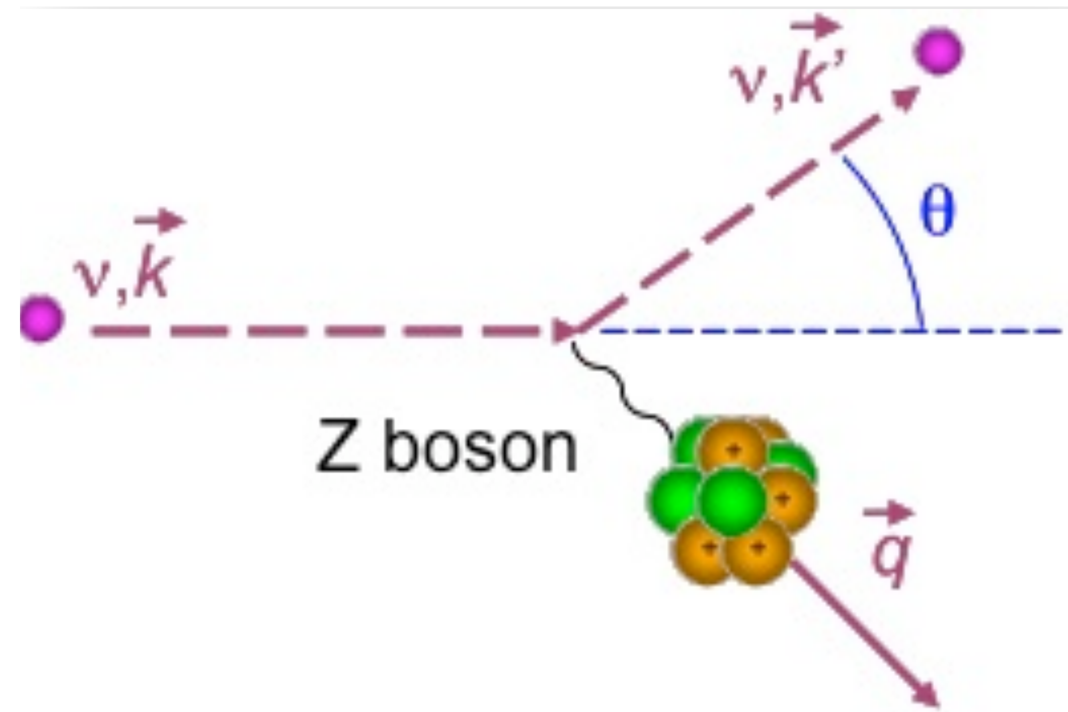
COHERENT ν Scattering

Phil Barbeau, Duke University

Coherent **ν**-Nucleus Scattering

- Predicted in 1974 with the realization of the weak neutral current: as yet unobserved
- Neutrino scatters coherently off all Nucleons → cross section enhancement: $\sigma \propto \mathbf{N^2}$
- Initial and final states must be identical: Neutral Current elastic scattering
- Nucleons must recoil in phase →low momentum transfer qR <1 → *very* low energy nuclear recoil



D. Z. Freedman, PRD 9 (5) 1974

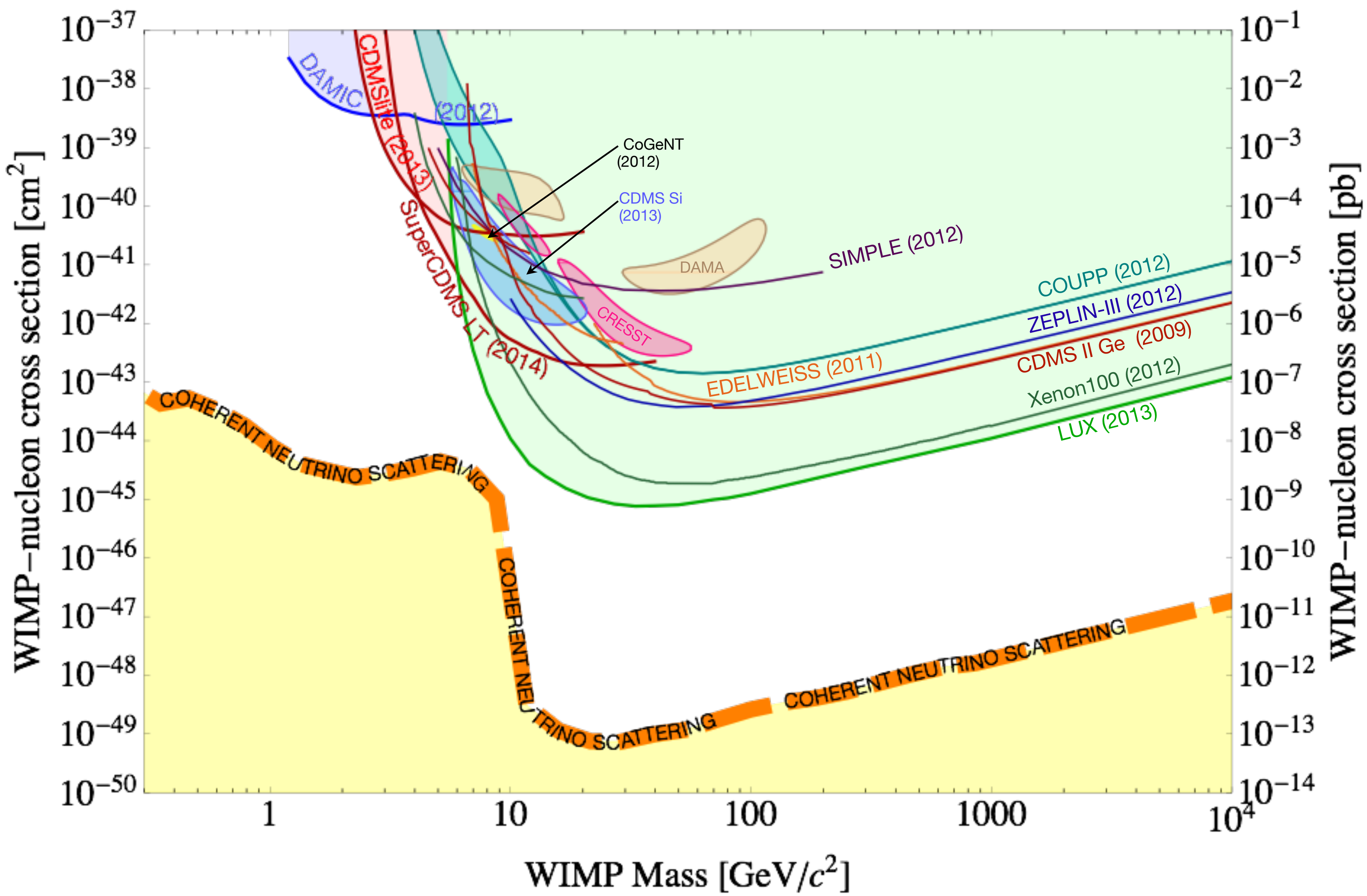
Why Measure Coherent $\boldsymbol{\nu}$-Nucleus Scattering?

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

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

Why Measure Coherent ν-Nucleus Scattering?

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

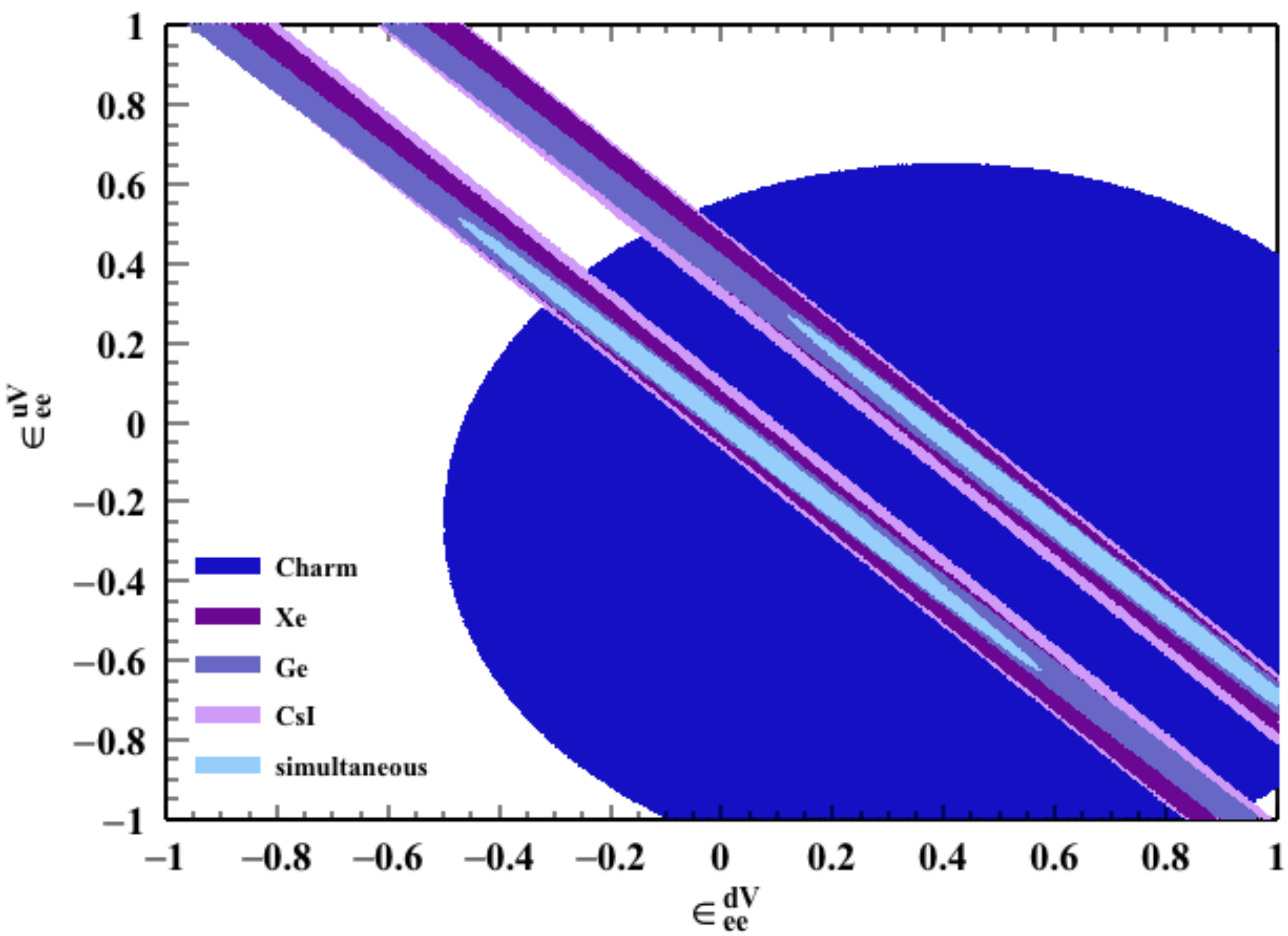


Why Measure Coherent **ν**-Nucleus Scattering?

- By measuring the relative rates on several nuclear targets we dramatically extend the sensitivity of searches for Non-Standard **ν** Interactions

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

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



Why Measure Coherent ν-Nucleus Scattering?

- A high-σ, neutral current detector would be a clean way to search for sterile **ν**'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

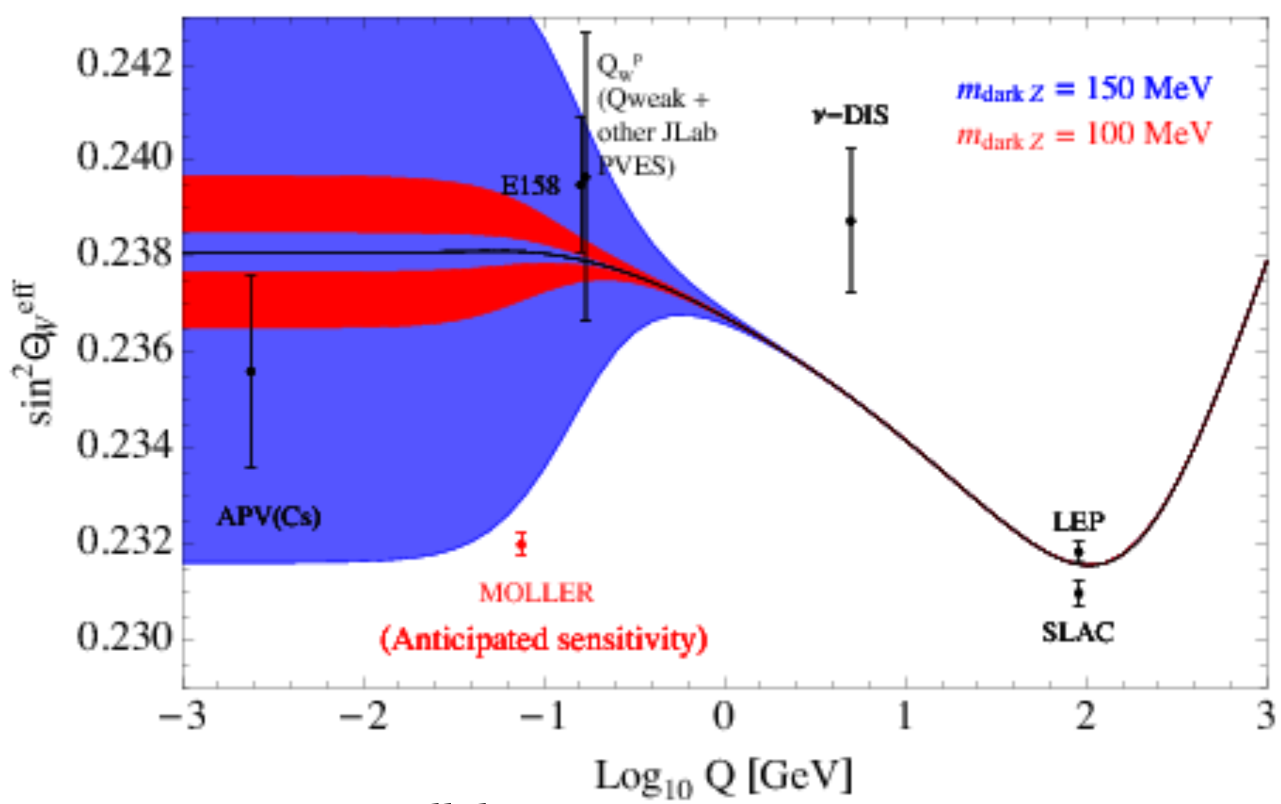
$$\sigma_{coh} \sim \frac{G_f^2 E^2}{4\pi}(Z(4\ sin^2\theta_w - 1) + N)^2$$

- 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



MOLLER Collaboration, arXiv:1411.4088

COHERENT SNS

Duke University
Indiana University
ITEP
LANL
LBNL
MEPhI

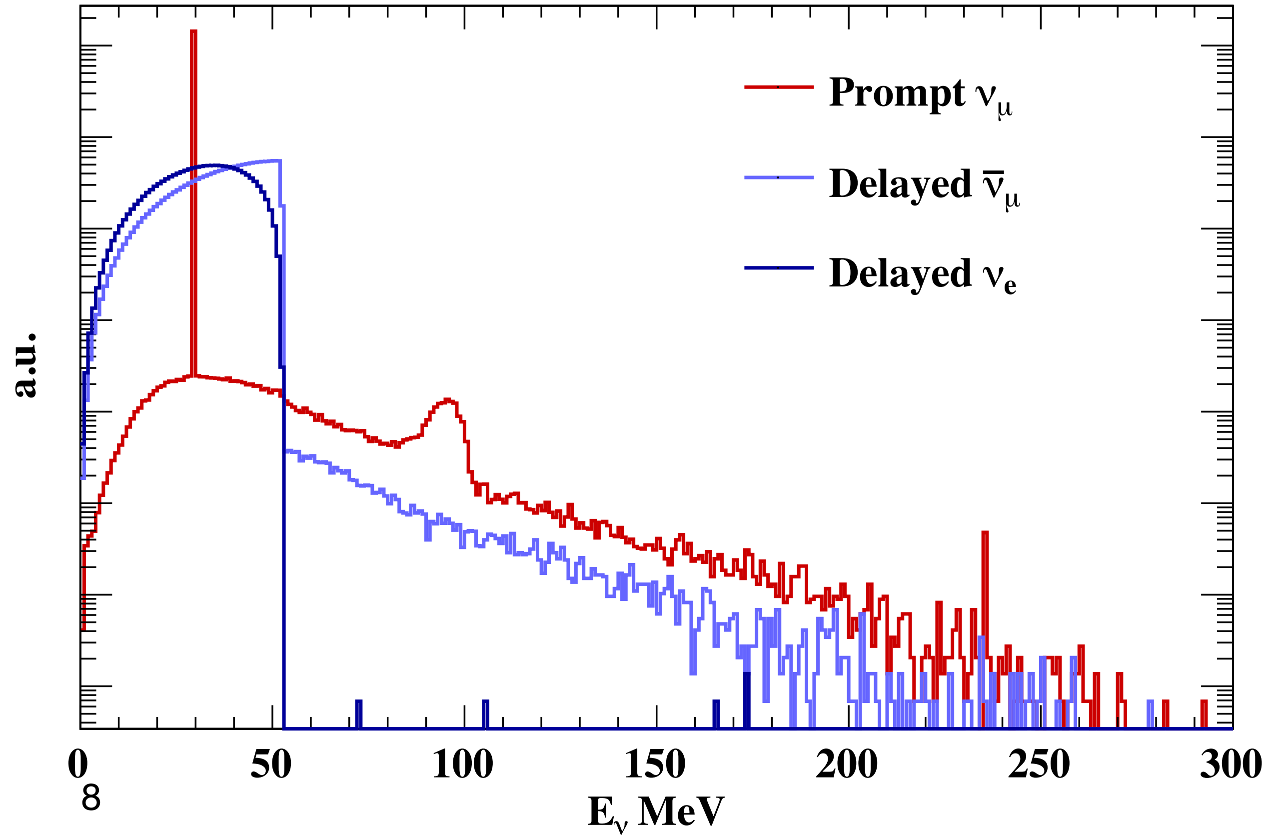
NC Central University
NC State University
New Mexico State University
ORNL
SNL

TUNL
UC Berkeley
University of Chicago
University of Florida
University of Tennessee
University of Washington

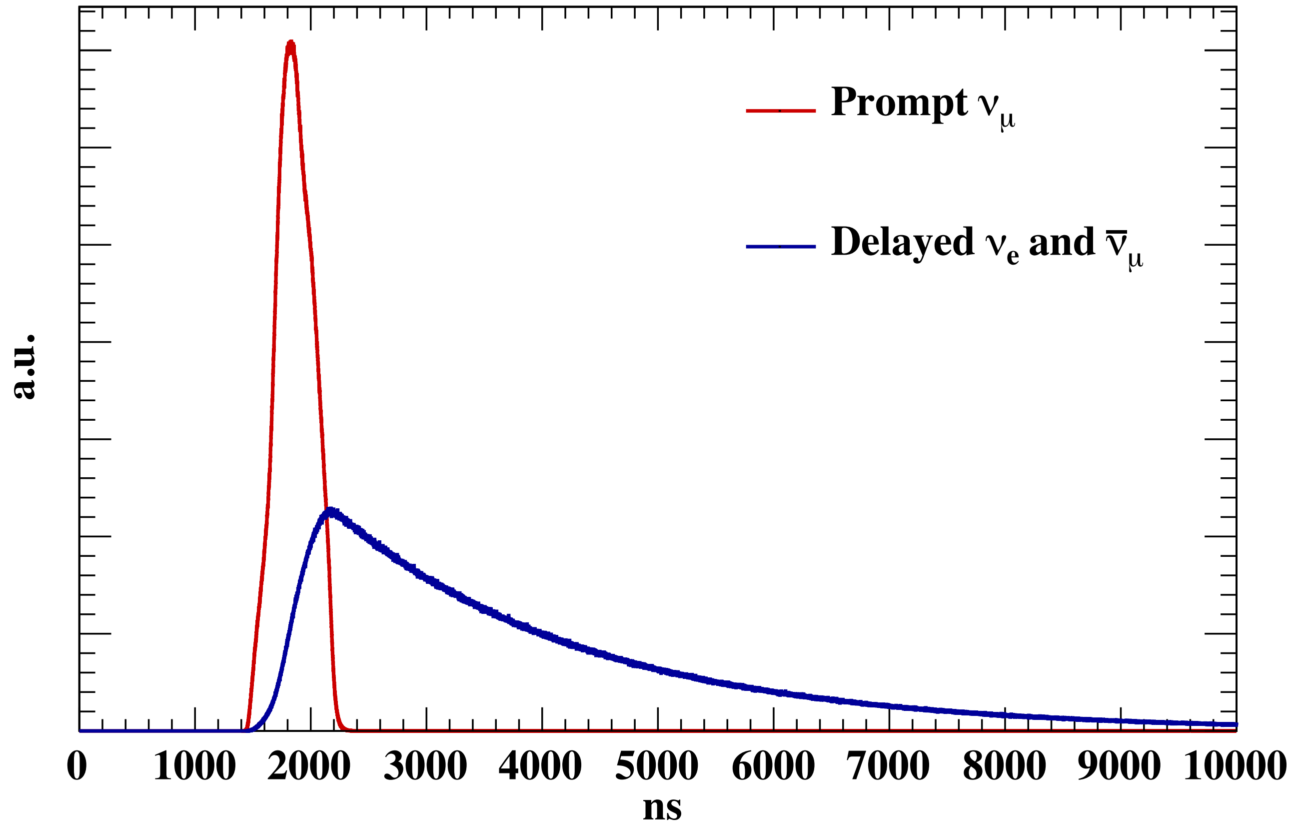
The Spallation Neutron Source

- Pion Decay-at-Rest Neutrino Source
- ν flux 4.3×10^7 ν cm^{-1} s^{-1} at 20 m
- Pulsed: 800 ns full-width at 60 Hz

<1% contamination from non-CEvNS scatters

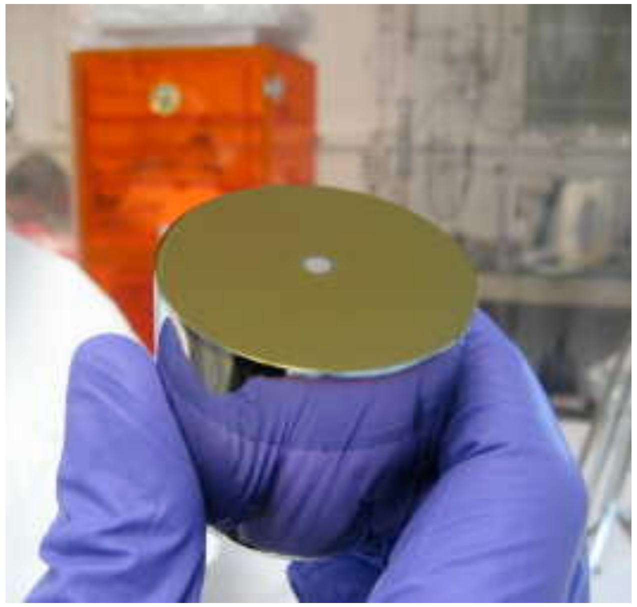


~4x10^-5 background reduction



How to Make an Unambiguous Measurement

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



P-Type Point Contact HPGe

Low-Background CsI[Na]

NaI[Tl]

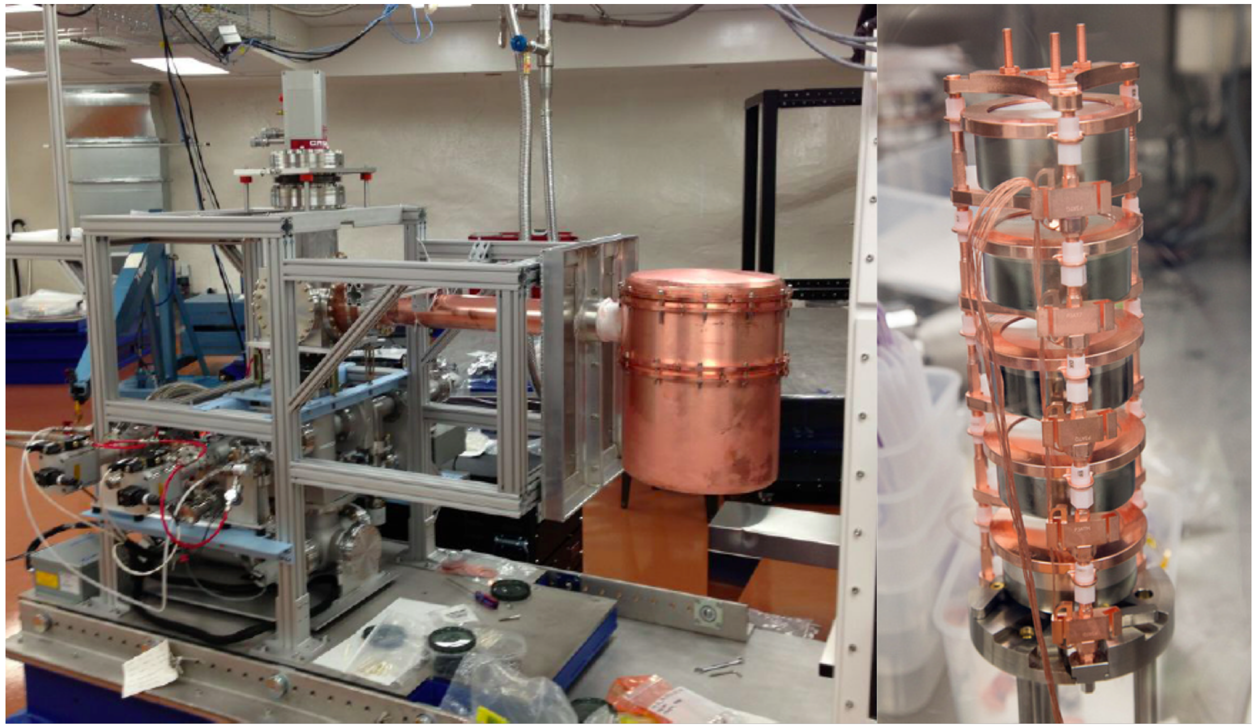
Single Phase LAr

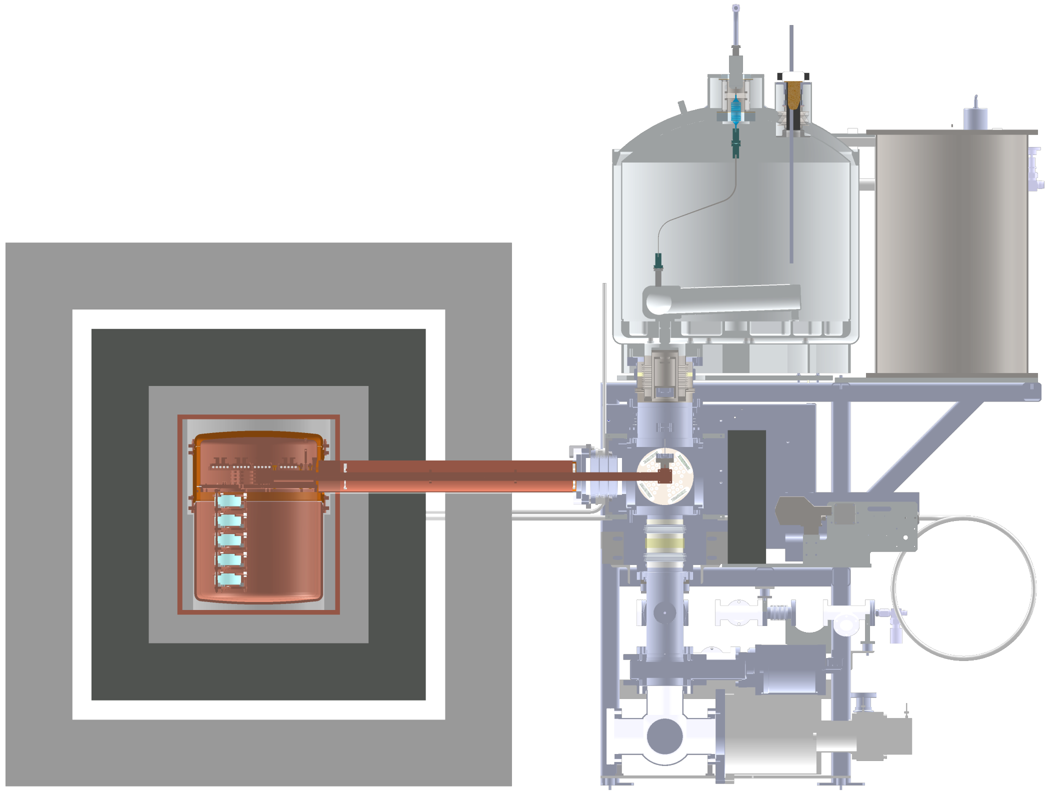
Detector Subsystems: CsI[Na]

- 14 kg low-background CsI[Na] crystal
- Large N: 74, 78
- Already installed at SNS

Detector Subsystems: HPGe PPCs

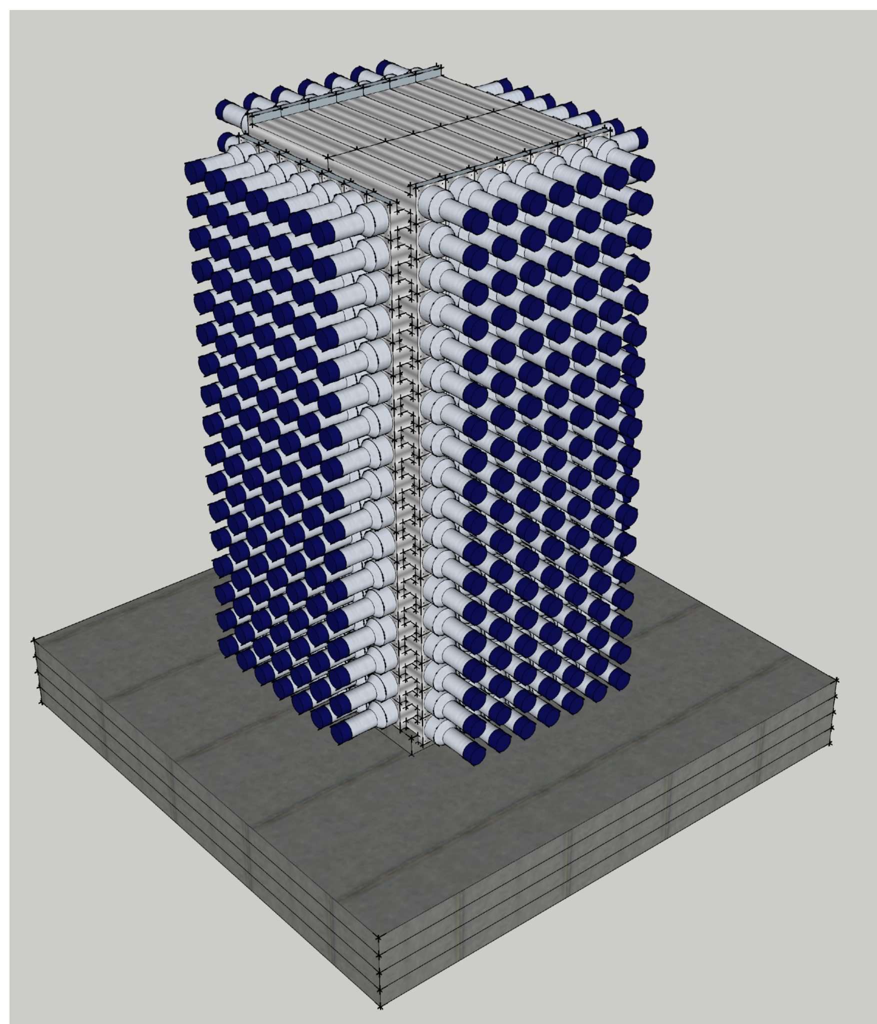
- Repurposed MAJORANA DETECTORS
- 5-10kg PPC detector mass
- Smaller N: 38-44
- Excellent resolution at low energies
- Well-measured quenching factor





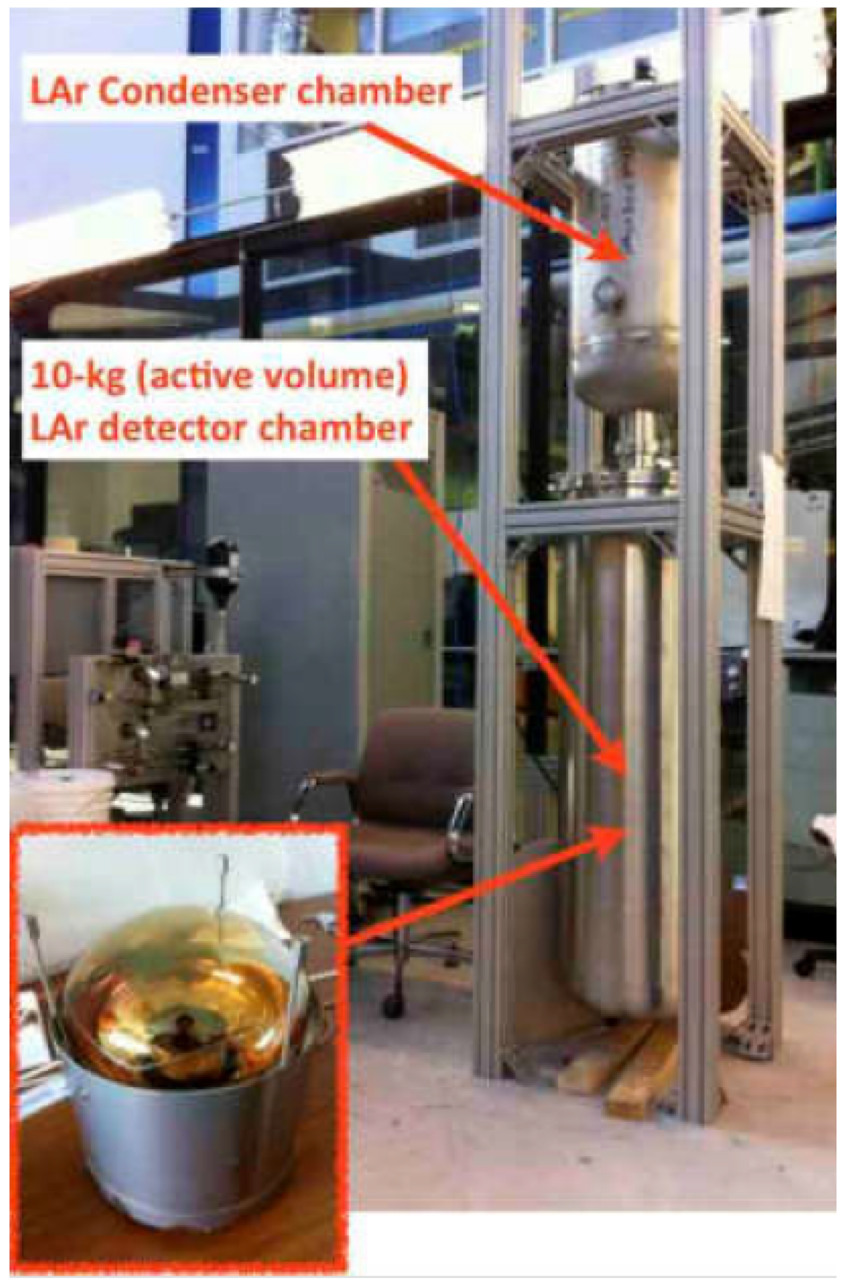
Detector Subsystems: NaI[Tl]

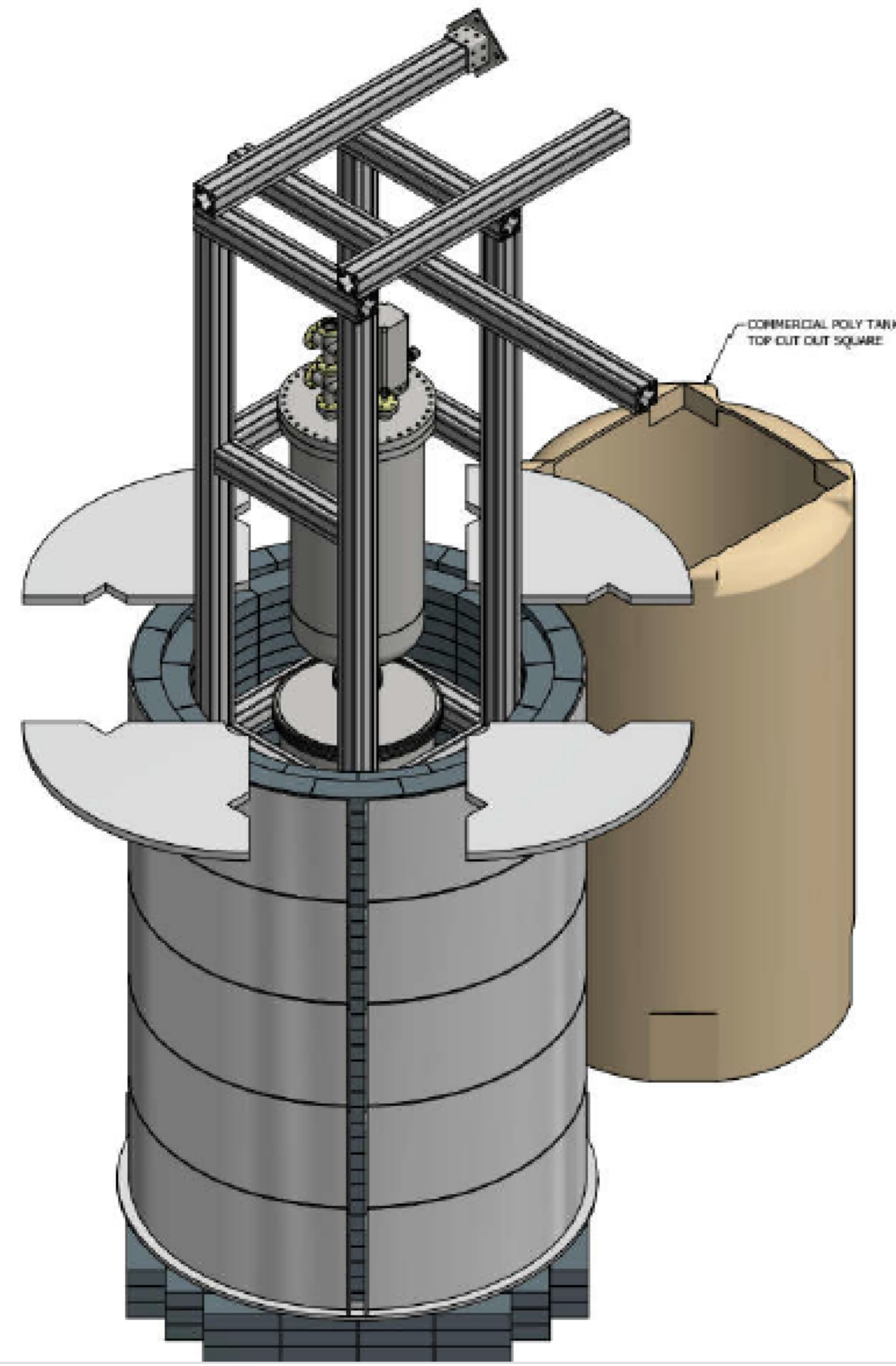
- Initial deployment 185 kgs
- Up to 9 tons in hand
- N = 23 for Na
- Instrumentation tests underway at Duke and UW
- QF understood



Detector Subsystems: Single Phase LAr

- Medium N: 40
- CENNS-10 Detector under consideration
- QF also known

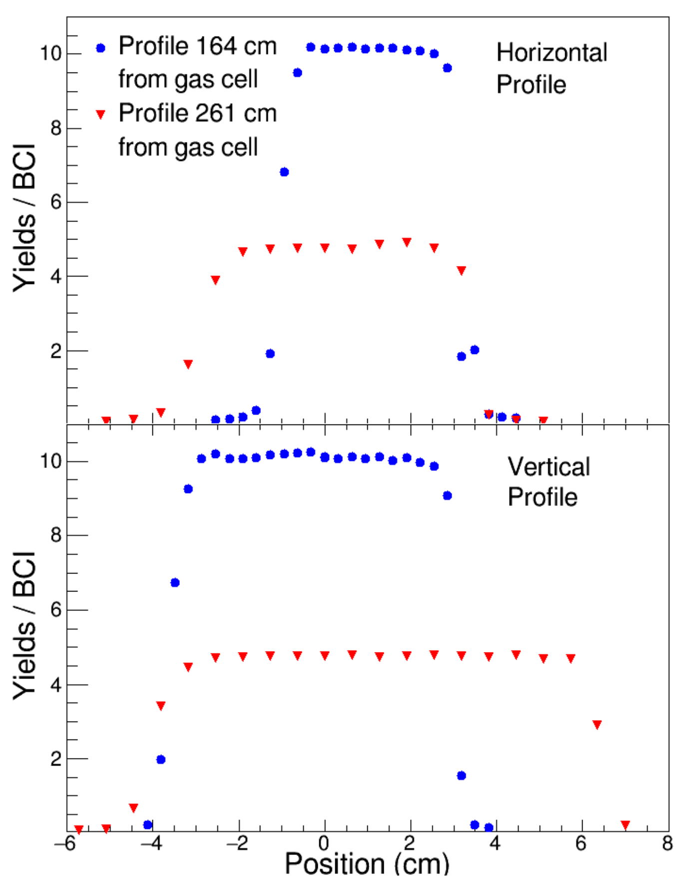


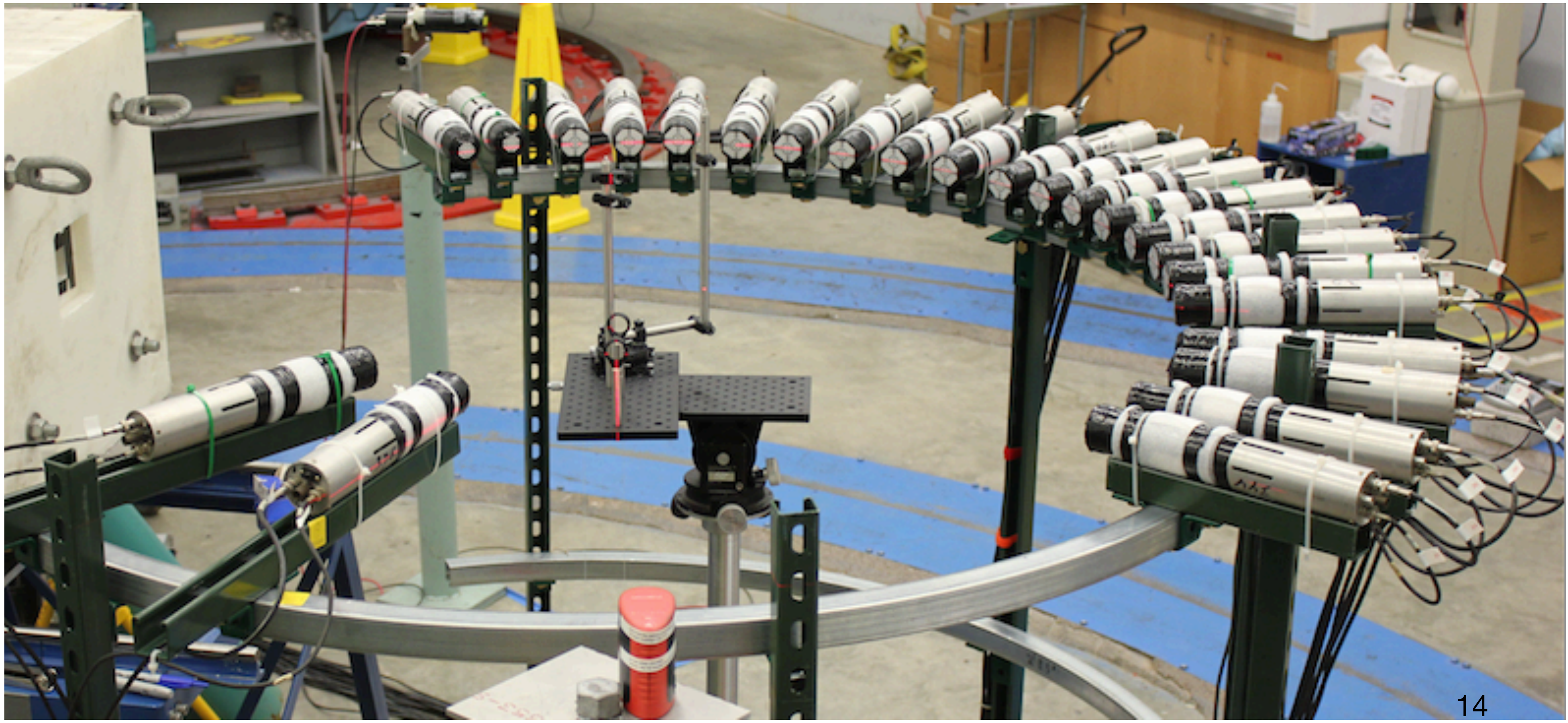


Quenching Factor Measurements

- A facility has been developed at Duke/TUNL to enable the precision calibration of all of these detectors. *CsI(Na) and NaI(Tl) data in the can. Quenching factor uncertainties are the dominant uncertainty on the cross-sections, after the beam flux.*

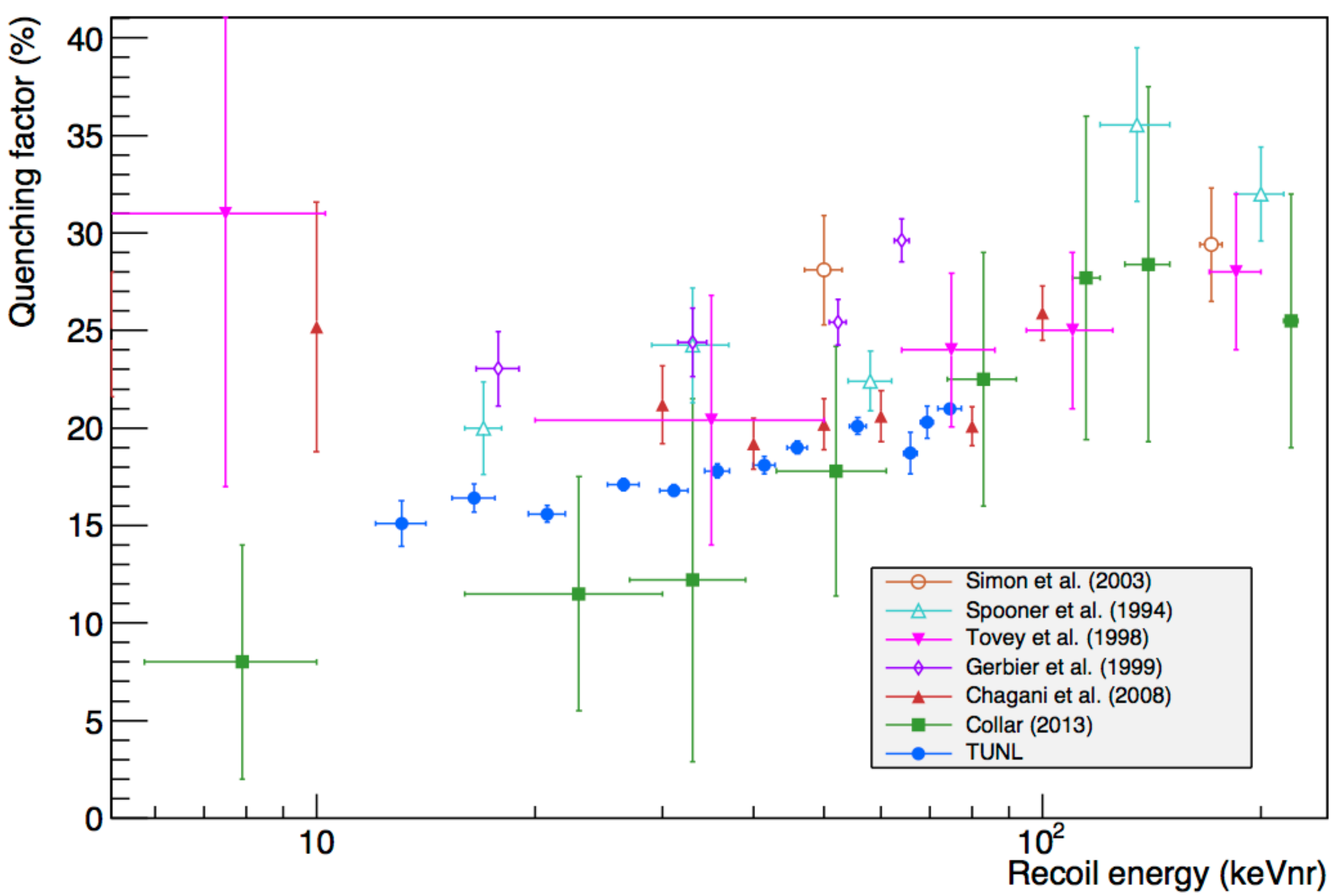
- The neutron beam is tunable (20 keV - 3 MeV), Monochromatic (3 keV width), collimated (1.5 cm) and pulsed (2 ns)





Quenching Factor Measurements

- The story of the quenching factors of Na recoils goes back a long way. High precision measurements recently performed by Duke and Princeton confirm ~ 15%.
- Recently remeasured CsI[Na] with encouraging results.



NaI[Tl]: Two primary measurement goals

- CEvNS on Na
- The electron neutrino Charged-Current interaction on ^{127}I

Isotope	Reaction Channel	Source	Experiment	Measurement (10^{-42} cm^2)	Theory (10^{-42} cm^2)
^{2}H	^{2}H(ν_e, e^-)pp	Stopped π/μ	LAMPF	52 ± 18(tot)	54 (IA) (Tatara *et al.*, 1990)
^{12}C	^{12}C$(\nu_e, e^-)^{12}$N$_{g.s.}$	Stopped π/μ	KARMEN	9.1 ± 0.5(stat) ± 0.8(sys)	9.4 [Multipole](Donnelly and Peccei, 1979)
		Stopped π/μ	E225	10.5 ± 1.0(stat) ± 1.0(sys)	9.2 [EPT] (Fukugita *et al.*, 1988).
		Stopped π/μ	LSND	8.9 ± 0.3(stat) ± 0.9(sys)	8.9 [CRPA] (Kolbe *et al.*, 1999b)
	^{12}C$(\nu_e, e^-)^{12}$N*	Stopped π/μ	KARMEN	5.1 ± 0.6(stat) ± 0.5(sys)	5.4-5.6 [CRPA] (Kolbe *et al.*, 1999b)
		Stopped π/μ	E225	3.6 ± 2.0(tot)	4.1 [Shell] (Hayes and S, 2000)
		Stopped π/μ	LSND	4.3 ± 0.4(stat) ± 0.6(sys)	
	^{12}C$(\nu_\mu, \nu_\mu)^{12}$C*	Stopped π/μ	KARMEN	3.2 ± 0.5(stat) ± 0.4(sys)	2.8 [CRPA] (Kolbe *et al.*, 1999b)
	^{12}C$(\nu, \nu)^{12}$C*	Stopped π/μ	KARMEN	10.5 ± 1.0(stat) ± 0.9(sys)	10.5 [CRPA] (Kolbe *et al.*, 1999b)
	^{12}C(ν_μ, μ^-)X	Decay in Flight	LSND	1060 ± 30(stat) ± 180(sys)	1750-1780 [CRPA] (Kolbe *et al.*, 1999b)
					1380 [Shell] (Hayes and S, 2000)
					1115 [Green's Function] (Meucci *et al.*, 2004)
	^{12}C$(\nu_\mu, \mu^-)^{12}$N$_{g.s.}$	Decay in Flight	LSND	56 ± 8(stat) ± 10(sys)	68-73 [CRPA] (Kolbe *et al.*, 1999b)
					56 [Shell] (Hayes and S, 2000)
^{56}Fe	^{56}Fe$(\nu_e, e^-)^{56}$Co	Stopped π/μ	KARMEN	256 ± 108(stat) ± 43(sys)	264 [Shell] (Kolbe *et al.*, 1999a)
^{71}Ga	^{71}Ga$(\nu_e, e^-)^{71}$Ge	^{51}Cr source	GALLEX, ave.	0.0054 ± 0.0009(tot)	0.0058 [Shell] (Haxton, 1998)
		^{51}Cr	SAGE	0.0055 ± 0.0007(tot)	
		^{37}Ar source	SAGE	0.0055 ± 0.0006(tot)	0.0070 [Shell] (Bahcall, 1997)
^{127}I	^{127}I$(\nu_e, e^-)^{127}$Xe	Stopped π/μ	LSND	284 ± 91(stat) ± 25(sys)	210-310 [Quasi-particle] (Engel *et al.*, 1994)

J. A. Formaggio and S. Zeller, Rev. Mod. Phys. 84, 1307 (2012)

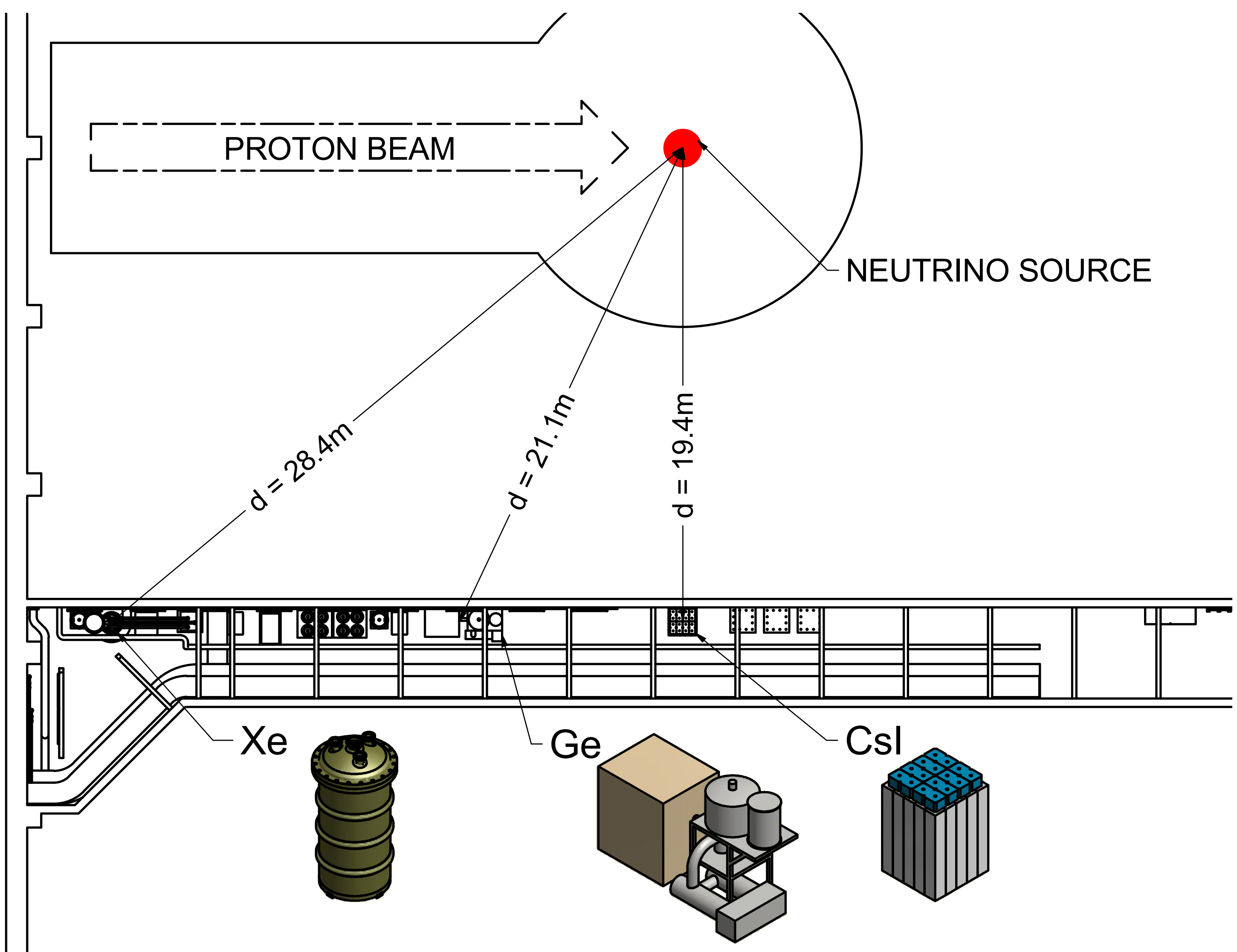
Backgrounds

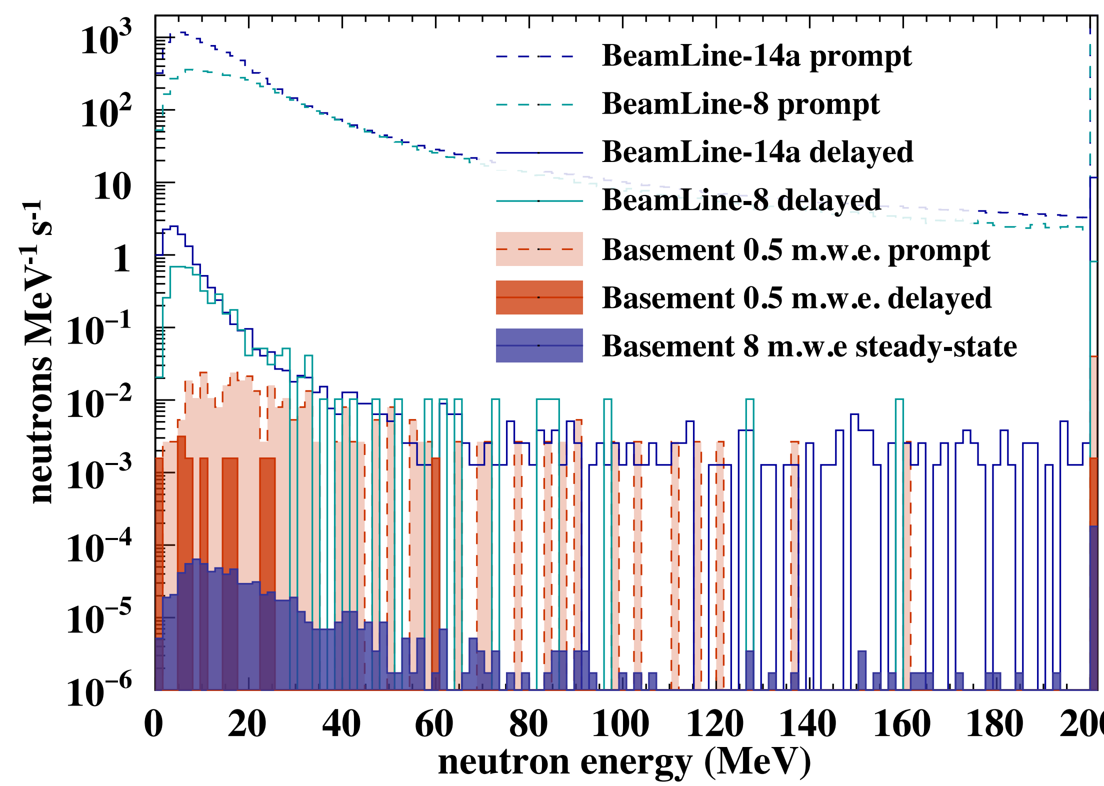
The SNS is a facility designed to produce neutrons (> 100 MeV), that are pulsed with the same time structure of the neutrinos (**with the exception of the characteristic decay time of the muon**).

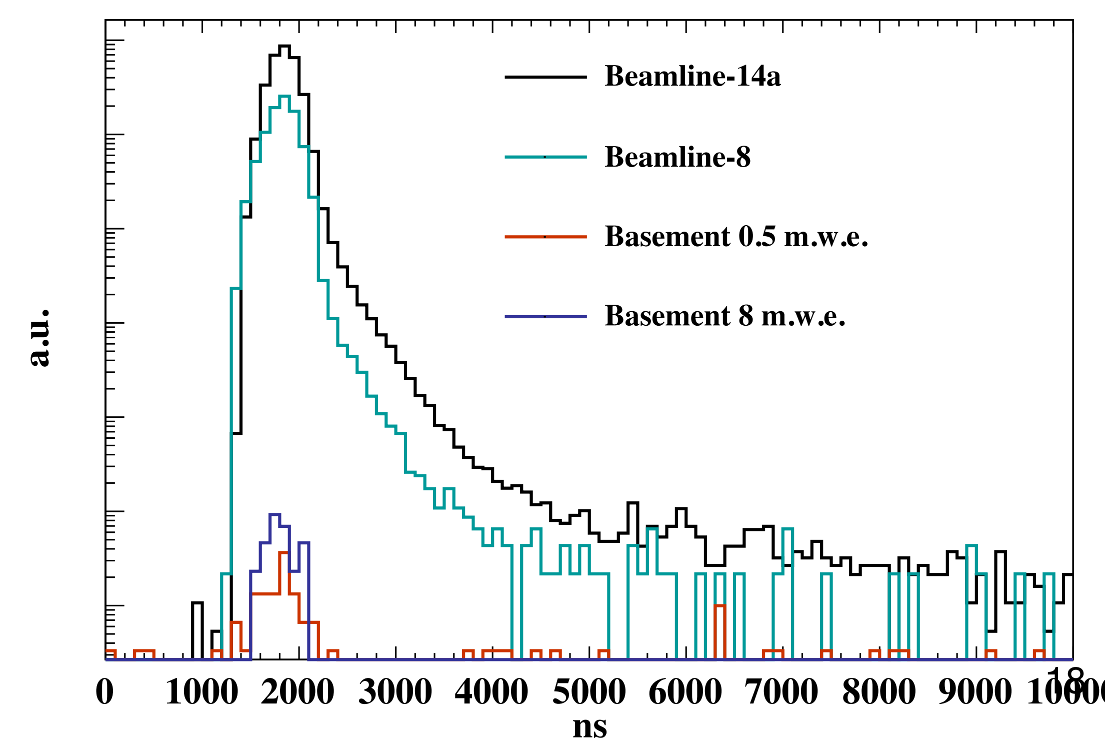
Neutron image of the SNS target, through shielding

Hunting for a Background-Free Location: Neutrino Alley

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



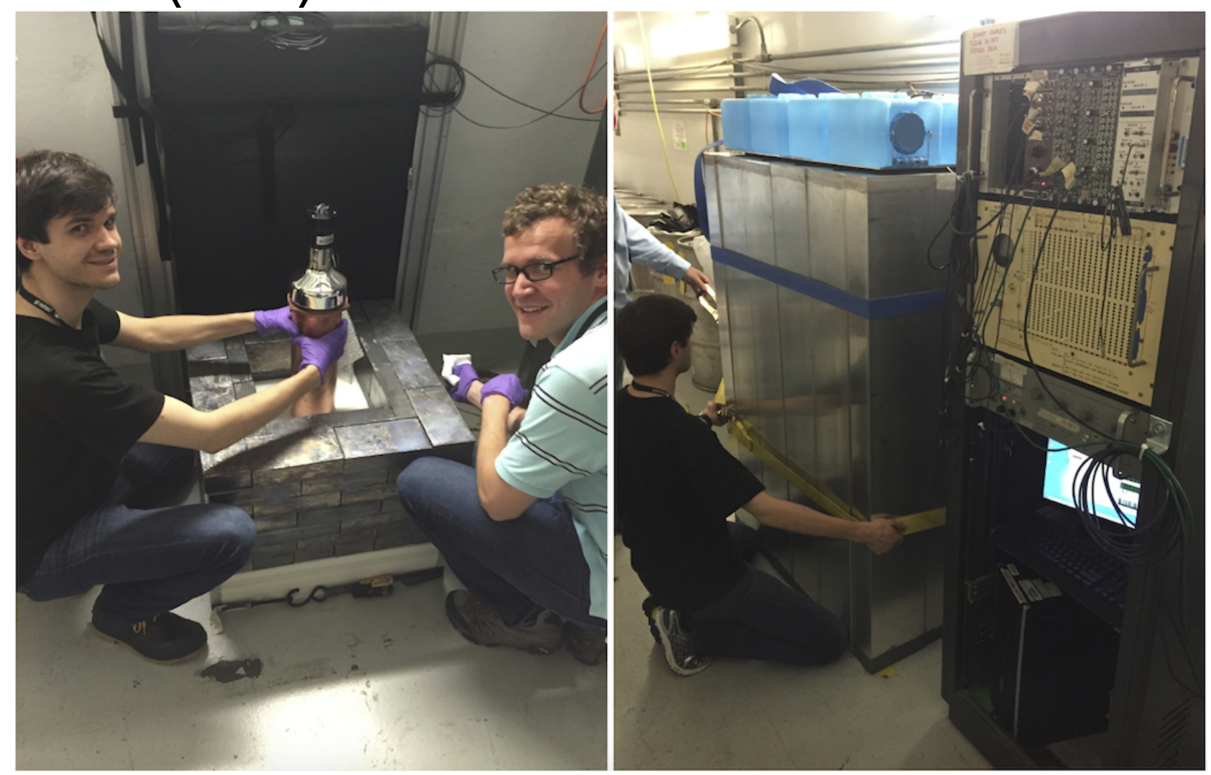




New Background: $\boldsymbol{\nu}$-induced neutrons (NINs)

- 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



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

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

NINs: Other uses

- NINs from Pb are fundamental mechanism for detection in HALO supernova neutrino detector [1]
- NIN interactions may influence nucleosynthesis in certain astrophysical environments [2]

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

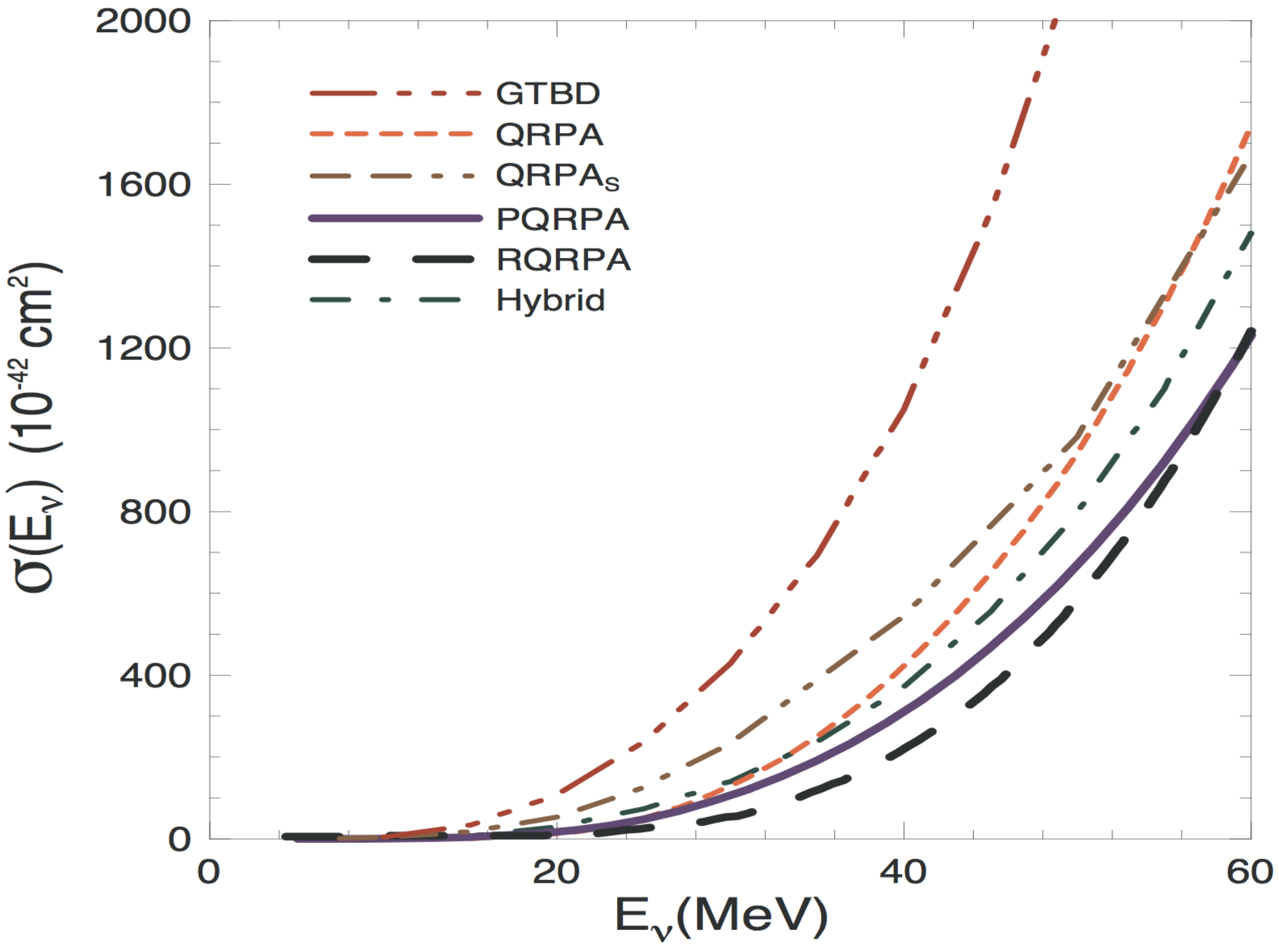
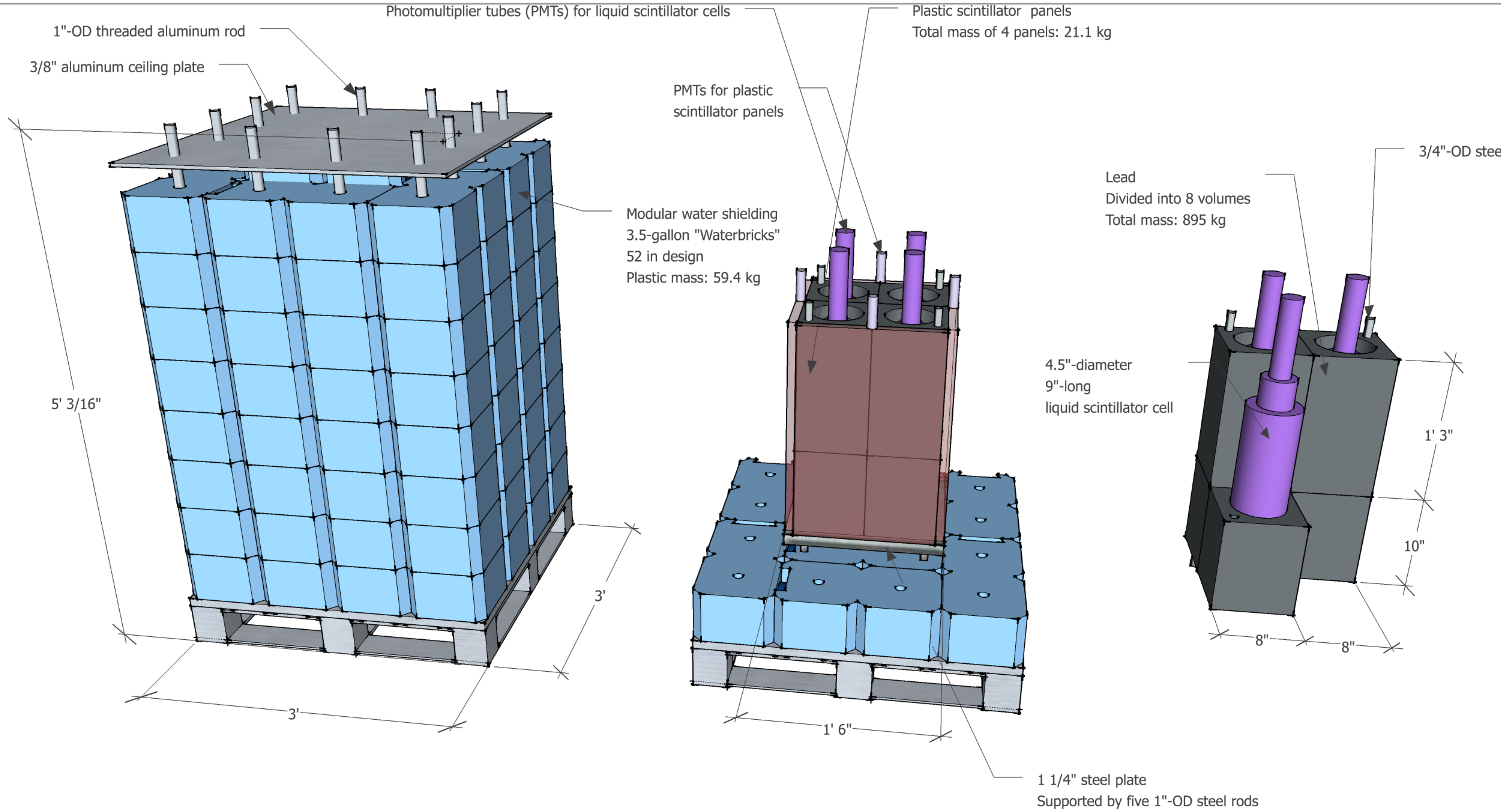


Figure from A.R. Samana and C.A. Bertulani, Phys. Rev. C (2008)

Measuring the ν-induced Neutrons

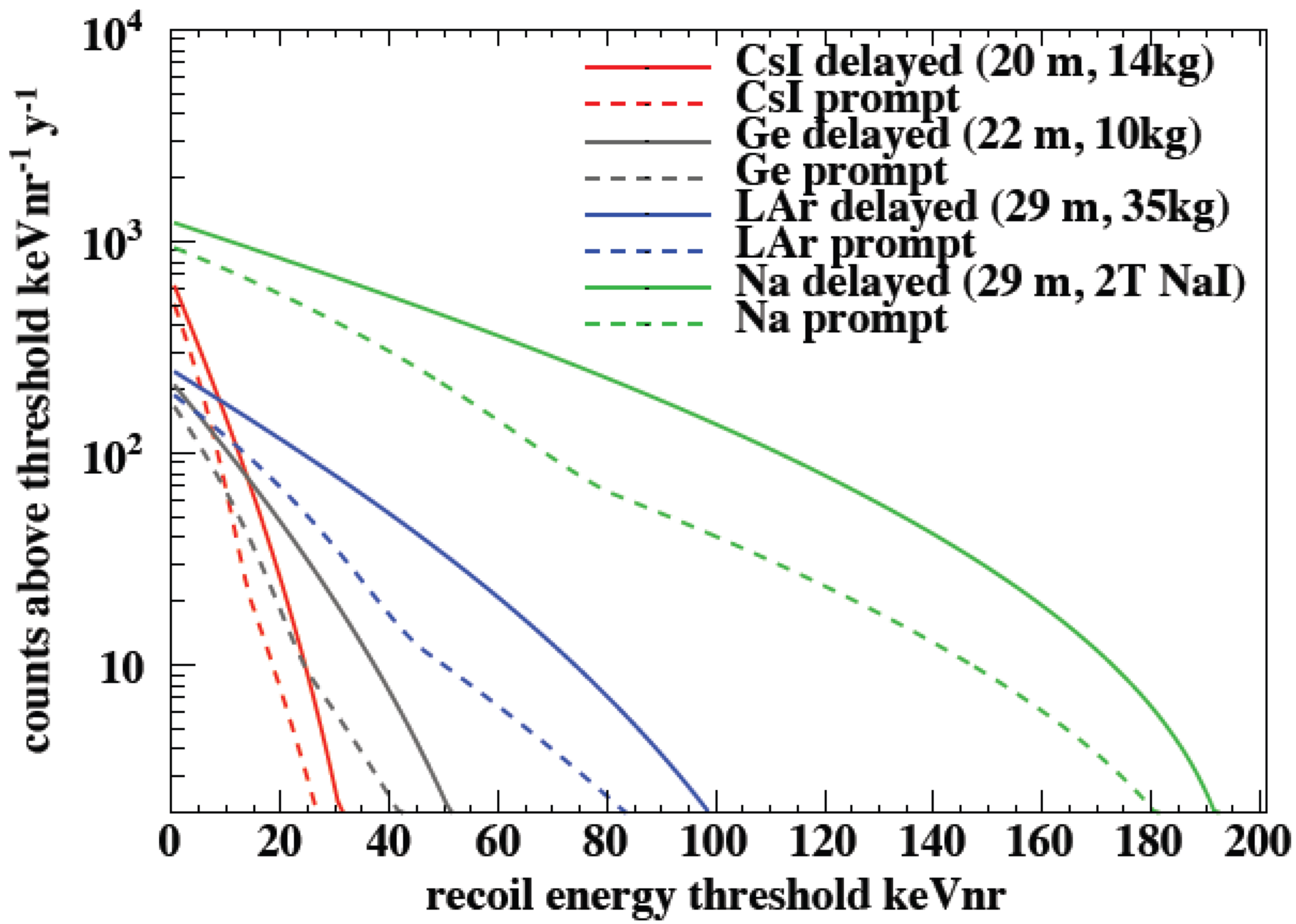


- Several palletized (mobile) targets with LS detectors delivered to the SNS
- Will measure neutrino-induced-neutrons on Pb, Fe and Cu

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

- The three on-site "neutrino-cubes" also provide nice, compact laboratories for other studies: NaI[Tl] CEvNS and $\boldsymbol{\nu}_e$ CC on ^{127}I

Expected Signals

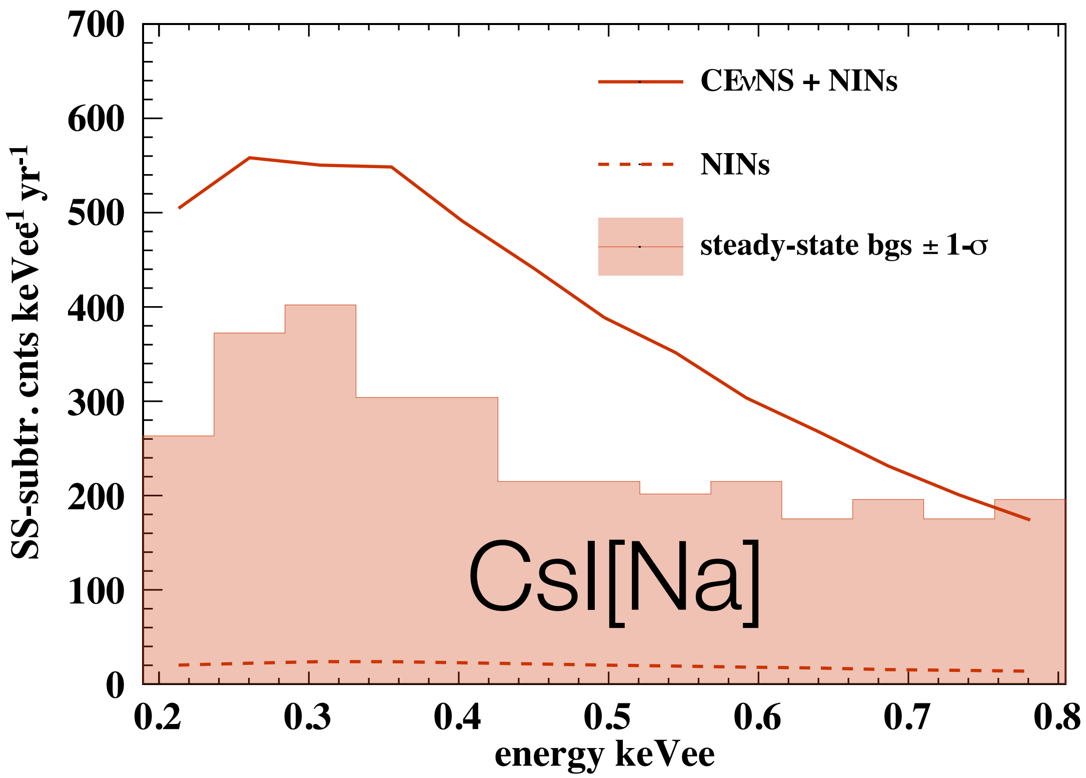


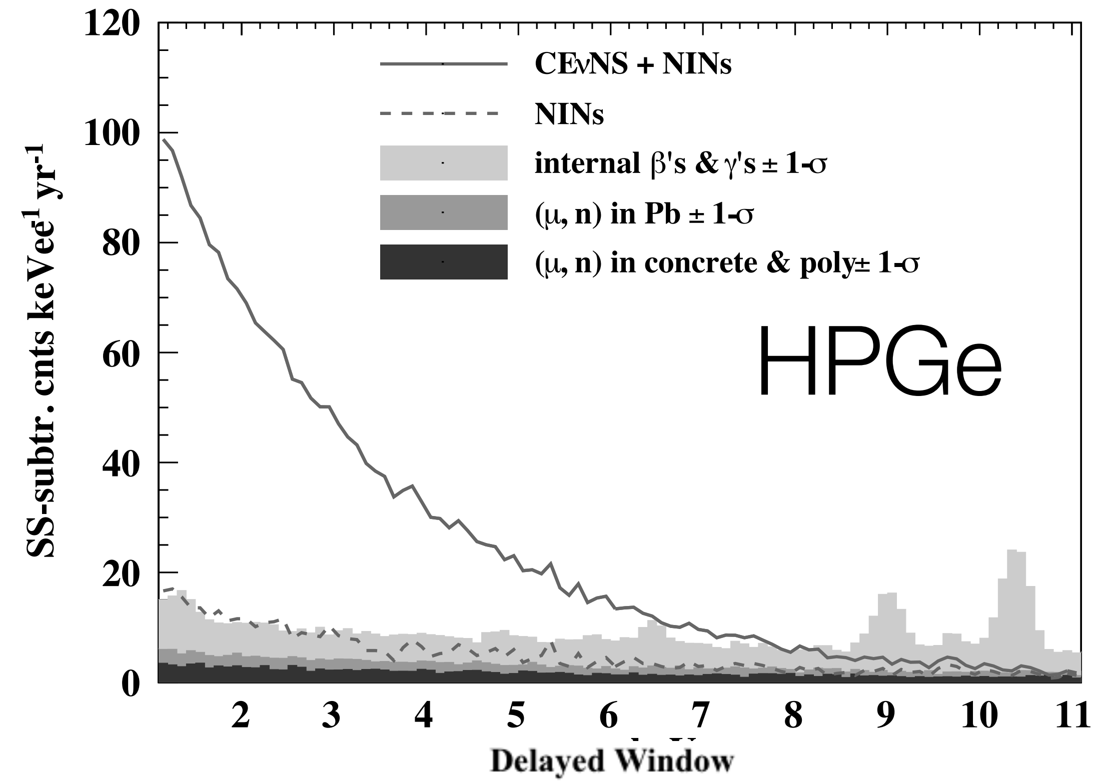
1.2 µs cut used to differentiate prompt and delayed neutrinos

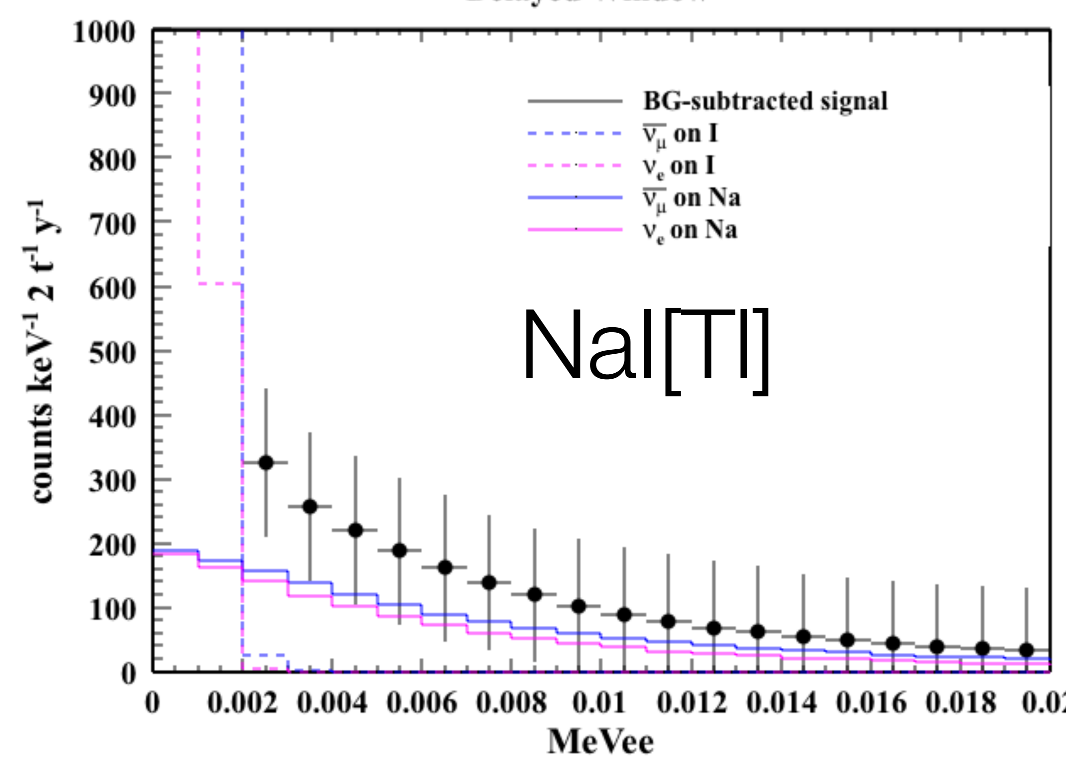
Rates depend on detector thresholds and quenching factors.

Thresholds and energy resolution effects not included.

Expected Signals



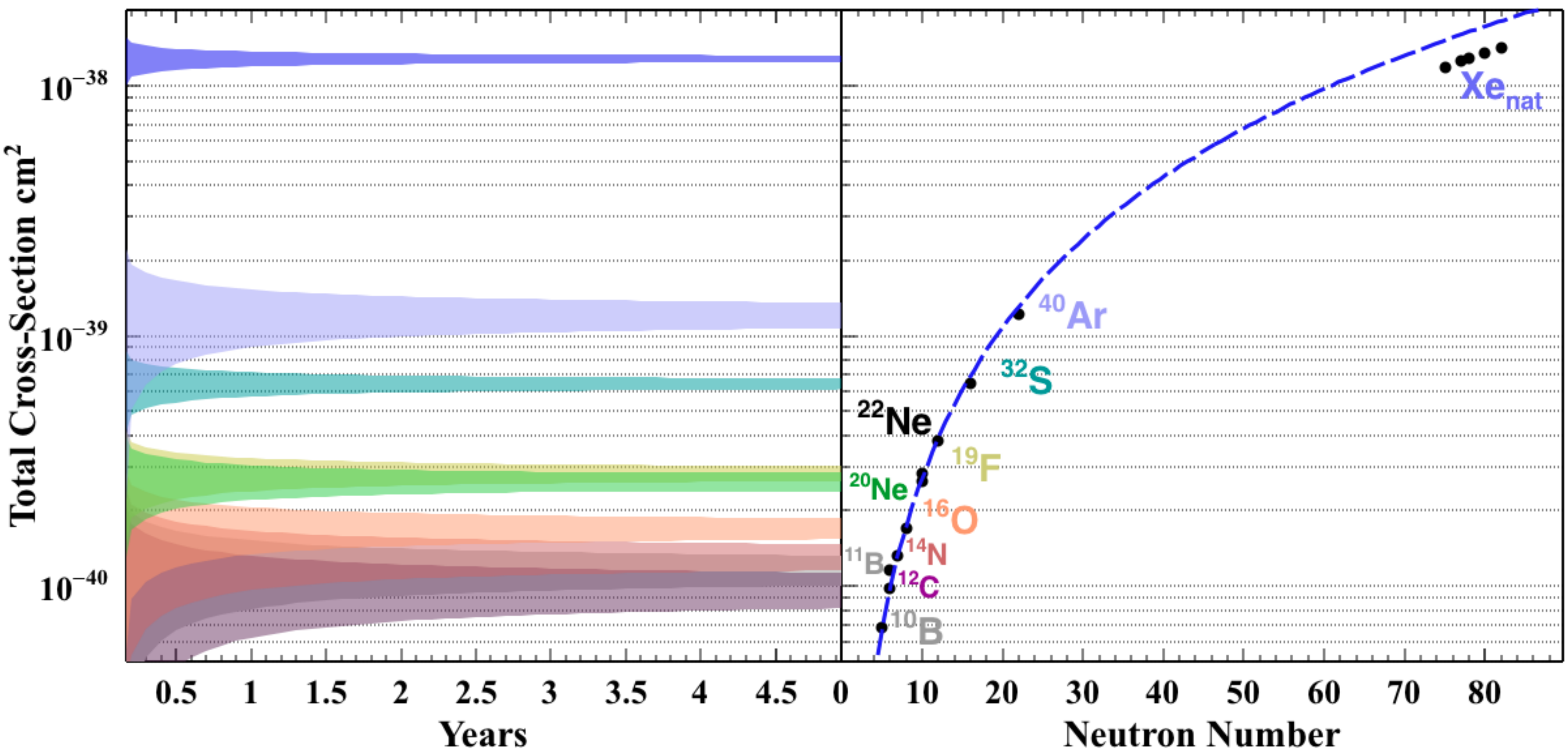




Steady-state background measured with anti-coincident triggers

NIN production rates inform the optimal shielding designs

Many Detectors working in Concert



- Statistics and systematics limited.
- 10% beam flux uncertainty not included

Summary

- A new collaboration has formed in 2013, 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] is in operation
- Several detectors to measure the **ν**-induced induced neutron emission cross-sections on Pb, Fe and Cu in operation
- 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 **($\sigma \sim N^2$)**