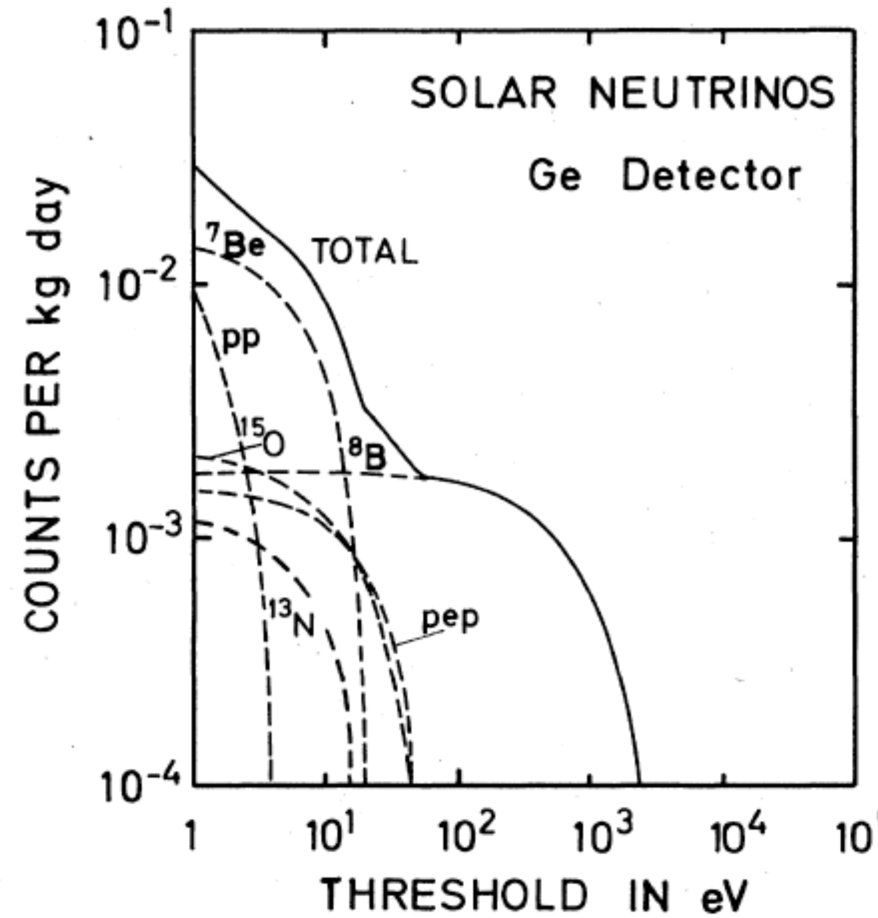
Recoils from Neutrinos: past, present, future

P. S. Barbeau & G. C. Rich for the COHERENT collaboration

A Historical Perspective

- D.Z. Freedman. “Coherent effects of a weak neutral current.” Phys. Rev. D9, 1389 (**1974**).
- A. Drukier and L. Stodolsky “Principles and applications of a neutral current detector for neutrino physics and astronomy.” Phys. Rev. D30, 2295 (**1984**).
- B. Cabrera, L. Krauss, F. Wilczek, “Bolometric Detection of Neutrinos.” Phys. Rev. Lett. 55, 25 (**1985**)

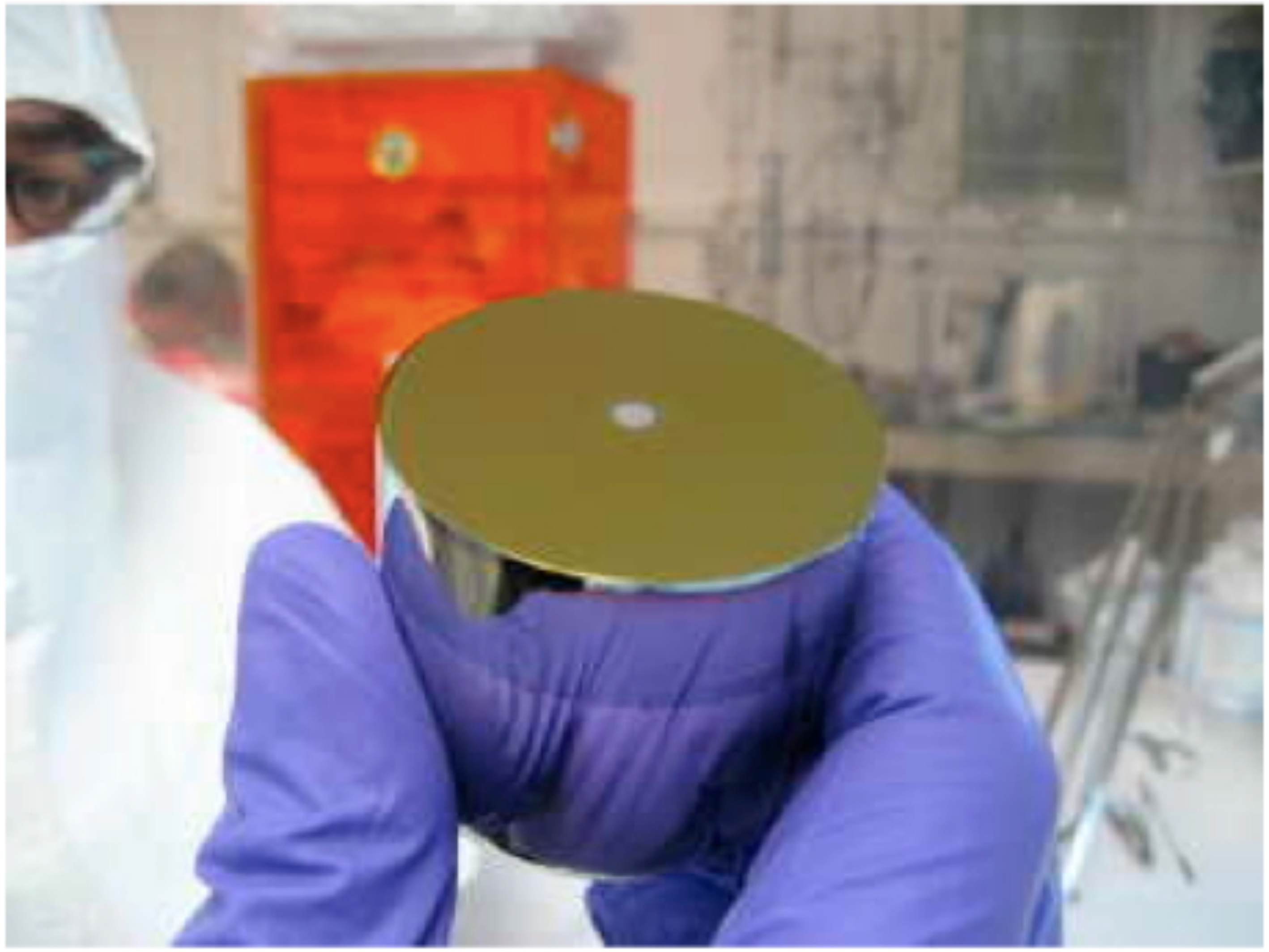
"We propose new detectors for bolometric measurement of low-energy ν interactions, including coherent nuclear elastic scattering. A new and more sensitive search for oscillations of reactor antineutrinos is practical (~100 Kg of Si), and would lay the groundwork for a more ambitious measurement of the spectrum pp, Be7 and B8 solar ν’s, and supernovae anywhere in our galaxy (~10 tons of Si).”



CoGeNT History

- CoGeNT: Coherent Germanium Neutrino Technology

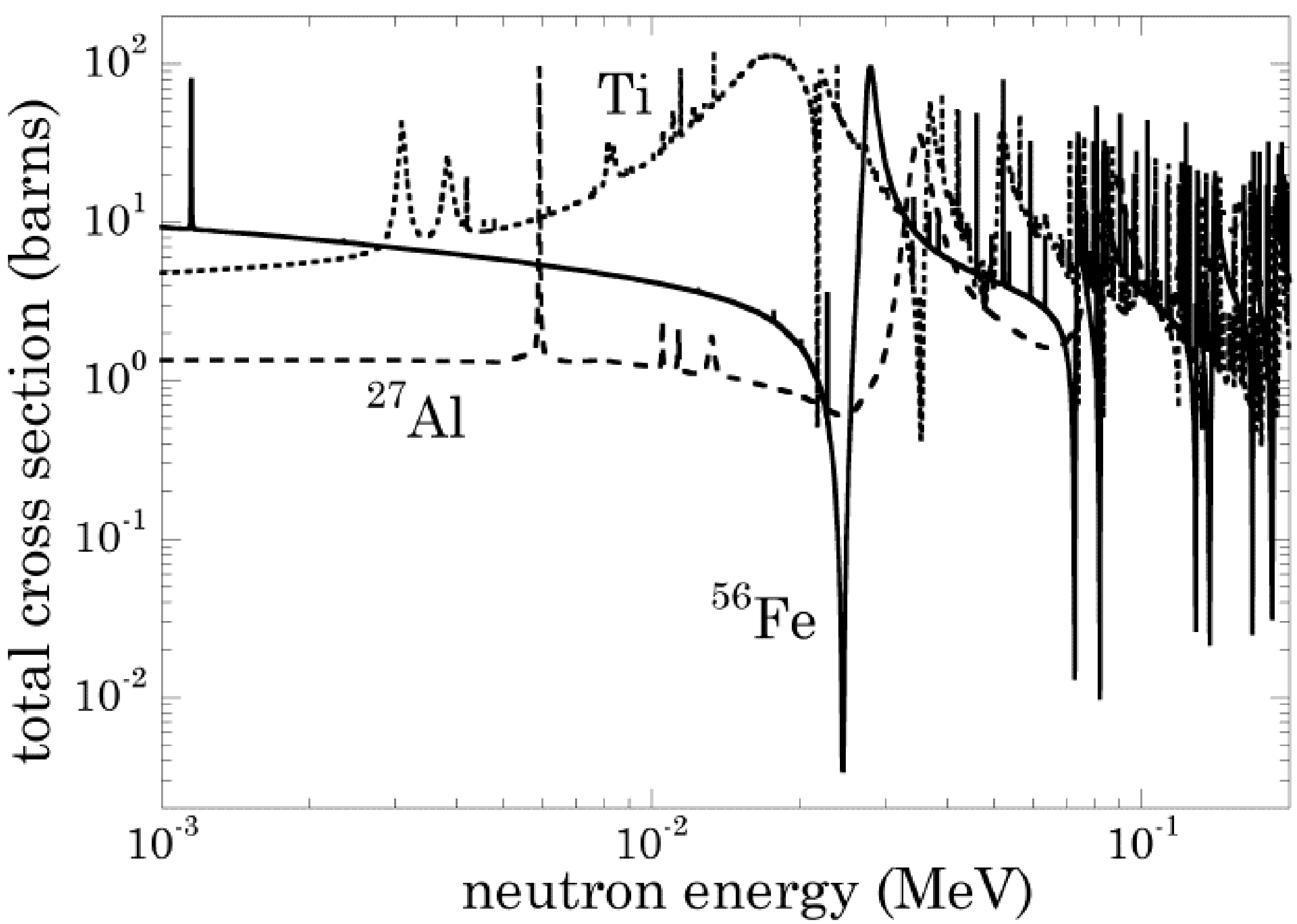
- The original intention of these low threshold detectors was a measurement of the coherent neutrino scattering cross-section at the SONGs reactor.

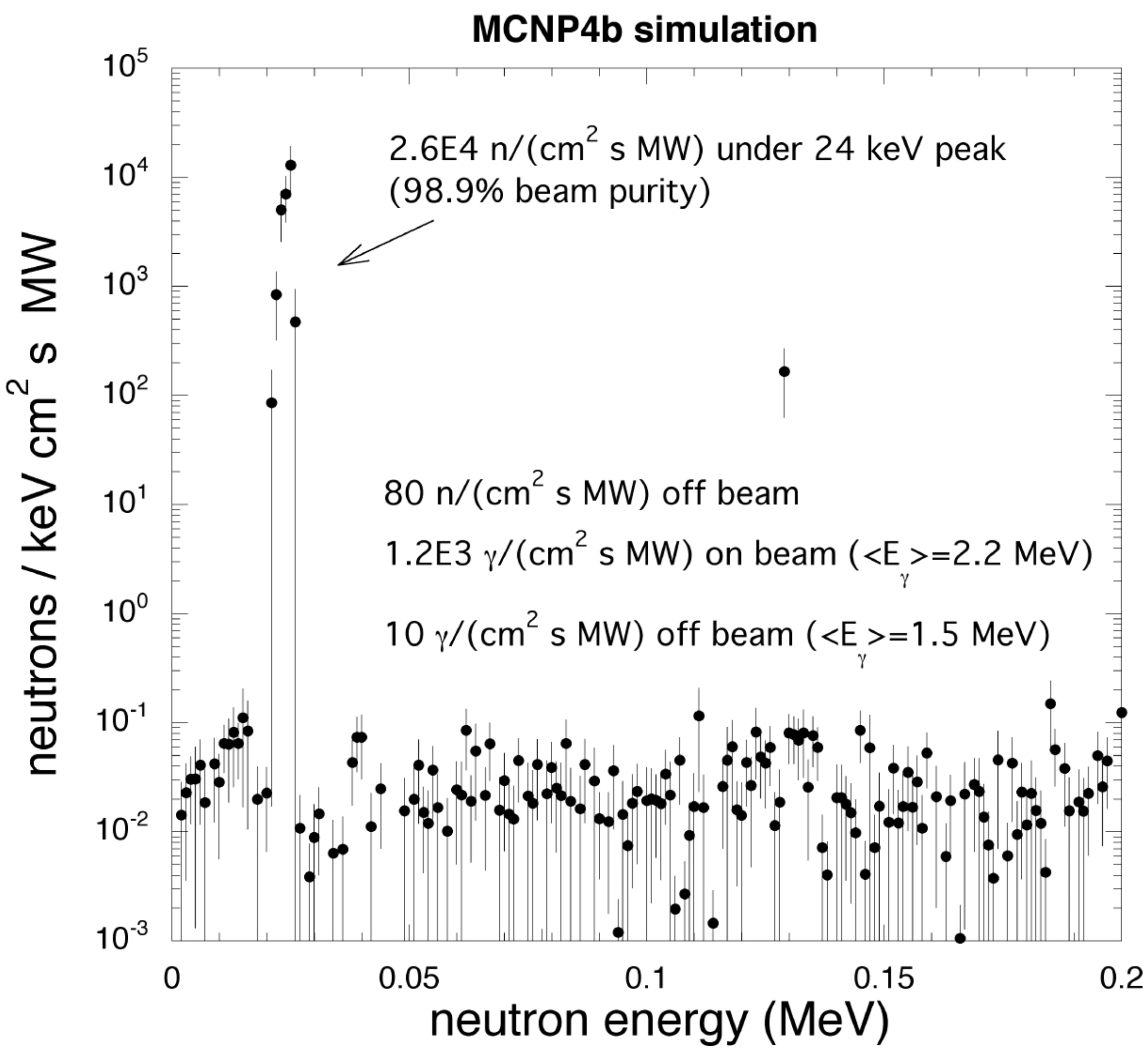


First Things First

- Before any deployment of this detector, we spent 3 years developing a facility that was capable of calibrating these detectors

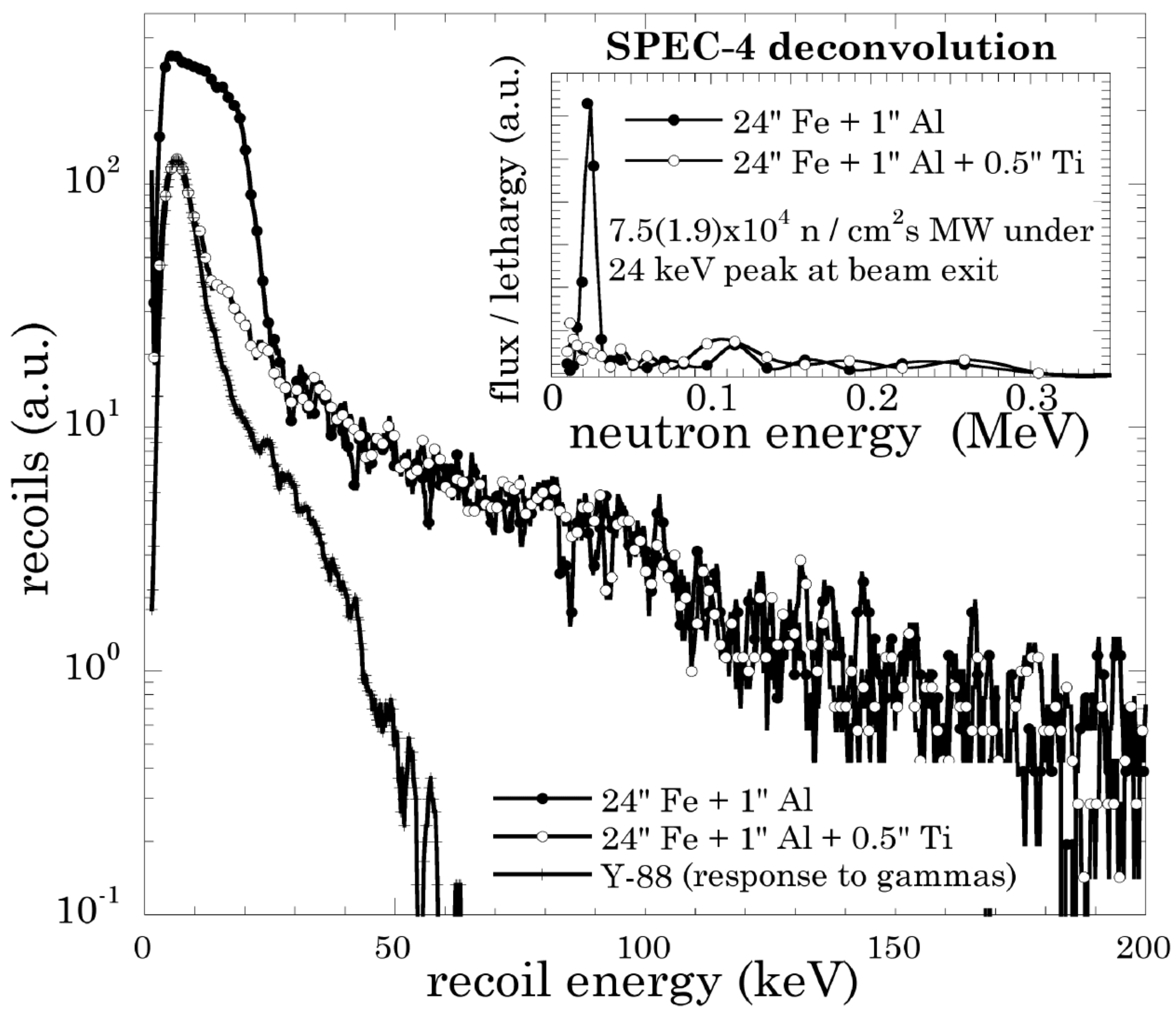
- **24 keV neutron beam** at the KSU Triga Reactor

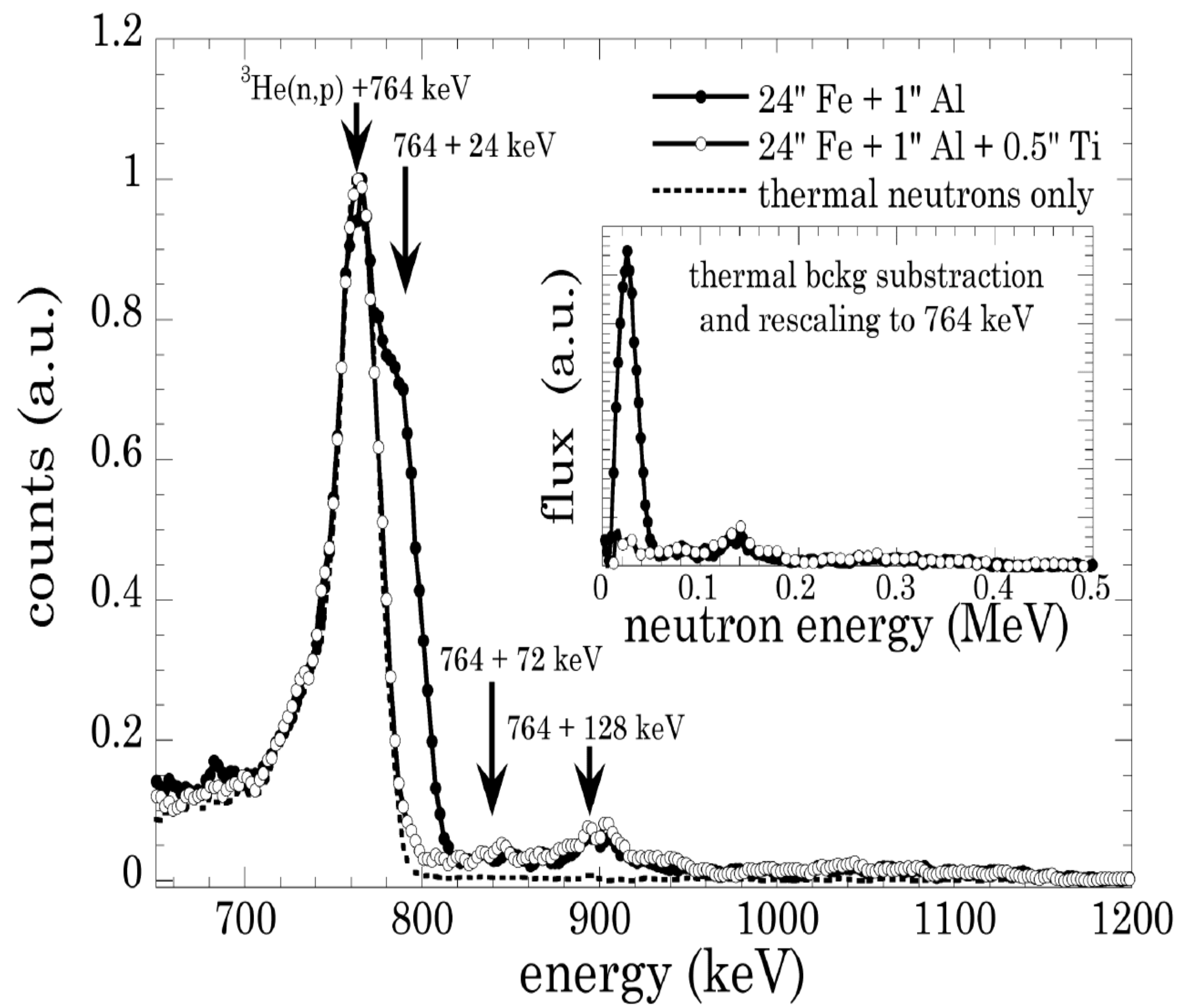




First Things First

- Thorough characterization of the beam with multiple detector technologies

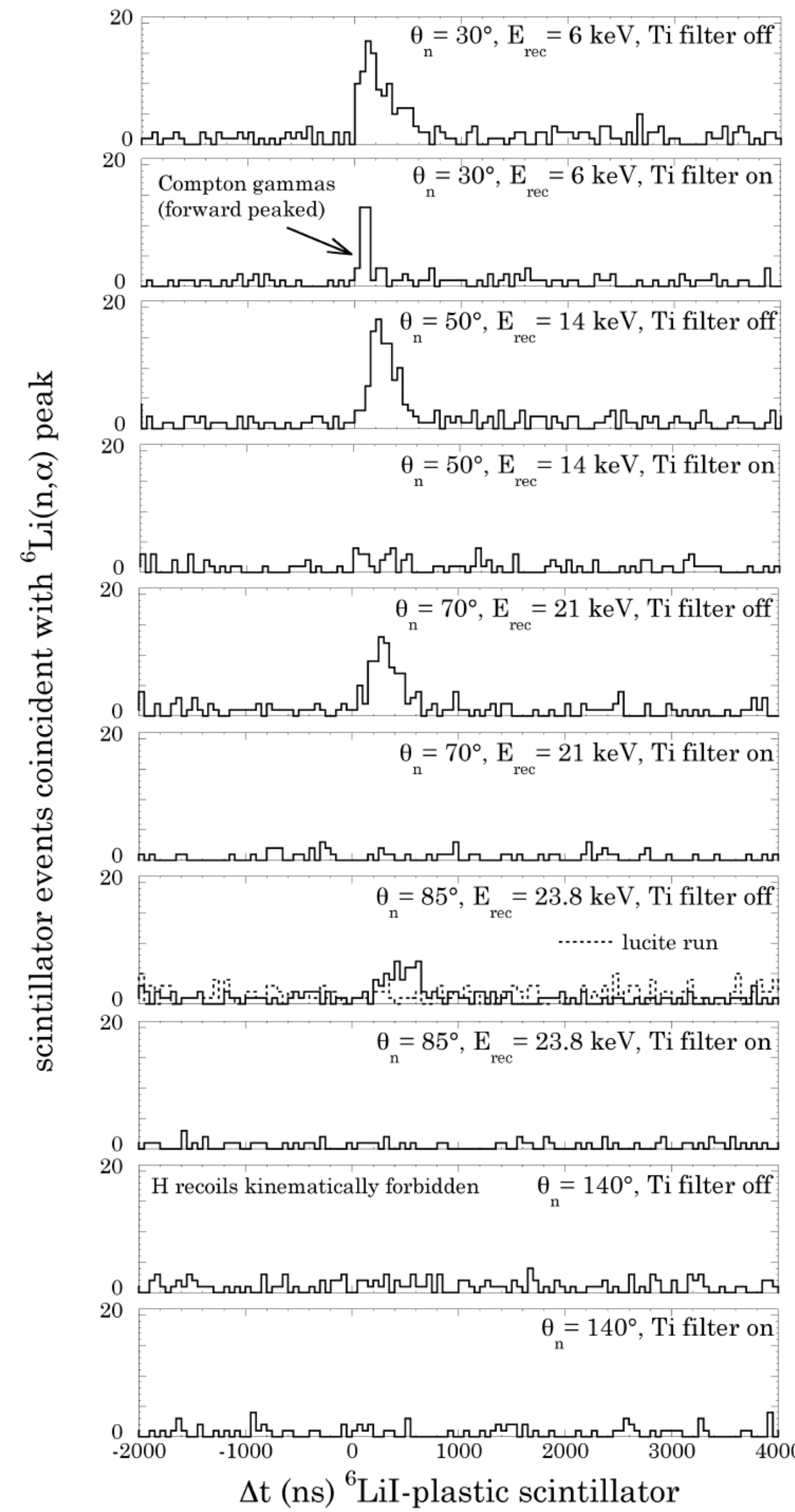




First Things First

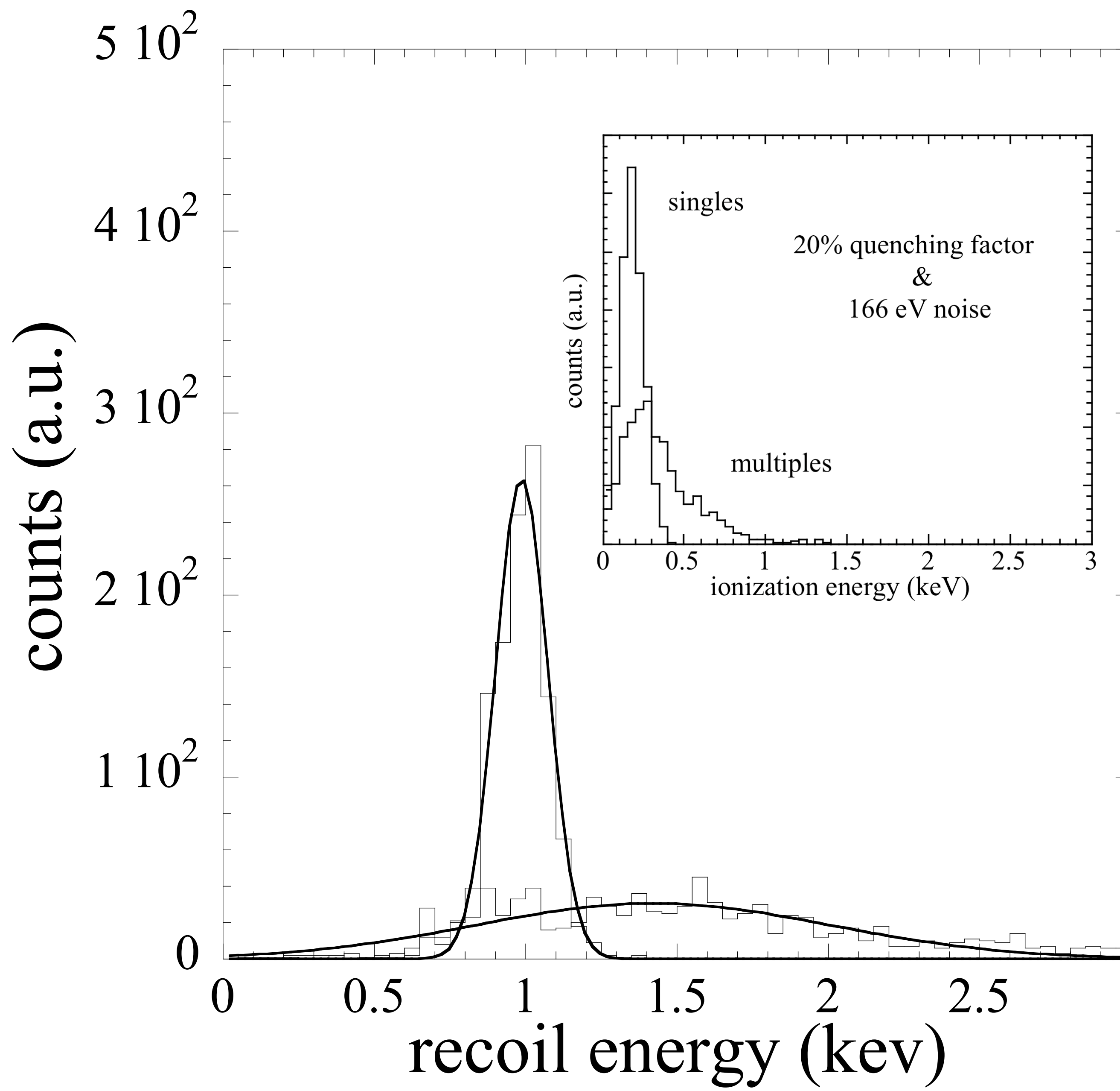
- Repeated MACRO experiment with plastic scintillator

Backing detector: ^{6}LiI[Eu]



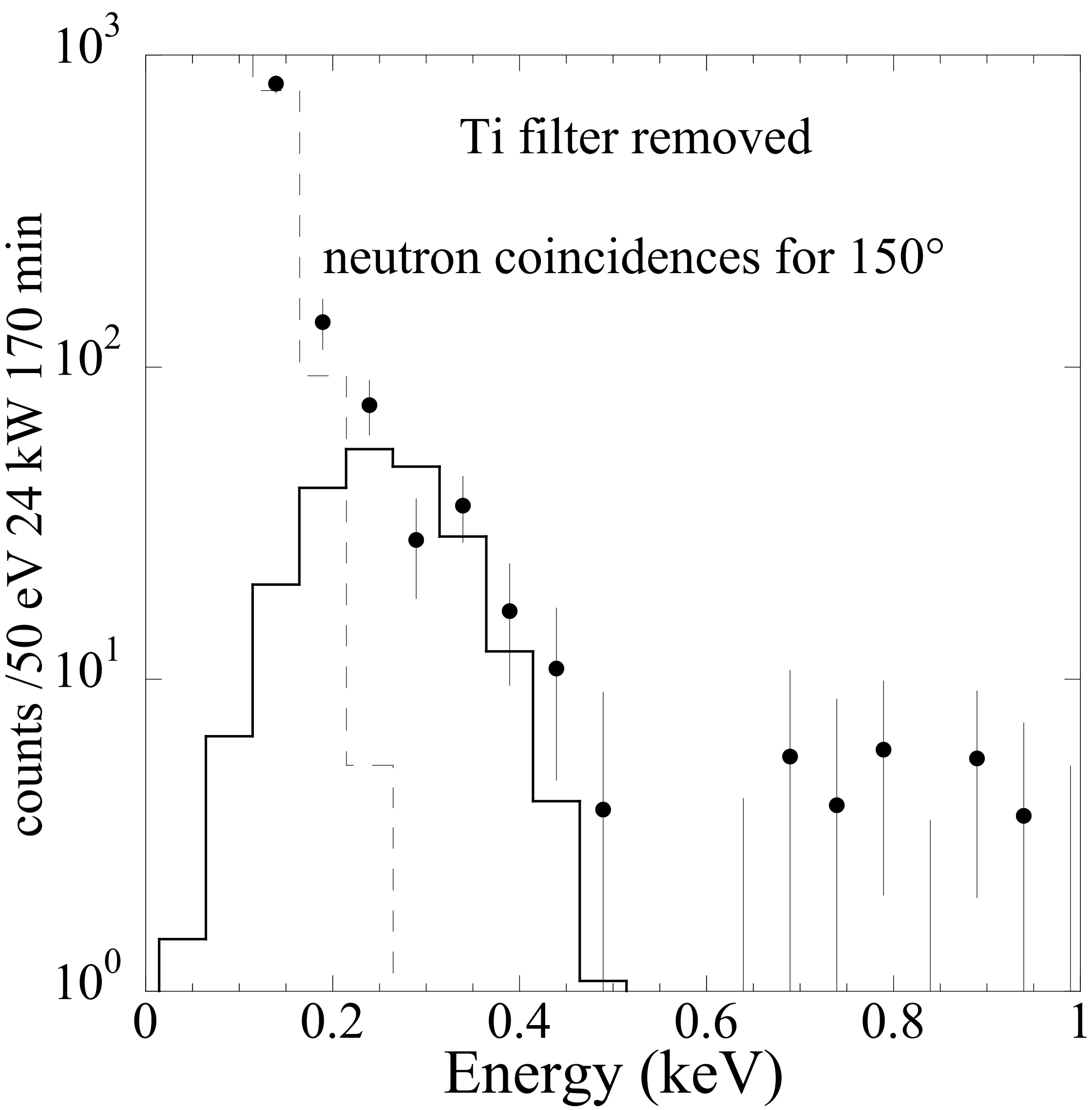
Calibration of the Detector

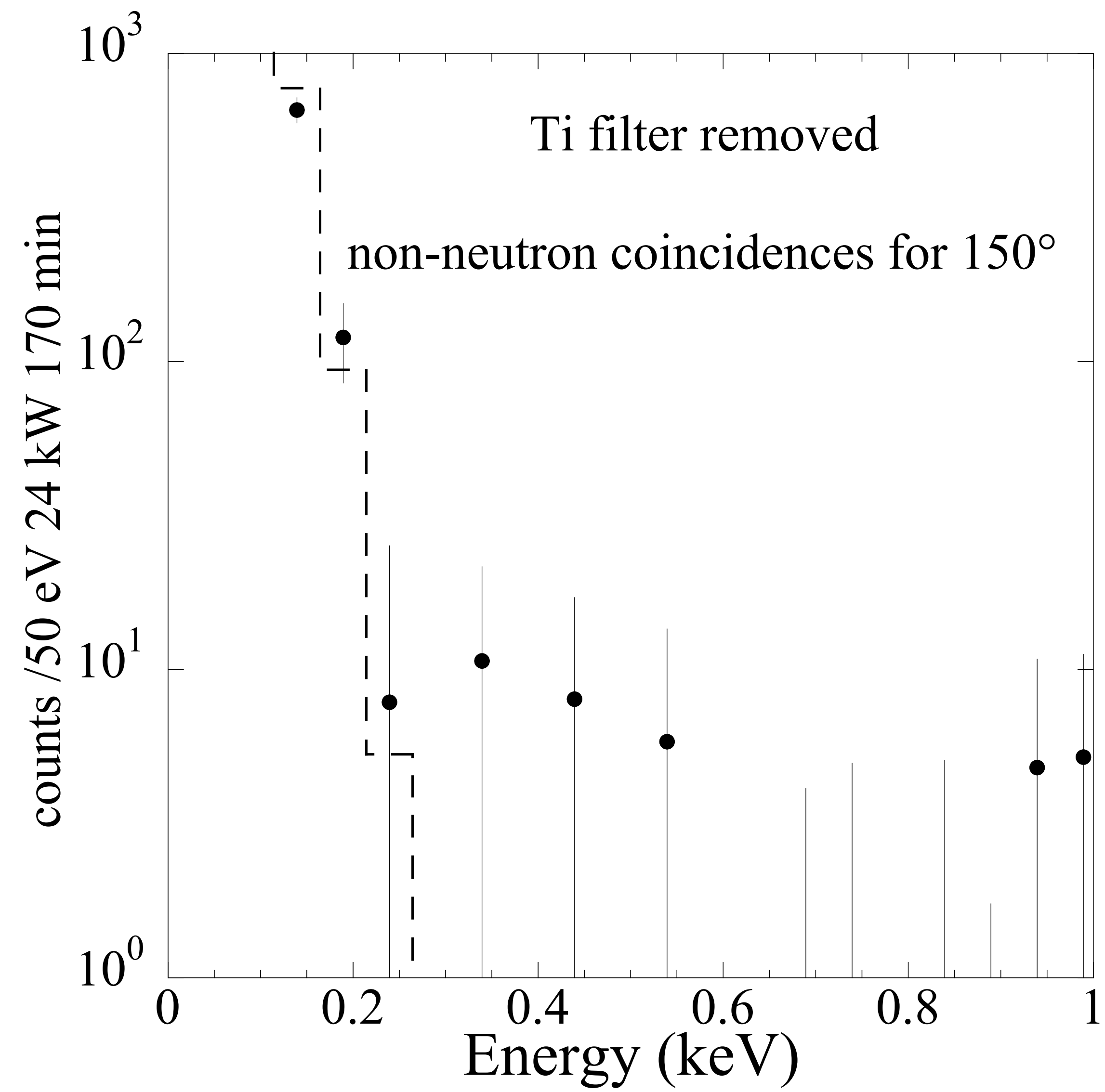
- The dominant uncertainty was due to multiple scattering in 450g detector



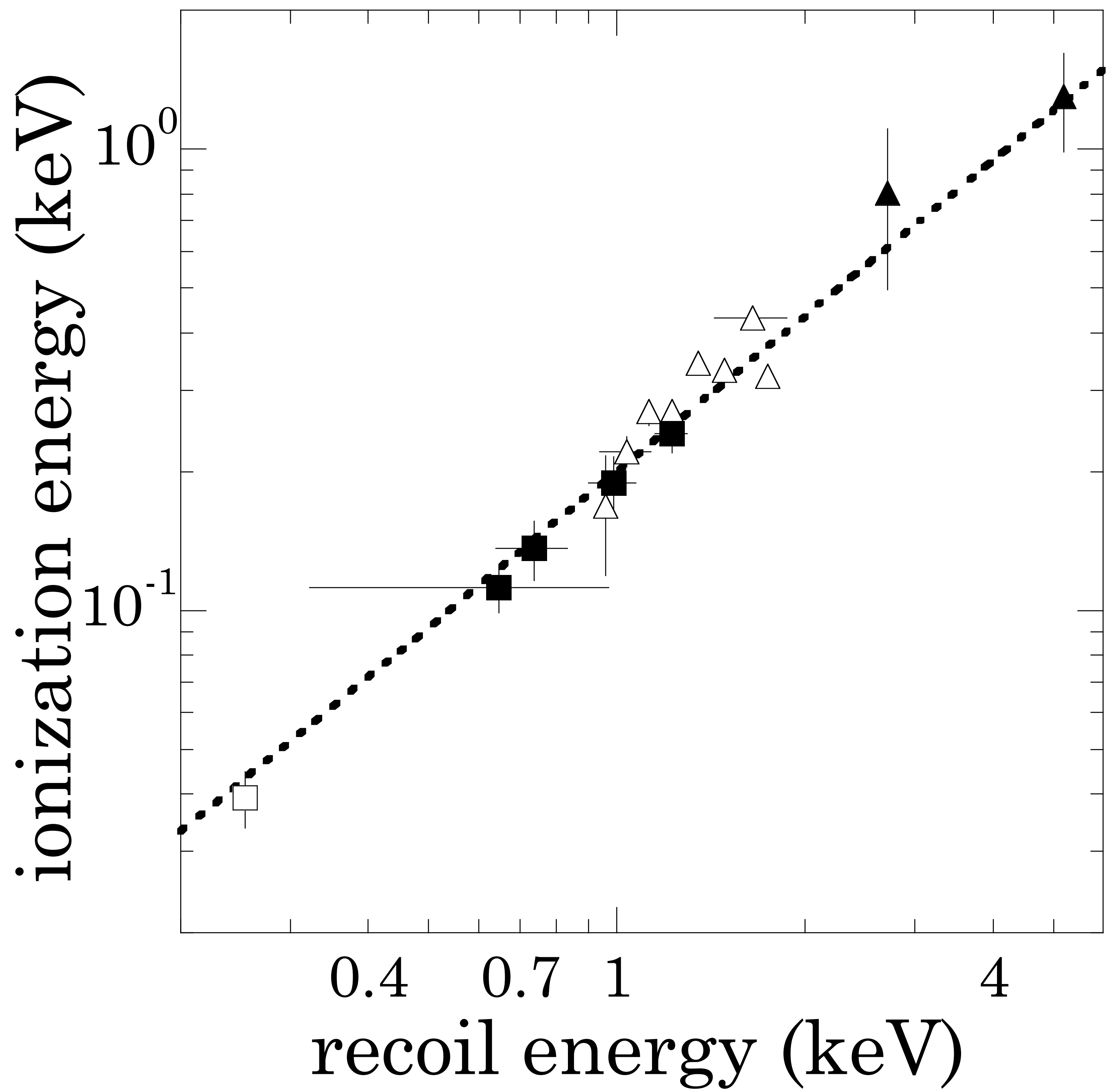
Calibration of the Detector

- Accidental backgrounds from environmental gammas, and spurious neutron recoils are subtracted by measuring anti-coincident events

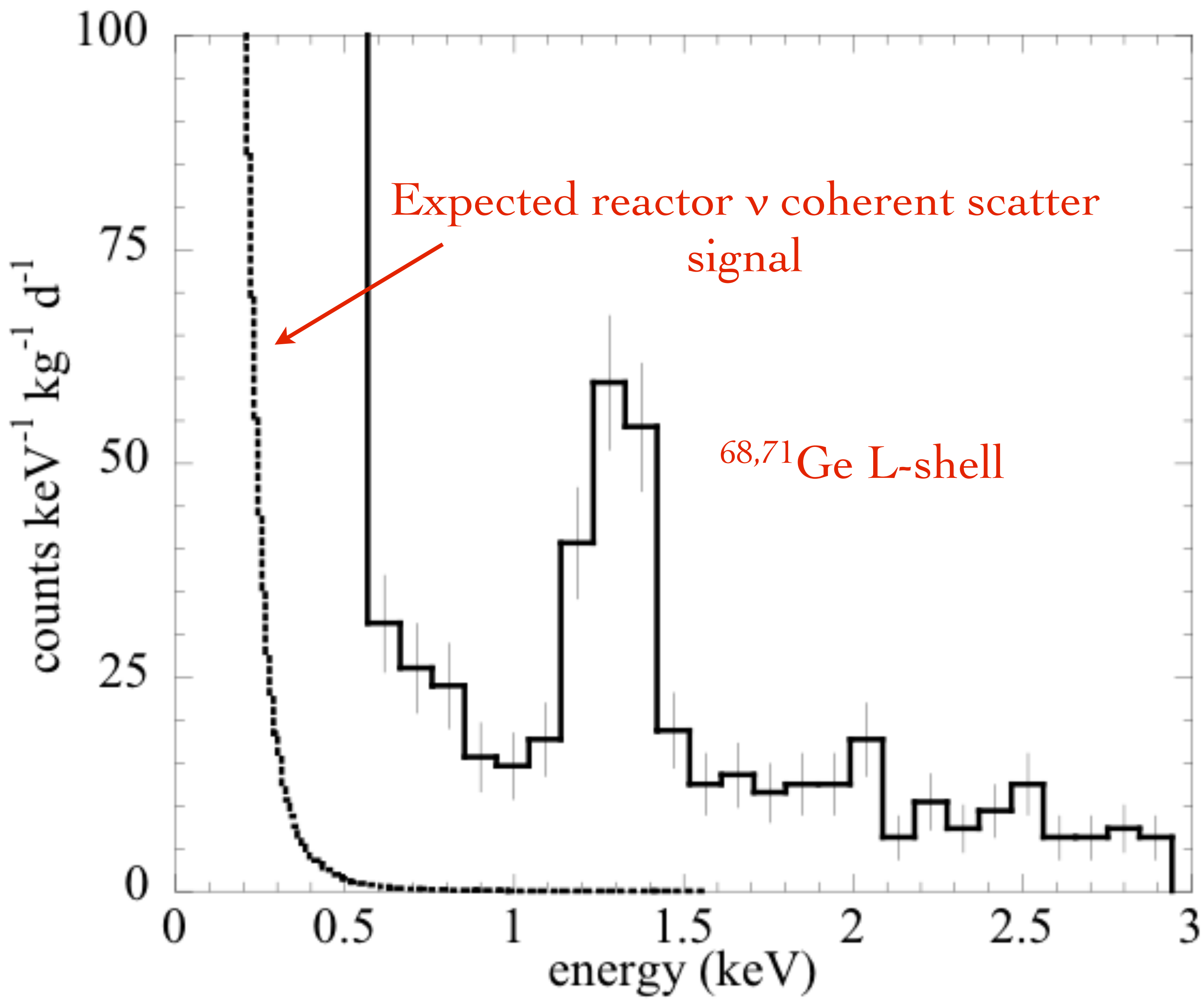




Direct Calibration for CoGeNT



CoGeNT Results



Present: the COHERENT Collaboration

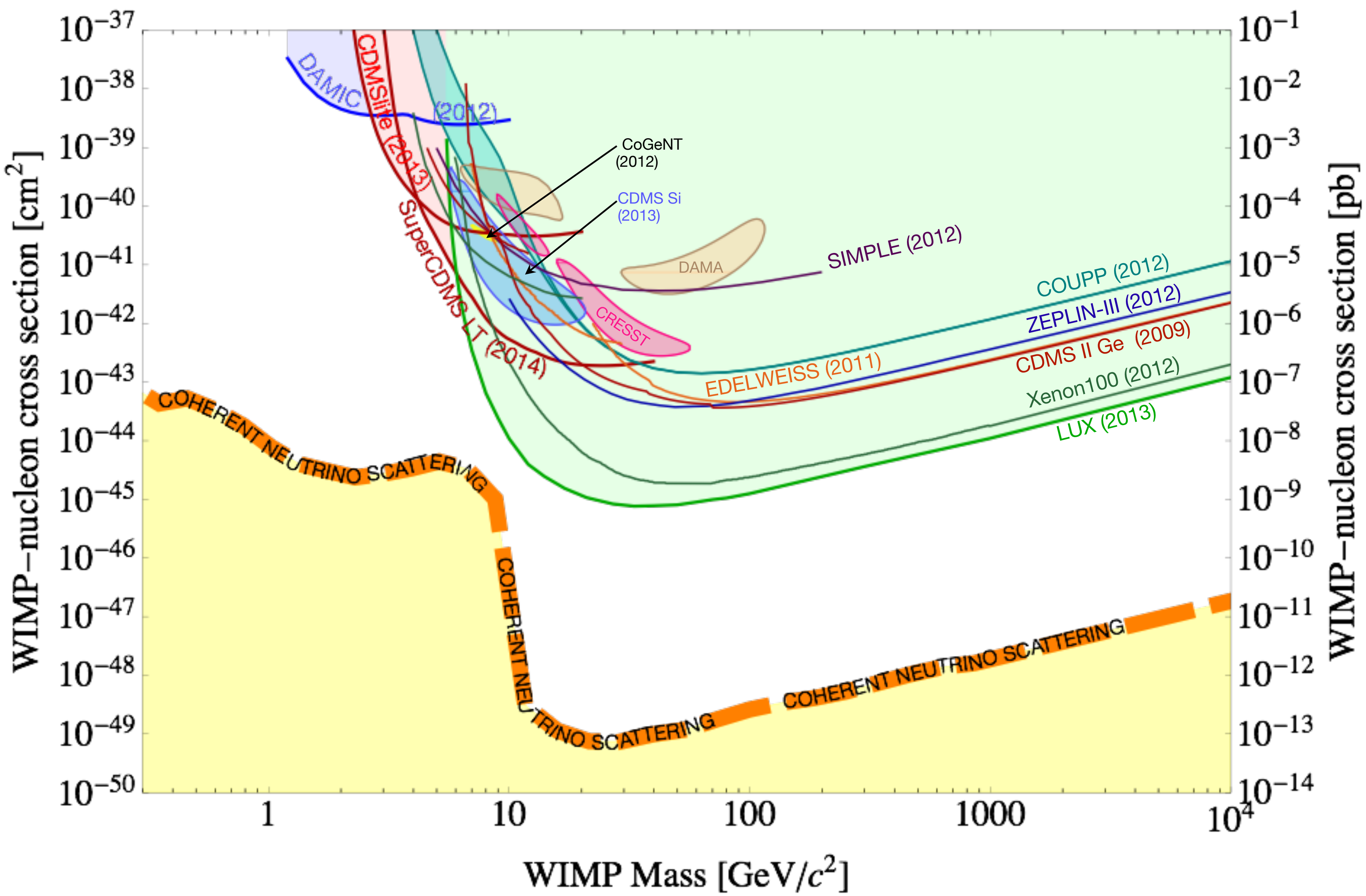
COHERENT SNS

Duke University
University of Florida
University of Chicago
University of Tennessee
ITEP
MEPhI
LBNL
University of California, Berkeley
NC State

ORNL
SNL
TUNL
Indiana University
LANL
NCCU
NMSU
University of Washington

Why Measure Coherent ν-Nucleus Scattering?

- CEvNS is an irreducible background for WIMP searches, and should be measured in order to validate background models and detector responses.



Why Measure Coherent $\boldsymbol{\nu}$-Nucleus Scattering?

- A high-σ, neutral current detector would be a clean way to search for sterile $\boldsymbol{\nu}$'s

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

- The development of a coherent neutrino scattering detection capability provides perhaps the best way to explore any sterile neutrino sector that could be uncovered with ongoing experiments.

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

- Coherent σ proportional to Q_W^2. A precision test of σ is a sensitive test of new physics above the weak scale. M_{top} and M_{higgs} are known → Remaining theoretical uncertainties ~0.2%

L. M. Krauss, PLB 269, 407

- Neutrino Magnetic Moments

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

- Measuring the neutron distribution functions (Form Factors)

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

- By measuring the relative rates on several nuclear targets we dramatically extend the sensitivity of searches for Non-Standard $\boldsymbol{\nu}$ Interactions

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

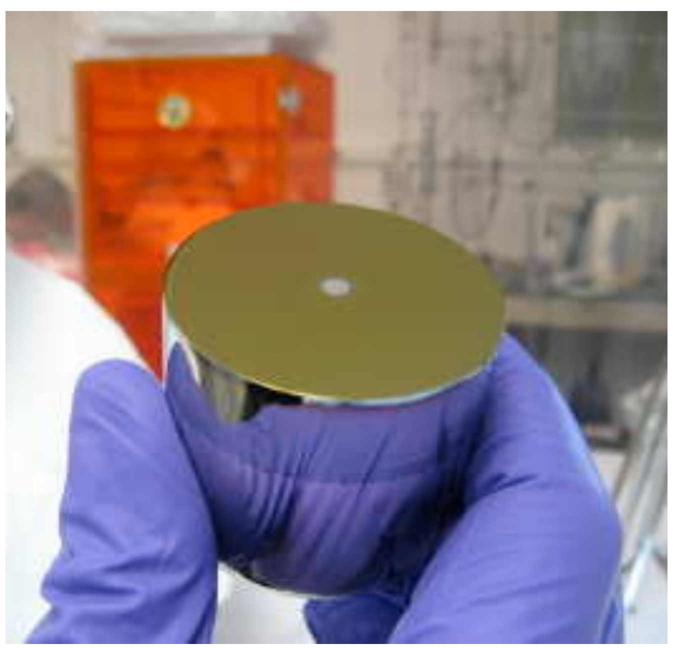
J. Barranco et al., JHEP0512:021,2005

- Largest σ in Supernovae dynamics. We should measure it to validate the models

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

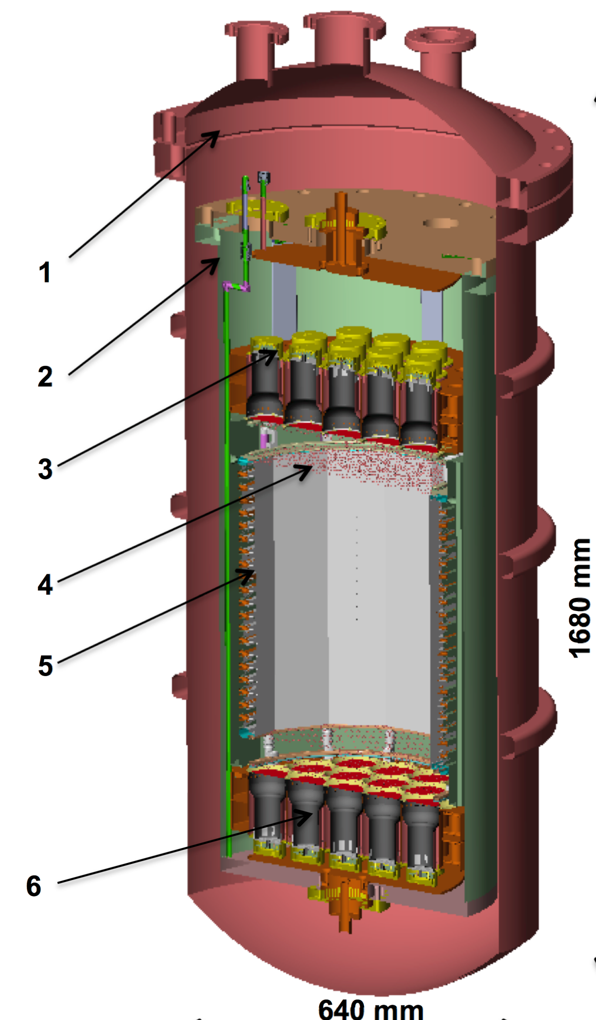
Large Mass, Low-Threshold, Low-Background Detectors

- COHERENT Collaboration's goal is the unambiguous measurement of CEvNS at Spallation Neutron Source (SNS)



P-Type Point Contact HPGe

Low-Background CsI(Na)

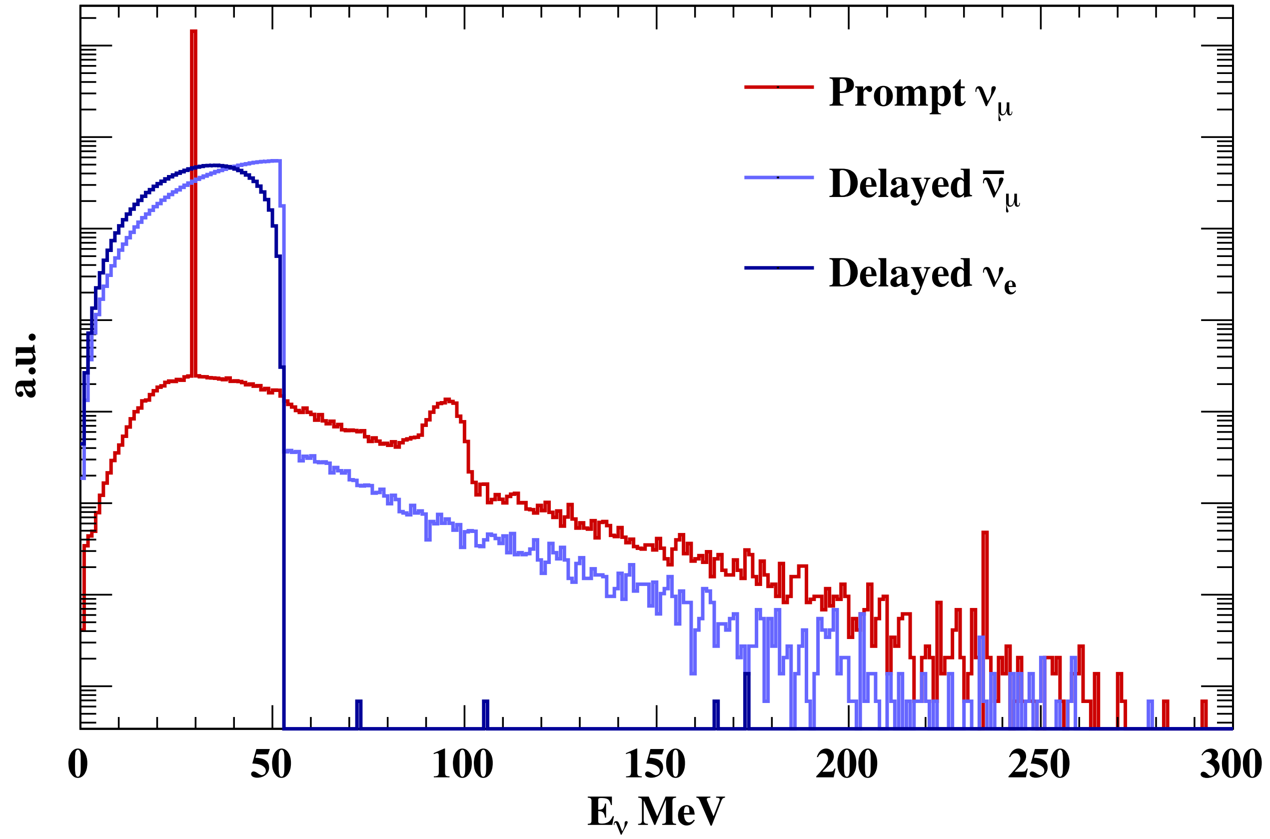


2-Phase LXe

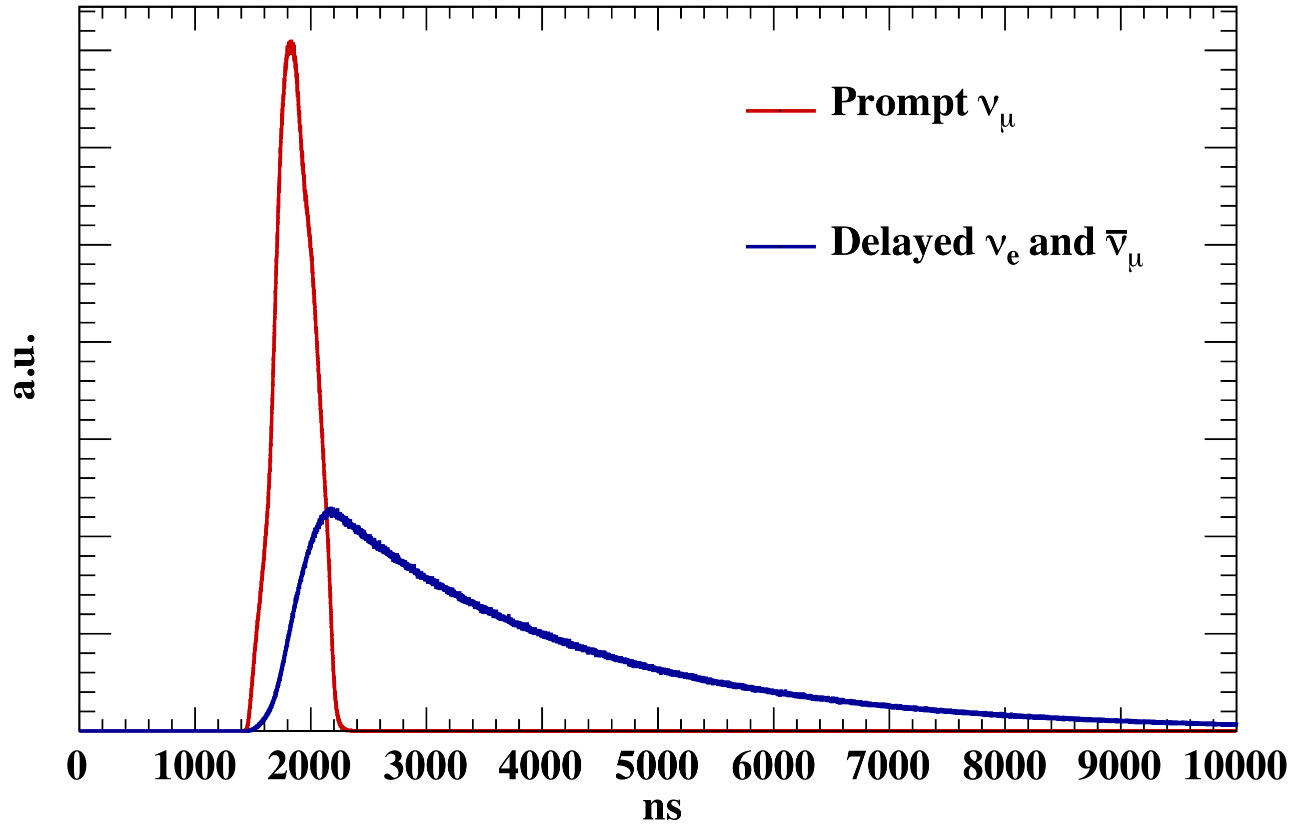
The Spallation Neutron Source

- Decay-at-Rest Neutrino Source
- ν flux 4.3×10^7 ν cm^{-2} s^{-1} at 20 m
- Pulsed: 350 ns half-width at 60 Hz

<1% contamination from non-CEvNS scatters

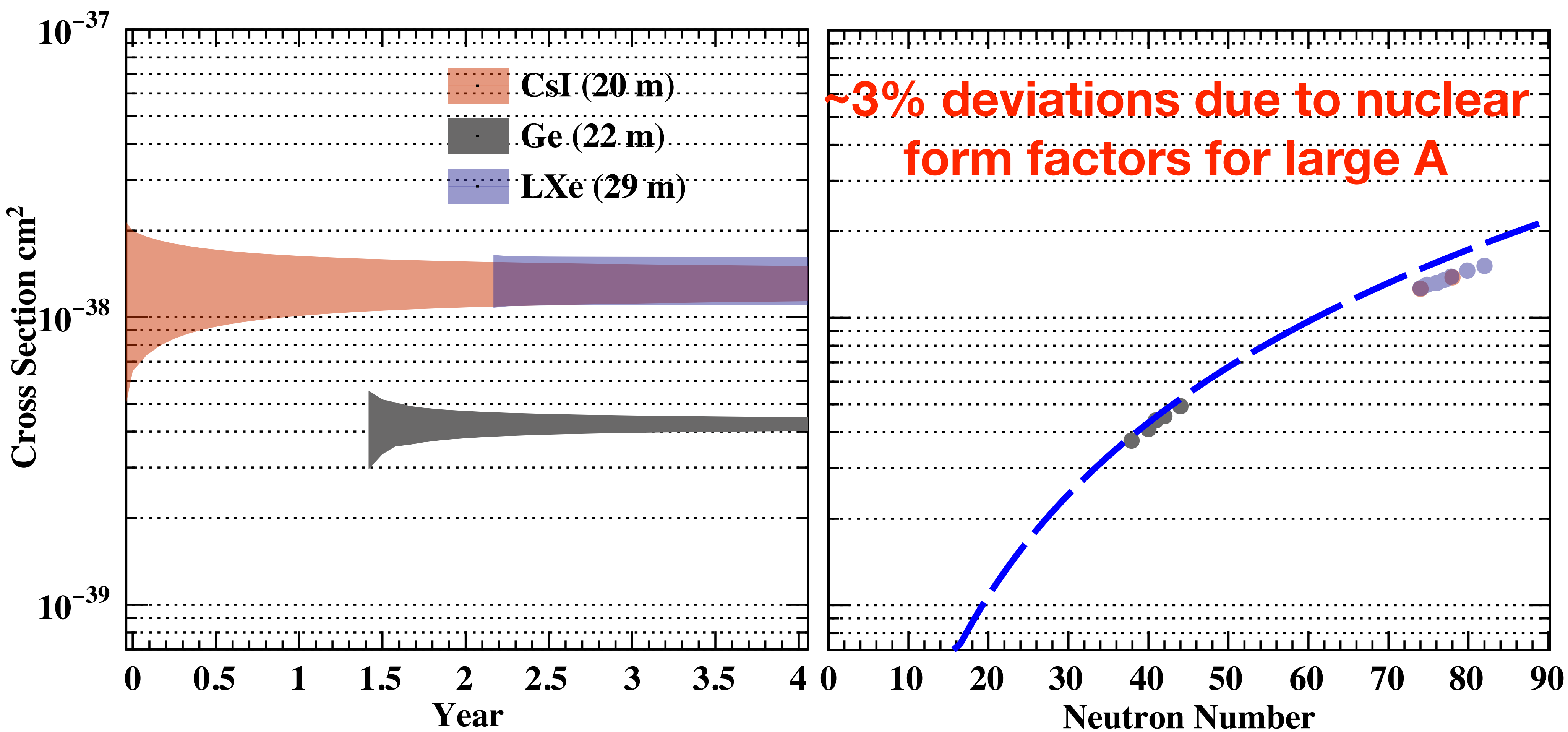


~4x10^-5 background reduction

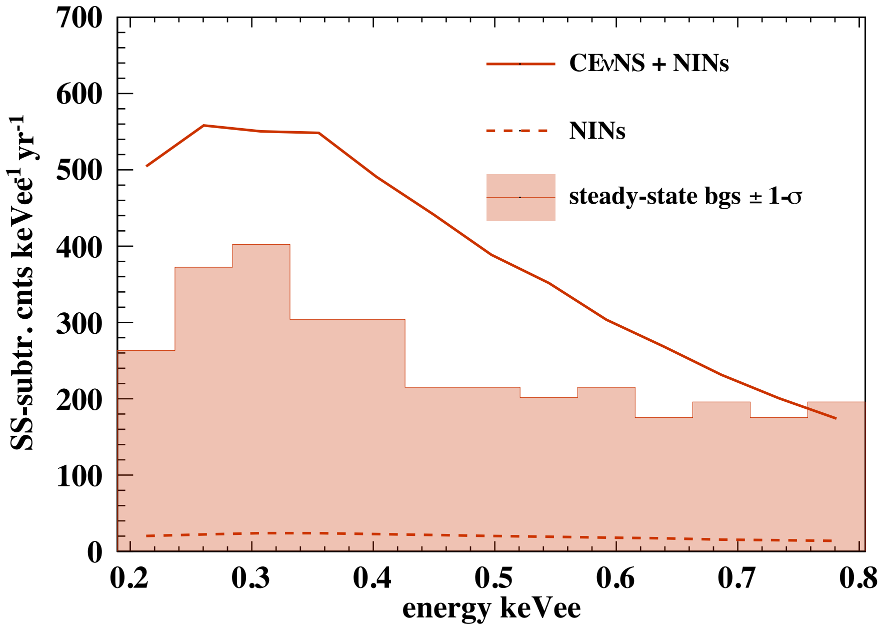


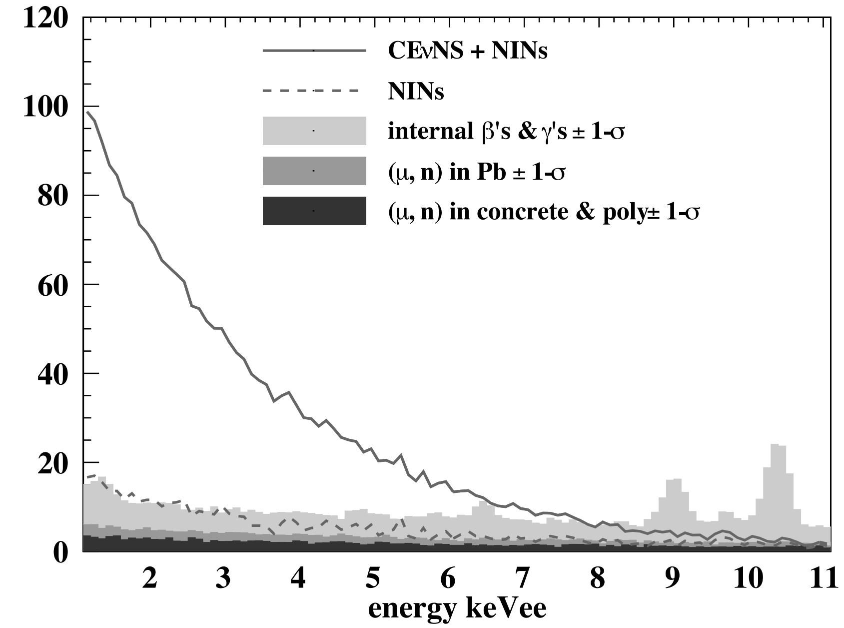
An unambiguous measurement

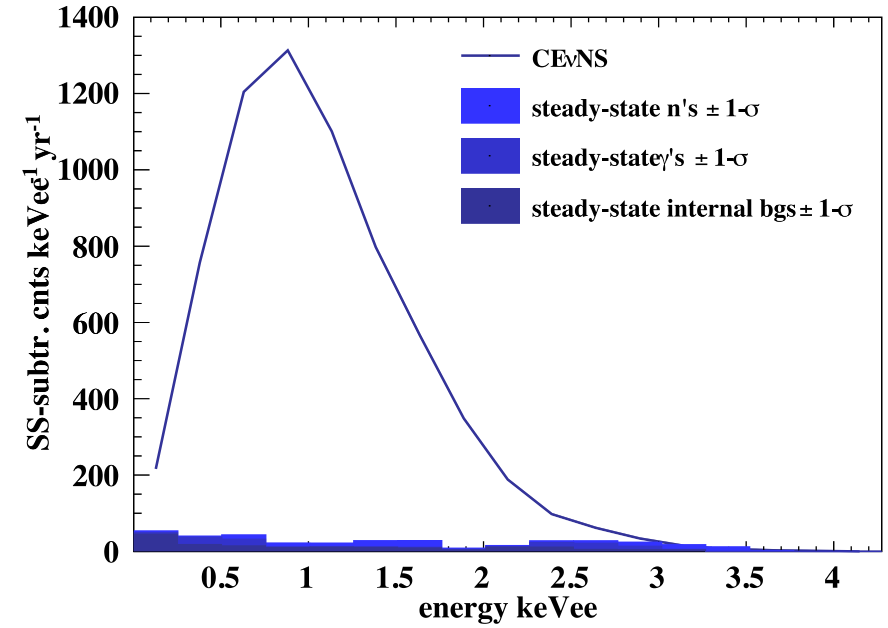
- Observe the pulsed ν time-structure
- Observe the 2.2 μs characteristic decay of delayed ν's
- Observe the N^2 cross-section behavior between targets



Expected Signals

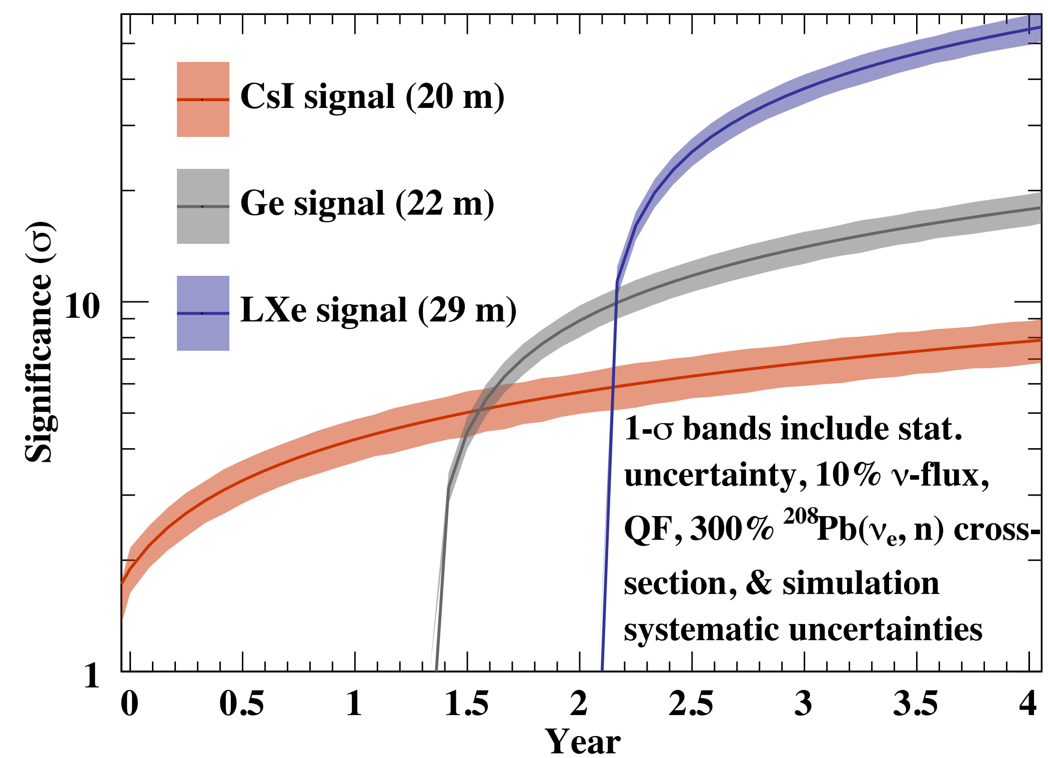






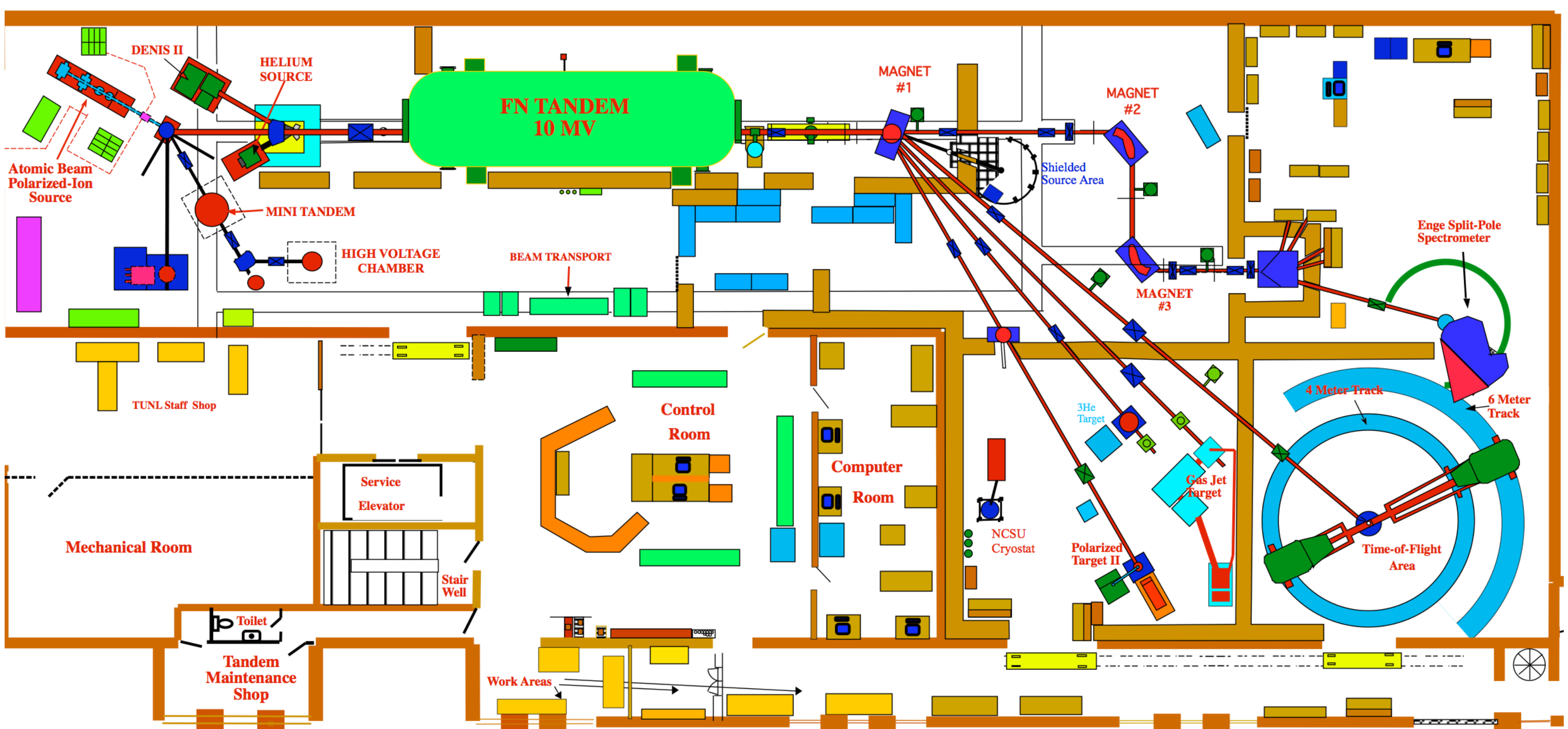
Steady-state background measured with anti-coincident triggers

NIN production rates inform the optimal shielding designs



Quenching Factor Measurements

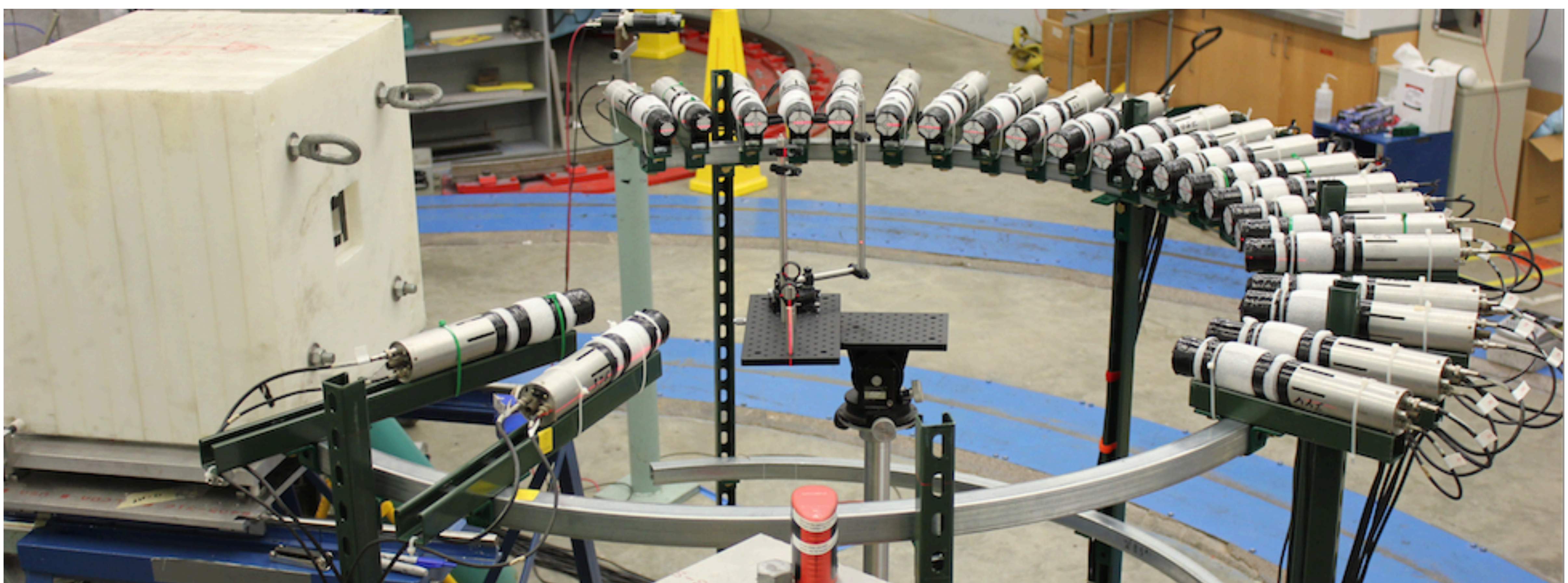
- A facility has been developed at Duke/TUNL to enable the precision detector calibration using $^{7}Li(p, n)^{7}Be$ reaction.
- Proton beam has 500 eV resolution. LiF target: 0.026 - 0.132 mg cm^{-2}
- The neutron beam is tunable (30 keV - 3 MeV), Monochromatic (~3 keV width), collimated (1.5 cm) and pulsed (2 ns), 10^4 n cm^{-2} hr^{-1} with 600 nA proton current for E_n = 580 keV



Quenching Factor Measurements

- Early measurements have used 24 backing detectors (plus one beam monitor at 0 degrees)

- Event trigger based on Coincidence between the Beam Pulse Monitor and backing detectors. Effort to minimize potential threshold effects.

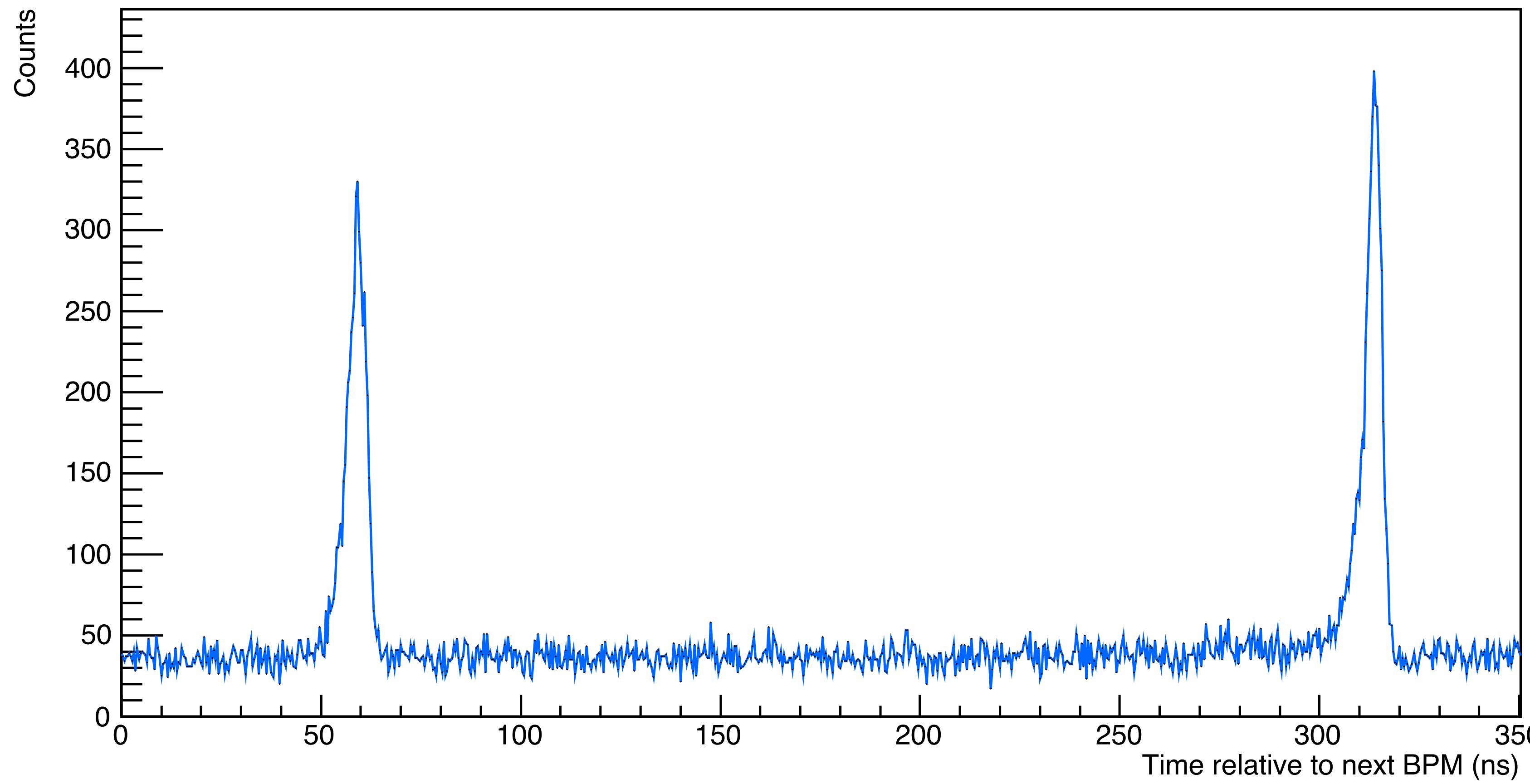


Neutron beam characteristics

- Neutrons and gammas are clearly separated by time of flight

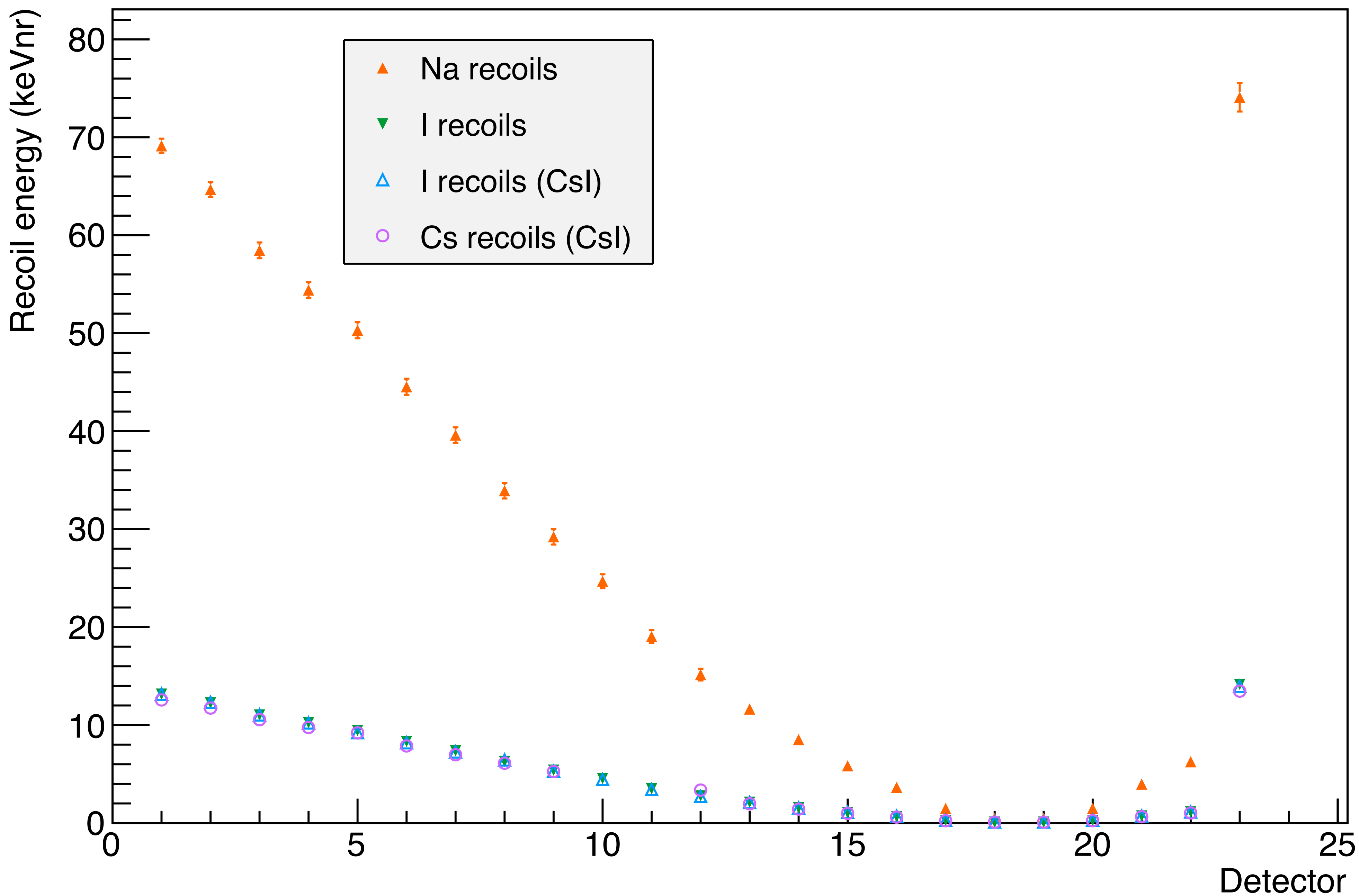
- Neutron energy and its resolution at 0 degrees can be reliably confirmed using TOF

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



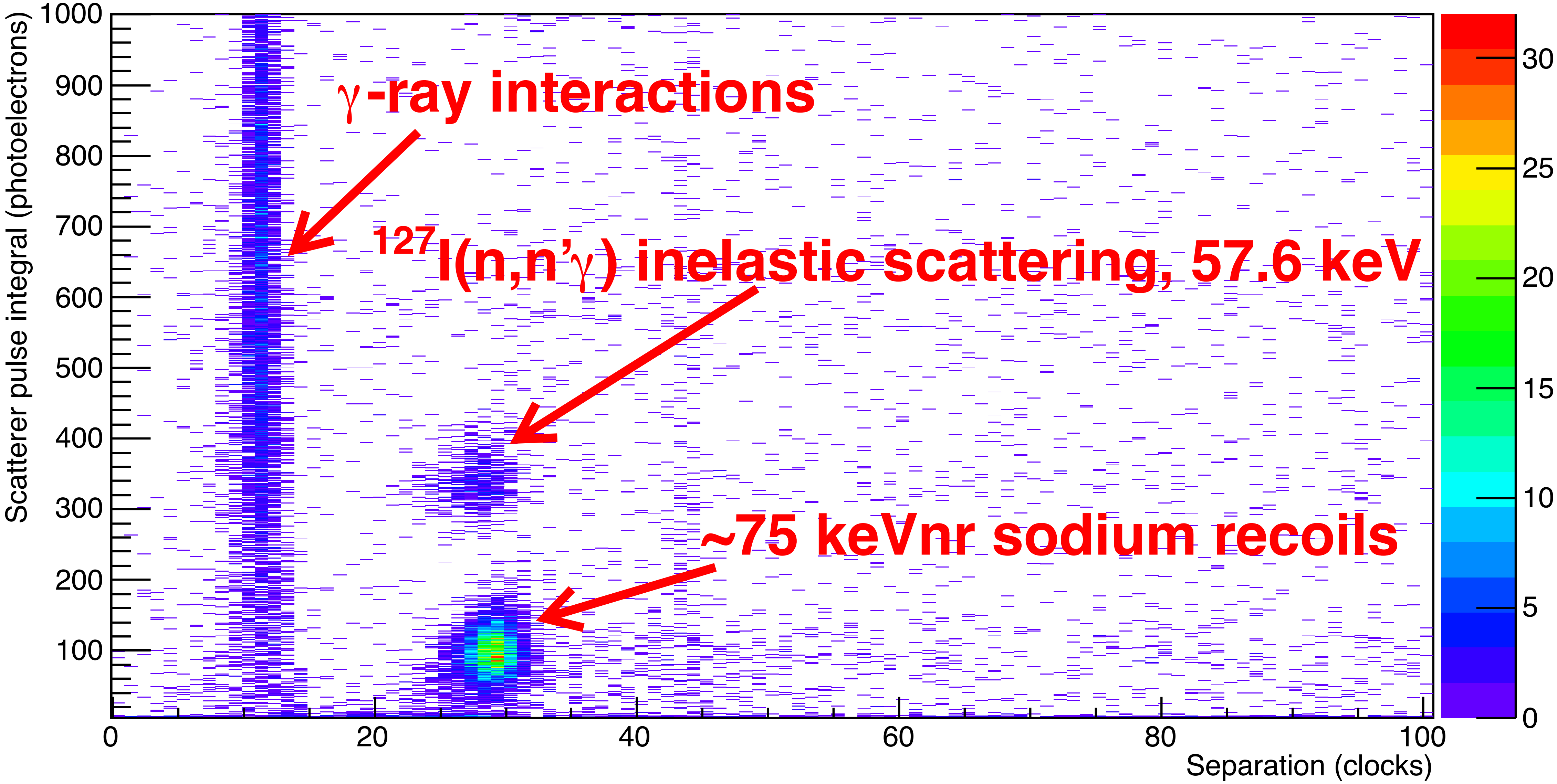
NaI(Tl) and CsI(Na) calibrations

MCNPX-predicted nuclear recoil energies

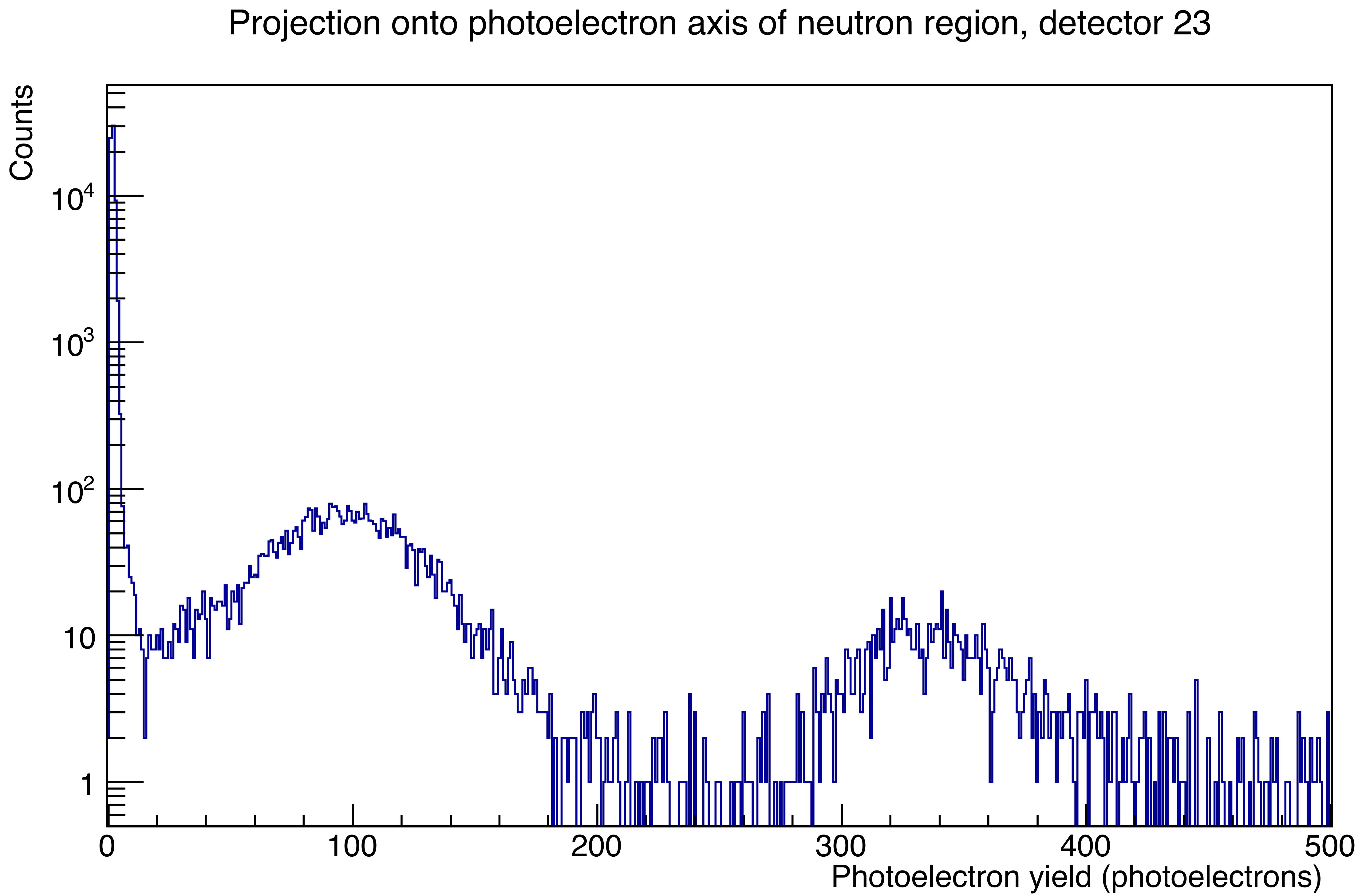


Initial results with NaI(Tl)

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

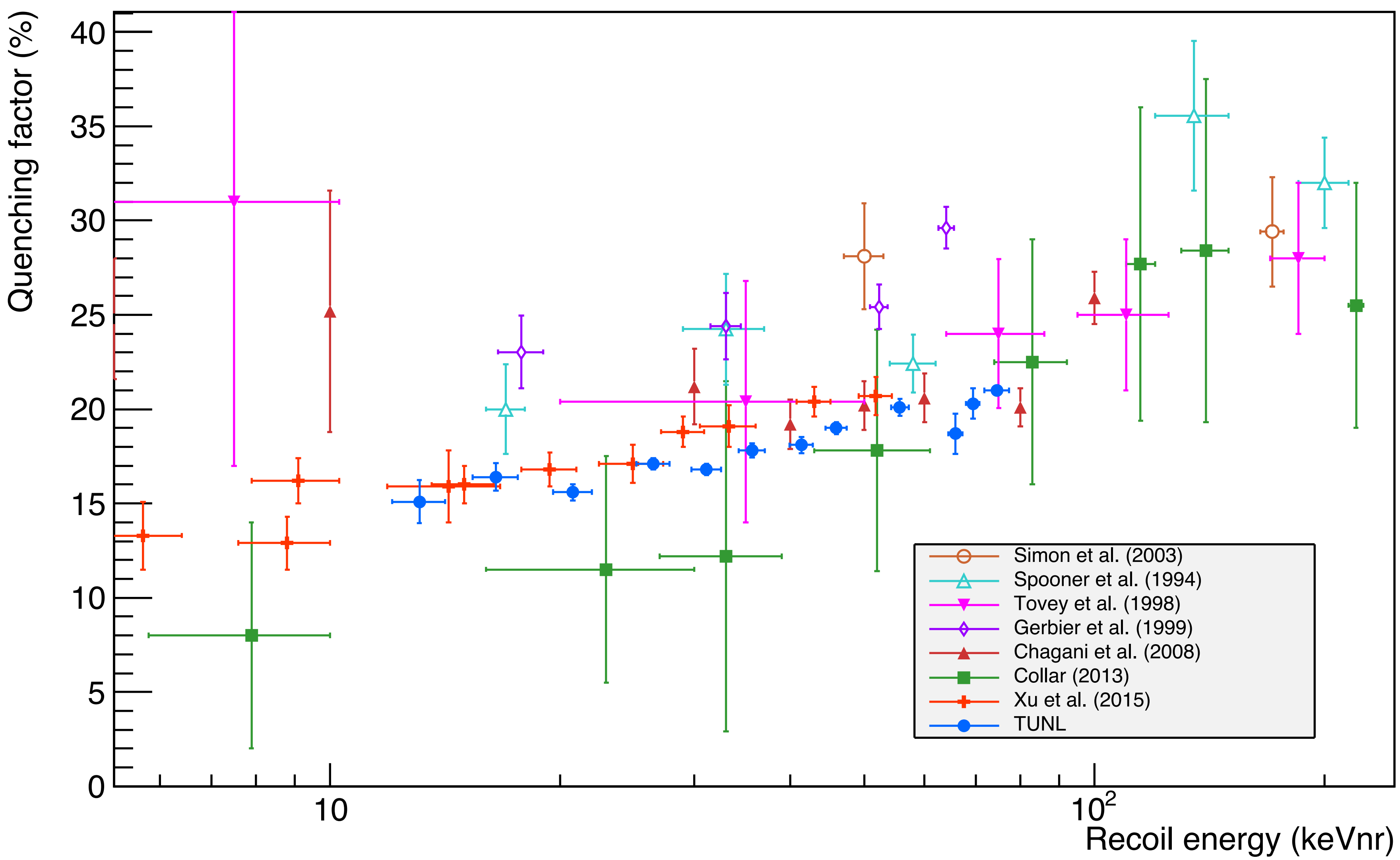


Projection onto PE yield axis of neutron ROI



Preliminary QF for Na recoils

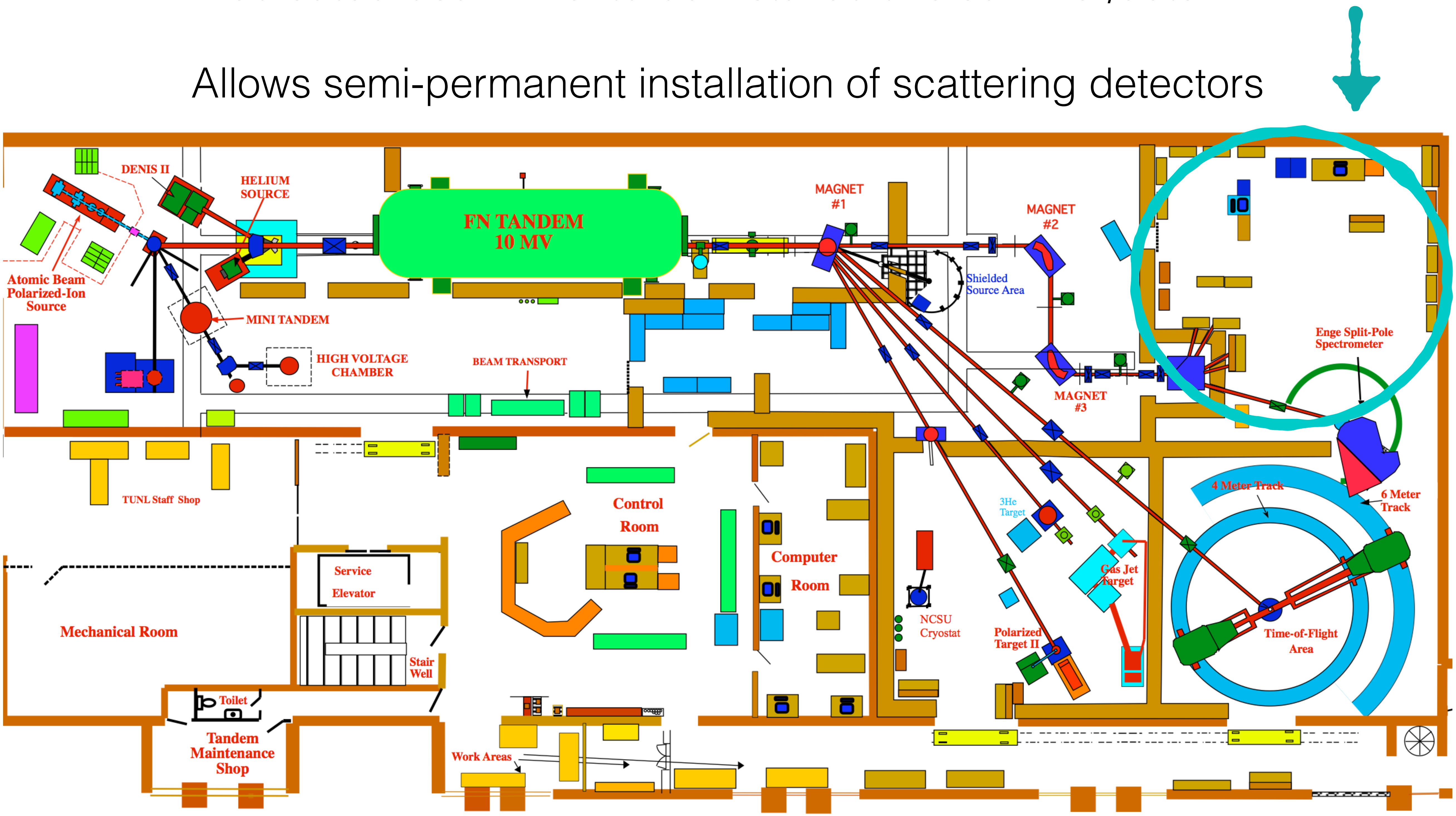
- Extraction of lower-energy QF complicated by unreliable backing detectors and trigger configuration - both issues are now corrected!



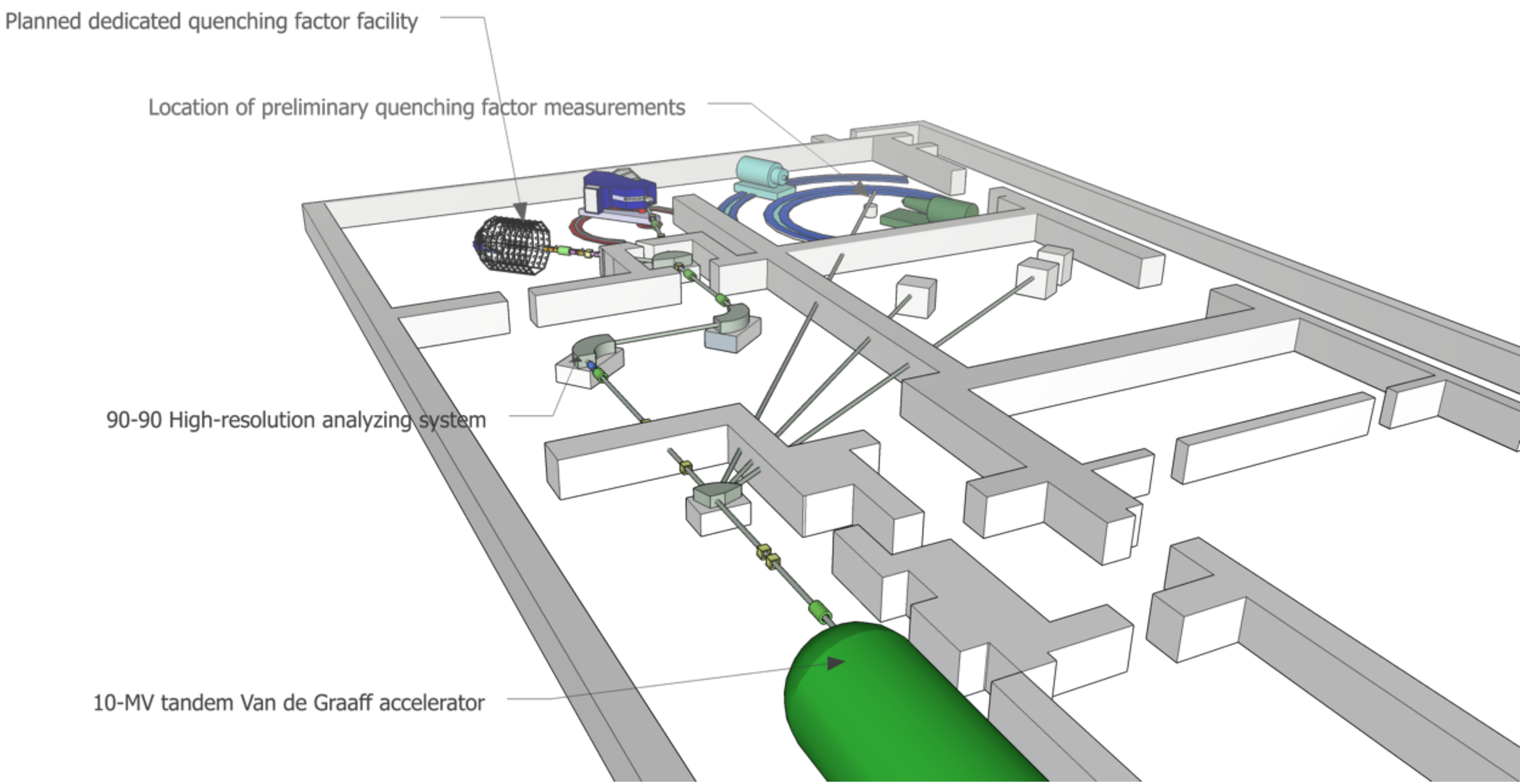
QF facility improvements

Dedicated beam line: to be installed this summer/autumn

Allows semi-permanent installation of scattering detectors

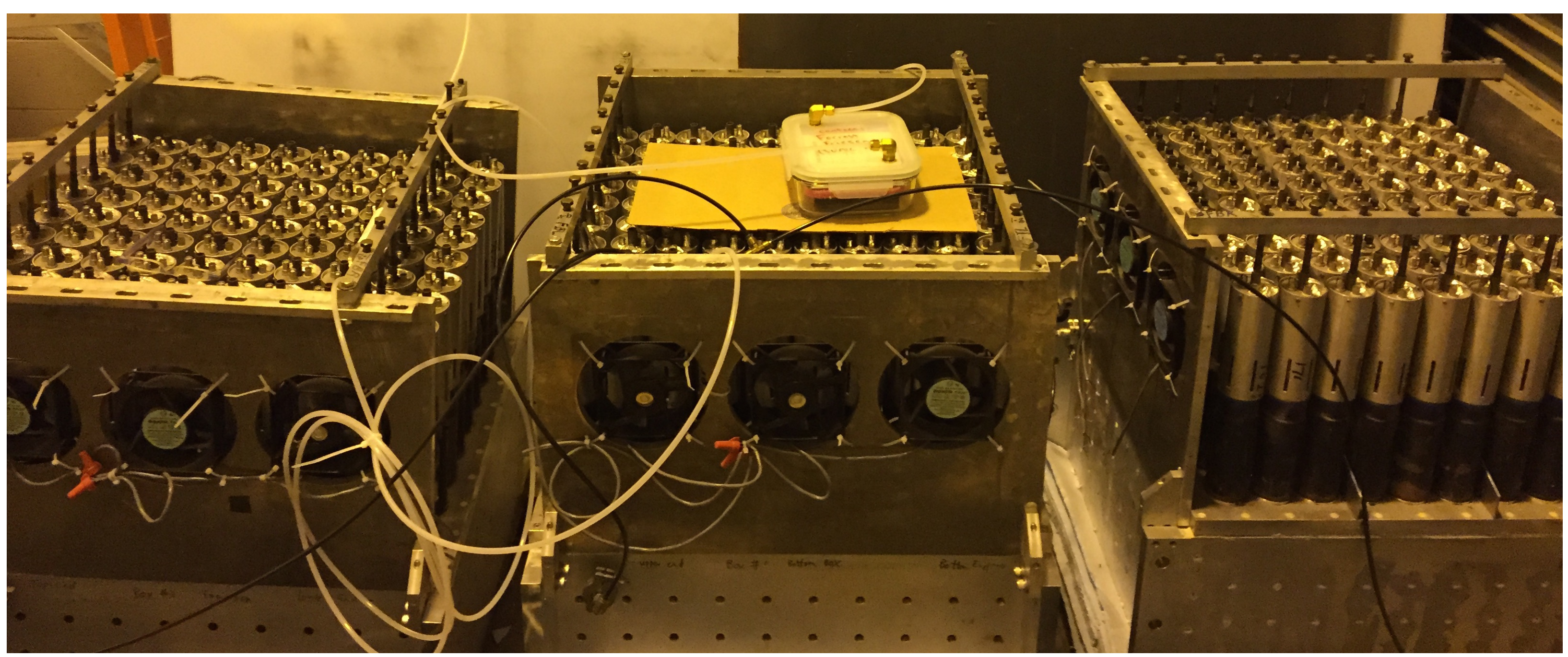


QF facility improvements



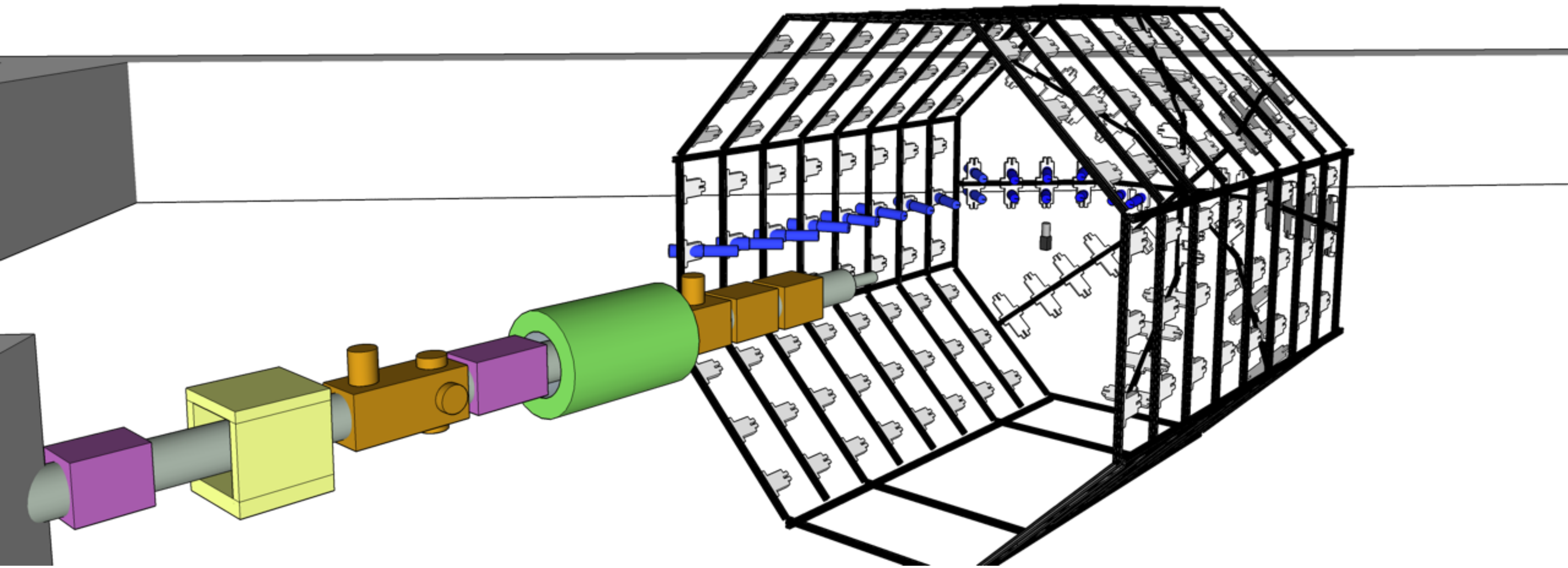
QF facility improvements

- Hundreds of PMTs available at TUNL
- More recoil angle coverage and/or greater standoff distances



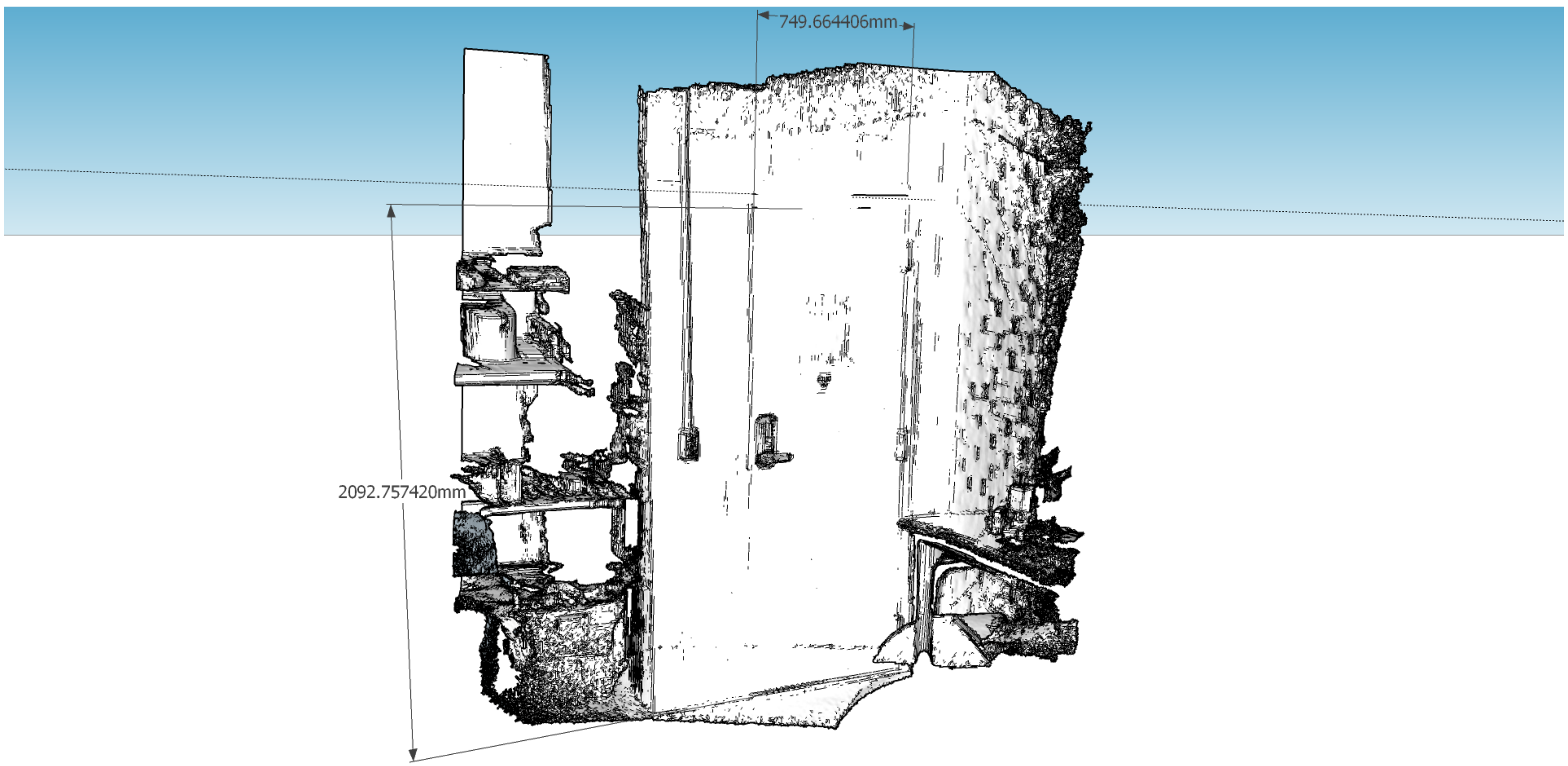
QF facility improvements

- PMT mounts are custom produced with 3D printers
- Allows rapid redesign of facility.
- Large θ and Φ coverage to increase solid angle, check systematics and test channeling



QF facility improvements

- 3D-scanning capabilities developed for detailed measurements of setup
- Simple, very-preliminary tests show decent agreement with measurements made by hand



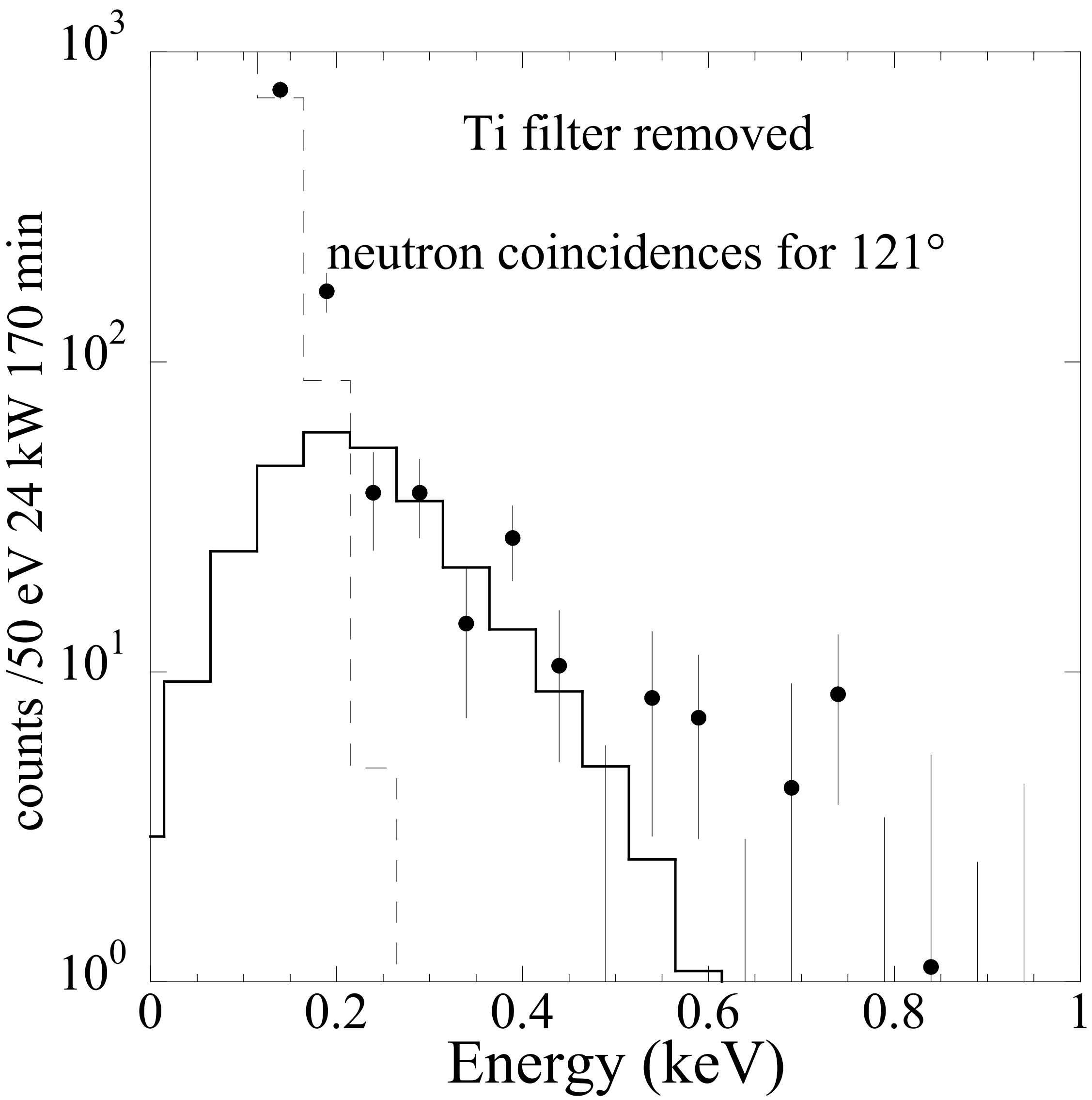
Summary

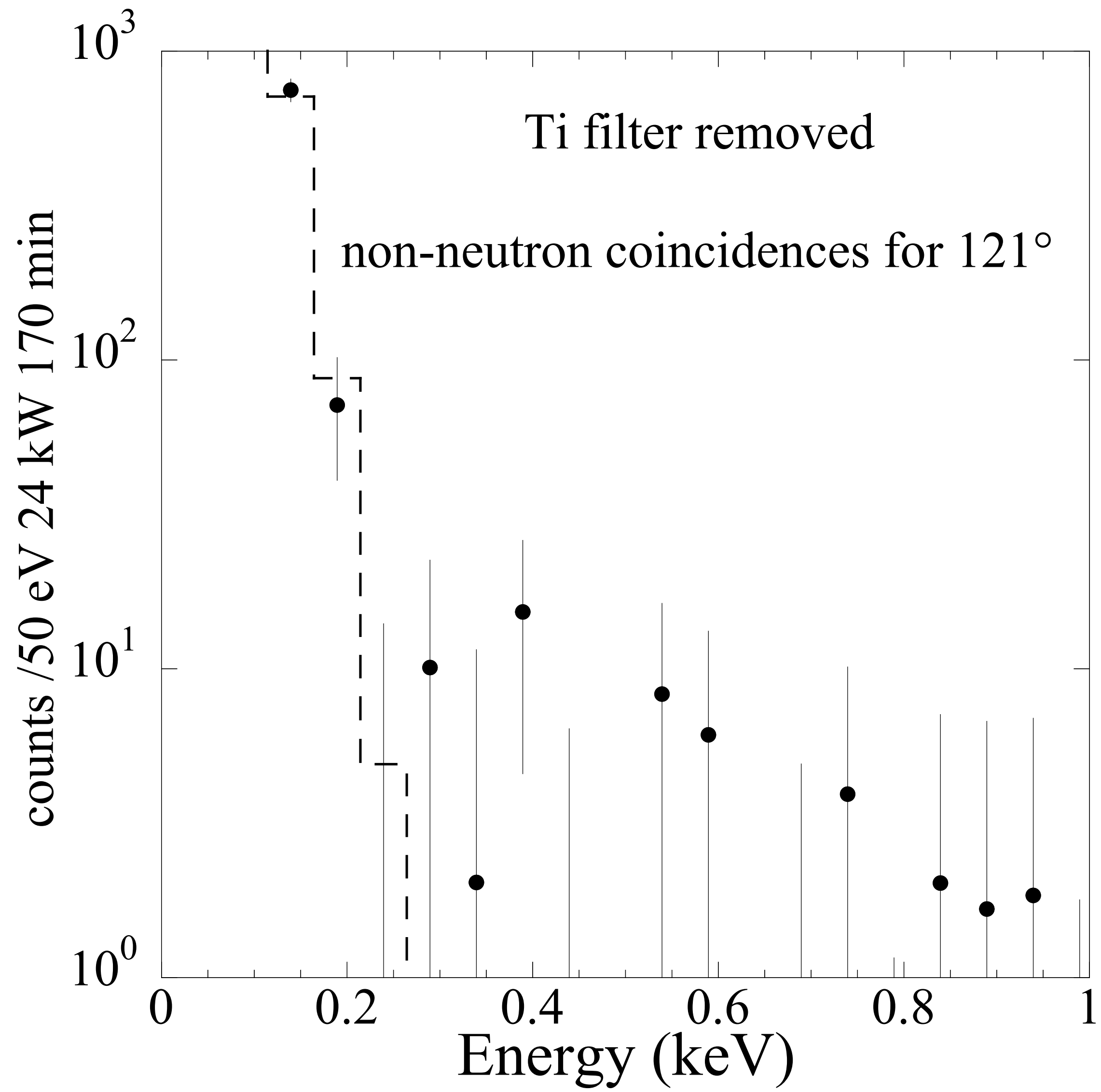
- A new collaboration has formed, combining the efforts of several groups that have been aiming towards a coherent neutrino-nucleus scattering measurement.
- Background studies indicate the basement as the optimal location
- CsI[Na] has already been delivered and installed
- Several detectors to measure the $\boldsymbol{\nu}$-induced induced neutron emission cross-sections on Pb, Fe and Cu installed an on their way
- We expect each detector sub-system to reach ~ 5$\boldsymbol{\sigma}$ significance for an excess, pulsed with the beam around year 2-2.5
- This will allow us to confirm that the signal is beam related **(pulsed nature)**, a result of ν's **(2.2 μs decay)** and due to CEvNS **($\boldsymbol{\sigma \sim N^2}$)**
- **The precision measurement of quenching factors is at the core of the experiment, and are absolutely necessary for the interpretation of our signals.**

Extra Slides

Calibration of the Detector

- Accidental backgrounds from environmental backgrounds, and spurious neutron recoils are subtracted by measuring anti-coincident events





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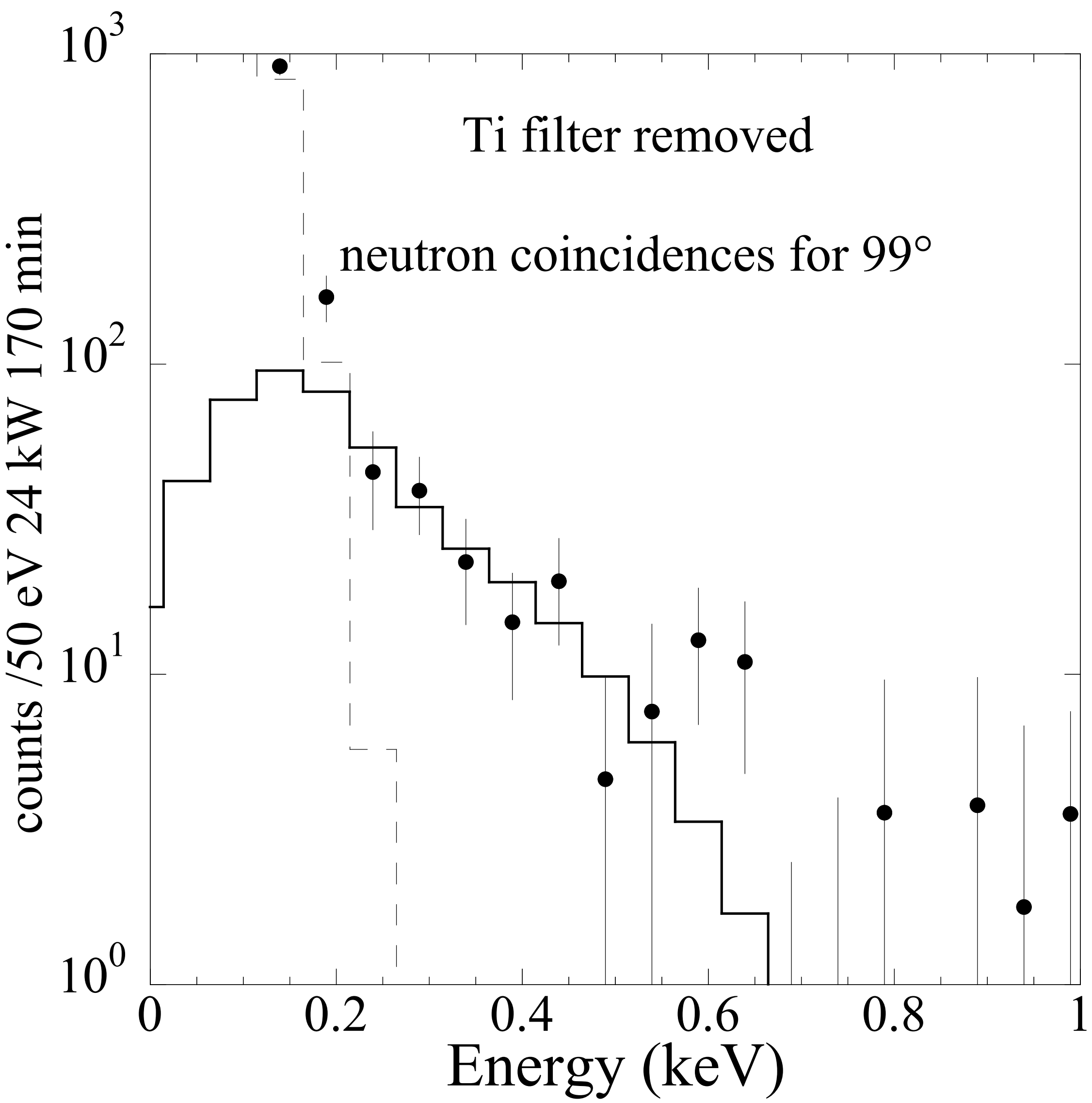
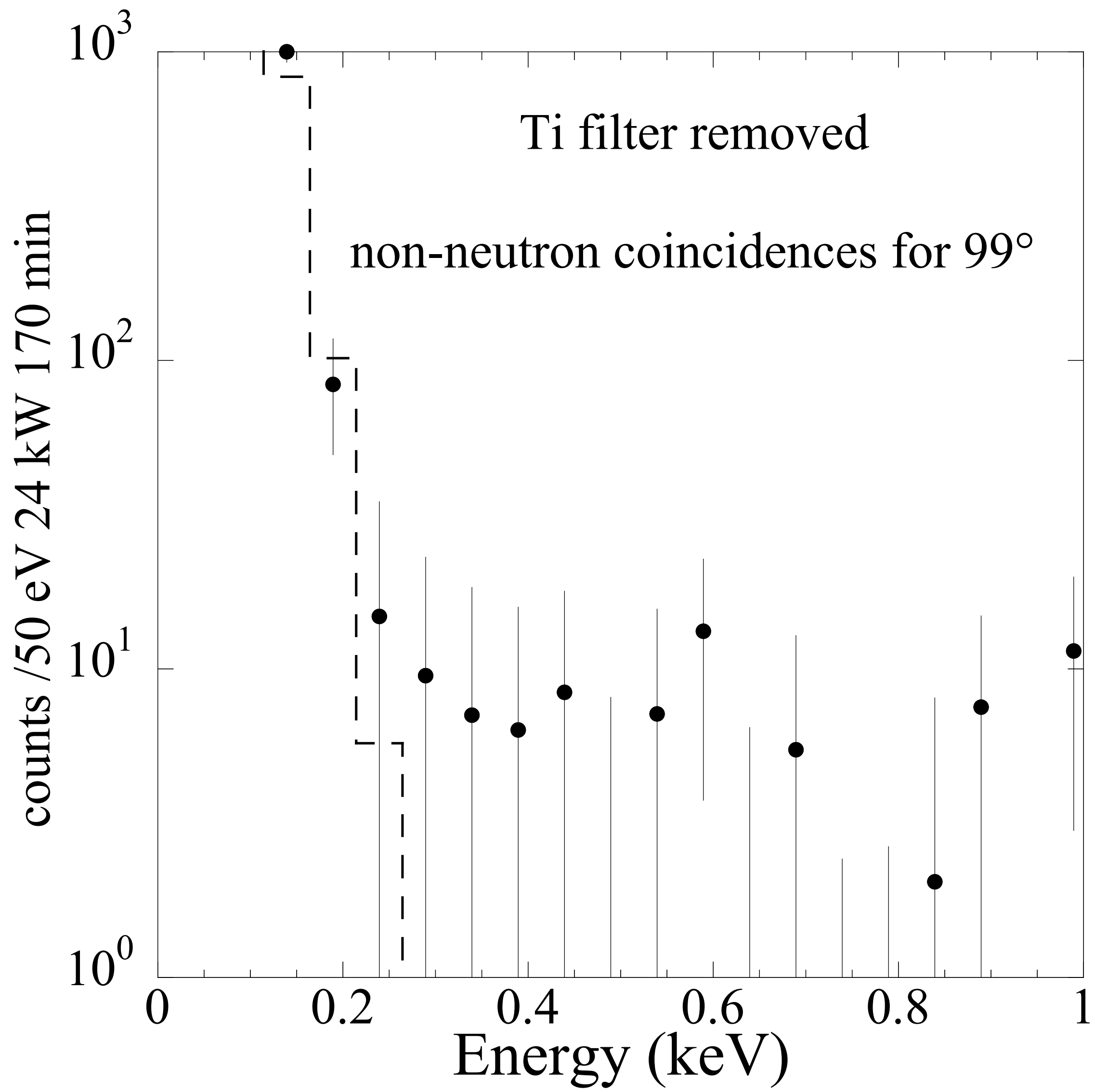




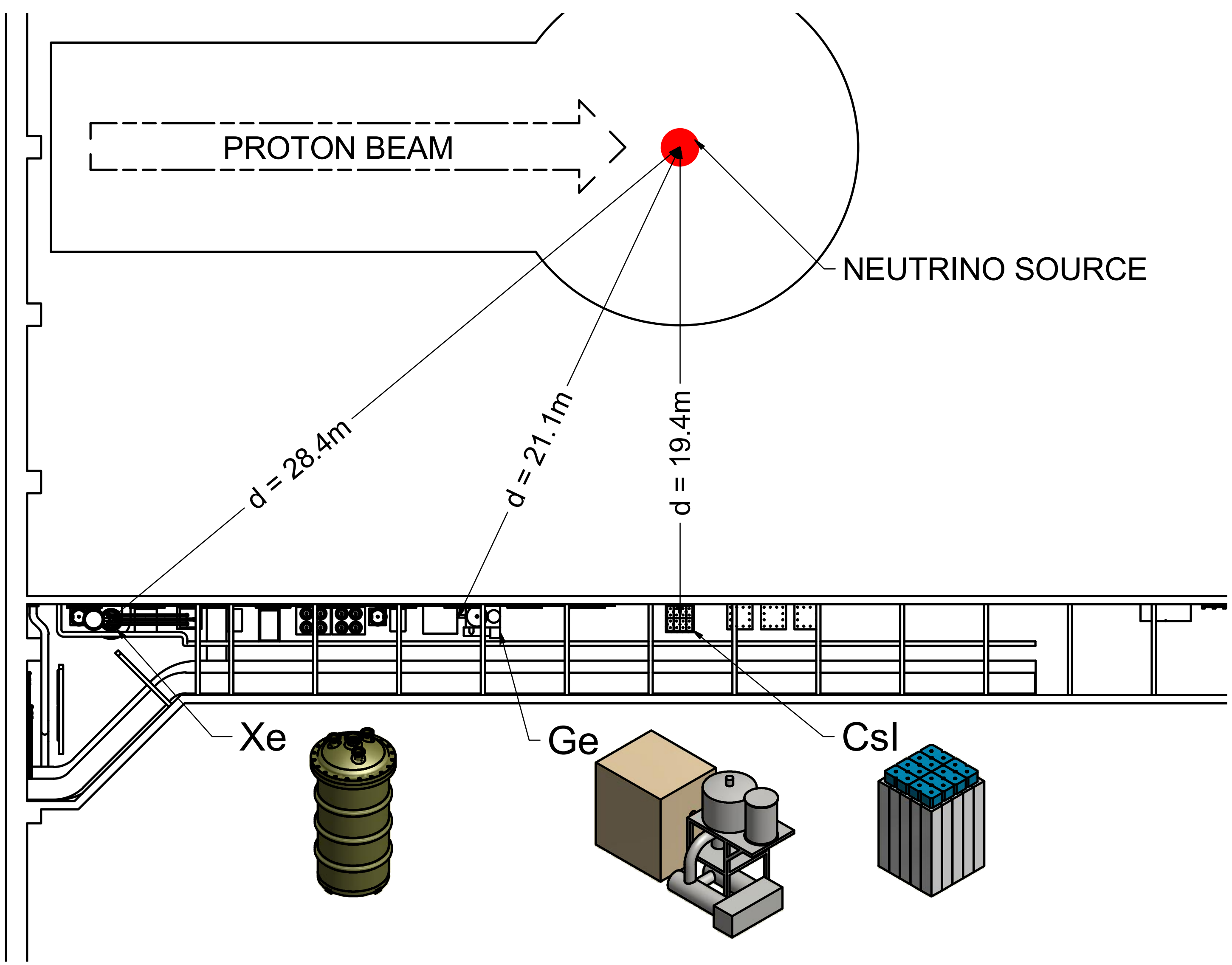
Backgrounds

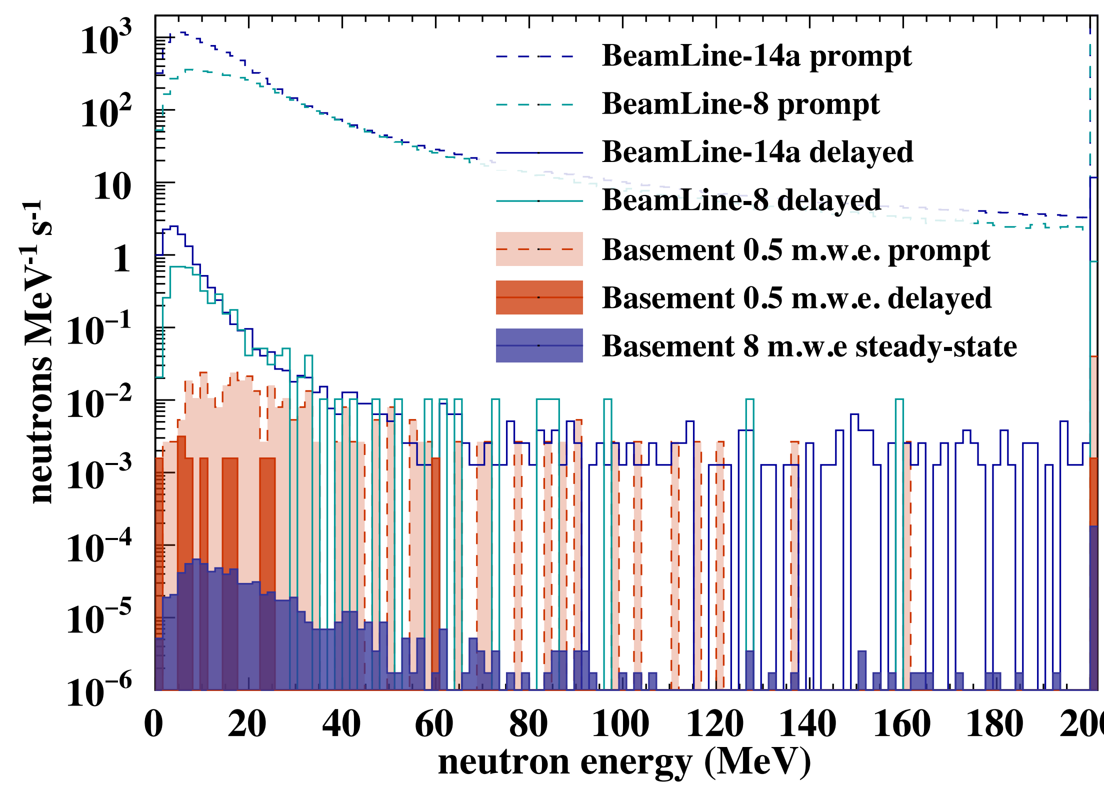
The SNS is a facility designed to produce neutrons (> 100 MeV), and that those neutrons are pulsed with the same time structure of the neutrinos (**with the exception of the characteristic decay time of the muon**).

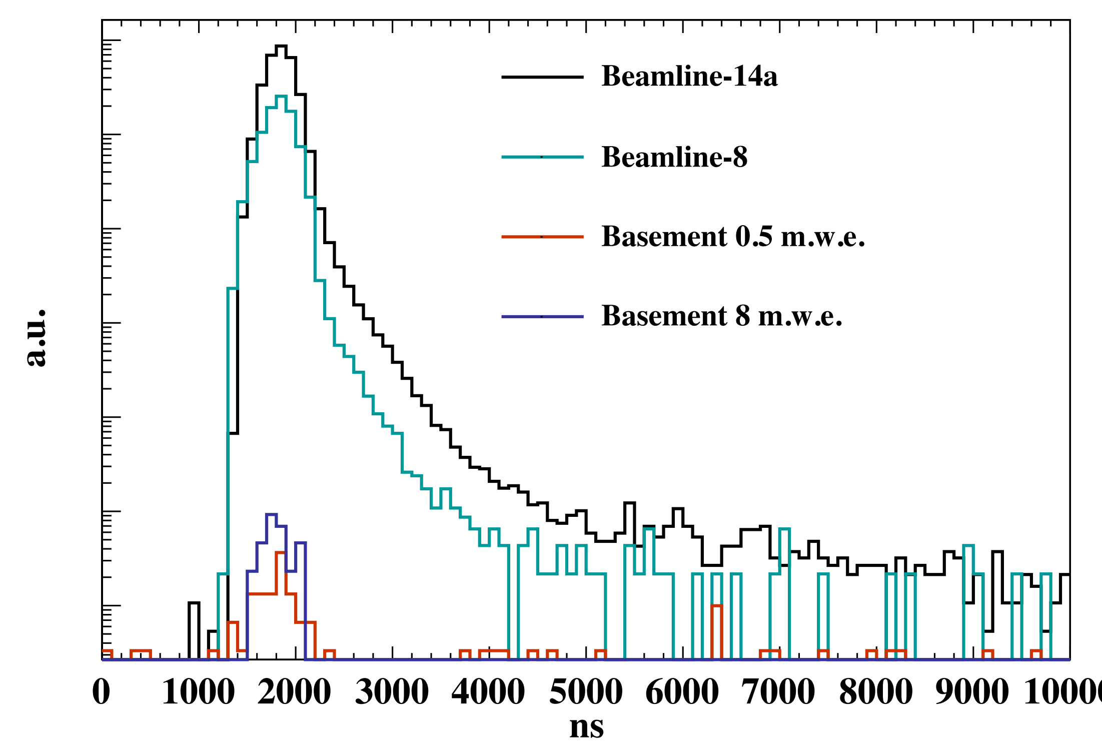
Coded aperture image of neutrons on the SNS floor

Hunting for a Background Free Location

- Extensive background measurement campaign since 2013 points to the SNS basement as the optimal location (>10^4 reduction)



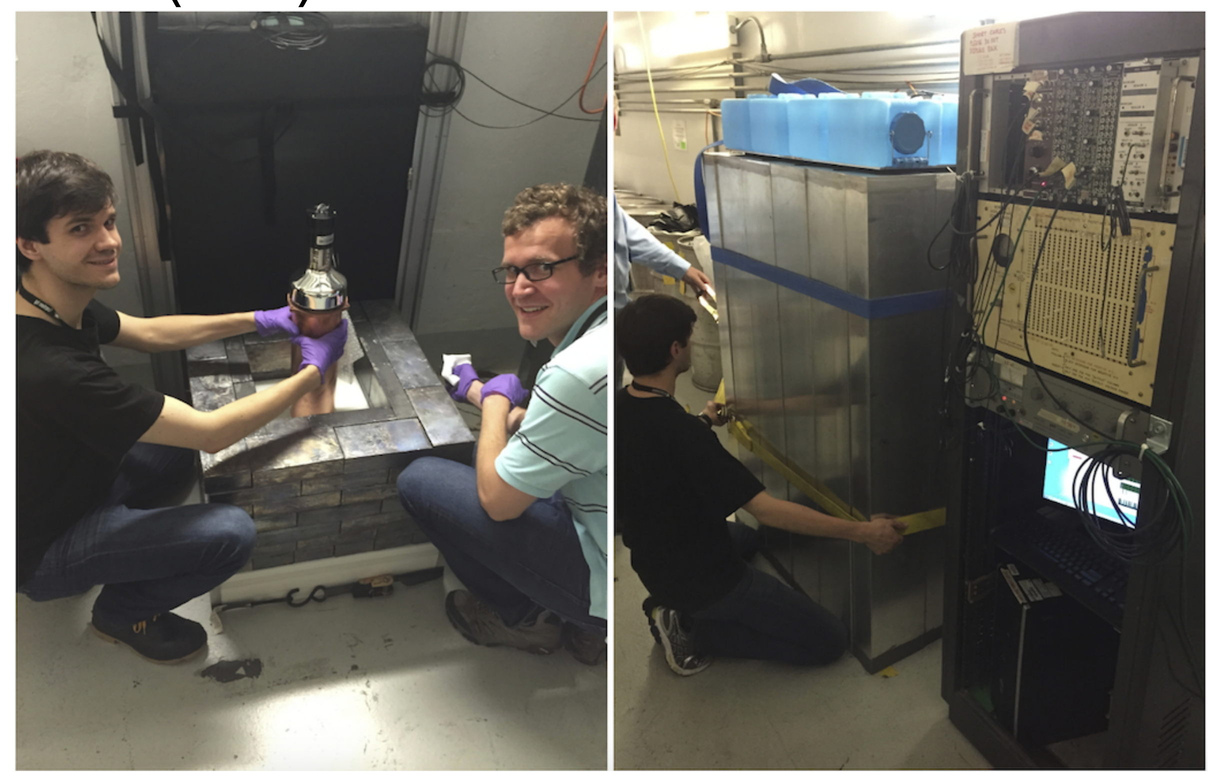




New Background: $\boldsymbol{\nu}$-induced neutrons (NINs)

- The detector shields use several tons of lead
- Neutrons can be produced near the detectors. They will be pulsed, and share the 2.2 μs decay time of the ν's
- Need to measure this $\boldsymbol{\sigma}$ and optimize the shields

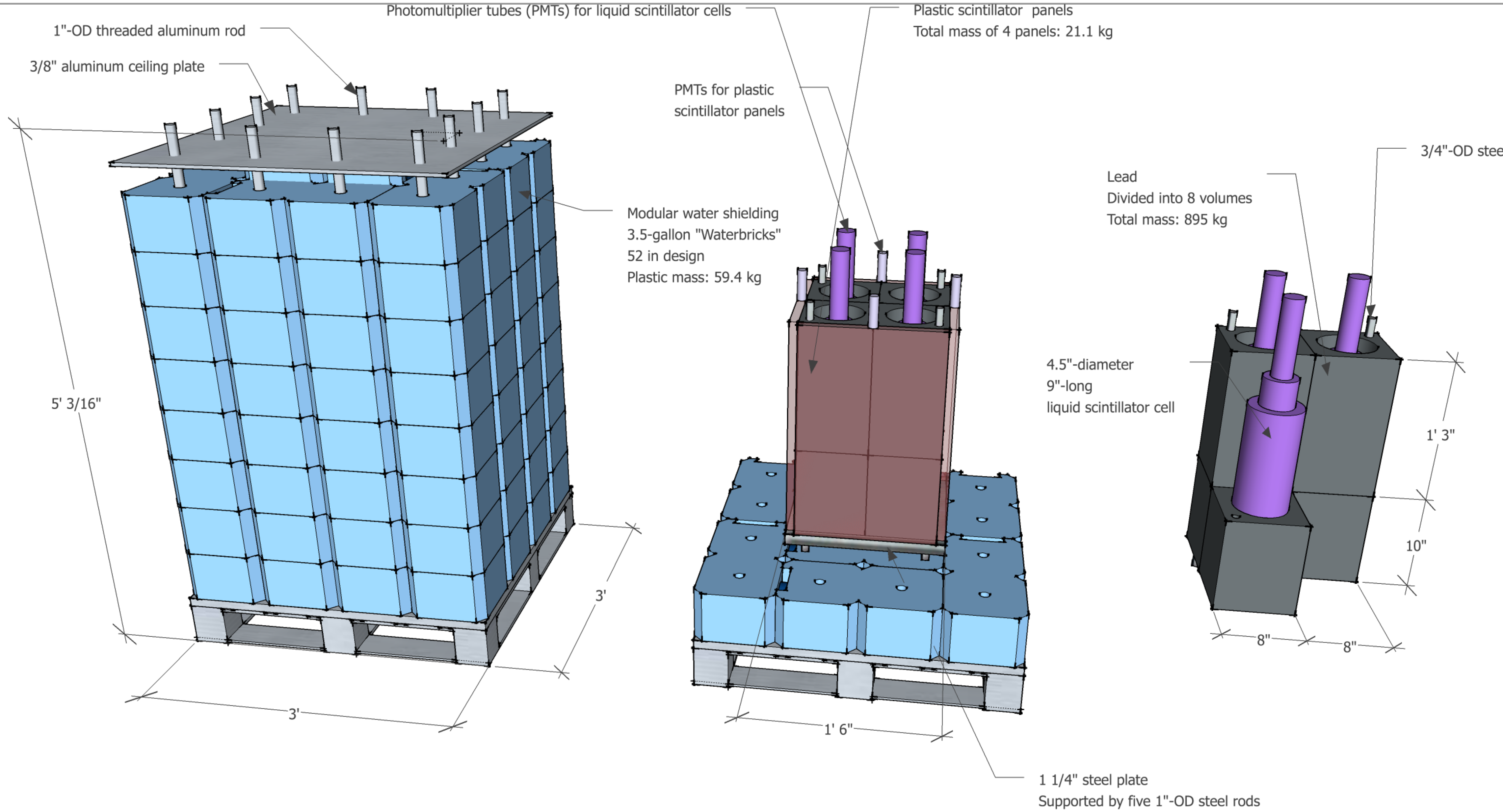
CsI(Na) detector and shield



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

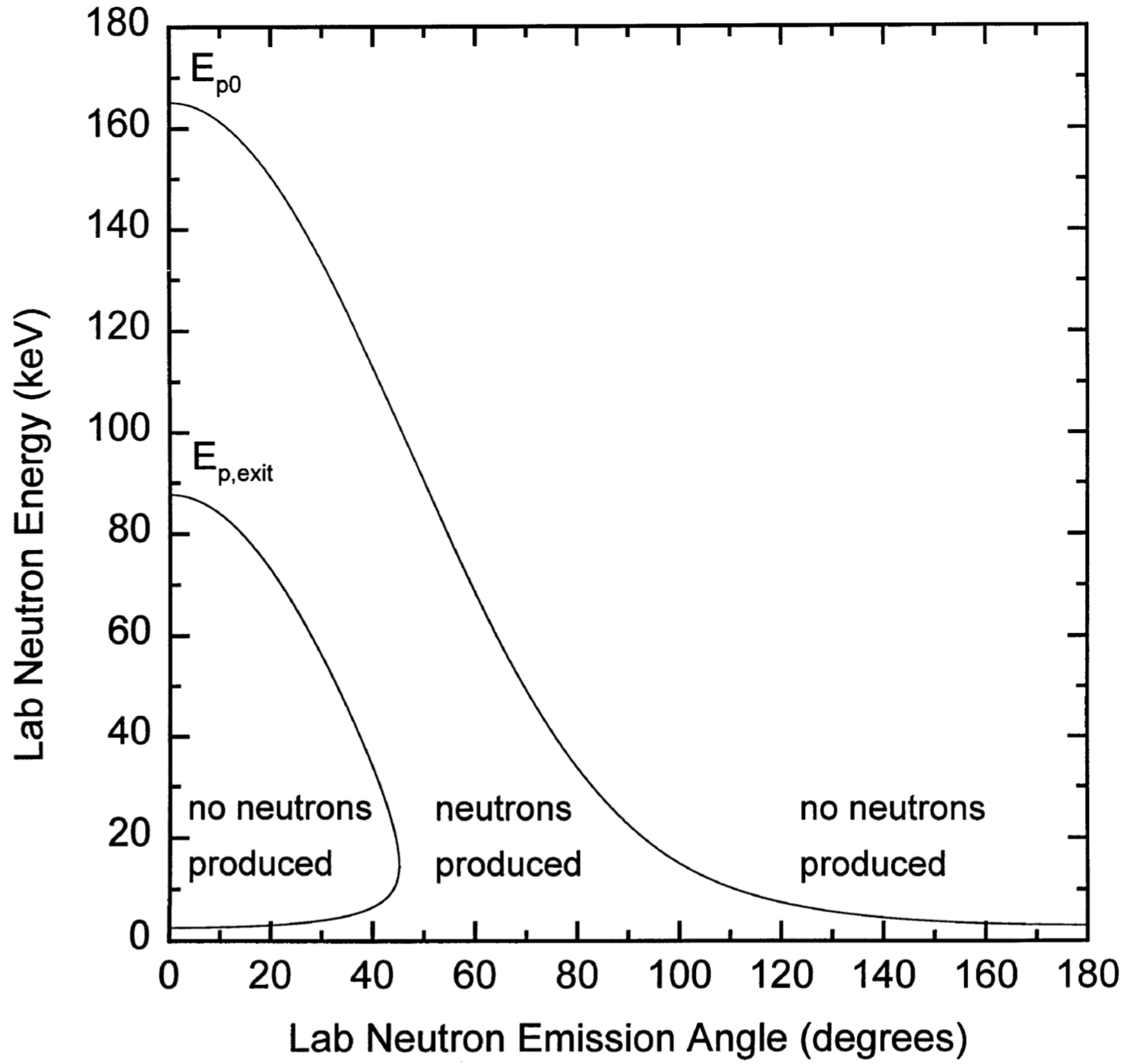
$$\nu_x +^{208} Pb \Rightarrow {}^{208}Pb^* + \nu_x' \qquad (NC)$$
$$\Downarrow$$
$${}^{208-y}Pb + x\gamma + yn.$$

Measuring the $\boldsymbol{\nu}$-induced neutrons



- Several palletized (mobile) targets with LS detectors delivered to the SNS
- Will measure neutrino-induced-neutrons on Pb, Fe and Cu

Neutron beam production



- 7Li(p,n) reaction at ~0 degrees [1]
- LiF evaporated onto thin, aluminum backings
  - Thin LiF layer, ~100-500 nm, limits proton straggling
  - High-purity Al (99.999%), 0.25-mm thick, limits neutron interactions in backing

[1] C.L. Lee, X.-L. Zhou, Nucl. Instrum. Meth. B 152, 1-11 (1999)