Coherent Elastic Neutrino-Nucleus Scattering

Kate Scholberg, Duke University
CNNP 2017
October 19, 2017

OUTLINE

-Coherent elastic neutrino-nucleus scattering (CEvNS)

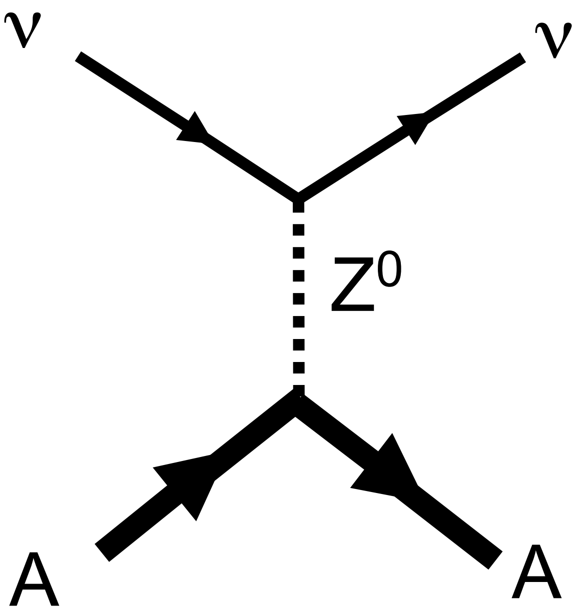
- Why measure it? Physics motivations
  (short and long term)
- How to measure CEvNS
- The COHERENT experiment at the SNS
- **First light** with CsI[Tl]
- Status and prospects for COHERENT

OUTLINE

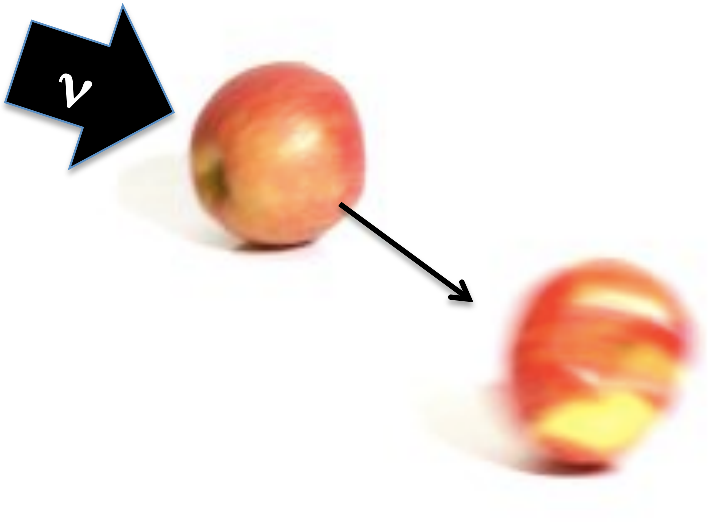
- **-Coherent elastic neutrino-nucleus scattering (CEvNS)**
- - Why measure it? Physics motivations
  (short and long term)
- - How to measure CEvNS
- - The COHERENT experiment at the SNS
- - **First light** with CsI[Tl]
- - Status and prospects for COHERENT

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



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

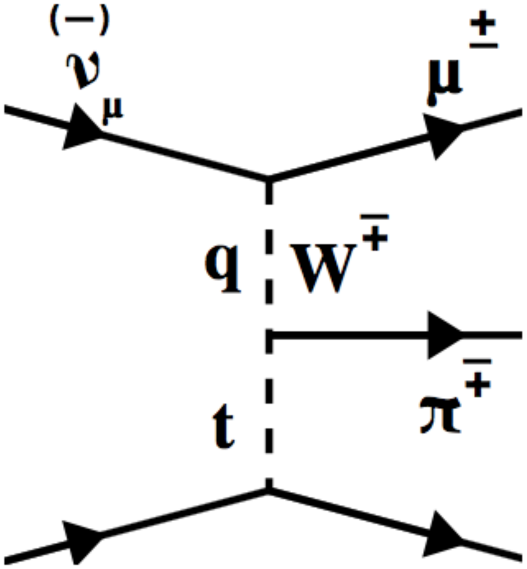
$$\frac{d\sigma}{d\Omega} \sim A^2 |f(\mathbf{k}', \mathbf{k})|^2$$

Momentum transfer $\mathbf{Q} = \mathbf{k}' - \mathbf{k}$

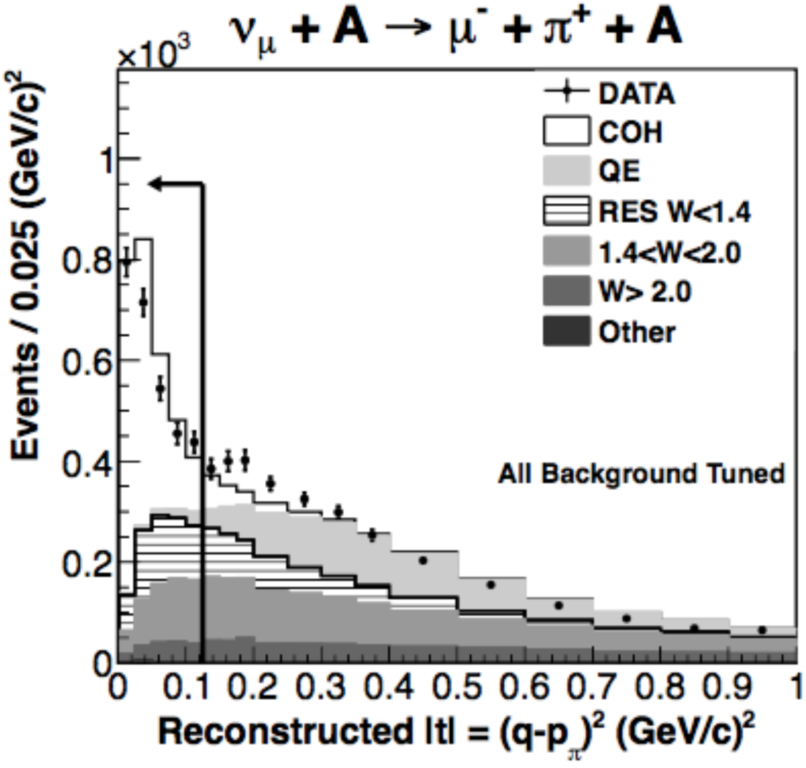
For $QR << 1$,

[total xscn] ~ A^2 * [single constituent xscn]

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



not
THAT!



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

`\begin{aside}`

Literature has CNS, CNNS, CENNS, ...

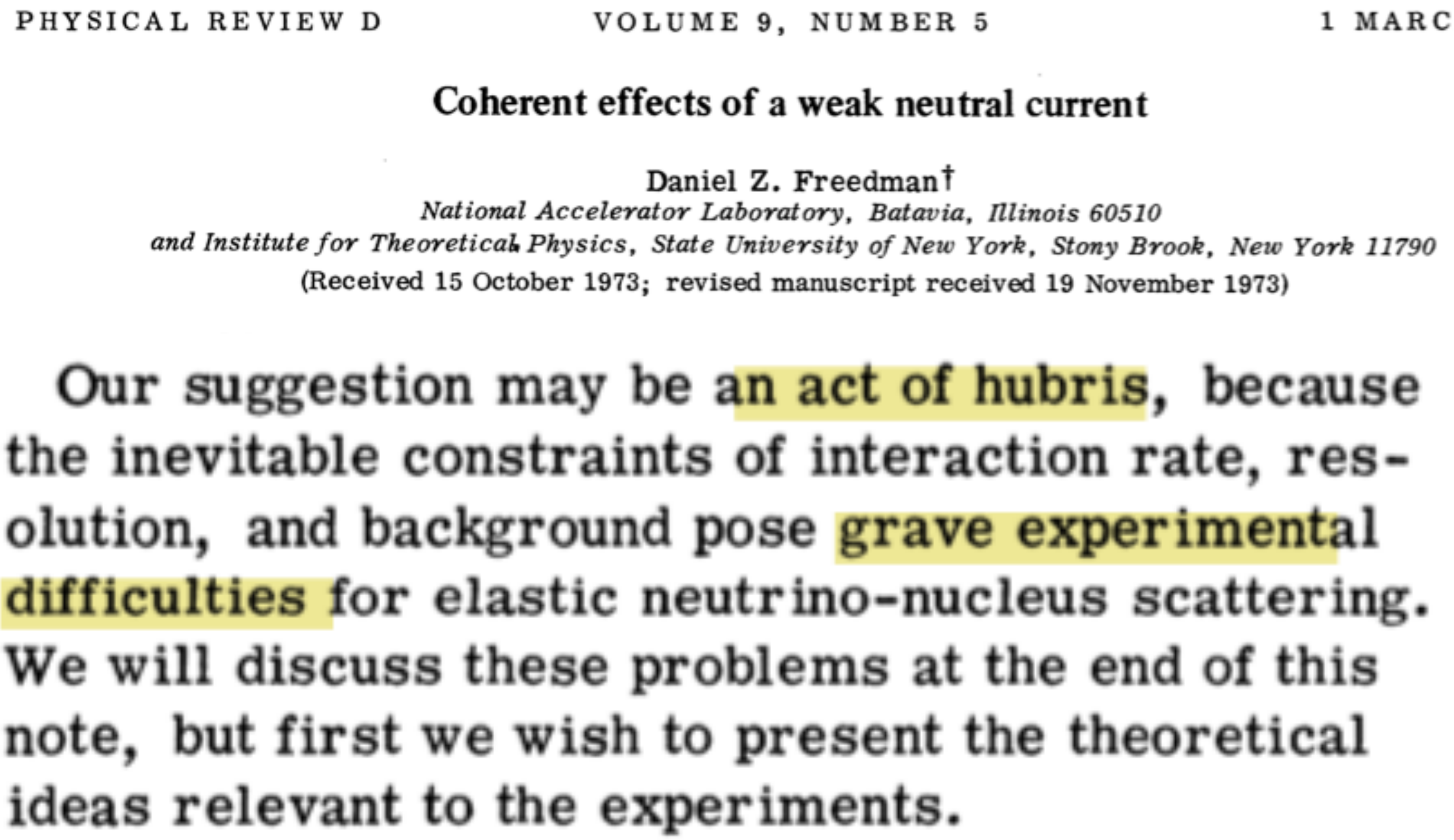
- I prefer including "E" for "elastic"... otherwise it gets frequently confused with coherent pion production at ~GeV neutrino energies
- I'm told "NN" means "nucleon-nucleon" to nuclear types
- CEνNS is a possibility but those internal Greek letters are annoying

➔**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.

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 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

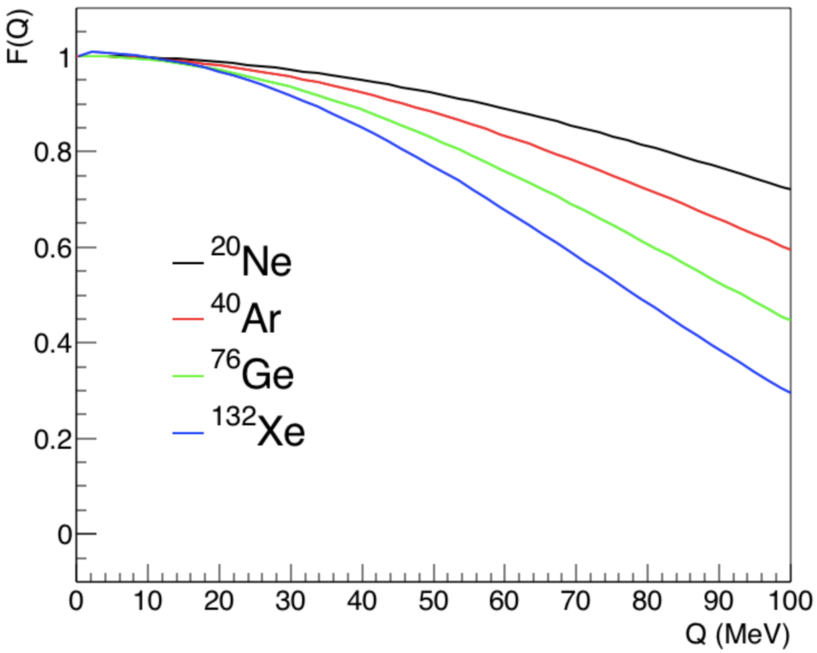
$$g_V^p = 0.0298$$
$$g_V^n = -0.5117$$
$$g_A^p = \pm 0.4955 \; (- \text{ for } \bar{\nu})$$
$$g_A^n = \mp 0.5121 \; (+ \text{ for } \bar{\nu})$$

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

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



form factor suppresses cross section at large Q

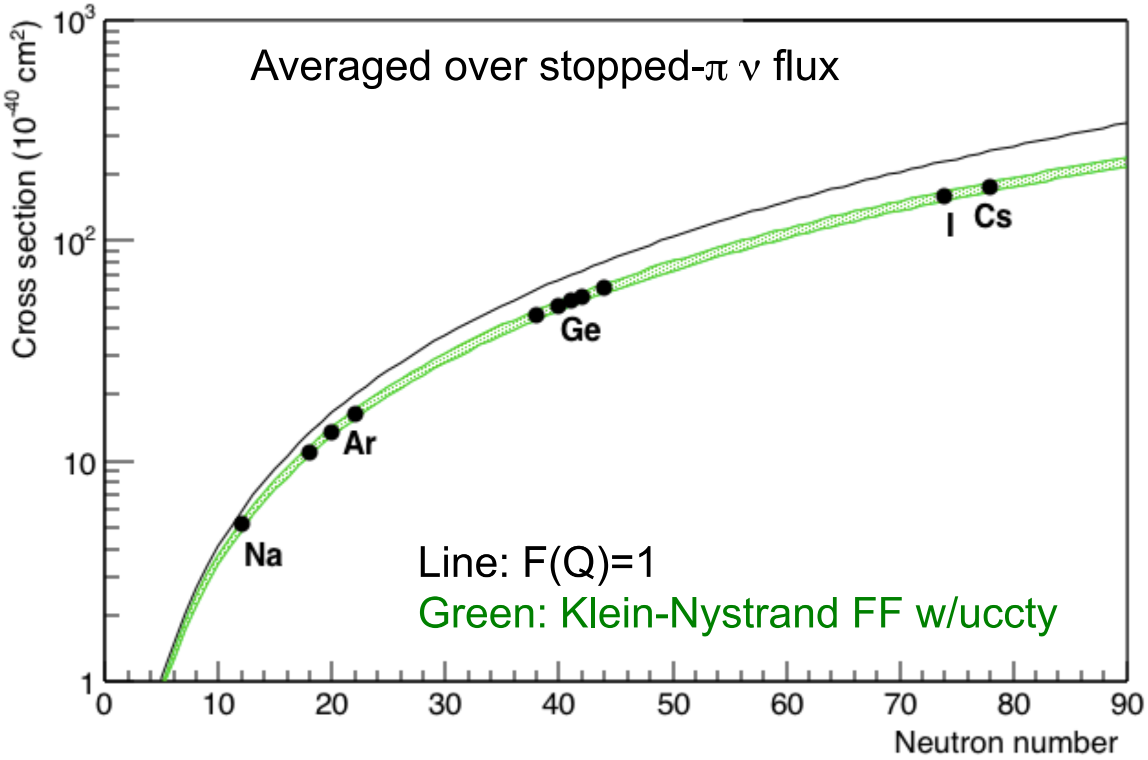
For $T \ll E_\nu$, neglecting axial terms:

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

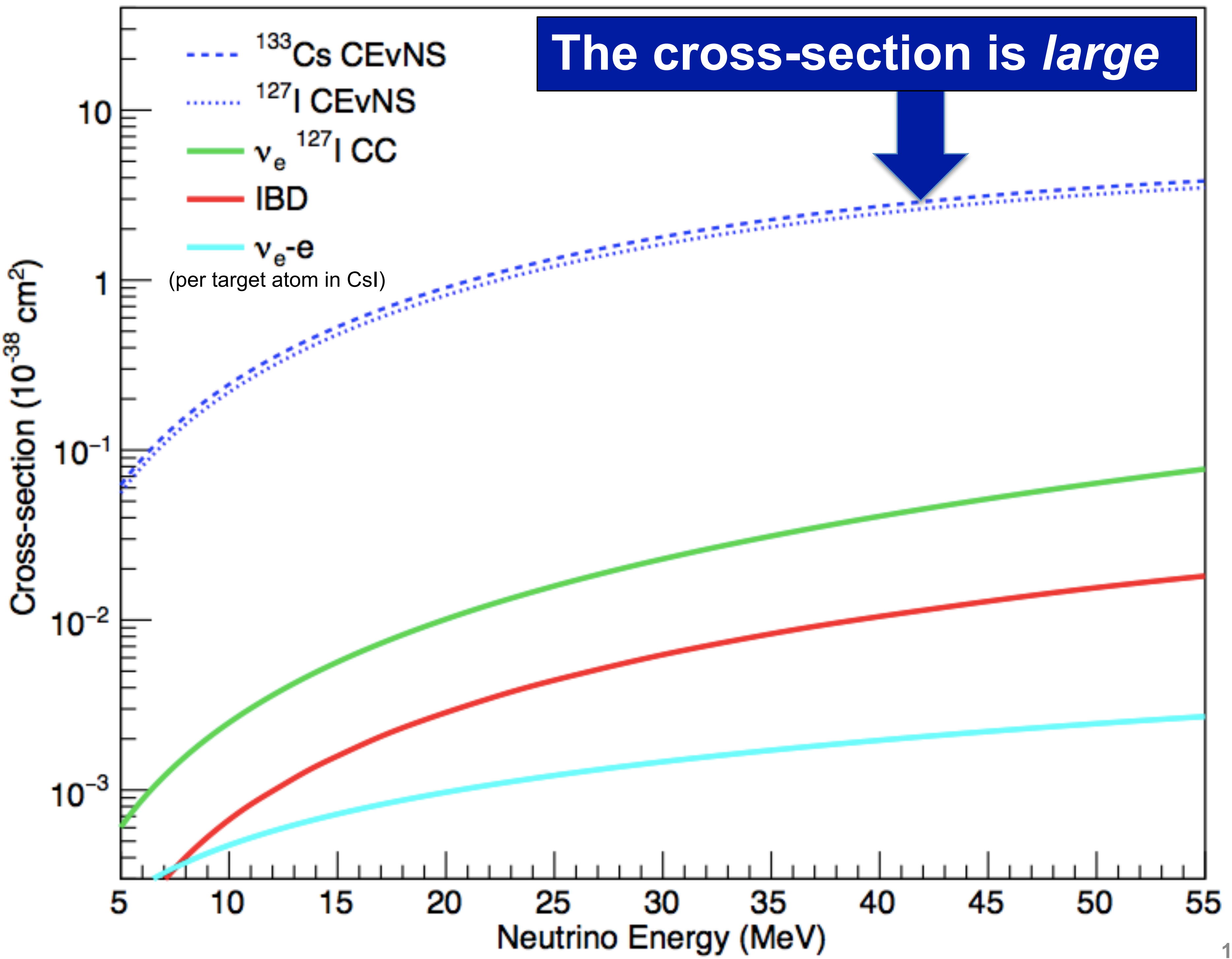
$$Q_W = N - (1 - 4\sin^2\theta_W)Z$$: weak nuclear charge

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

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

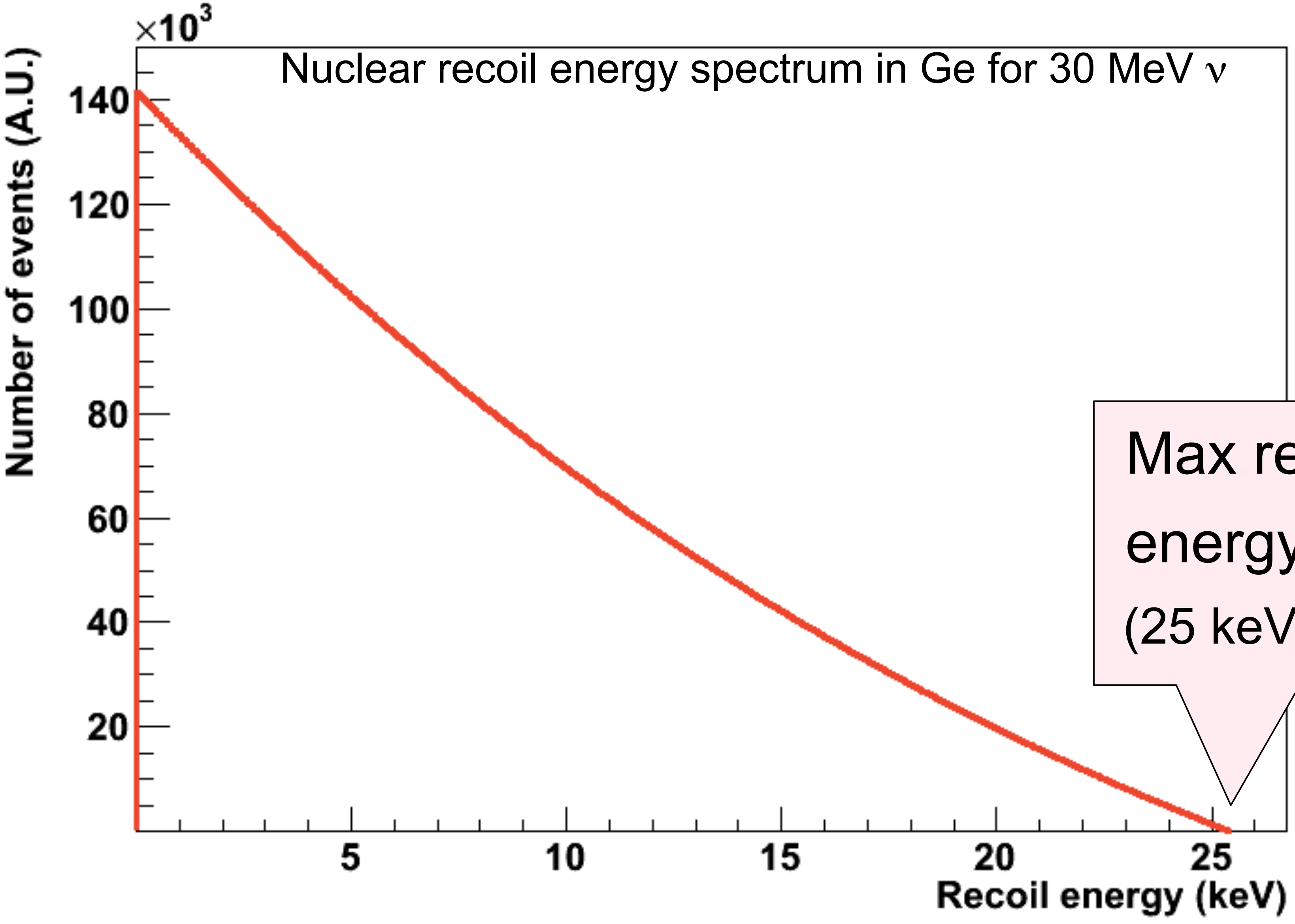

Averaged over stopped-π ν flux

Line: F(Q)=1
Green: Klein-Nystrand FF w/uccty



The cross-section is *large*

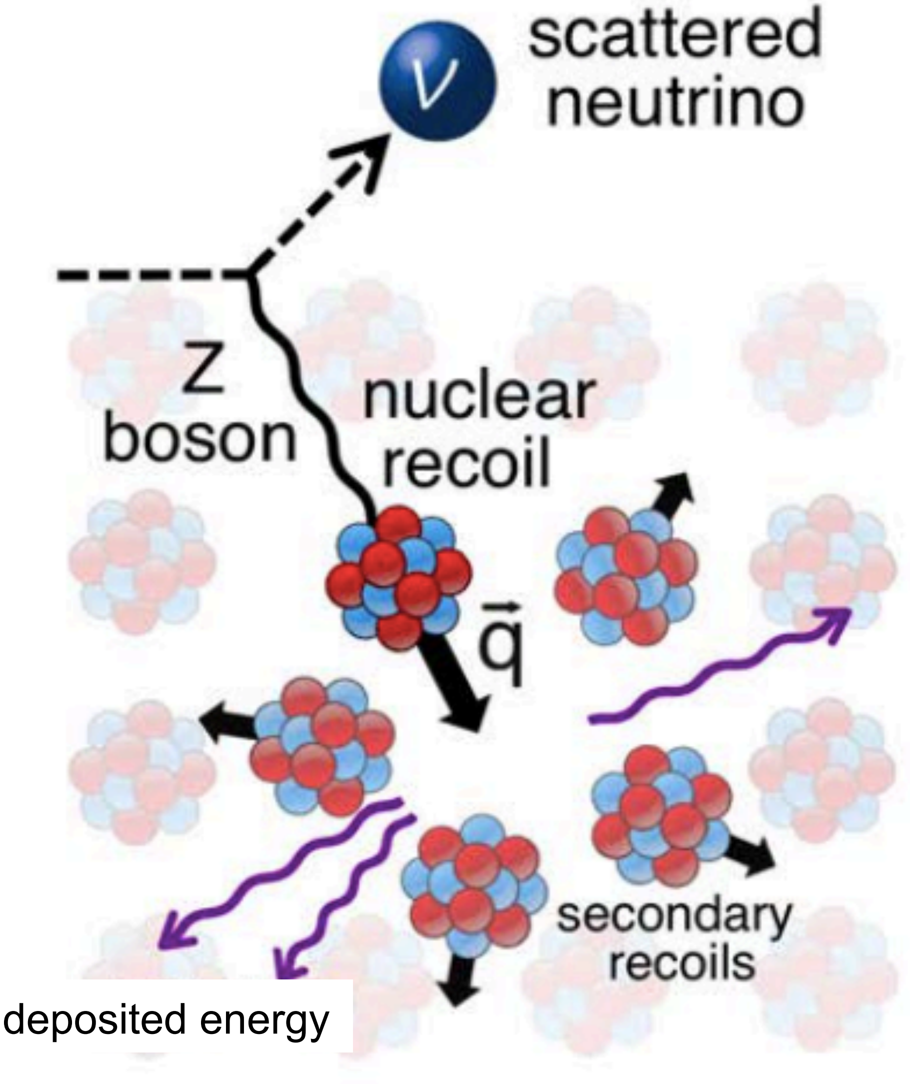
Large cross section (by neutrino standards) but hard to observe due to **tiny nuclear recoil energies:**



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



deposited energy

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

OUTLINE

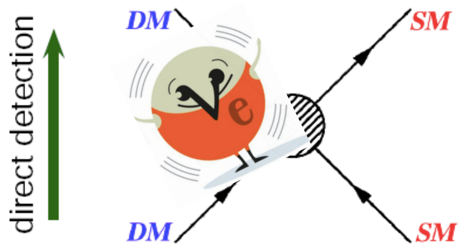
- Coherent elastic neutrino-nucleus scattering (CEvNS)
- **Why measure it? Physics motivations (short and long term)**
- How to measure CEvNS
- The COHERENT experiment at the SNS
- **First light** with CsI[Tl]
- Status and prospects for COHERENT

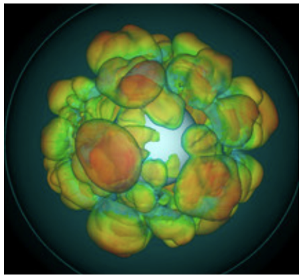
CEvNS: what's it good for?

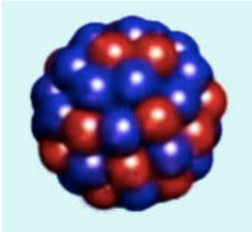
① So
② Many
③ Things
!

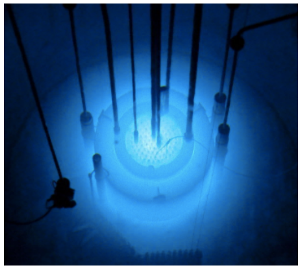
(not a
complete list!)

- **DM direct-detection expt bg/signal**
- 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)





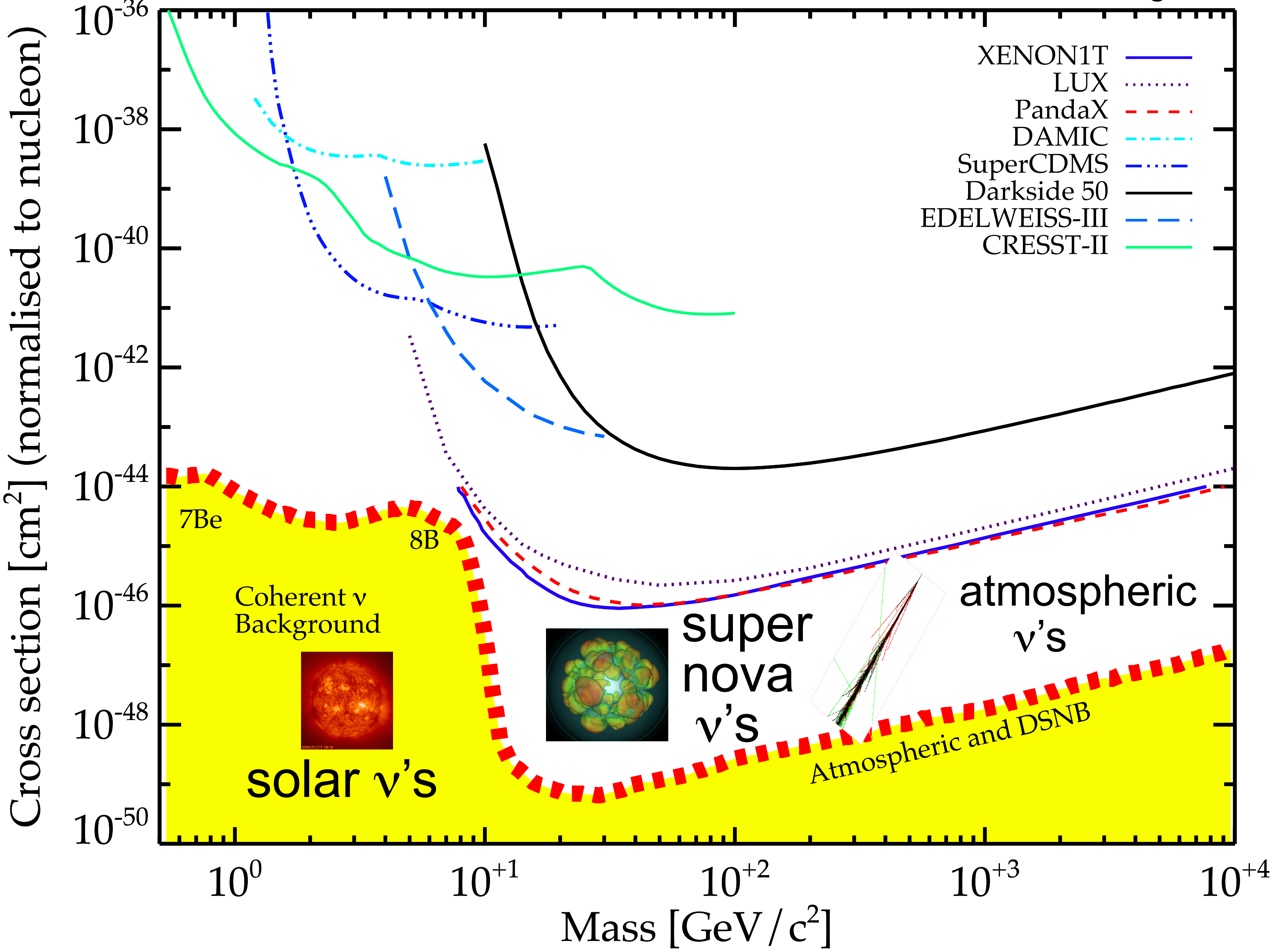




The so-called “neutrino floor” (**signal!**) for DM experiments

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

L. Strigari

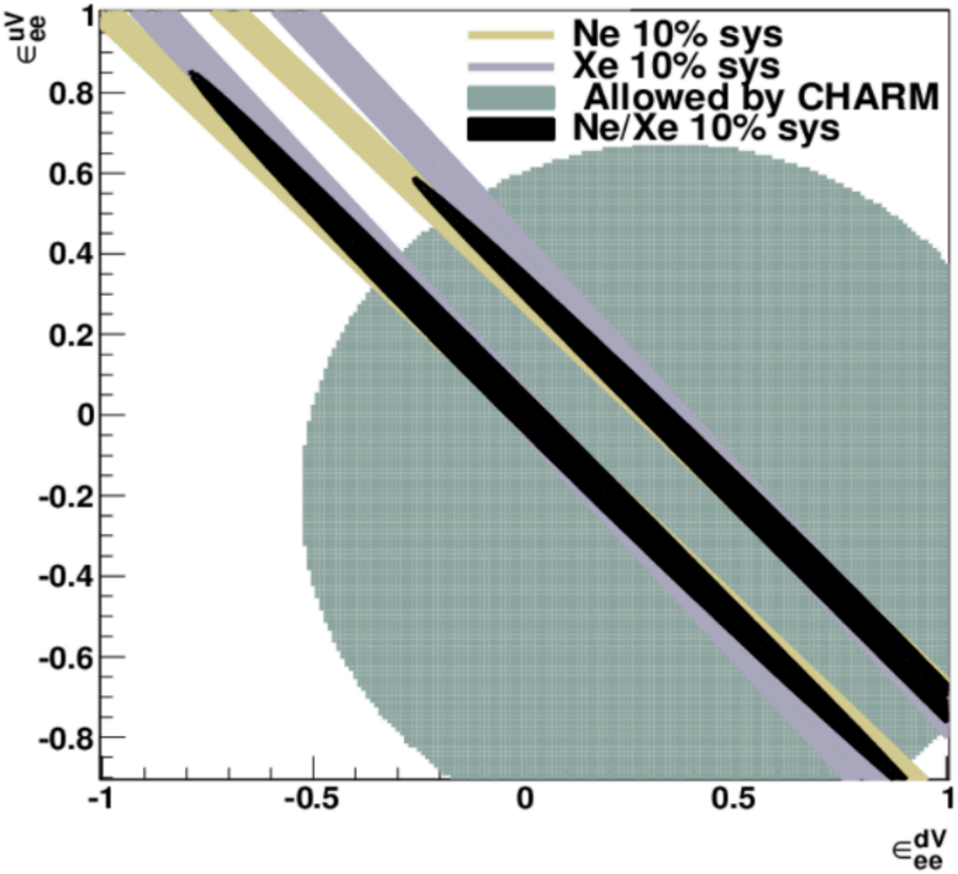


Measure CEvNS to understand nature of background/astro signal
(& detector response, DM interaction)

Non-Standard Interactions of Neutrinos:

new interaction **specific to ν's**

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



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

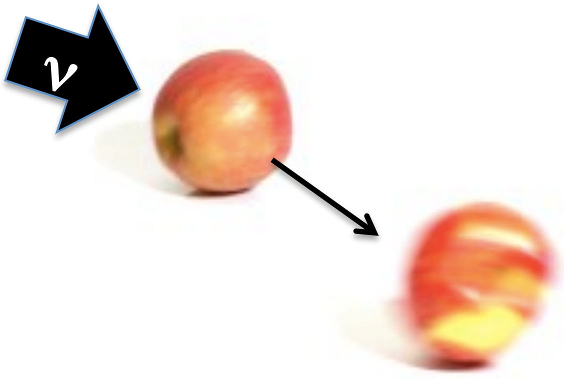
Can improve ~order of magnitude beyond CHARM limits with a first-generation experiment (for best sensitivity, want ***multiple targets***)

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

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

How to detect CEvNS?

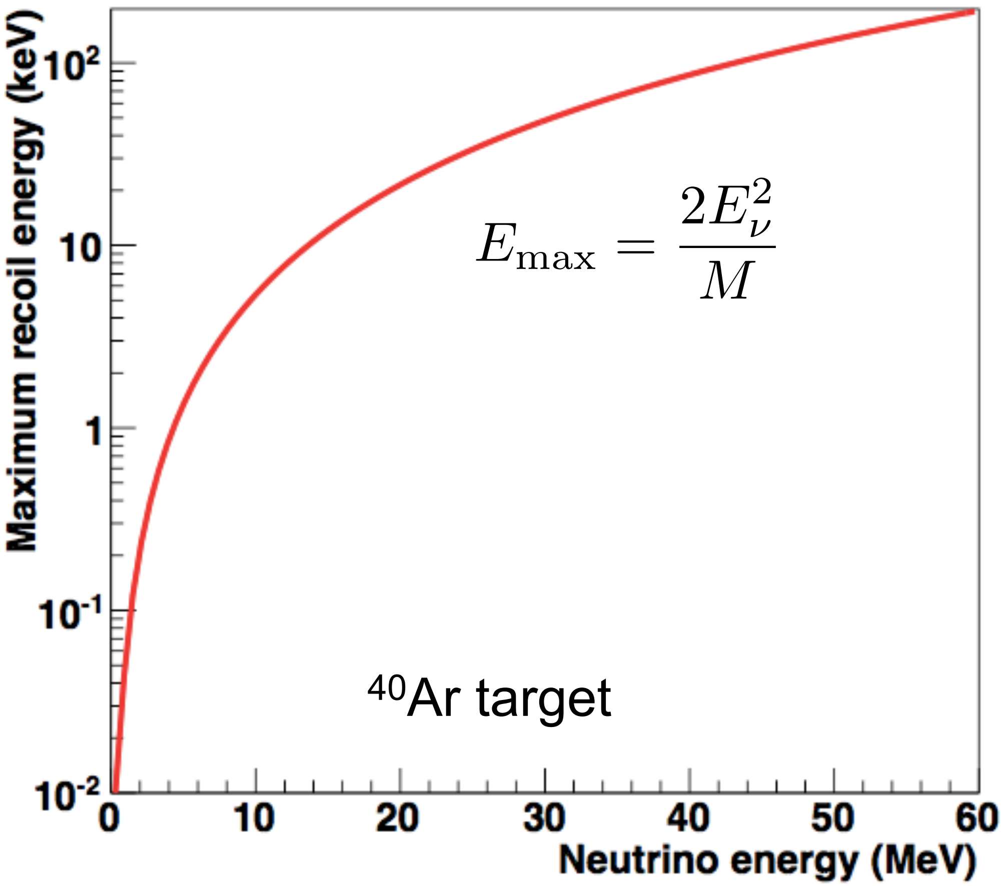


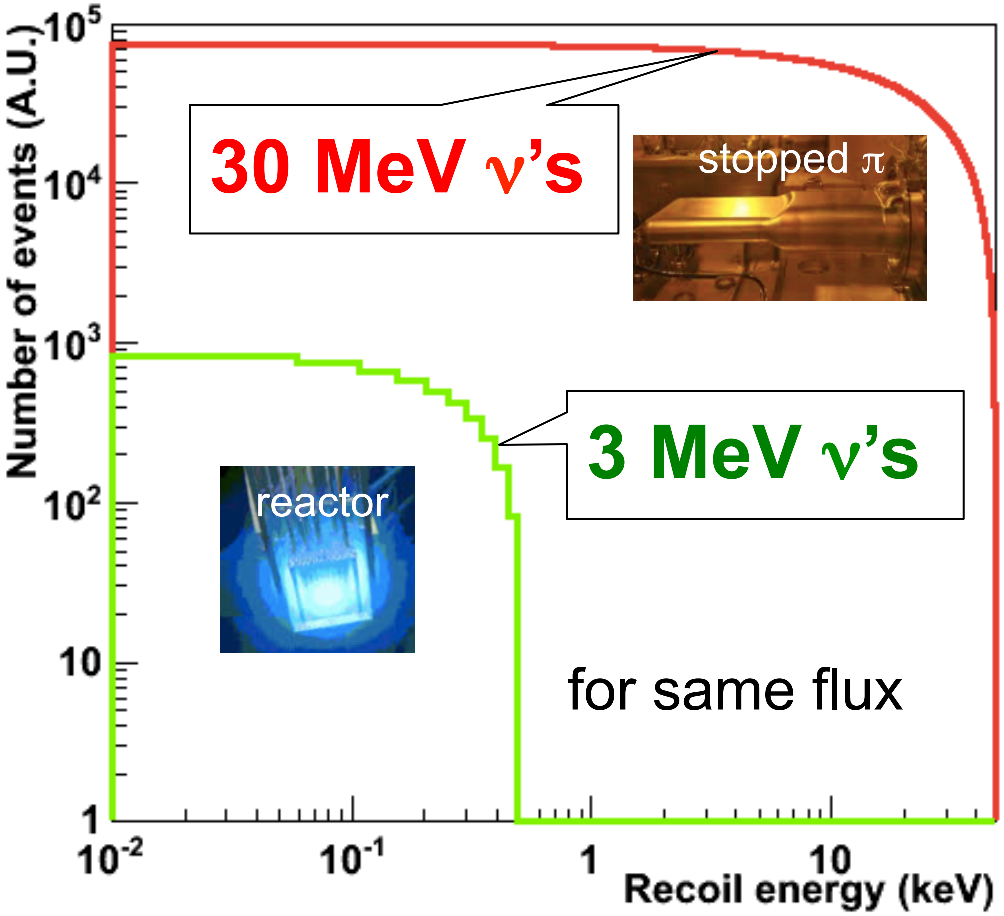
You need a neutrino source
and a detector

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, ...

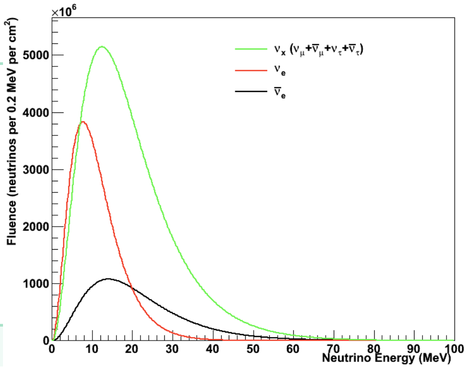
Both **cross-section and maximum recoil energy increase with neutrino energy**:





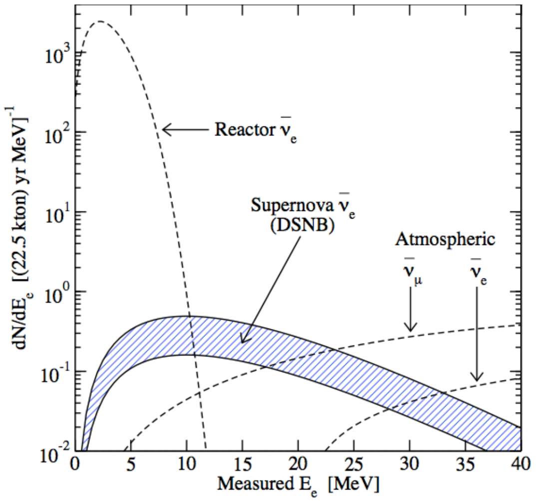
Want energy as large as possible while satisfying coherence condition: $Q \lesssim \frac{1}{R}$ (<~ 50 MeV for medium A)

Supernova burst neutrinos



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

Supernova relic neutrinos

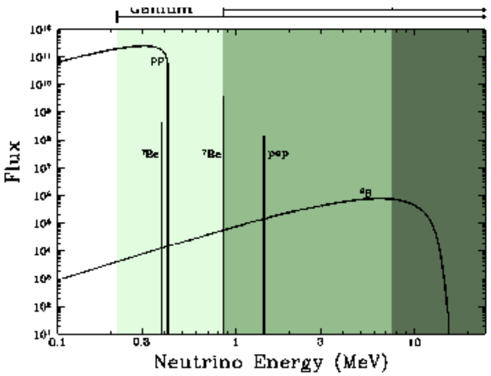


All flavors, low flux

Atmospheric neutrinos

Some component at low energy

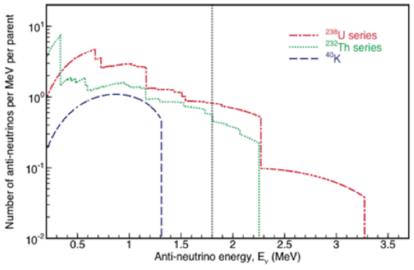
Solar neutrinos



Most flux below 1 MeV

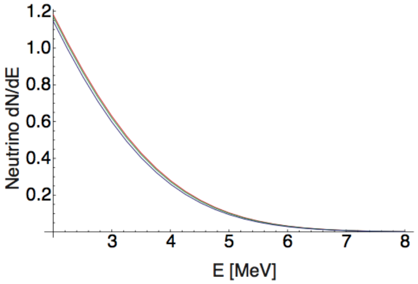
CEvNS eventually seen in DM expts

Geoneutrinos



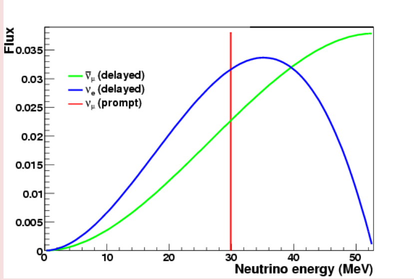
Very low energy

Reactors



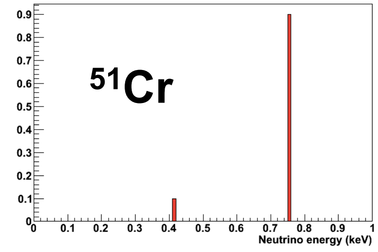
Low energy, but very
high fluxes possible; ~continuous
source, good bg rejection needed

Stopped pions
(decay at rest)



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

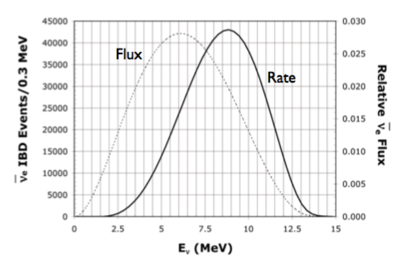
Radioactive sources
(electron capture)



Portable; can get very short
baseline, monochromatic

Low energy challenging

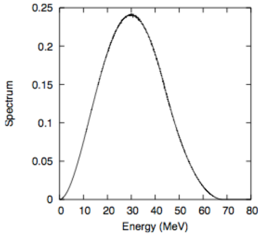
Beam-induced radioactive sources
(IsoDAR)



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

Does not exist yet

Low-energy beta beams

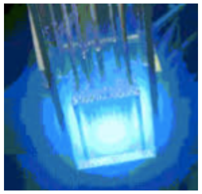
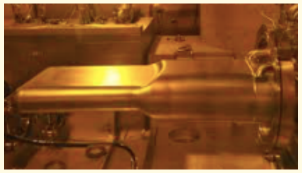


γ=10
boosted
^{18}Ne ν_e

Tunable energy, but
not pulsed

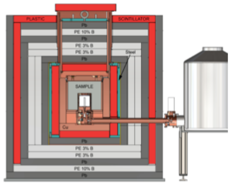
Does not exist yet

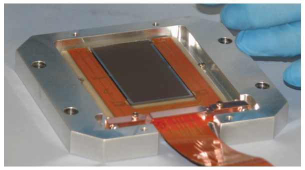
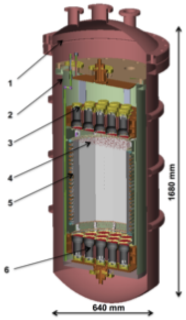
Reactor vs stopped-pion for CEvNS

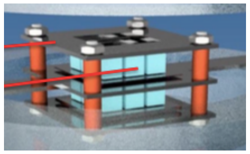
Source	**Flux/ ν's per s**	**Flavor**	**Energy**	**Pros**	**Cons**
Reactor 	2e20 per GW	nuebar	few MeV	• huge flux	• lower xscn • require very low threshold • CW
Stopped pion 	1e15	numu/ nue/ nuebar	0-50 MeV	• higher xscn • higher energy recoils • pulsed beam for bg rejection • multiple flavors	• lower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

Proposed Reactor CEvNS Experiments

Experiment	Technology	Location
CONUS	HPGe	Germany
Ricochet	Ge, Zn bolometers	France
CONNIE	Si CCDs	Brazil
RED	LXe dual phase	Russia
Nu-Cleus	Cryogenic $CaWO_4$, Al_2O_3 calorimeter array	Europe
MINER	Ge iZIP detectors	USA

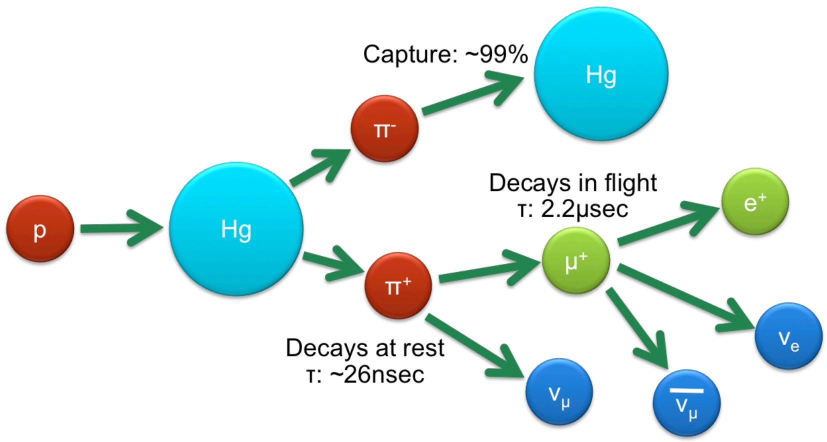


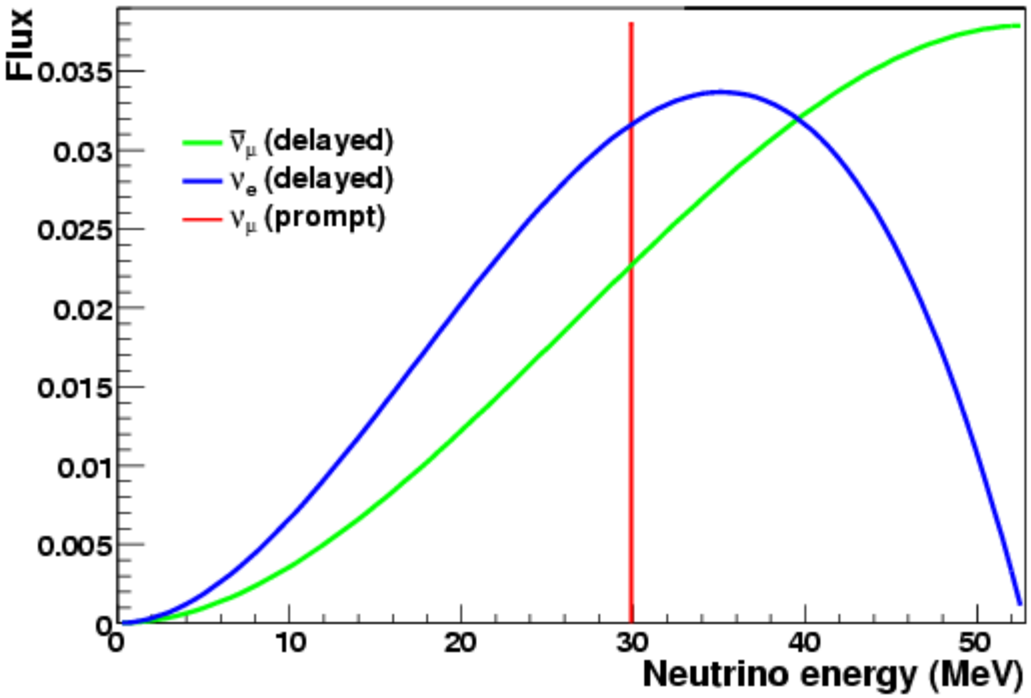






Novel low-background, low-threshold technologies

Stopped-Pion (πDAR) Neutrinos





$$\pi^{+} \longrightarrow \mu^{+} + \nu_{\mu}$$

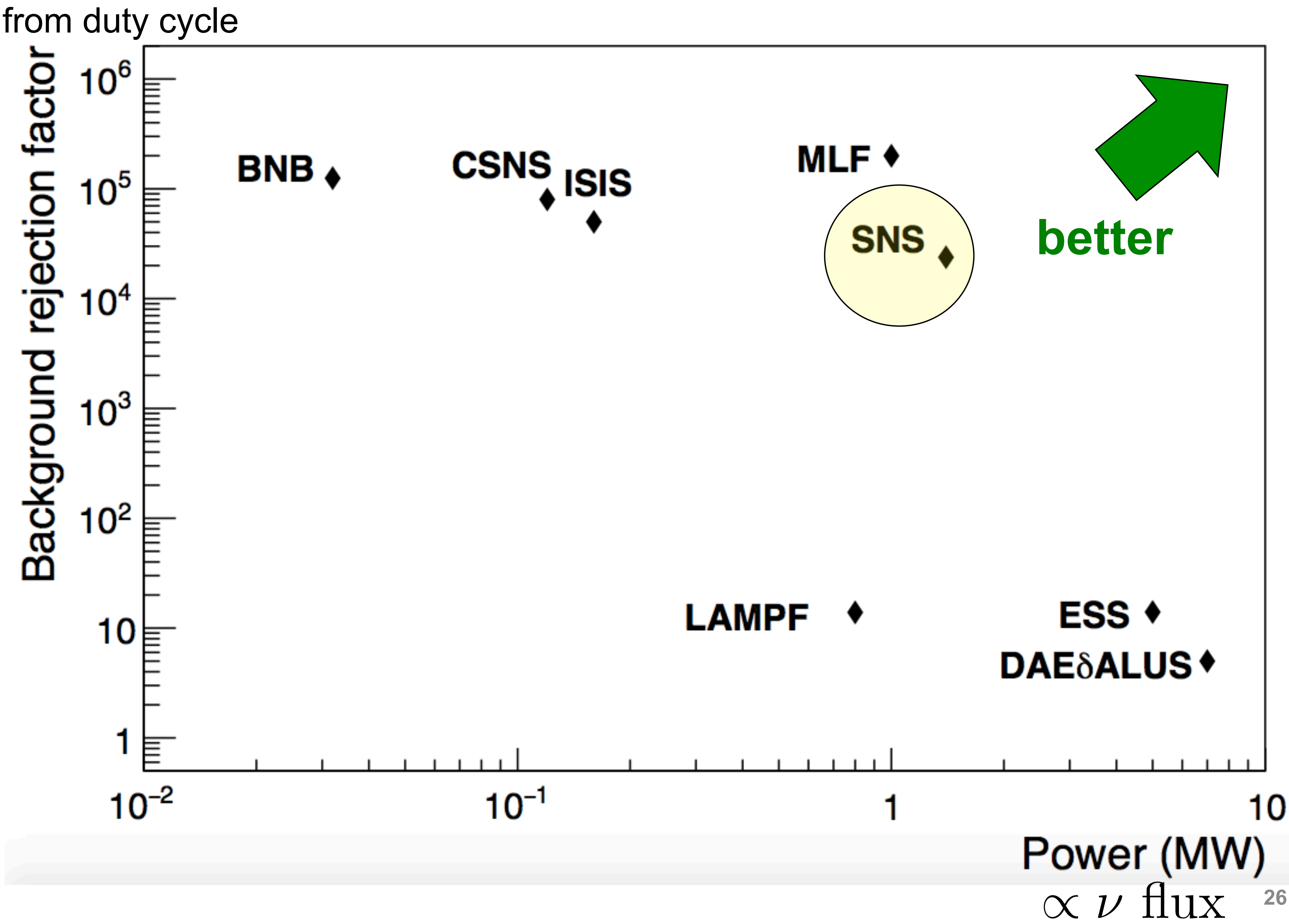
2-body decay: monochromatic 29.9 MeV ν_μ
PROMPT

$$\downarrow$$

$$\mu^{+} \longrightarrow e^{+} + \bar{\nu}_{\mu} + \nu_{e}$$

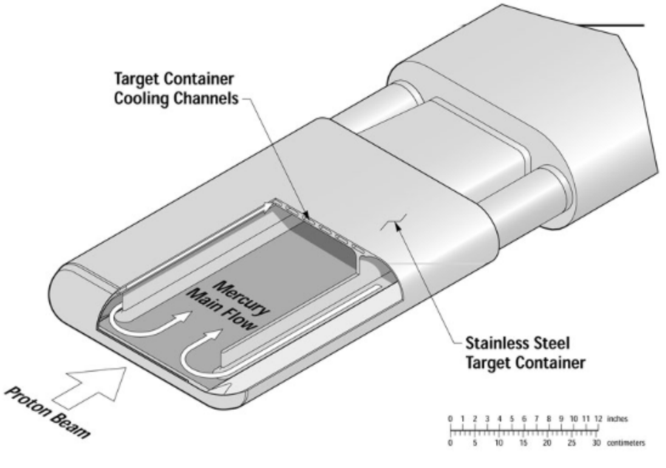
3-body decay: range of energies between 0 and $m_\mu/2$
DELAYED (2.2 μs)

Comparison of pion decay-at-rest ν sources



Spallation Neutron Source

Oak Ridge National Laboratory, TN

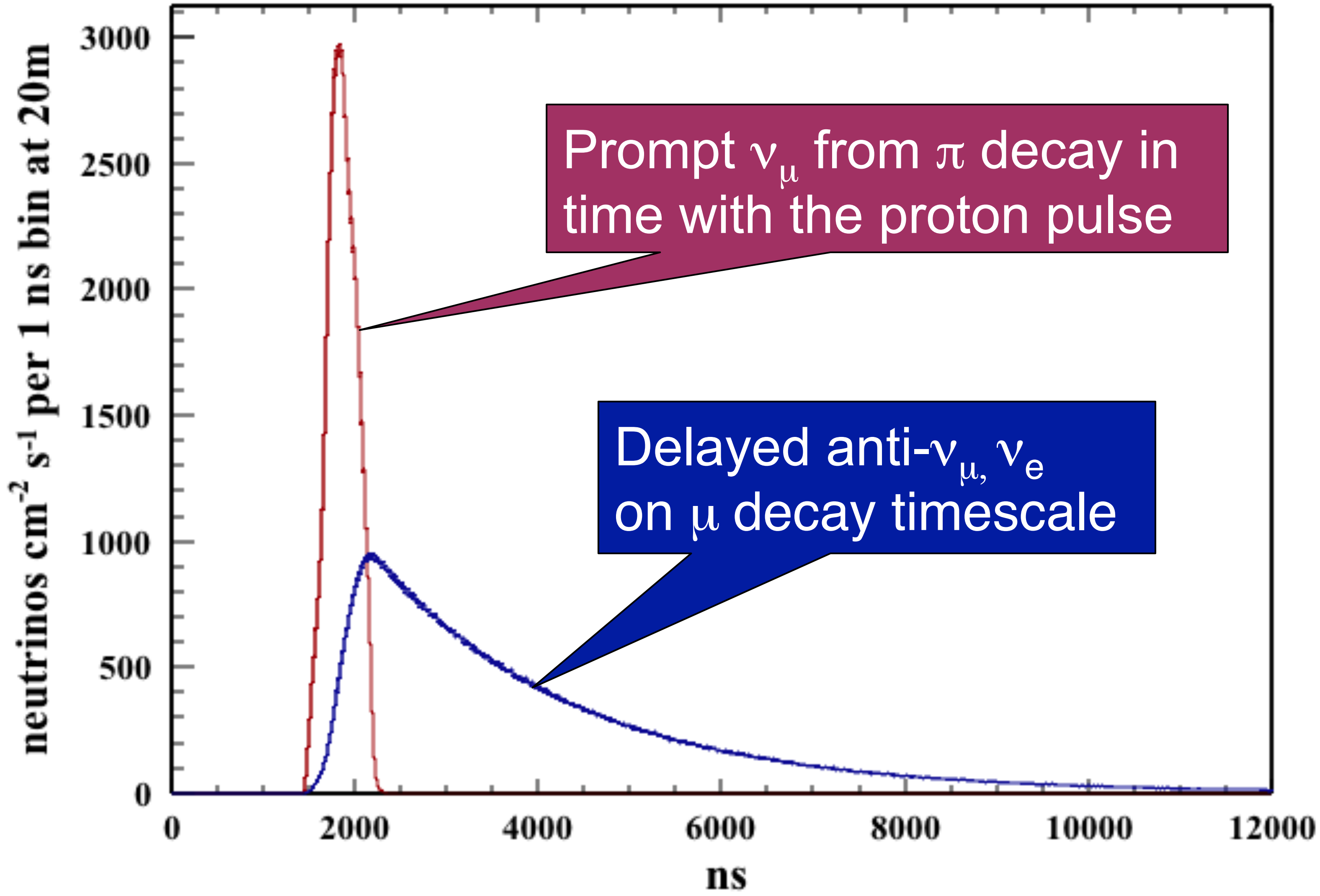


Proton beam energy: 0.9-1.3 GeV
Total power: 0.9-1.4 MW
Pulse duration: 380 ns FWHM
Repetition rate: 60 Hz
Liquid mercury target

The neutrinos are free!

Time structure of the SNS source

60 Hz *pulsed* source



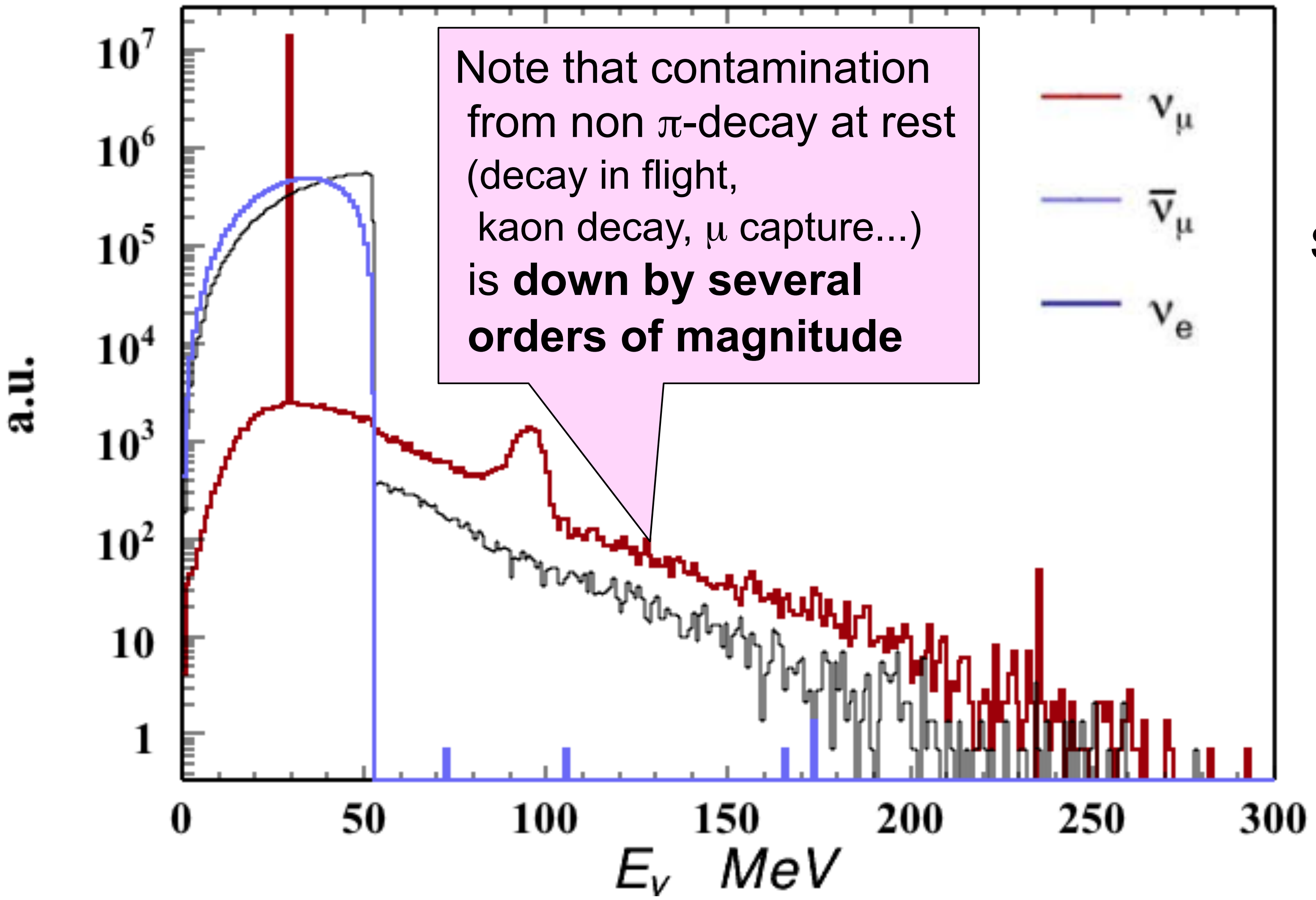
Prompt ν_μ from π decay in time with the proton pulse

Delayed anti-$\nu_{\mu,}$ ν_e on μ decay timescale

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



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

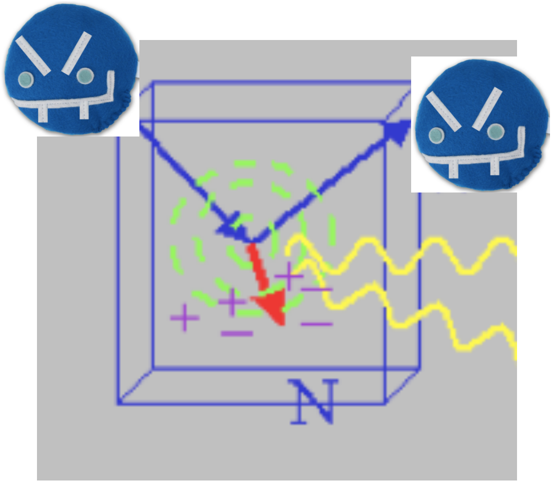
SNS flux (1.4 MW):
430 x 10^5 ν/cm²/s
@ 20 m

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

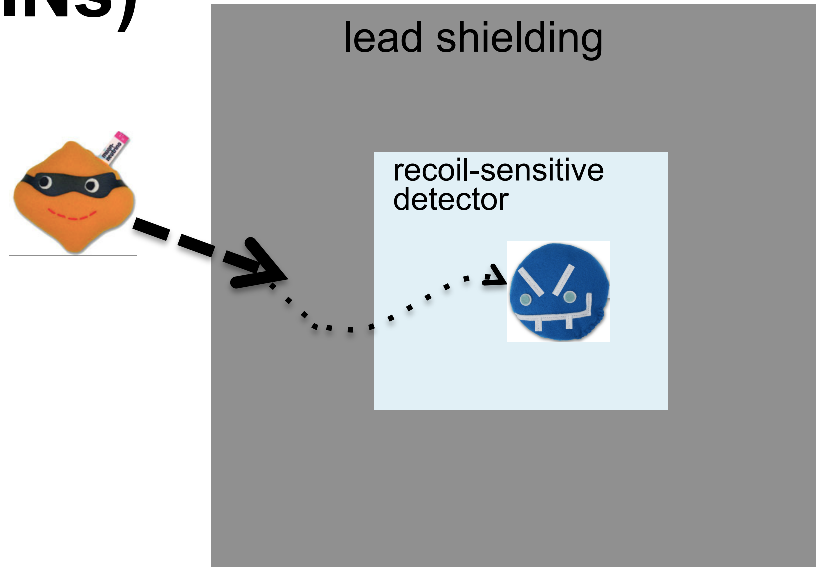
$\searrow$

1n, 2n emission

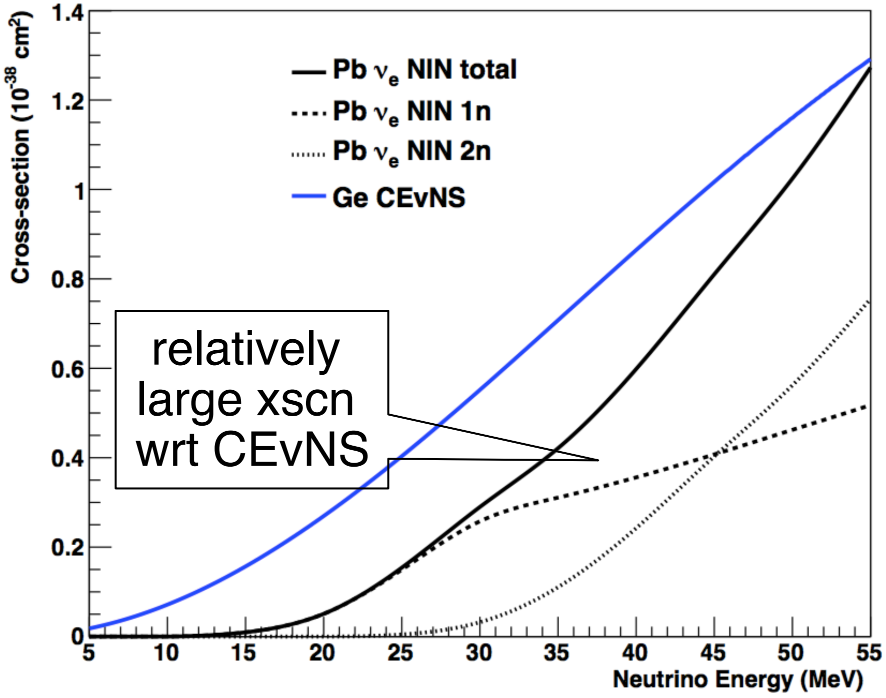
$\nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{208}\mathrm{Pb}^* + \nu_x$ NC

$\searrow$

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]



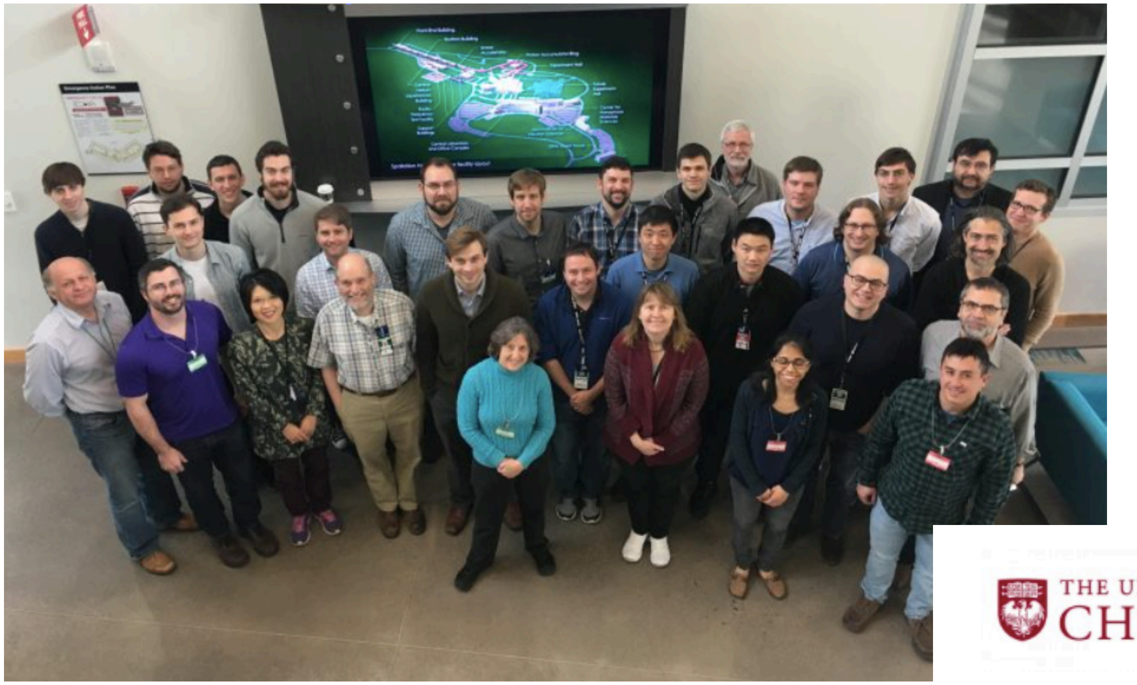
relatively large xscn wrt CEvNS

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

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 UT KNOXVILLE

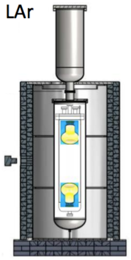
TUNL

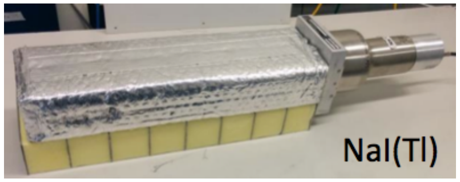
W UNIVERSITY of WASHINGTON

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

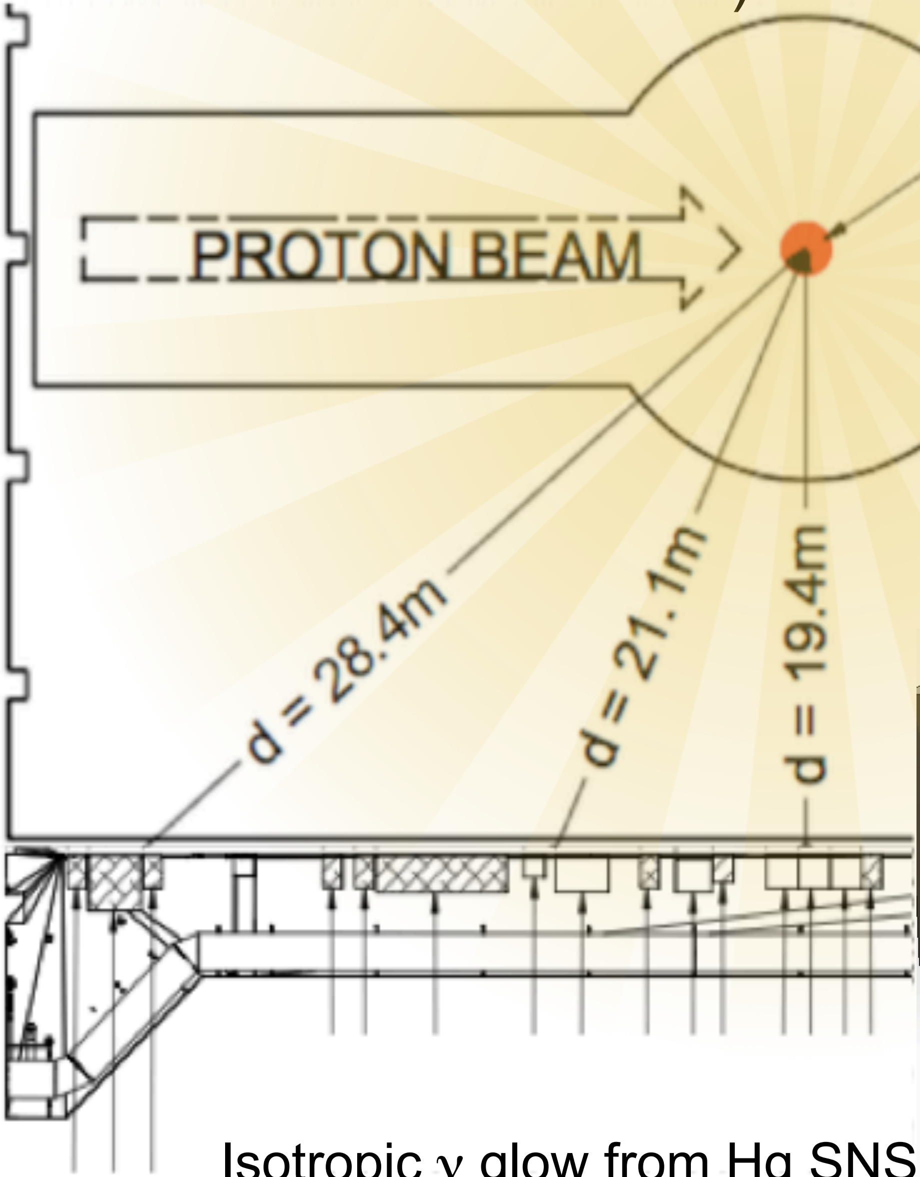
Multiple detectors for N^2 dependence of the cross section





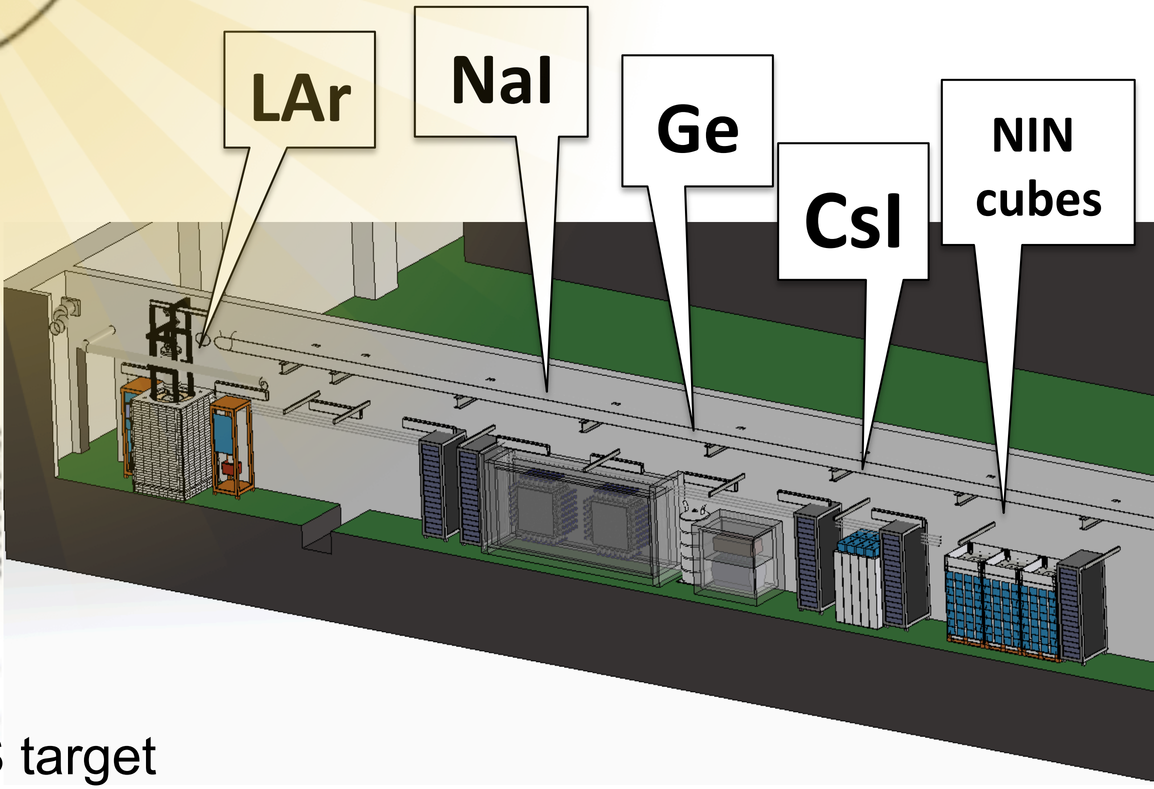
Siting for deployment in SNS basement

(measured neutron backgrounds low,
~ 8 mwe overburden)

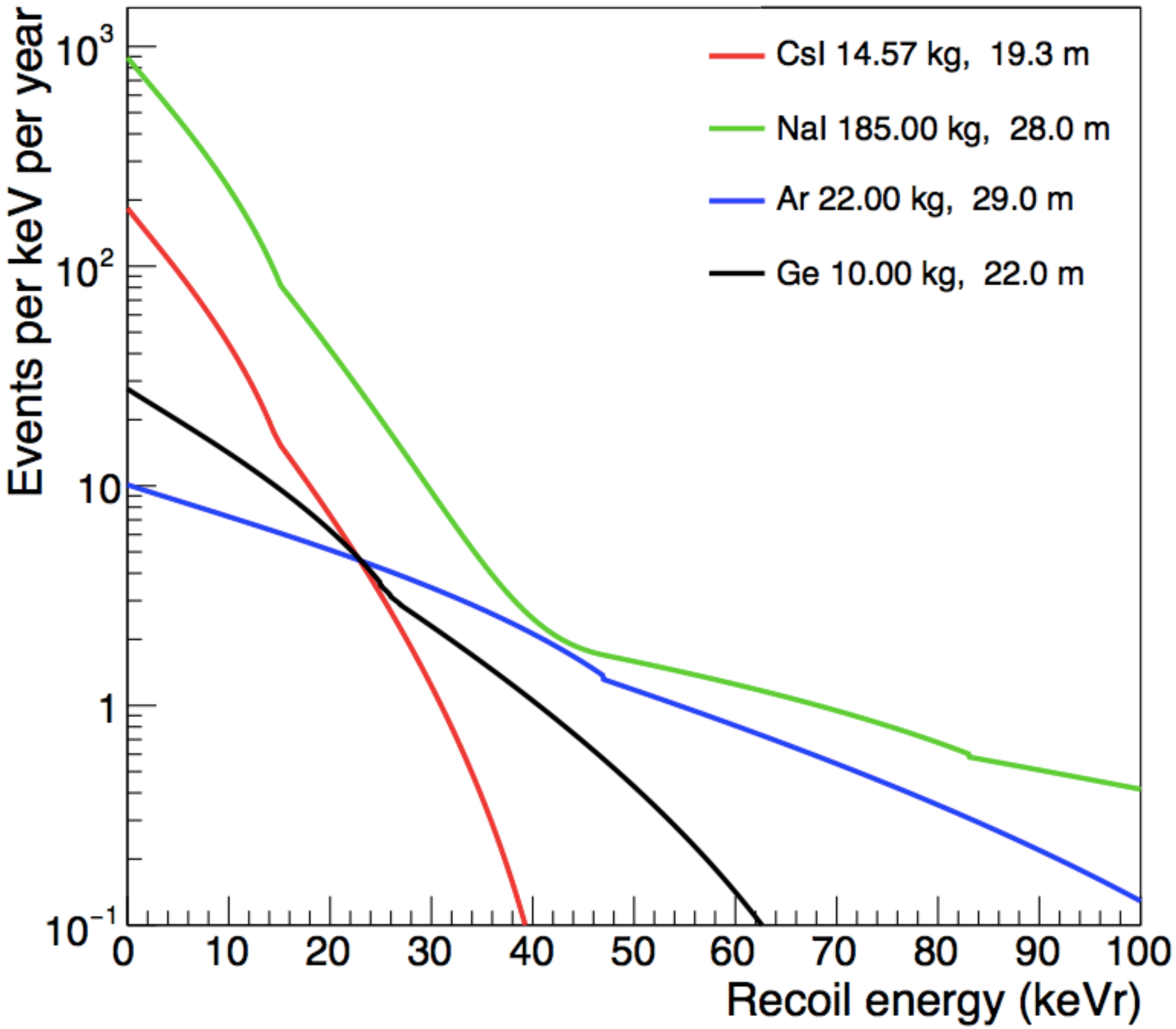


Isotropic ν glow from Hg SNS target

View looking
down “Neutrino Alley”



Expected recoil energy distribution

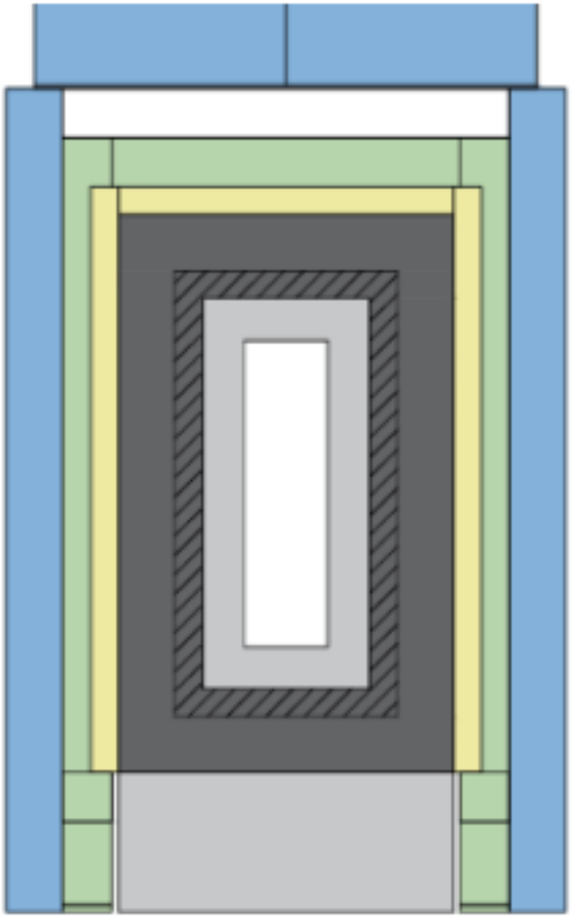


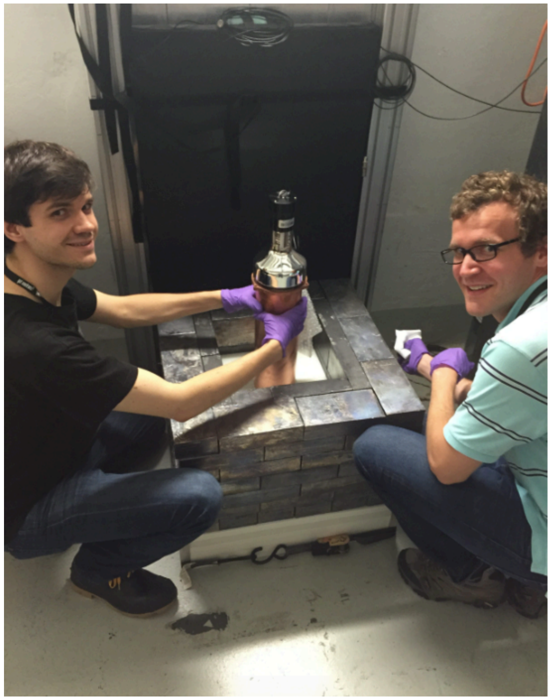
Includes prompt and delayed, all flavors, first 6000 ns

OUTLINE

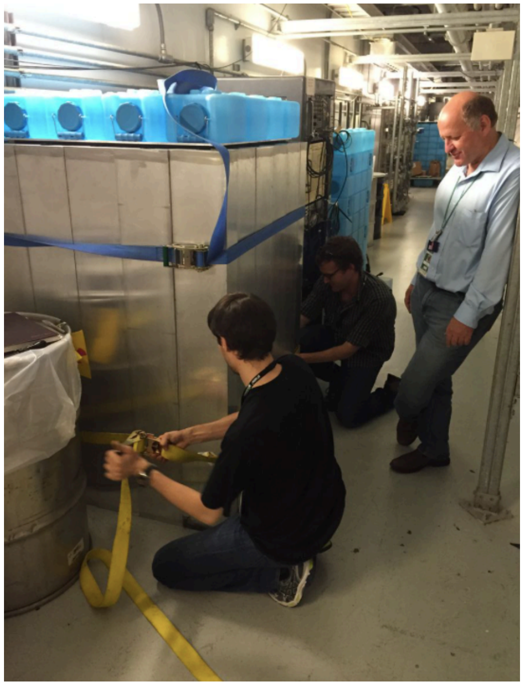
- Neutrinos and neutrino interactions
- Coherent elastic neutrino-nucleus scattering (CEvNS)
- Why measure it? Physics motivations
  (short and long term)
- How to measure CEvNS
- The COHERENT experiment at the SNS
- **First light with CsI[Tl]**
- Status and prospects for COHERENT

The CsI Detector in Shielding in Neutrino Alley at the SNS





A hand-held detector!

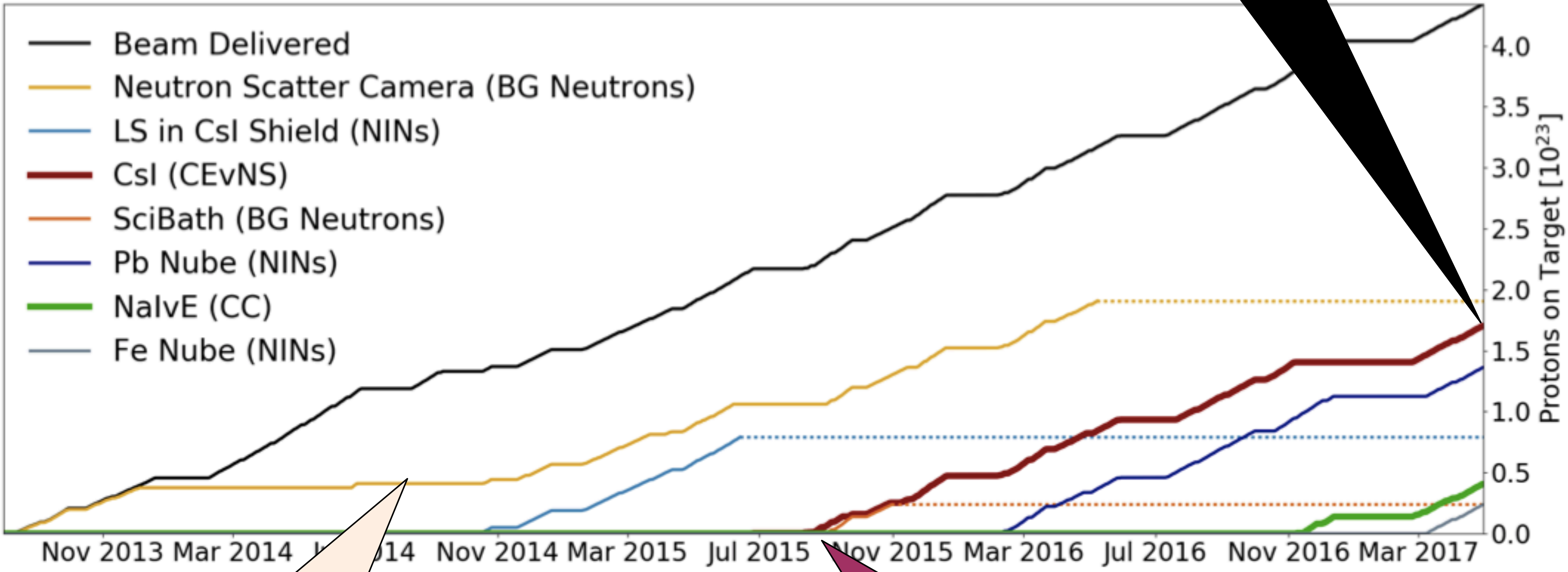


Almost wrapped up...

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)

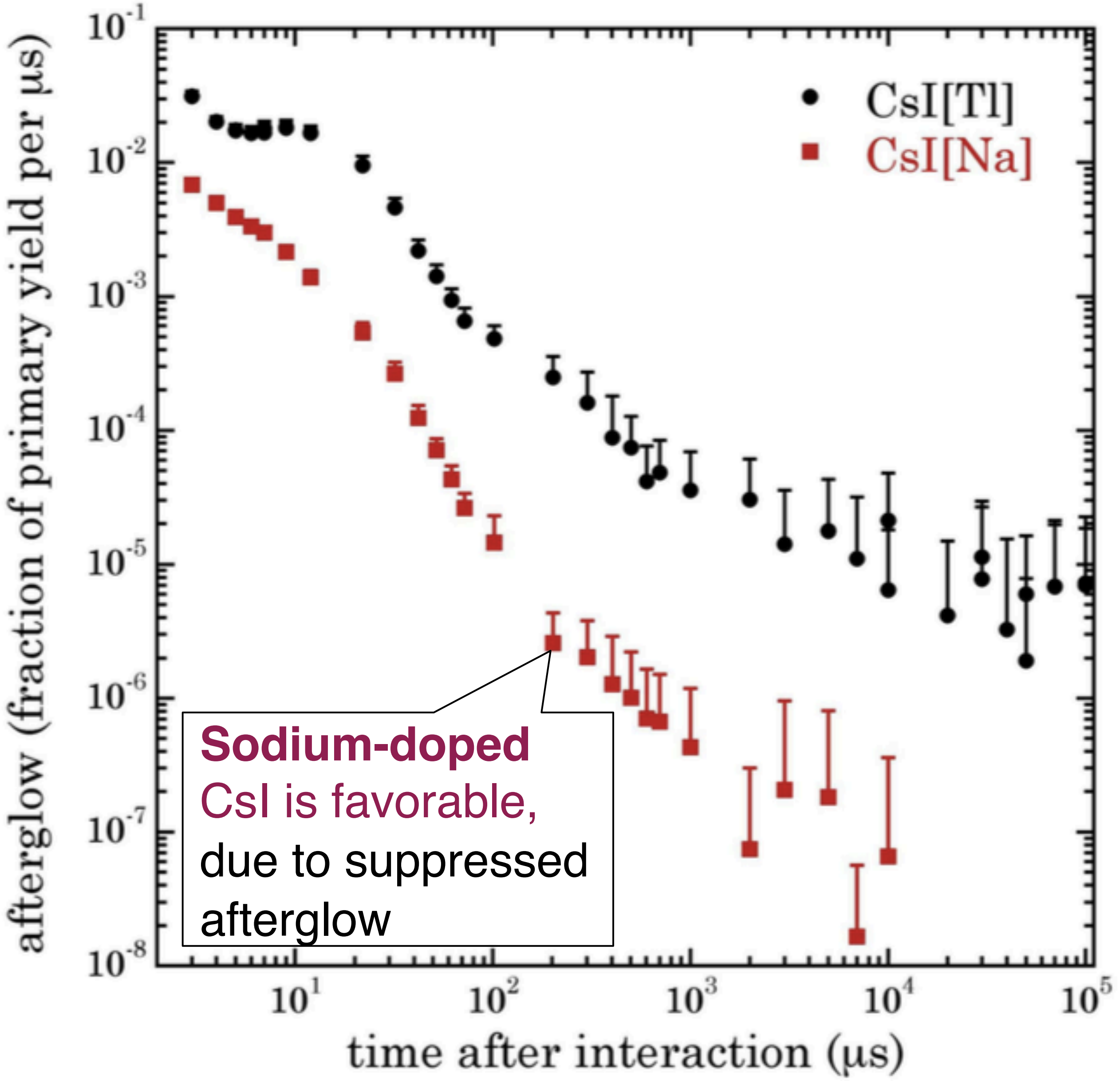


Neutron background data-taking for ~2 years before first CEvNS detectors

CsI data-taking starting summer 2015

The First COHERENT Result: CsI[Na]

Led by U. Chicago group



Sodium-doped CsI is favorable, due to suppressed afterglow

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

Scintillating crystal

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

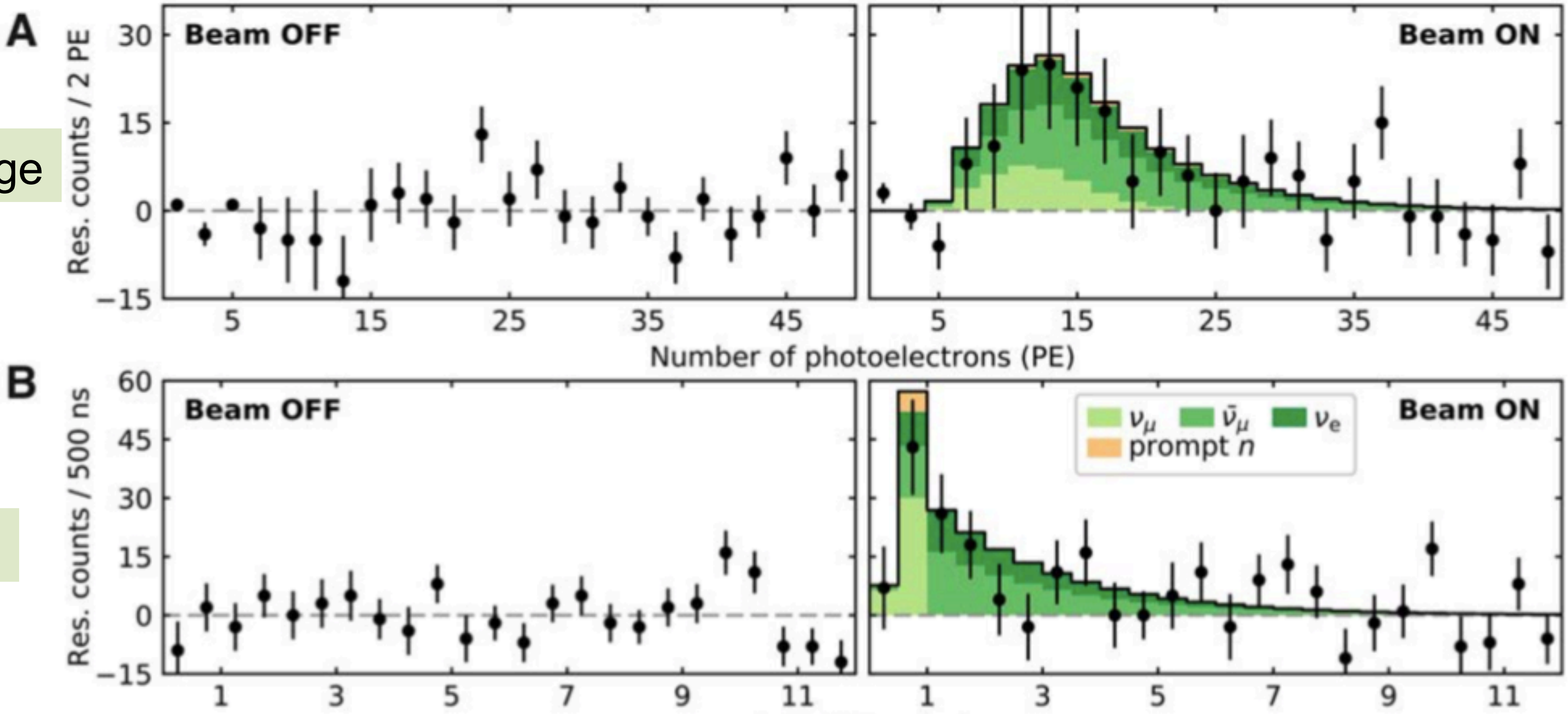
2 kg test crystal @U. Chicago.

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...

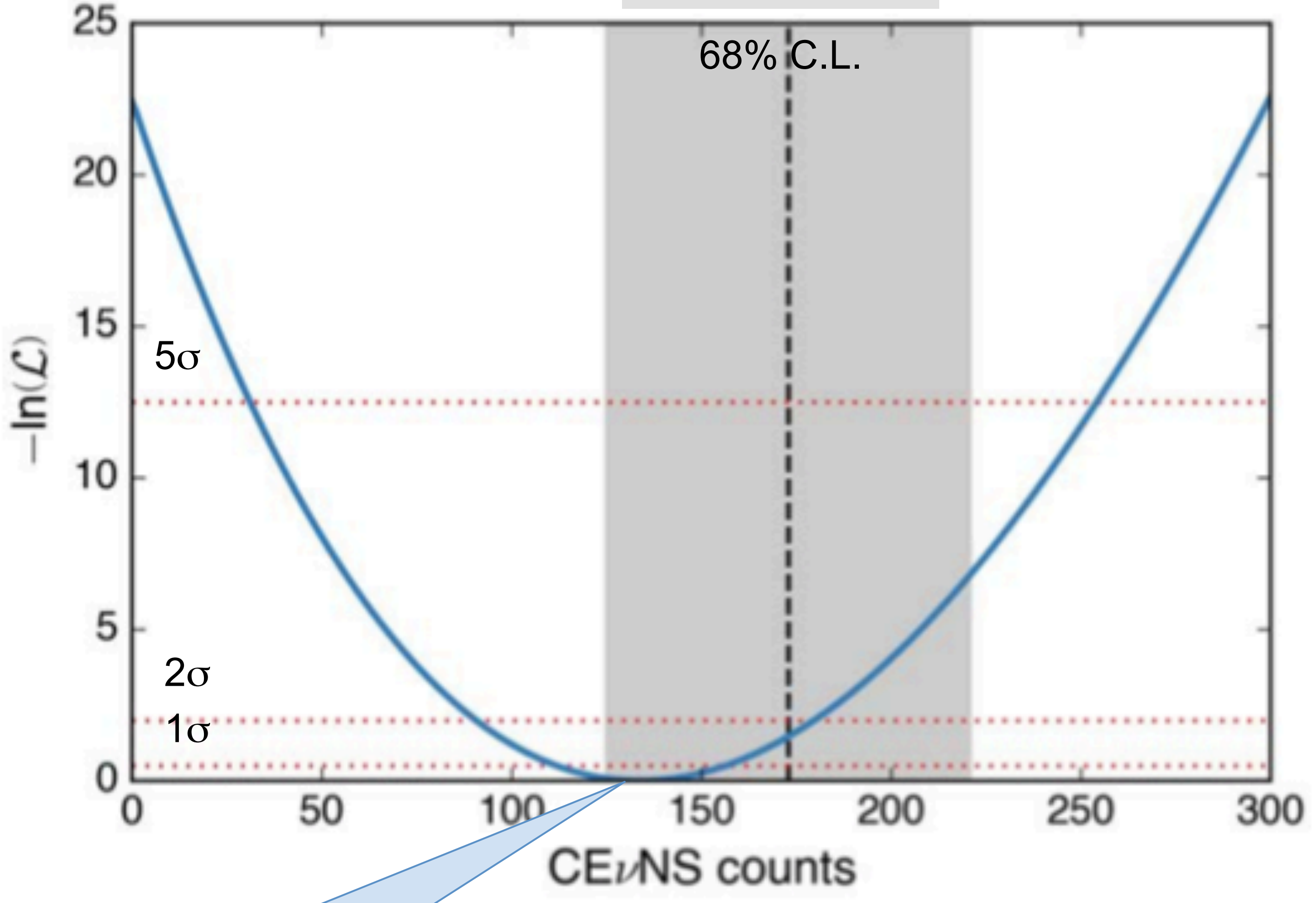
+ See all authors and affiliations

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

PRE 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



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

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

Signal, background, and uncertainty summary numbers

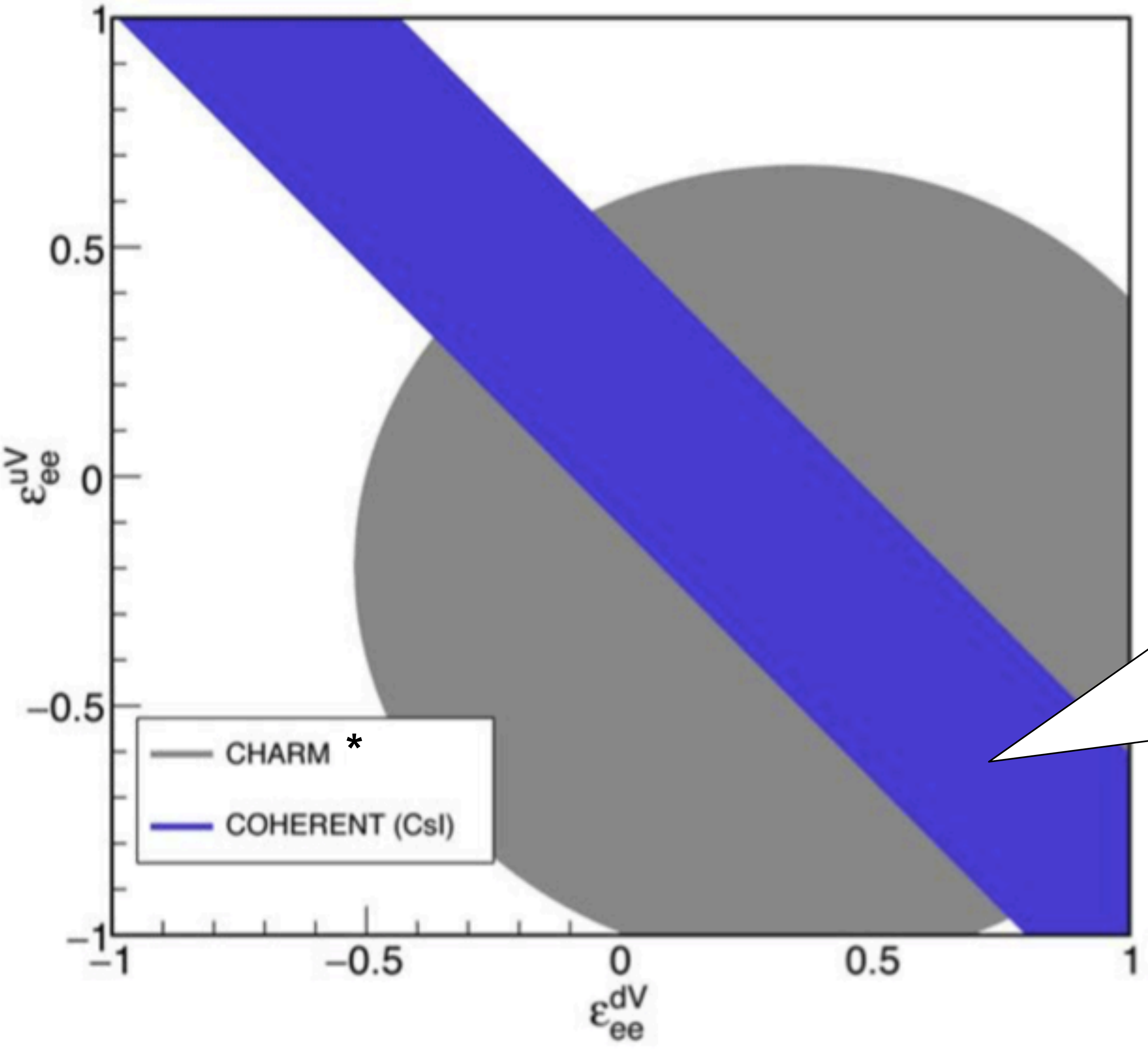
6 ≤ PE ≤ 30, 0 ≤ t ≤ 6000 ns

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 constraints for current CsI data set:



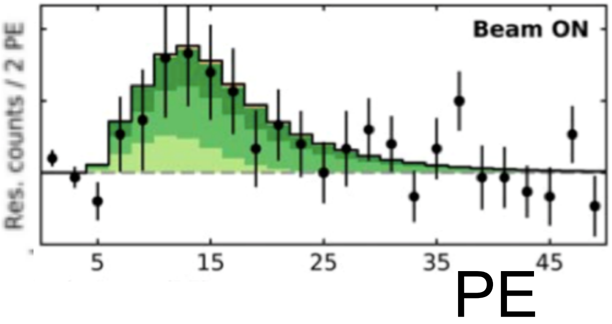
- Assume all other ε's zero

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

See also Coloma et al., arXiv:1708.02899

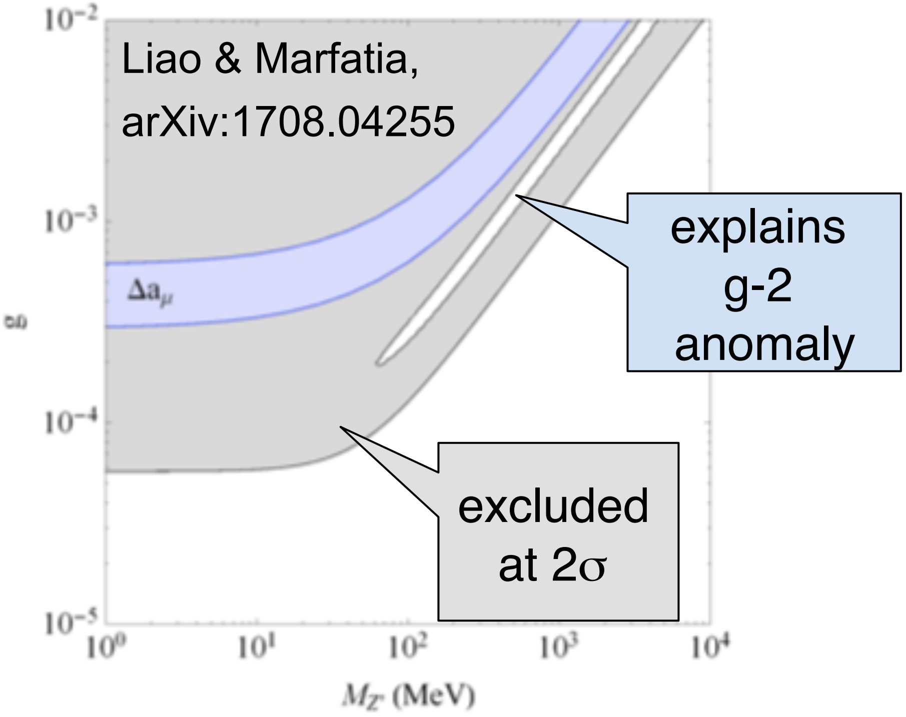
*CHARM constraints apply only to heavy mediators

This is the first measurement of low-energy NC neutrino-hadron interaction with **event-by-event *spectral information***



Some NC on d, ^{12}C, and a few CC in this energy range, but no final state energies J.A. Formaggio and G. Zeller, RMP 84 (2012) 1307-1341

Recent interpretations for particle & nuclear physics

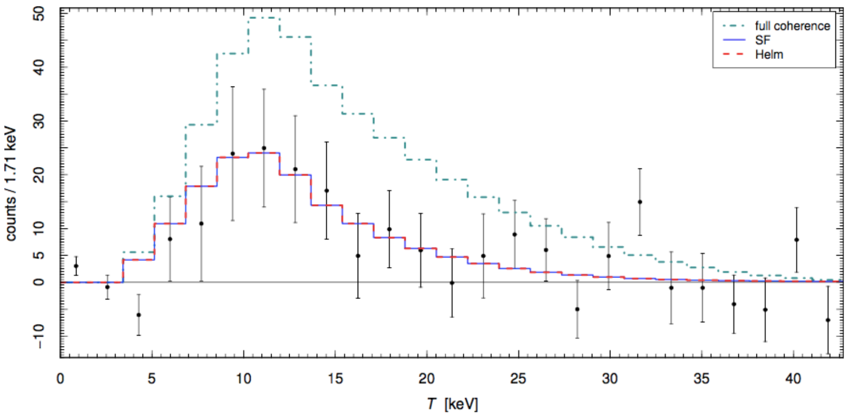


Liao & Marfatia, arXiv:1708.04255

explains g-2 anomaly

excluded at 2σ

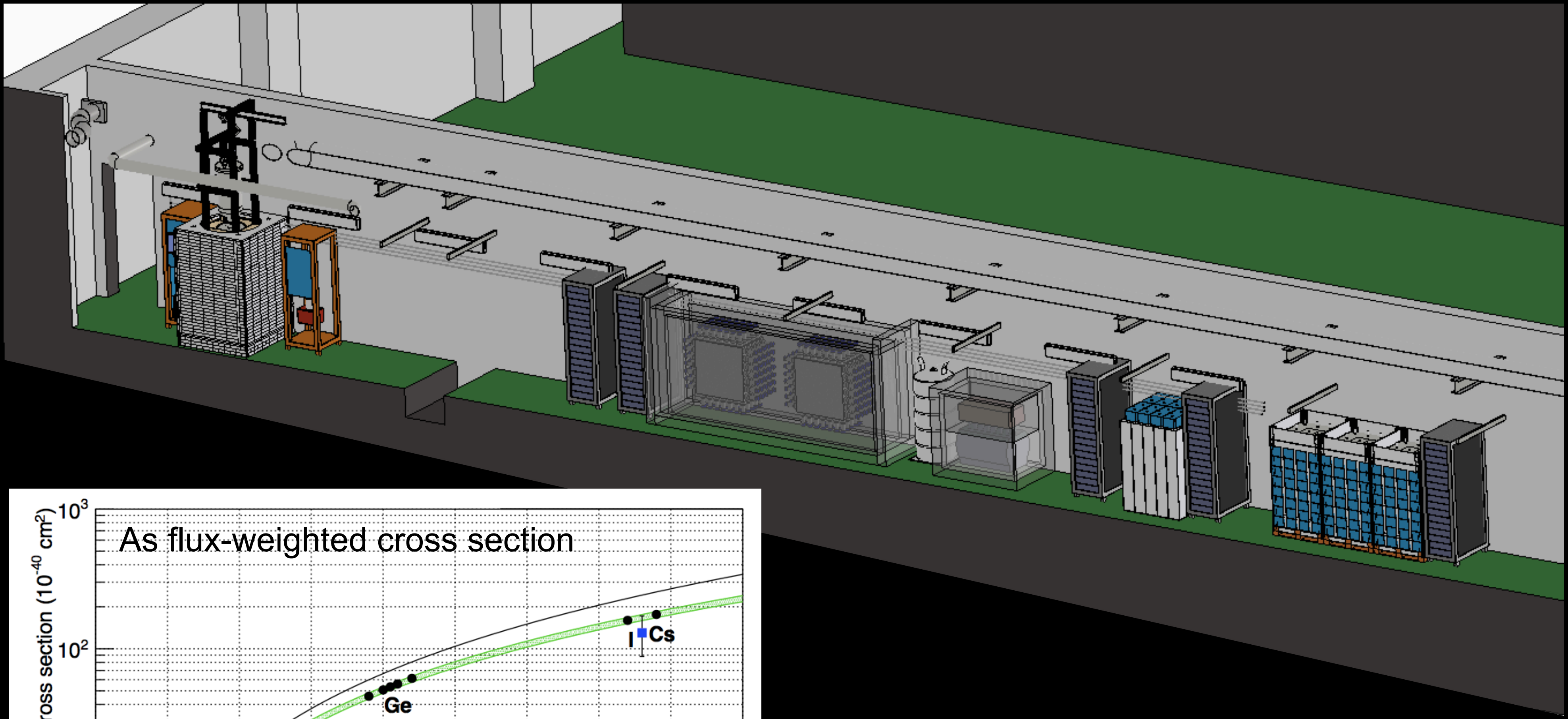
Cadeddu et al., arXiv:1710.02730

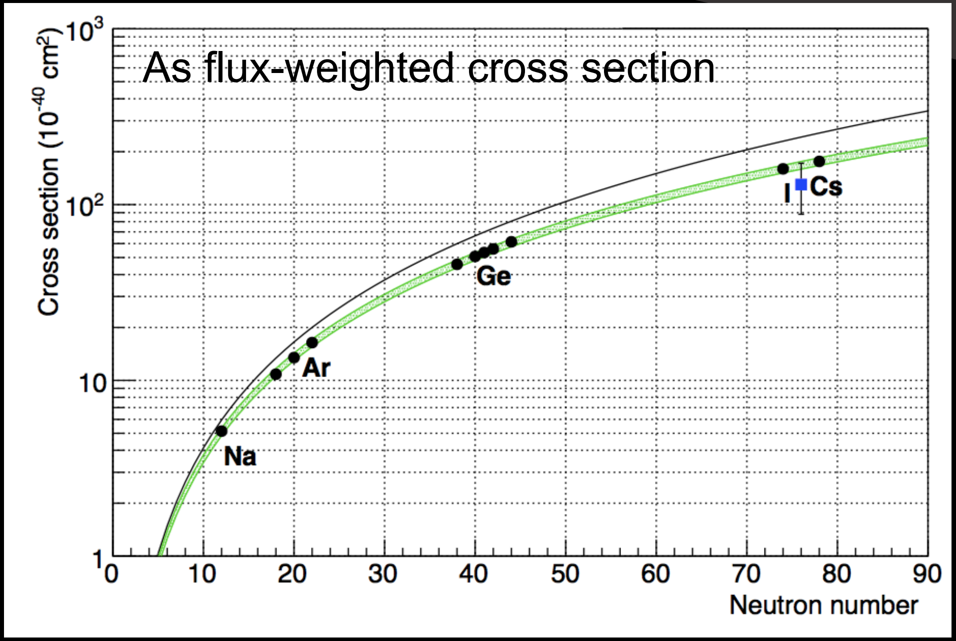


$$R_n = 5.5^{+0.9}_{-1.1}\ \mathrm{fm}$$

More soon from COHERENT, w/spectral uncertainties

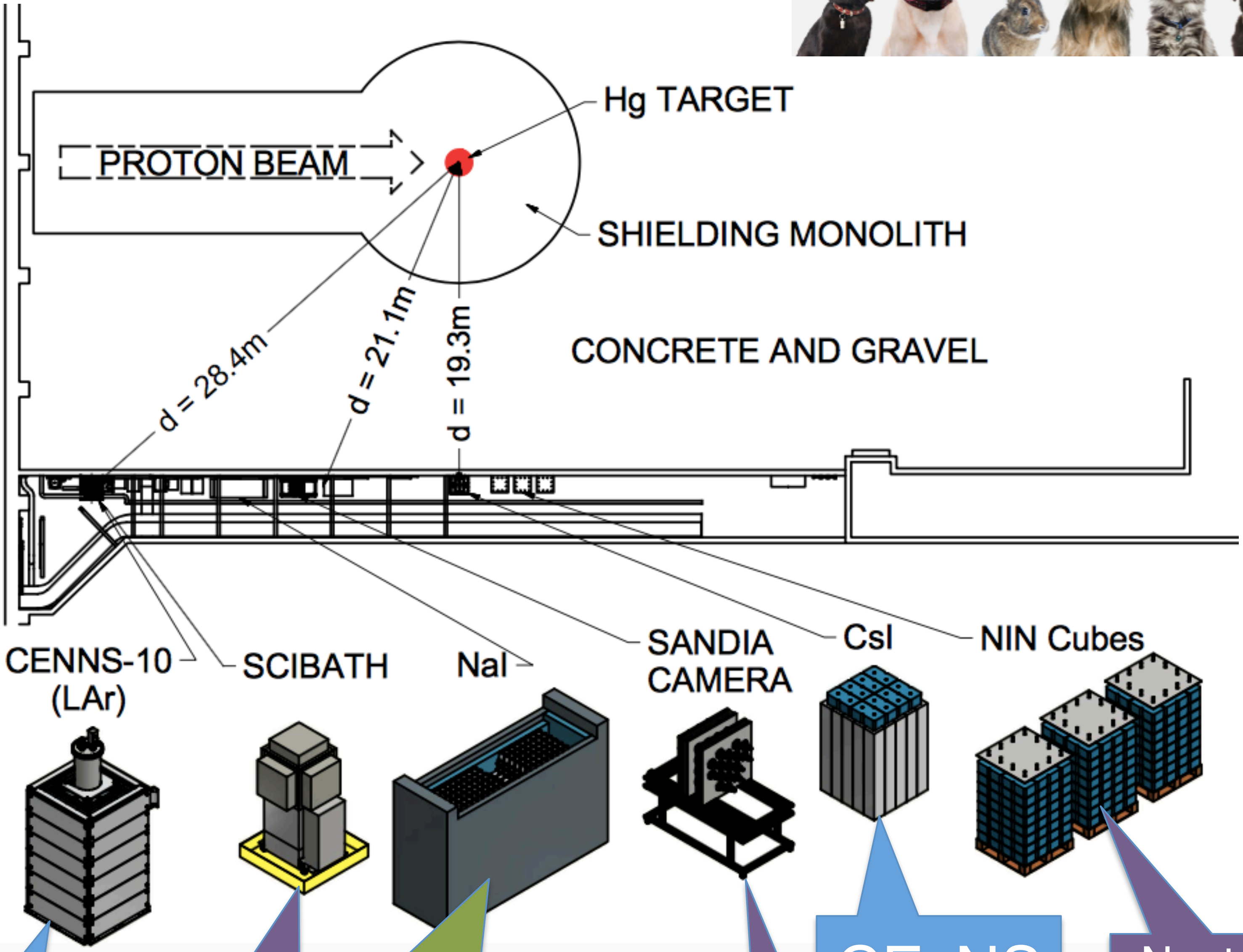
What's Next for COHERENT?





One down...
more to go

Deployments so far in Neutrino Alley



CEvNS

Neutron backgrounds

ν_eCC on ^{127}I

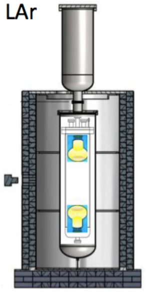
Neutron backgrounds

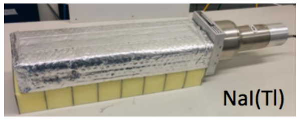
CEvNS

Neutrino-induced neutrons

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	2017
LAr	Single-phase	22	29	20	12/2016, upgraded summer 2017
NaI[Tl]	Scintillating crystal	185*/ 2000	28	13	*high-threshold deployment summer 2016

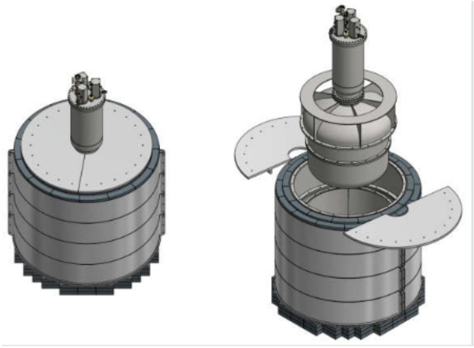


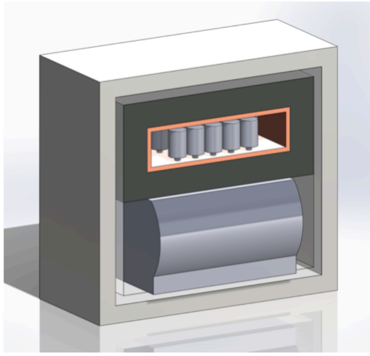


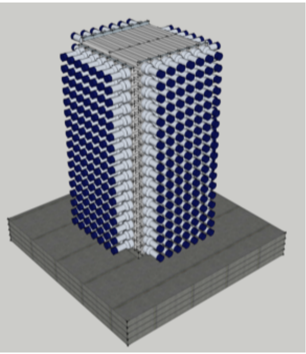
- CsI will continue running
- 185 kg of NaI installed in July 2016
    - taking data in high-threshold mode for CC on ^{127}I
    - PMT base modifications to enable low-threshold CEvNS running
- LAr single-phase detector installed in December 2016
    - upgraded w/TPB coating of PMT & Teflon, running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

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

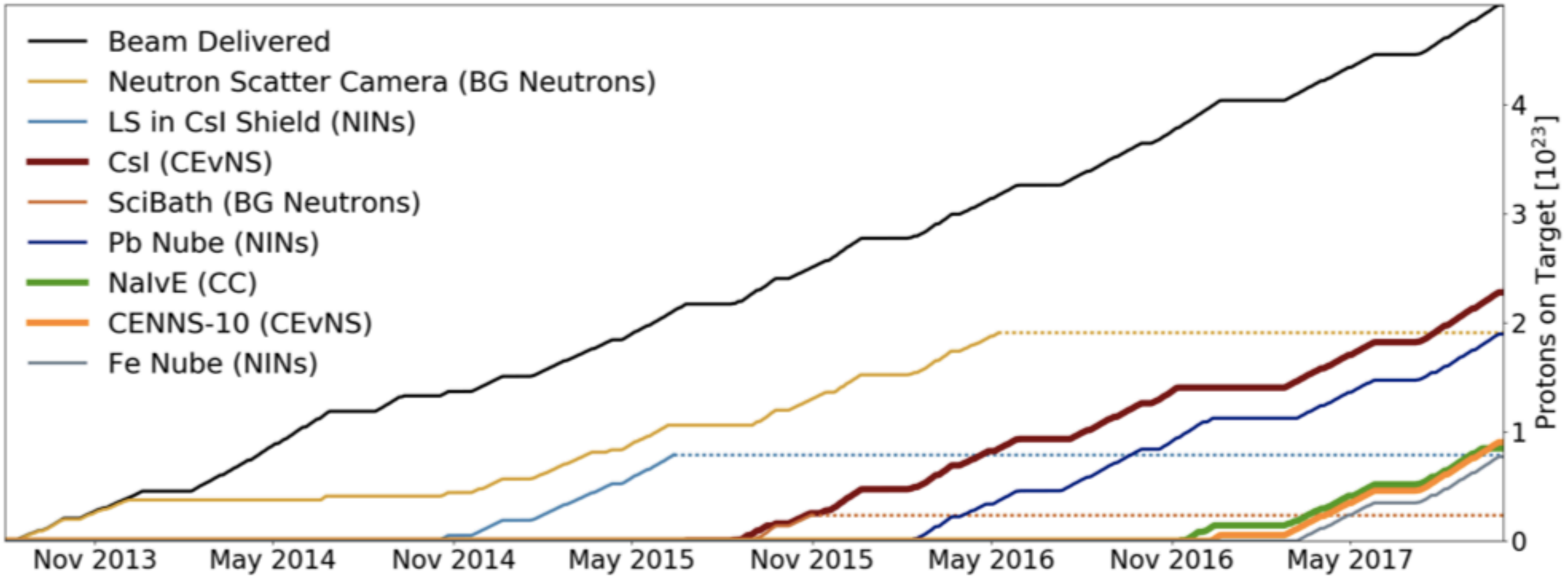


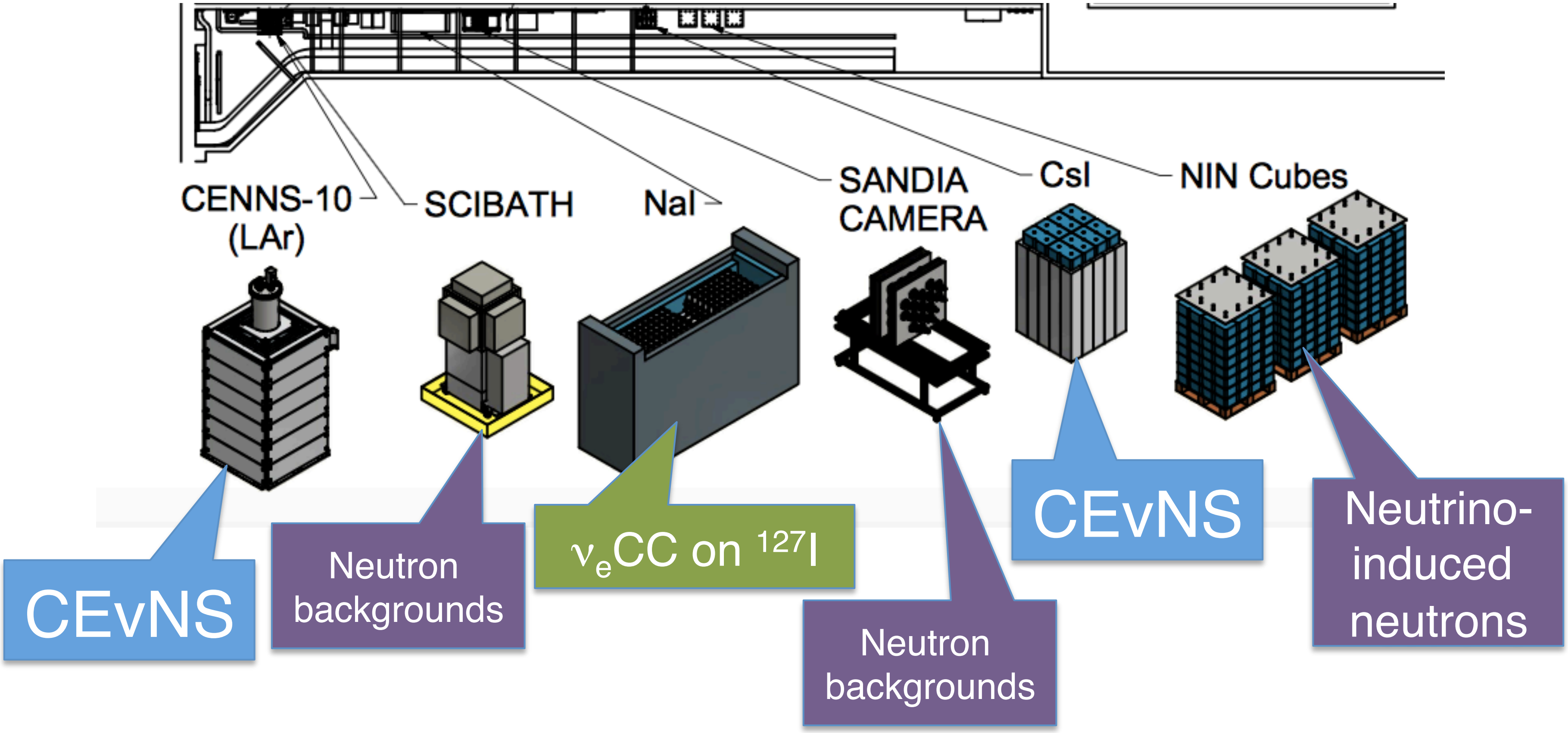




+ concepts for other targets

Protons on target delivered so far





CEvNS

Neutron backgrounds

ν_eCC on ^{127}I

Neutron backgrounds

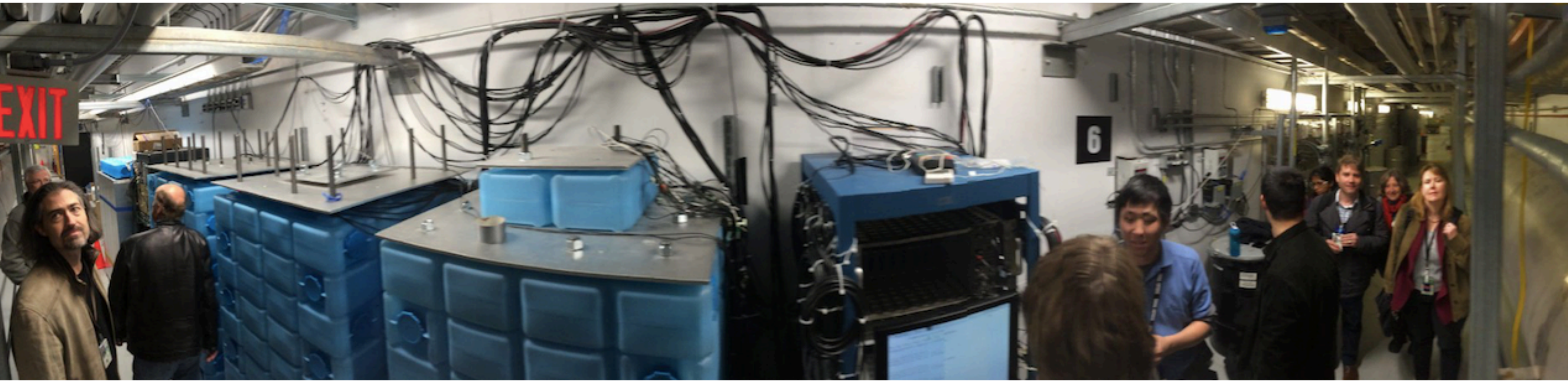
CEvNS

Neutrino-induced neutrons

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, astrophysics, 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...)