Status and plans for the COHERENT CEvNS Experiment

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on behalf of the COHERENT collaboration

Applied Antineutrino Physics 2015
Arlington, VA
December 8, 2015

Coherent, elastic neutrino-nucleus scattering (CEvNS)

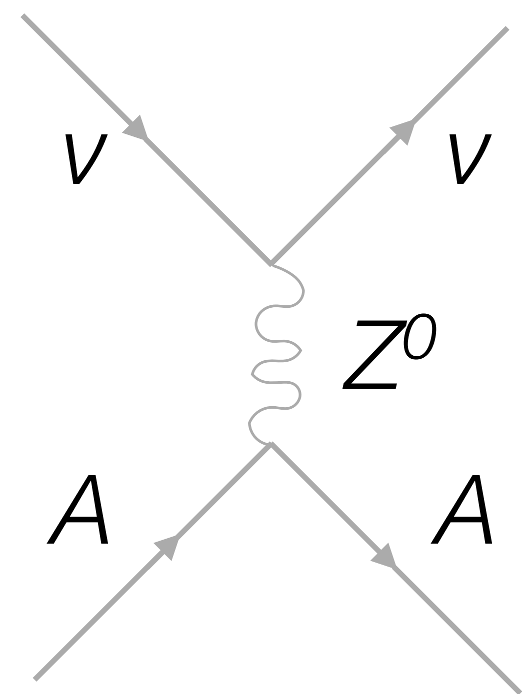
- Neutral-current (flavor-independent) process postulated by D.Z. Freedman in 1974 [1]

- 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]

- Expectation of existence is uncontroversial, but the process has never been detected

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

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



Very hard to observe experimentally

- Intense neutrino source needed with appropriate energy distribution (coherence is lost with higher energy)

- Signature of interaction is a nucleus recoiling with low (order 10 keV) energy, necessitating low-threshold, low-background detectors

Physics from CEvNS

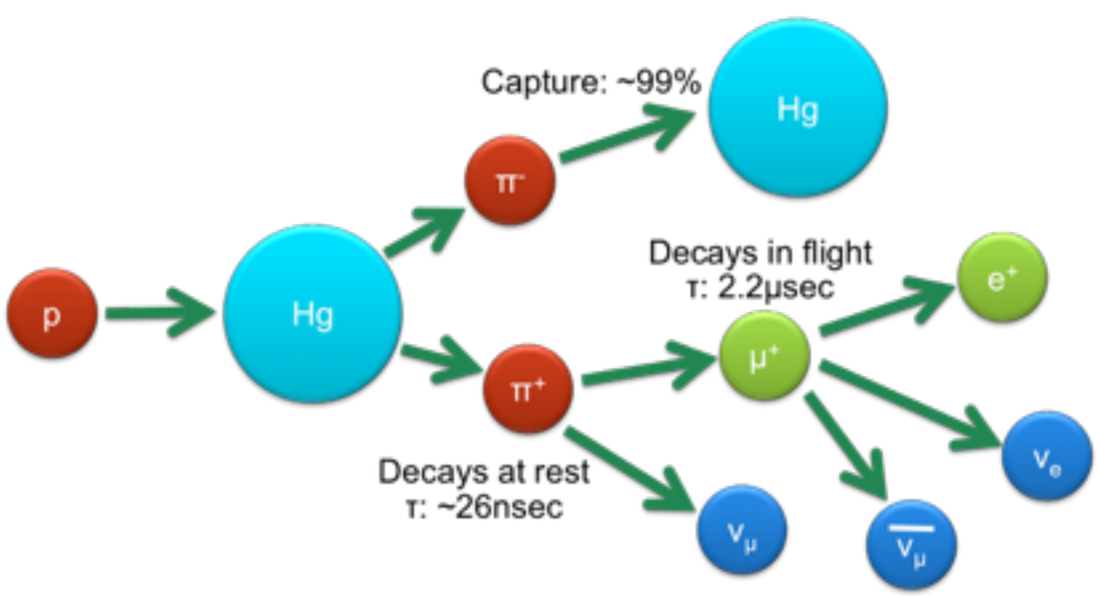
- Cross section provides a basic test of the standard model
- This interaction is relevant in extreme astrophysical environments, particularly core-collapse supernovae, where it may play a role in explosion dynamics
- Solar neutrinos and CEvNS will be an irreducible background in WIMP dark matter searches
- CEvNS also allows measurement of weak mixing angle, nuclear form factors and neutron distributions of nuclei, and is sensitive to non-standard neutrino interactions and neutrino magnetic moment
- As a neutral-current process, CEvNS is a natural candidate for use in searches for sterile neutrinos

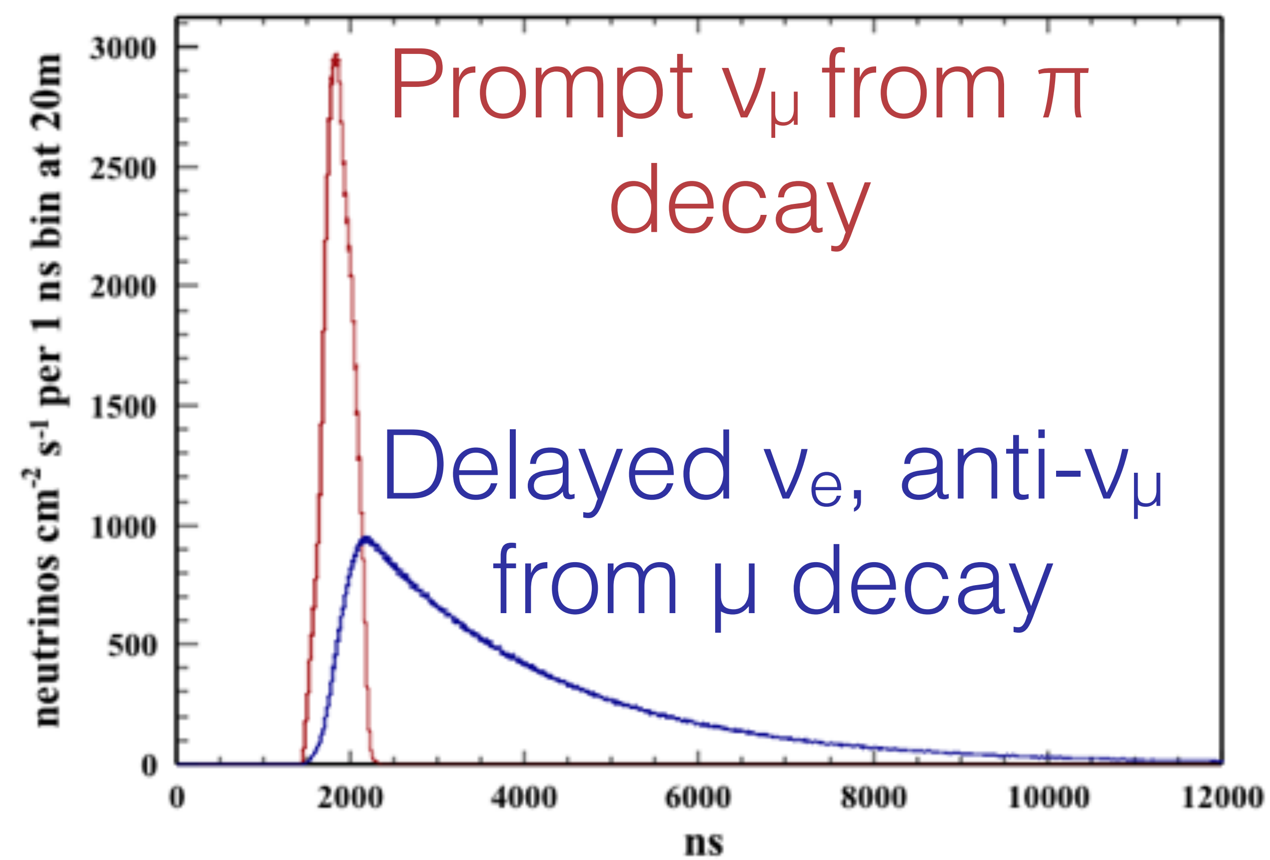
Enter: The COHERENT Collaboration

- Goal: **unambiguous observation** of CEvNS at the Spallation Neutron Source (SNS) using multiple nuclear targets / detector technologies
  - Leverage detector advances from dark-matter community
  - Utilize intense, pulsed neutrino source provided by SNS
- arXiv:1509.08702

Neutrinos from the SNS

- The SNS bombards a liquid Hg target with a ~1-GeV proton beam pulsed at 60 Hz; 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





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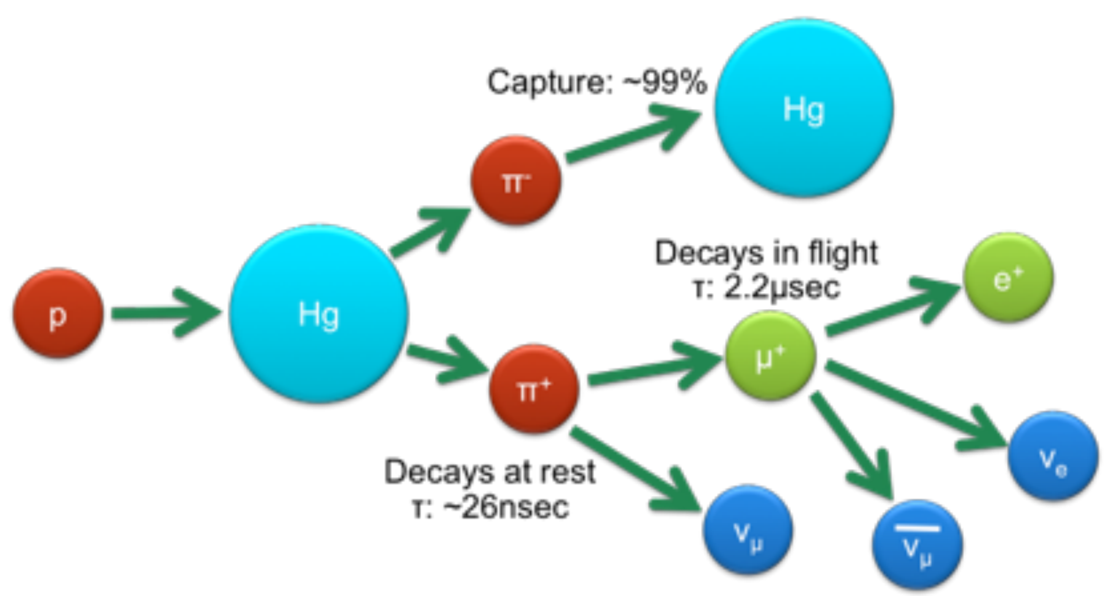
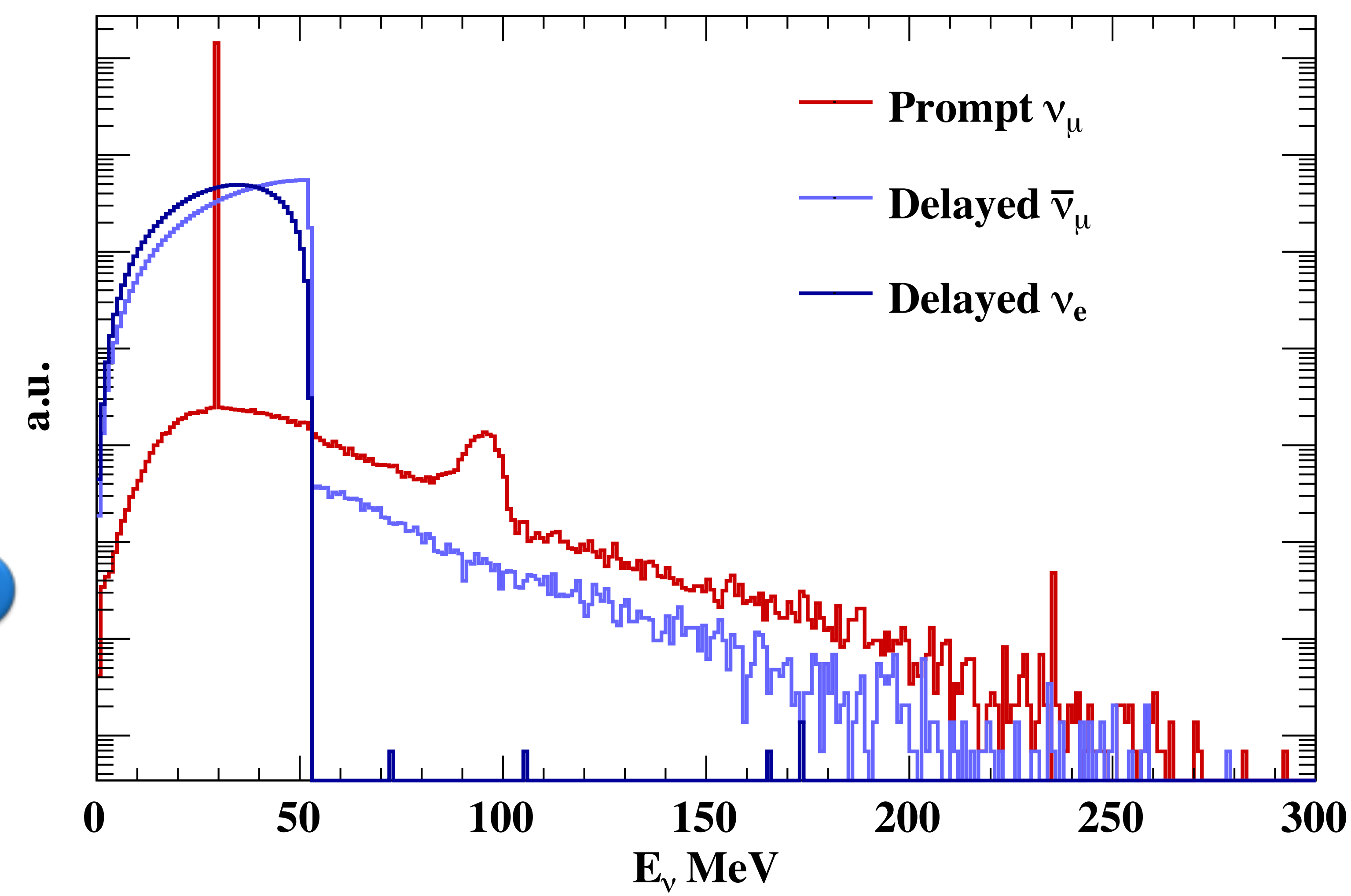
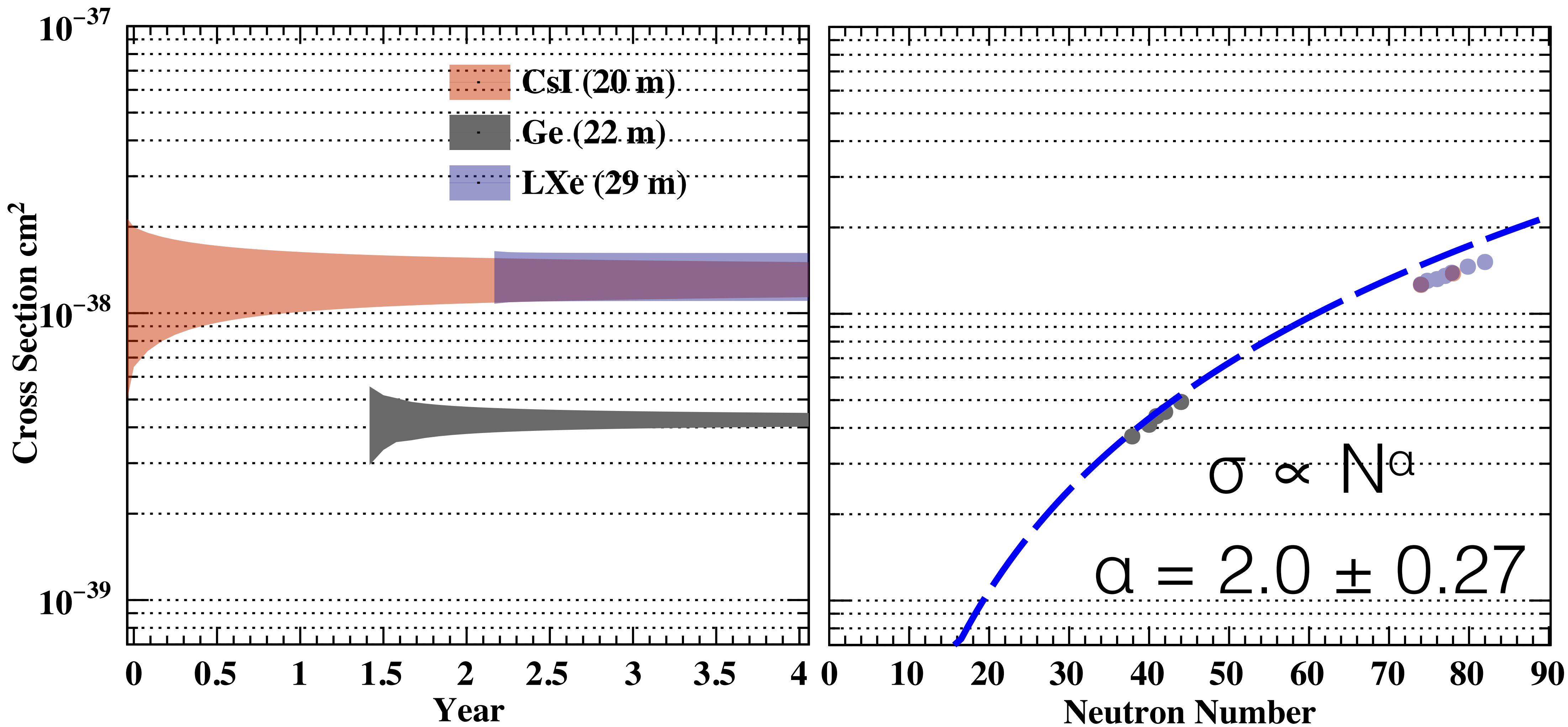




Multiple detector technologies within COHERENT

- Current scope includes CsI(Na), germanium p-type point contact detectors (PPCs), and dual-phase xenon
- By using all of these technologies/targets as part of the COHERENT effort, an unambiguous first observation of CEvNS can be produced

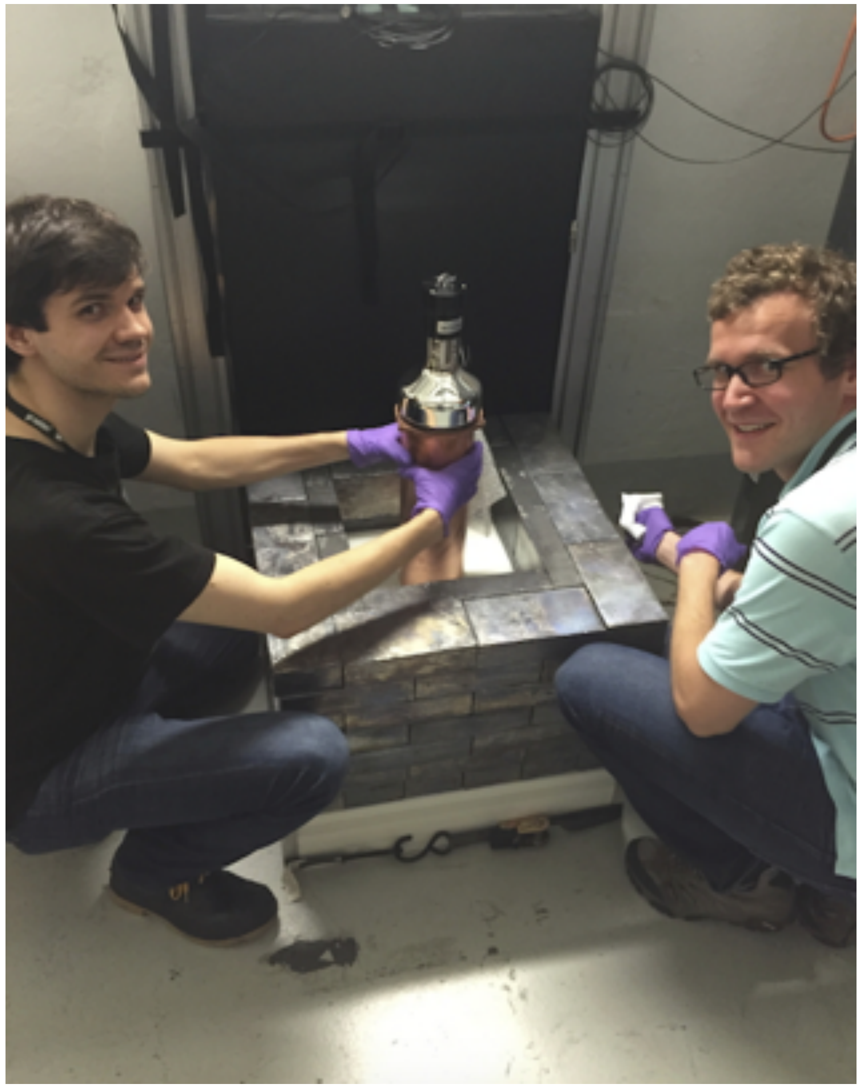
Unambiguous discovery of CEvNS through multiple detector technologies



- Observation of SNS-beam-coincident signal excess confirms *beam related*
- Observation of 2.2-μs decay time confirms *neutrino related*
- The use of multiple targets enables observation of N^2-dependence of cross section, characteristic of a coherent, neutral-current interaction

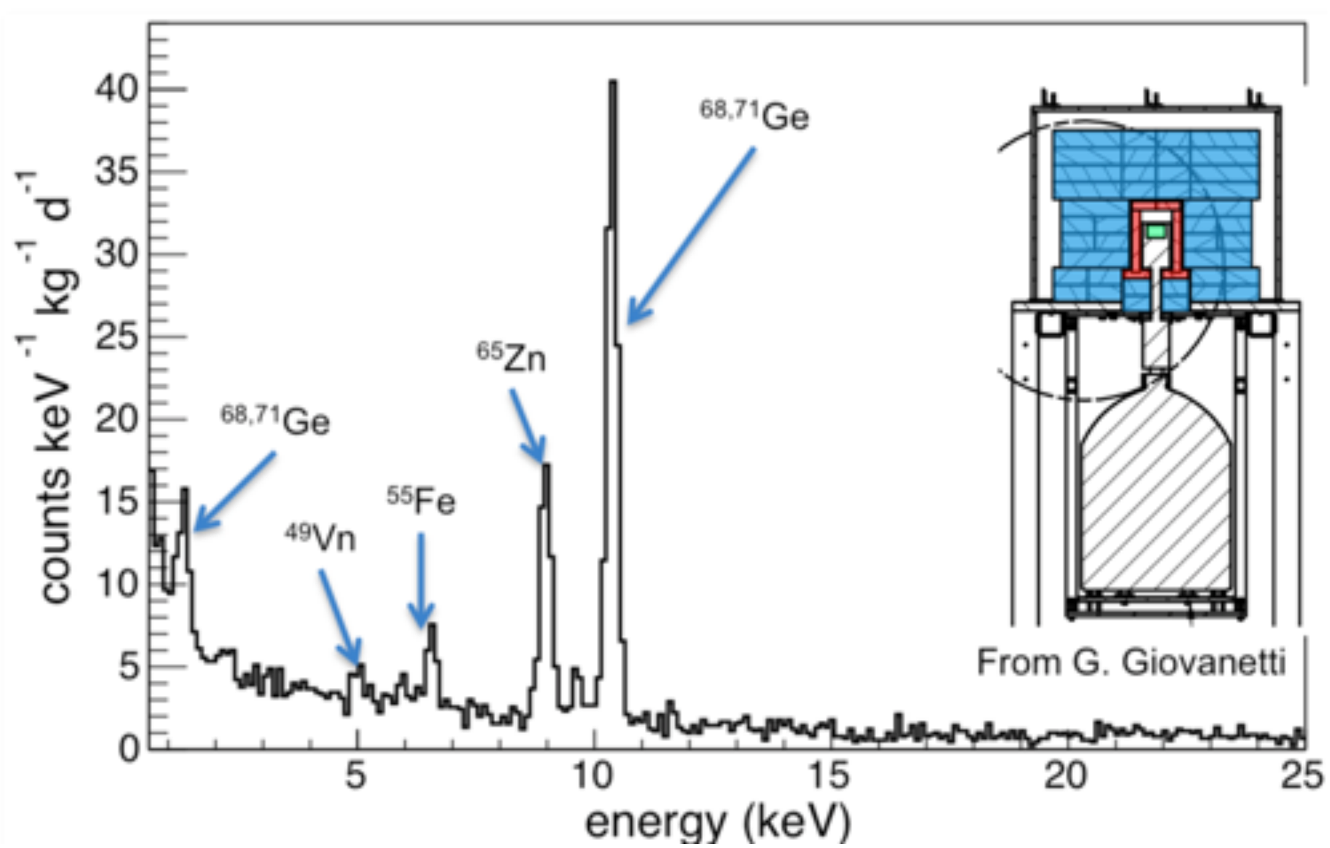
CEvNS with CsI(Na)

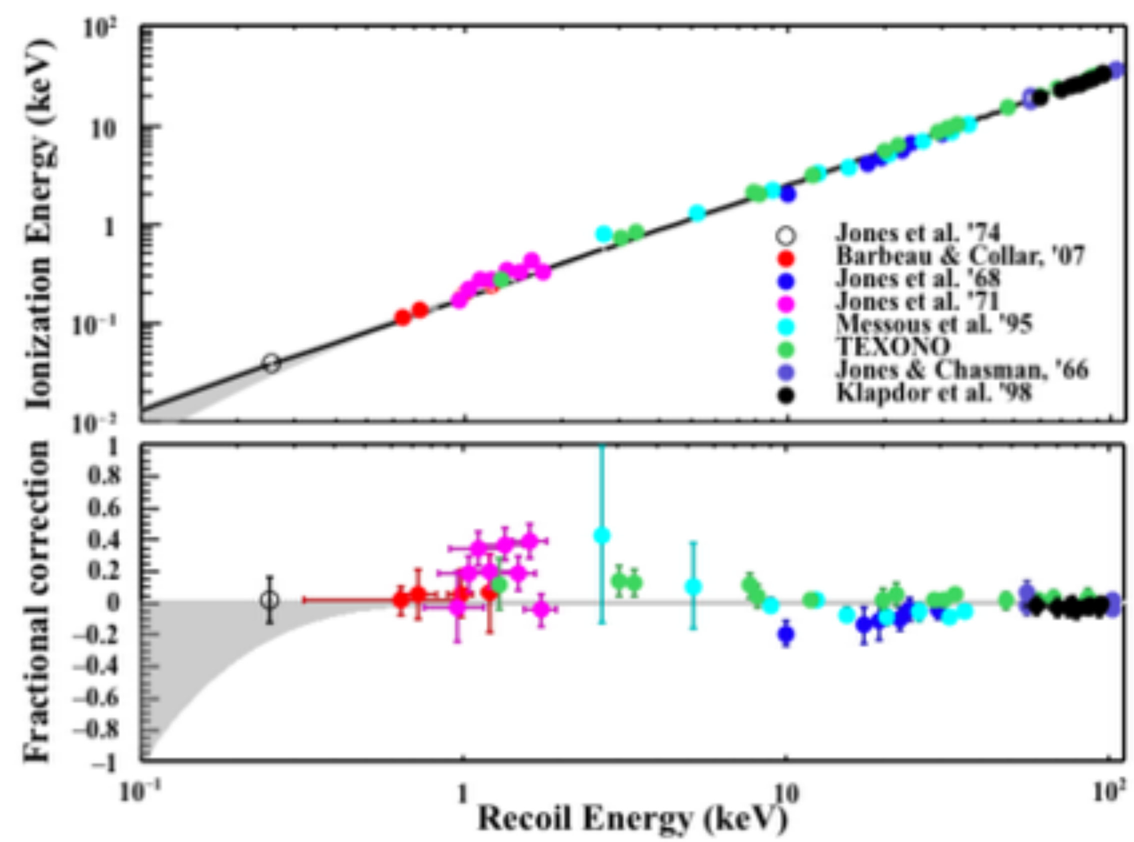
- With a 2-kg crystal, data taken at ~6 m.w.e. indicate sufficiently low backgrounds for CEvNS search @ 20 m from SNS target
- 14.6-kg crystal, *now deployed at the SNS*, has been characterized (good uniformity of light yield along length)
- CsI(Na) response to low-energy nuclear recoils has been measured by members of the COHERENT collaboration
  - Demonstrated threshold of ~7 keVnr (4 PE)



CEvNS with PPCs

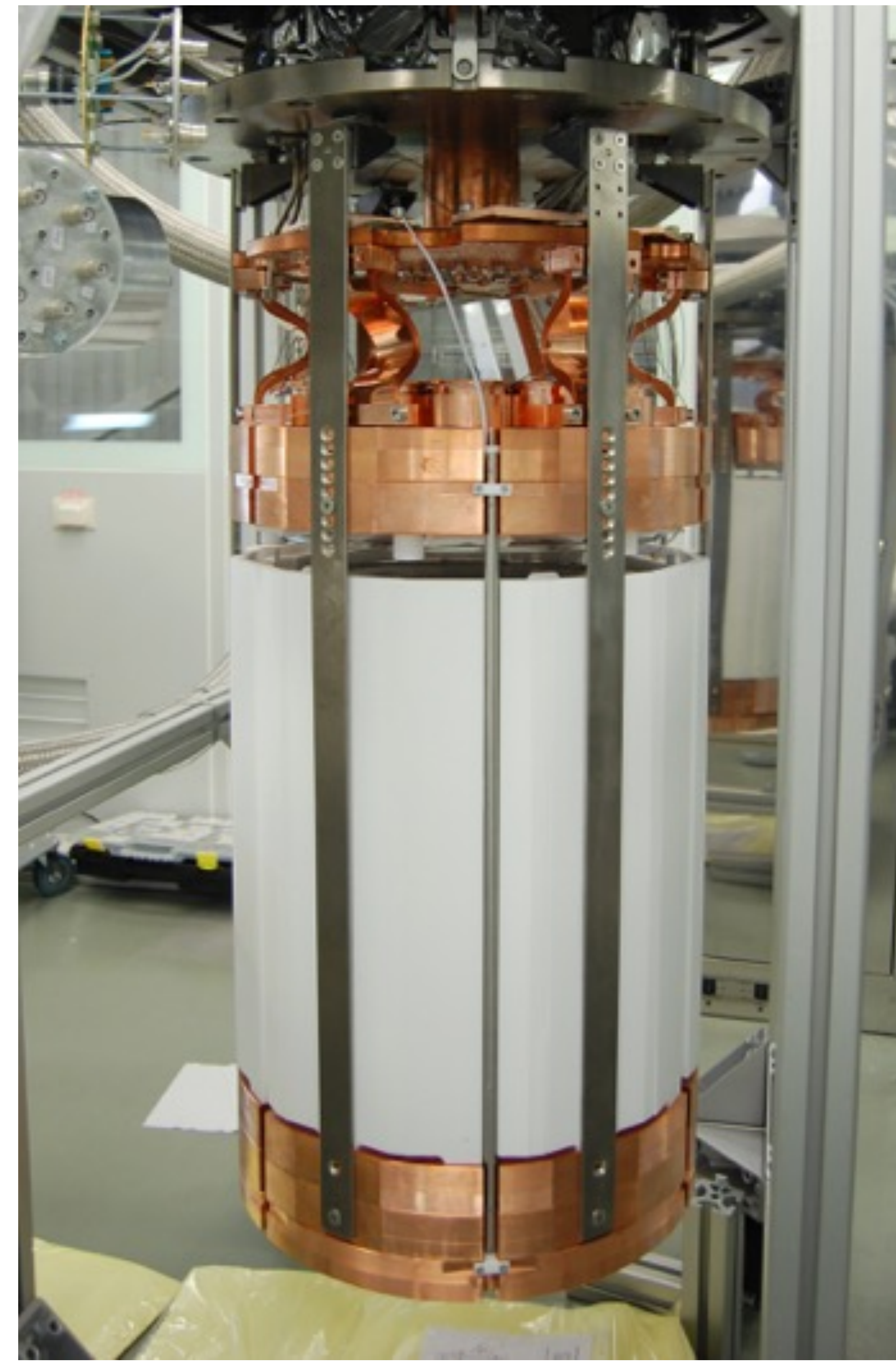
- Ge PPC technology can be realized in low-background systems with exceptionally low noise: **high resolution and low threshold**
- Signal (ionization) yield for CEvNS-relevant nuclear-recoil energies has been measured extensively; data agree well with theoretical predictions
- MAJORANA Executive Committee has endorsed the use of components from the MAJORANA Demonstrator Prototype, following decommissioning in Spring 2015, by COHERENT; working group led by R. Cooper (LBL) and M. Green (NCSU)





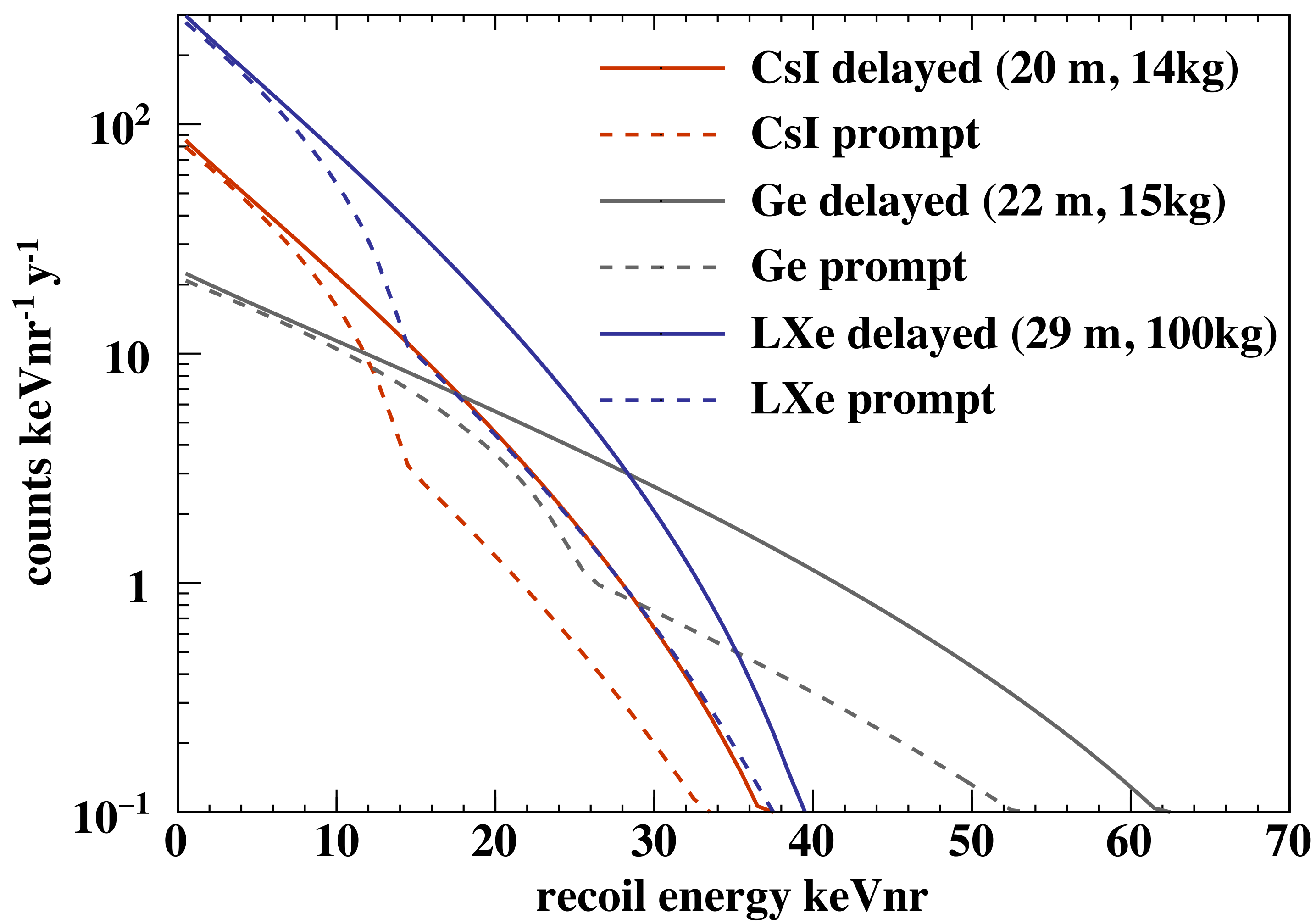
CEvNS with dual-phase xenon

- RED-100 detector built by COHERENT collaborators at MEPhI and ITEP (Moscow); working group led by Yu. Efremenko (UTK)
- ~250-kg total mass, ~100-kg fiducial
- > 1000 CEvNS counts/yr; S/N 10:1
- ORNL LDRD awarded to finance move of RED-100 to the SNS
- Subsequent talk by V. Belov will discuss this detector more thoroughly



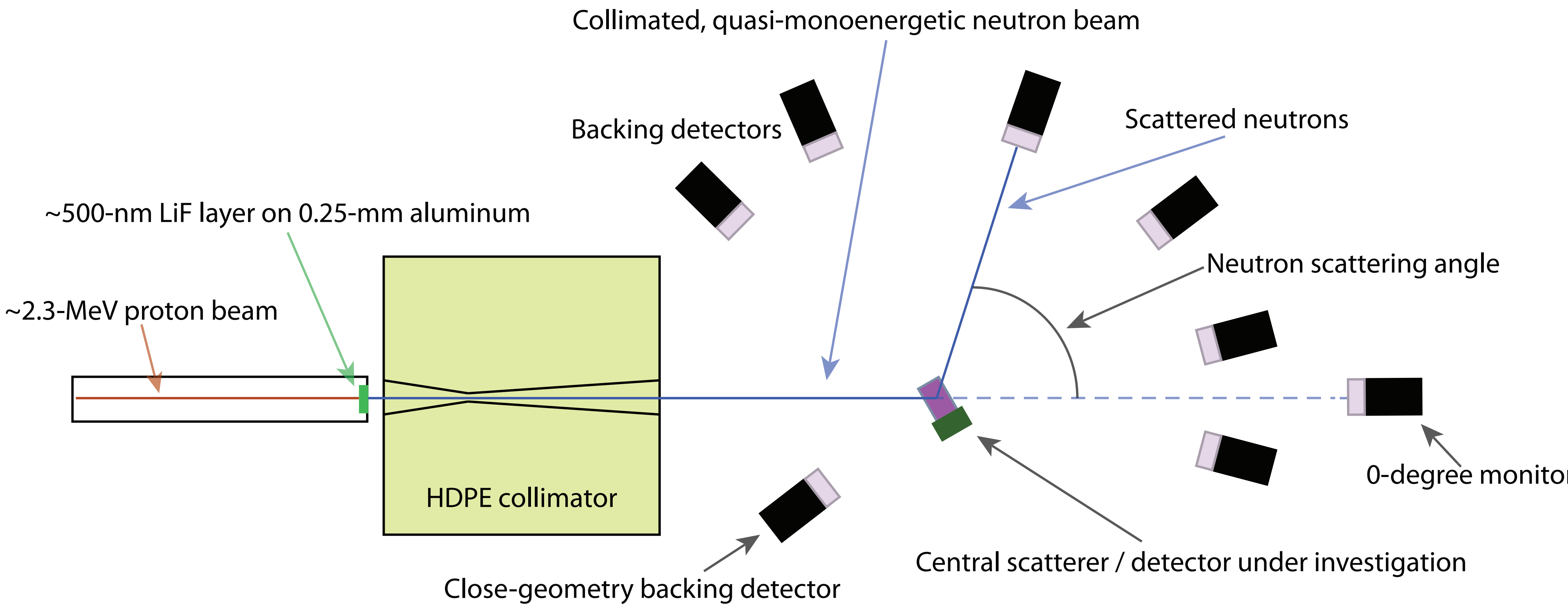
Low-energy nuclear recoils from CEvNS

- 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



Quenching factor measurements at TUNL

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



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

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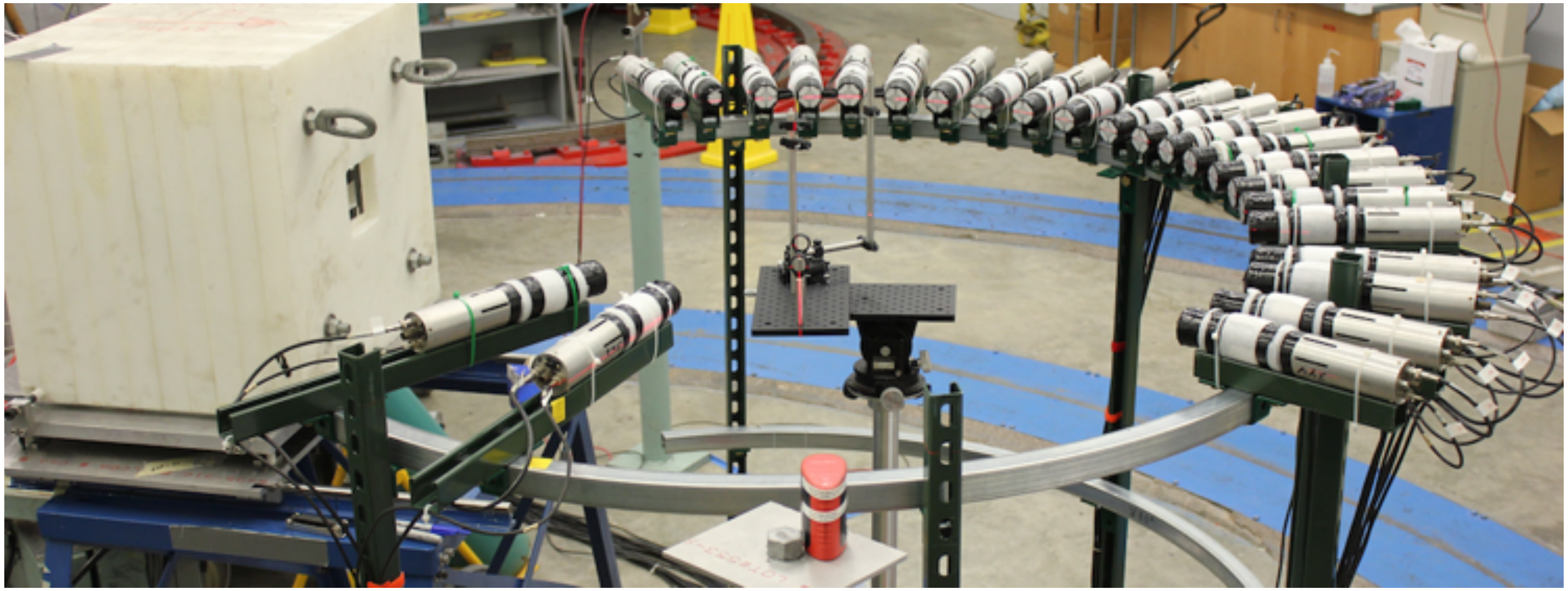

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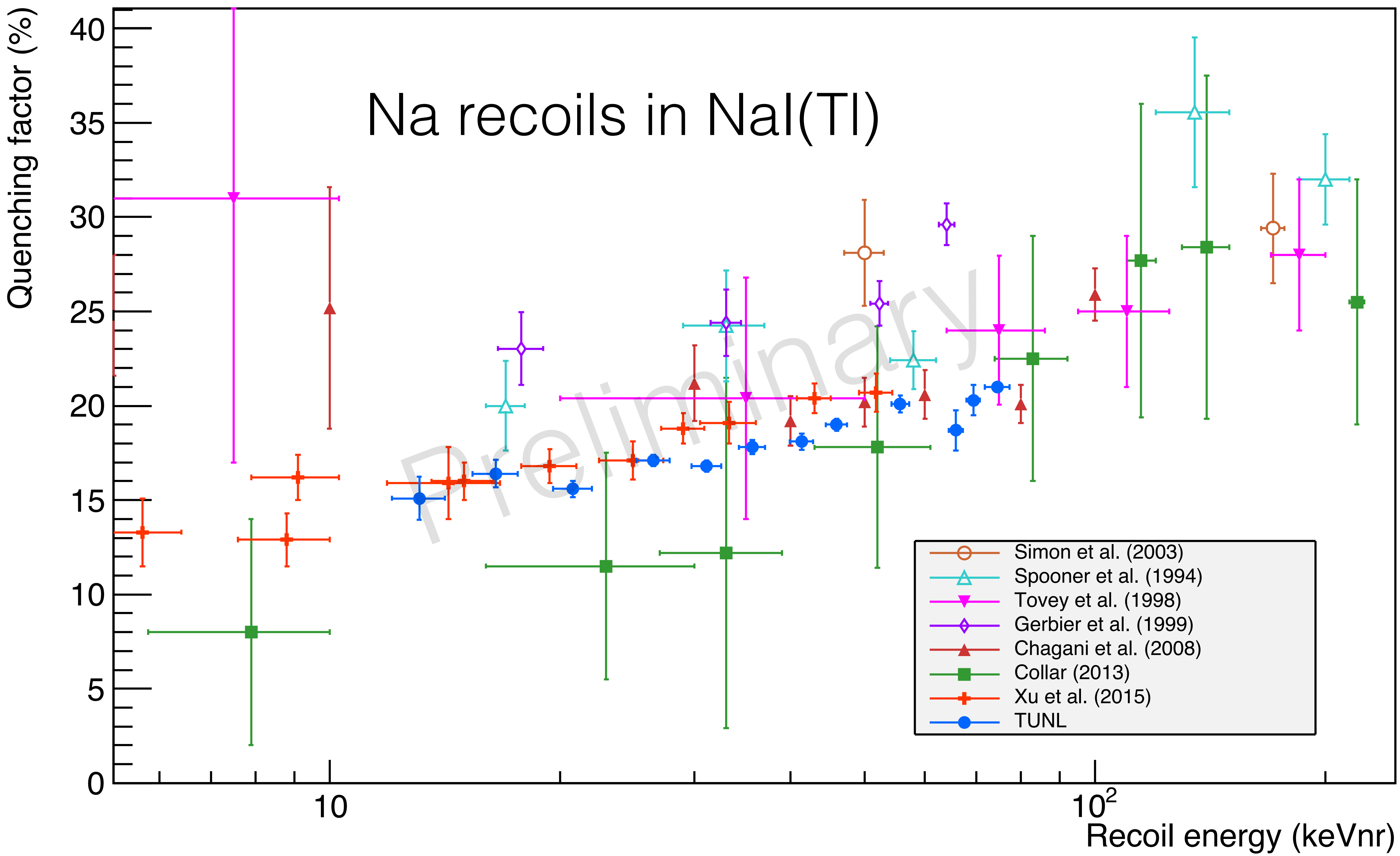
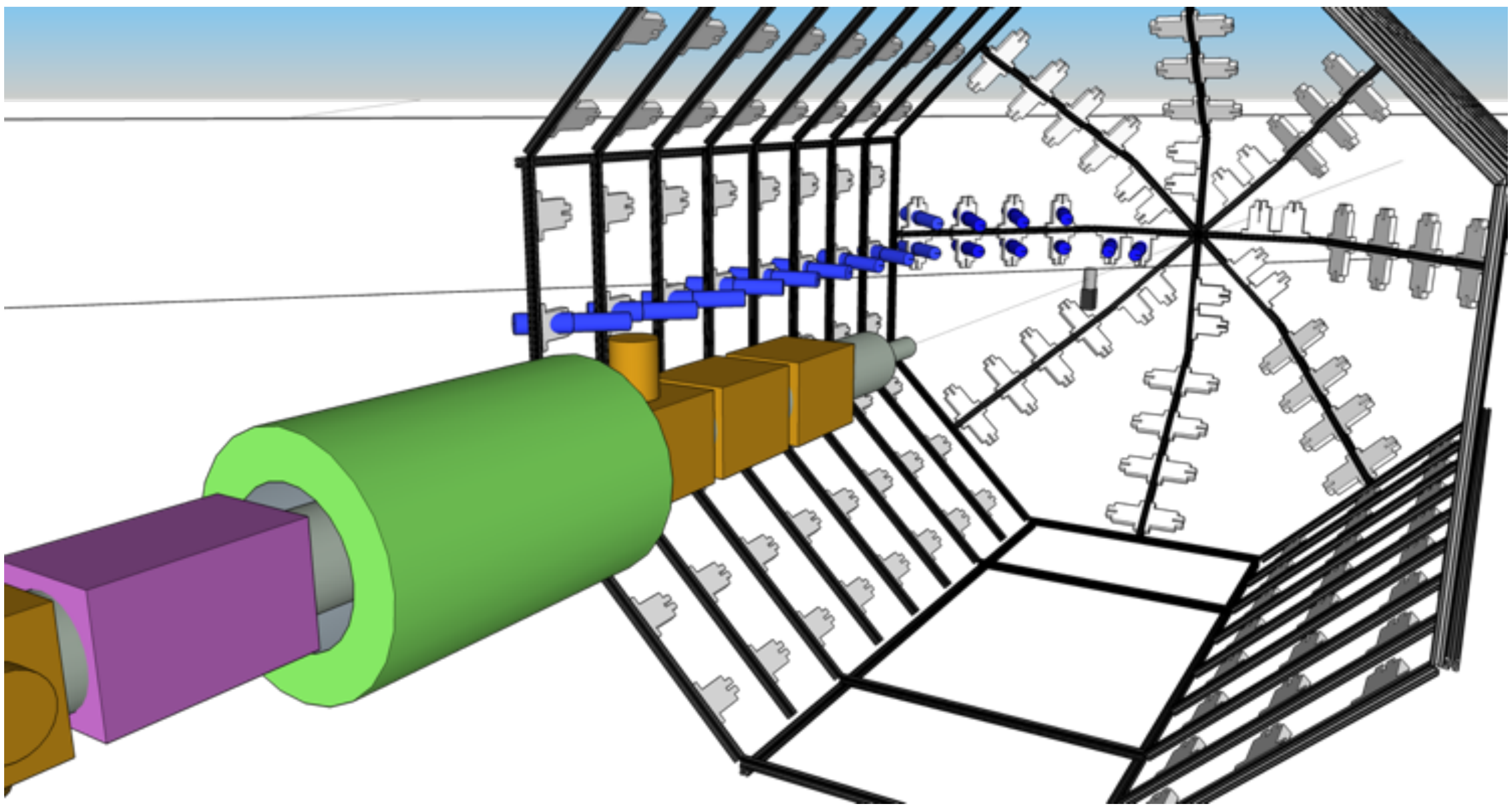


Quenching factor measurements at TUNL

New, dedicated location for quenching measurements and plans to expand backing detector array to include 300 detectors



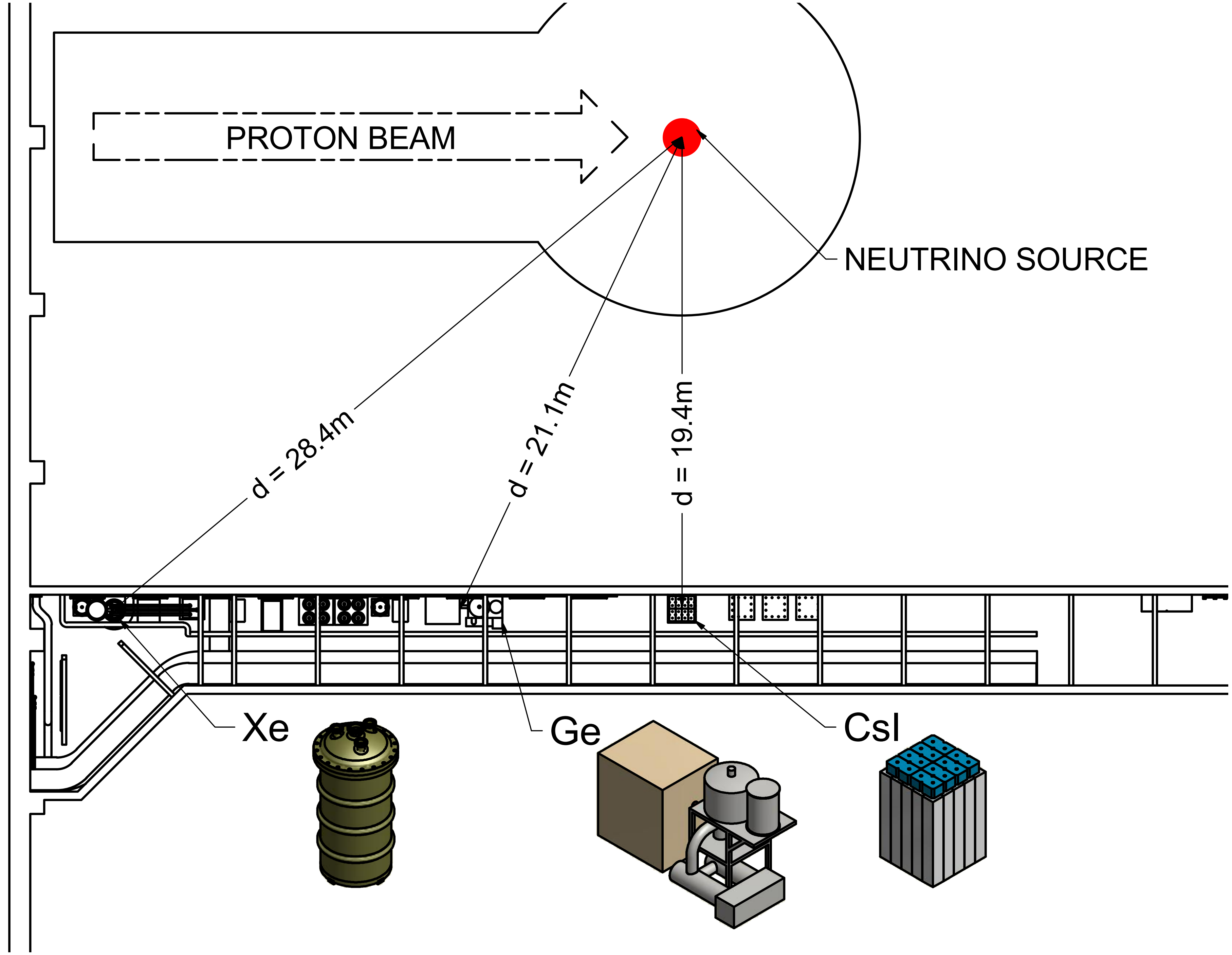
Quenching factor measurements at TUNL

New, dedicated location for quenching measurements and plans to expand backing detector array to include 300 detectors

(PMTs are in hand)

Backgrounds at the SNS

- Backgrounds depend on siting at SNS
- Detectors will be located in a basement hallway
    - ~8 m.w.e. overburden
    - 20- to 30-m from target



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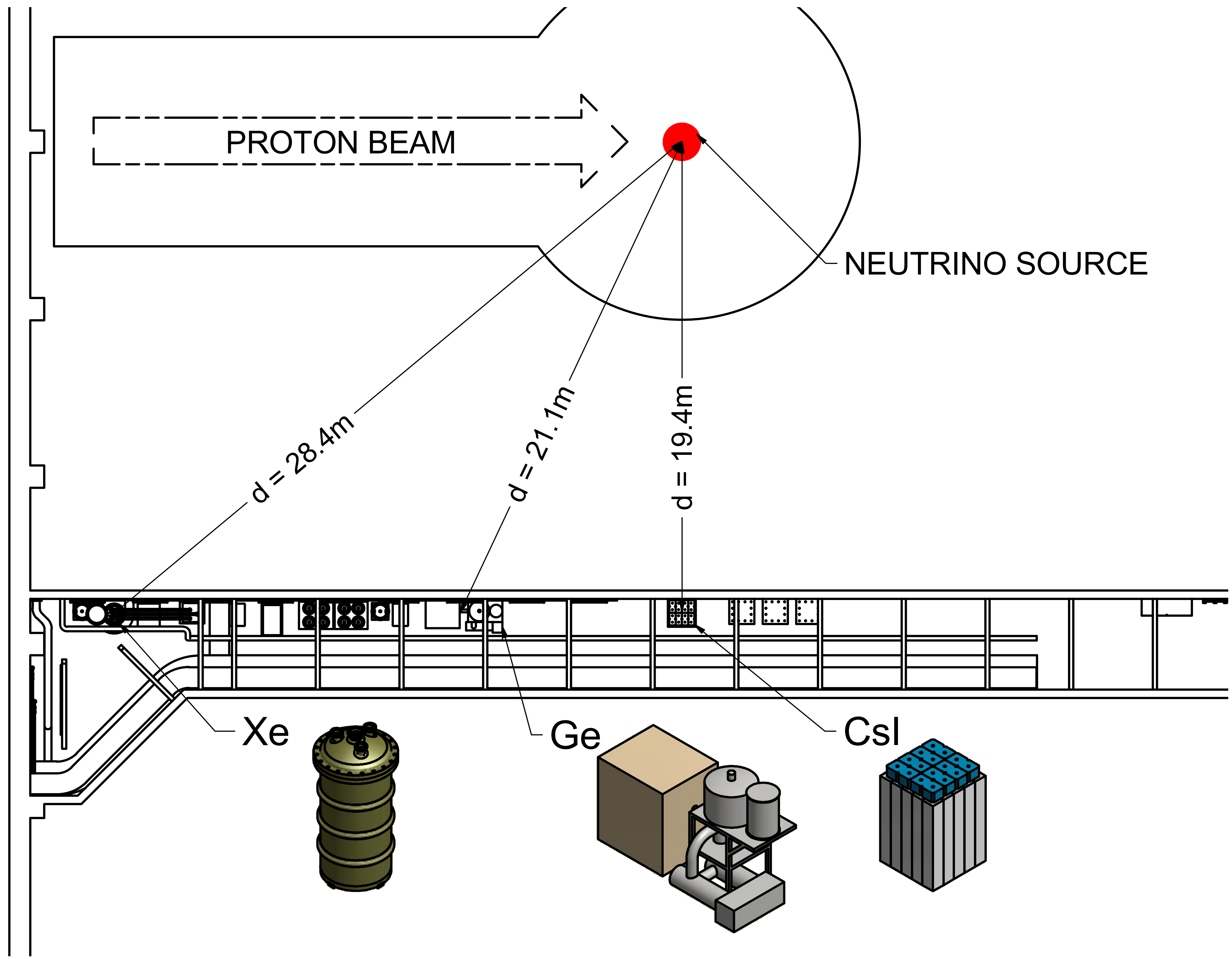
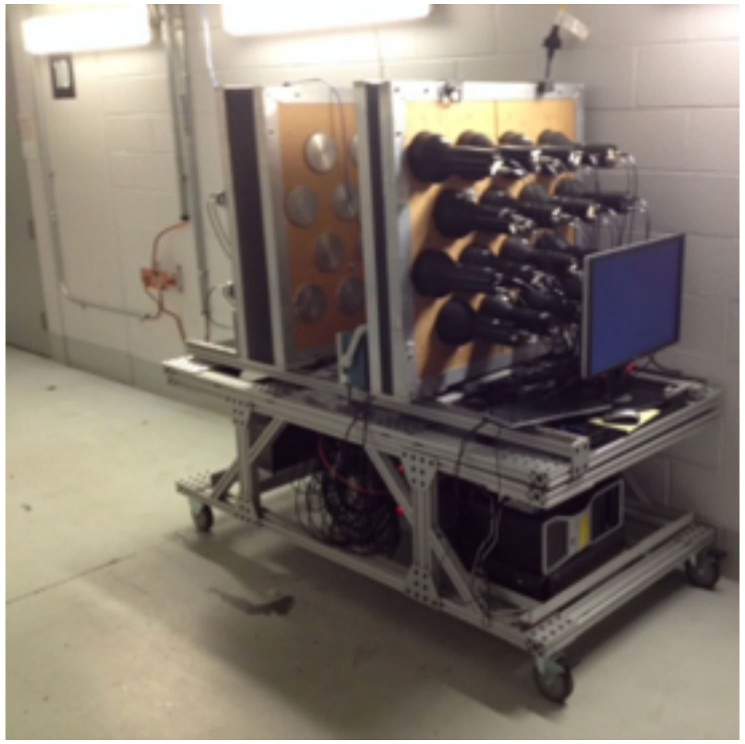


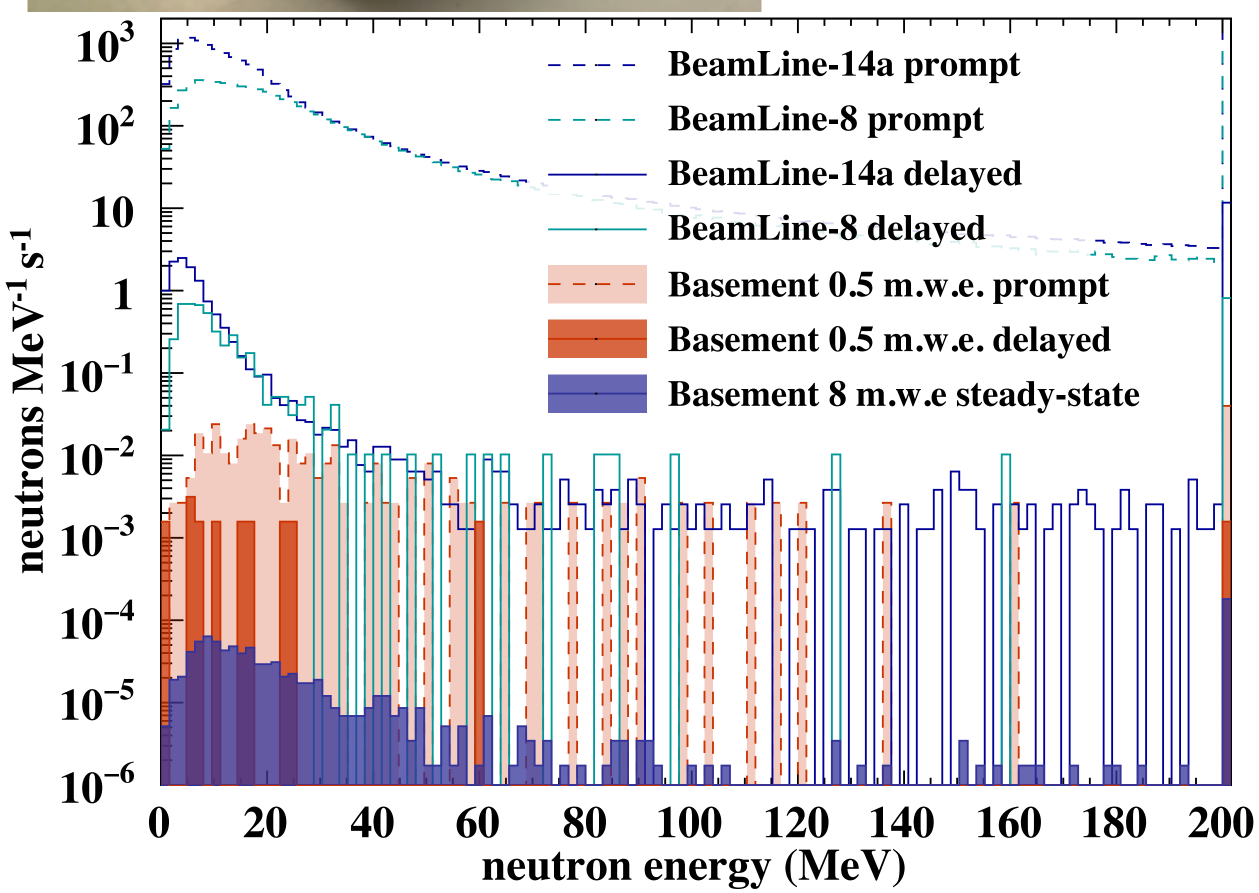
Modest reduction in cosmic backgrounds

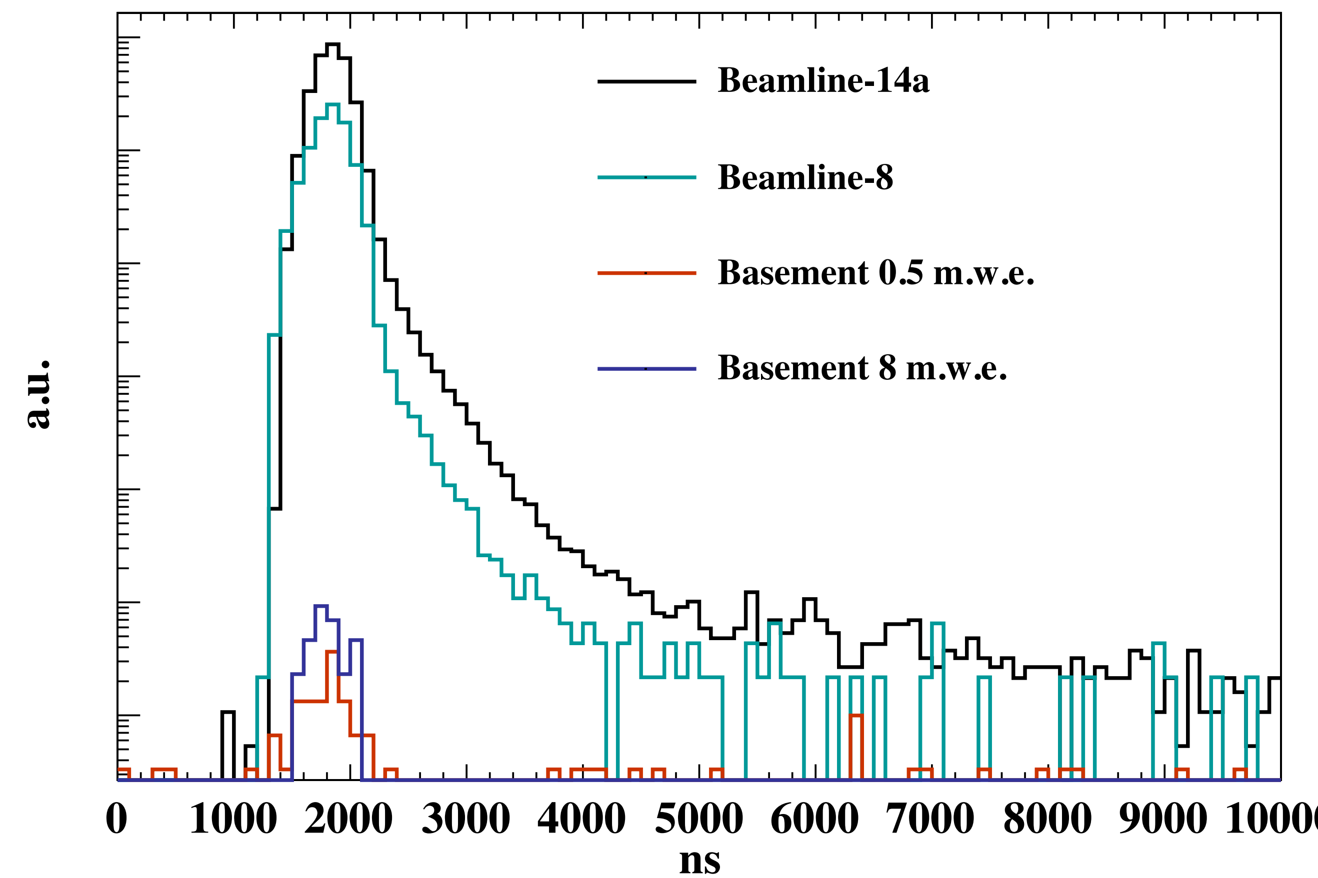
Neutrons at the SNS



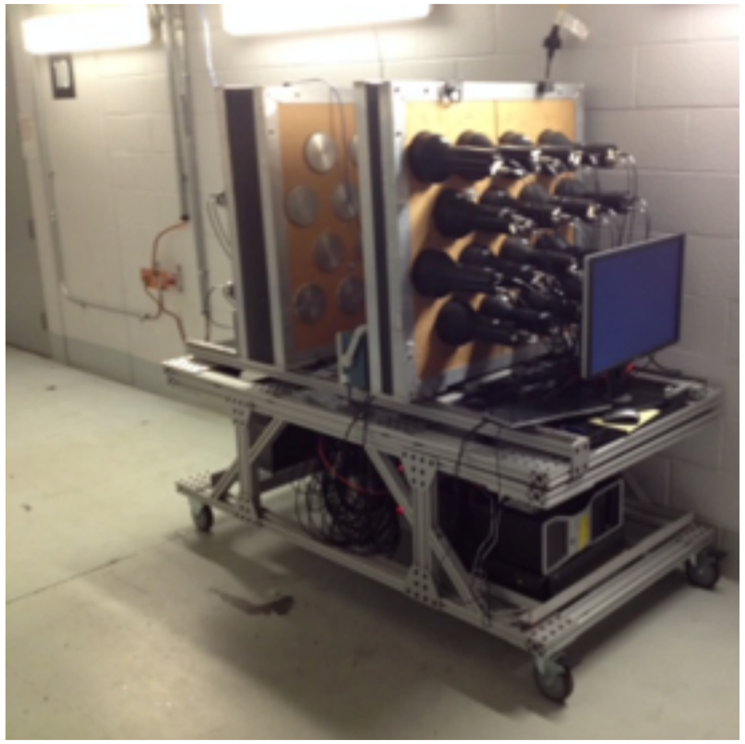
Neutron scatter camera (Sandia)

- 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



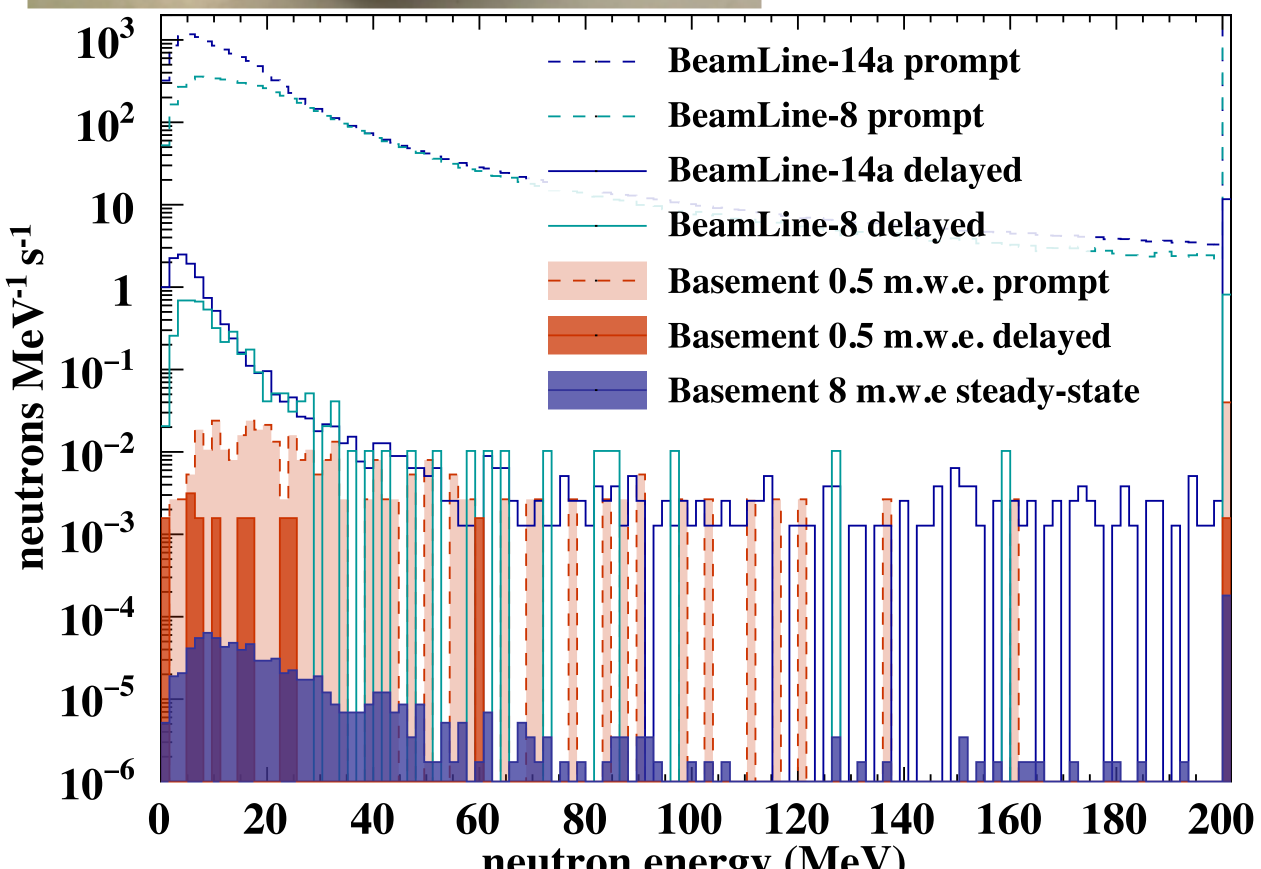


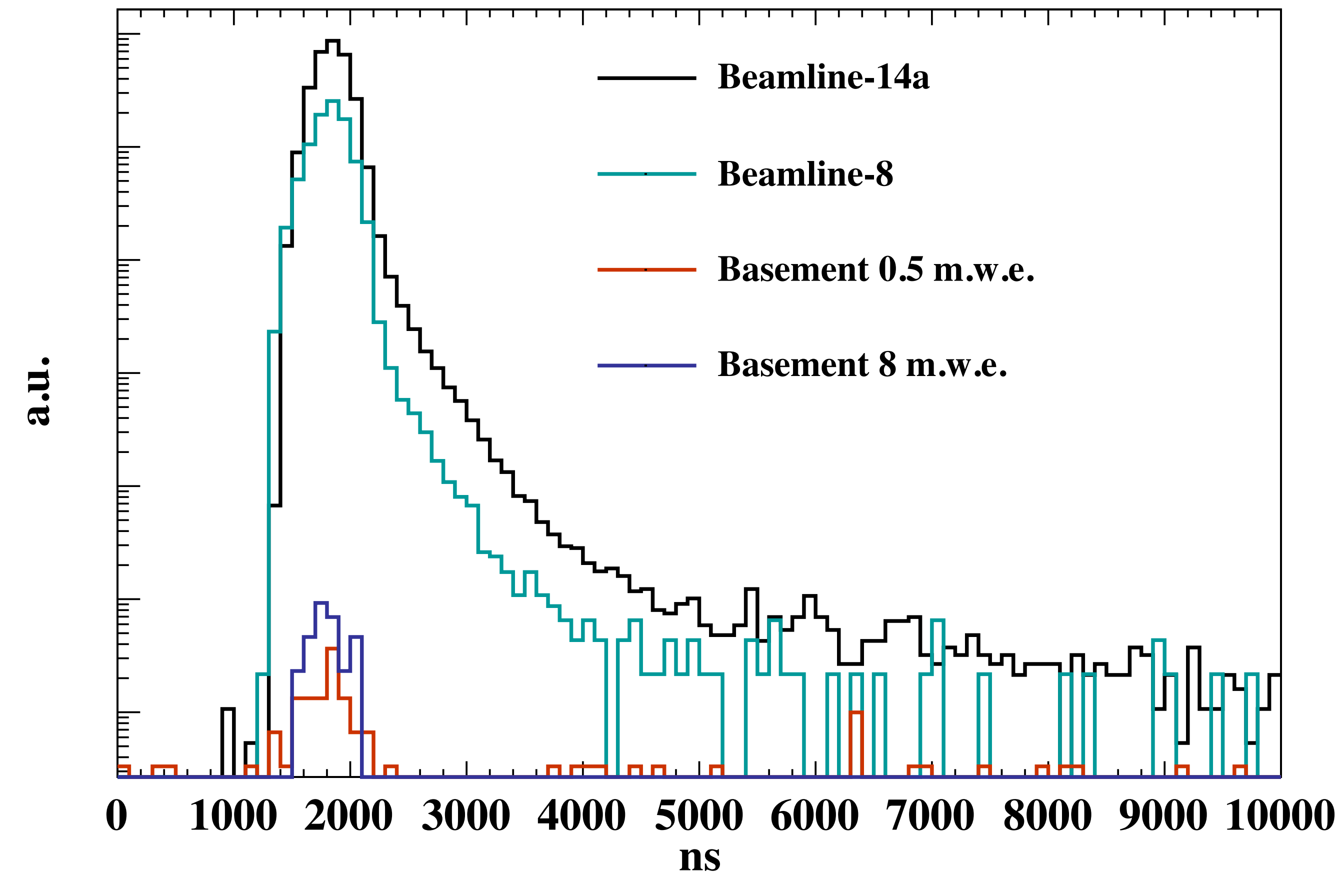
Neutrons at the SNS



>4 order of magnitude reduction from move to basement!

Beam-related neutron backgrounds are more narrowly distributed in time in basement locations

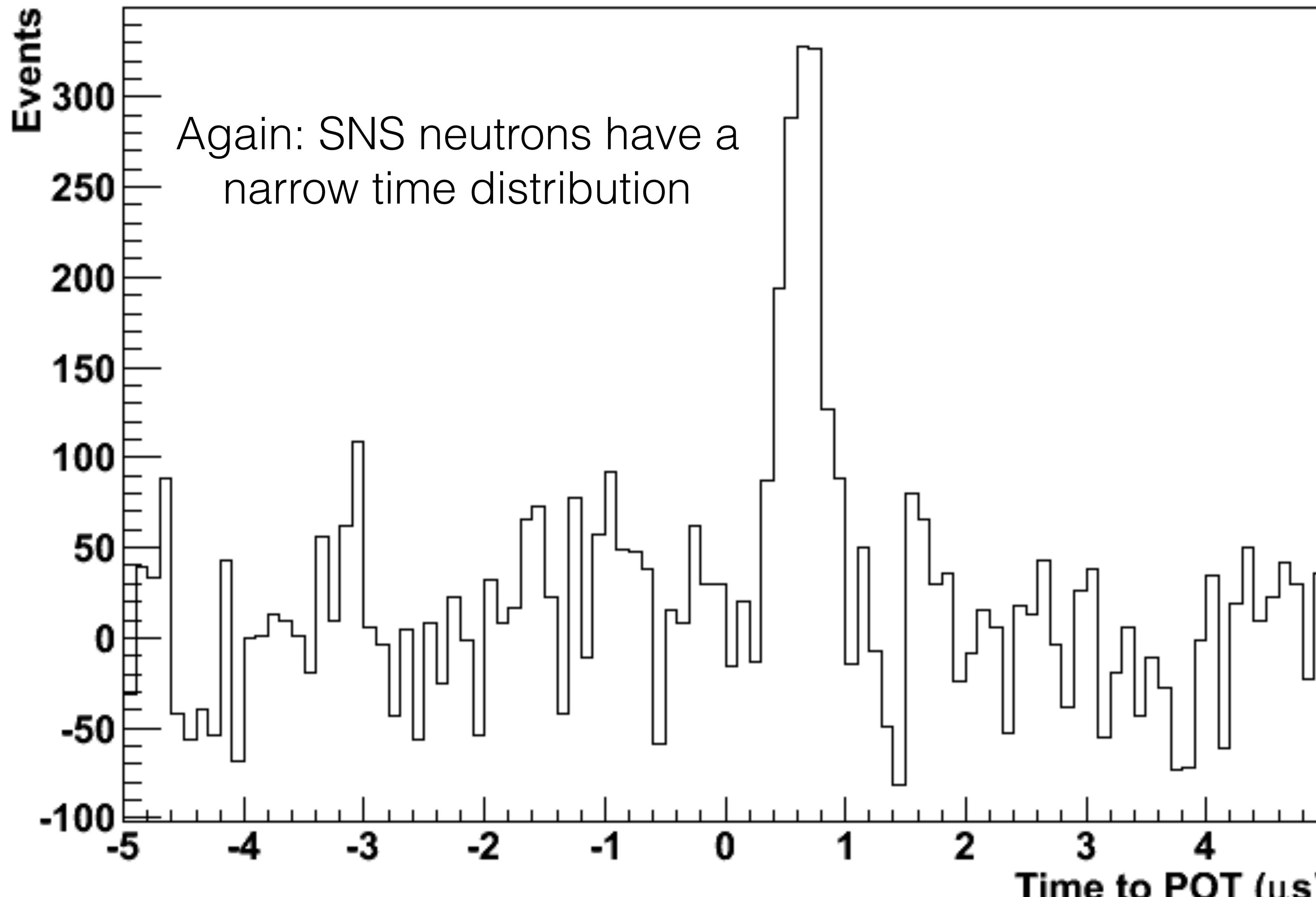




Neutrons at the SNS

SciBath (Indiana)

80L, liquid-scintillator-based tracking detector located at intended site of RED-100 deployment



Neutrino-induced neutrons (NINs)

- Neutrinos incident on shielding material can result in the emission of neutrons

- Theoretical predictions of cross section are strongly model dependent; plot at right shows total CC cross section for ^{56}Fe

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

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

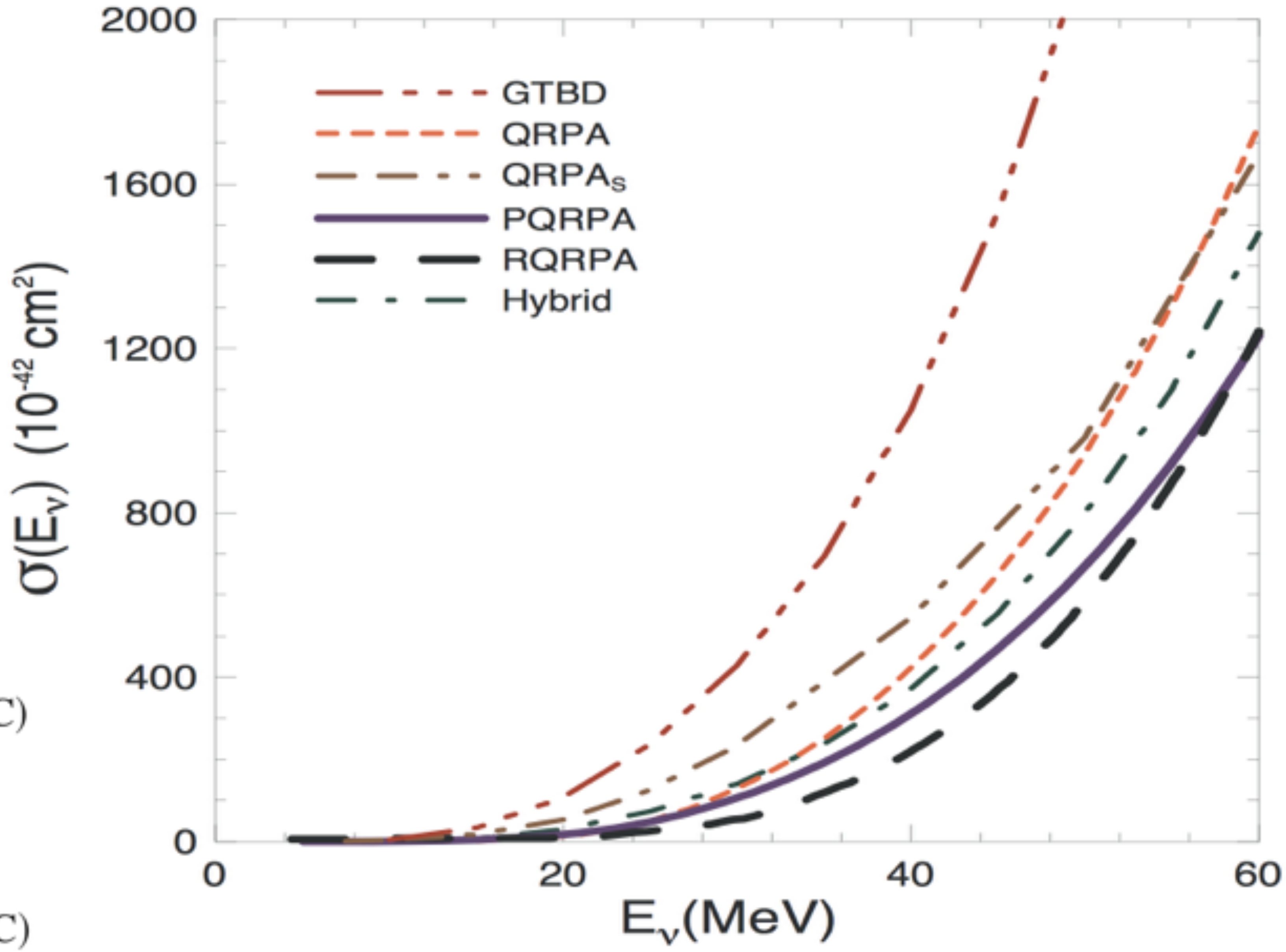


Figure from A.R. Samana and C.A. Bertulani, Phys. Rev. C (2008)

Neutrino-induced neutrons (NINs)

- Measurements of these cross sections have implications beyond background assessment
    - NINs from Pb are fundamental mechanism for detection in HALO supernova neutrino detector [1]
    - NIN interactions may influence nucleosynthesis in certain astrophysical environments [2]

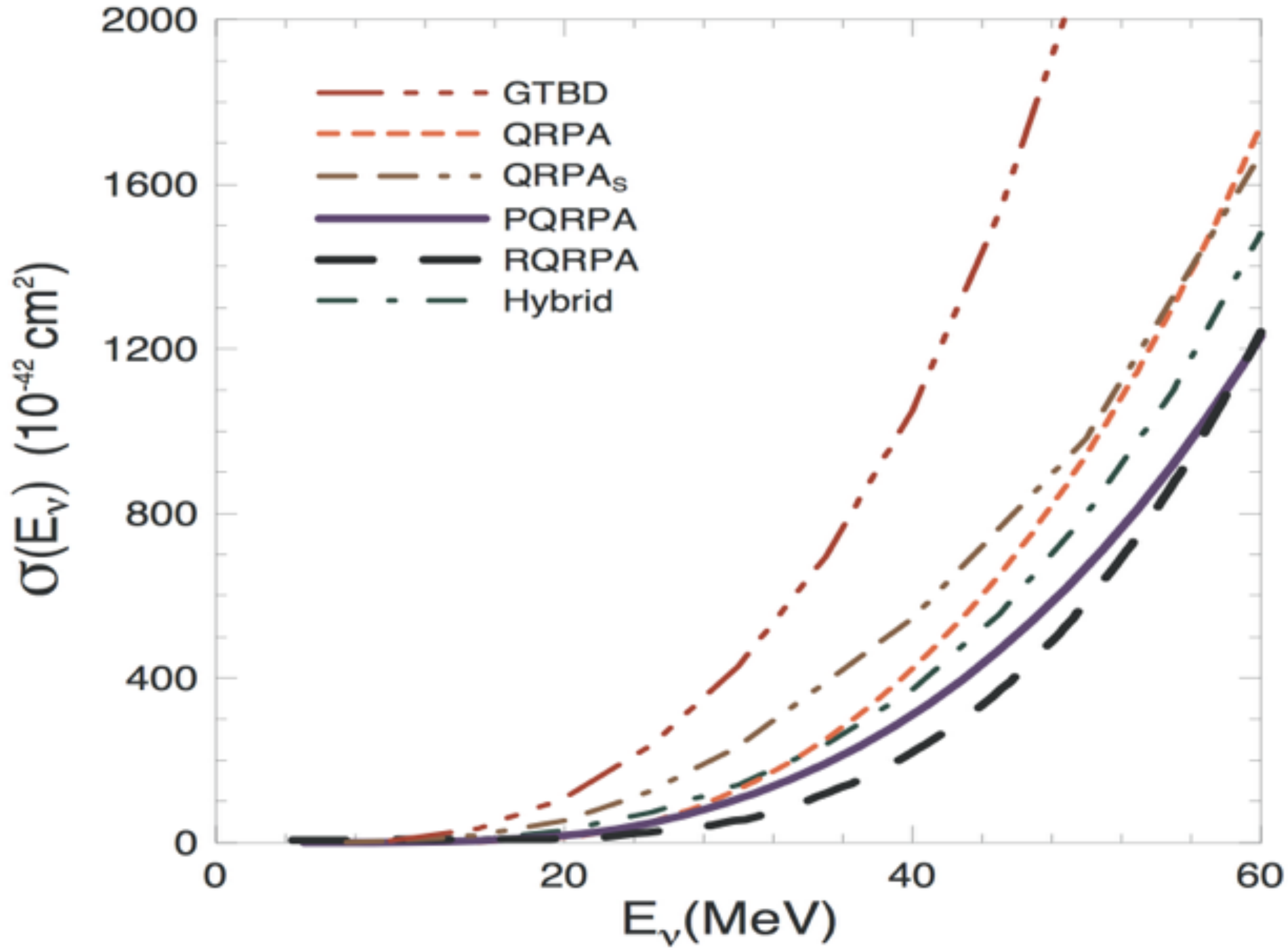
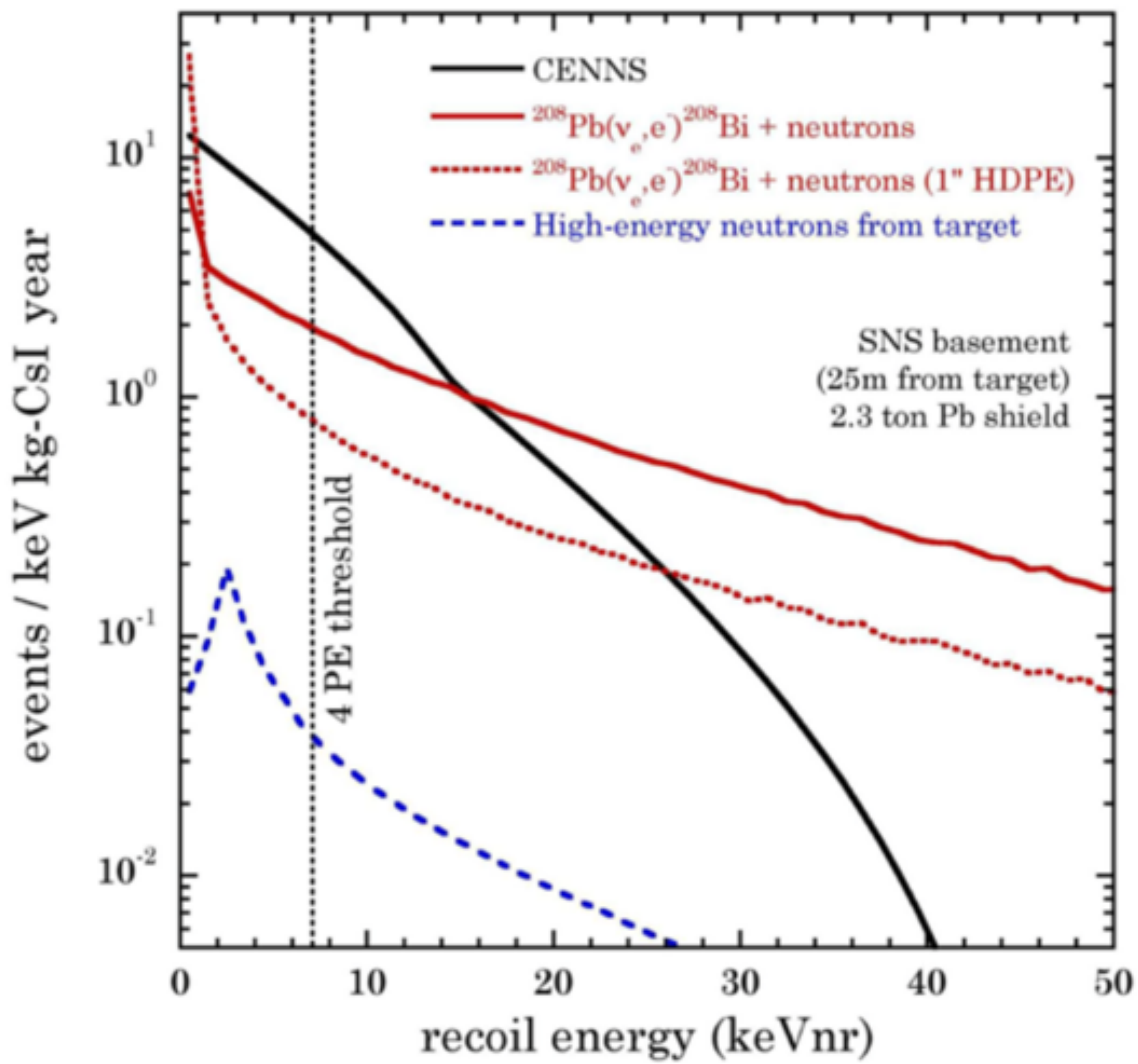


Figure from A.R. Samana and C.A. Bertulani, Phys. Rev. C (2008)

[1] C.A. Duba *et al.* J.Phys.Conf.Series 136 (2008)
[2] Y-Z. Qian *et al.*, Phys. Rev. C 55 (1997)

Neutrino-induced neutrons (NINs)

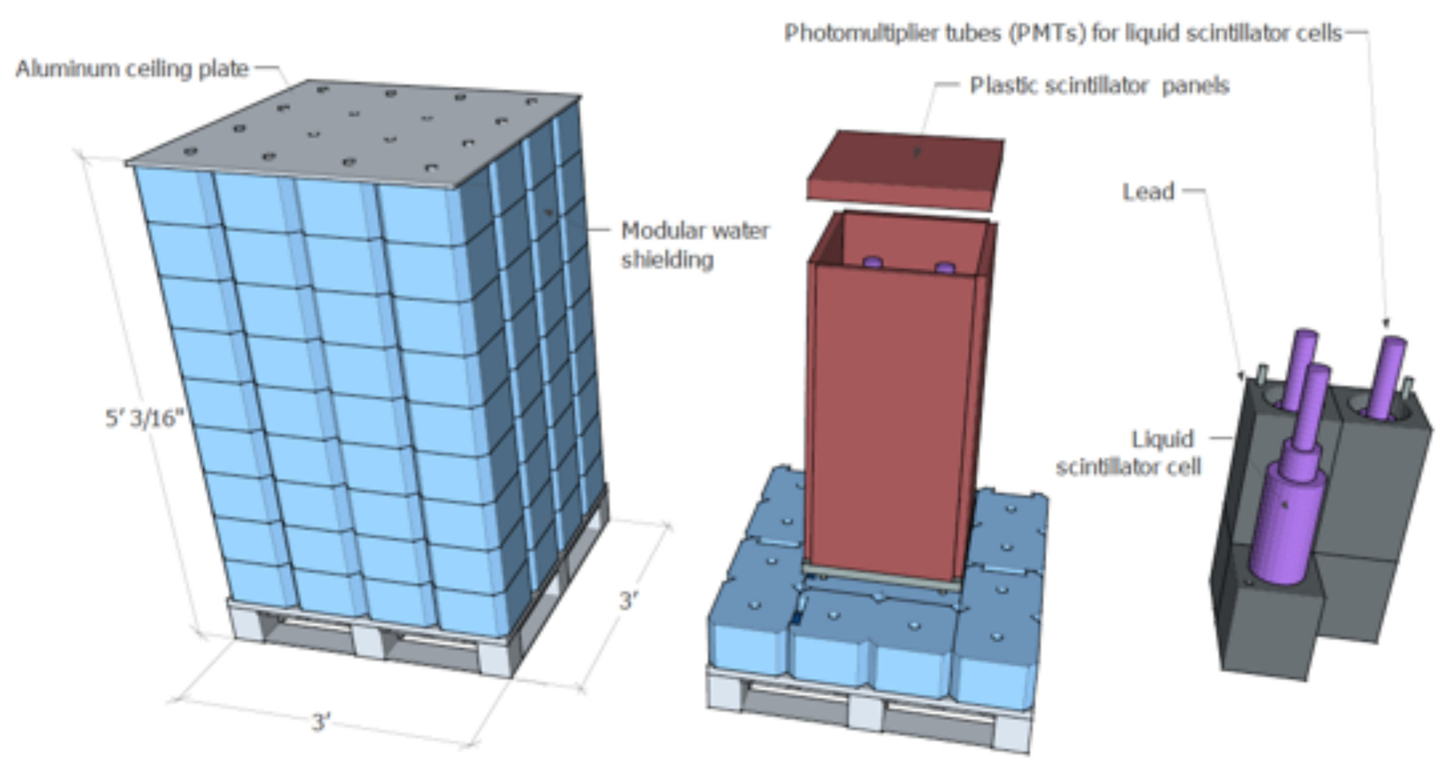
- Measurements of these cross sections have implications beyond background assessment
  - .. but NINs could be the dominant source of background depending on shield design!
  - Fortunately, close-proximity neutron shielding can be effective at reducing NINs



COHERENT SNS

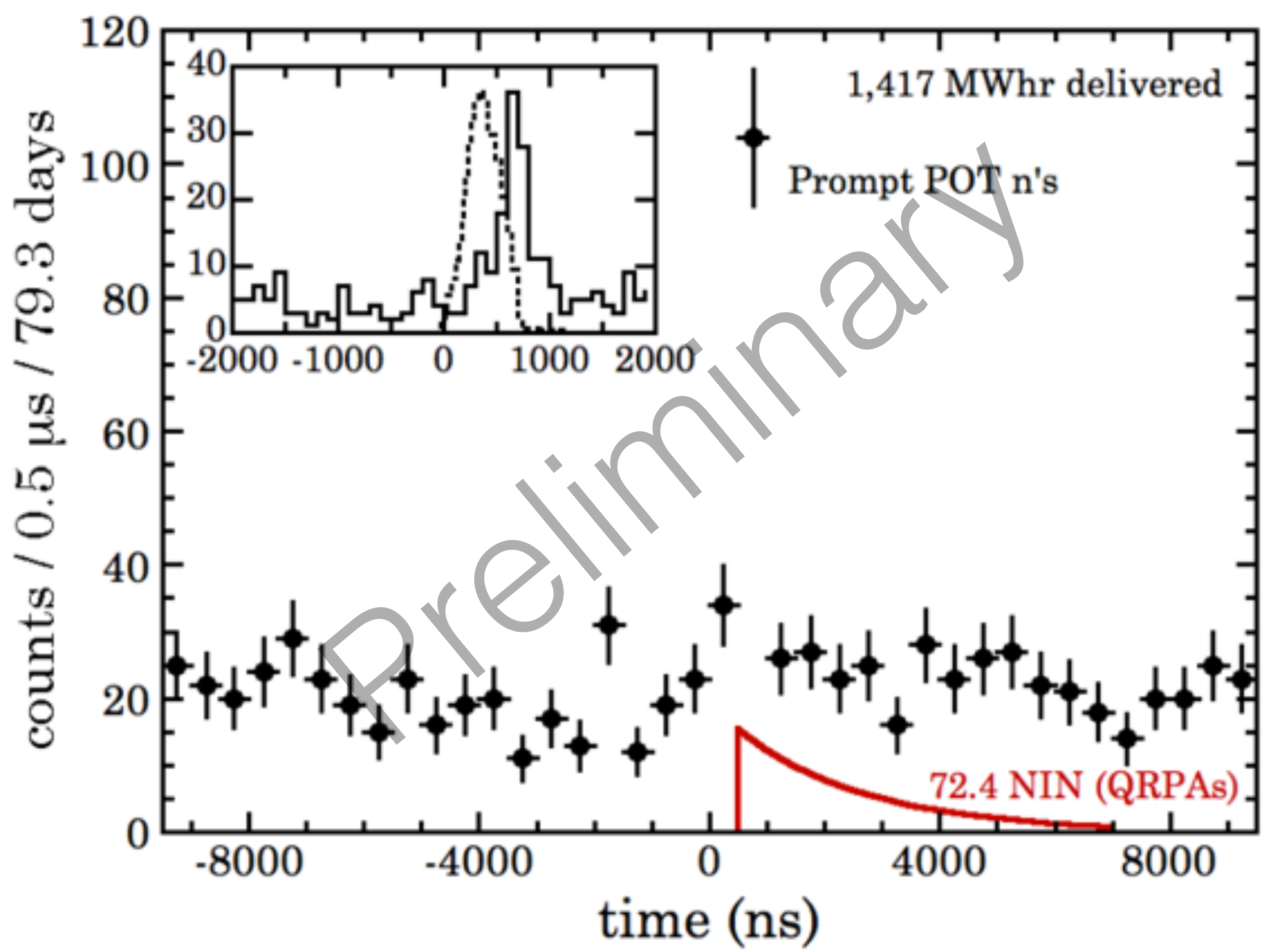
Measuring NINs at the SNS

- Two complementary efforts
  - *In situ* measurement inside CsI(Na) crystal cavity using LS cells
  - Dedicated, higher-statistics measurement using “neutrino cubes”



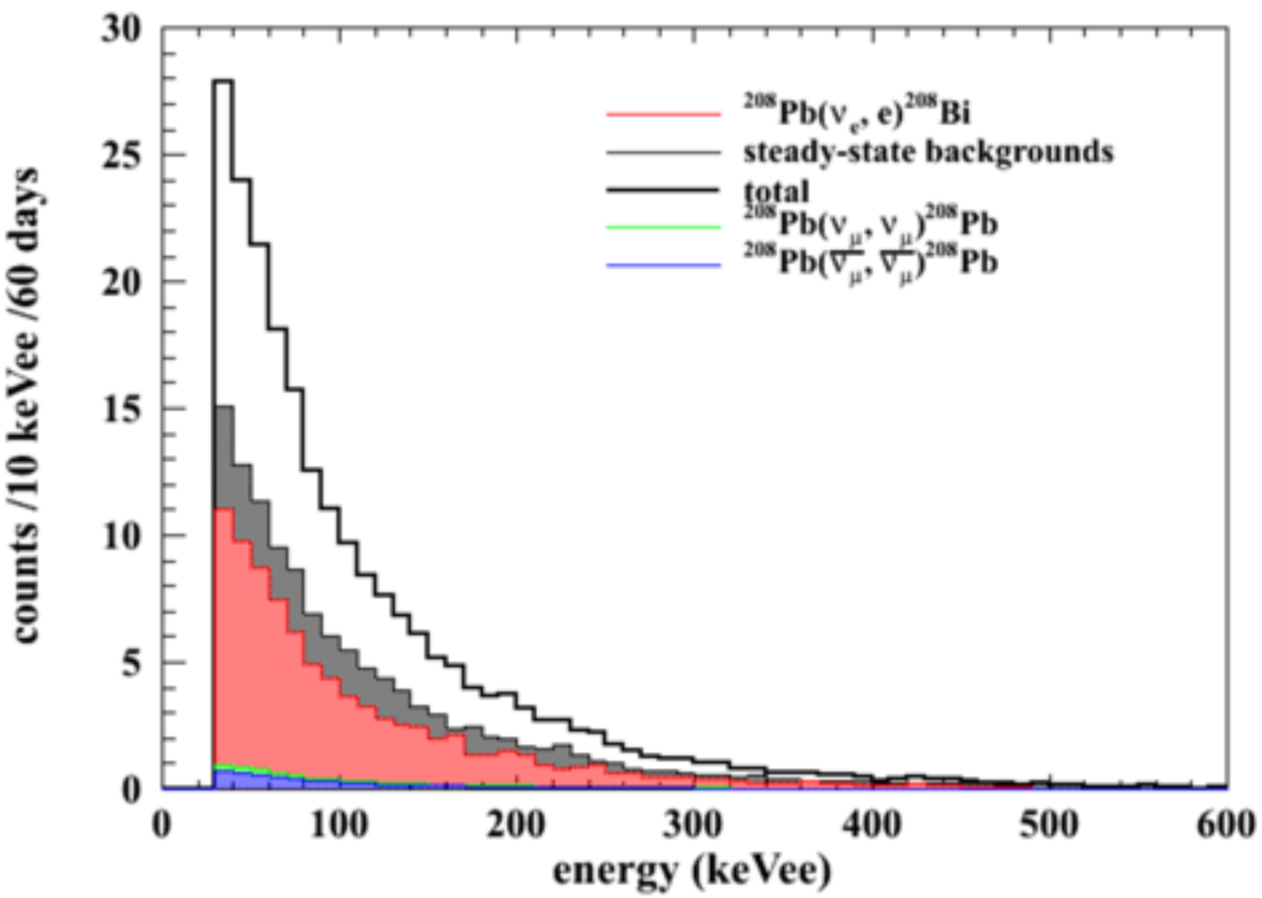
Measuring NINs at the SNS

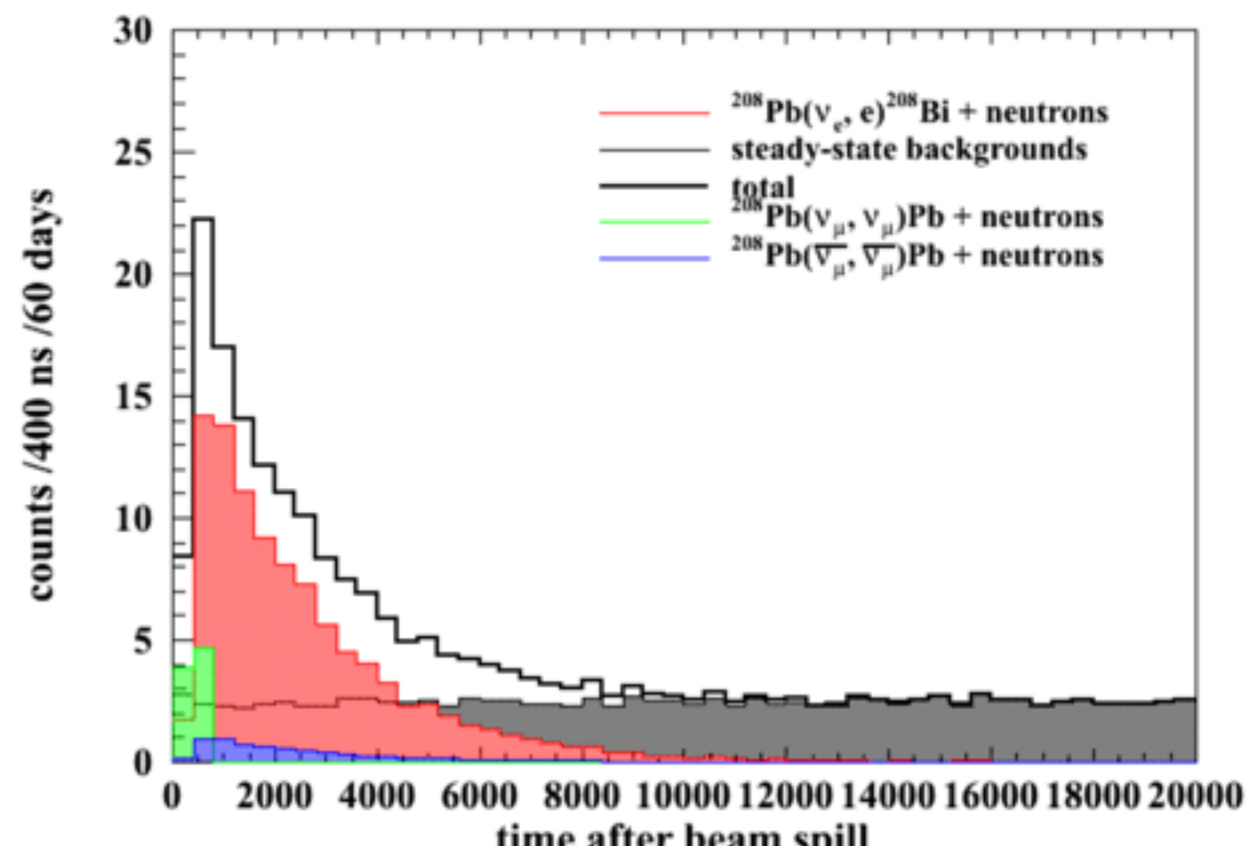
Preliminary indication from *in situ* background measurement for CsI(Na) suggests fast neutrons associated with beam will be few (<~1 n/day) and tightly correlated with SNS timing



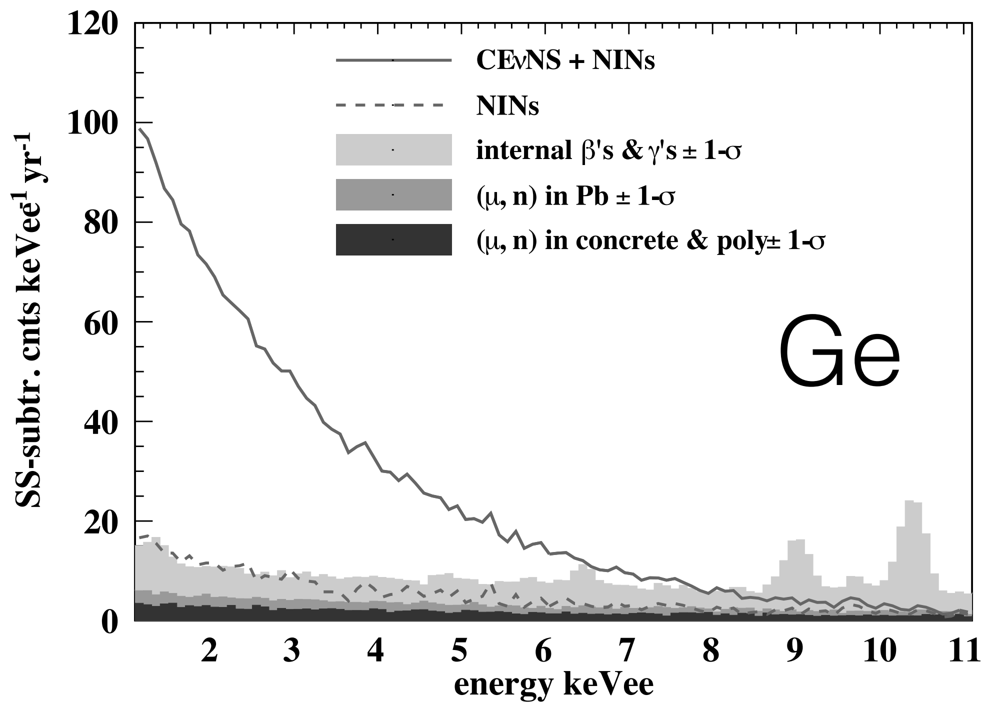
NIN measurements at the SNS: Neutrino cubes with lead

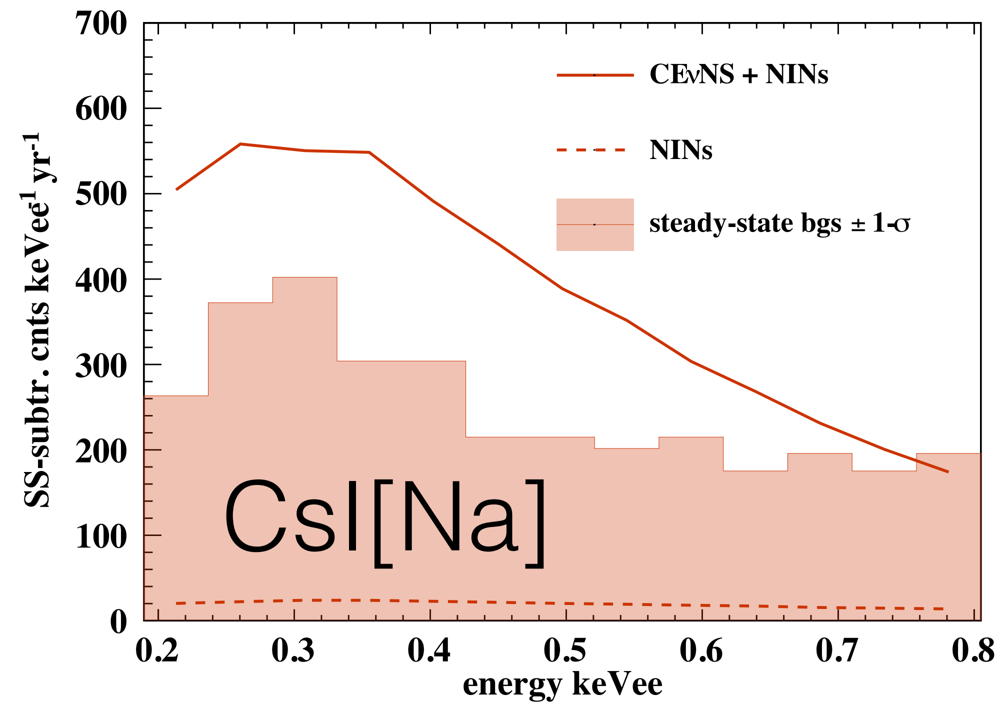
Anticipated NIN count rate in the lead neutrino cube assembly, positioned in its present location at the SNS (~20 m from target, ~8 m.w.e. overburden) and assuming a 30 keVee PSD threshold, is ~100 events in 60 days

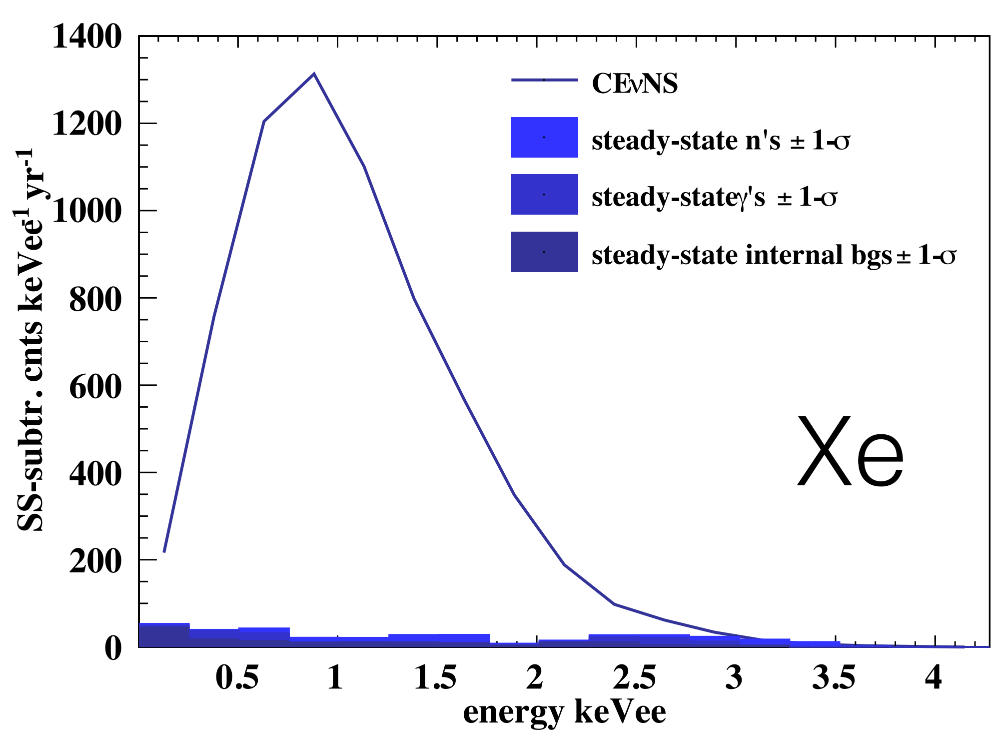


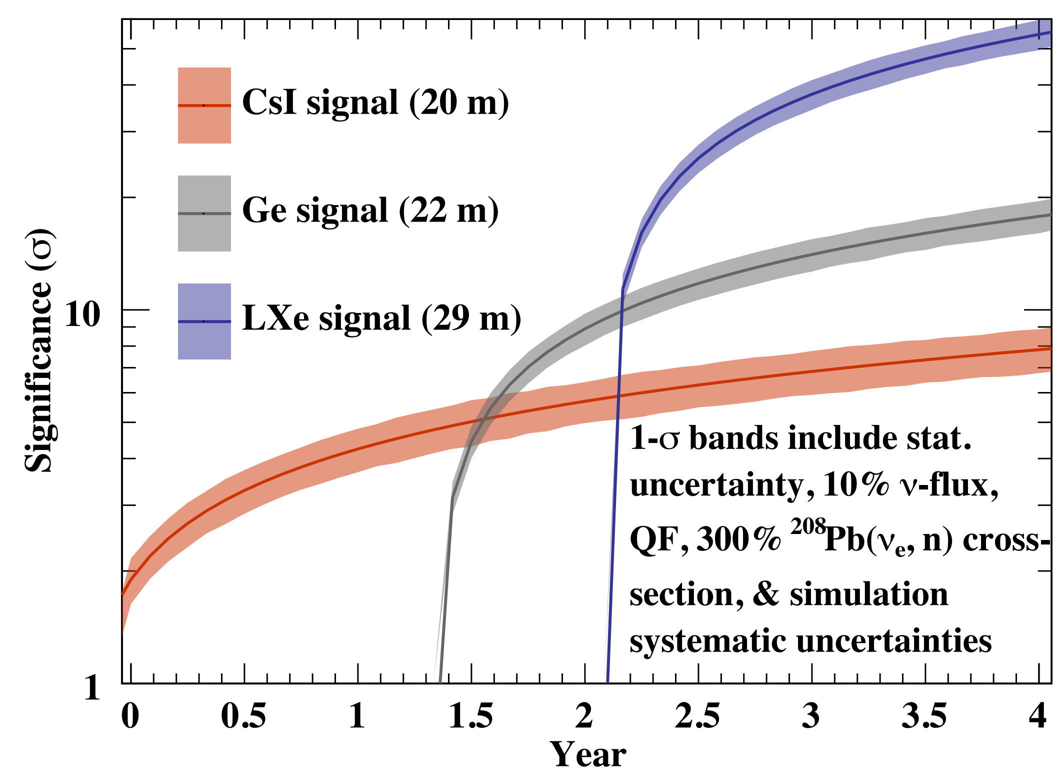


Anticipated signals



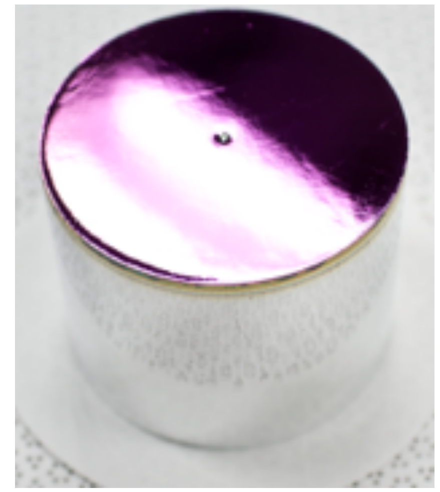






Tentative COHERENT timeline

CsI(Na)
- 14.6-kg crystal in place at SNS and collecting data



Germanium PPCs
- Possible deployment late 2016

2016 2017 2018

Next phases
NSI
Standard model tests
Neutron distributions

NIN measurements
- Pb neutrino cube commissioning underway now
- Fe and Cu to follow

RED-100 dual-phase Xe
- Move to ORNL early 2016
- > 1000 CEvNS counts per year: high-statistics CS and 2.2-us decay observation quickly obtained

COHERENT: neutrino scattering at the SNS

- Backgrounds in basement locations are increasingly-well understood; beam neutron contributions significantly lower in delayed neutrino time window
- Path toward unambiguous observation of CEvNS process with multiple proven and available detector technologies
    - CsI(Na) *taking data now*
    - LDRD awarded to finance deployment of RED-100 detector
    - MJD Prototype available - proposal submitted to fund deployment

COHERENT SNS

Sandia National Laboratories

Duke UNIVERSITY

THE UNIVERSITY of TENNESSEE UT KNOXVILLE

TUNL

NC STATE UNIVERSITY

W UNIVERSITY of WASHINGTON

OAK RIDGE National Laboratory

UF UNIVERSITY of FLORIDA The Foundation for The Gator Nation

Pacific Northwest NATIONAL LABORATORY

NORTH CAROLINA CENTRAL UNIVERSITY FOUNDED 1910

Berkeley UNIVERSITY OF CALIFORNIA

Los Alamos NATIONAL LABORATORY EST.1943

THE UNIVERSITY OF CHICAGO

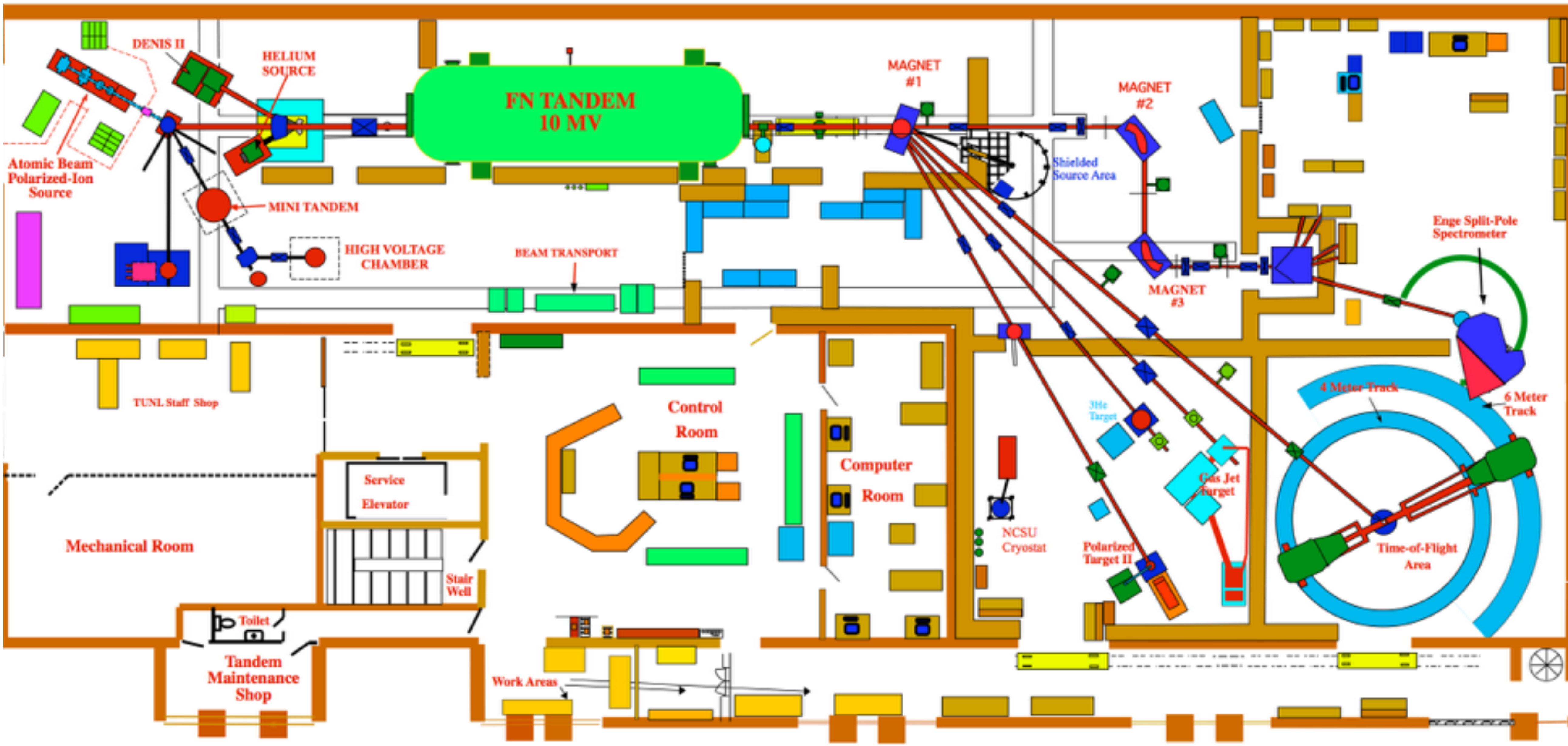
BERKELEY LAB

MEPhI

NM STATE UNIVERSITY

Backup

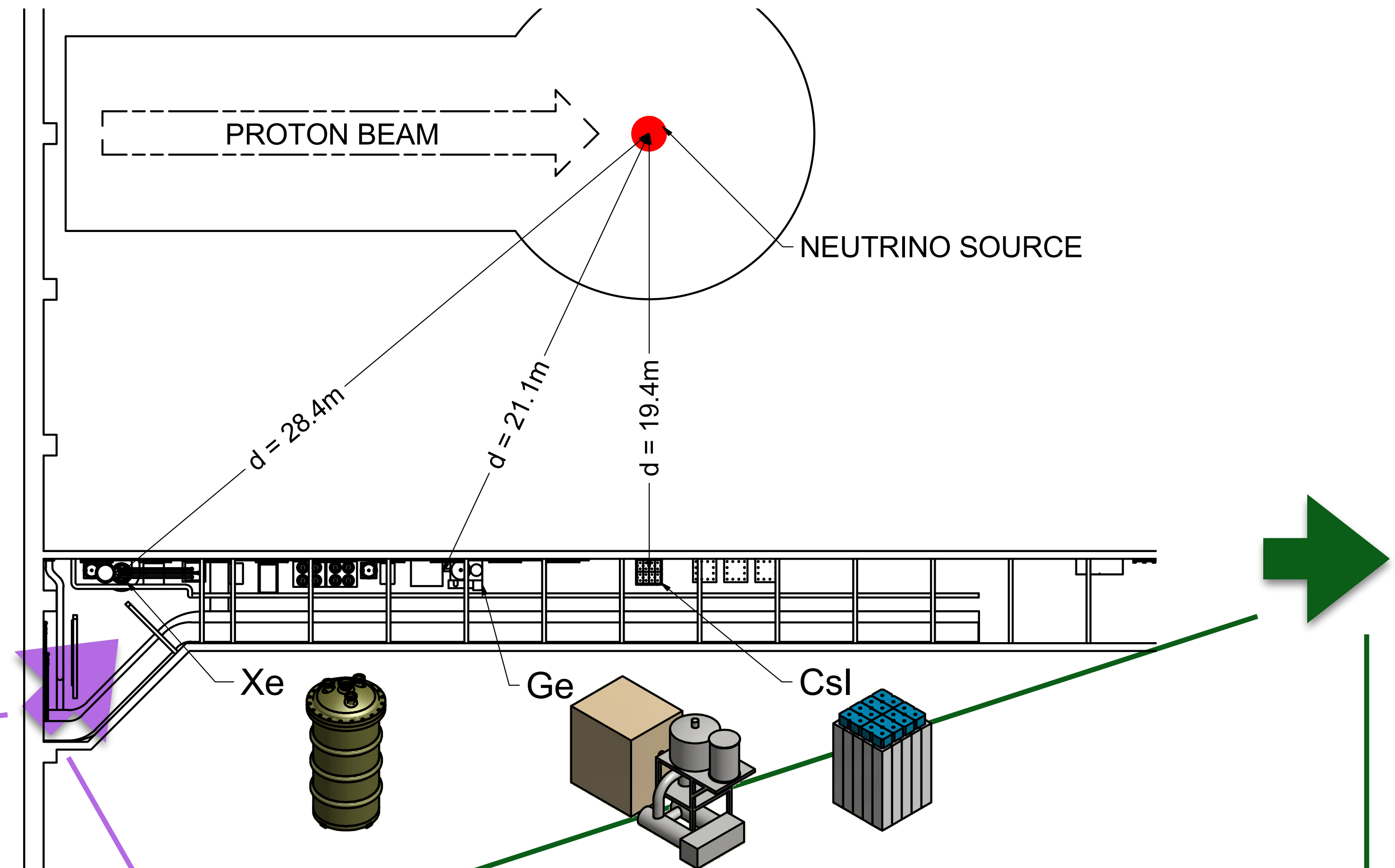
Tandem accelerator lab at TUNL

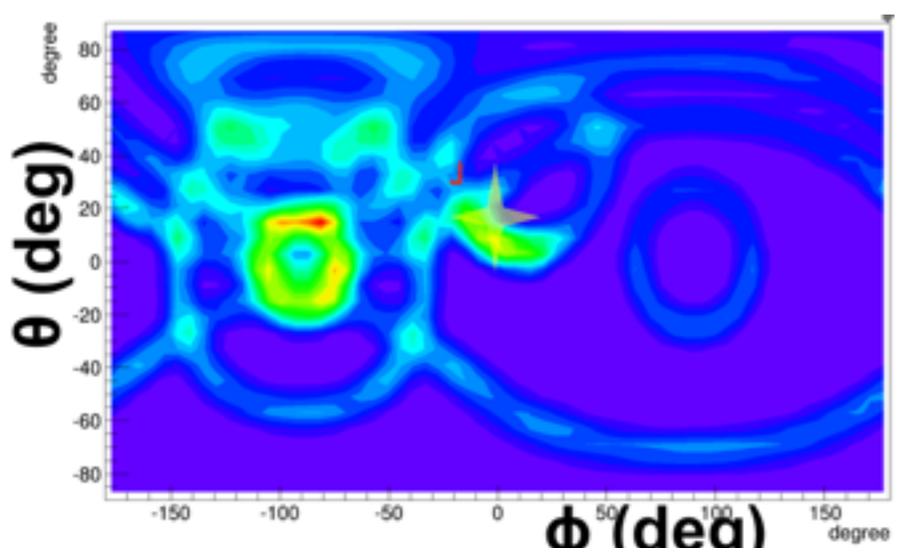


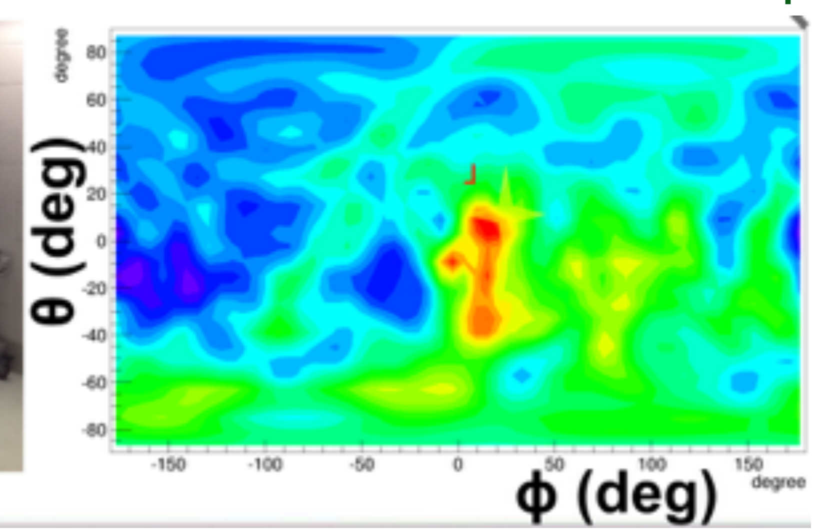
- 3 ion sources
- Beam can be bunched and chopped
- 10-MV maximum terminal voltage
- Numerous beam lines and experimental areas

Neutrons at the SNS

Sandia neutron-scatter camera has been deployed in separate basement locations

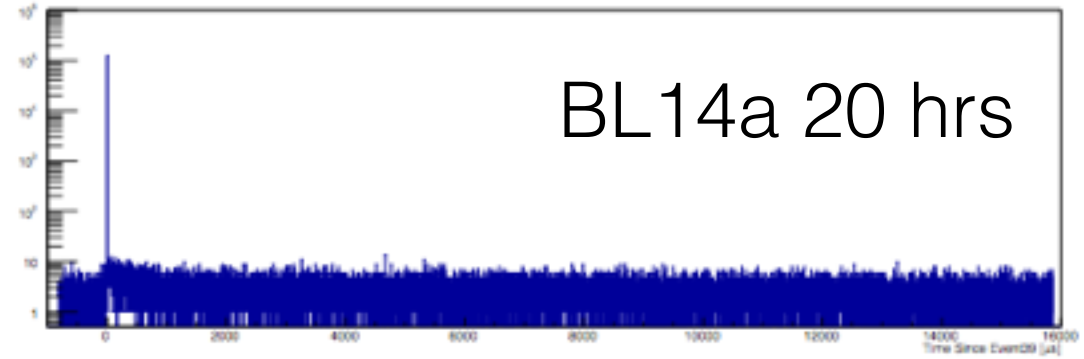




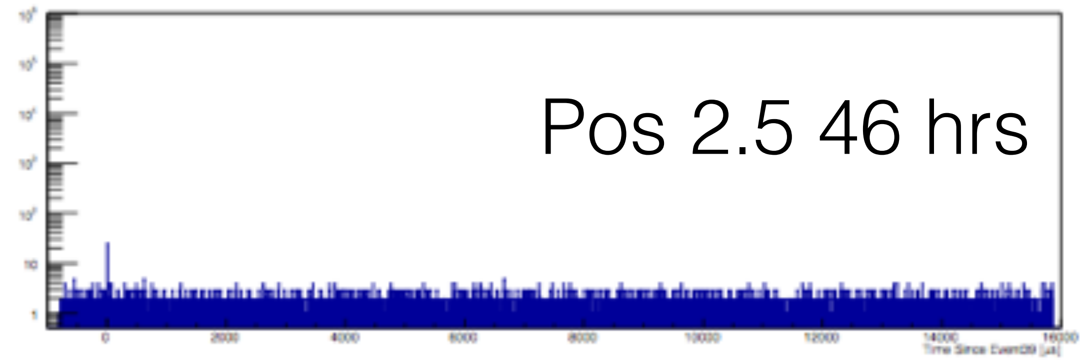


Neutrons at the SNS

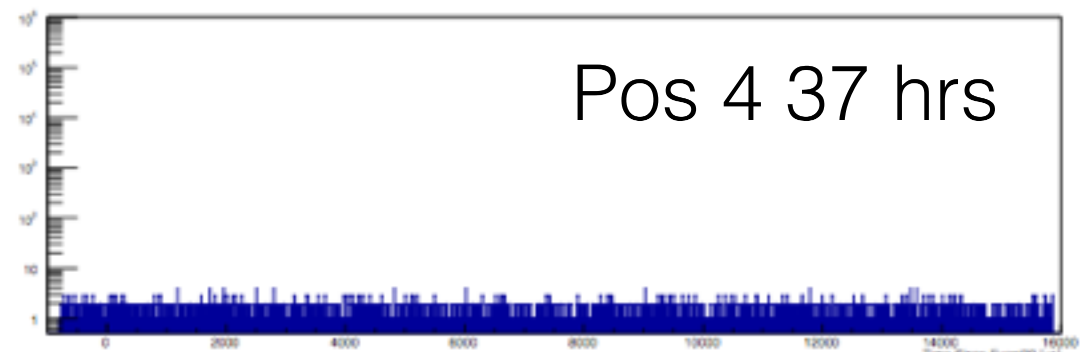
SNS instrument floor



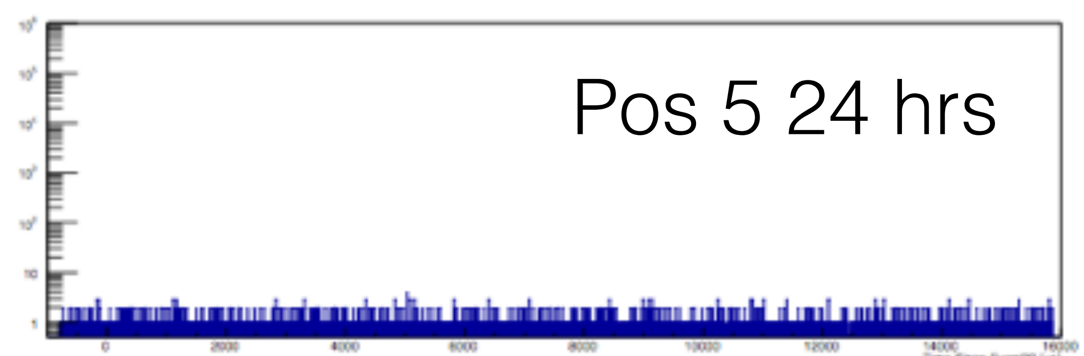
Xe



Ge



CsI(Na)



Data taken in all 3 site locations in the basement using 5-L EJ-301 LS cells

NIN measurements at the SNS

Two complementary routes within the COHERENT collaboration

Shielding assembly for CsI(Na) CEvNS detector: 2.3 tons of Pb. MCNP-PoliMi simulation suggests a ~4.4% efficiency for production of nuclear recoils in by neutrons spalled from the shield

Neutrino cubes: relatively efficient, modular design capable of holding different target materials (895 kg of lead, ~620 kg of steel, 710 kg of copper)

Both systems were installed at the SNS mid-September 2014. Located in the basement at ~20 m from the target with ~8 m.w.e. overburden

NIN measurements at the SNS: CsI(Na) shielding structure

- Lead shielding for the 15-kg CsI(Na) crystal has been moved into place at the SNS - 2.3 tons of lead

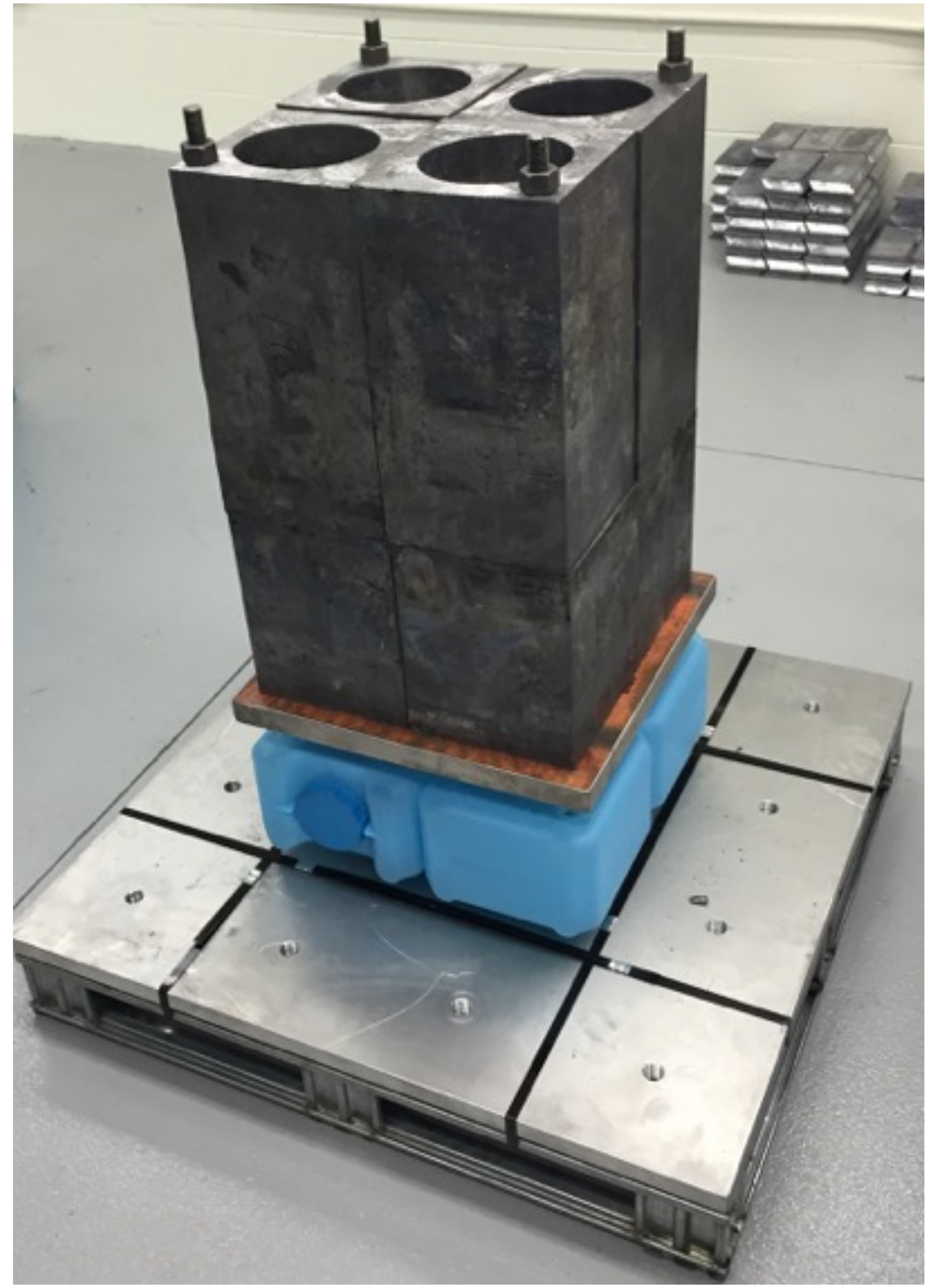
- Two liquid scintillator cells are in place within the detector cavity, allowing *in situ* measurement of gamma and neutron backgrounds for the CsI(Na) CEvNS search and an initial measurement of the NINs cross section

- MCNP-PoliMi simulation suggests a ~4.4% efficiency for production of nuclear recoils in by neutrons spalled from Pb

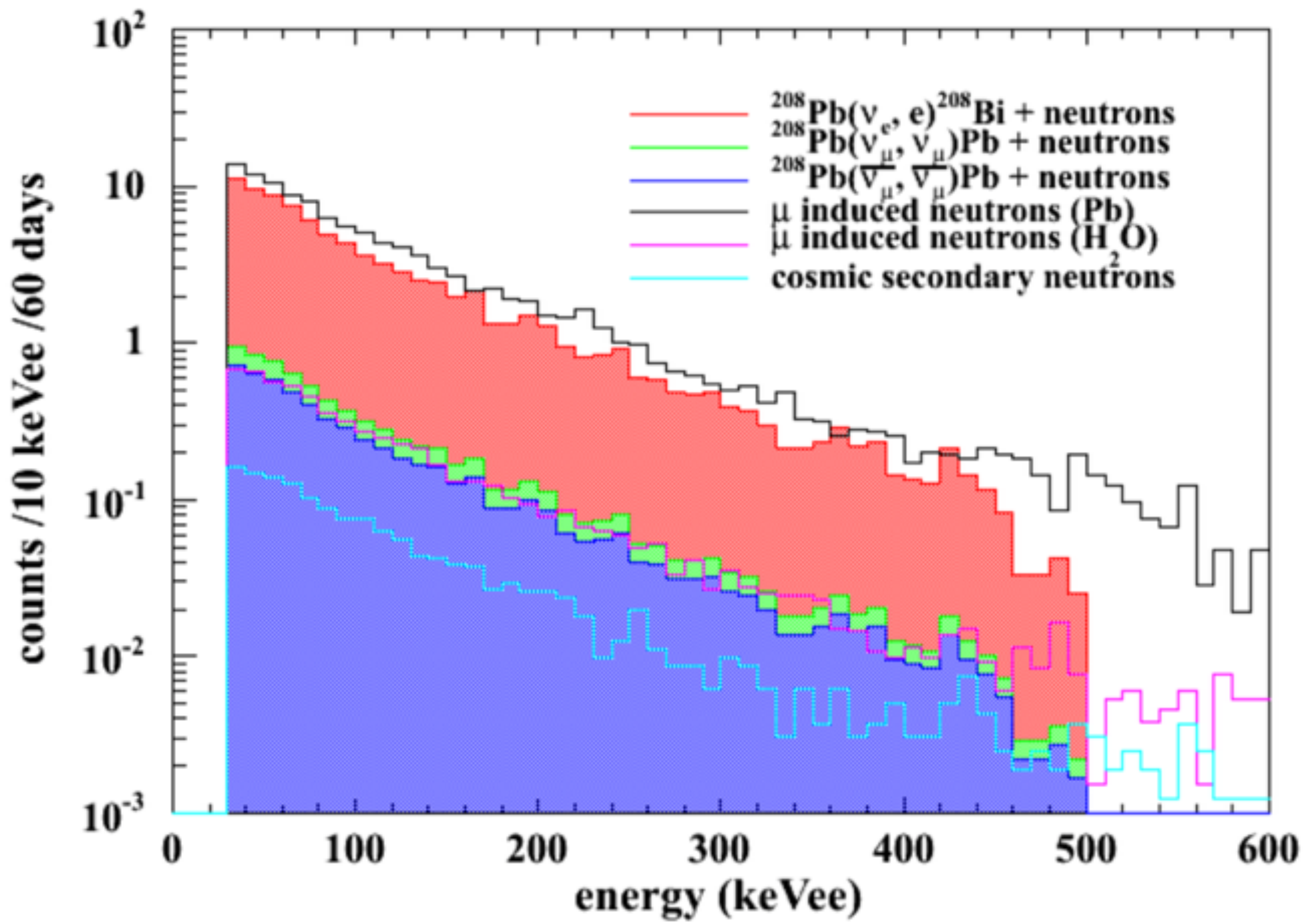
Neutrino cubes - Lead NINs

Lead target cast by Duke University Instrument Shop, total mass ~890 kg

Neutrino cubes - Lead NINs



NIN measurements at the SNS: Neutrino cubes with lead

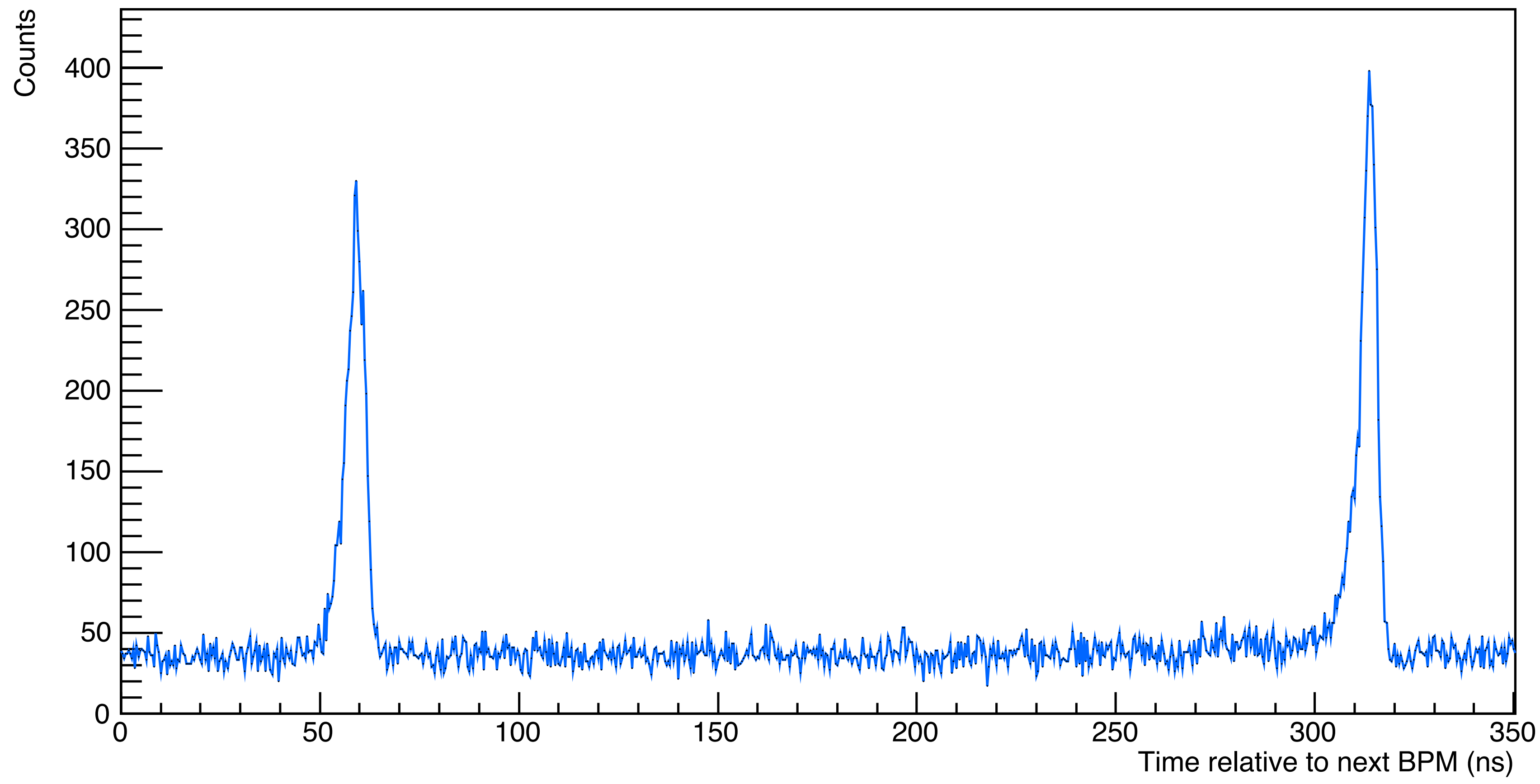


Initial MCNP simulations of the neutrino-cube geometry account for anticipated sources of background neutrons and NINs: many of the interactions result in low-energy (< 100 keVee) recoils in the scintillator, so a low threshold is important to maximize count rate

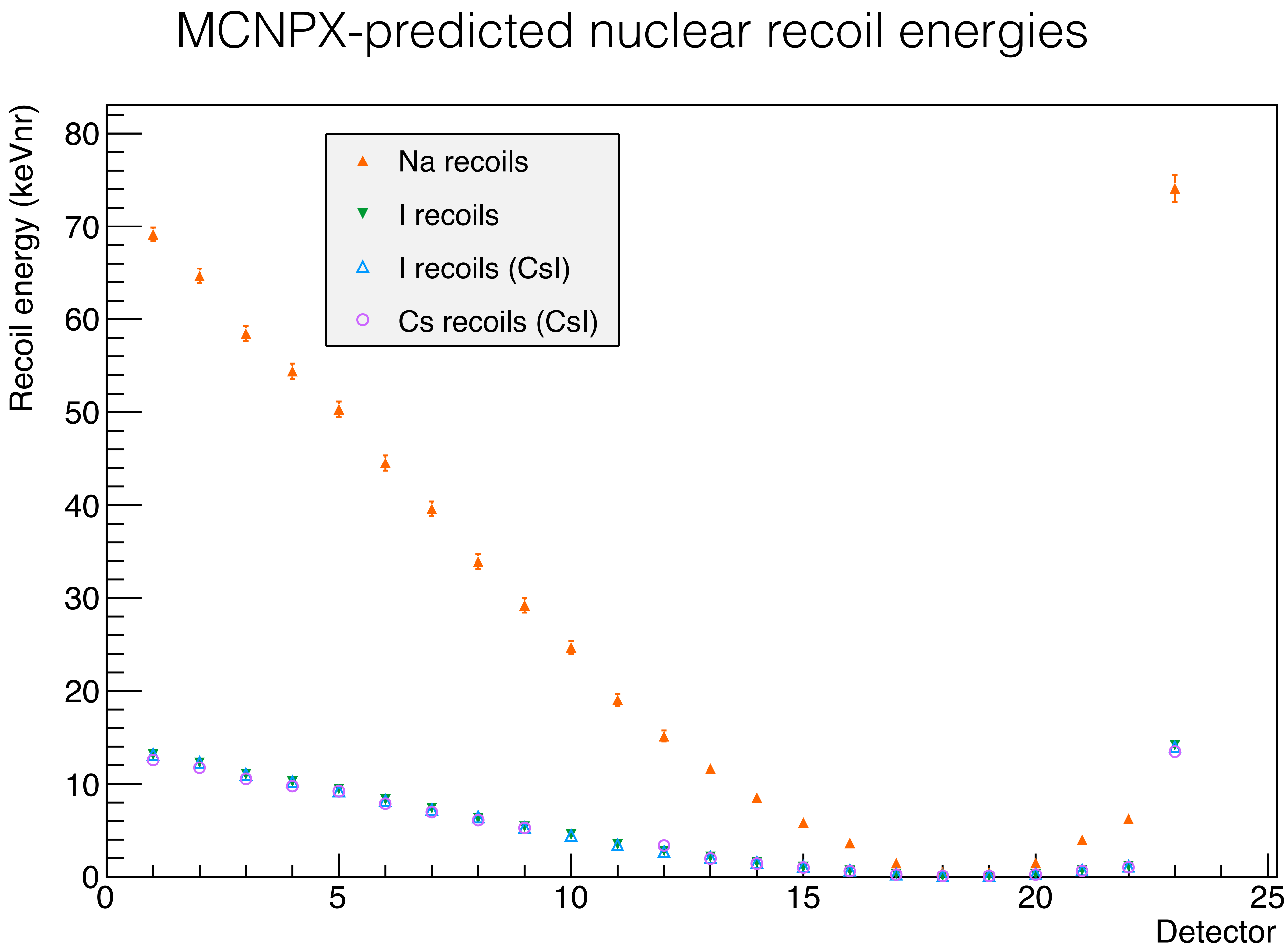
Neutron beam characteristics

- Neutron energy and its resolution at 0 degrees can be reliably confirmed using TOF

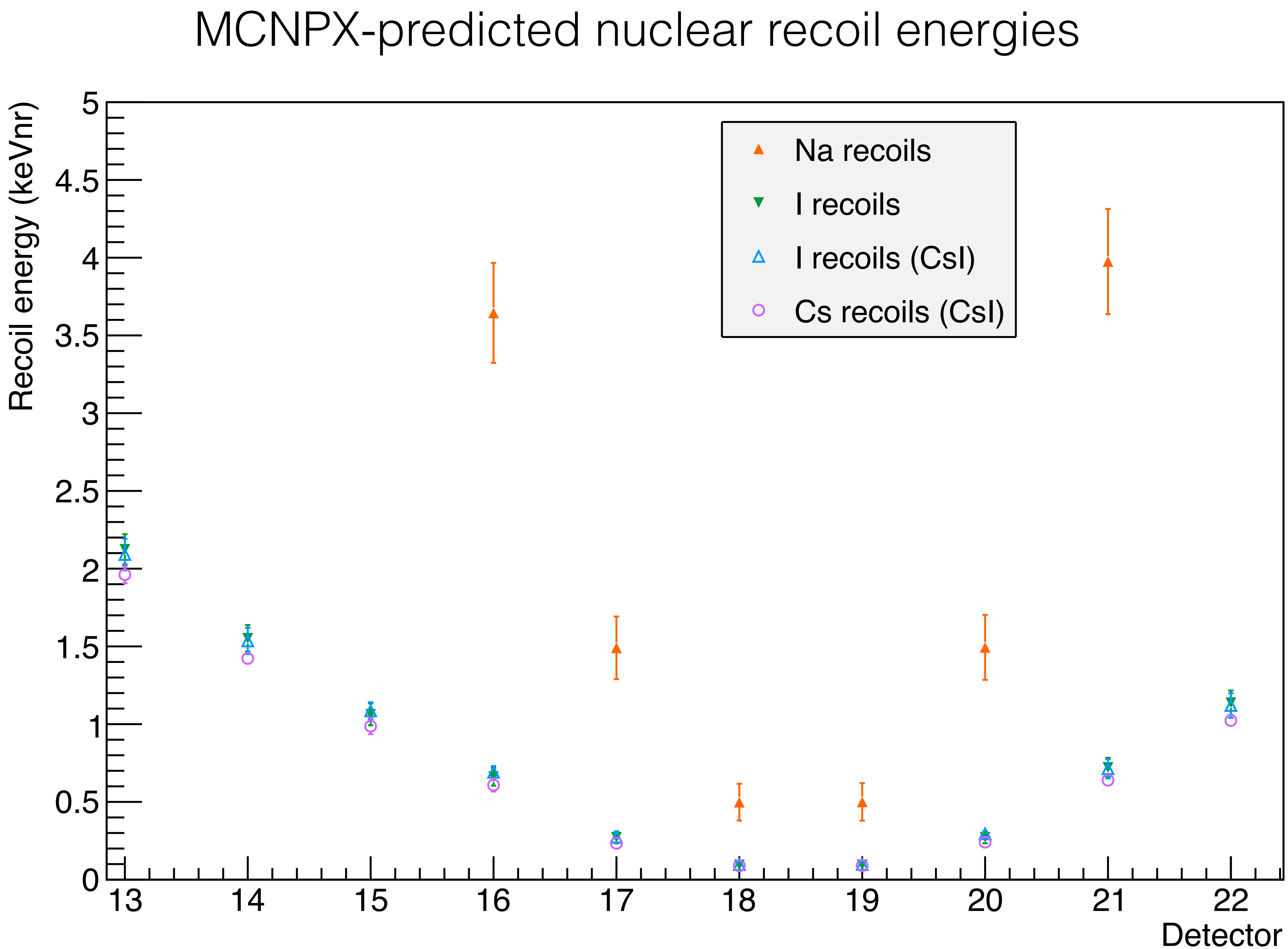
- Beam bursts are well contained in time (~10 ns)



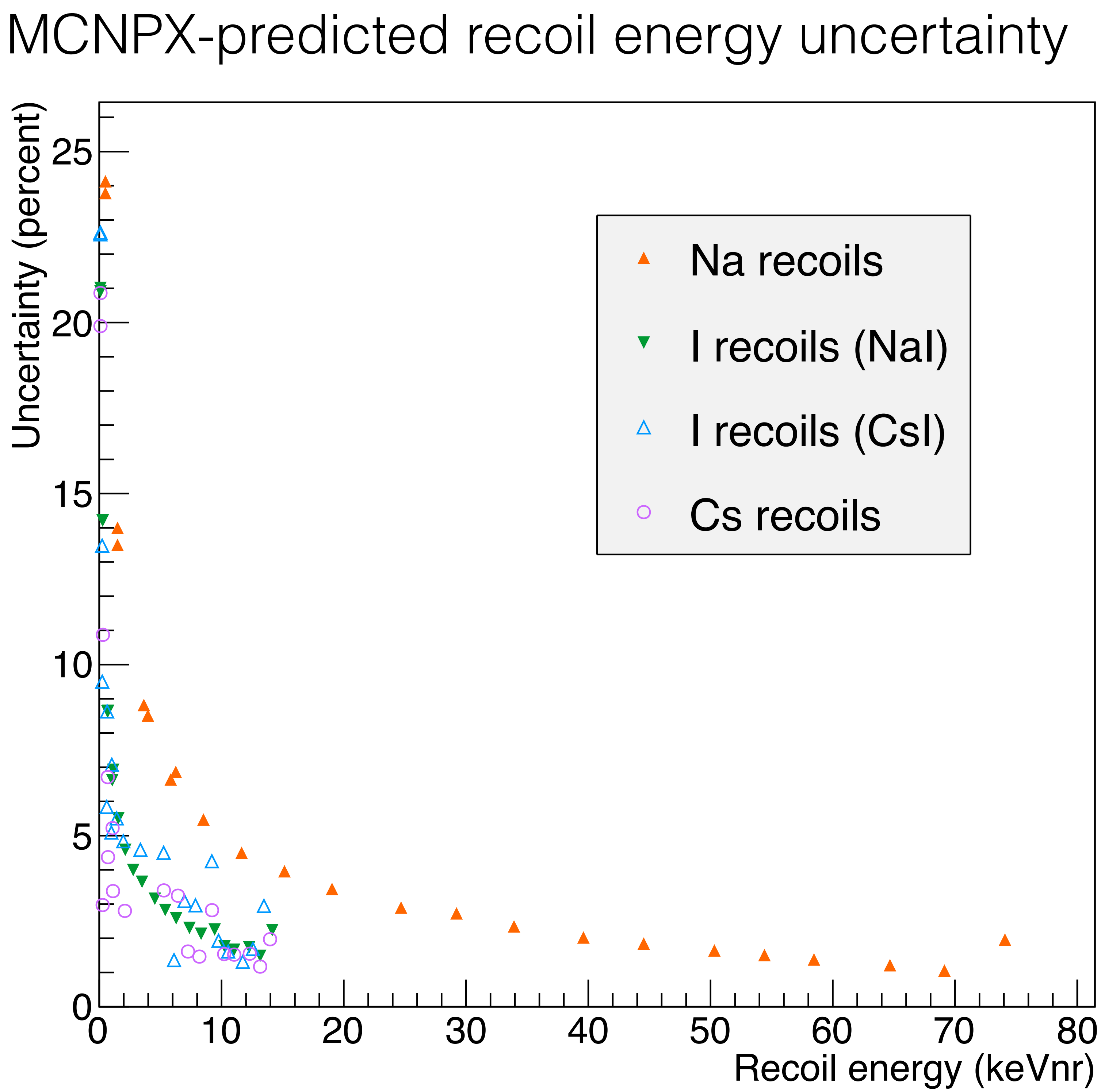
NaI(Tl) and CsI(Na) calibrations



NaI(Tl) and CsI(Na) calibrations

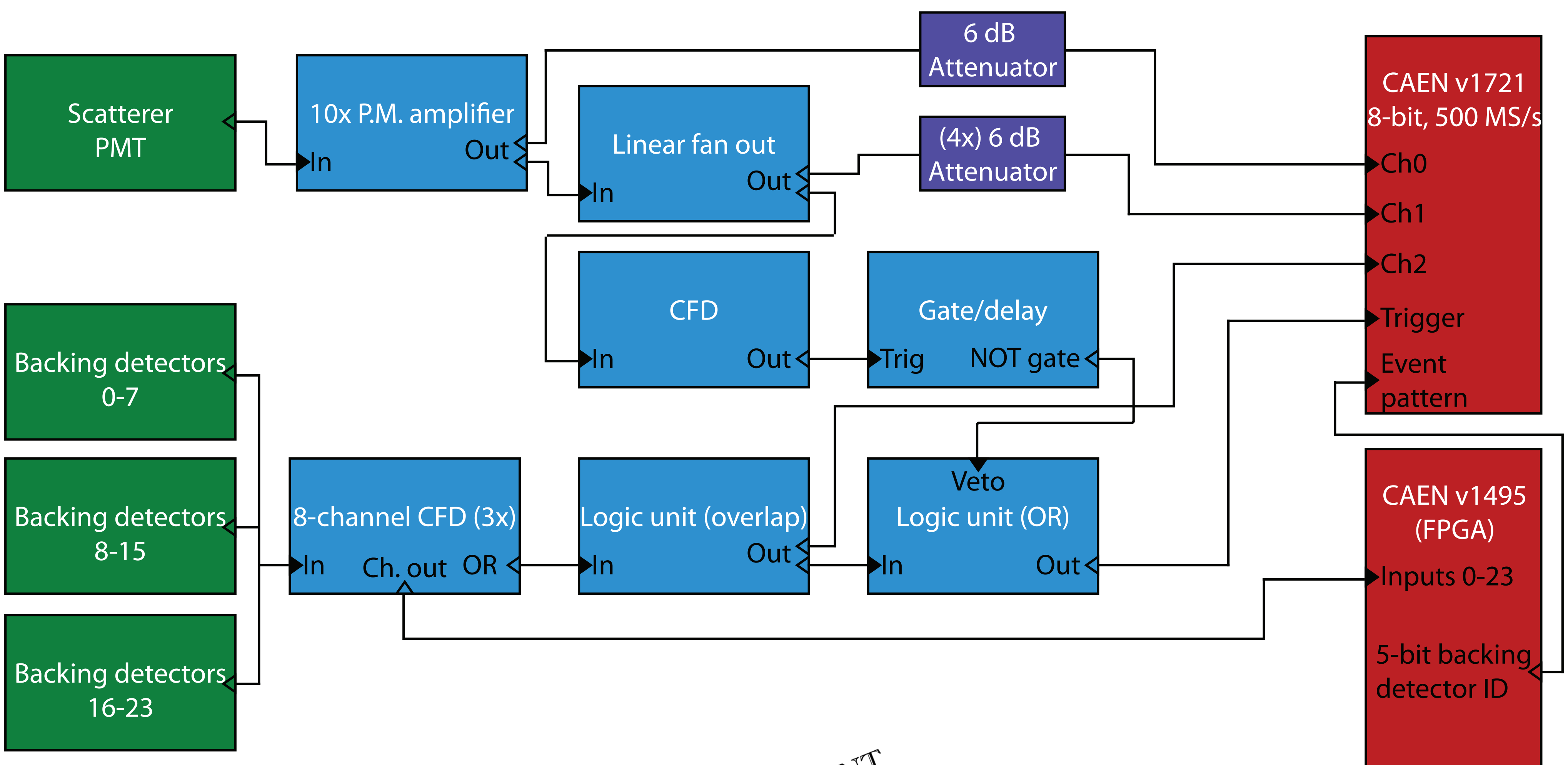


NaI(Tl) and CsI(Na) calibrations

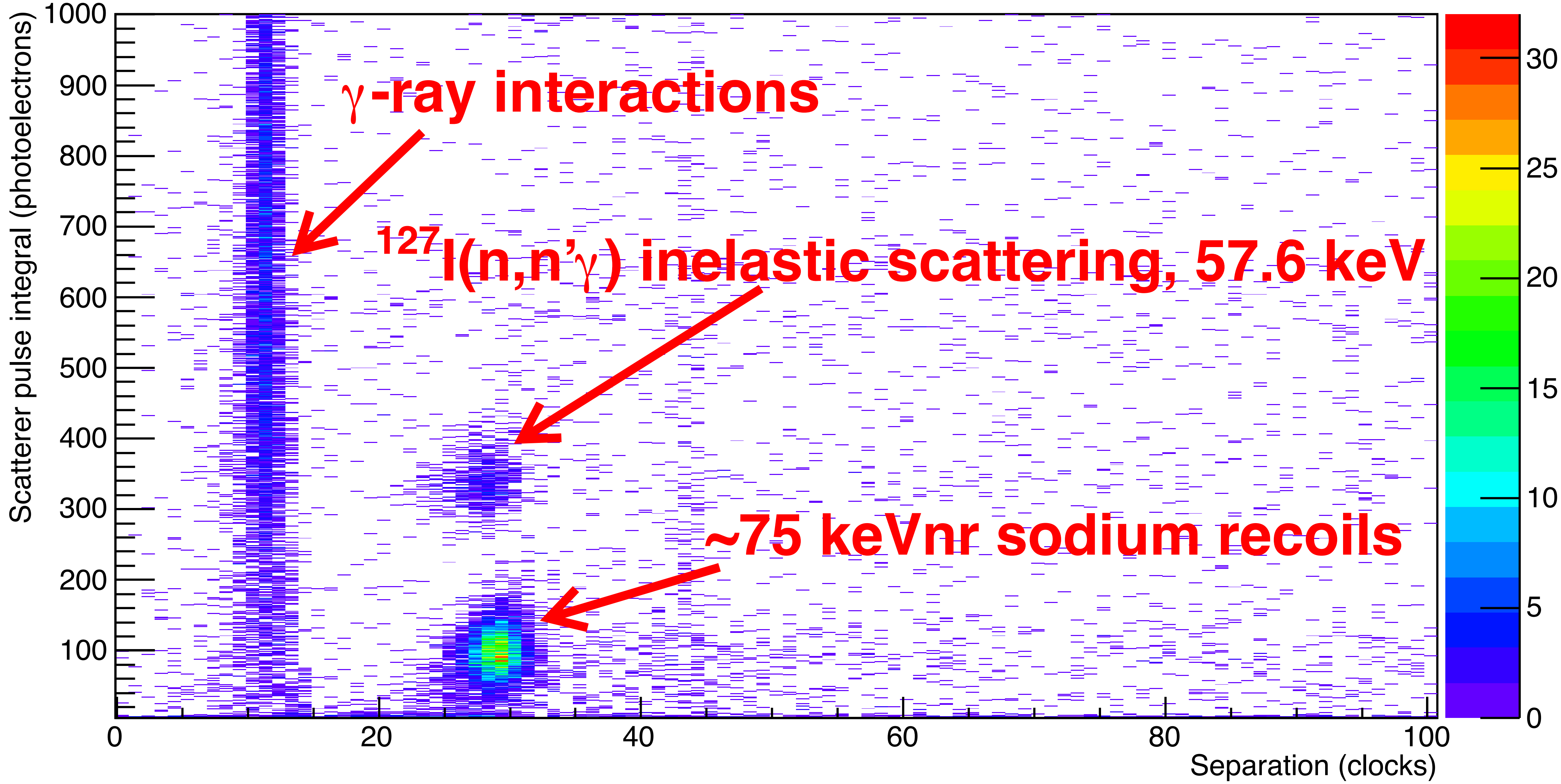


Electronics and DAQ

- Backing detector signals are not individually digitized (reduces data rate); only the OR of the backing detector CFDs is recorded
- FPGA generates a bit pattern which encodes the ID of the backing detector causing a trigger; this pattern is saved by the digitizer and associated with each event



Initial results with NaI(Tl)

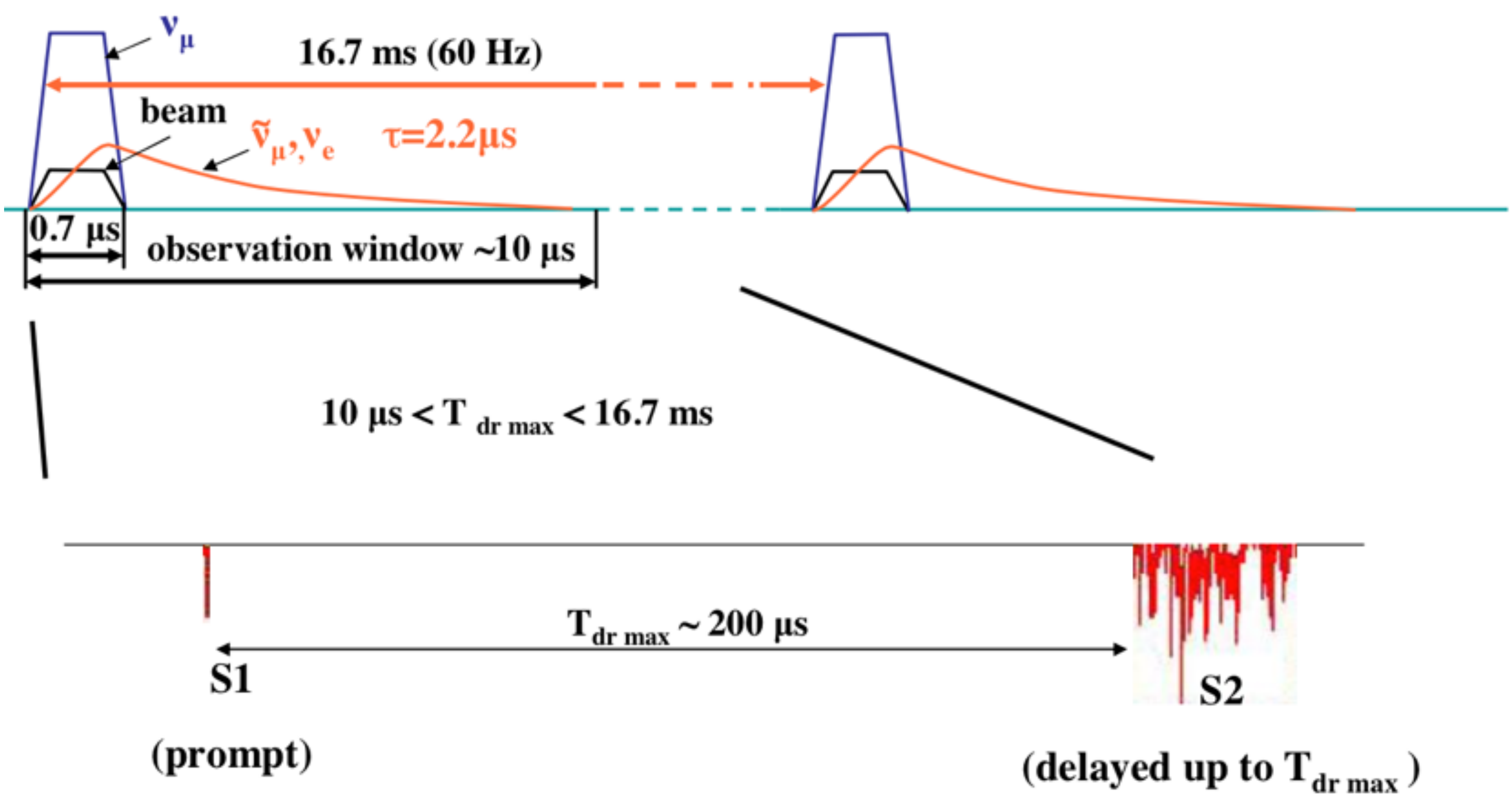


- Events triggered by high-angle backing detector, close geometry

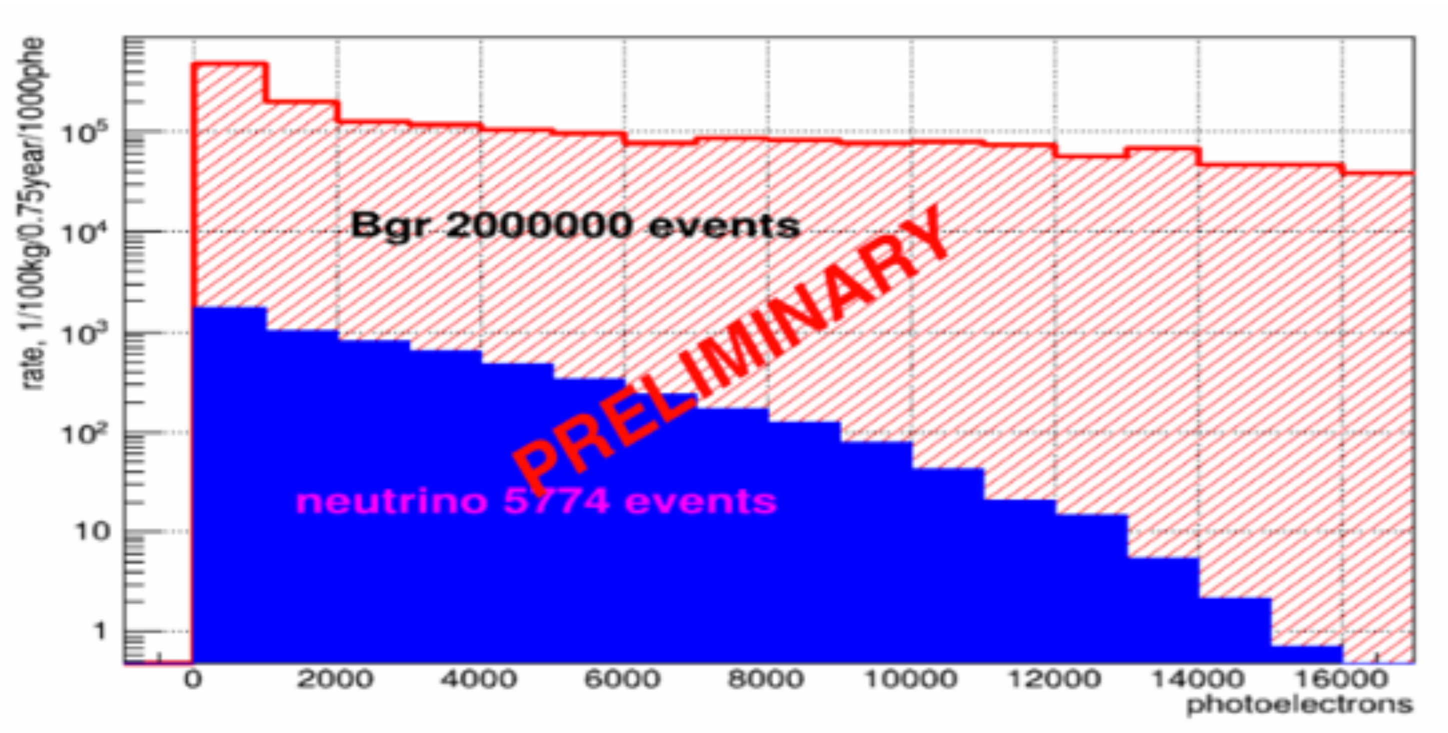
The right place and the right time

SNS timing characteristics can be exploited to dramatically reduce steady-state backgrounds

Example with RED-100: a 10-us window after beam pulse to detect S1 means a duty-factor of 1/1600

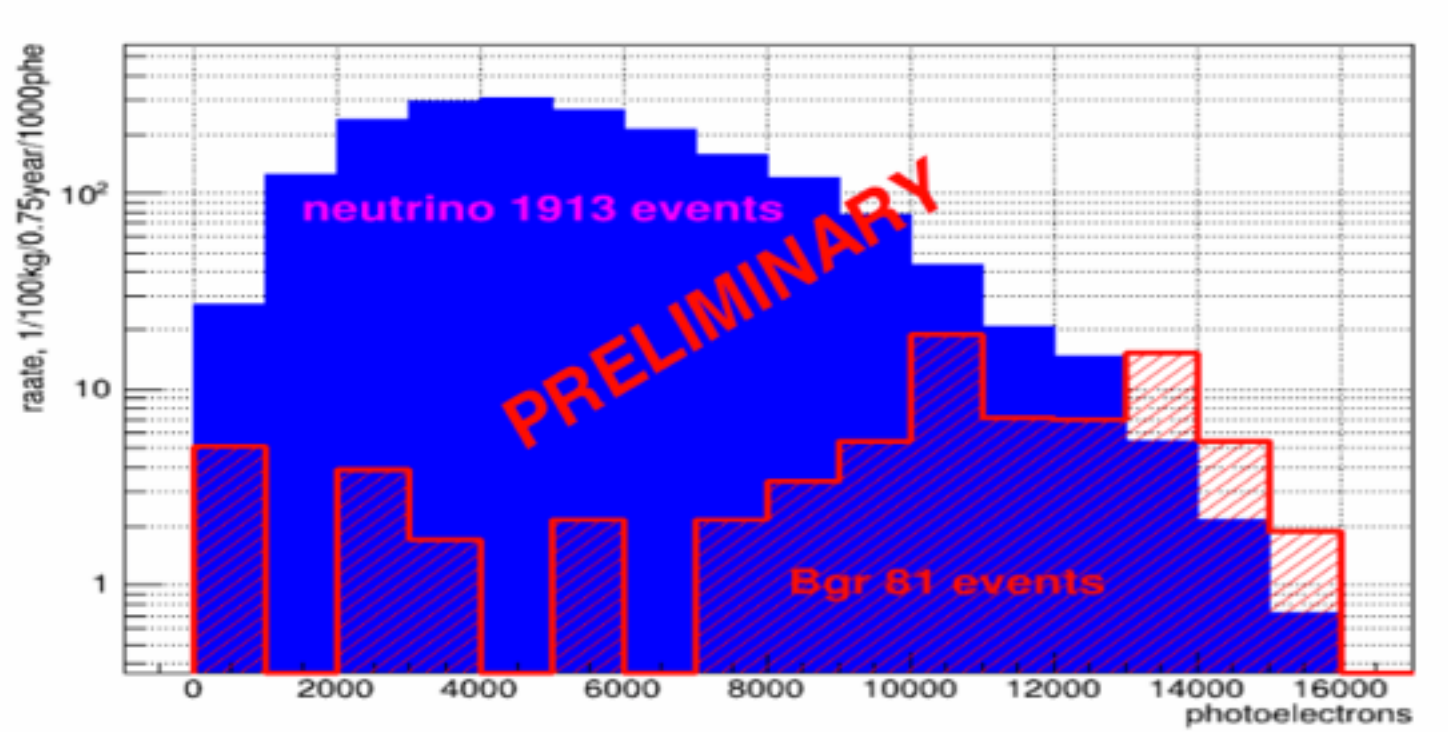


The right place and the right time



Benefit of timing cut is highlighted here for gamma backgrounds from cryostat in RED-100

No timing or energy cut



1/1600 duty factor applied and S1 > 2 phe