What we can learn from CEvNS?

(Coherent Elastic neutrino Nucleus Scattering)

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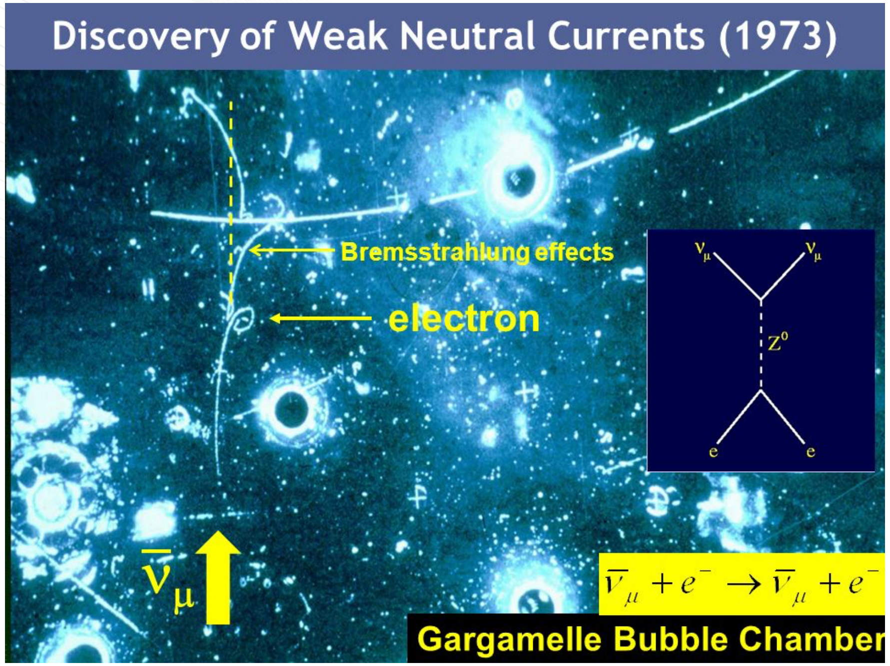
UTK/ORNL

5th International Conference on Particle Physics and Astrophysics
Moscow, Russia
October 8th 2020

Coherent Elastic neutrino Nucleus Scattering (CEvNS)

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



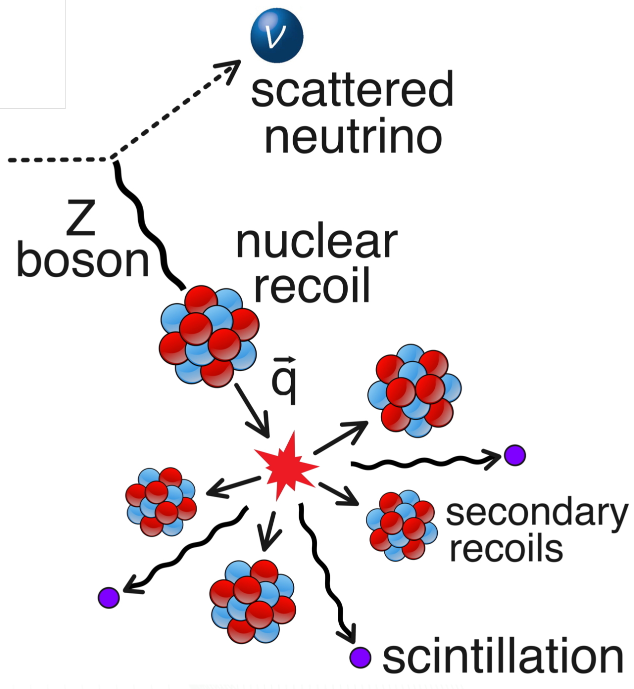
D.Z. Freedman PRD 9 (1974)

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 !!!

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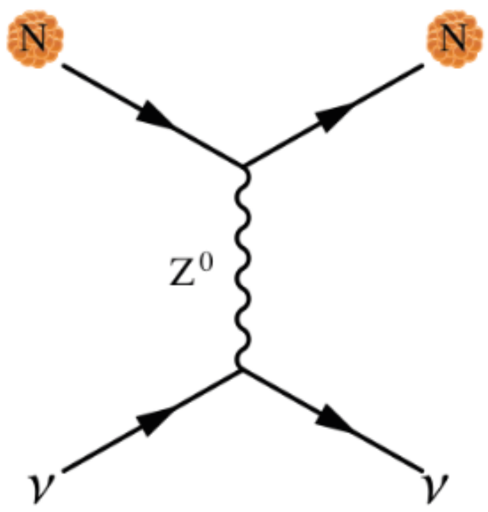
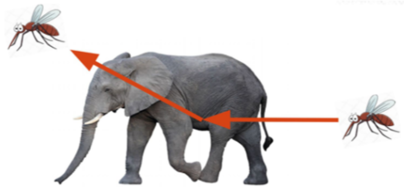
Coherent Elastic neutrino-Nucleus Scattering (CEvNS)

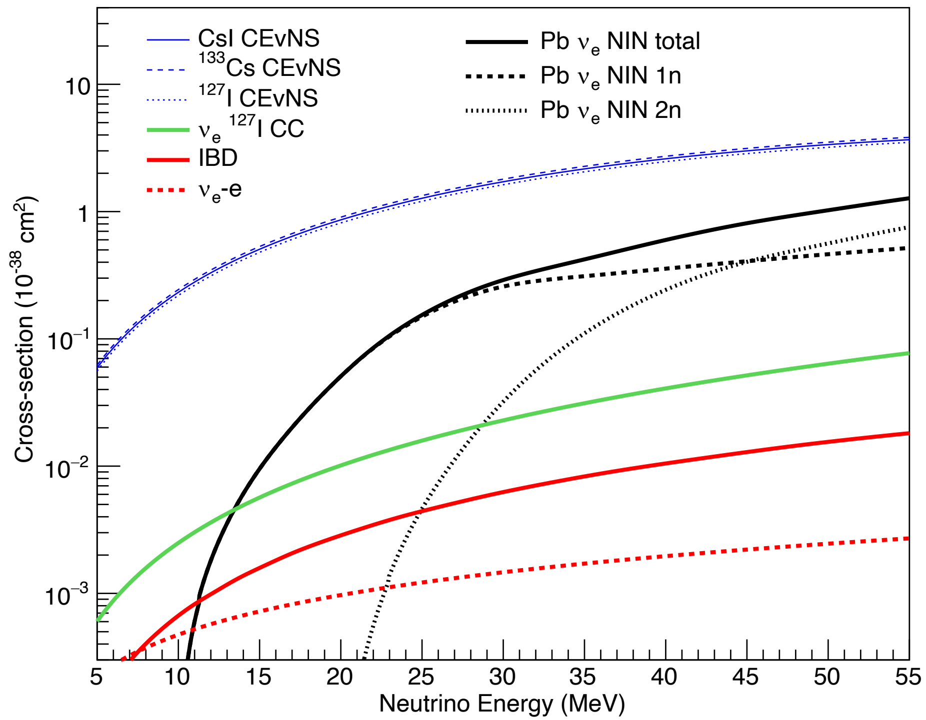




CEvNS cross-section is larger than any other neutrino interaction cross-sections at low energy, but it is hard to detect

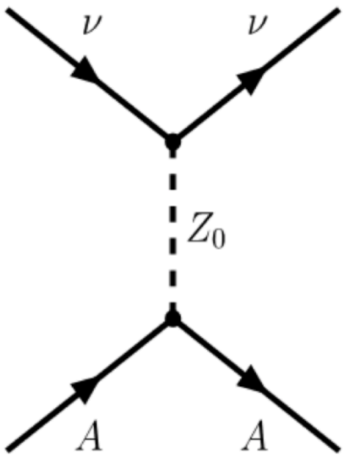
D.Z. Freedman PRD 9 (1974)

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.



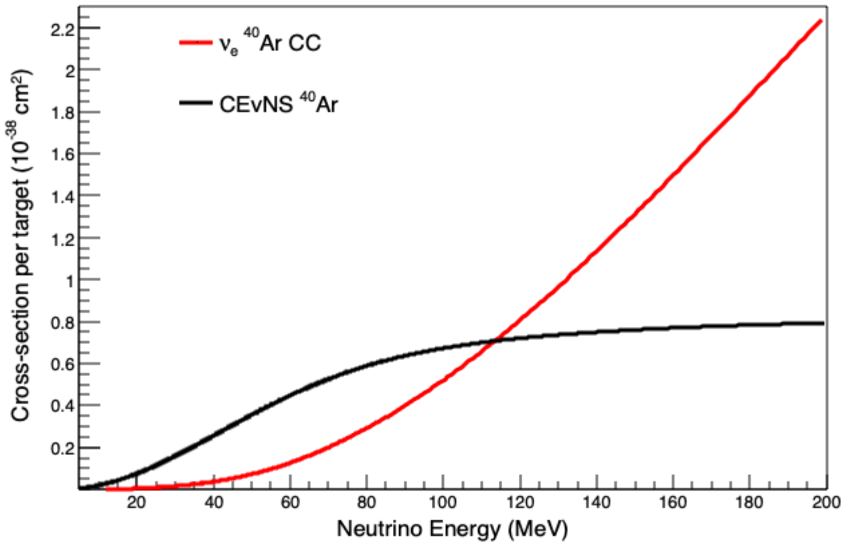
Nuclear Form Factor at CEvNS

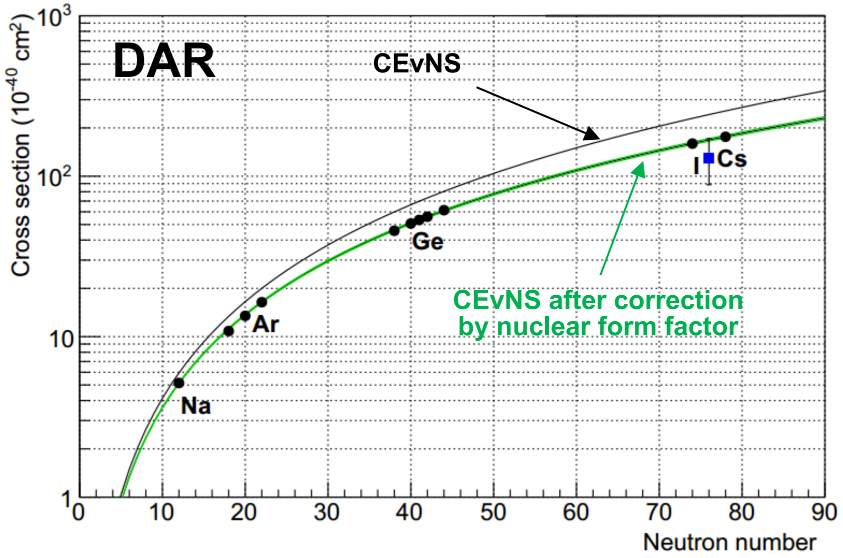
$$\frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2} k^2 (1 + \cos\theta) \frac{(N - (1 - 4\sin^2\theta_W)Z)^2}{4} F^2(Q^2)$$

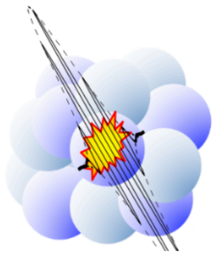


For energy above 50 MeV

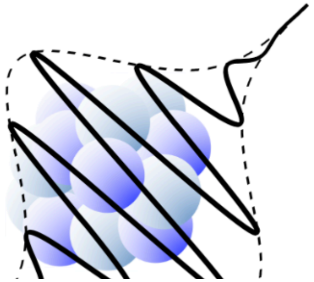
form factor starts to suppress cross section







High Q = short de Broglie wavelength



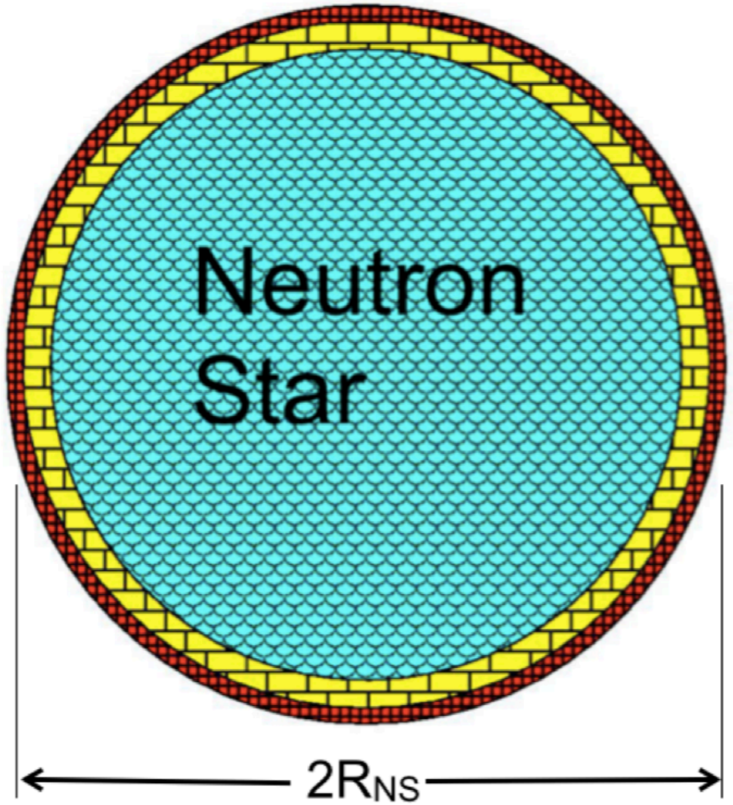
Low Q = long de Broglie wavelength

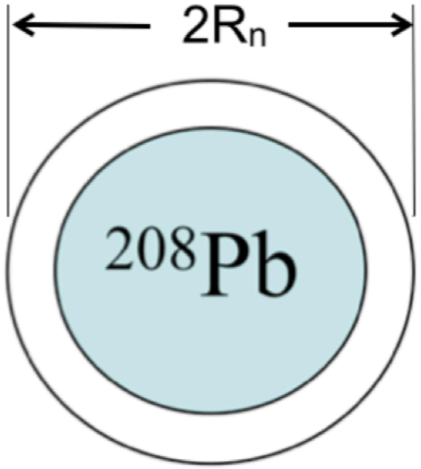
CEvNS belong to both Particle and Nuclear Physic

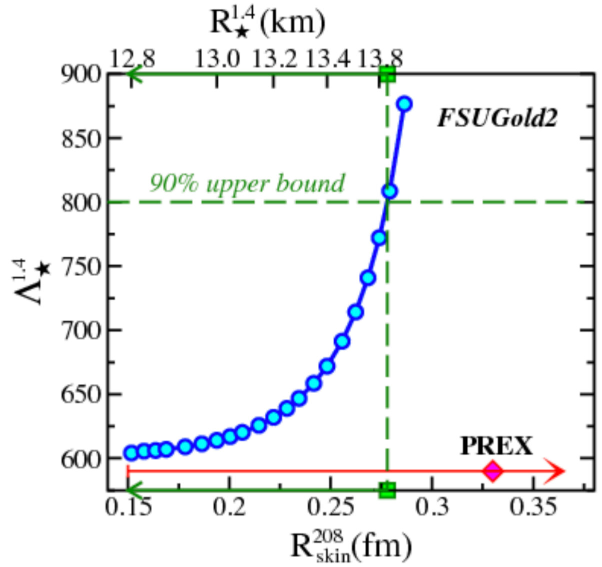
CEvNS will let to Measure Neutron Skin for Heavy Elements → input into neutron matter density

- 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



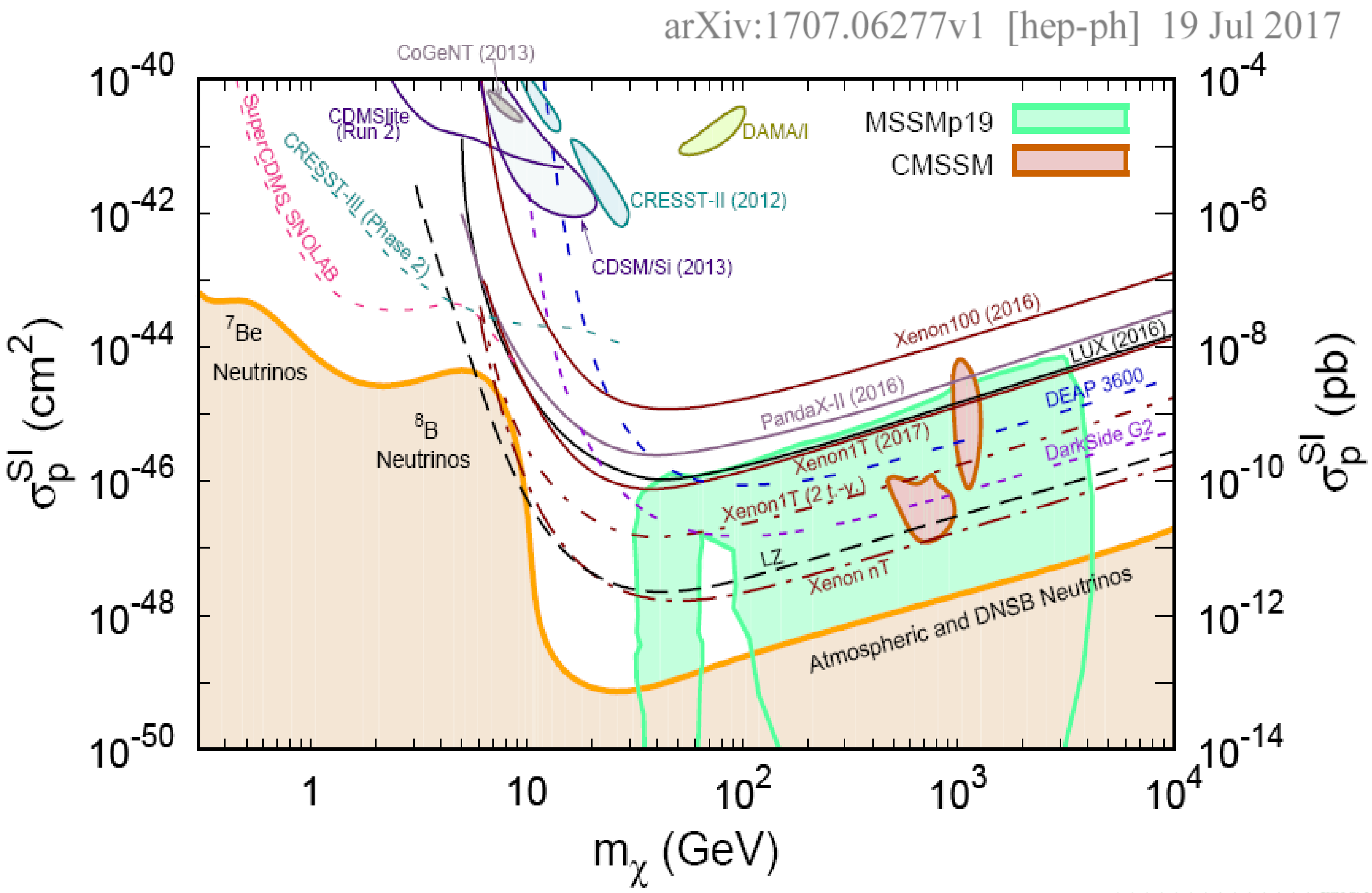




Fattoyev, F.J. *et al.* Phys.Rev.Lett. 120 (2018)

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

CEvNS is Neutrino Floor for DM Experiments



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

new interaction specific to ν's

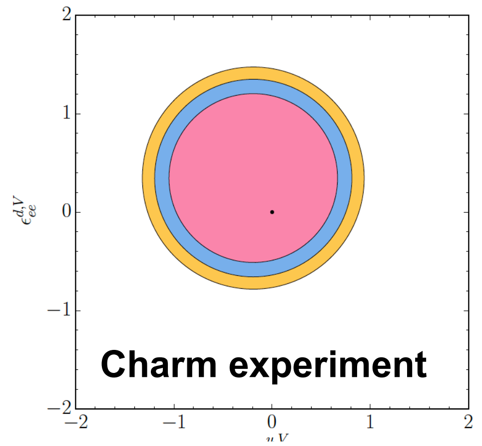
$$\mathcal{L}_{\nu H}^{NSI} = -\frac{G_F}{\sqrt{2}} \sum_{\substack{q=u,d \\ \alpha,\beta=e,\mu,\tau}} [\bar{\nu}_\alpha \gamma^\mu (1-\gamma^5)\nu_\beta] \times (\varepsilon_{\alpha\beta}^{qL}[\bar{q}\gamma_\mu(1-\gamma^5)q] + \varepsilon_{\alpha\beta}^{qR}[\bar{q}\gamma_\mu(1+\gamma^5)q])$$

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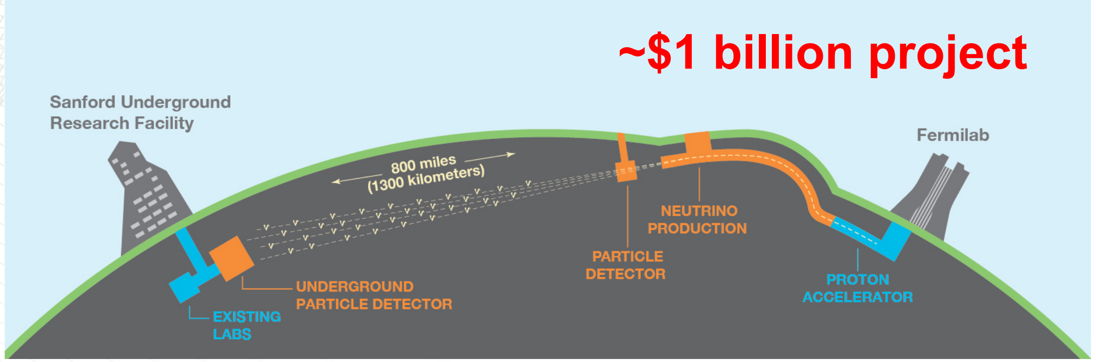
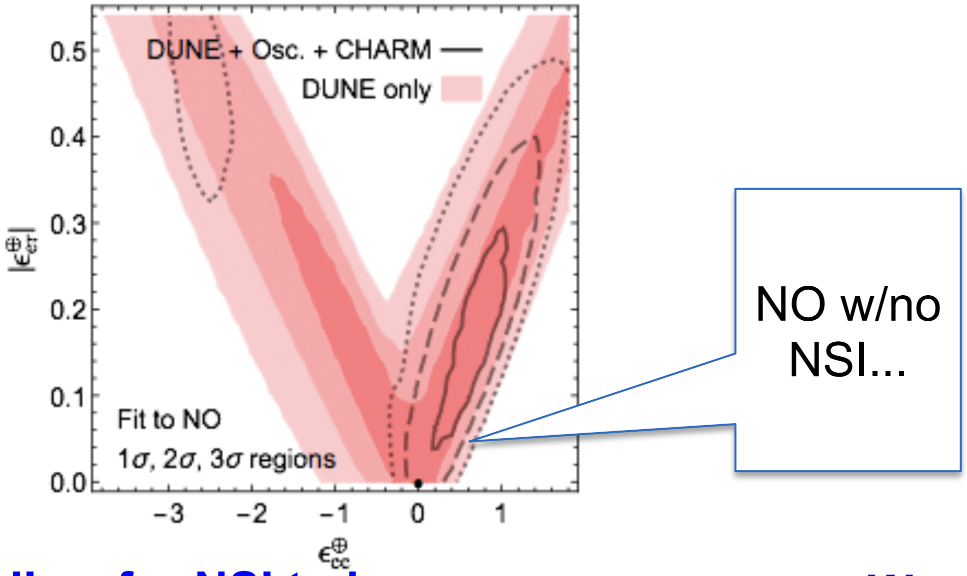
CEvNS are Important as a Probe for NSI.
NSI can create degeneracy for DUNE

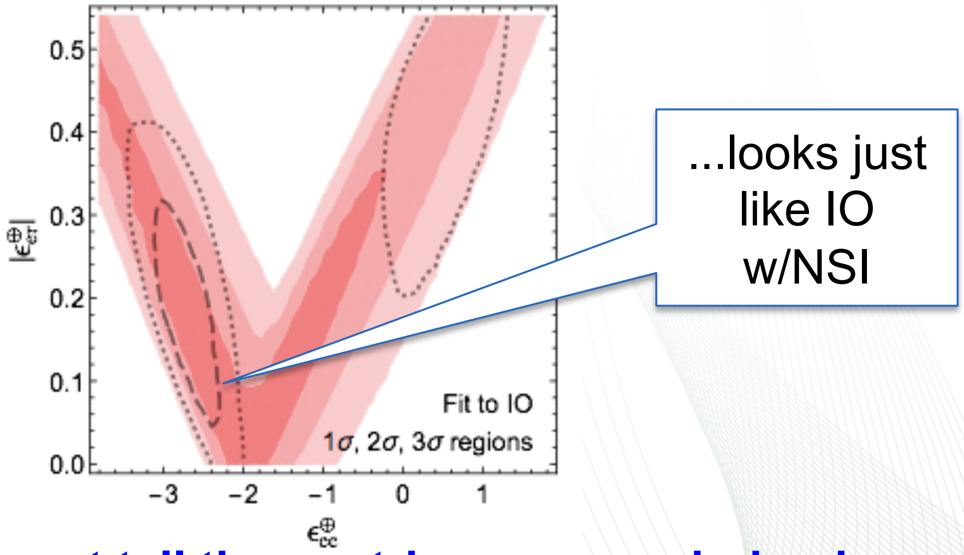


- **measuring the charge-parity (CP) violating phase CP,**
- **determining the neutrino mass ordering (the sign of Δm^2_{12})**
- **precision tests of the three-flavor neutrino oscillation paradigm**

Generalized mass ordering degeneracy in neutrino oscillation experiments

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





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

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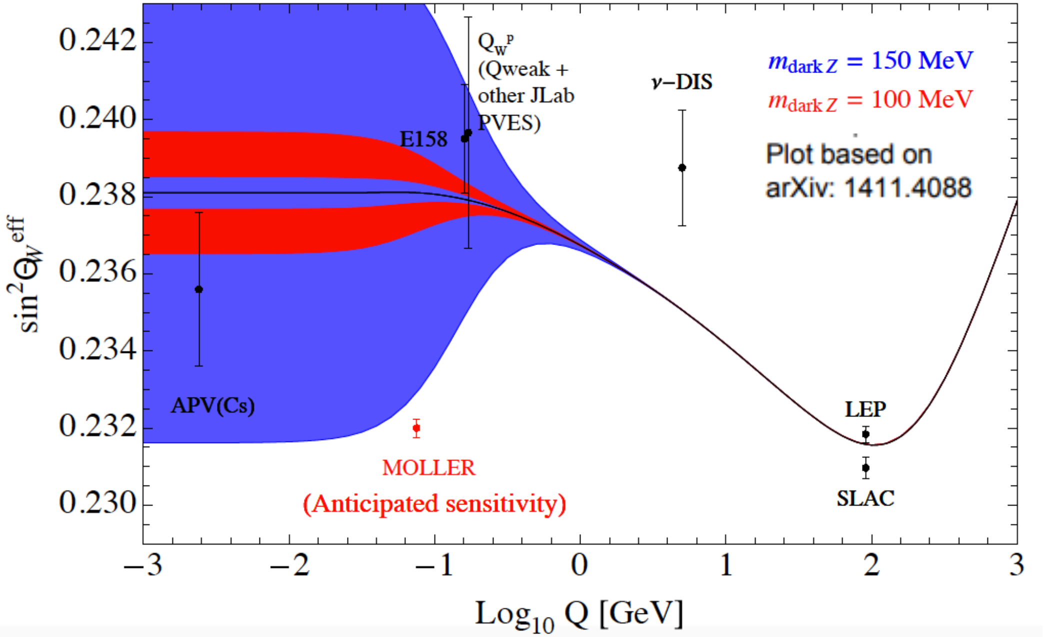
CEvNS is a new way to measure Electro-Week angle at Low Q

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

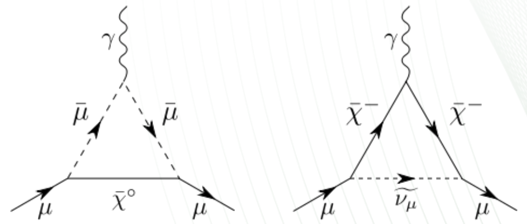
$$\sigma_{tot} = \frac{G_F^2 E_\nu^2}{4\pi}\left[Z\left(1-4\sin^2\theta_W\right)-N\right]^2 F^2(Q^2)$$

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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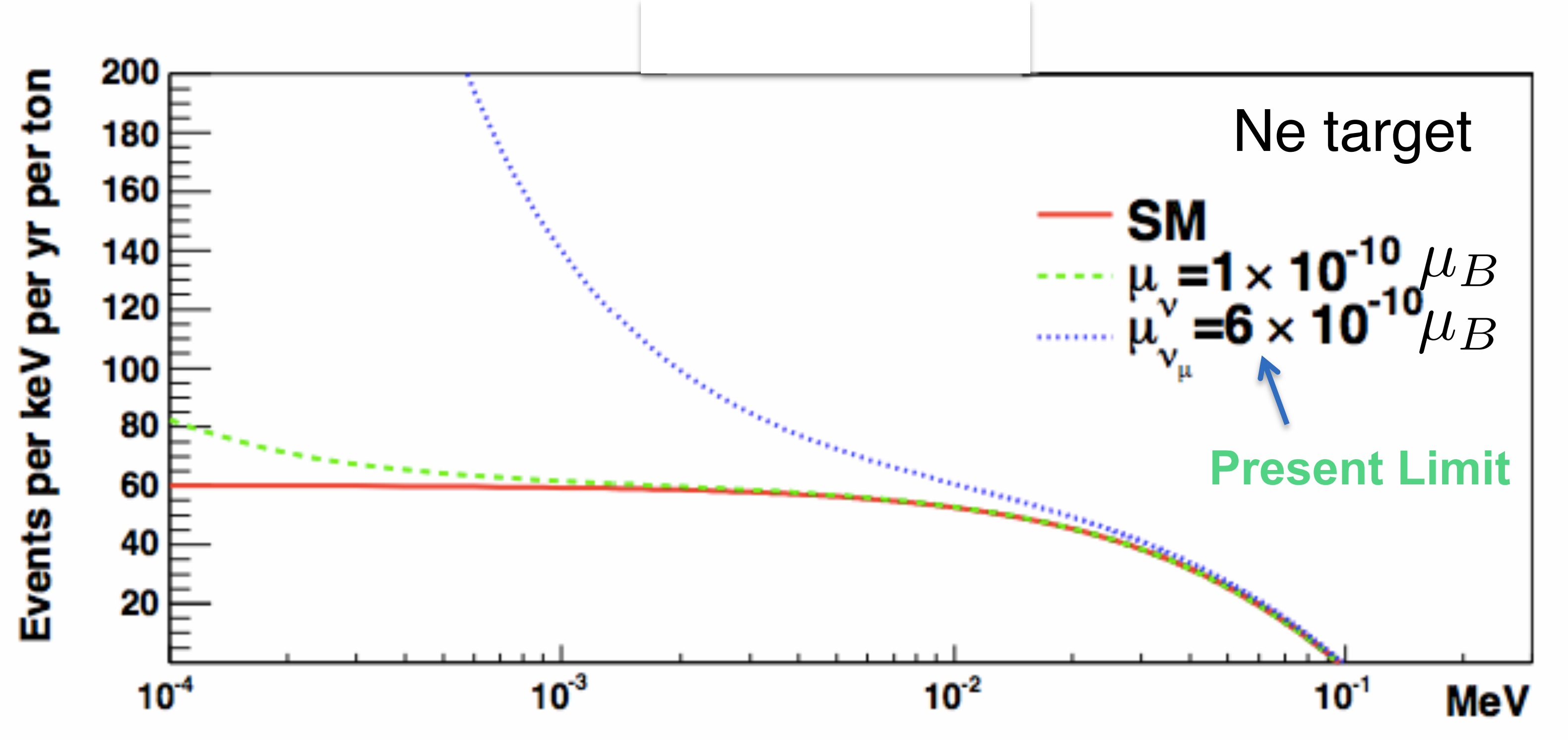
Search For Neutrino Magnetic Moment via CEvNS

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

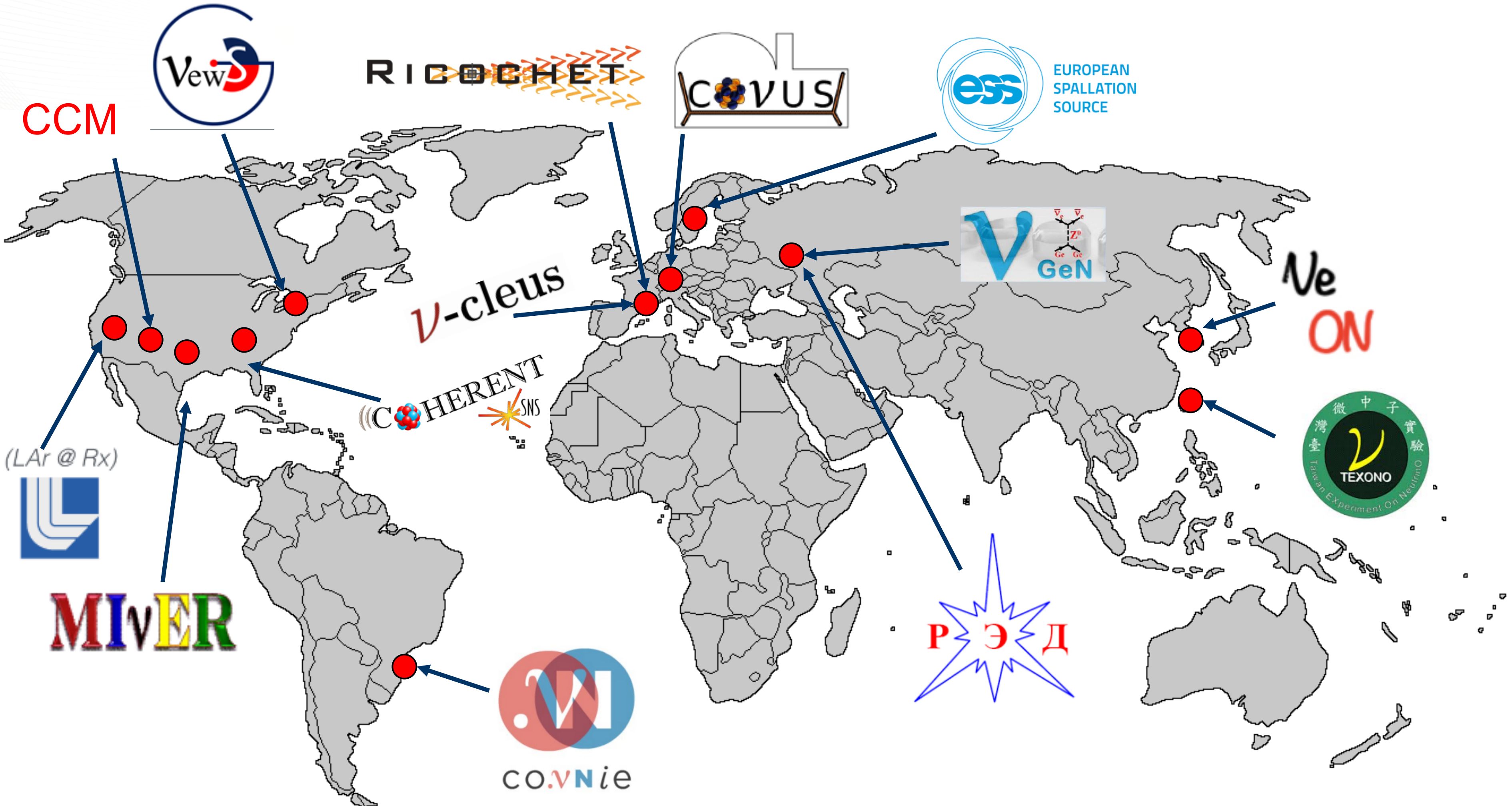
See also Kosmas et al., arXiv:1505.03202

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, ESS 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)

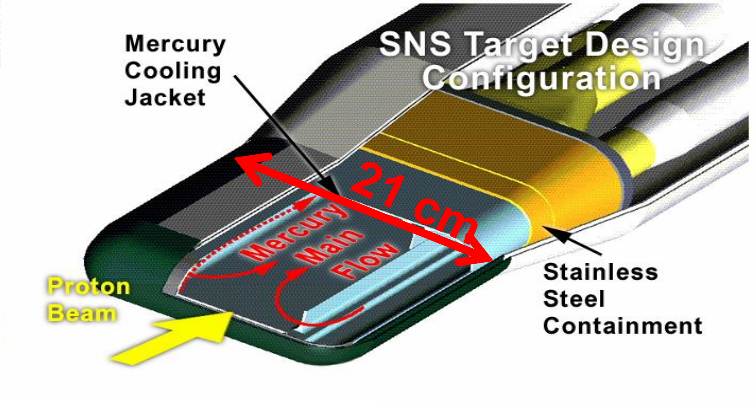
- It is world most powerful pulsed neutrino source. Presently it delivers 7 · 10^{20} POT daily *~10% of protons produce 3 neutrino flavors*
- Neutrino energies at SNS are ideal to study CEvNS.

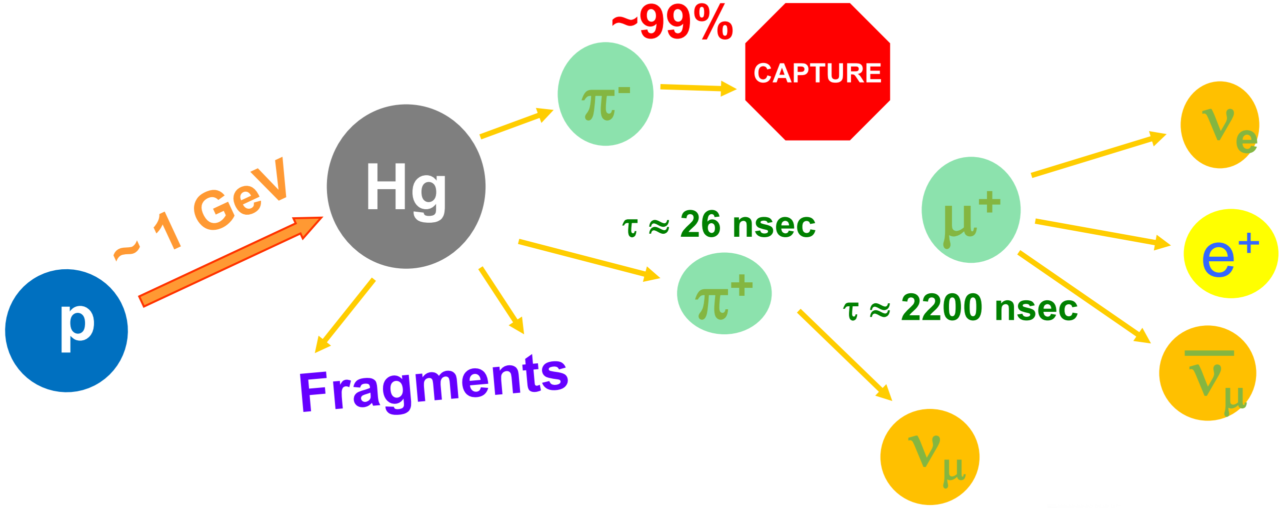
For 99% of neutrinos E_ν < 53 MeV

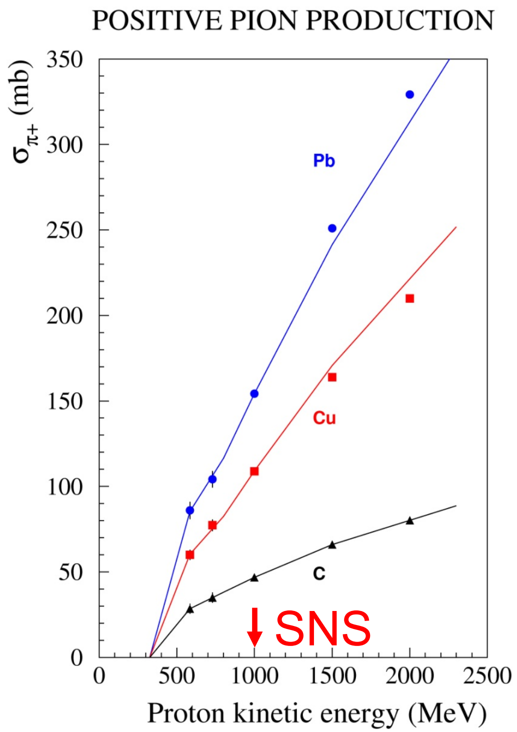
- Decay At Rest from pions and muons (DAR) gives very well-defined neutrino spectra
- Duty factor suppress steady state backgrounds by a factor of 2000.

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

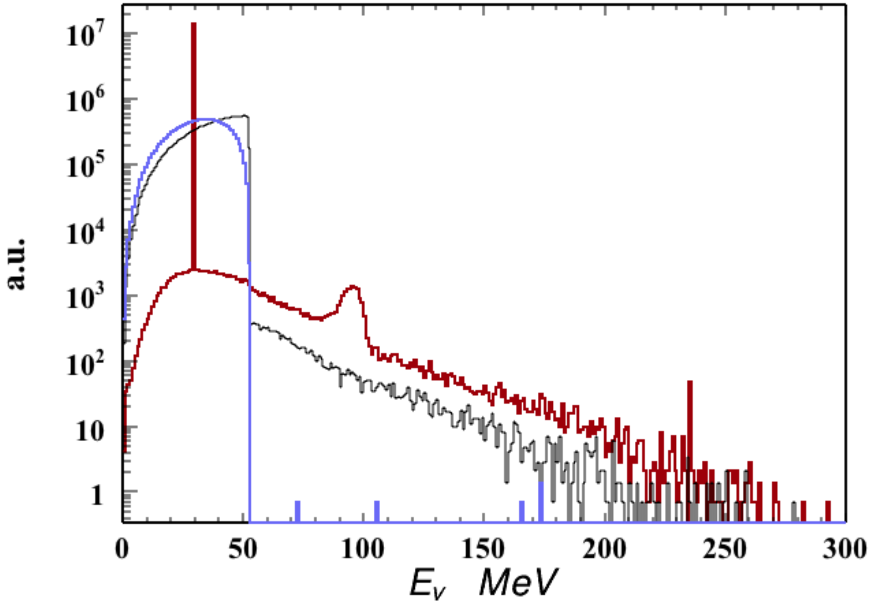
Neutrino Production at the SNS



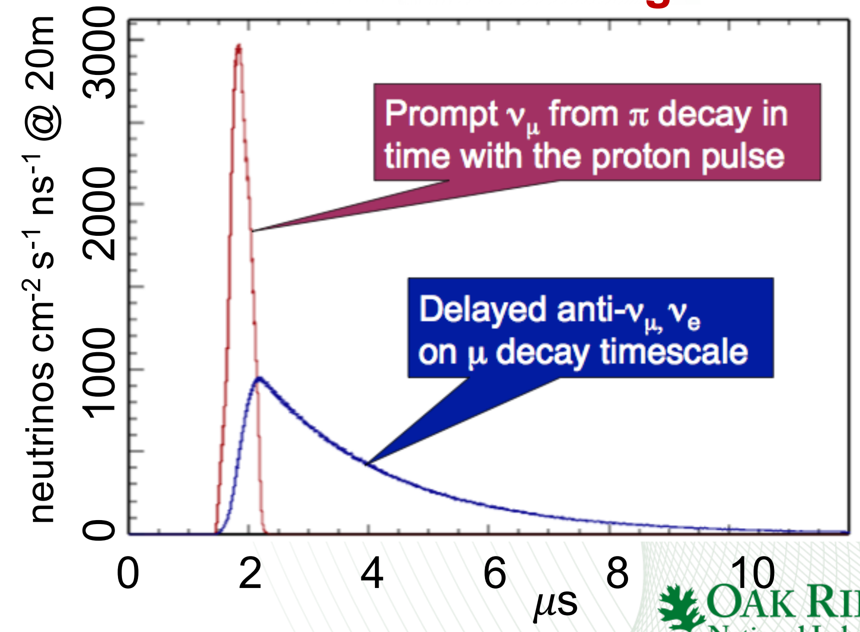




Neutrino Energy



Neutrino Timing



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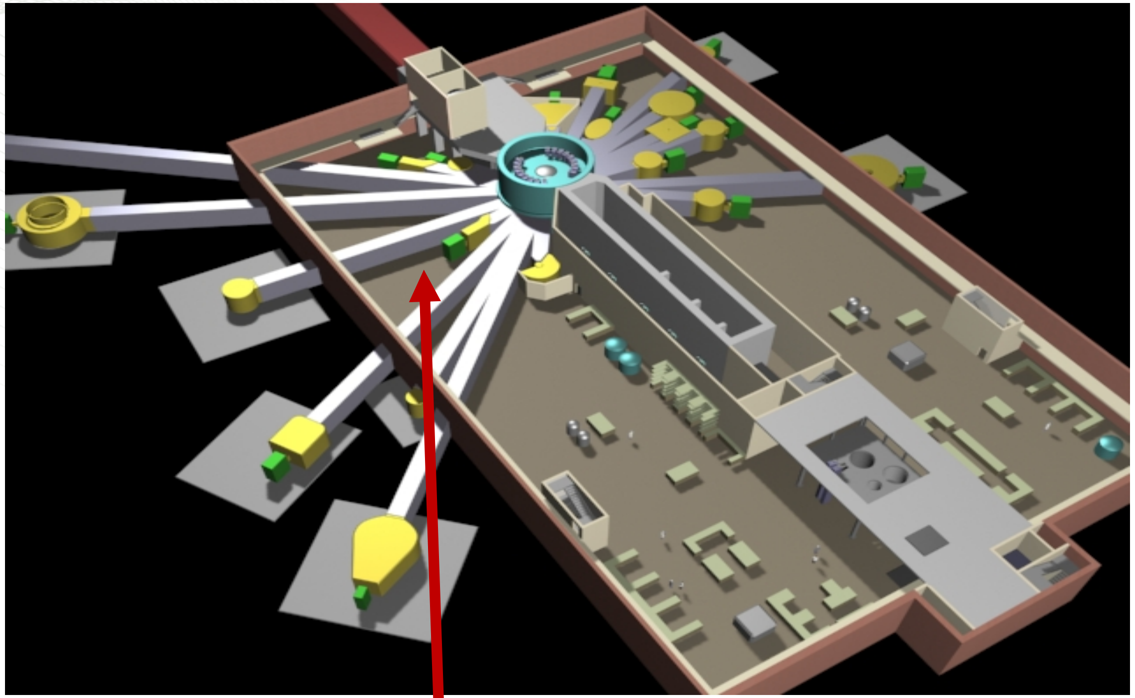
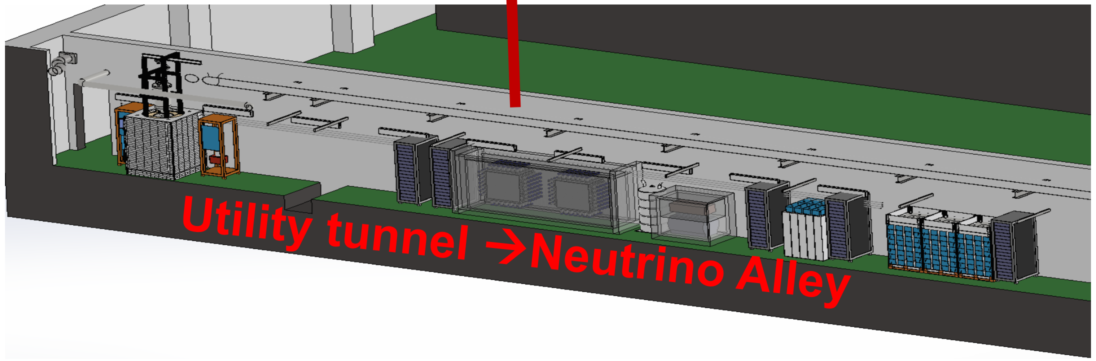
COHERENT is using "Neutrino Alley" at the SNS

After extensive BG 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. Well protected 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

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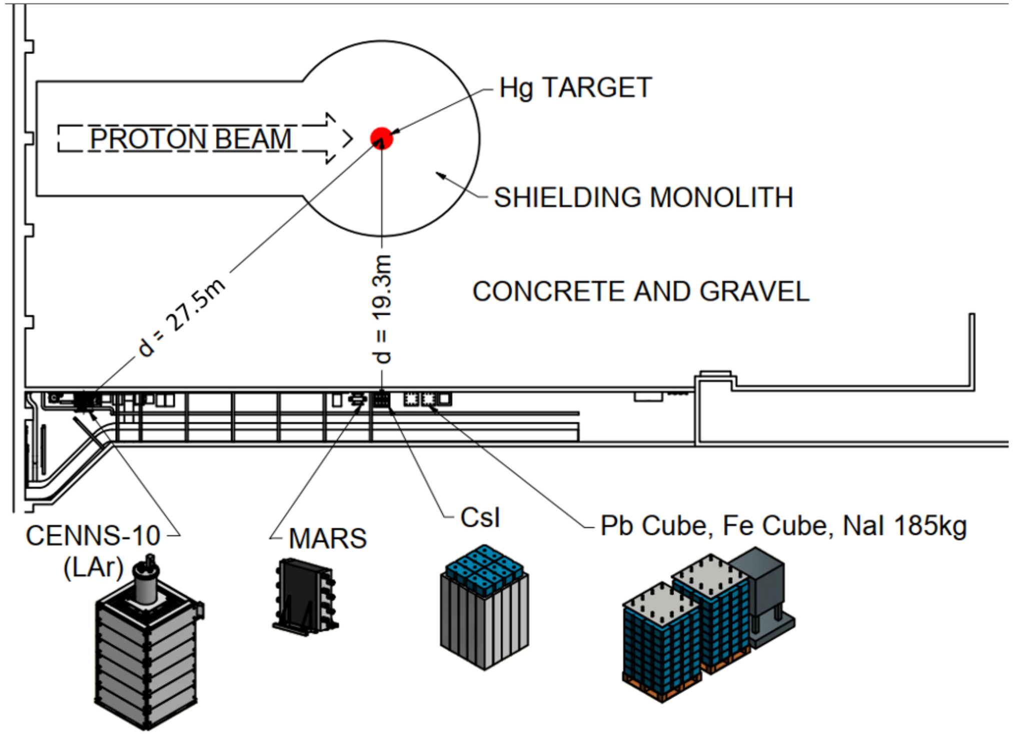
COHERENT at the SNS

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

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

- **19-28 meters from the target**
- **Enough place for a several detectors**



Detectors

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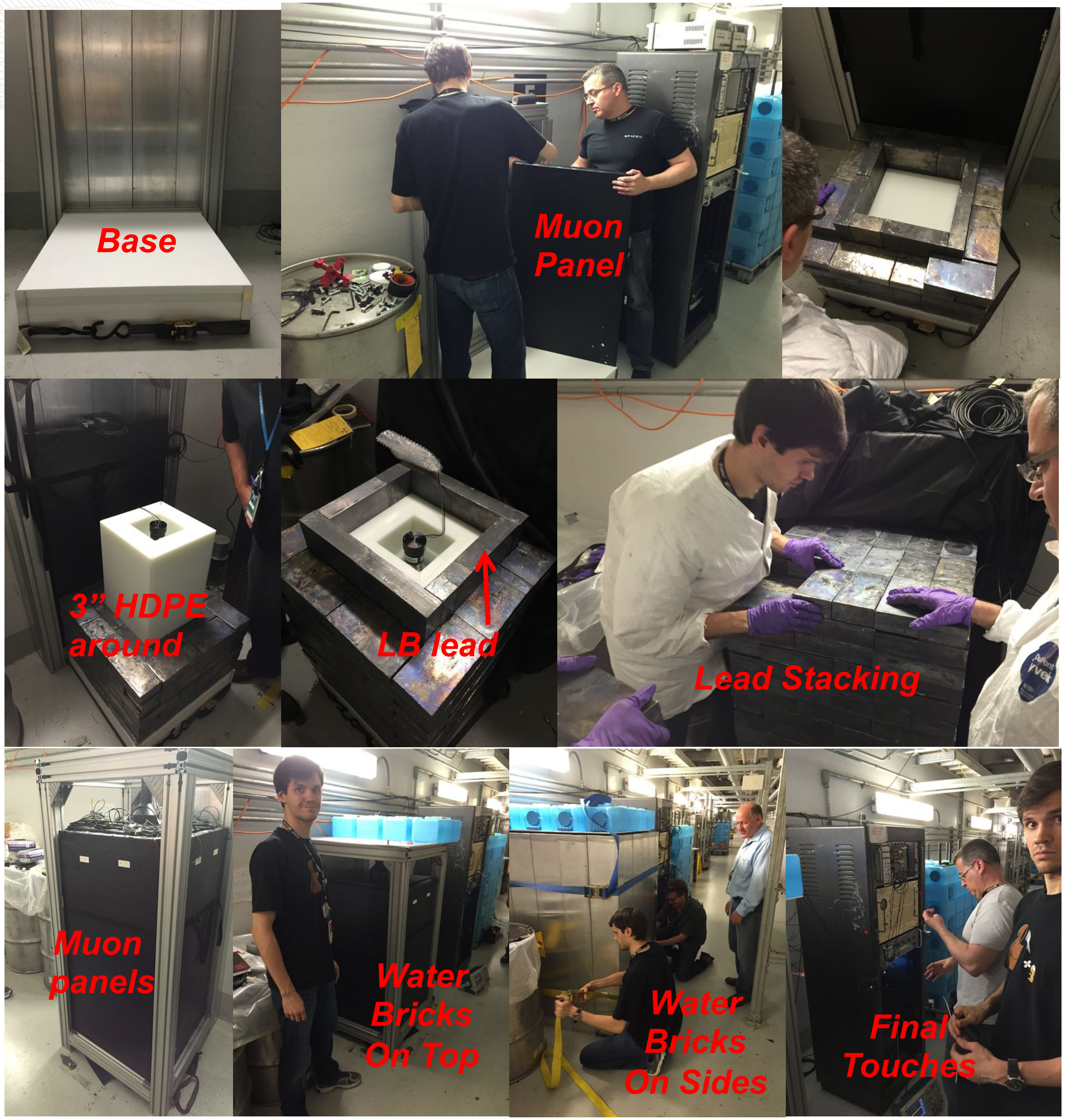
First Experiment: 14 kg CsI Detector



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

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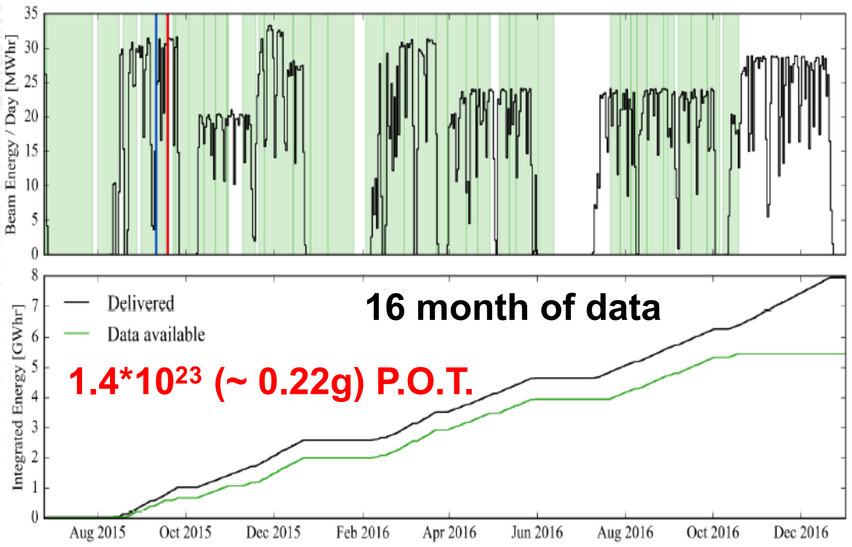
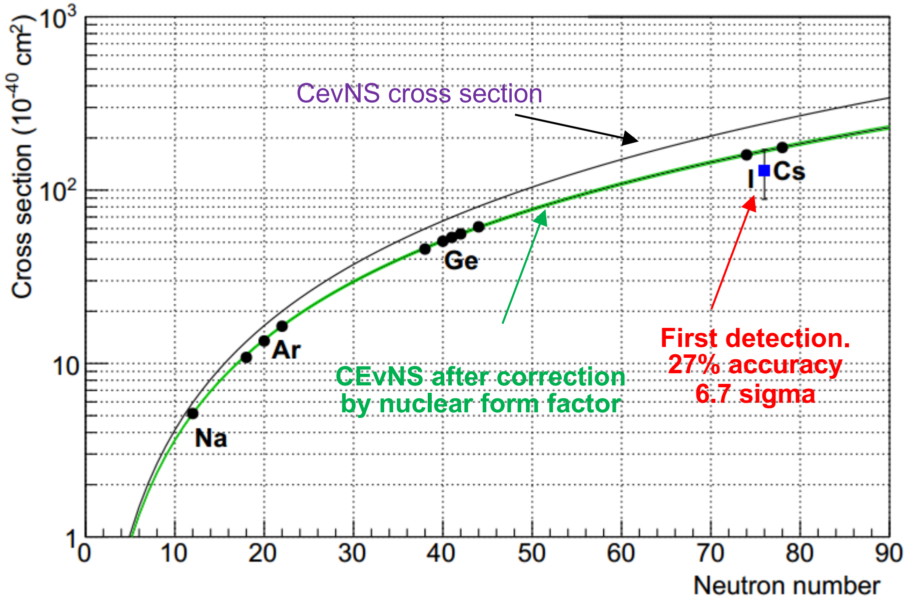
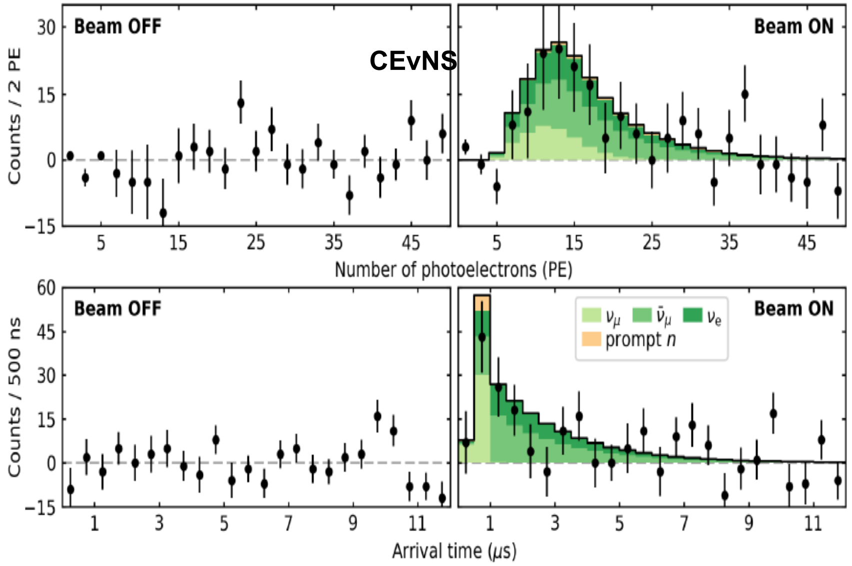
First Detection of CEvNS with CsI detector







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

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

Will publish updated result soon

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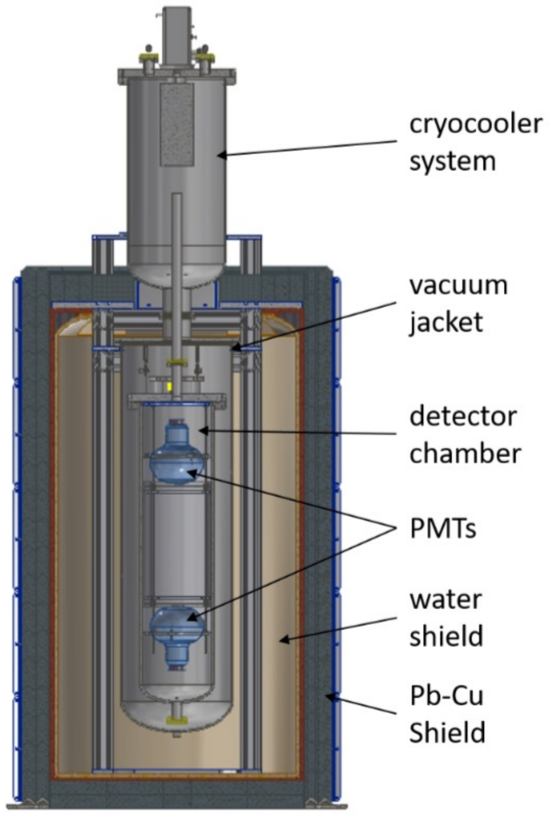
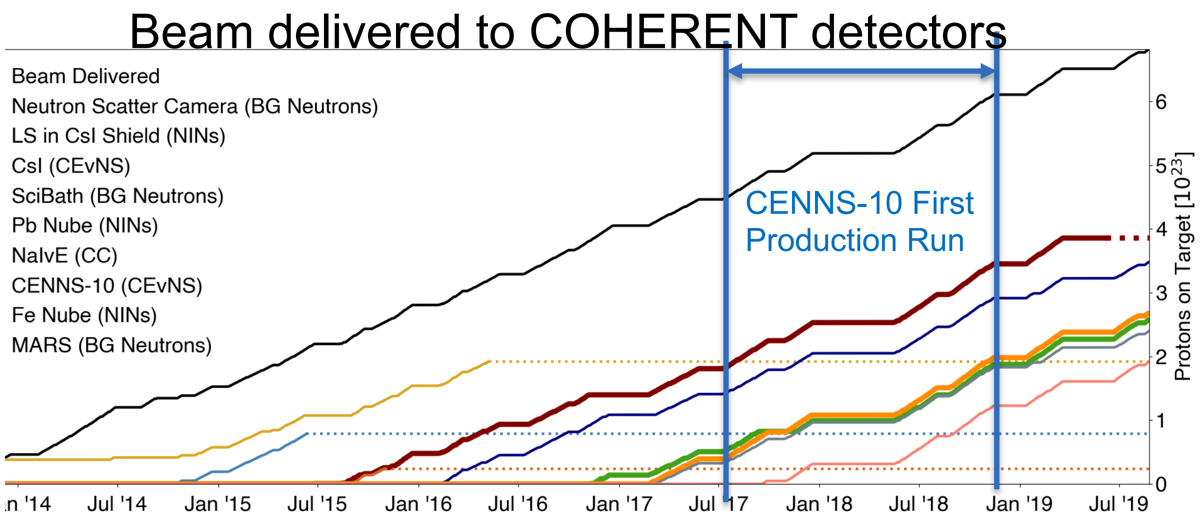
Argon Target

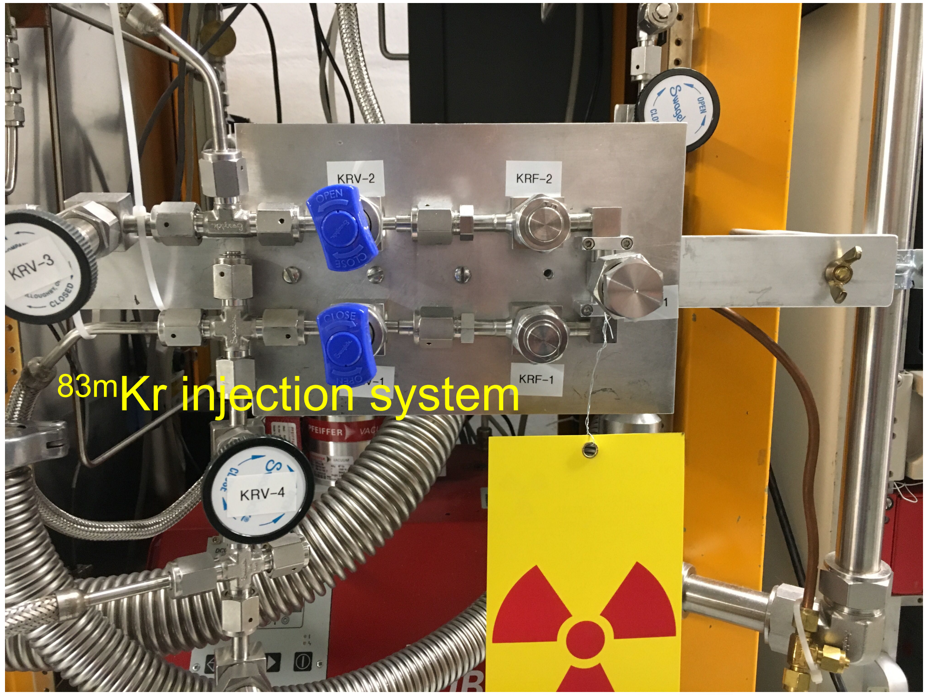
- Originally built in 2012-2014 by J. Yoo et al. at Fermilab for CEvNS effort at Fermilab
- Moved to the SNS for use in COHERENT late 2016 after upgrades at IU. Rebuild in 2017 at ORNL with new PMTs and TPB coating sputtered in vacuum. L.Y. increased by a factor of 10.
- 10 cm Pb/ 1.25 cm Cu/ 20 cm H_2O shielding
- 24 kg fiducial volume
- 2x 8" Hamamatsu PMTs, 18% QE at 400 nm
- Tetraphenyl butadiene (TPB) coated side reflectors/PMTs
- Production Run (July 2017-December 2018)
- Two independent analyses (USA and Moscow)

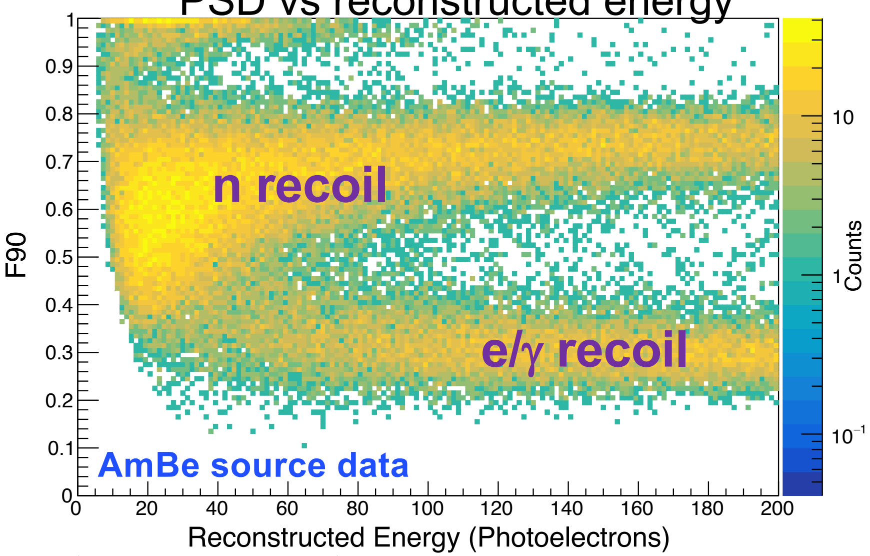


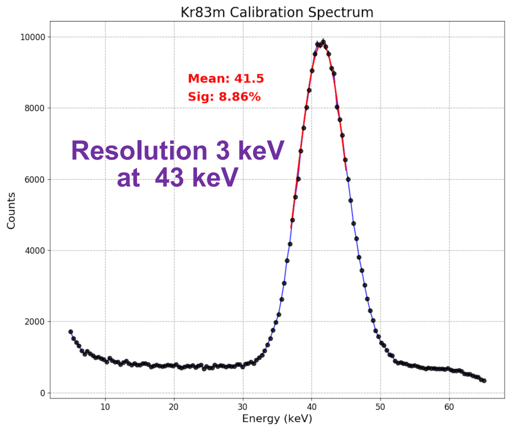


CENNS-10 Calibration

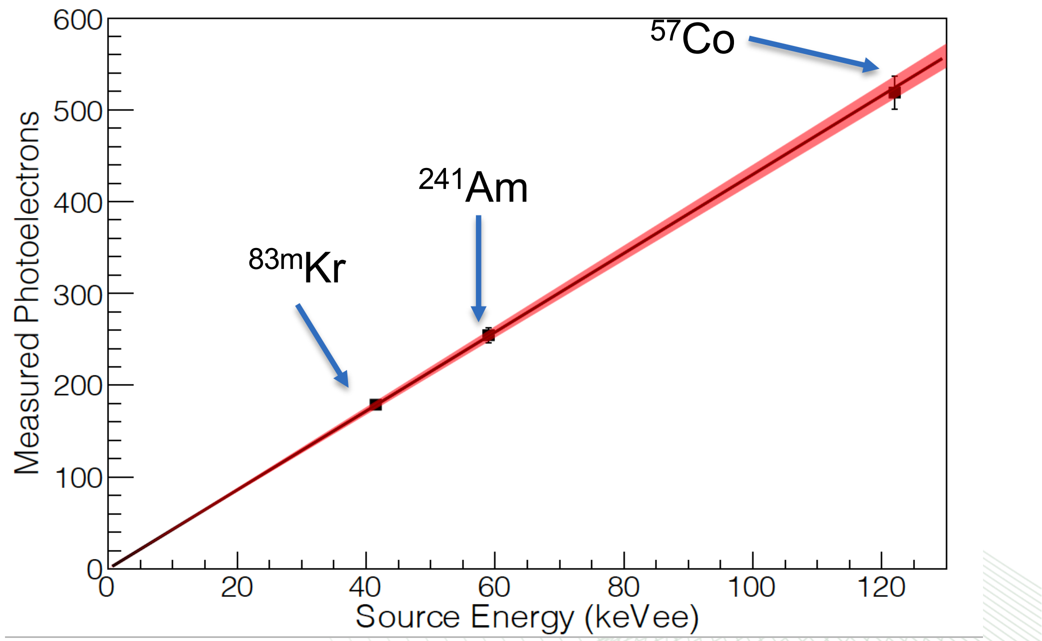
- Calibrate detector with variety of gamma sources
  - Measured light yield: 4.6 ± 0.4 photoelectrons/keVee
  - At ^{83m}Kr energy (41.5 keVee), mean reconstructed energy measured to 2%
    - 9.5% energy resolution at 41.5 keVee
- Calibrate detector nuclear recoil response using AmBe source





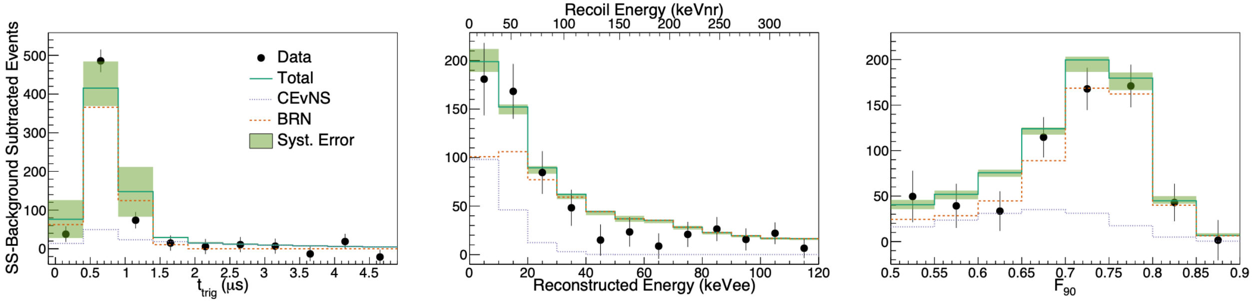


Reconstructed Energy (keVee)



Likelihood Fit Results

- 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



fit ranges	USA	Moscow
F_{90}	0.5 – 0.9	0.5 – 0.8
E (keVee)	0.0 – 120.0	4.1 – 30.6
t_{trig} (μs)	−0.1 – 4.9	−1.0 – 8.0
total events selected	3752	1466
predicted		
CEvNS	128 ± 17	101 ± 12
BRN, prompt	497 ± 160	226 ± 33
BRN, delayed	33 ± 33	
SS	3152 ± 25	1155 ± 45
total events predicted	3779	1482
fit		
CEvNS	159 ± 43	121 ± 36
BRN, prompt	553 ± 34	222 ± 23
BRN, delayed	10 ± 11	
SS	3131 ± 23	1112 ± 41
total events fit	3853	1455
fit systematic errors		
CEvNS F_{90} E dependence	4.5%	3.1%
CEvNS t_{trig} mean	2.7%	6.3%
BRN E dist.	5.8%	5.2%
BRN t_{trig} mean	1.3%	5.3%
BRN t_{trig} width	3.1%	7.7%
total CEvNS sys. error	8.5%	13%
fit results		
null significance (stat. only)	3.9σ	3.4σ
null significance (stat.+sys.)	3.5σ	3.1σ

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What Did We Learn After the First Results from the 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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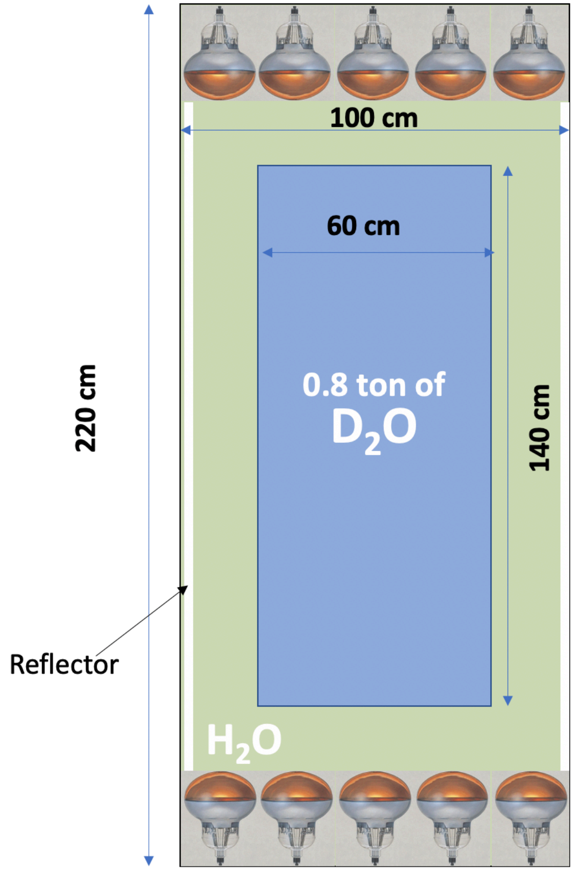
Concept of ~1-ton Heavy Water Detector

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 1 m width
  - Locations 20-29 meters from target

Will do CC measurement on Oxygen for SN support

Preliminary, not optimized layout

- 0.8 tons D_2O within acrylic inner vessel
- Water Cherenkov Calorimetry (no ring imaging)
- H_2O "tail catcher" for high energy e^-
- Outer light water vessel contains PMTs, PMT support structure, and optical reflector.
- Outer steel vessel to support shielding and veto

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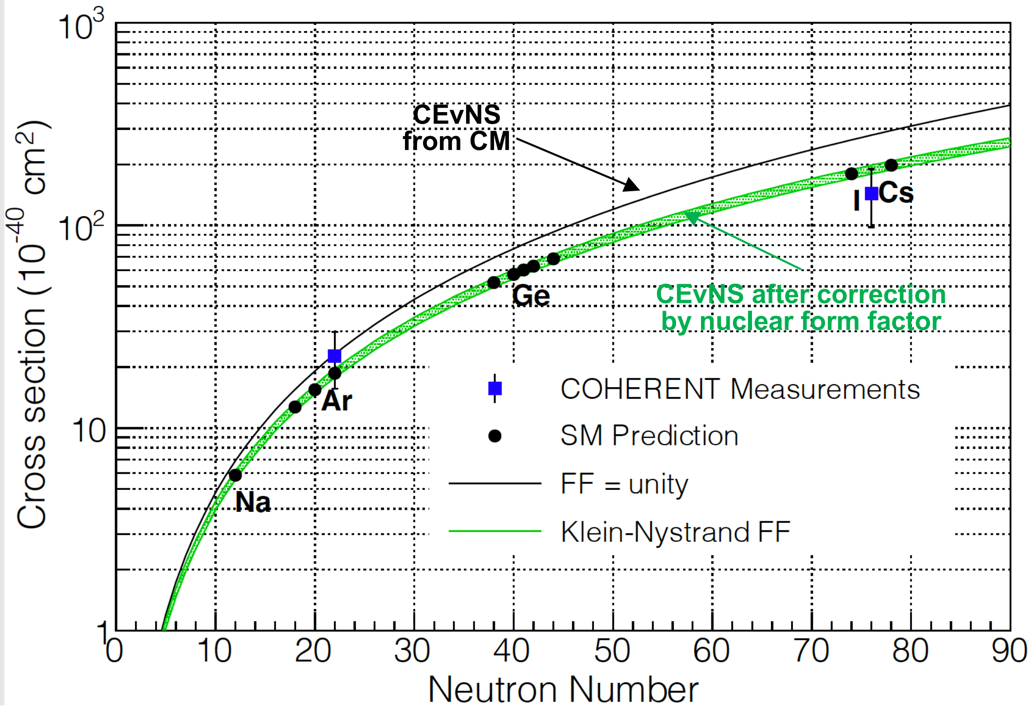
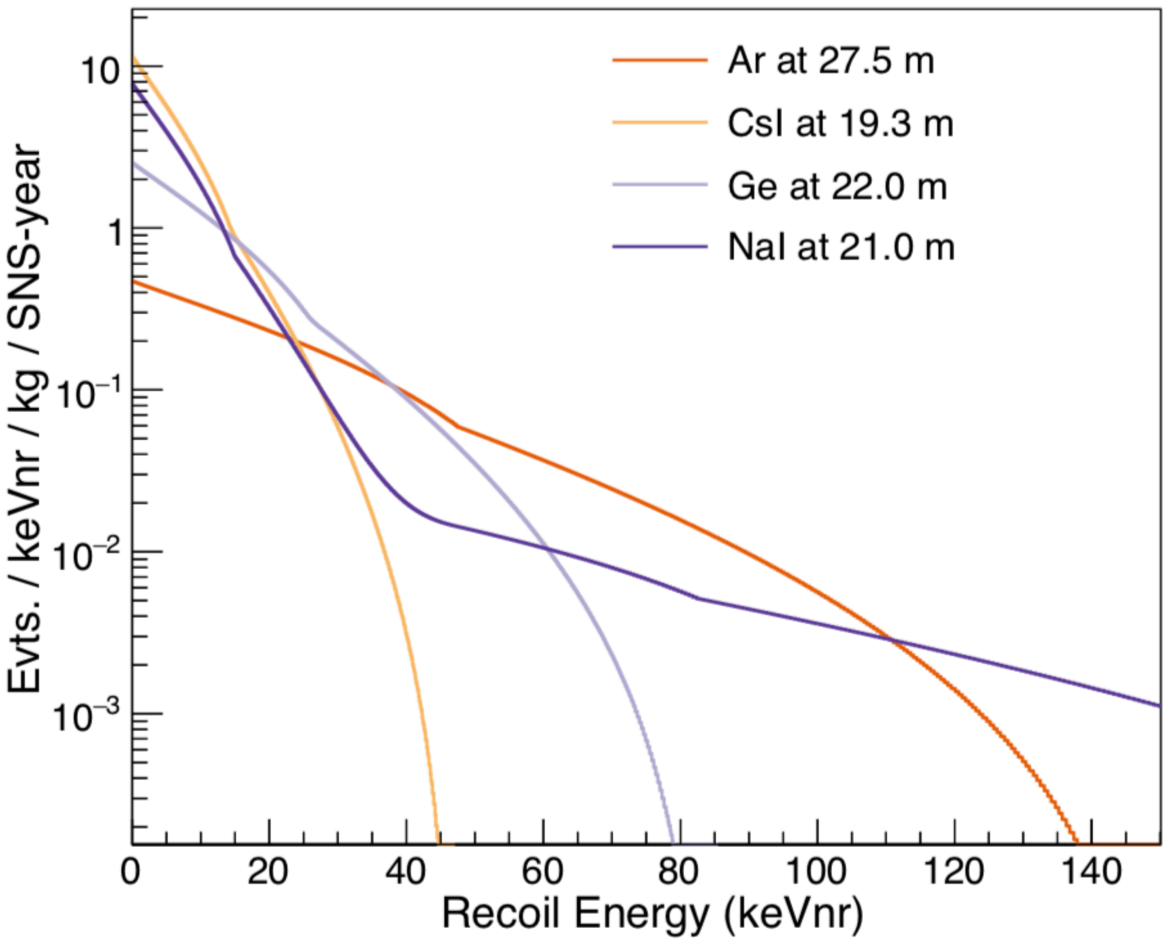
Long Term Program with Various Targets.





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

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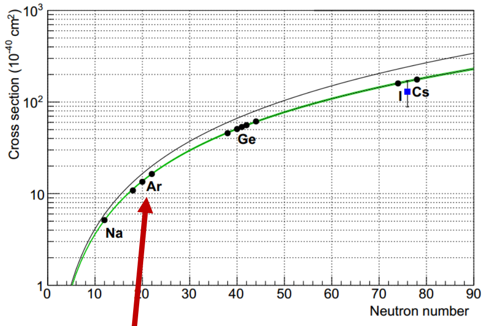
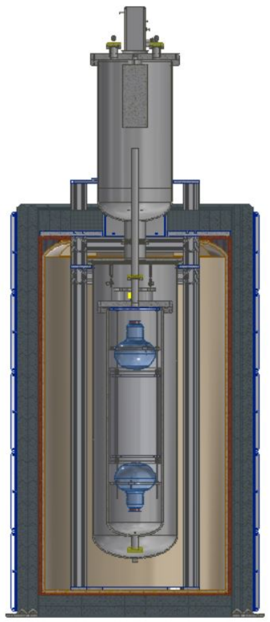
Future Activities - 1 ton LAr detector



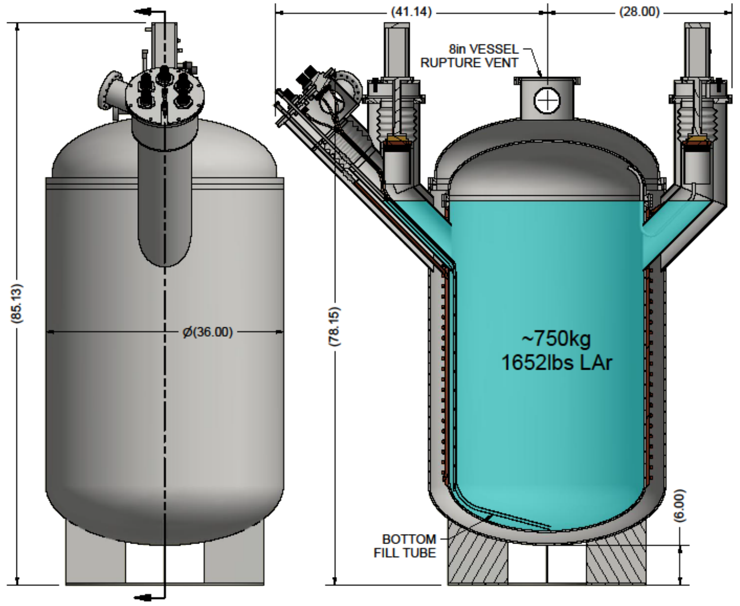
Need high statistics low background measurements of CEvNS

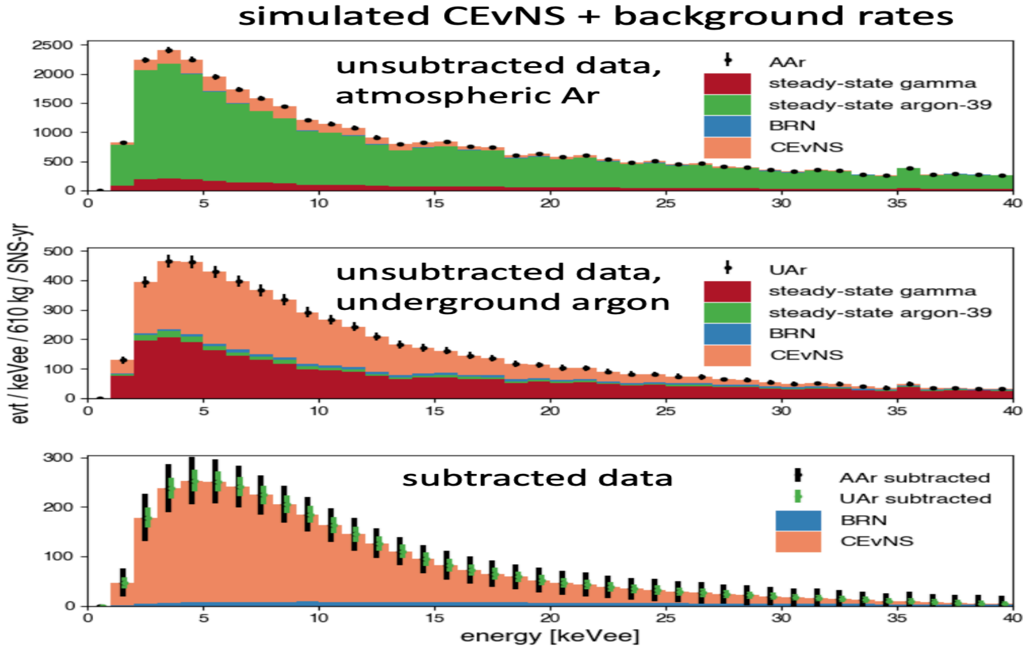
Transition from 22 kg to 1 ton LAr detector.



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

Will see 3kt of CEvNS events per year + CC



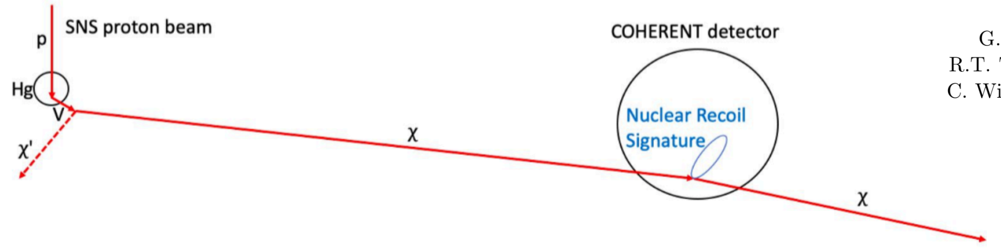


Interesting opportunity → Search for accelerator produced dark matter with LAr detector

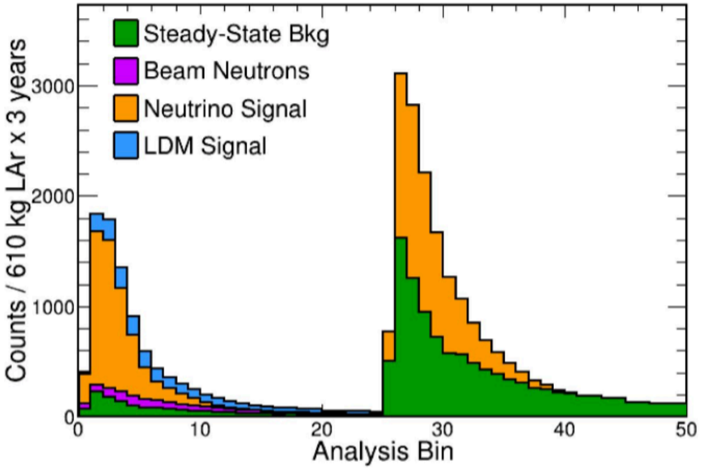
Sensitivity of the COHERENT Experiment to Accelerator-Produced Dark Matter

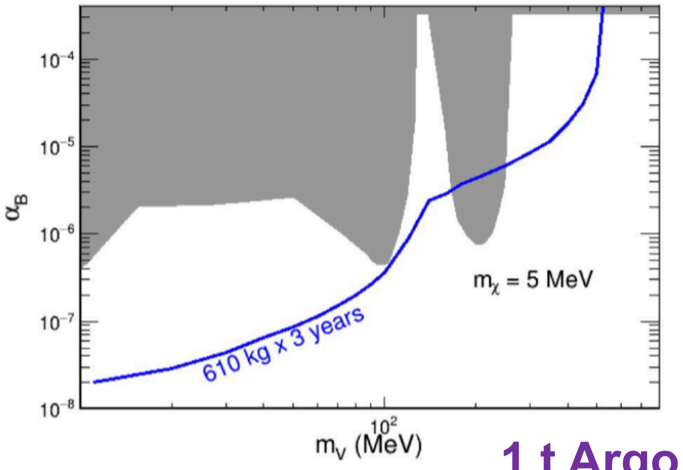
D. Akimov,[1,2] P. An,[3,4] C. Awe,[3,4] P.S. Barbeau,[3,4] B. Becker,[5] V. Belov,[1,2] M.A. Blackston,[6] A. Bolozdynya,[2] B. Cabrera-Palmer,[7] N. Chen,[8] E. Conley,[3] R.L. Cooper,[9,10] J. Daughhetee,[5] M. del Valle Coello,[11] J.A. Detwiler,[8] M.R. Durand,[8] Y. Efremenko,[5,6] S.R. Elliott,[10] 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]

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

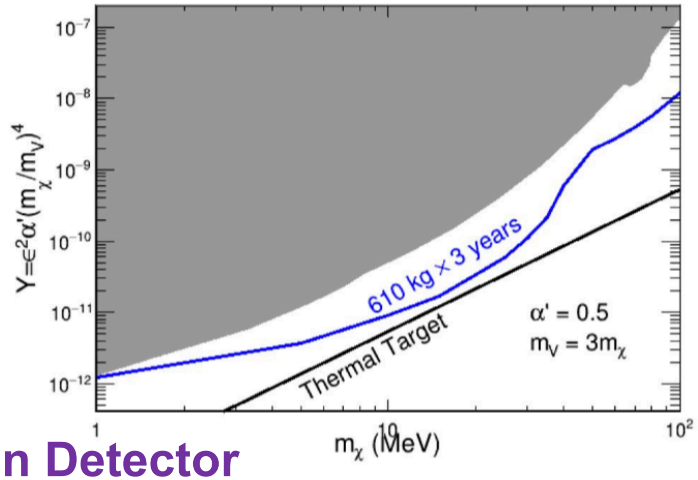


arXiv:1911.06422 [hep-ex]





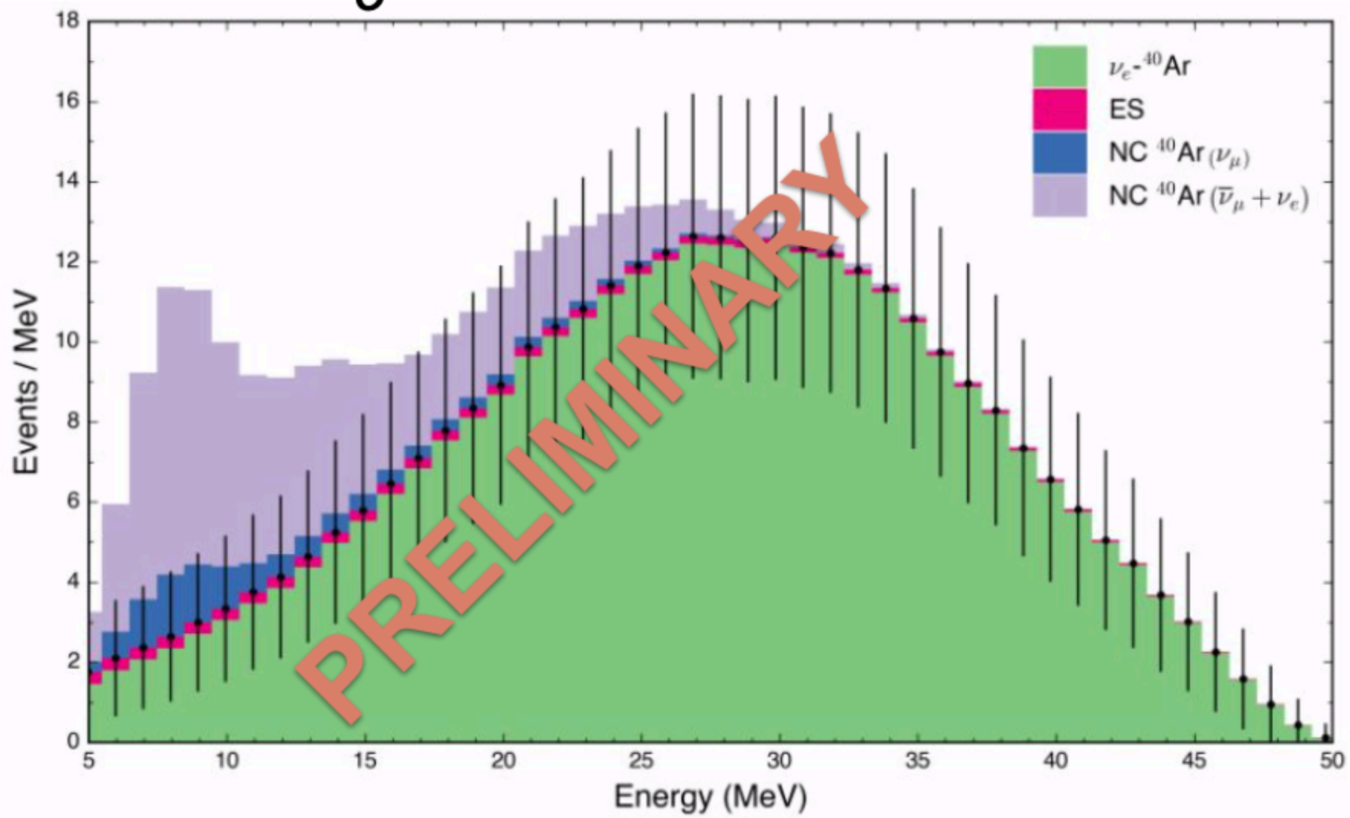
1 t Argon Detector



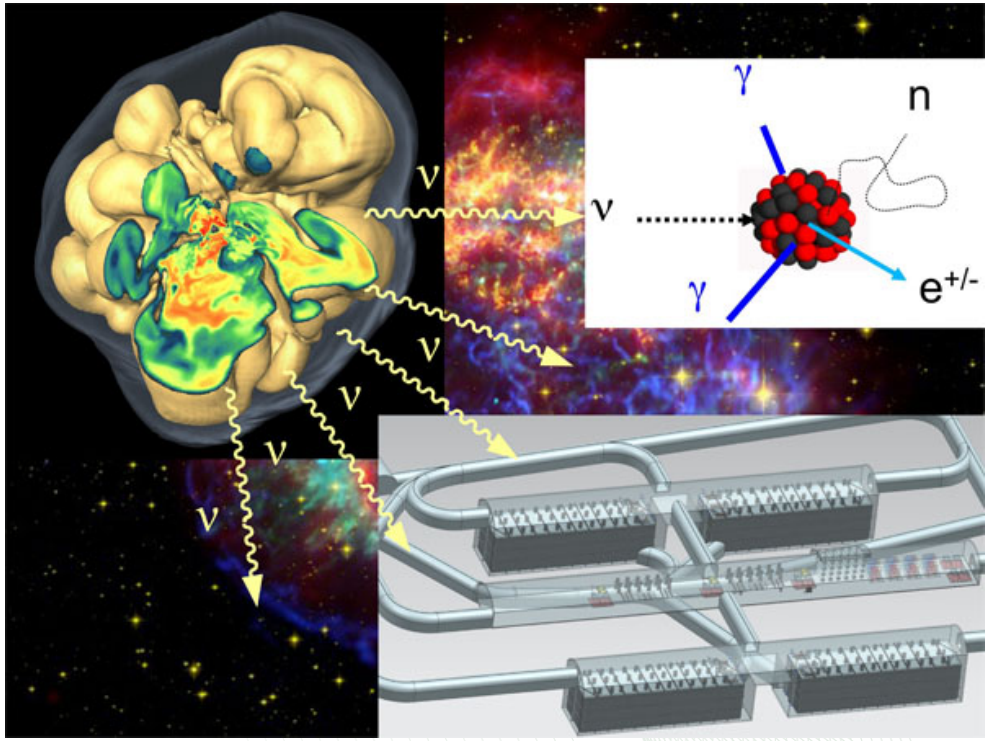
- Coherent cross section enhancement
- DM and CEvNS recoil spectra are different -- *delayed CEvNS provide constraint for prompt DM*
- Competitive constraints for ~10-30 MeV vector portal in neutrino alley
- Strong limits on baryonic portal

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 !!!

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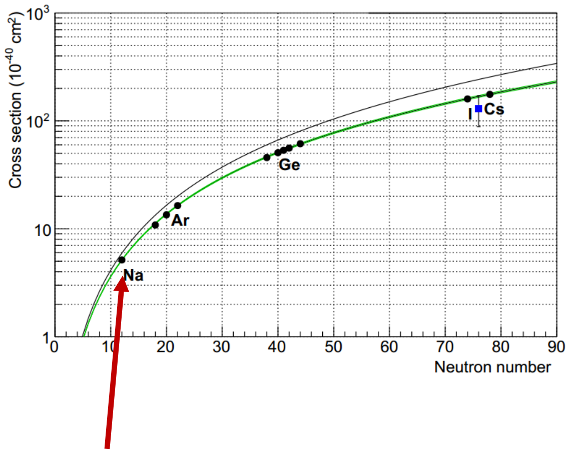
Large NaI Detectors Array

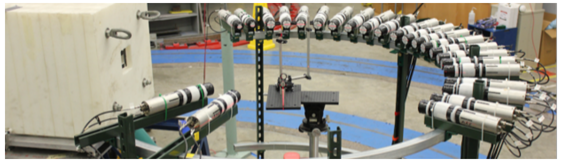


Transition from now deployed 185 kg to 2 ton array of NaI detectors

Detectors are available (thank you Dick Cheney)

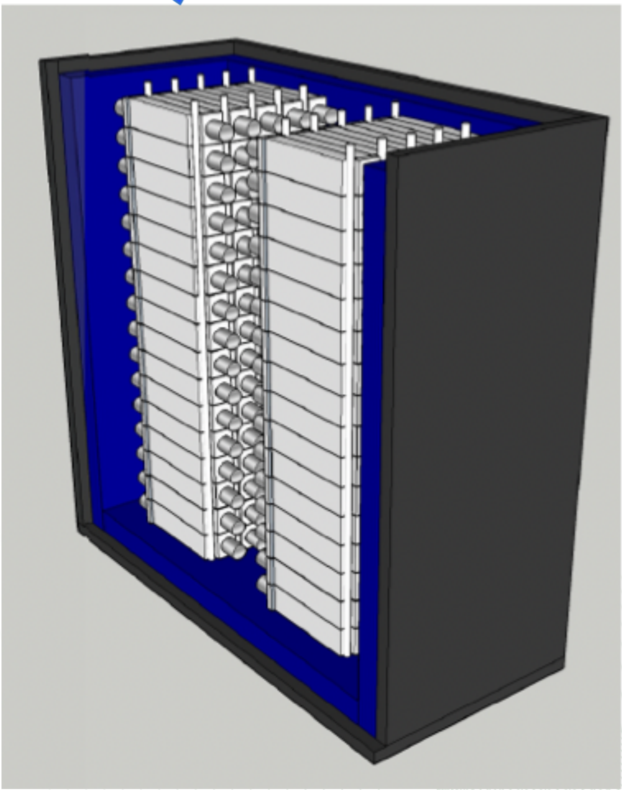
Need dual gain bases (prototypes has been build)

Program to measure Quenching Factors at TUNL (ongoing)

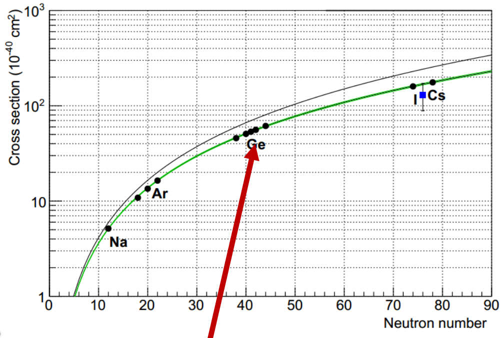


Need electronics and HV; some funds are secured

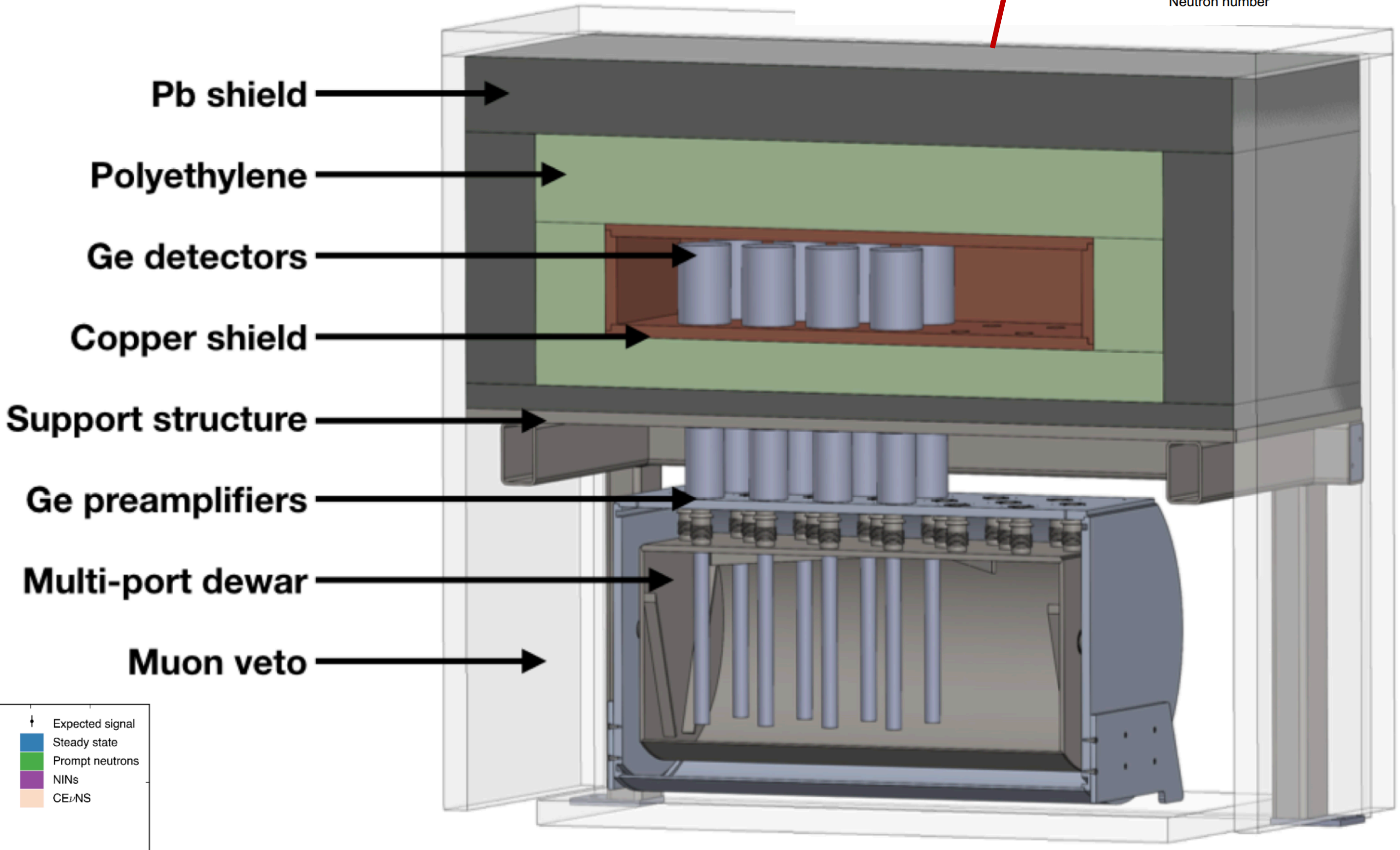
Potential to detect both CEvNS and CC reactions on Iodine

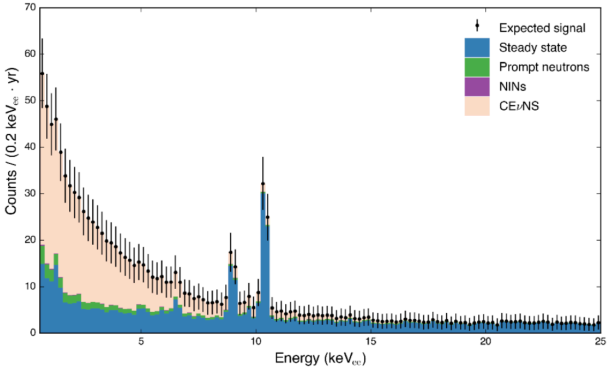


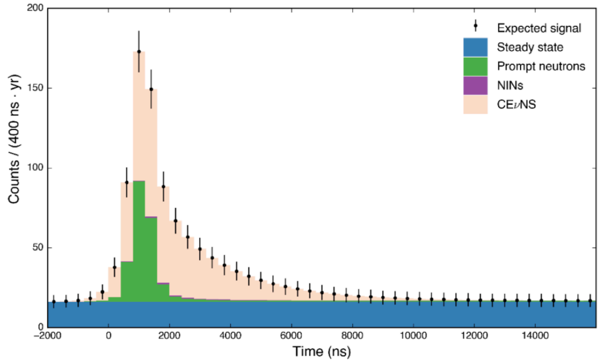
Germanium PPC array (funded by NSF)



- 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

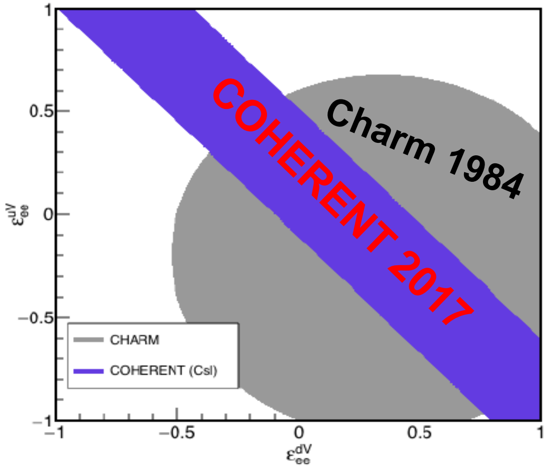
Neutrino Alley at the SNS is unique laboratory to study properties of CEvNS

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

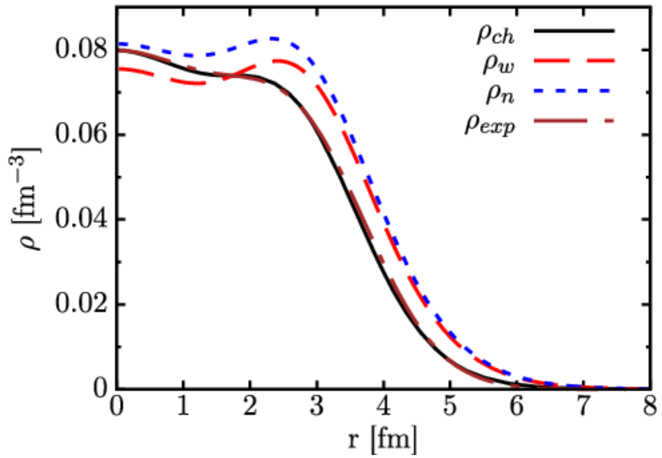
: 1t LAr(Xe), 1t D_2O, 3t NaI, and 16 kg Ge, Xe target?

Intrigue possibility to Detect CIvNS, proposed by Bednyakov and Naumov: *Phys.Part.Nucl.Lett.* 16 (2019) 6, 638-646

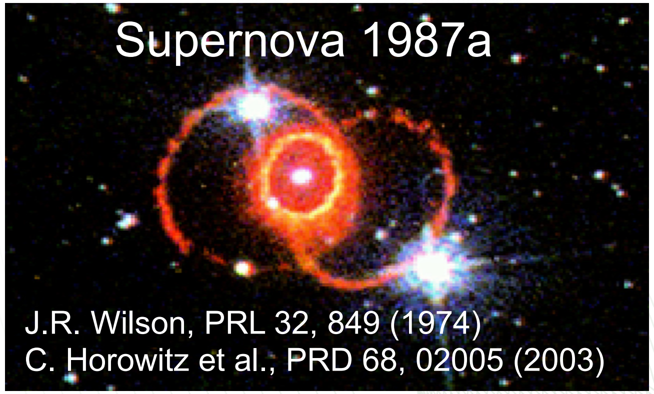
Particle Physics
NINs,Test of the SM, DM



Nuclear Physics
Form Factors, Axial Currents, Incoherent processes

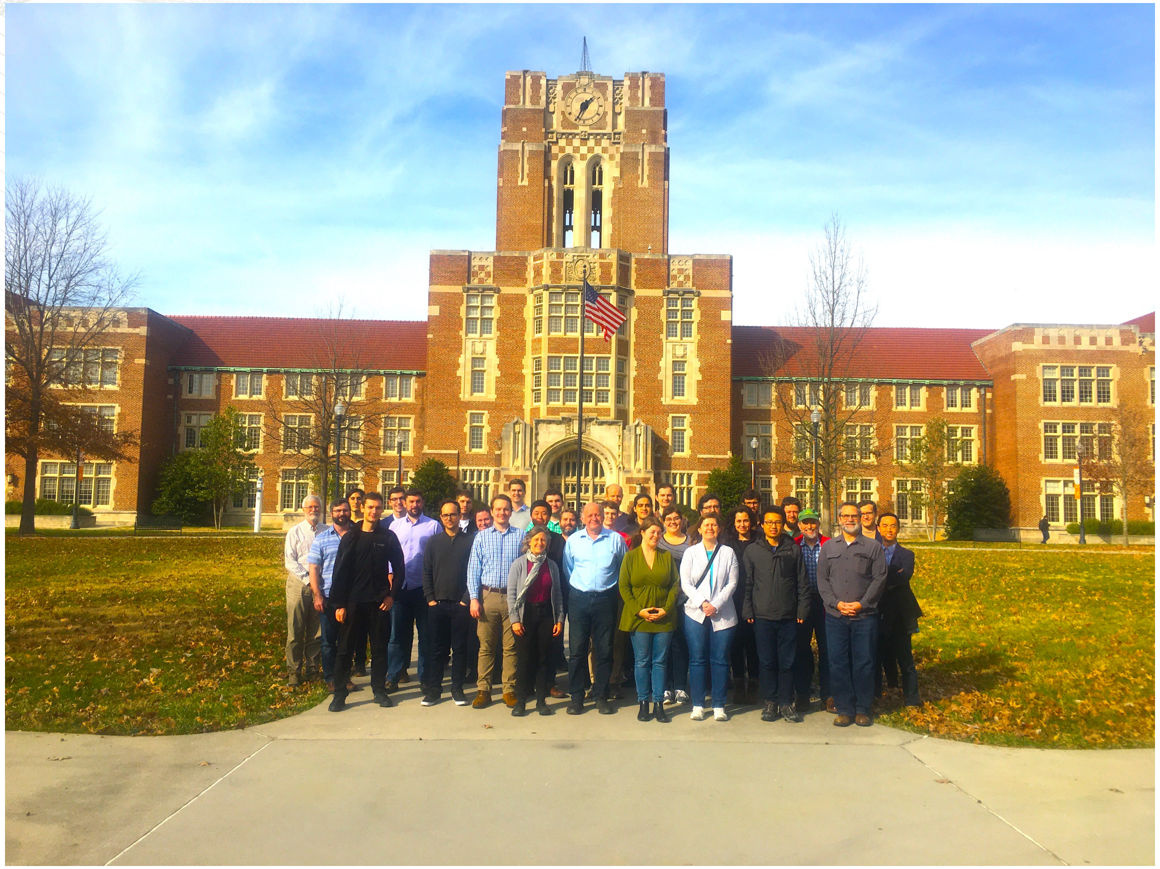


Astrophysics
Supernovae Cross Sections



See talk tomorrow with details about Ar results by A Kumpan.

COHERENT Collaboration



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