Coherent Elastic Neutrino-Nucleus Scattering:

First Light and Future Prospects of COHERENT

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For the COHERENT Collaboration

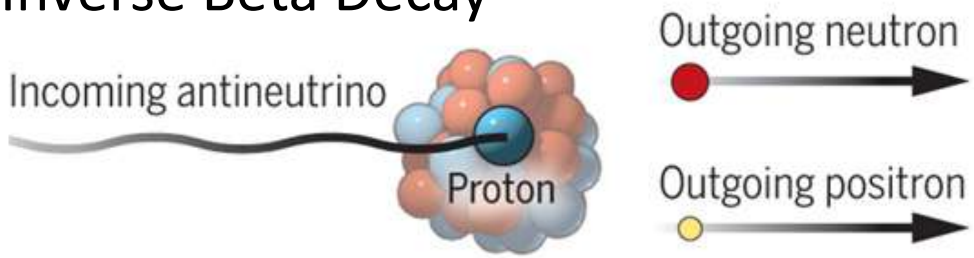
20th March 2019
XVIII International Workshop on Neutrino Telescope

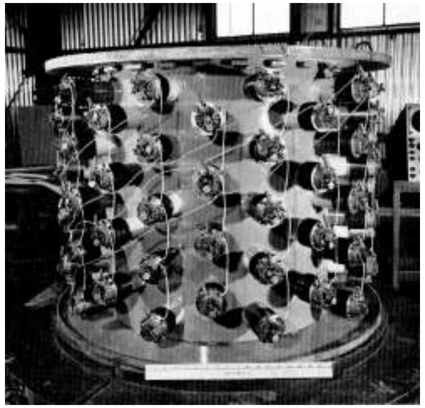
Outline

- CEνNS (Coherent Elastic ν Nucleus Scattering)
  - What is it?
  - How to detect?
- COHERENT experiment at SNS
  - Advantages of a Stopped Pion Source
  - **First Light: 1st detection of CEνNS ever!**
  - Future Prospects
- CEνNS Physics
  - Exotic physics
  - **Supernova observation** (*in honor of this conference's multimessengers theme*)
- Summary

How to Detect a Neutrino

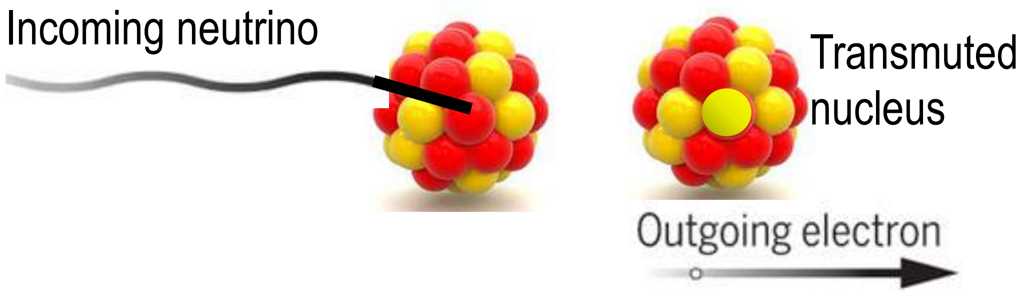
Inverse Beta Decay





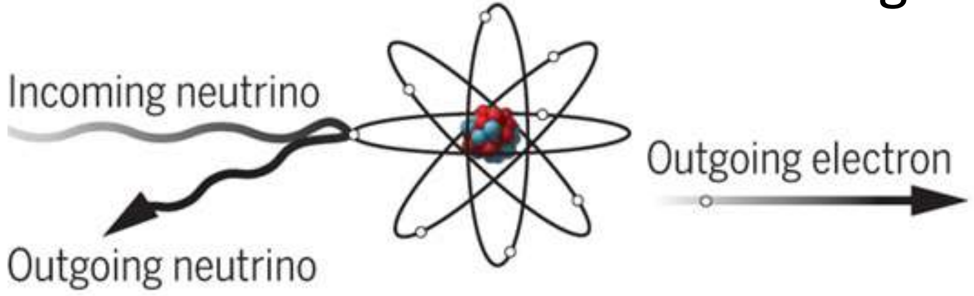
Cowan & Reines: First neutrino detector, 200L H_2O, 40 kg $CdCl_2$

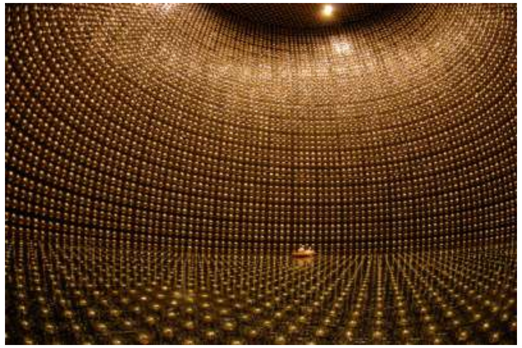
Neutrino Capture



Davis: Solar neutrino problem at Homestake, 378 kL CCl_2

Neutrino-electron elastic scattering



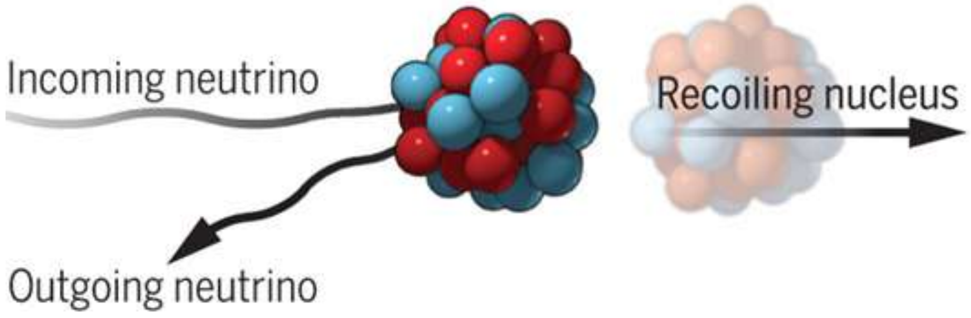


Super-Kamiokande: neutrino oscillation, 50 ML H_2O

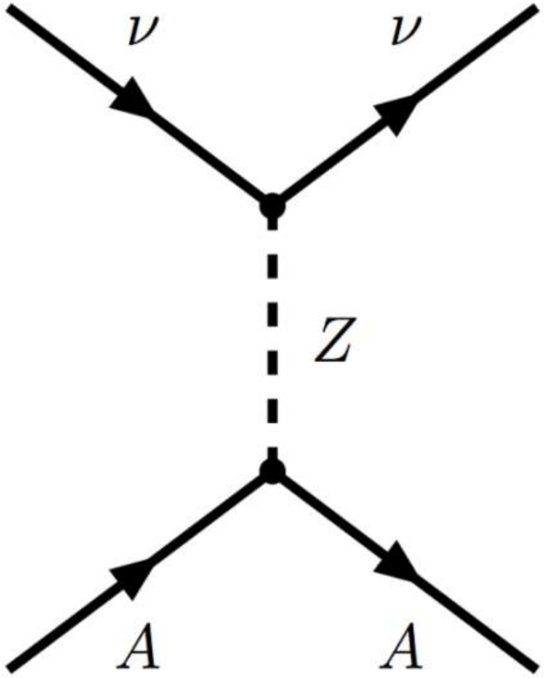
Graphics adapted from: V. Altounian, Science

Coherent Elastic ν-N Scattering

- **CEνNS (pronounced "sevens")**
- Standard Model allowed process
- Predicted in 1974
- Not observed until 2017



Graphic: V. Altounian, *Science*



- ν interacts coherently with the entire nucleus

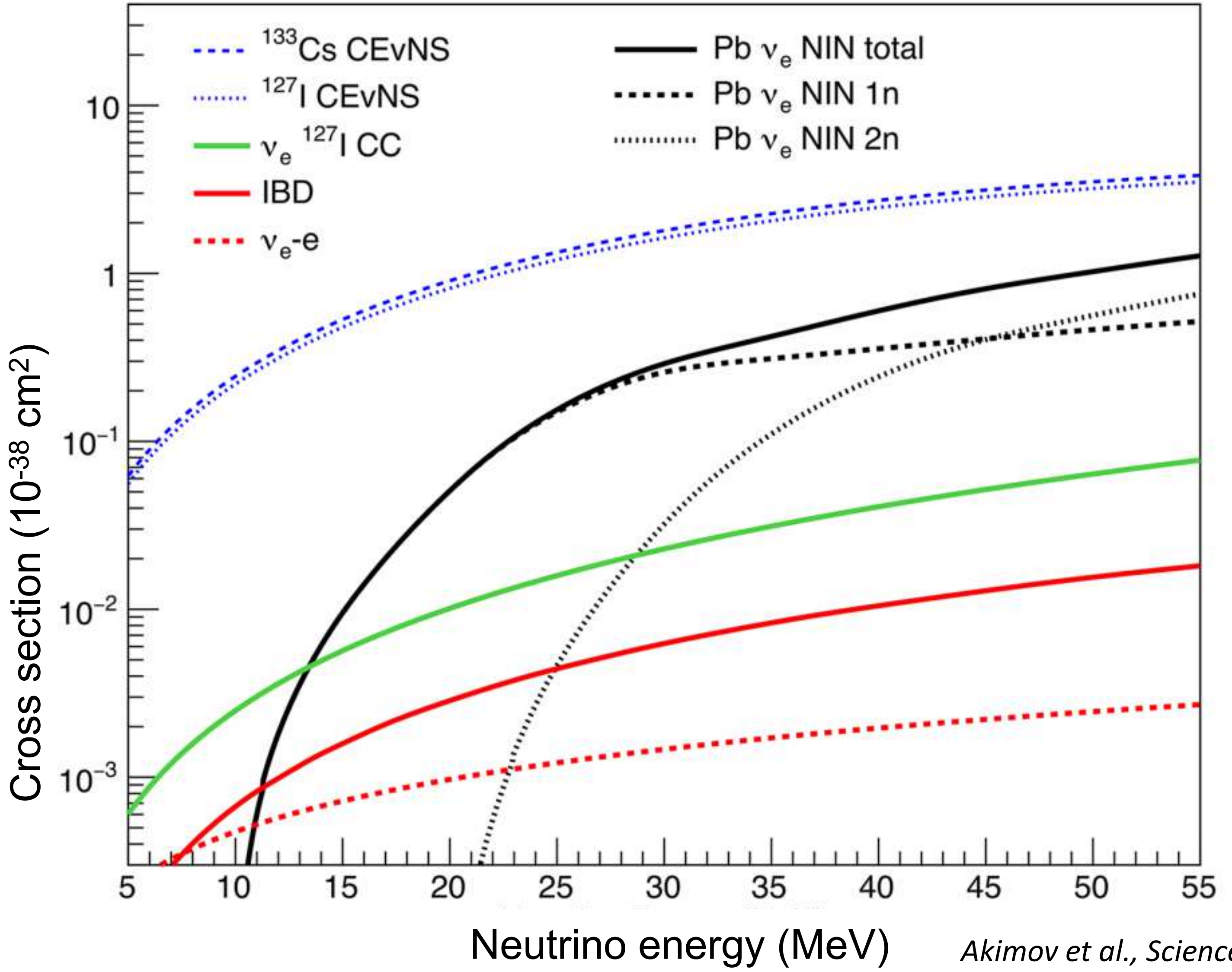
Coherent Elastic ν-N Scattering

Enhanced by *in phase* nucleon recoil

$$\sigma \approx \frac{G_F^2 N^2}{4\pi} E_\nu^2$$

CEνNS cross section can be orders of magnitude larger than that of IBD.

However…



Akimov et al., Science **357**, 1123 (2017)

So Why Hadn't We Seen It?

> 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.

*- D.Z. Freedman, Phys. Rev. D **9** (1974) 1389*

- Need $E_\nu \lesssim 50$ MeV
- Detecting nuclear recoil is hard
  - Tiny in energy, also quenched compared to electron recoils
- Cross section ~ 10^{-39} cm^2
- Need low threshold detector, but they are sensitive to backgrounds
- Need lots of neutrinos

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

Nuclear Recoil Detection

+

Low Threshold

= WIMP Dark Matter Detectors

There have been a lot of development in this field, particularly due to some "interesting" measurements from low threshold detectors

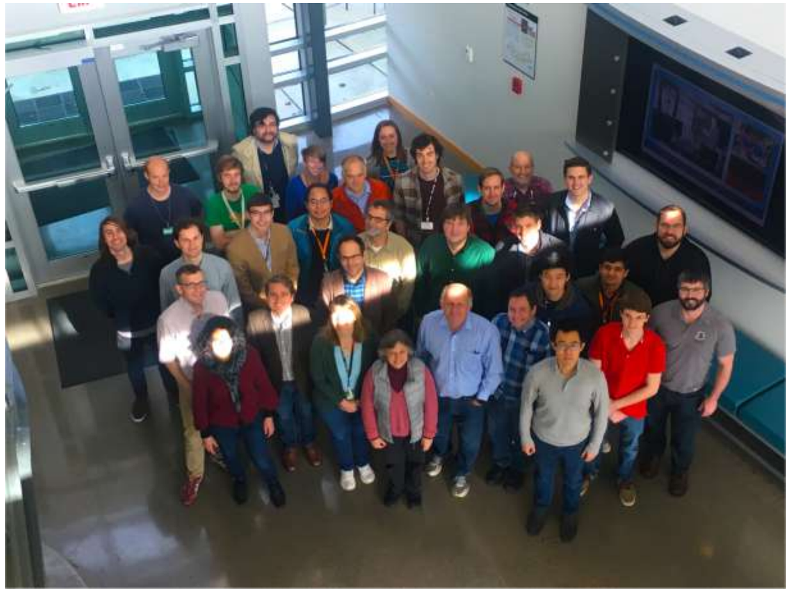
U.S. DEPARTMENT OF ENERGY

COHERENT SNS

NSF

NNSA National Nuclear Security Administration

CNEC Consortium for Nonproliferation Enabling Capabilities



KICP Kavli Institute for Cosmological Physics AT THE UNIVERSITY OF CHICAGO

Sandia National Laboratories

Duke UNIVERSITY

OAK RIDGE National Laboratory

W UNIVERSITY of WASHINGTON

THE UNIVERSITY of TENNESSEE UT KNOXVILLE

NORTH CAROLINA CENTRAL UNIVERSITY FOUNDED 1910

THE UNIVERSITY OF CHICAGO

UF UNIVERSITY of FLORIDA

MEPhI

NC STATE UNIVERSITY

Los Alamos NATIONAL LABORATORY EST. 1943

Carnegie Mellon University

LaurentianUniversity UniversitéLaurentienne

KAIST

TUNL

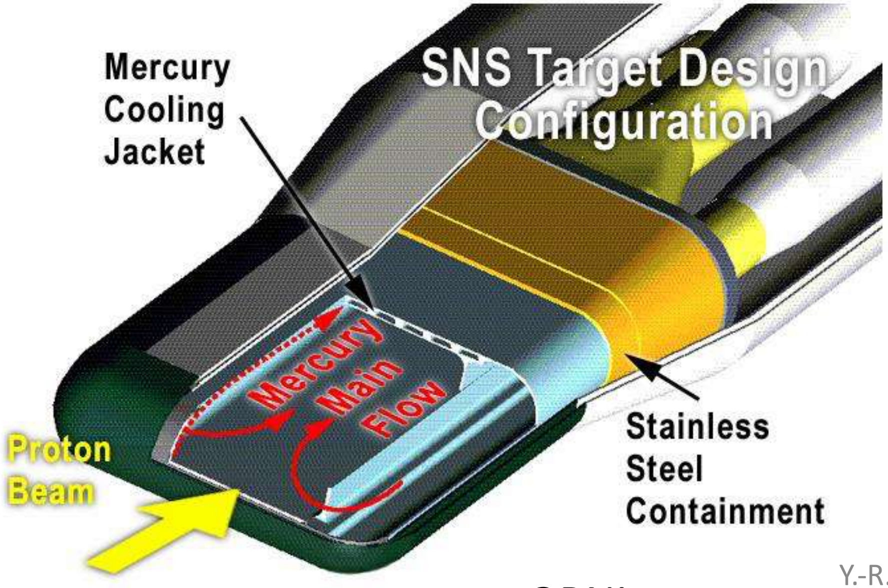
BERKELEY LAB

NM STATE UNIVERSITY

Spallation Neutr~~on~~ino Source

- Proton beam at ~1 GeV
  - 1.4 MW power
  - 9.6 x 10^{15} *p/s*
- Compact liquid Hg target
- Pulsed beam allows background rejection

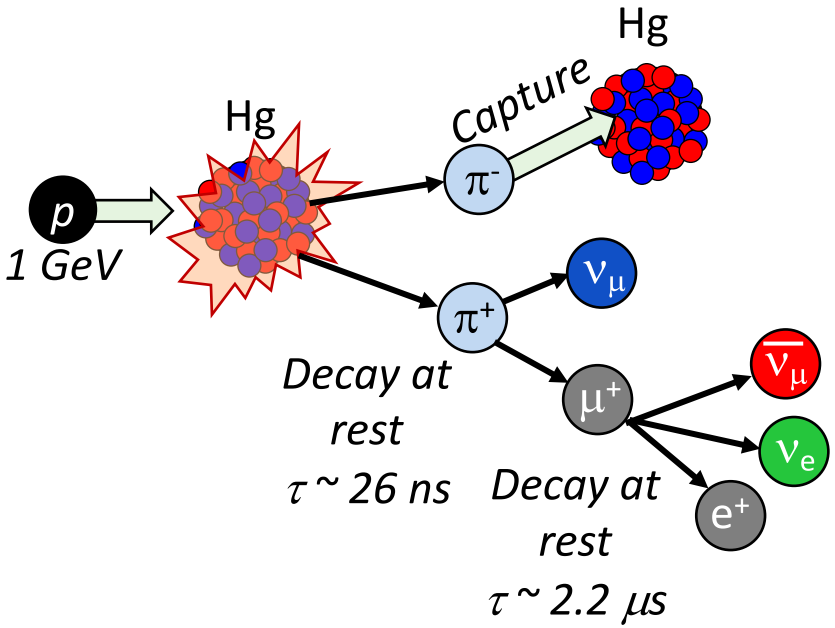
Oak Ridge, Tennessee, USA



ORNL

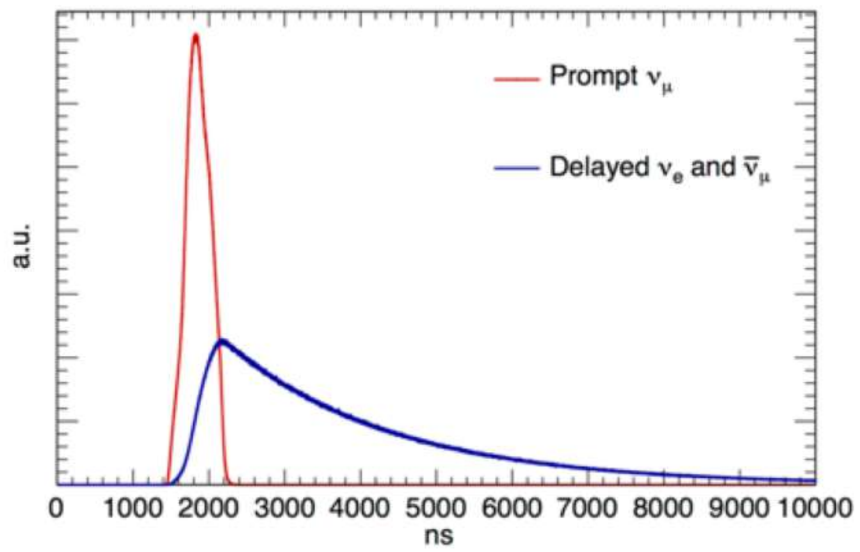
- Beam Pulse width: ~700 ns
- Repetition rate: 60 Hz
- Duty factor 2.28 x 10^{-5}

Stopped-Pion Source Neutrinos



Neutrino yield:

~ 0.24ν per proton

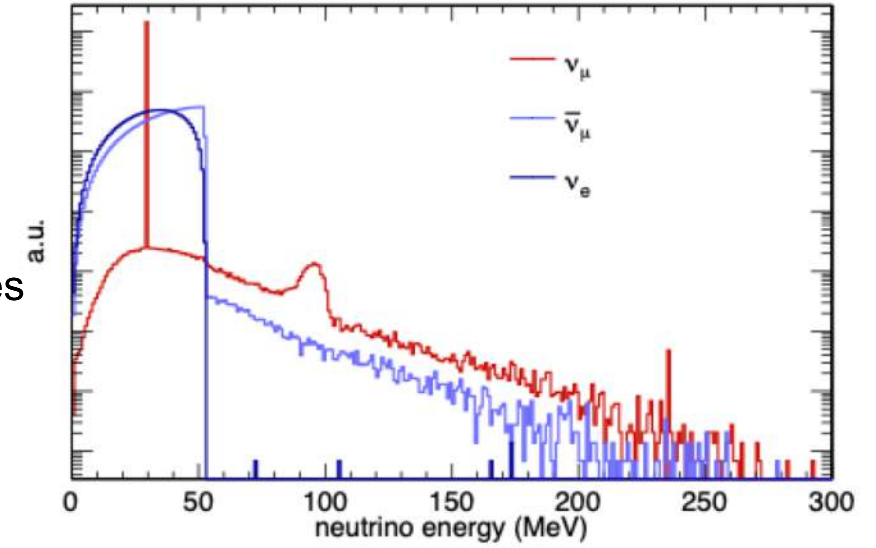


$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

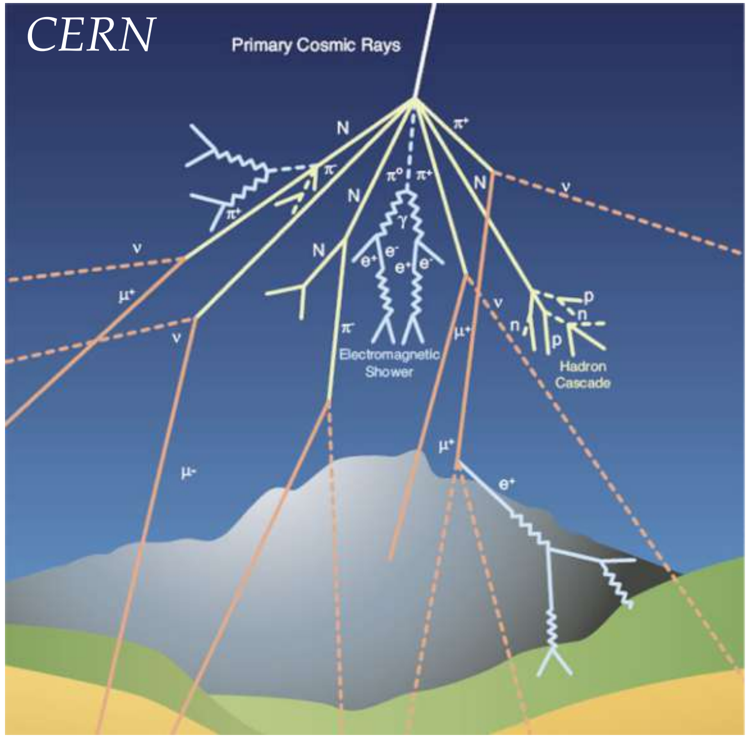
2-body decay: monochromatic 29.9 MeV ν_μ
PROMPT

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

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



Backgrounds: The Usual Suspects

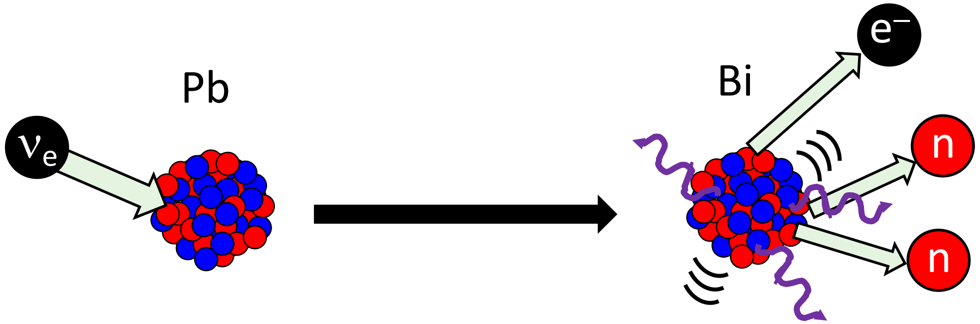


- Cosmic rays
  - (Very) modest 8 m.w.e. overburden in basement hallway
  - Scintillator panels around detectors provide μ veto

- Environmental radioactivity
  - Steady-state
  - Look for *excess* of beam-on events over beam-off

Backgrounds: Unusual Suspects

- Prompt SNS neutrons
  - 20-30 neutrons per proton on Hg target
  - Detectors > 19 m, through shielding, from target
- Neutrino-induced neutrons
  - νs should stimulate neutron emission from heavy nuclei in CC or NC interactions



  - Predicted by Standard Model (with lots of nuclear physics uncertainty) -- but not yet measured
  - "NINs" share neutrino time profile

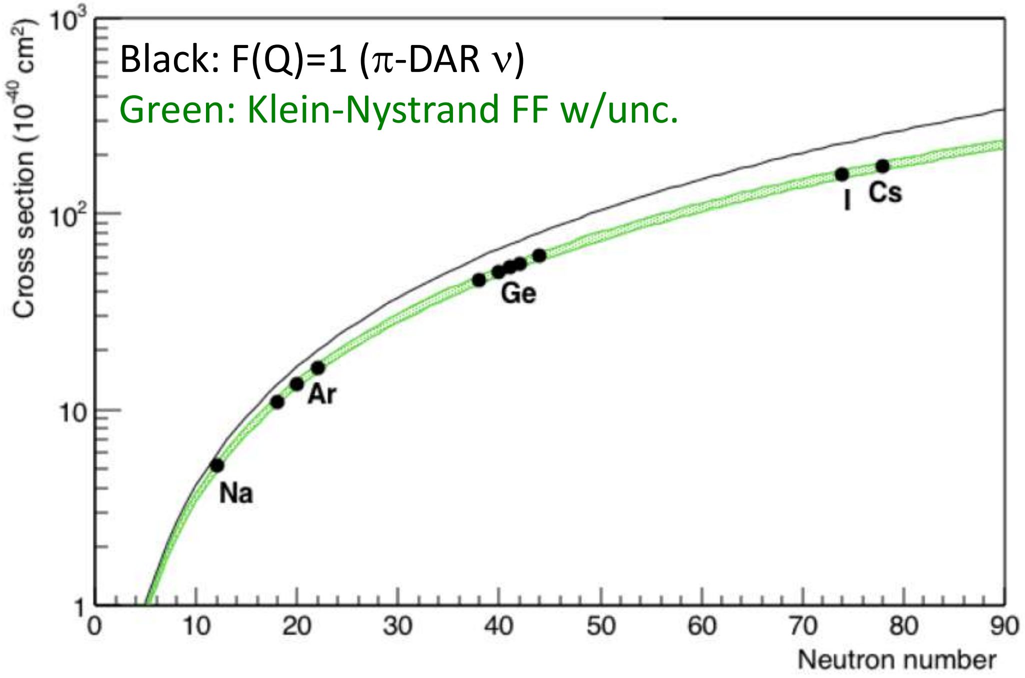
Benefits of a Detector Suite

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

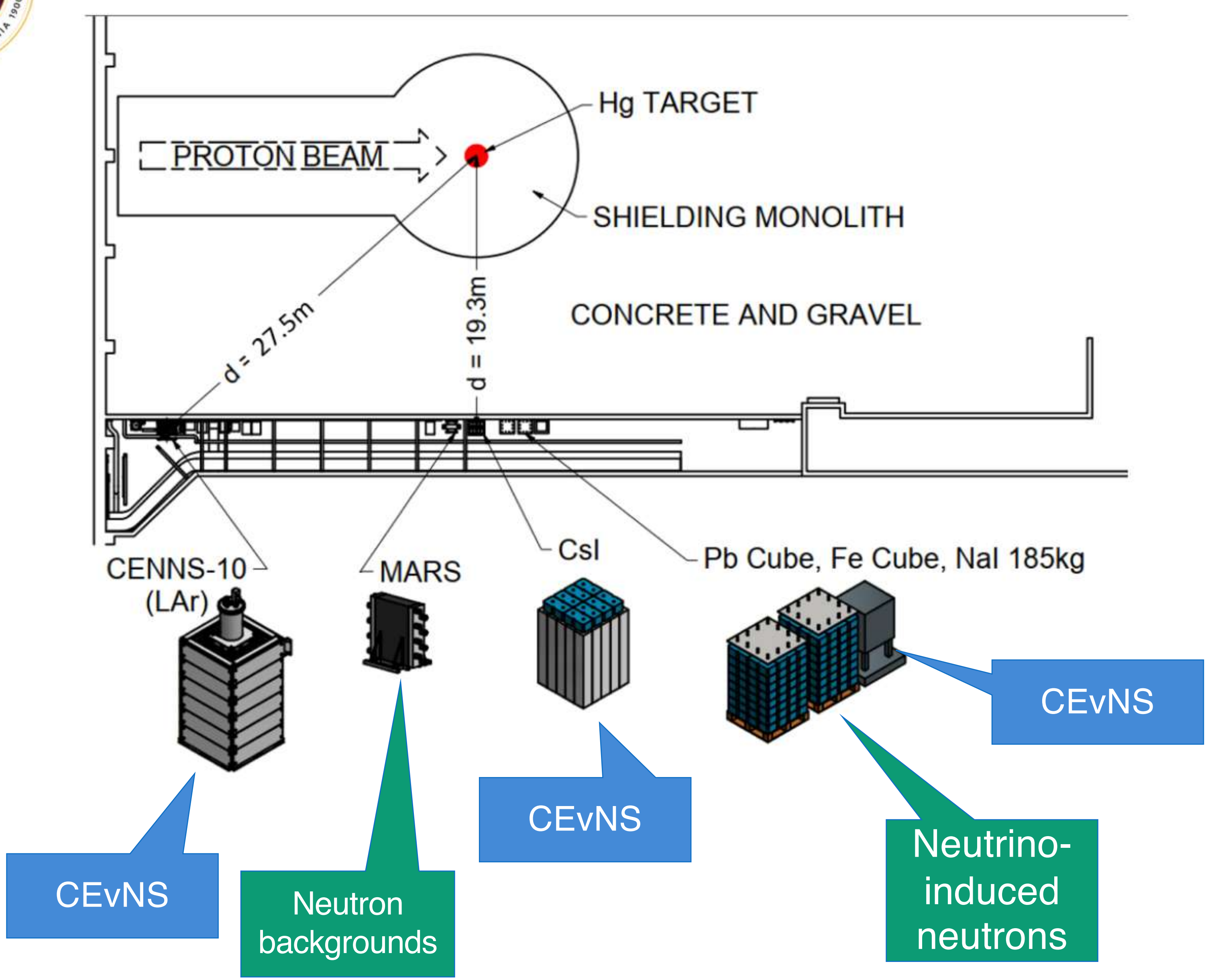
(spin-0 nucleus)

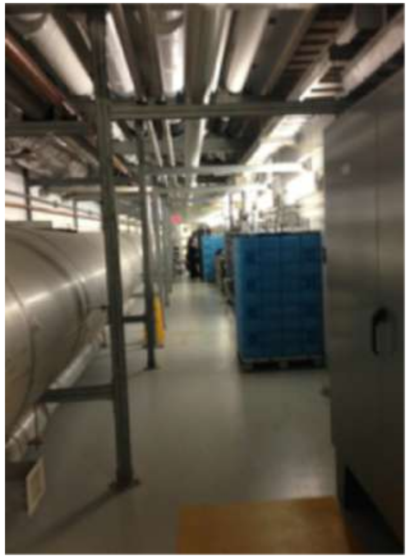
small proton weak charge

- Cross section goes approximately as N^2
  - **we can measure with multiple targets!**
  - CsI, Ar, NaI detectors deployed
  - Ge in the near future
- Shared backgrounds



Neutrino Alley Deployments: Current

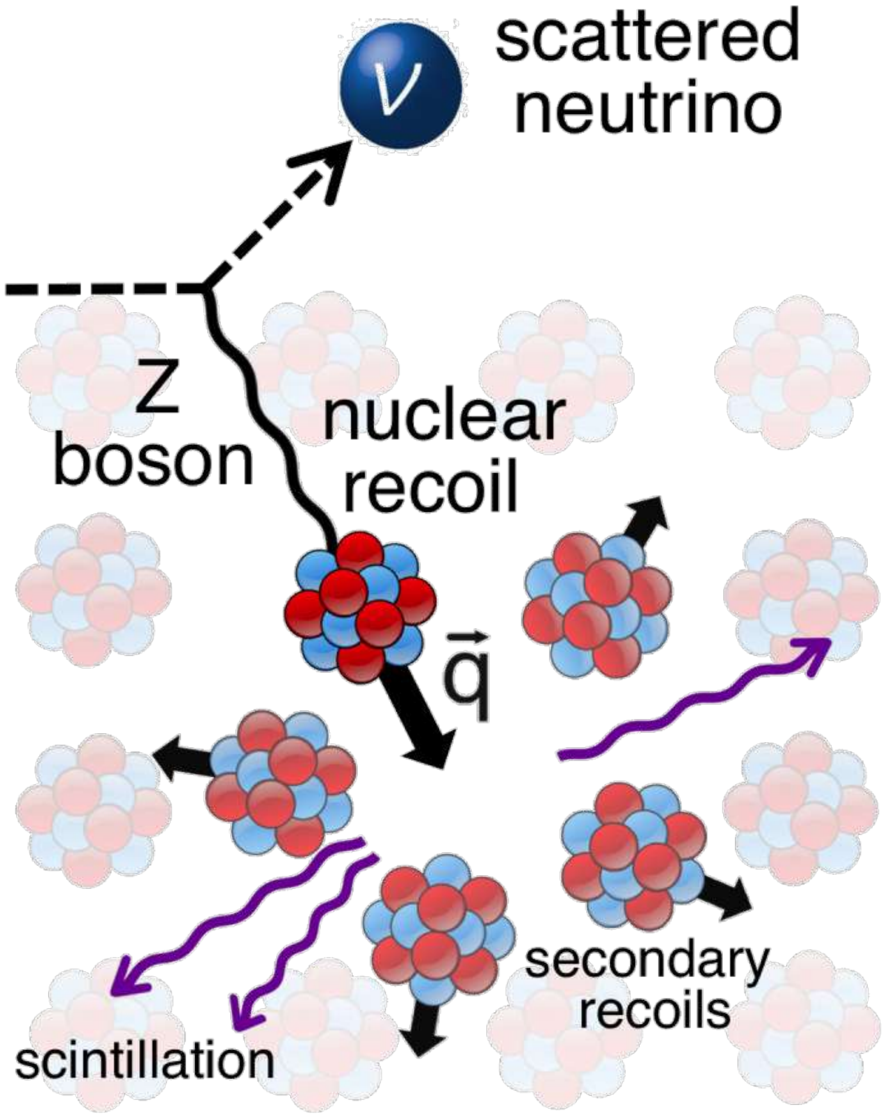




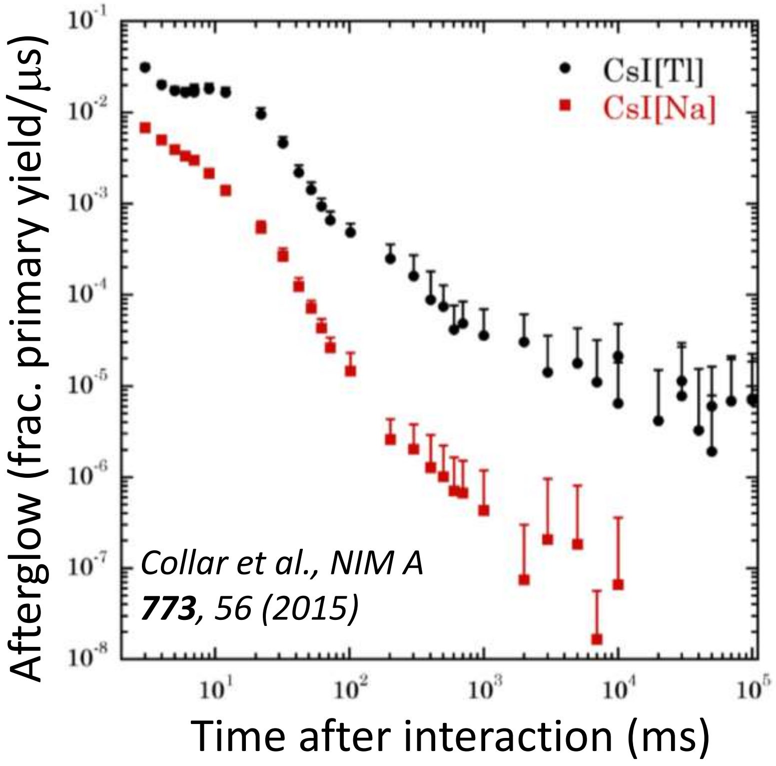
- CsI detector about to be decommissioned
- Ge detector will be added to the lineup soon

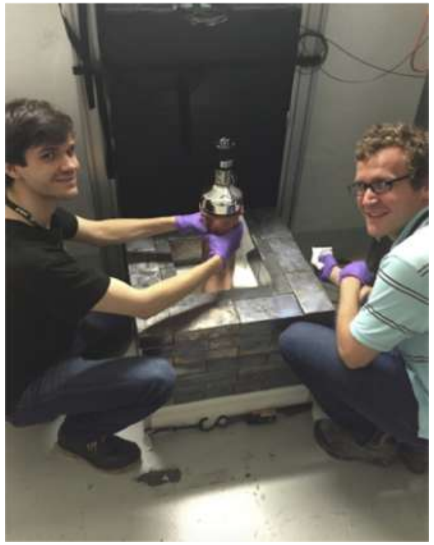
Approx ν flux at CsI[Na] location
1e7 ν / cm^2 / s / flavor

CsI[Na]



- Cs or I nucleus dislodged from crystal lattice
- Secondary recoils from neighbors
- Detect scintillation light in PMT

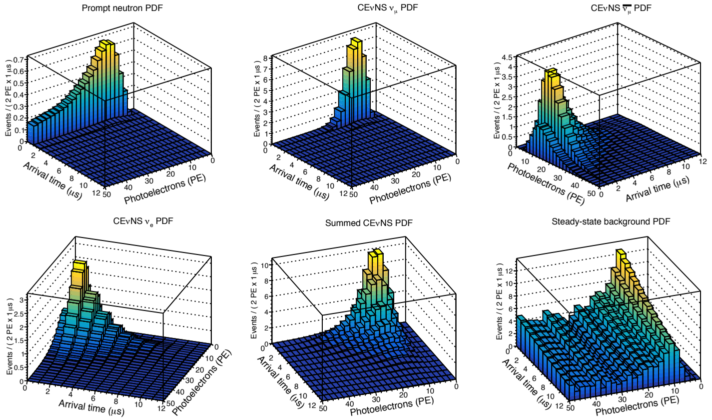


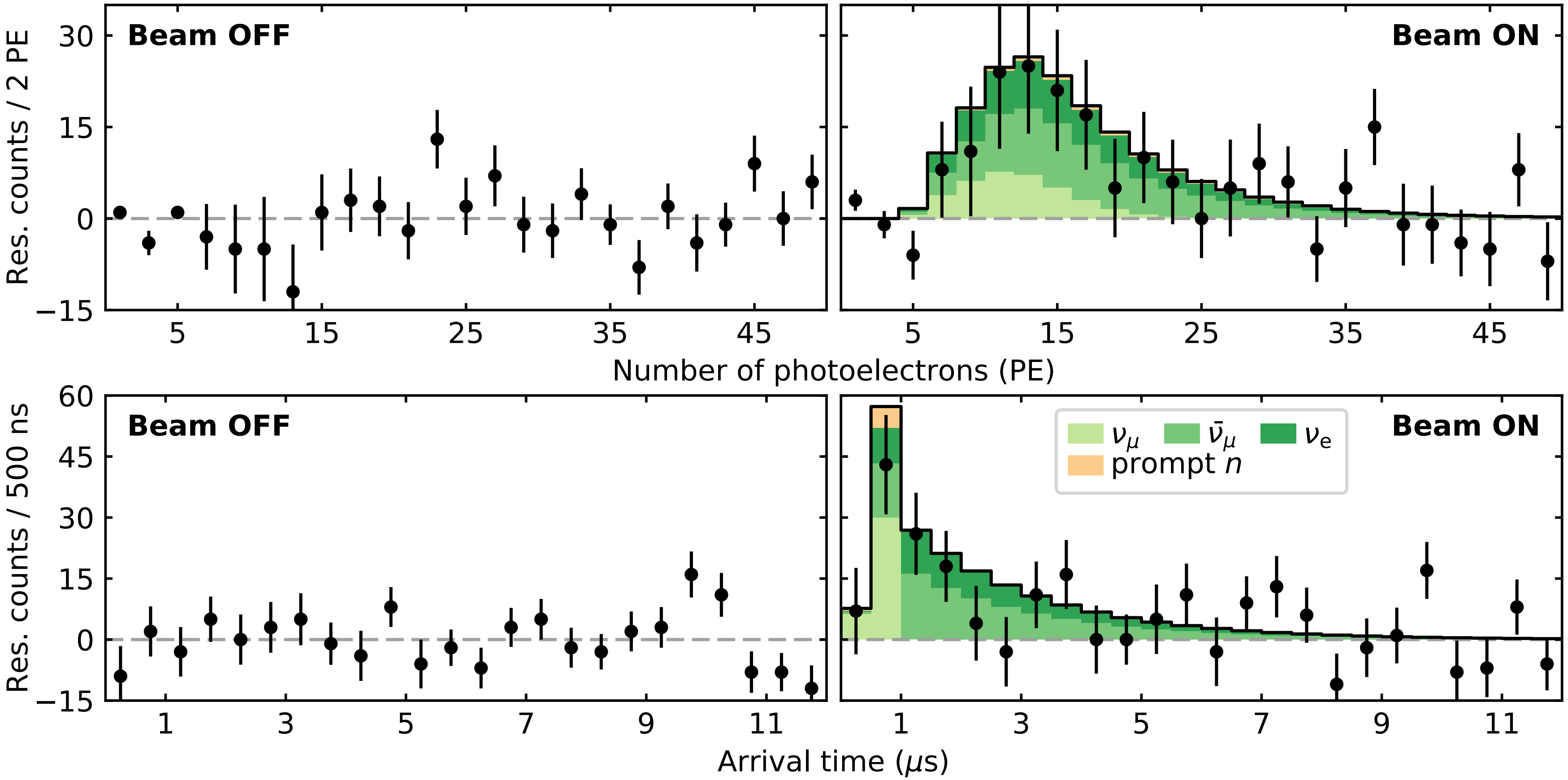


- CsI[Na]: 34 cm long, 14.57 kg
- PMT: R877-100 PMT by Hamamatsu
- Pb, HDPE, H_2O shields
- Muon veto

CEνNS At Last

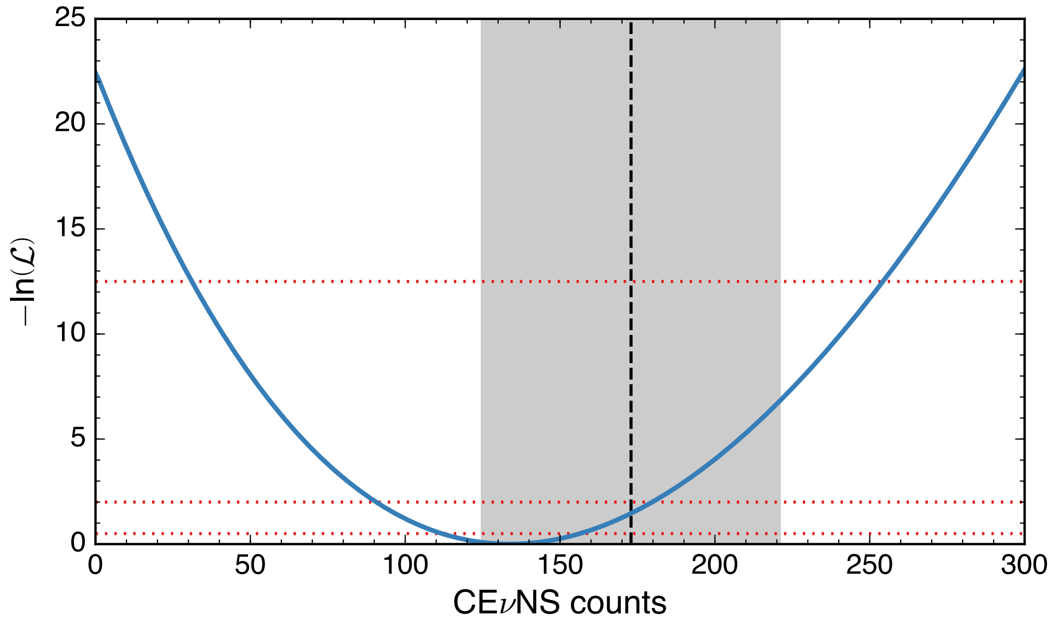
Akimov et al., Science ***357****, 1123 (2017)*





- 2D (Energy, Time) Profile Likelihood analysis
- Time analysis helped by knowledge of the pulsed neutron beam
- Binned 2D fit to the PDFs shown above

CEνNS At Last



- Beam exposure: ~6 GWhr, or ~1.4 × 1023 protons on target (0.22 grams of protons)
- Also analyzed as a simple counting experiment:
  - 136 ± 31 counts

Null case (no CEνNS) rejected at 6.7σ

Best fit: 132 ± 22 events in 308 days

SM Prediction: 173 ± 48 events in 308 days

Dominant systematic uncertainties on predicted rates

Quenching factor	25%
ν flux	10%
Nuc. form factor	5%
Analysis acceptance	5%

The CEνNS Heard 'Round the World'

SCIENTIFIC AMERICAN. SUBSCRIBE

PHYSICS

Ever-Elusive Neutrinos Spotted Bouncing Off Nuclei for the First Time

A new technology for detecting neutrinos represents a "monumental" advance for science

WIRED Physicists Capture the Elusive Neutrino Smacking Into an Atom's

SOPHIA CHEN SCIENCE 08.03.17 02:00 PM

SHARE 1278

PHYSICISTS CAPTURE THE ELUSIVE NEUTRINO SMACKING INTO AN ATOM'S CORE

ars TECHNICA BIZ & IT TECH SCIEN FORUMS

DID YOU FEEL SOMETHING? —

After 43 years, gentl neutrino is finally ob

We're actually able to detect a bump from the

JOHN TIMMER - 8/3/2017, 3:10 PM

Science

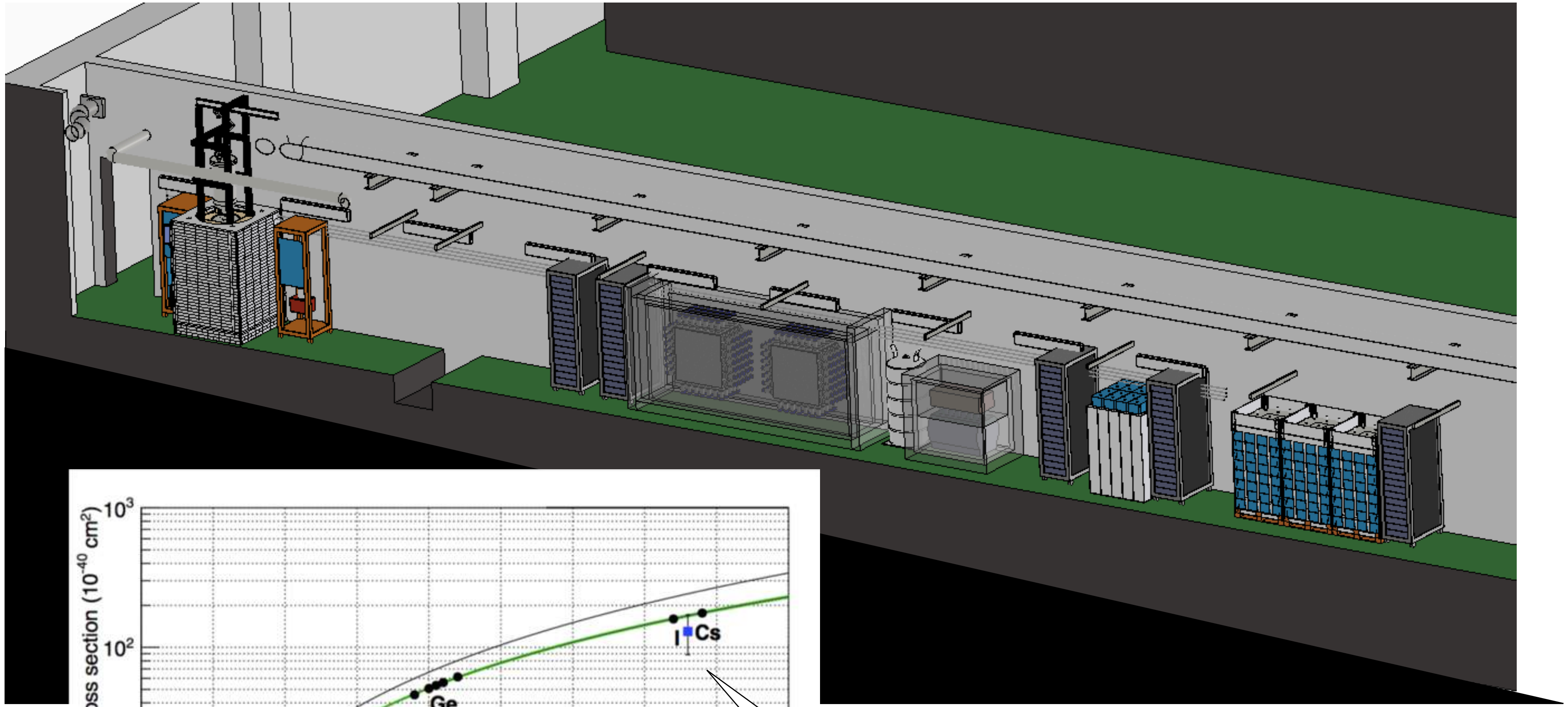
2017 BREAKTHROUGH OF THE YEAR

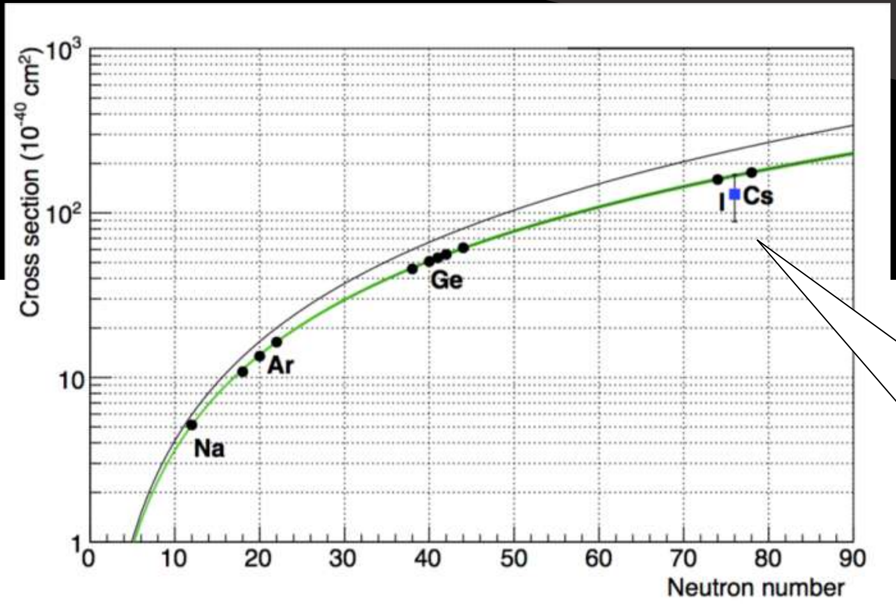
Cosmic convergence

RUNNERS-UP

- Life at the atomic level
- A tiny detector for the shiest particles
- Deeper roots for *Homo sapiens*
- Pinpoint gene editing
- Biology preprints take off
- A cancer drug's broad swipe
- A new great ape species
- Earth's atmosphere 2.7 million years ago
- Gene therapy triumph

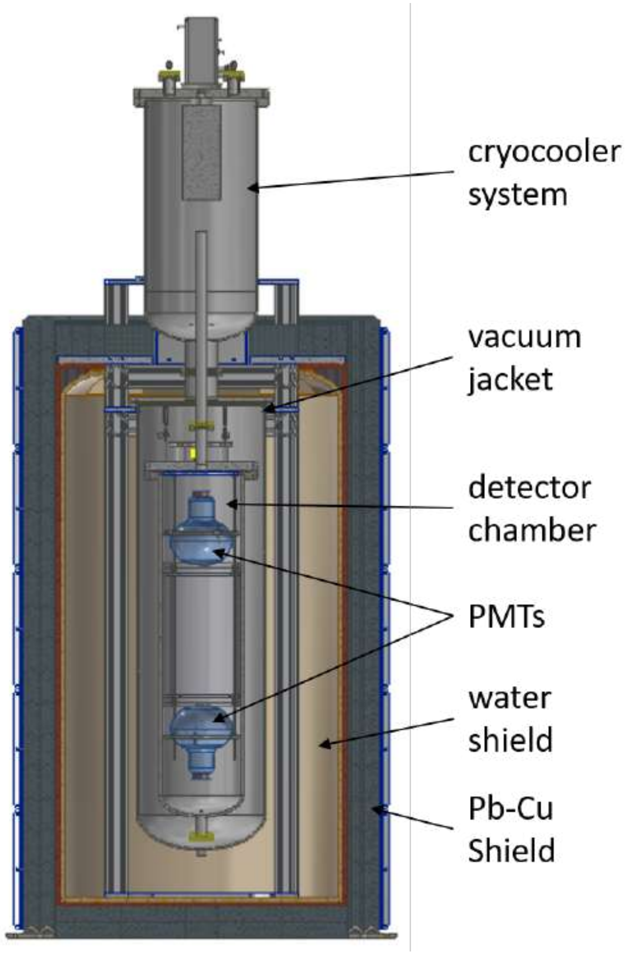
What's next for COHERENT?



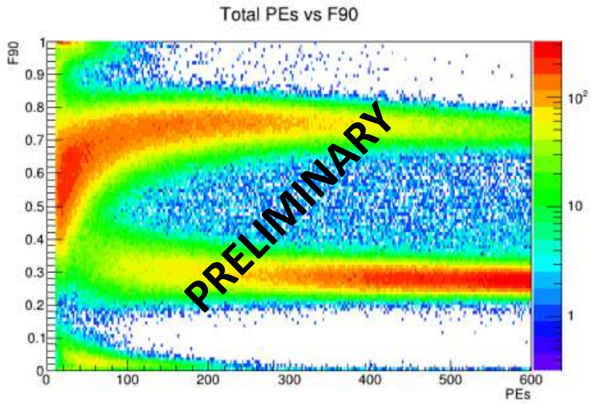


One measurement so far! Want to map out N^2 dependence

Current CEνNS : LAr (CENNS-10)



- Single-phase liquid argon detector with 22 kg fiducial volume
- Wavelength-shifting via TPB coatings on PMTs, Teflon lining
- Purification, recirculation of boiloff gas
- Pulse Shape Discrimination
  - Separate Nuclear Recoil vs. Electron Recoil Bands
- Upgraded configuration has 6.5 GWHr of data (August 2017 – present)



Will have results soon!

R. Tayloe, JINST 13 2018

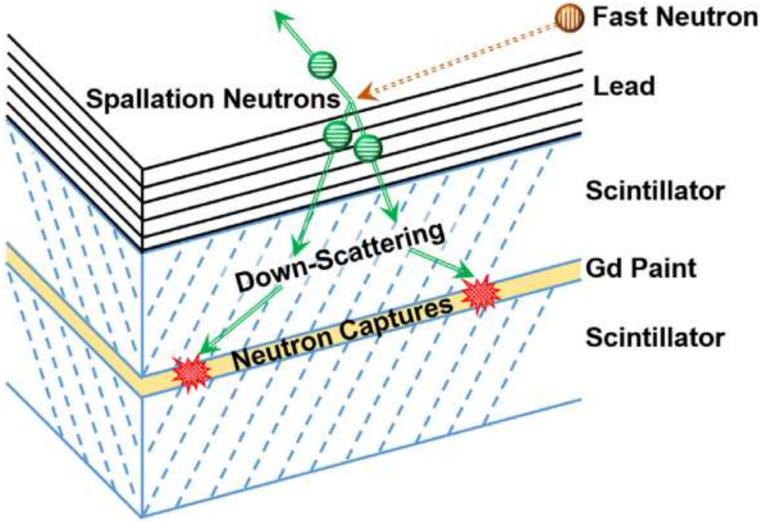
Current CEνNS R&D: NaI[Tl] (NaIνE prototype)

- Thallium doped sodium iodide scintillating inorganic crystals
- ^{23}Na has 12 neutrons -- easy to separate CEνNS on Na from CEνNS on I!
- 2 tons of instrumented NaI[Tl] detectors (7.7 kg each) from Department of Homeland Security

- Replacing PMT bases for higher gain needed for CEνNS search
- Currently, 185 kg NaI[Tl] deployed in summer 2016
  - Measuring backgrounds
  - Measuring CC cross-section of I^{127}
  - *Not sensitive to CEvNS*

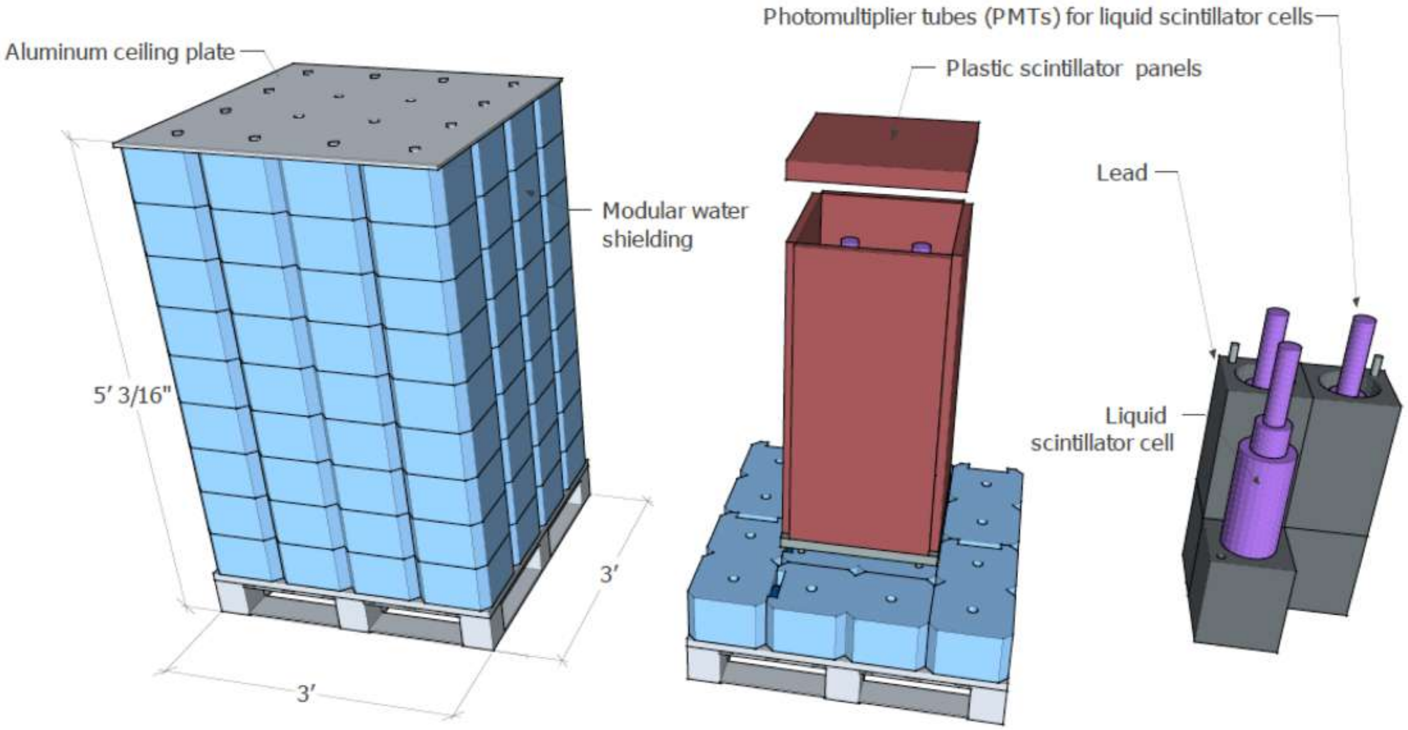
Current Background: Neutrons

- Multiplicity And Recoil Spectrometer (MARS)
  - A transportable neutron detection detector that has been deployed at KURF
- Plastic scintillator sheets interleaved with Gd (for neutron capture) coated Mylar
- Monitor the neutron flux from SNS



C. Roeckeretal. NIM A826 (2016) 21–30

Current Background: NINs by NUBES



- Neutrino Cubes (NUBES) are LS detector surrounded by Pb or Fe targets.
- Designed to measure neutrino-induced neutrons (NIN) for the first time.
  - CsI saw hint of this (2.9 σ).
- Eventually, *in situ* measurement give rates limit.

NIN is also the detection method for the HALO supernova observatory.

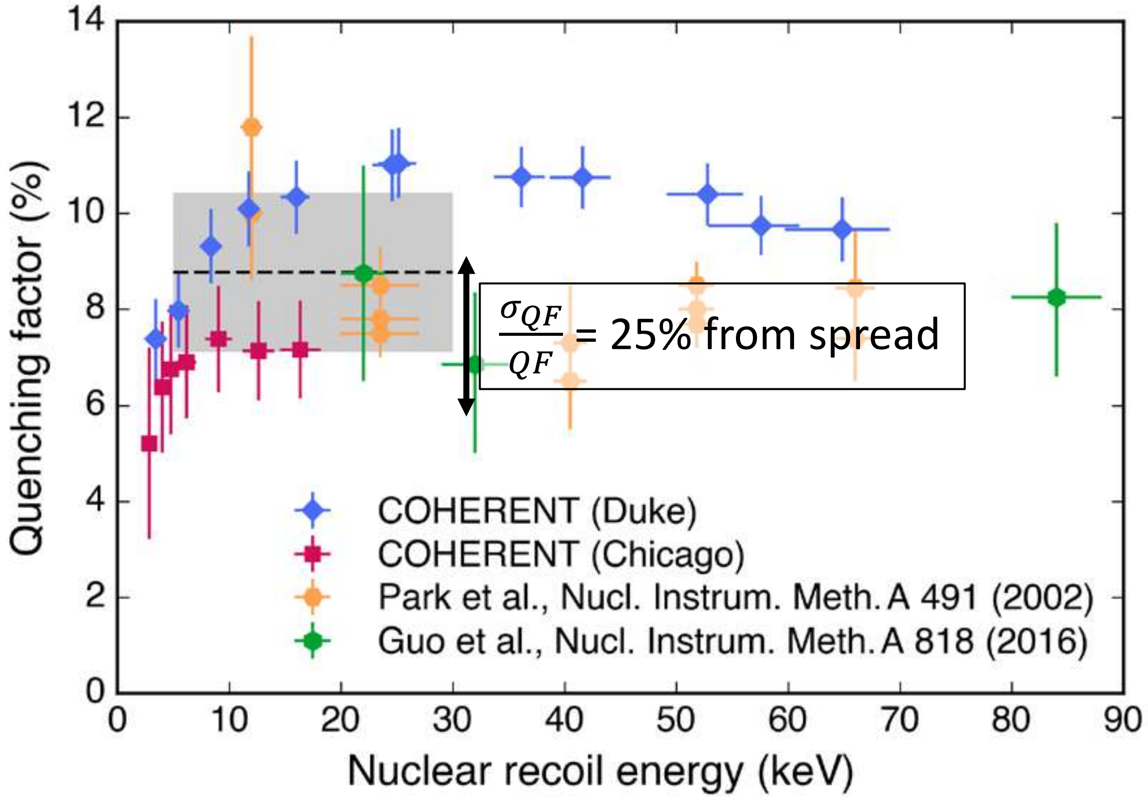
$$\nu_e + {}^{208}\text{Pb} \Rightarrow {}^{208}\text{Bi}^* + e^- \qquad \text{(CC)}$$
$$\Downarrow$$
$${}^{208-y}\text{Bi} + x\gamma + yn,$$

$$\nu_x + {}^{208}\text{Pb} \Rightarrow {}^{208}\text{Pb}^* + \nu_x' \qquad \text{(NC)}$$
$$\Downarrow$$
$${}^{208-y}\text{Pb} + x\gamma + yn.$$

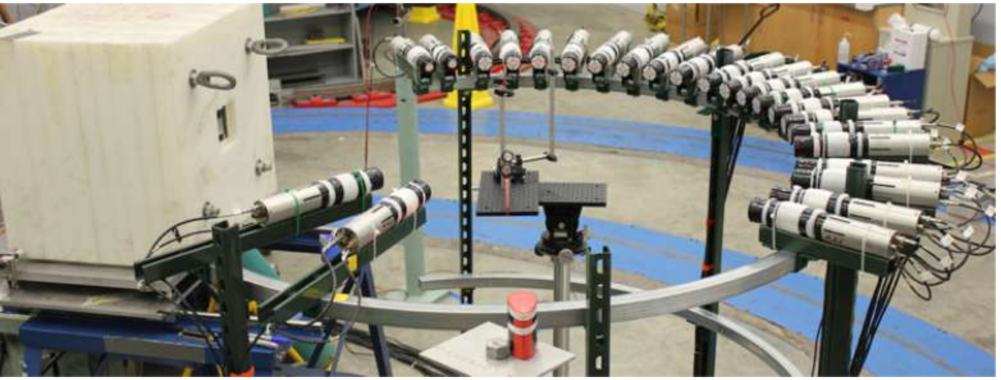
Quenching Factors

25% of the uncertainty!

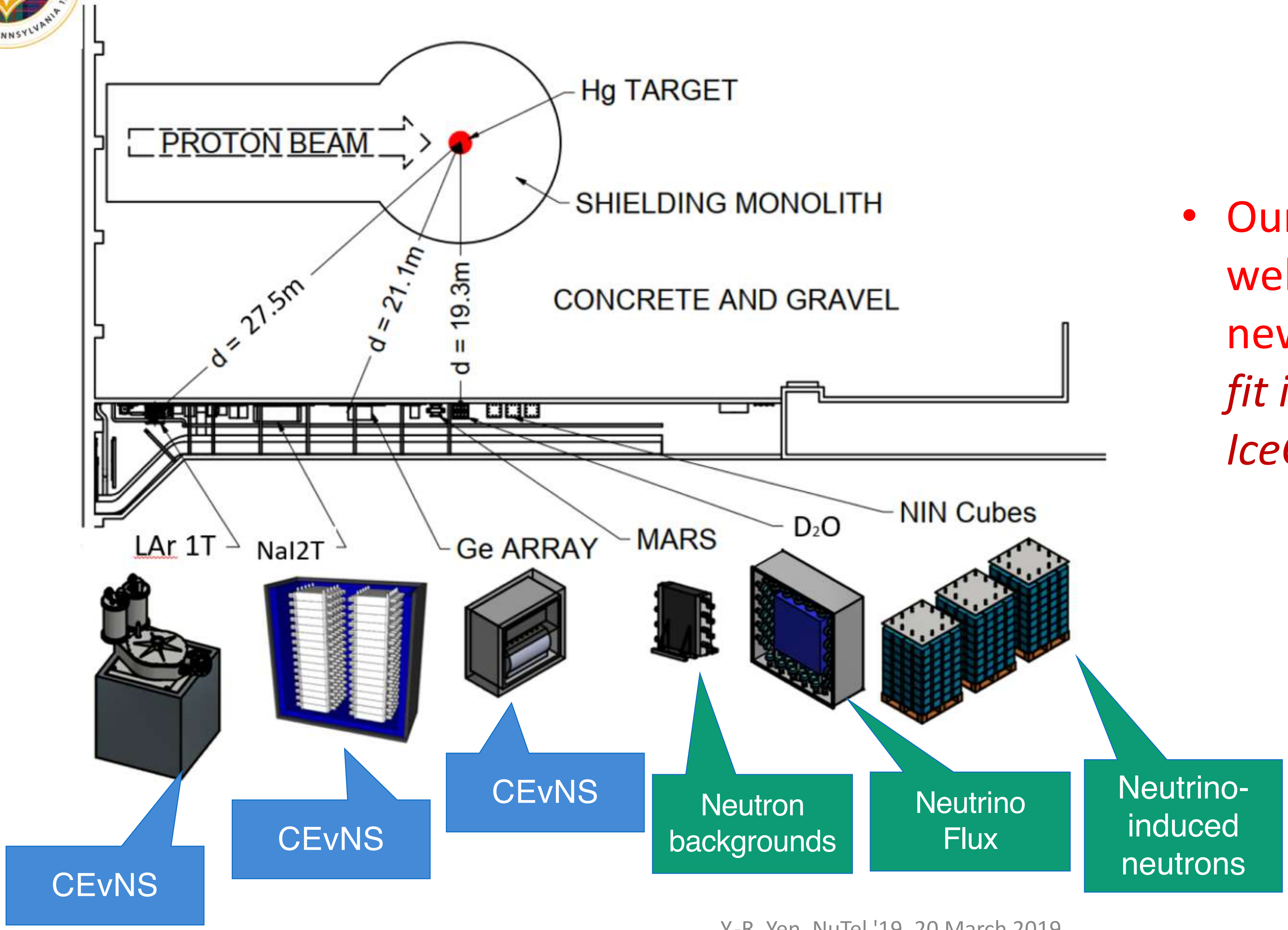
- Nuclear recoil energy collected less efficiently than other energy deposits
- Dedicated measurements with TUNL neutron beam
  - Smaller, sibling CsI[Na] detector
  - Angles of backing detectors give E_{nr}



*Akimov et al., Science **357**, 1123 (2017), suppl. mat.*



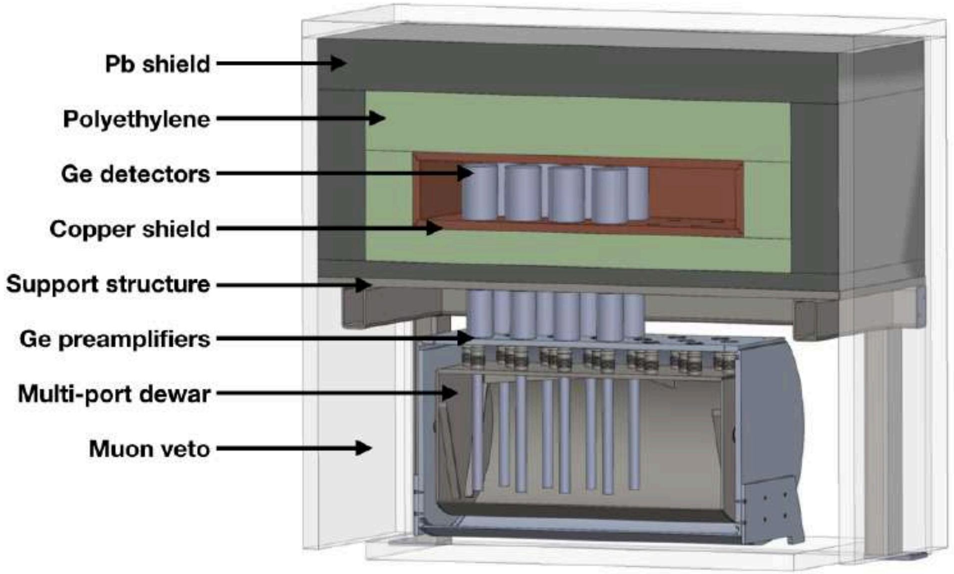
Neutrino Alley Deployments: Future

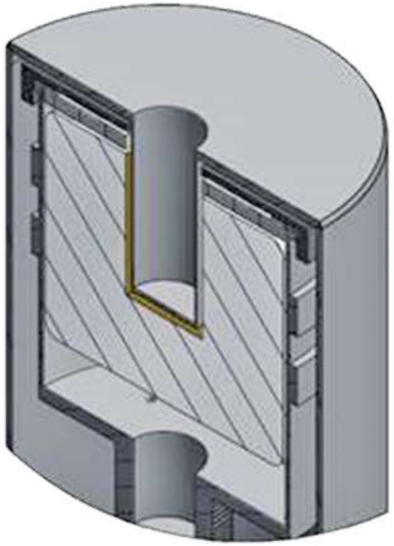


- Our collaboration always welcomes additions of new detectors! (*if it can fit in a hallway, sorry IceCube*)

Near Future CEνNS: Ge

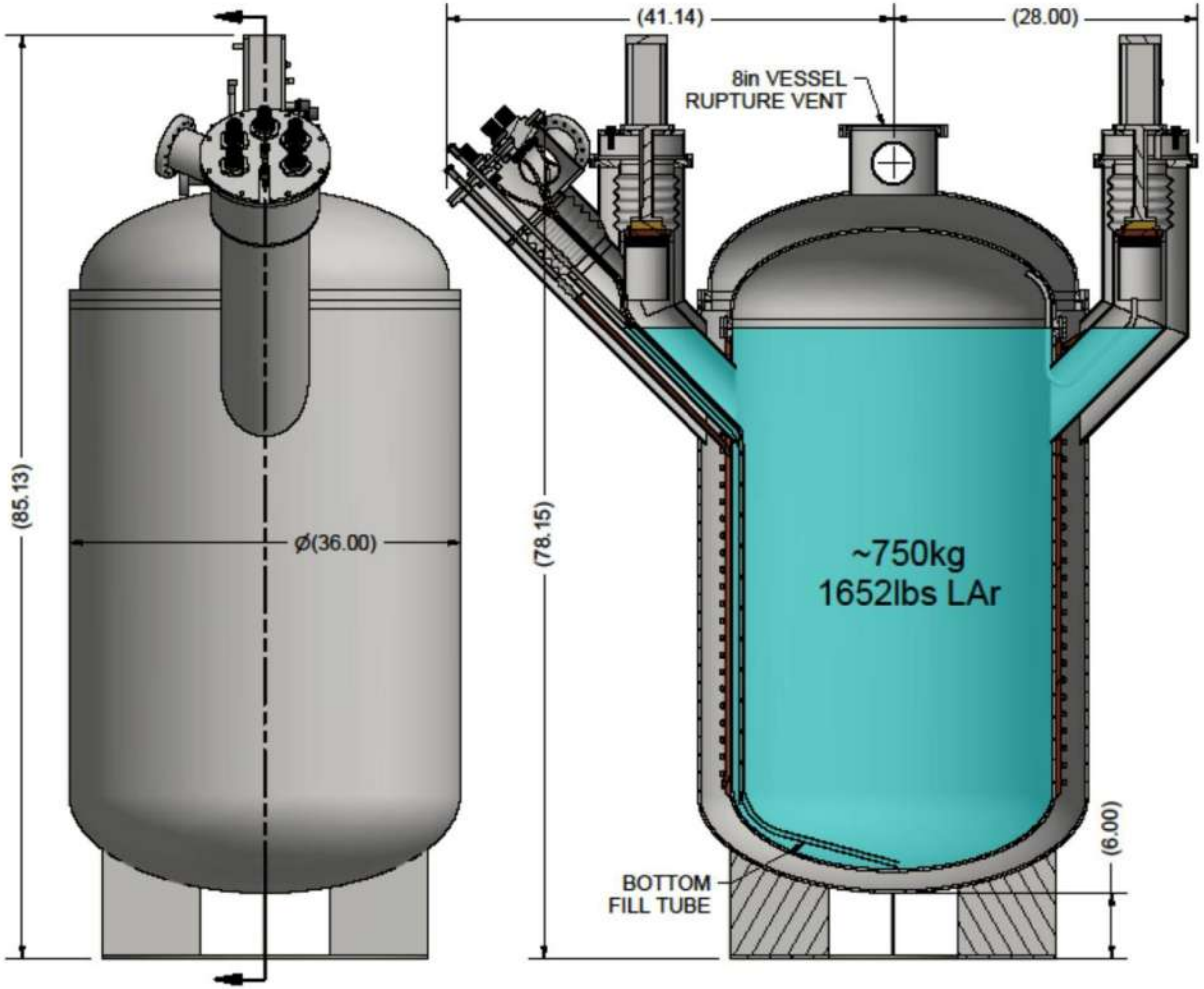
- P-type point contact (PPC) Ge detectors
- 16 kg (two 8 kg arrays)
- High resolution and low threshold for precision measurements





- Inherent electronic noise of the detector and preamplifier will be limited to <150 eV
- Noise-limited energy threshold of <0.4 keVee, equivalent to a CEνNS recoil threshold <2−2.5 keVnr

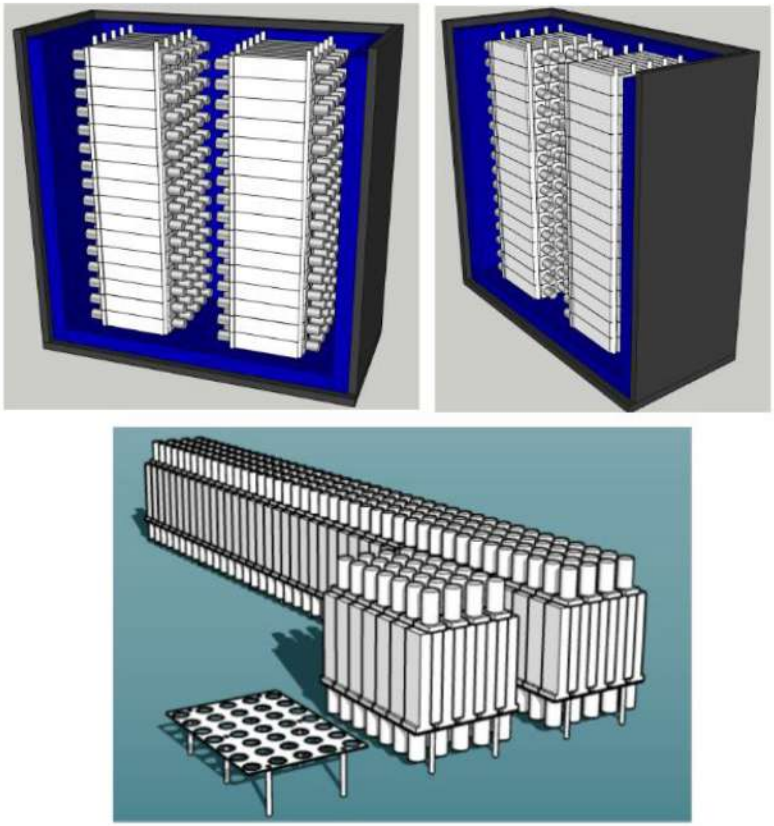
Future CEνNS : LAr (CENNS 750)



- Single-phase liquid argon
- 612 kg of fiducial volume
- Expect ~3000 events per SNS year
- Can also measure CC ν cross-section on Ar for DUNE

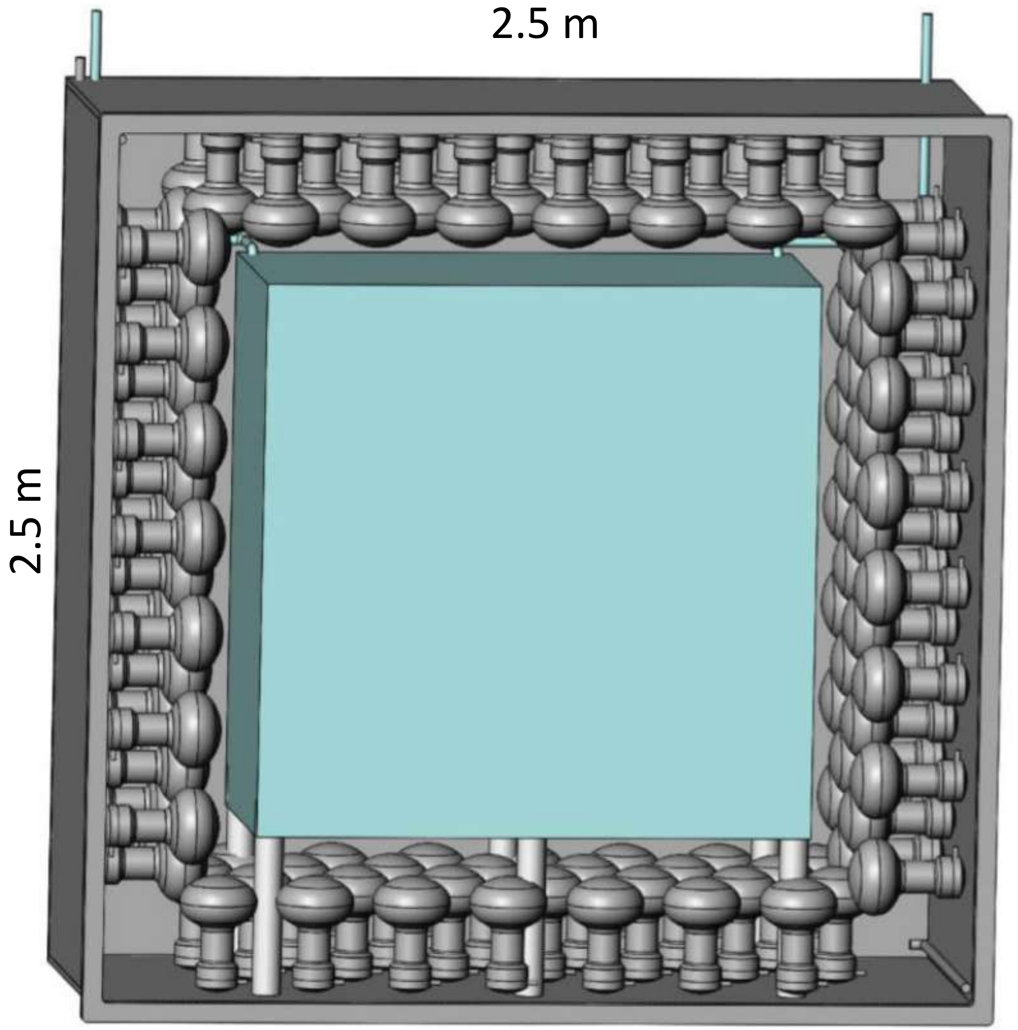
Future CEνNS: Ton-Scale NaI Array

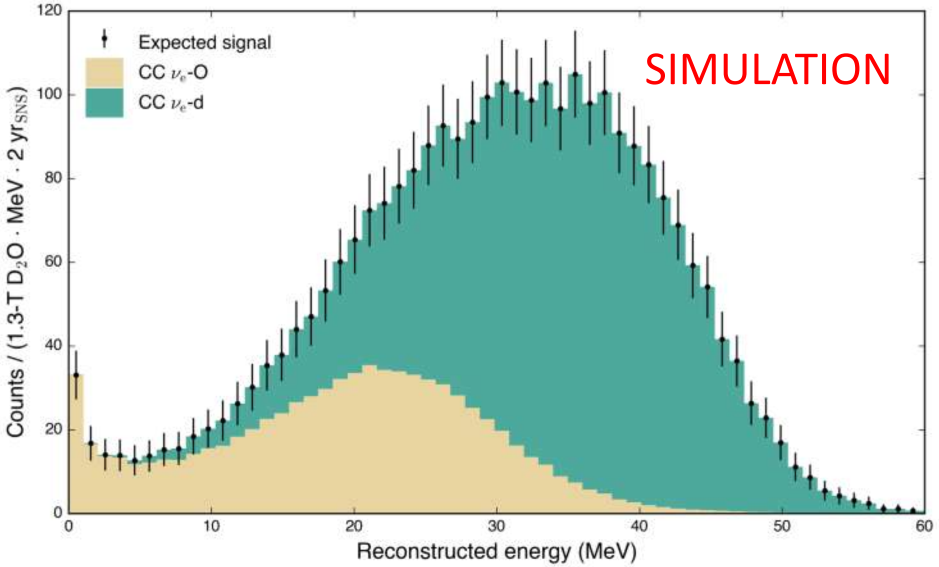
- Two stacks of 144-166 (2 tonne) sodium iodine scintillation crystal detector arrays
- Detectors will be developed using the experiences from the NaIνE prototype
- Data will also be improved from quenching factor measurements



10% of the uncertainty!

Future Background: Heavy Water (ν flux)



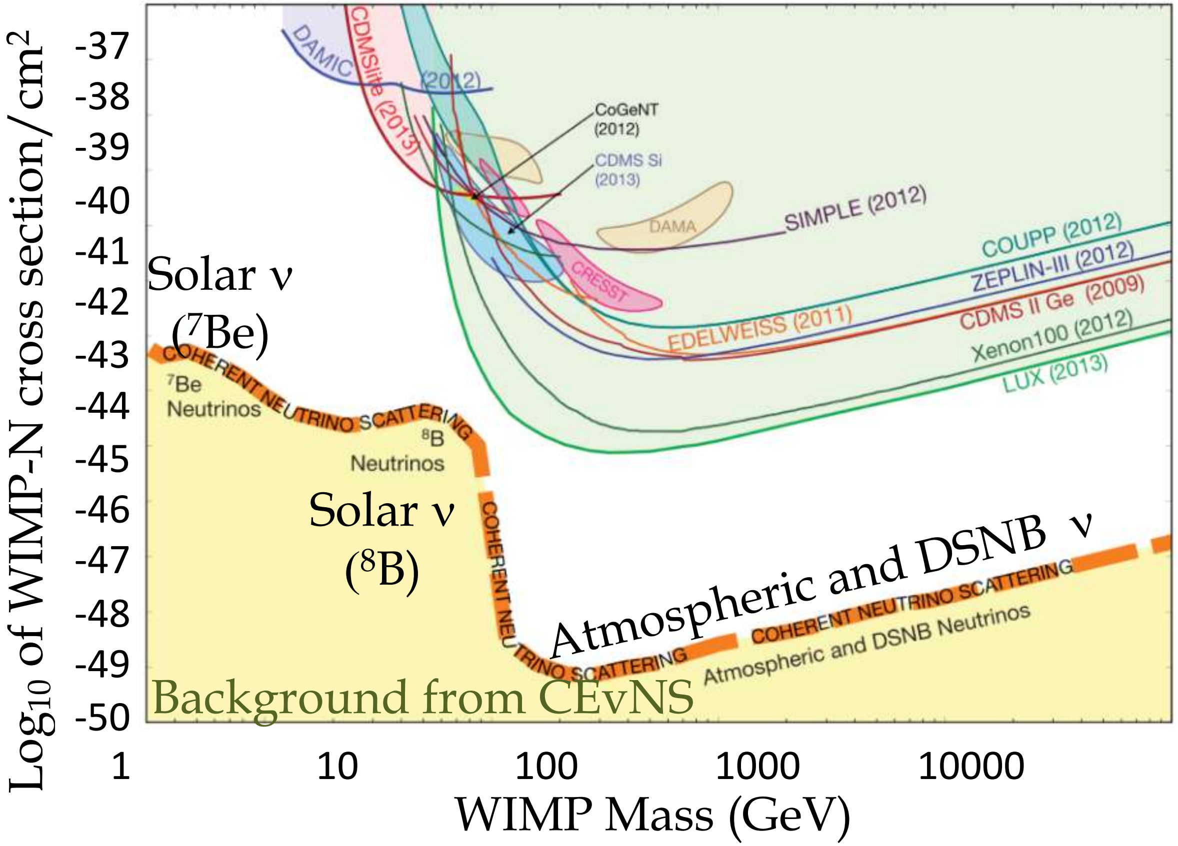


- Can use a heavy water (D_2O) detector to constrain this because the CC cross-section on deuterium is well known theoretically [1] and confirmed by measurements [2].

[1] S. Nakamura et al., Nucl. Phys. A 721 (2003)
[2] J. Formaggio and G.P. Zeller, Rev. Mod. Phys. 84 (2012)

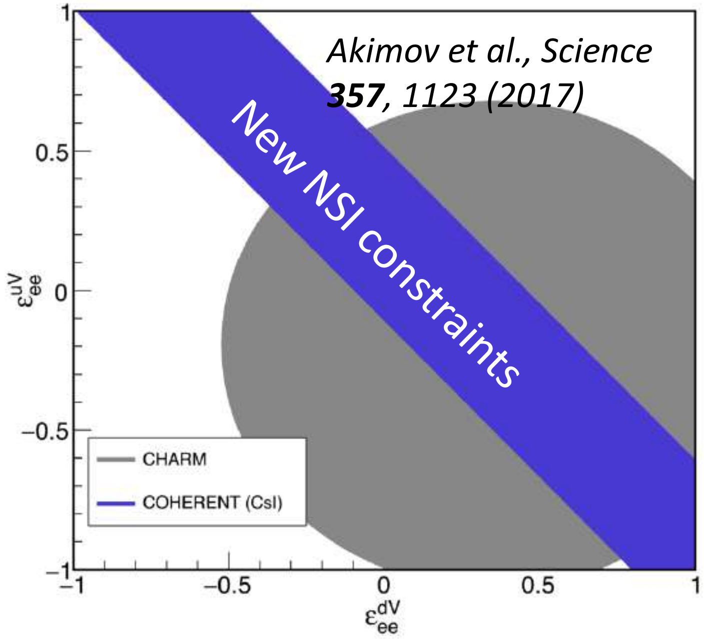
CEνNS Physics

- Background for next-generation WIMP searches
- Important for core-collapse supernova
- Interferes with non-standard neutrino interactions (NSI)



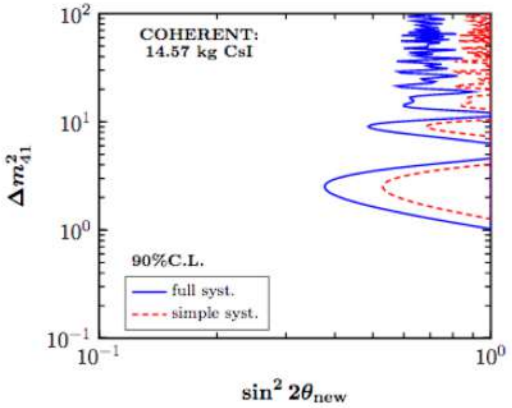
J. Billard, E. Figueroa-Feliciano, L. Strigari, Phys. Rev. D ***89*** *(2014) 023524*

Early Searches for New Physics



COHERENT constraints to conventional and exotic neutrino physics

T.S. Kosmas [1] and D.K. Papoulias [1]
[1] *Theoretical Physics Section, University of Ioannina, GR-45110 Ioannina, Greece*

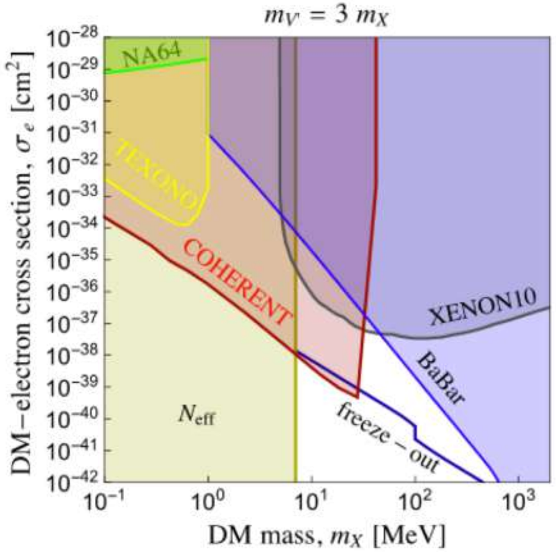


Kosmas and Papoulias, arXiv:1711.09773

First limits on sterile neutrinos from CEvNS (not yet competitive)

Constraining Photon Portal Dark Matter with TEXONO and COHERENT Data

Shao-Feng Ge [*1] and Ian M. Shoemaker [†2]

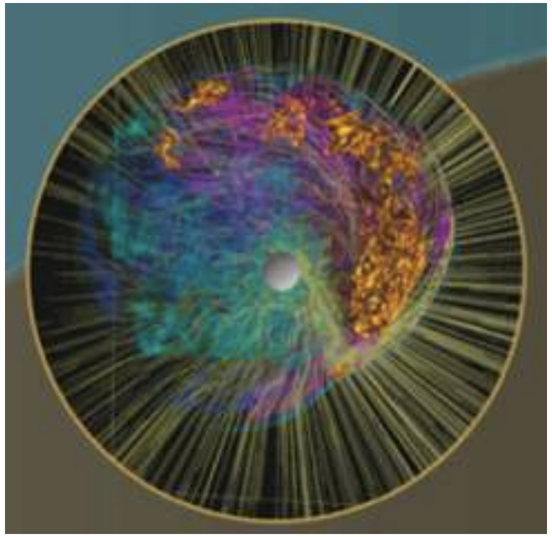


Ge and Shoemaker, arXiv:1710.10889

Limits on light dark matter interacting with SM via kinetic mixing of dark and SM photons

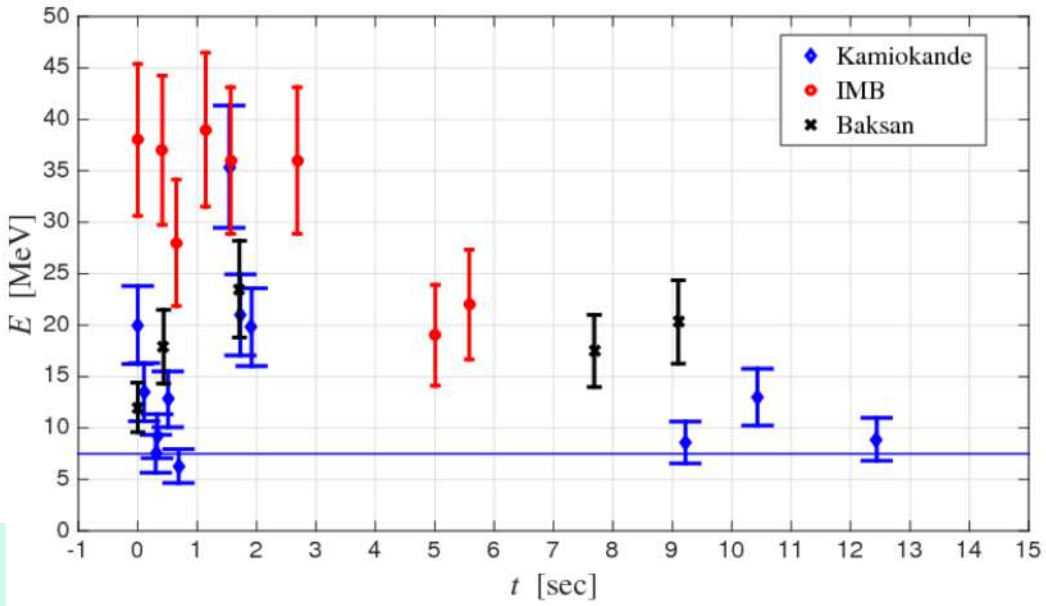
- Non-standard interactions!
- Light dark matter!
- Sterile neutrinos!

Supernova and Neutrino Detectors

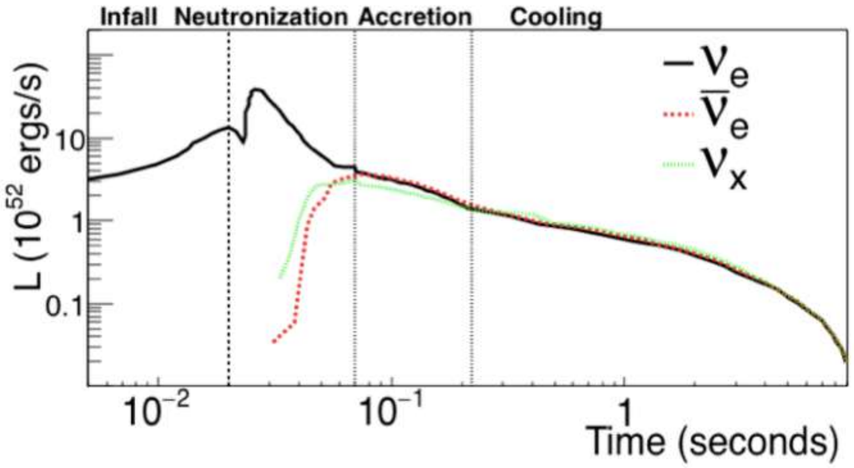


- Core collapse supernova release a lot of detectable neutrinos
- CEνNS interaction within supernova may also change the supernova physics models.

Supernova 1987A was "seen" by neutrino detectors

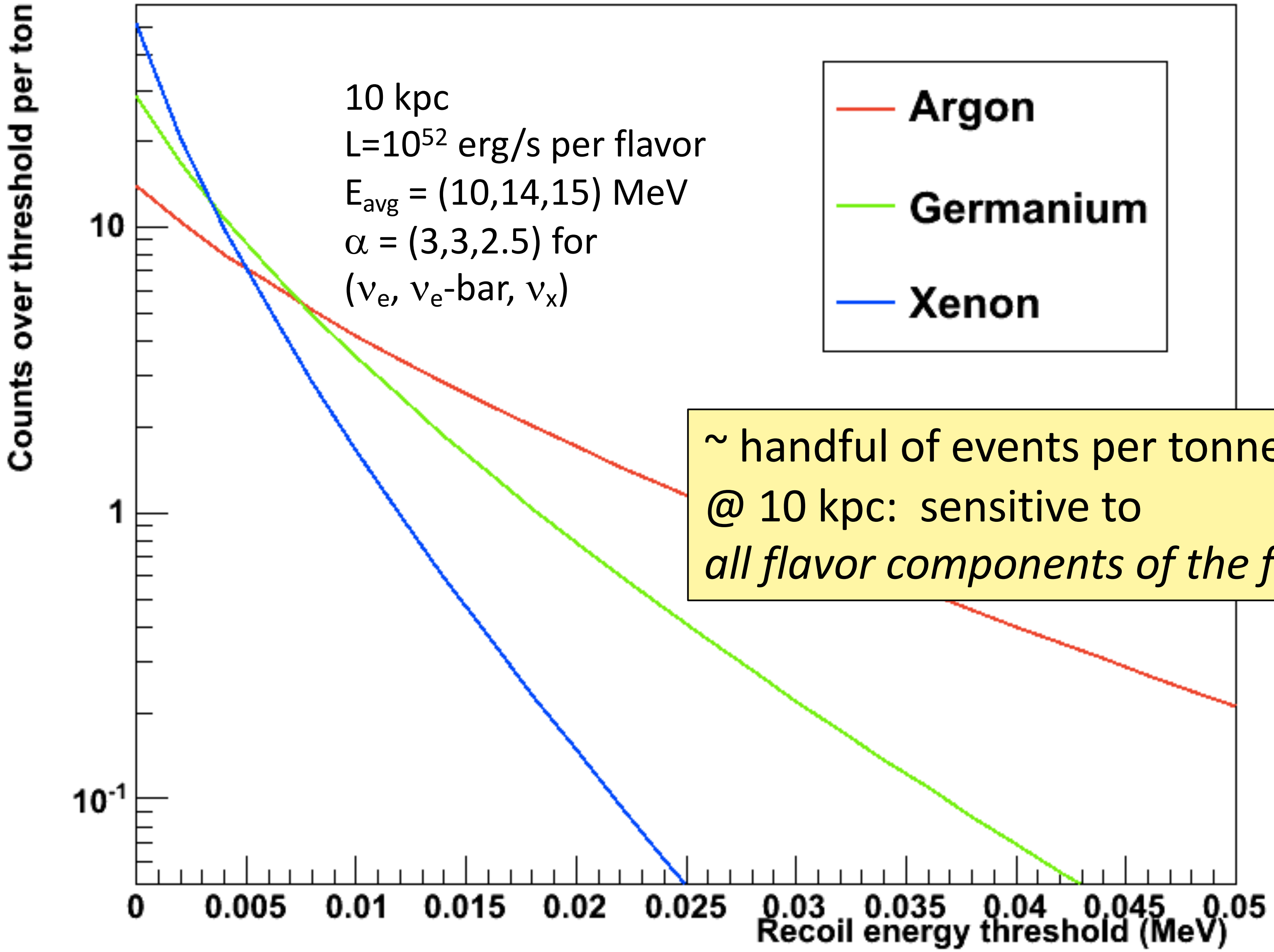


Blum, Kfir *et al.* Astrophys.J. 828 (2016) no.1, 31 arXiv:1601.03422



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

Supernova neutrinos in ton-scale Dark Matter detectors

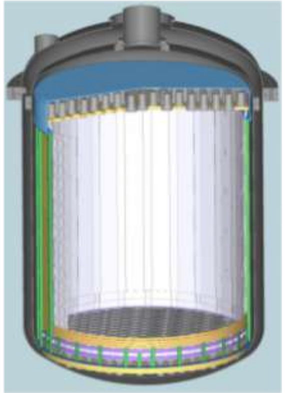


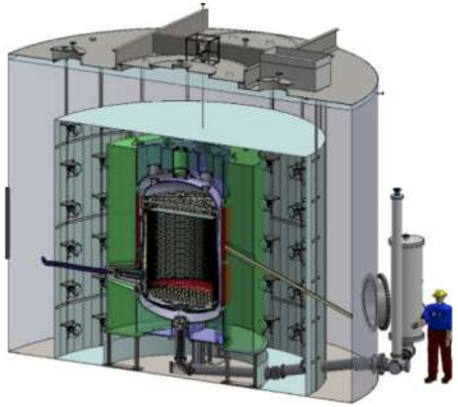
~ handful of events per tonne
@ 10 kpc: sensitive to
all flavor components of the flux

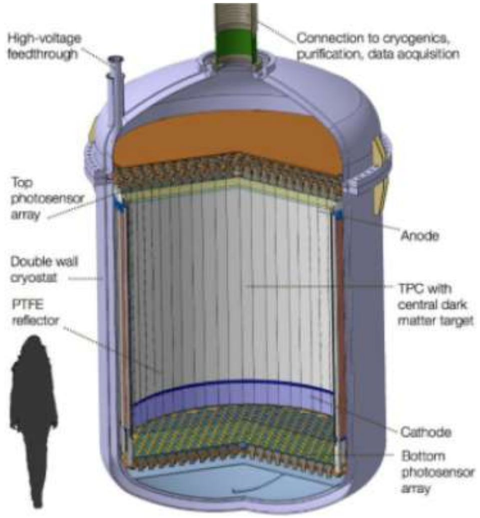
Slide from K. Scholberg

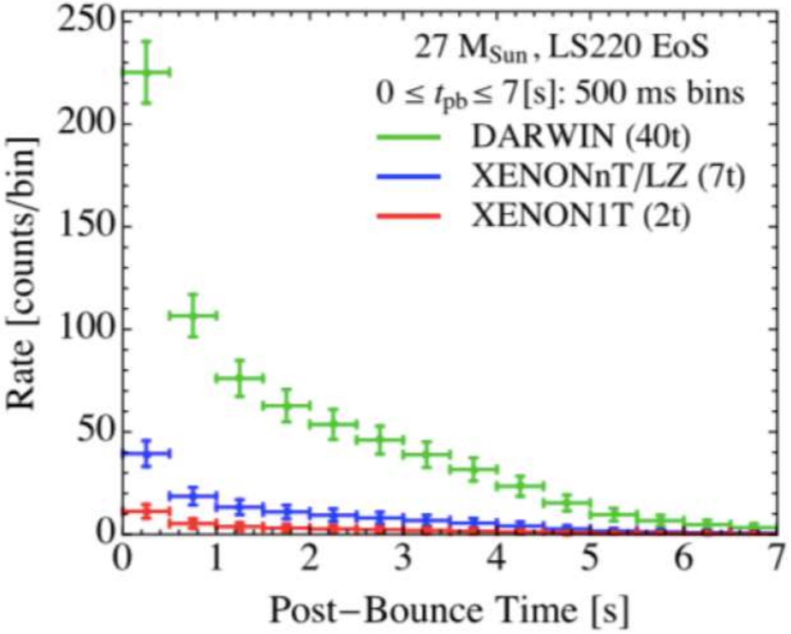
Dark Matter detectors examples: XENON/LZ/DARWIN

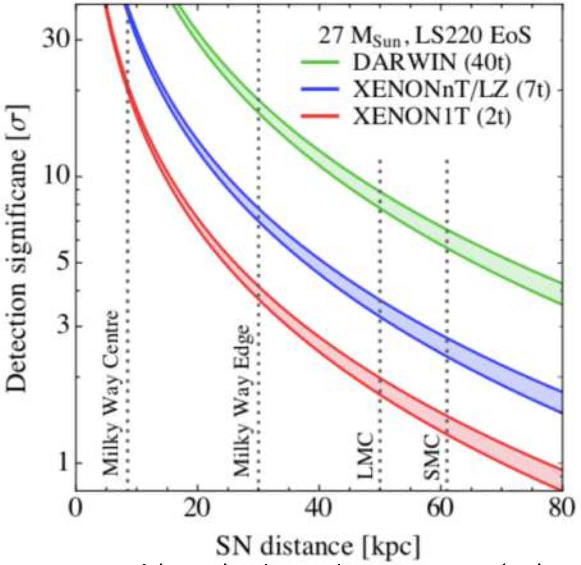
- Dual-phase xenon time projection chambers











Lang et al.(2016). *Physical Review D*, *94*(10), 103009. http://doi.org/10.1103/PhysRevD.94.103009

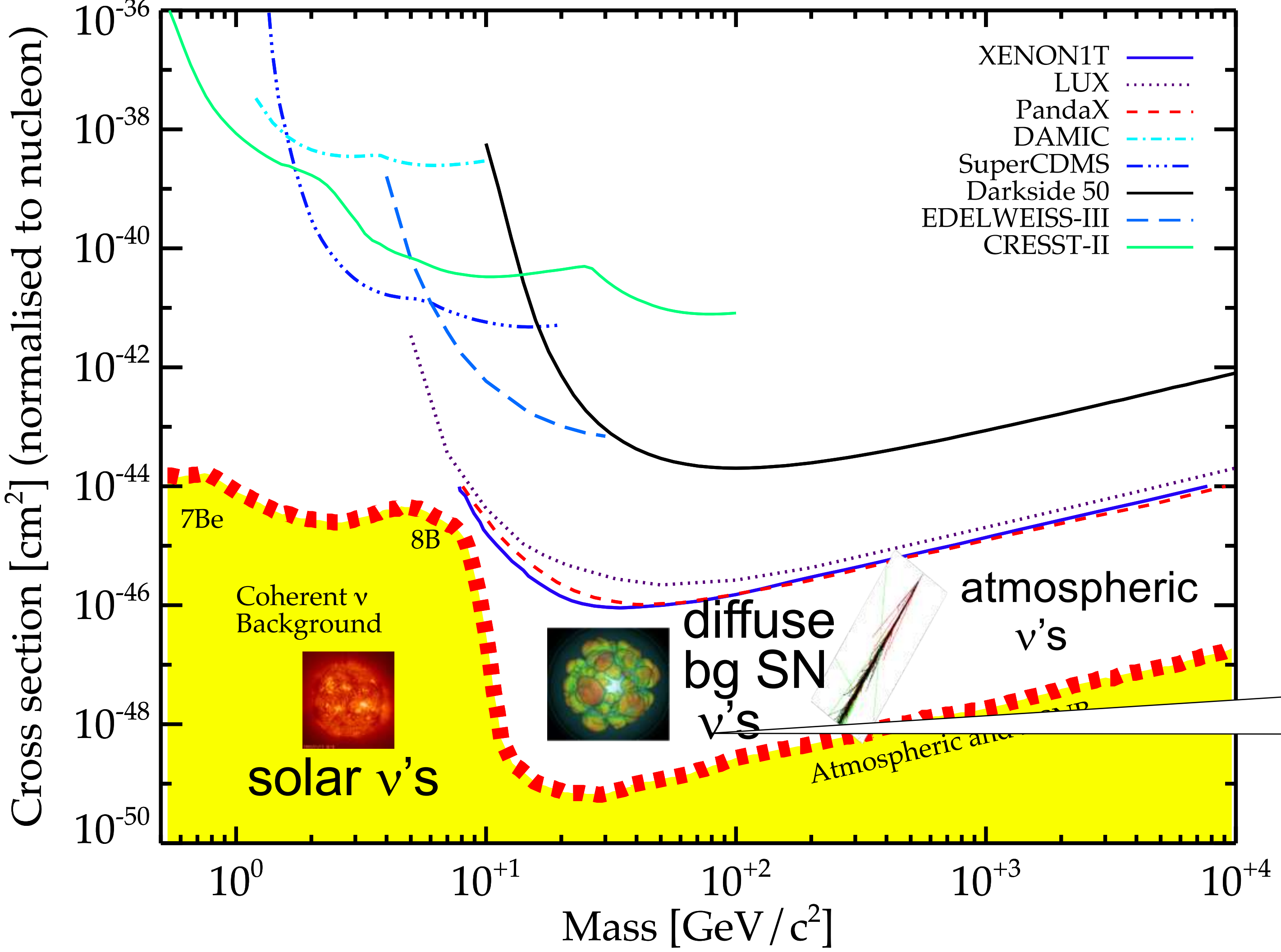
Sensitivity to detect Supernovae from outside our galaxy!

Slide from K. Scholberg

The so-called "neutrino floor" for DM experiments

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

L. Strigari



SN burst flux @ 10 kpc is 9-10 orders of magnitude greater than DSNB flux

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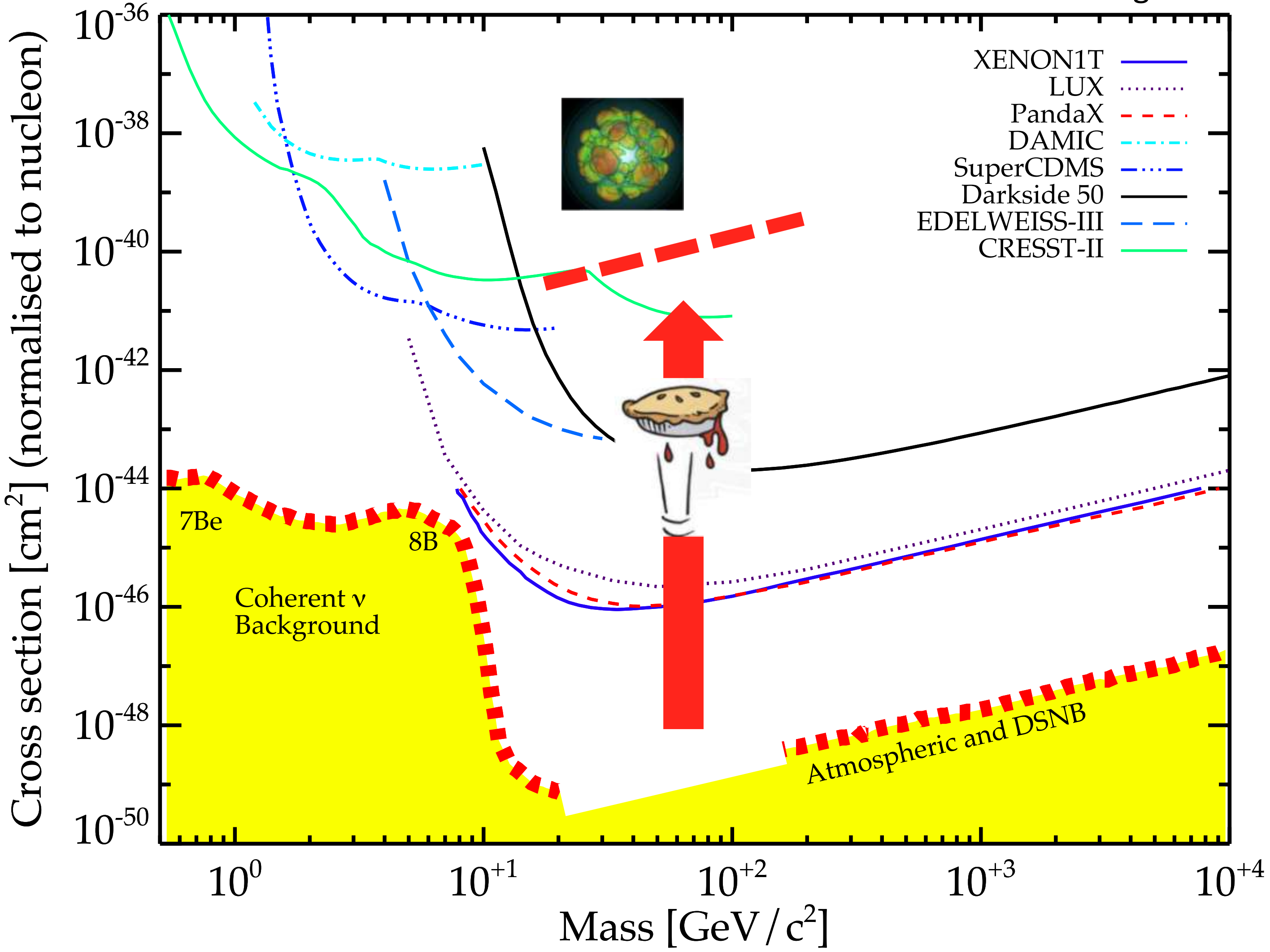
Think of a SN burst as “the ν floor coming up to meet you”

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

L. Strigari



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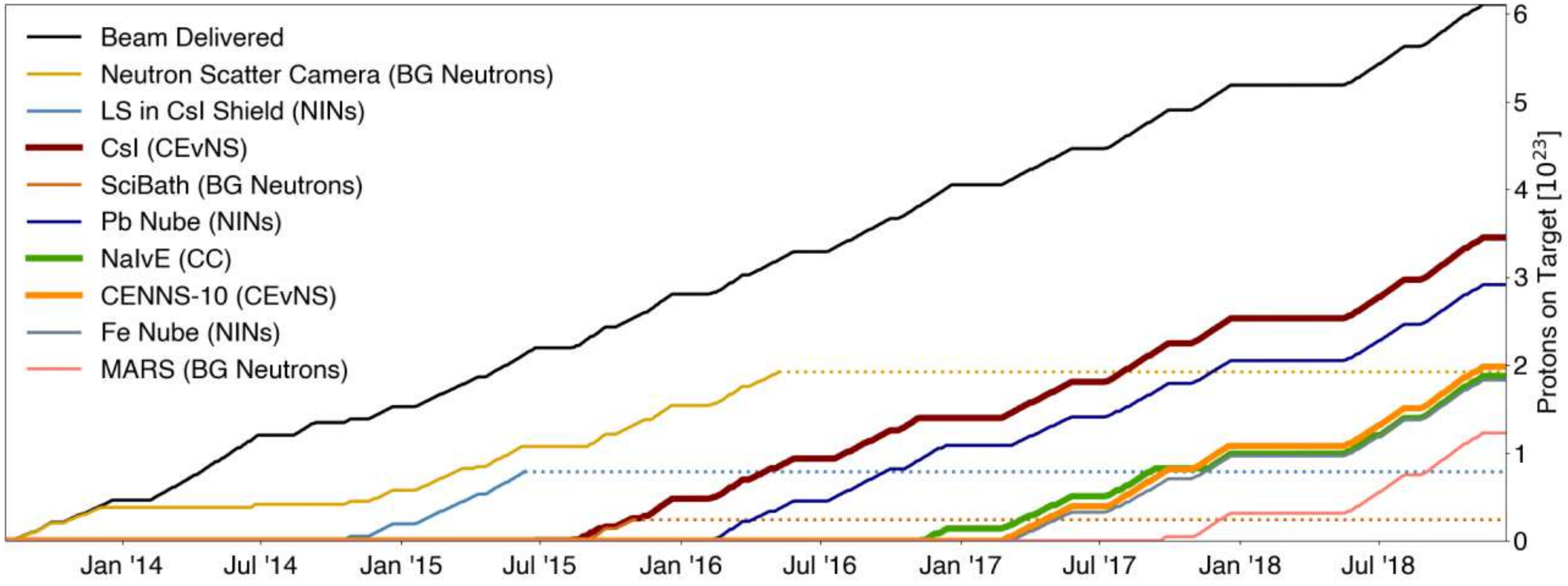
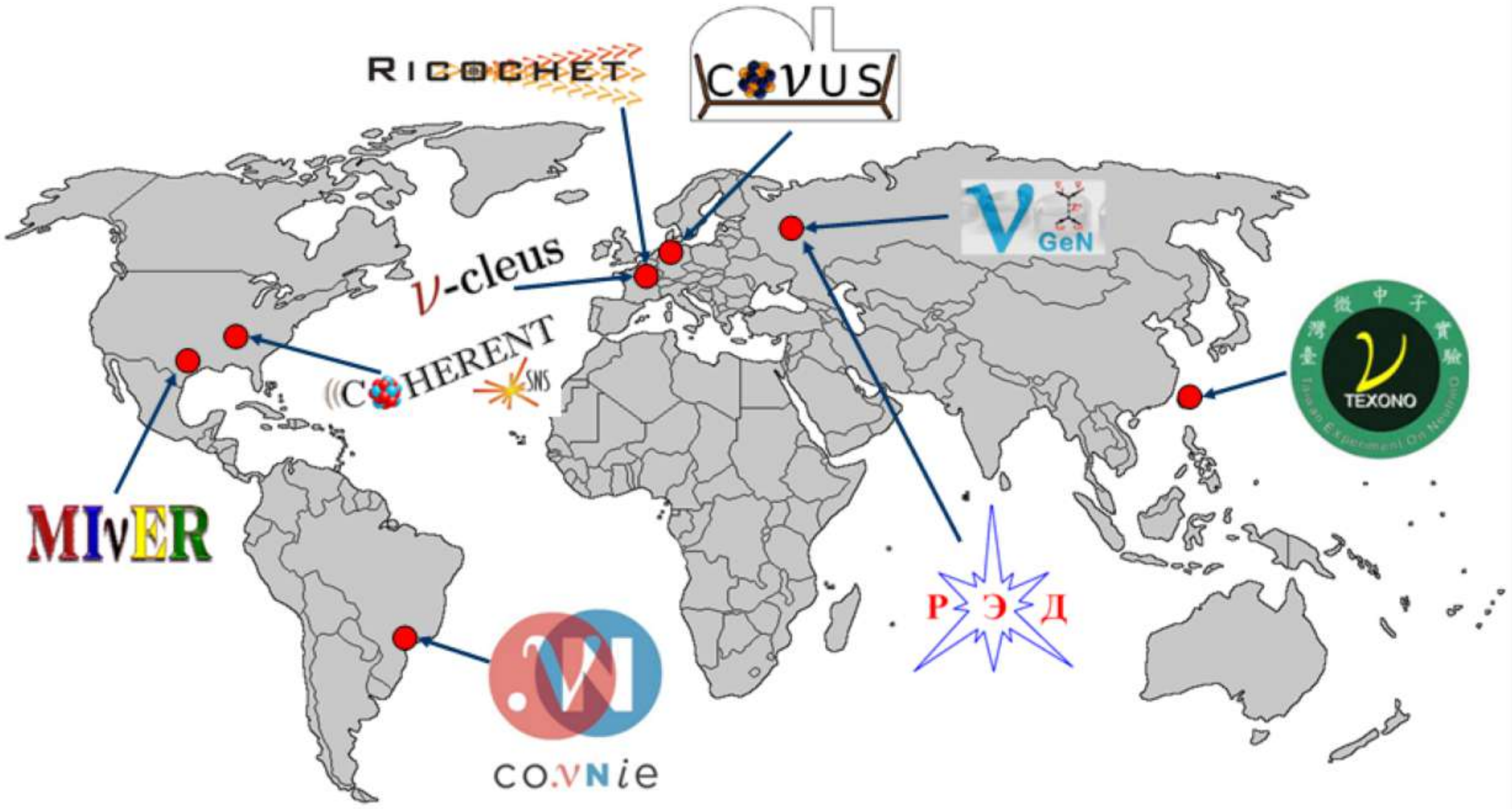
Summary

- CEνNS is another detectable neutrino interaction
- COHERENT at SNS is a suite of detectors designed to do precision measurements of both CEνNS and backgrounds in order to characterize this interaction
- Next generation of detectors has potential for Beyond the Standard Model physics
- CEνNS from supernova neutrino may be detectable from ton-scale (dark matter or neutrino) detectors
  - We are at the Dawn of CEνNS Astronomy?
  - Astrophysics can be inferred from those results if we have better understanding of the CEνNS interaction



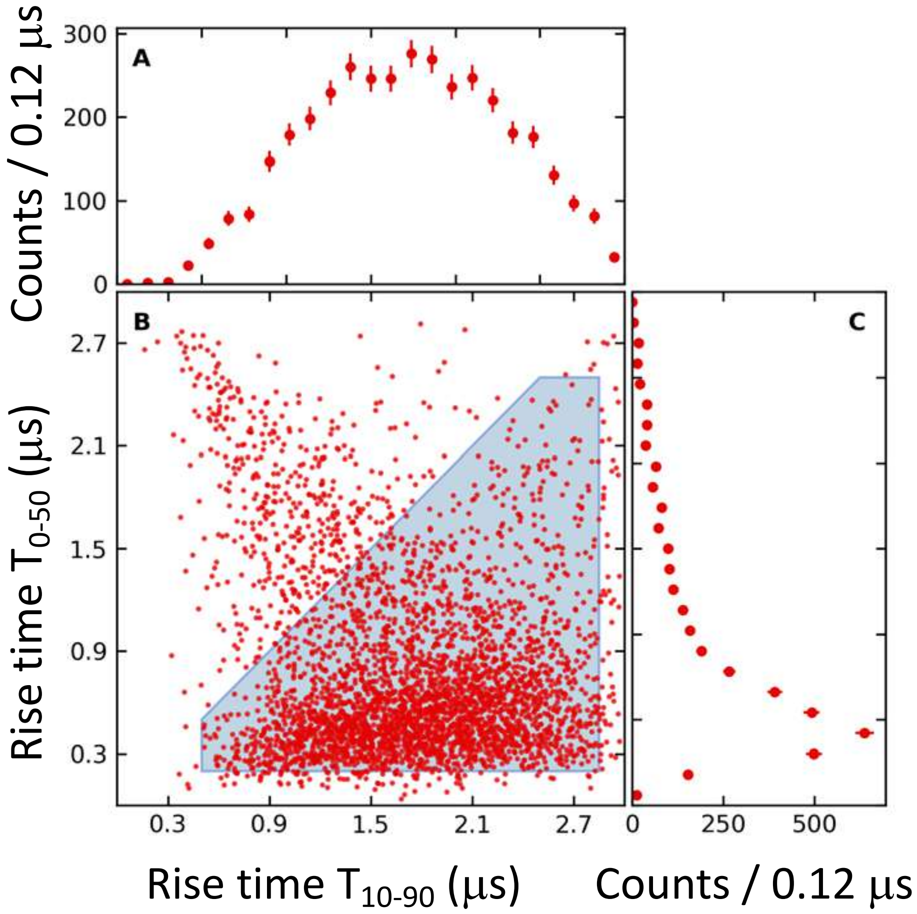
BACKUP SLIDES

CEvNS Around the World

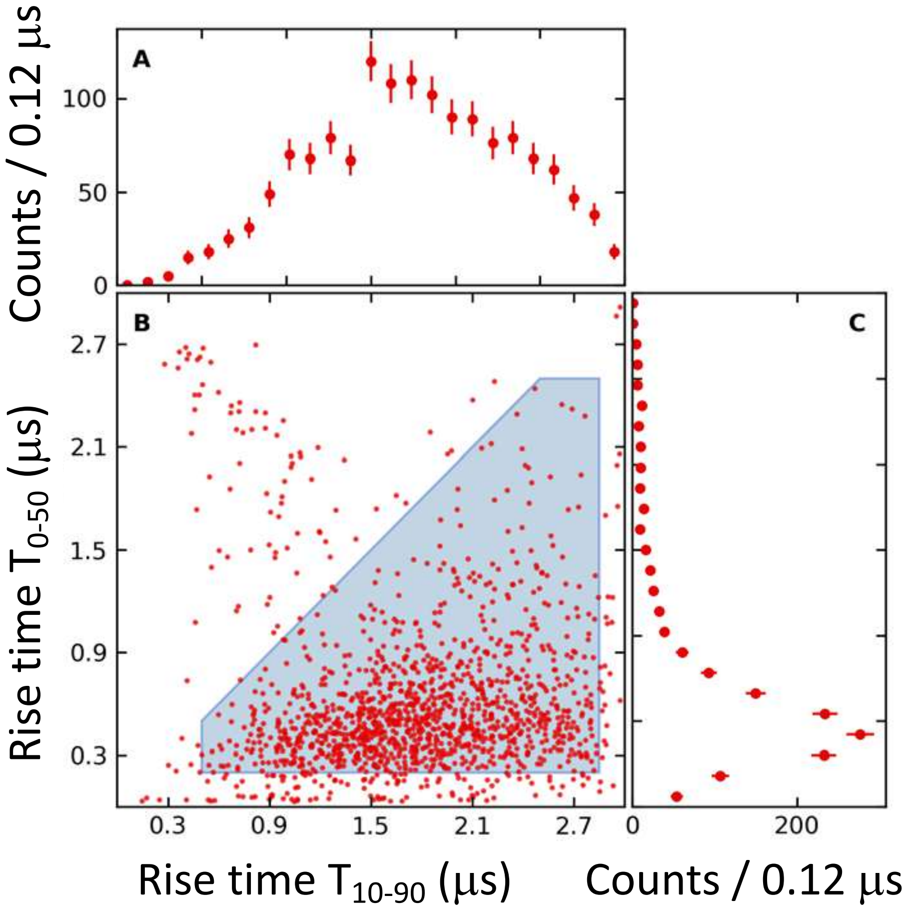


Pulse Shape Analysis

^{133}Ba calibration data

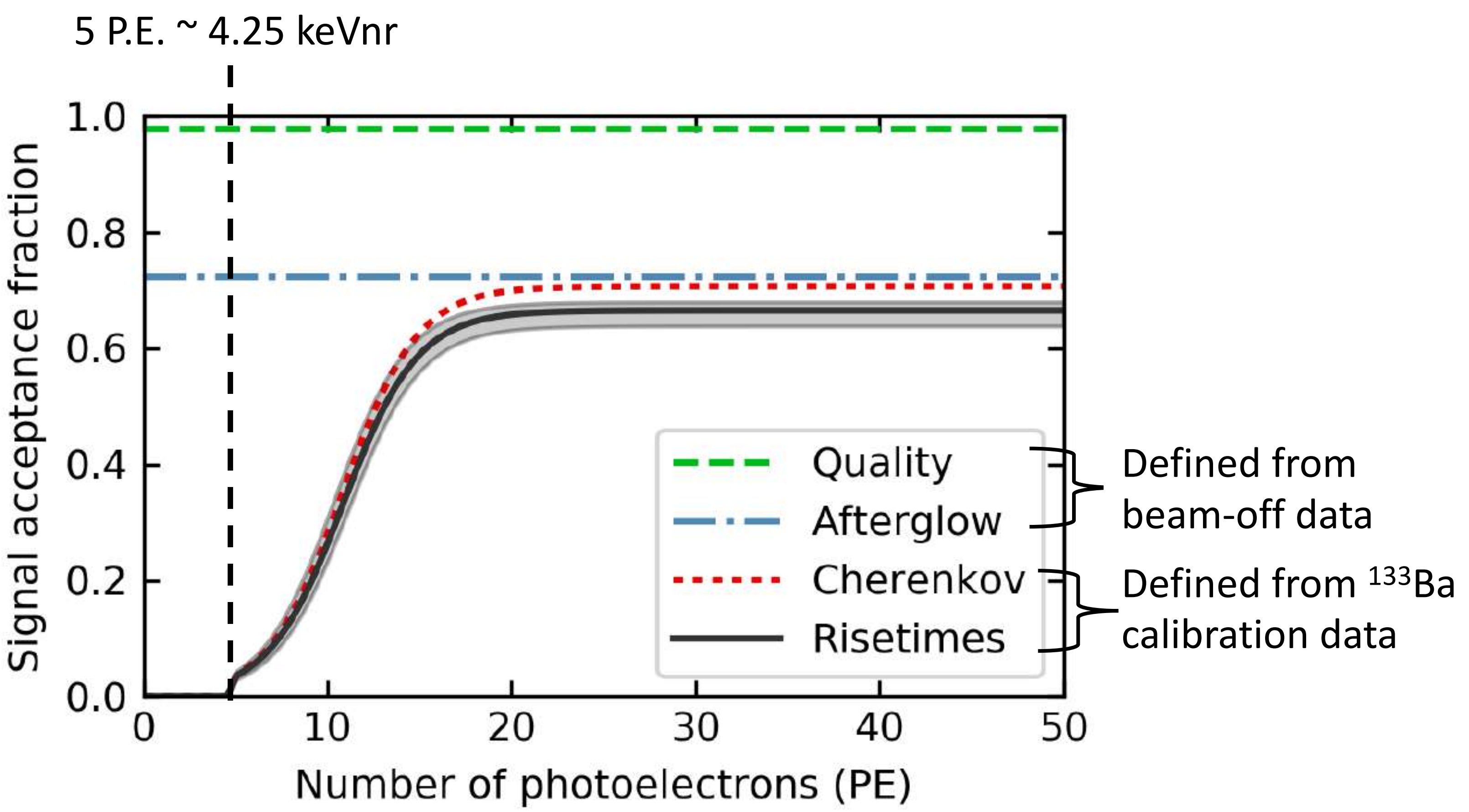


Beam-on SNS data



*Akimov et al., Science **357**, 1123 (2017), suppl. mat.*

Analysis Cuts



*Akimov et al., Science **357**, 1123 (2017), suppl. mat.*