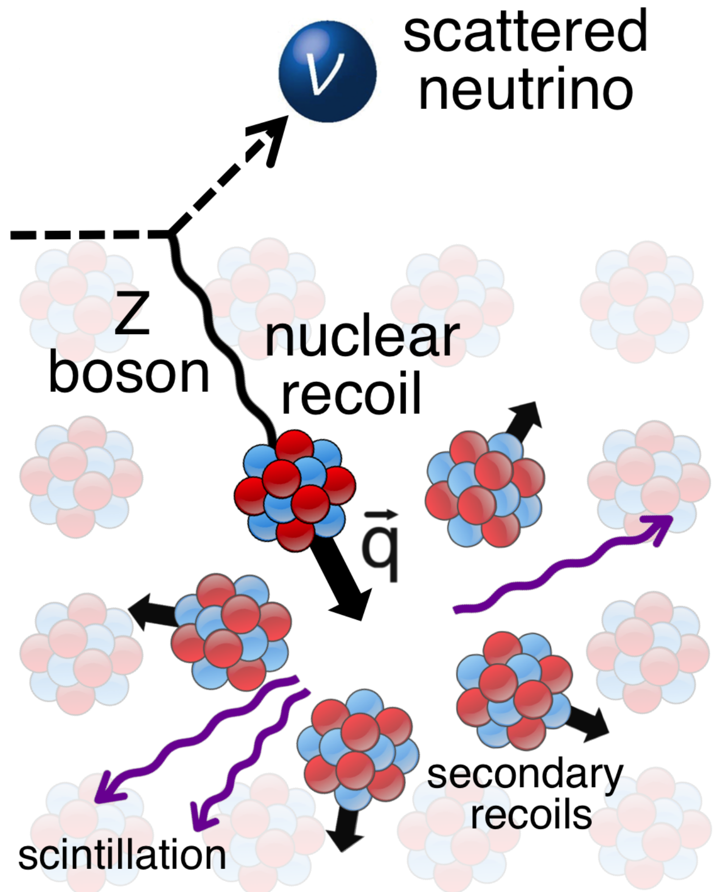
The Worlds Smallest Neutrino Detector

Phil Barbeau

Coherent ν-Nucleus Scattering



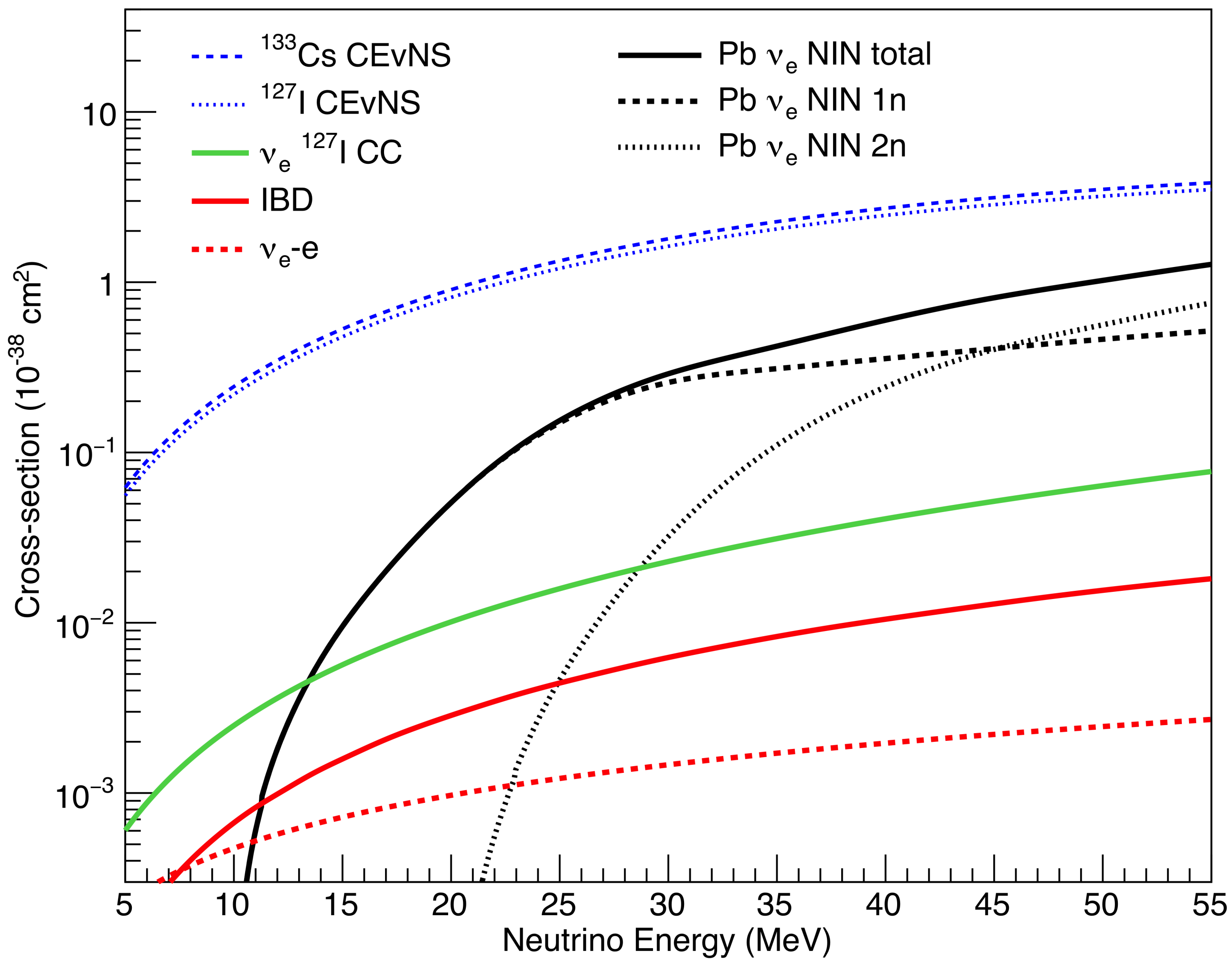
- 43 years ago, Coherent Elastic Neutrino-Nucleus Scattering (CEvNS) was predicted with the realization of the neutral weak current.

  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



Coherent **ν**-Nucleus Scattering: a new tool

- Largest σ in Supernovae dynamics.

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

- Non-standard Neutrino Interactions relevant for DUNE & LBL CP violation.

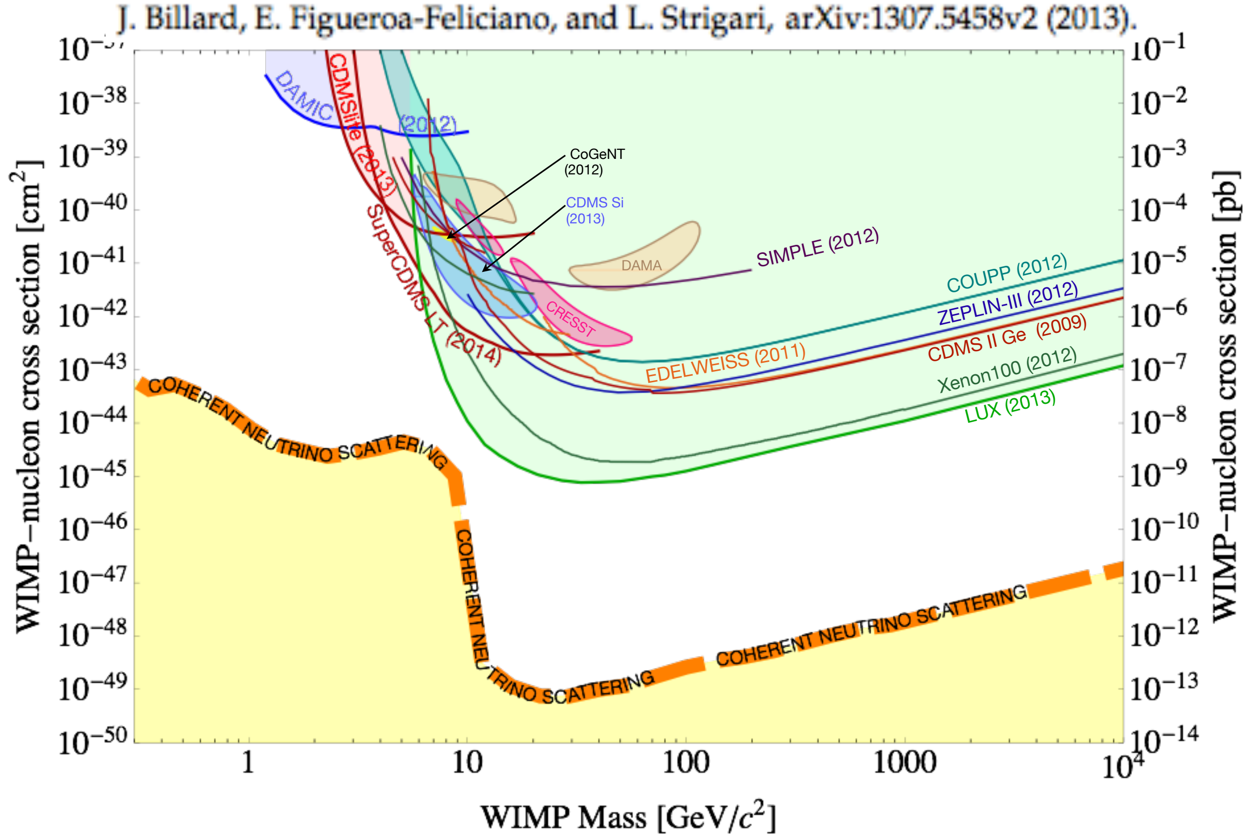
  K. Scholberg, Phys.Rev.D73:033005,2006

  J. Barranco et al., JHEP0512:021,2005

  Mehedi Masud, Poonam, Mehta, arXiv: 1603.01380

- CEvNS is an irreducible background from WIMP searches.

  J. Billard, E. Figueroa-Feliciano, and L. Strigari, arXiv:1307.5458v2 (2013).



- Sensitive tool for Sterile neutrino searches

  A. J. Anderson et al., PRD 86 013004 (2012)

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

- A precision test of σ is a sensitive test of new physics above the weak scale.

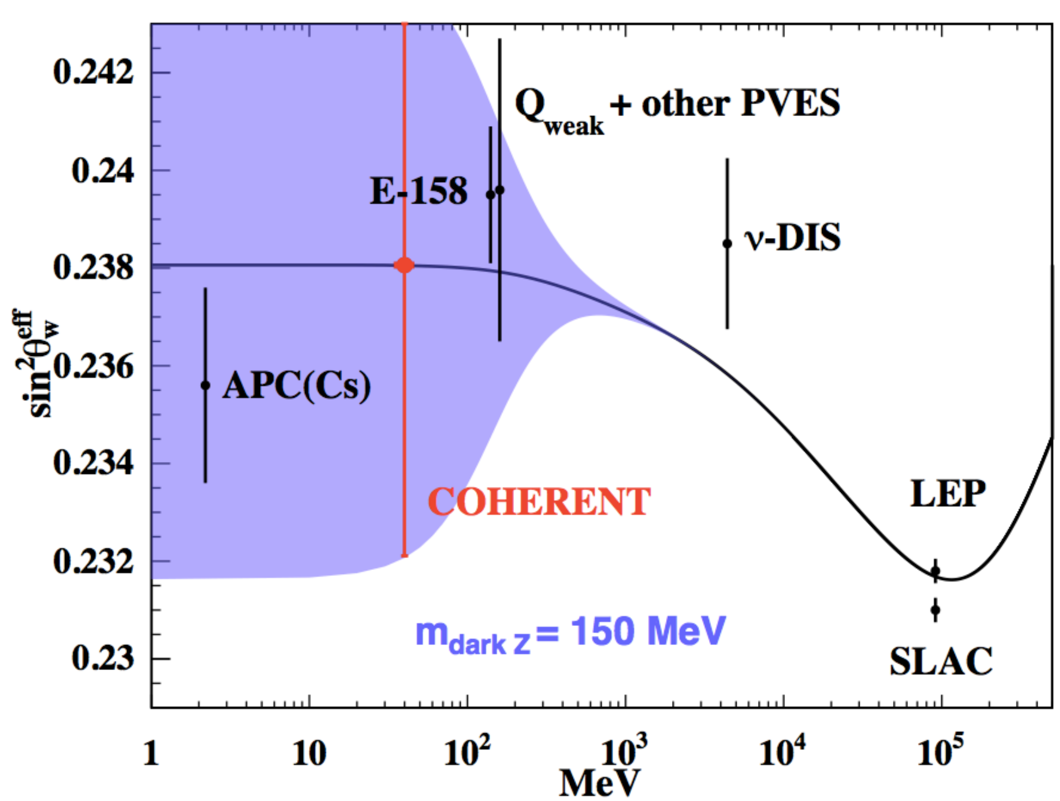
  L. M. Krauss, PLB 269, 407

- Neutrino Magnetic Moments

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

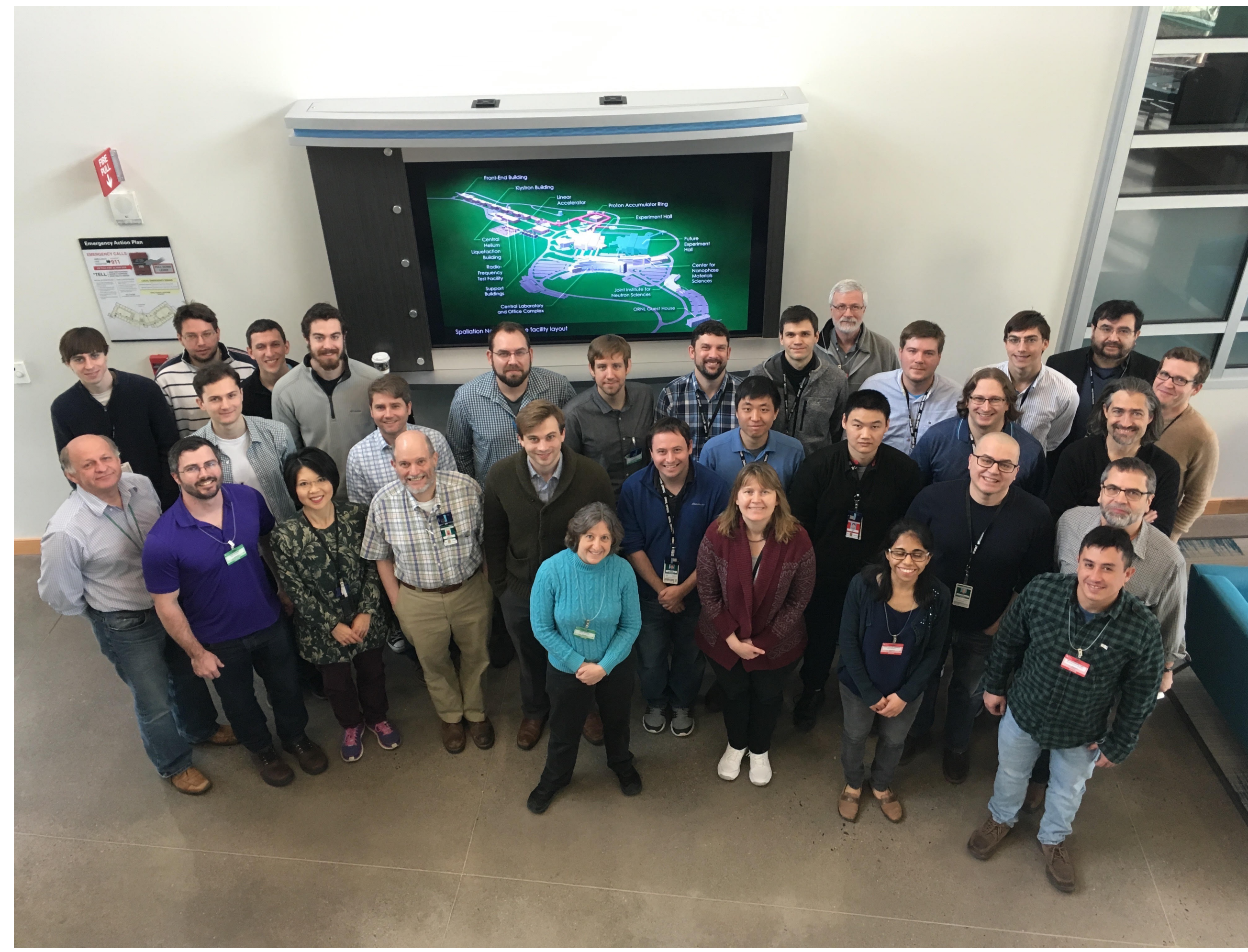
- Neutron distribution functions

  K. Patton, et al., PRC 86, 024216



The COHERENT SNS Collaboration

THE UNIVERSITY OF CHICAGO
Duke UNIVERSITY
UF UNIVERSITY of FLORIDA
KAIST
Laurentian University Université Laurentienne
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

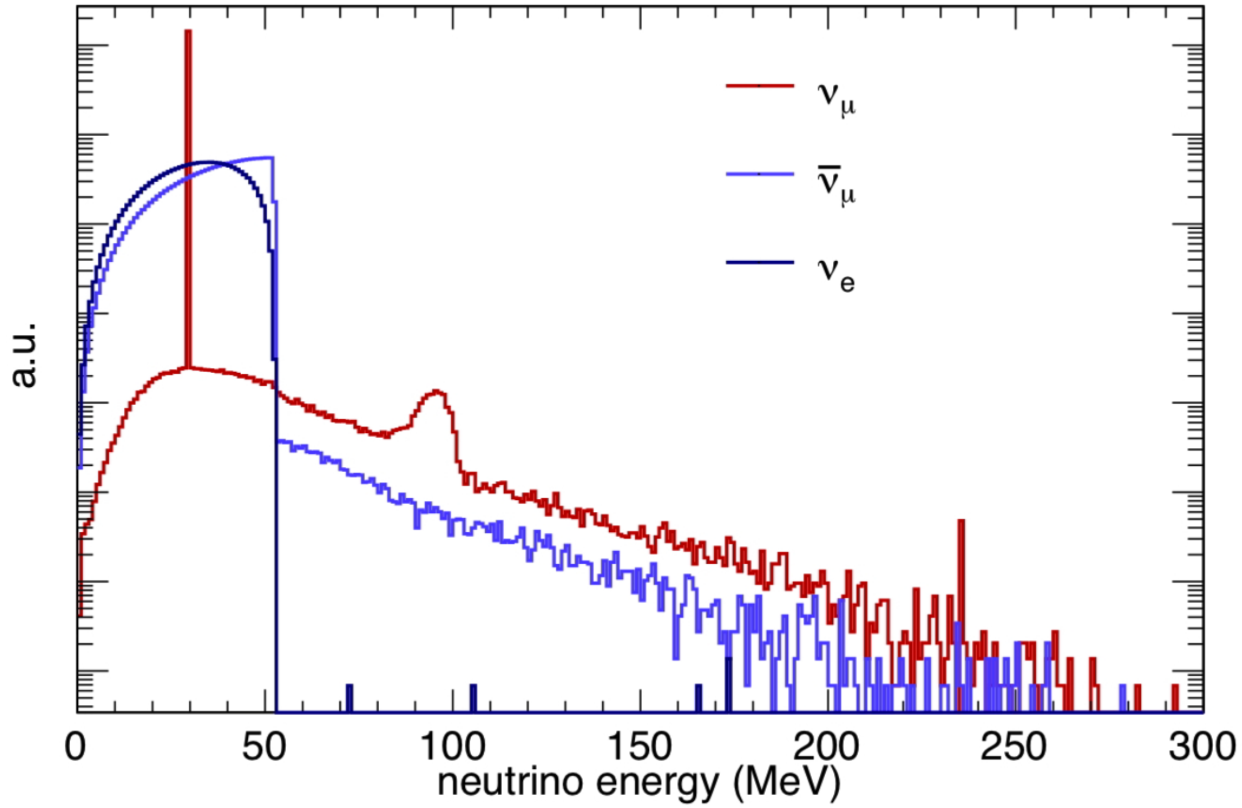


CNEC Consortium for Nonproliferation Enabling Capabilities
KICP
NNSA National Nuclear Security Administration
NSF
U.S. DEPARTMENT OF ENERGY

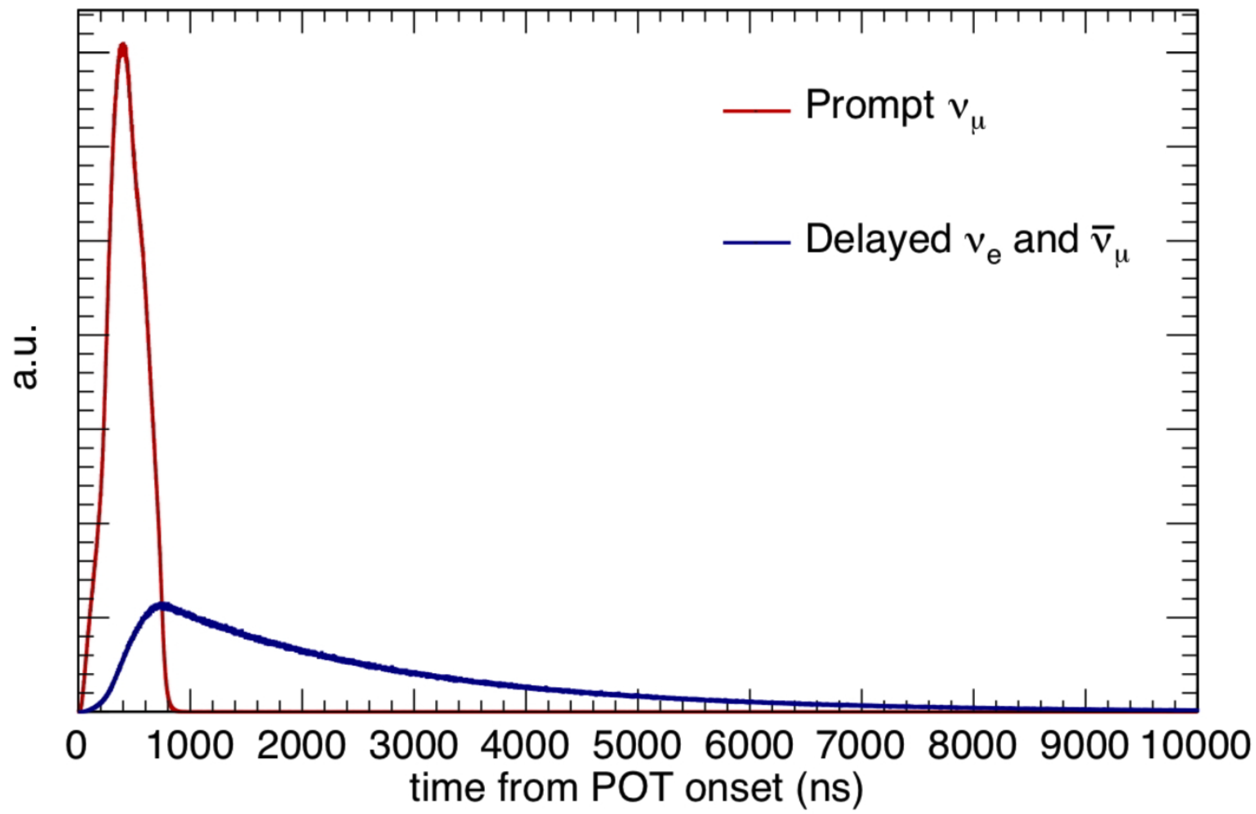
The Spallation Neutron Source

- 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



~4x10^{-5} background reduction



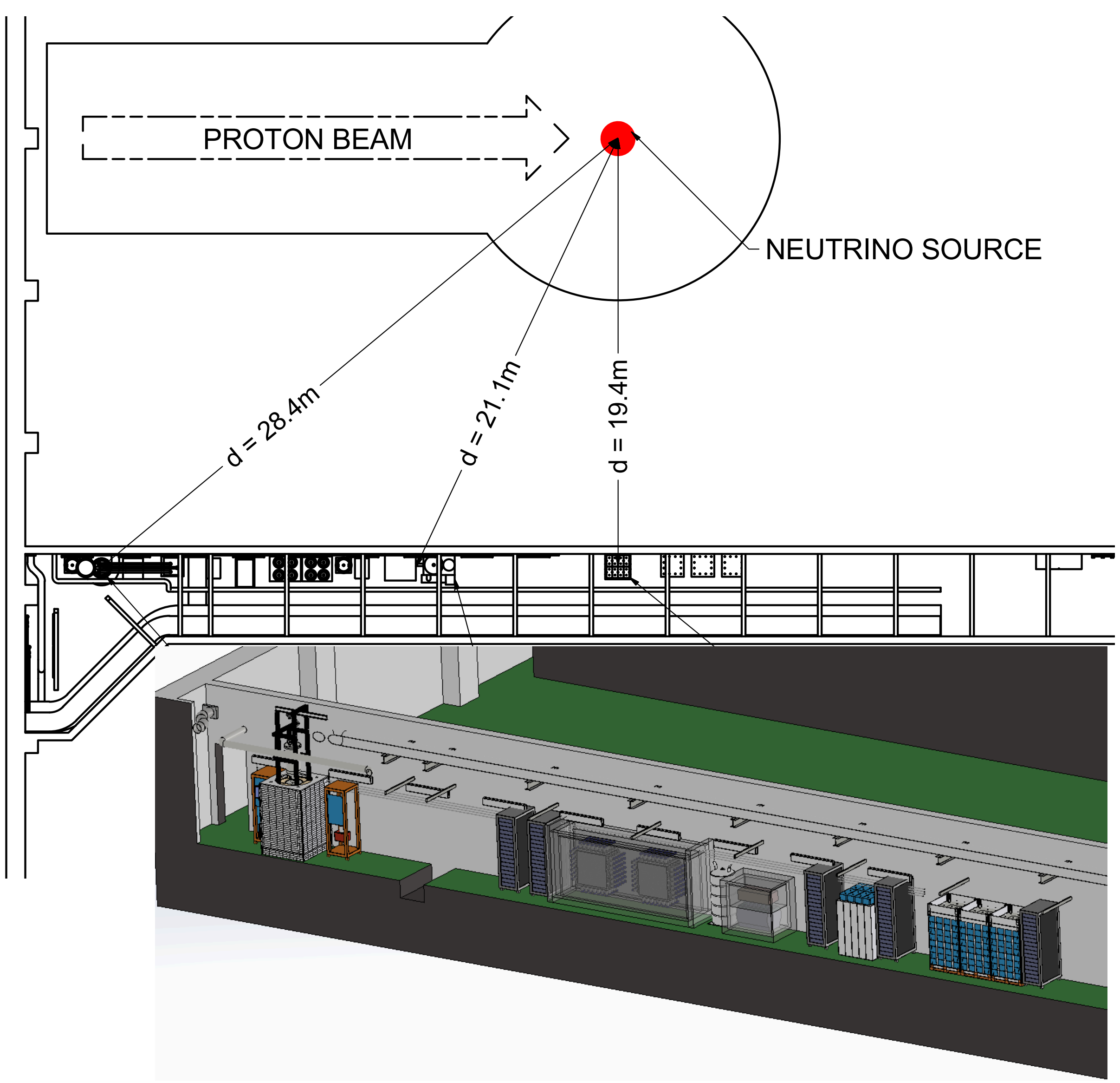
Backgrounds

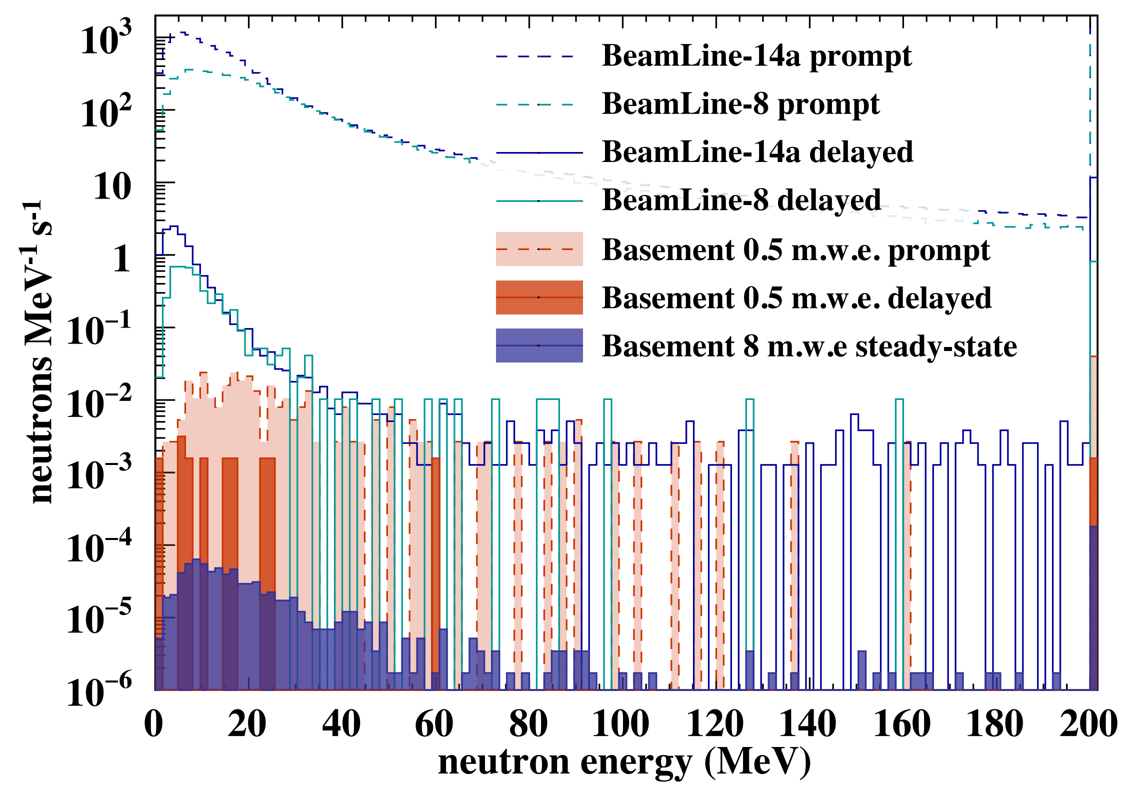
The SNS is a facility designed to produce neutrons (> 100 MeV), that are pulsed with the same time structure of the neutrinos (**with the exception of the characteristic decay time of the muon**).

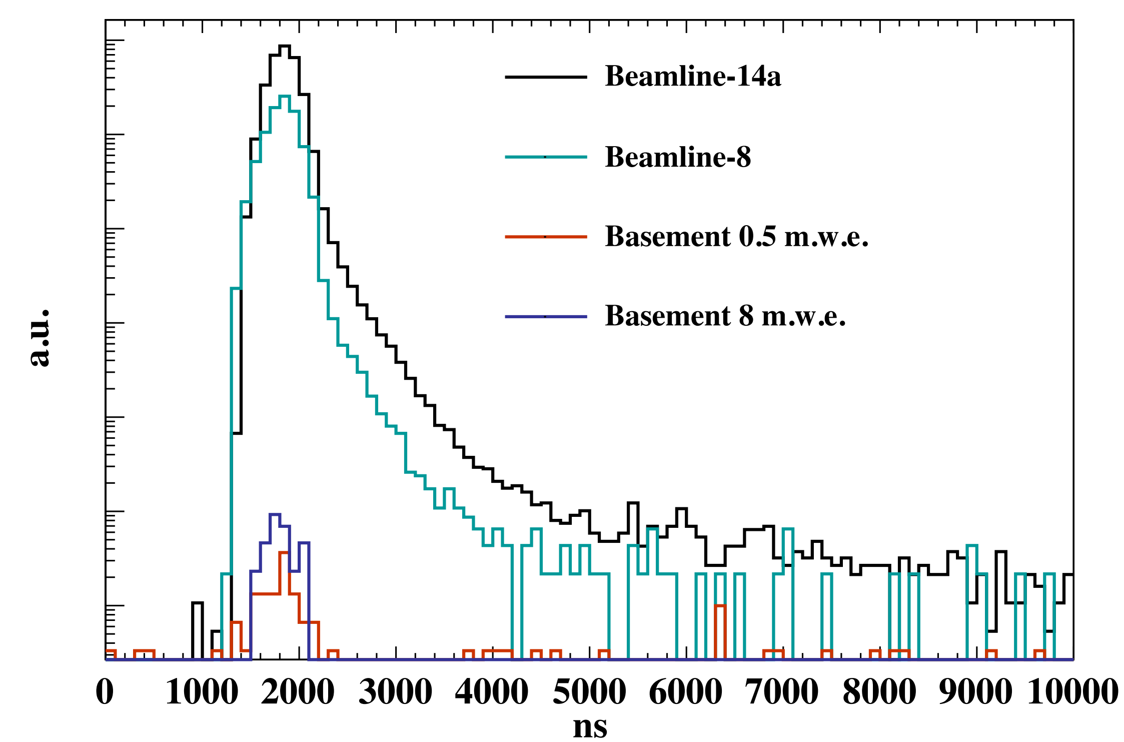
Neutron image of the SNS target, through shielding

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)

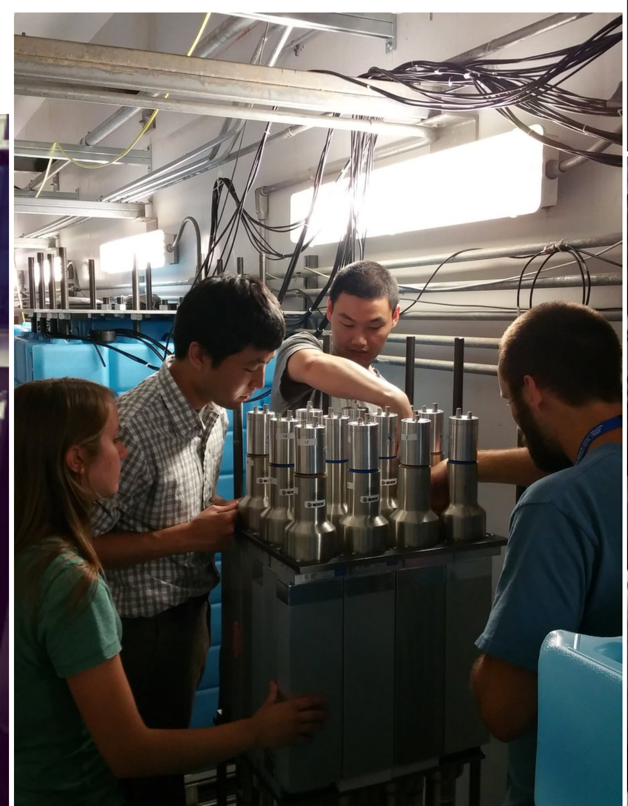


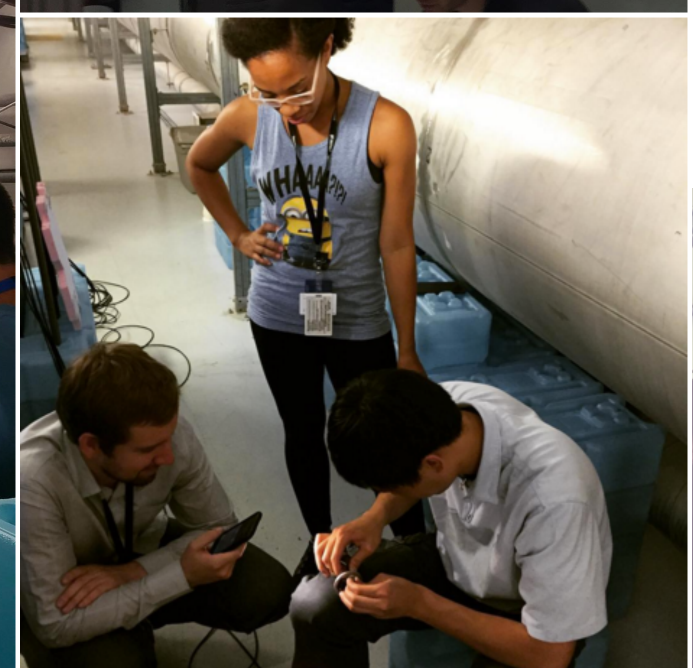




Neutrino Alley

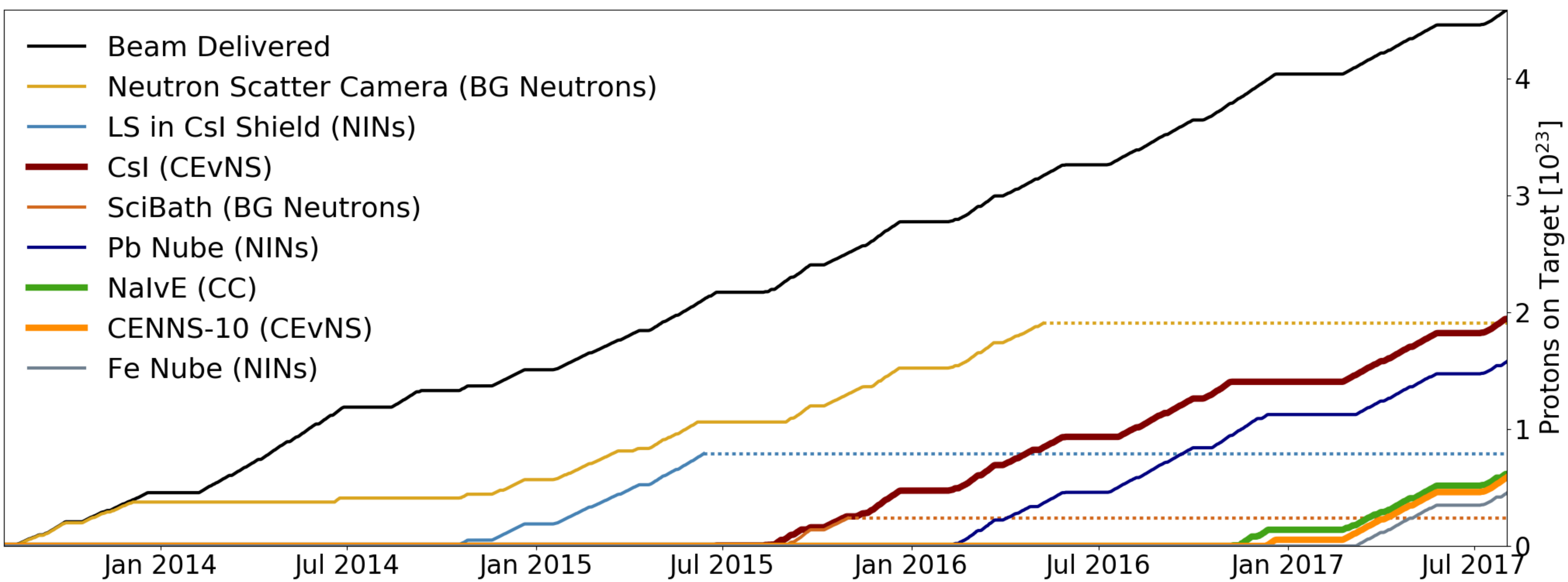
Detectors are accessible, but space constraints make design decisions challenging





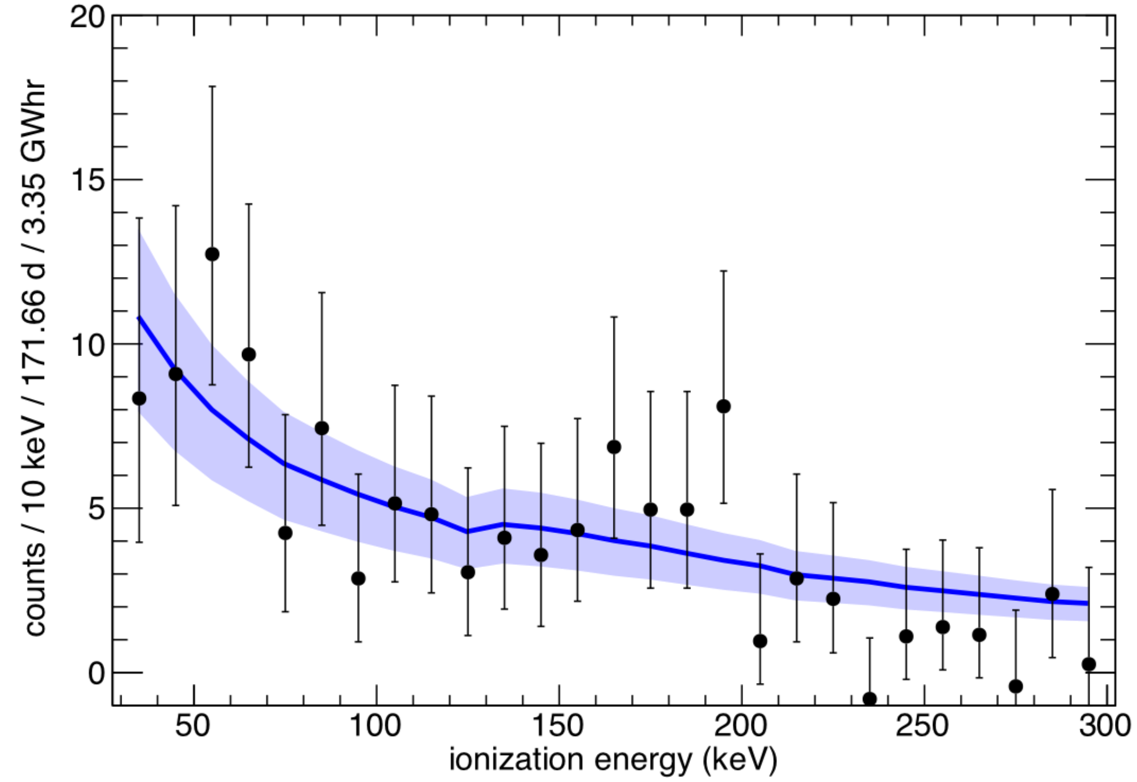
COHERENT Deployment Schedule

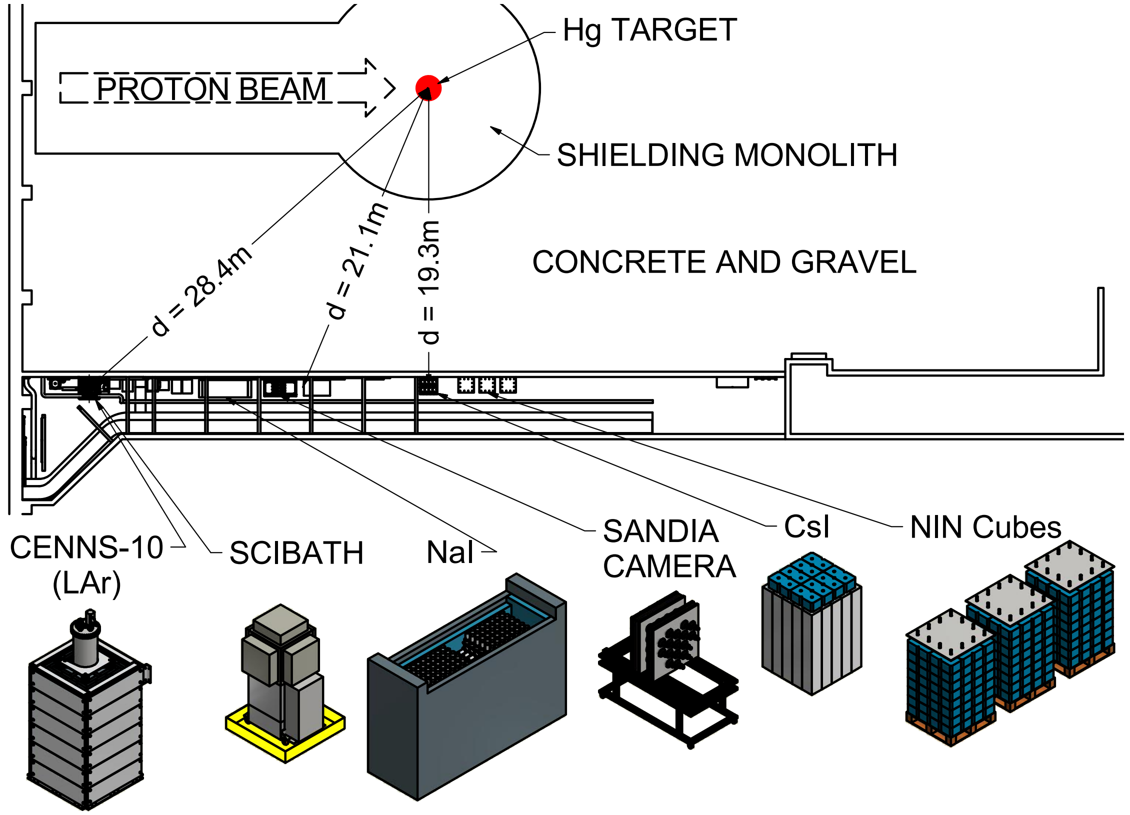
- ~ 4.5x10^{23} POT delivered while we have been operating some sort of detector
- 9 detectors have been deployed already
- 6 are currently operating

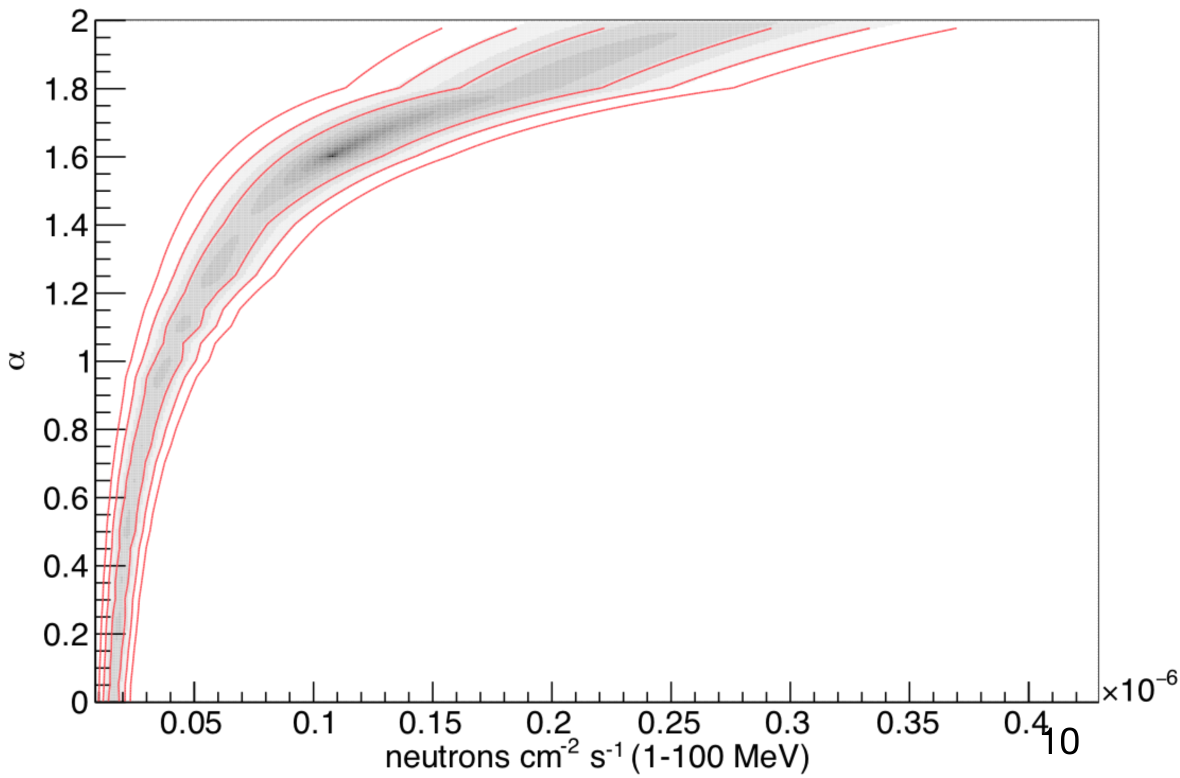


What about neutron backgrounds?

In situ measurement of the neutrons within the CsI shield prior to installation of CsI[Na] detector





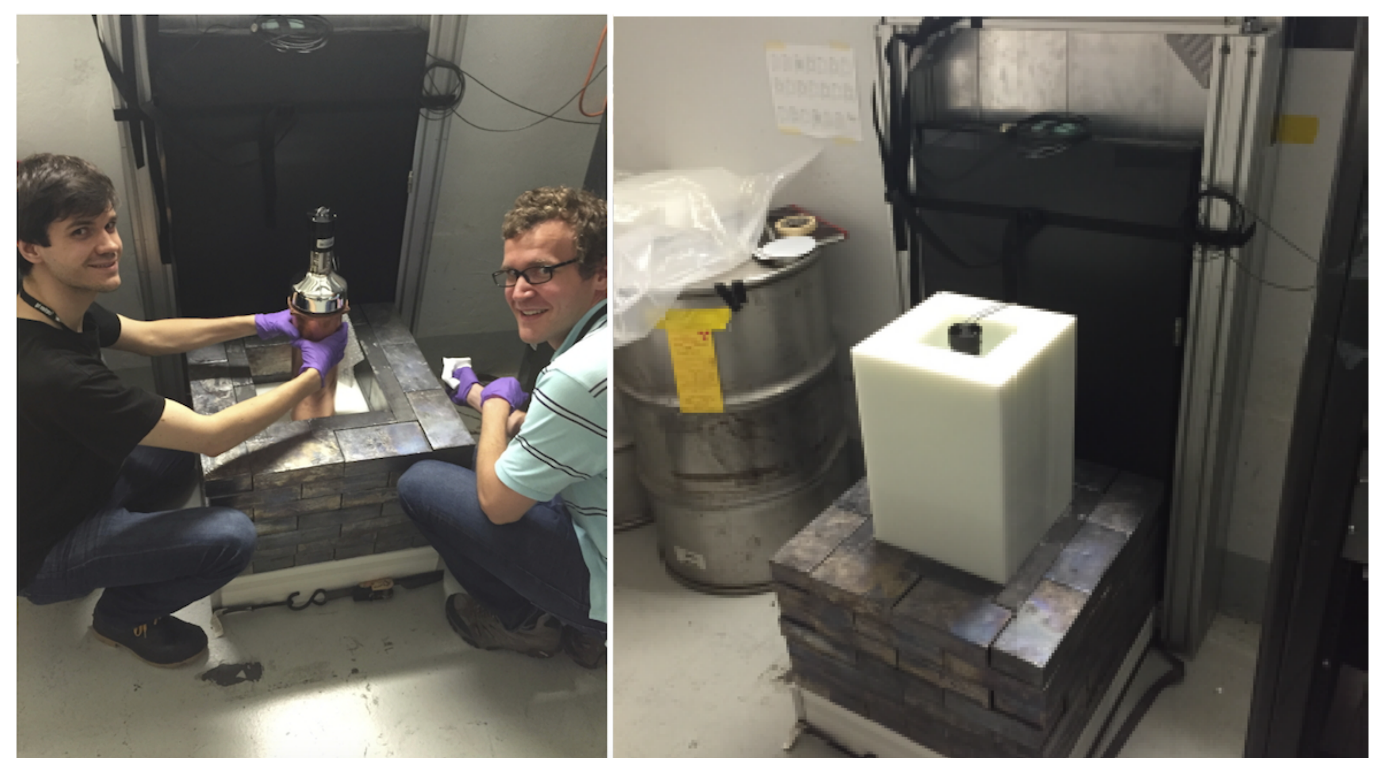


New Background: $\boldsymbol{\nu}$-induced Neutrons (NINs)

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

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

- The detector shields use several tons of lead, where neutrons can be produced
- They will be pulsed, and share the 2.2 μs decay time of the ν's



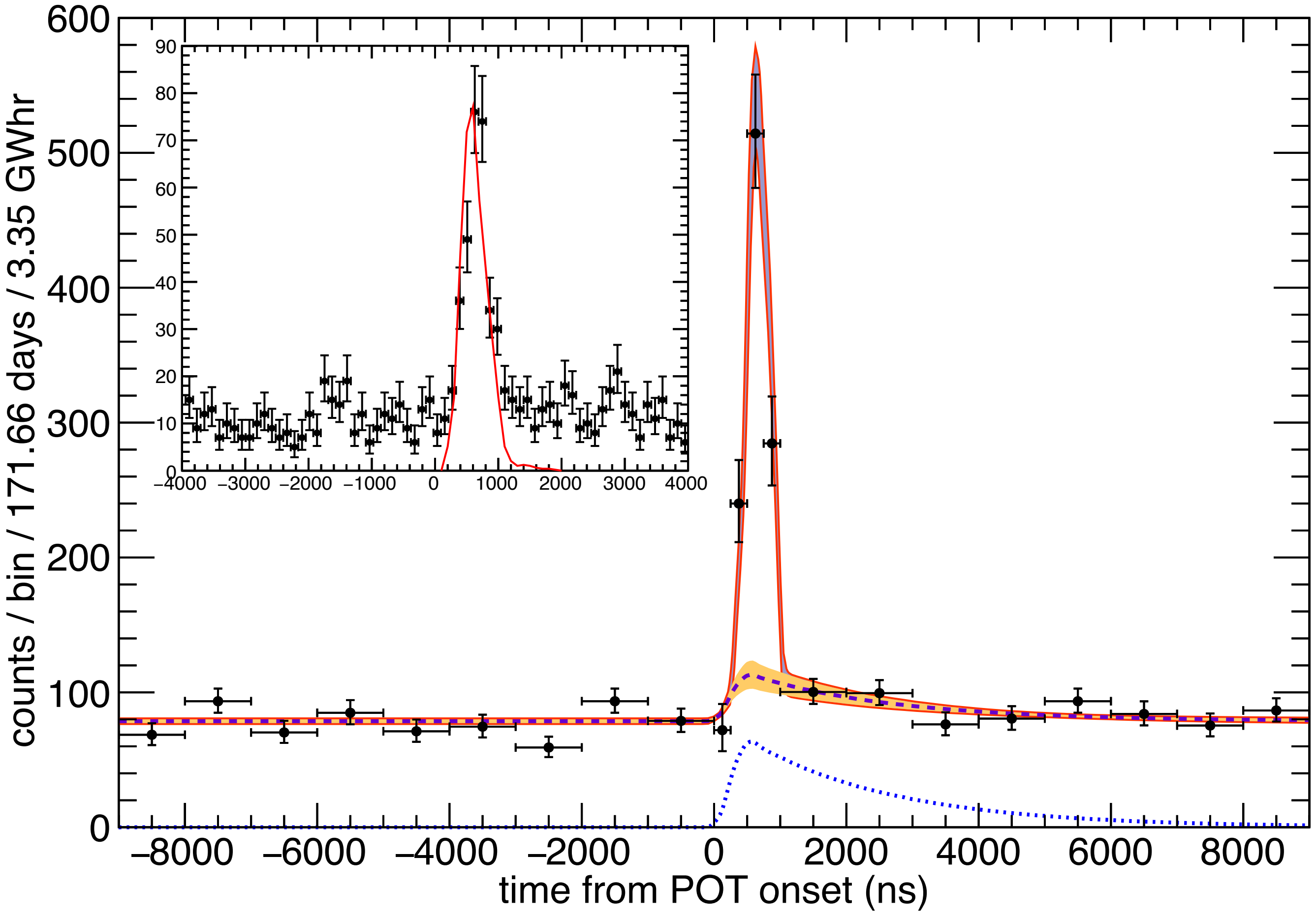
CsI(Na) detector and shield

New Background: ν-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)

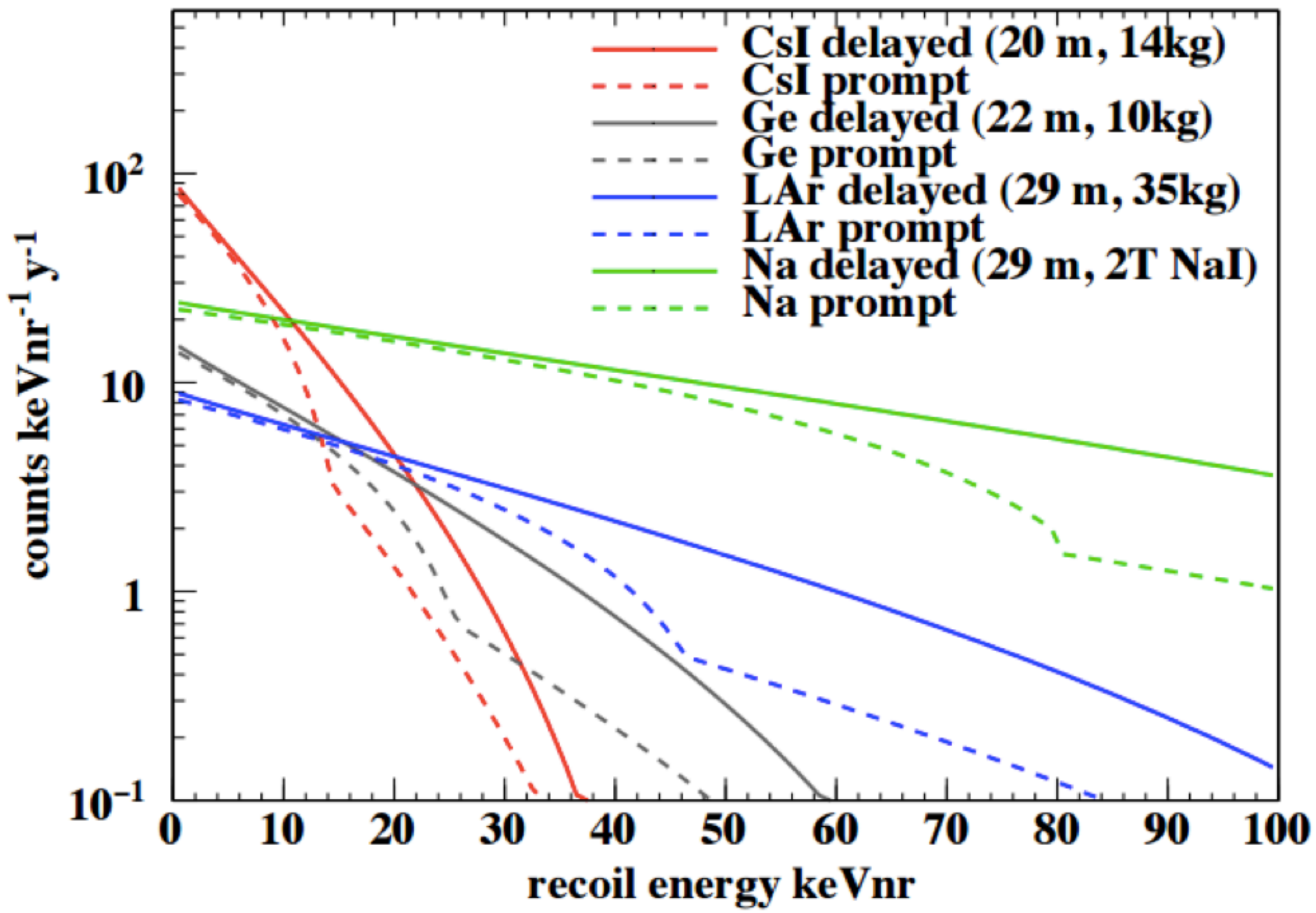
- Can be important process in many stellar environments

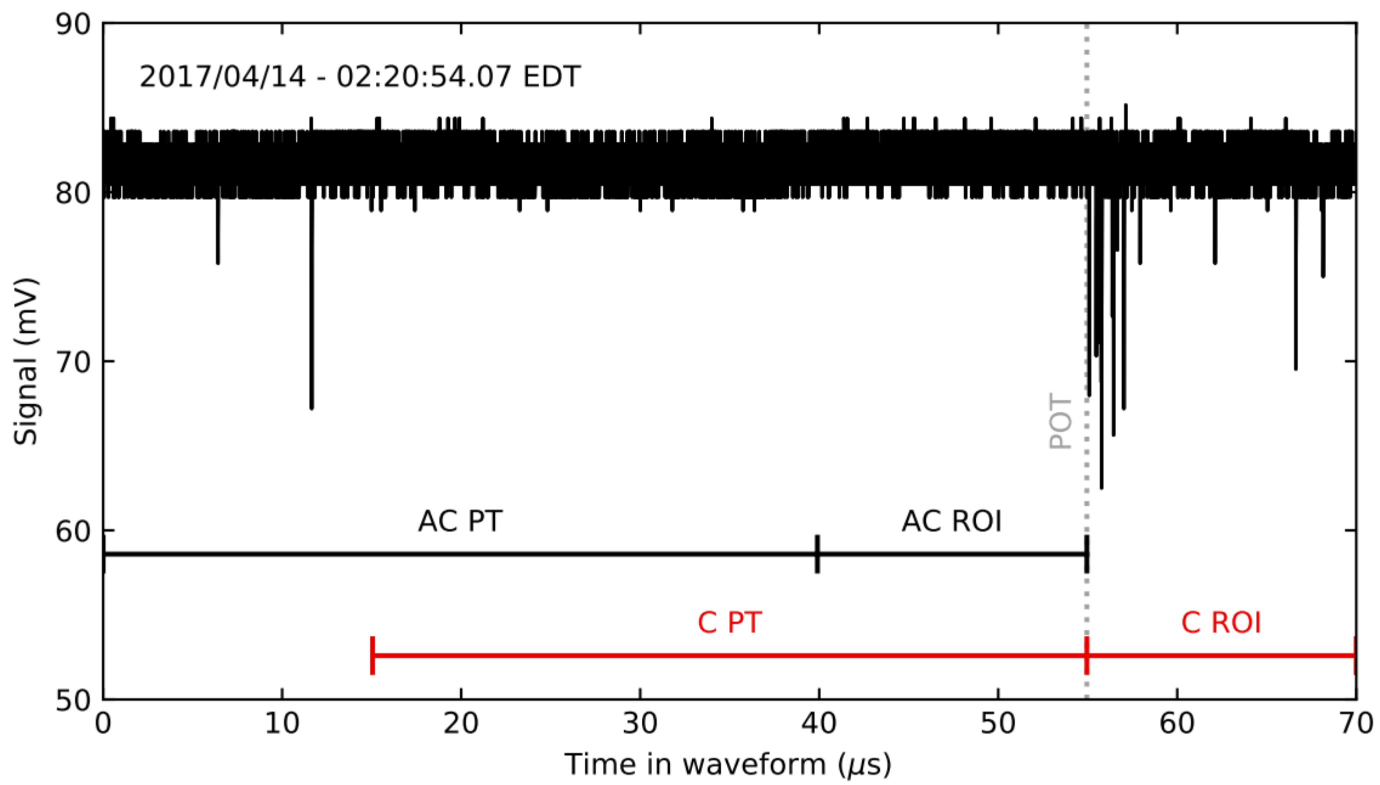


C.A. Duba *et al.* J.Phys.Conf.Series 136 (2008)
Y-Z. Qian *et al.*, Phys. Rev. C 55 (1997)
M. Athar, S. Ahmad and S. K. Singh., Nucl. Phys. A *764* (2006) 551-568

CsI[Na] Signals

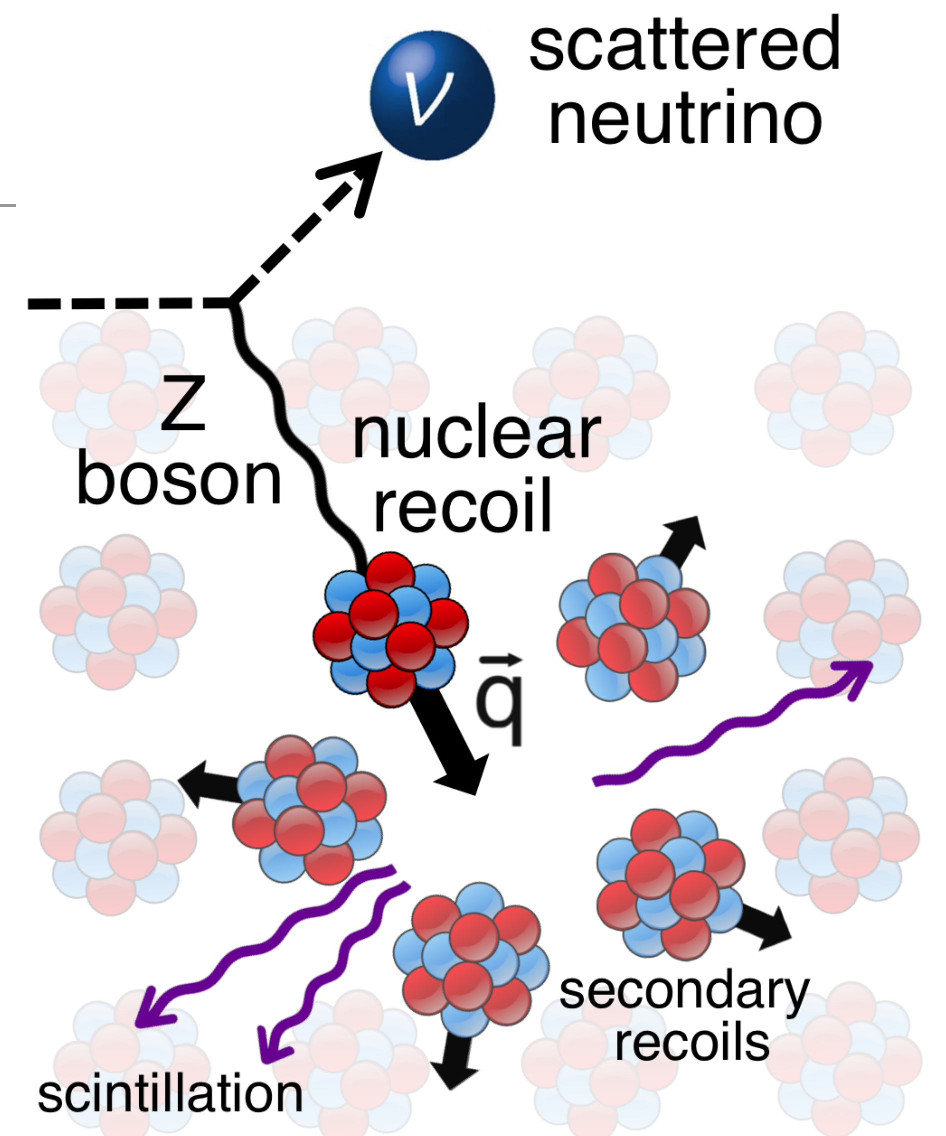
- Even at the SNS CEvNS gives rise to extremely low energy nuclear recoils
- ~ 1.2 PE/keV_{nr} after accounting for Quenching Factor for nuclear recoils
- expect 5-30 photoelectrons

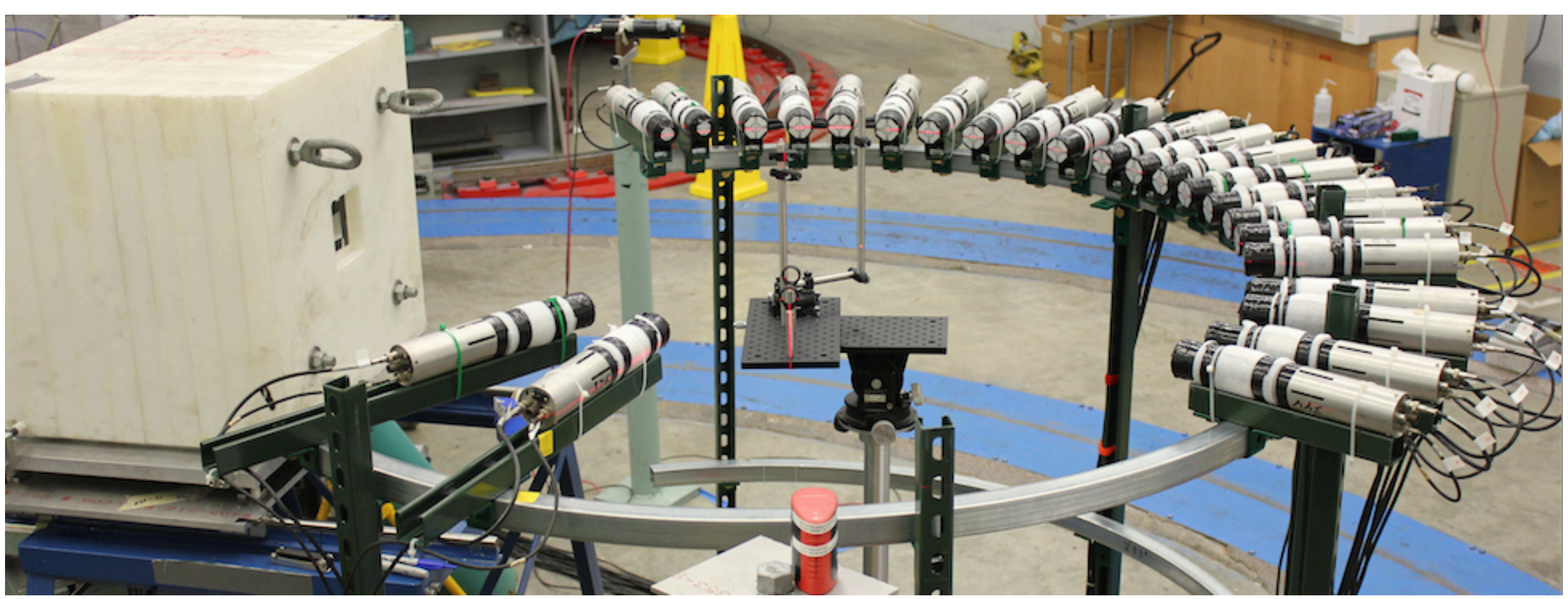


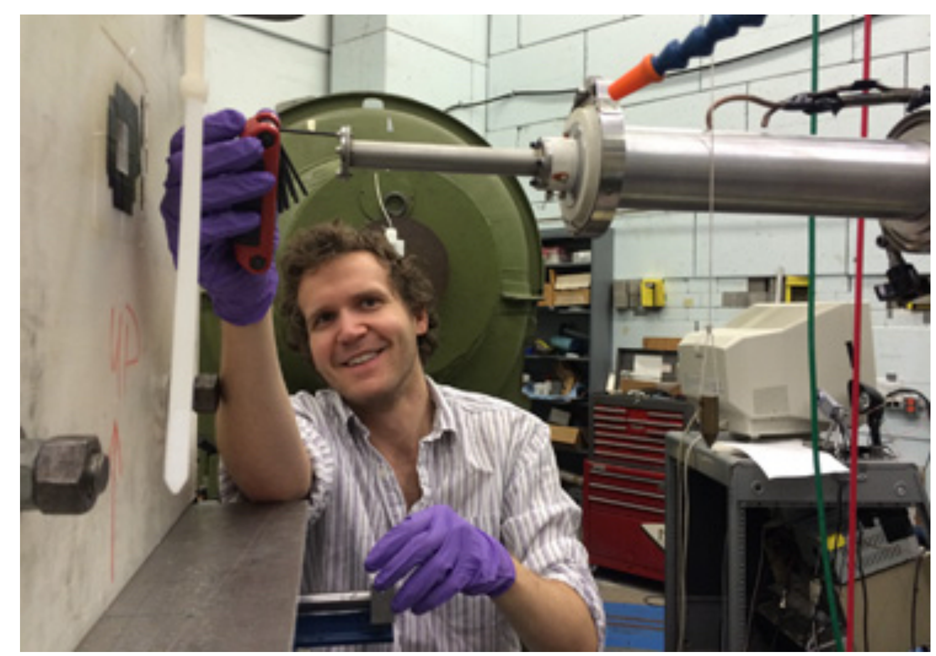


What is the Quenching Factor?

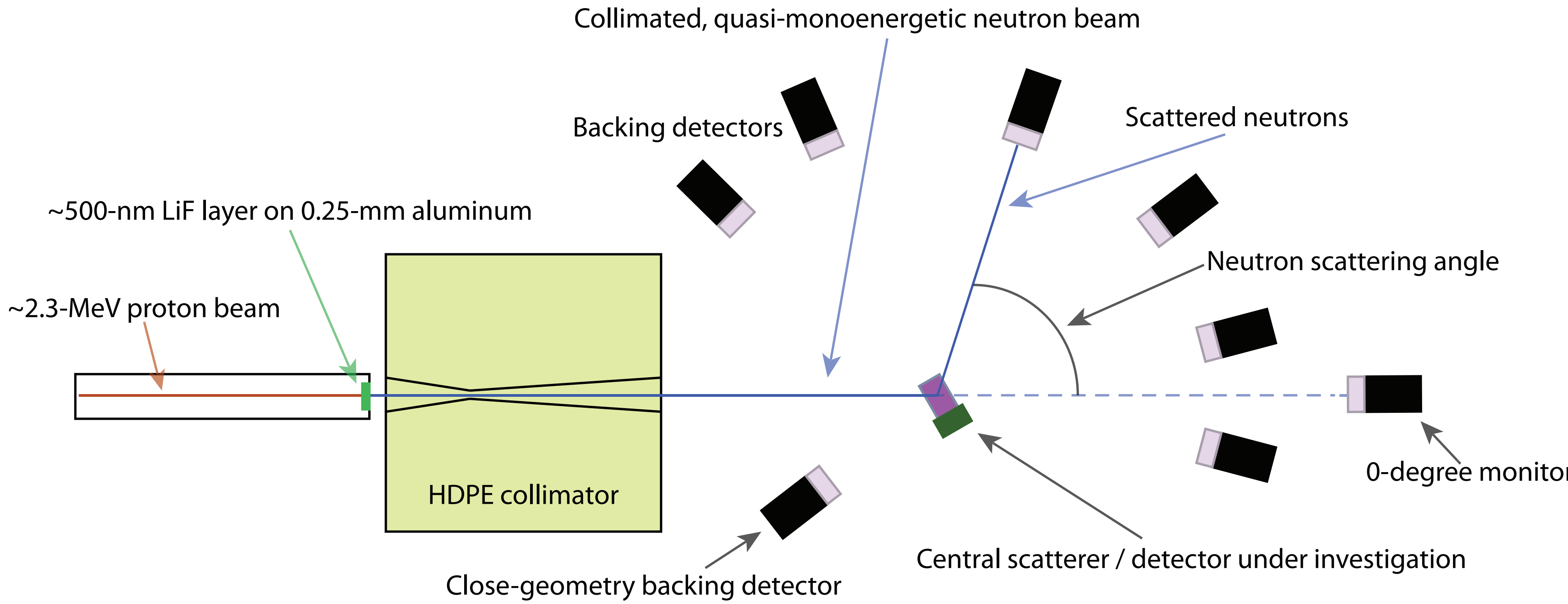
- This is largely unknown, and needs to be calibrated
- A facility is utilized at TUNL for precision detector calibrations in support of COHERENT

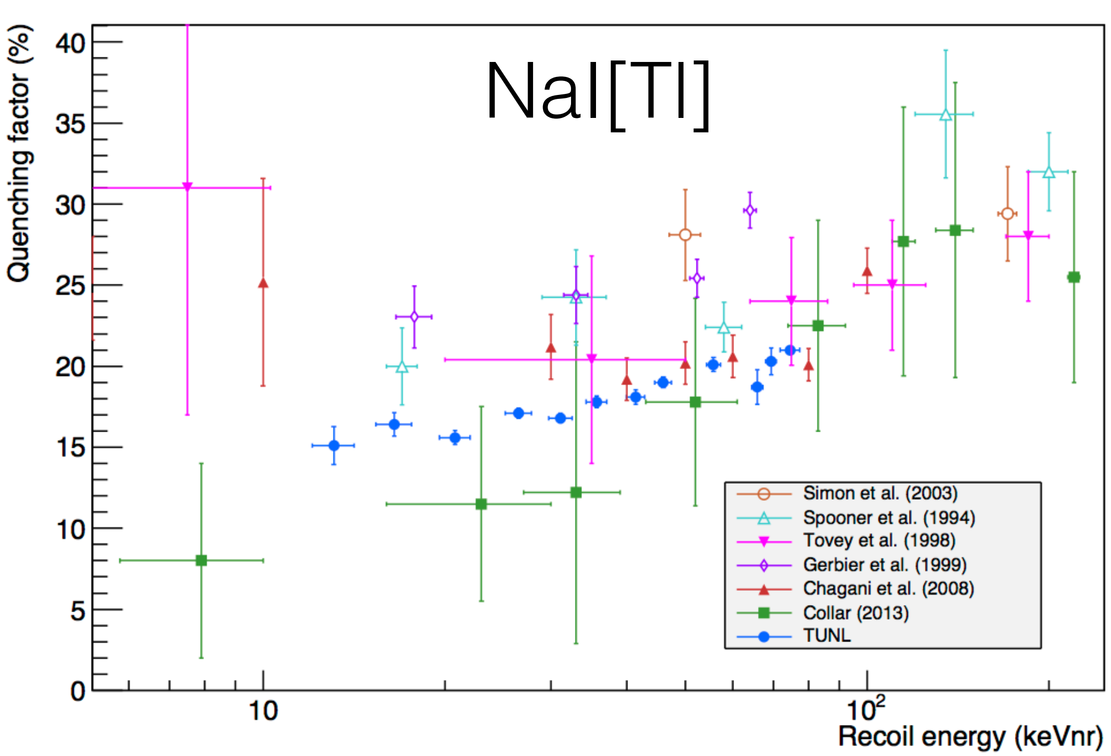


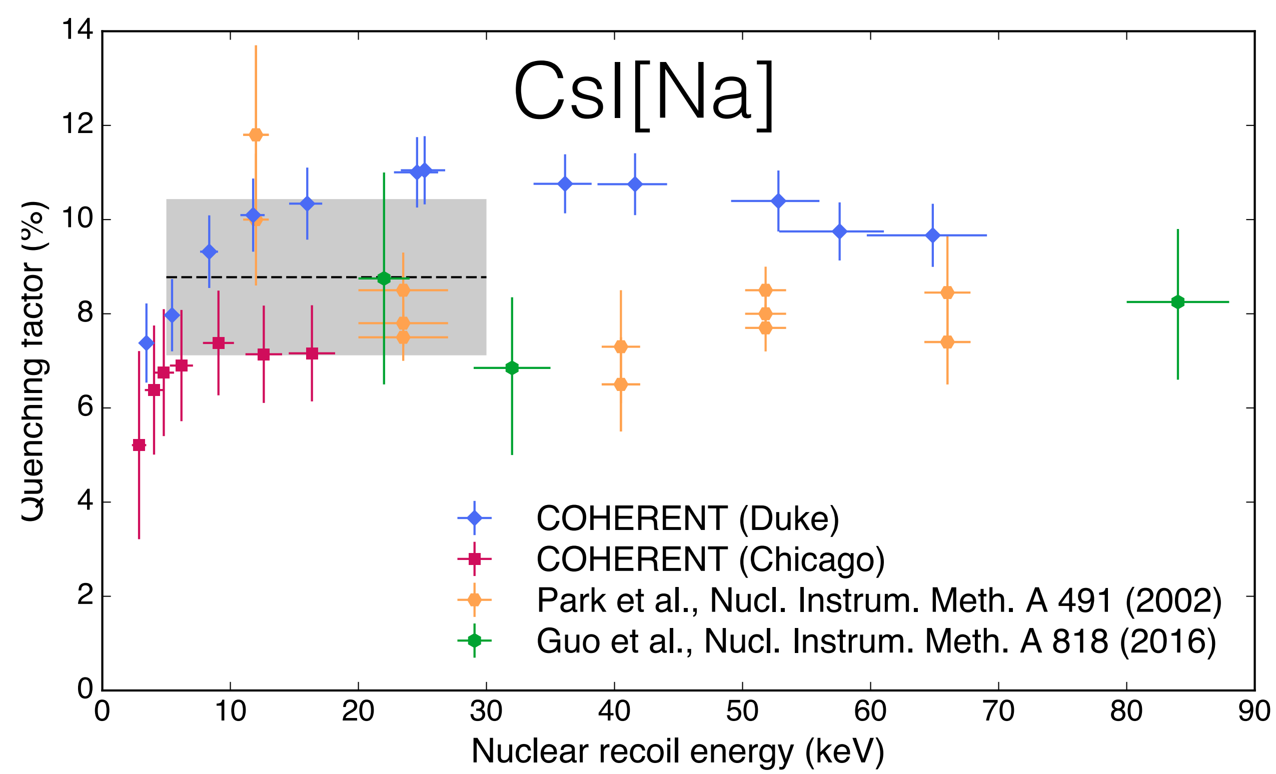




TUNL Quenching Factor Measurements

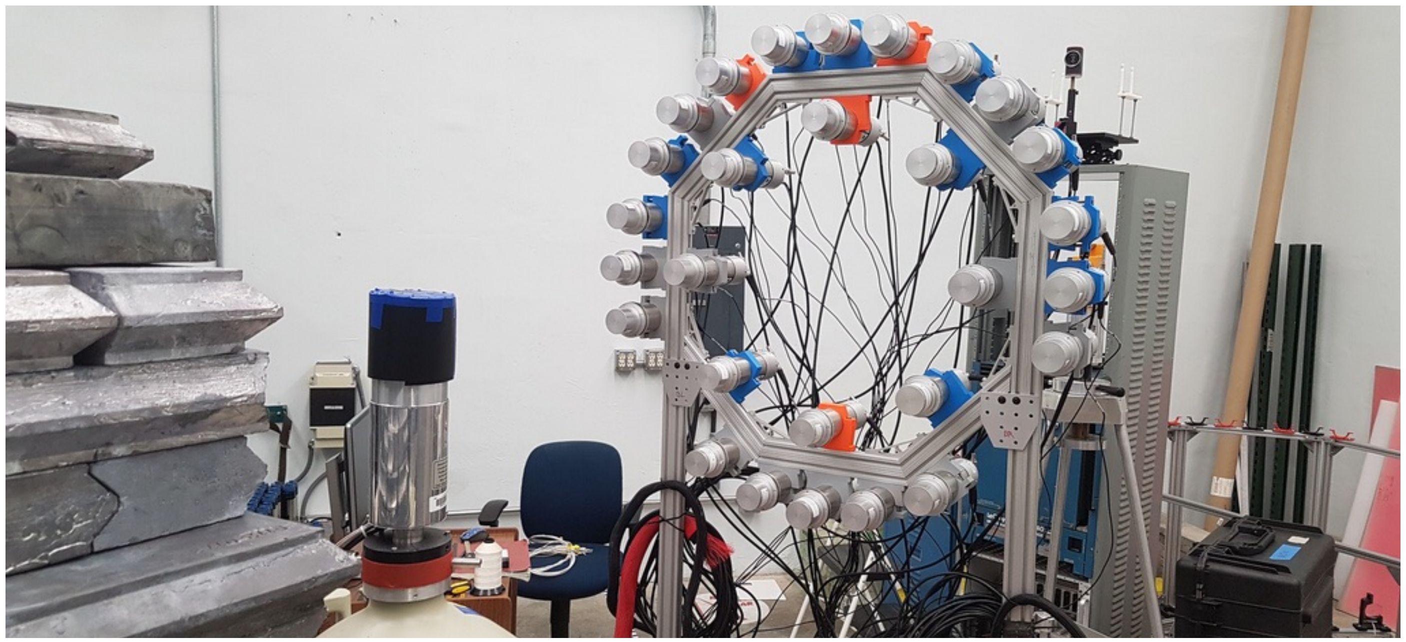


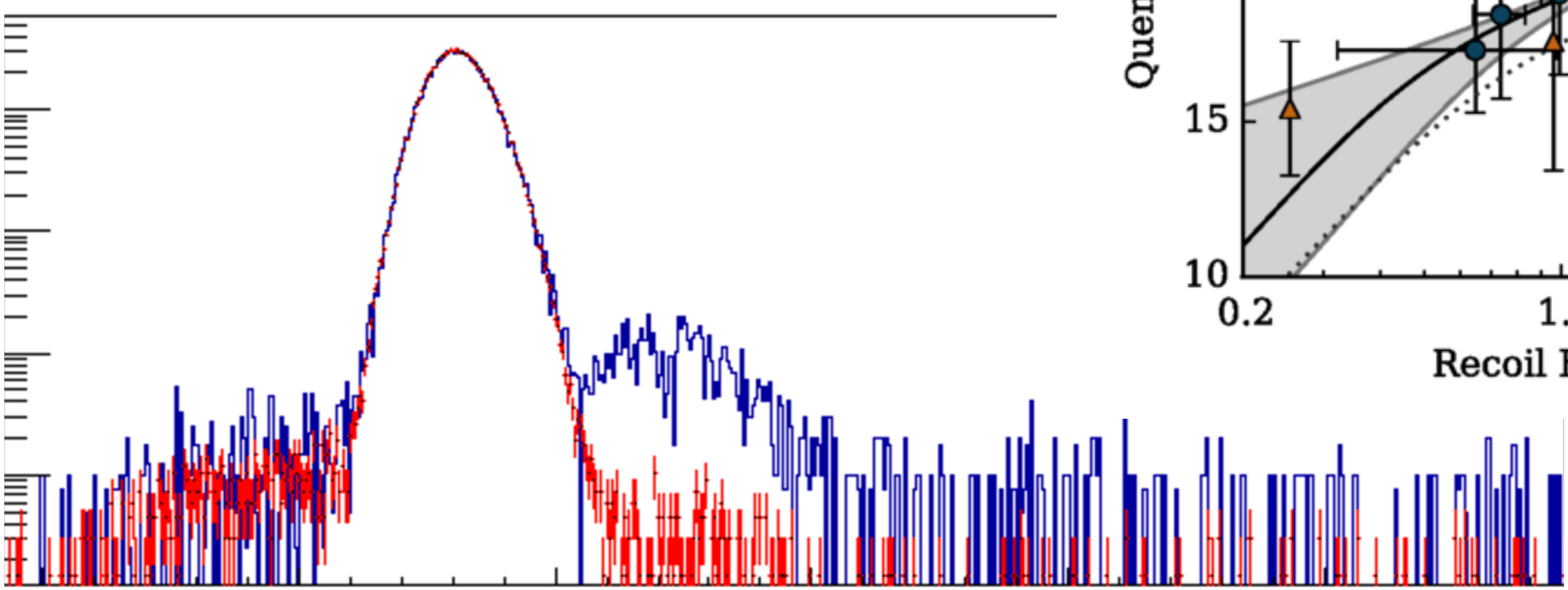


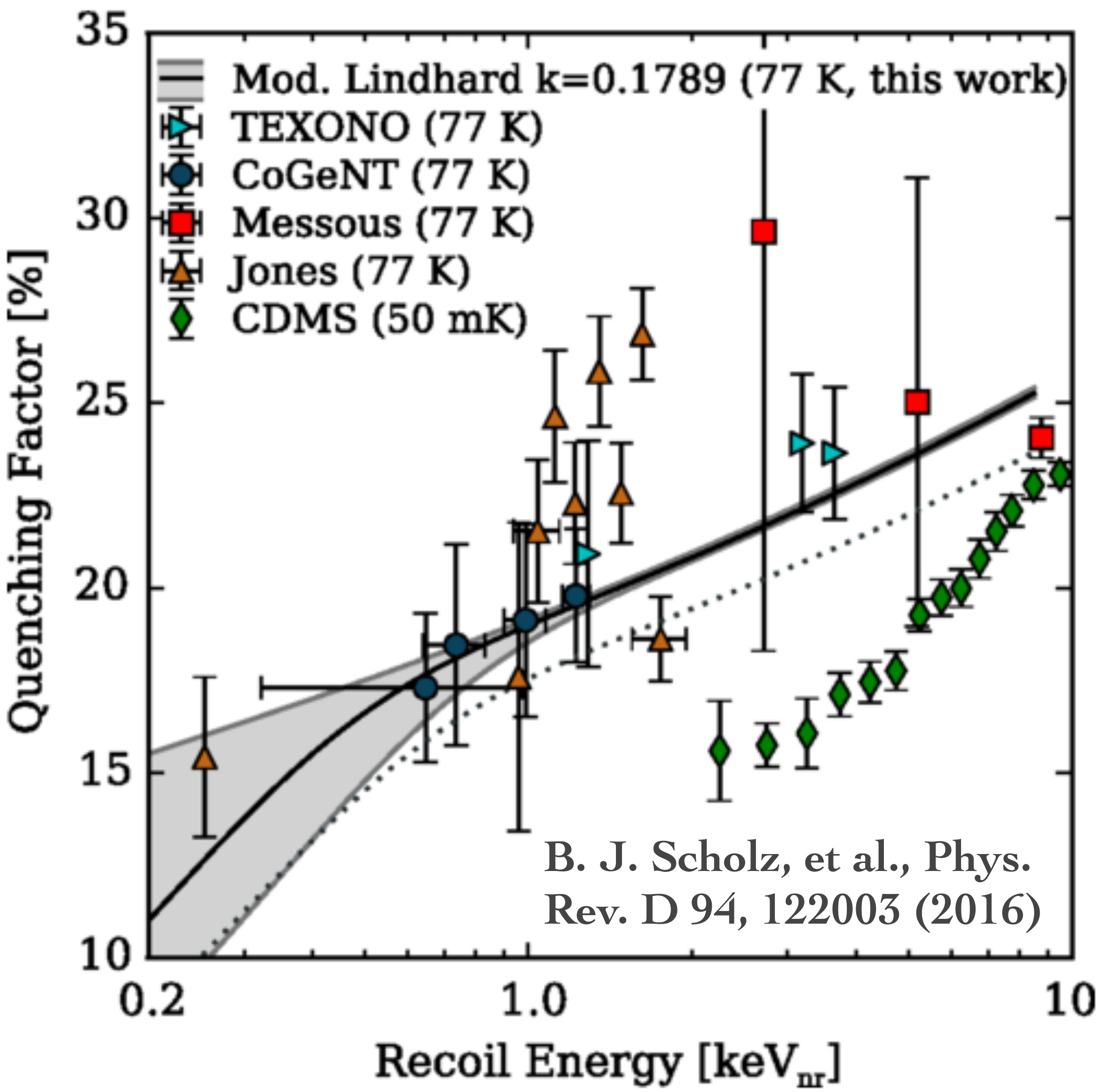


TUNL Quenching Factor Measurements

HPGe measurements provide strong systematic controls, including channeling

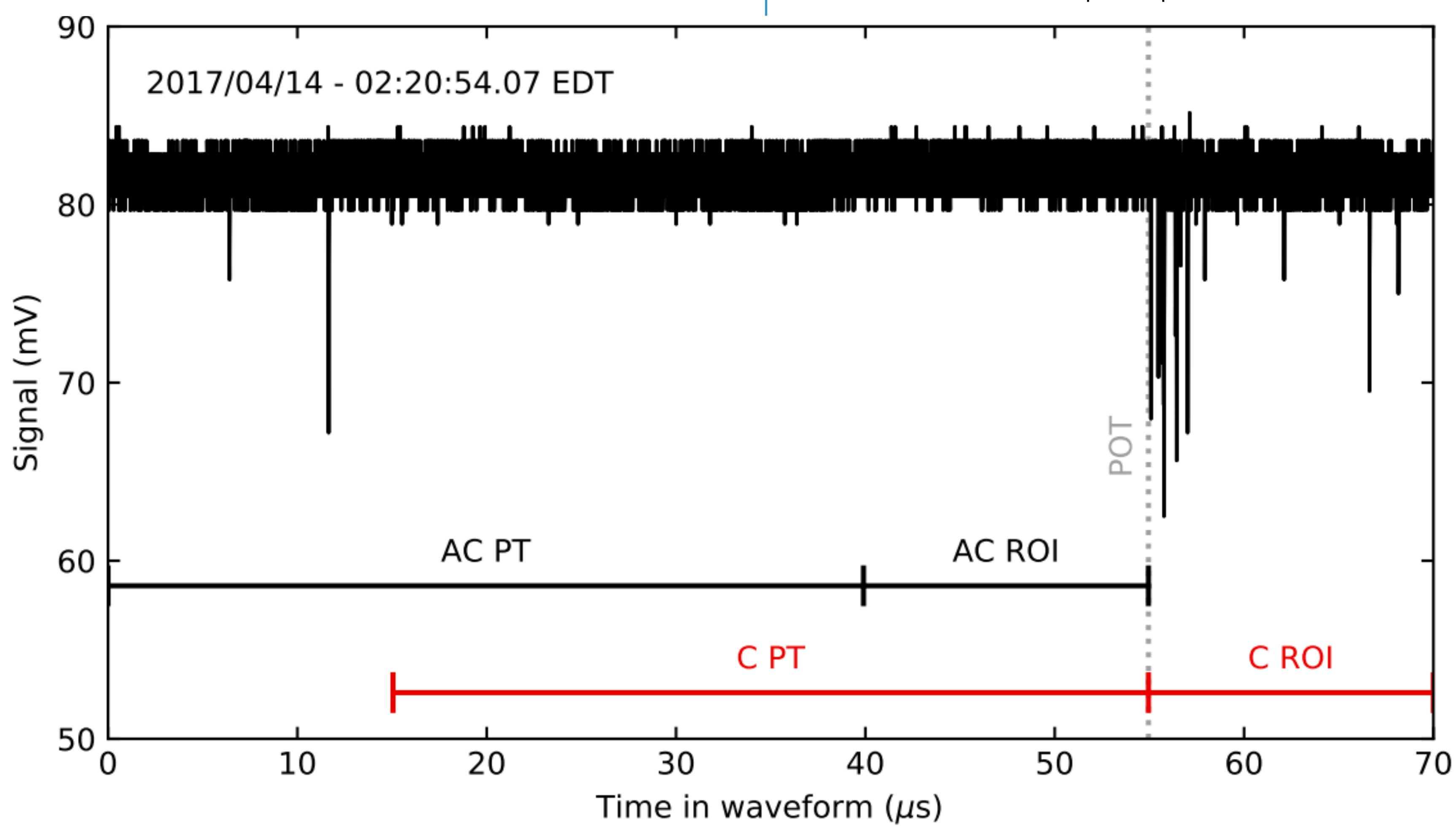




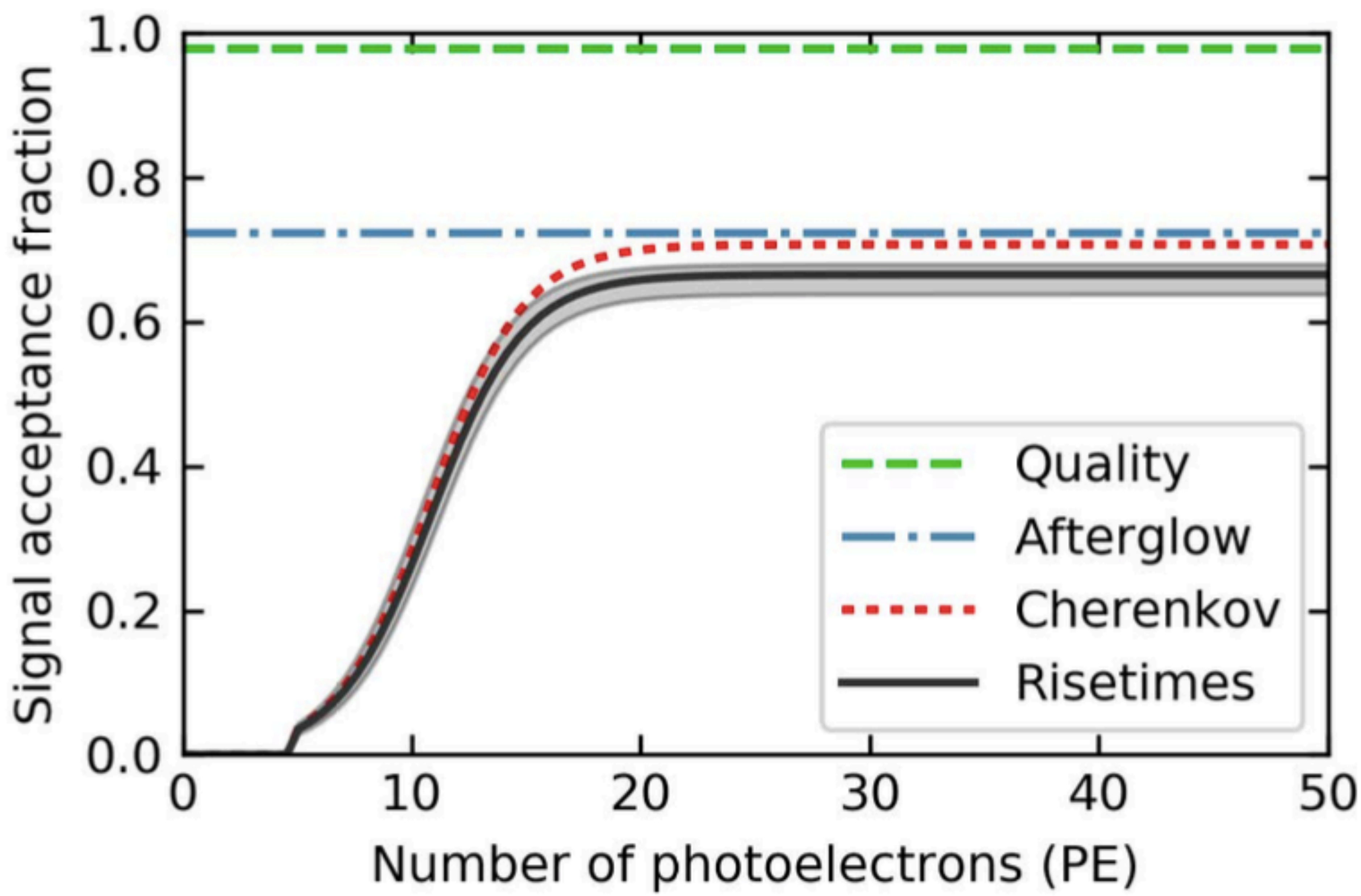


Waveform Analysis

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

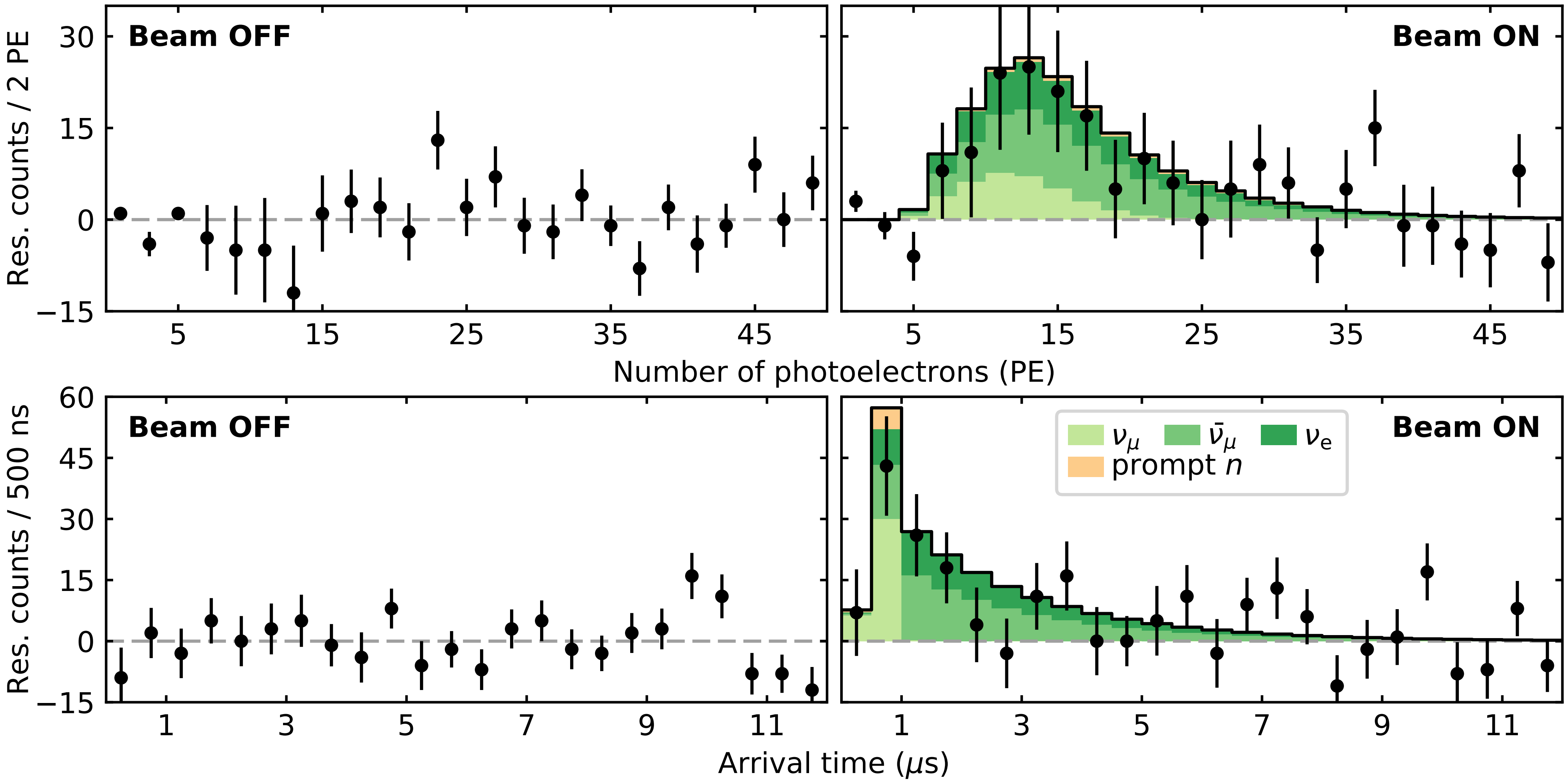


Event Selection Efficiencies



The Result

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



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

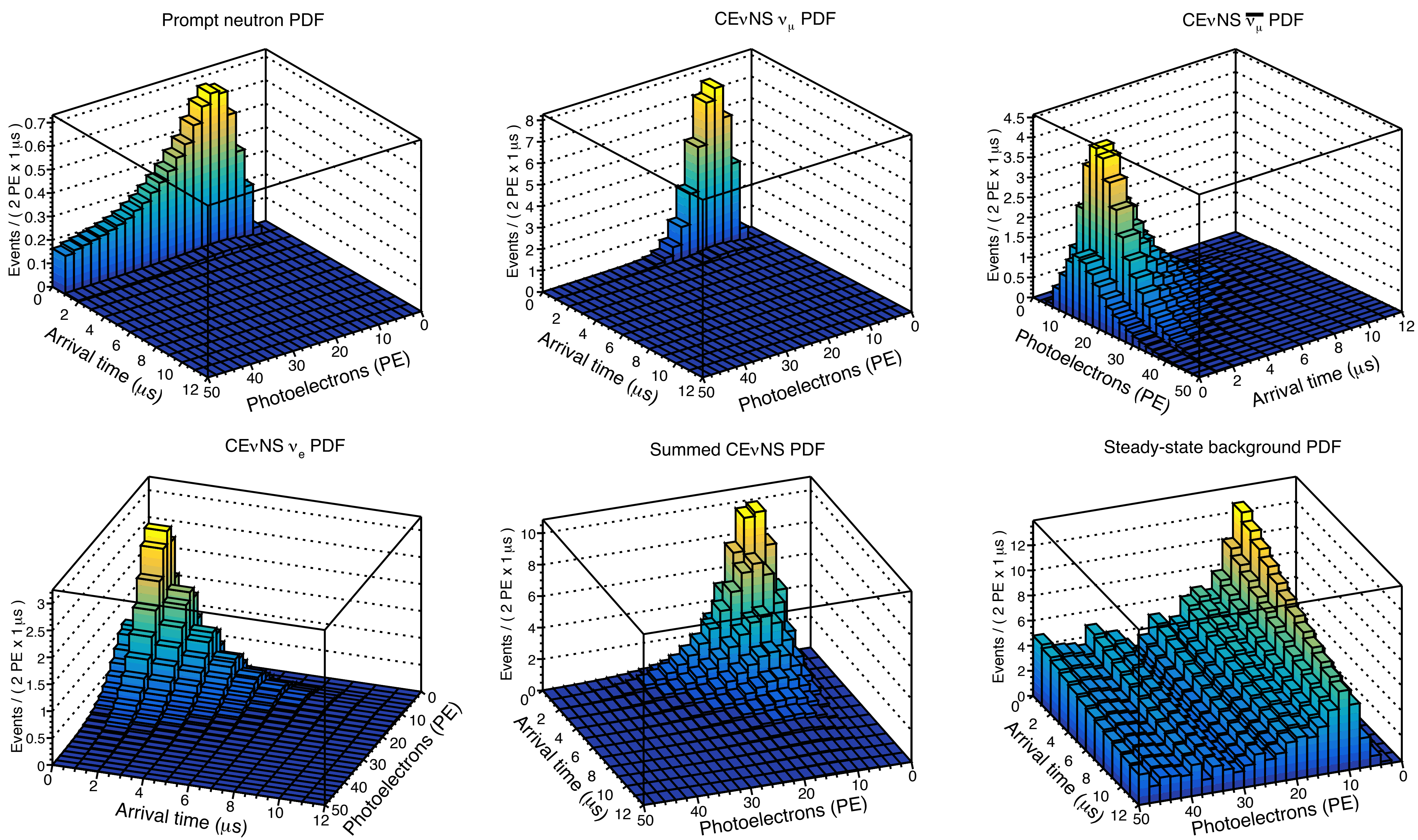
Science 03 Aug 2017:
eaao0990
DOI: 10.1126/science.aao0990

Peer Reviewed
← see details

The Result

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

- We 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



The Result

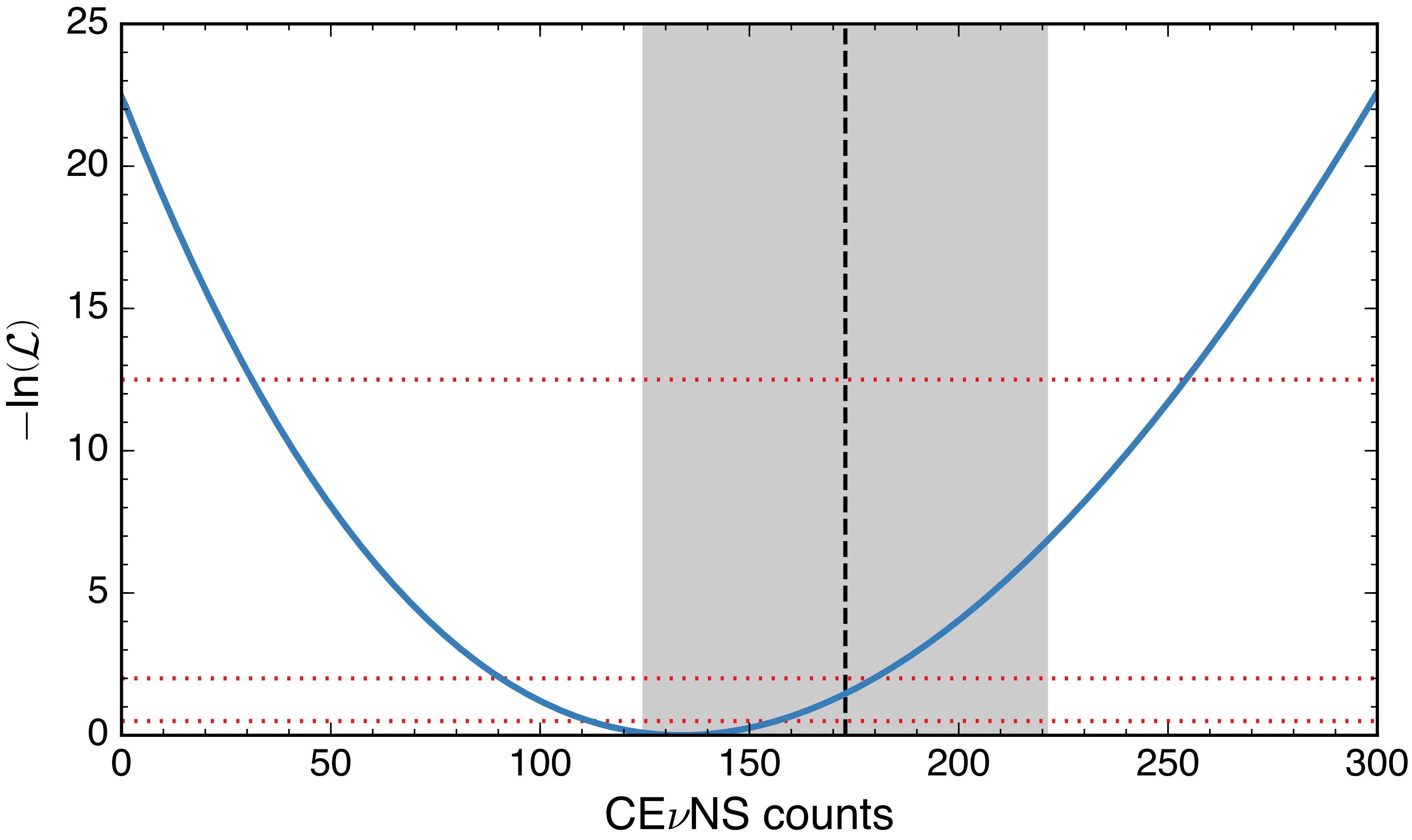
D. Akimov et al., Science 10.1126/science.aao0990 (2017).

- 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

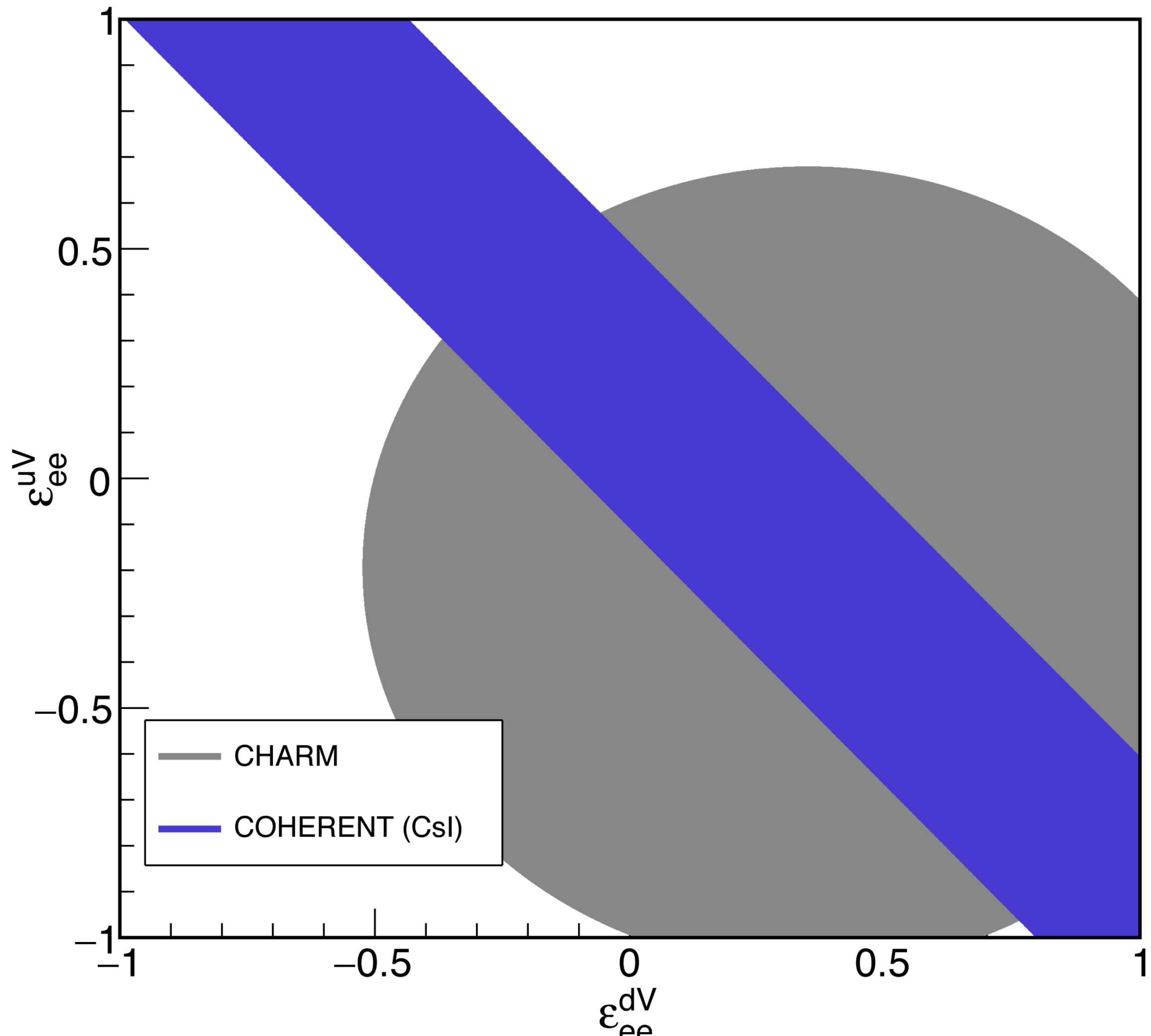
Event Selection	5%
Neutrino Flux	10%
Form Factor	5%
Quenching Factor	25%
Total uncertainty	**28%**

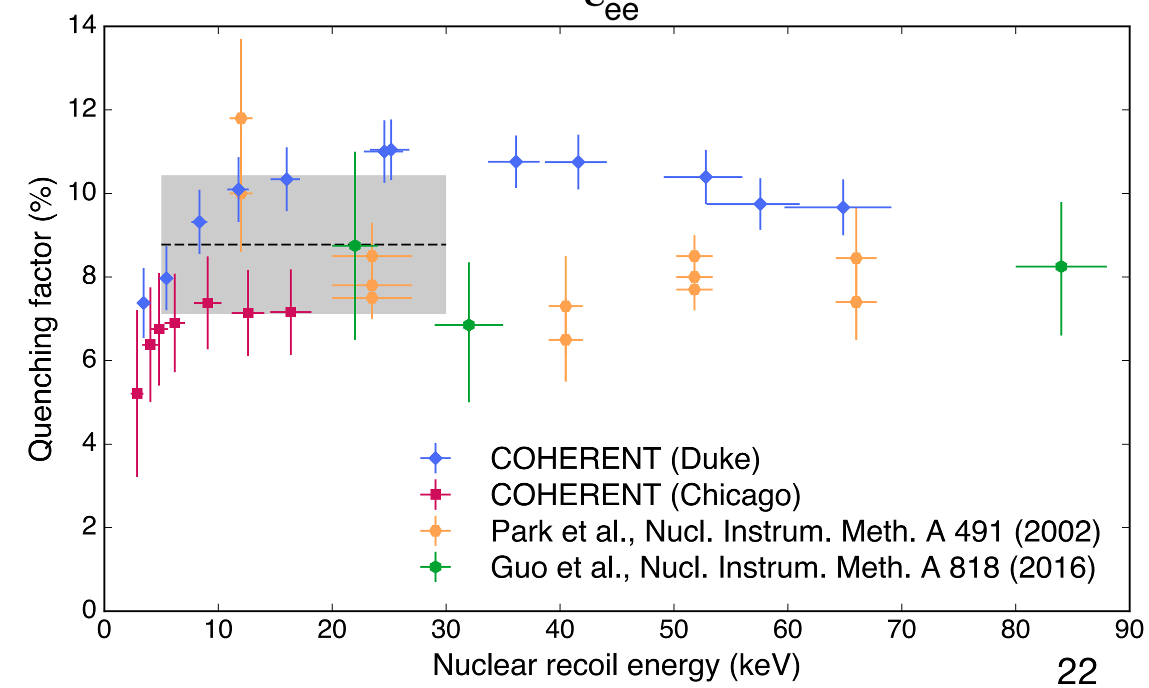
16% statistical uncertainty



Implications for Non-Standard Neutrino Interactions

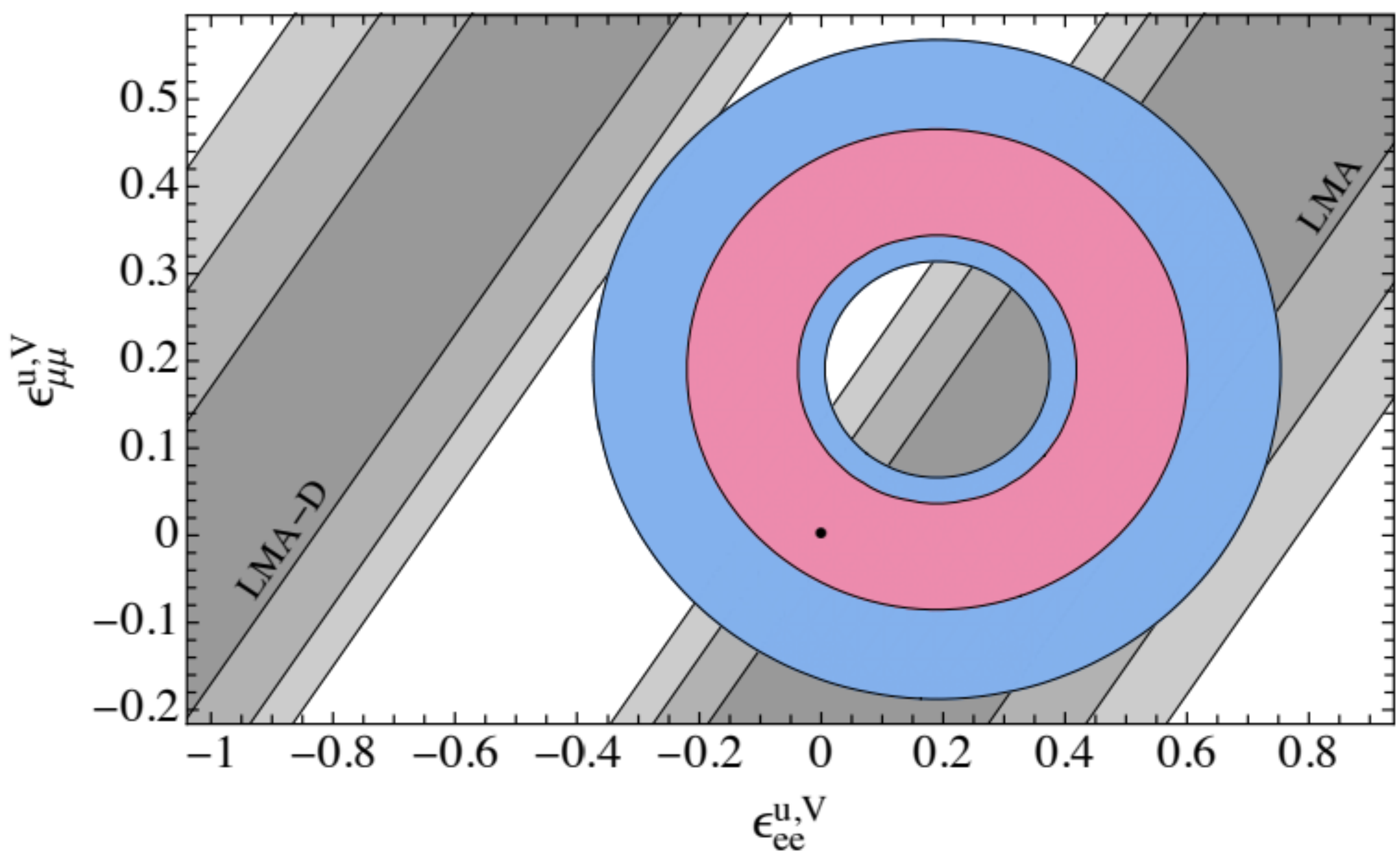
- First result improves constraints on non-universal NSI
- Low hanging fruit. We can expect significant improvement with more data, and when more COHERENT detectors report their results
- Uncertainty currently dominated by our knowledge of the quenching factor in CsI[Na] (~25%)
- Can factor out the ~10% neutrino flux uncertainty by measuring the ratio of interaction rates when the other COHERENT detectors report their results





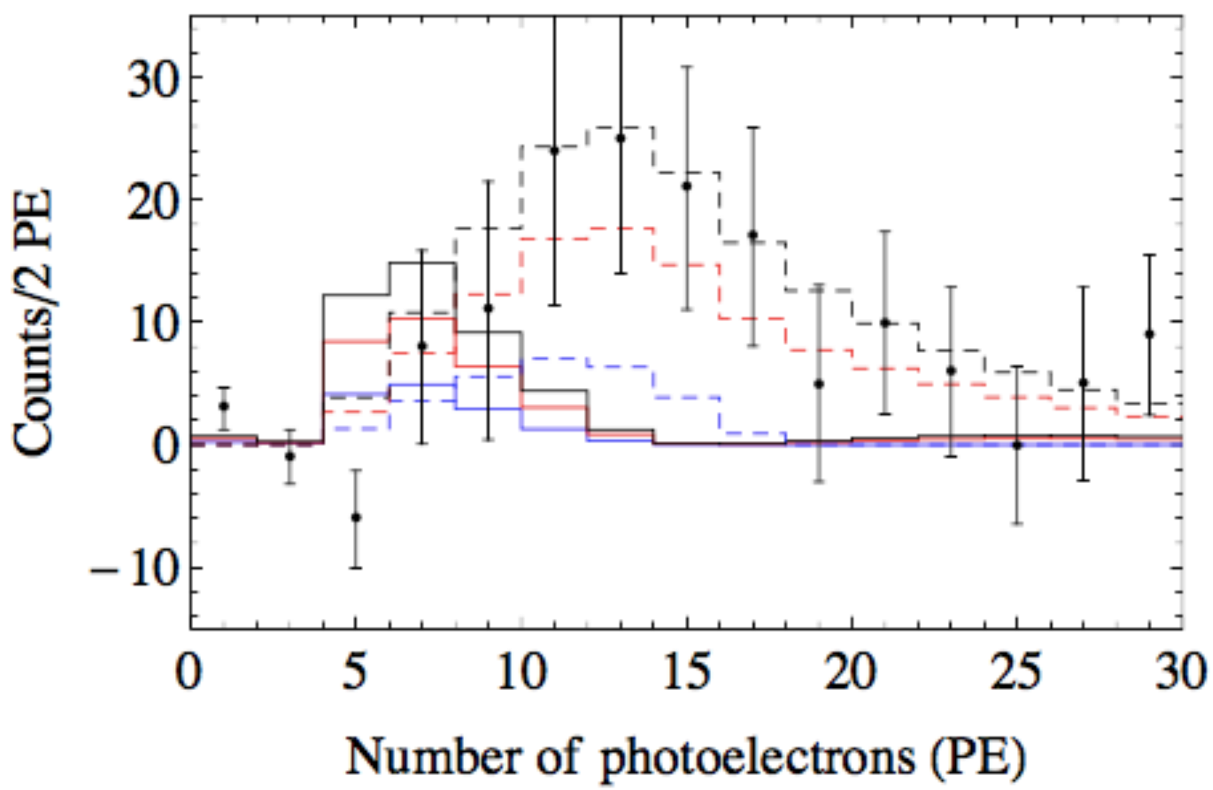
Implications for Non-Standard Neutrino Interactions

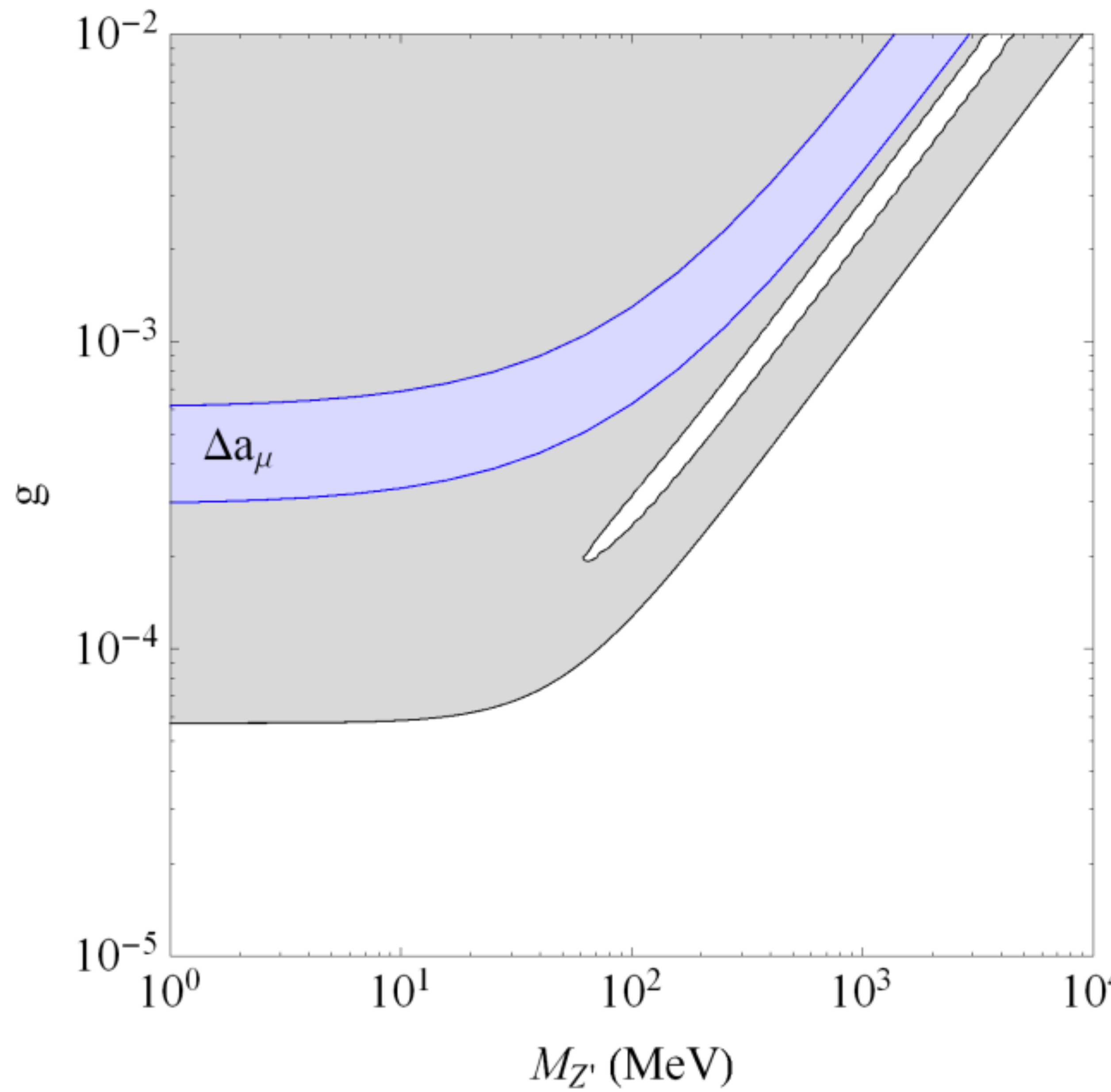
Current result already rules out (in combination with neutrino oscillation data) the Large Mixing Angle “Dark” solution. **Coloma et al, arXiv:1708.02899v1**



Implications for Non-Standard Neutrino Interactions

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

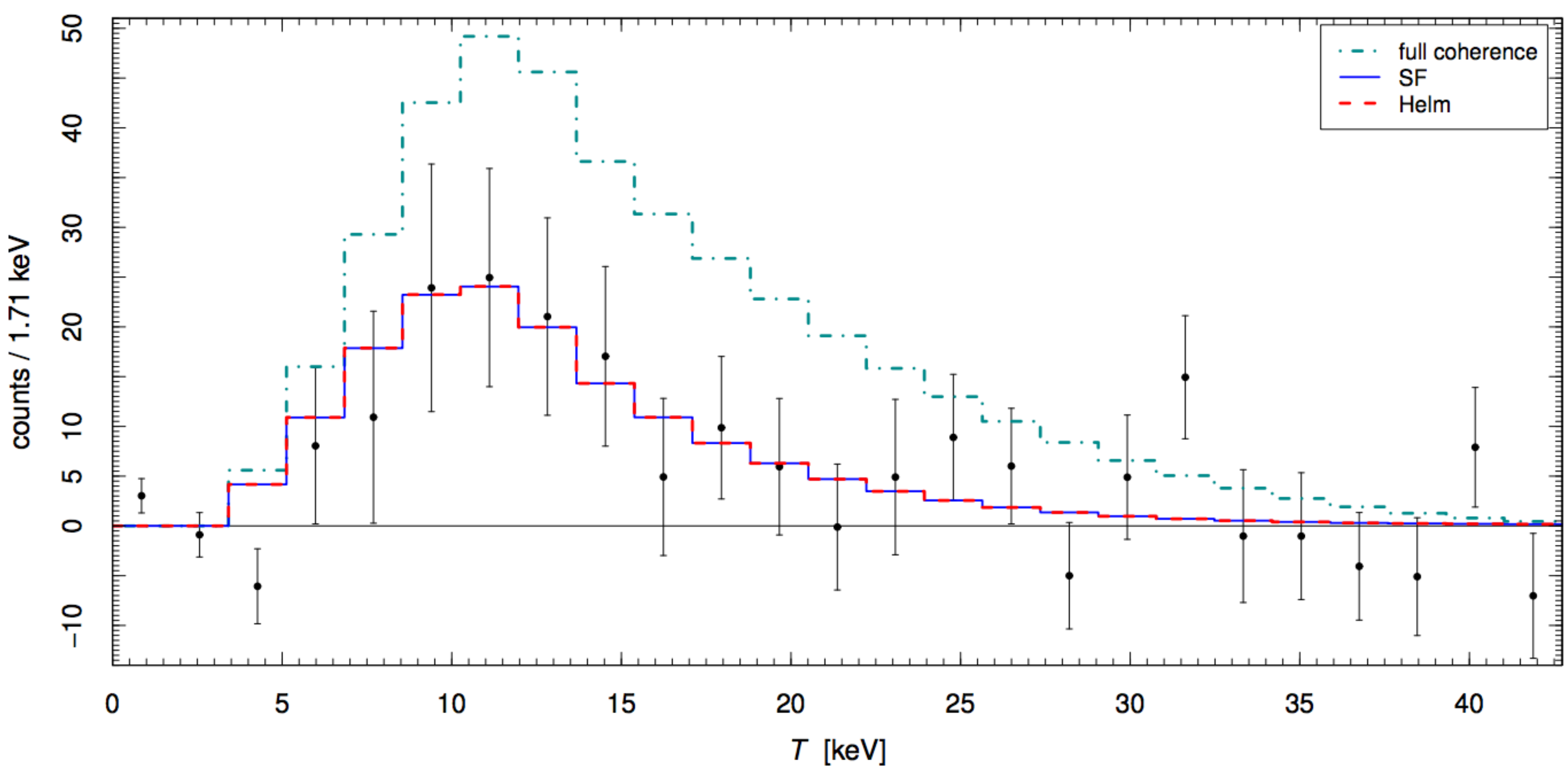




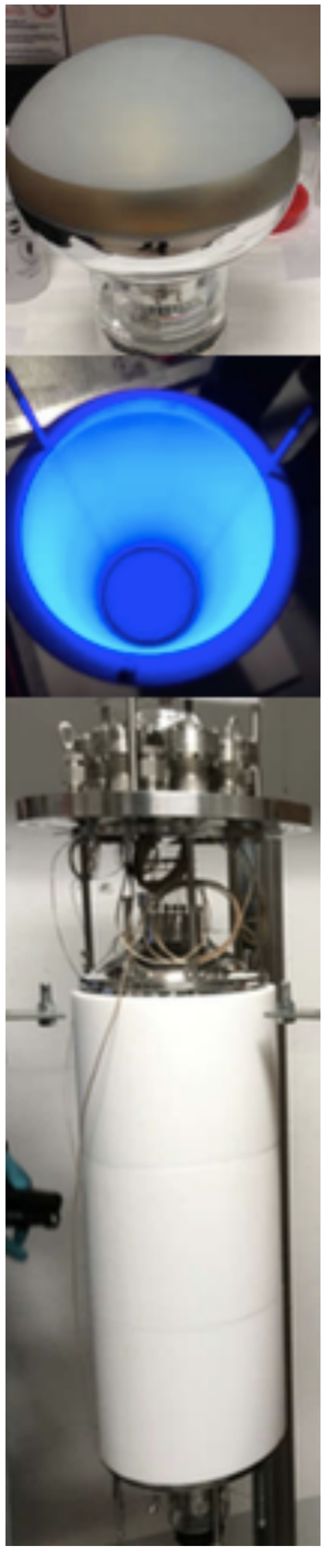
Implications Neutron Density Distribution?

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**

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

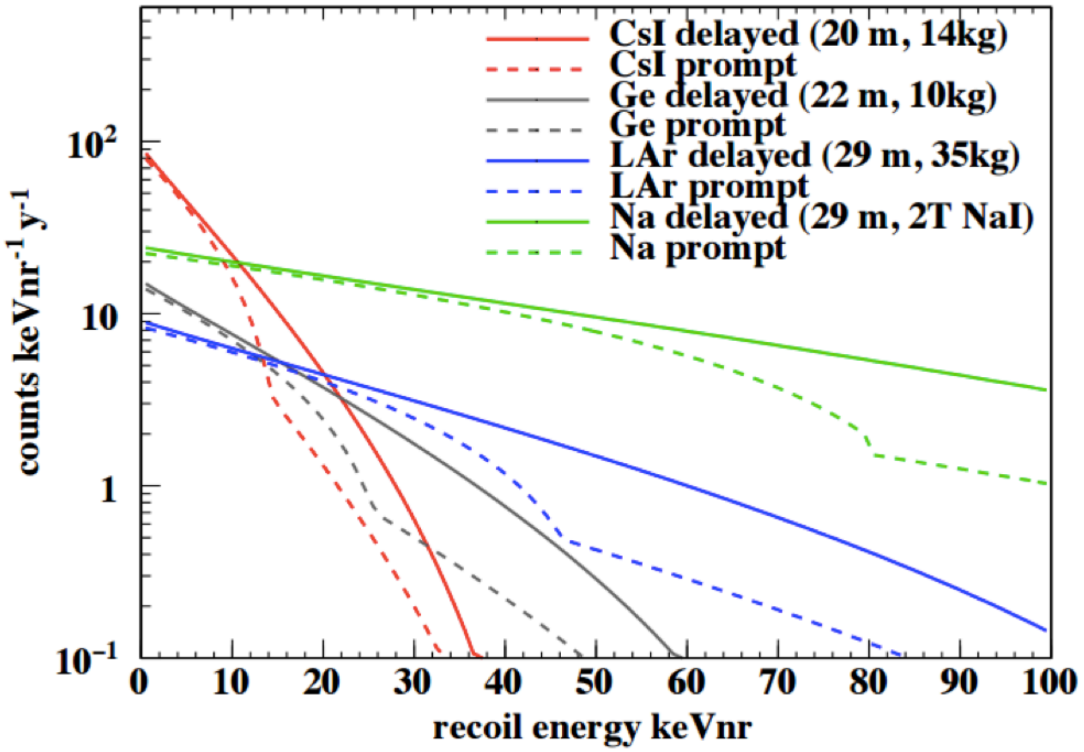


More COHERENT Detectors



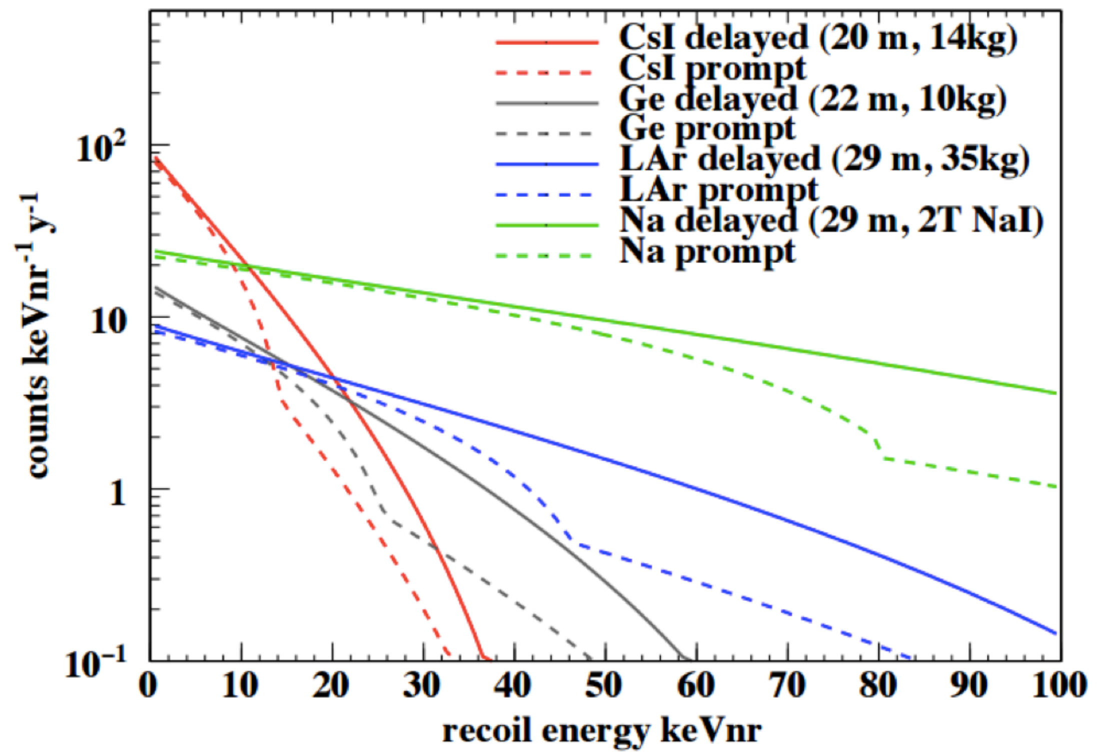
- A 22 kg liquid argon, single-phase detector is currently being commissioned at the SNS

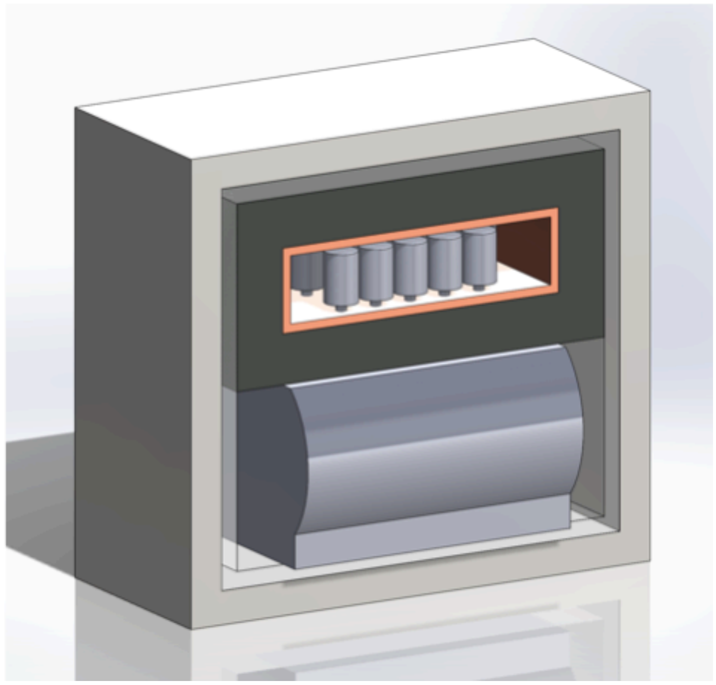
- ^{40}Ar nucleus is even-even and so can be used to help normalize the neutrino flux

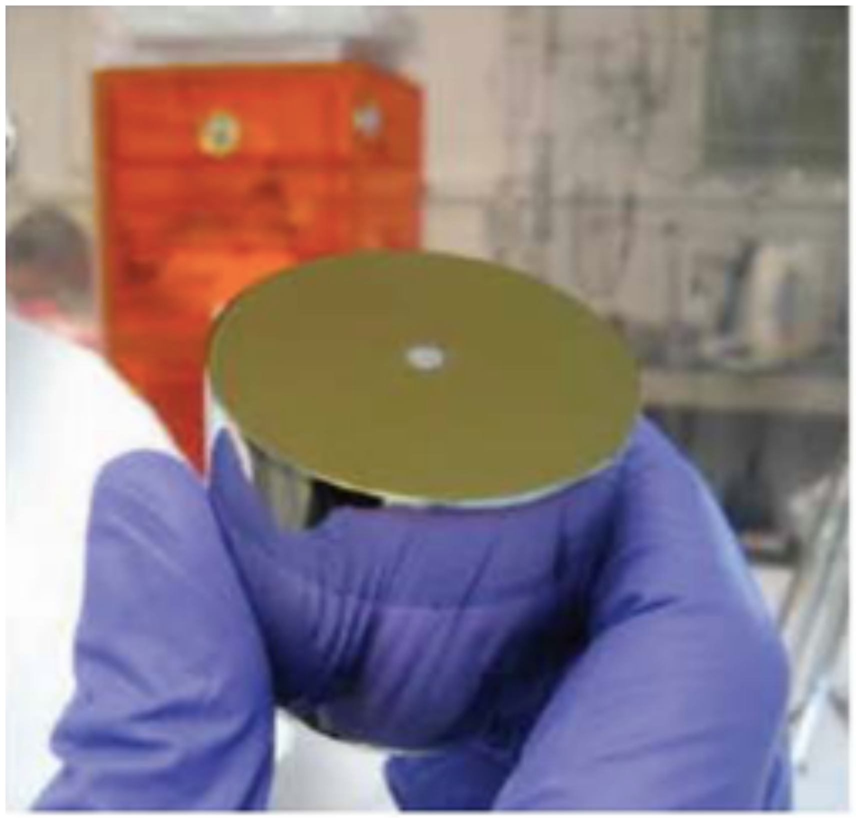


More COHERENT Detectors

- 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



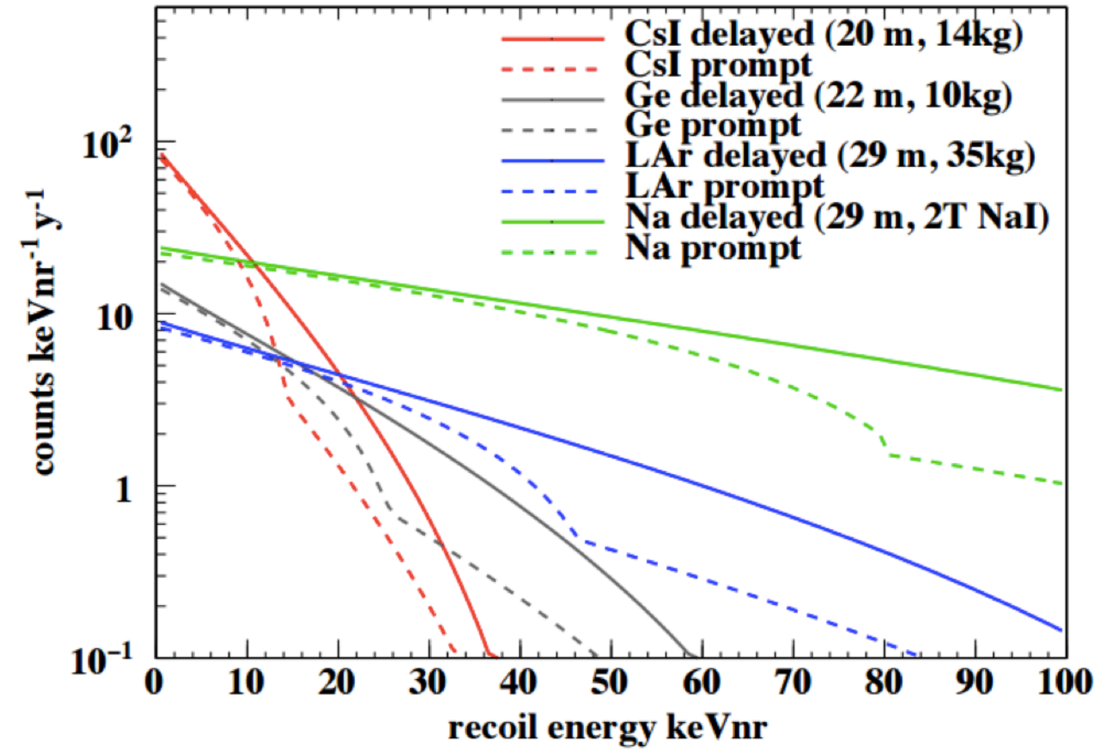


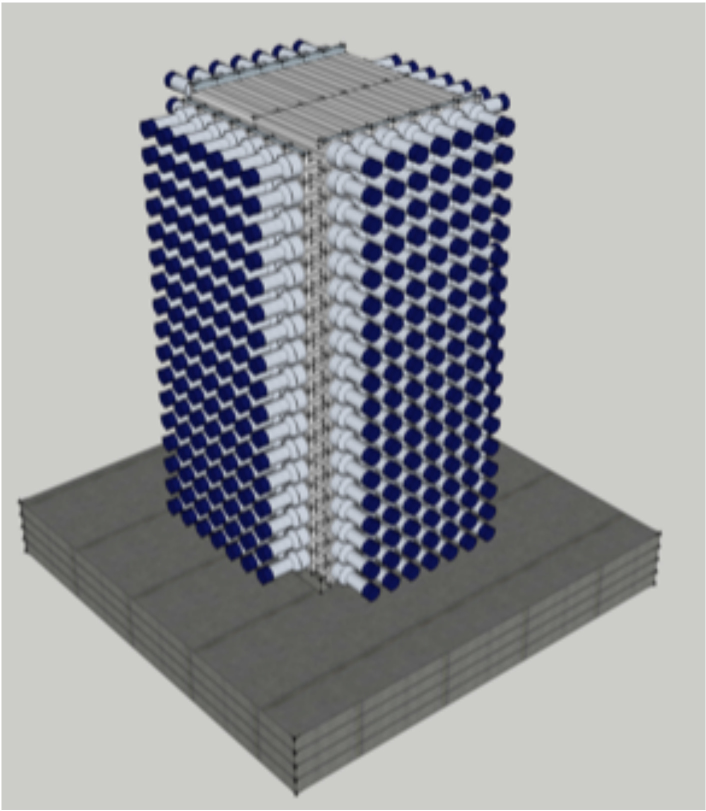


More COHERENT Detectors

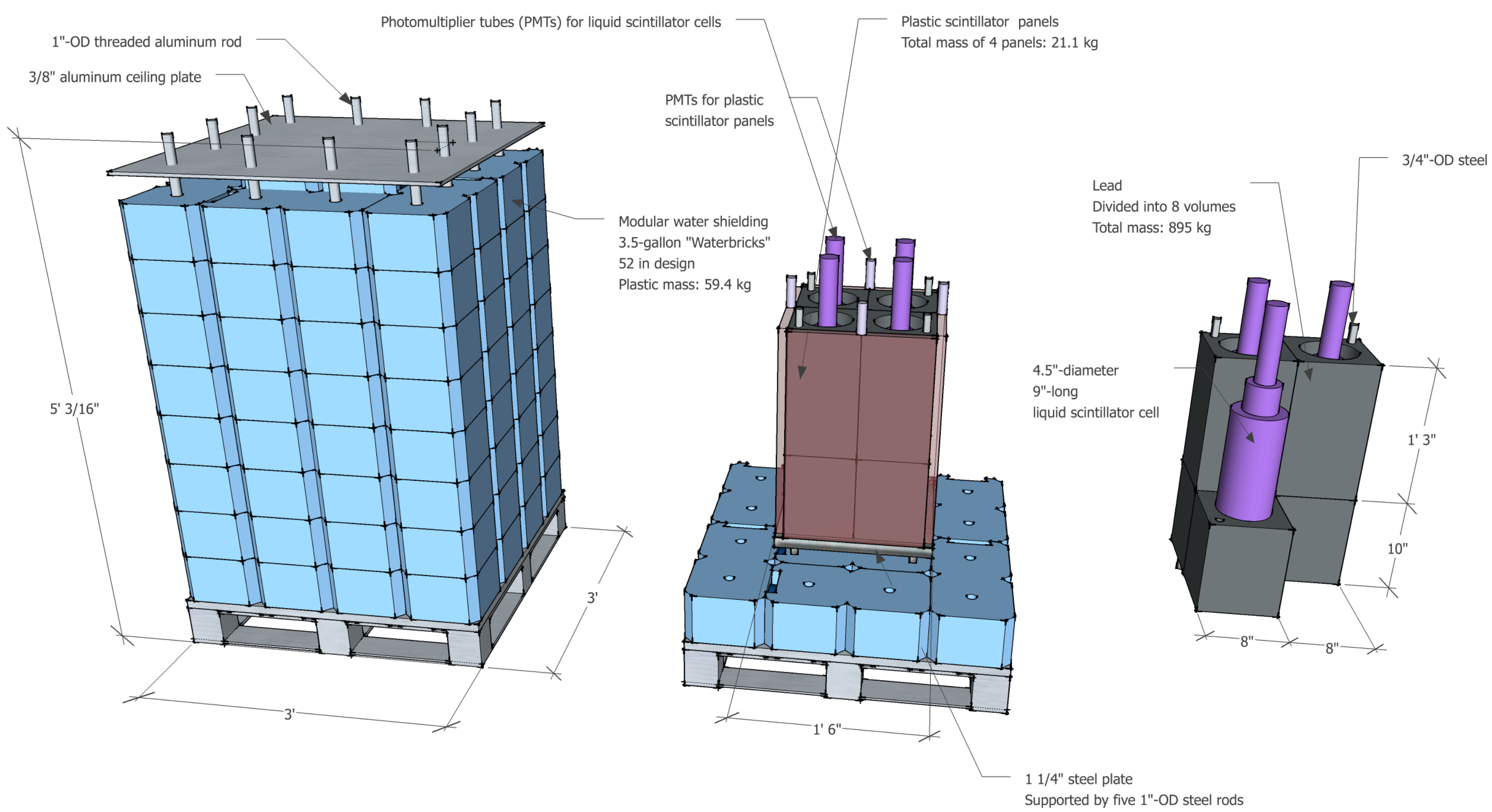
- A 185 kg NaI[Tl] array has been deployed to search for the ^{127}I charged-current reaction (important for understanding g_A renormalization with implications for neutrinoless double beta decay)

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





More in-COHERENT Detectors

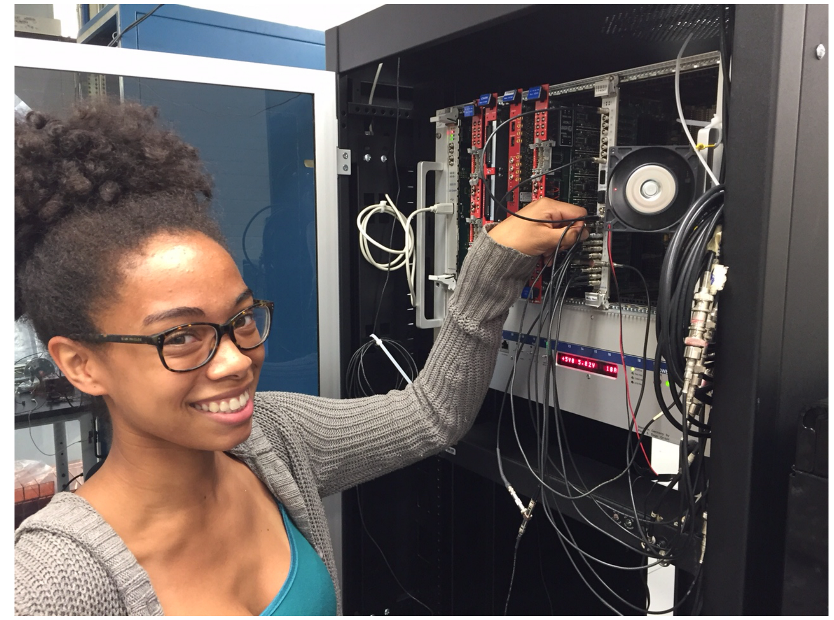


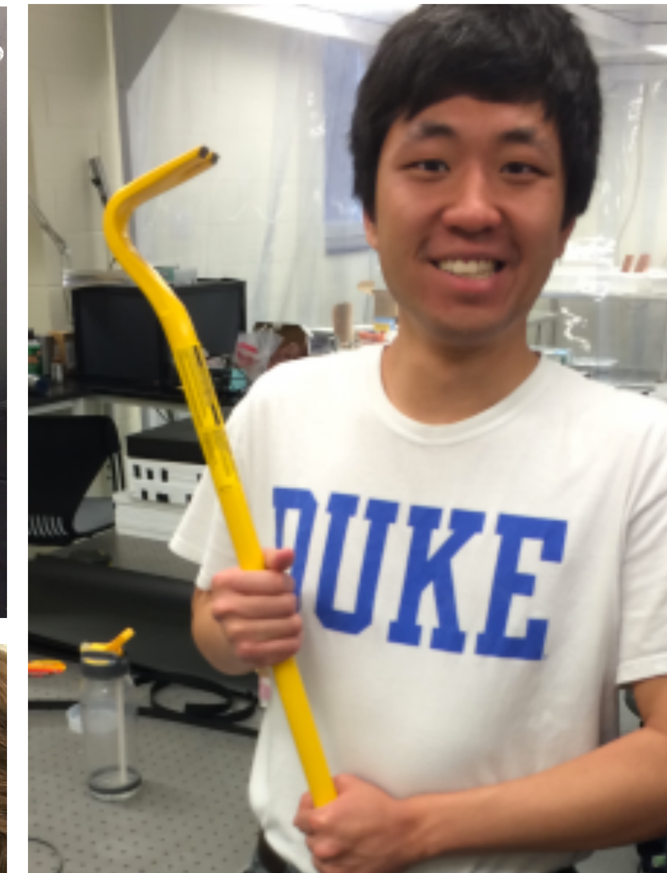
- Several palletized (mobile) targets with LS detectors delivered to the SNS
- Will measure neutrino-induced-neutrons on Pb (r-process nucleosynthesis & nuclear structure)
- and Fe (nuclear structure & SN shock revival)

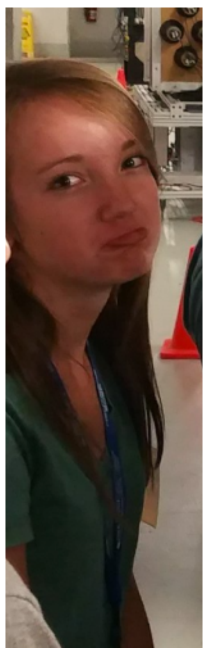
Where Do We Go From Here?

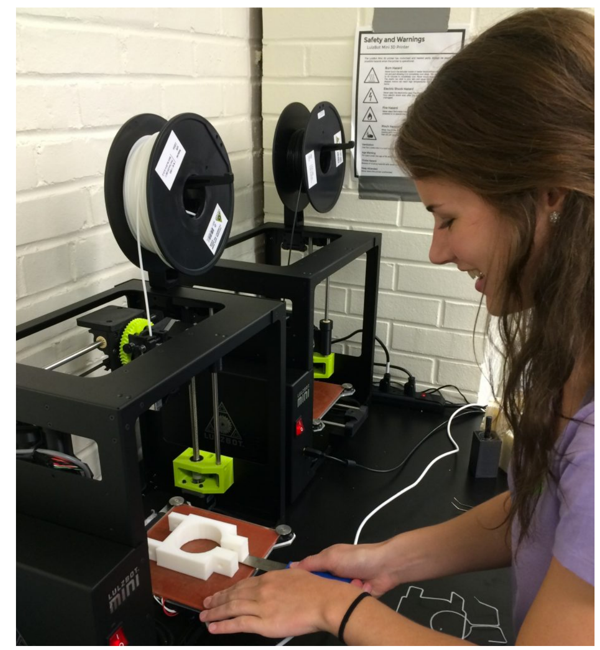
- More exposure for CsI[Na] detector & better QF errors
- A number of COHERENT detectors are now online (LAr, NaI[Tl]-185 kg, MARs neutron detector) with PPC HPGe coming soon and ton-scale NaI being designed!
- Neutrino Facility: This is a rich neutrino physics program for non-CEvNS cross-sections including CC cross-sections on ^{127}I, ^{56}Fe and ^{208}Pb
- We also look forward to a new era of miniaturized neutrino detector technology with several other collaborations coming on line soon (CONNIE, CONUS, MINER, RED, Ricochet, Nu-cleus)

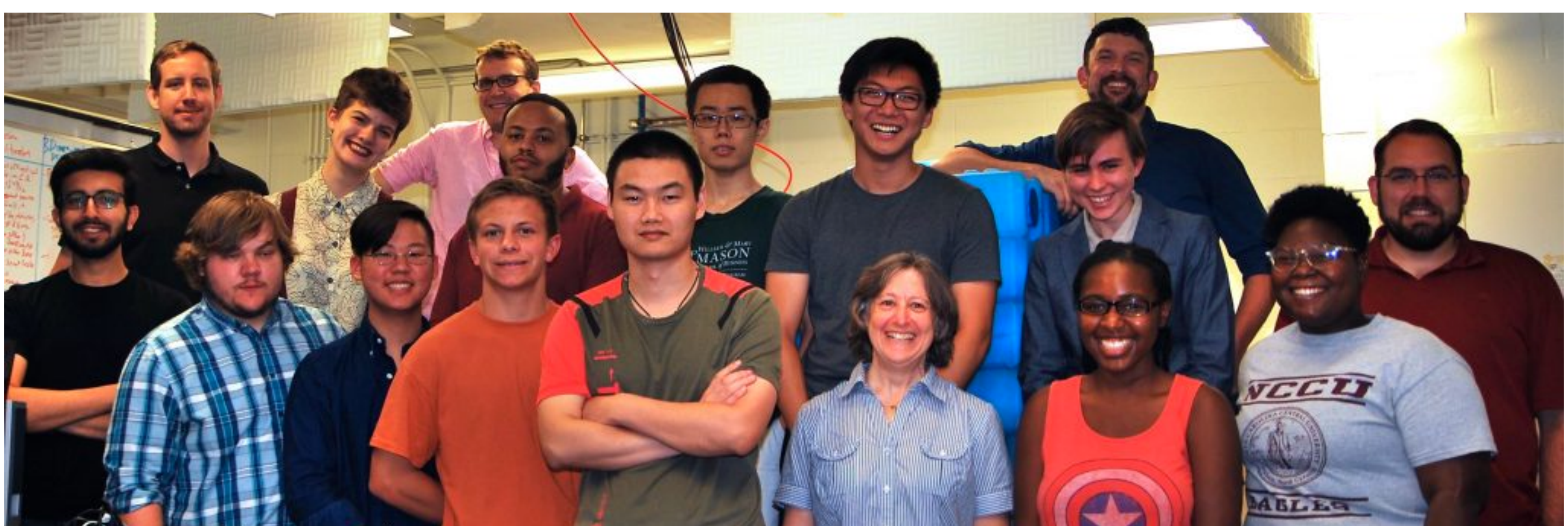
Thank you

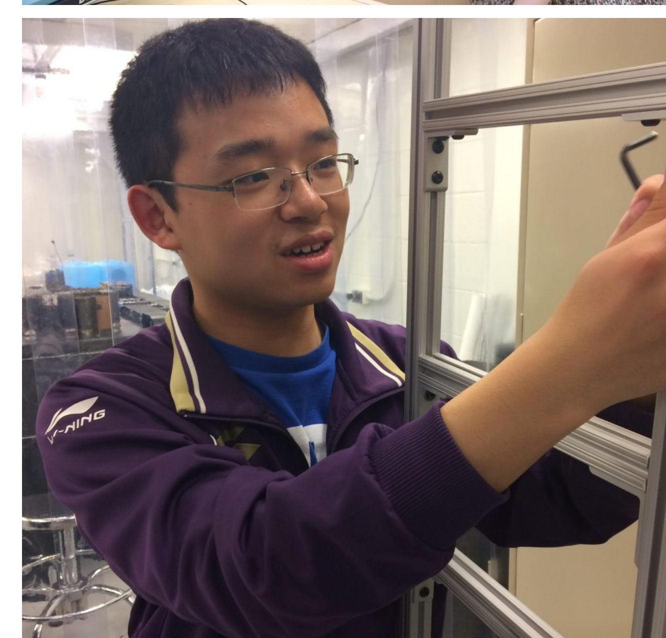






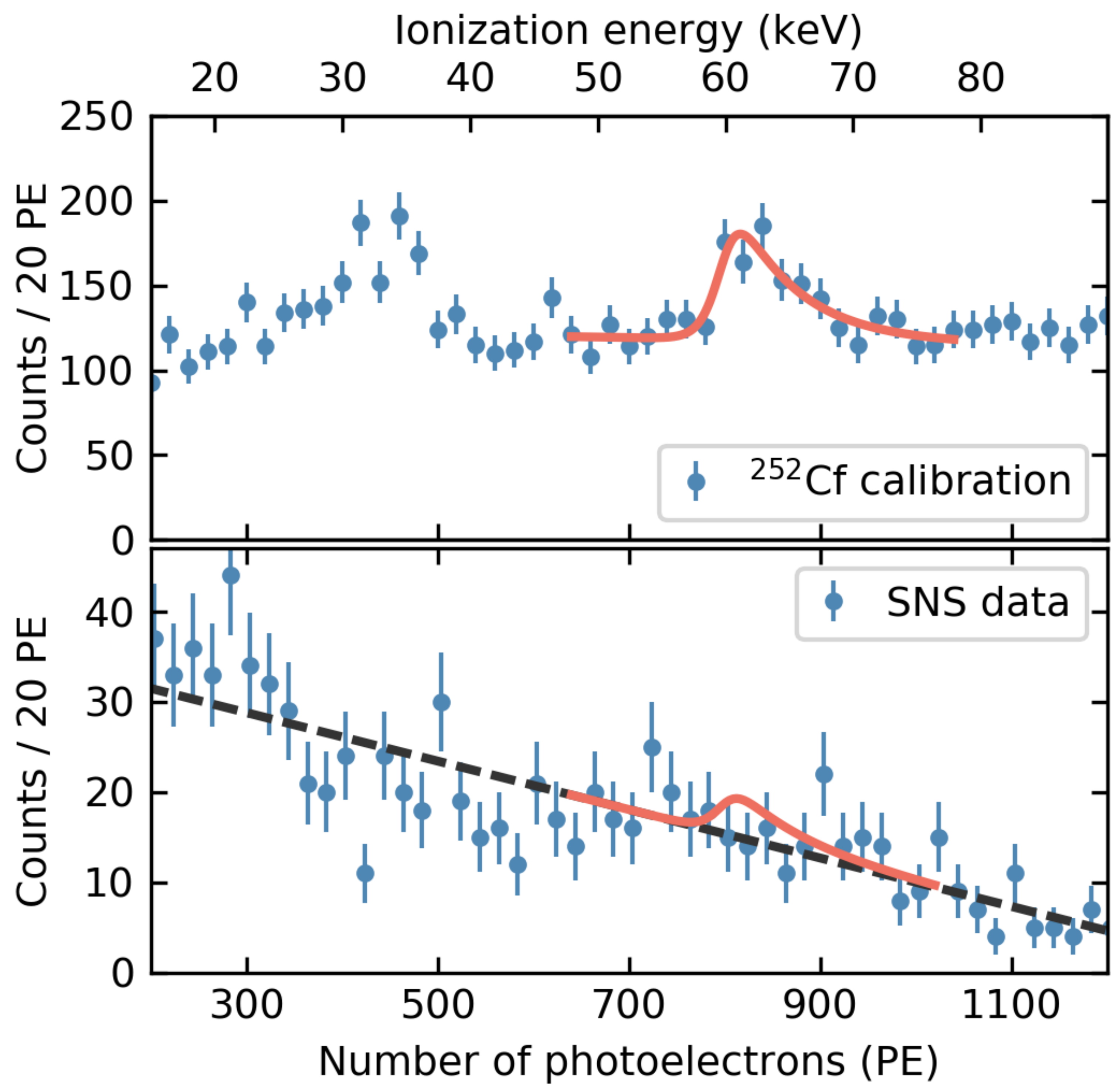






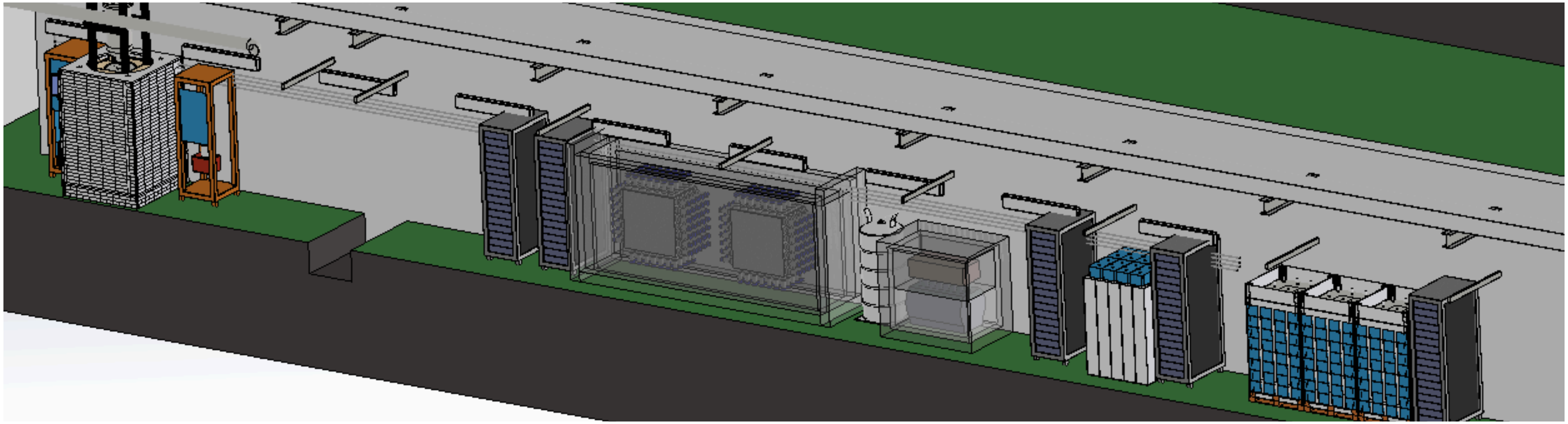
Inelastic Neutron Measurement

Inelastic neutron scattering lines in Cs serve as an in-situ measurement and confirmation of the neutron flux that the crystal is exposed to



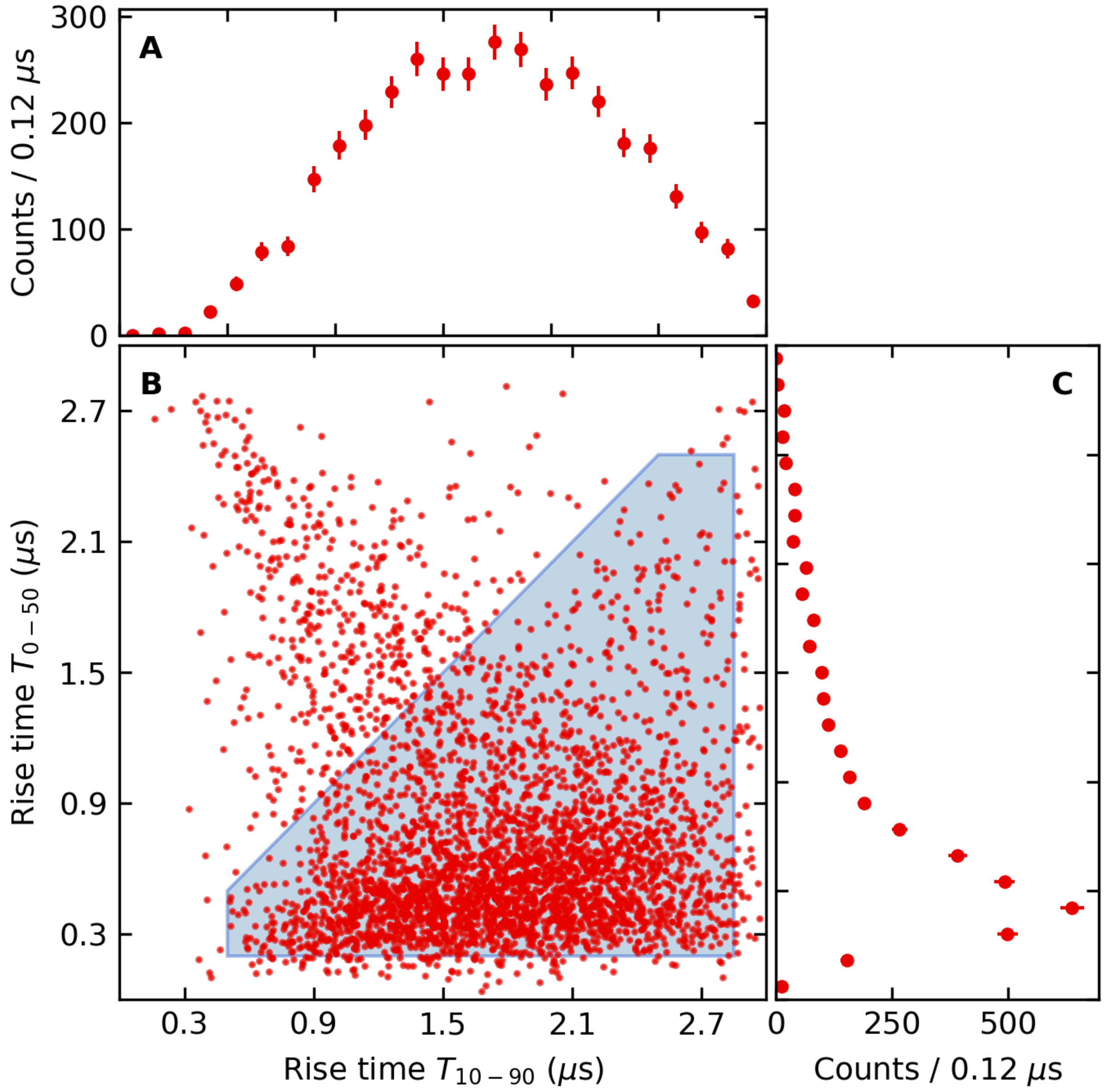
COHERENT CEvNS Detectors

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

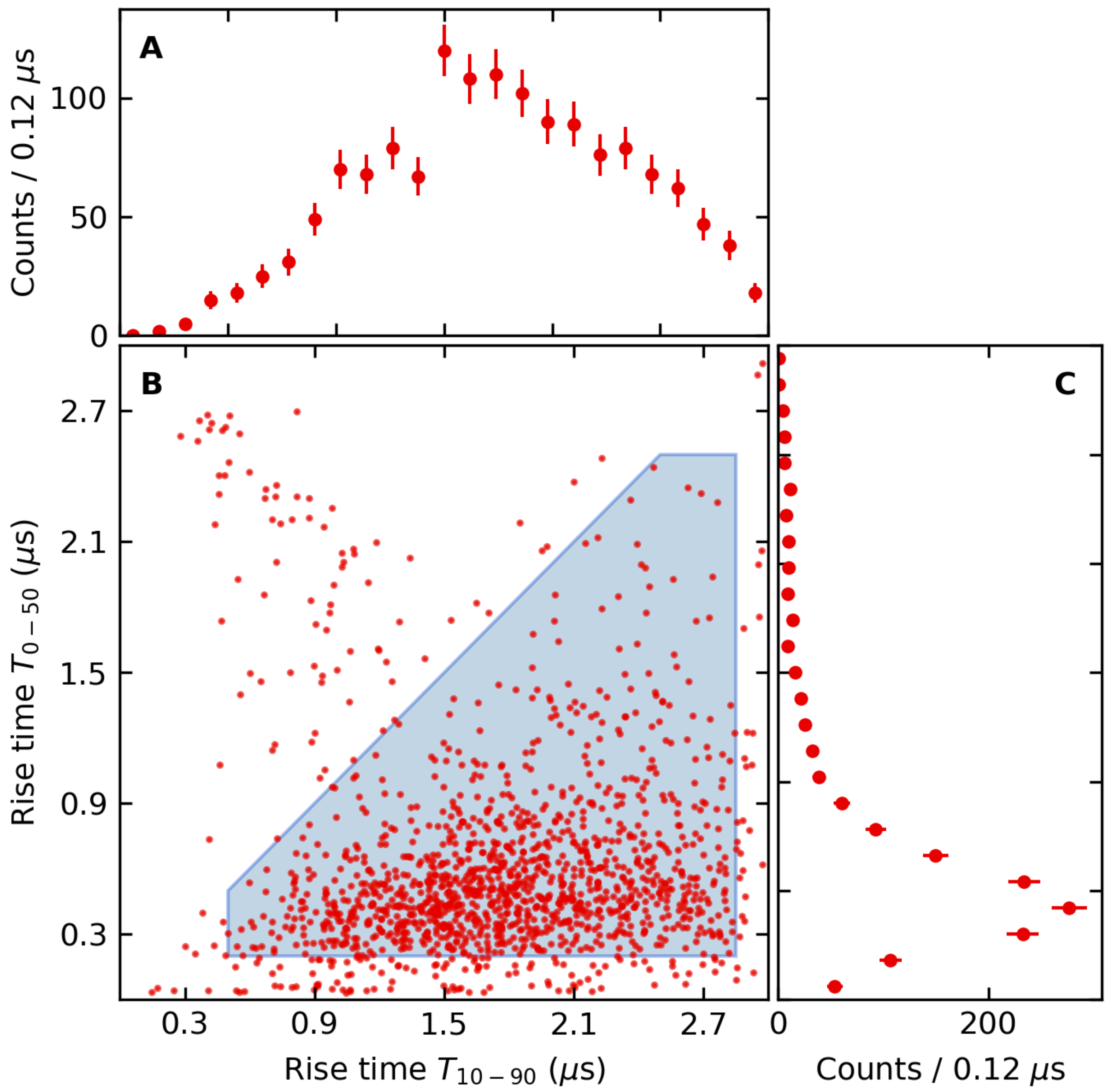


Risetime Cuts

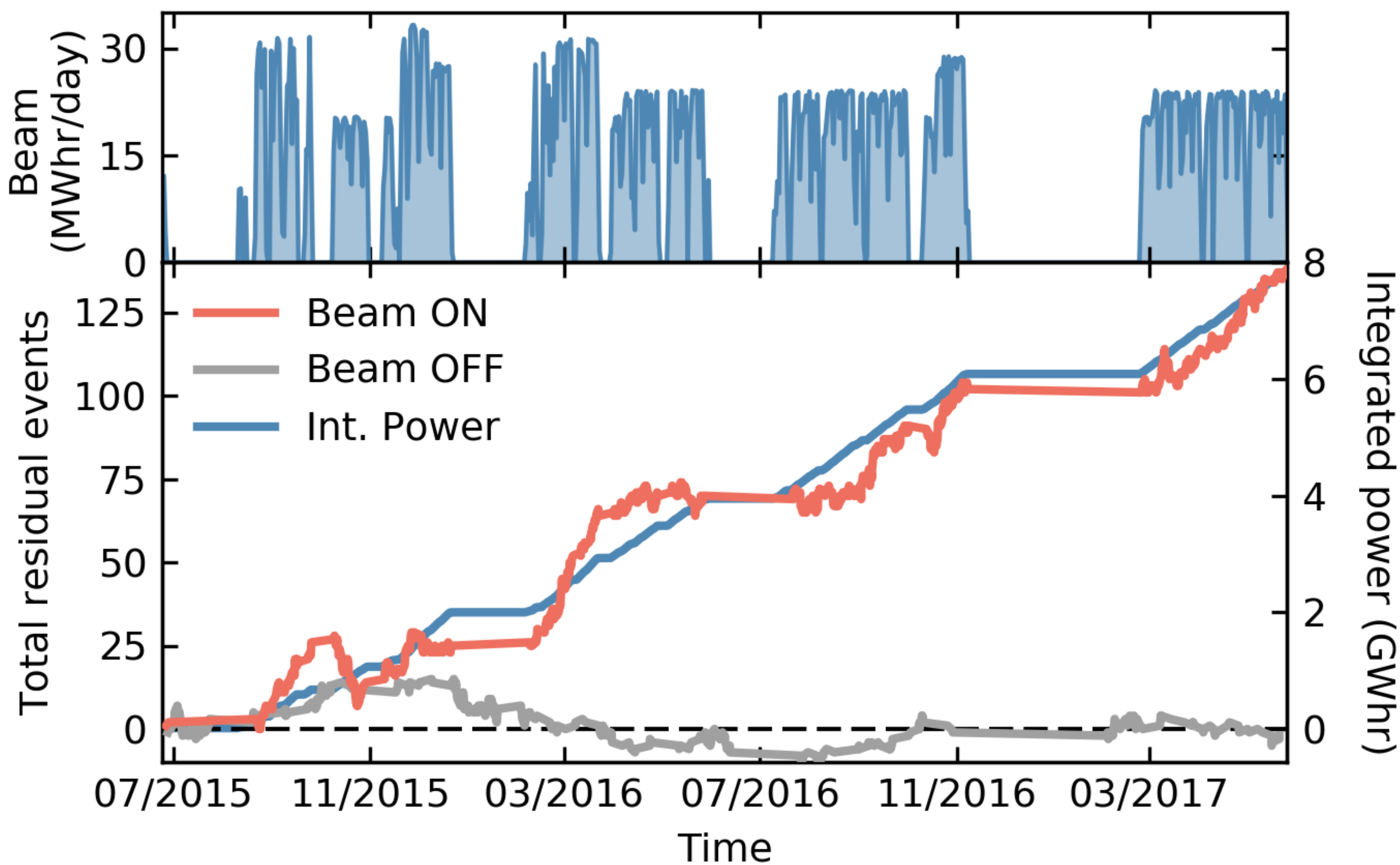
Ba Calibration data



SNS data

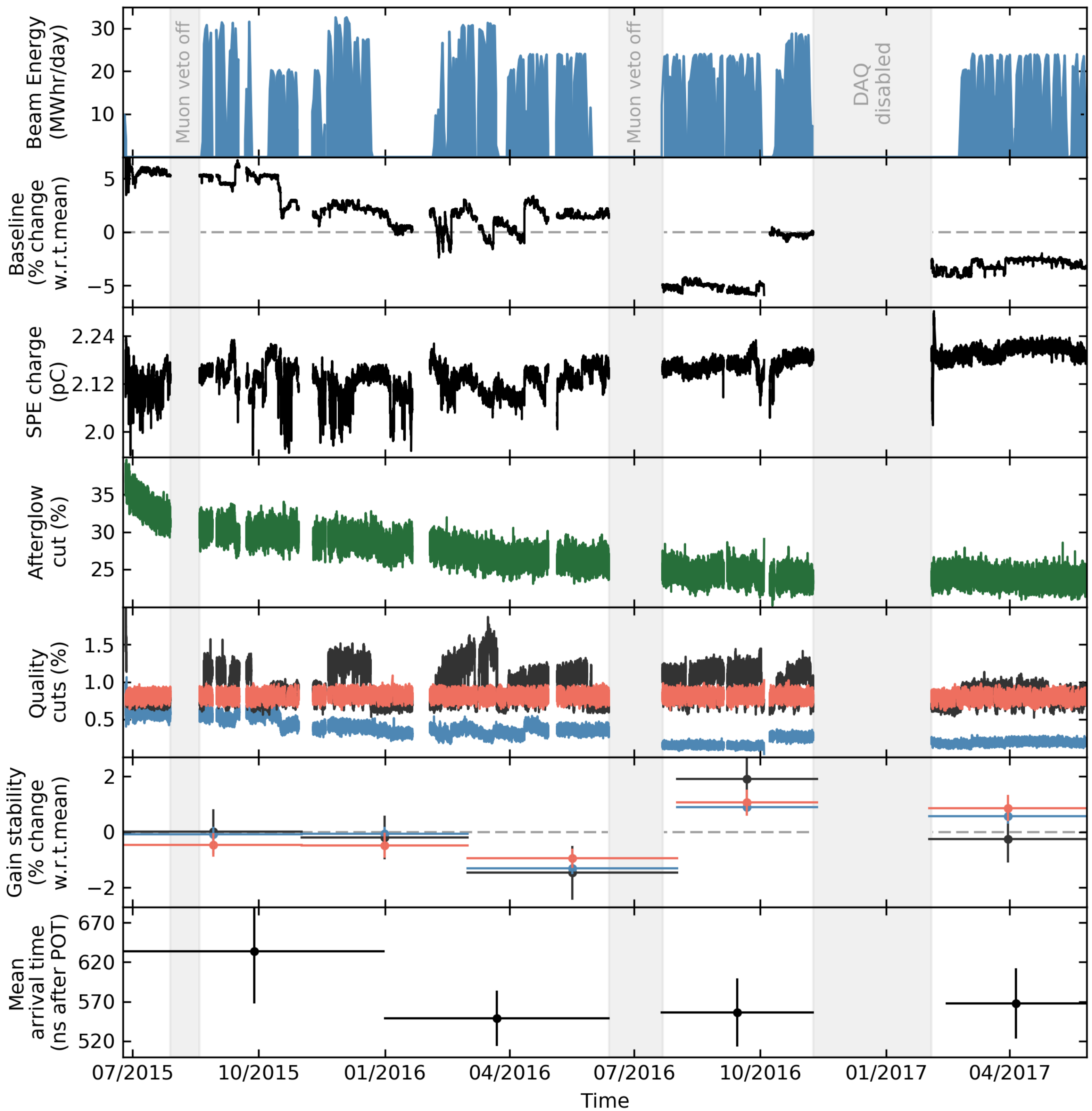


K-S Tests



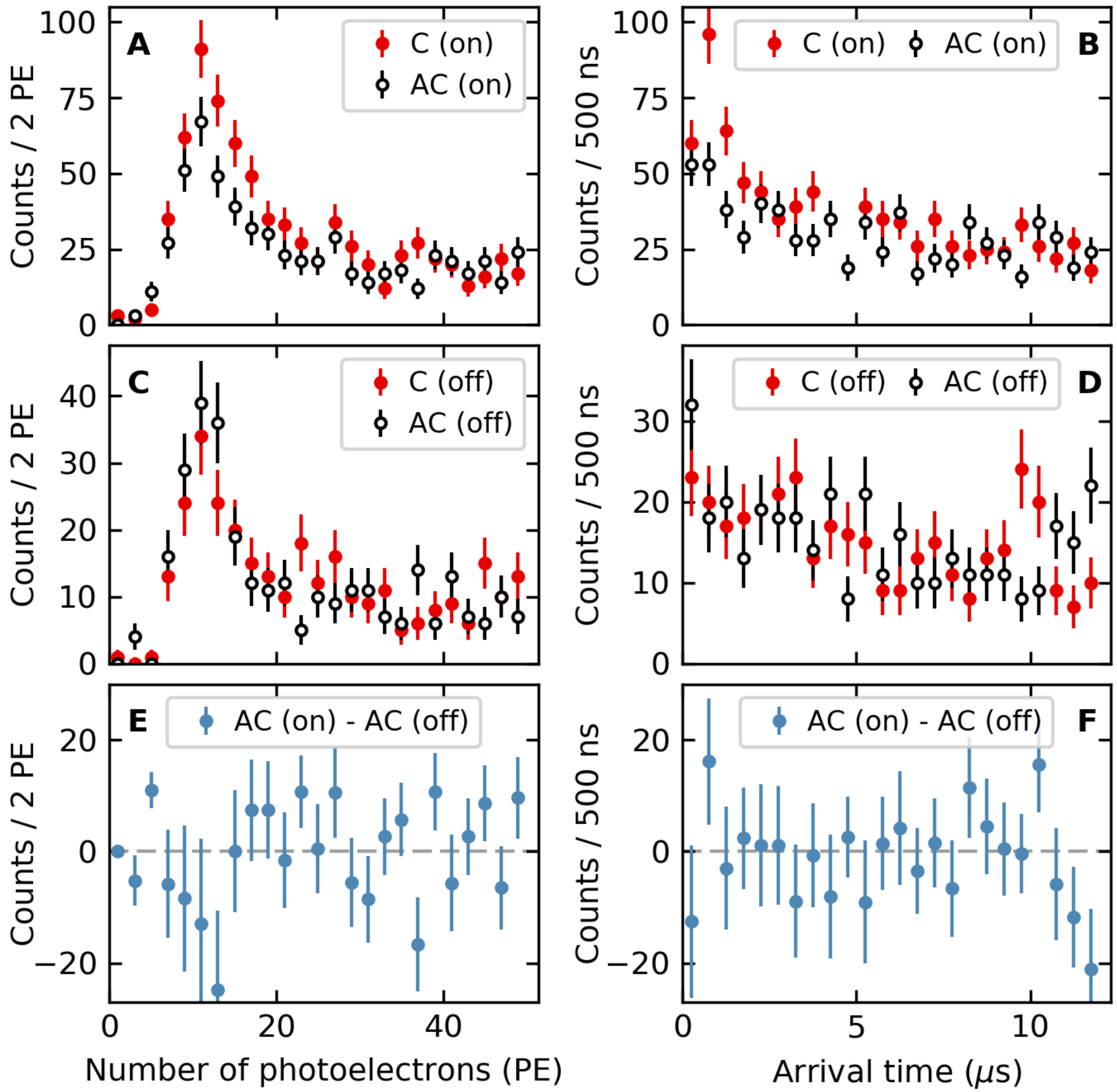
Beam (MWhr/day)
30
15
0
Total residual events
125
100
75
50
25
0
Beam ON
Beam OFF
Int. Power
Integrated power (GWhr)
8
6
4
2
0
07/2015
11/2015
03/2016
07/2016
11/2016
03/2017
Time

Stability



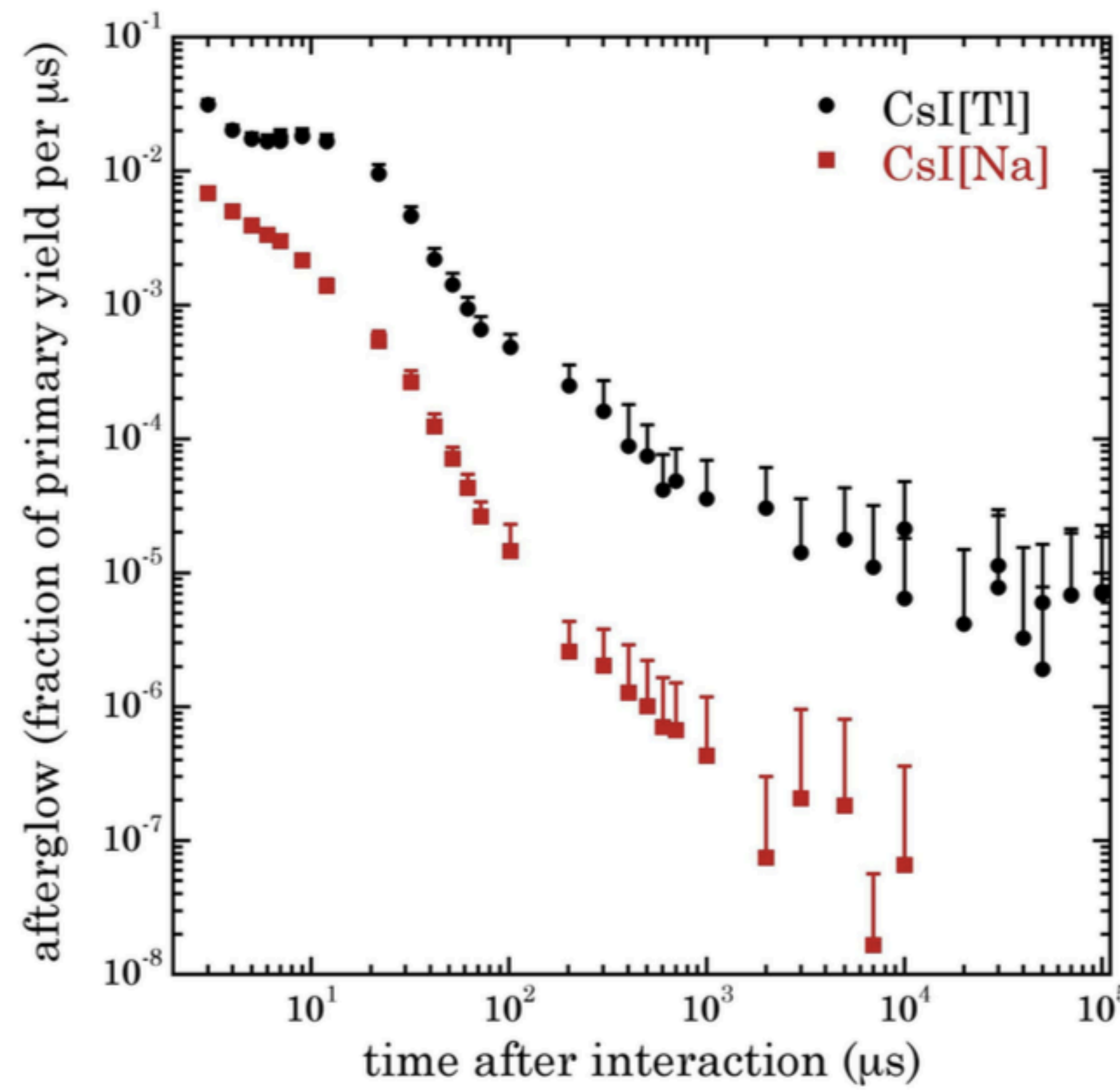
Beam Energy (MWhr/day)
30
20
10
Muon veto off
Muon veto off
DAQ disabled
Baseline (% change w.r.t.mean)
5
0
−5
SPE charge (pC)
2.24
2.12
2.0
Afterglow cut (%)
35
30
25
Quality cuts (%)
1.5
1.0
0.5
Gain stability (% change w.r.t.mean)
2
0
−2
Mean arrival time (ns after POT)
670
620
570
520
07/2015
10/2015
01/2016
04/2016
07/2016
10/2016
01/2017
04/2017
Time

Beam On/Off Spectra



Afterglow

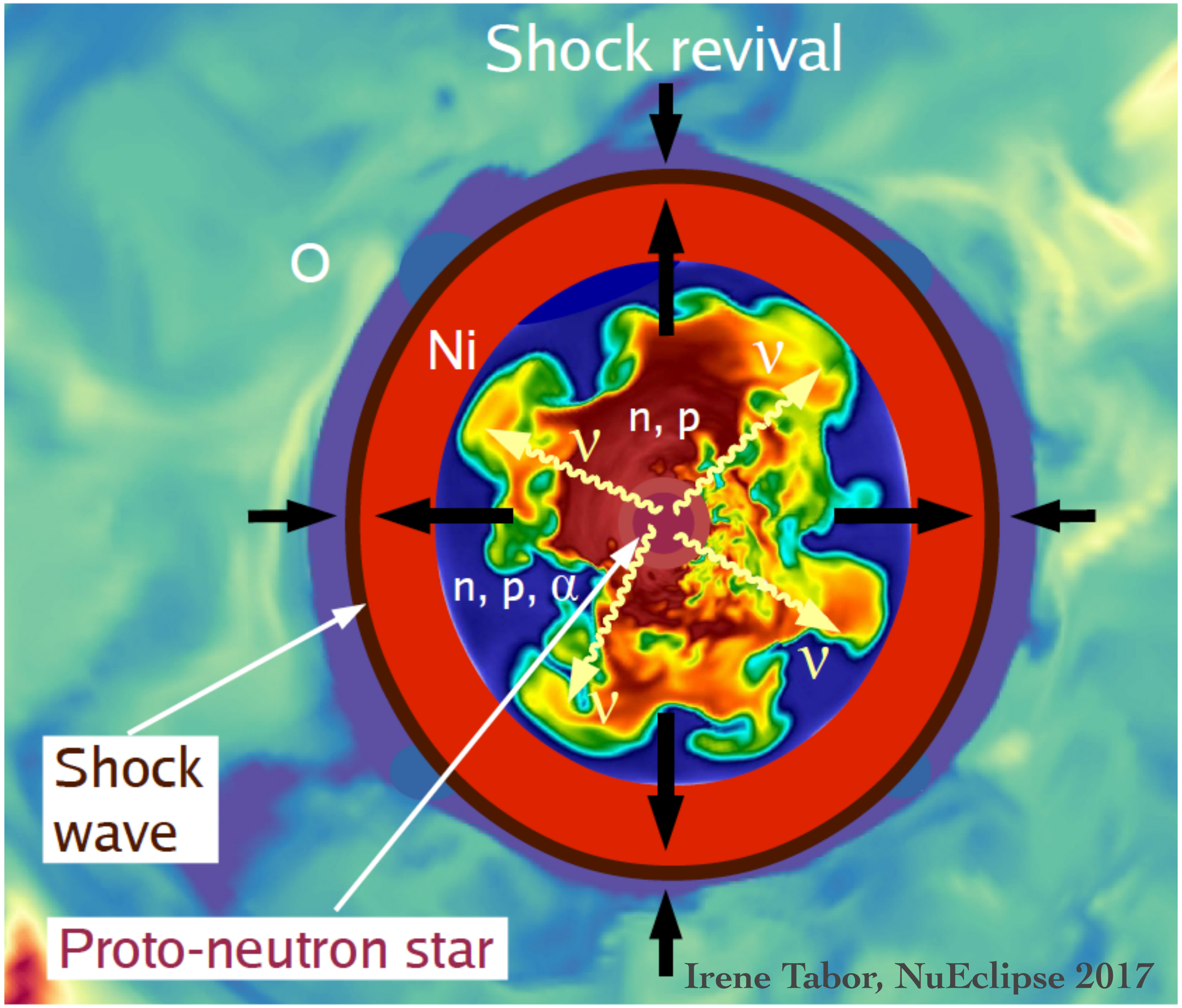
Cal[Na] scintillator was chosen because of it's high light yield, good overlap with PMT QE and low afterglow



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

Supernovas Don't Like to Explode

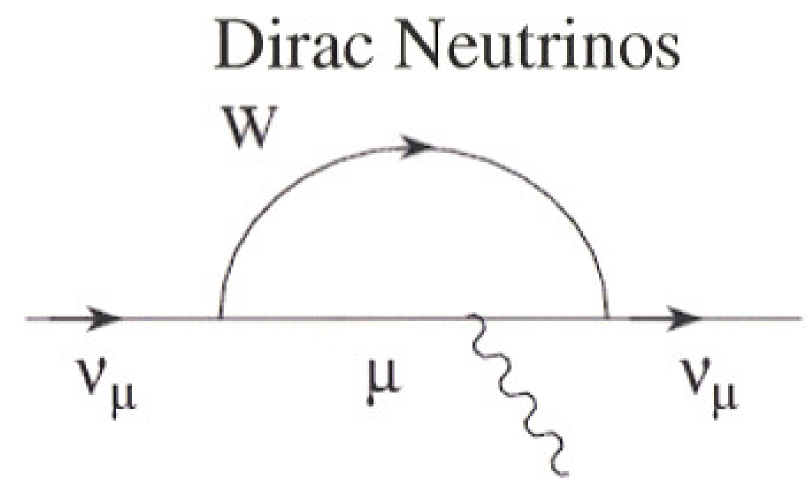
- Neutrinos carry 99% of the energy released (10^{53} ergs)
- CEvNS acts to reinvigorate stalled shock waves **J.R. Wilson, PRL 32 (74) 849**

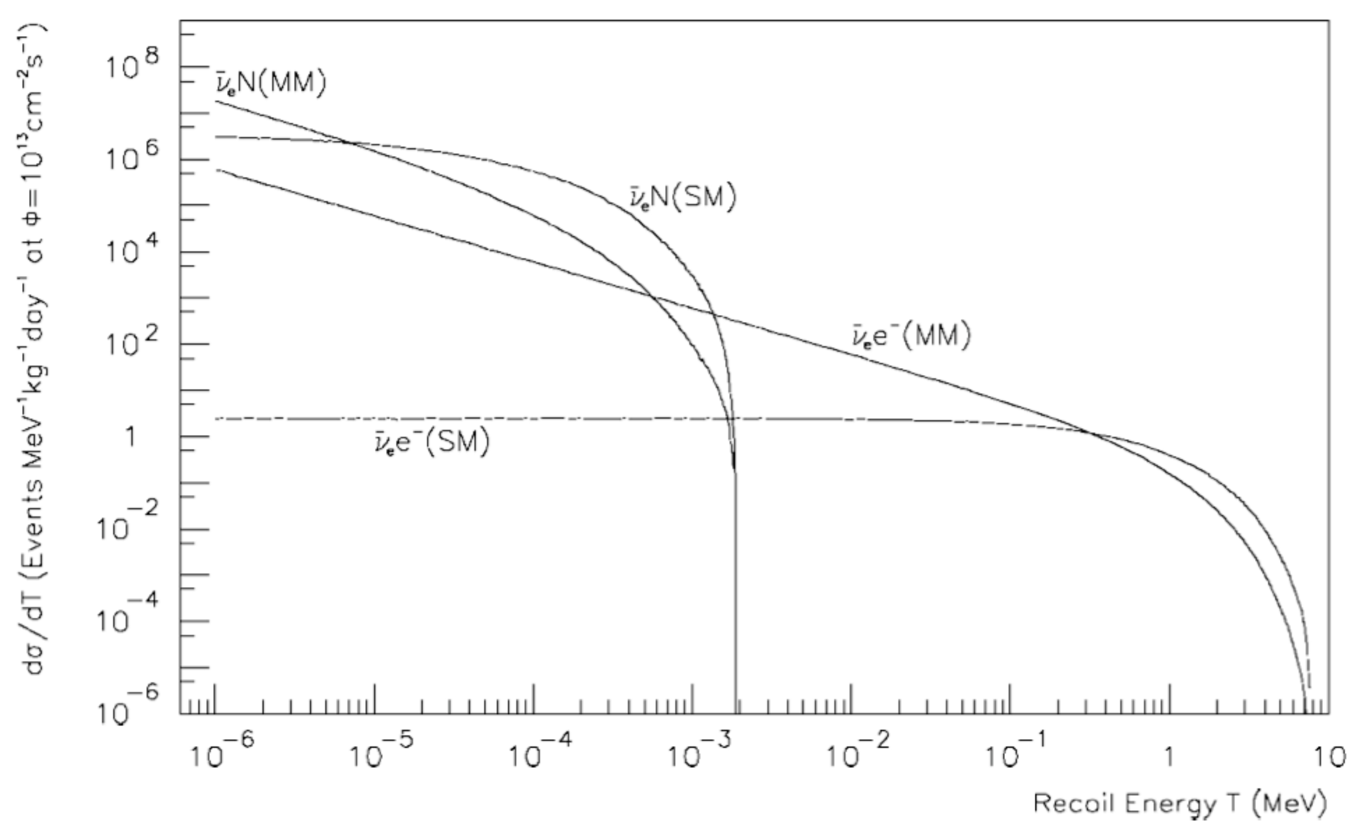


Electromagnetic Neutrino Interactions?

- 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





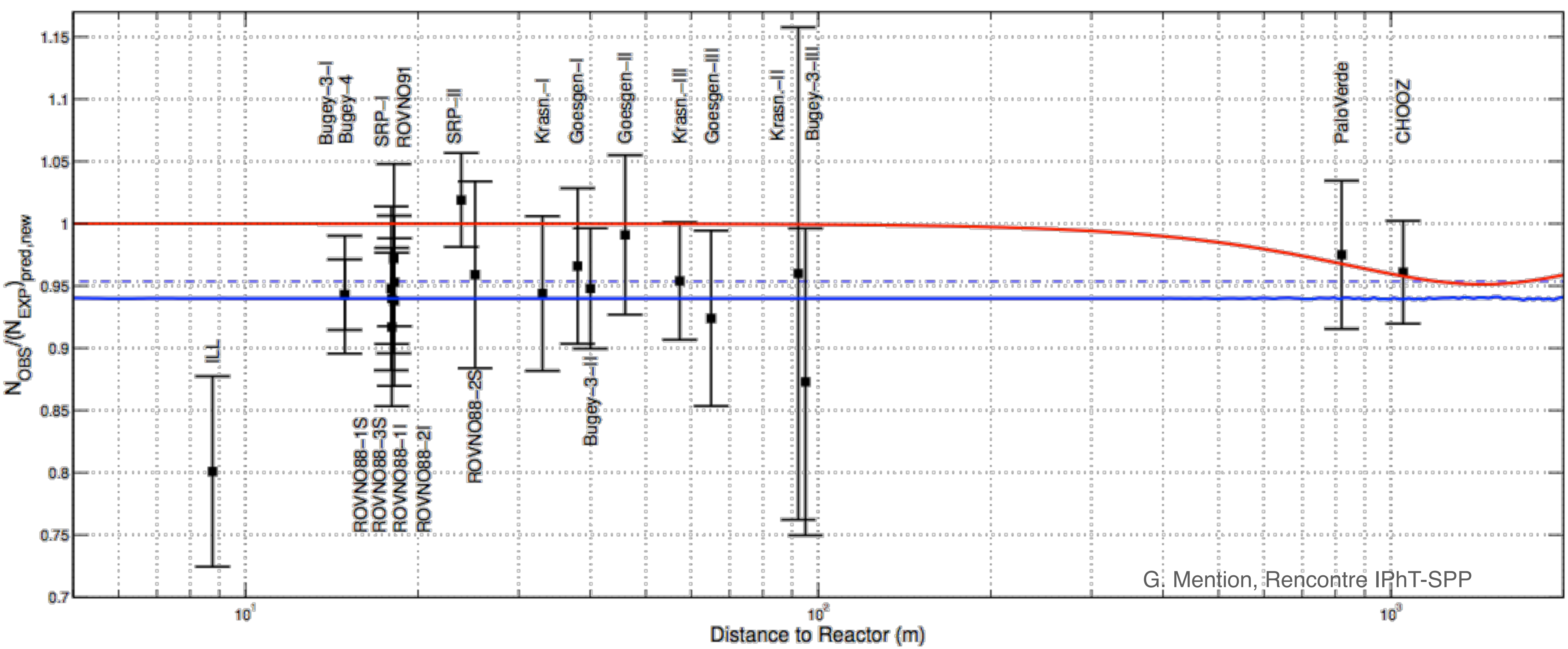
H. T. Wong and H.-B. Li. Mod. Phys. Lett., A20:1103–1117, 2005.

Searches for Sterile Neutrinos

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

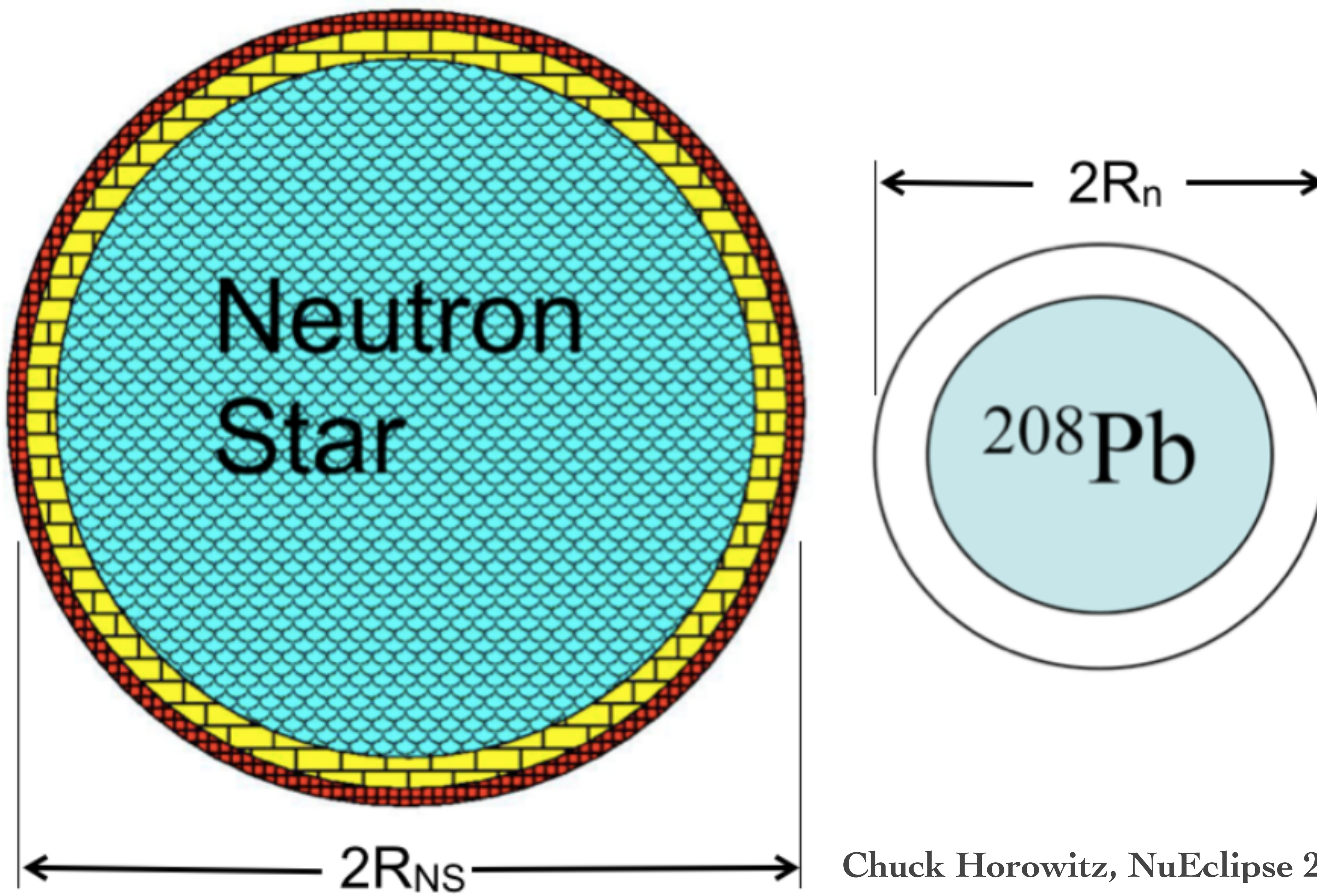
- CEvNS provides perhaps the best way to explore any sterile neutrino sector

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



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 $(g-2)_\mu$ 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