Observation of coherent, elastic neutrino-nucleus scattering and continued efforts of the COHERENT Collaboration

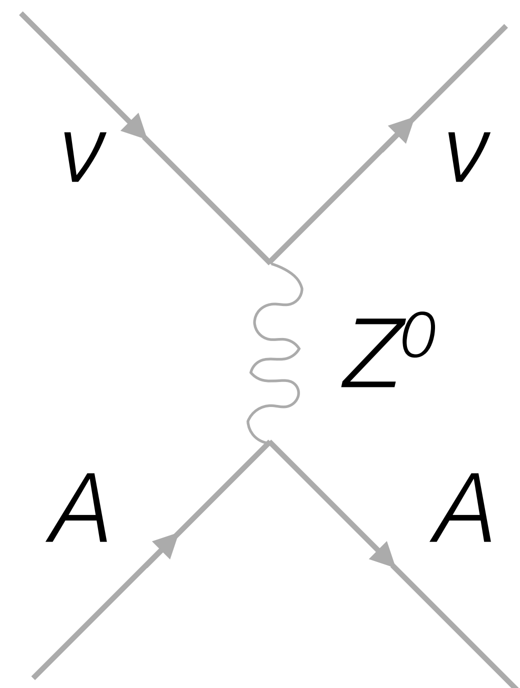
Grayson C. Rich
Enrico Fermi Institute and Kavli Institute for Cosmological Physics
University of Chicago

Recontres de Moriond
La Thuile, Aosta Valley, Italy
2018 March 15

Coherent, elastic neutrino-nucleus scattering (CEvNS)

- NC (flavor-independent) process postulated by D.Z. Freedman in 1974 [1]

- In a CEvNS 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 [2]



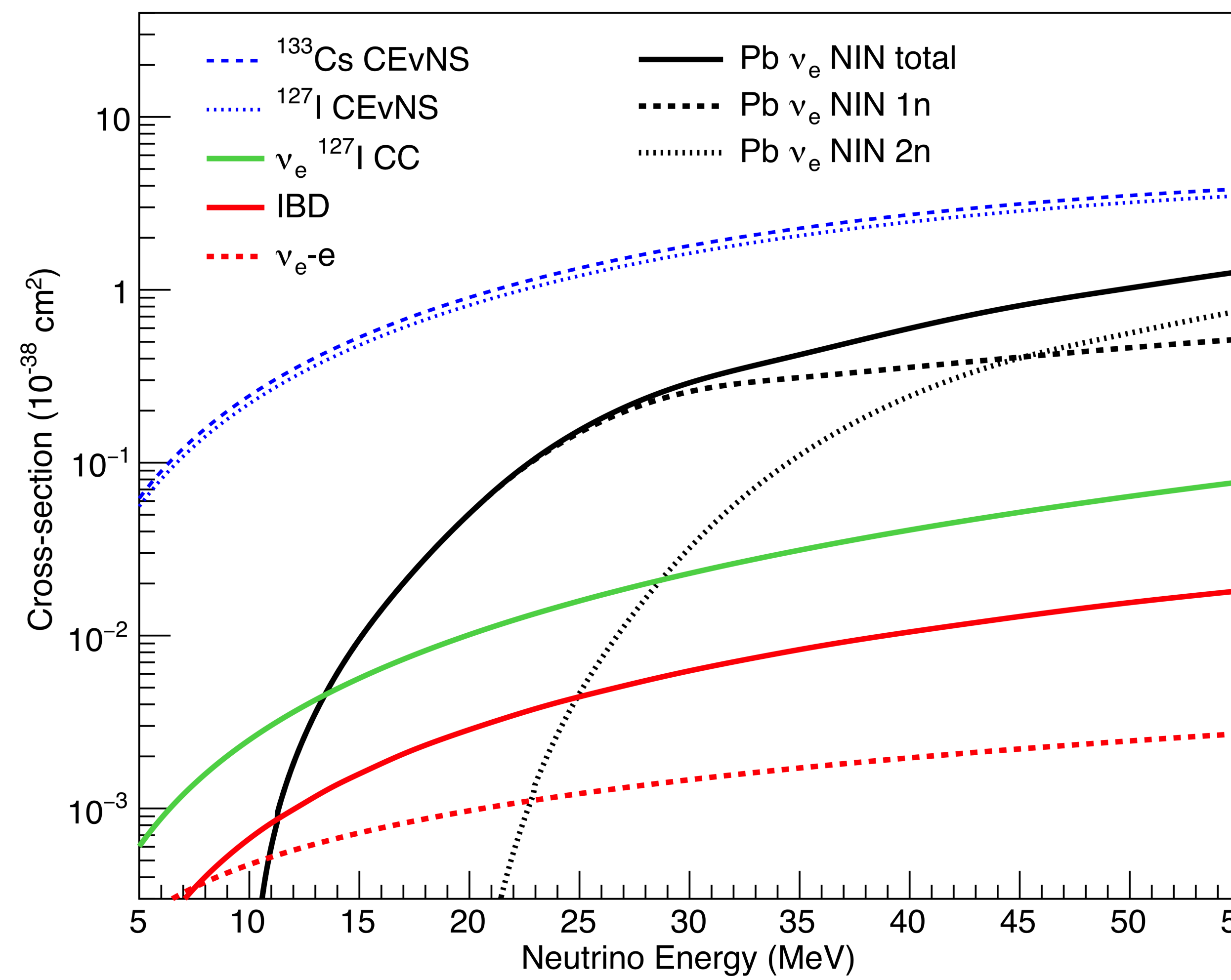
$$\sigma \approx \frac{G_F^2 N^2}{4\pi} E_\nu^2$$

[1] D.Z. Freedman, Phys Rev D 9 (1974)
[2] A. Drukier, L. Stodolsky, Phys Rev D 30 (1984)

Coherent, elastic neutrino-nucleus scattering (CEvNS)

- NC (flavor-independent) process postulated by D.Z. Freedman in 1974 [1]
- In a CEvNS 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 [2]

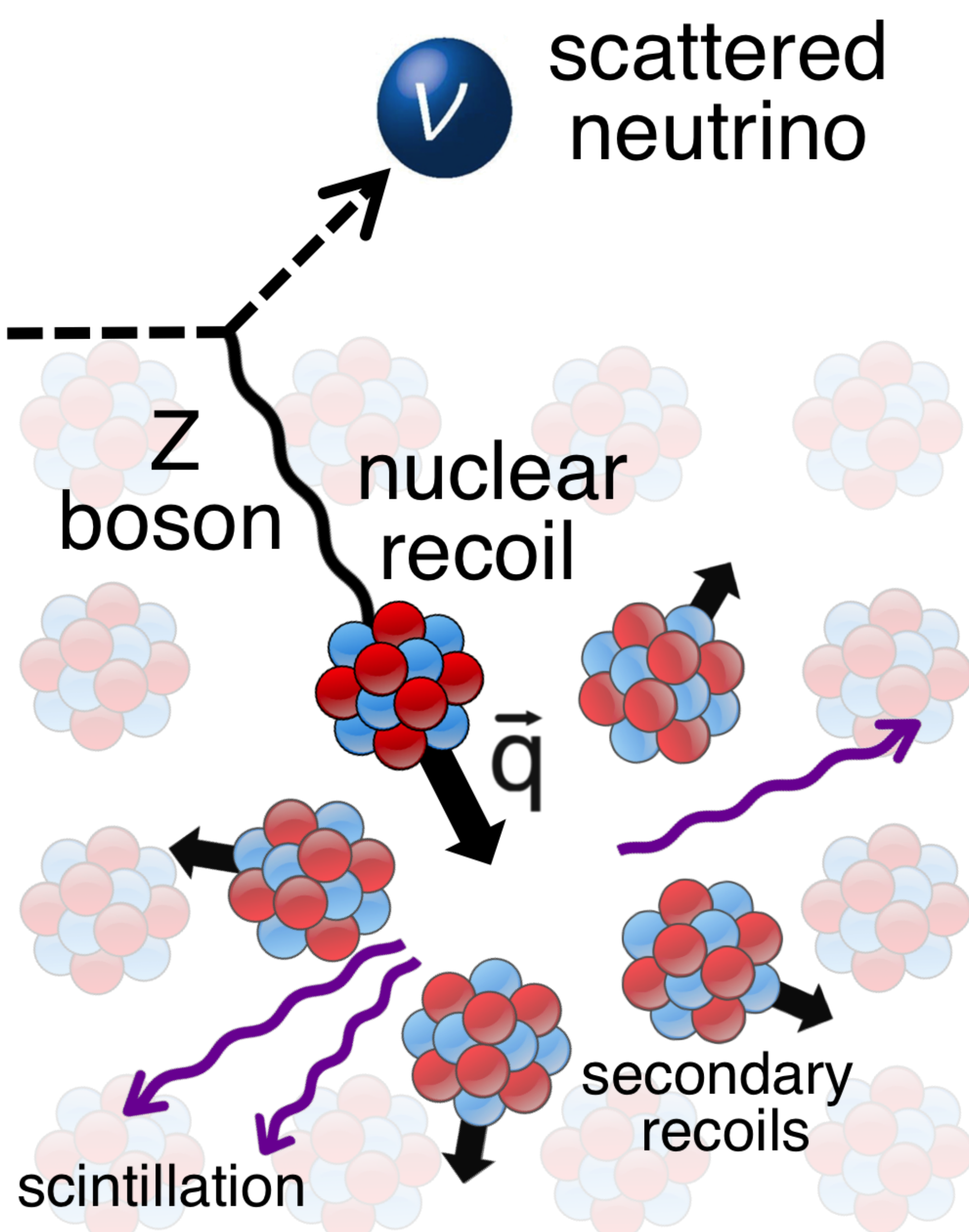
$$\sigma \approx \frac{G_F^2 N^2}{4\pi} E_\nu^2$$



Coherence results in a (relatively) large cross section, but…

[1] D.Z. Freedman, Phys Rev D 9 (1974)
[2] A. Drukier, L. Stodolsky, Phys Rev D 30 (1984)

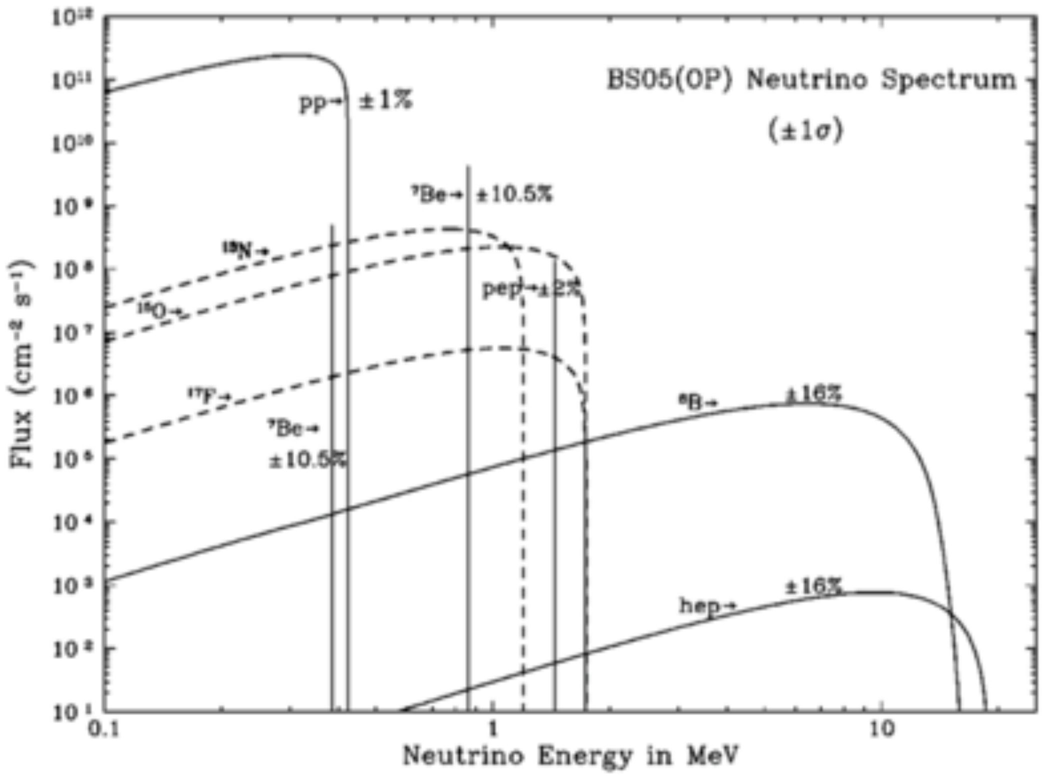
“An act of hubris”

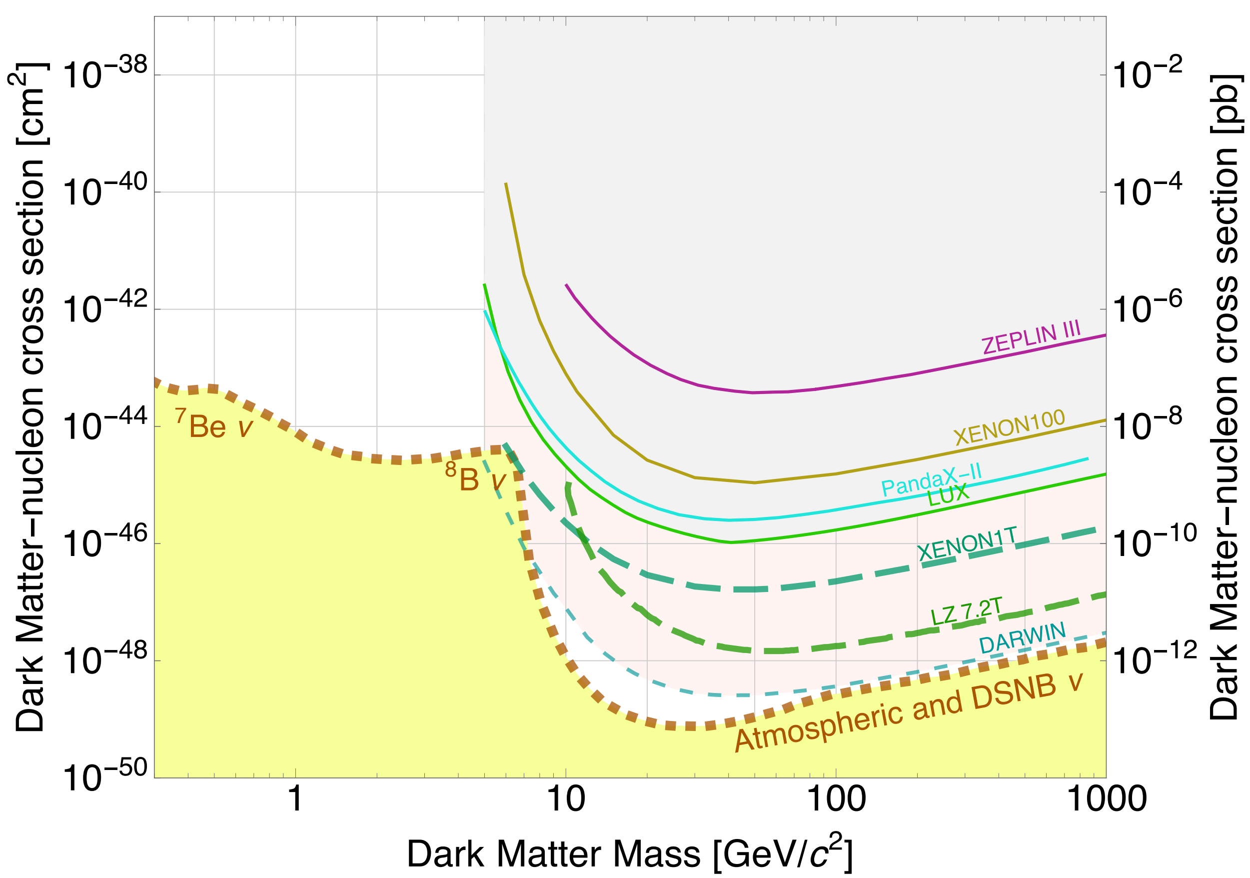


Several factors combine to make CEvNS an exceptionally challenging process to observe

- 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 electrons
  - Detector performance hard to calibrate
- Very sensitive detectors are very sensitive to backgrounds
  - Neutron backgrounds are particularly dangerous: produce low-energy nuclear recoils just like CEvNS
- Need an appropriate source of neutrinos

CEvNS in dark matter and astrophysics





- Primary burning processes in the sun produce neutrinos
- Next generation of WIMP detectors will begin to be sensitive to CEvNS from ^{8}B solar neutrino flux
  - Irreducible “neutrino floor” background
  - *In situ* test of calibration and sensitivity calculations
- CEvNS has long been thought to participate in core-collapse supernovae dynamics [1]
- Also provides mechanism for SNe neutrino detection [2]

[1] H.A. Bethe, Rev. Mod. Phys 62 (1990)
[2] C. Horowitz *et al.*, Phys. Rev. D 68 (2003)
Figures from: (top) Bahcall, Serenelli, Basu, ApJ 621 (2005), (bottom) http://cdms.berkeley.edu/limitplots/

Physics from CEvNS

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

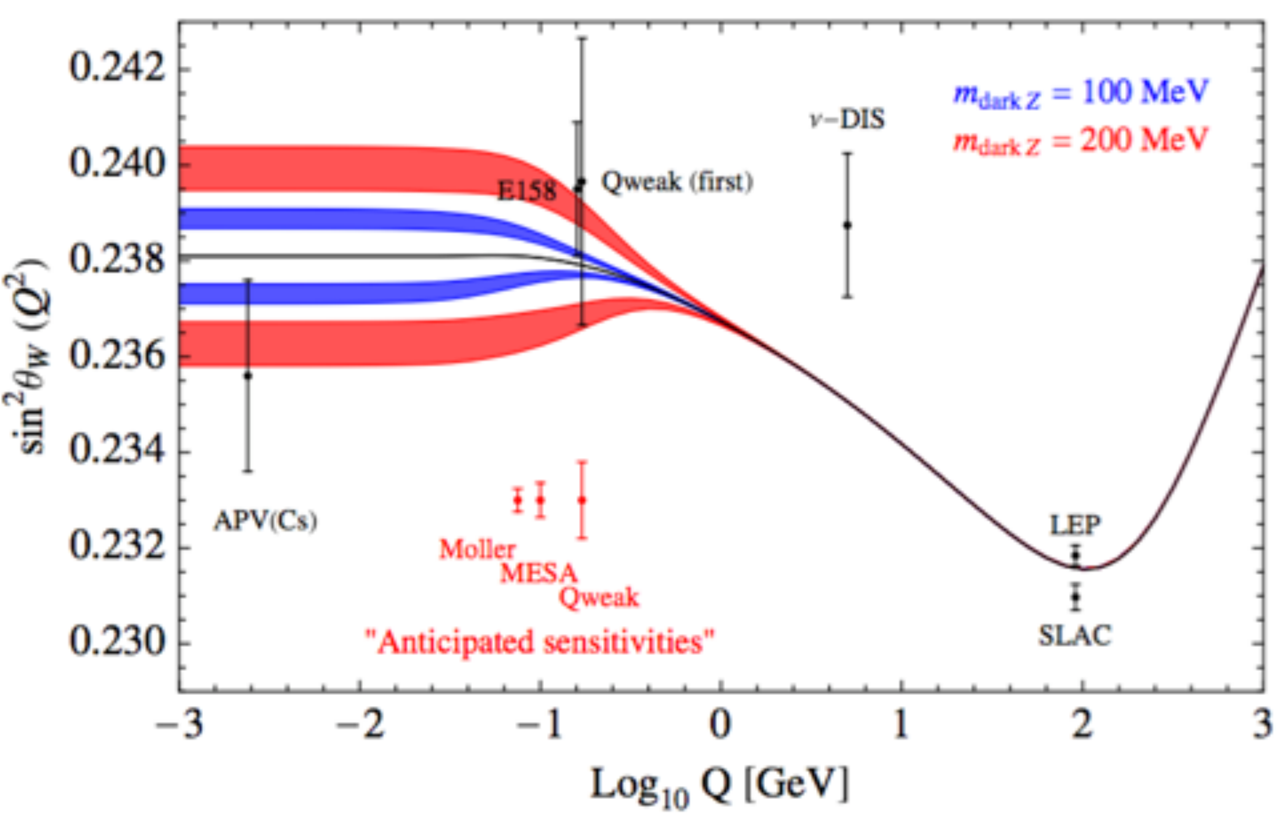
- Simplified differential cross section
  - Describes the distribution of nuclear recoil energies (*T*)
  - Assumes even-even (spherical) nucleus
  - Assumes no non-standard interactions (NSI)
- Begins to expose the physics possible with CEvNS

Physics from CEvNS

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

Weak mixing angle - measurement possible at low Q (~40 MeV/c)

- This region shows sensitivity to dark Z boson models [1]
- CEvNS measurement of Q_W^2 could be used to extract information about the neutrino charge radius [2]



Nuclear form factor - describes distribution of nuclear matter

- Enforces coherency requirement: goes to 0 at high Q
- Provides a way to measure neutron distributions using neutrino scattering [3]
  - Proton distributions well measured (e.g., electron scattering)
  - Neutron distributions are hard to measure, but PVES experiments have provided some data
- Possibly refine nuclear structure models
  - Improve insight into neutron-rich matter
  - Better understanding of neutron star EoS [4]

[1] H. Davoudiasl *et al.*, Phys Rev D 89 (2014)
[2] J. Papavassiliou *et al.*, arXiv:hep-ph/0512029 (2005)
[3] K. Patton *et al.*, Phys. Rev. C 86 (2012)
[4] C. Horowitz & J. Piekarewicz, Phys. Rev. Lett. 86 (2000)

Figure from [1]

Physics from CEvNS

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{2\pi}\left[(G_V+G_A)^2 + (G_V-G_A)^2\left(1-\frac{T}{E_\nu}\right)^2 - (G_V^2 - G_A^2)\frac{MT}{E_\nu^2}\right]$$

$$G_V = \left[\left(g_V^p + 2\sum\epsilon_{\alpha\beta}^{uV} + \sum\epsilon_{\alpha\beta}^{dV}\right)Z + \left(g_V^n + \sum\epsilon_{\alpha\beta}^{uV} + 2\sum\epsilon_{\alpha\beta}^{dV}\right)N\right]F_{\mathrm{nuclear}}^V\left(Q^2\right)$$

$$G_A = \left[\left(g_A^p + 2\sum\epsilon_{\alpha\beta}^{uA} + \sum\epsilon_{\alpha\beta}^{dA}\right)(Z_\uparrow - Z_\downarrow) + \left(g_A^n + \sum\epsilon_{\alpha\beta}^{uA} + 2\sum\epsilon_{\alpha\beta}^{dA}\right)(N_\uparrow - N_\downarrow)\right]F_{\mathrm{nuclear}}^A\left(Q^2\right)$$

- Epsilon terms correspond to neutrino interactions outside of SM (non-universal and flavor-changing neutral currents) [1]

Plus…

- Sensitivity to neutrino magnetic moment at very-low recoil energies [2]

- Possible avenue for sterile neutrino investigation in the form of a neutral-current disappearance search [3]

[1] J. Barranco *et al.*, Phys. Rev. D 76 (2007)
[2] S.J. Brice *et al.*, Phys. Rev. D 89 (2014)
[3] B.C. Cañas *et al.*, Phys. Lett. B 776 (2018)

Enter: The COHERENT Collaboration

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

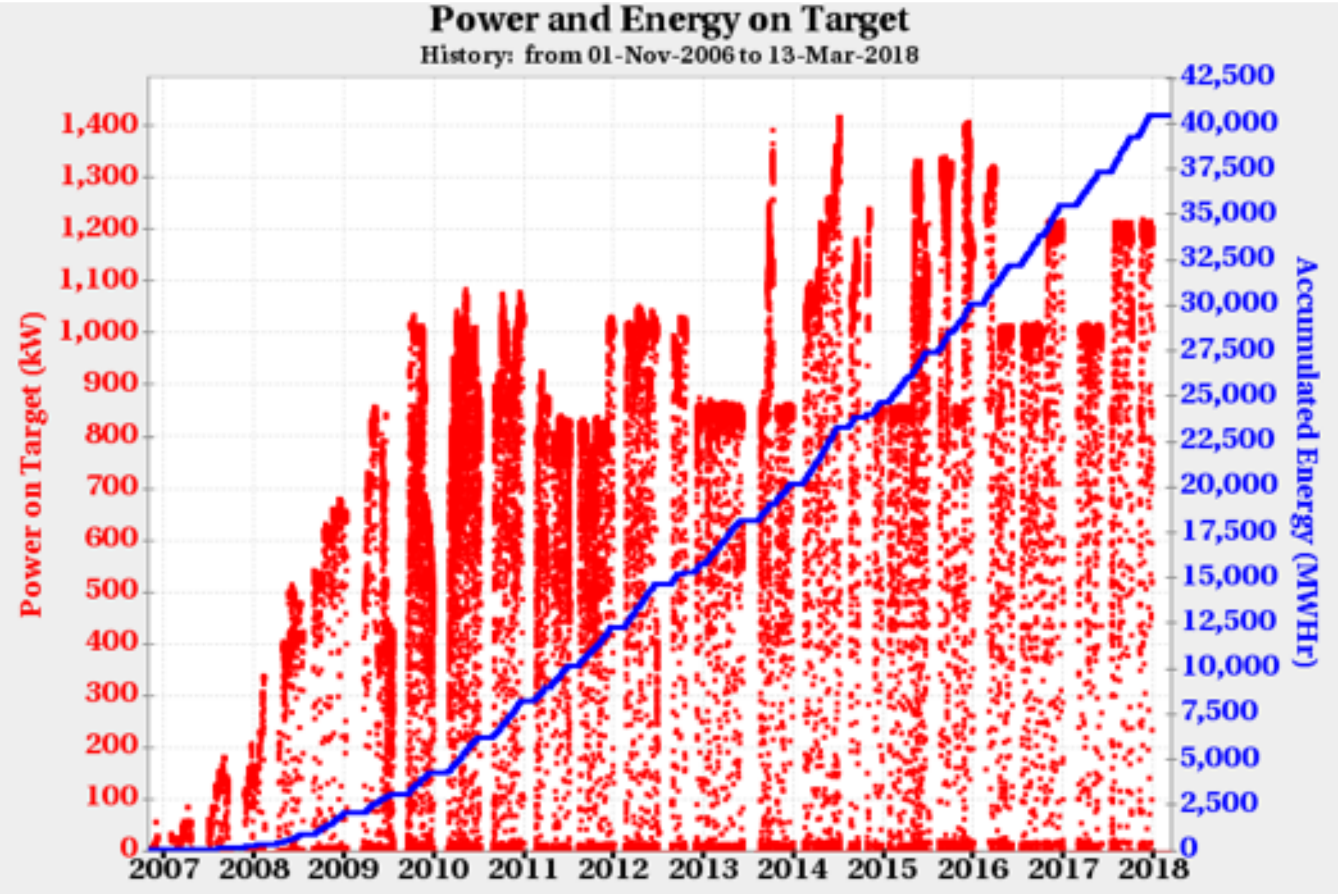
The Spallation Neutron Source

- 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

COHERENT SNS

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

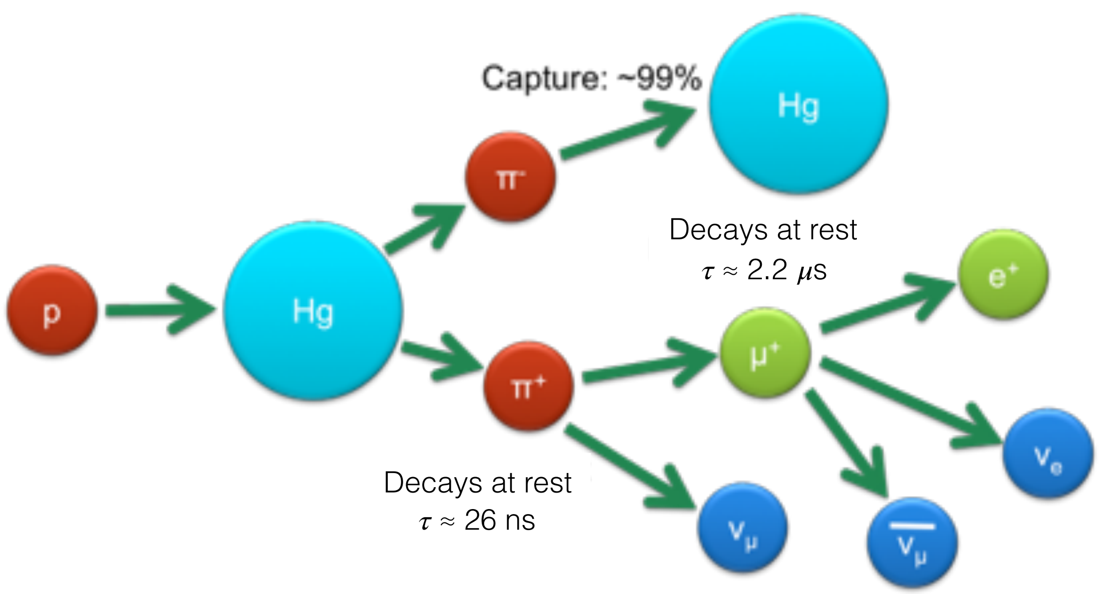
The Spallation Neutron Source

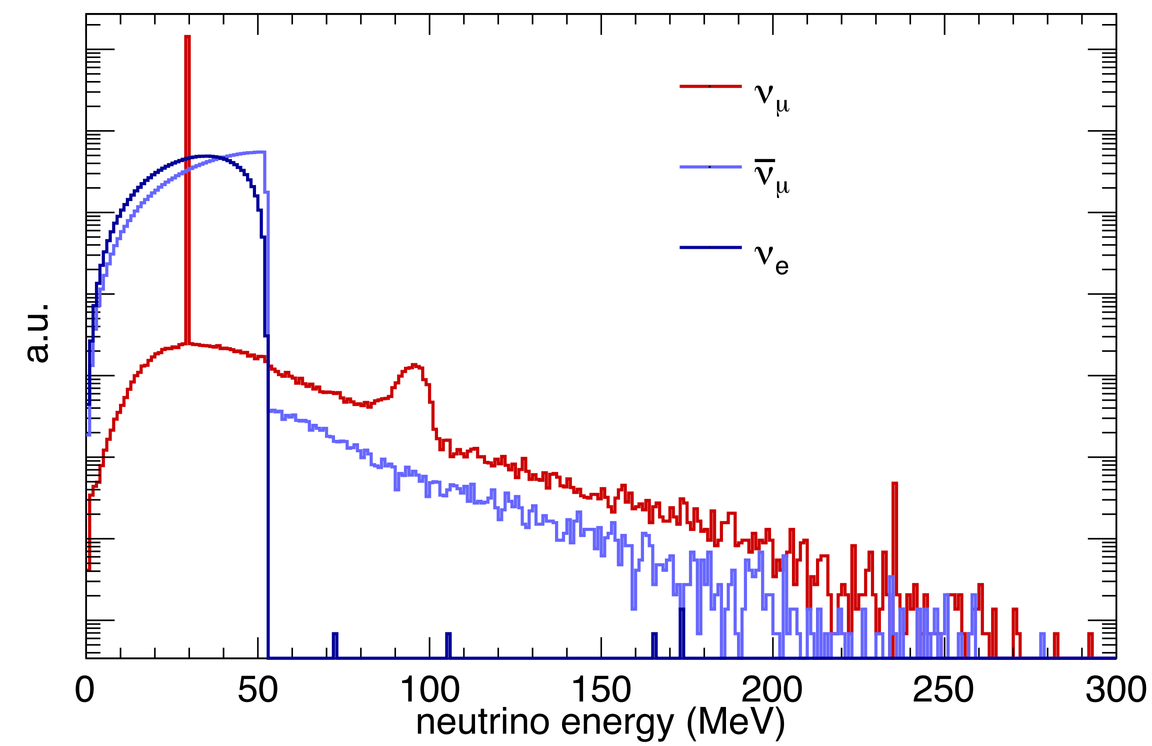


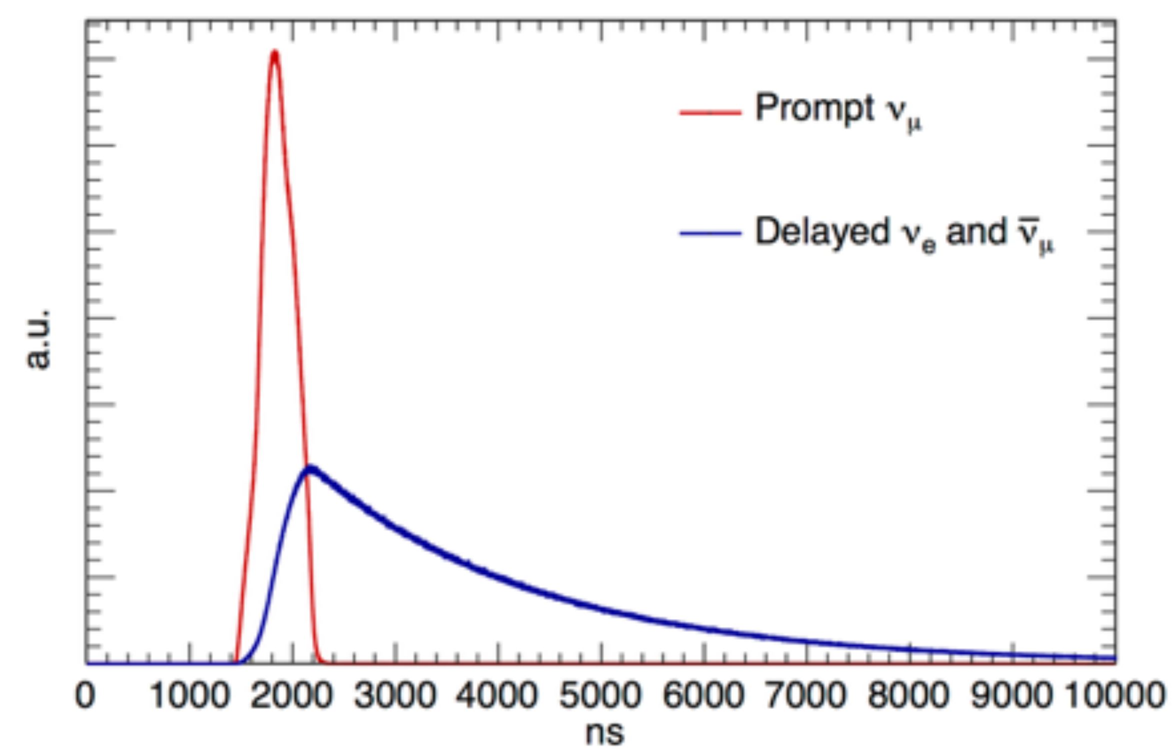
- Located at Oak Ridge National Lab, near Knoxville, TN, USA
- The SNS bombards a liquid mercury target with a ~1-GeV proton beam pulsed at 60 Hz; each beam pulse is ~700-ns wide
- Neutrinos are produced by decay of ***stopped*** *pions and muons*, resulting in flux with well-defined spectral and timing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

Figure from https://status.sns.ornl.gov/beam.jsp

The Spallation Neutron Source



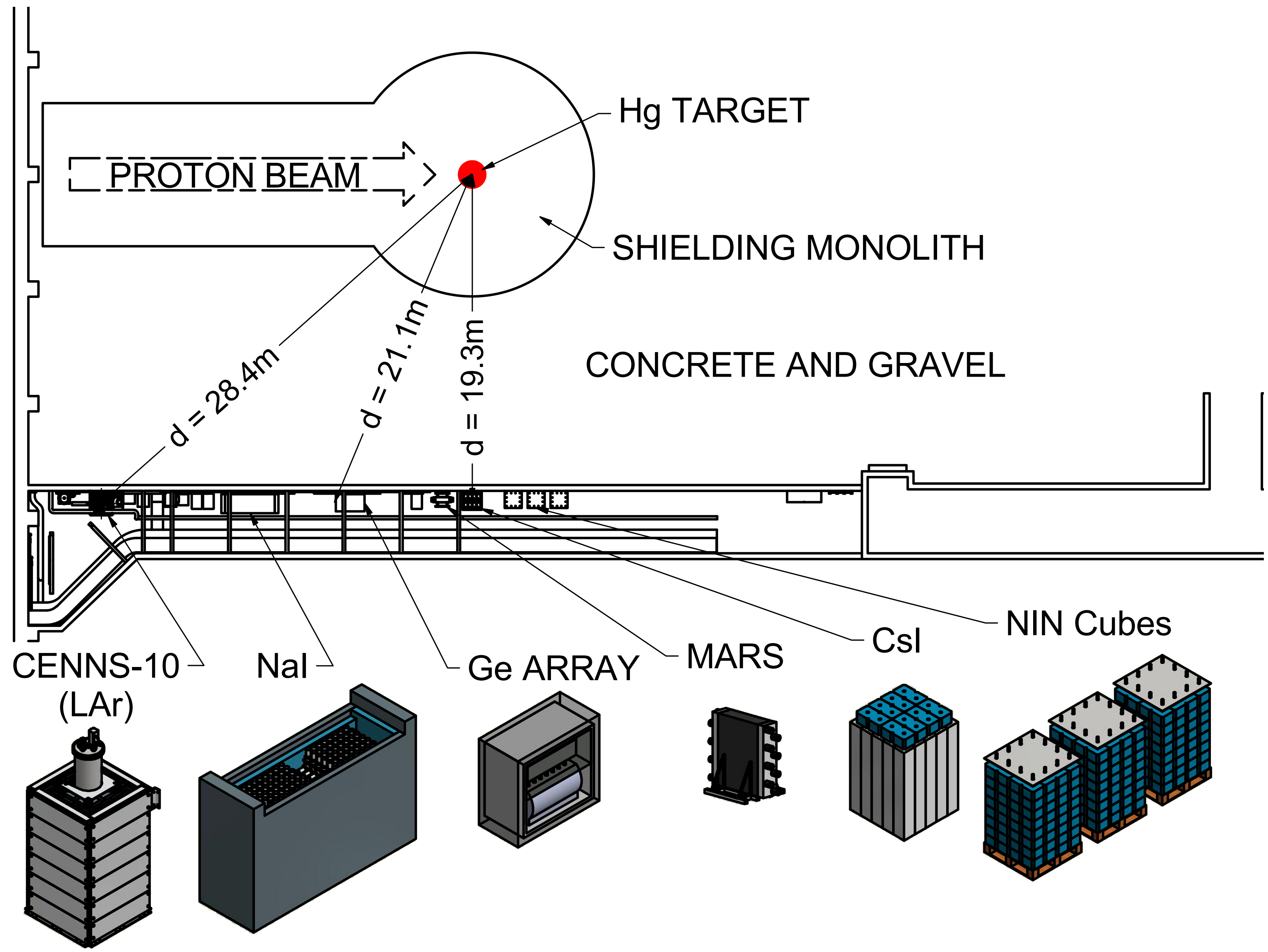




- High-fidelity GEANT4 simulation starts with proton beam; energy spectra very near analytical approximations
- Massive reduction in steady-state backgrounds through timing (O(1000)); facility-wide timing signal can be used to trigger DAQ, both during beam-on and -off periods

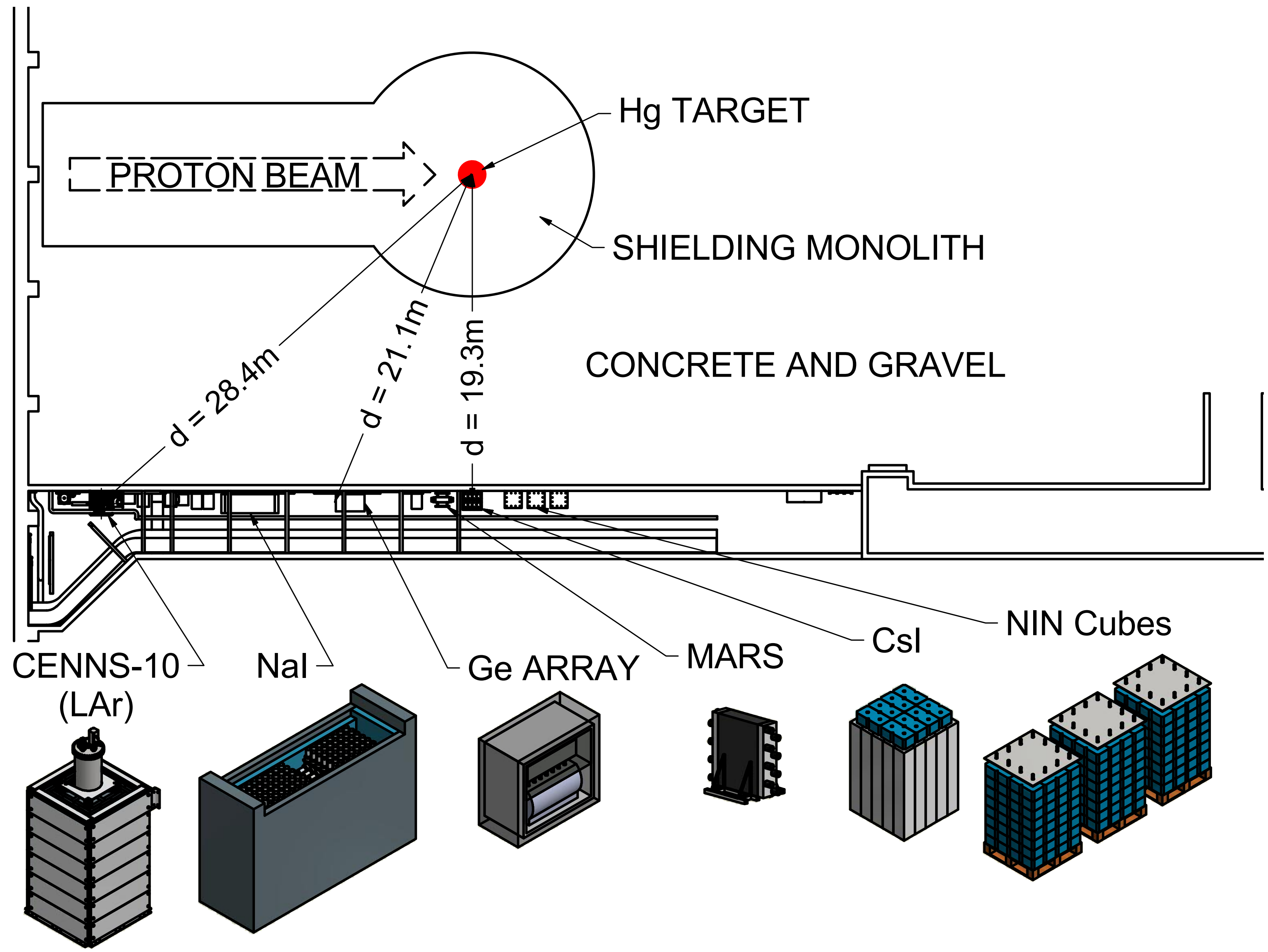
Siting and backgrounds

- Backgrounds depend significantly on siting at SNS
- Detectors located in a basement hallway
  - ~8 m.w.e. overburden
  - 20- to 30-m from target
- Extensive background measurement campaign involving numerous detector systems



Siting and backgrounds

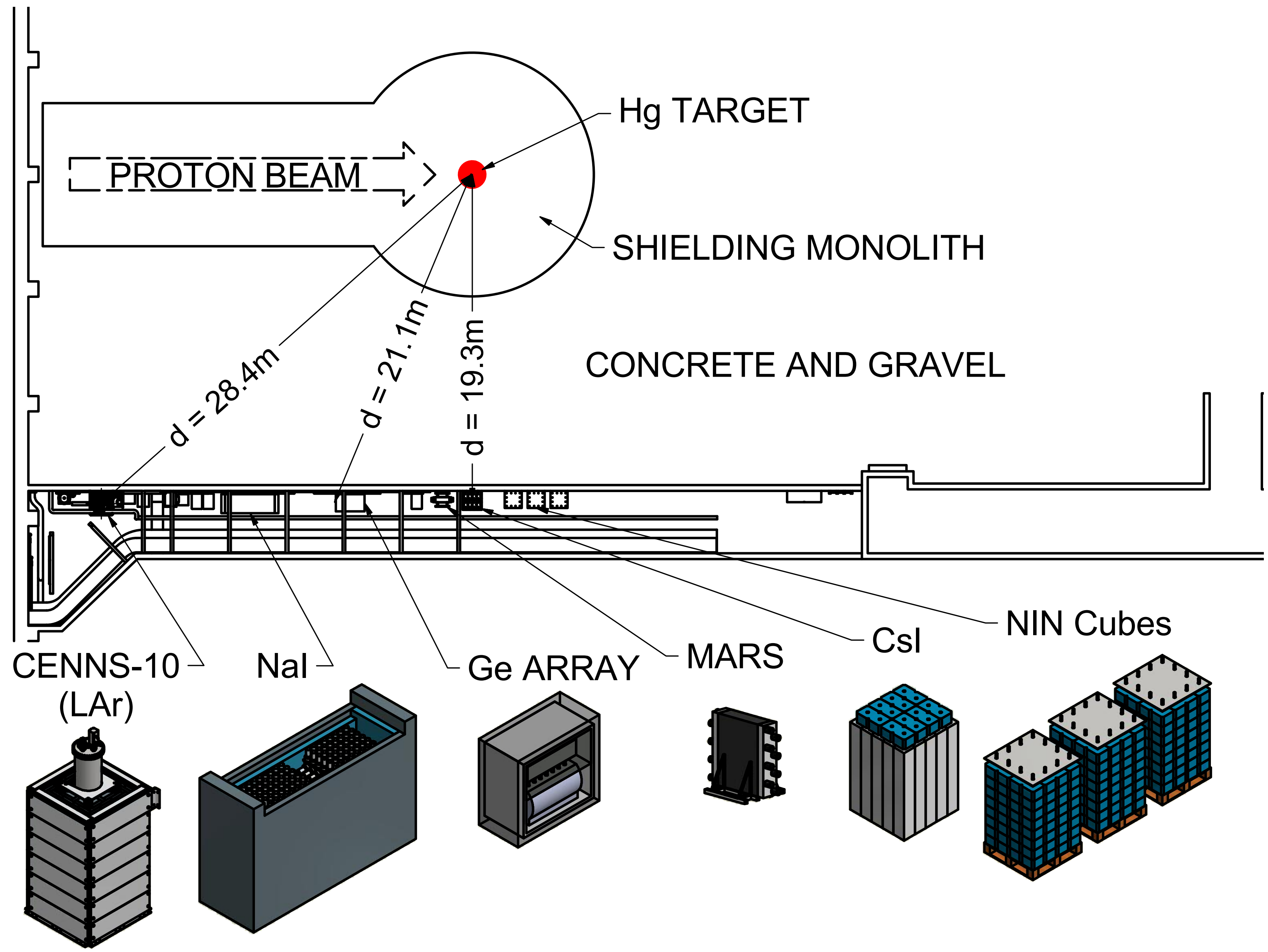
- Backgrounds depend significantly on siting at SNS
- Detectors located in ~~a basement hallway~~ *neutrino alley*
  - ~8 m.w.e. overburden
  - 20- to 30-m from target
- Extensive background measurement campaign involving numerous detector systems



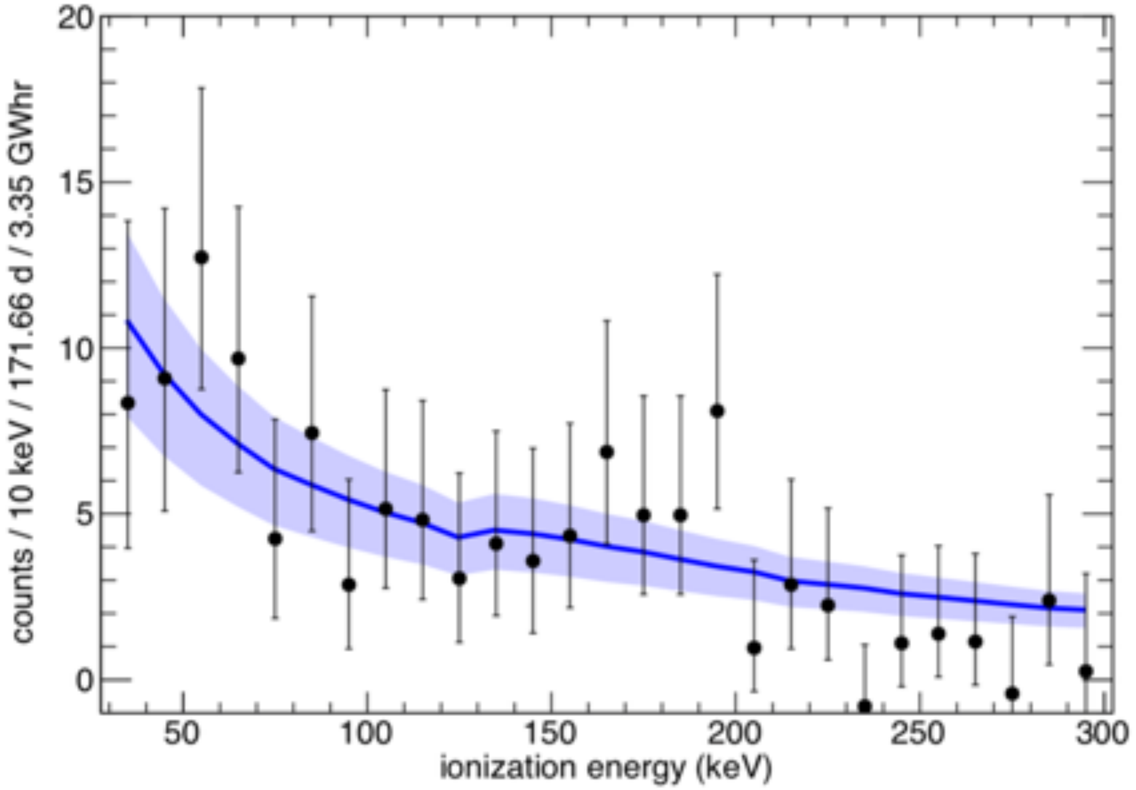
Siting and backgrounds

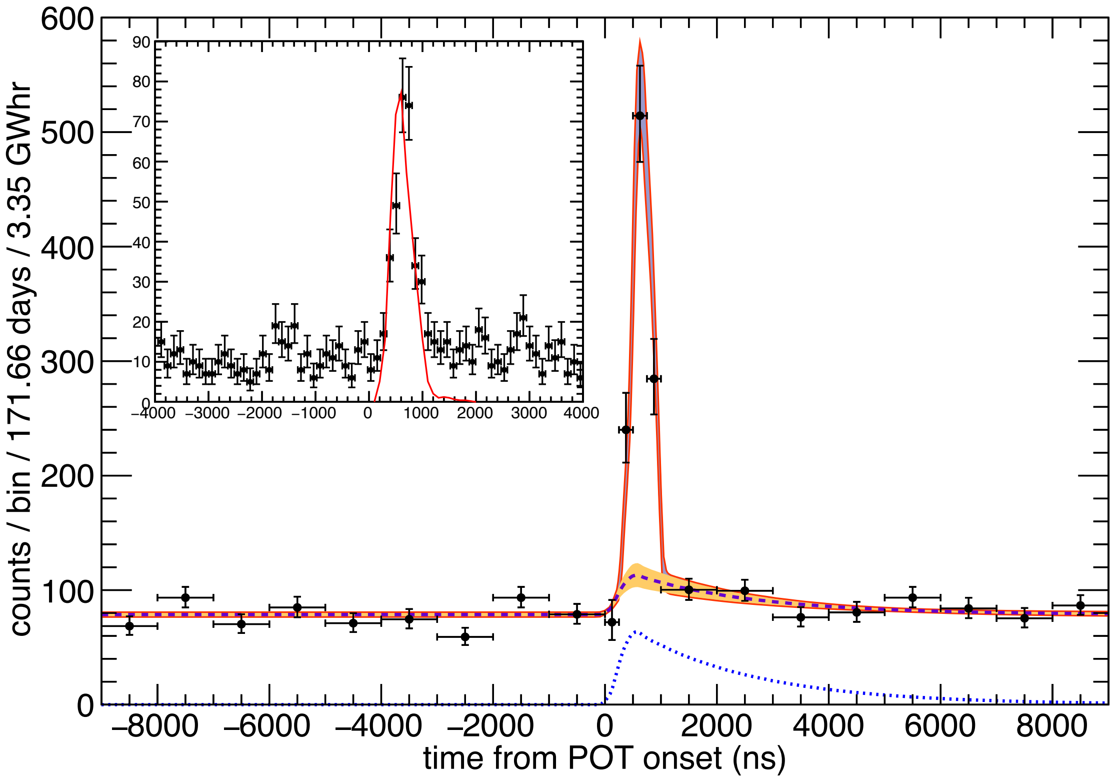
Primary backgrounds in neutrino alley

- Steady state components are suppressed strongly by timing and complemented by modest overburden
- Prompt SNS neutrons
- Neutrino-induced neutrons (NINs)



In situ measurement of neutron backgrounds



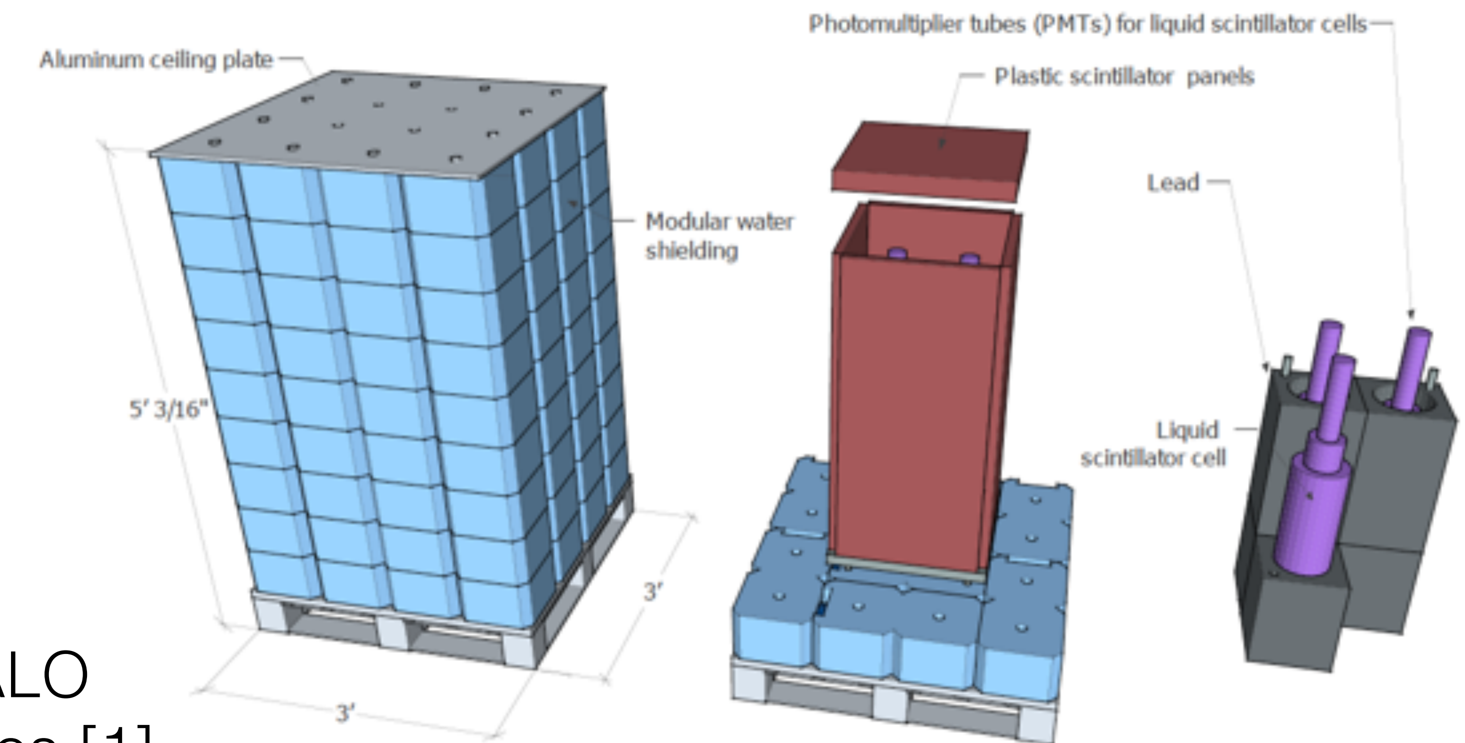


- Prior to CEvNS search, neutron detection system installed at location of CsI[Na] detector
- Data informed model of prompt SNS neutron energy distribution
- Established understanding of beam timing w.r.t. SNS timing signal

Neutrino-induced neutrons (NINs)

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

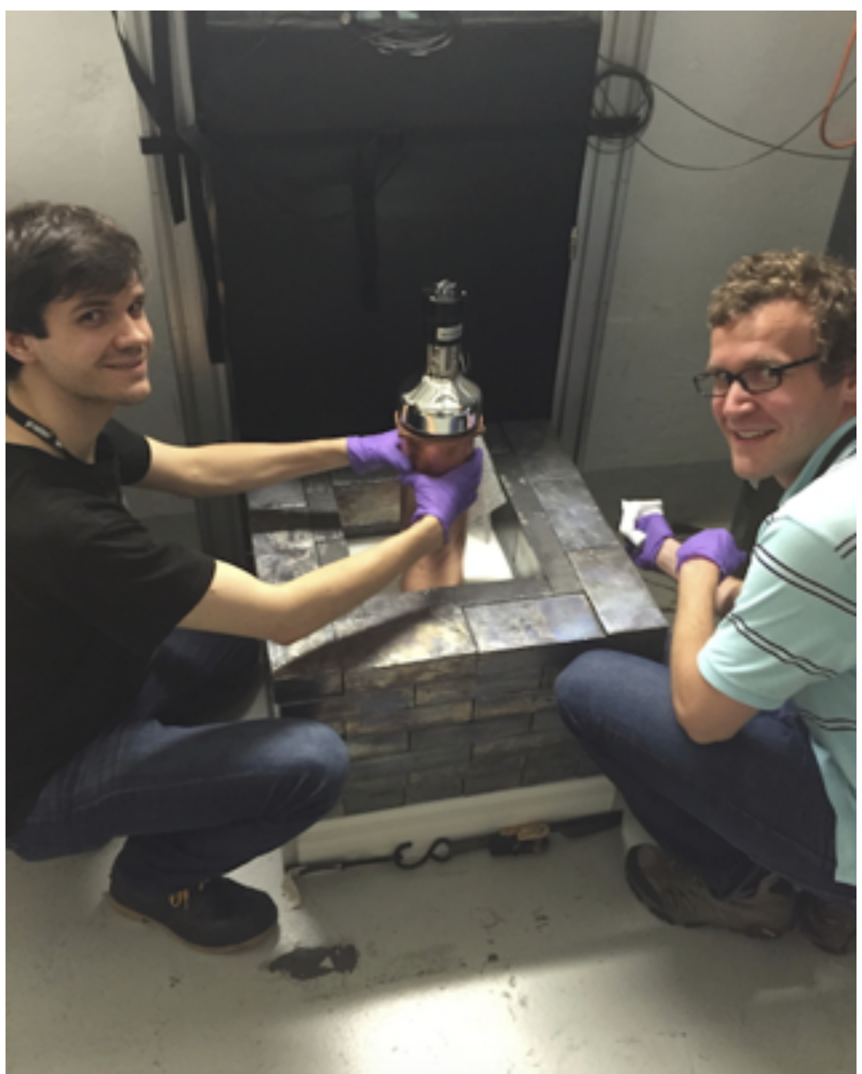
$$\nu_x + {}^{208}\mathrm{Pb} \;\Rightarrow\; {}^{208}\mathrm{Pb}^* + \nu_x' \qquad \text{(NC)}$$
$$\Downarrow$$
$${}^{208-y}\mathrm{Pb} + x\gamma + yn.$$



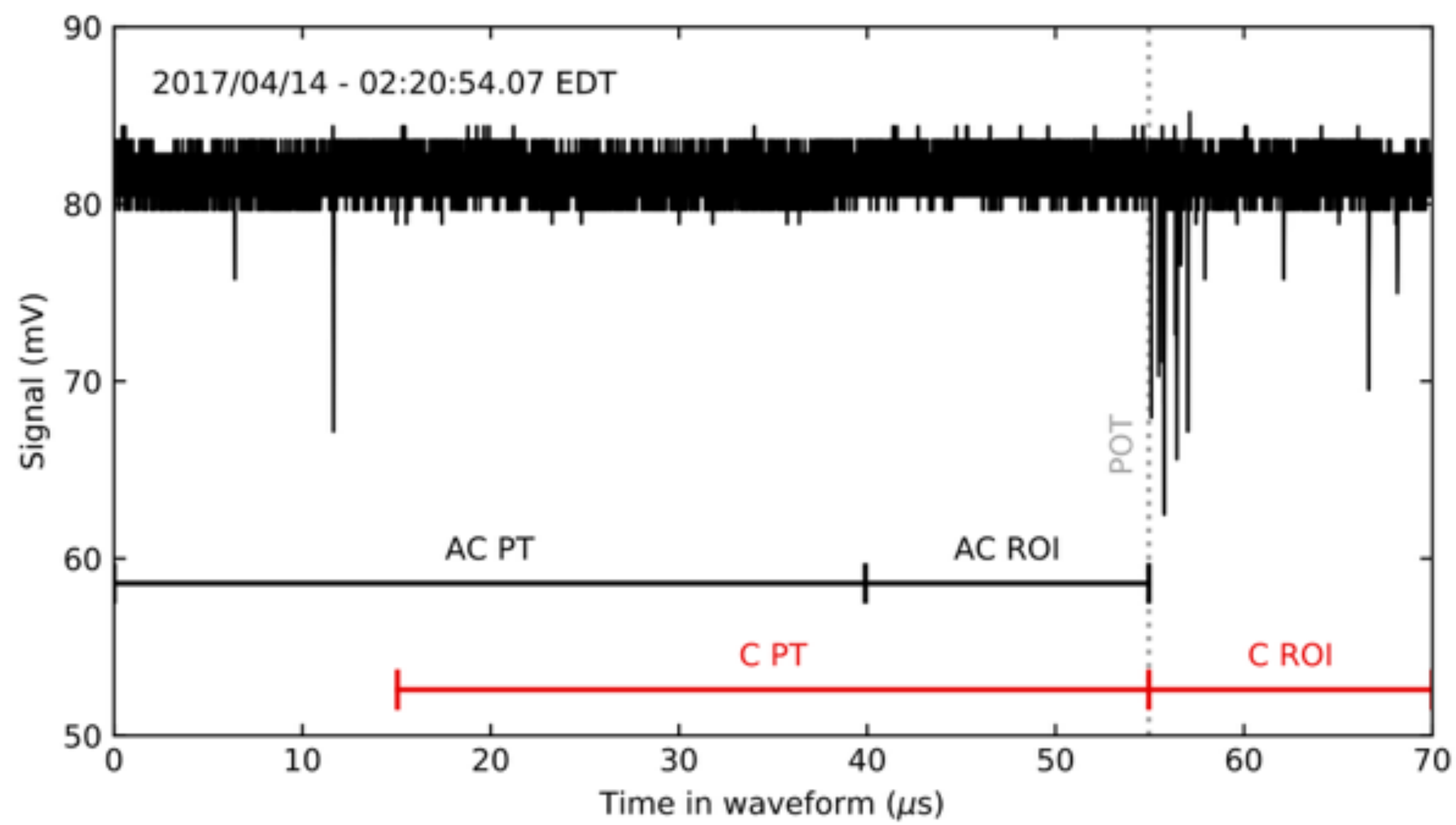
- Fundamental mechanism by which HALO intendeds to detect supernova neutrinos [1]
- Possible role in nucleosynthesis in certain astrophysical environments [2]
- *In situ* measurements give rate limit, plus ongoing measurement of process with "neutrino cubes"

[1] C.A. Duba *et al.* J. Phys. Conf. Series 136 (2008)
[2] Y-Z. Qian *et al.*, Phys. Rev. C 55 (1997)
NIN pathways from S.R. Elliott, Phys. Rev. C (2000)

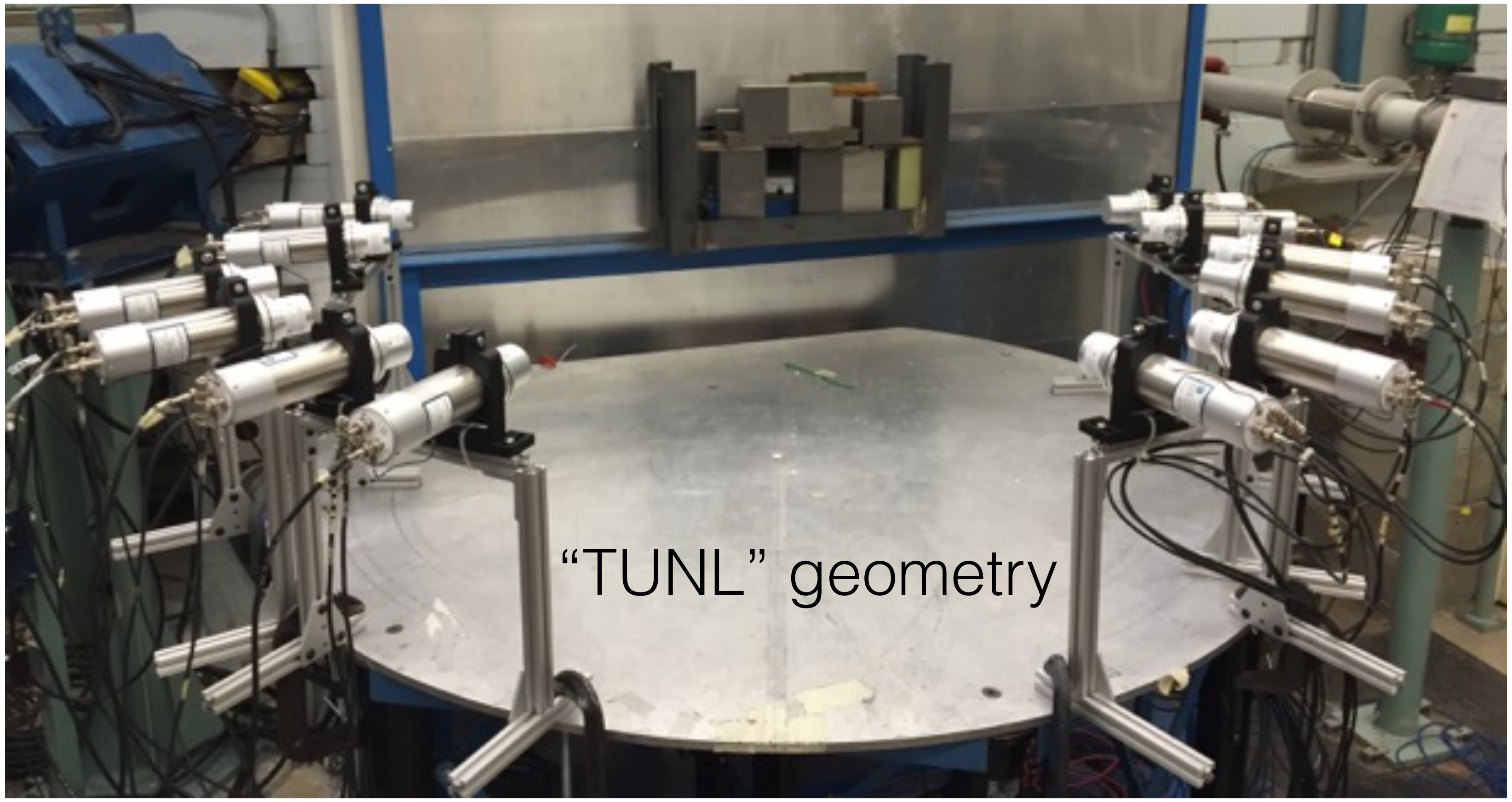
CEvNS with CsI[Na]

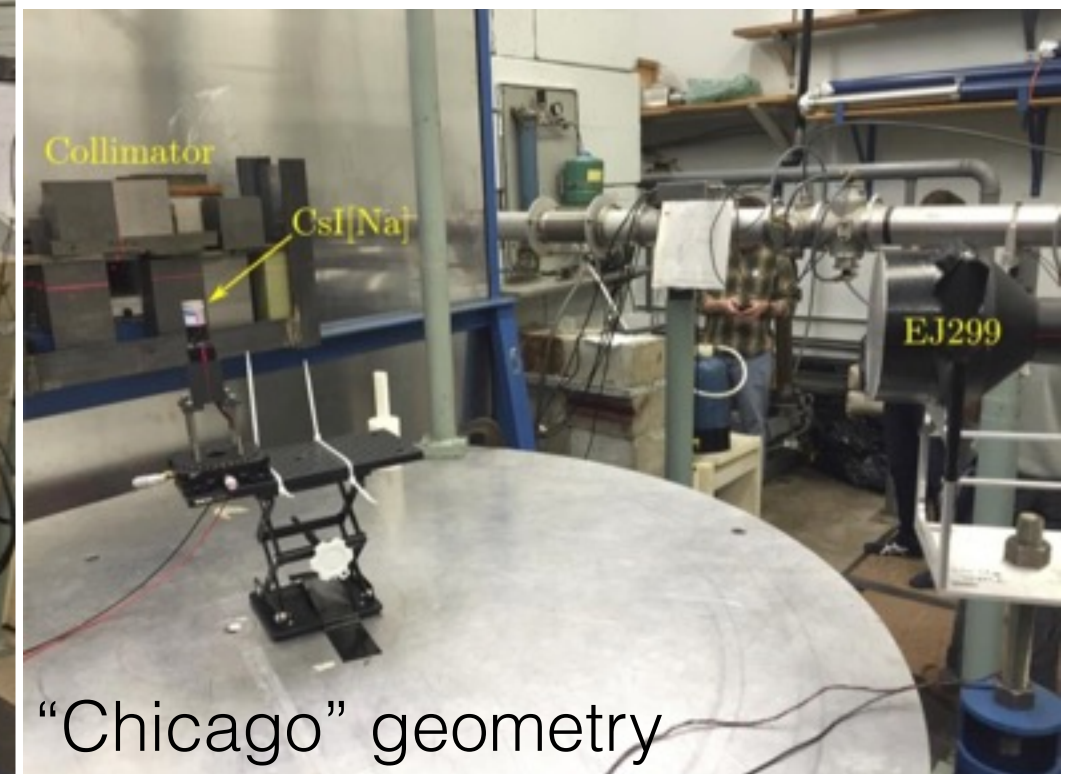


- 14.6-kg crystal made from low-background salts, encased in electroformed-copper can with PTFE reflector and synthetic silica window, surrounded by neutron and gamma shielding, including low-activity lead
- Deployed to SNS in June 2015
- Output of super-bialkali PMT with ~30% QE digitized for 70 μs, triggered by SNS timing signal; output of muon-veto system also digitized



Quenching factor measurements at TUNL

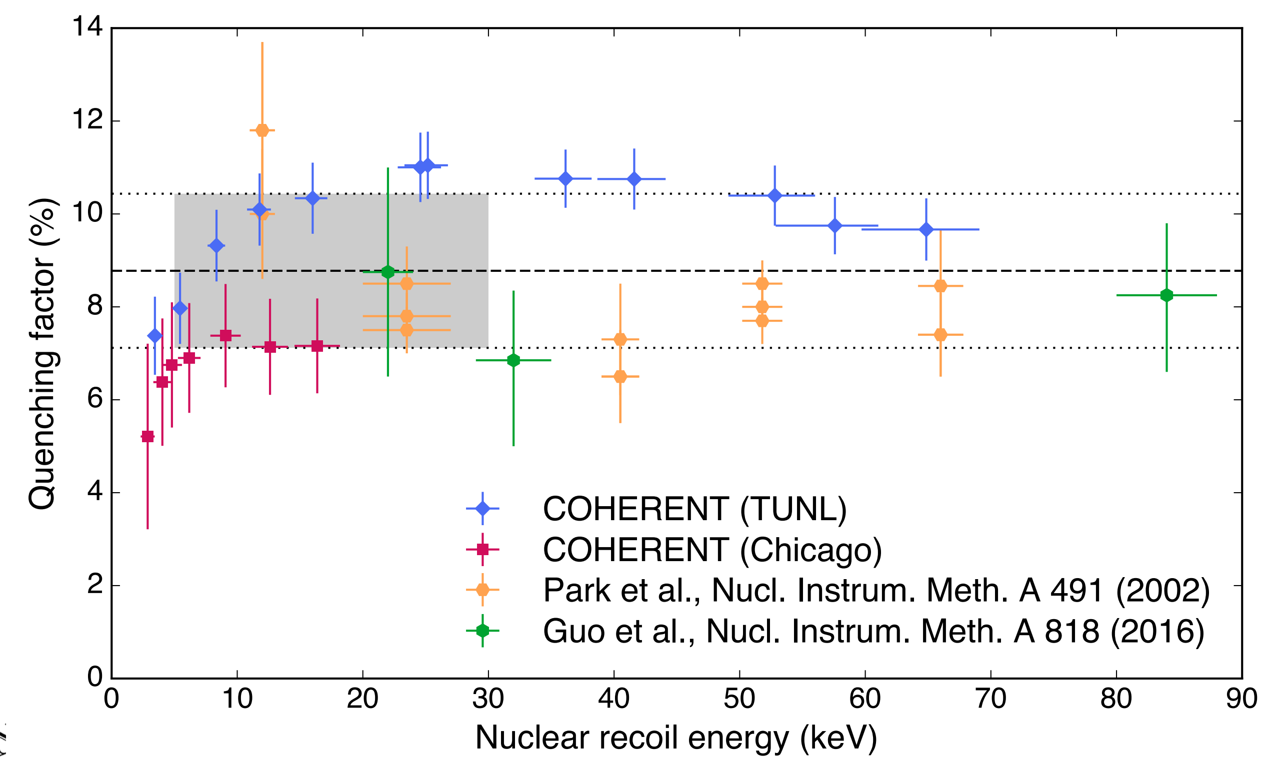




- Elastically scatter neutrons into "backing detectors" at known angles, corresponding to well-defined recoil energies

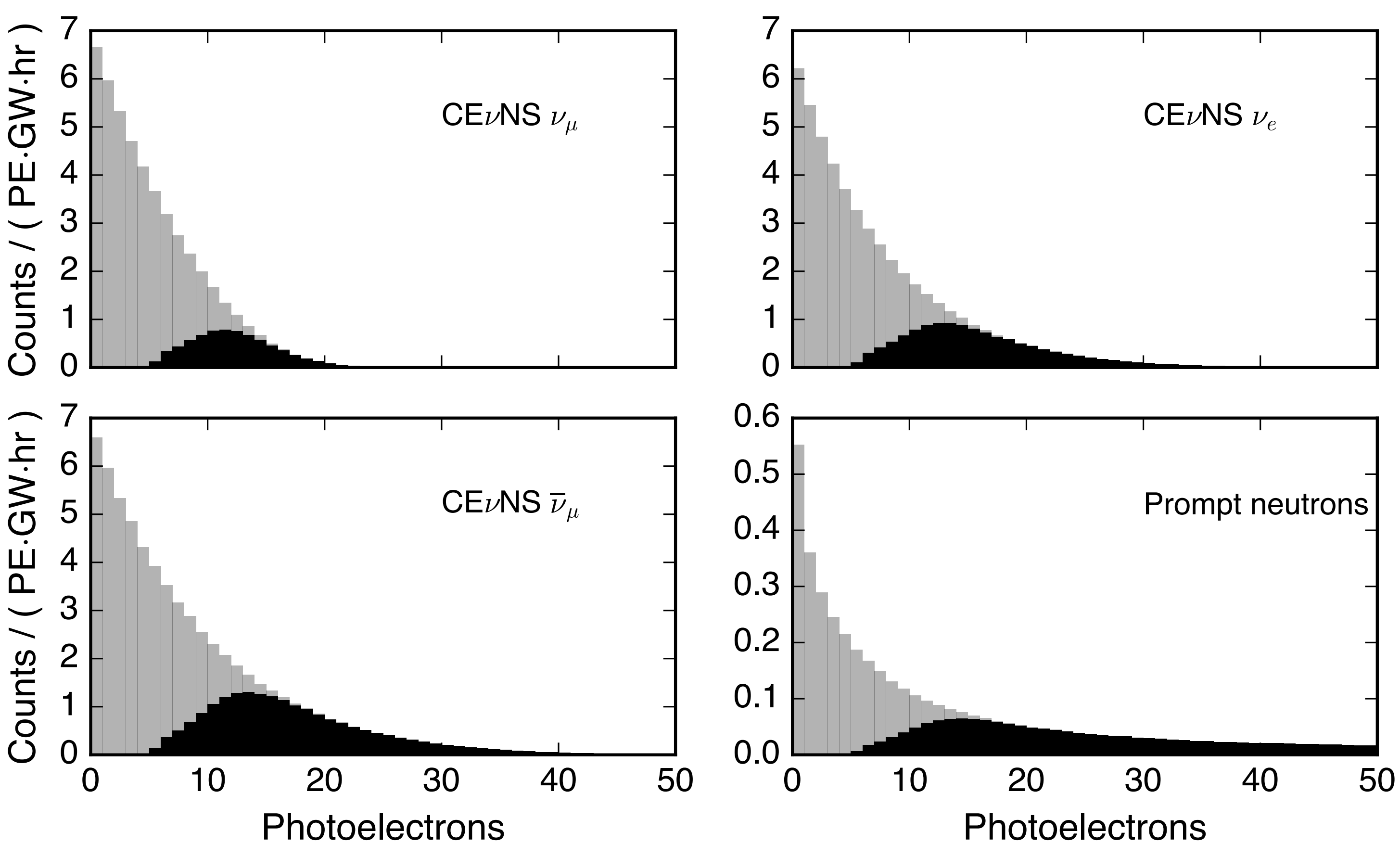
- Determine QF from global values in range from 5 to 30 keVnr: 8.78 ± 1.66%

- Disagreement between COHERENT measurements under (re)analysis



Rate and shape estimates

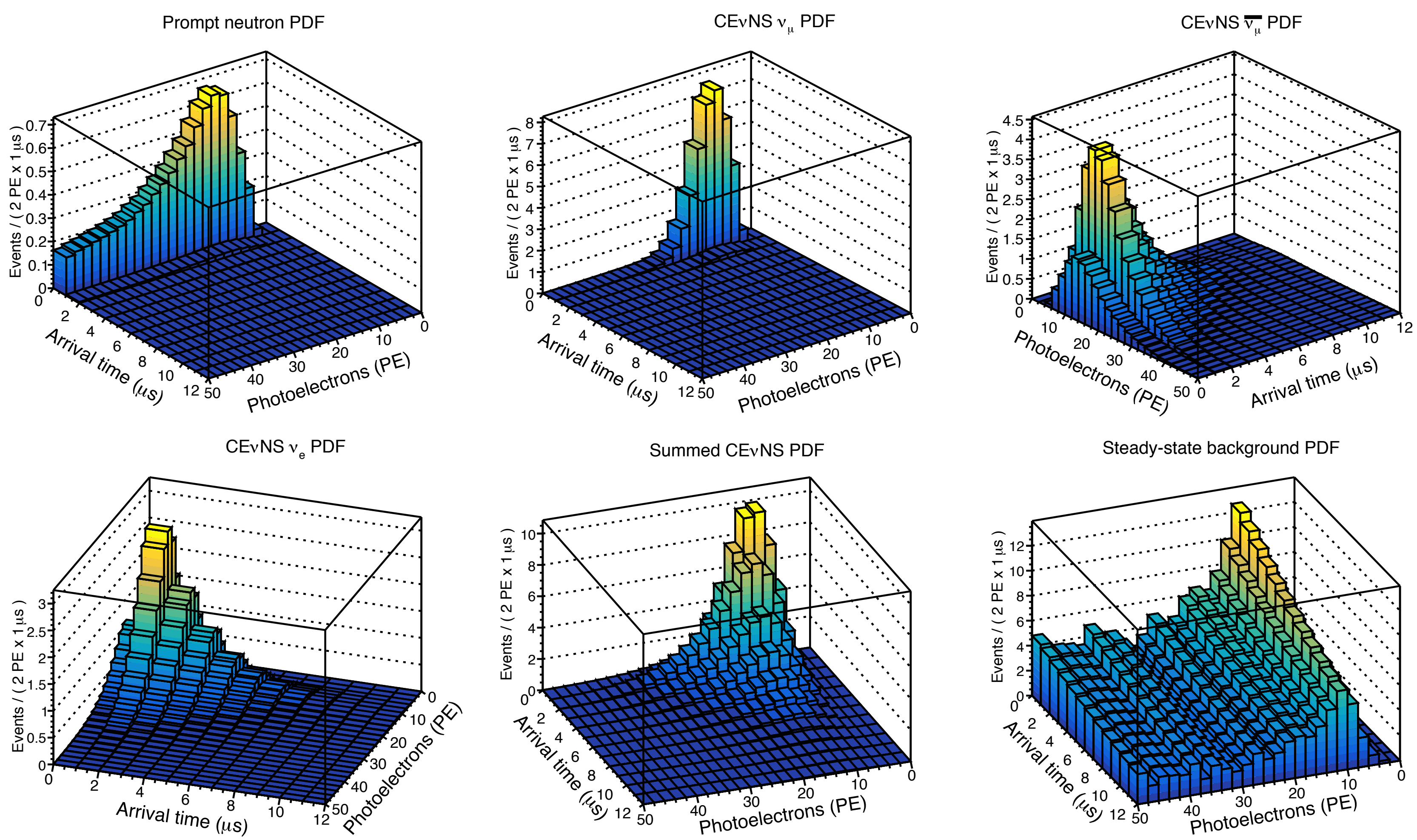
$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{2\pi}\left[(G_V + G_A)^2 + (G_V - G_A)^2\left(1 - \frac{T}{E_\nu}\right)^2 - (G_V^2 - G_A^2)\frac{MT}{E_\nu^2}\right]$$



- 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

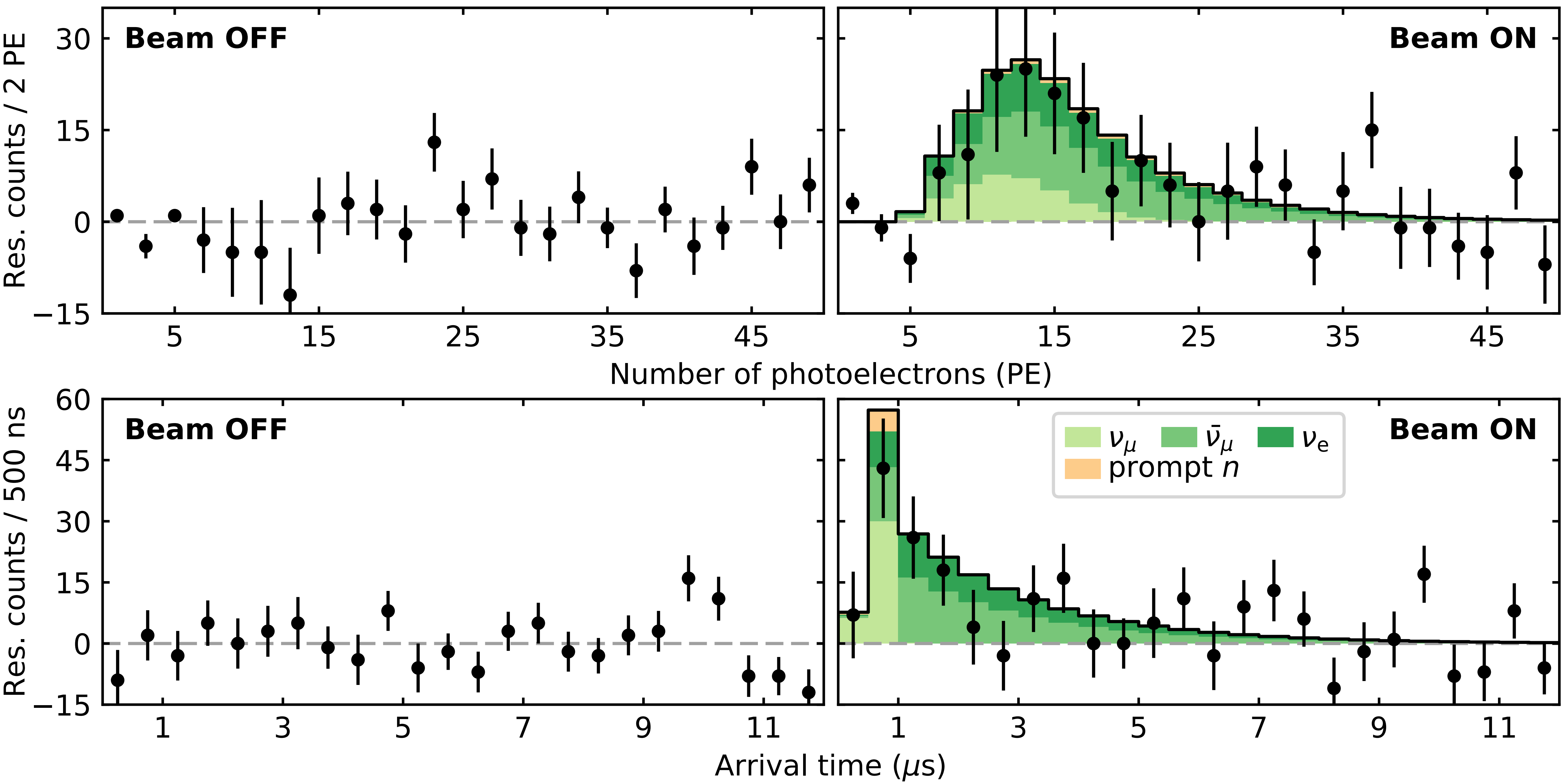
Rate and shape estimates

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{2\pi}\left[(G_V + G_A)^2 + (G_V - G_A)^2\left(1 - \frac{T}{E_\nu}\right)^2 - (G_V^2 - G_A^2)\frac{MT}{E_\nu^2}\right]$$



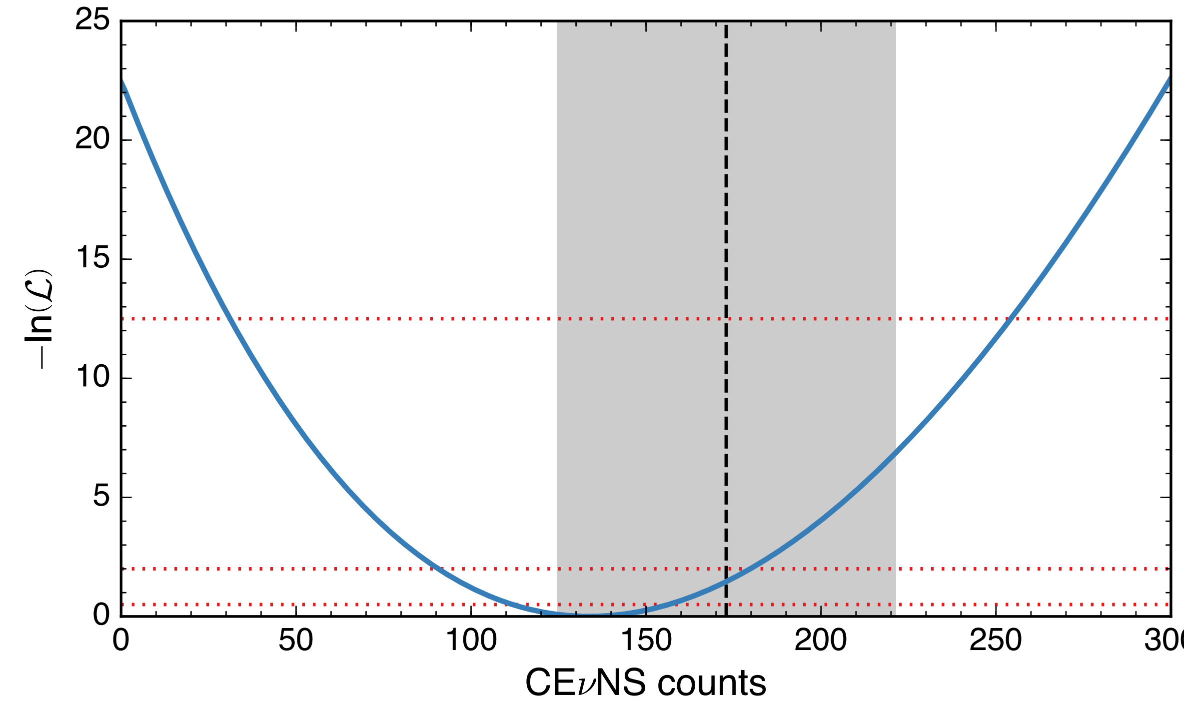
- Pulsed nature of beam facilitates analysis in time domain
- 2-D analysis (energy, time) makes use of all available information
- Ultimately performed binned 2-D profile likelihood analysis using PDFs shown here

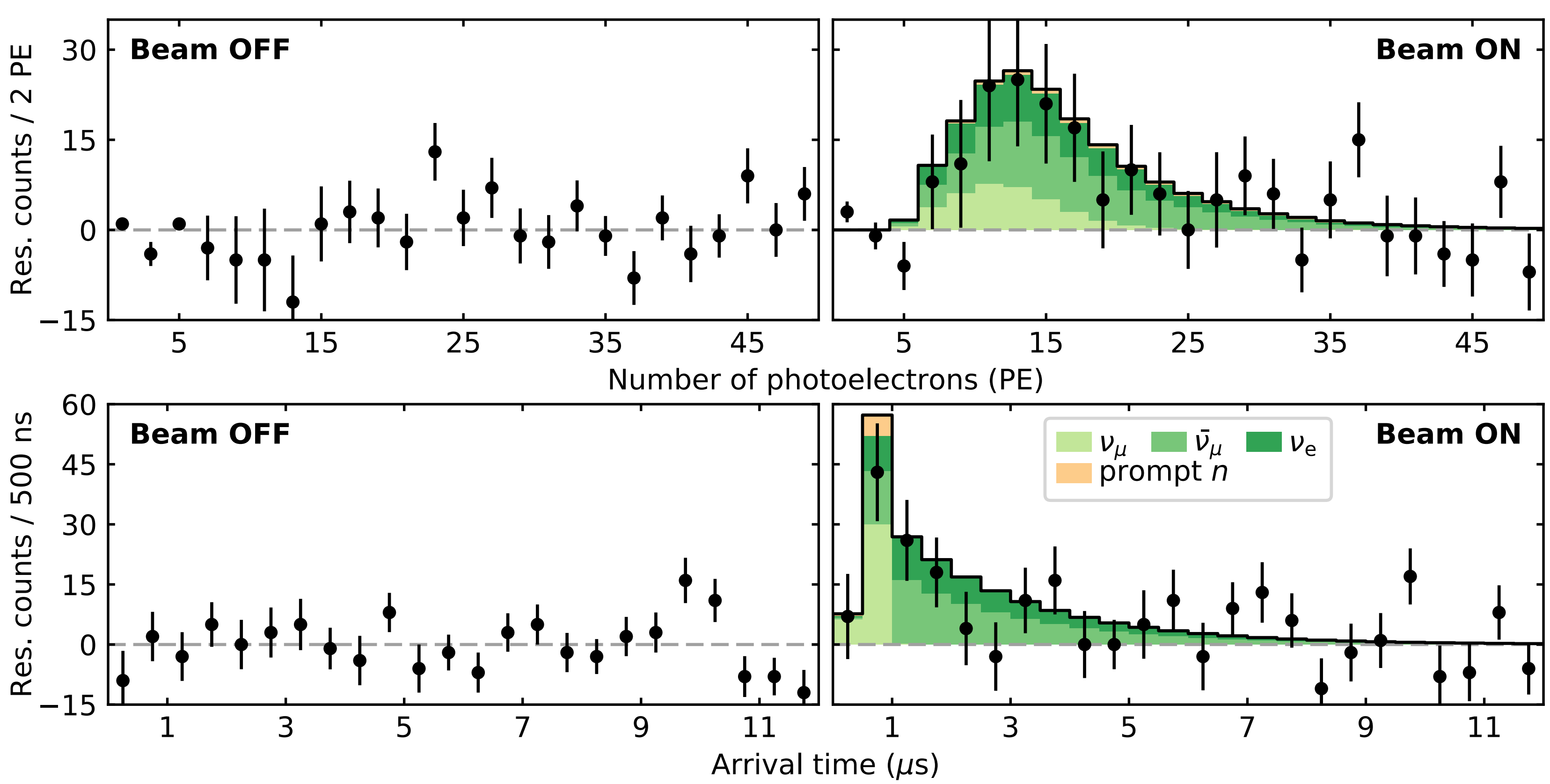
SM prediction and data

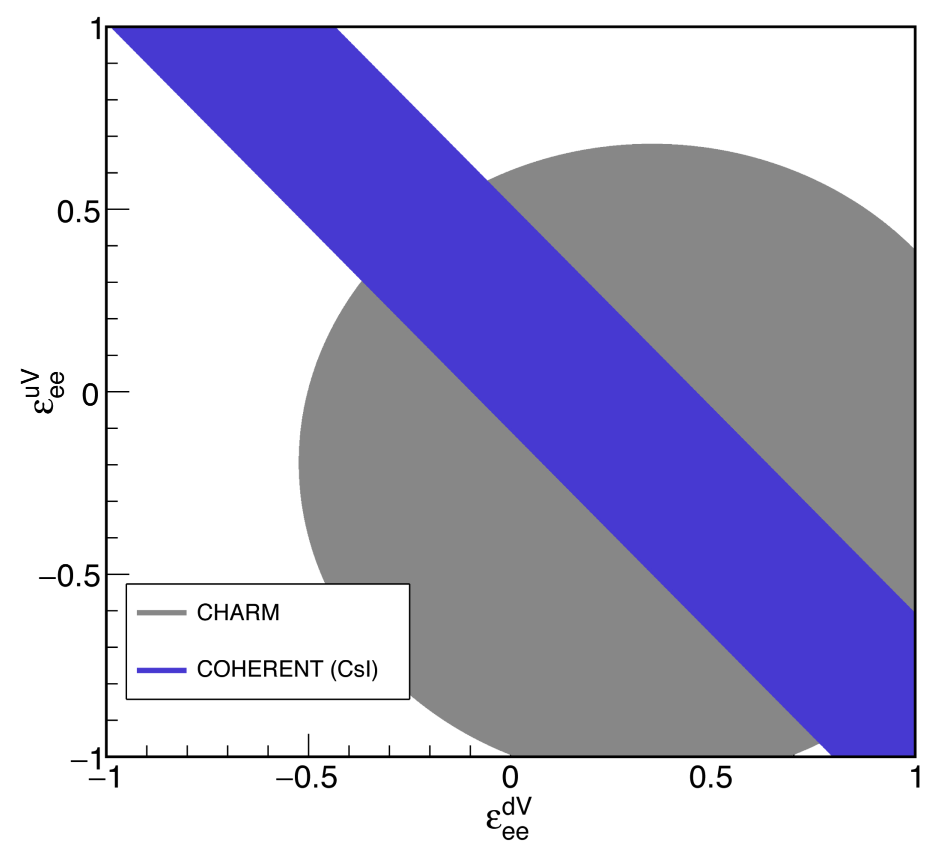


Results

- Analyzed as a simple counting experiment
  - 136 ± 31 counts
- 2-D profile likelihood analysis
  - 134 ± 22 counts
  - 77% ± 16% of the SM prediction of 173 ± 48
  - Null hypothesis disfavored at 6.7σ level relative to best-fit number of counts







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

Other CEvNS efforts

Other experiments bring considerable value

- N^2 cross section behavior still unobserved
- Alternative detector technologies offer promise, but need to be demonstrated
- Other neutrino sources — particularly reactors
  - Unique energy spectra, closer to SNe neutrino energies
  - Quite nicely complement NSI constraints from SNS-type neutrinos, global analyses powerful [1]
- Examples: CONNIE, MINER, CONUS, nuGEN, RICOCHET

[1] J.B. Dent *et al.*, arXiv:1711.03521 (2017)

COHERENT moving forward

- Goal: **unambiguous observation** of CEvNS at the Spallation Neutron Source (SNS) and **confirmation using multiple nuclear targets / detector technologies**

- 22-kg fiducial volume LAr detector collecting CEvNS data from 8/17

- ~10-kg HPGe PPC system planning moving forward

- 185-kg NaI[Tl] array collecting data now for CC cross section on ^{127}I
  - Improving electronics to reduce threshold and increase CEvNS sensitivity; *in situ* CEvNS background data has been collected
  - Planning for multi-ton array underway

- Neutrino cubes collecting data for measurement of NINs

- Conducting QF measurements with other targets and resolving CsI[Na] discrepancy

CENNS-10 LAr detector

Neutrino cubes

185-kg NaI[Tl] array

COHERENT moving forward

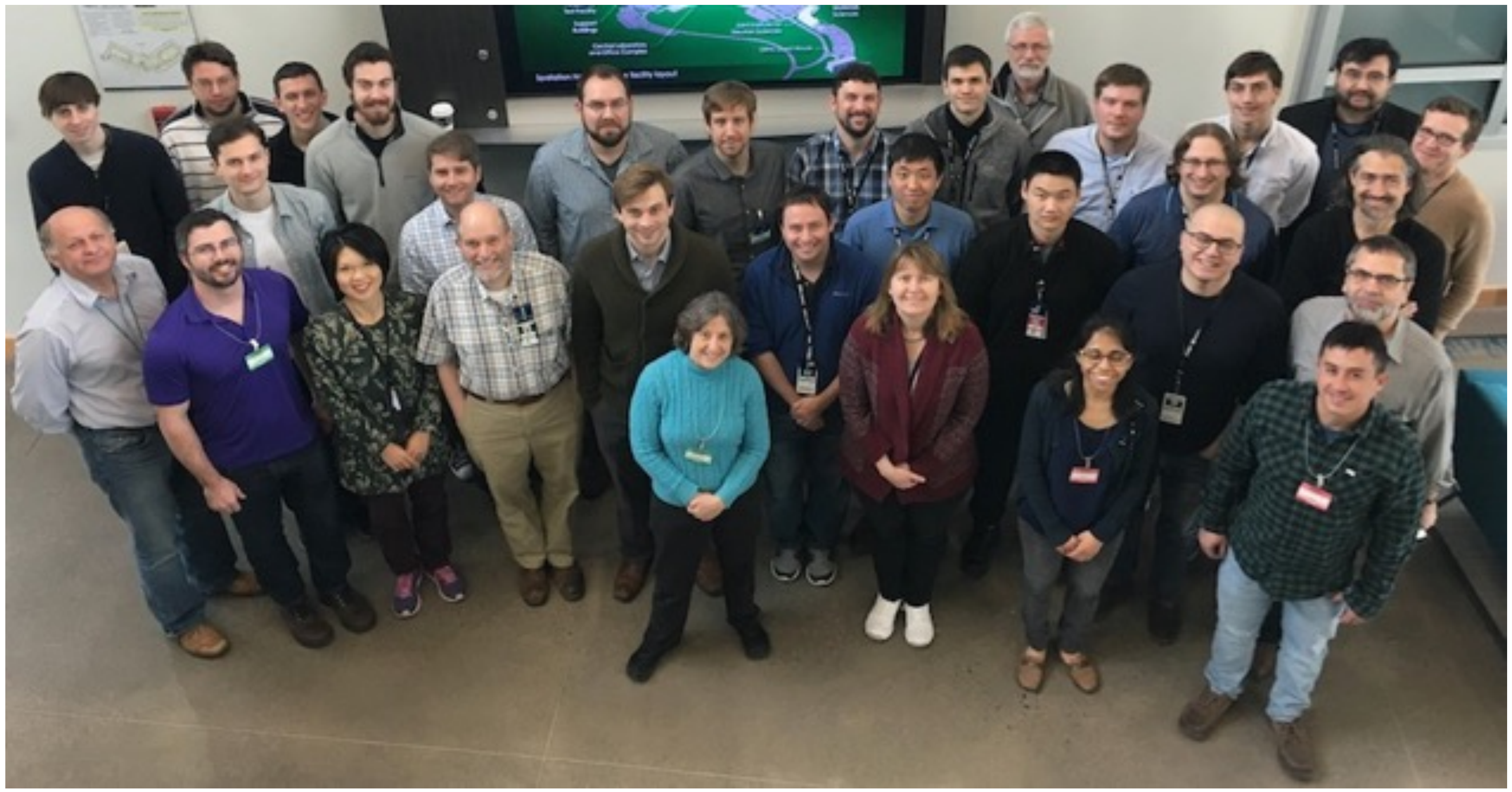
- Planning a release of data associated with first CEvNS result
  - Binned 2-D data, preserving granularity of presentation in publication
  - Beam timing data
  - Necessary calibration information, uncertainties, etc
- Welcome input or requests from theory/phenomenology communities!

CENNS-10 LAr detector

Neutrino cubes

185-kg NaI[TI] array

COHERENT SNS



MEPhI
Duke University
The University of Chicago
Oak Ridge National Laboratory
The University of Tennessee UT Knoxville
North Carolina Central University Founded 1910
NC State University
TUNL
W University of Washington
UF University of Florida
Carnegie Mellon University
Laurentian University Université Laurentienne
KAIST
Sandia National Laboratories
Los Alamos National Laboratory Est. 1943
Berkeley Lab
NM State University

Backup

Low-energy nuclear recoils from CEvNS

- Signature of CEvNS 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

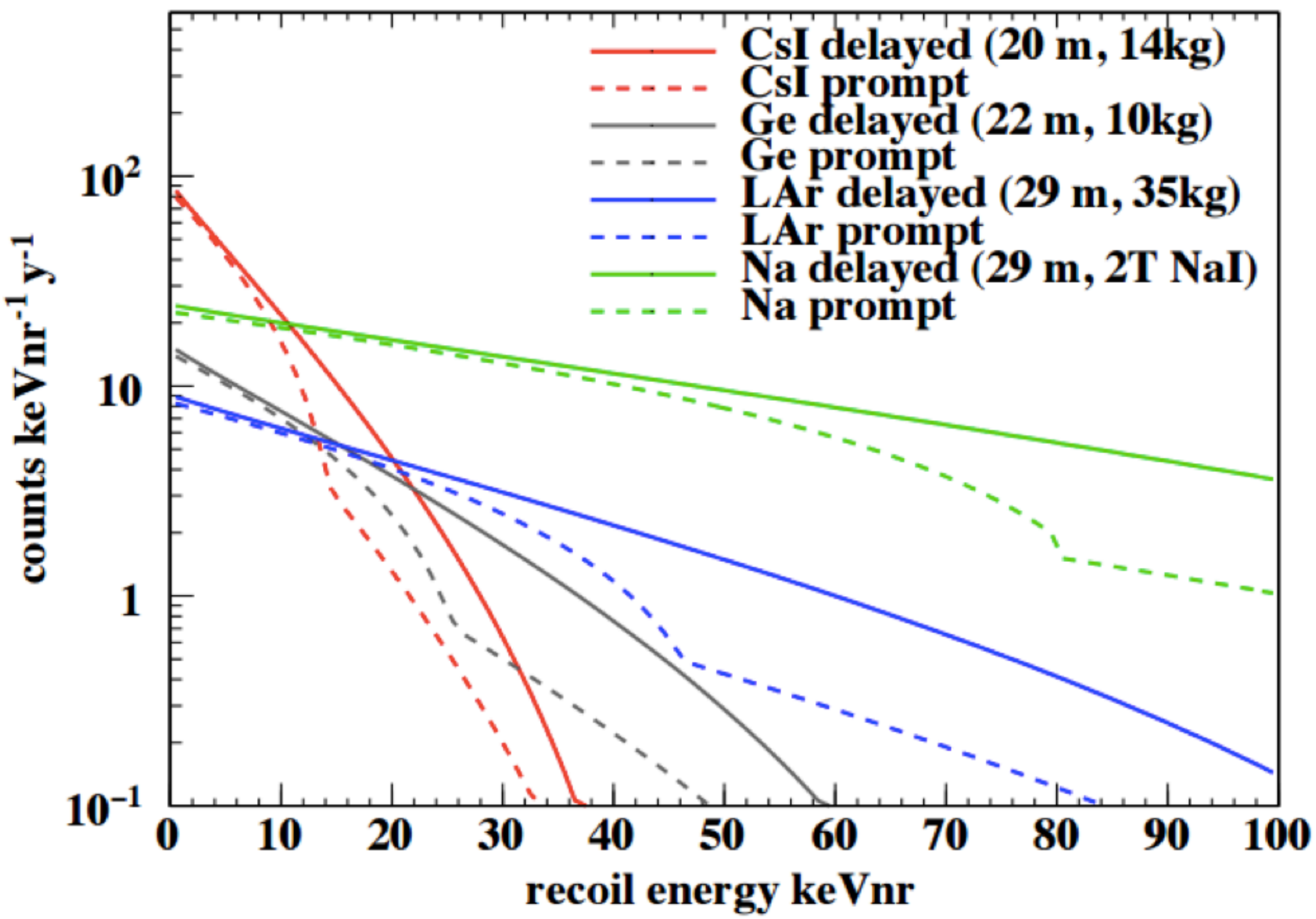
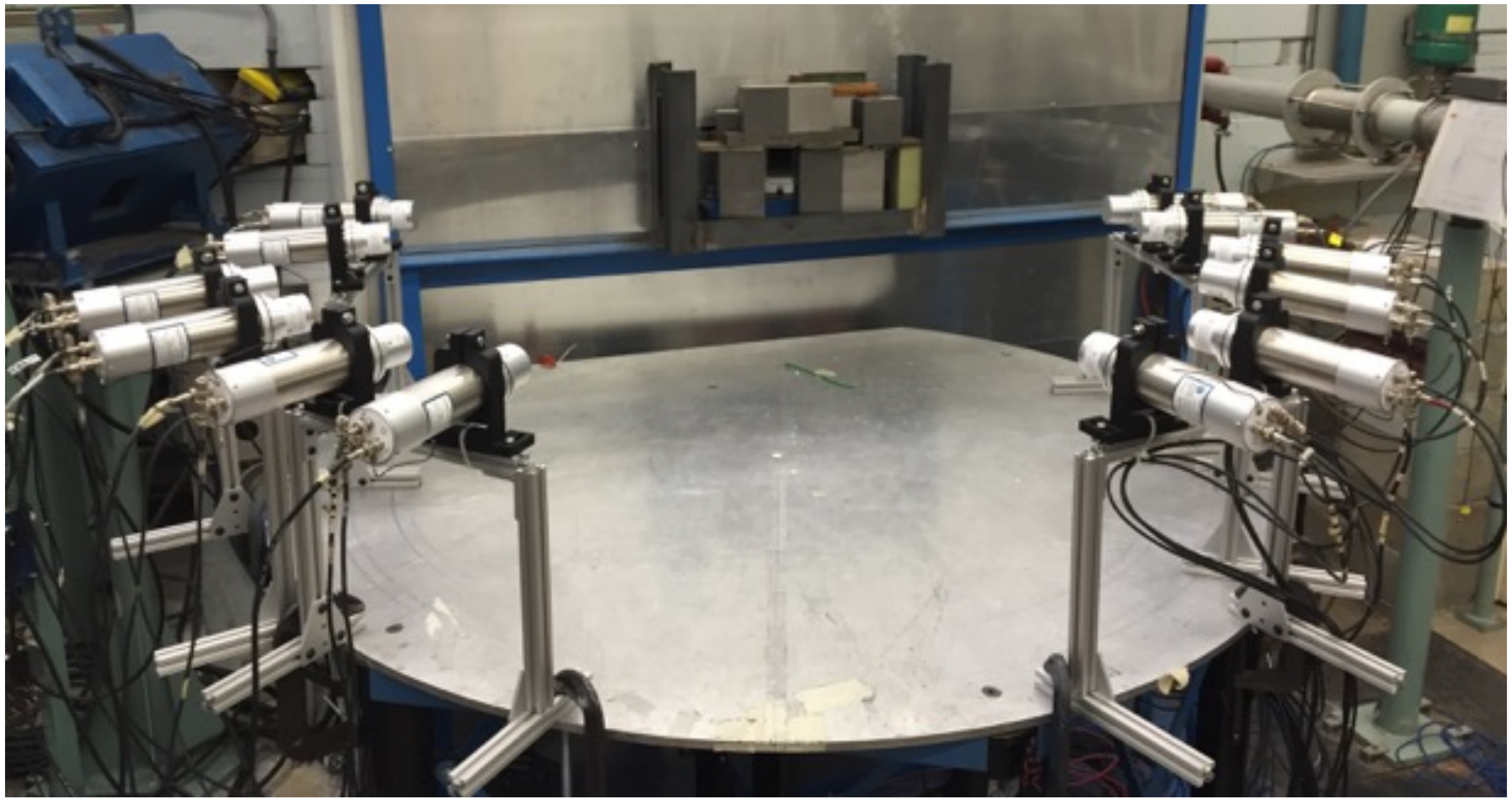


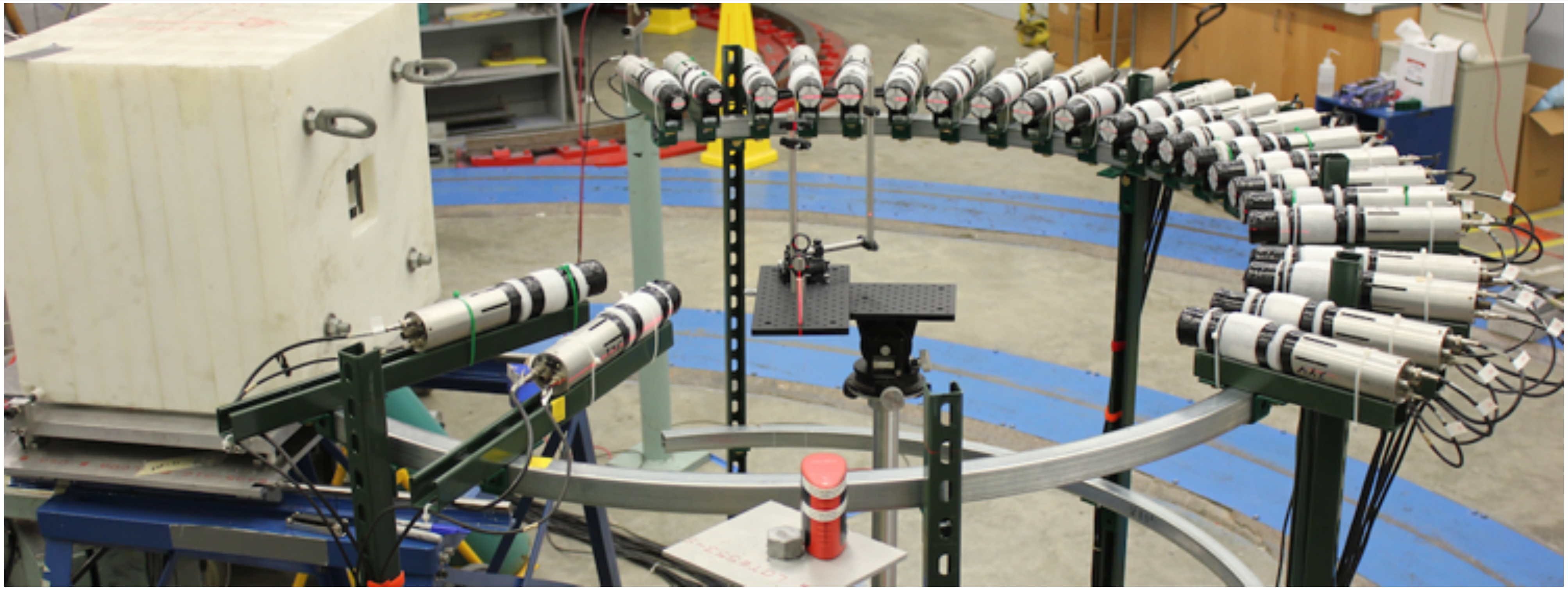
Figure from the COHERENT Collaboration

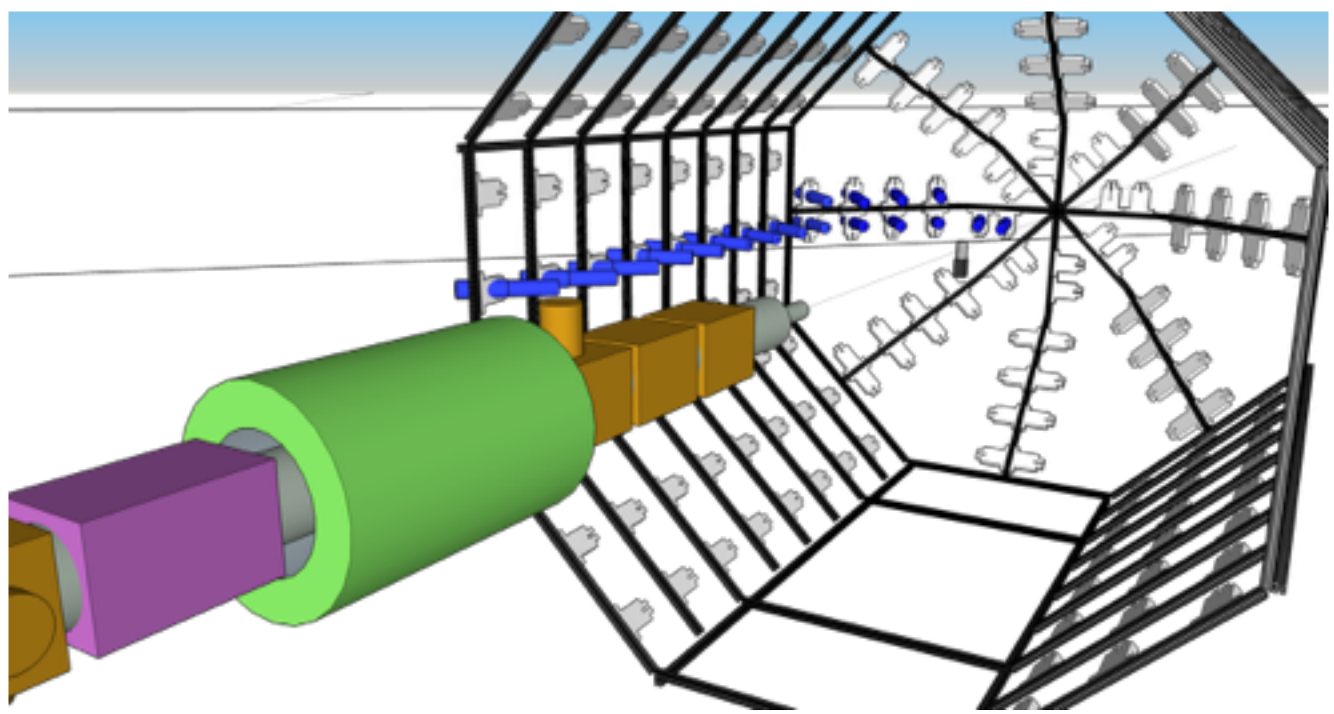
Quenching factor measurements at TUNL



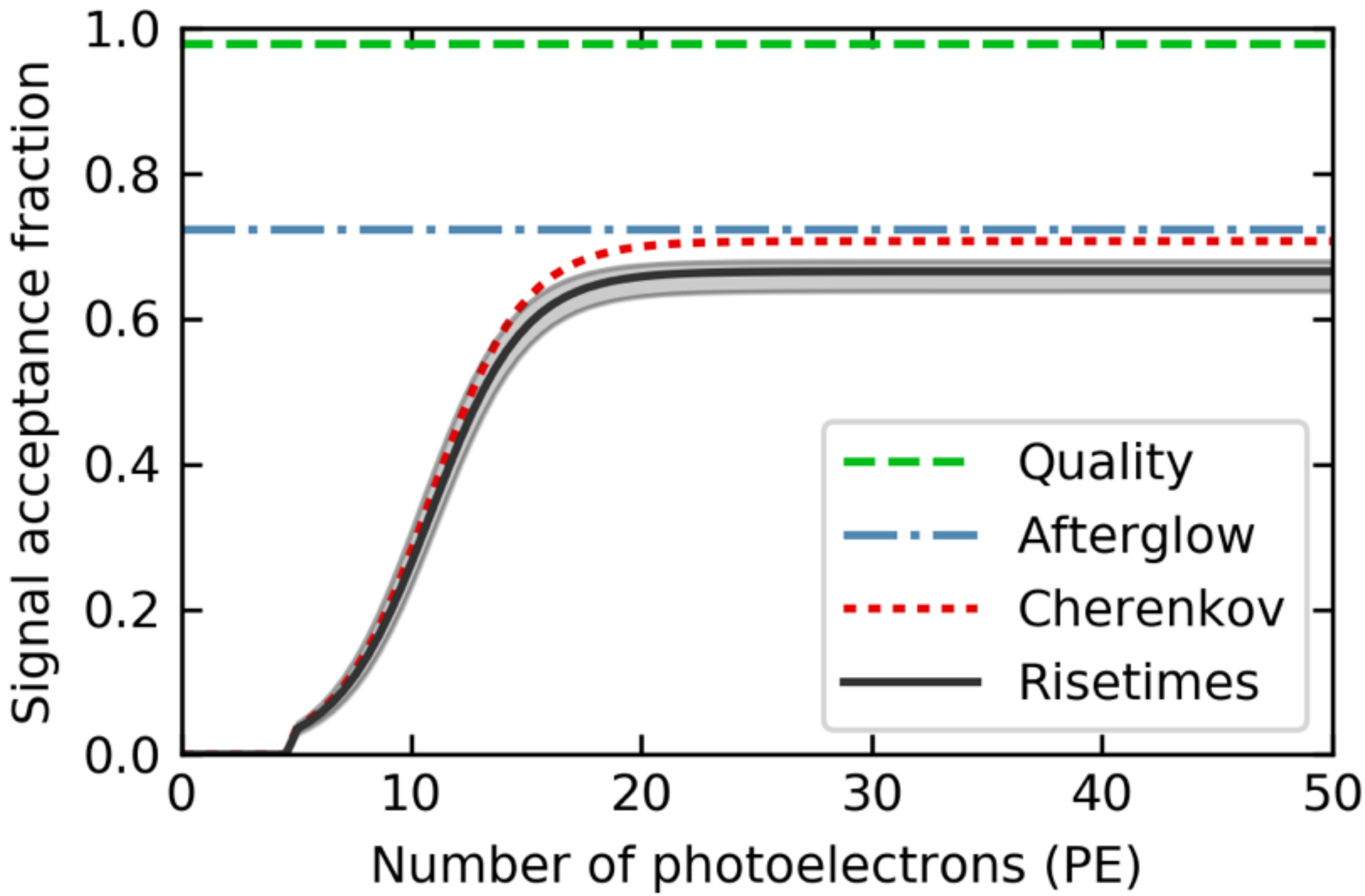
- Neutron beam produced by pulsed deuteron beam incident on deuterium gas cell
- Scattered neutrons detected by “backing detectors”
- Angle of backing detector selects well-defined nuclear recoil energy

Quenching factor measurements at TUNL

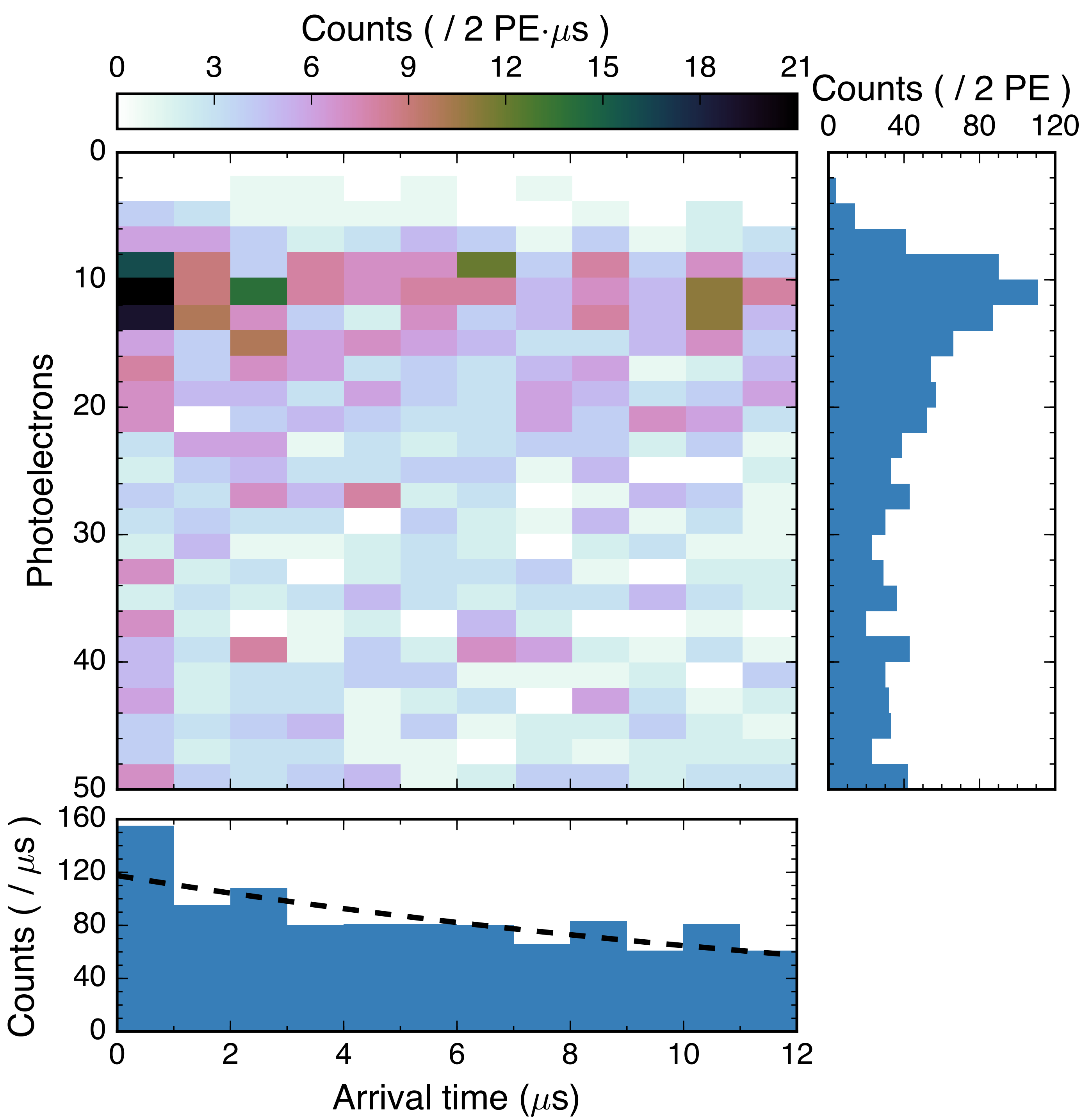




Analysis acceptance efficiency

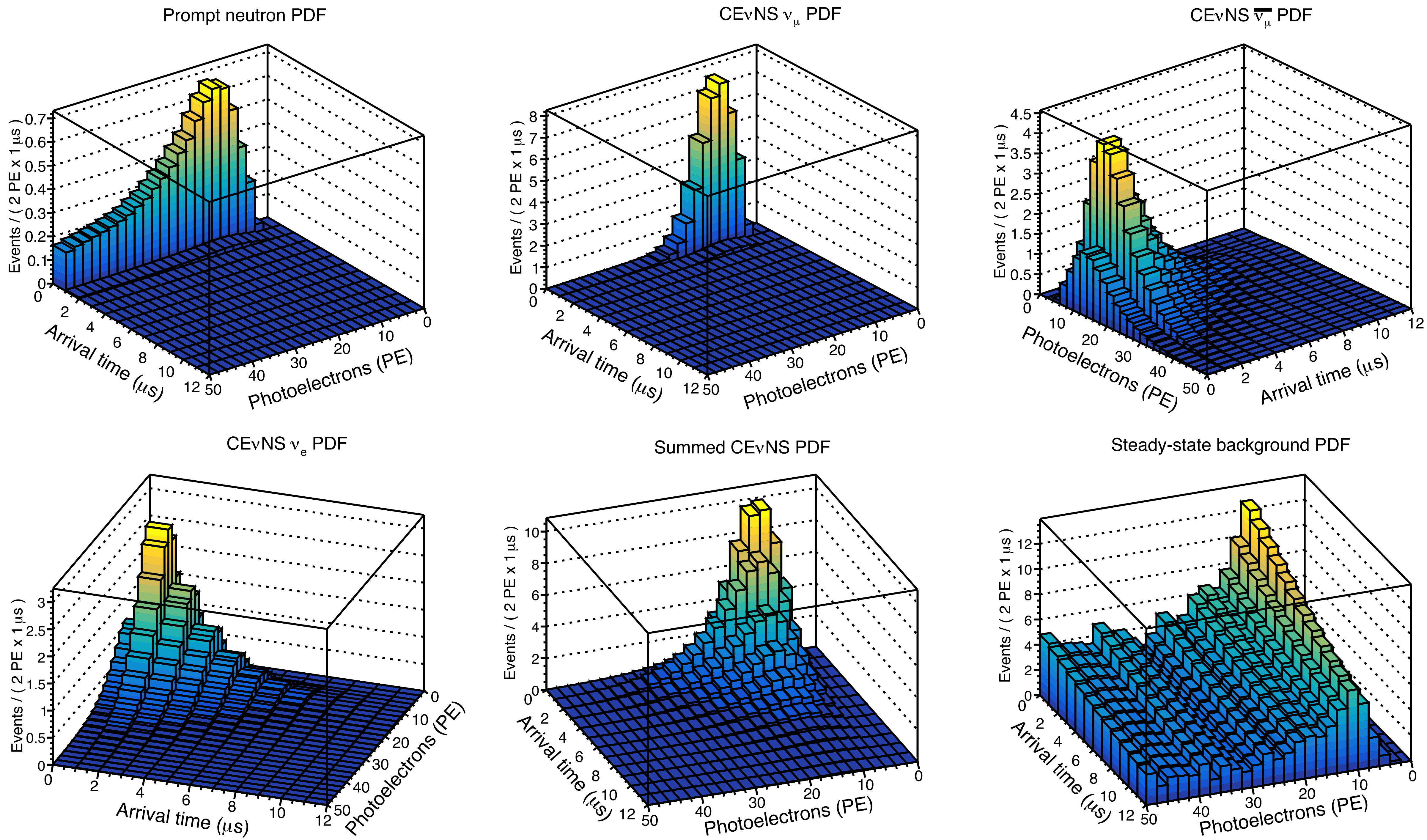


Background model for 2-D



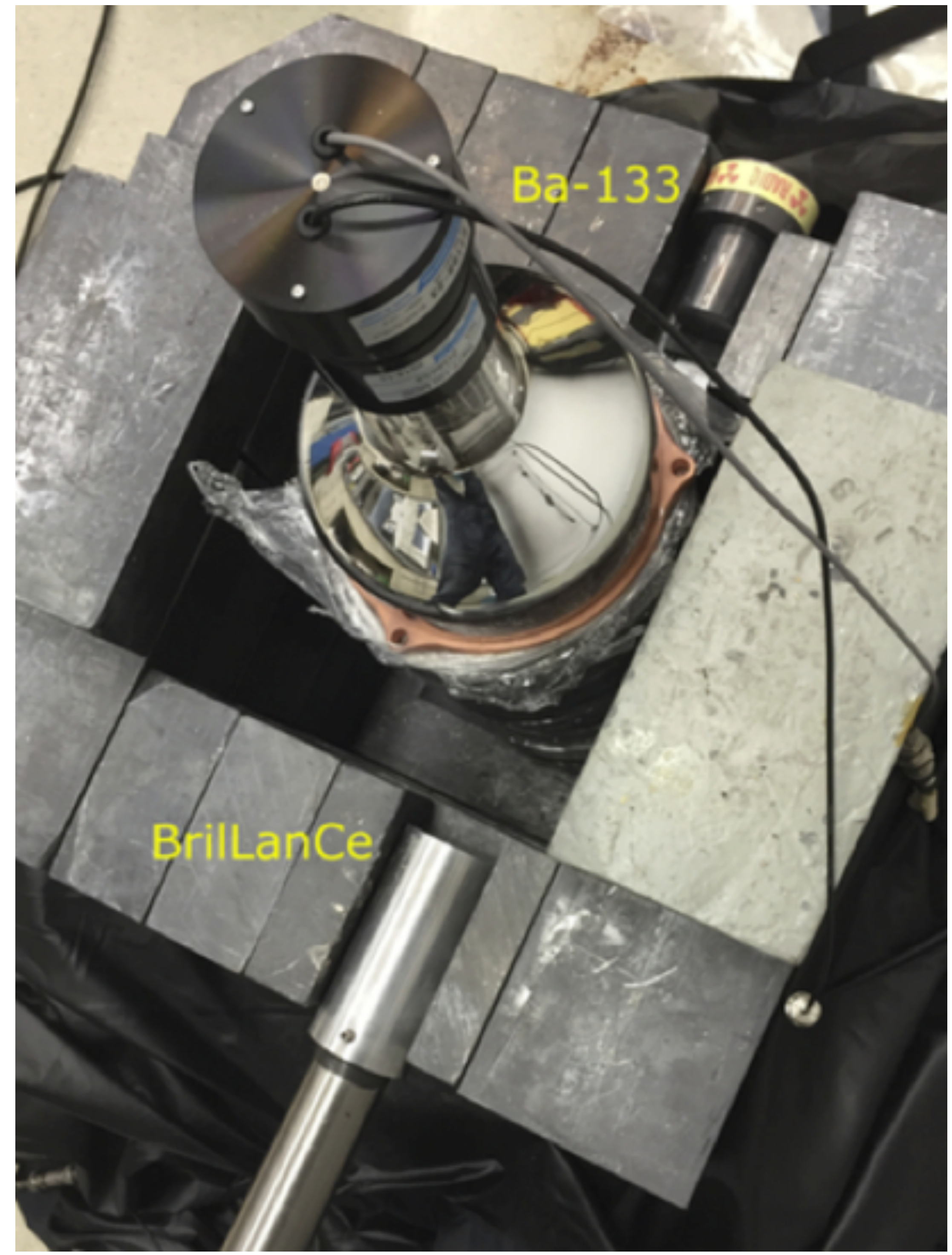
- Background model informed by anti-coincidence dataset
- Use "factorized" approach taking advantage of uncorrelated energy/time features
- Exponential fit to time projection, then used with energy projection to define model

Two-dimensional spectral component PDFs



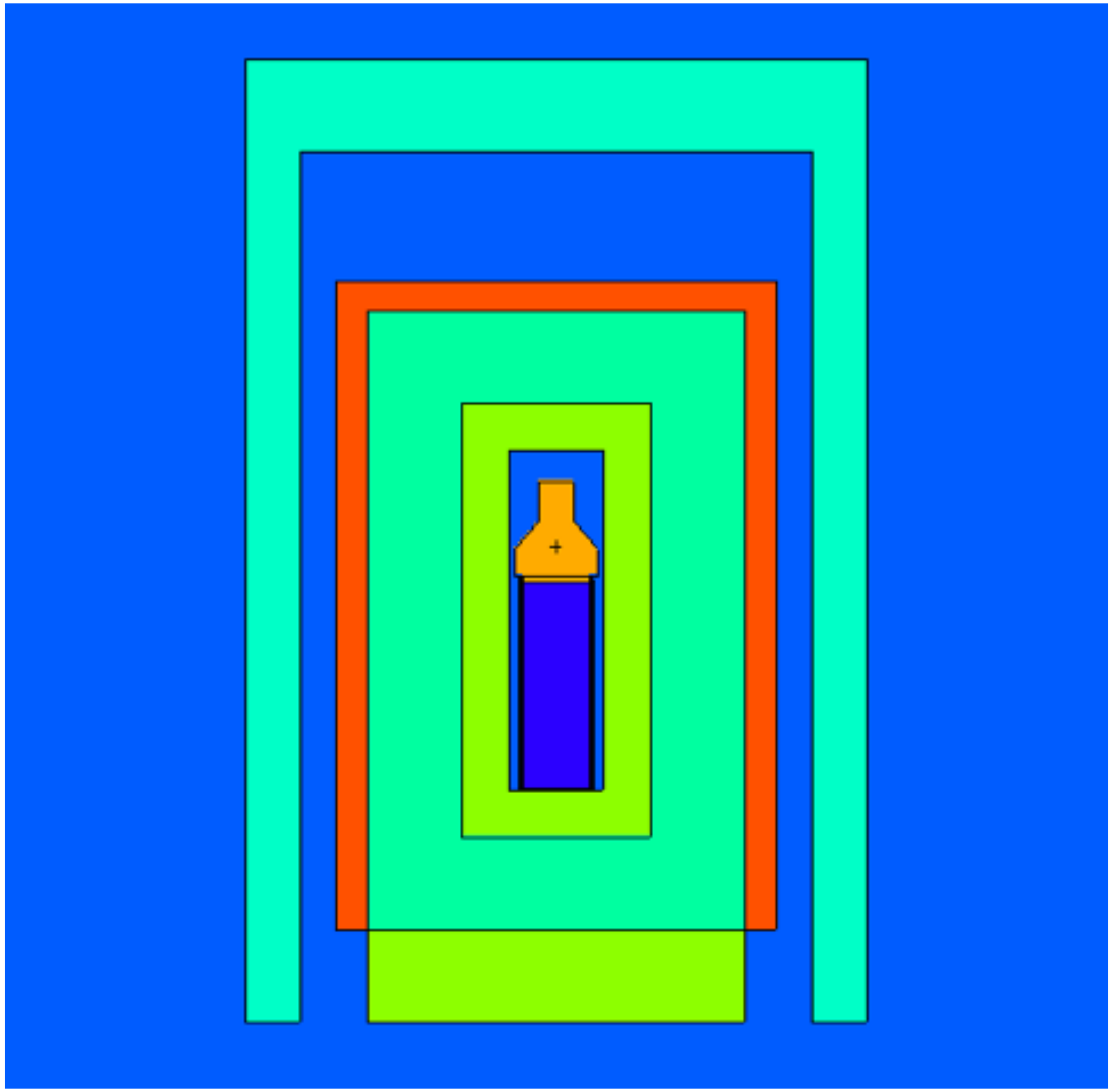
CEvNS with CsI[Na]

- 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

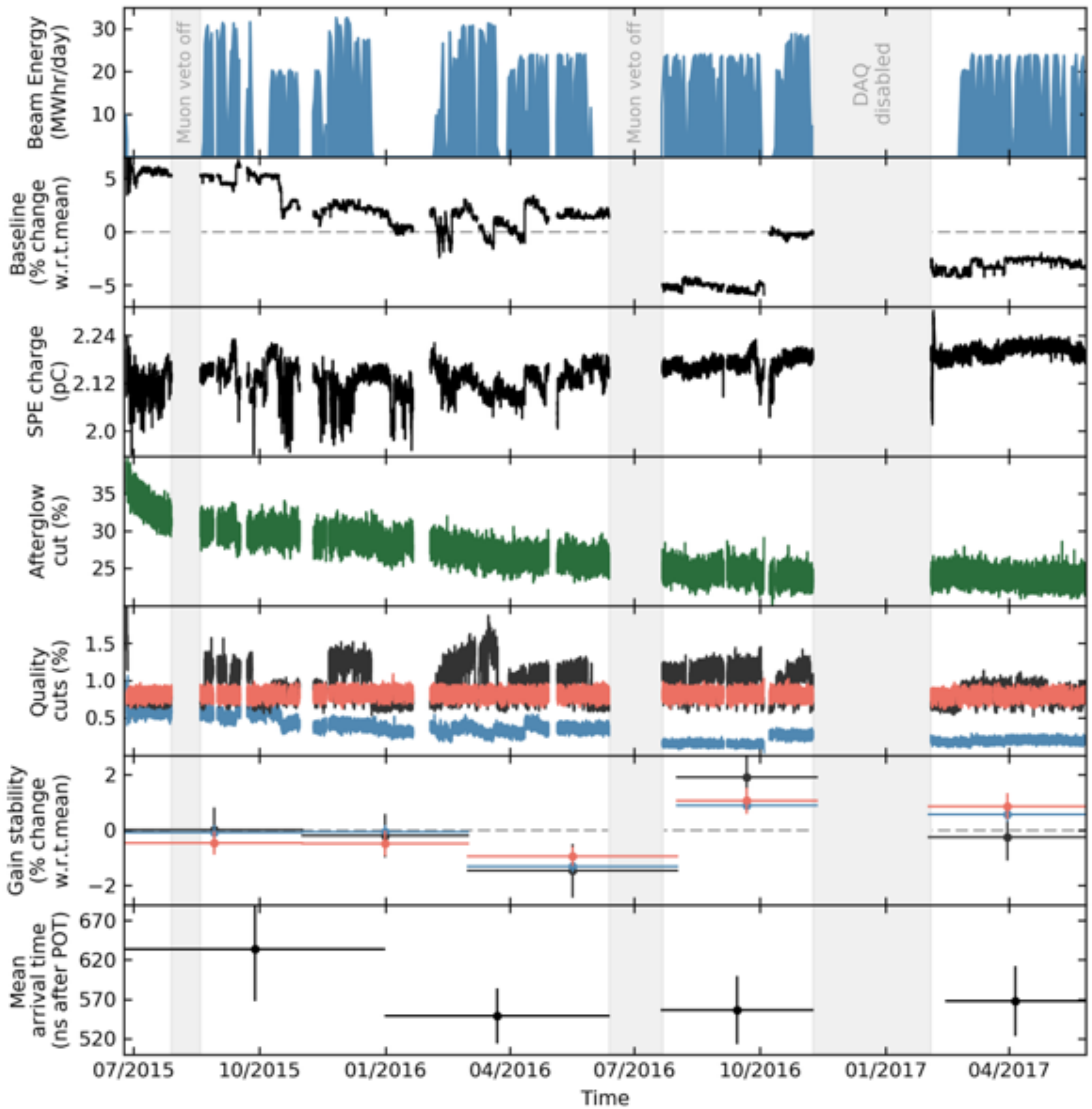


CEvNS with CsI[Na]

- 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



Stability and general health checks

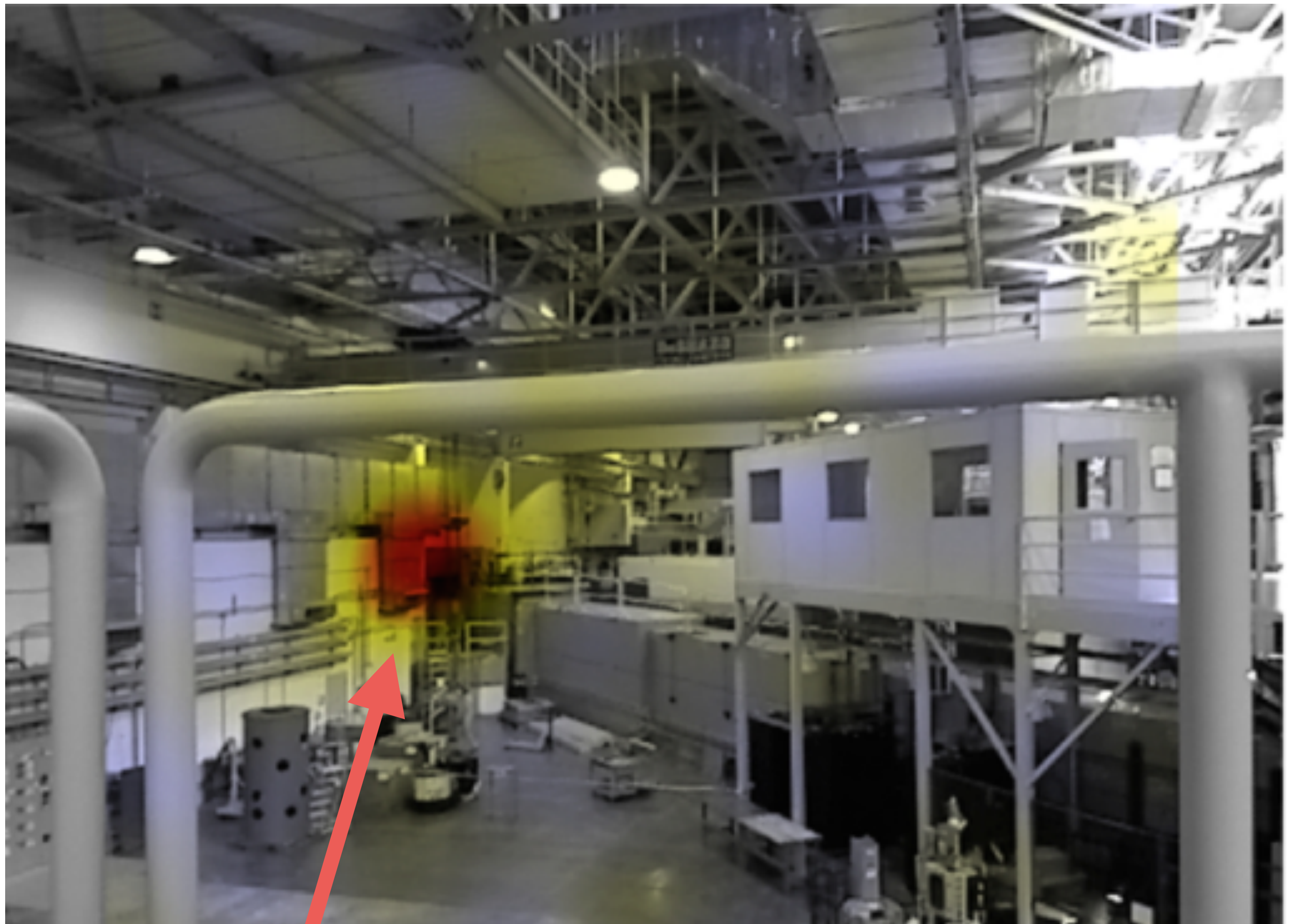


Neutrons at the SNS

- 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



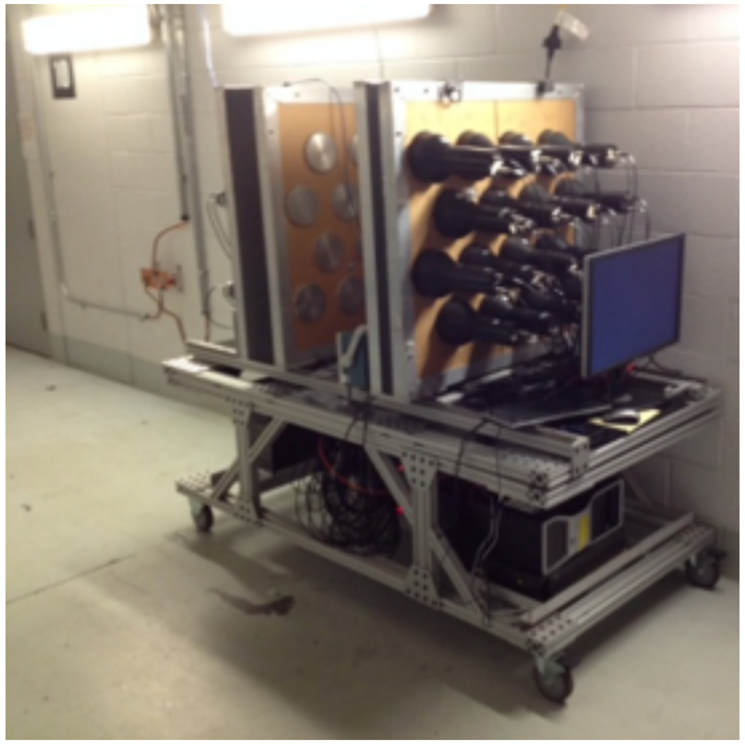
Coded-aperture neutron imager

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

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

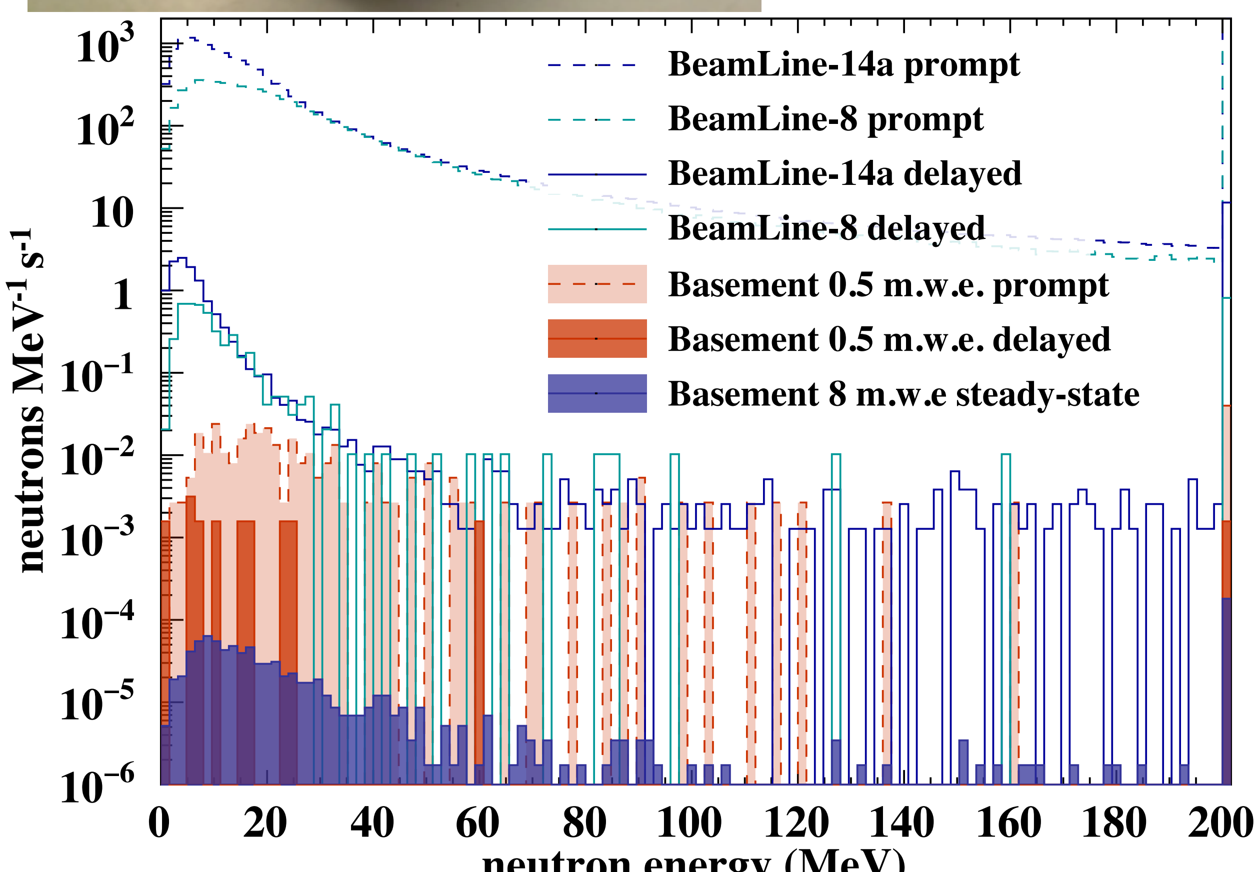
Target is “visible” through monolith shielding on the instrument floor

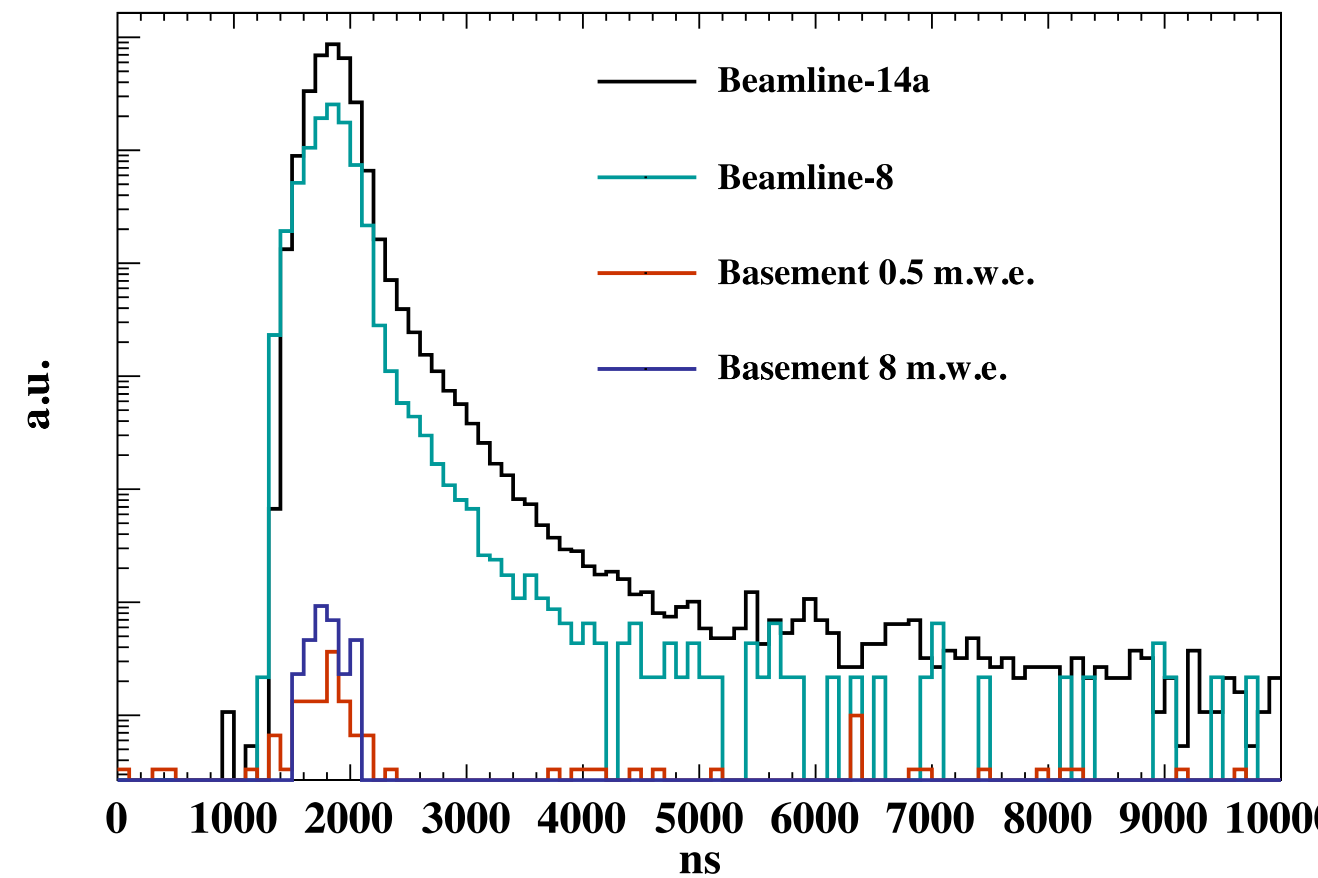
Neutrons at the SNS



Neutron scatter camera (Sandia)

- Two planes of liquid scintillator cells allow reconstruction of incident-neutron energy
- Neutron spectra and timing measured at several locations on instrument floor and in basement





COHERENT SNS