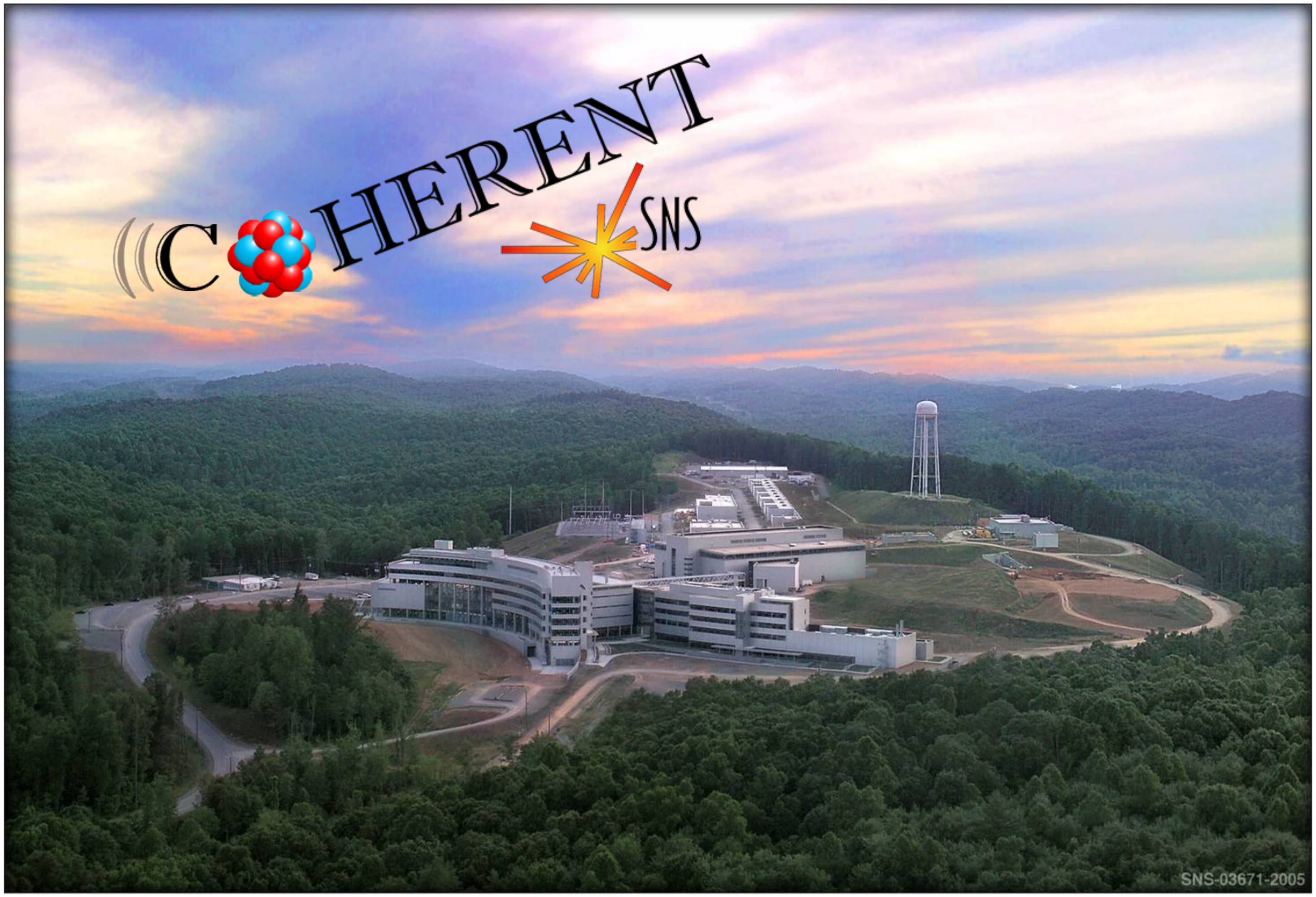
Observation of

Coherent Elastic Neutrino-Nucleus Scattering

by COHERENT



Kate Scholberg, Duke University

Gora

January 8, 2018

OUTLINE

-Coherent elastic neutrino-nucleus scattering
(CEvNS)

- Why measure it? Physics motivations
  (short and long term)
- How to measure CEvNS
- The COHERENT experiment at the SNS
- **First light** with CsI[Tl]
- Status and prospects for COHERENT

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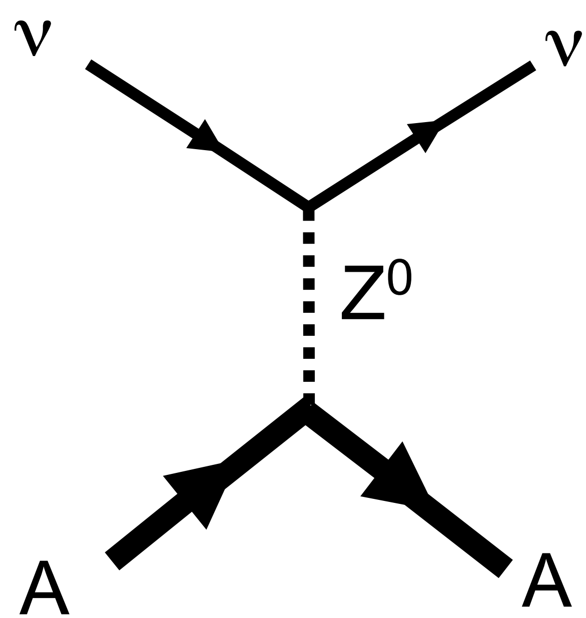
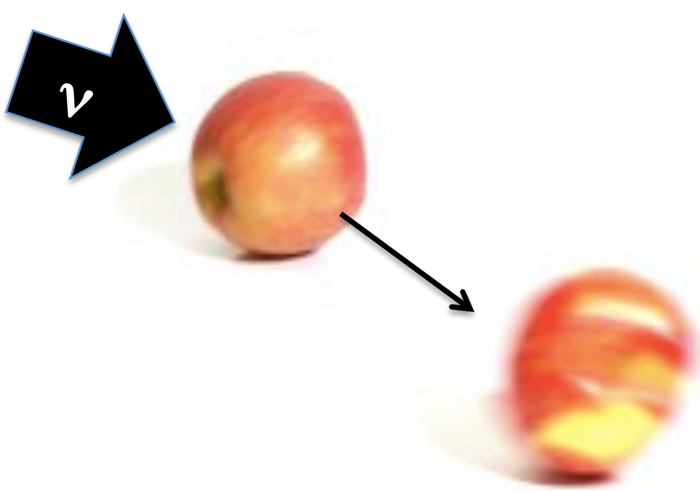
Coherent elastic neutrino-nucleus scattering (CEvNS)

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

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





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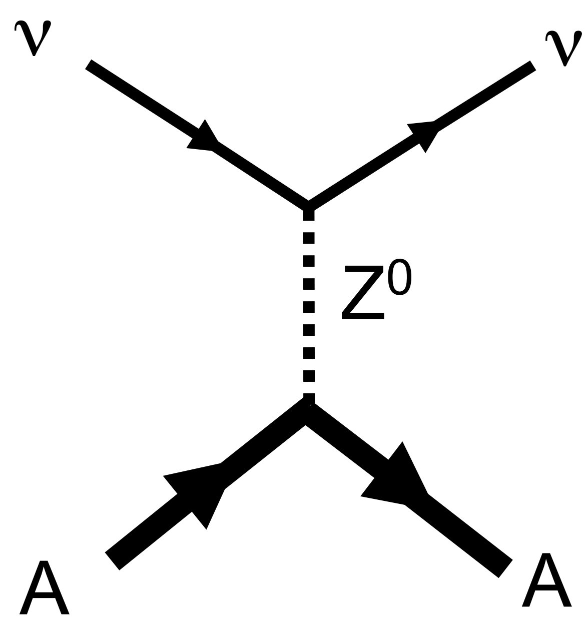
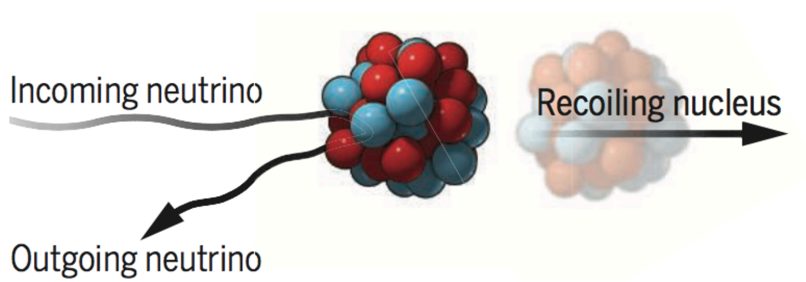


A neutrino smacks a nucleus via exchange of a Z, and the nucleus recoils as a whole; **coherent** up to E_ν~ 50 MeV

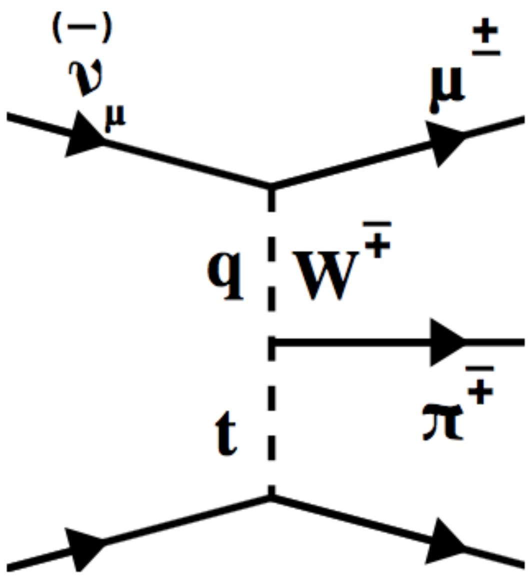


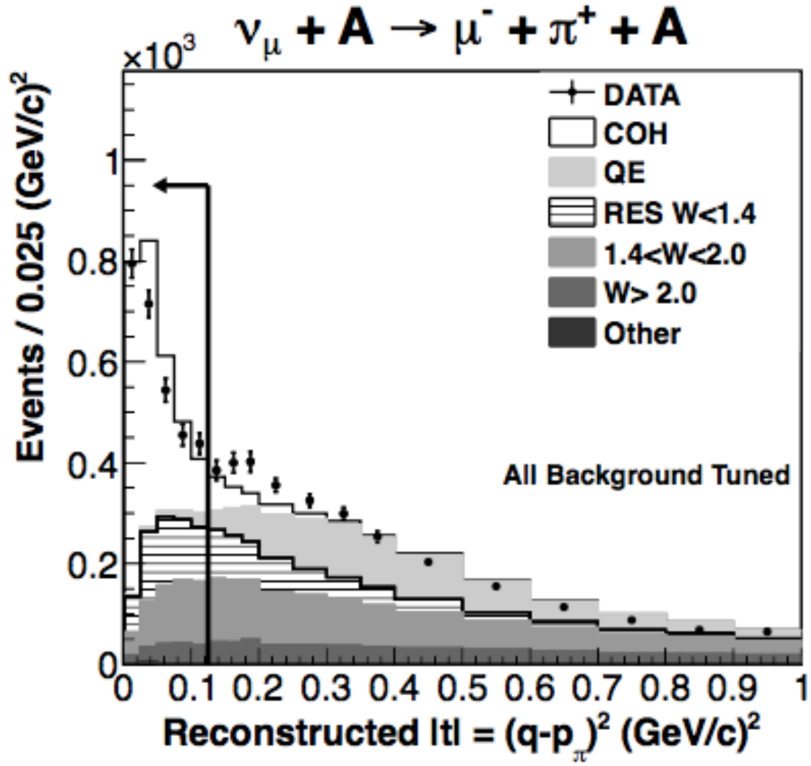
Nucleon wavefunctions in the target nucleus are **in phase with each other** at low momentum transfer

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

Image: J. Link *Science* Perspectives

This is ***not*** coherent pion production,
a strong interaction process ***(inelastic)***





A. Higuera et. al, MINERvA collaboration,
PRL 2014 113 (26) 2477

not
THAT!

\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 43 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.

Early theory explorations & proposals

Progress of Theoretical Physics, Vol. 54, No. 5, November 1975

Supernova Explosion and Neutral Currents of Weak Interaction

Katsuhiko SATO

Research Institute for Fundamental Physics
Kyoto University, Kyoto

(Received May 12, 1975)

Ann. Rev. Nucl. Sci. 1977. 27: 167–207

THE WEAK NEUTRAL CURRENT AND ITS EFFECTS IN STELLAR COLLAPSE

Daniel Z. Freedman
Institute for Theoretical Physics, State University of New York at Stony Brook, Stony Brook, New York 11790

David N. Schramm[1] *and David L. Tubbs*[2]
Enrico Fermi Institute (LASR), University of Chicago, Chicago, Illinois 60637

PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1984

Principles and applications of a neutral-current detector for neutrino physics and astronomy

A. Drukier and L. Stodolsky
Max-Planck-Institut für Physik und Astrophysik, Werner-Heisenberg-Institut für Physik, Munich, Federal Republic of Germany
(Received 21 November 1983)

Physics Letters B 269 (1991) 407–411

Low-energy neutrino detection and precision tests of the standard model

Lawrence M. Krauss [1,2]
Center for Theoretical Physics and Department of Astronomy, Sloane Laboratory, Yale University, New Haven, CT 06511, USA

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 = √ (2 M T): 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

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

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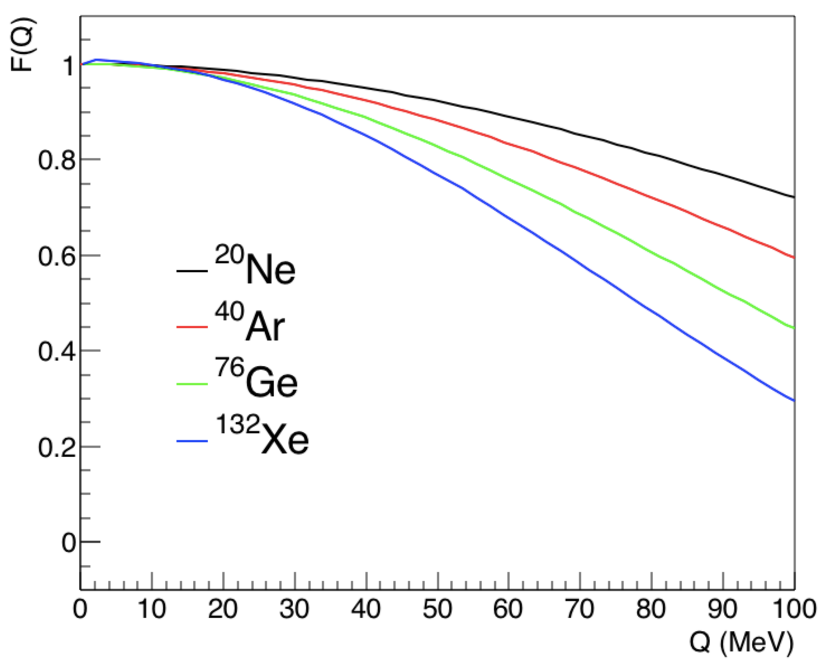
E_ν: neutrino energy
T: nuclear recoil energy
M: nuclear mass
$Q = \sqrt{(2MT)}$: momentum transfer

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



form factor suppresses cross section at large Q

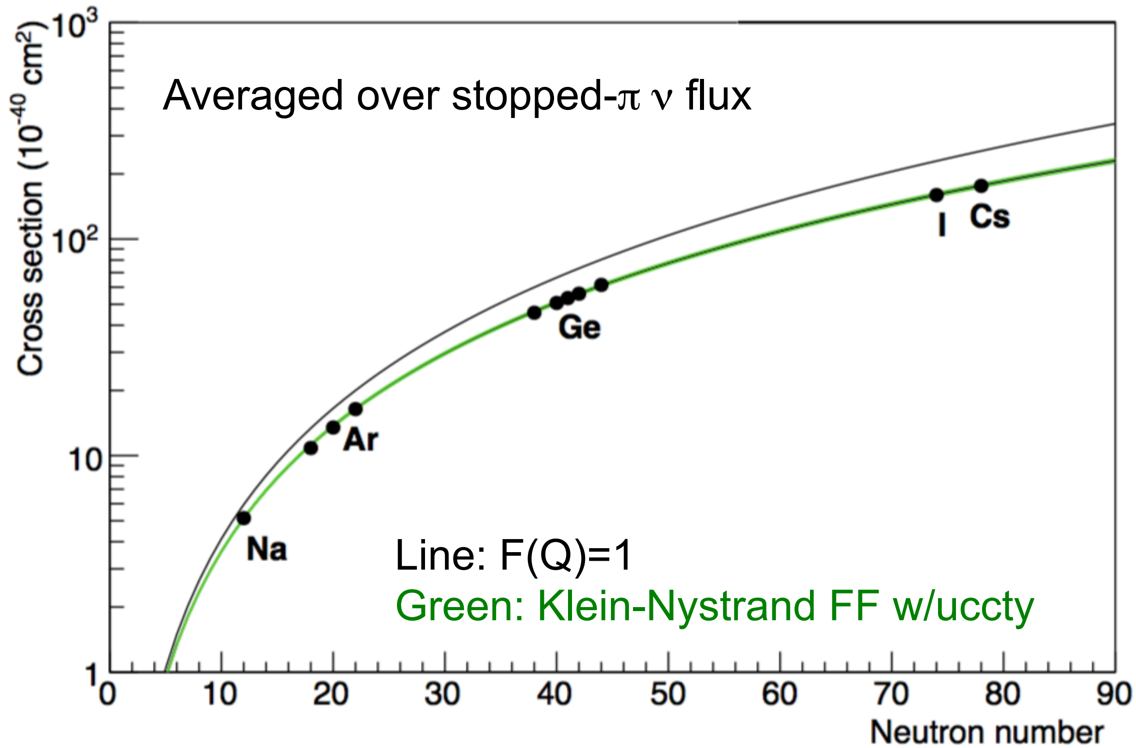
For T<<E_ν, neglecting axial terms:

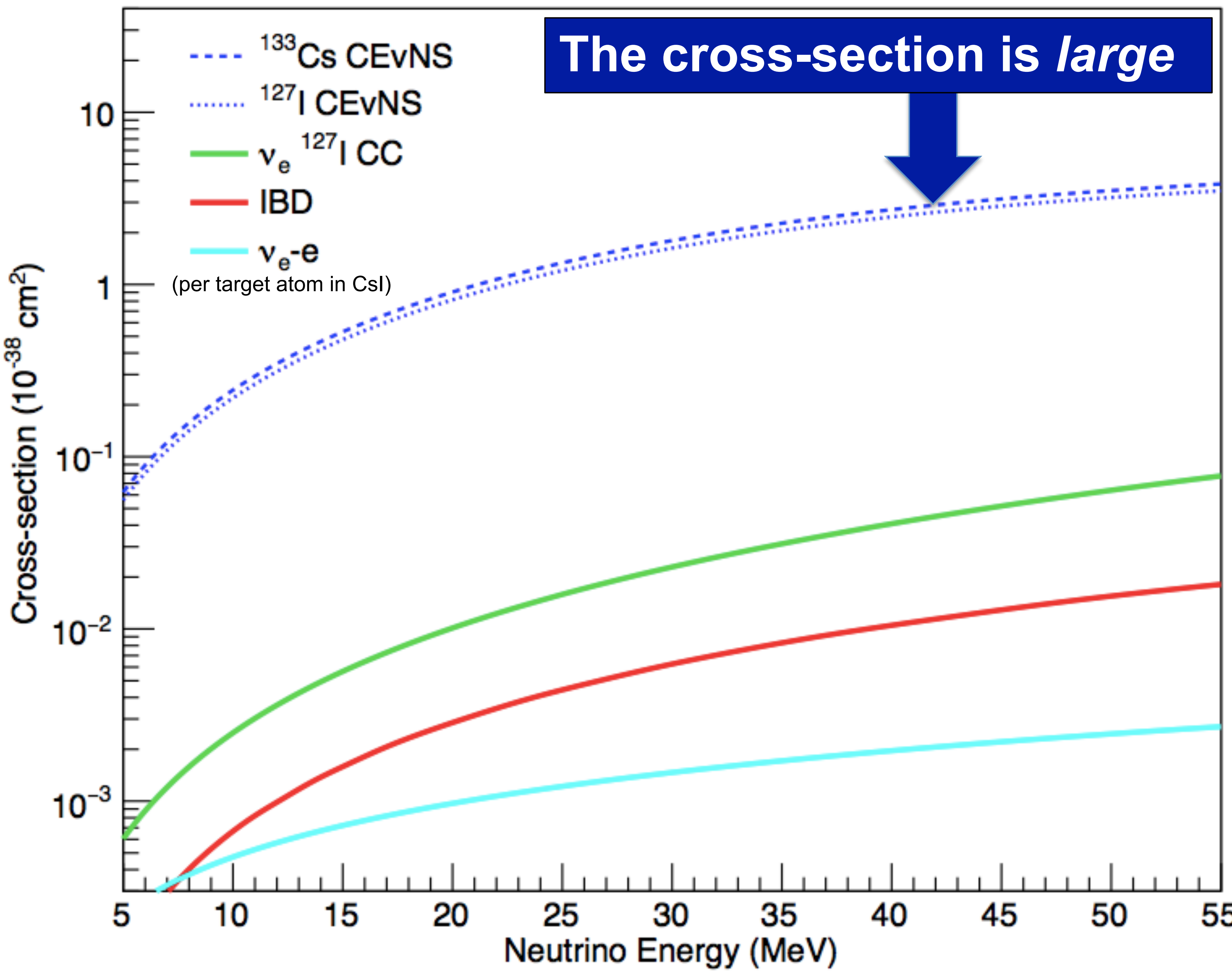
$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{2\pi} \frac{Q_W^2}{4} F^2(Q) \left(2 - \frac{MT}{E_\nu^2}\right)$$

$$Q_W = N - (1 - 4\sin^2\theta_W) Z$$: weak nuclear charge

$\sin^2\theta_W = 0.231$,
so protons unimportant

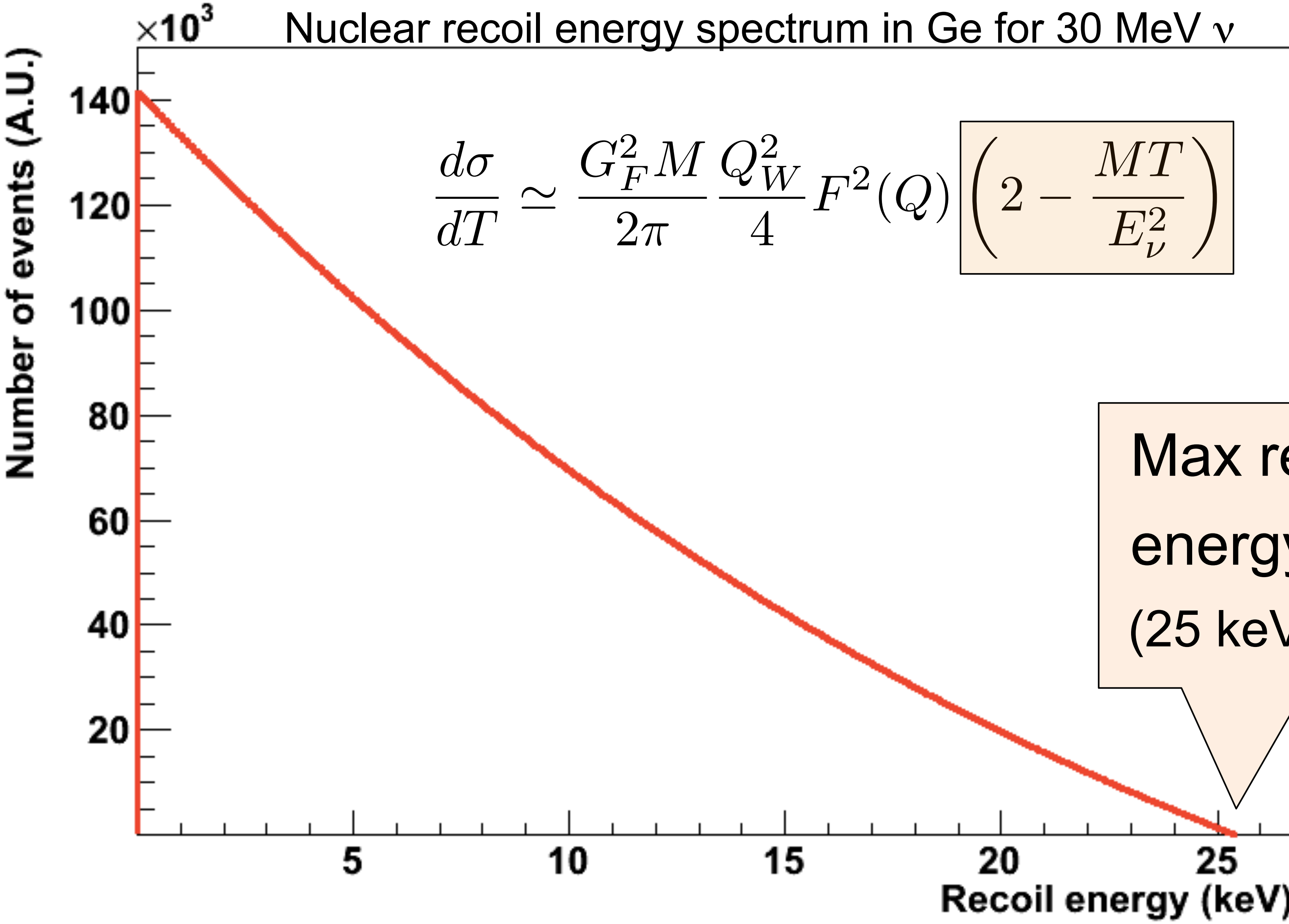
$$\Rightarrow \frac{d\sigma}{dT} \propto N^2$$





The cross-section is *large*
^{133}Cs CEvNS
^{127}I CEvNS
ν_e ^{127}I CC
IBD
ν_e-e
(per target atom in CsI)
Cross-section (10^{-38} cm^2)
10
1
10^{-1}
10^{-2}
10^{-3}
5
10
15
20
25
30
35
40
45
50
55
Neutrino Energy (MeV)

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

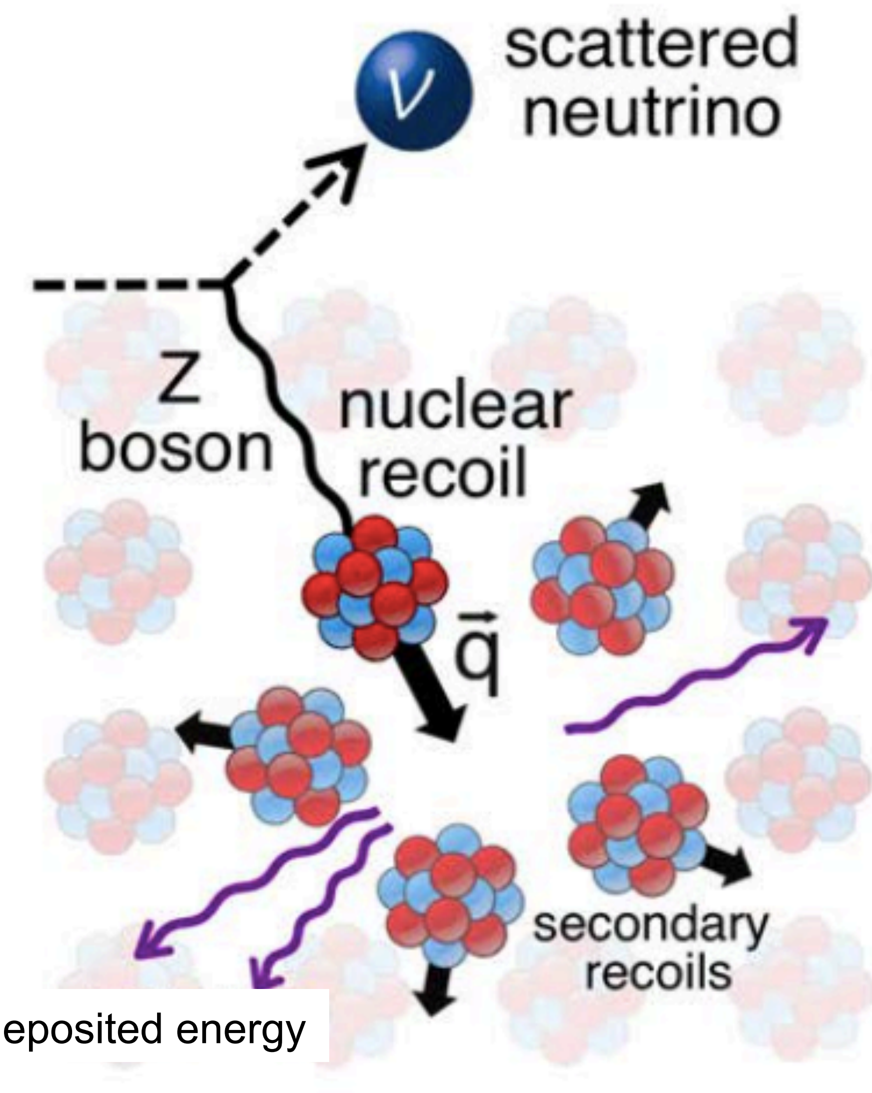


$$\frac{d\sigma}{dT} \simeq \frac{G_F^2 M}{2\pi} \frac{Q_W^2}{4} F^2(Q) \left(2 - \frac{MT}{E_\nu^2}\right)$$

Max recoil energy is $2E_\nu^2/M$ (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

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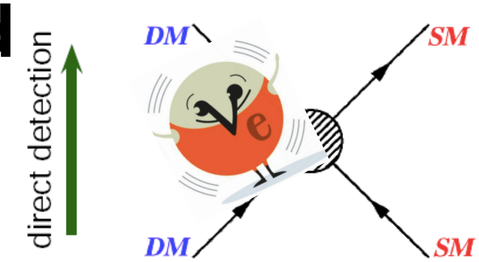
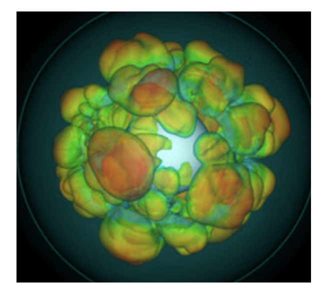
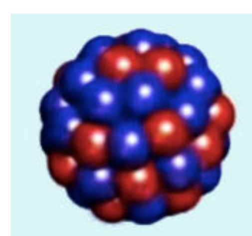
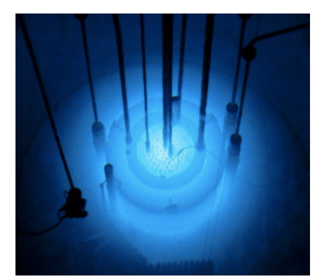
CEvNS: what's it good for? ① So ② Many ③ Things ! (not a complete list!)

- **Dark matter direct-detection background**
- Well-calculable cross section in SM:
  - $\sin^2\theta_{Weff}$ at low Q
  - **Probe of Beyond-the-SM physics**
    - Non-standard interactions of neutrinos
    - New NC mediators
    - Neutrino magnetic moment
- New tool for sterile neutrino oscillations
- **Astrophysical signals (solar & SN)**
- Supernova processes
- Nuclear physics:
  - Neutron form factors
  - g_A quenching
- Possible applications (reactor monitoring)





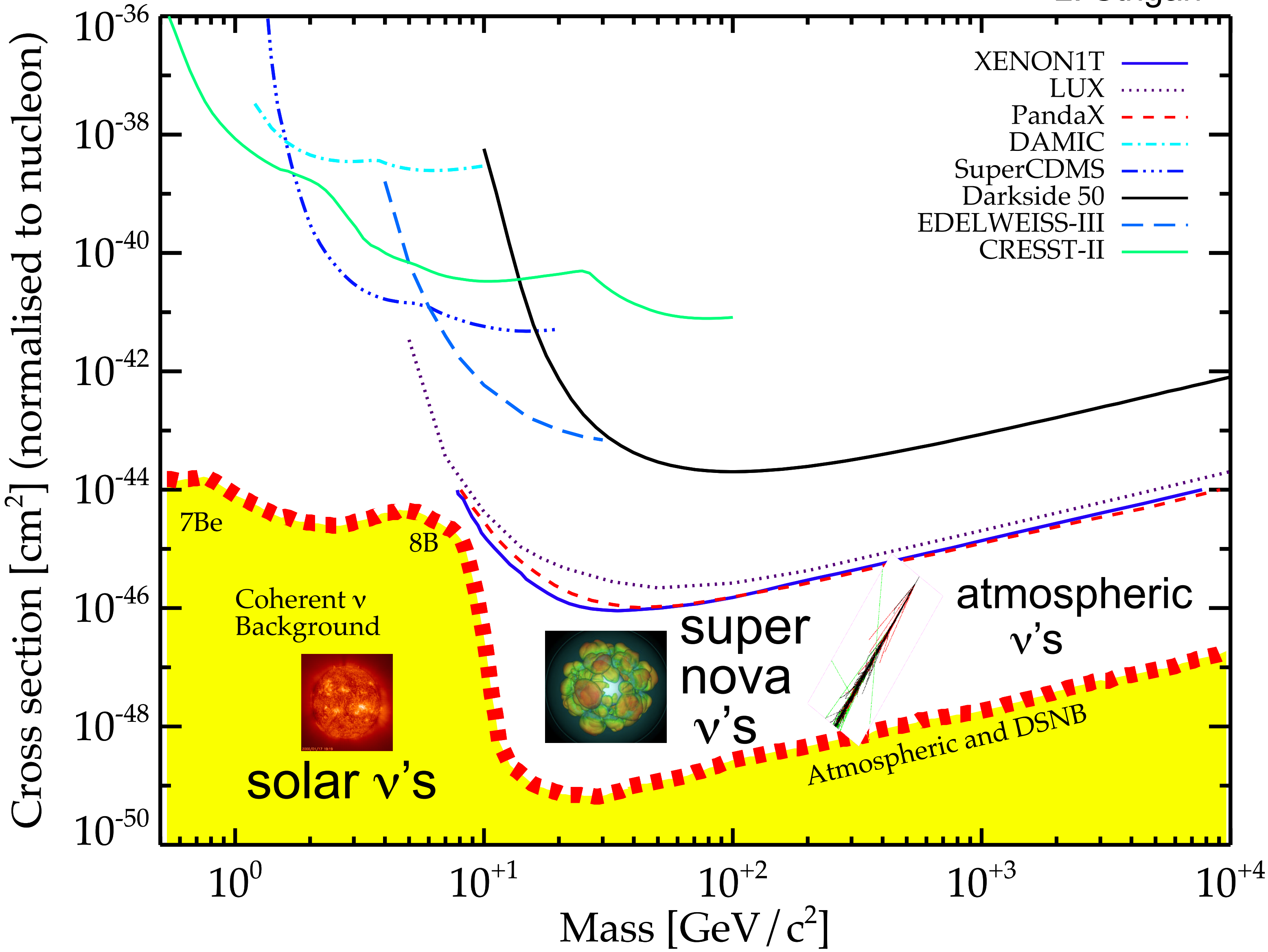




The so-called “neutrino floor” (**signal!**) for DM experiments

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

L. Strigari

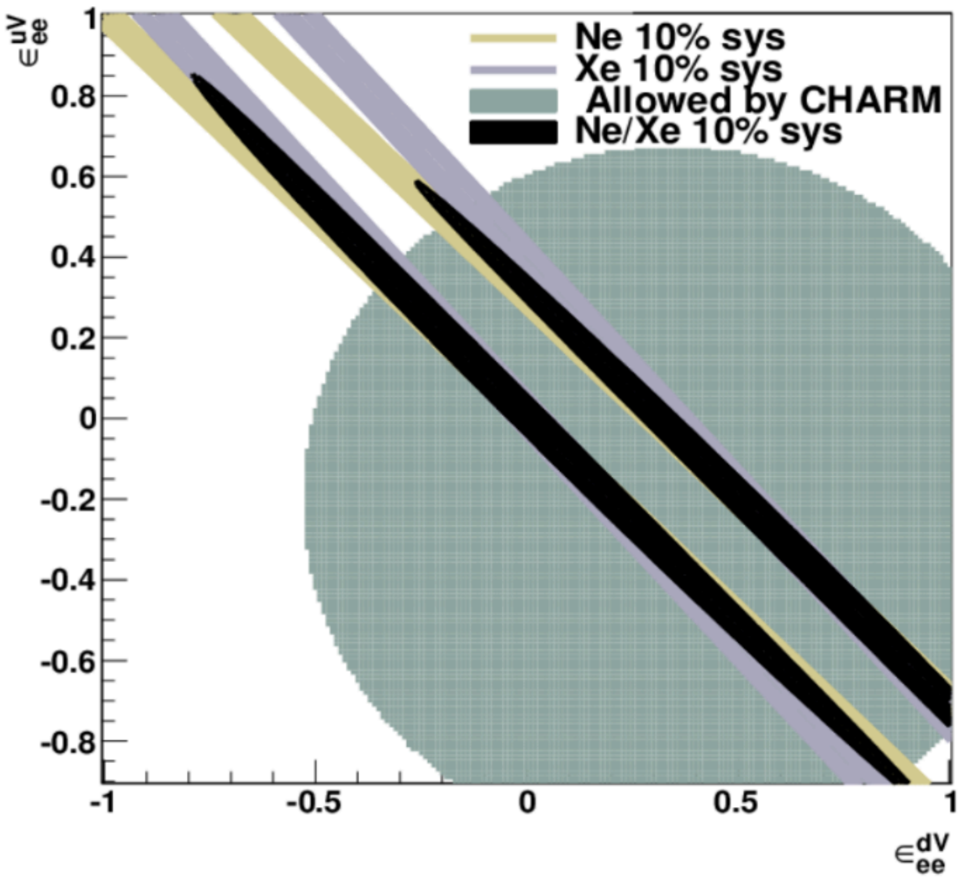


Measure CEvNS to understand nature of background/astro signal
(& detector response, DM interaction)

Non-Standard Interactions of Neutrinos:

new interaction **specific to ν's**

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



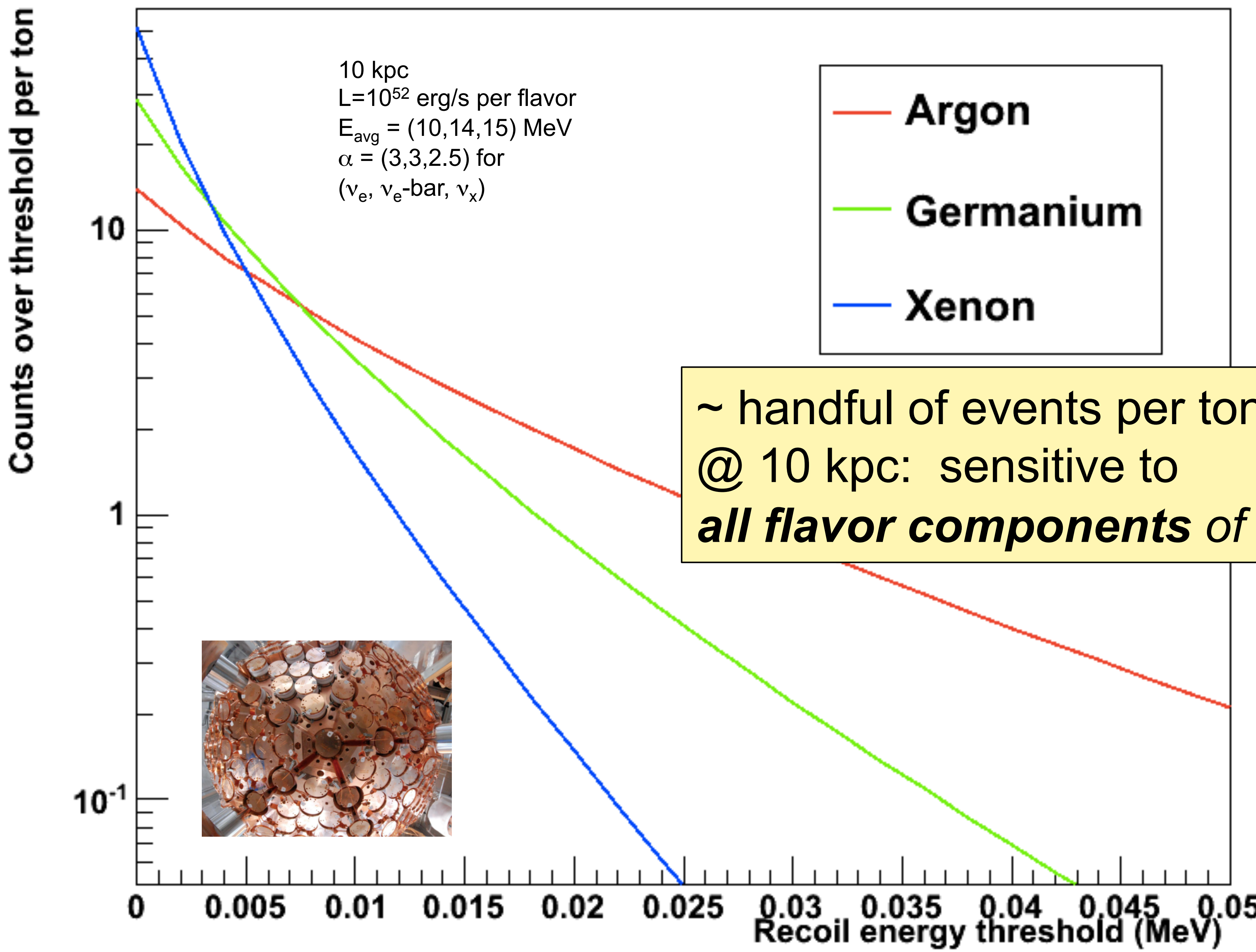
If these ε's are ~unity, there is a new interaction of ~Standard-model size... many not currently well constrained

J. Barranco et al., JHEP 0512 (2005), K. Scholberg, PRD73, 033005 (2006), 021

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

More studies: see https://sites.duke.edu/nueclipse/files/2017/04/Dent-James-NuEclipse-August-2017.pdf

Supernova neutrinos in tonne-scale DM detectors



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

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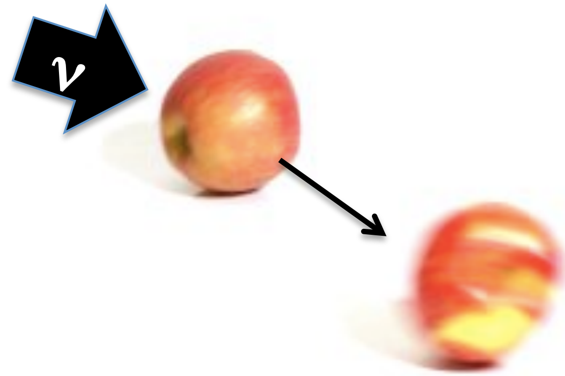
How to detect CEvNS?

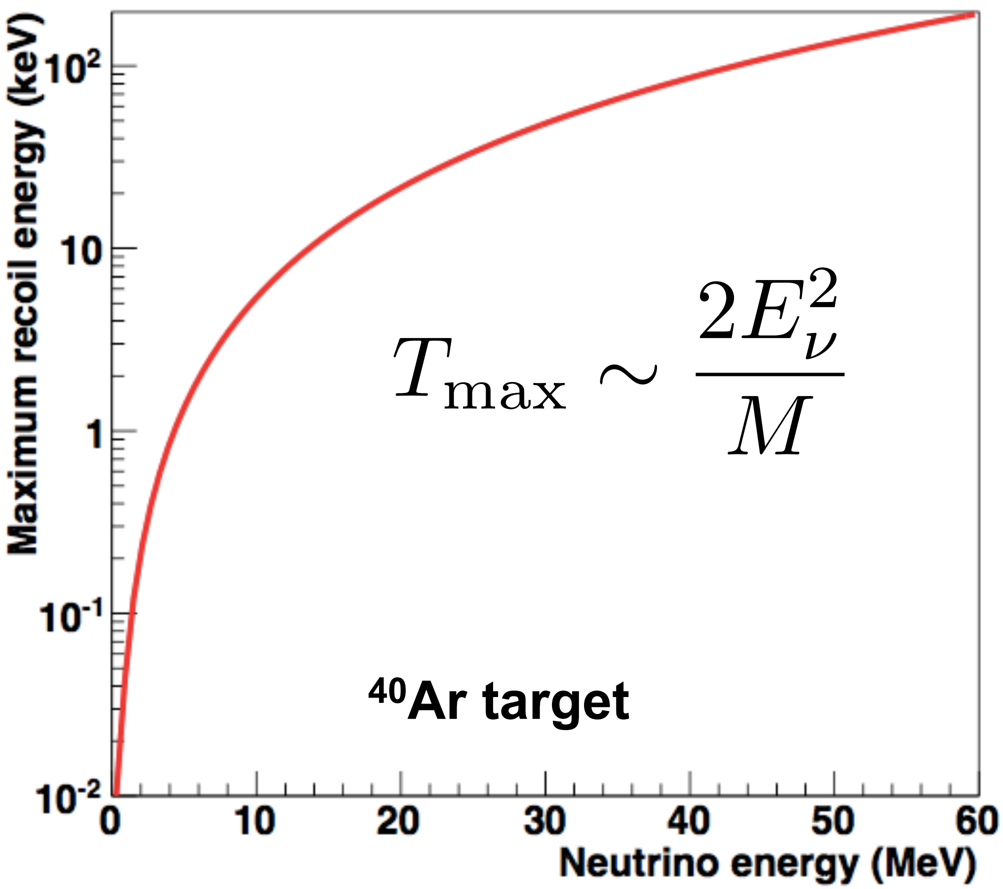


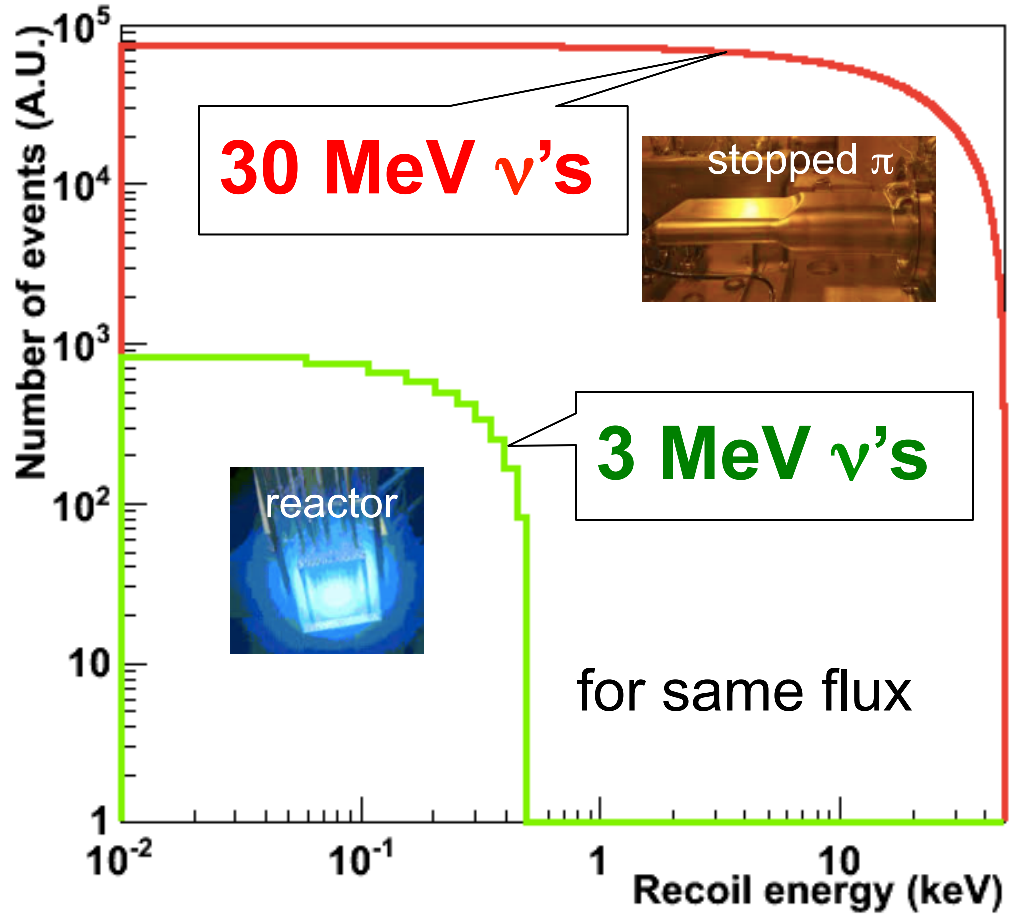
You need a neutrino source and a detector

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, ...

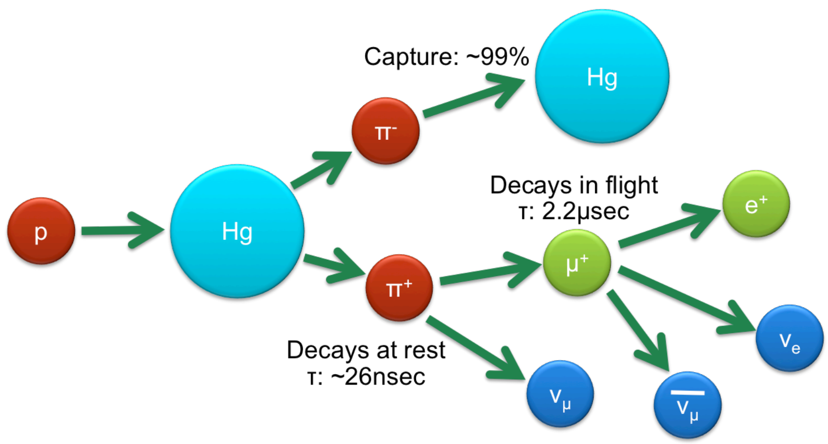
Both **cross-section** and **maximum recoil energy increase with neutrino energy**:

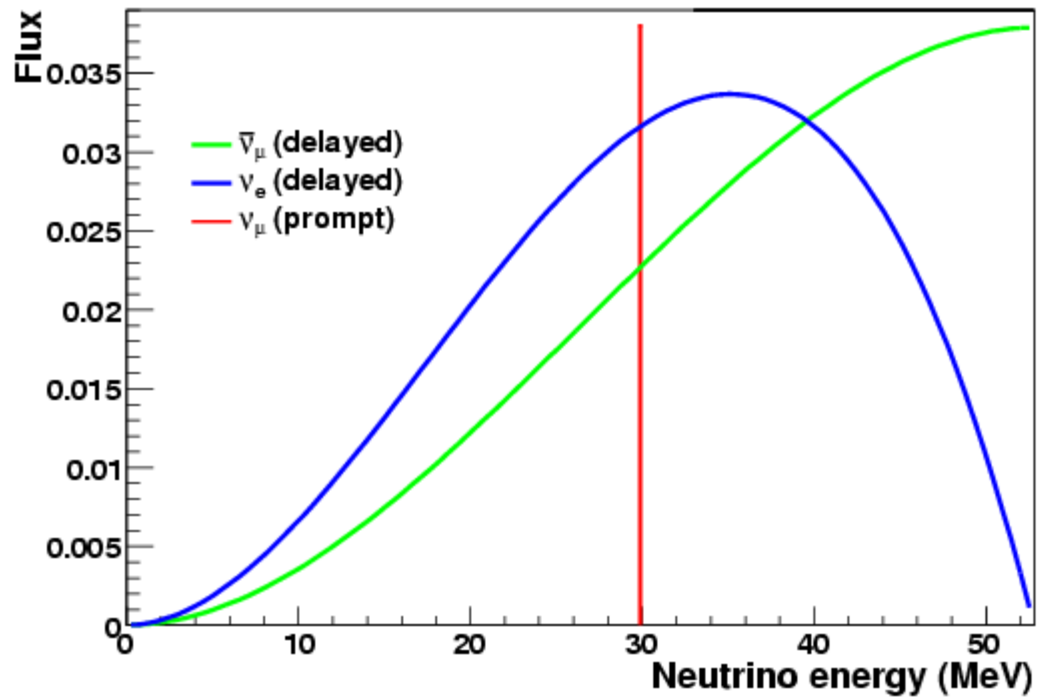




Want energy as large as possible while satisfying coherence condition: $Q \lesssim \frac{1}{R}$ (<~ 50 MeV for medium A)

Stopped-Pion (πDAR) Neutrinos





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

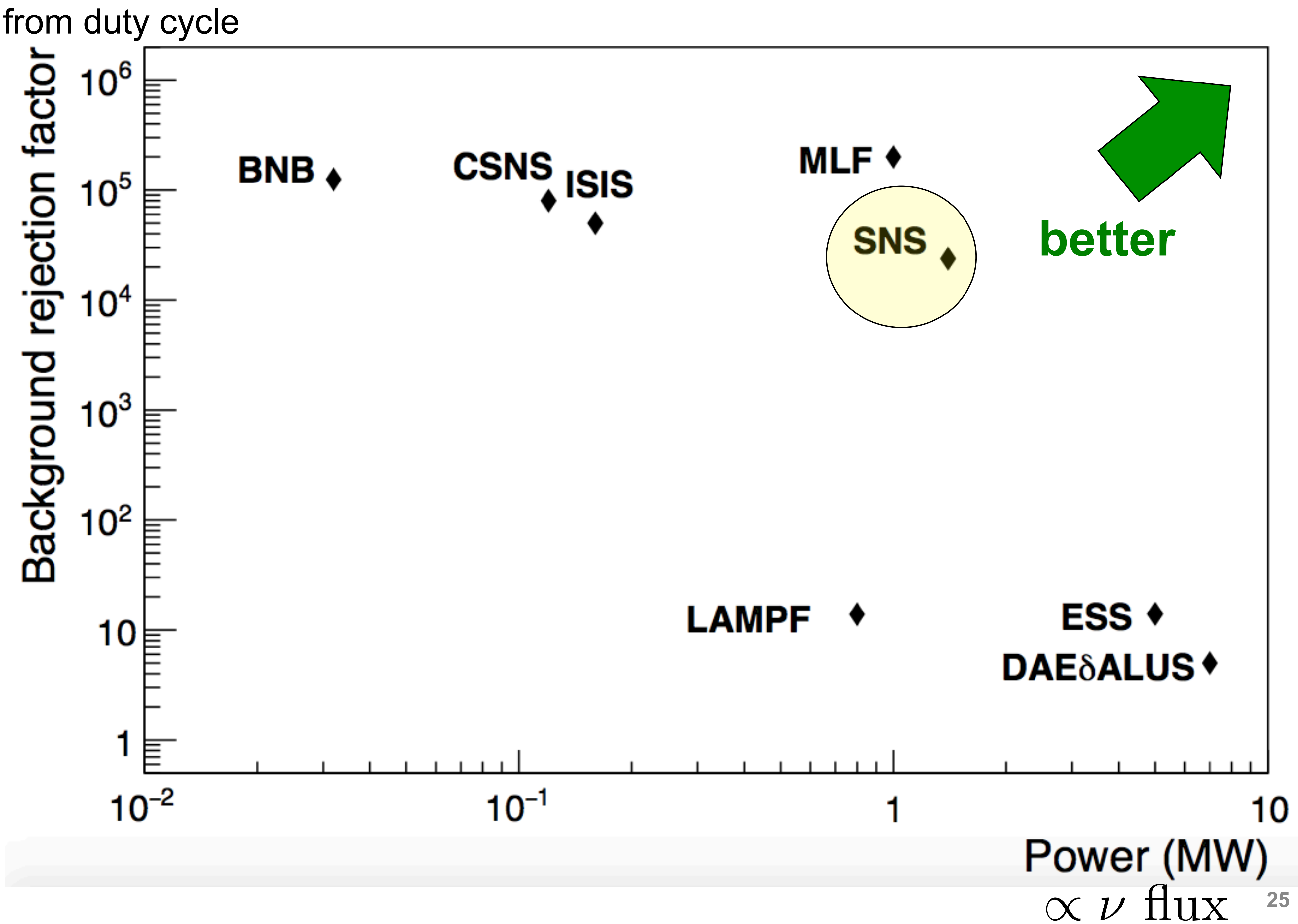
2-body decay: monochromatic 29.9 MeV ν_μ
PROMPT

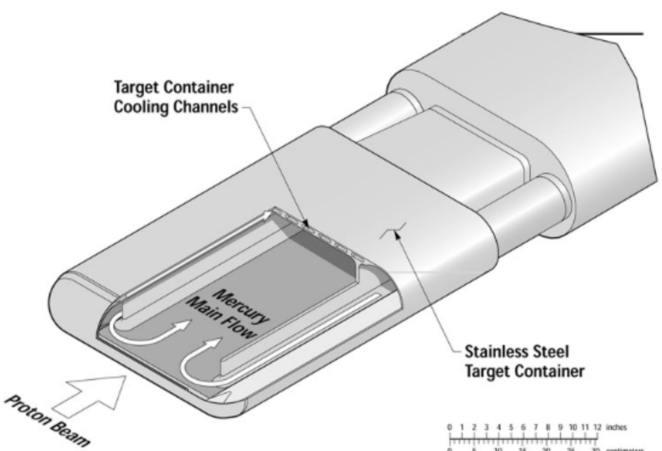
$$\downarrow$$

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

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

Comparison of pion decay-at-rest ν sources



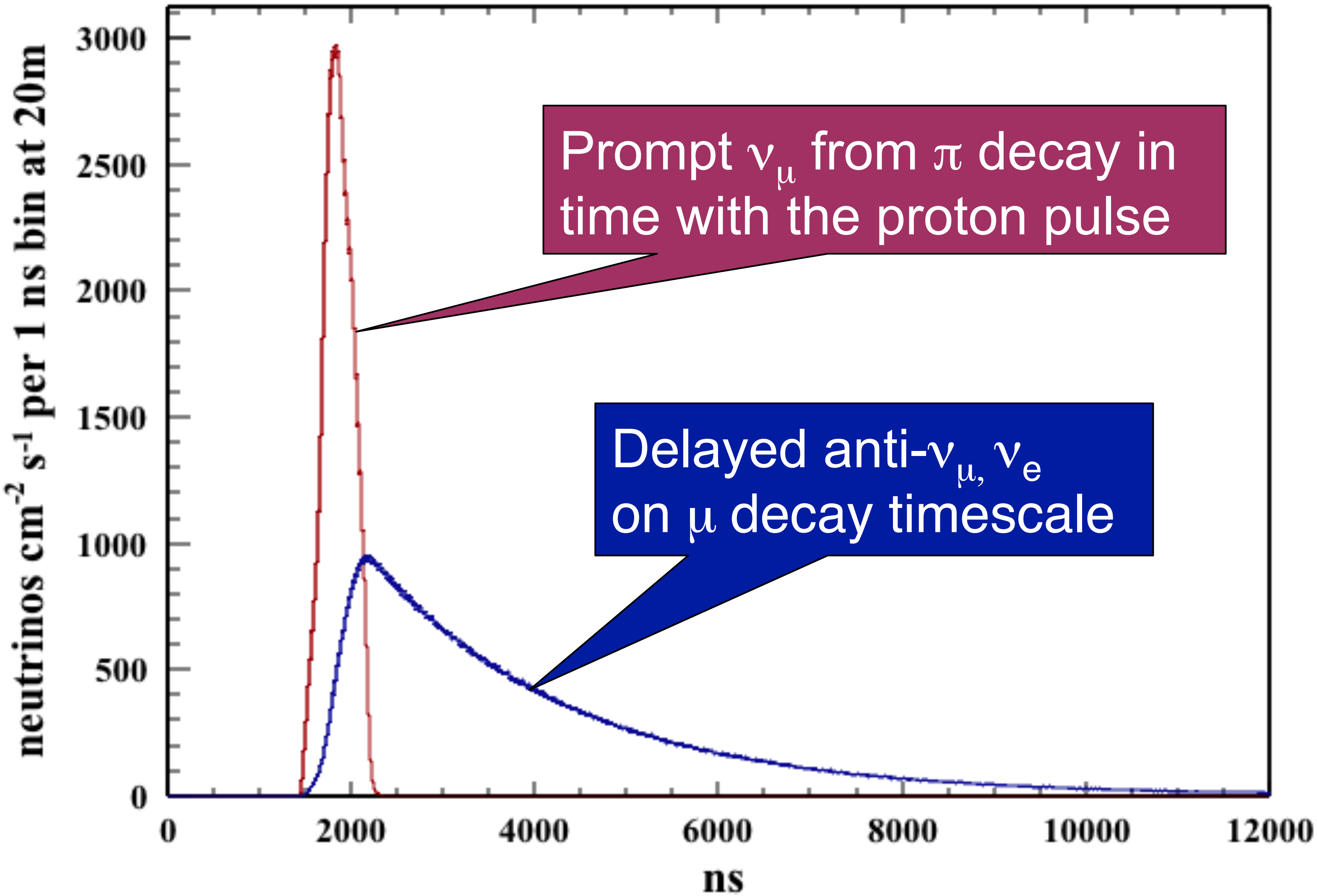


Proton beam energy: 0.9-1.3 GeV
Total power: 0.9-1.4 MW
Pulse duration: 380 ns FWHM
Repetition rate: 60 Hz
Liquid mercury target

The neutrinos are free!

Time structure of the SNS source

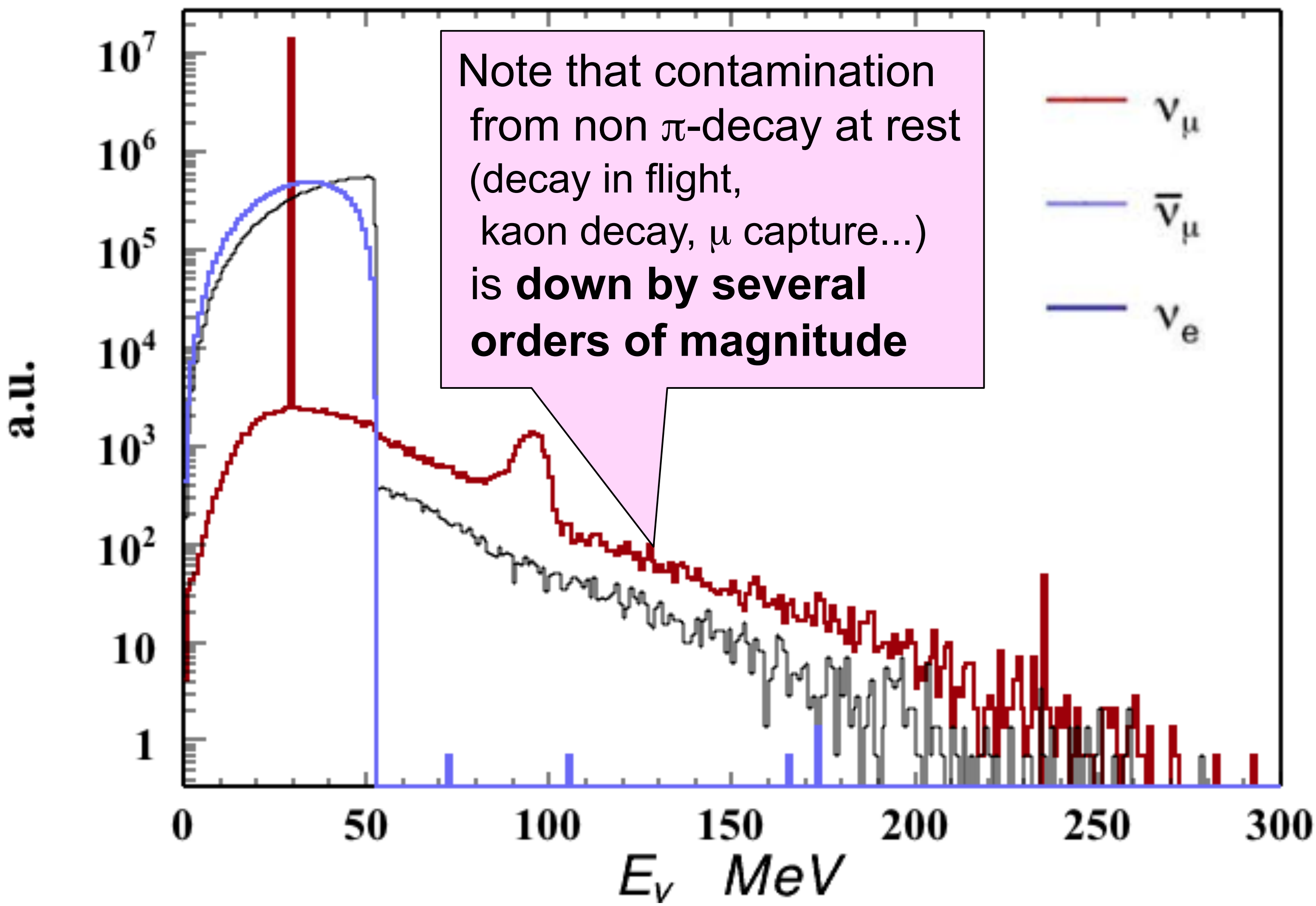
60 Hz *pulsed* source



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

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

0.08 neutrinos per flavor per proton on target



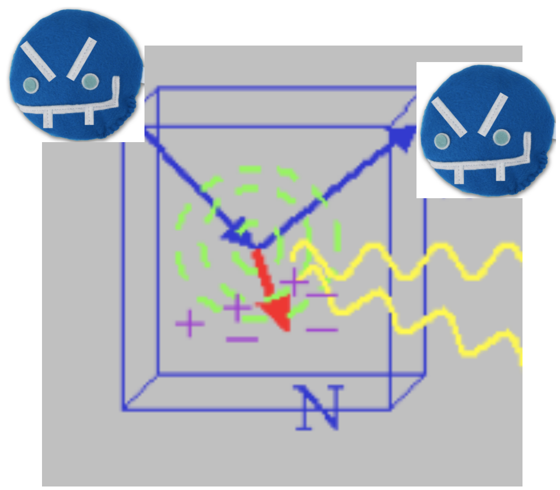
SNS flux (1.4 MW):
430 x 10^5 ν/cm²/s
@ 20 m

Backgrounds

Usual suspects:

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

Neutrons are especially not your 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"

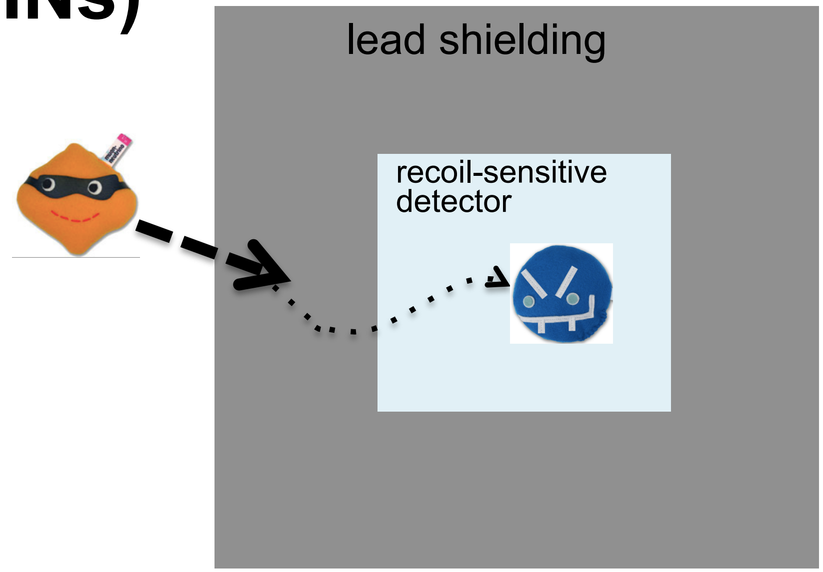
A "friendly fire" in-time background:
Neutrino Induced Neutrons (NINs)

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

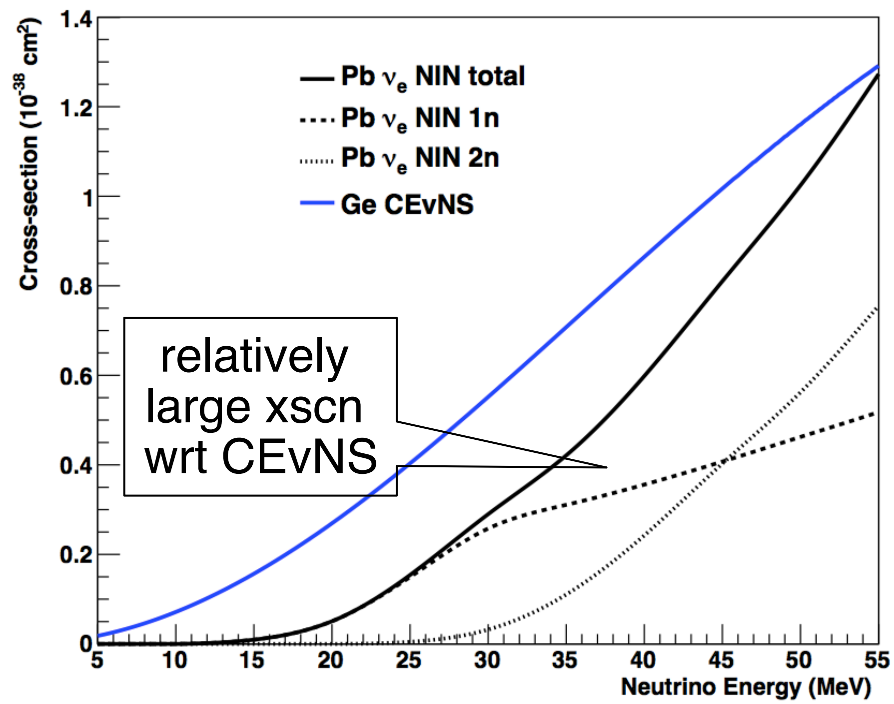
↘ 1n, 2n emission

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

↘ 1n, 2n, γ emission



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



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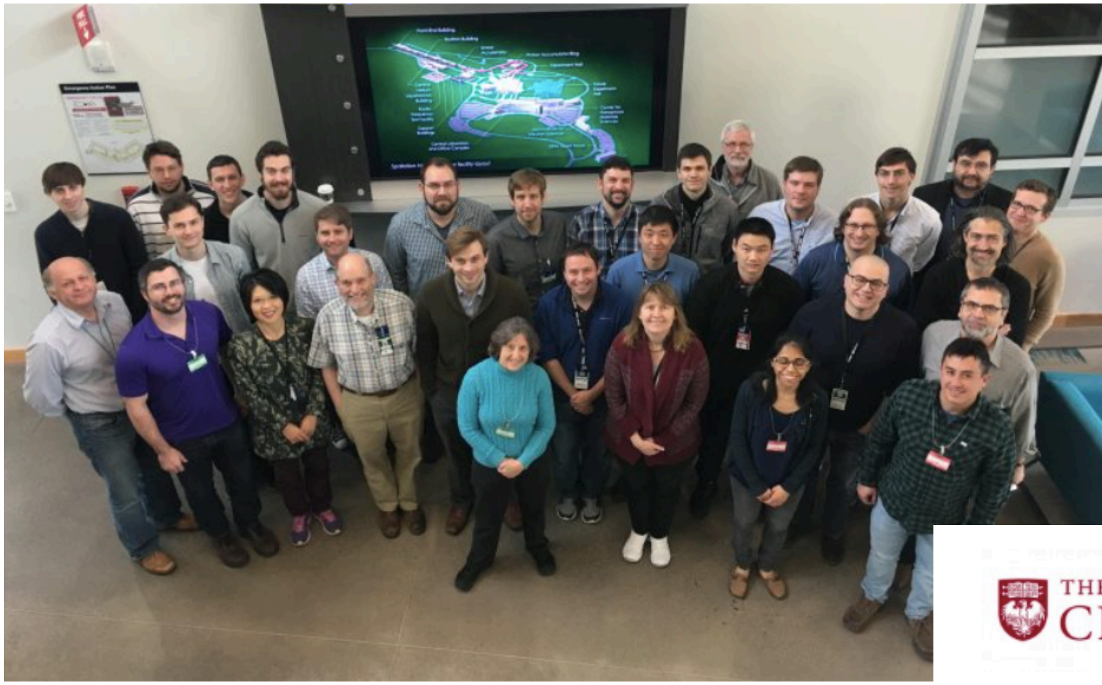
The COHERENT collaboration

http://sites.duke.edu/coherent



COHERENT
SNS SPALLATION NEUTRON SOURCE

~80 members,
19 institutions
4 countries

arXiv:1509.08702

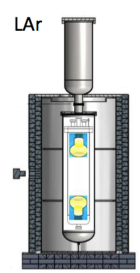
U.S. DEPARTMENT OF ENERGY Office of Science
NSF
KICP
NNSA National Nuclear Security Administration
CNEC

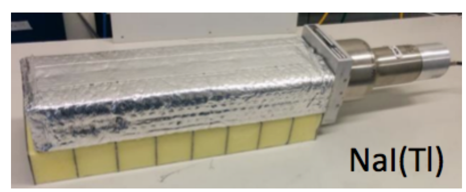
THE UNIVERSITY OF CHICAGO
Duke UNIVERSITY
UF UNIVERSITY of FLORIDA
KAIST
Laurentian University Université Laurentienne
Los Alamos NATIONAL LABORATORY EST. 1943
BERKELEY LAB
MEPhI
NORTH CAROLINA CENTRAL UNIVERSITY
NC STATE UNIVERSITY
NM STATE UNIVERSITY
OAK RIDGE National Laboratory
Carnegie Mellon University
Sandia National Laboratories
THE UNIVERSITY of TENNESSEE KNOXVILLE
TUNL
W UNIVERSITY of WASHINGTON

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	10	22	5
LAr	Single-phase flash	22	29	20
NaI[Tl]	Scintillating crystal flash	185*/ 2000	28	13

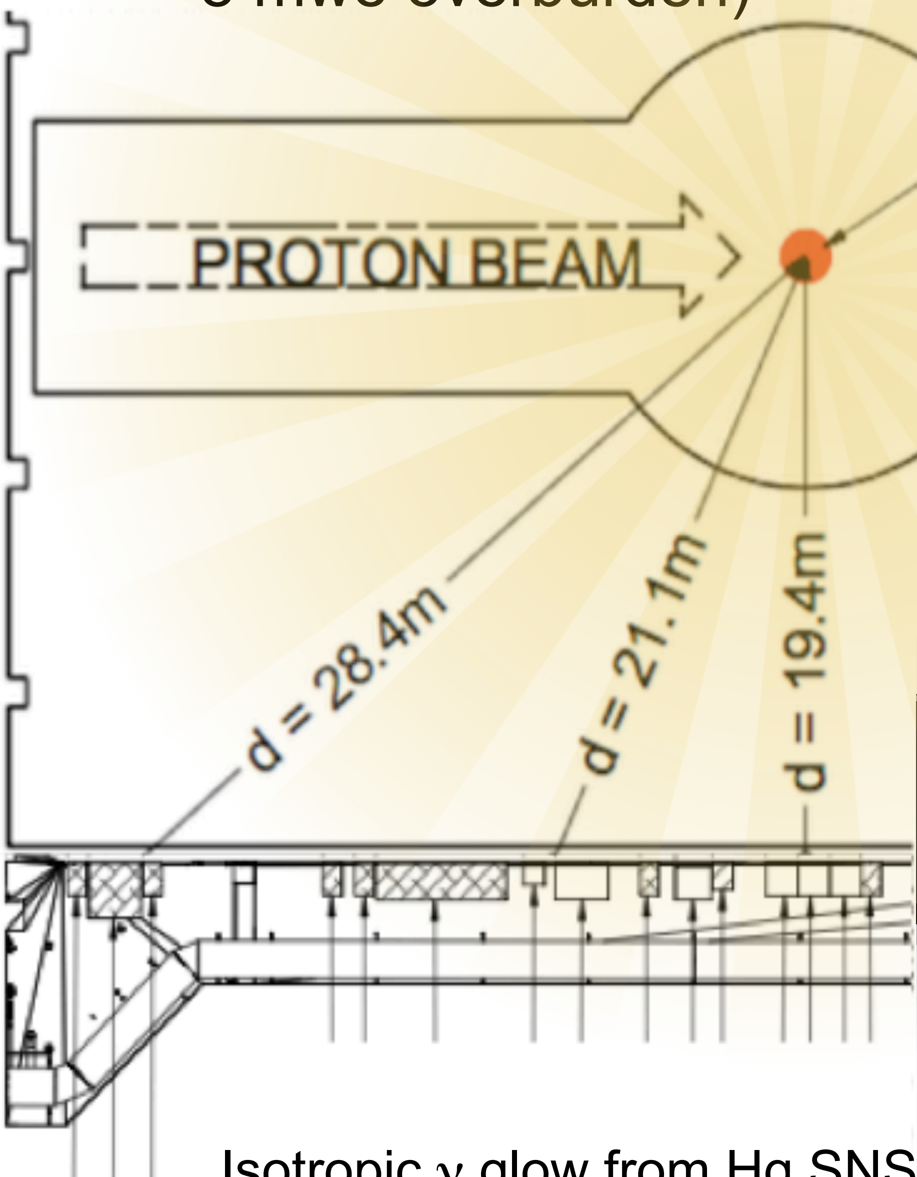
Multiple detectors for N^2 dependence of the cross section





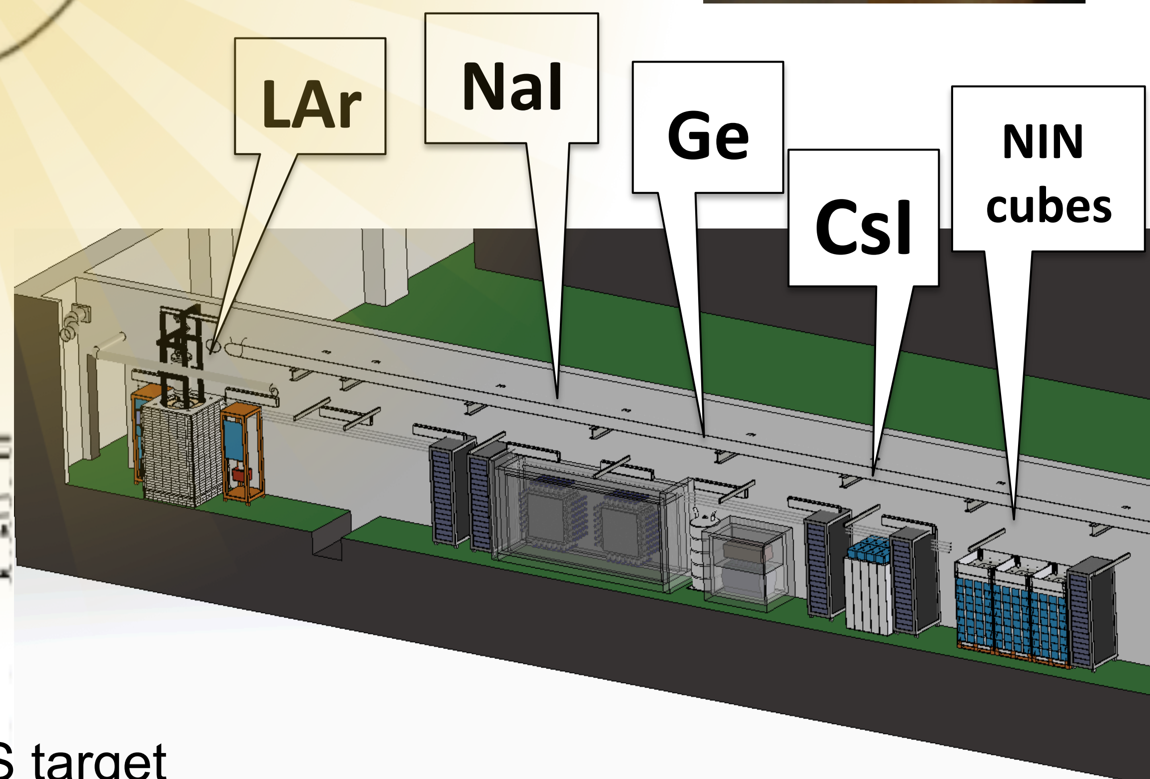
Siting for deployment in SNS basement

(measured neutron backgrounds low,
~ 8 mwe overburden)

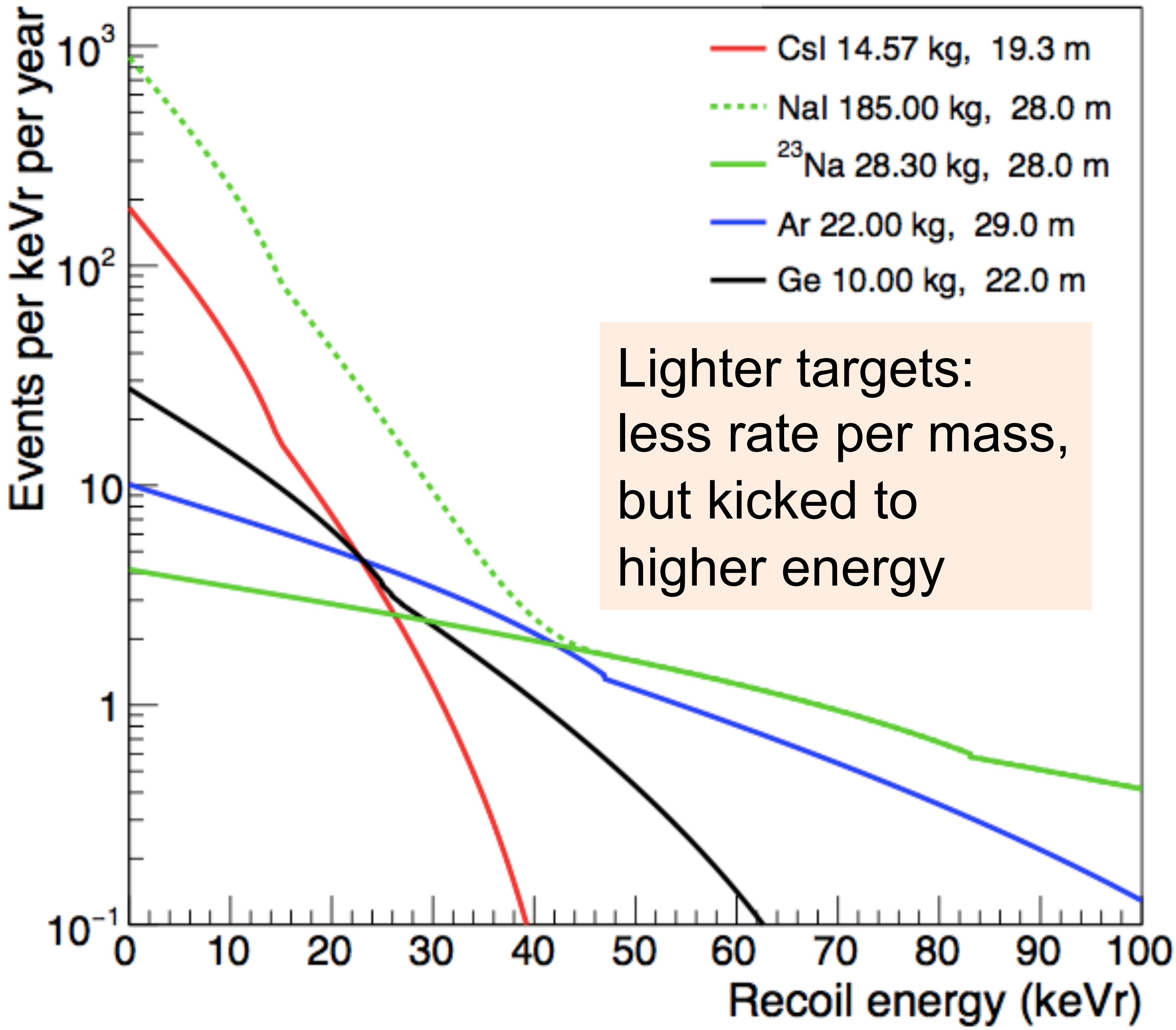


Isotropic ν glow from Hg SNS target

View looking down “Neutrino Alley”



Expected recoil energy distribution



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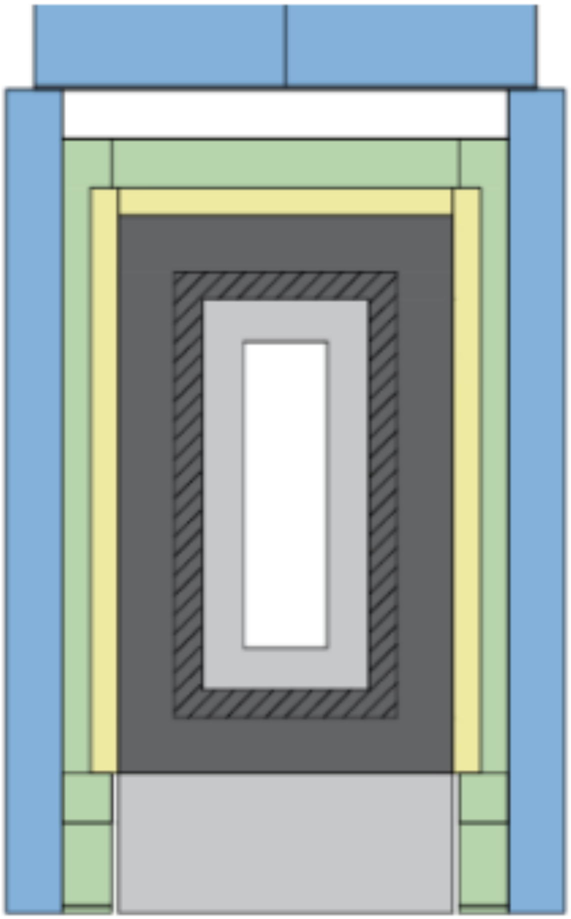
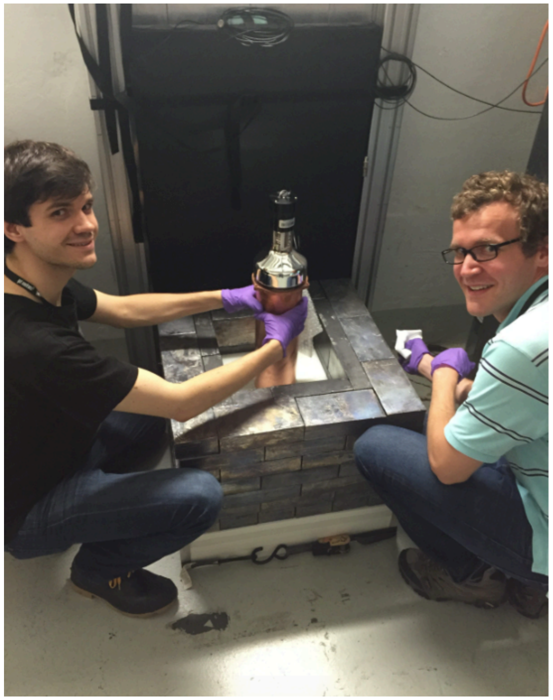
The CsI Detector in Shielding in Neutrino Alley at the SNS





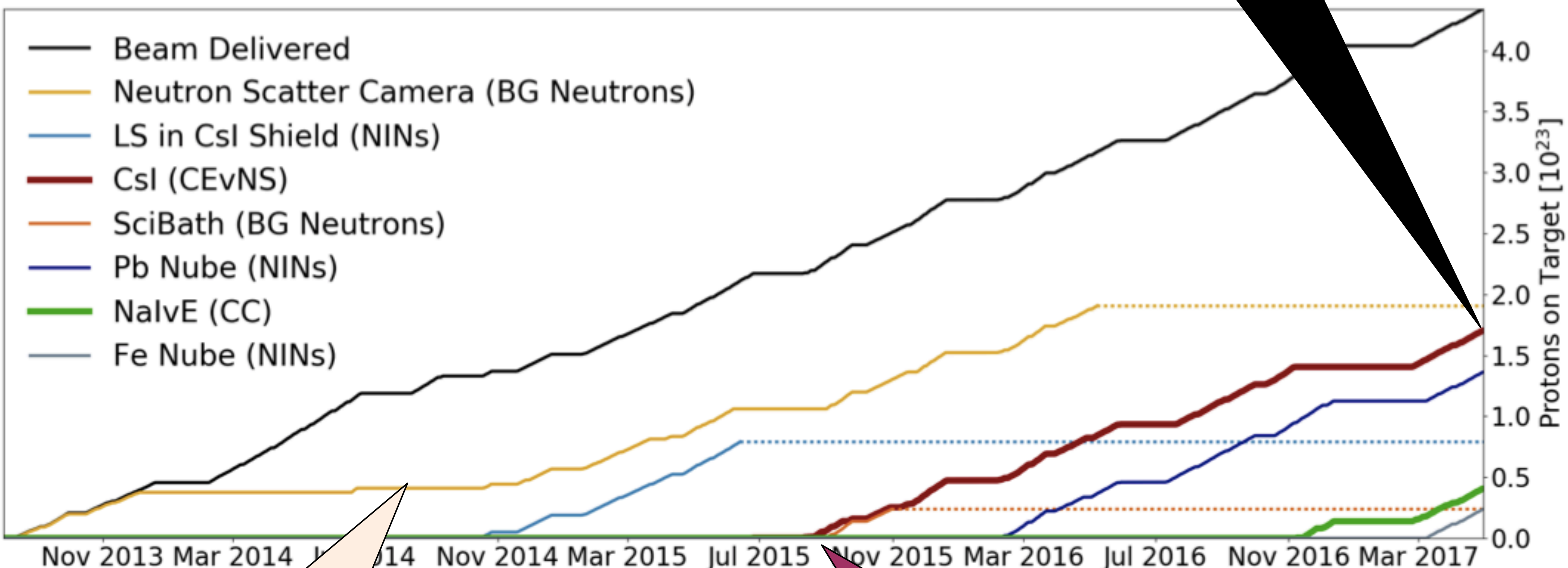
A hand-held detector!

Almost wrapped up...

Layer	HDPE*	Low backg. lead	Lead	Muon veto	Water
Thickness	3"	2"	4"	2"	4"
Colour					

COHERENT data taking

1.76 x10^{23} POT delivered to CsI (7.48 GWhr)

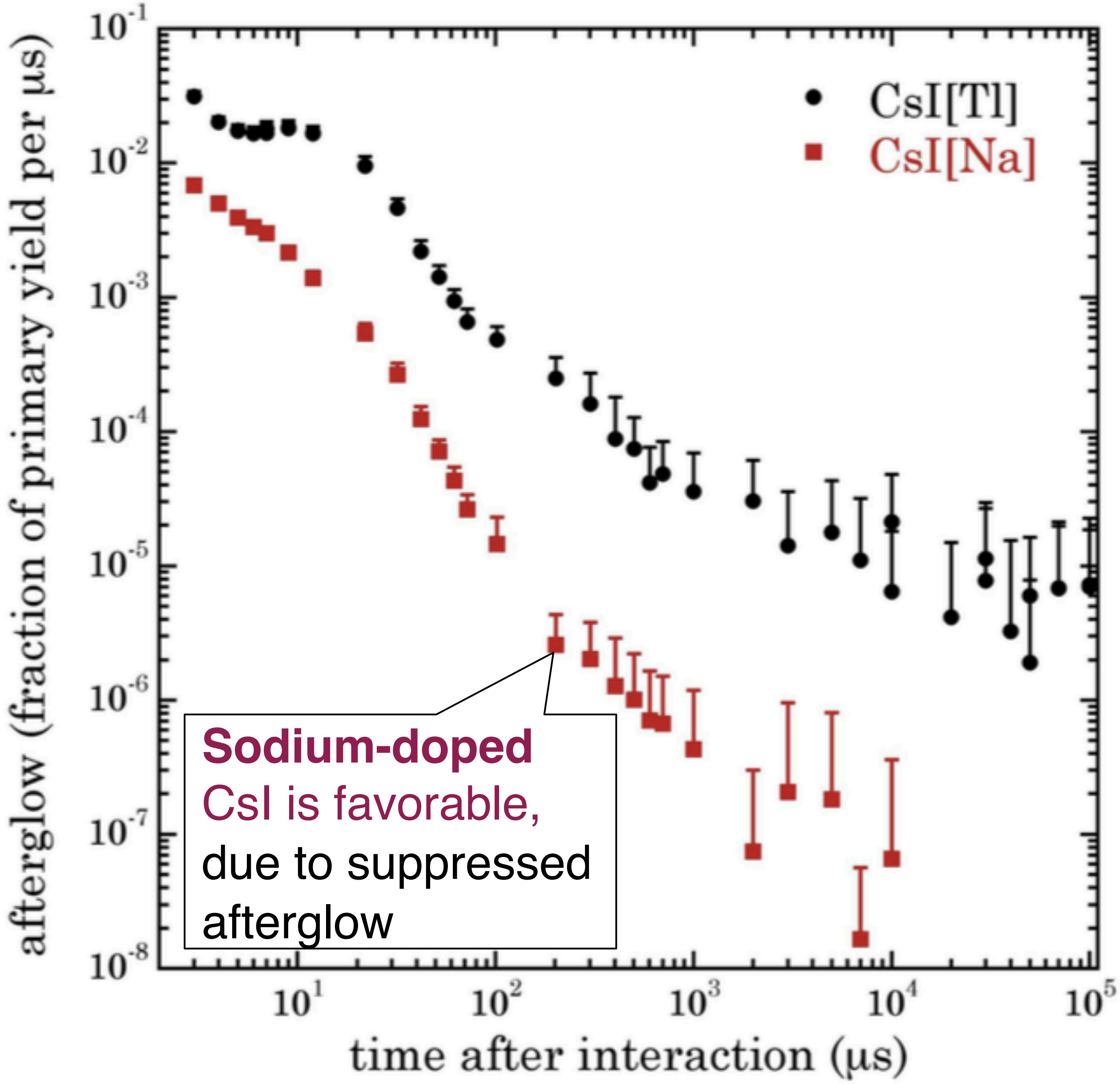


Neutron background data-taking for ~2 years before first CEvNS detectors

CsI data-taking starting summer 2015

The First COHERENT Result: CsI[Na]

Led by U. Chicago group



J.I. Collar et al., NIM A773 (2016) 56-67

Scintillating crystal

- high light yield
- low intrinsic bg
- rugged and stable
- room temperature
- inexpensive

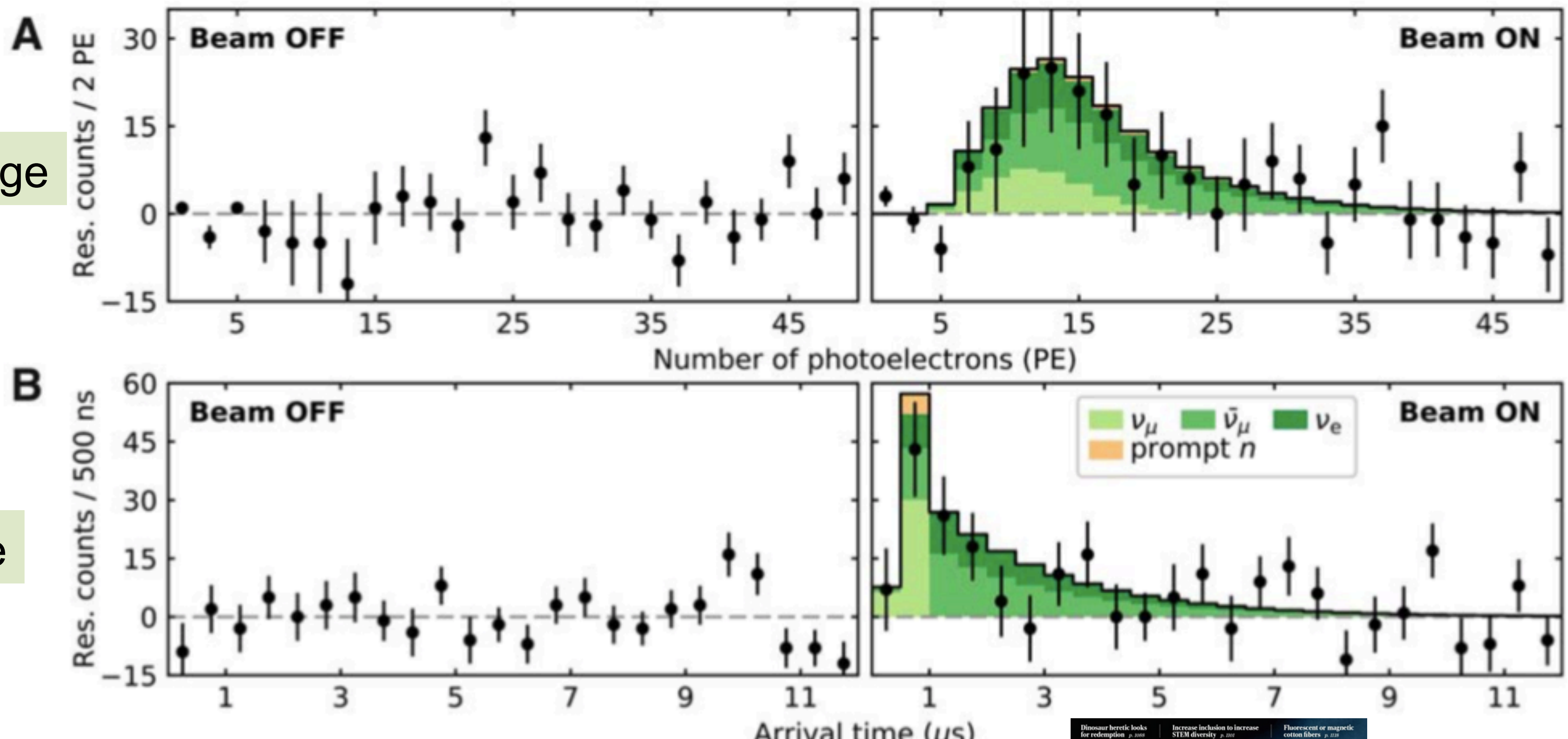
2 kg test crystal @U. Chicago.

Amcrys-H, Ukraine

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

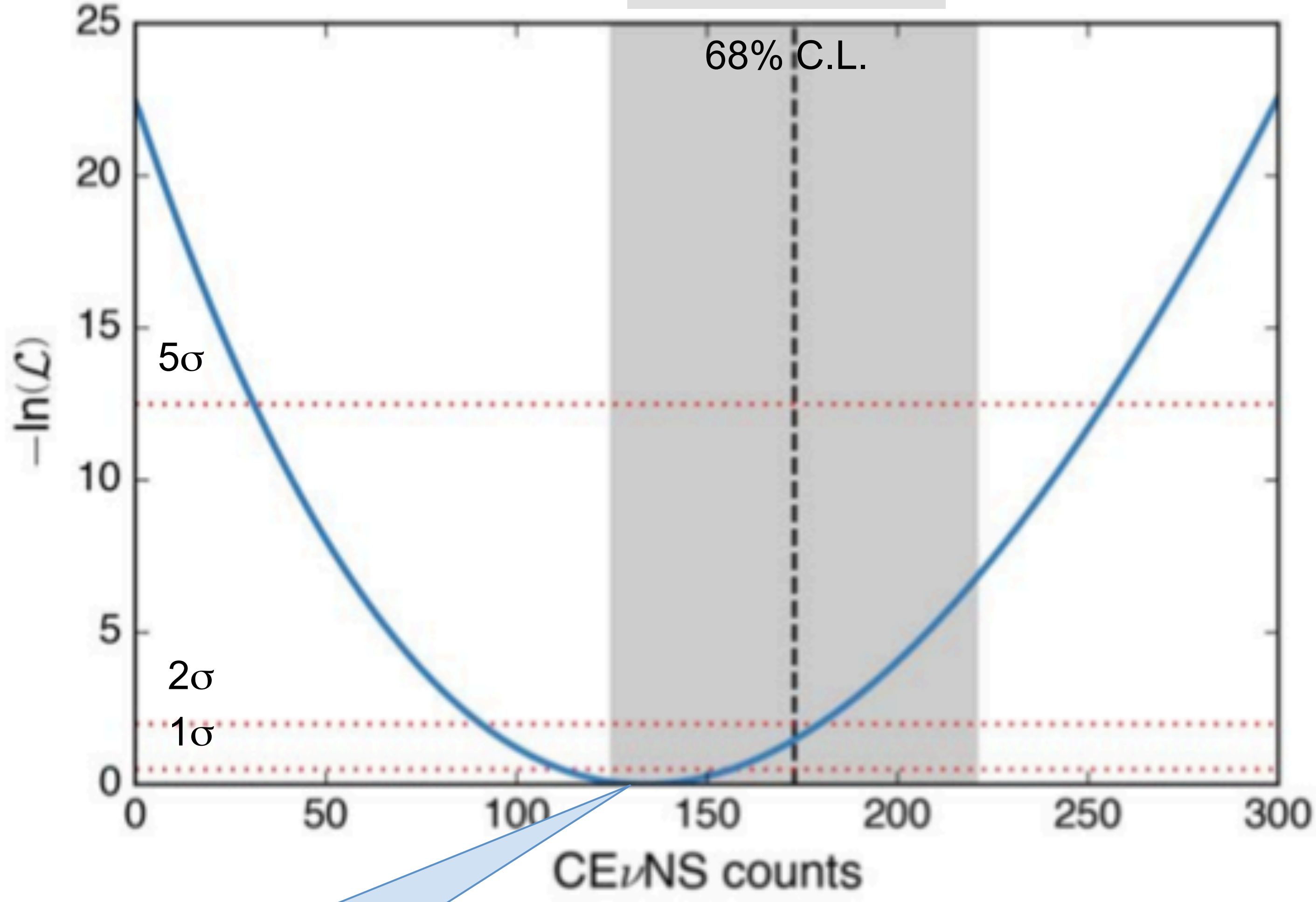
Science 03 Aug 2017:
eaao0990
DOI: 10.1126/science.aao0990

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

Signal, background, and uncertainty summary numbers

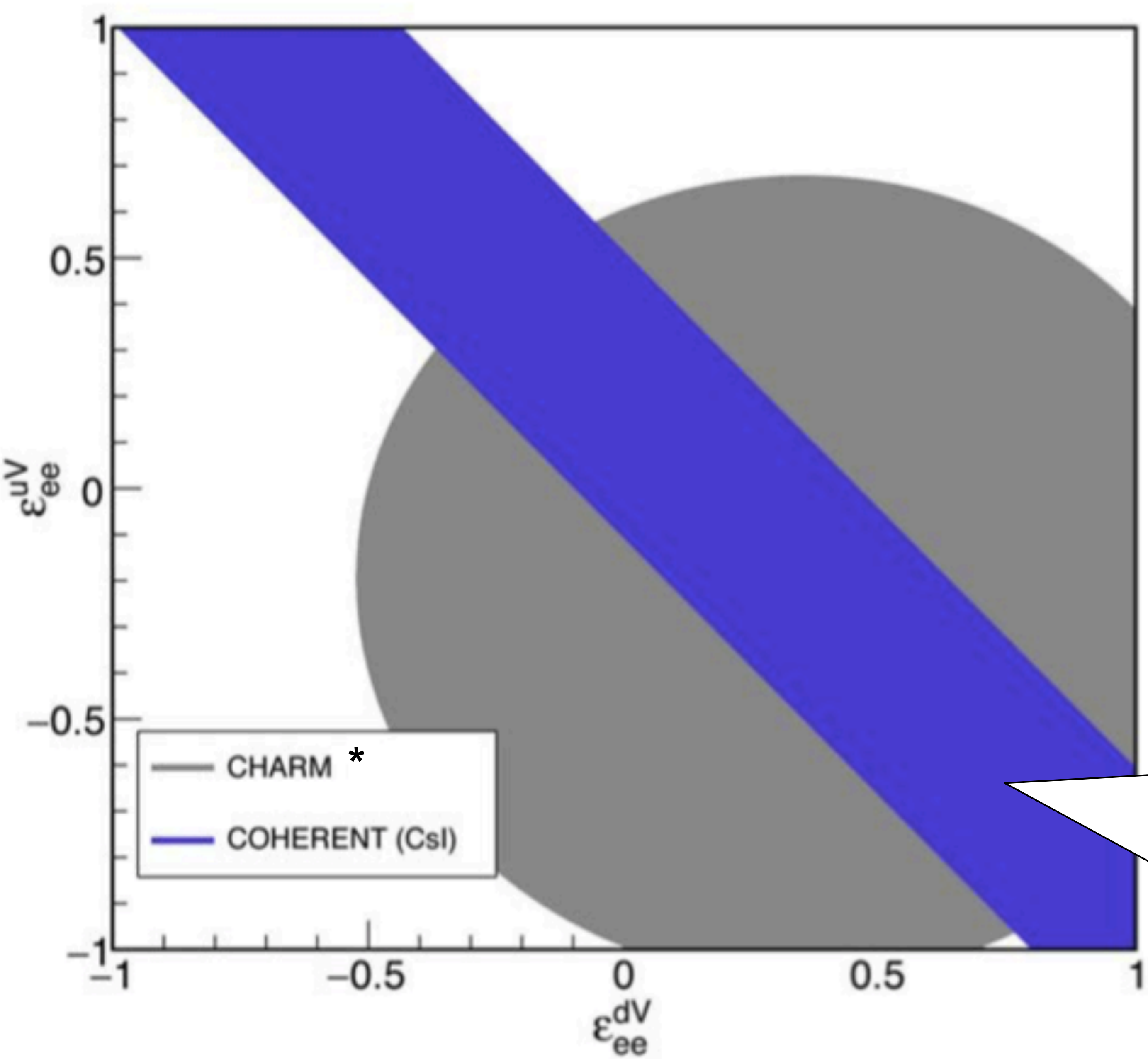
$6 \le PE \le 30$, $0 \le t \le 6000$ ns

Beam ON coincidence window	547 counts
Anticoincidence window	405 counts
Beam-on bg: prompt beam neutrons	7.0 ± 1.7
Beam-on bg: NINs (neglected)	4.0 ± 1.3
Signal counts, single-bin counting	136 ± 31
Signal counts, 2D likelihood fit	**134 ± 22**
Predicted SM signal counts	**173 ± 48**

Uncertainties on signal and background predictions	
Event selection	5%
Flux	10%
Quenching factor	25%
Form factor	5%
Total uncertainty on signal	**28%**
Beam-on neutron background	25%

Dominant uncertainty

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



- Assume all other ε's zero

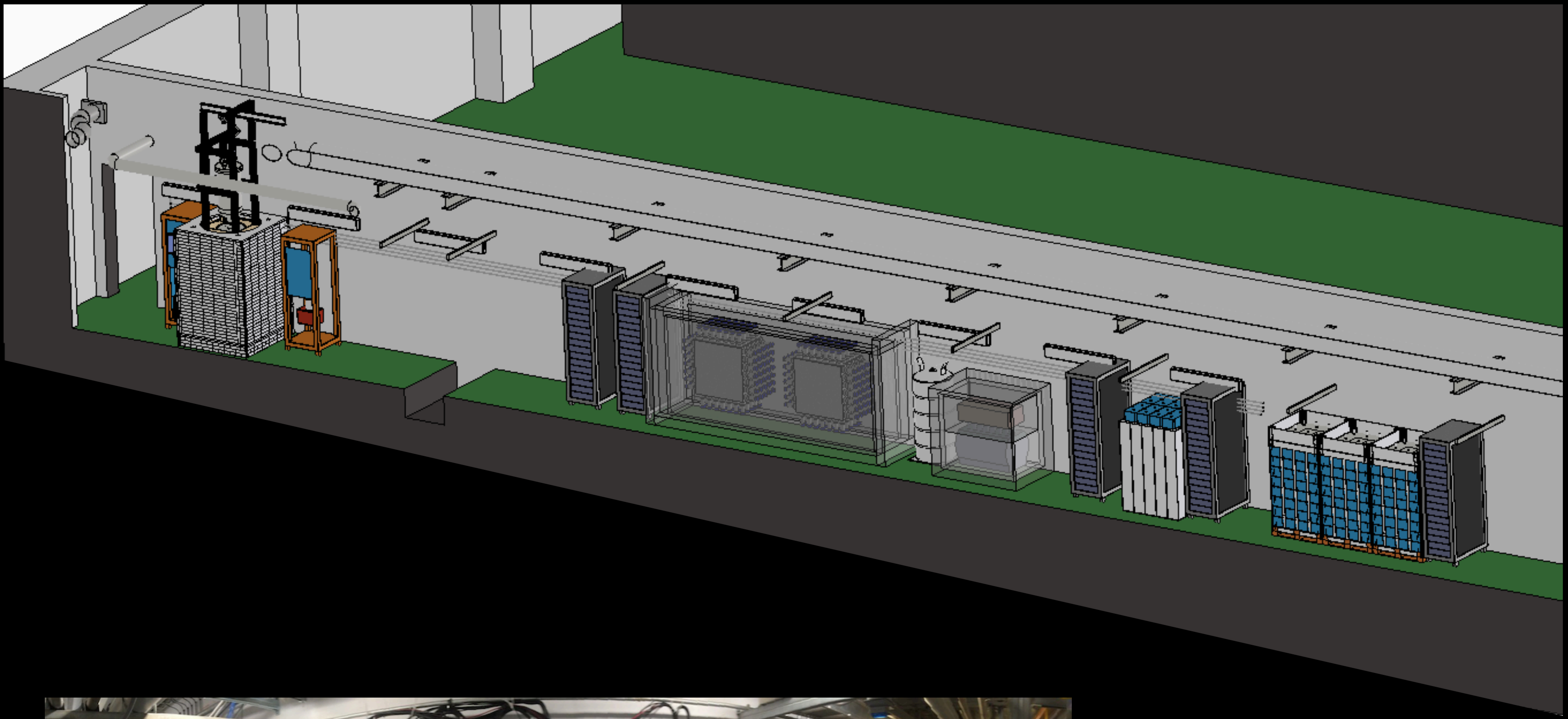
Parameters describing beyond-the-SM interactions outside this region disfavored at 90%

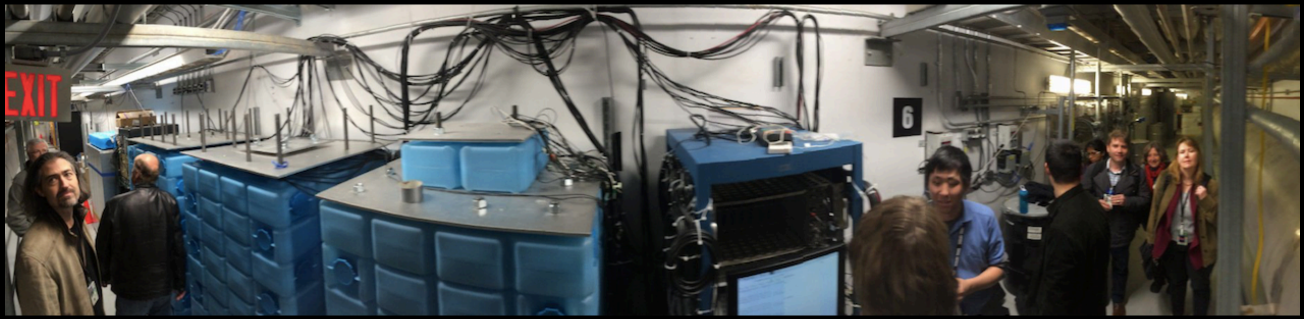
*CHARM constraints apply only to heavy mediators

OUTLINE

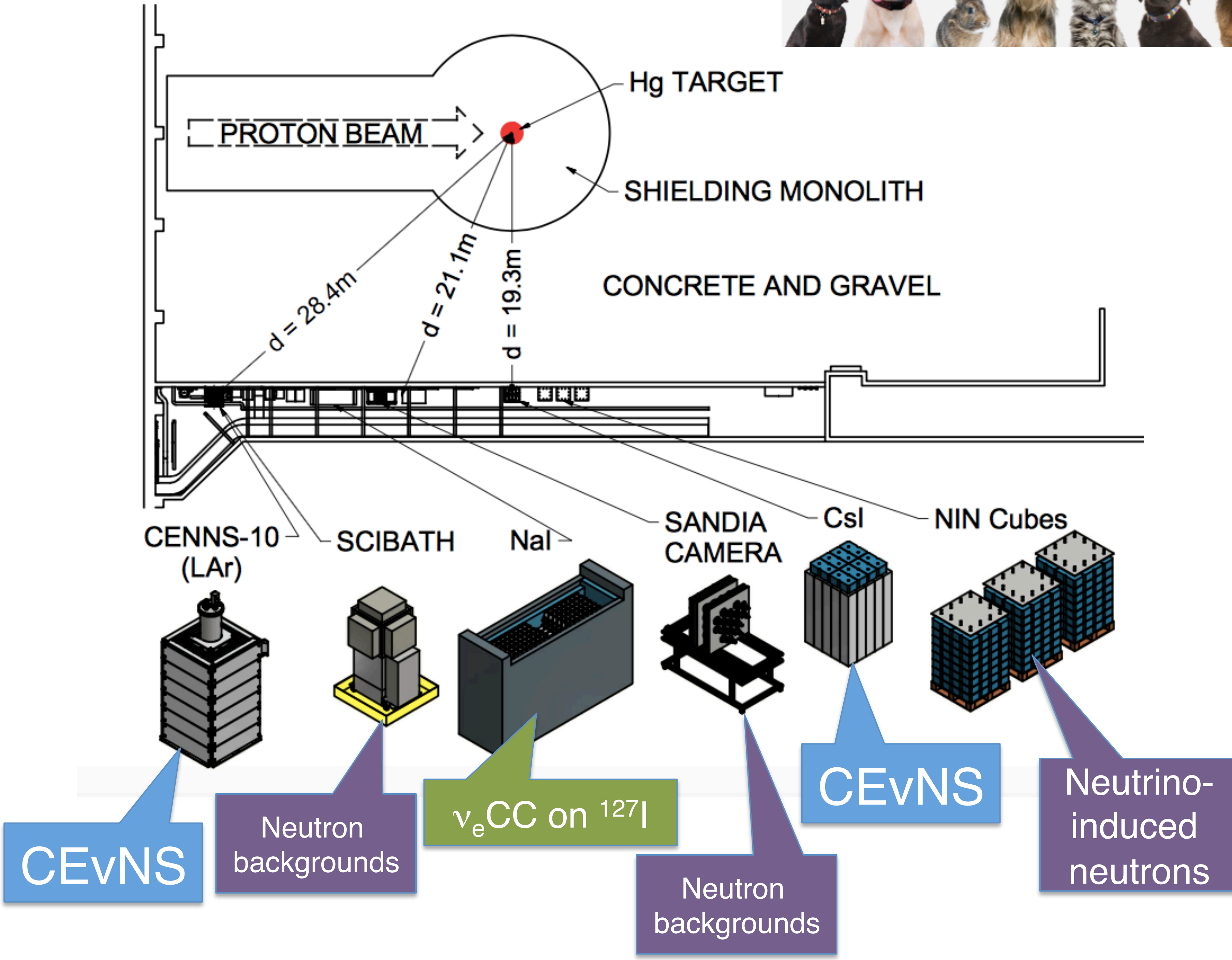
- Neutrinos and neutrino interactions
- Coherent elastic neutrino-nucleus scattering (CEvNS)
- Why measure it? Physics motivations (short and long term)
- How to measure CEvNS
- The COHERENT experiment at the SNS
- **First light** with CsI[Tl]
- **Status and prospects for COHERENT**

What's Next for COHERENT?



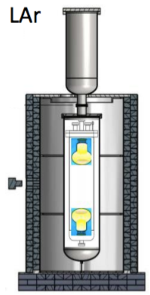


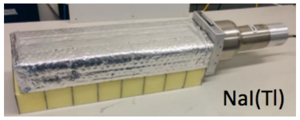
Deployments so far in Neutrino Alley



COHERENT **CEvNS** Detector Status and Near Future

Nuclear Target	Technology	Mass (kg)	Distance from source (m)	Recoil threshold (keVr)	Data-taking start date
CsI[Na]	Scintillating crystal	14.6	20	6.5	9/2015
Ge	HPGe PPC	10	22	5	2018
LAr	Single-phase	22	29	20	12/2016, upgraded summer 2017
NaI[Tl]	Scintillating crystal	185*/ 2000	28	13	*high-threshold deployment summer 2016

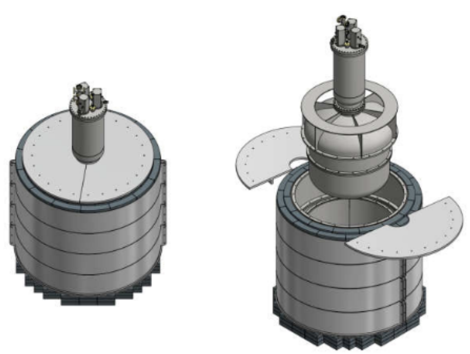



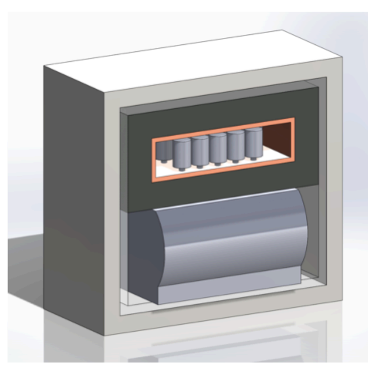


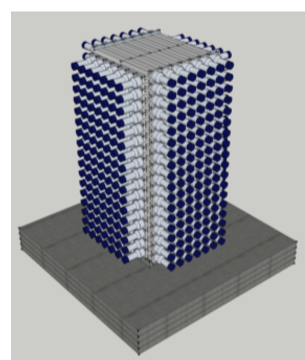
- CsI will continue running
- 185 kg of NaI installed in July 2016
  - taking data in high-threshold mode for CC on ^{127}I
  - PMT base modifications to enable low-threshold CEvNS running
- LAr single-phase detector installed in December 2016
  - upgraded w/TPB coating of PMT & Teflon, running since May 2017
- First Ge detectors to be installed early 2018

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

Nuclear Target	Technology	Mass (kg)	Distance from source (m)	Recoil threshold (keVr)	Data-taking start date	Possible Future
CsI[Na]	Scintillating crystal	14.6	20	6.5	9/2015	Finish data-taking
Ge	HPGe PPC	10	22	5	2017	Additional detectors, 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 tonne, up to 9 tonnes



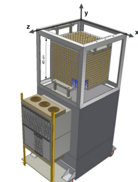


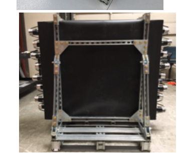


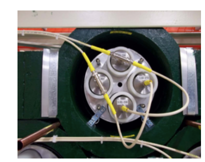
+ concepts for other targets

COHERENT Non-CEvNS Detectors (“In-COHERENT”)

Sandia Neutron Scatter Camera	Multiplane liquid scintillator	Neutron background	Deployed 2014-2016
SciBath	WLS fiber + liquid scintillator	Neutron background	Deployed 2015
NaI[Tl]	Scintillating crystal	ν_eCC	High-threshold deployment summer 2016
Lead Nube	Pb + liquid scintillator	NINs in lead	Deployed 2016
Iron Nube	Fe + liquid scintillator	NINs in iron	Deployed 2017
MARS	Plastic scintillator and Gd sandwich	Neutron background	Under deployment
Mini-HALO	Pb + NCDs	NINs in lead	In design







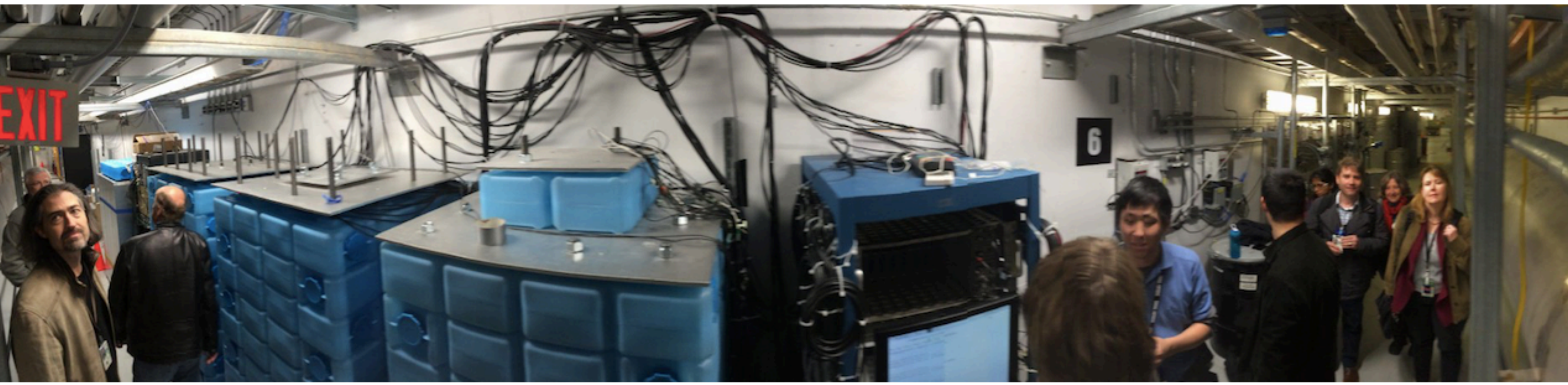
And many more ideas and activities for Neutrino Alley and beyond...

- Inelastic CC and NC in Ar, Pb, ...
- Other crystal or scint deployments in CsI shield
- Flux normalization using D_2O (well known xscn)
- Ancillary measurements: QF
- Directional detectors
- ...

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
  - DM bg, SM test, supernova, nuclear physics, ...
- **First measurement** by COHERENT CsI[Na] at the SNS
- Low-hanging fruit:

  meaningful bounds on ν Non-Standard Interactions

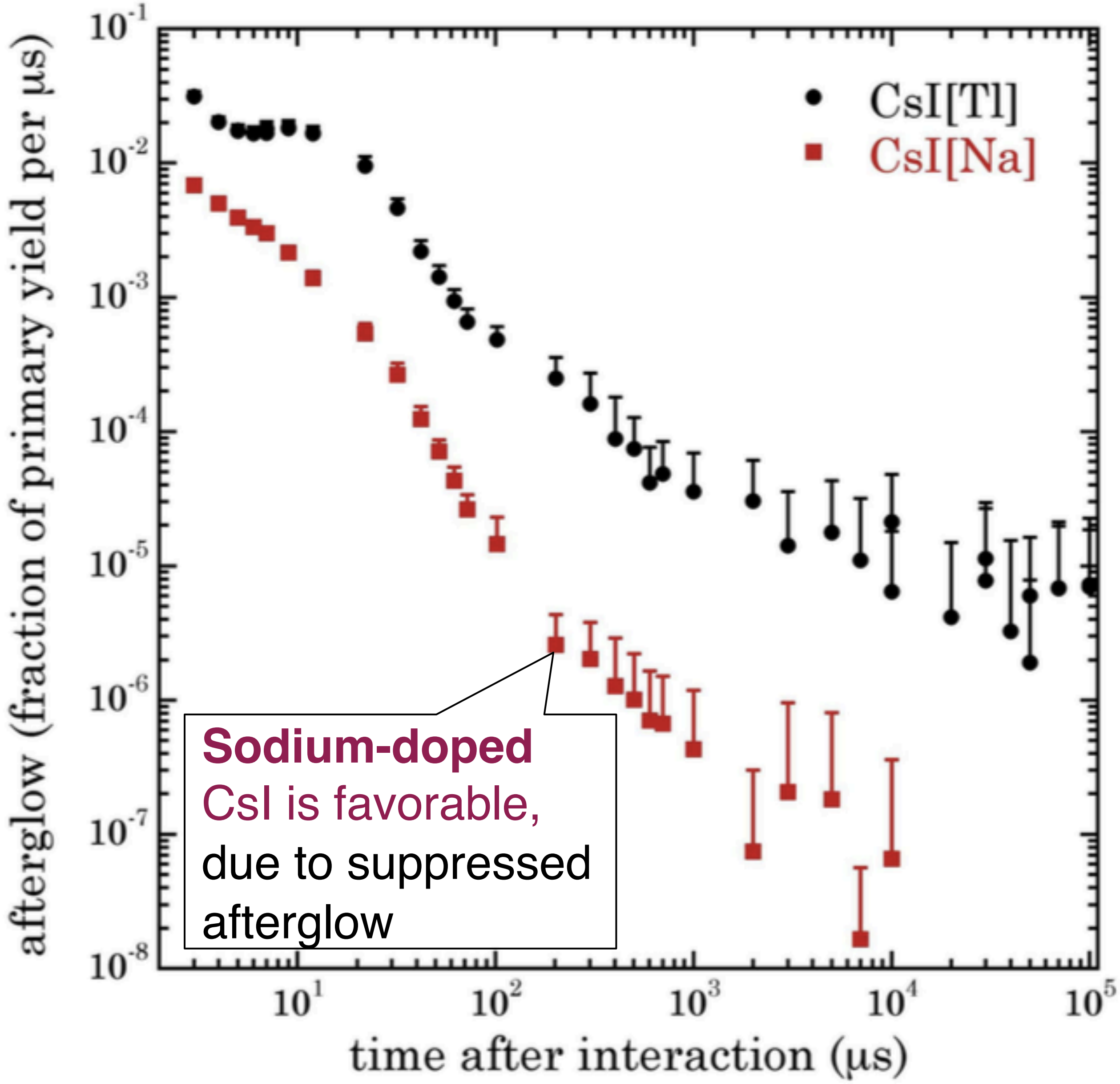


- **It's just the beginning....**
- Multiple targets, upgrades and new ideas in the works!
- Other CEvNS experiments will soon join the fun (CONNIE, CONUS, MINER, RED, Ricochet, Nu-cleus...)

Extras/backups

The First COHERENT Result: CsI[Na]

Led by U. Chicago group



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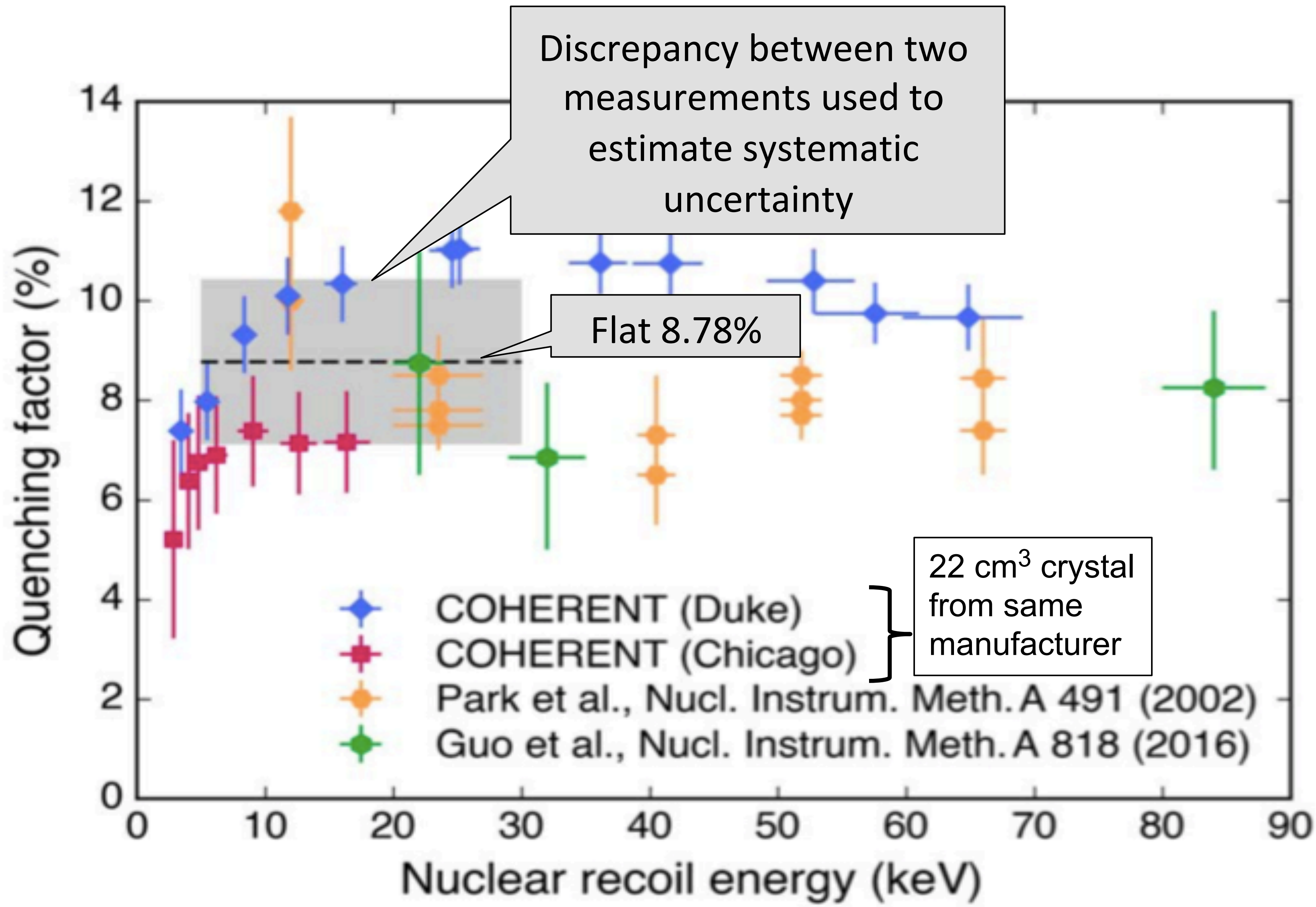
Scintillating crystal

- high light yield
- low intrinsic bg
- rugged and stable
- room temperature
- inexpensive

2 kg test crystal @U. Chicago.
Amcrys-H, Ukraine

CsI quenching factor measurements at TUNL w/ neutrons



13.348 pe/keVee * 0.0878 keVee/keVr = **1.2 pe/keVr**

ee light yield — QF