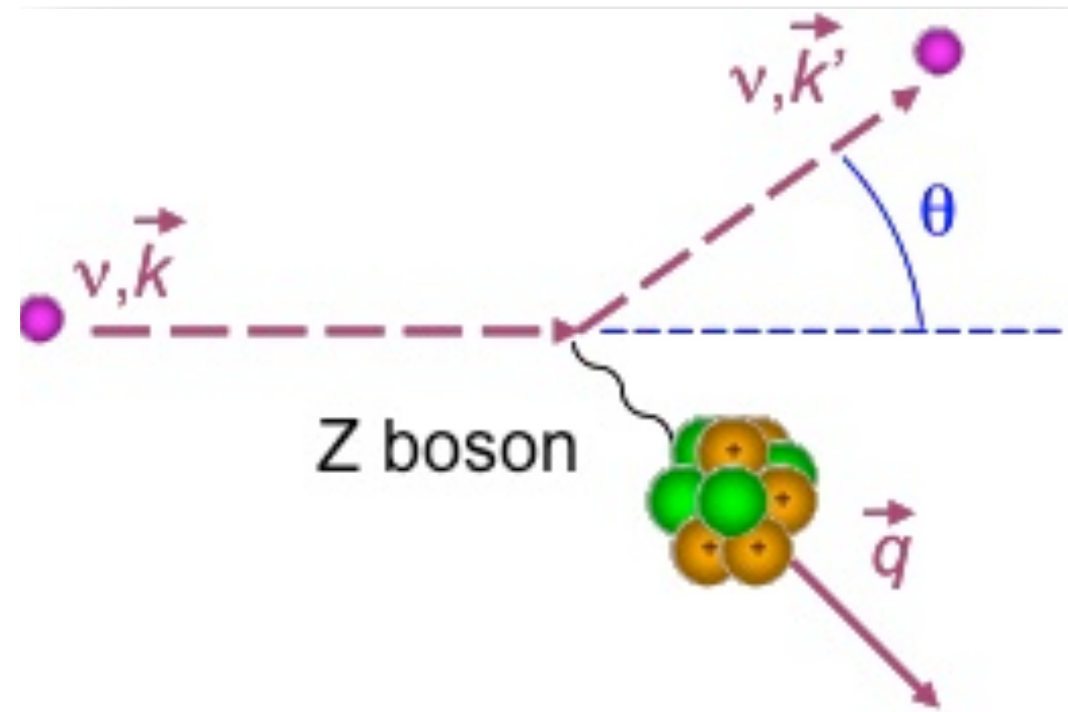
COHERENT SNS
ν Scattering

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: $\sigma \propto$ **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

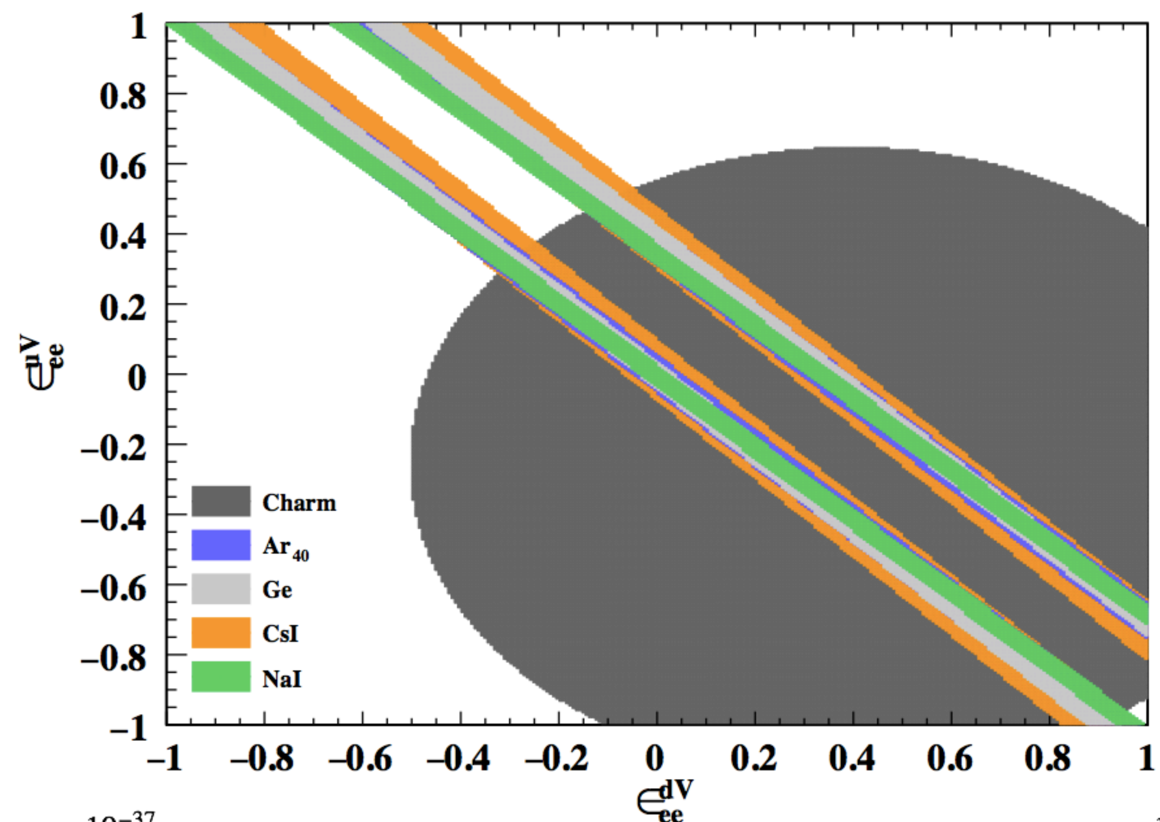
Why Measure Coherent **ν**-Nucleus Scattering?

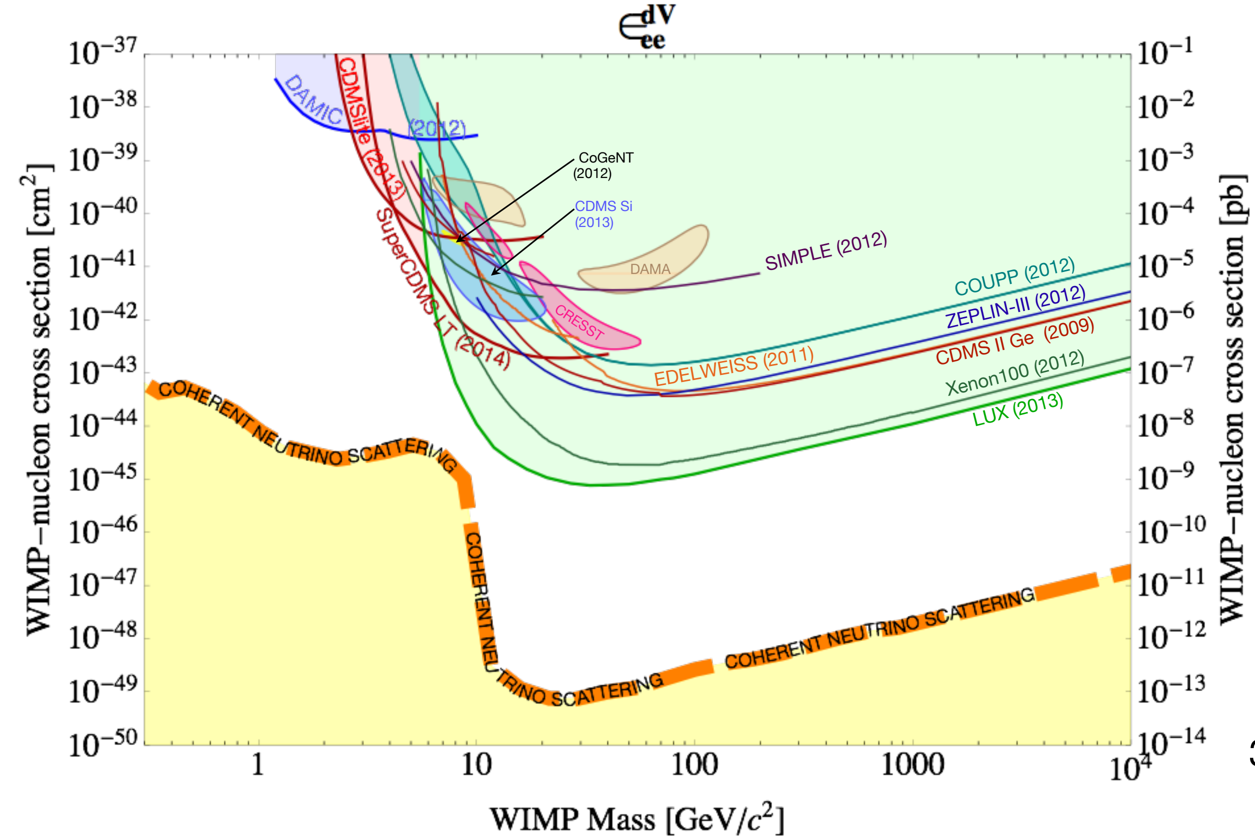
- Largest σ in Supernovae dynamics. We should measure it to validate the models
  J.R. Wilson, PRL 32 (74) 849

- 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

- NSI Relevance for DUNE & LBL CP violation.
  Mehedi Masud, Poonam, Mehta, arXiv: 1603.01380

- 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?

- 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

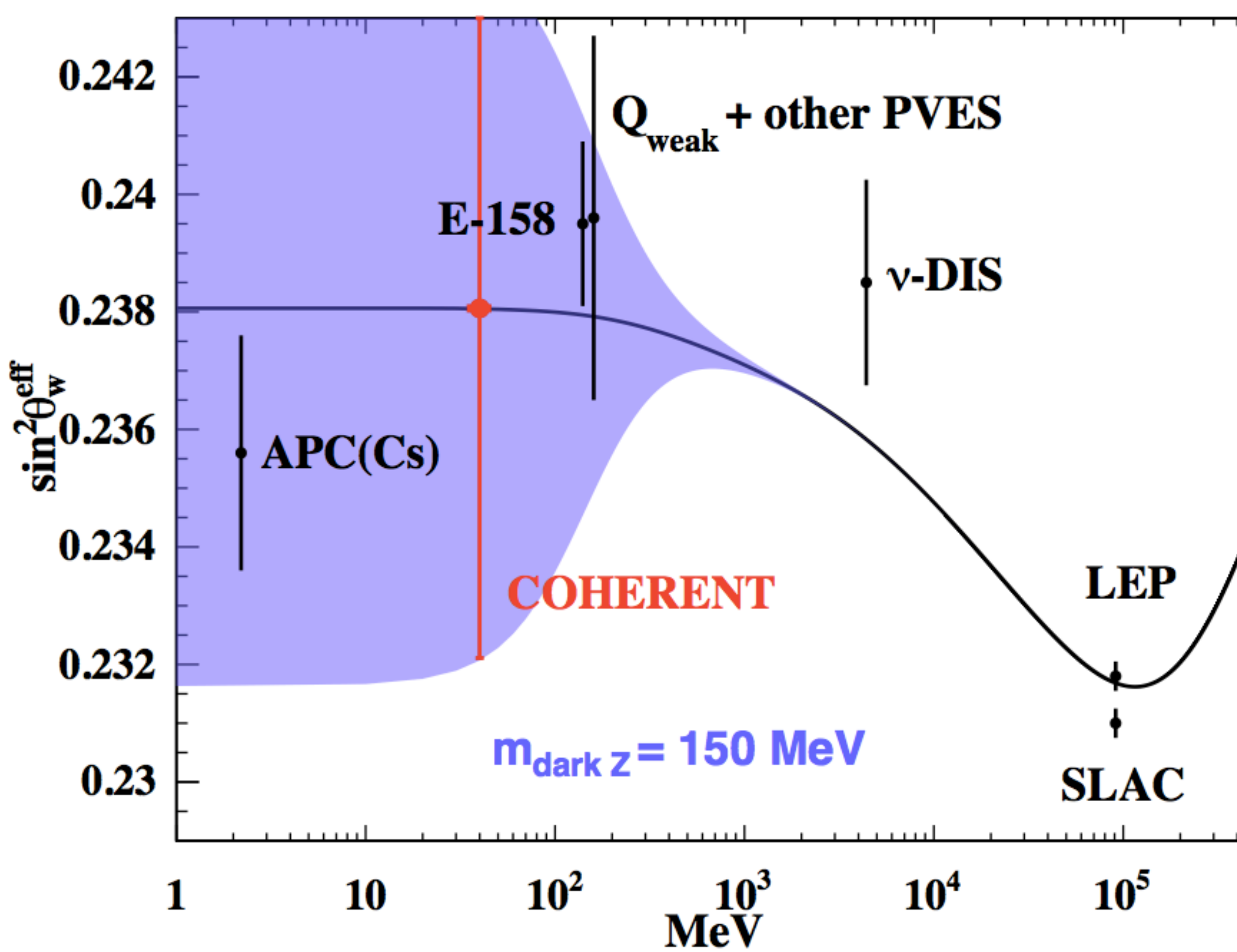
$$\sigma_{coh} \sim \frac{G_f^2 E^2}{4\pi}(Z(4\ sin^2\theta_w - 1) + N)^2$$

- Neutrino Magnetic Moments

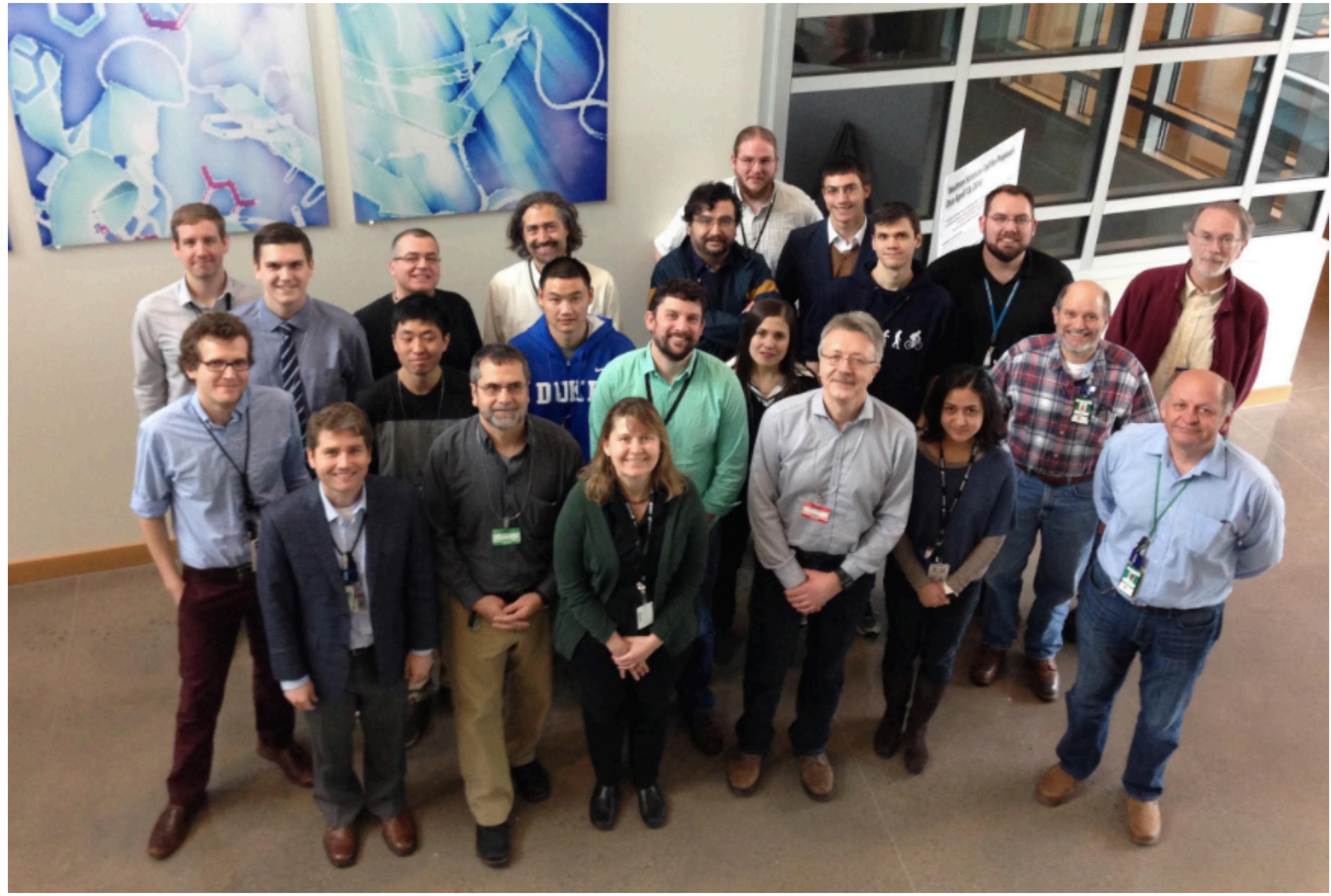
  A. C. Dodd, et al., PLB 266 (91), 434

- Measuring the neutron distribution functions (Form Factors)

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



COHERENT SNS



Duke University
Indiana University
ITEP
LANL
LBNL
MEPhI

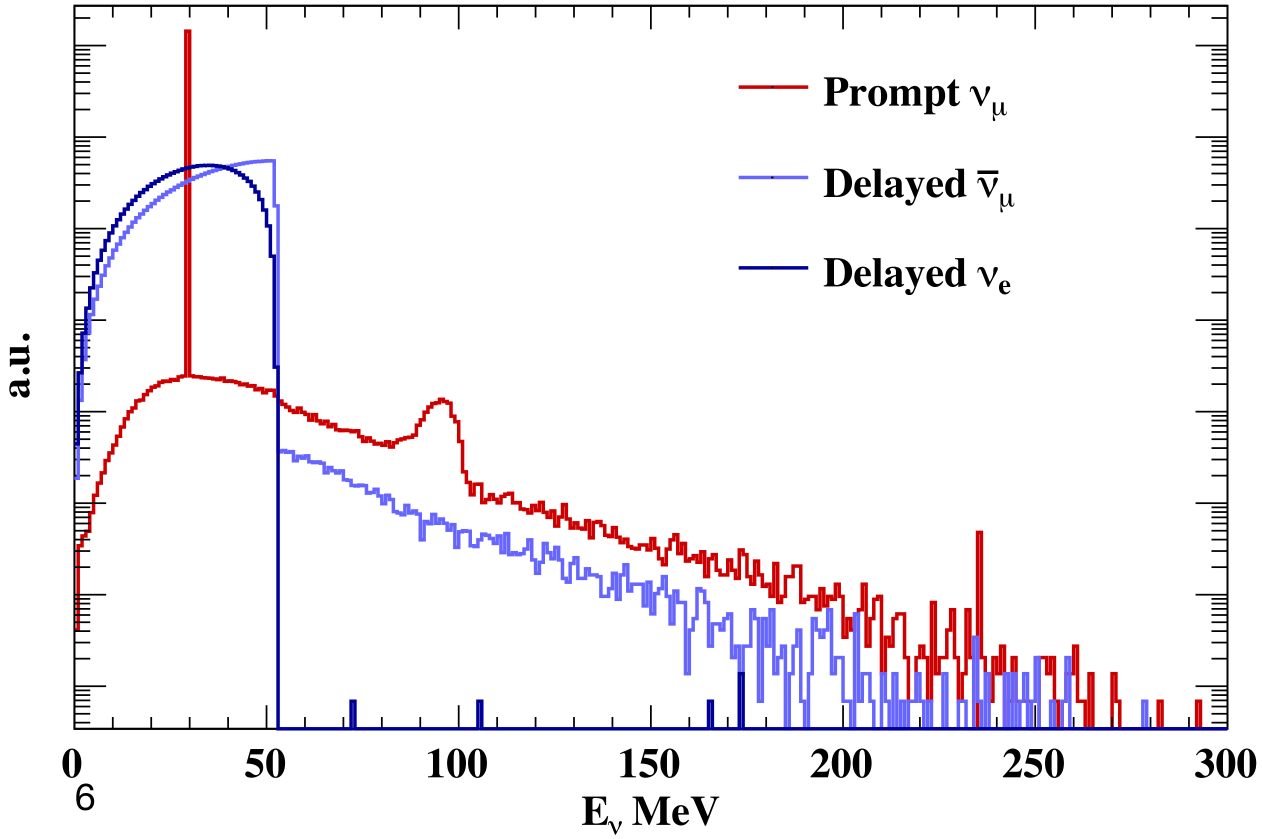
NC Central University
NC State University
New Mexico State University
ORNL
SNL

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

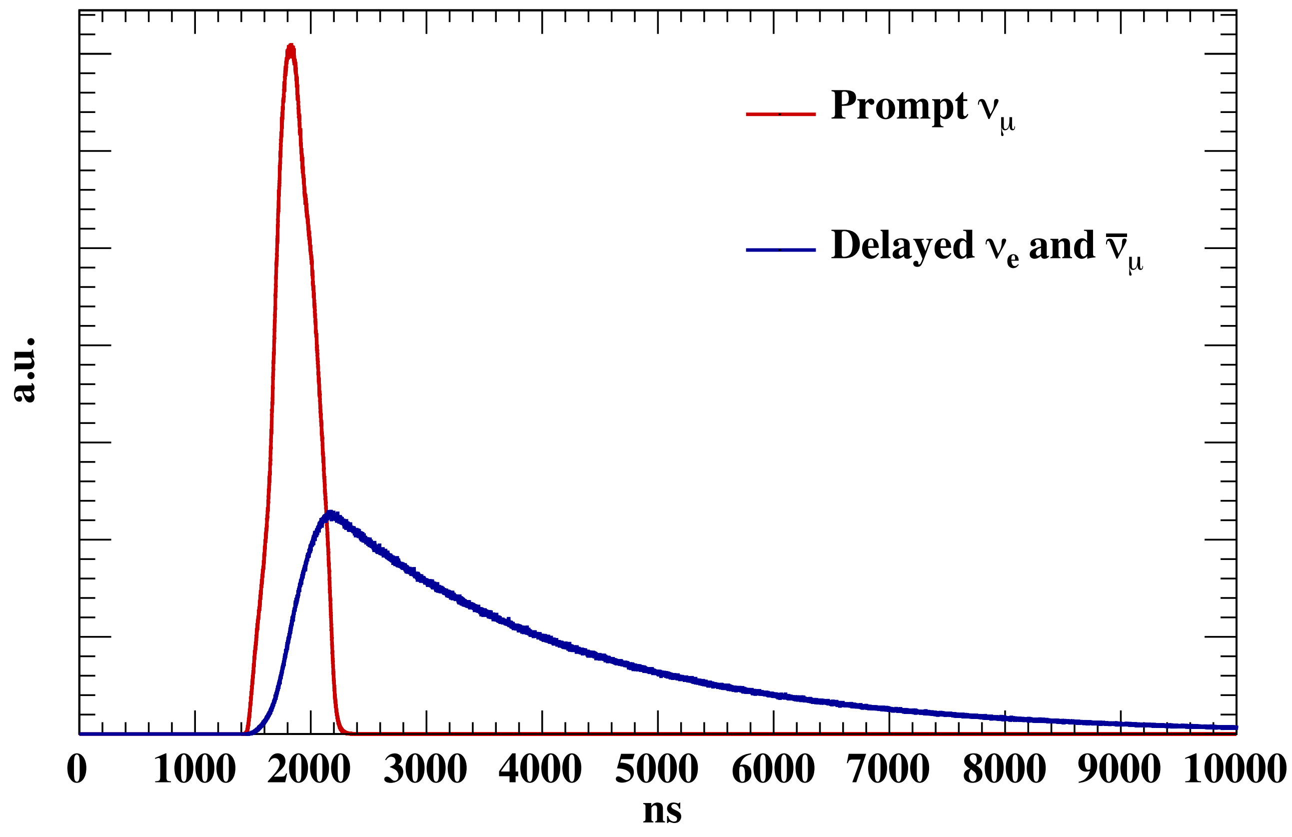
The Spallation Neutron Source

- Pion Decay-at-Rest Neutrino Source
- ν flux 4.3×10^{7} ν cm^{-2} s^{-1} at 20 m
- Pulsed: 800 ns full-width at 60 Hz

<1% contamination from non-CEvNS scatters

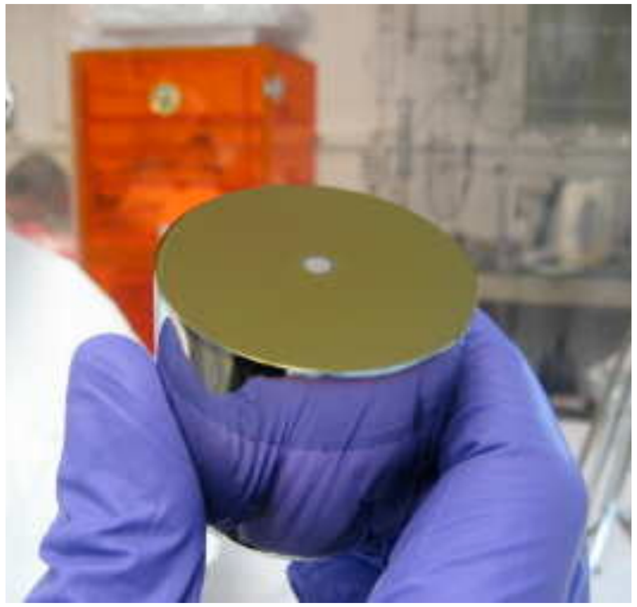


~4×10^{-5} background reduction



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

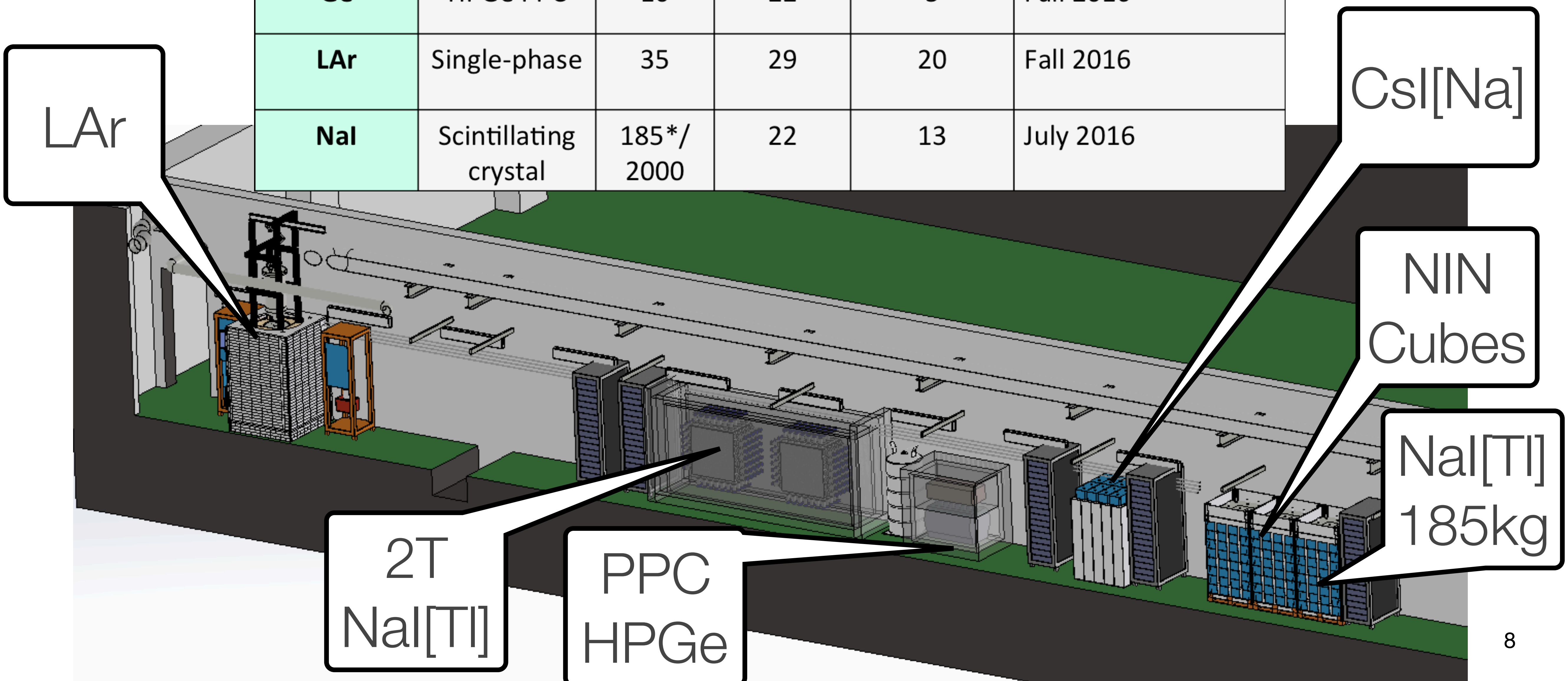
Low-Background CsI[Na]

NaI[Tl]

Single Phase LAr

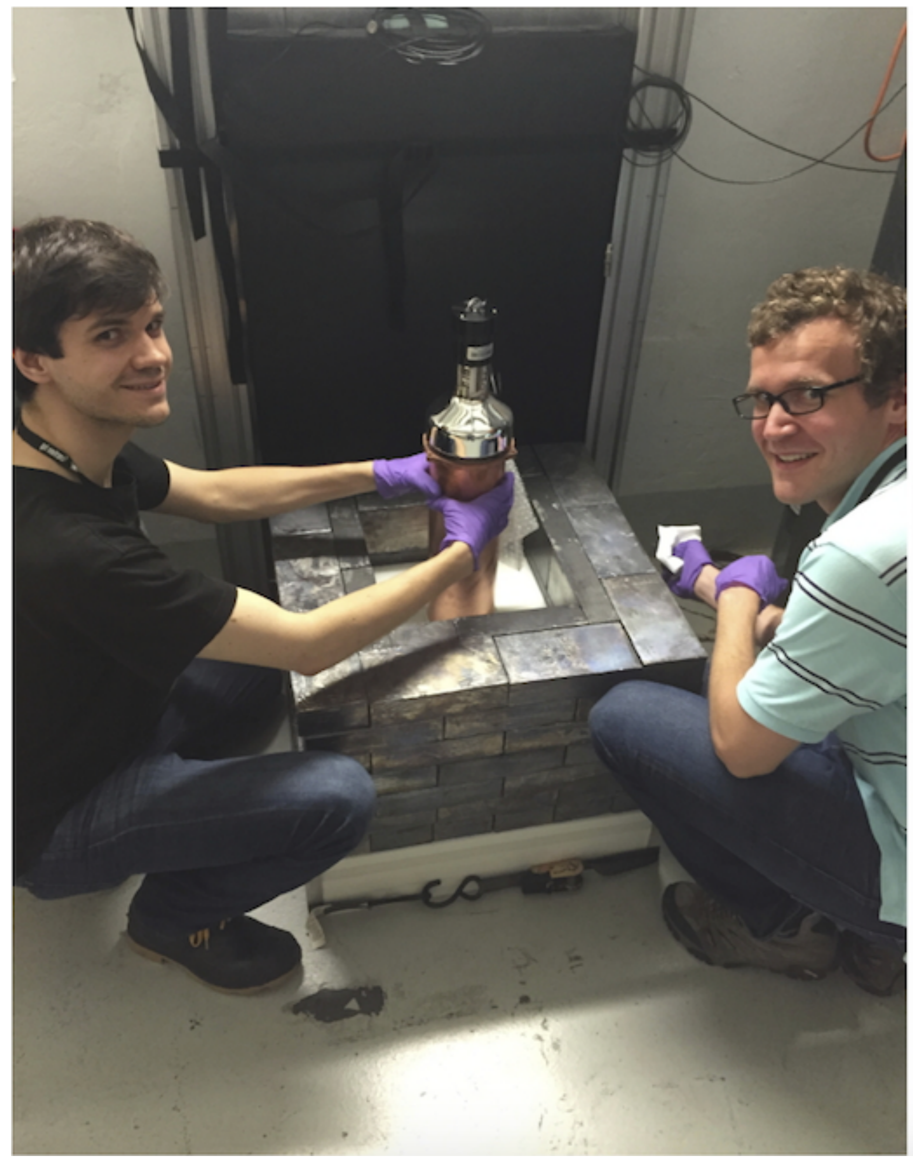
Detectors in "Neutrino Alley"

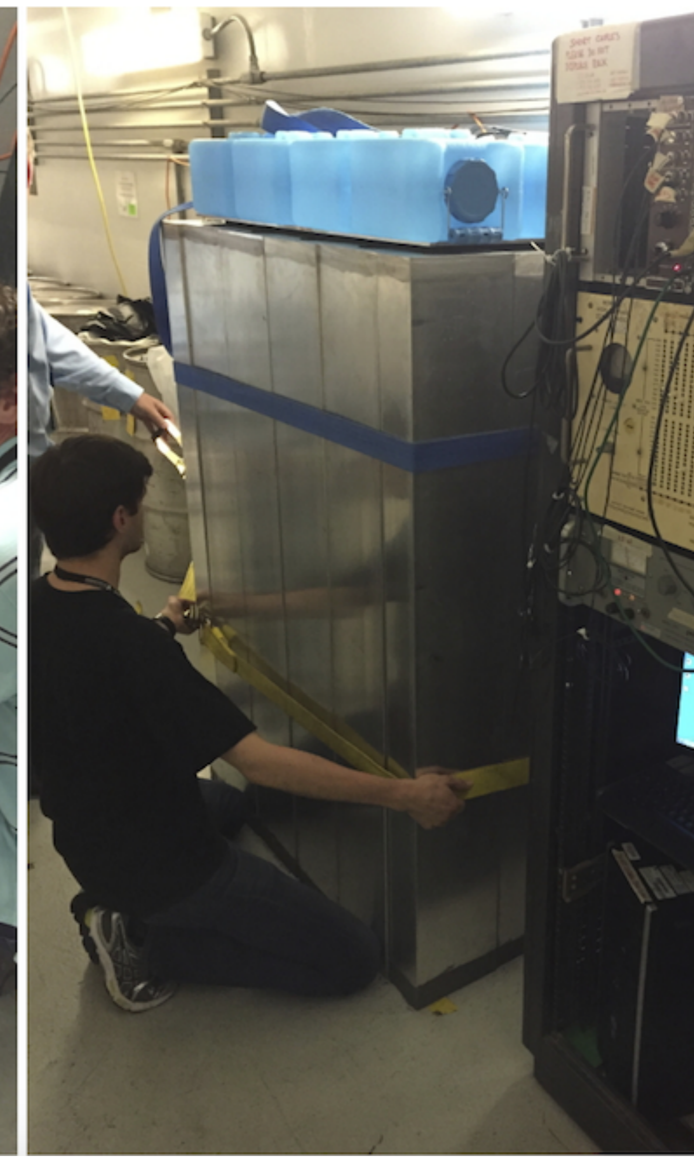
Nuclear Target	Technology	Mass (kg)	Distance from source (m)	Recoil threshold (keVr)	Data-taking start date; CEvNS detection goal
CsI[Na]	Scintillating crystal	14	20	6.5	9/2015; 3σ in 2 yr
Ge	HPGe PPC	10	22	5	Fall 2016
LAr	Single-phase	35	29	20	Fall 2016
NaI	Scintillating crystal	185*/ 2000	22	13	July 2016



Detector Subsystems: CsI[Na]

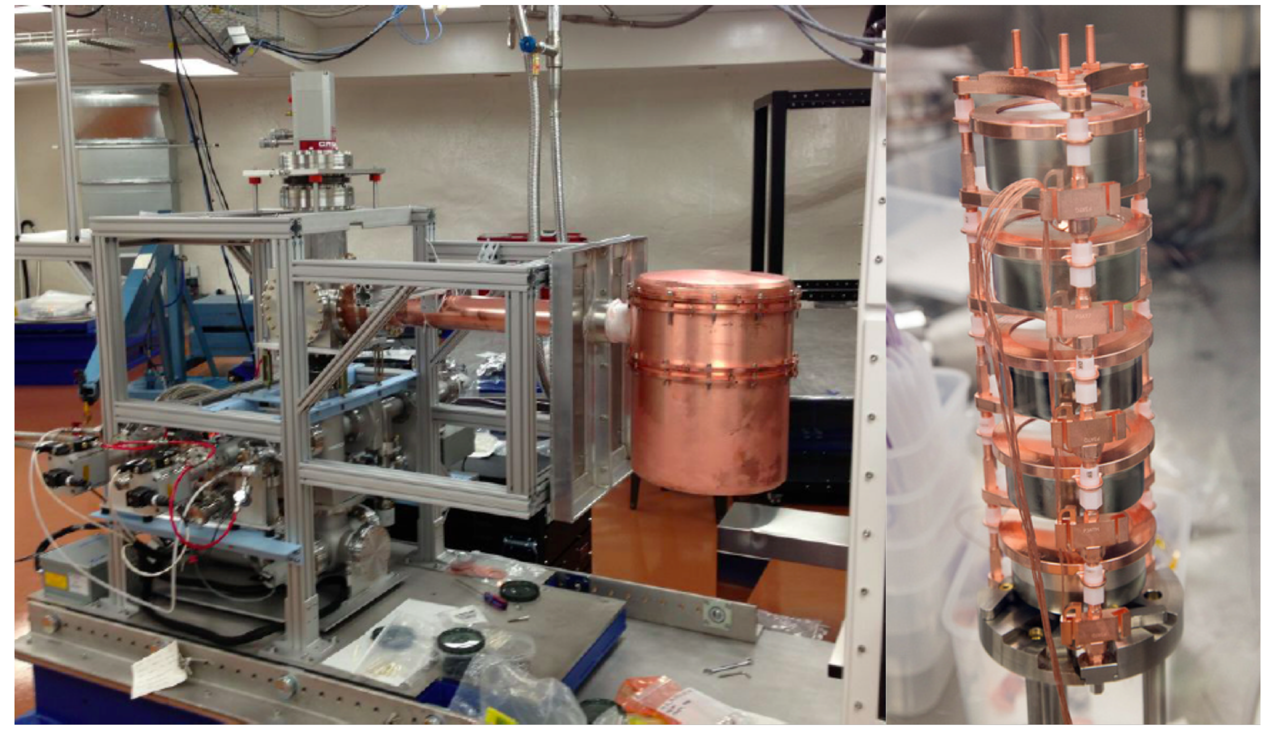
- 14 kg low-background CsI[Na] crystal
- Large N: 74, 78
- Already installed at SNS
- QF measured by collaboration

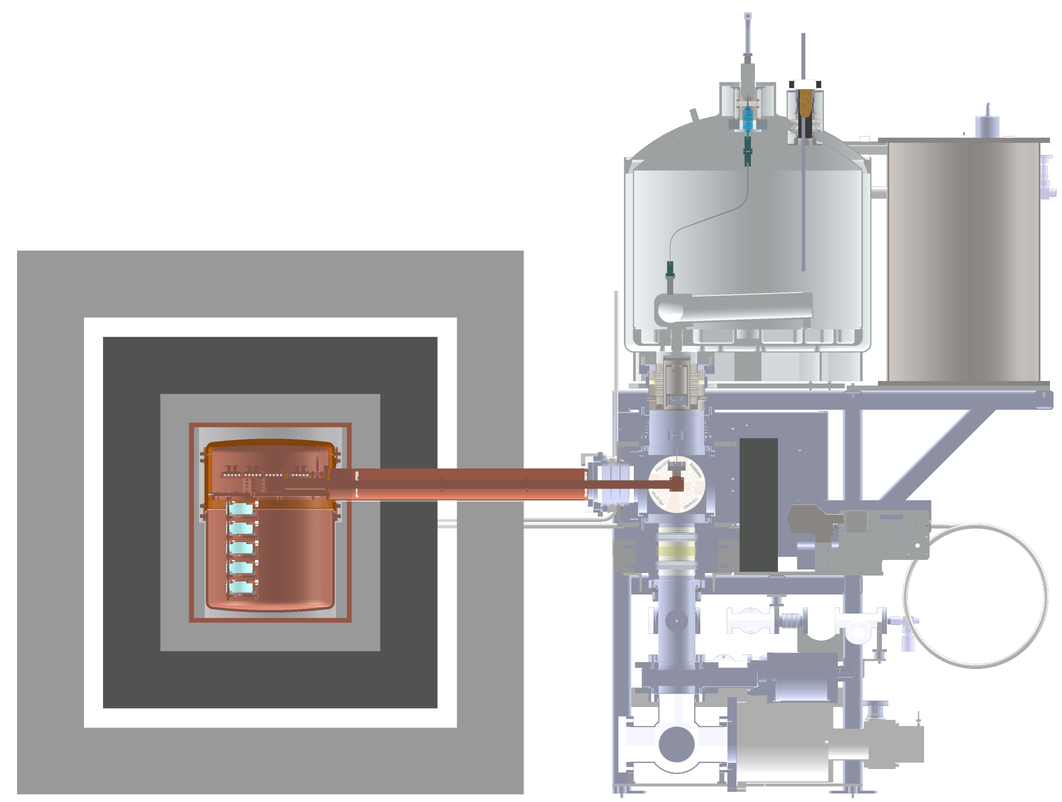




Detector Subsystems: HPGe PPCs

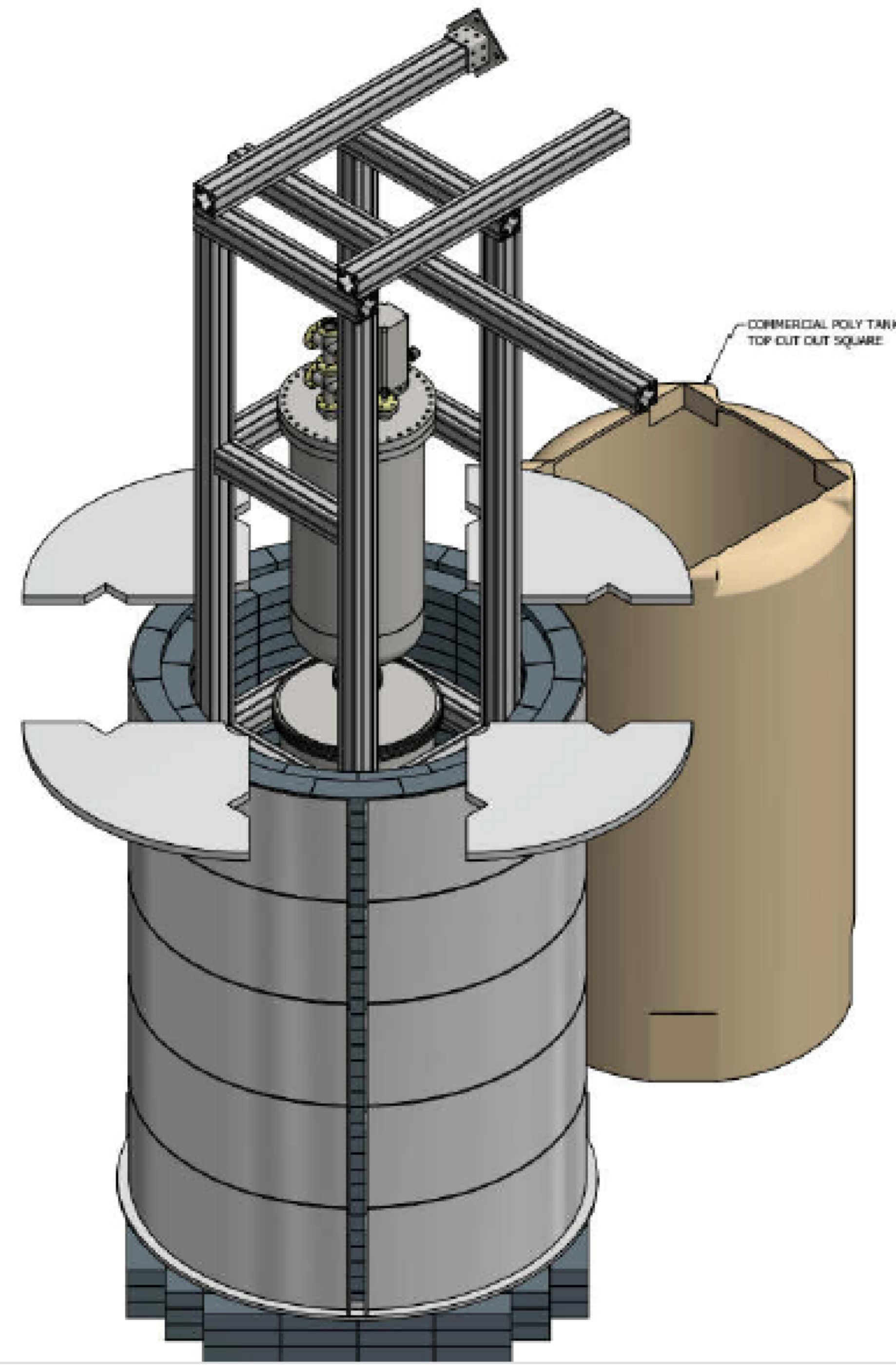
- Repurposed Majorana Detectors
- 5-10kg PPC detector mass
- Smaller N: 38-44
- Excellent resolution at low energies
- Well-measured quenching factor
- Installation of PPC Ge in Fall 2016





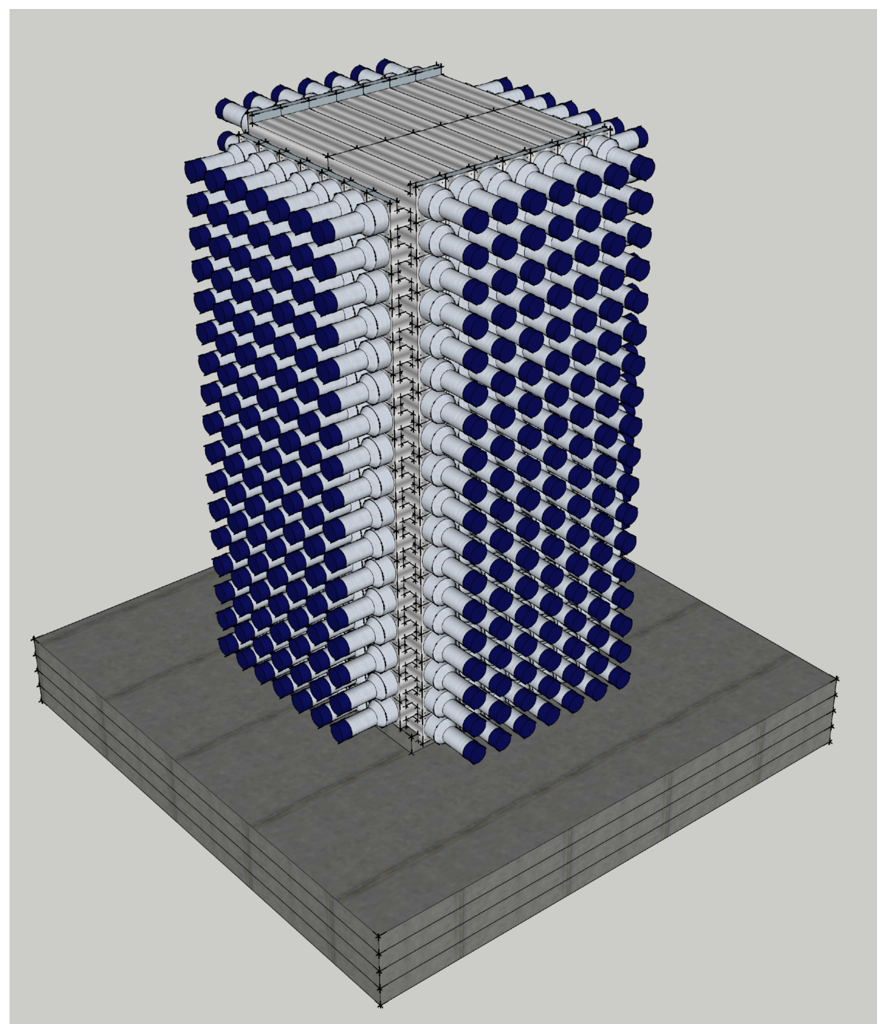
Detector Subsystems: Single Phase LAr

- Medium N: 40
- QF also known
- Installation Fall 2016

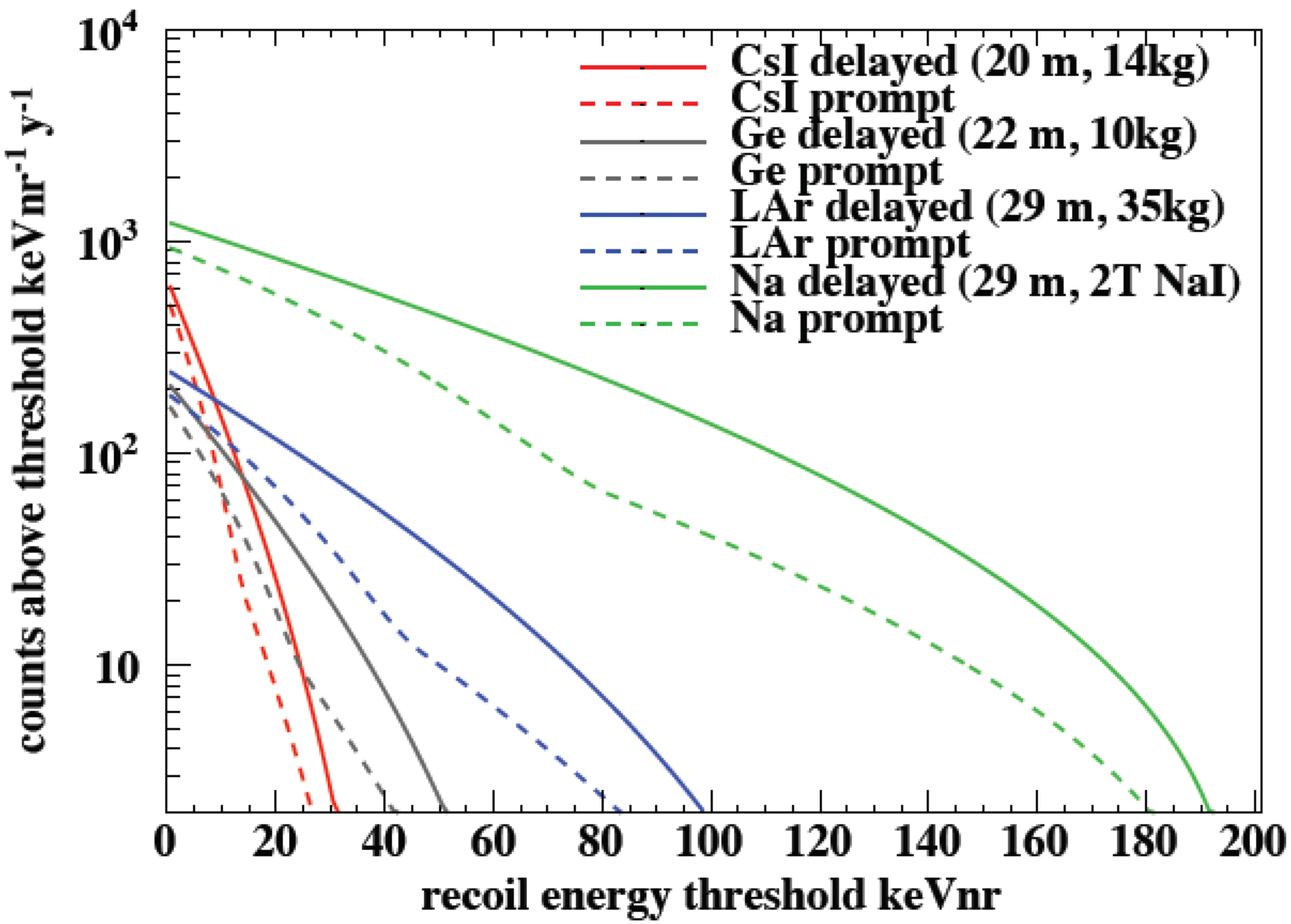


Detector Subsystems: NaI[Tl]

- Initial deployment 185 kgs
- Up to 9 T in hand
- N = 23 for Na
- Instrumentation tests underway at Duke and UW
- QF measured by collaboration



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.

NaI[Tl]: Two primary measurement goals

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

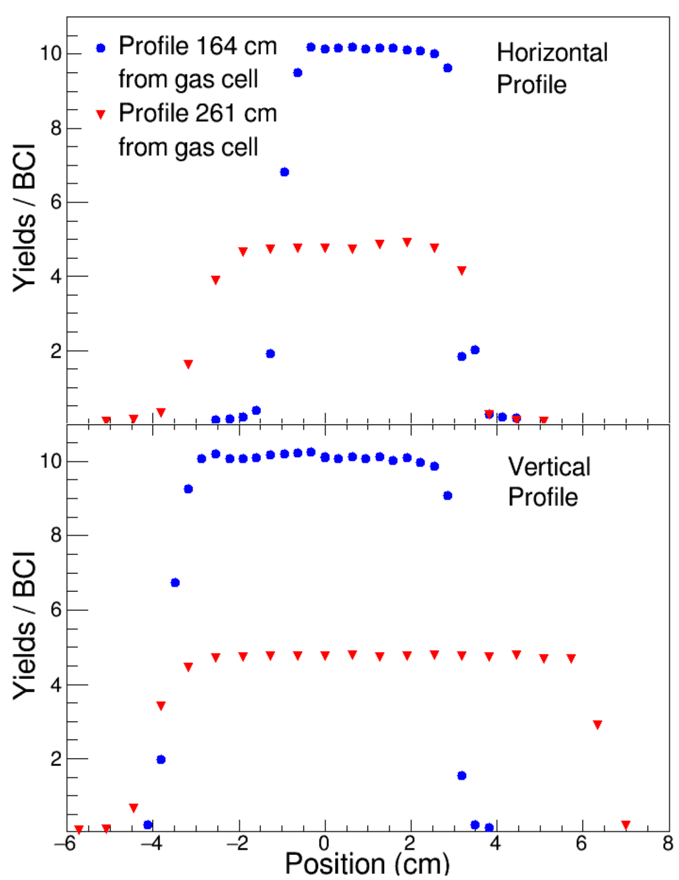
Isotope	Reaction Channel	Source	Experiment	Measurement (10^{-42} cm^2)	Theory (10^{-42} cm^2)
^{2}H	$^{2}\mathrm{H}(\nu_e, e^-)\mathrm{pp}$	Stopped π/μ	LAMPF	52 ± 18(tot)	54 (IA) (Tatara *et al.*, 1990)
^{12}C	$^{12}\mathrm{C}(\nu_e, e^-)^{12}\mathrm{N}_{\mathrm{g.s.}}$	Stopped π/μ	KARMEN	9.1 ± 0.5(stat) ± 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)
	$^{12}\mathrm{C}(\nu_e, e^-)^{12}\mathrm{N}^*$	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)	
	$^{12}\mathrm{C}(\nu_\mu, \nu_\mu)^{12}\mathrm{C}^*$	Stopped π/μ	KARMEN	3.2 ± 0.5(stat) ± 0.4(sys)	2.8 [CRPA] (Kolbe *et al.*, 1999b)
	$^{12}\mathrm{C}(\nu, \nu)^{12}\mathrm{C}^*$	Stopped π/μ	KARMEN	10.5 ± 1.0(stat) ± 0.9(sys)	10.5 [CRPA] (Kolbe *et al.*, 1999b)
	$^{12}\mathrm{C}(\nu_\mu, \mu^-)\mathrm{X}$	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)
	$^{12}\mathrm{C}(\nu_\mu, \mu^-)^{12}\mathrm{N}_{\mathrm{g.s.}}$	Decay in Flight	LSND	56 ± 8(stat) ± 10(sys)	68-73 [CRPA] (Kolbe *et al.*, 1999b)
					56 [Shell] (Hayes and S, 2000)
^{56}Fe	$^{56}\mathrm{Fe}(\nu_e, e^-)^{56}\mathrm{Co}$	Stopped π/μ	KARMEN	256 ± 108(stat) ± 43(sys)	264 [Shell] (Kolbe *et al.*, 1999a)
^{71}Ga	$^{71}\mathrm{Ga}(\nu_e, e^-)^{71}\mathrm{Ge}$	^{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	$^{127}\mathrm{I}(\nu_e, e^-)^{127}\mathrm{Xe}$	Stopped π/μ	LSND	284 ± 91(stat) ± 25(sys)	210-310 [Quasi-particle] (Engel *et al.*, 1994)

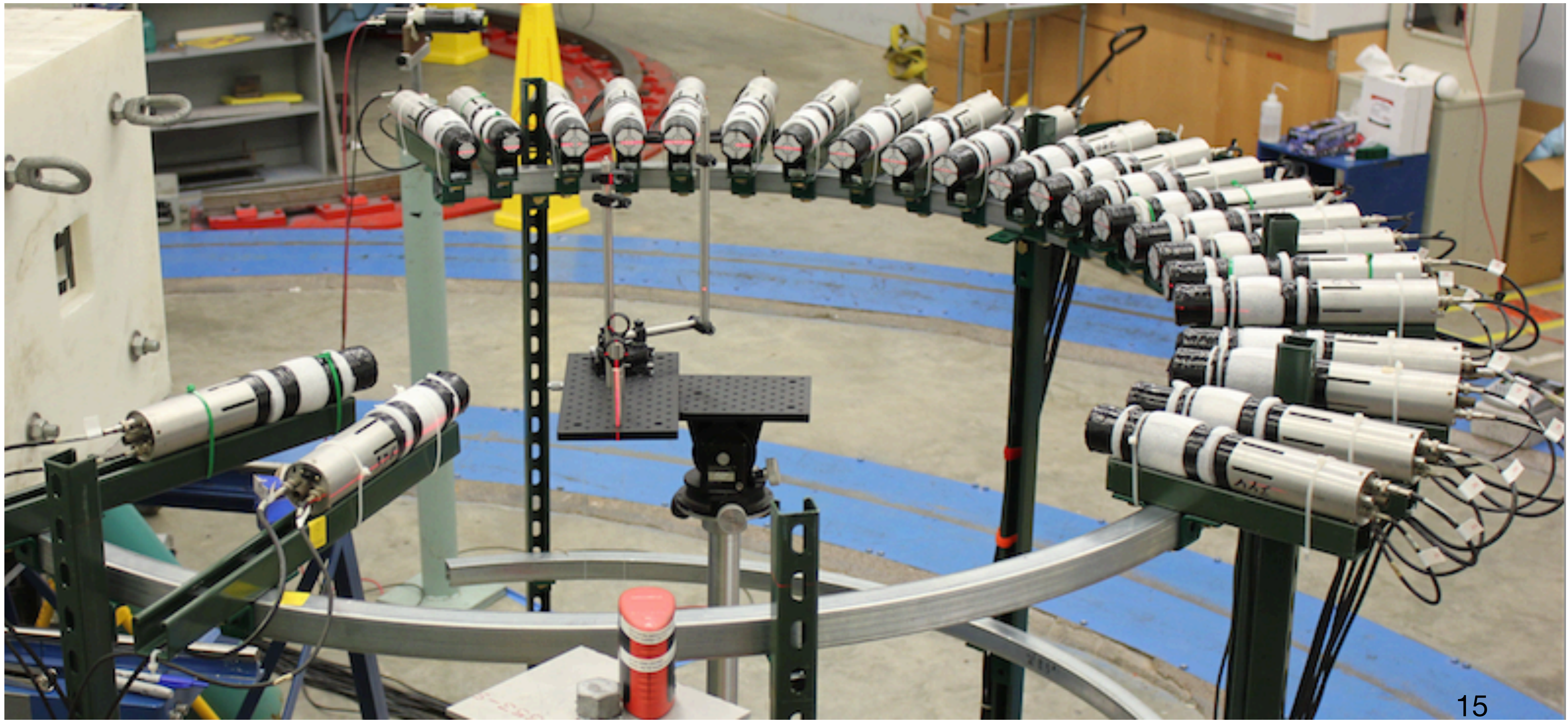
J. A. Formaggio and S. Zeller, Rev. Mod. Phys. 84, 1307 (2012)

A Quenching Factor Facility

- A facility has been developed at Duke/TUNL for precision detector calibrations. *CsI(Na) and NaI(Tl) data in the can.*

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

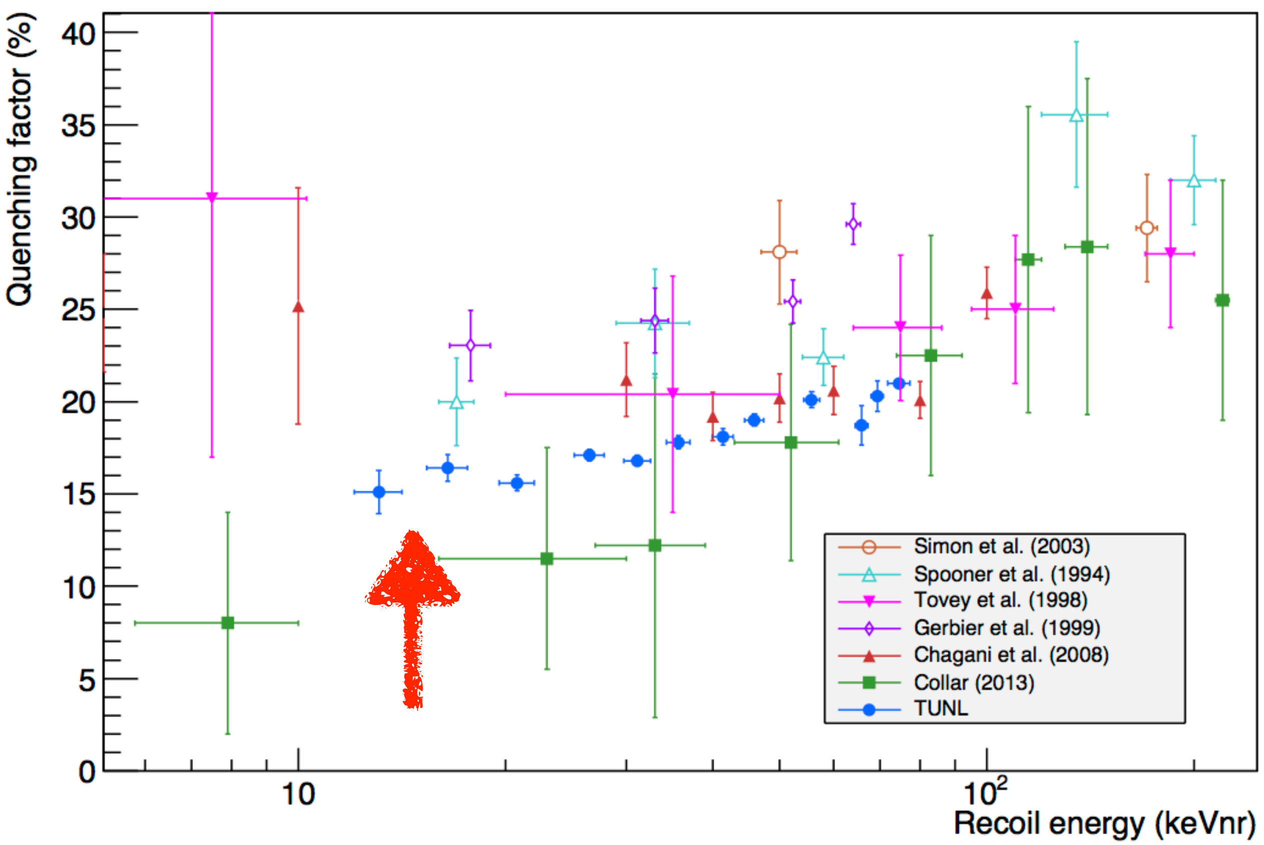




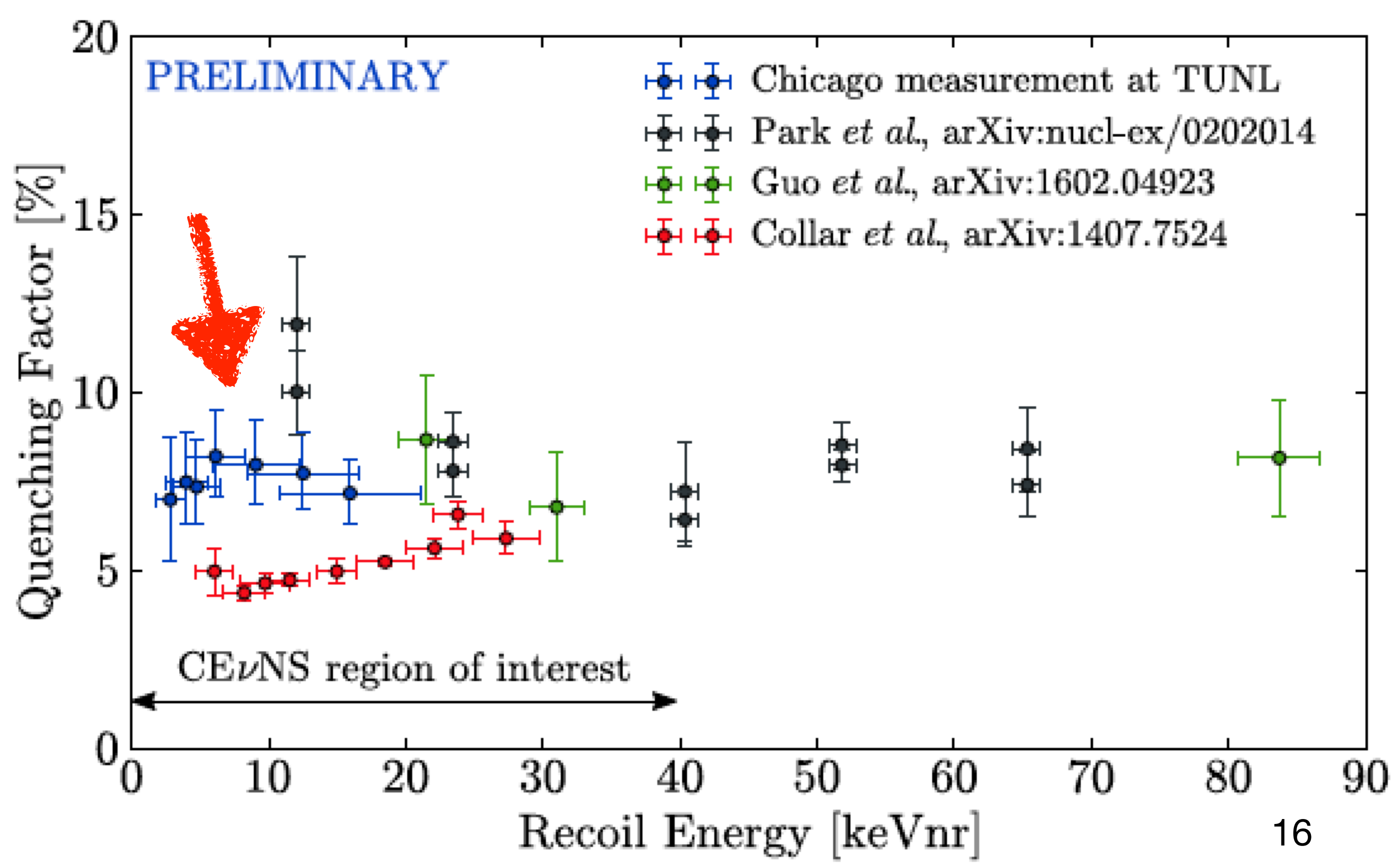
Quenching Factor Measurements

- High precision measurements of the Na QF in NaI[Tl] recently performed by Duke and Princeton confirm ~ 15%.
- Two independent QF measurements by Chicago and Duke group at TUNL. Duke measurements (being analyzed) extend to higher energies.
- LAr QF measurement planning in dedicated beam line early August.

Na in NaI[Tl]



CsI[Na]



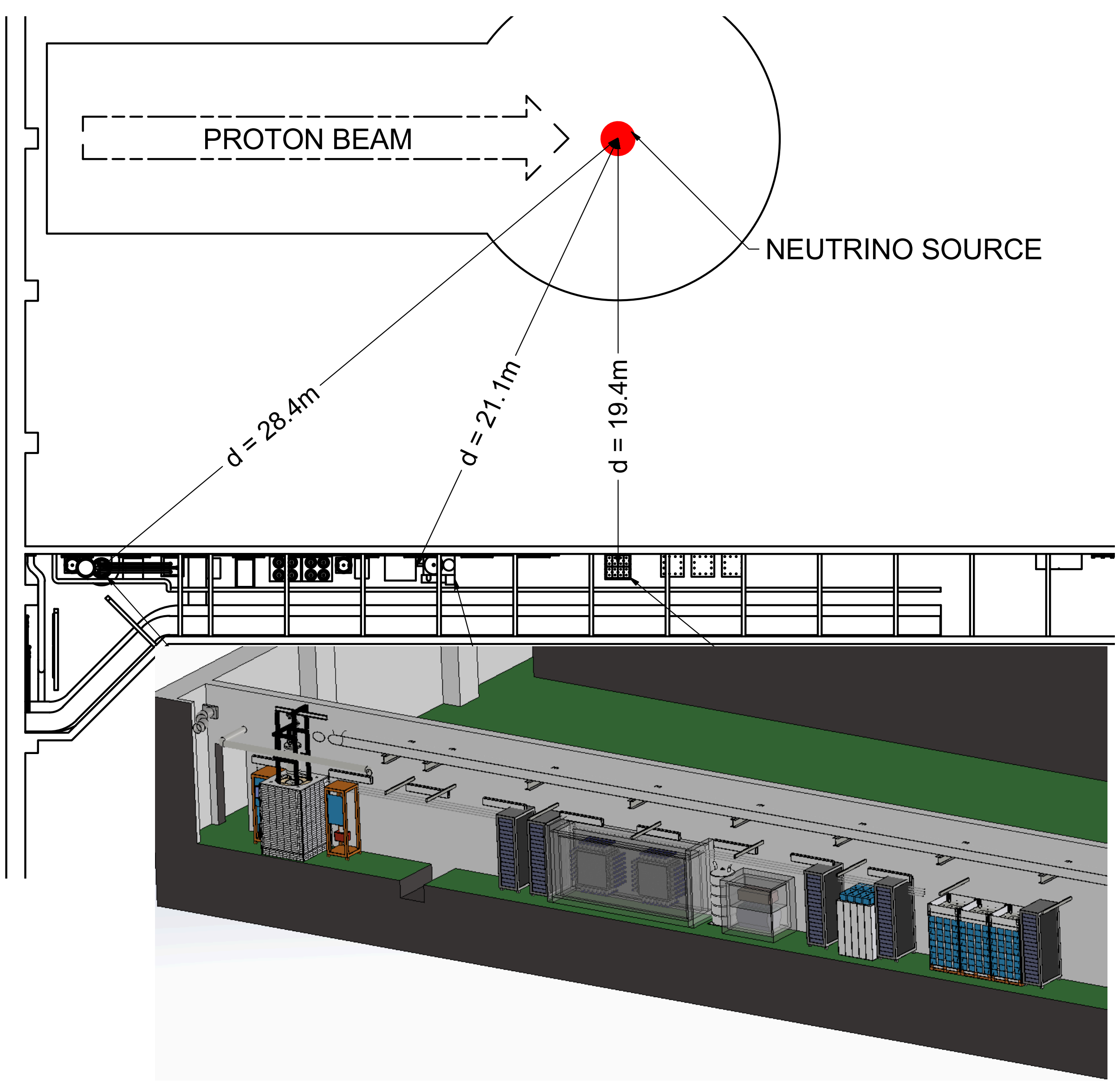
Backgrounds

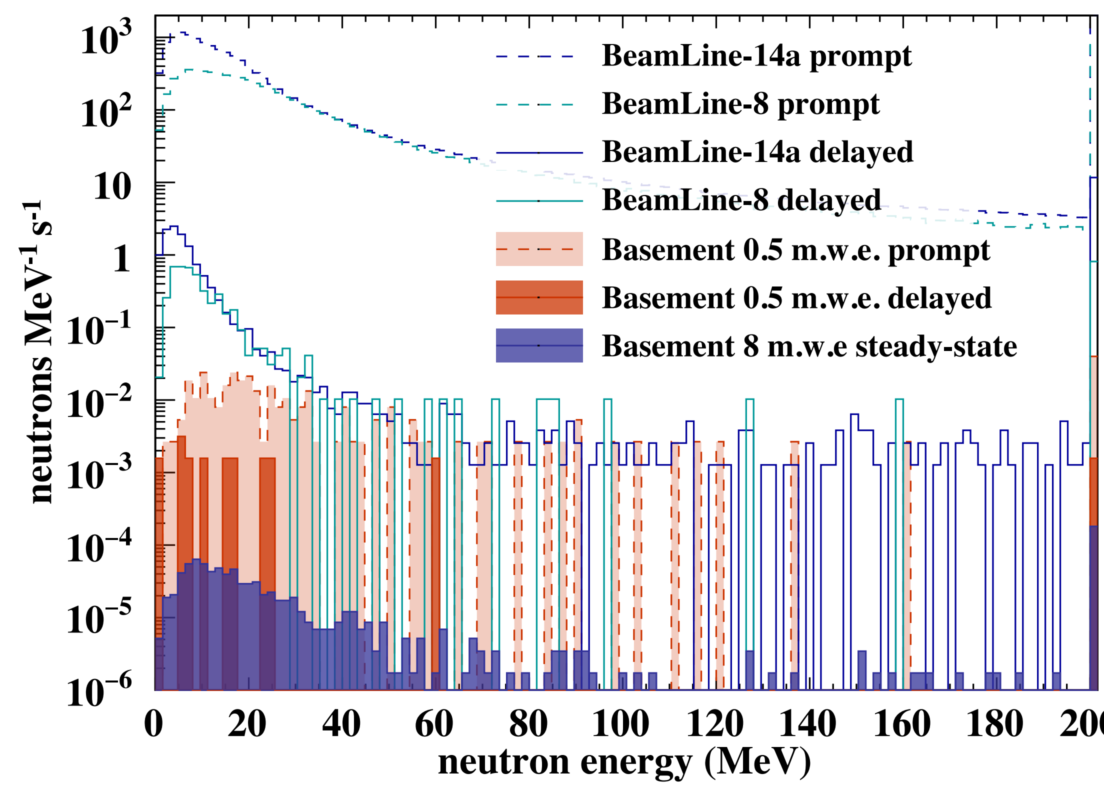
The SNS is a facility designed to produce neutrons (> 100 MeV), that are pulsed with the same time structure of the neutrinos (**with the exception of the characteristic decay time of the muon**).

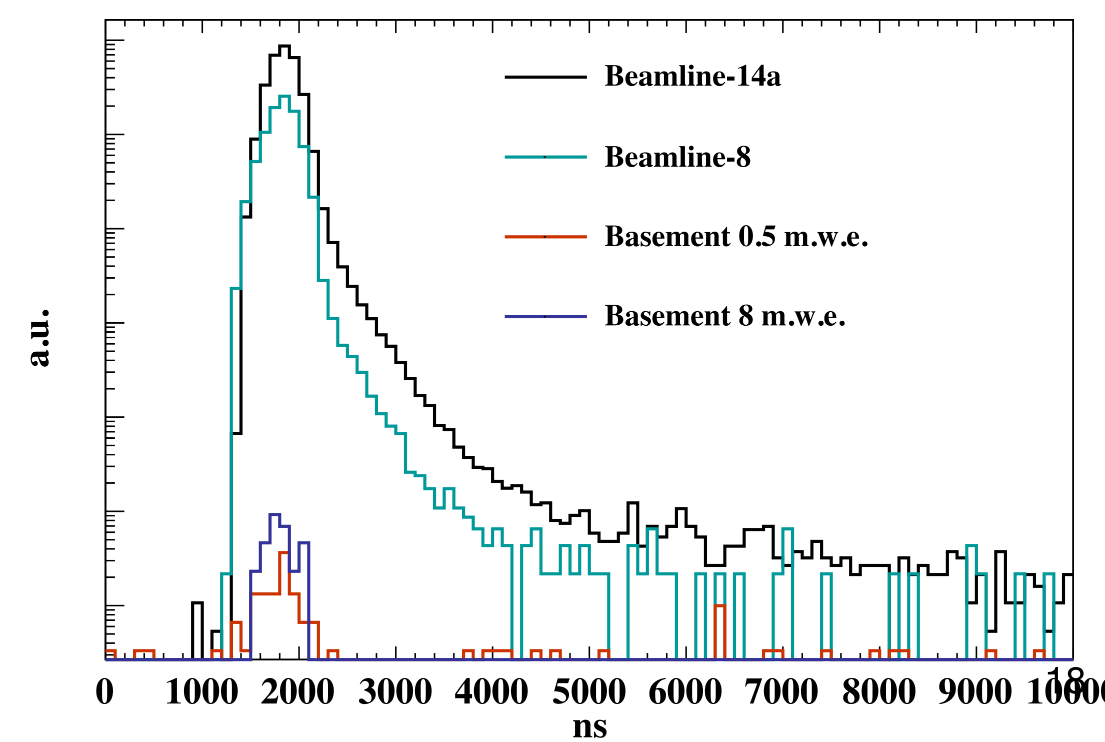
Neutron image of the SNS target, through shielding

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 of neutrons)



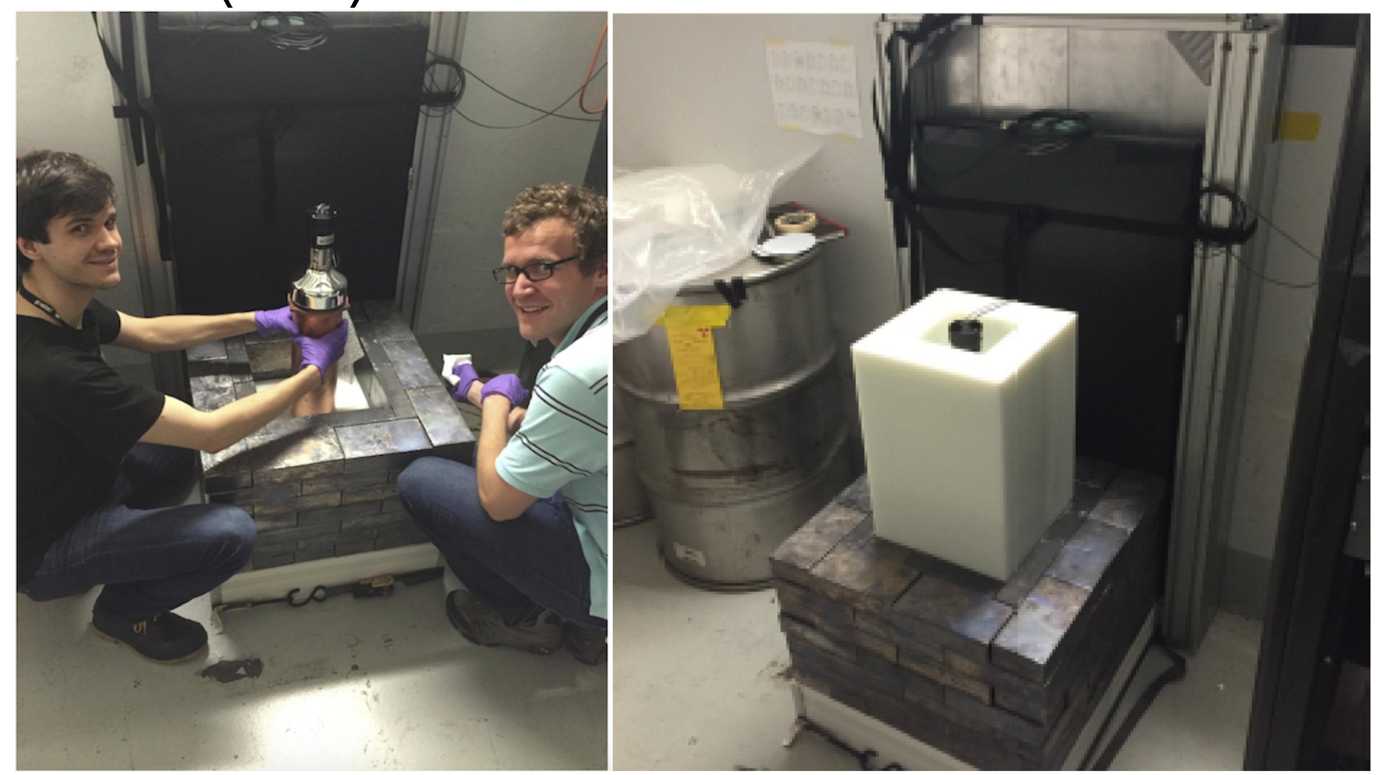




New Background: $\boldsymbol{\nu}$-induced neutrons (NINs)

- 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



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

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

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]

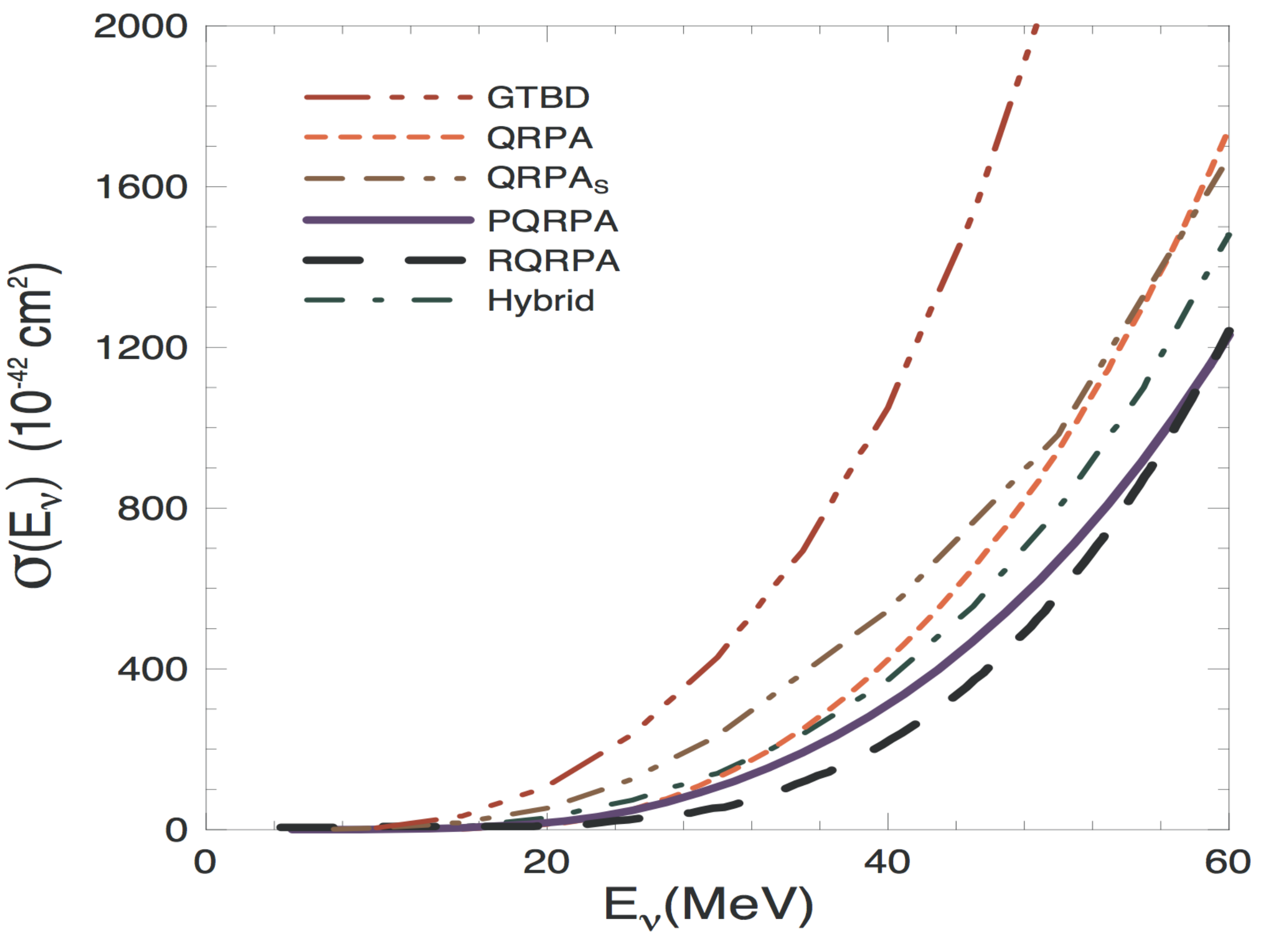
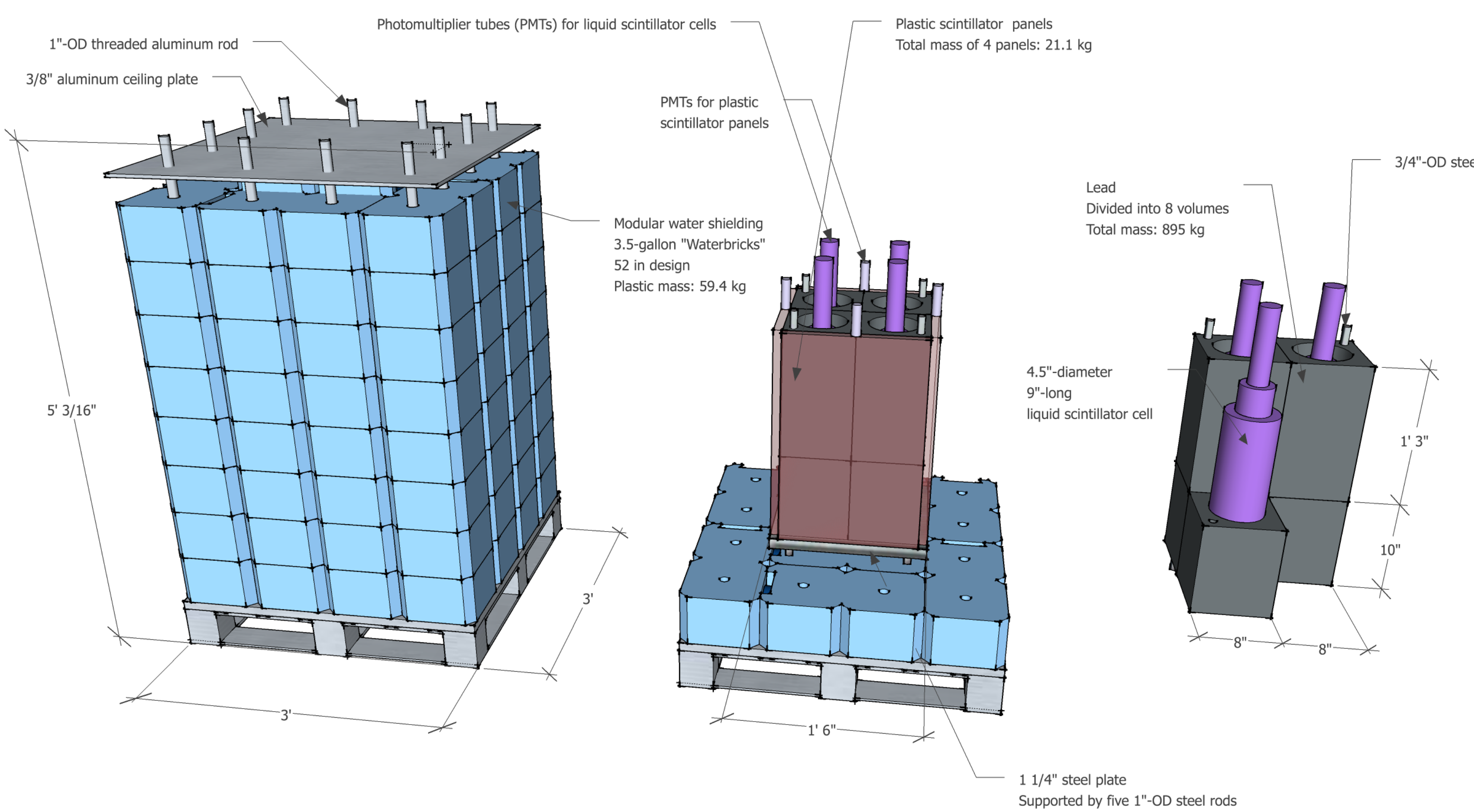


Figure from A.R. Samana and C.A. Bertulani, Phys. Rev. C (2008)

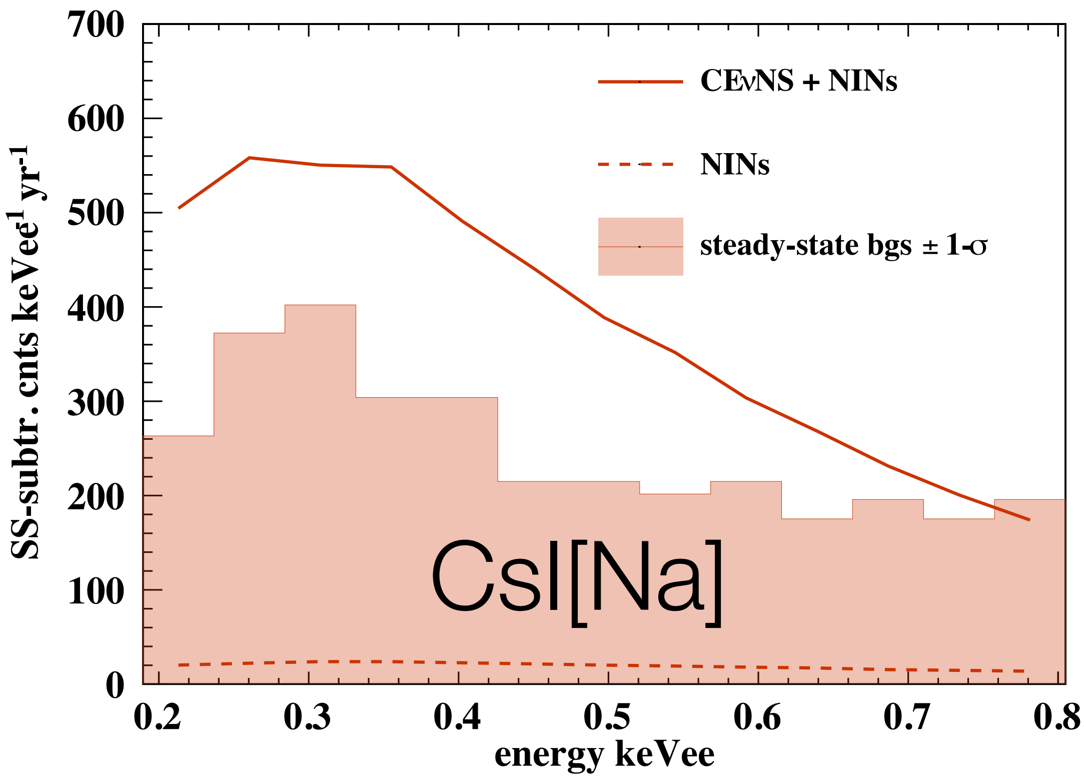
[1] C.A. Duba *et al.* J.Phys.Conf.Series 136 (2008)
[2] Y-Z. Qian *et al.*, Phys. Rev. C 55 (1997)

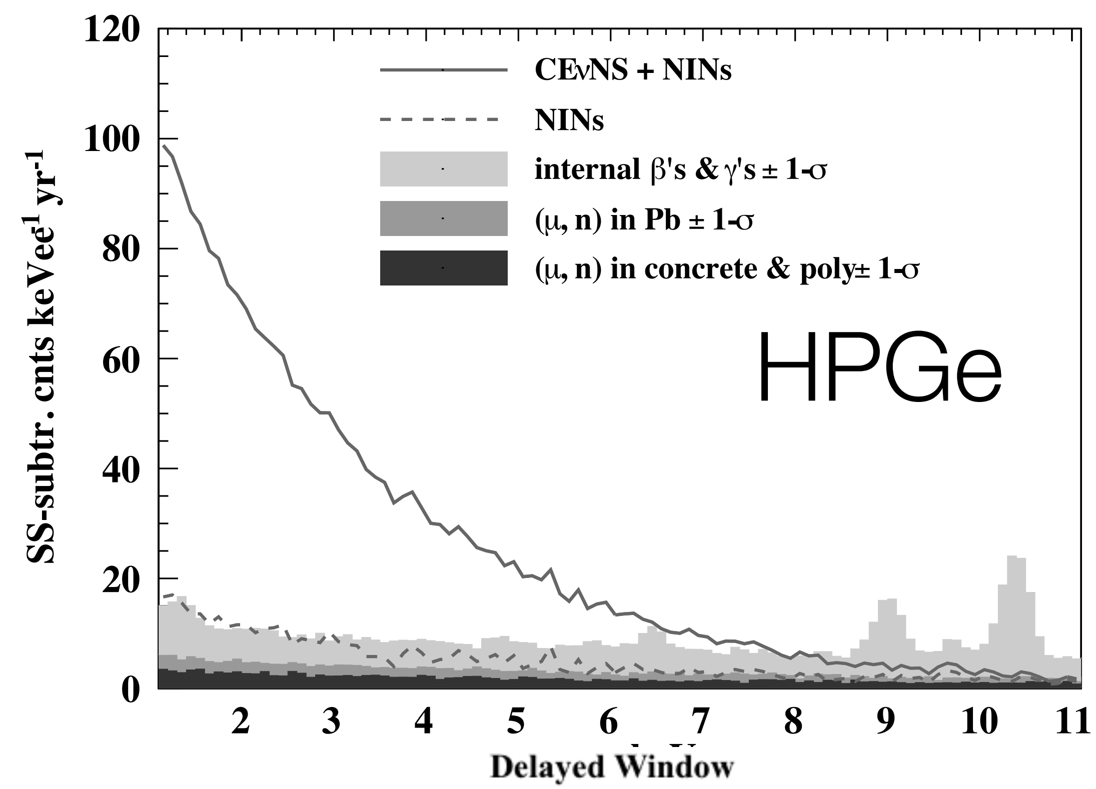
Measuring the ν-induced Neutrons

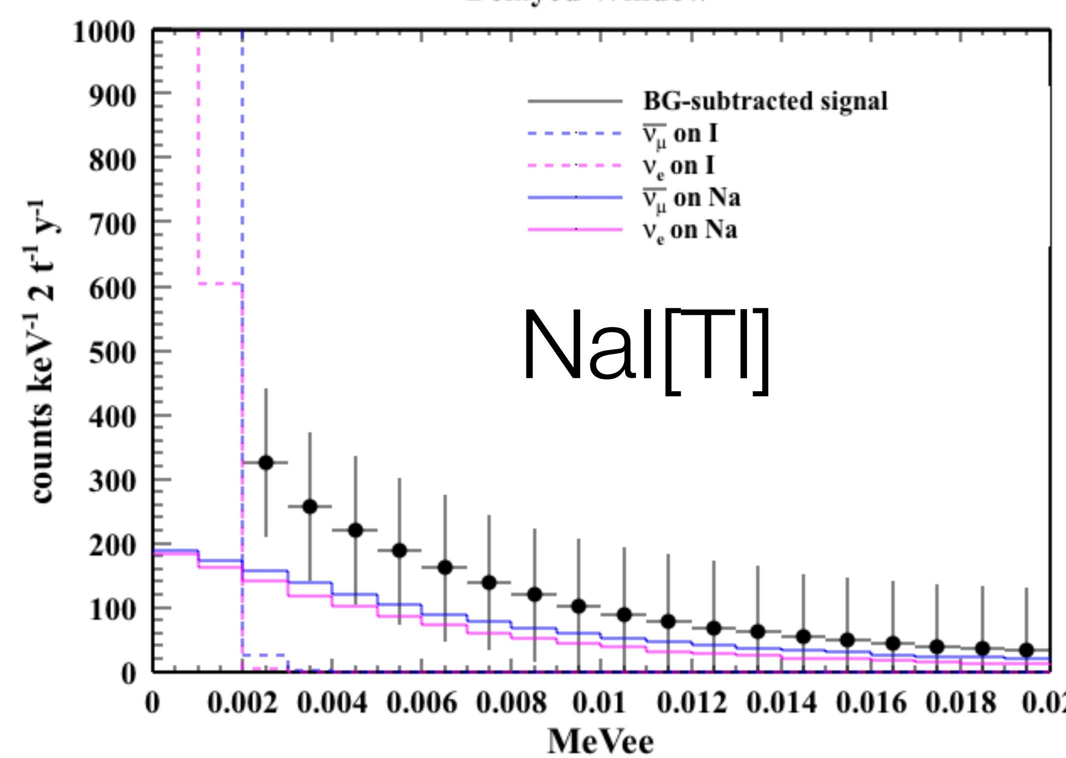


- Several palletized (mobile) targets with LS detectors delivered to the SNS
- Will measure neutrino-induced-neutrons on Pb (operating), Fe (deployed) & Cu (coming soon…)
- The three on-site “neutrino-cubes” also provide nice, compact laboratories for other studies: NaI[Tl] CEvNS and ν_e CC on I-127

Putting it all Together







Steady-state background measured with anti-coincident triggers

NIN production rates inform the optimal shielding designs

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, NaI[Tl] - 185 kg installed, NaI[Tl] 2T, PPC Ge and LAr deployment in Fall 2016

- 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 v’s **(2.2 μs decay)** and due to CEvNS **(σ~N^2)**