The Smallest Neutrino ***Detectors*** in the World

Phil Barbeau

Duke
UNIVERSITY

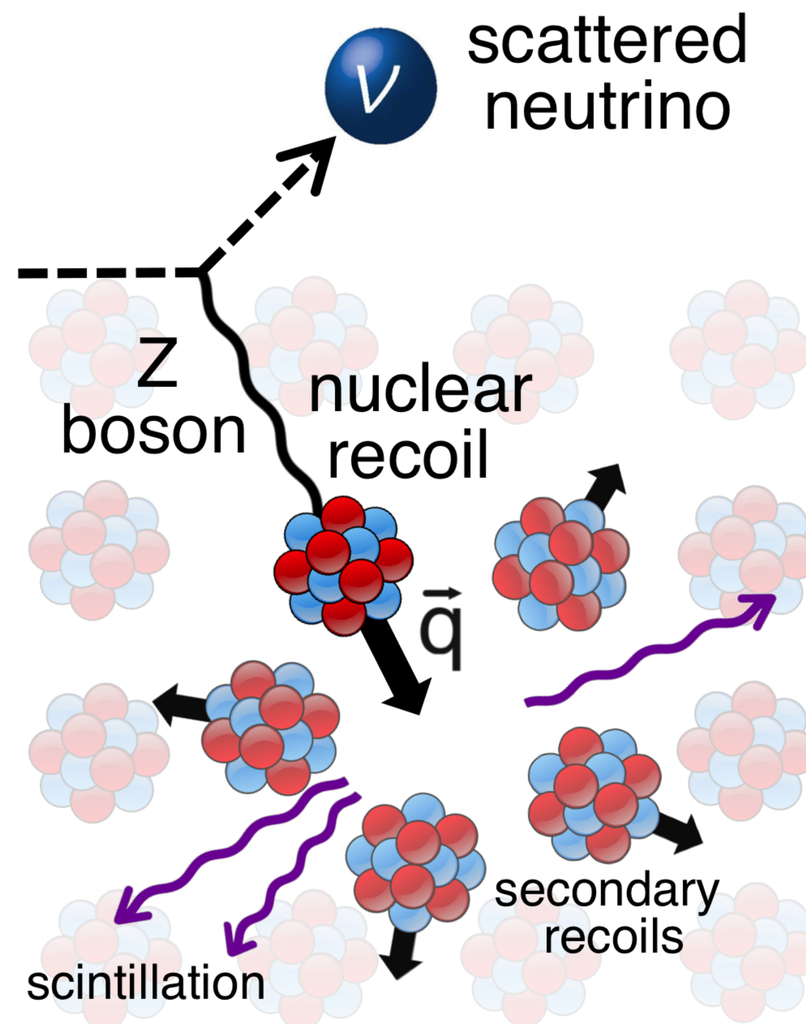
Coherent ν-Nucleus Scattering

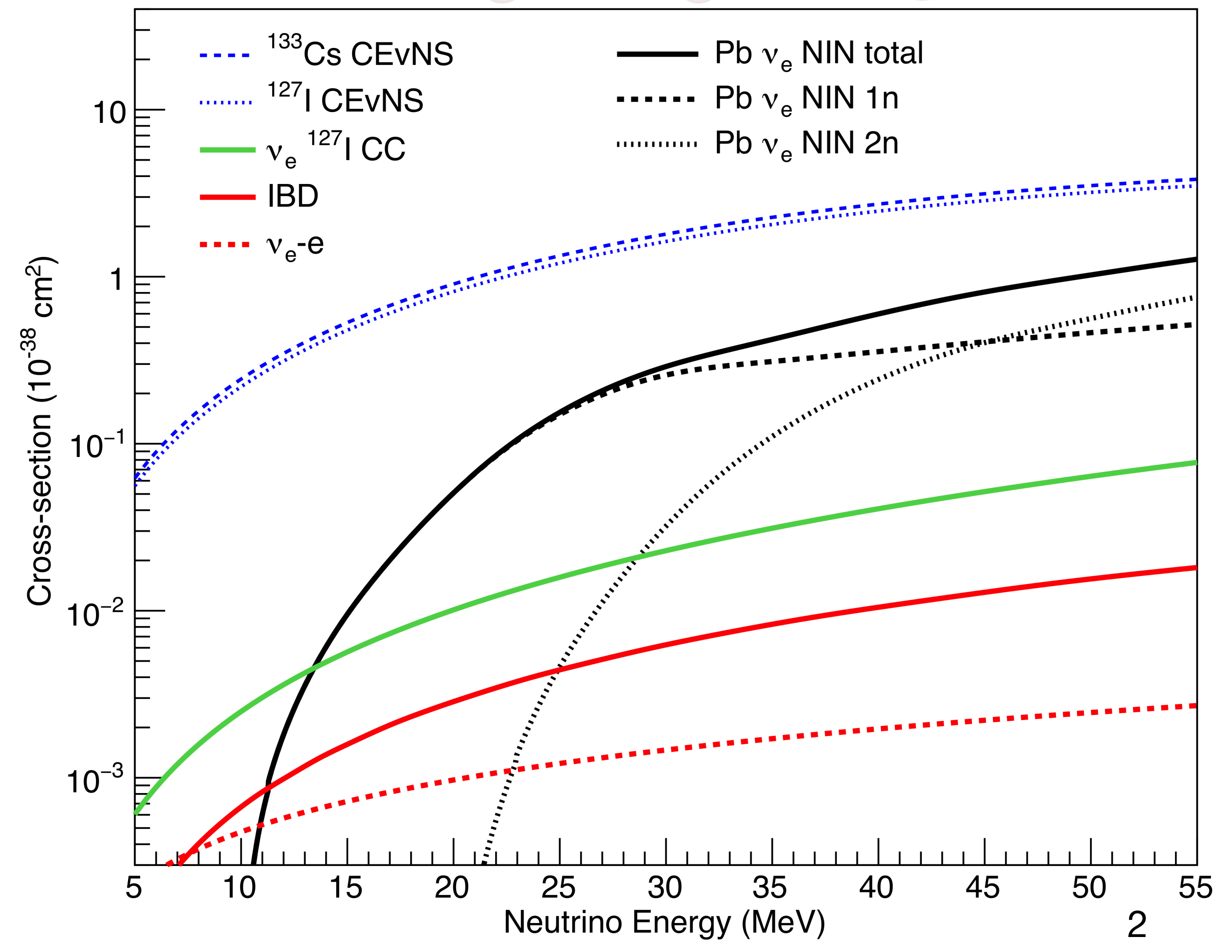
- 43 years ago, Coherent Elastic Neutrino-Nucleus Scattering (CEvNS) was predicted with the realization of the neutral weak current. D. Z. Freedman, PRD 9 (5) 1974

- Neutrino scatters coherently off all Nucleons → cross section enhancement: $\sigma \propto \mathbf{N^2}$

- Initial and final states must be identical: Neutral Current elastic scattering

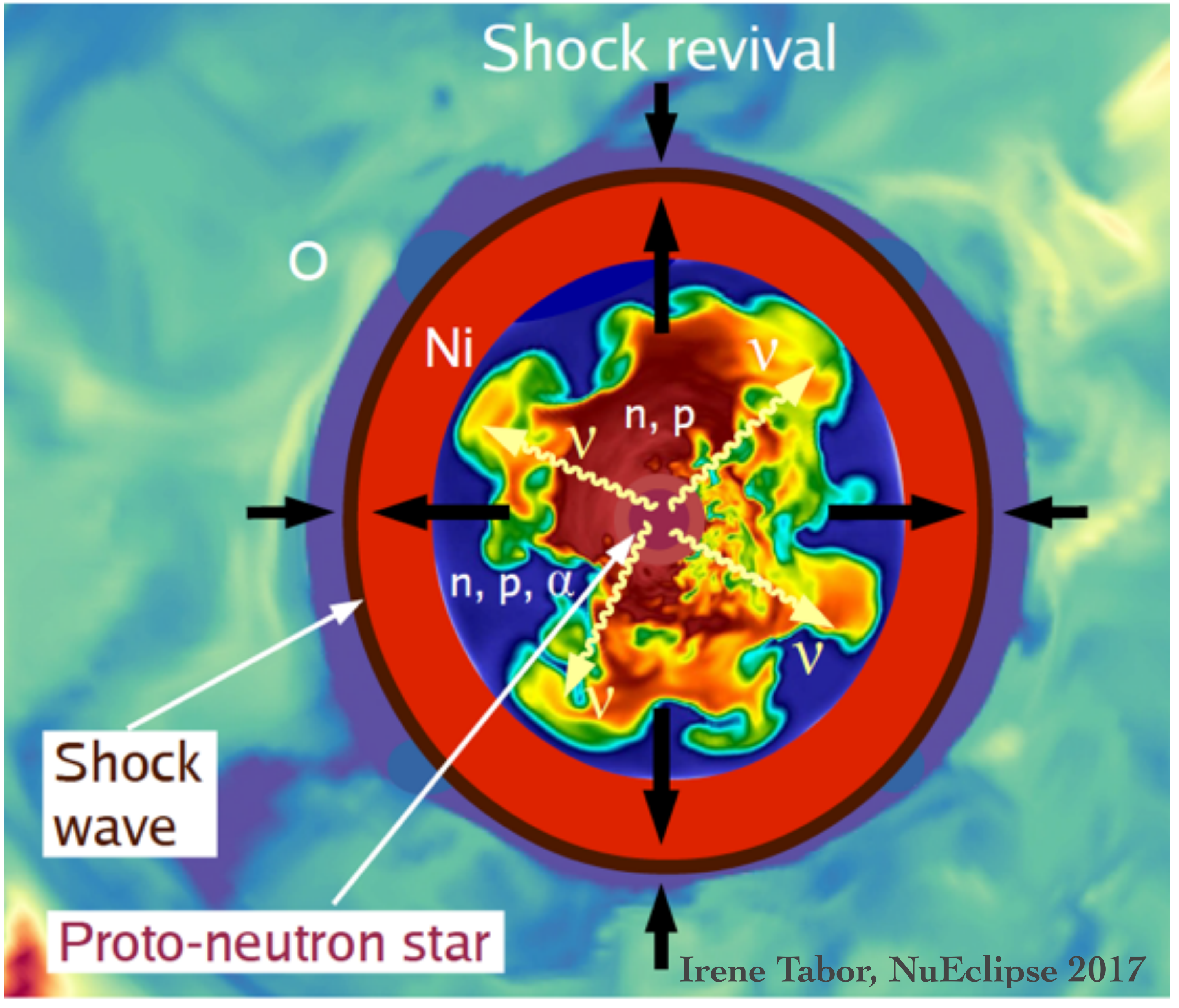
- Nucleons must recoil in phase →low momentum transfer qR <1 → *very* low energy nuclear recoil





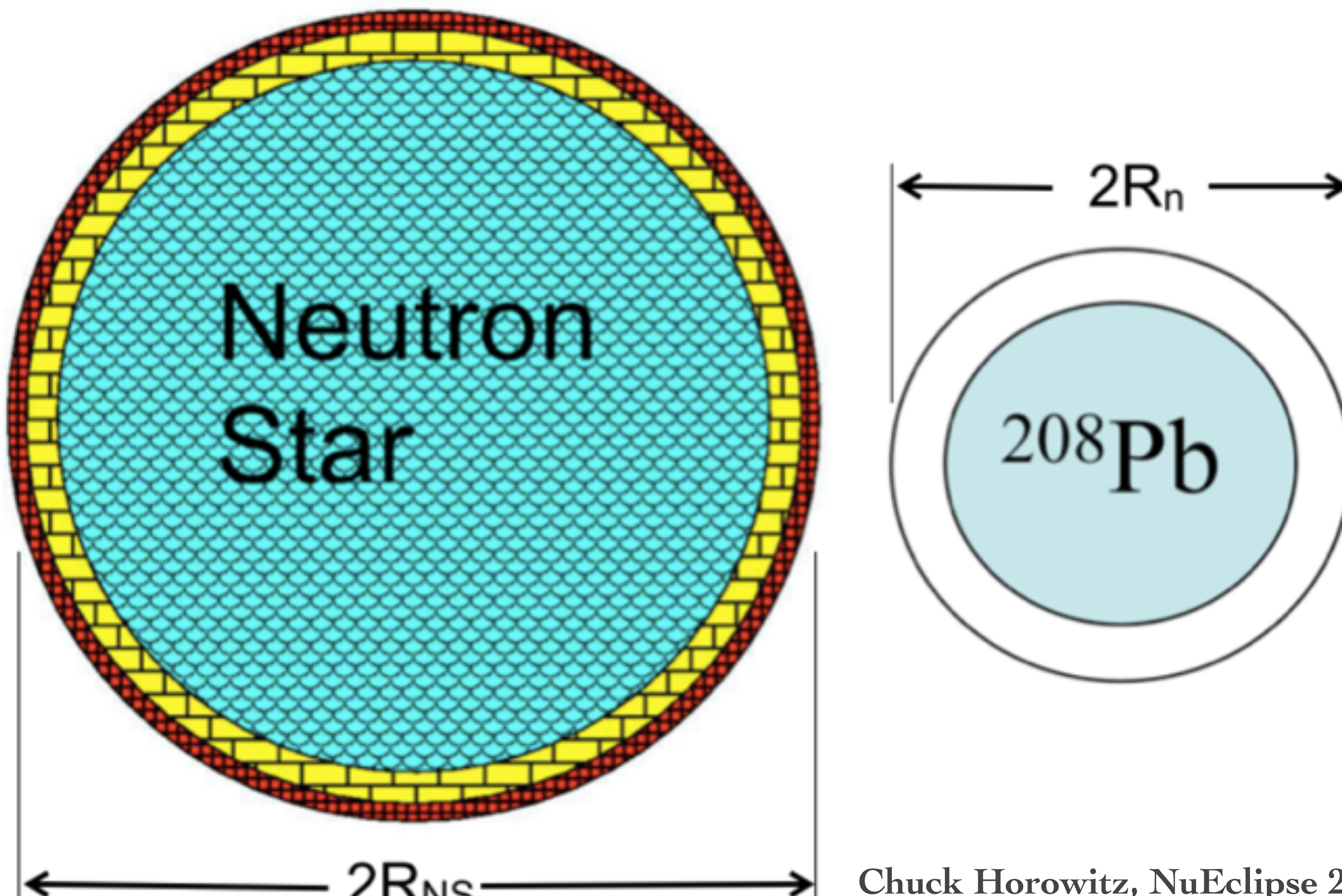
Supernovas Don’t Like to Explode

- Neutrinos carry 99% of the energy released (10^{53} ergs)
- CEvNS acts to reinvigorate stalled shock waves **J.R. Wilson, PRL 32 (74) 849**



Neutron Skin Depth

- Neutrons in nuclei are pushed out past the radius of protons
- The loss of coherence in CEvNS measures the neutron distribution, which has implications for neutron star structure and the equation of state



Chuck Horowitz, NuEclipse 2017

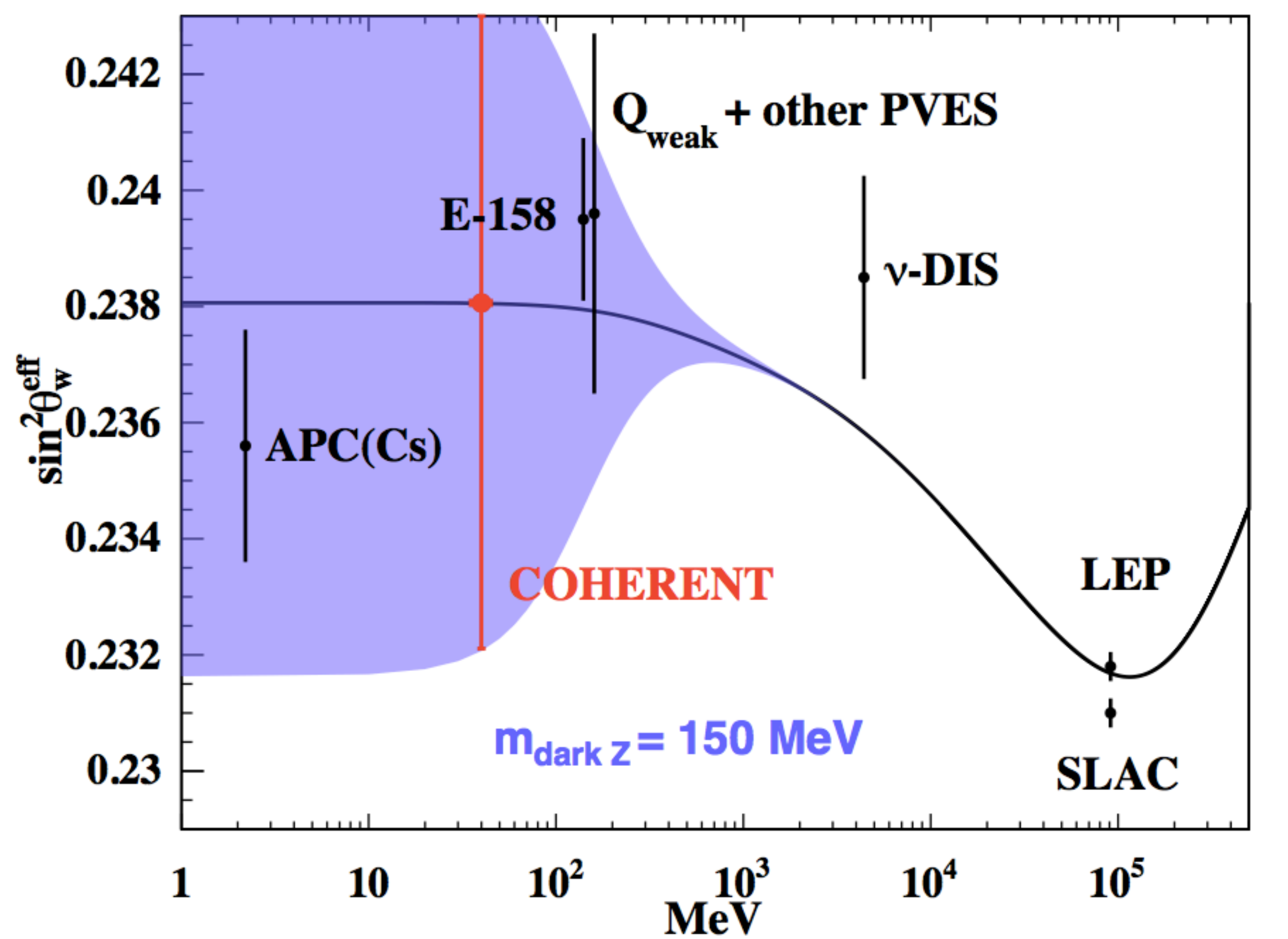
Are There More Neutral Currents?

- The CEvNS interaction rate is proportional to Q_W^2

$$\sigma_{coh} \sim \frac{G_f^2 E^2}{4\pi}(Z(4\ sin^2\theta_w - 1) + N)^2$$

- Supersymmetric extensions to the Standard Model can change the interaction rate and kinematics of CEvNS L. M. Krauss, PLB 269, 407
- Testable theories include models that can explain the $(g\text{-}2)_\mu$ anomaly and also play a role as Dark Matter
- Can also lead to “non-standard” neutrino interactions

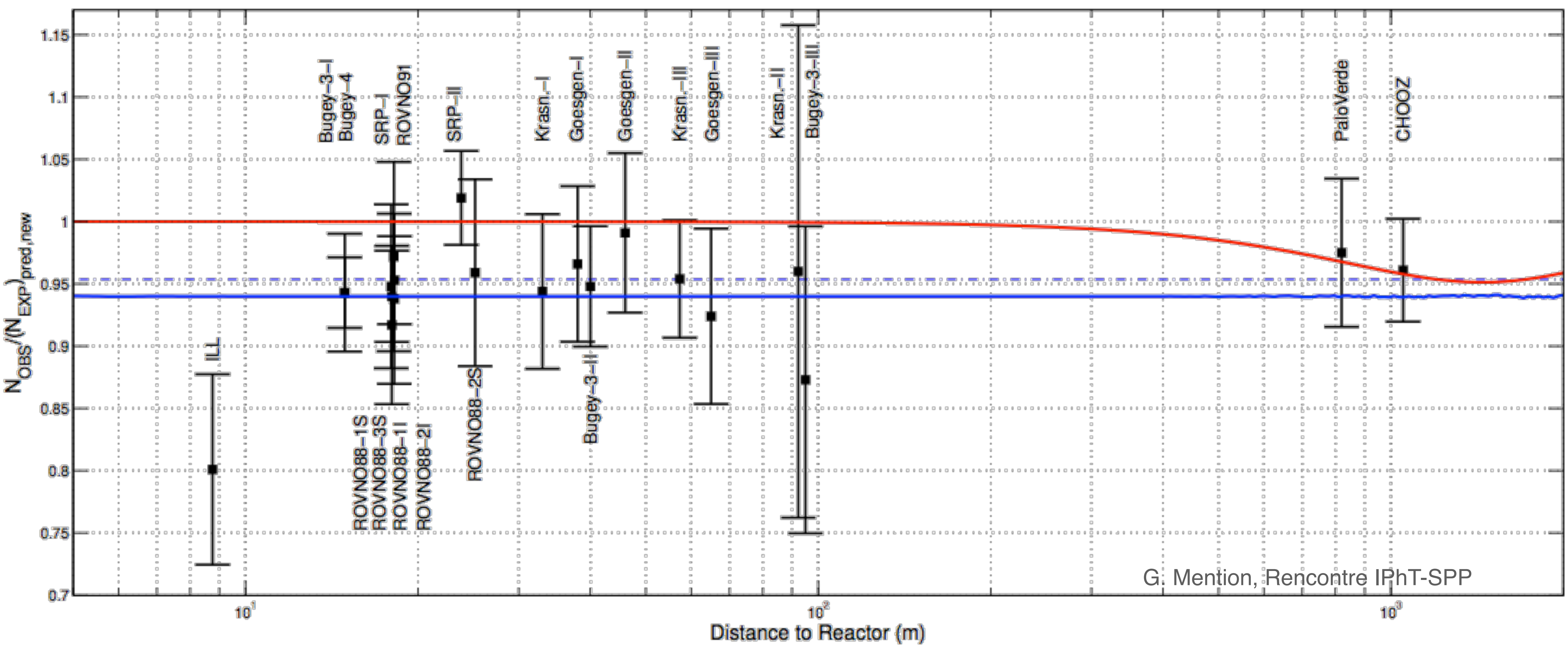
J. Barranco et al., JHEP0512:021, 2005
K. Scholberg, Phys.Rev.D73:033005, 2006



Searches for Sterile Neutrinos

- Several past experiments have observed anomalous behavior of neutrinos suggesting that they oscillate into sterile neutrinos.

- CEvNS provides perhaps the best way to explore any sterile neutrino sector
  A. Drukier & L. Stodolsky, PRD 30 (84) 2295



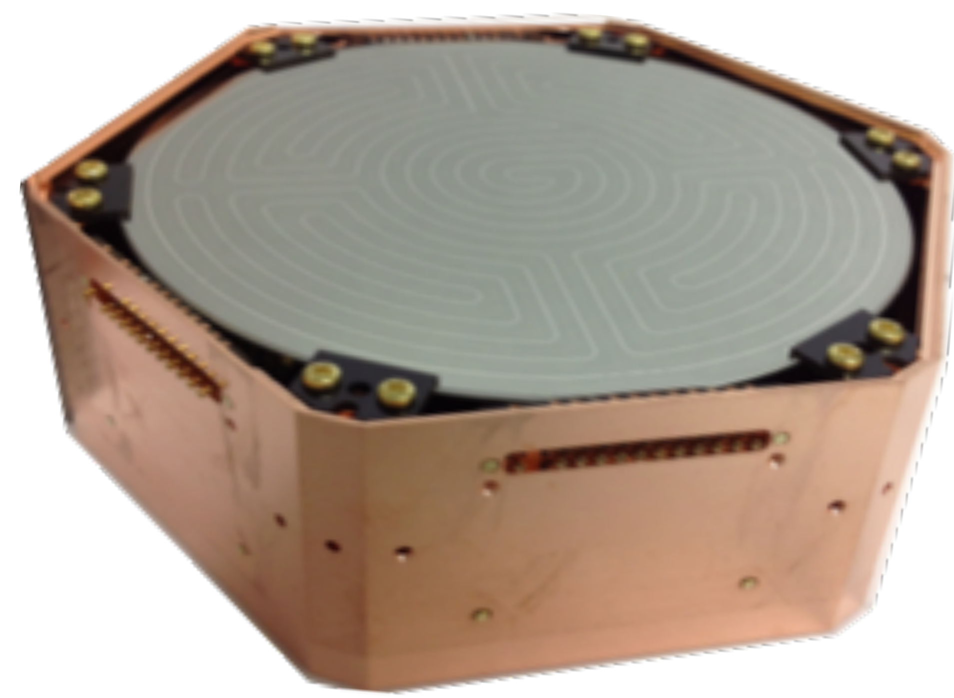
This Has Been Attempted Before…

- A new type of bolometric detector was proposed in 1984 by Drukier and Stodolsky and1985 by Blas Cabrera, Lawrence Krauss and Frank Wilczek

- Spallation targets, reactors and the sun suggested as neutrino sources (1984)

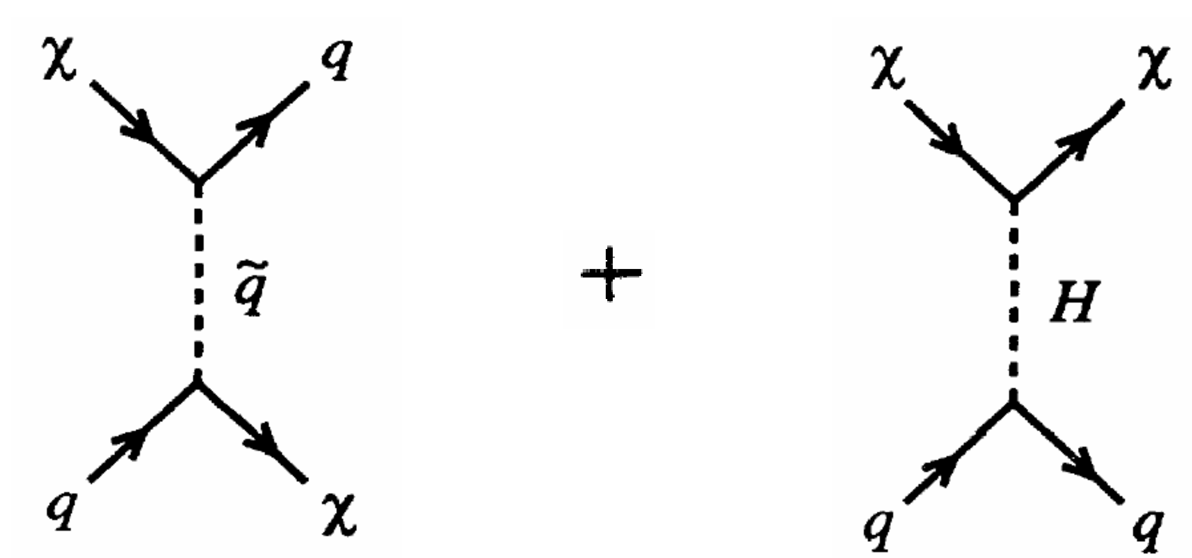
A. Drukier & L. Stodolsky, PRD 30 (84) 2295

B. Cabrera, L. Krauss, F. Wilczek, PRL 55, 25 (1985)



- This was the precursor to the CDMS and CRESST Dark Matter searches

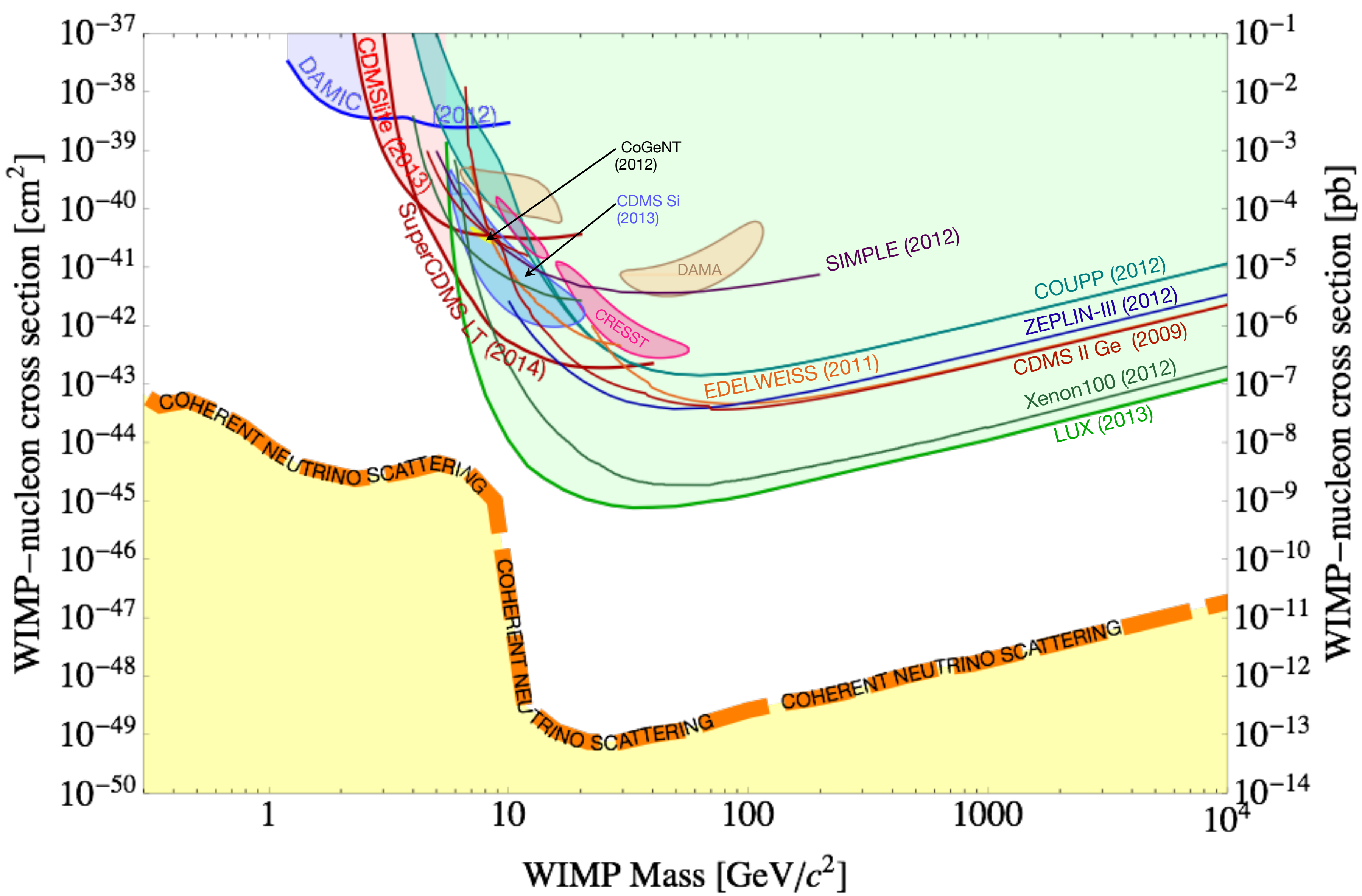
- It turns out looking for Dark Matter was easier



No Longer Just a Signal

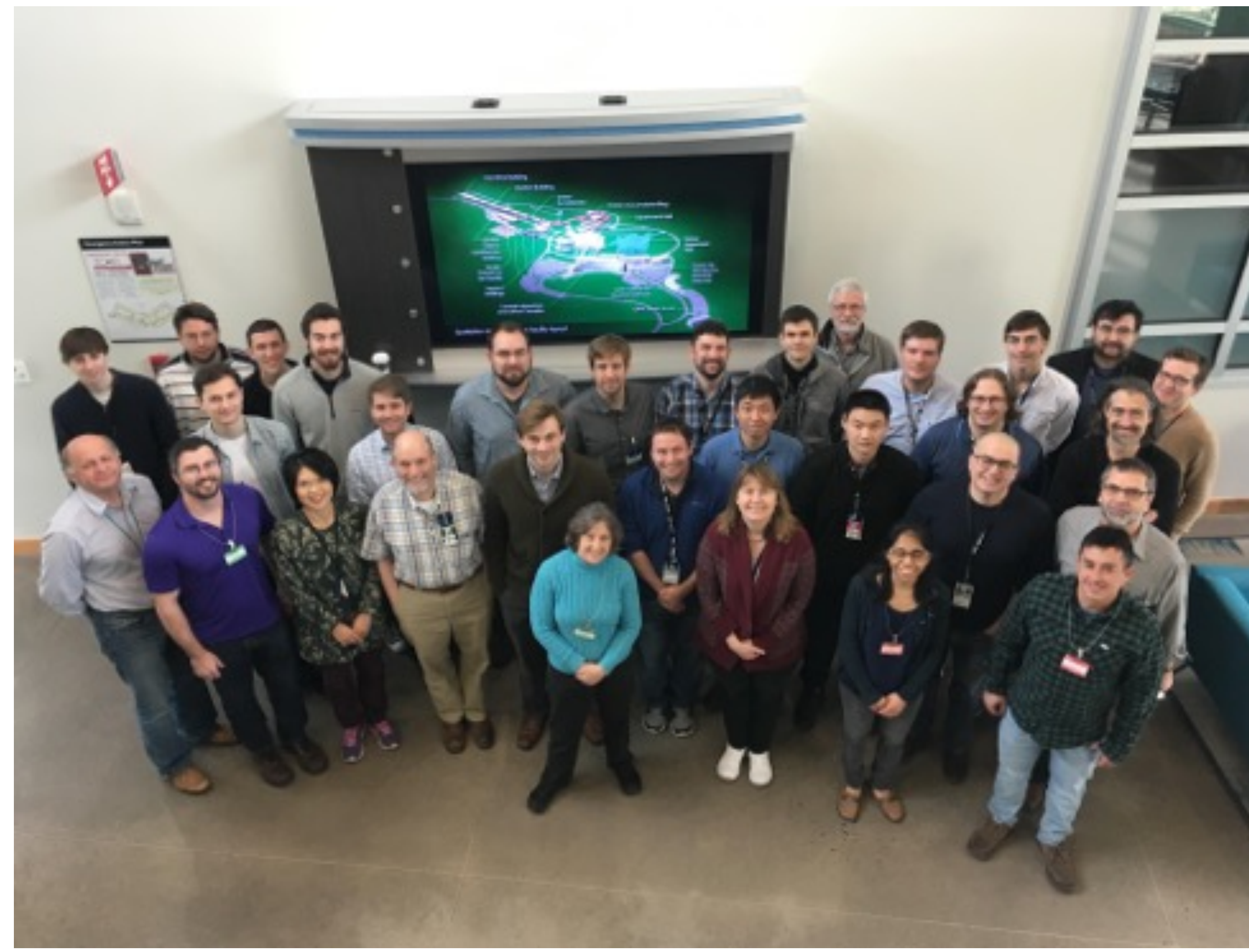
CEvNS is an irreducible background for WIMP searches.

Solar Neutrinos: A. Drukier & L. Stodolsky, PRD 30 (84) 2295



The COHERENT Collaboration

THE UNIVERSITY OF CHICAGO
Duke UNIVERSITY
UF UNIVERSITY of FLORIDA
KAIST
LaurentianUniversity UniversitéLaurentienne
Los Alamos NATIONAL LABORATORY EST. 1943
BERKELEY LAB
MEPhI
NORTH CAROLINA CENTRAL UNIVERSITY FOUNDED 1910
NC STATE UNIVERSITY
NM STATE UNIVERSITY
OAK RIDGE National Laboratory
Sandia National Laboratories
THE UNIVERSITY of TENNESSEE UT KNOXVILLE
TUNL
W UNIVERSITY of WASHINGTON

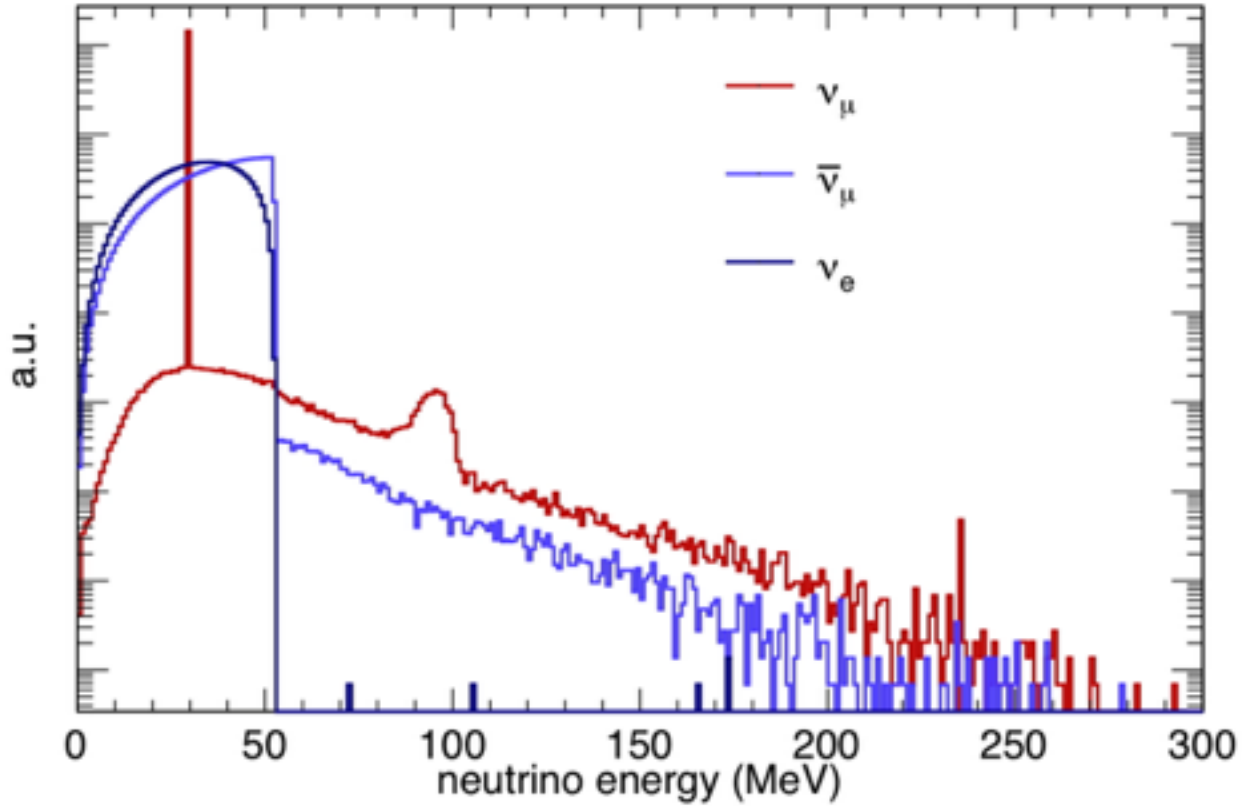


CNEC Consortium for Nonproliferation Enabling Capabilities
KICP
NNSA National Nuclear Security Administration
NSF
U.S. DEPARTMENT OF ENERGY

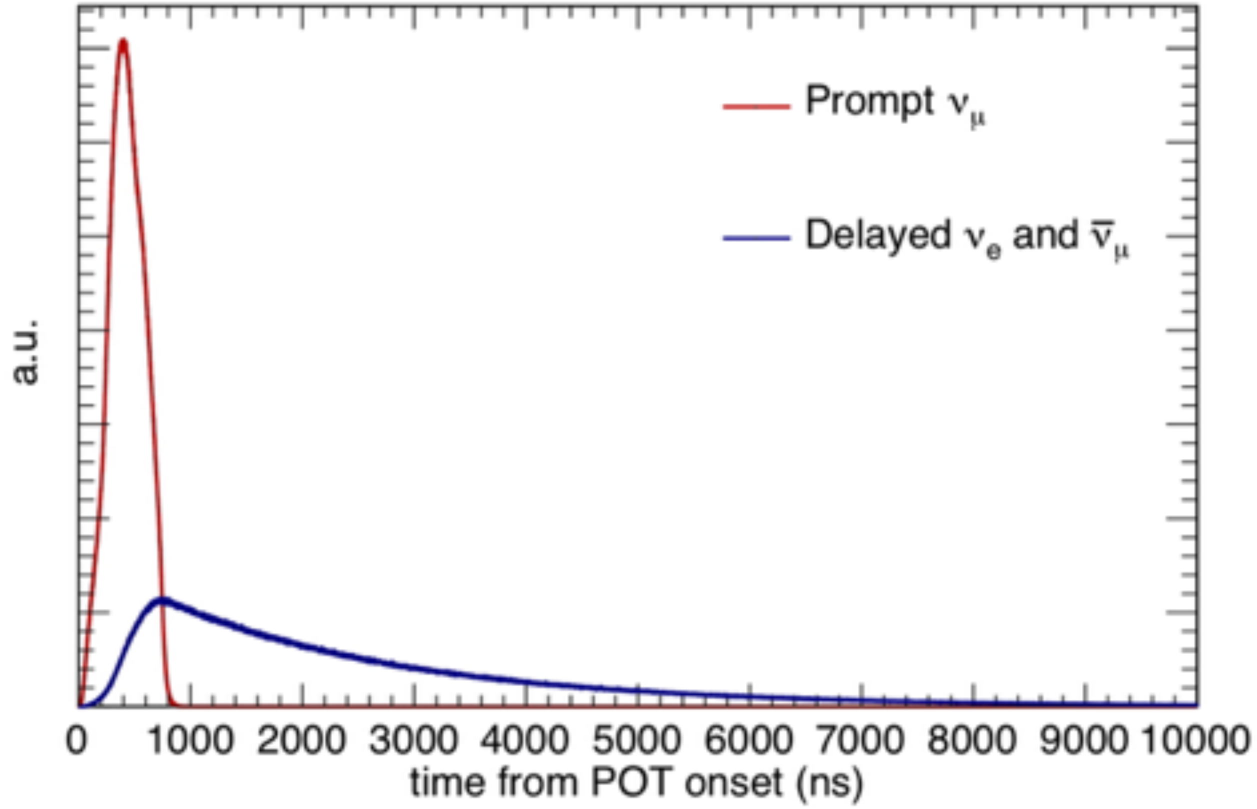
The Spallation Neutron Source

- Pion Decay-at-Rest Neutrino Source
- ν flux 4.3×10^{7} ν cm^{-2} s^{-1} at 20 m
- Pulsed: 800 ns full-width at 60 Hz

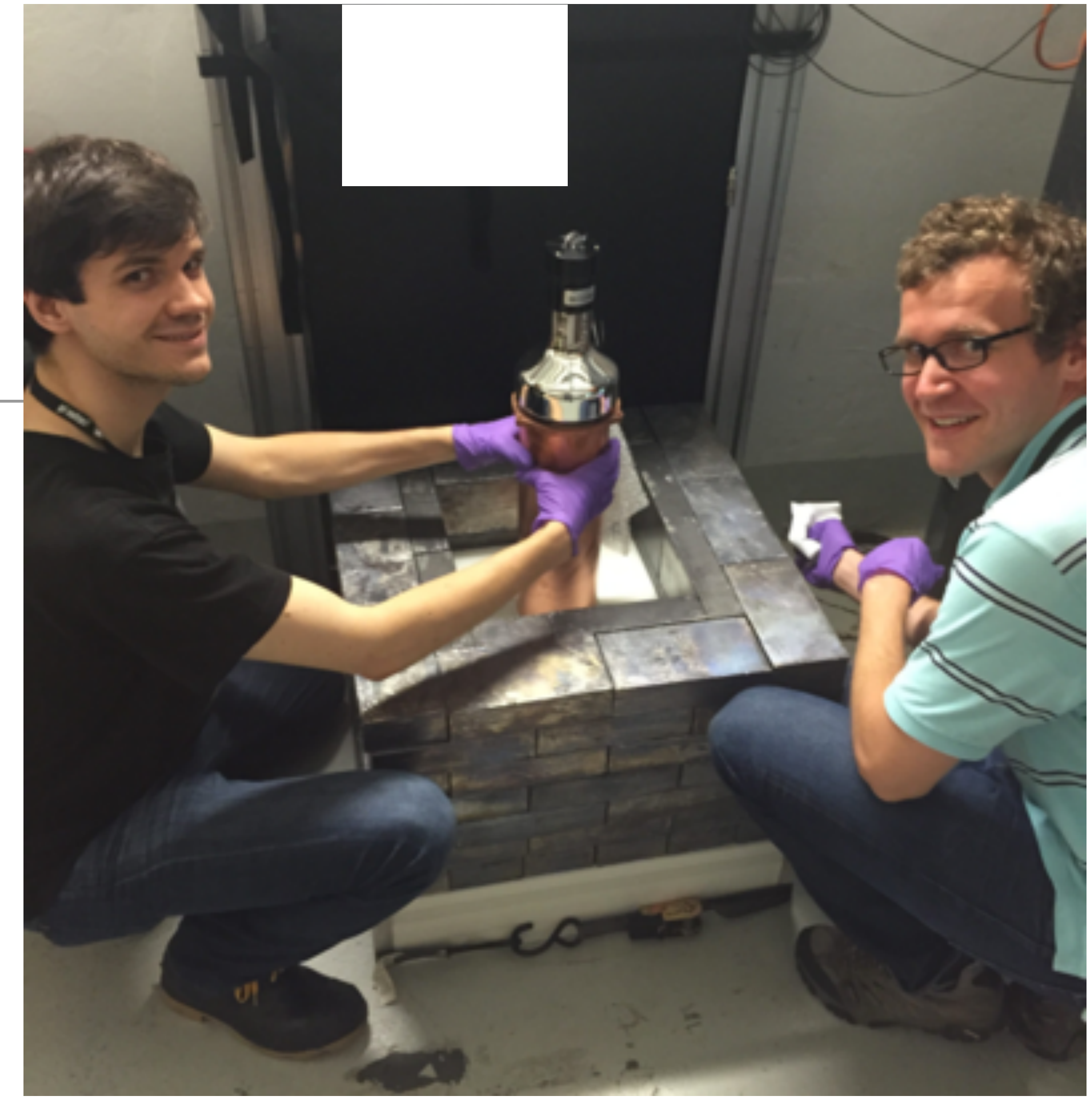
<1% contamination from non-CEvNS scatters



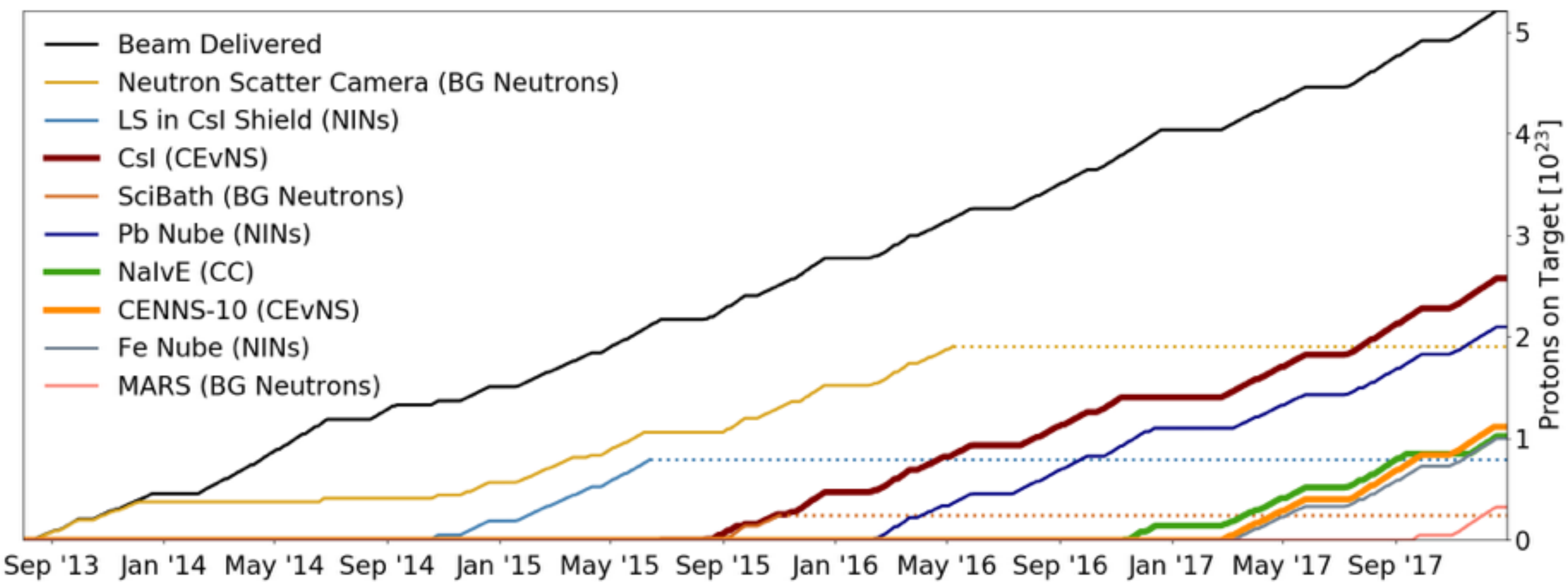
~4×10^{-5} background reduction



A Hand-Held Neutrino Detector

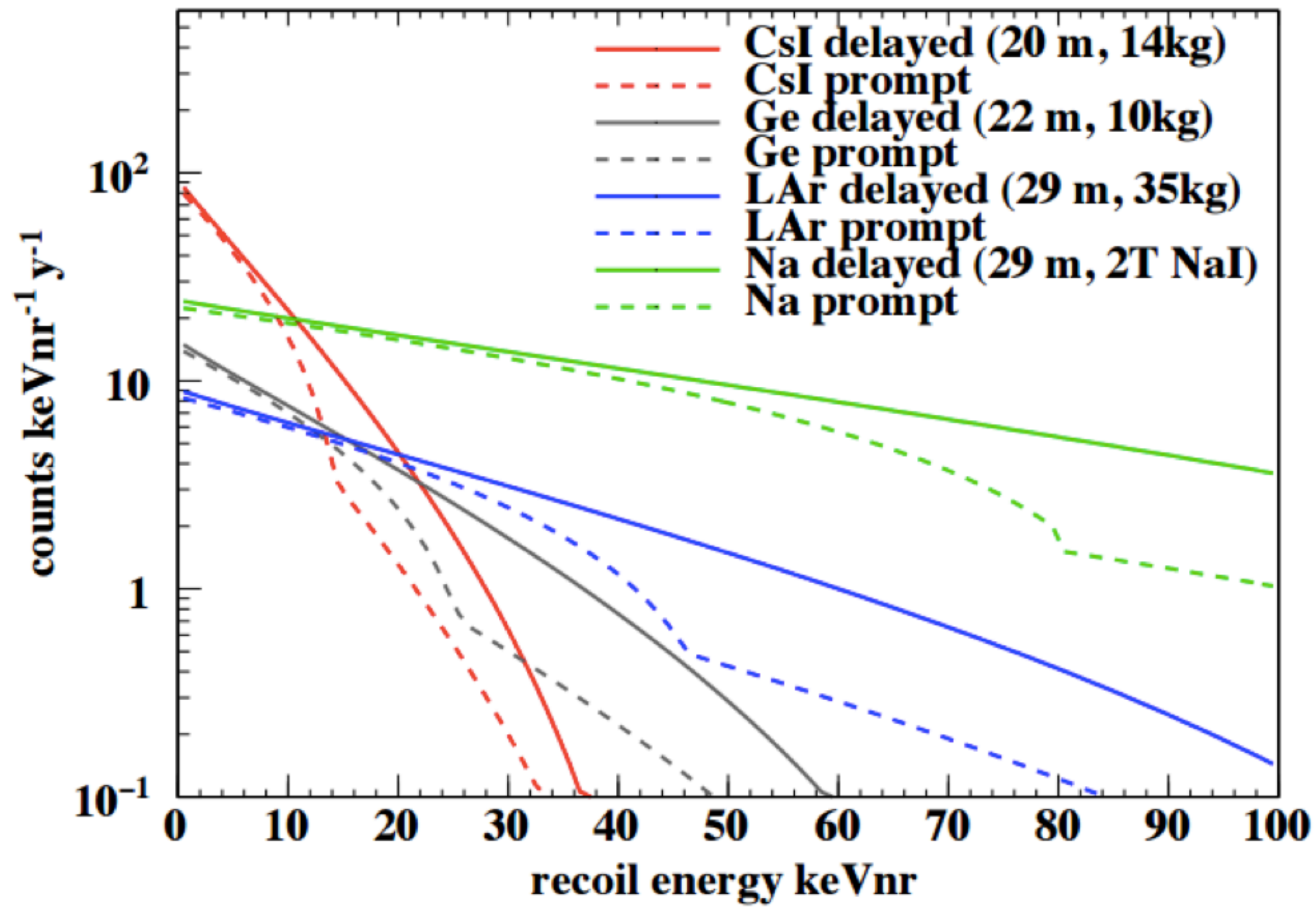


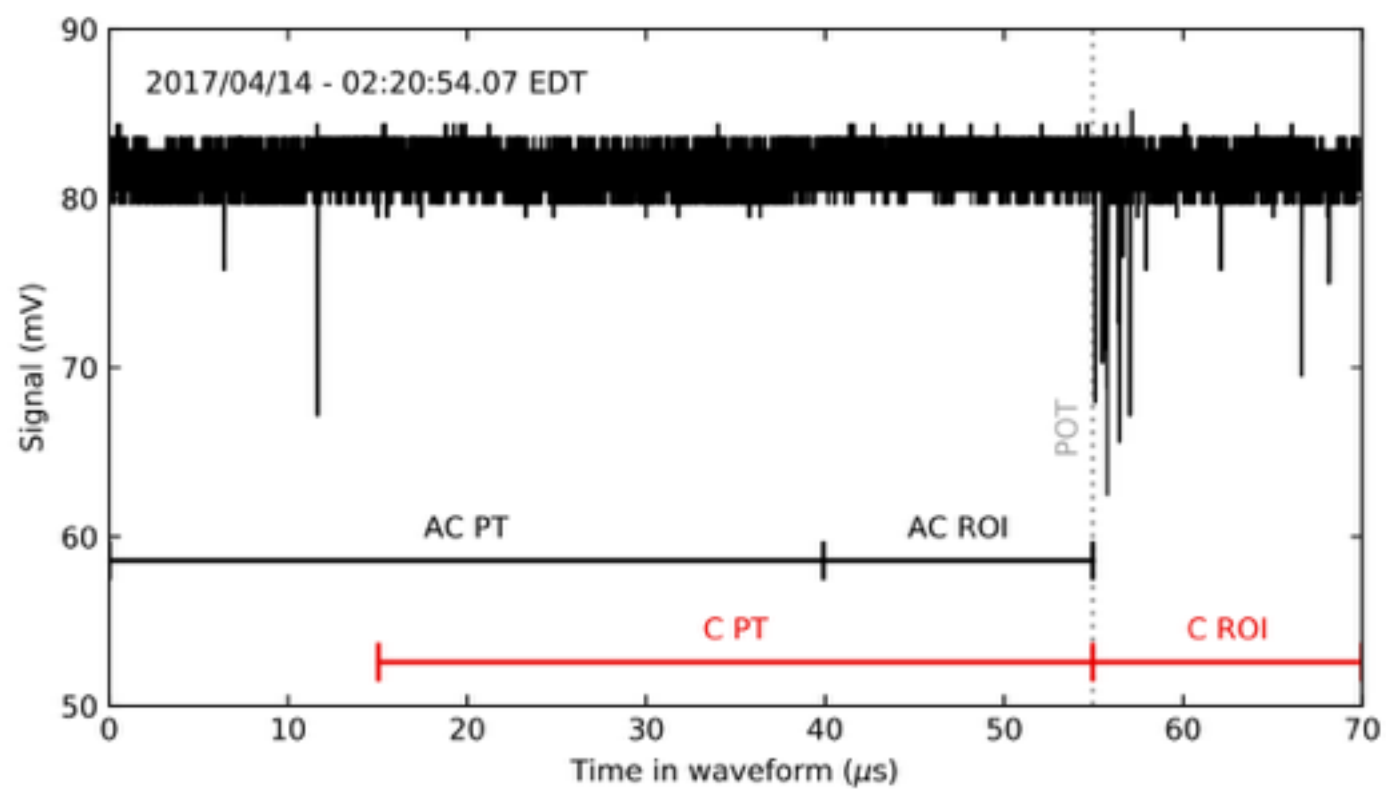
- 14.6 kg low-background CsI[Na] detector deployed to a basement location of the SNS in the summer of 2015
- ~ 2.6×10^{23} POT delivered and recorded since CsI began taking data



CsI[Na] Signals

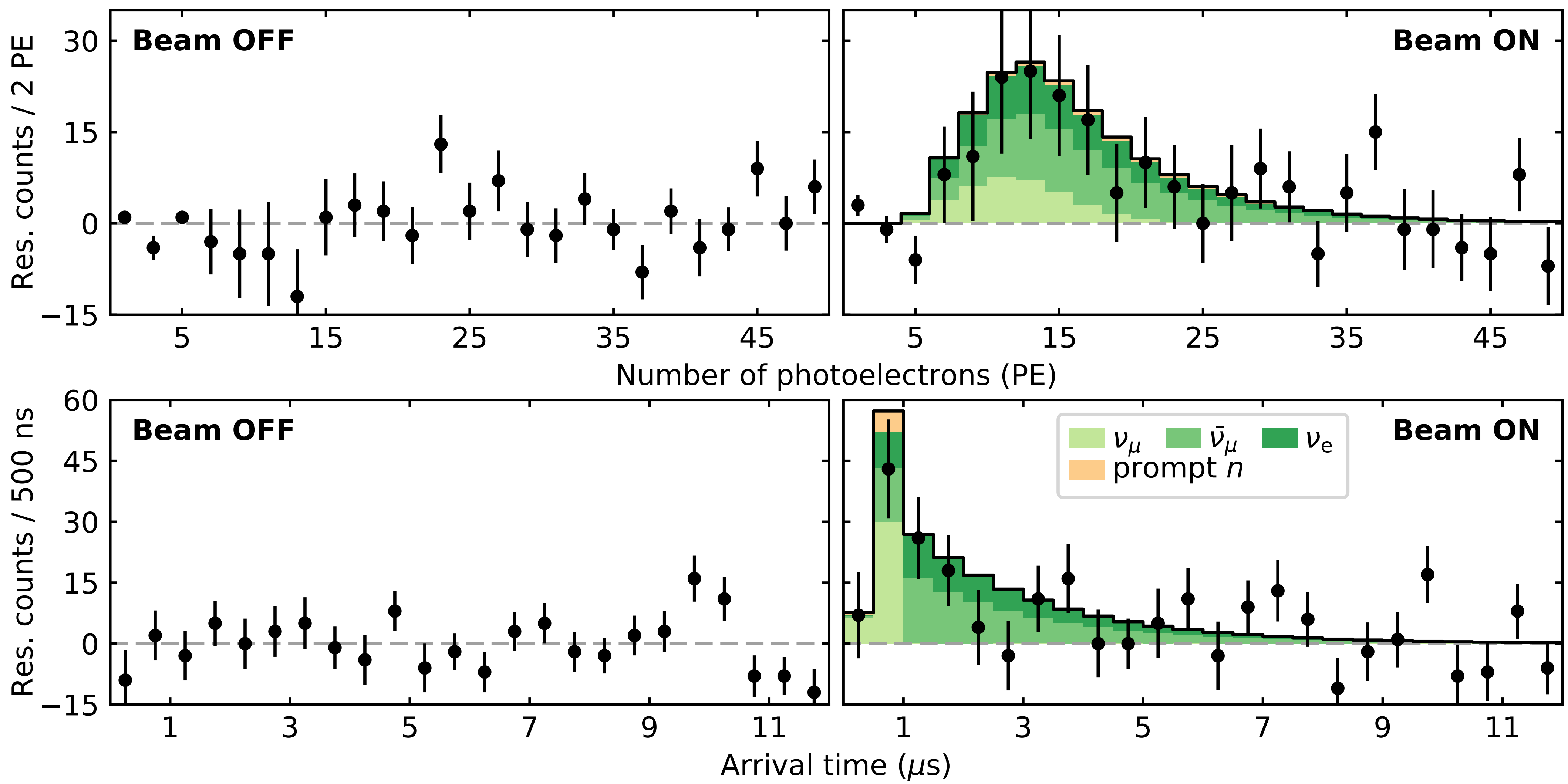
- Even at the SNS CEvNS gives rise to extremely low energy nuclear recoils
- ~ 1.2 PE/keV_{nr} after accounting for Quenching Factor for nuclear recoils
- expect 5-30 photoelectrons





The Result

D. Akimov et al., Science 10.1126/science.aao0990 (2017).



Observation of coherent elastic neutrino-nucleus scattering

D. Akimov[1,2], J. B. Albert[3], P. An[4], C. Awe[4,5], P. S. Barbeau[4,5], B. Becker[6], V. Belov[1,2], A. Brown[4,7], A. Bolozdy...

+ See all authors and affiliations

Science 03 Aug 2017:
eaao0990
DOI: 10.1126/science.aao0990

Peer Reviewed
← see details

The Result

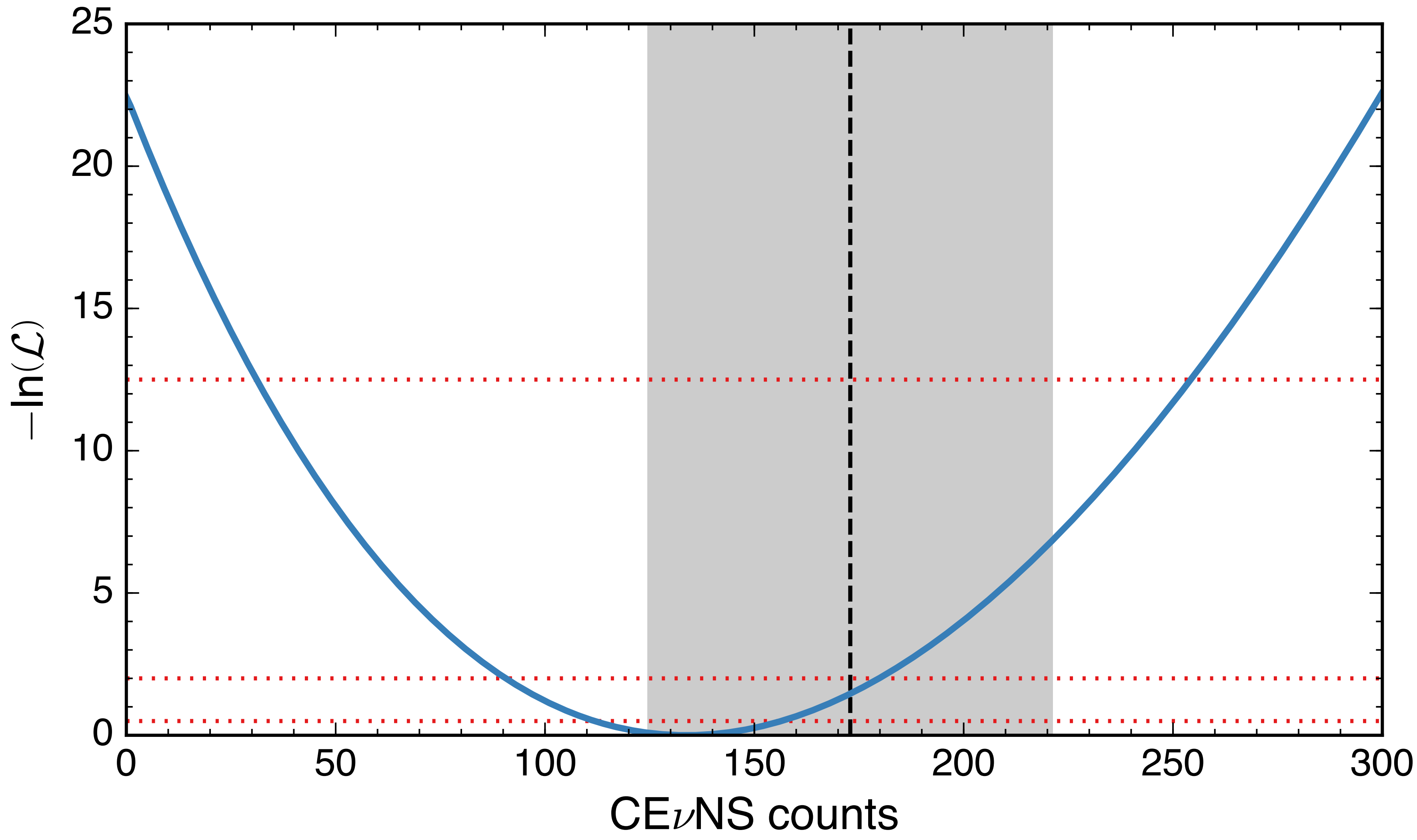
D. Akimov et al., Science 10.1126/science.aao0990 (2017).

- We report a **6.7 sigma** significance for an excess of events, that agrees with the standard model prediction to within **1 sigma**

Uncertainty on expected rate

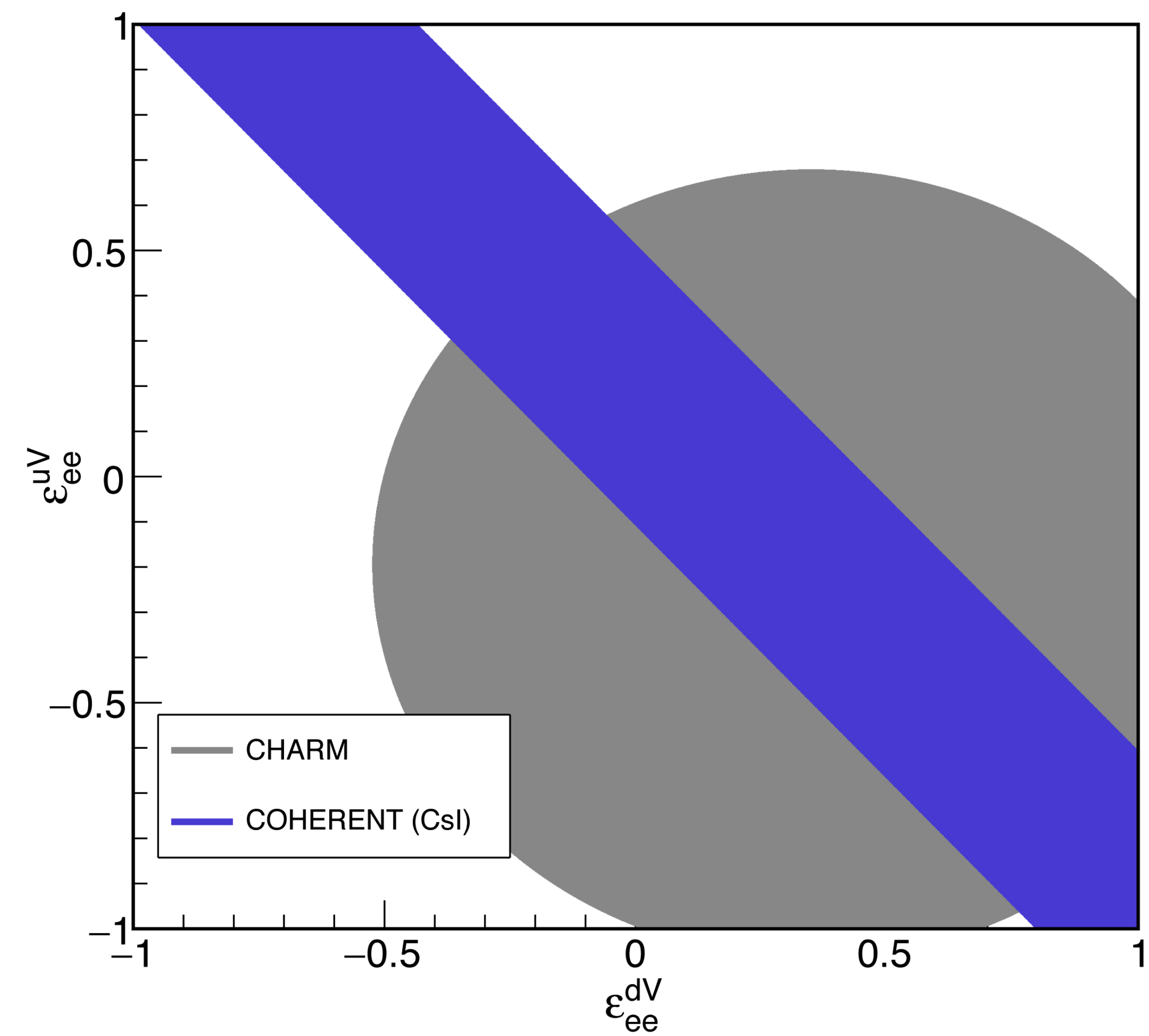
Event Selection	5%
Neutrino Flux	10%
Form Factor	5%
Quenching Factor	25%
Total uncertainty	**28%**

16% statistical uncertainty



Implications for Non-Standard Neutrino Interactions (COHERENT)

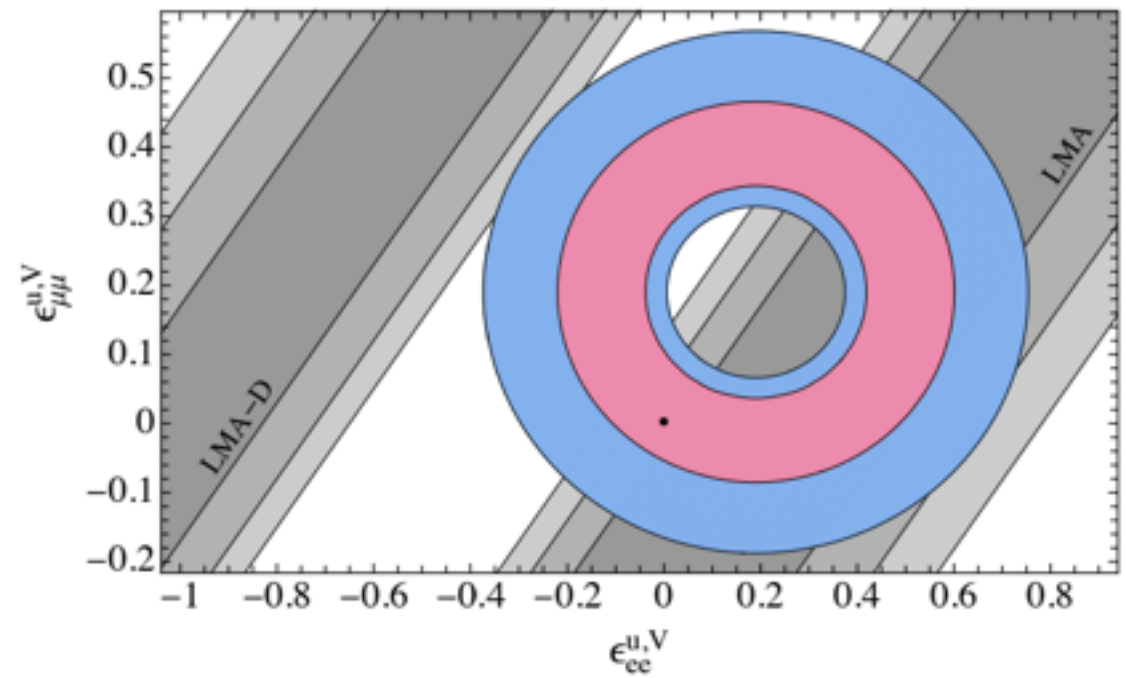
- First result improves constraints on non-universal NSI
- Low hanging fruit. We can expect significant improvement with more data, and when more COHERENT detectors report their results



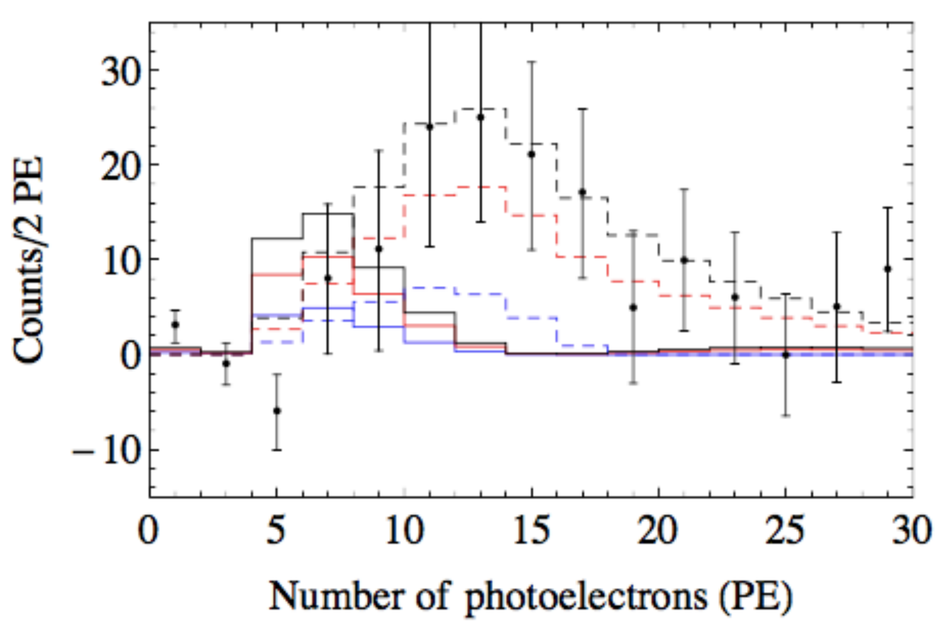
Implications for Non-Standard Neutrino Interactions

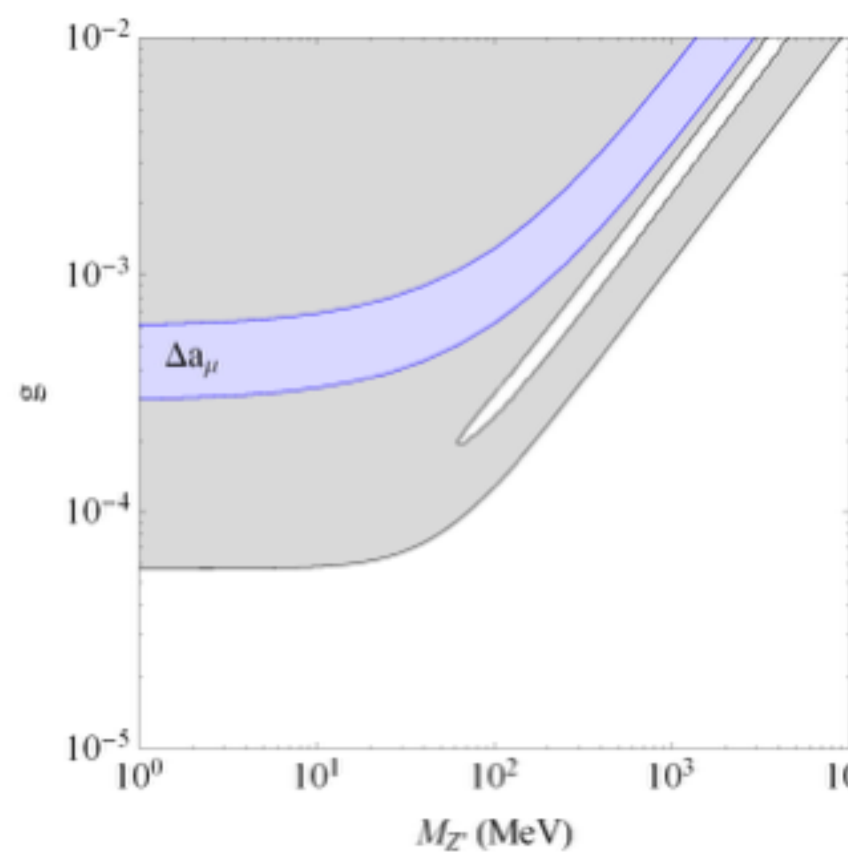
Current result already rules out (in combination with neutrino oscillation data) the Large Mixing Angle "Dark" solution.

Coloma et al, arXiv:1708.02899v1



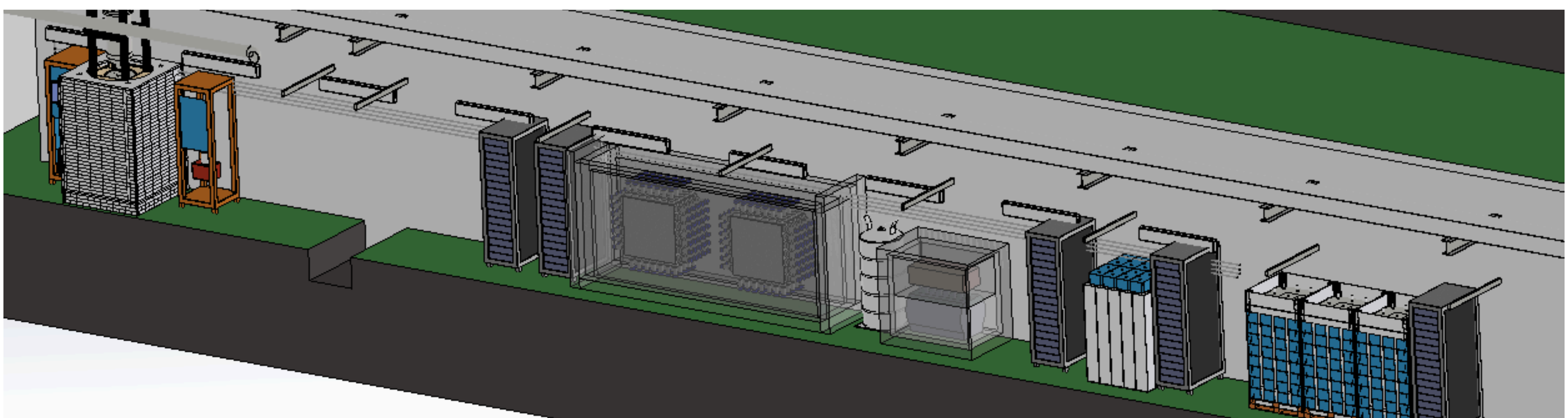
The result also finds tension (at 2 sigma) with a light-mass Z' dark mediator that can explain the $(g-2)_\mu$ anomaly. **Liao and Marfatia, arXiv:1708.04255v1**





COHERENT CEvNS Detectors Aiming for Precision

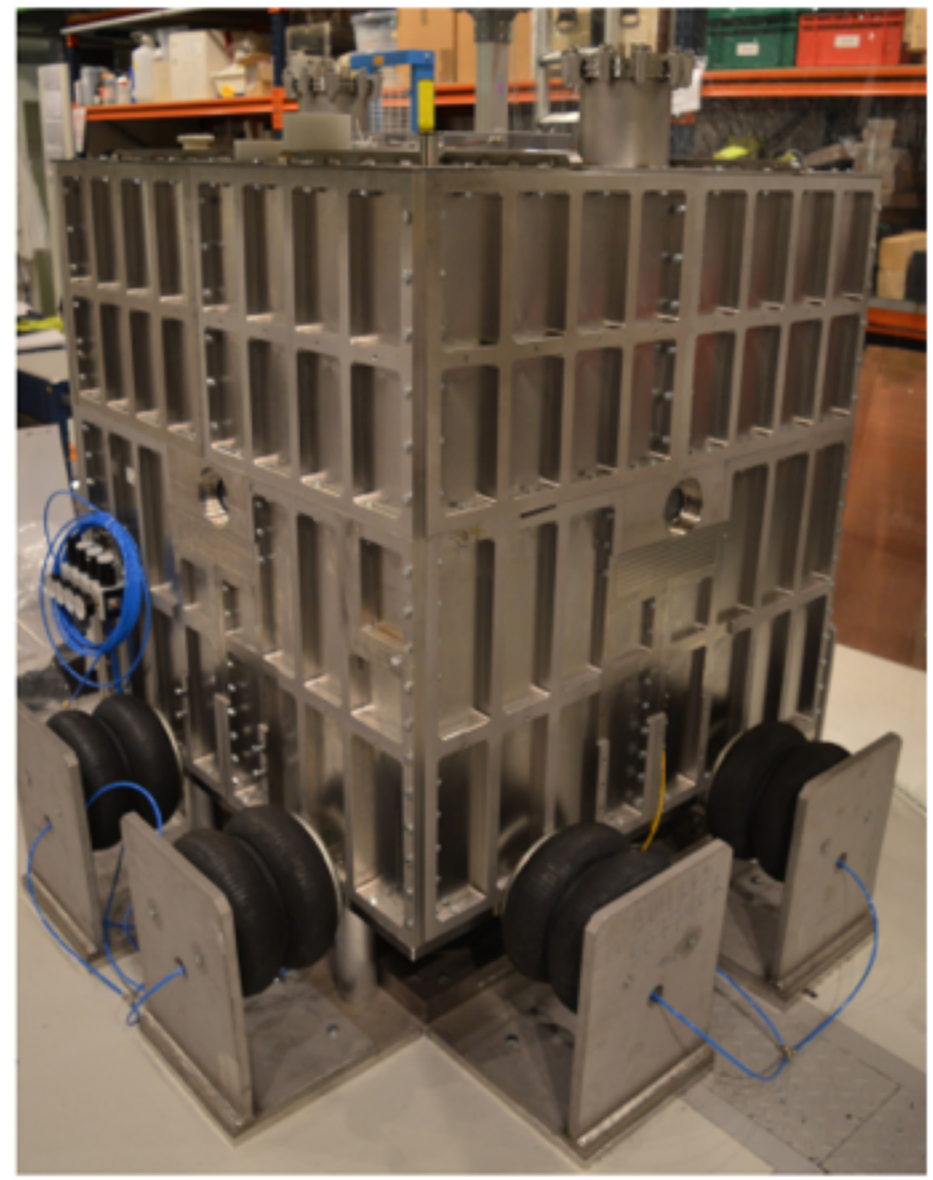
Nuclear Target	Technology	Mass (kg)	Distance from source (m)	Recoil threshold (keVr)
CsI[Na]	Scintillating Crystal	14.6	19.3	6.5
Ge	HPGe PPC	10	22	5
LAr	Single-phase	22	29	20
NaI[Tl]	Scintillating crystal	185*/ 2000	28	13



Open the Floodgates: CONUS

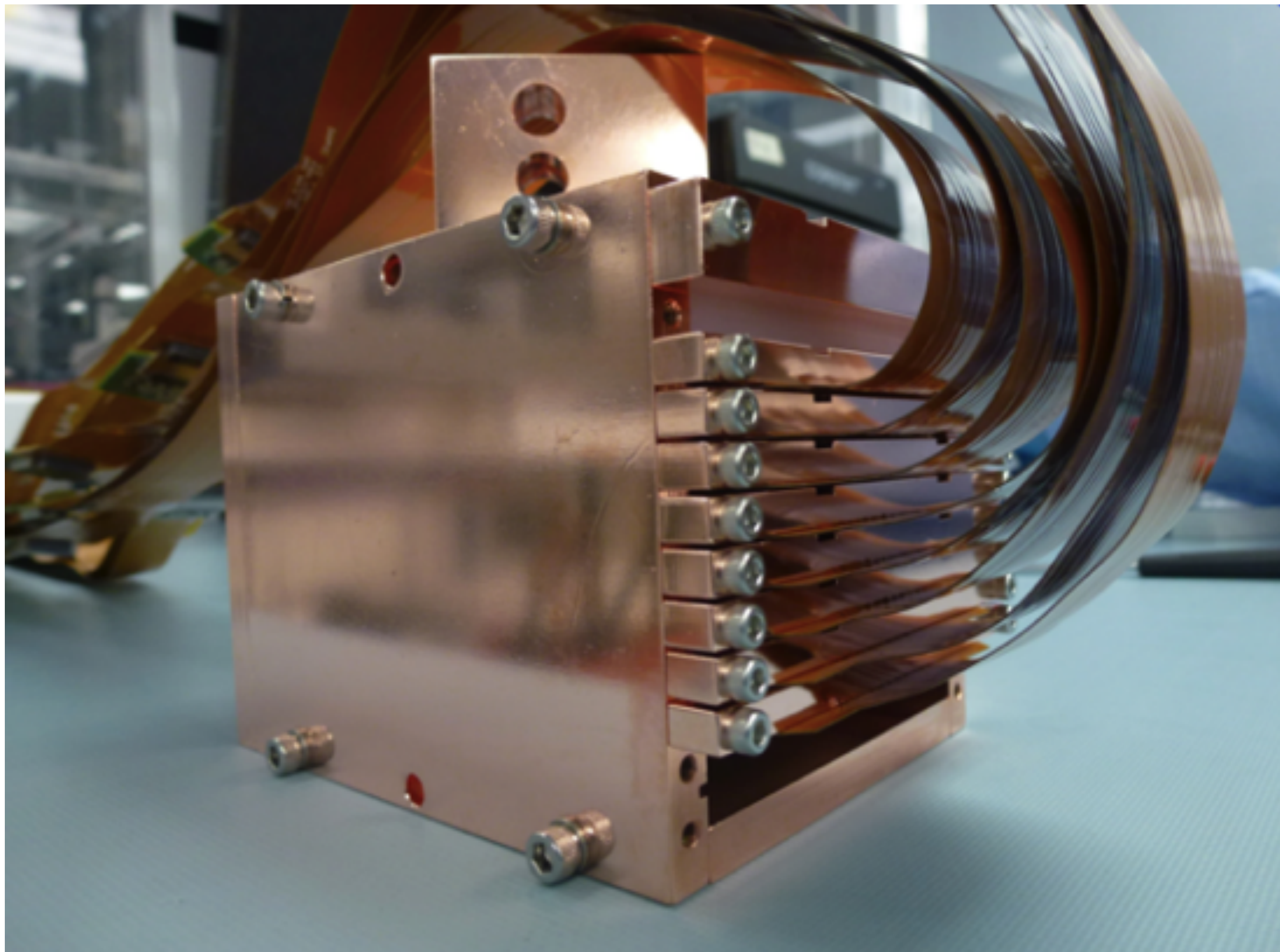
CONRAD Detector in CONUS Shield - during assembly

J. Hakenmuller, TAUP 2017



Low Threshold Ge detectors at the Brokdorf Reactor

Open the Floodgates: CONNIE



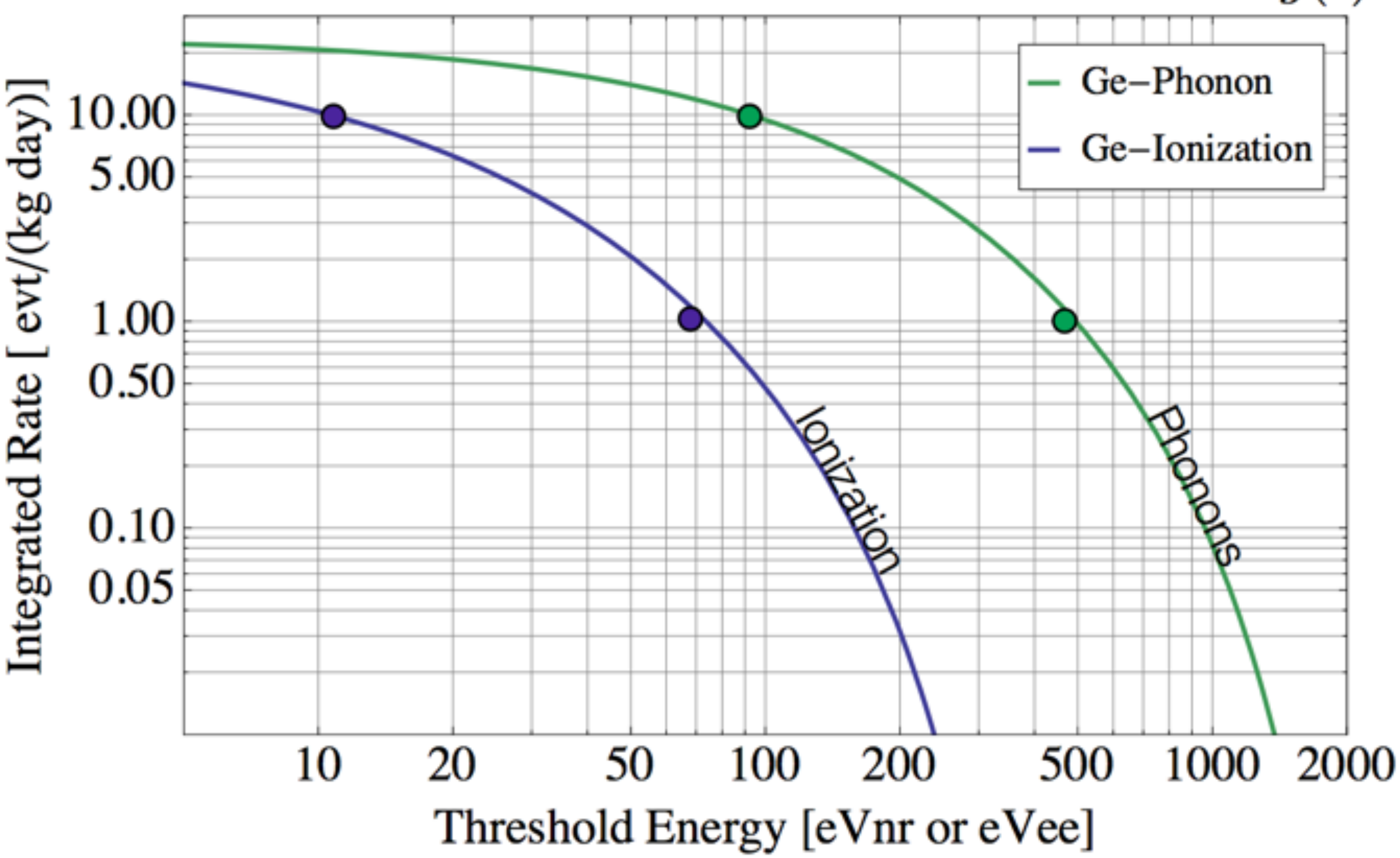
Ben Kilminster, VERTEX 2017

Low Threshold Si CCD detectors (~ 100 g!) at Angra #2

Open the Floodgates: Nu-Cleus, Ricochet, MINER…

Ionization readout requires much lower thresholds for the same rates

$$f_n = \frac{kg(\epsilon)}{1 + kg(\epsilon)}$$



*from Tali Figueroa and Adam Anderson

Ricochet Zn Detector

J. Formaggio, Table-Top Detectors (2017)

Cryogenic Bolometric detectors with extremely low phonon thresholds

This is Only the Beginning

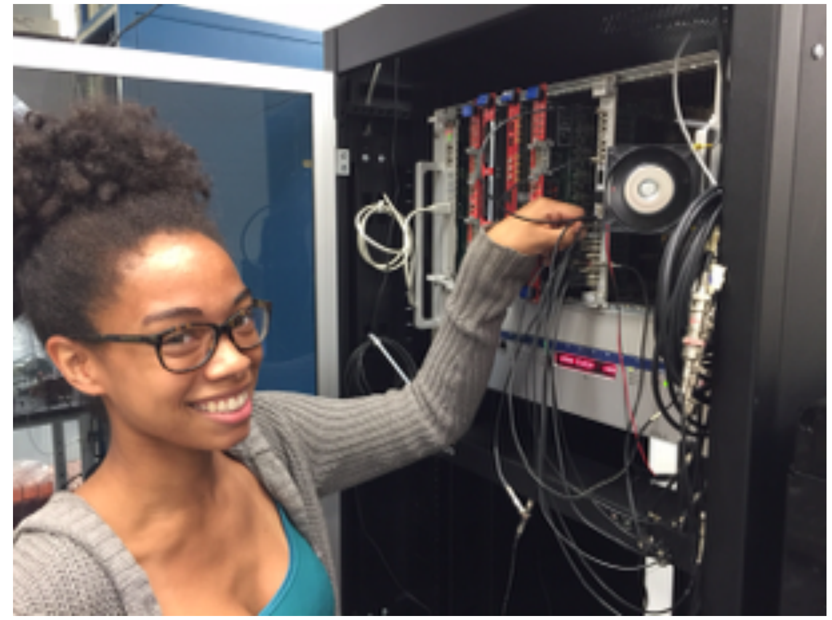
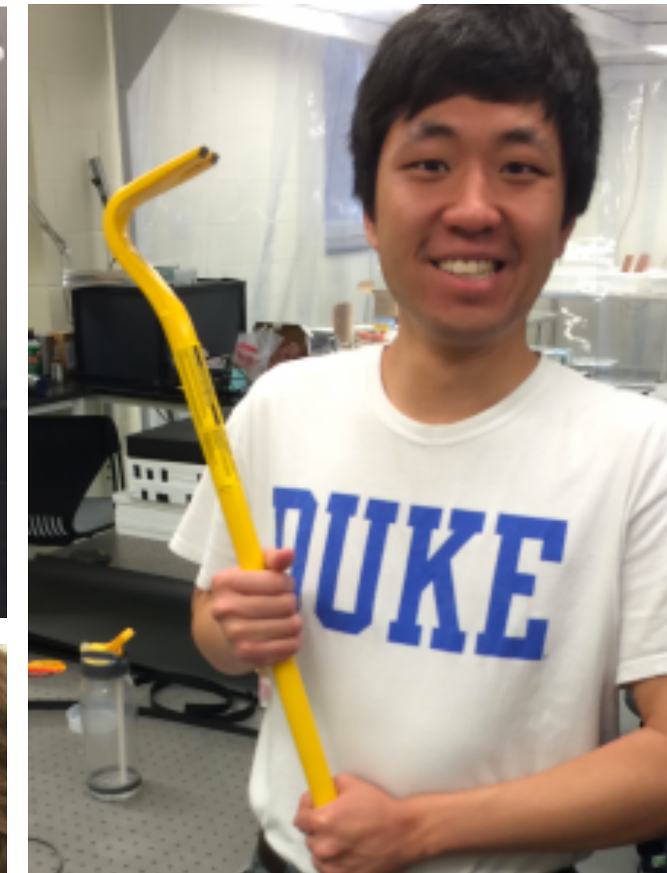
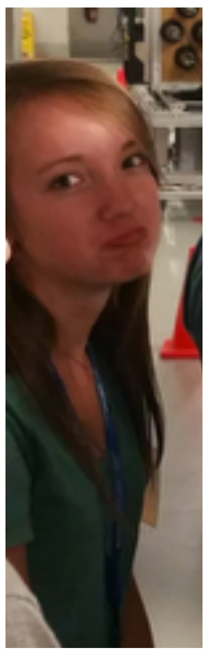
- After 43 years, CEvNS observed at 6.7 sigma CL.

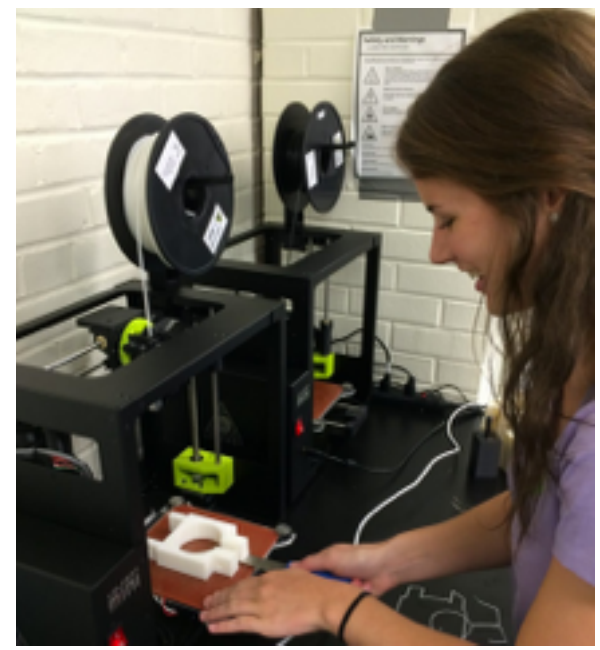
- COHERENT Continues to search for CEvNS (LAr, NaI[Tl], Ge PPCs)

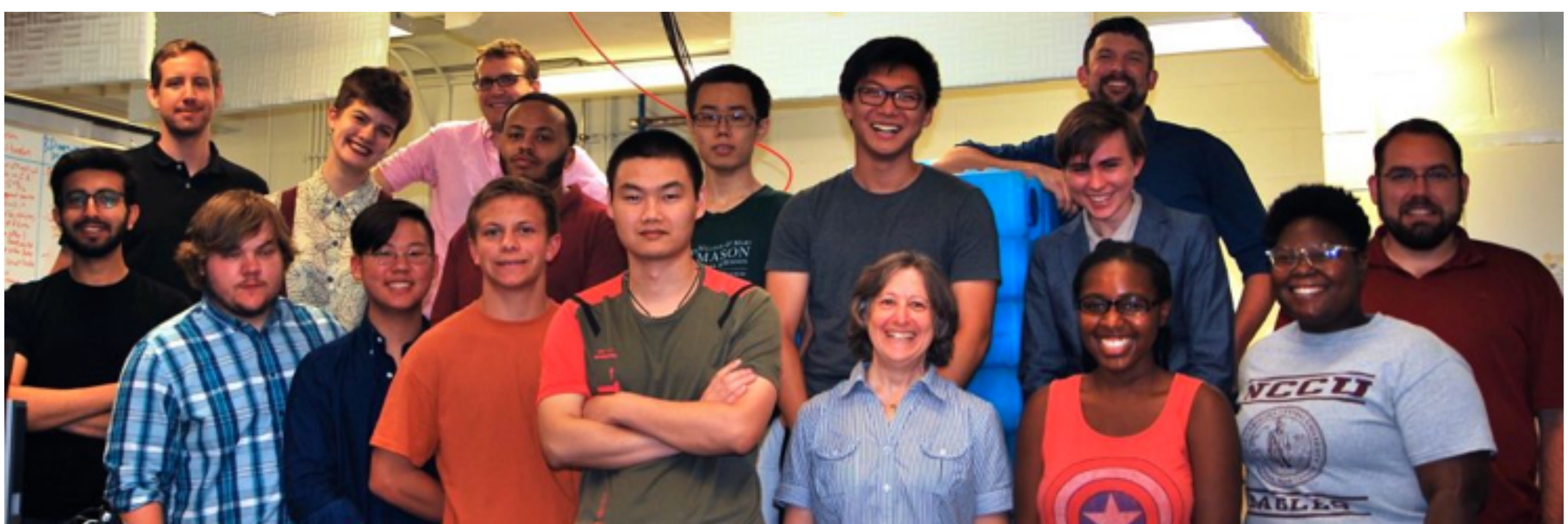
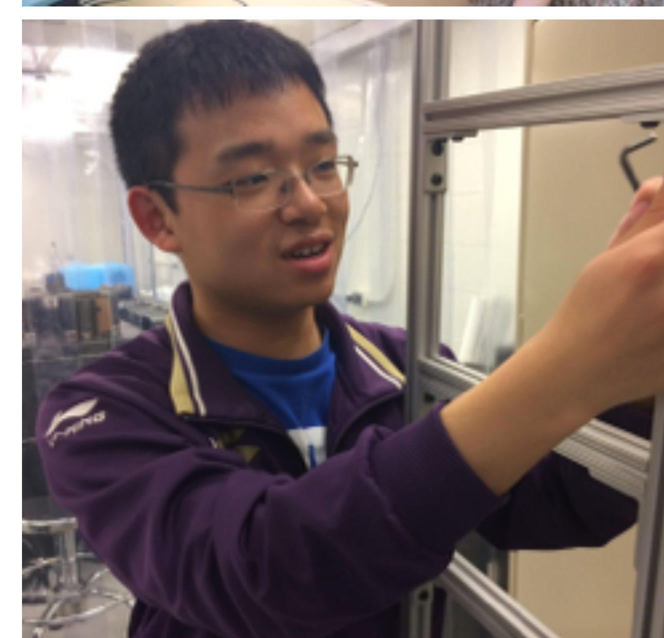
- A new era of miniaturized neutrino detector technology with several other collaborations coming on line (CONNIE, CONUS, MINER, RED, Ricochet, Nu-cleus)

- A treasure trove of physics can be studied—the best is yet to come!

Thank you

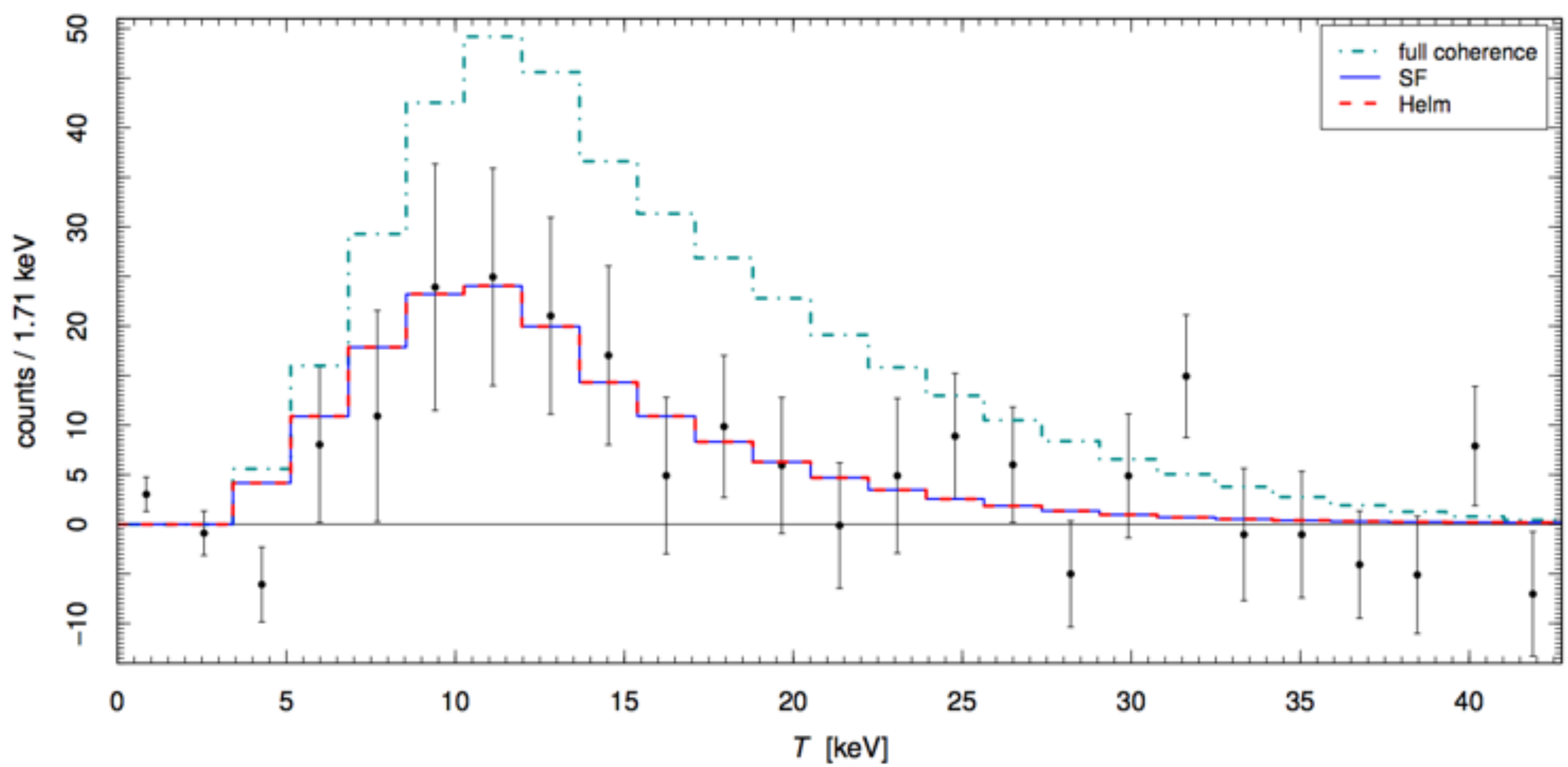



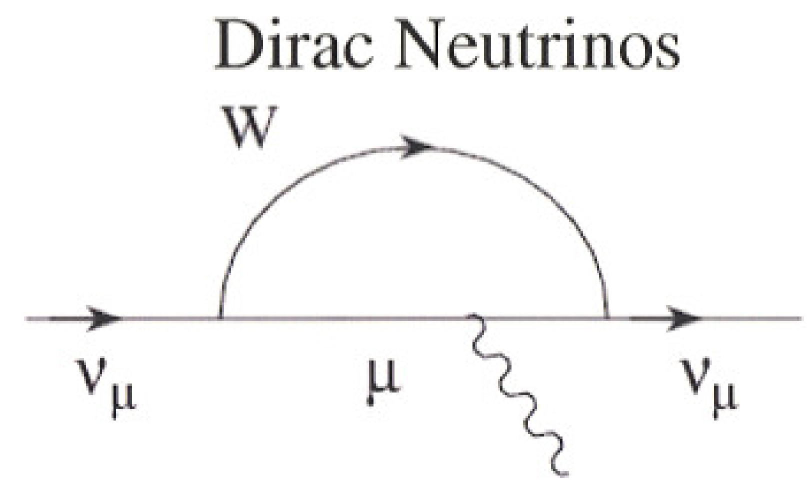
Implications Neutron Density Distribution?

Others have suggested that the COHERENT result shows 2.3 sigma evidence for nuclear structure suppression of full coherence **M. Cadeddu, et al., arXiv:1710.02730v2**

$$R_n - R_p \simeq 0.7^{+0.9}_{-1.1}$$

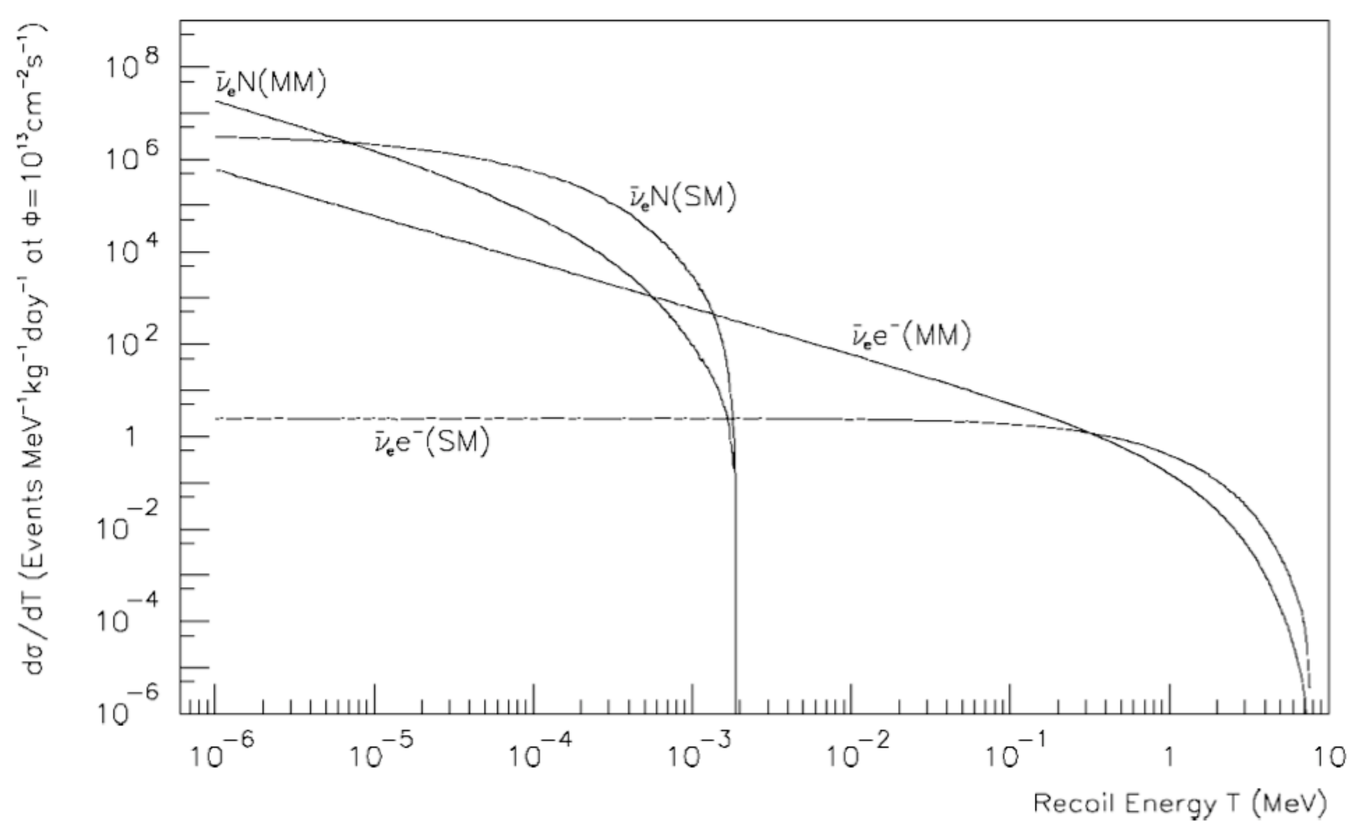


Electromagnetic Neutrino Interactions?



- Neutrino oscillation experiments have demonstrated that neutrinos have mass
- Which means they must have a magnetic moment
- CEvNS is particularly sensitive to any neutrino electromagnetic interactions

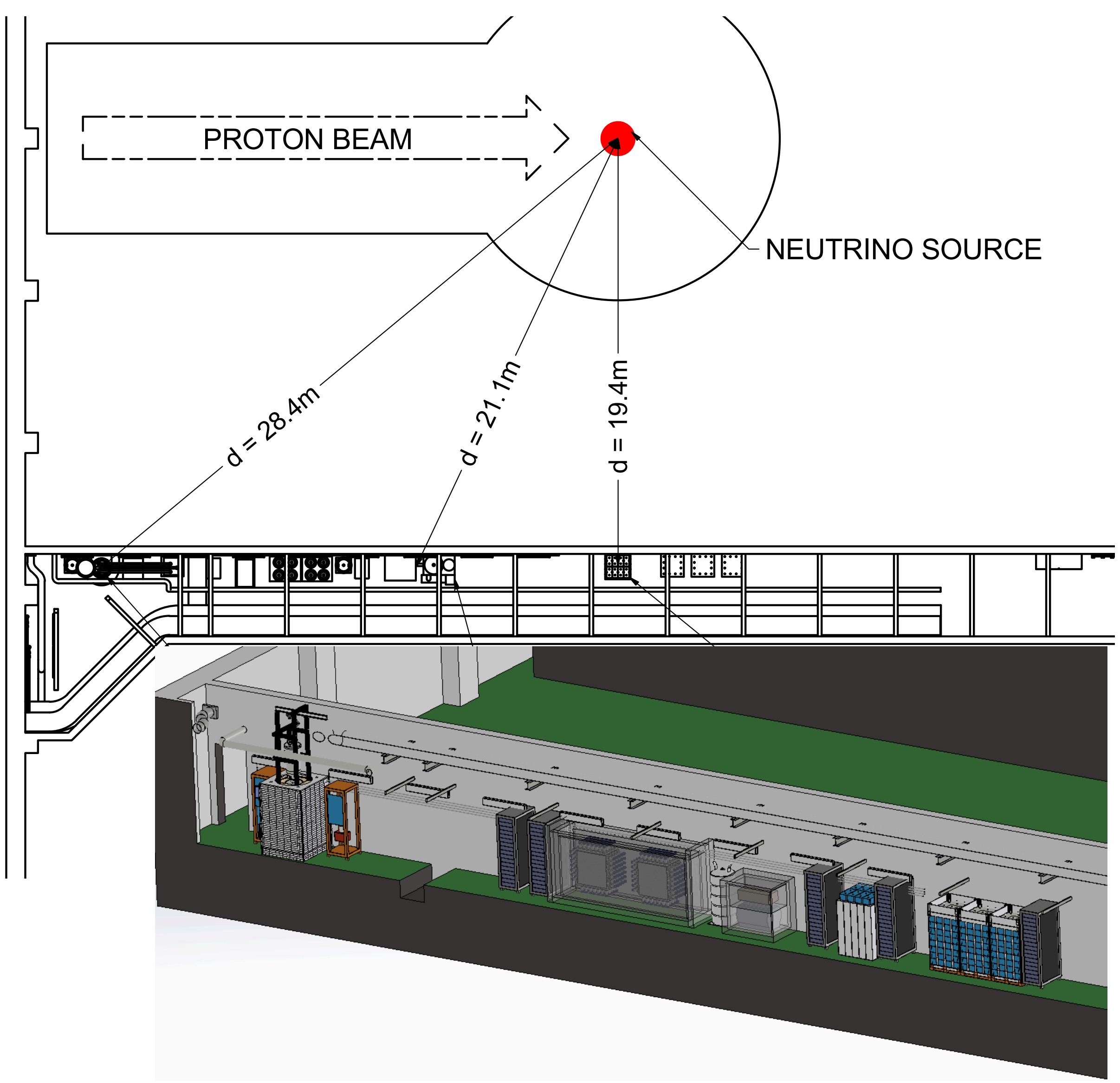
A. C. Dodd, et al., PLB 266 (91), 434

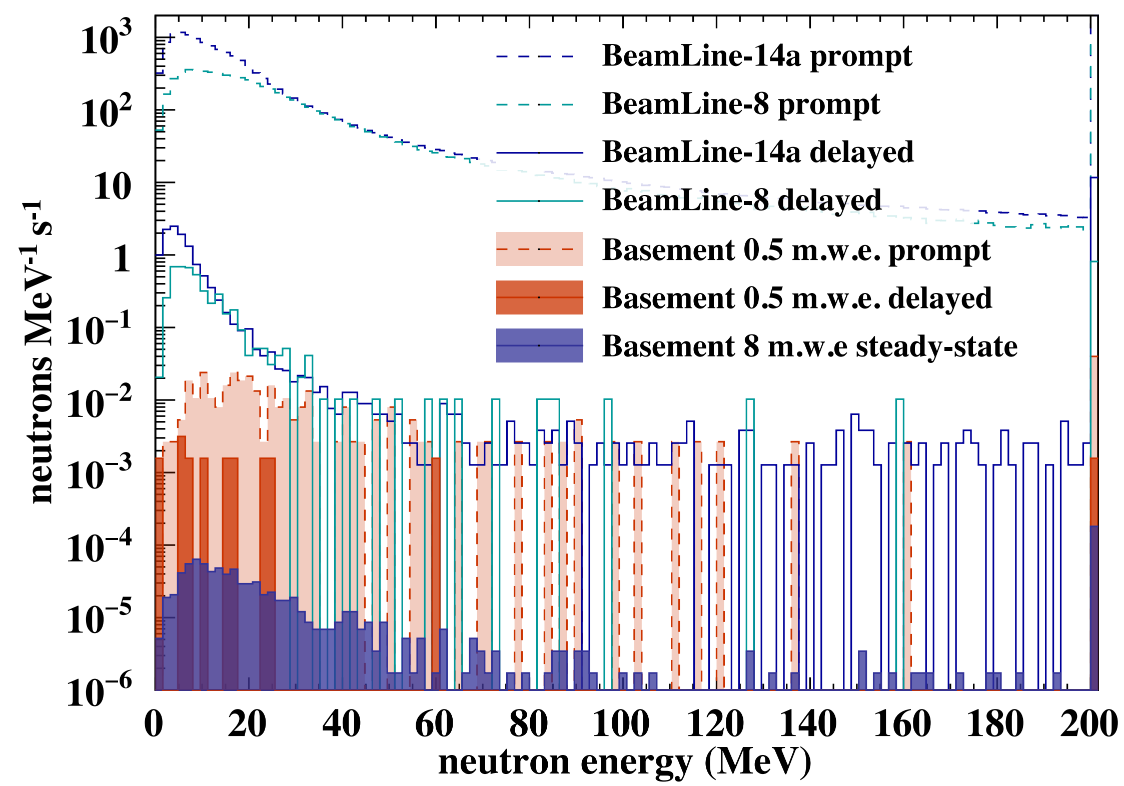


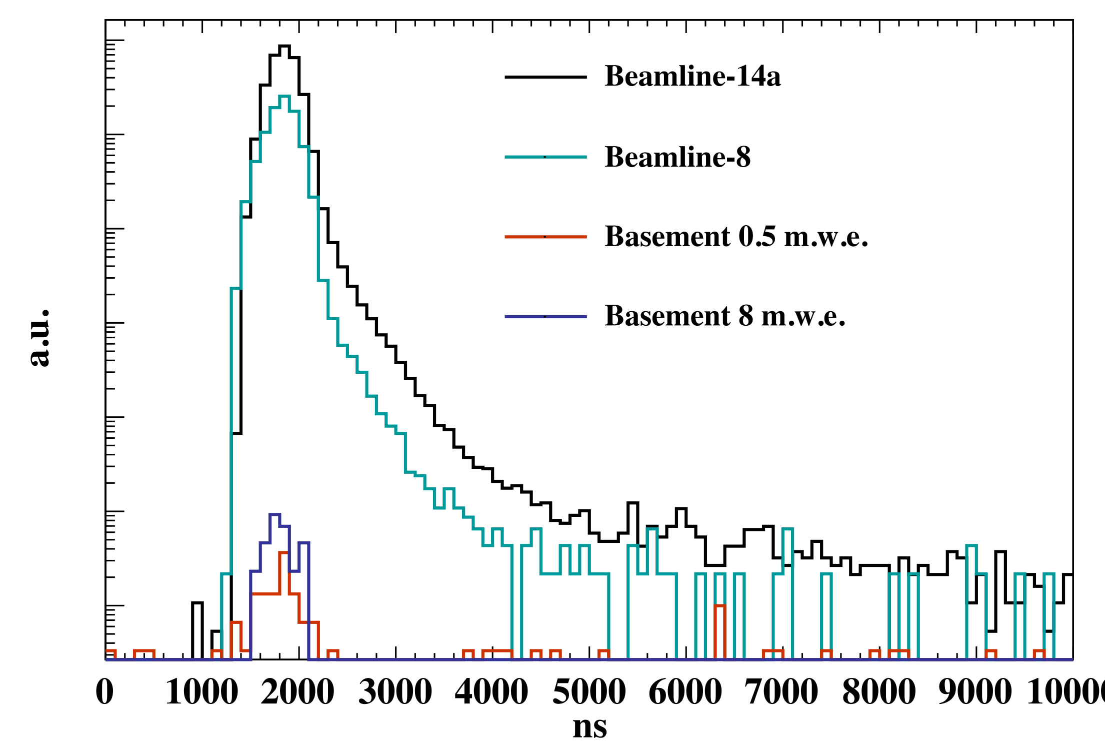
H. T. Wong and H.-B. Li. Mod. Phys. Lett., A20:1103–1117, 2005.

Hunting for a Background-Free Location

- Extensive background measurement campaign since 2013 pointed to the SNS basement as the optimal location (>10^4 reduction of neutrons)



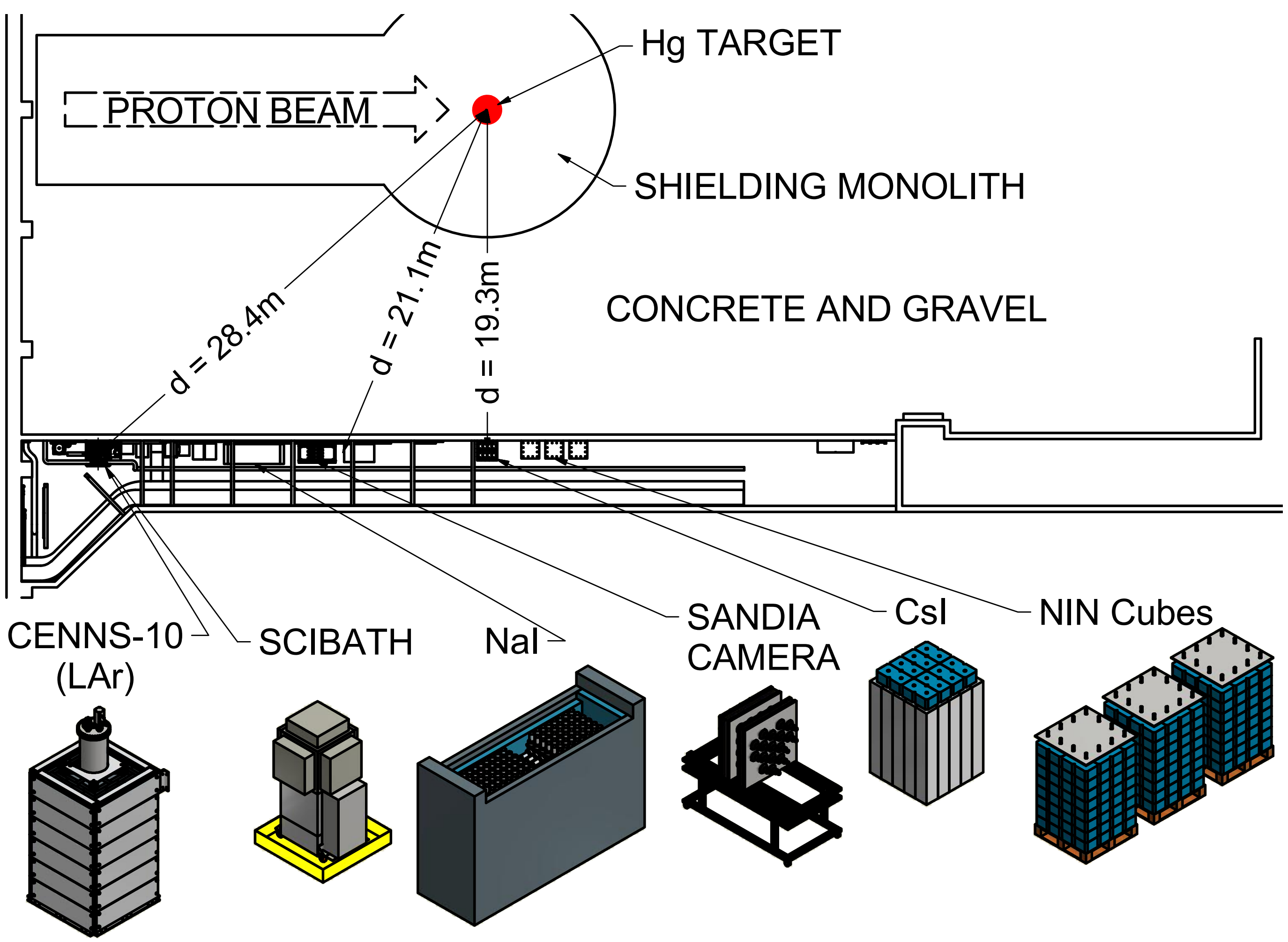


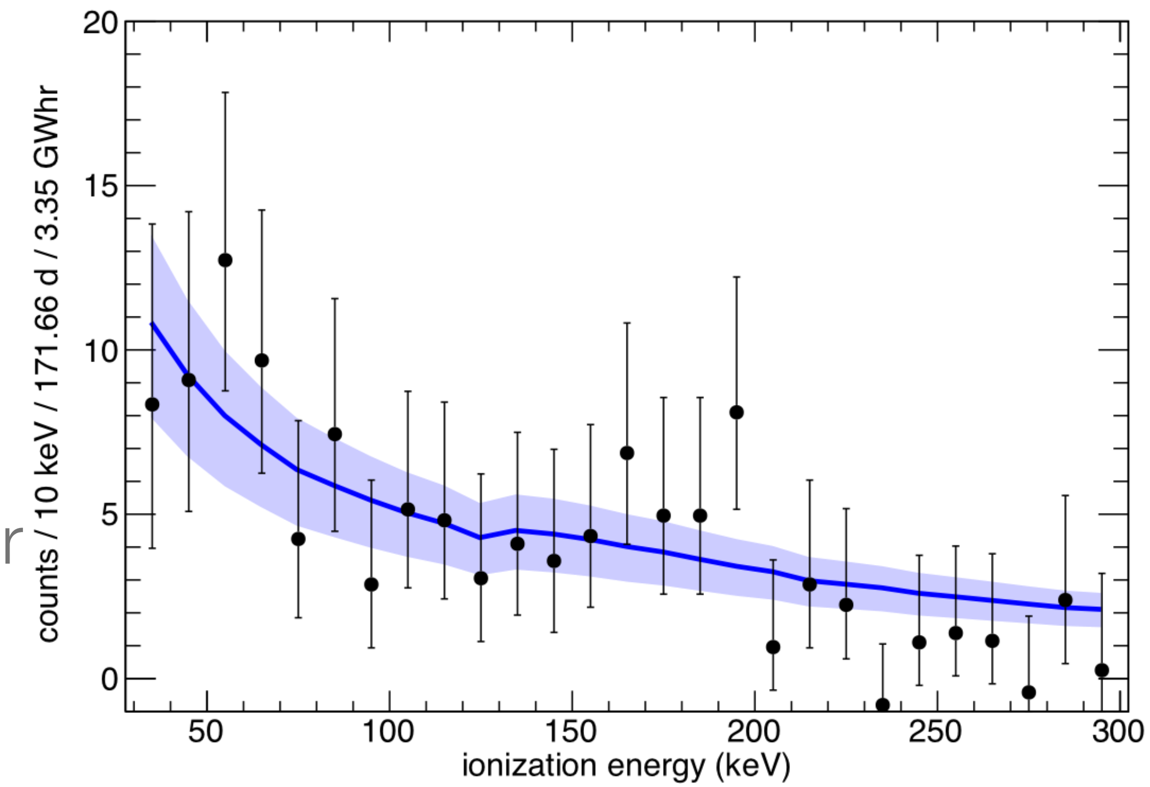


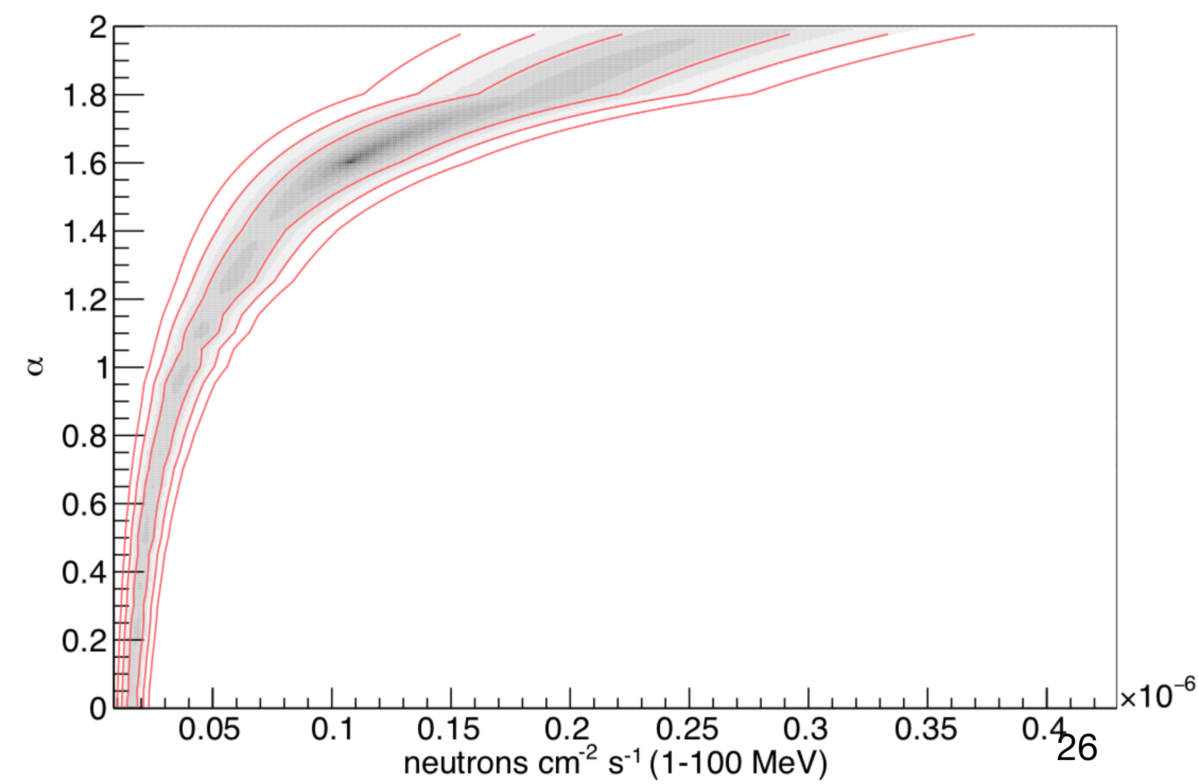
Measuring the Neutron Backgrounds

- **“Neutrino Alley”** mostly shields us from the copious flux of neutrons produced at the SNS

- We also performed an in-situ measurement of the neutrons with a liquid scintillator within the CsI shield prior to installation of CsI[Na] detector







New Background: $\boldsymbol{\nu}$-induced Neutrons (NINs)

- In-situ measurement also provides a constraint on this neutron-producing background in the lead shield of the detector

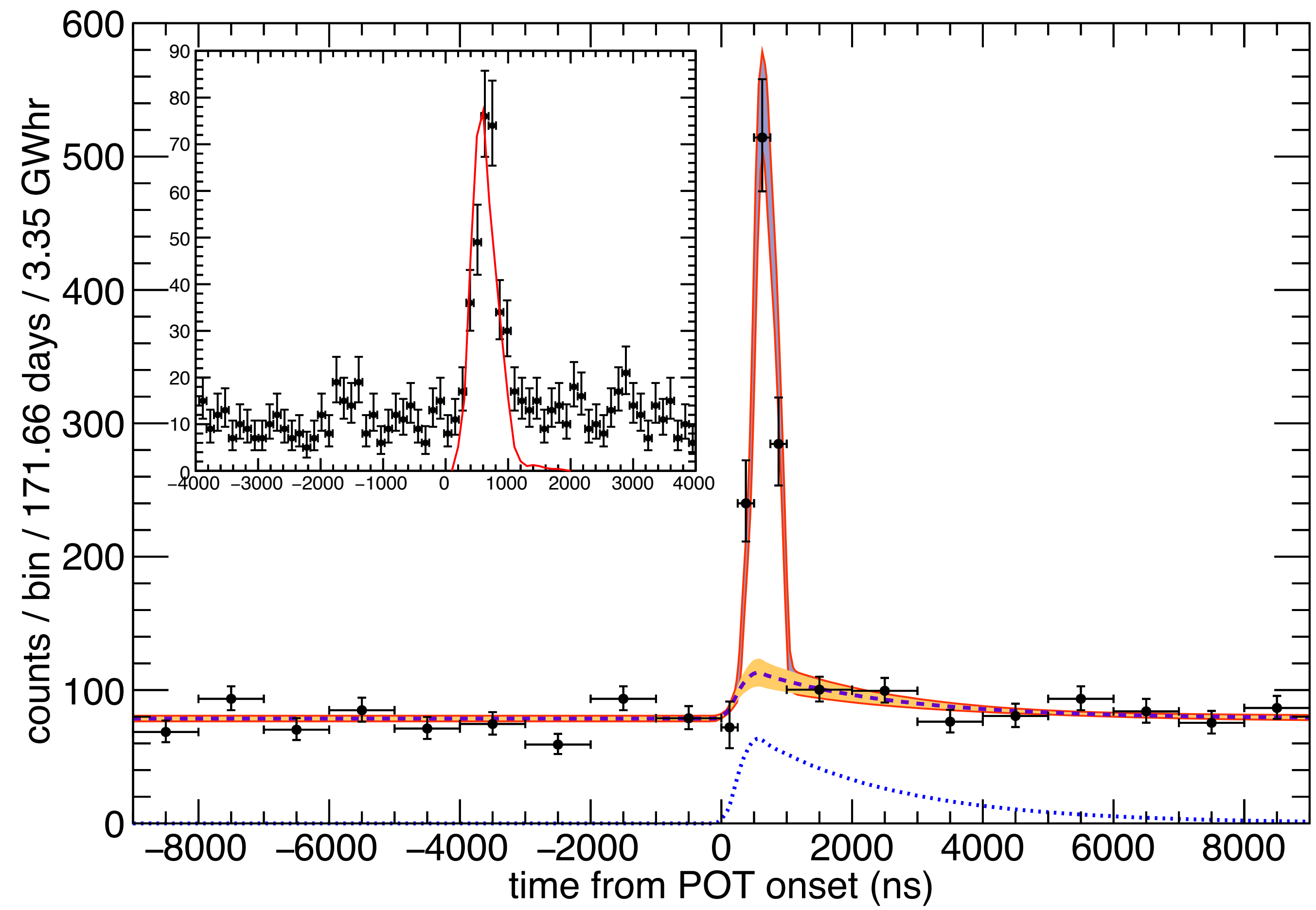
- First indications of neutrino-induced neutrons in Pb (a factor of 1.7 below theory prediction)

- Can be important process in many stellar environments

C.A. Duba *et al.* J.Phys.Conf.Series 136 (2008)
Y-Z. Qian *et al.*, Phys. Rev. C 55 (1997)
M. Athar, S. Ahmad and S. K. Singh., Nucl. Phys. A *764* (2006) 551-568

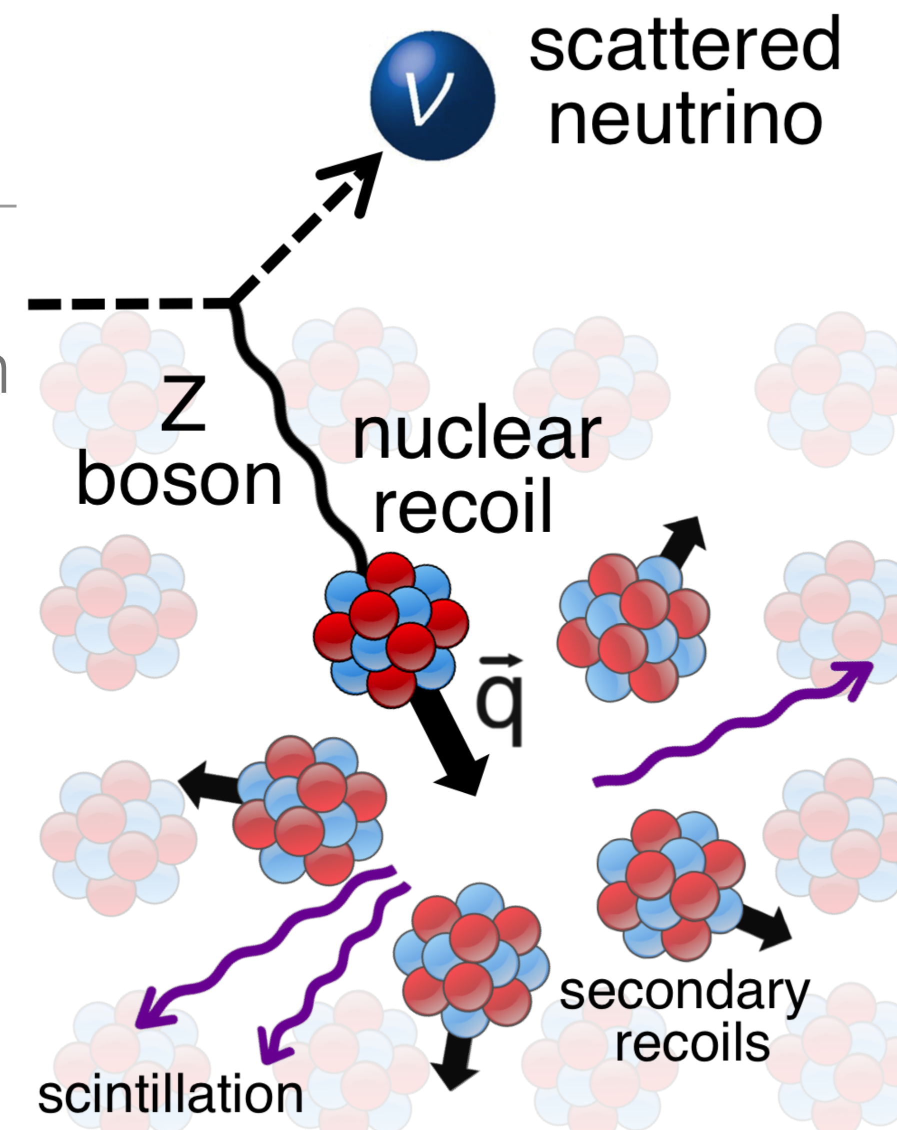
$$\nu_e + {}^{208}Pb \Rightarrow {}^{208}Bi^* + e^- \quad (CC)$$
$$\Downarrow$$
$${}^{208-y}Bi + x\gamma + yn$$

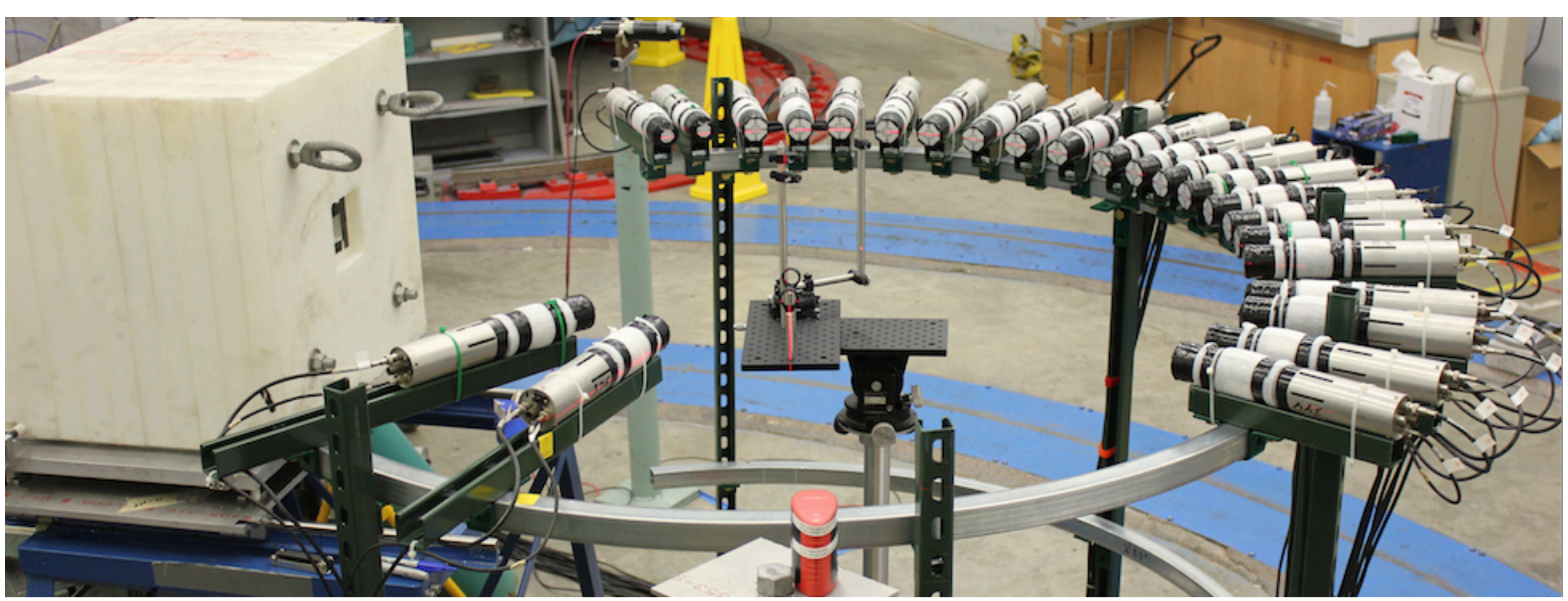
$$\nu_x + {}^{208}Pb \Rightarrow {}^{208}Pb^* + \nu_x' \quad (NC)$$
$$\Downarrow$$
$${}^{208-y}Pb + x\gamma + yn.$$

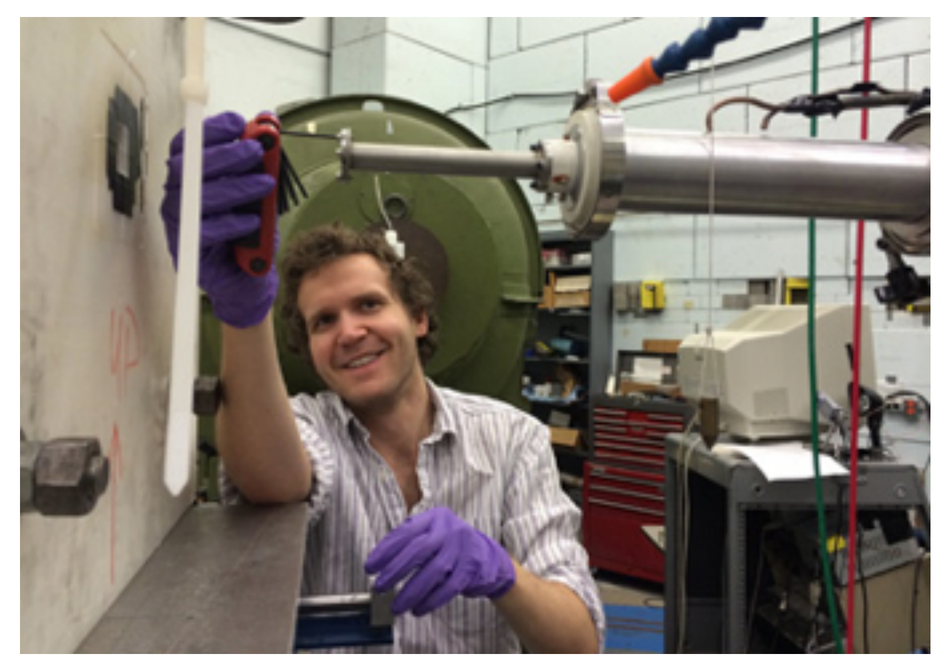


Quenching Factor?

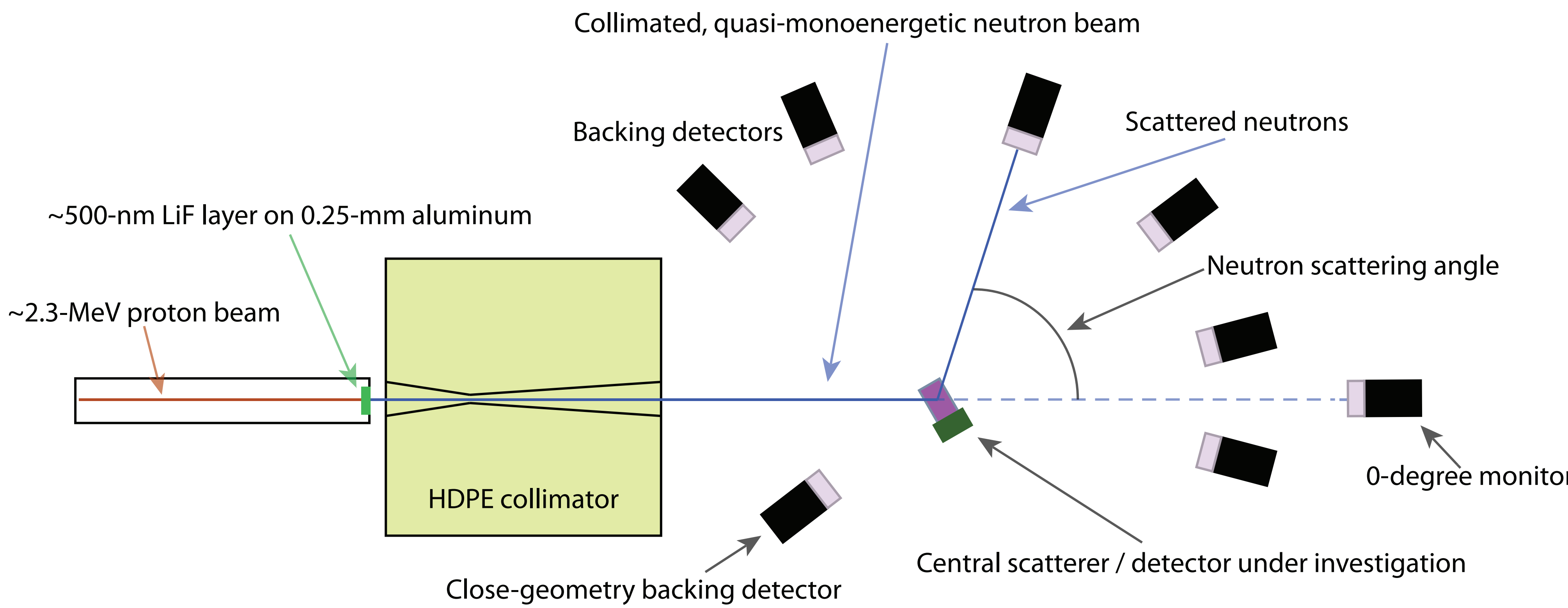
- Only a fraction of the energy of the recoil ends up in measurable channels
- This is largely unknown, and needs to be calibrated
- A facility has been developed at TUNL for precision detector calibrations in support of COHERENT

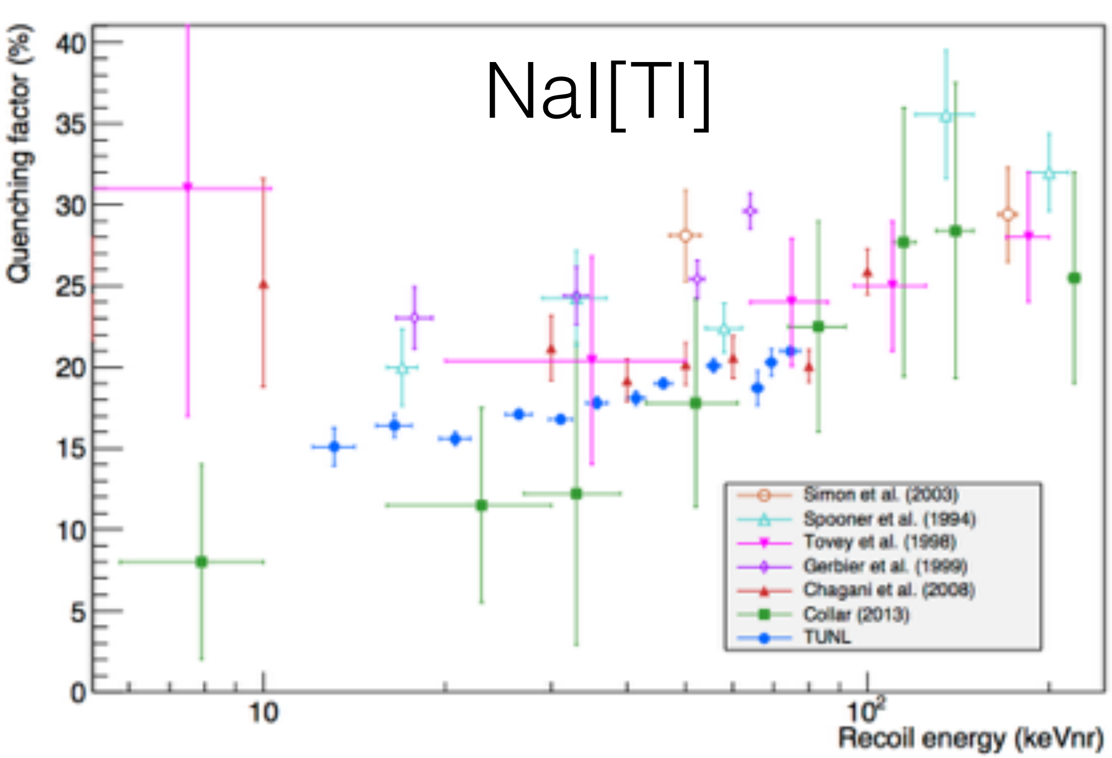


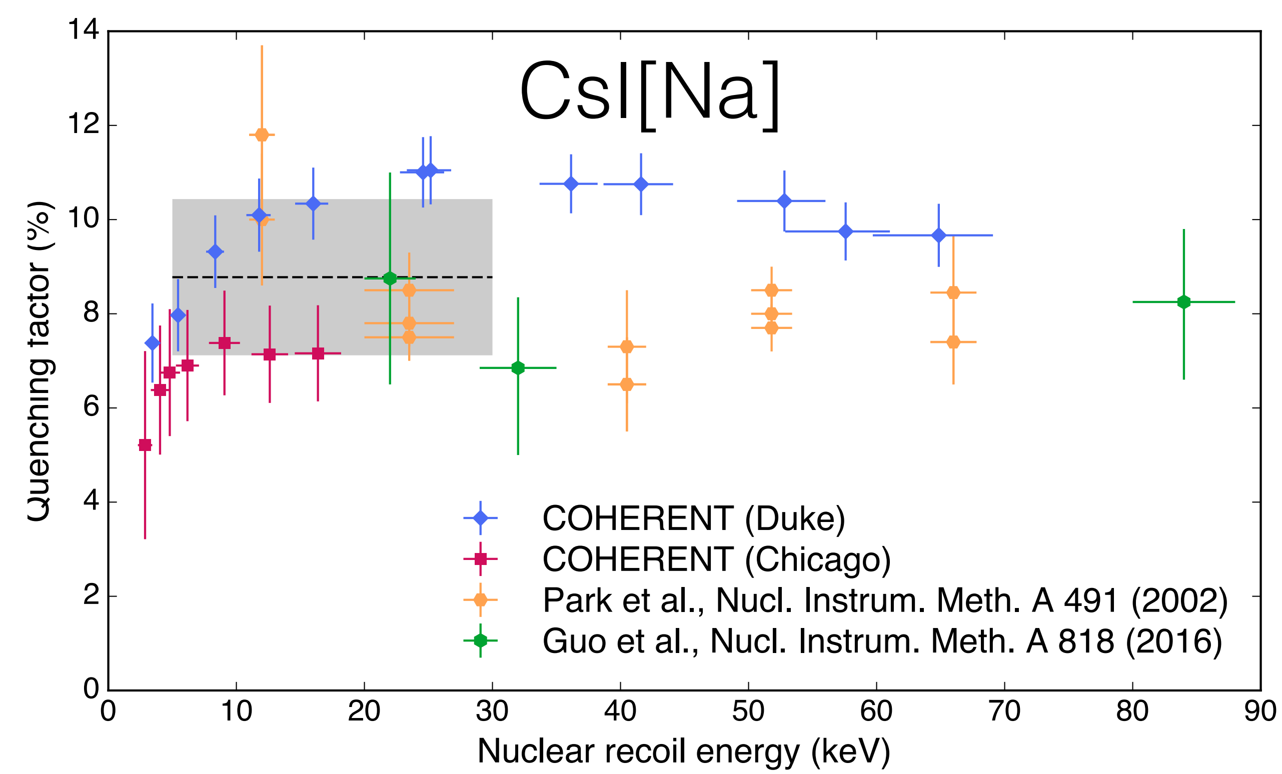




TUNL Quenching Factor Measurements

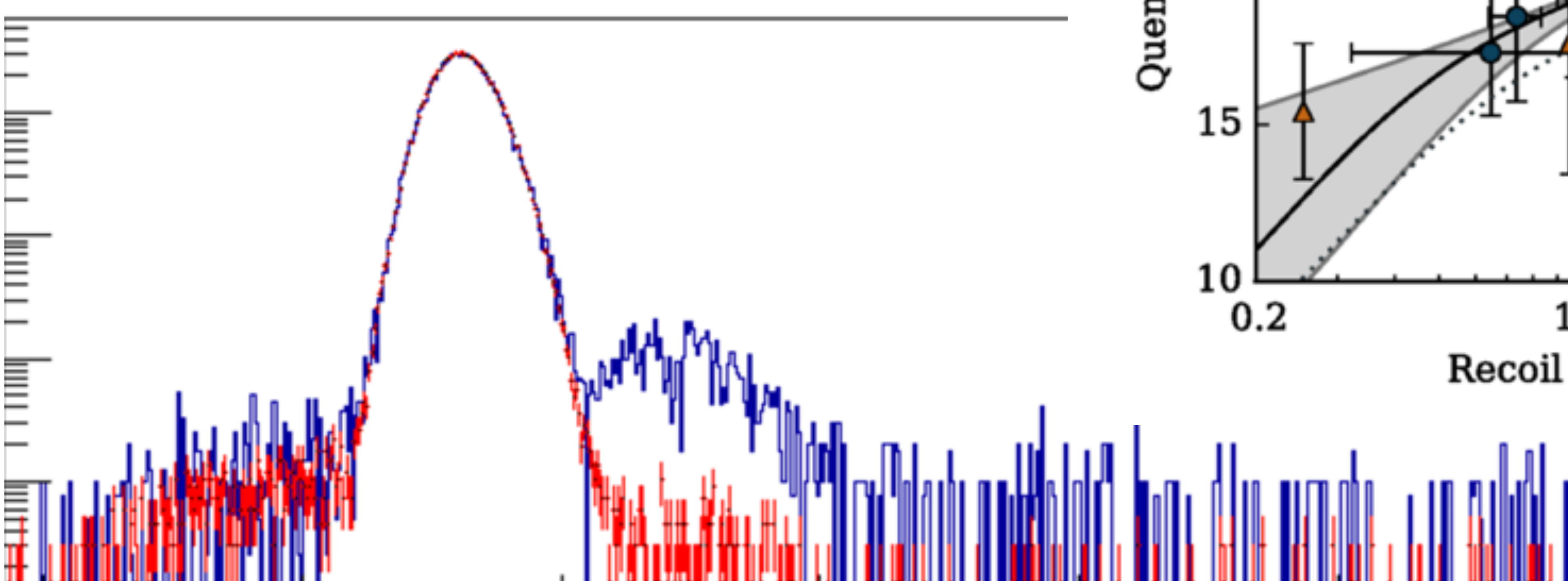


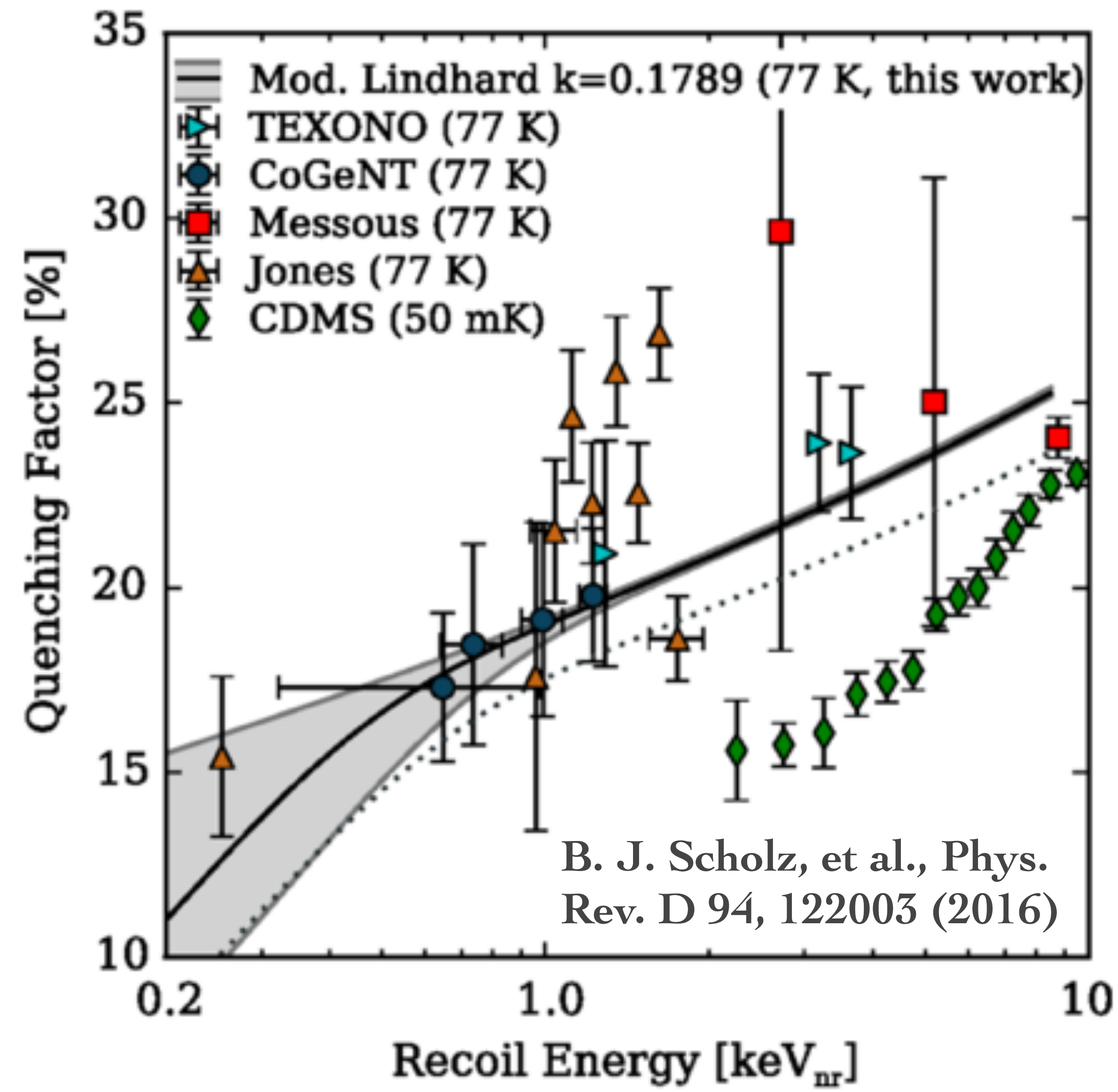




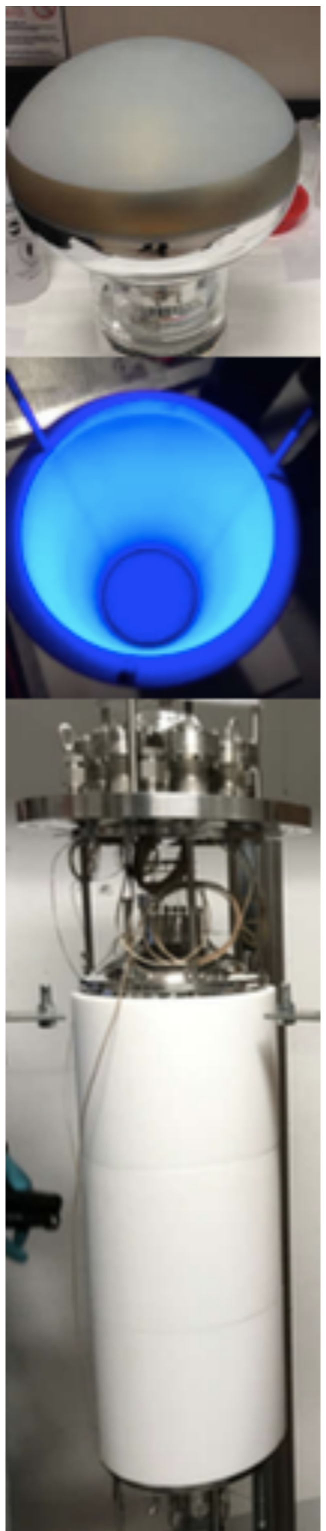
TUNL Quenching Factor Measurements

HPGe measurements provide strong systematic controls, including channeling

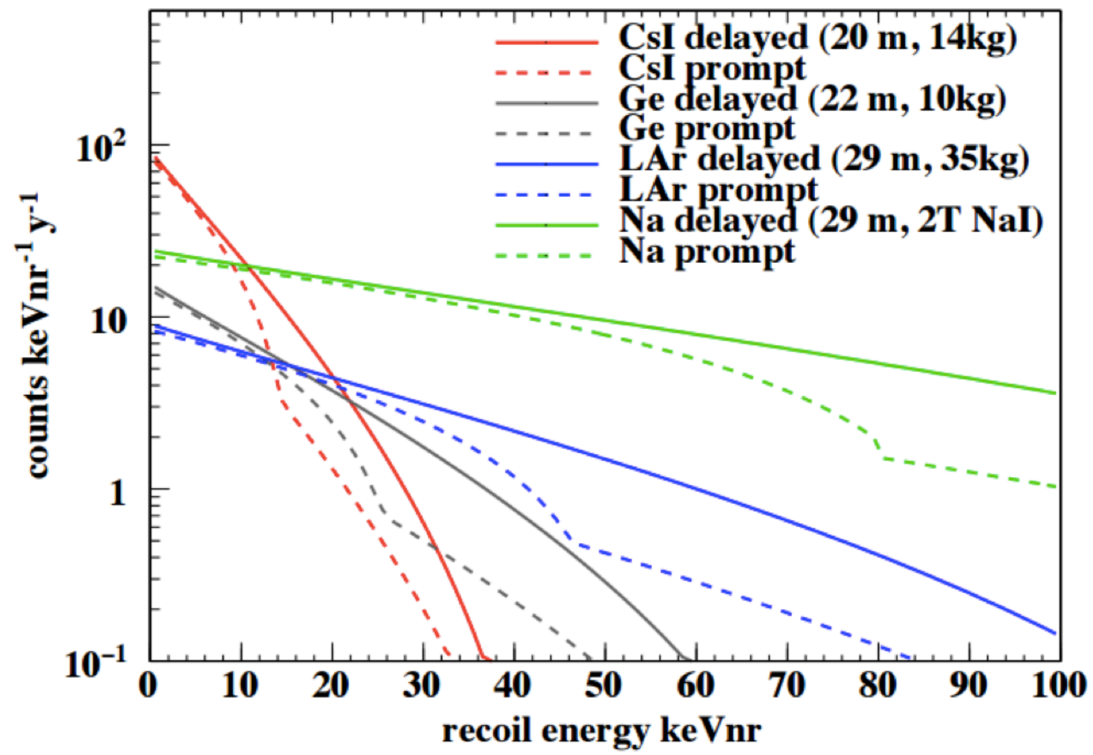




More COHERENT Detectors

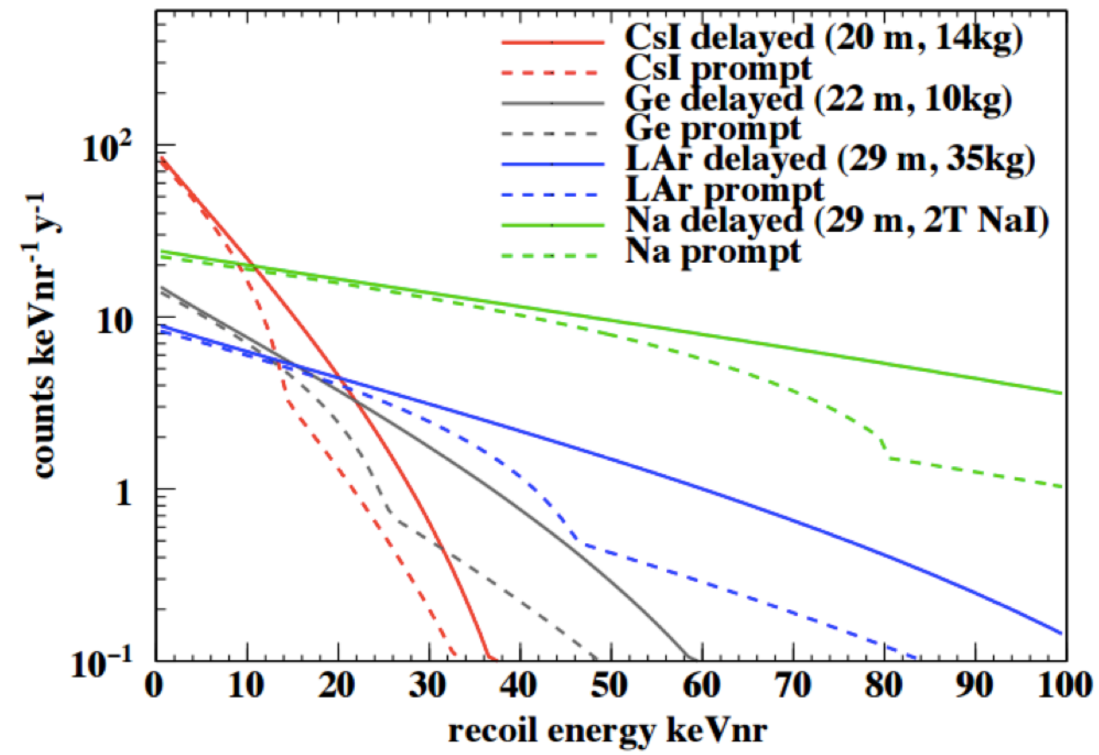


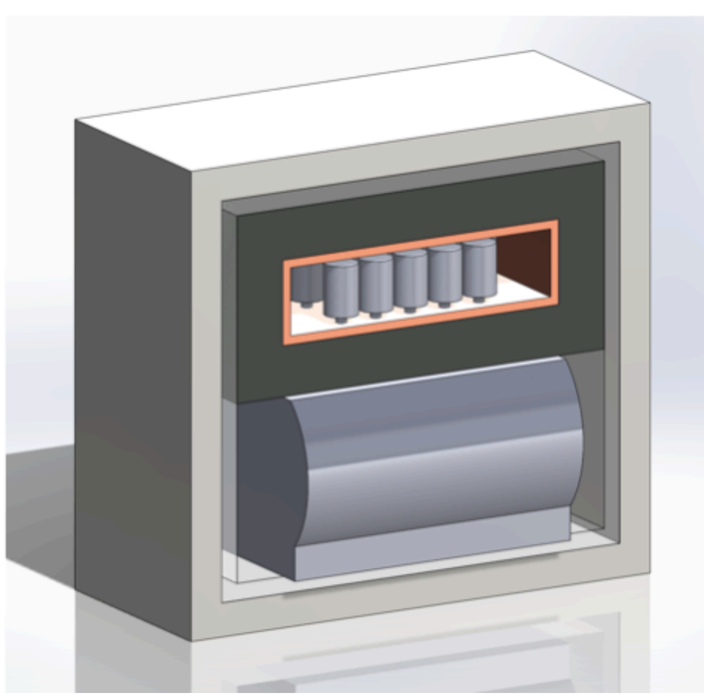
- A 22 kg liquid argon, single-phase detector is currently being commissioned at the SNS
- ^{40}Ar nucleus is even-even and so can be used to help normalize the neutrino flux

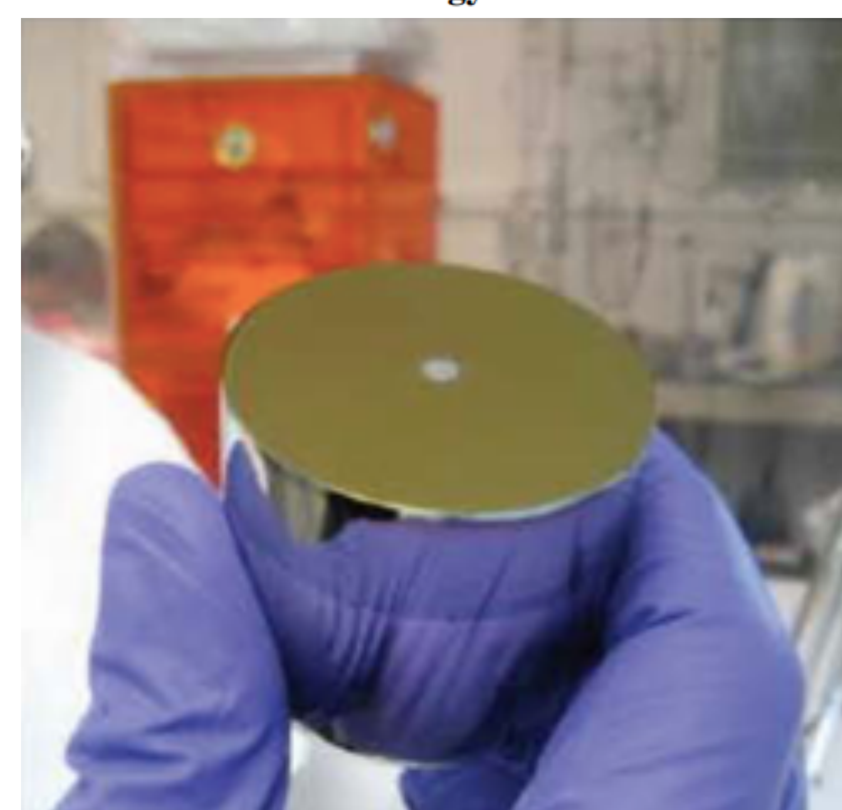


More COHERENT Detectors

- A 10 kg PPC germanium array is being designed
- Low-thresholds allow sensitive searches for Neutrino Magnetic Moments and light-mass, dark Z' mediators
- Exquisite energy resolution is useful for Neutron Form Factor measurements



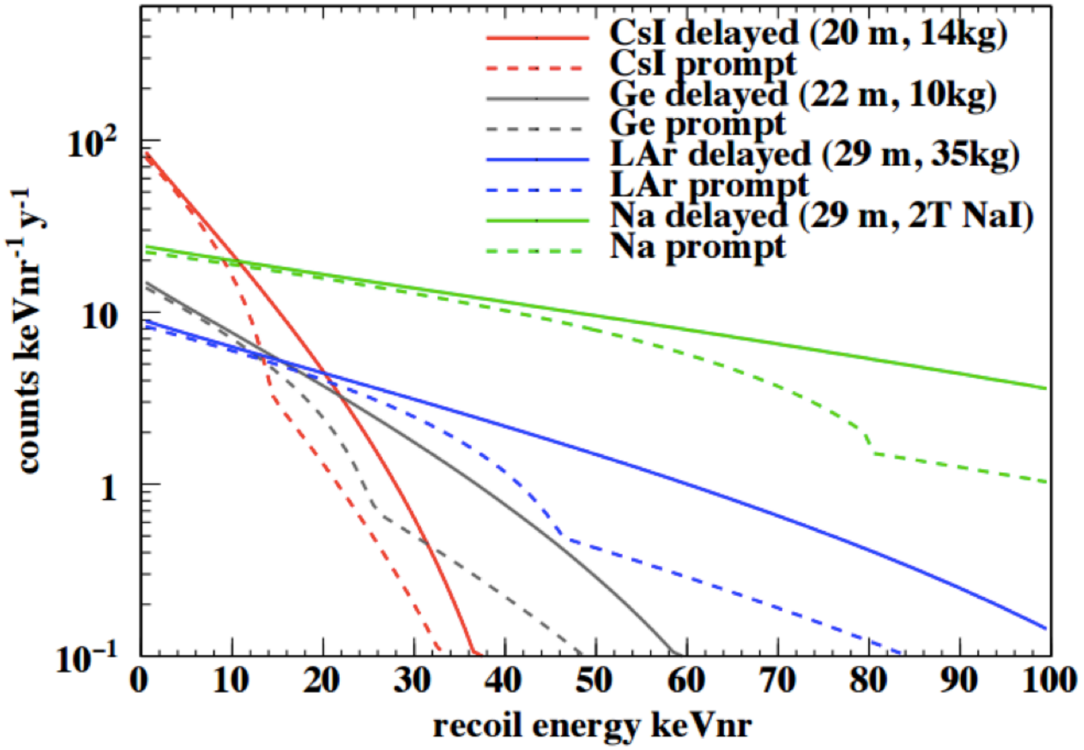


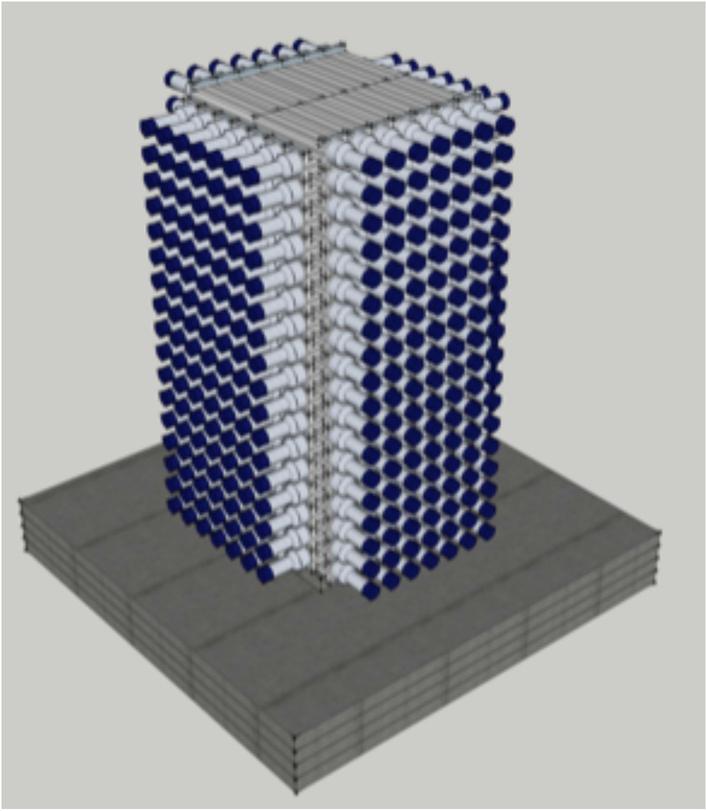


More COHERENT Detectors

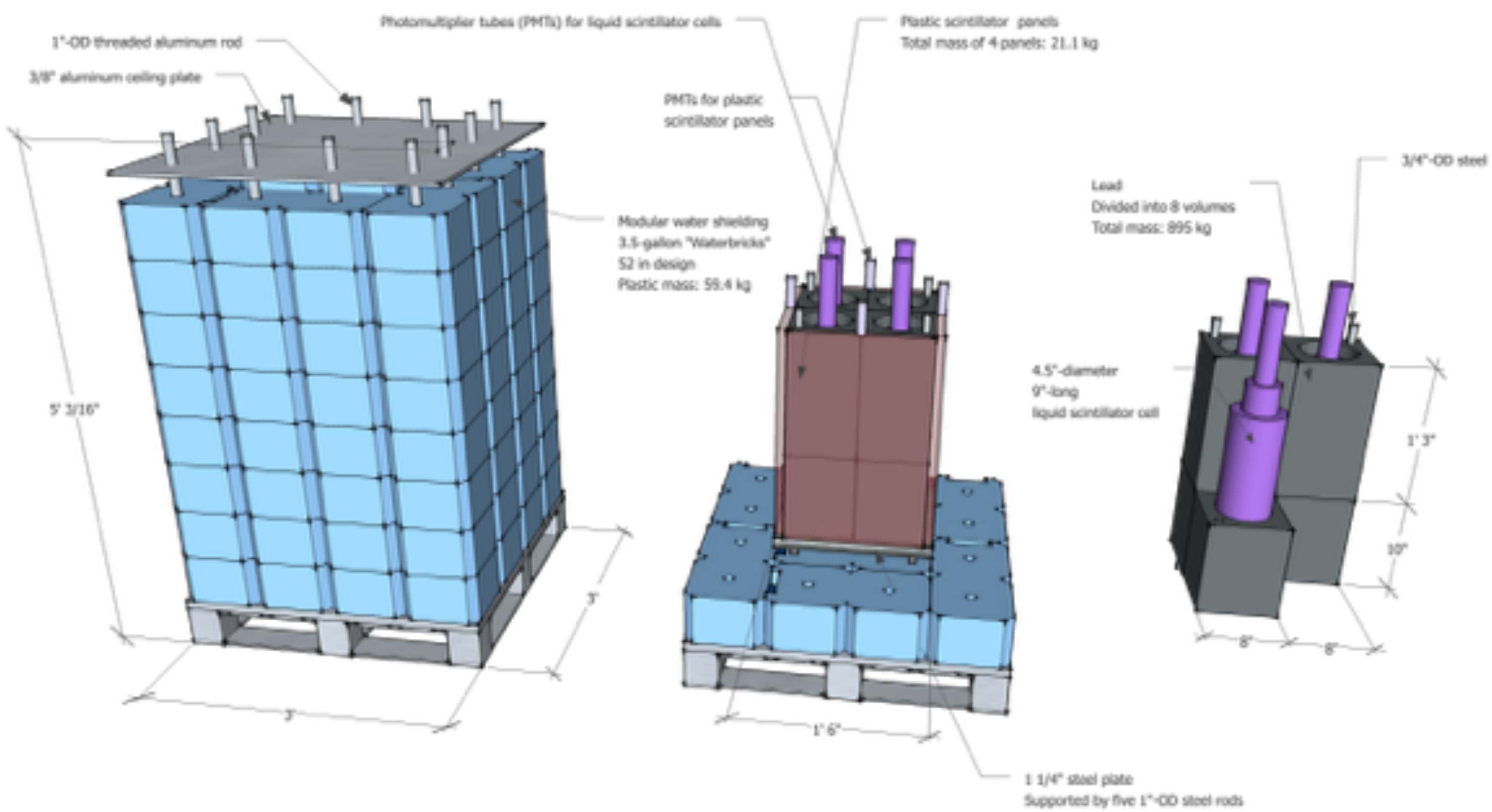
- A 185 kg NaI[Tl] array has been deployed to search for the ^{127}I charged-current reaction (important for understanding g_A renormalization with implications for neutrinoless double beta decay)

- A multi-ton array is being designed to measure CEvNS on Na (important for understanding axial currents)





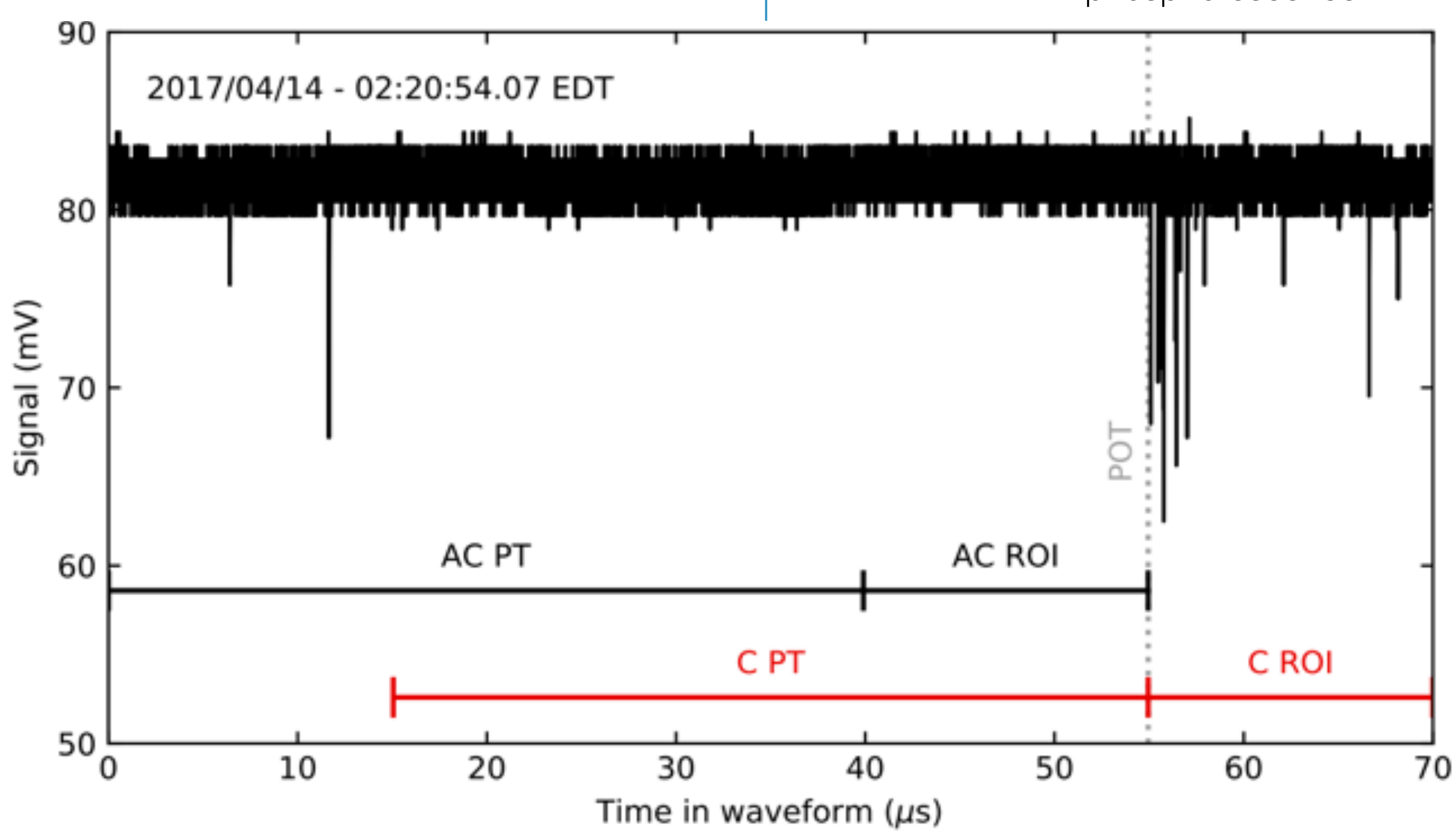
More in-COHERENT Detectors



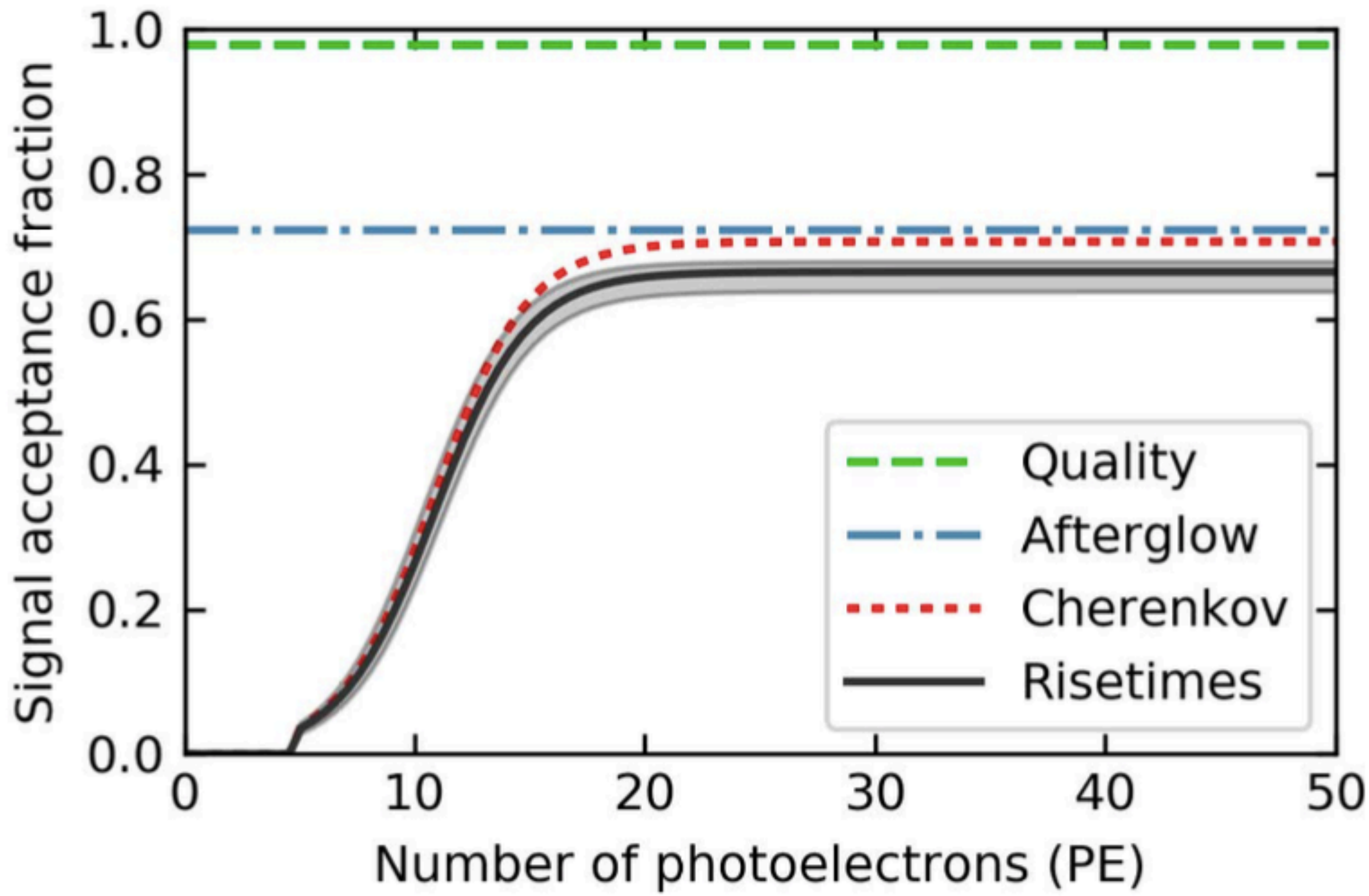
- Several palletized (mobile) targets with LS detectors delivered to the SNS
- Will measure neutrino-induced-neutrons on Pb (r-process nucleosynthesis & nuclear structure)
- and Fe (nuclear structure & SN shock revival)

Waveform Analysis

Remove Muon Veto coincidences (Quality)	Eliminates muon induced neutrons
Reject PMT saturation and digitizer railing (Quality)	Eliminates unusable events
Reject events with too many PE in pretrace (Afterglow)	Removes afterglow contamination of signal region
Reject Fast PE signals (Cherenkov)	Removes Cherenkov light contamination from interactions in quartz windows
Pulse-Shape cuts (Risetime)	Removes random groupings of dark counts and phosphorescence



Event Selection Efficiencies



The Result

D. Akimov et al., Science 10.1126/science.aao0990 (2017).

- We perform a binned ML fit for the CEvNS signal, including the constraints on the neutron backgrounds, and taking steady-state backgrounds from an anti-coincident window