Coherent Elastic Neutrino-Nucleus Scattering

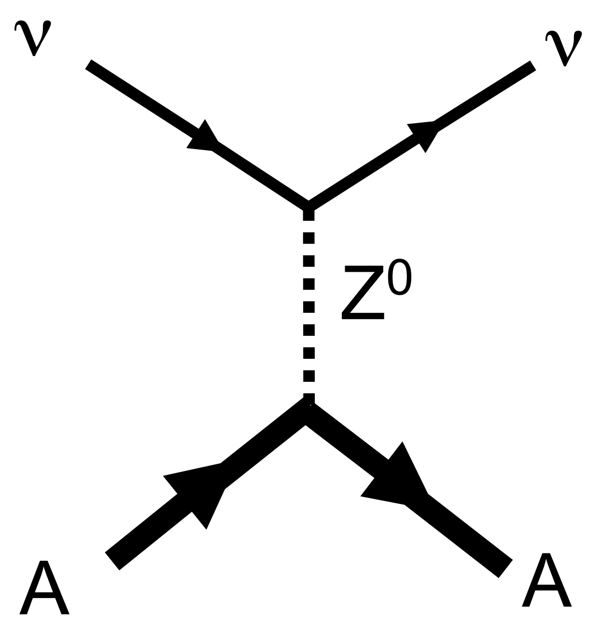
Kate Scholberg, Duke University
IPA 2018, Cincinnati
October 9, 2018

OUTLINE

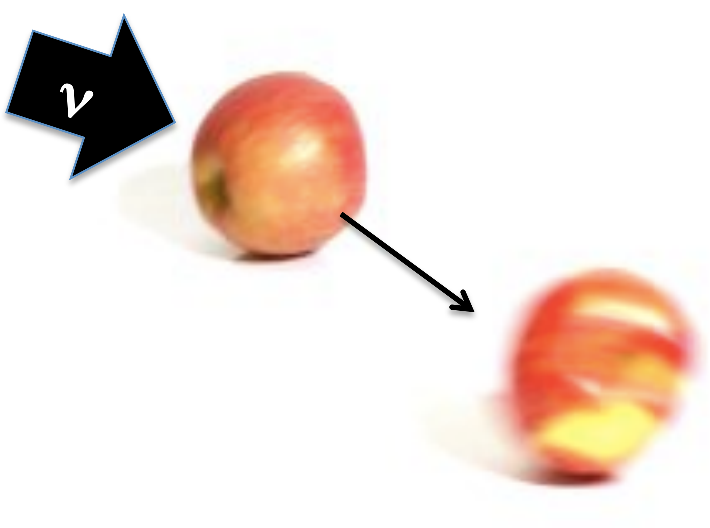
- Neutrinos and neutrino interactions
- Coherent elastic neutrino-nucleus scattering (CEvNS)
- Why measure it? Physics motivations
- How to measure CEvNS: reactors & πDAR
- The COHERENT experiment at the SNS
- **First light** with CsI[Tl]
- Future prospects

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_{ν}~ 50 MeV



Coherent elastic neutrino-nucleus scattering (CEvNS)

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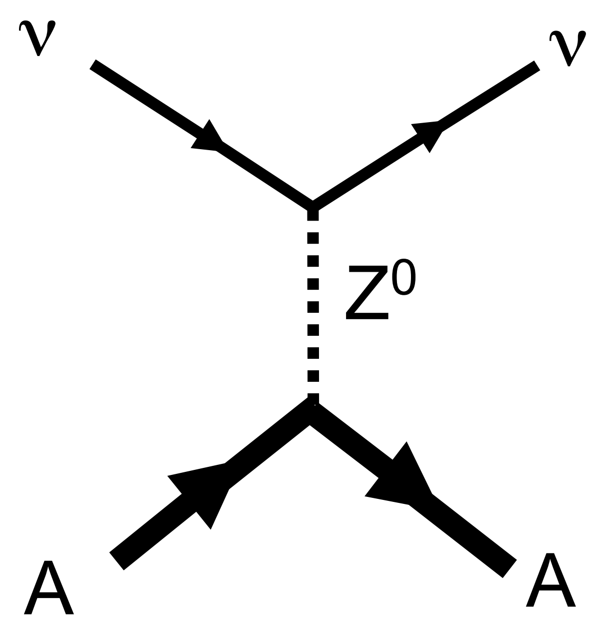
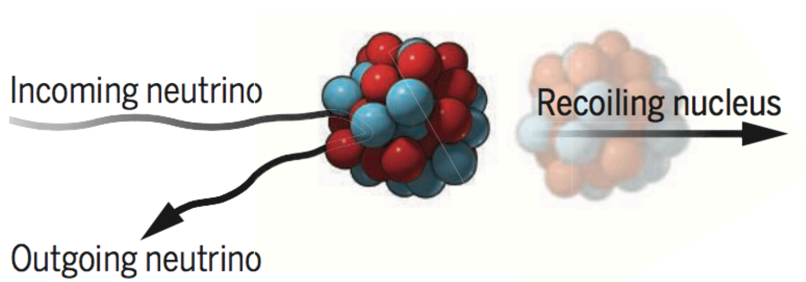


A neutrino smacks a nucleus via exchange of a Z, and the nucleus recoils as a whole; **coherent** up to $E_\nu \sim 50$ MeV



Nucleon wavefunctions in the target nucleus are **in phase with each other** at low momentum transfer

For $QR << 1$, [total xscn] $\sim A^2$ * [single constituent xscn]

A: no. of constituents

Image: J. Link *Science* Perspectives

\begin{aside}

Literature has CNS, CNNS, CENNS, ...

- I prefer including "E" for "elastic"... otherwise it gets frequently confused with coherent pion production at ~GeV neutrino energies
- I'm told "NN" means "nucleon-nucleon" to nuclear types
- CEνNS is a possibility but those internal Greek letters are annoying

➔**CEvNS**, pronounced "sevens"...

spread the meme!

\end{aside}

First proposed 44 years ago!

PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

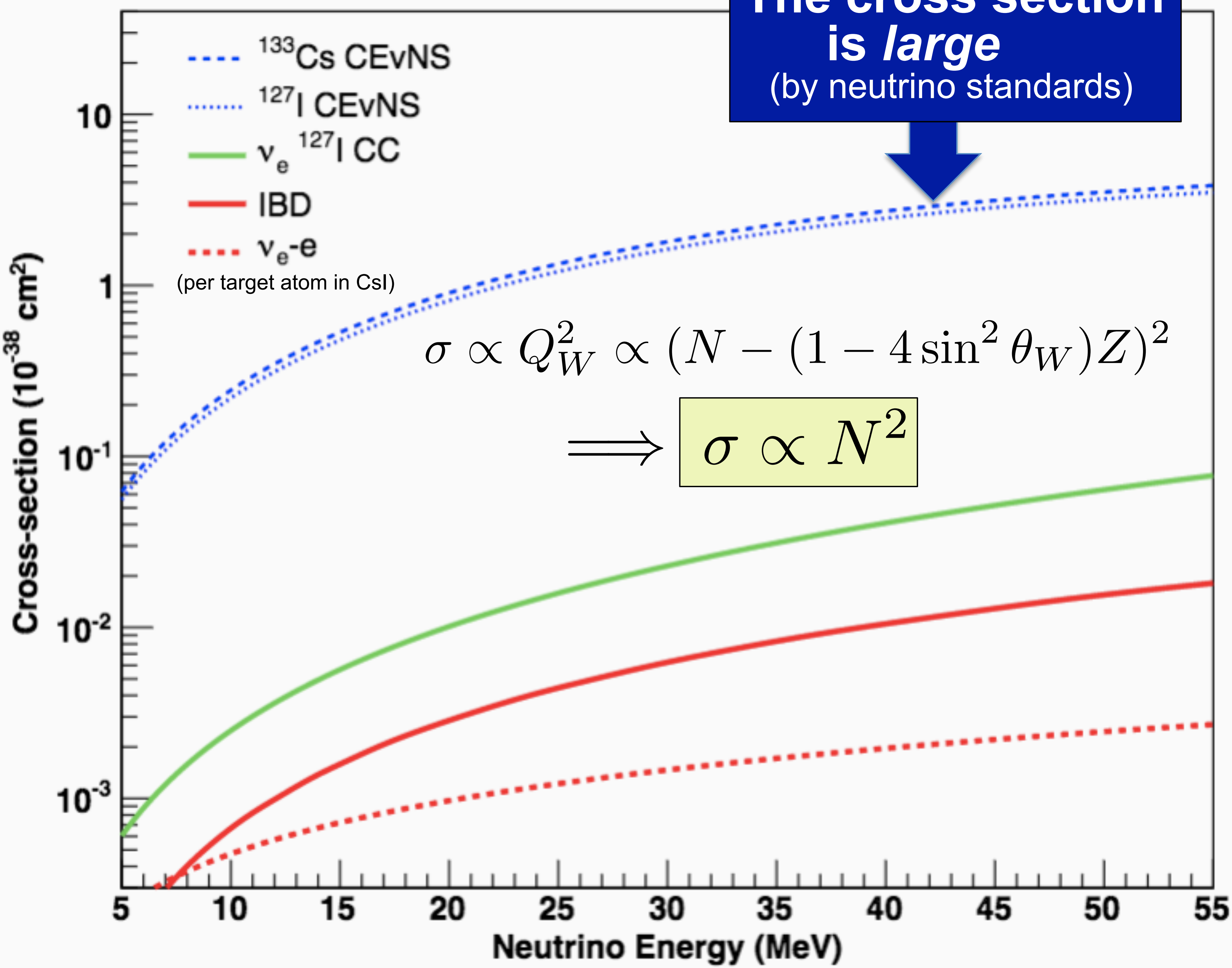
Coherent effects of a weak neutral current

Daniel Z. Freedman†
National Accelerator Laboratory, Batavia, Illinois 60510
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790
(Received 15 October 1973; revised manuscript received 19 November 1973)

Our suggestion may be an act of hubris, because the inevitable constraints of interaction rate, resolution, and background pose grave experimental difficulties for elastic neutrino-nucleus scattering. We will discuss these problems at the end of this note, but first we wish to present the theoretical ideas relevant to the experiments.

Also: D. Z. Freedman et al., “The Weak Neutral Current and Its Effect in Stellar Collapse”, Ann. Rev. Nucl. Sci. 1977. 27:167-207

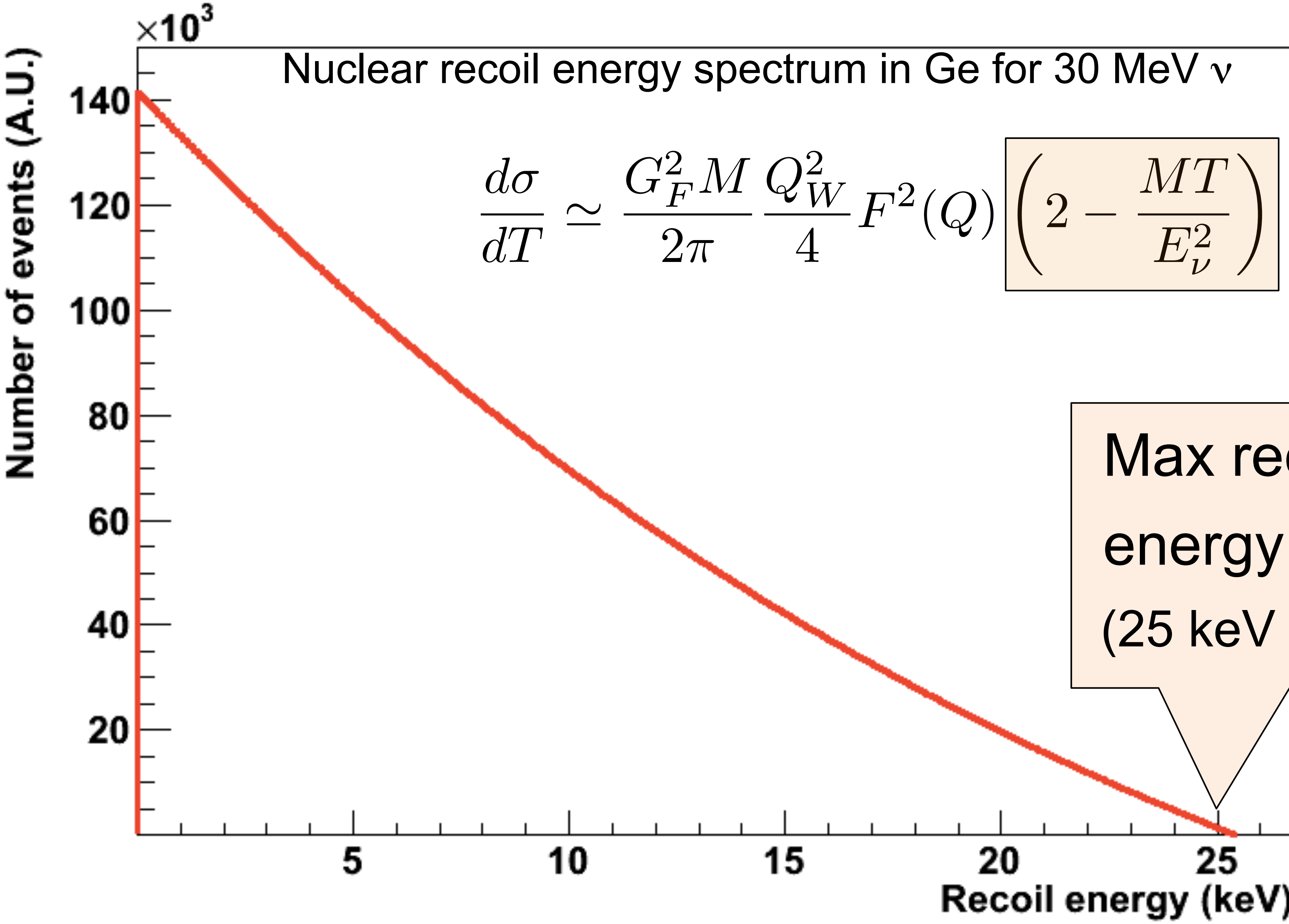
The cross section is *large*
(by neutrino standards)



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

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

Large cross section (by neutrino standards) but hard to observe due to **tiny nuclear recoil energies:**

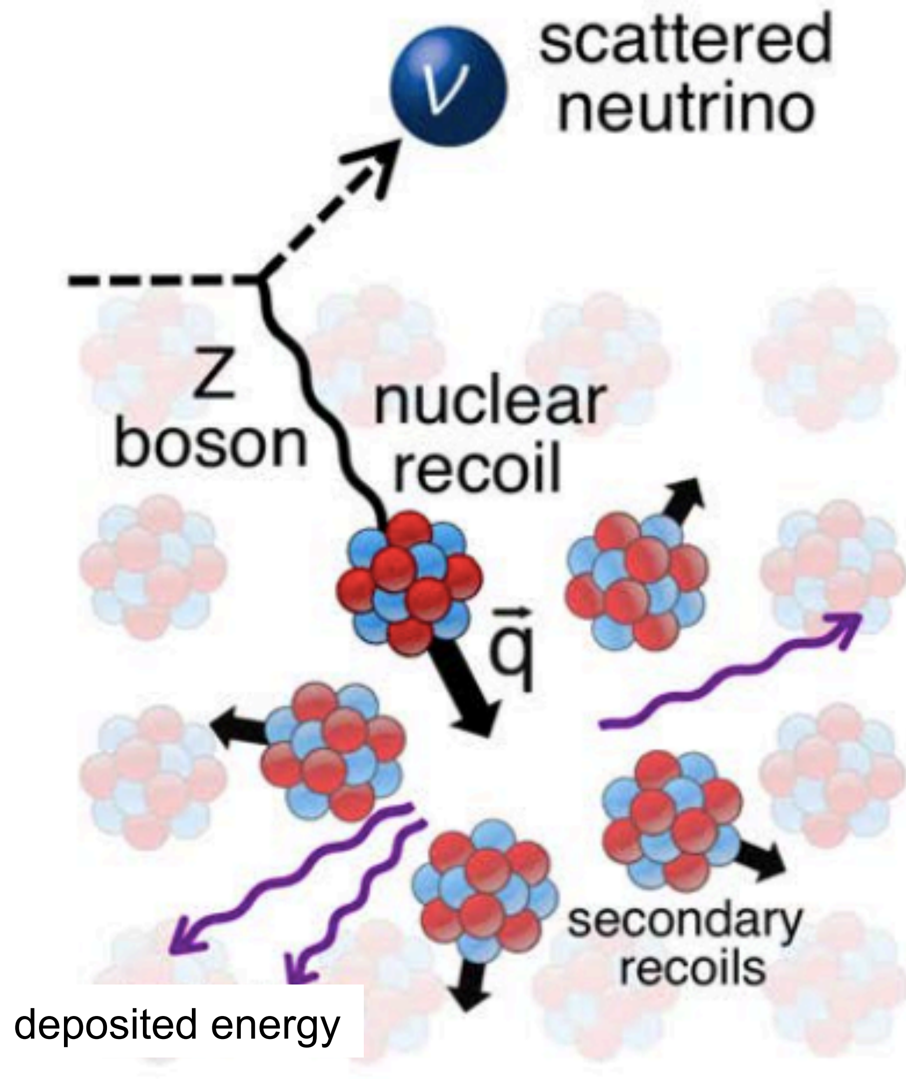


$$\frac{d\sigma}{dT} \simeq \frac{G_F^2 M}{2\pi} \frac{Q_W^2}{4} F^2(Q) \left(2 - \frac{MT}{E_\nu^2}\right)$$

Max recoil energy is $\sim 2E_\nu^2/M$
(25 keV for Ge)

The only experimental signature:

tiny energy deposited by nuclear recoils in the target material

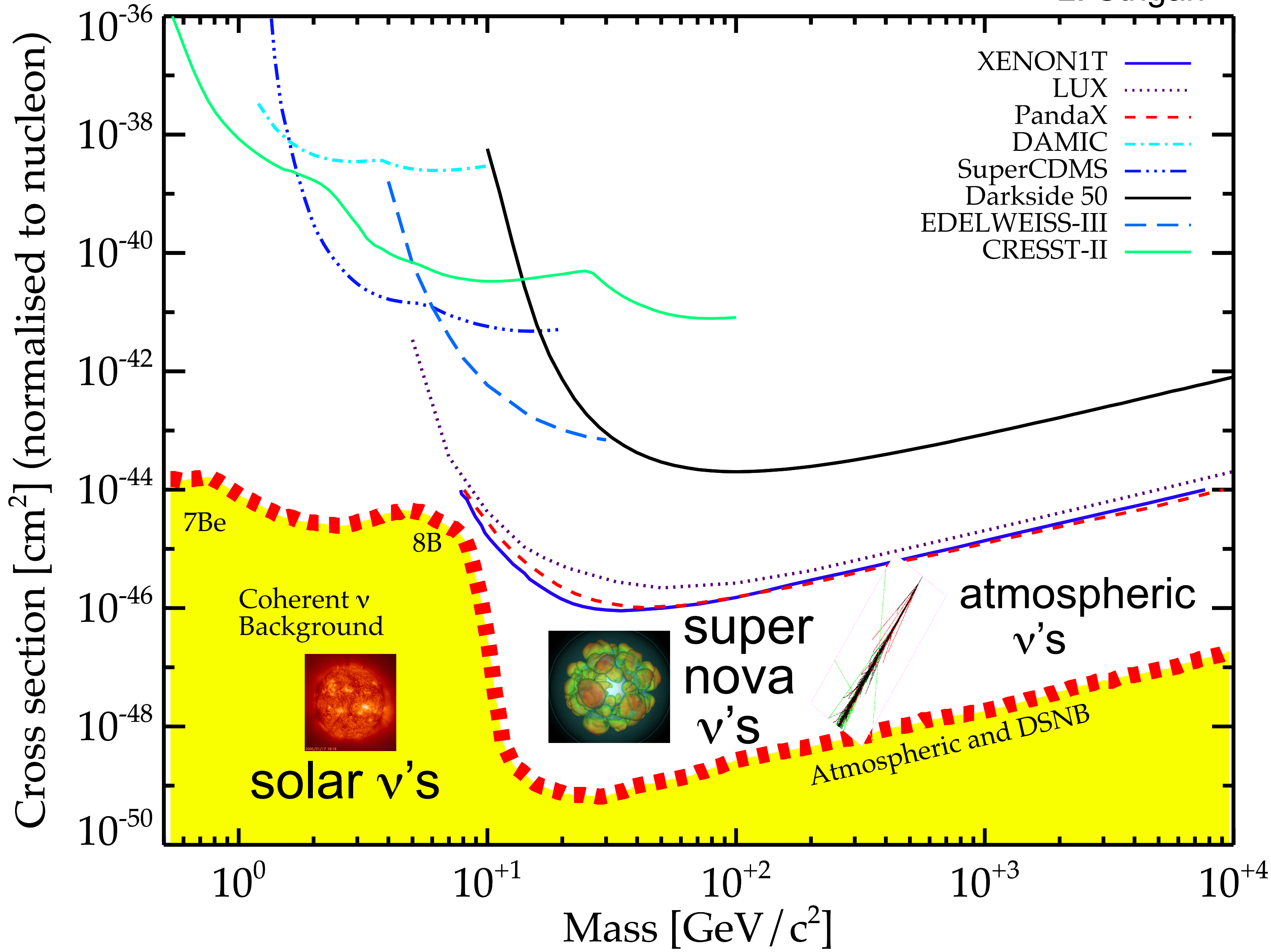


➔ **WIMP dark matter detectors** developed over the last ~decade are sensitive to ~ keV to 10's of keV recoils

The so-called “neutrino floor” (**signal!**) for DM experiments

J. Monroe & P. Fisher, 2007 J. Billard, E. Figueroa-Feliciano, and L. Strigari, arXiv:1307.5458v2 (2013).

L. Strigari



Measure CEvNS to understand nature of background/astro signal
(& detector response, DM interaction)

The cross section is cleanly predicted in the Standard Model

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{\pi} F^2(Q) \left[(G_V + G_A)^2 + (G_V - G_A)^2 \left(1 - \frac{T}{E_\nu}\right)^2 - (G_V^2 - G_A^2)\frac{MT}{E_\nu^2} \right]$$

E_ν: neutrino energy
T: nuclear recoil energy
M: nuclear mass
$Q = \sqrt{(2MT)}$: momentum transfer

G_V, G_A: SM weak parameters

vector $G_V = g_V^p Z + g_V^n N,$ ← dominates

axial $G_A = g_A^p (Z_+ - Z_-) + g_A^n (N_+ - N_-)$ ← small for most nuclei, zero for spin-zero

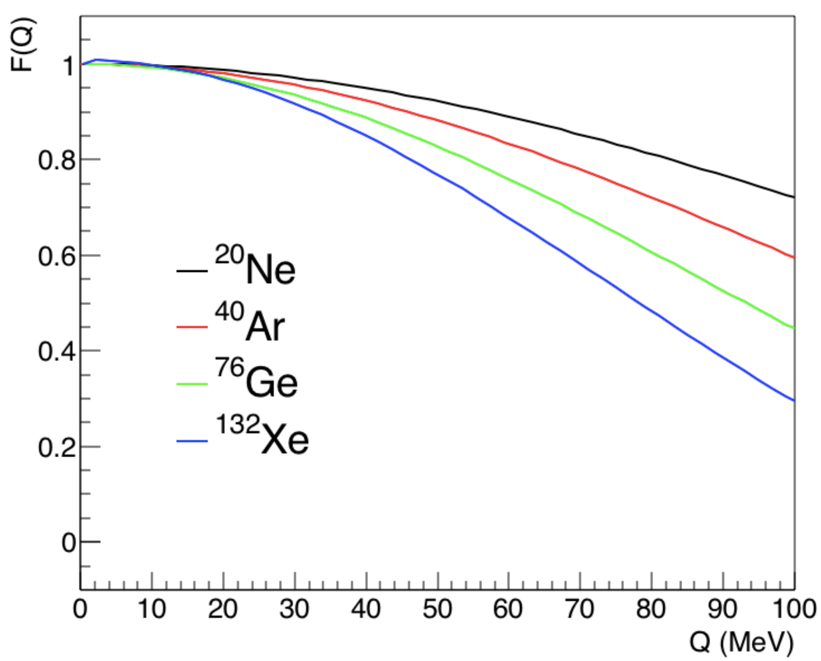
$$g_V^p = 0.0298$$
$$g_V^n = -0.5117$$
$$g_A^p = 0.4955$$
$$g_A^n = -0.5121.$$

The cross section is cleanly predicted in the Standard Model

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{\pi} F^2(Q) \left[(G_V + G_A)^2 + (G_V - G_A)^2 \left(1 - \frac{T}{E_\nu}\right)^2 - (G_V^2 - G_A^2)\frac{MT}{E_\nu^2} \right]$$

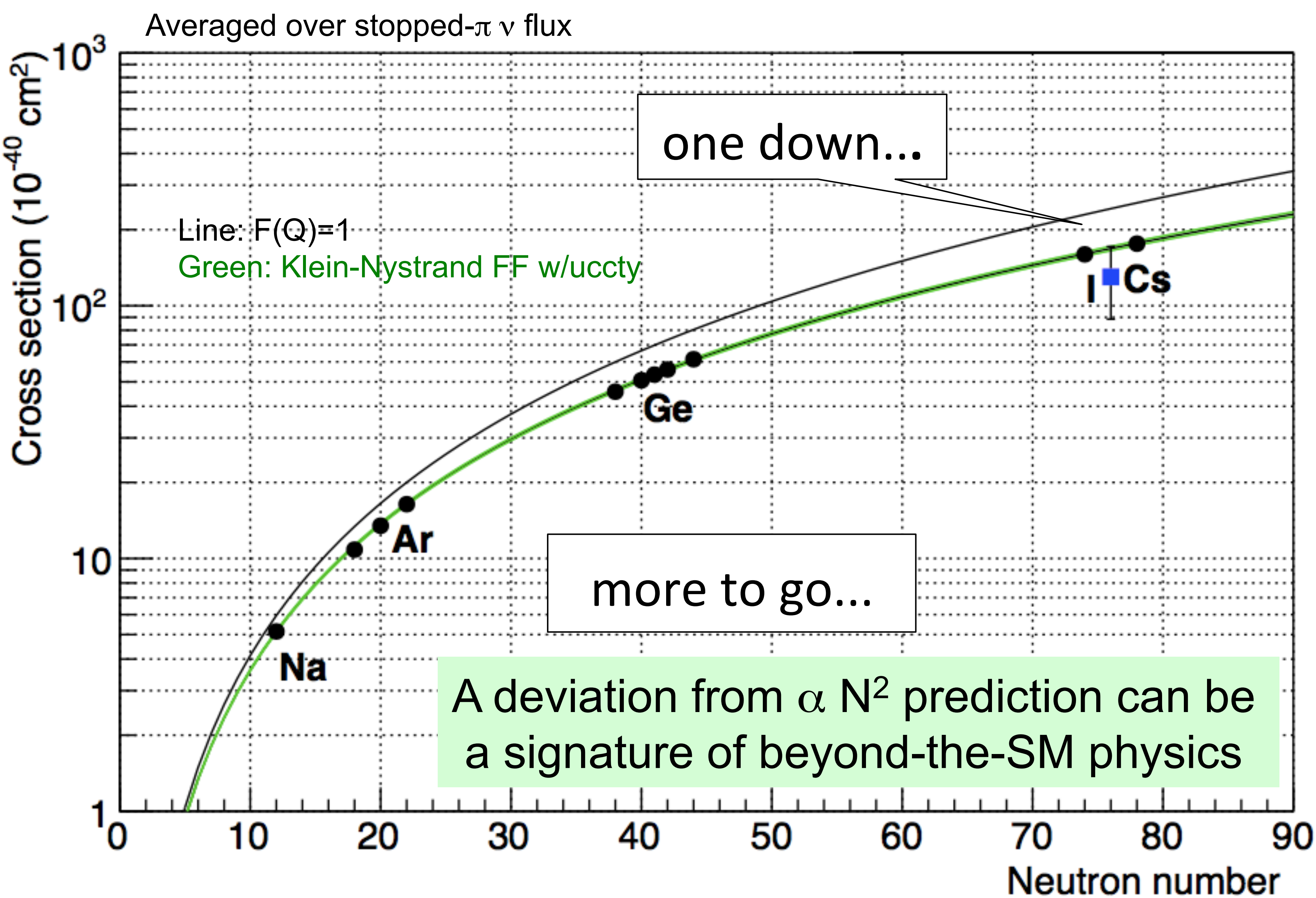
E_ν: neutrino energy
T: nuclear recoil energy
M: nuclear mass
Q = $\sqrt{(2MT)}$: momentum transfer

F(Q): nuclear **form factor**, <~5% uncertainty on event rate

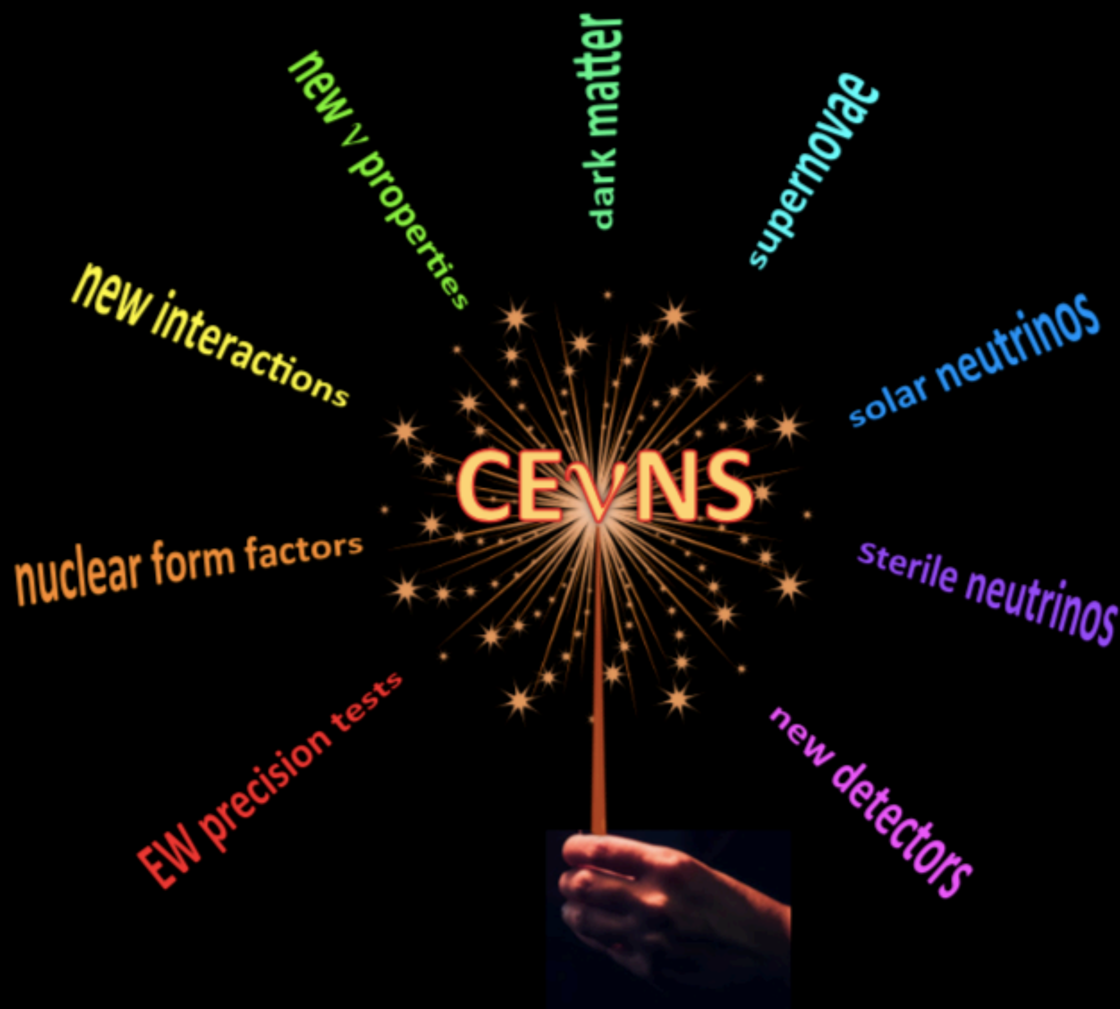


form factor suppresses cross section at large Q

Need to measure N^2 dependence of the CEvNS xscn



Why measure CEvNS?



E. Lisi
Neutrino 2018

One example: hunting for **new interactions**
"Beyond-the-Standard-Model"

Searching for BSM Physics with CEvNS

A first example: simple counting to constrain **non-standard interactions (NSI)** of neutrinos with quarks

Davidson et al., JHEP 0303:011 (2004)
Barranco et al., JHEP 0512:021 (2005)

"Model-independent" parameterization

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

ε's parameterize new interactions

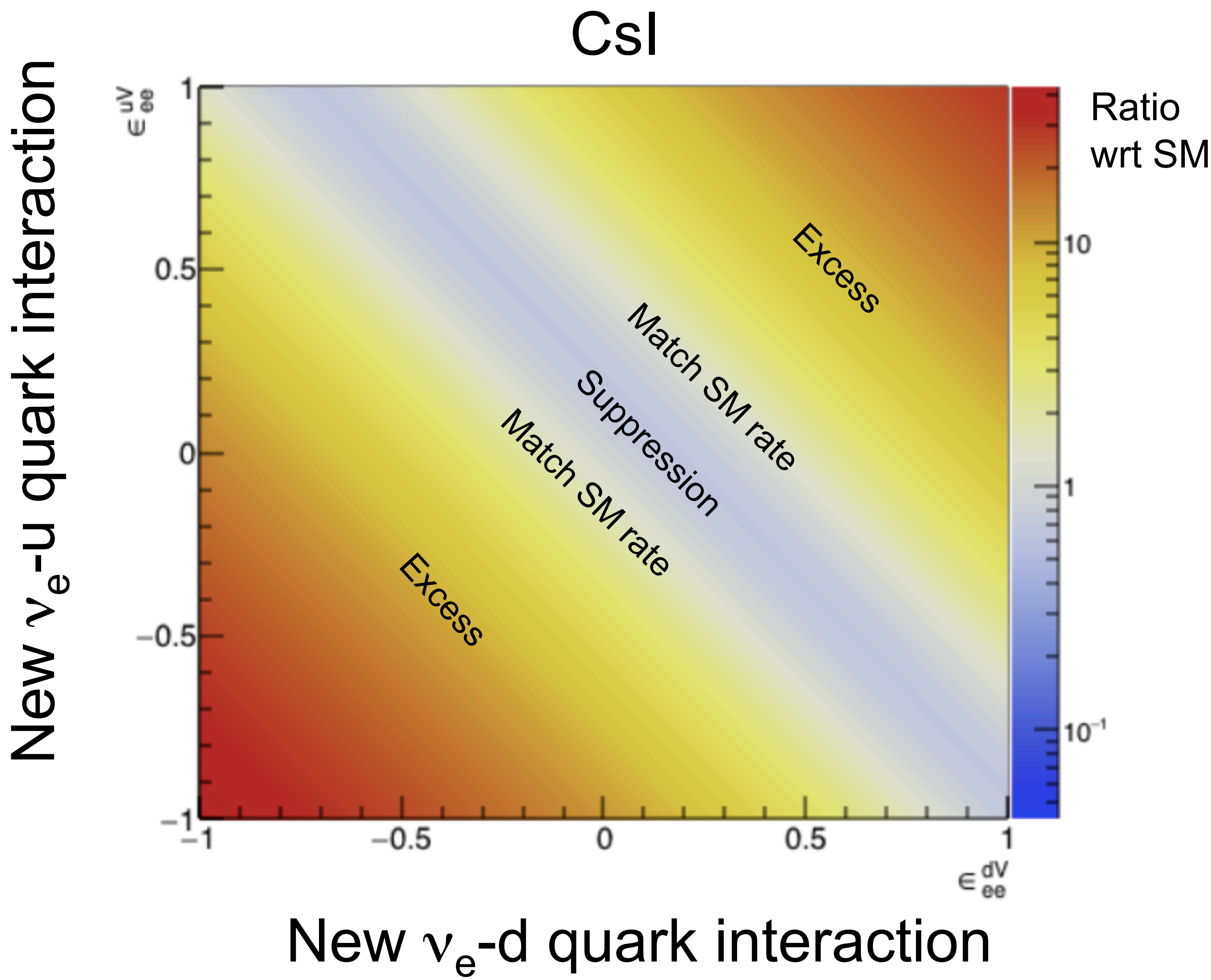
"Non-Universal": ε_{ee}, $\varepsilon_{\mu\mu}$, $\varepsilon_{\tau\tau}$

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

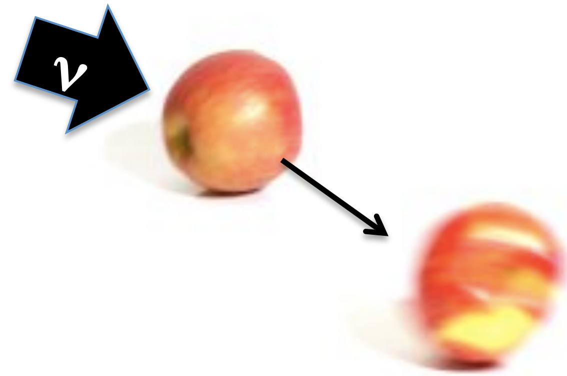
⇒ some are quite poorly constrained (~unity allowed)

Signatures of **Beyond-the-Standard-Model Physics**

Look for a CEvNS **excess** or **deficit** wrt SM expectation



How to detect CEvNS?

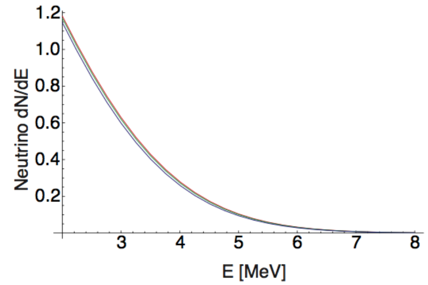


You need a neutrino source
and a detector

What do you want for your ν source?

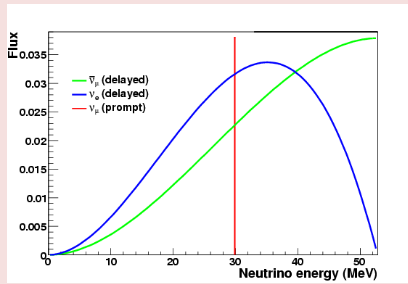
- ✓ High flux
- ✓ Well understood spectrum
- ✓ Multiple flavors (physics sensitivity)
- ✓ Pulsed source if possible, for background rejection
- ✓ Ability to get close
- ✓ Practical things: access, control, ...

Reactors



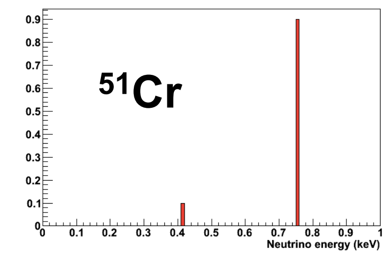
Low energy, but very high fluxes possible; ~continuous source, good bg rejection needed

Stopped pions (decay at rest)



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

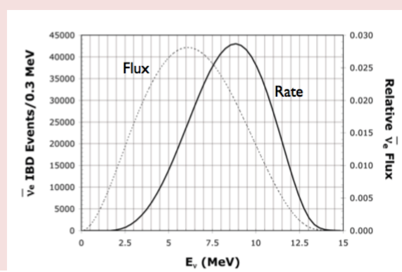
Radioactive sources (electron capture)



Portable; can get very short baseline, monochromatic

Low energy challenging

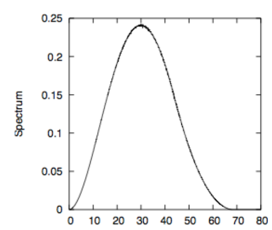
Beam-induced radioactive sources (IsoDAR)



Relatively compact, higher energy than reactor; time structure not sharp

Does not exist yet

Low-energy beta beams

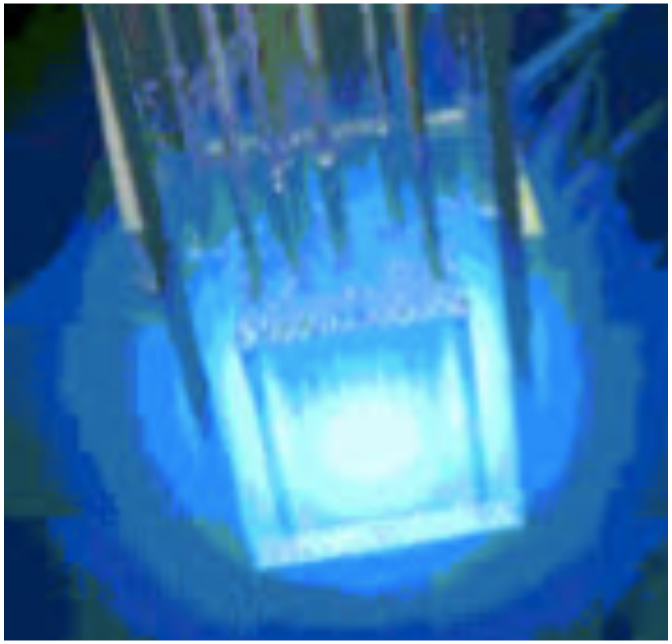


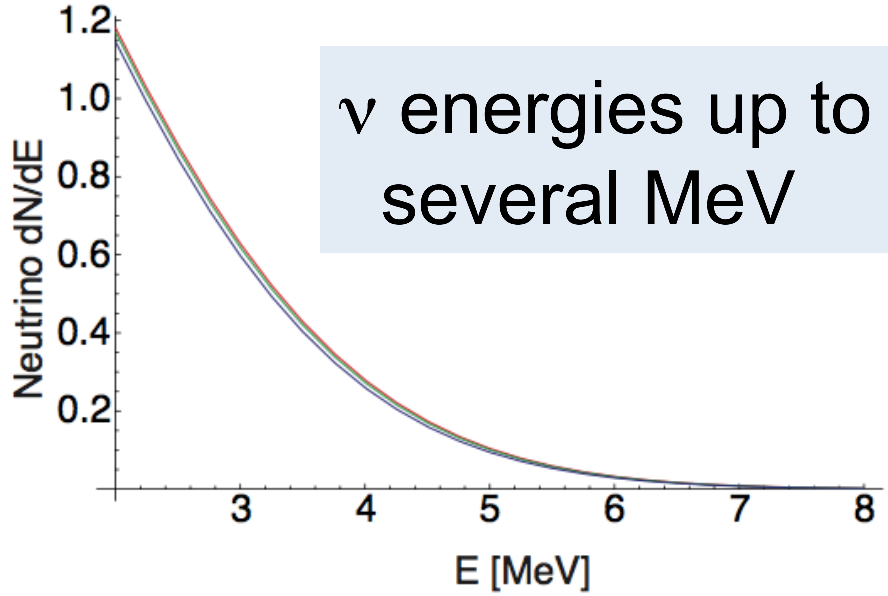
γ=10 boosted ^{18}Ne ν_e

Tunable energy, but not pulsed

Does not exist yet

Neutrinos from nuclear reactors

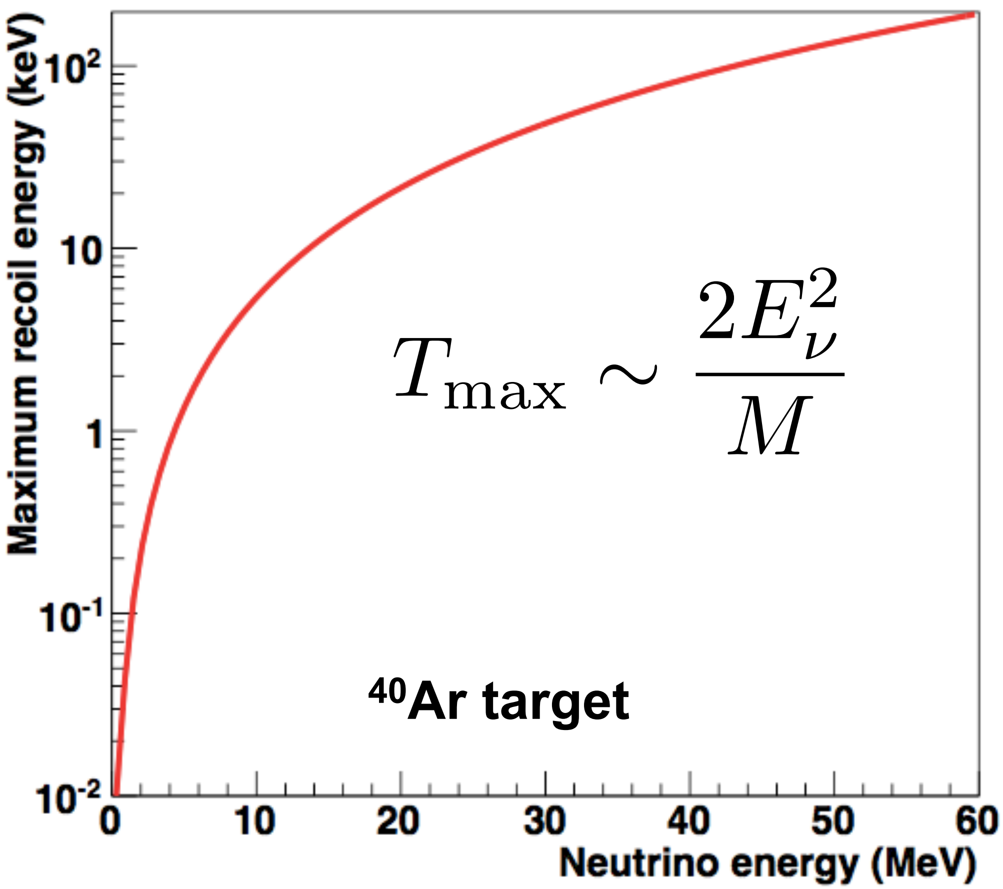


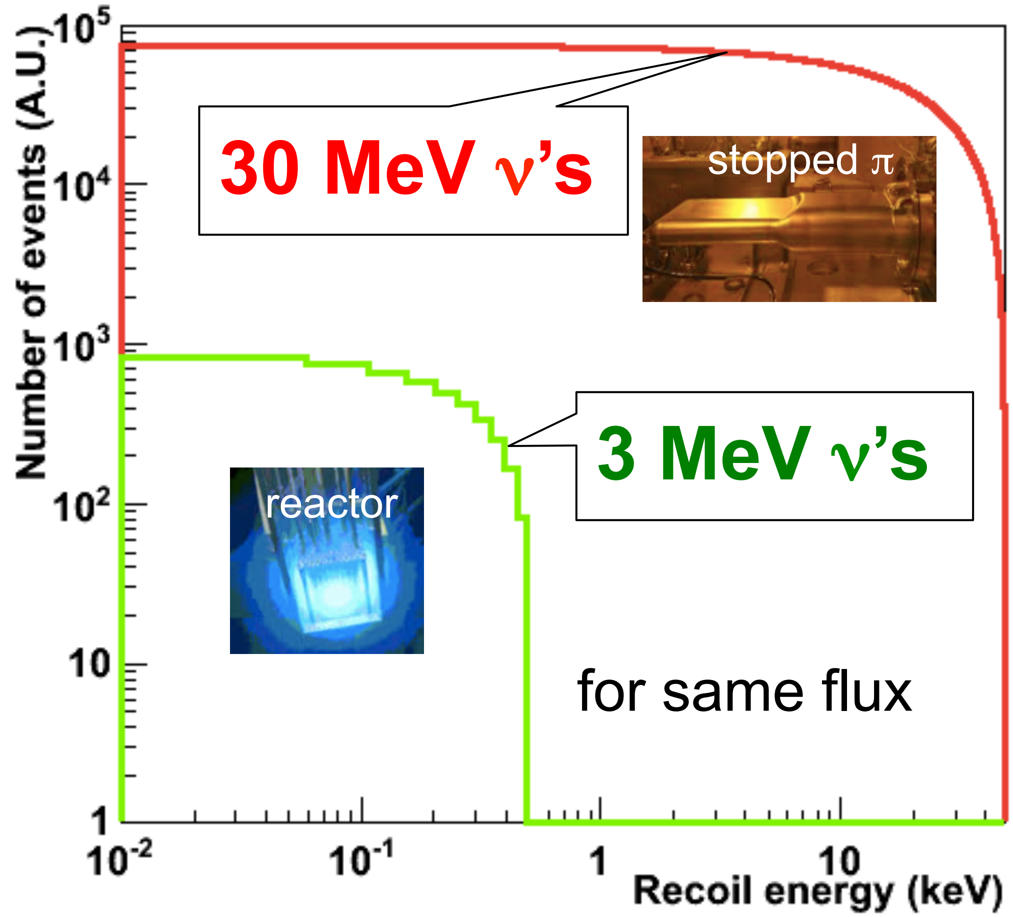


ν energies up to several MeV

- ν_e-bar produced in fission reactions (one flavor)
- **huge fluxes possible**: ~2×10^{20} s^{-1} per GW
- several CEvNS searches past, current and future at reactors, but **recoil energies<keV** and backgrounds make this very challenging

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



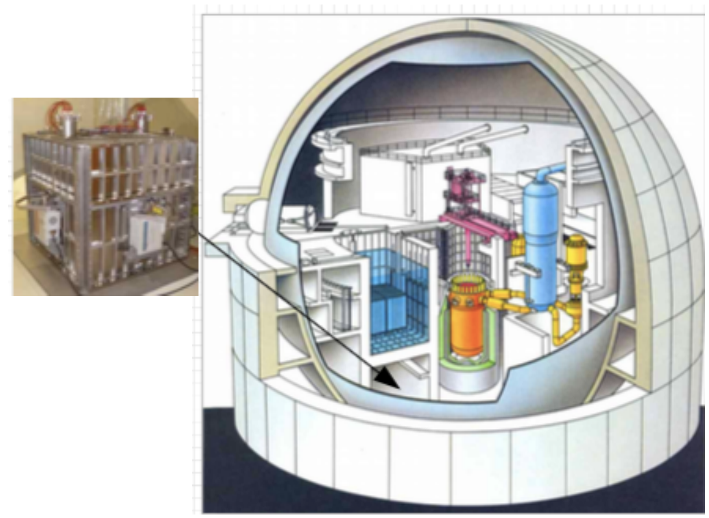


Want energy as large as possible while satisfying coherence condition: $Q \lesssim \frac{1}{R}$ (<~ 50 MeV for medium A)

from Neutrino 2018:

CONUS reports **first hint of reactor CEvNS**

- Brokdorf 3.9 GW reactor
- 17 m from core
- 4 kg Ge PPC
- ~300 eV threshold



Rate comparison (all detectors):

	counts	counts/(d·kg) (*)
reactor OFF (114 kg*d)	582	
reactor ON (112 kg*d)	653	
ON-OFF (exposure corr.)	84	0.94
Significance	2.4 σ	2.3 σ

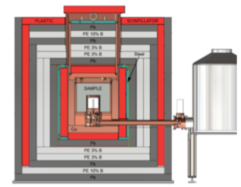
(*) Including stat. uncertainty and above efficiencies

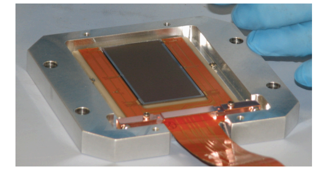
Some systematics still under study

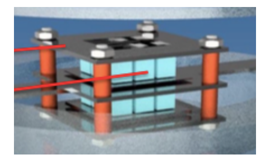
W. Maneschg, Nu2018

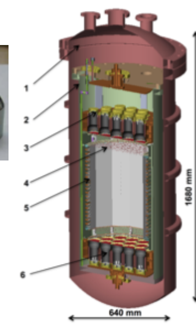
Reactor CEvNS Efforts Worldwide

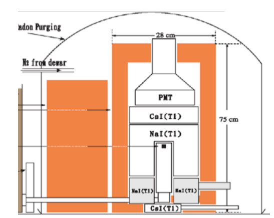
Experiment	Technology	Location
CONNIE	Si CCDs	Brazil
CONUS	HPGe	Germany
MINER	Ge/Si cryogenic	USA
Nu-Cleus	Cryogenic $CaWO_4$, Al_2O_3 calorimeter array	Europe
νGEN	Ge PPC	Russia
RED-100	LXe dual phase	Russia
Ricochet	Ge, Zn bolometers	France
TEXONO	p-PCGe	Taiwan







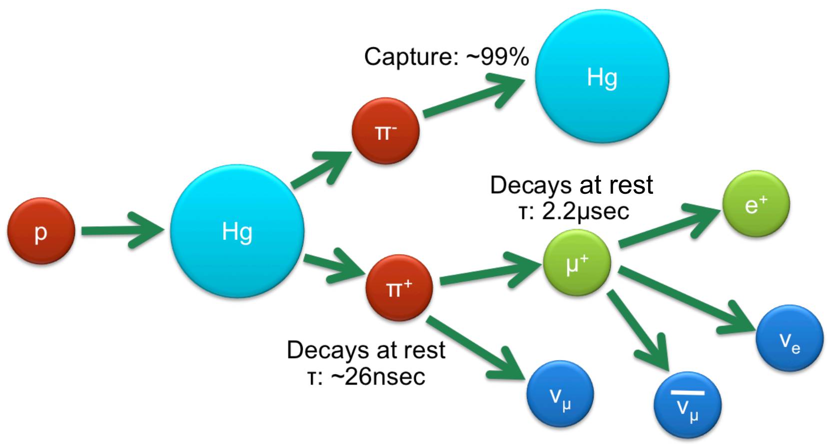


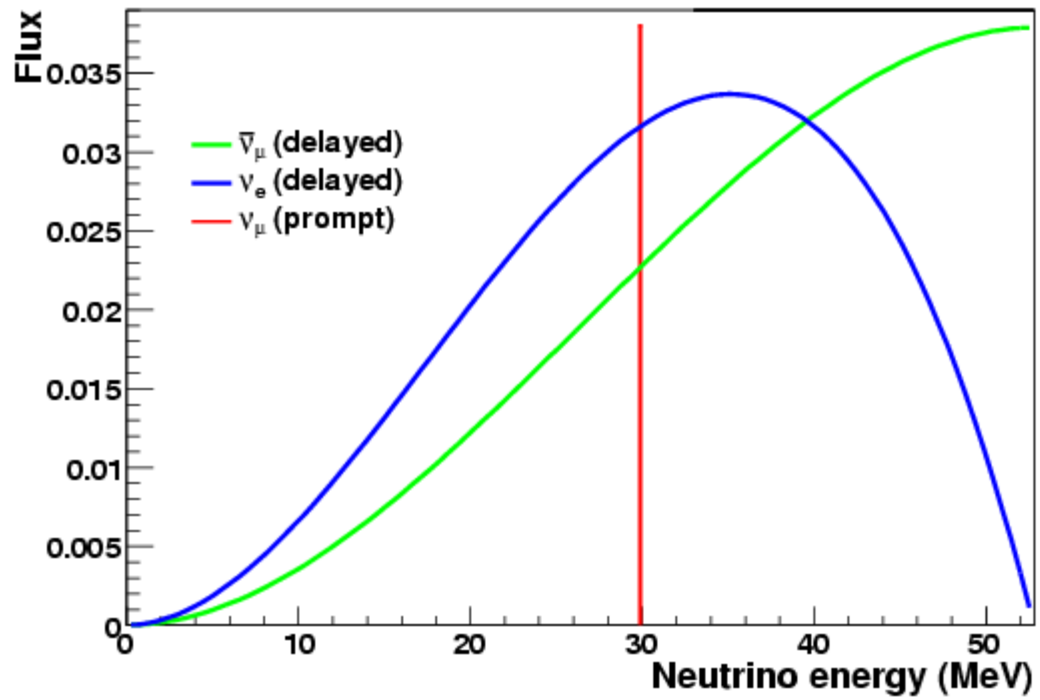


Many novel low-background, low-threshold technologies

See H. Wong, Nu2018 talk for a more detailed survey

Stopped-Pion (πDAR) Neutrinos





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

2-body decay: monochromatic 29.9 MeV ν_μ
PROMPT

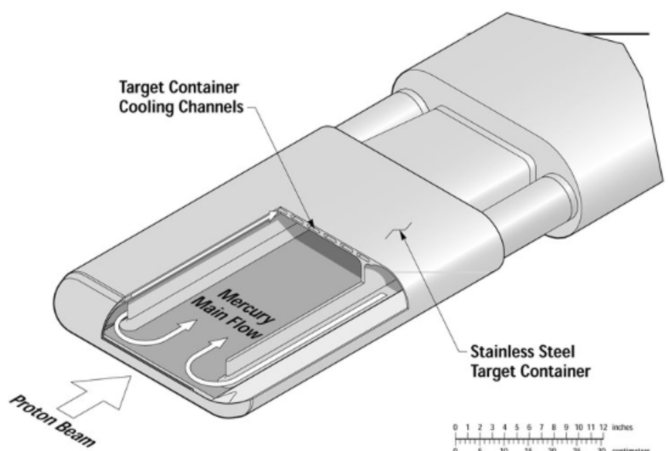
$$\downarrow$$

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

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

Spallation Neutron Source

Oak Ridge National Laboratory, TN

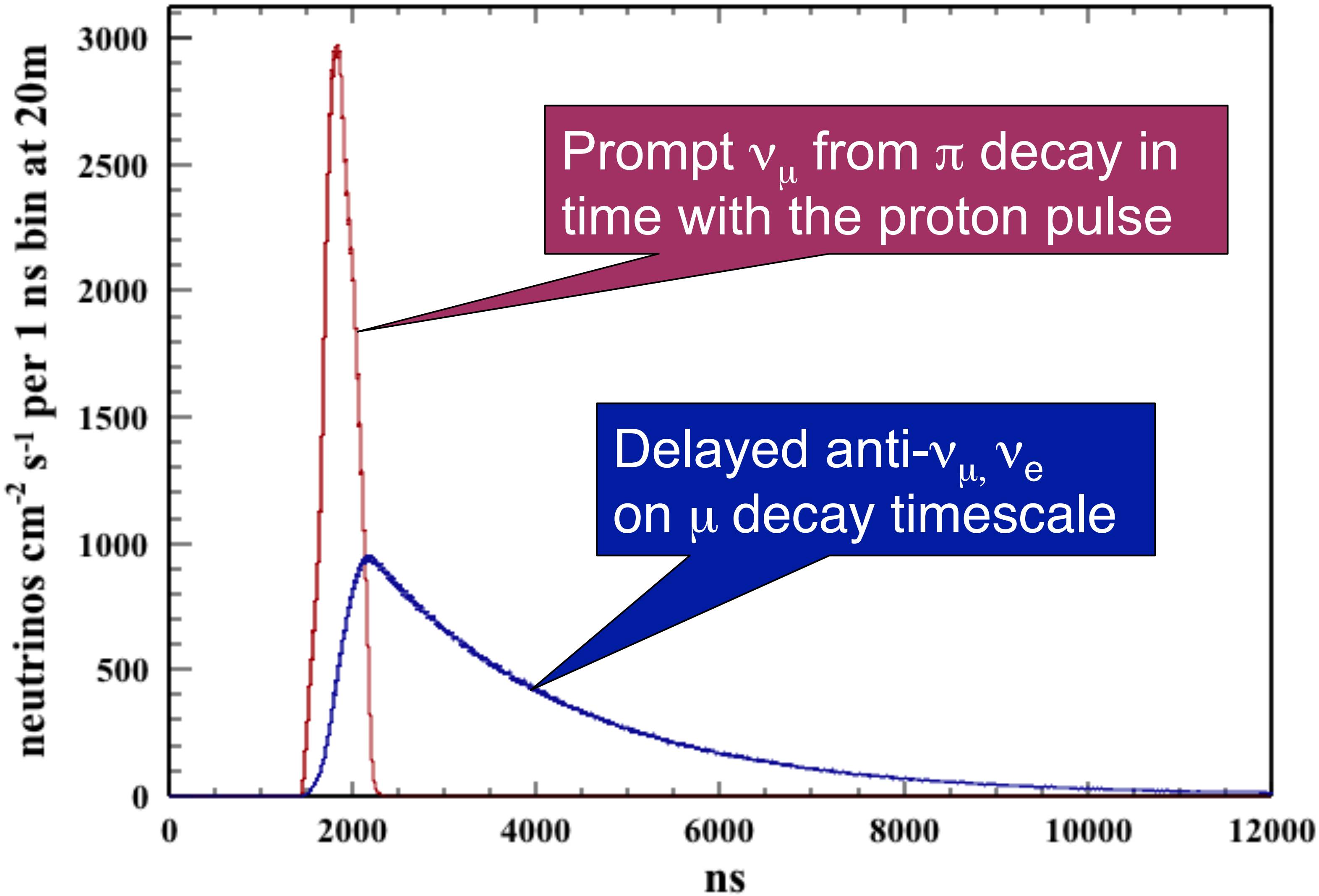


Proton beam energy: 0.9-1.3 GeV
Total power: 0.9-1.4 MW
Pulse duration: 380 ns FWHM
Repetition rate: 60 Hz
Liquid mercury target

The neutrinos are free!

Time structure of the SNS source

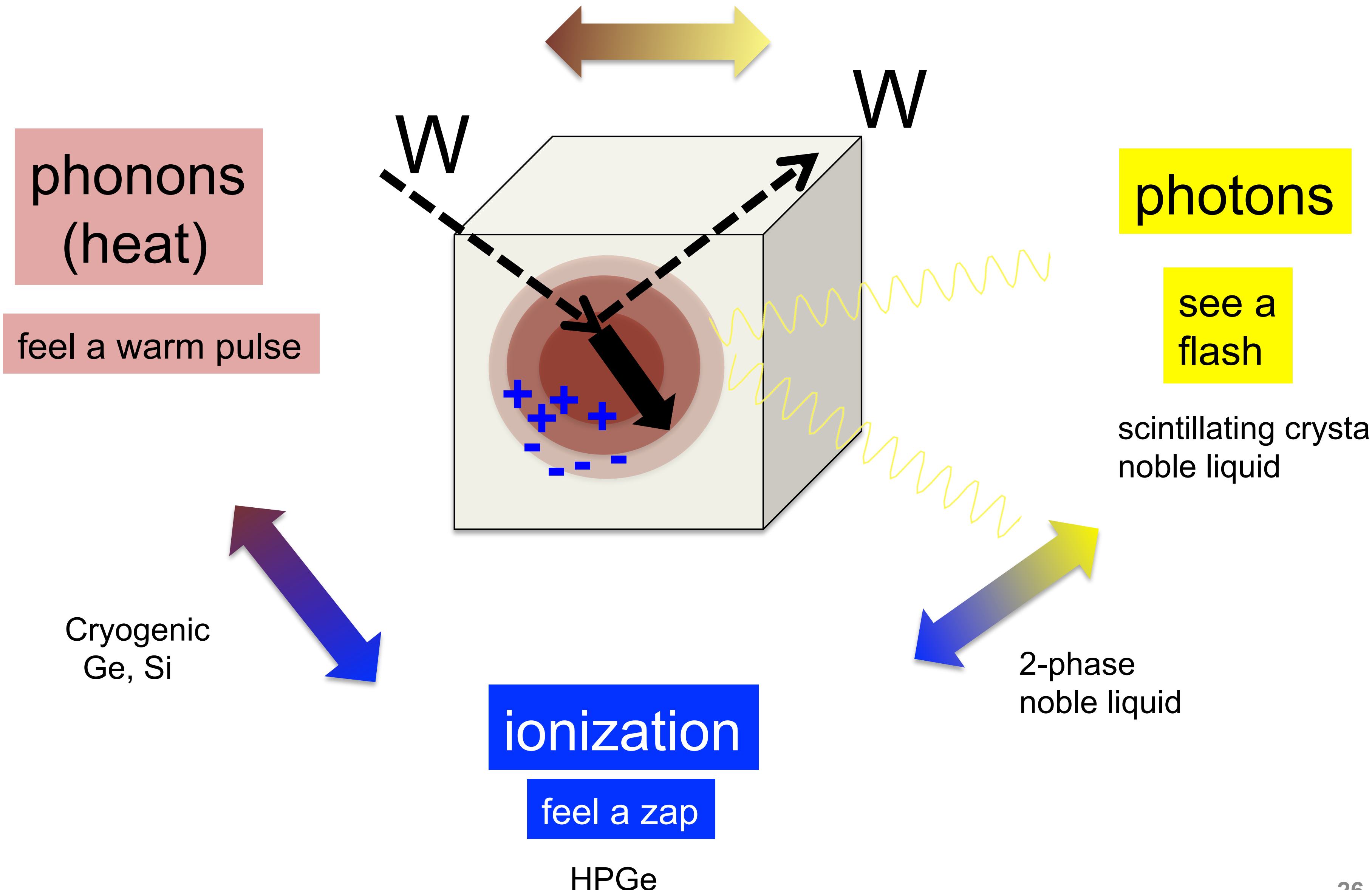
60 Hz *pulsed* source



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

Now, ***detecting*** the tiny kick of the neutrino...

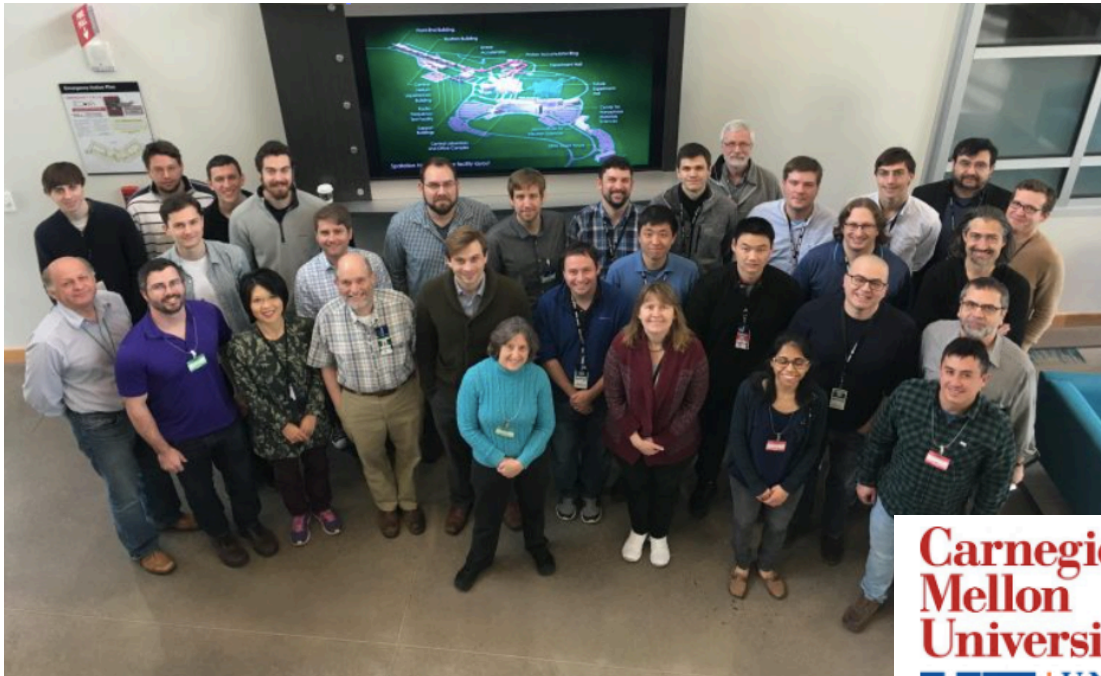
This is just like the tiny thump of a WIMP;
we benefit from the last few decades of low-energy nuclear recoil detectors



http://dmrc.snu.ac.kr/english/intro/intro1.html

The COHERENT collaboration

http://sites.duke.edu/coherent



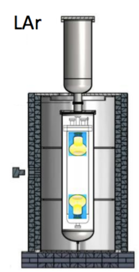
~80 members,
20 institutions
4 countries

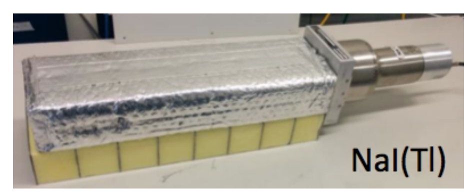
arXiv:1509.08702

COHERENT CEvNS Detectors

Nuclear Target	Technology	Mass (kg)	Distance from source (m)	Recoil threshold (keVr)
CsI[Na]	Scintillating crystal flash	14.6	19.3	6.5
Ge	HPGe PPC zap	6	22	<5
LAr	Single-phase flash	22	29	20
NaI[Tl]	Scintillating crystal flash	185*/ 2000	28	13

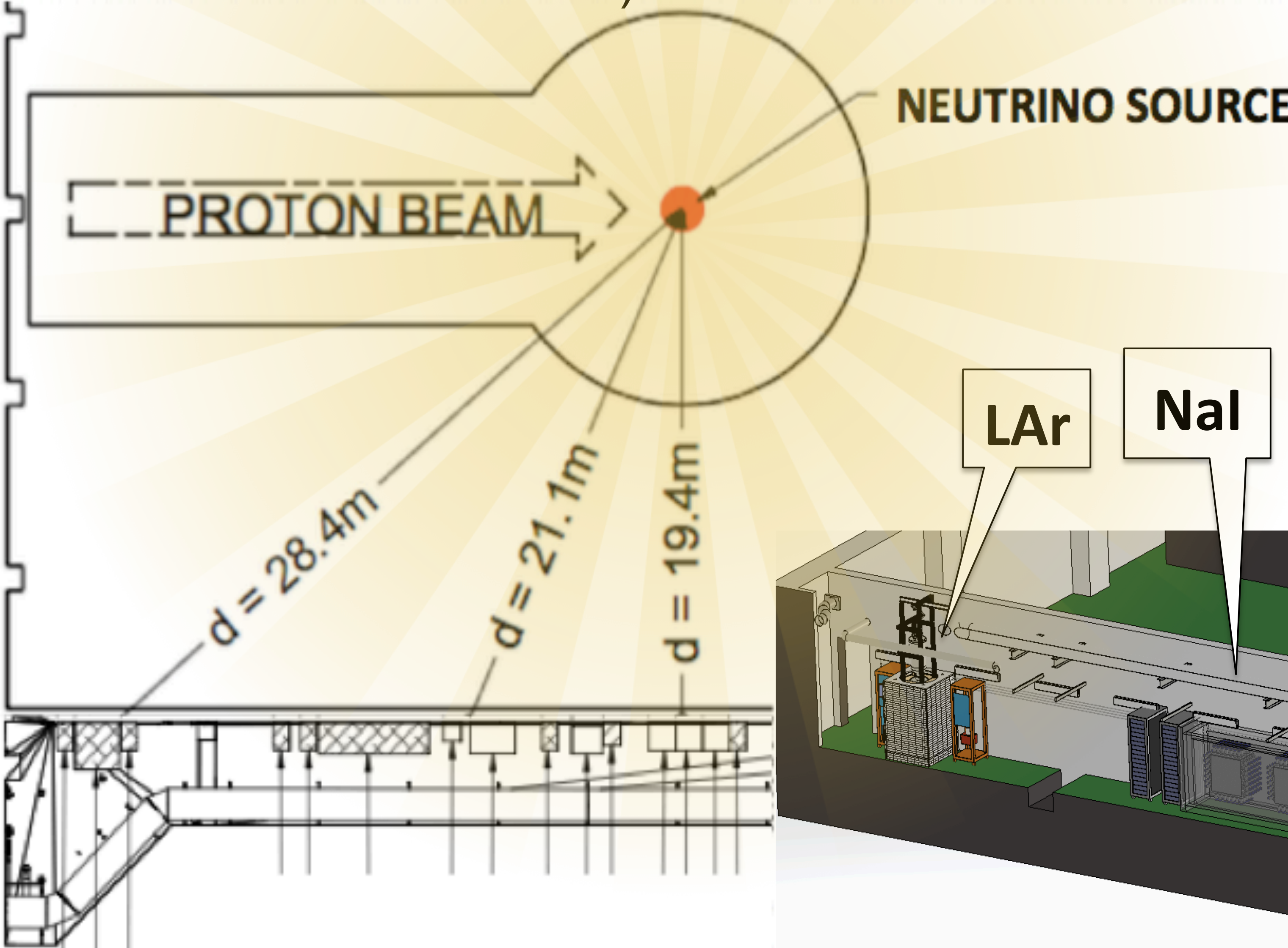
Multiple detectors for N^2 dependence of the cross section





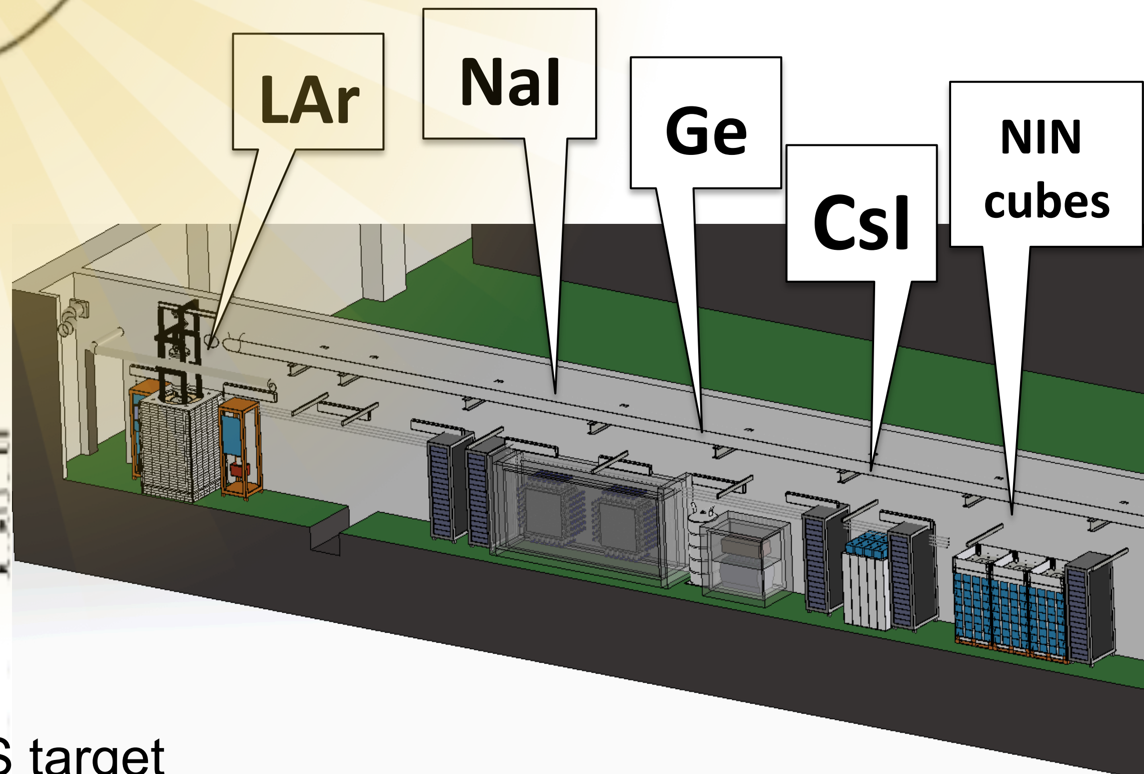
Siting for deployment in SNS basement

(measured neutron backgrounds low,
~ 8 mwe overburden)

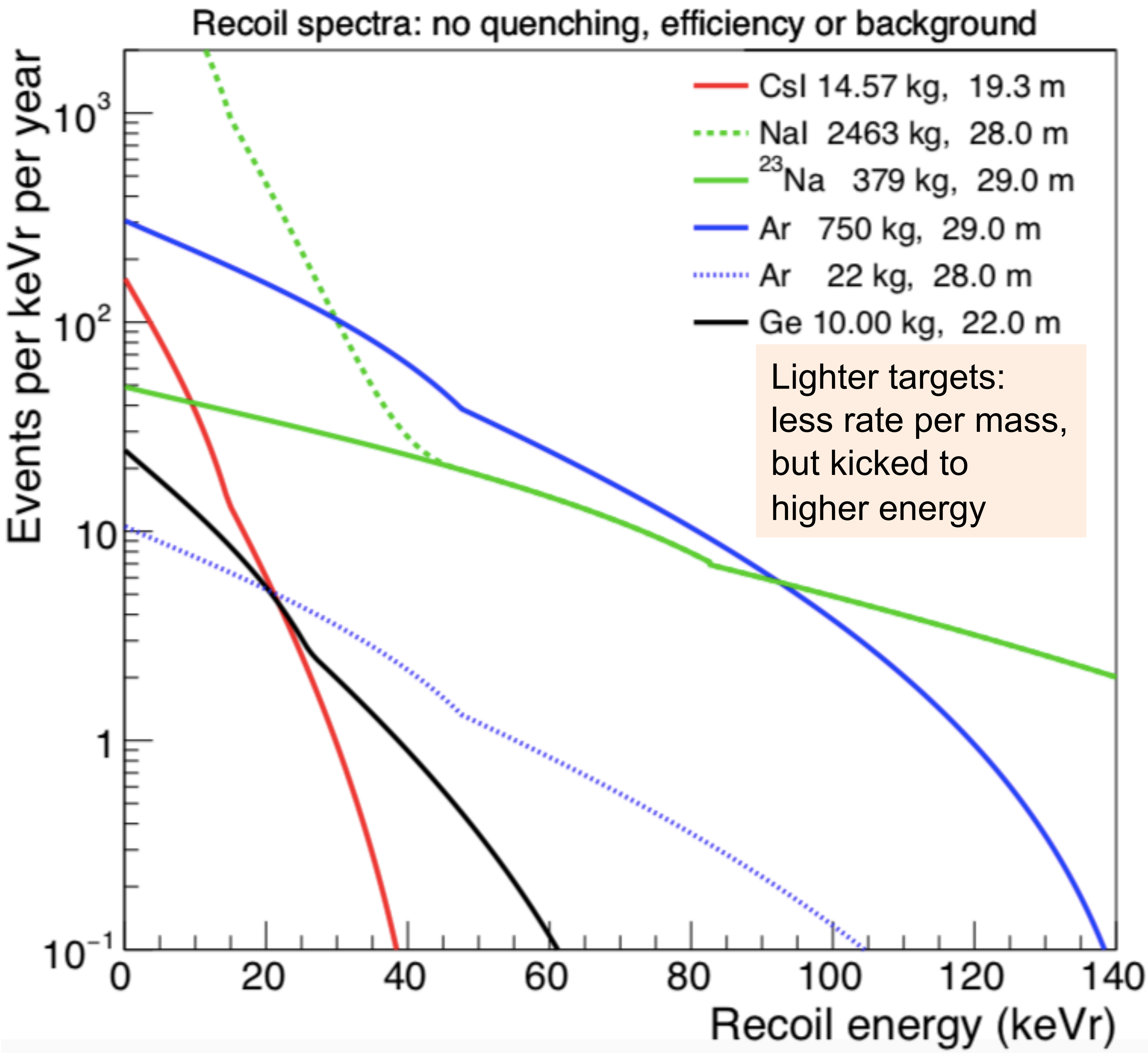


Isotropic ν glow from Hg SNS target

View looking down “Neutrino Alley”



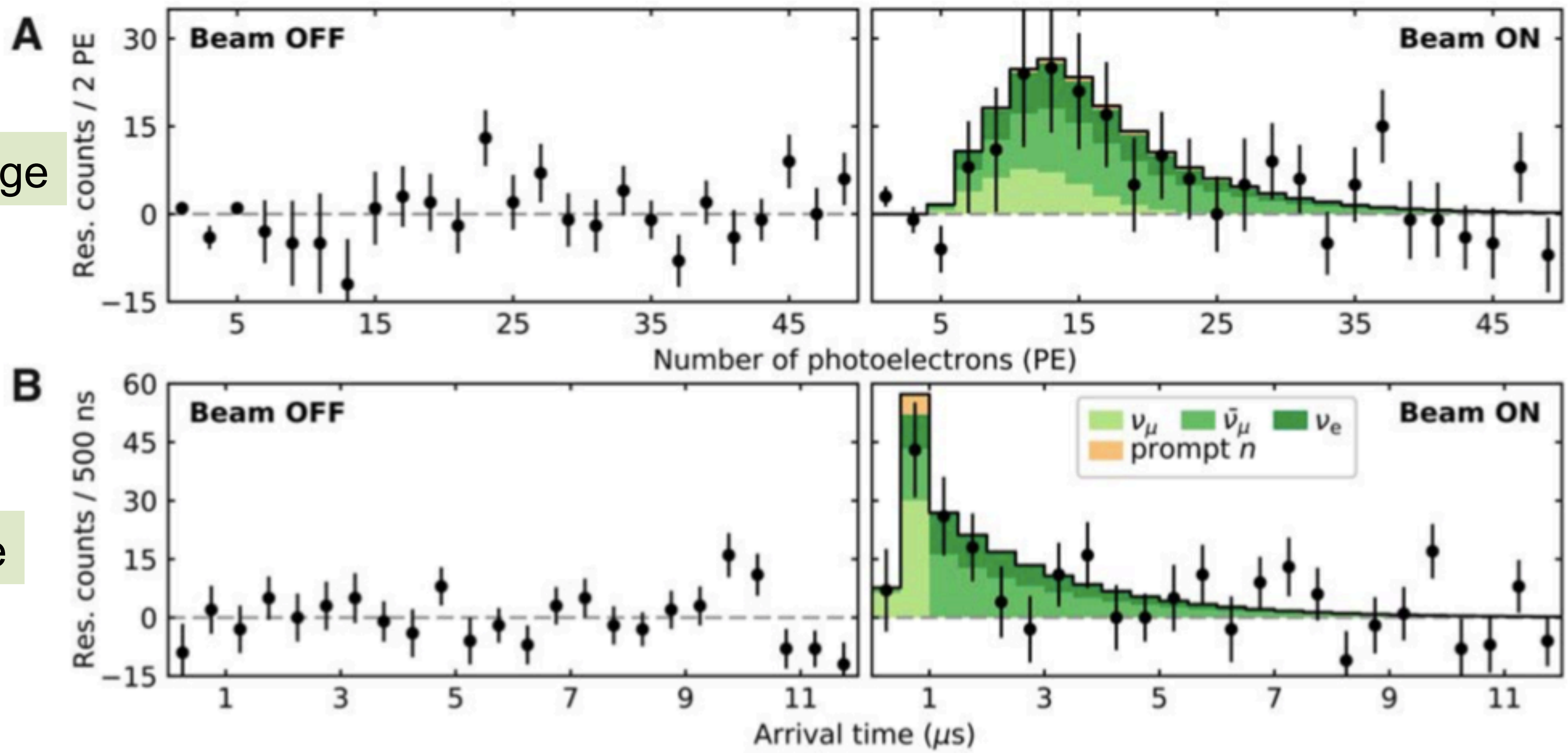
Expected recoil energy distribution



First light at the SNS with 14.6-kg CsI[Na] detector

Charge

Time



Observation of coherent elastic neutrino-nucleus scattering

D. Akimov[1,2], J. B. Albert[3], P. An[4], C. Awe[4,5], P. S. Barbeau[4,5], B. Becker[6], V. Belov[1,2], A. Brown[4,7], A. Bolozdy...

+ See all authors and affiliations

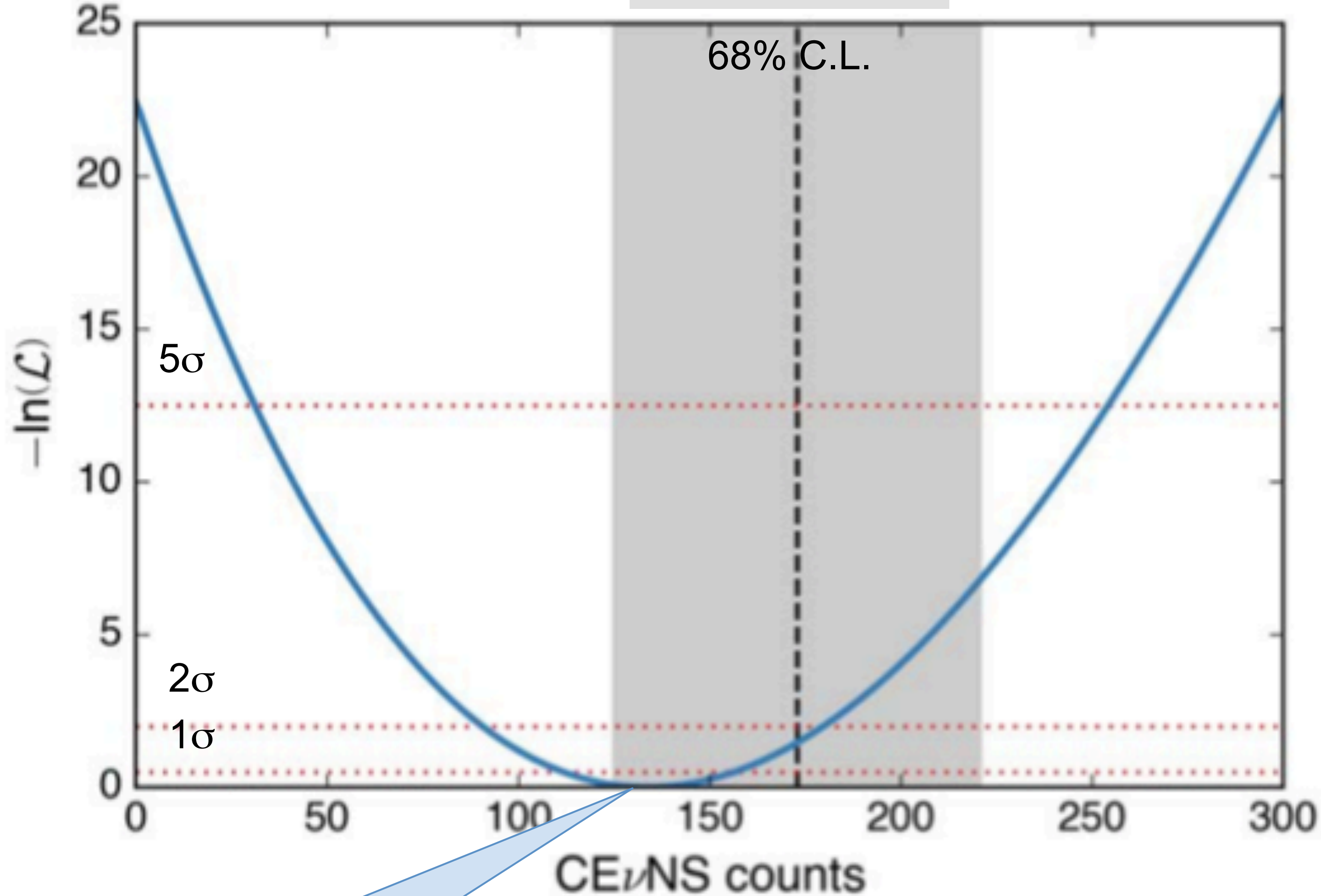
Science 03 Aug 2017:
eaao0990
DOI: 10.1126/science.aao0990

Peer Reviewed
← see details

D. Akimov et al., *Science*, 2017
http://science.sciencemag.org/content/early/2017/08/02/science.aao0990

Results of 2D energy, time fit

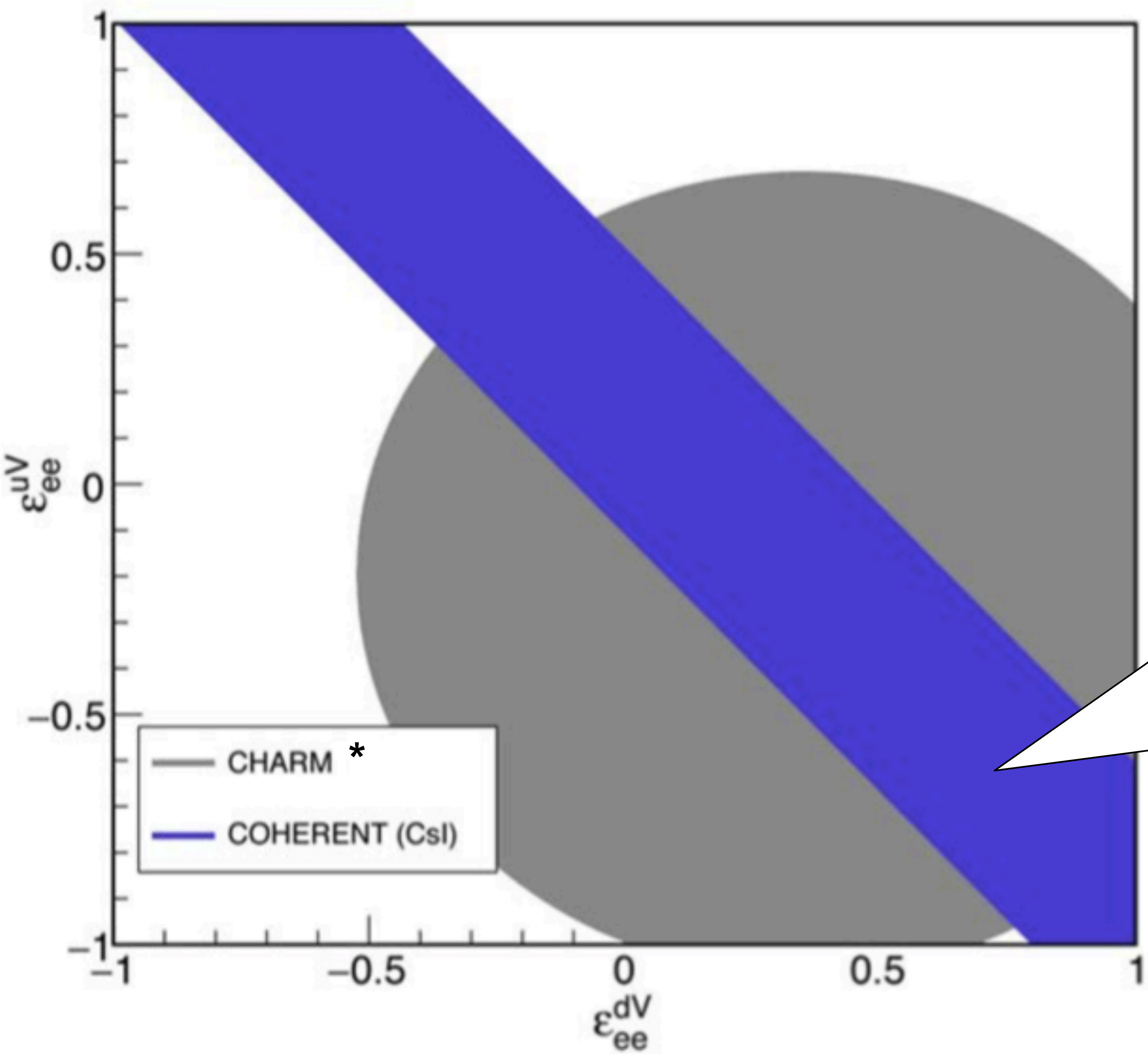
SM prediction, 173 events



Best fit: **134 ± 22** observed events

No CEvNS rejected at 6.7σ, consistent w/SM within 1σ

Neutrino non-standard interaction constraints for current CsI data set:



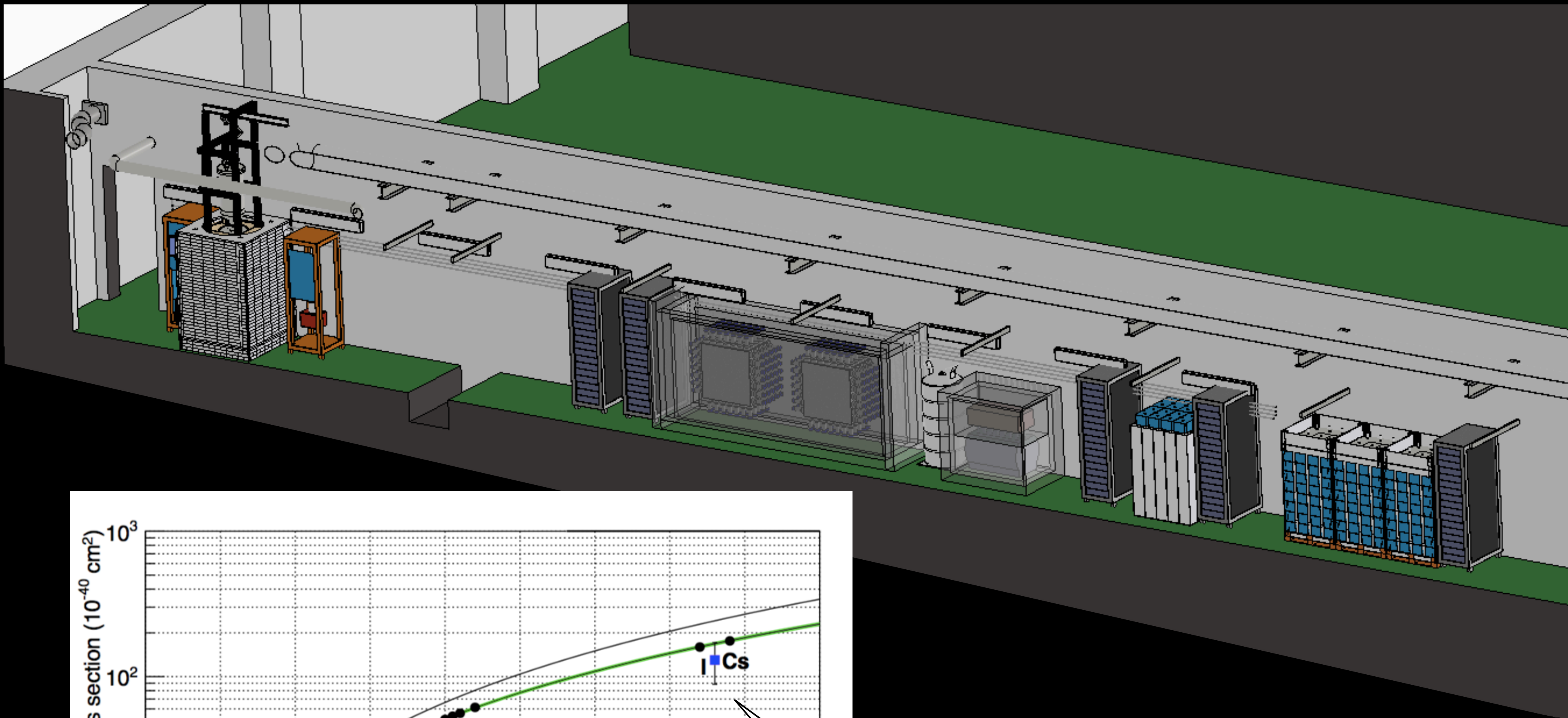
- Assume all other ε's zero

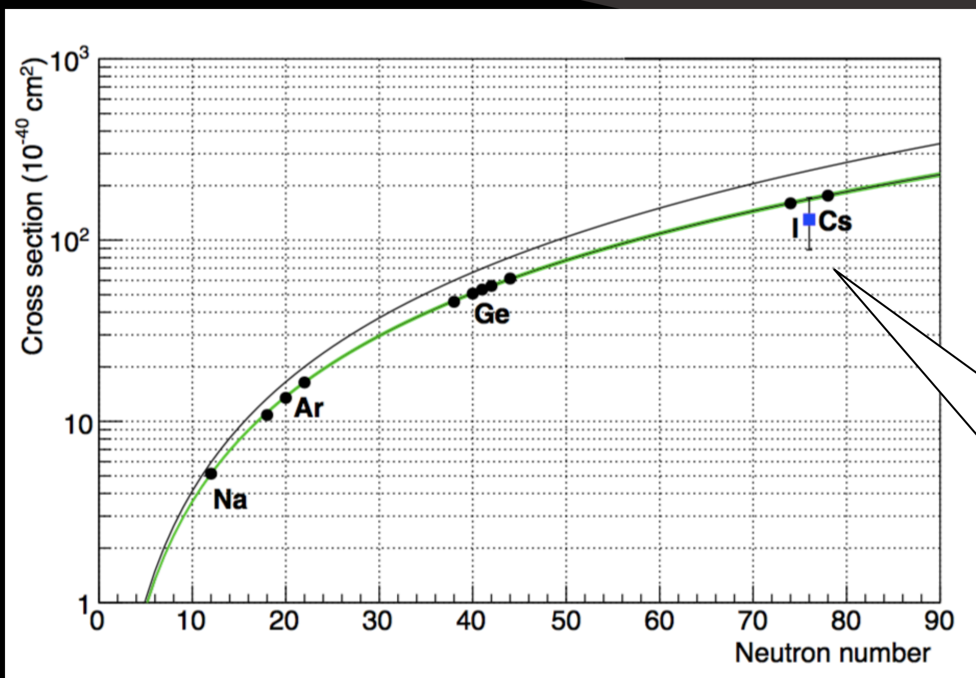
Parameters describing beyond-the-SM interactions outside this region disfavored at 90%

See also Coloma et al., arXiv:1708.02899

*CHARM constraints apply only to heavy mediators

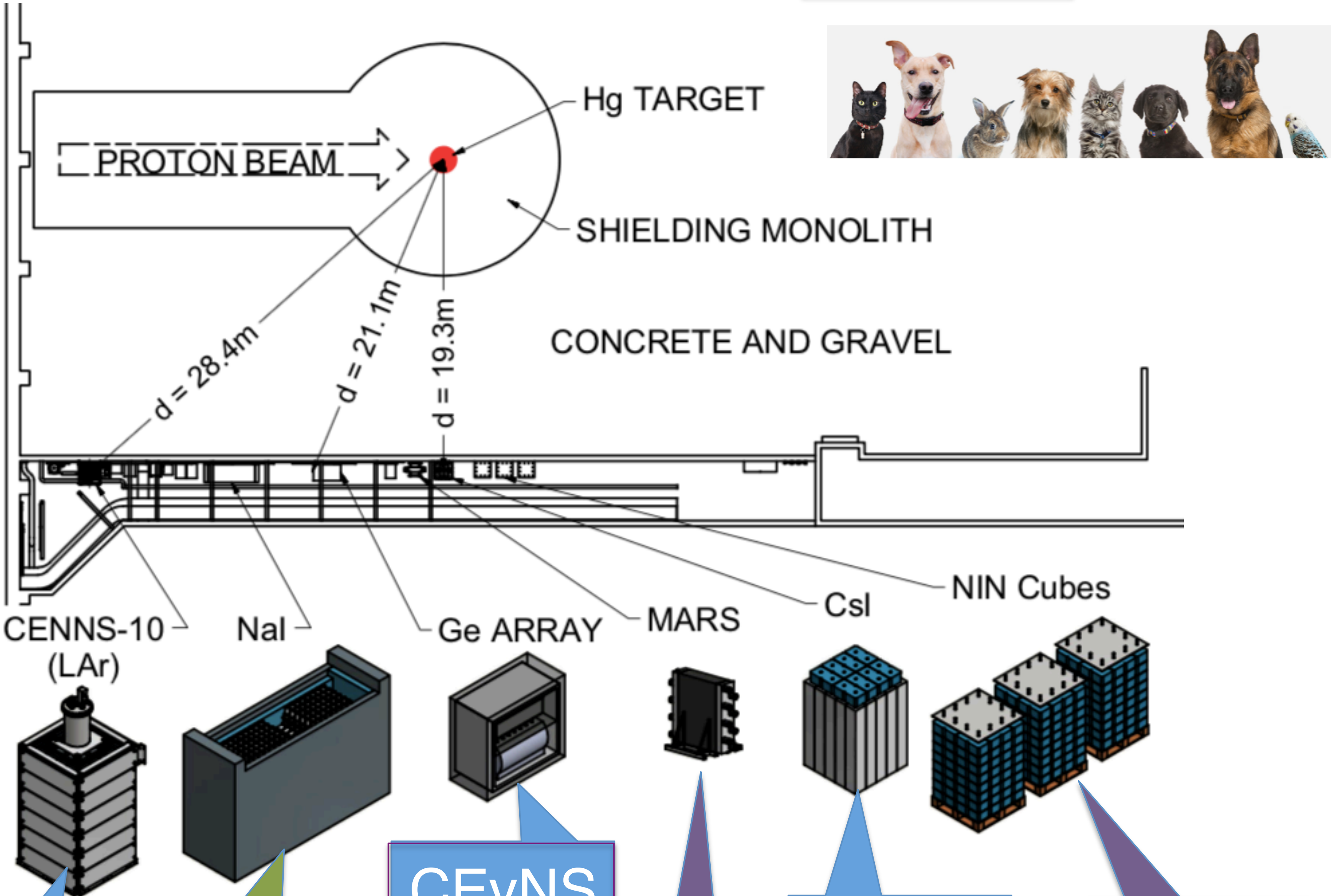
What’s Next for COHERENT?





One measurement so far! Want to map out N^2 dependence

Neutrino Alley Deployments: current & near future



CEvNS

ν_eCC on ^{127}I

CEvNS

CEvNS

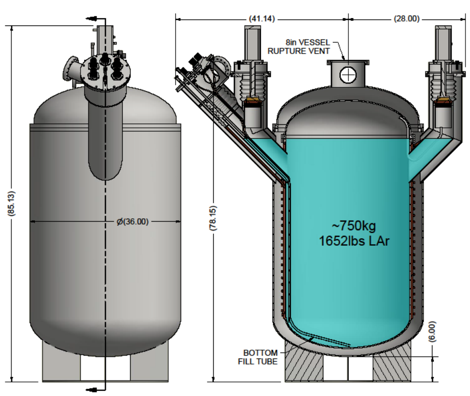
Neutron backgrounds

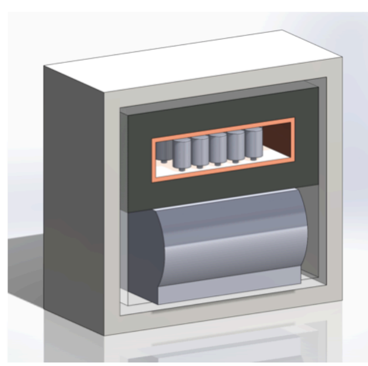
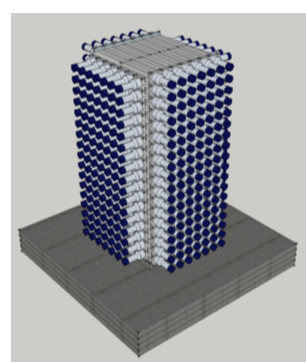
CEvNS

Neutrino-induced neutrons

COHERENT **CEvNS** Detector Status and **Farther Future**

Nuclear Target	Technology	Mass (kg)	Distance from source (m)	Recoil threshold (keVr)	Data-taking start date	Future
CsI[Na]	Scintillating crystal	14.6	20	6.5	9/2015	Finish data-taking
Ge	HPGe PPC	6	22	5	2019	~2.5-kg detectors
LAr	Single-phase	22	29	20	12/2016, upgraded summer 2017	Expansion to ~1 tonne scale
NaI[Tl]	Scintillating crystal	185*/ 2000	28	13	*high-threshold deployment summer 2016	Expansion to 2.5 tonne, up to 9 tonnes

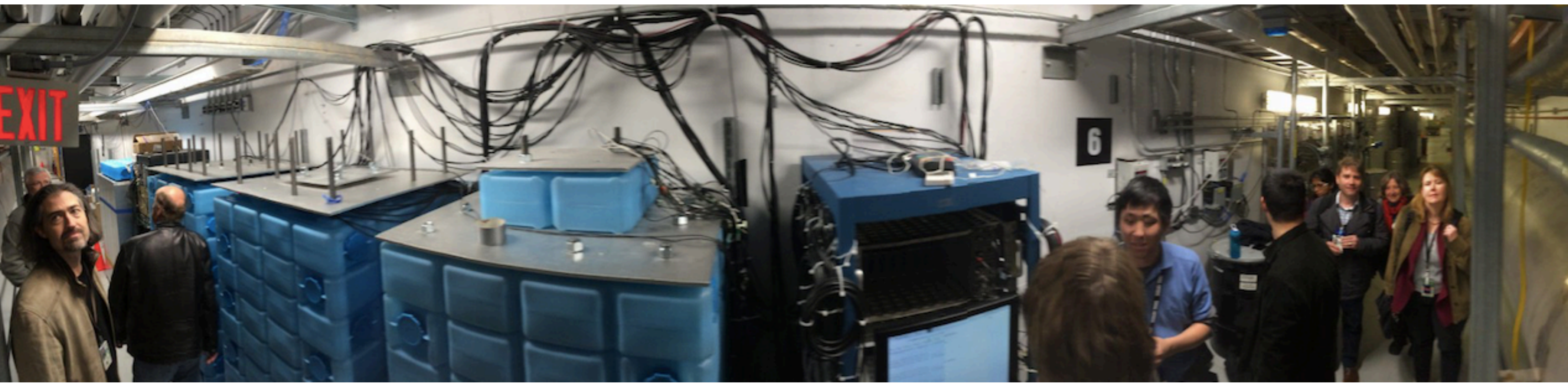


+ concepts for other targets

Summary

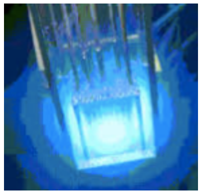
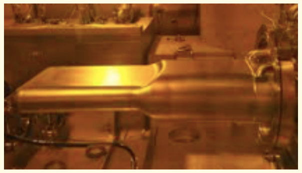
- **CEvNS:**
  - large cross section, but tiny recoils, α N^2
  - accessible w/low-energy threshold detectors, plus extra oomph of stopped-pion neutrino source
- **First measurement** by COHERENT CsI[Na] at the SNS
- **Meaningful bounds on beyond-the-SM physics**



- **It’s just the beginning....**
- Multiple targets, upgrades and new ideas in the works!
- Other CEvNS experiments at reactors are joining the fun (**CONUS**, CONNIE, MINER, RED, Ricochet, Nu-cleus...)

Extras/Backups

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

zenodo

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April 25, 2018

Dataset Open Access

COHERENT Collaboration data release from the first observation of coherent elastic neutrino-nucleus scattering

Akimov, D; Albert, J.B.; An, P.; Awe, C.; Barbeau, P.S.; Becker, B.; Belov, V.; Blackston, M.A.; Bolozdynya, A.; Brown, A.; Burenkov, A.; Cabrera-Palmer, B.; Cervantes, M.; Collar, J.I.; Cooper, R.J.; Cooper, R.L.; Cuesta, C.; Daughhetee, J.; Dean, D.J.; del Valle Coello, M.; Detwiler, J.; D'Onofrio, M.; Eberhardt, A.; Efremenko, Y.; Elliott, S.R.; Etenko, A.; Fabris, L.; Febbraro, M.; Fields, N.; Fox, W.; Fu, Z.; Galindo-Uribarri, A.; Green, M.P.; Hai, M.; Heath, M.R.; Hedges, S.; Hornback, D.; Hossbach, T.W.; Iverson, E.B.; Kaemingk, M.; Kaufman, L.J.; Klein, S.R.; Khromov, A.; Ki, S.; Konovalov, A.; Kovalenko, A.; Kremer, M.; Kumpan, A.; Leadbetter, C.; Li, L.; Lu, W.; Mann, K.; Markoff, D.M.; Melikyan, Y.; Miller, K.; Moreno, H.; Mueller, P.E.; Naumov, P.; Newby, J.; Orrell, J.L.; Overman, C.T.; Parno, D.S.; Penttila, S.; Perumpilly, G.; Radford, D.C.; Rapp, R.; Ray, H.; Raybern, J.; Reyna, D.; Rich, G.C.; Rimal, D.; Rudik, D.; Salvat, D.J.; Scholberg, K.; Scholz, B.; Sinev, G.; Snow, W.M.; Sosnovtsev, V.; Shakirov, A.; Suchyta, S.; Suh, B.; Tayloe, R.; Thornton, R.T.; Tolstukhin, I.; Vanderwerp, J.; Varner, R.L.; Virtue, C.J.; Wan, Z.; Yoo, J.; Yu, C.-H.; Zawada, A.; Zderic, A.; Zettlemoyer, J.

Triangle Universities Nuclear Laboratory

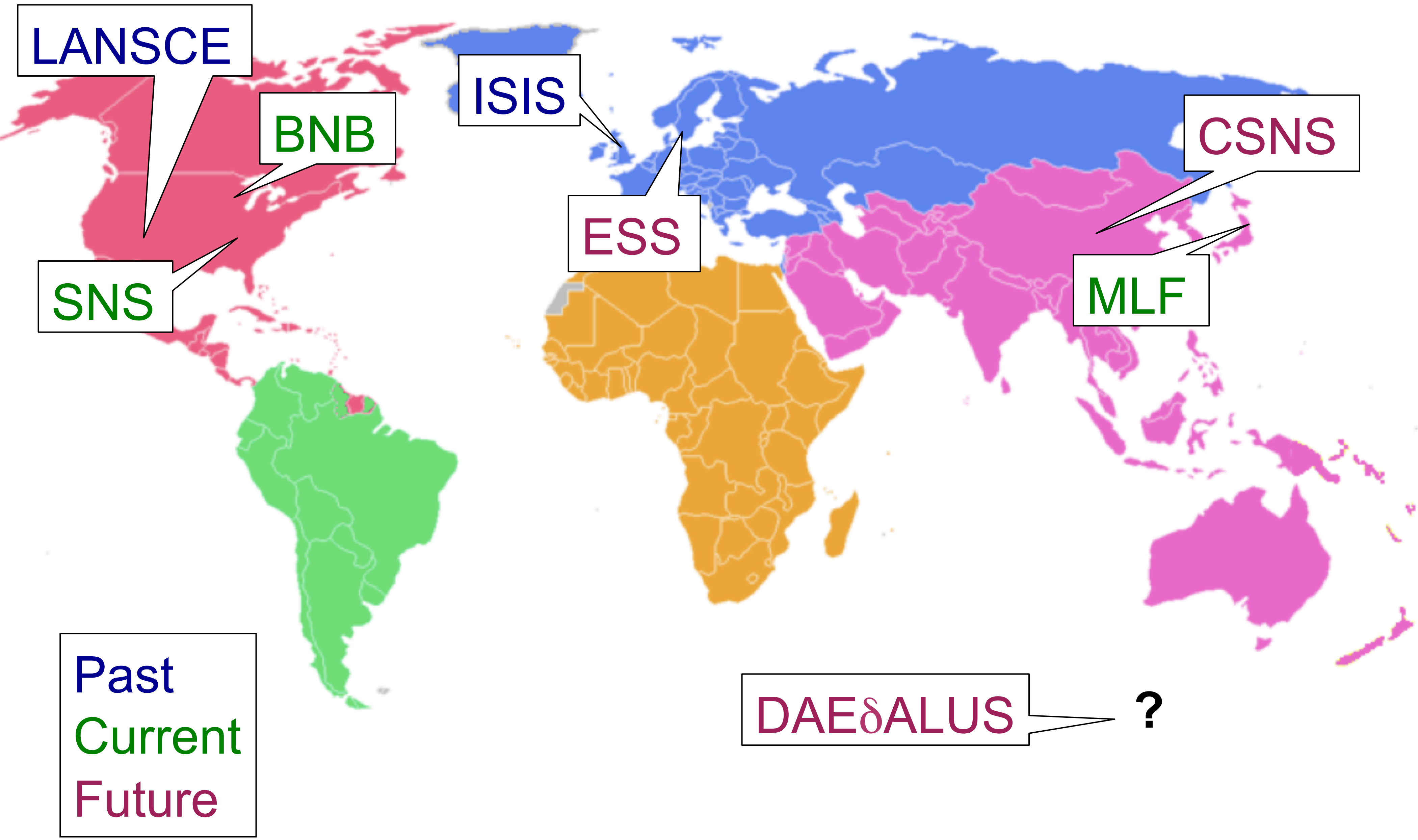
Release of COHERENT Collaboration data associated with the first observation of coherent elastic neutrino-nucleus scattering (CEvNS), as published in Science (DOI: 10.1126/science.aao0990) and also available as arXiv:1708.01294[nucl-ex].

This data set should enable researchers to extend the study of CEvNS as desired. Future COHERENT Collaboration results will have similar data releases.

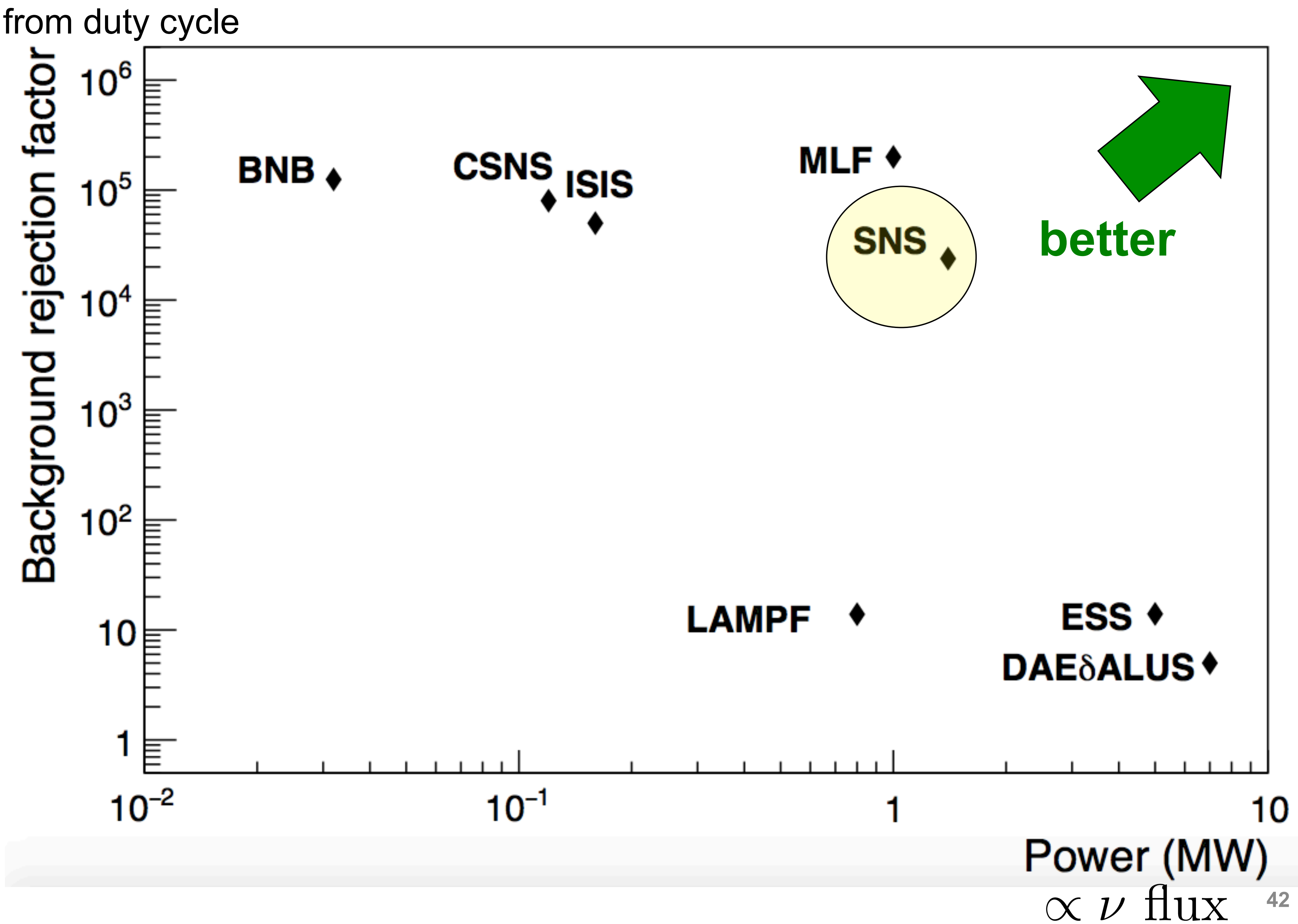
Available for theorists

“pyCEvNS” collaboration

Stopped-Pion Neutrino Sources Worldwide

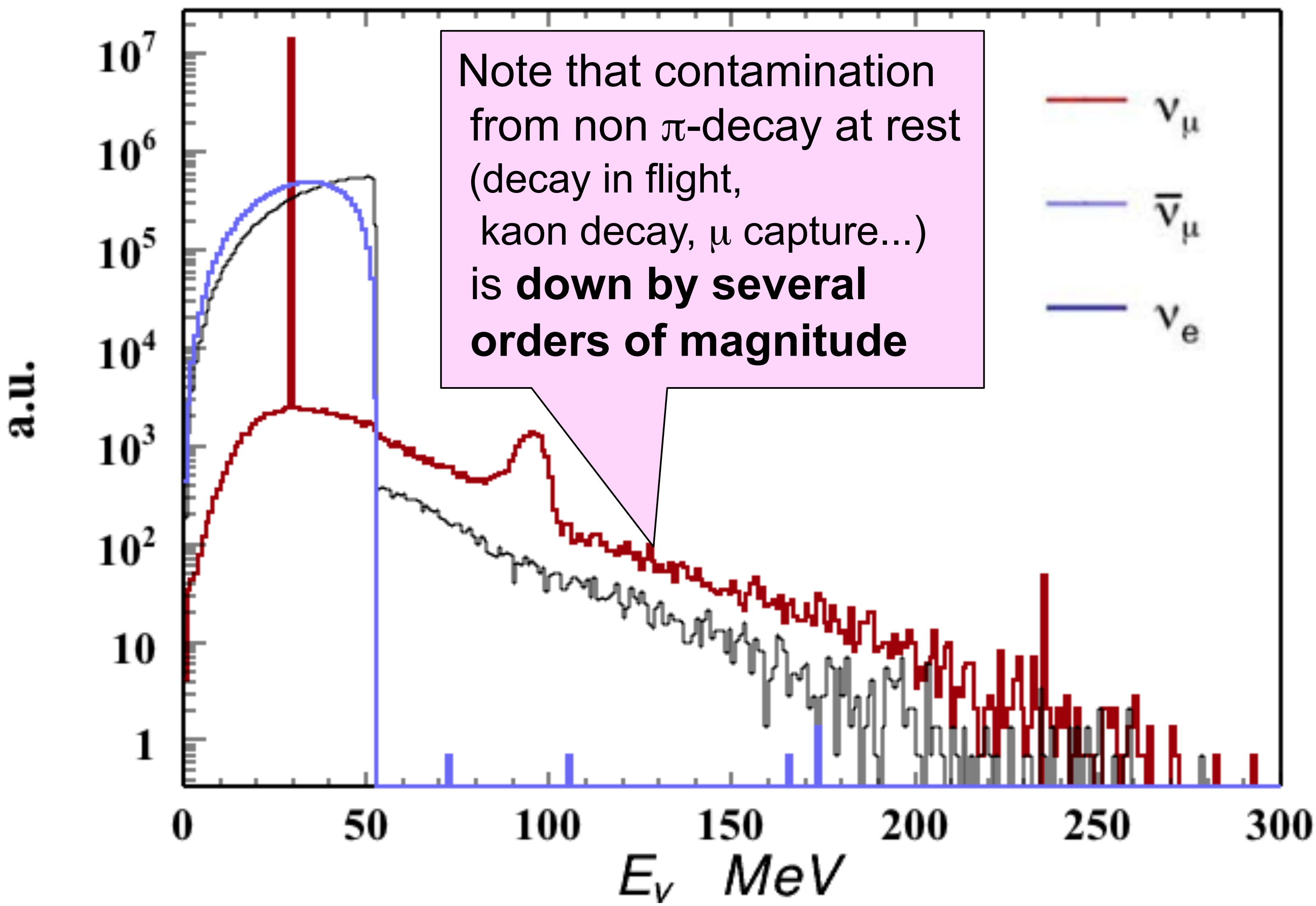


Comparison of pion decay-at-rest ν sources



The SNS has **large, extremely clean** stopped-pion ν flux

0.08 neutrinos per flavor per proton on target



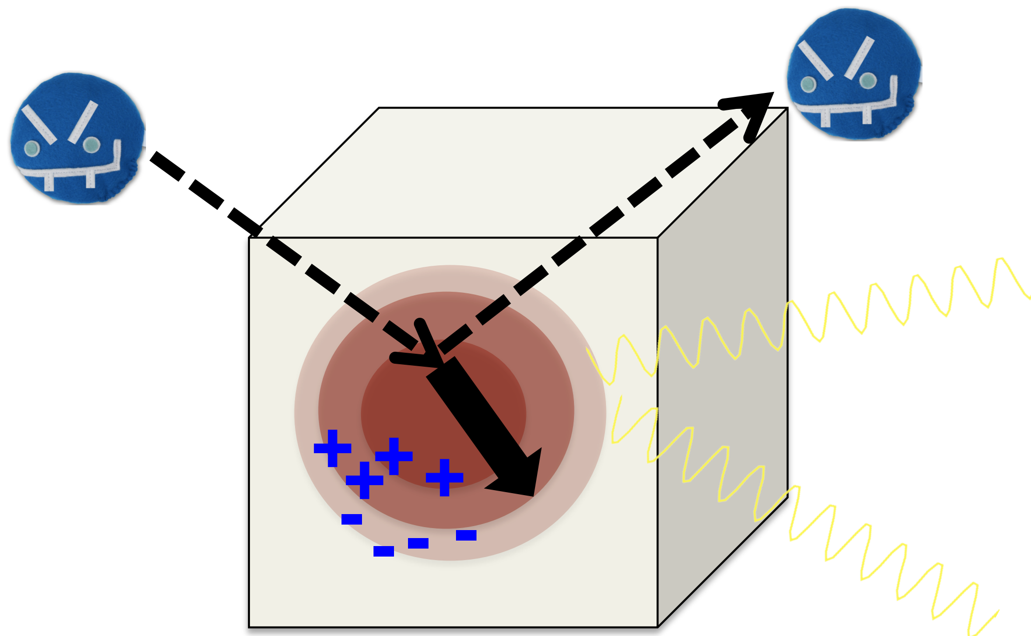
SNS flux (1.4 MW):
430 x 10^5 ν/cm^2/s
@ 20 m

Backgrounds

Usual suspects:

- cosmogenics
- ambient and intrinsic radioactivity
- detector-specific noise and dark rate

Neutrons are especially not our friends*



Steady-state backgrounds can be *measured* off-beam-pulse
... in-time backgrounds must be carefully characterized

*Thanks to Robert Cooper for the “mean neutron”

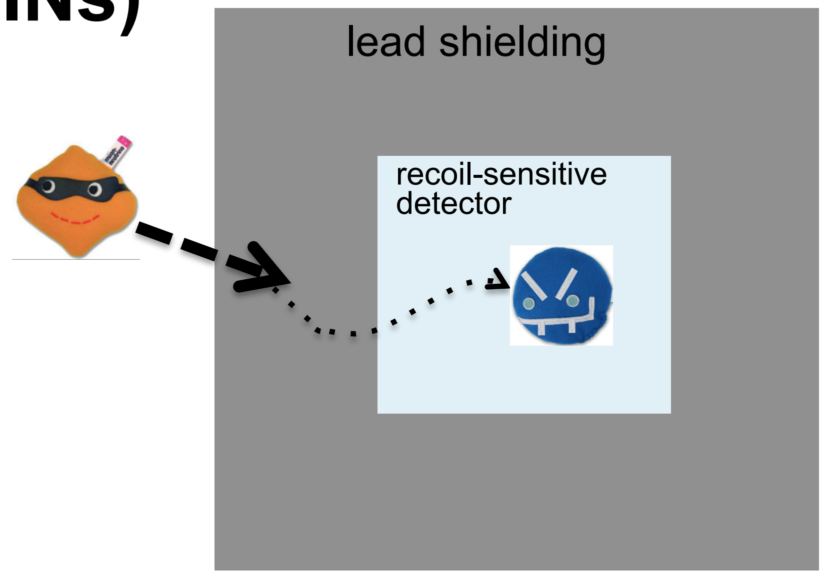
A "friendly fire" in-time background:
Neutrino Induced Neutrons (NINs)

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

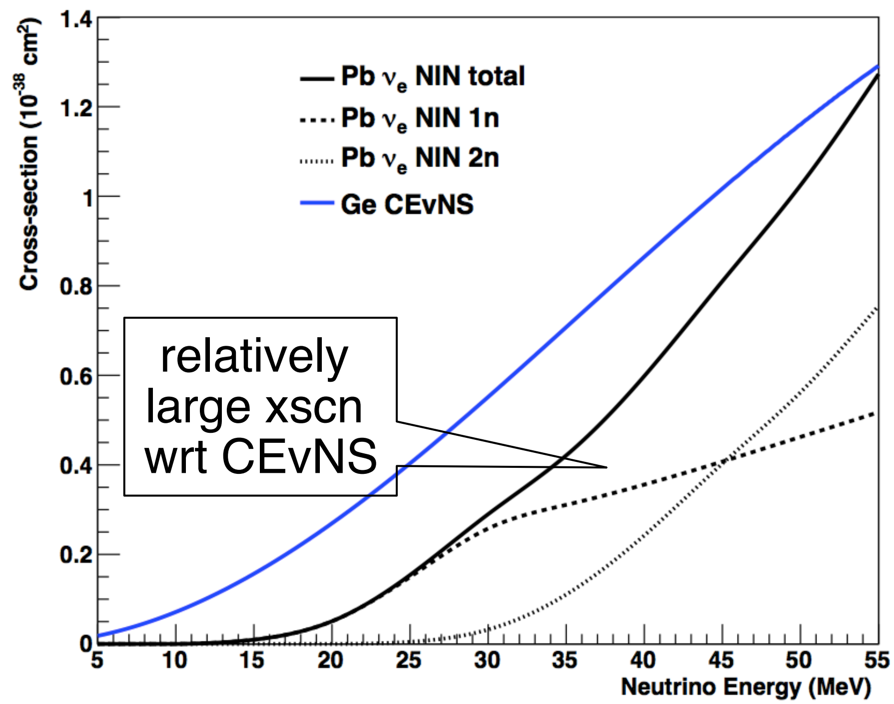
↘ 1n, 2n emission

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

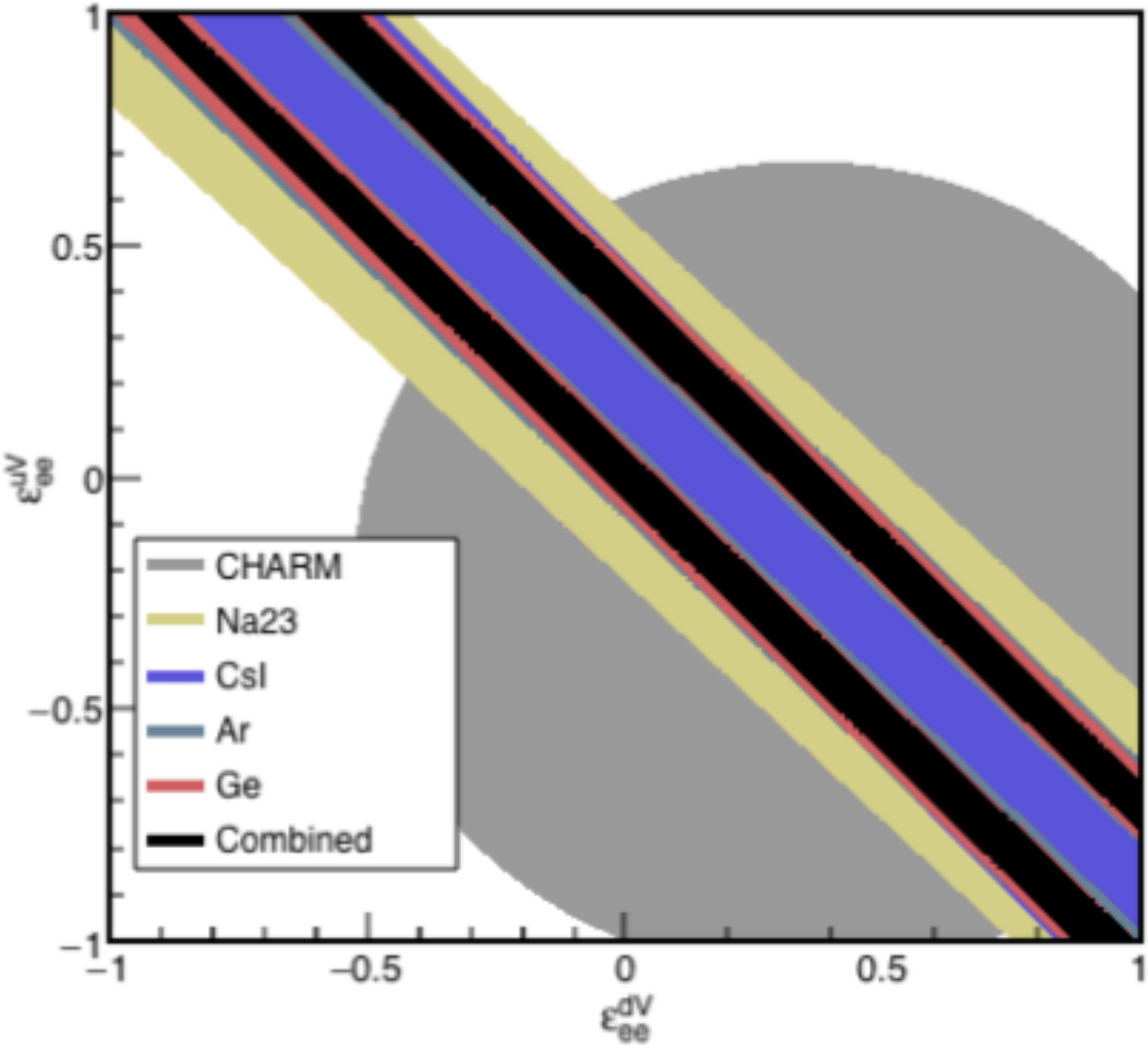
↘ 1n, 2n, γ emission



- potentially non-negligible background from shielding
- requires careful shielding design
- large uncertainties (factor of few) in cross-section calculation
- [Also: a signal in itself, e.g, HALO SN detector]



Projected future sensitivities for NSI

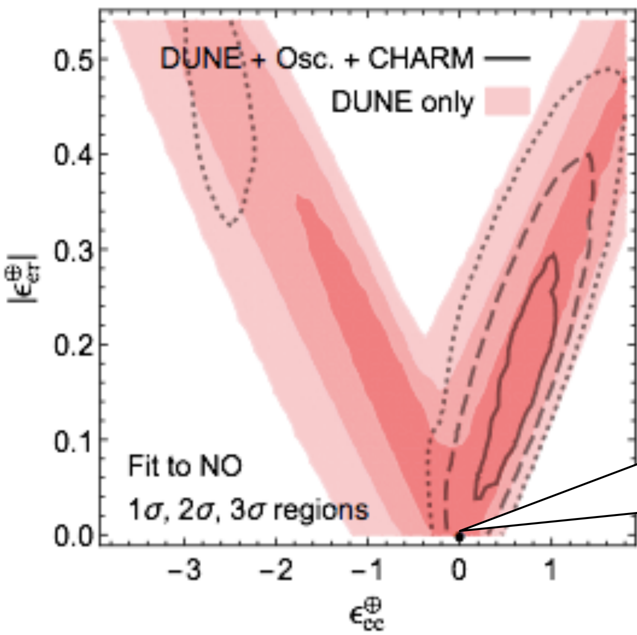


Combination of targets improves sensitivity

Generalized mass ordering degeneracy in neutrino oscillation experiments

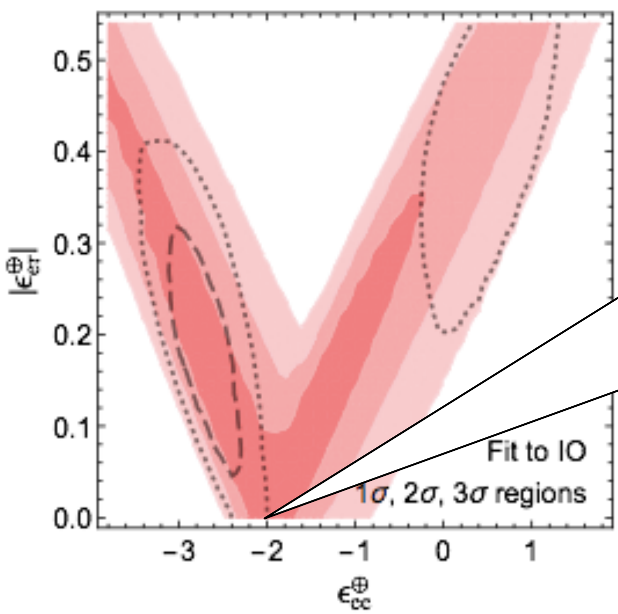
Pilar Coloma[1] and Thomas Schwetz[2]

Phys.Rev. D94 (2016) no.5, 055005,
Erratum: Phys.Rev. D95 (2017) no.7, 079903
P. Coloma et al., JHEP 1704 (2017) 116



Normal ordering w/no NSI...

If you allow for NSI, an ambiguity exists in determining mass ordering w/ LBL experiments**:**
"LMA-Dark"



...looks just like inverted ordering w/NSI

Same answer for

$$\Delta m^2_{31} \to -\Delta m^2_{31} + \Delta m^2_{21} = -\Delta m^2_{32}\,,$$
$$\sin\theta_{12} \to \cos\theta_{12}\,,$$
$$\delta \to \pi - \delta\,,$$
$$(\epsilon_{ee} - \epsilon_{\mu\mu}) \to -(\epsilon_{ee} - \epsilon_{\mu\mu}) - 2\,,$$
$$(\epsilon_{\tau\tau} - \epsilon_{\mu\mu}) \to -(\epsilon_{\tau\tau} - \epsilon_{\mu\mu})\,,$$
$$\epsilon_{\alpha\beta} \to -\epsilon^*_{\alpha\beta} \quad (\alpha \neq \beta)$$

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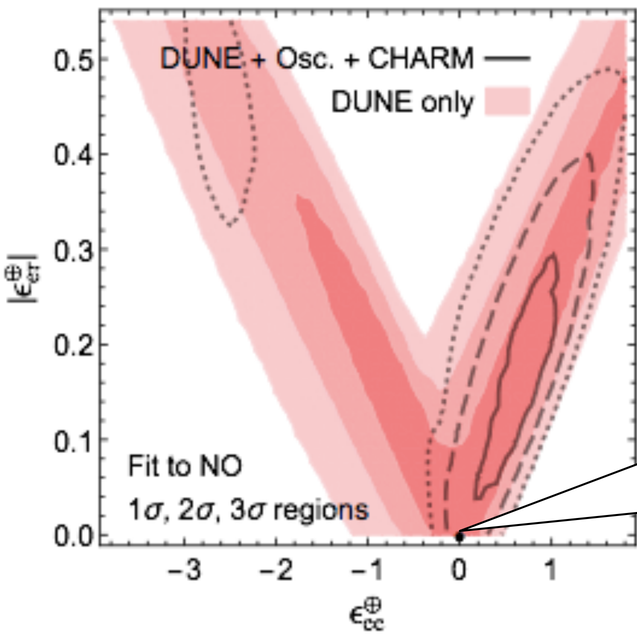

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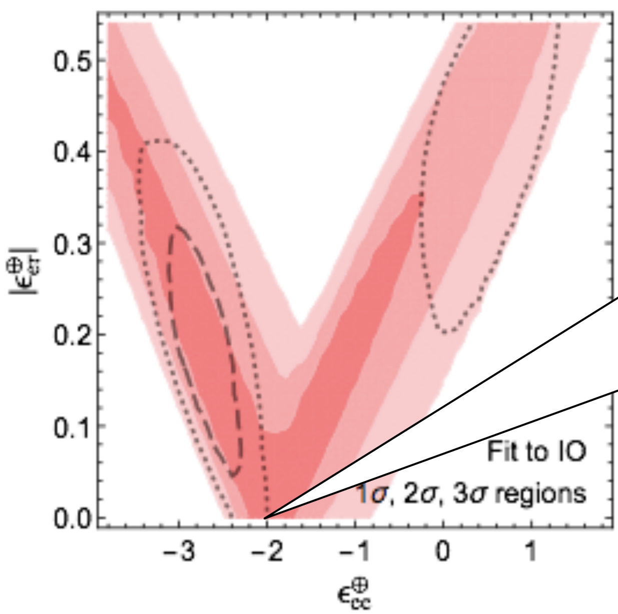


...looks just like inverted ordering w/NSI

CEvNS measurements can place significant constraints to **resolve the LMA-D ambiguity** if SM rate is measured

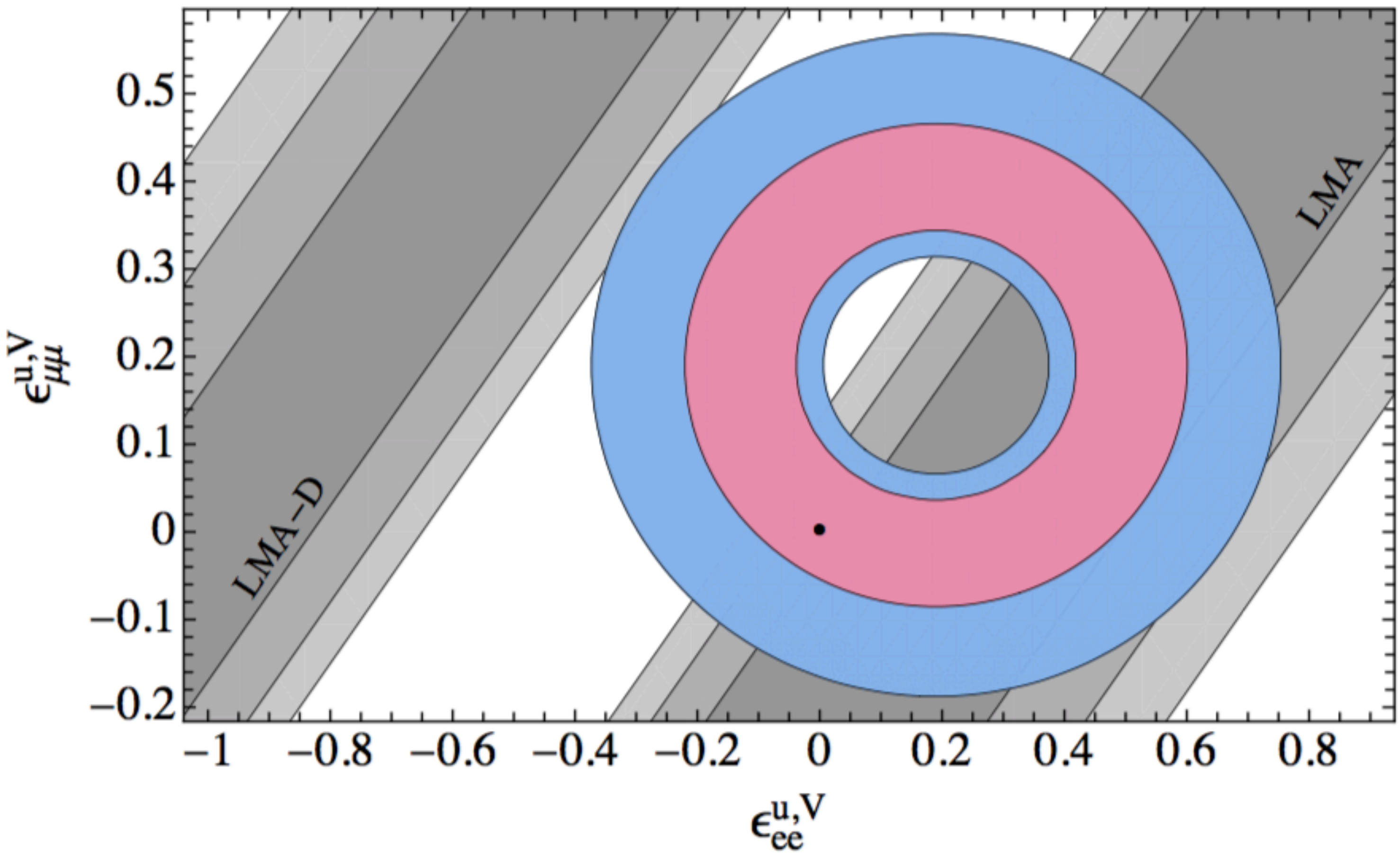
OR, could *confirm an NSI signature* observed by DUNE

A COHERENT enlightenment of the neutrino Dark Side

Pilar Coloma,[1,*] M. C. Gonzalez-Garcia,,[2,3,4,†] Michele Maltoni,,[5,‡] and Thomas Schwetz[6,§]

Phys.Rev. D96 (2017) no.11, 115007

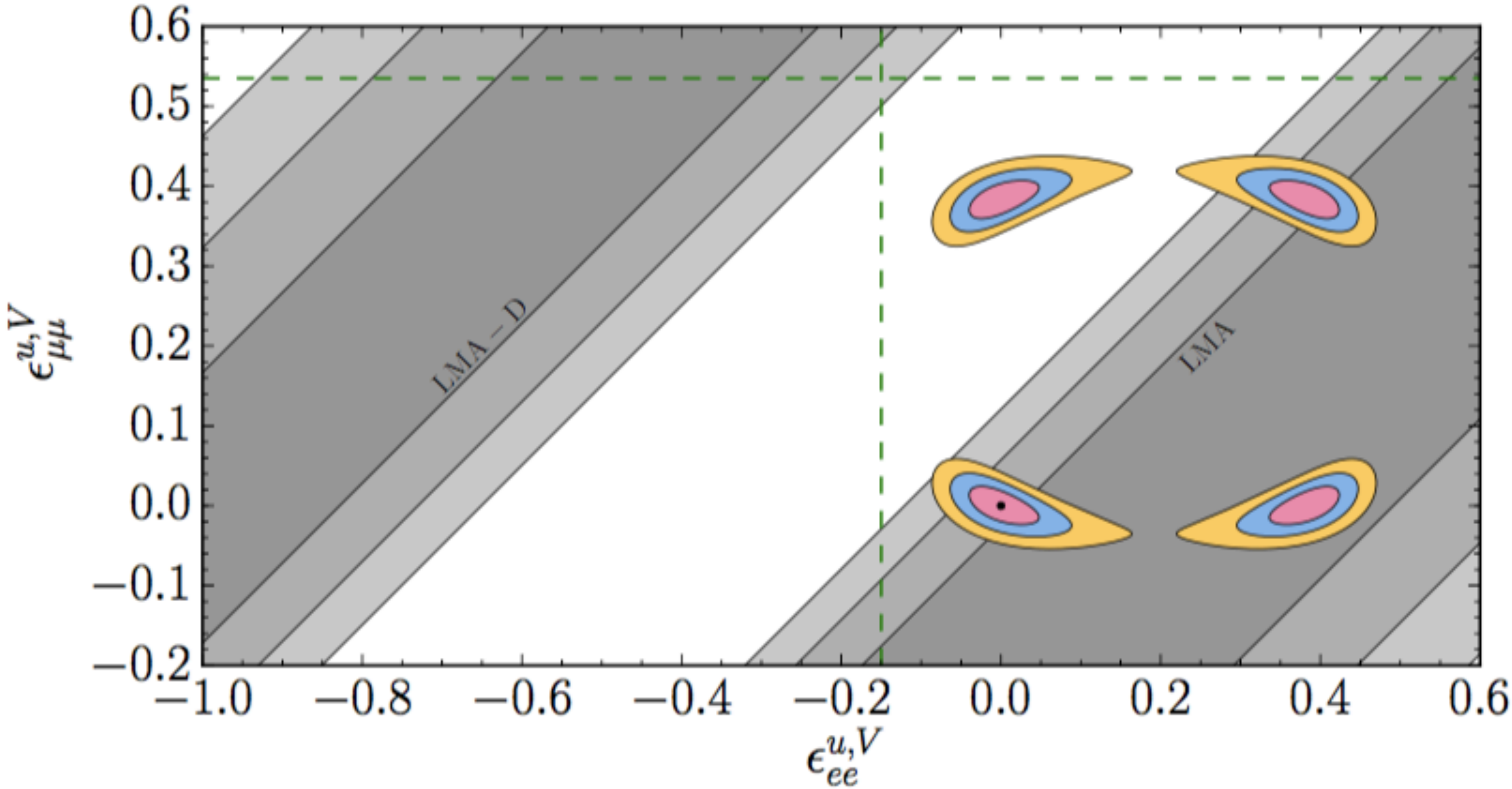
1σ, 2σ allowed regions projected in (ε_{ee}^{uV}, $\varepsilon_{\mu\mu}^{uV}$) plane



First COHERENT results are already disfavoring LMA-D

P. Coloma et al., JHEP 1704 (2017) 116

Future COHERENT results will fully exclude LMA-D



Another phenomenological analysis, making use of spectral fit:

COHERENT constraints on nonstandard neutrino interactions

Jiajun Liao and Danny Marfatia

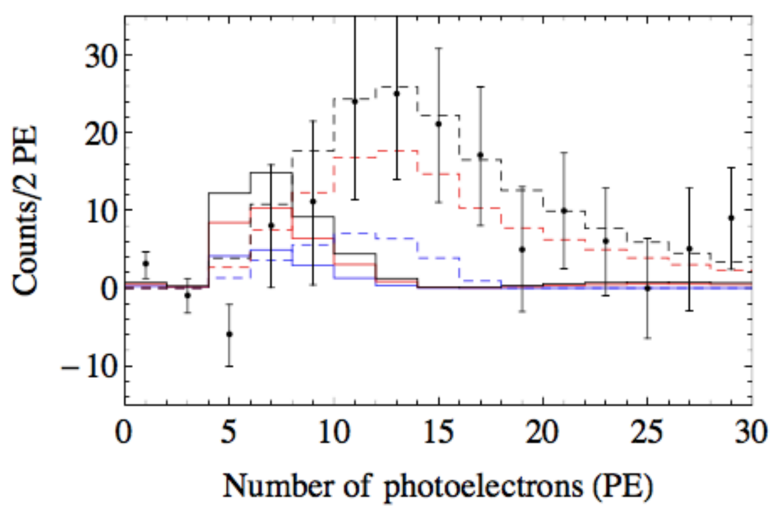
arXiv:1708.04255

SM weak charge

Effective weak charge in presence of light vector mediator Z'

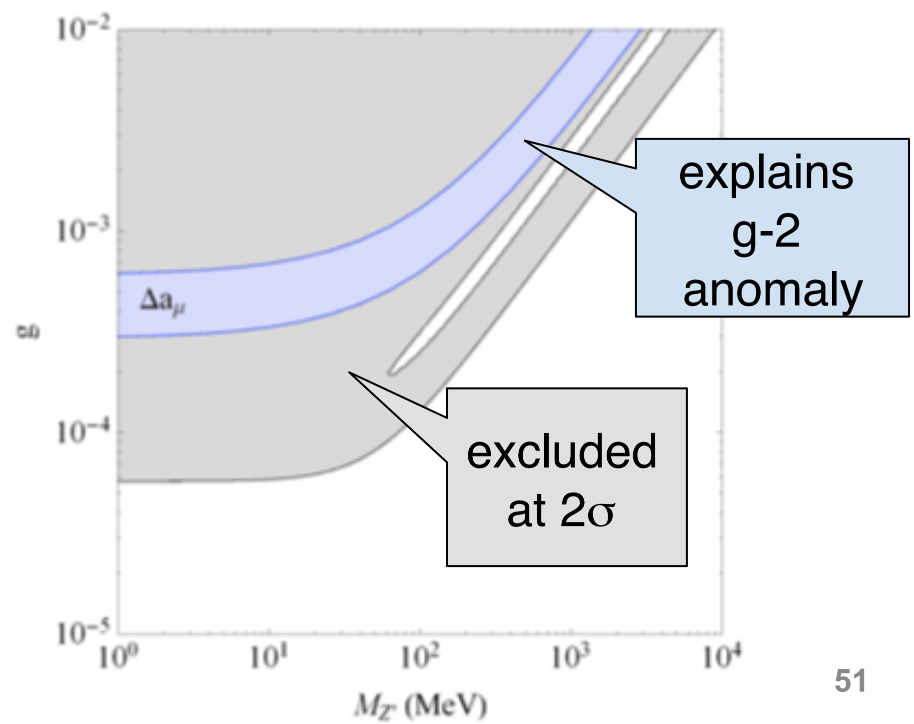
$$Q^2_{\alpha,\mathrm{SM}} = (Z g_p^V + N g_n^V)^2 \;\Rightarrow\; Q^2_{\alpha,\mathrm{NSI}} = \left[Z\left(g_p^V + \frac{3g^2}{2\sqrt{2}G_F(Q^2+M_{Z'}^2)}\right) + N\left(g_n^V + \frac{3g^2}{2\sqrt{2}G_F(Q^2+M_{Z'}^2)}\right)\right]^2$$

- Q^2-dependence ➔ *affects recoil spectrum*
- 2 parameters: g, $M_{Z'}$



Dashed: SM
Solid: NSI w/ $M_{Z'}$ = 10 MeV, $g=10^{-4}$

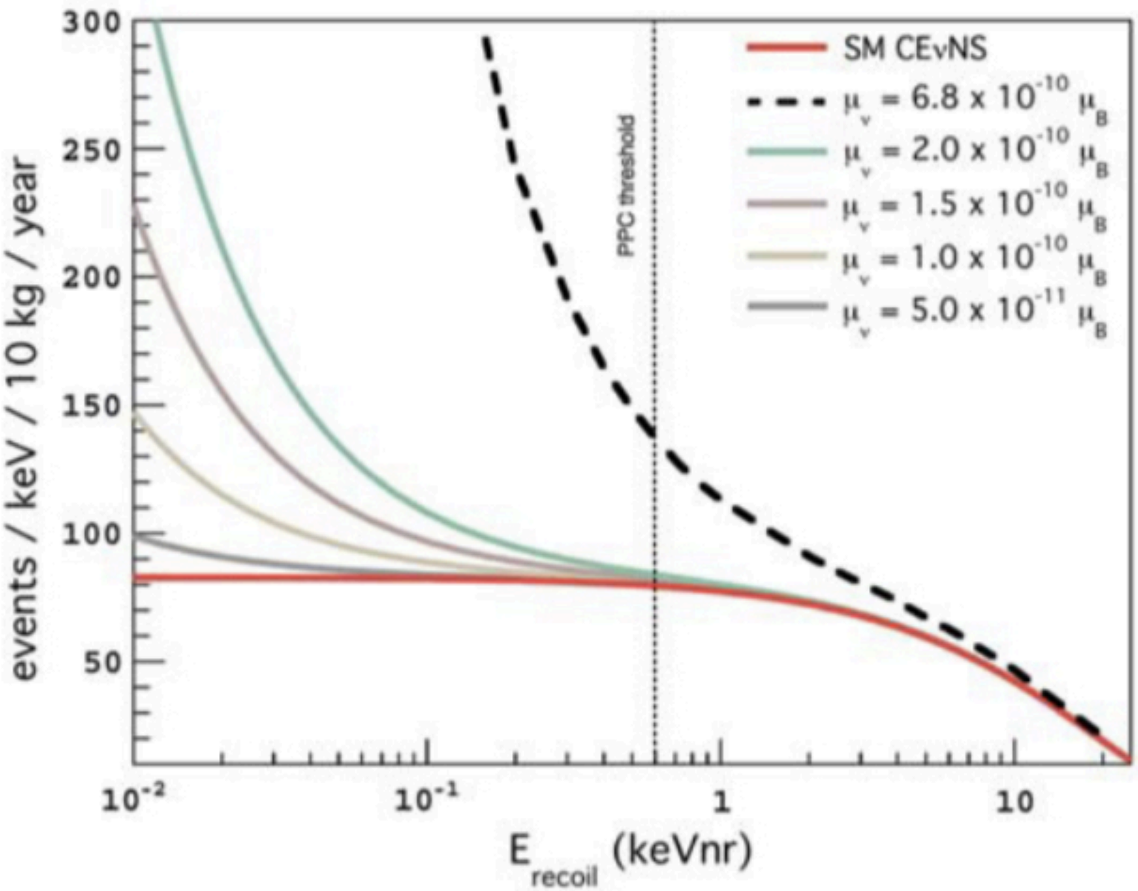
Blue: ν_μ
Red: $\nu_\mu + \nu_\mu$_bar
Black: $\nu_\mu + \nu_\mu$_bar + ν_e



Neutrino magnetic moment

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

$$\left(\frac{d\sigma}{dT}\right)_m = \frac{\pi\alpha^2\mu_\nu^2 Z^2}{m_e^2}\left(\frac{1-T/E_\nu}{T}+\frac{T}{4E_\nu^2}\right)$$



➔requires very low energy threshold (i.e., Ge)

See also Kosmas et al., arXiv:1505.03202

More in Juan's talk

Nuclear physics with CEvNS

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

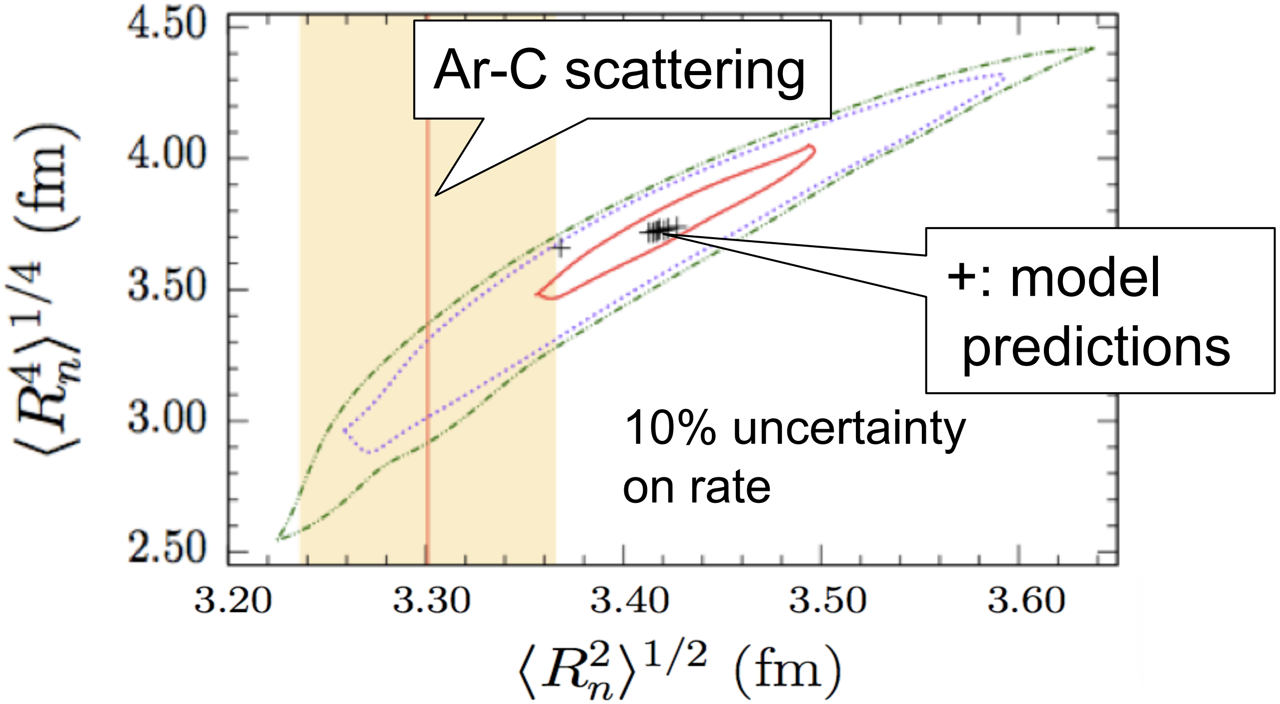
K. Patton et al., PRC86 (2012) 024612

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{2\pi}\frac{Q_W^2}{4}F^2(Q)\left(2 - \frac{MT}{E_\nu^2}\right)$$

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

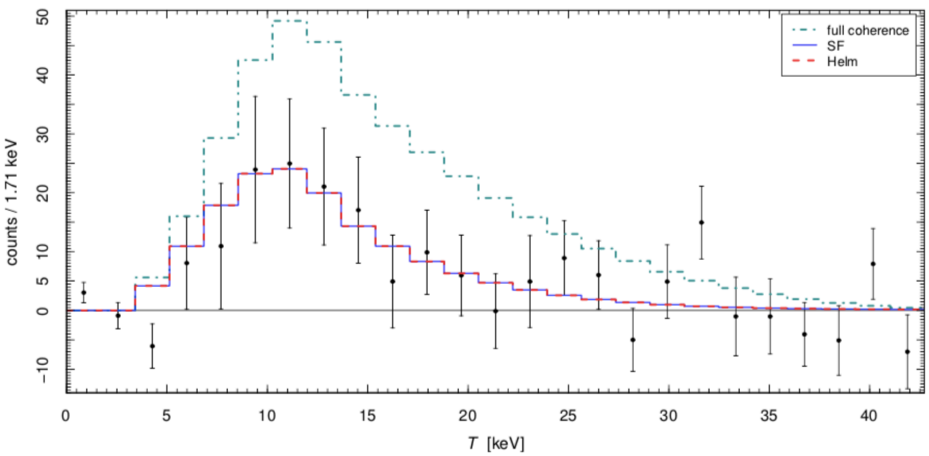
Fit recoil ***spectral shape*** to determine the $F^2(Q)$ moments
(requires very good energy resolution,good systematics control)

Example:
tonne-scale experiment
at πDAR source



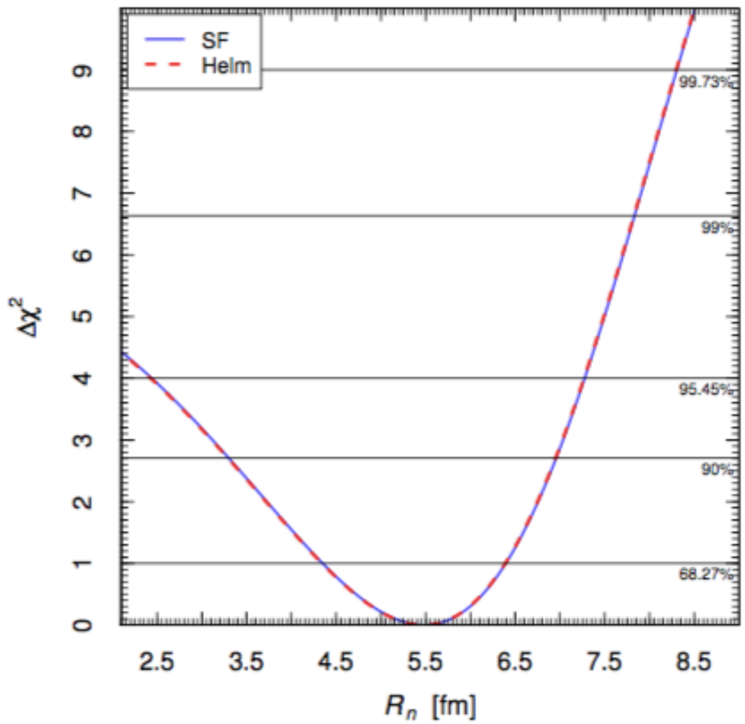
Sensitivity to R_n in the recoil spectrum shape

M. Cadeddu, C. Giunti, Y. F. Li, and Y. Y. Zhang. "Average CsI neutron density distribution from COHERENT data." (2017). 1710.02730.



$$F_N^{\rm Helm}(q^2) = 3\,\frac{j_1(qR_0)}{qR_0}\,e^{-q^2s^2/2},$$

$$R_n = 5.5^{+0.9}_{-1.1}\ \text{fm}. \qquad \Delta R_{np} \simeq 0.7^{+0.9}_{-1.1}\ \text{fm}.$$



- Fit to neutron radius w/ ~18% uncertainty, but does not handle bin-by-bin correlation of systematics
- Also some info on neutron skin

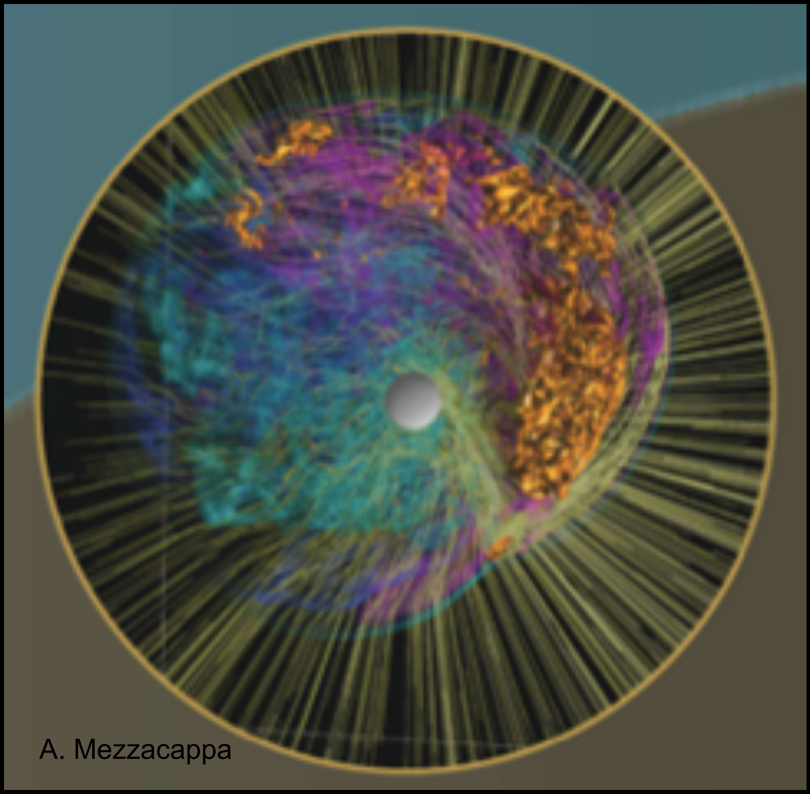
More in Rex's talk

Neutrinos from core-collapse supernovae

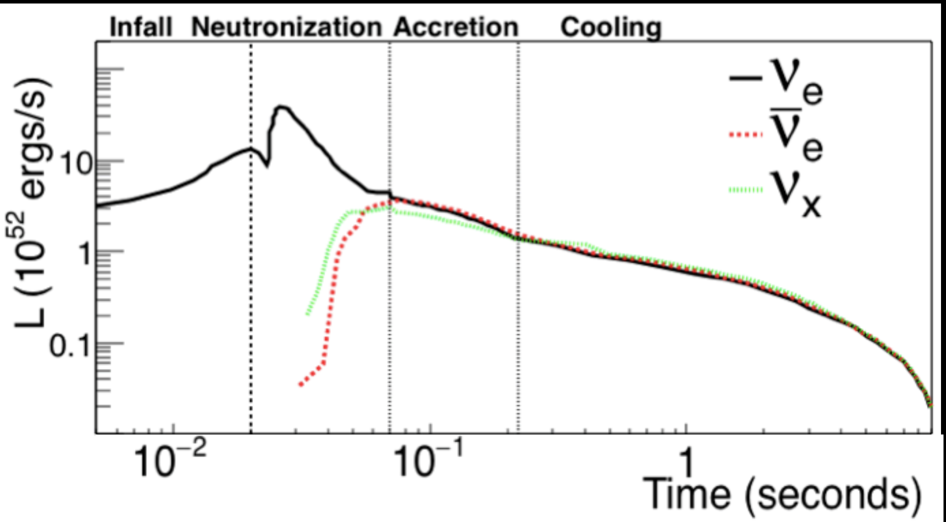
When a star's core collapses, ~99% of the gravitational binding energy of the proto-nstar goes into ν's of ***all flavors*** with ~tens-of-MeV energies

(Energy *can* escape via ν's)

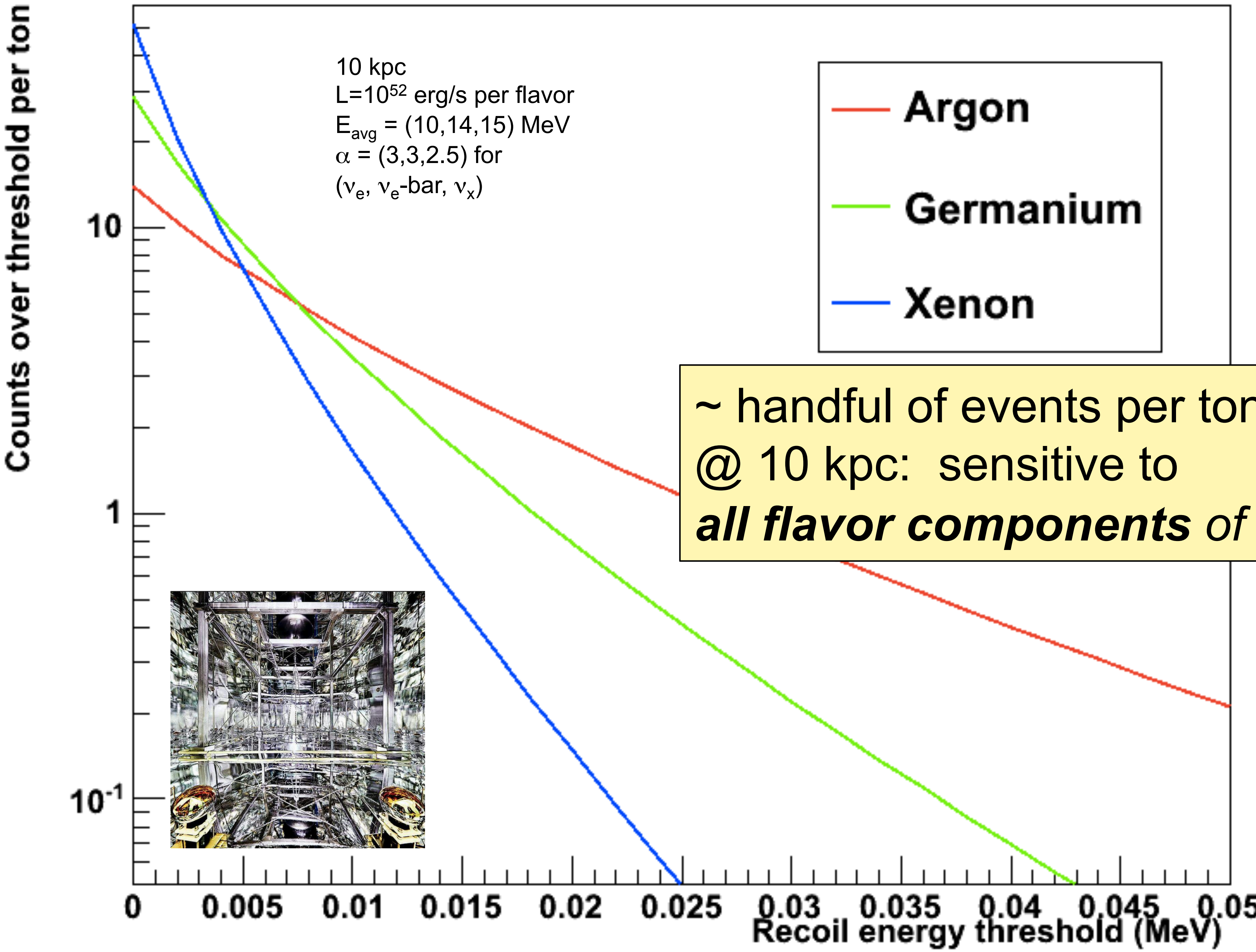
Mostly ν-$\bar{\nu}$ pairs from proto-nstar cooling



Timescale: *prompt* after core collapse, overall Δt~10's of seconds



Supernova neutrinos in tonne-scale DM detectors



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