neutrino-nucleus scattering with COHERENT experiment

R. Tayloe, Indiana U.
for the COHERENT collaboration

Outline

- physics of CEvNS
- COHERENT at ORNL/SNS
- discovery of CEvNS
- Future plans

The 14th International Workshop on the Dark Side of the Universe
DSU 2018
25 - 29 June 2018
LAPTh, Annecy, France
LAPTh

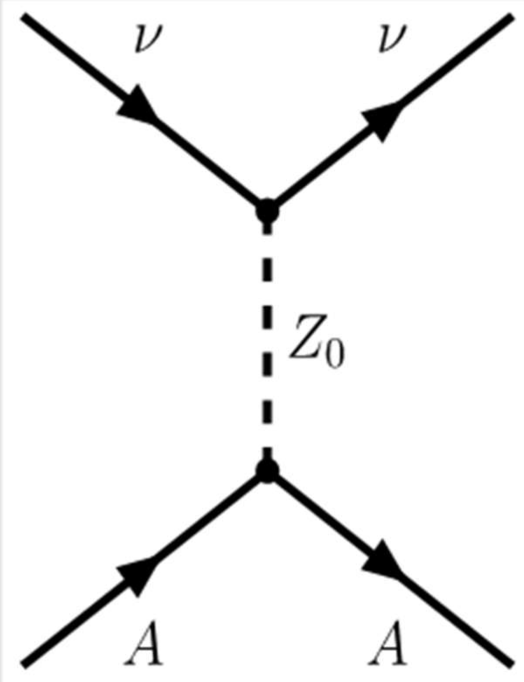
Coherent Elastic ν-Nucleus Scattering:

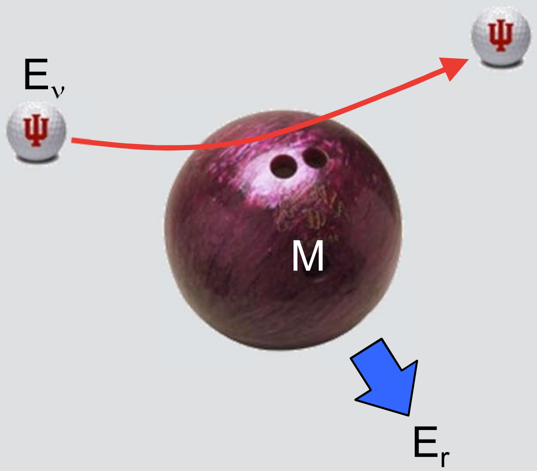
"CEvNS":

Coherent Elastic ν-Nucleus Scattering: νA→νA

Neutrino scatters with low momentum transfer coherently, elastically from entire nucleus (eg Cs, I, Ar) . For a large nucleus, R_N~few fm, and:

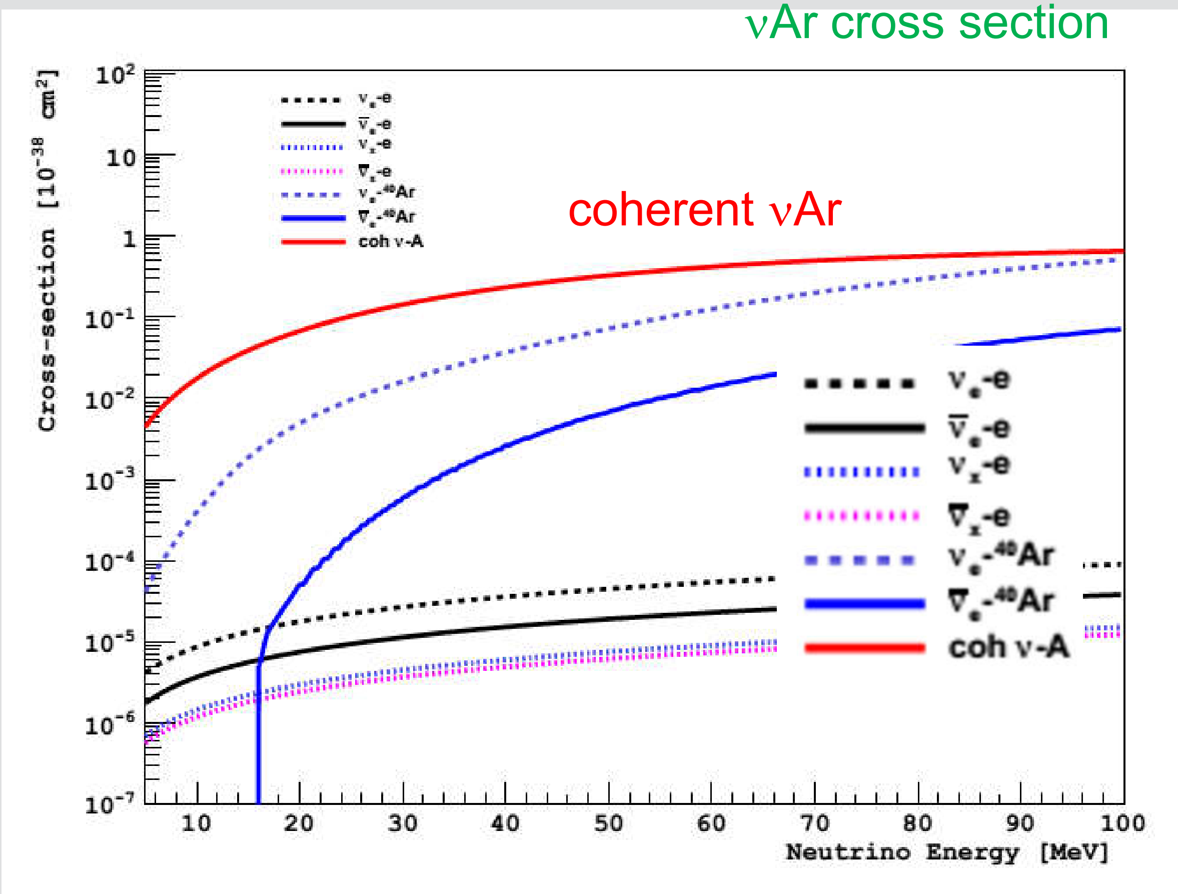
$$E_\nu \lesssim \frac{hc}{R_N} \cong 50 \text{ MeV}$$





Coherent Elastic ν-Nucleus Scattering:

Cross section is large… in fact largest ν channel at O(10 MeV) on heavier nuclei, eg Ar



and has distinctive N^2 dependence

$$\frac{d\sigma}{dE} = \frac{G_F^2}{4\pi}[(1-4\sin^2\theta_w)Z-(A-Z)]^2 M\left(1-\frac{ME}{2E_\nu^2}\right)F(Q^2)^2$$

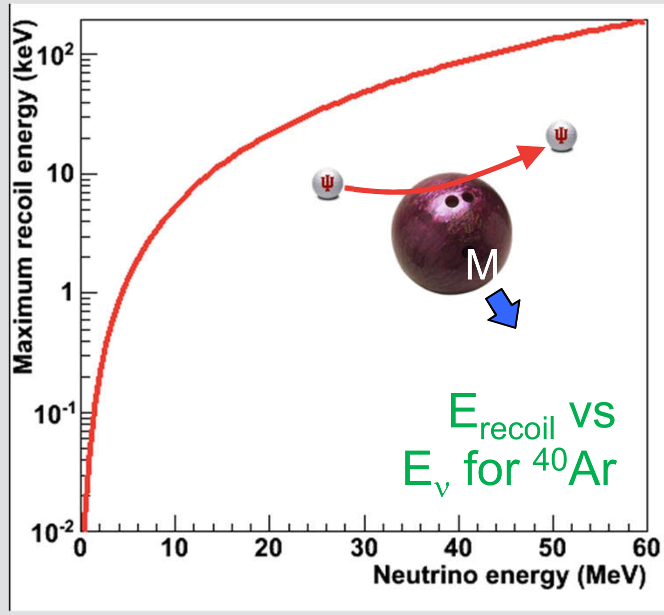
Small

N^2

<u>Coherent Elastic ν-Nucleus Scattering:</u>

.. but recoil energy is quite small:

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



only recently

And so, the CEvNS process has ^ ~~never~~ been observed… 40 years after its prediction...

PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

Coherent effects of a weak neutral current

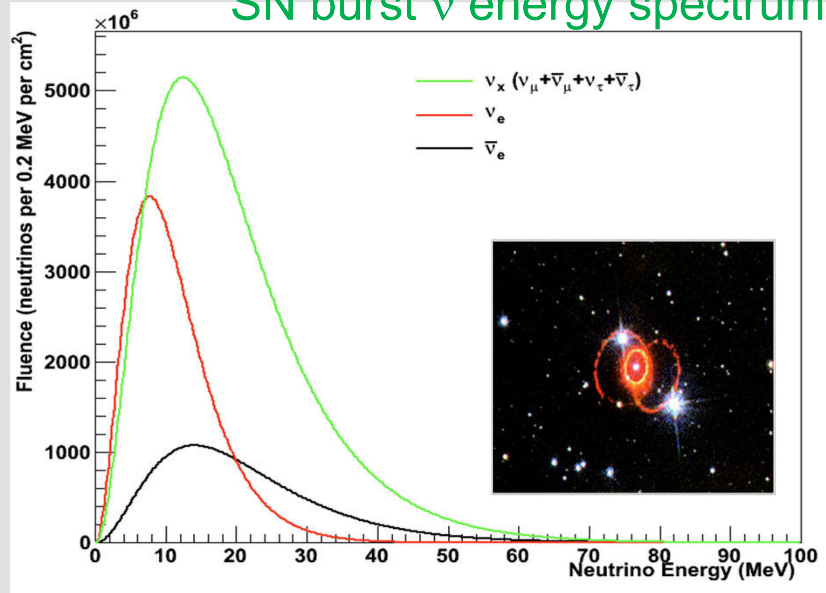
Daniel Z. Freedman†
National Accelerator Laboratory, Batavia, Illinois 60510
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790
(Received 15 October 1973; revised manuscript received 19 November 1973)

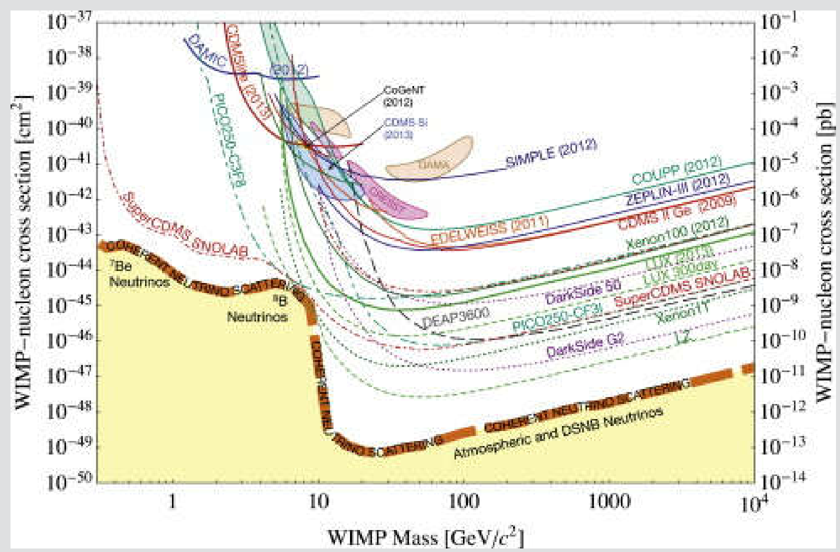
Coherent Elastic ν-Nucleus Scattering:

Physics reach of CEvNS:

- Understanding supernovae (SN):
  - Expected to be important in core-collapse SN and
  - possible SN detection channel.
- Standard Model tests, eg: NSI, $\sin^2 \theta_W$, neutrino magnetic moments
- Nuclear Physics: nuclear form factors
- ν oscillations: Investigation of $\nu_{sterile}$ oscillations
- reactor monitoring (non-proliferation)
- Dark Matter:
  - Important background for O(10-ton) direct searches
  - detectors sensitive for accelerator produced DM…

SN burst ν energy spectrum





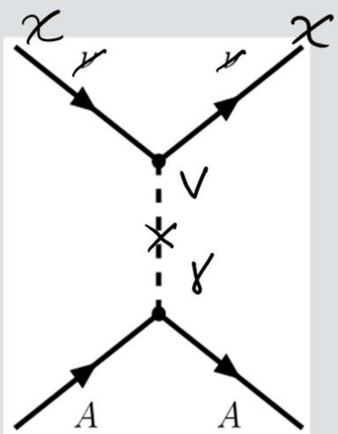
CEvNS physics:

Search for accelerator-produced, low-mass, dark matter

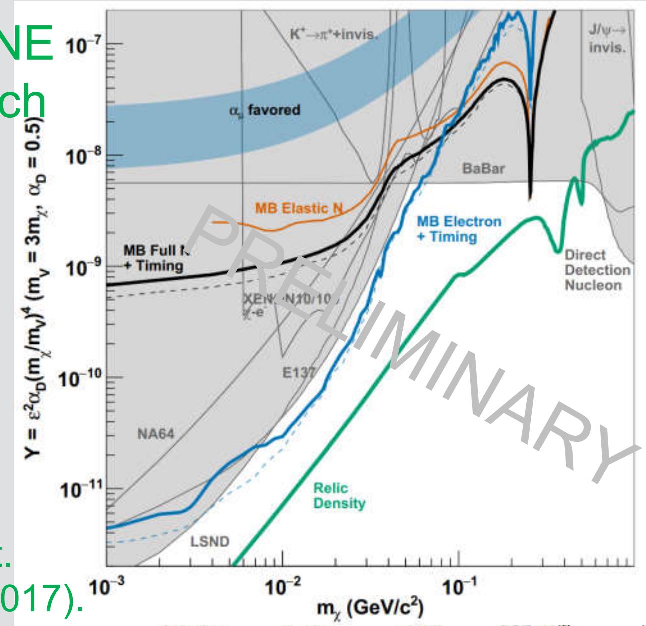
Via:

$$p \to \text{Hg} \to \pi^{0,\pm}$$

$$\pi^0 \longrightarrow \gamma + V^{(*)} \longrightarrow \gamma + \chi^\dagger + \chi$$

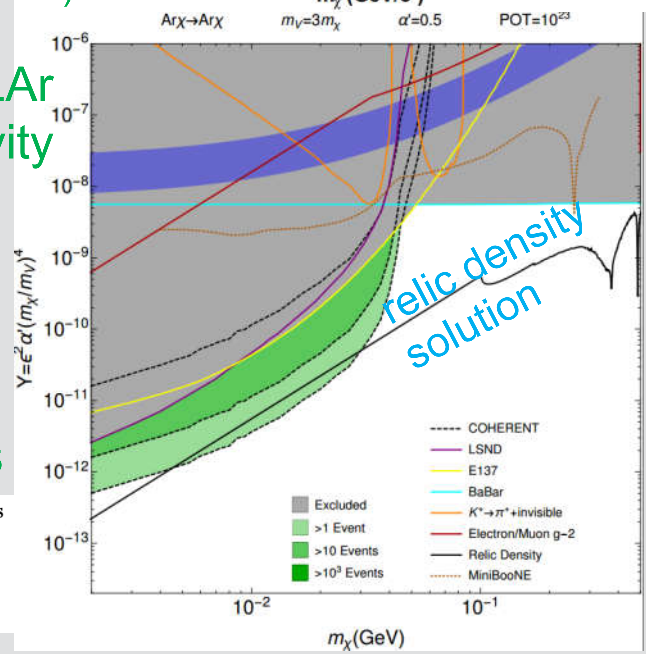


MiniBooNE DM search



New results, follow up to: Phys. Rev. Lett. 118, 221803 (2017).

1 ton-year LAr SNS DM sensitivity



arXiv:1505.07805

Light new physics in coherent neutrino-nucleus scattering experiments

Patrick deNiverville,[1] Maxim Pospelov,[1,2] and Adam Ritz[1]

[1] *Department of Physics and Astronomy, University of Victoria, Victoria, BC V8P 5C2, Canada*
[2] *Perimeter Institute for Theoretical Physics, Waterloo, ON N2J 2W9, Canada*
(Dated: May 2015)

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  - Expected to be important in core-collapse SN and
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- Standard Mod… neut…
- Nucle…
- ν osci… chann…
- reactor monitoring (non-proliferation)
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  - detectors sensitive for accelerator produced DM…

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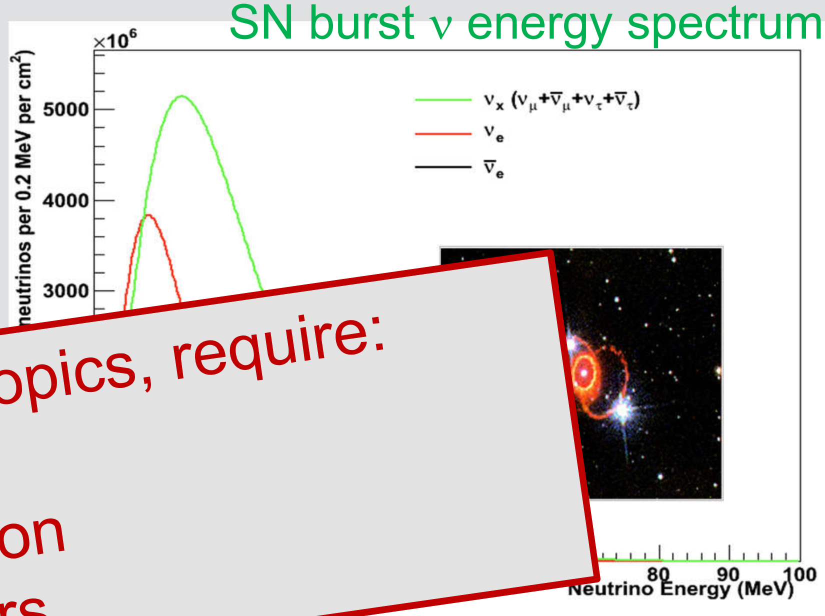
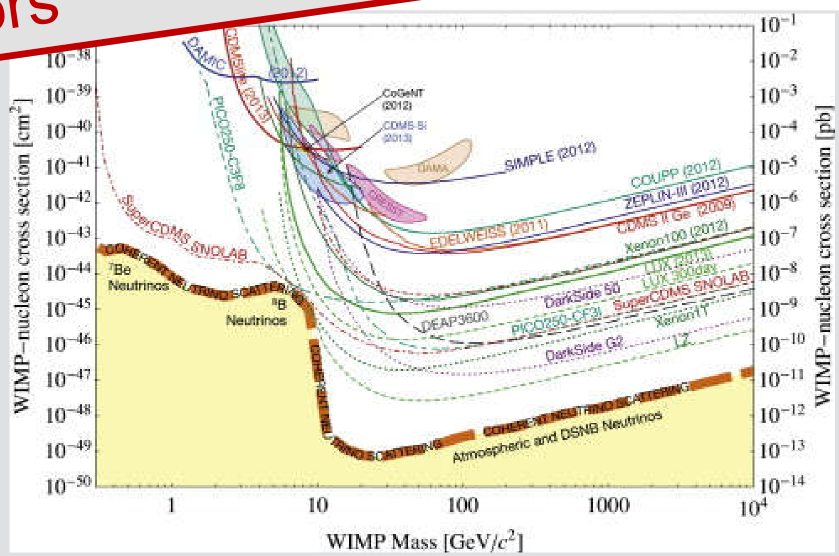




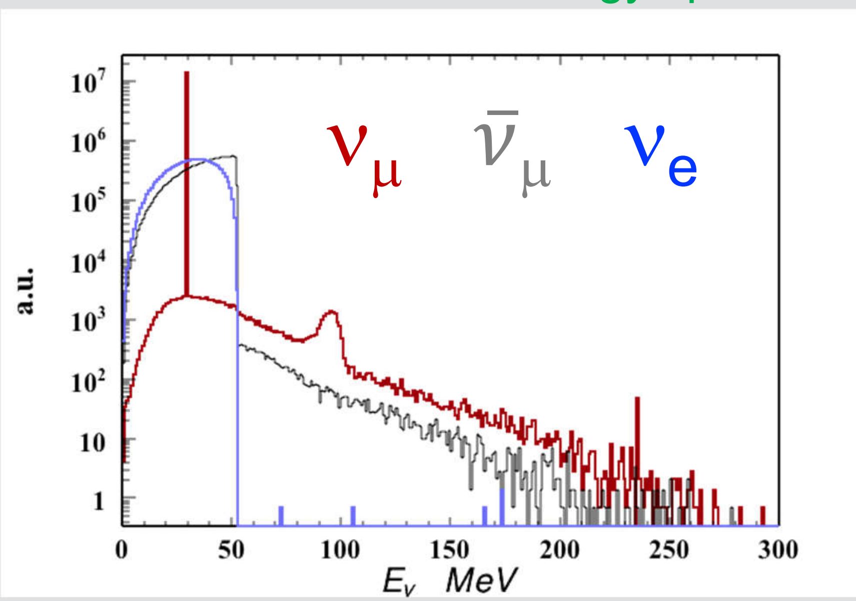
To realize these physics topics, require:
- intense ν source
- Low-background location
- Low-threshold detectors

<u>COHERENT experiment at SNS/ORNL</u>

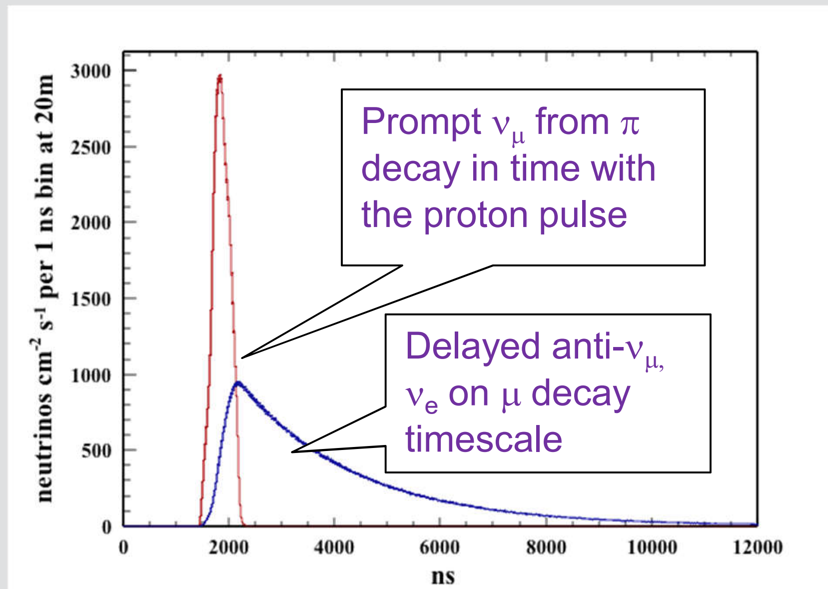
ORNL Spallation Neutron Source (SNS) is also a world-class ν source:

- intense proton beam (1.3MW, 1 GeV)
- pulsed (60 Hz, 600ns spill time)…
- ~ 5000MWhr/year
- ~ 2E23 POT/yr!

SNS ν energy spectrum



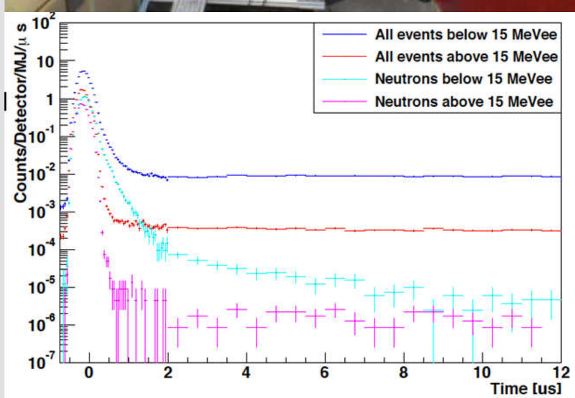
SNS ν time distribution



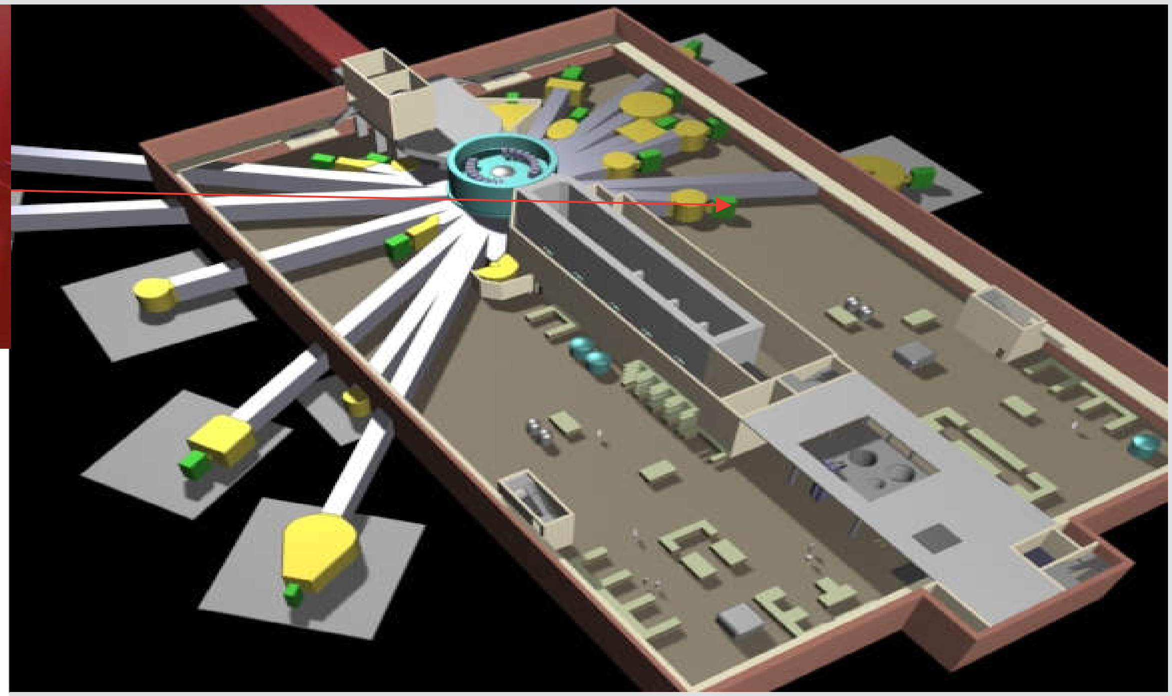
COHERENT experiment at SNS/ORNL

Neutron backgrounds at the 1.3 MW SNS?
(much work went into this question)

Sandia scatter camera



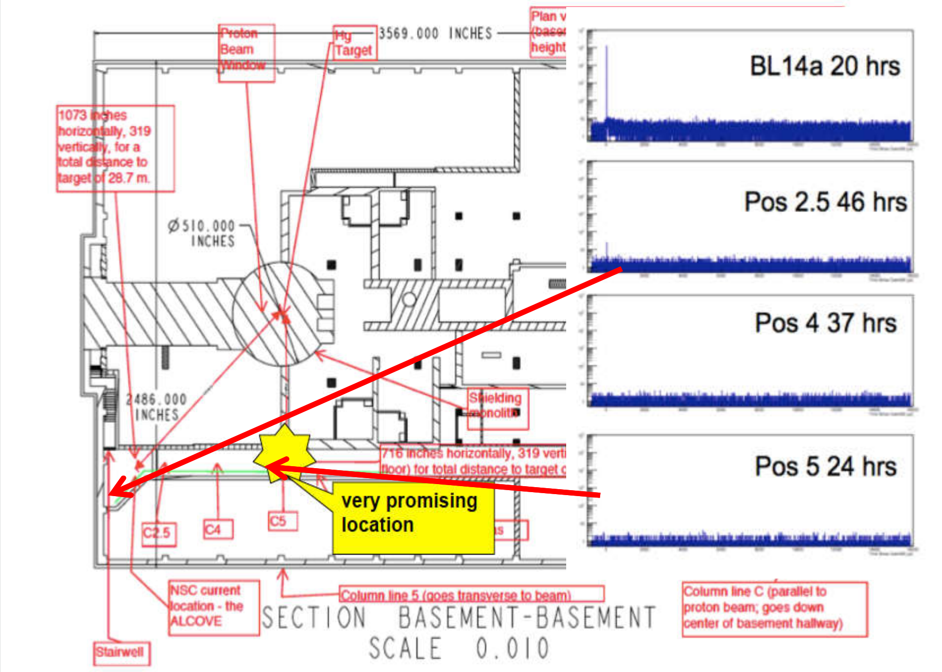
SNS target building

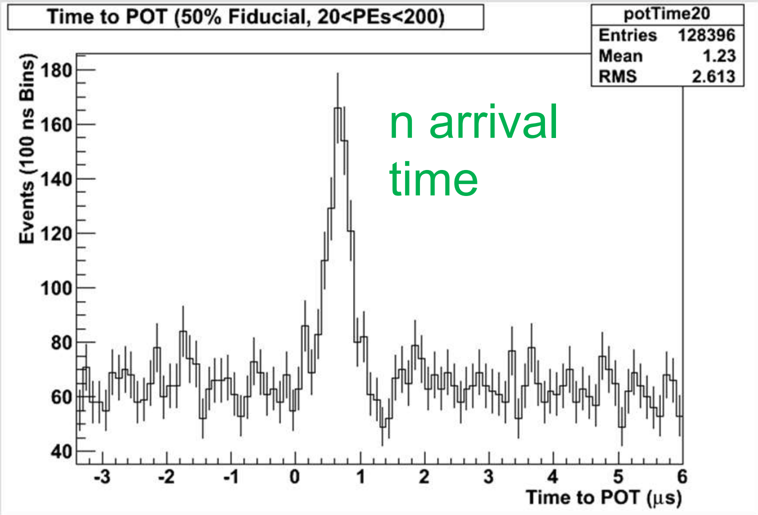


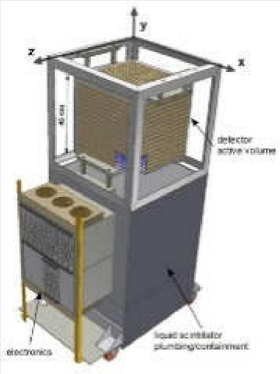
neutron flux ~10^5 too high on target building, main floor

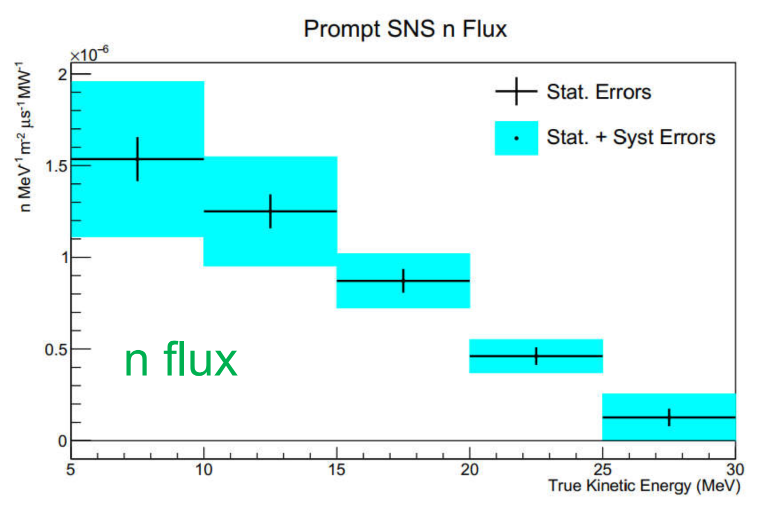
COHERENT experiment at SNS/ORNL

Found a quiet basement location with low beam-related and cosmic neutron rate



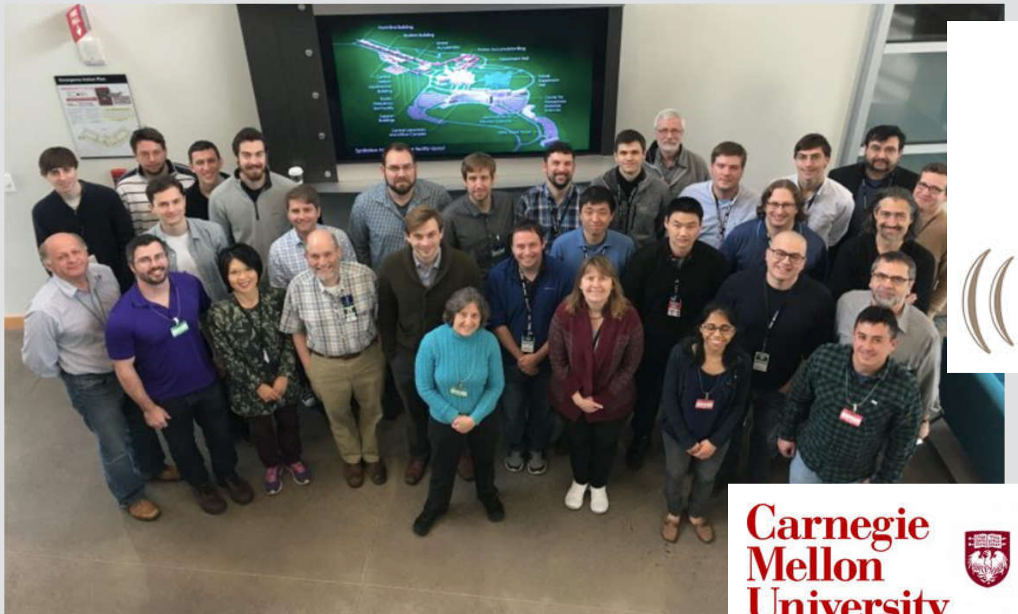






The COHERENT collaboration

http://coherent.ornl.gov



COHERENT
SNS
SPALLATION NEUTRON SOURCE

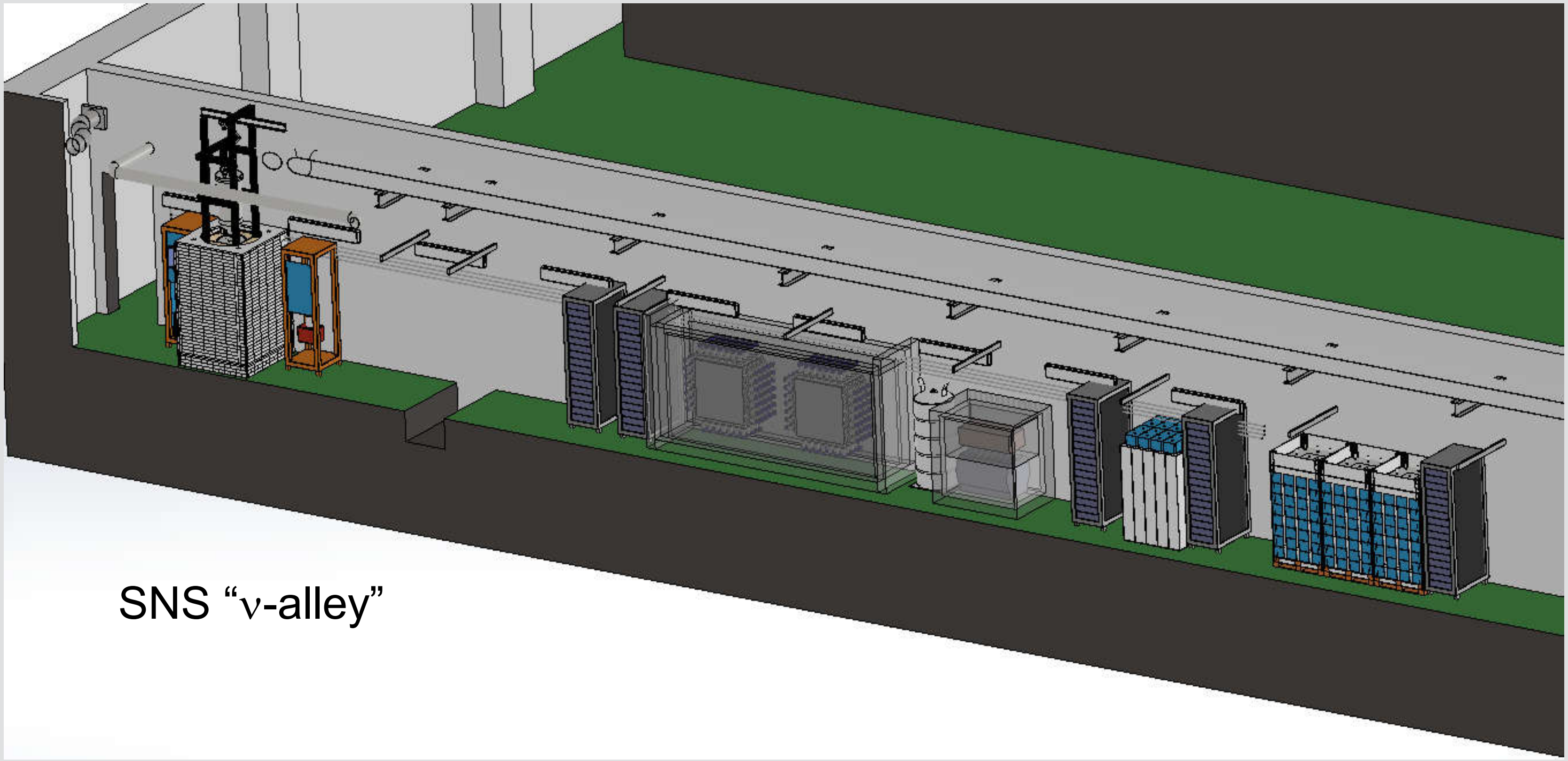
~80 members,
18 institutions
4 countries

arXiv:1509.08702

Carnegie Mellon University
THE UNIVERSITY OF CHICAGO
Duke UNIVERSITY
UF UNIVERSITY of FLORIDA
KAIST
Laurentian University Université Laurentienne
Los Alamos NATIONAL LABORATORY EST. 1943
MEPhI
NORTH CAROLINA CENTRAL UNIVERSITY FOUNDED 1910
NC STATE UNIVERSITY
NM STATE UNIVERSITY
OAK RIDGE National Laboratory
Sandia National Laboratories
THE UNIVERSITY of TENNESSEE KNOXVILLE
TUNL
UNIVERSITY of WASHINGTON
CNEC
KICP
NNSA National Nuclear Security Administration
NSF
U.S. DEPARTMENT OF ENERGY Office of Science

COHERENT experiment at SNS/ORNL

- SNS “ν-alley” for COHERENT
- 20-29 m from target



SNS “ν-alley”

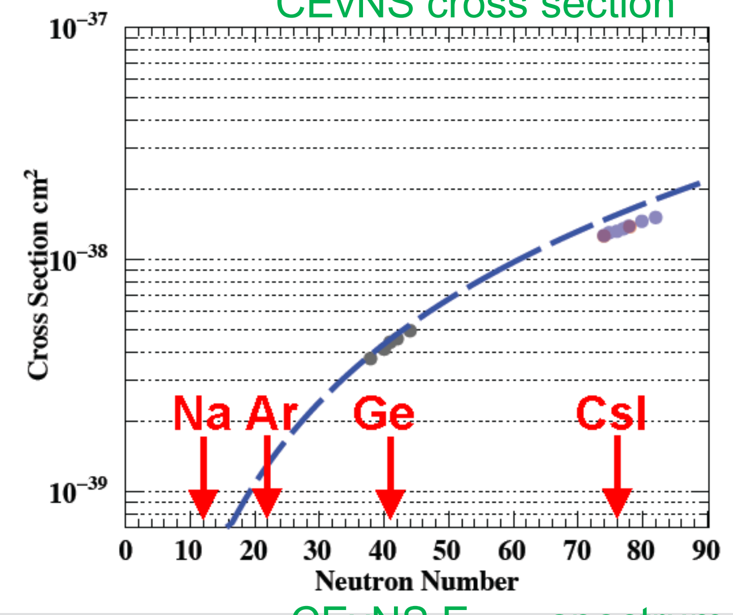
COHERENT experimental strategy at SNS/ORNL

1st goal: Measure N^2 dependence of CEvNS process

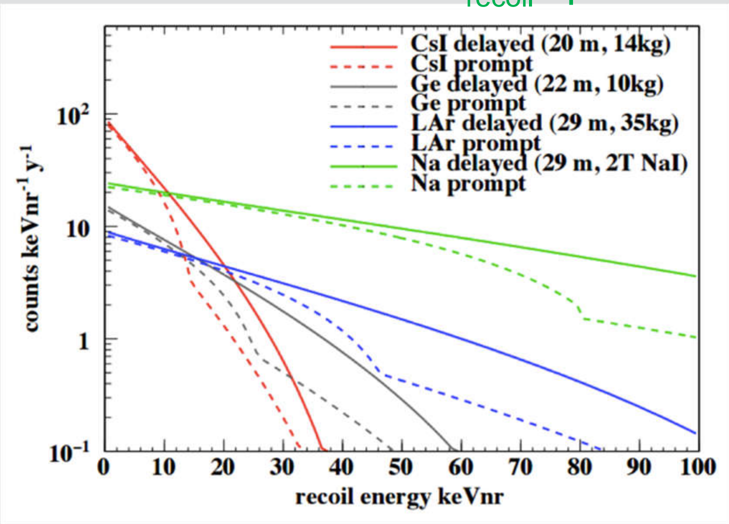
with multiple targets/detector technologies

- (event rate)/kg is high, so relatively small (10-100 kg) detectors sufficient
- radiological background requirements fairly modest, because of pulsed beam
- need low E thresholds !

CEvNS cross section



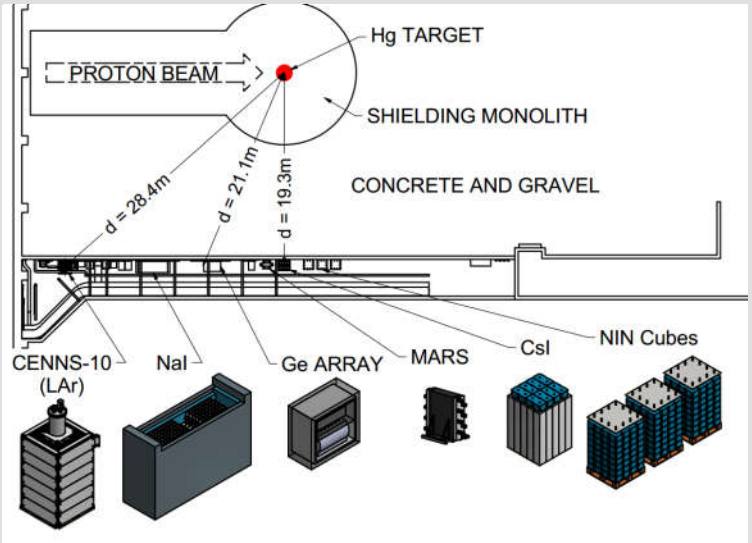
CEvNS E_{recoil} spectrum



COHERENT detectors

nuclear target	technology	mass (kg)	source distance (m)	recoil threshold (keVr)
CsI[Na]	Scintillating crystal	14.6	19.3	6.5
Ge	HPGe PPC	6	22	0.6
LAr	Single-phase	22	29	20
NaI[Tl]	Scintillating crystal	185/2000	28	13

For more details:
arXiv:1803.09183



COHERENT detectors

1st results
from CsI this past
summer (2017)!

nuclear target	technology	mass (kg)	source distance (m)	recoil threshold (keVr)
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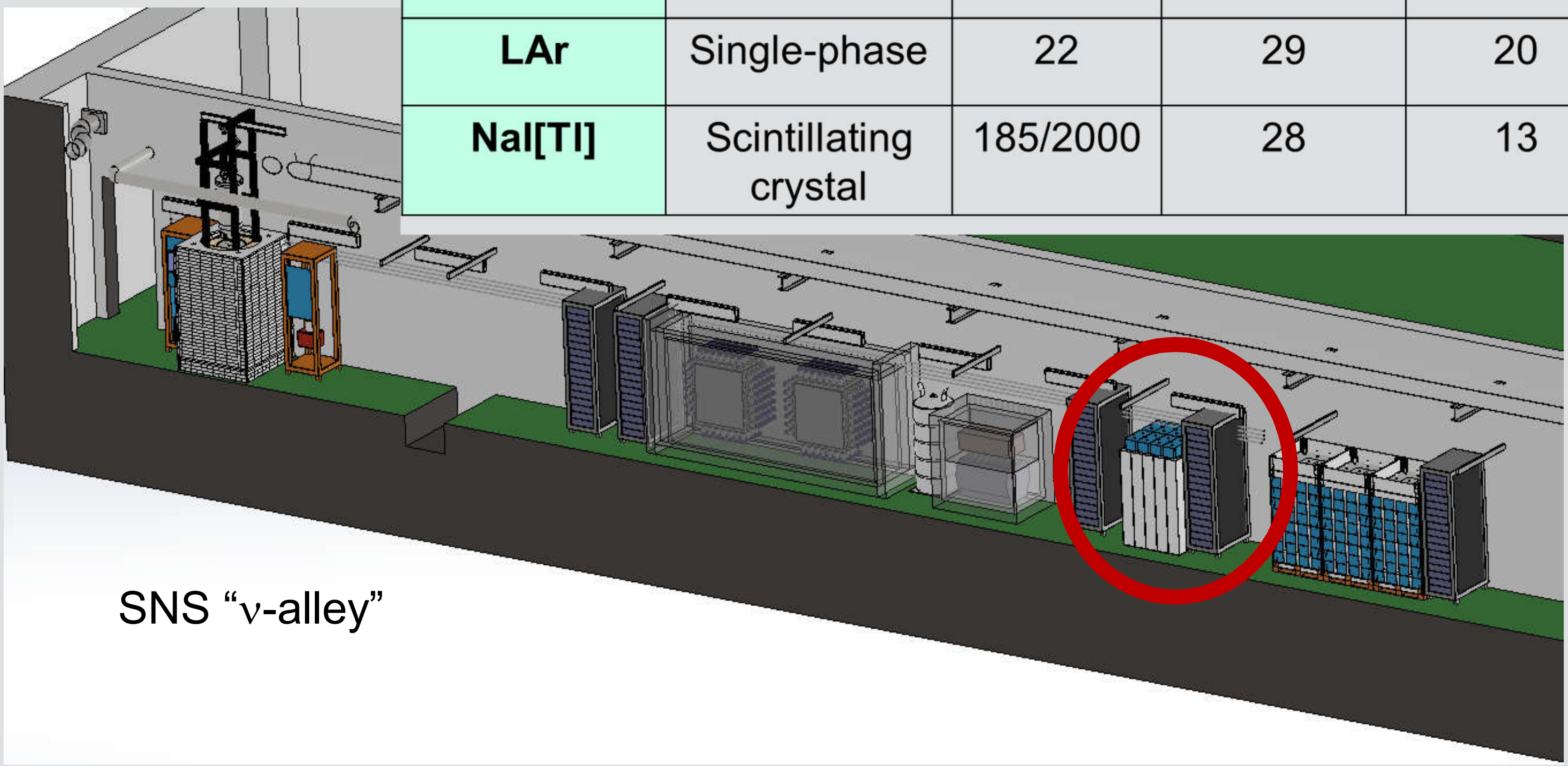


COHERENT with CsI[Na]

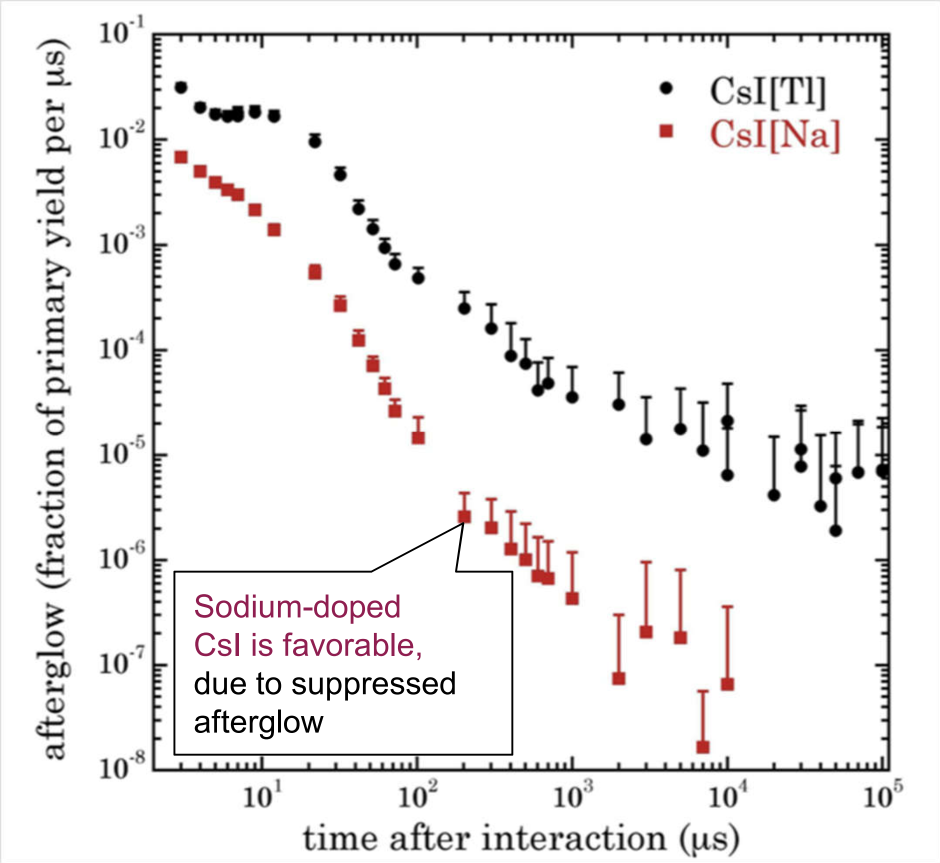
CsI scintillating crystal:

- 14.6 kg sodium-doped CsI
- high light yield (13.35 pe/keVee)
- uniform within ~2%
- low intrinsic bg
- room temperature
- Readout with Hamamatsu R877-100 13cm dia. PMT

2 kg test crystal @U. Chicago.

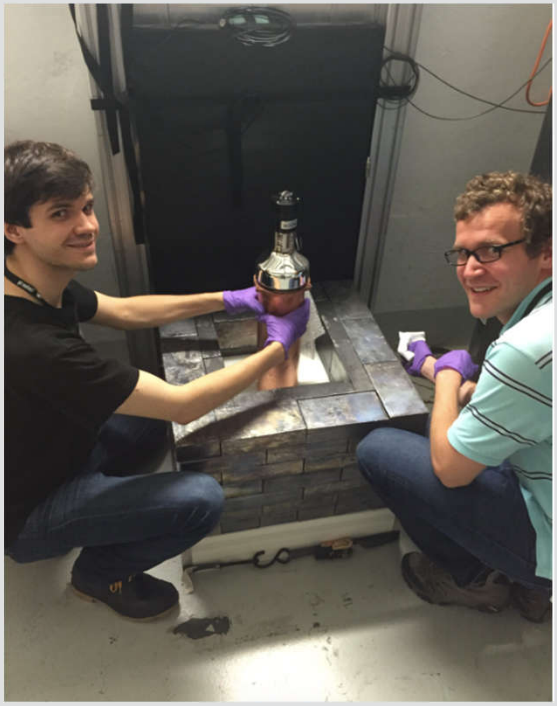
Amcrys-H, Ukraine

J.I. Collar et al., NIM A773 (2016) 56-67

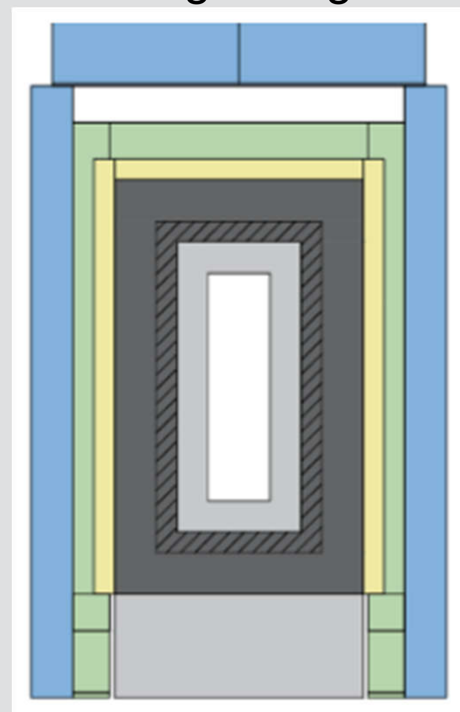


COHERENT with CsI[Na]

Installed in ν-alley at ORNL SNS in summer 2015:



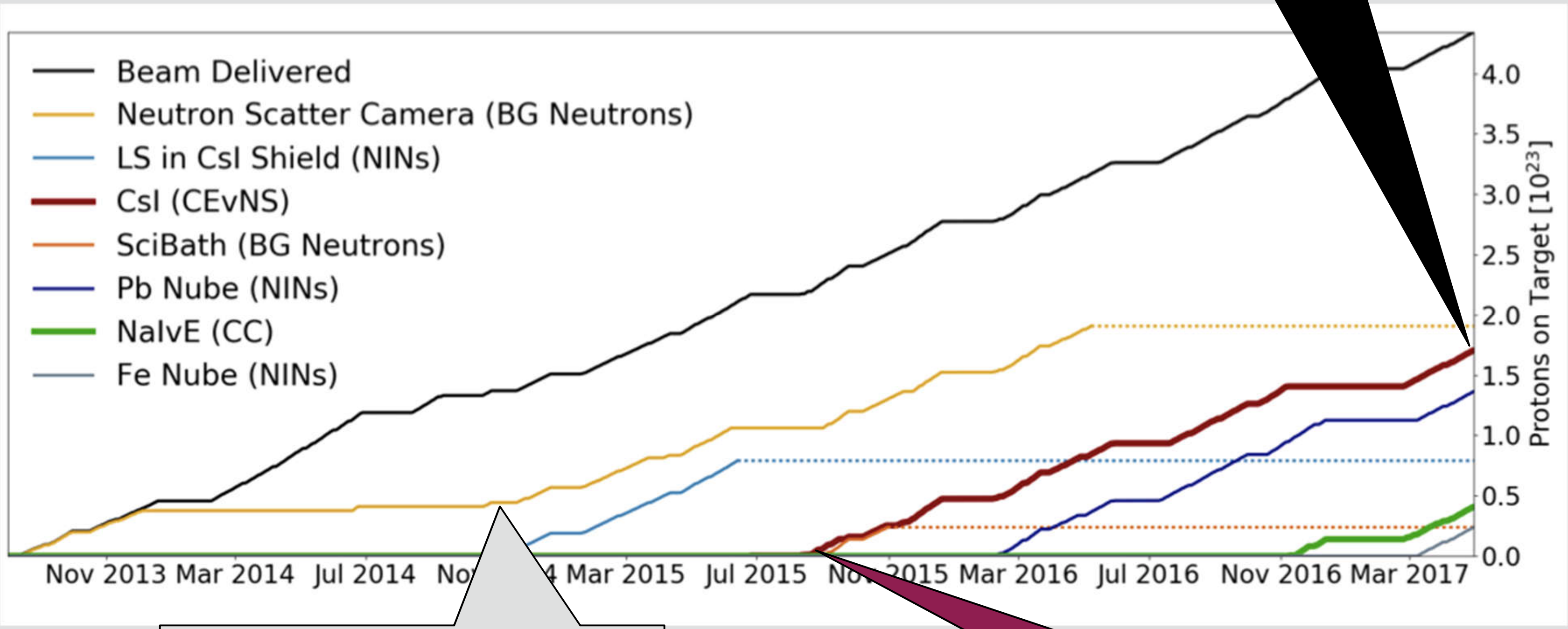
shielding config:



Layer	HDPE*	Low backg. lead	Lead	Muon veto	Water
Thickness	3"	2"	4"	2"	4"
Colour					

COHERENT: data collection

1.76 x10^{23} POT delivered to CsI (7.48 GWhr)



Neutron background data-taking for ~2 years before first CEvNS detectors

CsI data-taking starting summer 2015

COHERENT, CsI analysis:

Overall strategy:

- count beam-on low-energy events (nuclear recoils)
- subtract steady state backgrounds from beam-off data
- measure/subtract beam-related backgrounds (neutrons):
  - external
  - neutrino-induced neutrons (“NIN”s)

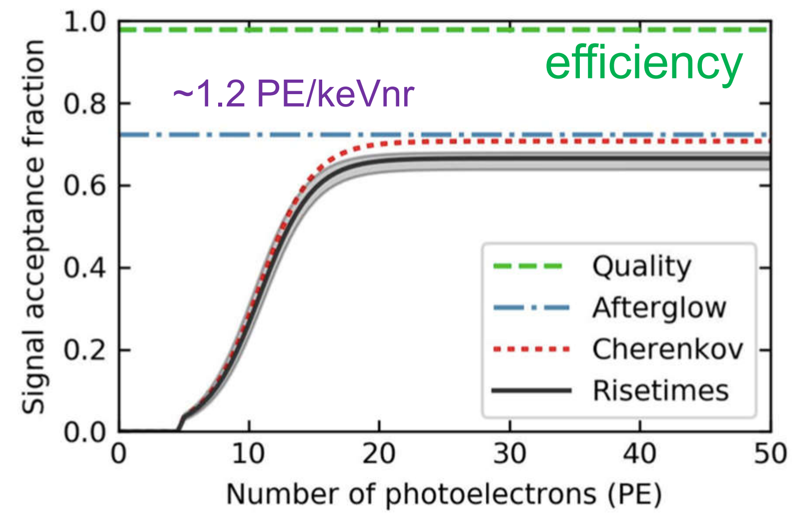
$\nu_e + {}^{208}Pb \rightarrow {}^{208}Bi^* + e^-$ CC

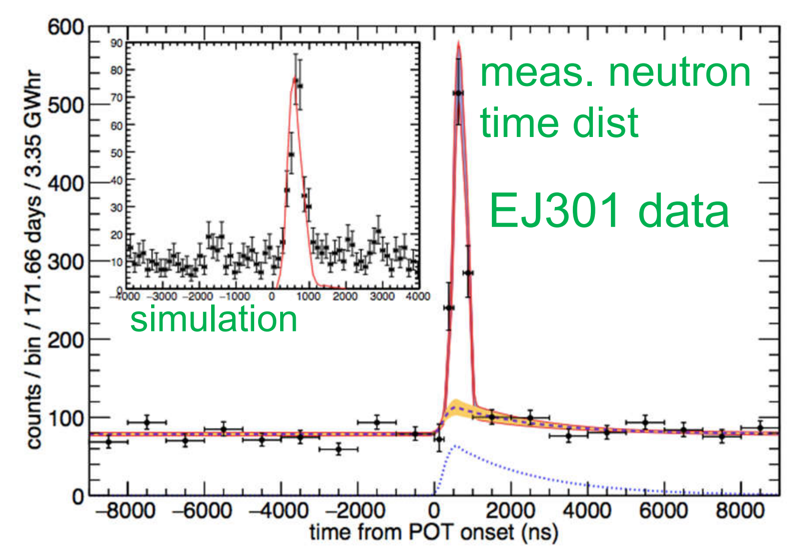
↘ 1n, 2n emission

$\nu_x + {}^{208}Pb \rightarrow {}^{208}Pb^* + \nu_x$ NC

↘ 1n, 2n, γ emission

- 2 independent analyses with slightly different cut optimization yield consistent results
- “Analysis I” presented here





COHERENT, CsI results:

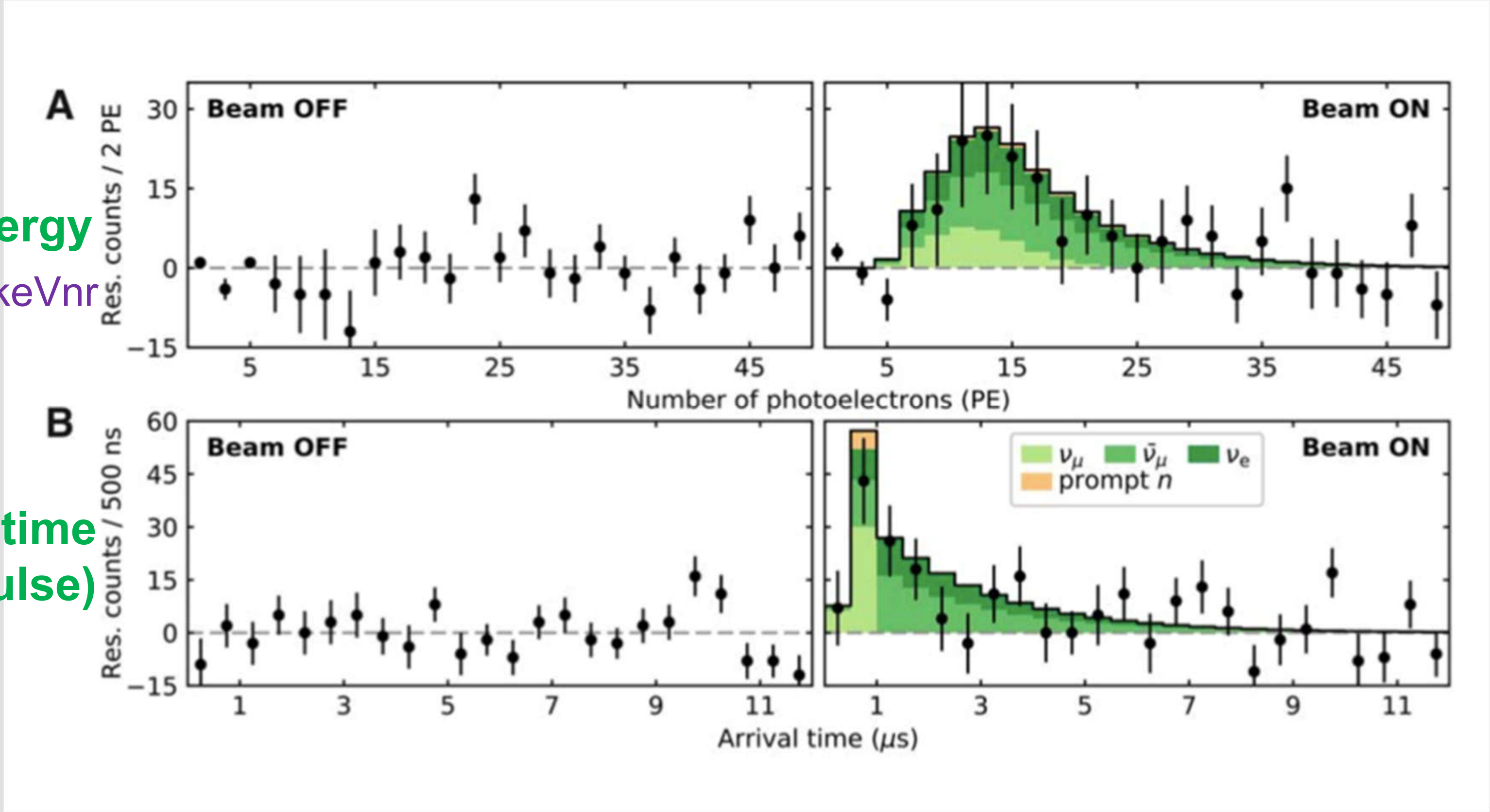
Steady-state-background subtracted data:

~Energy

~1.2 PE/keVnr

time

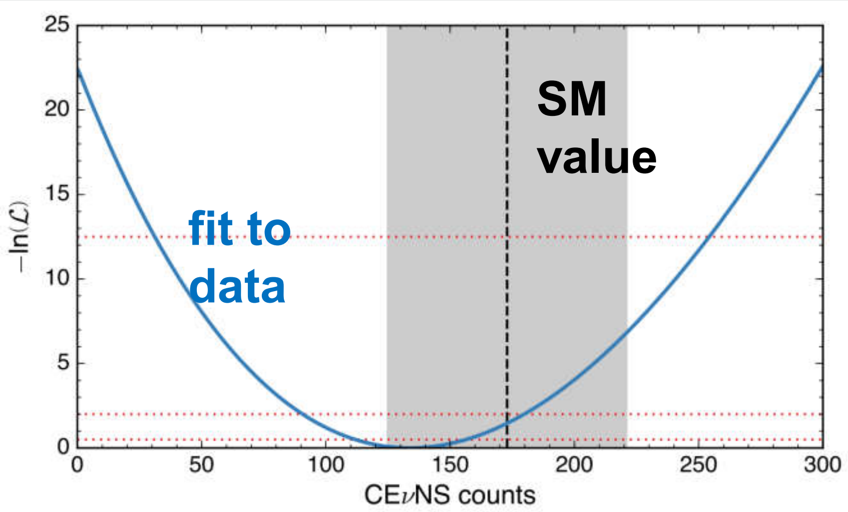
(wrt ν pulse)



COHERENT, CsI results:

Likelihood analysis: 2D in energy (pe) and time

- best fit of data: 134 ± 22 CEvNS events
- SM prediction: 173 ± 48 CEvNS events
- Null hypothesis (=no CEvNS) rejected at 6.7σ
- consistent w/SM within 1σ



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, single-bin counting	136 ± 31
Signal counts, 2D likelihood fit	**134 ± 22**
Predicted SM signal counts	**173 ± 48**

$6 \leq PE \leq 30$, $0 \leq t \leq 6000$ ns

Uncertainties on signal and background predictions	
Event selection	5%
Flux	10%
Quenching factor	25%
Form factor	5%
Total uncertainty on signal	**28%**
Beam-on neutron background	25%

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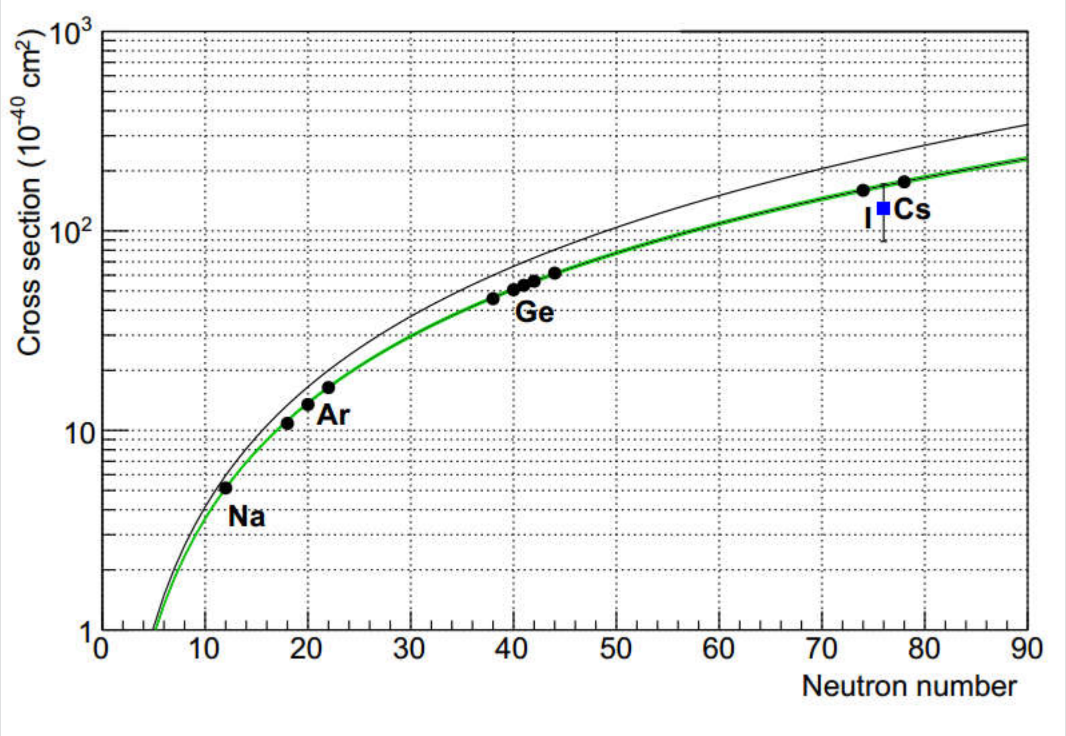

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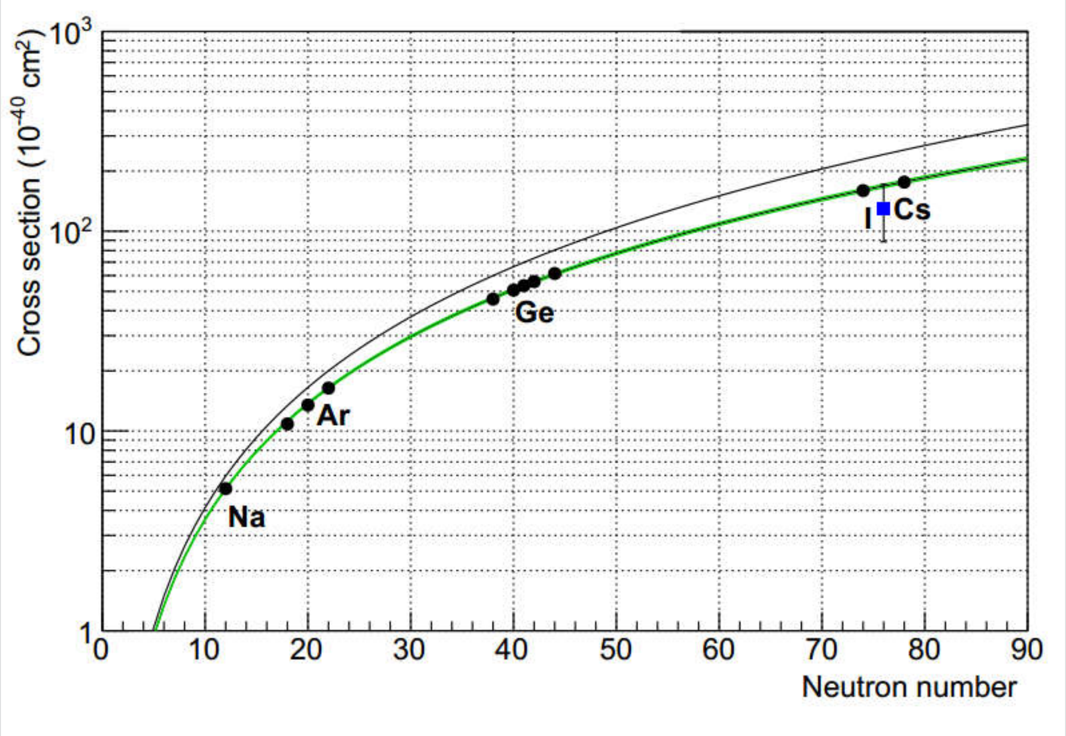
For more details:
D. Akimov *et al.*, *Science*
10.1126/science.aao0990 (2017)

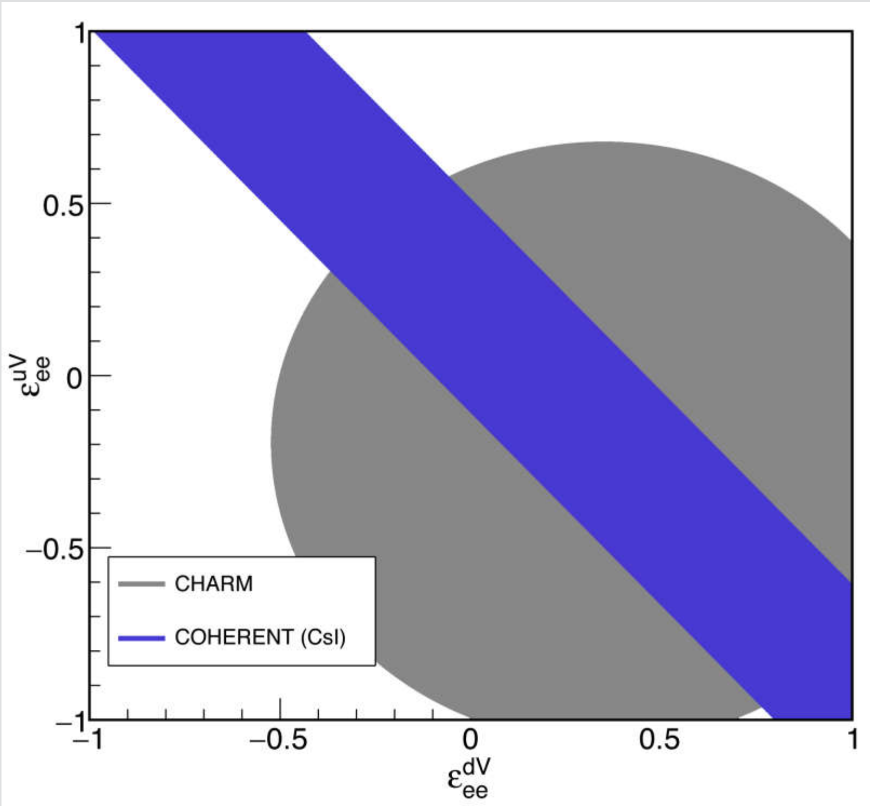


COHERENT, CsI results:

Non-Standard Interactions (NSI) specific to neutrinos

- Simple one-bin analysis
- Assume all other ε's zero

χ^2 fit results for current CsI data set: 90% allowed region



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

Also:

- NSI limits rel. to ν oscillations
  eg: arXiv:1708.02 899
- Vector portal DM
  eg: arXiv:1710.10889

Expecting more with more precise data to come ….

COHERENT detectors

In next few years:

nuclear target	technology	mass (kg)	source distance (m)	recoil threshold (keVr)
CsI[Na]	Scintillating crystal	14.6	19.3	6.5
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LAr	Single-phase	22	29	20
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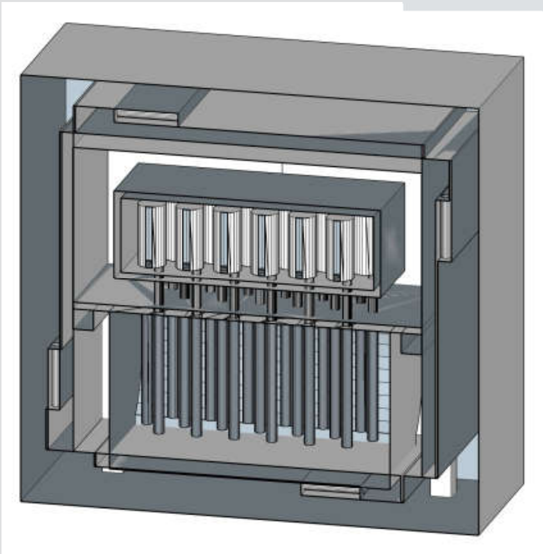

COHERENT detectors

Currently running
Analysis in progress

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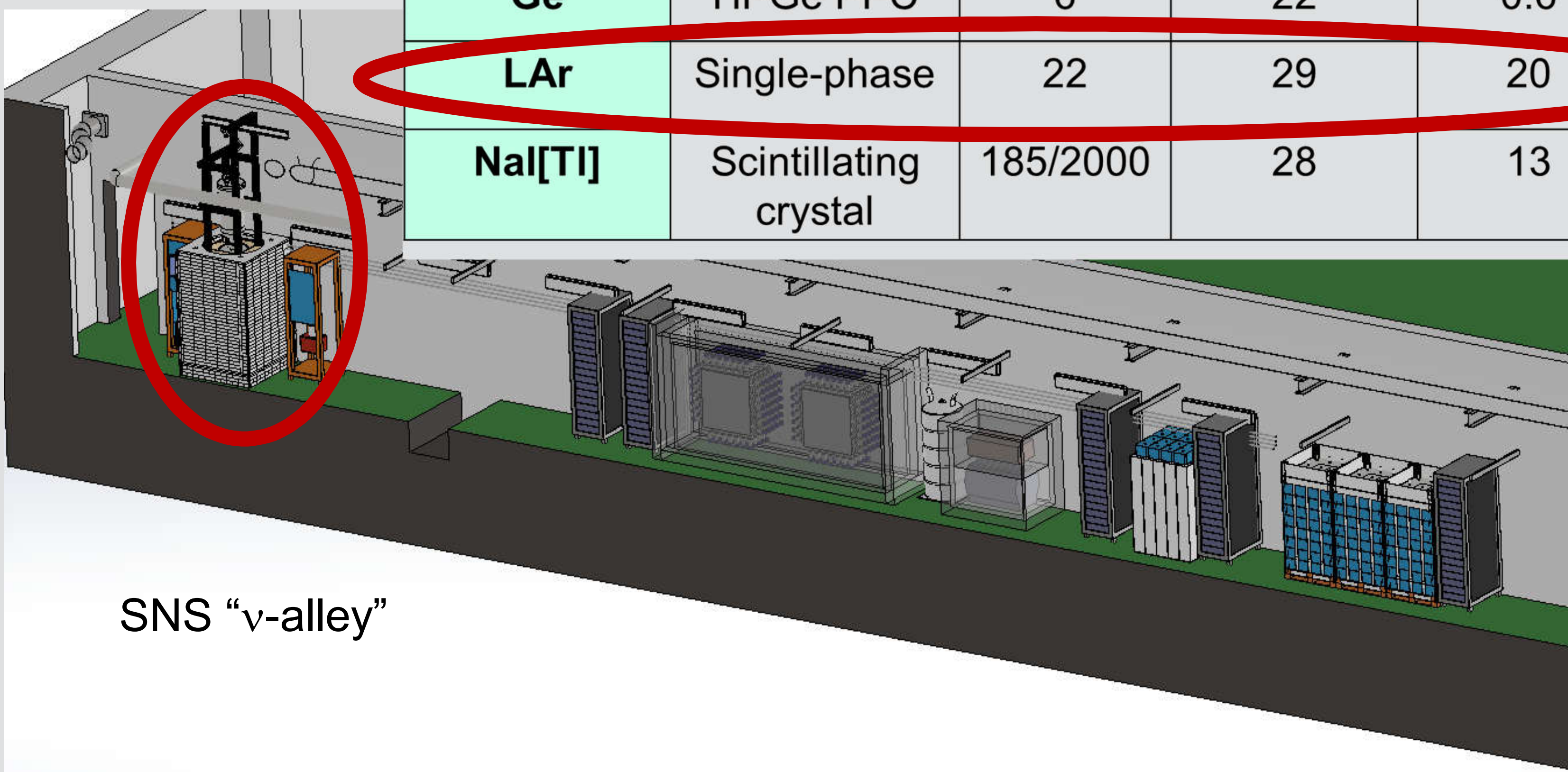
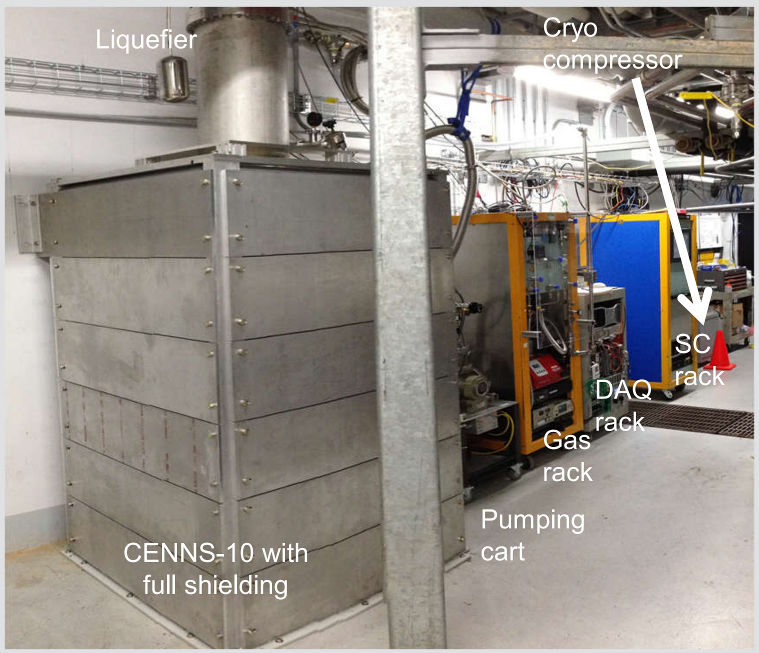
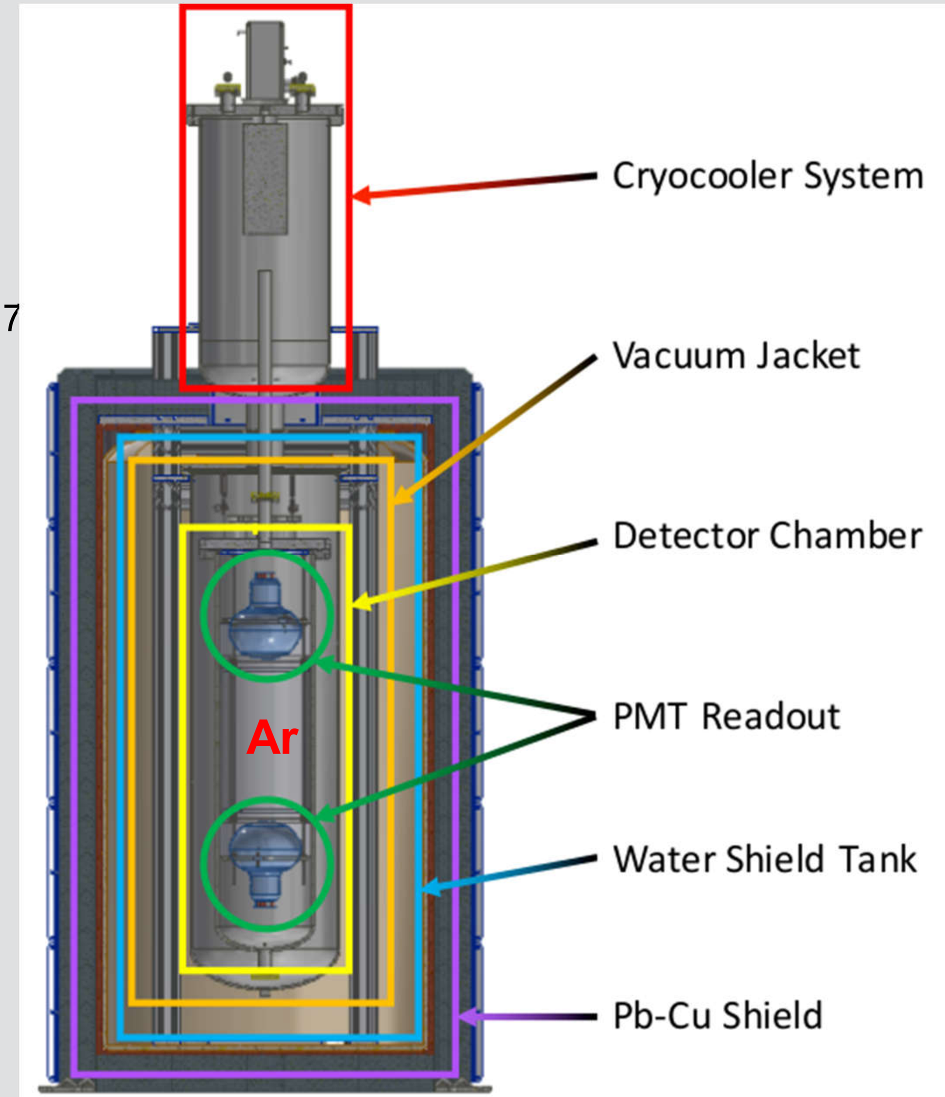


The CENNS-10 (LAr) Detector:

Specs:

- Built at FNAL, moved to ORNL Fall 16
- 22 kg LAr fiducial volume
- 2 × Hamamatsu 8”PMTs
- TPB-coated PMTs/teflon side walls
- Energy threshold ≈ 20keVnr
- Pb/Cu/H2O shield
- Running in current configuration since 7/17
- Expect ≈140 CEvNS events/SNS-year

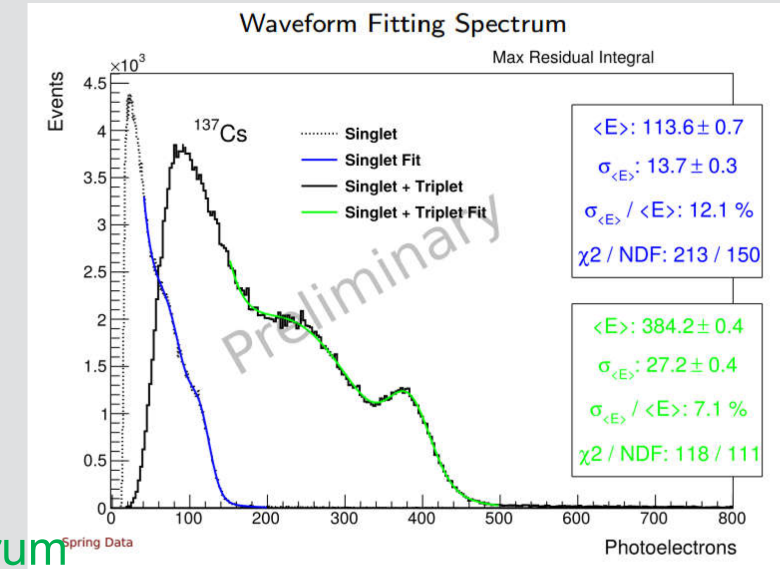




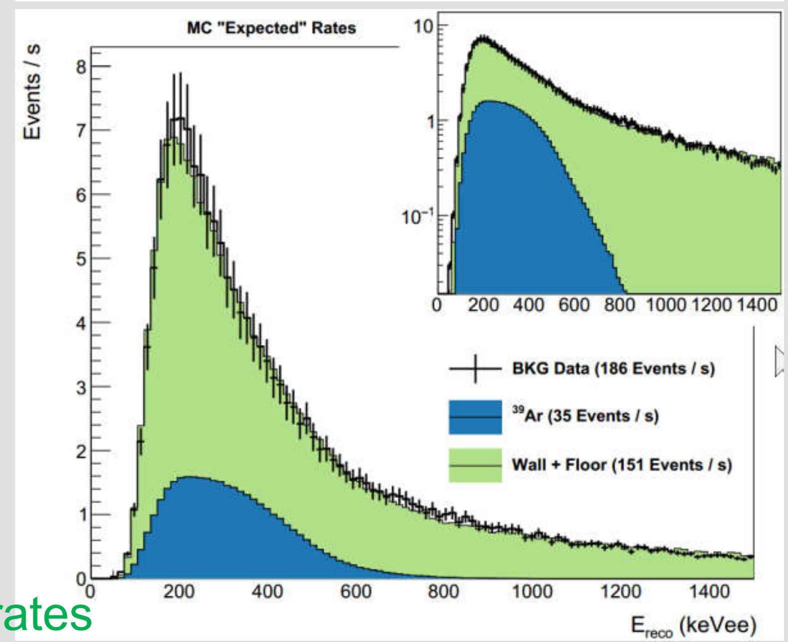
The CENNS-10 (LAr) Detector

Spring17 data
- lower light yield, since upgraded
- Pre-shielding, will calibrate backgrounds
- ~0.5 PEs/keVee

^{137}Cs spectrum



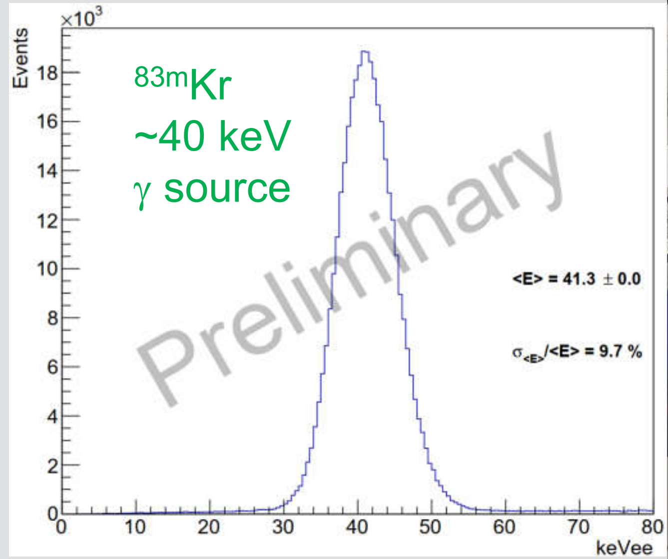
Pre-shielding Steady-state background rates

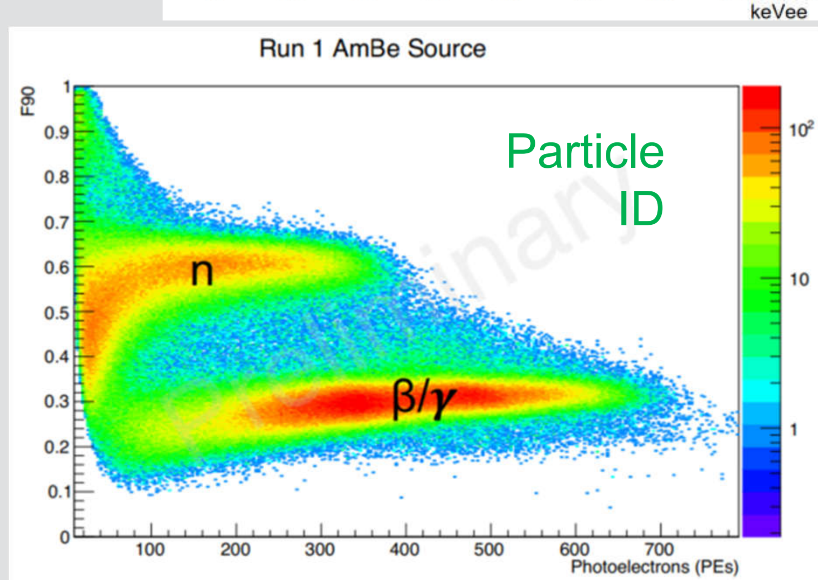


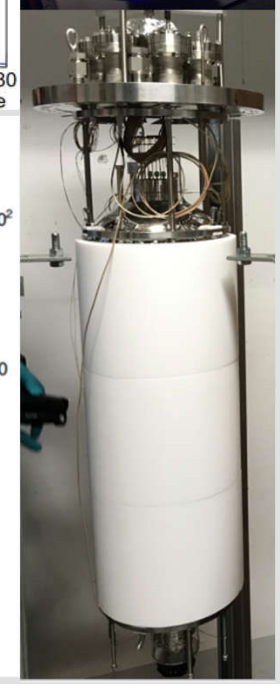
The CENNS-10 (LAr) Detector

7/17-current data:

- light yield improved to ~3-4 PE/keV
- PSD, threshold energy look adequate for confirmation of CEvNS with ^{40}Ar





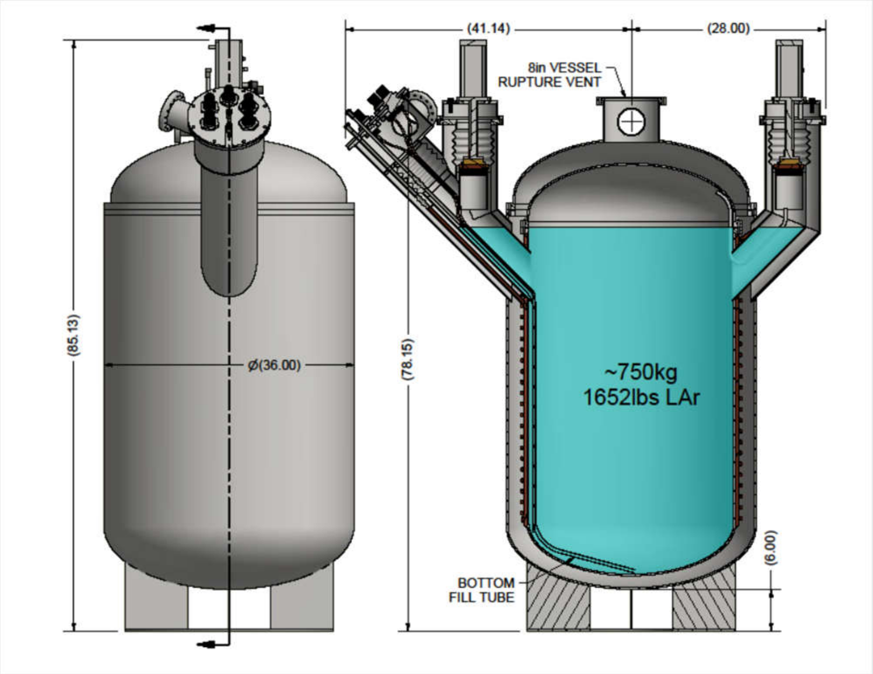


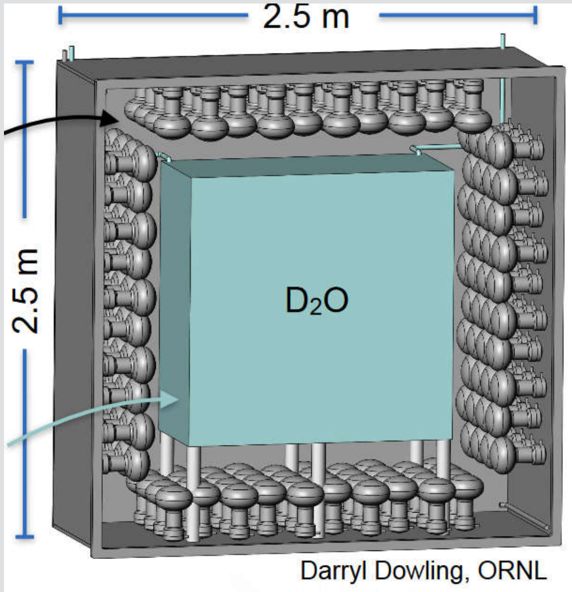
Future for COHERENT

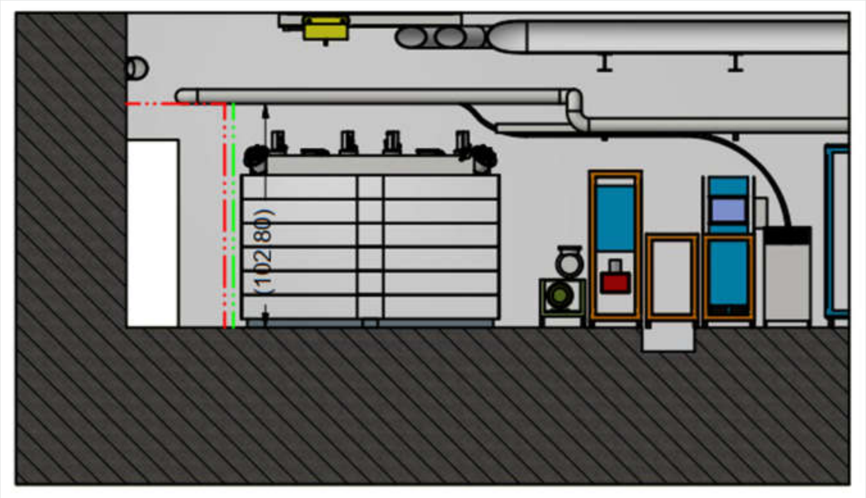
- 7/17 – current data
  should provide 1st CEvNS LAr signal
- Future data from Ge, NaI

- proposal in progress for larger detectors:
  - O(1 ton) liquid noble gas detector w/underground Ar
  - D_2O for flux normalization

- .. for full physics of CEvNS.

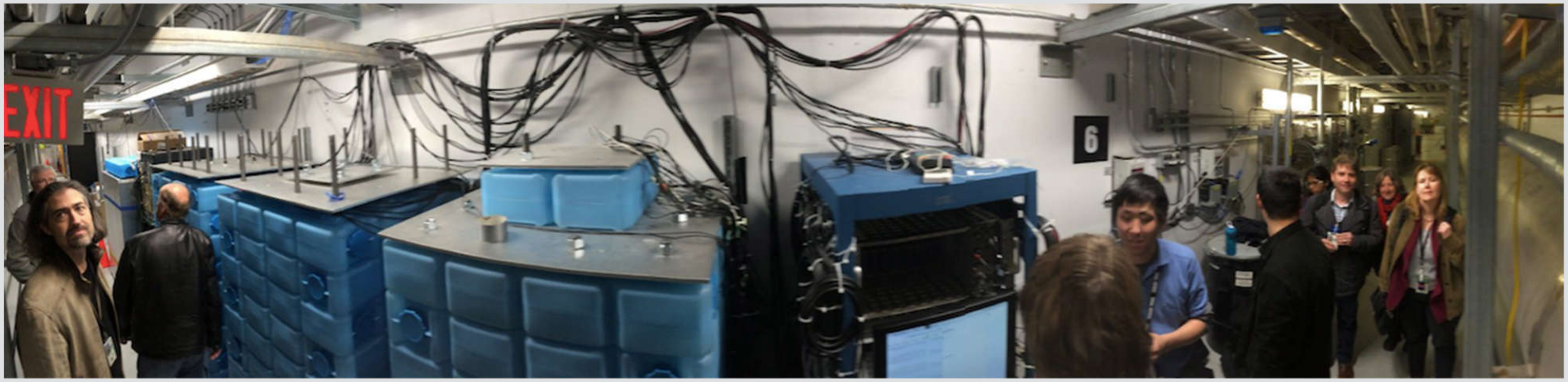






Summary:

- First measurement of CEvNS in COHERENT CsI[Na] at the SNS!
- Potential physics output of CEvNS will drive further work on improved/larger detectors



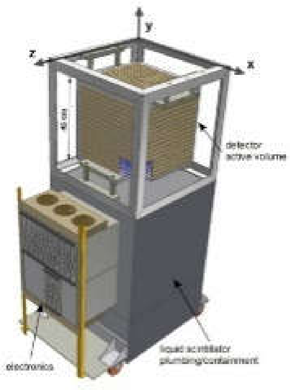
Thanks to COHERENT collab for great work (and material for this talk!)

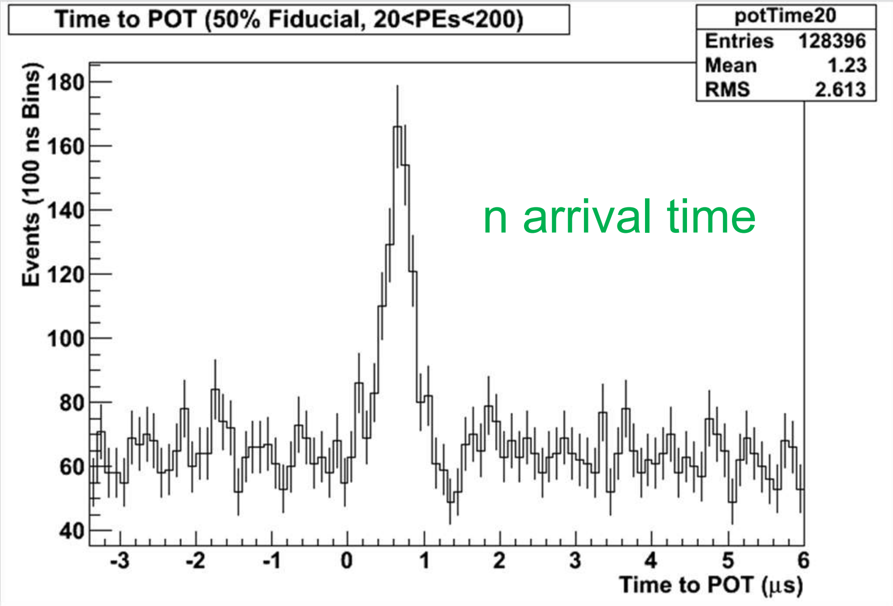
Backups

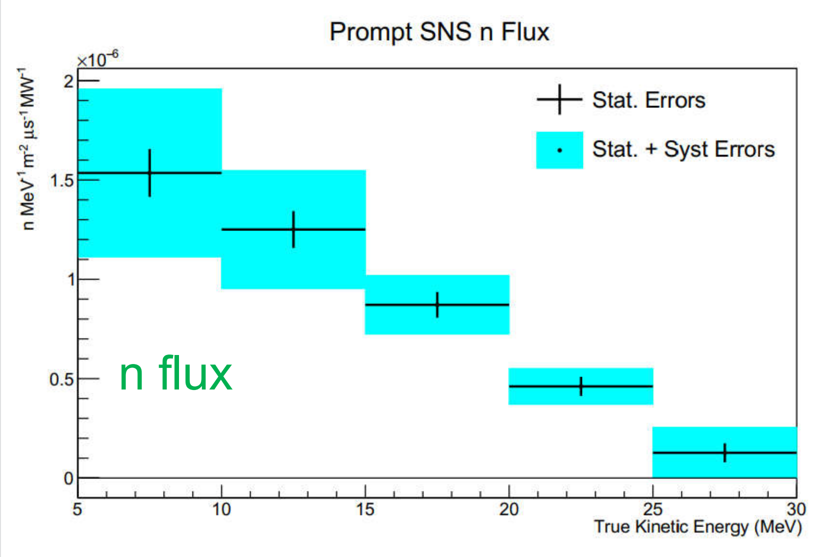
COHERENT experiment at SNS/ORNL

Measured n-fluxes:

- n flux ~4.0×10^{-5} n m^{-2} $spill^{-1}$
- about 10^4 lower than Fermilab BNB with existing shielding
- and all prompt (in time with p beam)







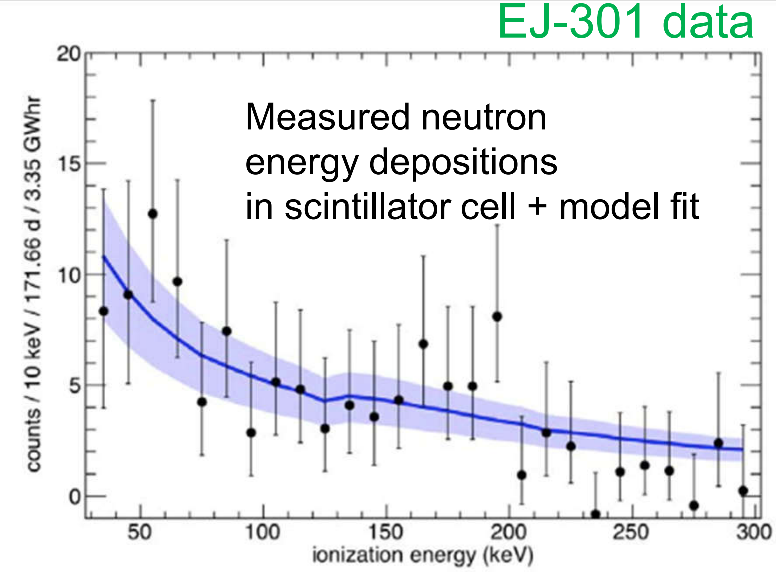
COHERENT, CsI data analysis:

Neutron backgrounds:

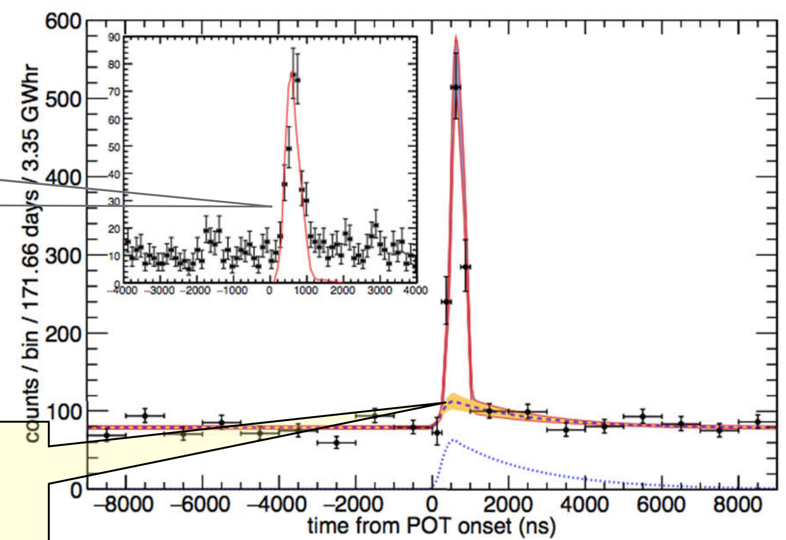
- Evaluated using EJ-301 liquid scintillator cell deployed inside CsI shielding before CsI deployment
- Consistent with Geant4 simulation for SNS production & shielding

Expect: 0.93 ± 0.23 beam n events/GWhr
0.54 ± 0.18 NIN events/GWhr

=> <~11 neutron events in CsI dataset



G4 sim

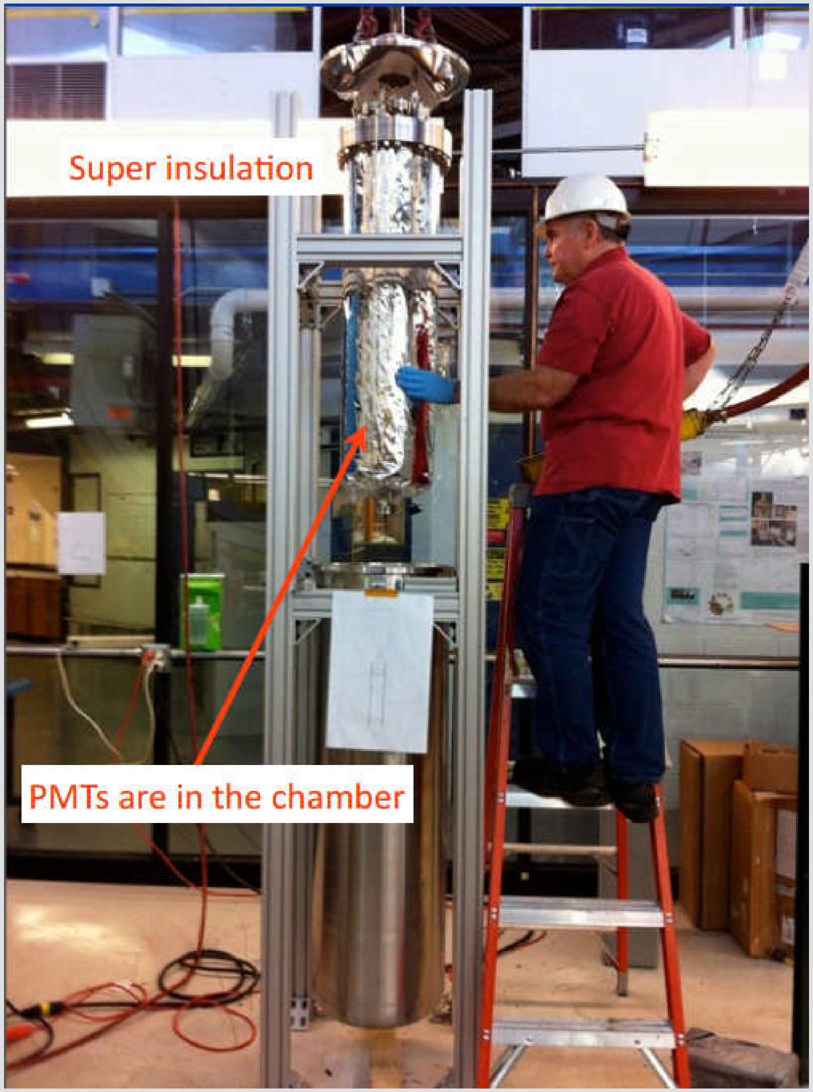


NINs: non-zero component at 2.9σ (factor ~1.7 lower than prediction)

The CENNS-10 detector

timeline:

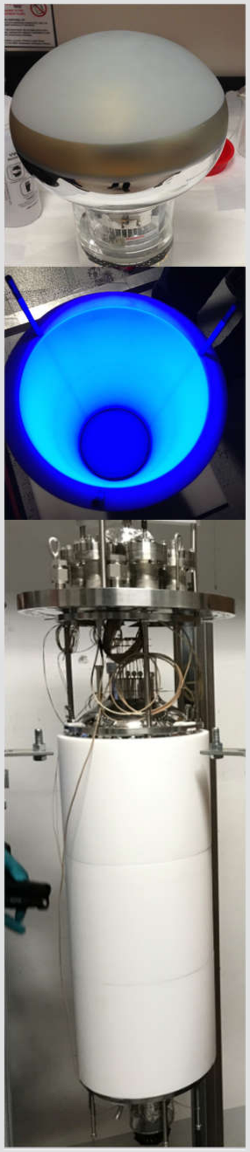
- ('12-'15) built at Fermilab for CENNS@Fermilab effort led by J. Yoo (now at KAIST) along with: A. Lathrop, R. Flores, R. Schmidt, E. Voirin, D. Markley, R. Davila, D. Butler, L. Harbacek
- (2015) moved to Indiana U. for commissioning, upgrades, neutron tests
- (2016) installed at SNS for COHERENT

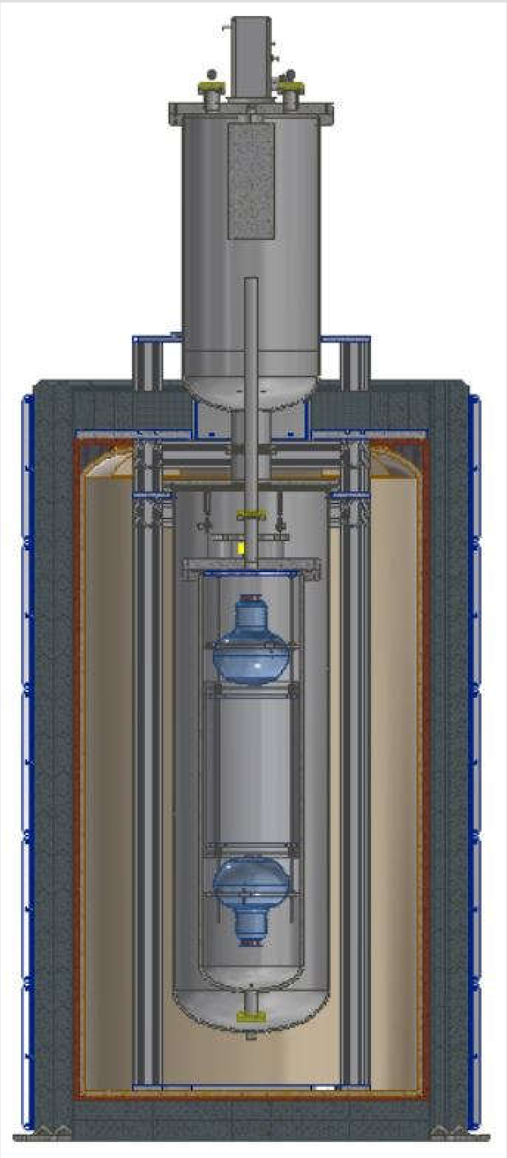


The CENNS-10 (LAr) Detector:

CENNS-10 SNS timeline:

- 10-12/2016: (re)build detector at SNS
- 12/16, 3-5/17: run with TPB-acrylic parts, E_{thresh}~100keVnr
  "Spring17" data:
  CEvNS measurement not possible, will constrain beam-related bckgrds
- 6/17: upgrade: TPB-Teflon reflectors, new TPB-coated PMTs, added 4" Pb shielding
- 7/17-12/17: ran in upgraded mode, E_{thresh}~20keVnr
  "Summer17" data:
  2.8GWhr collected



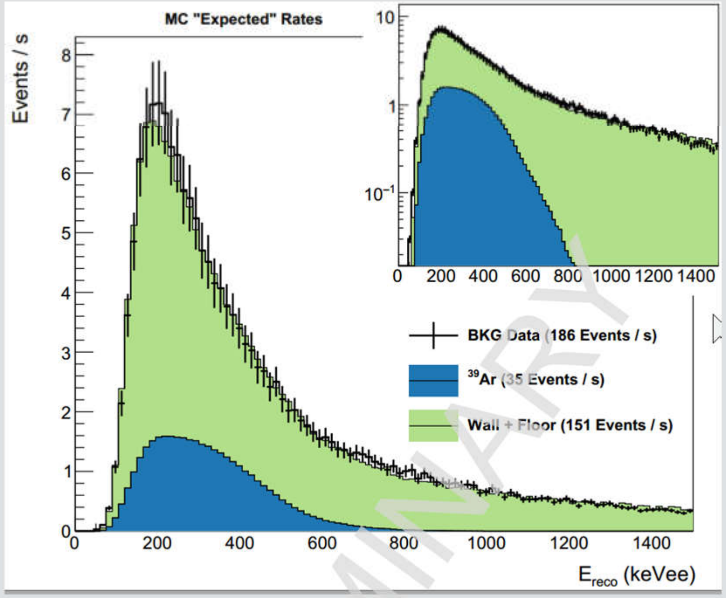


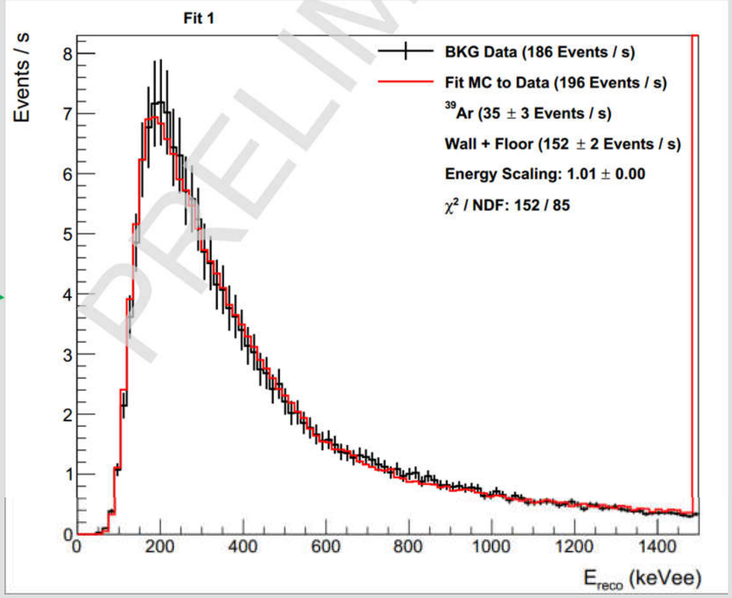
^{39}Ar in Spring '17 data:

- from CENNS-10, stage 1 config: TPB-acrylic sides, no Pb shielding, beam-off (lower 511keV γ rate)
- background-collection threshold ~100 keVee
- ~0.5 PE/keV $\Rightarrow$ E threshold ~ 80keVnr

- comparison to expected rates from environmental γ measurements + 1 Bq/kg ^{39}Ar + detector/shielding MC, very good agreement to expected

- fit with background allowed to float $\Rightarrow$ 1 Bq/kg ^{39}Ar $\pm$ 10%



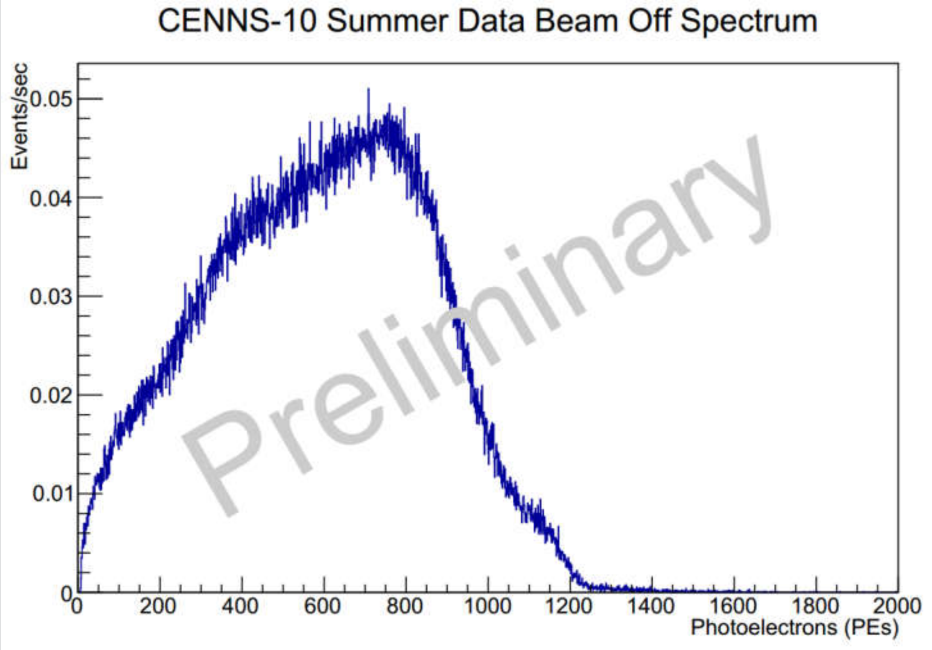


^{39}Ar in Summer '17 data:

- from CENNS-10, upgraded config: TPB-Teflon sides, full Pb shielding, beam-off
- background-collection threshold ~20 keVee
- ~3 PE/keV ⇒
  E threshold ~ 20keVnr

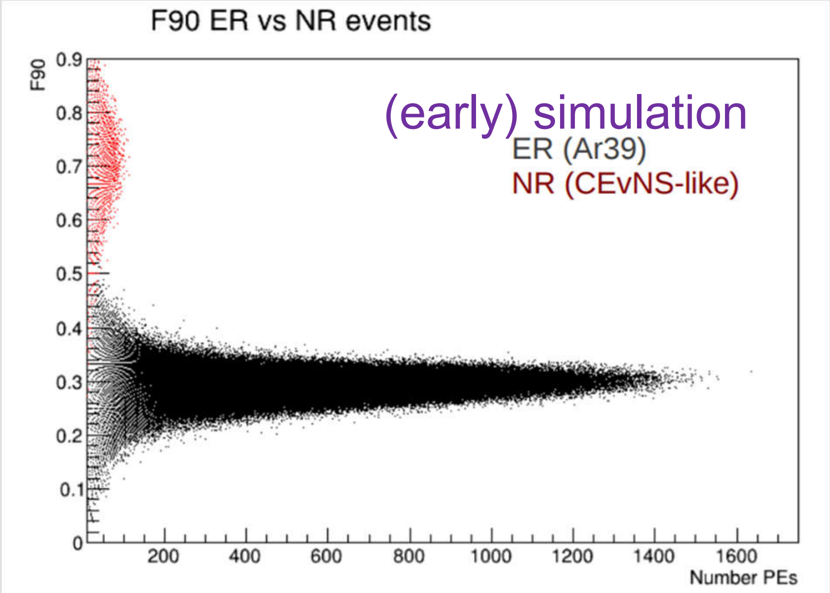
- observed spectrum consistent with ~1 Bq/kg, negligible envir. γ rate

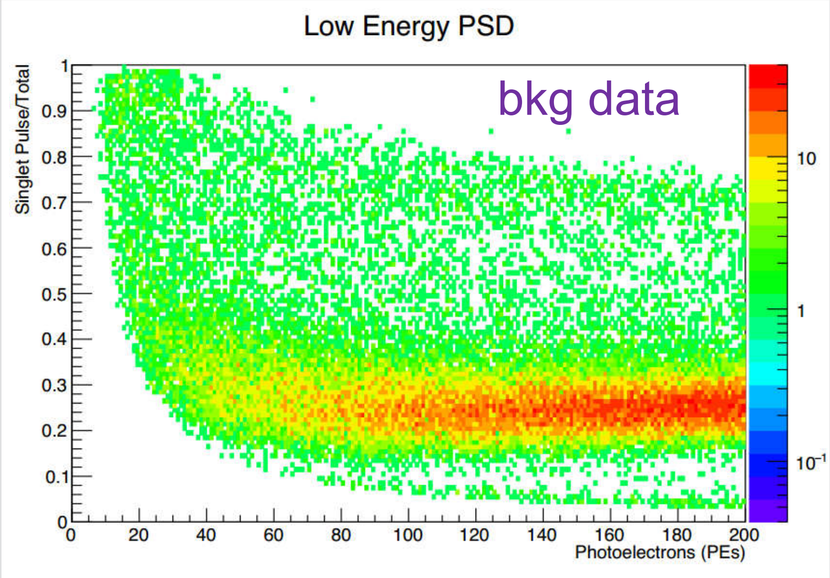
- energy calibration, MC tuning, etc in progress



^{39}Ar in Summer '17 data:

- PSD separates ^{39}Ar from CEvNS signal
- initial simulations show that separation is adequate and ^{39}Ar background can be completely suppressed.
- However, real events may prove more challenging and we are currently understanding that in the data

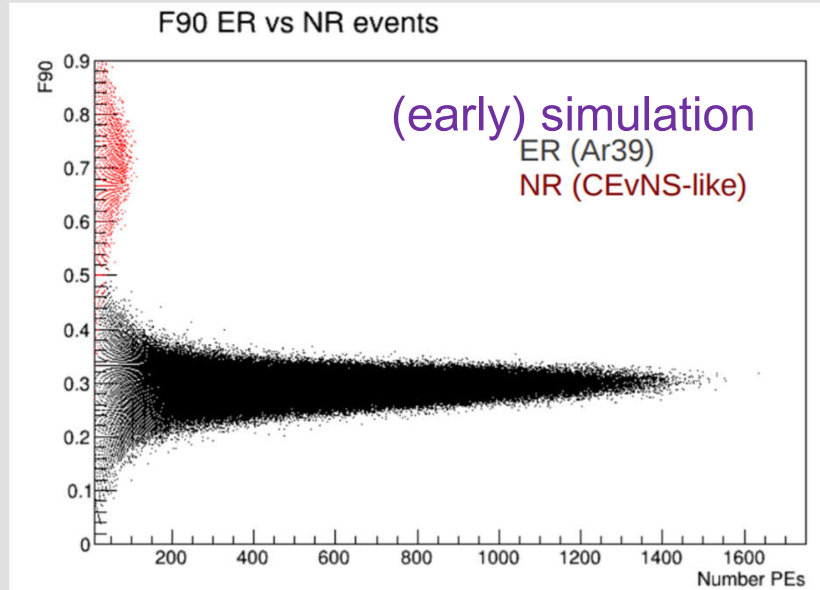


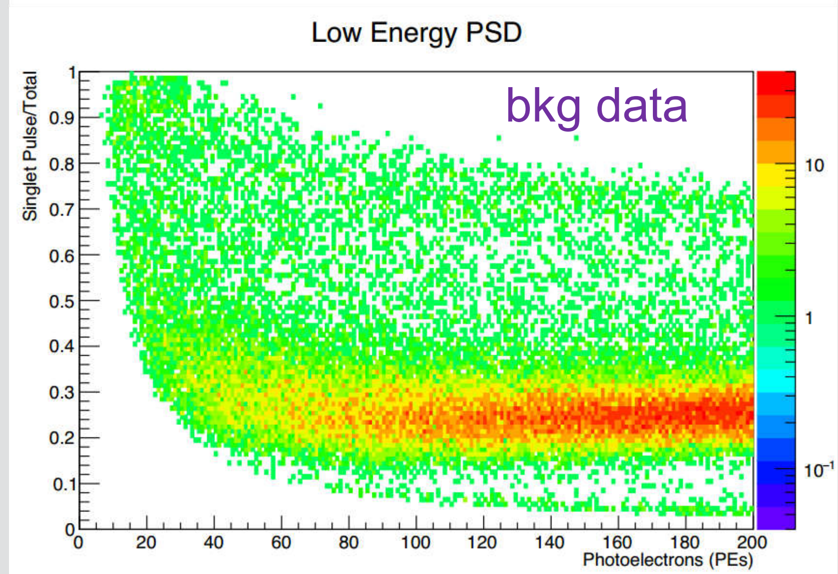


^{39}Ar in CEvNS data:

Some (rough) rate calculations:

- 100 CEvNS events/ SNS yr in 20kg with 20 keVnr threshold
- beam-on livetime = 200 mins (10μs window x 60 Hz)
- 1Bq/kg 39Ar $\Rightarrow$ 240k events in 1 SNS-yr ~50k in ROI (20-200 PE)
- reduce to 500 evs backgnd (as with CsI data set)
- then PSD requirements are:
    - atmos. Ar: 1% leakage
    - underground Ar w/20x reduction, 20% leakage allowed
    - if 100x ^{39}Ar suppression, then S:B = 5:1 before any PSD
- A powerful improvement, esp with larger detectors!





DM sensitivities with CsI in COHERENT

Constraining Photon Portal Dark Matter with TEXONO and COHERENT Data

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November 10, 2017

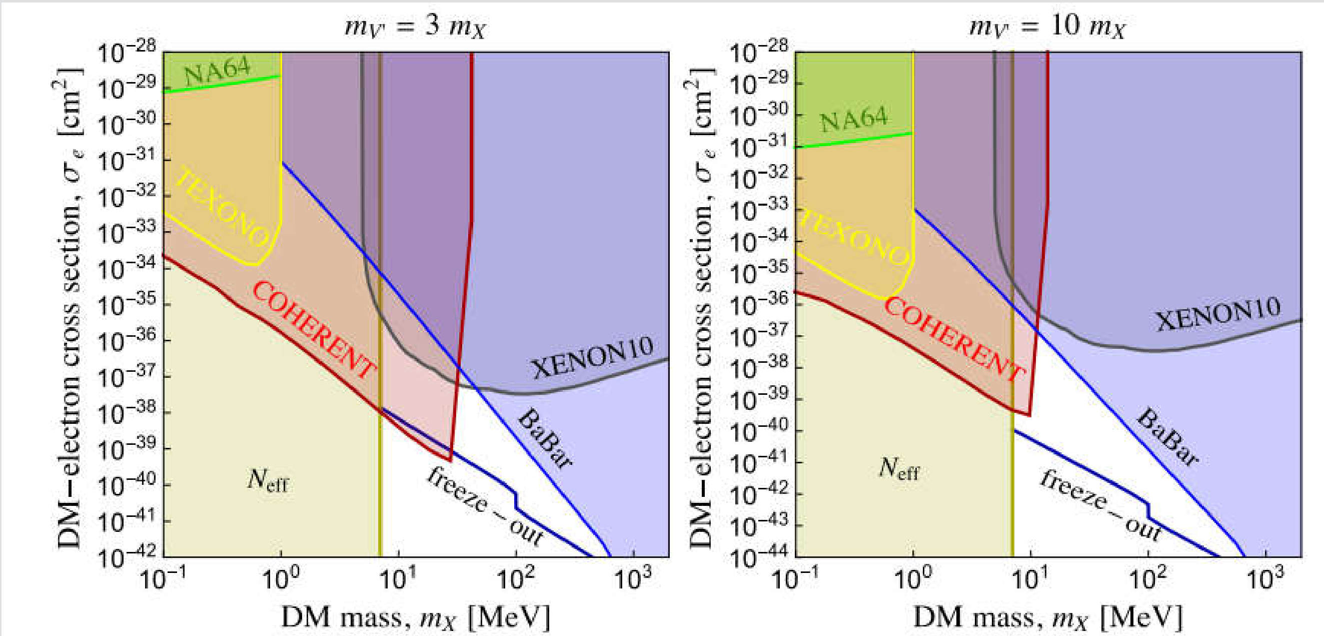

Fig. 3: The COHERENT bounds derived in this work in the context of other bounds on DM interacting with a kinetically mixed dark photon. See Sec. 5 for a description of these additional bounds. Additional bounds can be found in [29]. The left and right panels take $m_{V'} = 3\ m_X$ and $m_{V'} = 10\ m_X$ respectively.