

Coherent elastic neutrino-nucleus scattering (CE ν NS)

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Atomic nuclei as laboratories for BSM physics

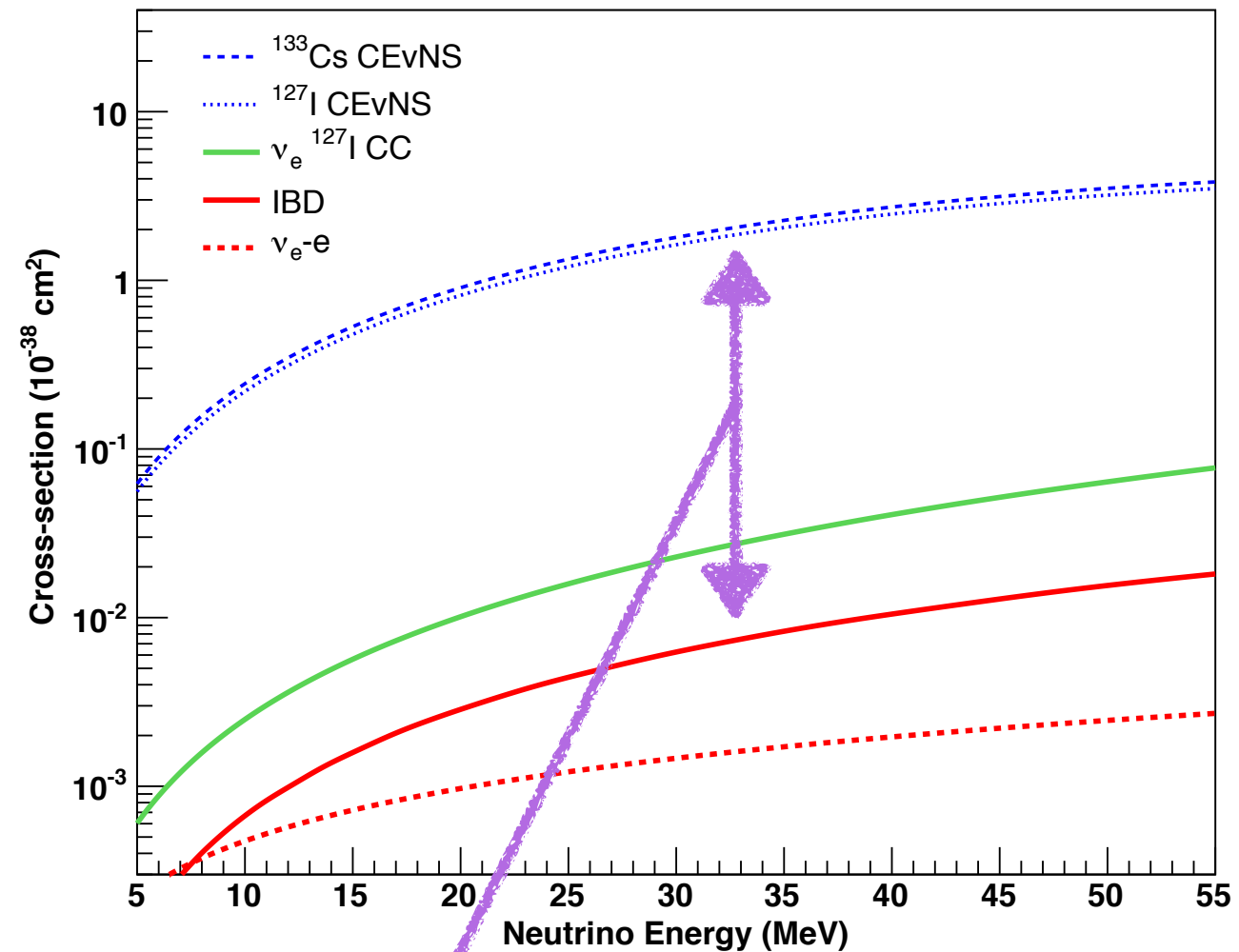
Trento, IT (ECT*)

15 April, 2019

Coherent elastic neutrino-nucleus scattering (CE ν NS)

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

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

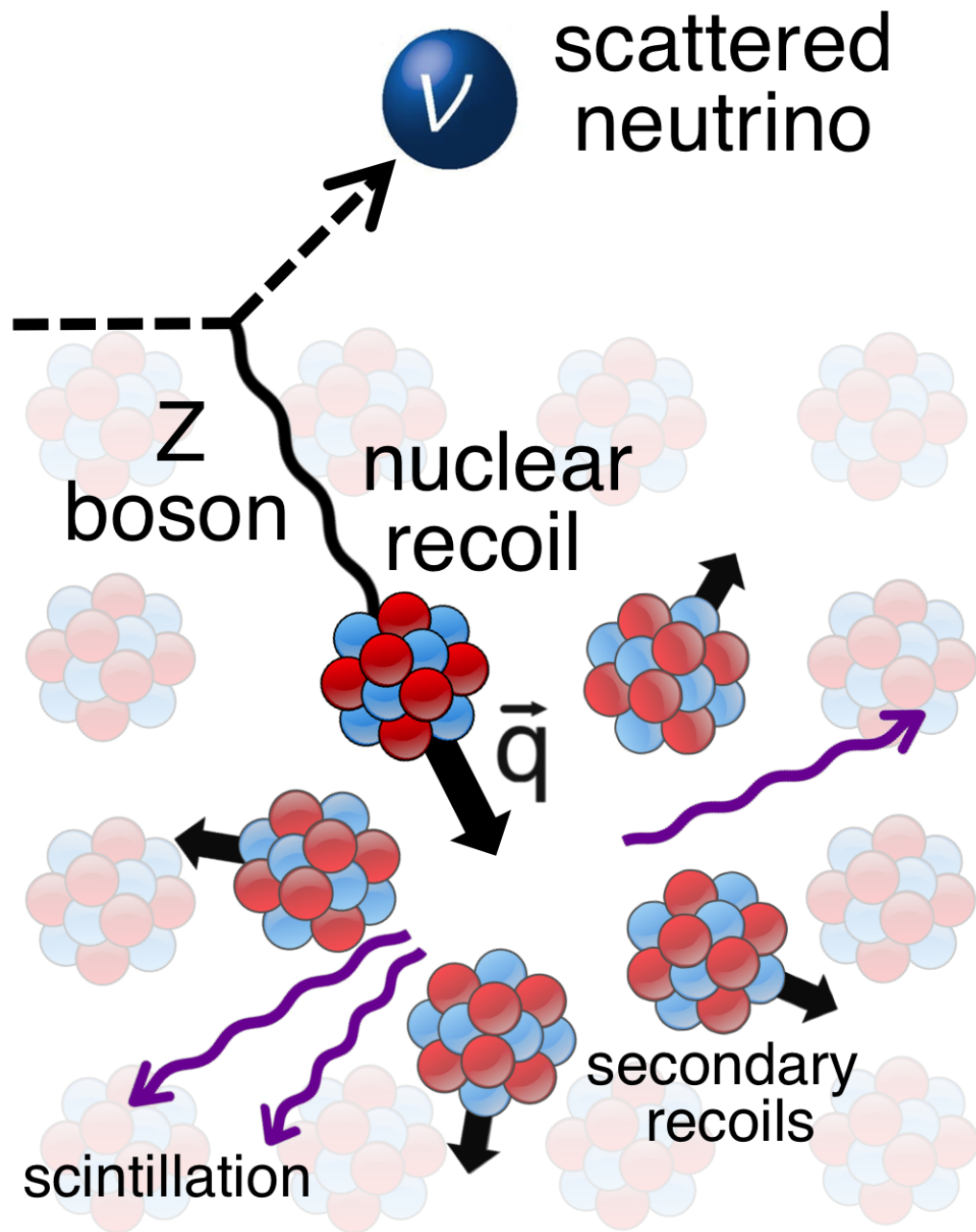


Cross section can be orders of magnitude larger than IBD process used to first observe neutrinos!

“An act of hubris”

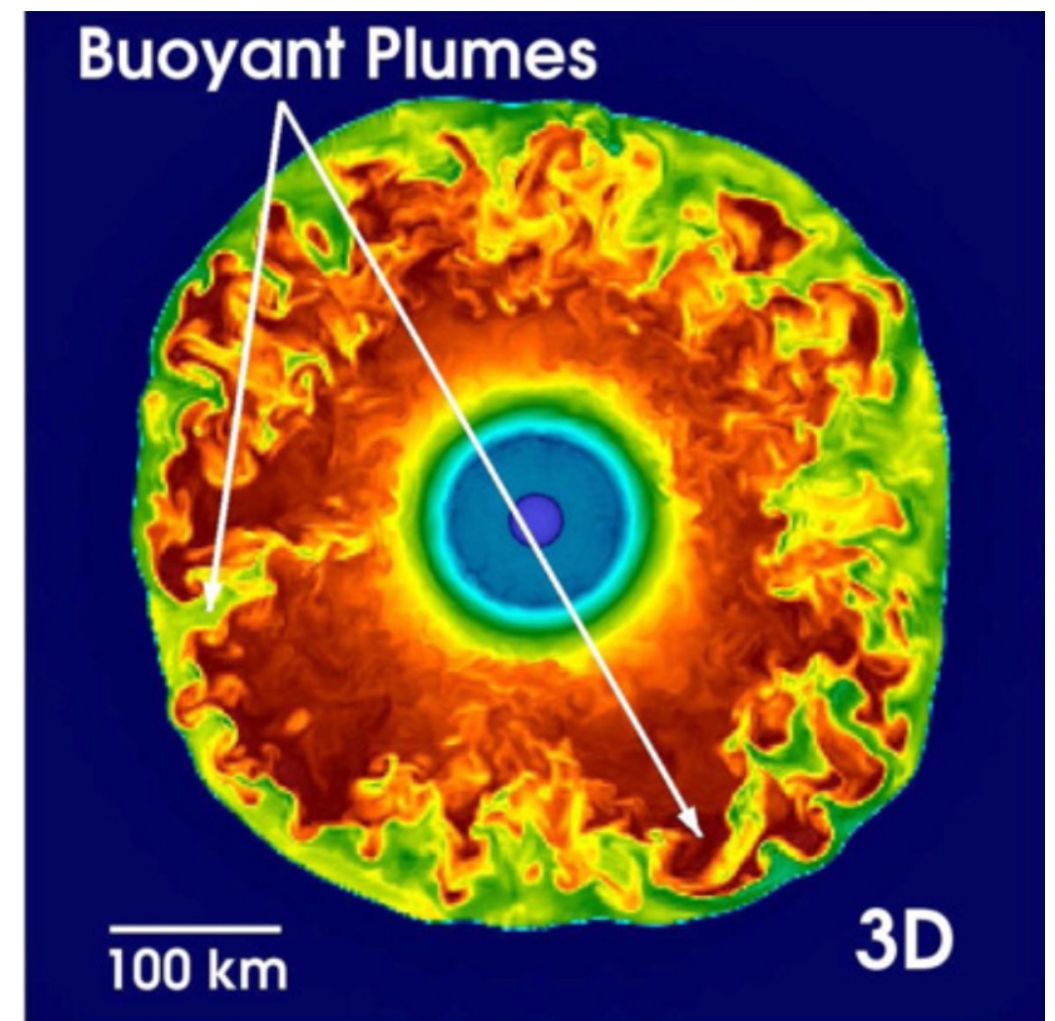
Freedman [1] noted that several factors combine to make CE ν NS an exceptionally challenging process to observe

- Need an appropriate source of neutrinos
- 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 CE ν NS



CE ν NS and supernovae

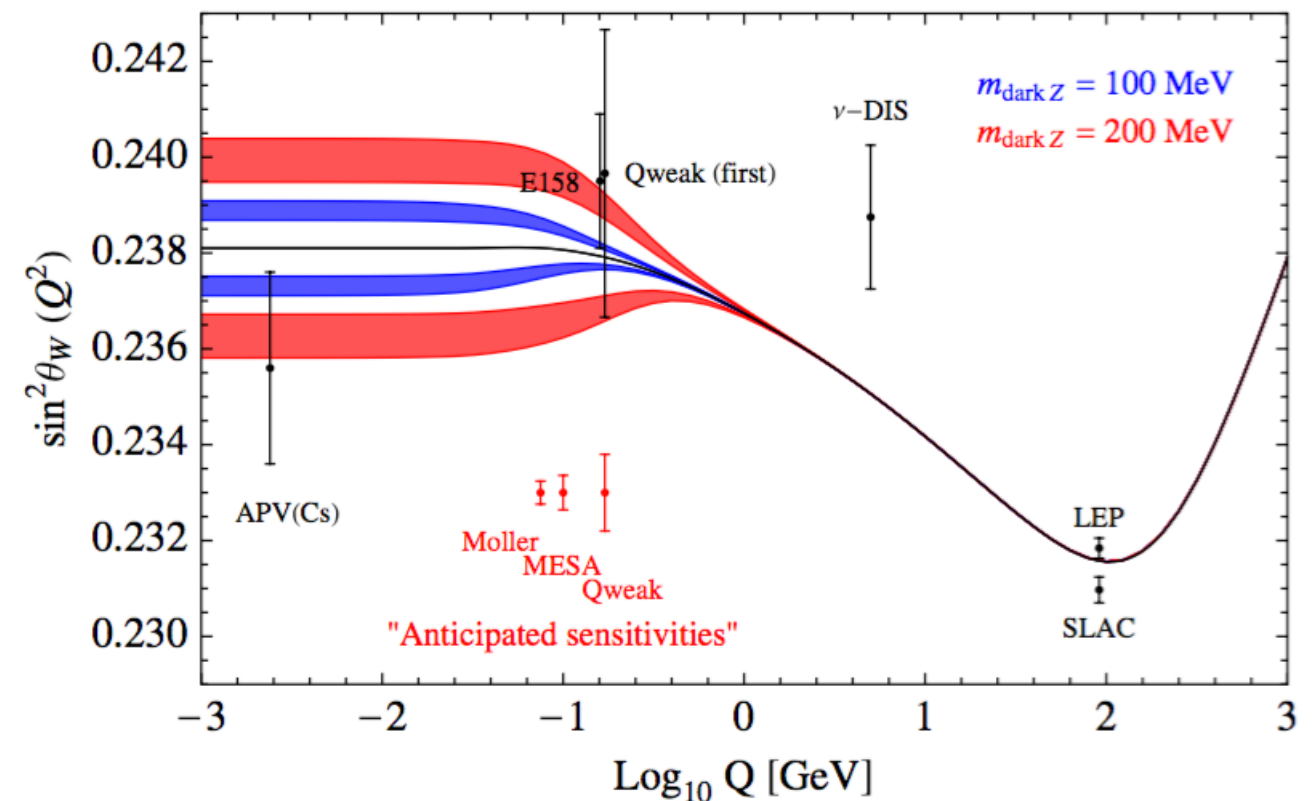
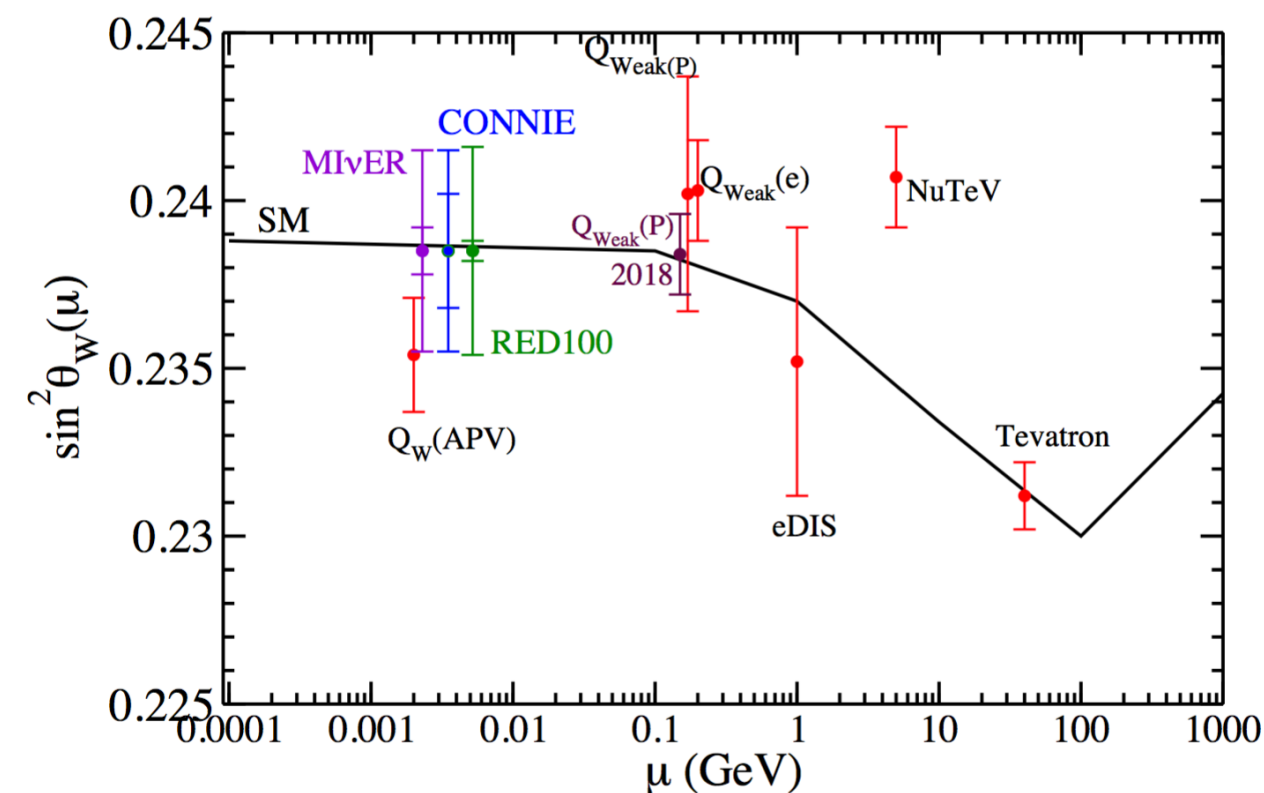
- Freedman immediately recognized CE ν NS could be significant in core-collapse supernovae
 - ~99% of radiated energy, $\sim 10^{53}$ ergs, carried in $\sim 10^{58}$ neutrinos
 - The comparatively large CE ν NS cross section presents a viable way to couple neutrino flux to stellar matter
- Supernova models generally failed to explode, but neutrinos could help
 - “Delayed shock” mechanism, where neutrinos re-energize the explosion, persists for a long time as a possible explanation [1]
- Neutrino opacity in certain regions may still be significantly influenced by CE ν NS [2,3]
- CE ν NS also presents a way to *detect* the neutrinos from supernovae [4]
 - Neutrinos can possibly carry information otherwise unavailable
 - CE ν NS-based detectors could see ~few events per ton for a CCSNe at 10 kpc [4]



- [1] H.A. Bethe, Rev. Mod. Phys 62 (1990)
[2] K.G. Balas, K. Langanke, G. Martínez-Pinedo, Prog. Part. Nucl. Phys. 85 (2015), 1503.08095
[3] S.W. Bruenn, A. Mezzacappa, Phys. Rev. D 56 (1997)
[4] C. Horowitz *et al.*, Phys. Rev. D 68 (2003)
Image from J.W. Murphy, J.C. Dolence, A. Burrows, Ap. J. 771 (2013)

Physics from CE ν NS

$$\frac{d\sigma}{dT} = \frac{G_F^2}{2\pi} M \left[2 - \frac{2T}{E_\nu} + \left(\frac{T}{E_\nu} \right)^2 - \frac{MT}{E_\nu^2} \right] \frac{Q_W^2}{4} (F(Q^2))^2$$



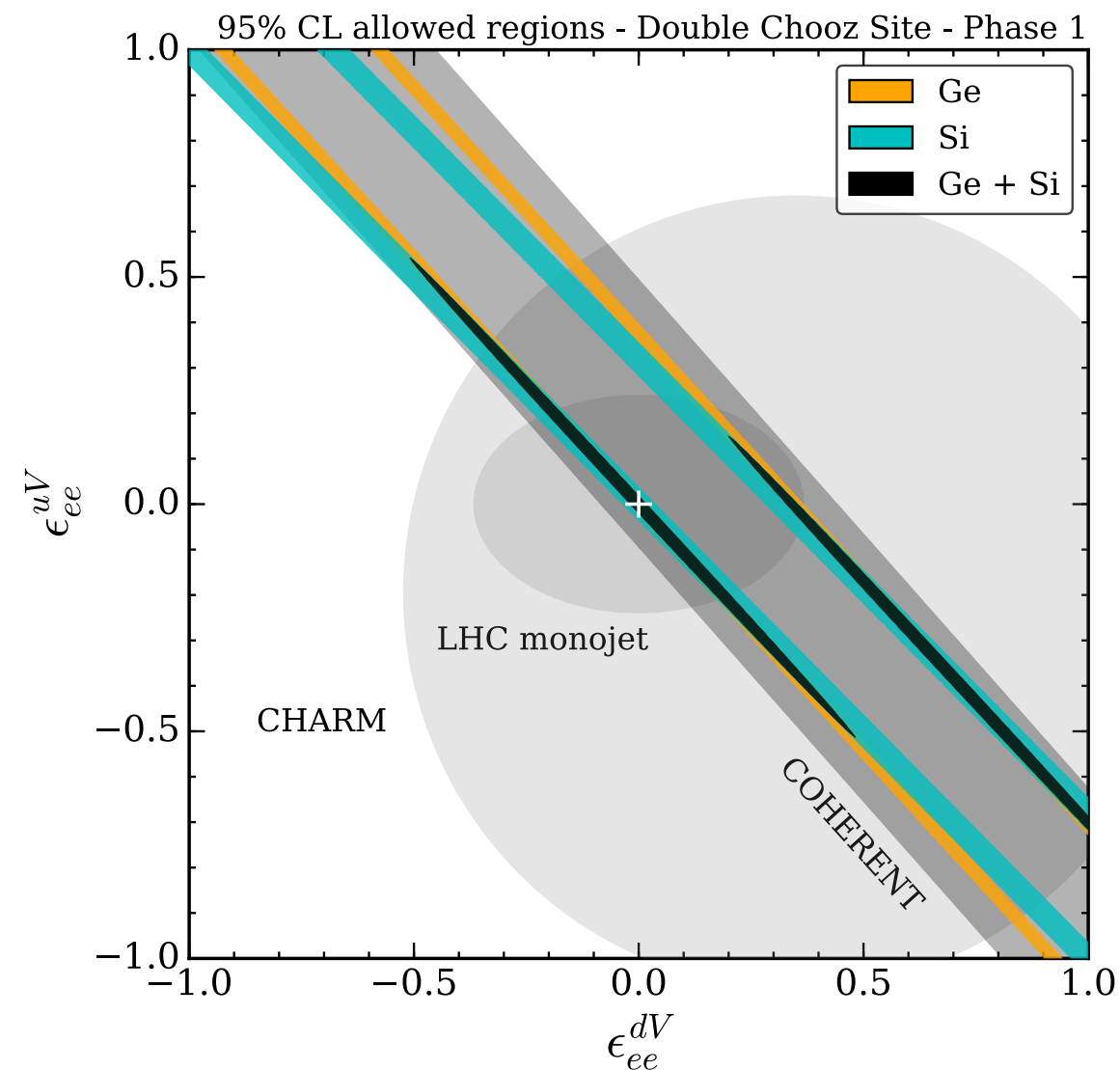
Weak mixing angle - Unique probe of Q_W^2 at a unique Q in a region sensitive to dark-Z boson models [1,2]

Neutral-current sterile neutrino search - all-flavor disappearance experiment [3,4]

- [1] B.C. Cañas *et al.*, 1806.01310
 - [2] H. Davoudiasl *et al.*, Phys. Rev. D 89 (2014)
 - [3] A.J. Anderson *et al.*, Phys. Rev. D 86 (2012)
 - [4] B.C. Cañas *et al.*, Phys. Lett. B (776) (2018), 1708.09518
- Left figure from [1], right from [2]

Physics from CE ν NS

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



Non-standard neutrino interactions - Additional terms added to SM lagrangian, with the effect of modifying the weak charge. Thus, this is manifested as an overall scaling of the expected CE ν NS cross section

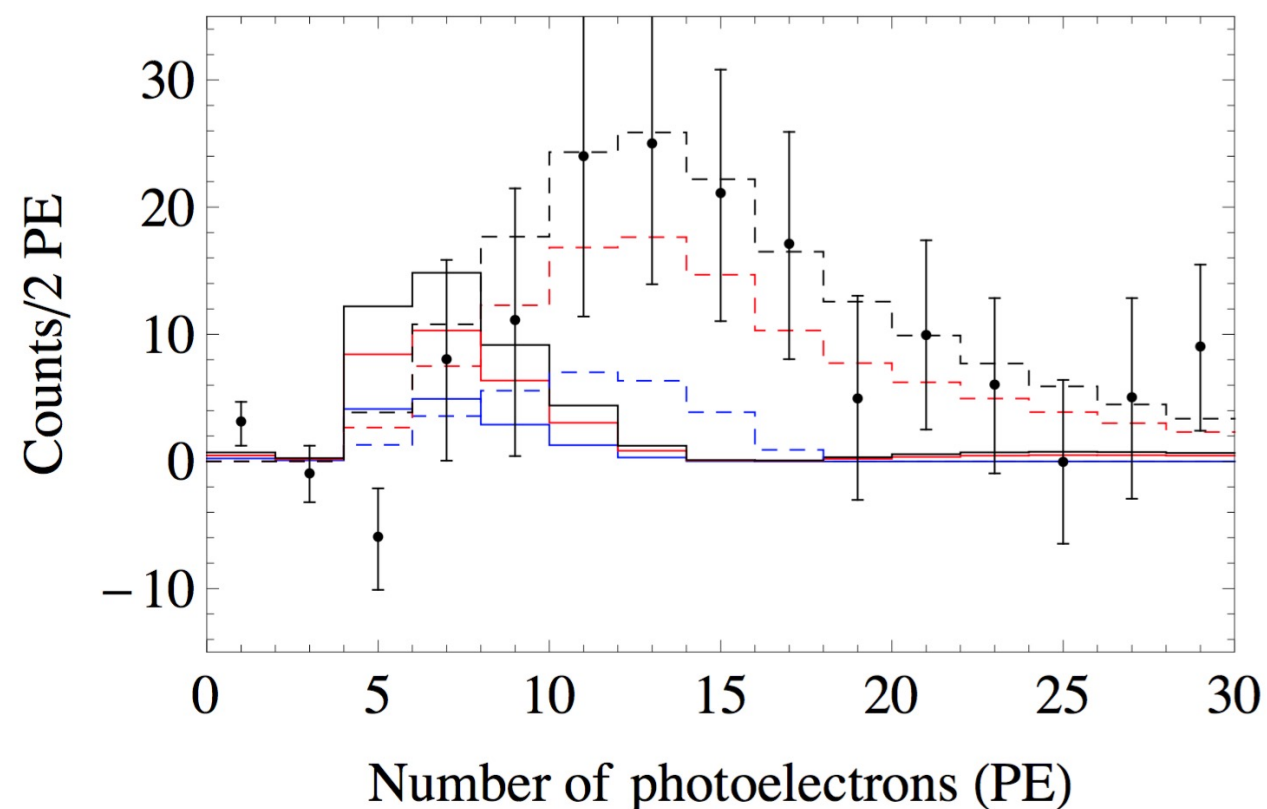
CE ν NS shows dependence on both non-universal and flavor-changing neutral currents.

Targets with different N/Z ratios provide degeneracy-breaking strength in u and d couplings shown in figure at left

These assume heavy mediator!

Physics from CE ν NS

$$Q_{\alpha,\text{NSI}}^2 = \left[Z \left(g_p^V + \frac{3g^2}{2\sqrt{2}G_F(Q^2 + M_{Z'}^2)} \right) + N \left(g_n^V + \frac{3g^2}{2\sqrt{2}G_F(Q^2 + M_{Z'}^2)} \right) \right]^2$$



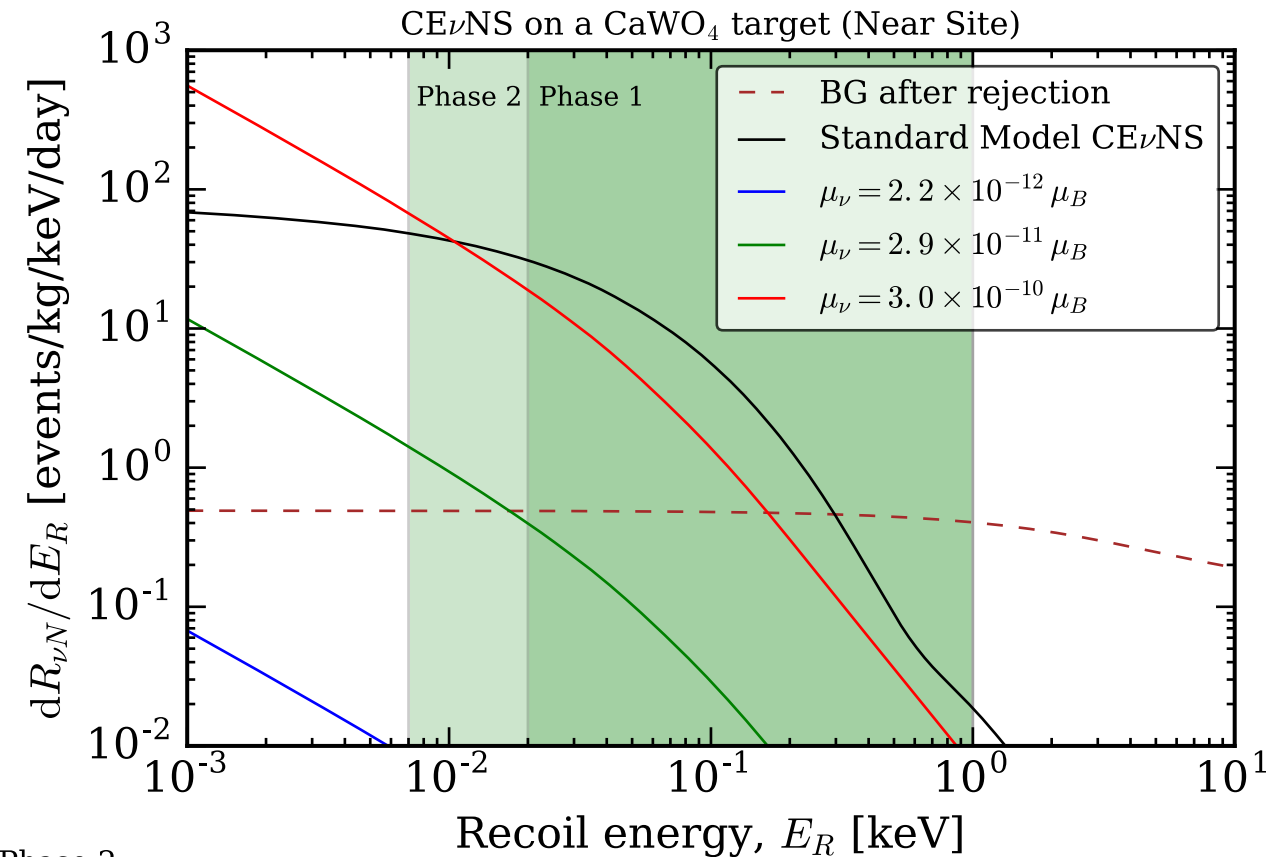
- With a light mediator, the NSI contributions are manifested somewhat differently
- Weak charge still modified, but now there is a Q^2 dependence
 - Result is a spectral distortion, not an overall rate scaling [1]

Physics from CE ν NS

Fundamental properties of neutrinos -

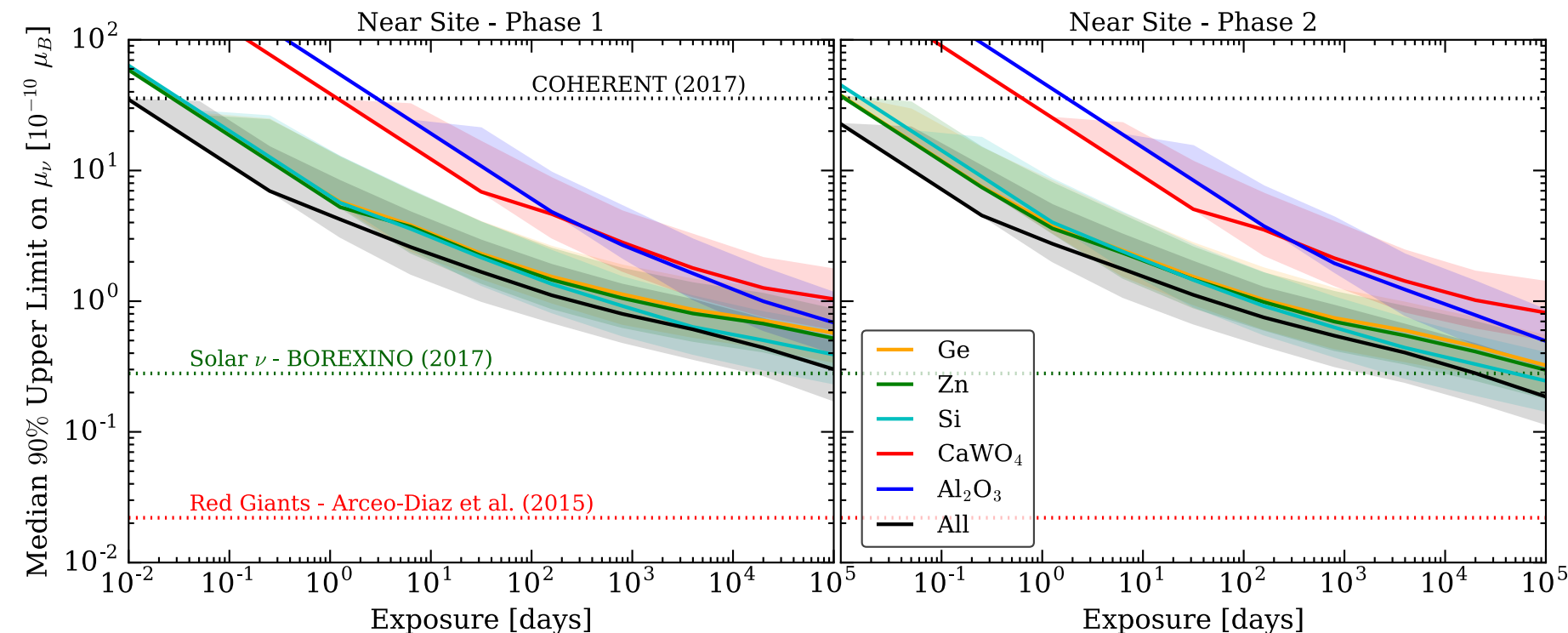
sensitivity to neutrino electromagnetic properties (e.g., magnetic moment, charge radius) [1,2] *and* lift degeneracy of “dark side” solution to θ_{12} that would complicate mass-order determination from oscillation experiments [3]

Plots show predictions for contributions from neutrino magnetic moment and sensitivity for specific experimental cases



Magnetic moment introduces spectral change at very-low energy recoils

Existing limits from BOREXINO and red giant cooling are hard to match



[1] K. Scholberg, Phys. Rev. D 73 (2006)

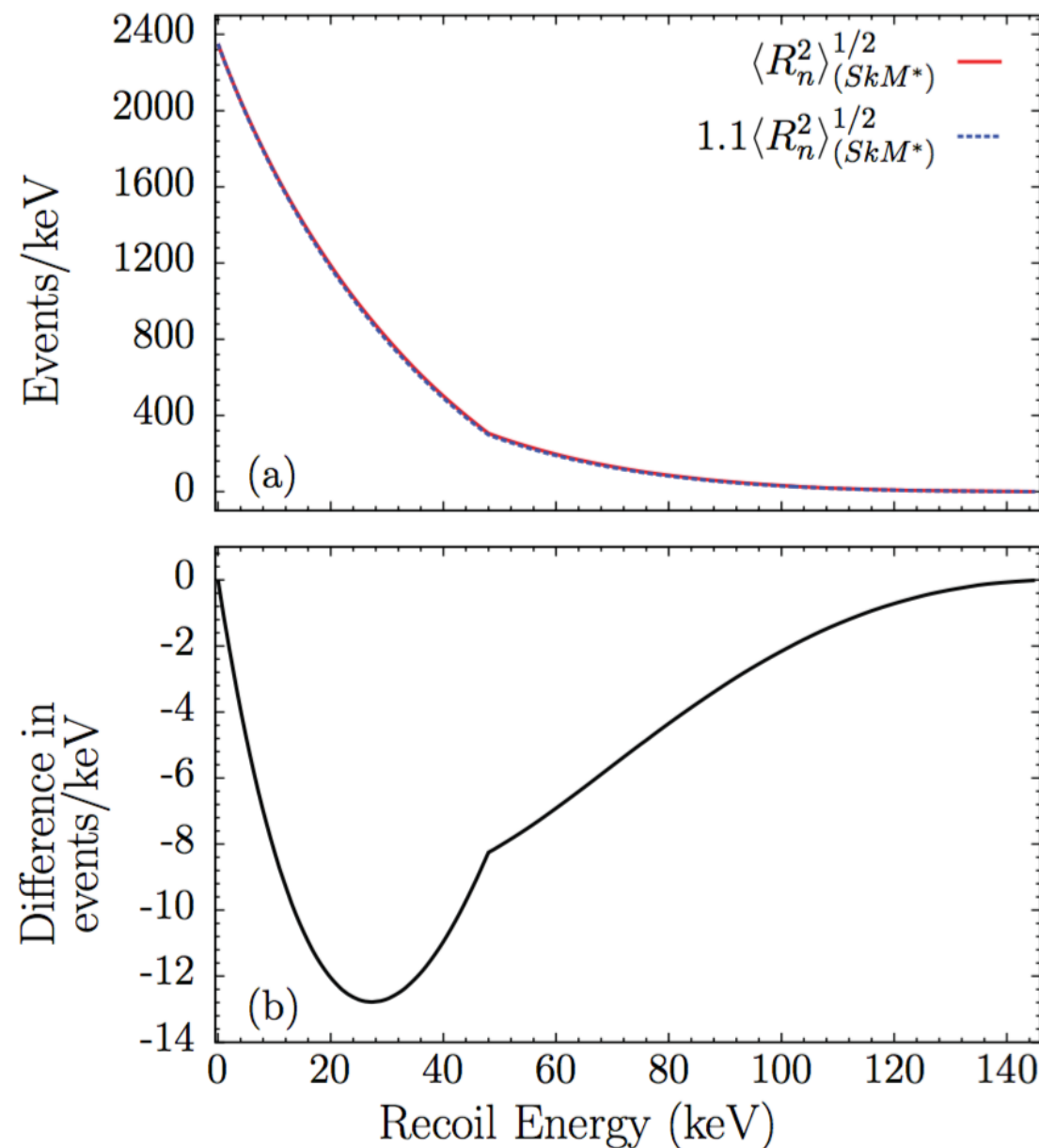
[2] J. Billard, J. Johnston, B. Kavanagh, arXiv:1805.01798

[3] P. Coloma *et al.*, Phys. Rev. D 96 (2017)

Figs from [2]

CE ν NS as a tool for nuclear physics

- CE ν NS is sensitive to the distribution of neutrons in nuclei



- Can be used to measure this distribution [1], which is otherwise very challenging
- Won't be competitive with purpose-built experiments (e.g., PREX and CREX) in foreseeable future, but more flexible - can (somewhat) easily measure neutron distribution in different nuclei
- This input can refine nuclear structure models and improve understanding of neutron star EoS [2]
- CE ν NS-based monitoring of nuclear reactors may be possible, creating new tools for non-proliferation
 - CE ν NS allows for miniaturization of neutrino detectors
 - Can possibly extend reach below IBD threshold [3]

[1] K. Patton *et al.*, Phys. Rev. C 86 (2012)

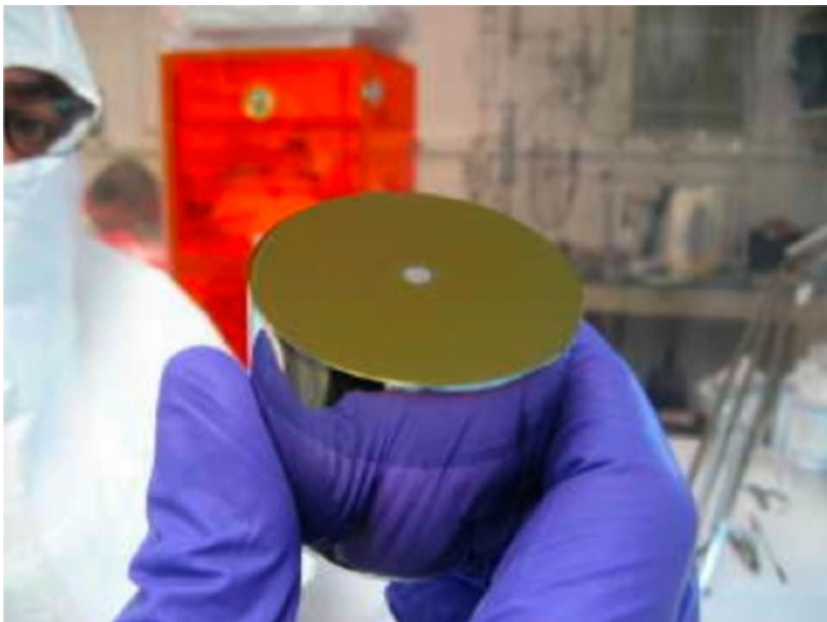
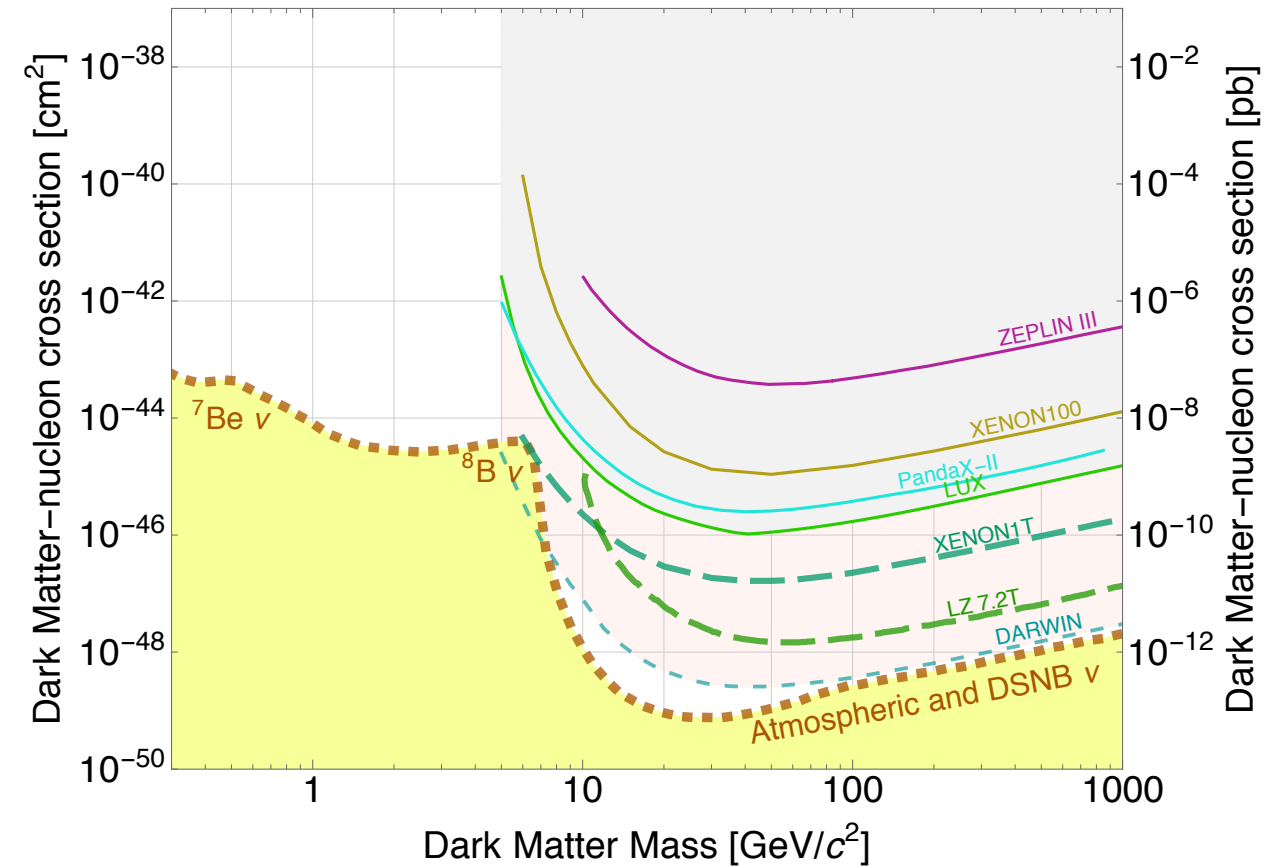
[2] C. Horowitz & J. Piekarewicz, Phys. Rev. Lett. 86 (2000)

[3] B.K. Cogswell & P. Huber, Sci. Glob. Sec. 24 (2016)

Figure from [1]

CE ν NS becomes a background

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

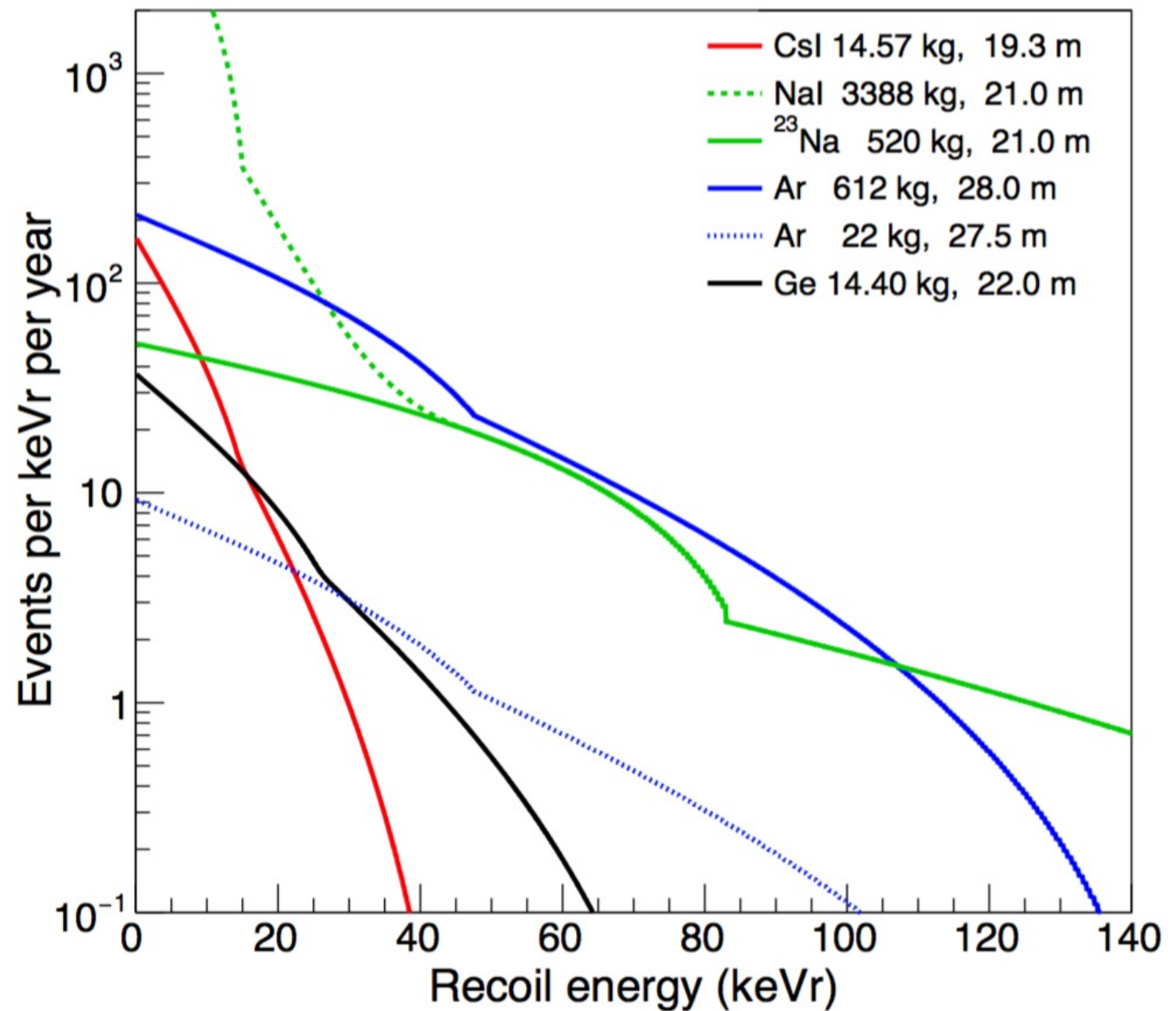


P.S. Barbeau, Ph.D. thesis (UChicago 2009)

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

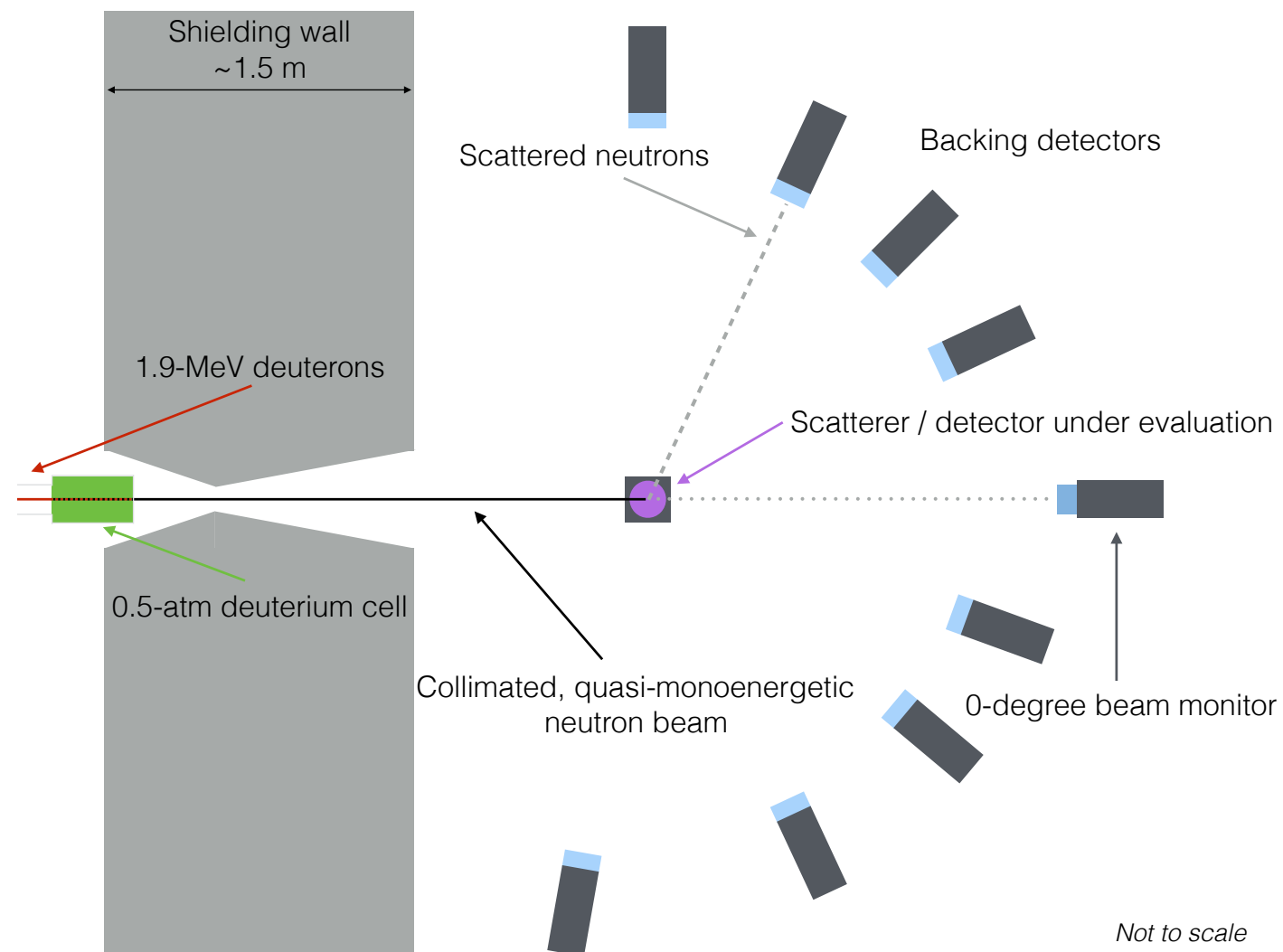
Low-energy nuclear recoils from CE ν NS

- Signature of CE ν NS 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



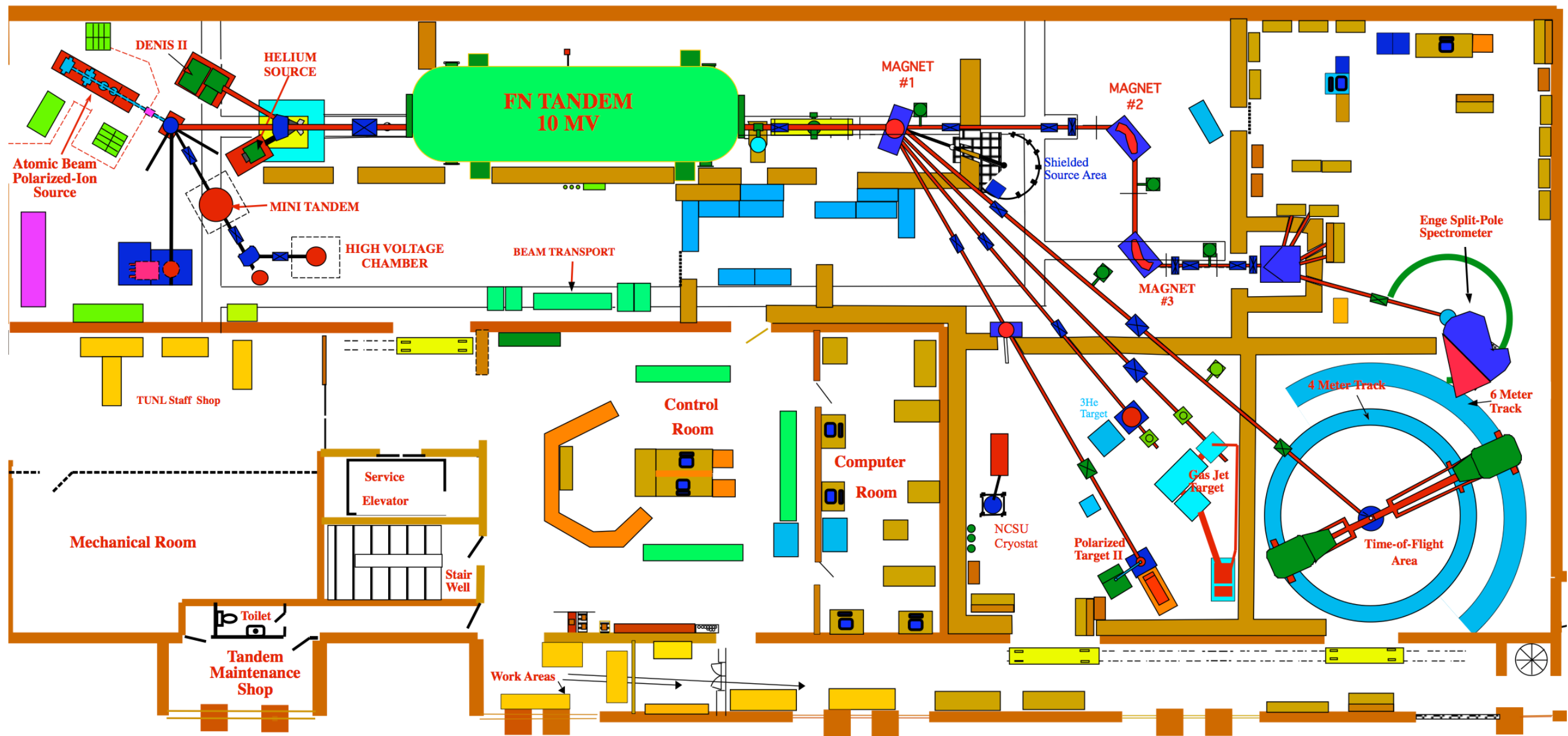
Low-energy nuclear recoils from neutron scattering

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



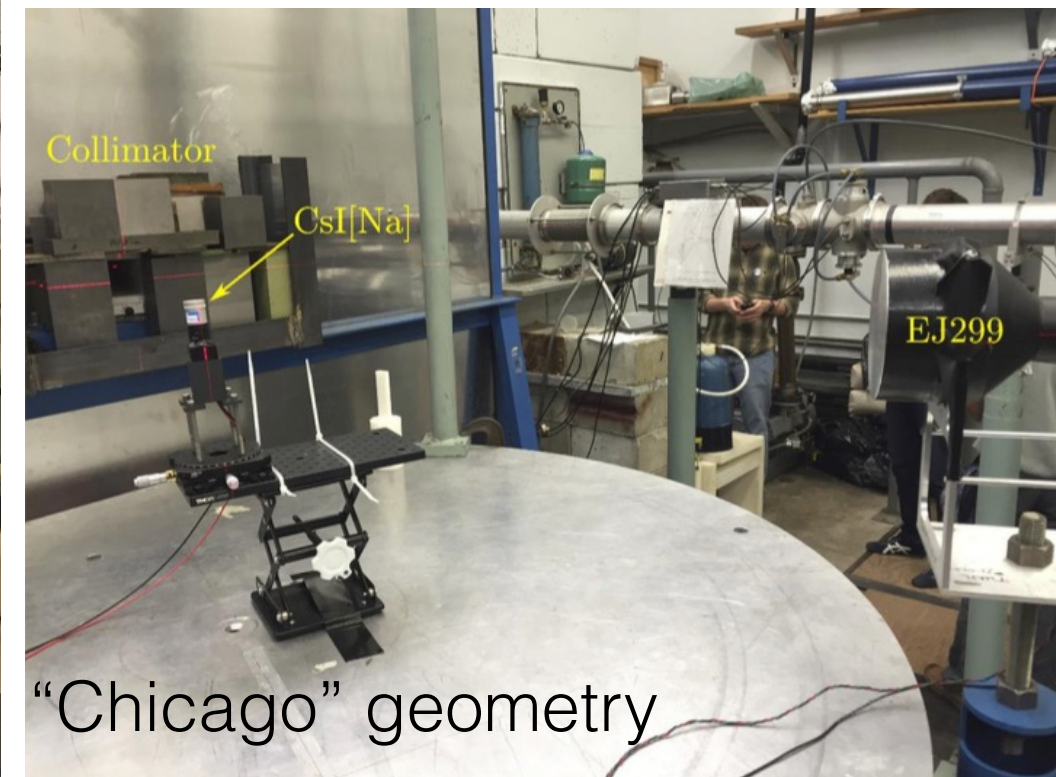
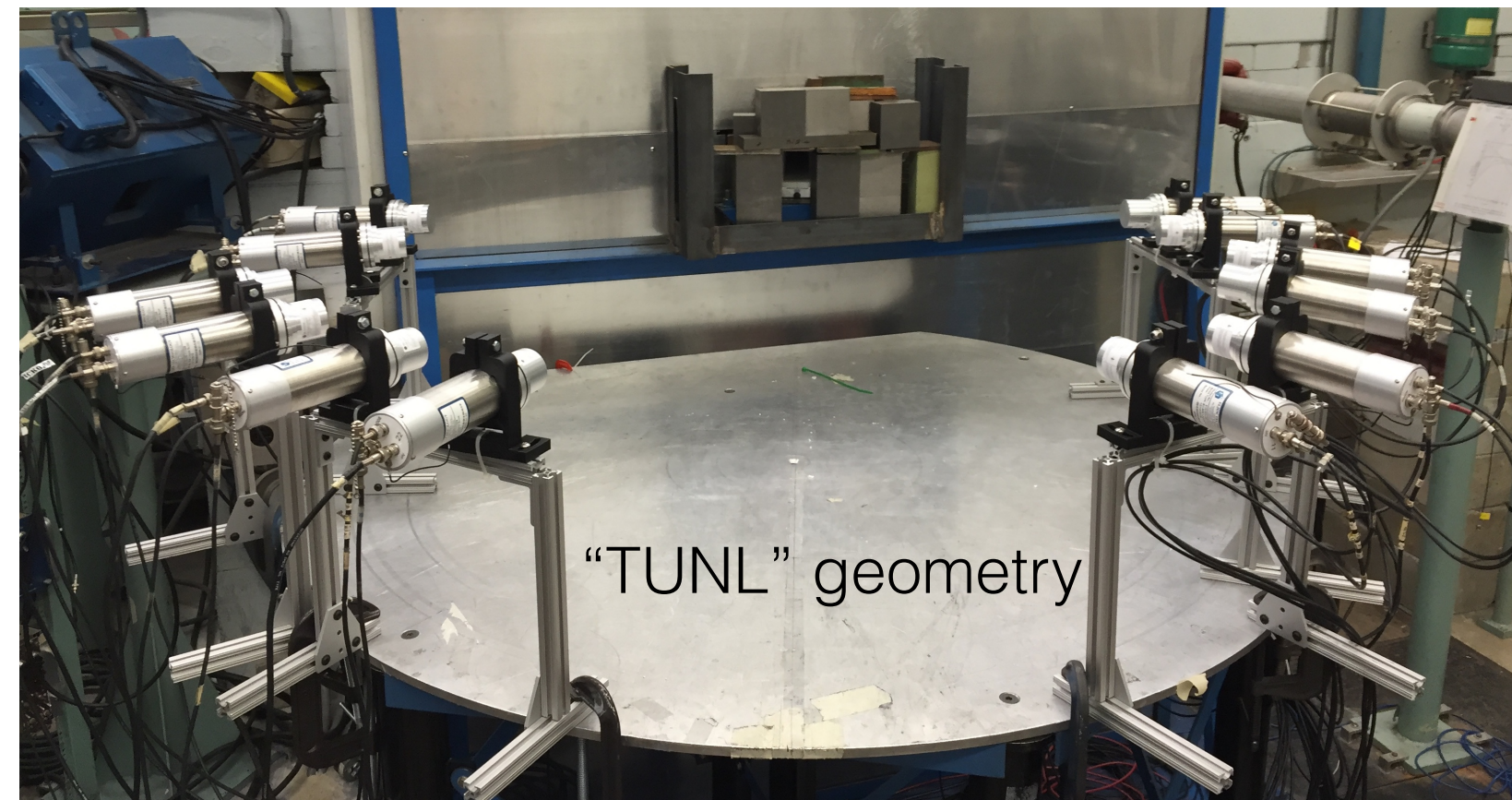
$$\Delta E = 2E_n \frac{M_n^2}{(M_n + M_T)^2} \left(\frac{M_T}{M_n} + \sin^2 \theta - (\cos \theta) \sqrt{\left(\frac{M_T}{M_n} \right)^2 - \sin^2 \theta} \right)$$

Tandem accelerator lab at TUNL



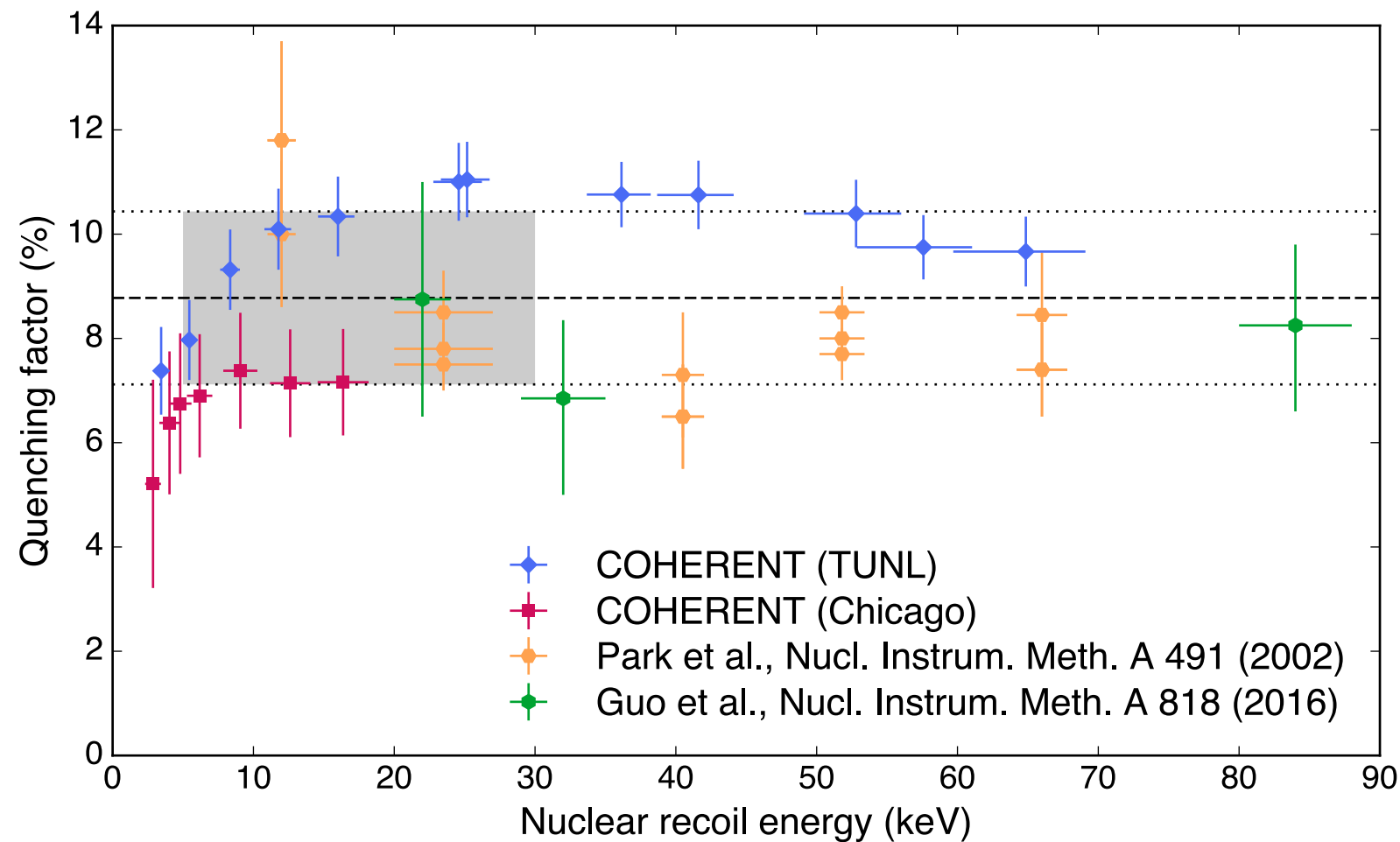
- 3 ion sources
- 10-MV maximum terminal voltage
- Beam can be bunched and chopped
- Numerous beam lines and experimental areas

Quenching factor measurements at TUNL



- Neutron beam produced by pulsed deuteron beam incident on deuterium gas cell
- Scattered neutrons detected by “backing detectors”
- Angle of backing detector selects well-defined nuclear recoil energy

Results of COHERENT CsI[Na] QF measurements



- Determine QF from global values in range from 5 to 30 keVnr
 - $8.78 \pm 1.66\%$
- Both COHERENT measurements show downward trend at lower recoil energies
- Disagreement between COHERENT measurements under (re)analysis
 - *Very promising developments towards resolving this discrepancy!*

The COHERENT Collaboration

- Goal: **unambiguous observation** of CE ν NS 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 CE ν NS detector: CsI[Na]

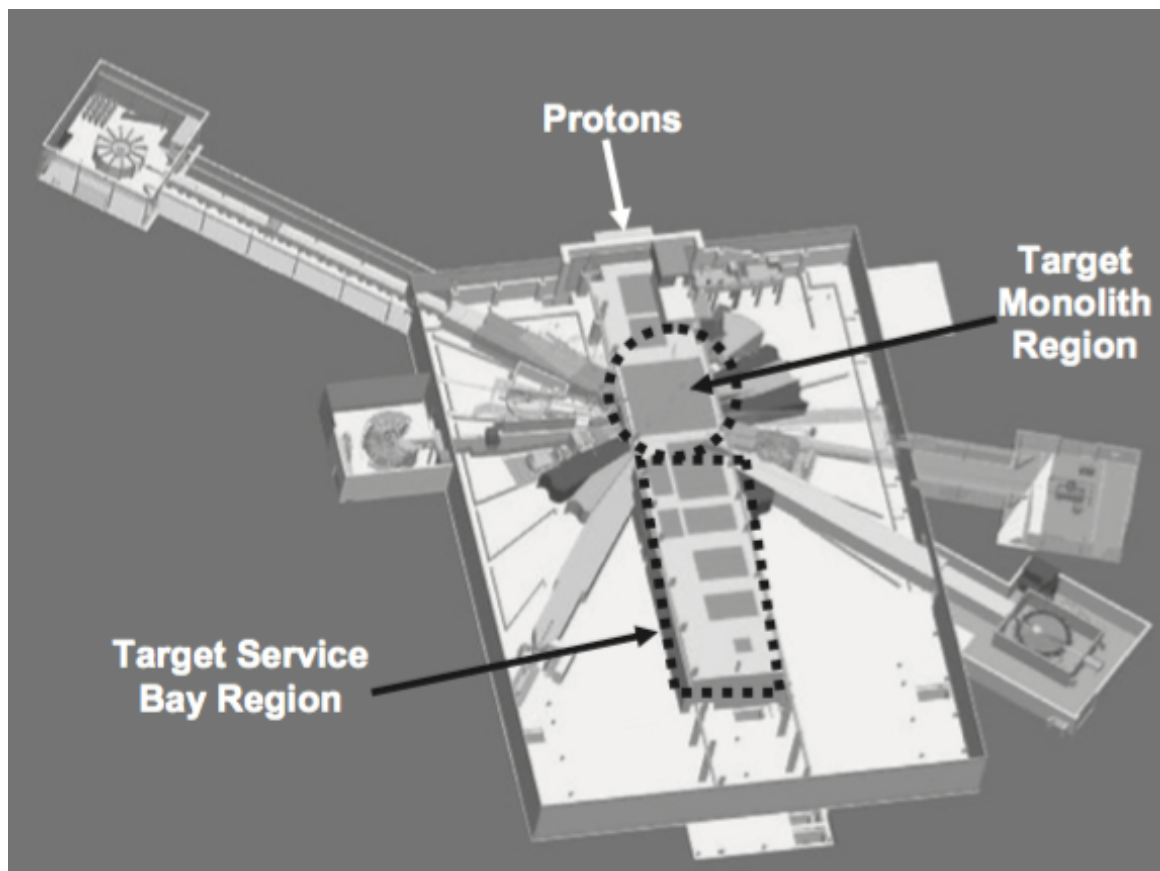
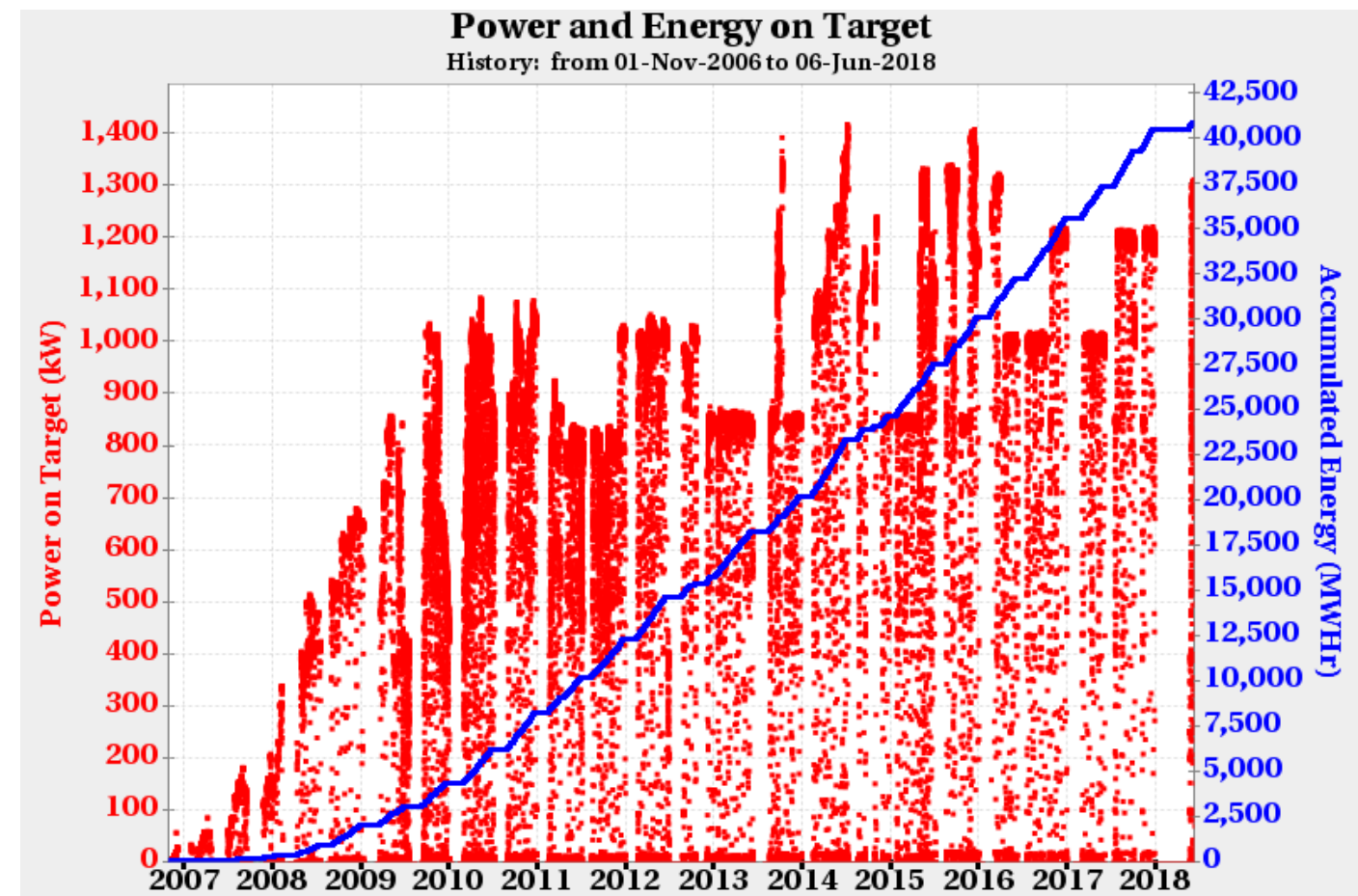


The Spallation Neutron Source



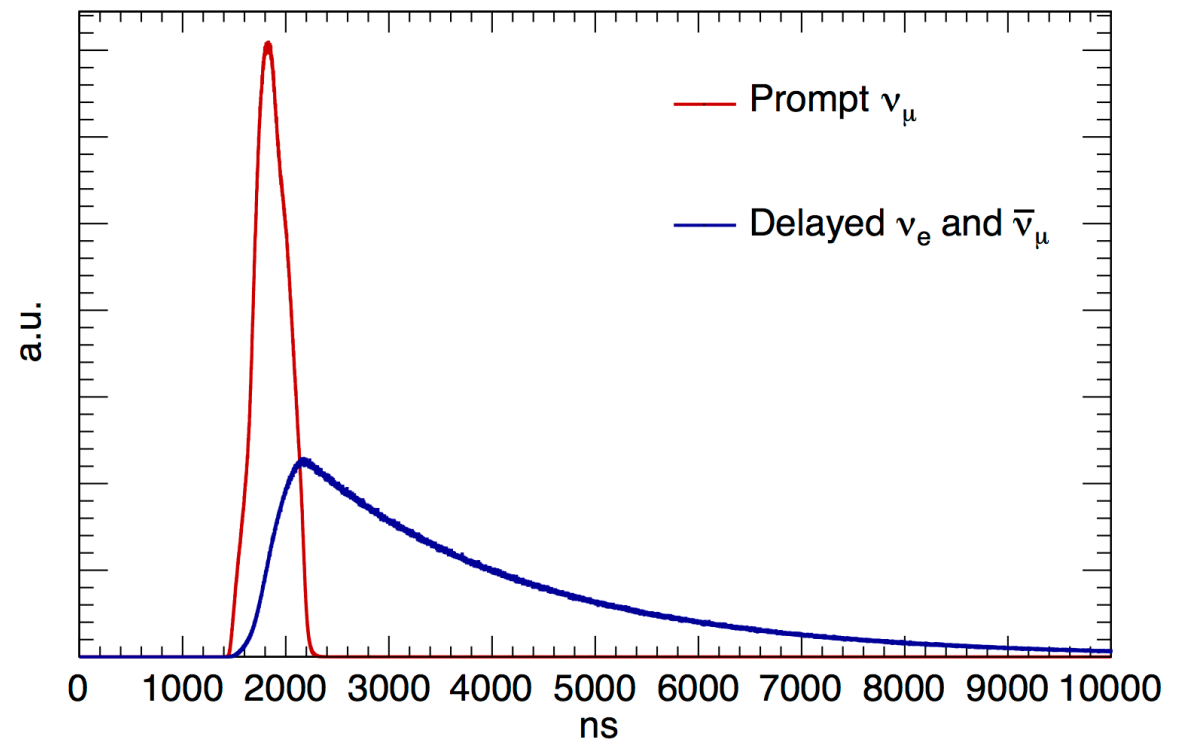
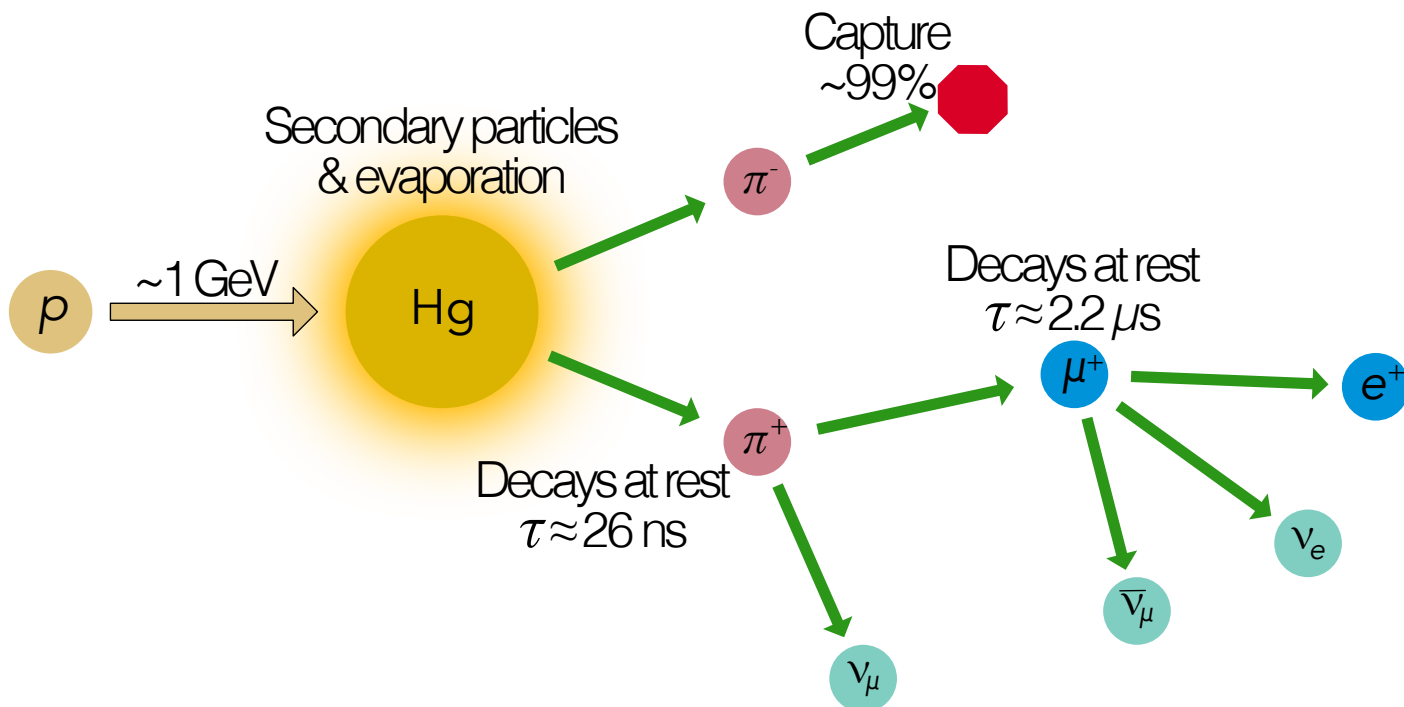
- Located at Oak Ridge National Lab, near Knoxville, TN, USA
- The SNS bombards a liquid mercury target with a ~ 1 -GeV proton beam pulsed at 60 Hz; each beam pulse is ~ 700 -ns wide
- Neutrinos are produced by decay of ***stopped*** pions and muons, resulting in flux with well-defined spectral and timing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

The Spallation Neutron Source

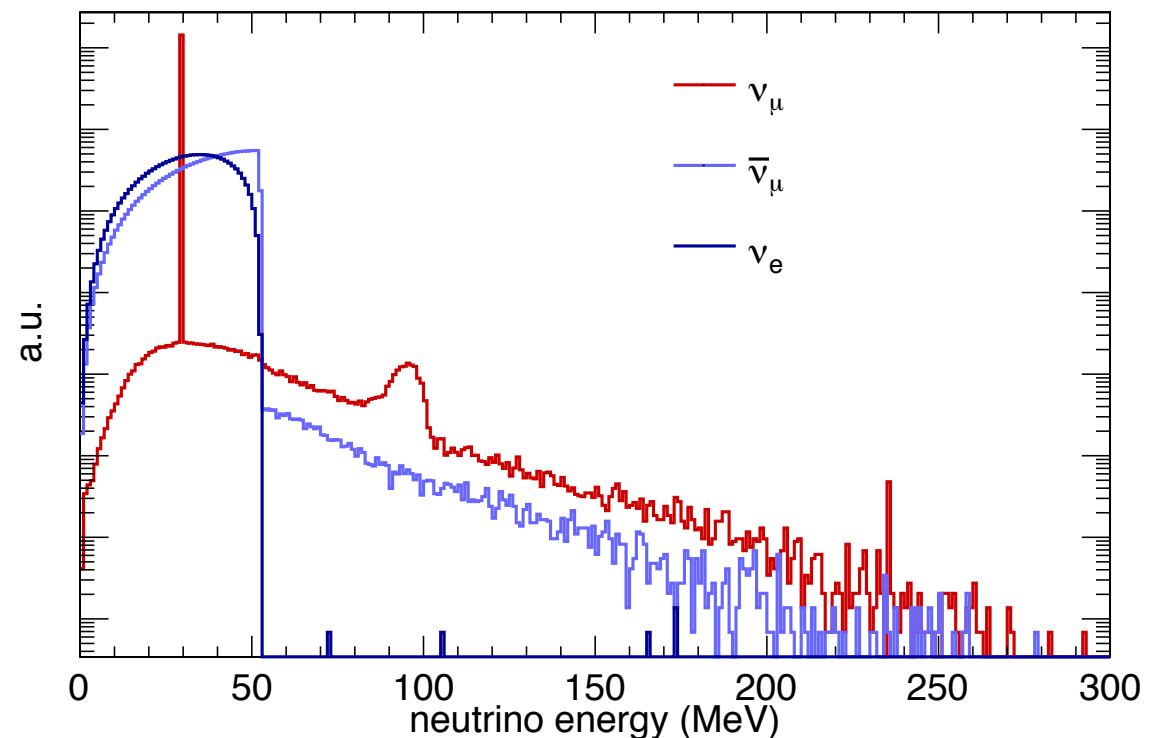


Most intense pulsed neutron source in the world

The Spallation 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



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”

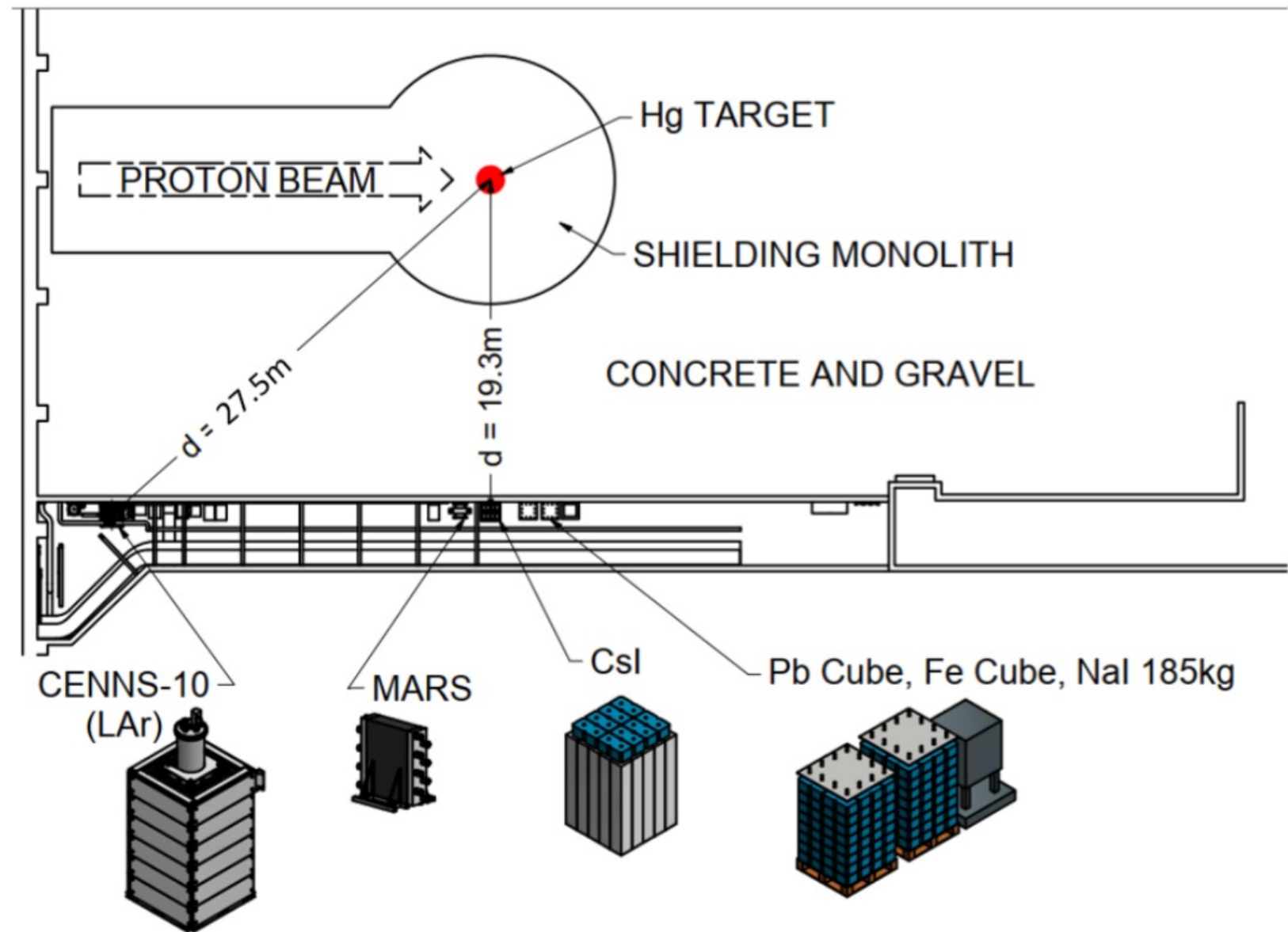
In case you forgot: SNS is a billion-plus dollar facility dedicated to neutrons

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



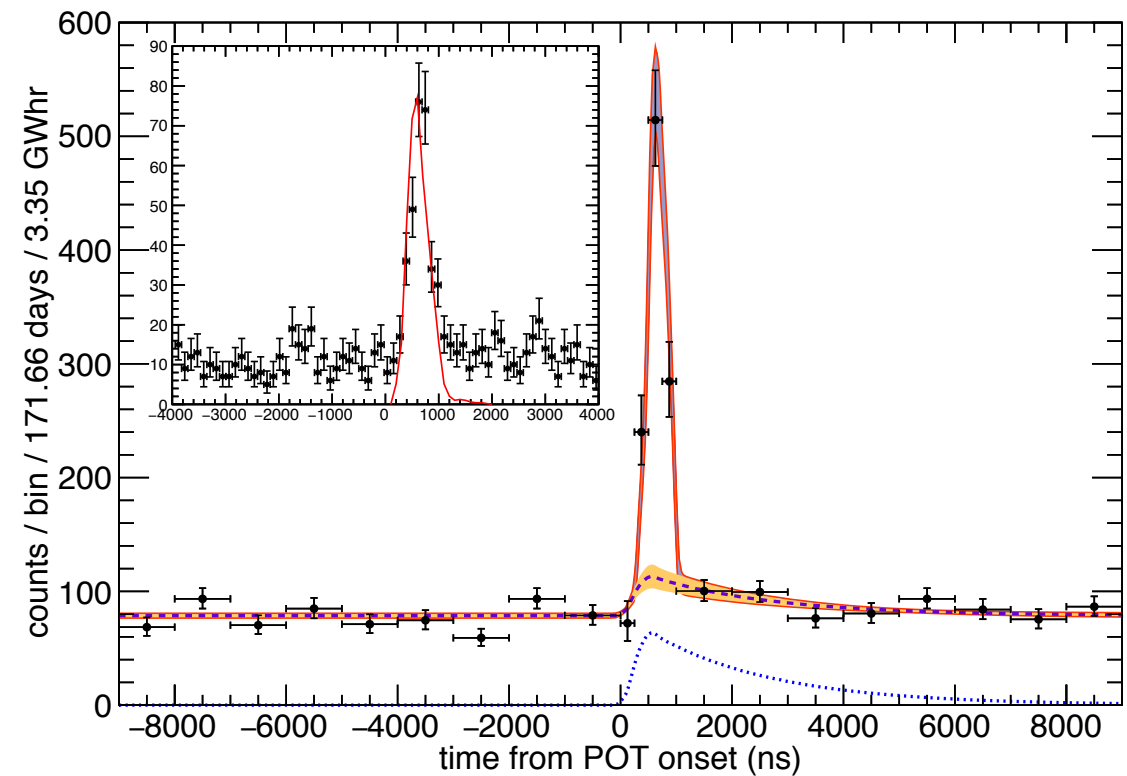
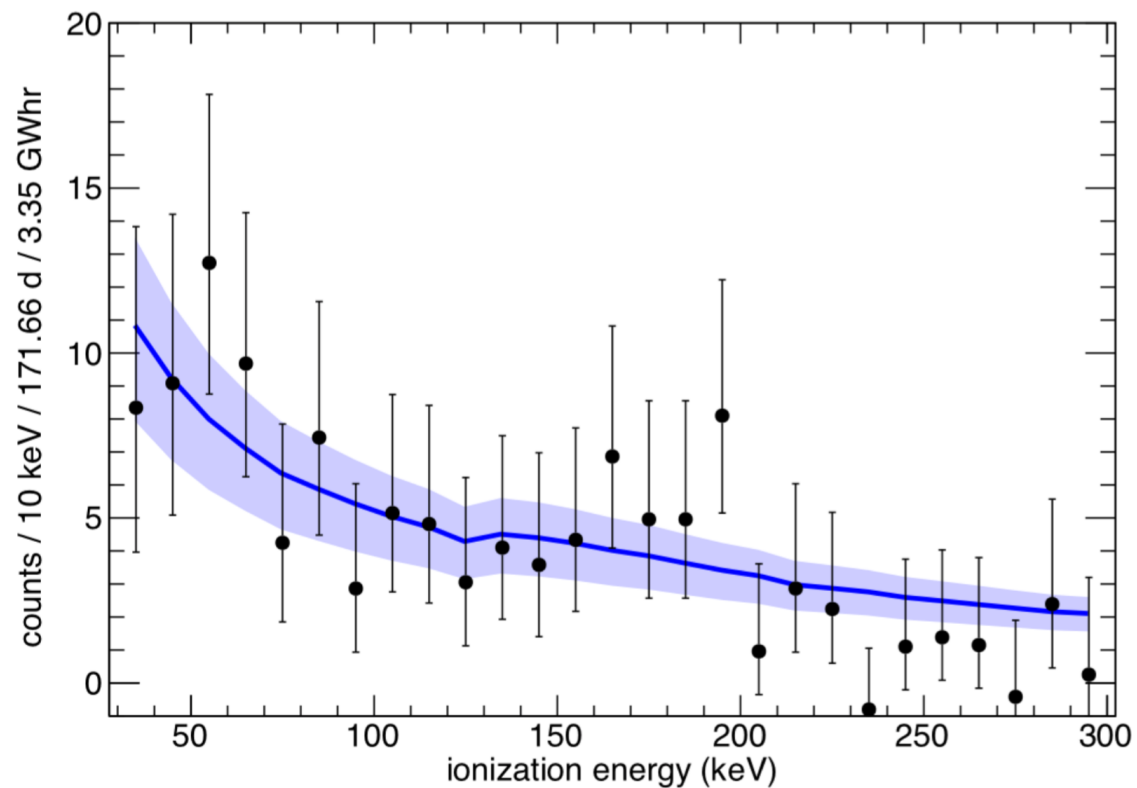
Siting and backgrounds

- 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)

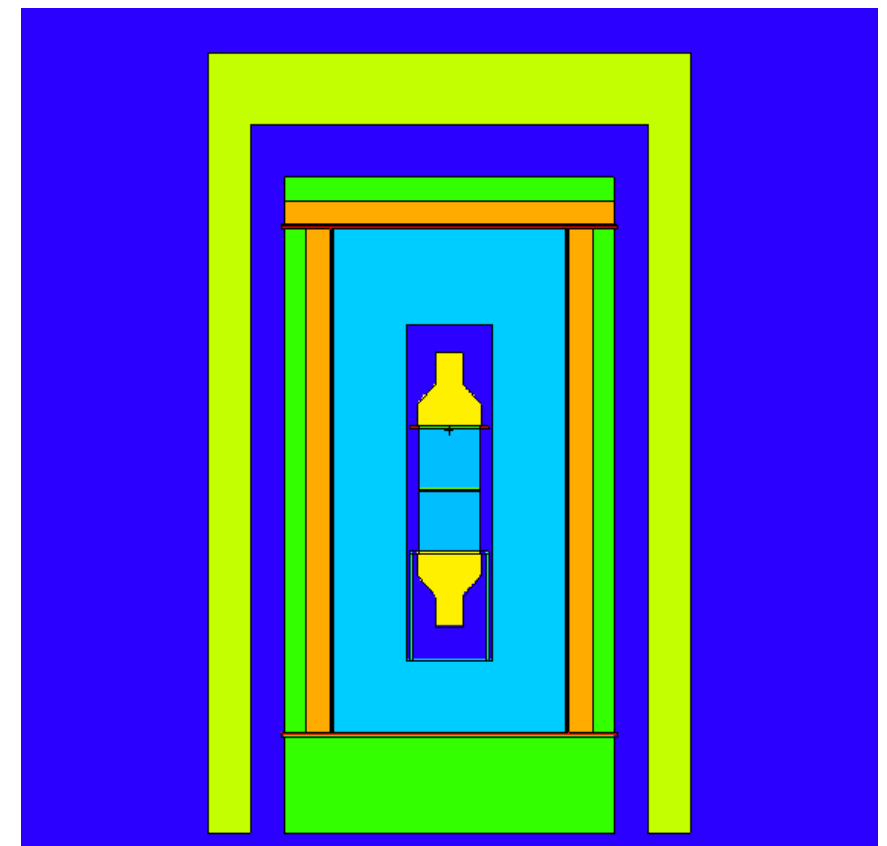


Approx ν flux at CsI[Na] location
 $1e7 \nu / \text{cm}^2 / \text{s} / \text{flavor}$

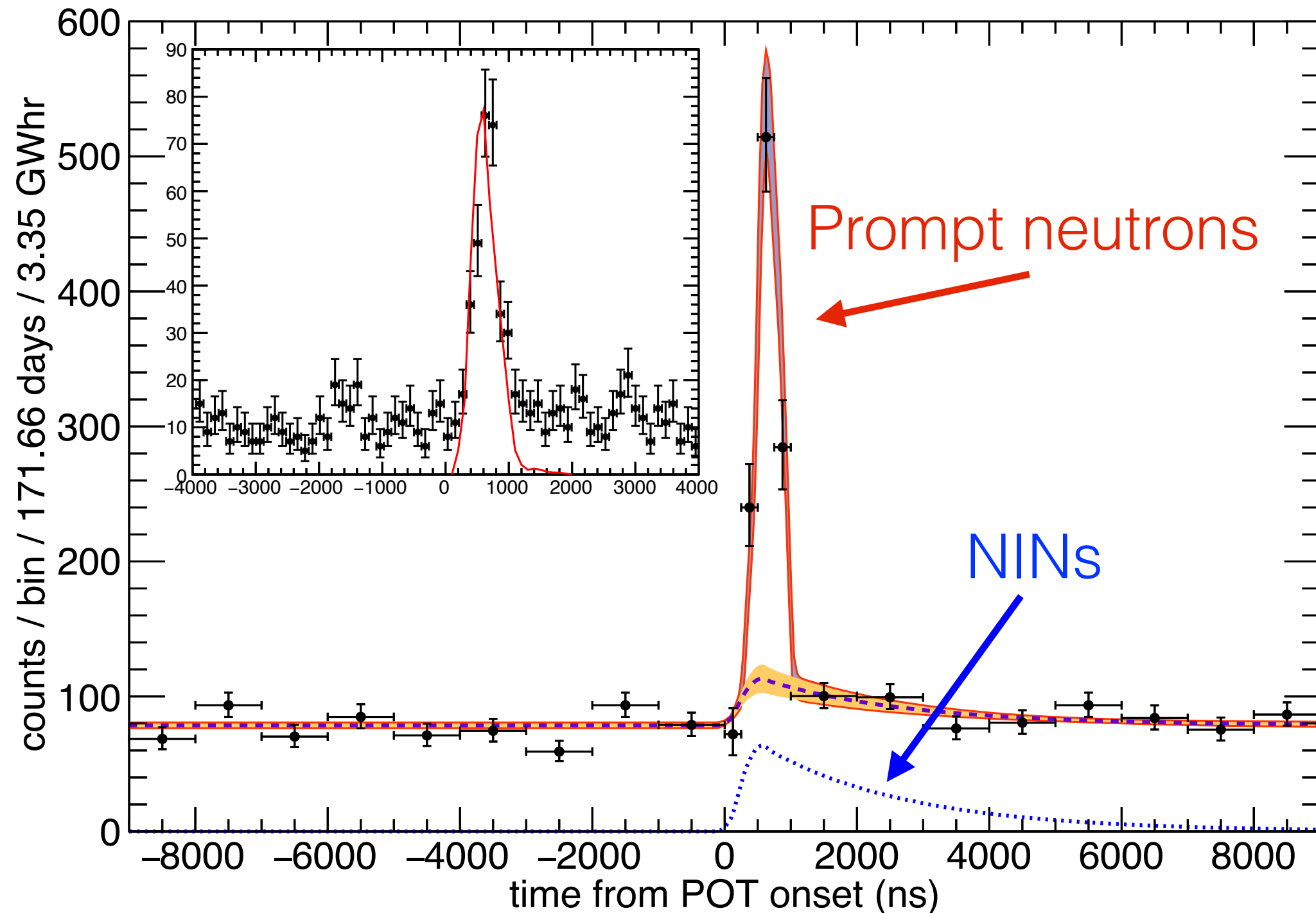
In situ measurement of neutron backgrounds



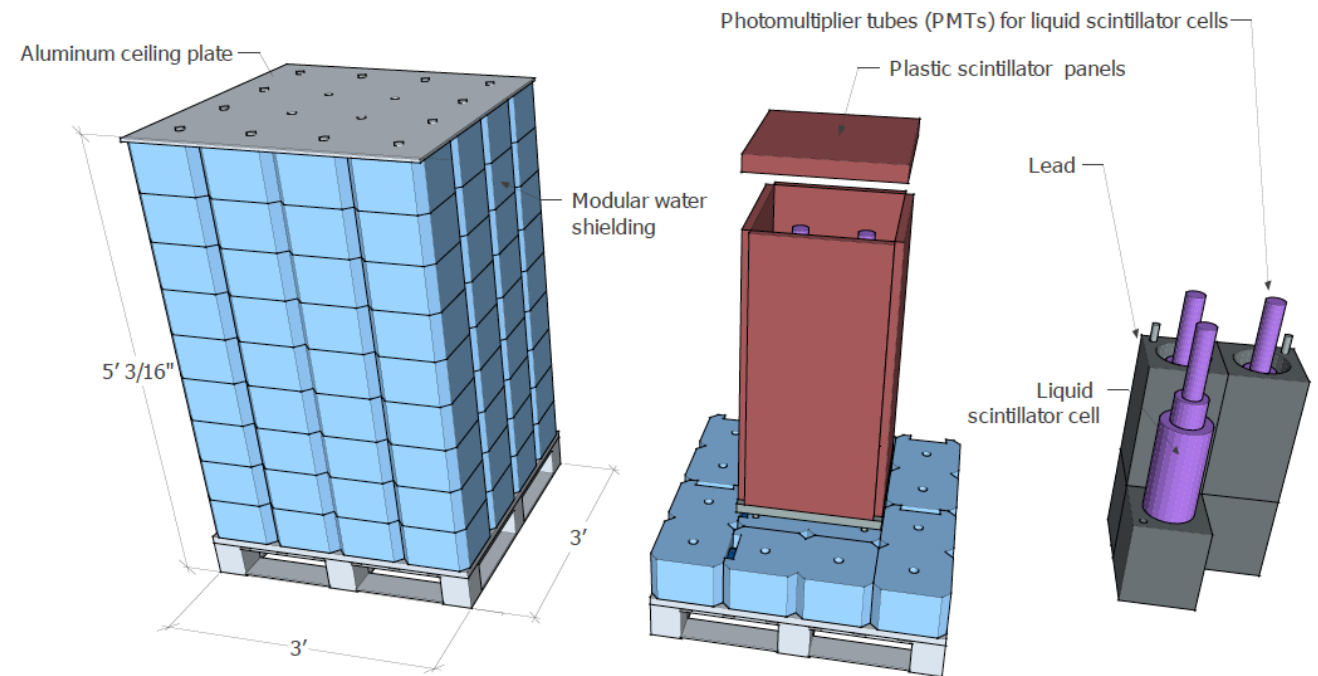
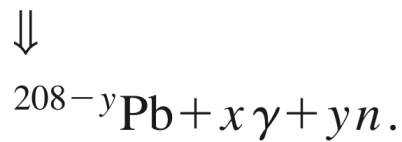
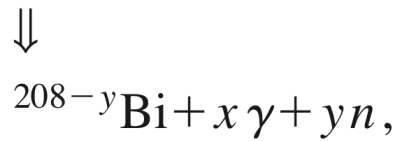
- Prior to CE ν NS search, neutron detection system installed at location of CsI[Na] detector
- Data informed model of prompt SNS neutron energy distribution
- Established understanding of beam timing w.r.t. SNS timing signal



In situ measurement of neutron backgrounds



Neutrino-induced neutrons (NINs)



Neutrino cube design (top) and simulation geometry for *in situ* NIN measurement for CsI[Na] deployment (bottom)

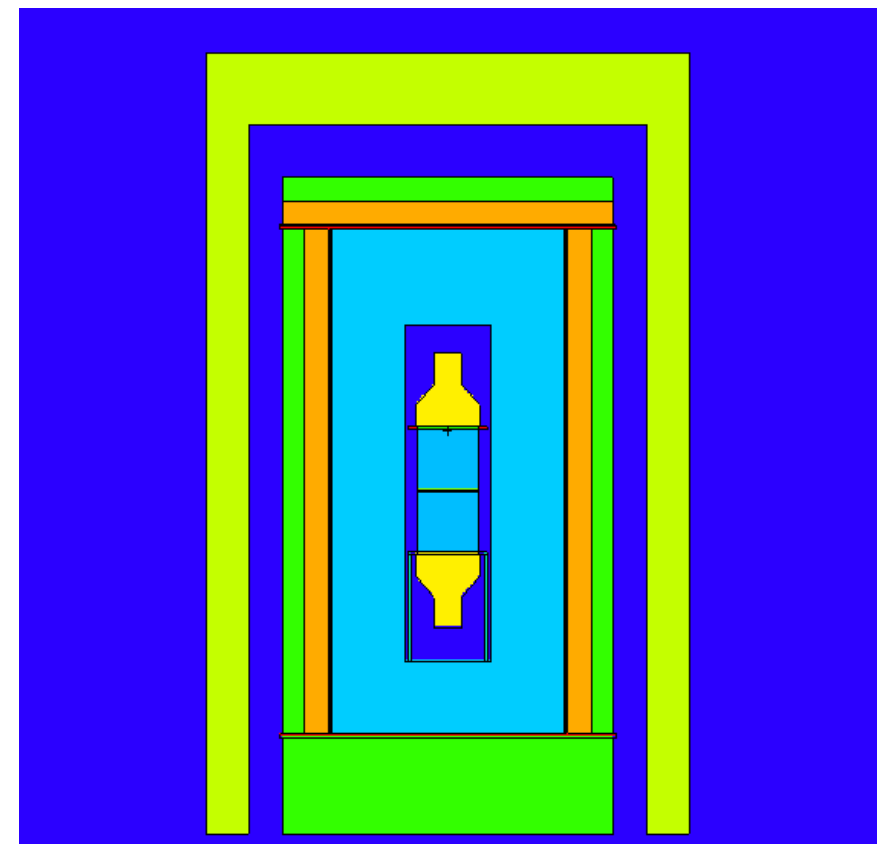
- Dominant background for CE ν NS measurement with naïve shielding configuration, but interesting physics of its own
 - Possible role in nucleosynthesis in certain astrophysical environments [1]
 - NIN production on Pb is the fundamental mechanism by which HALO intends to detect supernova neutrinos [2]
 - Process has never before been measured, considerable variation in theoretical predictions ($\sim 3\times$) [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)

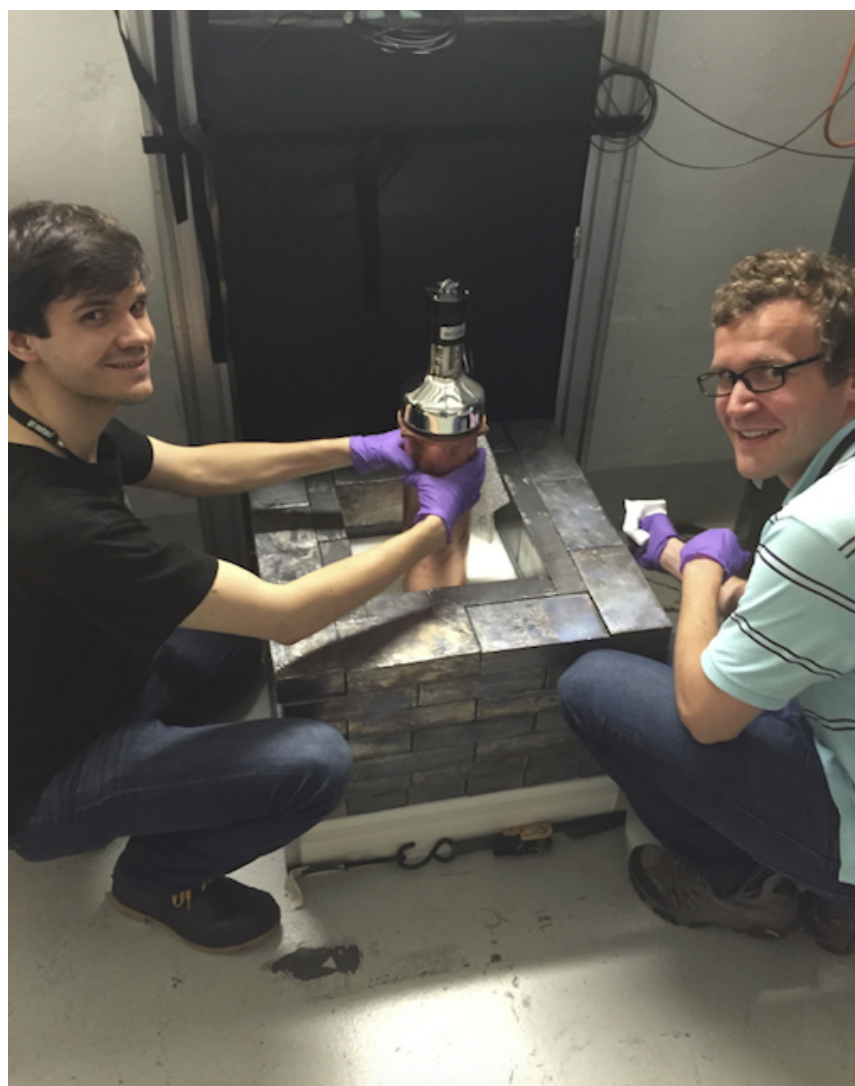
NIN pathways from S.R. Elliott, Phys. Rev. C (2000)



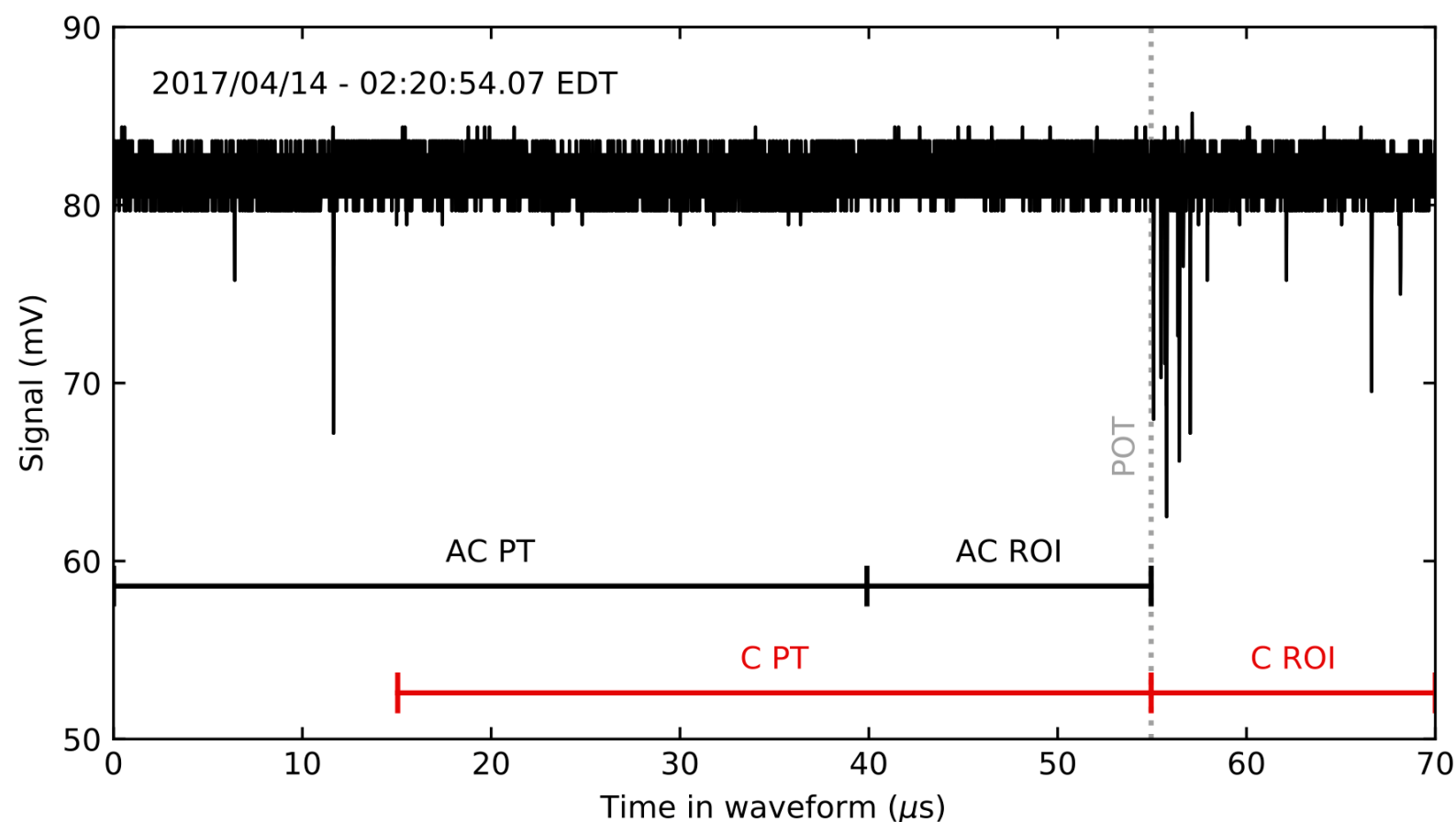
CE ν NS with CsI[Na]



Deployed to SNS in June 2015

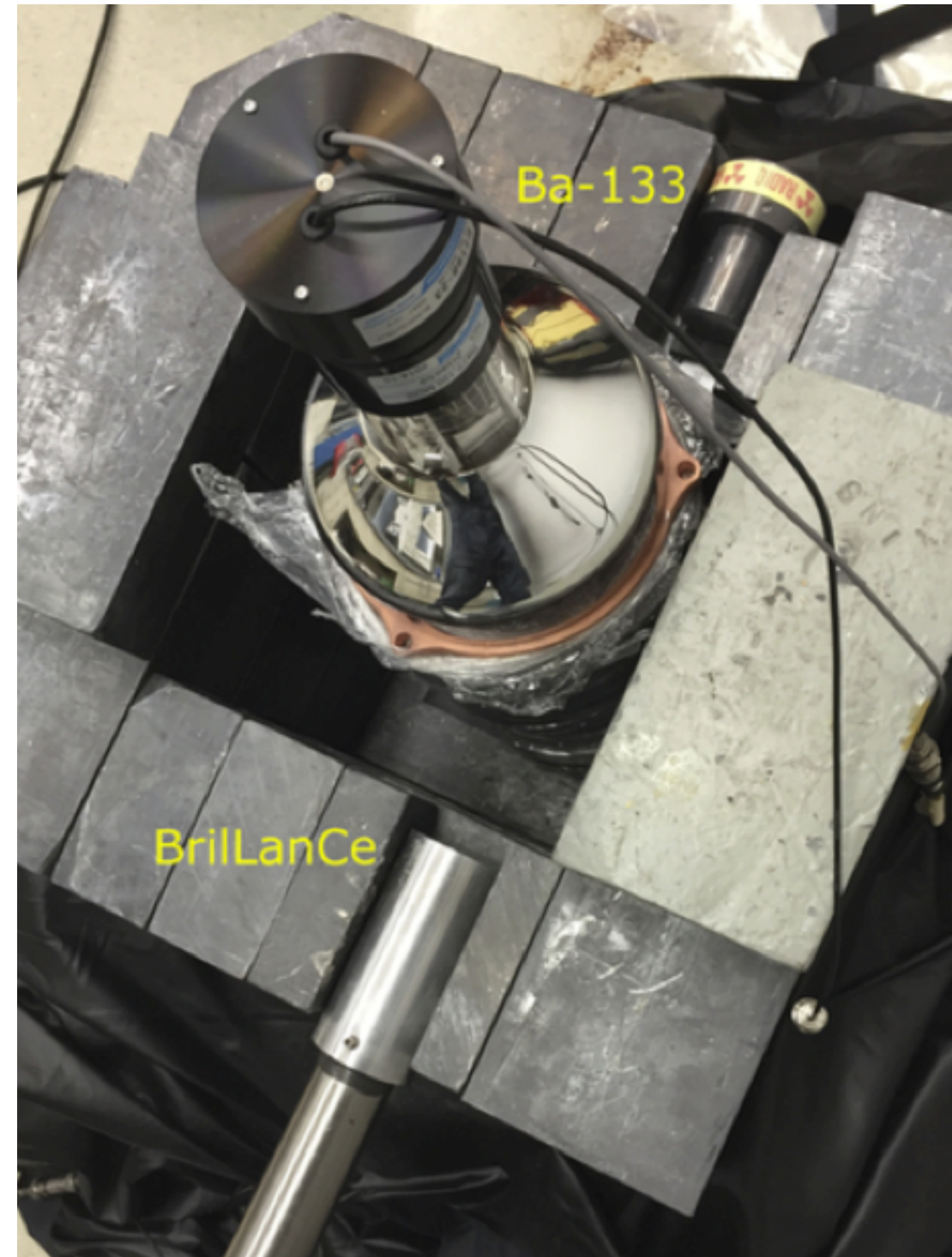


- 14.6-kg crystal made from low-background salts, encased in electroformed-copper can with PTFE reflector and synthetic silica window, surrounded by neutron and gamma shielding, including low-activity lead
- Development led by University of Chicago [1]
- Output of super-bialkali PMT with $\sim 30\%$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

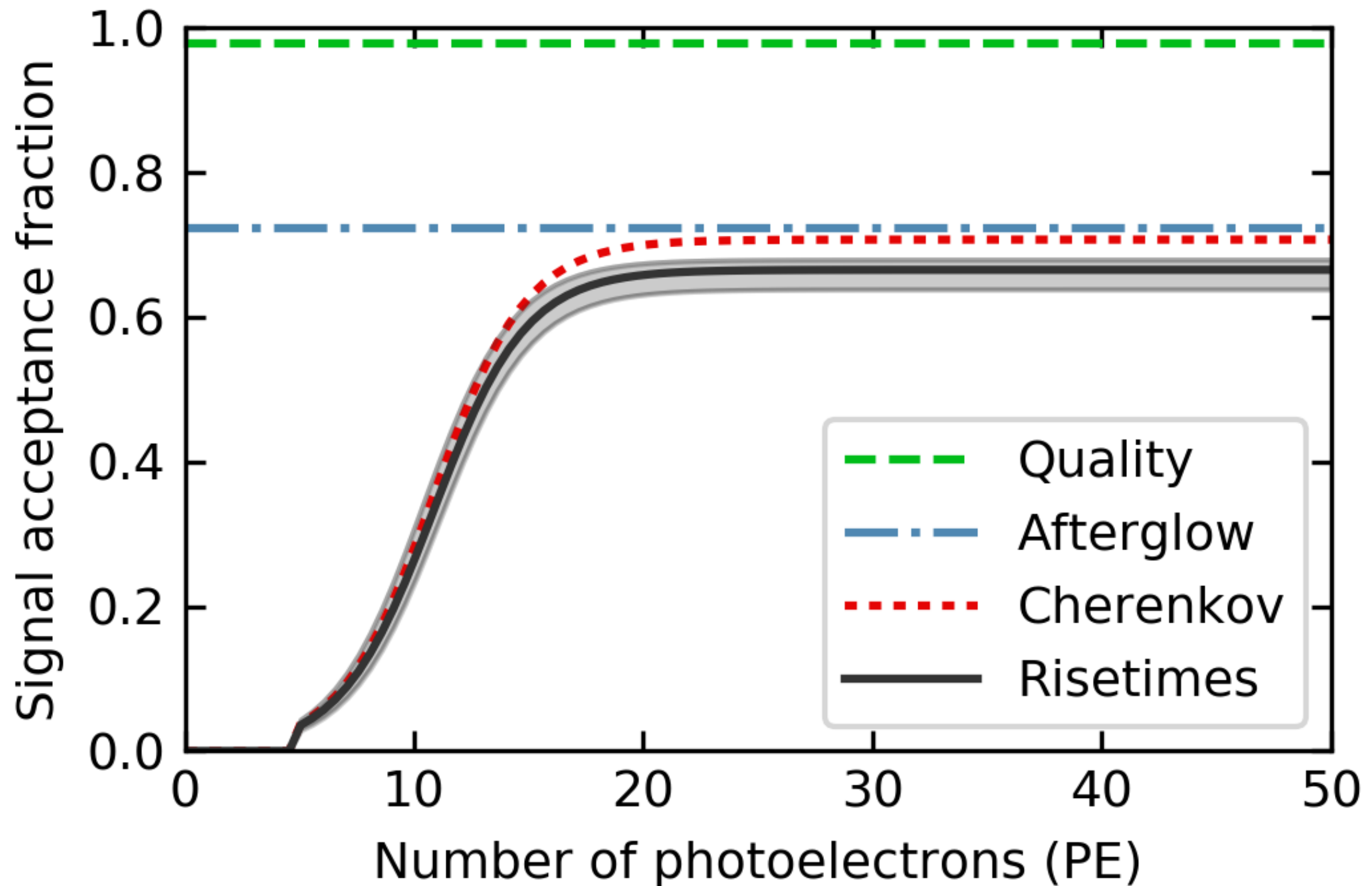


CE ν NS with CsI[Na]

- 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

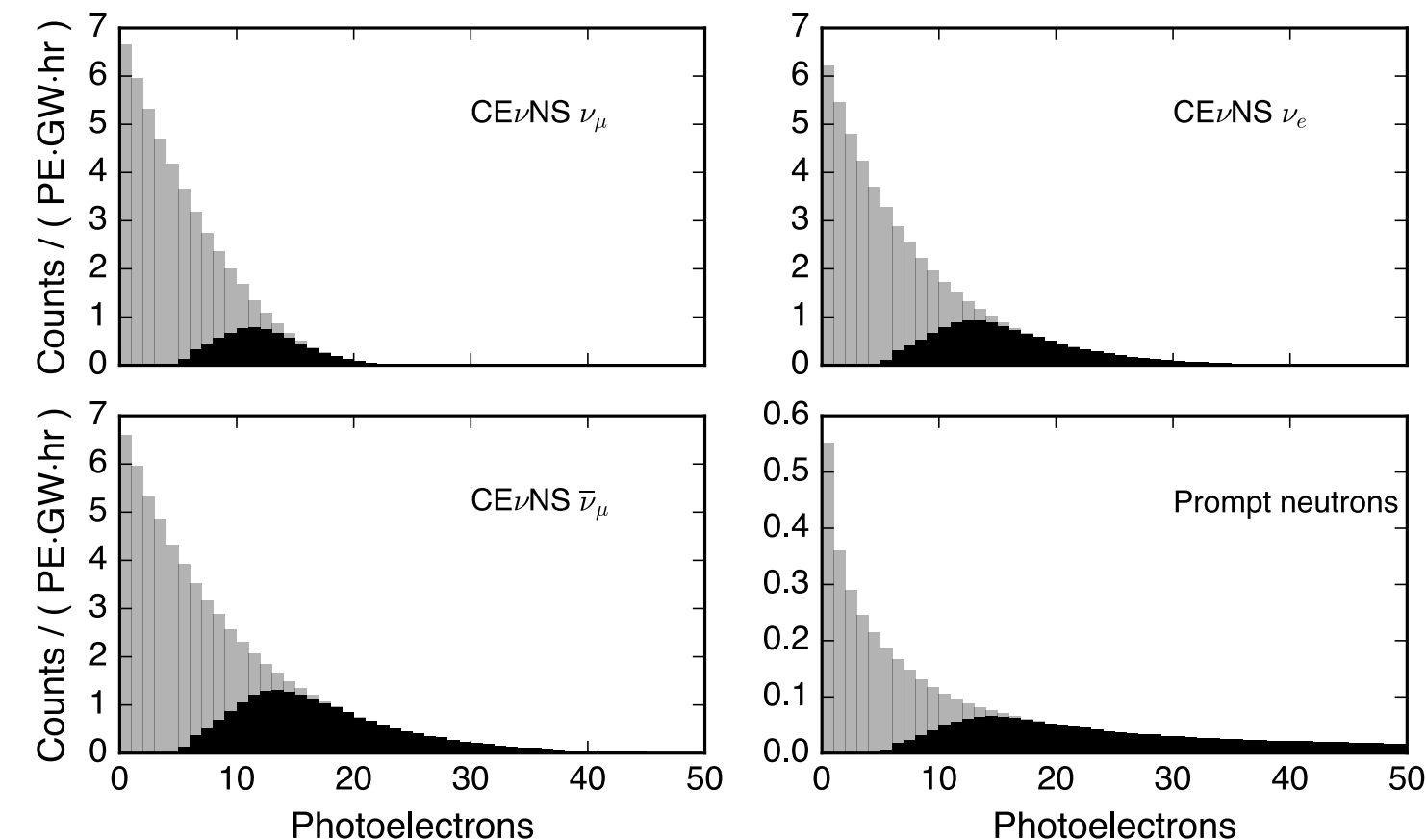


Analysis acceptance efficiency



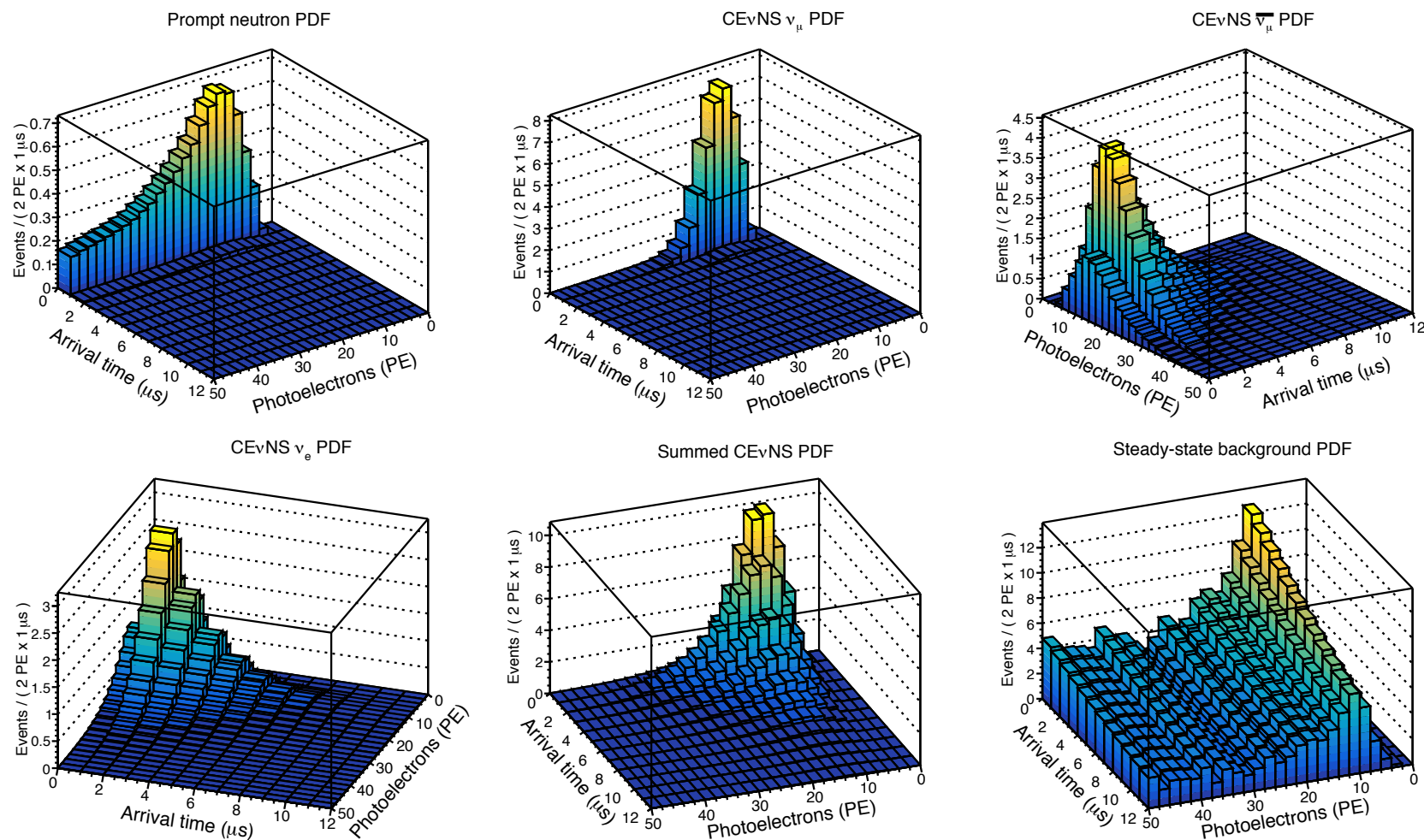
Rate and shape estimates

Raw CEvNS recoils Observed CEvNS recoils



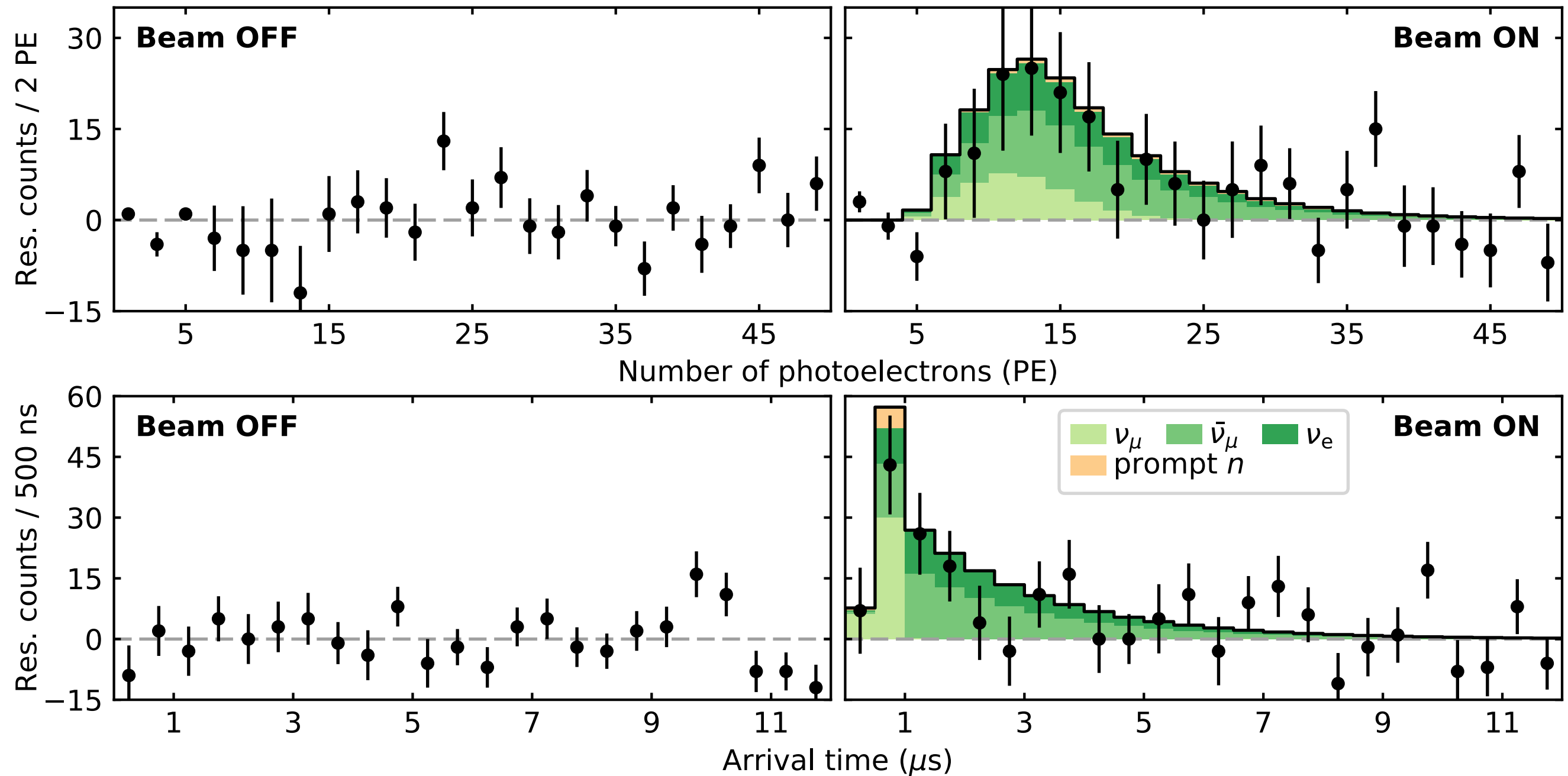
- Predict recoil distributions assuming SM - convert to photoelectrons using carefully determined calibrations
- *In situ* neutron measurements inform spectral model of prompt SNS neutrons
- Acceptance efficiency applied to models to produce beam-power-normalized PDFs in energy space

Rate and shape estimates



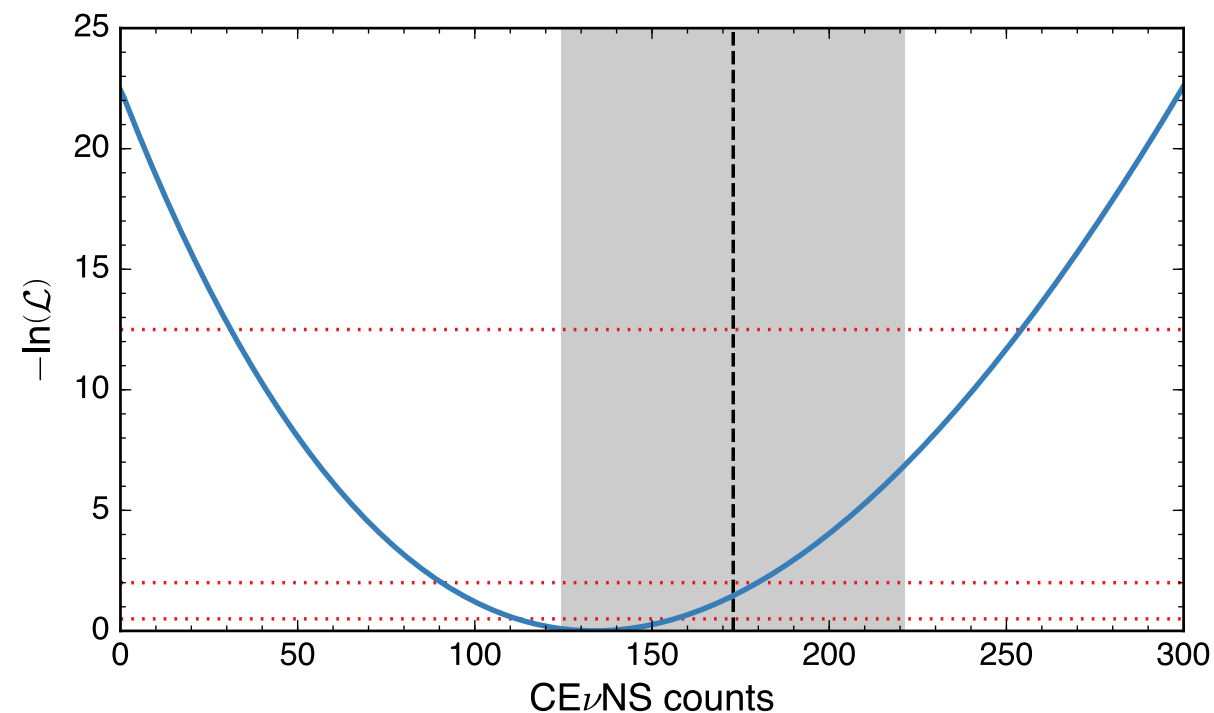
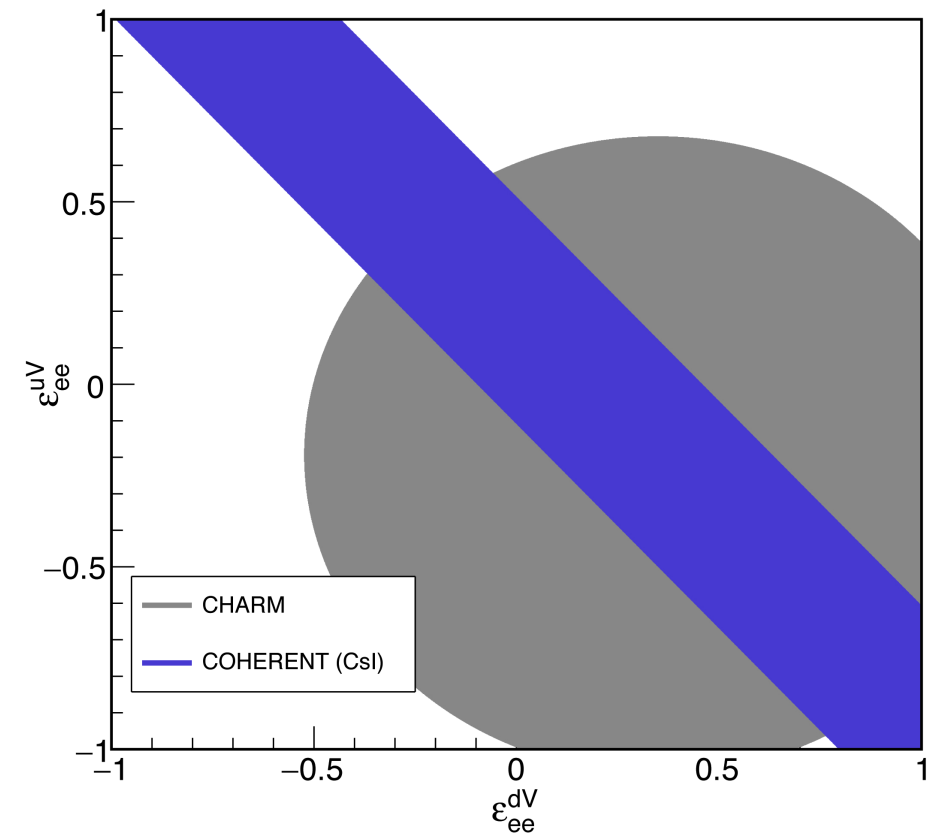
- Pulsed nature of beam facilitates analysis in time domain
- 2-D analysis (energy, time) makes use of all available information
- Ultimately performed binned 2-D profile likelihood analysis using PDFs shown here
 - Assumes Standard Model
 - Incorporates knowledge of detector response, analysis acceptance,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

SM prediction and data



Results

- Beam exposure: ~ 6 GWhr, or $\sim 1.4 \times 10^{23}$ 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 $1\text{-}\sigma$ of SM prediction of 173 ± 48
 - Null hypothesis disfavored at $6.7\text{-}\sigma$ 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%

CE ν NS observation data release

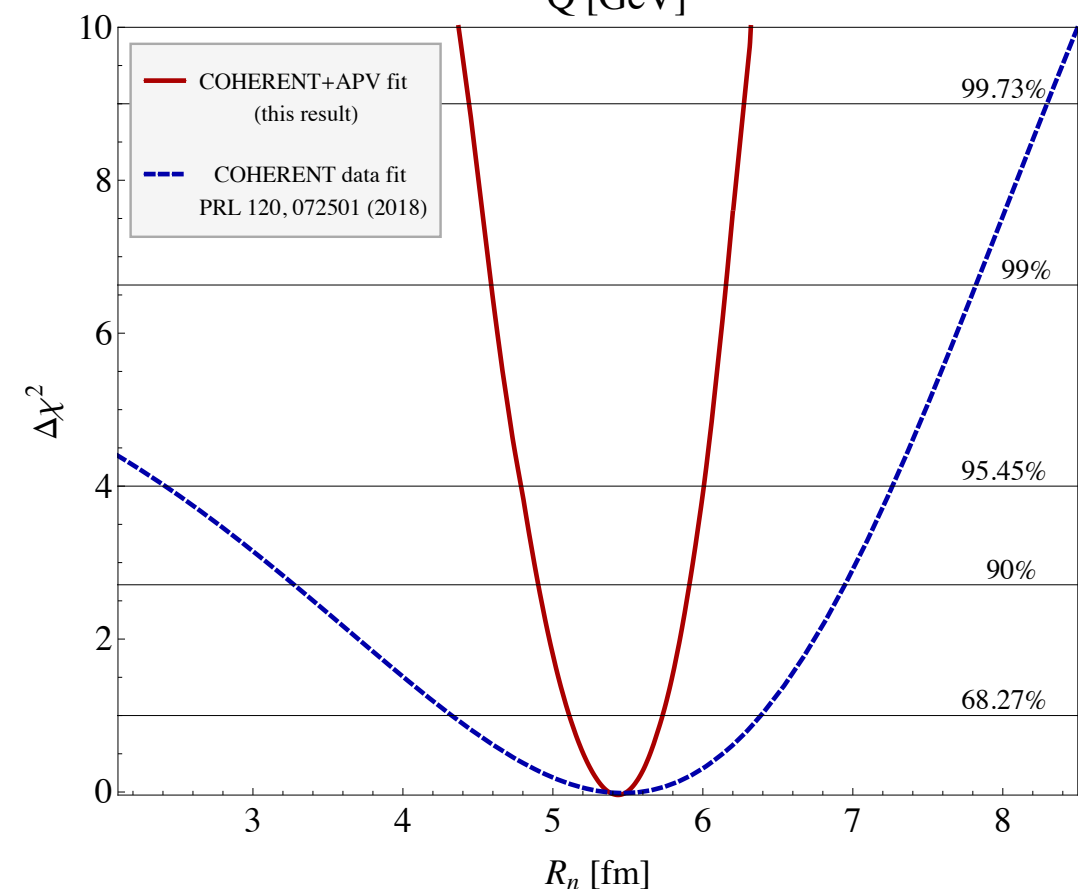
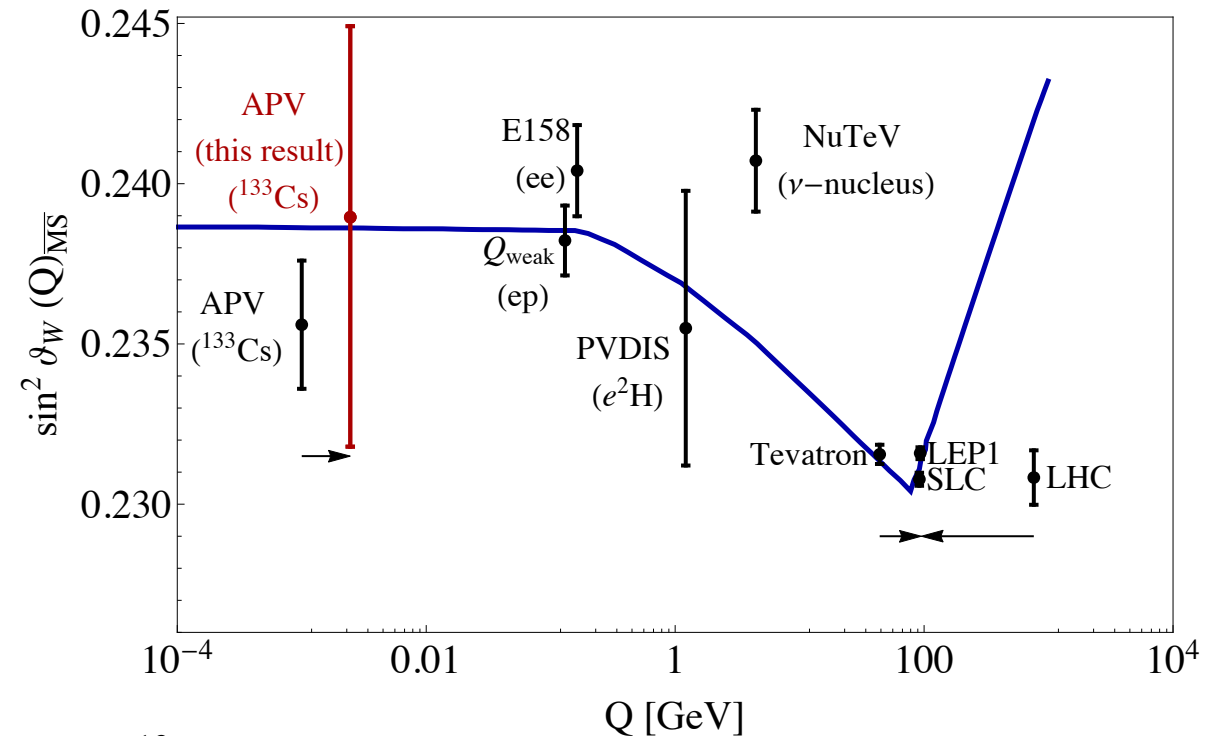
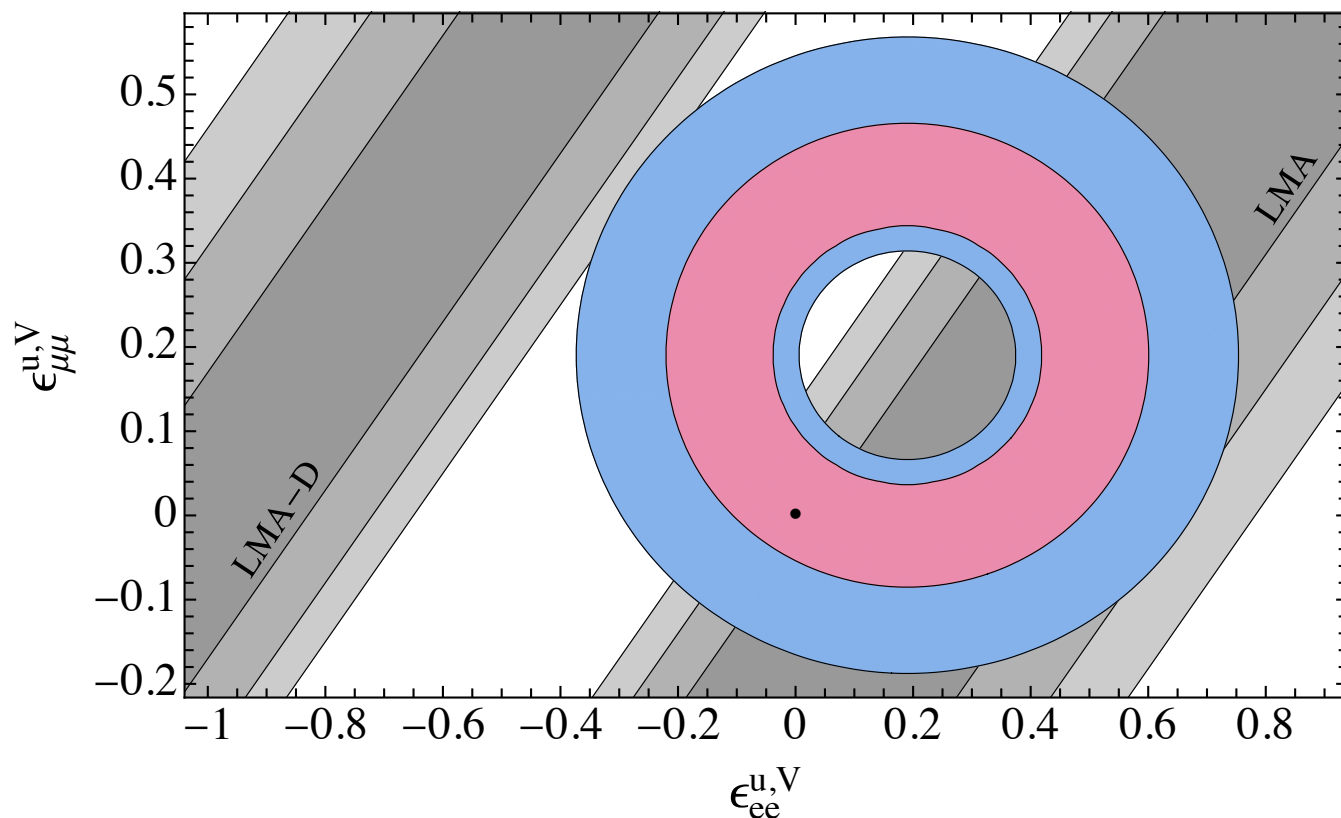


- Data that constituted CE ν NS observation has been packaged and is publicly available
 - <http://dx.doi.org/10.5281/zenodo.1228631>
 - <https://coherent.ornl.gov/data>
- Should include all information necessary to perform further analyses on CsI[Na] data
 - Binned data for coincidence and anticoincidence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

Early physics from COHERENT result

Even with limited statistics, interesting studies have already shown the power of CE ν NS; here are just a few..

- LMA-D disfavored by data [1]
- Neutron distribution measured [2,3]
- Influence on APV Q_W^2 measurement [3]

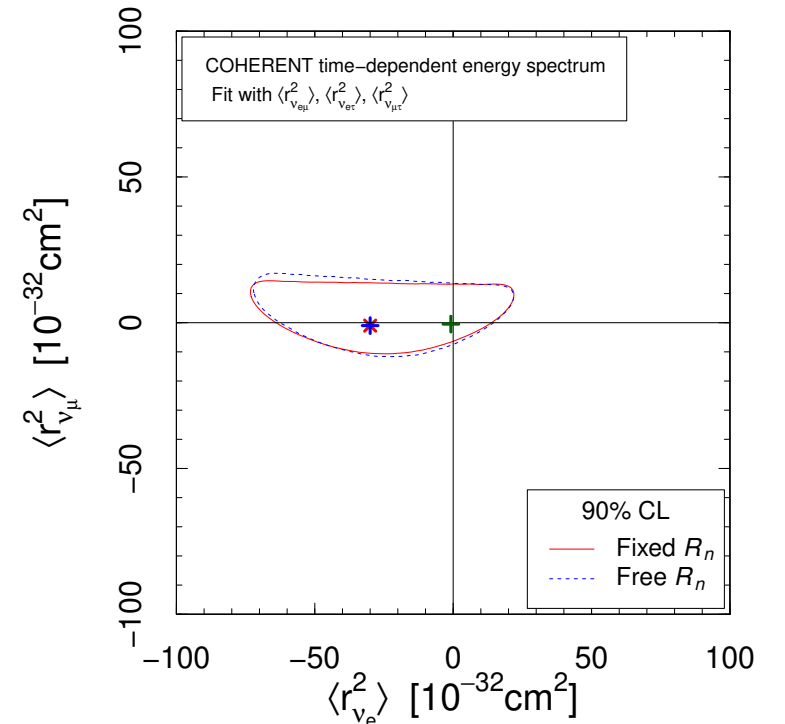
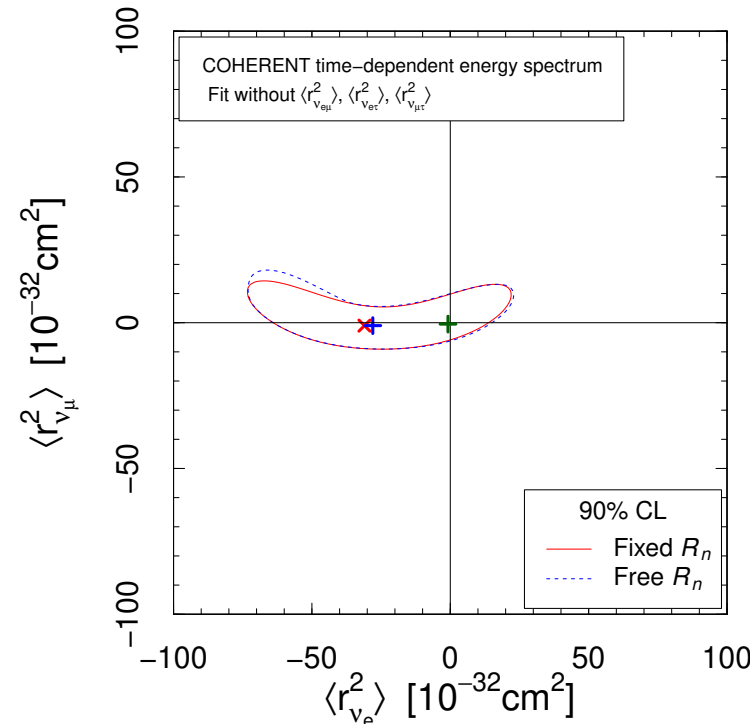
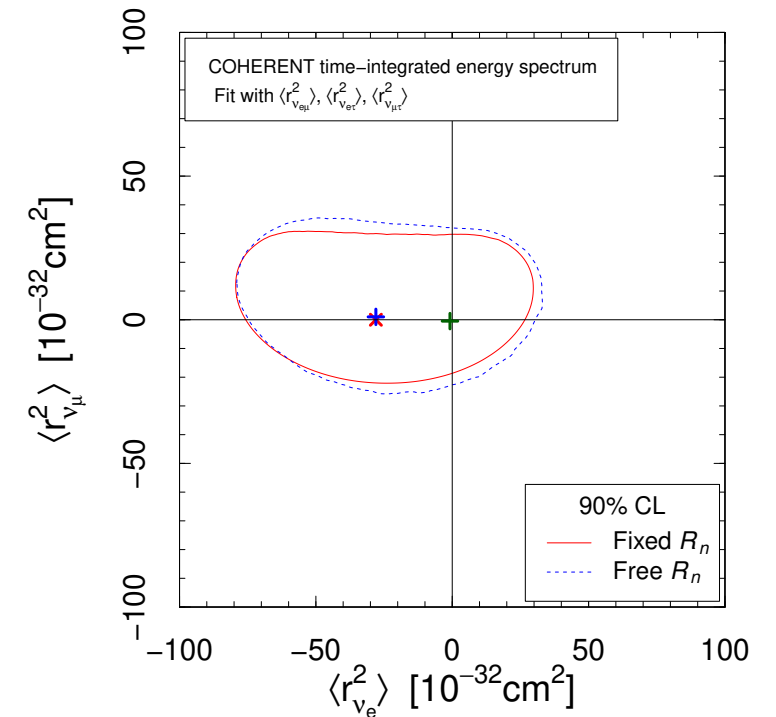
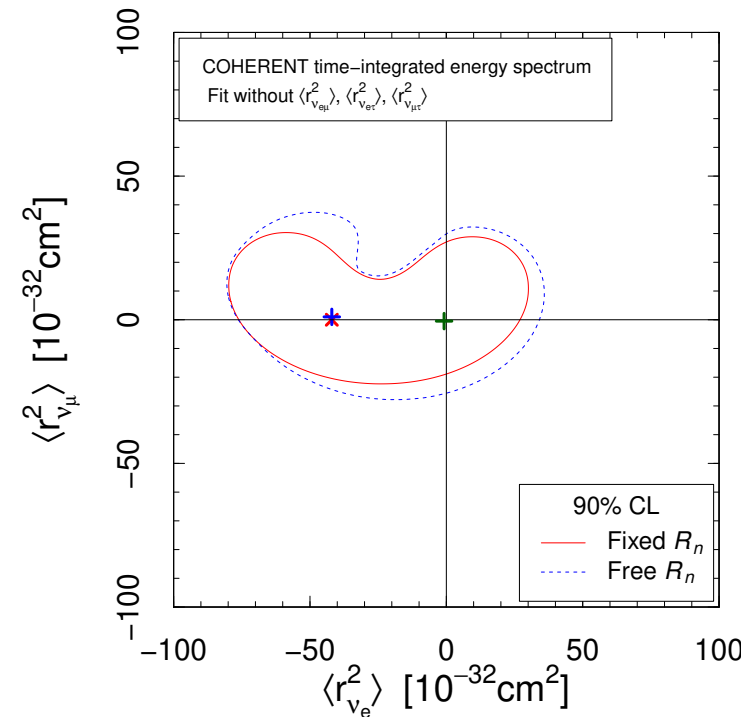
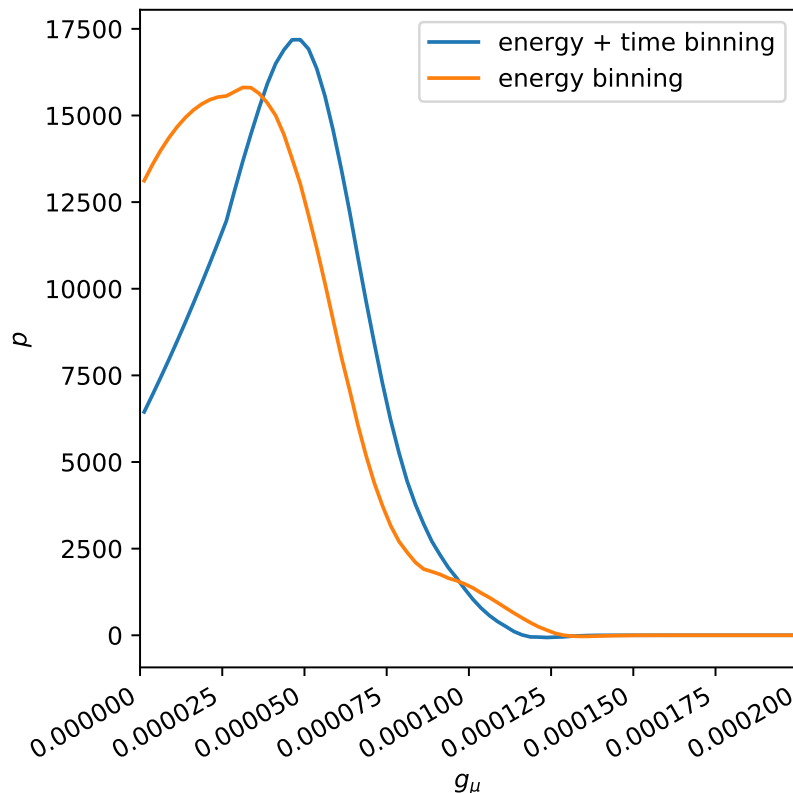


- [1] P. Coloma *et al.*, Phys. Rev. D 96 (2017) 1708.02899
 [2] M. Cadeddu *et al.*, Phys. Rev. Lett. 120 (2018) 1710.02730
 [3] M. Cadeddu & F. Dordei, 1808.10202

Left figure from [1], others from [3]

Early physics from COHERENT result

- COHERENT data can be analyzed in both time and energy space
- Prompt and delayed neutrino populations have different flavor compositions and energy distributions
- Simultaneous 2-D analysis can provide improved physics reach (e.g., [1,2])



[1] M. Cadeddu *et al.*, Phys. Rev. D 98 (2018), 1810.05606

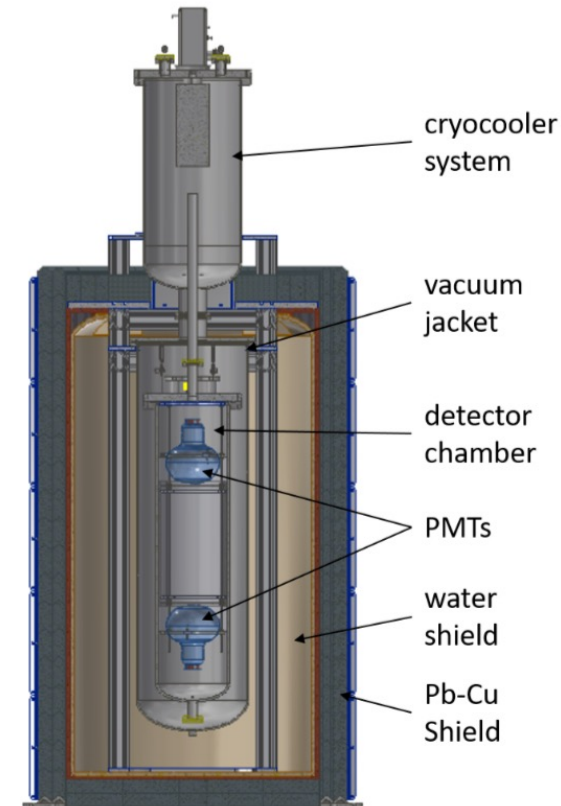
[2] B. Dutta, S. Liao, S. Sinha, & L. Strigari, 1903.10666

L figure from [2], R figures from [1]

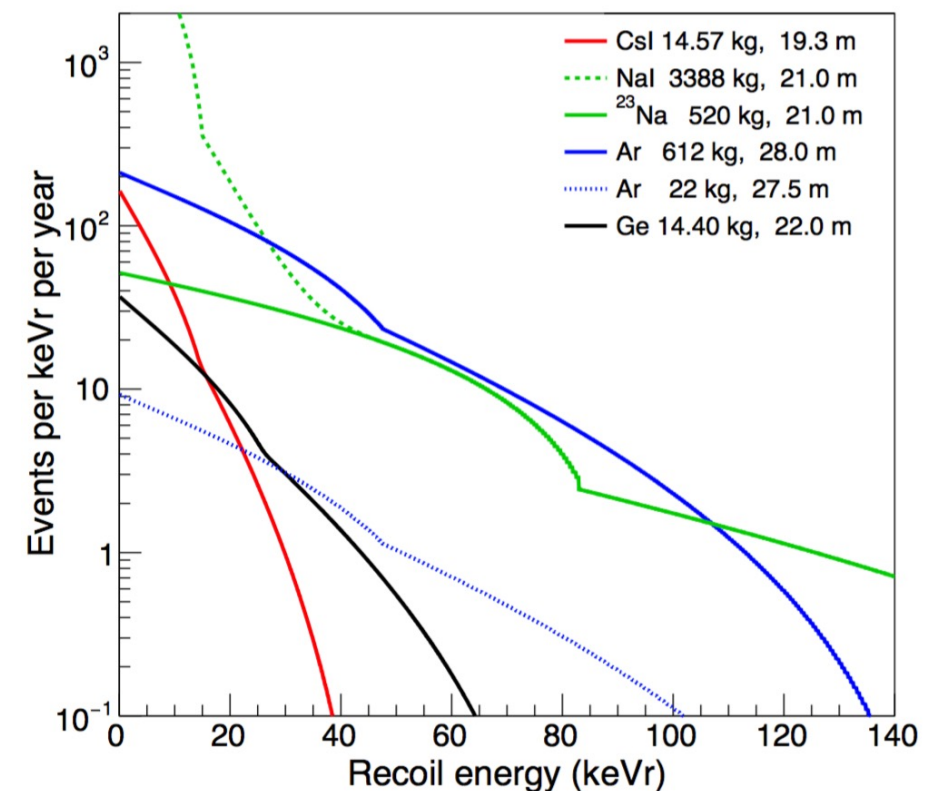
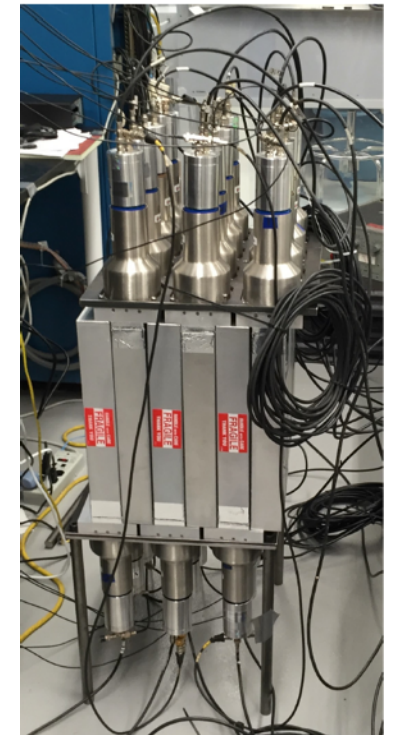
COHERENT physics moving forward

- Measure NINs cross section in ^{208}Pb , ^{56}Fe
 - Exploring upgrades to detection system
- Measure ^{127}I CC cross section
 - 185-kg NaI ν E collecting low-gain CC data now; continue in multi-ton phase in parallel with high-gain mode
 - Sensitivity to g_A quenching with $Q \sim \mathcal{O}(10 \text{ MeV})$
- N^2 dependence of $\text{CE}\nu\text{NS}$ cross section
 - Several distinct N values represented in COHERENT suite of experiments
 - ~22-kg LAr detector already collecting $\text{CE}\nu\text{NS}$ data, plans for ~10 kg of Ge PPCs and multi-T NaI[Tl]
- Begin to perform precision $\text{CE}\nu\text{NS}$ 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



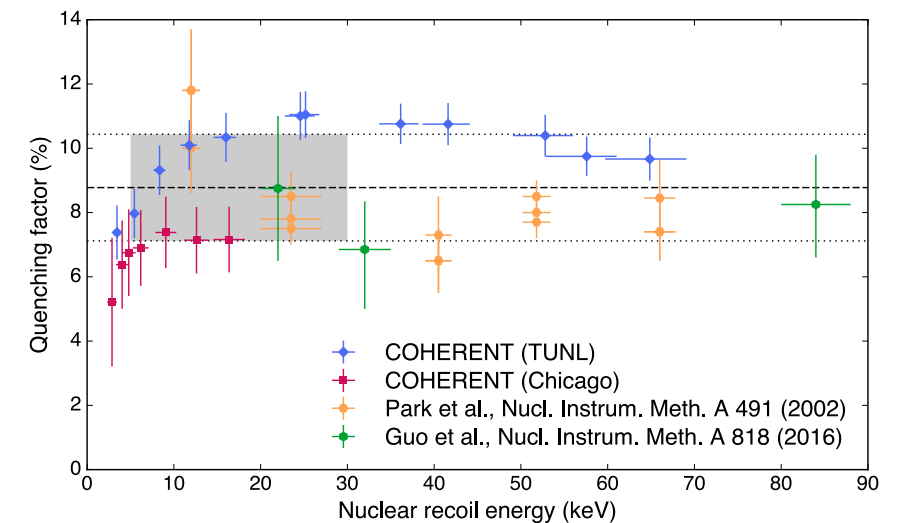
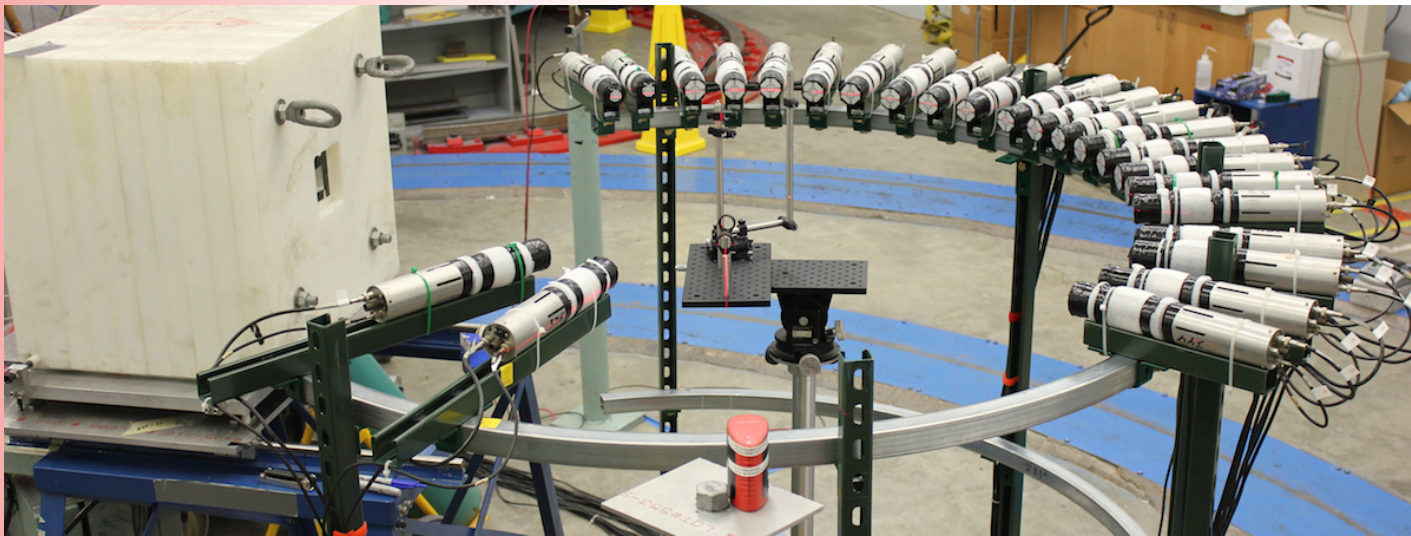
NaI ν E: NaI[Tl] neutrino experiment



Reducing dominant systematic uncertainties

Quenching factors

- Understanding of QF is crucial for *all* CE ν NS 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]

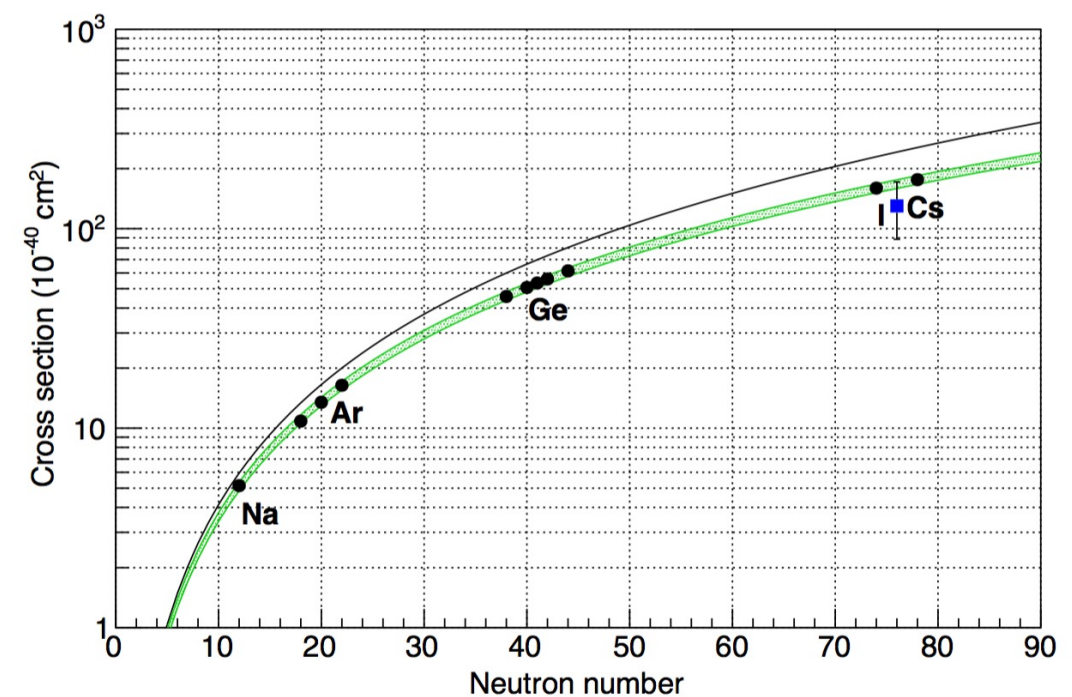
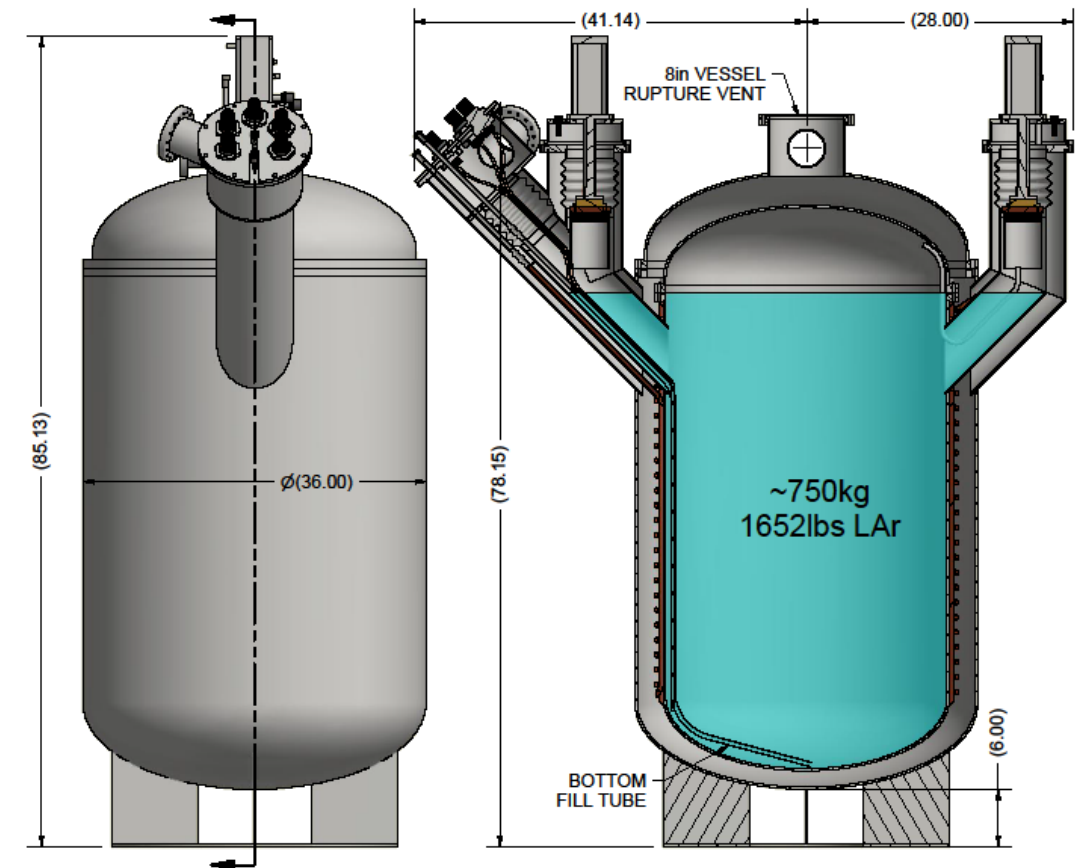
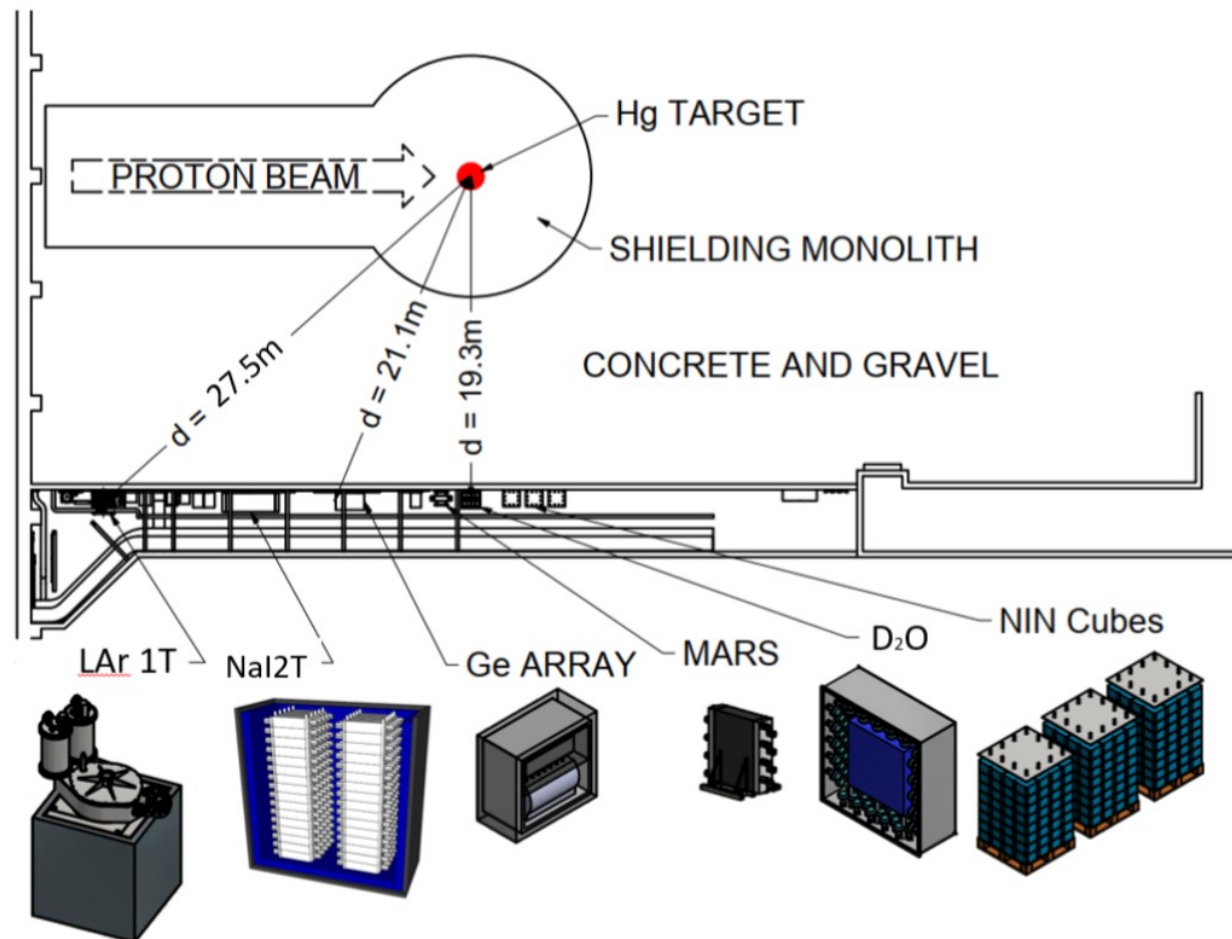


- Indirect approaches to flux determination possible (e.g., improved input for models or direct measurement of pion production at SNS)
- Conceptual design stages of a D₂O detector for neutrino alley relying on CC interaction on D
 - D cross section is relatively well understood theoretically [1] and previous measurements agree with predictions [2]

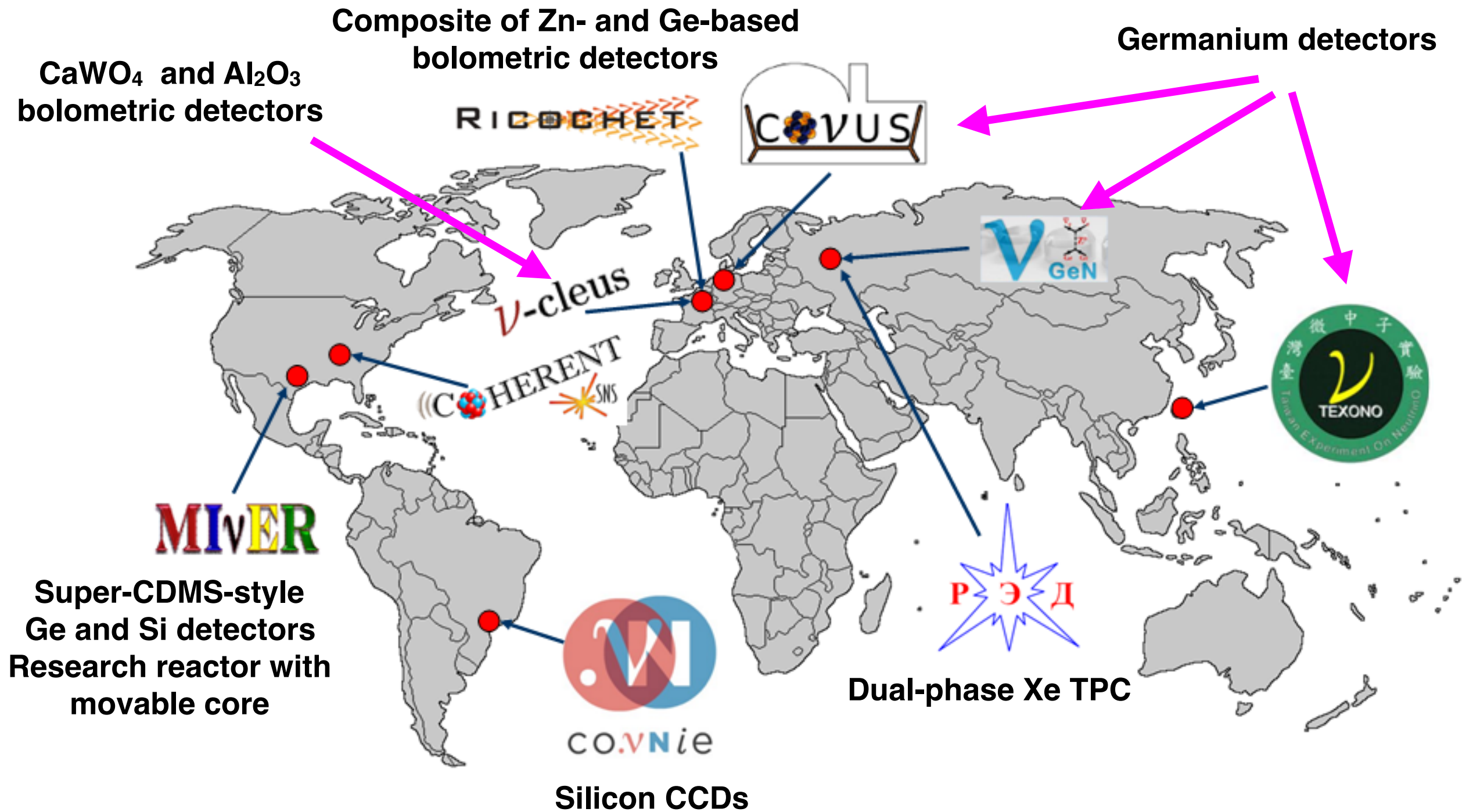
ν flux
normalization

Future of COHERENT

- Next stages of COHERENT CE ν NS measurements will be a considerable scale up
 - Beginning plans for ~750-kg LAr detector, exploring use of underground argon, SiPM readout, etc. *Potential for measuring neutrino-argon cross sections for DUNE and sensitivity to accelerator-produced dark matter.*
 - Development advancing for multi-ton NaI[Tl] detector capable of simultaneous CC and CE ν NS measurement; designing new PMT-base electronics to facilitate this parallel measurement
- Flux normalization measurements benefit all COHERENT experiments; early design stages

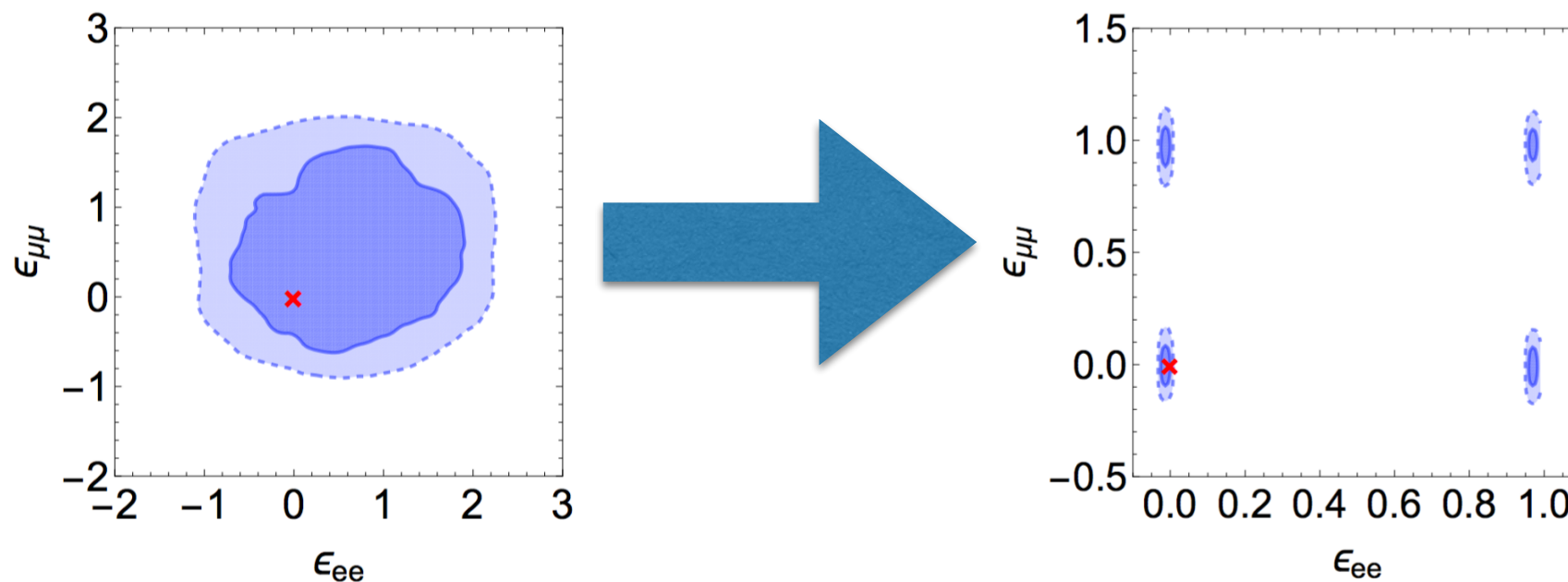


Global CE ν NS efforts



Complementarity of CE ν NS efforts

- The distinct efforts seeking to measure CE ν NS are *highly complementary*
- At the simplest level, different detectors or sources allow for independent systematics
- Different nuclear targets and different sources (energies/flavor composition) allow for isolation of certain physics sensitivities
 - NSI parameter constraints are *significantly* improved when accelerator and reactor experiments are combined in a joint analysis of projected measurements [1]
 - Reactor experiments are not very sensitive to nuclear form factor and some other Q -dependent effects while stopped-pion experiments do have this sensitivity



Only the beginning...

- CE ν NS 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 CE ν NS with numerous detectors (LAr, NaI[Tl], Ge PPCs) in addition to several other efforts
 - Working towards performing *precision* CE ν NS 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
- Tremendous amount of physics left to be done with CE ν NS



THE MAGNIFICENT CEvNS

A WORKSHOP EXPLORING

COHERENT ELASTIC NEUTRINO-NUCLEUS SCATTERING

NOVEMBER 2-3, 2018

PHYSICS RESEARCH CENTER

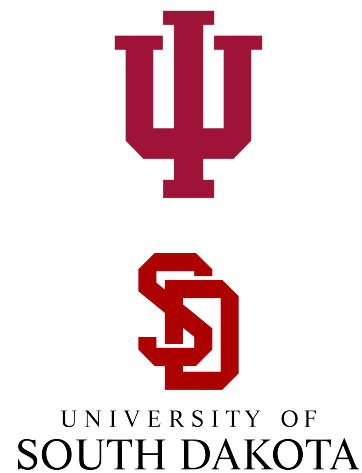
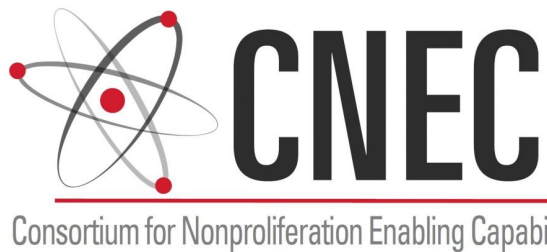
UNIVERSITY OF CHICAGO

CHICAGO, IL USA

- Brought together the broader community of CEvNS researchers at a moment of increasing activity related to, and interest in, the process
 - Experimental participants provided a survey of the landscape for current and upcoming CEvNS efforts
 - Theory/pheno participants discussed possible physics reach and had productive discussions regarding some open questions in the literature
- <http://kicp-workshops.uchicago.edu/2018-CEvNS/>
- ***Will have a second iteration***, with an emphasis on continuing the strong contact between theorists and experimentalists, helping guide future efforts to maximize the physics impact of the CEvNS community
 - Nov./Dec. 2019, likely in area around Duke University (Durham, NC, US)
 - *If interested, let me know*



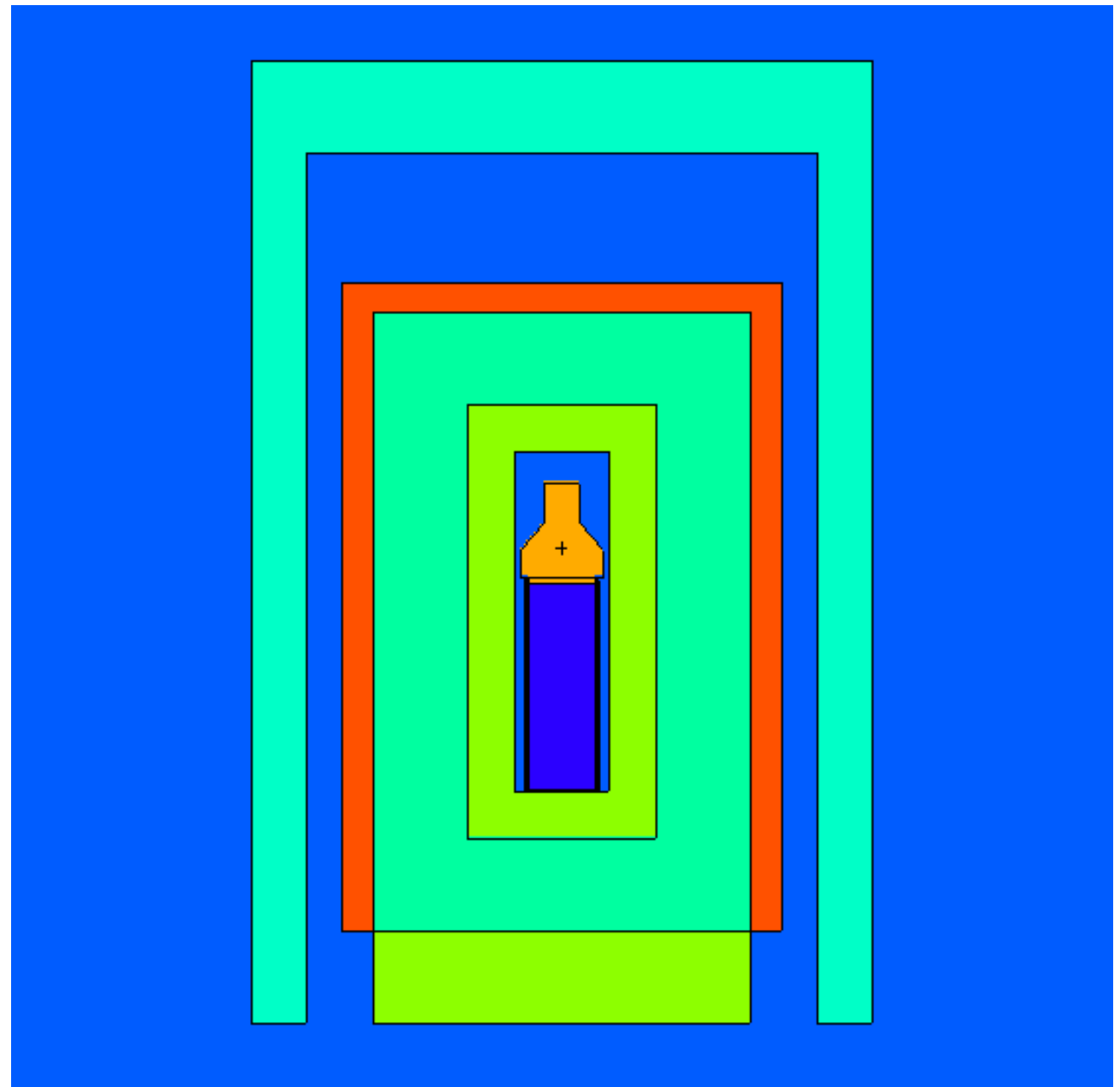
U.S. DEPARTMENT OF
ENERGY



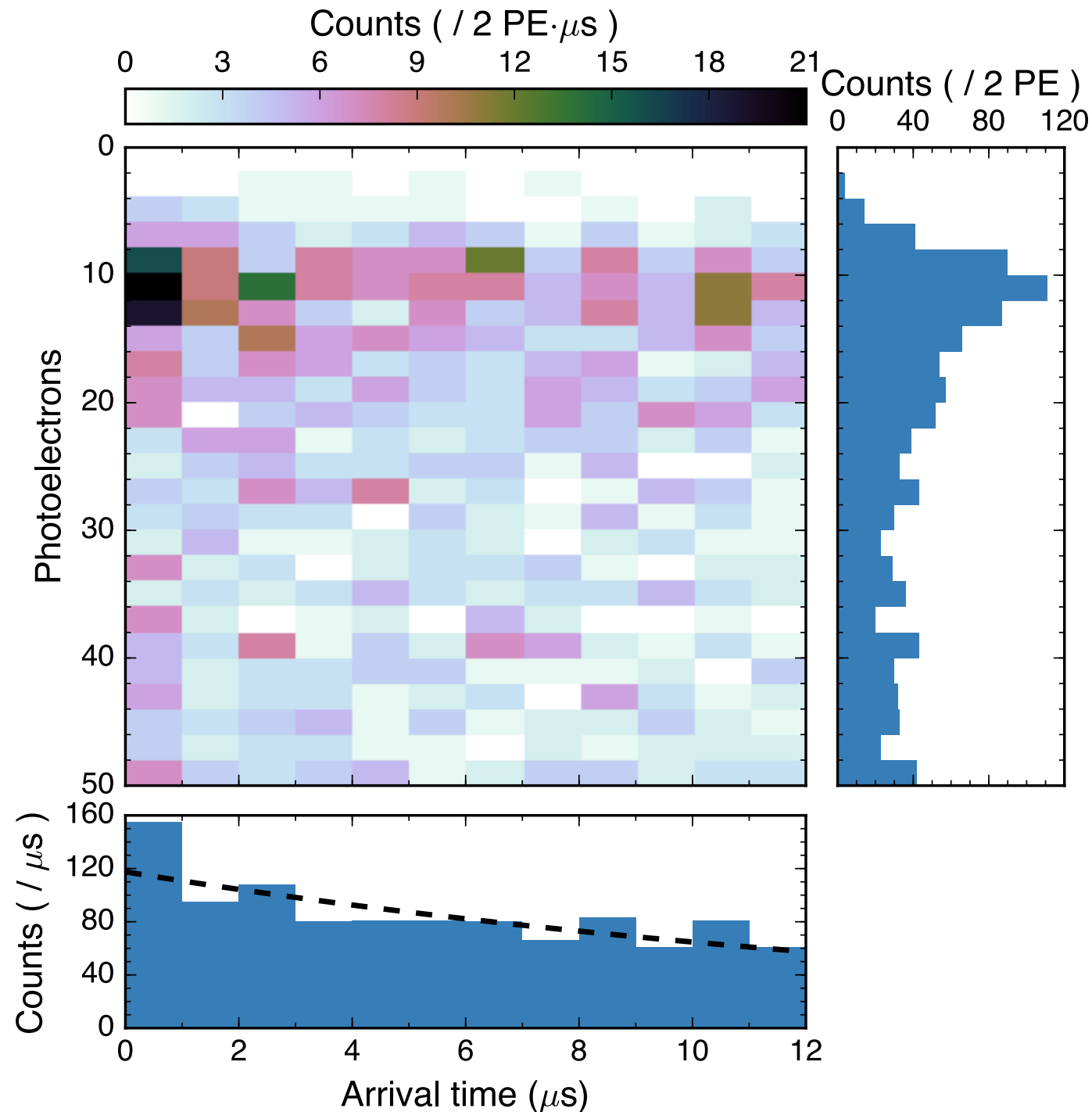
Backup

CE ν NS 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

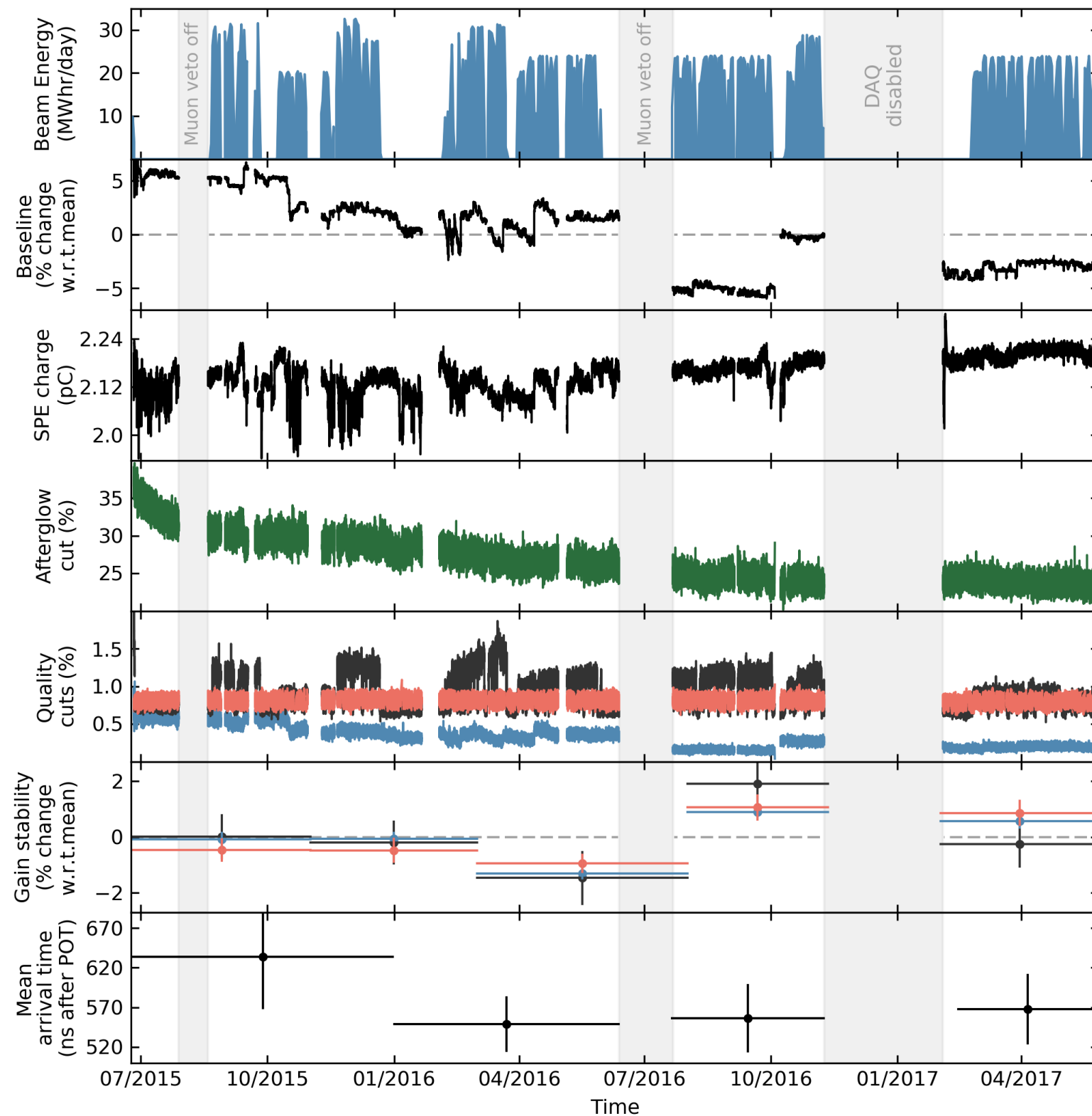


Background model for 2-D

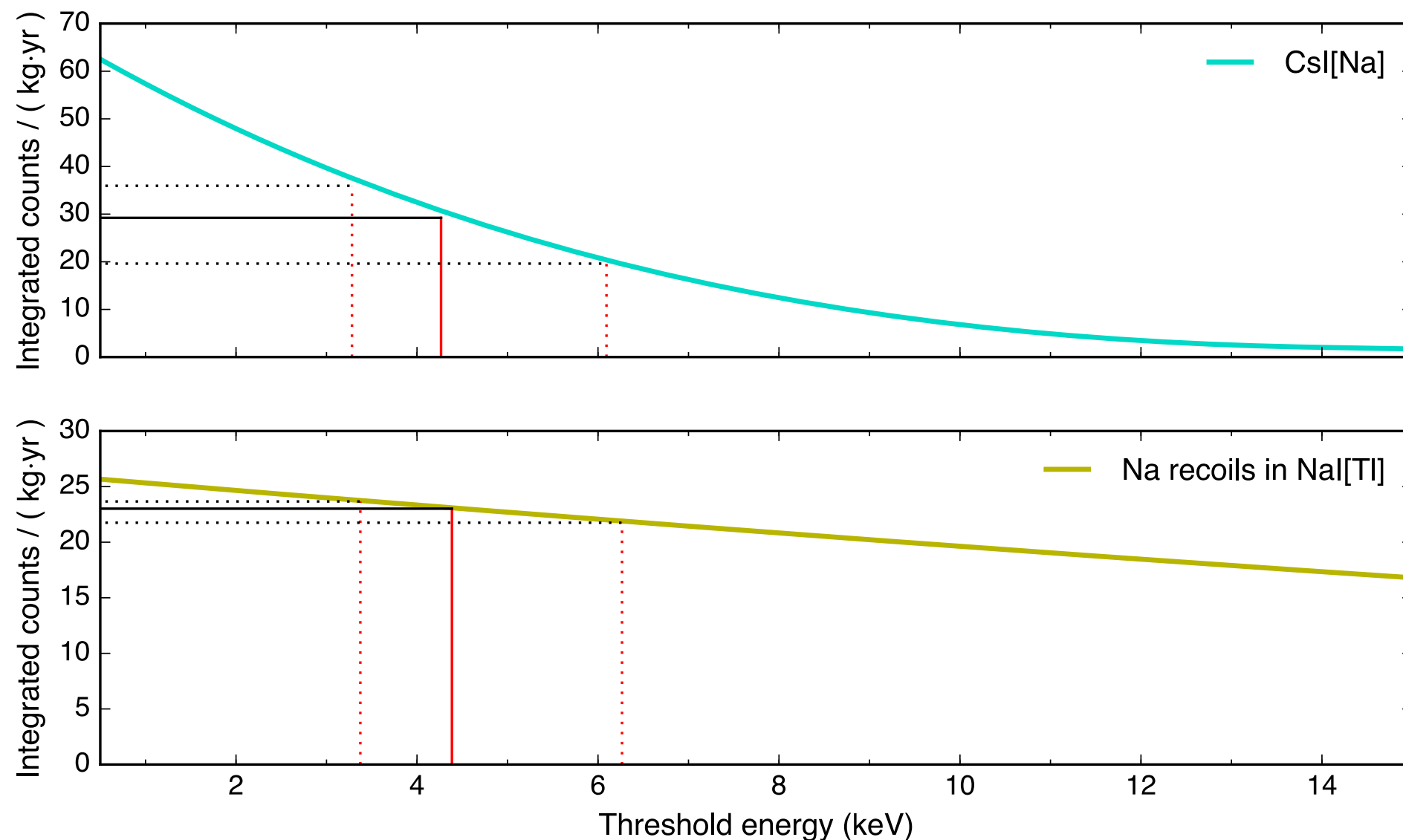


- Background model informed by anti-coincidence dataset
- Use “factorized” approach taking advantage of uncorrelated energy/time features
- Exponential fit to time projection, then used with energy projection to define model

Stability and general health checks



Low-energy nuclear recoils from CE ν NS



- Simple model: assume 30% uncertainty on QF for both Csl[Na] and NaI[Tl]
 - NaI[Tl] counts above threshold has resulting ~5% uncertainty
 - Csl[Na] counts ~30% uncertainty