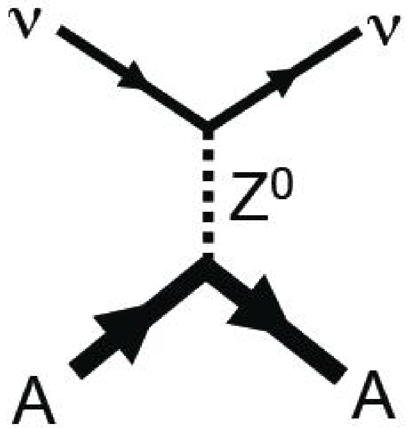
Coherent Elastic Neutrino-Nucleus Scattering Expeirments

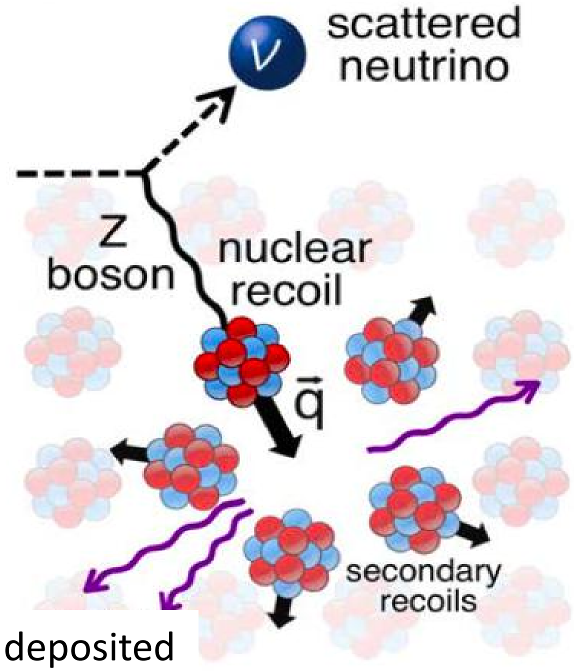
Diane Markoff
NC Central University
Triangle Universities Nuclear Laboratory
Member of the COHERENT Collaboration

What is Coherent Elastic Neutrino-Nucleus Scattering?

A neutrino elastically scatters off a nucleus via exchange of a Z, and the nucleus recoils as a whole; Coherent process up to E_ν ~ 50 MeV

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





deposited
energy

Initial and final states must be identical
- neutral current elastic scattering

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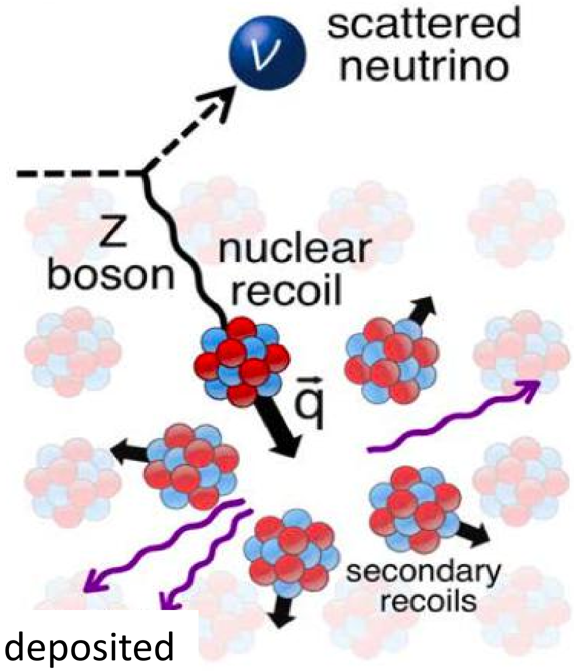


deposited
energy

Neutrino scatters coherently off all nucleons - creates enhancement of the reaction cross section

Well understood Standard Model calculation - differential cross section with respect to T, the nuclear recoil energy, dependence on neutron number

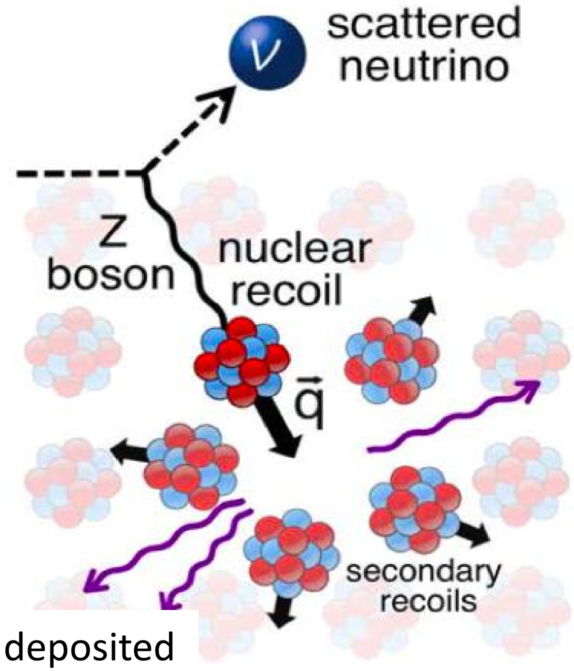
$$\frac{d\sigma}{dT} \propto N^2$$

What is Coherent Elastic Neutrino-Nucleus Scattering?

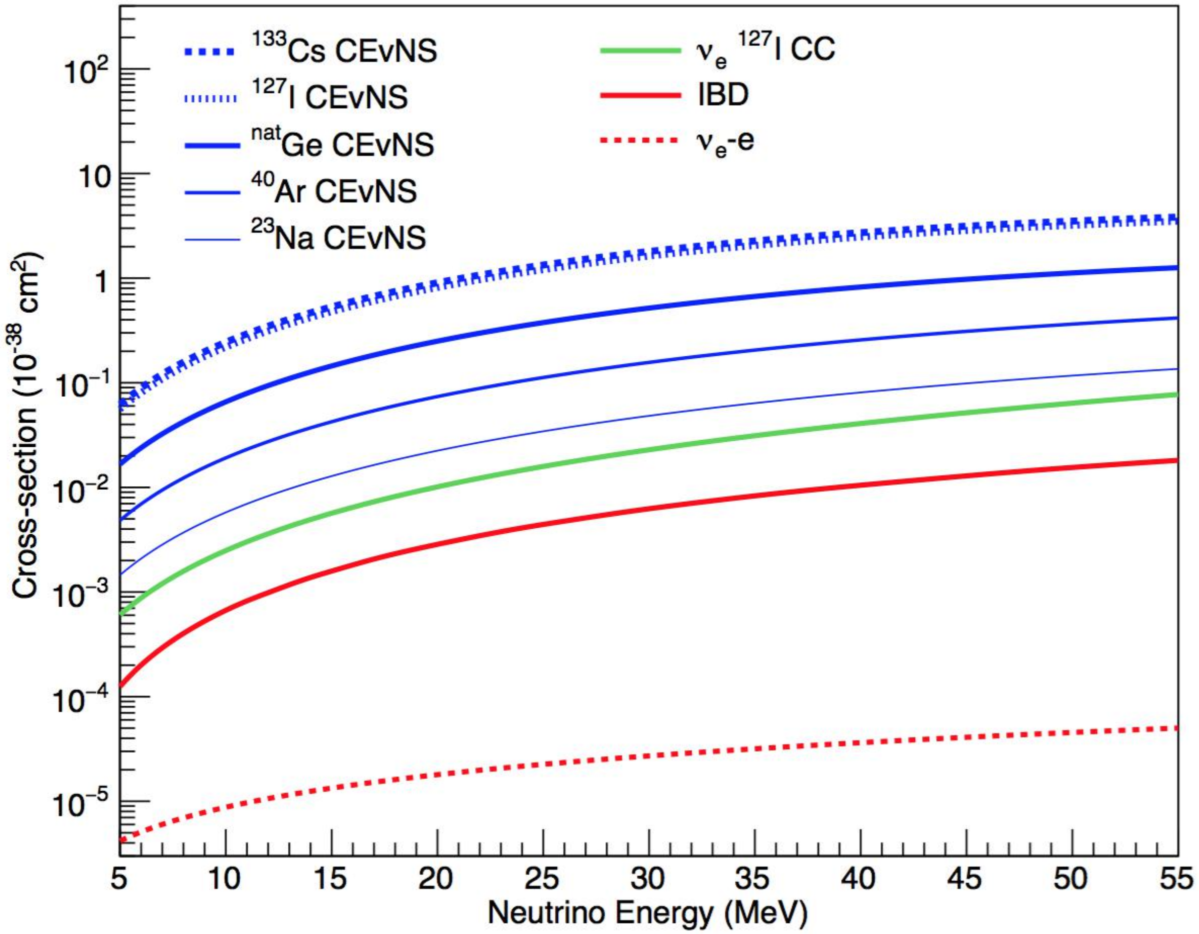
Cross section Enhancement

N^2 Dependence

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



deposited energy

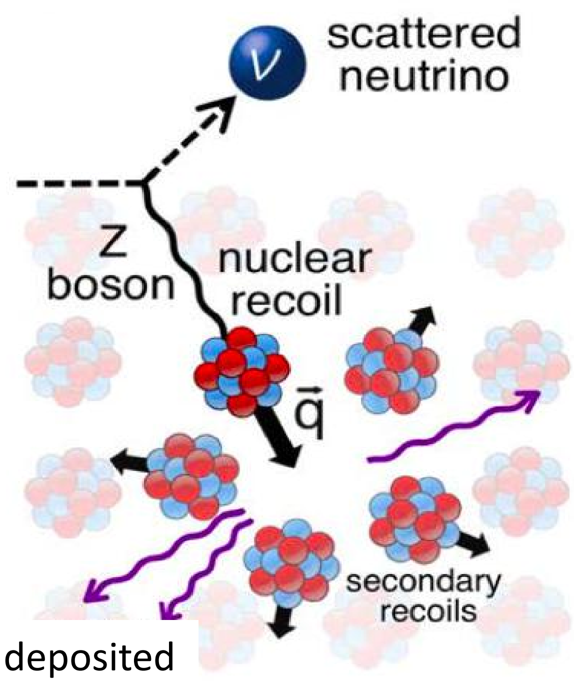


What is Coherent Elastic Neutrino-Nucleus Scattering?

Nucleons must recoil in phase

→low momentum transfer qR <1

→ very low energy nuclear recoil



deposited
energy

Experimental signature - nuclear recoil

less than about 50 keV of energy deposited

from nuclear recoil (Difficult at best!)

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

Example: ~ 30 MeV ν on Ge gives 25 keV recoil energy

First proposed 44 years ago!

PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

Coherent effects of a weak neutral current

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

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

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

Overall Physics Reach of CEvNS

- Supernovae: Expected to be important in core-collapse SN processes and possible SN detection channel. CEvNS rates may help reinvigorate stalled shock waves.
  Information on all-flavor ν flux and spectrum.

- Possible measurement mechanism for sterile neutrino search

- Nuclear Physics: nuclear form factors
  g_A quenching - relevant for double beta decay reaction rates
  neutron skin depth - nuclear weak radius relevant for neutron stars

- Dark Matter: Important background for 10-ton direct searches

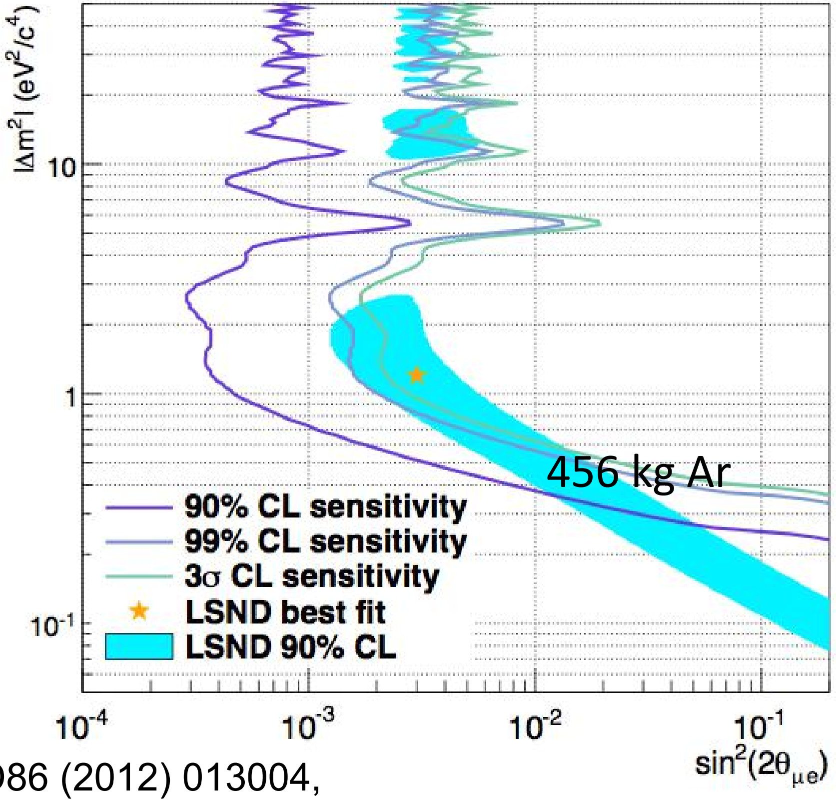
- Standard Model tests, eg: $\sin^2 \theta_{Weff}$ for low Q (sensitive to dark Z boson models)
  non-standard interactions (NSI) of neutrinos - constrain parameters
  (NSI quark-ν interactions may interfere with interpreation of DUNE and NOVA results)
  neutrino magnetic moment

Oscillations to sterile neutrinos with CEvNS

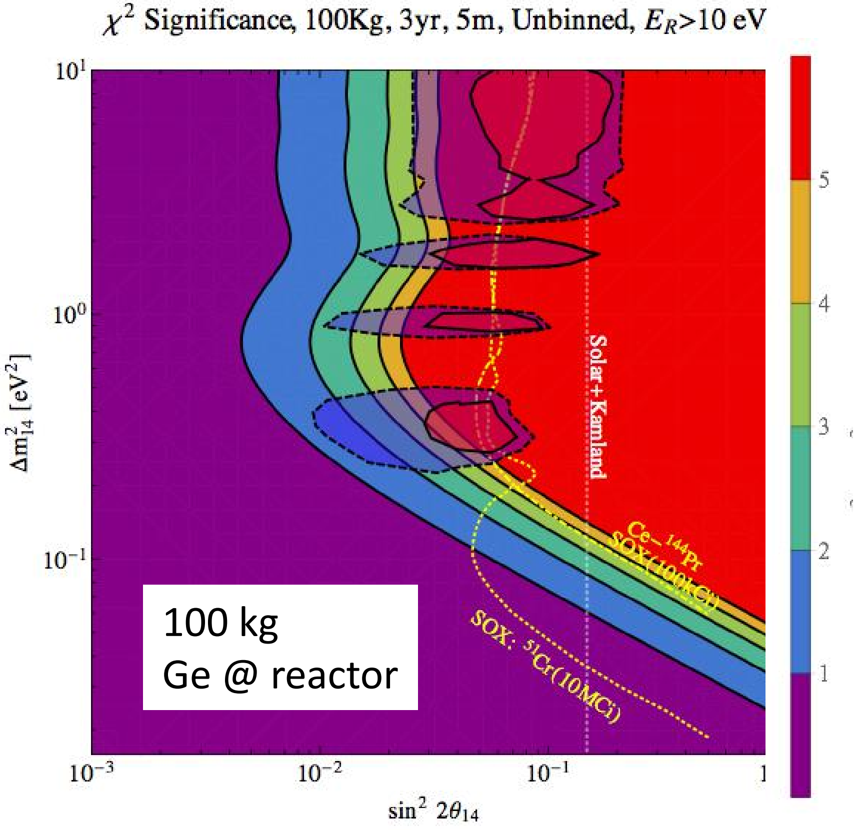
Similar/movable detectors at multiple baselines - look for deficit and spectral distortion vs L,E

Examples:

Multi-πDAR sources at different baselines (20 & 40 m)



Anderson et al., PRD86 (2012) 013004, arXiv:1201.3805



B. Dutta et al, arXiv:1511.02834

We have found that the planned TEXONO and COHERENT experiments offer good prospects of providing key information concerning the existence of light sterile neutrinos....could be complementary to charged-current appearance and disappearance searches. Kosmas et al. arXiv:1703.00054v2 [hep-ph] September 2017

CEvNS for understanding g_A quenching - $g_A^{eff} \approx 0.7 g_A$

CEvNS Cross Section

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

$$G_V \approx \tfrac{1}{2} N F(Q^2) \qquad\qquad G_A \sim (net\, spin) F^A(Q^2)$$

If the nucleus has spin, then axial terms contribute to the cross section

Axial contribution proportional to 1/N is larger for light nuclei

- contributes to shape changes in the cross section

We are investigating the CEvNS sensitivity and N dependence

Gail McLaughlin - NuEclipse presentation Agust 2017

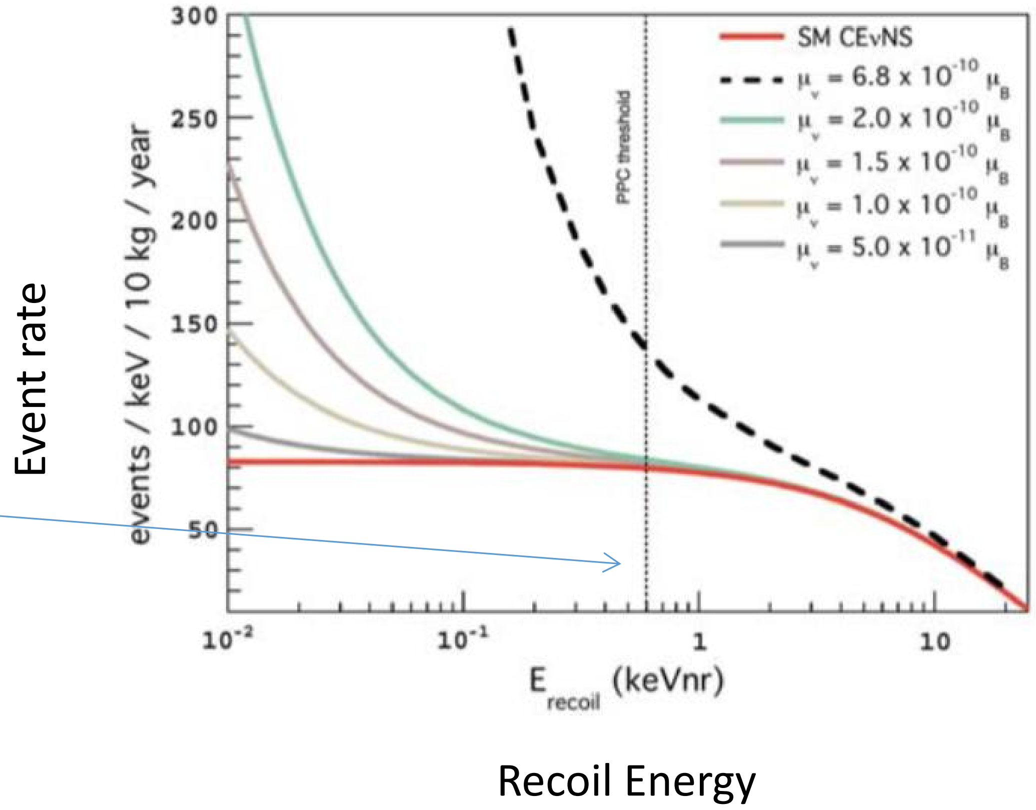
Review of g_A quenching - Suhonen Neutrino 2018

CEvNS to Measure Neutrino Magnetic Moment

Signature is distortion at low recoil energy E

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

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



<u>neutrino magnetic moment</u> should exist since m≠0

CEvNS is particularly sensitive to neutrino electromagnetic interactions

H.T. Wong and H.B. Li, Mod. Phys. Lett. A20:1103-1117,(2005)

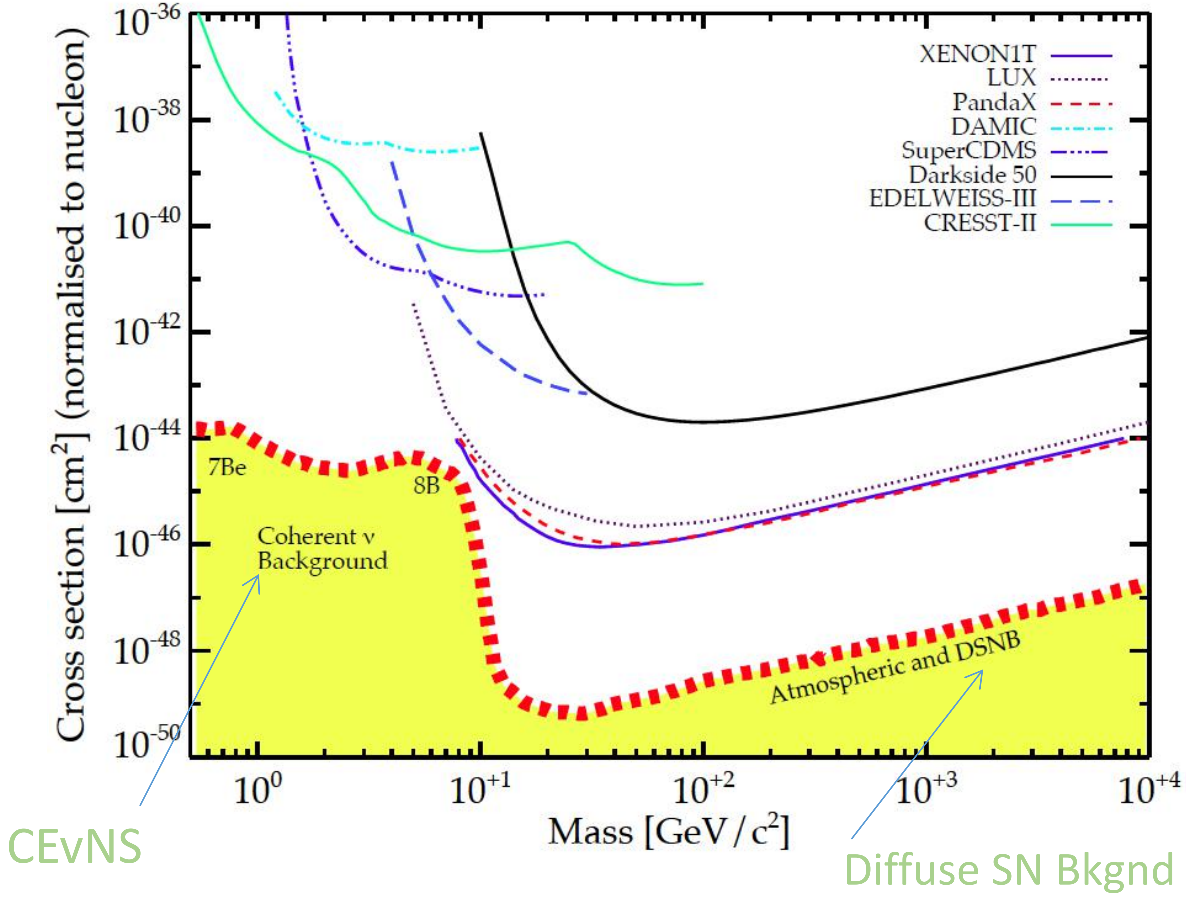
See also Kosmas et al., arXiv:1505.03202

“Neutrino Floor” for Dark Matter Direct Searches

Important low-energy background for 10 ton DM experiments

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

See for example Gelmini, Takhistov, Witte arXiv: 1804.01638v2 [hep-ph] for a discussion on the effect of neutrino interactions on the sensitivity of dark-matter experiments.



L. Strigari Private Communication October 2017

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

Historical Perspective - How to Measure CEvNS

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)

PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses 1—10^6 GeV; particles with spin-dependent interactions of typical weak strength and masses 1—10^2 GeV; or strongly interacting particles of masses 1—10^{13} GeV.

CEvNS experiment → DM Experiments → CEvNS Experiments

Better detector technology - based on years of Dark Matter expeirment development

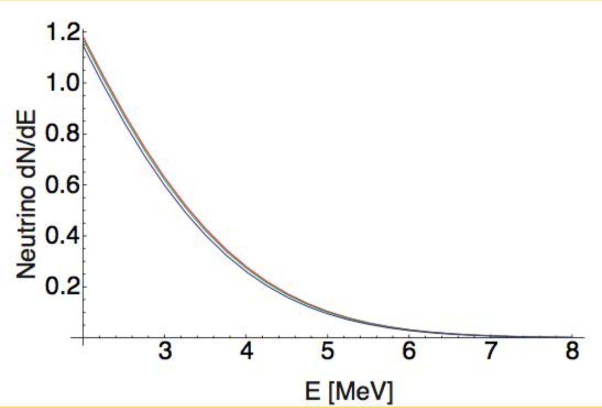
WIMP dark matter detectors developed over the last ~decade
are sensitive to ~ keV to 10's of keV recoils

Stronger neutrino sources - access to close proximity

CEvNS Measurements - Human Based Sources

Reactors

~ 2 e20 ν/s

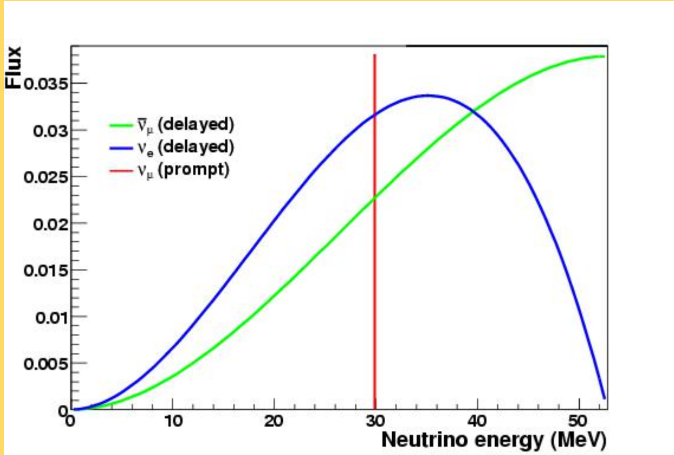


Low energy,
but very high fluxes possible;
~continuous source,
good background rejection needed

recoil energies < 1 keV

Stopped pions
(decay at rest)

~ 1 e15 ν/s



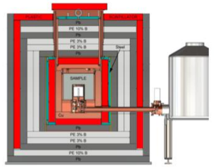
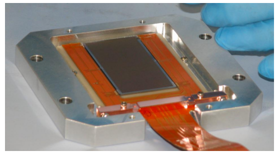
High energy,
pulsed beam possible for good background rejection;
possible neutron backgrounds

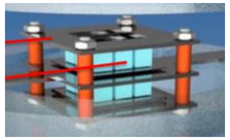
multiple flavors

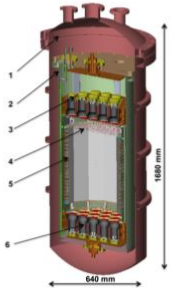
- prompt ν_μ (red)
- delayed ν_μ-bar (green)
- delayed ν_e (blue)

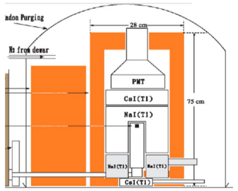
Reactor CEvNS Efforts Worldwide

Experiment	Technology	Features	Location
CONNIE	Si CCDs	100 g, 30 m from 3.8 MW core	Angra II, Brazil
COνUS	HPGe	4 kg; 17 m from 4 GW core	Brokdorf, Germany
MINER	Ge/Si cryogenic	10 kg, down to 2 m, 1 MW core	TAMU Texas, USA
Nu-Cleus	Cryogenic $CaWO_4$, Al_2O_3 calorimeter array	gram scale, short range ~ 10 m from two 4.6 GW cores	Chooze Reactors, France
νGEN	Ge PPC	1.6 kg; 10 - 12 m from 3 GW core	Kalinin, Russia
RED-100	LXe dual phase	100 kg, 19 m from 3 GW core	KNPP, Russia
Ricochet	Ge, Zn bolometers	355 m/467 m from two 4.6 GW cores	Chooze Reactors, France
TEXONO	p-PCGe	1 kg, 28 m from 4 GW core	Kuo-Sheng Taiwan







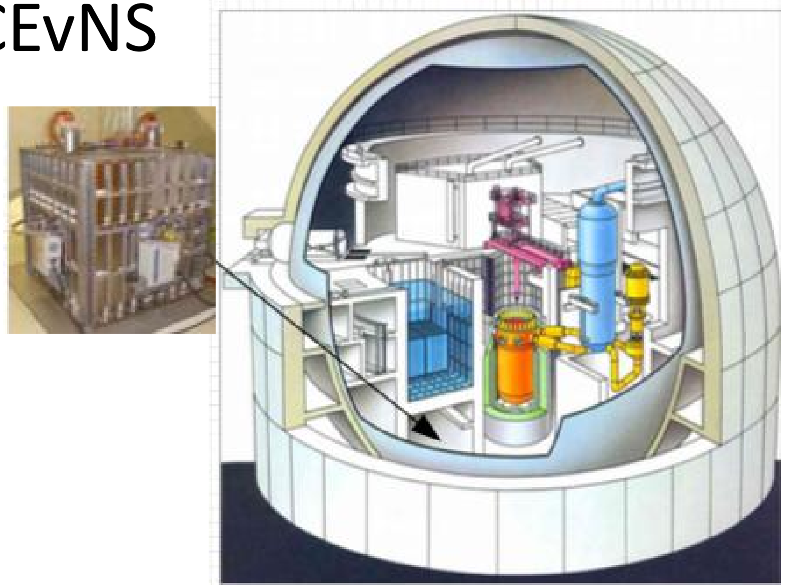
Many novel low-background, low-threshold technologies

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

from Neutrino 2018:

COνUS reports first hint of reactor CEvNS

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



Rate comparison (all detectors):

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

(*) Including stat. uncertainty and above efficiencies

Some systematics still under study

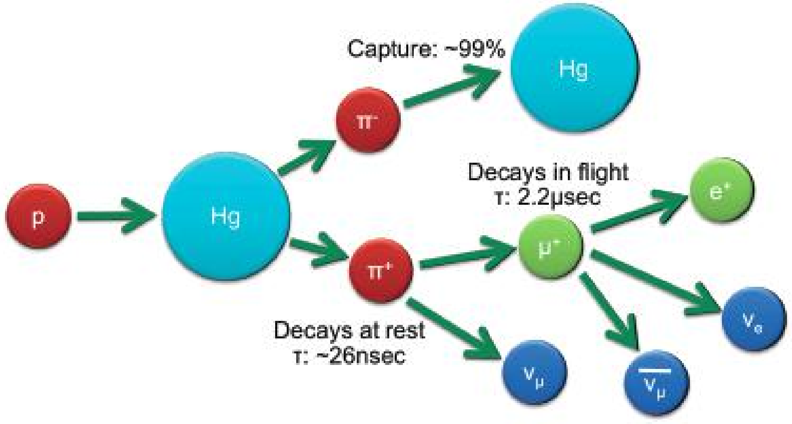
W. Maneschg, Nu2018

Stopped Pion Source: Spallation Neutron Source Oak Ridge National Laboratory (ORNL) Tennessee

Proton beam energy: 0.9-1.3 GeV
Total power: 0.9-1.4 MW
About 1 MW at 1 GeV proton energy
Pulse duration: 380 ns FWHM
Repetition rate: 60 Hz
Liquid mercury target

Spallation Neutron Source - neutrino source 'for free'

SNS Neutrino Beam Timing Profile



$\pi^+ \rightarrow \mu^+ + \nu_\mu$ — 2-body decay: monochromatic 29.9 MeV ν_μ PROMPT

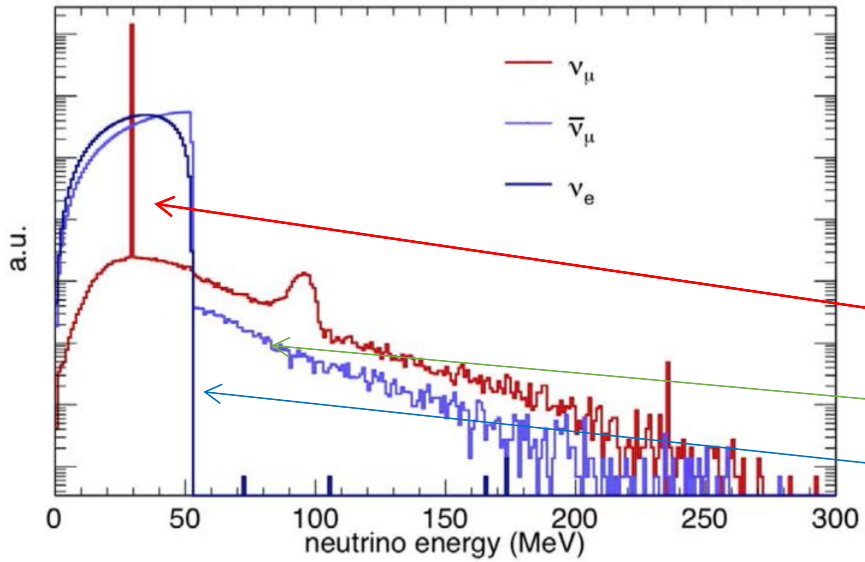
$\downarrow$

$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$ — 3-body decay: range of energies between 0 and $m_\mu/2$ DELAYED (2.2 μs)

~10^7 cm^{-2}s^{-1} per flavor

ν flux 4.3×10^{-7} ν/cm²/s at 20 meters

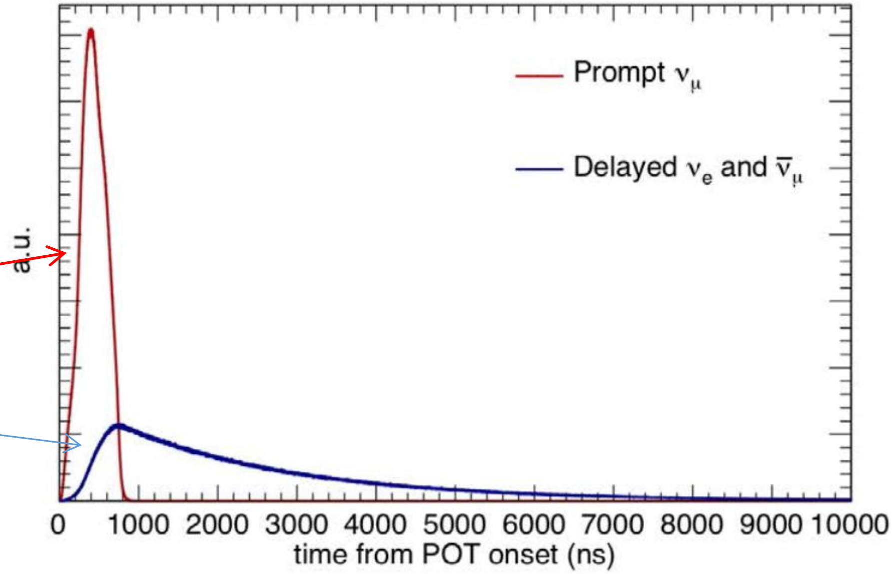
Produces sharply pulsed time structure for background rejection factor ~ 10^{-4}



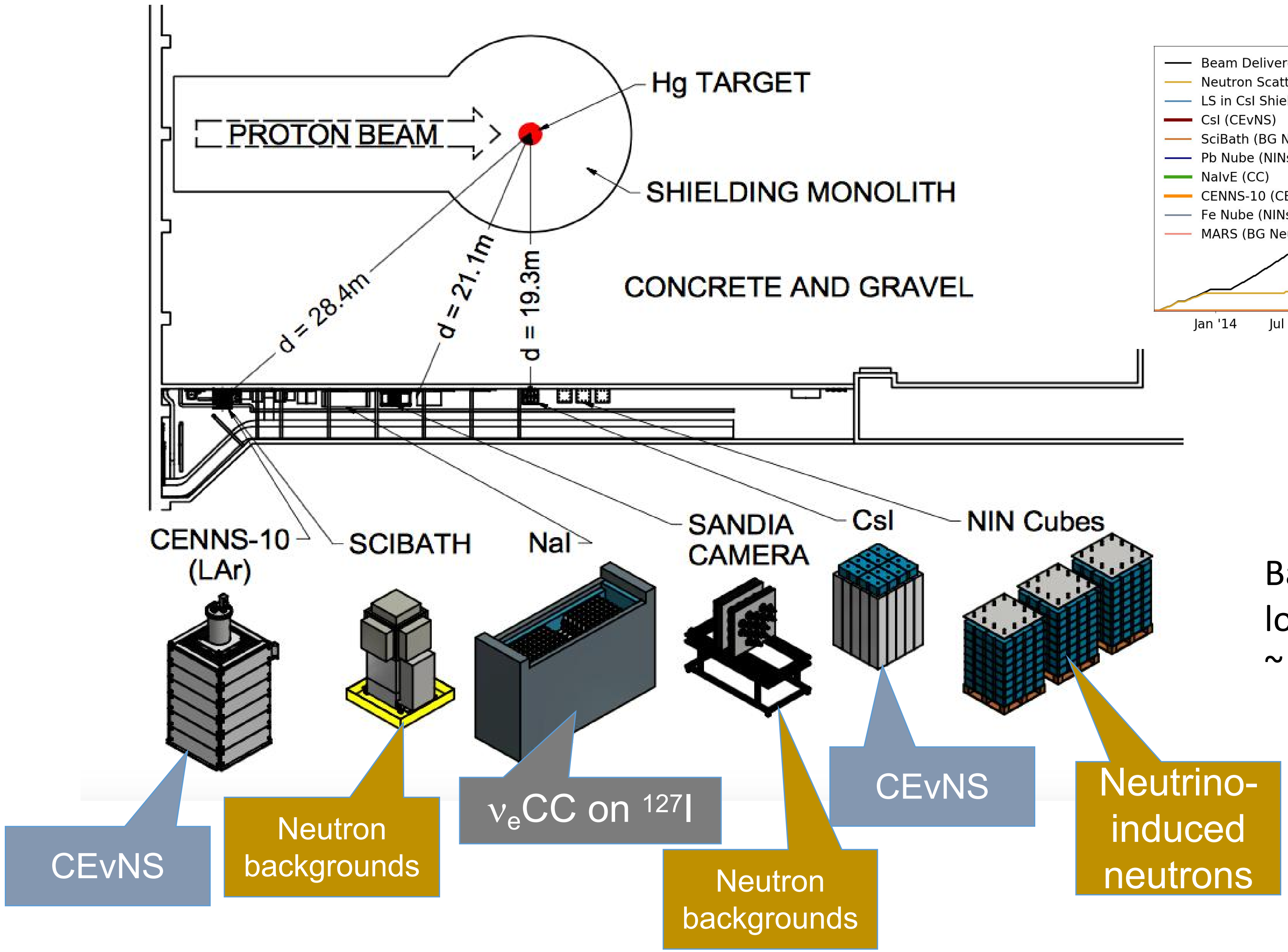
Prompt ν_μ

delayed ν_μ–bar

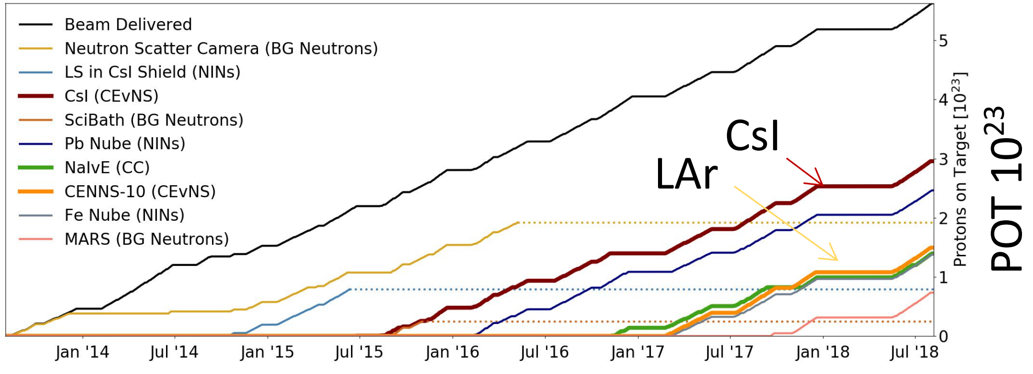
delayed ν_e



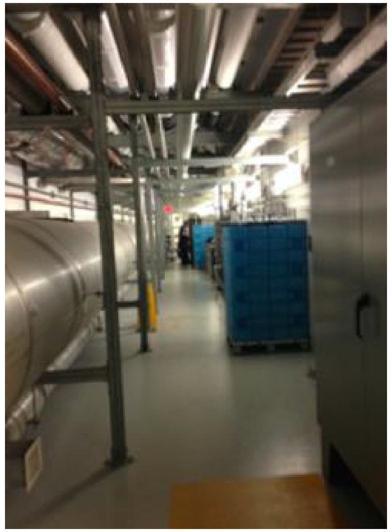
Deployments in Neutrino Alley



Protons on Target



View looking down "Neutrino Alley"



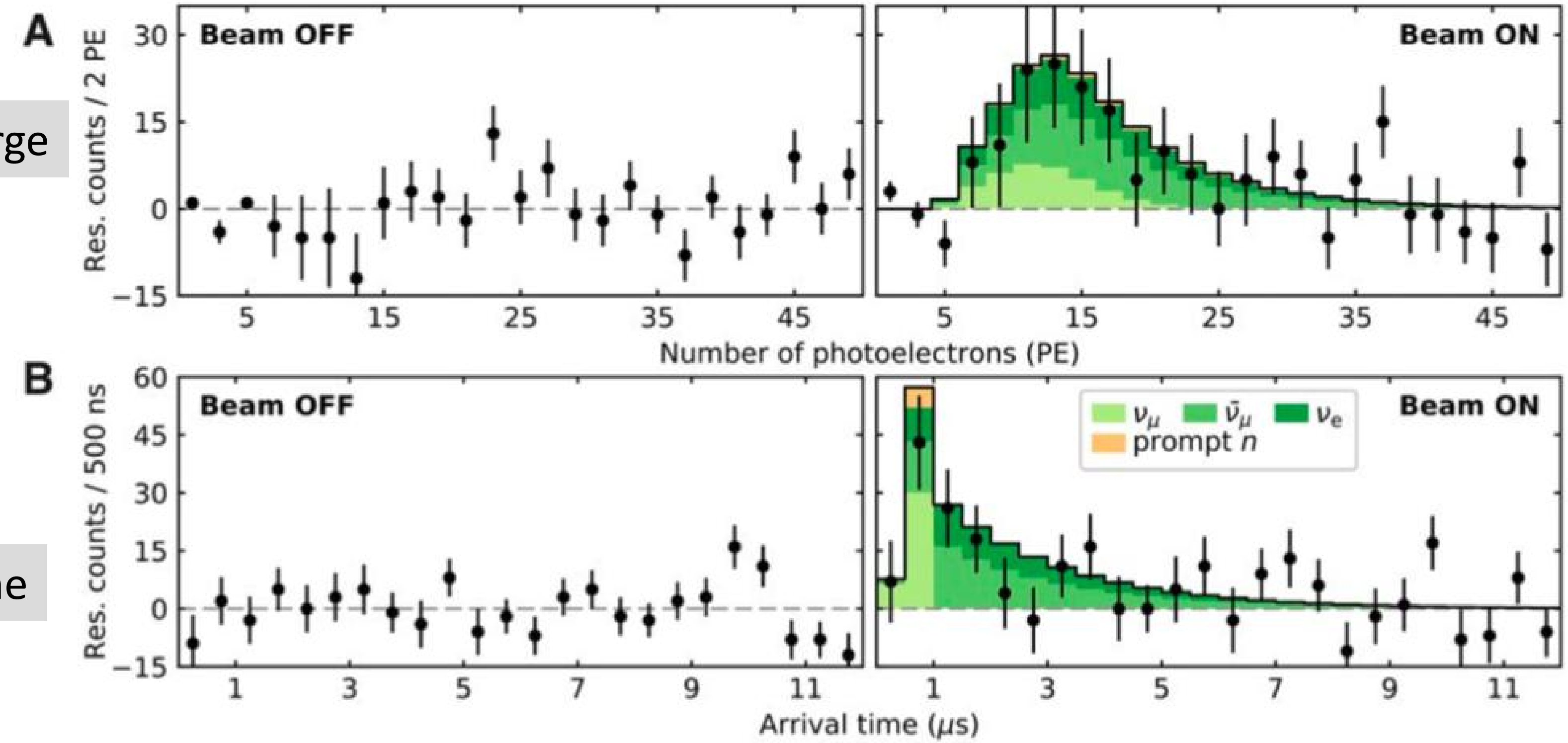
Basement siting
low neutron flux
~ 8 mwe overburden

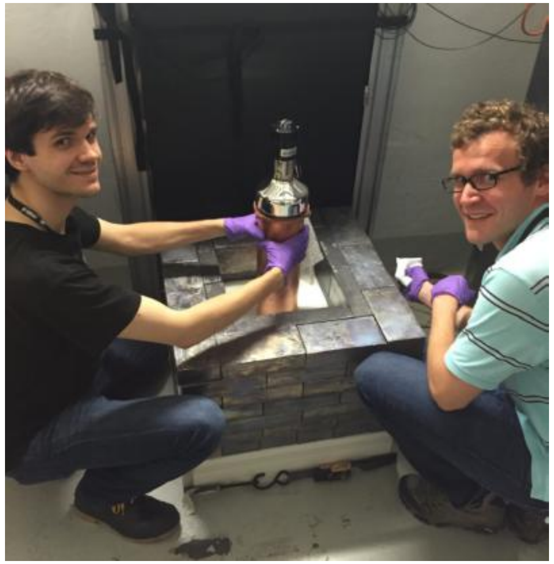
Neutron detectors removed - replaced with MARS a neutron monitoring detector

First Observation of CEvNS - 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...

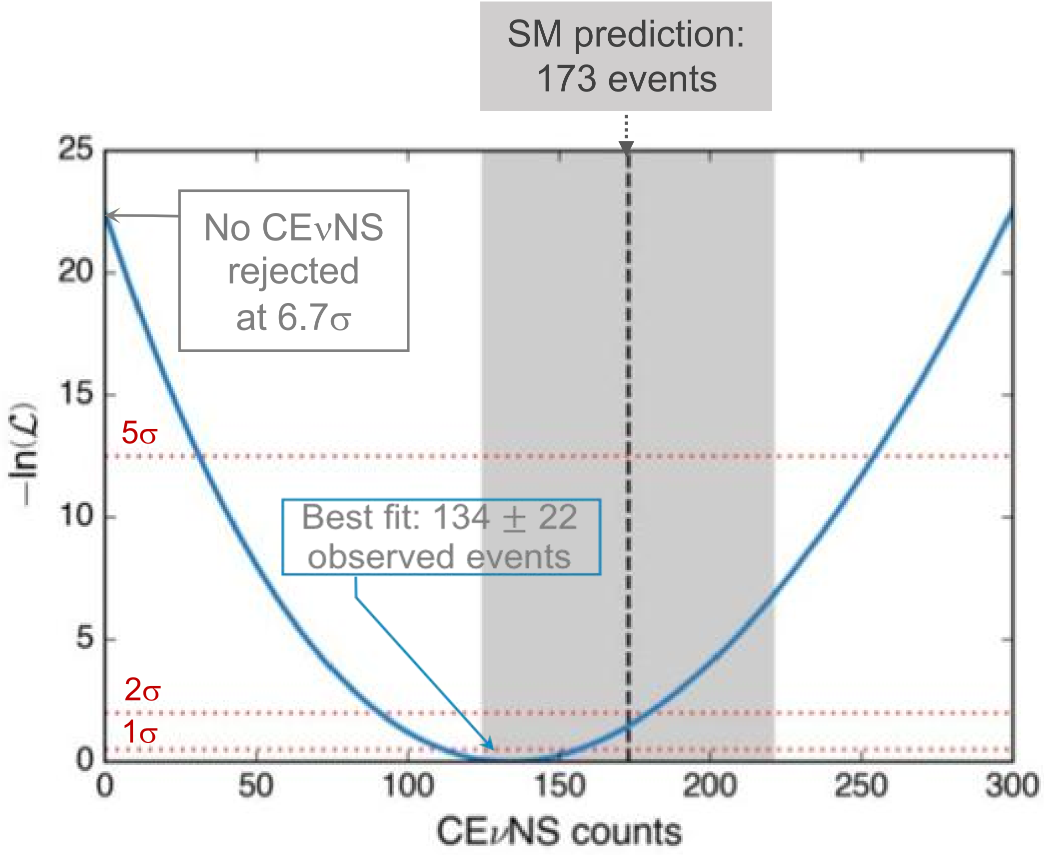
+ See all authors and affiliations

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

First Observation of CEvNS - at the SNS with 14.6-kg CsI[Na] detector



We report a 6.7 σ significance for an excess of events, that agrees with the Standard Model prediction to 1 σ.

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

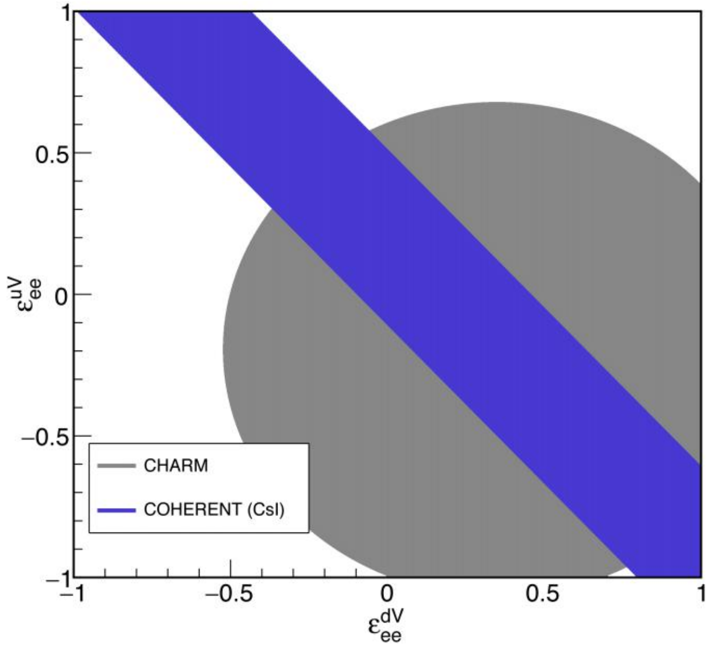
Beyond the Standard Model Constraints on NSI

A COHERENT enlightenment of the neutrino Dark Side

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

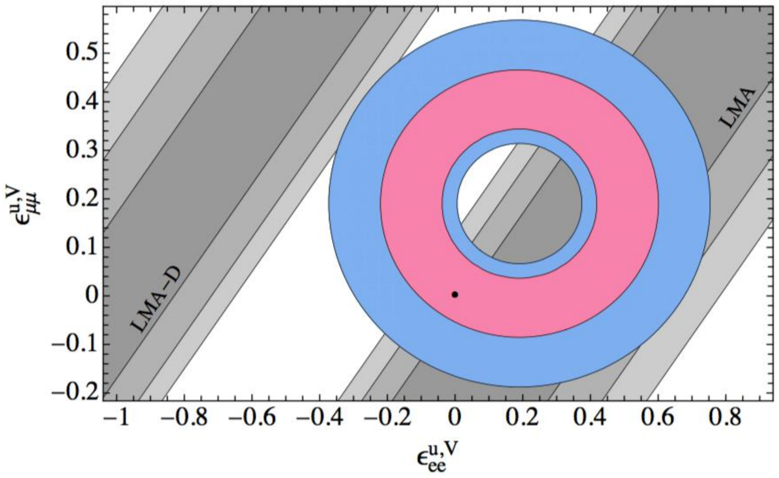
Phys.Rev. D96 (2017) no.11, 115007

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



$$g_V^p \to g_V^p + 2\epsilon_{ee}^{uV} + \epsilon_{ee}^{dV}$$
$$g_V^n \to g_V^n + \epsilon_{ee}^{uV} + 2\epsilon_{ee}^{dV}$$

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



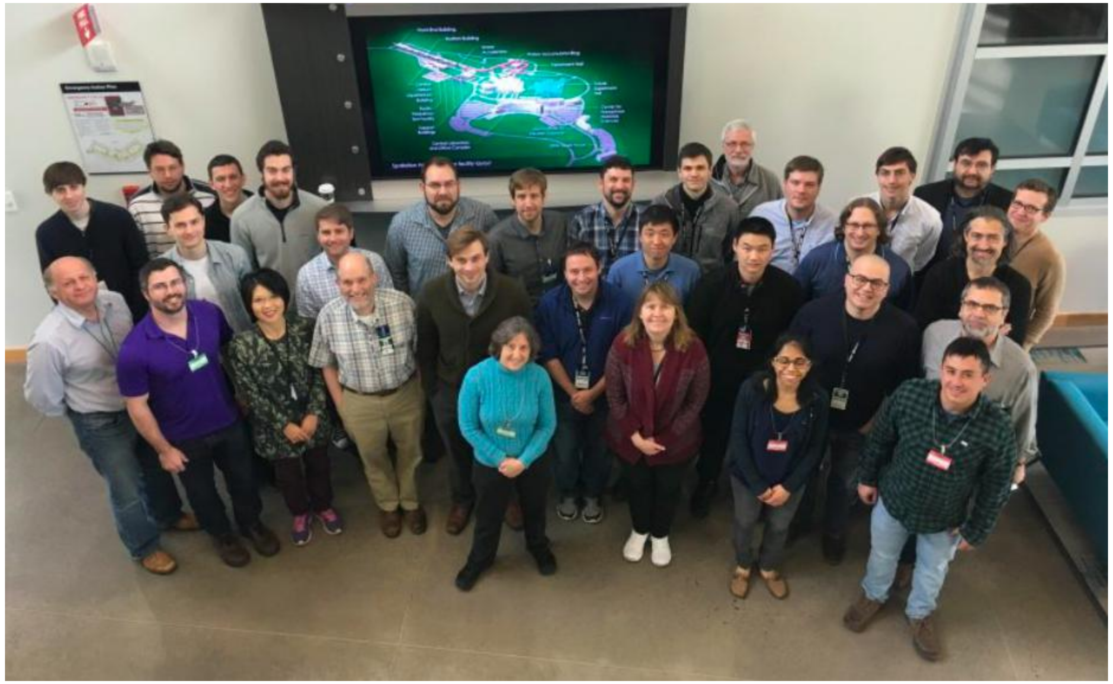
1σ, 2σ allowed regions projected in (ε_{ee}^{uV}, $\varepsilon_{\mu\mu}^{uV}$) plane

First COHERENT results are already disfavoring LMA-D

The COHERENT collaboration

http://sites.duke.edu/coherent

COHERENT
SNS
SPALLATION NEUTRON SOURCE



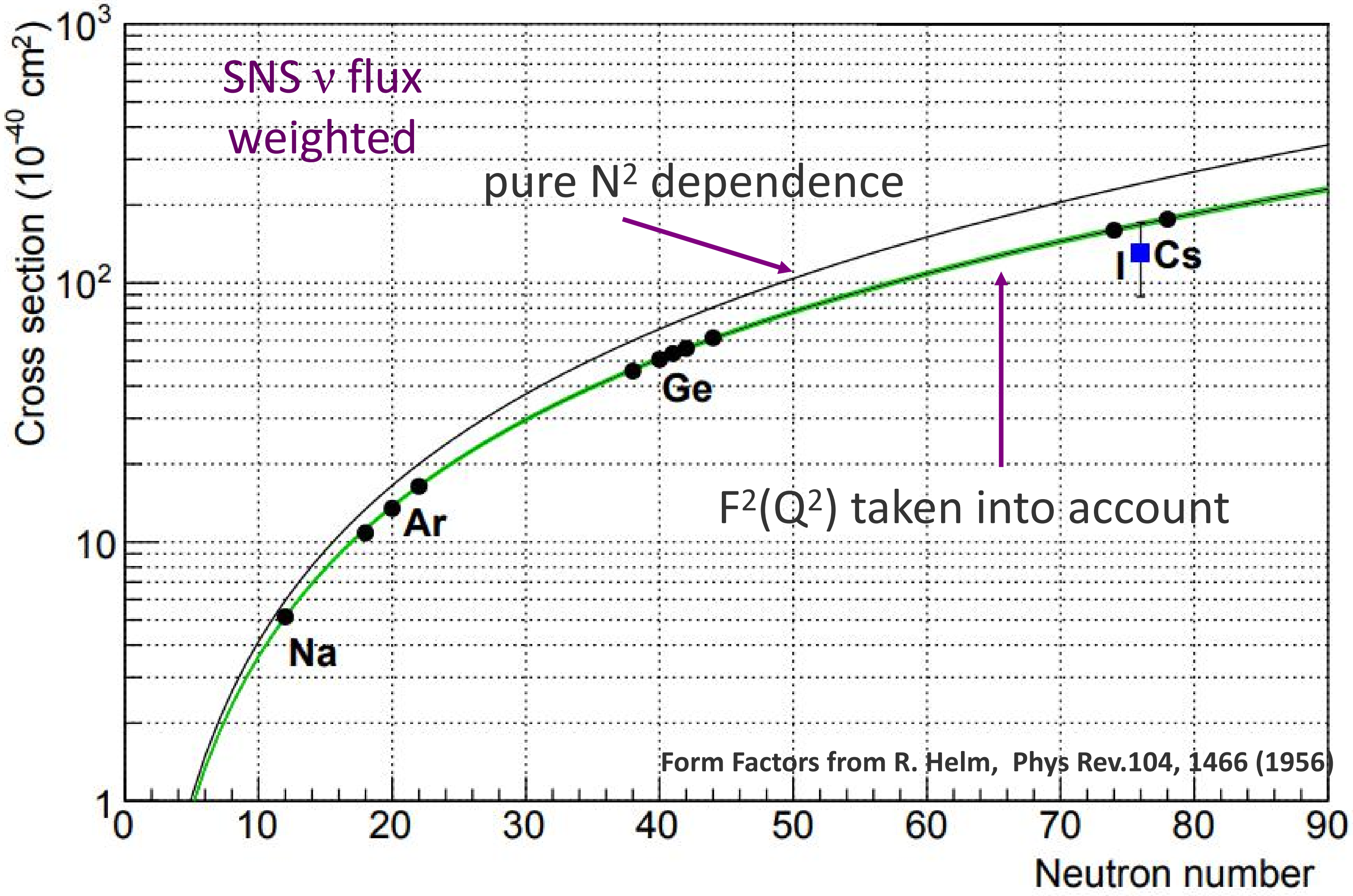
~80 members, 20 institutions, 4 countries

Carnegie Mellon University
THE UNIVERSITY OF CHICAGO
Duke UNIVERSITY
UF UNIVERSITY of FLORIDA
KAIST
Laurentian University
Université Laurentienne
Los Alamos NATIONAL LABORATORY EST. 1943
MEPhI
NORTH CAROLINA CENTRAL UNIVERSITY FOUNDED 1910
NC STATE UNIVERSITY
NM STATE UNIVERSITY
OAK RIDGE National Laboratory
Sandia National Laboratories
THE UNIVERSITY of TENNESSEE UT KNOXVILLE
TUNL
W UNIVERSITY of WASHINGTON
Tufts UNIVERSITY
VT VIRGINIA TECH.

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

DMM supported by NSF-HRD-1601174

COHERENT PLAN - SUITE OF TARGET MASSES
Physics Motivation - Neutron Distribution Functions



$$\frac{d\sigma}{dT} \prec (N - (1 - 4\sin^2\theta_W)Z)^2 F^2(Q^2)$$

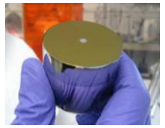
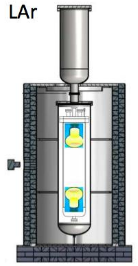
Multiple detectors also provide neutrino flux comparisons.
In addition, developing D_2O target system for flux measurement.

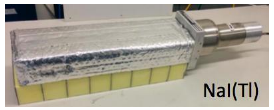
K. Patton et al., PRC 86, 024216 (2012)

The COHERENT Experimental Program

To unambiguously measure the coherent neutrino-nucleus cross section in multiple nuclei.
Development of precision measurements.

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



Under development: D_2O based neutrino flux calibration measurement.... and much more!

Summary - CEvNS

- First unambiguous measurement in CsI made by the COHERENT collaboration at a stopped pion source, SNS located at ORNL
- Look forward to COνUS reactor result in the near term.
- Look forward to published 22 kg LAr result from COHERENT and possible updated CsI result.
- Expect additional experiment measurement results in next years.
- A number of papers use COHERENT measurement for limiting neutrino non-standard interactions - we'll see improvements with more results

Develop high-precision CEvNS techniques for sensitivity to Beyond Standard Model physics and open opportunities to apply this technique for precision studies of neutrino properties and nuclear physics

→ tool of tomorrow's neutrino physicists

APS-DNP/JPS HAW2018 Meeting

Wednesday evening - Mini-symposium Intersection of Neutrino Physics and Nuclear Physics

CN.00007: Measurement of CEvNS with COHERENT at the ORNL SNS - Rex Tayloe

CN.00008: First Results from a CEvNS Search with the CENNS-10 Liquid Argon Detector - Matthew R Heath

CN.00009: Observation of Supernova Neutrino Bursts via CEvNS - Adryanna Smith

CN.00010: A Ton-Scale NaI Detector to Measure Coherent Neutrino-Nucleus Scattering and the Charged Current Neutrino Interaction on Iodine - Diane Markoff

FN.00001: A Precision Neutrino Flux Detector at the Spallation Neutron Source - Jason Newby

GA.00002: Division of Nuclear Physics Dissertation Award: First observation of coherent elastic neutrino-nucleus scattering and its future in searches for new physics - Grayson Rich

HA.00115: Characterization of SiPMs for COHERENT's proposed 1-ton Liquid Argon Detector - Benjamin Rand