COHERENT Elastic Neutrino-Nucleus Scattering

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IPA 2016, Orsay, France

September 6, 2016

OUTLINE

- **Coherent elastic neutrino-nucleus scattering**

- Why measure it? **Physics motivations**
  (short and long term)

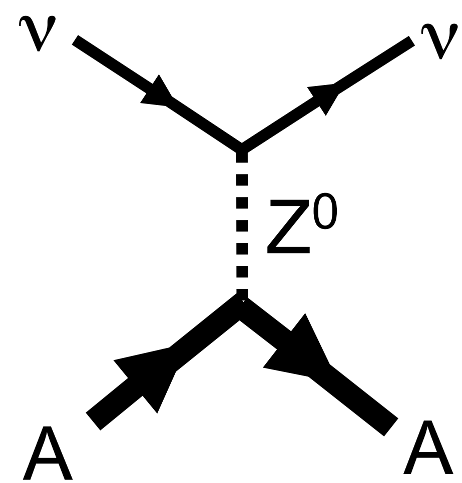
- How to measure it?
  - stopped pion sources and reactors

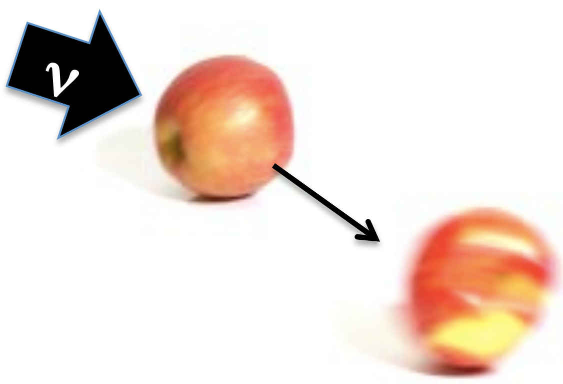
- Experiments going after CEvNS
  - **The COHERENT Experiment at the Spallation Neutron Source**

Coherent elastic neutrino-nucleus scattering (CEvNS)

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

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





- Important in SN processes & detection
- Well-calculable cross-section in SM:
  SM test, probe of neutrino NSI
- Dark matter direct detection background
- Neutron form factors
- 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, ...

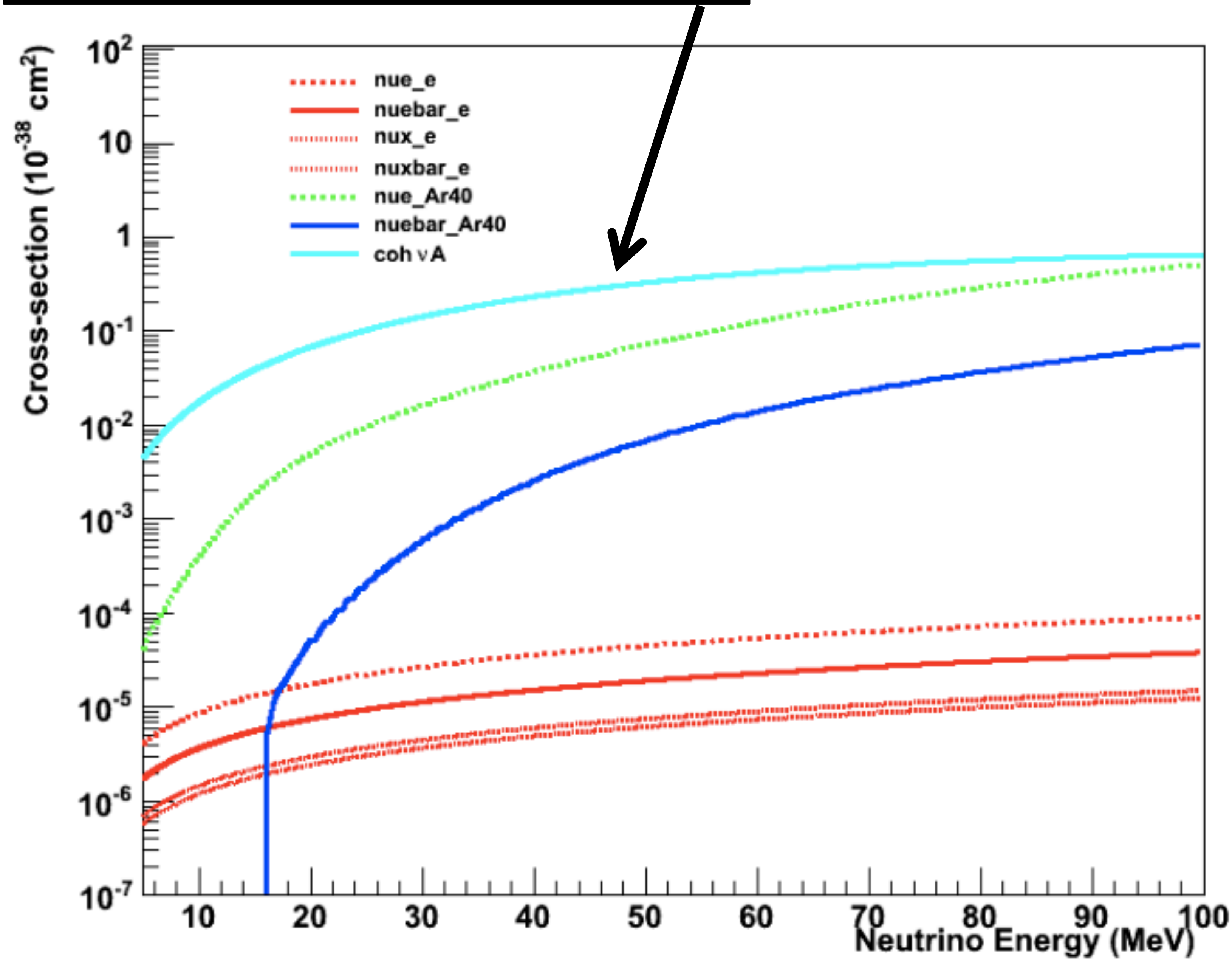
- I prefer including “E” for “elastic”... otherwise HEP types constantly confuse it with coherent pion production at ~ GeV energies
- I’m told “NN” means “nucleon-nucleon” to nuclear types (also CENNS is now a collaboration!)
- CEνNS is a possibility but those internal Greek letters are annoying

➔**CEvNS**, pronounced “sevens”...

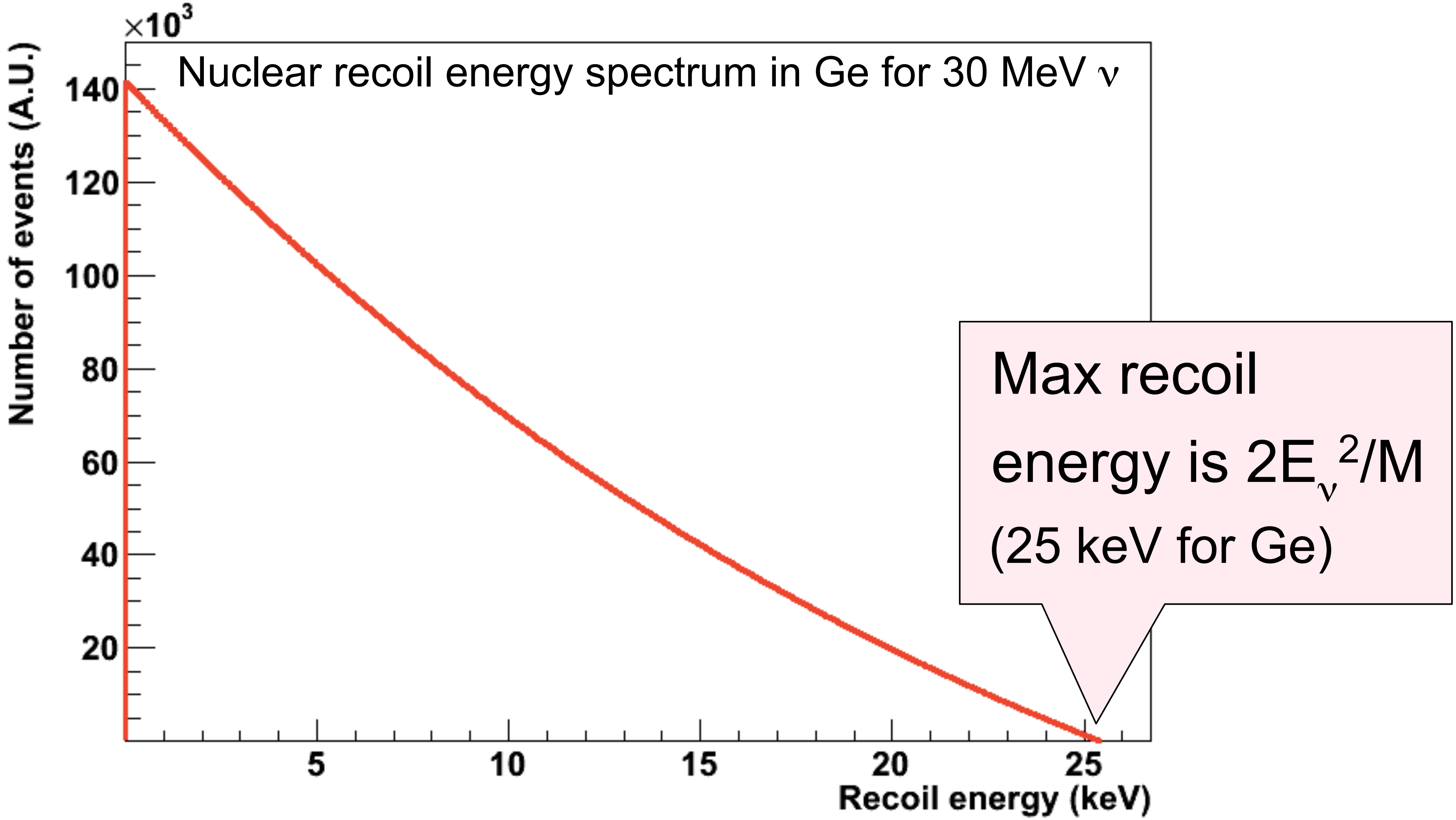
spread the meme!

\end{aside}

The cross-section is *large*

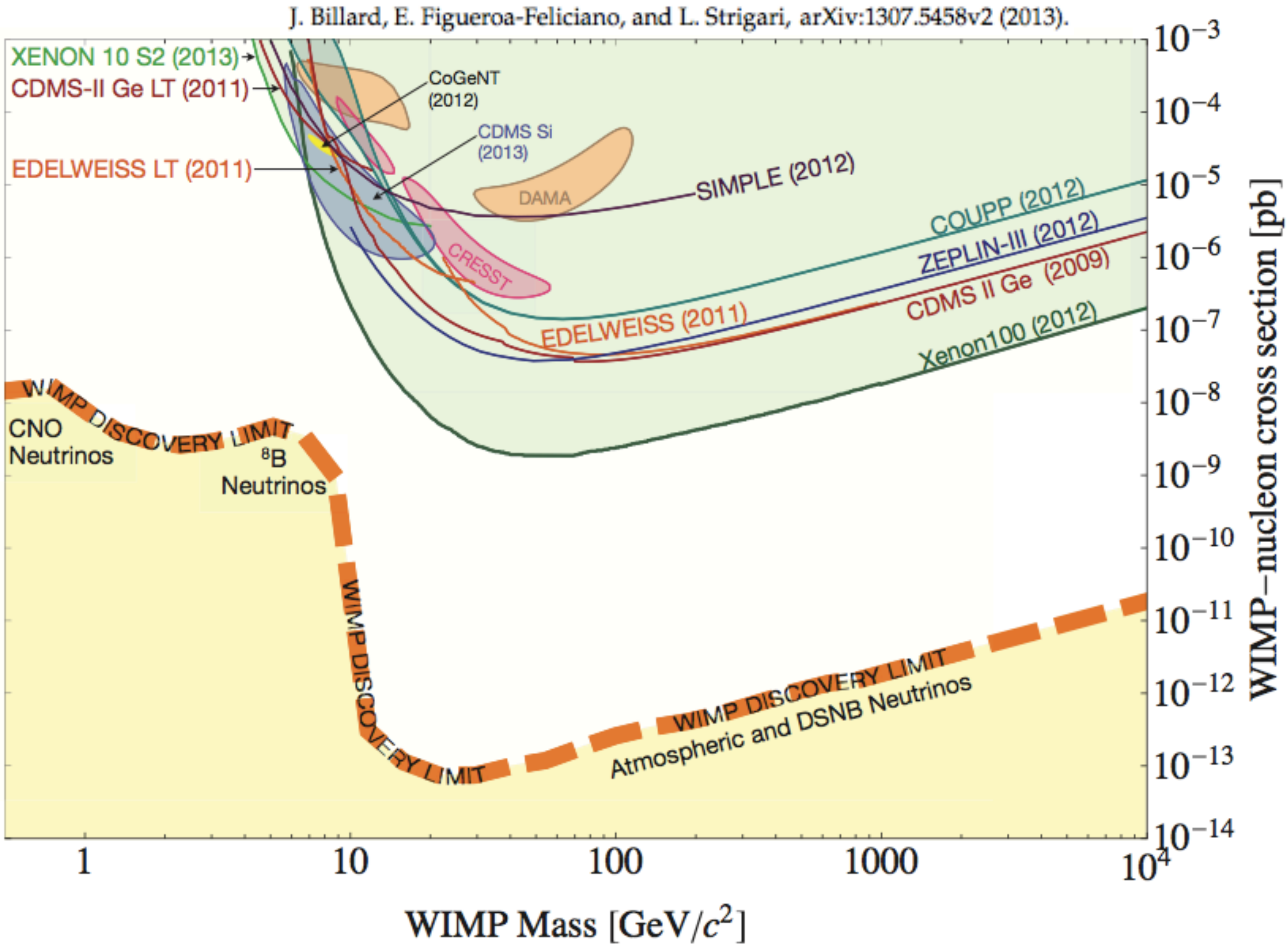


Large cross section, but never observed due to **tiny nuclear recoil energies:**



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

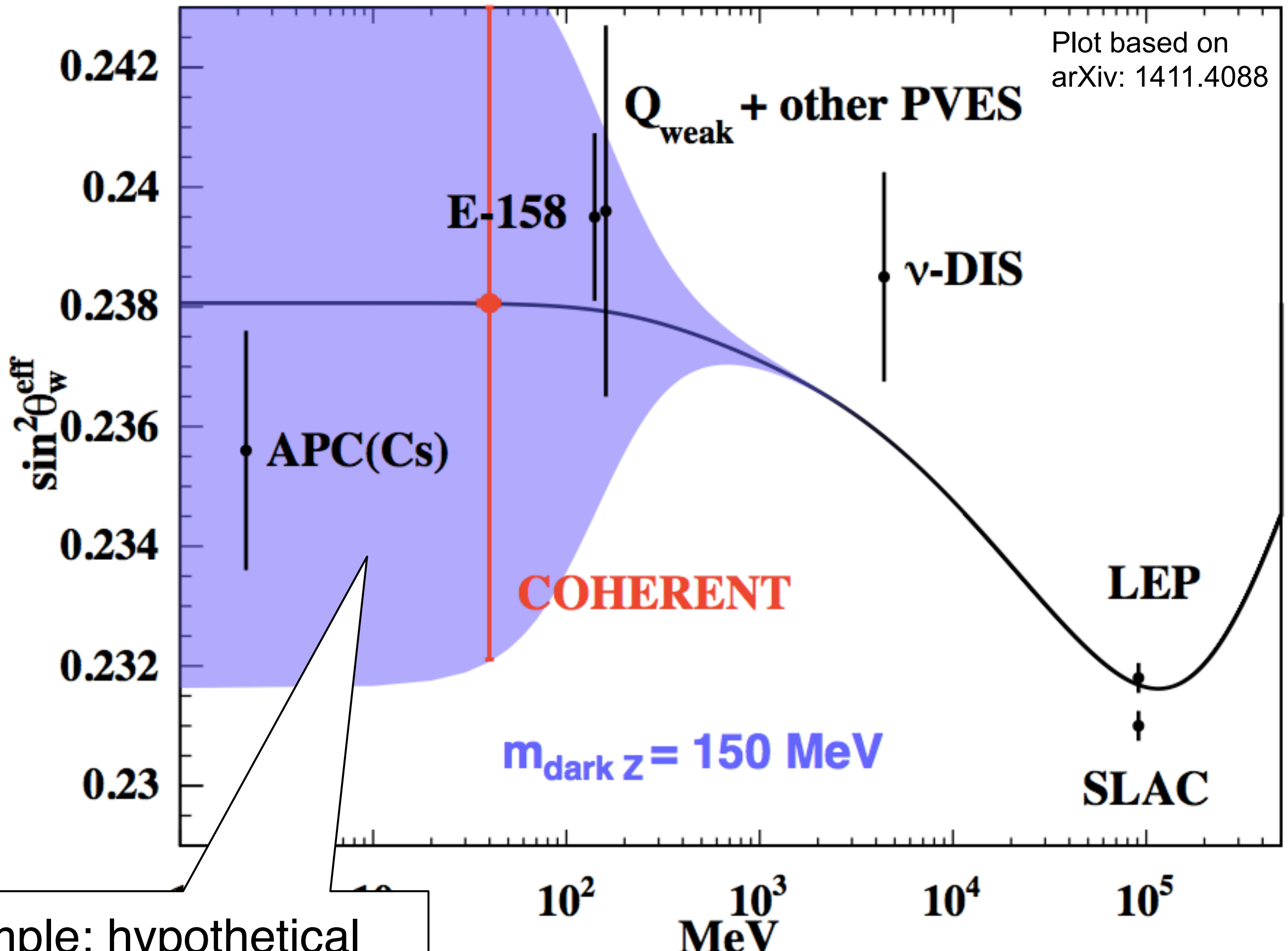
CEvNS from natural neutrinos creates ultimate background for direct DM search experiments



Understand nature of background (& detector response)

Clean SM prediction for the rate ➔ measure $\sin^2\theta_W$eff ;
deviation probes new physics

$$\sigma \sim \frac{G_f^2 E^2}{4\pi}(N - (1 - 4\sin^2\theta_W)Z)^2$$



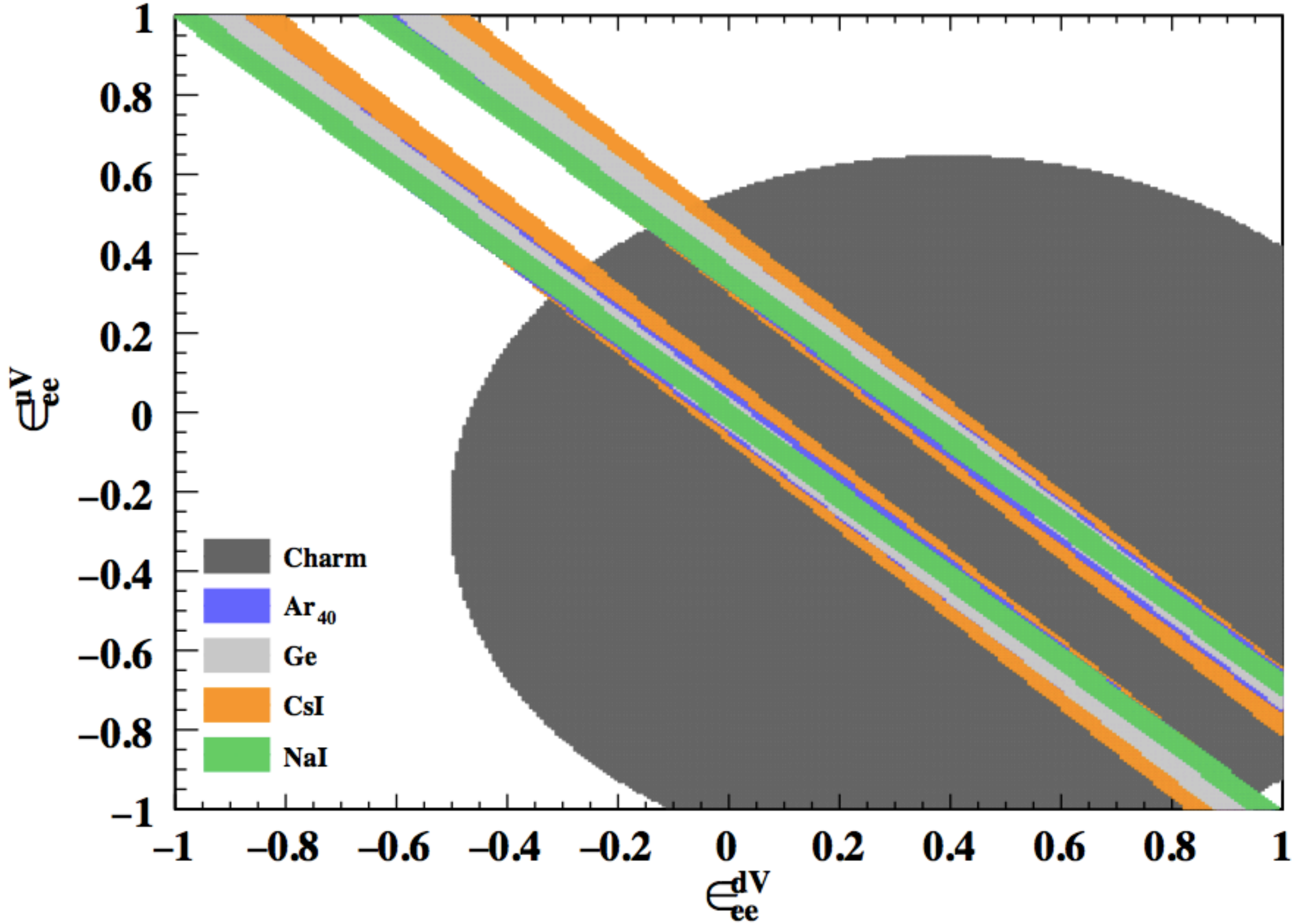
Example: hypothetical dark Z mediator (explanation for g-2 anomaly)

CEvNS sensitivity is @ low Q; need sub-percent precision to compete w/ electron scattering & APV, but **new channel**

Non-Standard Interactions of Neutrinos:

new interaction **specific to ν's**

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



Can improve ~order of magnitude beyond CHARM limits with a first-generation experiment (for best sensitivity, want ***multiple targets***)

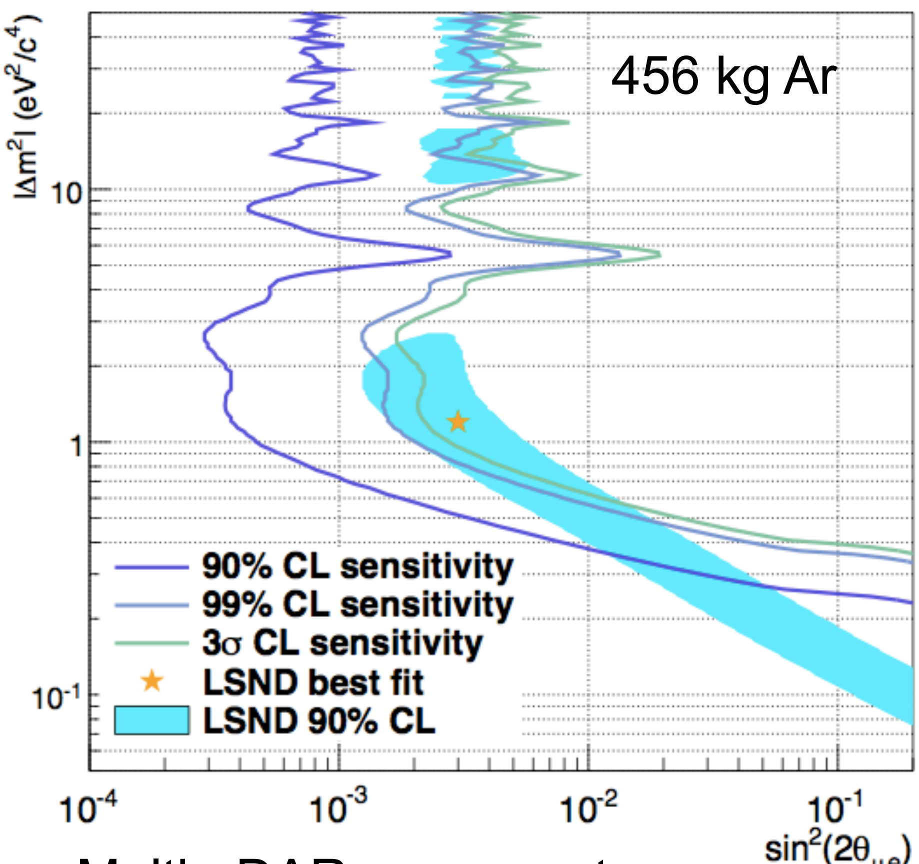
K. Scholberg, PRD73, 033005 (2006)

Oscillations to sterile neutrinos w/CEvNS

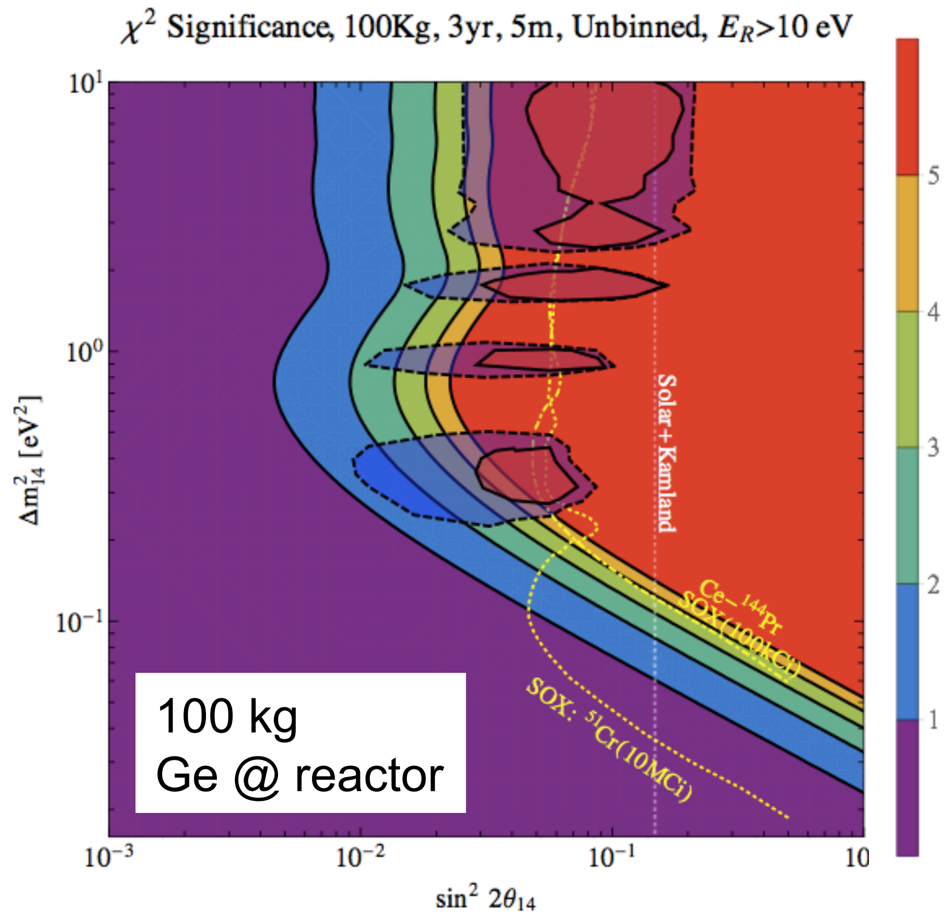
(NC is flavor-blind): a potential new tool;

look for deficit and spectral distortion vs L,E

Examples:



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



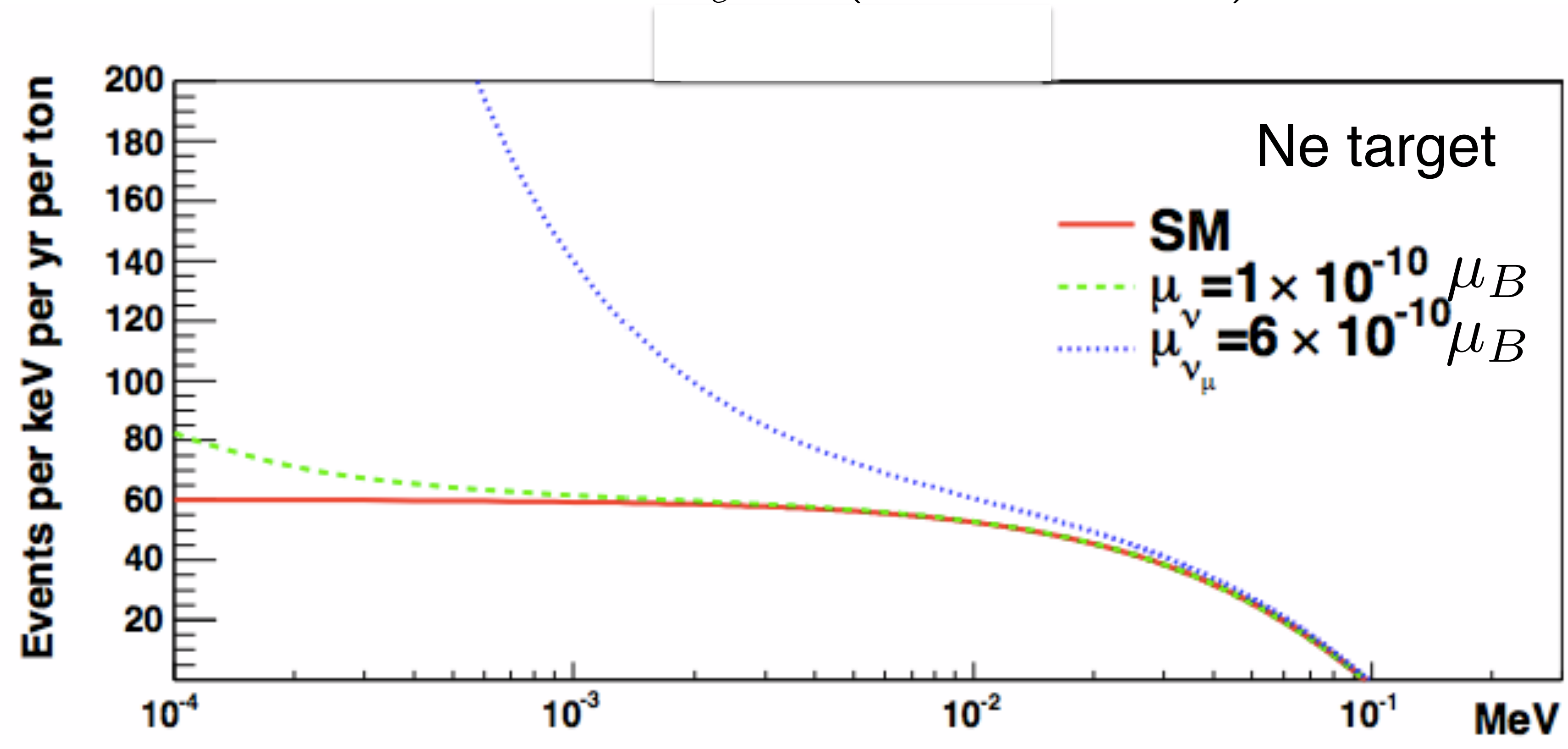
B. Dutta et al, arXiv:1511.02834

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

Neutrino magnetic moment

Signature is **distortion at low recoil energy E**

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



➔requires low energy threshold

See also Kosmas et al., arXiv:1505.03202

Nuclear physics with coherent elastic scattering

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

P. S. Amanik and G. C. McLaughlin, J. Phys. G 36:015105

K. Patton et al., PRC86 (2012) 024612

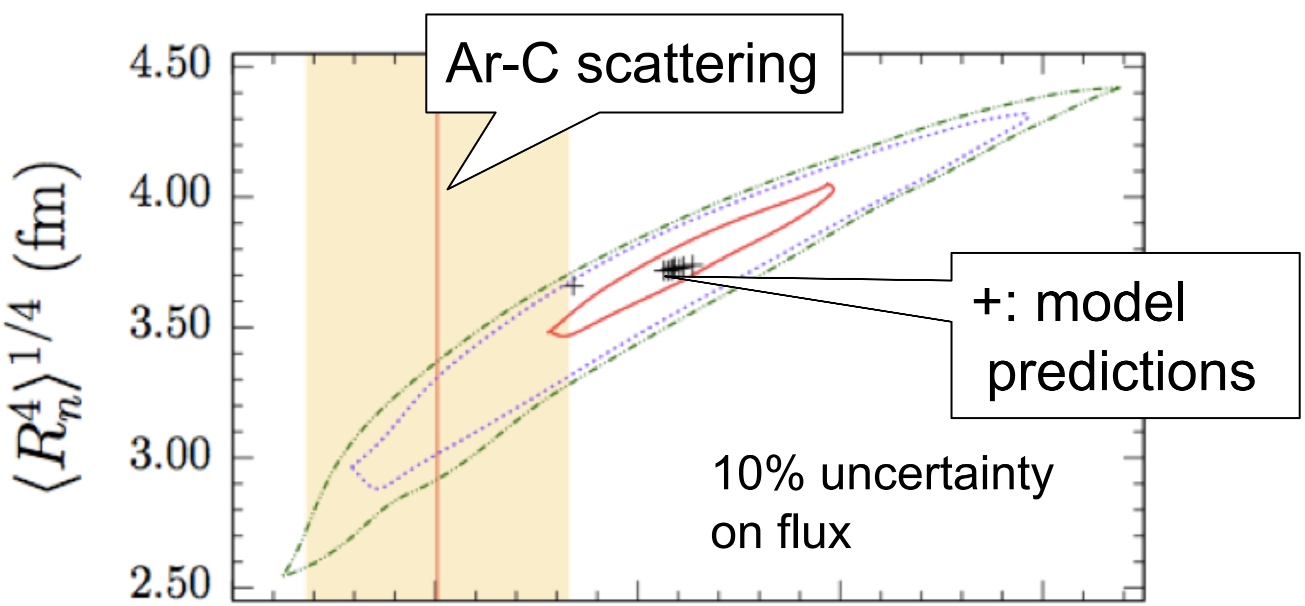
$$\frac{d\sigma}{dT}(E,T) = \frac{G_F^2}{2\pi} M \left[2 - \frac{2T}{E} + \left(\frac{T}{E}\right)^2 - \frac{MT}{E^2}\right] \frac{Q_W^2}{4} F^2(Q^2)$$

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

Fit recoil ***spectral shape*** to determine the $F(Q^2)$ moments

(requires very good energy resolution,good systematics control)

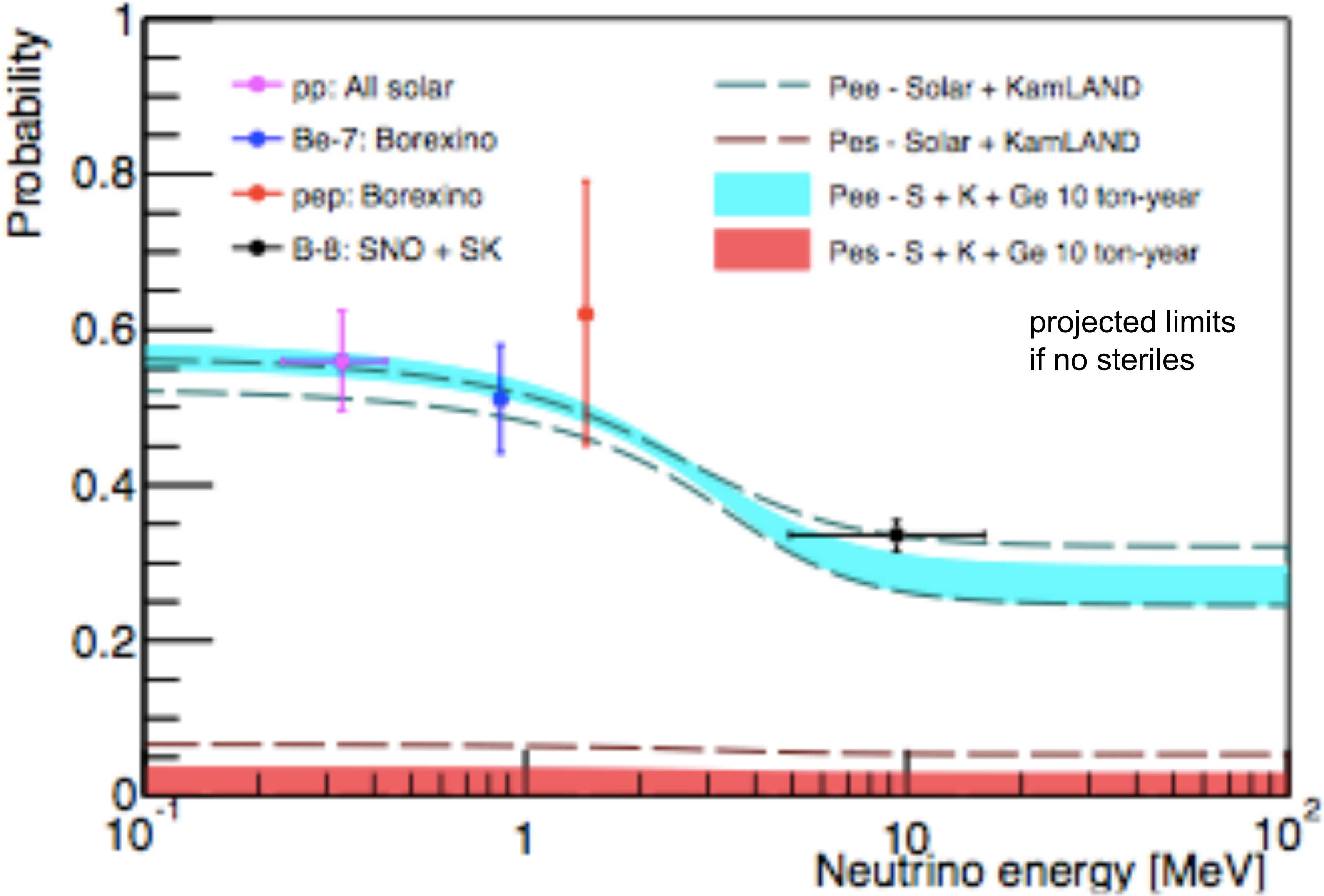
Example:
tonne-scale experiment at πDAR source



Also note: tonne-scale underground look at **astrophysical neutrinos**

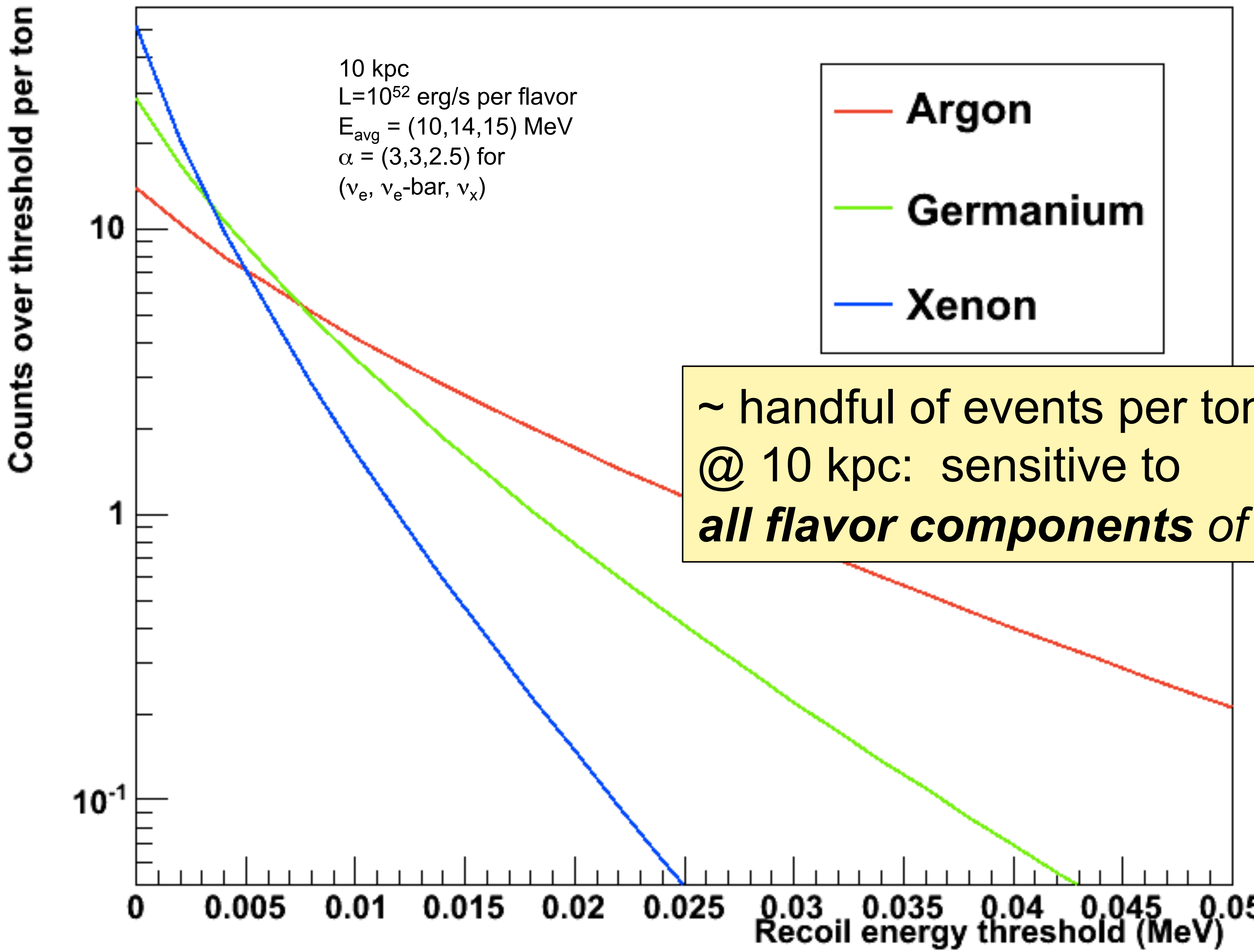
Solar neutrinos

Billard et al., arXiv:1409.0050



Rule out sterile oscillations using CEvNS (NC)

Supernova neutrinos in tonne-scale DM detectors



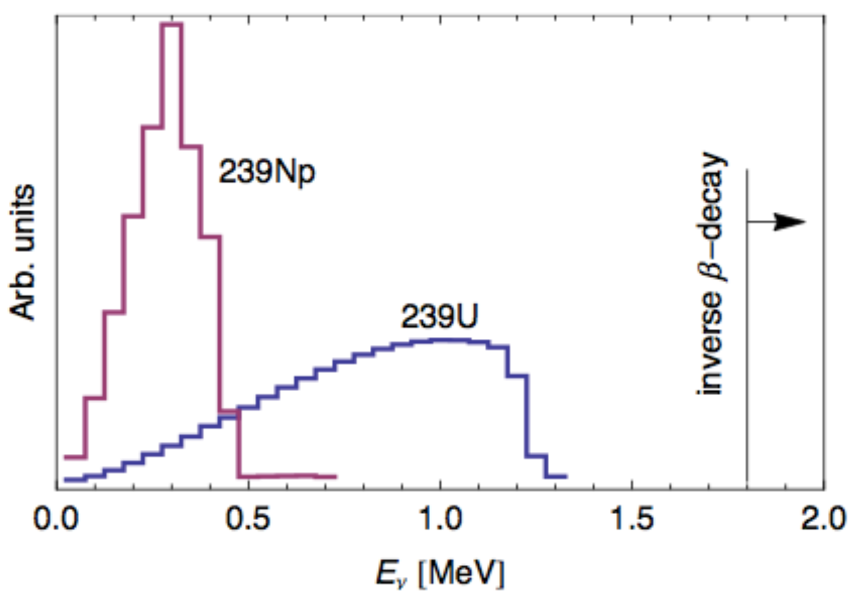
~ handful of events per tonne
@ 10 kpc: sensitive to
all flavor components *of the flux*

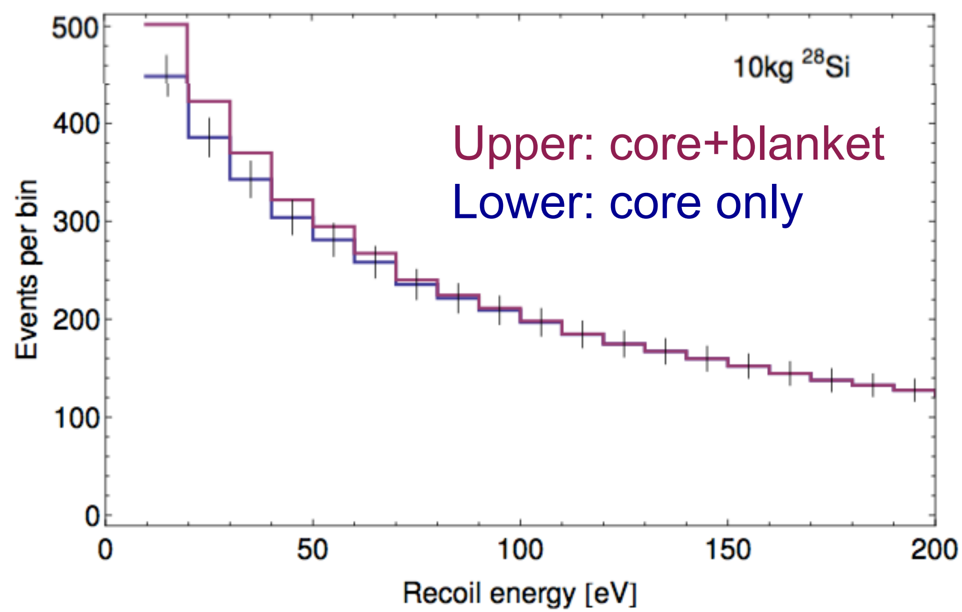
A practical application in nuclear safeguards:

P. Huber, talk at NA/NT workshop, Manchester, May 2015

Presence of **plutonium breeder blanket** in a reactor has ν spectral signature

$$^{238}\mathrm{U} + n \rightarrow {}^{239}\mathrm{U} \xrightarrow{\beta} {}^{239}\mathrm{Np} \xrightarrow{\beta} {}^{239}\mathrm{Pu}$$

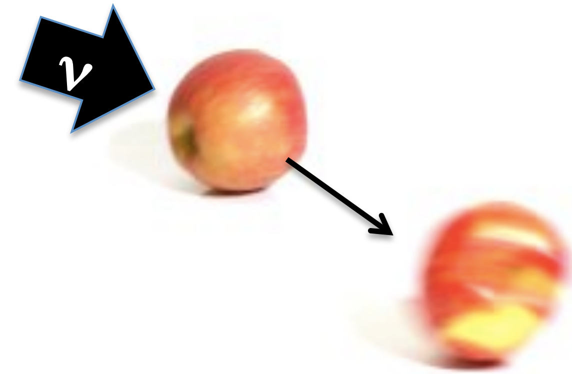




ν spectrum is below IBD threshold

➔ accessible with CEvNS, but require low recoil energy threshold

How to detect CEvNS?

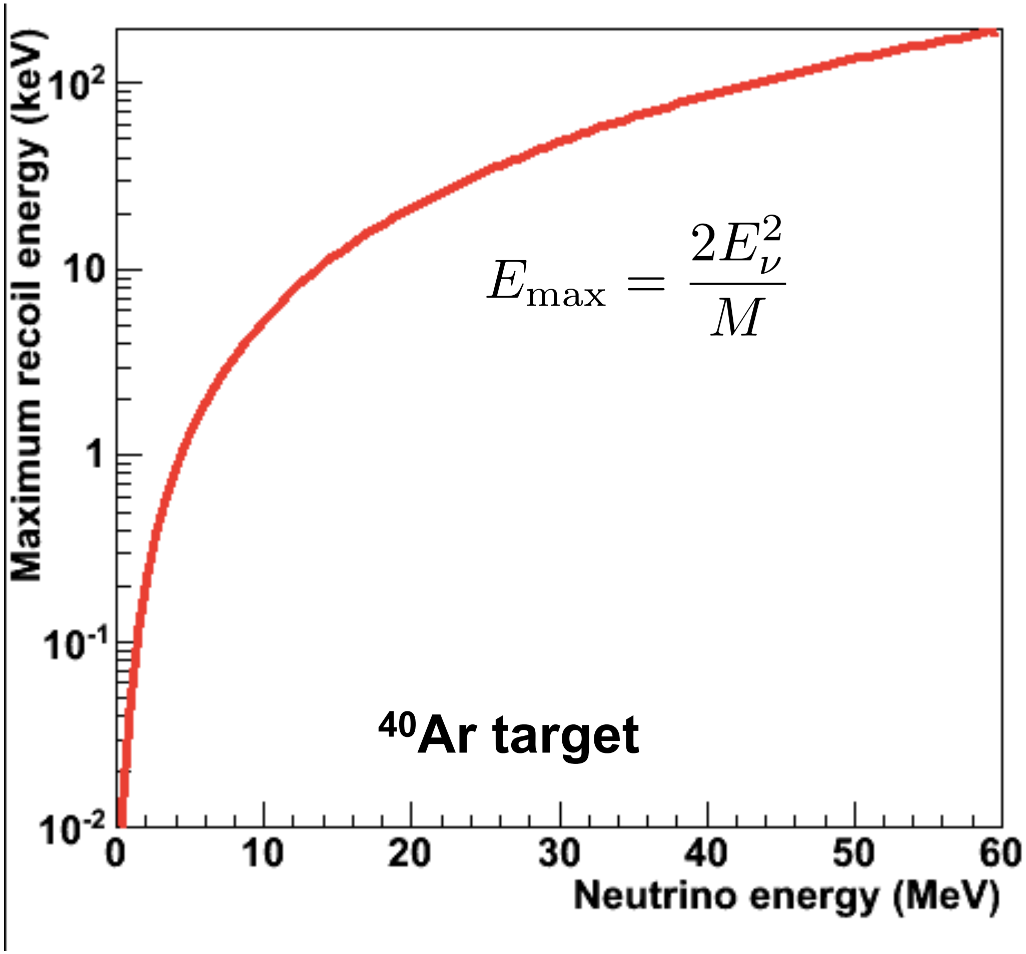


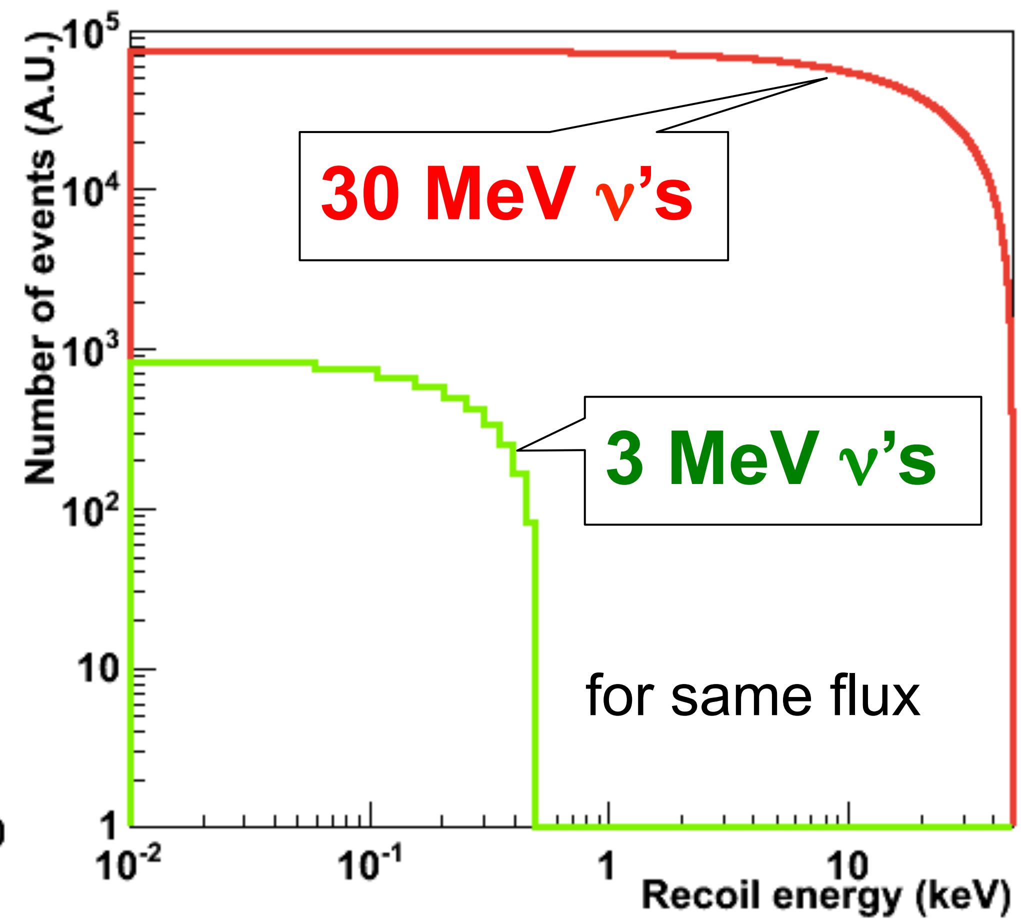
➔ Need low recoil threshold
& discrimination
(WIMP-style detector)

What do you want for your ν source?

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

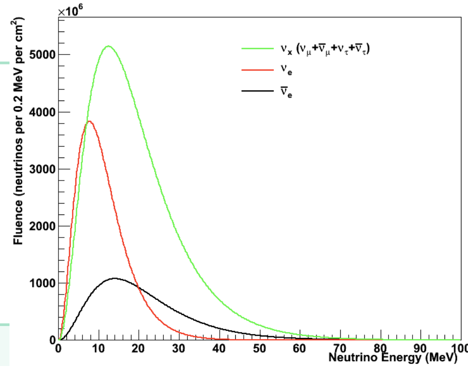
Both **cross-section and maximum recoil energy increase with neutrino energy**:





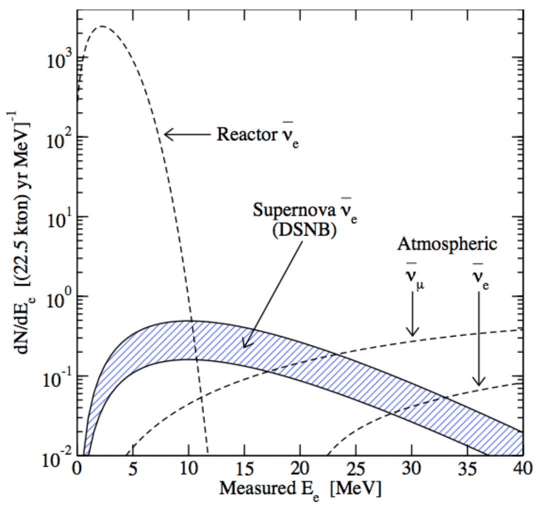
Want energy as large as possible while satisfying coherence condition: $Q \lesssim \frac{1}{R}$ (<~ 50 MeV for medium A)

Supernova burst neutrinos



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

Supernova relic neutrinos

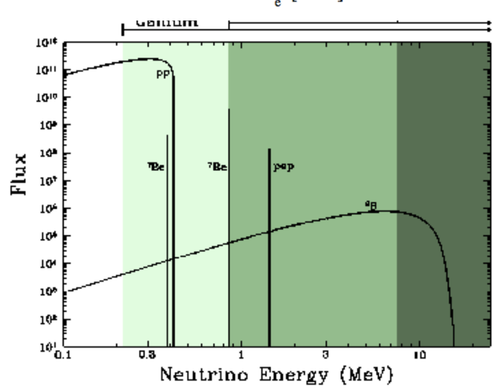


All flavors, low flux

Atmospheric neutrinos

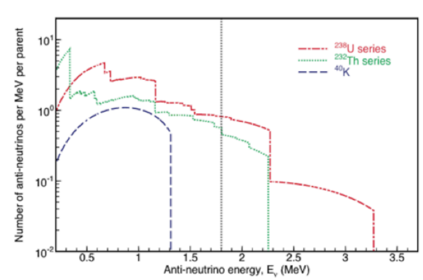
Some component at low energy

Solar neutrinos



Most flux below 1 MeV

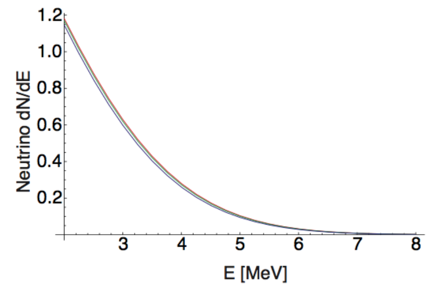
Geoneutrinos



Very low energy

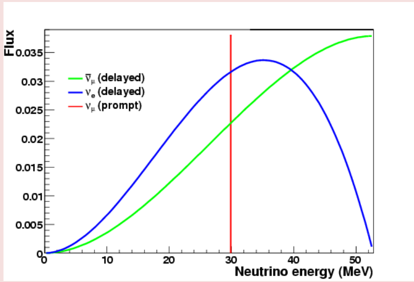
Coherent scattering eventually a bg for DM expts

Reactors



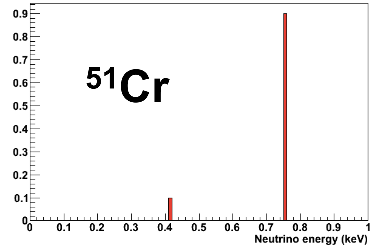
Low energy, but very high fluxes possible; ~continuous source, good bg rejection needed

Stopped pions
(decay at rest)



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

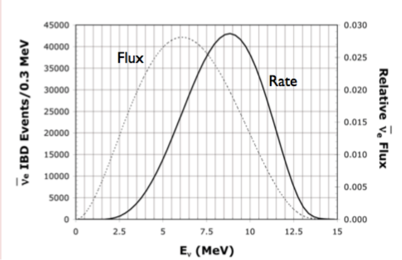
Radioactive sources
(electron capture)



Portable; can get very short baseline, monochromatic

Low energy challenging

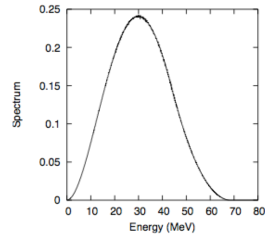
Beam-induced radioactive sources
(IsoDAR)



Relatively compact, higher energy than reactor; not pulsed

Does not exist yet

Low-energy beta beams



γ=10 boosted ^{18}Ne ν_e

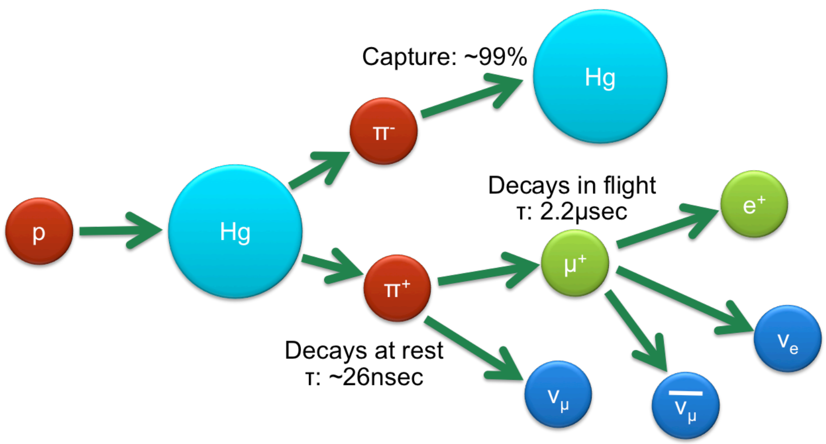
Tunable energy, but not pulsed

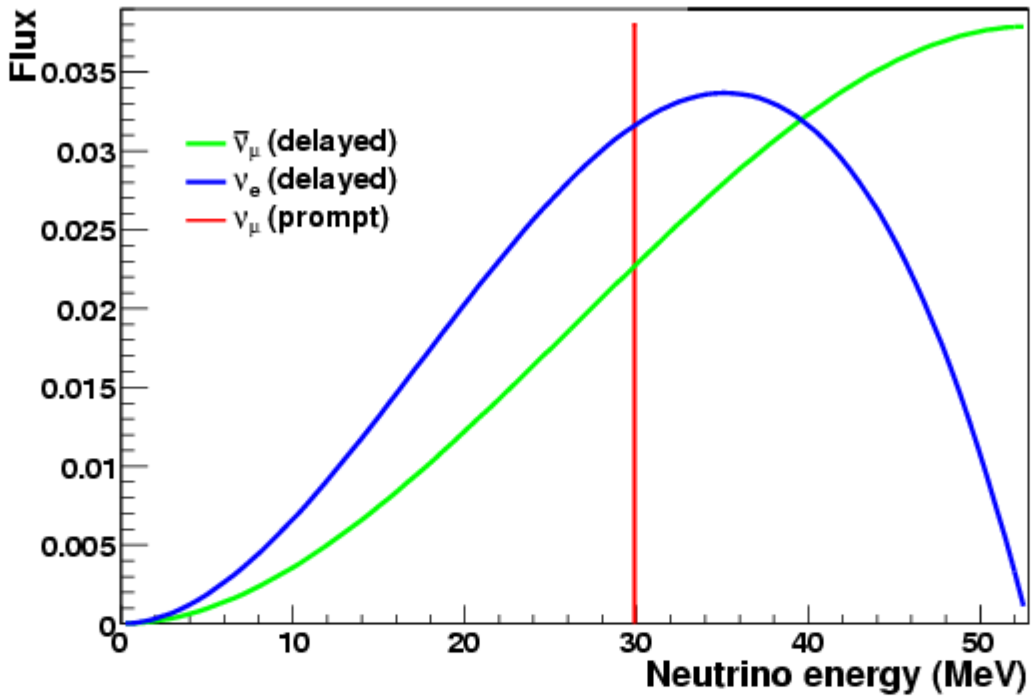
Does not exist yet

Reactor vs stopped-pion for CEvNS

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

Stopped-Pion (πDAR) Neutrinos





$$\pi^+ \to \mu^+ + \nu_\mu$$

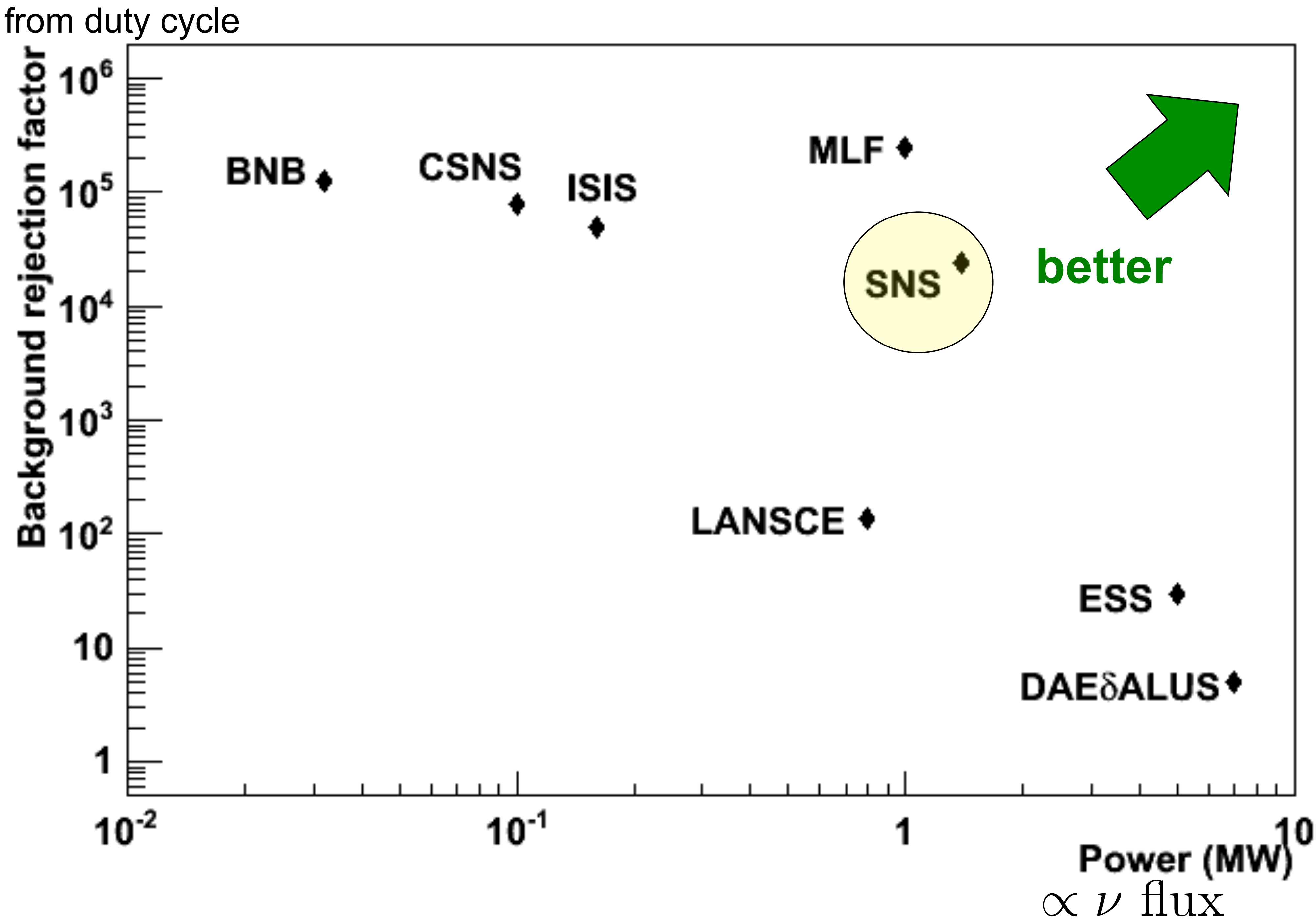
2-body decay: monochromatic 29.9 MeV ν_μ
PROMPT

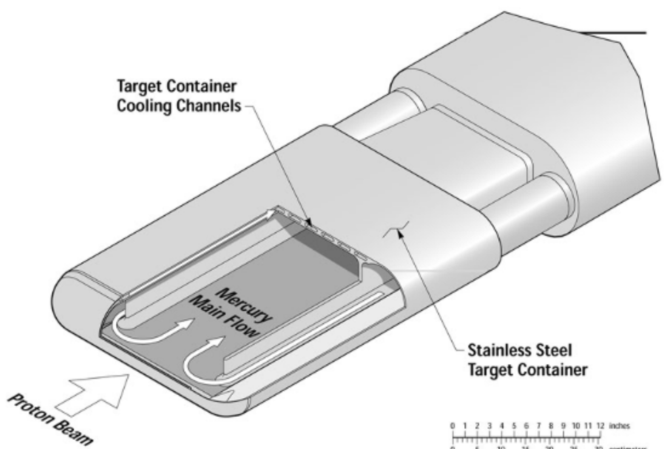
$$\downarrow$$

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

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

Comparison of pion decay-at-rest ν sources

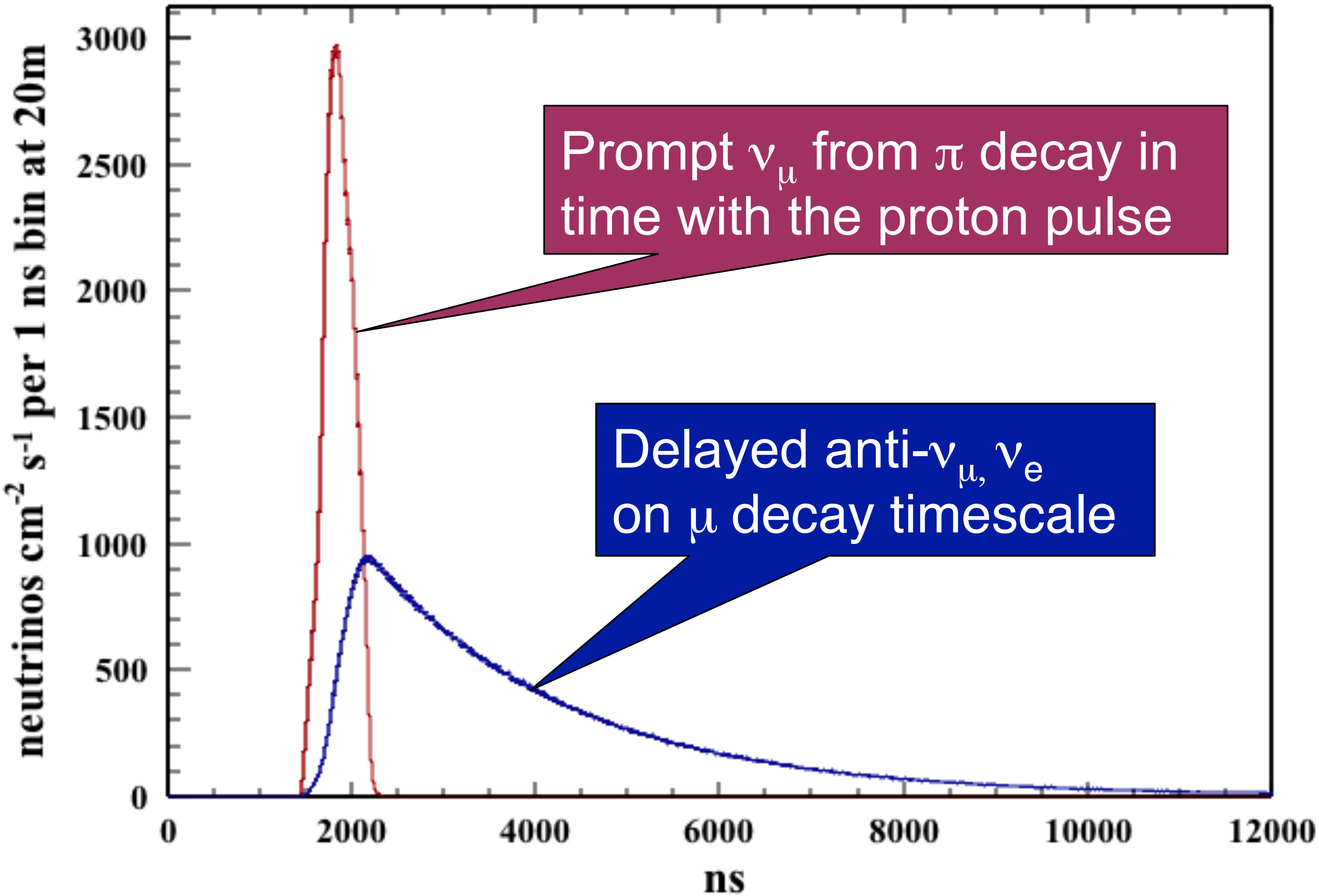




Proton beam energy: 0.9-1.3 GeV
Total power: 0.9-1.4 MW
Pulse duration: 380 ns FWHM
Repetition rate: 60 Hz
Liquid mercury target

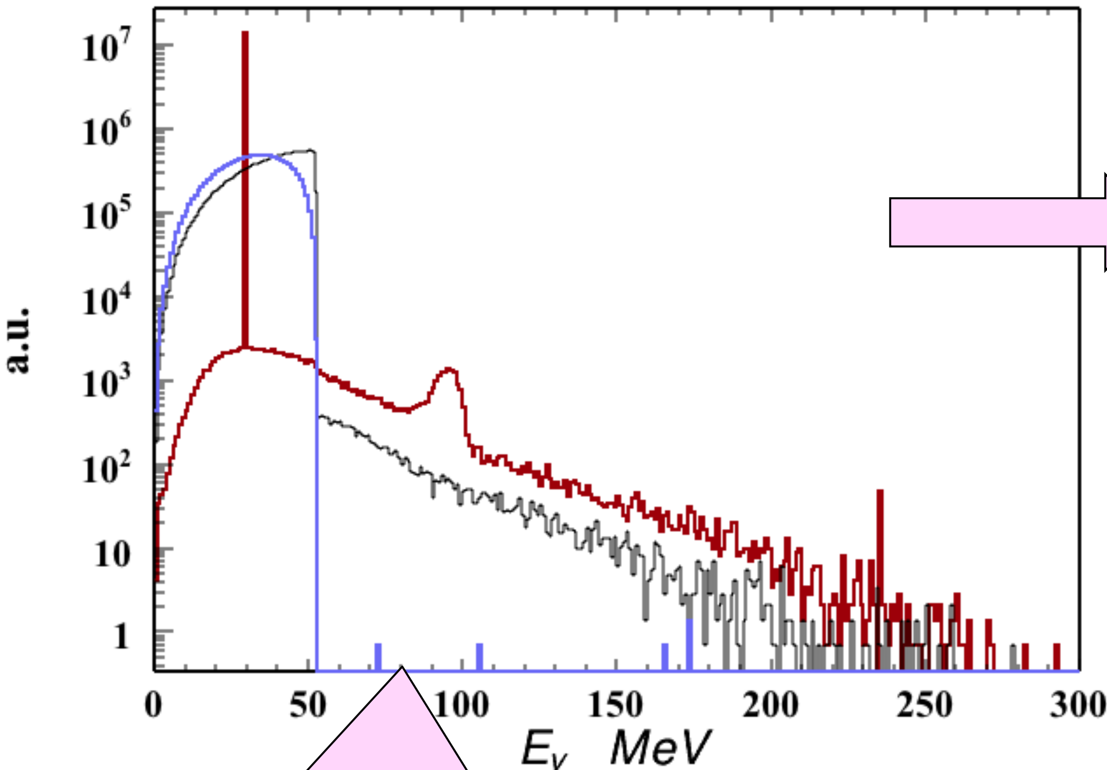
Time structure of the SNS source

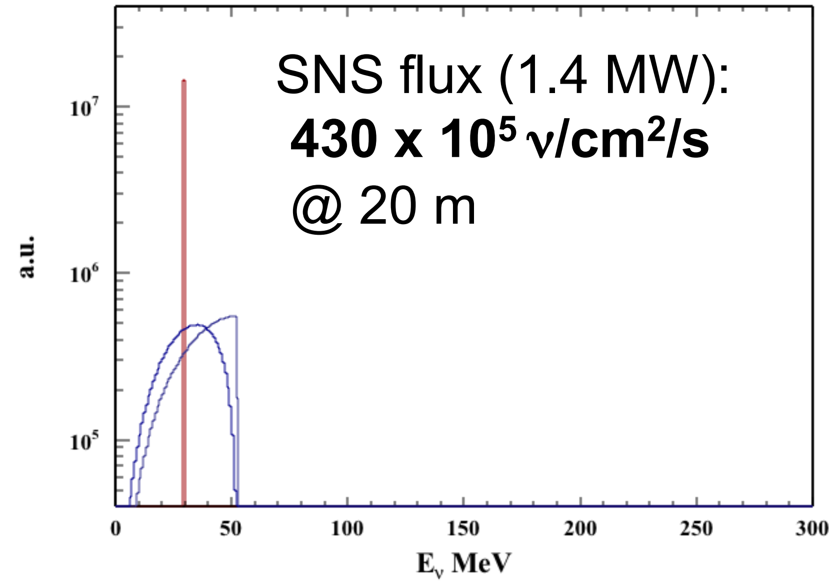
60 Hz *pulsed* source

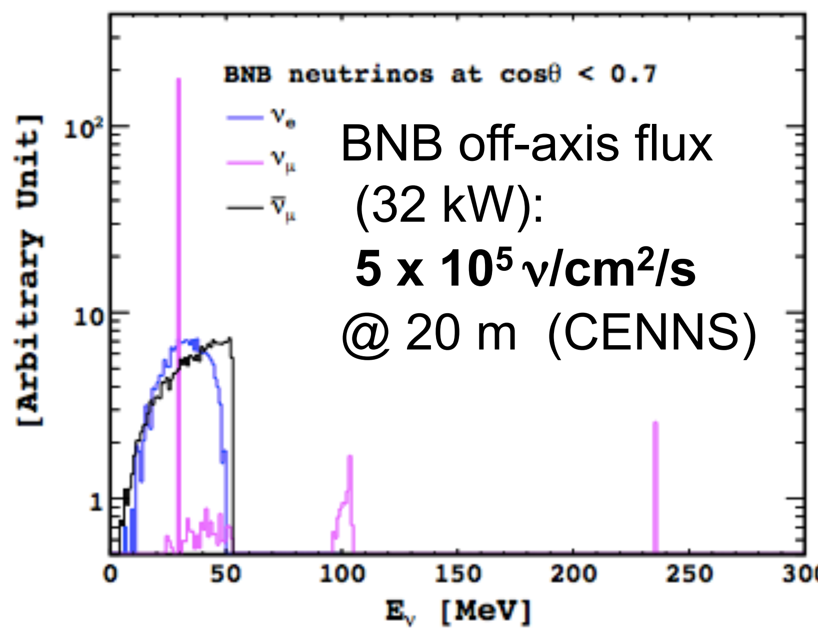


Background rejection factor ~few x 10^{-4}

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**

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

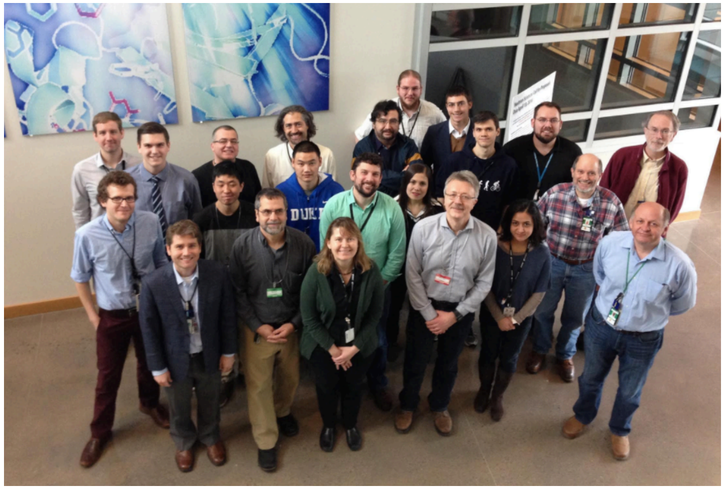
These are *not* crummy old cast-off neutrinos...

They are of the highest quality!

The COHERENT collaboration

arXiv:1509.08702

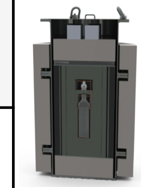
Institution	Board Member
University of California, Berkeley	Kai Vetter
University of Chicago	Juan Collar
Duke University	Kate Scholberg
University of Florida	Heather Ray
Indiana University	Rex Tayloe
Institute for Theoretical and Experimental Physics, Moscow	Dmitri Akimov
Lawrence Berkeley National Laboratory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

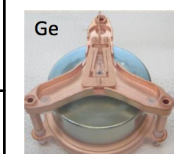


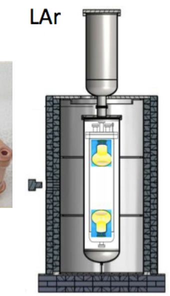
- Collaboration: ~65 members, 16 institutions (USA+ Russia)

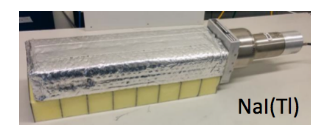
COHERENT Detectors and Status

Nuclear Target	Technology	Mass (kg)	Distance from source (m)	Recoil threshold (keVr)	Data-taking start date; CEvNS detection goal
CsI[Na]	Scintillating Crystal	14	20	6.5	9/2015; 3σ in 2 yr
Ge	HPGe PPC	10	22	5	Fall 2016
LAr	Single-phase	35	29	20	Fall 2016
NaI[Tl]	Scintillating crystal	185*/ 2000	28	13	*high-threshold deployment to start, summer 2016



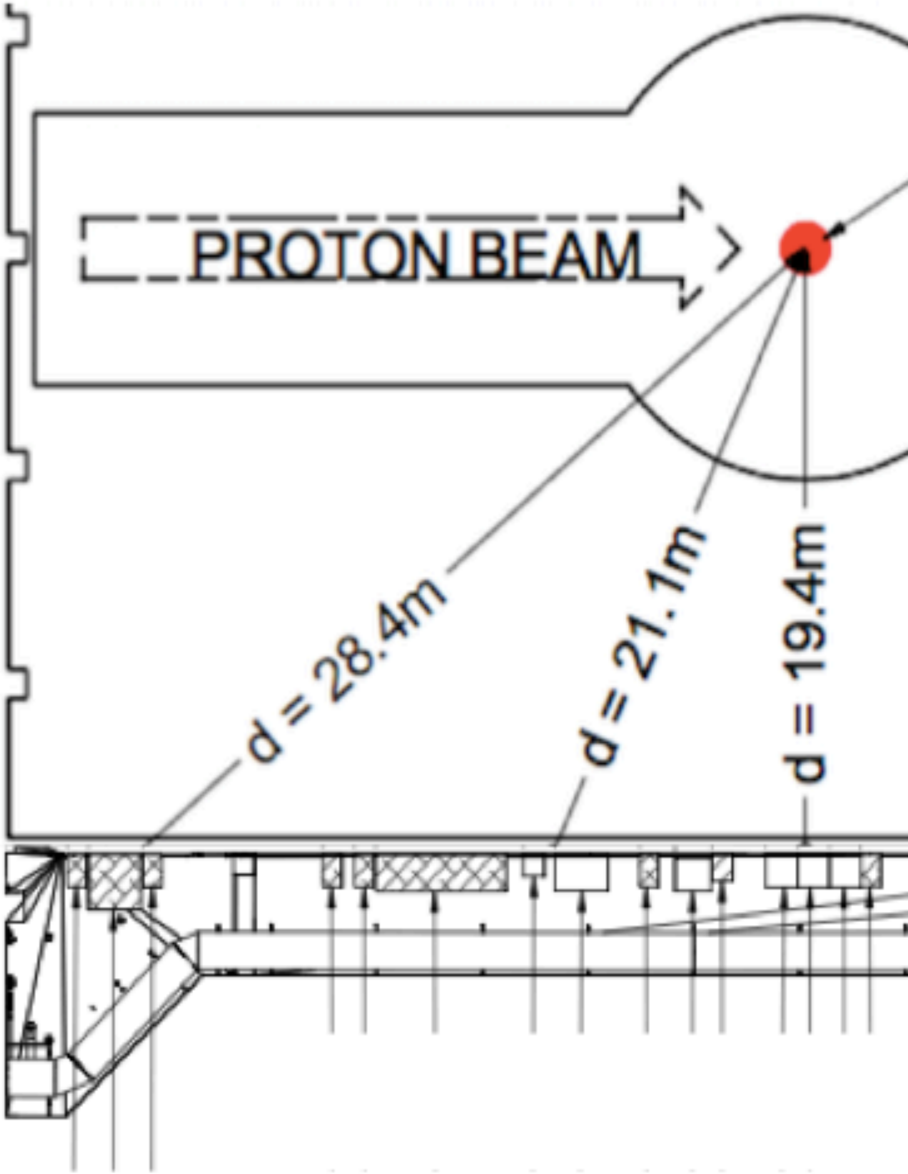




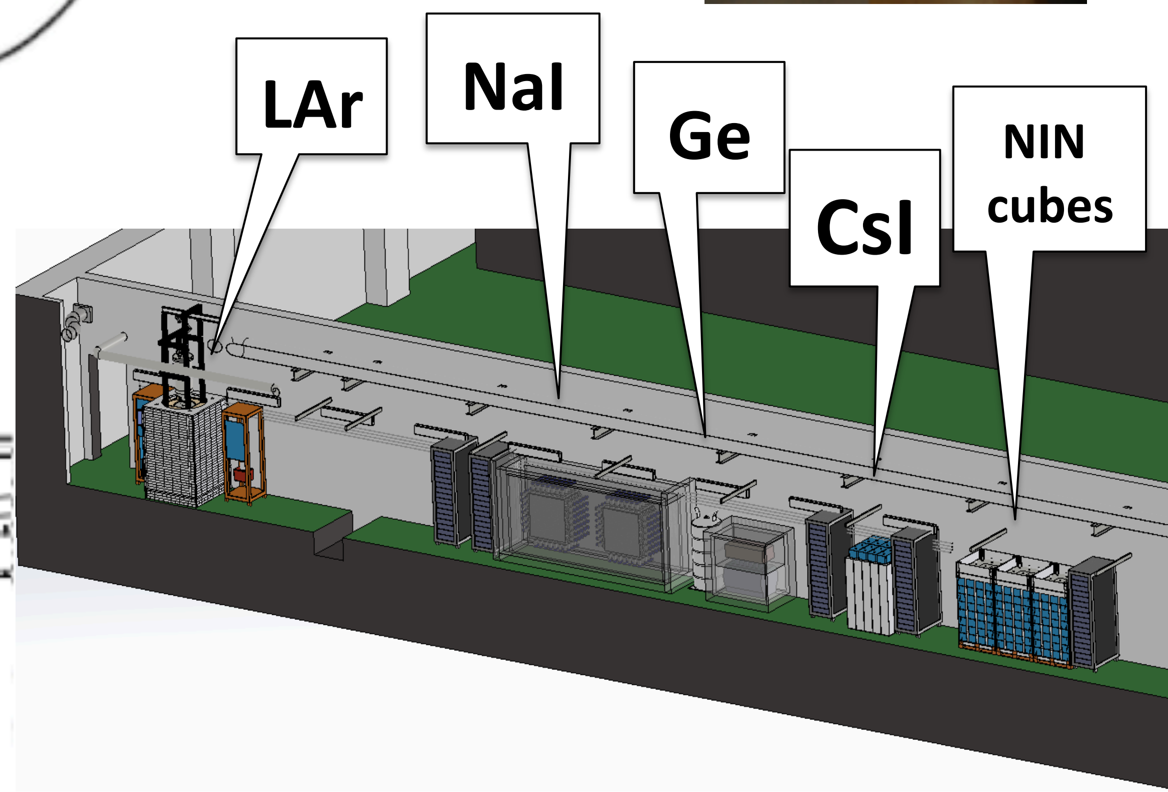


- CsI installed July 2015; 185 kg of NaI in July 2016
- Two more detectors to be deployed with resources in hand, fall 2016
- For 5σ discovery, **need larger detectors**

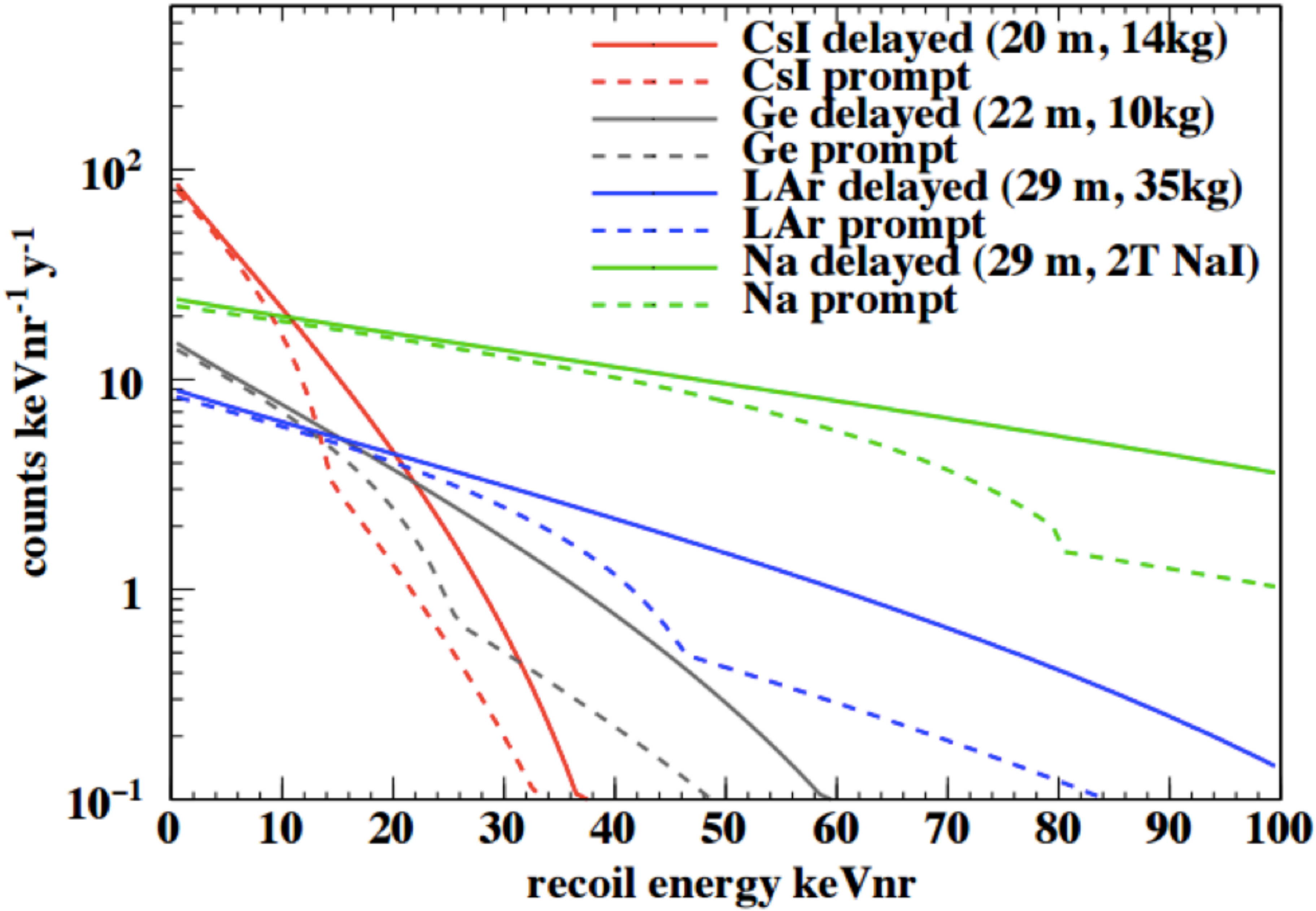
Siting for deployment in SNS basement
(measured neutron backgrounds low)



View looking down "Neutrino Alley"



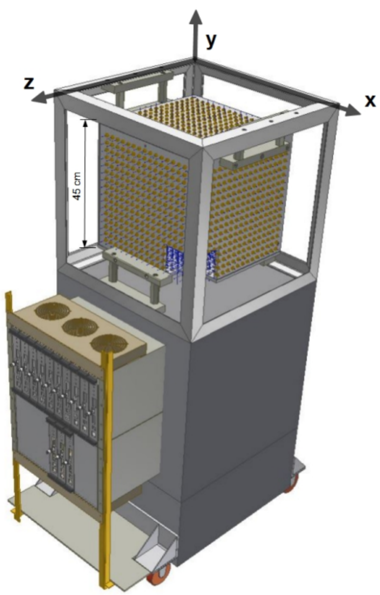
Expected recoil signals

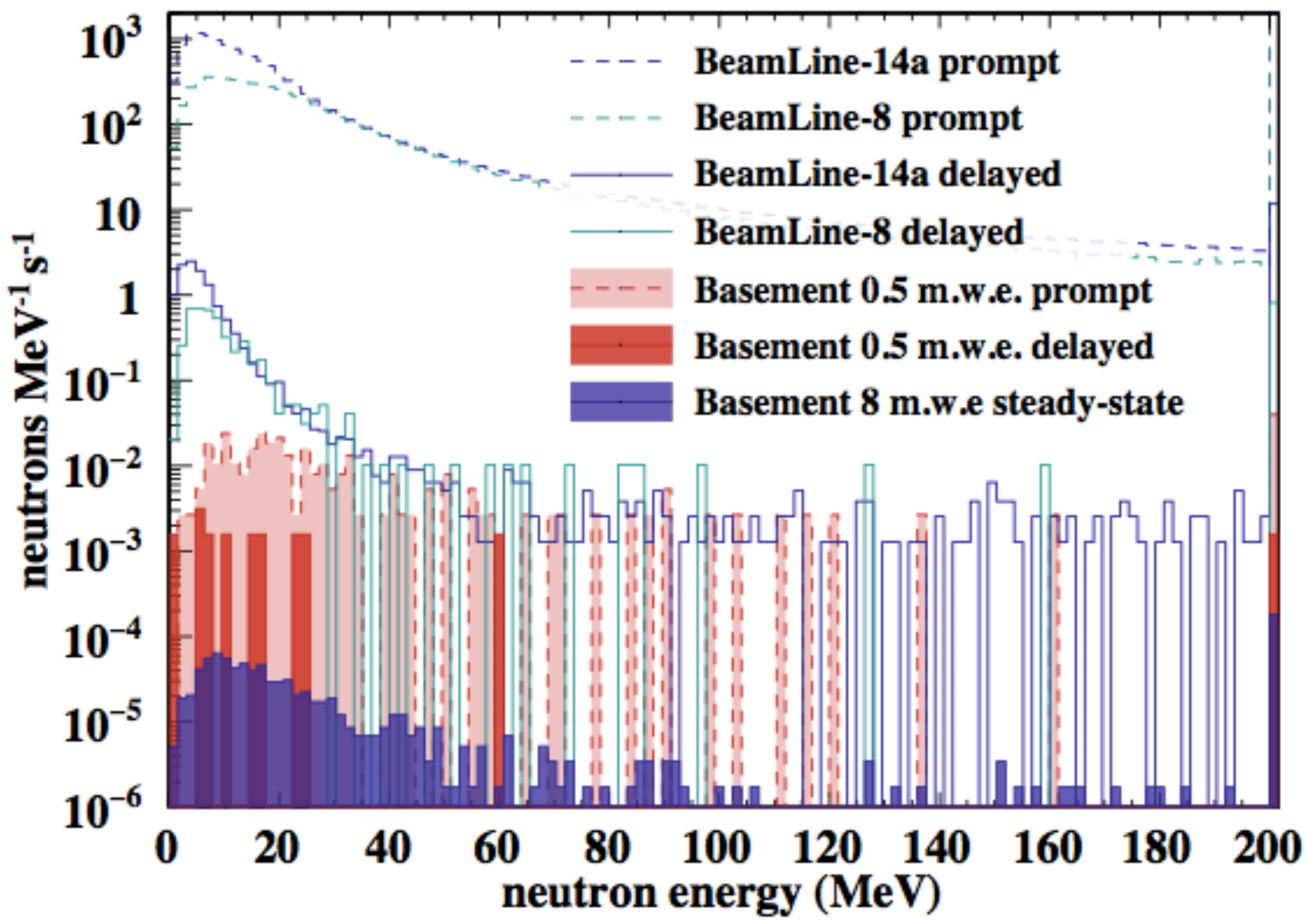


Prompt defined as first μs; note some contamination from ν_e and ν_μ-bar

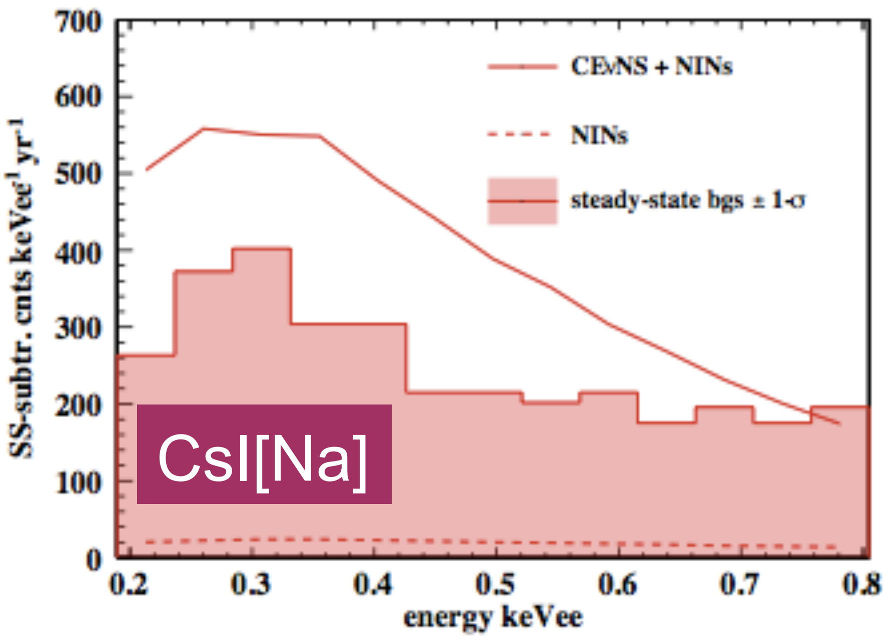
Neutron Backgrounds

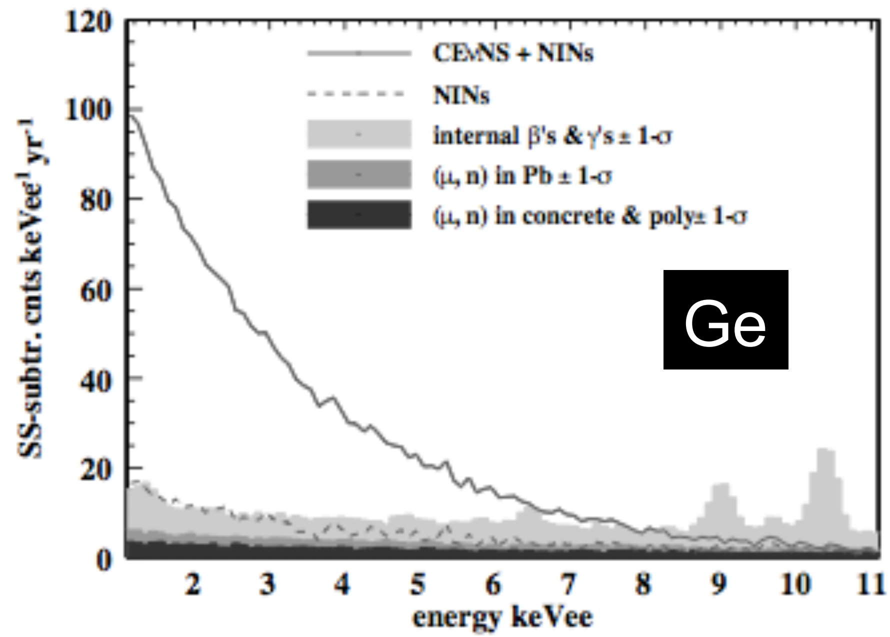
Several background measurement campaigns have shown that Neutrino Alley is neutron-quiet

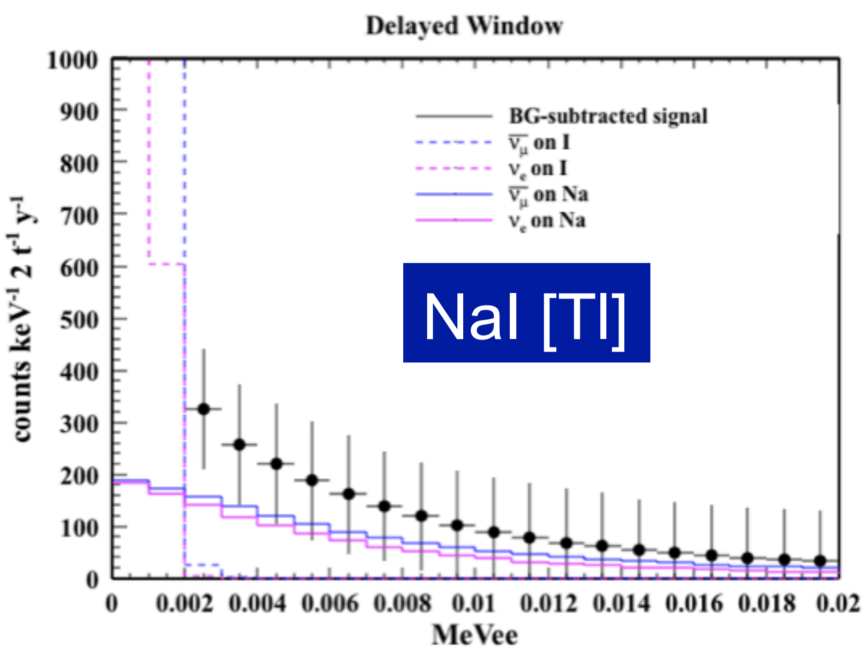




Realistic steady-state-bg-subtracted recoil spectra (keVee/MeVee) compared to 1σ background fluctuations







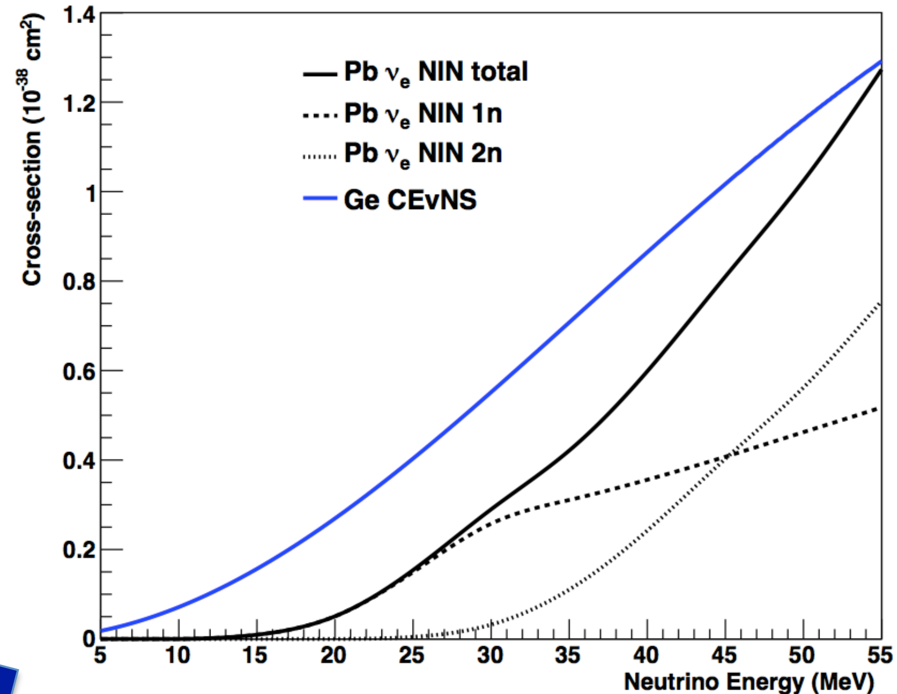
Currently measuring *neutrino-induced neutrons* in lead, (iron, copper), ...

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

↘ 1n, 2n emission

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

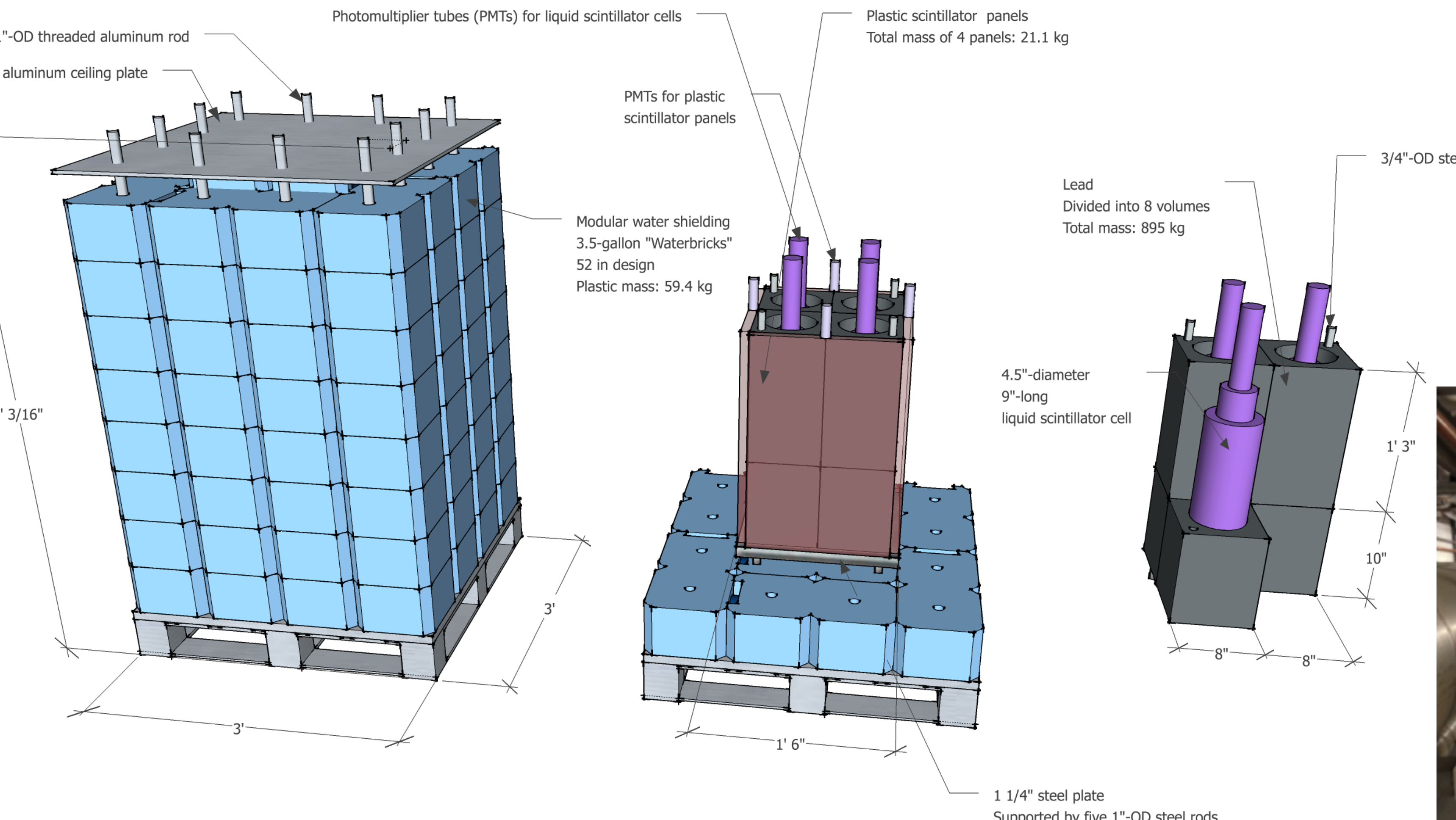
↘ 1n, 2n, γ emission



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

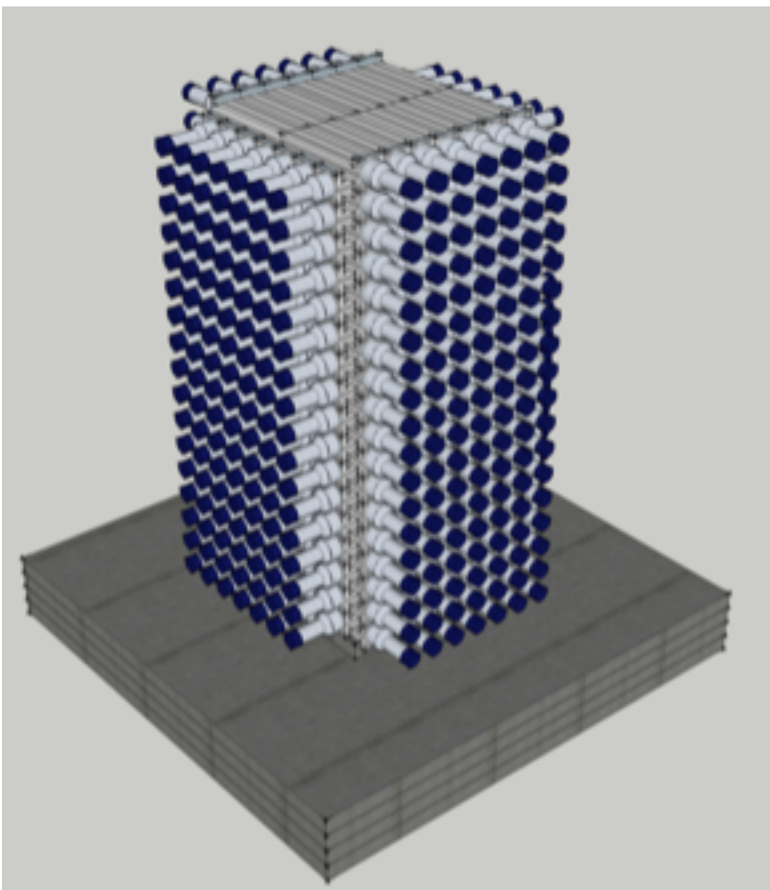
NIN measurement in SNS basement

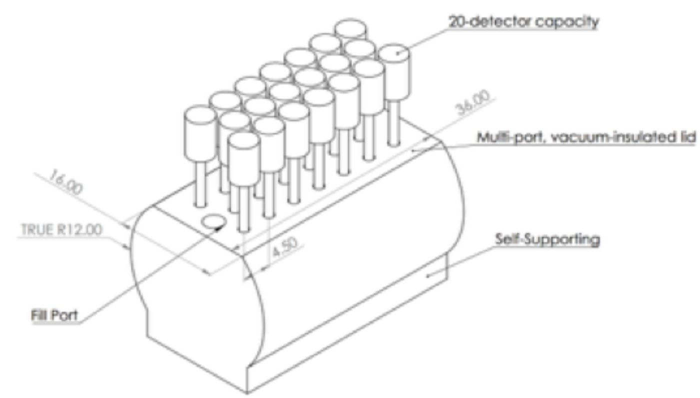
- Scintillator inside CsI detector lead shield (now)
- Liquid scintillator surrounded by lead (swappable for other NIN targets) inside water shield



Potential upgrades

- additional Ge detectors
- larger LAr (up to few 100 kg)
- up to 7 ton NaI if threshold demonstrated
- additional targets/detectors





~5σ in ~ 2 years with demonstration of N^2 dependence

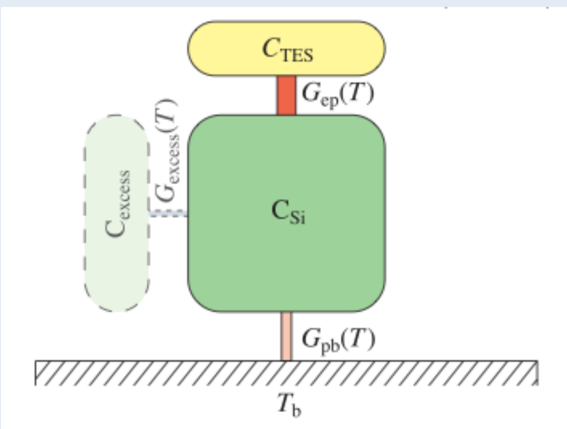
The Low-Energy Recoil Frontier:

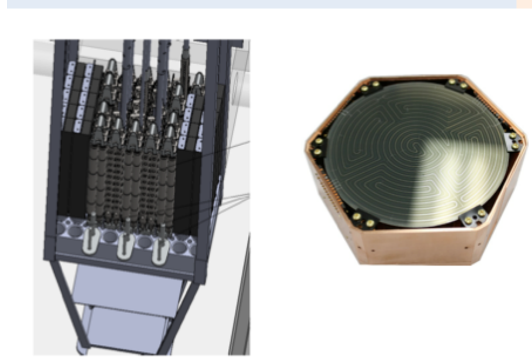
There is strong physics motivation to extend recoil energy threshold to sub-keV (reactor & source ν's)

(magnetic moment, sterile osc w/small L, reactor monitoring, astrophysics,...)

Cryogenic solid-state bolometers

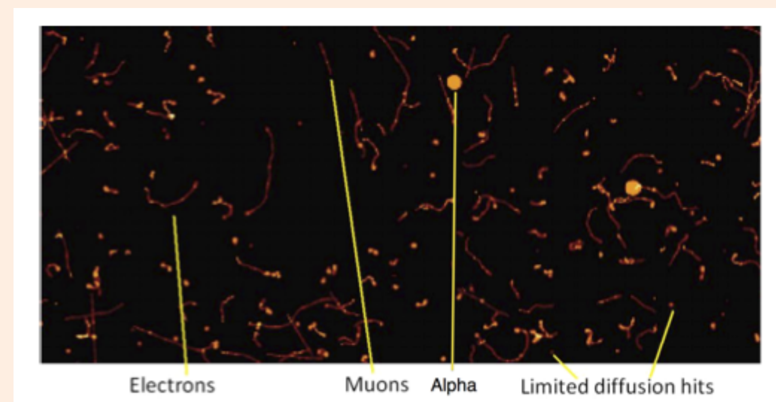
RICOCHET | **MINER**





J. Formaggio, E. Figueroa-Feliciano, and A. Anderson, PRD D 85, 013009 (2012)
Mirabolfathi et al., 1510.00999

Silicon CCDs (CONNIE)



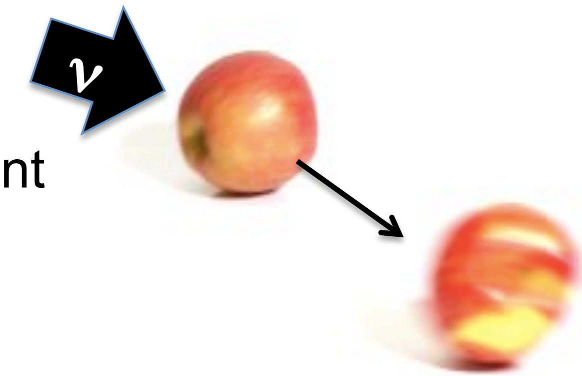
Moroni et al.,
Phys.Rev. D91 (2015) 7, 072001

(+ Ge PPCs, spherical TPCs, ...)

It's all about the backgrounds...

Summary

CEvNS offers many physics prospects!



- DM bg, detector response
- SM test: weak mixing angle, NSI, ν magnetic moment
- SN physics, SN & solar ν's
- Neutron form factors
- Sterile oscillations
- Nuclear safeguard applications

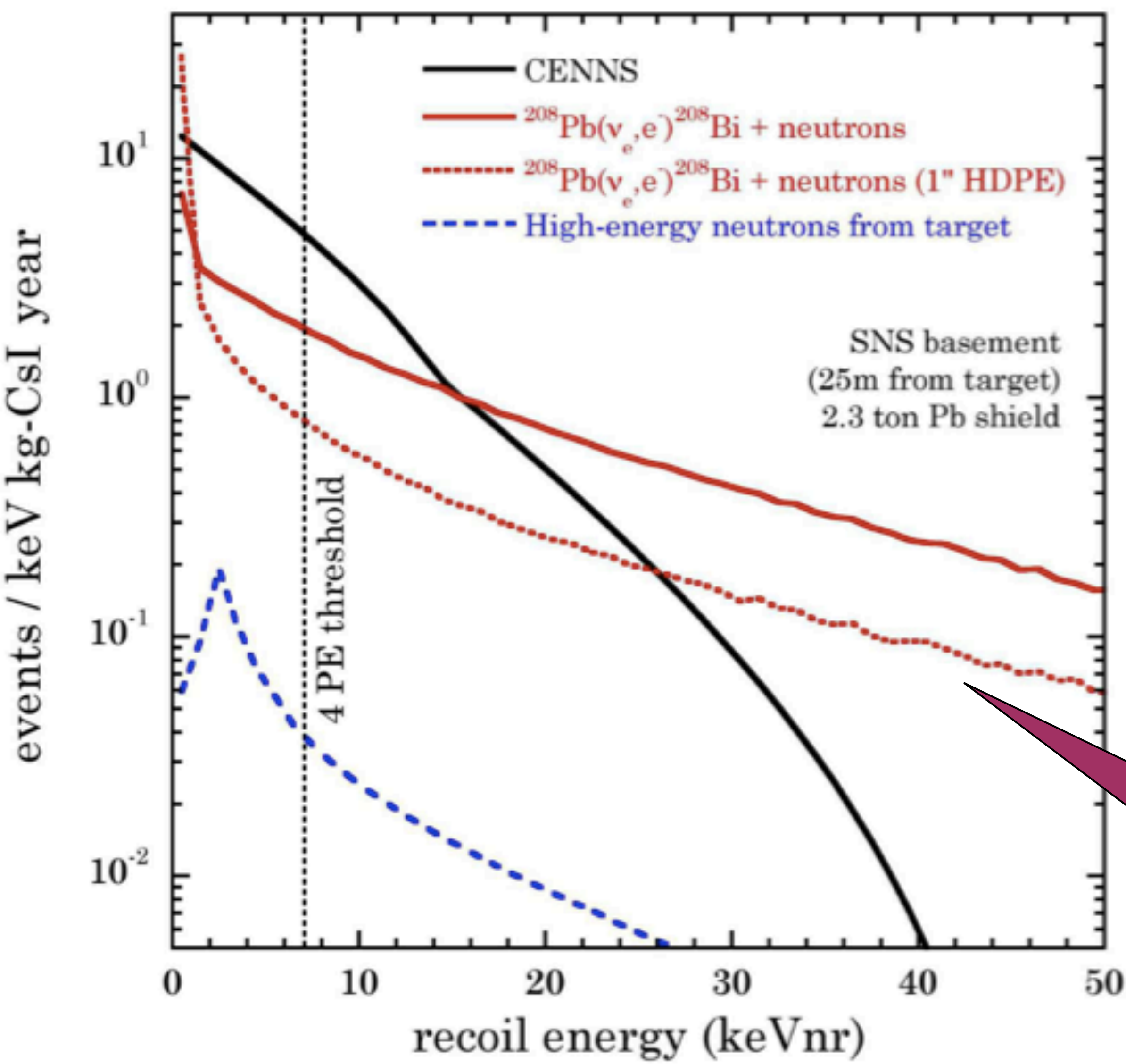
For first measurements, requirements are stringent;
systematic uncertainties may eventually become limiting
need multiple targets, well-understood neutrino source

Stopped-pion sources an attractive first prospect: high energy ν's, good bg rejection → COHERENT@ SNS

Reactor sources are attractive for high flux, flexibility
Radioactive sources attractive for oscillometry → low-energy frontier: RICOCHET, MINER, CONNIE, ...

Extras/backups

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



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

J. Collar et al., Nucl.Instrum.Meth. A773 (2014) 56