Cross Section Measurements for Supernova Neutrinos

Kate Scholberg, Duke University

Flavor Observations with SN Neutrinos, Seattle, August 2016

This is a (somewhat) gentler regime than many neutrino cross section regimes...

~GeV+ neutrinos can create a quite a mess ...

~tens of MeV neutrinos are not as disruptive, but still leave non-trivial debris ...

OUTLINE

Low-energy cross sections overview

Supernova-neutrino-relevant cross sections

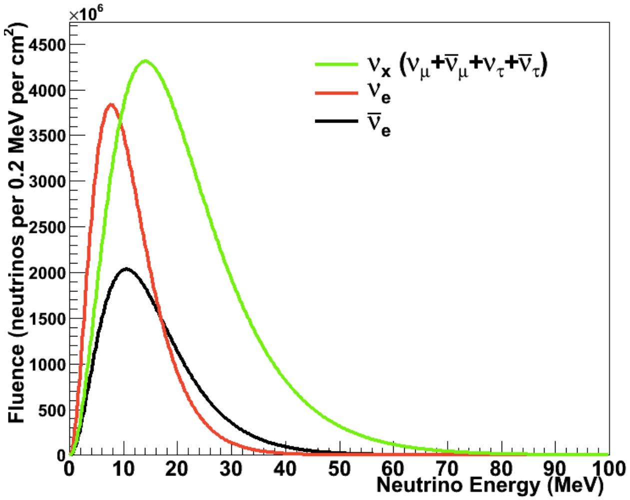
water, argon, lead, ...

coherent elastic neutrino-nucleus scattering (CEvNS)

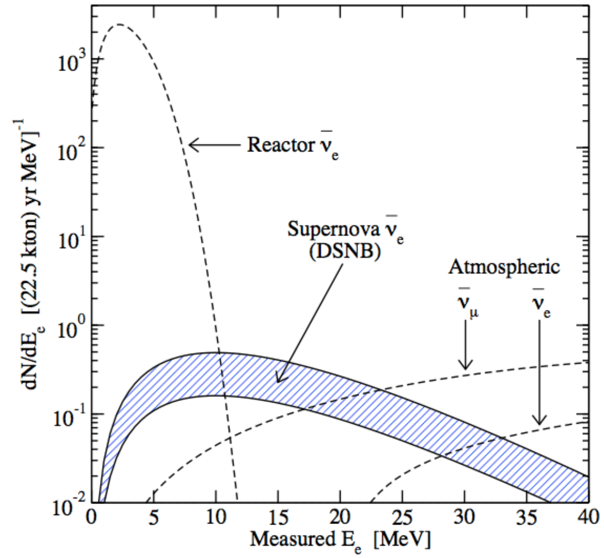
Measurements with **stopped-pion sources**

Experiments proposed and underway

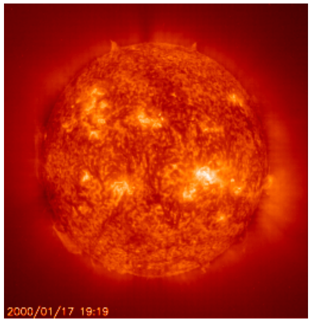
Neutrino interactions in the few-100 MeV range are relevant for:

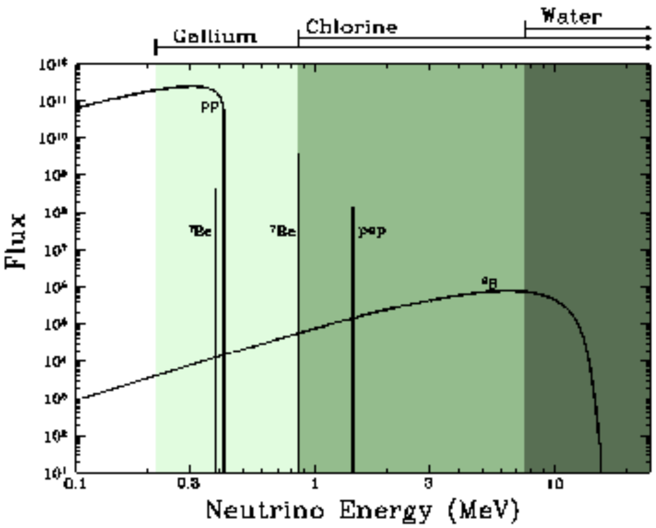


supernova neutrinos, burst & relic

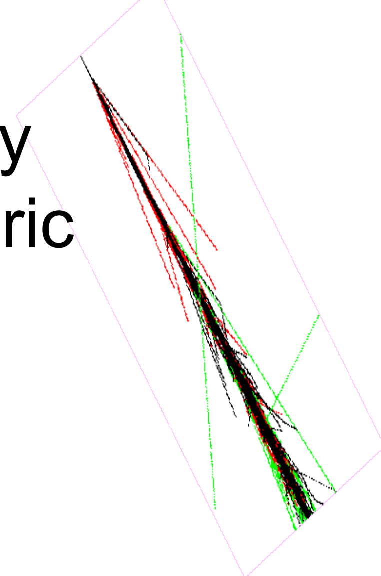


solar neutrinos



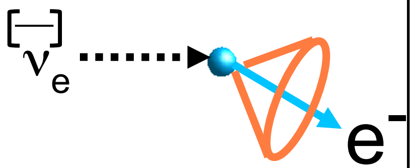
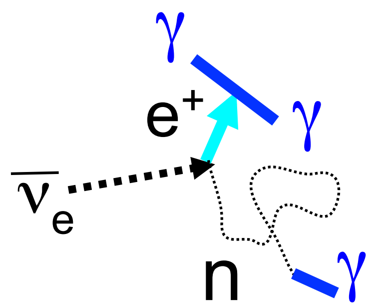
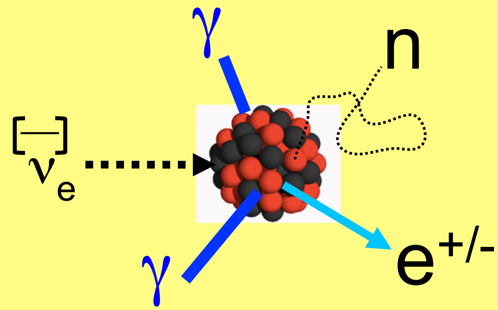
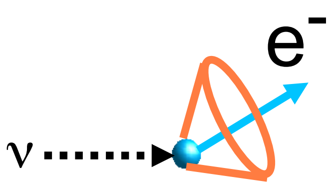
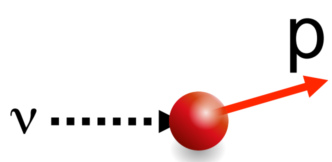
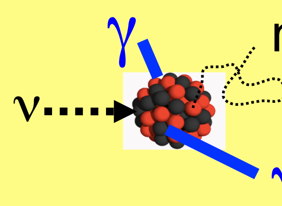
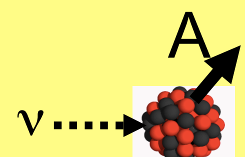


low energy atmospheric neutrinos



Physics: oscillation, SM tests, astrophysics

Neutrino Interactions in the tens-of-MeV regime

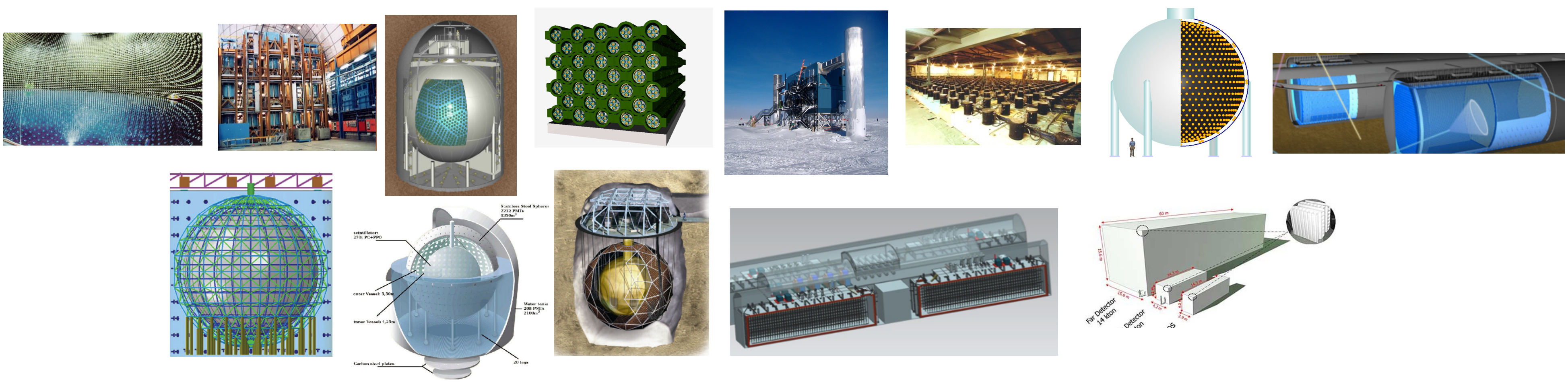
	Electrons	**Protons**	**Nuclei**
Charged current	Elastic scattering $\nu + e^- \to \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \to e^+ + n$ 	$\nu_e + (N, Z) \to e^- + (N-1, Z+1)$ $\bar{\nu}_e + (N, Z) \to e^+ + (N+1, Z-1)$  Various possible ejecta and deexcitation products
Neutral current	 Useful for pointing	Elastic scattering  very low energy recoils	$\nu + A \to \nu + A^*$  $\nu + A \to \nu + A$  Coherent elastic (CEvNS)

IBD & ES well understood... **interactions w/nuclei less well understood**

Nuclei of particular interest for SN detection

carbon
oxygen
argon
lead

} detector materials for current and future supernova neutrino detectors



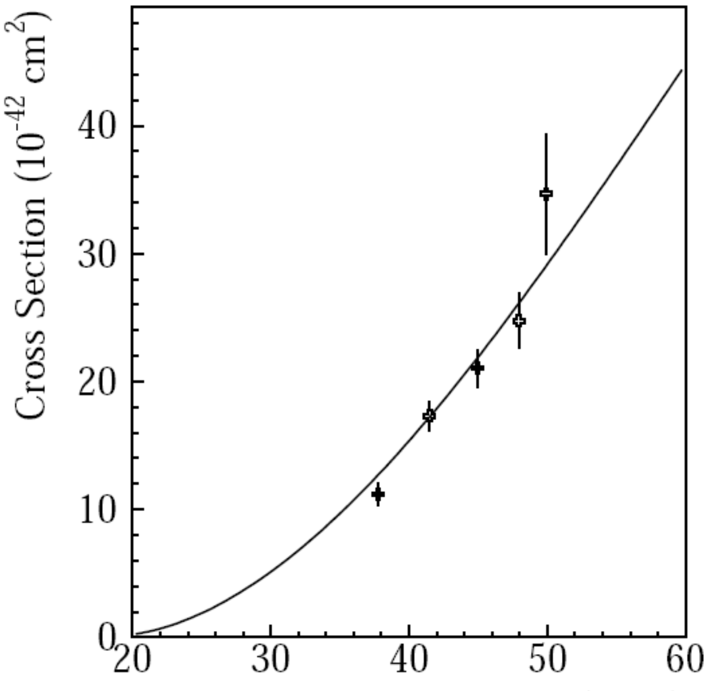
(These are not the only nuclei:
additional nuclei are of interest for other detectors;
supernova explosion physics, supernova nucleosynthesis)

.. but so far ^{12}**C is the *only* heavy nucleus** with ν interaction x-sections well (~10%) measured in the tens of MeV regime

e.g.

LSND

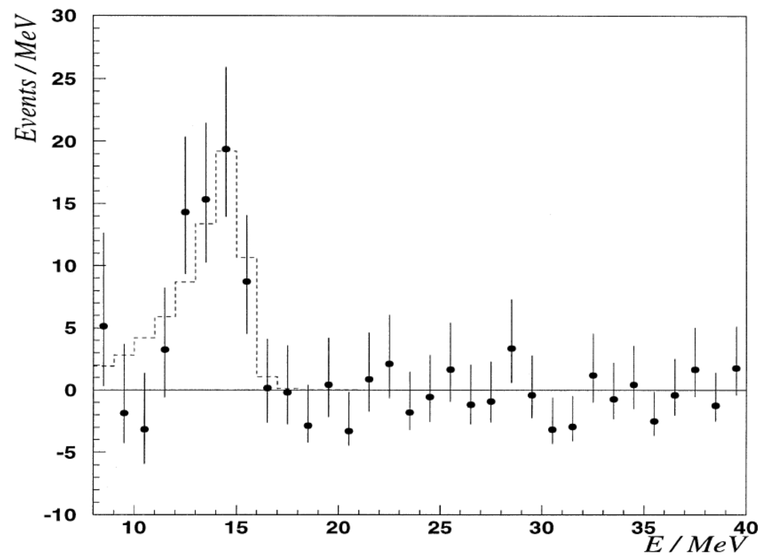
Phys. Rev. C 66 (2002) 015501



$$^{12}C(\nu_e, e^-)^{12}N_{g.s.}$$

Karmen

Phys. Lett. B 423 (1998) 15-20

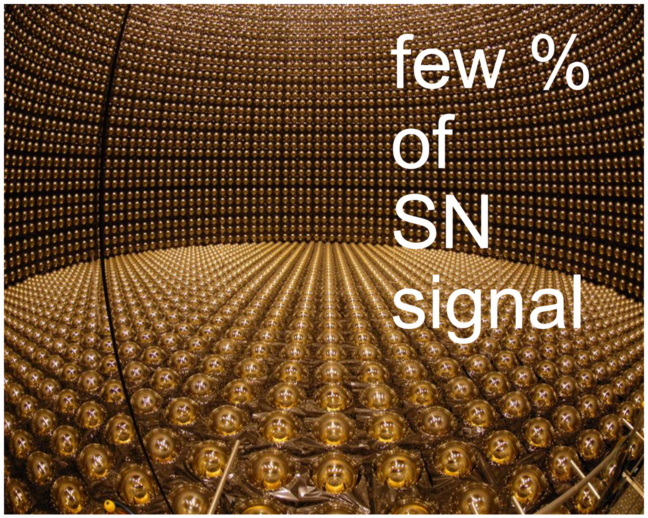


$$^{12}\mathrm{C}(\nu_\mu \nu_\mu')\,^{12}\mathrm{C}^*(1^+,1;15.1\ \mathrm{MeV})$$

Need: oxygen (water), lead, argon, ...

Example 1: interactions on oxygen nuclei

CC interactions

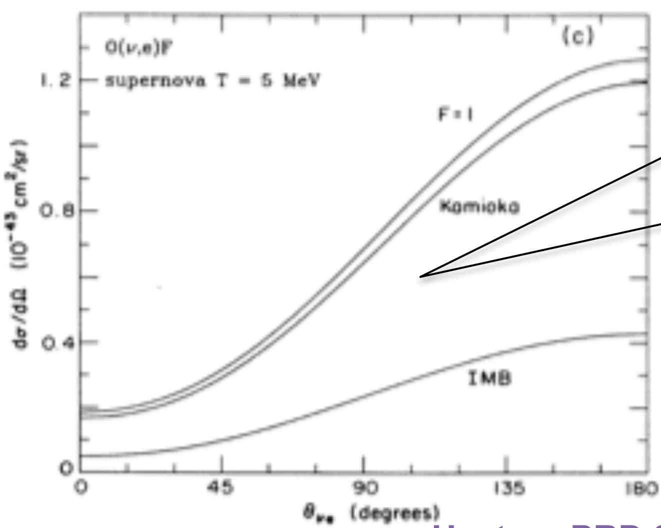


variety of final state ejecta

Kolbe, Langanke, Vogel: PRD 66, (2002) 013007

TABLE III. Partial cross sections for charged-current neutrino-induced reactions on ^{16}O. Fermi-Dirac distributions with $T=4$ MeV and $T=8$ MeV and zero chemical potential have been assumed. The cross sections are given in units of 10^{-42} cm^2, exponents are given in parentheses.

Neutrino reaction	$\sigma, T=4$ MeV	$\sigma, T=8$ MeV
total	1.91 (−1)	1.37 (+1)
$^{16}O(\nu_e,e^- p)^{15}O$(g.s.)	1.21 (−1)	6.37 (+0)
$^{16}O(\nu_e,e^- p\gamma)^{15}O^*$	4.07 (−2)	3.19 (+0)
$^{16}O(\nu_e,e^- np)^{14}O^*$	3.92 (−4)	1.76 (−1)
$^{16}O(\nu_e,e^- pp)^{14}N^*$	2.61 (−2)	3.26 (+0)
$^{16}O(\nu_e,e^- \alpha)^{12}N^*$	1.16 (−3)	1.31 (−1)
$^{16}O(\nu_e,e^- p\alpha)^{11}C^*$	2.17 (−3)	5.66 (−1)
$^{16}O(\nu_e,e^- n\alpha)^{11}N(p)^{10}C^*$	1.11 (−6)	3.28 (−3)



Angular distributions are interesting

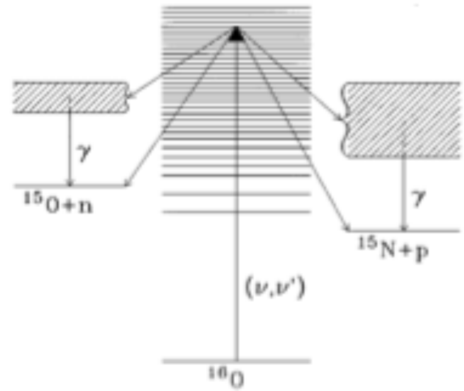
Haxton: PRD 36, (1987) 2283

TABLE IV. Partial cross sections for charged-current antineutrino-induced reactions on ^{16}O. Fermi-Dirac distributions with $T=5$ MeV and $T=8$ MeV and zero chemical potential have been assumed. The cross sections are given in units of 10^{-42} cm^2, exponents are given in parentheses.

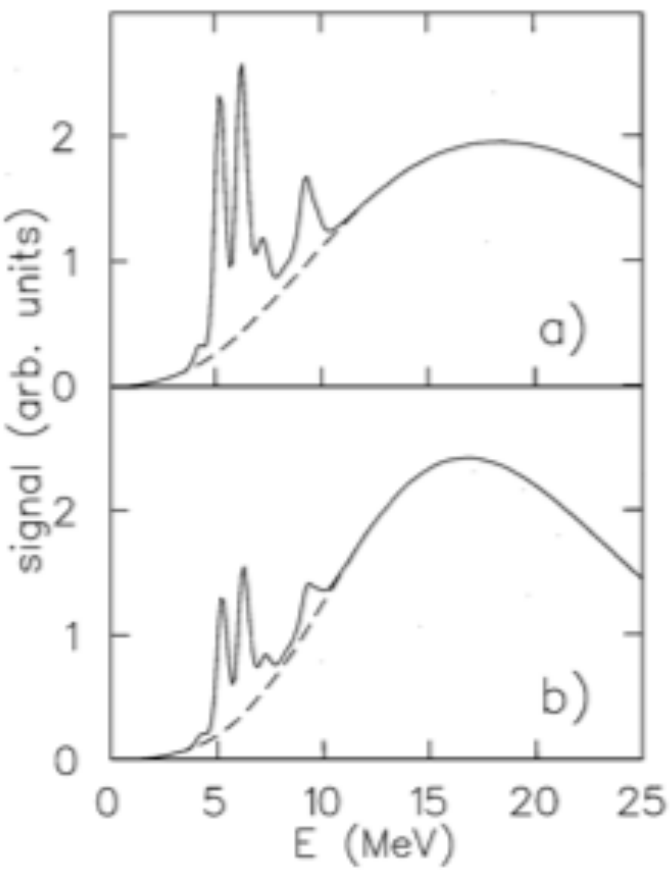
Neutrino reaction	$\sigma, T=5$ MeV	$\sigma, T=8$ MeV
total	1.05 (+0)	9.63 (+0)
$^{16}O(\bar{\nu}_e,e^+)^{16}N$(g.s.)	3.47 (−1)	2.15 (+0)
$^{16}O(\bar{\nu}_e,e^+ n)^{15}N$(g.s.)	5.24 (−1)	4.81 (+0)
$^{16}O(\bar{\nu}_e,e^+ n\gamma)^{15}N^*$	1.47 (−1)	1.90 (+0)
$^{16}O(\bar{\nu}_e,e^+ np)^{14}C^*$	4.56 (−3)	1.38 (−1)
$^{16}O(\bar{\nu}_e,e^+ nn)^{14}N^*$	5.50 (−3)	1.81 (−1)
$^{16}O(\bar{\nu}_e,e^+ \alpha)^{12}B^*$	1.07 (−2)	1.91 (−1)
$^{16}O(\bar{\nu}_e,e^+ n\alpha)^{11}B^*$	6.20 (−3)	2.16 (−1)

NC interactions on oxygen nuclei

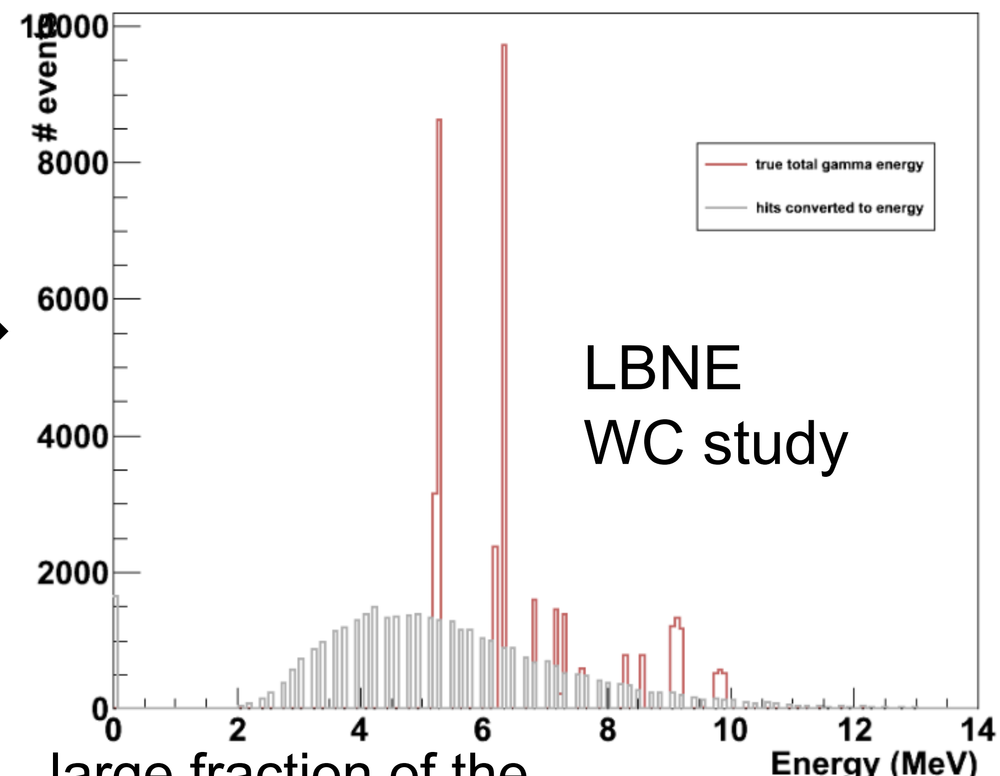
Final states from
NC excitation



Langanke, Vogel, Kolbe:
PRL 76, (1996) 2629



Observed γ energy per event



LBNE
WC study

large fraction of the
γ energy is lost in Compton scatter

Example 2: interactions on argon nuclei

Charged-current absorption

$$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$$

Dominant

$$\bar{\nu}_e + {}^{40}Ar \rightarrow e^+ + {}^{40}Cl^*$$

Neutral-current excitation

$$\nu_x + {}^{40}Ar \rightarrow \nu_x + {}^{40}Ar^*$$

Not much information in literature

Elastic scattering

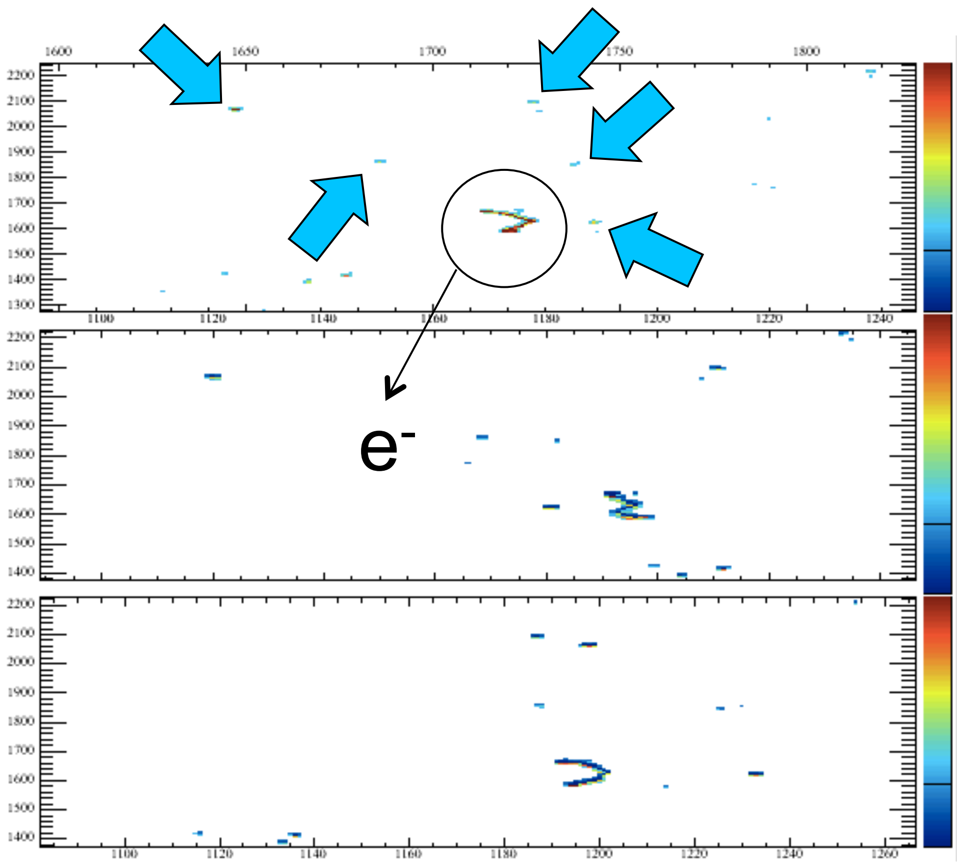
$$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$$

Can use for pointing

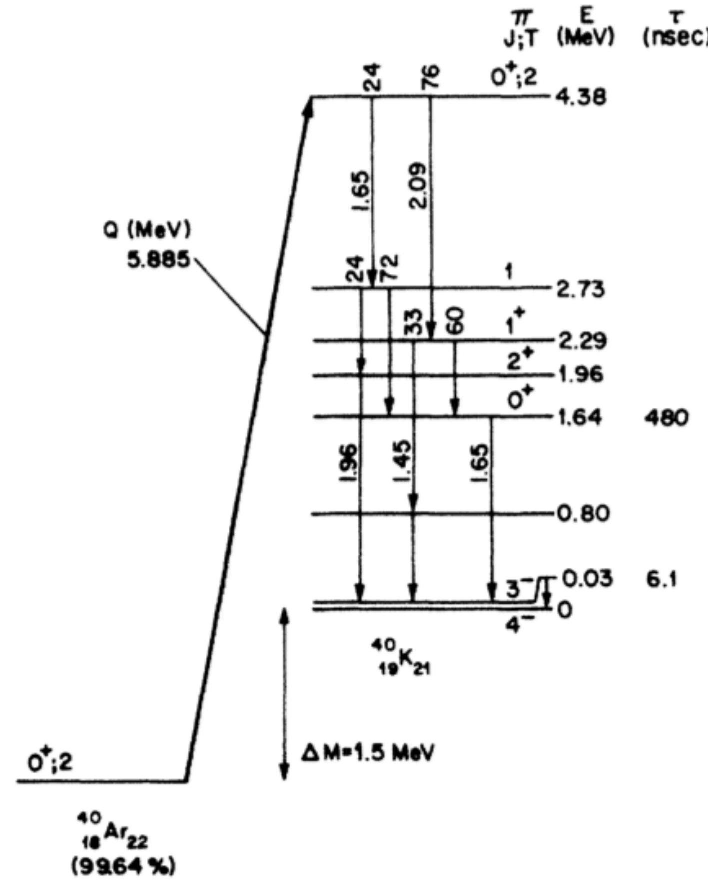
- In principle can tag modes with
- deexcitation gammas (or lack thereof)...

Can we tag ν_e CC interactions in argon using nuclear deexcitation γ's?

$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$



MicroBooNE geometry (LArSoft)



20 MeV ν_e, 14.1 MeV e^-, simple model based on R. Raghavan, PRD 34 (1986) 2088

Improved modeling based on ^{40}Ti (^{40}K mirror) β decay measurements possible

Direct measurements (and theory) needed!

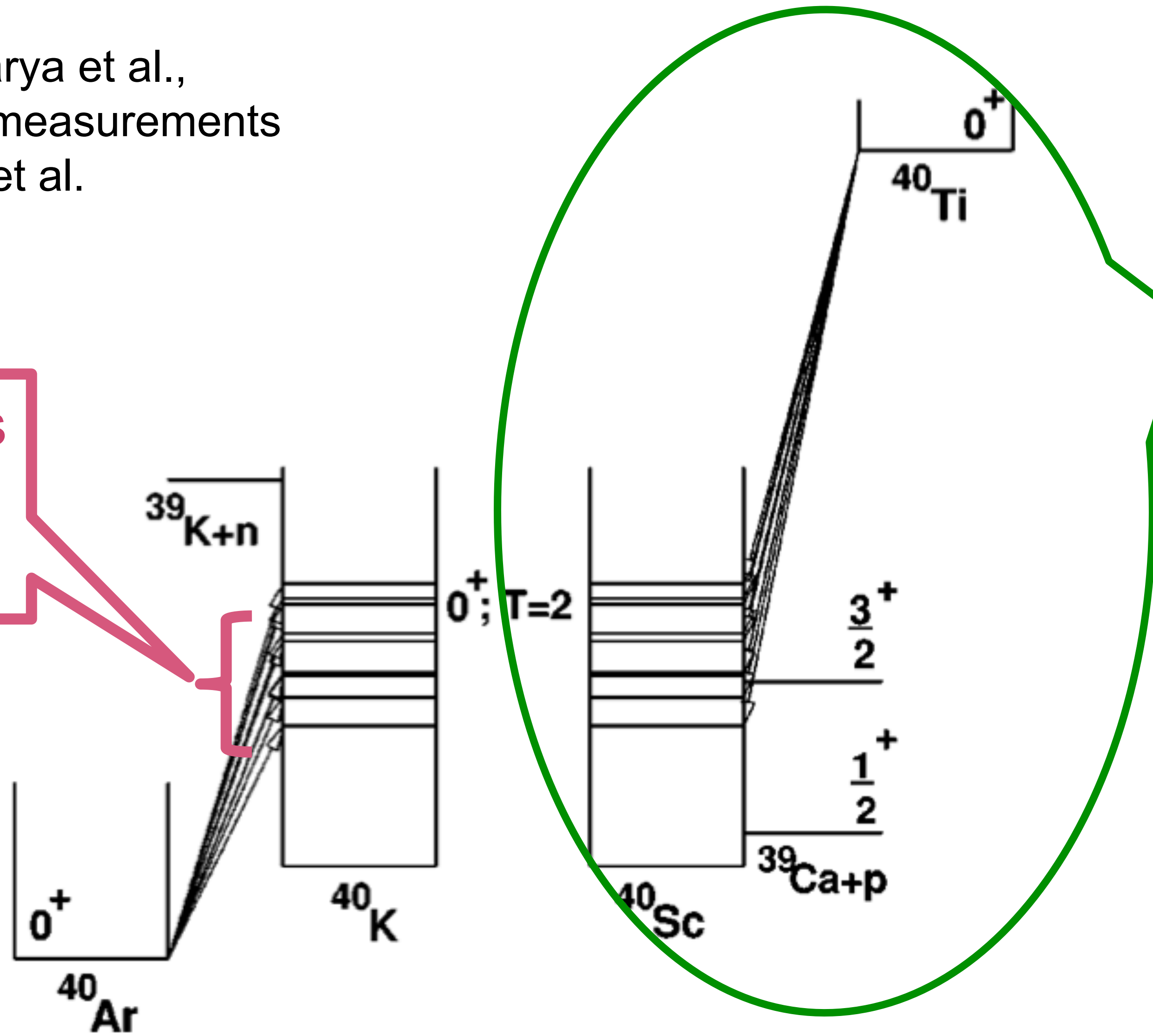
Need to understand efficiency for given technology

… in fact there can be transitions to intermediate states, adding to the cross section (and complicating the γ-tag)

PHYSICAL REVIEW C VOLUME 58, NUMBER 6 DECEMBER 1998

Neutrino absorption efficiency of an ^{40}Ar detector from the β decay of ^{40}Ti

M. Bhattacharya et al., and newer measurements by Trinder et al.



these states can be populated

measure relative strengths with βdk of ^{40}Ti to mirror nucleus

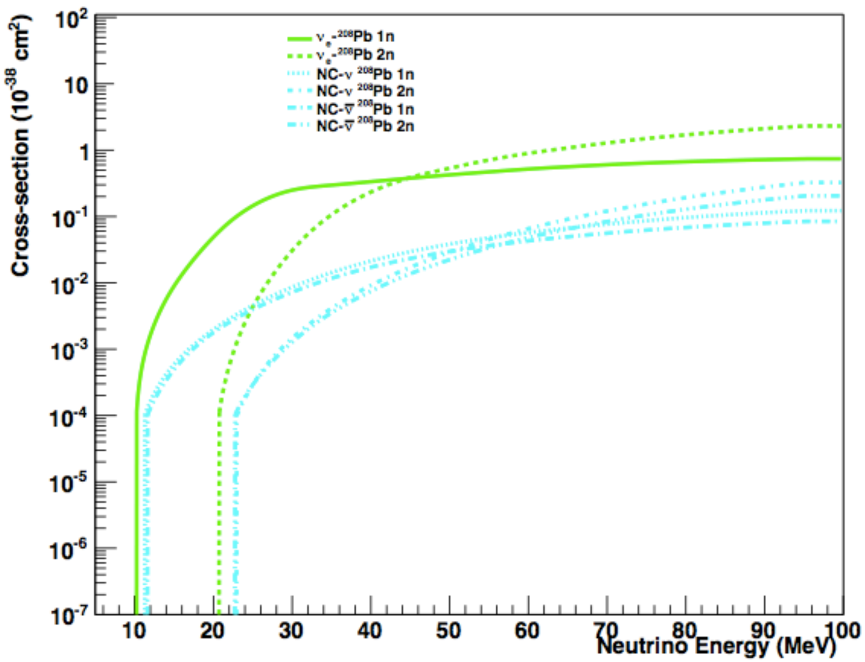
Example 3: interactions on lead nuclei

$\nu_e + {}^{208}Pb \rightarrow {}^{208}Bi^* + e^-$ CC, E_{thr}=18 MeV

↘ 1n, 2n emission

$\nu_x + {}^{208}Pb \rightarrow {}^{208}Pb^* + \nu_x$ NC

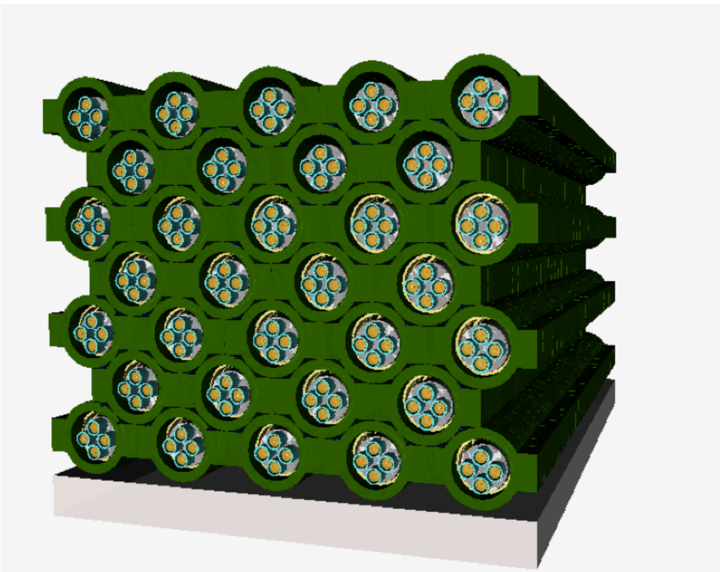
↘ 1n, 2n, γ emission



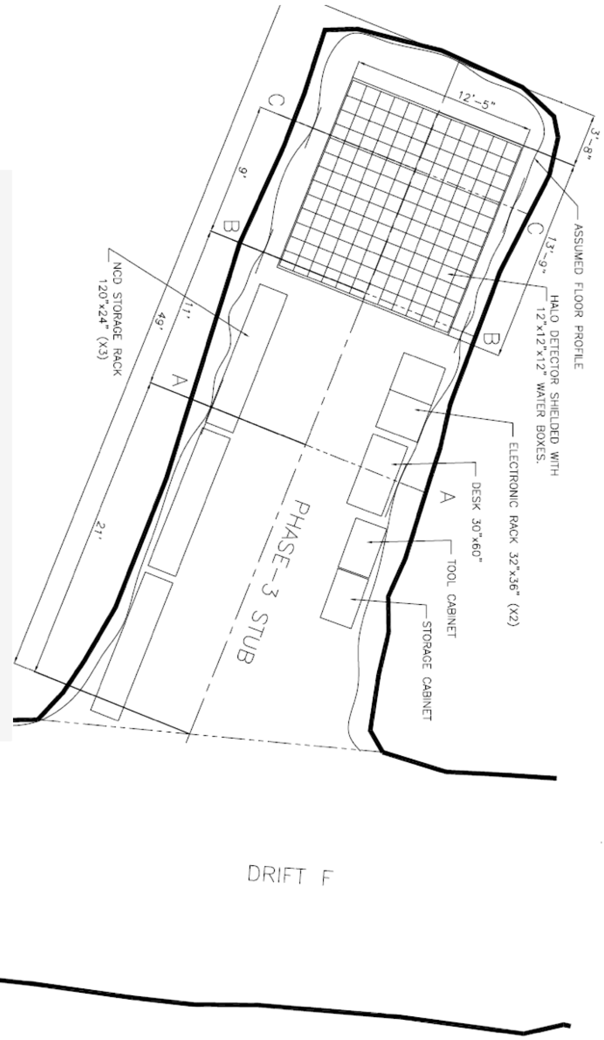
Relative rates depend on ν energy
⇒ spectral sensitivity

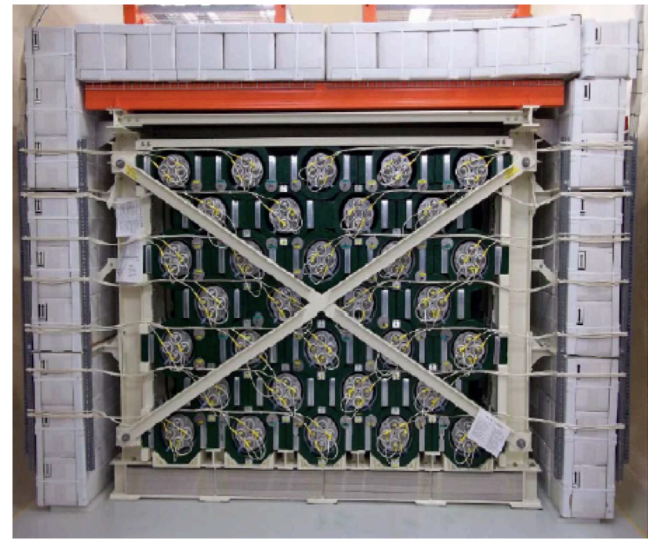
J. Engel, G. C. McLaughlin, and C. Volpe. What can be learned with a lead-based supernova-neutrino detector? *Phys. Rev.*, D67:013005, 2003.

HALO at SNOLAB



thesis



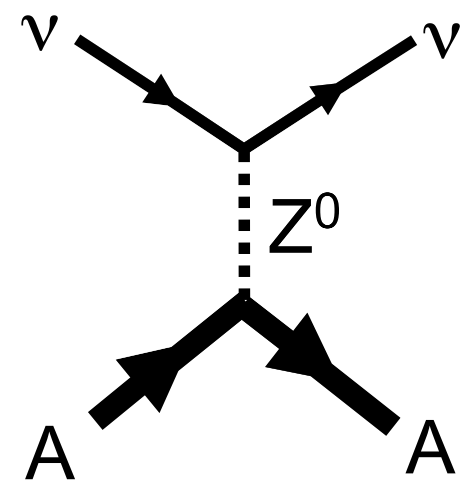


SNO ^{3}He counters + 79 tons of Pb: few-40 events @ 10 kpc

Coherent elastic neutrino-nucleus scattering (CEvNS)

$\nu + A \rightarrow \nu + A$

A neutrino smacks a nucleus via exchange of a Z, and the nucleus recoils as a whole; **coherent** up to $E_\nu \sim 50$ MeV



- Important in **SN processes & detection**
- Well-calculable cross-section in SM: SM test, probe of neutrino NSI
- Dark matter direct detection background
- Possible applications (reactor monitoring)

$$\frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2} k^2 (1 + \cos\theta) \frac{(N - (1 - 4\sin^2\theta_W)Z)^2}{4} F^2(Q^2)$$

$$\propto N^2$$

\begin{aside}

Literature has CNS, CNNS, CENNS, ...

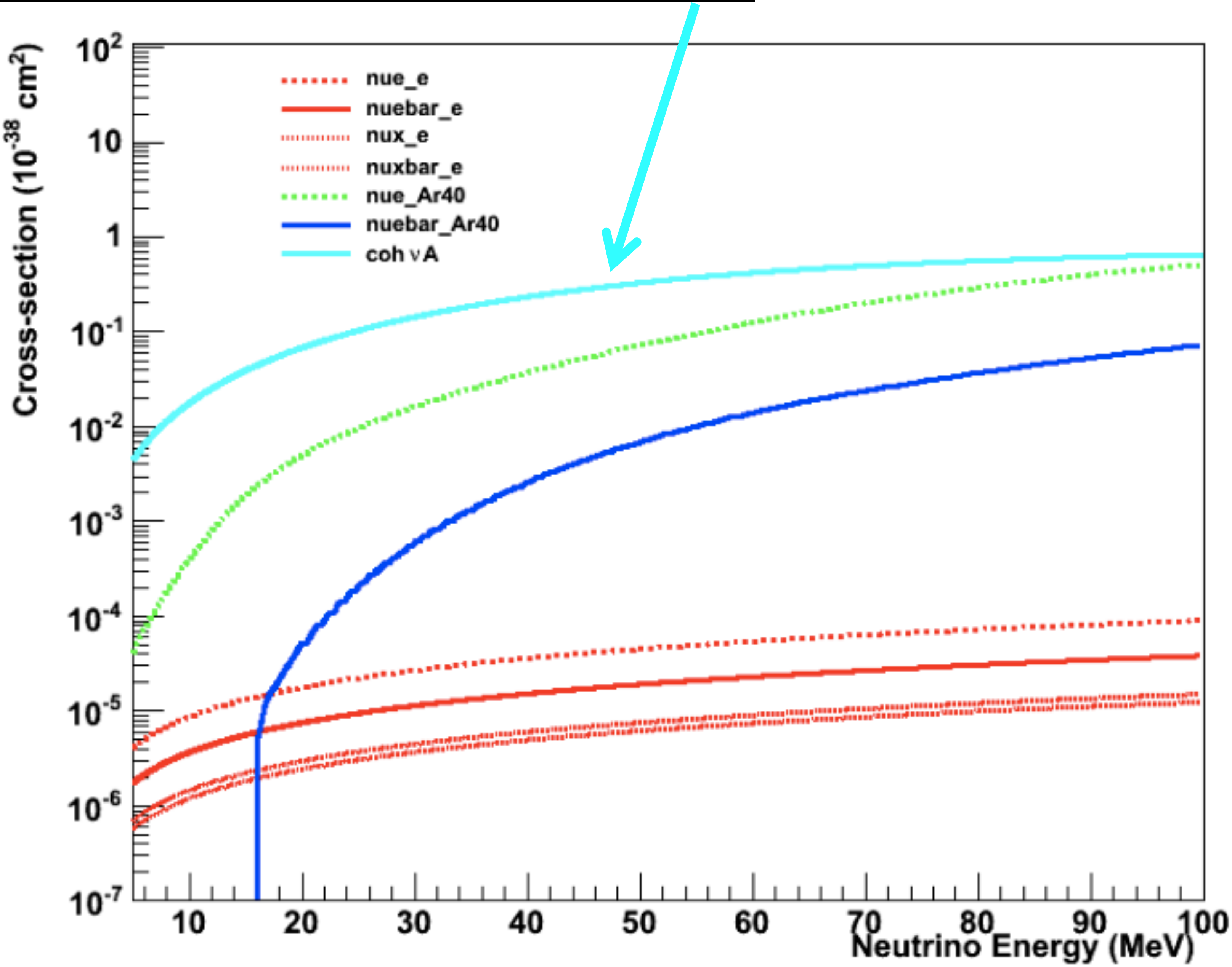
- I prefer including “E” for “elastic”... otherwise NuInt types constantly confuse it with coherent pion production at ~ GeV energies
- I’m told “NN” means “nucleon-nucleon” to nuclear types (also CENNS is now a collaboration!)
- CEνNS is a possibility but those internal Greek letters are annoying

➔**CEvNS**, pronounced “sevens”...

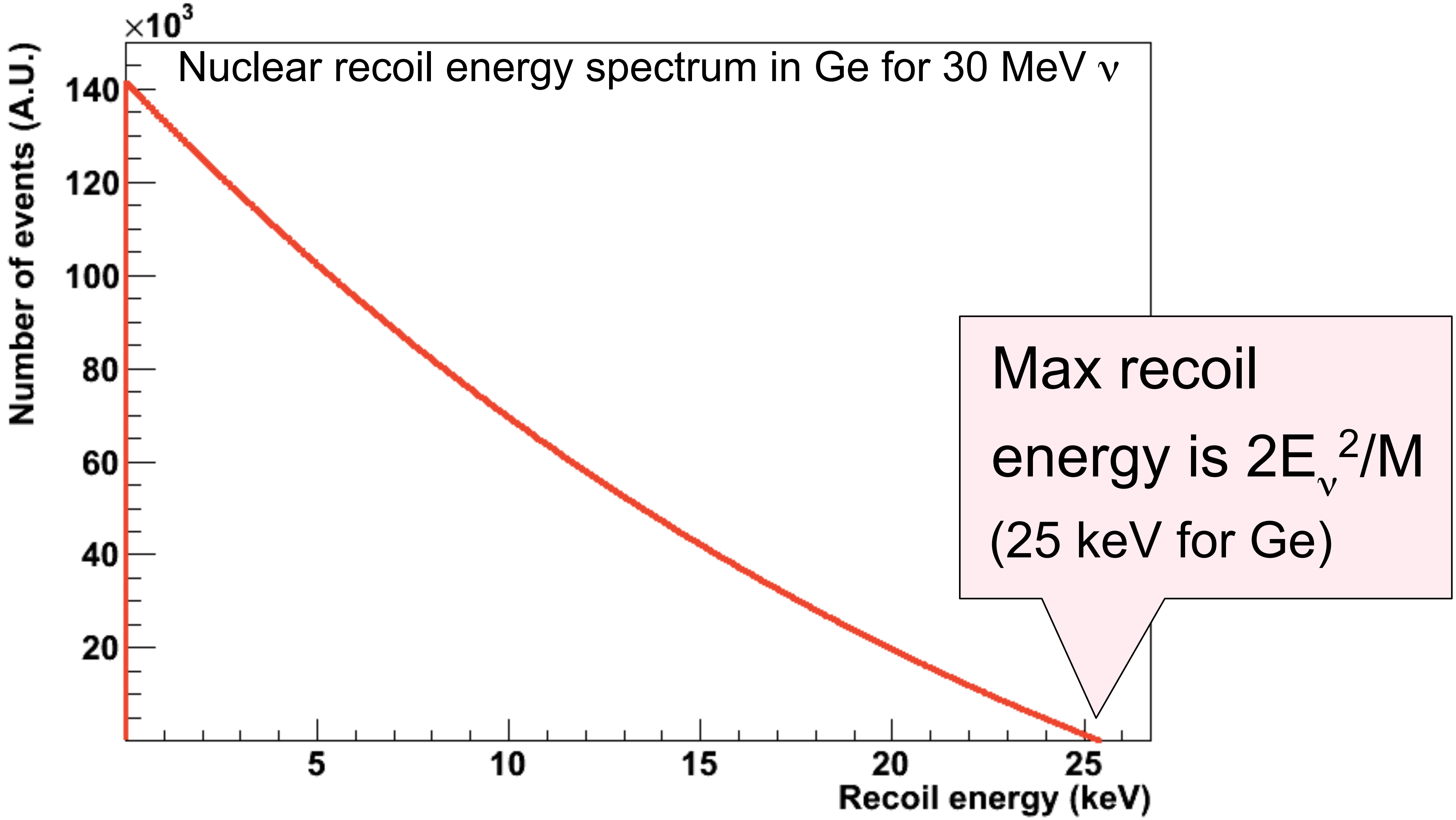
spread the meme!

\end{aside}

The cross-section is *large*

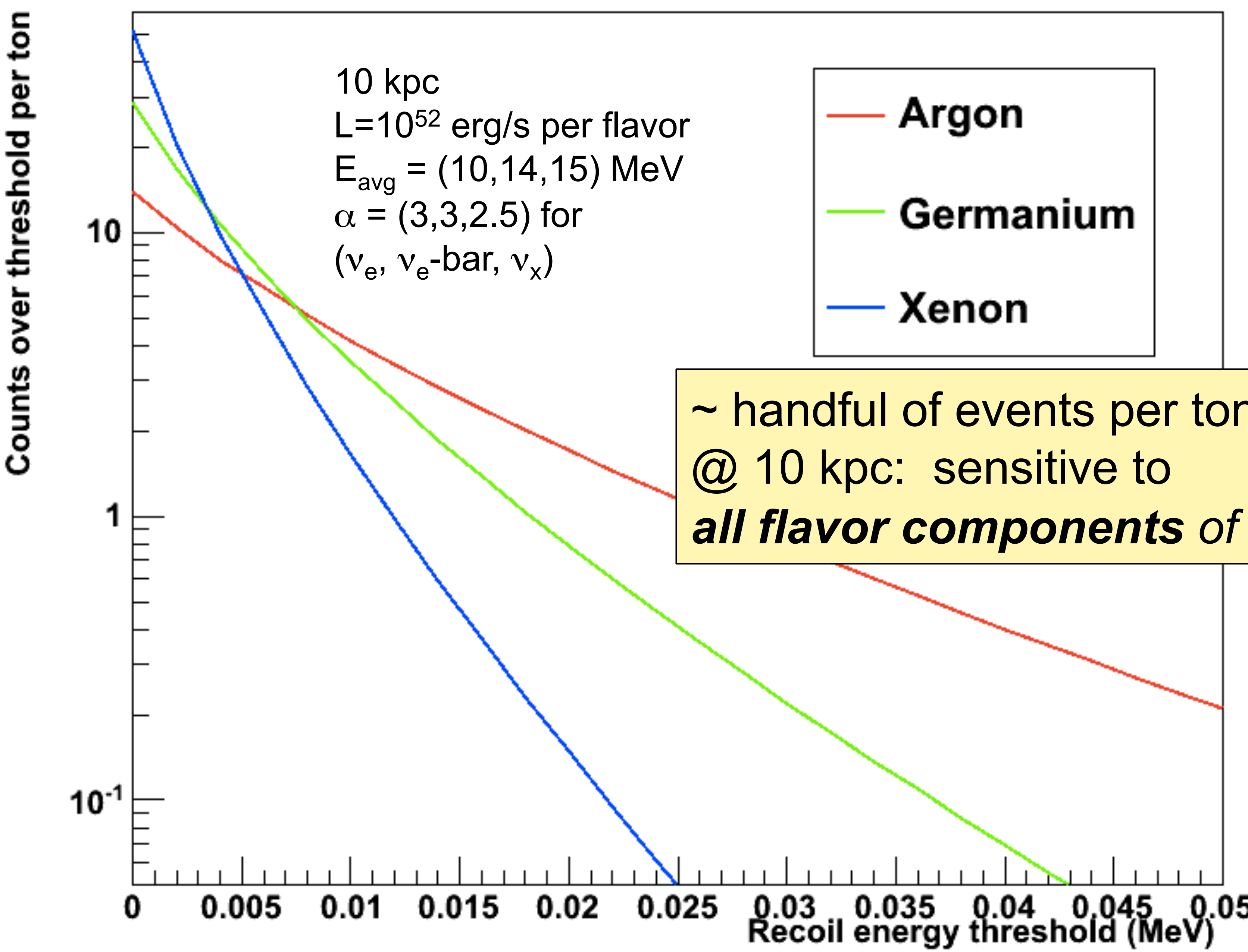


Large cross section, but never observed due to **tiny nuclear recoil energies:**



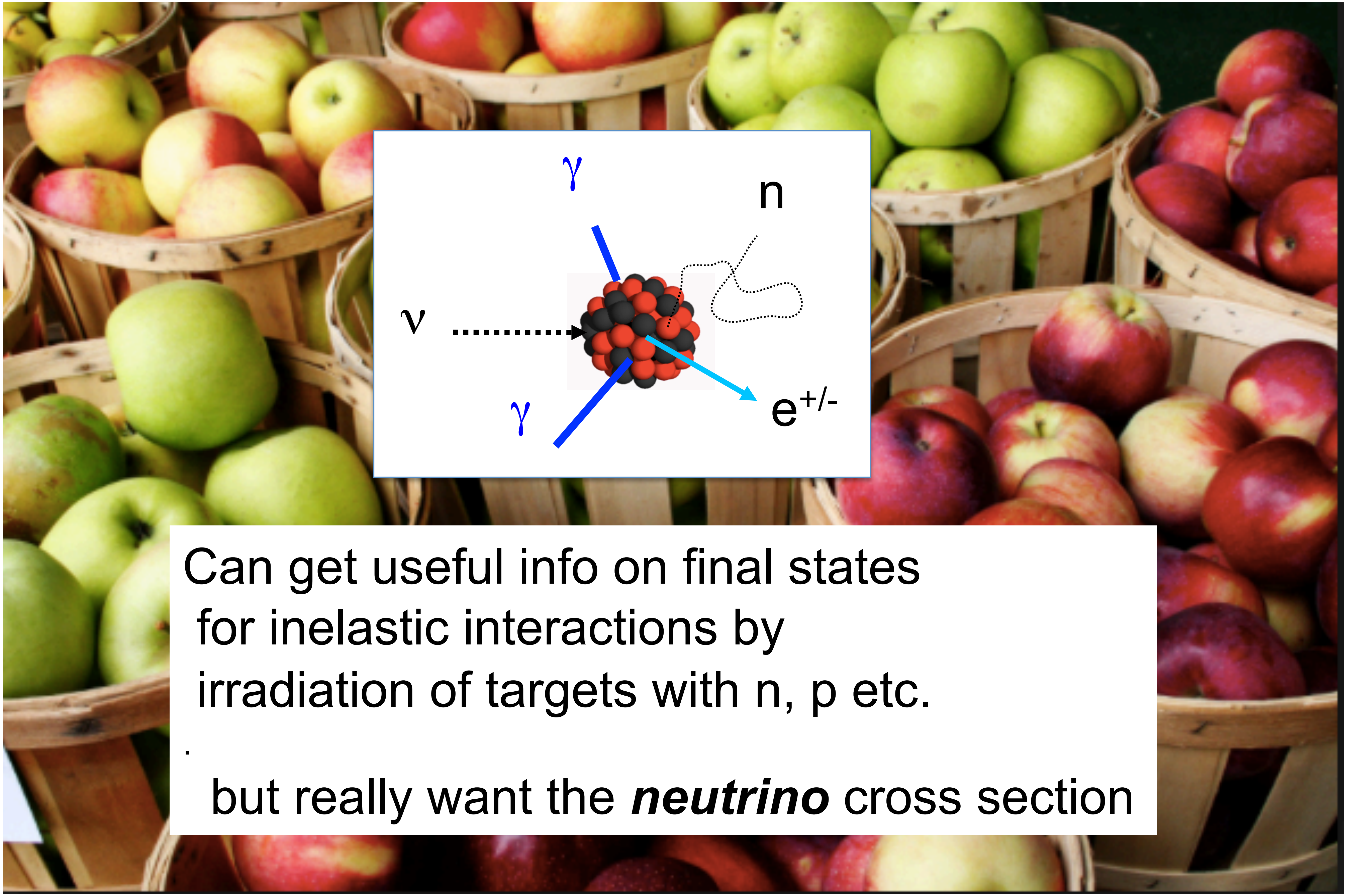
➔ but **WIMP dark matter detectors** developed over the last ~decade are sensitive to ~ keV to 10's of keV recoils

>~tonne-scale underground DM detectors can measure supernova neutrinos (and solar)



~ handful of events per tonne @ 10 kpc: sensitive to ***all flavor components*** *of the flux*

How can we *measure* these cross sections?

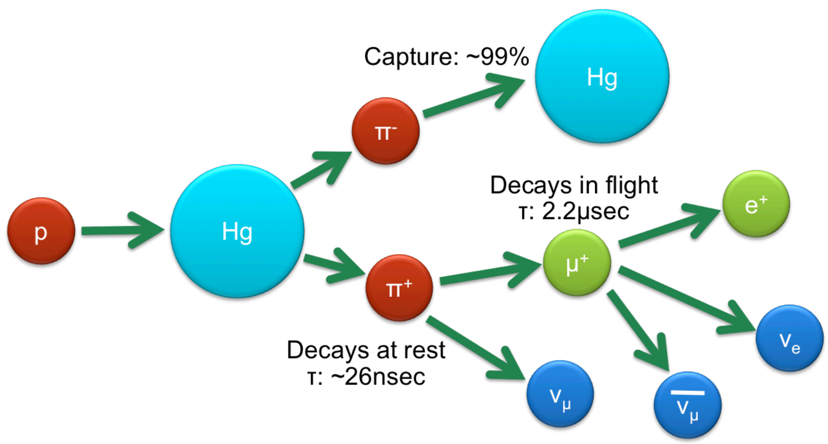


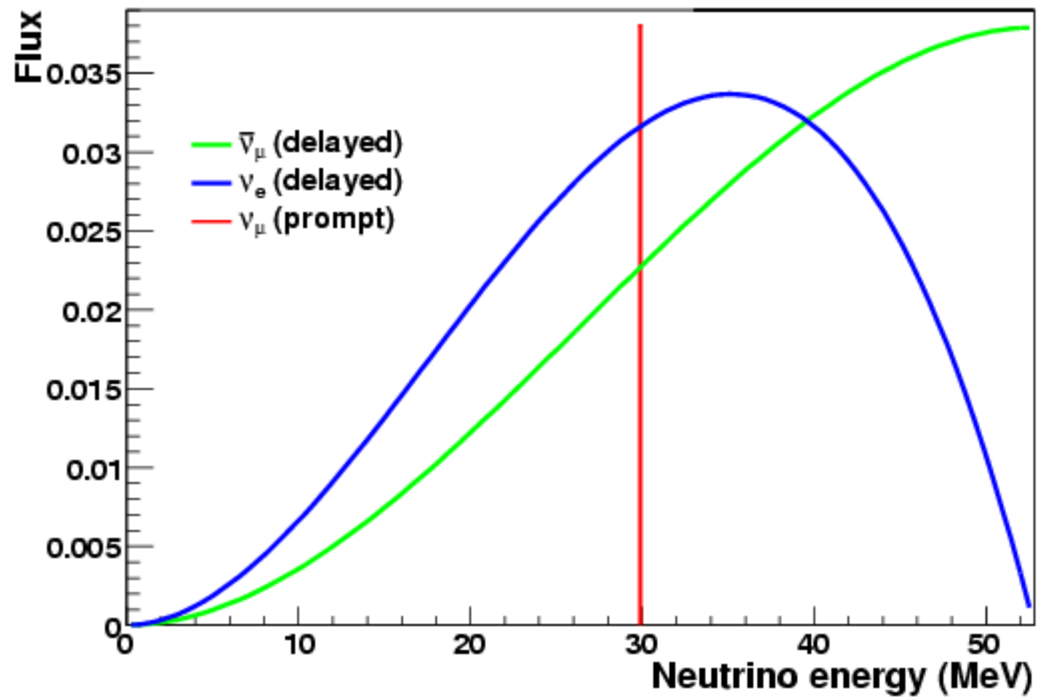
Can get useful info on final states
for inelastic interactions by
irradiation of targets with n, p etc.

.

but really want the ***neutrino*** cross section

Stopped-Pion (πDAR) Neutrinos





$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$

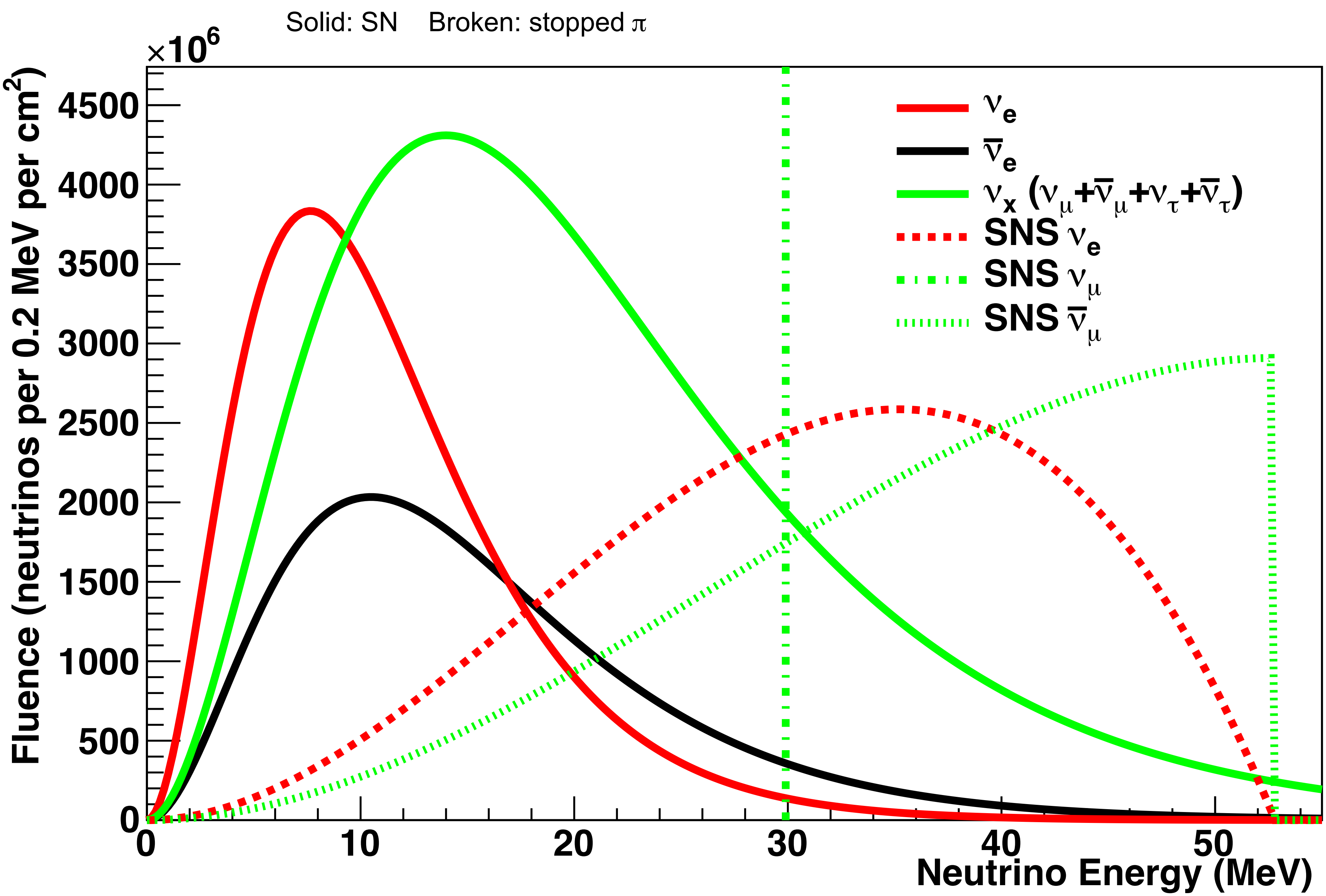
2-body decay: monochromatic 29.9 MeV ν_μ
PROMPT

$$\downarrow$$

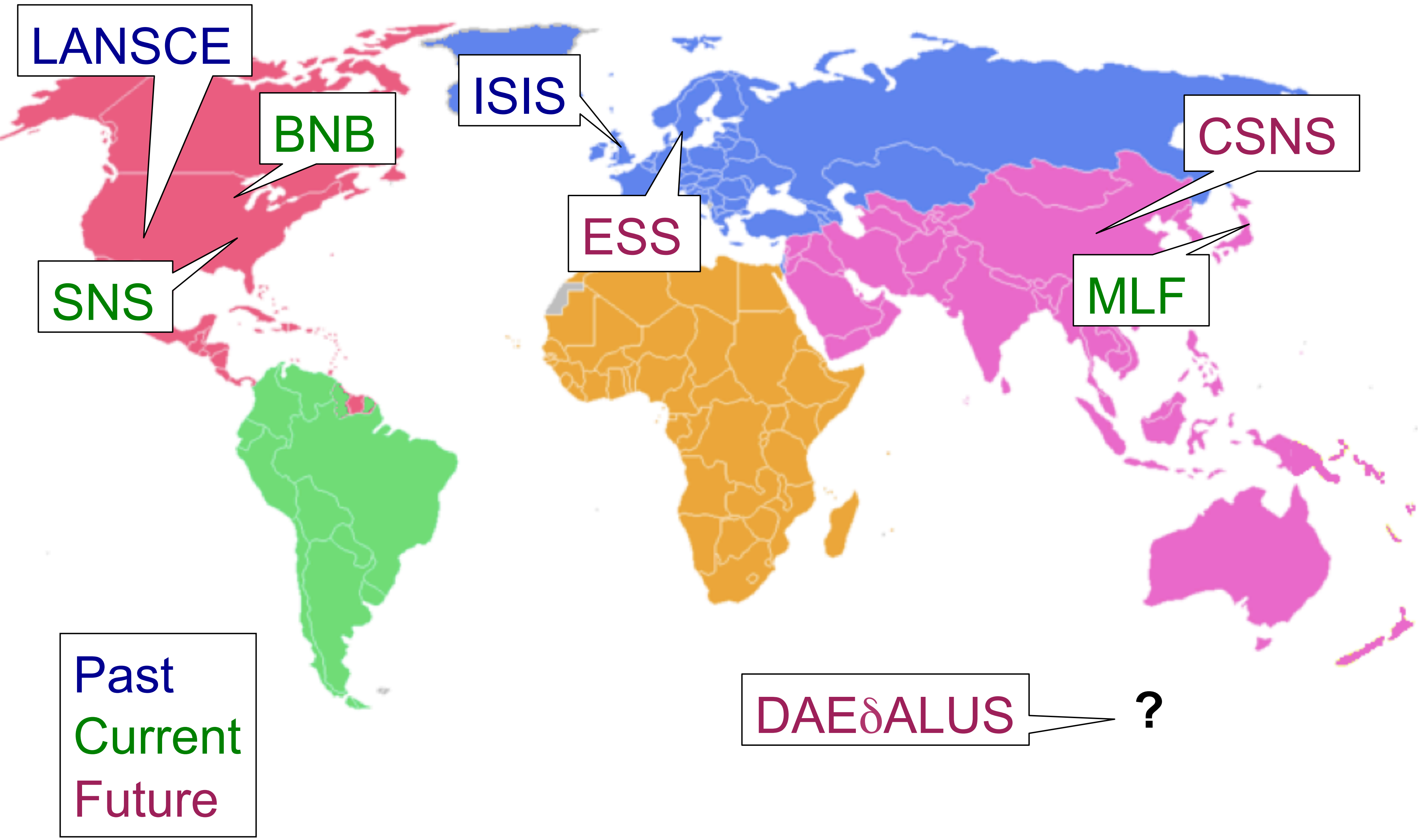
$$\mu^+ \longrightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

3-body decay: range of energies
between 0 and $m_\mu/2$
DELAYED (2.2 μs)

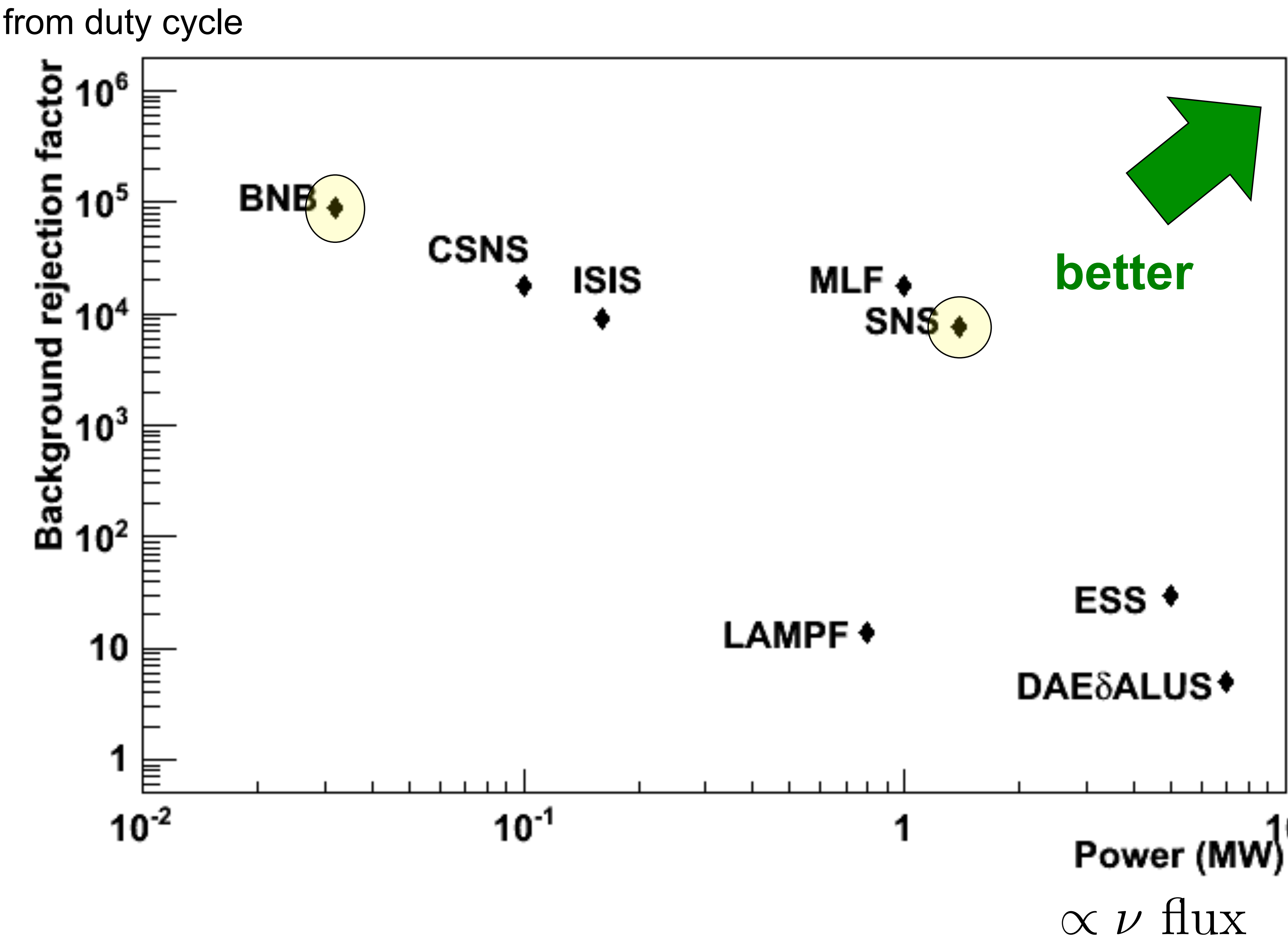
Good overlap w/ SN spectrum



Stopped-Pion Sources Worldwide



Comparison of pion decay-at-rest ν sources



Experiments at stopped-π neutrino sources

Location	Past	Ongoing	Future/ Proposed
LANSCE	LSND		
ISIS	KARMEN		
J-PARC MLF (JSNS)			E56, KPIPE
FNAL BNB			CENNS, CAPTAIN-BNB
SNS		COHERENT	OscSNS, CAPTAIN
FNAL NuMI			Concepts
CSNS			Liquid scint?
ESS			Concepts

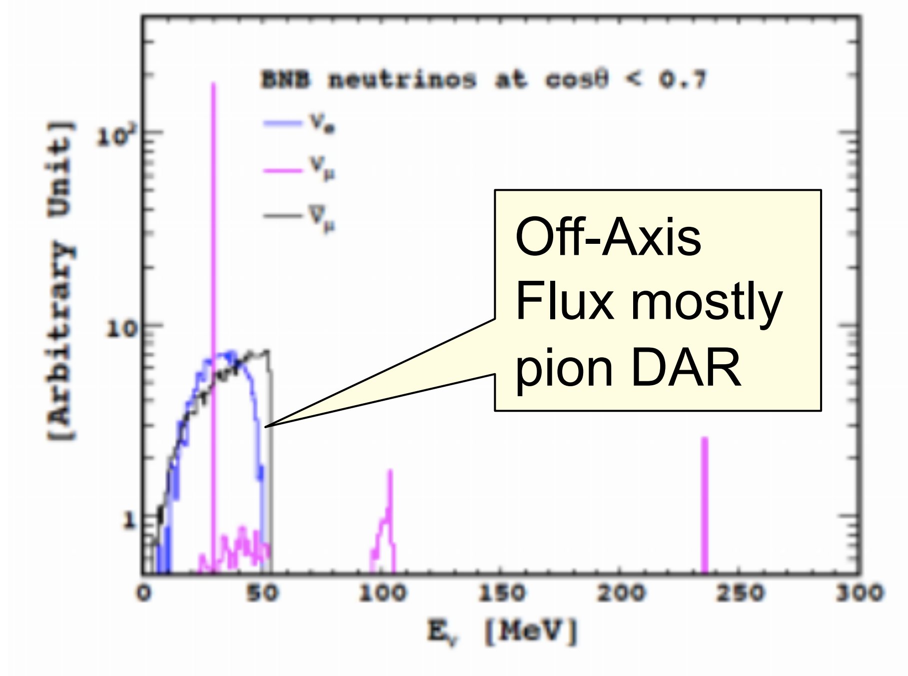
BLUE: cross-section measurements made or recently proposed

Experiments at stopped-π neutrino sources

Location	Past	Ongoing	Future/ Proposed
LANSCE	**LSND**		
ISIS	**KARMEN**		
J-PARC MLF (JSNS)			E56, KPIPE
FNAL BNB			**CENNS, CAPTAIN-BNB**
SNS		**COHERENT**	OscSNS, **CAPTAIN**
FNAL NuMI			Concepts
CSNS			Liquid scint?
ESS			Concepts

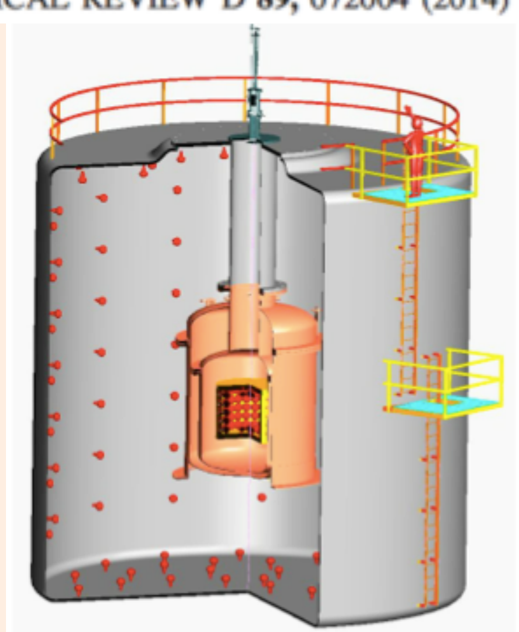
Look in more detail at these

Cross-Section Experiment Concepts @ the FNAL Booster Neutrino Beam

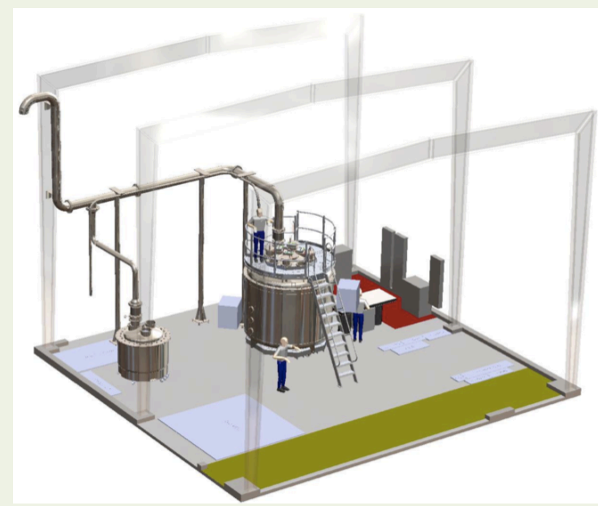


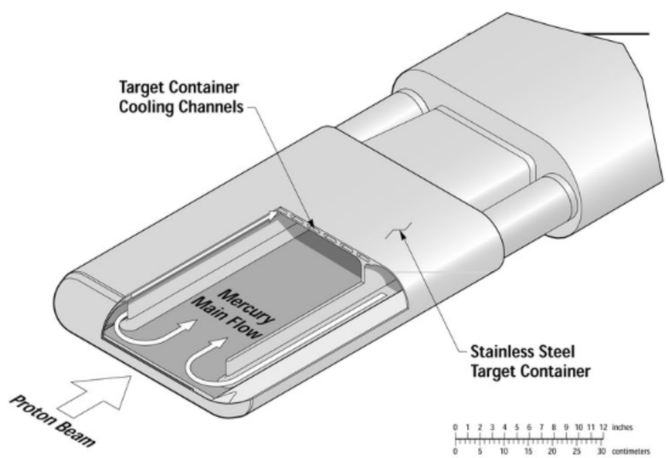
CENNS experiment to measure CEvNS: LAr single-phase

PHYSICAL REVIEW D 89, 072004 (2014)



CAPTAIN-BNB experiment (5-ton LAr TPC) proposed to measure ν-Ar x-scns *[was deferred for CAPTAIN -MINERvA ... now back to low-E focus?]*





Proton beam energy: 0.9-1.3 GeV

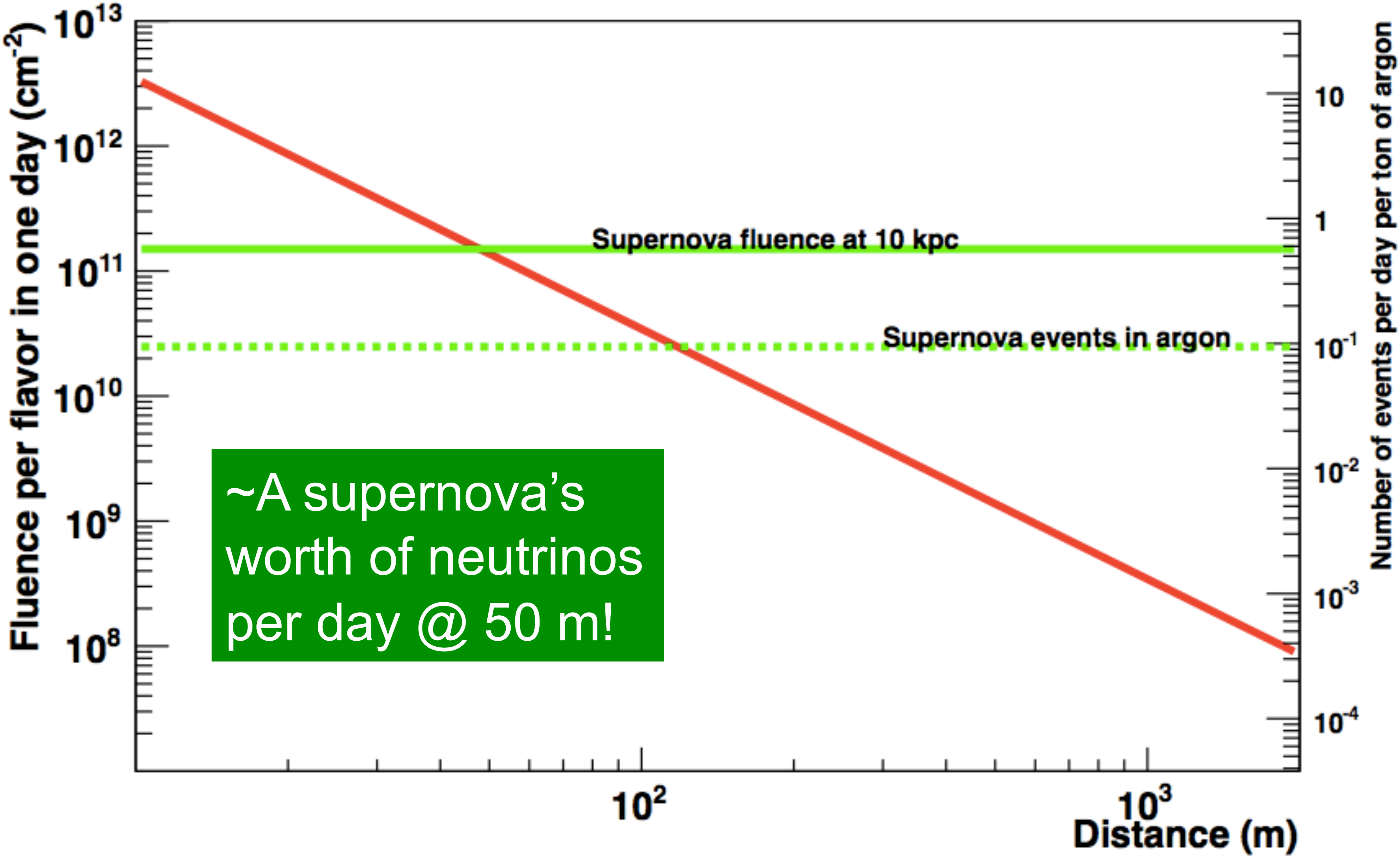
Total power: 0.9-1.4 MW

Pulse duration: 380 ns FWHM

Repetition rate: 60 Hz

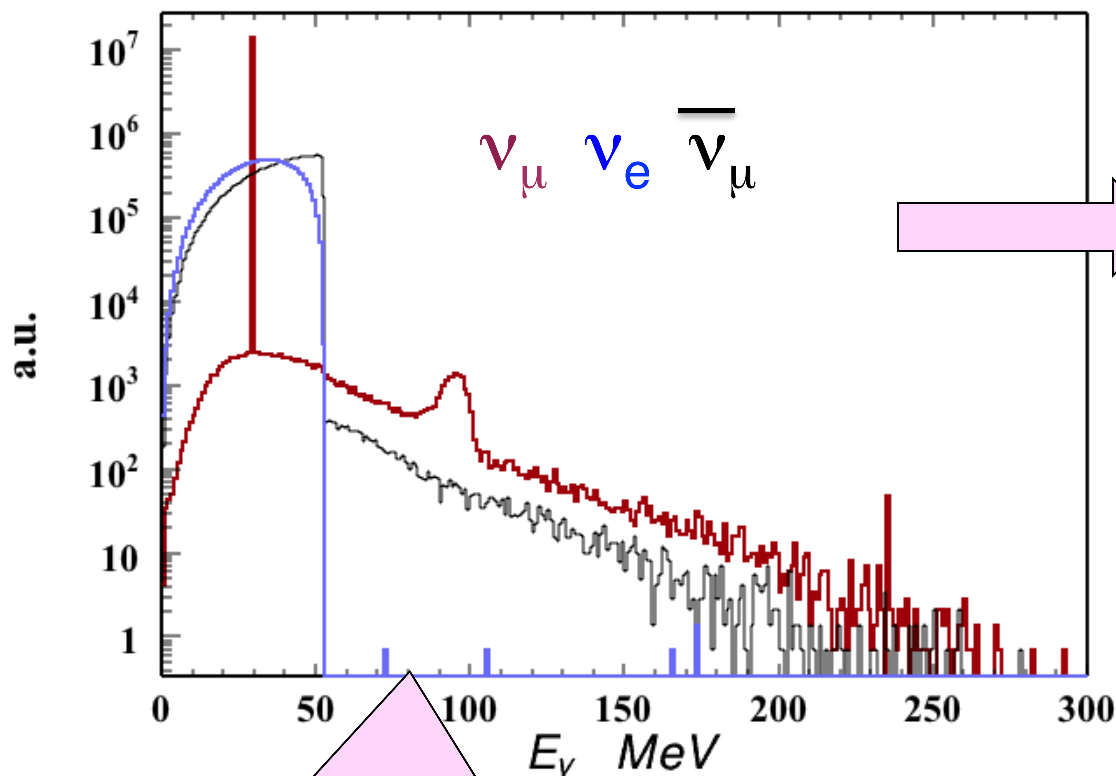
Liquid mercury target

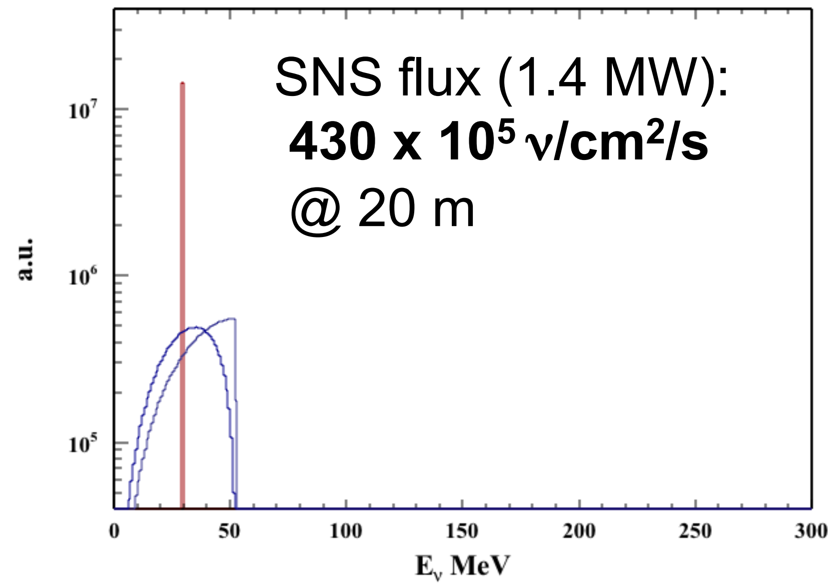
The SNS has **large, extremely clean** DAR ν flux



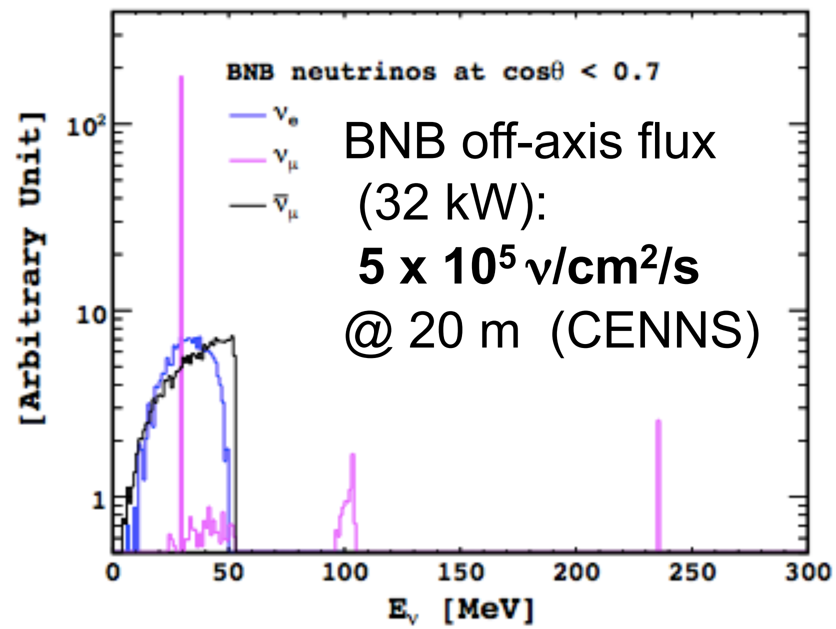
~A supernova's worth of neutrinos per day @ 50 m!

The SNS has **large, extremely clean** DAR ν flux





SNS flux (1.4 MW):
430 x 10⁵ ν/cm²/s
@ 20 m

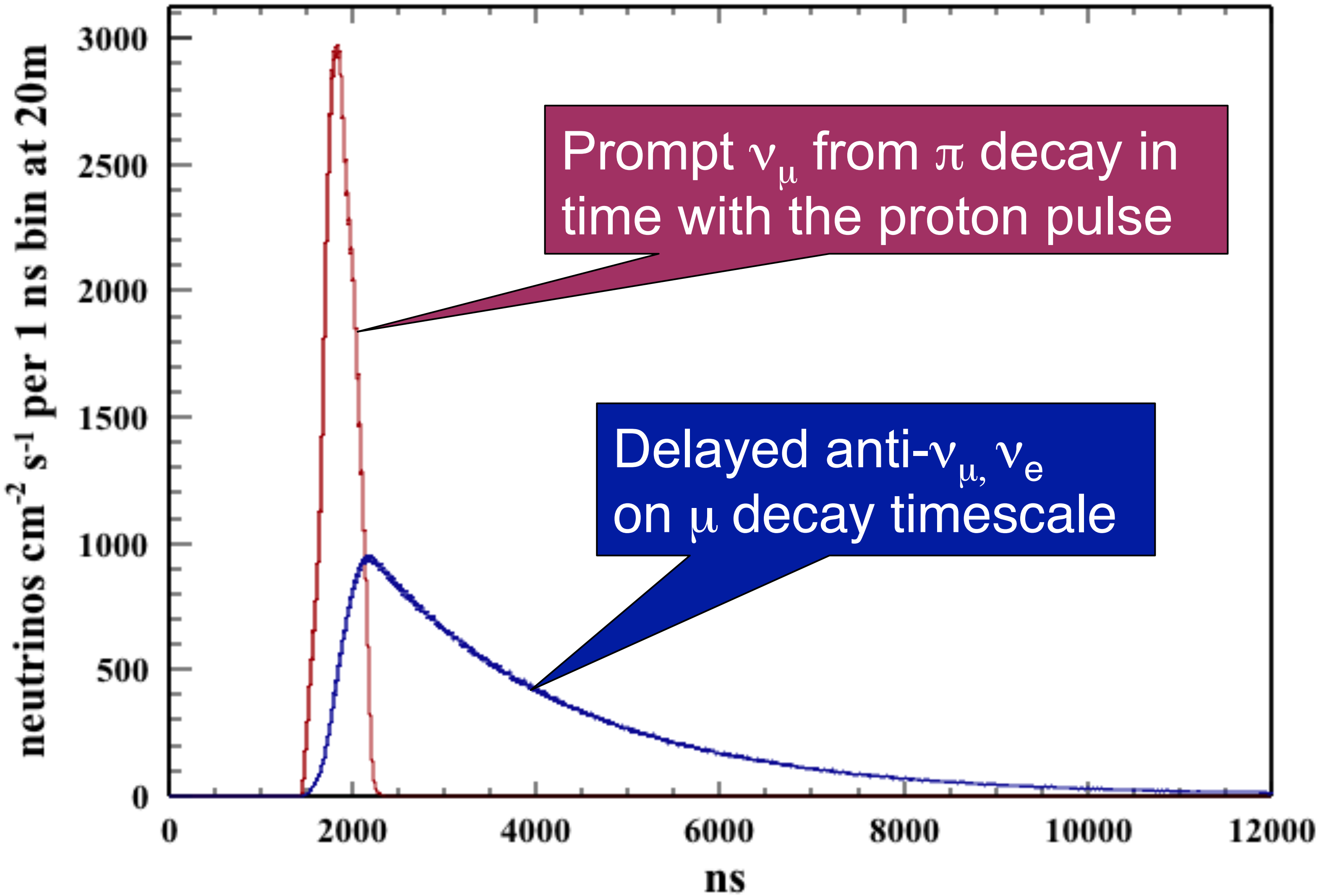


BNB off-axis flux (32 kW):
5 x 10⁵ ν/cm²/s
@ 20 m (CENNS)

Note that contamination from non π-decay at rest (decay in flight, kaon decay, μ capture...) is **down by several orders of magnitude**

Time structure of the SNS source

60 Hz *pulsed* source

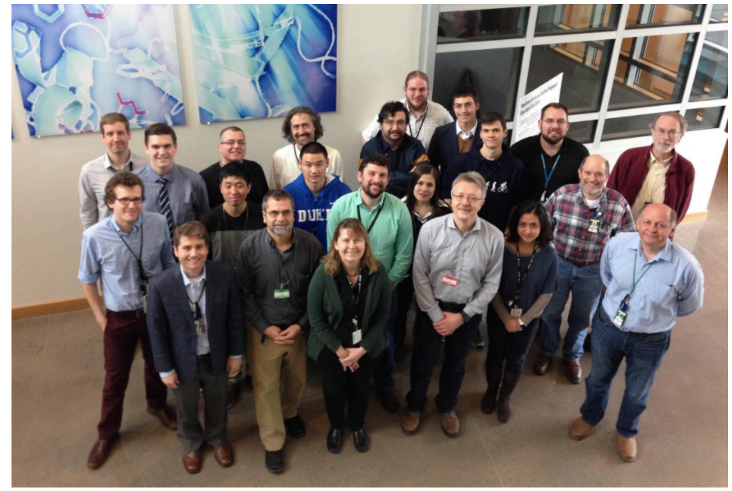


Background rejection factor ~few x 10^{-4}

The COHERENT collaboration

arXiv:1509.08702

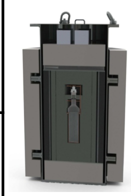
Institution	Board Member
University of California, Berkeley	Kai Vetter
University of Chicago	Juan Collar
Duke University	Kate Scholberg
University of Florida	Heather Ray
Indiana University	Rex Tayloe
Institute for Theoretical and Experimental Physics, Moscow	Dmitri Akimov
Lawrence Berkeley National Laboratory	Ren Cooper
Los Alamos National Laboratory	Steve Elliott
National Research Nuclear University MEPhI	Alex Bolozdynya
New Mexico State University	Robert Cooper
North Carolina Central University	Diane Markoff
North Carolina State University	Matt Green
Oak Ridge National Laboratory	Jason Newby
Sandia National Laboratories	David Reyna
University of Tennessee, Knoxville	Yuri Efremenko
Triangle Universities Nuclear Laboratory	Phil Barbeau
University of Washington	Jason Detwiler

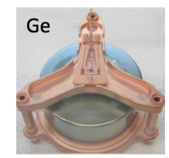


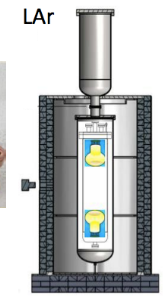
- Collaboration: ~65 members, 16 institutions (USA+ Russia)

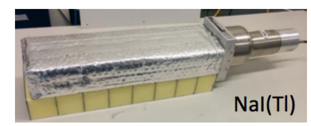
COHERENT Detectors and Status

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[Tl]	Scintillating crystal	185*/ 2000	28	13	*high-threshold deployment to start, summer 2016



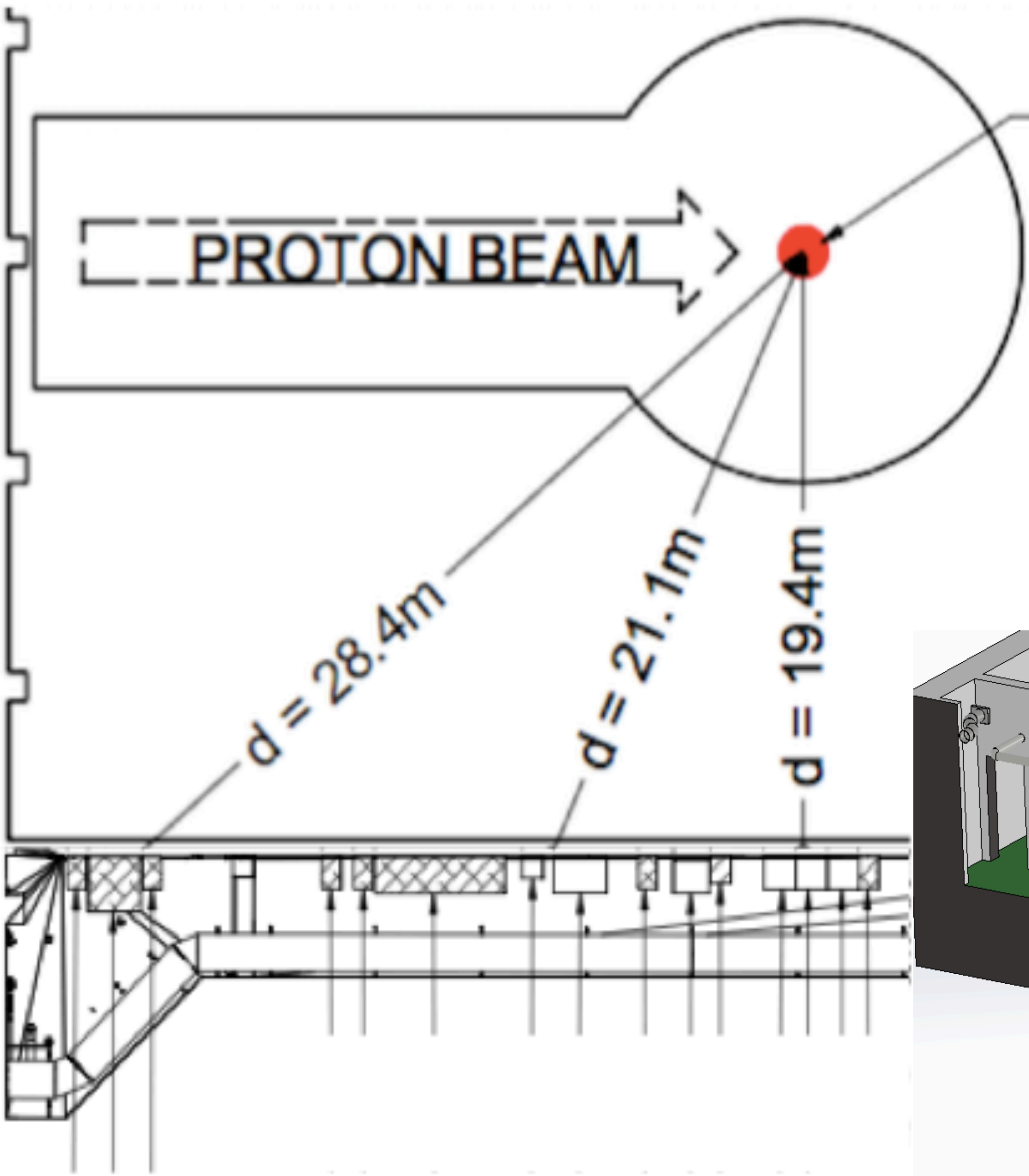




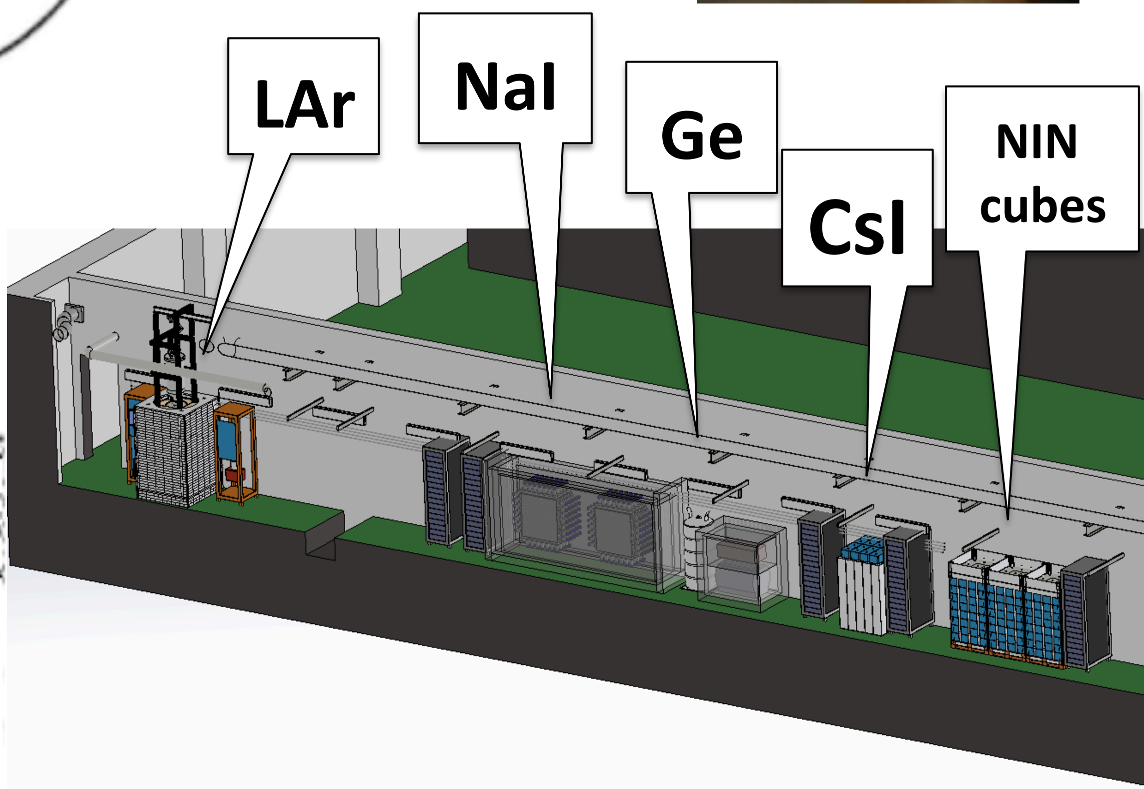


- CsI installed July 2015; 185 kg of NaI in July 2016
- Two more detectors to be deployed with resources in hand, fall 2016

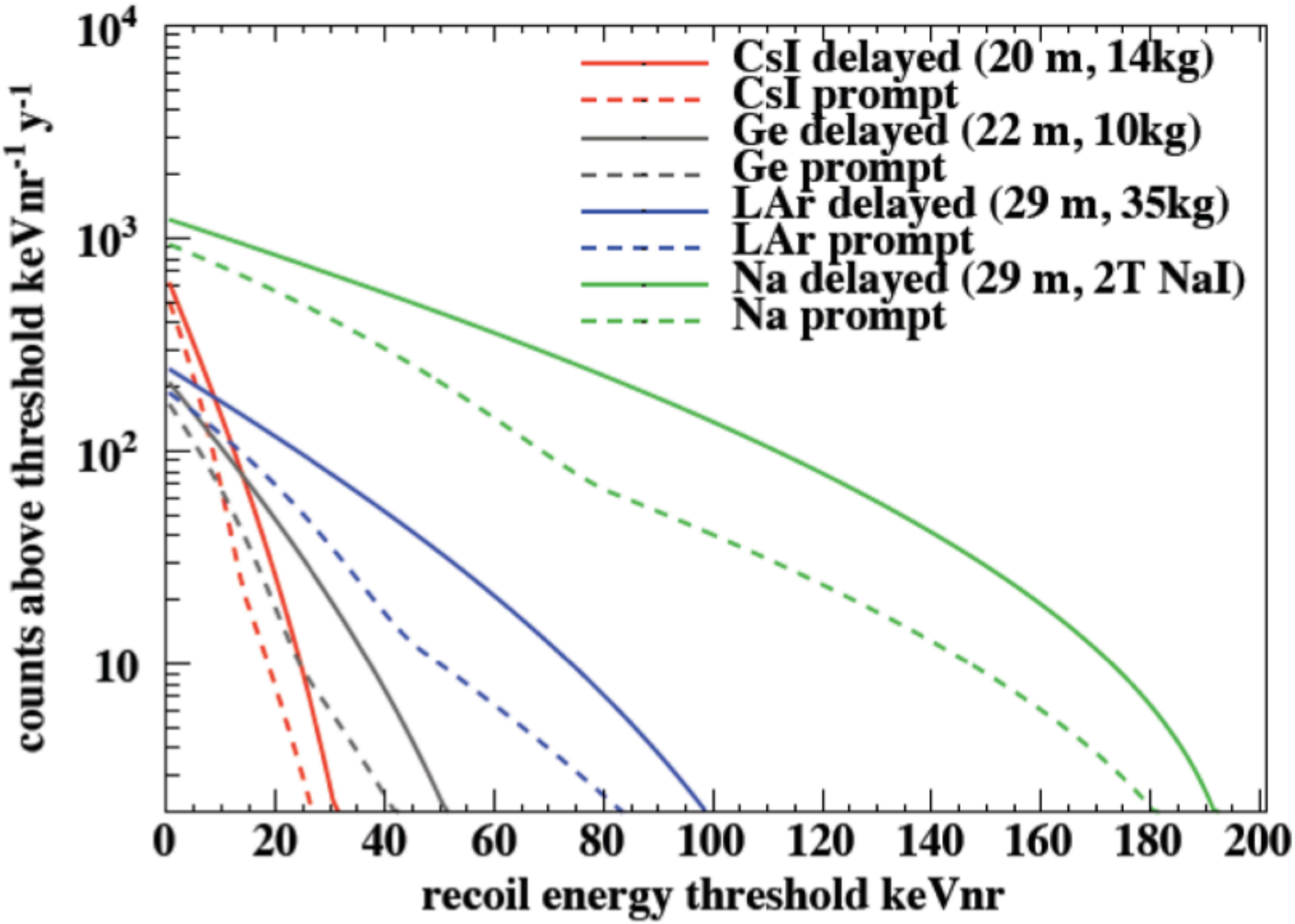
Siting for deployment in SNS basement
(measured neutron backgrounds low)



View looking down “Neutrino Alley”

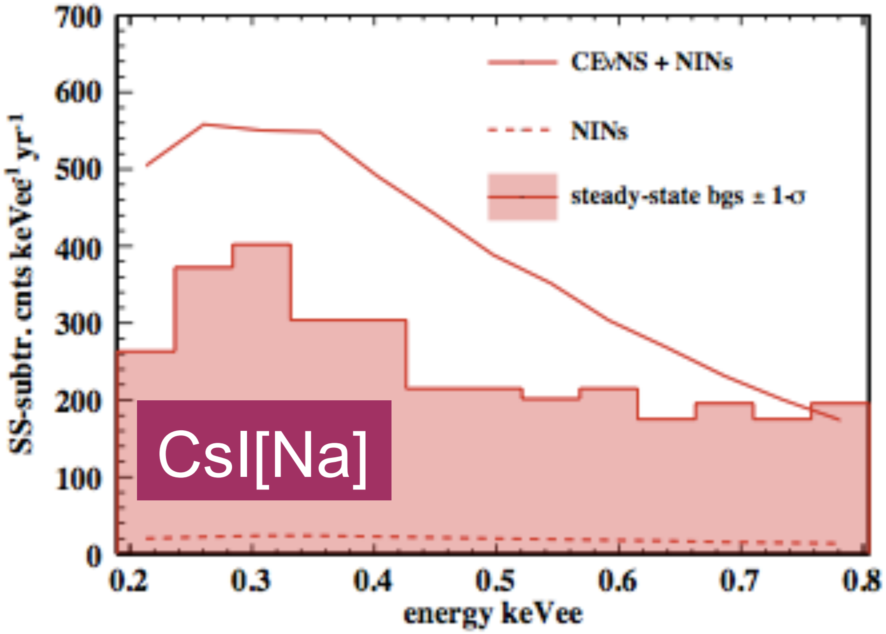


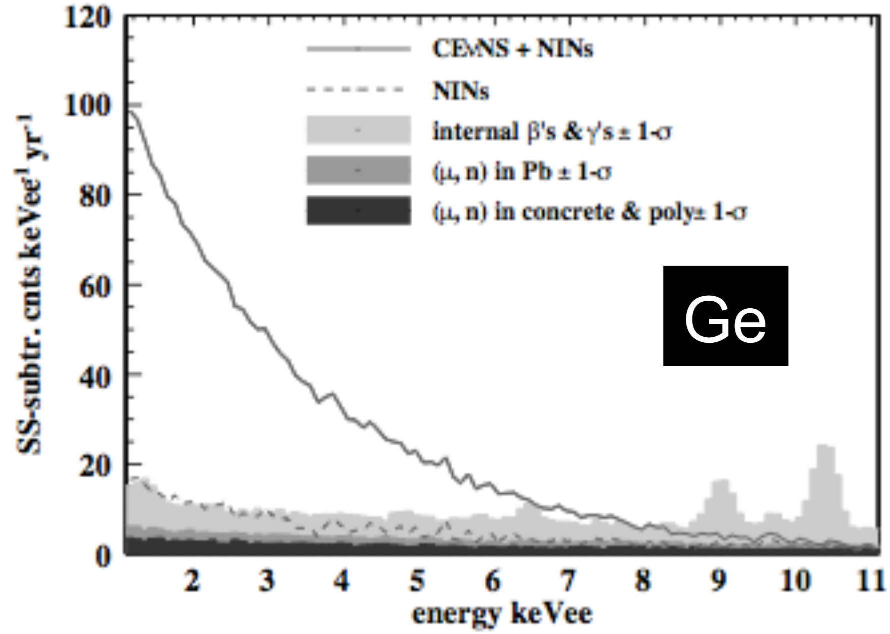
Expected recoil signals

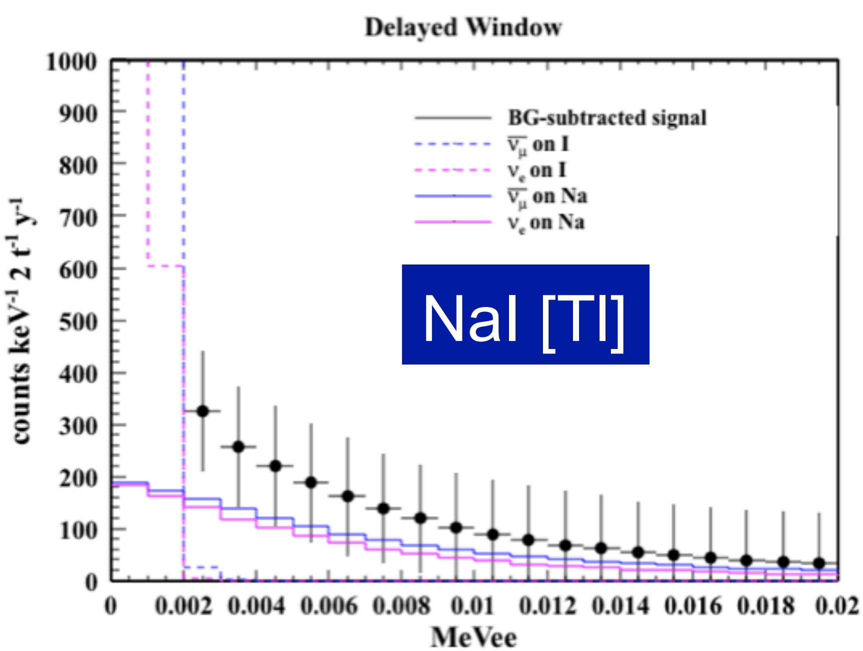


Prompt defined as first μs; note some contamination from ν_e and ν_μ-bar

Realistic steady-state-bg-subtracted recoil spectra (keVee/MeVee) compared to 1σ background fluctuations







Note:
also CC on ^{127}I
in high-gain mode

Currently measuring *neutrino-induced neutrons* in lead, (iron, copper), ...

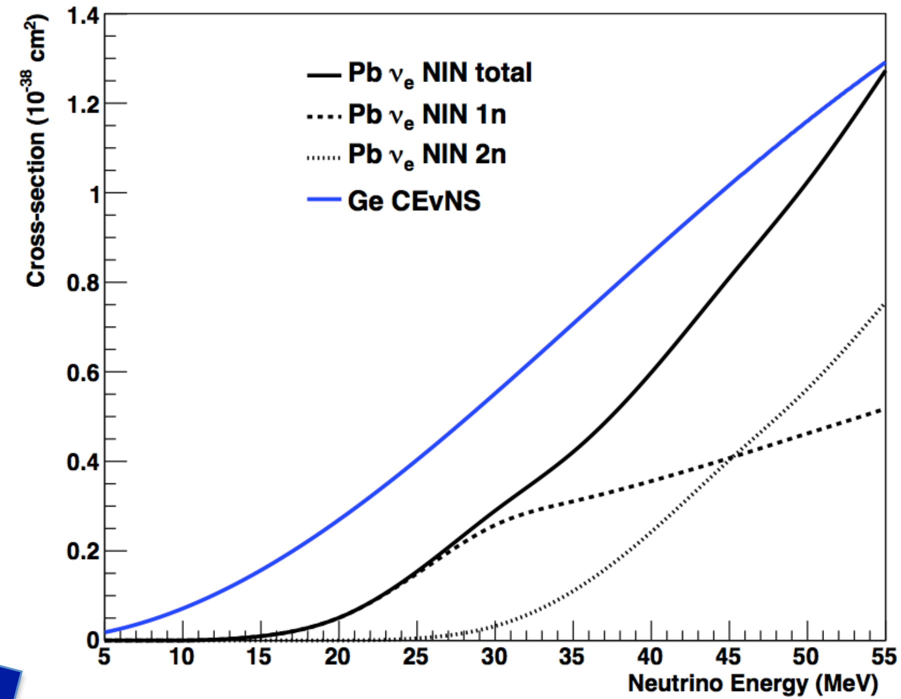
$\nu_e + {}^{208}Pb \rightarrow {}^{208}Bi^* + e^-$ CC

↘ 1n, 2n emission

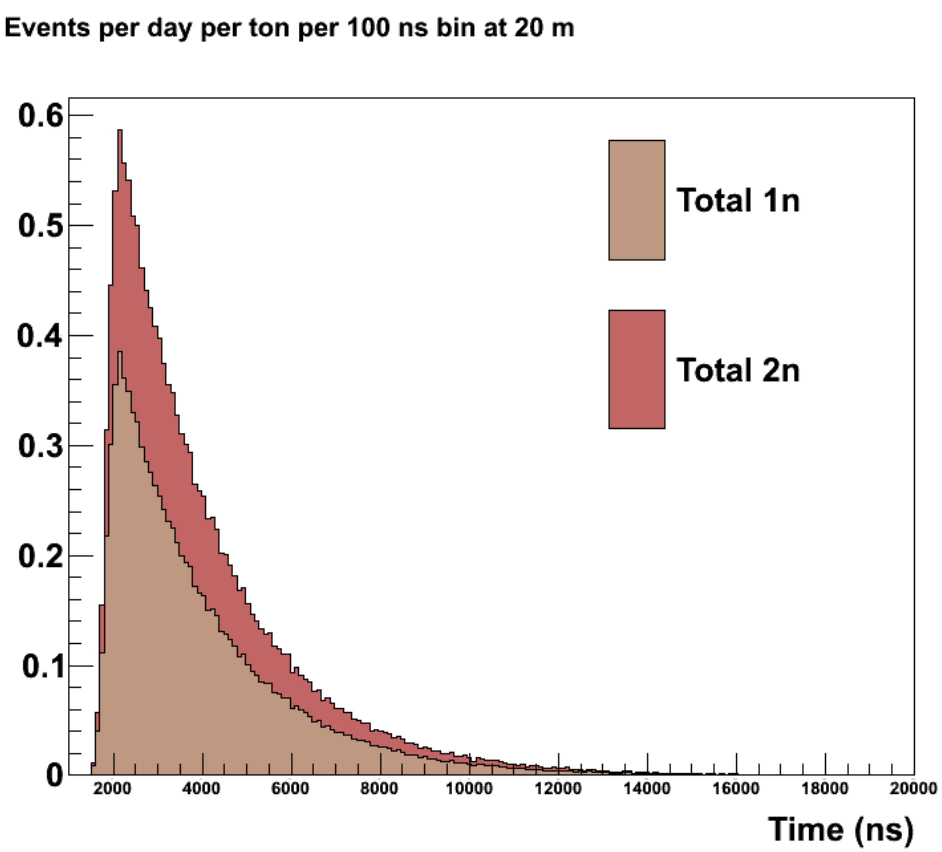
$\nu_x + {}^{208}Pb \rightarrow {}^{208}Pb^* + \nu_x$ NC

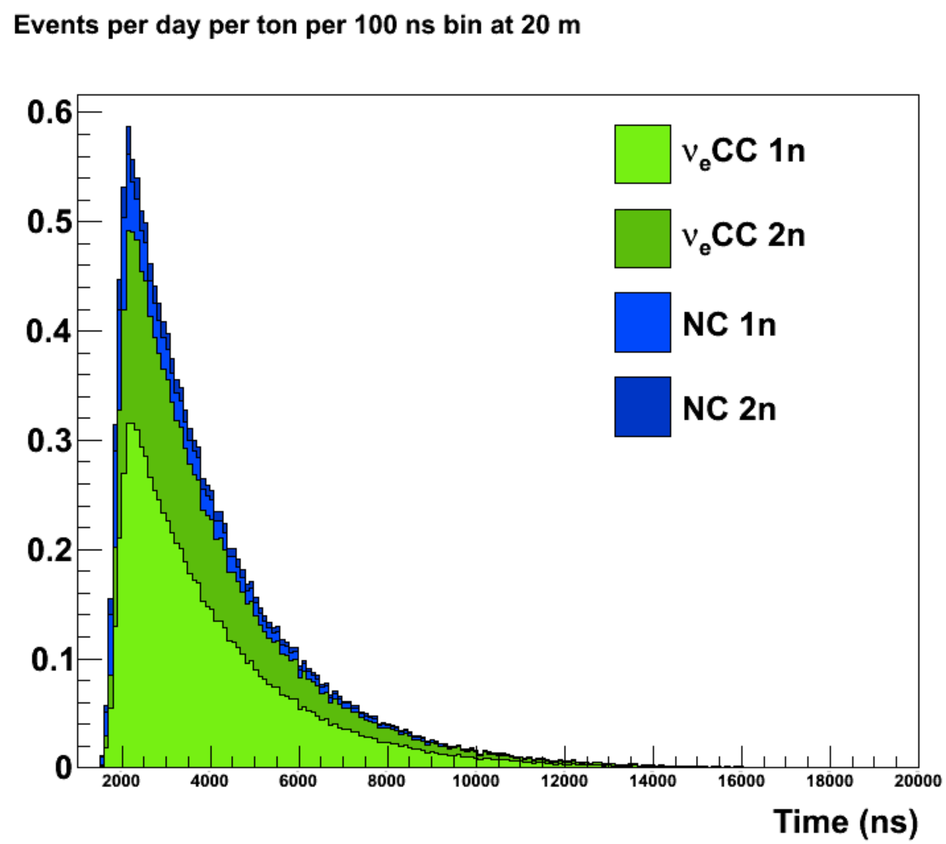
↘ 1n, 2n, γ emission

- likely a non-negligible background, especially in lead shield
- valuable in itself, e.g. HALO
- short-term physics output



Total 1n and 2n interactions expected vs time wrt beam pulse



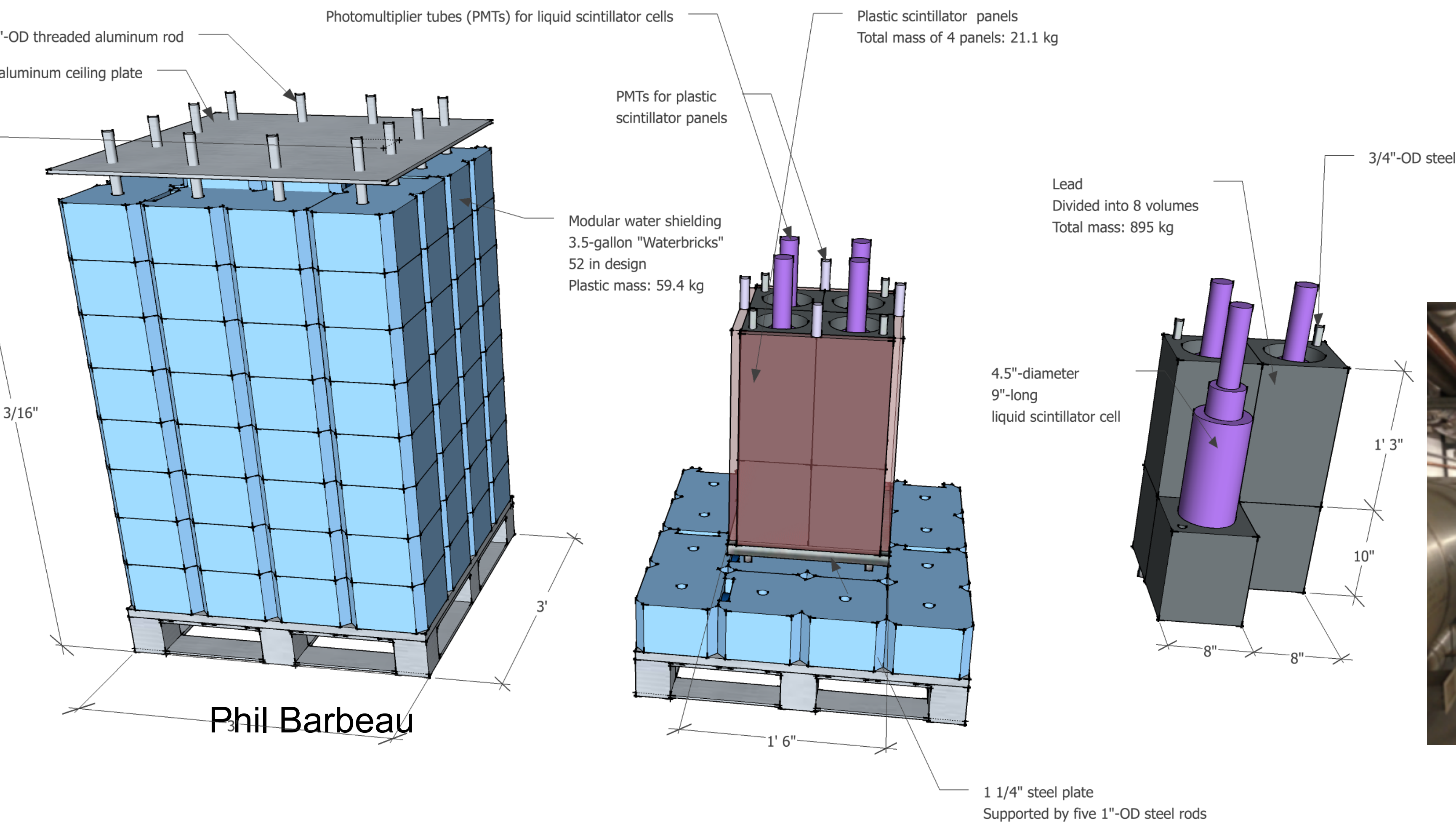


Integral: **9.6 single-neutron** and **5.2 double-neutron** events per day @ 20 m

Normalization: 7.2e14 neutrinos per flavor per second from the source

NIN measurement in basement

- Scintillator inside CsI detector lead shield (now)
- Liquid scintillator surrounded by lead inside water shield (swappable for other NIN targets: Fe, Cu, ...)
- Data analysis underway



Phil Barbeau

Summary

Cross sections on nuclei in the few tens-of-MeV regime
are poorly understood (theoretically and experimentally)
... **especially relevant for SN neutrinos**

Stopped-pion ν sources offer opportunities for these measurements

CEvNS also never before measured (SM test, DM bg); now within reach with WIMP detector technology

COHERENT@ SNS going after this
... next measurement may be **NINs on lead**
(bg for CEvNS and of SN relevance in itself)

Need for more measurements!   Ar!!!, O, ...