Low-Energy Neutrino Interactions

Kate Scholberg, Duke University
Final State Nucleons for Neutrino-Nucleus Interactions
Jefferson Lab, May 15, 2015

Moving to a (somewhat) gentler regime...

~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:
physics motivation

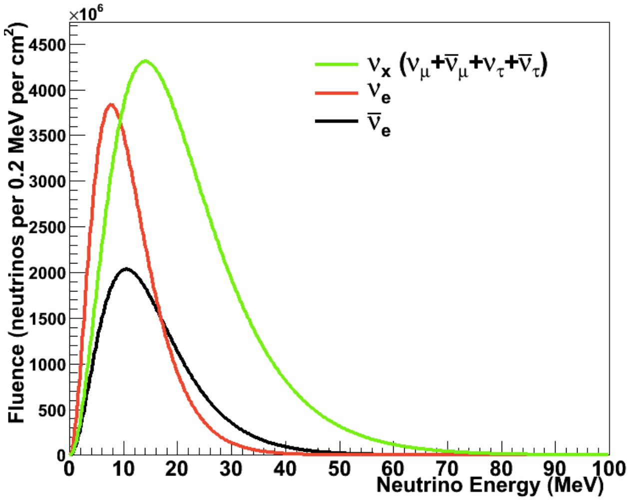
Supernova-neutrino-relevant cross sections:
water, argon, lead ...

Measurements with a π **decay-at-rest** ν **sources**

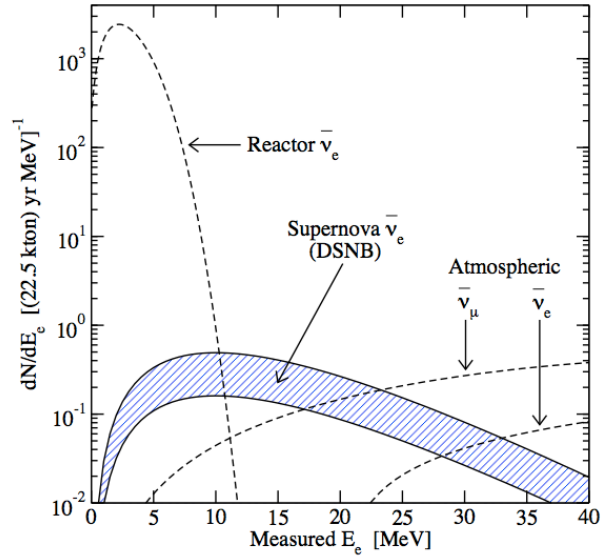
Coherent elastic neutrino-nucleus scattering (CEvNS)

Work underway and prospects

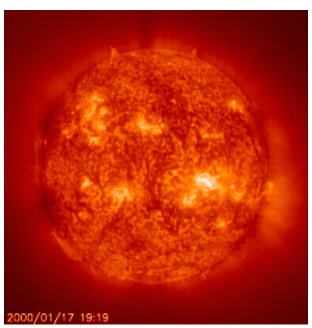
Neutrino interactions in the few-100 MeV range are relevant for:

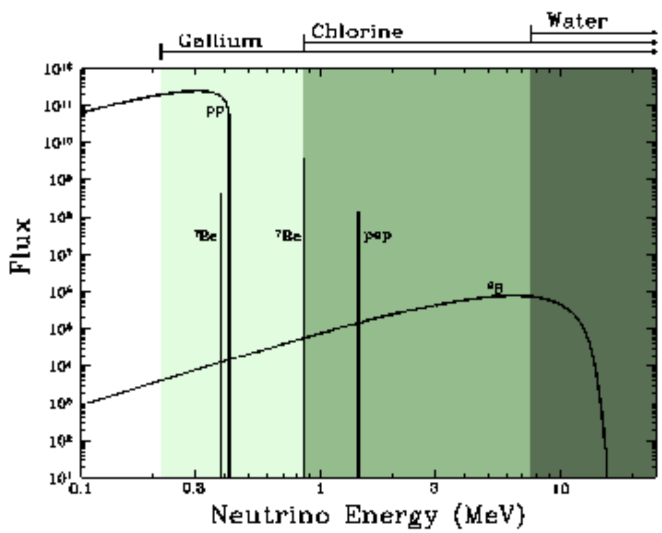


supernova neutrinos, burst & relic

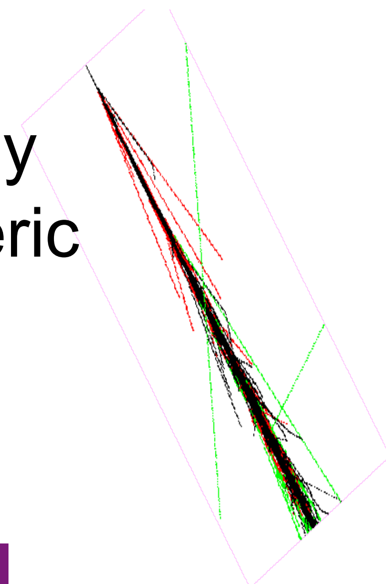


solar neutrinos





low energy atmospheric neutrinos

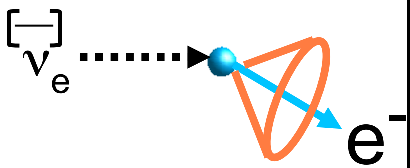


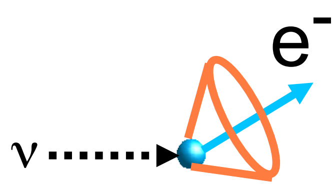
Physics: oscillation, SM tests, astrophysics

Neutrino Interactions in the tens-of-MeV regime

<table>
<tr><th></th><th>Electrons</th><th></th><th></th></tr>
<tr><td>Charged current</td><td rowspan="2">Elastic scattering

$\nu + e^- \rightarrow \nu + e^-$





Useful
for pointing</td><td></td><td></td></tr>
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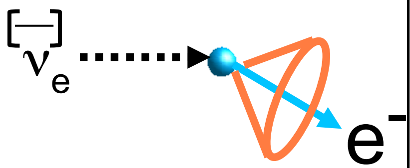
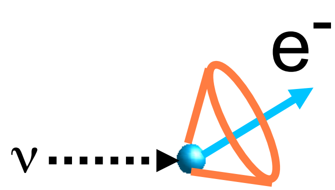
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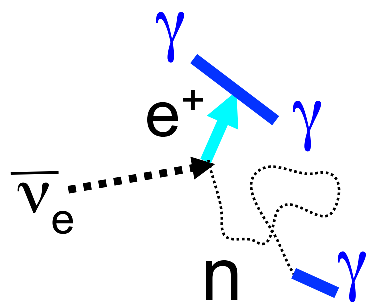
$\bar{\nu}_e + p \rightarrow e^+ + n$

</td><td></td></tr>
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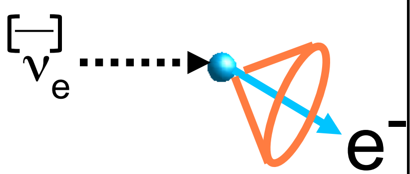
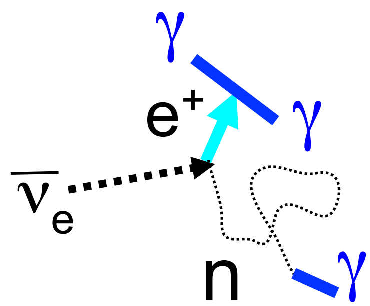
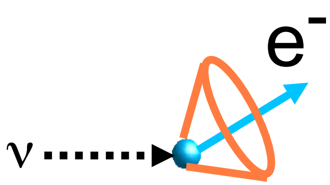
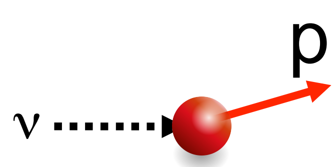
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$ 	
Neutral current	 Useful for pointing	Elastic scattering  very low energy recoils	

Neutrino Interactions in the tens-of-MeV regime

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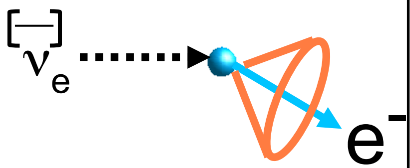
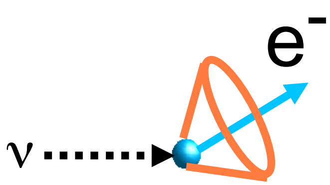
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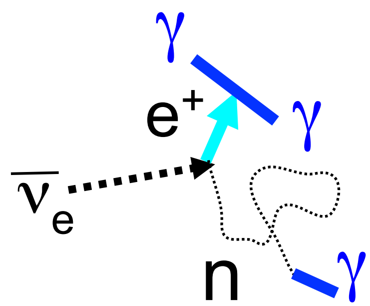</td><td>$\nu_e + (N, Z) \rightarrow e^- + (N-1, Z+1)$
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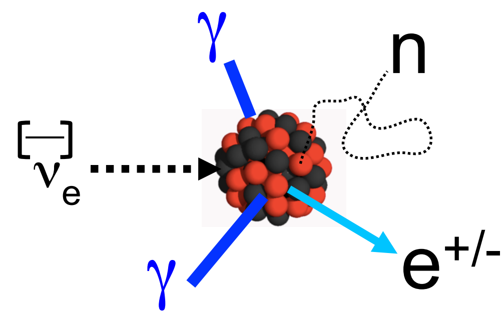
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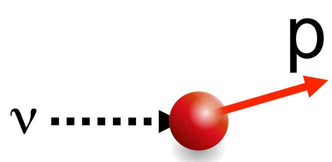
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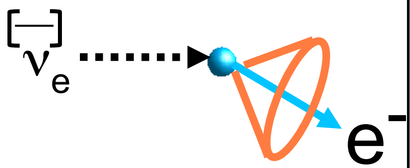
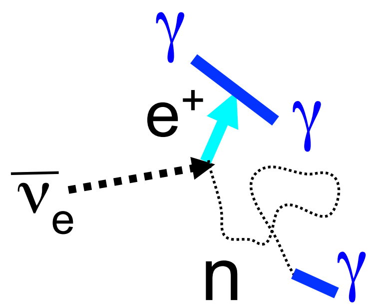
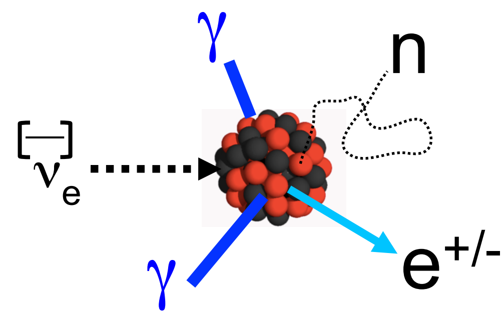
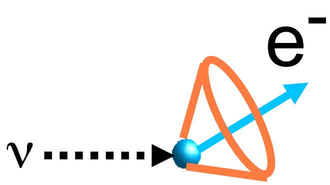
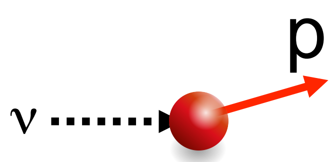
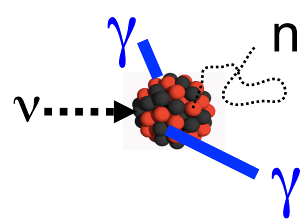
Neutrino Interactions in the tens-of-MeV regime

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

Various possible ejecta and deexcitation products

Neutrino Interactions in the tens-of-MeV regime

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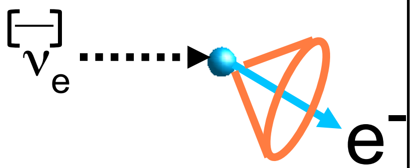
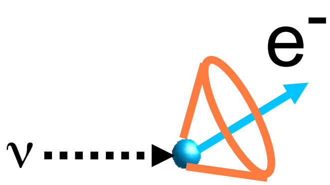
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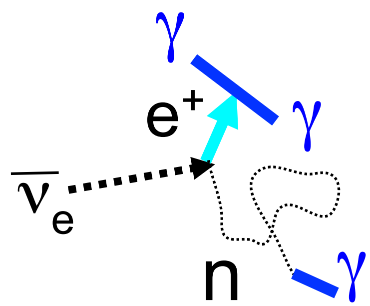</td>
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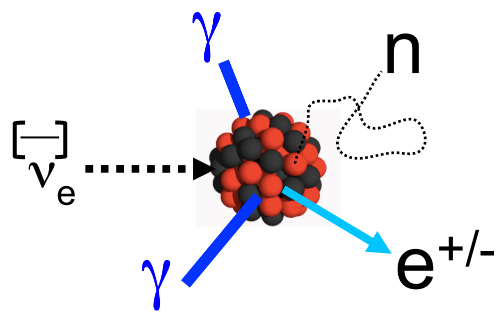
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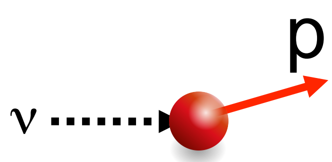
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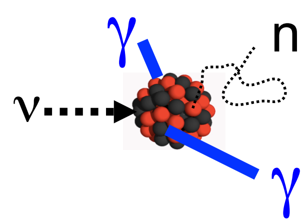
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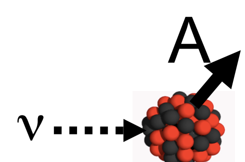
Coherent elastic (CEvNS)</td>
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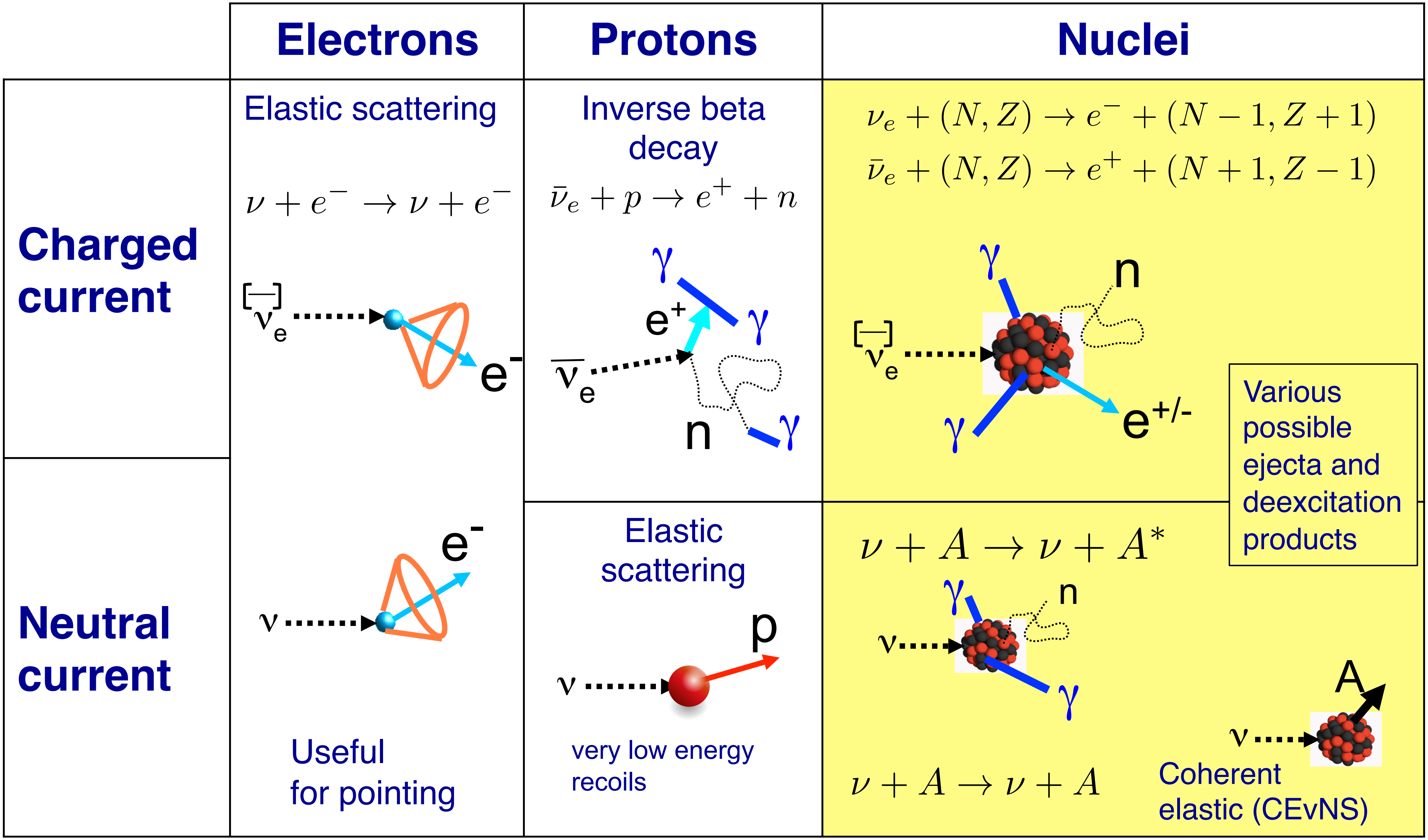
Neutrino Interactions in the tens-of-MeV regime

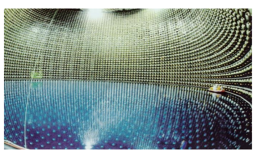


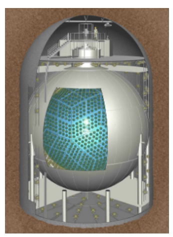
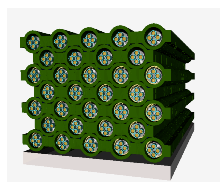
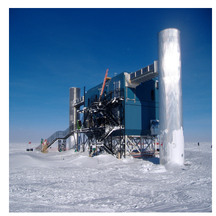
IBD & ES well understood... **interactions w/nuclei less well understood**

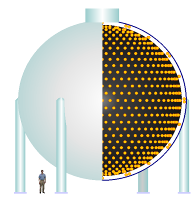
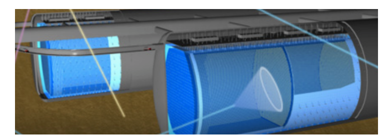
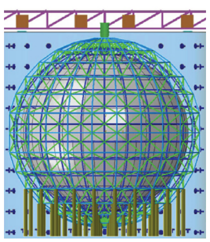
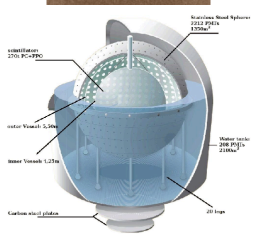
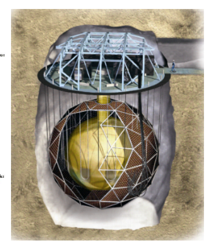
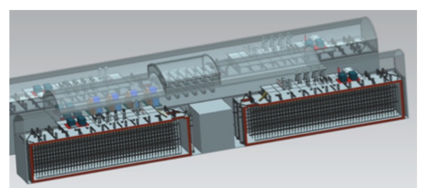
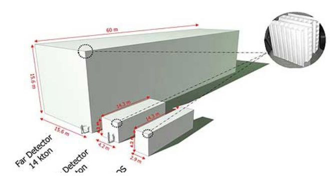
Nuclei of particular interest:

carbon
oxygen
argon
lead

detector materials for current and future supernova neutrino detectors

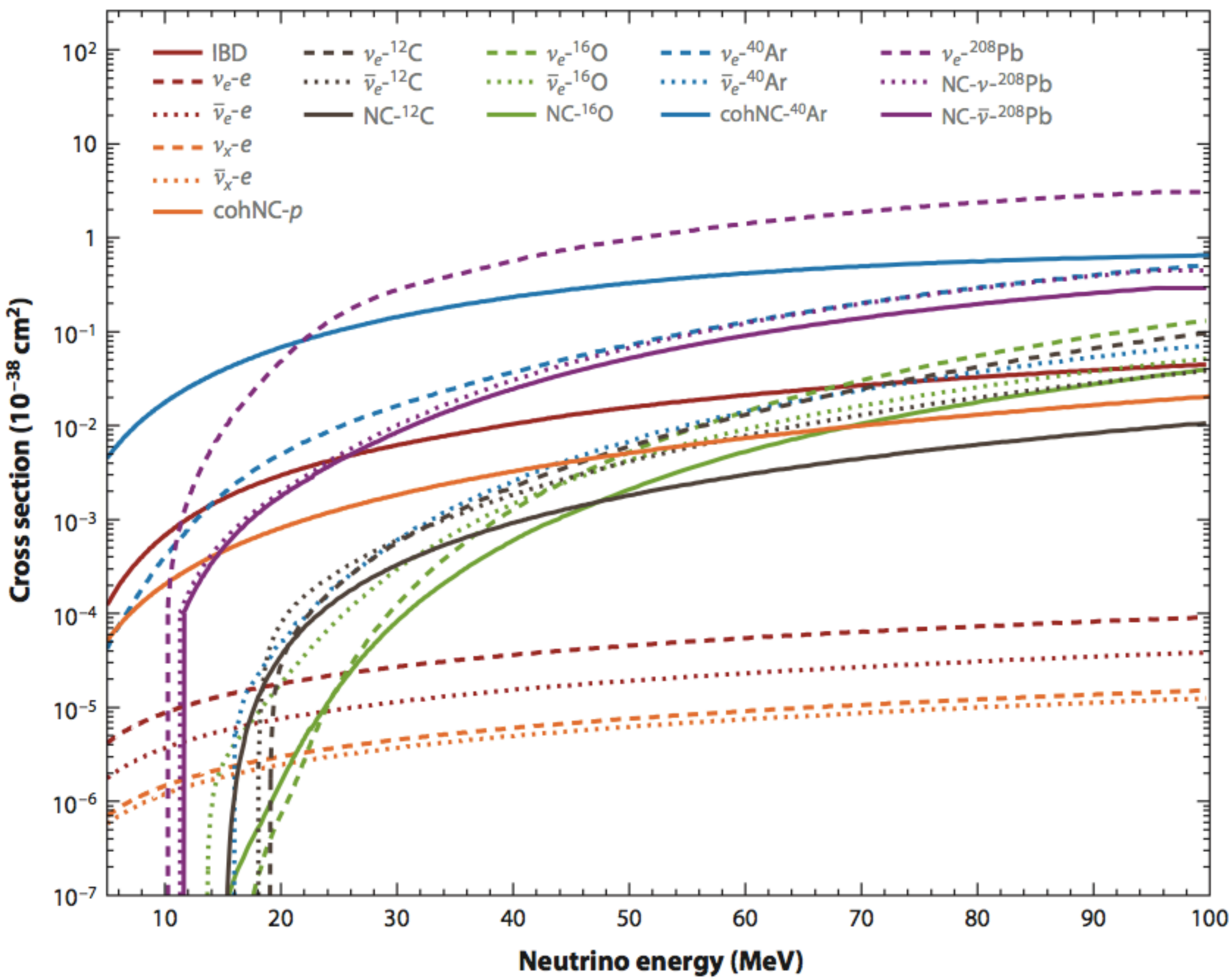


(These are not the only nuclei:
additional nuclei are of interest for other detectors;
supernova explosion physics, supernova nucleosynthesis)

Cross-sections in this energy range



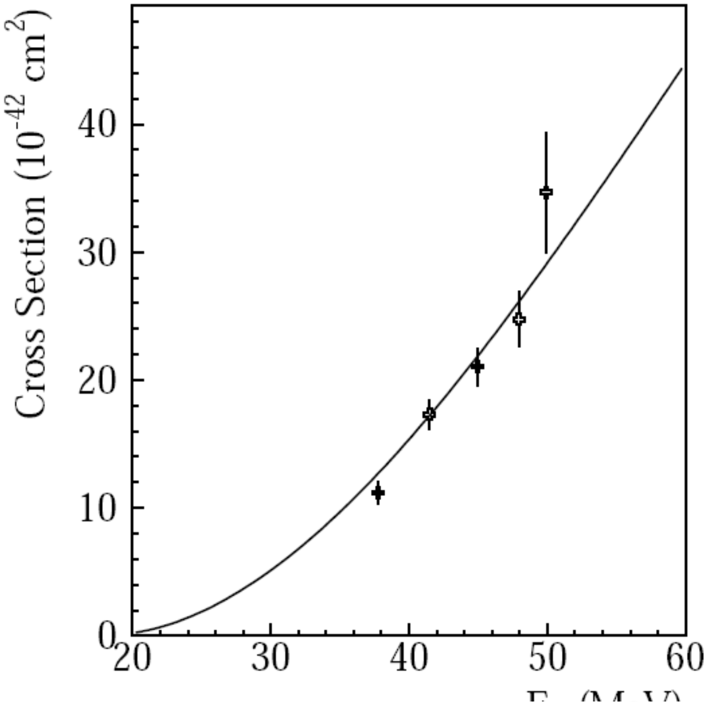
Of these, IBD and ES on electrons well understood...

.. 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

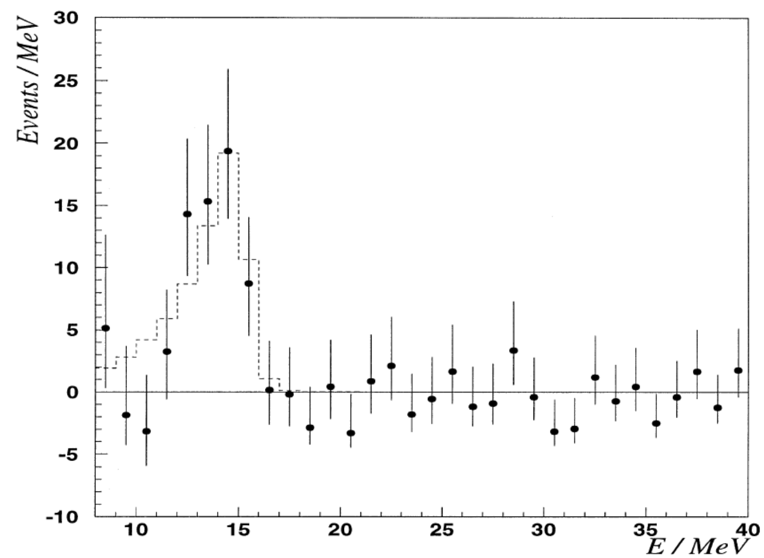
Phys. Rev. C 66 (2002) 015501



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

Karmen

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

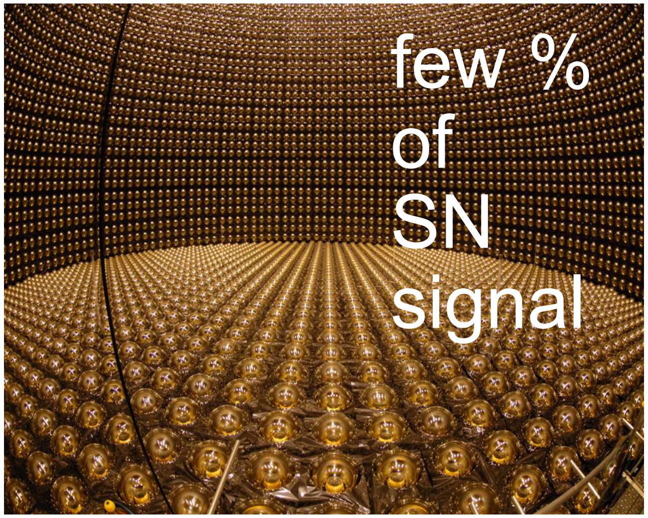


$$^{12}C(\nu_\mu \nu_\mu')\, ^{12}C^*(1^+,1;15.1\ \mathrm{MeV})$$

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

<u>Example 1</u>: interactions on oxygen nuclei

CC interactions

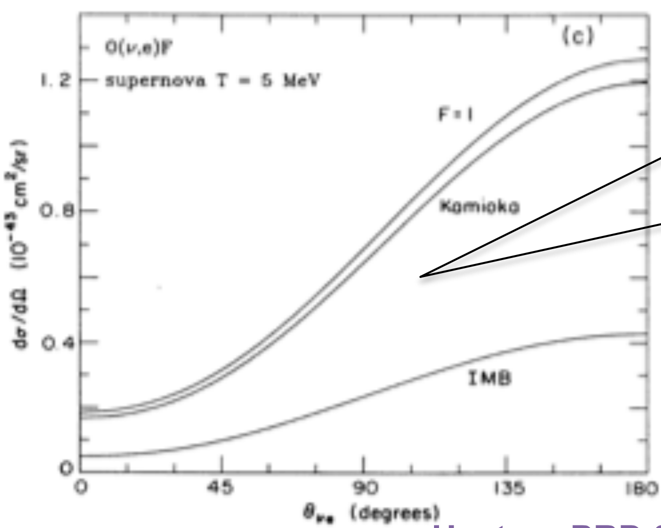


variety of final state ejecta

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

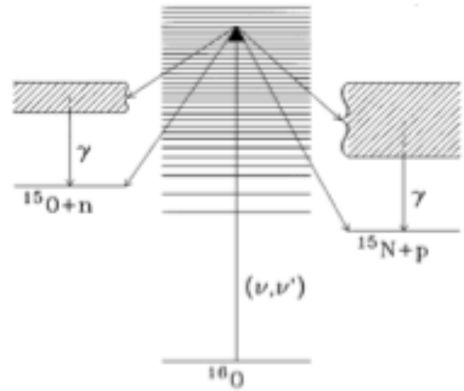
Haxton: PRD 36, (1987) 2283

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.

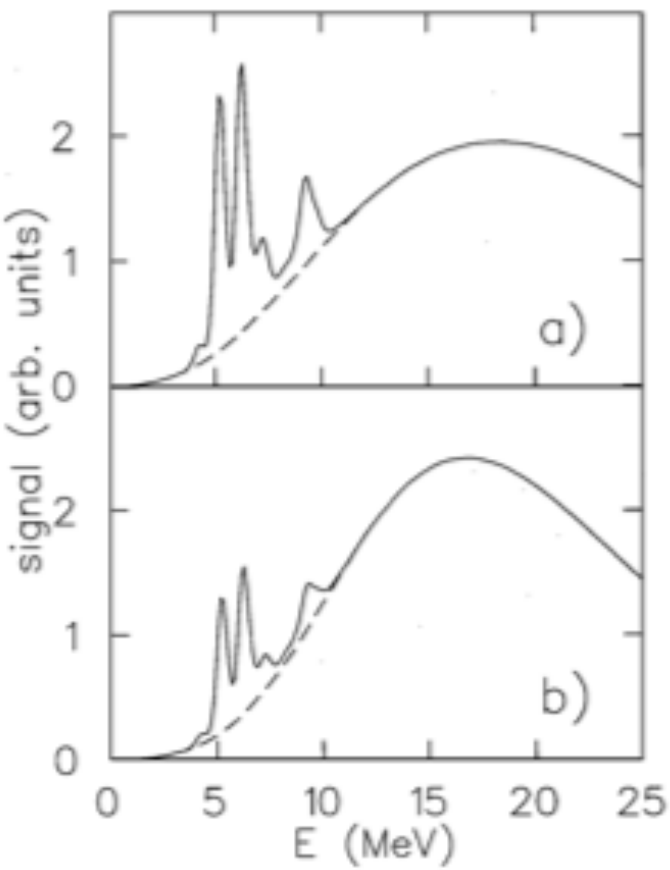
Neutrino reaction	$\sigma, T=5$ MeV	$\sigma, T=8$ MeV
total	1.05 (+0)	9.63 (+0)
$^{16}O(\bar{\nu}_e,e^+)^{16}N(g.s.)$	3.47 (−1)	2.15 (+0)
$^{16}O(\bar{\nu}_e,e^+ n)^{15}N(g.s.)$	5.24 (−1)	4.81 (+0)
$^{16}O(\bar{\nu}_e,e^+ n\gamma)^{15}N^*$	1.47 (−1)	1.90 (+0)
$^{16}O(\bar{\nu}_e,e^+ np)^{14}C^*$	4.56 (−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

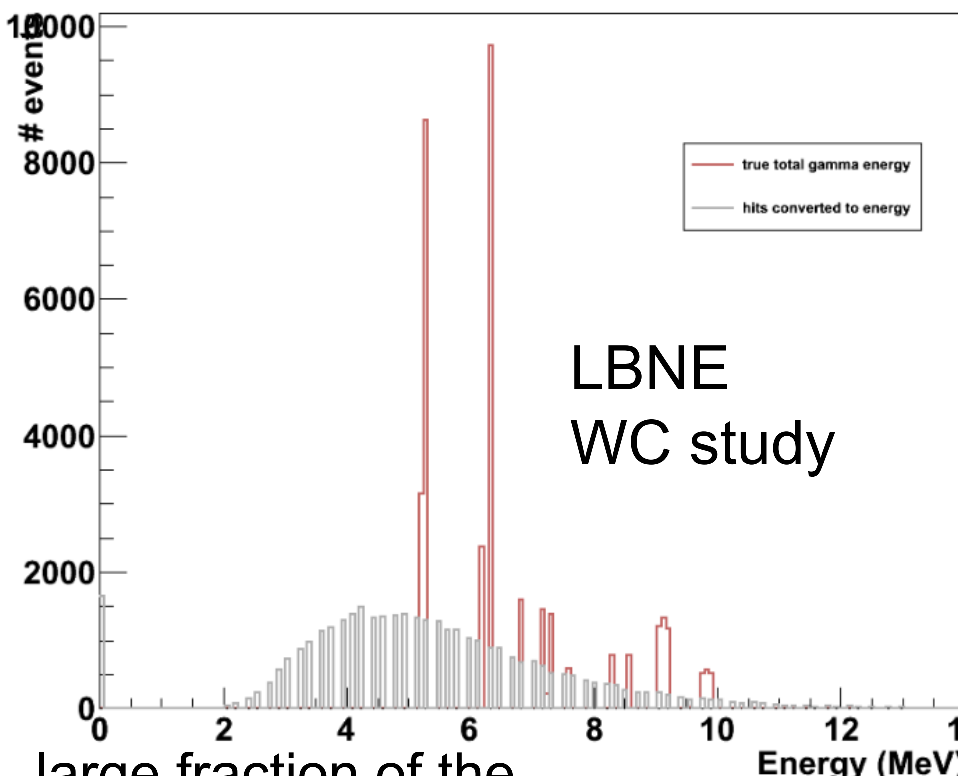
Final states from
NC excitation



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

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

Dominant

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

Neutral-current excitation

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

Not much information in literature

Elastic scattering

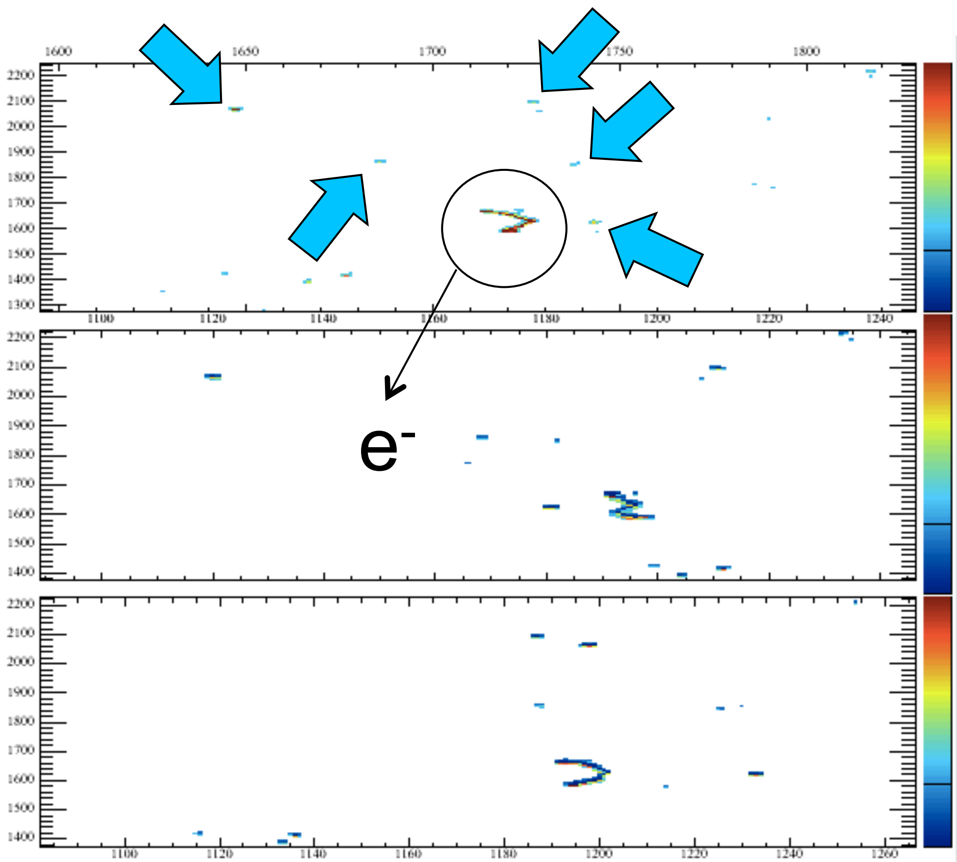
$$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$$

Can use for pointing

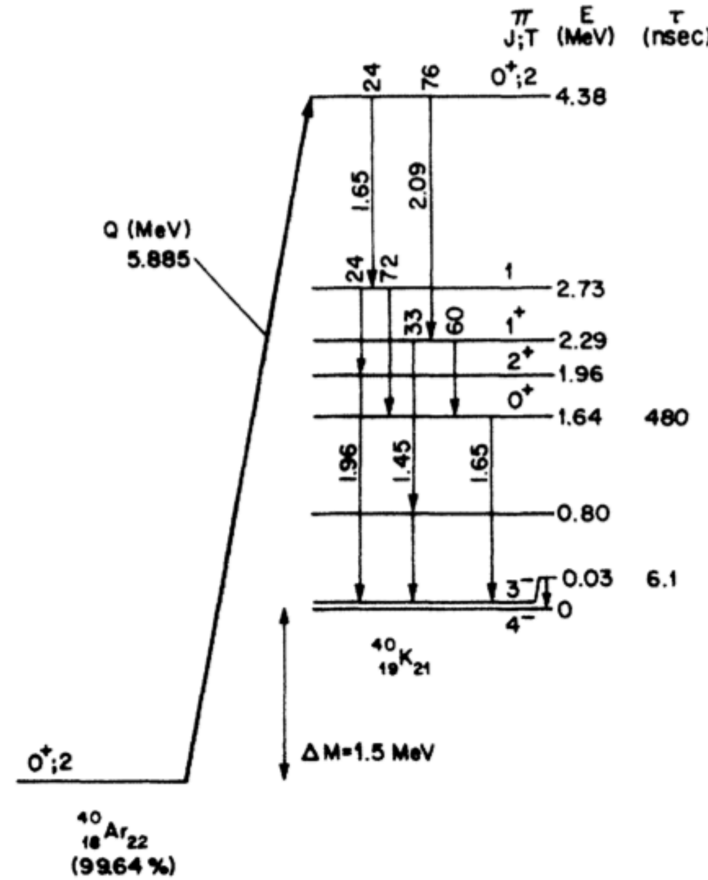
- In principle can tag modes with
- deexcitation gammas (or lack thereof)...

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!

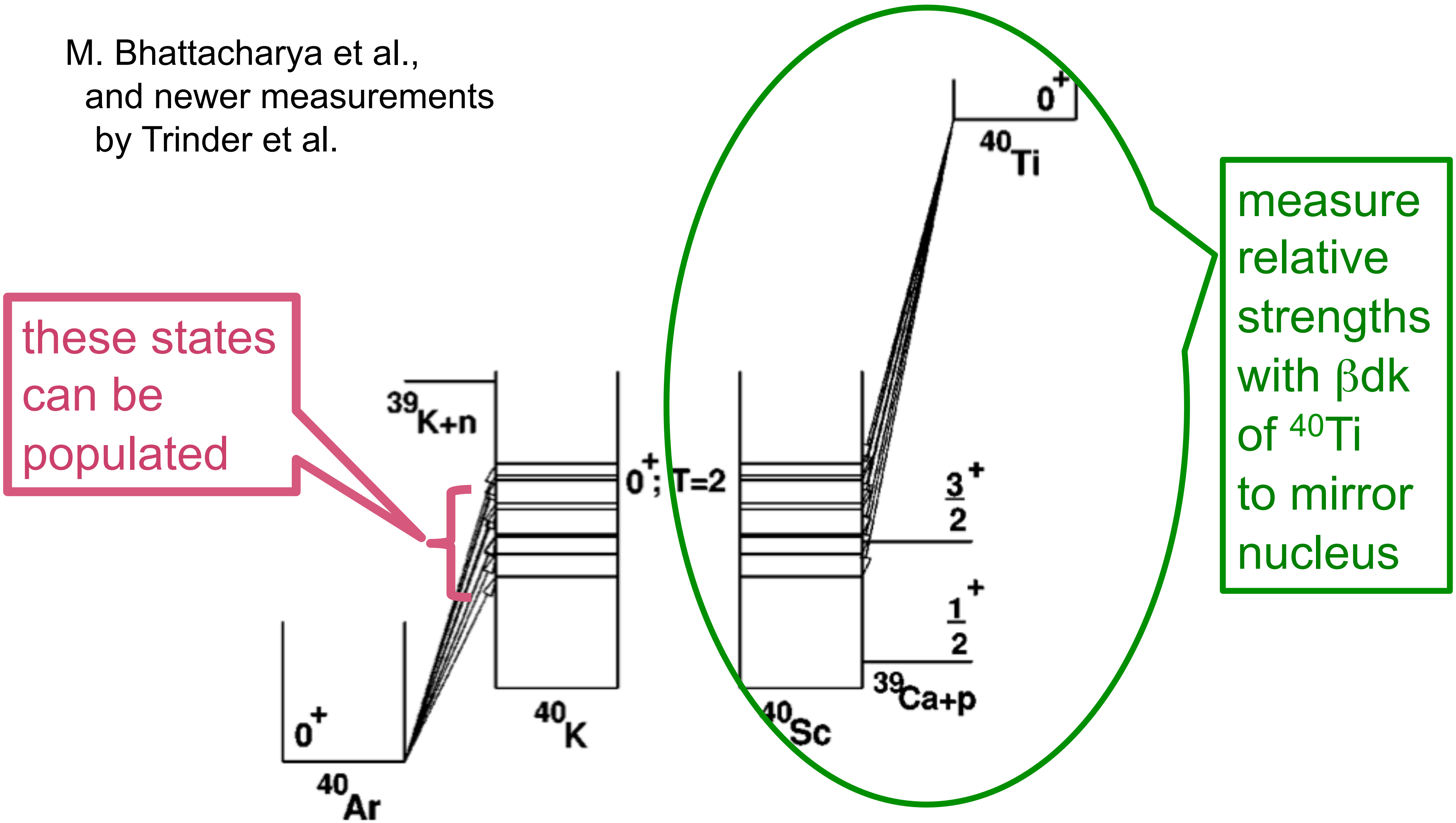
Need to understand efficiency for given technology

… 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.



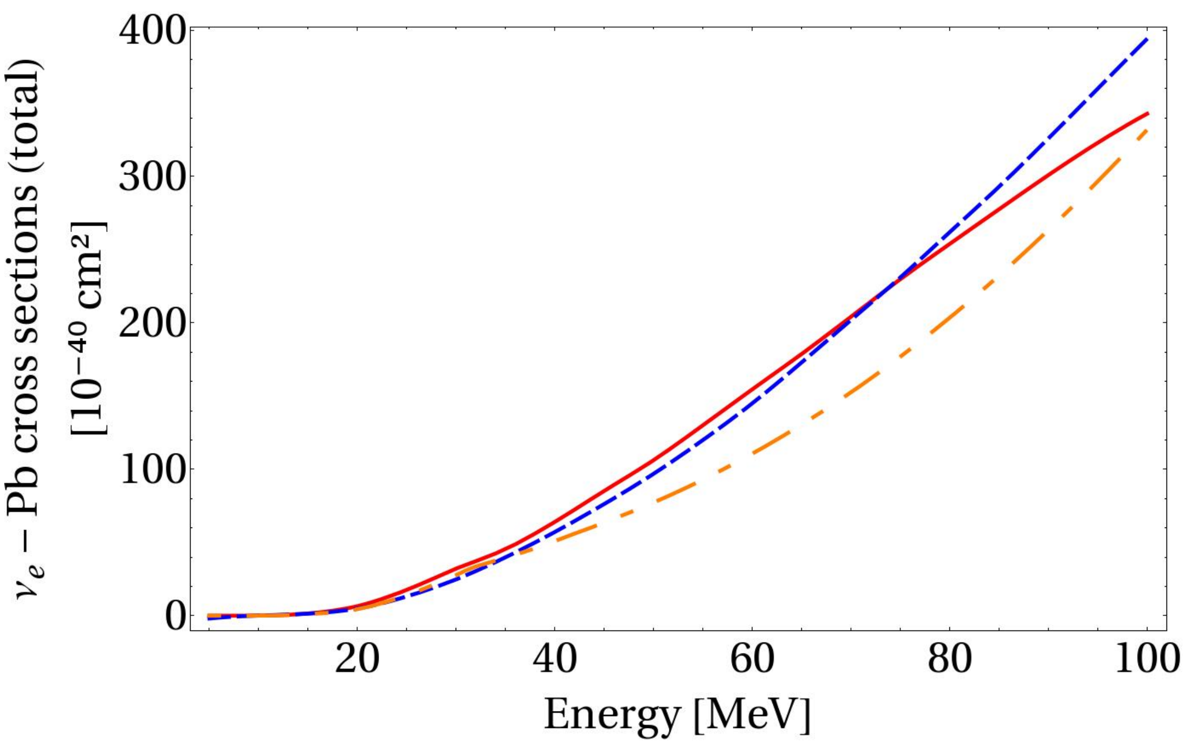
Example 3: interactions on lead nuclei

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

1n, 2n emission

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

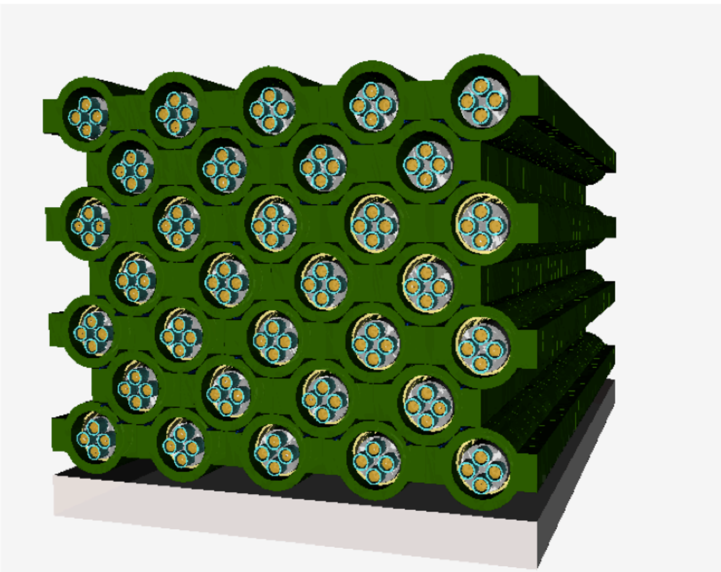
1n, 2n, γ emission



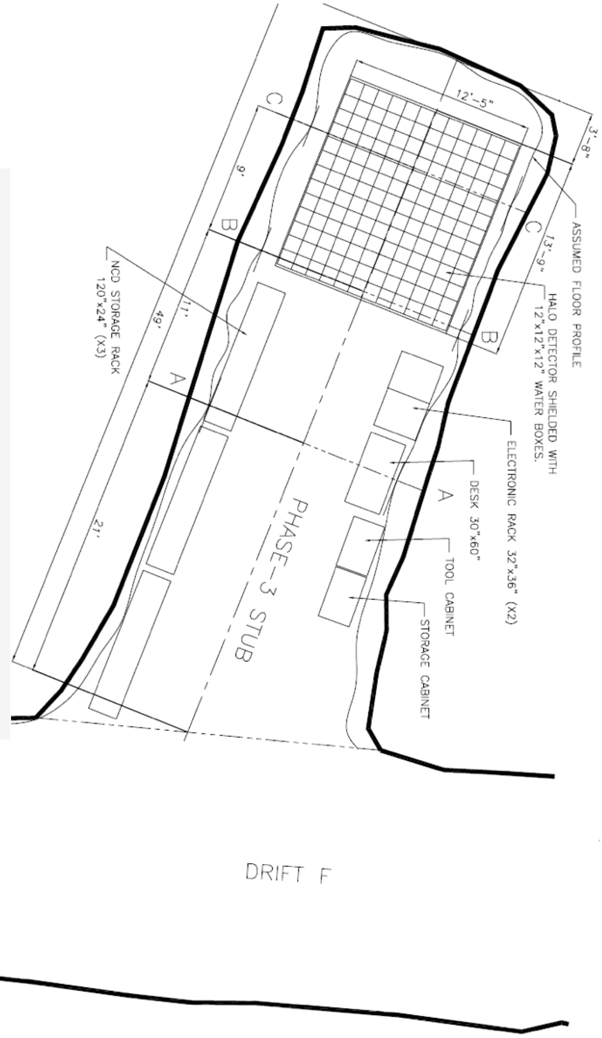
Relative rates depend on ν energy
$\Rightarrow$ spectral sensitivity
(oscillation sensitivity)

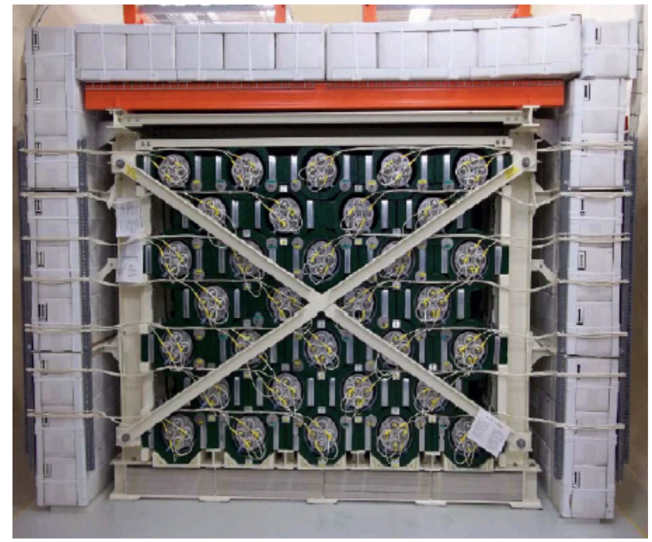
From C. Volpe, TPC10 workshop
Solid: J.Engel, et al. PRD 67, 013005 (2003)
Dashed: E. Kolbe *et al.*, PRC 63, 025802 (2001)
Dashed-dotted: N. Paar (private communication)

HALO at SNOLAB



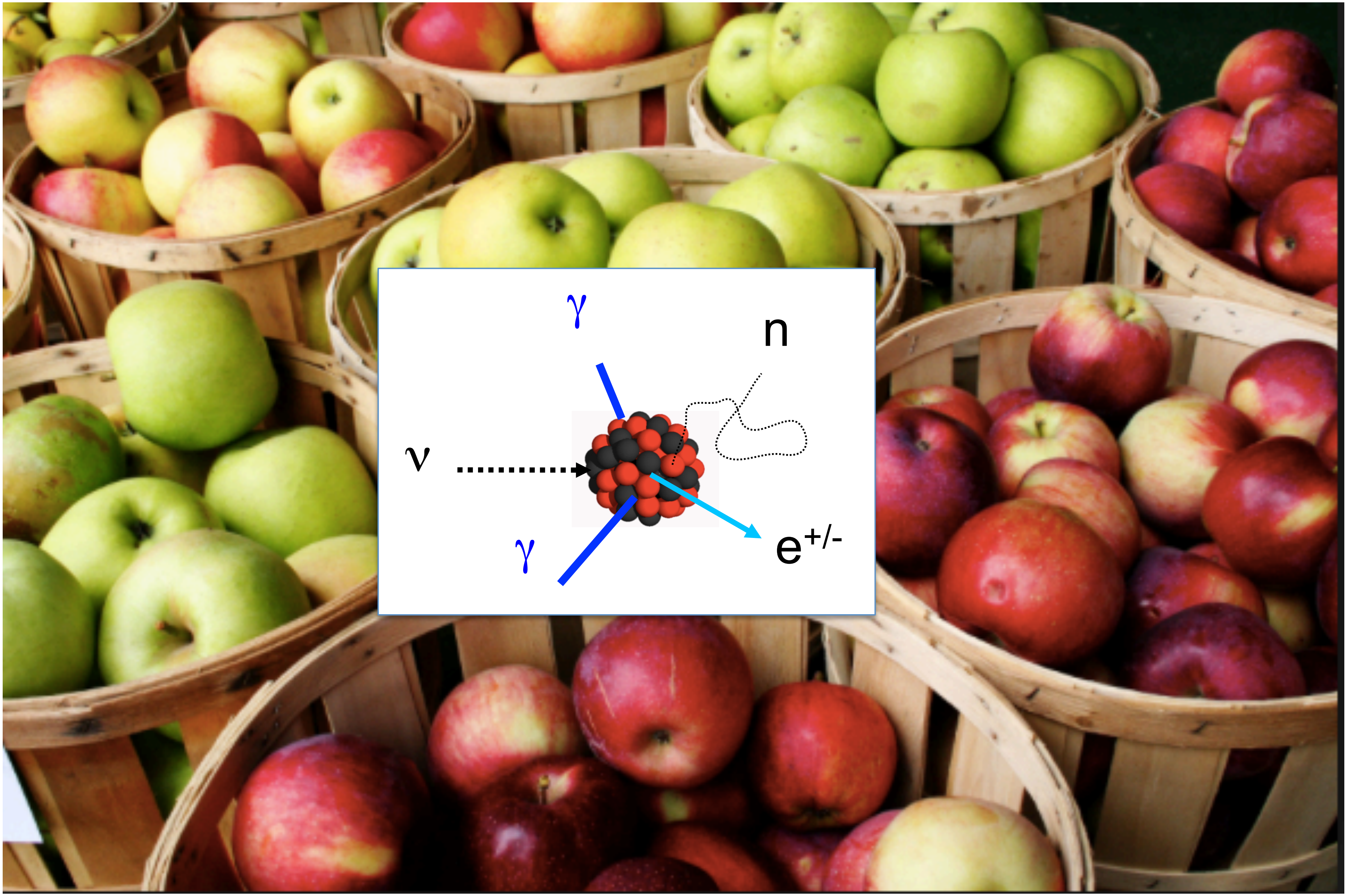
thesis



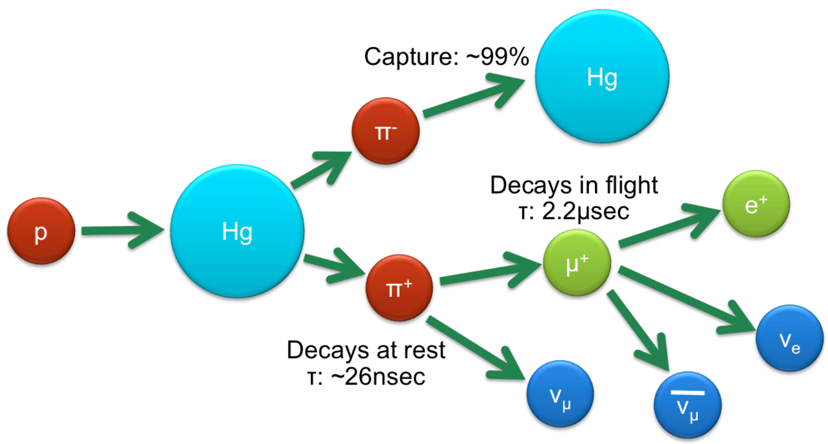


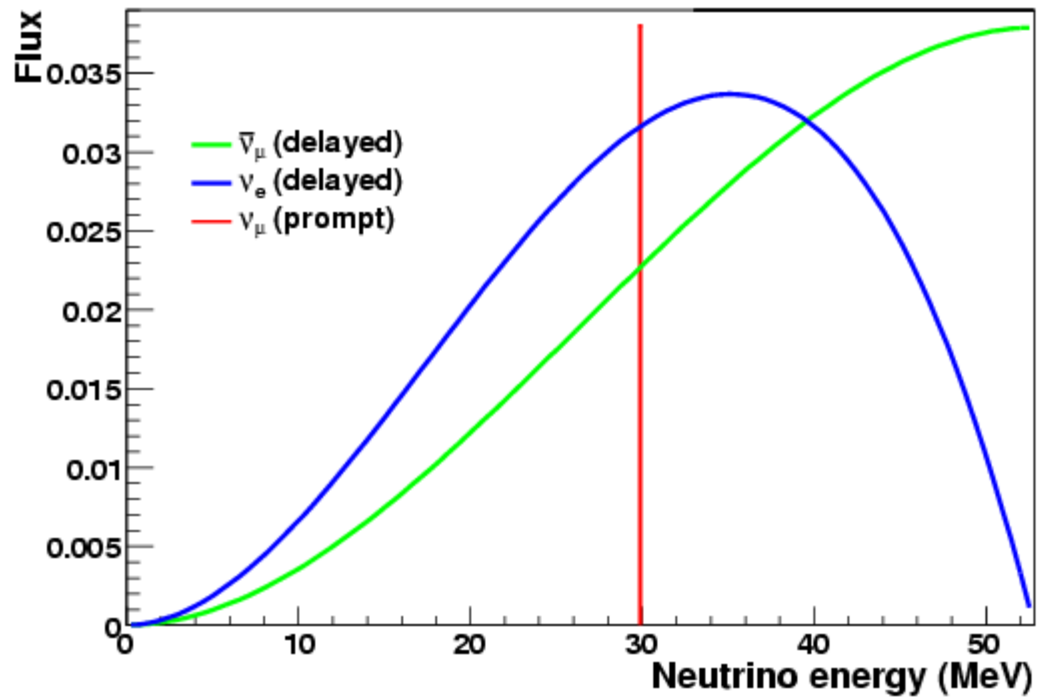
SNO ^{3}He counters + 79 tons of Pb: ~40 events @ 10 kpc

How can we *measure* these cross sections?



Stopped-Pion (πDAR) Neutrinos





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

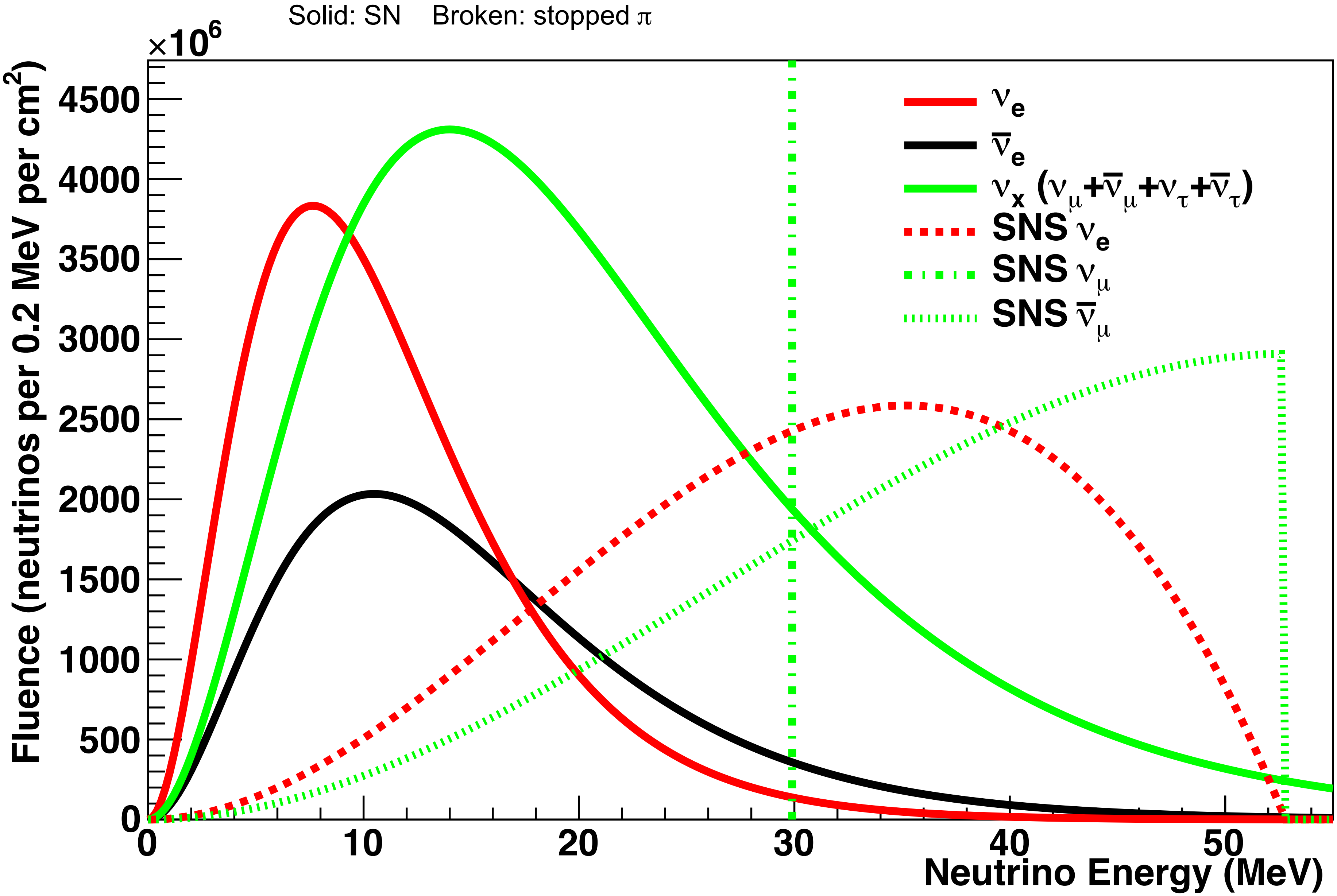
2-body decay: monochromatic 29.9 MeV ν_μ
PROMPT

$$\downarrow$$

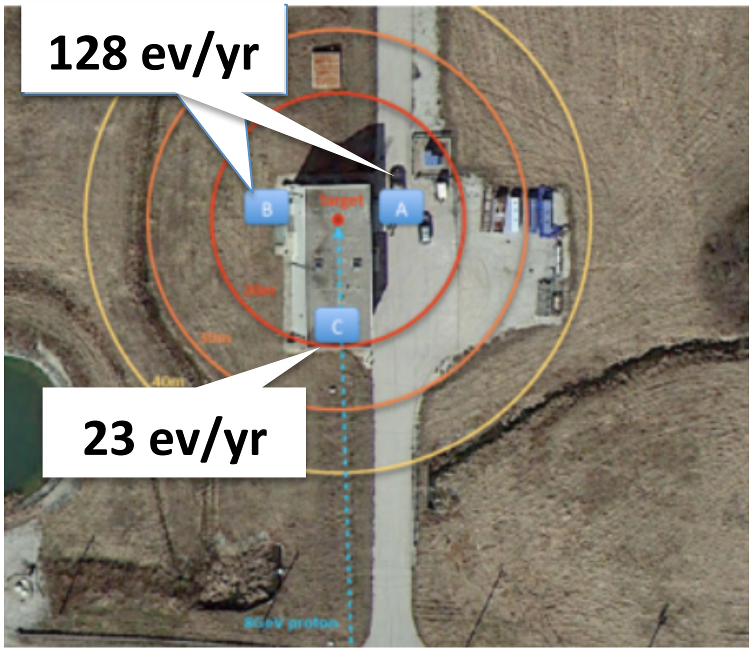
$$\mu^+ \longrightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

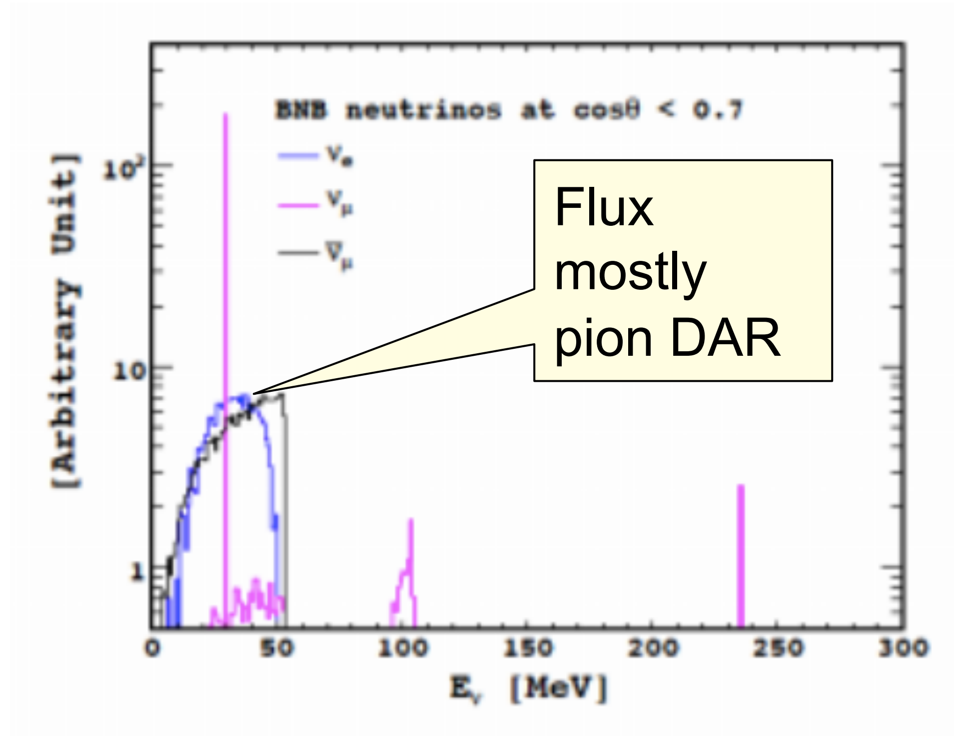
3-body decay: range of energies between 0 and $m_\mu/2$
DELAYED (2.2 μs)

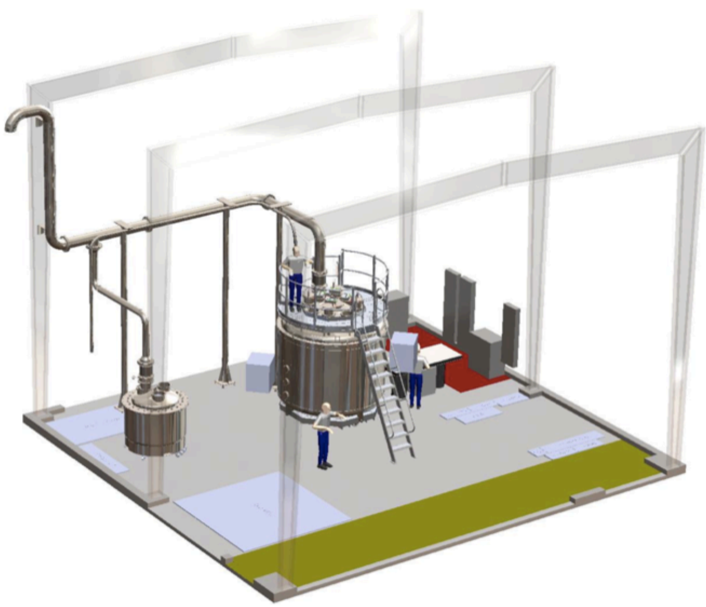
Good overlap w/ SN spectrum



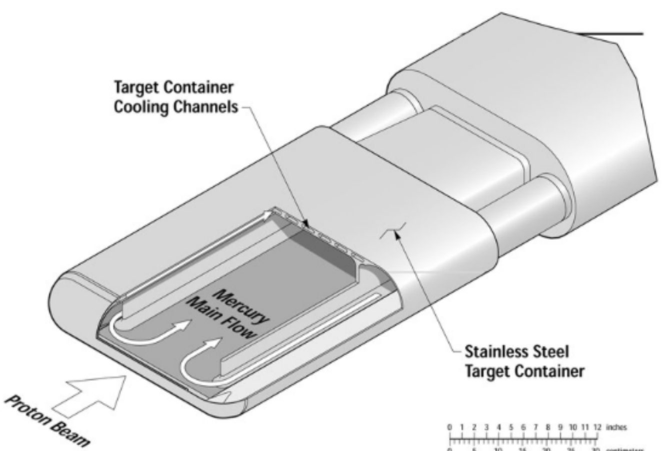
Far-off-axis neutrinos at the FNAL Booster Neutrino Beam could be used for this:







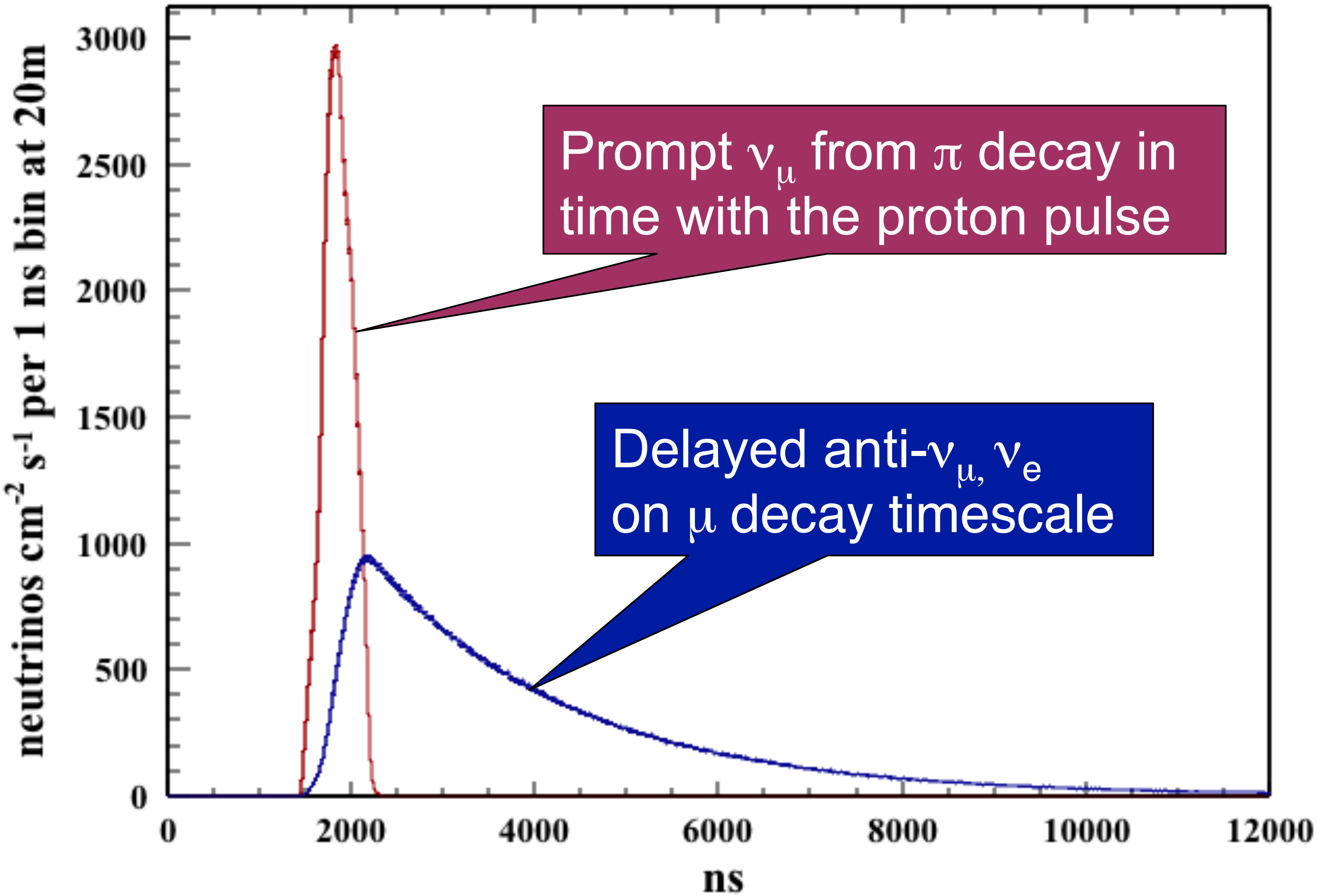
CAPTAIN-BNB experiment (5-ton LAr TPC) proposed to measure ν-Ar x-scns



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

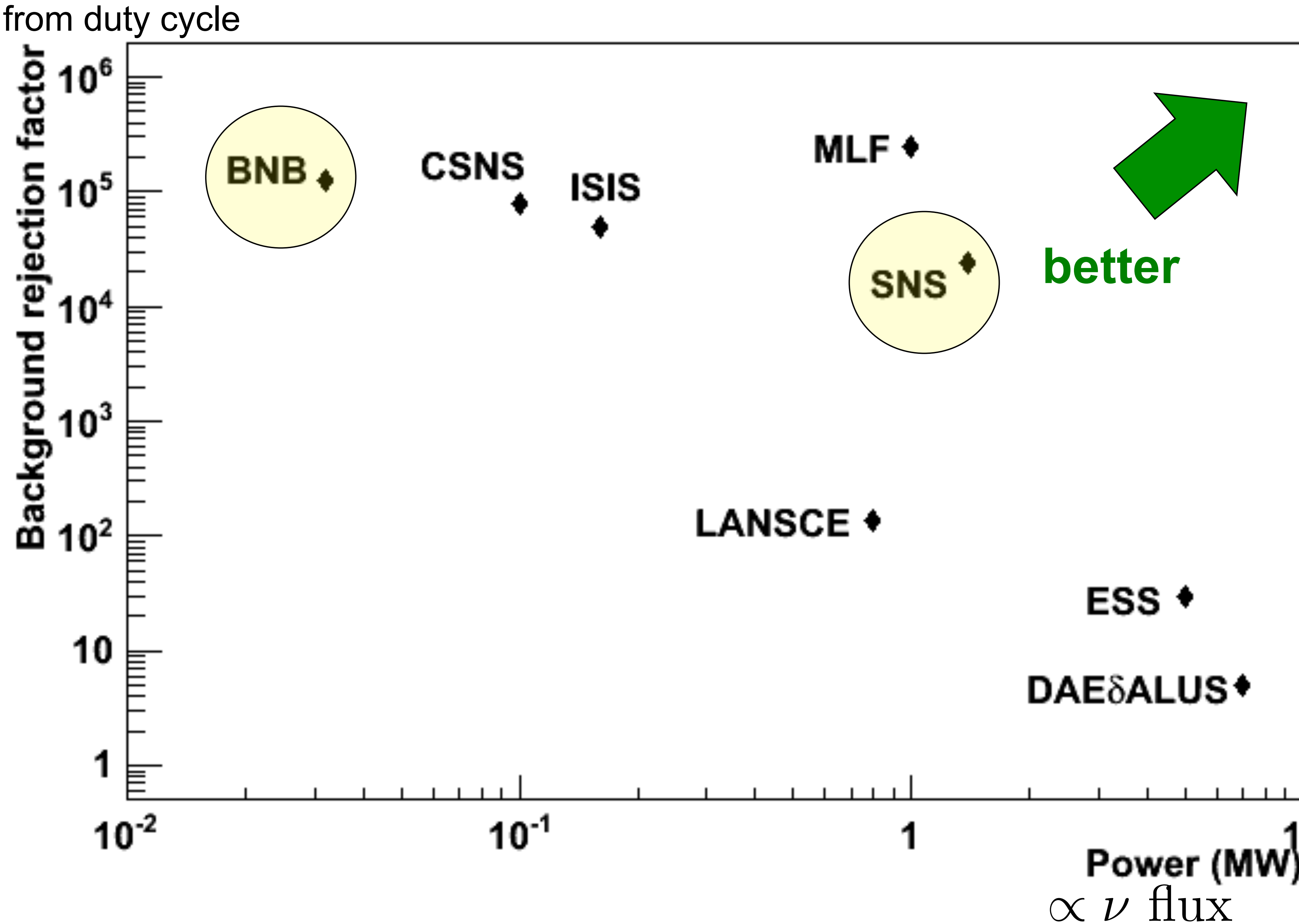
Time structure of the SNS source

60 Hz *pulsed* source

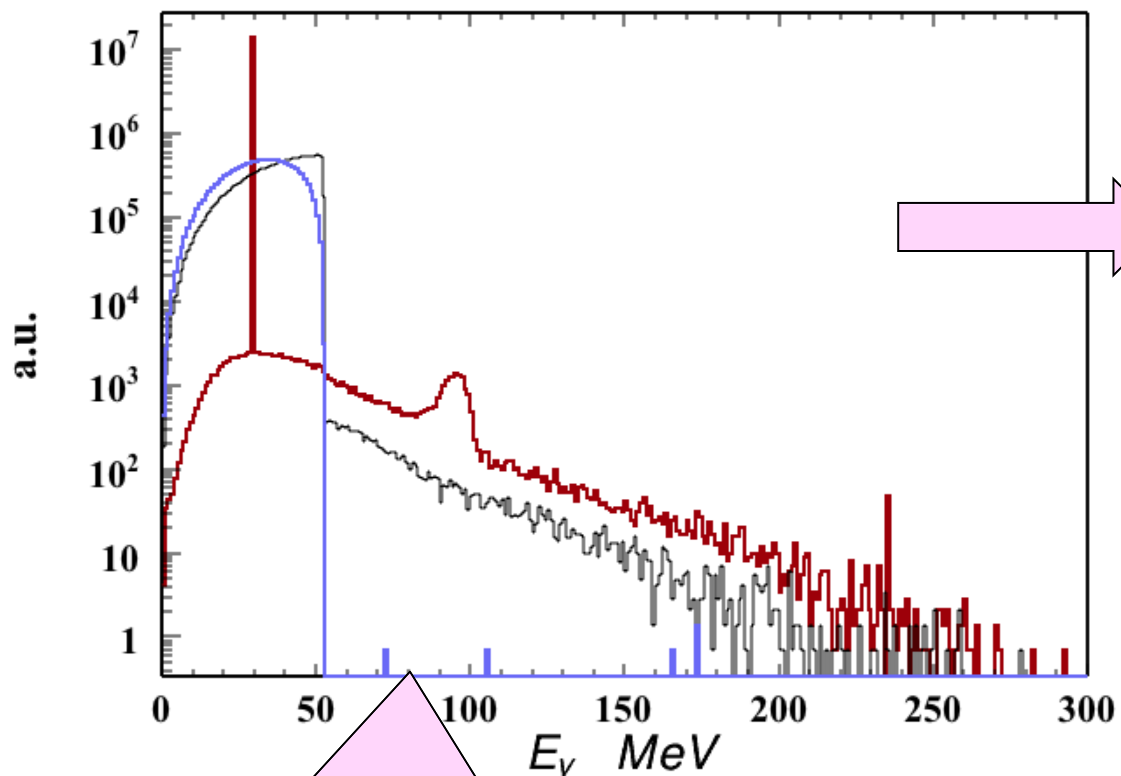


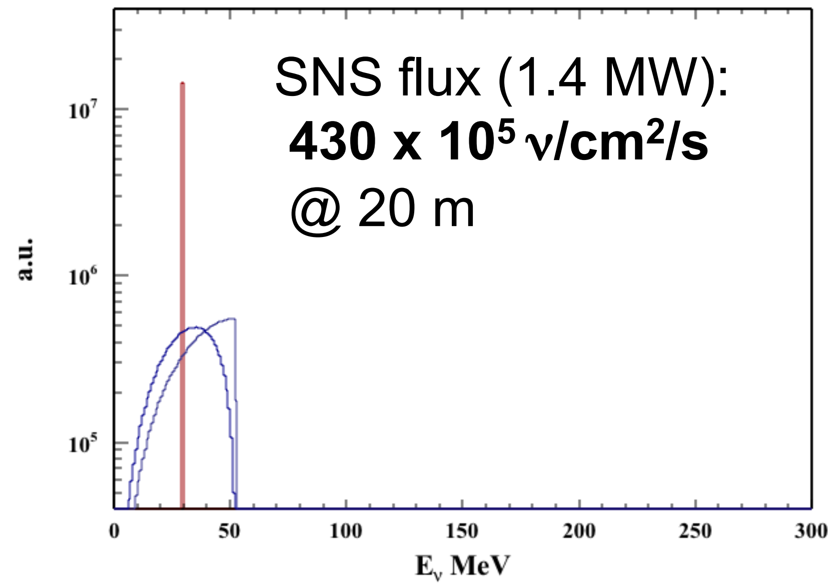
Background rejection factor ~few x 10^{-4}

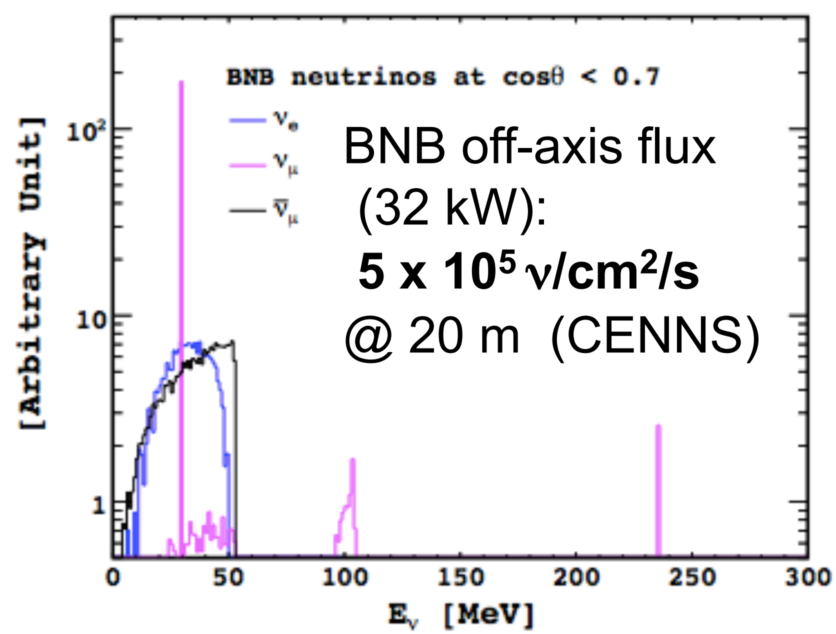
Comparison of pion decay-at-rest ν sources



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



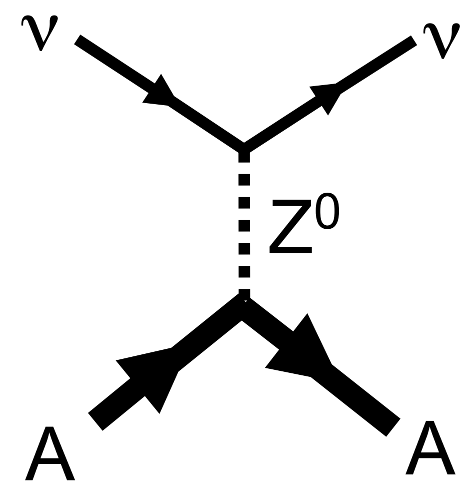




Note that contamination from
non π-decay at rest
(decay in flight, kaon decay, μ capture...)
is **down by several orders of magnitude**

Coherent elastic neutrino-nucleus scattering (CEvNS)

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



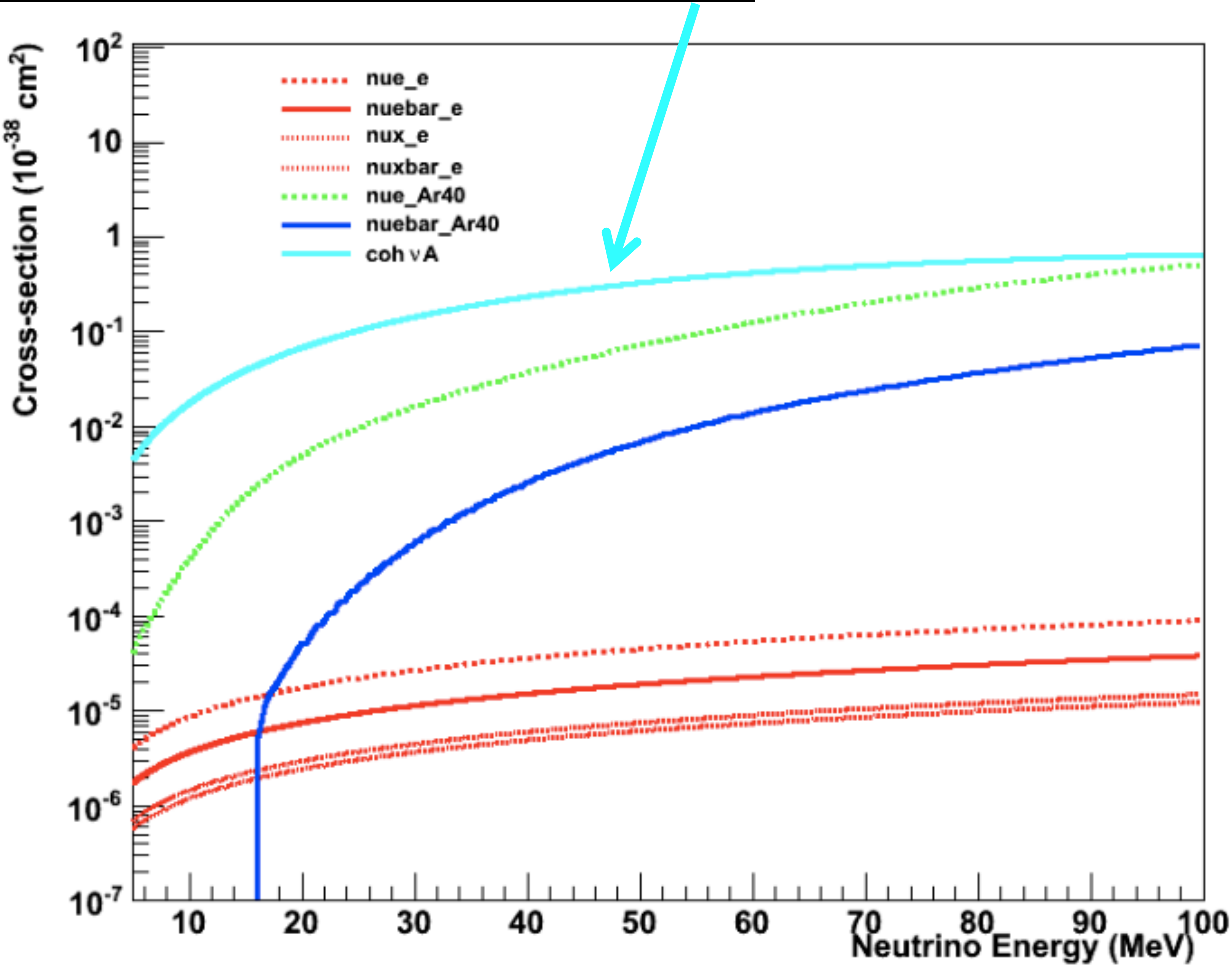
A neutrino smacks a nucleus via exchange of a Z, and the nucleus recoils as a whole; **coherent** up to E_ν ~ 50 MeV

- 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)

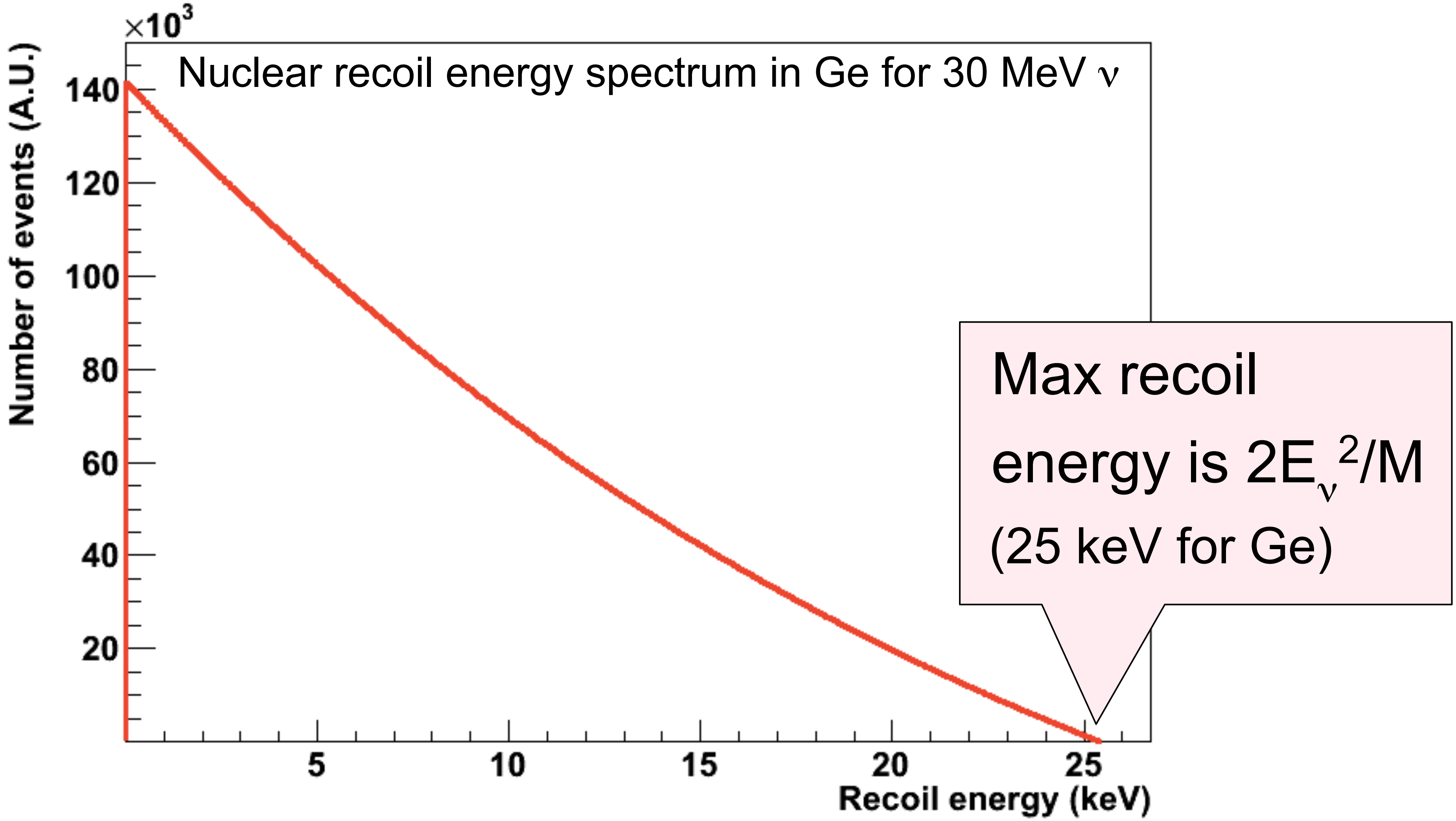
$$\frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2} k^2 (1 + \cos\theta) \frac{(N - (1 - 4\sin^2\theta_W)Z)^2}{4} F^2(Q^2)$$

$$\boxed{\propto N^2}$$

The cross-section is *large*

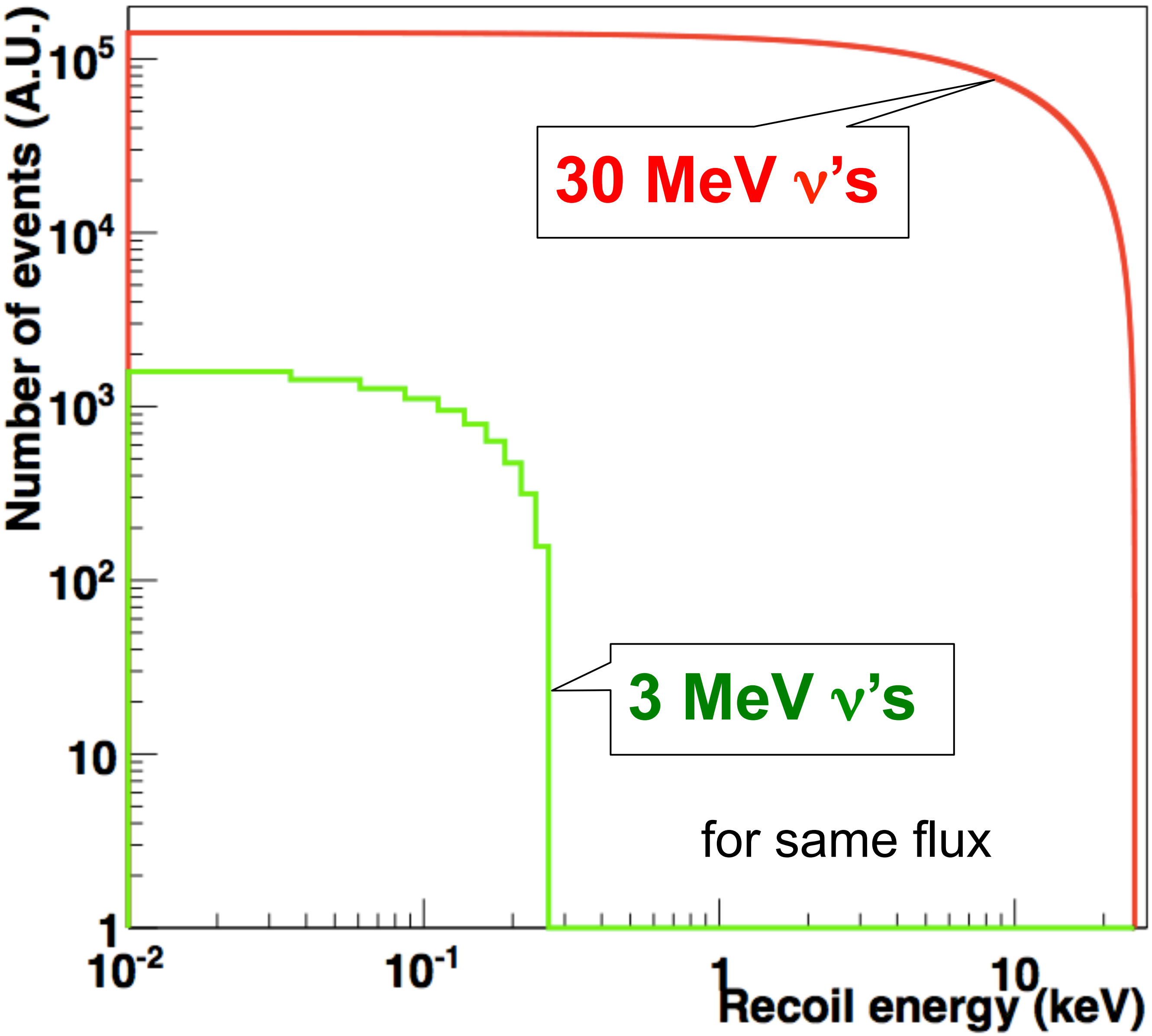


Large cross section, but never observed due to **tiny nuclear recoil energies:**



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

Why use the 10's of MeV neutrinos from π decay at rest?
➔higher-energy neutrinos are advantageous, because both **cross-section and maximum recoil energy increase with ν energy**



Reactor experiments (RICOCHET, CONNIE, COGeNT etc.) can take advantage of very large flux (~factor of 10^4) but require very low energy thresholds, where background can be daunting; radioactive source experiments require even lower thresholds

Two collaborations aiming to use πDAR for CEvNS measurement:

CENNS @ FNAL BNB: single-phase LAr

PHYSICAL REVIEW D **89**, 072004 (2014)

A method for measuring coherent elastic neutrino-nucleus scattering at a far off-axis high-energy neutrino beam target

COHERENT @ ORNL SNS: CsI, Ge, LXe, ...

arXiv.org > hep-ex > arXiv:1310.0125

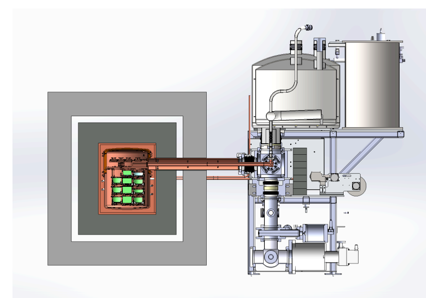
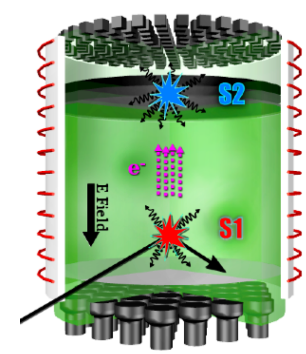
High Energy Physics – Experiment

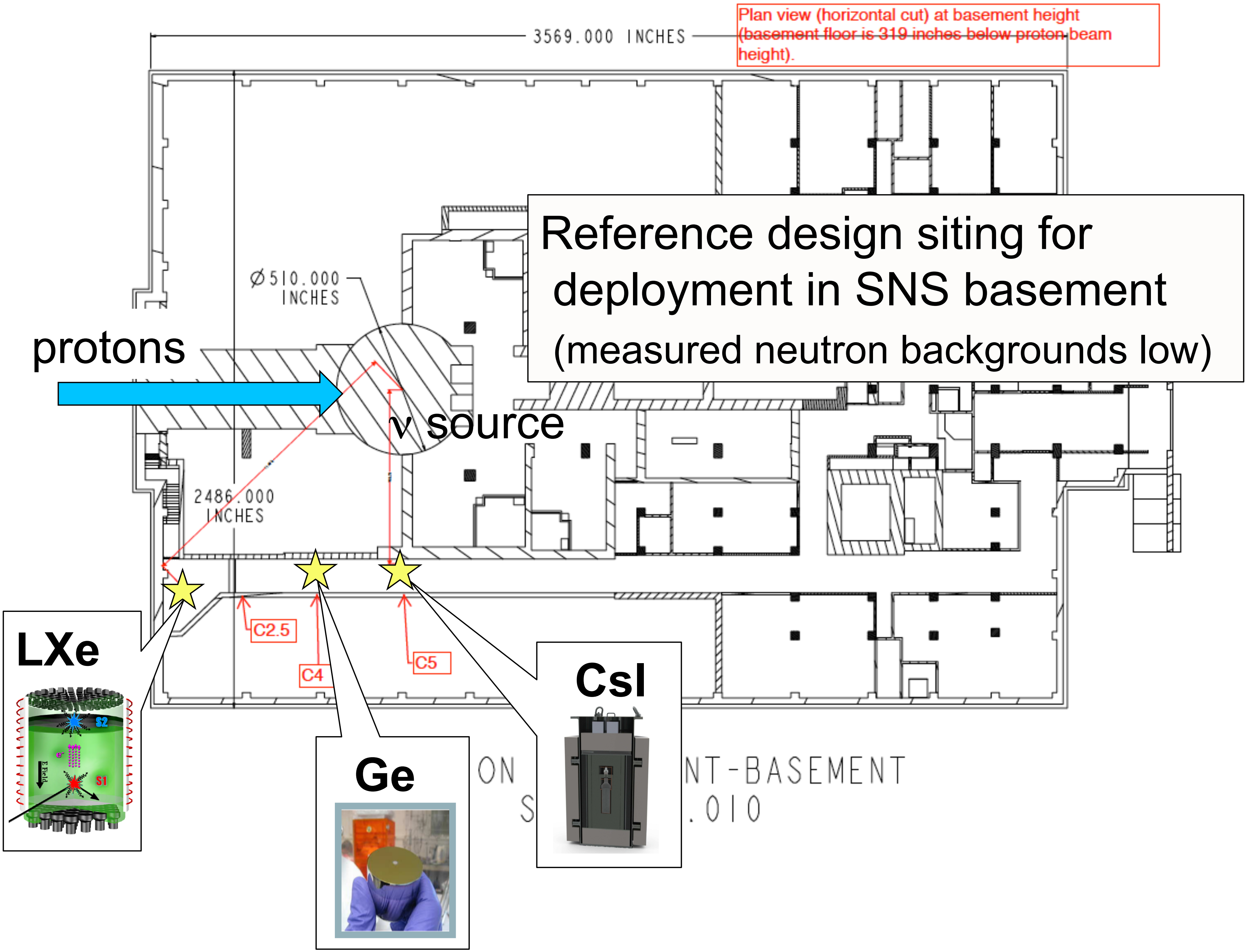
Coherent Scattering Investigations at the Spallation Neutron Source: a Snowmass White Paper

COHERENT at the Spallation Neutron Source

`fsnutown.phy.ornl.gov/fsnufiles/positionpapers/Coherent_PositionPaper.pdf`

COHERENT detector subsystems

Nuclear Target	Technology	Mass (kg)	Distance from source (m)	Recoil threshold (keVr)	
CsI[Na]	Scintillating Crystal	14	20	6.5	
Ge	HPGe PPC	10-20	20	5	
Xe	Two-phase LXe TPC	100	32	4	


Plan view (horizontal cut) at basement height
(basement floor is 319 inches below proton beam
height).
3569.000 INCHES
Reference design siting for
deployment in SNS basement
(measured neutron backgrounds low)
Ø510.000
INCHES
protons
ν source
2486.000
INCHES
C2.5
C4
C5
LXe
Ge
CsI
S2
S1
E Field
ON
NT-BASEMENT
S
.010

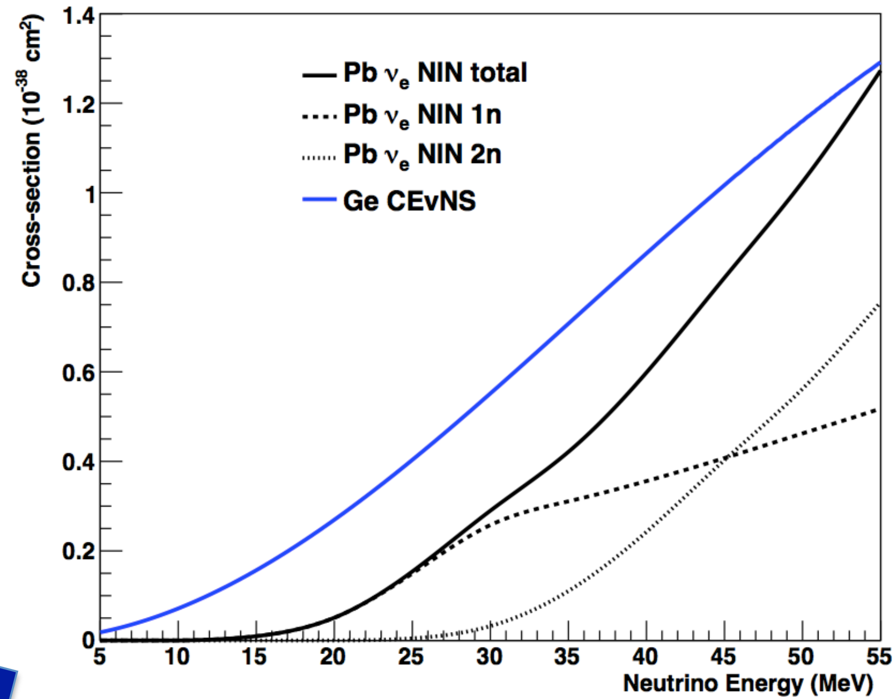
Currently measuring *neutrino-induced neutrons* in lead, (iron, copper), ...

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

$\searrow$ 1n, 2n emission

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

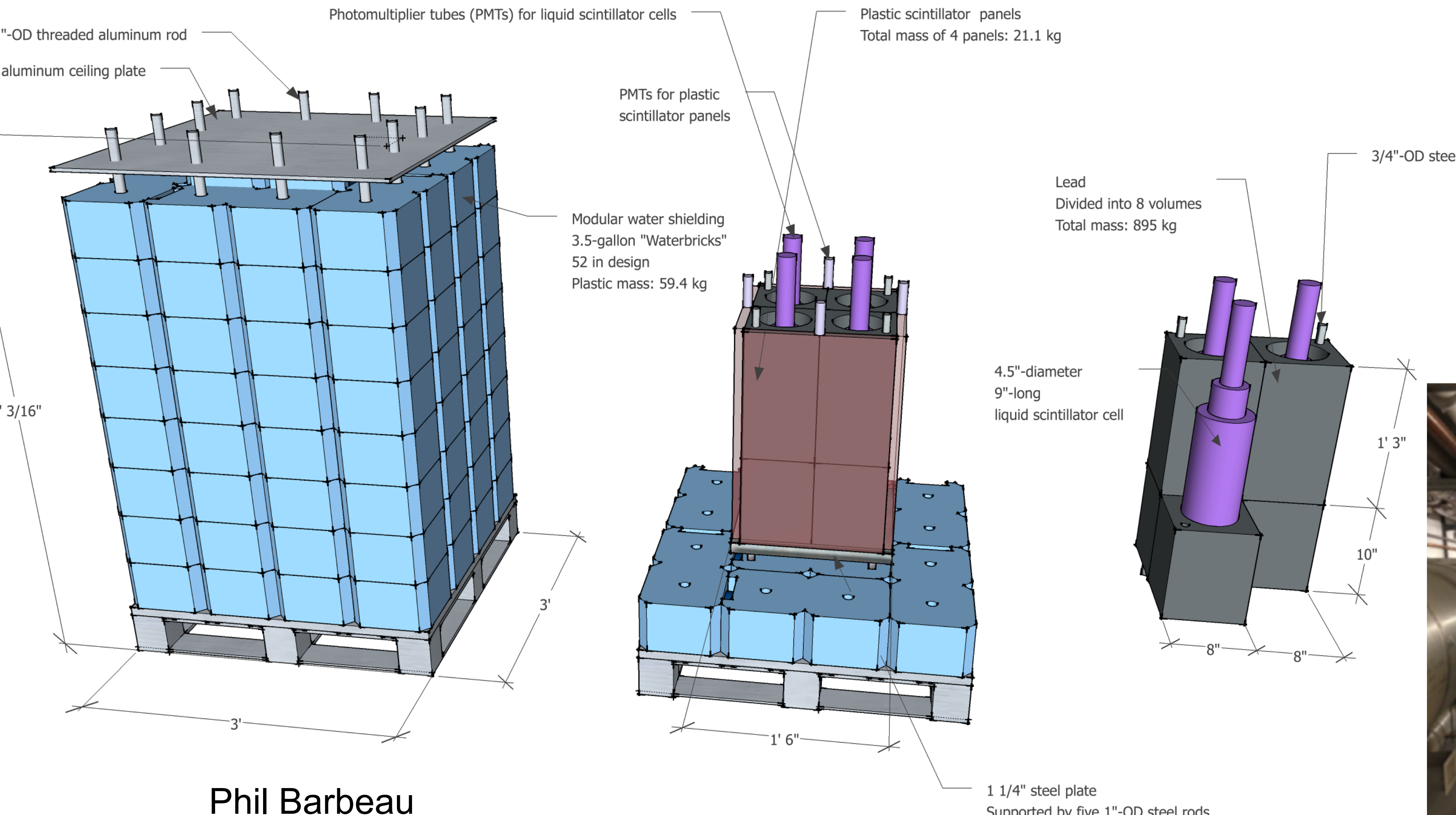
$\searrow$ 1n, 2n, γ emission



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

NIN measurement in basement

- Scintillator inside CsI detector lead shield (now)
- Liquid scintillator surrounded by lead (swappable for other NIN targets) inside water shield



Phil Barbeau

Summary

Cross sections on nuclei in the few tens-of-MeV regime
are very 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 and **CENNS@BNB** going after this
... next measurement may be **NINs on lead**
(bg for CEvNS and of SN relevance in itself)