The COHERENT experiment with LAr

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on behalf of COHERENT Collaboration

Novosibirsk, 27.02.2020, INSTR2020

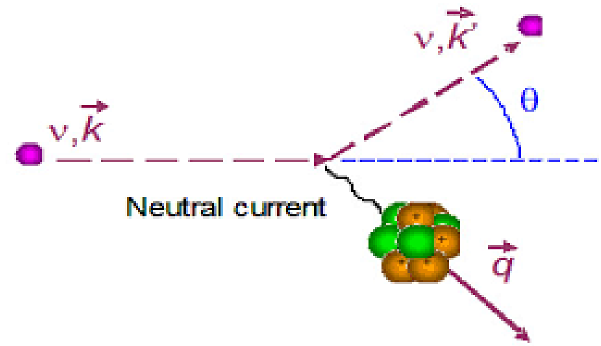
Coherent Elastic Neutrino Nucleus scattering

0.1126/science.aao0990

CEvNS is a fundamental process predicted in 1974 and observed for the first time by the COHERENT Collaboration in 2017

$$\nu + A \rightarrow \nu' + A'$$

D.Z. Freedman, Phys. Rev. D 9 (1974)
V.B. Kopeliovich and L.L. Frankfurt, ZhETF Pis. Red. 19 (1974)

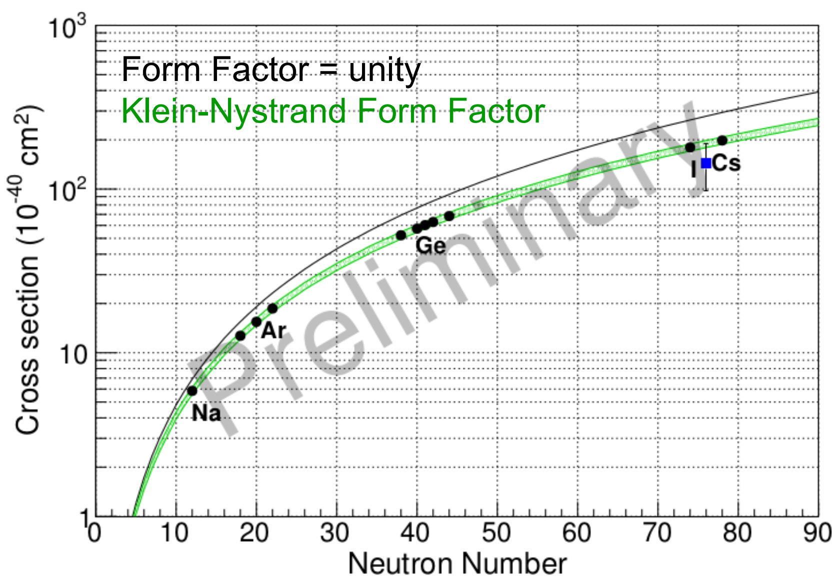


Total cross section of the process can be described by the formula:

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

$$\sigma_{tot} \approx \frac{G_F^2 N^2}{4\pi} E_\nu^{\,2} \sim N^2 \qquad Q \le \frac{1}{R}$$

$\sigma_{CEvNS} > \sigma_{IBD} \sim 10^{-42} cm^{-2}$ at least by 2 orders of magnitude



S. R. Klein and J. Nystrand., Phys. Rev. C 60, 014903 (1999)

The COHERENT Collaboration

~80 members,
~20 institutions
4 countries

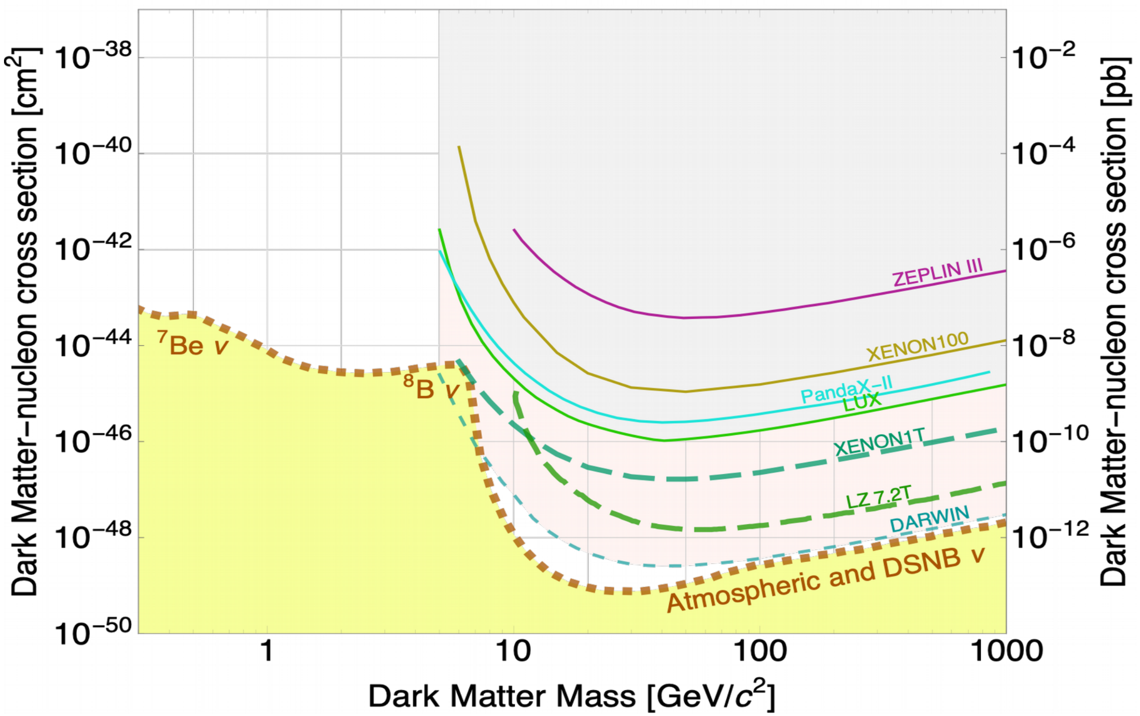
http://coherent.ornl.gov/

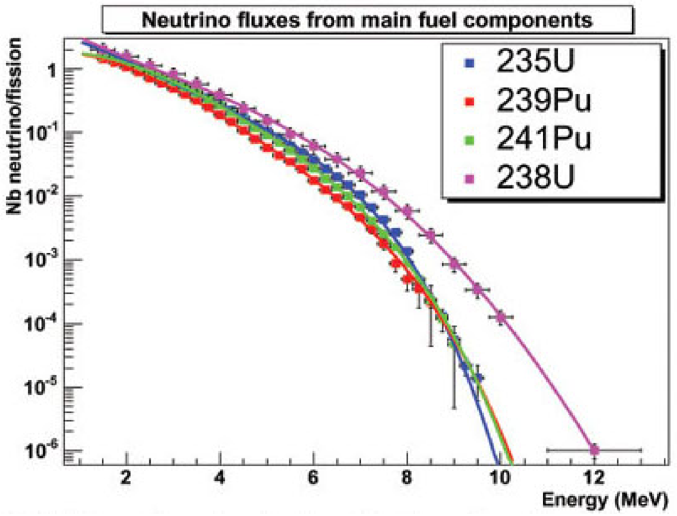
Physics Implications

The most important physics implications of CEvNS are:

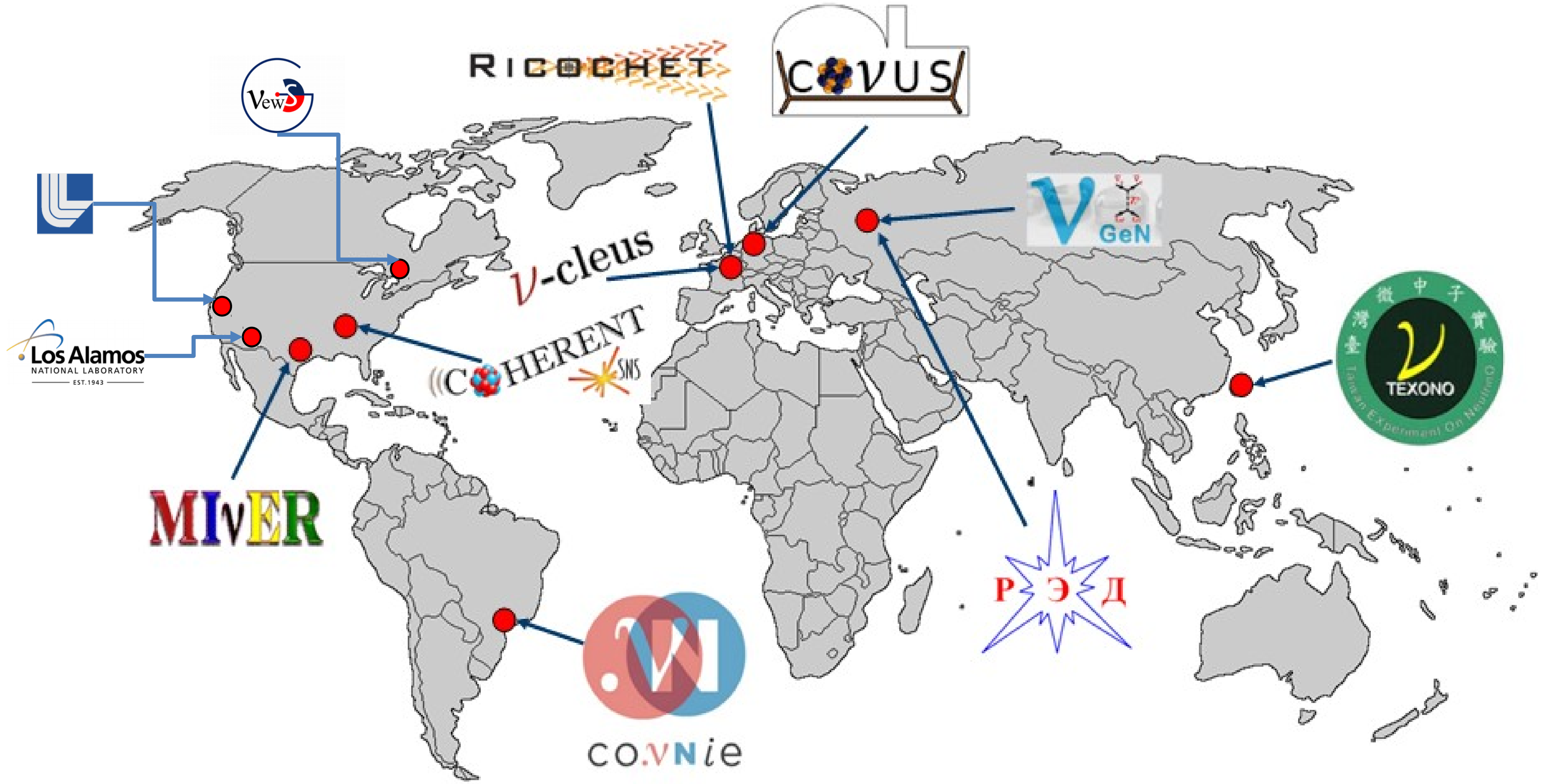
- Physics Beyond the Standard Model
  - Non Standard Interactions
  - Background to Dark Matter searches
- Reactor Monitoring

http://cdms.berkeley.edu/limitplots/



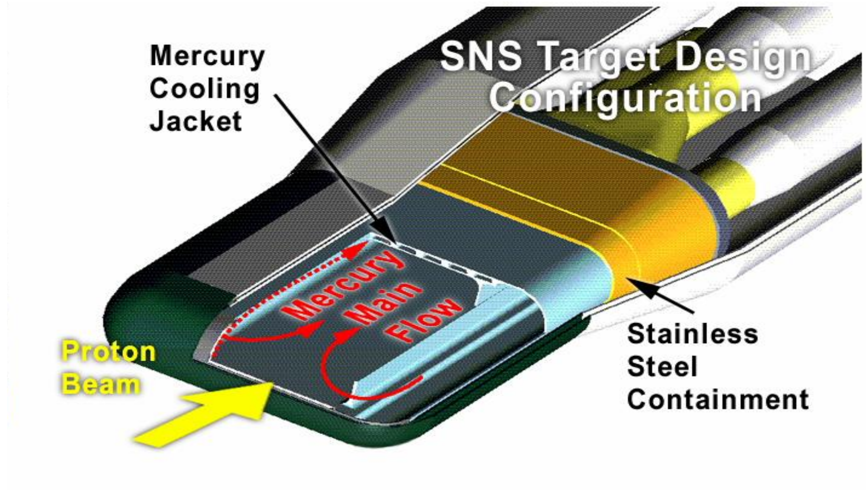


CEvNS Around The World



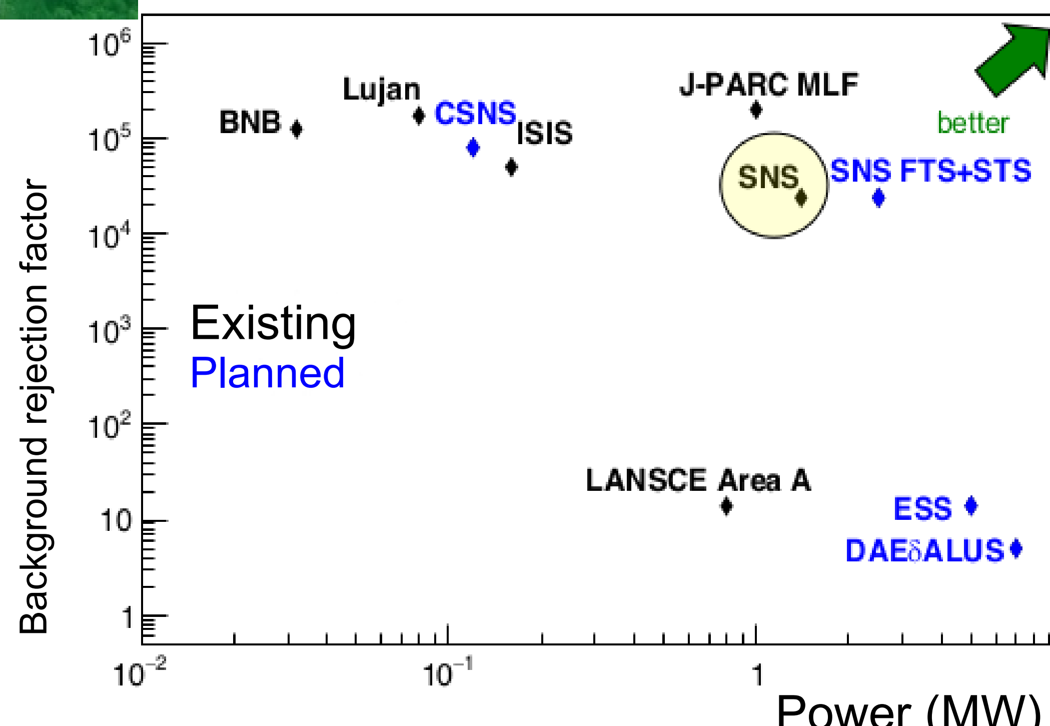
Spallation Neutron Source (SNS)

Oak Ridge, Tennessee, USA

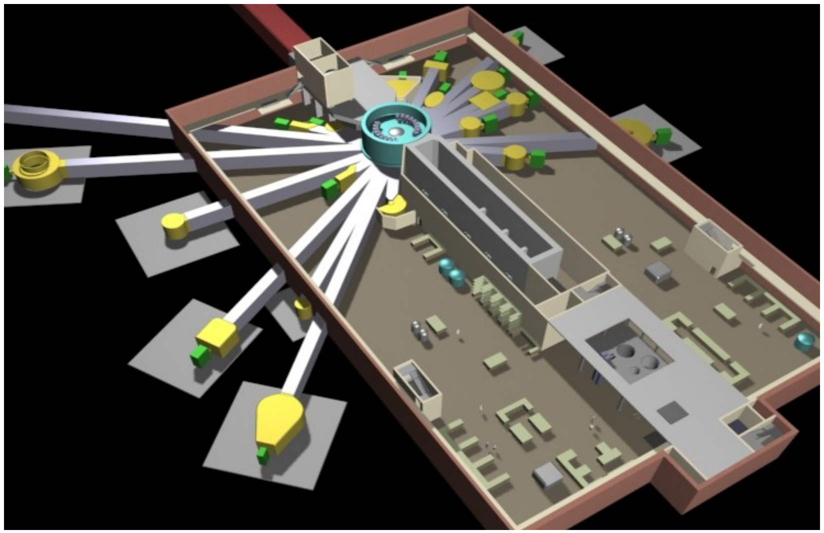


At the moment SNS has the best combination of:

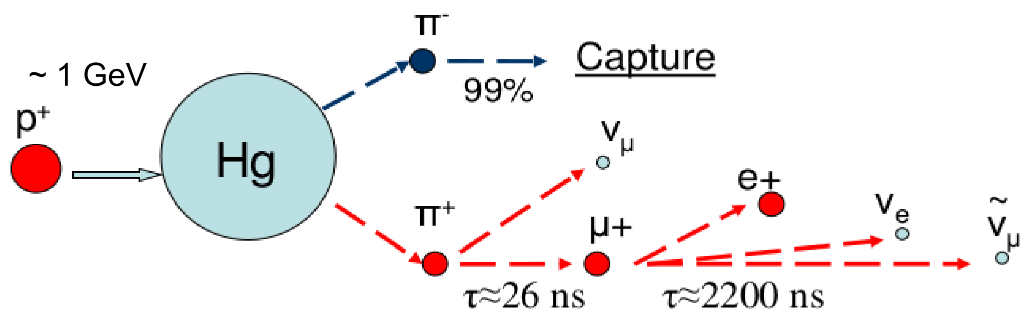
- Beam Power (1.4 MW)
- Mercury Target
- Background rejection factor due to its duty cycle



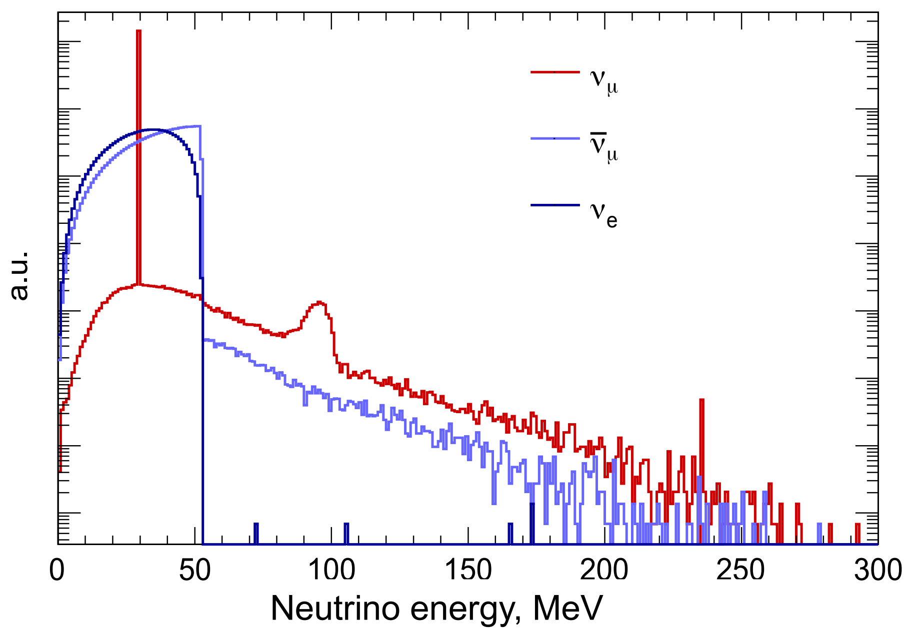
SNS as a neutrino source



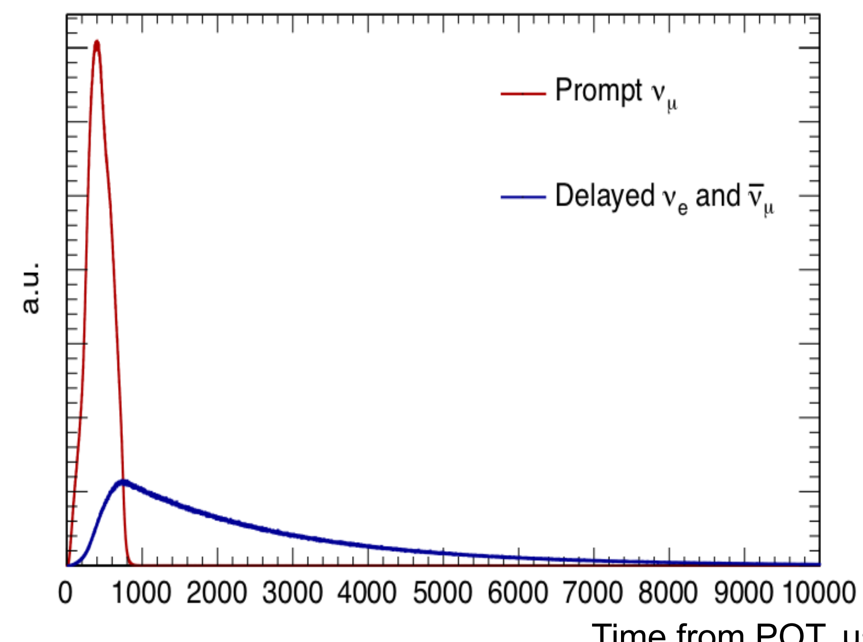
Proton beam energy ~ 1 GeV
Repetition rate — 60 Hz (bunch FWHM is 350 ns)
Neutrino Flux — $4.3 \cdot 10^{7}$ $cm^{-2}s^{-1}$ at 20 m



SNS neutrino energy spectrum



SNS neutrino timing



COHERENT at the SNS

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

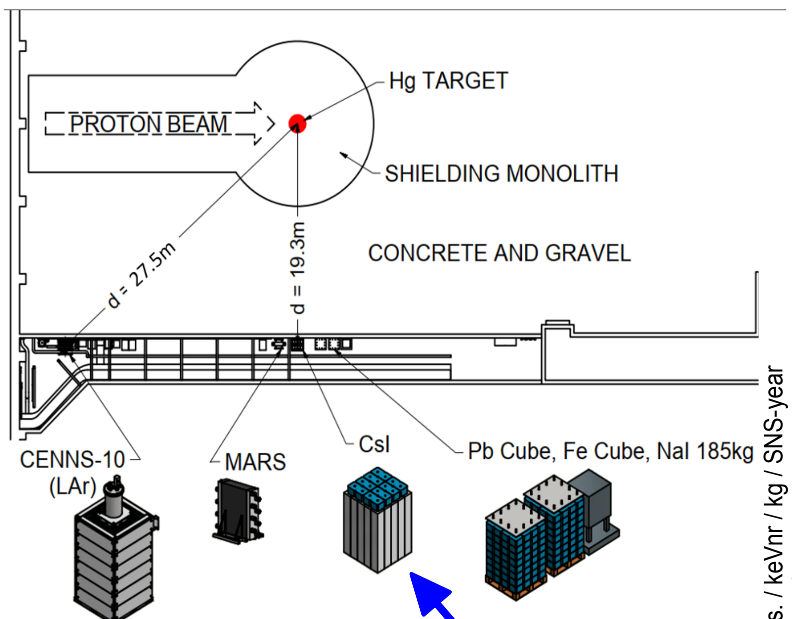
- 19-28 meters from Hg target
- Extremely low backgrounds

Multitarget experiment

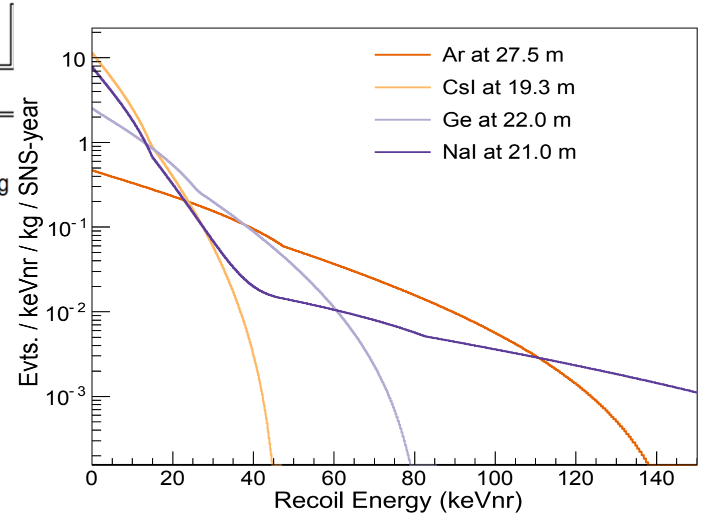
Nuclear Target	Technology	Mass (kg)	Distance from source (m)	Recoil Threshold (keVnr)
CsI[Na]	Scintillating crystal	14.6	19.3	6.5
LAr	Single-phase	24	27.5	20
NaI[Tl]	Scintillating crystal	185 → 3338	28	13
Ge	HPGe PPC	16	20	2-2.5

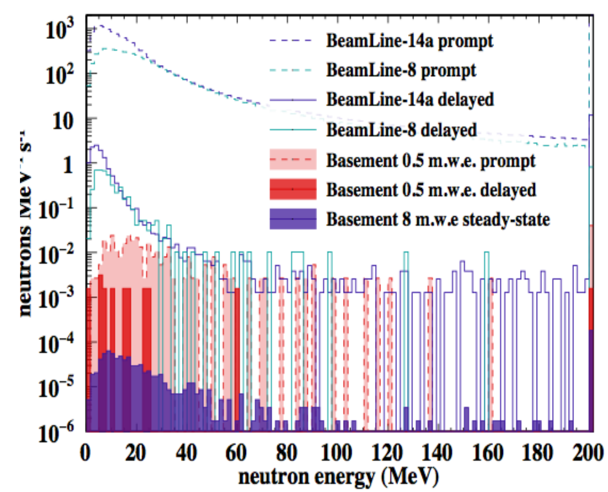
Result is obtained

Will be deployed



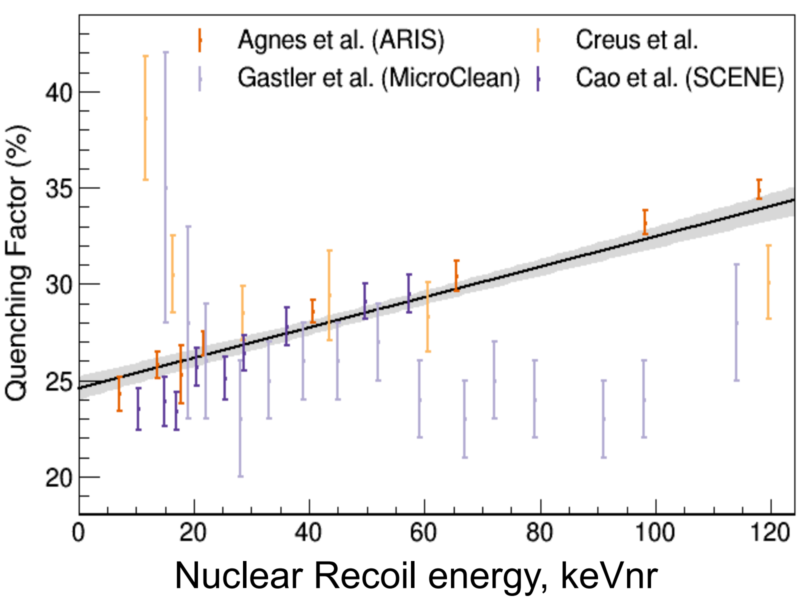
First observation

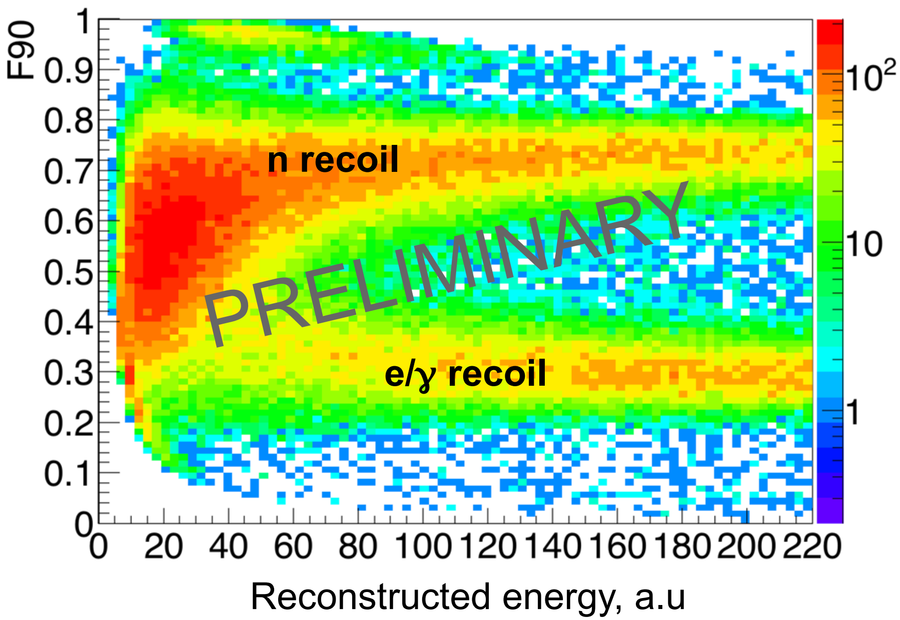




Liquid Argon for CEvNS

- Low N nucleus for CEvNS measurement
- Large scintillation yield of 40 photons/keVee
- Well-measured quenching factor
- Pulse shape discrimination (PSD)/Particle ID (PID) capabilities for nuclear/electron recoil separation
  - ~6 ns singlet light
  - ~1.6 μs triplet light
- Electron recoil (ER) events mostly triplet light, Nuclear recoil (NR) events mostly singlet light



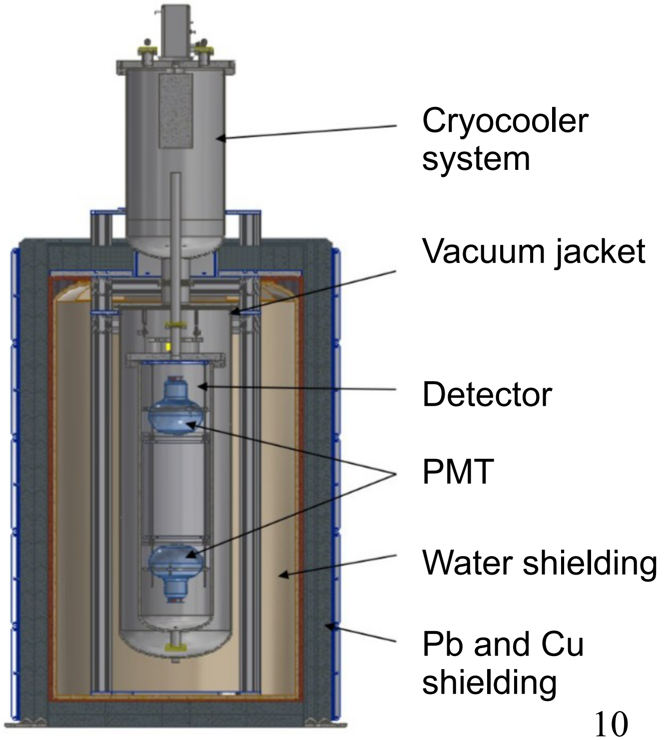


CENNS-10 Liquid Argon Detector

CENNS-10 was deployed at the SNS at 2016

Detector key features:

- 24 kg fiducial volume
- 2 x 8” Hamamatsu PMTs, 18% QE at 400 nm
- Tetraphenyl butadiene (TPB) coated side reflectors and PMT windows
- Pb (10 cm), Cu (1.25 cm), H_2O (20 cm) shielding
- Engineering Run (early 2017): high threshold, no lead shielding: **(Phys. Rev. D100 (2019) no.11, 115020)**
- First Production Run (July 2017-December 2018): improved threshold, blind analysis with two parallel groups, publication is expected soon



Parallel Blind Analyses

To reduce potential bias on result during analysis procedure CENNS-10 First Production Run was analysed by US-based and Russian-based (NRNU MEPhI, ITEP) groups in parallel:

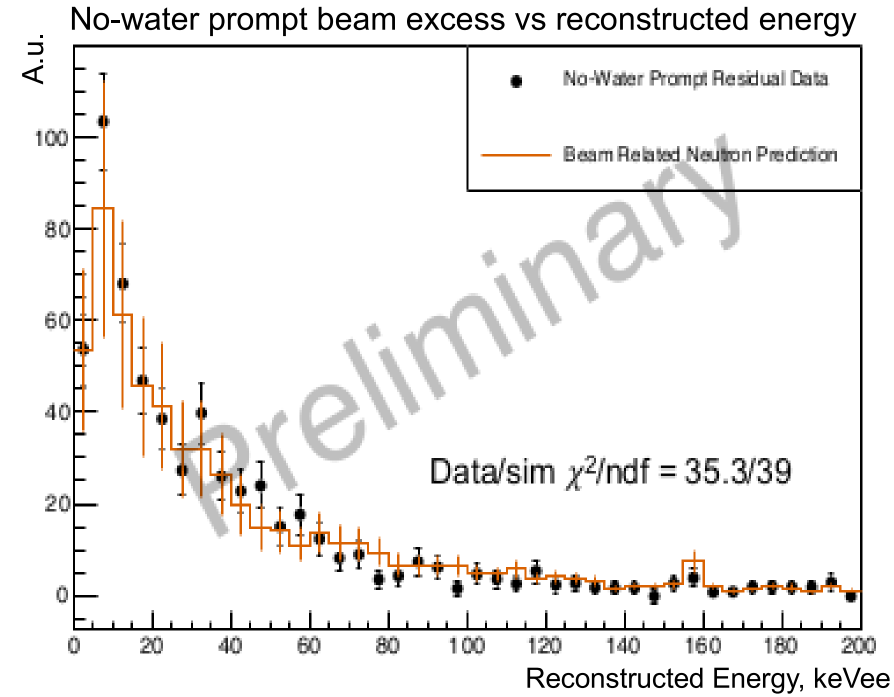
1. Common CENNS-10 Monte Carlo model was created;
2. SNS beam-on data were not seen until cuts finalized;
3. No cut-values or results shared between groups before data opening

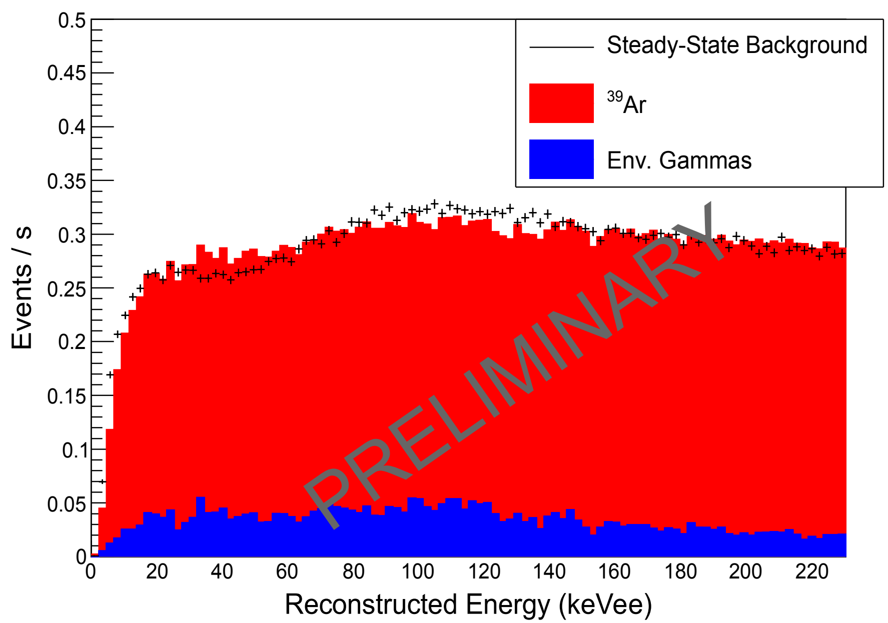
This talk is focused on Russian-based group analysis results

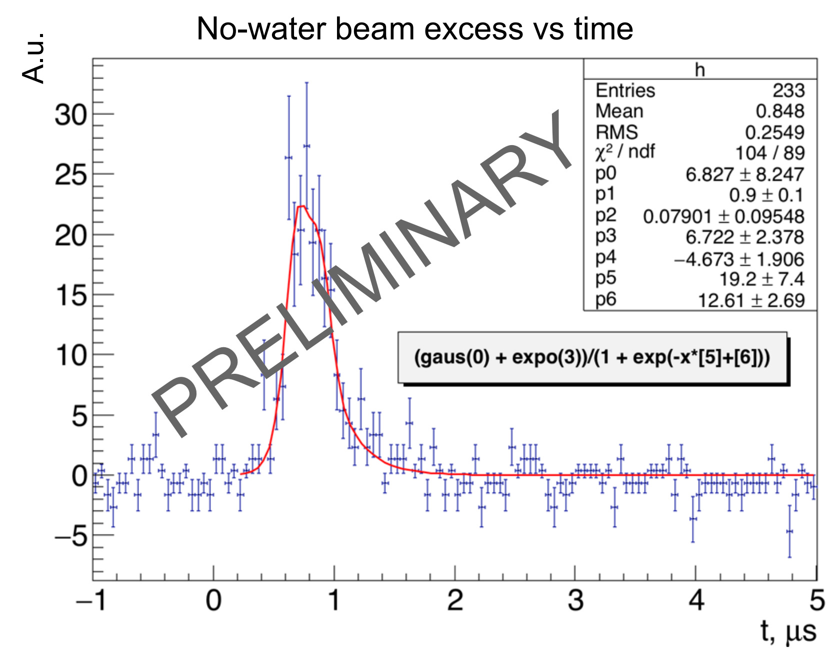
Backgrounds

Background components:

- Beam related neutron (BRN) normalization from no-water shielding data
- Main beam-unrelated component is ^{39}Ar with full shielding
  - Directly measured through off-beam triggers







Predicted Event Distributions for Likelihood Analysis

Perform 3D binned likelihood analysis in energy, F90, and time:

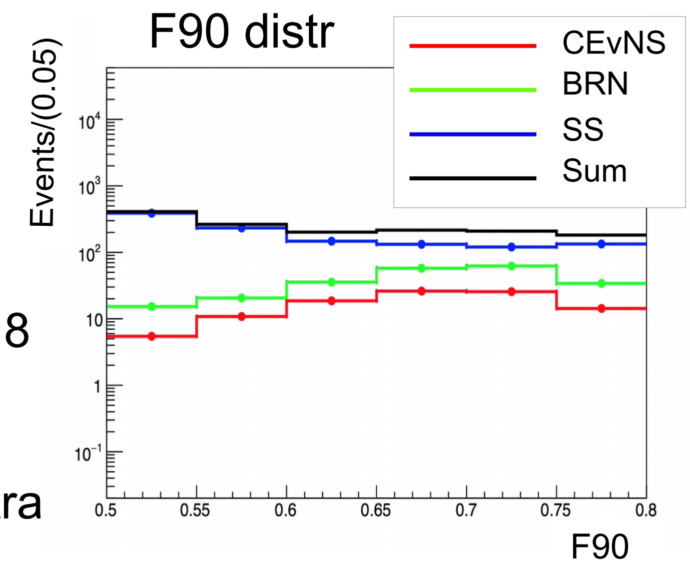
Cuts

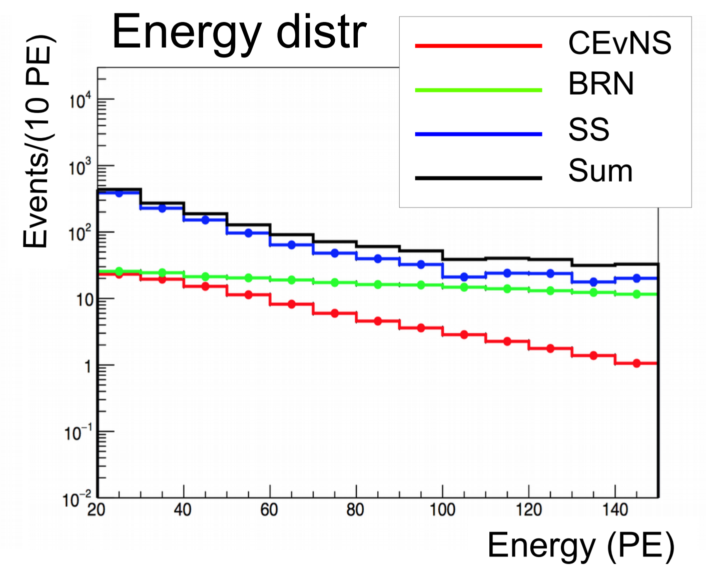
- Quality cut;
- Time cut: -1 - 8 us
- Energy cut: 20-150 PE
- Fiducial volume cut: 0.2-0.8
- F90 cut: 0.5-0.8

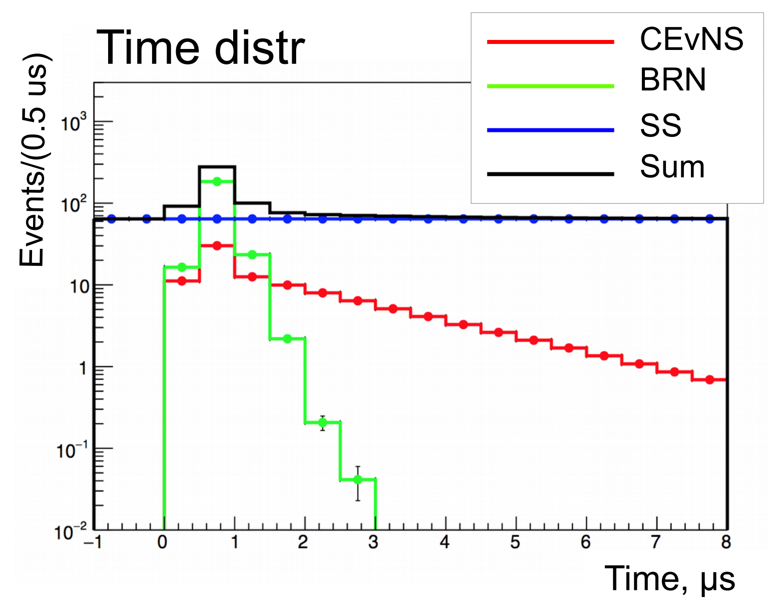
Neutrons and neutrino spectra were simulated

Steady-State background was extracted from “strobe” (off-beam) data

Shapes of distributions







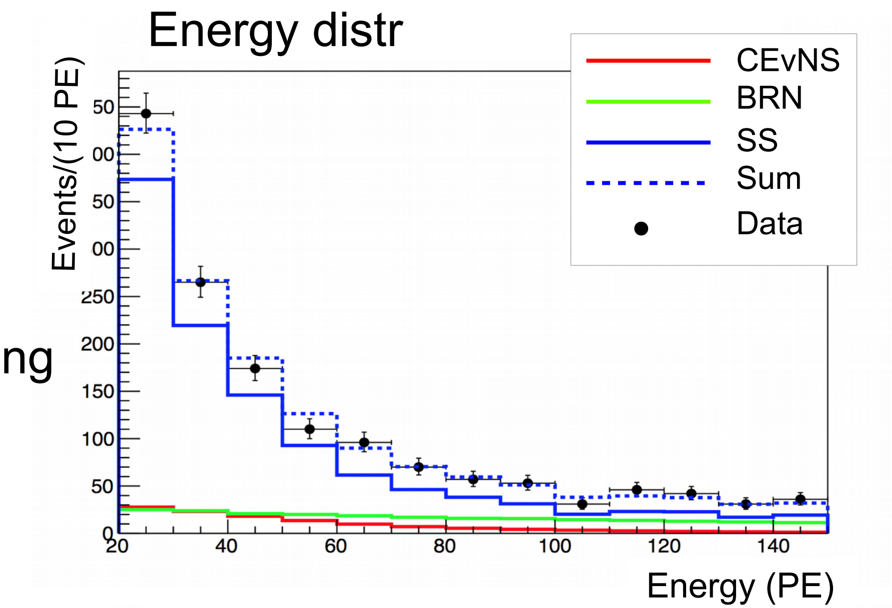
Predictions

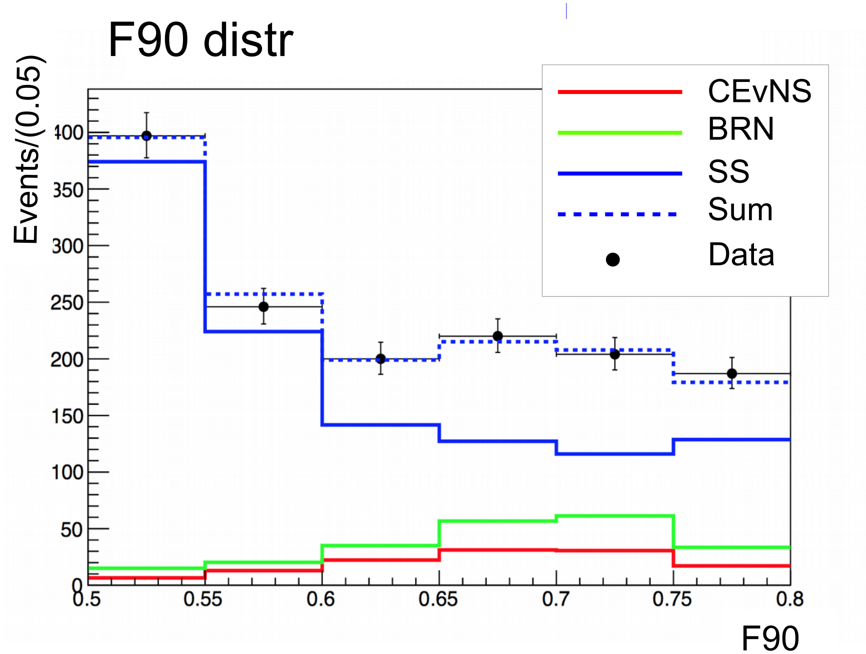
CEvNS	101 ± 12
Beam Related Neutrons (BRN)	226 ± 33
Steady-State Bkg (SS)	1155 ± 45

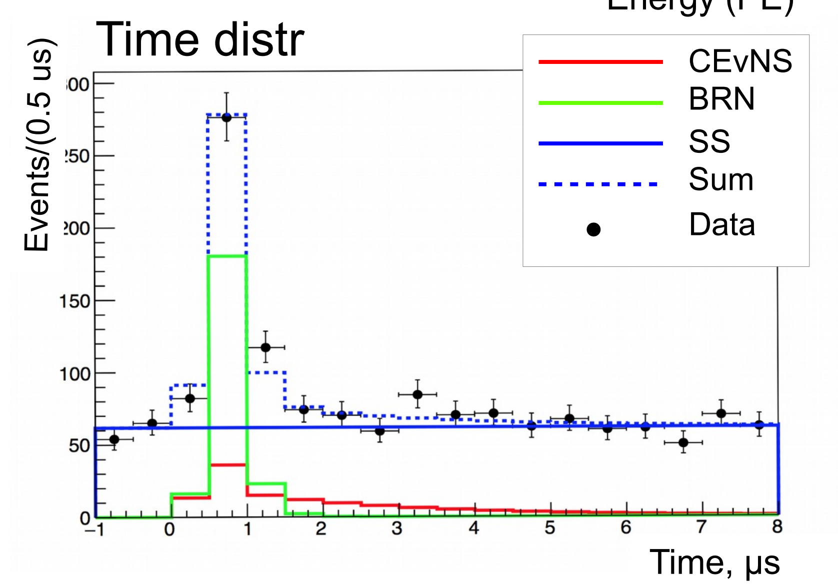
After all the preparations were done beam data were opened

Experimental Data Fit

- Presence of CEvNS fits data well
- Fit systematic error is ~ 13%
  - Obtained on Monte Carlo before unboxing







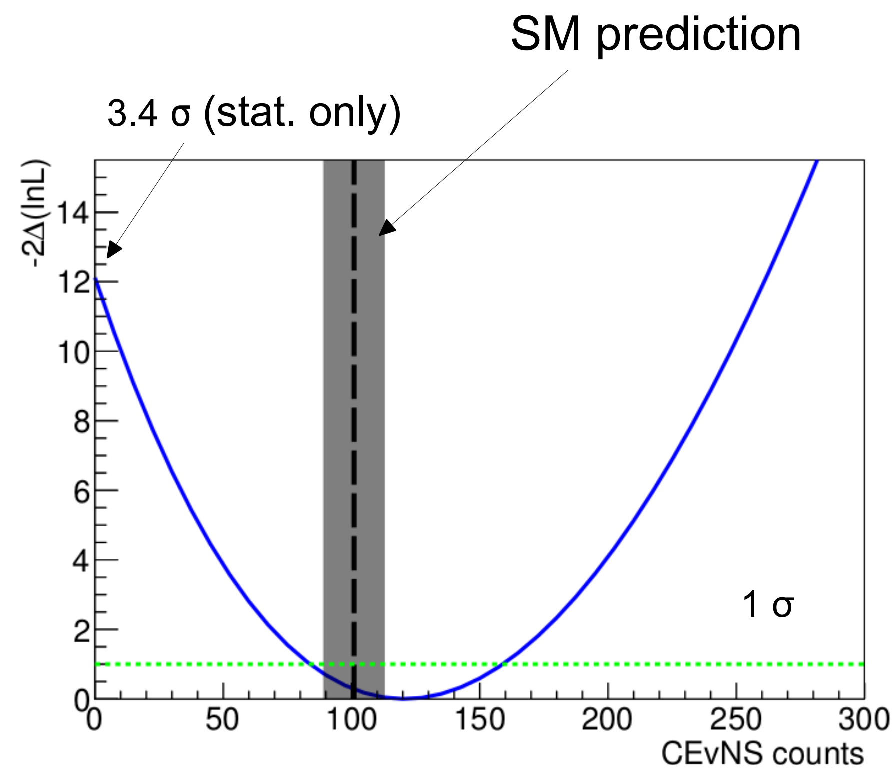
Likelihood Fit Results

3D binned likelihood analysis in energy, F90, time space

Best fit CEvNS counts of:

121 ± 36 (stat.) ± 15 (syst.)

- Result (stat. only) rejects null hypothesis at 3.4 σ
- Result (stat. + syst.) rejects null hypothesis at ~ 3.1 σ
- Best fit result within 1σ of SM prediction



Predictions and analysis results

Data component	Predictions	Analysis results
CEvNS	101 ± 12	121 ± 36 (stat.) ± 15 (syst.)
BRN	226 ± 33	222 ± 23
SS	1155 ± 45	1112 ± 41

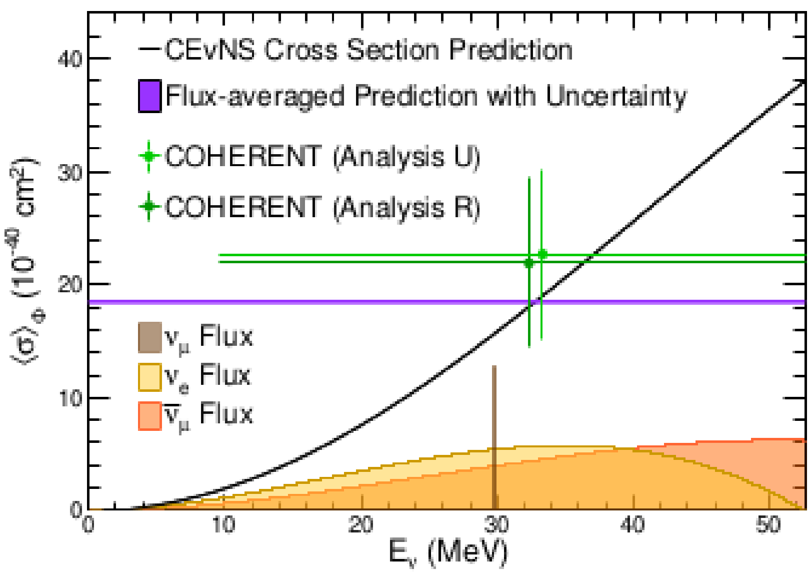
Analysis results comparison

	Russian-based group		US-based group	
Data Component	Predictions	Analysis results	Predictions	Analysis results
CEvNS	101 ± 12	121 ± 36 (stat.) ± 15 (syst.)	128 ± 17	159 ± 43 (stat.) ± 14 (syst.)
BRN	226 ± 33	222 ± 23	497 ± 160	553 ± 34
SS Bkg	1155 ± 45	1112 ± 41	3154 ± 25	3131 ± 23

Flux averaged CEvNS cross-section:

$$\sigma_{meas} = \frac{N_{meas}}{N_{SM}} \sigma_{SM} = (2.2 \pm 0.7) \times 10^{-39} \ \ cm^2$$

Both analyses find significant excess of events within 1σ of SM predictions



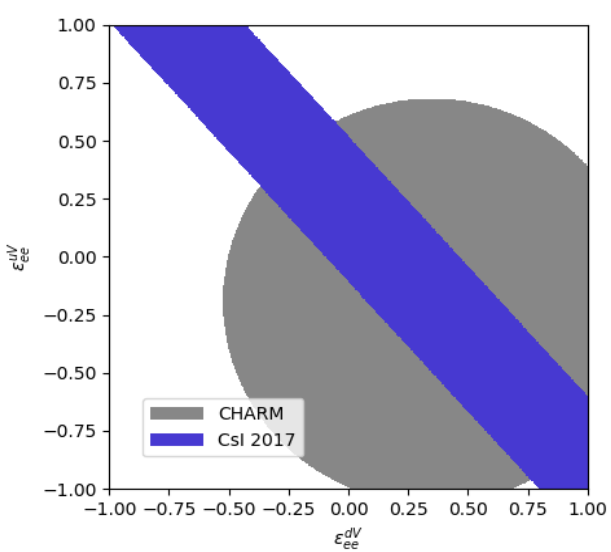
Non-Standard Interactions (NSI)

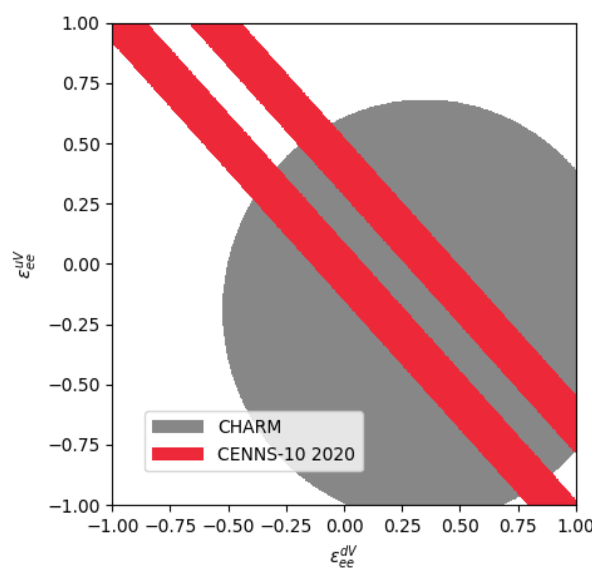
Compute allowed regions in NSI parameter space

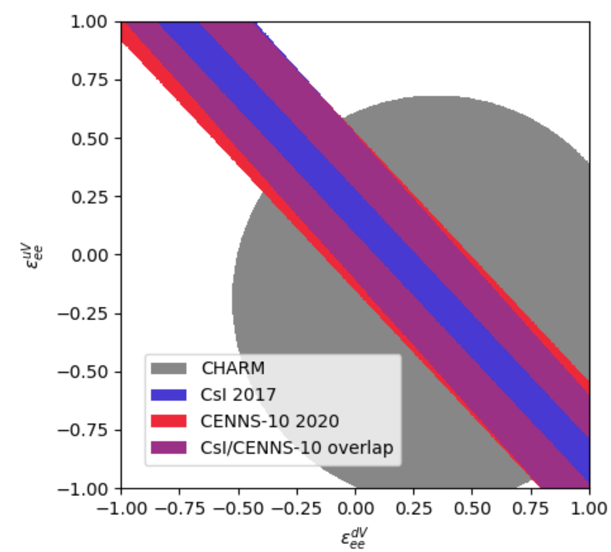
$$Q_W^2 \rightarrow Q_{\rm NSI}^2 = 4\left[N\left(-\frac{1}{2}+\epsilon_{ee}^{uV}+2\epsilon_{ee}^{dV}\right)+Z\left(\frac{1}{2}-2\sin^2\theta_W+2\epsilon_{ee}^{uV}+\epsilon_{ee}^{dV}\right)\right]^2$$

Limitations:

- Specifically ν_e flavor-preserving quark-vector coupling parameter space
- Set all other ε = 0







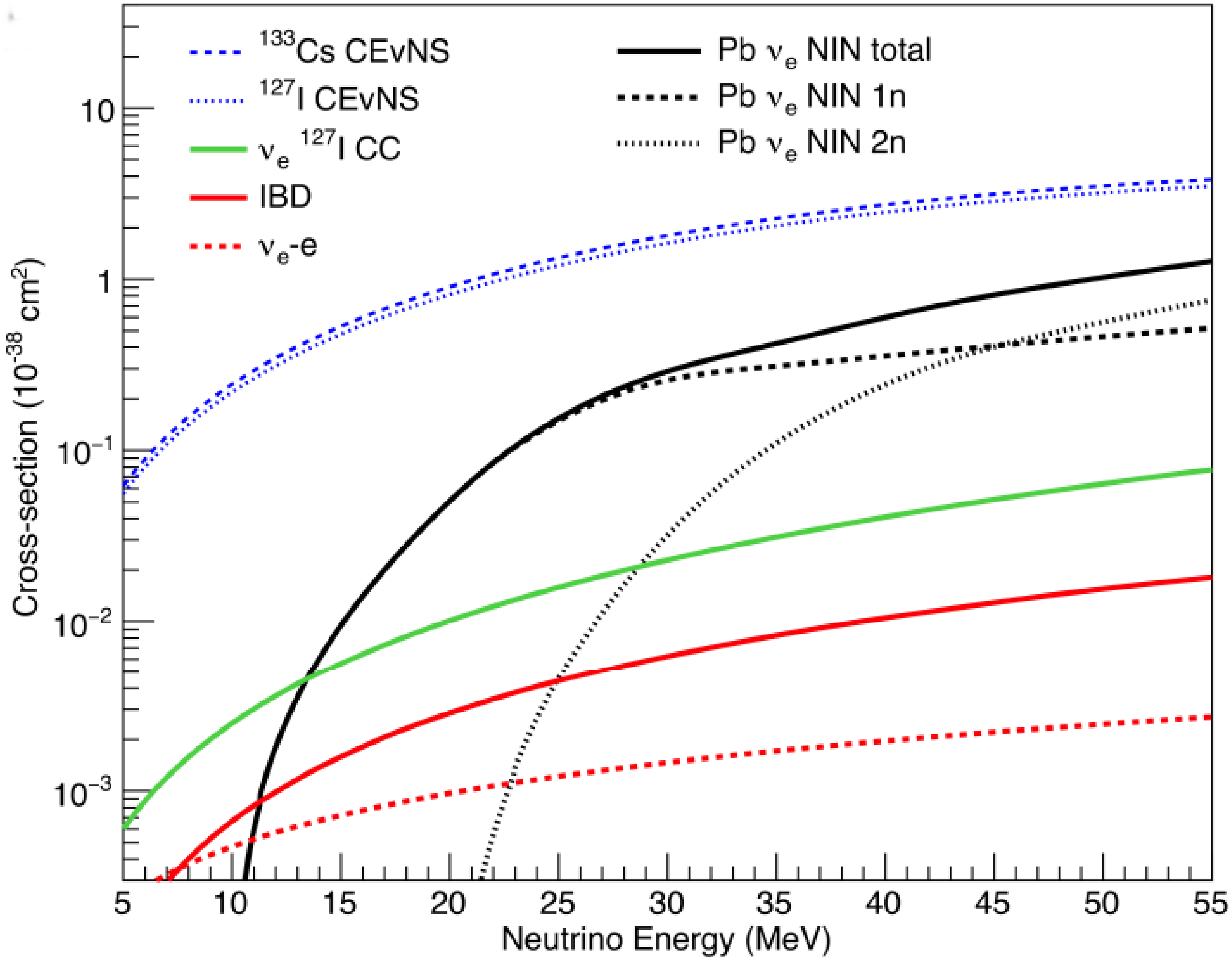
Summary

The COHERENT experiment at the SNS has a rich program to measure CEvNS after first observation in 2017

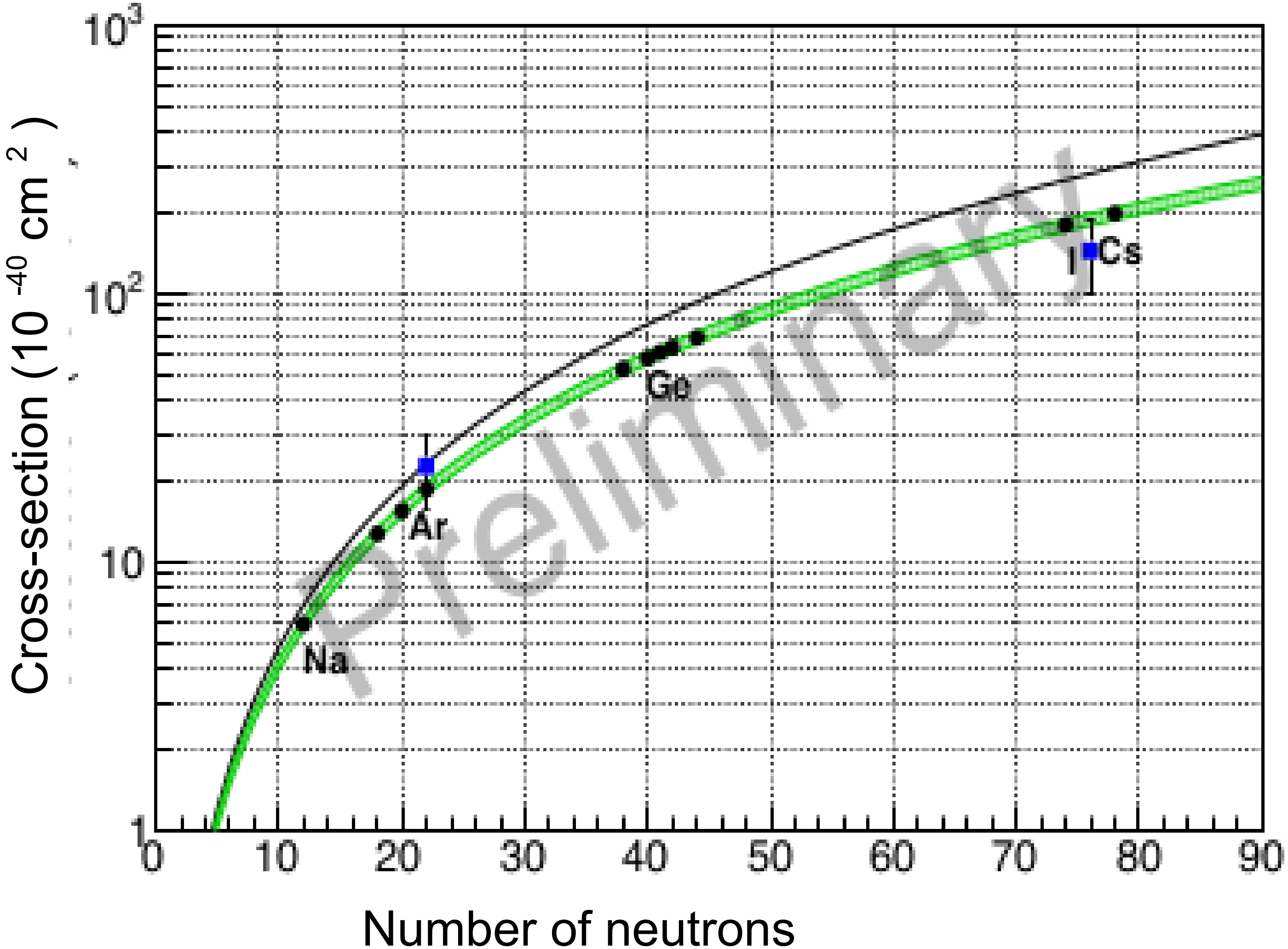
- First low-*N* measurement of CEvNS on ^{40}Ar with CENNS-10 detector
  - ➔ More then 3σ detection of CEvNS in ^{40}Ar with first production data
- Results are consistent with predictions of the Standard Model

BackUp

Neutrino processes cross-section



CEvNS Cross Section

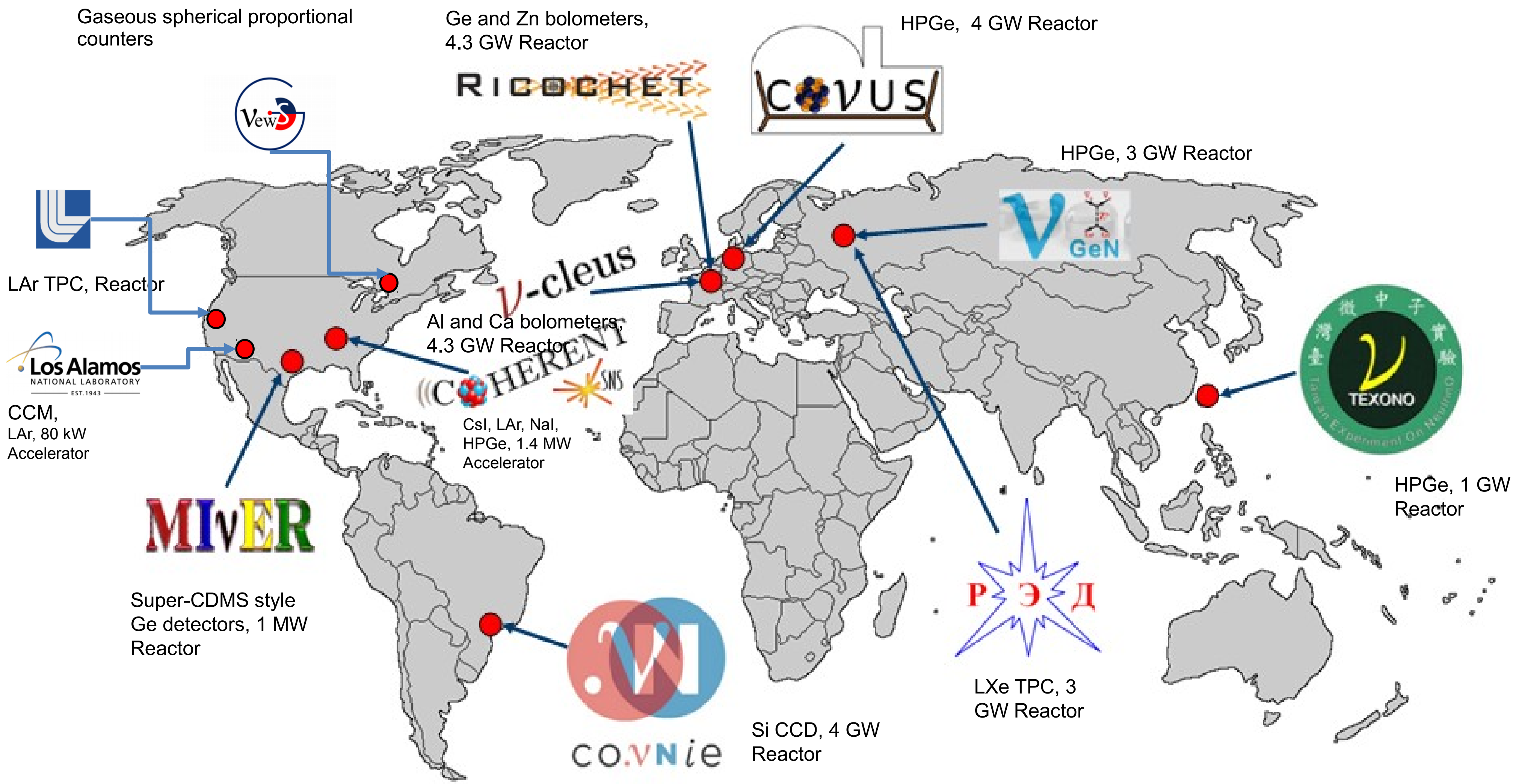


Flux averaged CEvNS cross-section:

$$\frac{N_{meas}}{N_{SM}} = 1.2 \pm 0.4$$

$$\sigma_{meas} = \frac{N_{meas}}{N_{SM}} \sigma_{SM} = (2.2 \pm 0.7) \times 10^{-39} \ cm^2$$

CEvNS Around The World



Non-Standard Interactions (NSI)

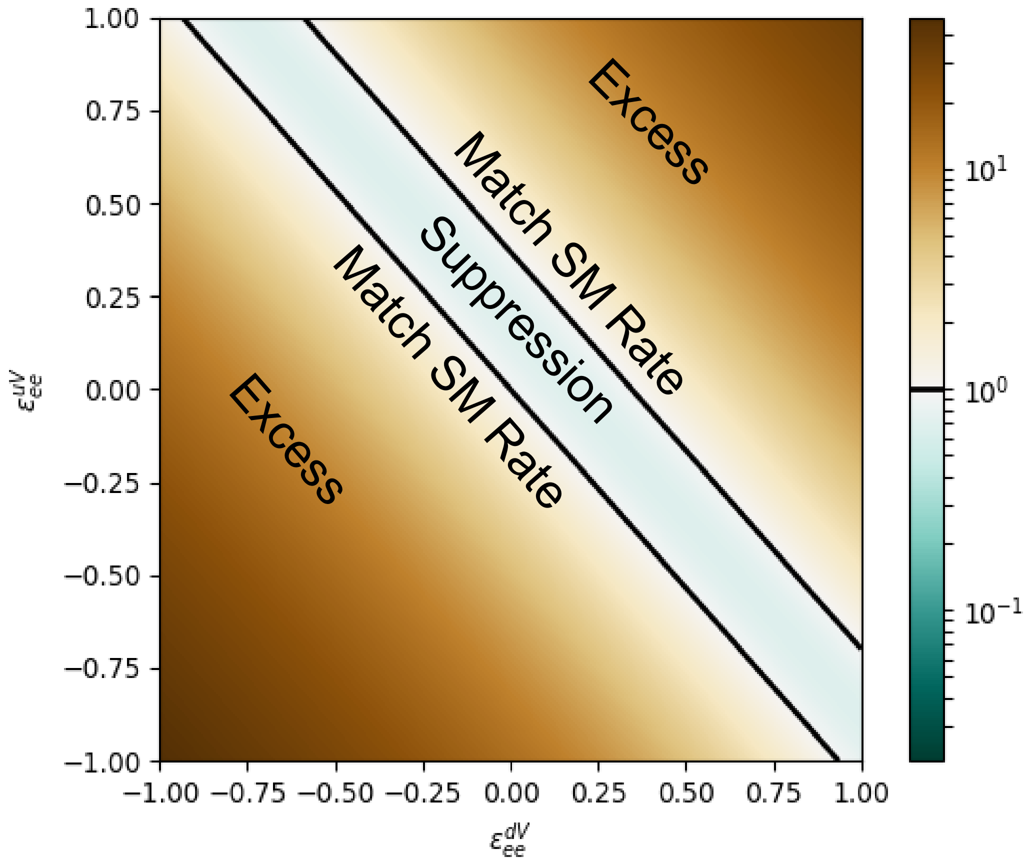
- Addition to SM Lagrangian

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \epsilon^{f,P}_{\alpha\beta}(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)(\bar{f}\gamma_\mu P f)$$

  - Modifies weak charge
  - NSI manifest as scaling of
  - expected CEvNS cross section
- CEvNS sensitive to both non-universal and flavor changing neutra currents

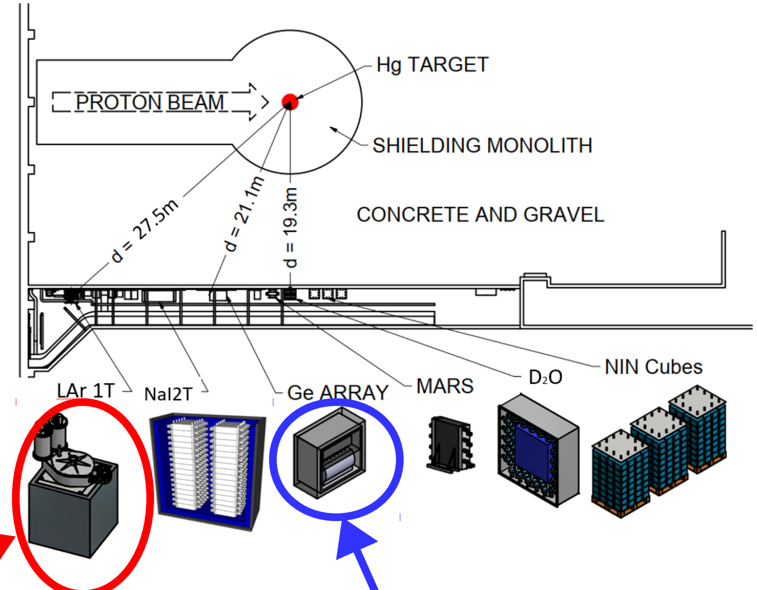
J. Barranco *et al.* , Phys. Rev. D 76 (2007)

J. Billard, J. Johnston, B. Kavanagh, arXiv:1805.01798



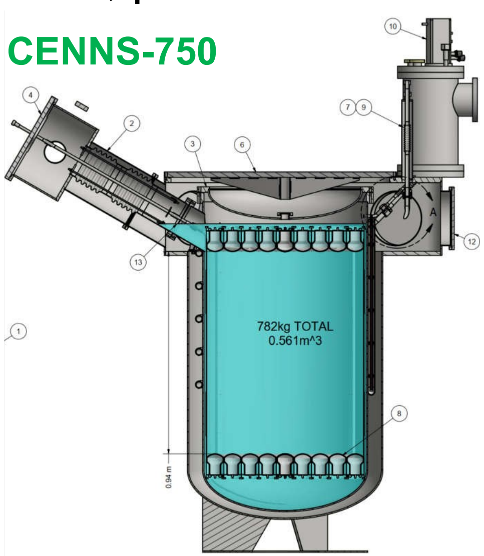
$$Q_W^2 \to Q_{\rm NSI}^2 = 4\left[N\left(-\frac{1}{2}+\epsilon_{ee}^{uV}+2\epsilon_{ee}^{dV}\right)+Z\left(\frac{1}{2}-2\sin^2\theta_W+2\epsilon_{ee}^{uV}+\epsilon_{ee}^{dV}\right)\right]^2$$

Future COHERENT Efforts: CENNS-750 & HPGE



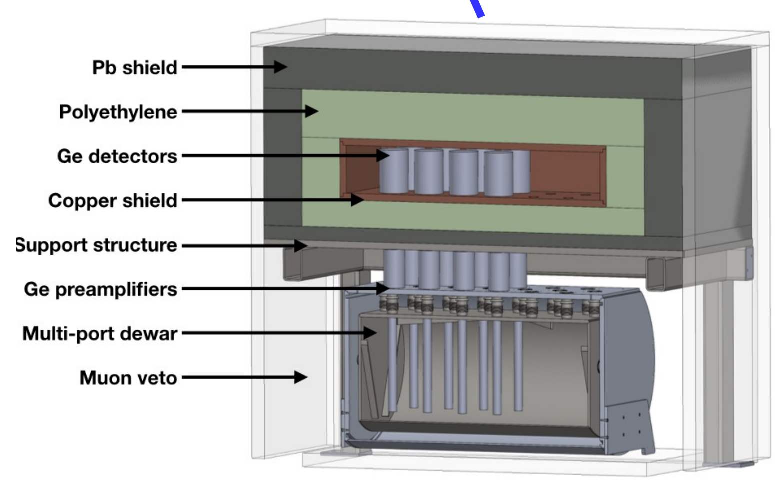
CENNS-750:

- Single-phase LAr calorimeter, 610 kg fiducial mass
- Based on the successful work with CENNS-10
- Expect ~20 keVnr threshold in ~25x LAr volume, push for lower



COHERENT LAr 1T conceptual design

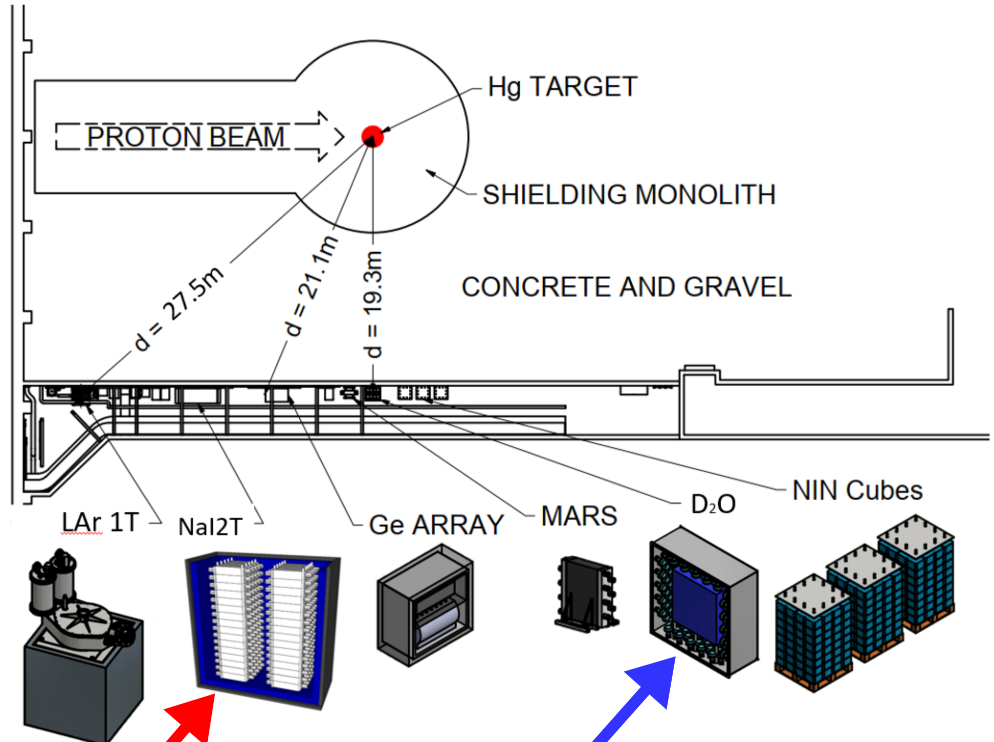
16 kg of HPGe detectors for CEvNS measurement

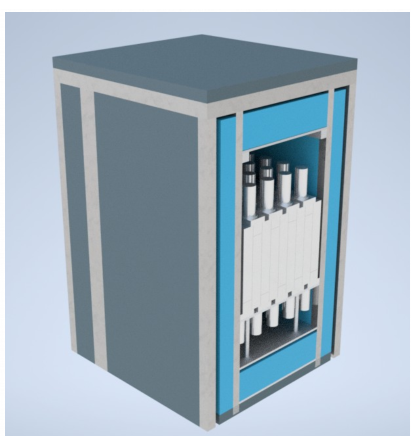


COHERENT Ge conceptual design

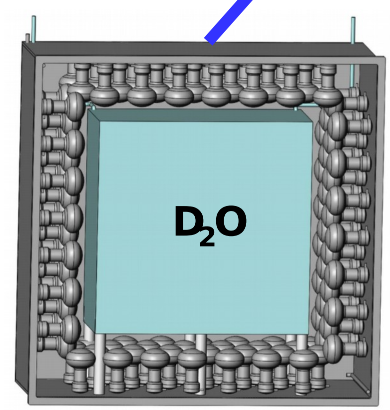
Future COHERENT efforts: NaI[Tl] & D_2O

- Ton-scale NaI[Tl] detector array for simultaneous CEvNS/^{127}I charged current measurements
- Ton-scale D_2O Cherenkov detector to reduce neutrino flux uncertainty:
  - ν_e-d charged current cross section theoretically known to 2-3%





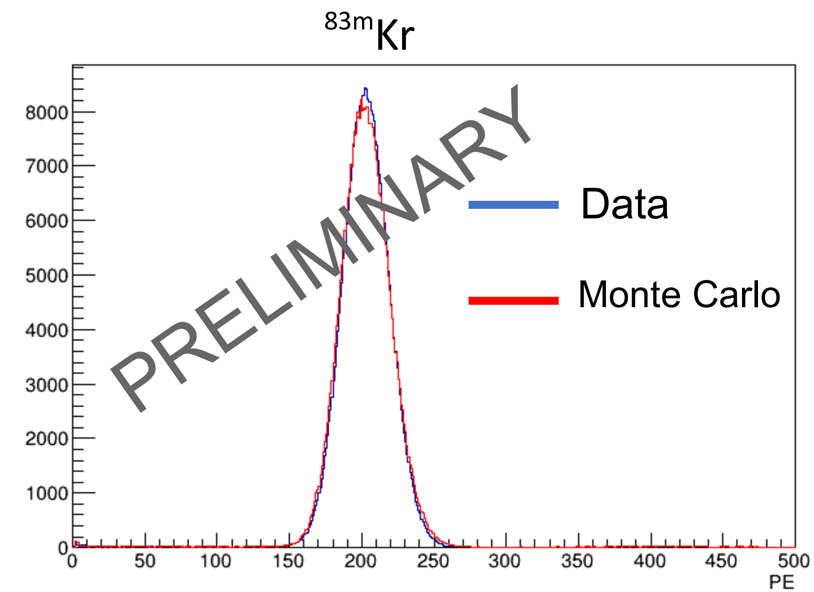
Modular ton-scale NaI[Tl] concept

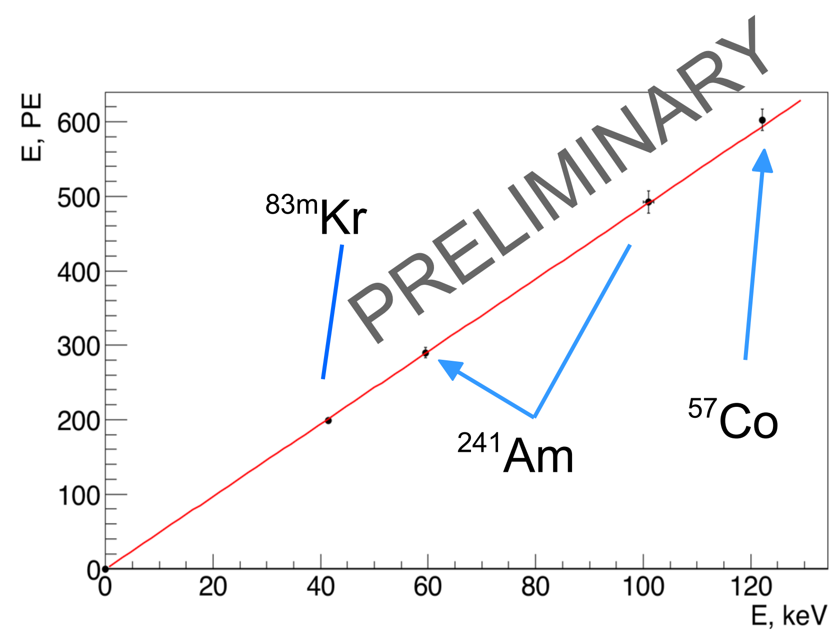


Ton-scale D_2O concept

CENNS-10 Calibrations

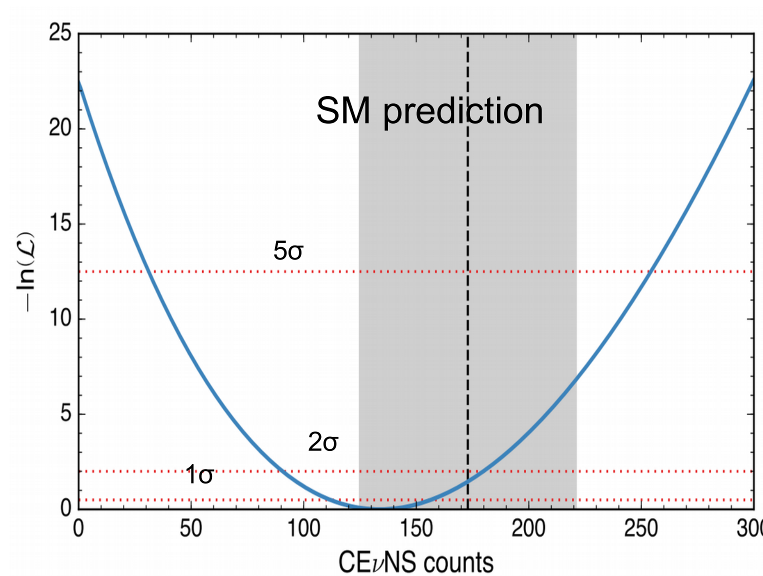
- Calibrate detector with different gamma sources:
  - ^{57}Co
  - ^{83m}Kr
  - ^{241}Am
- Measured light yield: 4.6 ± 0.4 PE/keV
- Detector resolution is 9.1% at 41.5 keV
- Calibrate detector nuclear recoil response using AmBe source





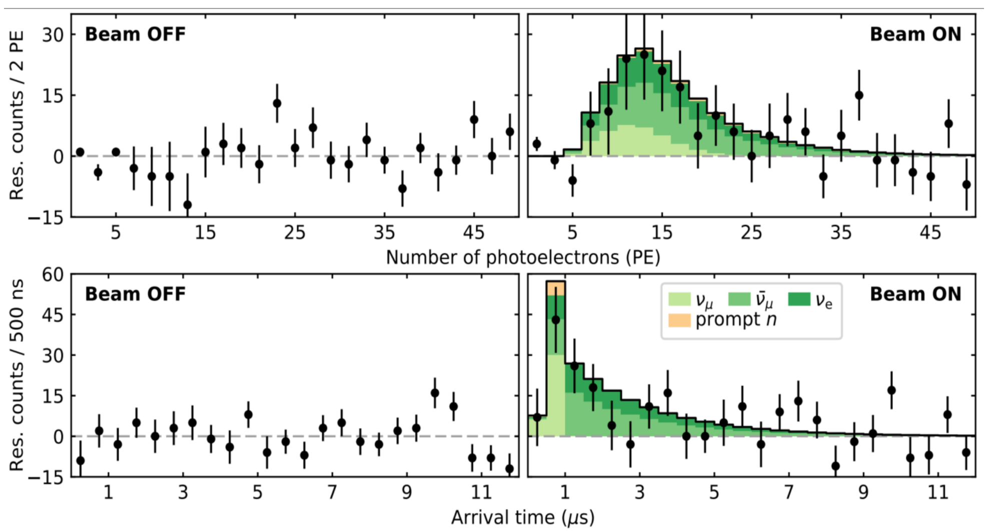
Discovery of CEvNS

- 14.6 kg CsI crystal
- Maximum Likelihood fit to data gives: 134 ± 22 CEvNS events
- Standard model predicts 173 ± 48 CEvNS events
- Null result rejected at 6.7σ
- New constraints on NSI
- More data available

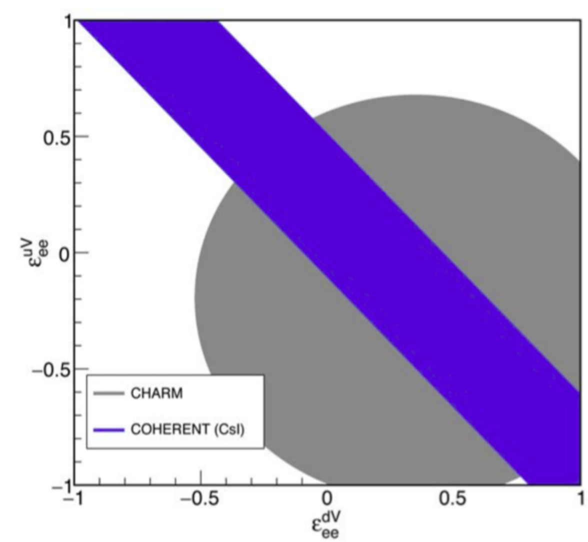


10.1126/science.aao0990

Energy

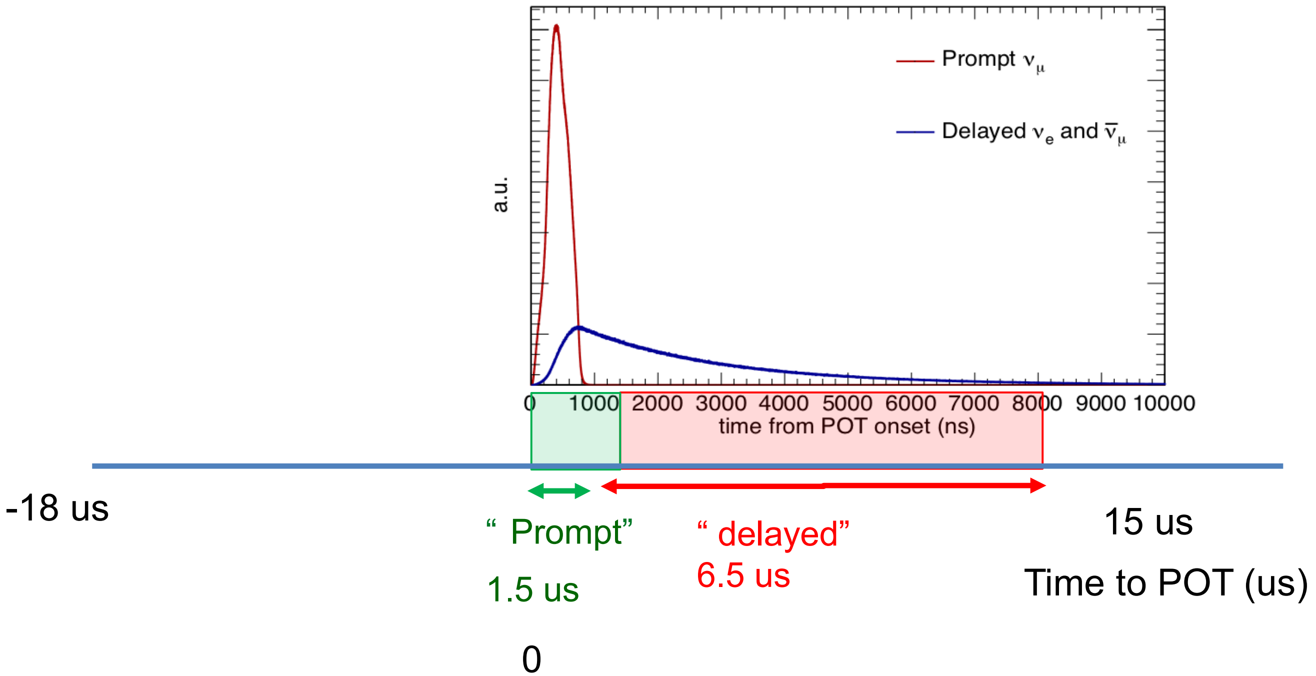


Time relative to beam pulse



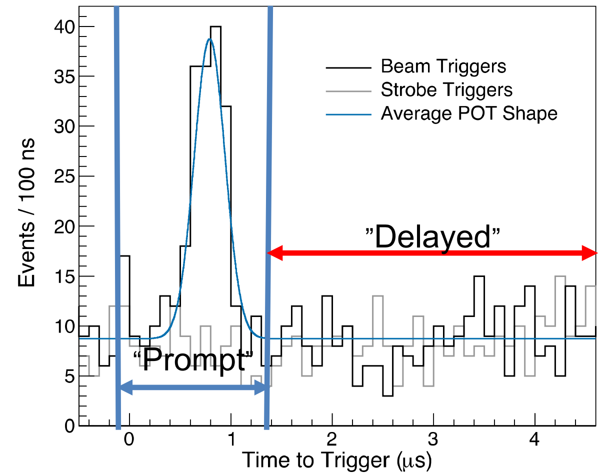
SNS Trigger

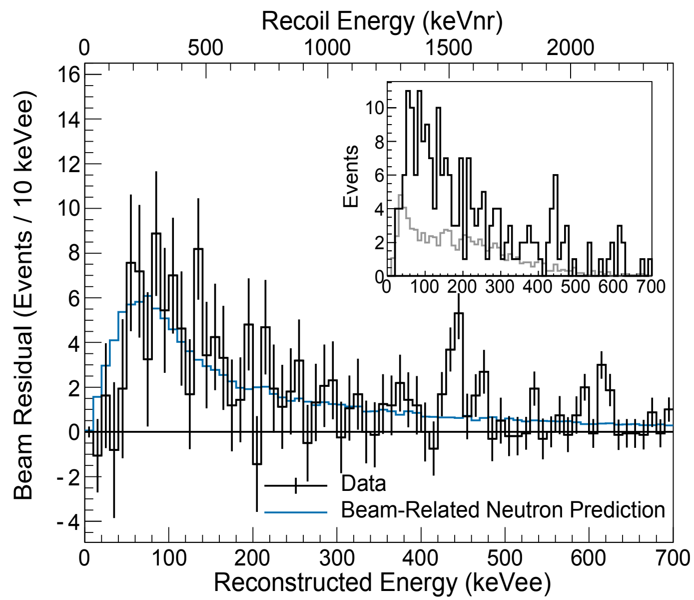
- SNS provides neutrinos in two regions after protons on target (POT): ”prompt” (0-1.5 μs after POT) and “delayed” (1.5-5 μs after POT).
- Beam-related neutron background measured only in prompt window. Delayed neutron measurements consistent with zero.
- Identical off-beam trigger 14 ms after accelerator trigger to measure beam-unrelated backgrounds in-situ.



Neutron Background Characterization

- Data from Engineering Run, analysis of 1.8 GWhr of SNS beam data from February-May 2017
- TPB coated acrylic backed by Teflon reflector and TPB coated acrylic disk
- Threshold (80 keVnr) not low enough for 0.2 sensitive CEvNS search
- Optimized cuts based on signal/noise
- Beam-related excess consistent with previous measurements/simulations
  - Delayed window excess consistent with zero due to high threshold and small beam sample
  - Use to constrain prompt beam-related neutron backgrounds for FirstProduction Run
- Also, place limit on CEvNS cross section





Engineering Run results:

Phys. Rev. D100 (2019) no.11, 115020
M. R. Heath (IU PhD Thesis) (2019)
http://inspirehep.net/record/1744690?ln=en

PRD Editor's Suggestion

Event Selection

Quality cuts:

- Signal start is on 20 ns window
- Waveform has only one event

Time cut:

- Event should be inside prompt or delayed time window

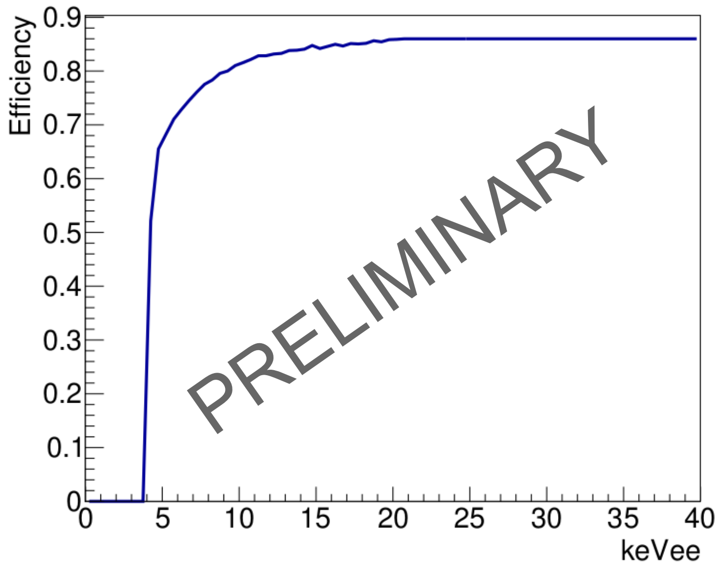
Energy cut:

- Region 4-30 keVee allowed;

Fiducial Volume (F.V.) cut:

- Ratio of top PMT light to full amount of light detected is 0.2-0.8;

- PSD cut



Systematic Errors

CEvNS Rate Measurement Errors

Error Source	Uncertainty
Energy region	4.7%
PSD distribution shape	3.3%
Fiducial Volume	1.2%
Nuclear Form Factor	3%
SNS Predicted Neutrino Flux	10%
Other systematic sources	1%
Total Error:	**12.0%**

Additional Likelihood Fit Shape-Related Errors

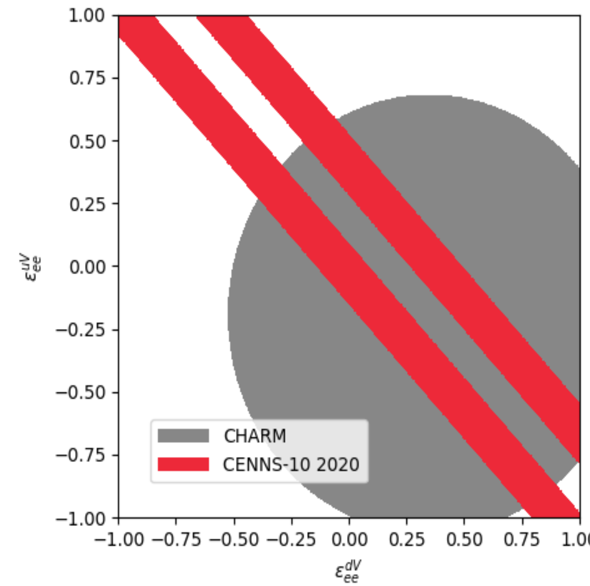
Error Source	Uncertainty
PSD distribution shape	3.1%
CEvNS Arrival Mean Time	6.3%
BRN Arrival Time Mean	5.3%
BRN Arrival Time Width	7.7%
BRN distribution shape	5.2%
Other systematic sources	<1%
Total Error:	**12.8%**

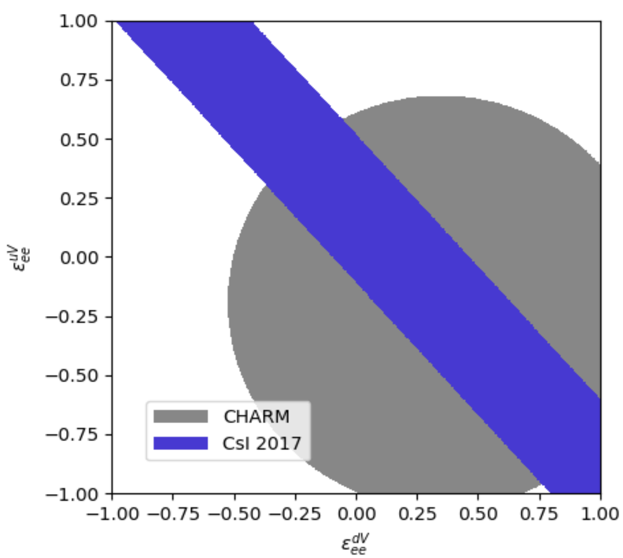
Non-Standard Interactions (NSI)

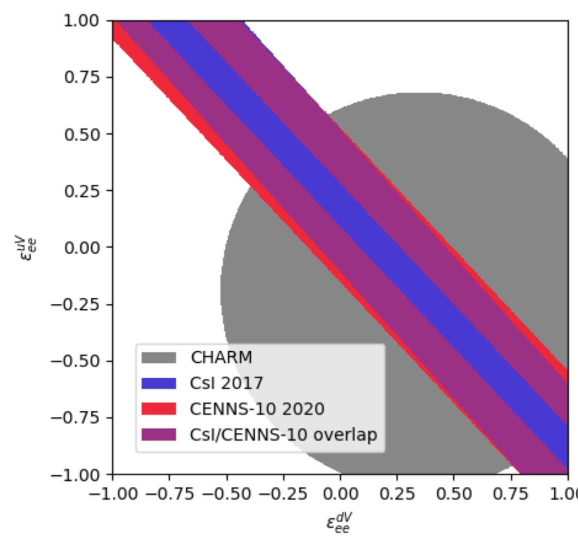
Compute allowed regions in NSI parameter space

Limitations:

- Specifically ν_e flavor-preserving quark-vector coupling parameter space
- Set all other ε = 0







Plots from G. Sinev (Duke)