Experimental Astroparticle Physics Seminar

Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)

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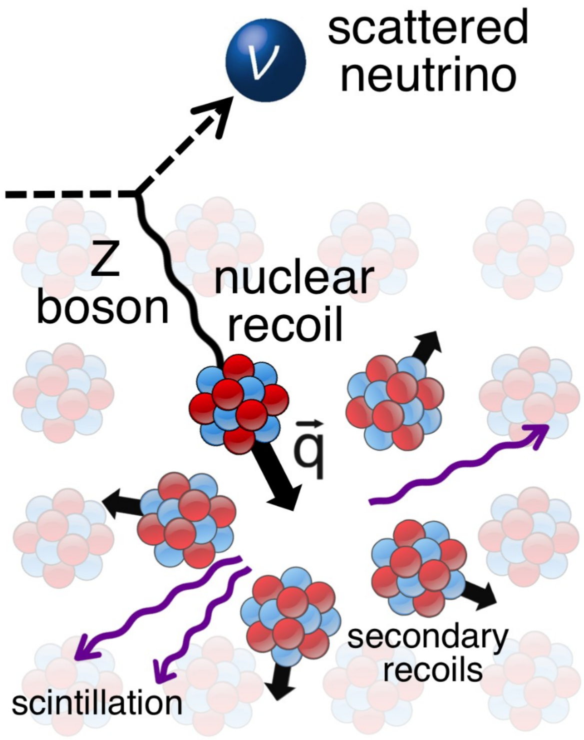
Outline

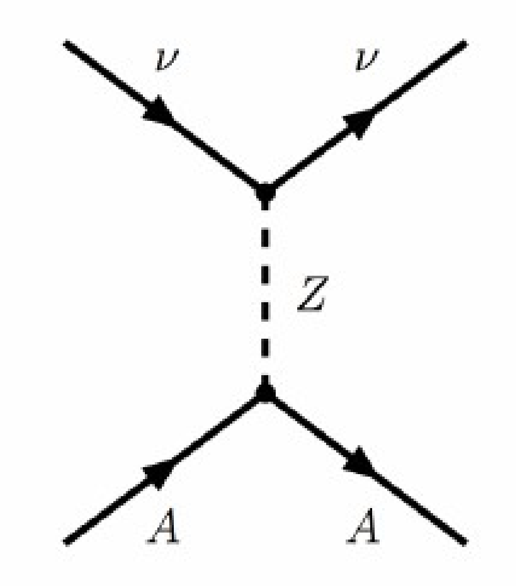
- Introduction to CEvNS
- Motivation to detect CEvNS signal
- Aspects related to the COHERENT experiment
- Future prospects

Timeline

- First proposed in 1974 by Daniel Freedman “Coherent effects of a weak neutral current” -- [*“Our suggestion may be an act of hubris, because the inevitable constraints of interaction rate, resolution and background pose grave experimental difficulties.”*]
- Late 1970s: CEvNS considered in Supernova processes
- 1980s: Possible designs for detectors
- Search for black matter → detectors usable for CEvNS
- 2017: (finally) First detection of CEvNS signal

Basic Principle





Coherent scattering:

Neutrino energy ~ <50 MeV

(momentum transferred)*(size of nucleus) << 1

Nucleons not “resolved” by the neutrino

Signal of CEvNS:

recoil of the nucleus – extremely small

difficult to detect (few keV)

CEvNS Cross Section

where, Fermi constant
scattering angle
weak nuclear charge
form factor at momentum transfer, ; with,

: weak nuclear charge

$$\boxed{\boxed{Z\left(4\sin^2\Theta_w-1\right)+N}}$$

arXiv:1110.3536v3

One can analyze from this expression:

$$\frac{d\sigma}{d(\cos\ \theta)} = \frac{G_f^2}{8\pi}\left[Z\left(4\sin^2\Theta_w - 1\right) + N\right]^2 E^2\left(1 + \cos\ \theta\right)$$

- Weak mixing angle, → (e hanceme t of the cross-section)
- Large cross-section compared to other neutrino interactions → smaller detectors

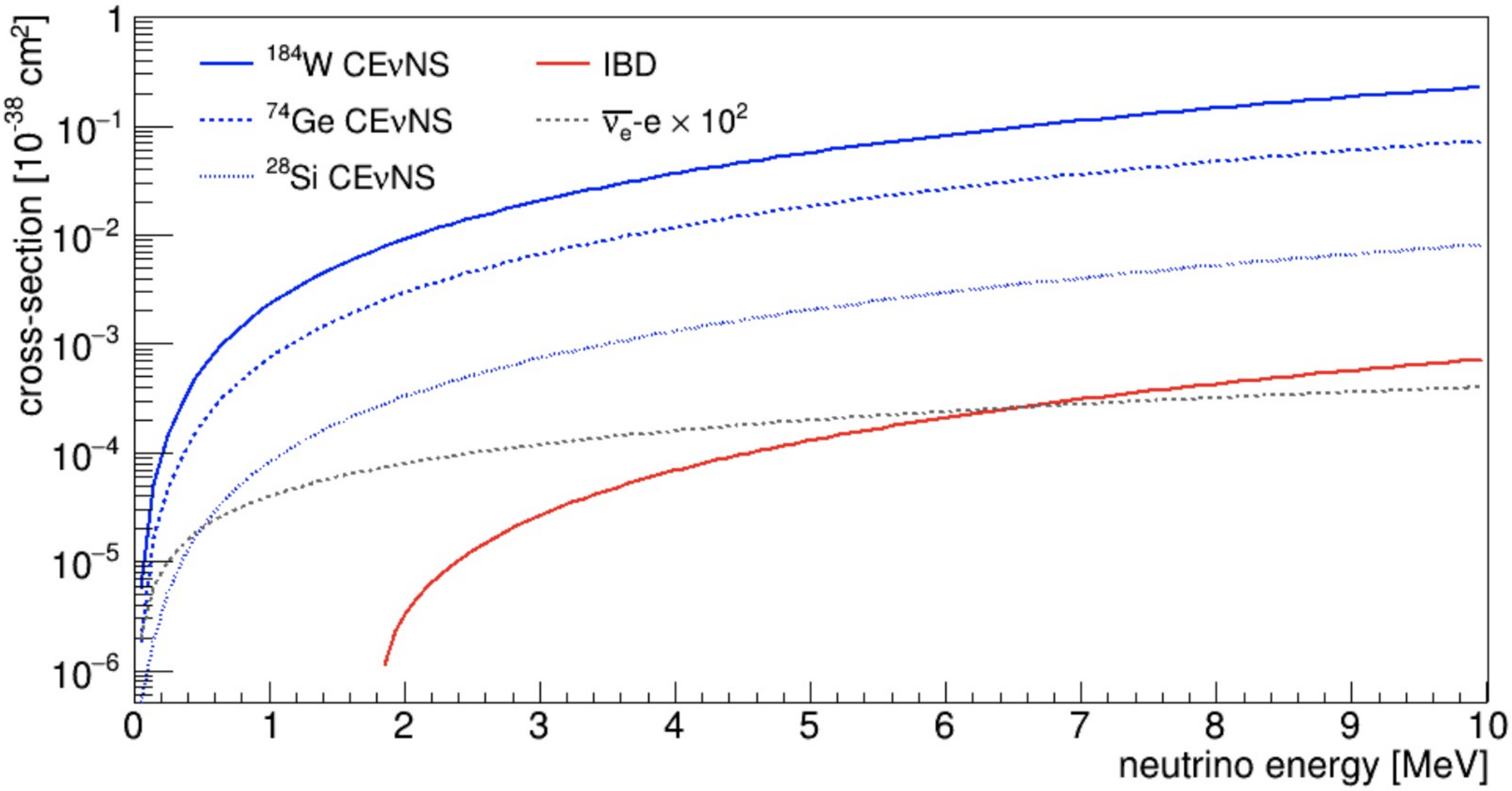
Integrating out for and expressing it per kilogram of the detector

$$\sigma \approx 2.5\times 10^{-18}\frac{N^2}{A}¿$$

Phys. Rev. D 30(11), Principles and applications of a neutral-current detector for neutrino physics and astronomy, 1984

One find that for flux , we obtain a rate of 30 CEvNS/hour for only **1 kg** of Pb

Comparison of Cross Sections for neutrino interactions

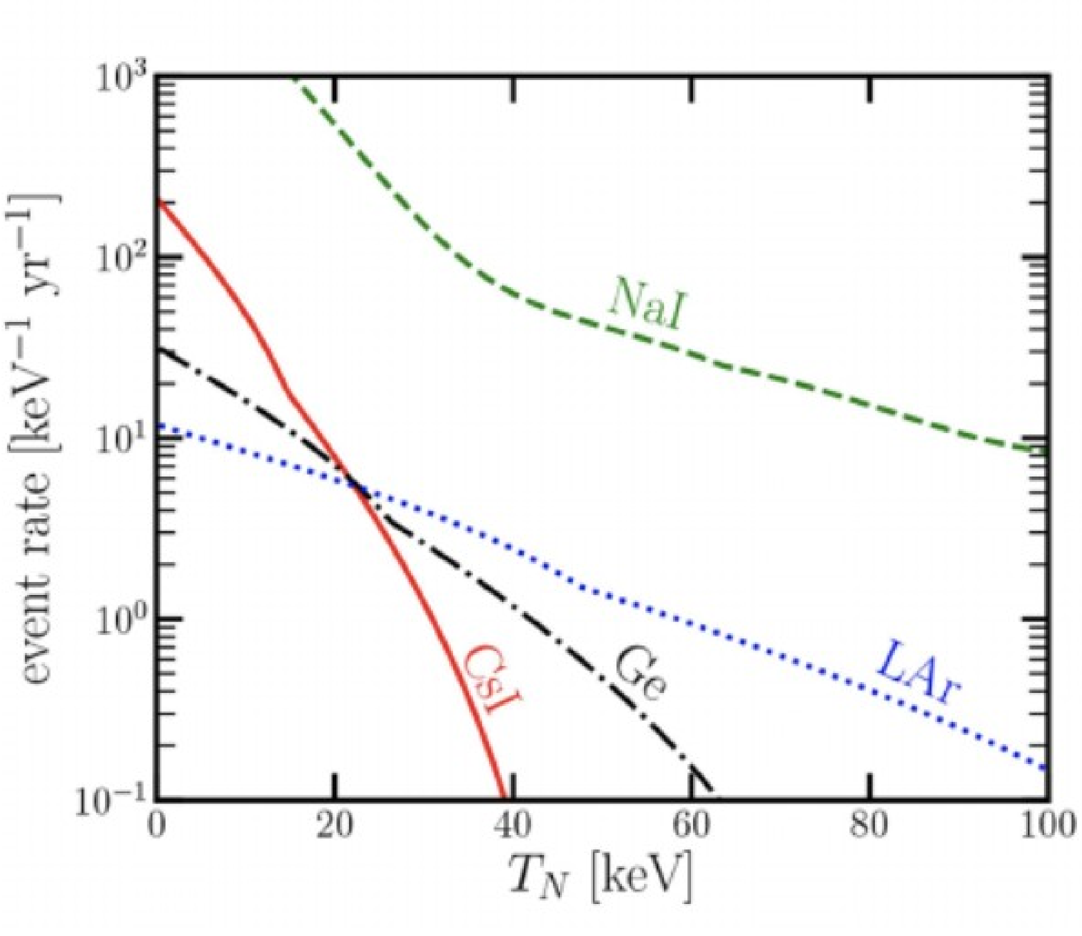


Choice of Target Nucleus

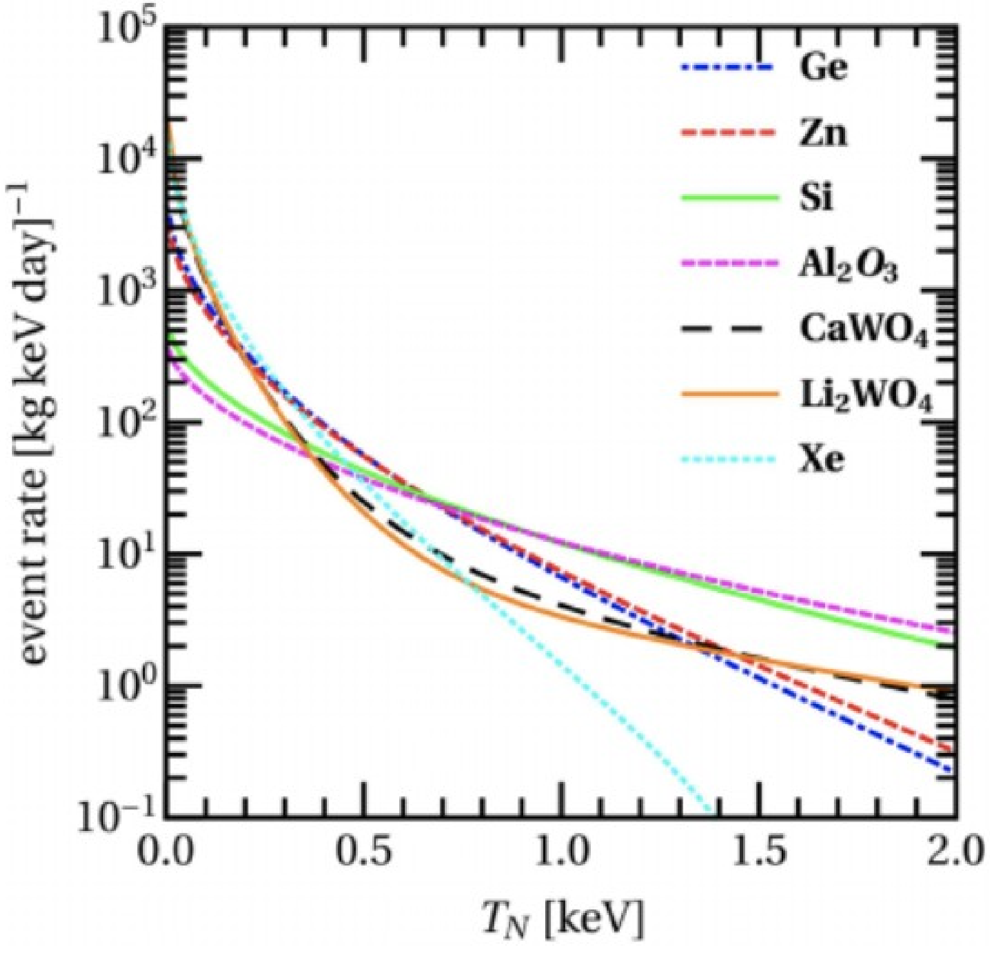
Cross section:

Recoil energy:

→ High A-nuclei: large cross section but lower recoil energy



10^3
10^2
10^1
10^0
10^{-1}
event rate [keV^{-1} yr^{-1}]
NaI
CsI
Ge
LAr
0
20
40
60
80
100
T_N [keV]



10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
event rate [kg keV day]$^{-1}$
Ge
Zn
Si
Al_2O_3
$CaWO_4$
Li_2WO_4
Xe
0.0
0.5
1.0
1.5
2.0
T_N [keV]

Motivation

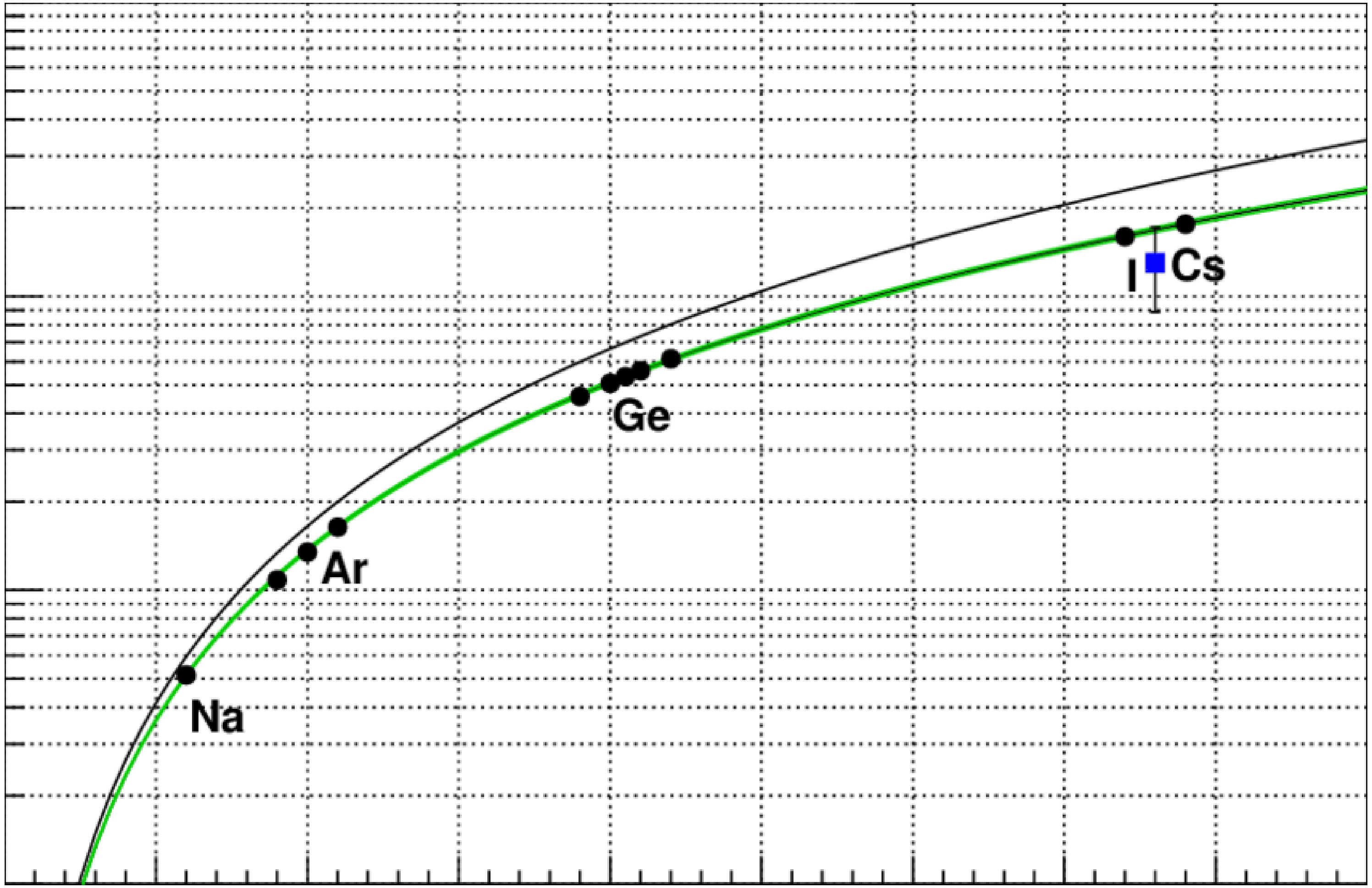
- CEvNS is an important process in supernovae
- Sterile neutrino oscillations
- Dark Matter searches
- Nuclear physics
  - neutron form factor
- Test for SM
  - weak mixing angle
- Probing physics beyond the SM

Core Collapse Supernovae

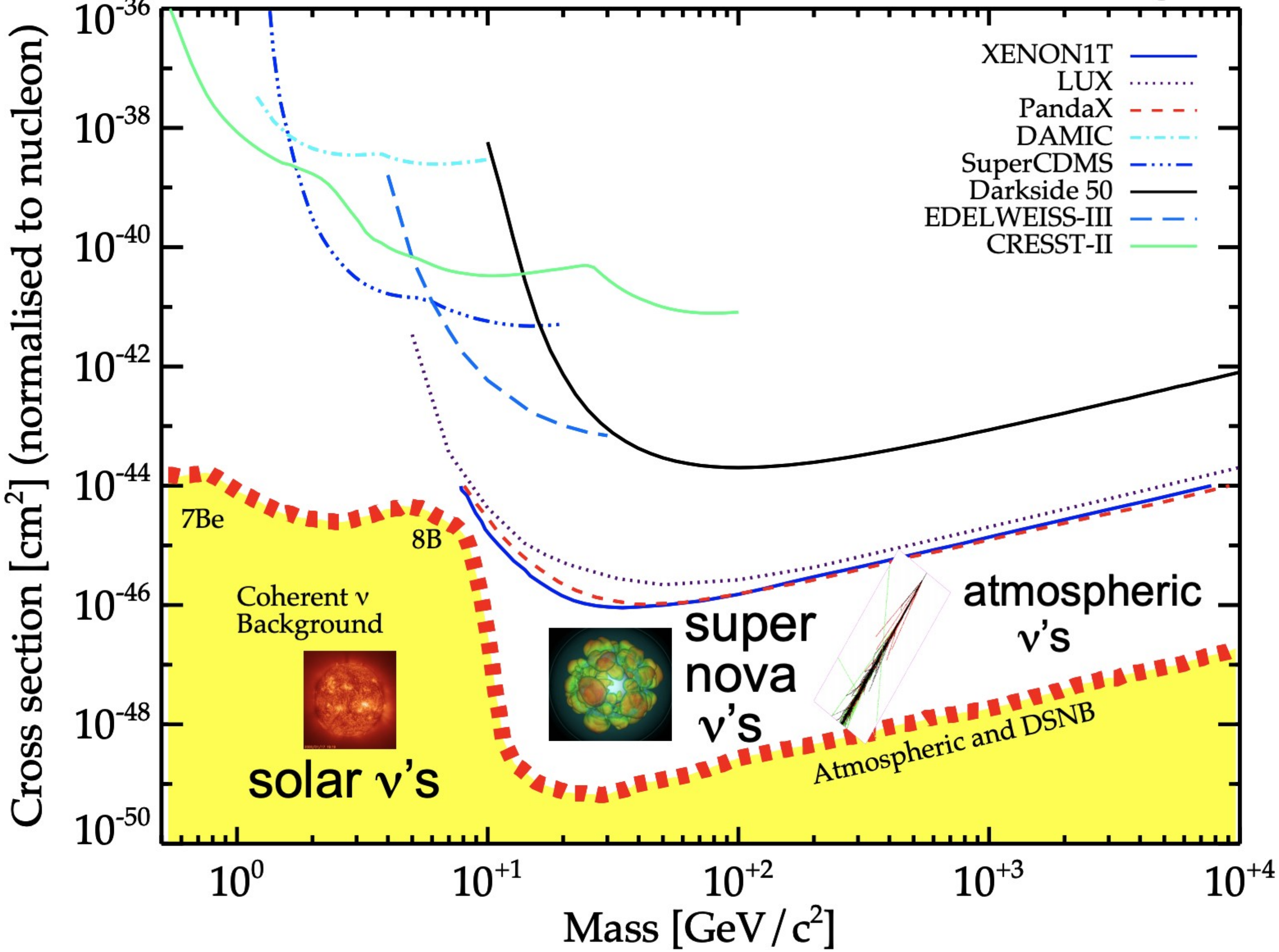
- 99% of gravitational binding energy goes into neutrinos of all flavours
- Energy of a few 10s of MeV
- Large cross section is needed for information
- 0.1 s after beginning of core collapse: CEvNS processes in core trap Neutrinos

→ Knowledge important for SN calculations

Neutron Form Factor



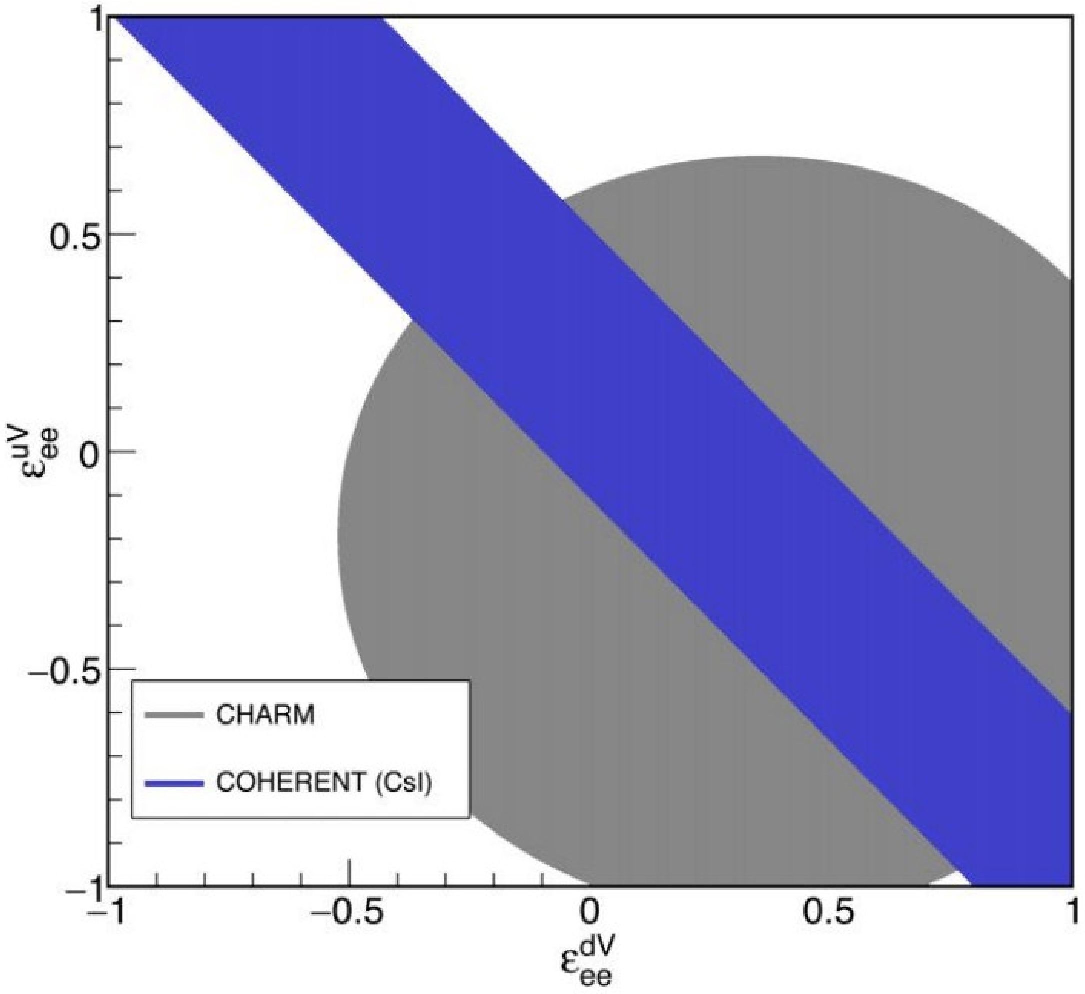
Dark Matter Searches: Neutrino Floor

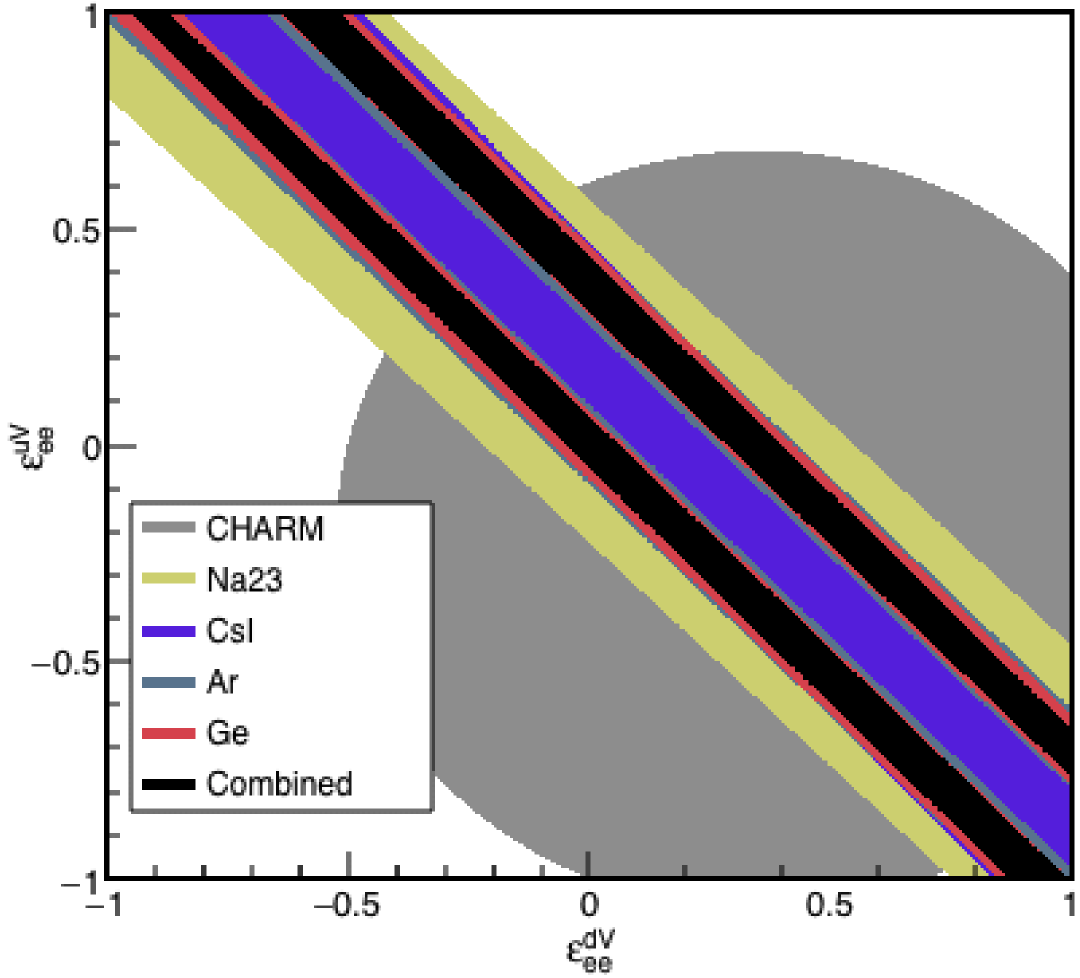

J. Monroe & P. Fisher, 2007

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

L. Strigari

Constraints On NSI

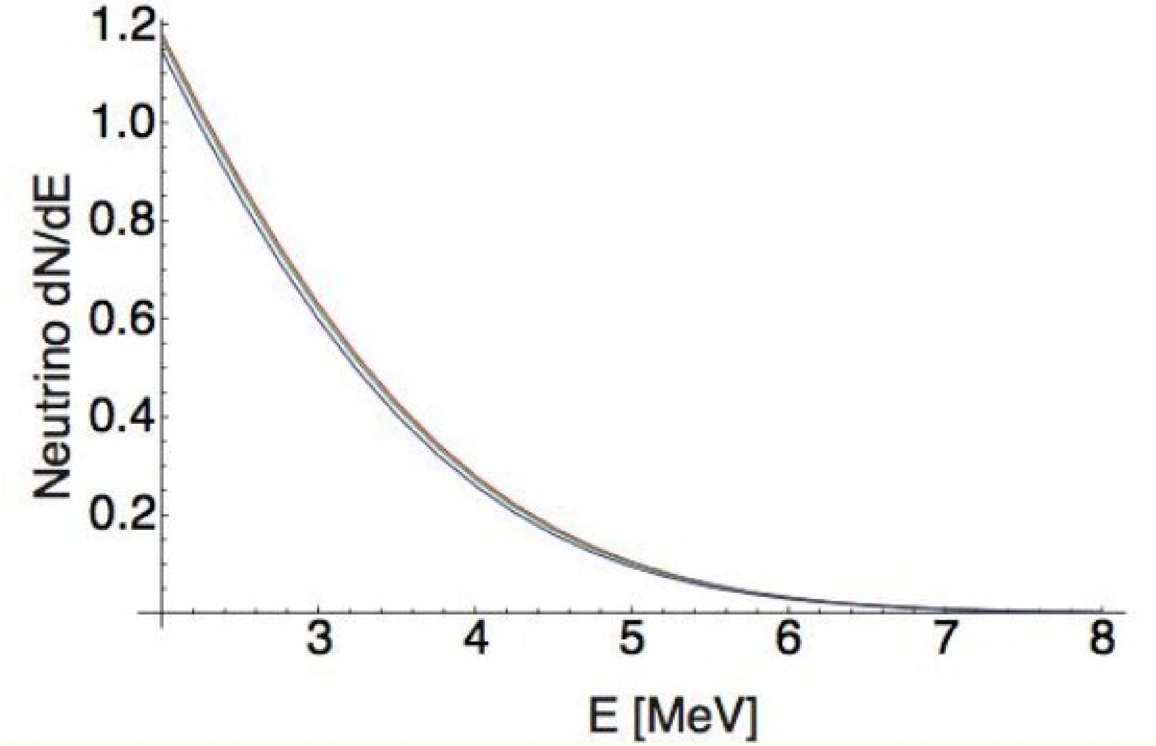




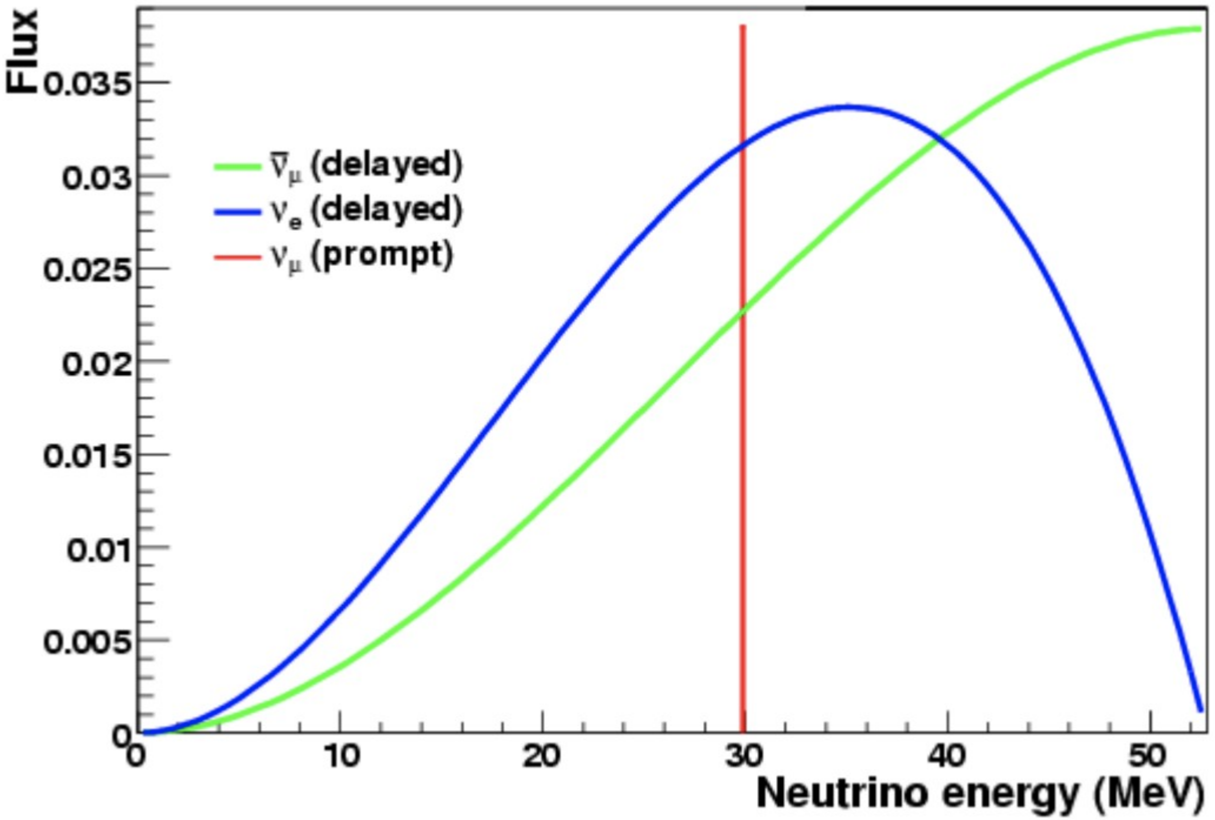
Neutrino Sources (used as of now)

	Flux	Energy	Flavour	
Reactors		Few MeVs	electron	+ high flux - low energy - continous - lower cross section
Stopped Pion		0-50 MeV	muon	+ higher energy + pulsed + higher cross section - lower flux - neutron background

Reactor



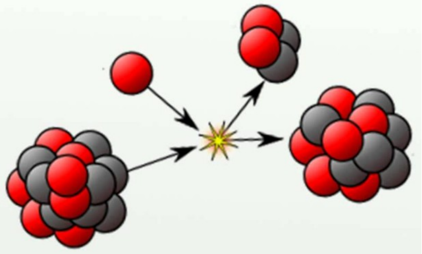
Stopped Pion



CEvNS Detectors

- Scintillation Detectors
  - Nuclear recoils keV, very hard for sub-keV
  - Inorganic crystals: CsI, NaI,…
- Phonon Detectors (thermal)
  - Suitable for nuclear recoils below 100 eV
  - Ge, Si, ..
- Ionization
  - Nuclear recoils keV, hard for sub-keV
  - GePPCs, Si CCDs, Ar/Xe TPCs
- Bubble chambers
  - not possible for sub-keV nuclear recoils
  - Superheated liquids

Spallation Neutron Source (SNS), Oak Ridge Laboratory, USA



→ High energy protons hit mercury target

→ Stopped pion decay

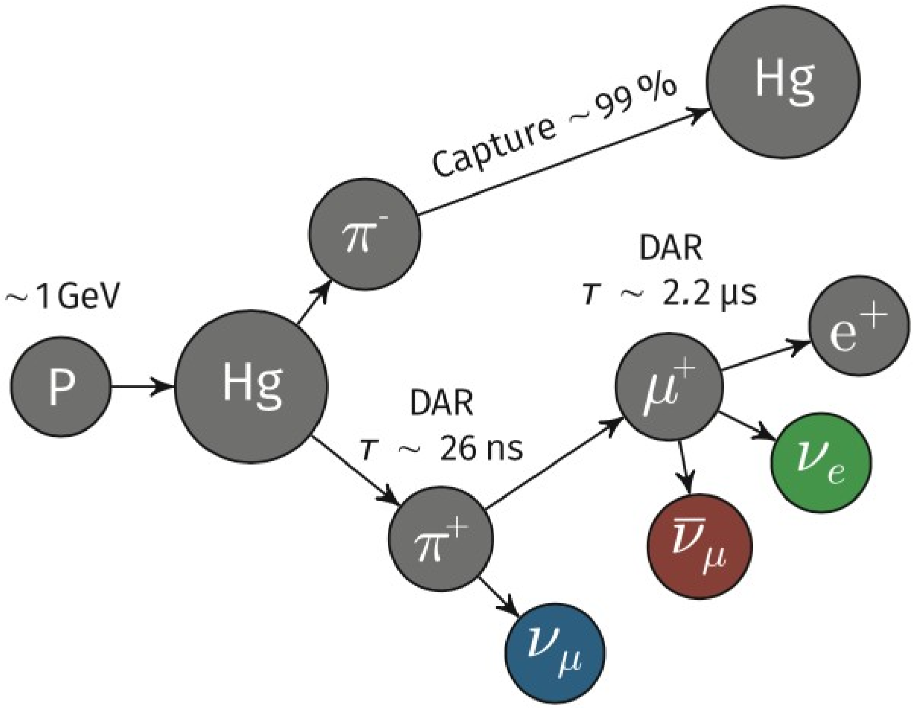
→ “neutrino alley”

Power: 1.4 MW
Proton energy: 1 GeV
Pulse width: 340 ns FWHM
Repetition rate: 60 Hz

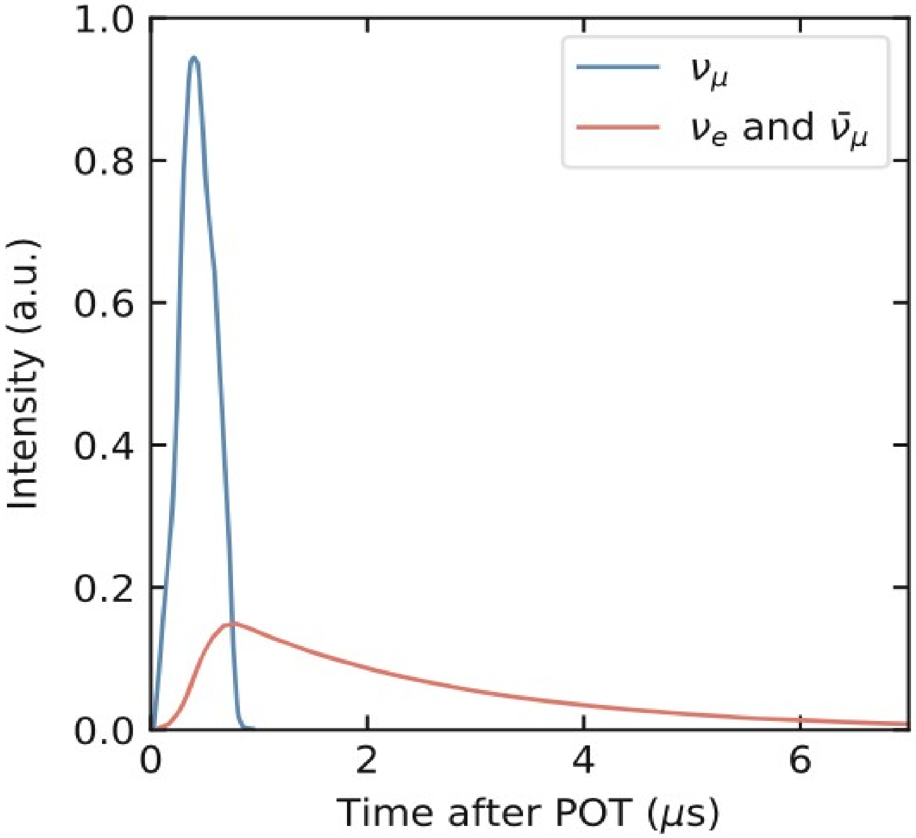
The COHERENT collaboration:

80 researchers, 20 institutions, 4 countries

Neutrino Production

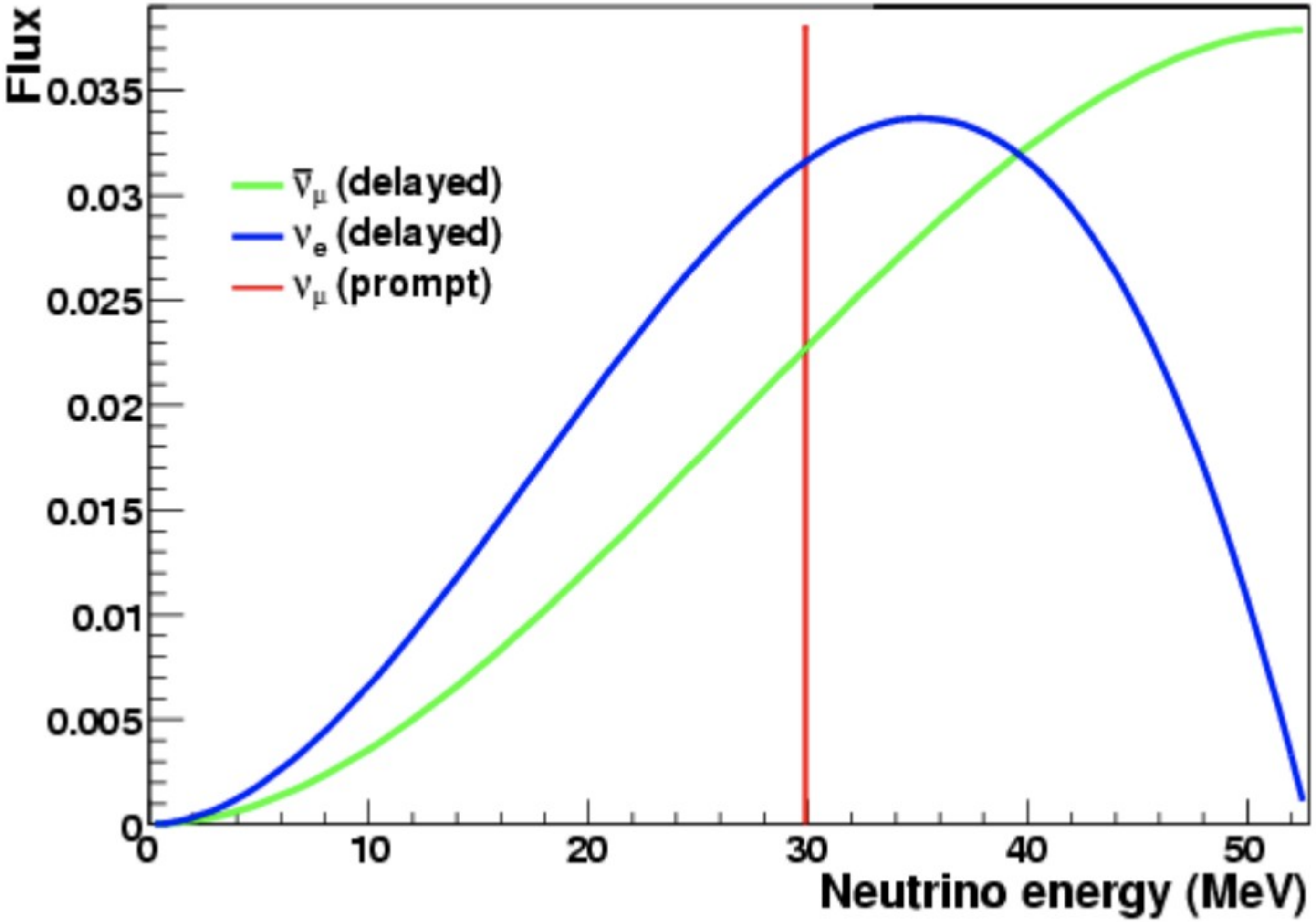


DAR – Decayed-At-Rest

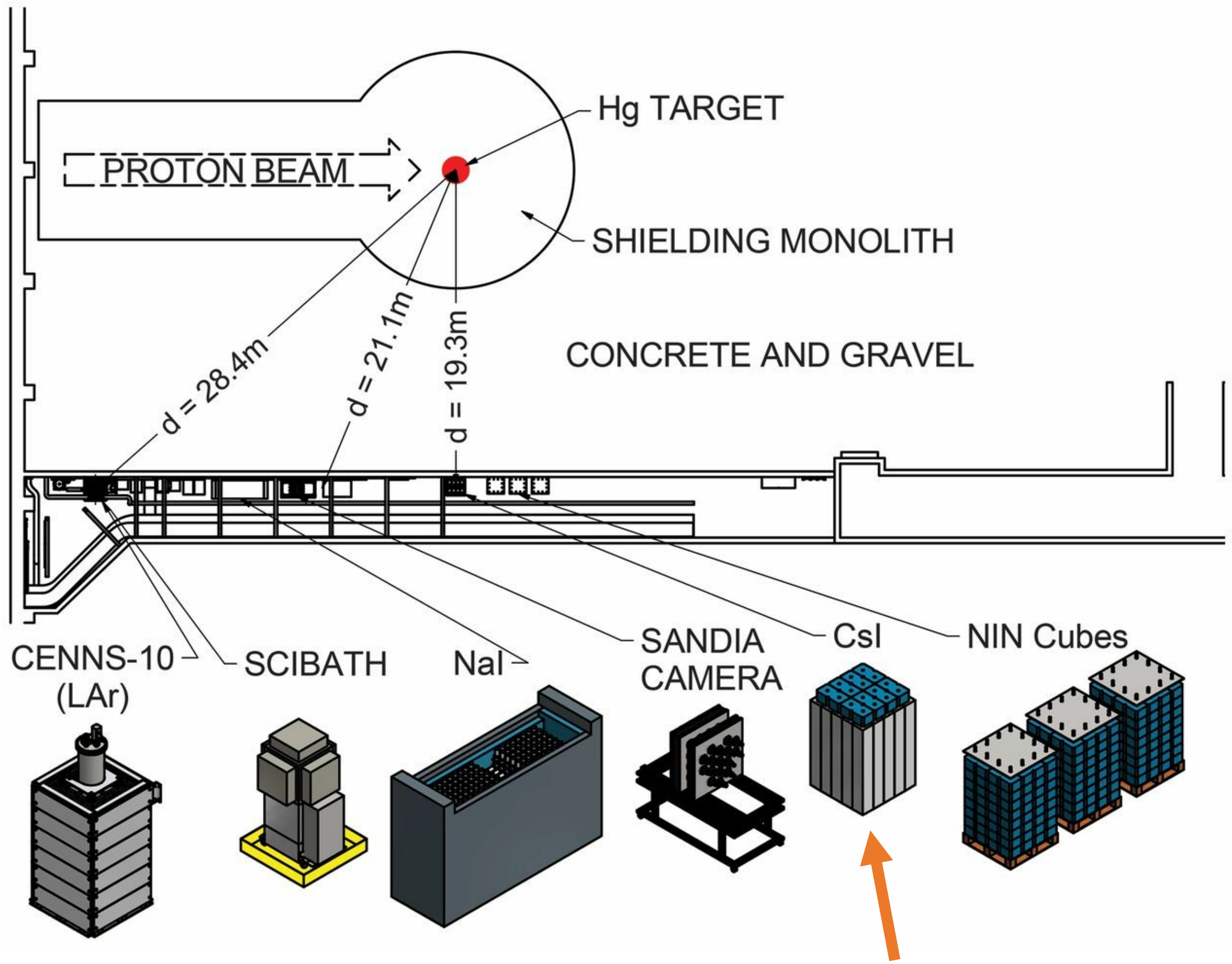


POT – Protons-On-Target

D. Akimov et al. Science 2017;357:1123-1126


Flux
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
$\bar{\nu}_\mu$ (delayed)
ν_e (delayed)
ν_μ (prompt)
0
10
20
30
40
50
Neutrino energy (MeV)

“Neutrino Alley”



CEvNS

CEvNS

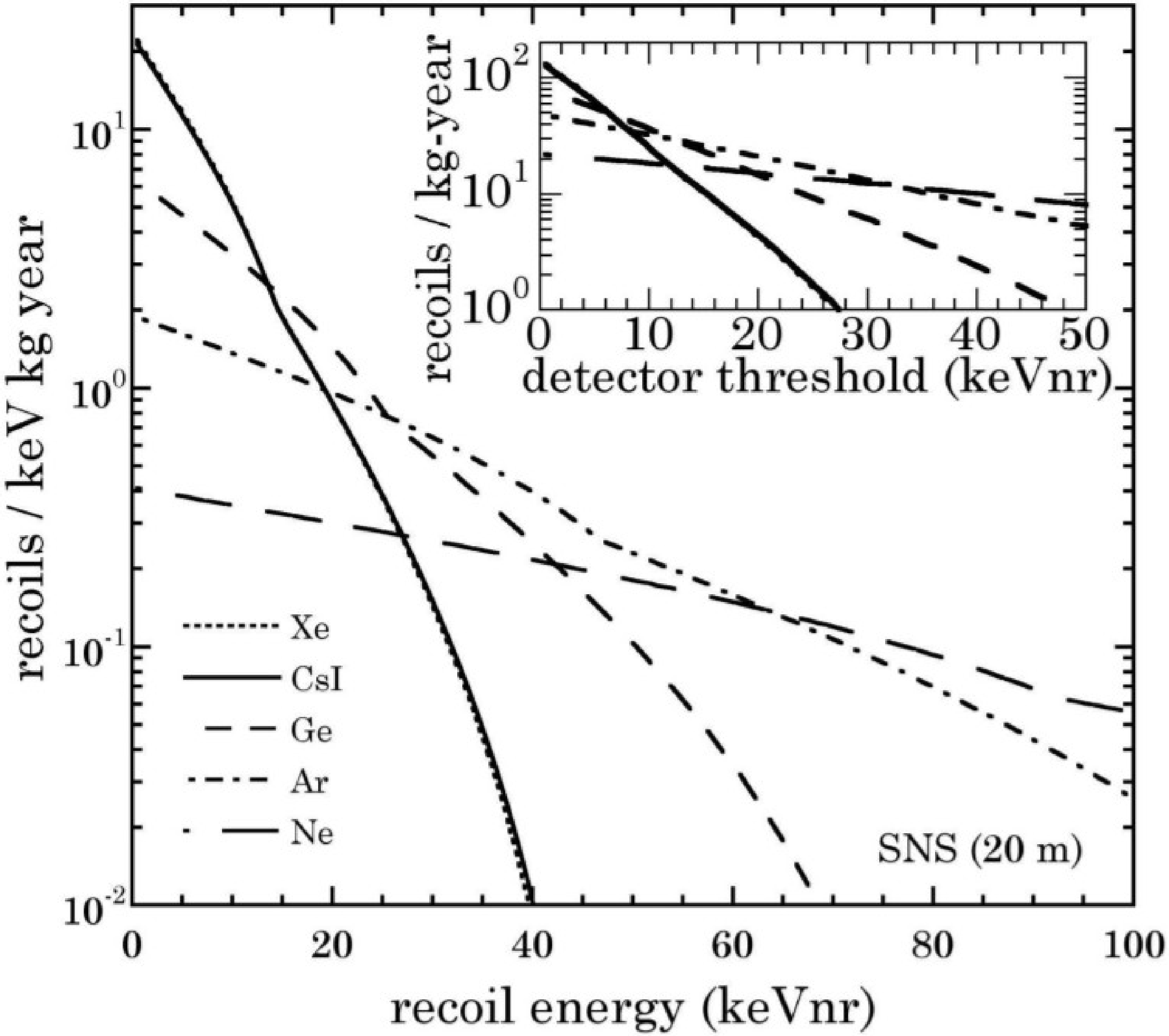
D. Akimov et al. Science 2017;357:1123-1126

Science
AAAS

Advantages of CsI[Na] detector

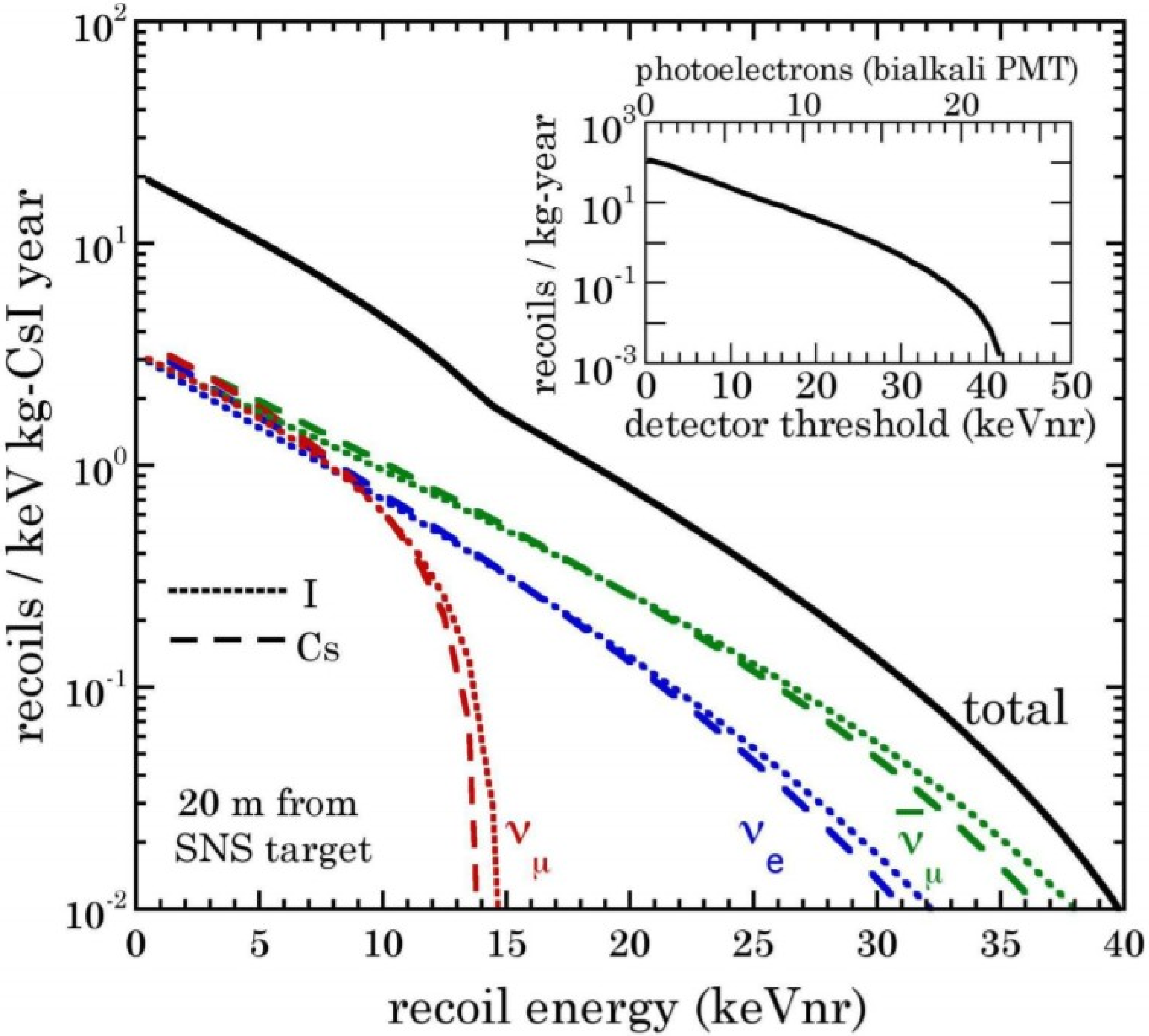
It’s an inorganic scintillator detector

High mass of both recoiling species, Cs and I



Advantages of CsI[Na] detector

Simplified response as nearly identical species



Advantages of CsI[Na] detector

- High mass of both recoiling species, Cs and I
- Simplified response as nearly identical species
- ~7 keV threshold with conventional bialkali PMT
- Convenient signal for background neutron monitoring
- Crystals are naturally low in internal radioactivity
- Shorter duration of the afterglow (when compared to CsI[Tl])
- High light yield (twice yield of photoelectrons against CsI[Tl])

Characterization + Detector and Shielding Design CsI[Na]

- Background estimates & reduction (neutrons, NIN, cosmic rays)
- Need to estimate *Quenching factor* (crucial!)

  [Quenching factor of 4.5% was used]

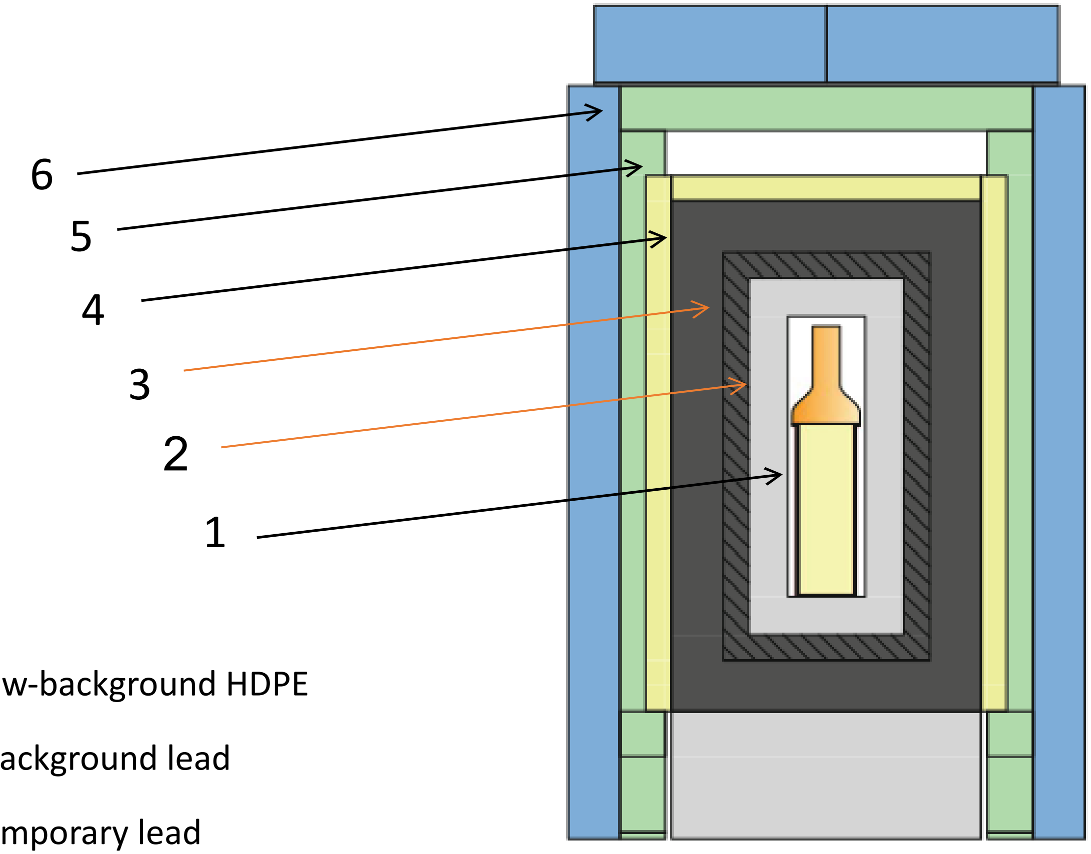
- Finally: 10 photoelectrons correspond to 12 keV(nuclear recoil)

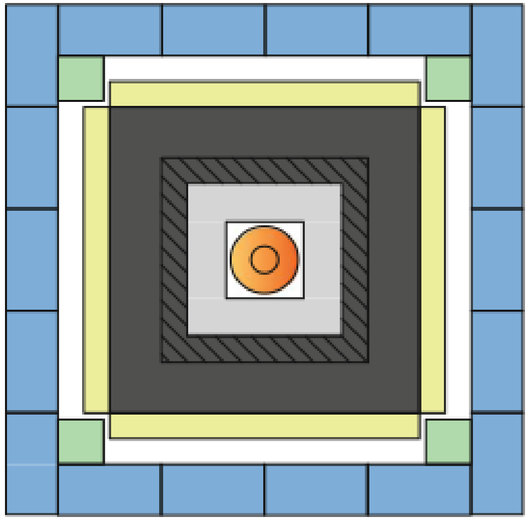
- Crystal samples screened for radioactive contaminants

  [presence of ^{40}K, ^{134}Cs, ^{137}Cs – responsible for internal low-energy background in this scintillator]

- Crystals wrapped in PTFE expanded-membrane reflector & innermost 7.5 cm HDPE
- Crystals encapsulated in electroformed OFHC Copper cans
- Ultra-low background (ULB) lead present around the detector (within 1 inch)
- Shielding against thermal neutrons – borated silicone, cadmium sheet
- 7 plastic scintillator muon veto panel

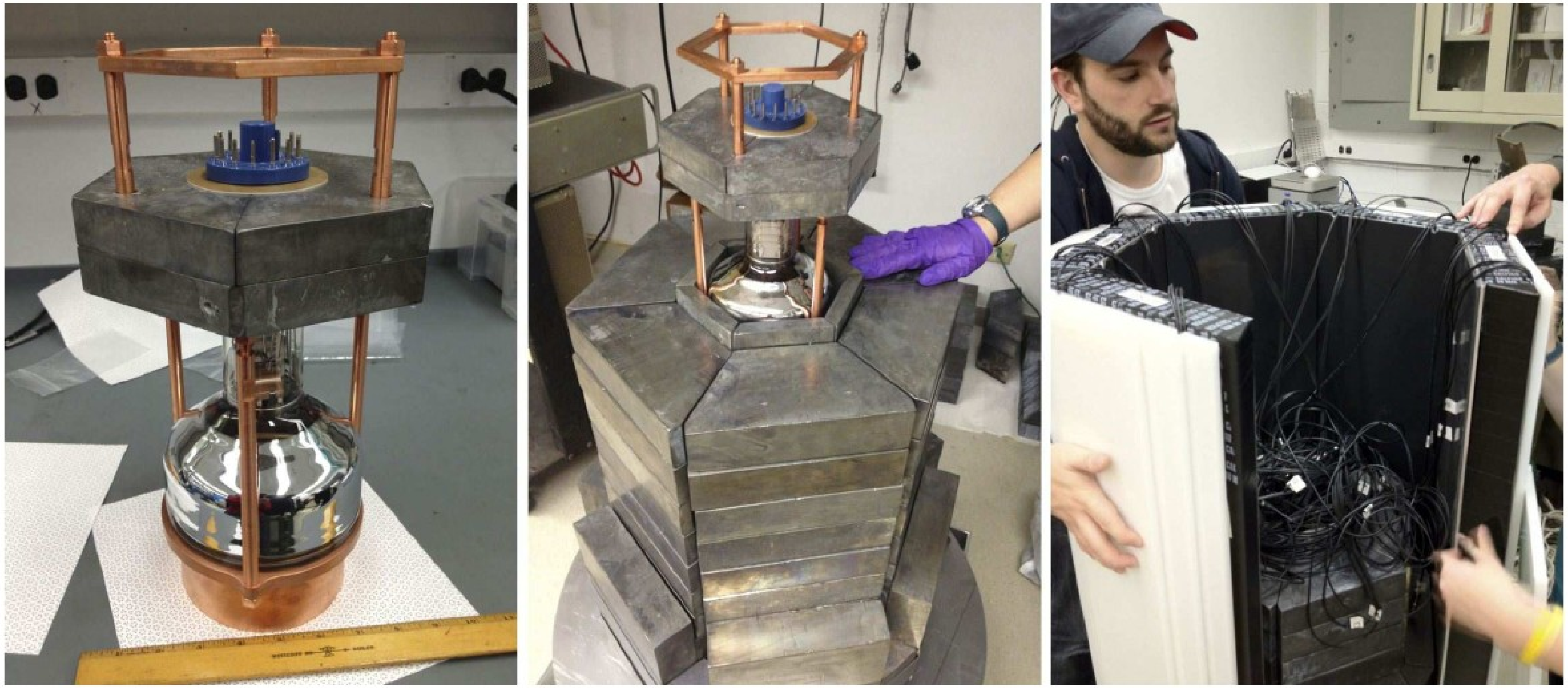
Schematic of the CsI[Na] shielding at the SNS



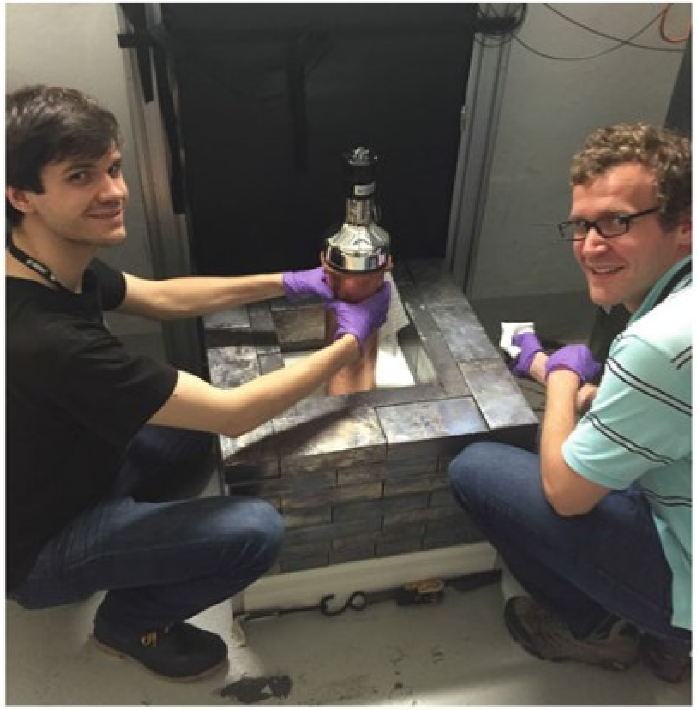


1. 3 inches of low-background HDPE
2. 2 in. of low-background lead
3. 4 in. of contemporary lead
4. 2 in. thick muon veto
5. Al Bosch-Rexroth extrusions
6. Al tanks filled with water, water-bricks

Chapter 5: First Observation of Coherent Elastic Neutrino-Nucleus Scattering, Bjorn Scholz, Springer - 2018



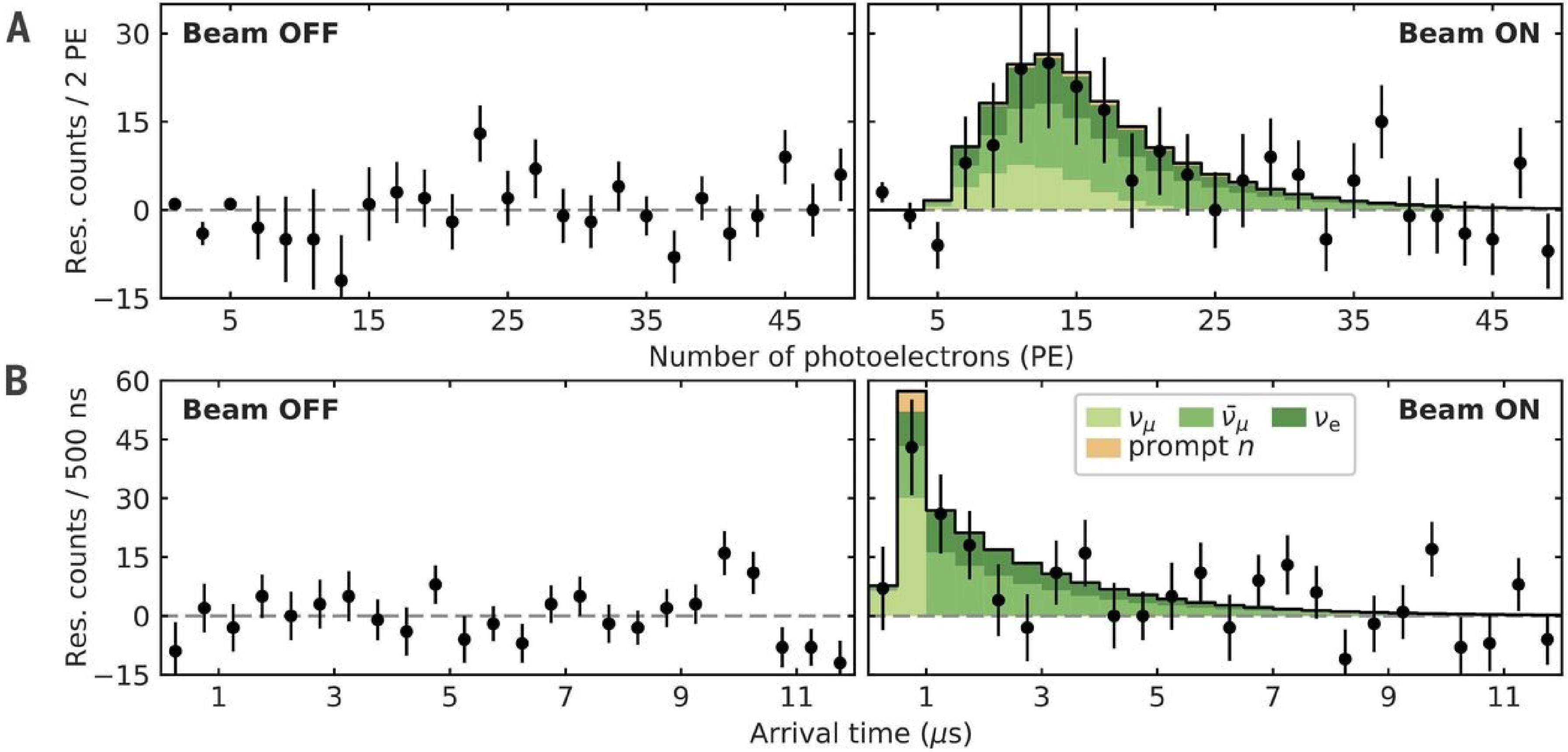
- Left: CsI[Na] Crystal and the PMT
- Center: The unfinished lead castle
- Right: muon veto panels



CsI[Na] Experiment (14.57 kg)

6.7 CL

First observation of CevNS by COHERENT in 2017. 43 years after its prediction!



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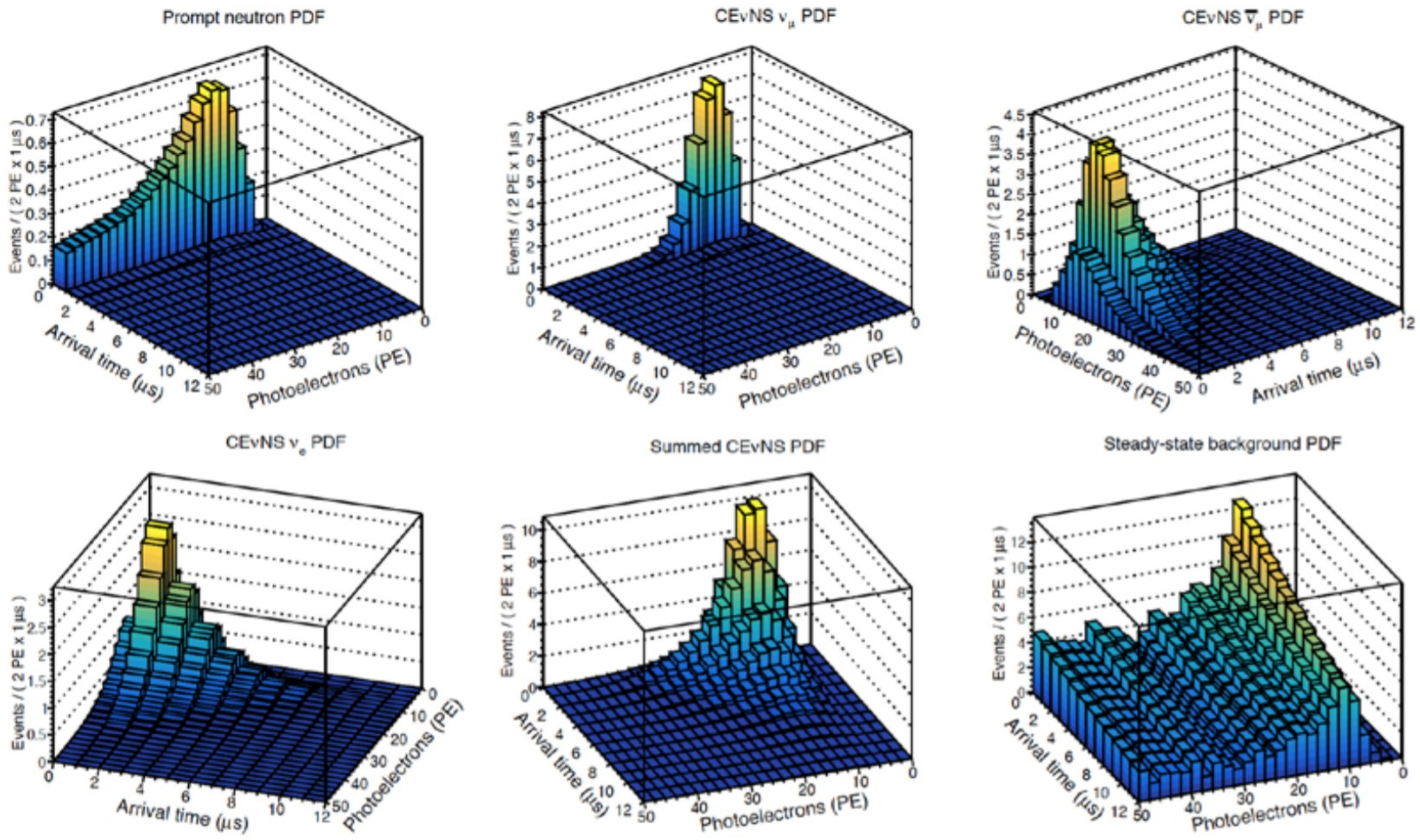
Science AAAS



Prompt neutron PDF

CEvNS ν_μ PDF

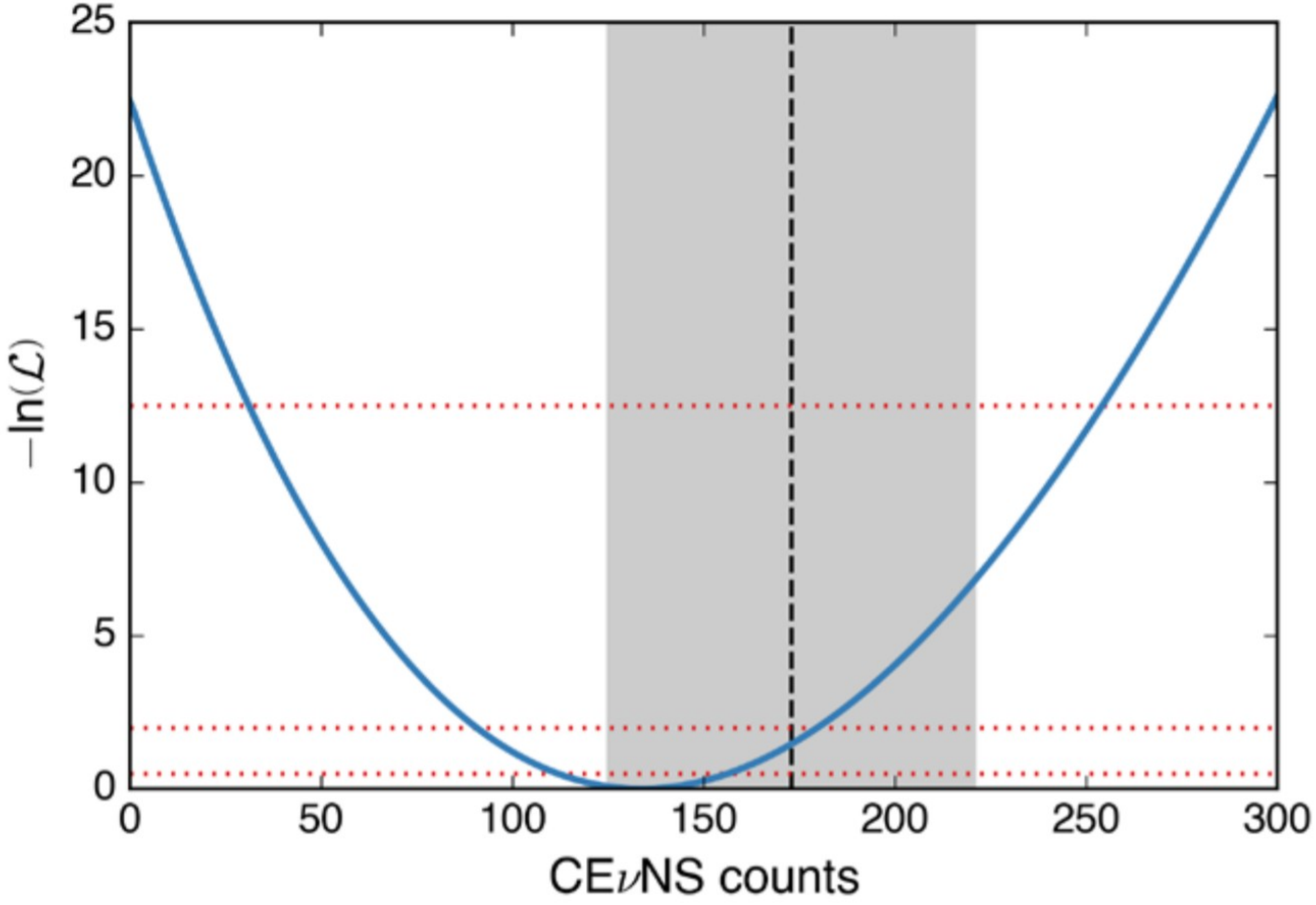
CEvNS $\overline{\nu}_\mu$ PDF

CEvNS ν_e PDF

Summed CEvNS PDF

Steady-state background PDF

D. Akimov *et. al*, Supplementary Materials for Observation of coherent elastic neutrino-nucleus scattering, Science 2017



D. Akimov *et. al*, Supplementary Materials for Observation of
coherent elastic neutrino-nucleus scattering, Science 2017

Future

- Many current and future experiments
- Upgrades for COHERENT experiment at SNS planned
- Improving detector designs to detect eV nuclear recoils (will have a positive impact in the searches for dark matter)
- Important role in search for new answers and BSM physics

Experiment	T_{th}	Baseline (m)	Target	Mass (kg)	Technology	Source
COHERENT [93]	6.5 keV	19.3	CsI[Na]	14.57	Scintillating crystal	π-DAR SNS
	5 keV	22	Ge	10	HPGe PPC	
	20 keV	29	LAr	2×10^3	Single phase	
	13 keV	28	NaI[Tl]	185*/3388	Scintillating crystal	
CCM [94]	10–20 keV	20–40	LAr	10^4	Scintillation	π-DAR Lujan
CONUS [95]	300 eV	17	Ge	4	HPGe	NPP 3.9 GW
MINER [47]	10 eV	1	Ge/Si	30	cryogenic	NPP 1 MW
CONNIE [96]	28 eV	30	Si	1	Si CCDs	NPP 3.8 GW
Ricochet [50]	50–100 eV	<10	Ge/Zn	10	Ge, Zn bolometers	NPP 8.54 GW
NUCLEUS [97]	20 eV	<10	$CaWO_4$ Al_2O_3	10^{-3}	Cryogenic $CaWO_4$ Al_2O_3 calorimeter array	NPP 8.54 GW
RED100 [98]	500 eV	19	Xe	100	LXe dual phase	NPP 3 GW
vGEN	350 eV	10	Ge	4×0.4	Ge PPC	NPP 3 GW
TEXONO [99]	150–200 eV	28	Ge	1	p-PCGe	NPP 2×2.9 GW

What did we looked at? For what it’s worth…

Introduction

- What is meant by coherent scattering?
- How does the cross-section for such a process vary?
- How do you detect such scattering?

Motivation

- Probe for Beyond the SM physics
- Important process in supernovae
- Novel detectors – progress in Dark Matter searches

The COHERENT experiment

- Neutrino source at the SNS, Oak Ridge Laboratory
- Detector design (CsI[Na])
- First detection of such a scattering (CEvNS)

Future prospects

- What other collaborations for detecting this scattering?
- Dark Matter searches