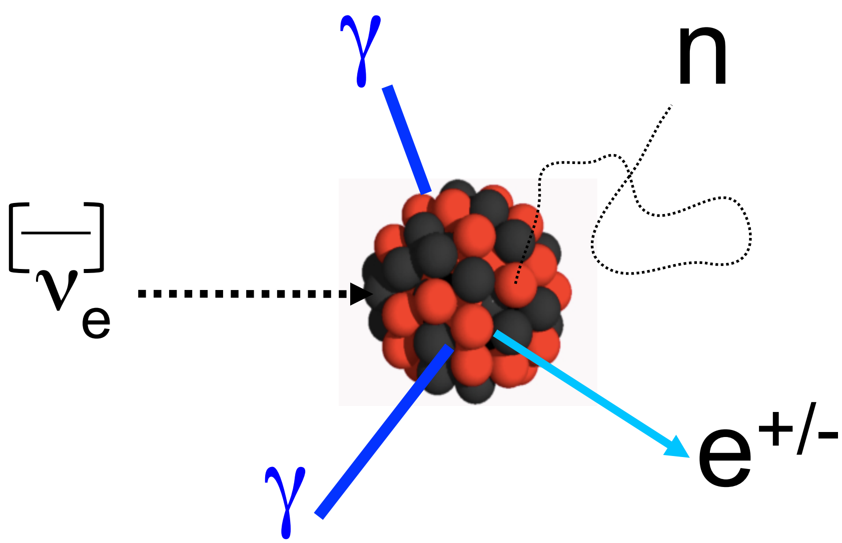
Low-Energy Neutrino Scattering



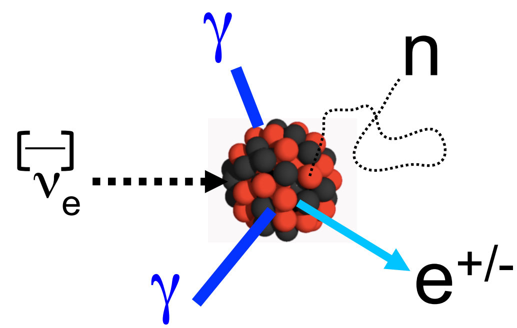
Kate Scholberg

Fundamental Symmetries Town Hall meeting

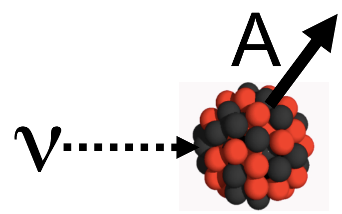
September 28, 2014

I will cover:

Neutrino-nucleus cross sections
in the few ten of MeV range
(relevant for supernova-neutrino physics)



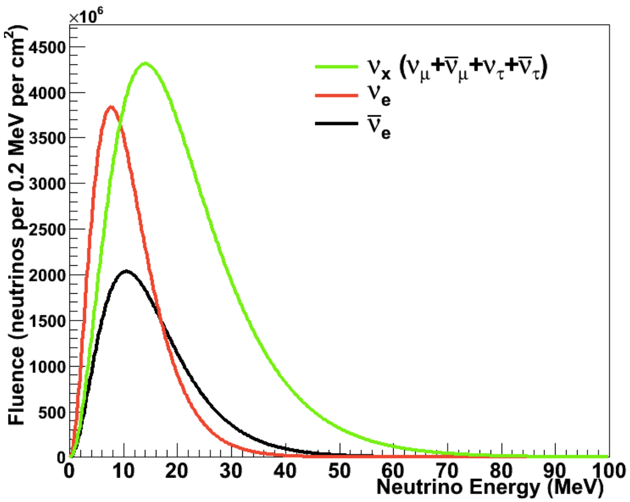
Coherent elastic
neutrino-nucleus scattering



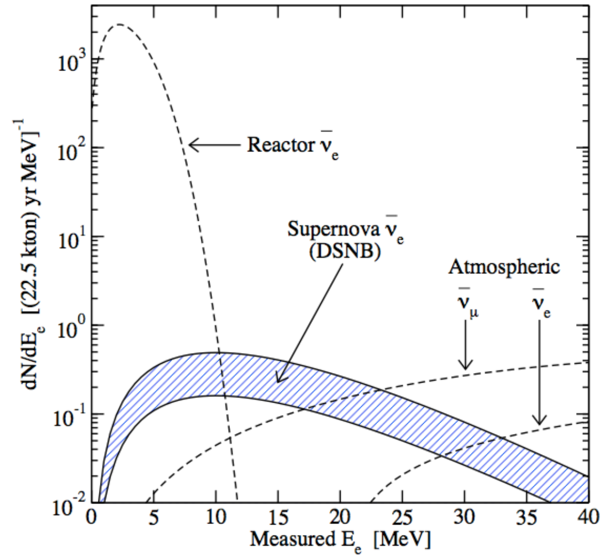
Prospects for measurements

The COHERENT Collaboration	COHERENT at the Spallation Neutron Source
The MINERvA and CAPTAIN Collaborations	MINERvA and CAPTAIN: Probing the Nucleus with Neutrino Scattering
A. Hime, R. Tayloe, and J. Yoo	Measuring Coherent Elastic Neutrino Nucleus Scattering at an Off-Axis High-Energy Neutrino Beam Target

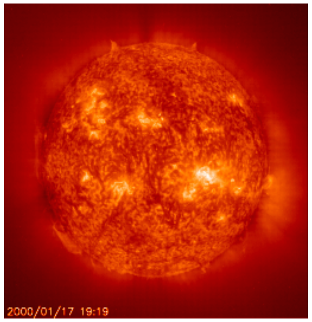
Neutrino interactions in the few-100 MeV range are relevant for:

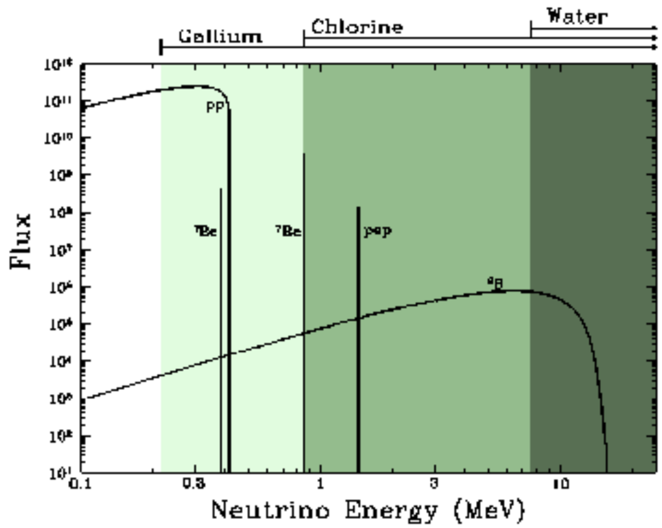


supernova neutrinos, burst & relic

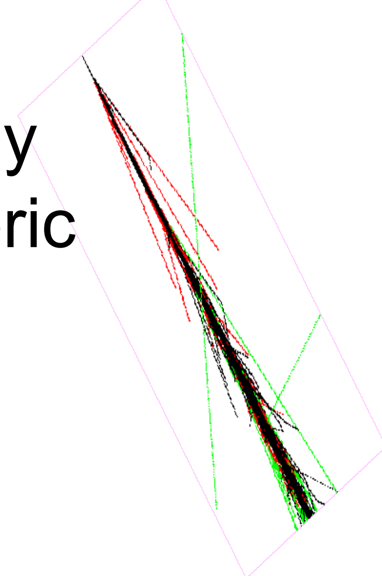


solar neutrinos



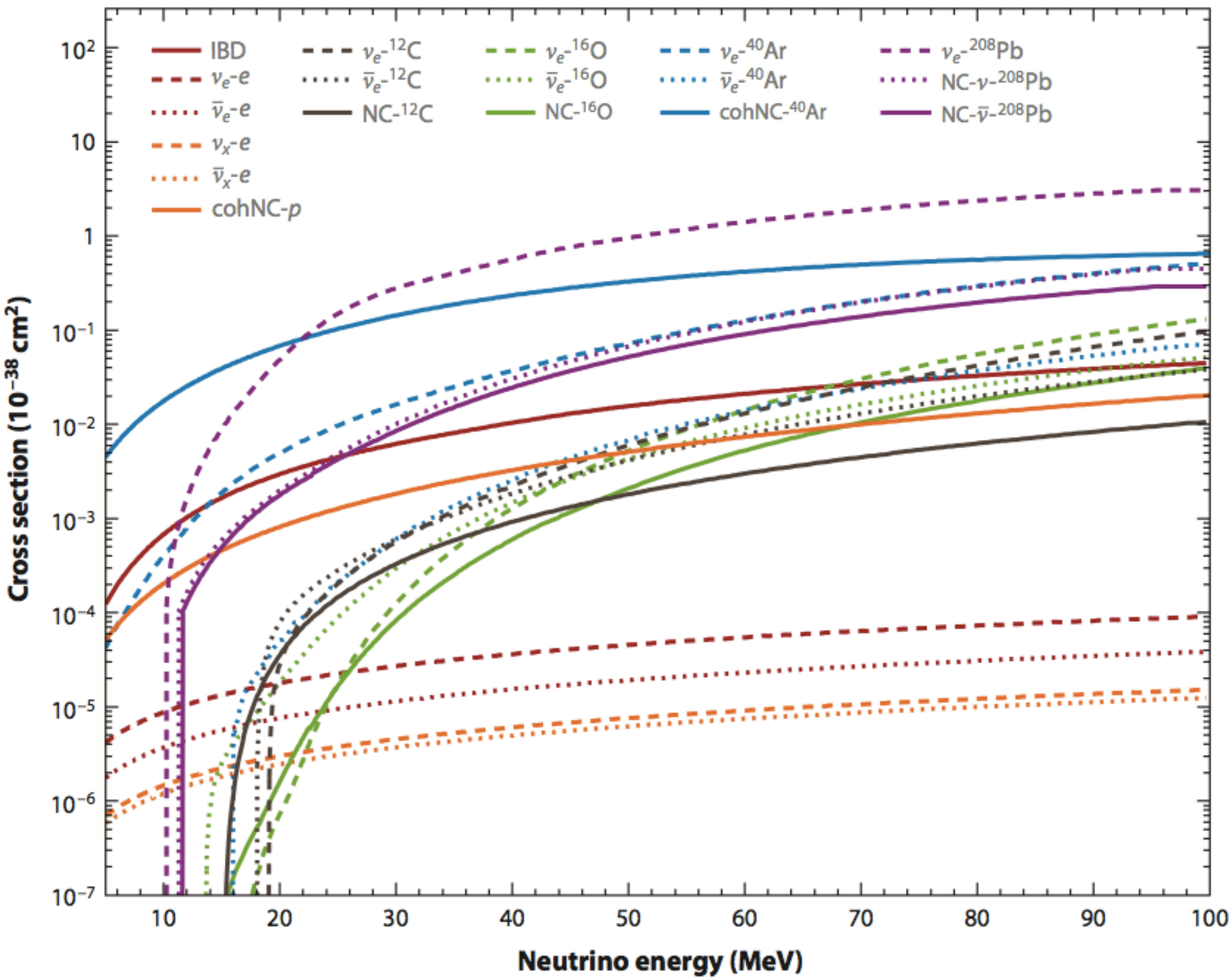


low-energy atmospheric neutrinos



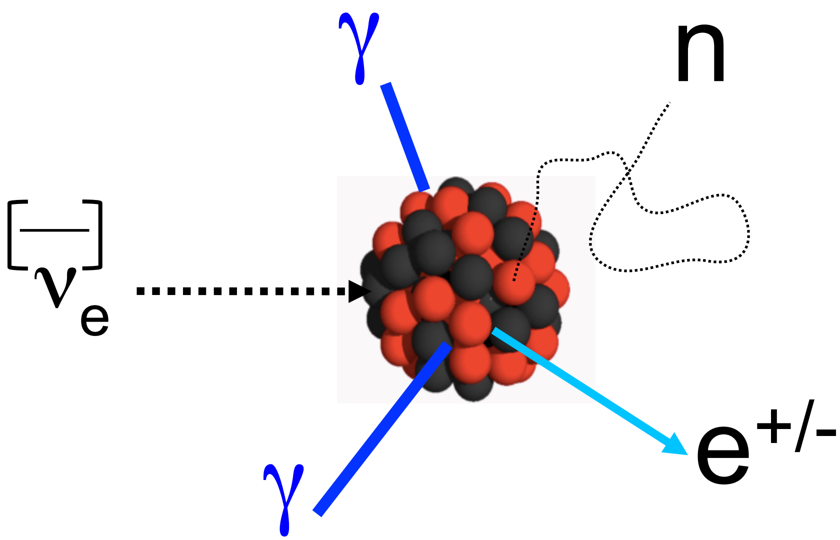
Physics: oscillation, SM tests, astrophysics

Cross-sections in this energy range



IBD and ES on electrons well understood... but so far only ^{12}C is the *only* heavy nucleus with ν interaction cross sections well (~10%) measured in the tens of MeV regime

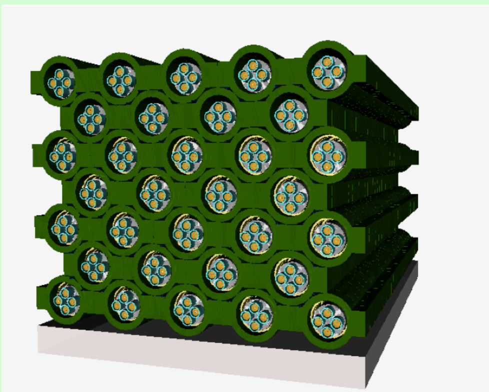
Both the cross sections *and* the distribution of observable products matter experimentally...



....understanding of nuclear physics is critical!

Relevant current examples for SN neutrino detection:

Lead



HALO
at
SNOLAB

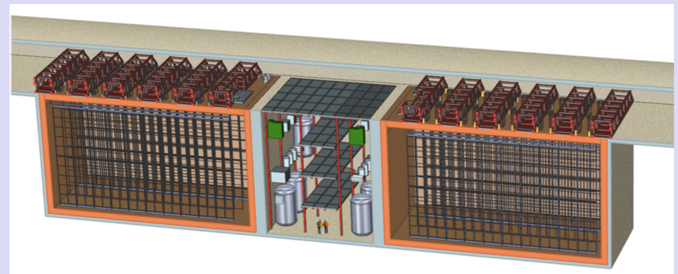
$\nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{208}\mathrm{Bi}^* + e^-$

↘ 1n, 2n emission

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

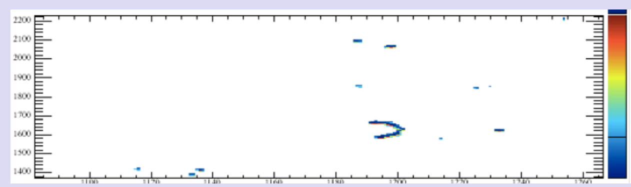
↘ 1n, 2n, γ emission

Argon



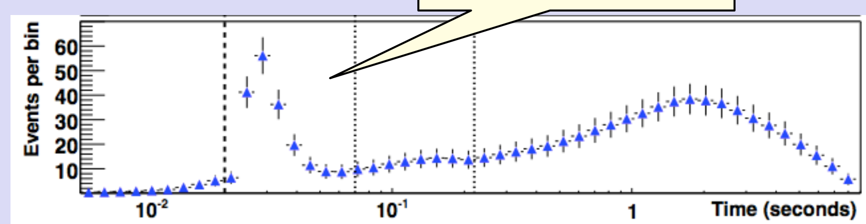
LBNE

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

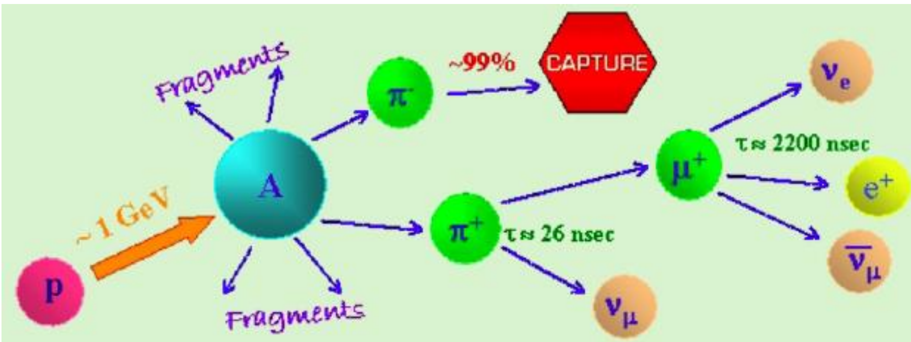


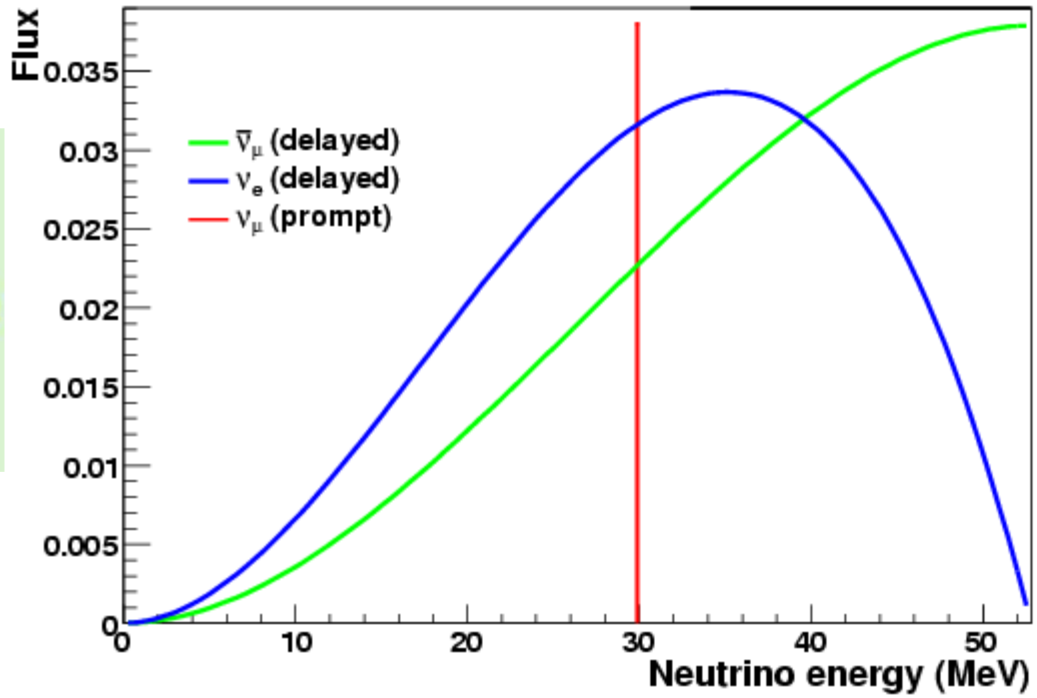
electron
+ γ's

Neutronization
burst visible



Stopped-Pion (DAR) Neutrinos





$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

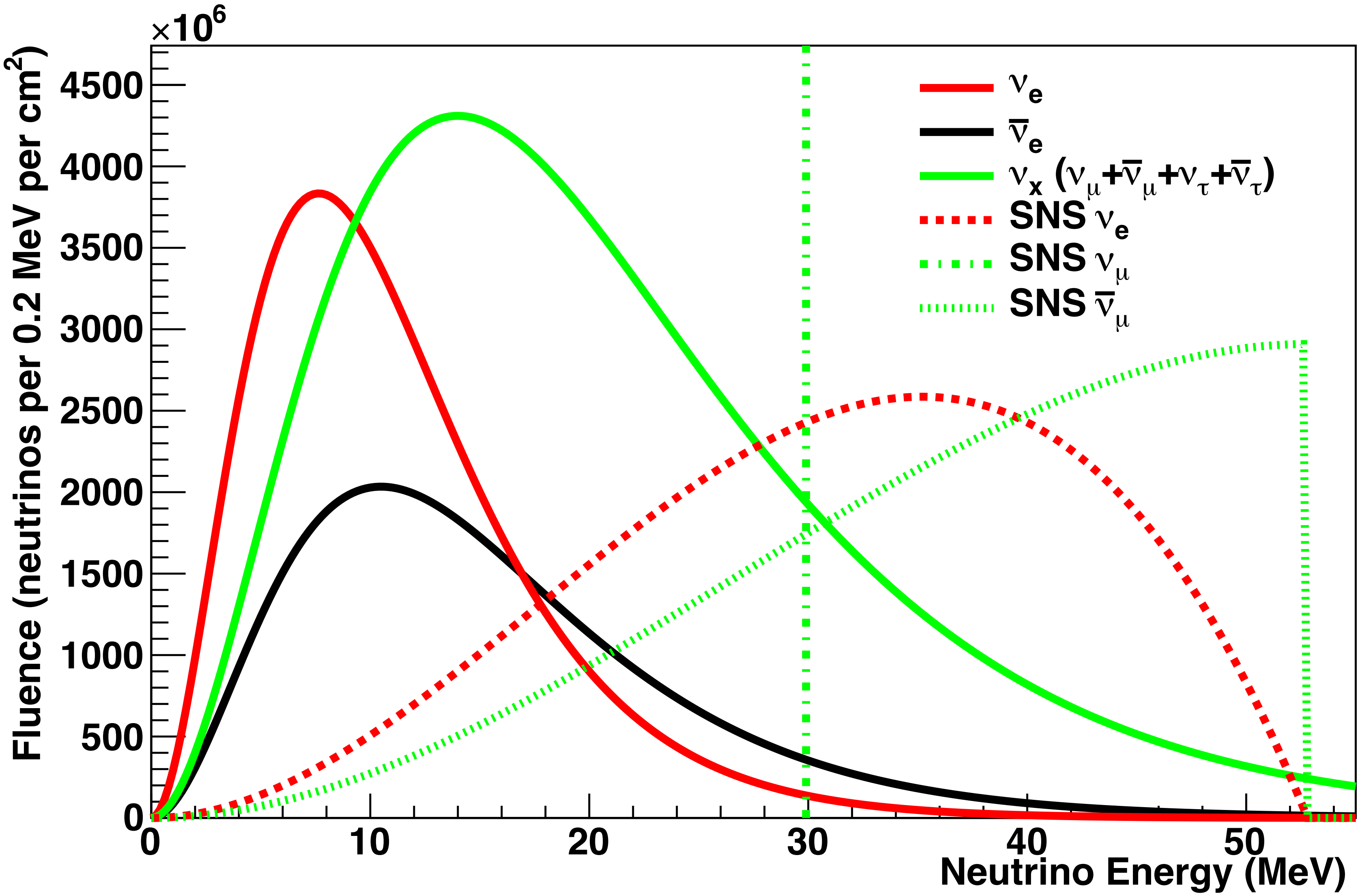
2-body decay: monochromatic 29.9 MeV ν_μ
PROMPT

$$\downarrow$$

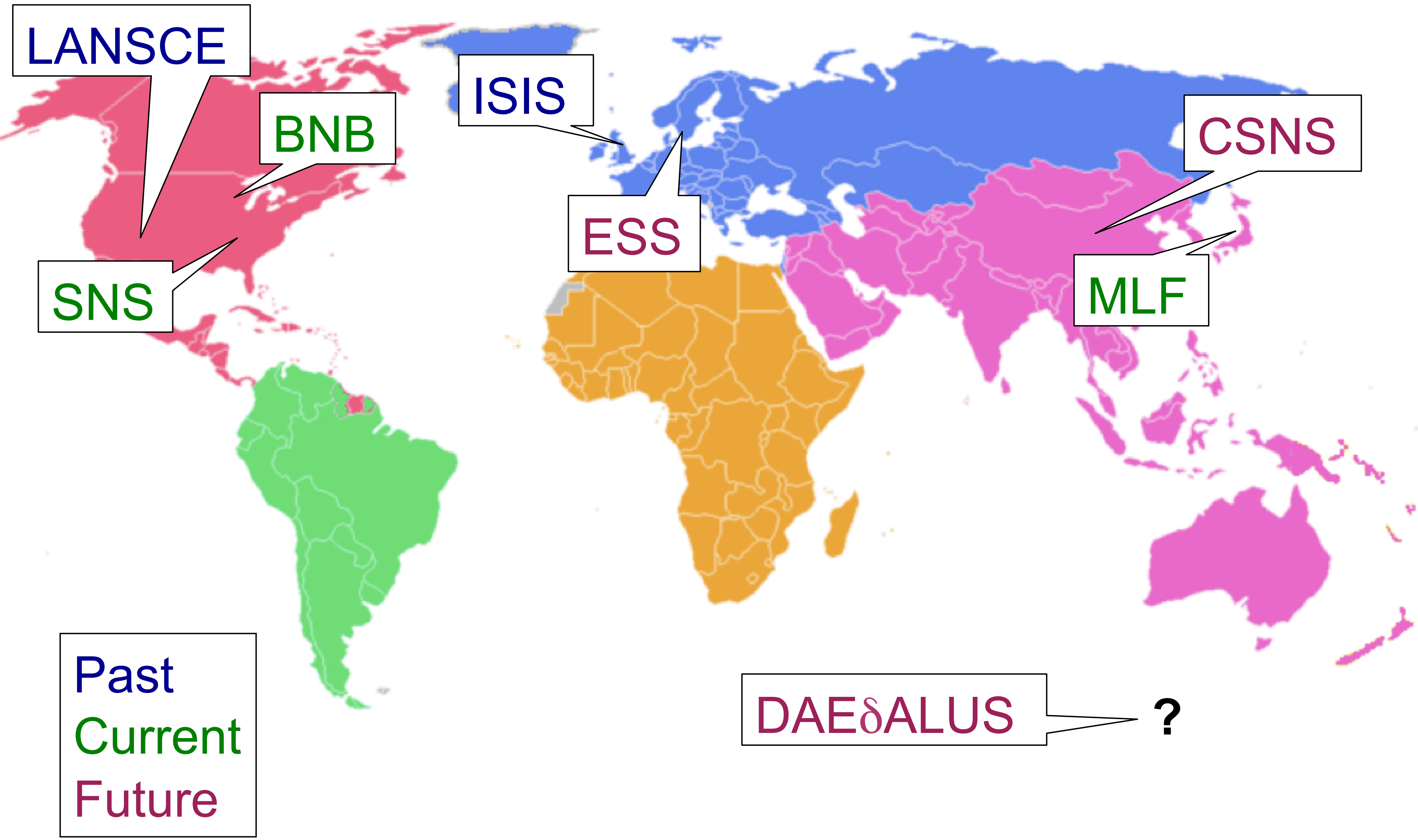
$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

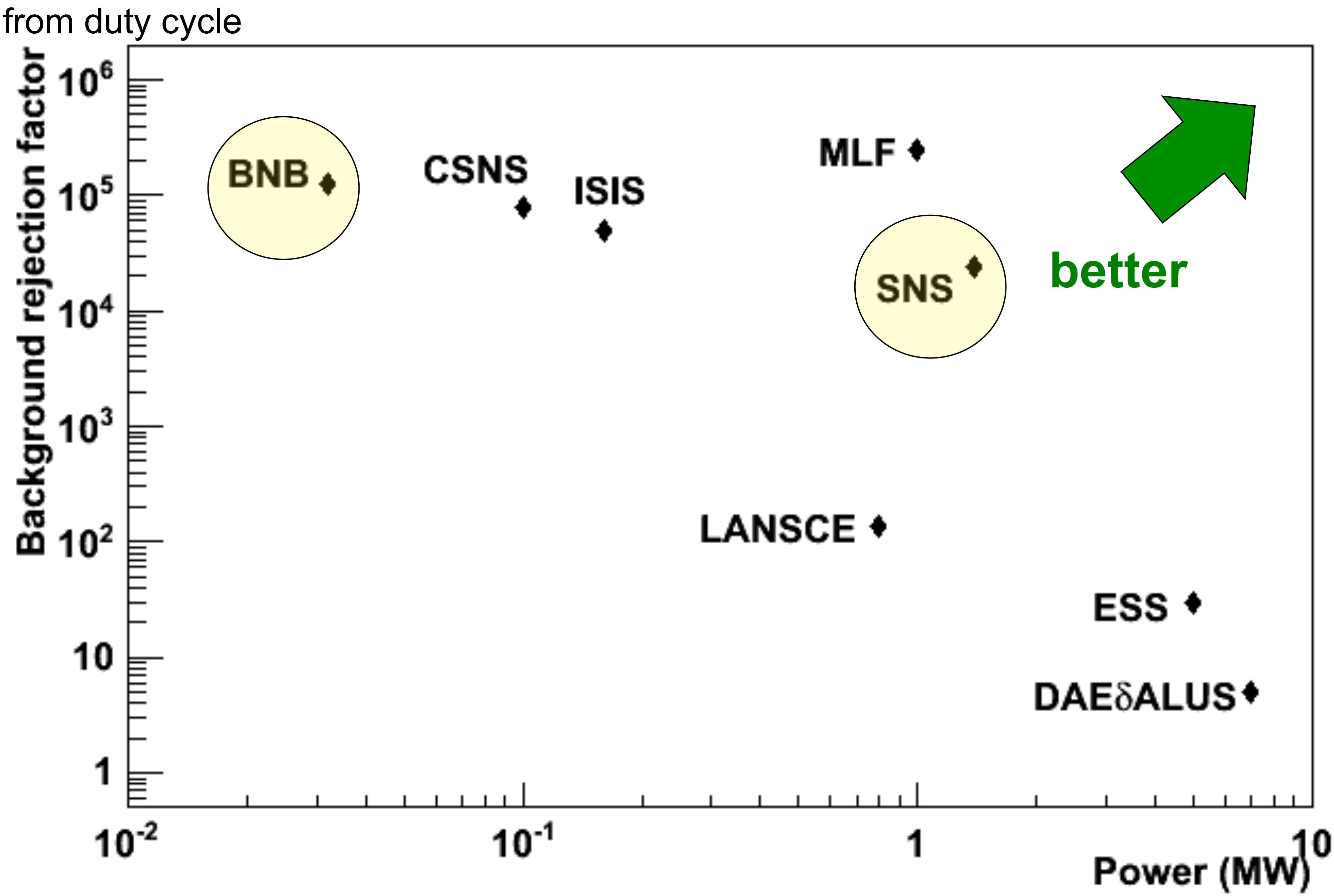
3-body decay: range of energies between 0 and $m_\mu/2$
DELAYED (2.2 μs)

Supernova neutrino spectrum overlaps very nicely with stopped π neutrino spectrum



Stopped-Pion Sources Worldwide

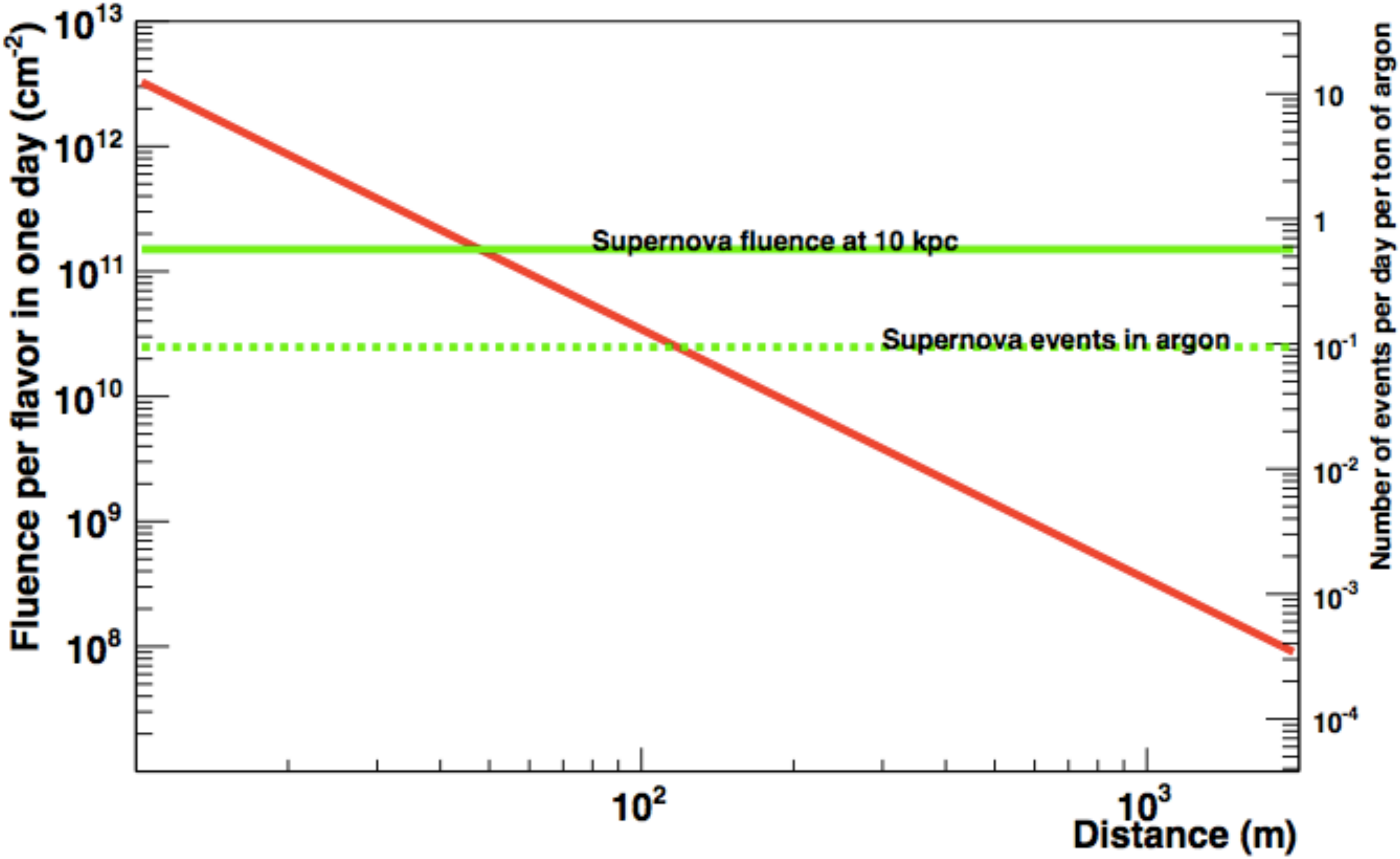




from duty cycle
Background rejection factor
10^6
10^5
10^4
10^3
10^2
10
1
BNB
CSNS
ISIS
MLF
SNS
better
LANSCE
ESS
DAEδALUS
10^-2
10^-1
1
10
Power (MW)

Spallation Neutron Source at ORNL

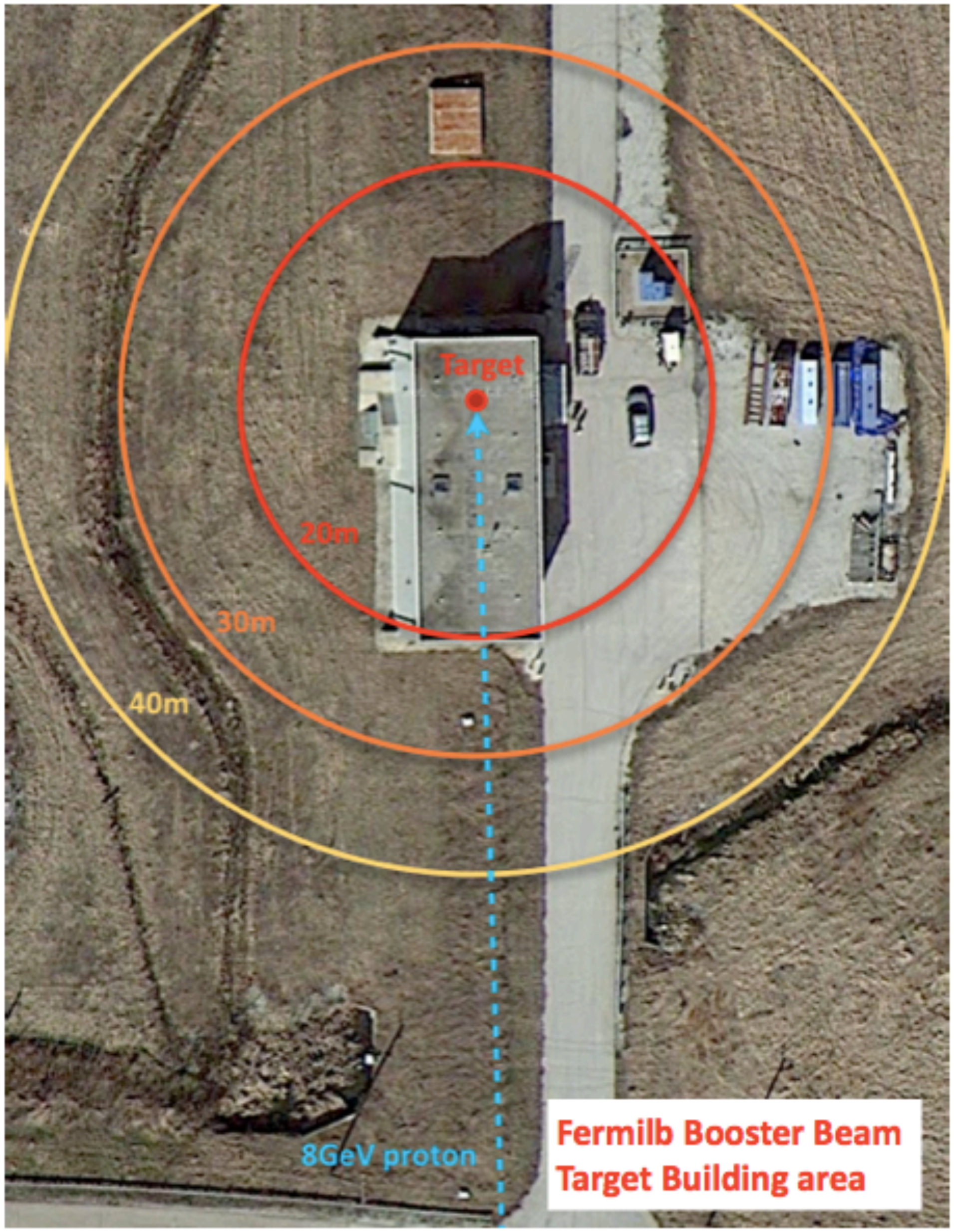
Fluence at ~50 m from the stopped pion source amounts to ~ a supernova a day!

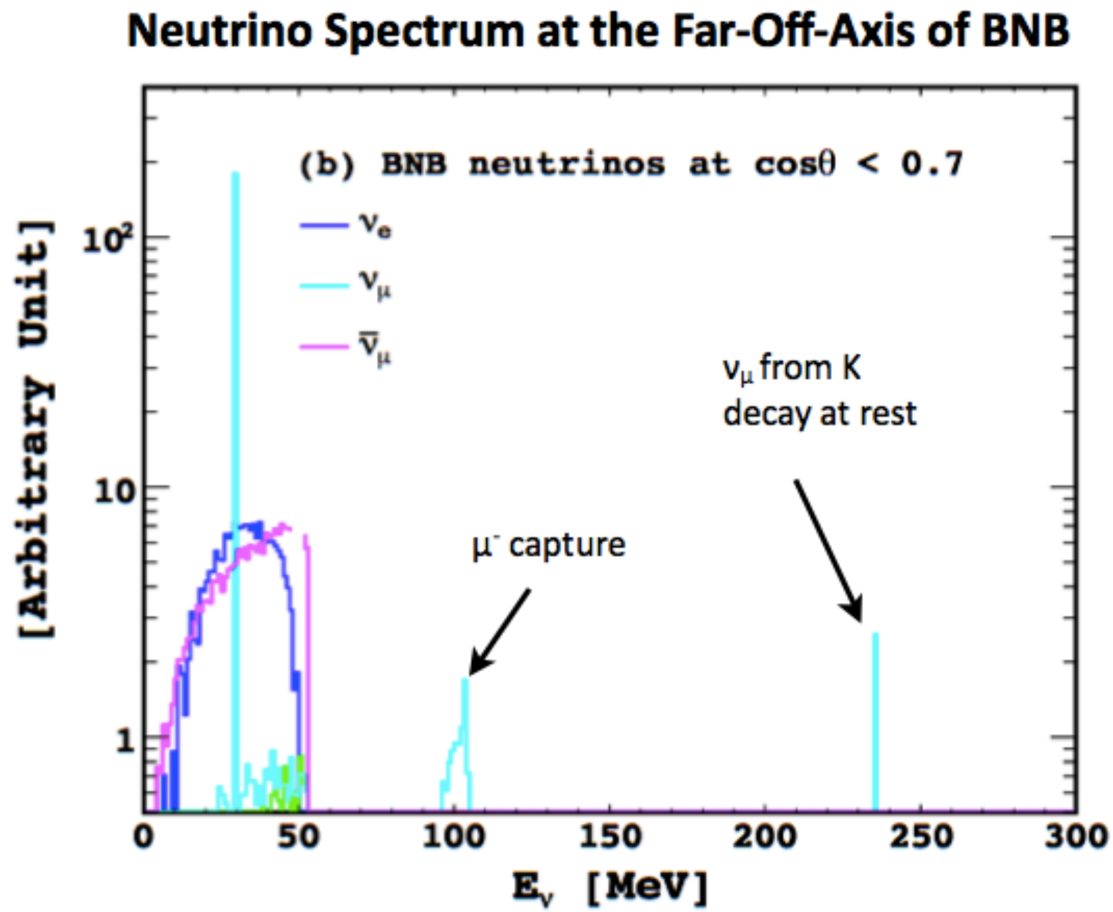


Another possibility: very far off axis at the FNAL BNB

Neutrino Energy Spectrum and Flux

J. Yoo

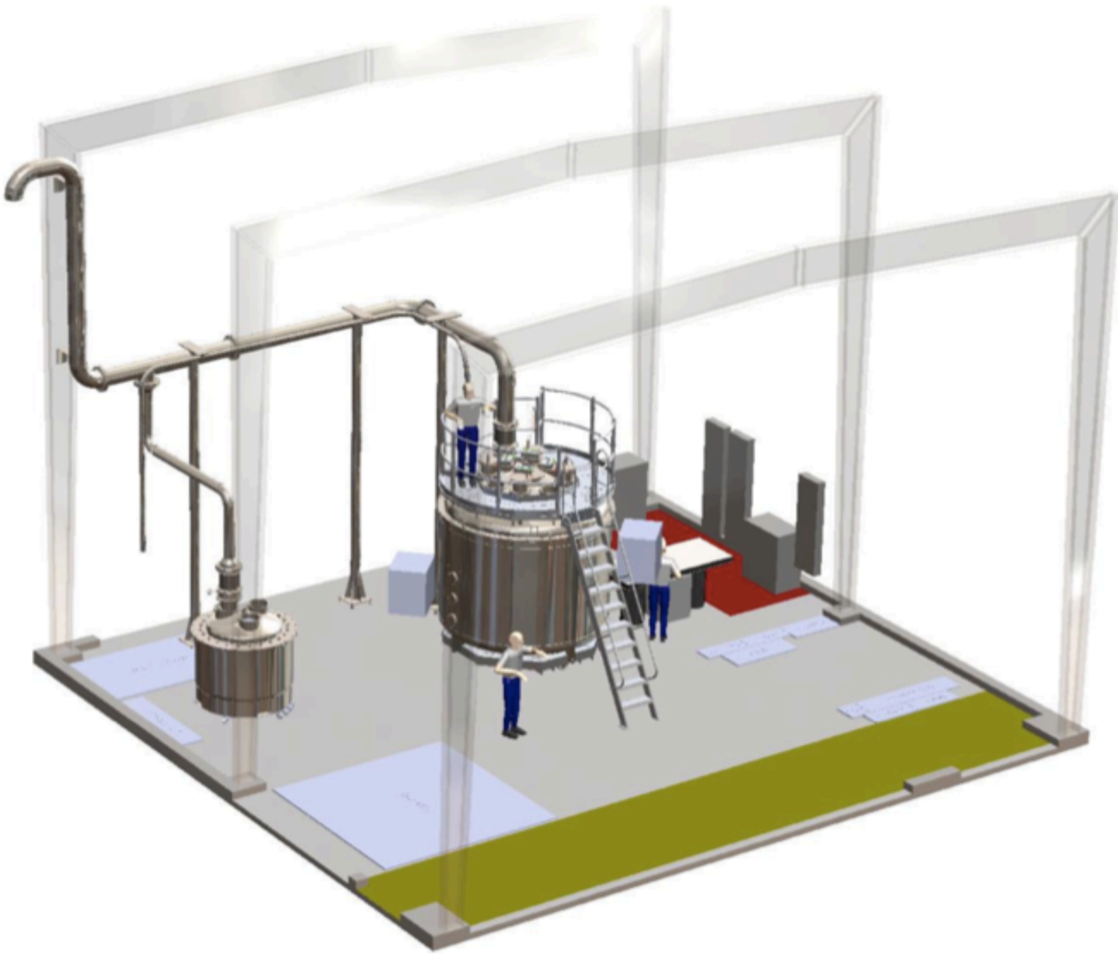




- Dominant neutrino production process at the far-off-axis is **pion decay at rest**
- **ϕ(BNB) ≅ 5x10^5 ν/cm^2/s per flavor @20m from the target**

CAPTAIN

CRYOGENIC APPARATUS FOR PRECISION TESTS OF ARGON INTERACTIONS WITH NEUTRINOS



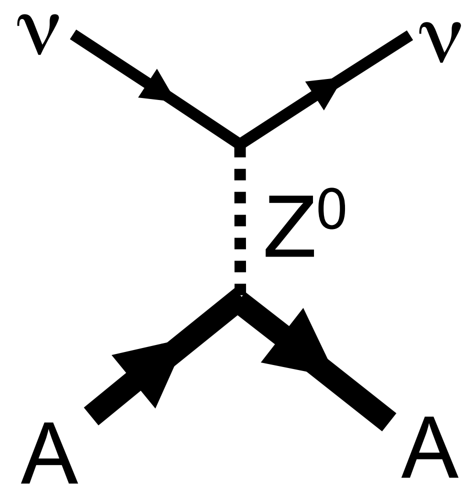
Small, portable LAr TPC (LBNE R&D)

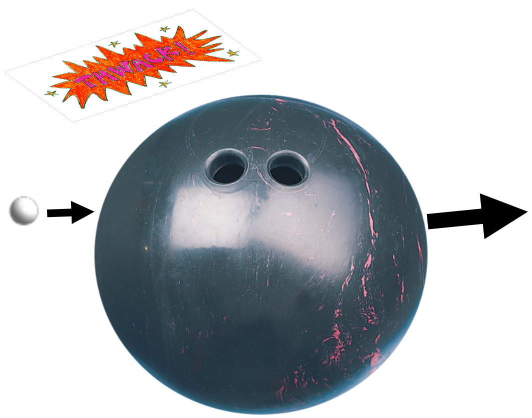
- neutrons
- high-energy neutrinos (NuMI)
- low-energy neutrinos (BNB, possibly SNS)

Another process: Coherent neutral current neutrino-nucleus elastic scattering

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

A neutrino smacks a nucleus via exchange of a Z, and the nucleus recoils

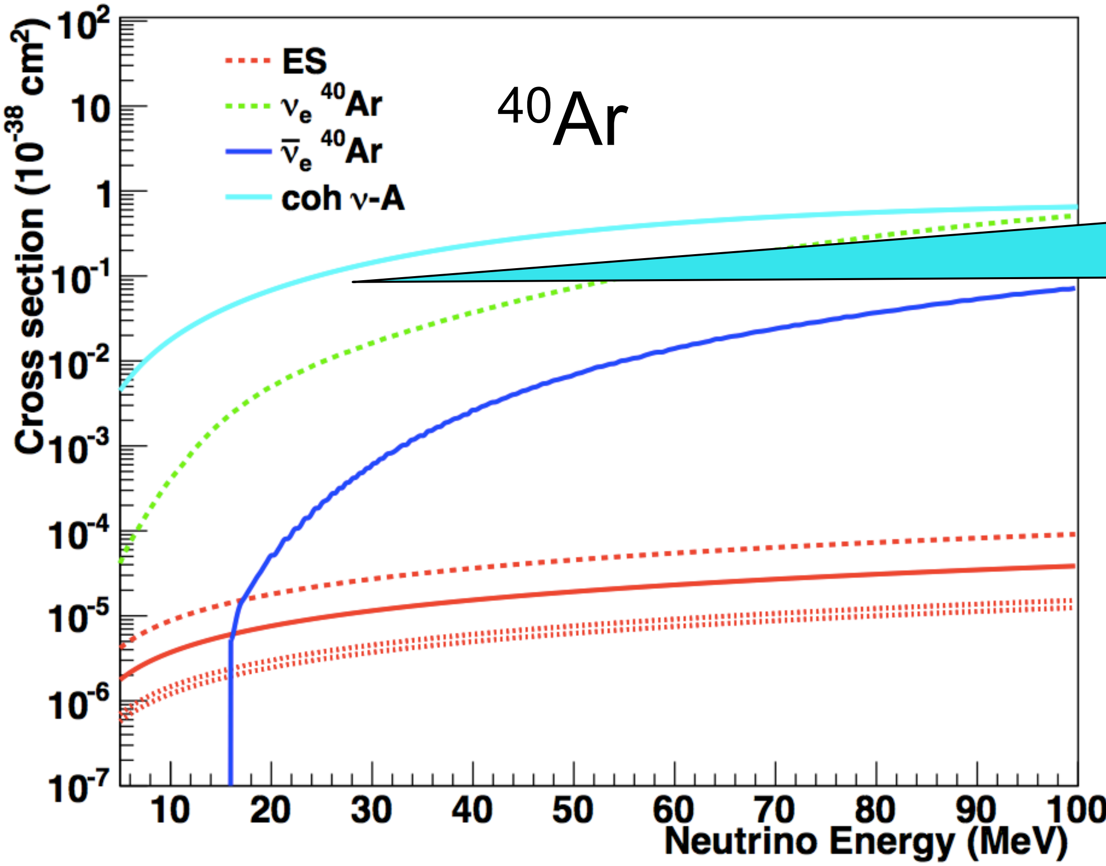




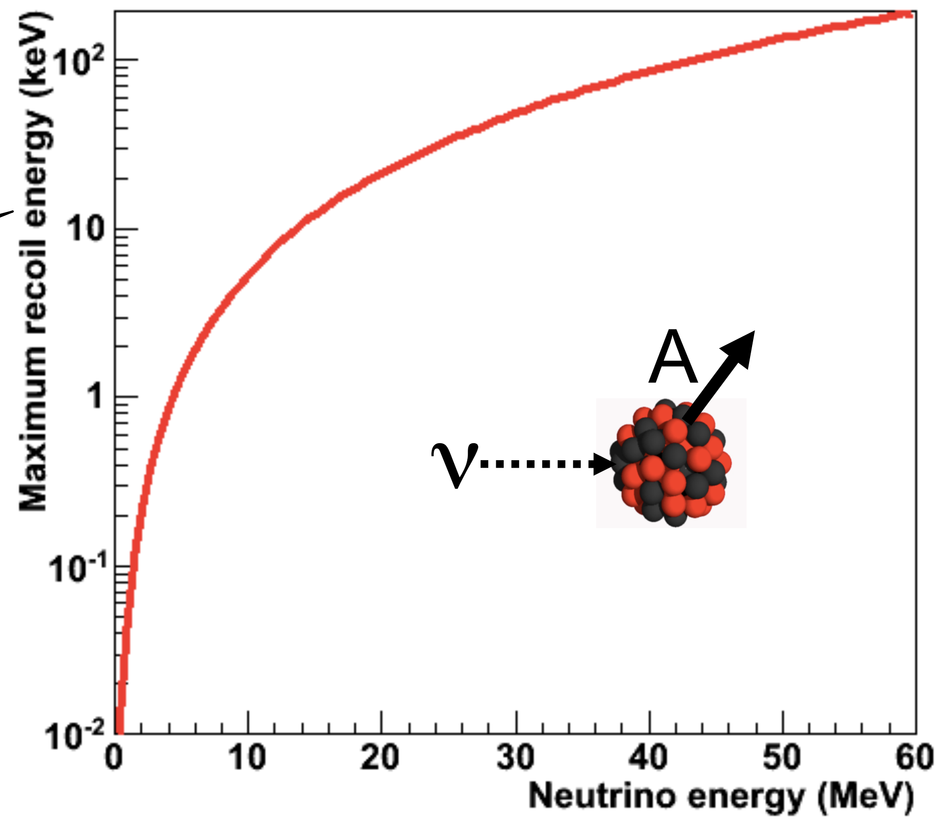
- Coherent up to $E_\nu \sim 50$ MeV
- Important in SN processes & detection
- Well-calculable cross-section in SM
- Possible applications (reactor monitoring)

A. Drukier & L. Stodolsky, PRD 30:2295 (1984)
Horowitz et al. , PRD 68:023005 (2003) astro-ph/0302071

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



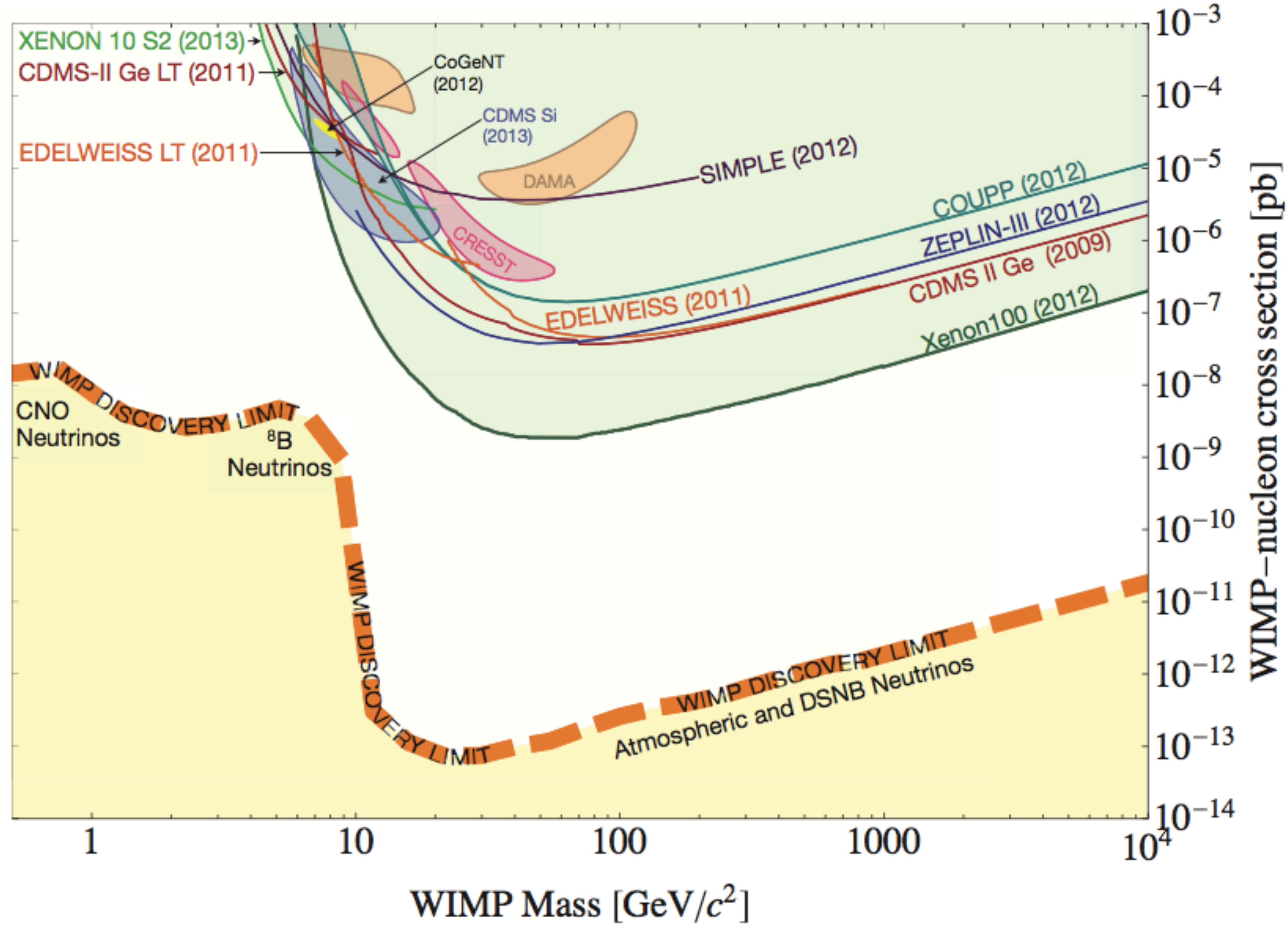
very large CENNS cross section



but only tiny recoil energies

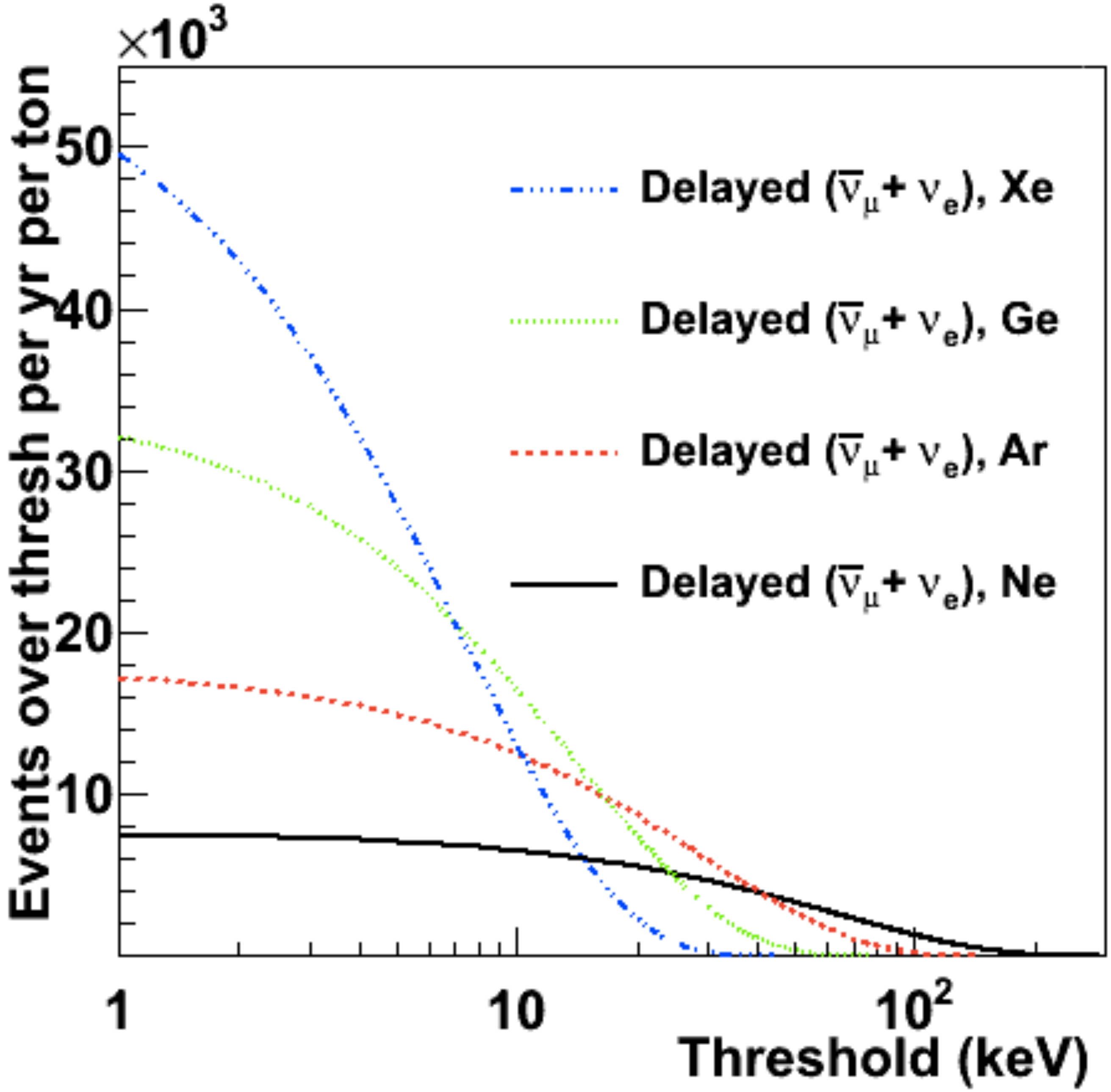
Never before observed...
but now within reach with
WIMP detection technology
 + reactors or stopped-π sources

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



J. Billard, E. Figueroa-Feliciano, and L. Strigari, arXiv:1307.5458v2 (2013).

Integrated SNS CENNS yield for various targets



20 m

Lighter nucleus
⇒ expect fewer interactions, but more at higher energy

Many possible detector technologies

Physics reach for CENNS experiments

Basically, any deviation from SM x-scn is interesting...

- **Standard Model weak mixing angle:**
  could measure to ~5% (new channel)
- **Non Standard Interactions (NSI) of neutrinos:**
  could significantly improve constraints
- **(Neutrino magnetic moment):**
  hard, but conceivable; need low energy sensitivity
- **(Sterile oscillations):**
  hard, but also conceivable

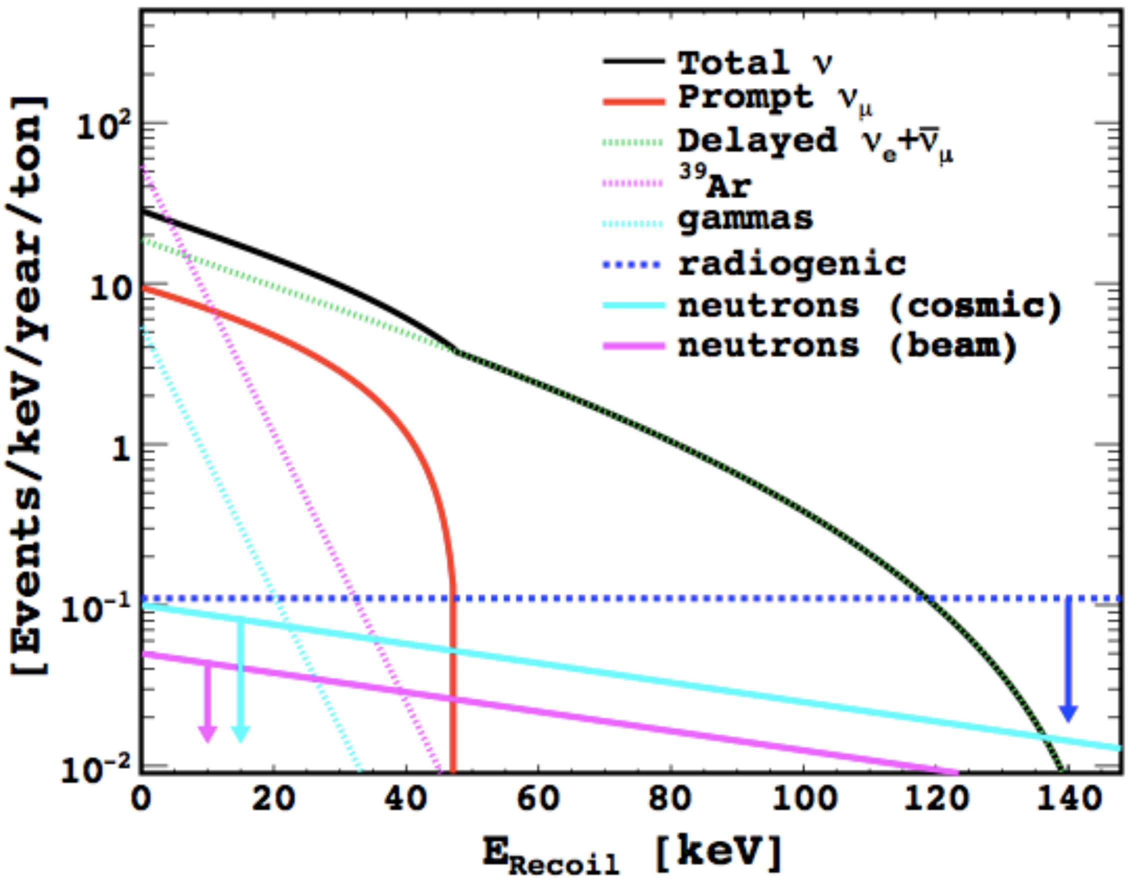
At a level of experimental precision better than that on the nuclear form factors:

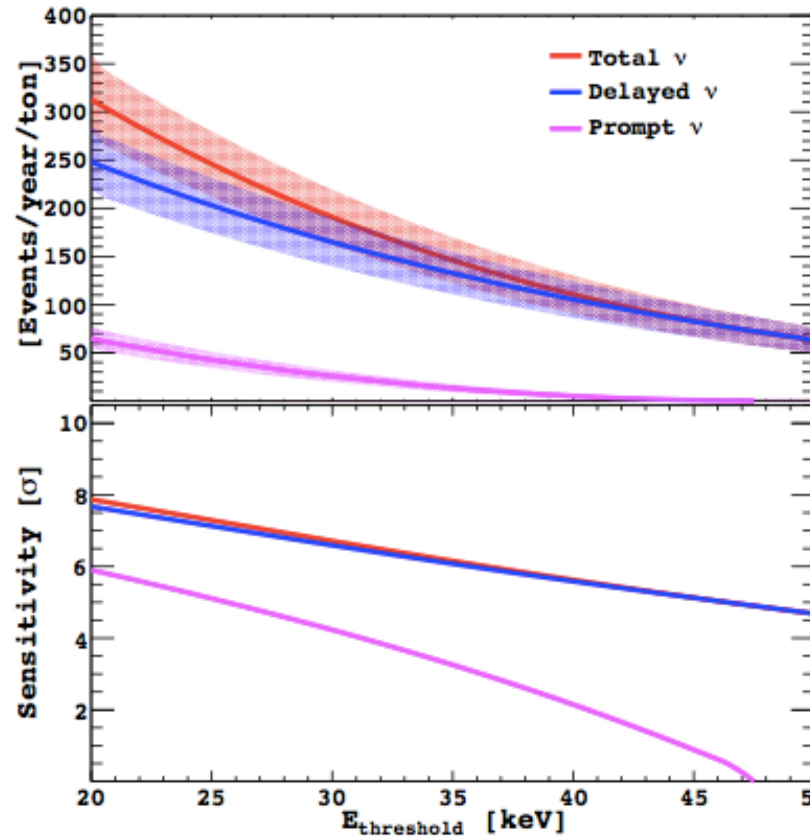
- **Neutron form factor:**
  hard but conceivable; need good energy resolution,
  control of systematics

Coherent Elastic Neutrino Nucleus Scattering (@Fermilab)

Sensitivity for Discovery

J. Yoo





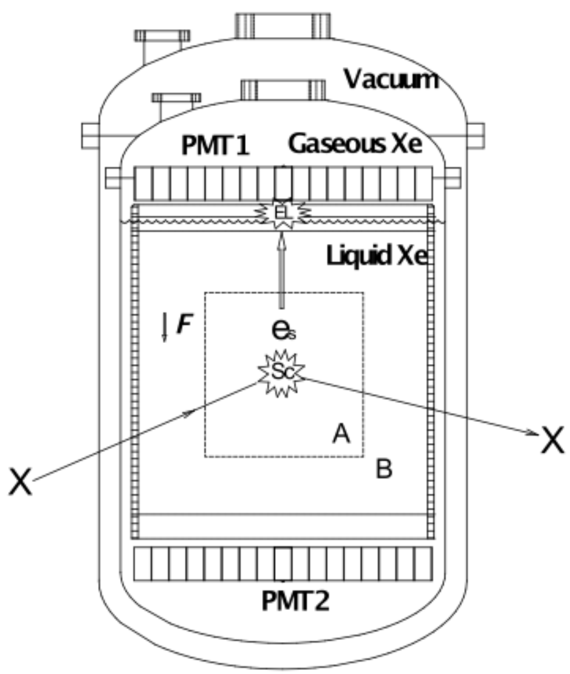
- **7 sigma discovery** with 1-year-ton LAr detector (MiniCLEAN style) operation at BNB (with 25keV detector threshold and 20m from the target)
  → for details Phys.Rev.D89 072004 (2014); arXiv:1311.5958

- CENNS & CAPTAIN collaborations are planing neutron shielding study in fall 2014 (@BNB)

COHERENT collaboration @ SNS

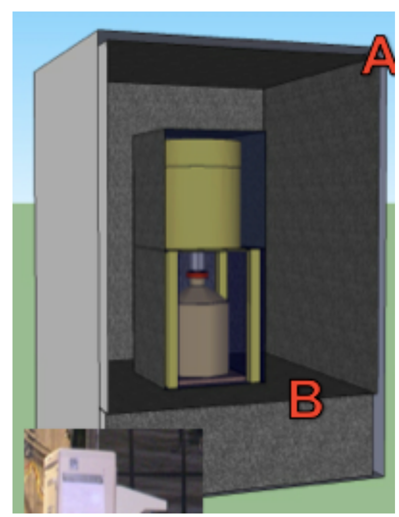
Three possible technologies under consideration

Two-phase LXe

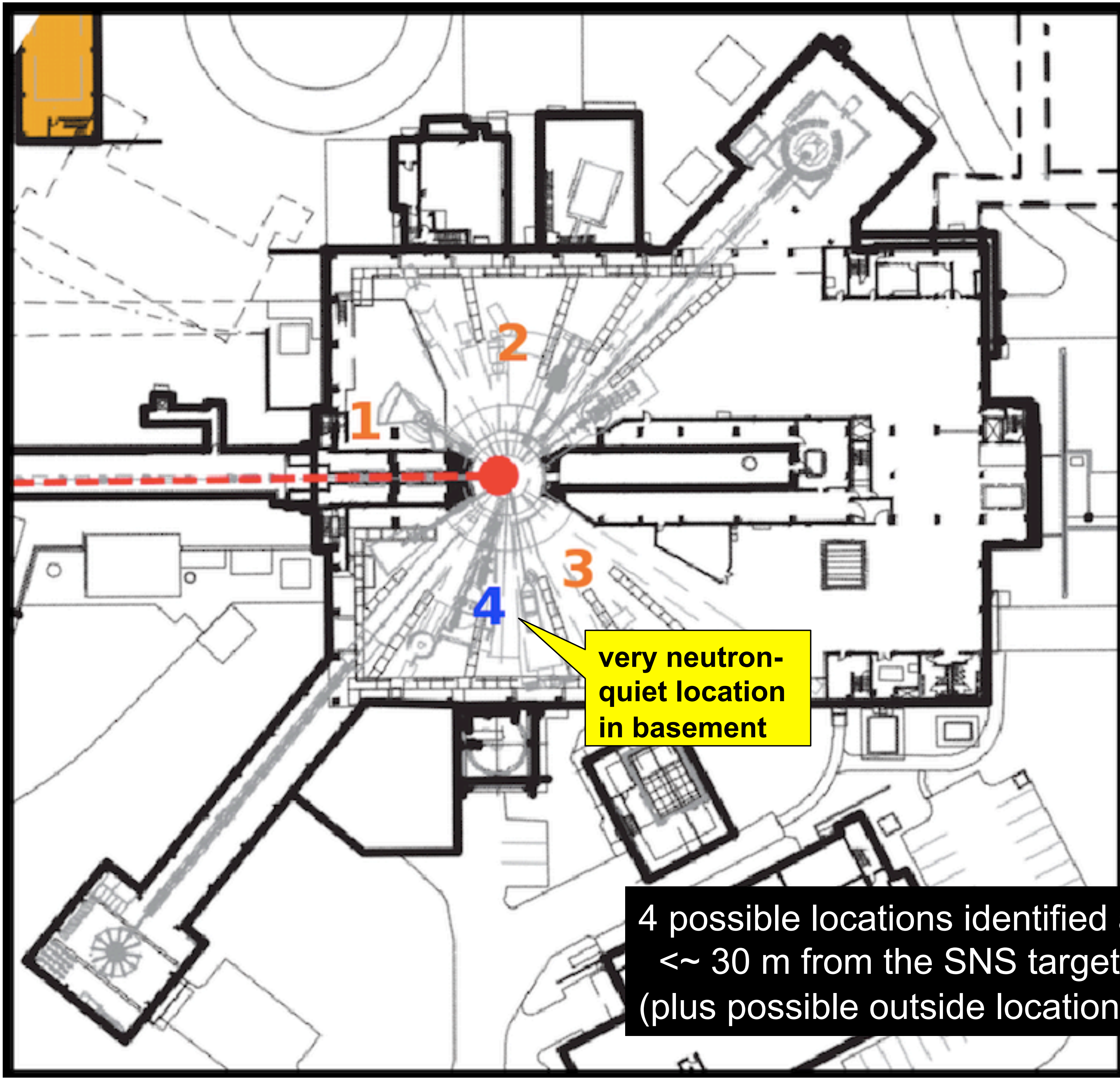


arXiv:1310.0125

CsI

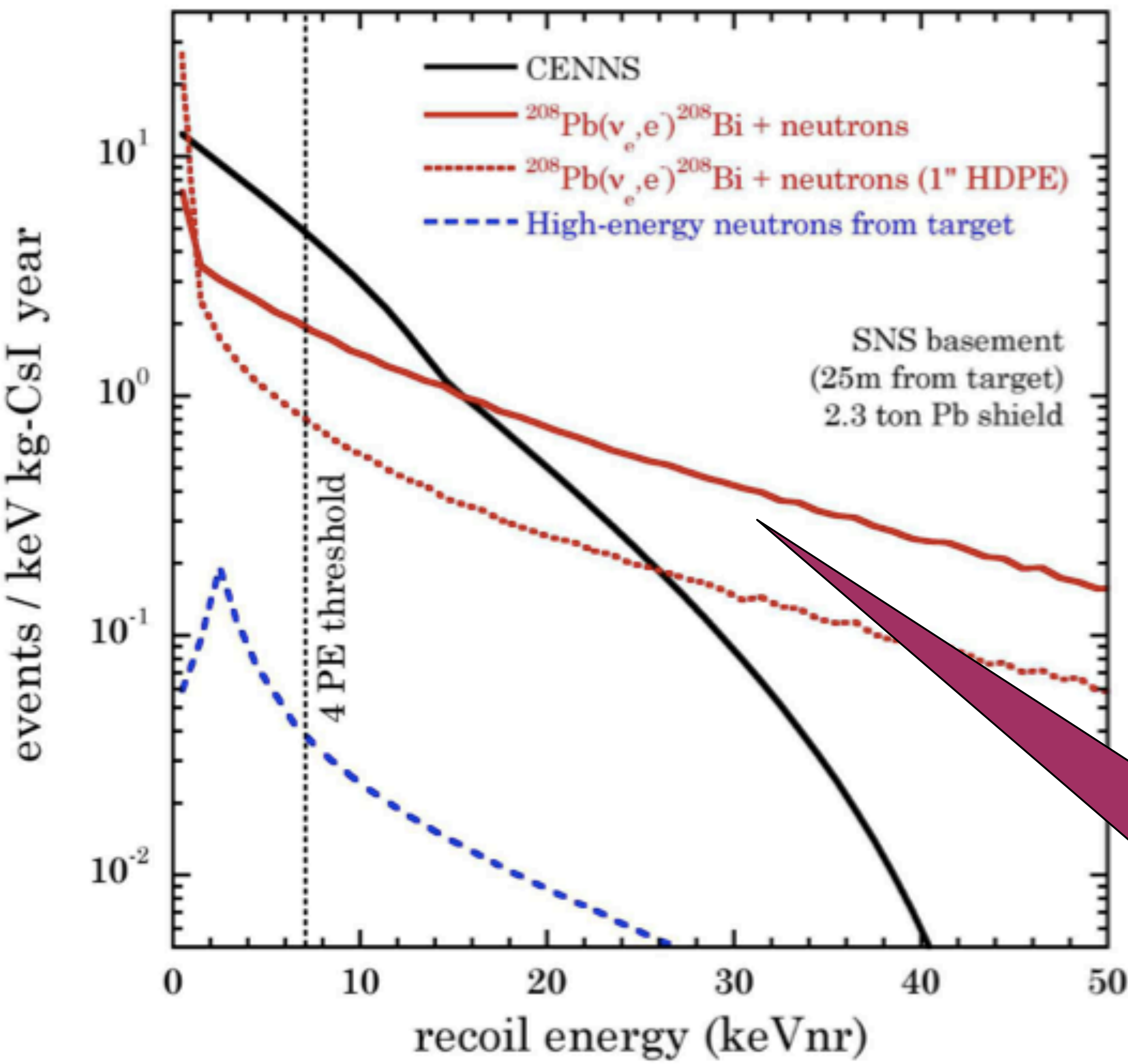


HPGe PPC



4 possible locations identified at <~ 30 m from the SNS target (plus possible outside locations)

Estimate for a specific configuration (CsI[Na] in lead shield):



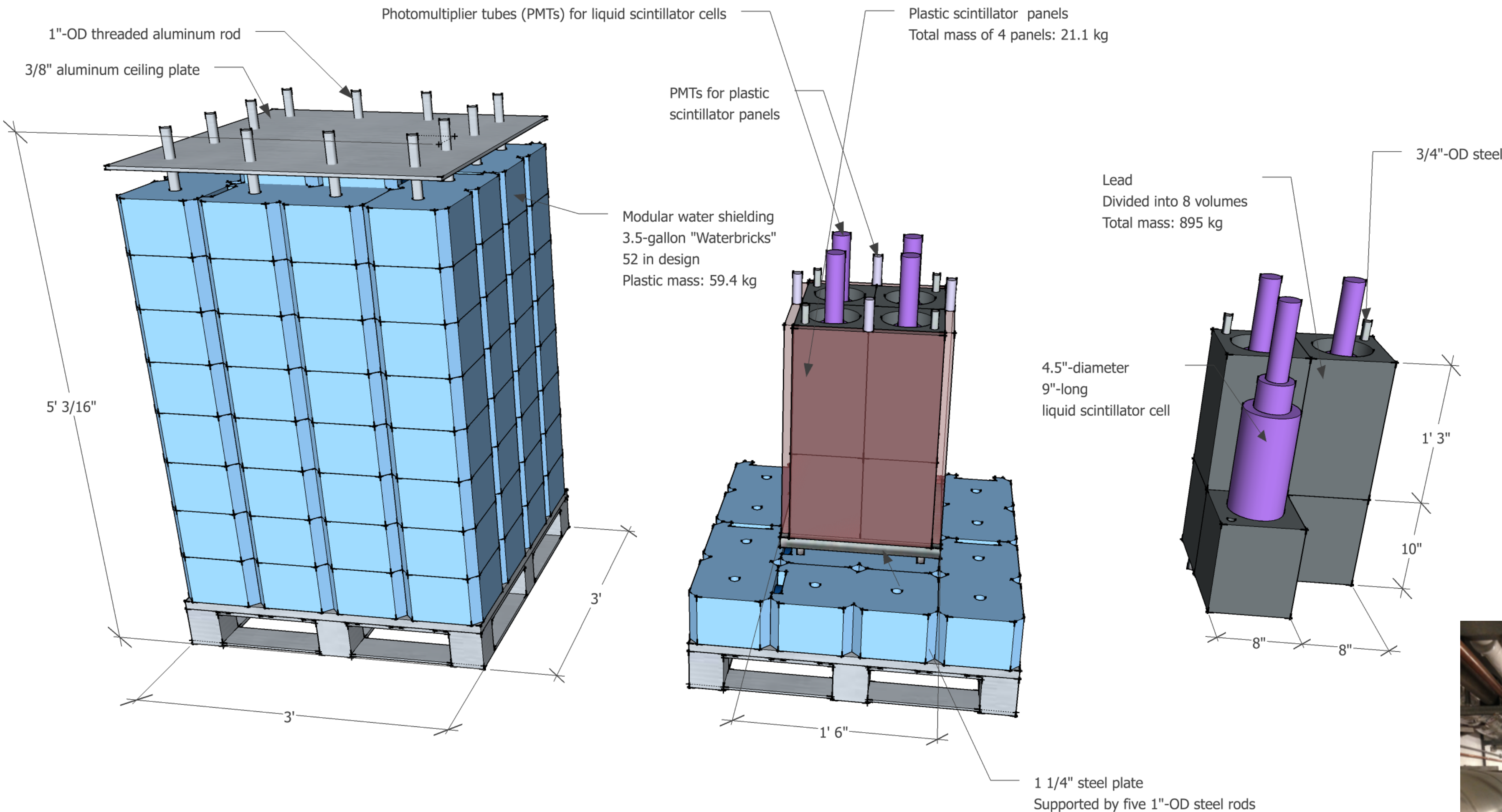
J.I. Collar et al., arXiv:1407.7524

Neutrino-induced neutrons (NINs) not negligible w/lead shield! ➔ need careful shielding design

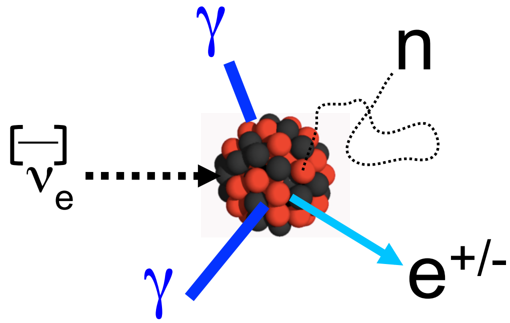
COHERENT collaboration NIN measurement in basement

- Scintillator inside CsI detector lead shield
- Liquid scintillator surrounded by lead (swappable)
  inside water shield

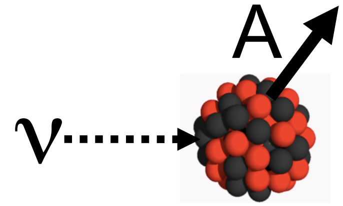
Phil Barbeau



In SNS basement →



Summary



Low-energy neutrino interaction x-sections are relevant in a number of regimes, and especially for SN neutrinos

oscillation physics,
astrophysics,
Standard Model tests

CC & NC interactions on nuclei poorly known...

only ^{12}C measured to ~10% level: **need measurement & theory!**

CENNS detection offers physics opportunities and is within reach with low-threshold detectors

Stopped-π sources offer very promising prospects...

CENNS @ BNB/FNAL,
COHERENT @ SNS/ORNL

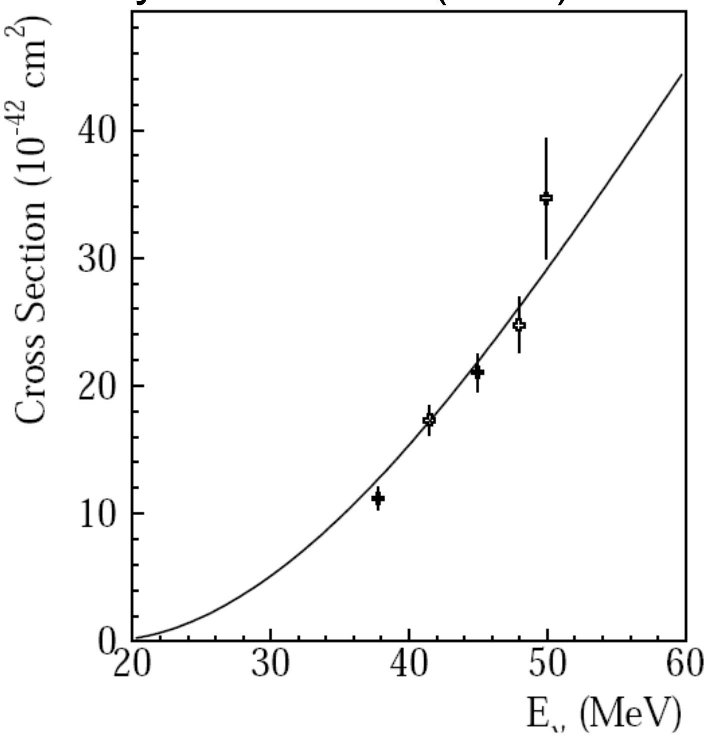
Also: reactors (e.g. RICOCHET)

Extras/Backups

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

LSND

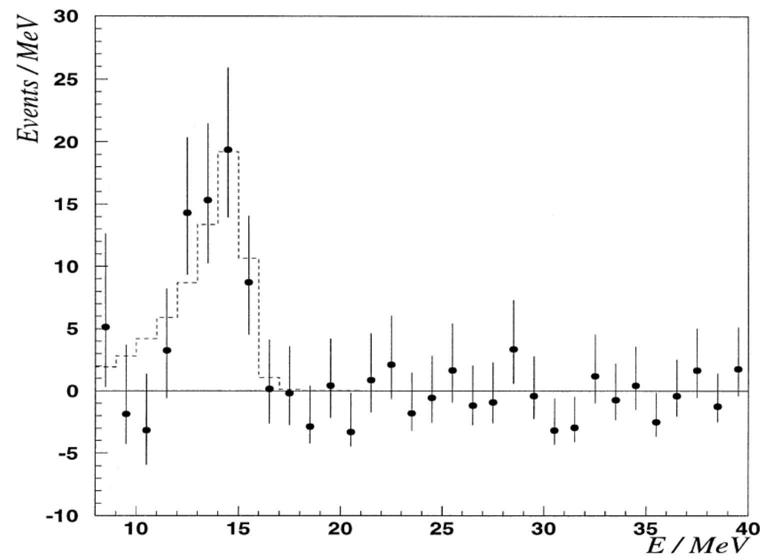
Phys. Rev. C 66 (2002) 015501



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

Karmen

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



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

Of interest for SN detection: oxygen (water), lead, iron, argon...

(And: additional nuclei are of interest for other detectors; supernova explosion physics, supernova nucleosynthesis)

More information

Comprehensive white paper on neutrino physics opportunities at the SNS

arXiv.org > hep-ex > arXiv:1211.5199

Search or Articl

High Energy Physics – Experiment

Opportunities for Neutrino Physics at the Spallation Neutron Source: A White Paper

A. Bolozdynya, F. Cavanna, Y. Efremenko, G. T. Garvey, V. Gudkov, A. Hatzikoutelis, W. R. Hix, W. C. Louis, J. M. Link, D. M. Markoff, G. B. Mills, K. Patton, H. Ray, K. Scholberg, R. G. Van de Water, C. Virtue, D. H. White, S. Yen, J. Yoo

(Submitted on 22 Nov 2012)

Snowmass white paper on CENNS measurements

arXiv.org > hep-ex > arXiv:1310.0125

Search or Artic

High Energy Physics – Experiment

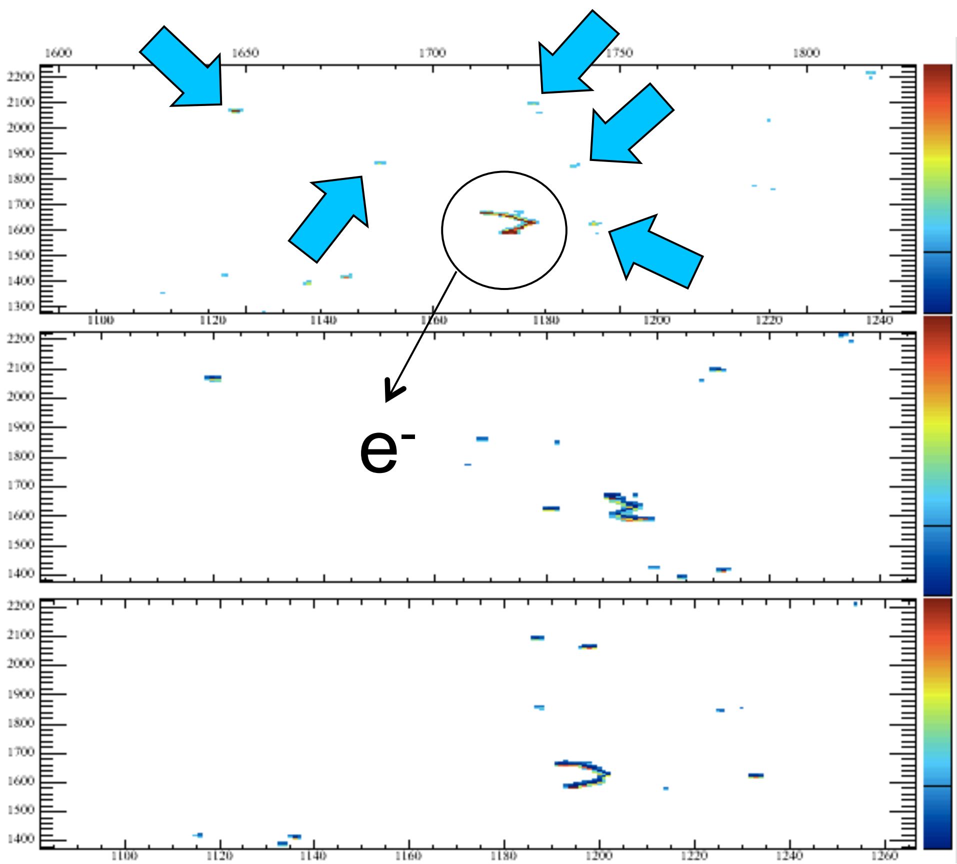
Coherent Scattering Investigations at the Spallation Neutron Source: a Snowmass White Paper

D. Akimov, A. Bernstein, P. Barbeau, P. Barton, A. Bolozdynya, B. Cabrera-Palmer, F. Cavanna, V. Cianciolo, J. Collar, R.J. Cooper, D. Dean, Y. Efremenko, A. Etenko, N. Fields, M. Foxe, E. Figueroa-Feliciano, N. Fomin, F. Gallmeier, I. Garishvili, M. Gerling, M. Green, G. Greene, A. Hatzikoutelis, R. Henning, R. Hix, D. Hogan, D. Hornback, I. Jovanovic, T. Hossbach, E. Iverson, S.R. Klein, A. Khromov, J. Link, W. Louis, W. Lu, C. Mauger, P. Marleau, D. Markoff, R.D. Martin, P. Mueller, J. Newby, J. Orrell, C. O'Shaughnessy, S. Pentilla, K. Patton, A.W. Poon, D. Radford, D. Reyna, H. Ray, K. Scholberg, V. Sosnovtsev, R. Tayloe, K. Vetter, C. Virtue, J. Wilkerson, J. Yoo, C.H. Yu

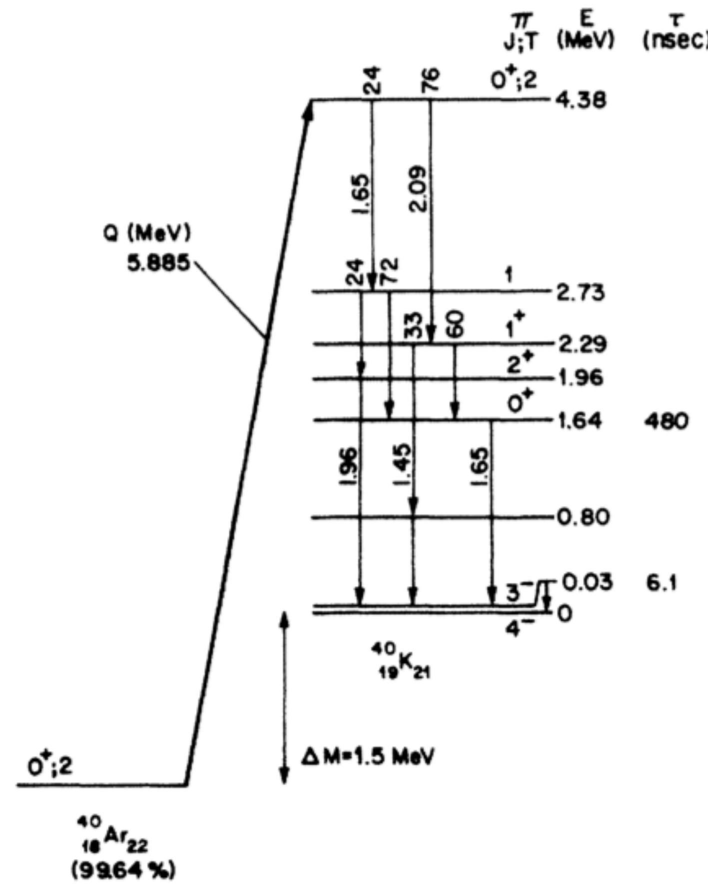
"CSI" is now "COHERENT"

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

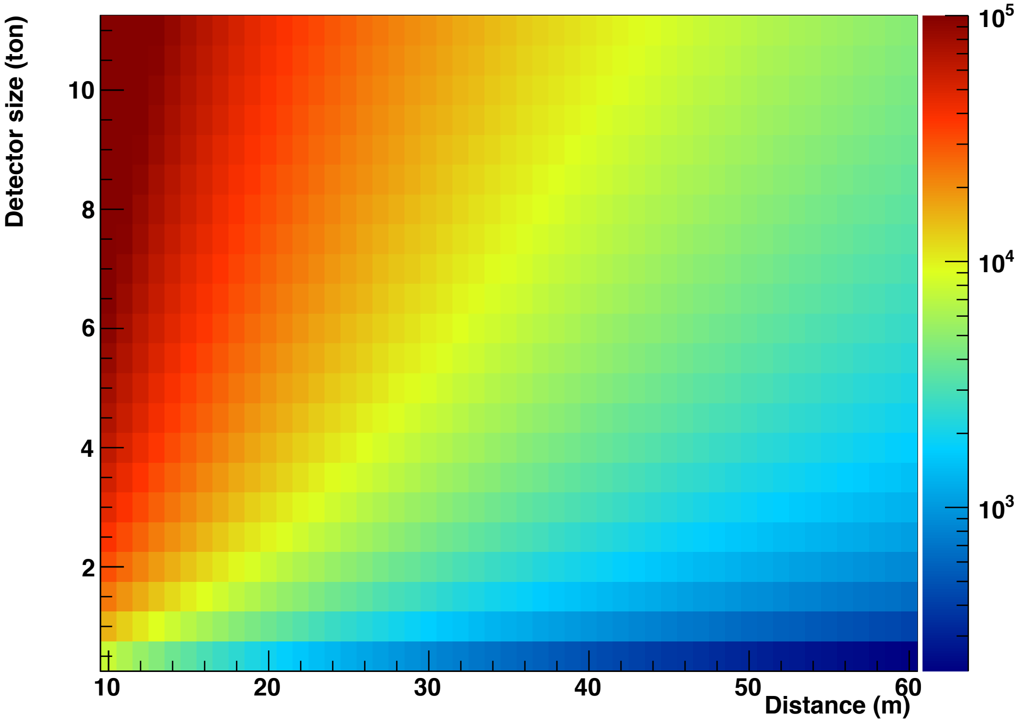
... better modeling based on ^{40}Ti (^{40}K mirror) β decay measurements

... **need more measurements and theory!**

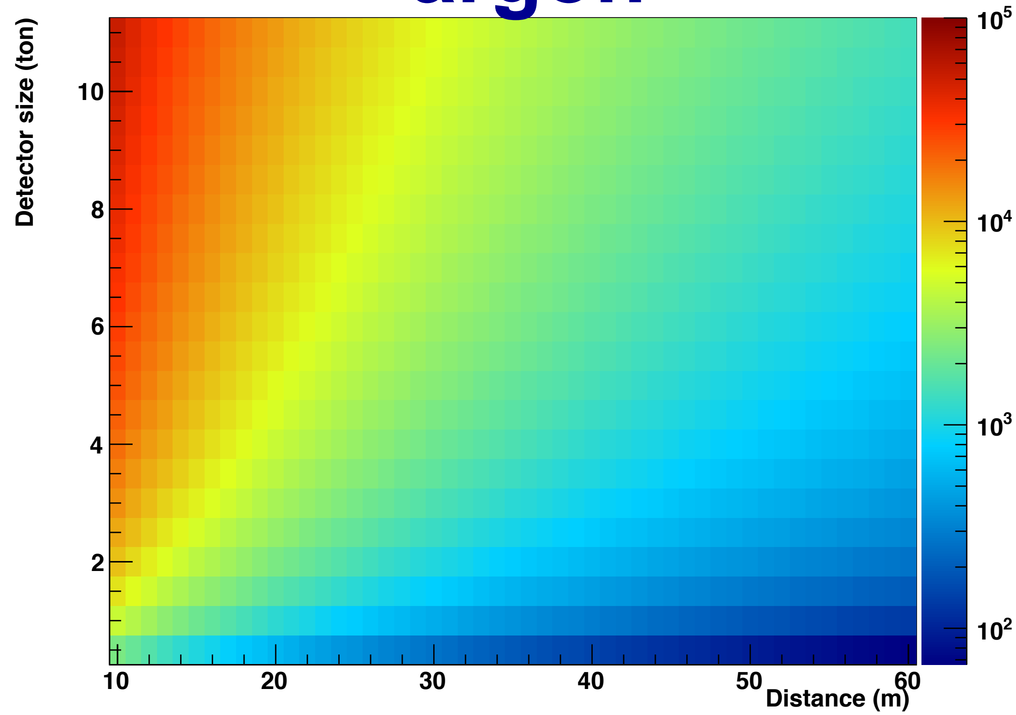
Total events per year at the SNS as a function of distance and mass

just scaling as α 1/R^2, α M

lead

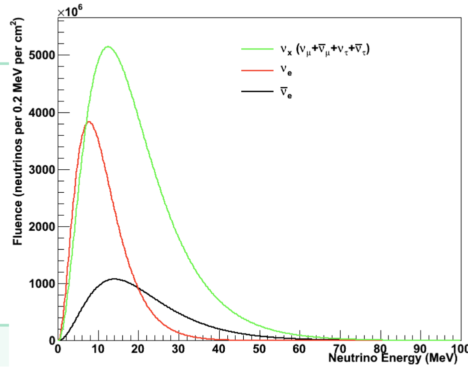


argon



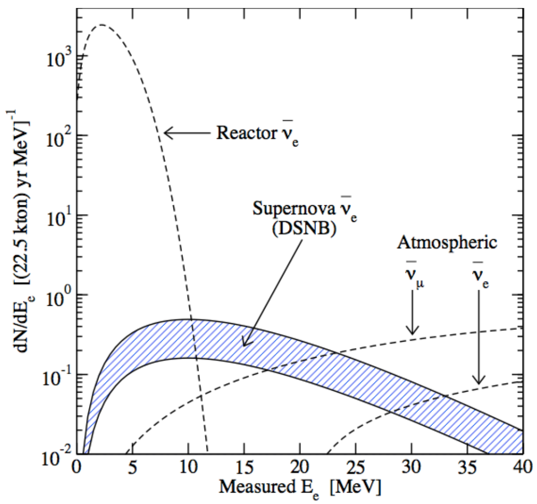
~10^3 events per few tons at 30 m

Supernova burst neutrinos



Every ~30 years in the Galaxy,~few 10's of sec burst, all flavors

Supernova relic neutrinos

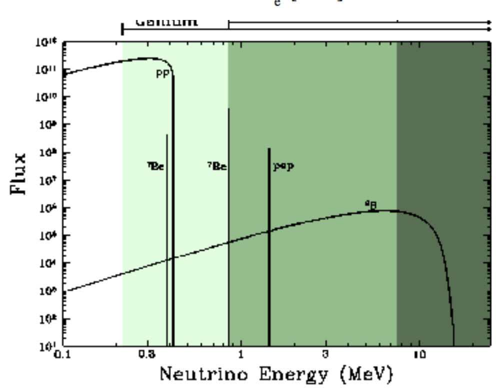


All flavors, low flux

Atmospheric neutrinos

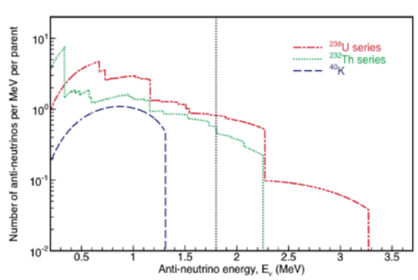
Some component at low energy

Solar neutrinos



Most flux below 1 MeV

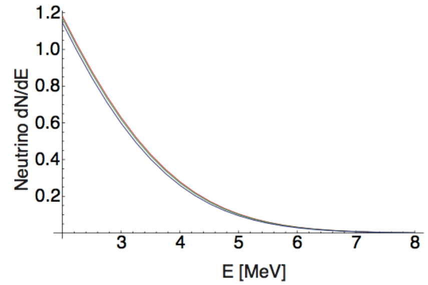
Geoneutrinos



Very low energy

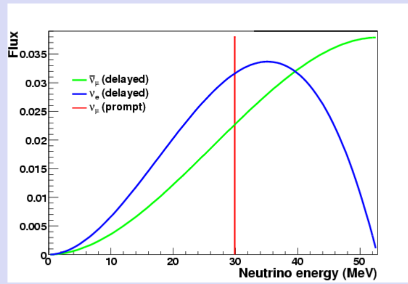
Coherent scattering eventually a bg for DM expts

Reactors



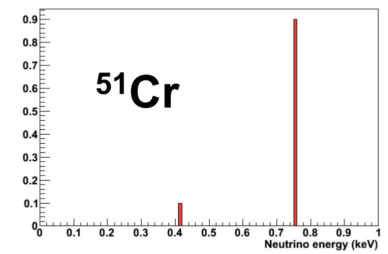
Low energy, but very high fluxes possible; ~continuous source good bg rejection needed

Stopped pions (decay at rest)



High energy, pulsed beam possible for good background rejection; possible neutron backgrounds

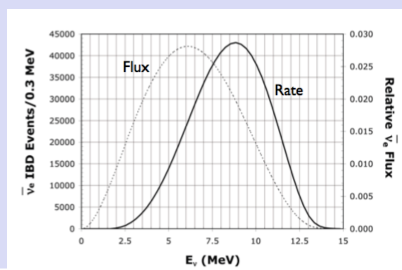
Radioactive sources



Portable; can get very short baseline

Too low energy

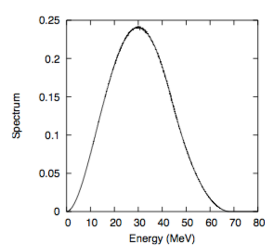
Beam-induced radioactive sources (IsoDAR)



Relatively compact, higher energy than reactor; not pulsed

Does not exist yet

Low-energy beta beams



γ=10 boosted ^{18}Ne ν_e

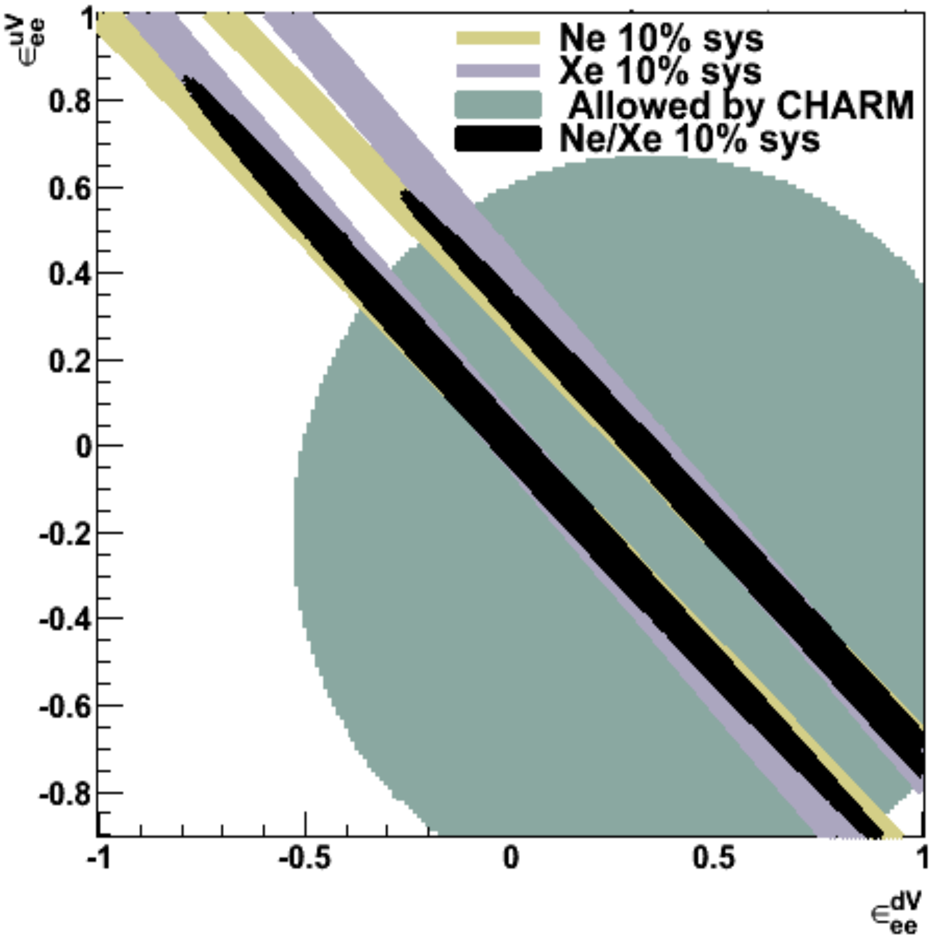
Tunable energy, but not pulsed

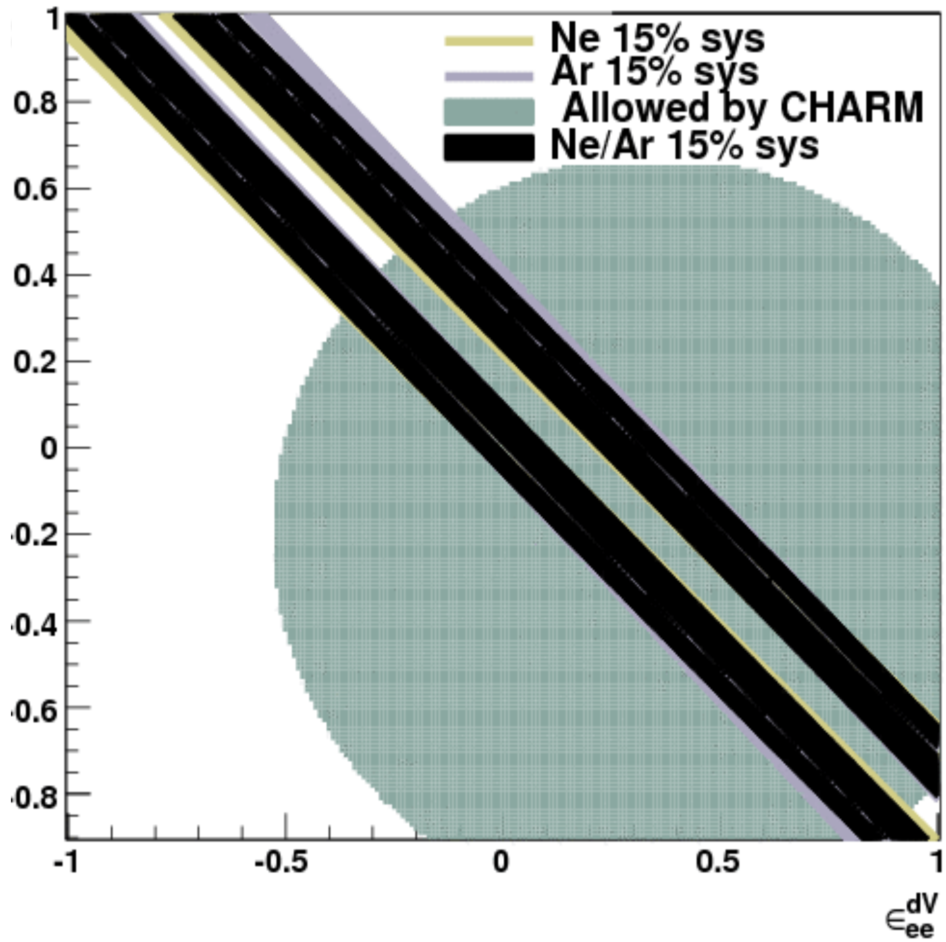
Does not exist yet

Reactor vs stopped-pion for CENNS

Source	Flux/ ν's per s	Flavor	Energy	Pros	Cons
Reactor	2e20 s^{-1} per GW	nuebar	few MeV	• huge flux	• lower xscn • require very low threshold • CW
Stopped pion	1e15 s^{-1}	numu/ nue/ nuebar	0-50 MeV	• higher xscn • higher energy recoils • pulsed beam for bg rejection • all flavors	• lower flux • potential fast neutron in-time bg

Non-Standard Interactions of Neutrinos



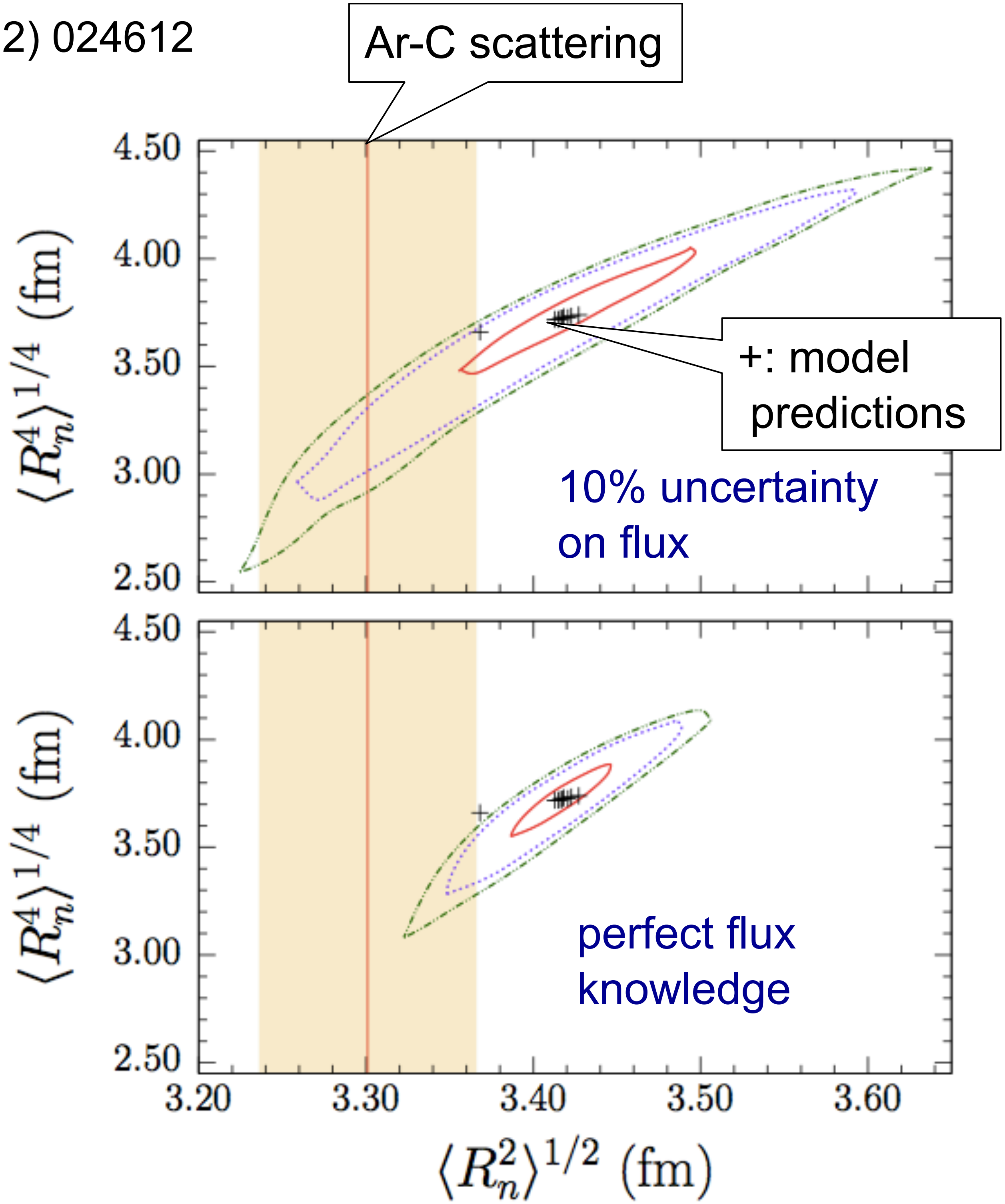


Can improve ~order of magnitude beyond CHARM limits with a first-generation experiment

(for best sensitivity, want *multiple targets*)

K. Patton et al., PRC86 (2012) 024612
arXiv:1207.0693

Example: 3.5 tonnes of Ar at SNS (16 m)



Will require stringent control of uncertainties on recoil energy

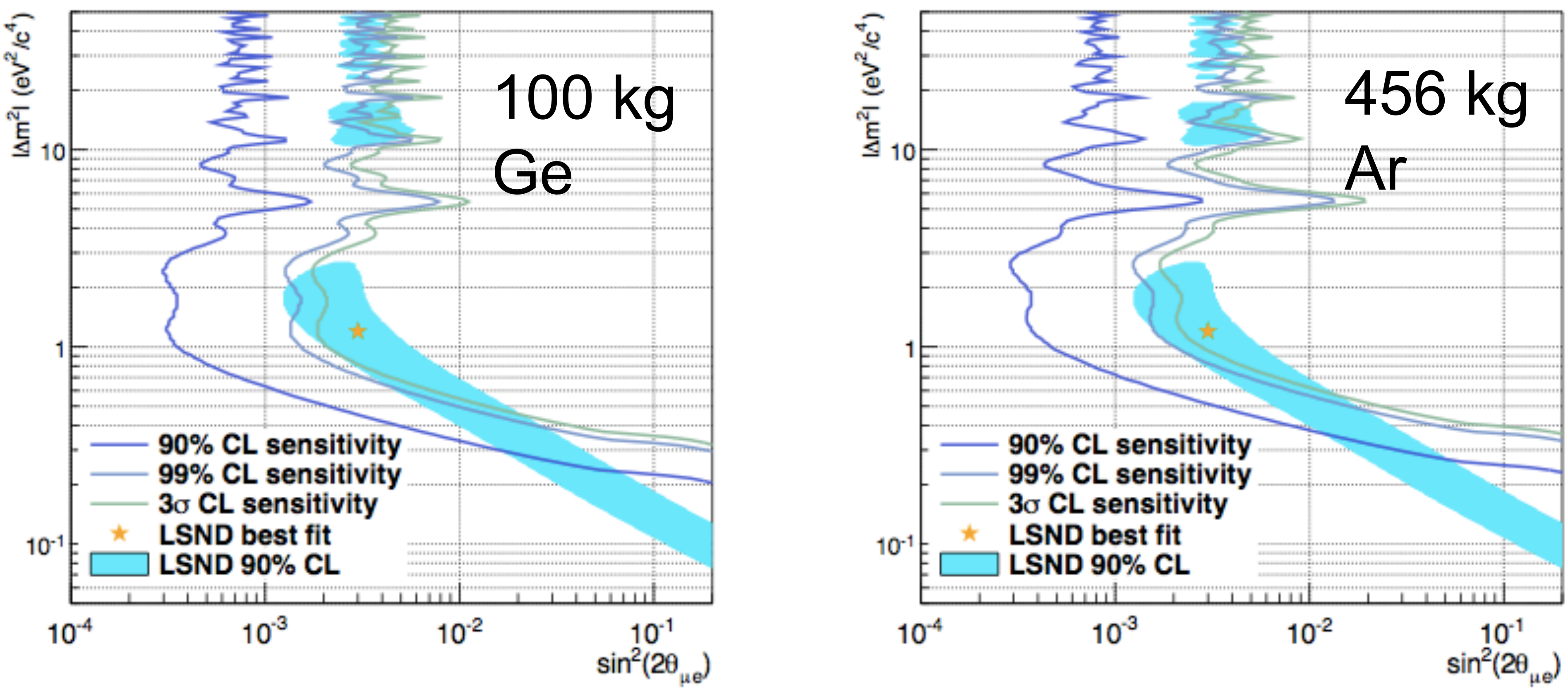
Oscillations to sterile neutrinos w/CENNS

(NC is flavor-blind)

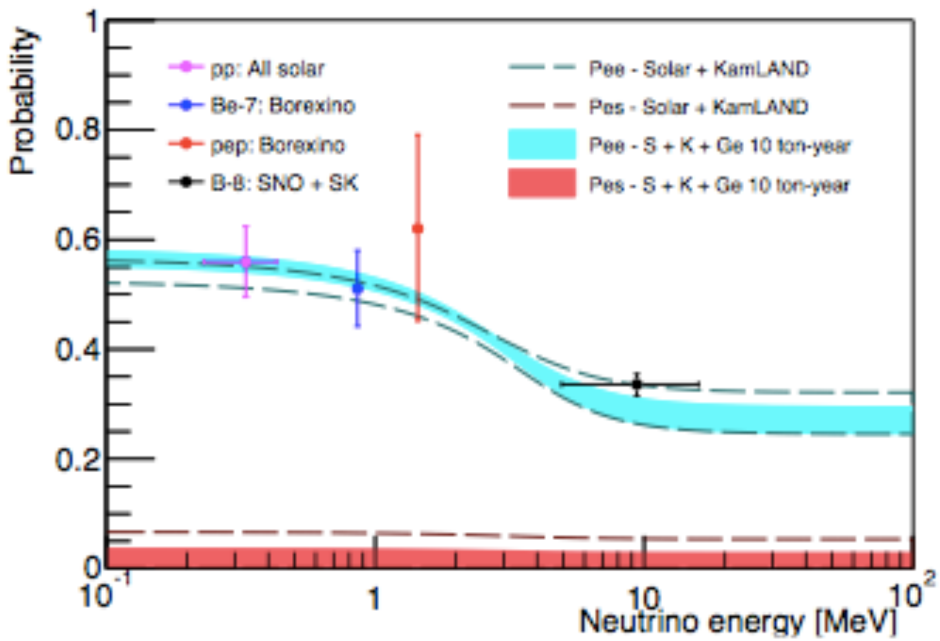
A. Anderson et al., PRD86 (2012) 013004, arXiv:1201.3805

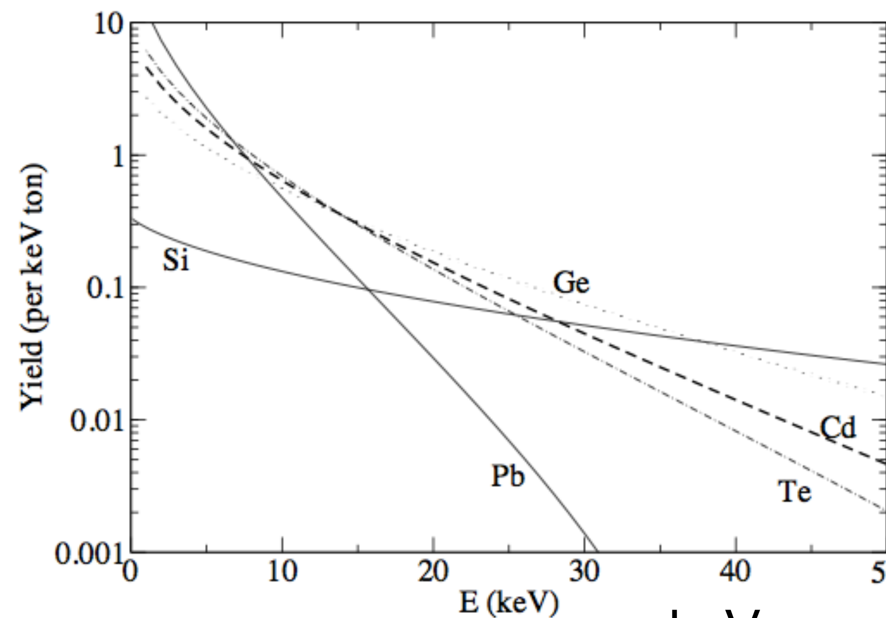
Multi-cyclotron sources at different baselines (20 & 40 m)

look for deficit and spectral distortion



Also note: tonne-scale underground detectors can do **astrophysics**





Billard et al., arXiv:1409.0050

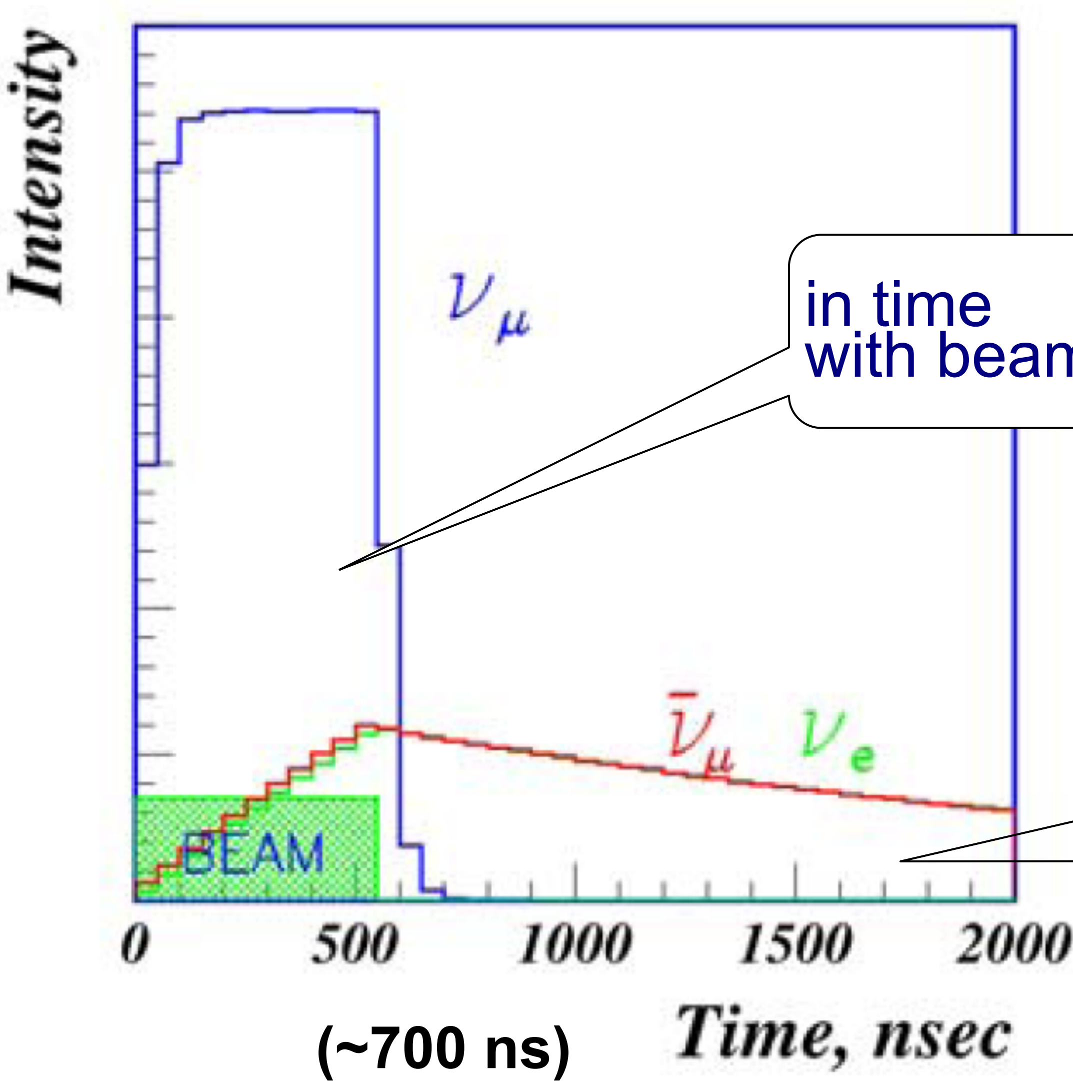
Horowitz et al., PRD68 (2003) 023005

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

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

Time structure of the SNS source

F. Avignone and Y. Efremenko, J. Phys. G: 29 (2003) 2615-2628

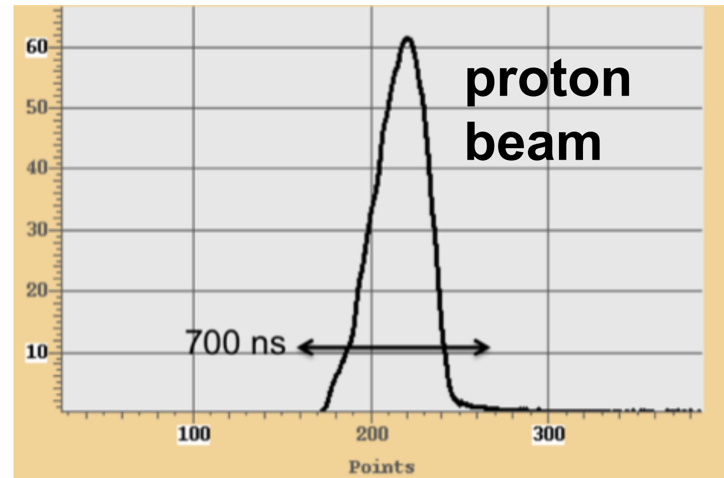


in time with beam

(~700 ns)

delayed on μ decay timescale (2.2 μs)

60 Hz *pulsed* source



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

Neutrino flux: few times 10^7 /s/cm^2 at 20 m

~0.13 per flavor per proton

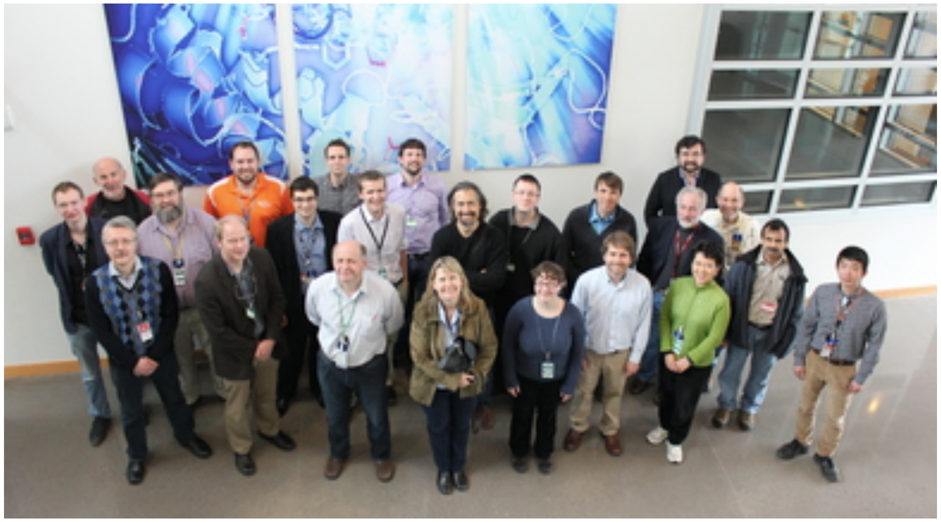
Possible phases of stopped-pion coherent νA scattering experiments

Phase	Detector Scale	Physics Goal	Comments
Phase I	Few to few tens of kg	First detection	Precision flux/ systematics not needed
Phase II	Tens to hundreds of kg	SM test, NSI searches, oscillations	Start to get systematically limited
Phase III	Tonne to multi-tonne	Neutron structure, neutrino magnetic moment, ...	Control of systematics will be dominant issue; multiple targets

The COHERENT collaboration

We now have a charter and a Collaboration Board

University of California, Berkeley
University of Chicago
Duke University
University of Florida
Indiana University
Institute for Theoretical and Experimental Physics, Moscow
Lawrence Berkeley National Laboratory
Los Alamos National Laboratory
National Research Nuclear University MEPhI
North Carolina Central University
Oak Ridge National Laboratory
Pacific Northwest National Laboratory
Sandia National Laboratory
University of Tennessee, Knoxville
Triangle Universities Nuclear Laboratory



~ 45 collaborators presently
Actively recruiting more

From Heather Ray (UF): ν flux simulation by Dipak Rimal

Energy Spectra of Neutrinos

- 50 M protons on target:
  - 50 jobs with 1 M events in each

Total ν's in the world volume

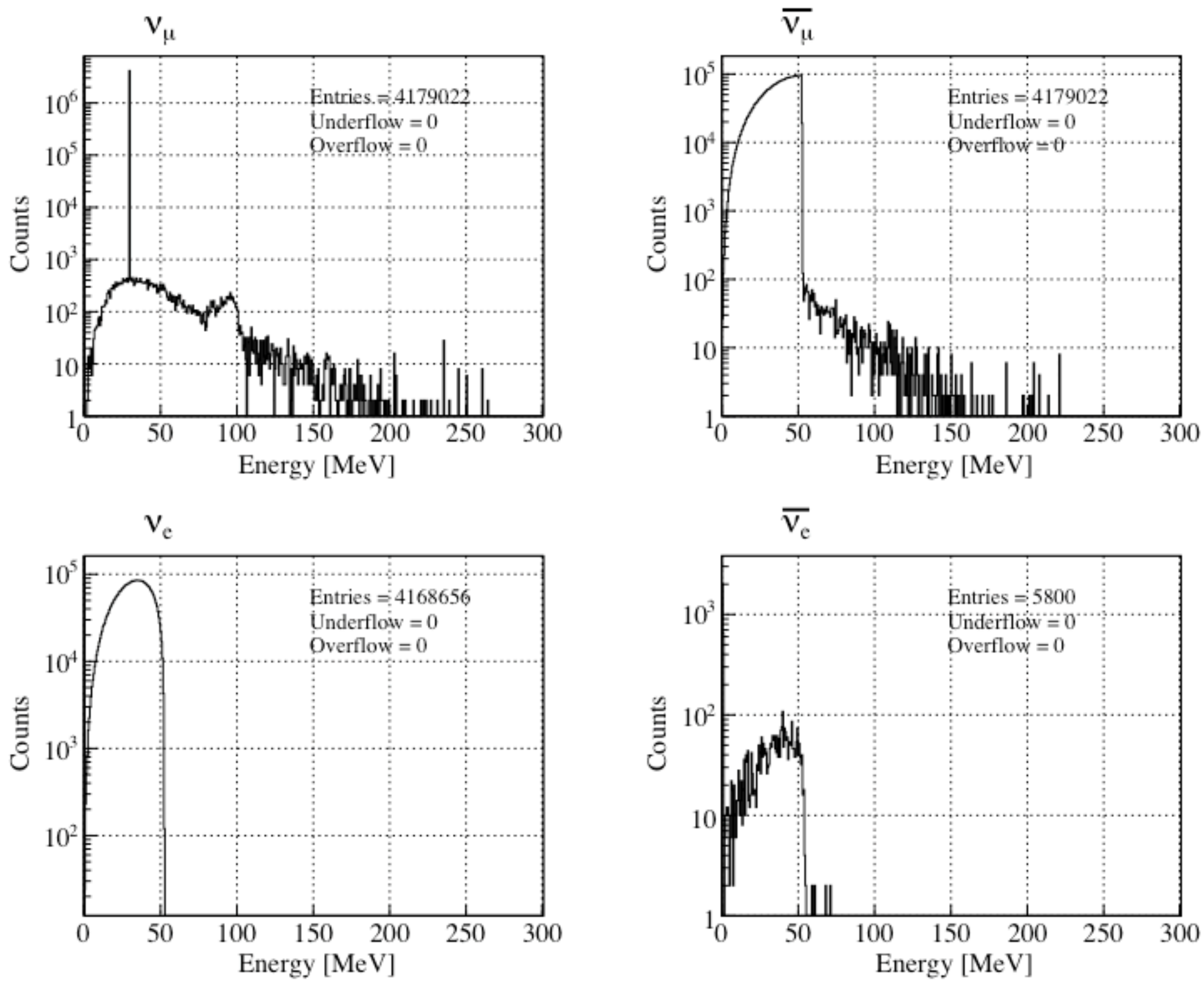
ν_μ = 4179022

$\bar{\nu}_\mu$ = 4179022

ν_e = 4268656

$\bar{\nu}_e$ = 5800

Includes neutrinos from decay at rest (DAR) and decay in flight (DIF) of the pions/muons



COHERENT is currently working on next step:

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

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

↘ 1n, 2n emission

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

↘ 1n, 2n, γ emission

- likely a non-negligible background that we must understand, especially in lead shield
- valuable in itself, e.g. HALO supernova detector at SNOLAB
- short-term physics output