Cross Section Measurements for Supernova Neutrinos

Kate Scholberg, Duke University

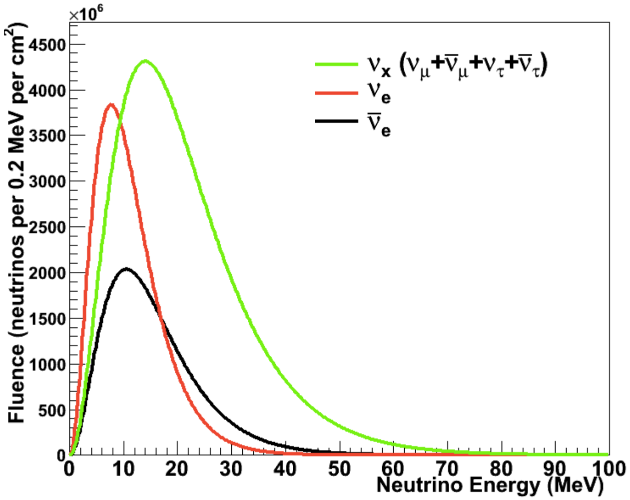
NuInt 2015, Osaka, November 2015

This is a (somewhat) gentler regime than most topics at NuInt...

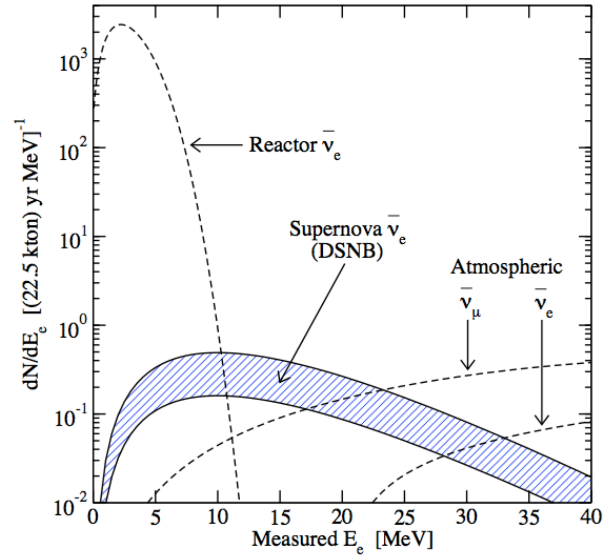
~GeV+ neutrinos can create a quite a mess ...

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

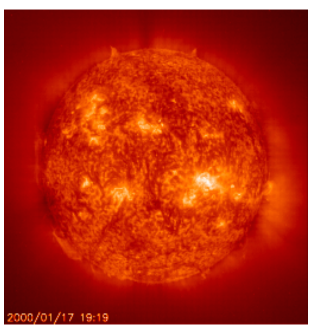
Neutrino interactions in the few-100 MeV range are relevant for:

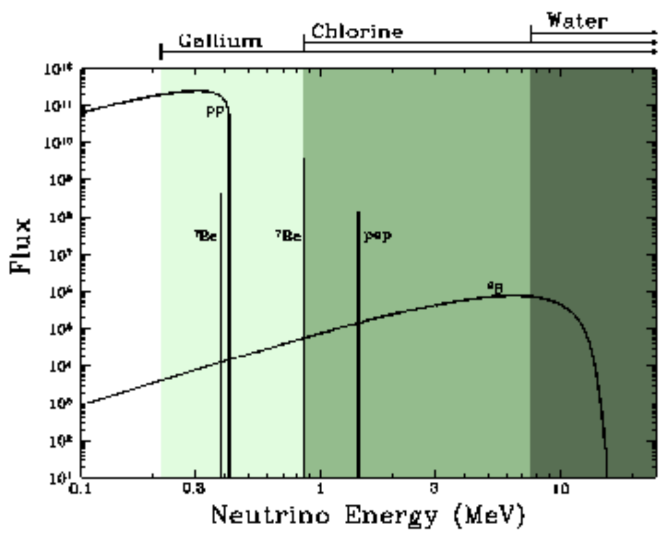


supernova neutrinos, burst & relic

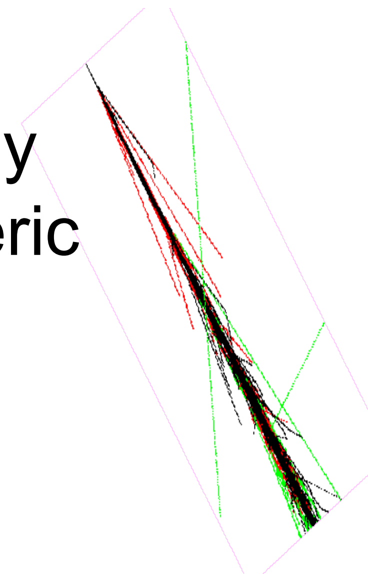


solar neutrinos



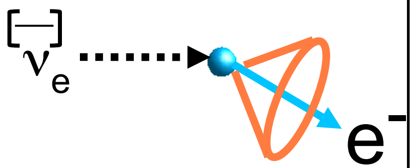
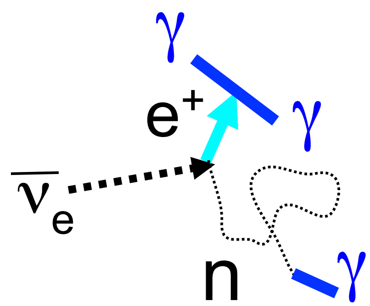
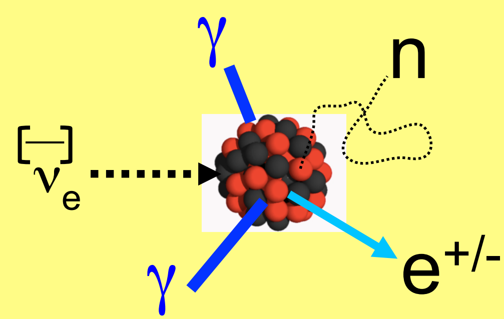
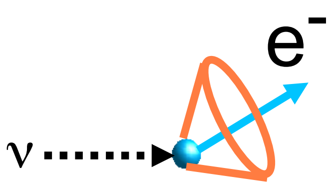
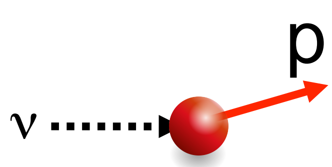
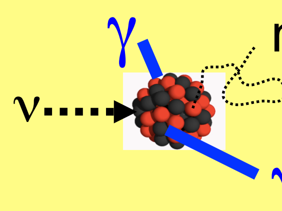
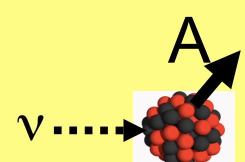


low energy atmospheric neutrinos



Physics: oscillation, SM tests, astrophysics

Neutrino Interactions in the tens-of-MeV regime

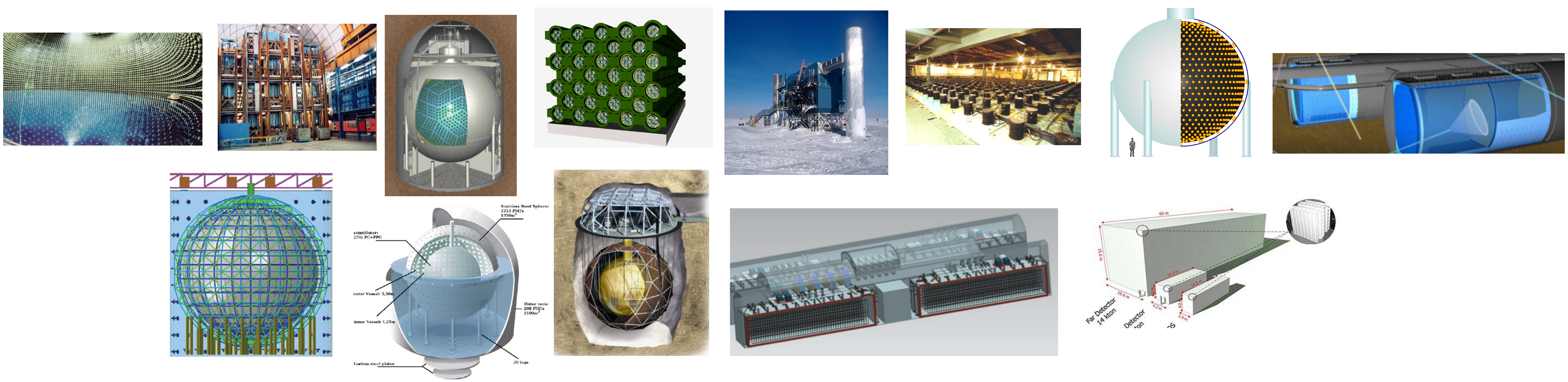
	Electrons	**Protons**	**Nuclei**
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$ 	$\nu_e + (N, Z) \rightarrow e^- + (N-1, Z+1)$ $\bar{\nu}_e + (N, Z) \rightarrow e^+ + (N+1, Z-1)$  Various possible ejecta and deexcitation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



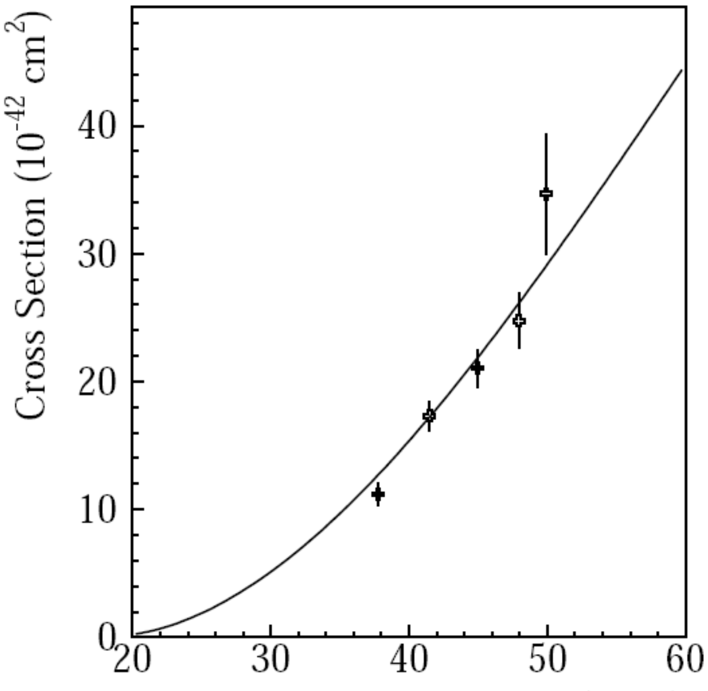
(These are not the only nuclei:
additional nuclei are of interest for other detectors;
supernova explosion physics, supernova nucleosynthesis)

.. 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

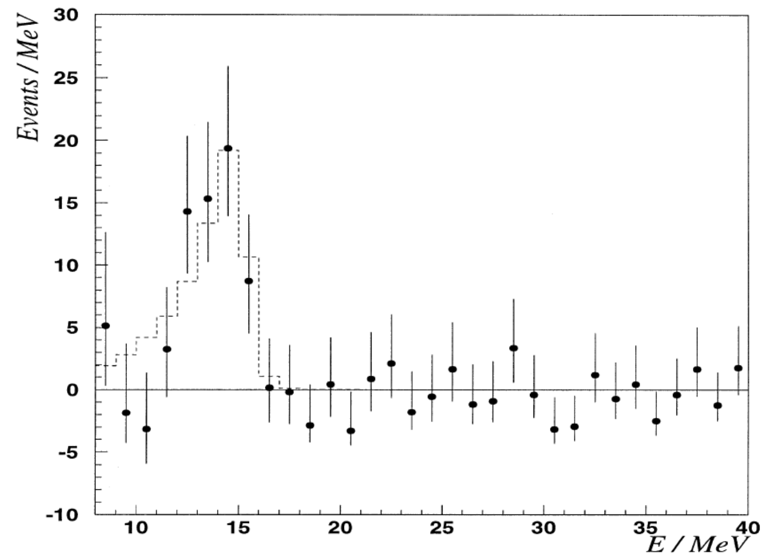
Phys. Rev. C 66 (2002) 015501



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

Karmen

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



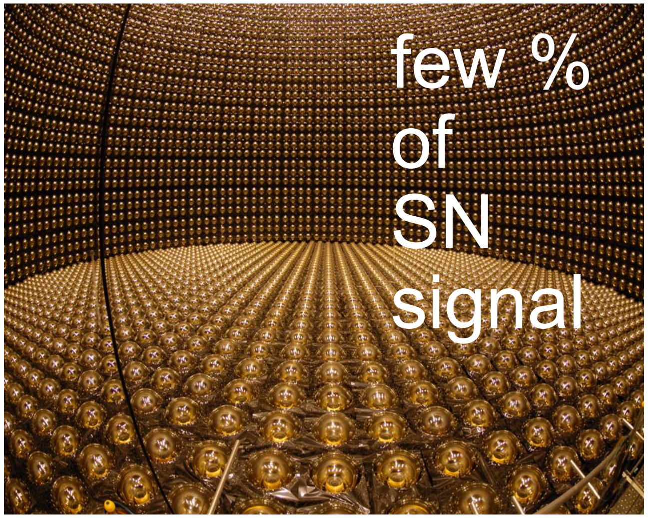
$$^{12}\mathrm{C}(\nu_\mu \nu_\mu')\,^{12}\mathrm{C}^*(1^+,1;15.1\ \mathrm{MeV})$$

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

Example 1: interactions on oxygen nuclei

CC interactions

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



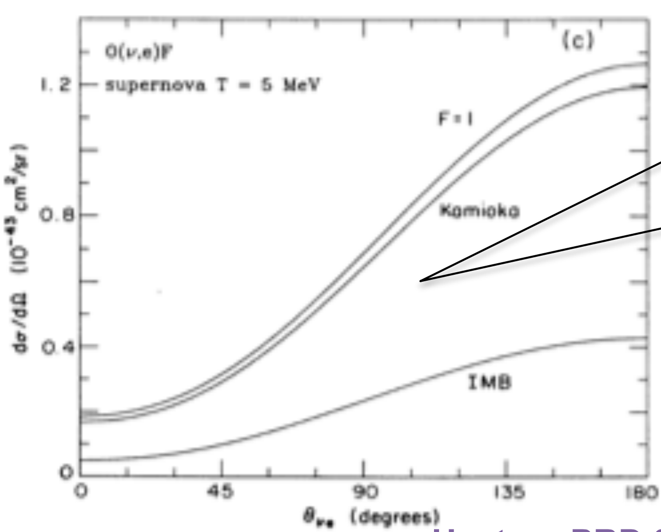
variety of final state ejecta

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)

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)

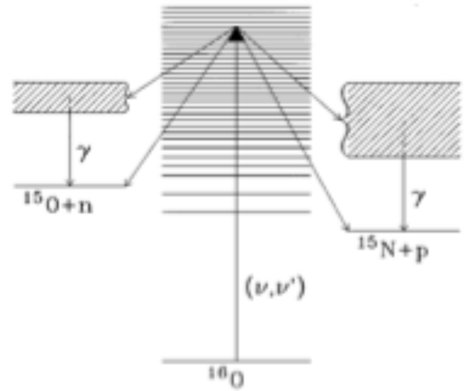


Angular distributions are interesting

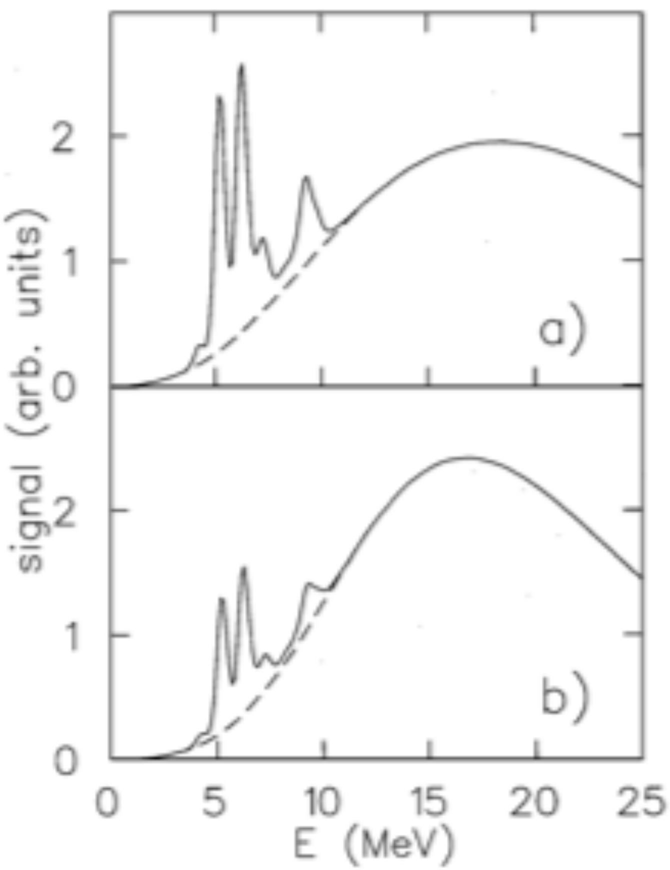
Haxton: PRD 36, (1987) 2283

NC interactions on oxygen nuclei

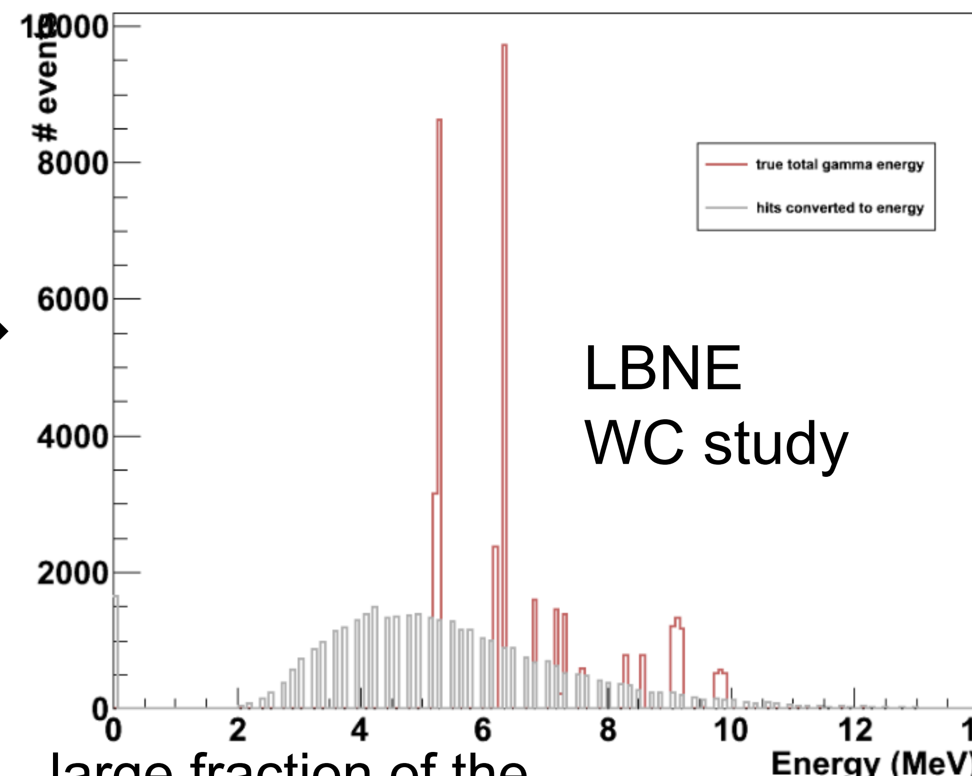
Final states from
NC excitation



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

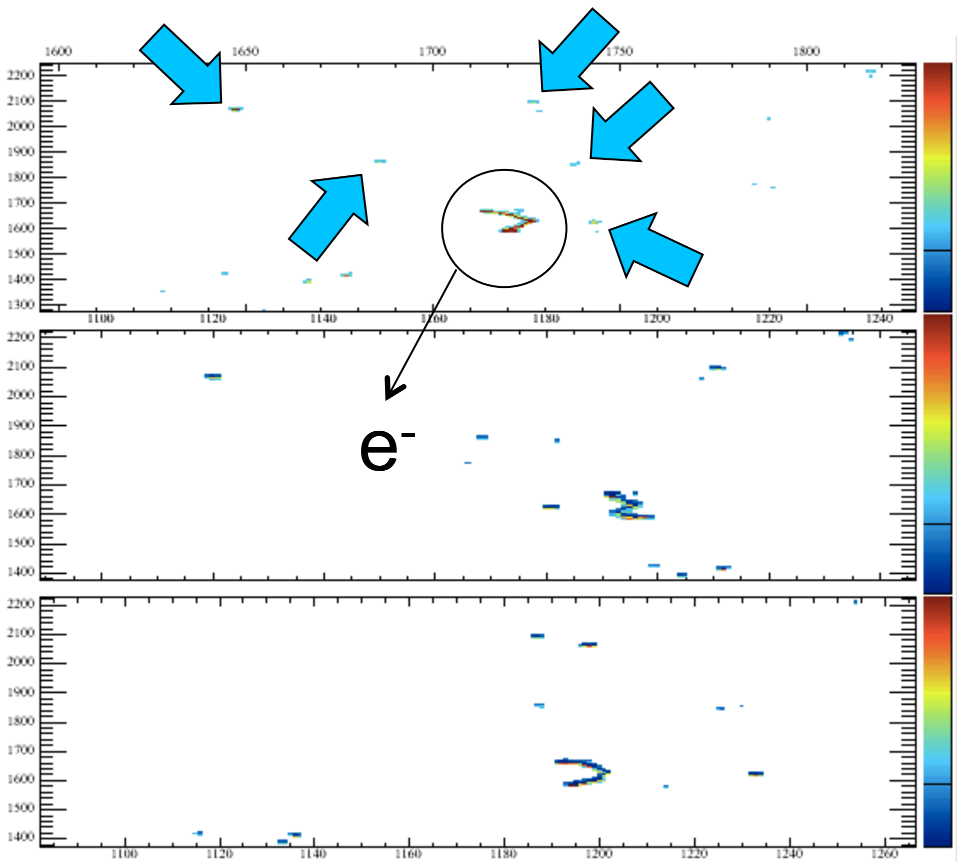
$$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$$

Can use for pointing

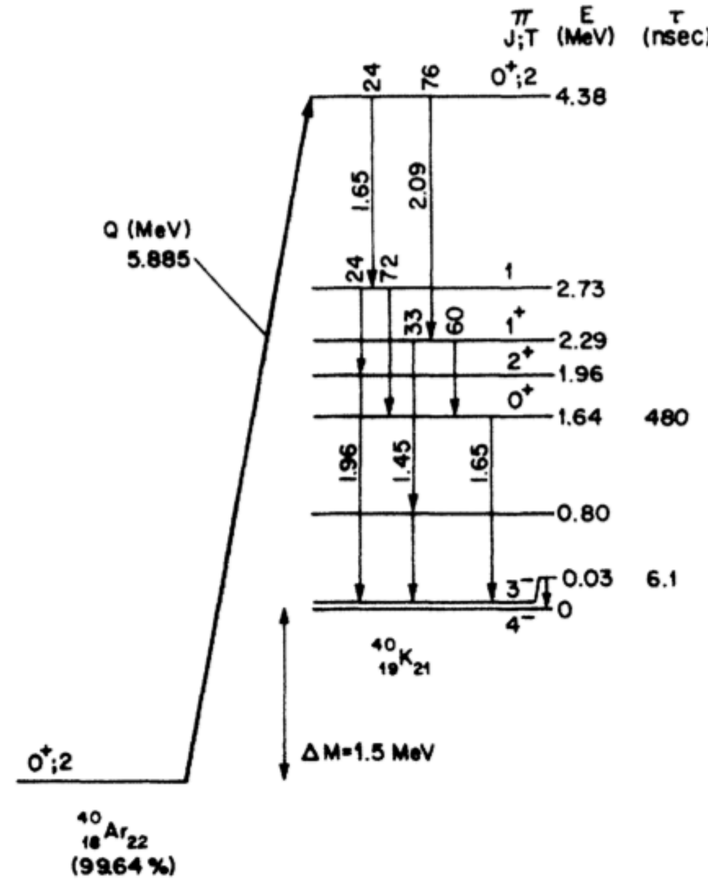
- In principle can tag modes with
- deexcitation gammas (or lack thereof)...

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!

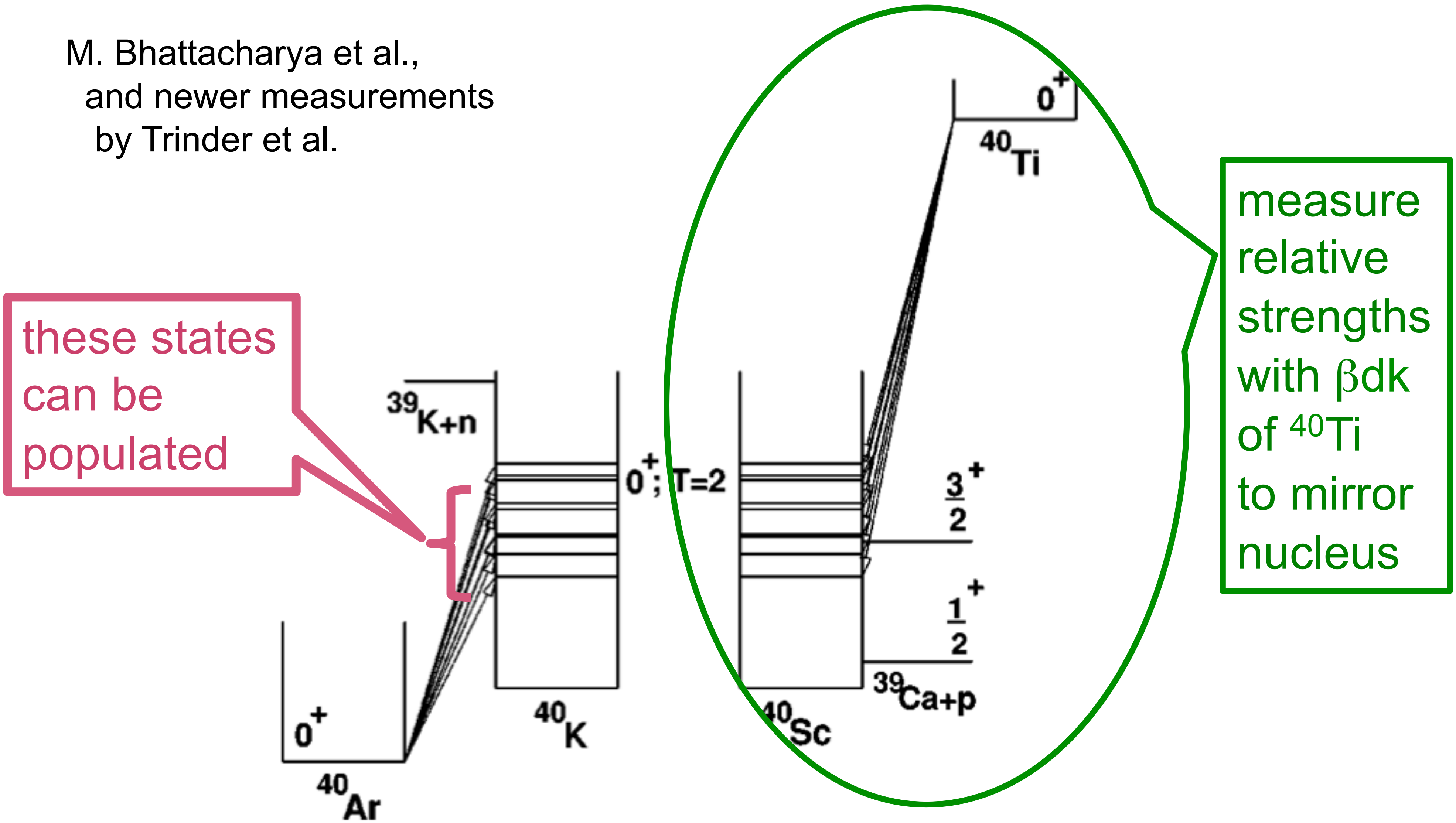
Need to understand efficiency for given technology

… 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.



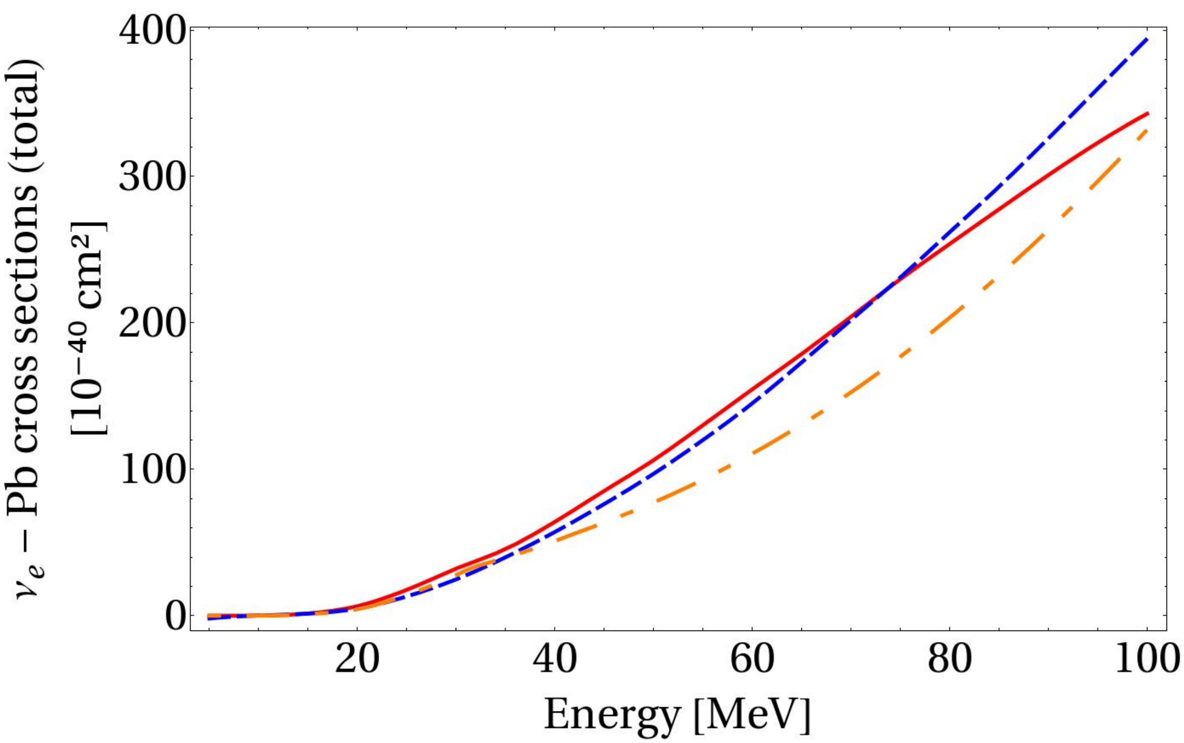
Example 3: interactions on lead nuclei

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

(oscillation sensitivity)

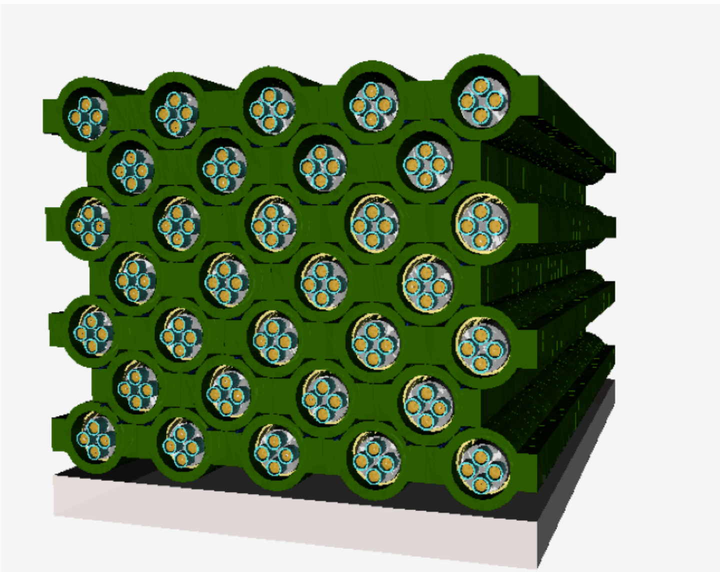
From C. Volpe, TPC10 workshop

Solid: J.Engel, et al. PRD 67, 013005 (2003)

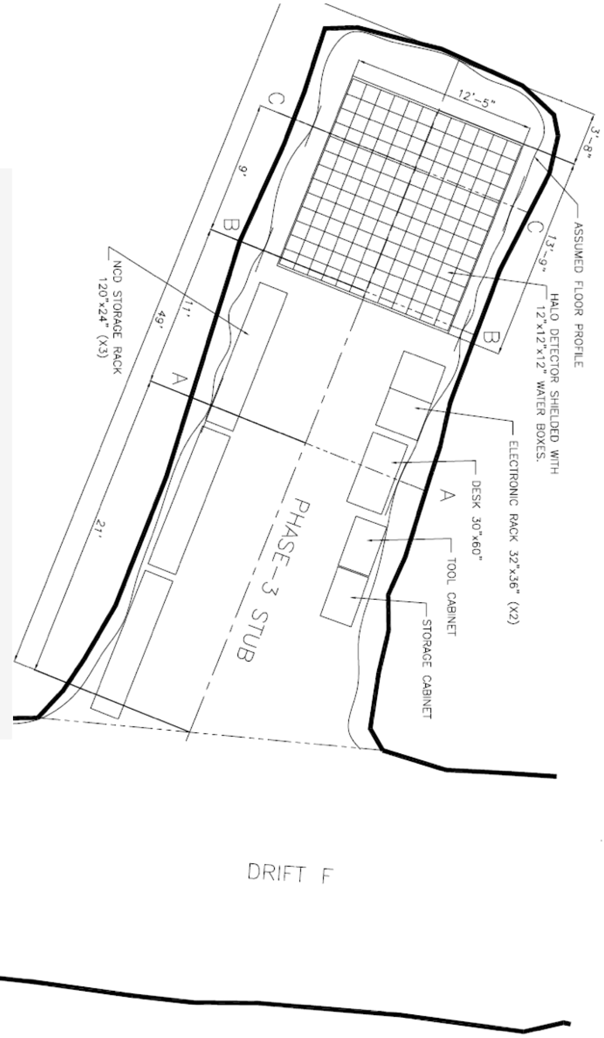
Dashed: E. Kolbe *et al.*, PRC 63, 025802 (2001)

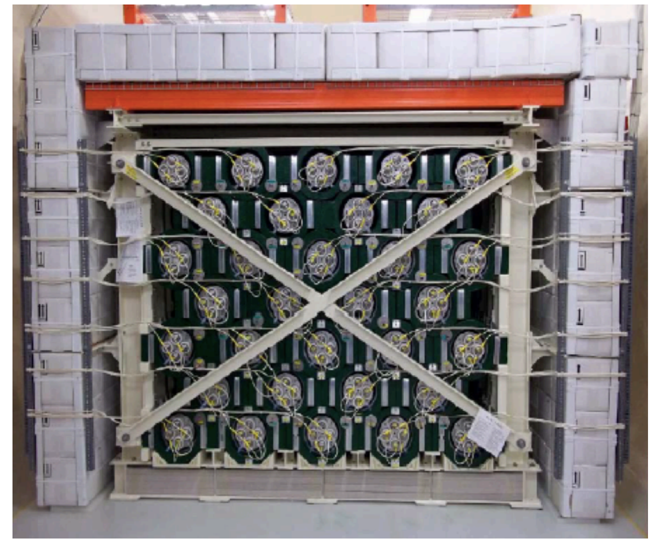
Dashed-dotted: N. Paar (private communication)

HALO at SNOLAB



thesis



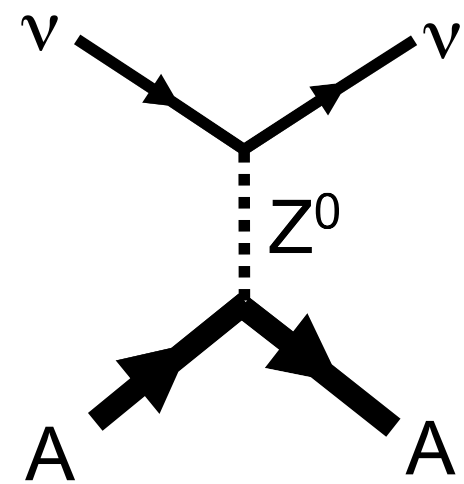


SNO ^{3}He counters + 79 tons of Pb: ~40 events @ 10 kpc

Coherent elastic neutrino-nucleus scattering (CEvNS)

ν + A → ν + 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, ...

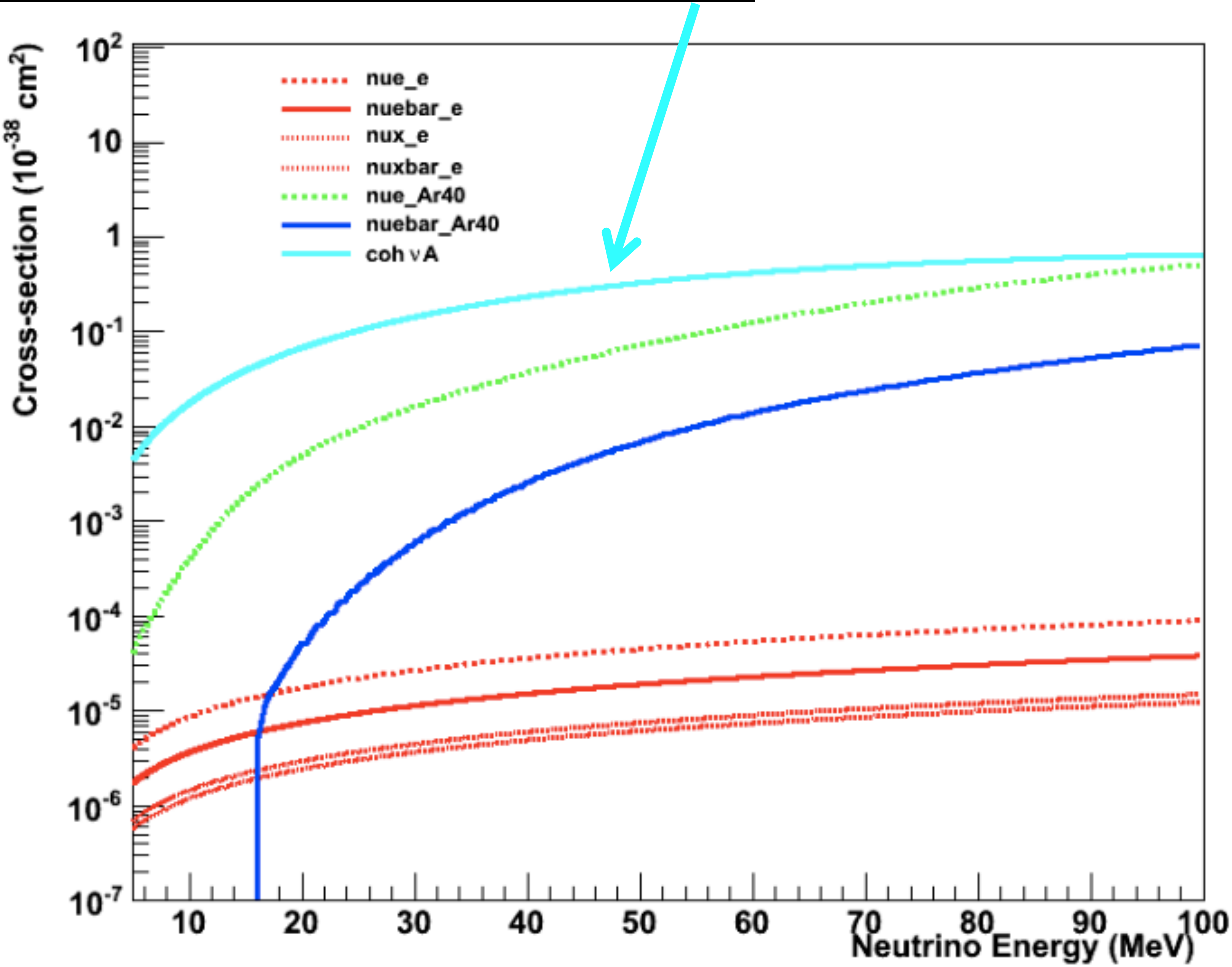
- I prefer including "E" for "elastic"... otherwise NuInt types constantly confuse it with coherent pion production at ~ GeV energies
- I'm told "NN" means "nucleon-nucleon" to nuclear types (also CENNS is now a collaboration!)
- CEνNS is a possibility but those internal Greek letters are annoying

➔**CEvNS**, pronounced "sevens"...

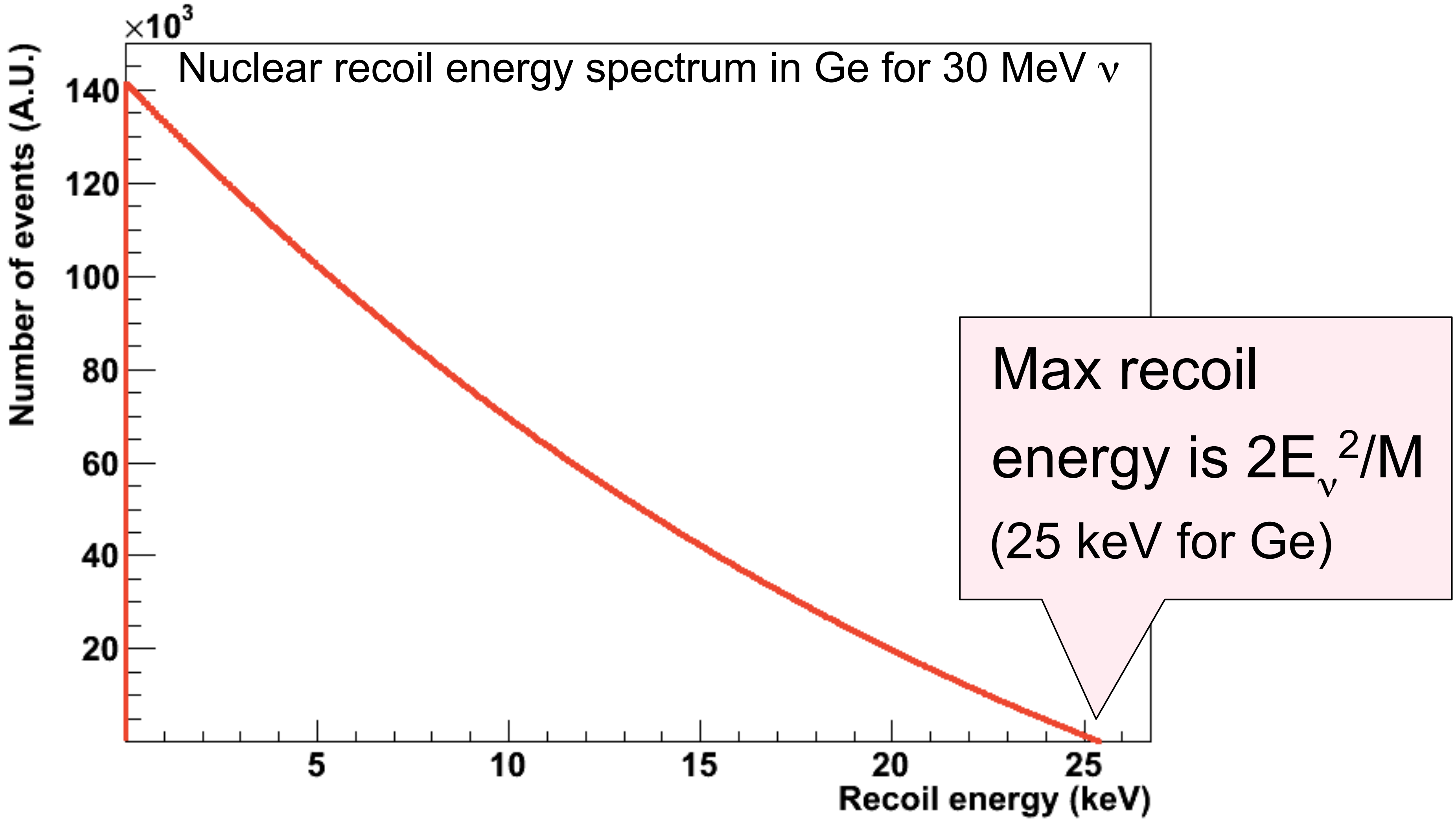
spread the meme!

\end{aside}

The cross-section is *large*

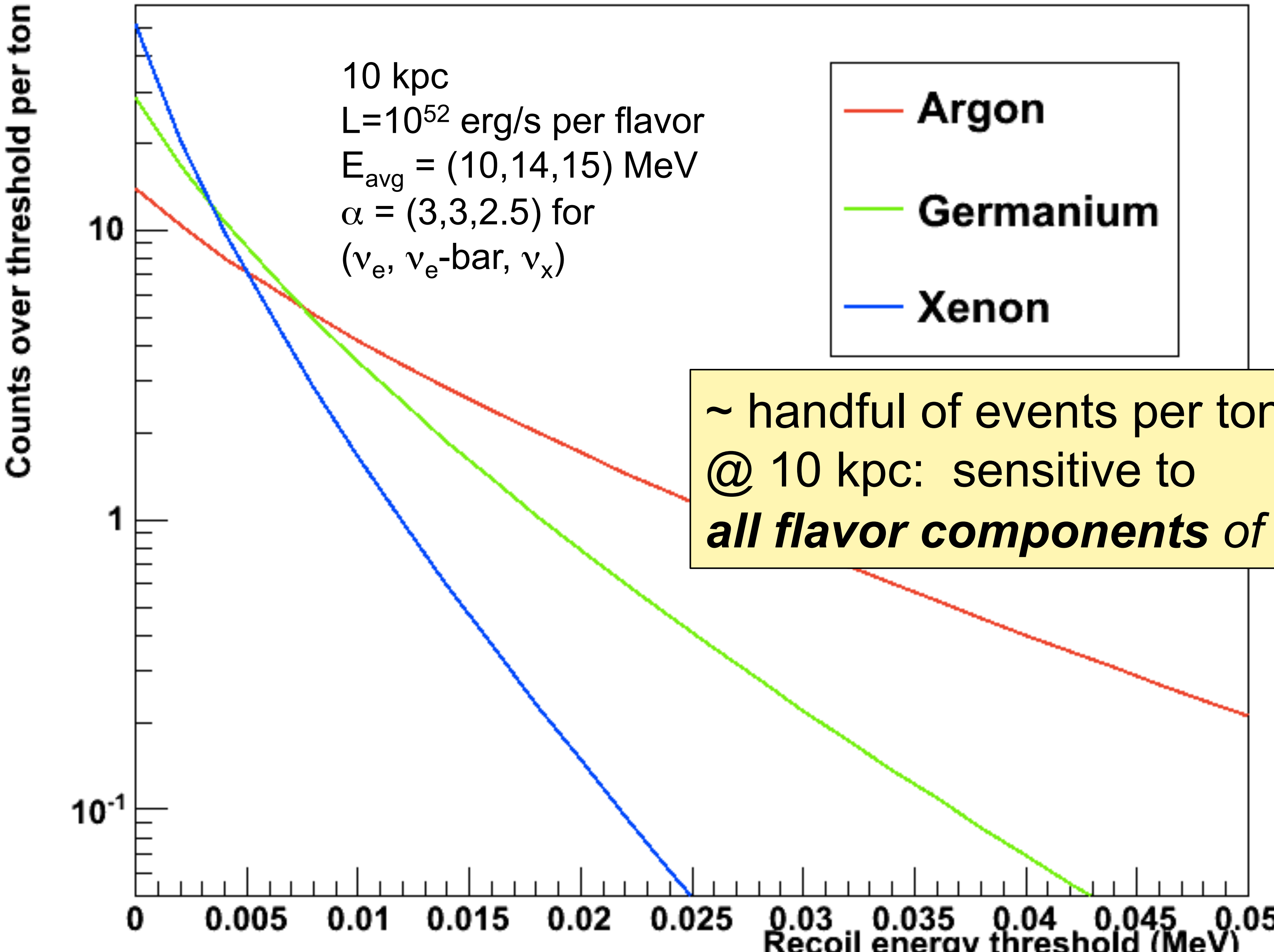


Large cross section, but never observed due to **tiny nuclear recoil energies:**



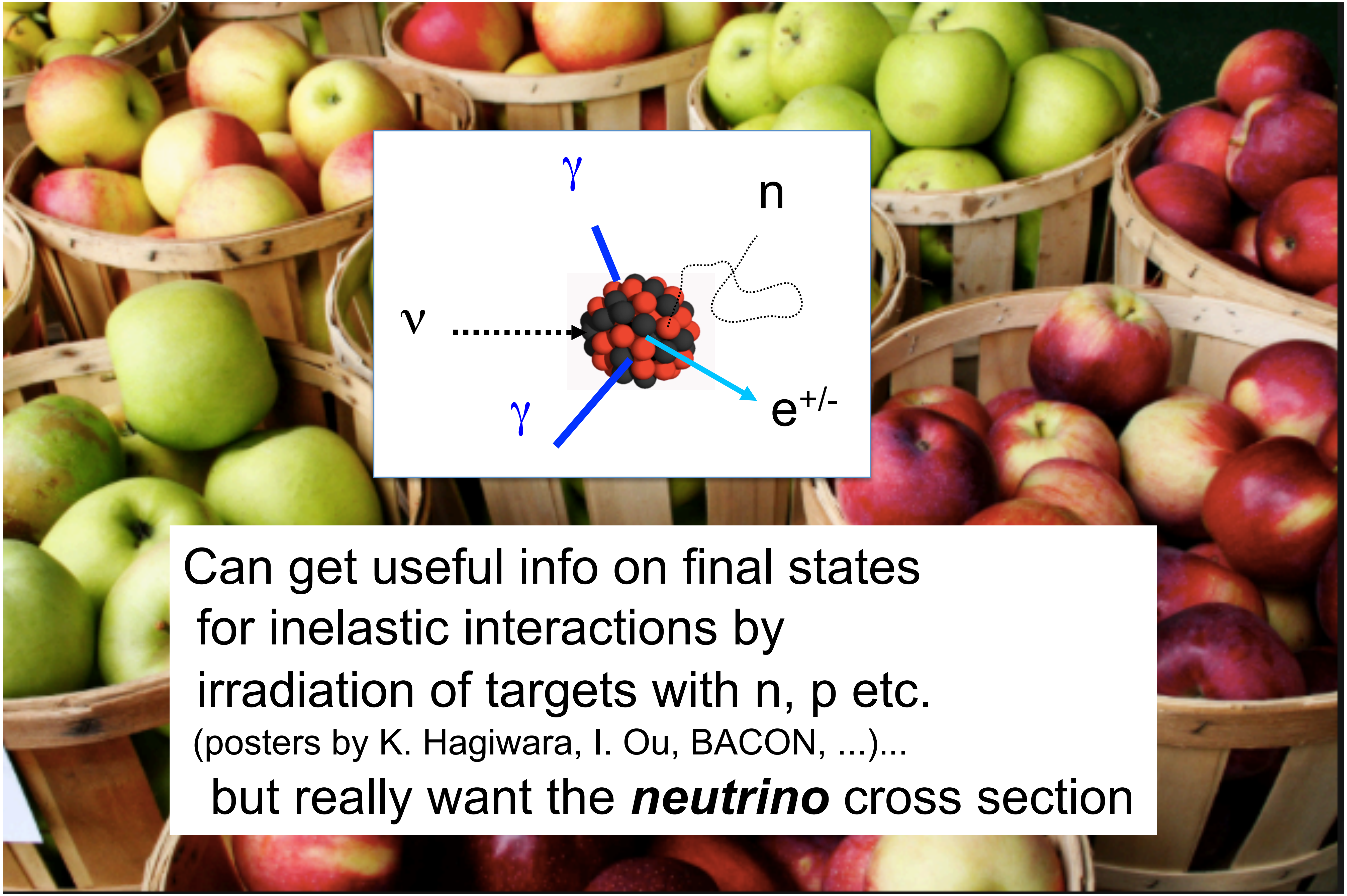
➔ but **WIMP dark matter detectors** developed over the last ~decade are sensitive to ~ keV to 10's of keV recoils

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



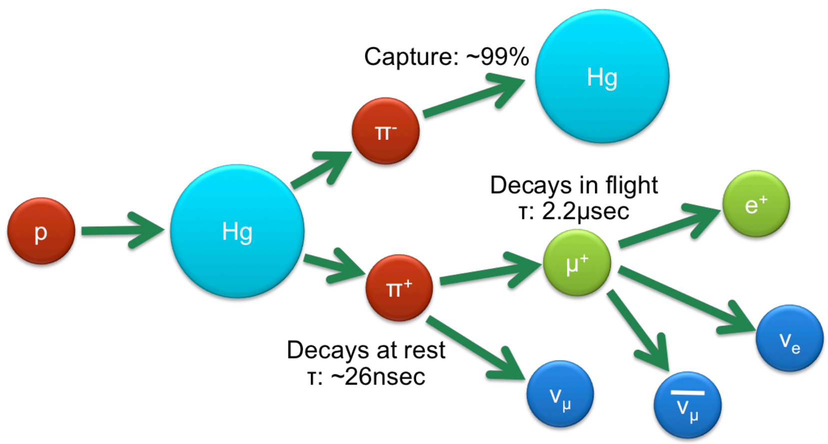
~ handful of events per tonne @ 10 kpc: sensitive to ***all flavor components*** *of the flux*

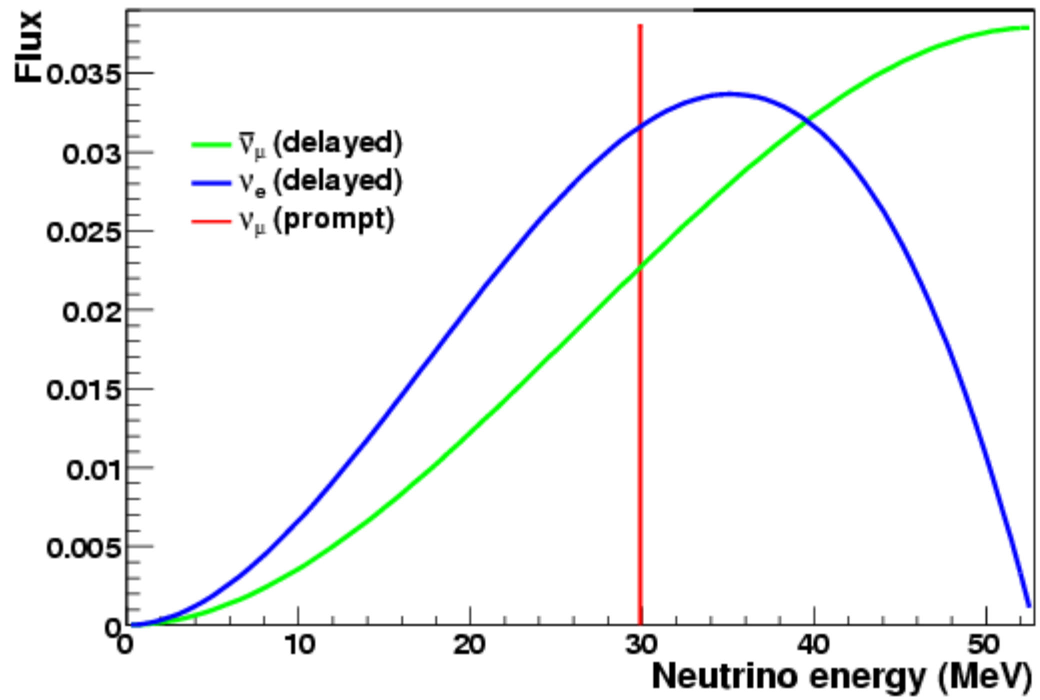
How can we *measure* these cross sections?



Can get useful info on final states
for inelastic interactions by
irradiation of targets with n, p etc.
(posters by K. Hagiwara, I. Ou, BACON, ...)...
but really want the ***neutrino*** cross section

Stopped-Pion (πDAR) Neutrinos





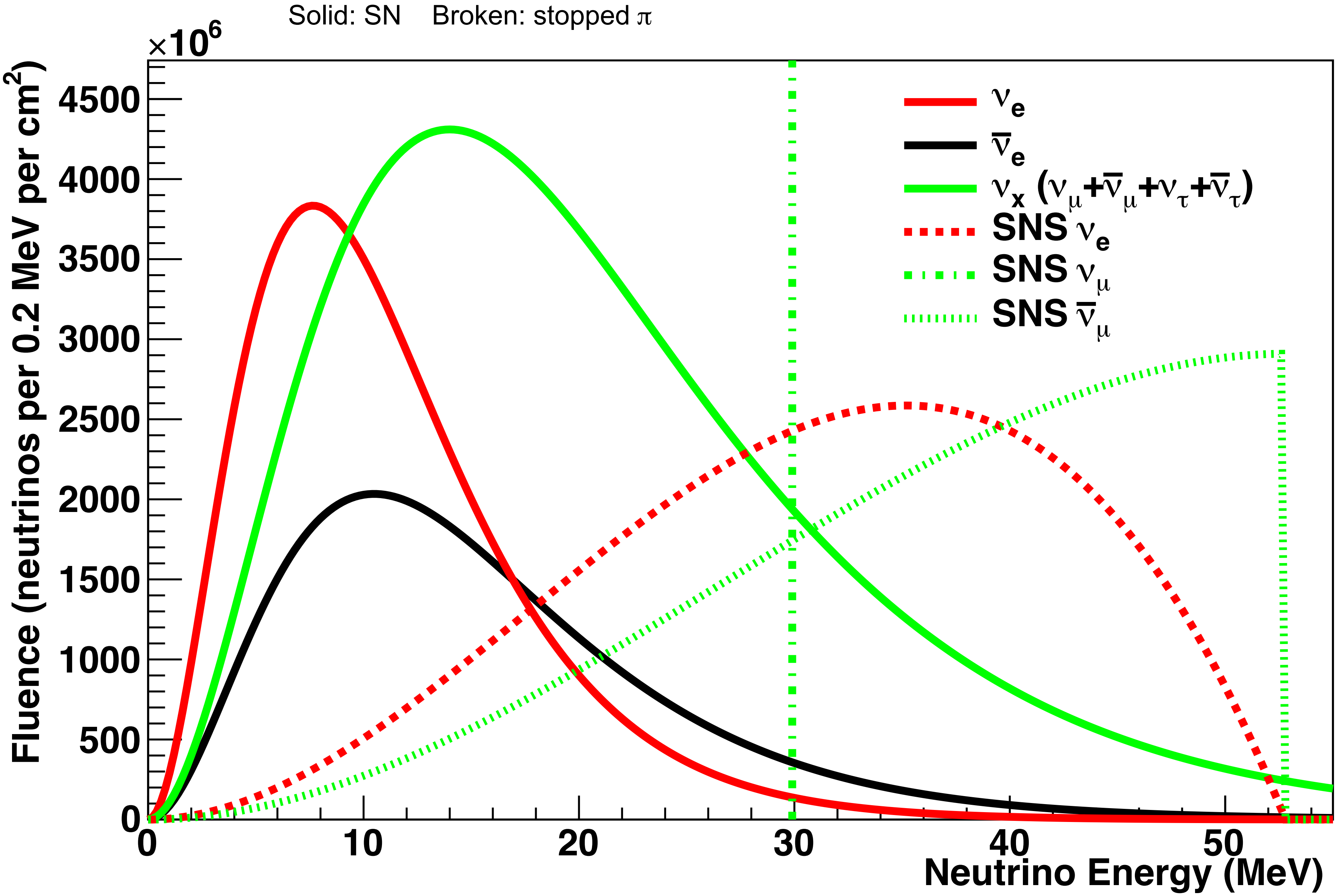
$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$

2-body decay: monochromatic 29.9 MeV ν_μ
PROMPT

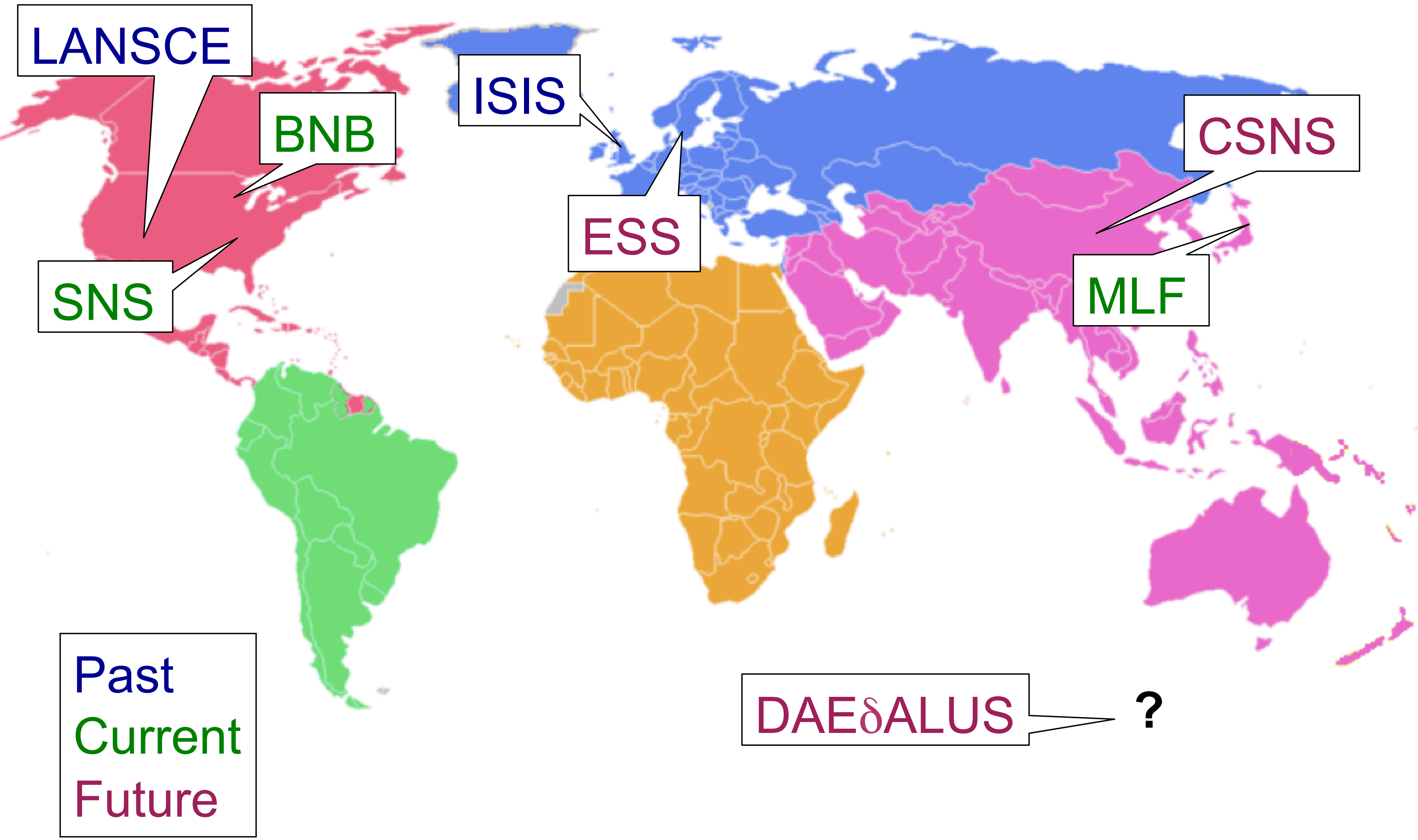
$$\mu^+ \longrightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

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

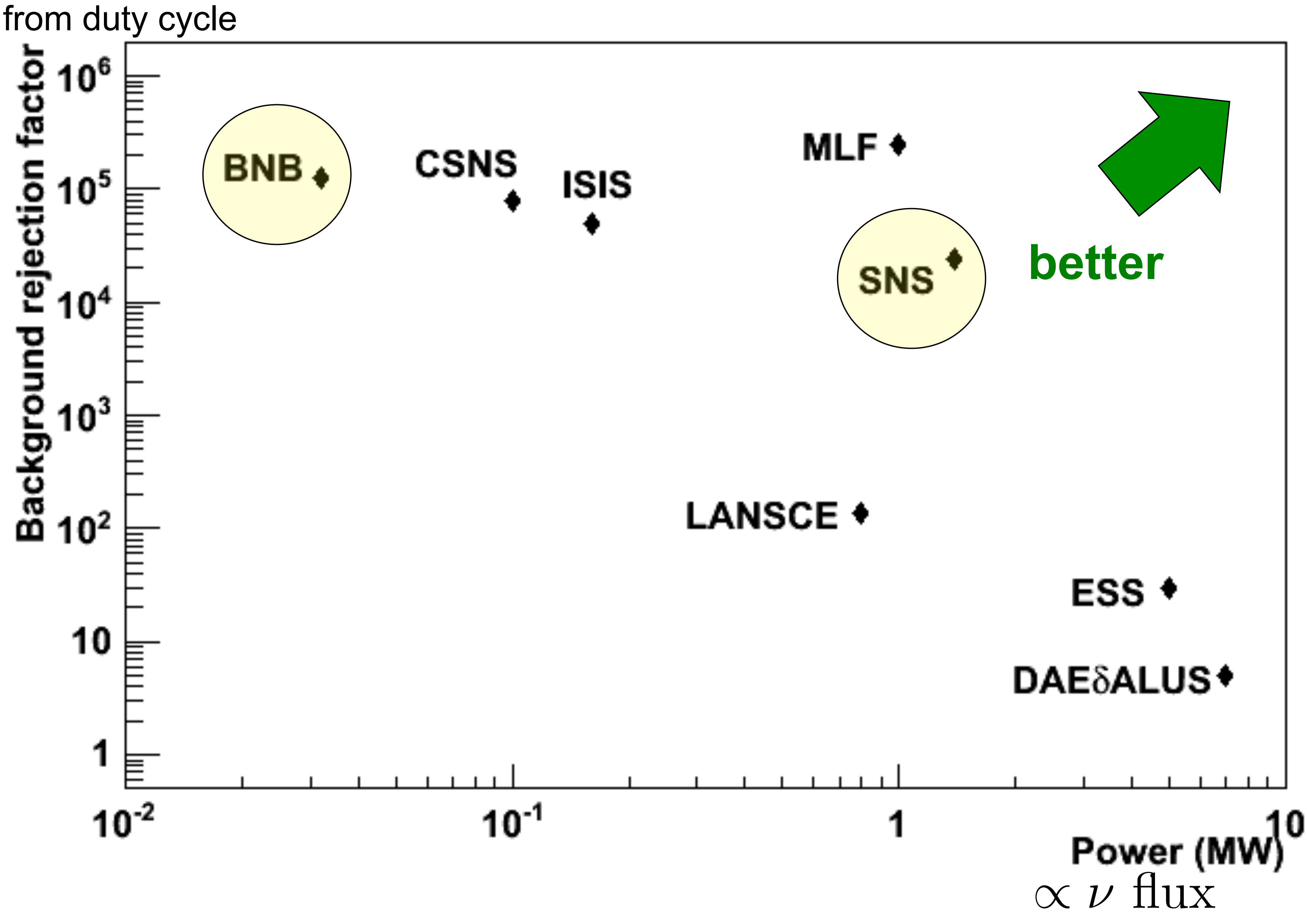
Good overlap w/ SN spectrum



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
CSNS			Liquid scint?
ESS			Concepts

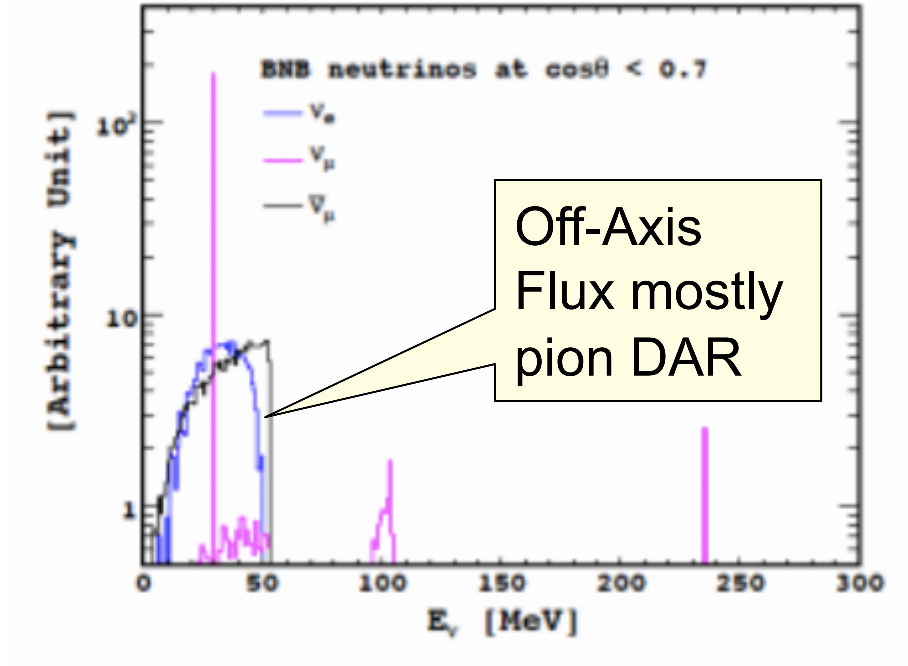
BLUE: cross-section measurements

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**
CSNS			Liquid scint?
ESS			Concepts

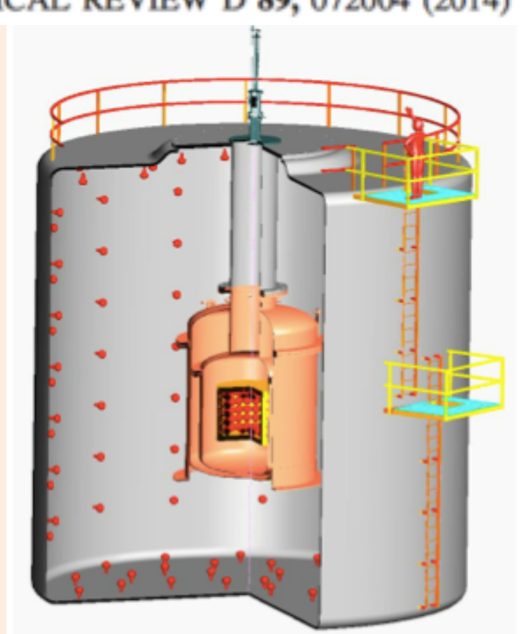
Look in more detail at these

Cross-Section Experiments @ the FNAL Booster Neutrino Beam

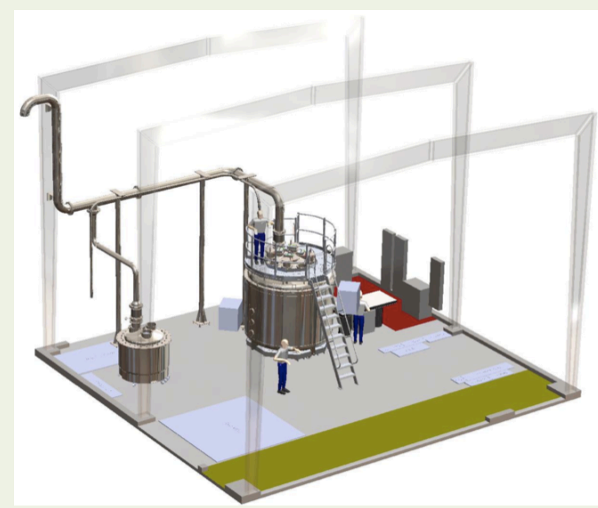


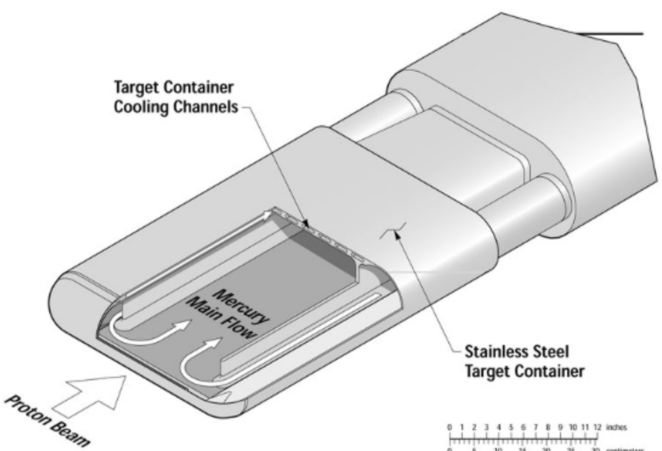
CENNS experiment
to measure CEvNS:
LAr single-phase

PHYSICAL REVIEW D 89, 072004 (2014)



CAPTAIN-BNB experiment
(5-ton LAr TPC)
proposed
to measure
ν-Ar x-scns
[deferred for CAPTAIN -MINERvA]





Proton beam energy: 0.9-1.3 GeV

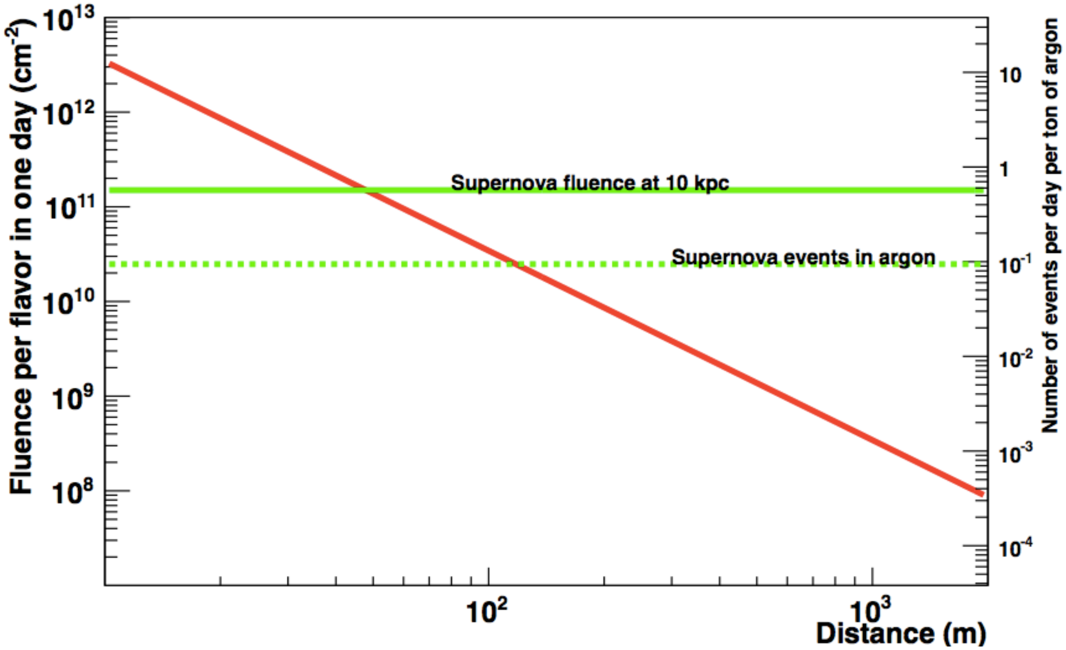
Total power: 0.9-1.4 MW

Pulse duration: 380 ns FWHM

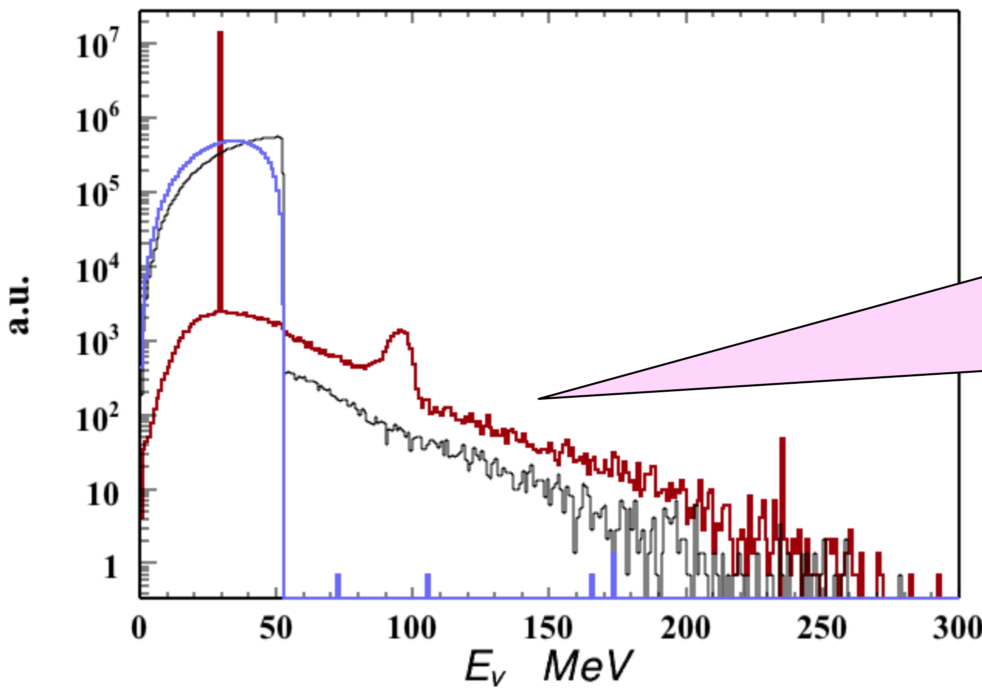
Repetition rate: 60 Hz

Liquid mercury target

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



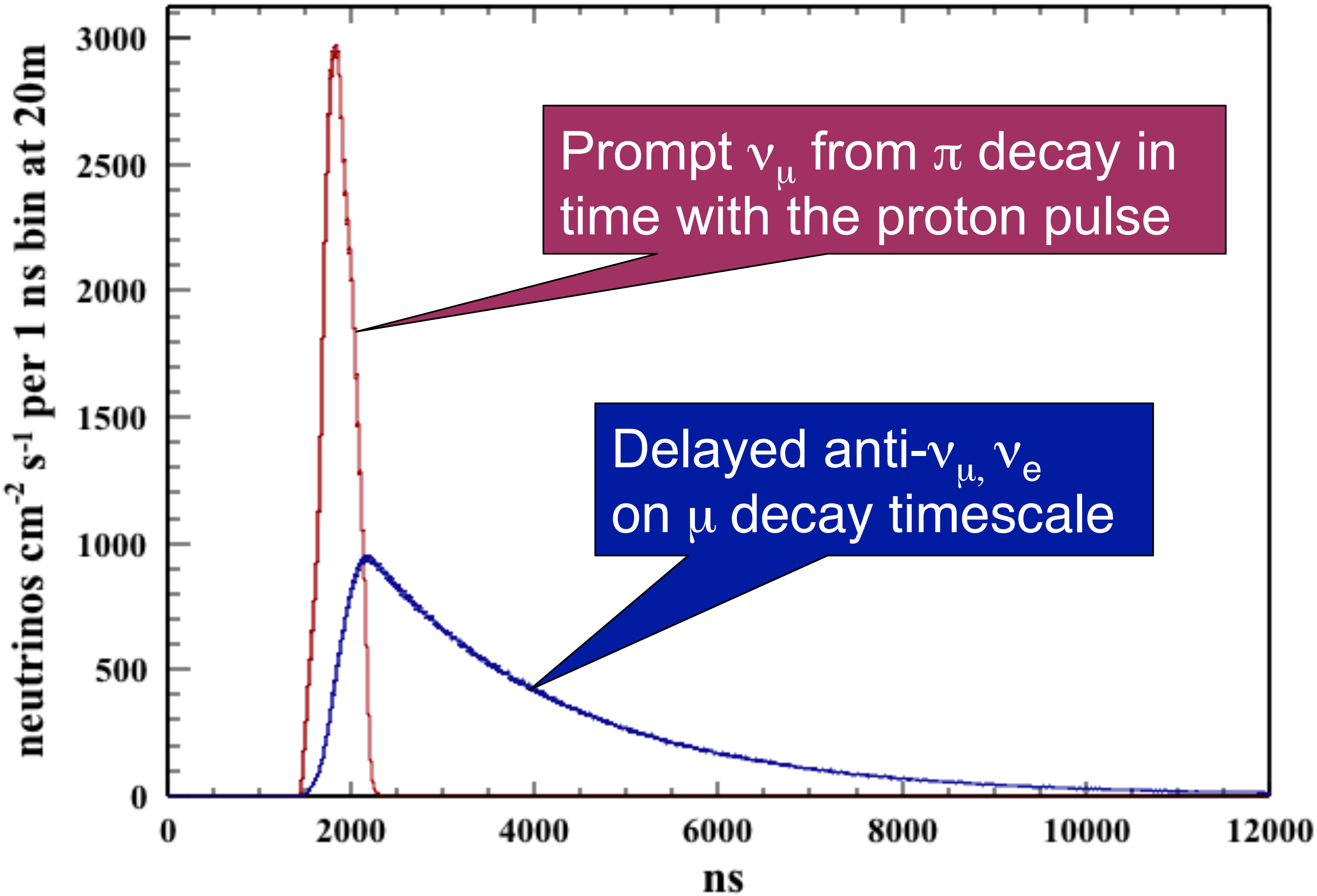
SNS flux (1.4 MW):
430 x 10^5 ν/cm^2/s
@ 20 m



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

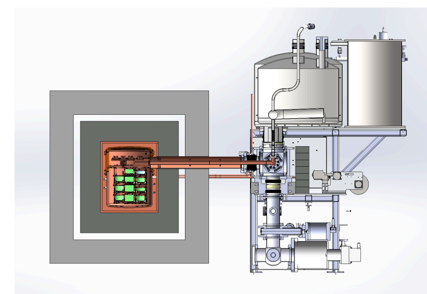
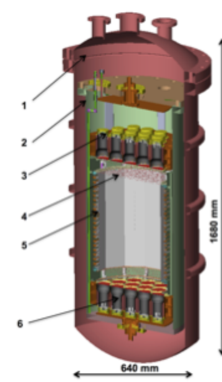
Time structure of the SNS source

60 Hz *pulsed* source



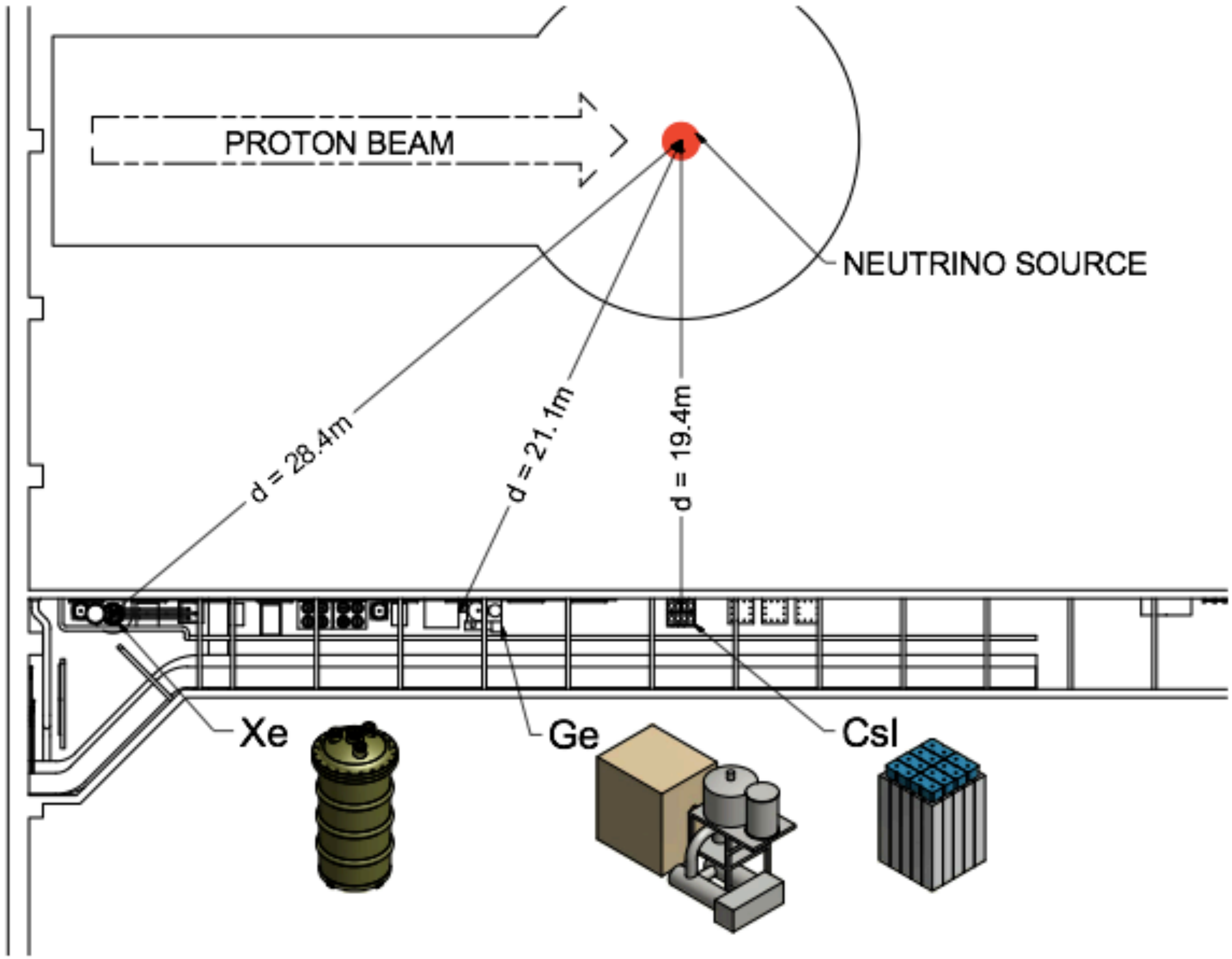
Background rejection factor ~few x 10^{-4}

COHERENT detector subsystems

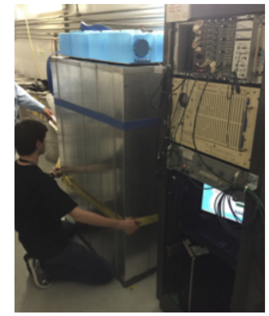
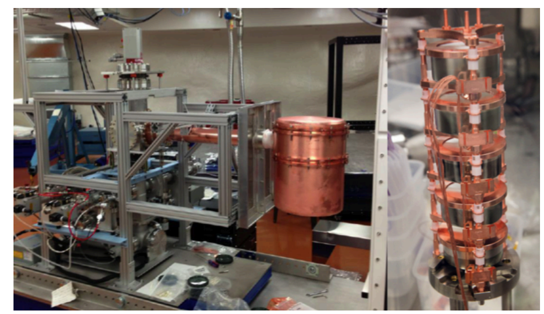
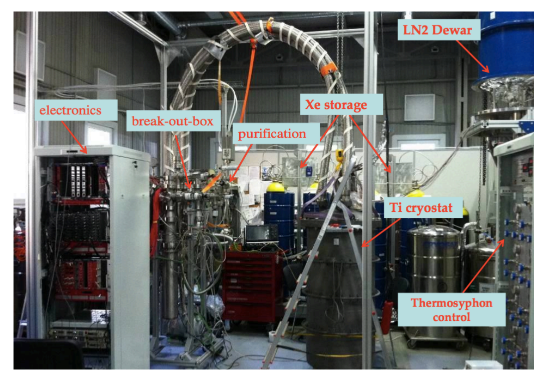
Nuclear Target	Technology	Mass (kg)	Distance from source (m)	Recoil threshold (keVr)	
CsI[Na]	Scintillating Crystal	14	20	6.5	
Ge	HPGe PPC	15	20	5	
Xe	Two-phase LXe TPC	100	32	4	

arXiv:1509.08702

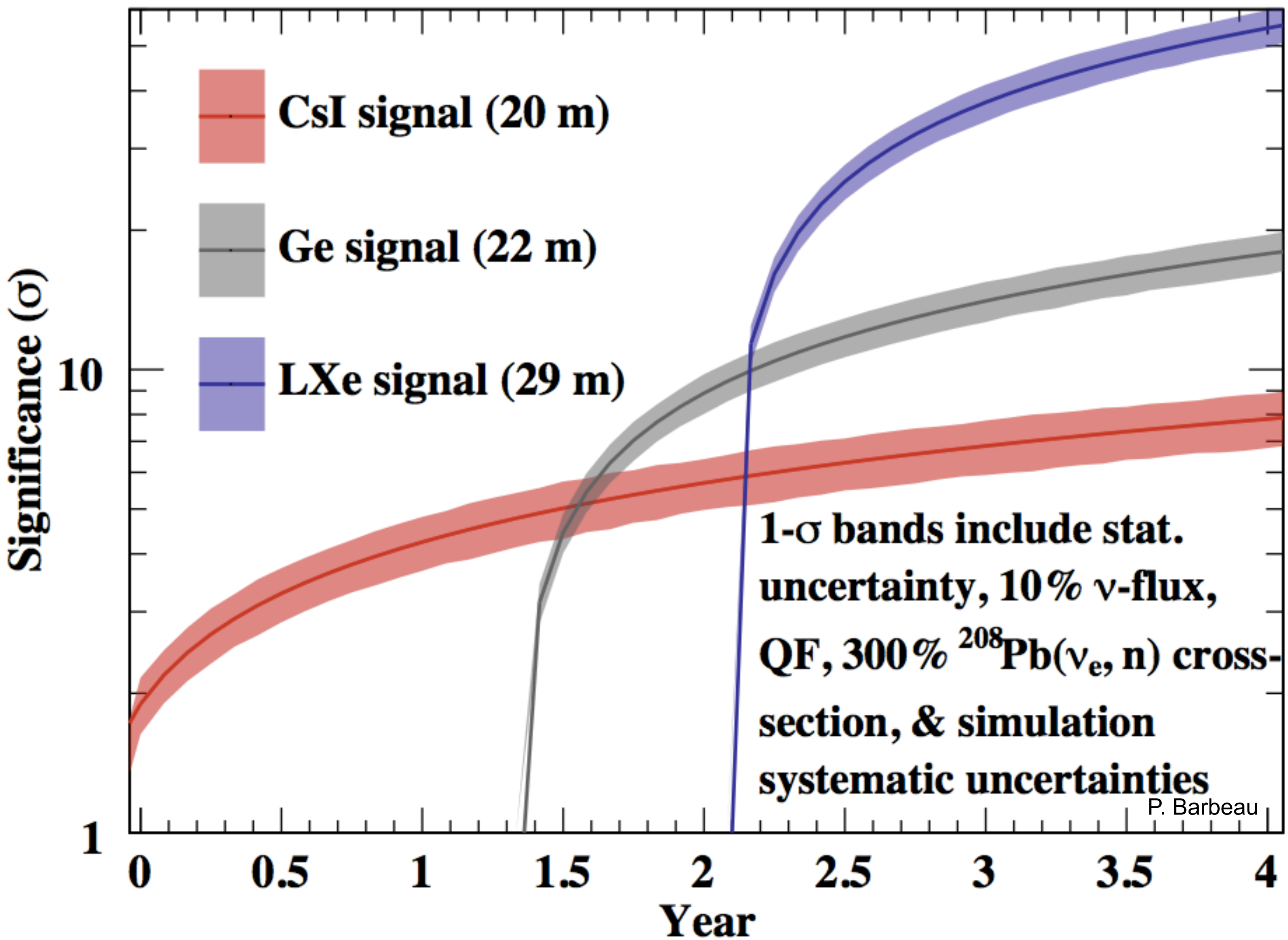
Reference design siting for deployment in SNS basement
(measured neutron backgrounds low)



COHERENT status

Nuclear Target	Technology	Status	
CsI[Na]	Scintillating Crystal	Installed in SNS basement	
Ge	HPGe PPC	10 kg + equipment pledged from MAJORANA	
Xe	Two-phase LXe TPC	Detector constructed in Russia @ MEPhI	

Sensitivity vs running time



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

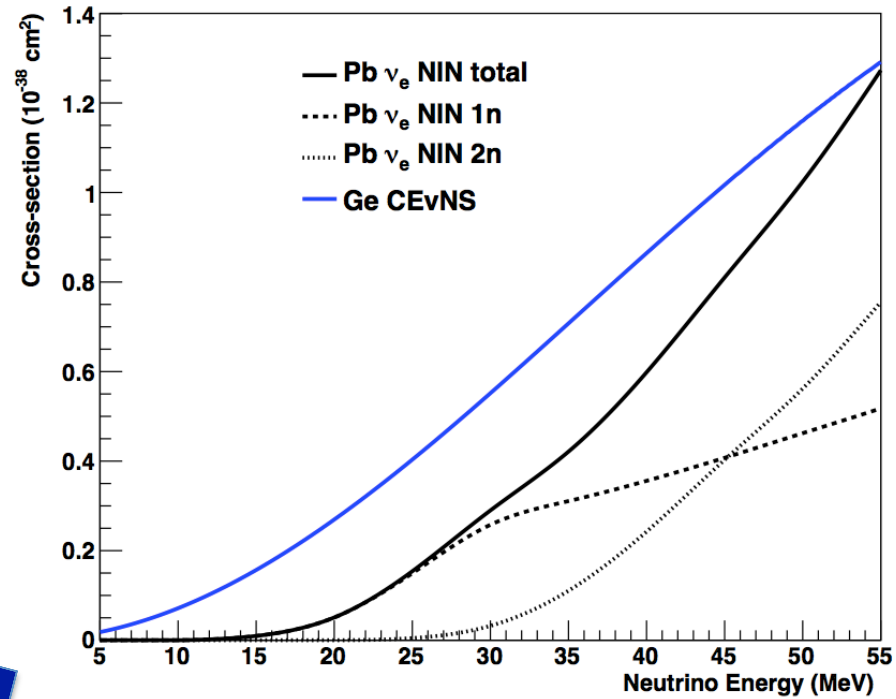
$\nu_e + {}^{208}Pb \rightarrow {}^{208}Bi^* + e^-$ CC

↘ 1n, 2n emission

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

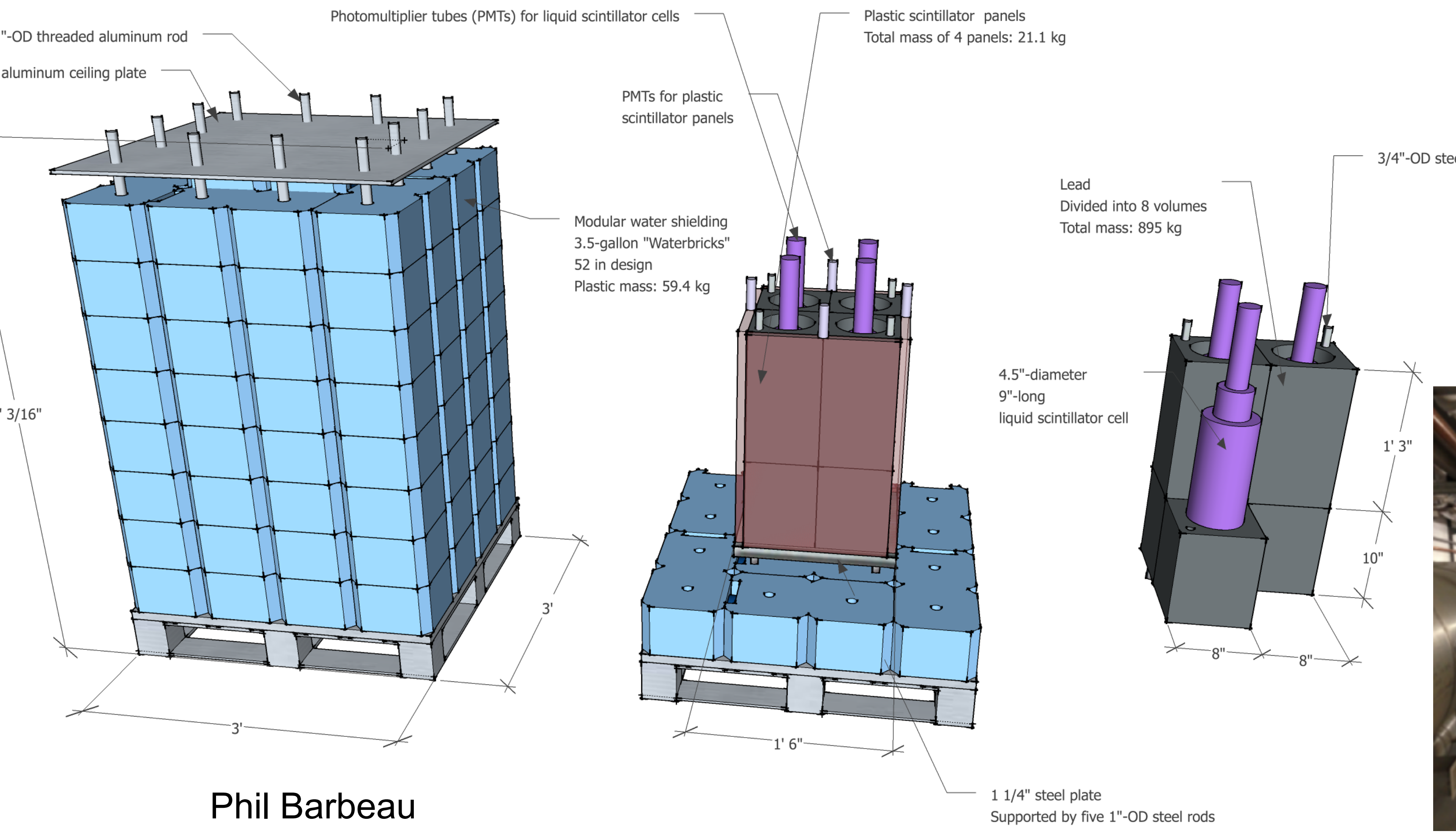
↘ 1n, 2n, γ emission

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



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, ...)



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 and **CENNS@BNB** going after this

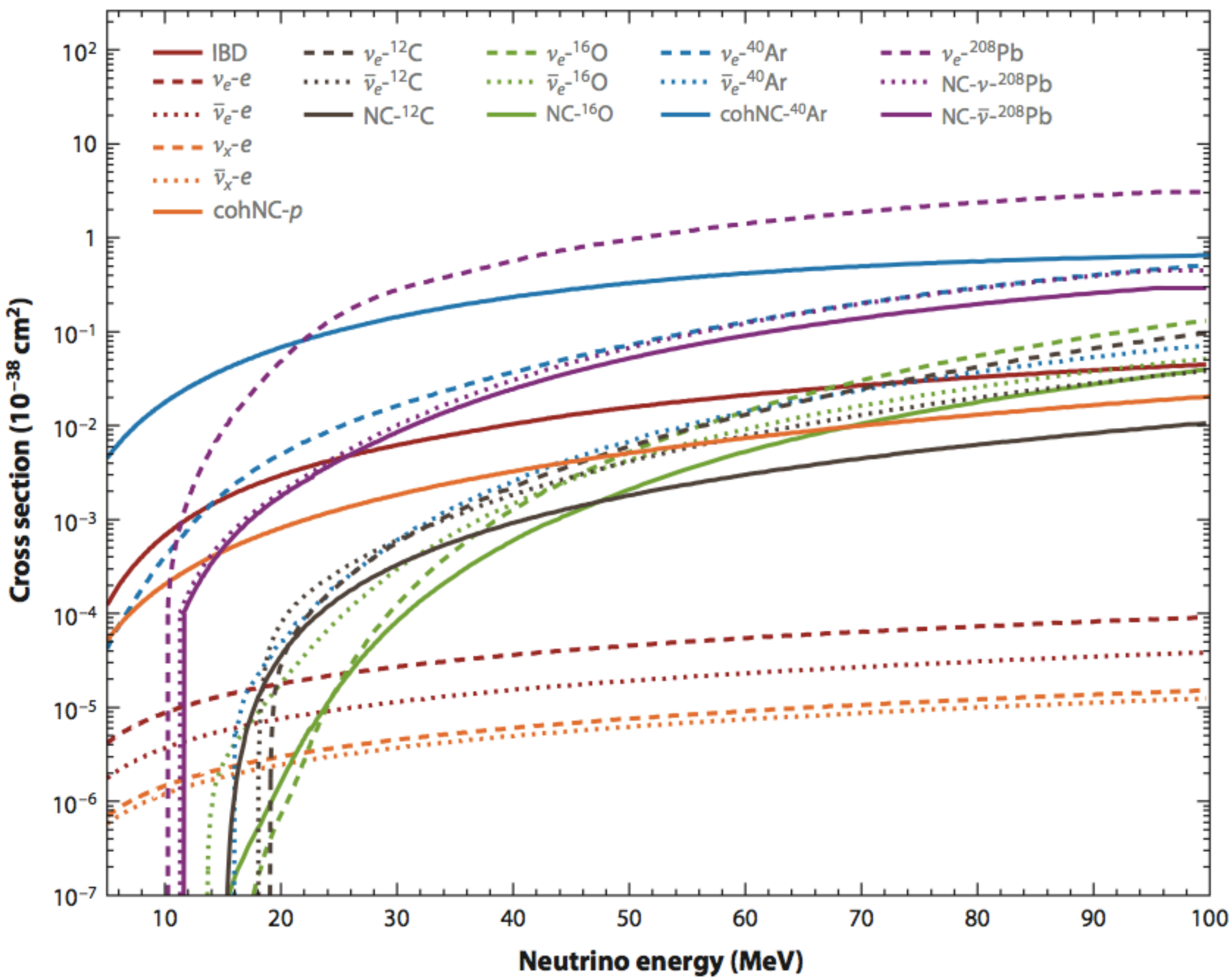
... next measurement may be **NINs on lead**

(bg for CEvNS and of SN relevance in itself)

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

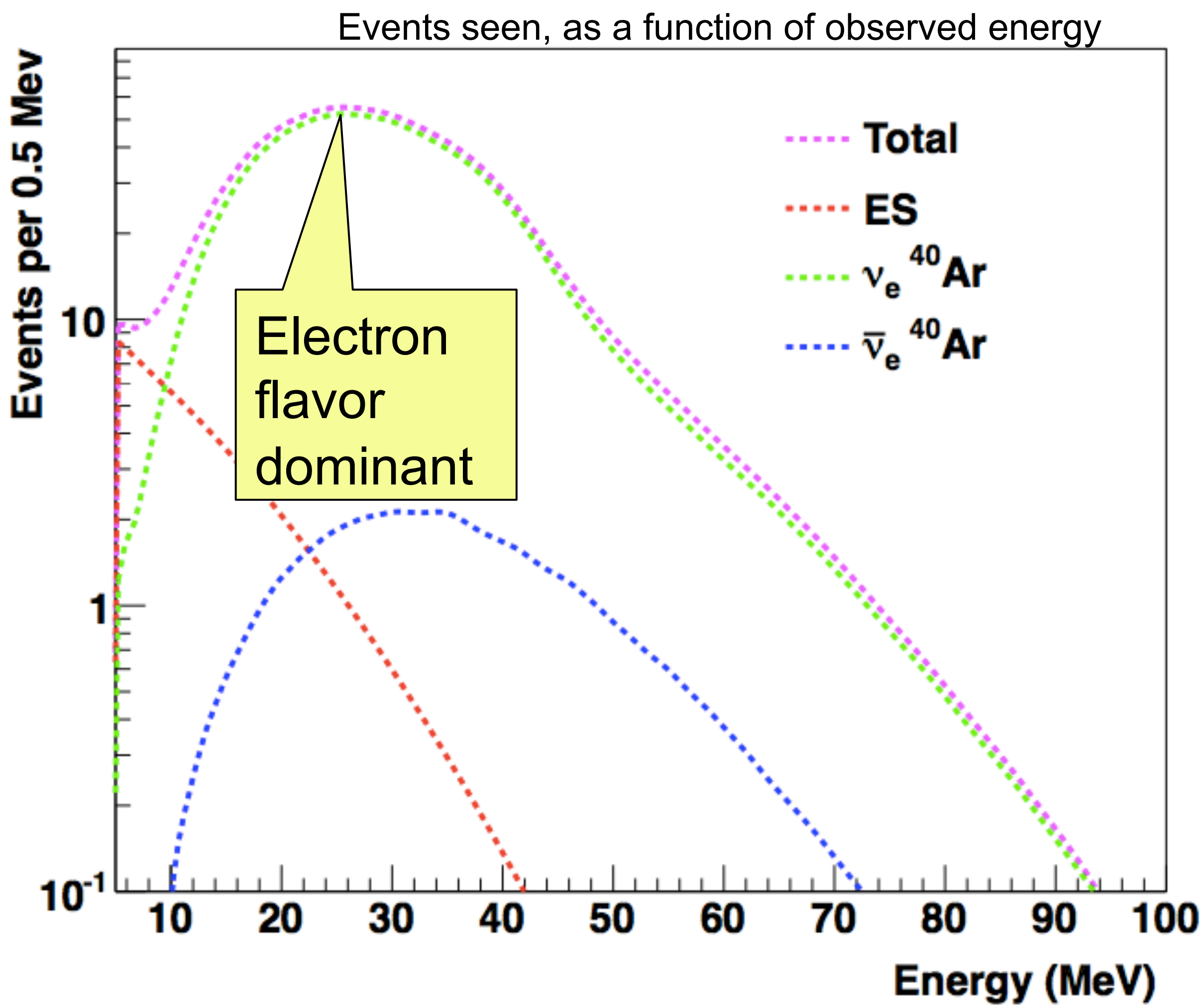
Extras/backups

Cross-sections in this energy range



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

Supernova signal in a liquid argon detector

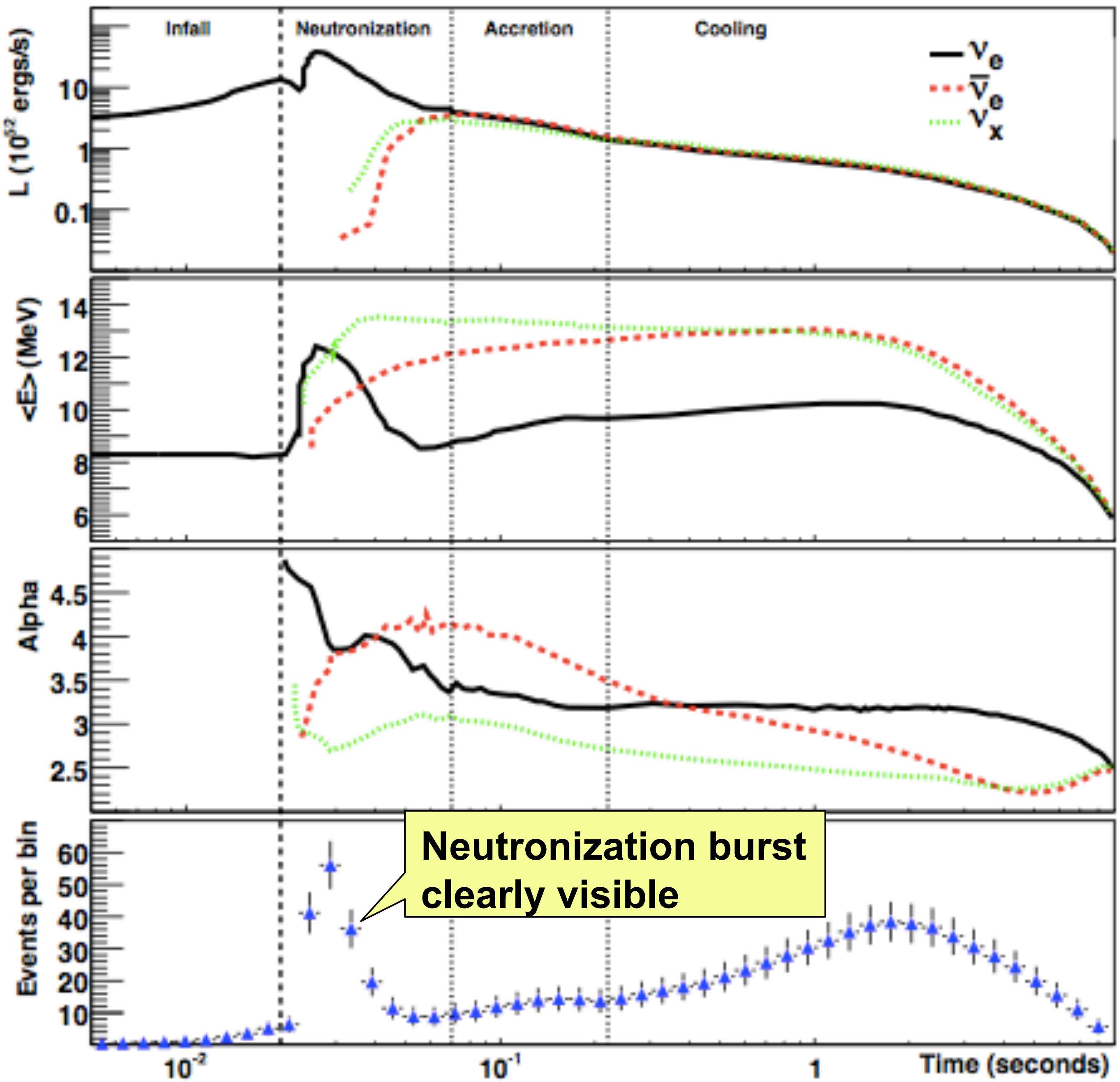


For 34 kton @ 10 kpc,
GKVM model.
ICARUS resolution

Channel	Events "Livermore" model	Events "GKVM" model
$\nu_e + ^{40}\mathrm{Ar} \rightarrow e^- + ^{40}\mathrm{K}^*$	2308	2848
$\overline{\nu}_e + ^{40}\mathrm{Ar} \rightarrow e^+ + ^{40}\mathrm{Cl}^*$	194	134
$\nu_x + e^- \rightarrow \nu_x + e^-$	296	178
Total	**2794**	**3160**

There is significant model variation

Example of supernova burst signal in 34 kton of LAr



luminosity

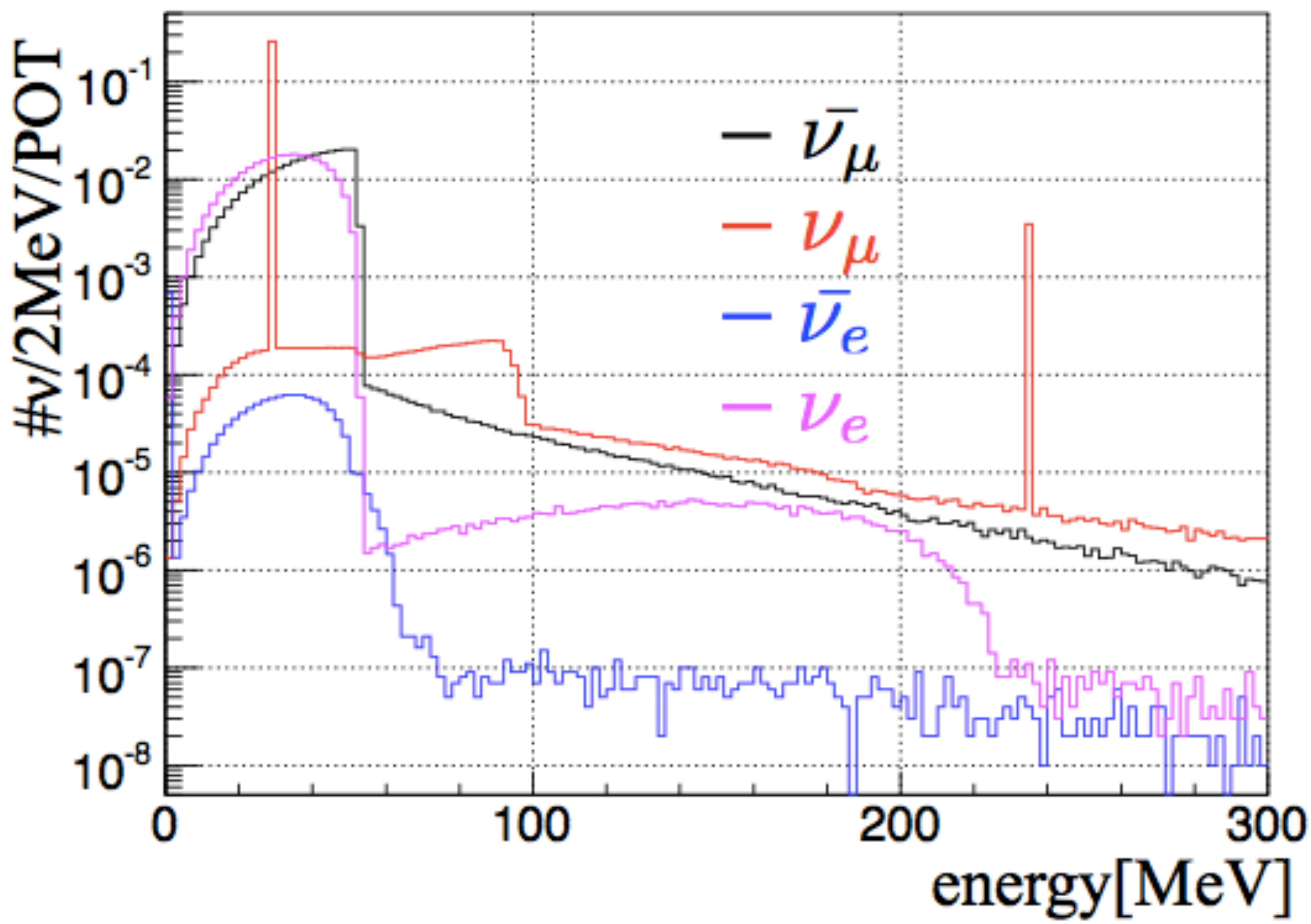
average ν energy

pinching
(large α ➔ suppressed tails)

See the ν_e light curve!

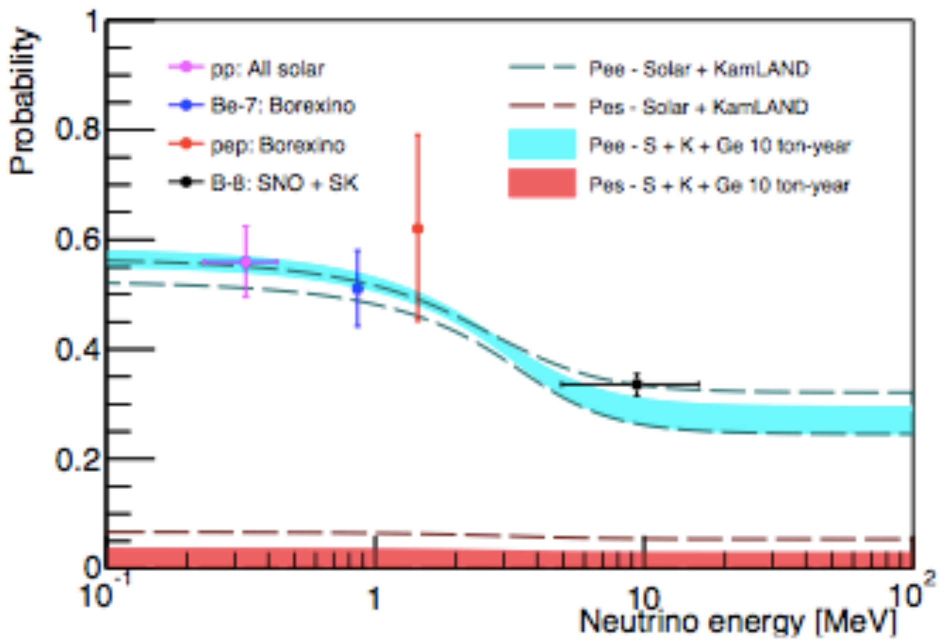
Flux from Huedepohl et al., PRL 104 (2010) 251101 ("Garching") @ 10 kpc; assuming Bueno et al. resolution

J-PARC MLF

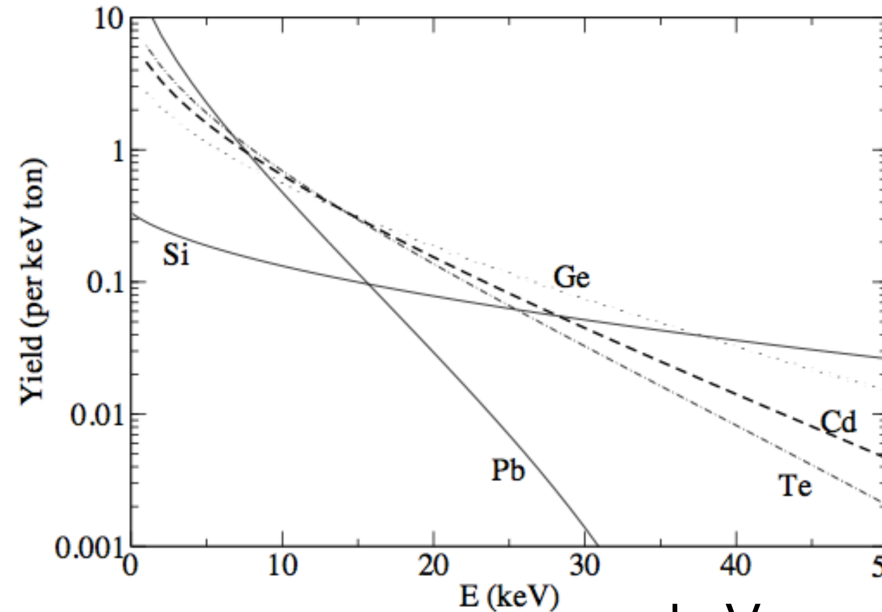


#ν/2MeV/POT
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
0
100
200
300
energy[MeV]
$\bar{\nu}_\mu$
ν_μ
$\bar{\nu}_e$
ν_e

Tonne-scale underground DM detectors can measure **solar and supernova neutrinos**



Billard et al., arXiv:1409.0050

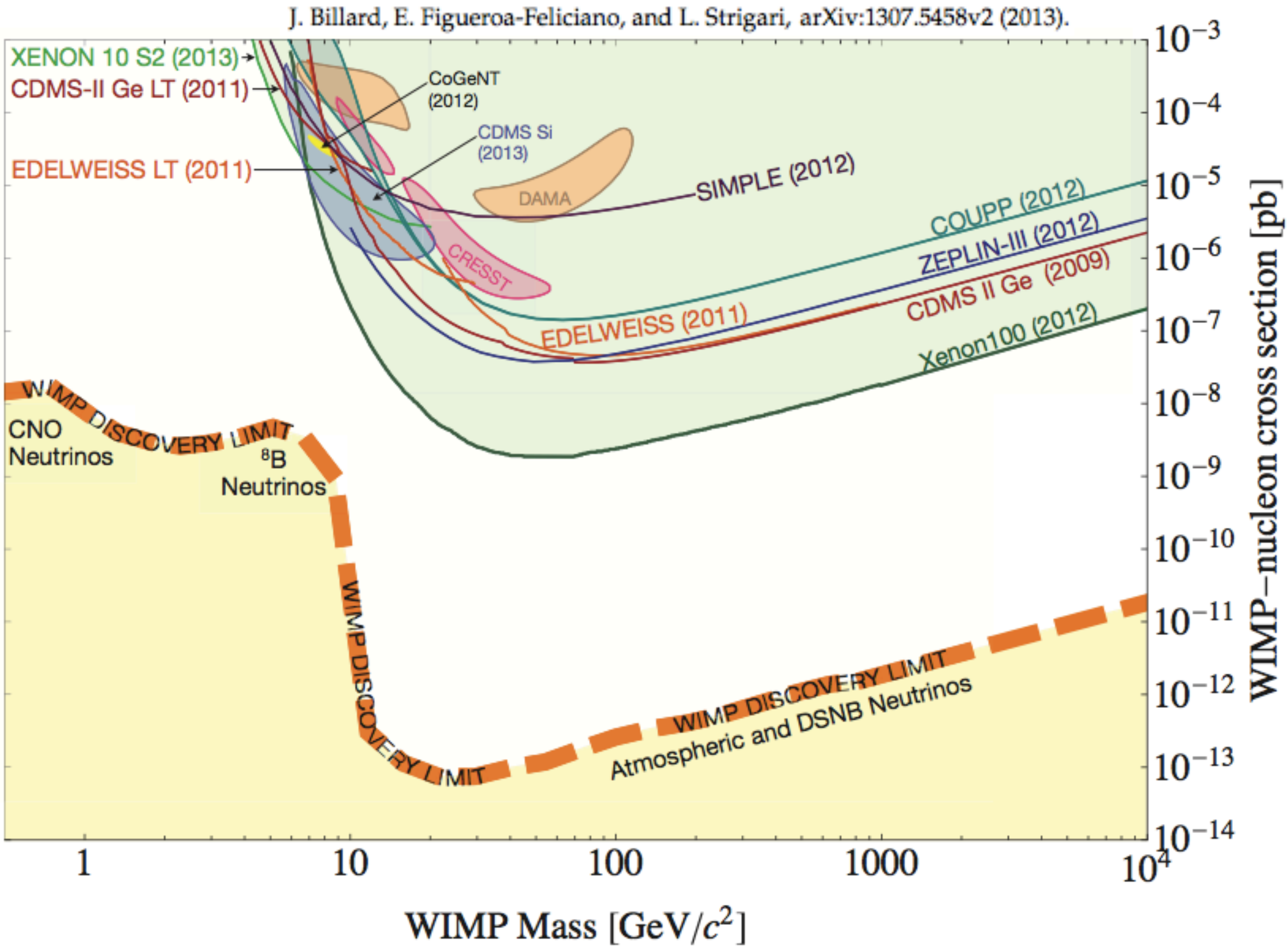


Horowitz et al., PRD68 (2003) 023005

Solar neutrinos:
rule out sterile oscillations
using CEvNS (NC)

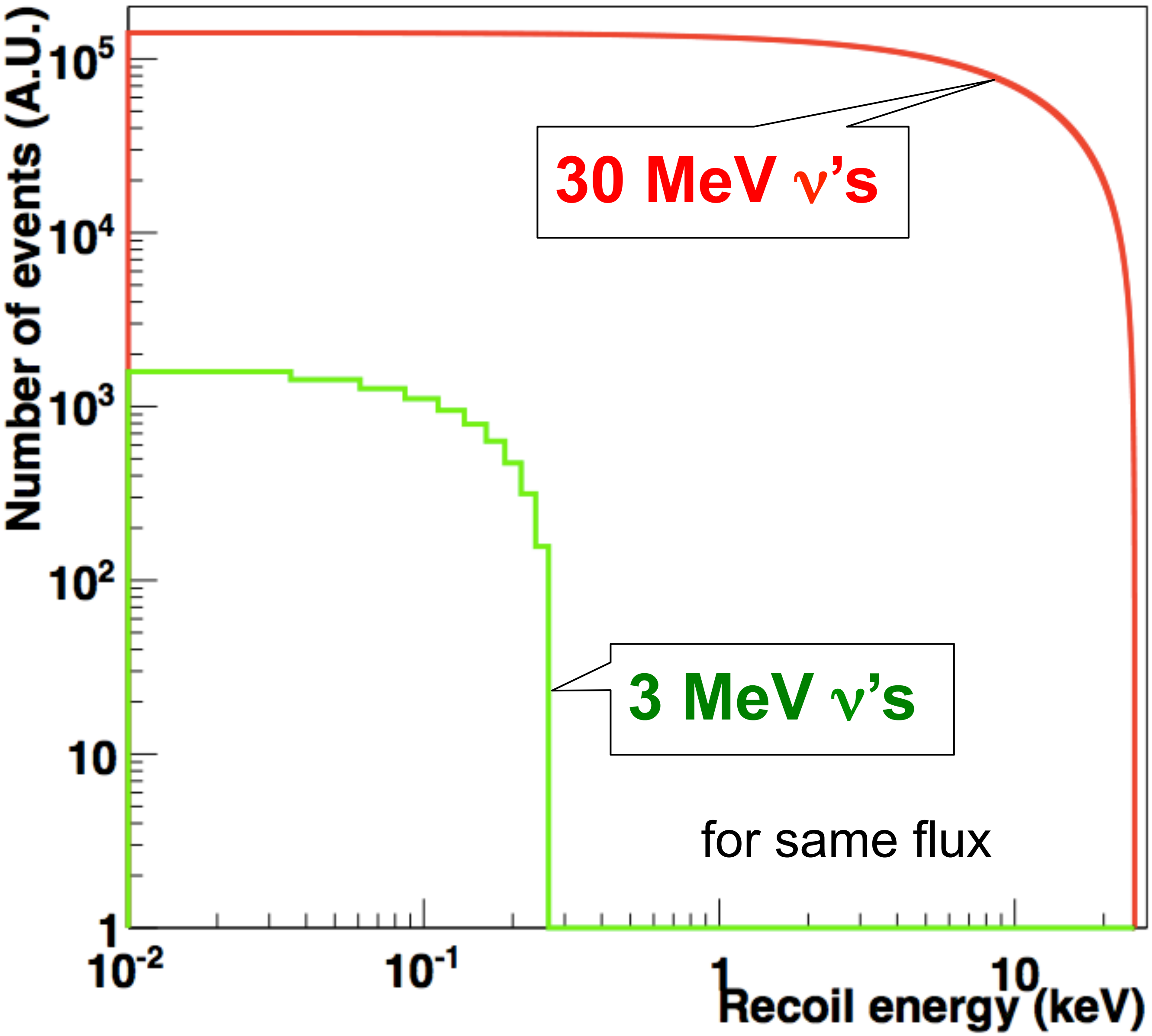
Supernova neutrinos:
~ handful of events per tonne
@ 10 kpc: sensitive to
***all flavor components** of the flux*

CEvNS from natural neutrinos creates ultimate background for direct DM search experiments



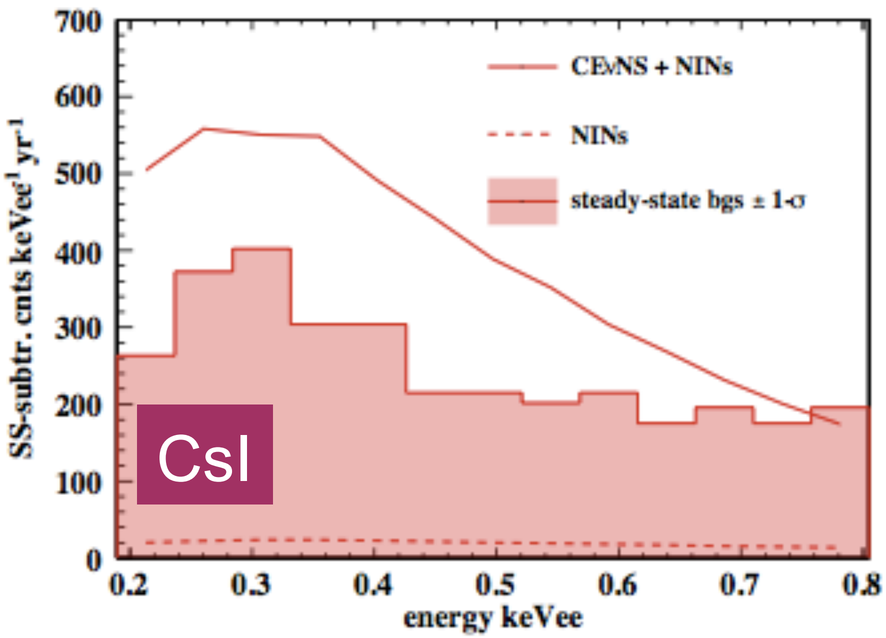
Understand nature of background (& detector response)

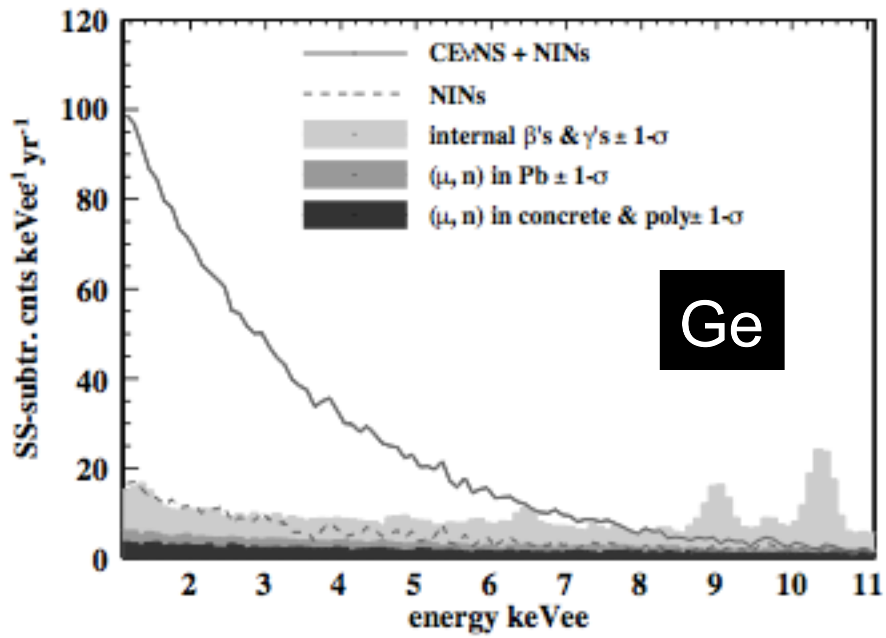
Why use the 10's of MeV neutrinos from π decay at rest?
➔higher-energy neutrinos are advantageous, because both
cross-section and maximum recoil energy increase with ν energy

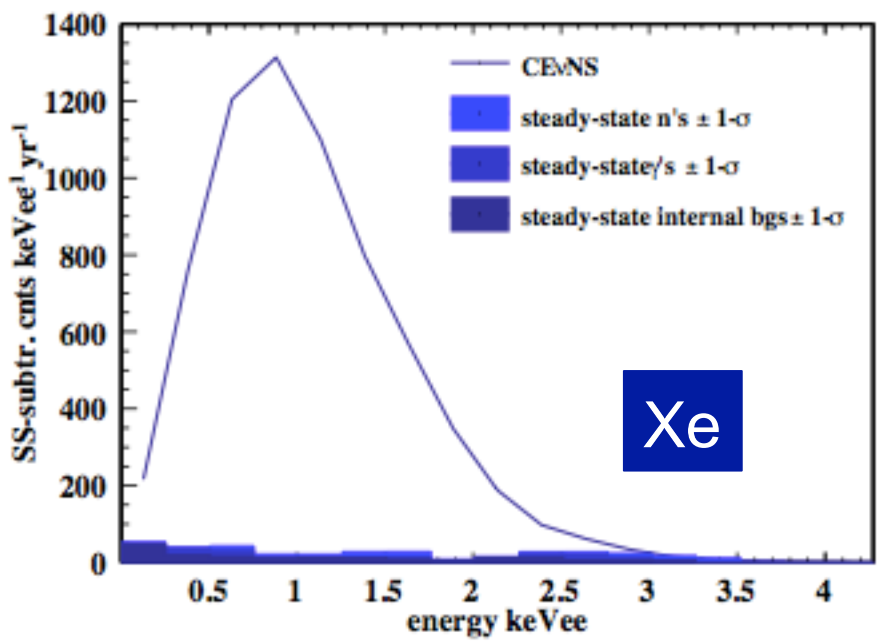


Reactor experiments (RICOCHET, CONNIE, COGeNT etc.) can take advantage of very large flux (~factor of 10^4) but require very low energy thresholds, where background can be daunting; radioactive source experiments require even lower thresholds

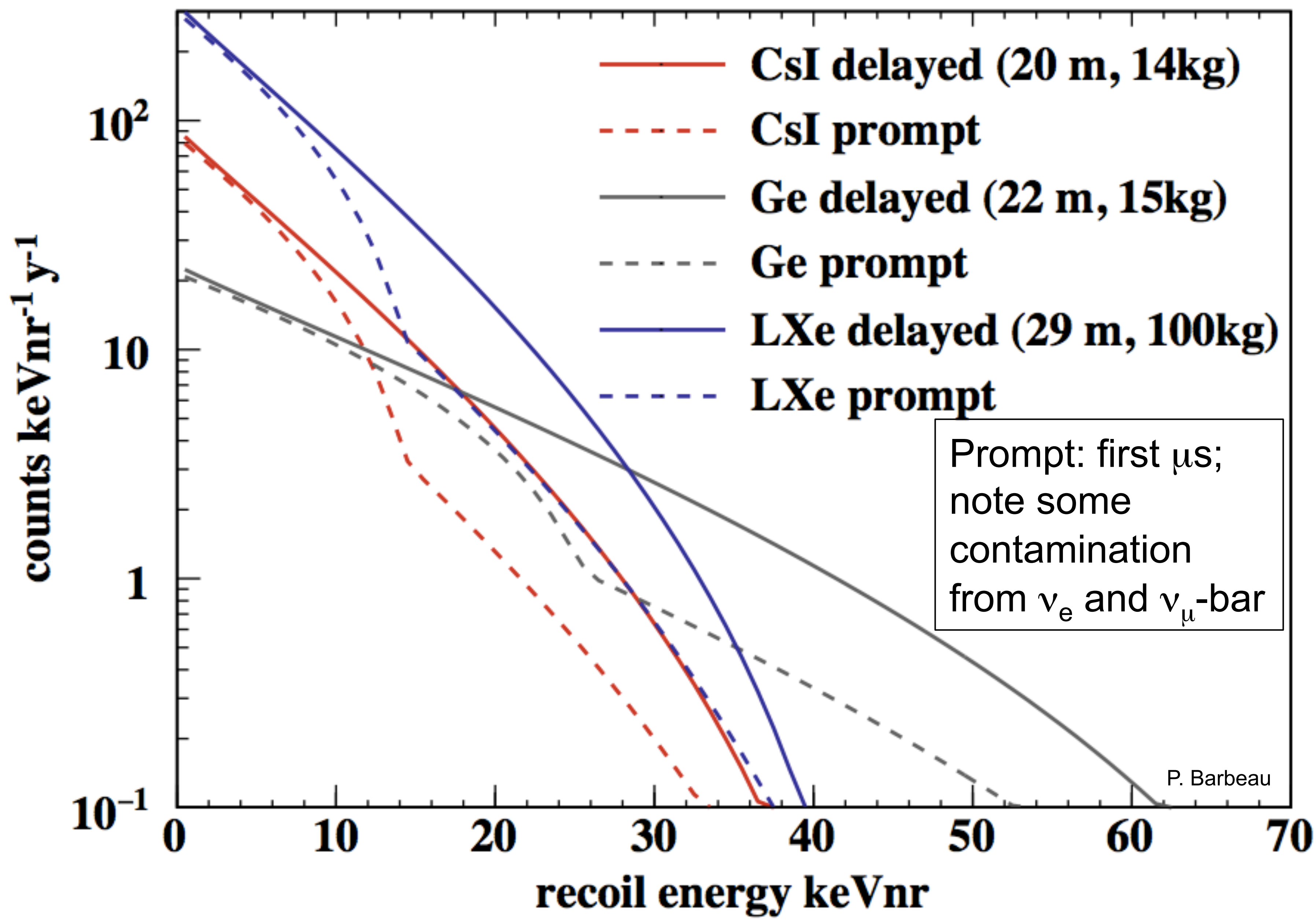
Realistic steady-state-bg-subtracted recoil spectra (keVee) compared to 1σ background fluctuations





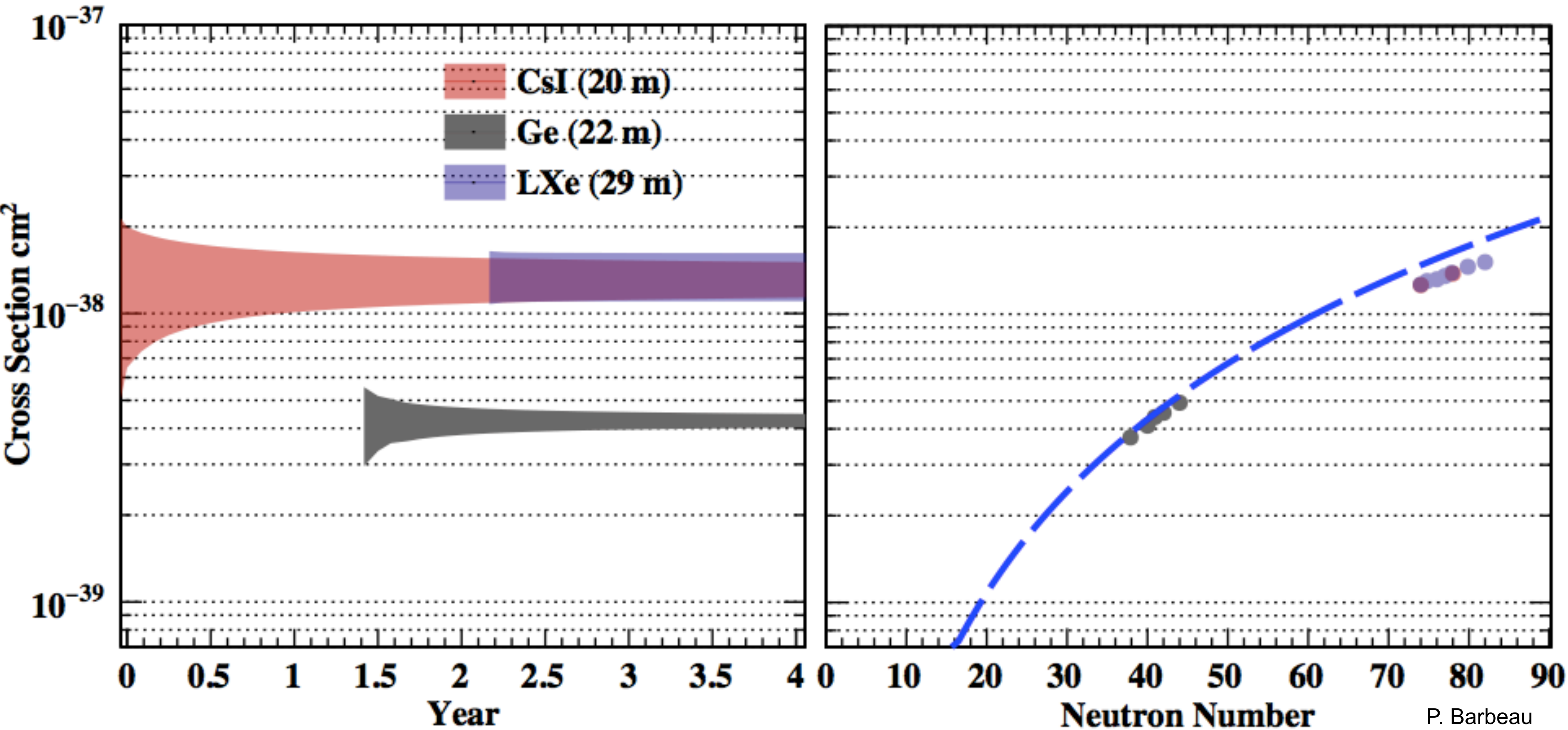


CEvNS recoil rates in the three subsystems



Expected precision on CEvNS N^2 xscn measurement vs time

N^2 dependence of the x-scn



P. Barbeau

Systematically dominated primarily due to uncertainty on quenching factors @ threshold: Ge: 2%; CsI[Na]: 7%; LXe: 13% (see G. Rich talk on QF)