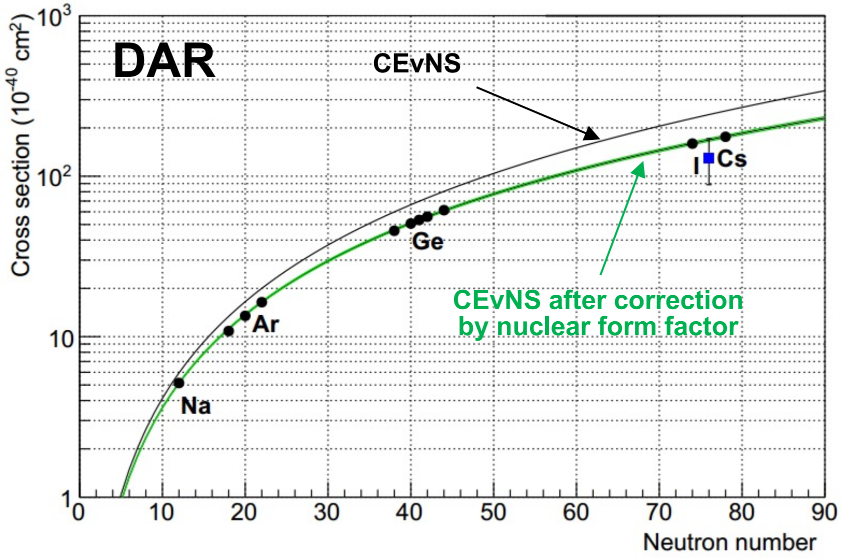
$$\frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2}k^2(1+\cos\theta)\frac{(N-(1-4\sin^2\theta_W)Z)^2}{4}F^2(Q^2)$$

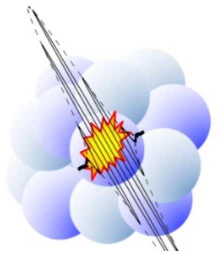


For energy above 50 MeV

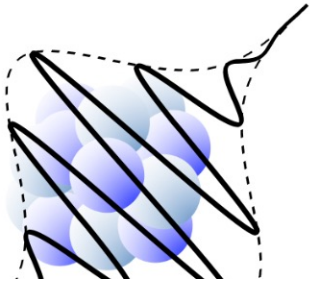
form factor starts to suppress cross section







High Q = short de Broglie wavelength



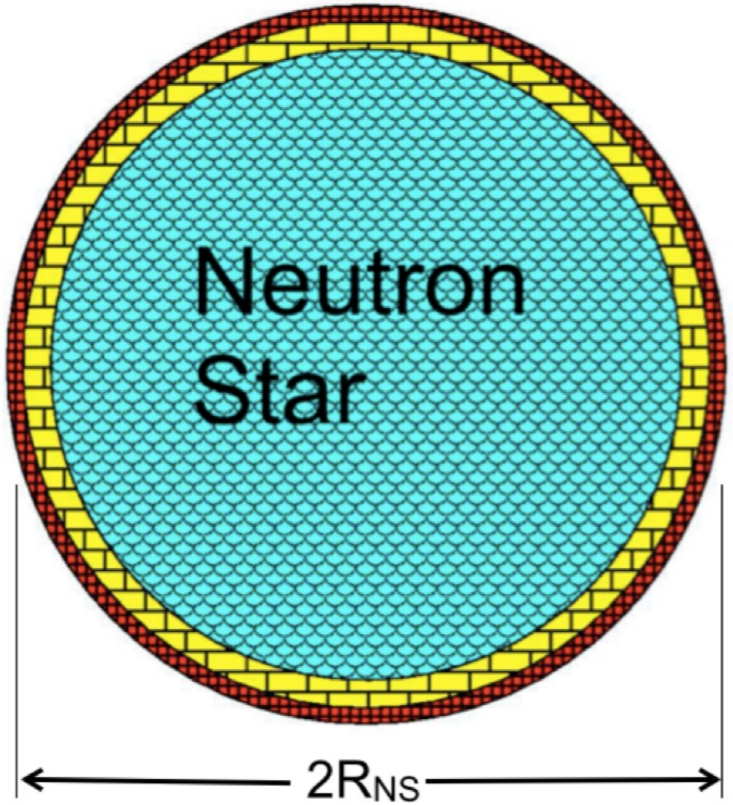
Low Q = long de Broglie wavelength

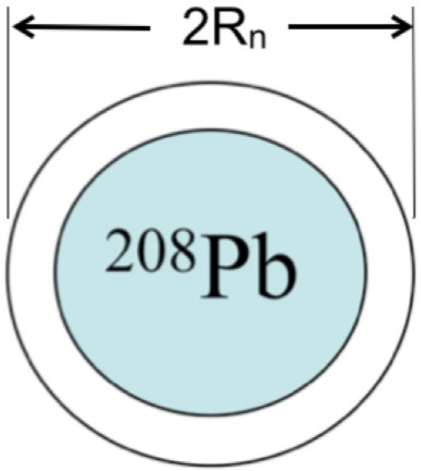
CEvNS belong to both Particle and Nuclear Physic

CEvNS will let to Measure Neutron Skin for Heavy Elements → input into neutron matter density

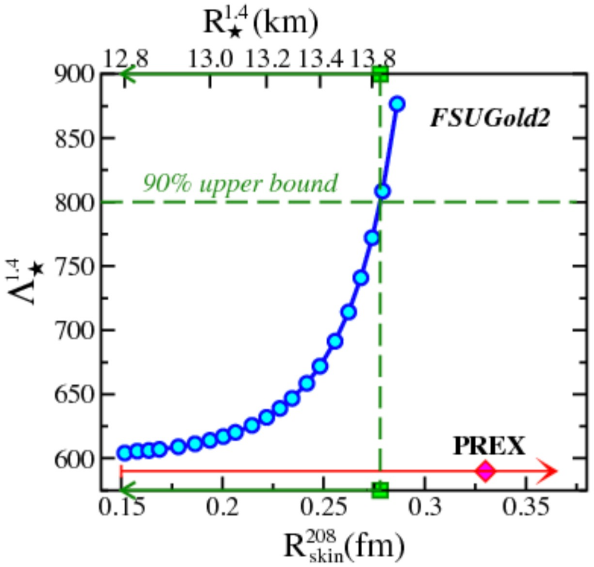
- Pressure of neutron matter pushes neutrons out against surface tension ==> R_n-R_p of ^{208}Pb correlated with P of neutron matter.
- Radius of a neutron star also depends on P of neutron matter.
- Measurement of R_n (^{208}Pb) in laboratory has important implications for the structure of neutron stars.

C.Horowitz



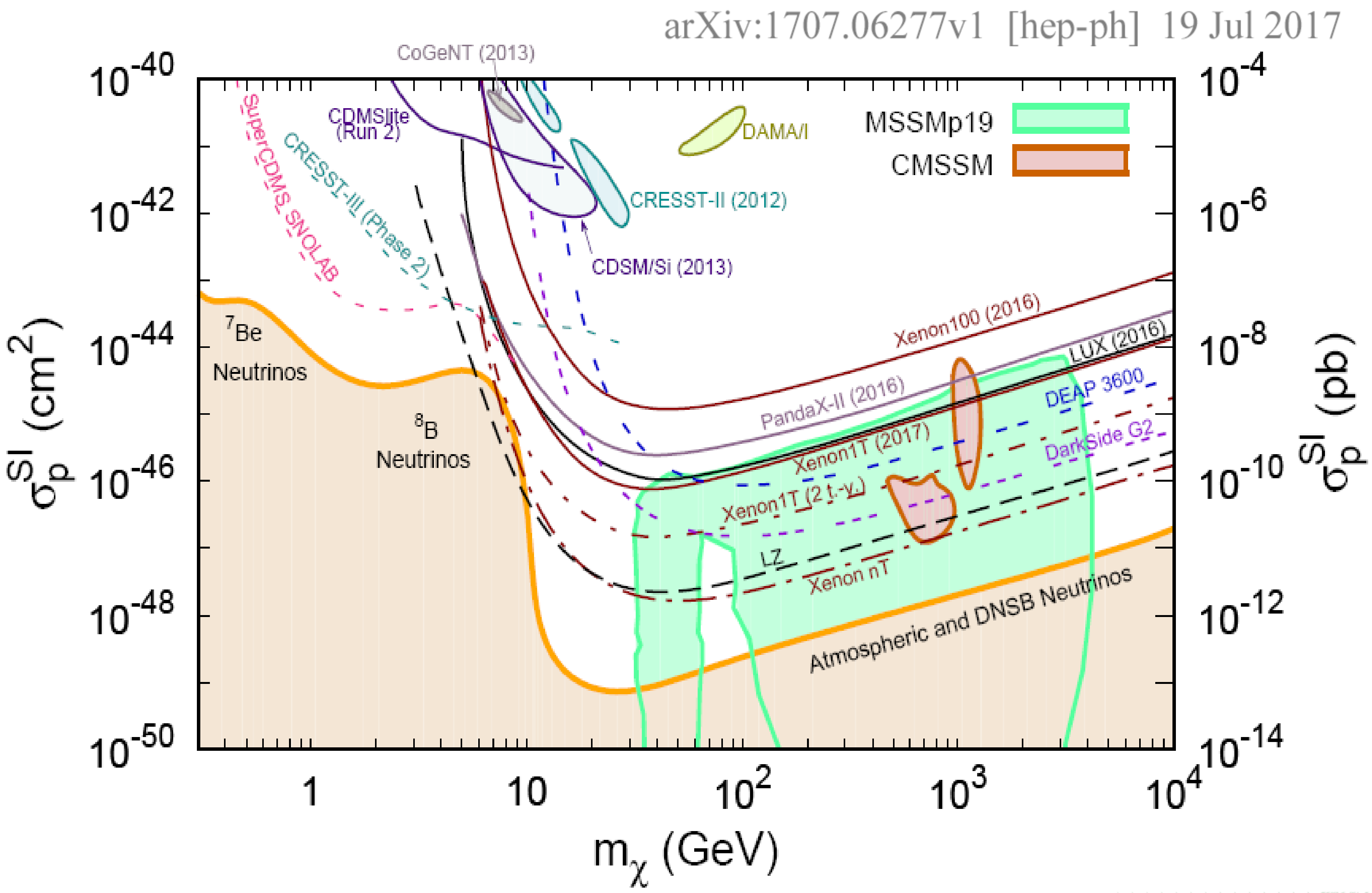


Neutron star is 18 orders of magnitude larger than Pb nucleus but has same neutrons, strong interactions, and equation of state.



Fattoyev, F.J. *et al.* Phys.Rev.Lett. 120 (2018)

CEvNS is Neutrino Floor for DM Experiments



CEvNS is a Probe of Non-Standard Neutrino Interactions (NSI)

new interaction specific to ν's

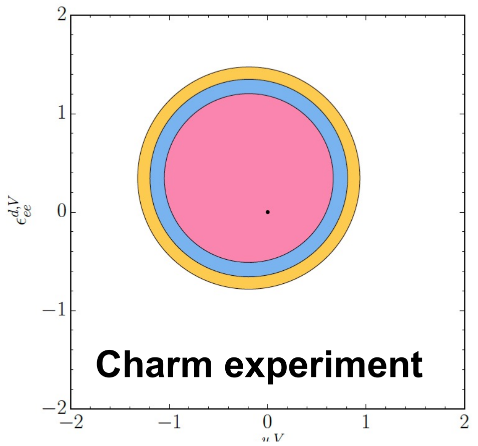
$$\mathcal{L}_{\nu H}^{NSI} = -\frac{G_F}{\sqrt{2}} \sum_{\substack{q=u,d \\ \alpha,\beta=e,\mu,\tau}} [\bar{\nu}_\alpha \gamma^\mu (1-\gamma^5)\nu_\beta] \times (\varepsilon_{\alpha\beta}^{qL}[\bar{q}\gamma_\mu(1-\gamma^5)q] + \varepsilon_{\alpha\beta}^{qR}[\bar{q}\gamma_\mu(1+\gamma^5)q])$$

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

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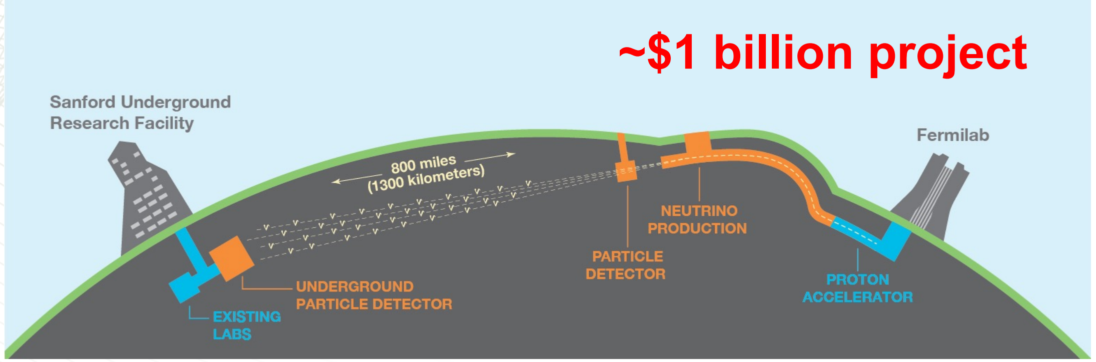
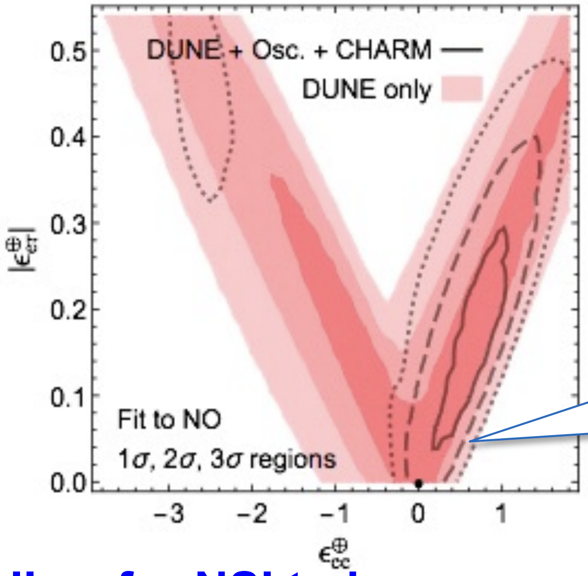
CEvNS are Important as a Probe for NSI.
NSI can create degeneracy for DUNE



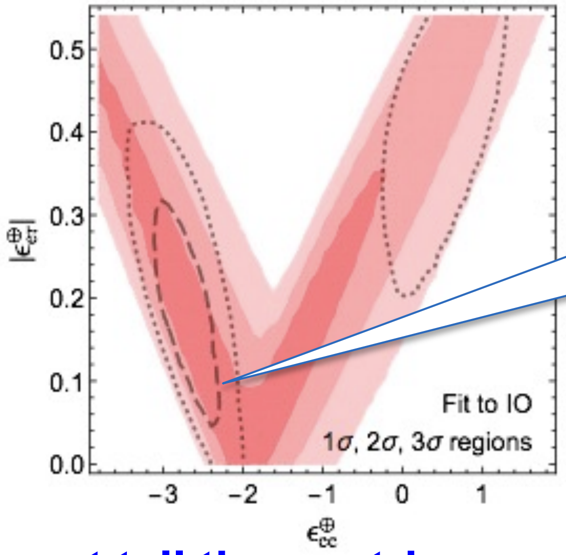
- **measuring the charge-parity (CP) violating phase CP,**
- **determining the neutrino mass ordering (the sign of Δm^2_{12})**
- **precision tests of the three-flavor neutrino oscillation paradigm**

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 have non-zero contribution, degeneracy appears.

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

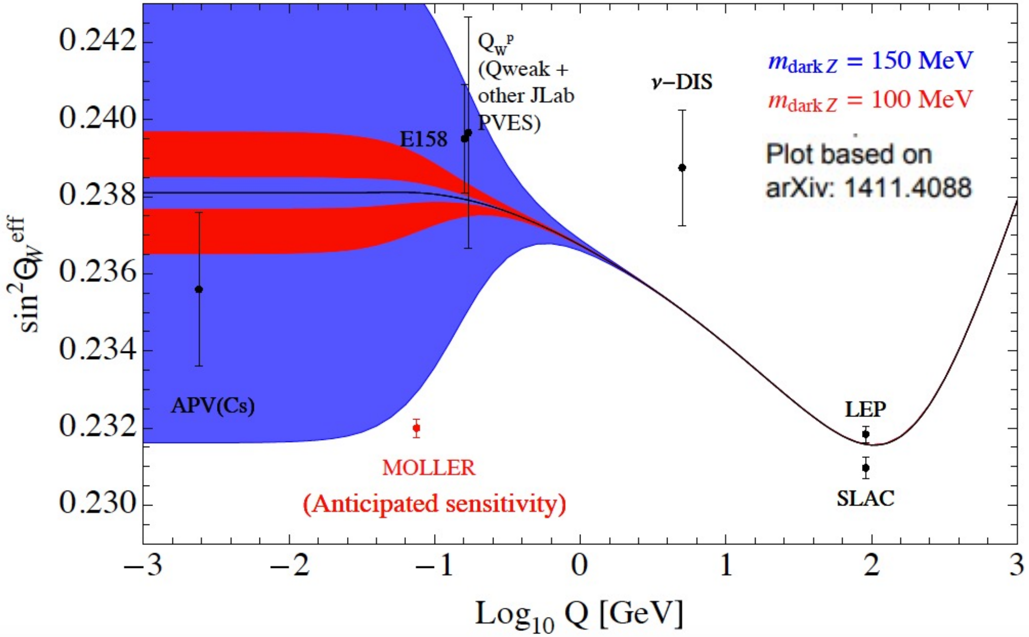
CeVNS is a new way to measure Electro-Week angle at Low Q

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

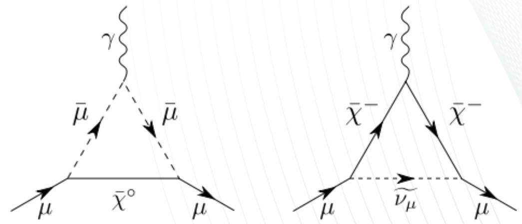
$$\sigma_{tot} = \frac{G_F^2 E_\nu^2}{4\pi}\left[Z\left(1-4\sin^2\theta_W\right)-N\right]^2 F^2(Q^2)$$

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 and 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

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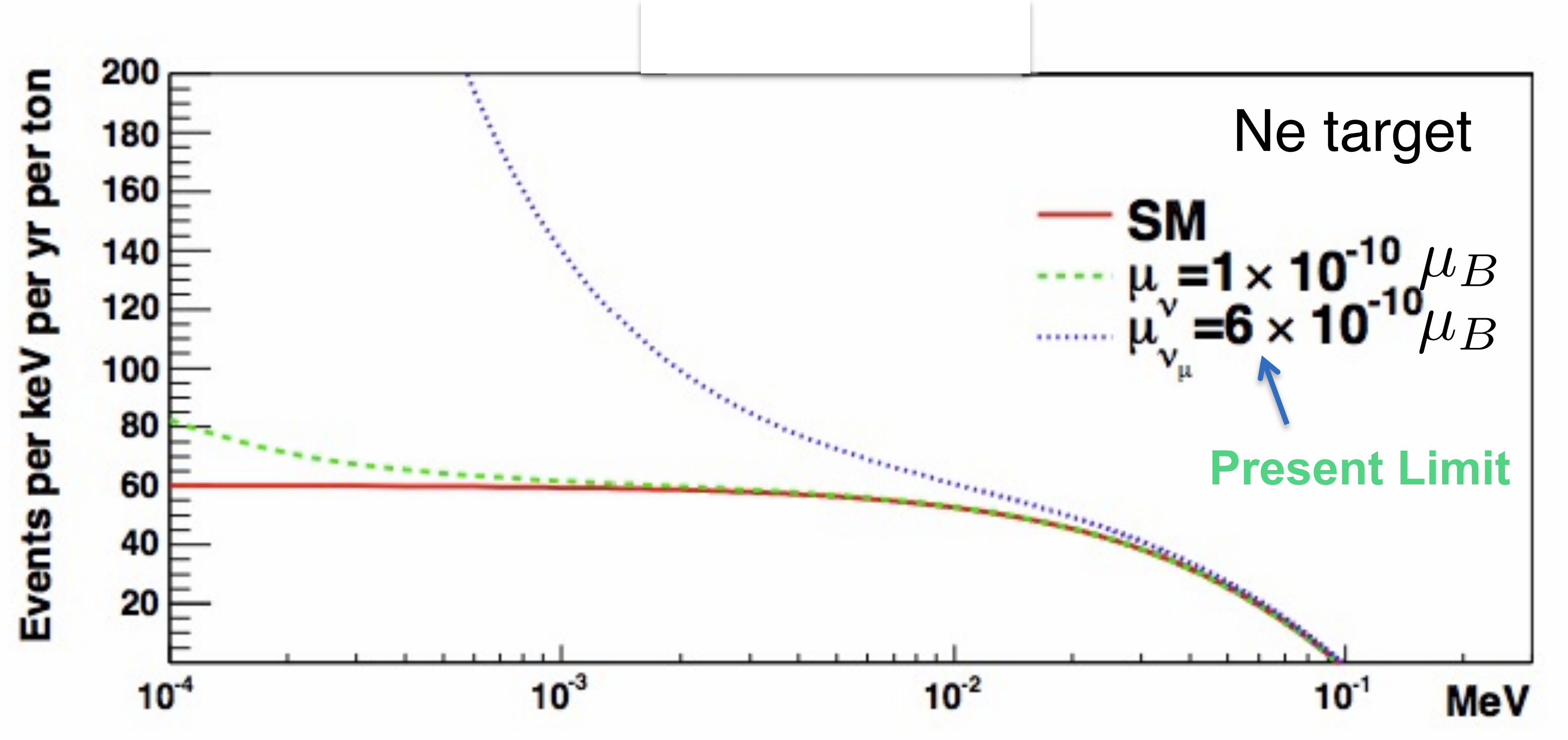
Search For Neutrino Magnetic Moment via CEvNS

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

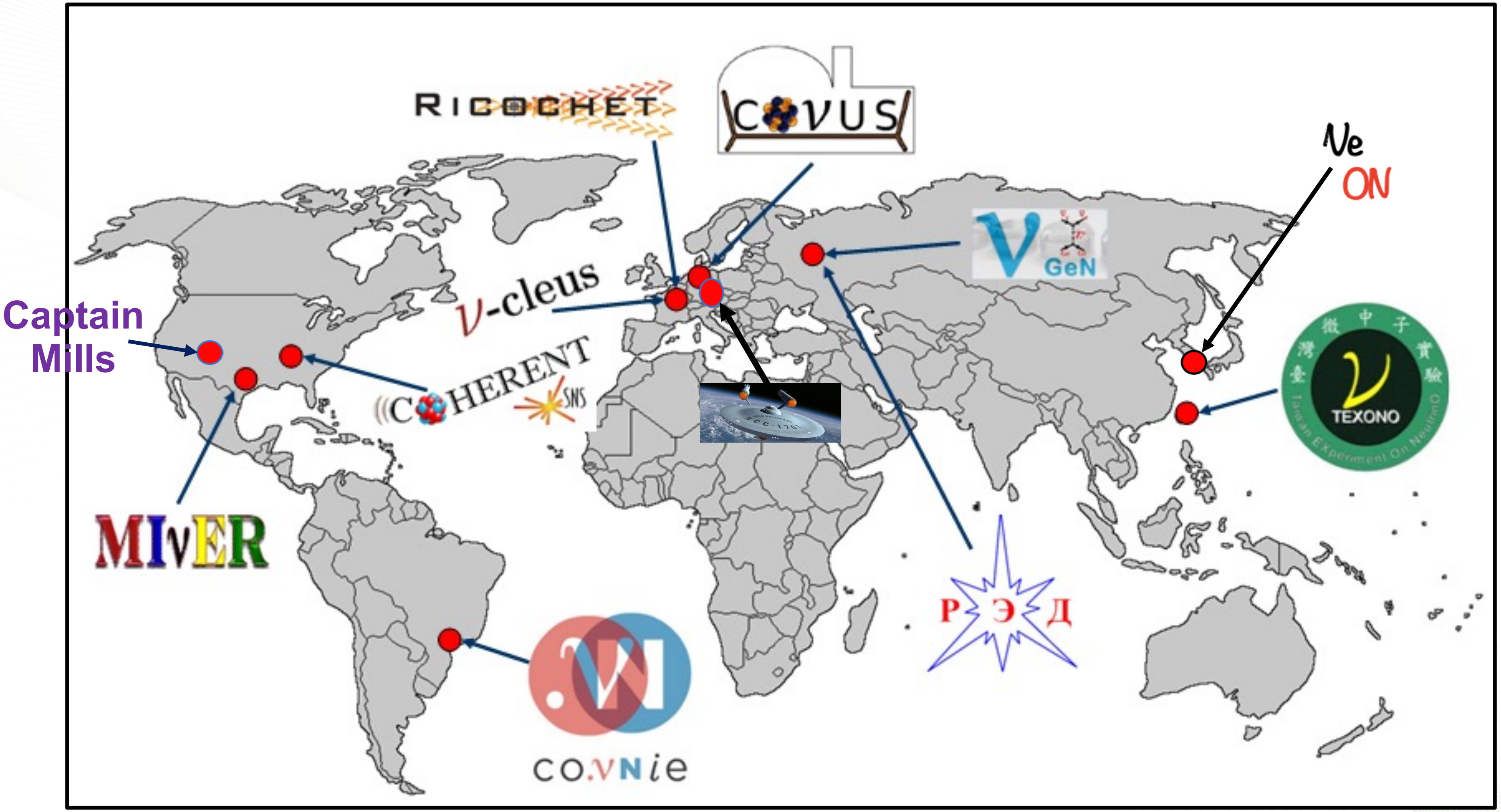
See also Kosmas et al., arXiv:1505.03202

CEvNS important for Understanding of Supernova Dynamics

Large effect from CEvNS on Supernovae dynamics.
We should measure it to validate the models

J.R. Wilson, PRL 32 (74) 849

Worldwide Efforts to Measure CEvNS



Except COHERENT and Captain Mills collaboration, all others are attempting to use nuclear reactors as a neutrino source

Nuclear reactors gave a large constant low energy neutrino flux

COHERENT Is Using Spallation Neutron Source (SNS) → (SvS)

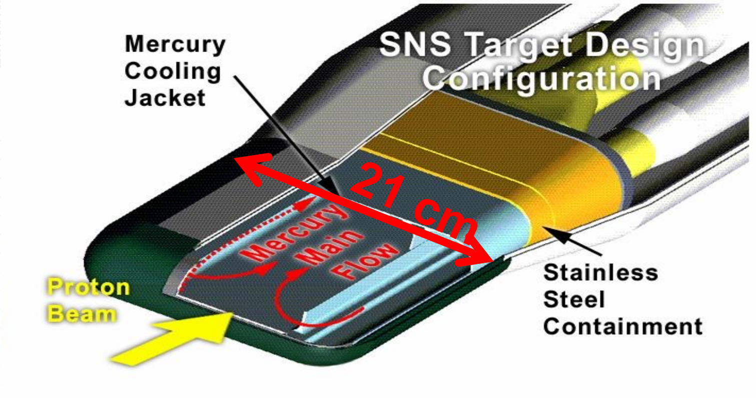
- It is world most powerful pulsed neutrino source. Presently it delivers 7 · 10^{20} POT daily *~10% of protons produce 3 neutrino flavors*
- Neutrino energies at SNS are ideal to study CEvNS.

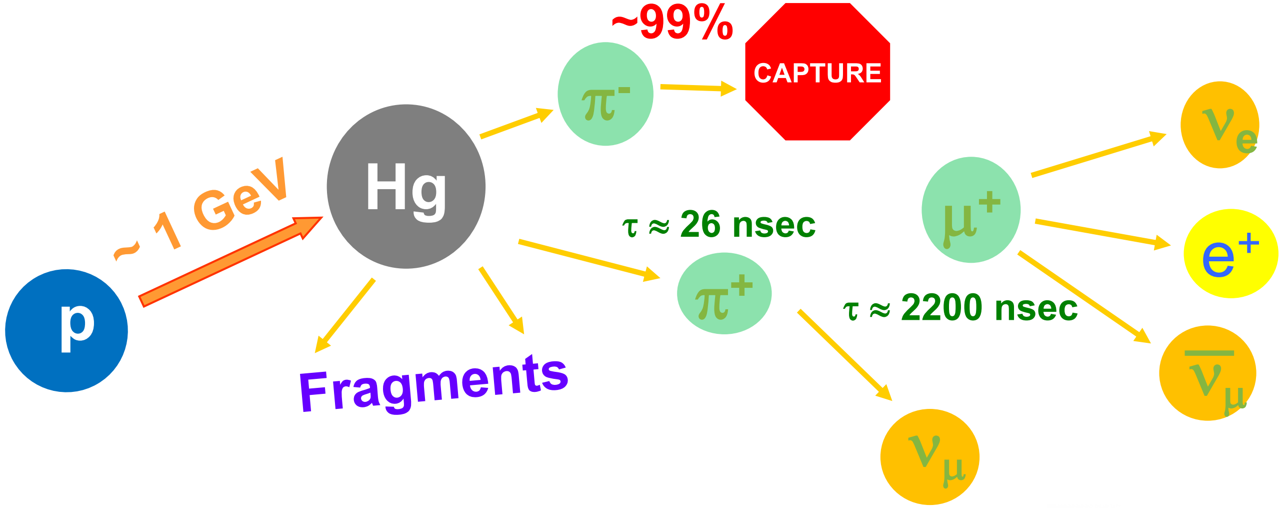
  For 99% of neutrinos $E_\nu < 53$ MeV

- Decay At Rest from pions and muons (DAR) gives very well-defined neutrino spectra
- Duty factor suppress steady state backgrounds by a factor of 2000.

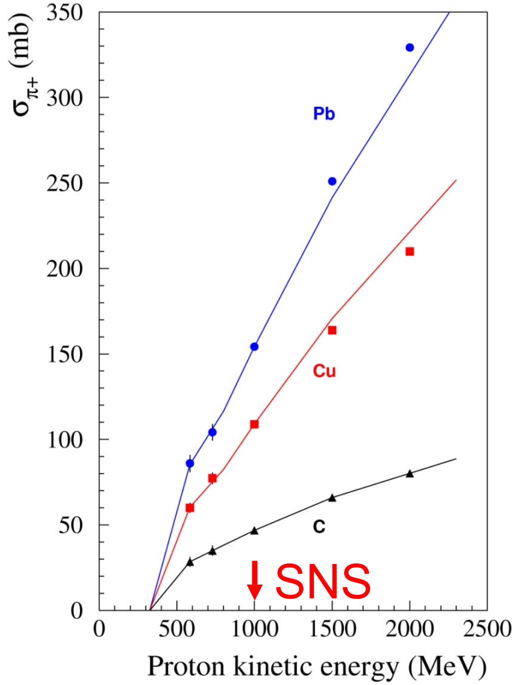
  It is like being at the 1000 m.w.e underground

Neutrino Production at the SNS

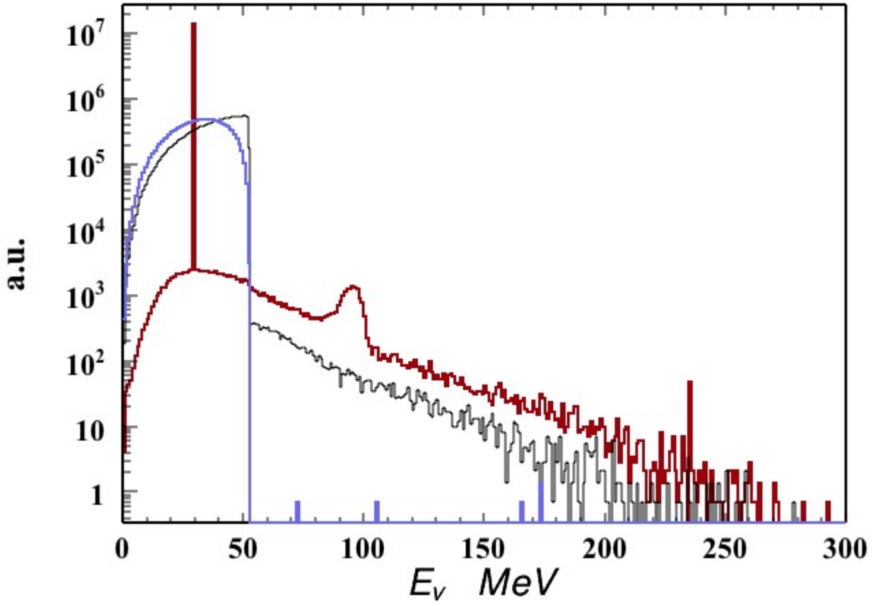




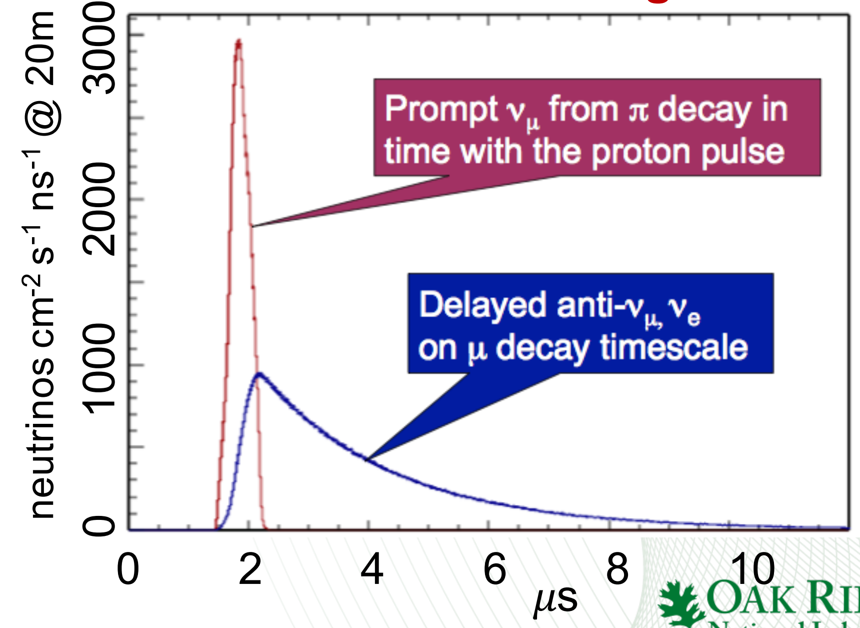
POSITIVE PION PRODUCTION



Neutrino Energy



Neutrino Timing



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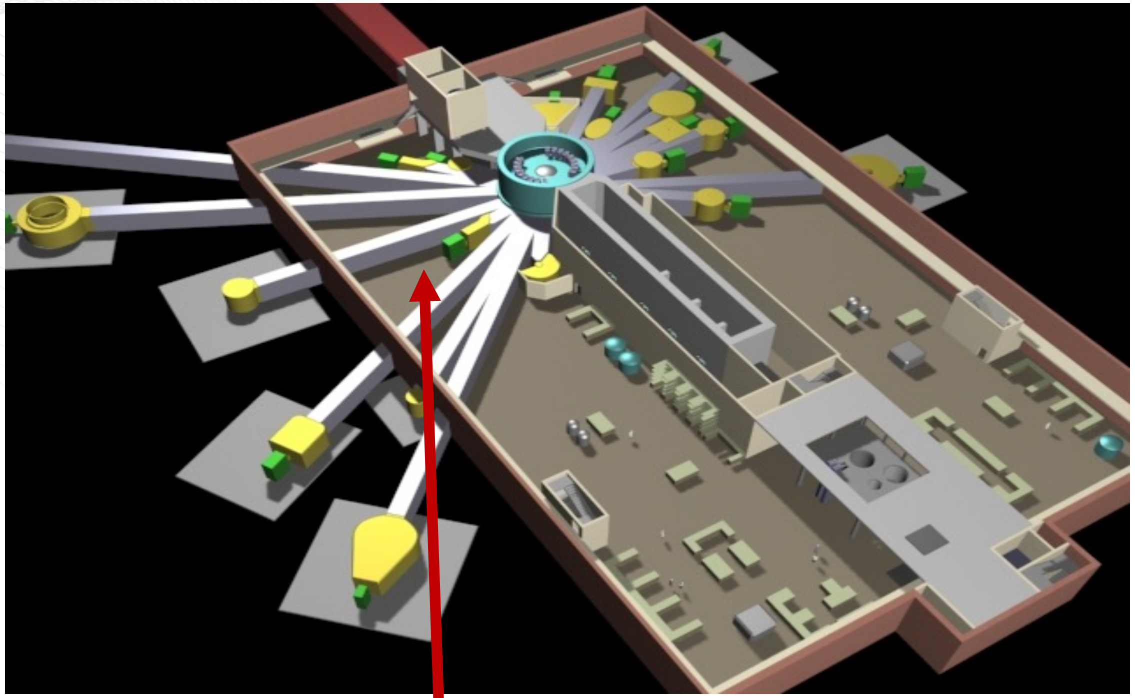
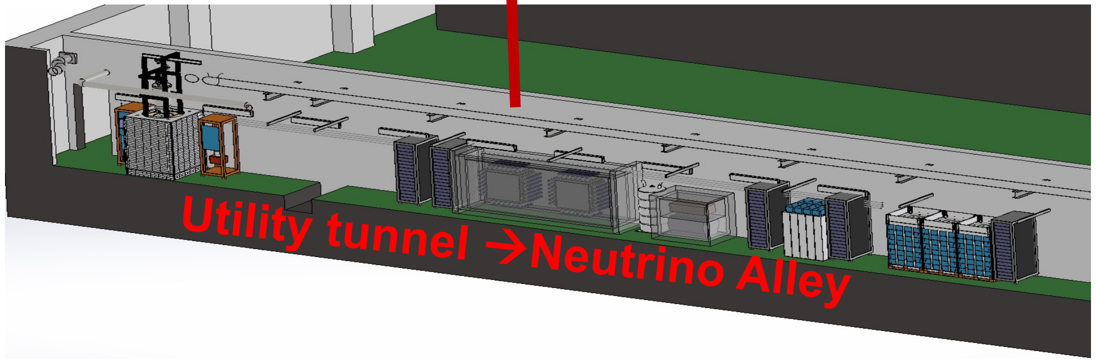
COHERENT is using “Neutrino Alley” at the SNS

After extensive background studies we find a well protected location at the SNS basement





Physicists who are trying to put neutrino detector next to a powerful neutron source should always remember:
The Legend of Icarus

don’t try to fly too close to the sun

Neutrino Alley is 20-30 meters from the target. Space between the target and the alley is completely filled with steel, gravel and concrete. This gives good protection from SNS neutrons.

There are 10 M.W.E. of shielding from above, enough to kill hadronic component of cosmic rays and attenuate muon flux by a factor of 3

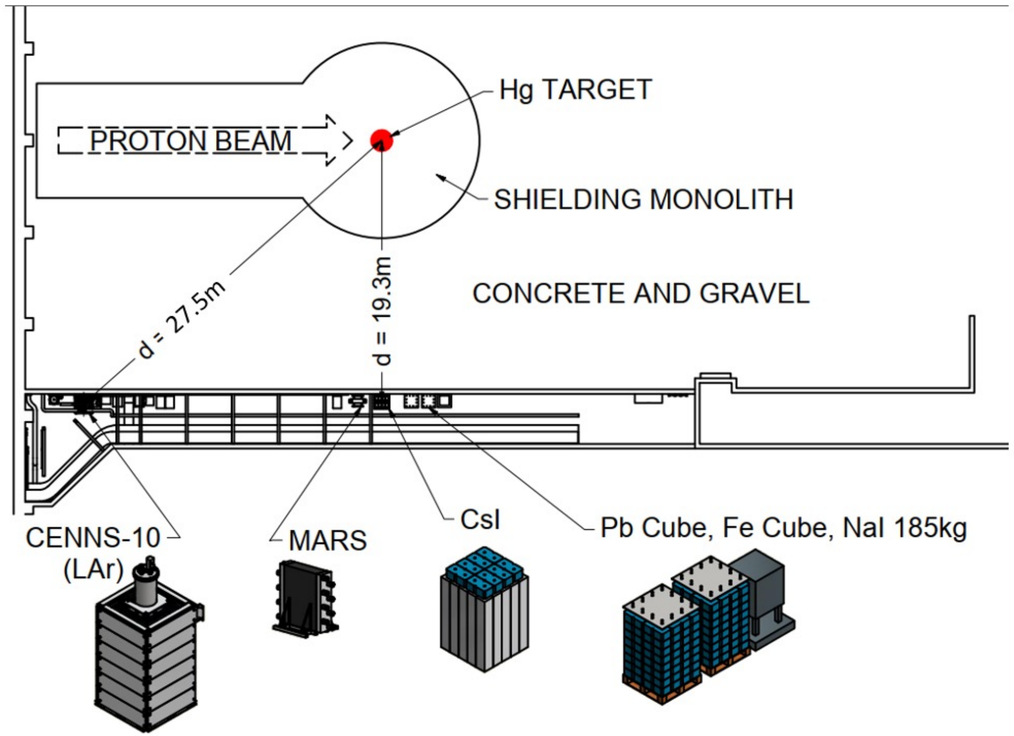
COHERENT at the SNS

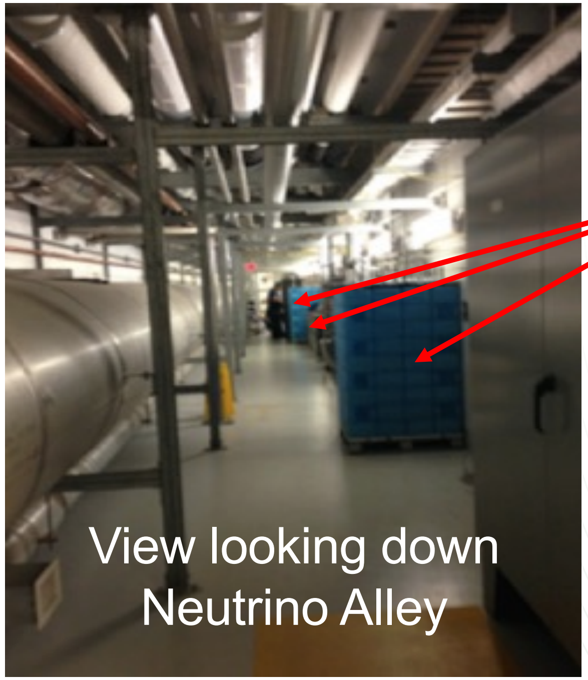
Location in basement of SNS target building ("Neutrino Alley")

19-28 meters from the target

Enough place for a several detectors

Nuclear Target	Technology	Mass (kg)	Distance from source (m)	Recoil Threshold (keVnr)
CsI[Na]	Scintillating crystal	14.6	19.3	6.5
Ge	HPGe PPC	16	20	2-2.5
LAr	Single-phase	24	27.5	20
NaI[Tl]	Scintillating crystal	185*/3338	28	13





Detectors

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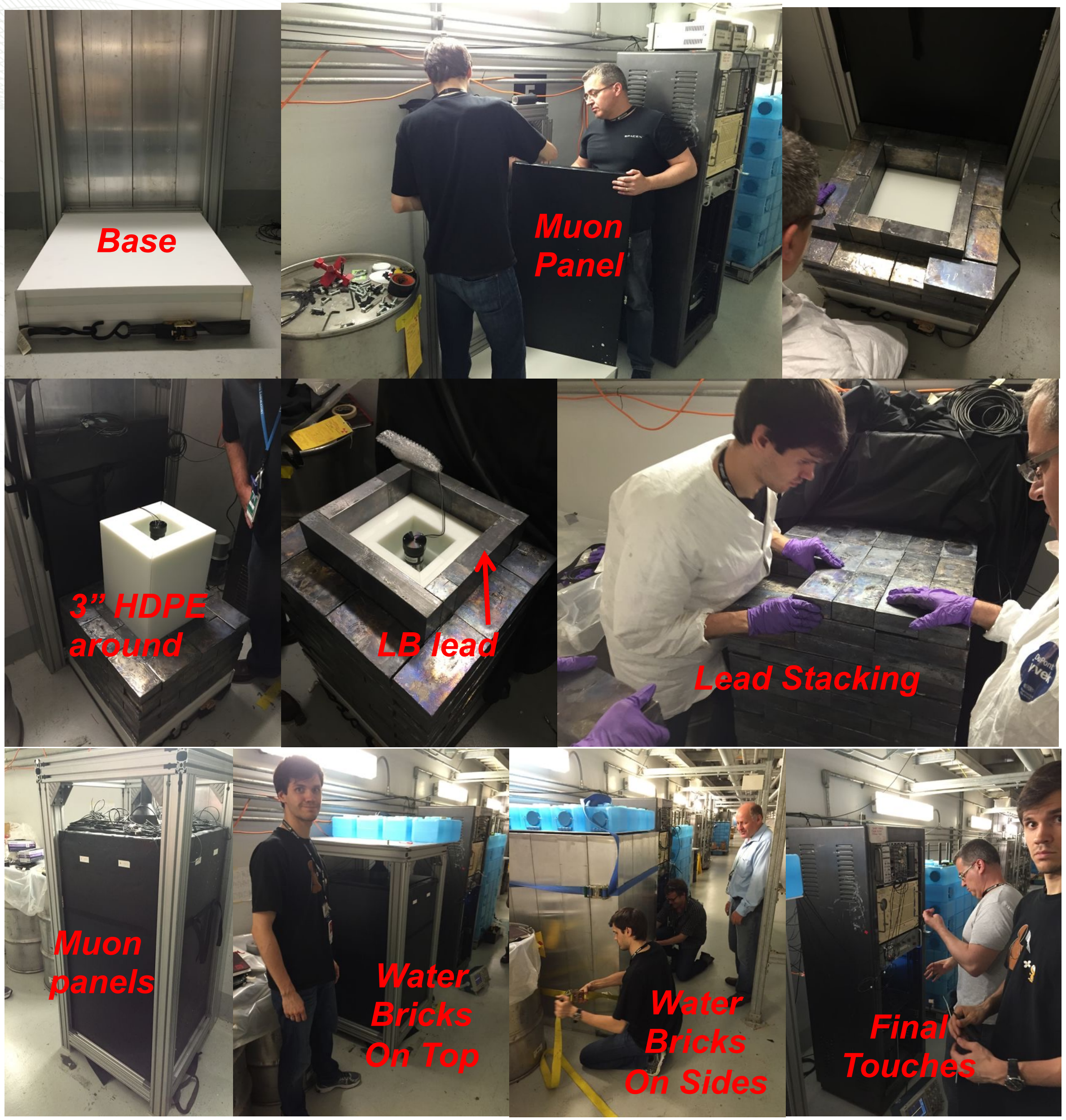
First Experiment: 14 kg CsI Detector



Years of preparations, simulations, and shielding optimizations.

One day to install and to commission !!!

Single 14 kg CsI crystal.

Crystal has been custom grown from preselected low background materials

Layers of dedicated shielding:

Poly to protect from NINs

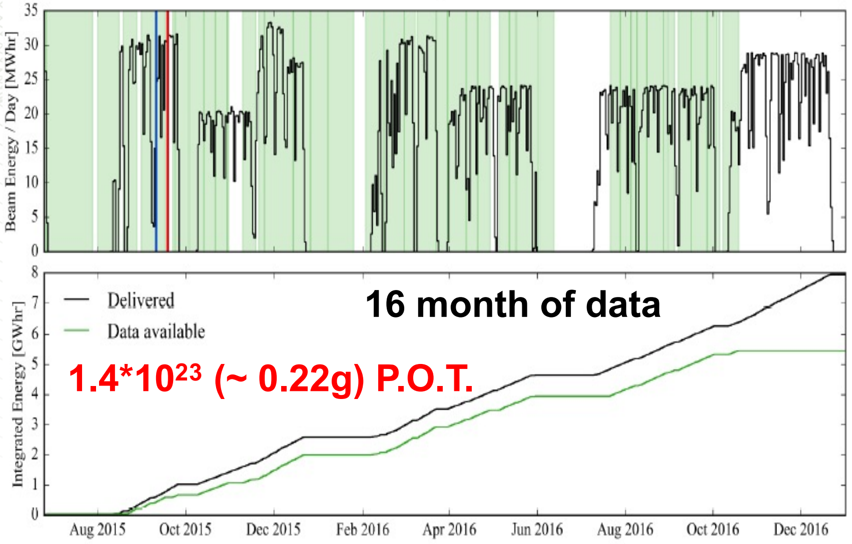
Low background lead

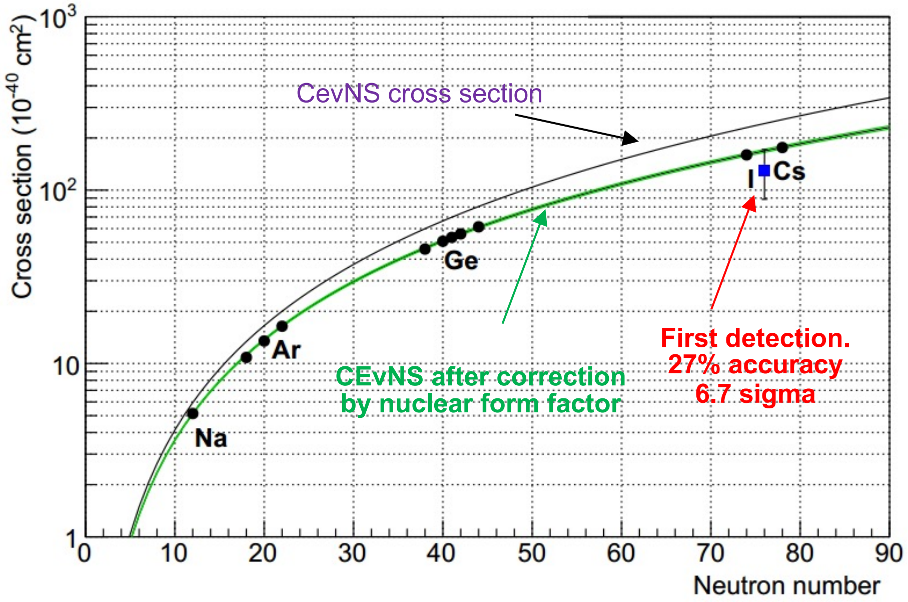
Regular good quality lead

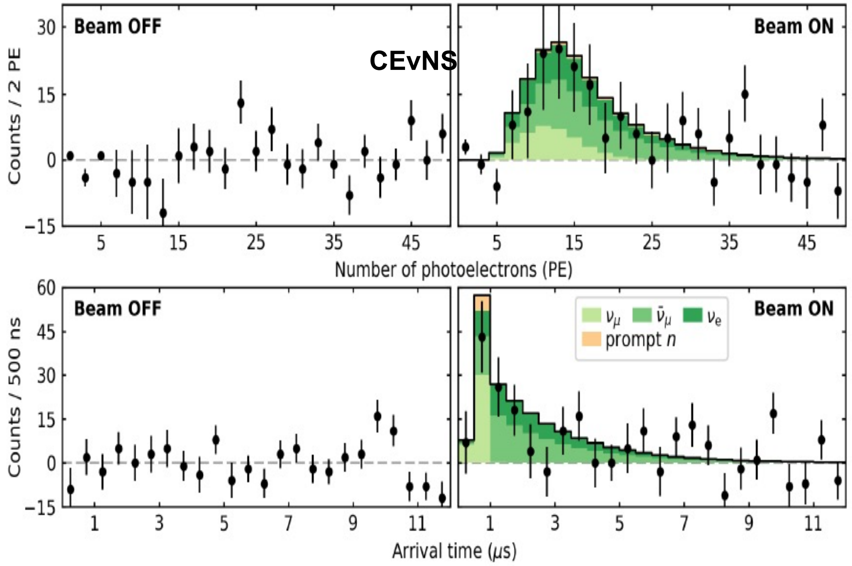
Veto system

Water shielding

First Detection of CEvNS with CsI detector







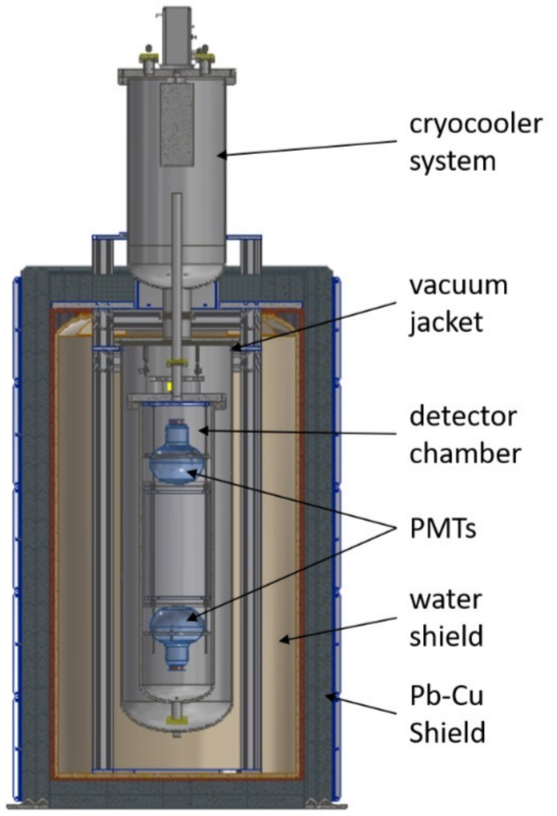
First working, handheld neutrino detector -14kg!!!

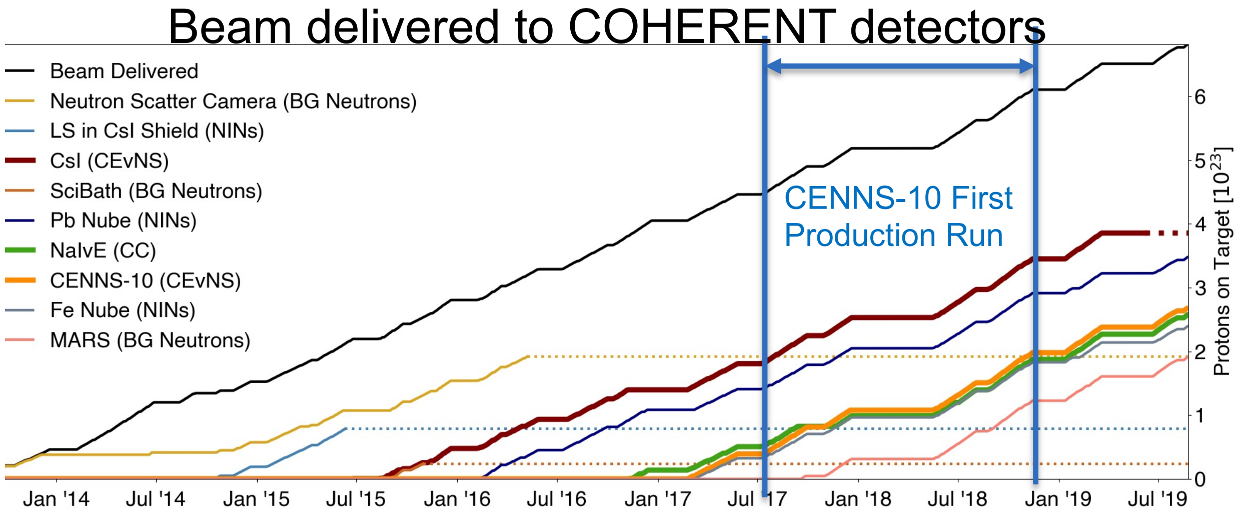
Presently we have x2.5 times more statistics, and better understanding of quenching

Will publish updated result very soon

Argon Target

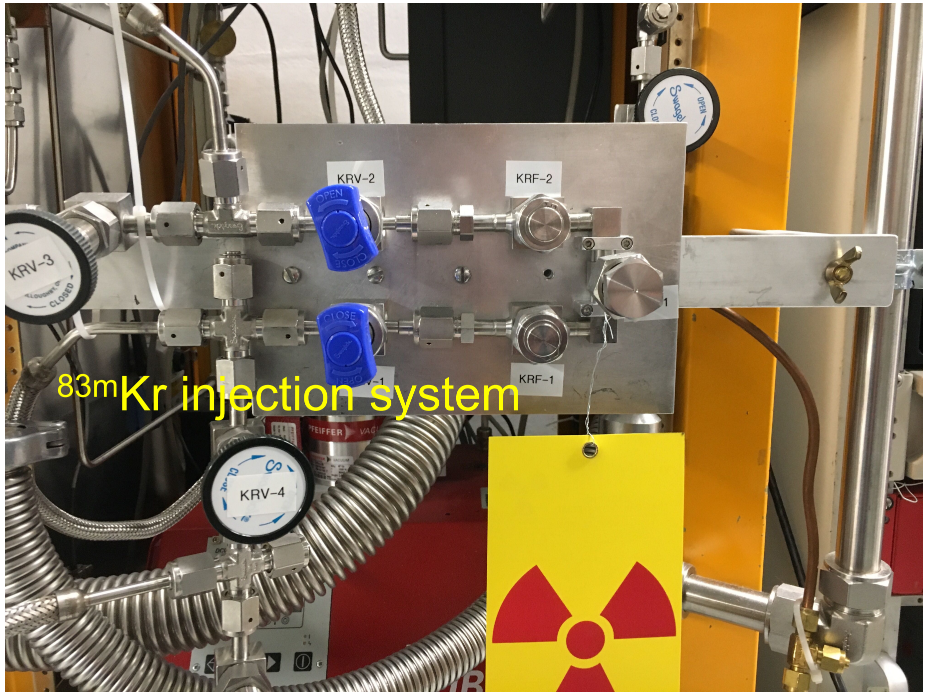
- Originally built in 2012-2014 by J. Yoo et al. at Fermilab for CEvNS effort at Fermilab
- Moved to the SNS for use in COHERENT late 2016 after upgrades at IU. Rebuild in 2017 at ORNL with new PMTs and TPB coating sputtered in vacuum. L.Y. increased by a factor of 10.
- 10 cm Pb/ 1.25 cm Cu/ 20 cm H_2O shielding
- 24 kg fiducial volume
- 2x 8” Hamamatsu PMTs, 18% QE at 400 nm
- Tetraphenyl butadiene (TPB) coated side reflectors/PMTs
- Production Run starting July 2017.



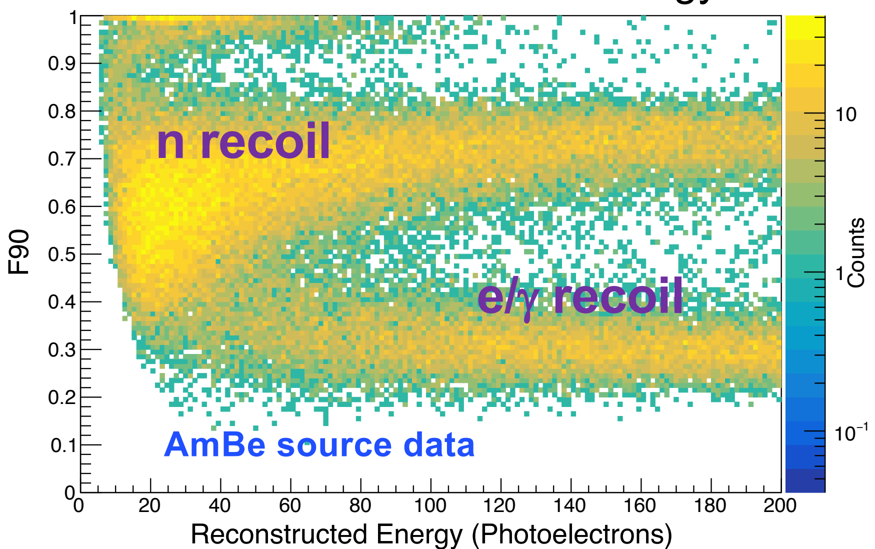


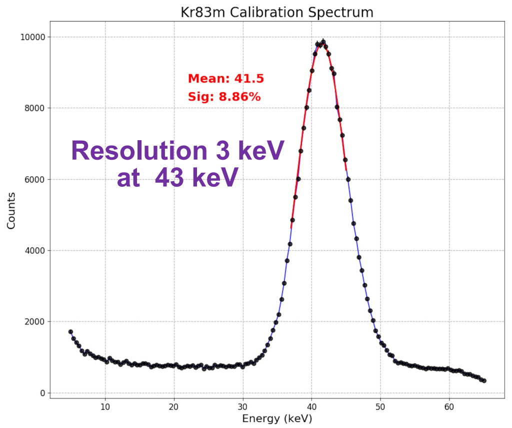
CENNS-10 Calibration

- Calibrate detector with variety of gamma sources
  - Measured light yield: 4.6 ± 0.4 photoelectrons/keVee
  - At ^{83m}Kr energy (41.5 keVee), mean reconstructed energy measured to 2%
    - 9.5% energy resolution at 41.5 keVee
- Calibrate detector nuclear recoil response using AmBe source

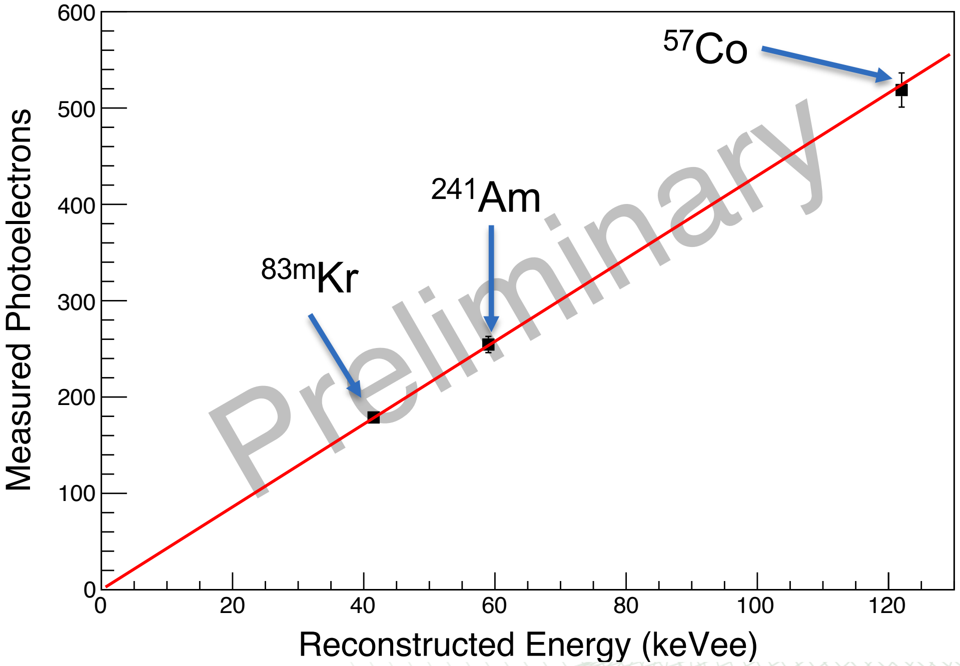


PSD vs reconstructed energy





Reconstructed Energy (keVee)

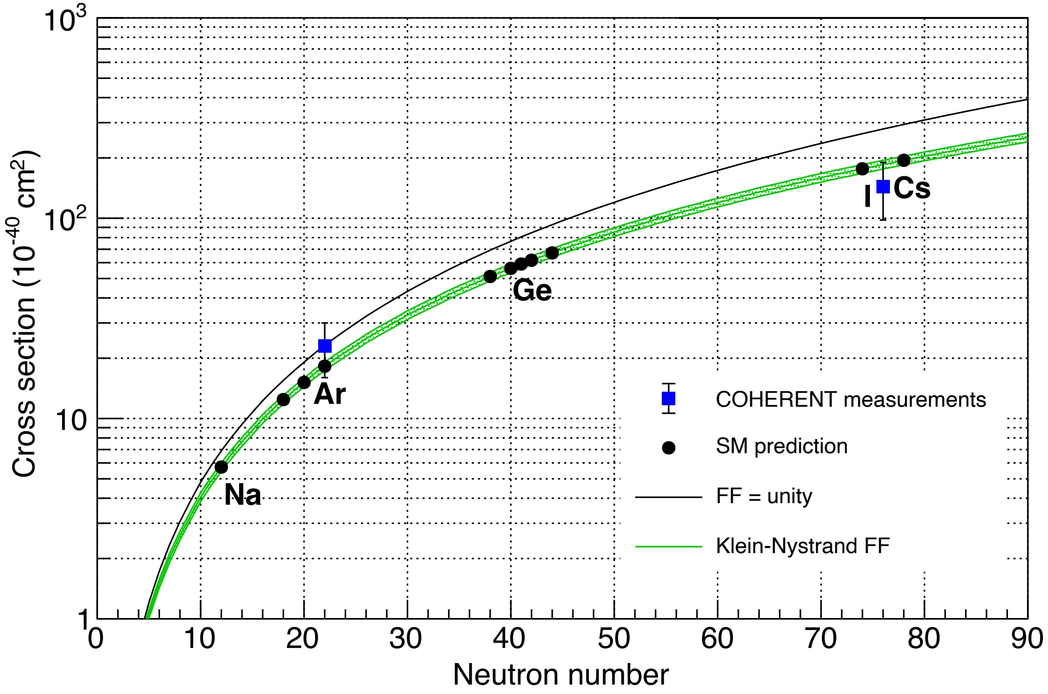


Likelihood Fit Results

Predicted SM CEvNS	128 ± 17
Predicted Beam Related Neutrons	497 ± 160
Predicted Beam Unrelated Background	3154 ± 25
Predicted Late Beam Related Neutrons	33 ± 33

Data Events	3752
Fit CEvNS	159 ± 43 (stat.) ± 14 (syst.)
Fit Beam Related Neutrons	553 ± 34
Fit Beam Unrelated Background	3131 ± 23
Fit Late Beam Related Neutrons	10 ± 11
2Δ(-lnL)	15.0
Null Rejection Significance	3.5σ (stat. + syst.)

- 3D binned likelihood analysis in energy, F90, time space
  - Include both prompt and delayed time regions
- Best fit CEvNS counts of 159 ± 43 (stat.) ± 14 (syst.)
  - Result (stat. only) rejects null hypothesis at 3.9σ
  - Result (stat. + syst.) rejects null hypothesis at 3.5σ
  - Best fit result within 1σ of SM prediction
  - Wilks' Theorem checked with fake data



Presently we accumulated 3 times more statistics.
New results are coming soon

What Did We Learn After the First Results from COHERENT?

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 "optimized" to study CEvNS

Now know how to detect CEvNS

So far, we have only three binary answers "*Yes, Yes, and Yes*"

Next step is precision study of CEvNS to search for unknowns !!!

For two first our results major systematical uncertainty is the knowledge of Neutrino Flux at the SNS ~10%

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Concept of Heavy Water Detector

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

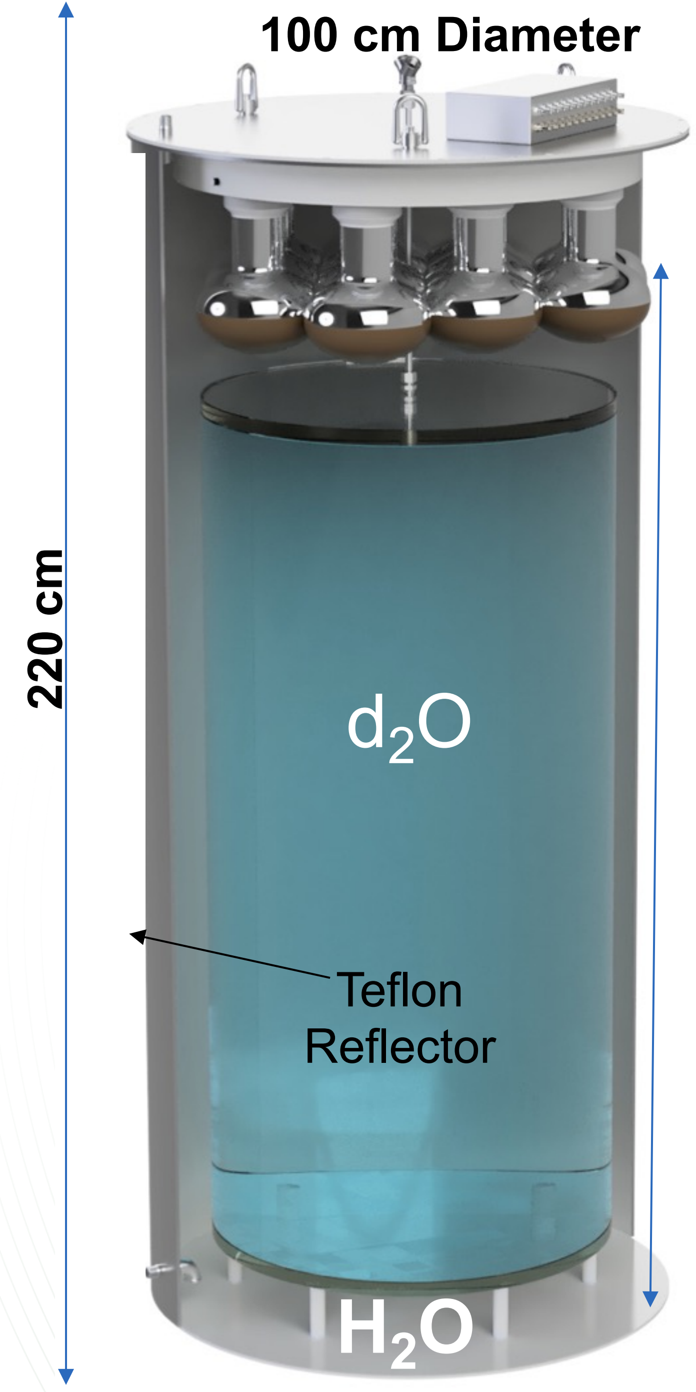
Detector calibration with Michel Electrons from cosmic muons (same energy range)

- Neutrino Alley space constraints for the D2O detector:
  - 1 m depth x 2.3 m height x 3 m width
- Locations 20-29 meters from target

Will do CC measurement on Oxygen for SN support

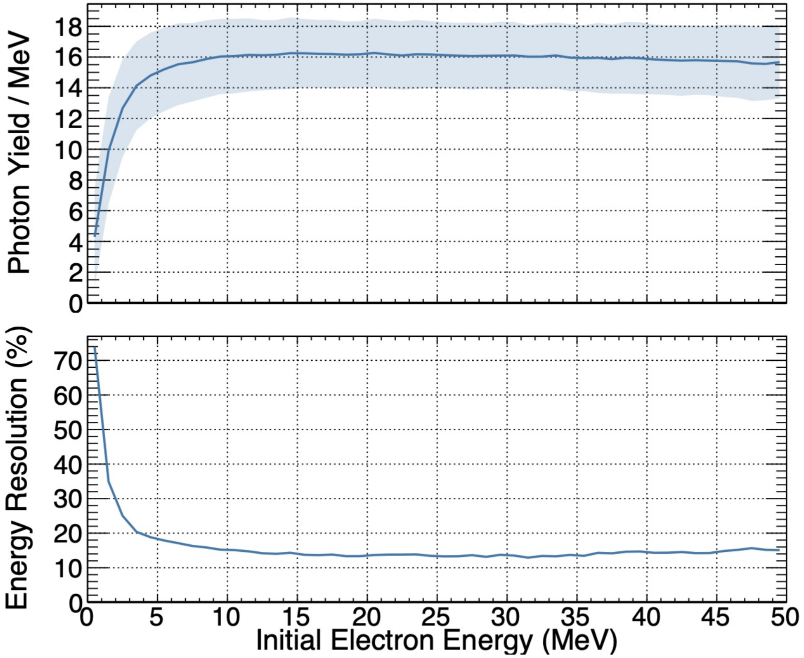
Specifications

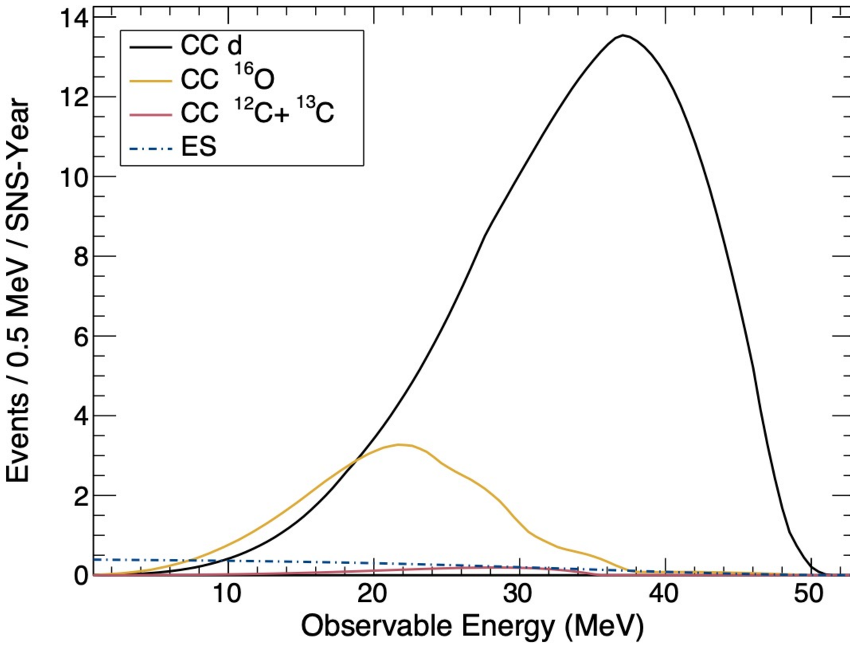
- 0.8 tons D_2O within acrylic inner vessel
- Water Cherenkov Calorimetry
- H_2O “tail catcher” for high energy e$^-$
- Outer light water vessel contains PMTs, PMT support structure, and optical reflector.
- Outer steel vessel to
- Lead Shielding
- Hermetic veto system

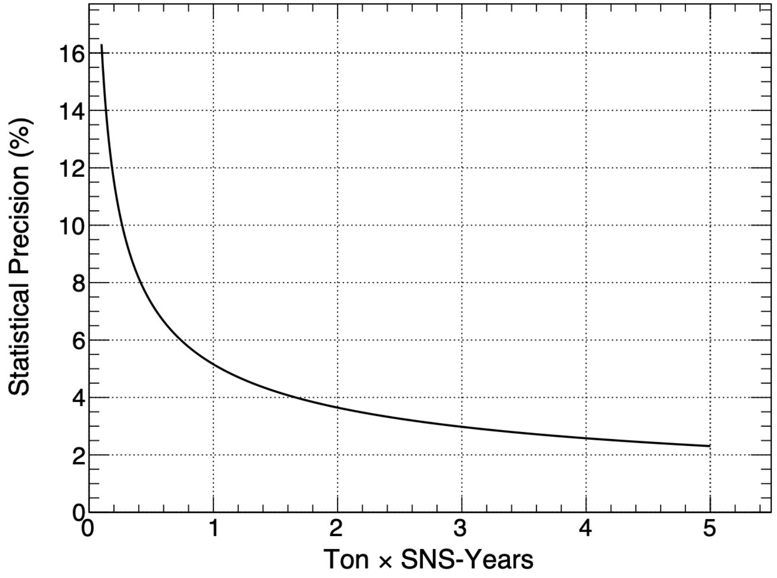


Predictions for d_2O detector response

See JINST 16 (2021) 08, P08048





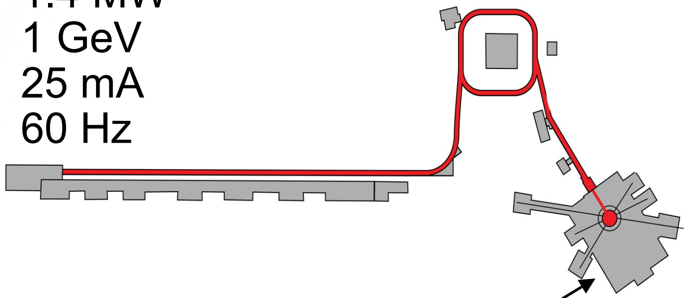


SNS Future

Today

- 900 users
- Materials at atomic resolution and fast dynamics

1.4 MW
1 GeV
25 mA
60 Hz

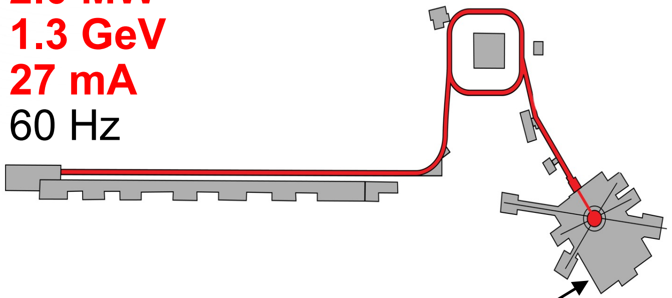


FTS
1.4 MW
60 Hz

2024 after PPU

- **1000+** users
- Enhanced capabilities

2.0 MW
1.3 GeV
27 mA
60 Hz



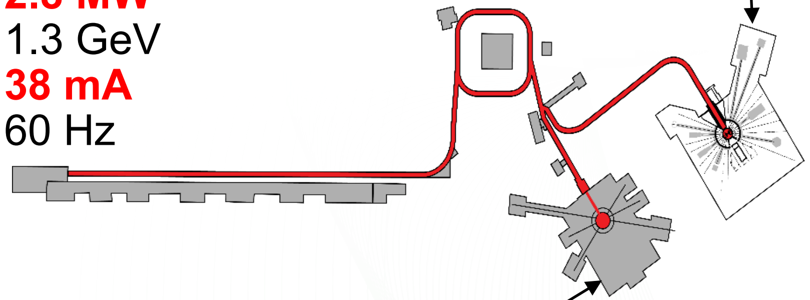
FTS
2 MW
60 Hz

2028 after STS

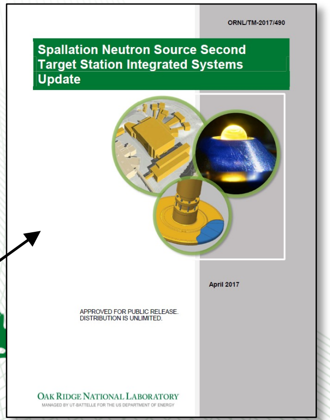
- **2000+** users
- Hierarchical materials, time-resolution and small samples

STS
0.7 MW
15 Hz

2.8 MW
1.3 GeV
38 mA
60 Hz



FTS
2 MW
45 pulses/sec


ORNL/TM-2017/490

Spallation Neutron Source Second Target Station Integrated Systems Update

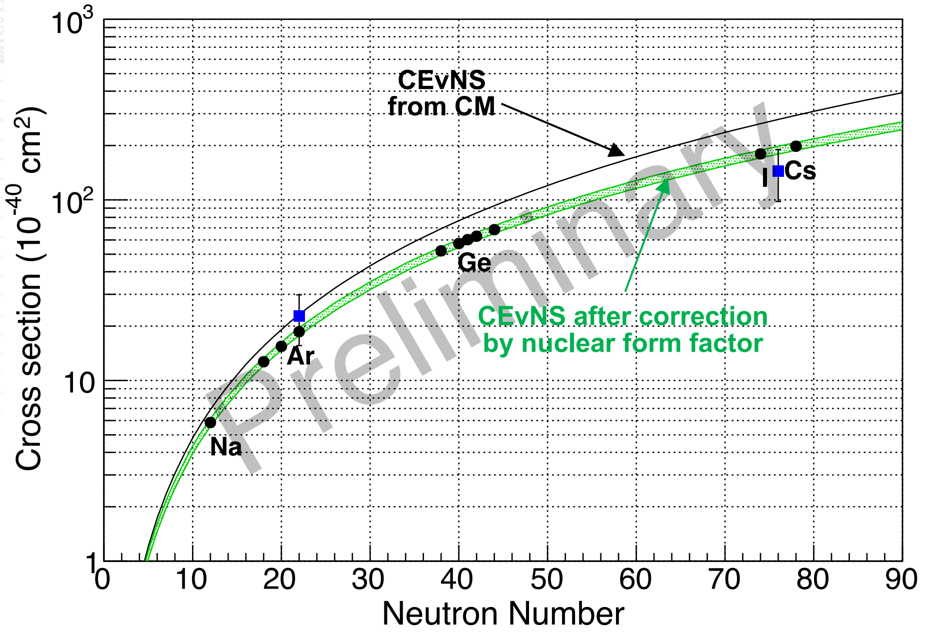
April 2017

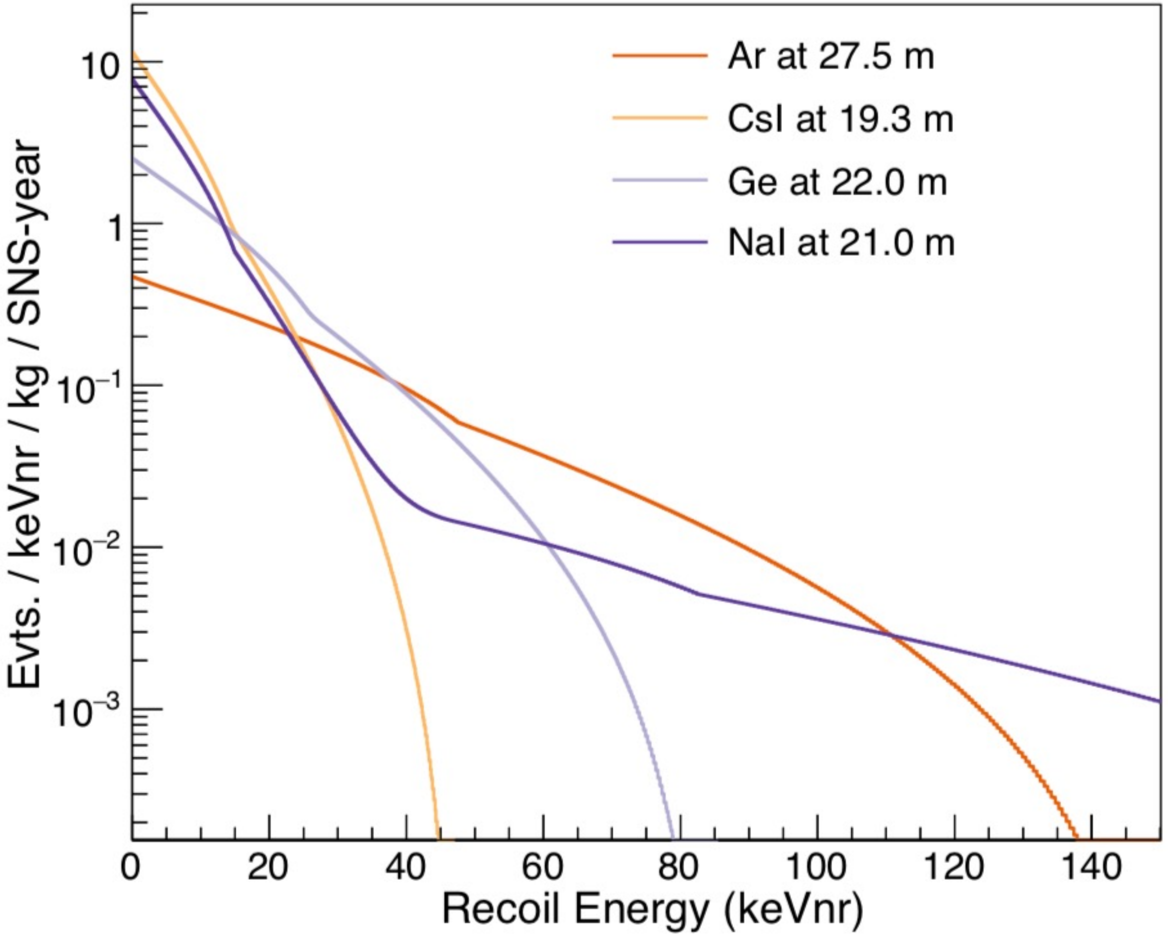
APPROVED FOR PUBLIC RELEASE. DISTRIBUTION IS UNLIMITED.

Oak Ridge National Laboratory

The choice of 15 Hz and 0.7 MW resulted from a detailed analysis of STS design (reviewed by a panel of experts in 2017) and optimizes performance of STS without impacting performance of FTS

Long Term Program with Various Targets.

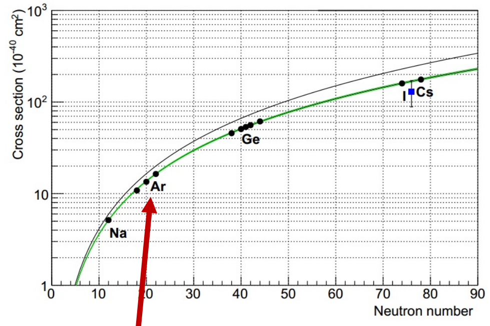




To untangle effects of nuclear form factors we need measurements at a wide range of target masses: Light, Middle, and Heavy

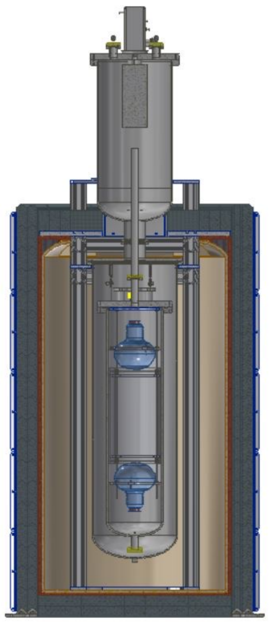
To have handle on axial current it is interesting to have close targets with different spins. Example ^{40}Ar s=0 and ^{23}Na s=3/2

Future Activities - 1 ton LAr detector



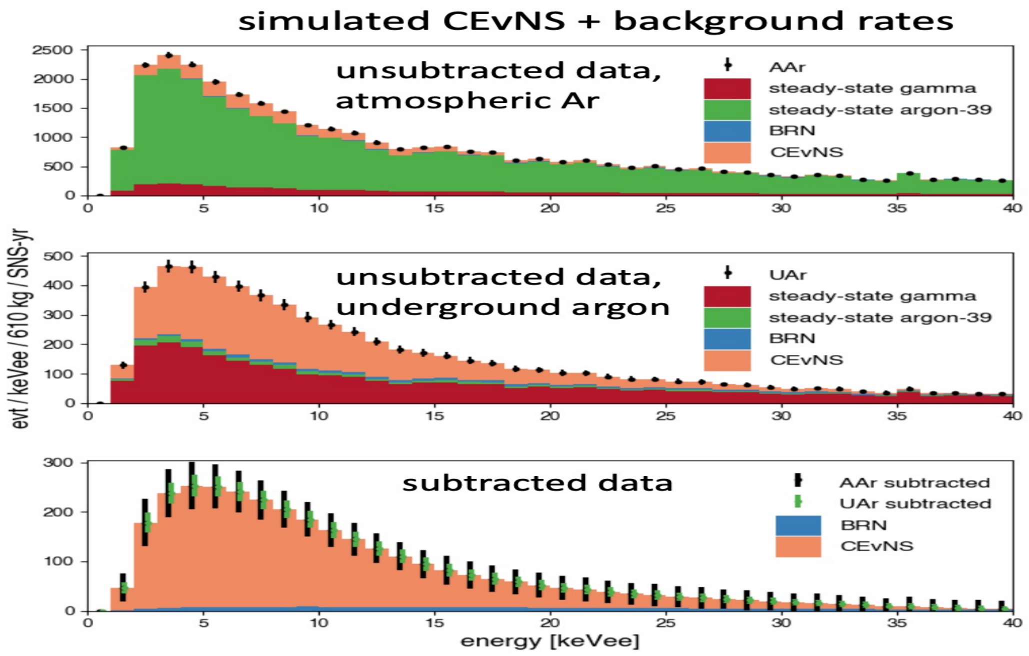
Need high statistics low background measurements of CEvNS

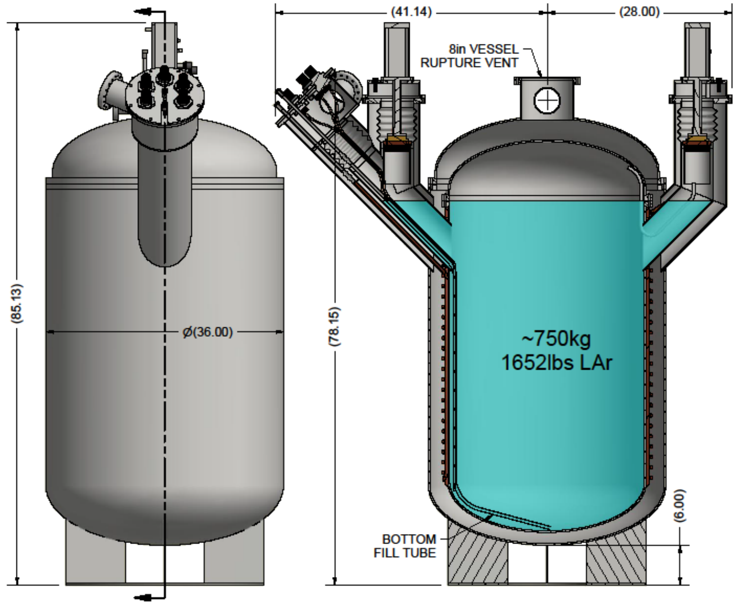
Transition from 22 kg to 1 ton LAr detector.



Can fit at the same place where presently is CENSS-10

Will see 3kt of CEvNS events per year + CC



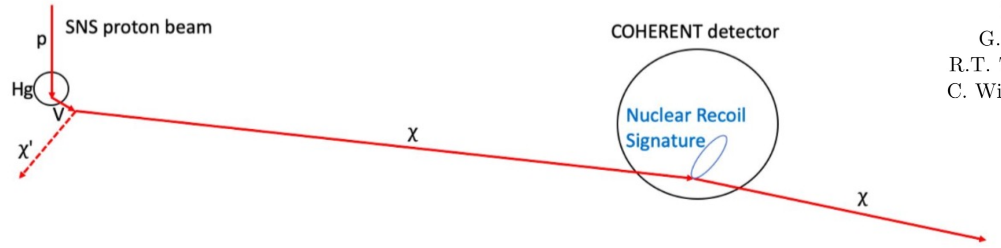


Interesting opportunity → Search for accelerator produced dark matter with LAr detector

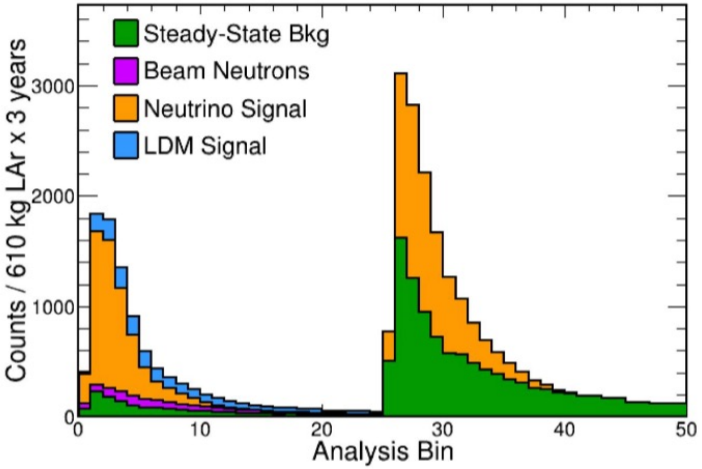
Sensitivity of the COHERENT Experiment to Accelerator-Produced Dark Matter

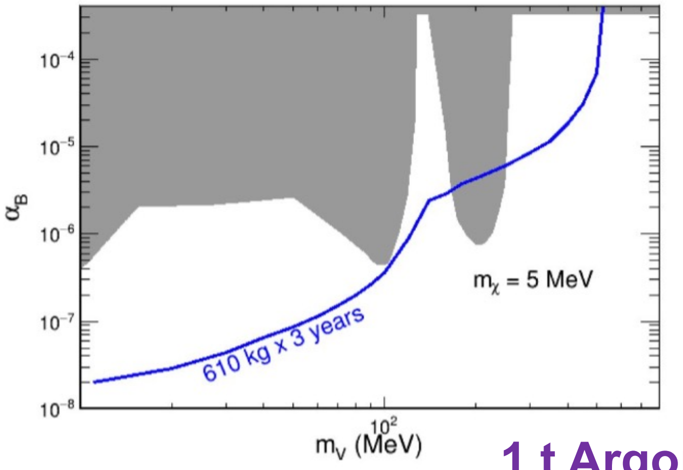
D. Akimov,[1,2] P. An,[3,4] C. Awe,[3,4] P.S. Barbeau,[3,4] B. Becker,[5] V. Belov,[1,2] M.A. Blackston,[6] A. Bolozdynya,[2] B. Cabrera-Palmer,[7] N. Chen,[8] E. Conley,[3] R.L. Cooper,[9,10] J. Daughhetee,[5] M. del Valle Coello,[11] J.A. Detwiler,[8] M.R. Durand,[8] Y. Efremenko,[5,6] S.R. Elliott,[10] L. Fabris,[6] M. Febbraro,[6] W. Fox,[11] A. Galindo-Uribarri,[5,6] M.P. Green,[4,6,12] K.S. Hansen,[8] M.R. Heath,[6,11] S. Hedges,[3,4] T. Johnson,[3,4] M. Kaemingk,[9] L.J. Kaufman,[11,*] A. Khromov,[2] A. Konovalov,[1,2] E. Kozlova,[1,2] A. Kumpan,[2] L. Li,[3,4] J.T. Librande,[8] J.M. Link,[13] J. Liu,[14] K. Mann,[4,6] D.M. Markoff,[4,15] H. Moreno,[9] P.E. Mueller,[6] J. Newby,[6] D.S. Parno,[16] S. Penttila,[6] D. Pershey,[3] D. Radford,[6] R. Rapp,[16] H. Ray,[17] J. Raybern,[3] O. Razuvaeva,[1,2] D. Reyna,[7] G.C. Rich,[18] D. Rudik,[1,2] J. Runge,[3,4] D.J. Salvat,[11] K. Scholberg,[3] A. Shakirov,[2] G. Simakov,[1,2] G. Sinev,[3] W.M. Snow,[11] V. Sosnovtsev,[2] B. Suh,[11] R. Tayloe,[11] K. Tellez-Giron-Flores,[13] R.T. Thornton,[11,10] I. Tolstukhin,[11,†] J. Vanderwerp,[11] R.L. Varner,[6] C.J. Virtue,[19] G. Visser,[11] C. Wiseman,[8] T. Wongjirad,[20] J. Yang,[20] Y.-R. Yen,[16] J. Yoo,[21] C.-H. Yu,[6] and J. Zettlemoyer[11]

$$\mathcal{L} = \mathcal{L}_\chi - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu - \frac{\epsilon}{2}V^{\mu\nu}F_{\mu\nu} + q_B g' V_\mu J_B^\mu + \cdots$$

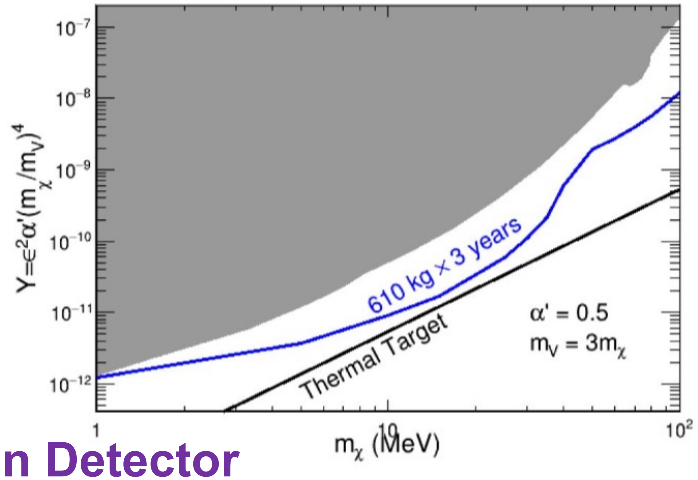


arXiv:1911.06422 [hep-ex]





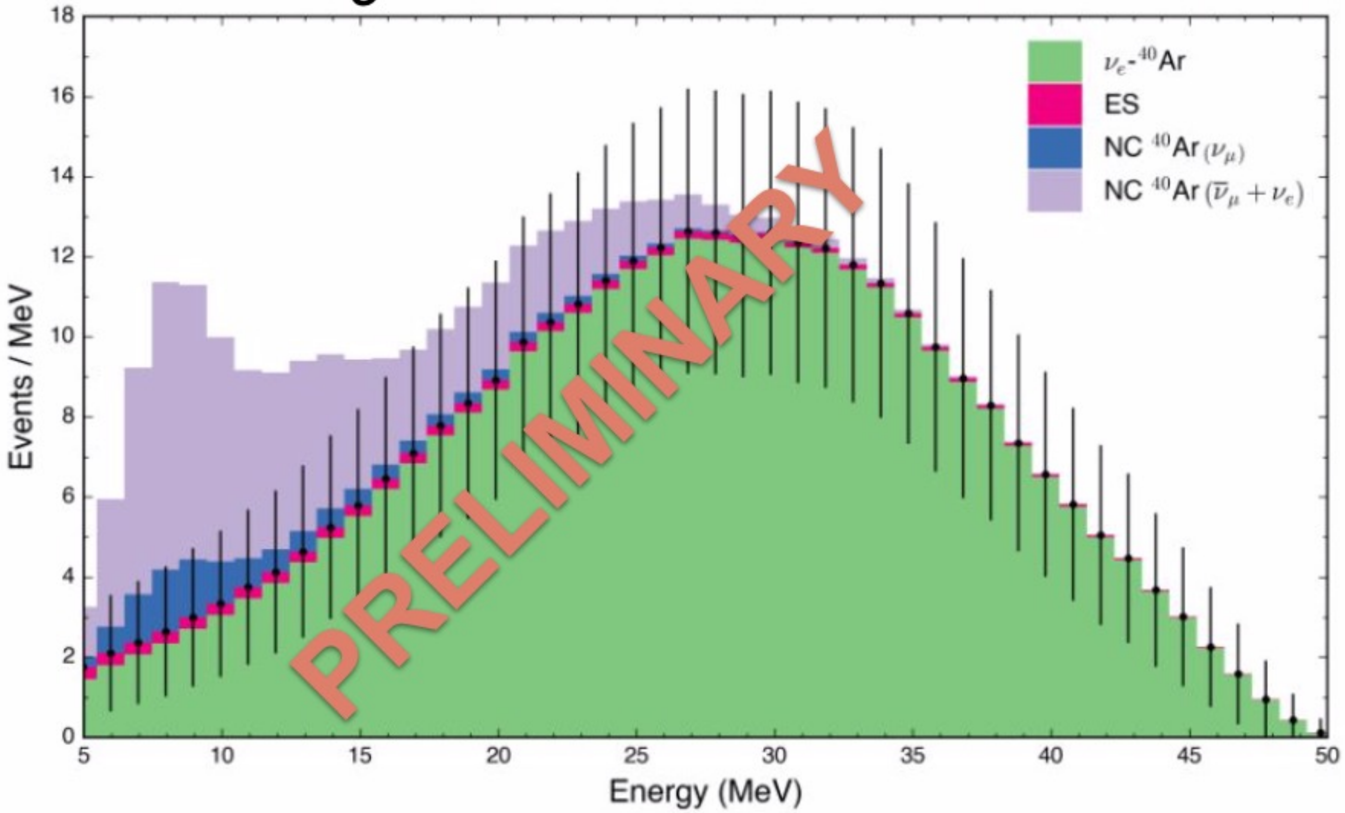
1 t Argon Detector



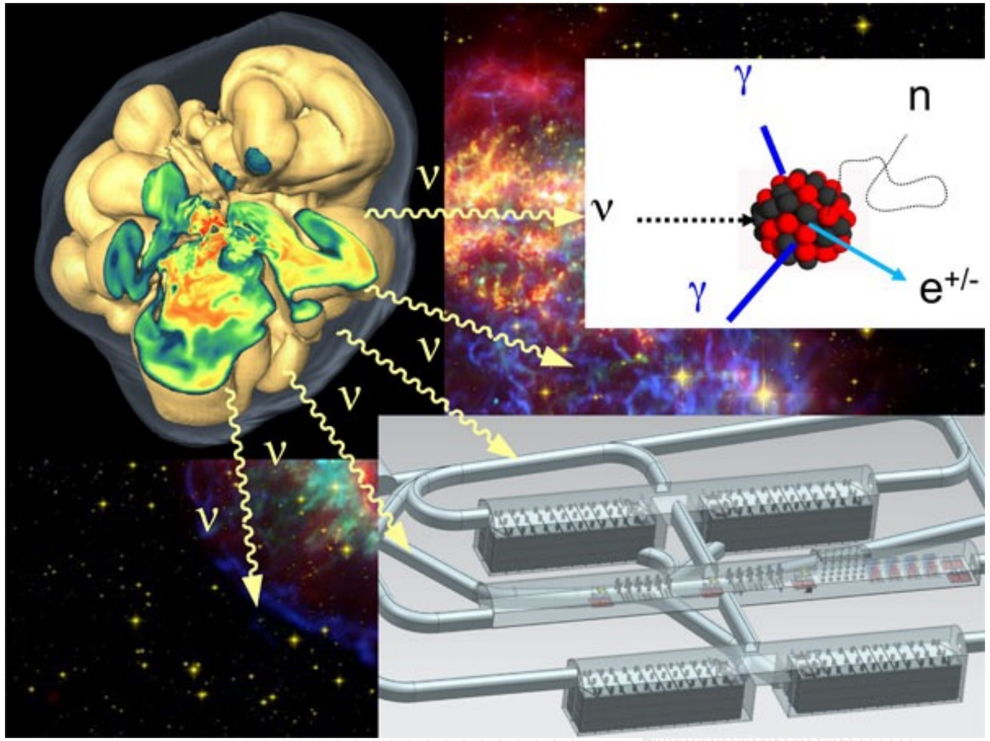
- Coherent cross section enhancement
- DM and CEvNS recoil spectra are different -- *delayed CEvNS provide constraint for prompt DM*
- Competitive constraints for ~10-30 MeV vector portal in neutrino alley
- Strong limits on baryonic portal

Same One Ton LAr Detector Can Measure Neutrino CC on Argon

$$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$$



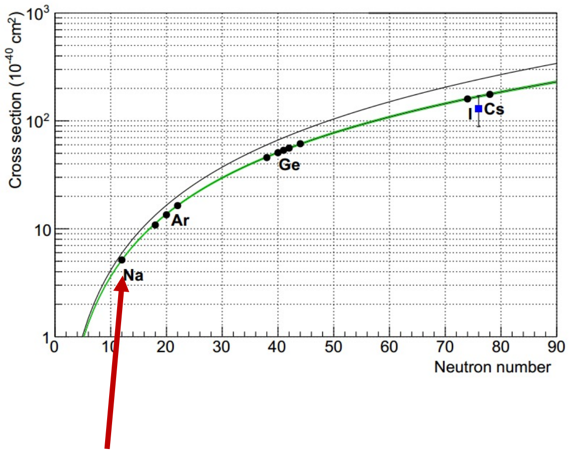
This is the channel to detect Supernovae Neutrino signal at DUNE



This is reaction which is never been measured !!!

Oak Ridge National Laboratory

Large NaI Detectors Array Deployment later this year

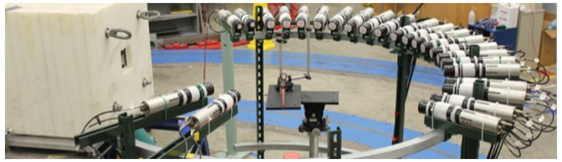


Transition from now deployed 185 kg to 2 ton array of NaI detectors

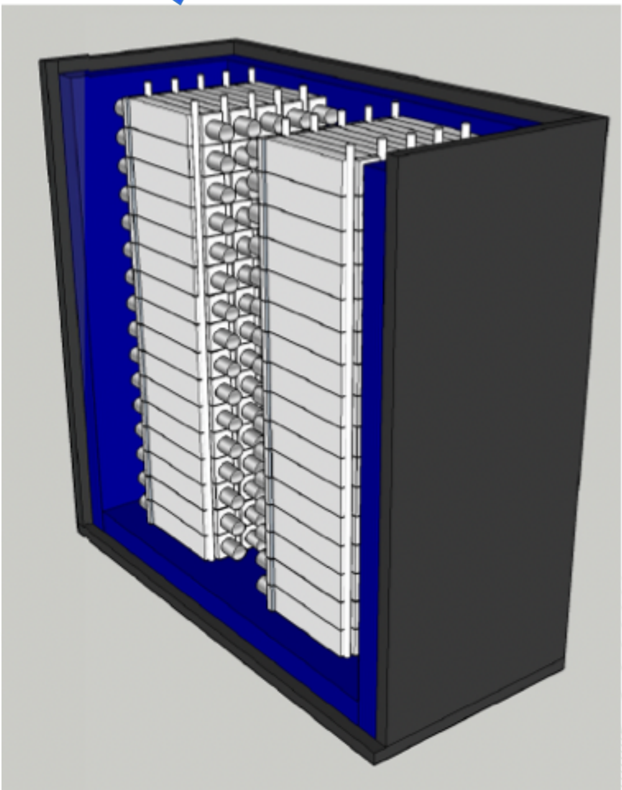
Detectors are available

Need dual gain bases to look for CEvNs and CC

Program to measure Quenching Factors at TUNL

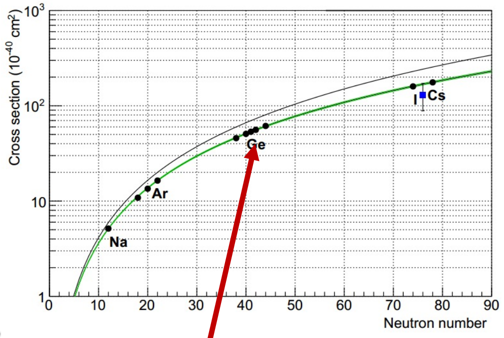


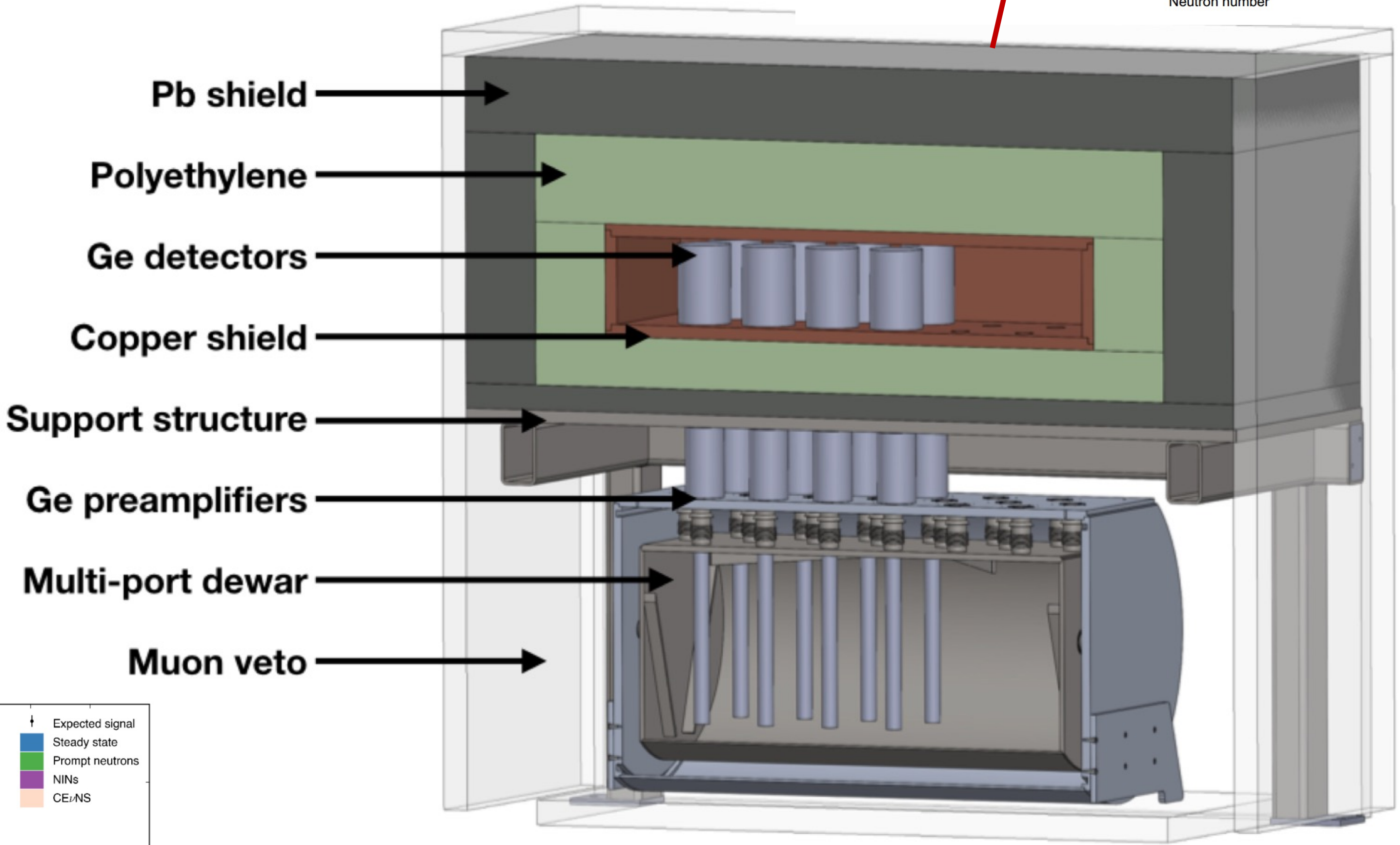
Potential to detect both CEvNS and CC reactions on Iodine

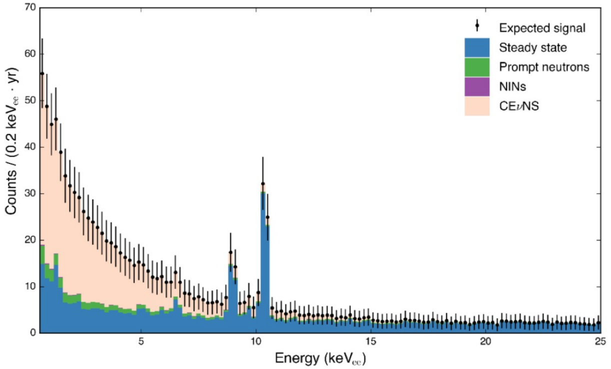


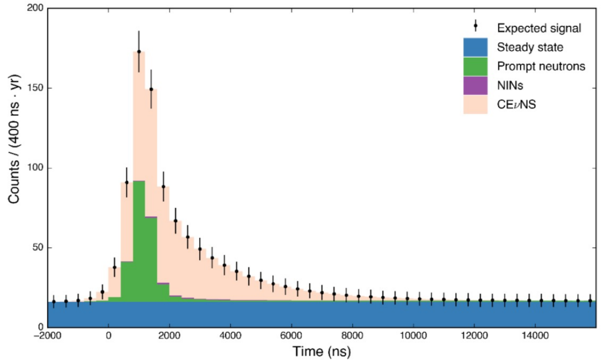
Germanium PPC array
Deployment later this year

- Estimate 500 - 600 CEvNS events/year in a 16 kg array.
- Electronic noise from detector + preamp limited to < 150 eV FWHM.
  - Results in an energy threshold of ~0.4 keVee, roughly 2-2.5 keVnr.
- Cryostat already available.









Summary

Detection of CEvNS on CsI and Ar targets opened new portal to look for physics beyond the SM

Neutrino Alley at the SNS is unique laboratory to study properties of CEvNS

COHERENT Collaboration is planning to build and deploy in a near future new sets of experiments:

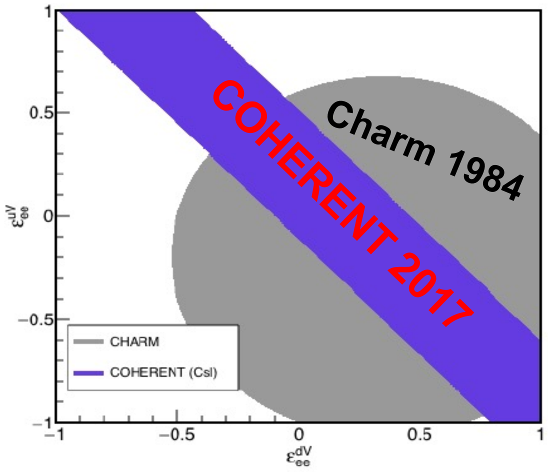
: 1t LAr(Xe), 1t D_2O, 3t NaI, and 16 kg Ge, Xe target?

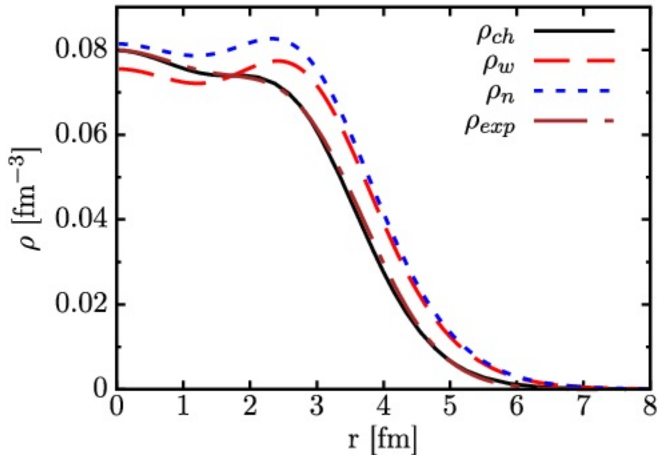
Particle Physics
NINs,Test of the SM, DM

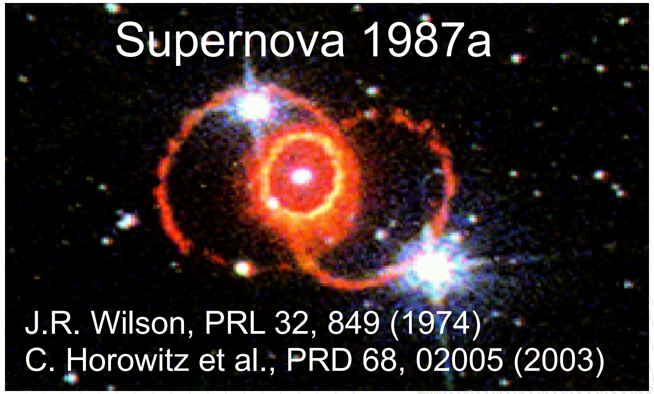
Nuclear Physics
Form Factors, Axial Currents, Incoherent processes

Astrophysics
Supernovae Cross Sections

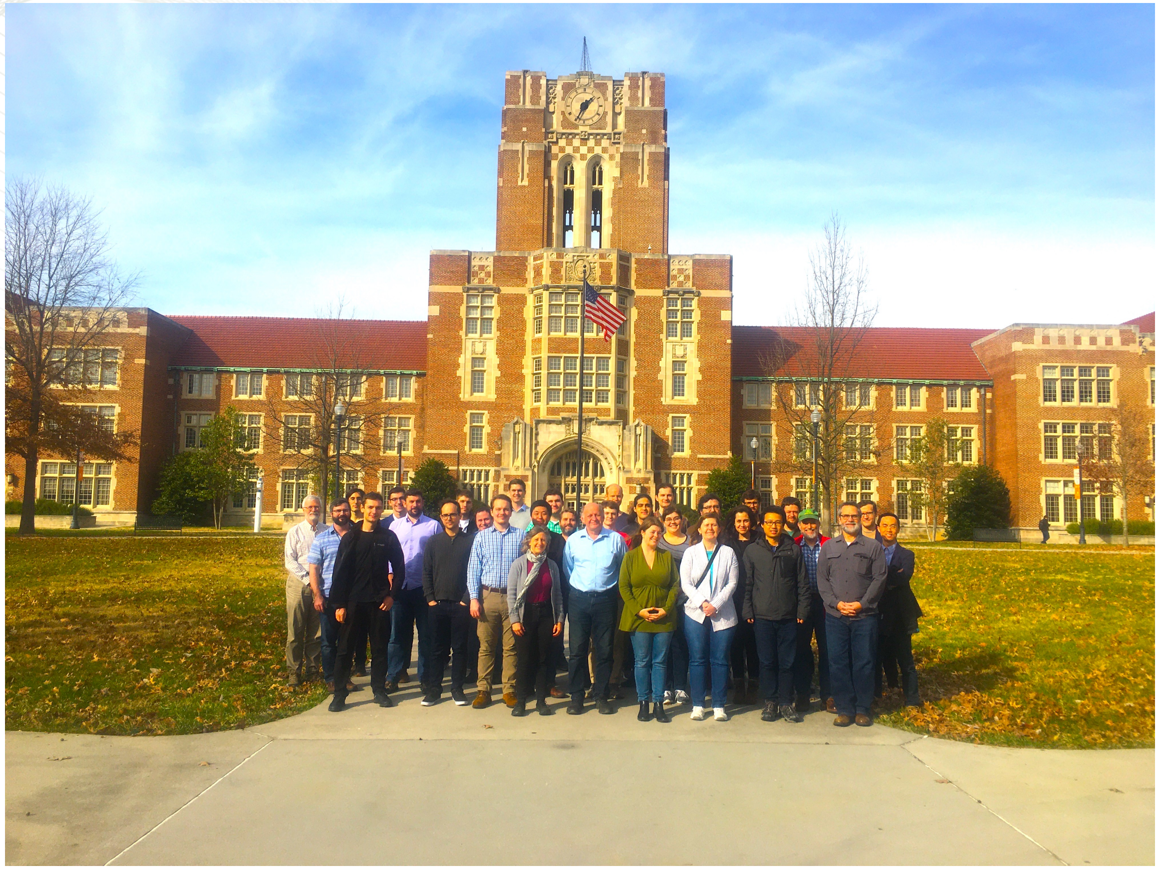
See motivational opening talk by Karlheinz Langanke







COHERENT Collaboration



21 Institutions (USA, Russia, Canada, Korea)