COHERENT Neutrino Physics at the Spallation Neutron Source

Kate Scholberg, Duke University
University of Virginia HEP seminar
October 29, 2014

OUTLINE

- Coherent elastic neutrino-nucleus scattering

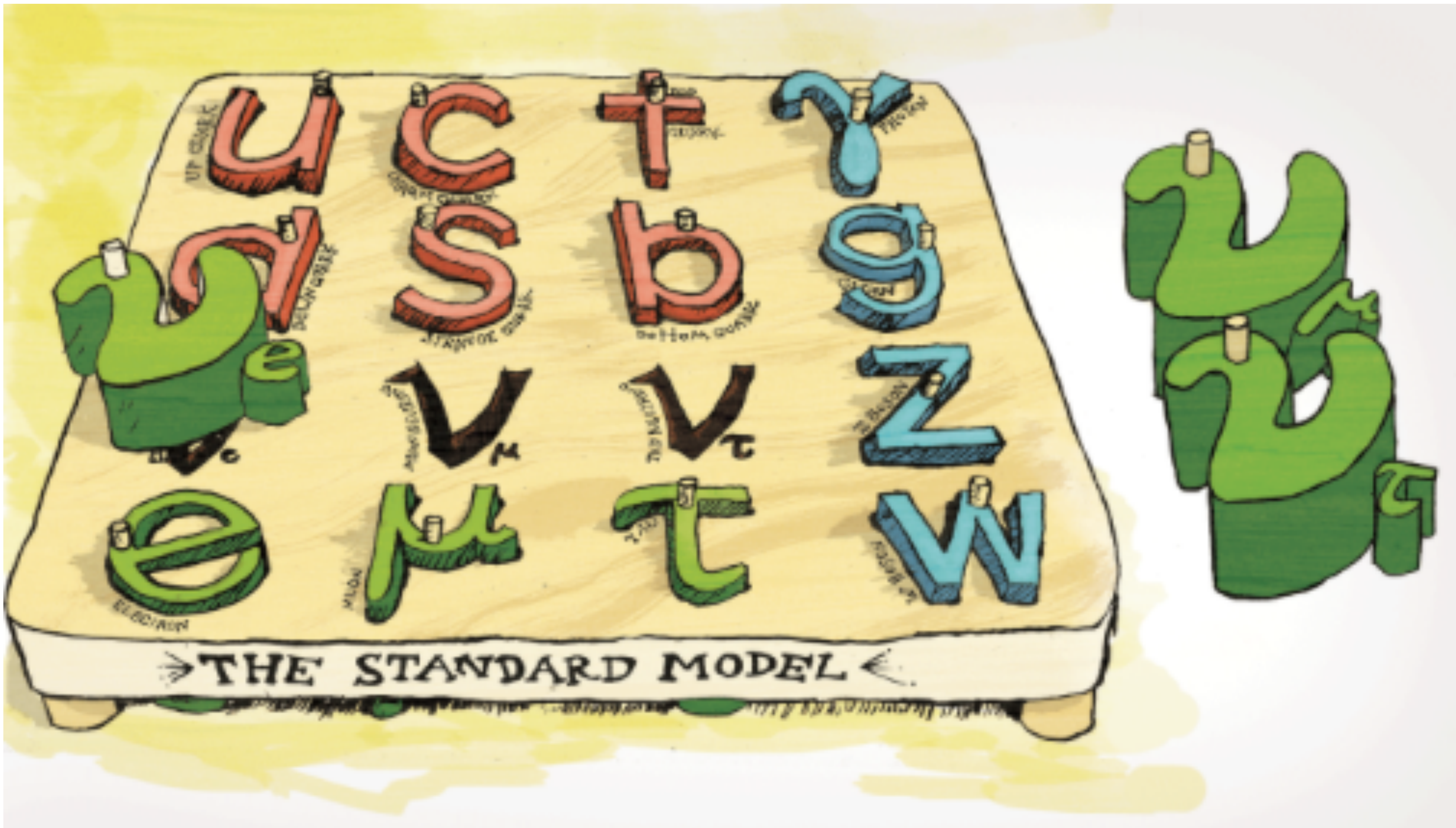
- Possible sources and detectors;
  emphasis on stopped-pion neutrinos

- Physics reach of a CENNS experiment

- Prospects for near-future measurements
  COHERENT @ ORNL

Neutrino physics has been tremendously successful over the past two decades..

We now have a pretty robust, simple 3-flavor neutrino model...
but neutrinos are weird, and still many properties unexplored

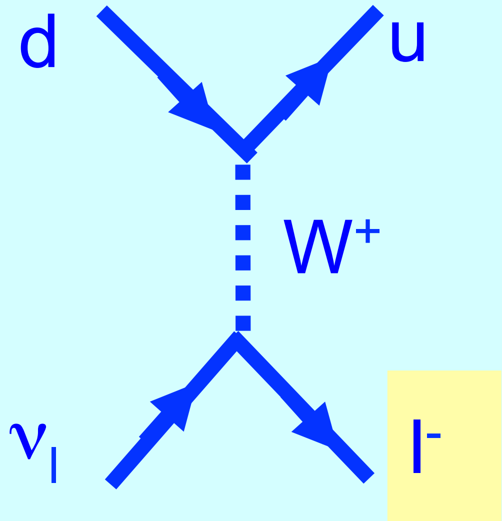


Symmetry magazine

Neutrino Interactions with Matter

Neutrinos are aloof but not *completely* unsociable

Charged Current (CC)

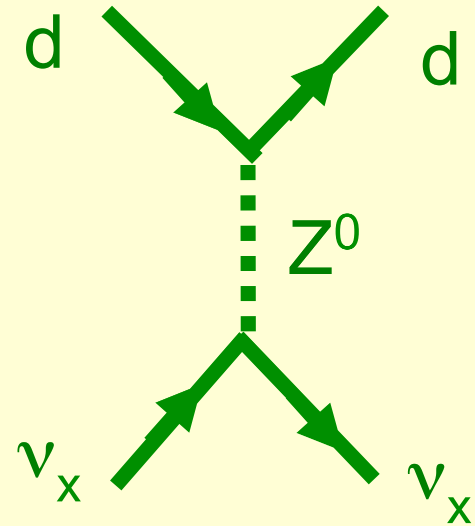


$$\nu_l + N \rightarrow l^{\pm} + N'$$

Produces lepton
with flavor corresponding
to neutrino flavor

(must have enough energy
to make lepton)

Neutral Current (NC)

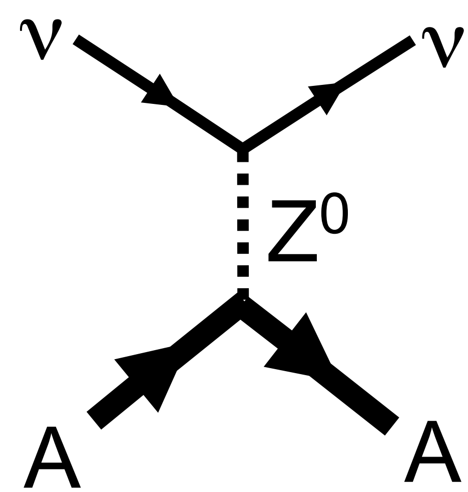


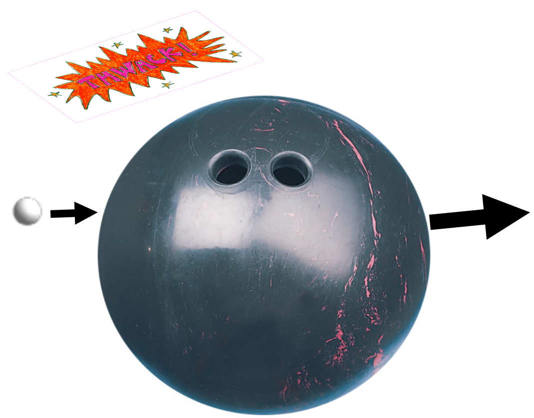
Flavor-blind

Zoom in on: Coherent neutral current elastic neutrino-nucleus scattering (CENNS)

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

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





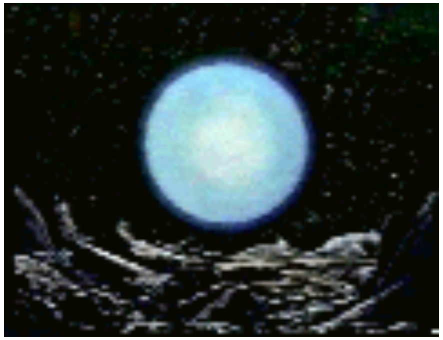
- Coherent up to $E_\nu \sim 50$ MeV
- Important in SN processes & detection
- Well-calculable cross-section in SM
- Possible applications (reactor monitoring)

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

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

Why try to measure this?

- It's never been done!



- Important in supernova processes
- Important for supernova ν detection

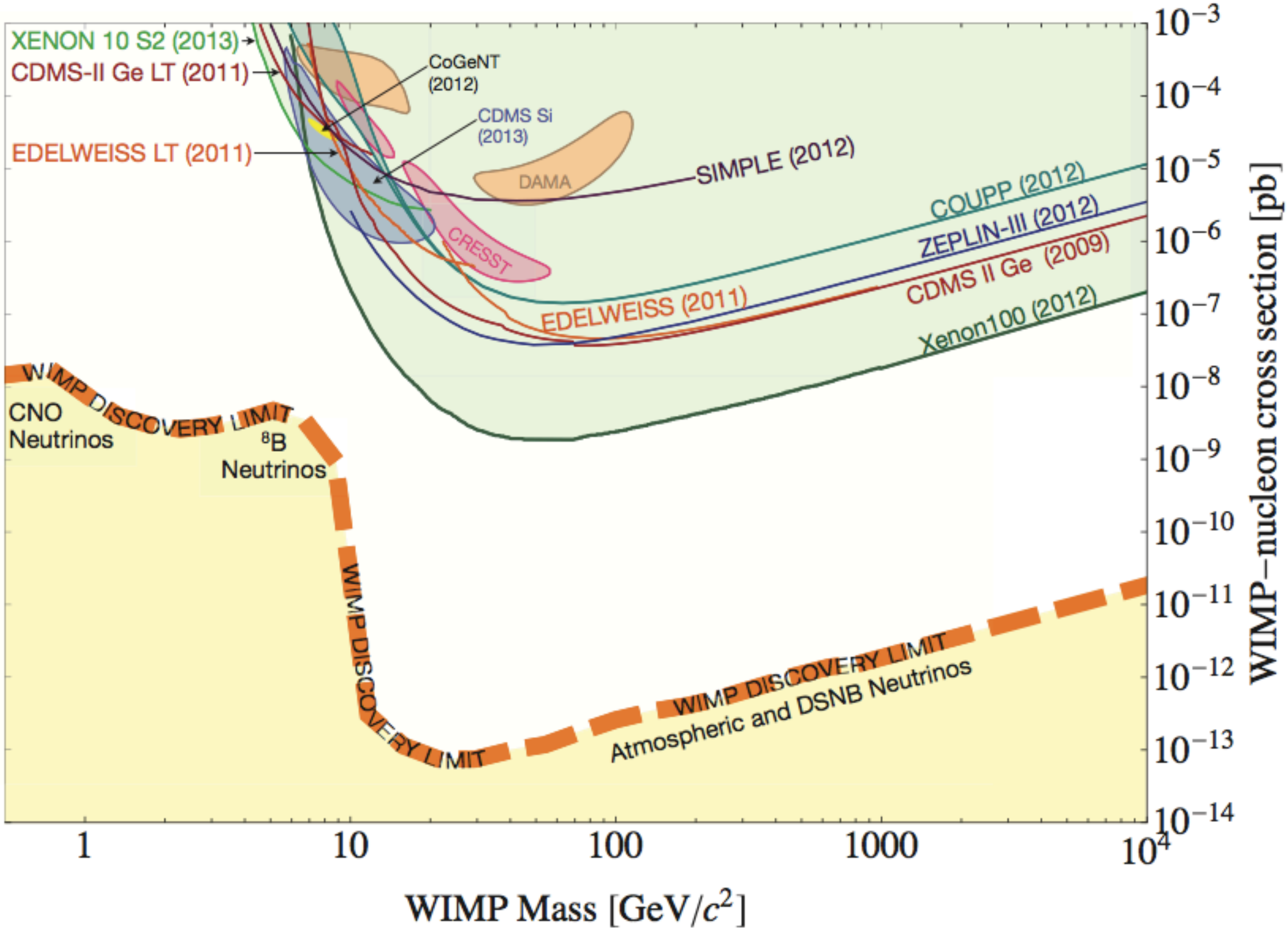
- Deviations from expected x-scn
  may indicate non-SM processes

???

- Possibly even applications...

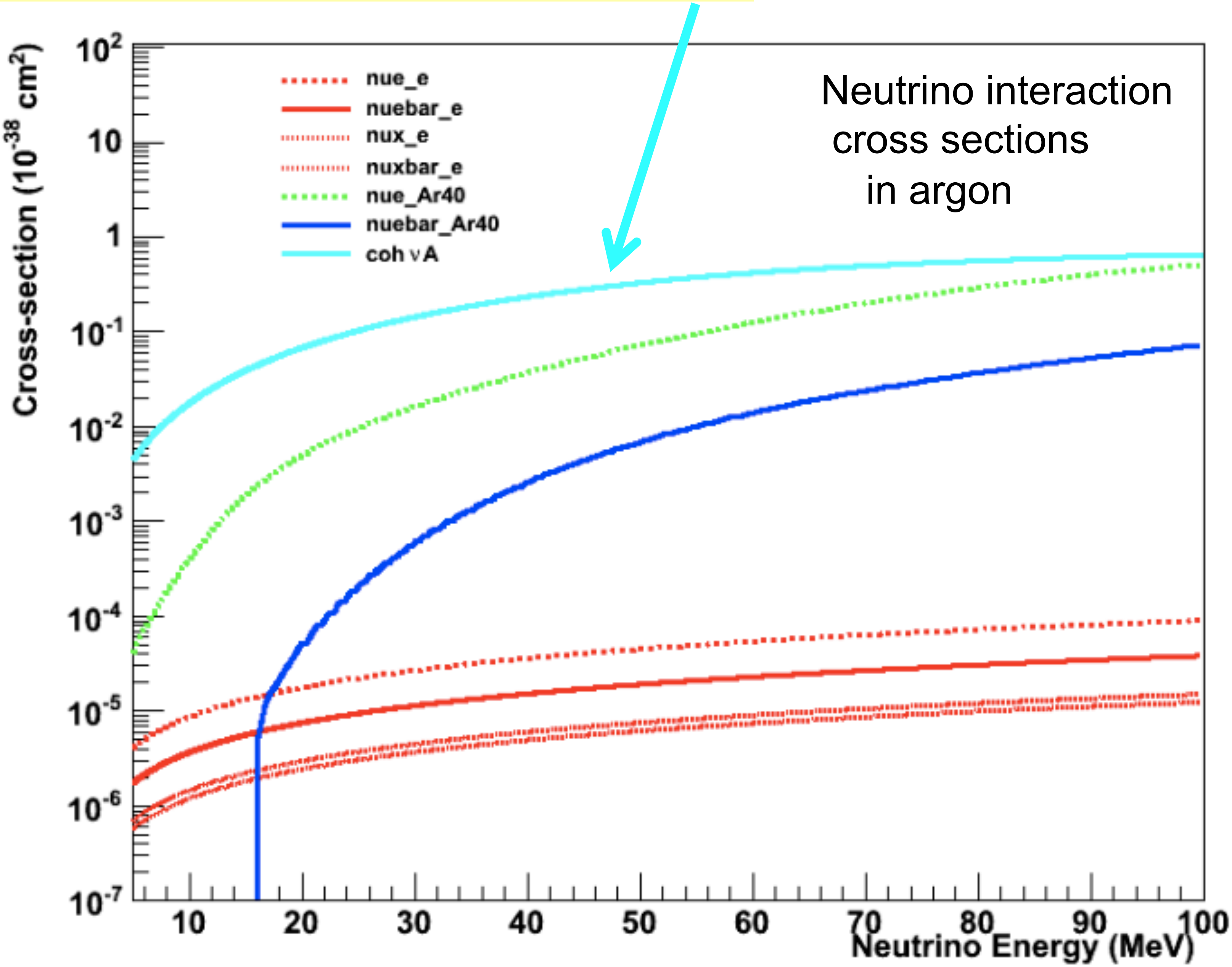
e.g. Barbeau et al., IEEE Trans. Nucl. Sci. 50: 1285 (2003)
C. Hagmann & A. Bernstein, IEEE Trans. Nucl. Sci 51:2151 (2004)

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



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

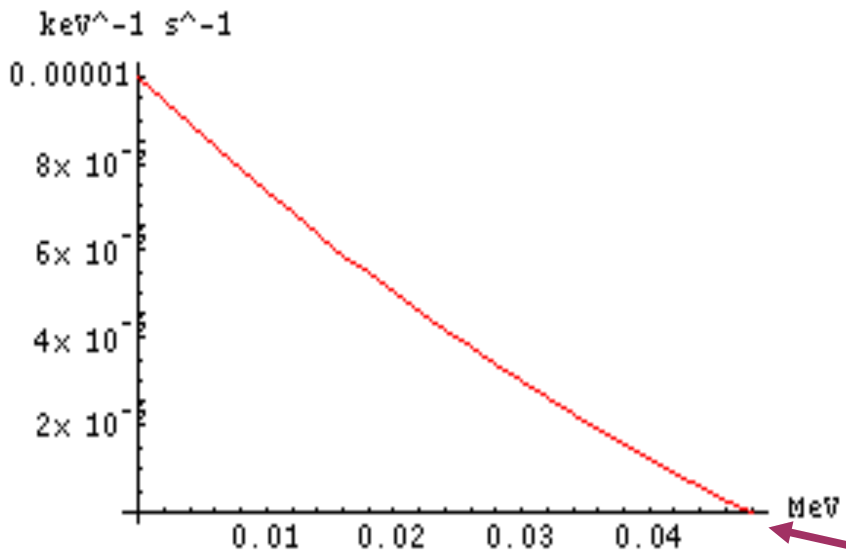
The cross-section is *large*



But CENNS has never been observed...

Why not?

Nuclear recoil energy spectrum for 30 MeV ν



Max recoil energy is $2E_\nu^2/M$ (48 keV for Ar)

Recoil energies are tiny!

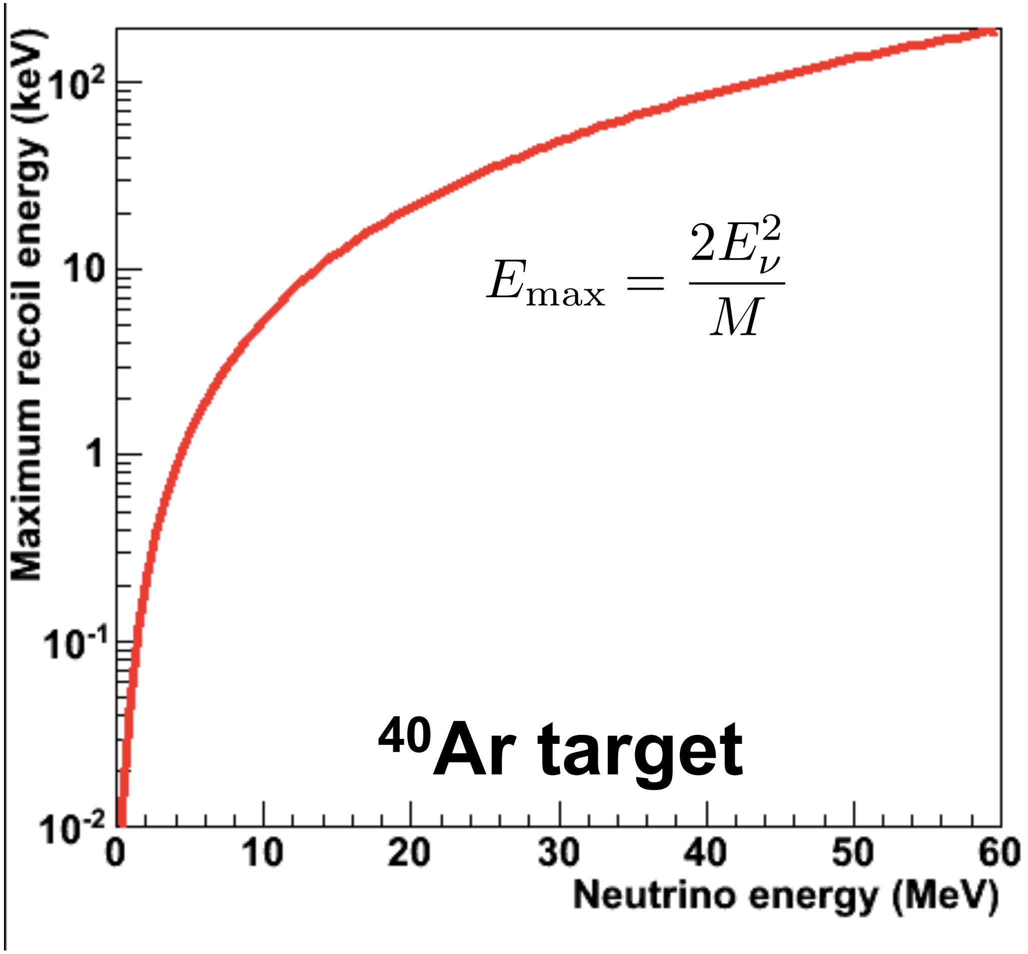
Most neutrino detectors (water, gas, scintillator) have thresholds of at least ~MeV:

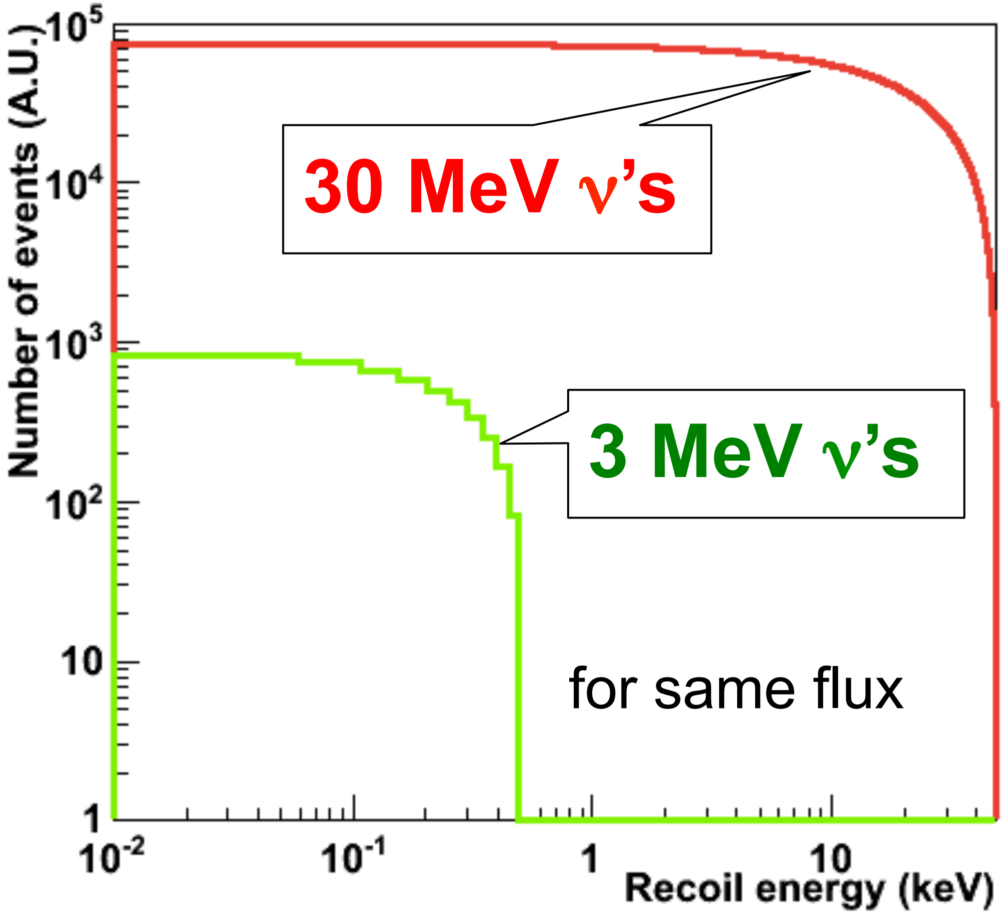
so these interactions are hard to see...

➔ **but WIMP detectors developed over the last ~decade are sensitive**

What do you want to detect CENNS?

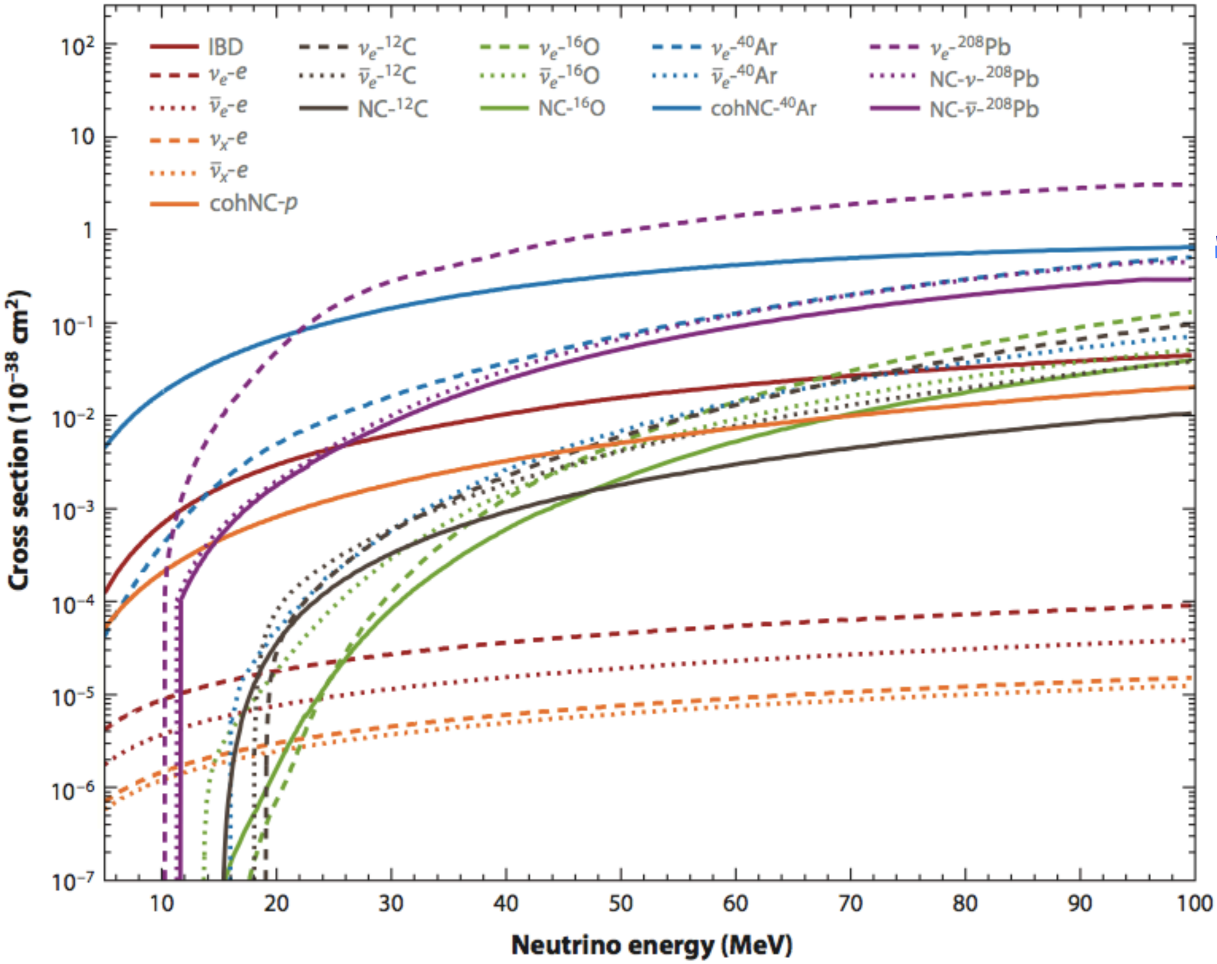
High-energy neutrinos, because both cross-section and maximum recoil energy increase with neutrino energy





... but...

... neutrino energy should not be *too* high...



CC, NC QE & nQE

coherent elastic

The coherent cross-section flattens, but inelastic cross-section increases (eventually start to scatter off *nucleons*)

➔ **want E_ν~ 50 MeV to satisfy** $Q \lesssim \frac{1}{R}$

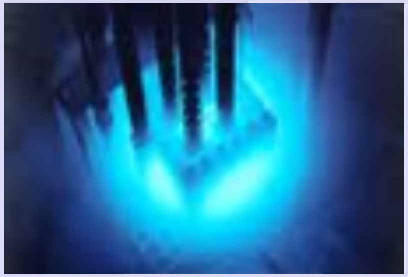
What do you want in a neutrino source for CENNS detection (and physics)?

- ✓ High flux
- ✓ Well understood spectrum
- ✓ Multiple flavors
- ✓ Pulsed source if possible, for background rejection
- ✓ Ability to get close
- ✓ Practical things: access, control, ...

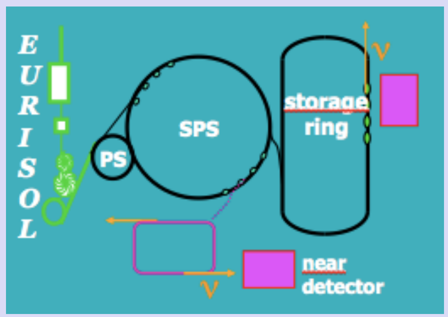
Potential sources for detection of coherent scattering

Artificial sources

reactor neutrinos

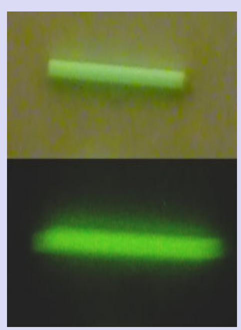


low energy
beta beams



stopped
pions

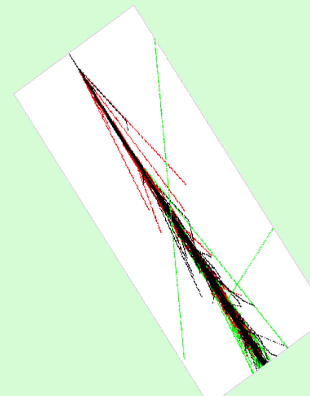
radioactive
sources

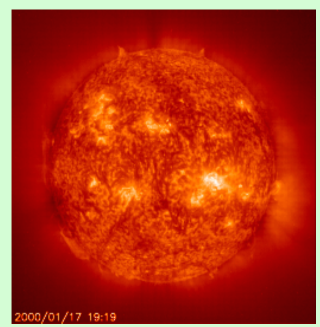


Natural sources

supernova neutrinos,
burst &
relic

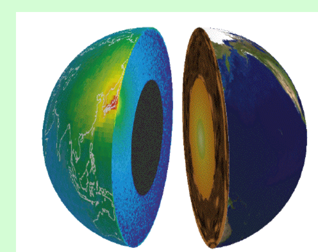
low energy
atmospheric
neutrinos



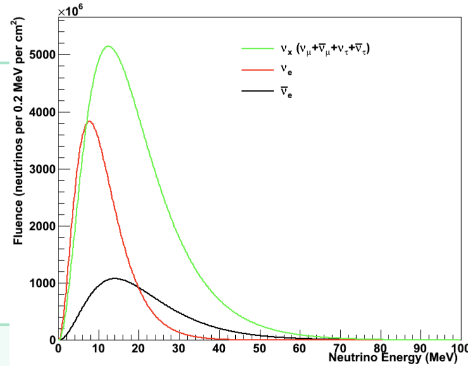


solar
neutrinos

geo
neutrinos

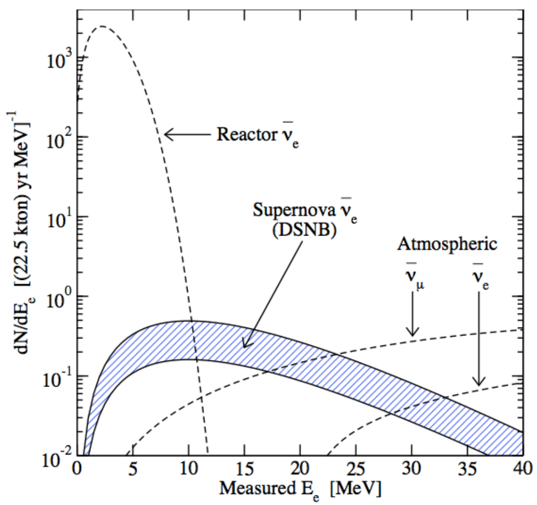


Supernova burst neutrinos



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

Supernova relic neutrinos

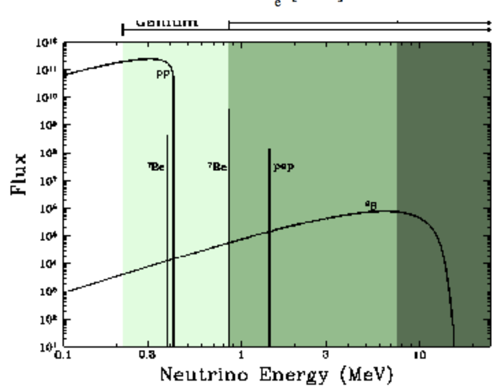


All flavors, low flux

Atmospheric neutrinos

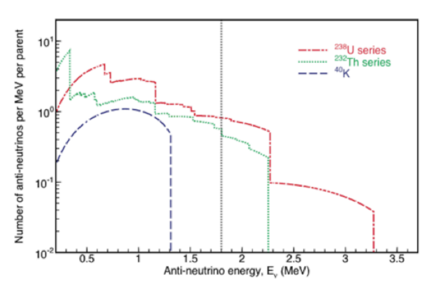
Some component at low energy

Solar neutrinos



Most flux below 1 MeV

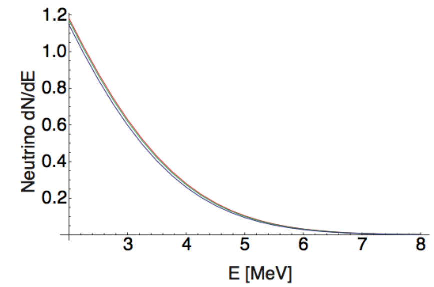
Geoneutrinos



Very low energy

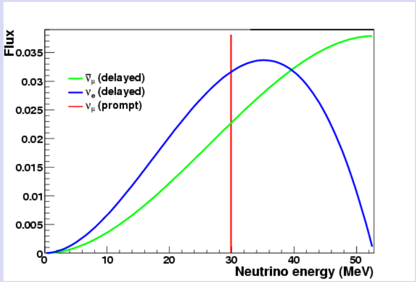
Coherent scattering eventually a bg for DM expts

Reactors



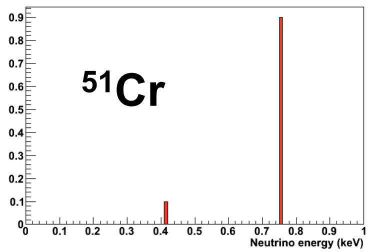
Low energy, but very high fluxes possible; ~continuous source good bg rejection needed

Stopped pions (decay at rest)



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

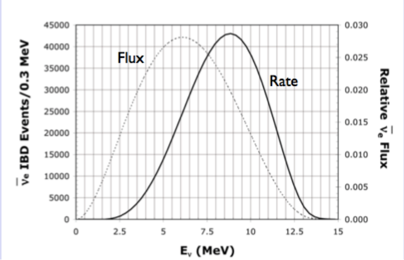
Radioactive sources



Portable; can get very short baseline

Too low energy

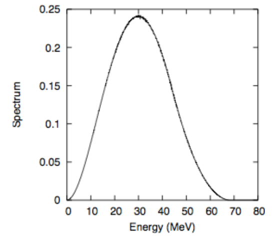
Beam-induced radioactive sources (IsoDAR)



Relatively compact, higher energy than reactor; not pulsed

Does not exist yet

Low-energy beta beams

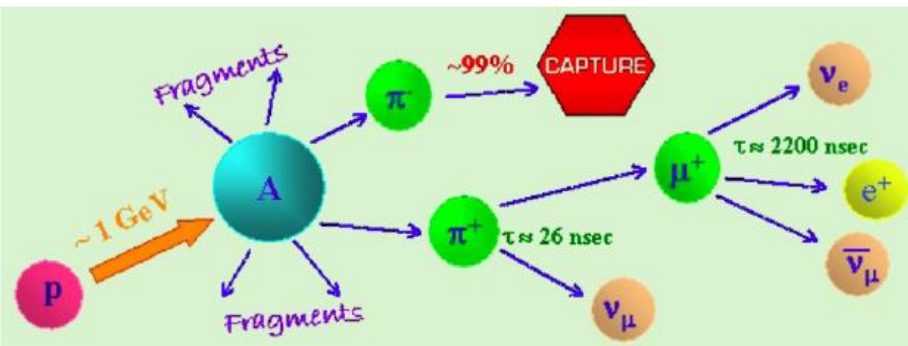


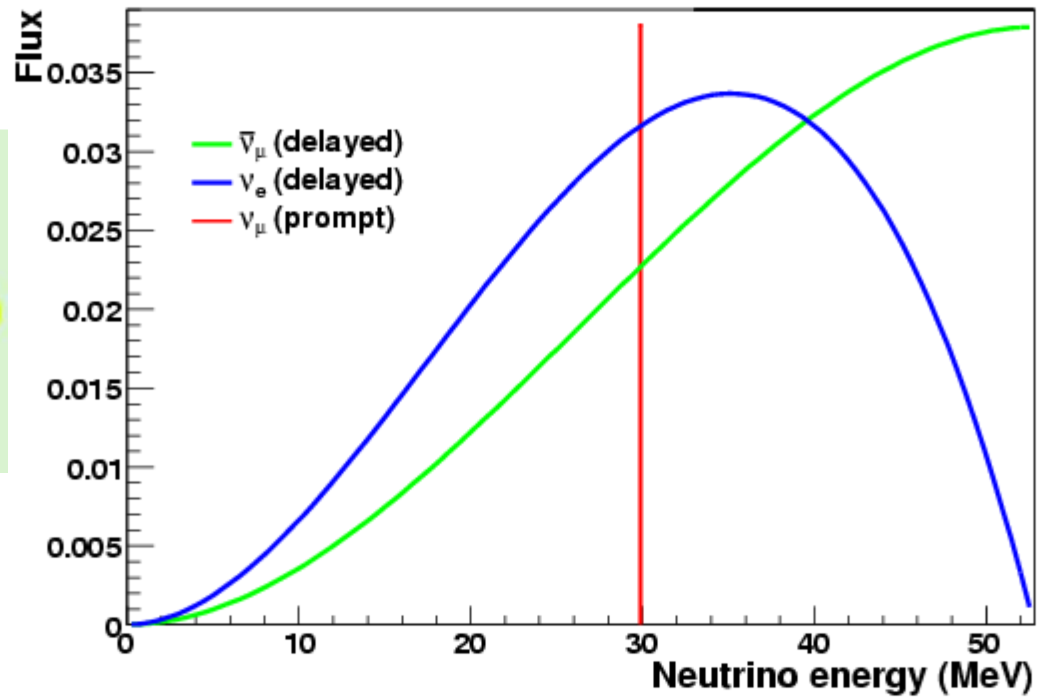
γ=10 boosted ^{18}Ne ν_e

Tunable energy, but not pulsed

Does not exist yet

Stopped-Pion (DAR) Neutrinos





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

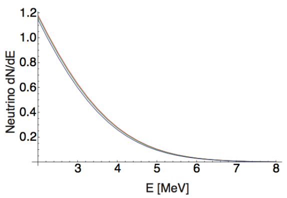
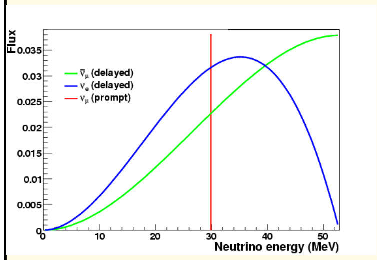
2-body decay: monochromatic 29.9 MeV ν_μ
PROMPT

$$\downarrow$$

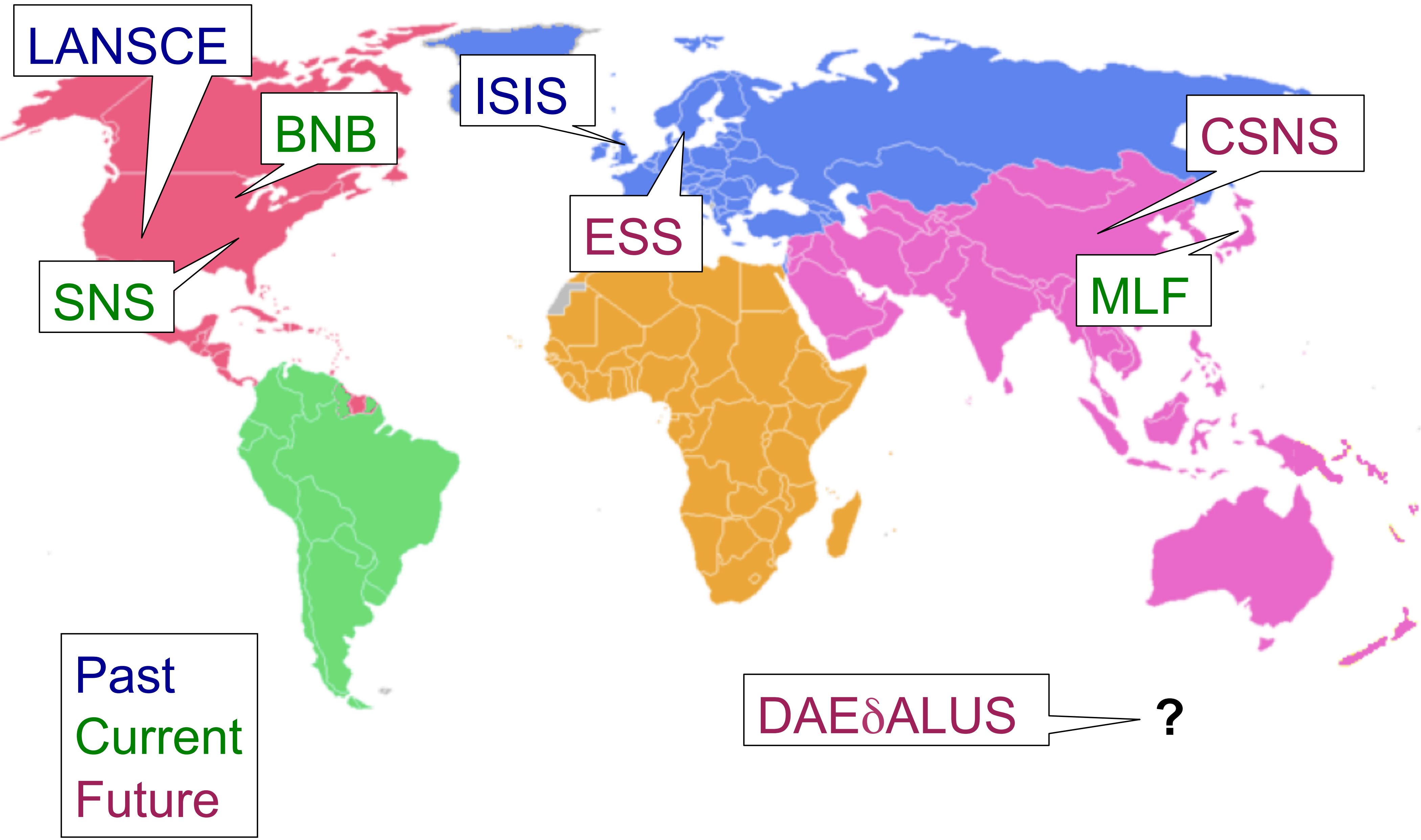
$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

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

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

Stopped-Pion Sources Worldwide

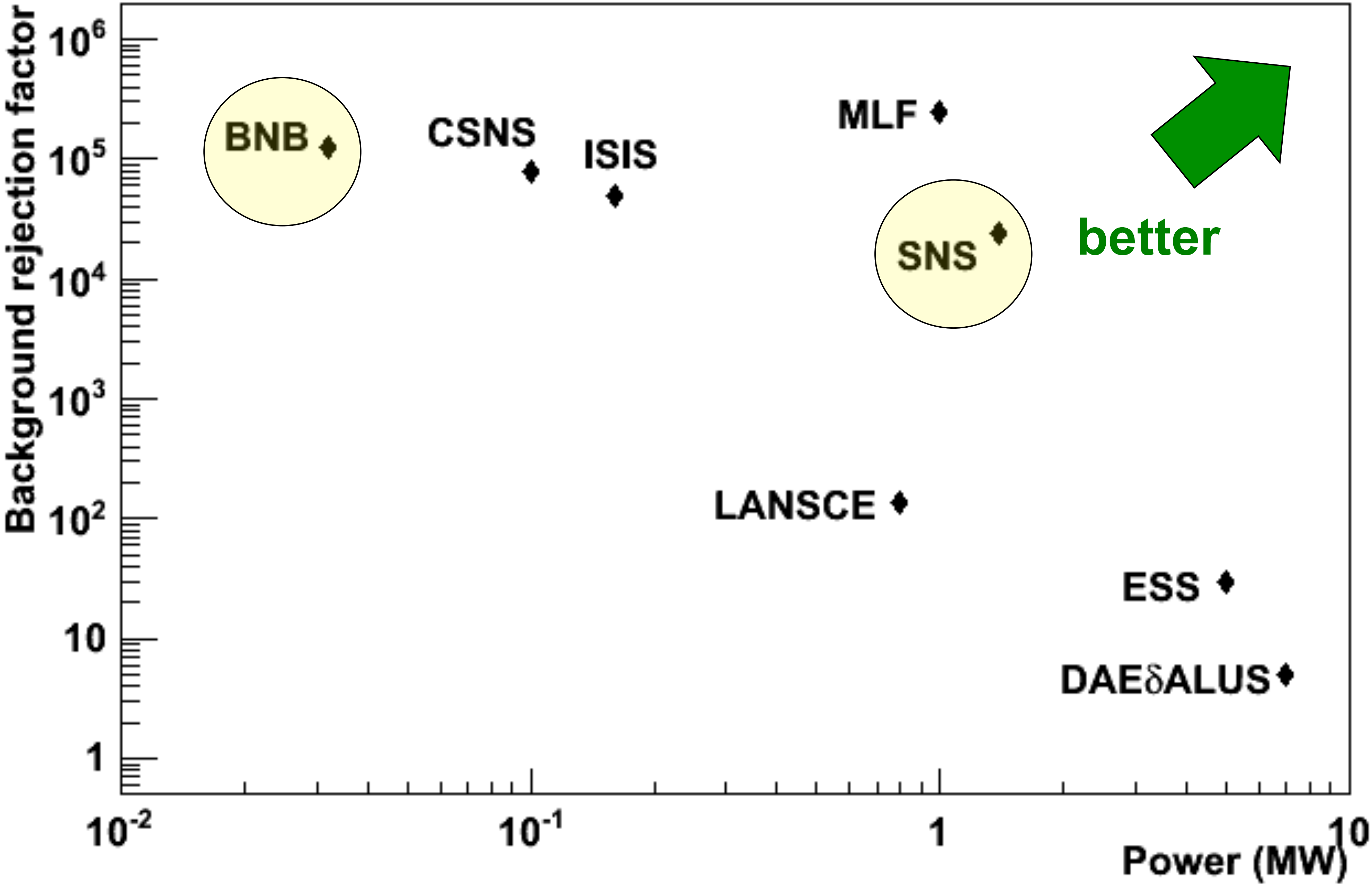


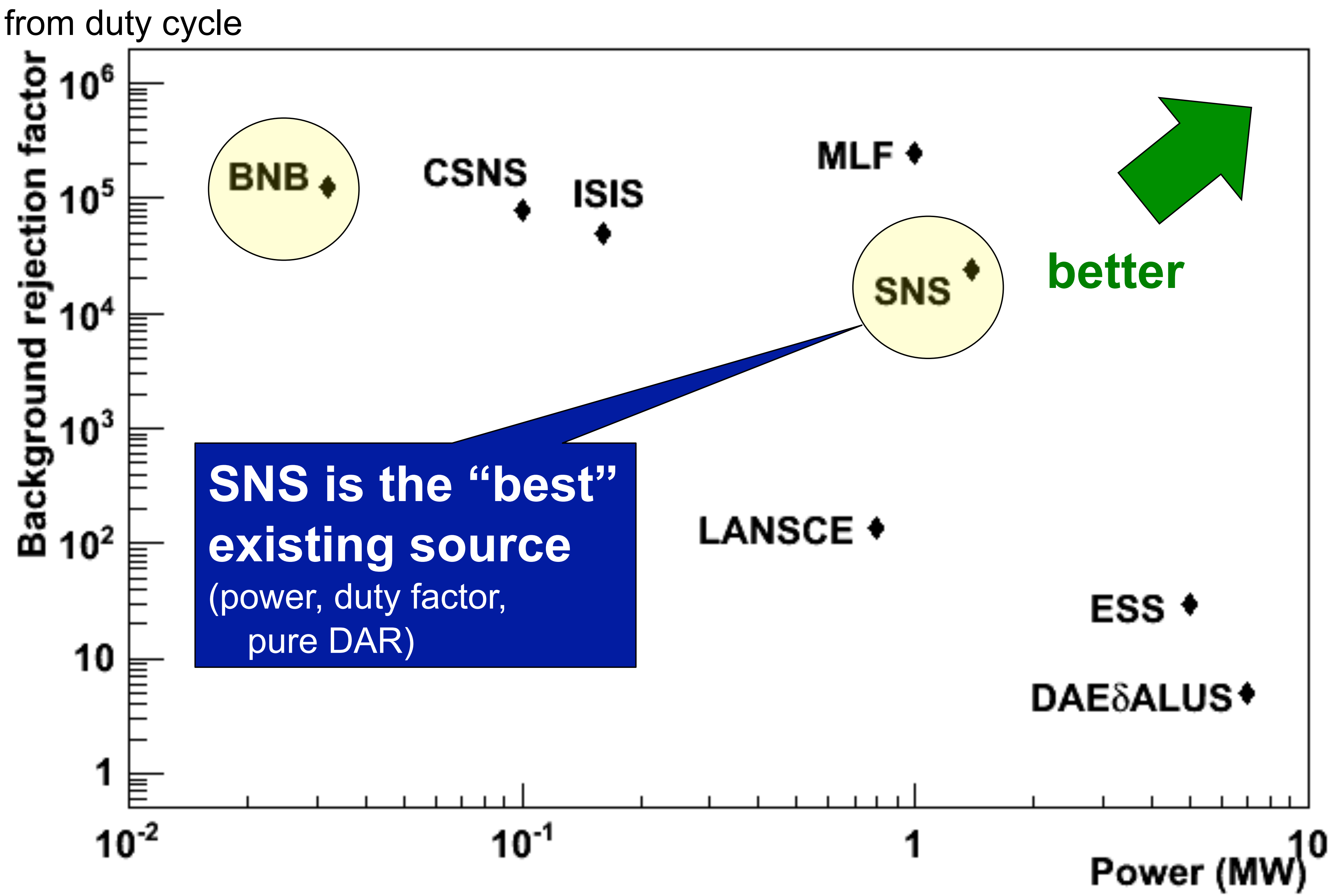
Stopped-pion neutrino sources

Facility	Location	Proton Energy (GeV)	Power (MW)	Bunch Structure	Rate
LANSCE	USA (LANL)	0.8	0.8	600 μs	120 Hz
ISIS	UK (RAL)	0.8	0.16	2×200 ns	50 Hz
BNB	USA (FNAL)	8	0.032	1.6 μs	5-11 Hz
SNS	USA (ORNL)	1.3	1	700 ns	60 Hz
MLF	Japan (J-PARC)	3	1	$2 \times$ 60-100 ns	25 Hz
CSNS	China (planned)	1.6	0.1	$<$500 ns	25 Hz
ESS	Sweden (planned)	1.3	5	2 ms	17 Hz
DAEδALUS	TBD (planned)	0.7	$\approx 7 \times 1$	100 ms	2 Hz

Want: - very high-intensity ν's
- ~below kaon threshold (low energy protons)
- nearly all decay at rest
- narrow pulses (small duty factor to mitigate bg)

from duty cycle




from duty cycle
Background rejection factor
10^6
10^5
10^4
10^3
10^2
10
1
10^{-2}
10^{-1}
1
10
Power (MW)
BNB
CSNS
ISIS
MLF
SNS
better
LANSCE
ESS
DAEδALUS
SNS is the "best" existing source
(power, duty factor,
pure DAR)

Spallation Neutron Source at ORNL

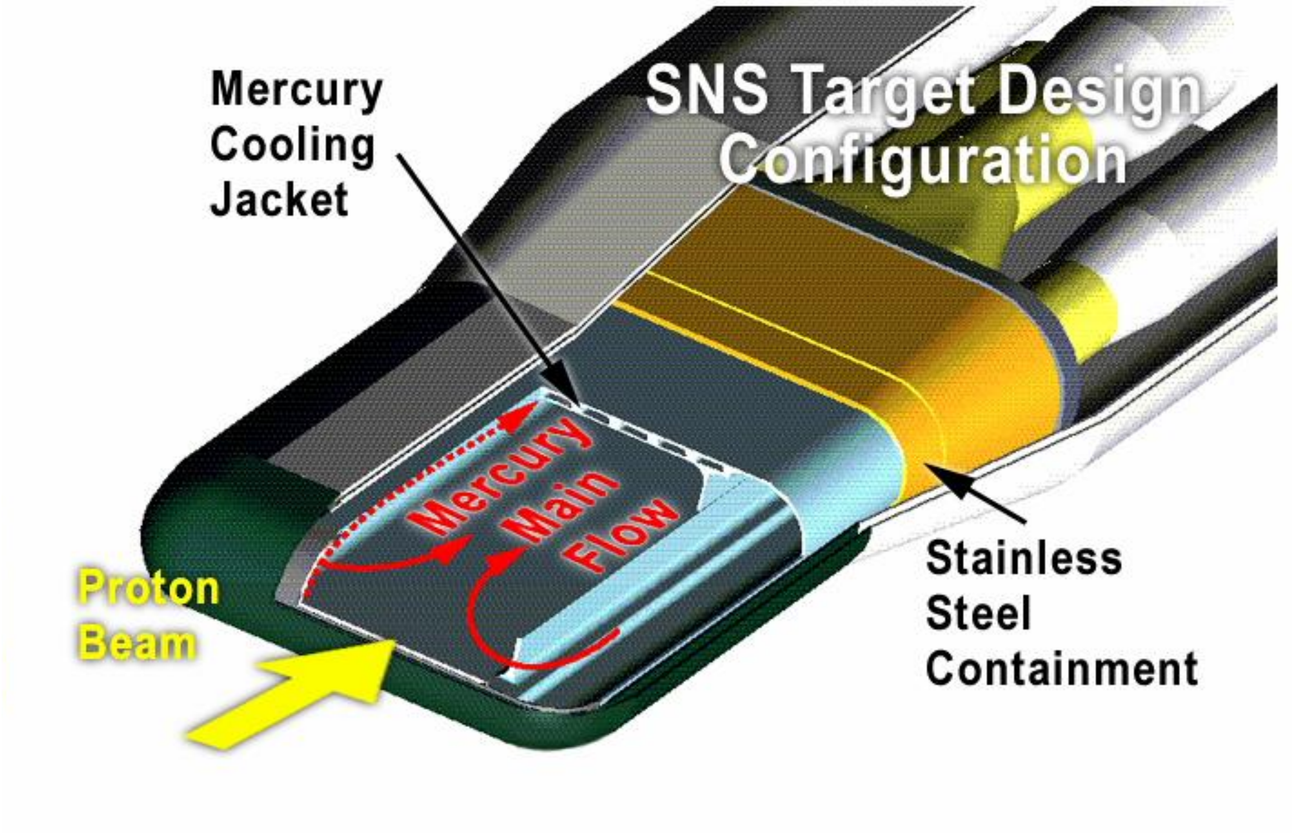
1.3 GeV proton linear accelerator

Accumulator ring

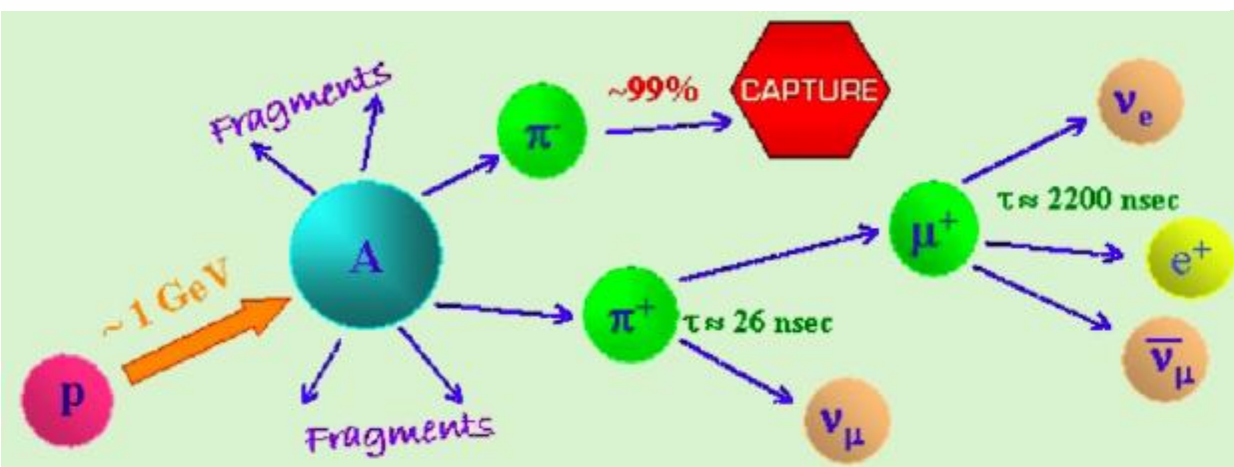
Main target

Y. Efremenko

The SNS as a Stopped-Pion Neutrino Source

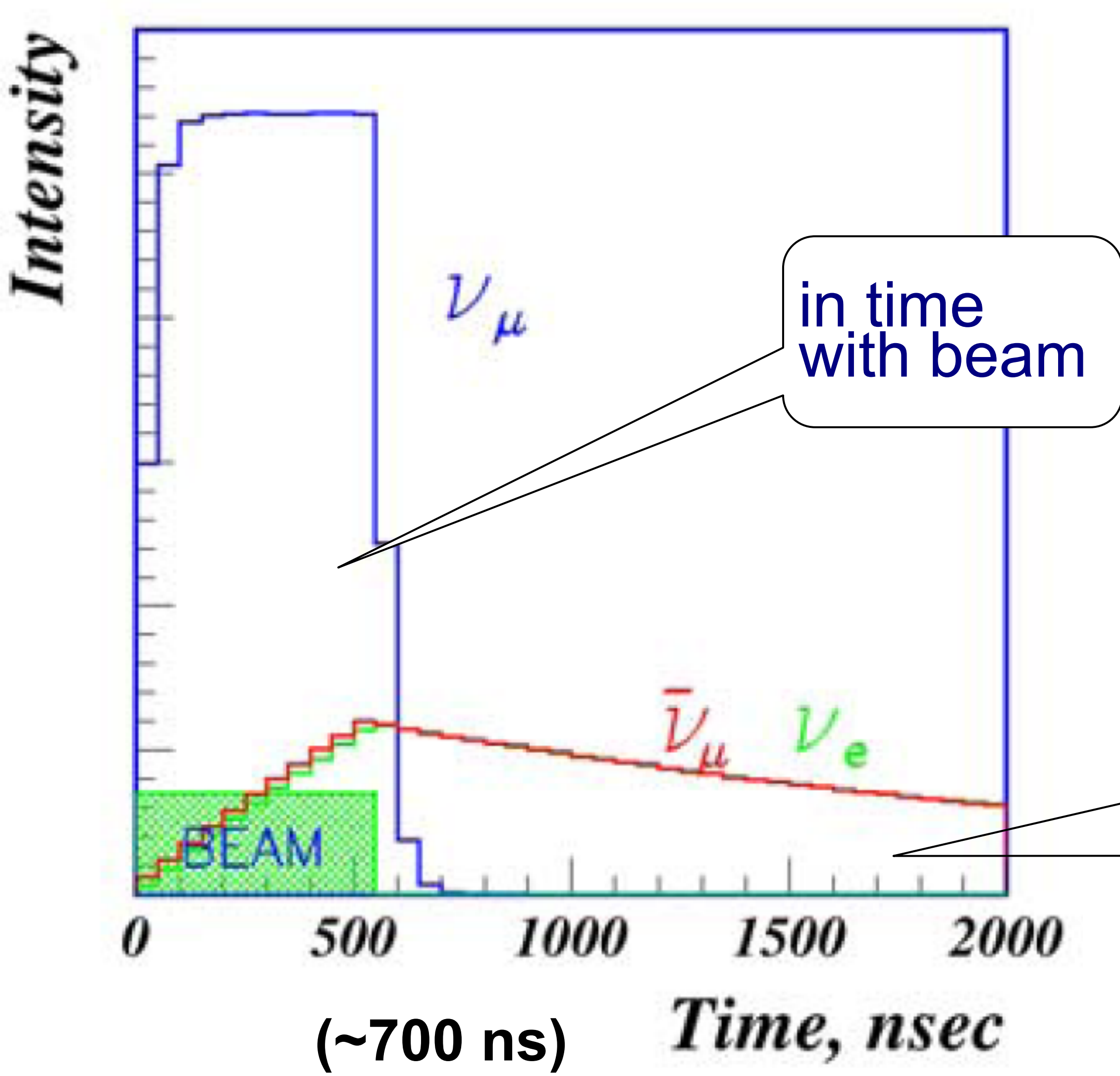


In addition to kicking out neutrons, protons on target create copious pions:
π^- get captured;
π^+ slow and decay at rest

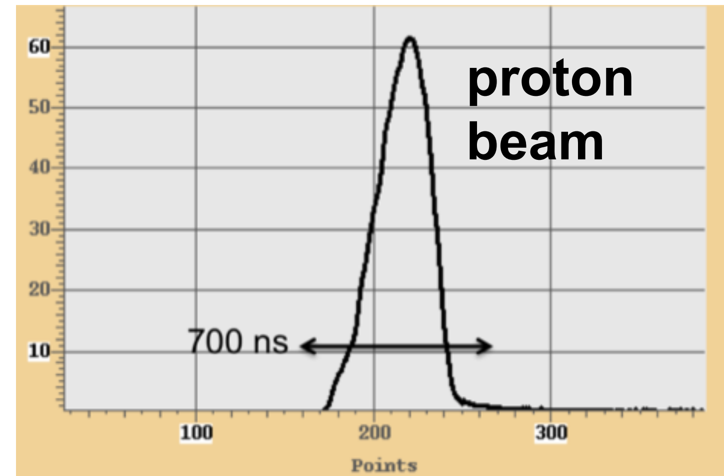


Time structure of the SNS source

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



60 Hz *pulsed* source



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

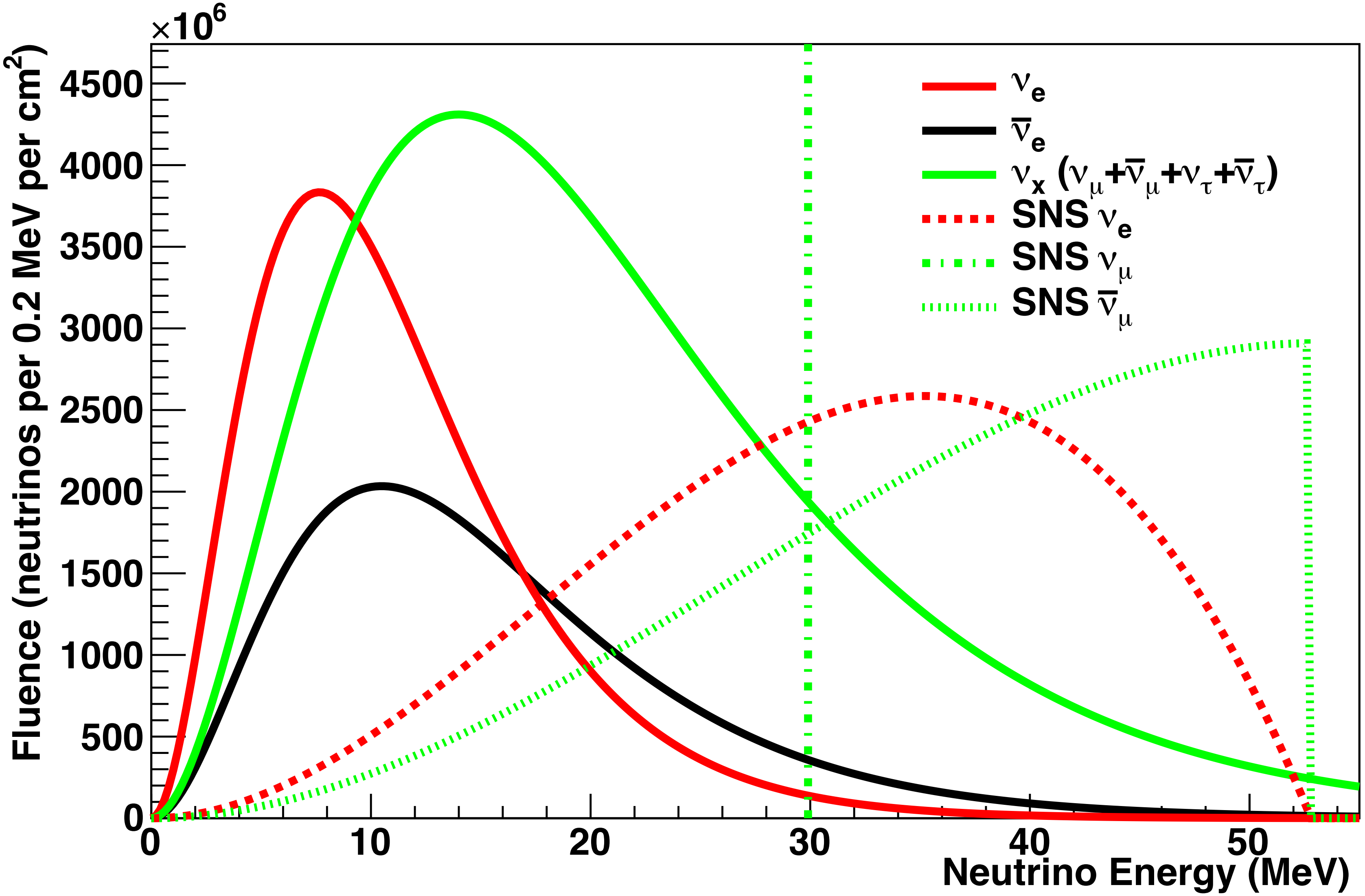
Neutrino flux: few times 10^7 /s/cm^2 at 20 m

~0.13 per flavor per proton

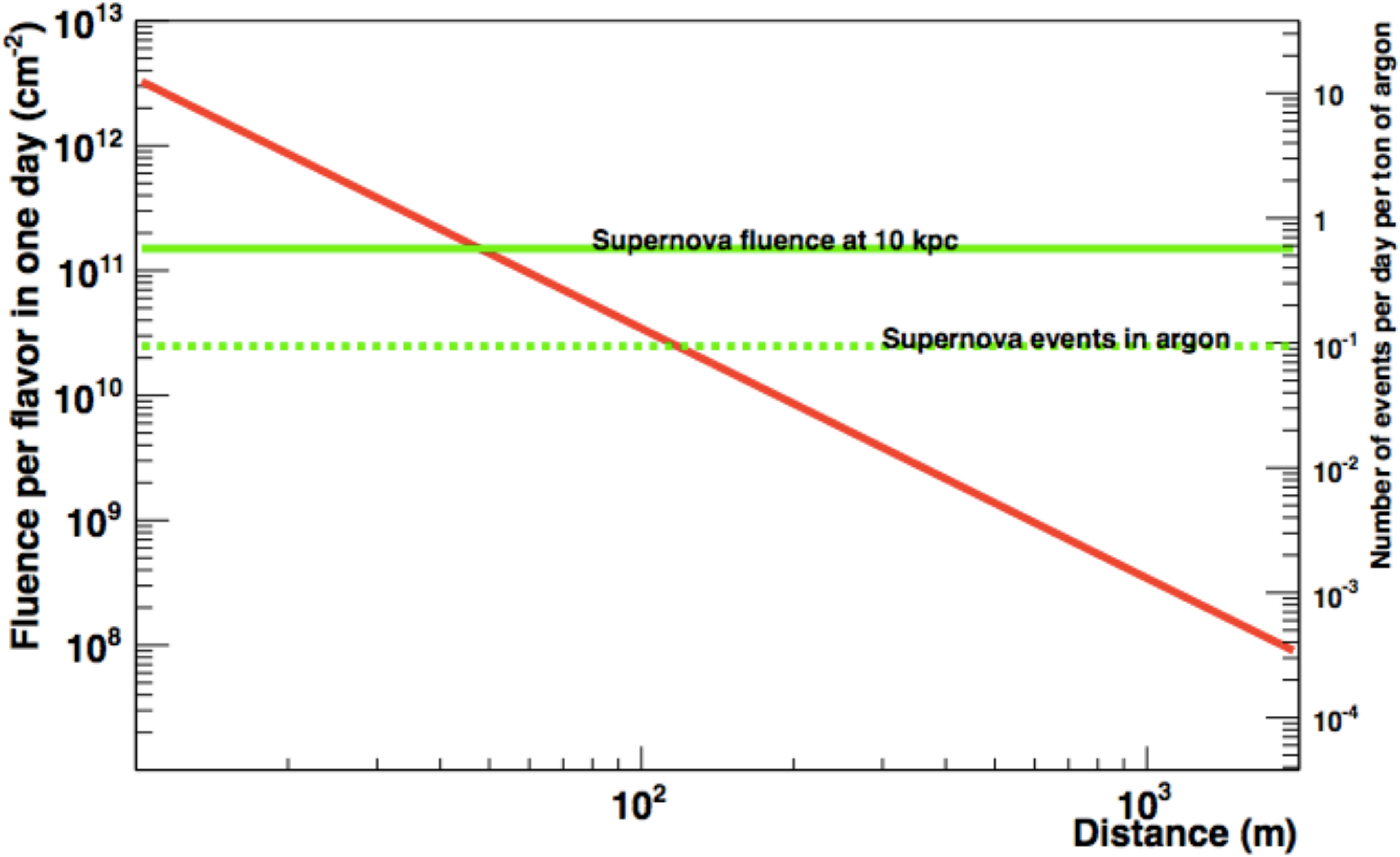
These are *not* crummy old cast-off neutrinos...

They are of the highest quality!

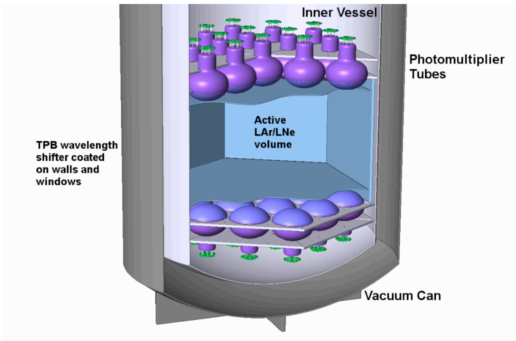
Supernova neutrino spectrum overlaps very nicely with stopped π neutrino spectrum

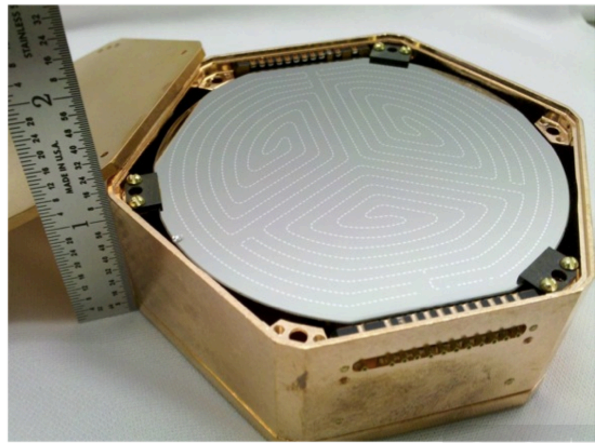


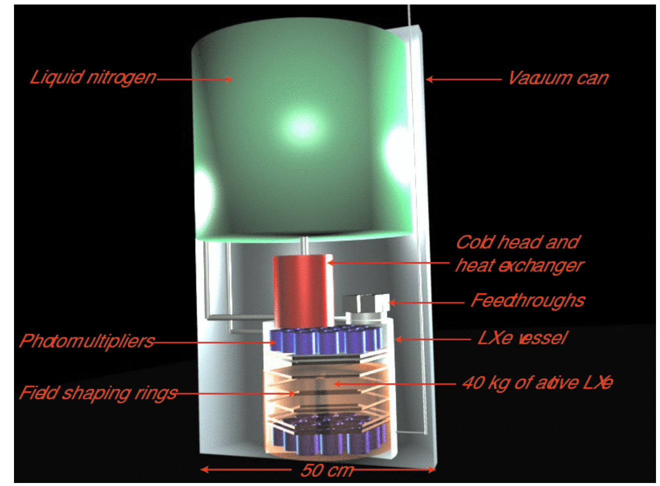
Fluence at ~50 m from the stopped pion source amounts to ~ a supernova a day!



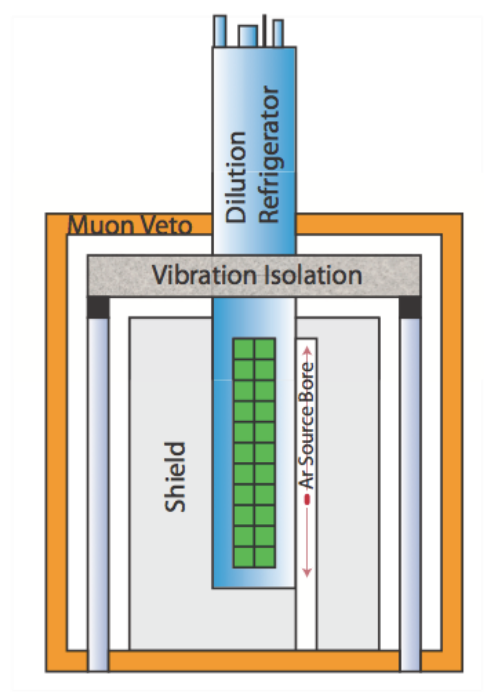
Detector possibilities: various DM-style strategies

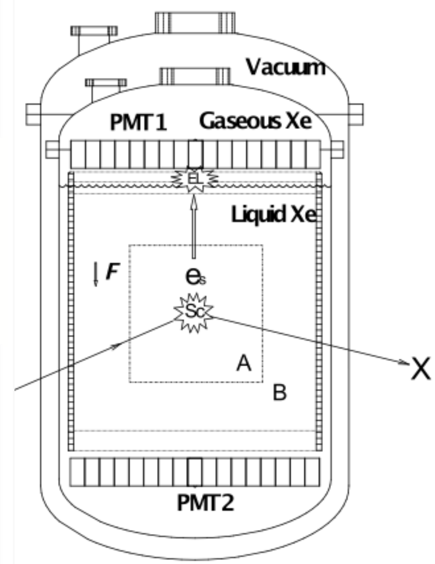


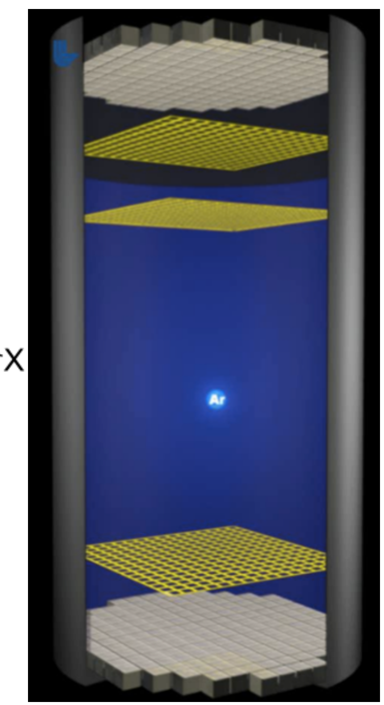




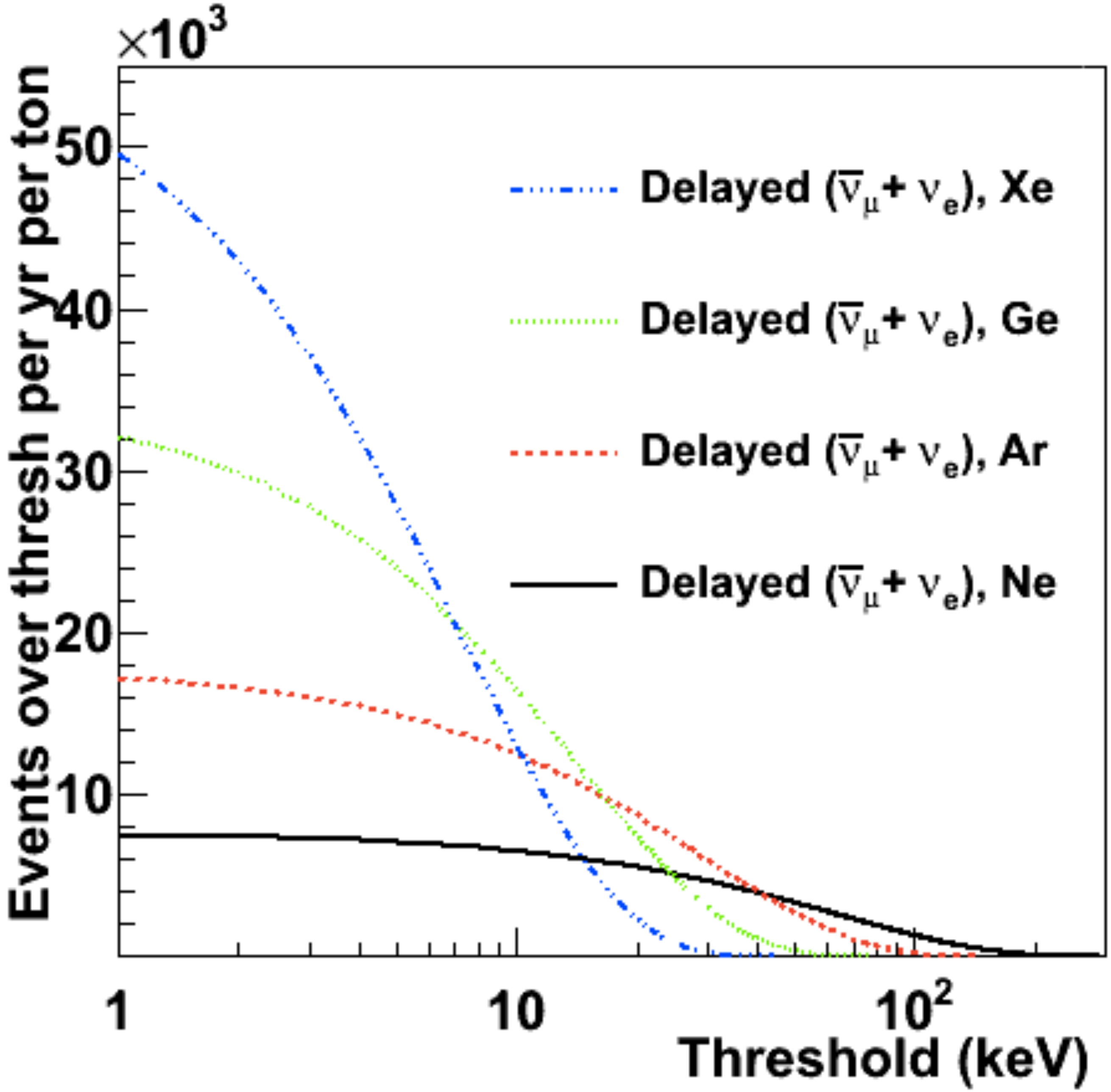
few to tens of keV nuclear recoil sensitivity







Integrated SNS CENNS yield for various targets



20 m

Lighter nucleus
$\Rightarrow$ expect fewer interactions, but more at higher energy

What physics could be learned from measuring this?

KS, Phys. Rev D 73 (2006) 033005

Basically, any deviation from SM cross-section is interesting...

- Weak mixing angle
- Non Standard Interactions (NSI) of neutrinos
- Neutrino magnetic moment
- Sterile oscillations
- ...
- Nuclear physics

Weak mixing angle

L. M. Krauss, Phys. Lett. B 269 (1991) 407-411

Absolute rate in SM is proportional to

$$(N - (1 - 4\sin^2\theta_W)Z)^2$$

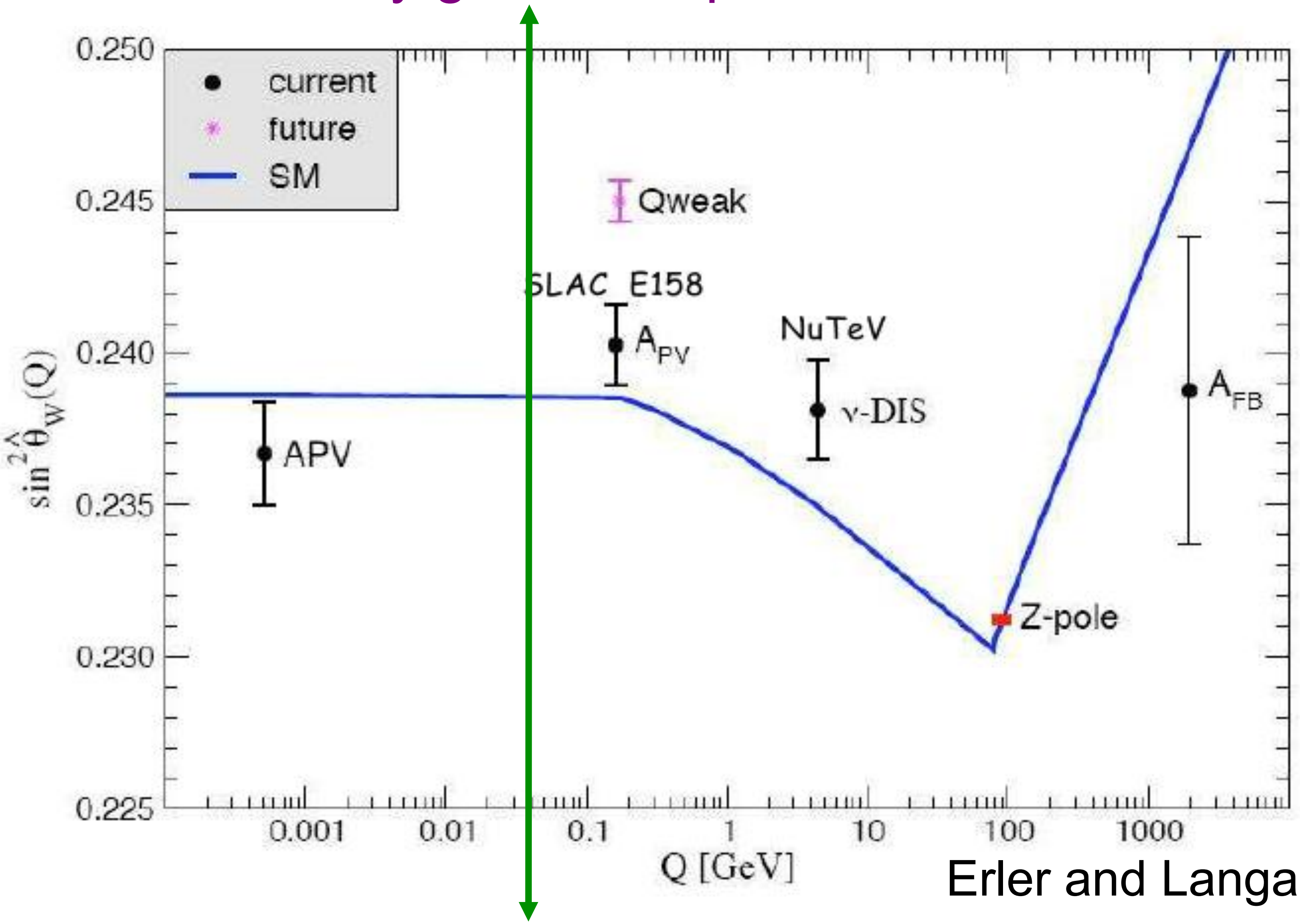
Momentum transfer at SNS is Q~ 0.04 GeV/c

If absolute cross-section can be measured to ~10%,
Weinberg angle can be known to ~5%

First-generation measurement not competitive:

(assuming ~10% systematic error on rate)

... could eventually get to few percent (limited by nuclear physics)



Erler and Langacker, PDG

However note it's a

unique channel and independent test

Consider Non-Standard Interactions (NSI) specific to neutrinos + quarks

Model-independent parameterization

Davidson et al., JHEP 0303:011 (2004) hep-ph/0302093
Barranco et al., JHEP 0512:021 (2005) hep-ph/0508299

$$\mathcal{L}_{\nu H}^{NSI} = -\frac{G_F}{\sqrt{2}} \sum_{\substack{q=u,d \\ \alpha,\beta=e,\mu,\tau}} [\bar{\nu}_\alpha \gamma^\mu (1-\gamma^5)\nu_\beta] \times (\varepsilon_{\alpha\beta}^{qL}[\bar{q}\gamma_\mu(1-\gamma^5)q] + \varepsilon_{\alpha\beta}^{qR}[\bar{q}\gamma_\mu(1+\gamma^5)q])$$

NSI parameters

'Non-Universal': ε_{ee}, $\varepsilon_{\mu\mu}$, $\varepsilon_{\tau\tau}$

Flavor-changing: $\varepsilon_{\alpha\beta}$, where $\alpha\neq\beta$

$\Rightarrow$ focus on poorly-constrained (~unity allowed)

ε_{ee}^{uV}, ε_{ee}^{dV}, $\varepsilon_{\tau e}^{uV}$, $\varepsilon_{\tau e}^{dV}$

Cross-section for CENNS including NSI terms

For flavor α, spin zero nucleus:

$$\left(\frac{d\sigma}{dE}\right)_{\nu_\alpha A} = \frac{G_F^2 M}{\pi} F^2(2ME)\left[1 - \frac{ME}{2k^2}\right] \times$$

$$\{[Z(g_V^p + 2\varepsilon_{\alpha\alpha}^{uV} + \varepsilon_{\alpha\alpha}^{dV}) + N(g_V^n + \varepsilon_{\alpha\alpha}^{uV} + 2\varepsilon_{\alpha\alpha}^{dV})]^2$$ non-universal

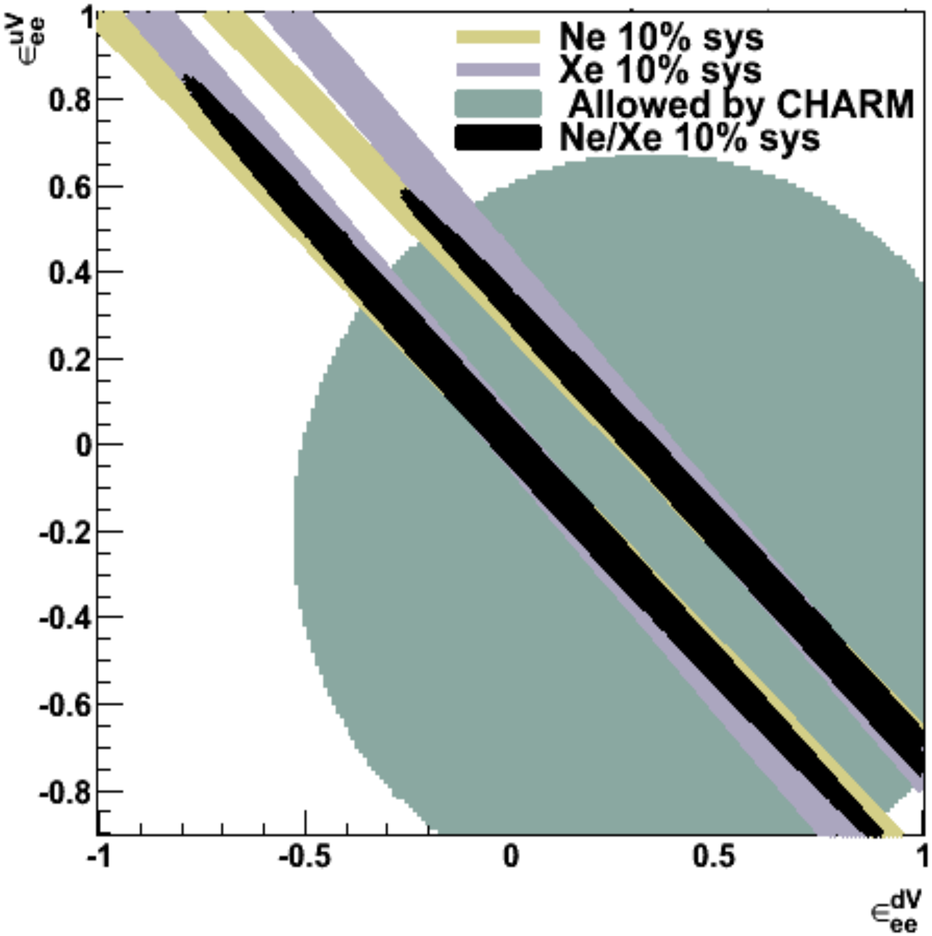
$$+ \sum_{\alpha \neq \beta} [Z(2\varepsilon_{\alpha\beta}^{uV} + \varepsilon_{\alpha\beta}^{dV}) + N(\varepsilon_{\alpha\beta}^{uV} + 2\varepsilon_{\alpha\beta}^{dV})]^2\}$$ flavor-changing

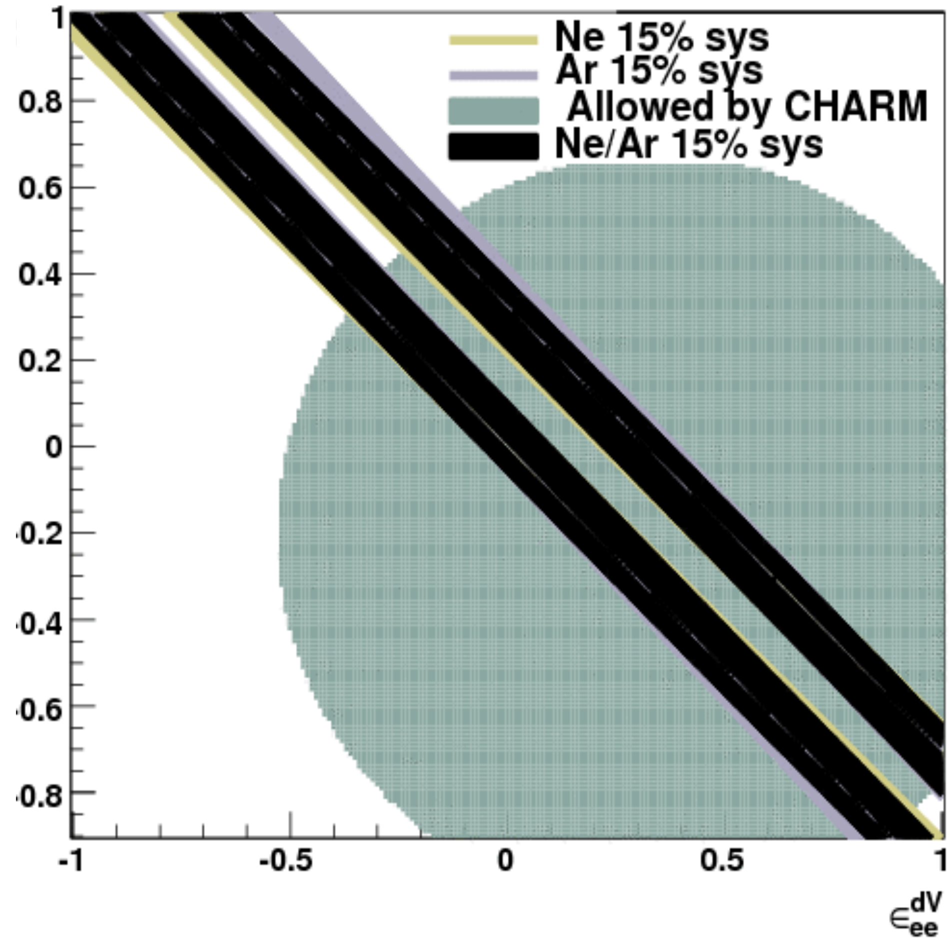
$$g_V^p = (\frac{1}{2} - 2\sin^2\theta_W), \quad g_V^n = -\frac{1}{2}$$ SM parameters

$$\varepsilon_{\alpha\beta}^{qV} = \varepsilon_{\alpha\beta}^{qL} + \varepsilon_{\alpha\beta}^{qR}$$

- NSI affect total cross-section,
  not differential shape of recoil spectrum
- size of effect depends on N, Z
  (different for different elements)
- ε's can be negative and parameters can cancel

Non-Standard Interactions of Neutrinos





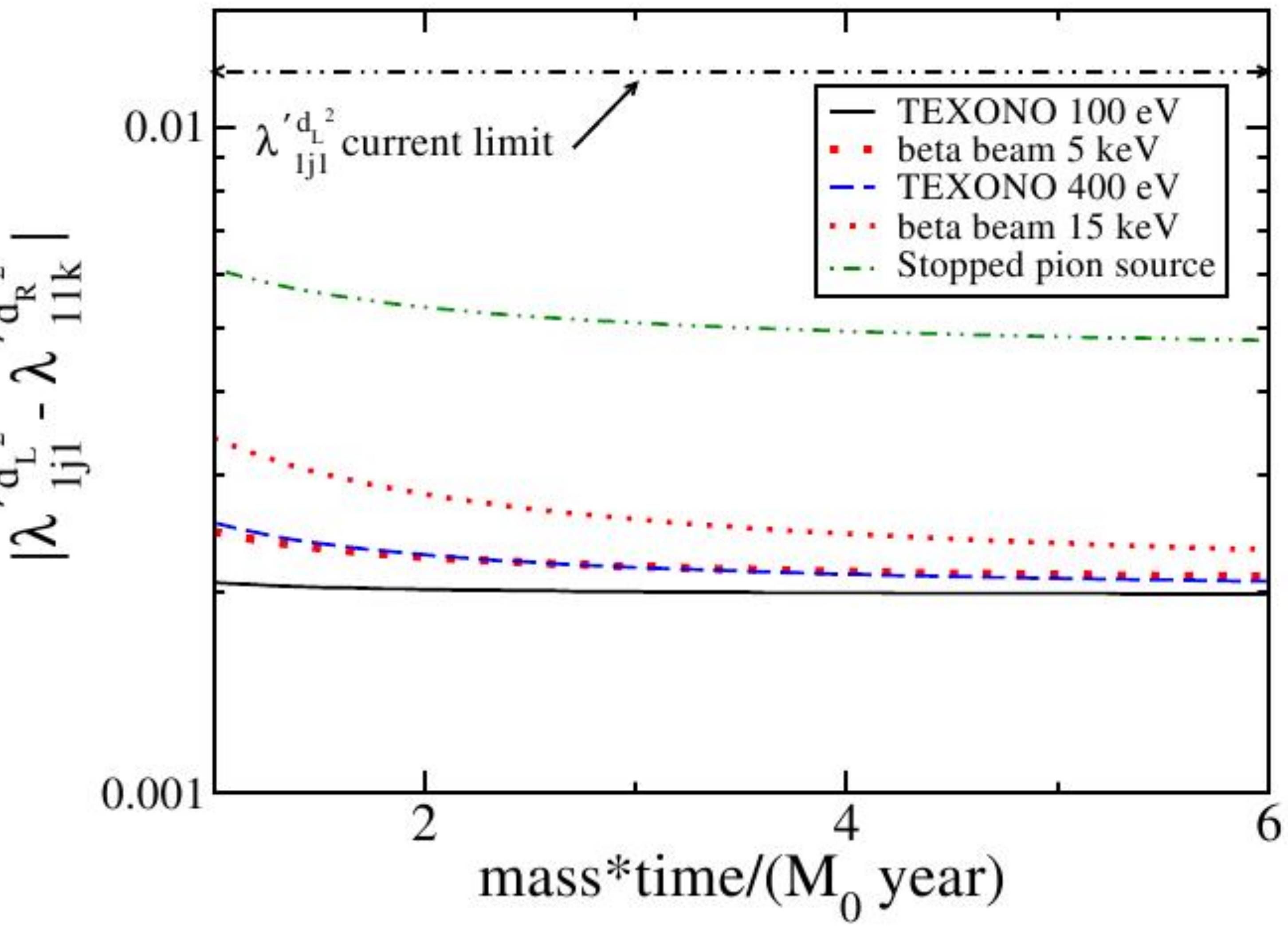
Can improve ~order of magnitude beyond CHARM limits with a first-generation experiment

(for best sensitivity, want *multiple targets*)

J. Barranco, O.G. Miranda, T.I. Rashba,
Phys. Rev. D 76: 073008 (2007) hep-ph/0702175:

Low energy neutrino experiments sensitivity to physics beyond the Standard Model

Specific NSI models: Z', leptoquark,
SUSY with broken R-parity



Combination of targets will help

(Y. Efremenko, P. Barbeau)

$$\mathrm{rate} \propto (N - (1 - 4\sin^2\theta_W)Z)^2$$

For 1% uncertainty on the *ratio* of rates in two different targets, get uncertainty on $\sin^2\theta_W$:

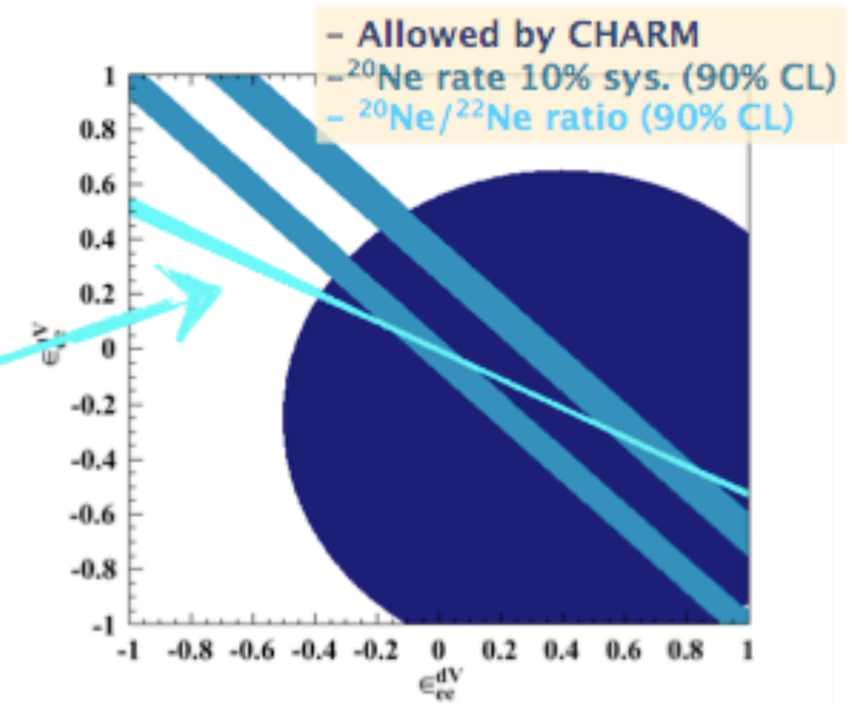
Ar/Ne	2.6%
Xe/Ne	1.5%
Xe/Ar	3.9%

NSI Search with ^{20}Ne-^{22}Ne

$$\frac{d\sigma}{dT}_{coh} = \frac{G_f^2 M}{2\pi} = G_V^2\left(1 + \left(1 - \frac{T}{E_\nu}\right)^2 - \frac{MT}{E_\nu}\right)$$

$$G_V = ((g_v^p + 2\epsilon_{ee}^{uV} + \epsilon_{ee}^{dV})Z + (g_v^n + \epsilon_{ee}^{uV} + 2\epsilon_{ee}^{dV})N)F_{nucl}^V(Q^2)$$

- We take advantage of the precision in the ^{20}Ne/^{22}Ne system (^{132}Xe/^{136}Xe system less sensitive)
- If we include the SM radiative corrections, as well as statistical & systematic uncertainties, the ratio of the interaction rates for ^{20}Ne/^{22}Ne gives (For several tons of Ne)



P. Barbeau

Neutrino magnetic moment

Prediction of Standard Model: $\mu_\nu \sim 10^{-19} \mu_B \left(\frac{m_\nu}{1 \text{ eV}} \right)$

but extensions predict larger ones

Current best experimental limits:

Best limit from lack of distortion of ν-e elastic scattering x-scn , for reactor anti-ν_e's (GEMMA)

For ν_μ, best limit is from LSND ν_μ-e scattering

VALUE (10^{-10} μ_B)	CL%	DOCUMENT ID		TECN	COMMENT
< **0.32**	90	[122] BEDA	10	CNTR	Reactor $\overline{\nu}_e$
< **6.8**	90	[123] AUERBACH	01	LSND	$\nu_e e$, $\nu_\mu e$ scattering
< **3900**	90	[124] SCHWIENHO...	01	DONU	$\nu_\tau e^- \rightarrow \nu_\tau e^-$

Astrophysical limits:

(red giant cooling, SN1987A)

$$\mu_\nu < 10^{-10} - 10^{-12} \mu_B$$

Magnetic moment effect on the CENNS scattering rate

P. Vogel & J. Engel, PRD 39 (1989) 3378

SM cross-section:

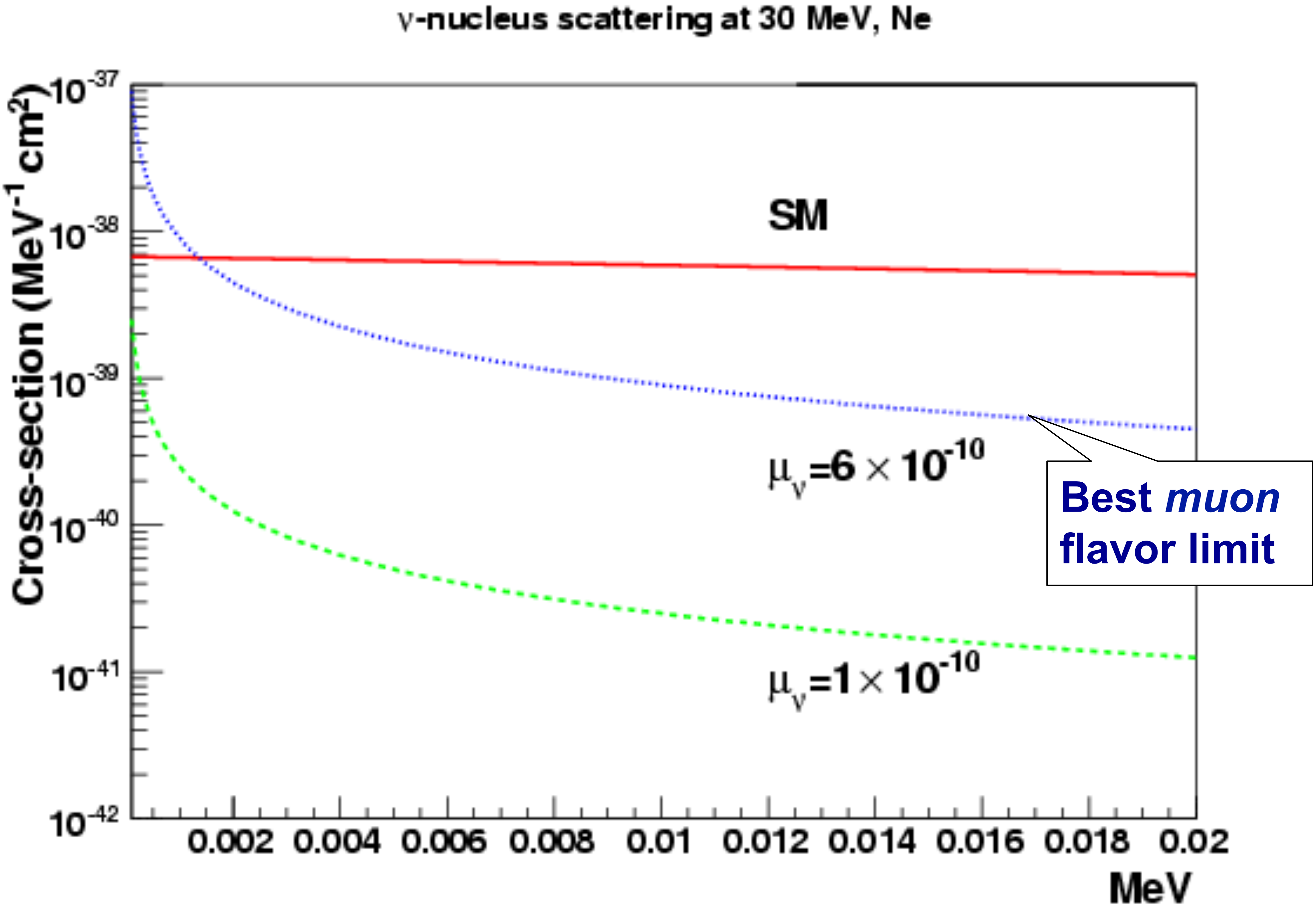
$$\frac{d\sigma}{dE} = \frac{G^2}{\pi} M \left(1 - \frac{ME}{2k^2}\right) \frac{N - (1 - 4\sin^2\theta_W)Z)^2}{4} F^2(Q^2)$$

Magnetic cross-section:

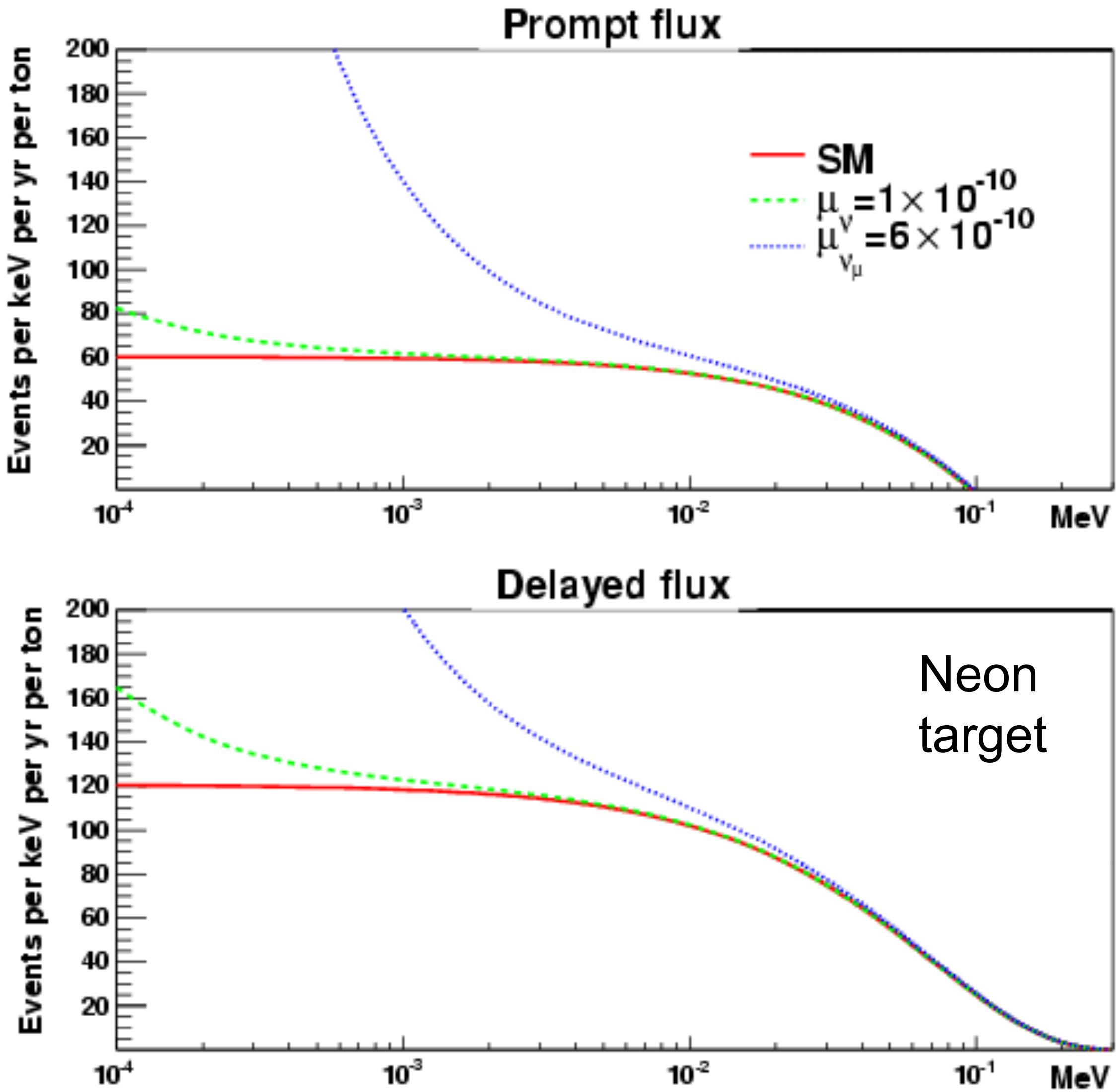
$$\frac{d\sigma}{dE} = \frac{\pi\alpha^2\mu_\nu^2 Z^2}{m_e^2} \left(\frac{1 - E/k}{E} + \frac{E}{4k^2}\right)$$

(factor Z^2 instead of Z for electrons)

Cross-sections for 30 MeV ν



Differential yield at the SNS: muon and electron flavors



Impossible to see excess for $\mu_\nu=10^{-10}$ for 10 keV threshold

....but several % excess over SM background at ~10 keV for $\mu_\nu=6\times10^{-10}\ \mu_B$

Experimentally hard! But maybe doable

Nuclear physics with coherent elastic scattering

If systematics can be reduced to ~ few % level,
we could start to explore nuclear form factors

P. S. Amanik and G. C. McLaughlin, J. Phys. G 36:015105, 2009 hep-ph.0707.4191
K. Patton et al., arXiv:1207.0693,

$$\frac{d\sigma}{dT}(E,T) = \frac{G_F^2}{2\pi} M \left[2 - \frac{2T}{E} + \left(\frac{T}{E}\right)^2 - \frac{MT}{E^2}\right] \frac{Q_W^2}{4} F^2(Q^2)$$

Form factor: encodes information about nucleon (primarily neutron) distributions

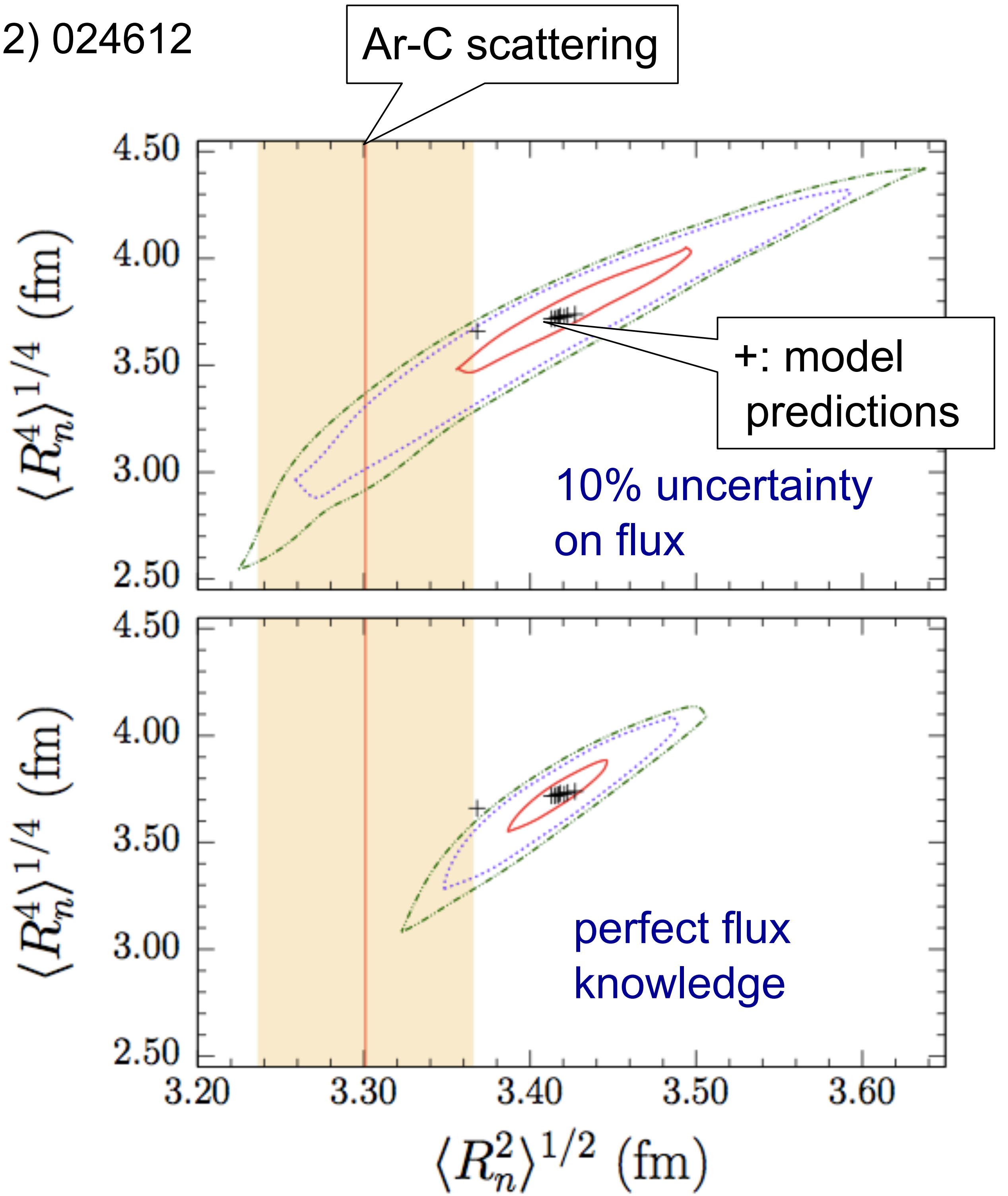
$$F_n(Q^2) \approx \int \rho_n(r) \left(1 - \frac{Q^2}{3!} r^2 + \frac{Q^4}{5!} r^4 - \frac{Q^6}{7!} r^6 + \cdots \right) r^2 dr$$

$$\approx N \left(1 - \frac{Q^2}{3!} \langle R_n^2 \rangle + \frac{Q^4}{5!} \langle R_n^4 \rangle - \frac{Q^6}{7!} \langle R_n^6 \rangle + \cdots \right).$$

Fit recoil *spectral shape* to determine these moments
(requires very good energy resolution)

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

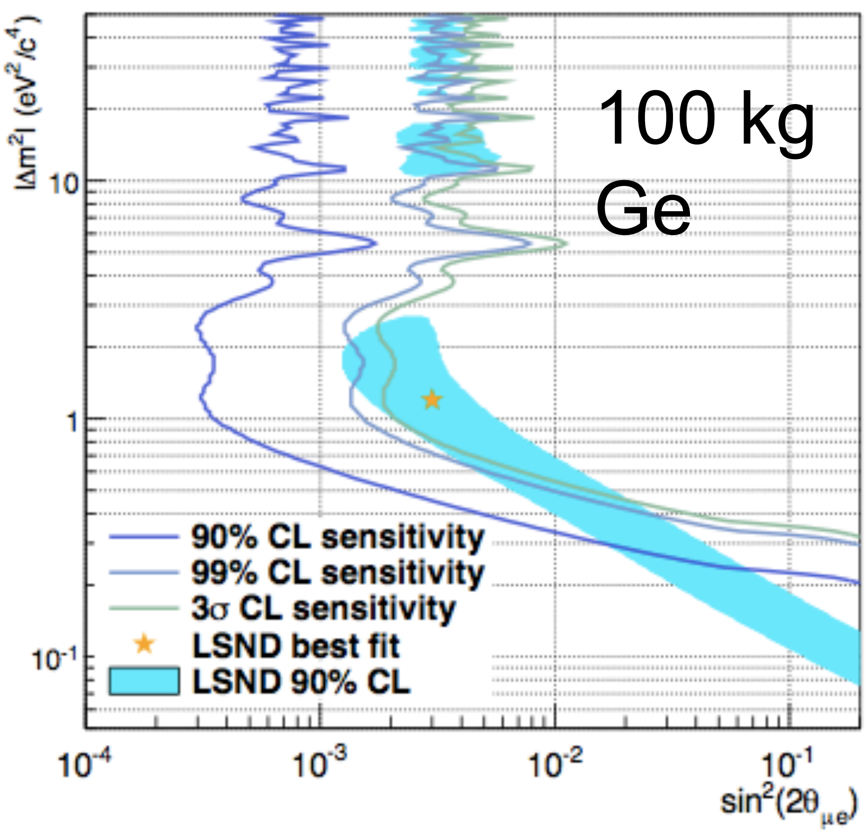
Oscillations to sterile neutrinos w/CENNS

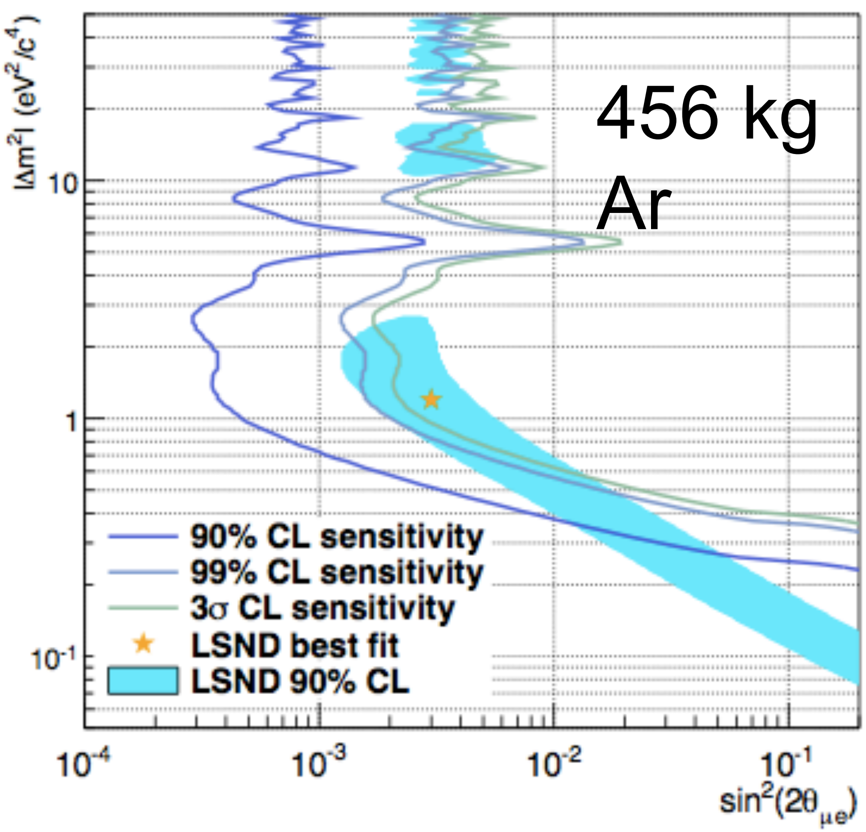
(NC is flavor-blind)

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





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

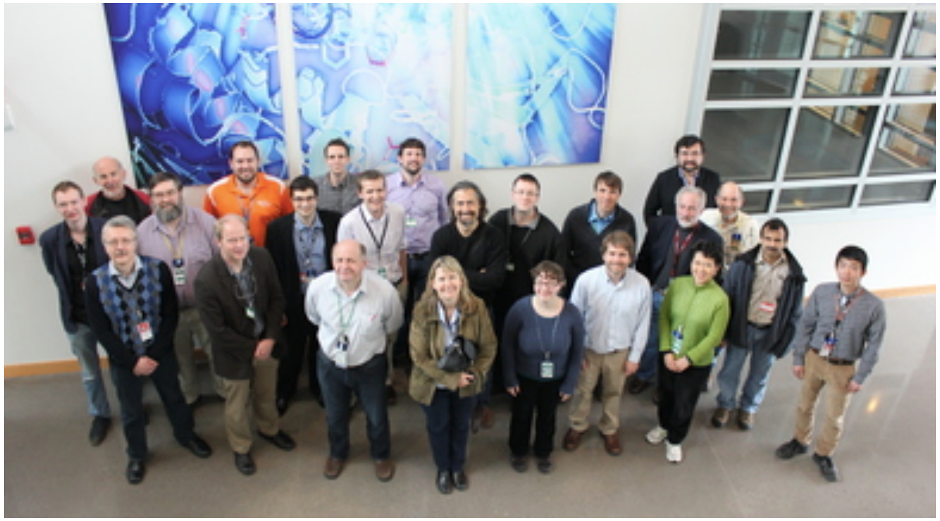
Possible phases of stopped-pion coherent νA scattering experiments

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



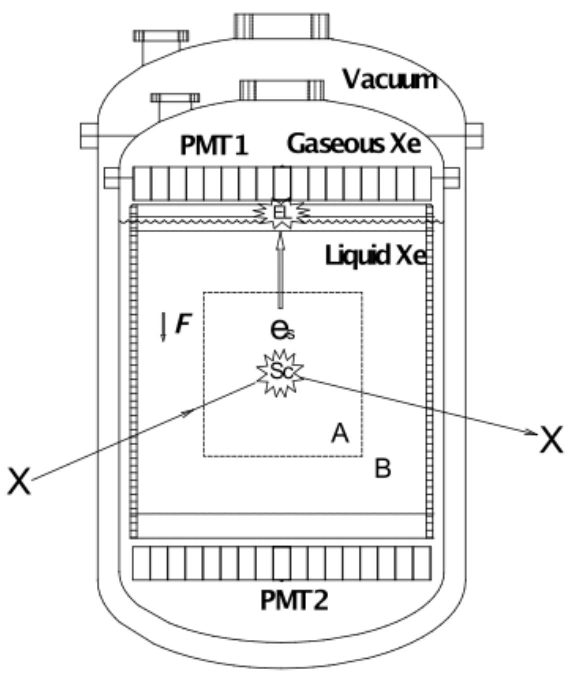
~ 45 collaborators presently

Actively recruiting more

COHERENT collaboration @ SNS

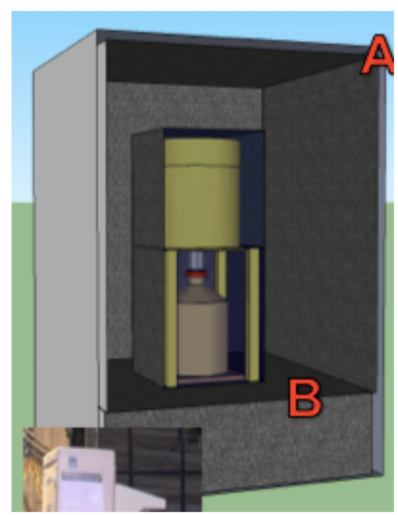
Three possible technologies under consideration

Two-phase LXe

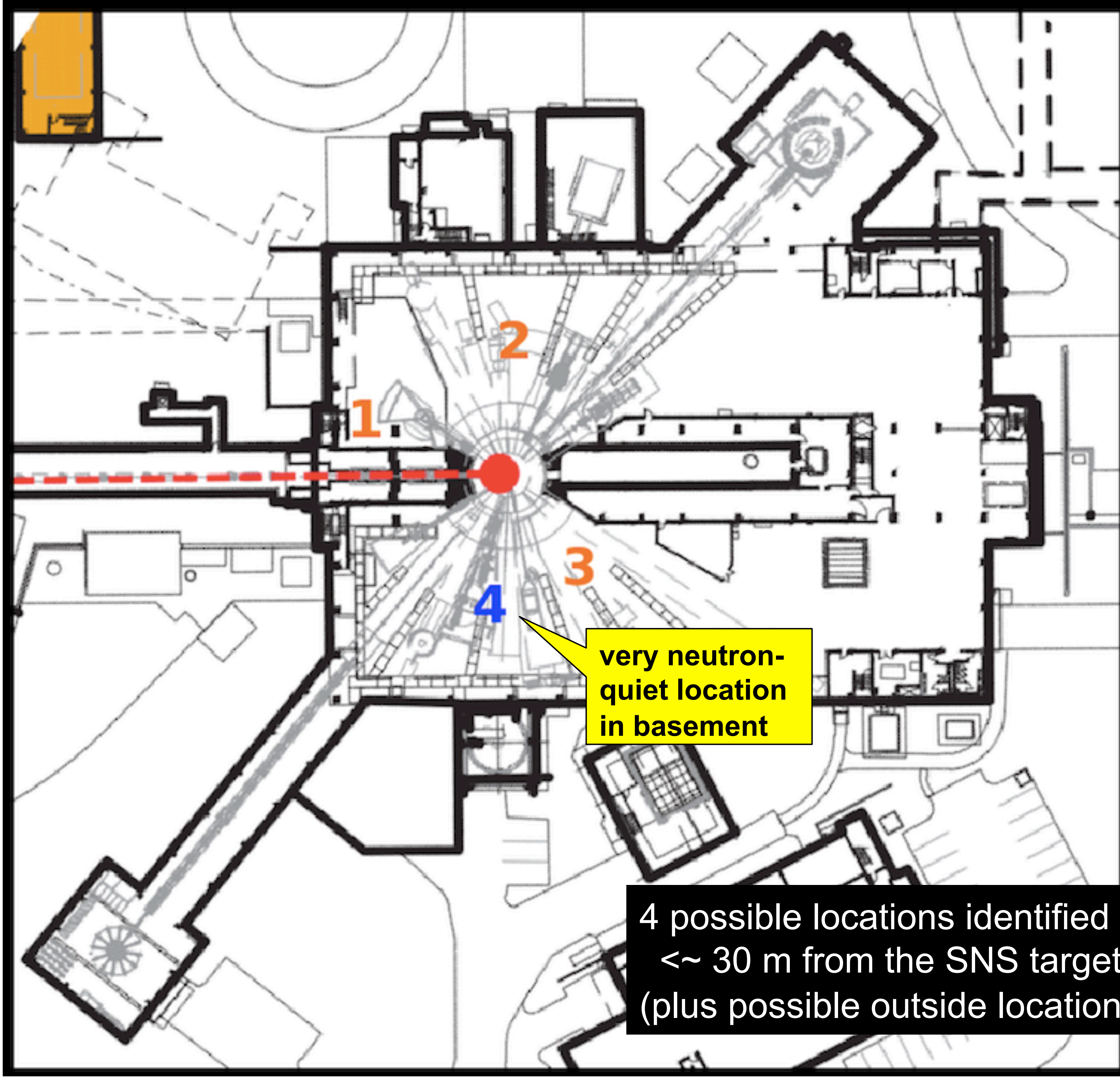


arXiv:1310.0125

CsI

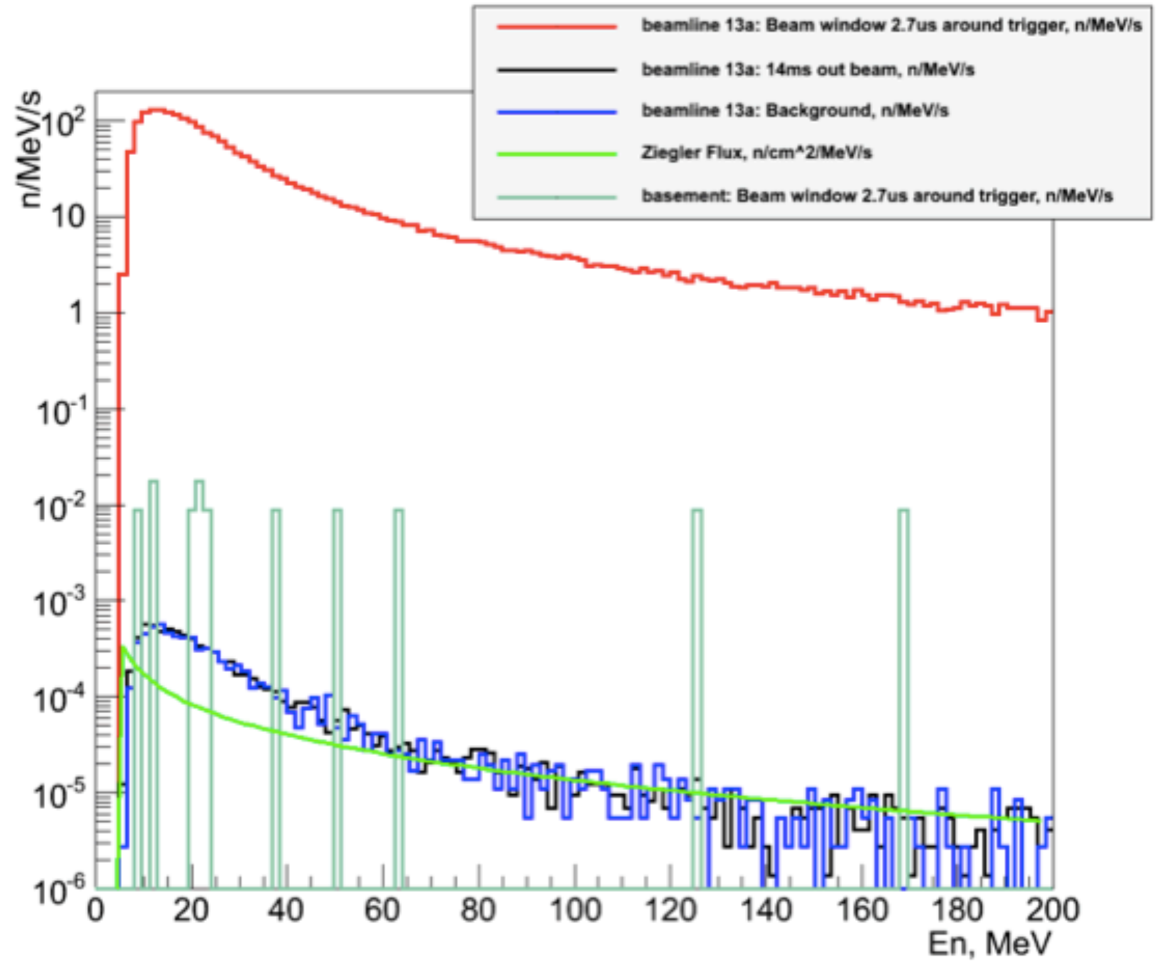


HPGe PPC



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

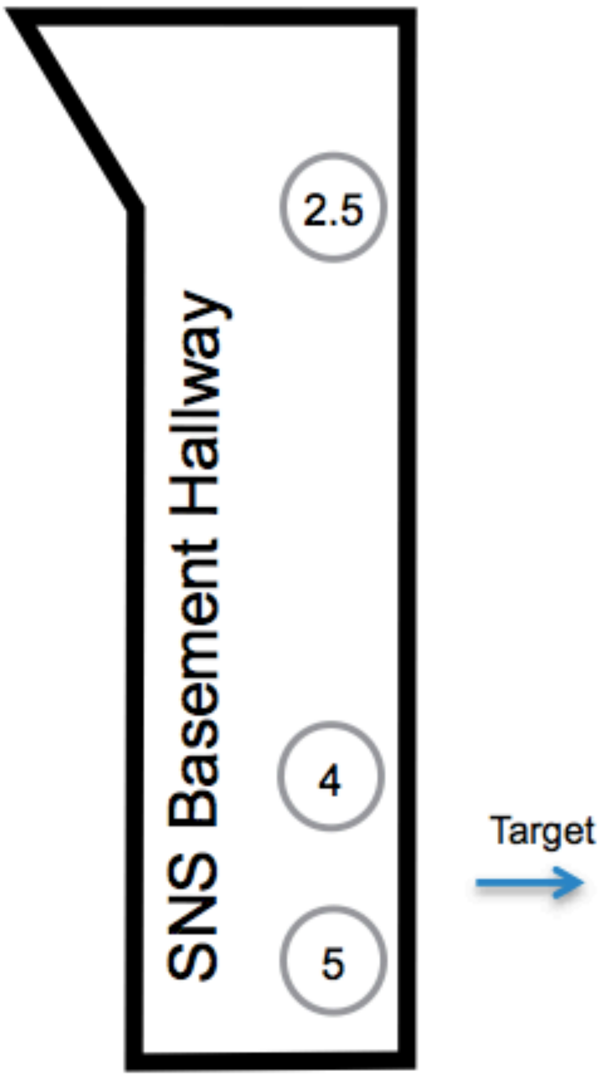
Neutron Background Measurements w/ Scintillator

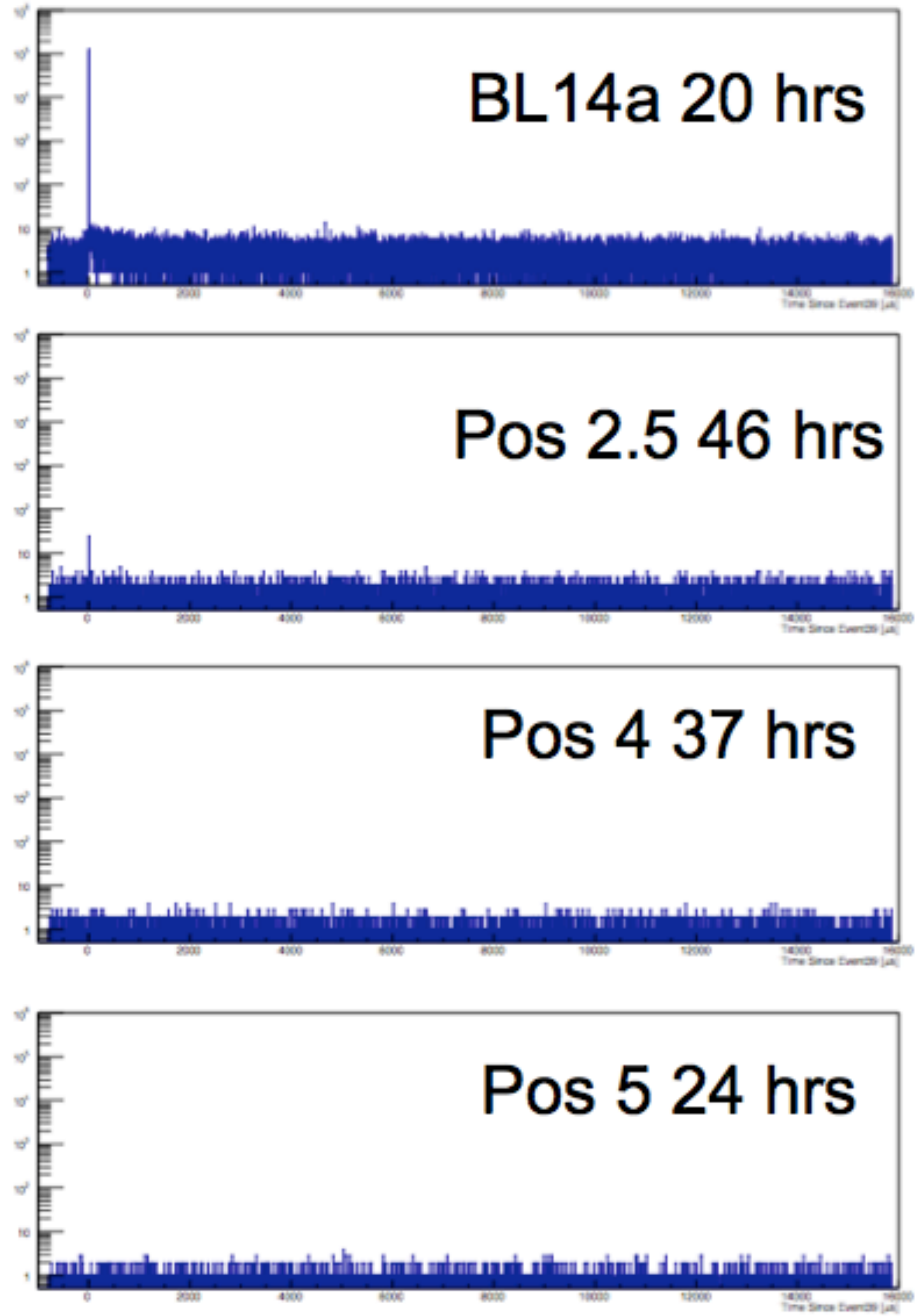


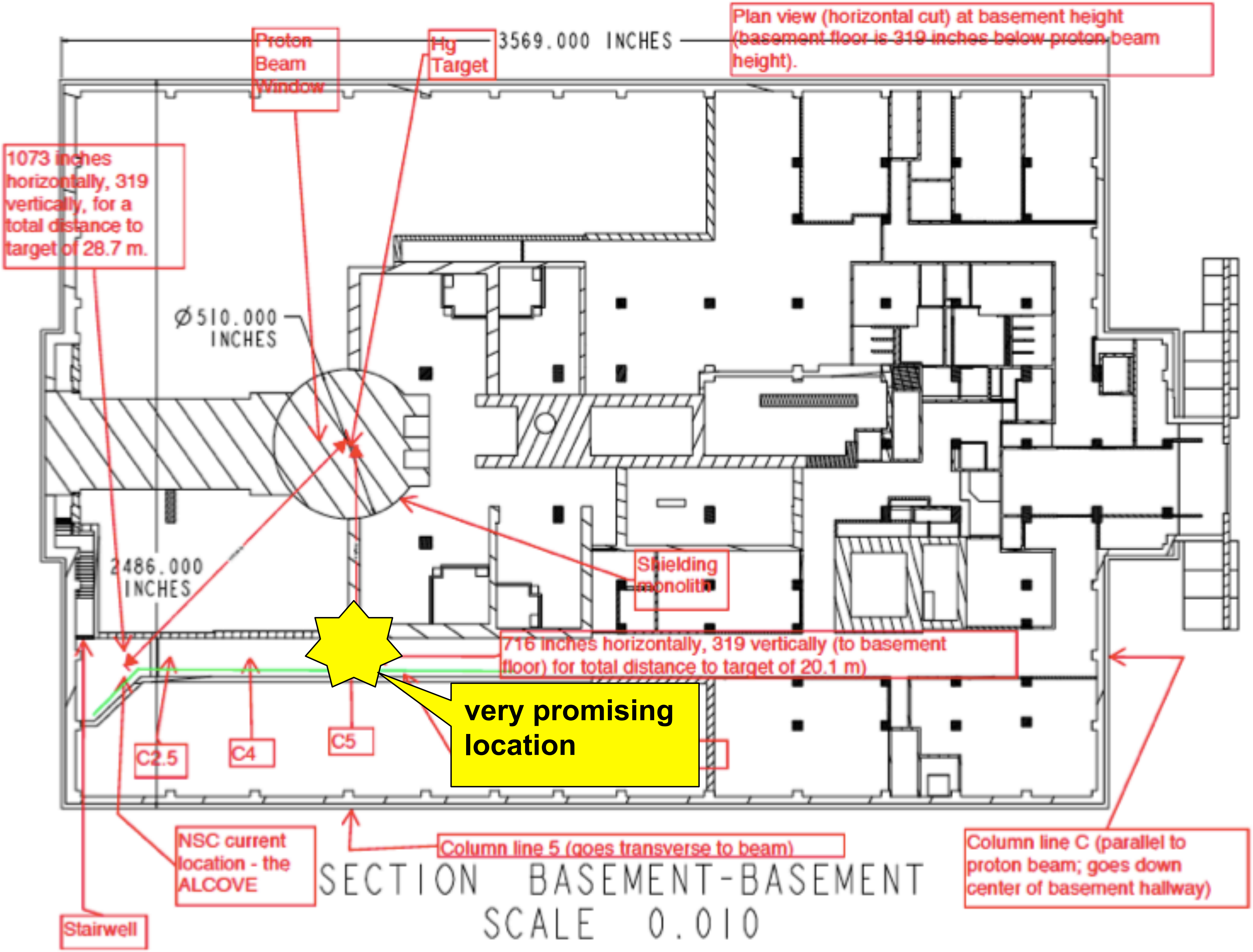
Results: high flux
on surface, quiet in basement

Looking down the basement hallway

The good news: very neutron-quiet in basement! (site 4)






3569.000 INCHES
Plan view (horizontal cut) at basement height (basement floor is 319 inches below proton beam height).
Proton Beam Window
Hg Target
1073 inches horizontally, 319 vertically, for a total distance to target of 28.7 m.
Ø510.000 INCHES
2486.000 INCHES
Shielding monolith
716 inches horizontally, 319 vertically (to basement floor) for total distance to target of 20.1 m)
very promising location
C2.5
C4
C5
NSC current location - the ALCOVE
Stairwell
Column line 5 (goes transverse to beam)
Column line C (parallel to proton beam; goes down center of basement hallway)
SECTION BASEMENT-BASEMENT
SCALE 0.010

SNS basement pictures

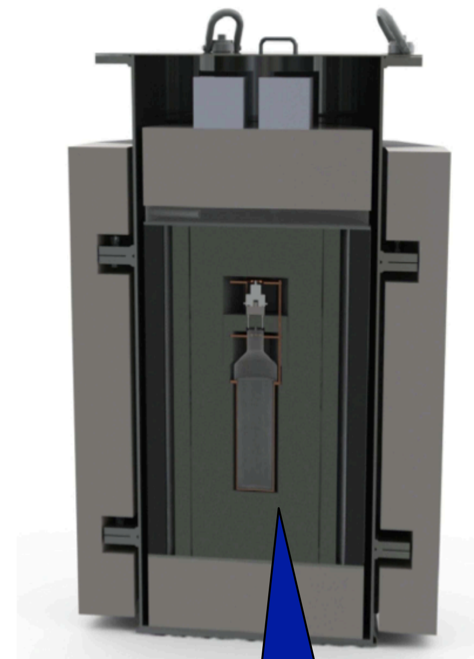
COHERENT is currently working on next step:
focus on measuring *neutrino-induced neutrons*
in lead, (iron, copper), ...

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

$\searrow$ 1n, 2n emission

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

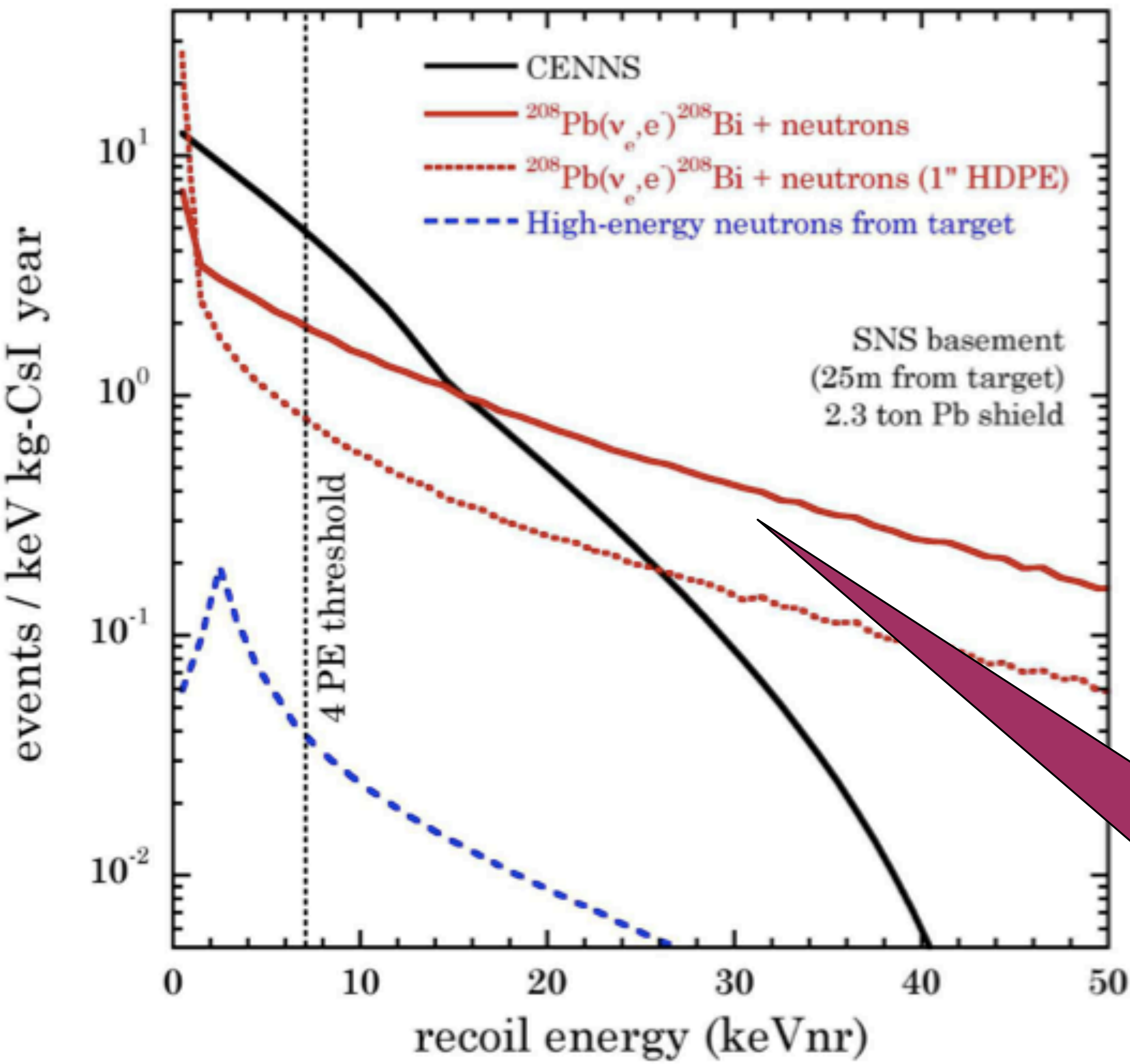
$\searrow$ 1n, 2n, γ emission



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

Neutrino-induced neutrons (NINs) are neutron source!

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



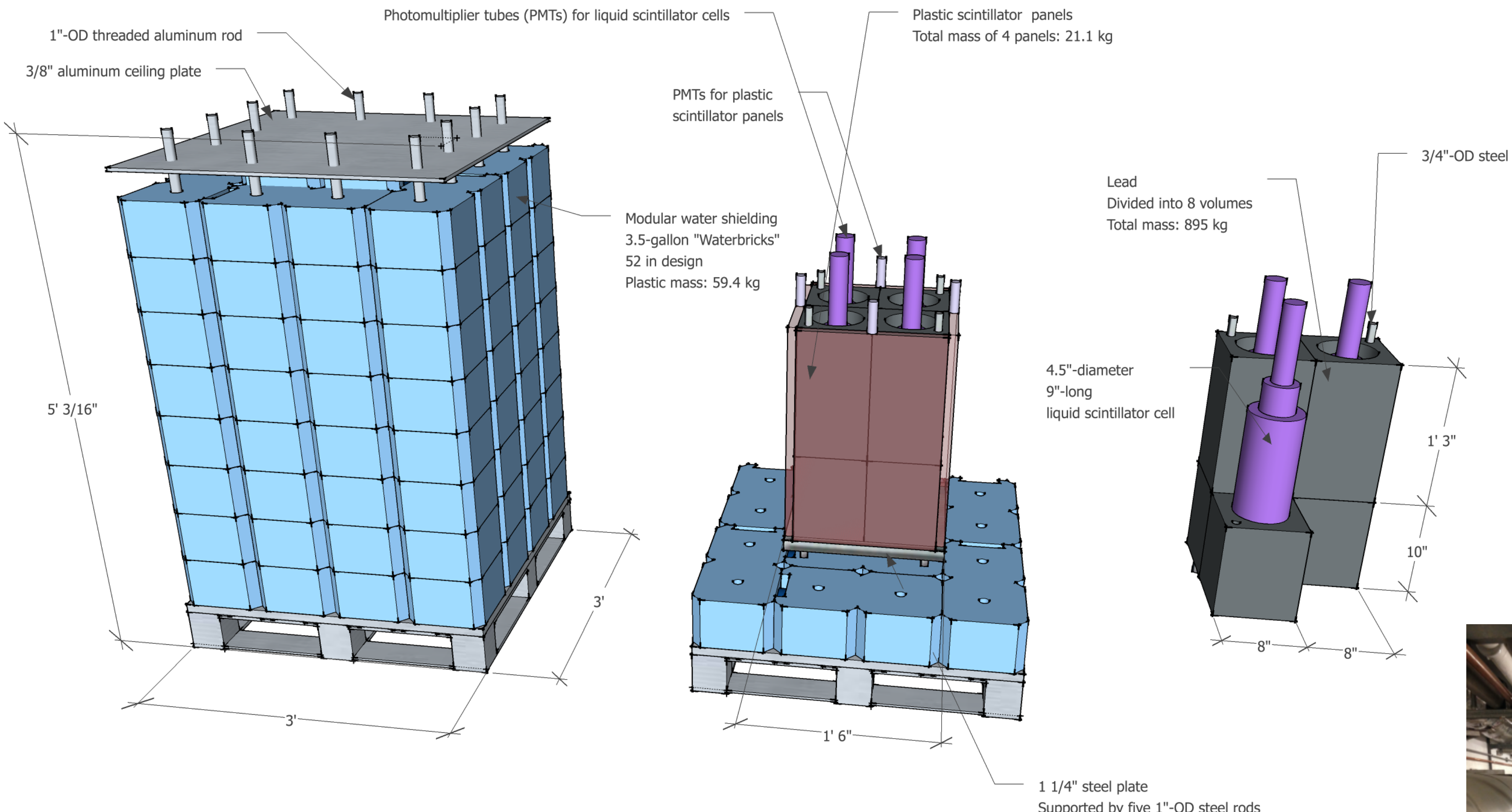
Neutrino-induced neutrons (NINs) not negligible w/lead shield ➔ need careful shielding design

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

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

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

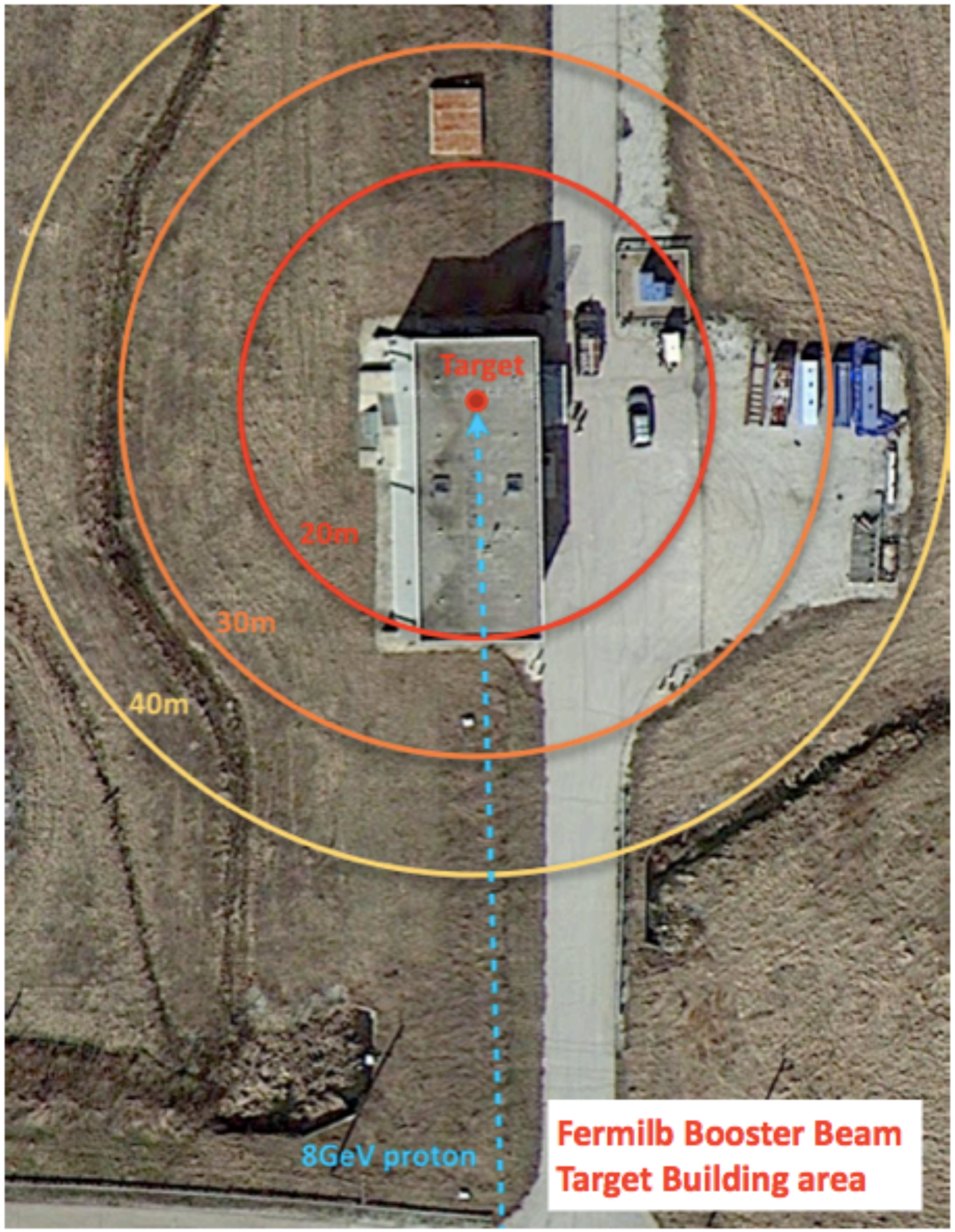
D. Akimov, A. Bernstein, P. Barbeau, P. Barton, A. Bolozdynya, B. Cabrera-Palmer, F. Cavanna, V. Cianciolo, J. Collar, R.J. Cooper, D. Dean, Y. Efremenko, A. Etenko, N. Fields, M. Foxe, E. Figueroa-Feliciano, N. Fomin, F. Gallmeier, I. Garishvili, M. Gerling, M. Green, G. Greene, A. Hatzikoutelis, R. 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

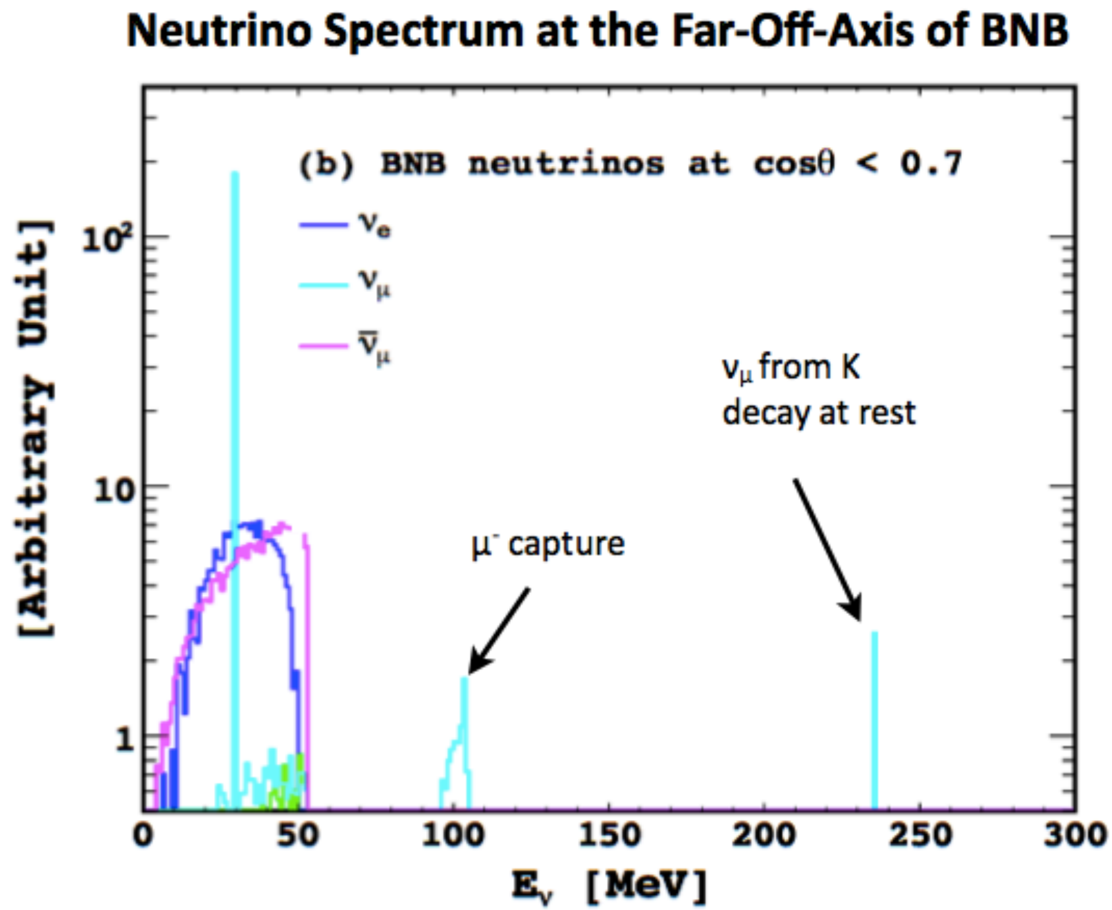
“CSI” is now “COHERENT”

Another possibility: very far off axis at the FNAL BNB

J. Yoo

Neutrino Energy Spectrum and Flux





- 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**

Summary

Coherent elastic neutrino-nucleus scattering
offers many physics prospects!
- neutrino NSI is the low-hanging fruit
- multi-tonne-scale experiments will have broad program

For first-generation measurements, requirements are not stringent;
systematic uncertainties may eventually become limiting
need multiple targets, well-understood neutrino source

Stopped-pion sources are attractive for high energy
neutrinos, good background rejection
First measurement may be possible on a short timescale
NINs even shorter timescale, and interesting in themselves

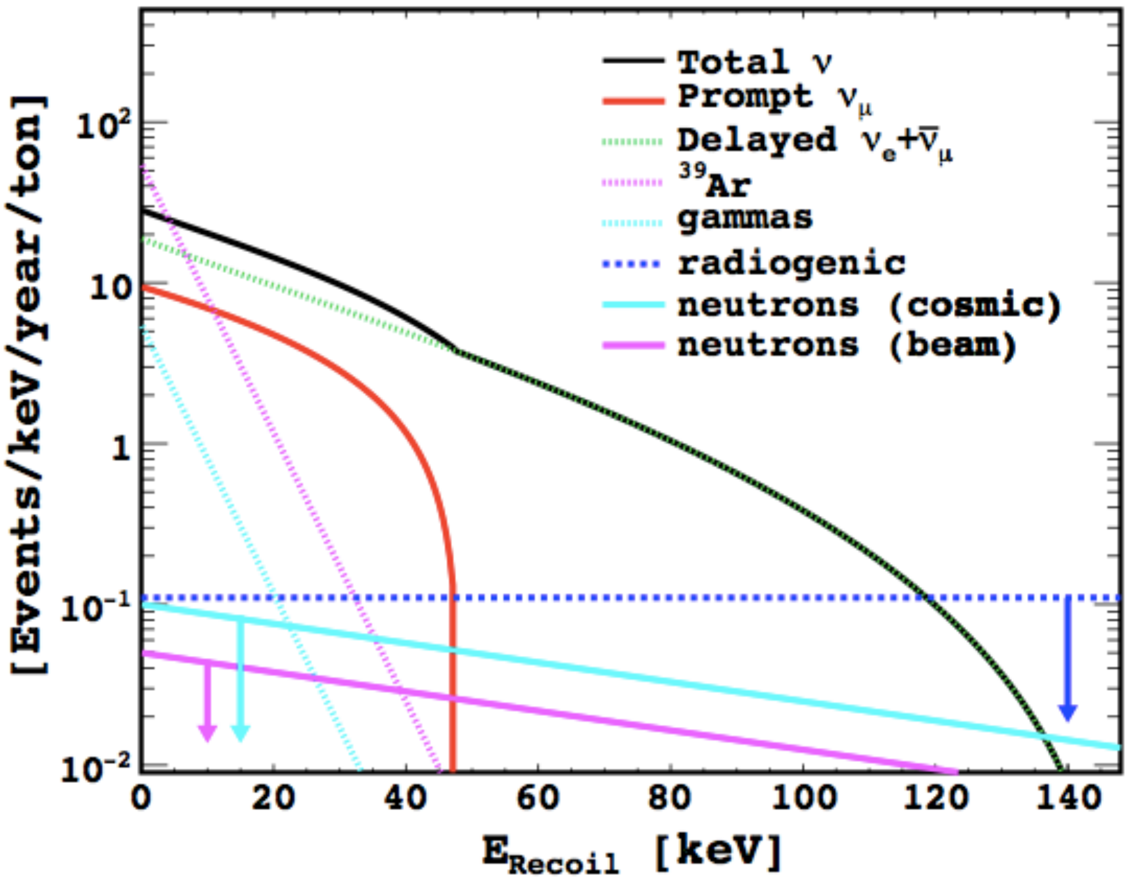
A "COHERENT" strategy is coming together

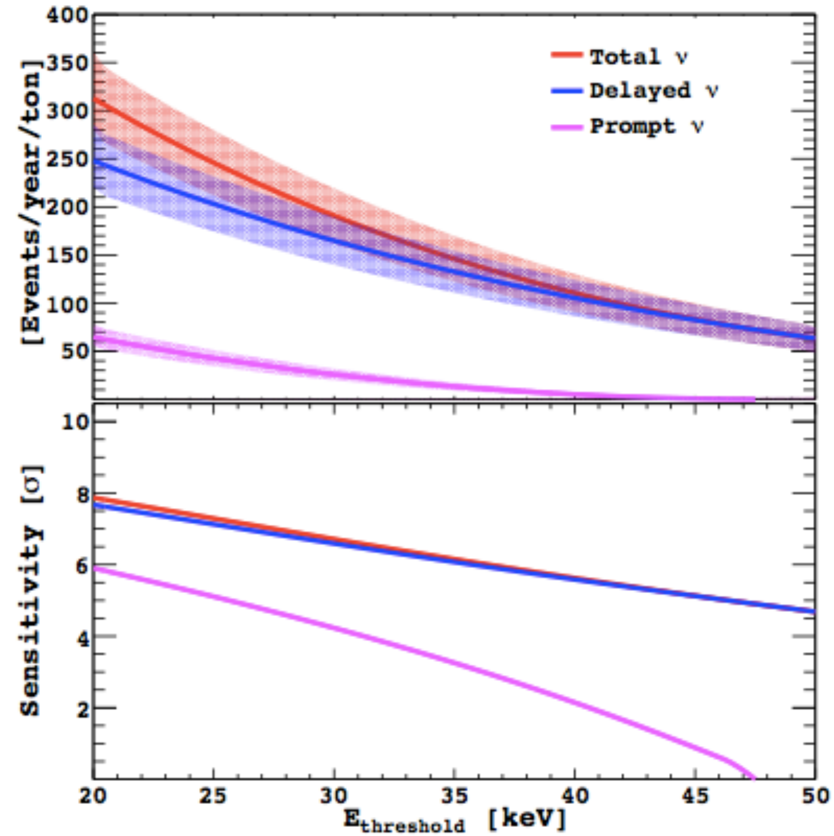
Extras/Backups

Coherent Elastic Neutrino Nucleus Scattering (@Fermilab)

Sensitivity for Discovery

J. Yoo

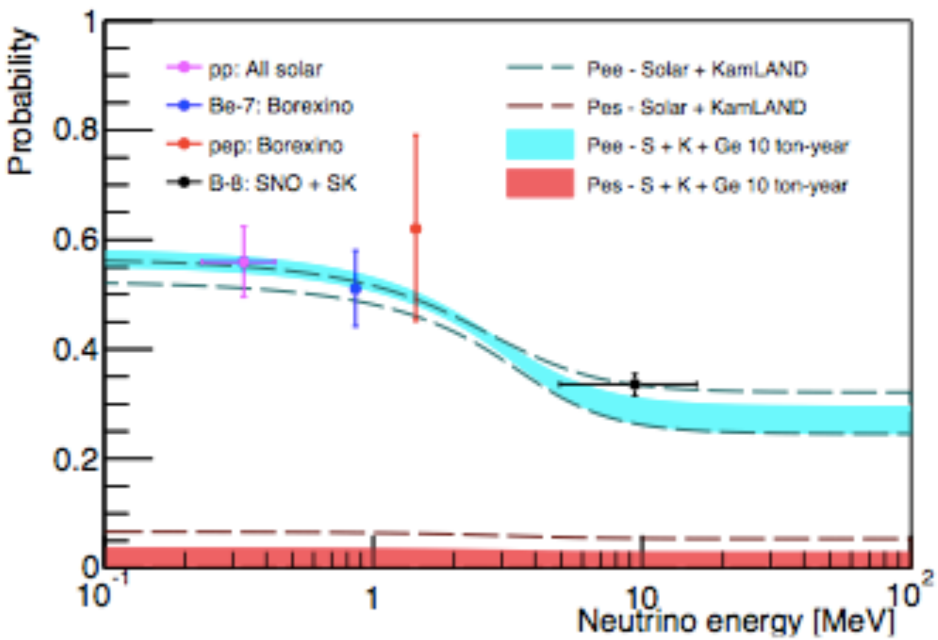


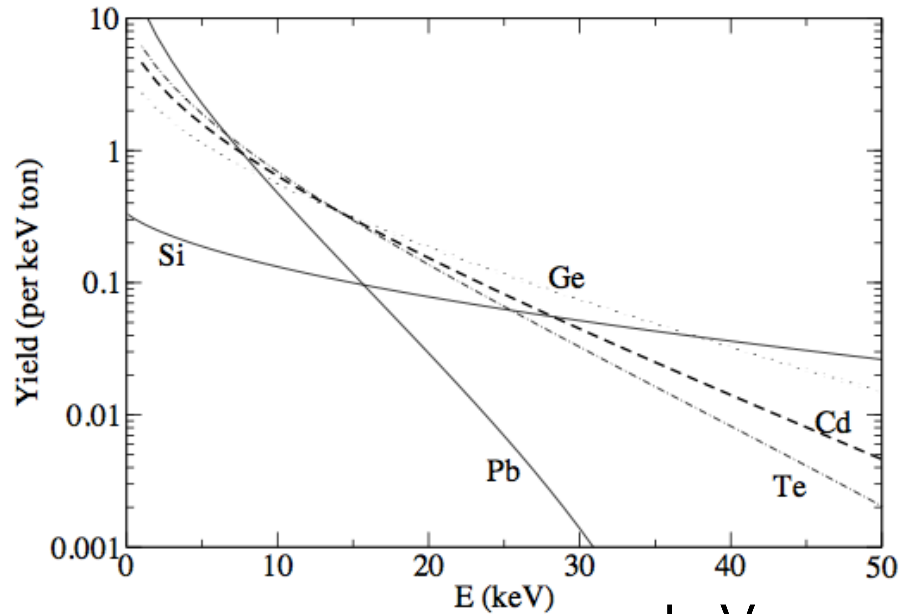


- **7 sigma discovery** with 1-year-ton LAr detector (MiniCLEAN style) operation at BNB (with 25keV detector threshold and 20m from the target)
  → for details Phys.Rev.D89 072004 (2014); arXiv:1311.5958

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

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*

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