# COHERENT Elastic Neutrino-Nucleus Scattering


Kate Scholberg, Duke University

Neutrinos in Nuclear Physics, Knoxville, TN

July 31, 2016

# OUTLINE

- **Coherent elastic neutrino-nucleus scattering**

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

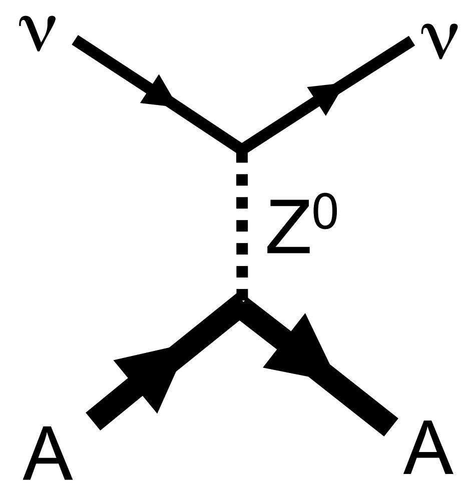
- How to measure it?
  - stopped pion sources and reactors

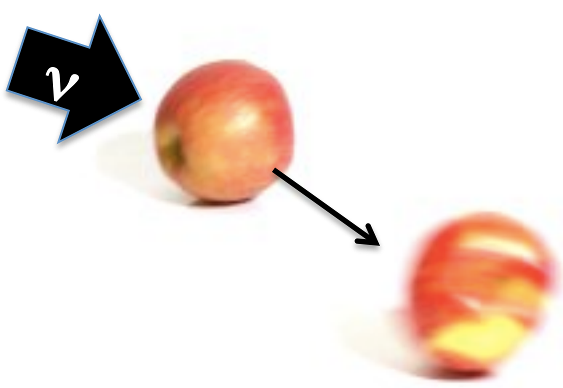
- Experiments going after CEvNS
  - **The COHERENT Experiment at the Spallation Neutron Source**

# 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 $E_\nu$~ 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)

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

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

\begin{aside}

Literature has CNS, CNNS, CENNS, ...

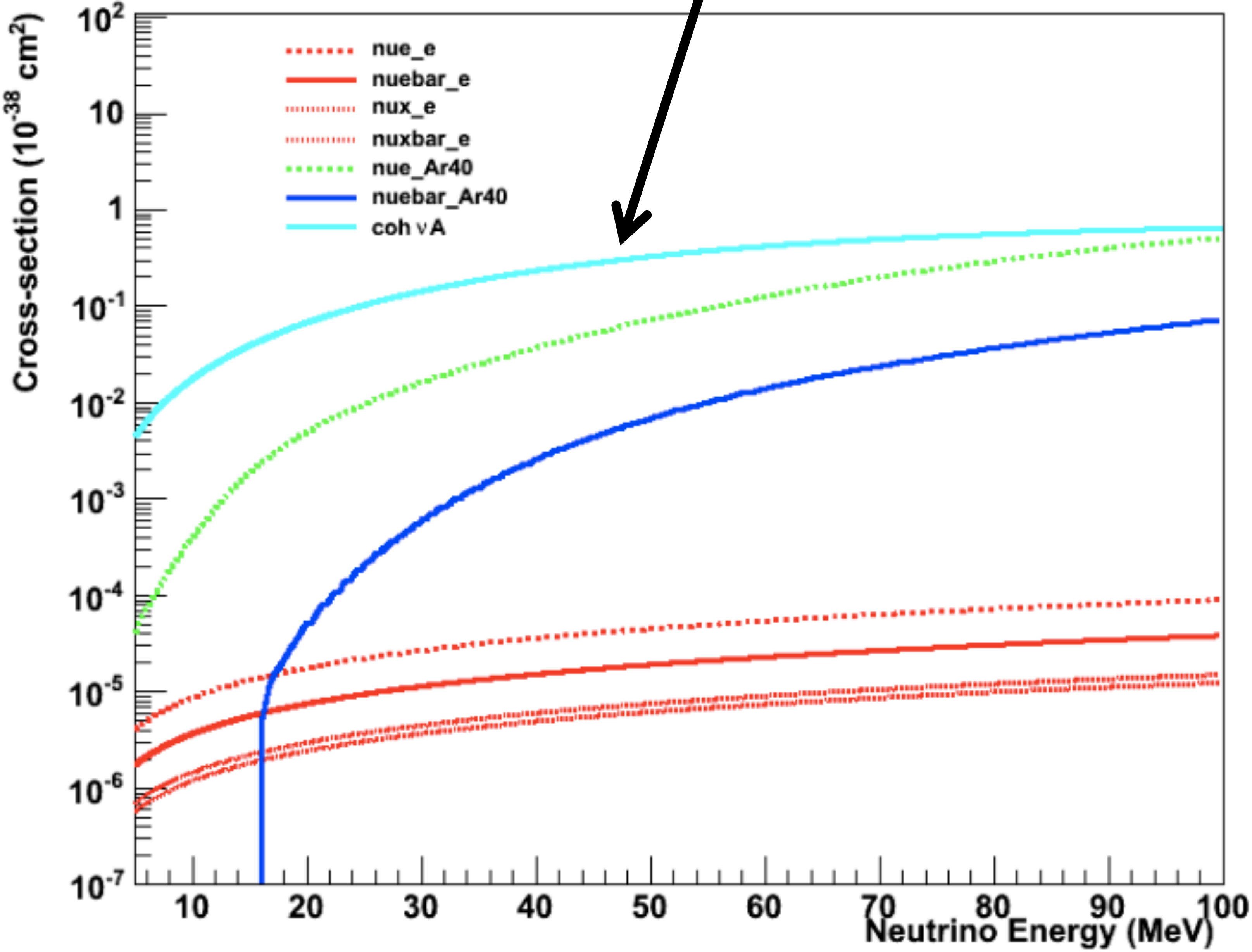
- I prefer including "E" for "elastic"... otherwise HEP types constantly confuse it with coherent pion production at ~ GeV energies
- I'm told "NN" means "nucleon-nucleon" to nuclear types (also CENNS is now a collaboration!)
- CE$\nu$NS is a possibility but those internal Greek letters are annoying

➔**CEvNS**, pronounced "sevens"...

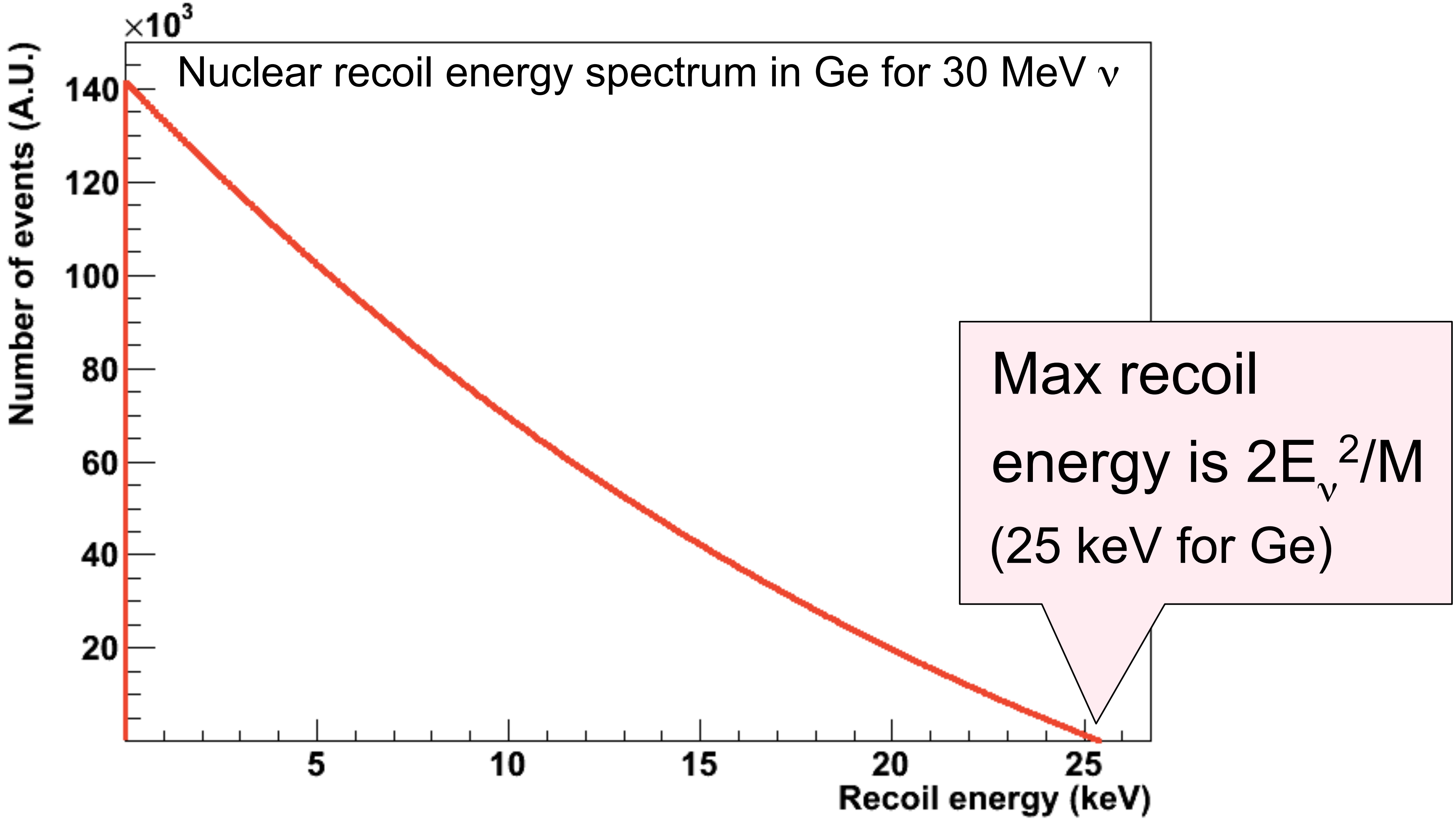
spread the meme!

\end{aside}

# The cross-section is *large*

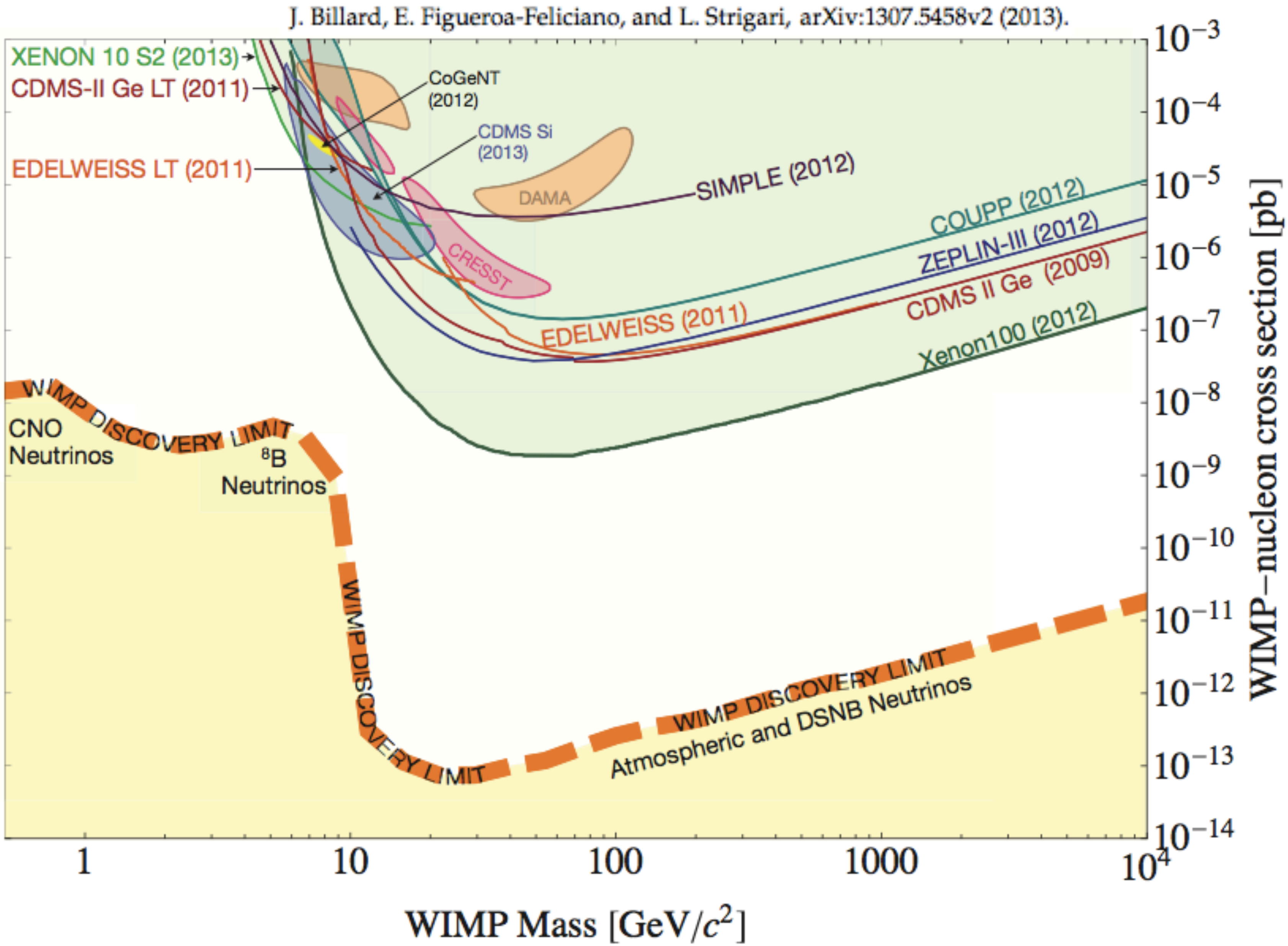


**Large cross section**, but never observed due to **tiny nuclear recoil energies:**




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

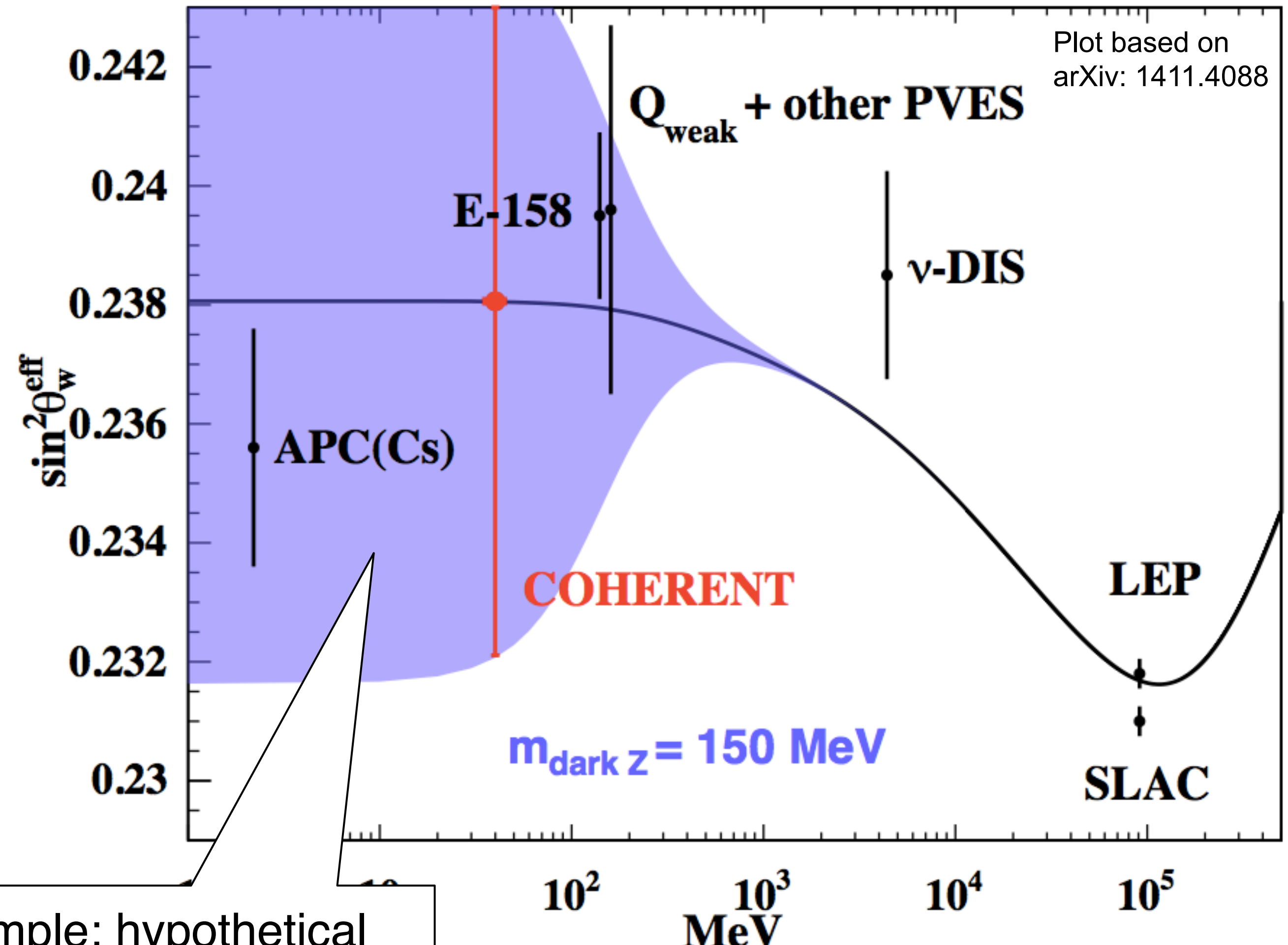
# CEvNS from natural neutrinos creates ultimate background for direct DM search experiments




Understand nature of background (& detector response)

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

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



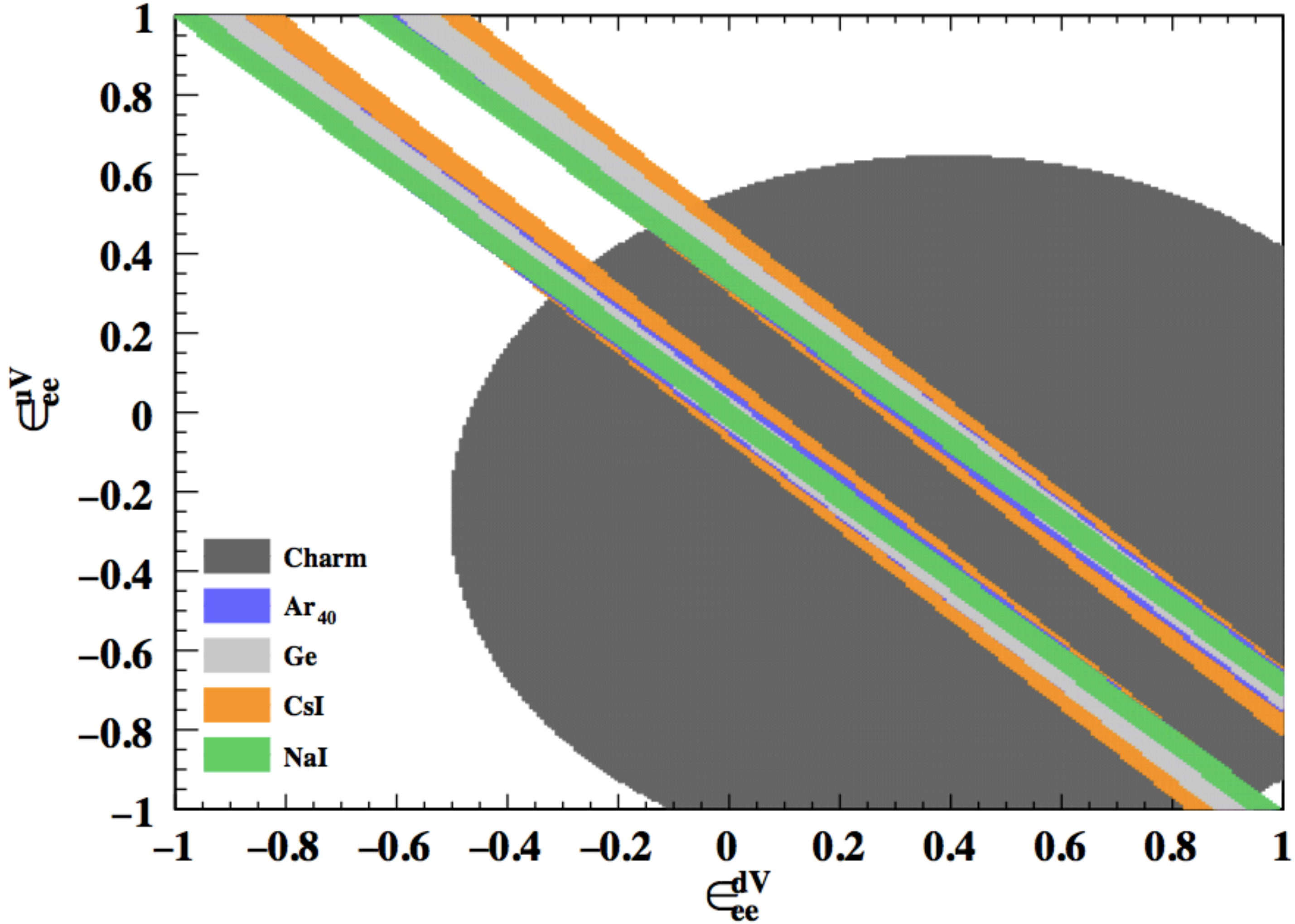

Example: hypothetical dark Z mediator (explanation for g-2 anomaly)

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***)

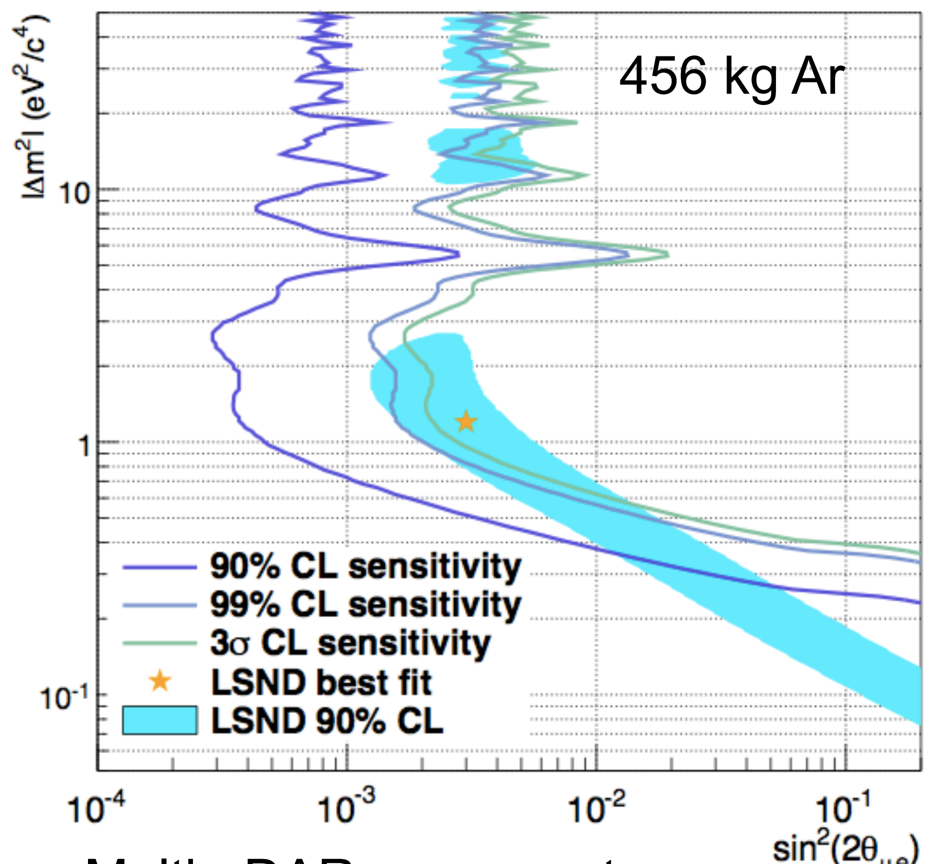
K. Scholberg, PRD73, 033005 (2006)

# Oscillations to sterile neutrinos w/CEvNS

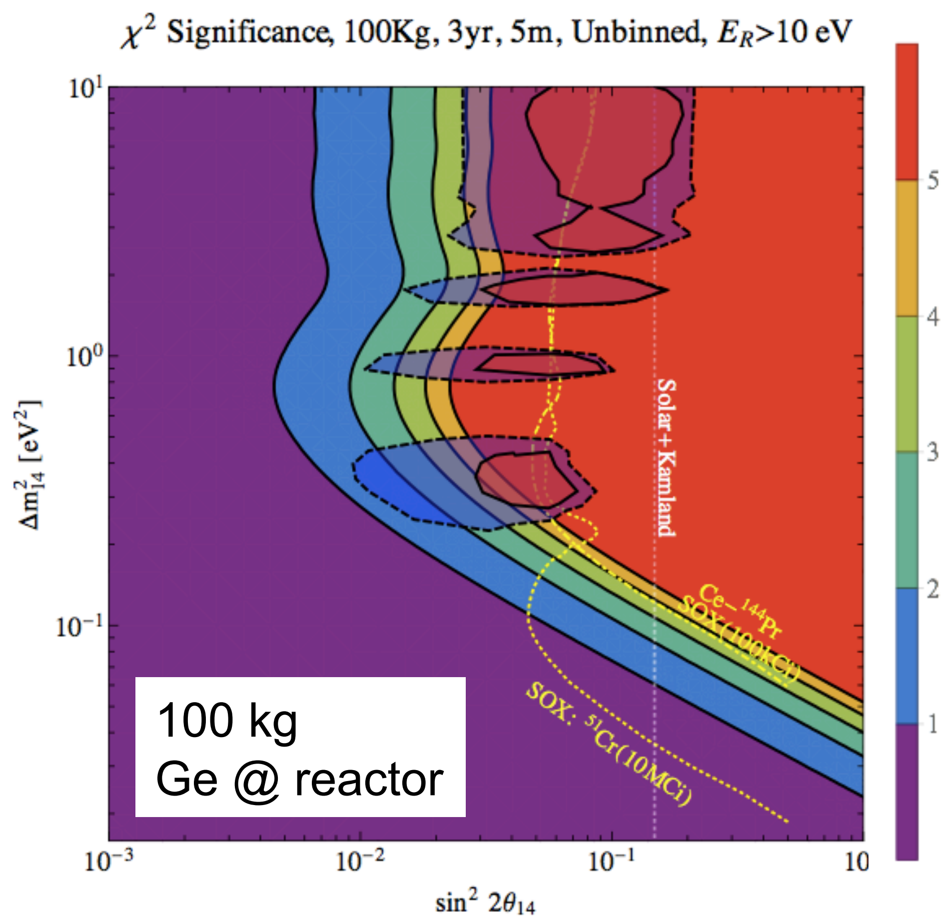
(NC is flavor-blind): a potential new tool;

**look for deficit and spectral distortion vs L,E**

Examples:




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



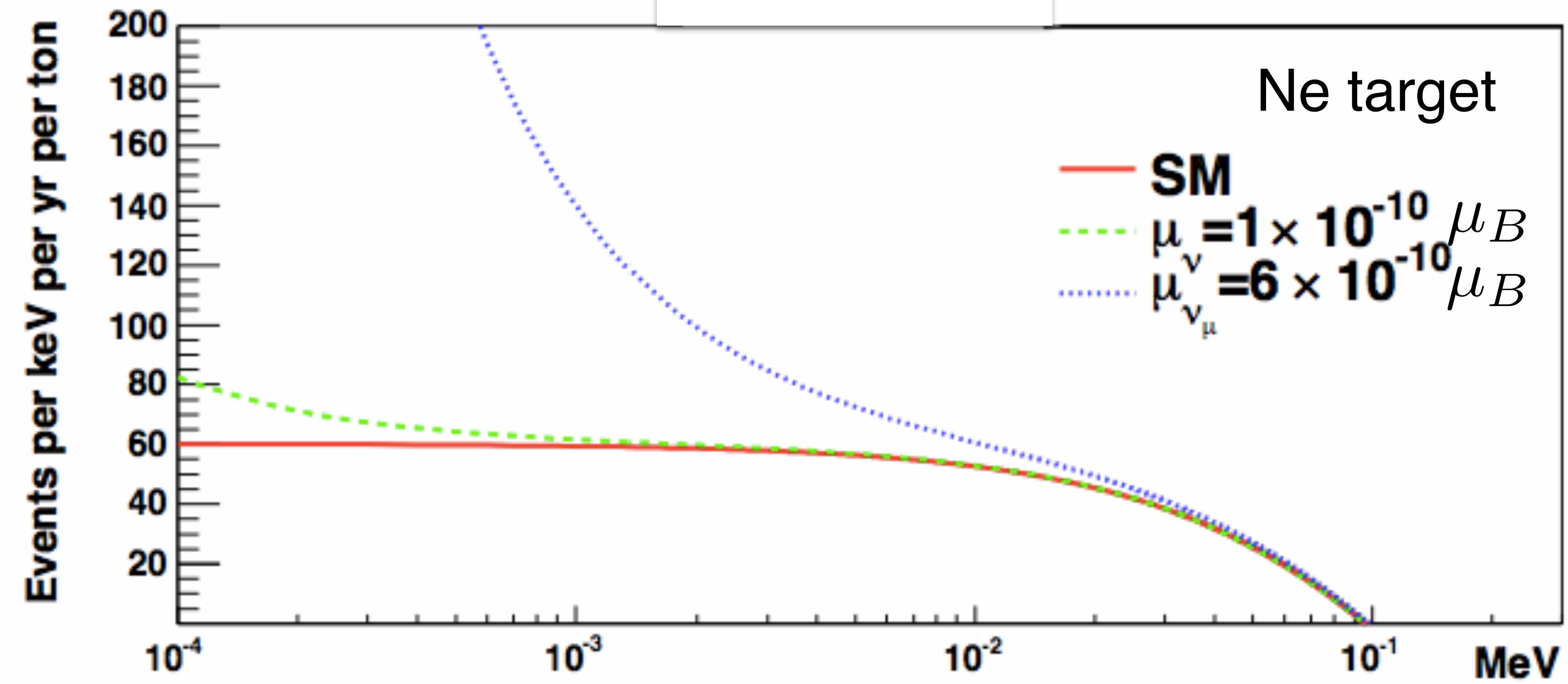

B. Dutta et al, arXiv:1511.02834

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

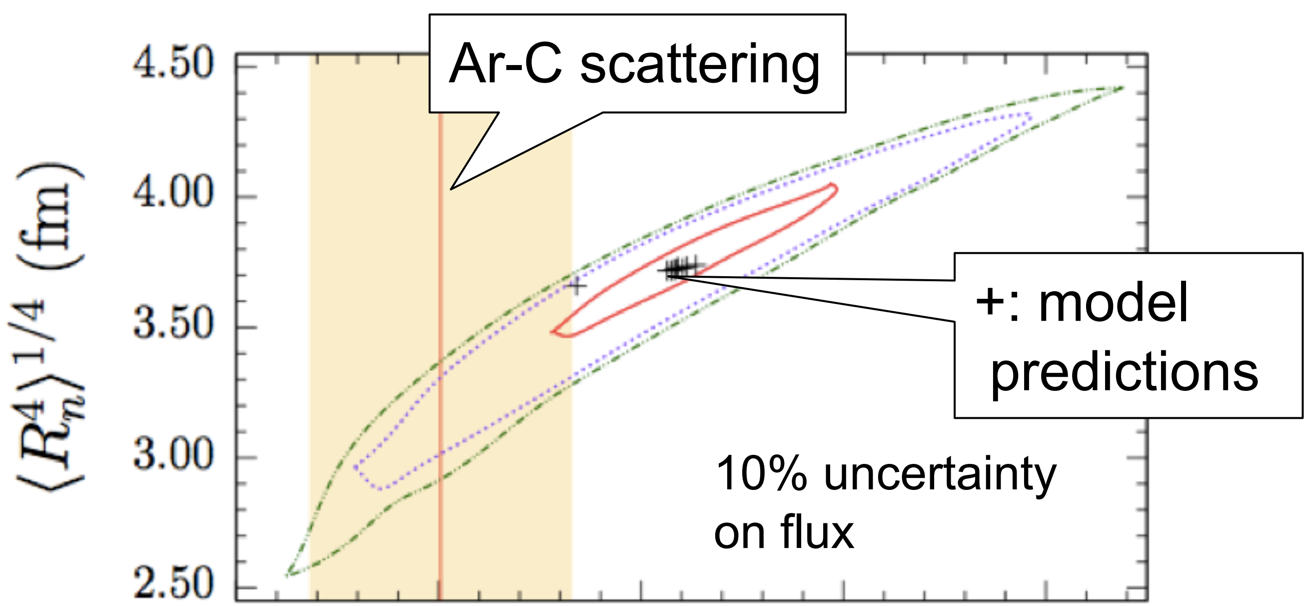
$$\frac{d\sigma}{dT}(E,T) = \frac{G_F^2}{2\pi} M \left[2 - \frac{2T}{E} + \left(\frac{T}{E}\right)^2 - \frac{MT}{E^2}\right] \frac{Q_W^2}{4} F^2(Q^2)$$

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)

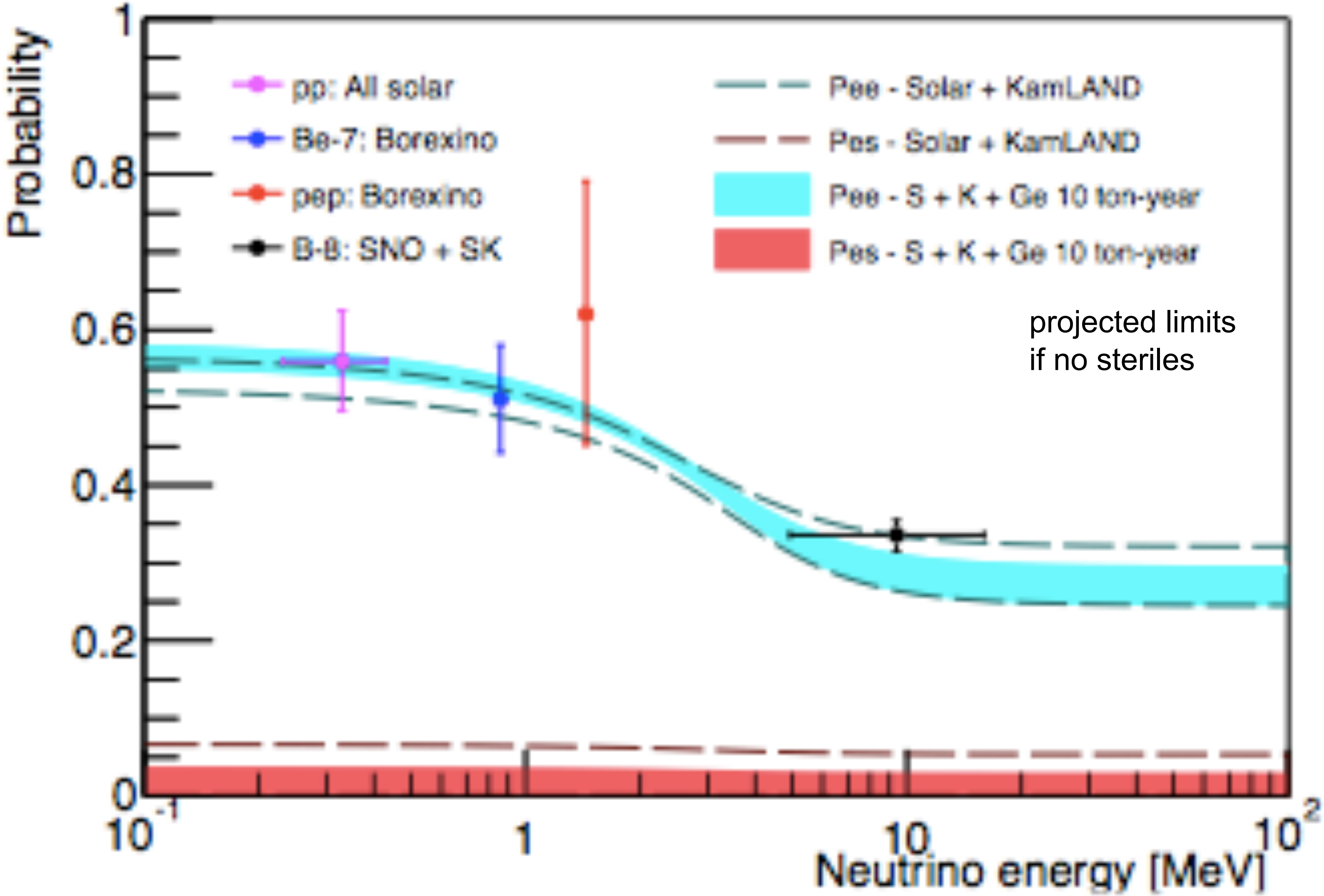
Example:
tonne-scale
experiment
at $\pi$DAR source



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

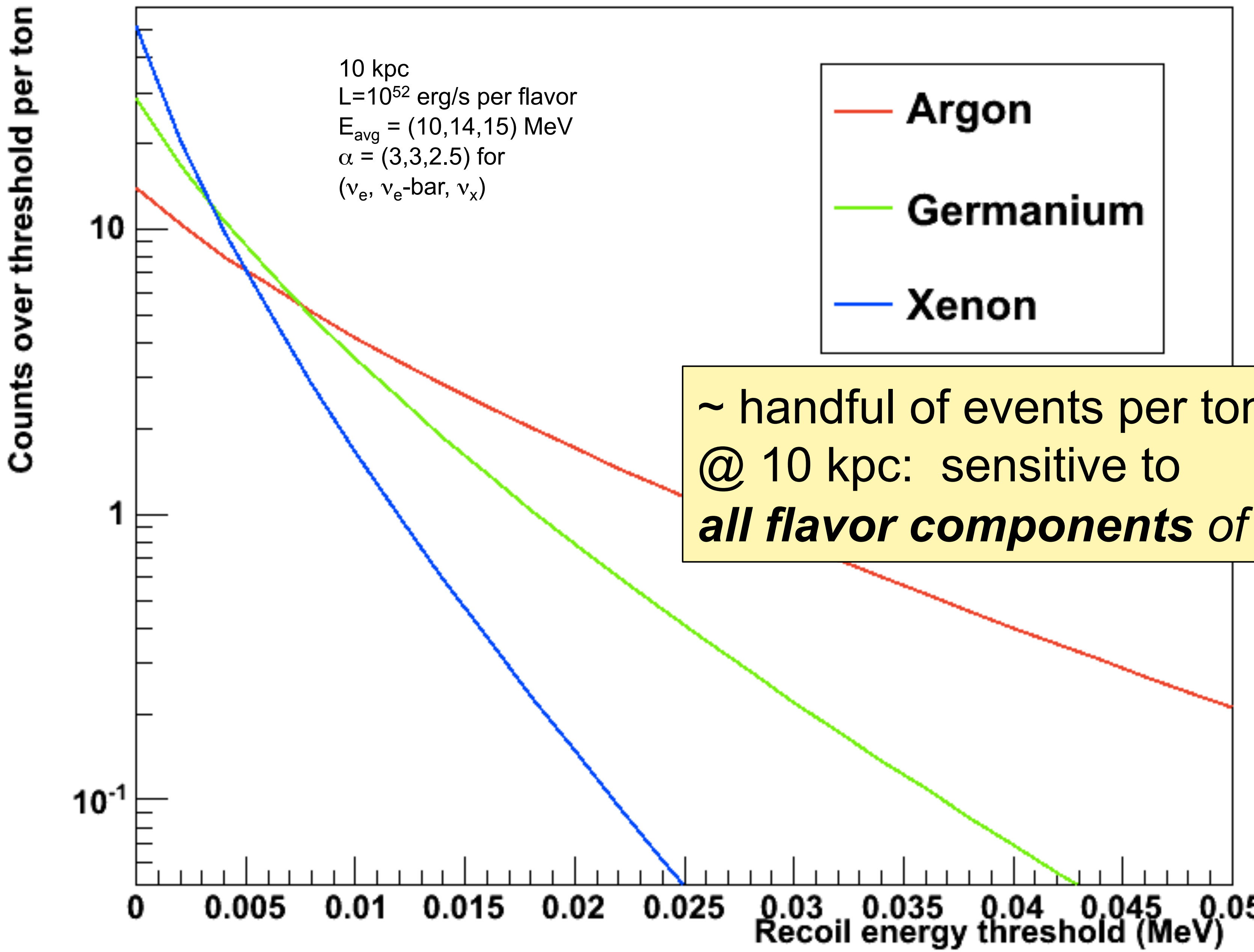
**Solar neutrinos**

Billard et al., arXiv:1409.0050




Rule out sterile oscillations using CEvNS (NC)

# Supernova neutrinos in tonne-scale DM detectors



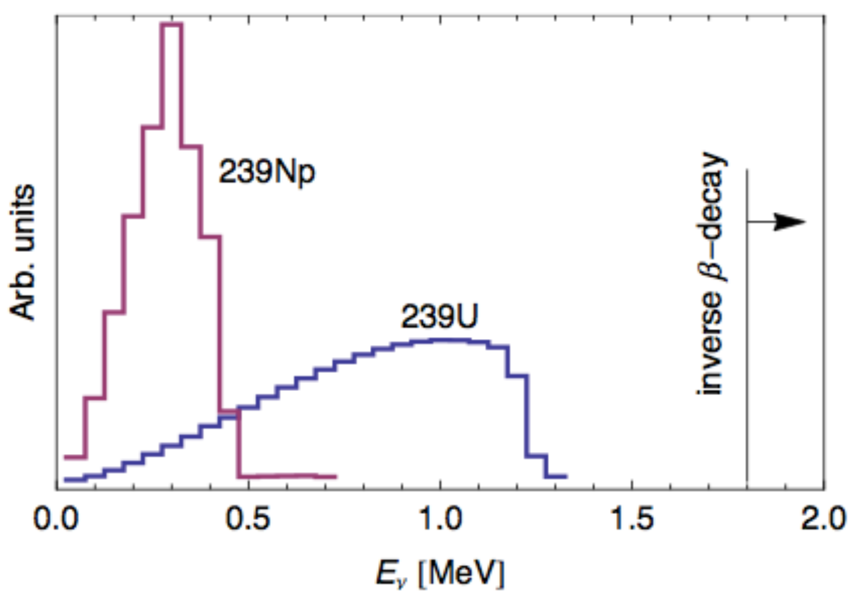

~ handful of events per tonne
@ 10 kpc: sensitive to
***all flavor components*** *of the flux*

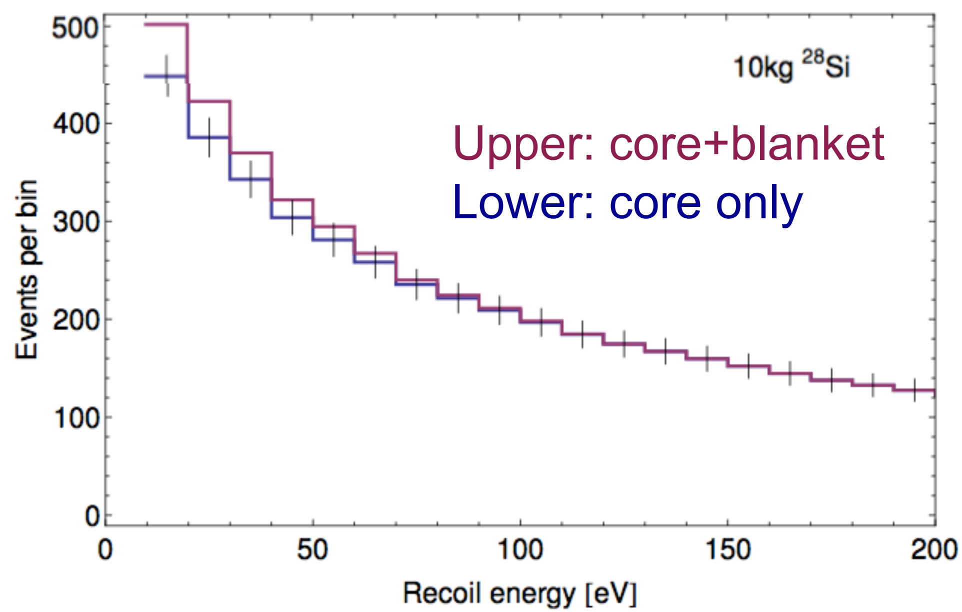
# A practical application in nuclear safeguards:

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

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

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

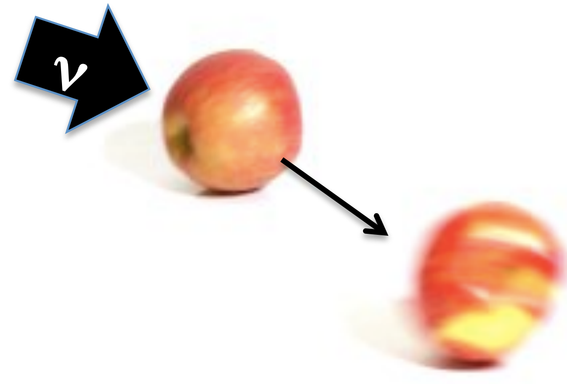



ν spectrum is below IBD threshold

➔ accessible with CEvNS, but require low recoil energy threshold

## How to detect CEvNS?

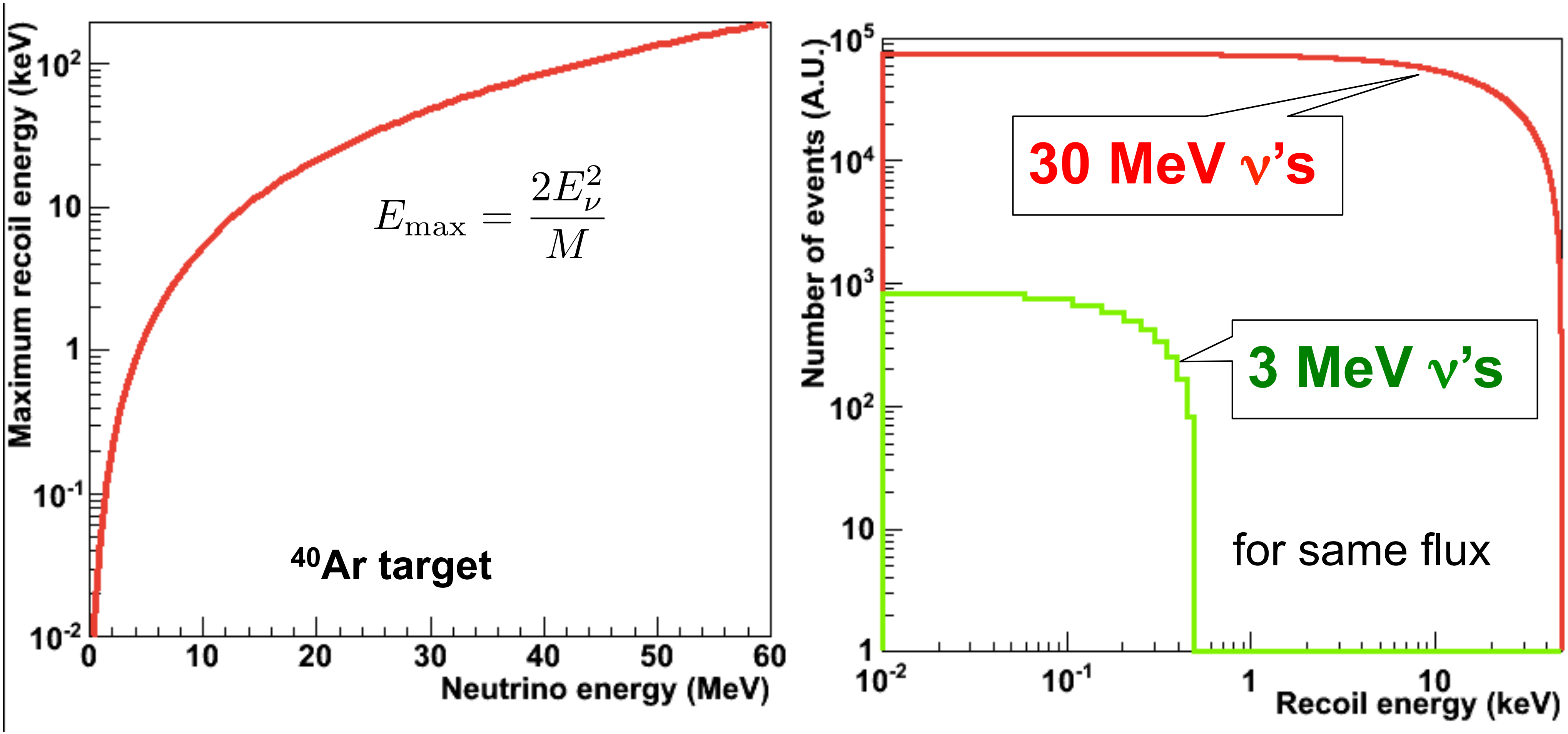



→ Need low recoil threshold & discrimination
(WIMP-style detector)

## What do you want for your $\nu$ source?

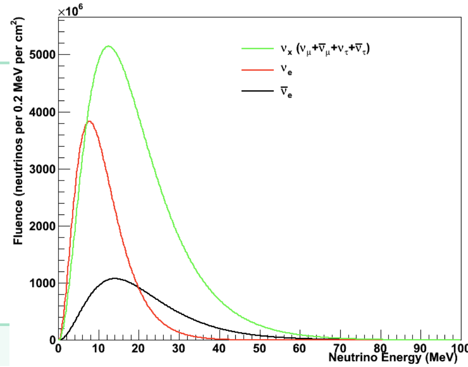
- ✓ High flux
- ✓ Well understood spectrum
- ✓ Multiple flavors (physics sensitivity)
- ✓ Pulsed source if possible, for background rejection
- ✓ Ability to get close
- ✓ Practical things: access, control, ...

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



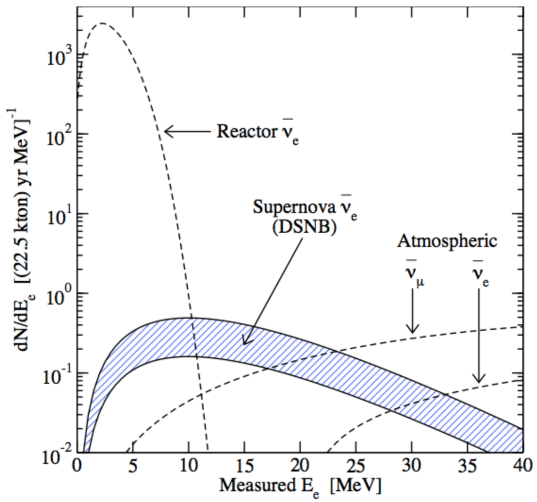

Want energy as large as possible while satisfying coherence condition: $Q \lesssim \frac{1}{R}$ (<~ 50 MeV for medium A)

**Supernova burst neutrinos**




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

**Supernova relic neutrinos**

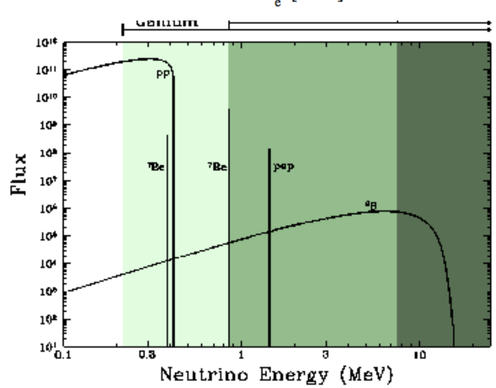



All flavors, low flux

**Atmospheric neutrinos**

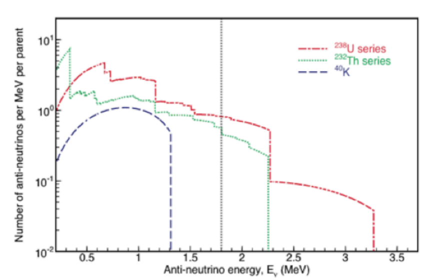
Some component at low energy

**Solar neutrinos**



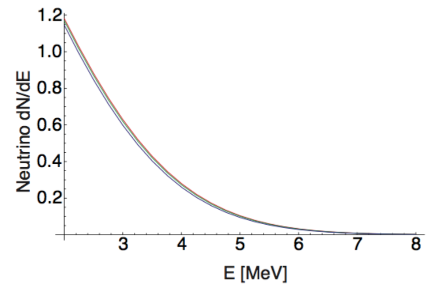
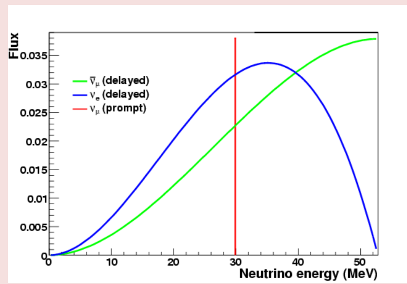
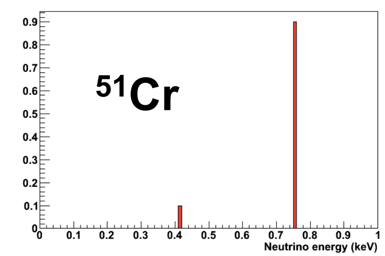
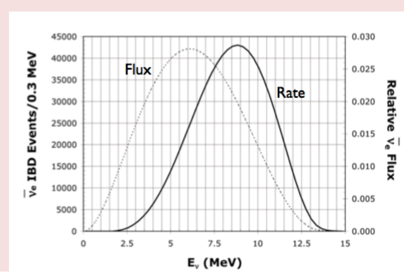
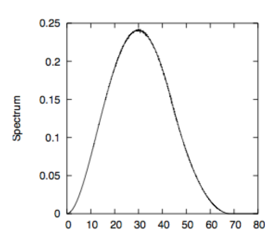

Most flux below 1 MeV

**Geoneutrinos**




Very low energy

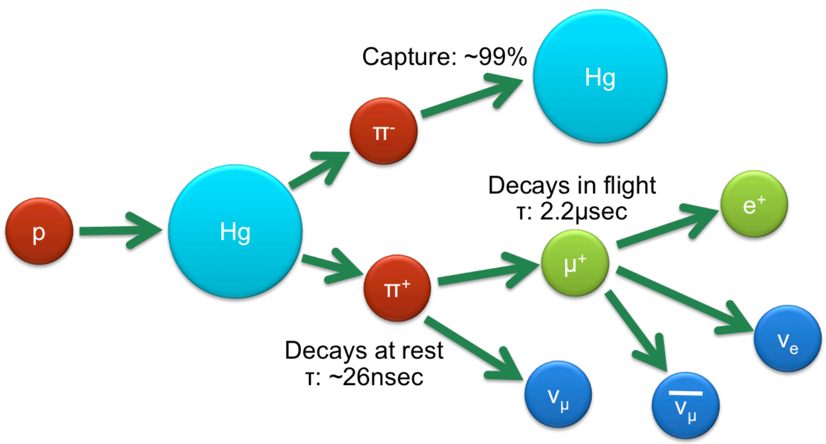
**Coherent scattering eventually a bg for DM expts**

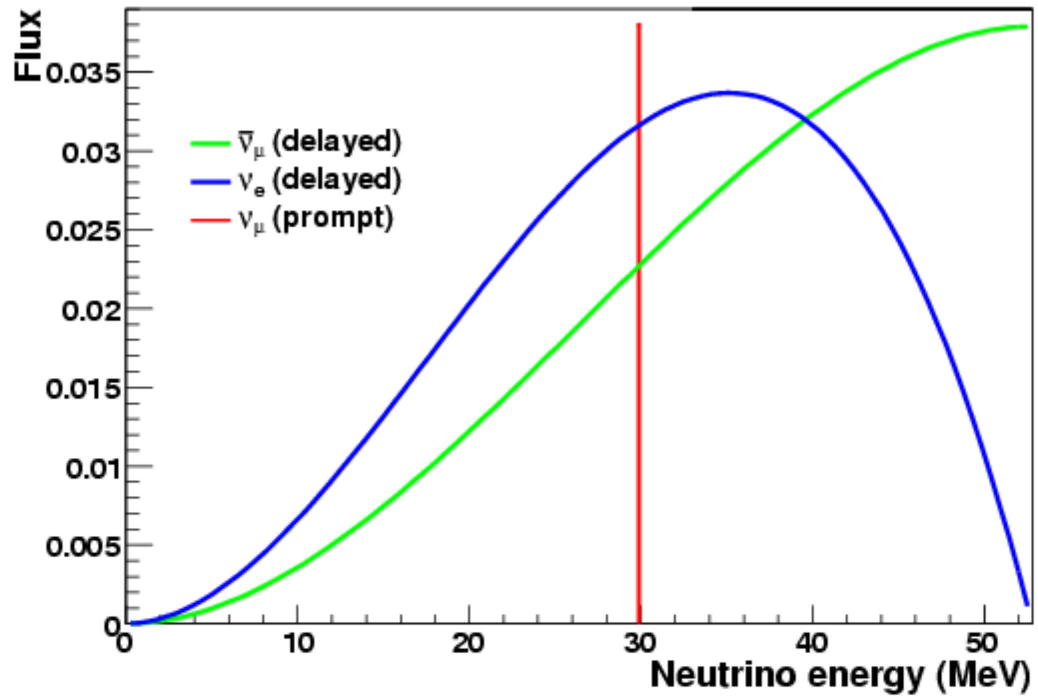
| | | |
|---|---|---|
| **Reactors** |  | Low energy, but very high fluxes possible; ~continuous source, good bg rejection needed |
| **Stopped pions** (decay at rest) |  | High energy, pulsed beam possible for good background rejection; possible neutron backgrounds |
| **Radioactive sources** (electron capture) |  | Portable; can get very short baseline, monochromatic<br>**Low energy challenging** |
| **Beam-induced radioactive sources** (IsoDAR) |  | Relatively compact, higher energy than reactor; not pulsed<br>**Does not exist yet** |
| **Low-energy beta beams** |  $\gamma$=10 boosted $^{18}$Ne $\nu_e$ | Tunable energy, but not pulsed<br>**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<br>• require very low threshold<br>• CW |
| **Stopped pion** | 1e15 | numu/ nue/ nuebar | 0-50 MeV | • higher xscn<br>• higher energy recoils<br>• pulsed beam for bg rejection<br>• multiple flavors | • lower flux<br>• potential fast neutron in-time bg |

# Stopped-Pion (πDAR) Neutrinos




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

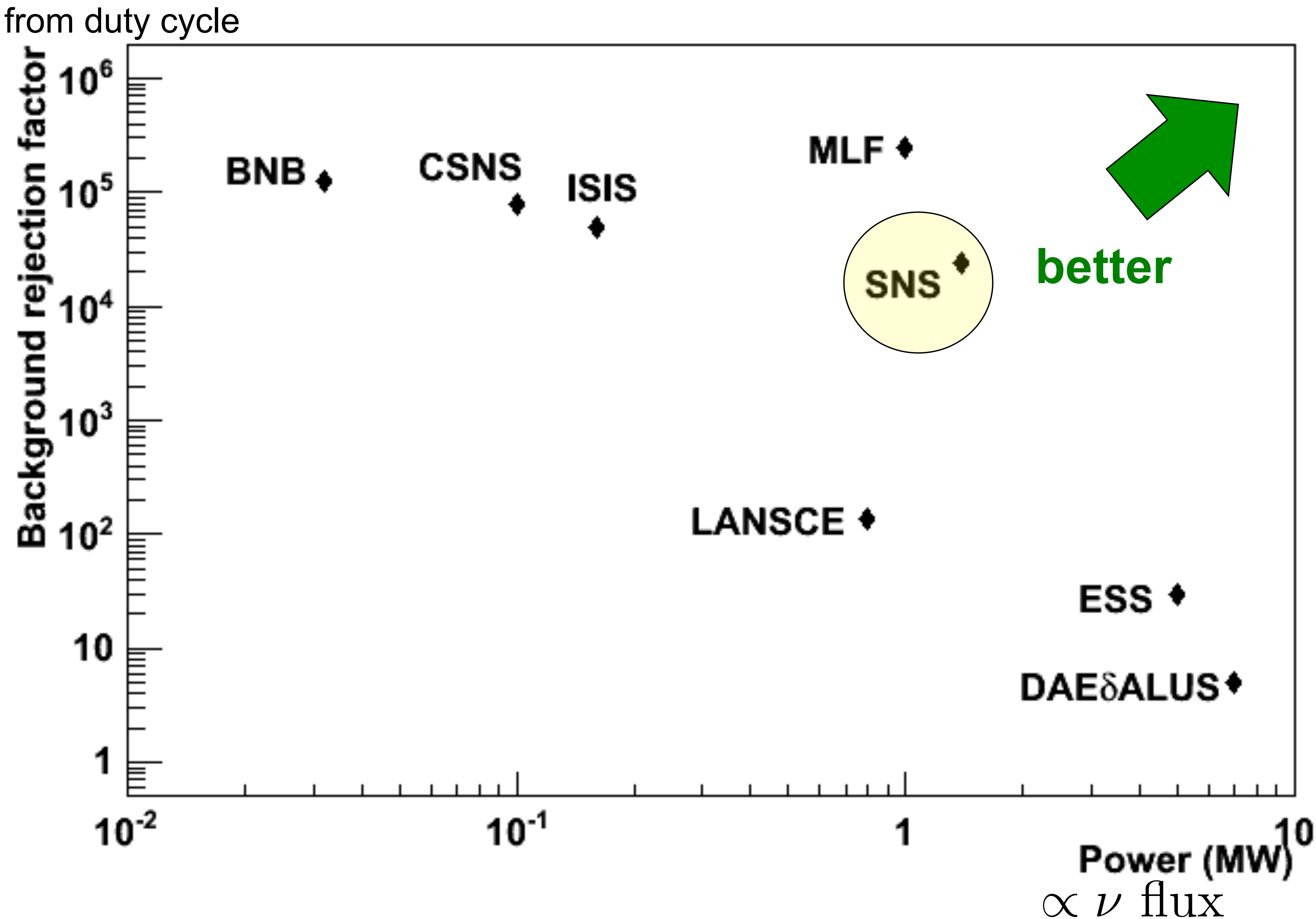
2-body decay: monochromatic 29.9 MeV $\nu_\mu$
PROMPT

$$\downarrow$$

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

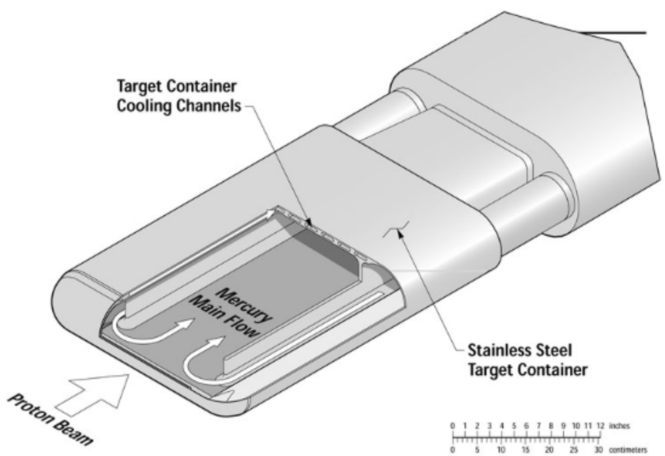
3-body decay: range of energies between 0 and $m_\mu/2$
DELAYED (2.2 μs)

# Comparison of pion decay-at-rest $\nu$ sources



# Spallation Neutron Source

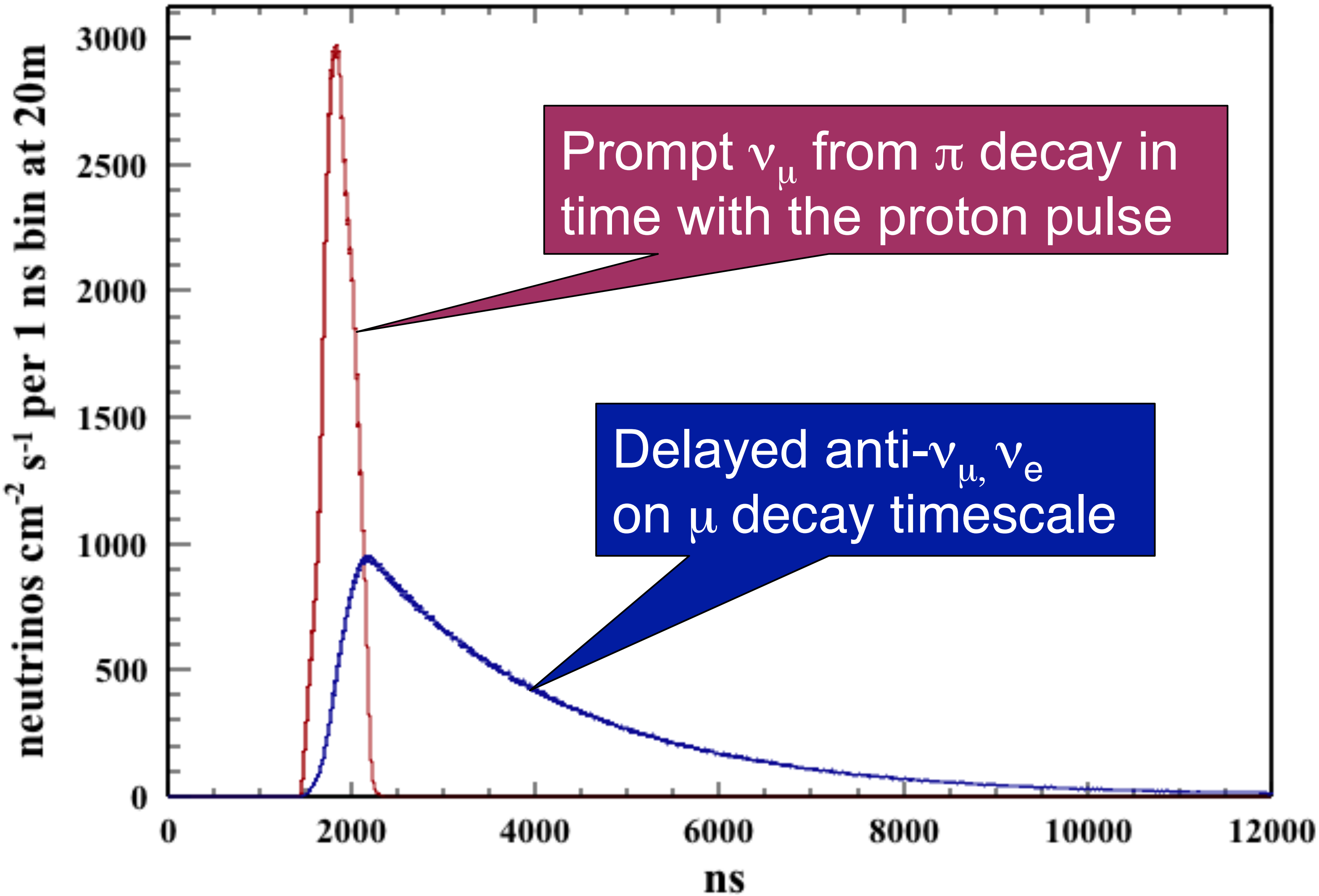
Oak Ridge National Laboratory, TN




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

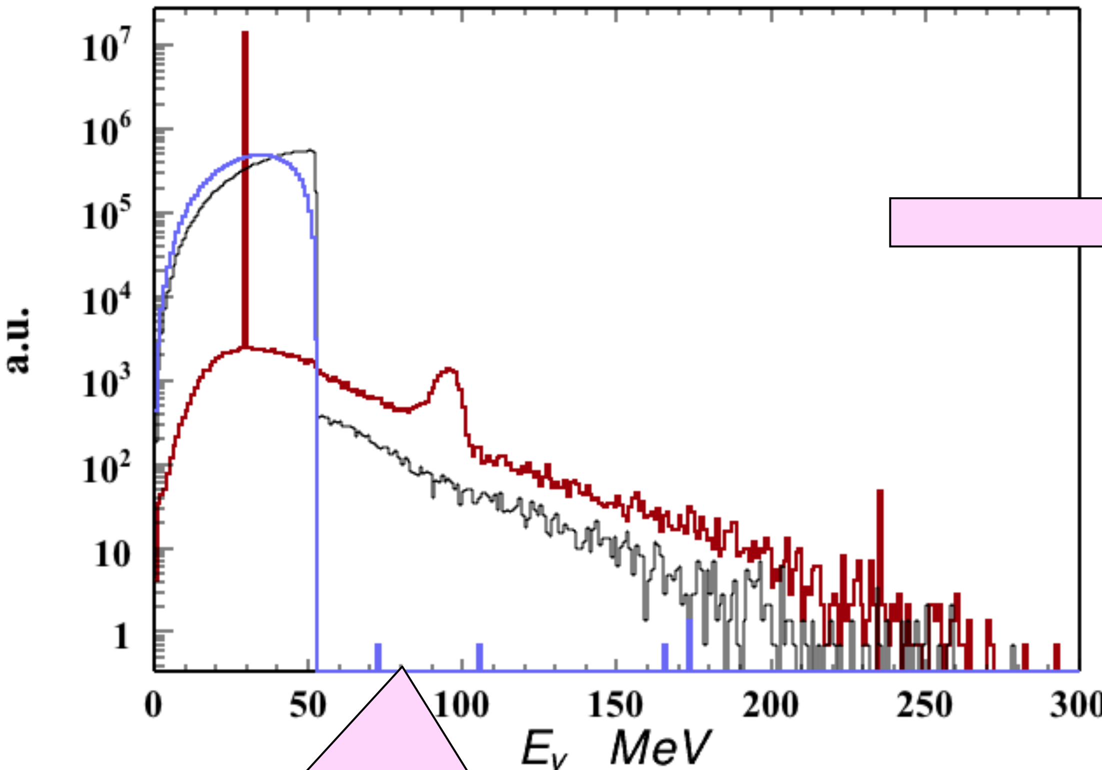
# Time structure of the SNS source

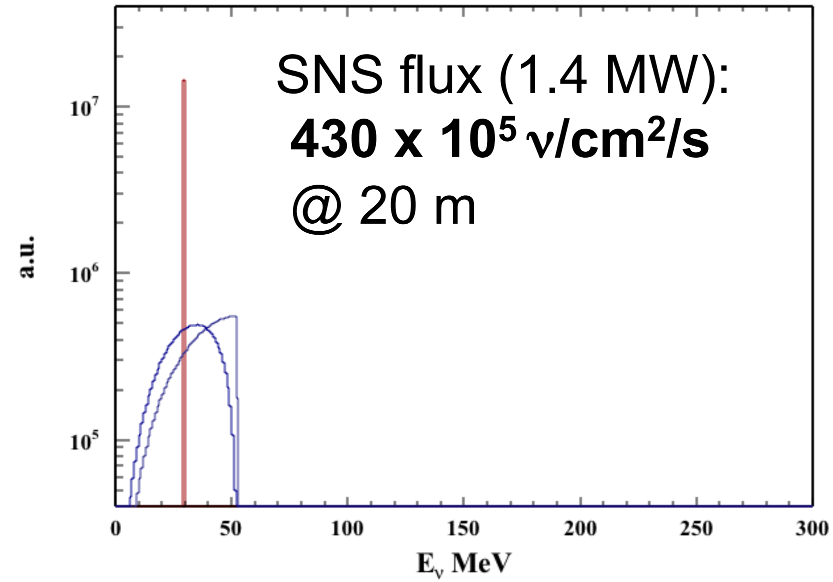
60 Hz *pulsed* source



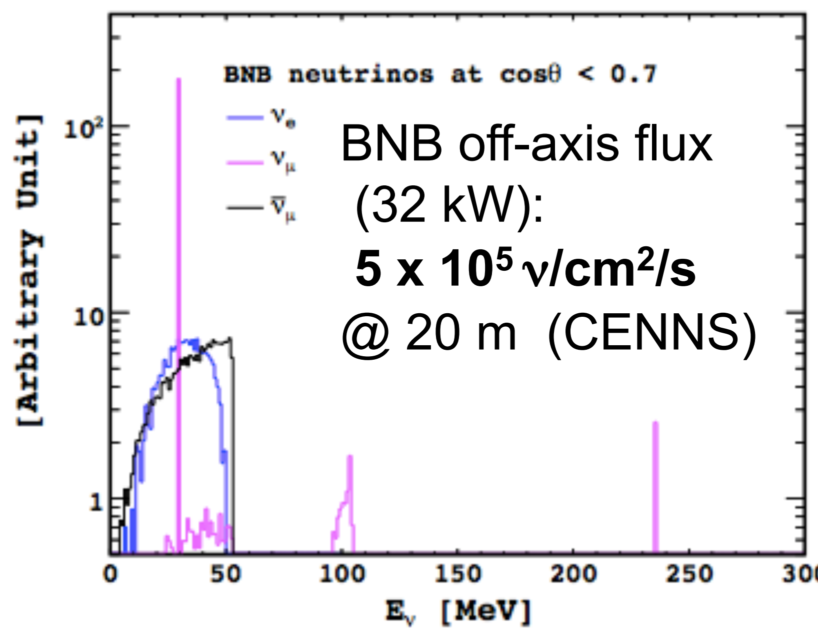

**Background rejection factor ~few x $10^{-4}$**

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



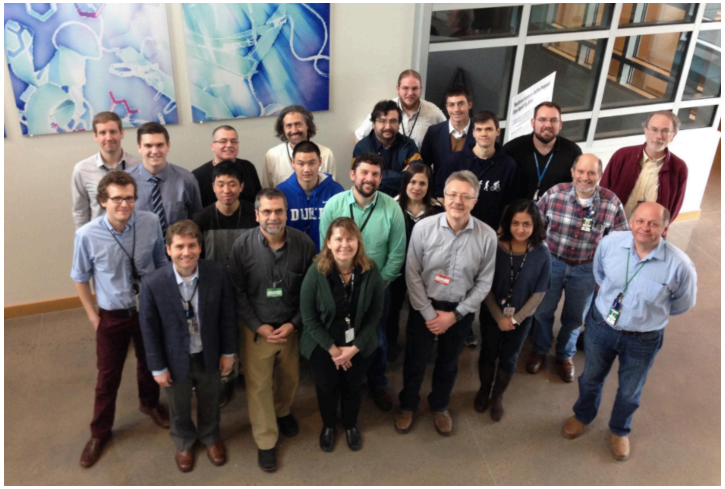

Note that contamination from non π-decay at rest (decay in flight, kaon decay, μ capture...) is **down by several orders of magnitude**



# The COHERENT collaboration

arXiv:1509.08702

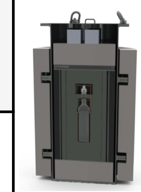
| Institution | Board Member |
|---|---|
| University of California, Berkeley | Kai Vetter |
| University of Chicago | Juan Collar |
| Duke University | Kate Scholberg |
| University of Florida | Heather Ray |
| Indiana University | Rex Tayloe |
| Institute for Theoretical and Experimental Physics, Moscow | 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 |

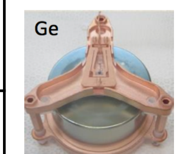


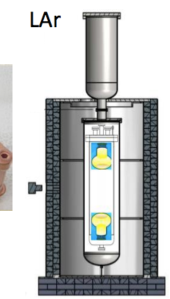
- Collaboration: ~65 members, 16 institutions (USA+ Russia)

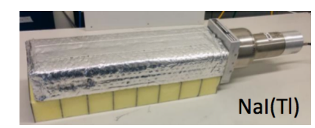
# COHERENT Detectors and Status

| 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 |



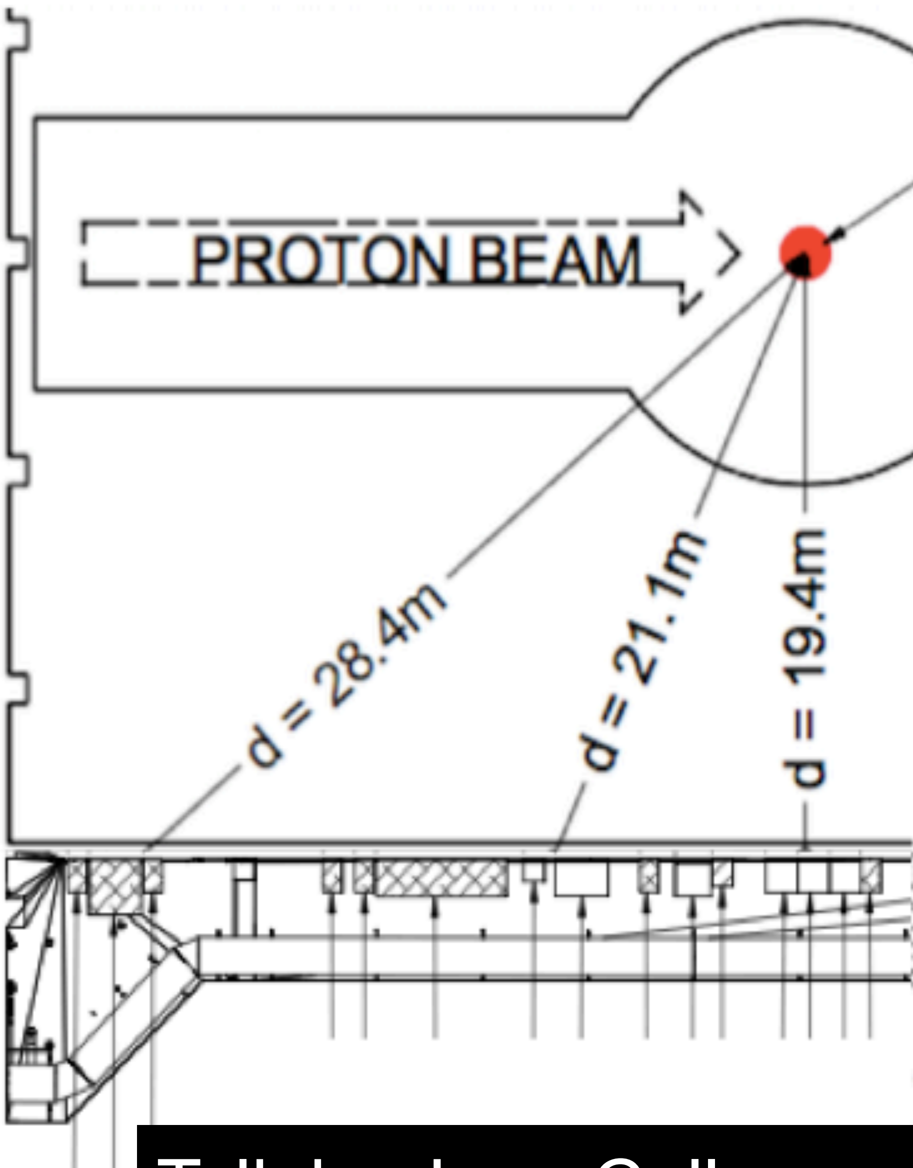


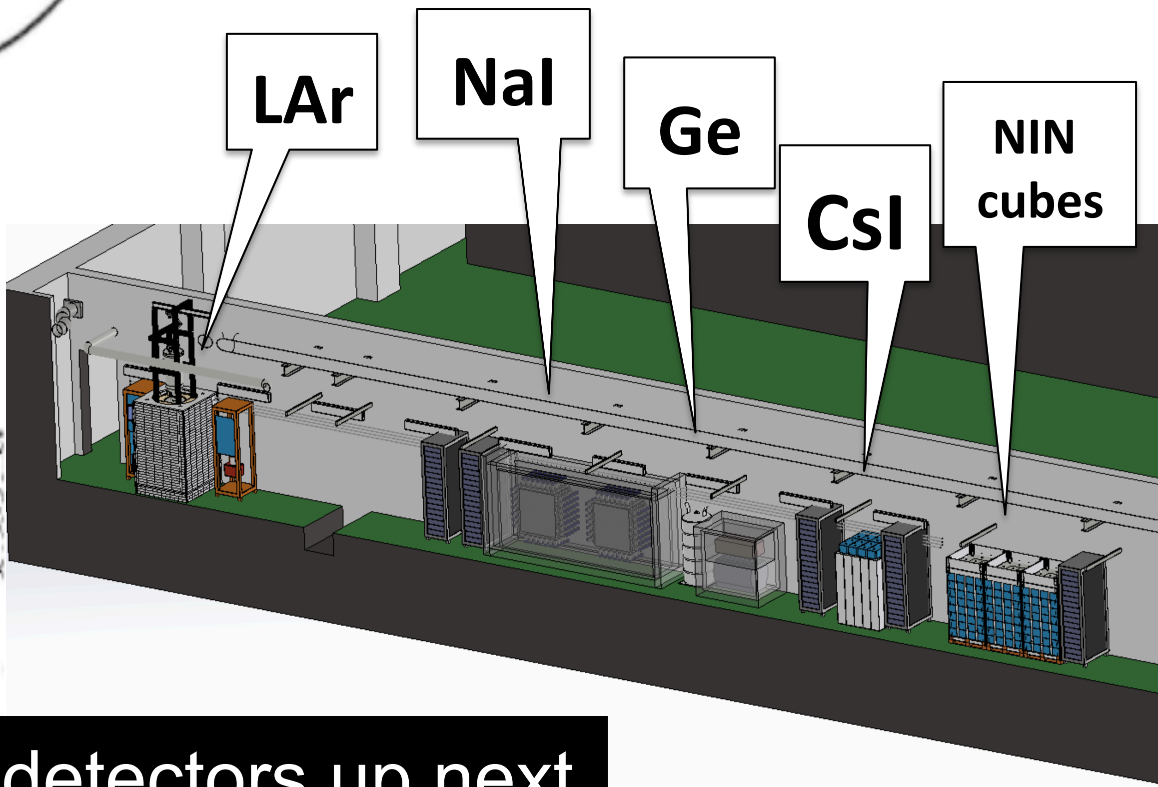




- CsI installed July 2015; 185 kg of NaI in July 2016
- Two more detectors to be deployed with resources in hand, fall 2016
- For 5σ discovery, **need larger detectors**

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

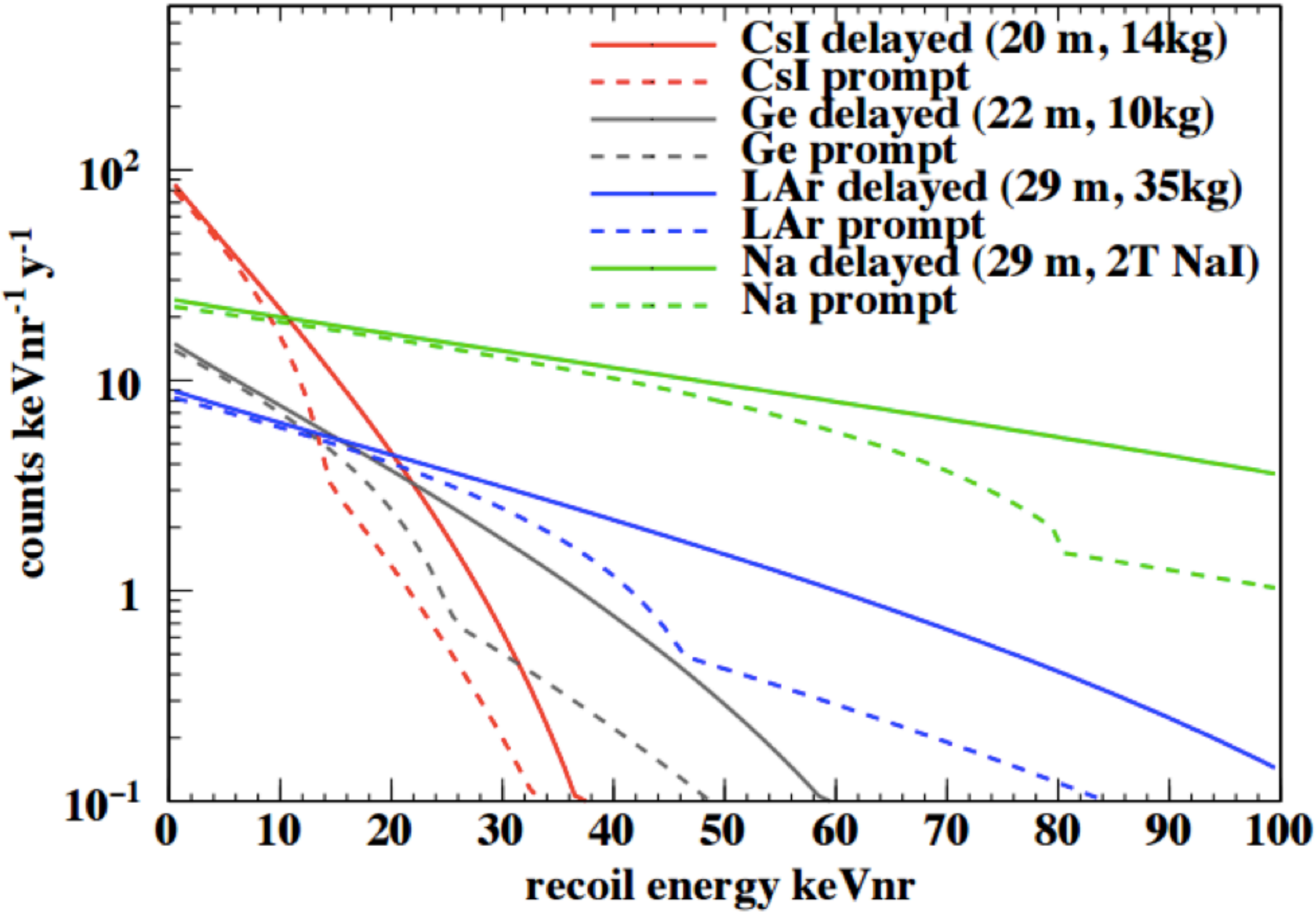



View looking
down "Neutrino Alley"




Talk by Juan Collar on detectors up next

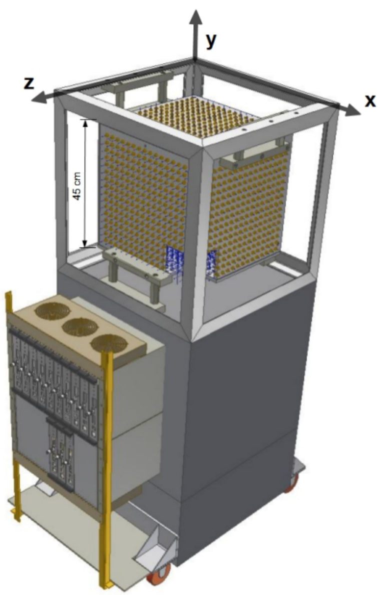
# Expected recoil signals

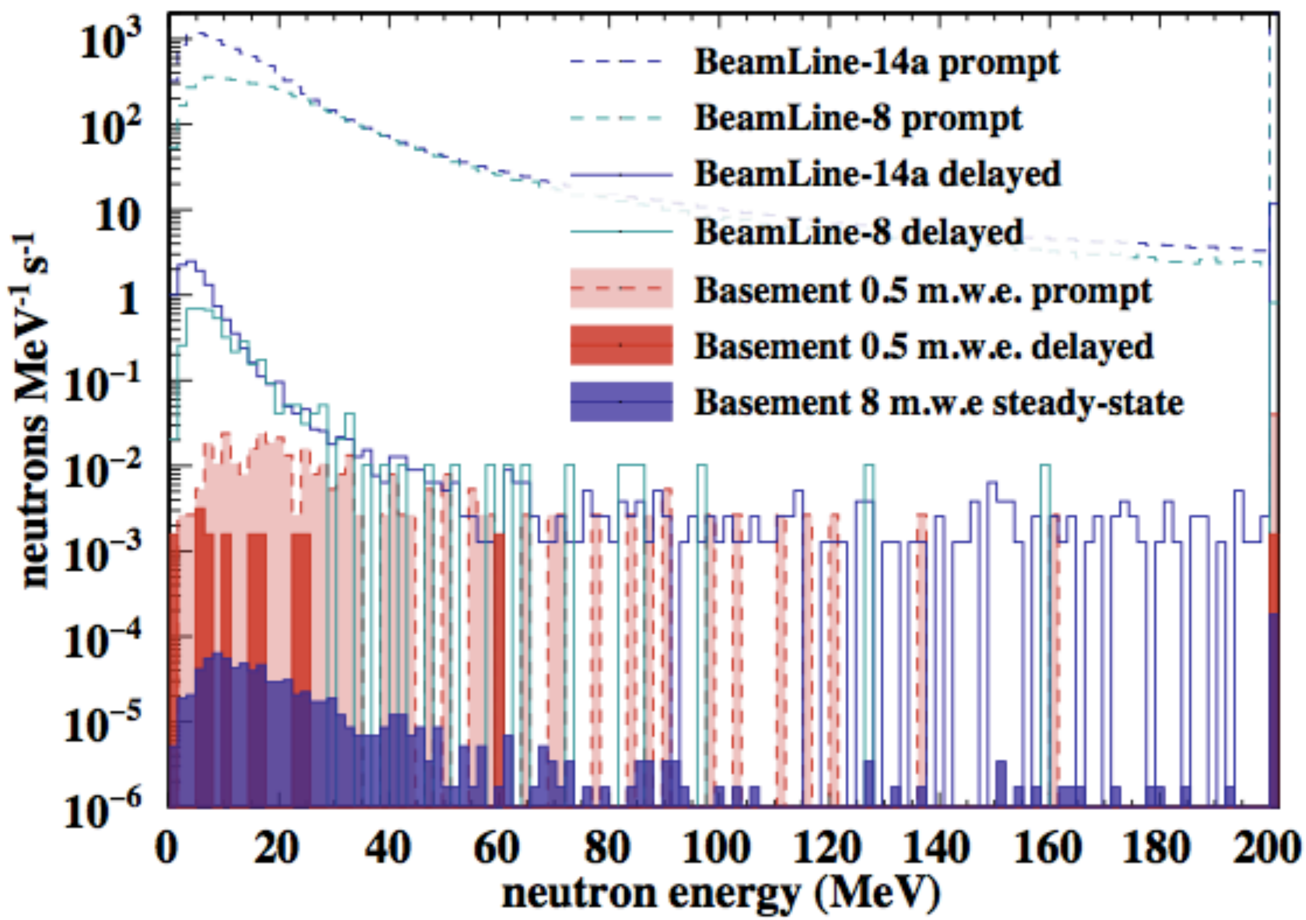



Prompt defined as first $\mu$s; note some contamination from $\nu_e$ and $\nu_\mu$-bar

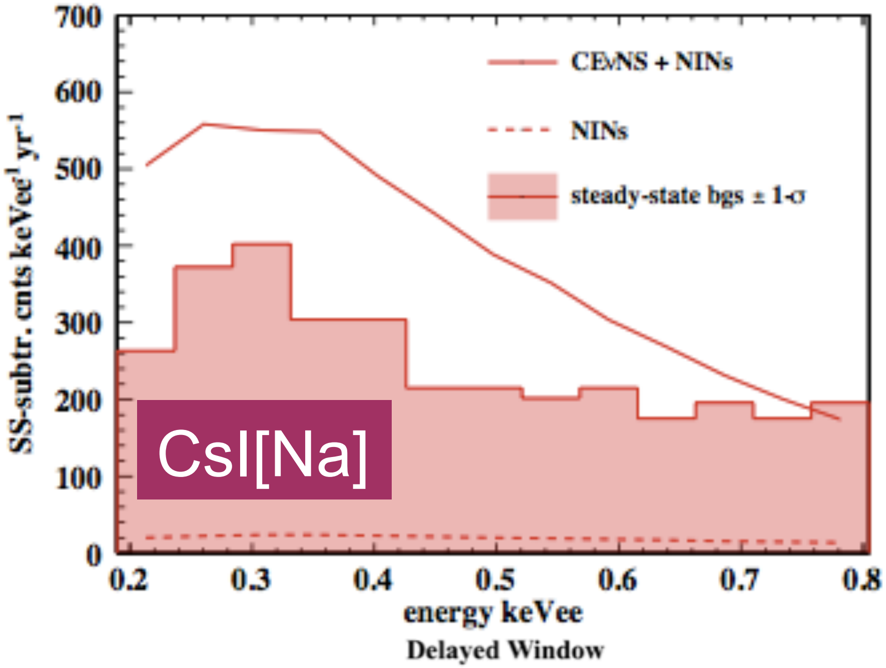
# Neutron Backgrounds

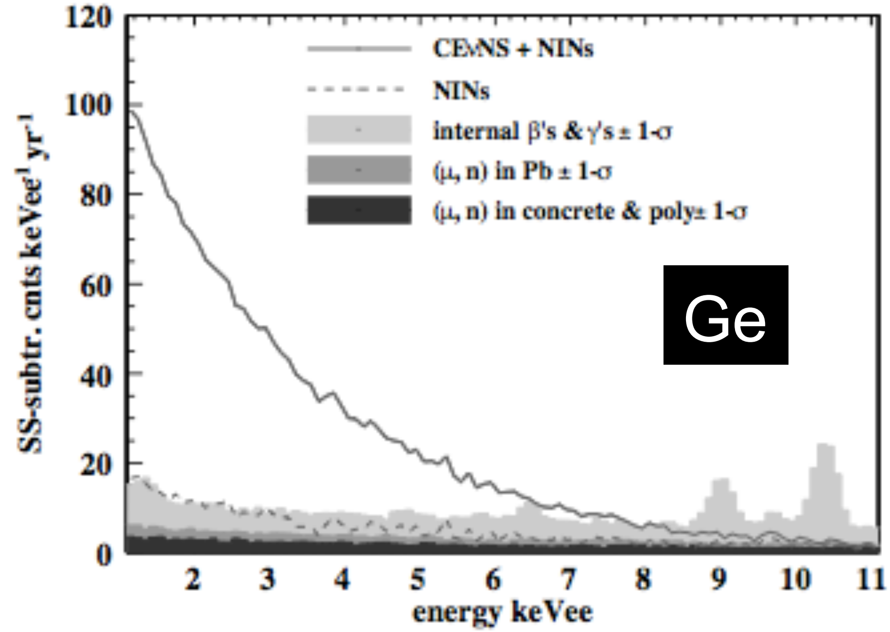
Several background measurement campaigns have shown that Neutrino Alley is neutron-quiet

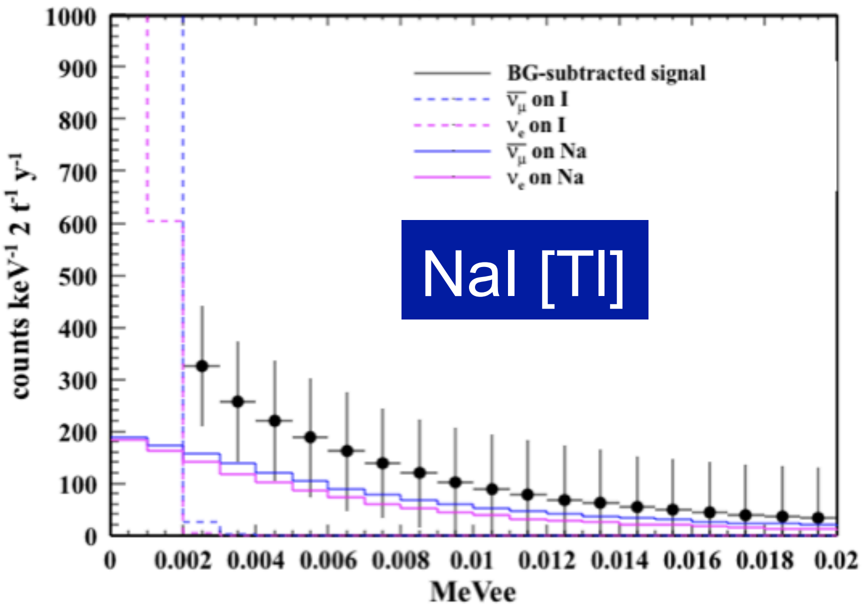


# Realistic steady-state-bg-subtracted recoil spectra (keVee/MeVee) compared to 1σ background fluctuations




**Talk by Juan Collar on detectors up next**

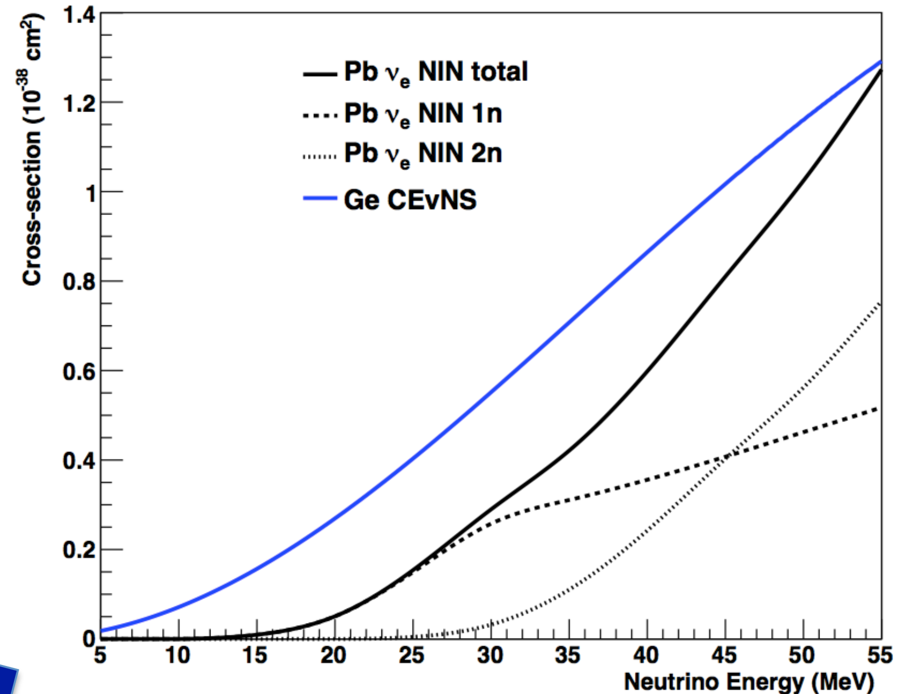
# Currently measuring *neutrino-induced neutrons* in lead, (iron, copper), ...

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

1n, 2n emission

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

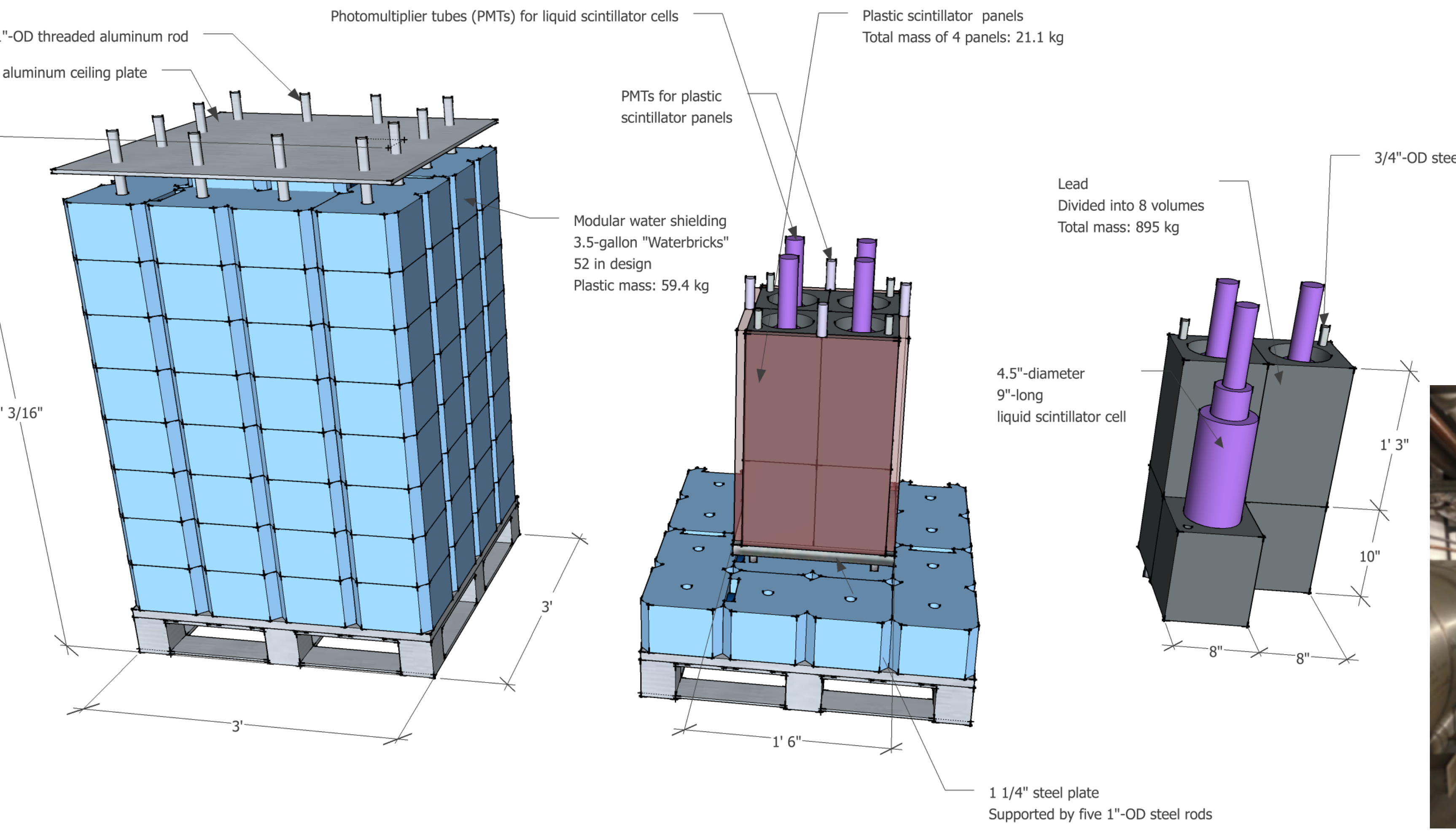
1n, 2n, $\gamma$ emission




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

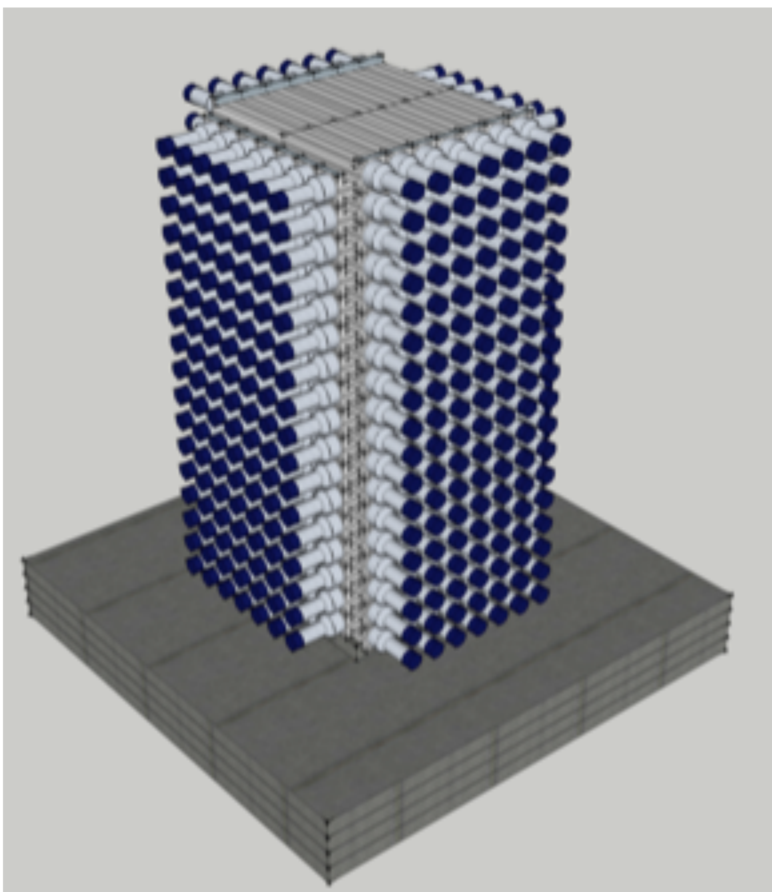
# NIN measurement in SNS basement

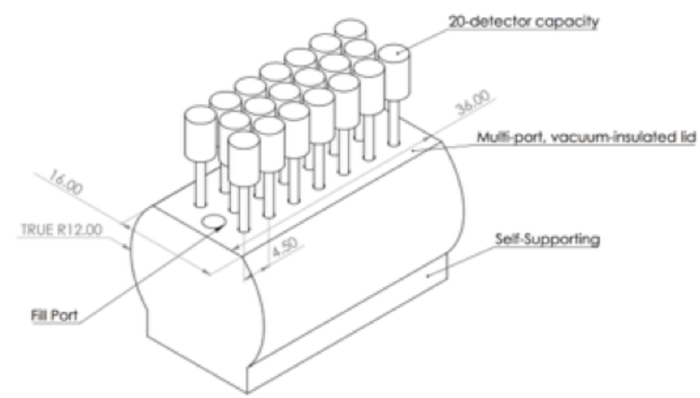
- Scintillator inside CsI detector lead shield (now)
- Liquid scintillator surrounded by lead (swappable for other NIN targets) inside water shield




# Potential upgrades

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






$\sim 5\sigma$ in ~ 2 years
with demonstration
of $N^2$ dependence

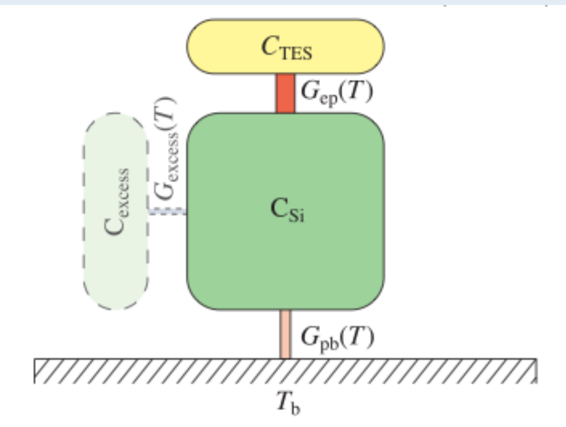
# The Low-Energy Recoil Frontier:

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

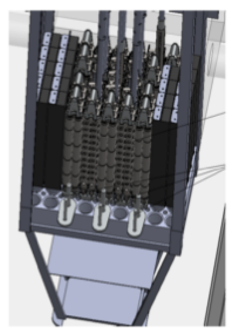
(magnetic moment, sterile osc w/small L, reactor monitoring, astrophysics,...)

## Cryogenic solid-state bolometers

### RICOCHET



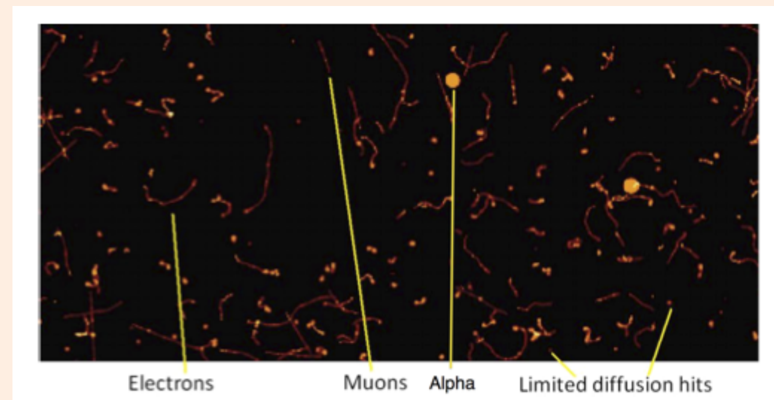

### MINER



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

Mirabolfathi et al., 1510.00999

## Silicon CCDs (CONNIE)



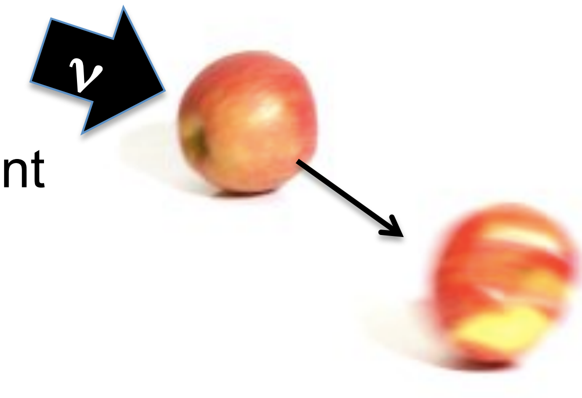

Moroni et al., Phys.Rev. D91 (2015) 7, 072001

(+ 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, $\nu$ magnetic moment
- SN physics, SN & solar $\nu$'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 $\nu$'s, good bg rejection

COHERENT@ SNS

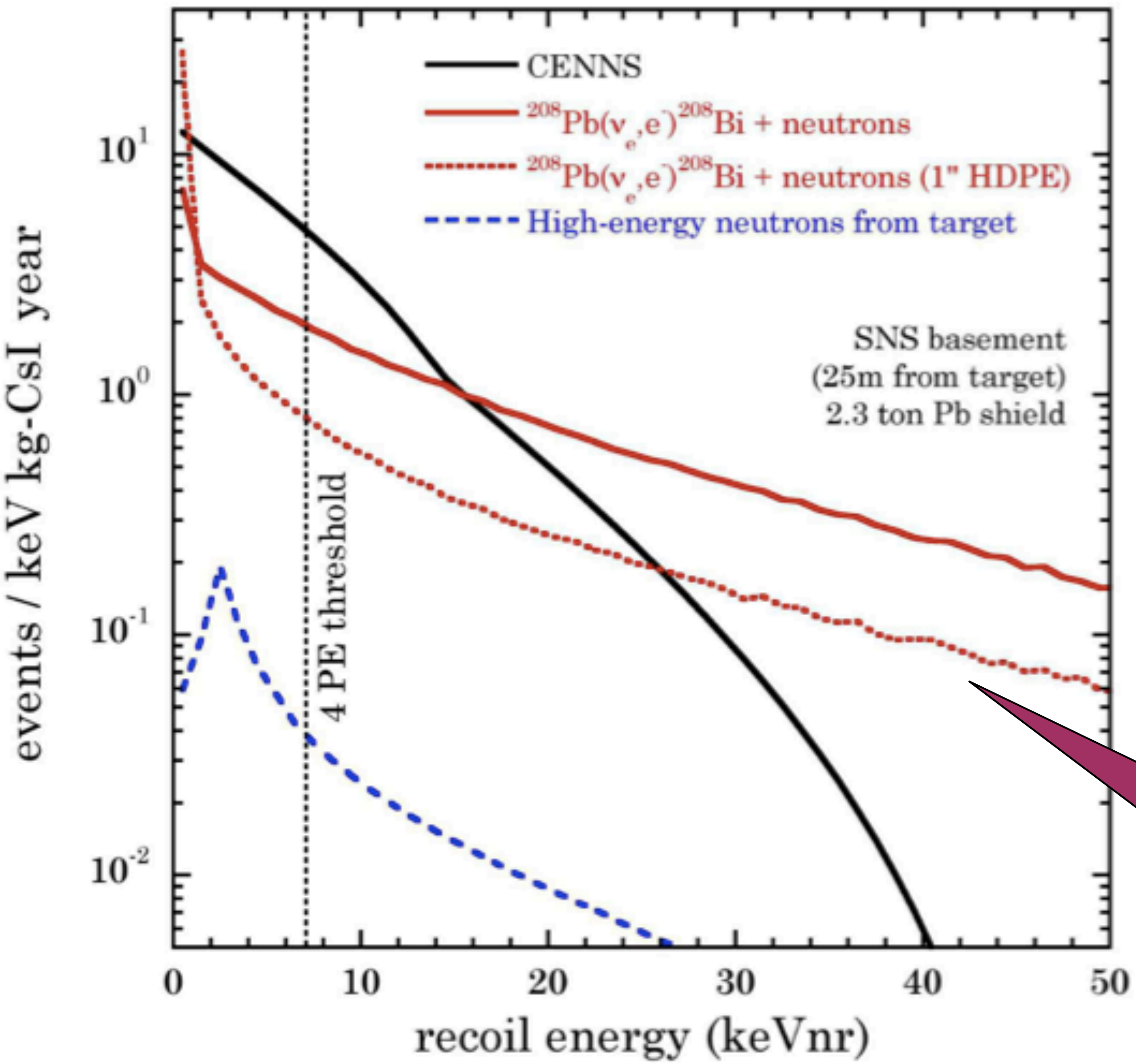
Reactor sources are attractive for high flux, flexibility

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