First Observation of Coherent Elastic Neutrino-Nucleus Scattering and continued efforts of the COHERENT Collaboration

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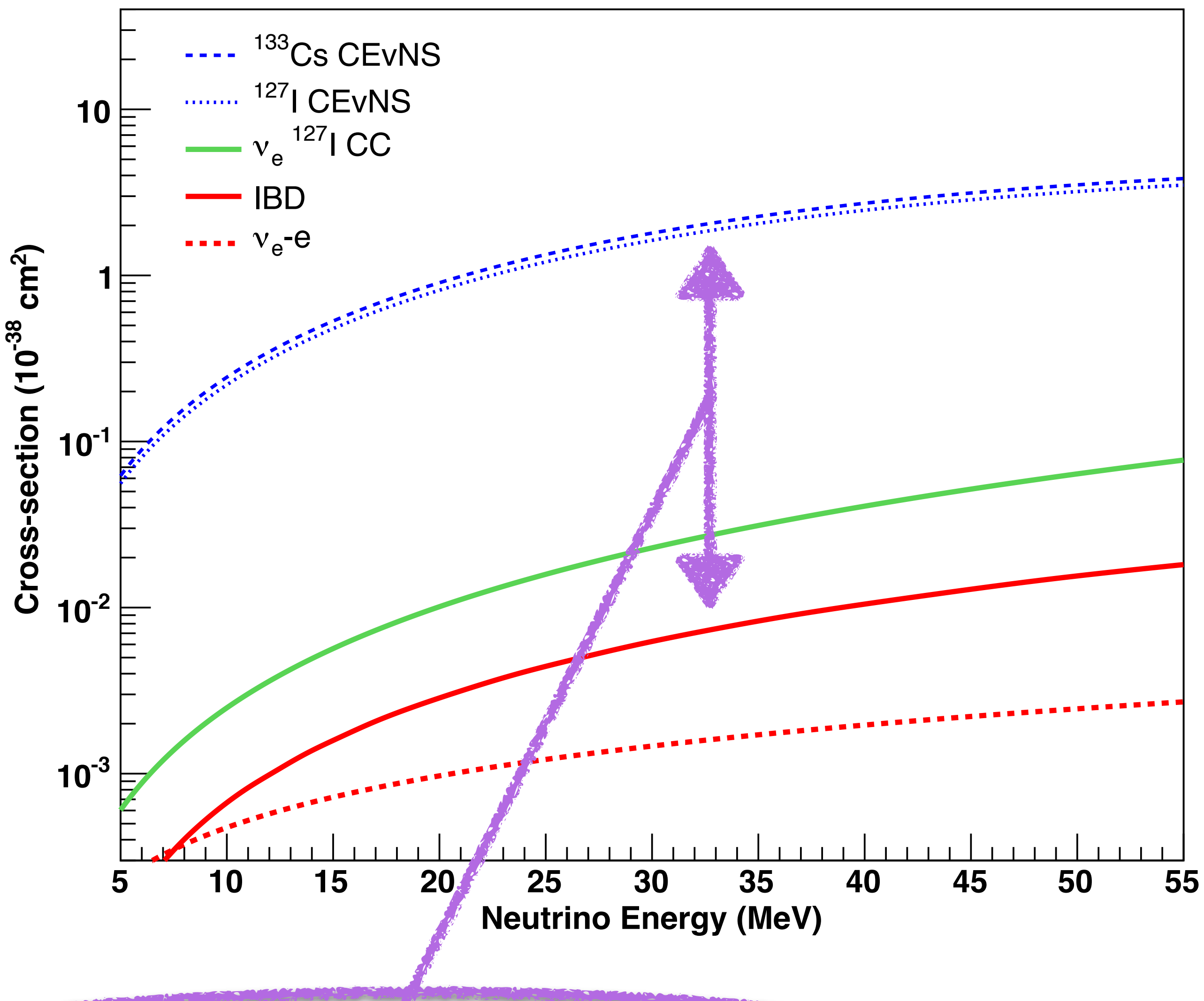
Kavli Institute for Cosmological Physics
AT THE UNIVERSITY OF CHICAGO

Coherent elastic neutrino-nucleus scattering (CEνNS)

- NC (flavor-independent) process postulated by D.Z. Freedman [1] / Kopeliovich & Frankfurt [2] in 1974

- In a CEνNS interaction, a neutrino scatters off of a nucleus whose nucleons recoil *in phase*, resulting in an enhanced cross section; total cross section scales approximately like N^2

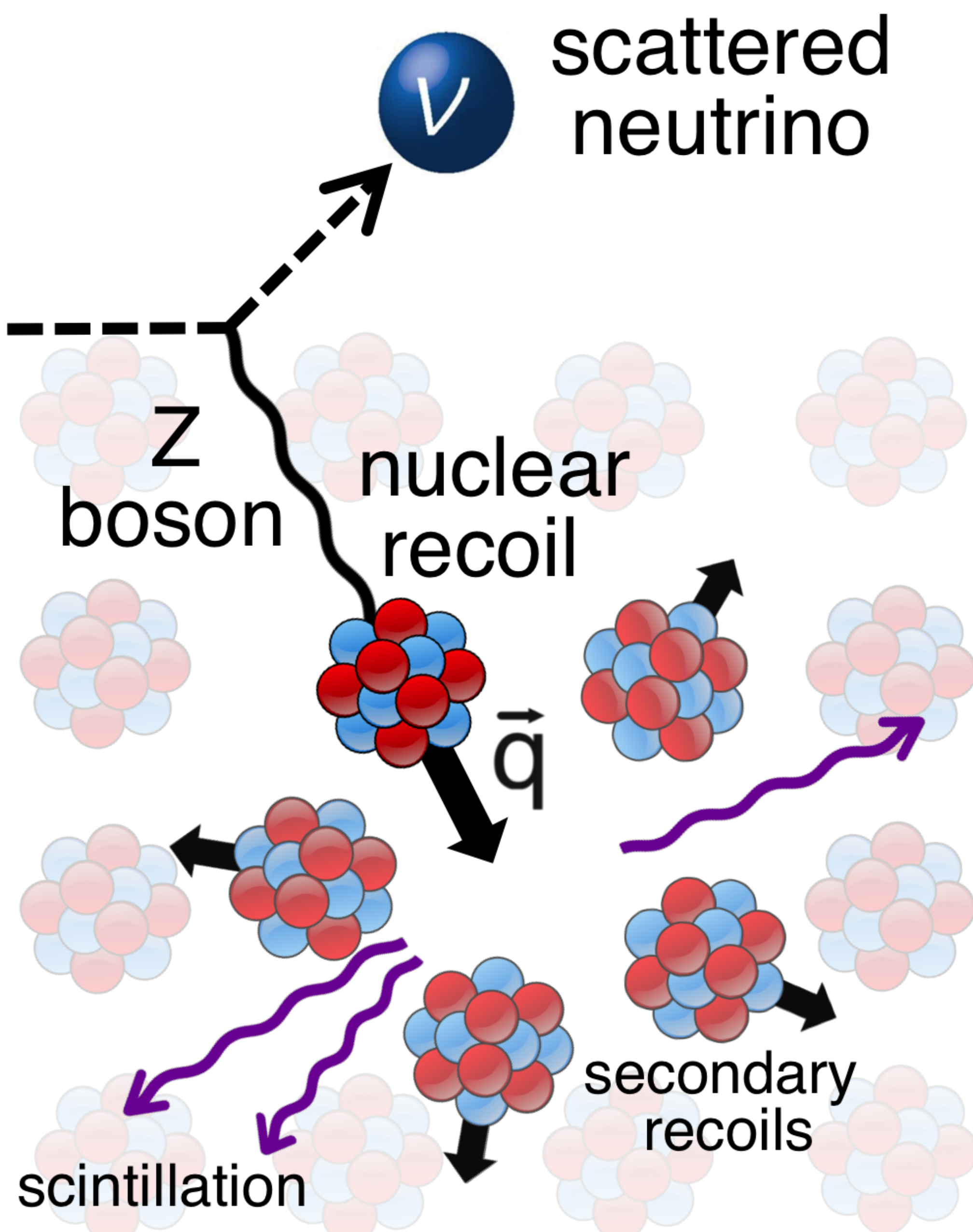
$$\sigma \approx \frac{G_F^2 N^2}{4\pi} E_\nu^2$$



Cross section can be orders of magnitude larger than IBD process used to first observe neutrinos!

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

"An act of hubris"



Freedman [1] noted that several factors combine to make CEνNS an exceptionally challenging process to observe

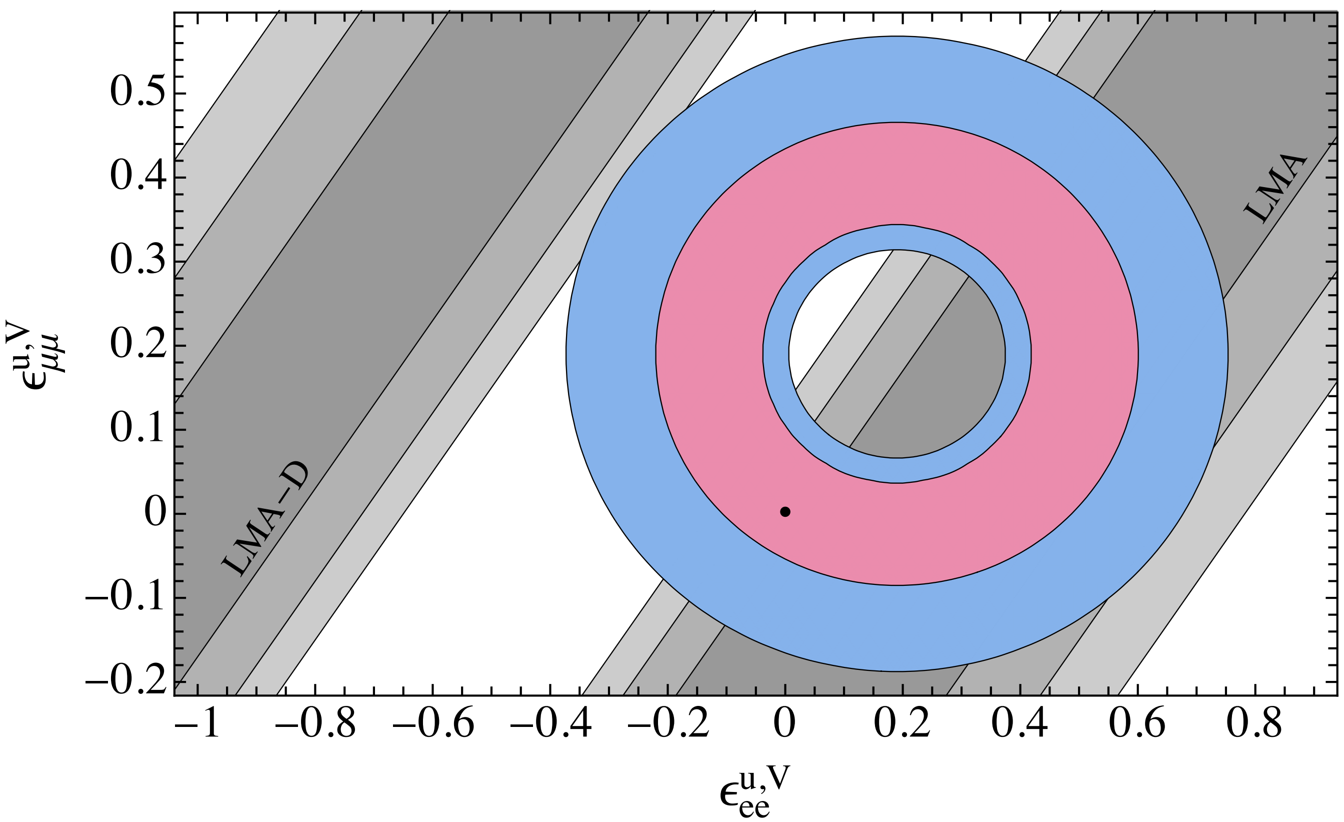
- Only evidence of the interaction is a low-energy recoiling nucleus
  - Heavier nuclei: higher cross section but lower recoil energies
  - Nuclear recoil signal yields are quenched, i.e. reduced compared to signal from electrons of same energy by a factor called the quenching factor (QF)
  - Detector performance hard to calibrate
- Very-low-threshold detectors are very sensitive to backgrounds
  - Neutron backgrounds are particularly dangerous: produce low-energy nuclear recoils just like CEνNS
- Need an appropriate source of neutrinos

[1] D.Z. Freedman, Phys. Rev. D 9 (1974)

Physics from CEνNS

Supernova physics - Could play a role in dynamics of core-collapse SNe [1] and offers potential way to *observe* SNe neutrinos [2]

Weak mixing angle - Unique probe of Q_W^2 at a unique Q in a region sensitive to dark Z boson models [3]



Non-standard neutrino interactions - explicit dependence on non-universal and flavor-changing neutral currents [4]

Nuclear form factor - Provides a way to measure neutron distributions using neutrino scattering [5], possibly refining nuclear structure models and informing understanding of neutron star EoS [6]

Fundamental properties of neutrinos - sensitivity to effective neutrino charge radius and magnetic moment [7] *and* lift degeneracy of "dark side" solution to θ_{12} that would complicate mass-order determination from oscillation experiments [8]

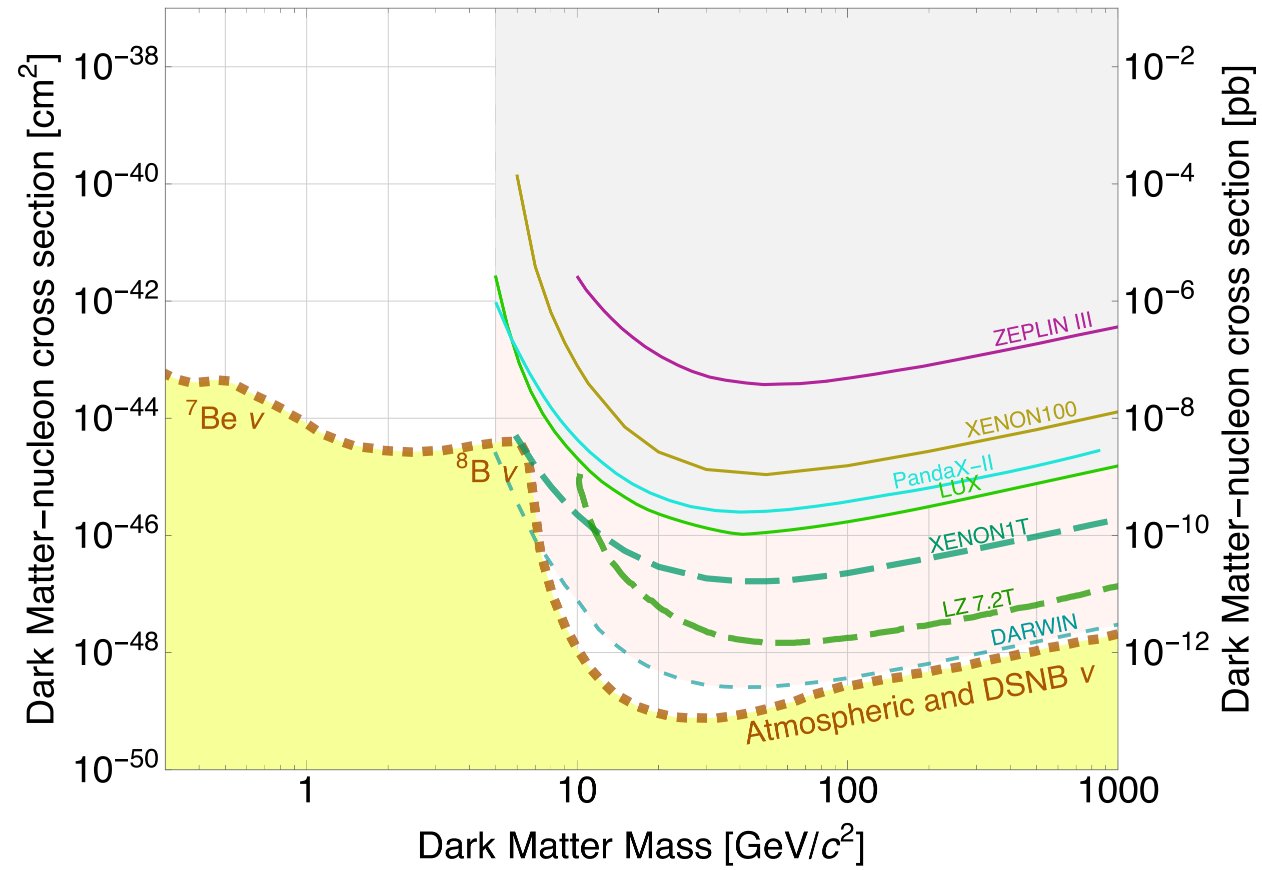
Neutral-current sterile neutrino search - all-flavor disappearance experiment [9]

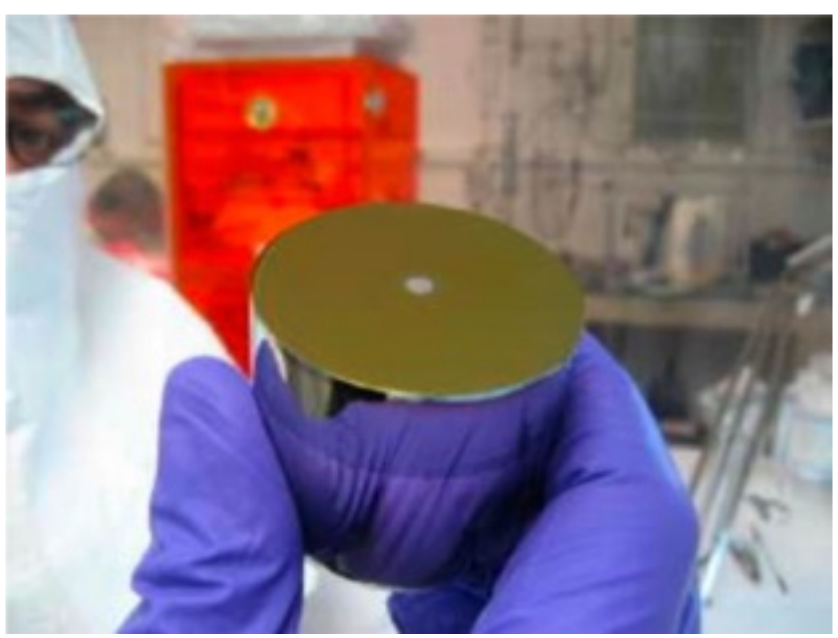
[1] D.Z. Freedman, Phys. Rev. D 9 (1974)
[2] C. Horowitz *et al.*, Phys. Rev. D 68 (2003)
[3] H. Davoudiasl *et al.*, Phys. Rev. D 89 (2014)
[4] J. Barranco *et al.*, Phys. Rev. D 76 (2007)
[5] K. Patton *et al.*, Phys. Rev. C 86 (2012)
[6] C. Horowitz & J. Piekarewicz, Phys. Rev. Lett. 86 (2000)
[7] K. Scholberg, Phys. Rev. D 73 (2006)
[8] P. Coloma *et al.*, Phys. Rev. D 96 (2017)
[9] A.J. Anderson *et al.*, Phys. Rev. D 86 (2012)

Figure from [8]

CEνNS becomes a background

- Goodman & Witten recognize utility of CEνNS-sensitive detectors as potential dark matter detectors [1]
  - DM and CEνNS interactions are both coherent scattering processes with the same detectable signature (gently recoiling nuclei)
- Numerous instances of proposed CEνNS detectors turning instead into competitive DM searches





P.S. Barbeau, Ph.D. thesis (UChicago 2009)

- Tremendous advances in detector technology to build more sensitive DM searches
- Next generation of WIMP detectors will begin to be sensitive to CEνNS from ^{8}B solar neutrino flux
  - This “neutrino floor” brings the CEνNS and DM relationship full circle

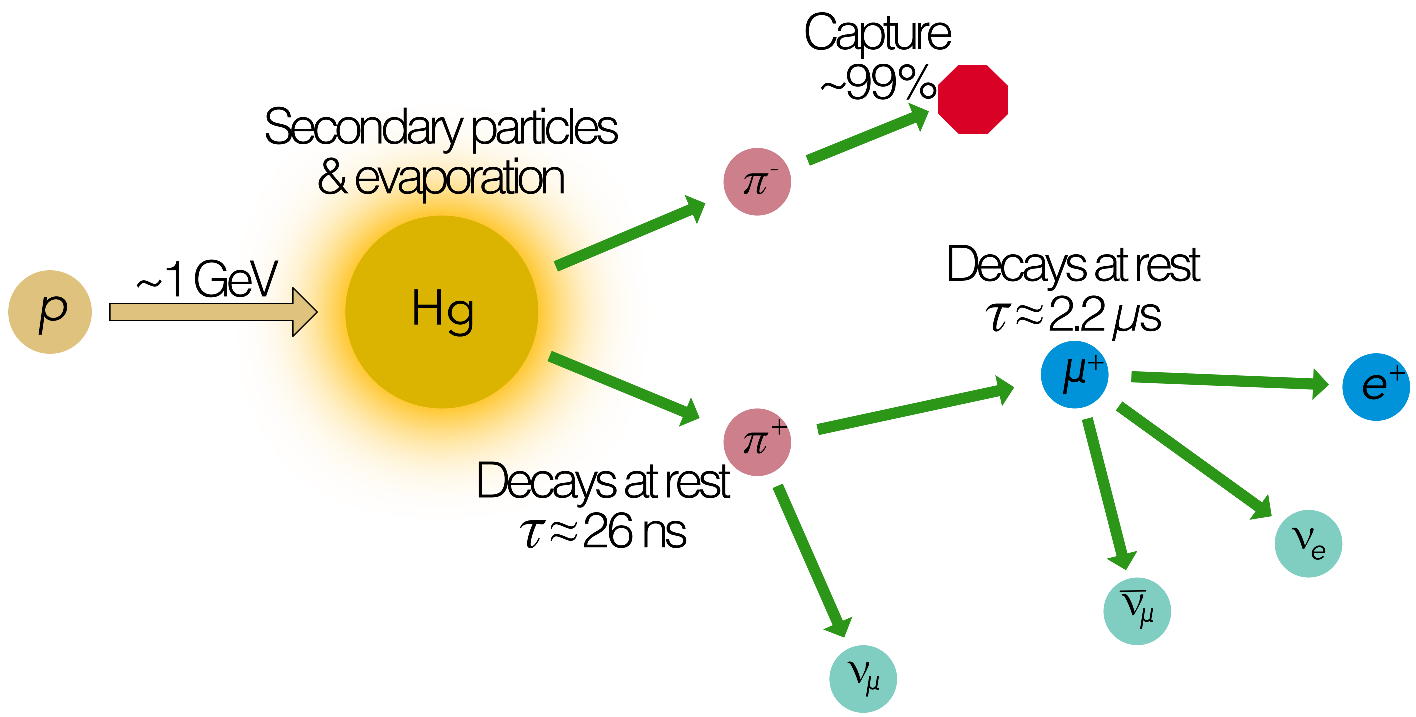
[1] M.W. Goodman, E. Witten, Phys Rev D 31 (1985)
Figure from http://cdms.berkeley.edu/limitplots/

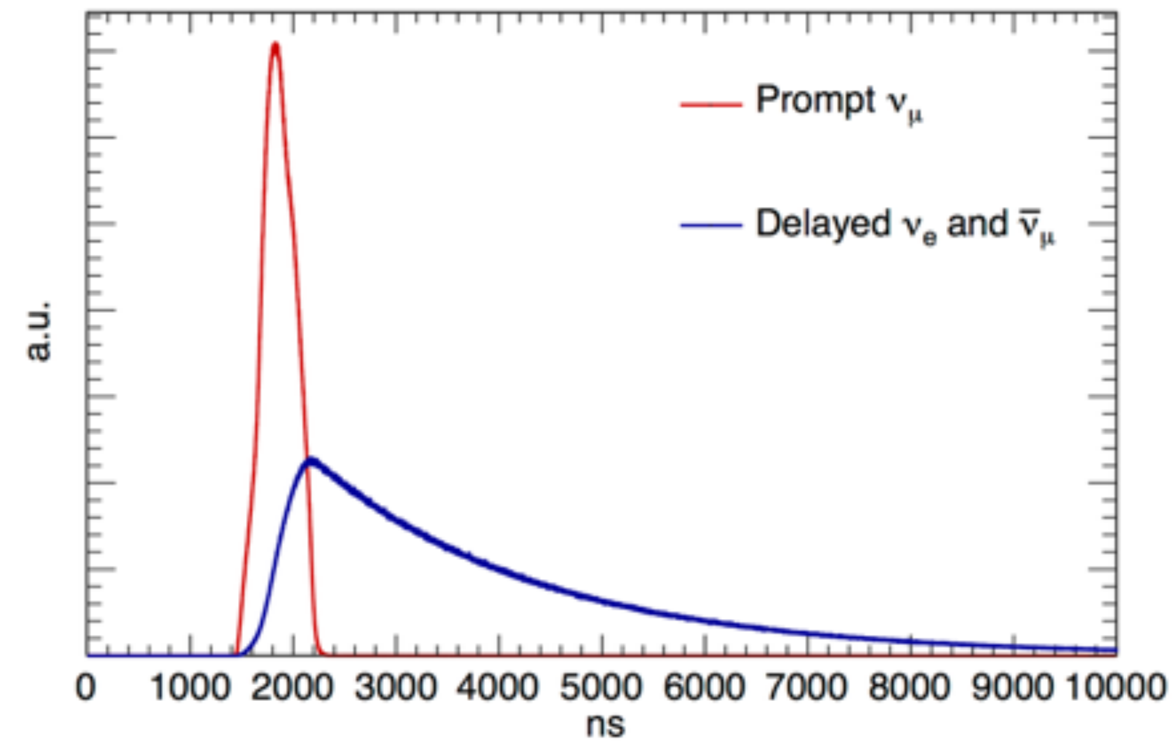
The Spallation Neutron Source

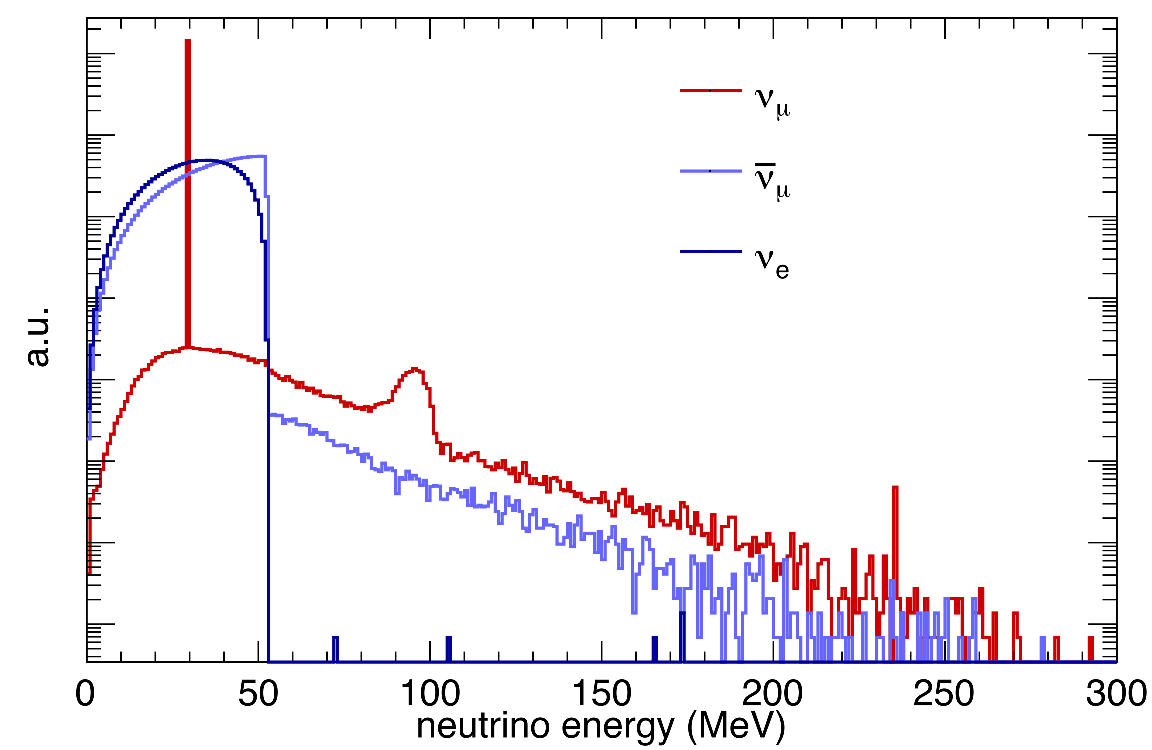
- Located at Oak Ridge National Lab, near Knoxville, TN, USA
- The SNS bombards a liquid mercury target with a ~1-GeV proton beam pulsed at 60 Hz; each beam pulse is ~700-ns wide
  - Power generally > 1 MW - most intense pulsed neutron source in the world!
- Neutrinos are produced by decay of ***stopped** pions and muons*, resulting in flux with well-defined spectral and timing characteristics
  - Most intense pulsed *neutrino* source in the world!

Image from https://neutrons.ornl.gov/sns

The Spallation ~~Neutron~~ Neutrino Source



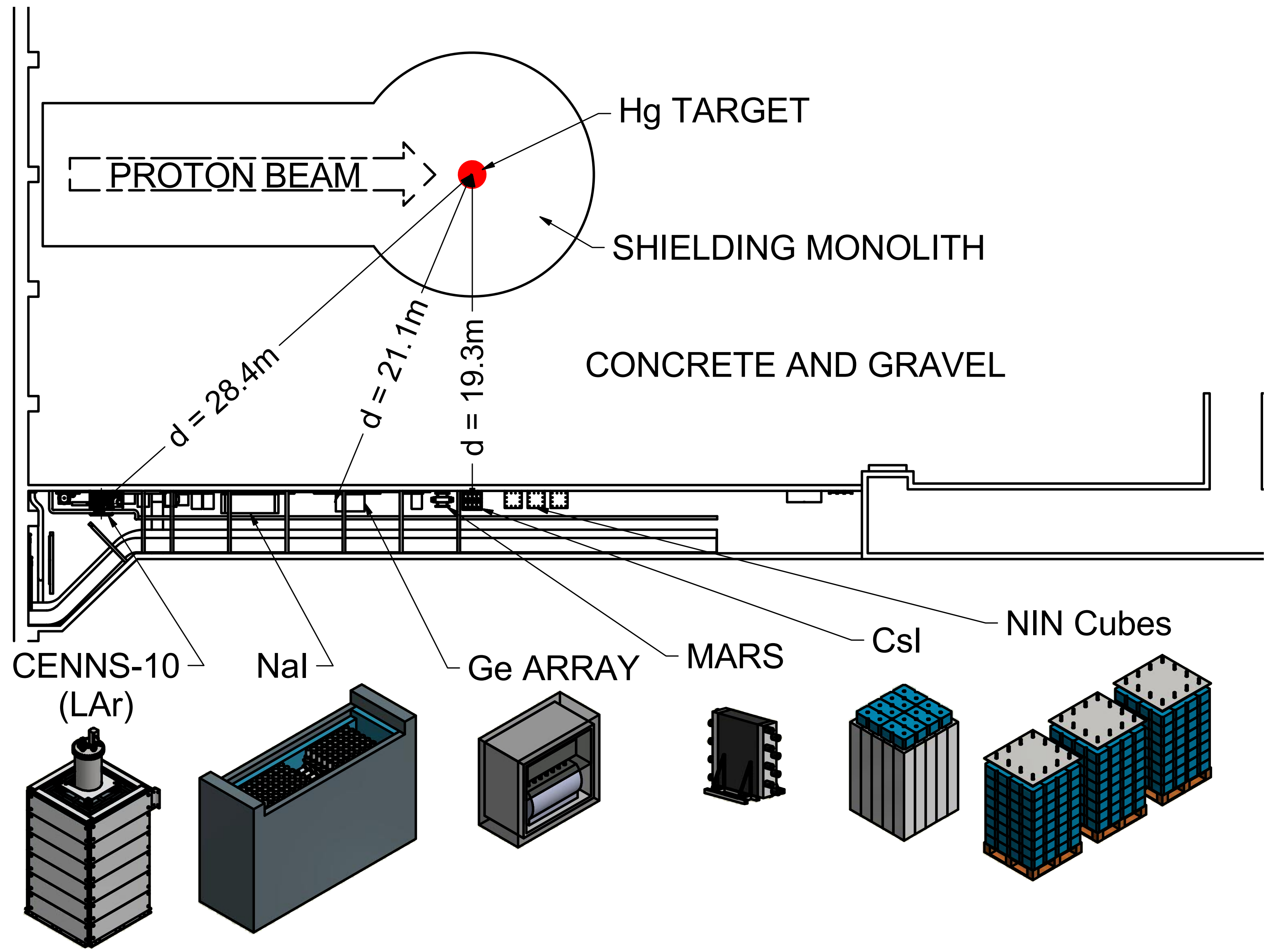




- High-fidelity GEANT4 simulation starts with proton beam; energy spectra very near analytical approximations
- Massive reduction in steady-state backgrounds through timing ($\mathcal{O}(1000)$); facility-wide timing signal can be used to trigger DAQ, both during beam-on and -off periods

Siting and backgrounds

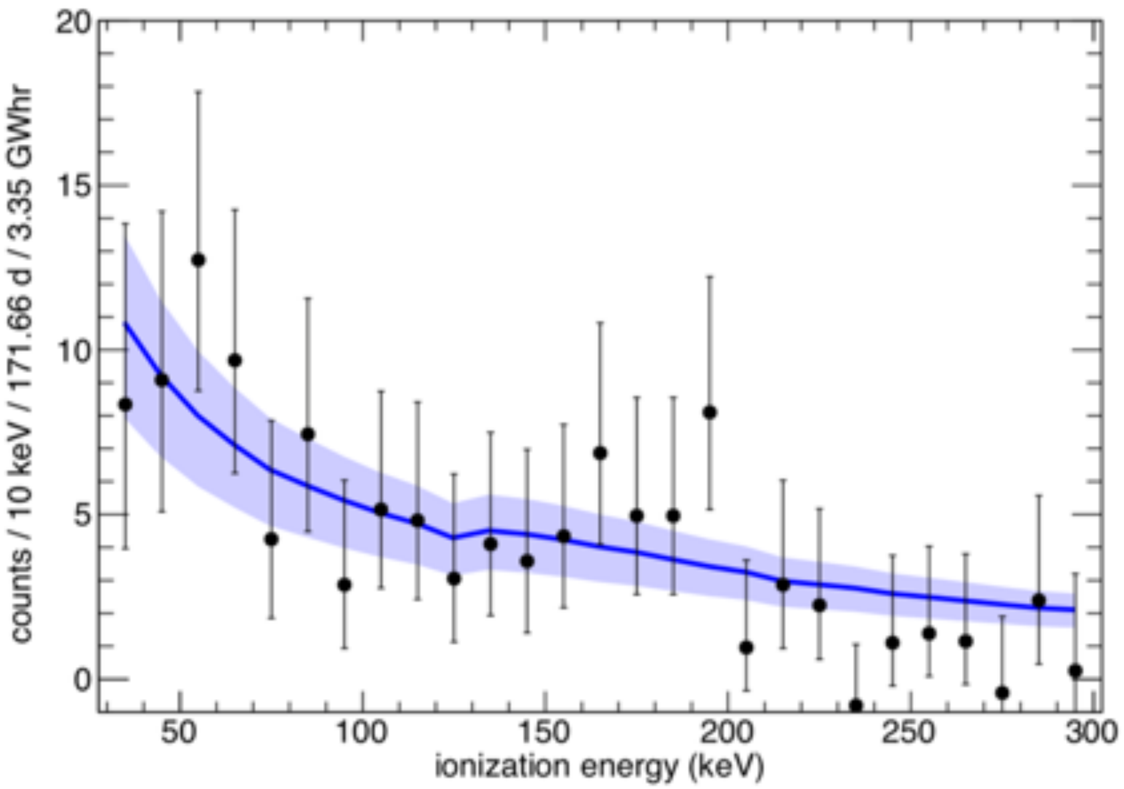
- Backgrounds depend significantly on siting at SNS
  - Extensive background measurement campaign
- COHERENT experiments located in ~~a basement hallway~~ *neutrino alley*
  - ~8 m.w.e. overburden
  - 20- to 30-m from target
- Primary backgrounds in neutrino alley:
  - Prompt SNS neutrons
  - Neutrino-induced neutrons (NINs)

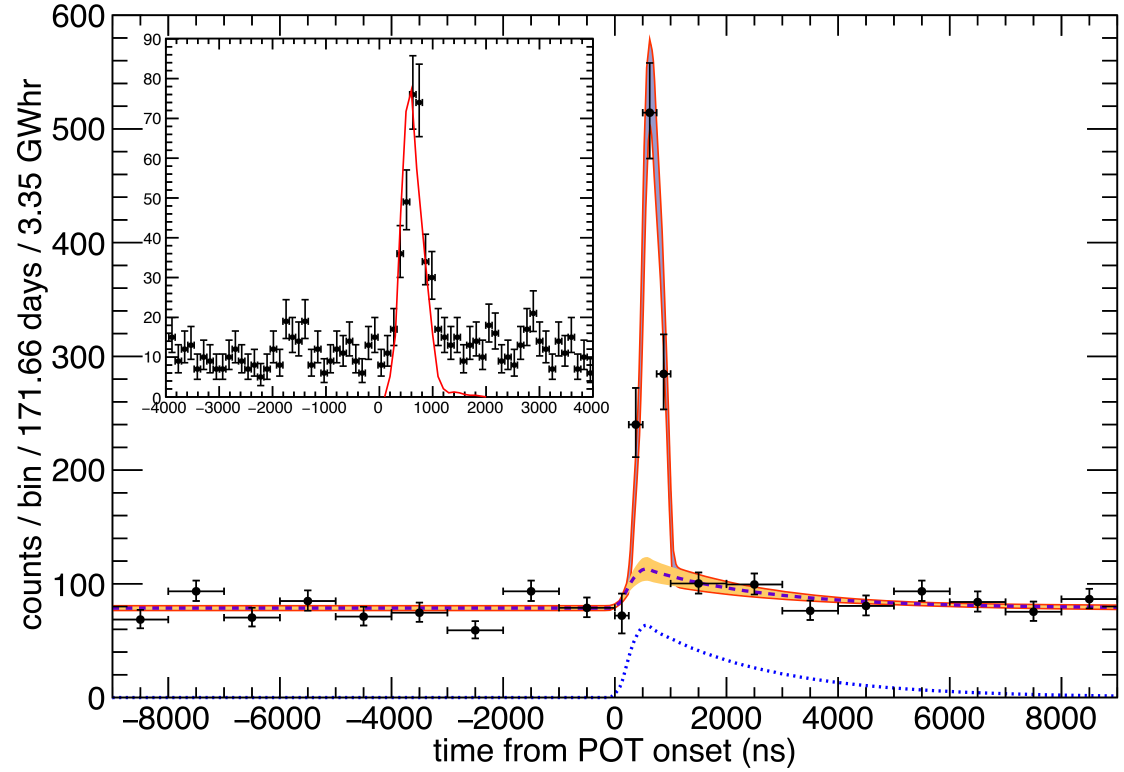


Approx ν flux at CsI[Na] location

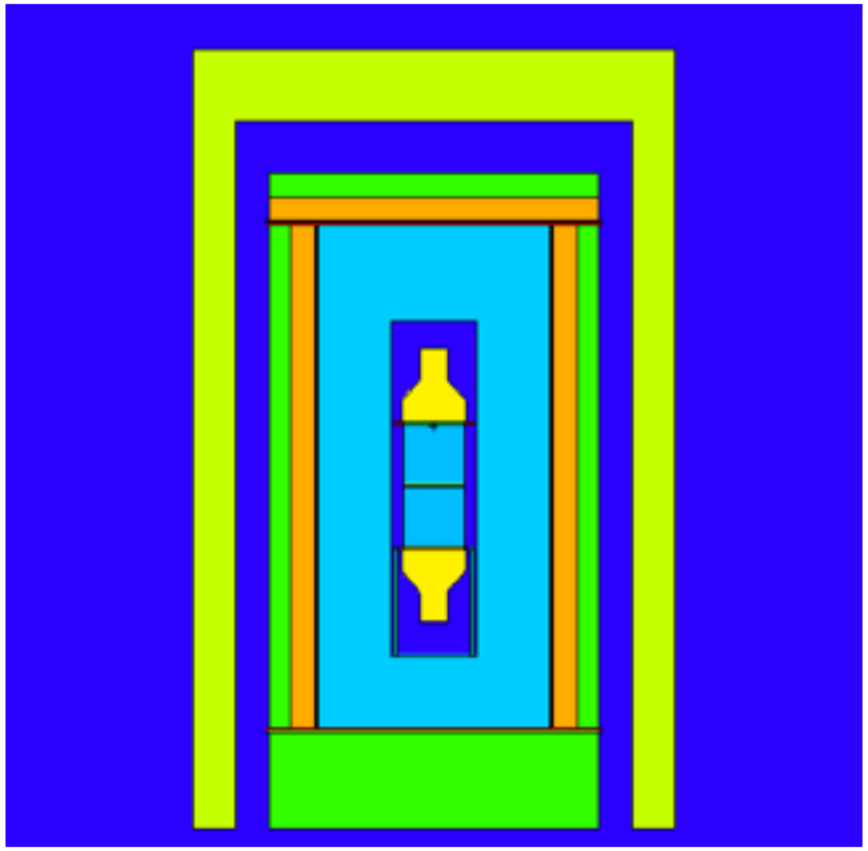
1e7 ν / cm^2 / s / flavor

In situ measurement of neutron backgrounds

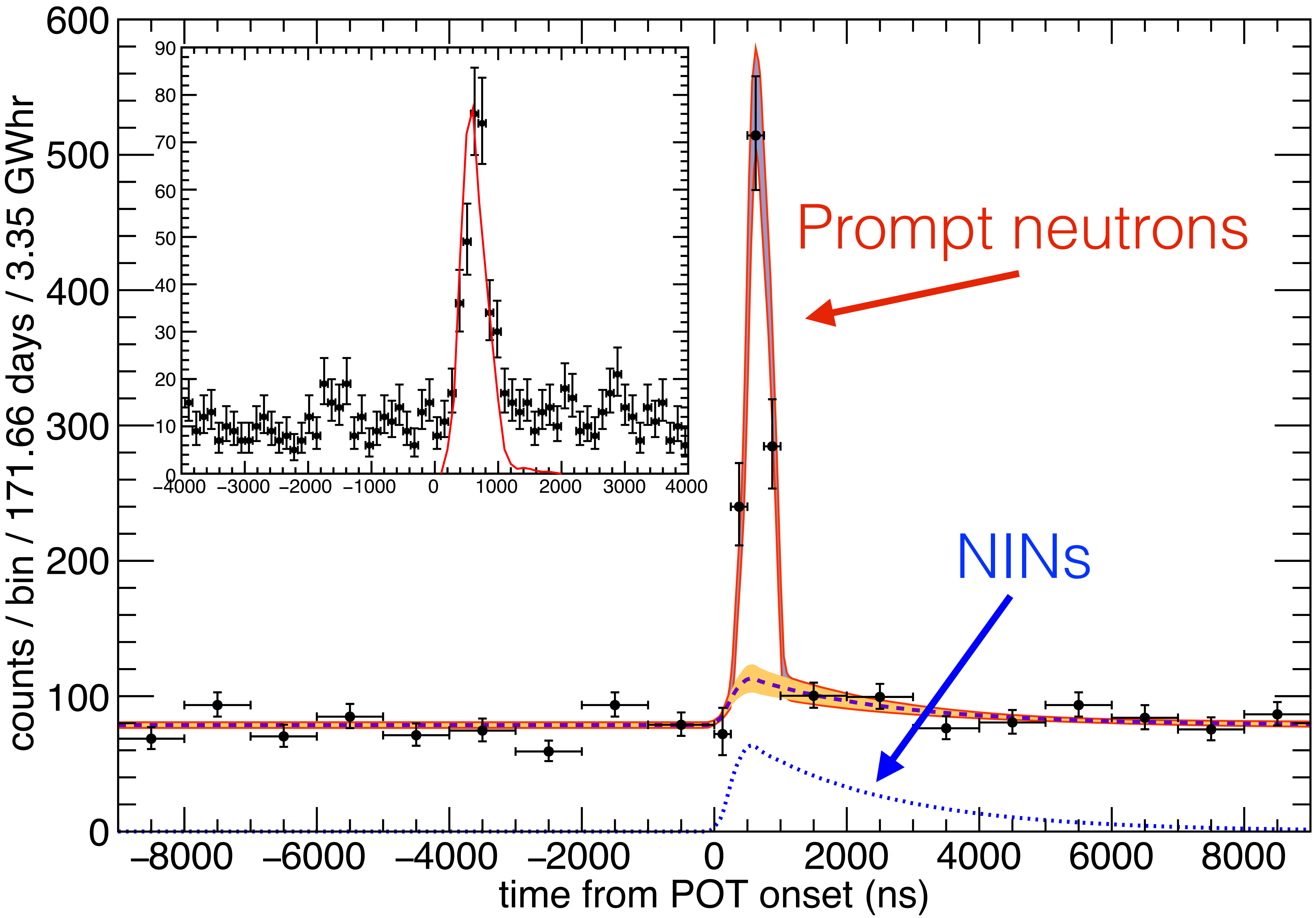




- Prior to CEνNS search, neutron detection system installed at location of CsI[Na] detector
- Data informed model of prompt SNS neutron energy distribution
- Established understanding of beam timing w.r.t. SNS timing signal



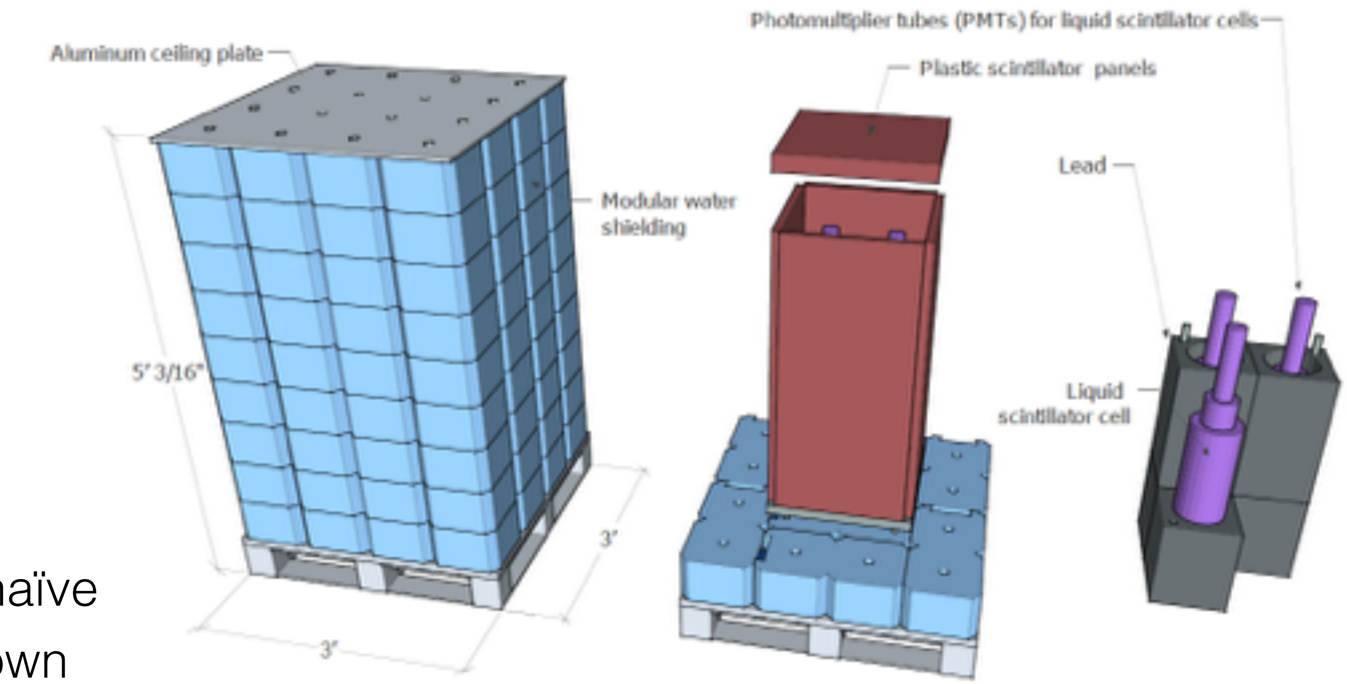
In situ measurement of neutron backgrounds



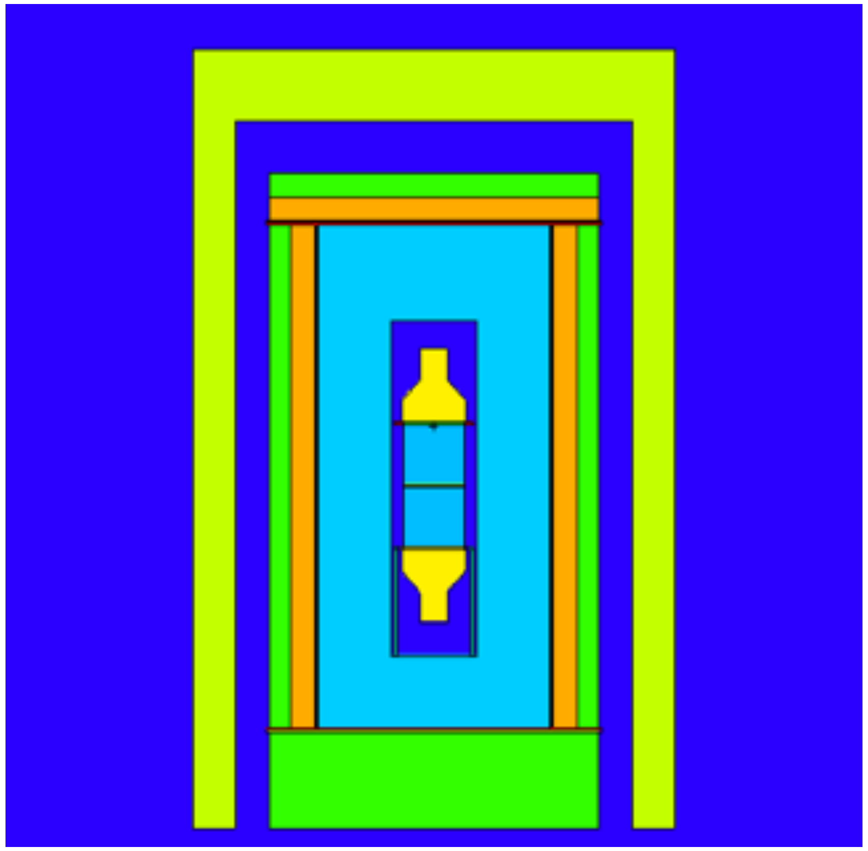
Neutrino-induced neutrons (NINs)

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

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



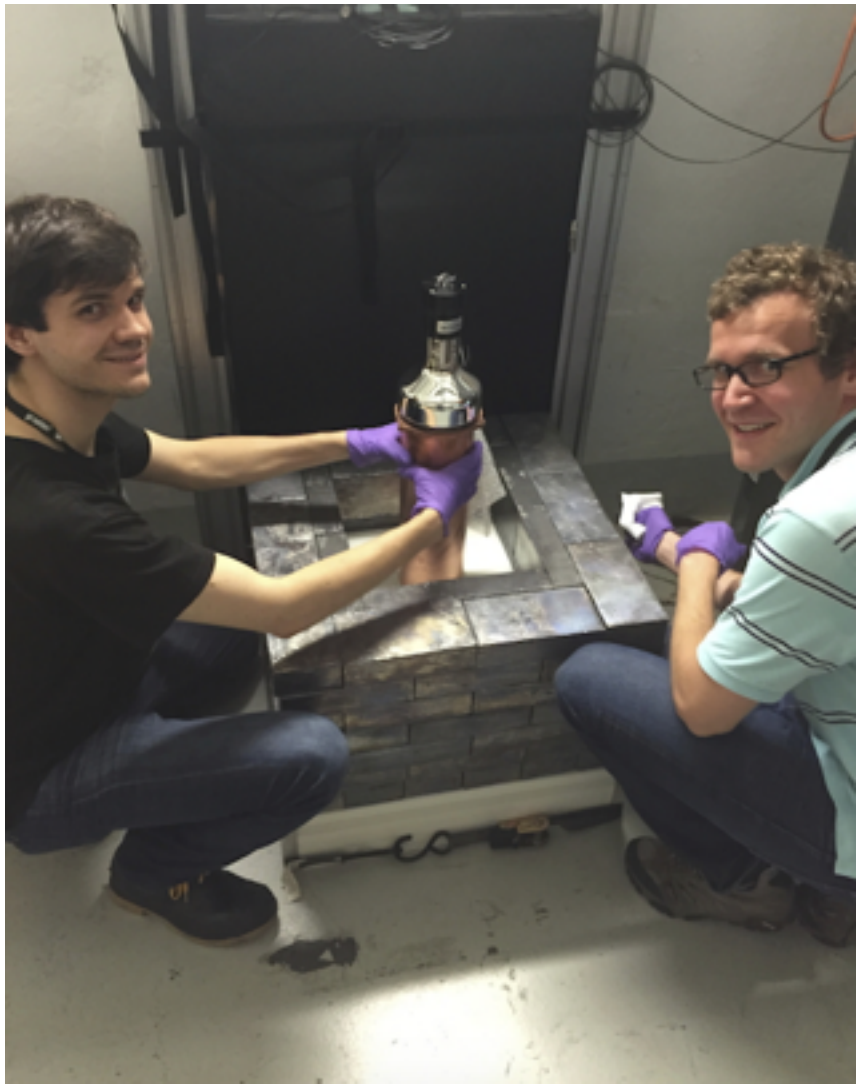
- Dominant background for CEνNS measurement with naïve shielding configuration, but interesting physics of its own
  - Possible role in nucleosynthesis in certain astrophysical environments [1]
  - NIN production on Pb is the fundamental mechanism by which HALO intendeds to detect supernova neutrinos [2]
  - Process has never before been measured, considerable variation in theoretical predictions (~3x) [3]
- *In situ* measurements give rate limit, plus ongoing measurement of process with “neutrino cubes”



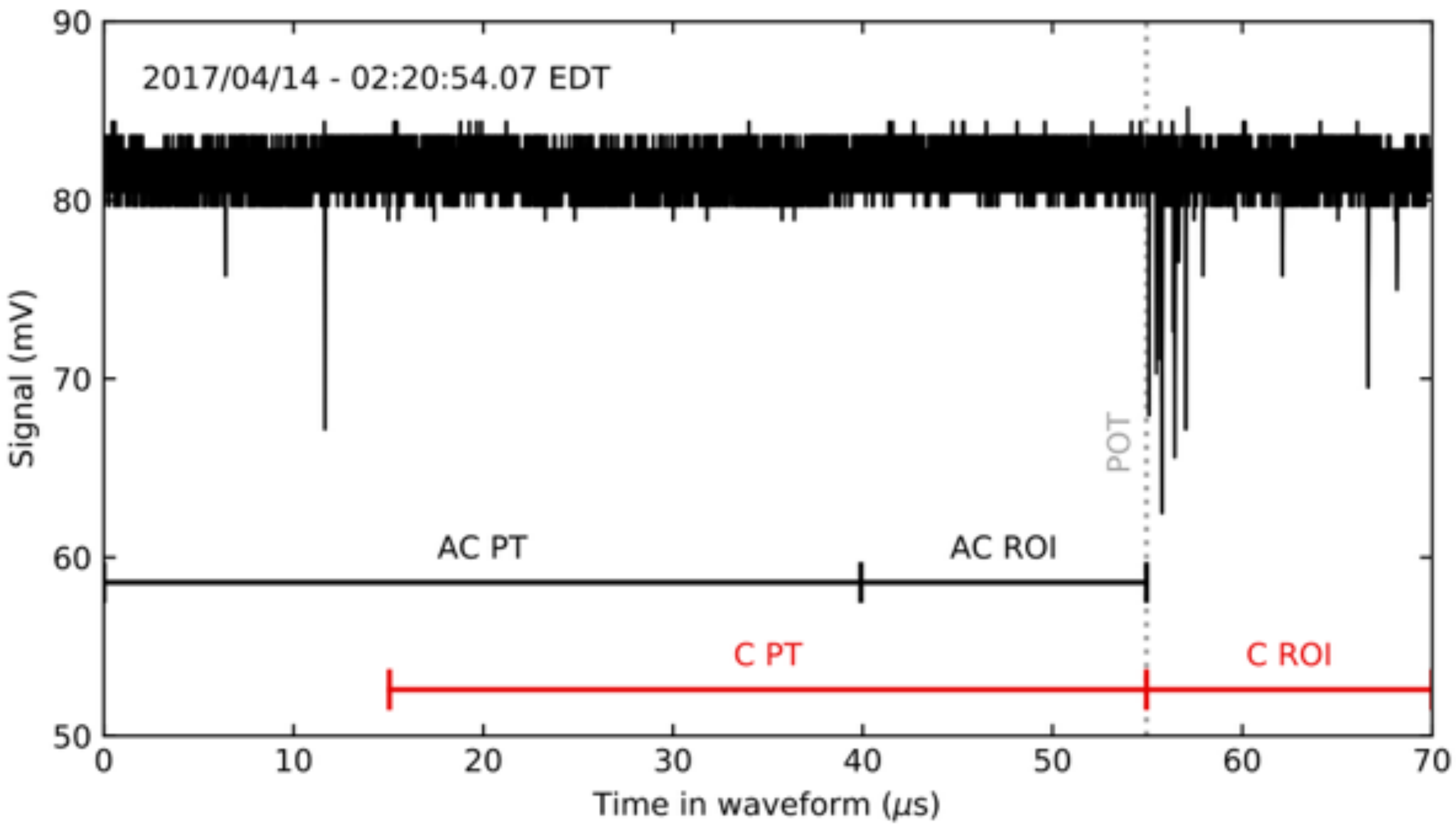
[1] Y-Z. Qian *et al.*, Phys. Rev. C 55 (1997)
[2] C.A. Duba *et al.* J. Phys. Conf. Series 136 (2008)
[3] C. Volpe, N. Auerbach, G. Colò, and N. Van. Giai, Phys. Rev. C 65 (2002)
NIN pathways from S.R. Elliott, Phys. Rev. C (2000)

CEνNS with CsI[Na]

Deployed to SNS in June 2015



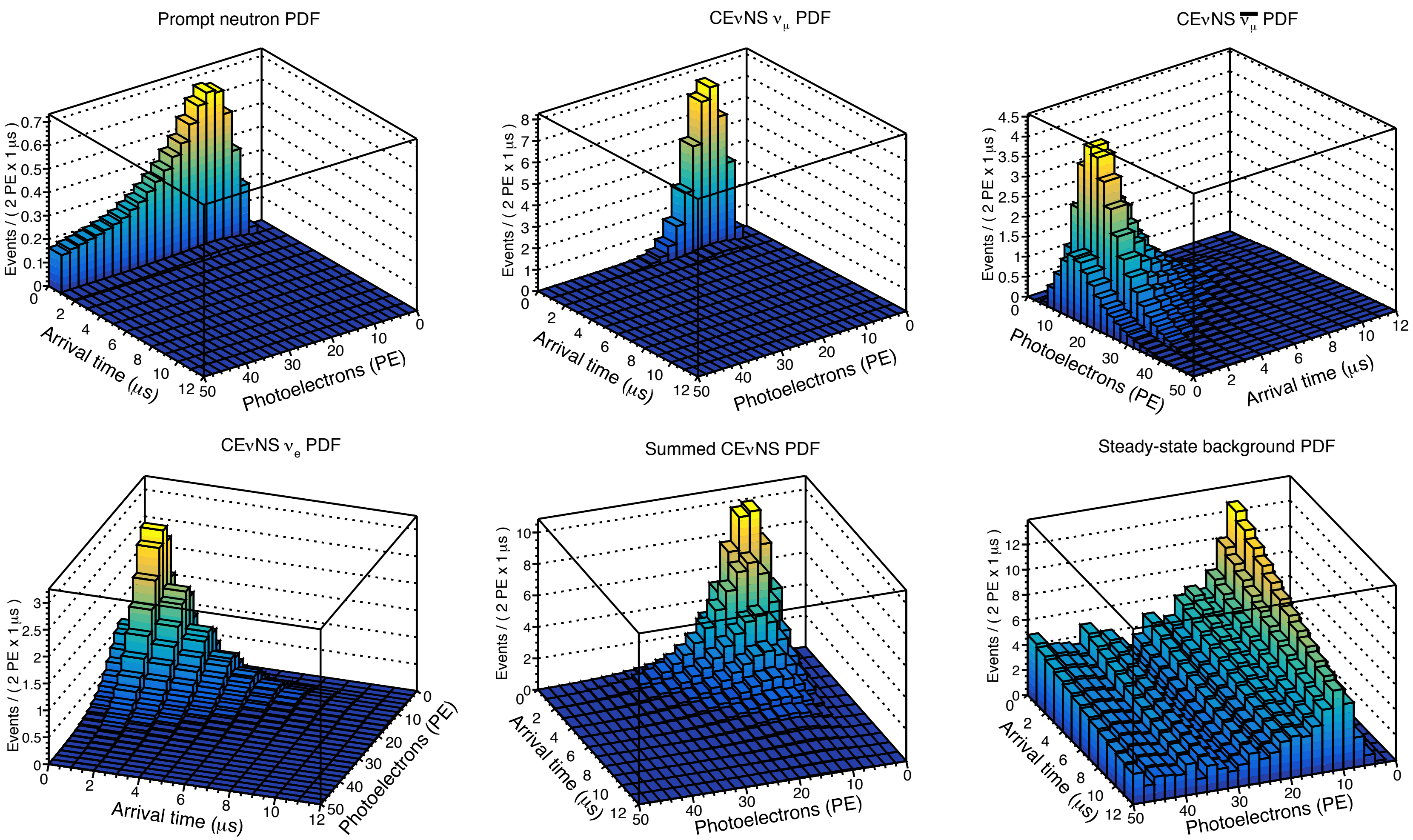
- 14.6-kg crystal made from low-background salts, encased in electroformed-copper can with PTFE reflector and synthetic silica window, surrounded by neutron and gamma shielding, including low-activity lead
- Development led by University of Chicago [1]
- Output of super-bialkali PMT with ~30% QE digitized for 70 μs, triggered by SNS timing signal



COHERENT SNS

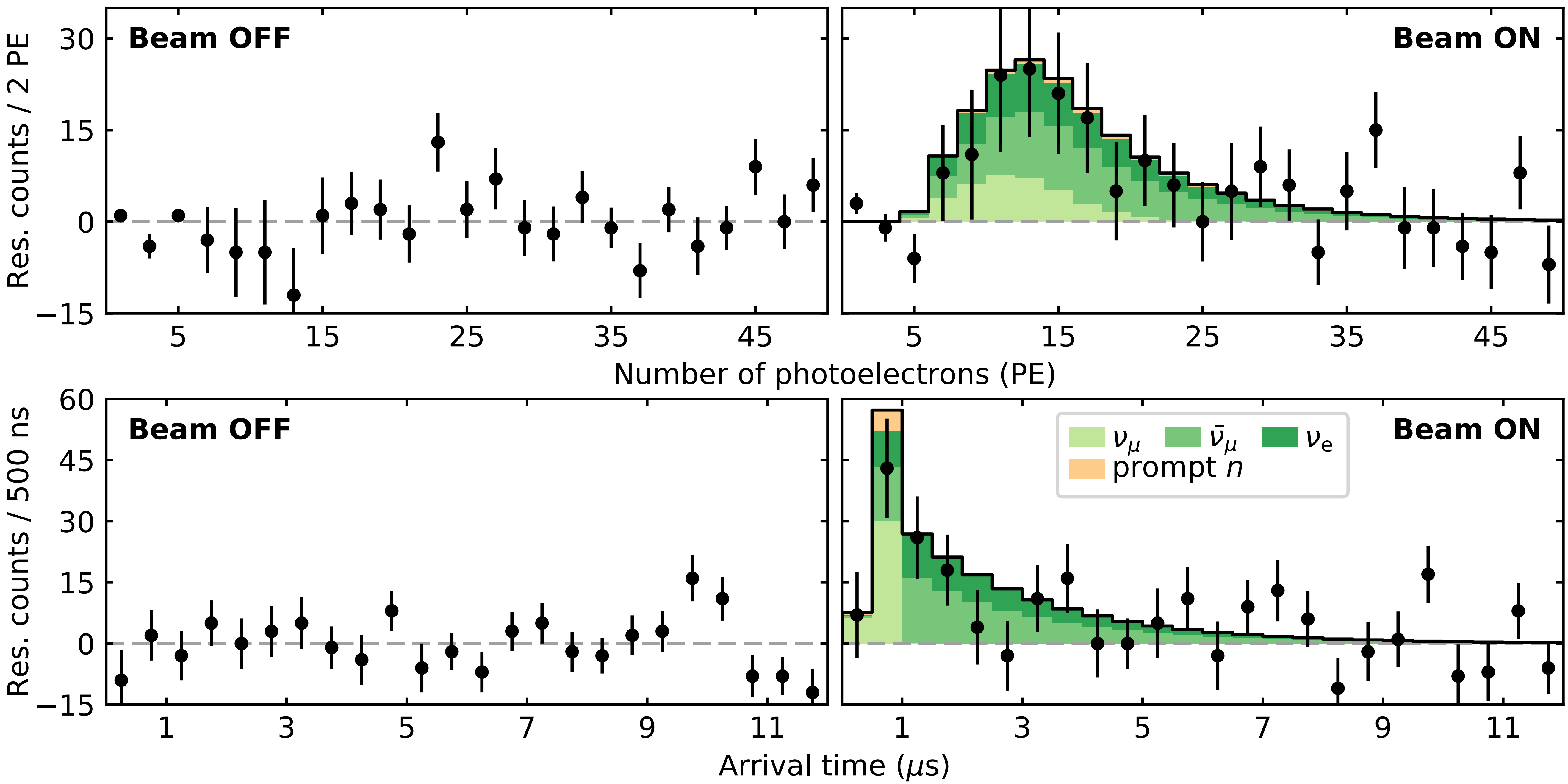
[1] J.I. Collar *et al.*, Nucl. Instrum. Meth. A 773 (2015)

Rate and shape estimates



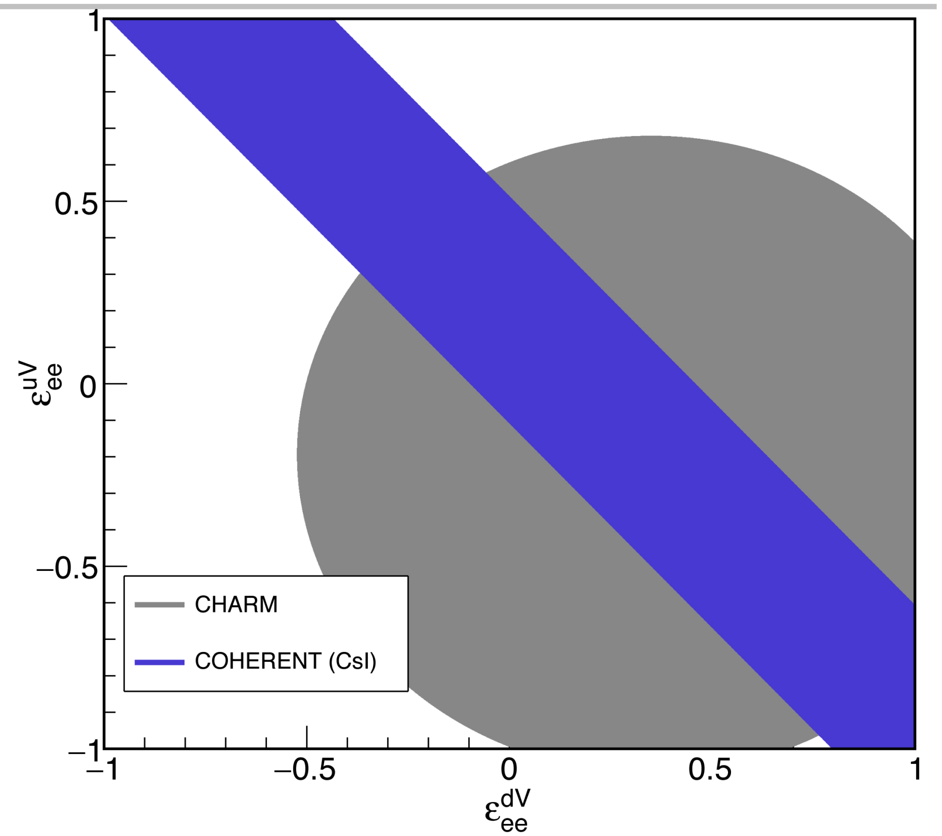
- Pulsed nature of beam facilitates analysis in time domain
- 2-D analysis (energy, time) makes use of all available information
- Ultimately performed binned 2-D profile likelihood analysis using PDFs shown here
  - Assumes Standard Model
  - Incorporates knowledge of detector response, analysis acceptance, etc

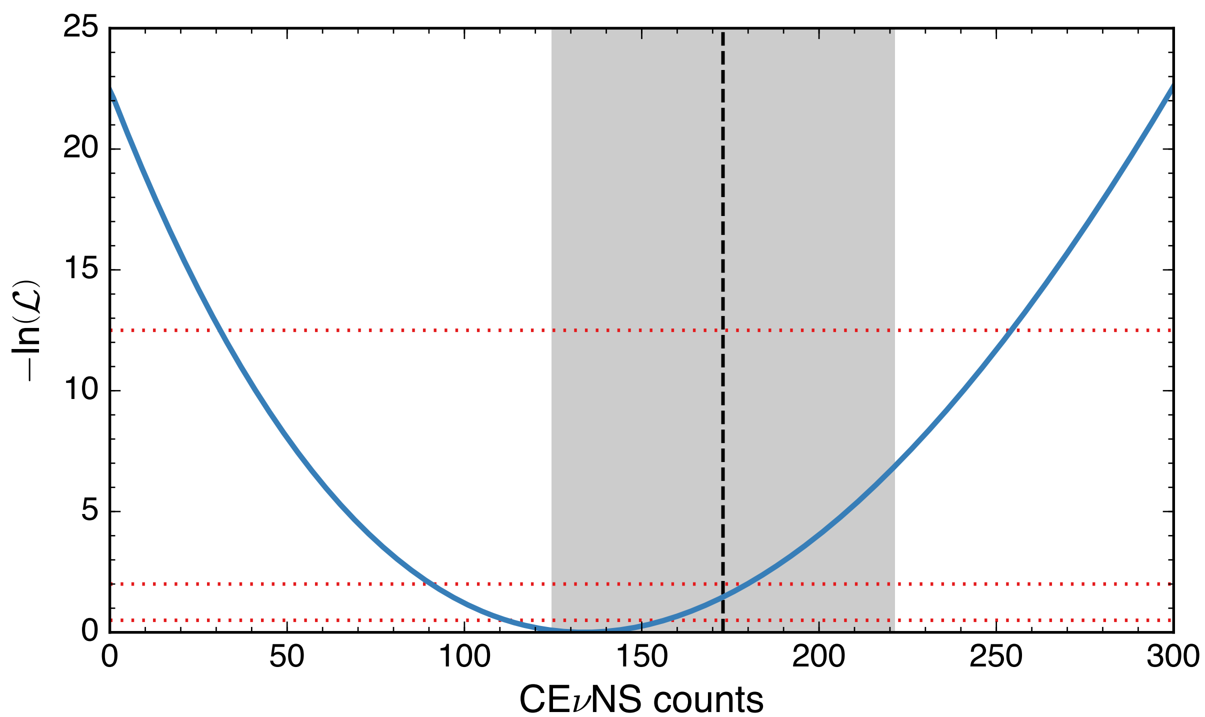
SM prediction and data



Results

- Beam exposure: ~6 GWhr, or ~1.4 × 10^{23} protons on target (0.22 grams of protons)
- Analyzed as a simple counting experiment
  - 136 ± 31 counts
- 2-D profile likelihood analysis
  - 134 ± 22 counts, within 1-σ of SM prediction of 173 ± 48
  - Null hypothesis disfavored at 6.7-σ level relative to best-fit number of counts
- Able to further constrain some NSI parameters





Dominant systematic uncertainties on predicted rates

Quenching factor	25%
ν flux	10%
Nuc. form factor	5%
Analysis acceptance	5%

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

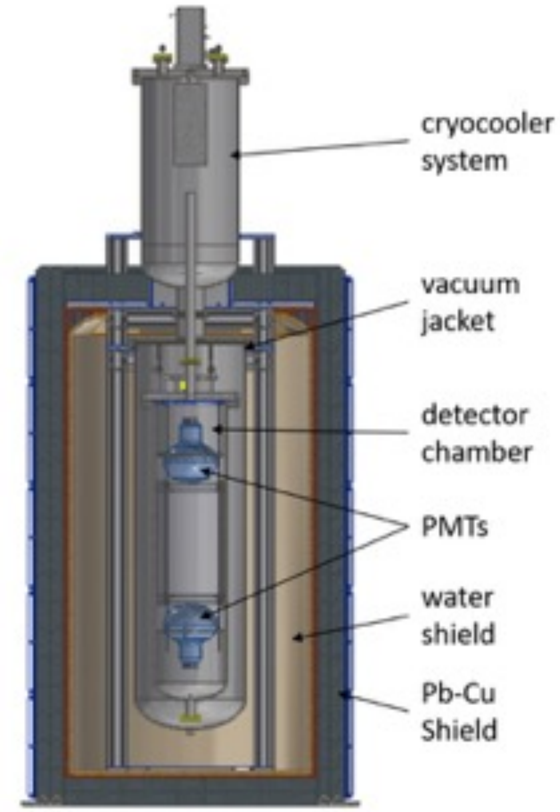
CEνNS observation data release

- Data that constituted CEνNS observation has been packaged and is publicly available
  - http://dx.doi.org/10.5281/zenodo.1228631
  - https://coherent.ornl.gov
- Should include all information necessary to perform further analyses on CsI[Na] data
  - Binned data for coincidence and anticoincidence regions for both SNS on and off; prompt-neutron model
  - Descriptions and values for relevant systematics
- Collaboration intends to continue practice of data releases

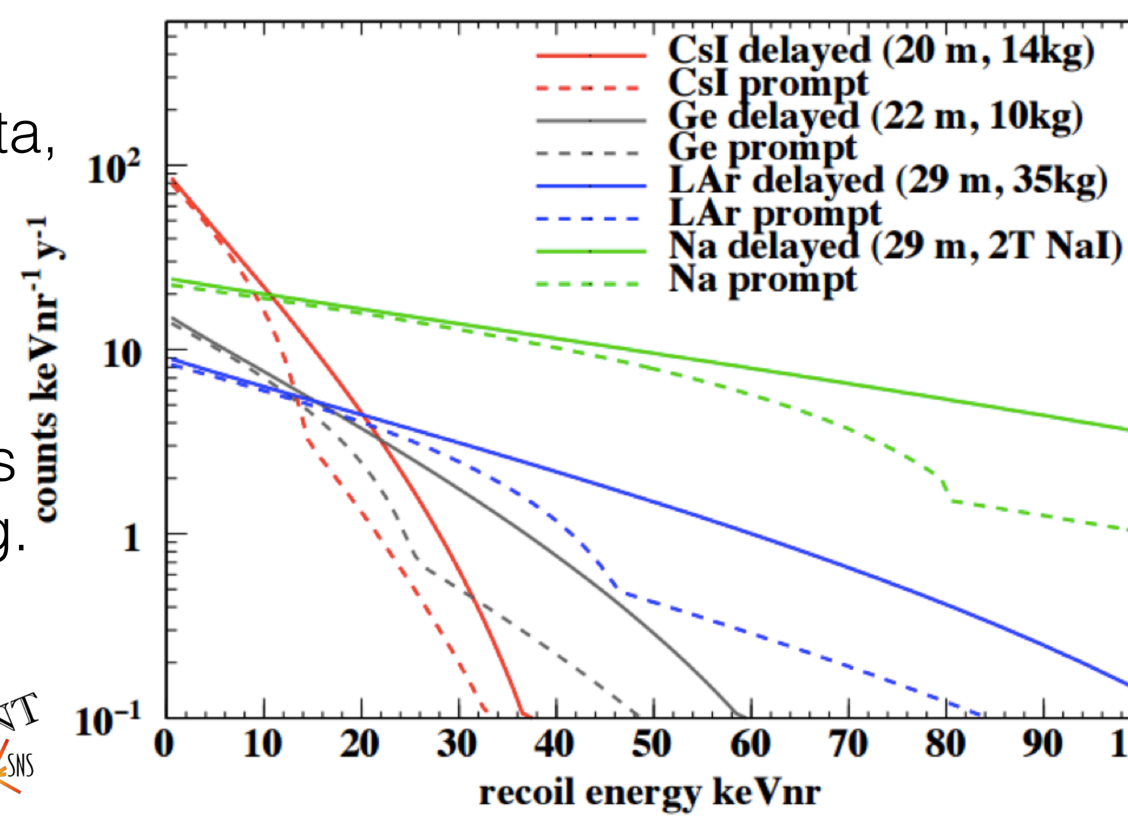
COHERENT physics moving forward

- Measure NINs cross section in ^{208}Pb, ^{56}Fe
  - Upgrades to detection system planned in cooperation with PROSPECT
- Measure ^{127}I CC cross section
  - 185-kg NaIνE collecting low-gain CC data now
  - Sensitivity to g_A quenching with Q~$\mathcal{O}$(10 MeV)
- N^2 dependence of CEνNS cross section
  - Several distinct *N* values represented in COHERENT suite of experiments
  - 22-kg LAr detector already collecting CEνNS data, plans for 10 kg of Ge PPCs and multi-ton NaI[Tl]
- Begin to perform precision CEνNS measurements
  - High-resolution, low-threshold detectors, such as Ge PPCs, enable access to exciting physics, e.g. electromagnetic properties of neutrinos

CENNS-10 LAr detector



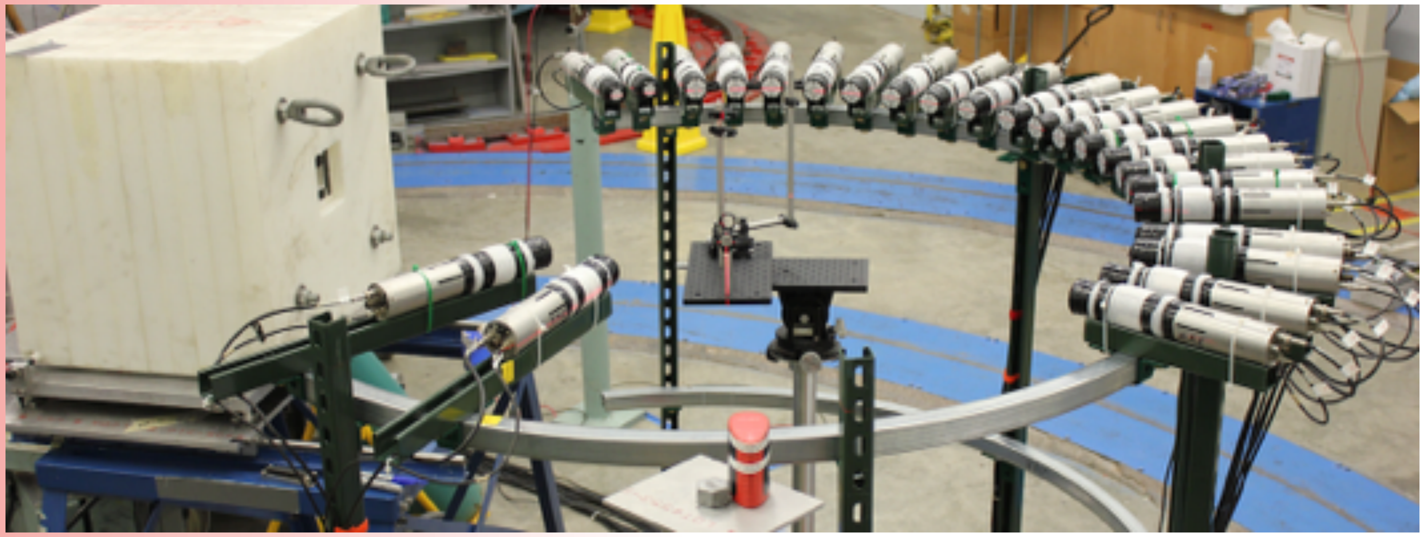
NaIνE: NaI[Tl] neutrino experiment

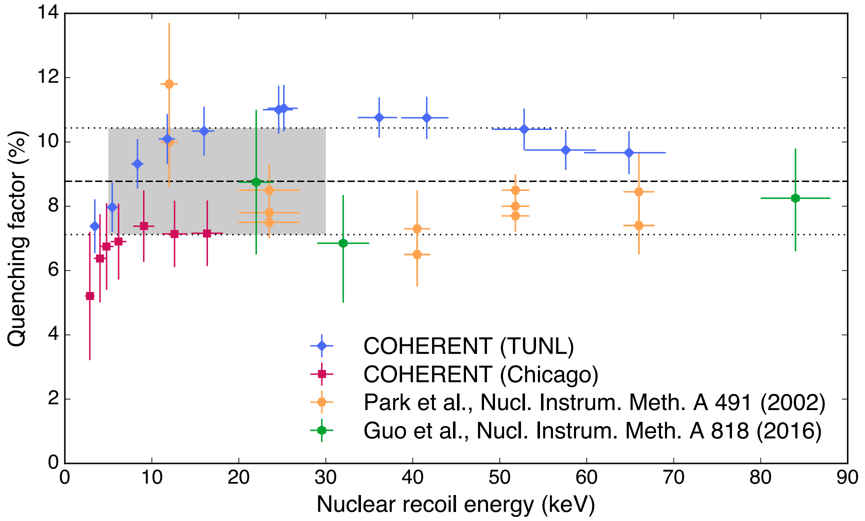


Reducing dominant systematic uncertainties

Quenching factors

- Understanding of QF is crucial for *all* CEνNS measurements
  - Reanalyzing original data and collecting new data to resolve discrepancy in COHERENT QF measurements for CsI[Na]
  - Some data already collected and future measurements planned for Ge and NaI[Tl]





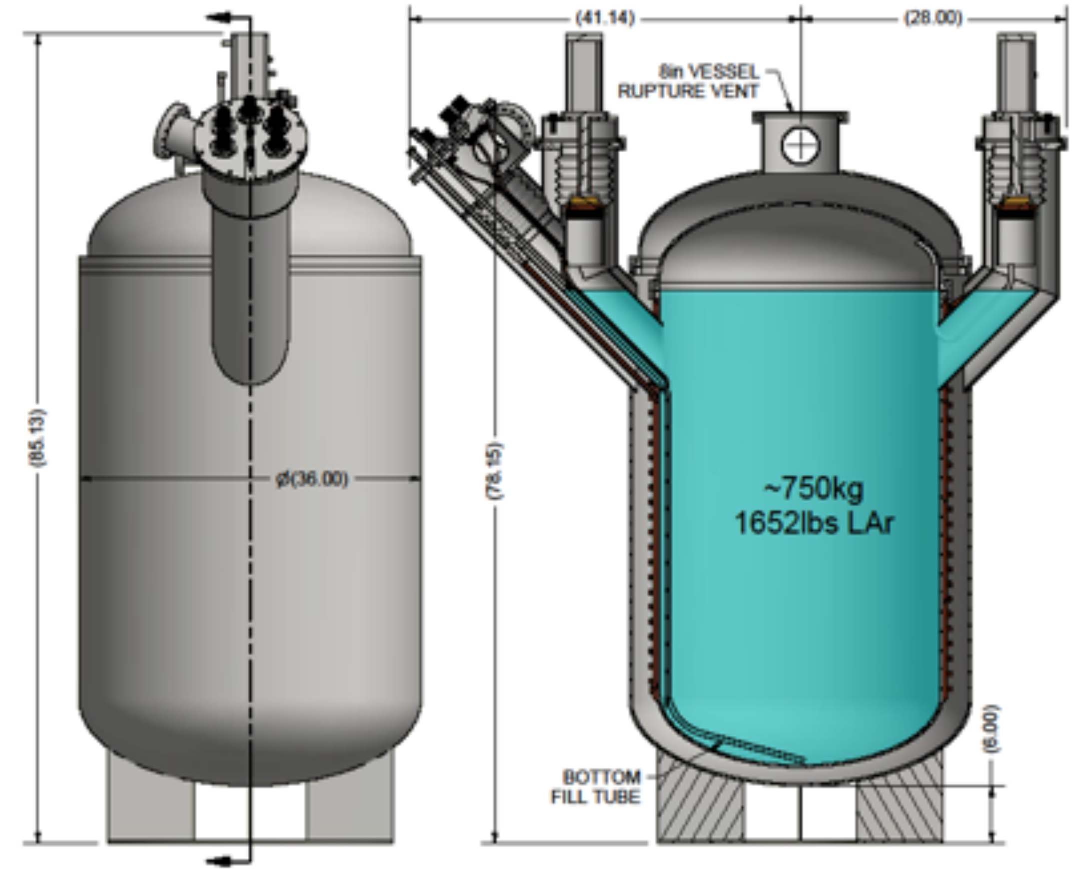
ν flux normalization

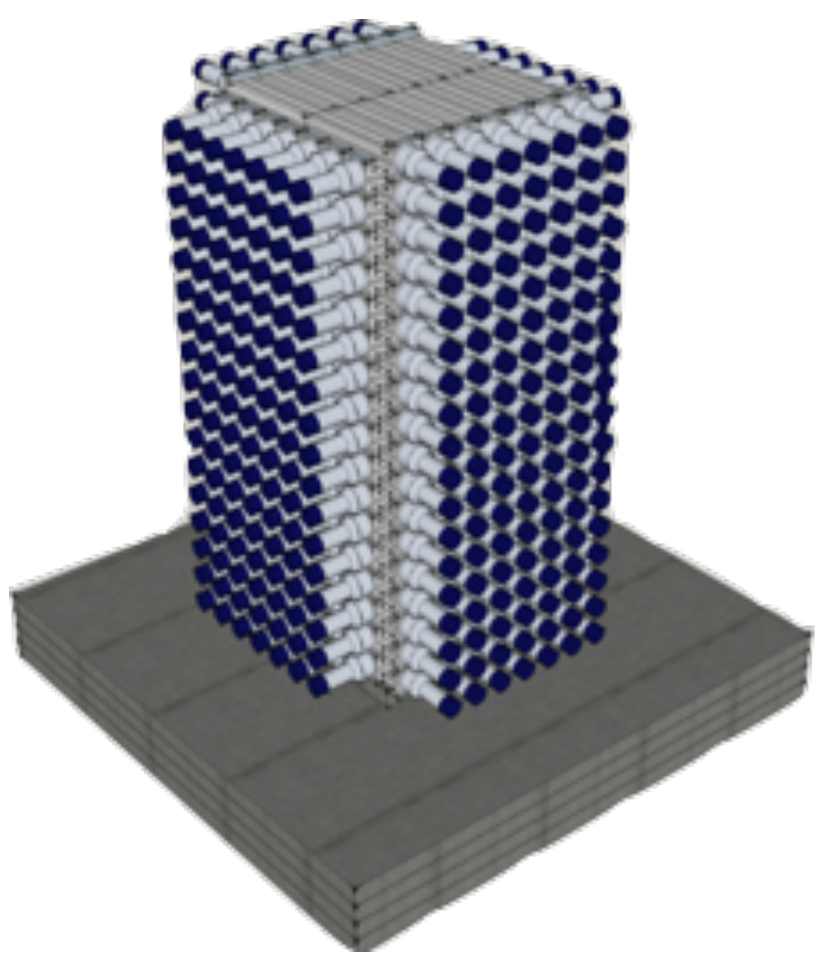
- Indirect approaches to flux determination possible (e.g., improved input for models or direct measurement of pion production at SNS)
- Conceptual design stages of a D_2O detector for neutrino alley relying on CC interaction on D
  - D cross section is relatively well understood theoretically [1] and previous measurements agree with predictions [2]

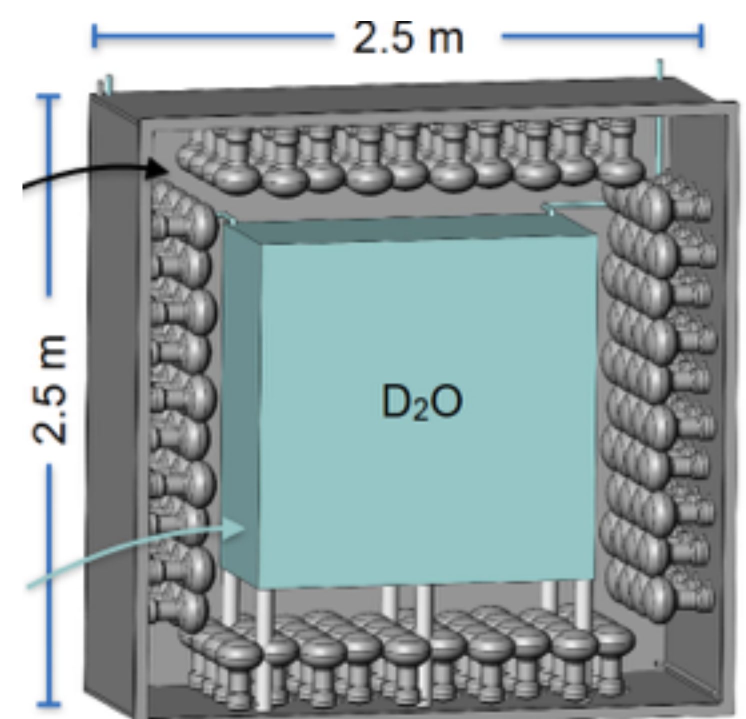
[1] S. Nakamura *et al.*, Nucl. Phys. A 721 (2003)
[2] J. Formaggio and G.P. Zeller, Rev. Mod. Phys. 84 (2012)

Future of COHERENT

- Next stages of COHERENT CEνNS measurements will be a considerable scale up
  - Beginning plans for $\mathcal{O}$(1 ton) LAr detector using underground argon
  - Development advancing for multi-ton NaI[Tl] detector capable of simultaneous CC and CEνNS measurement; designing new PMT-base electronics to facilitate this parallel measurement
- Flux normalization measurements benefit all COHERENT experiments; early design stages

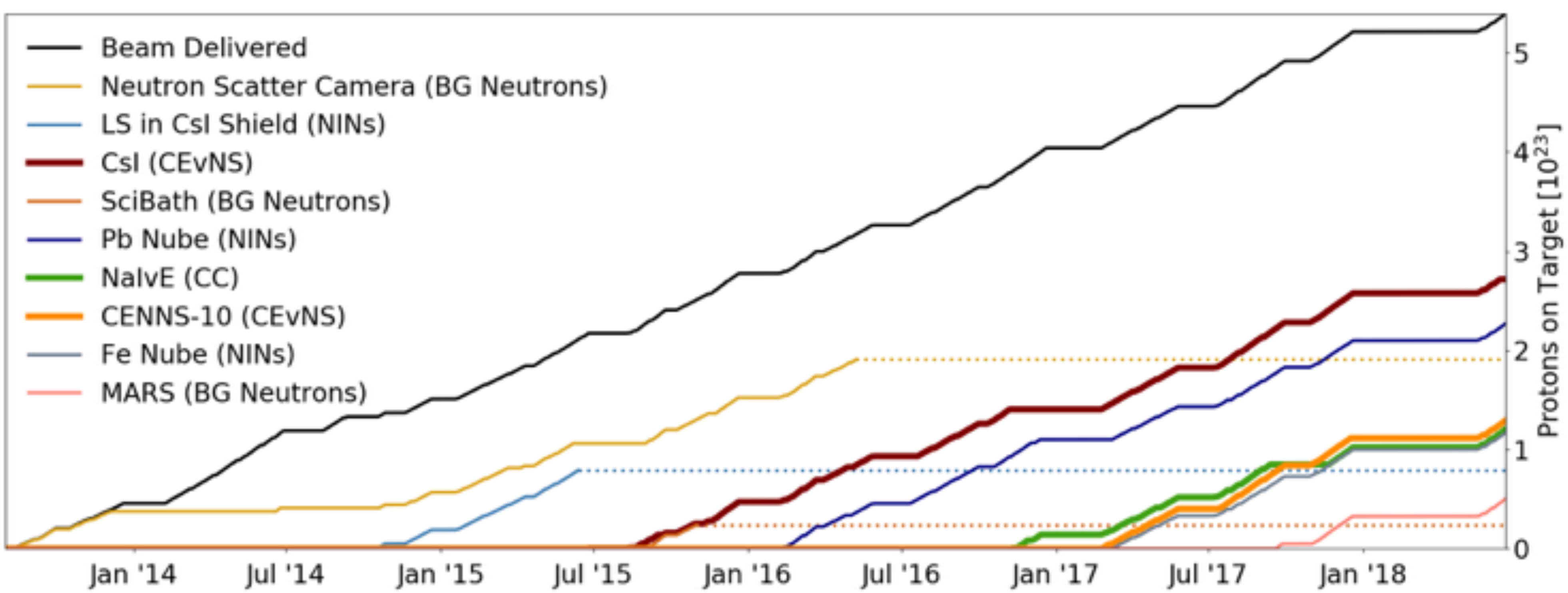






Only the beginning…

- CEνNS predicted in 1974 but unobserved until 2017
  - Observed at 6.7-σ level using 14.6-kg CsI[Na] scintillator deployed at pulsed, stopped-pion ν source (SNS)
- COHERENT continues to search for CEνNS with numerous detectors (LAr, NaI[Tl], Ge PPCs) in addition to several other efforts
  - Working towards performing *precision* CEνNS measurements
- Many other groups seeking observation with many different kinds of detectors, different neutrino sources
  - Examples: CONNIE, CONUS, MINER, Nu-CLEUS, nuGEN, RICOCHET, RED-100
  - These efforts are *complementary!* Joint analyses using different detectors and/or sources are very powerful [1]
- Tremendous amount of physics left to be done with CEνNS
  - Important complement to oscillation measurement program through lifting of LMA-D ambiguity



COHERENT SNS

[1] J.B. Dent *et al.*, Phys. Rev. D 97 (2018)

COHERENT SNS

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

CNEC Consortium for Nonproliferation Enabling Capabilities

Sandia National Laboratories

Duke UNIVERSITY

NSF

KICP Kavli Institute for Cosmological Physics AT THE UNIVERSITY OF CHICAGO

OAK RIDGE National Laboratory

THE UNIVERSITY of TENNESSEE UT KNOXVILLE

UNIVERSITY of WASHINGTON

NORTH CAROLINA CENTRAL UNIVERSITY FOUNDED 1910

NC STATE UNIVERSITY

Carnegie Mellon University

Laurentian University Université Laurentienne

MEPhI

KAIST

THE UNIVERSITY OF CHICAGO

TUNL

Los Alamos NATIONAL LABORATORY EST. 1943

UF UNIVERSITY of FLORIDA

BERKELEY LAB

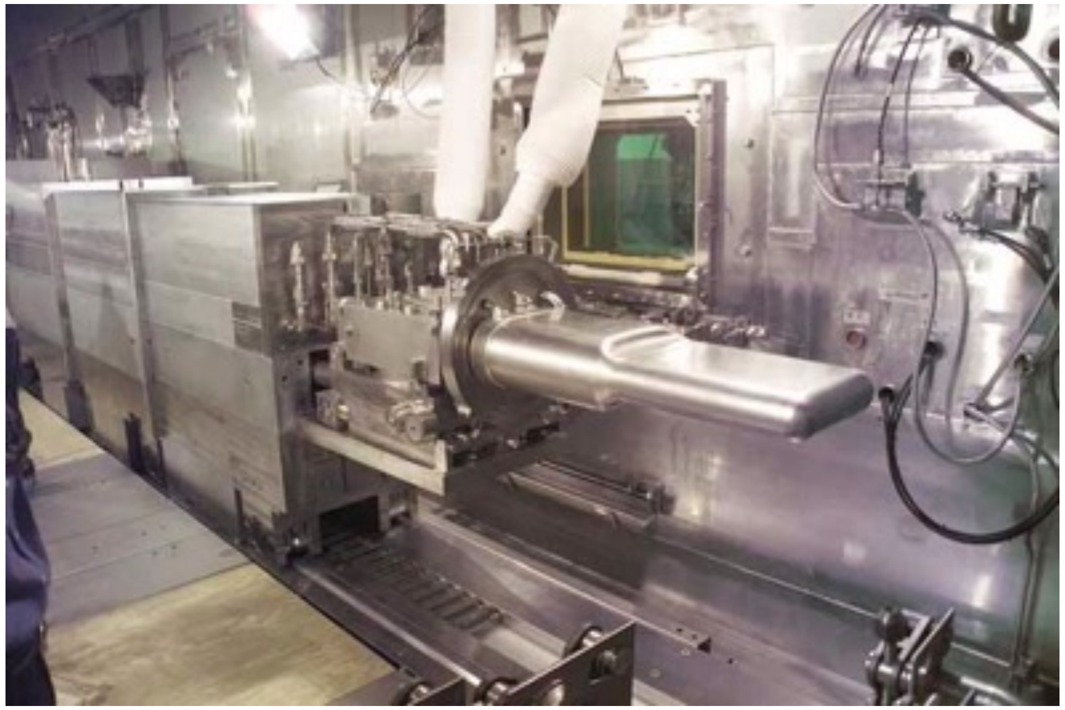
NM STATE UNIVERSITY

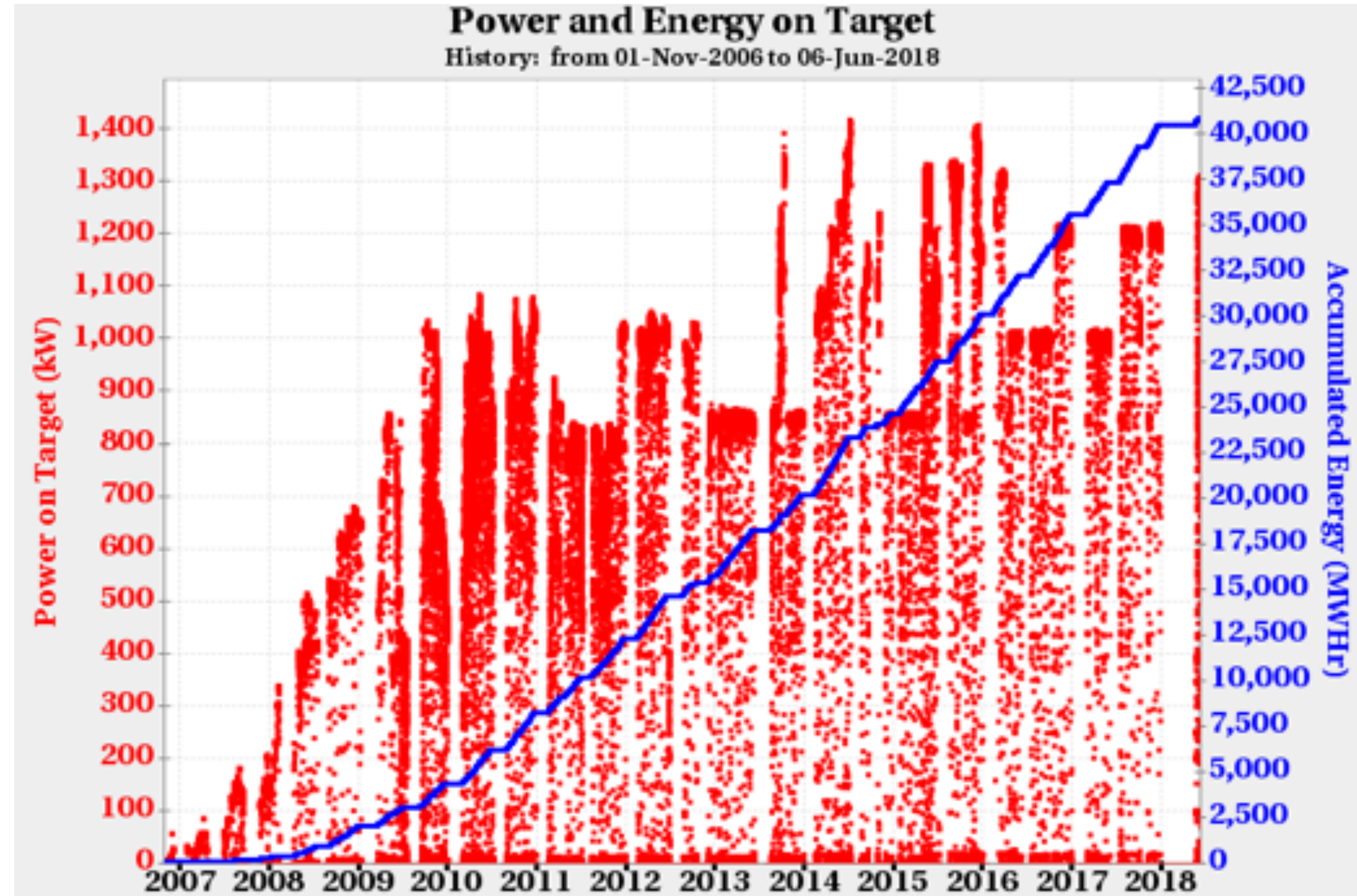
Backup

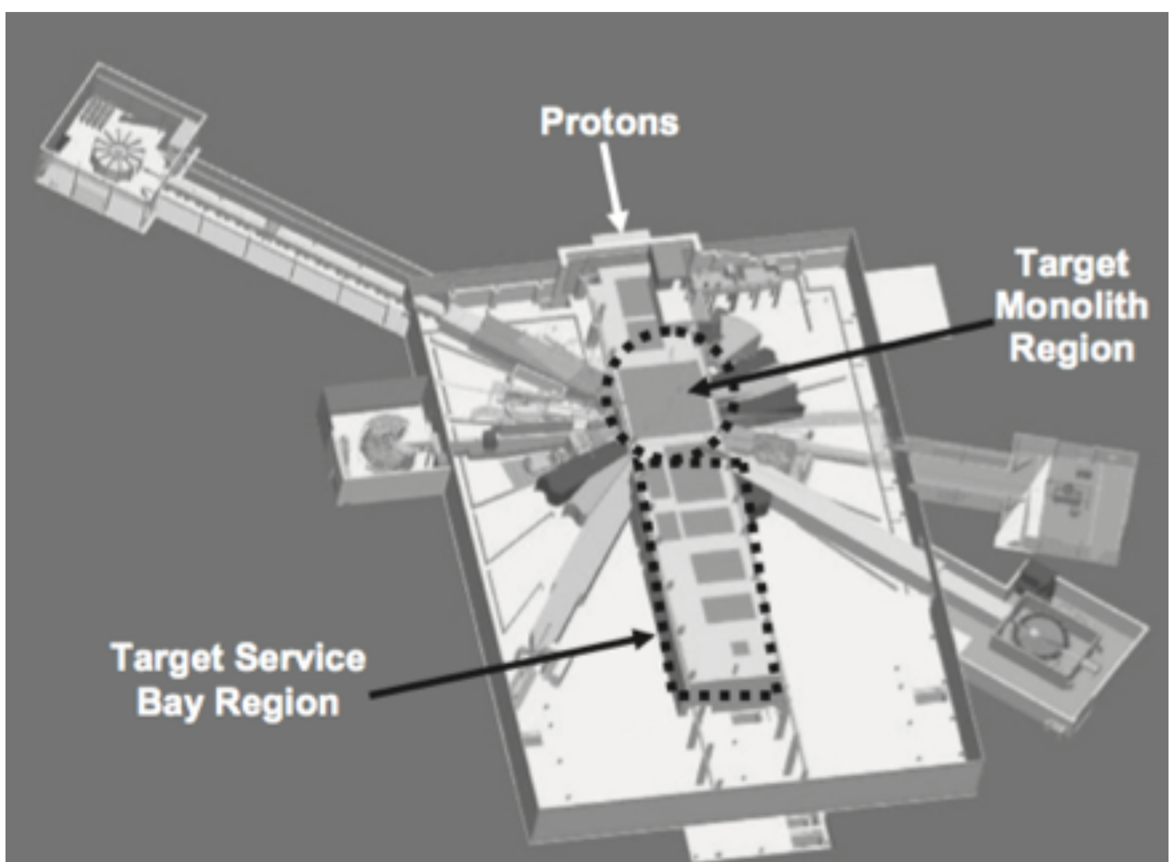
Enter: The COHERENT Collaboration

- Goal: **unambiguous observation** of CEνNS using multiple nuclear targets / detector technologies
  - Leverage detector advances from dark-matter community
  - Utilize intense, pulsed neutrino source provided by Spallation Neutron Source (SNS)
  - Use of different nuclear targets allows for measurement of characteristic N^2 cross-section dependence and some added analysis advantages
- Pioneering CEνNS detector: CsI[Na]

The Spallation Neutron Source







Most intense pulsed neutron source in the world

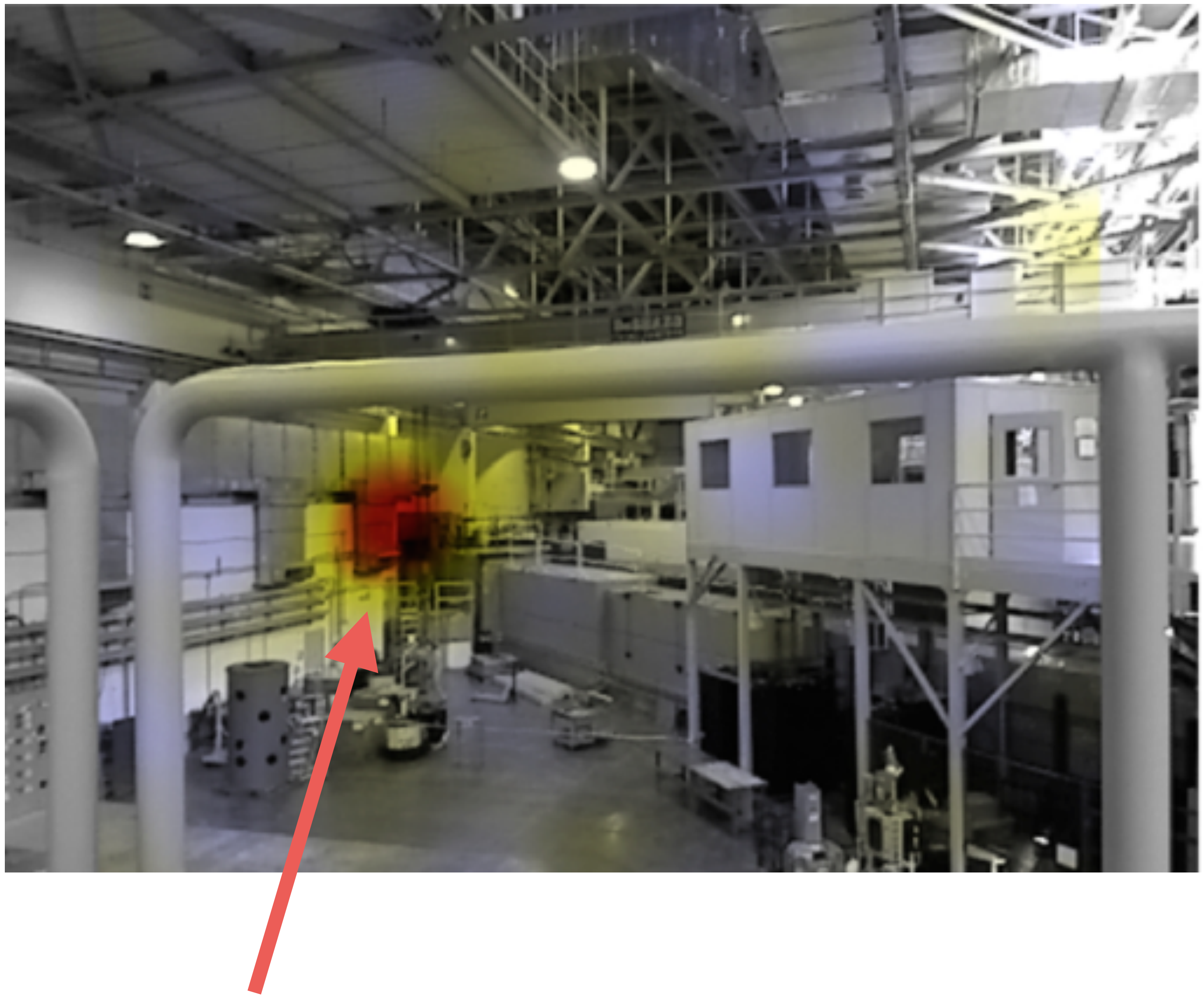
Images from: (top) https://neutrons.ornl.gov,
(bottom) J.R. Haines *et al.*, Nucl Instrum Meth A 764 (2014)
Figure from https://status.sns.ornl.gov/beam.jsp

Neutrons at the SNS

- Extensive neutron-background measurement campaign at various locations using several detector systems
- Leverages expertise and hardware from the various member institutions




Neutrons at the SNS



Coded-aperture neutron imager

- Built by ORNL collaborators
- Intended for nuclear security applications
- Takes a picture of target area “in neutrons”

Reminder: SNS is a billion-plus dollar facility dedicated to neutrons

Target is “visible” through monolith shielding on the instrument floor

Low-energy nuclear recoils from CEνNS

- Signature of CEνNS in a detector is a low-energy nuclear recoil
- To properly interpret collected data, it is of paramount importance that detector response at these *nuclear recoil* energies be well understood
- Uncertainty in detector threshold translates into uncertainty in measured cross section
  - Situation worse for heavier targets

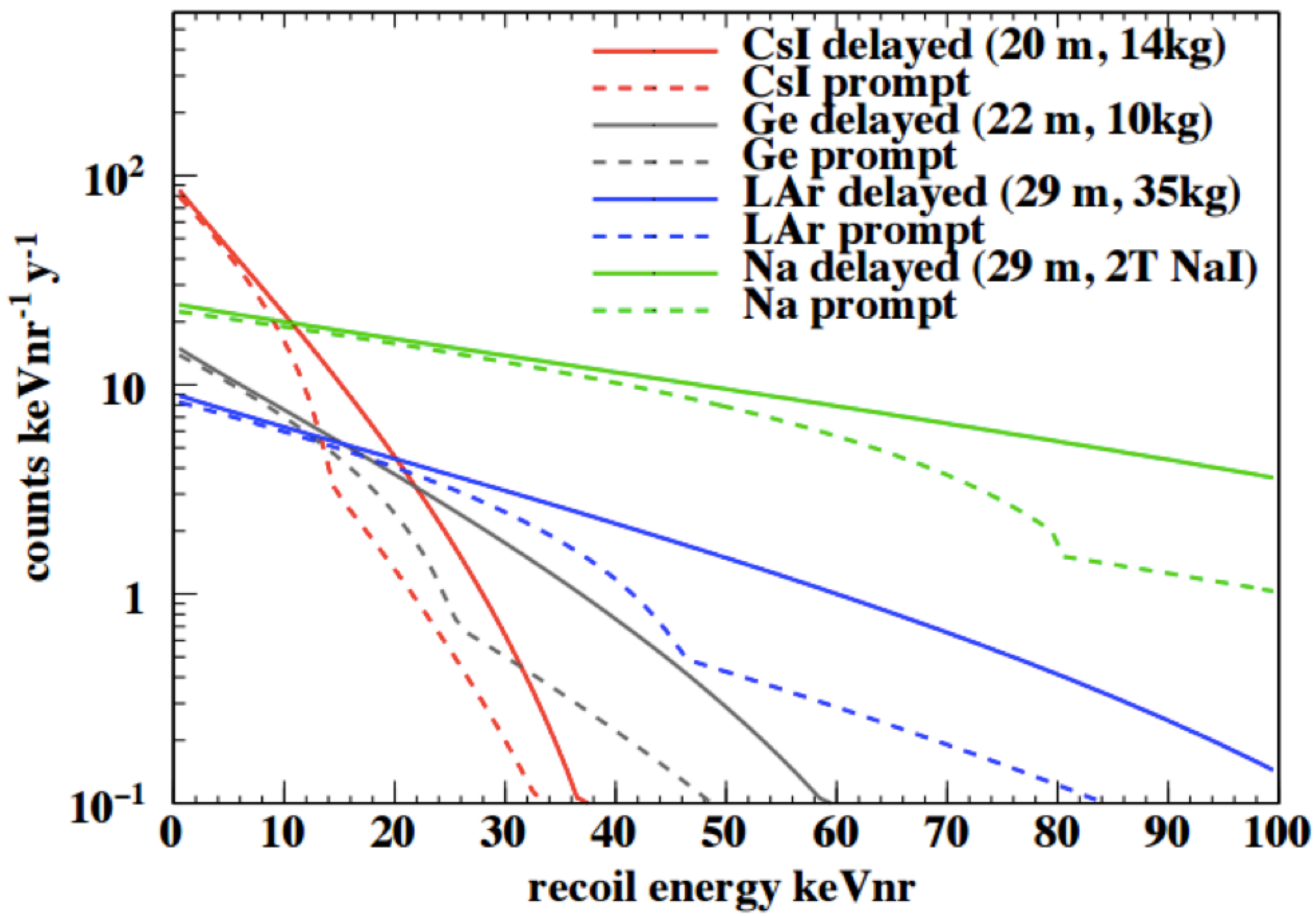
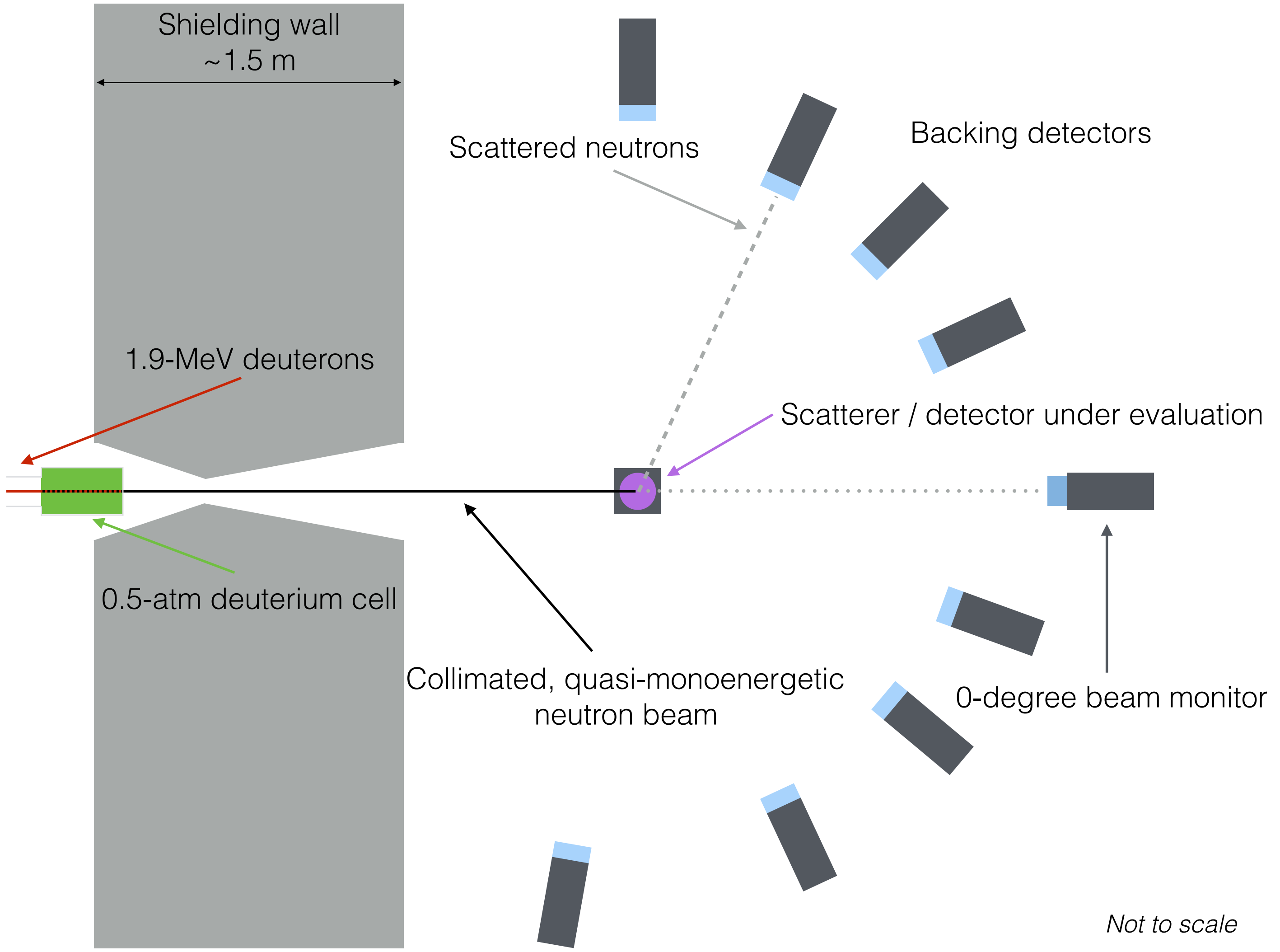


Figure from the COHERENT Collaboration

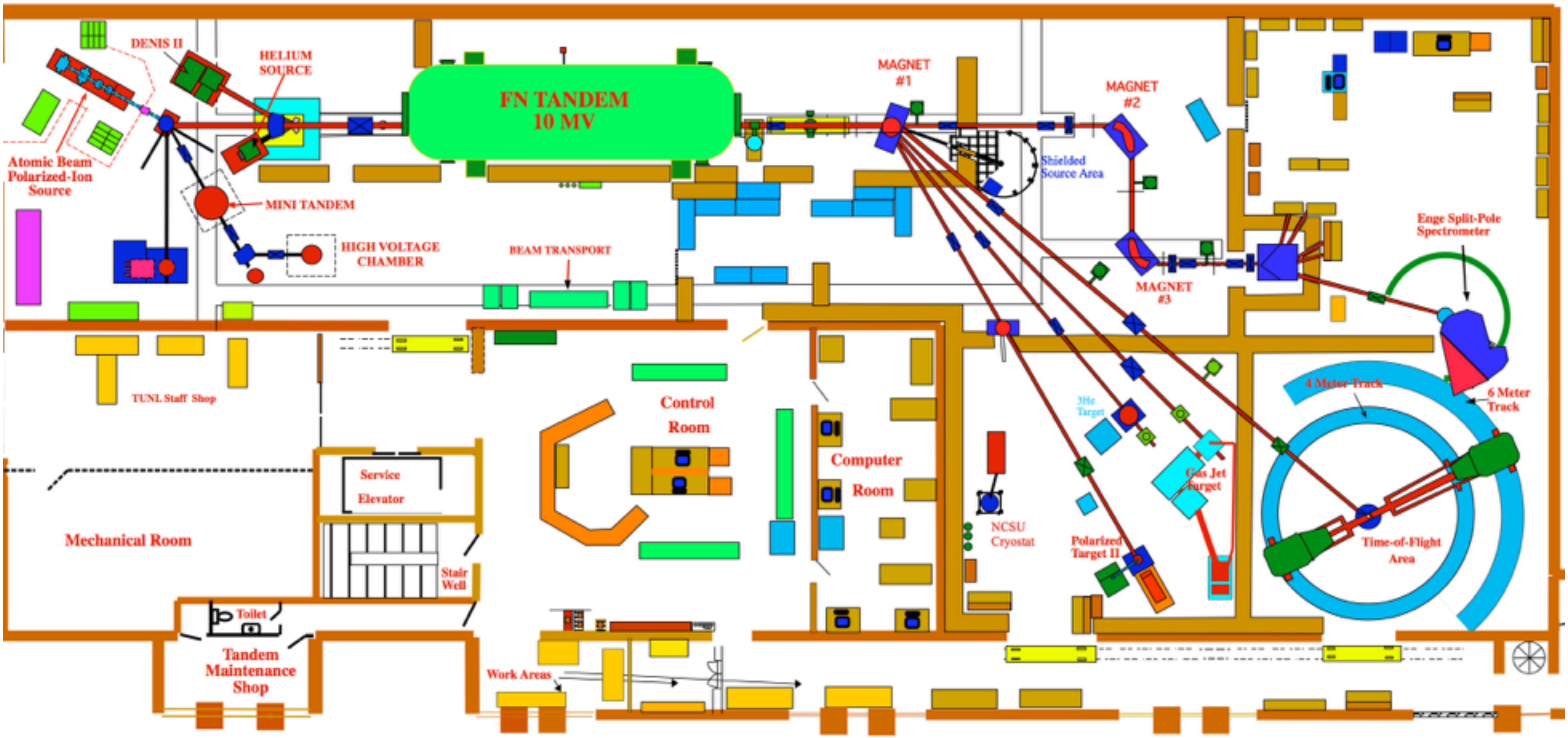
Low-energy nuclear recoils from neutron scattering

- Quasi-monoenergetic neutron beam scattered by central detector into fixed angles covered by “backing” detectors; nuclear recoil energy kinematically well defined



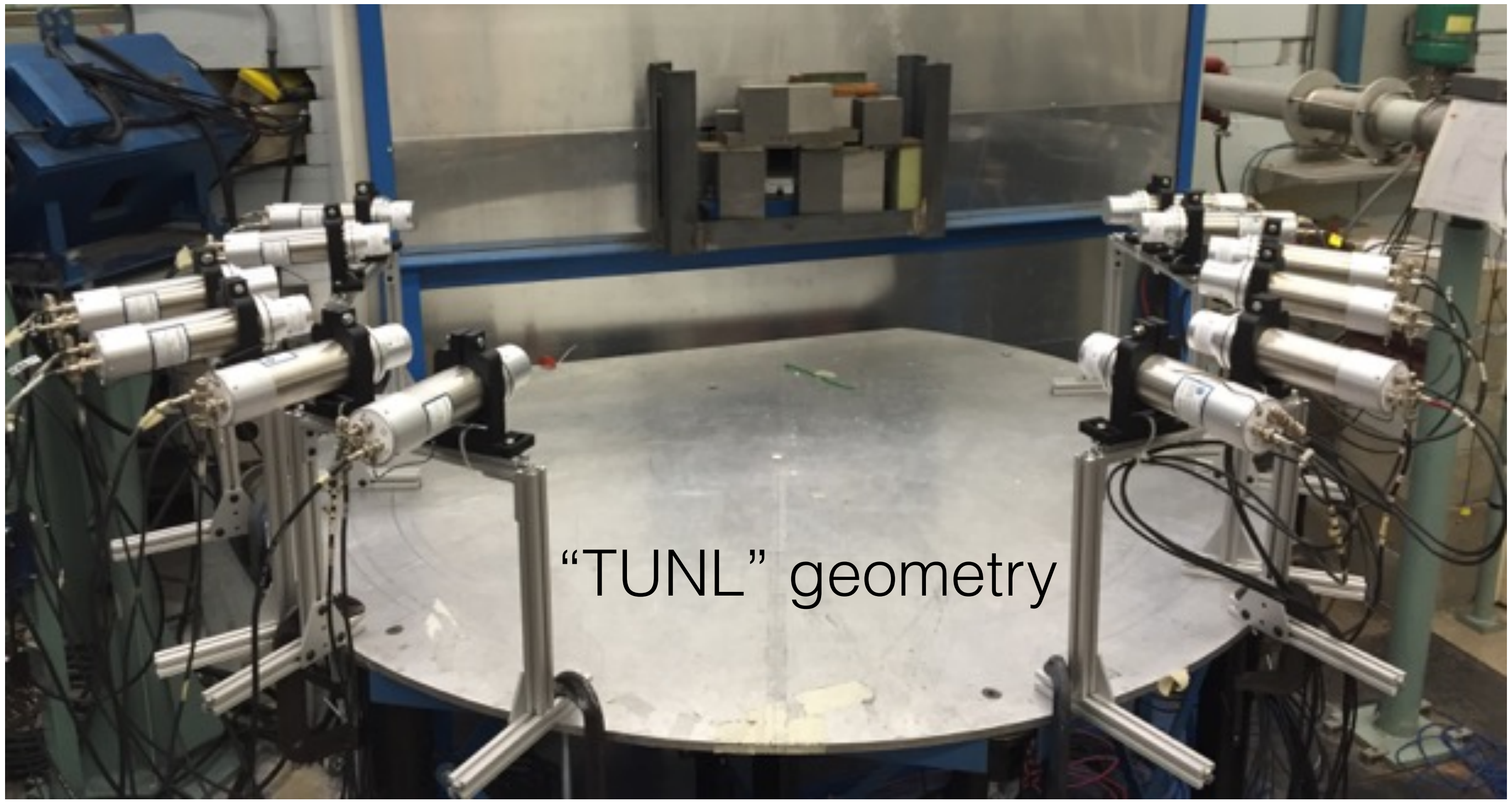
$$\Delta E = 2E_{\mathrm{n}} \frac{M_{\mathrm{n}}^2}{(M_{\mathrm{n}}+M_{\mathrm{T}})^2} \left(\frac{M_{\mathrm{T}}}{M_{\mathrm{n}}} + \sin^2\theta - (\cos\theta)\sqrt{\left(\frac{M_{\mathrm{T}}}{M_{\mathrm{n}}}\right)^2 - \sin^2\theta} \right)$$

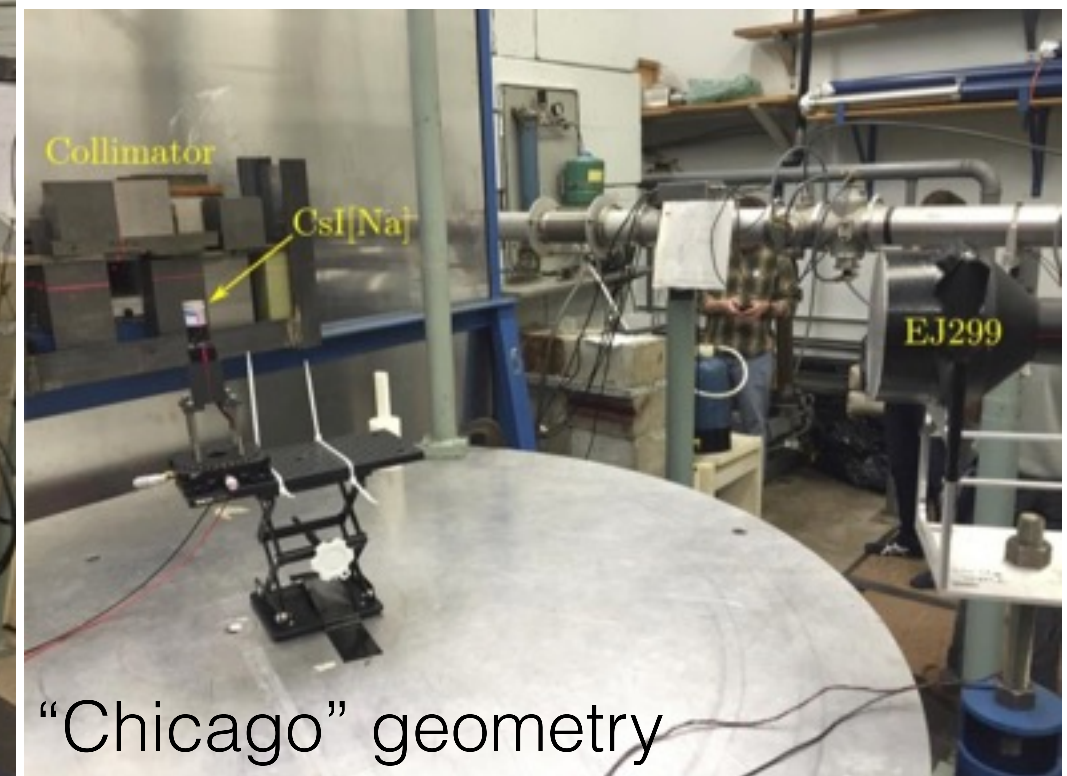
Tandem accelerator lab at TUNL



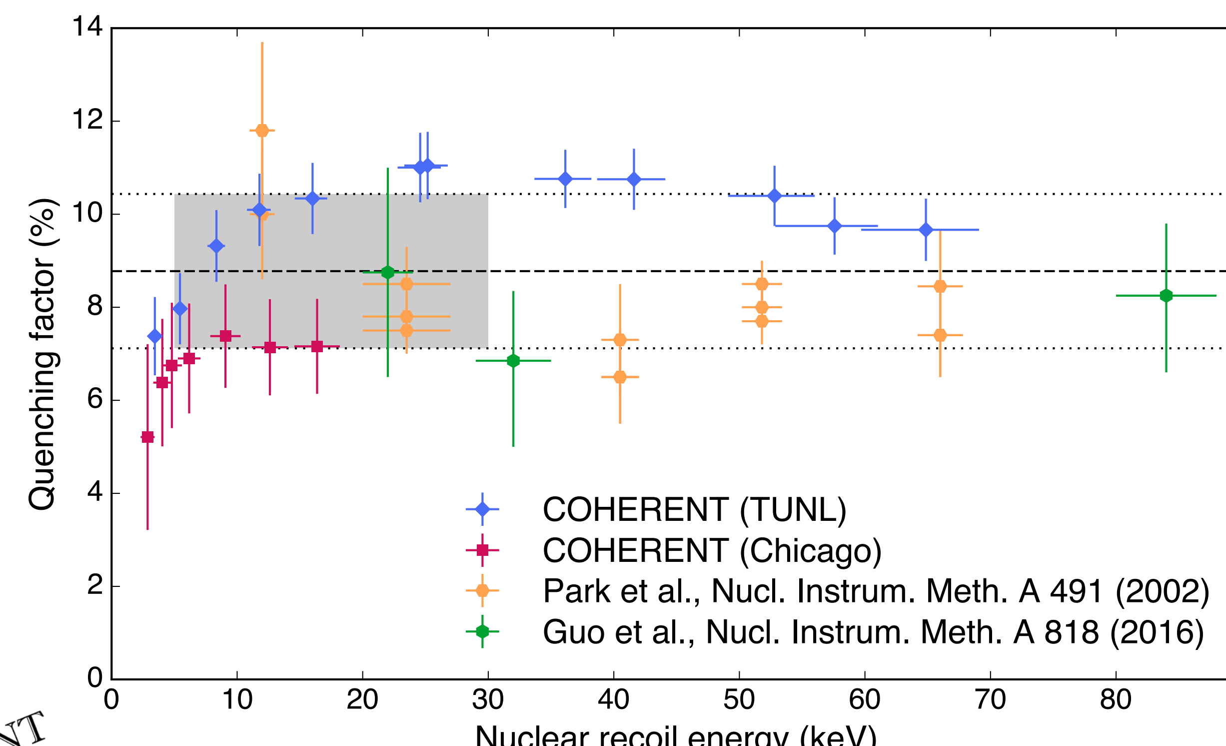
- 3 ion sources
- Beam can be bunched and chopped
- 10-MV maximum terminal voltage
- Numerous beam lines and experimental areas

Quenching factor measurements at TUNL

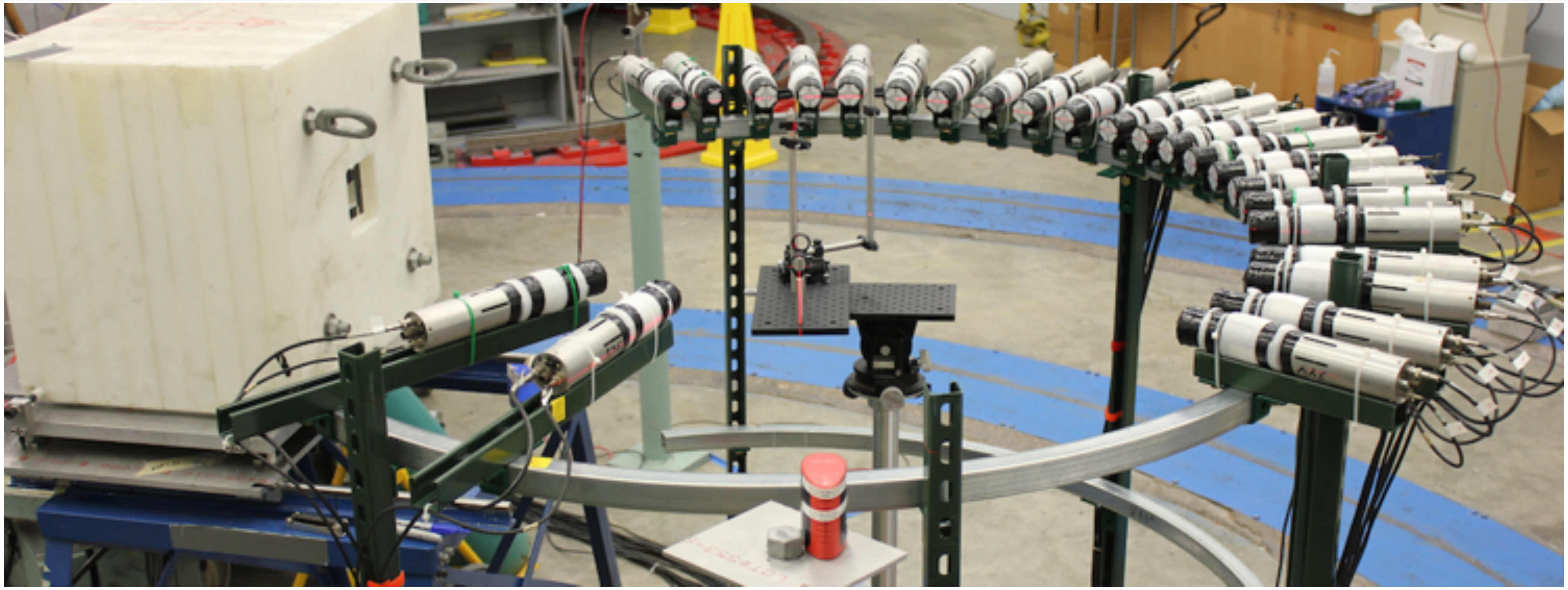


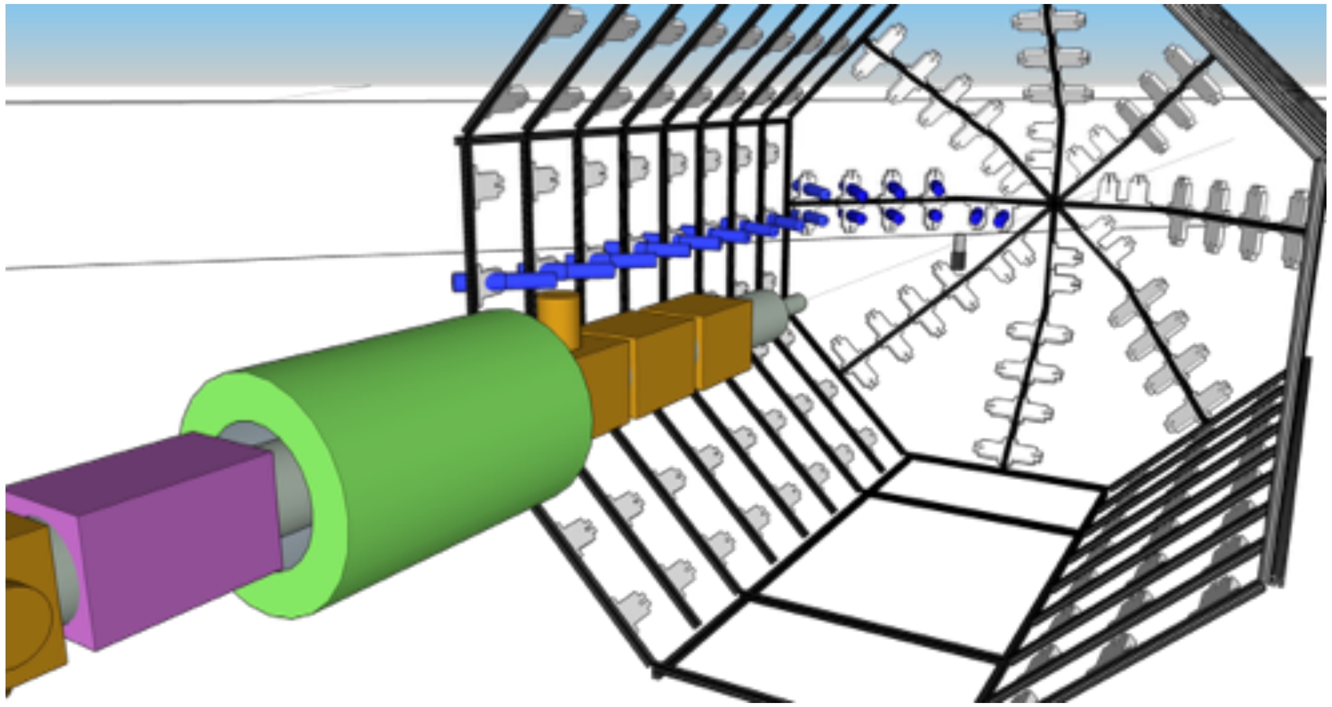


- Elastically scatter quasi-monoenergetic neutrons into “backing detectors” at known angles
  - Each backing detector associated with events having well-defined nuclear recoil energies
- Determine QF from global values in range from 5 to 30 keVnr: 8.78 ± 1.66%



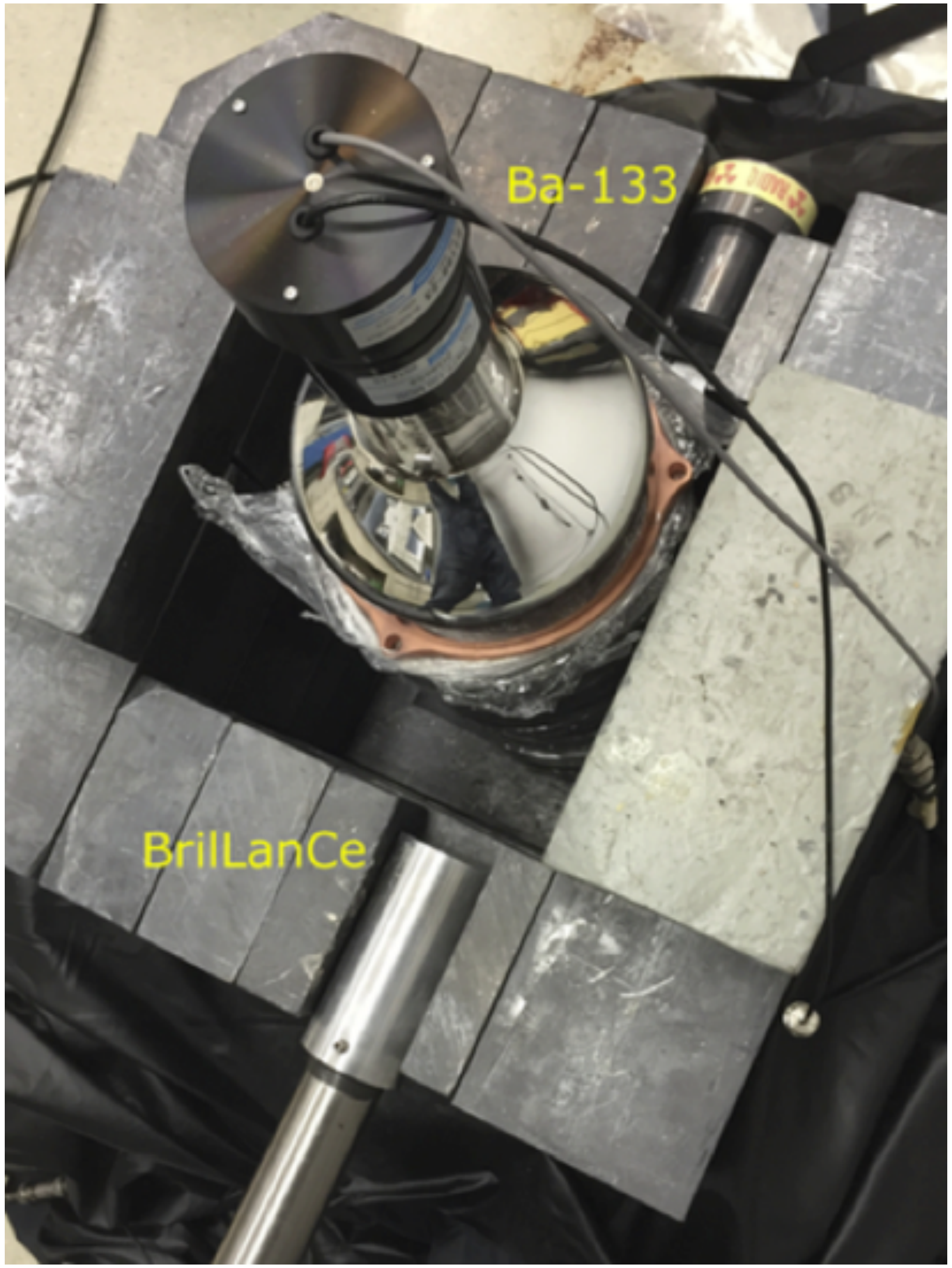
Quenching factor measurements at TUNL



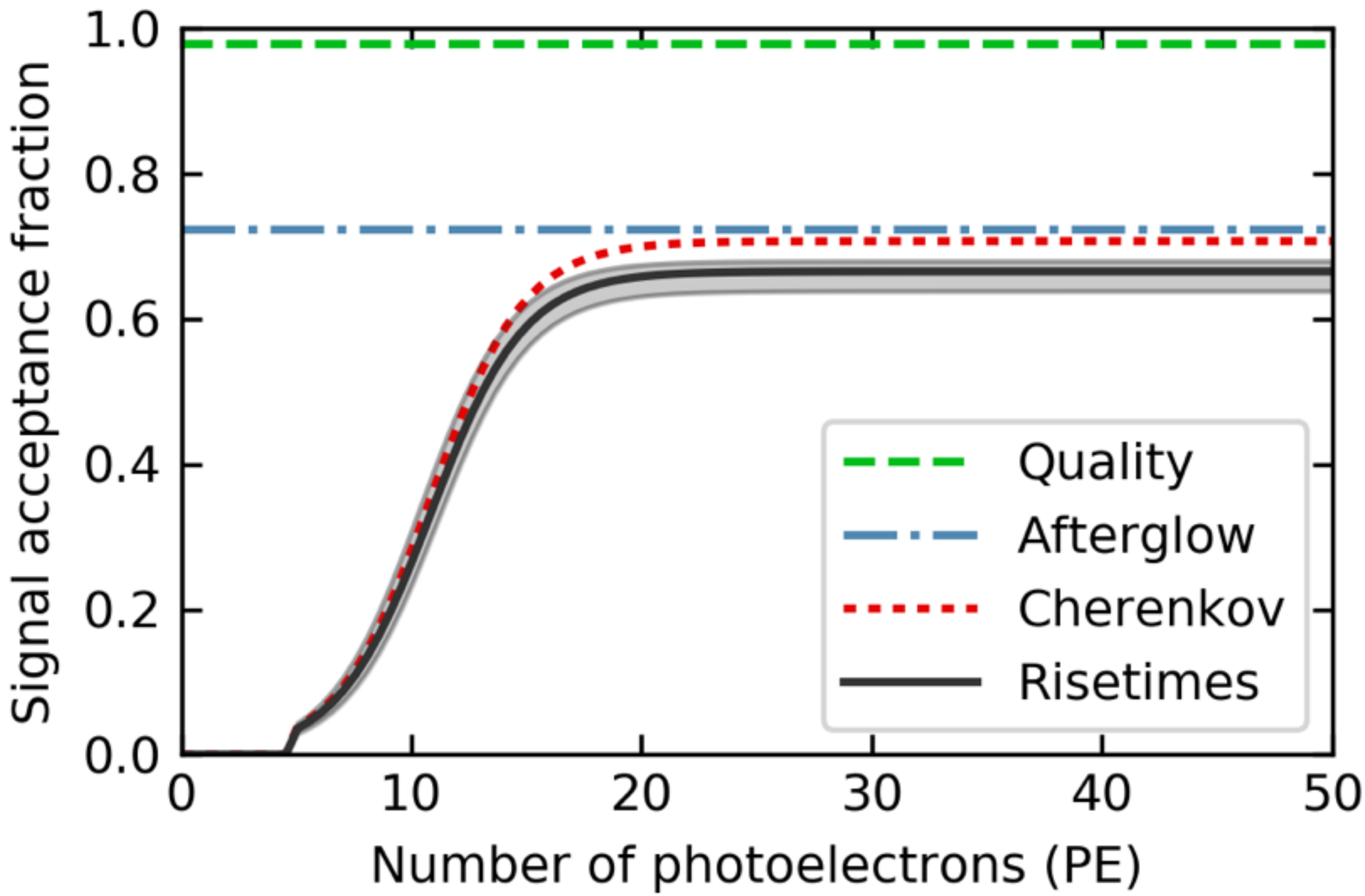


CEνNS with CsI[Na]

- Prior to deployment, careful characterizations in Chicago
- Uniformity along length confirmed
- Response to low-energy gamma rays assessed via small-angle Compton scattering
- Allows tuning of cuts to reject spurious events but accept low-energy depositions in the CsI

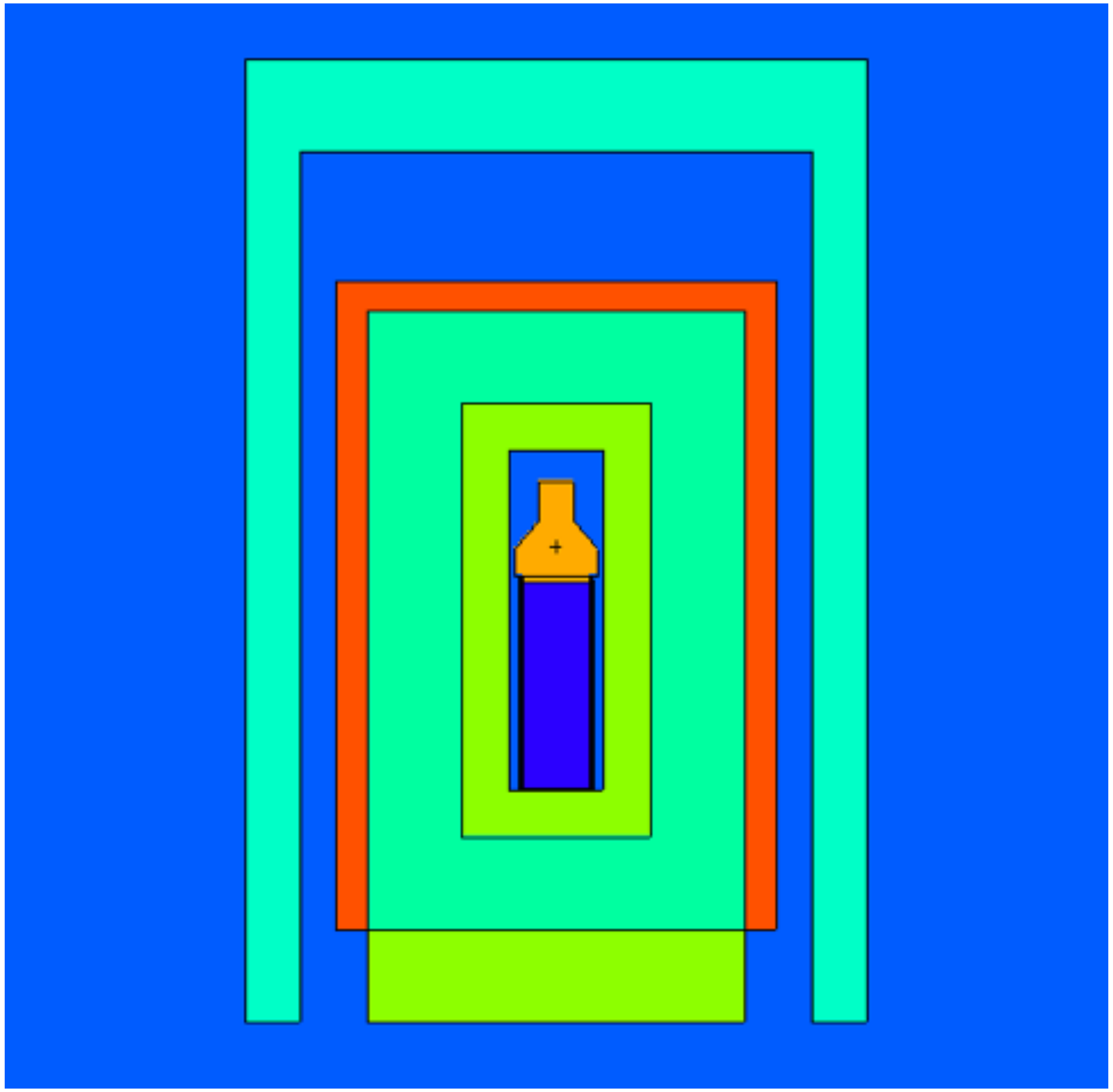


Analysis acceptance efficiency



CEνNS with CsI[Na]

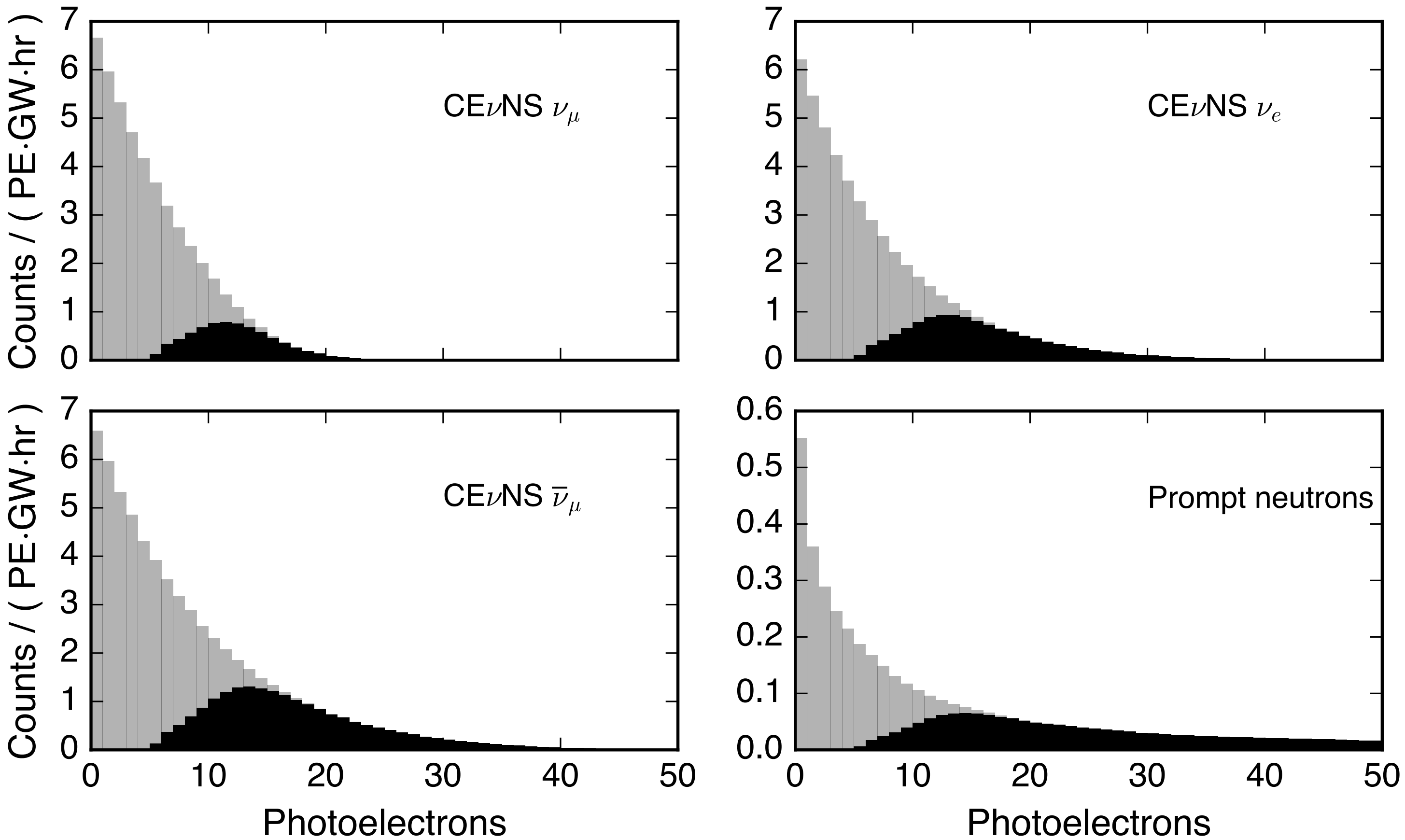
- Several layers of shielding
  - 7.5-cm-thick inner HDPE layer (addressing NINs)
  - 5-cm low-activity lead
  - 10-cm contemporary lead
  - 5-cm plastic-scintillator muon veto
  - 9+ cm water shielding on sides and top



Rate and shape estimates

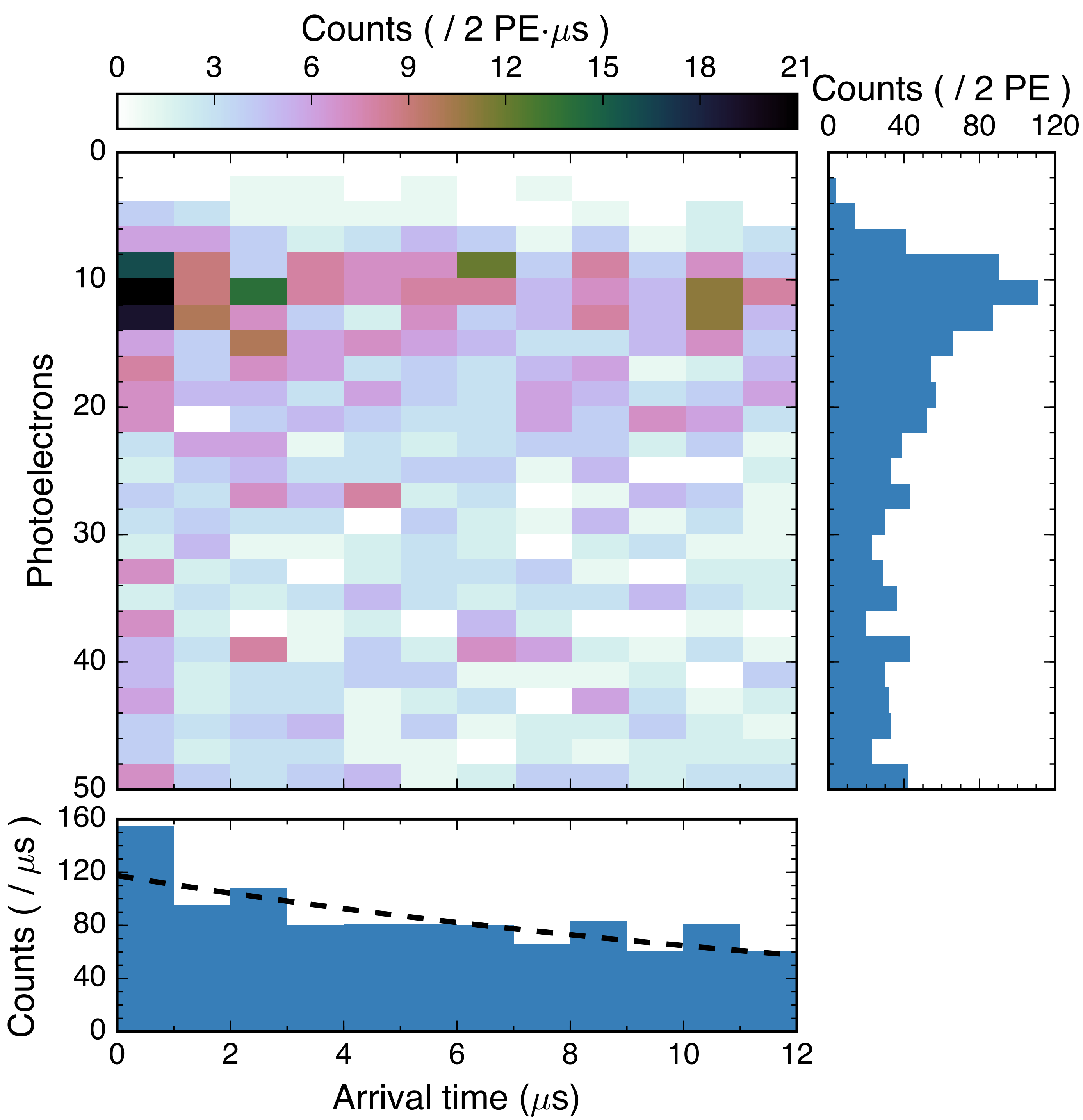
Raw CEvNS recoils

Observed CEvNS recoils



- Predict recoil distributions assuming SM - convert to photoelectrons using carefully determined calibrations
- *In situ* neutron measurements inform spectral model of prompt SNS neutrons
- Acceptance efficiency applied to models to produce beam-power-normalized PDFs in energy space

Background model for 2-D



- Background model informed by anti-coincidence dataset
- Use "factorized" approach taking advantage of uncorrelated energy/time features
- Exponential fit to time projection, then used with energy projection to define model

Stability and general health checks