Implications for the first measurement of coherent elastic neutrino-nucleus scattering

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Outline

(1) Fundamentals of CEνNS

(2) The COHERENT experiment

results, prospects and beyond

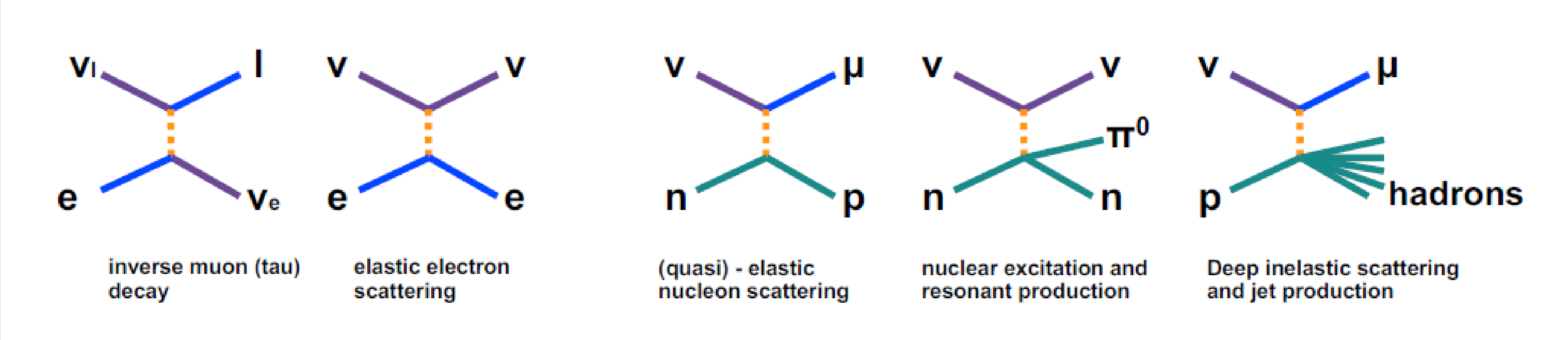
(3) Implications

Particle physics, nuclear physics, astrophysics, application

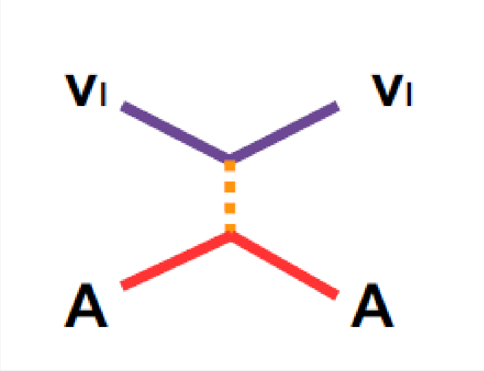
Neutrino interactions with Matter

The Standard Model has six different interactions of neutrinos with matter:

(1) 5 have already been detected



(2) 1 has so far not been detected:

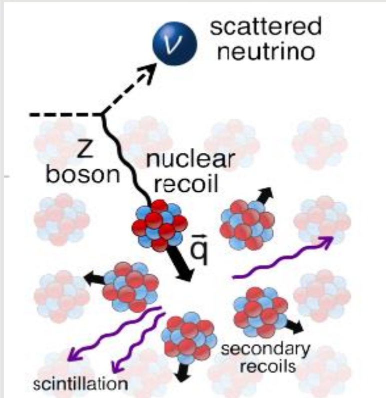


Coherent neutrino-nucleus scattering: CEνNS

(a) conceptually important
(b) useful method to test new physics
(c) importance of astrophysics and cosmology

Freedman, Phys.Rev. D9 (1974) 5; Drukier, Stodolsky, Phys.Rev. D30 (1984) 2295

All started 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

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.

In analogy to the coherent behavior of electron-nucleus scattering

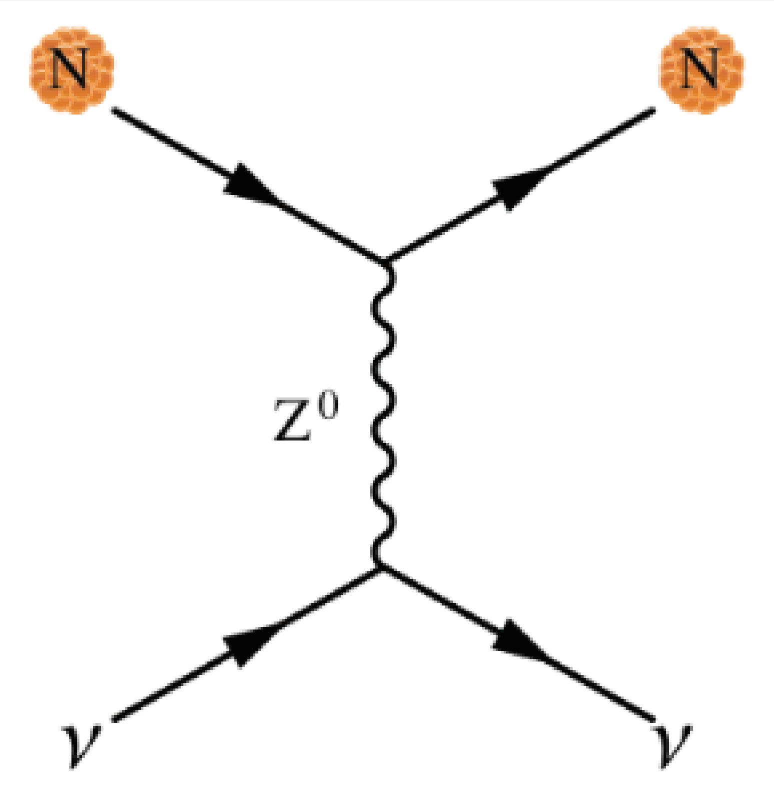
Why coherent?

Z-exchange of a neutrino with nucleus

(a) Neutrino wavelength > size of nucleus: Q*R<< 1

(b) Nucleon wave-functions in the target nucleus are in phase with each other at low momentum transfer: nucleus recoils as a whole

(c) So the cross section should be proportional to A^2



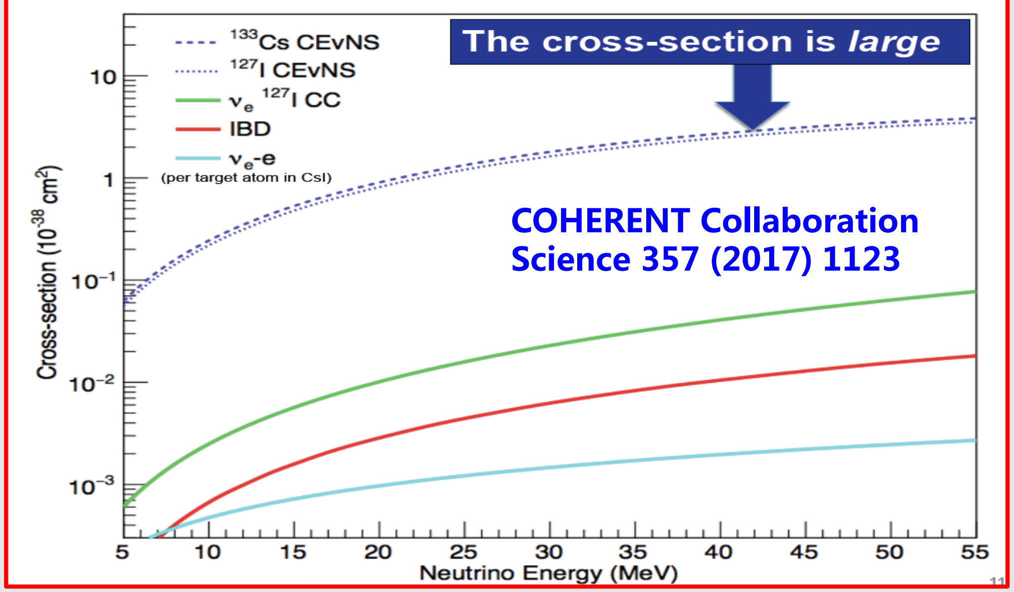
→ Enhanced cross section for heavy nuclei

Coherency hold up to ~ 50 MeV

The cross section: within & beyond SM

$$\frac{d\sigma_{\nu\text{-}\mathcal{N}}}{dT}(E,T) \simeq \frac{G_{\mathrm{F}}^2 M}{4\pi}\left(1-\frac{MT}{2E^2}\right)$$

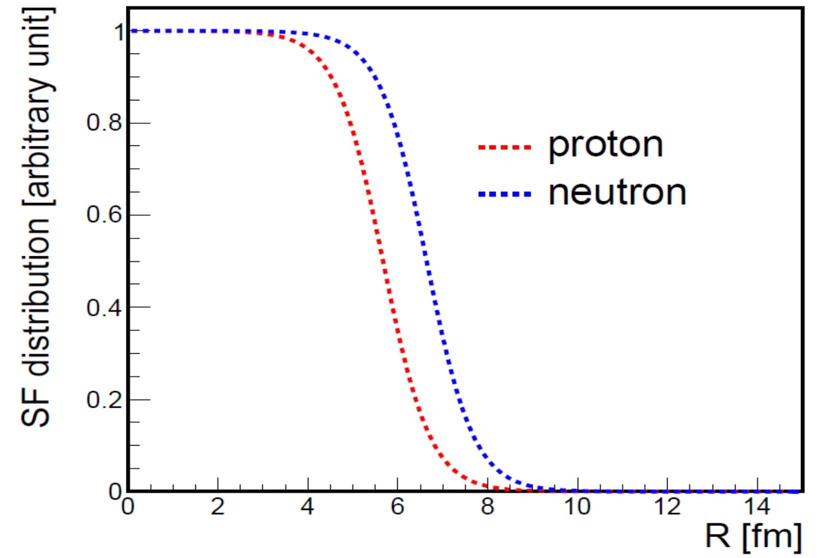
$$\epsilon = 1 - 4\sin^2\vartheta_{\mathrm{W}} \qquad \times \left[N F_N(q^2) - \epsilon Z F_Z(q^2)\right]^2$$

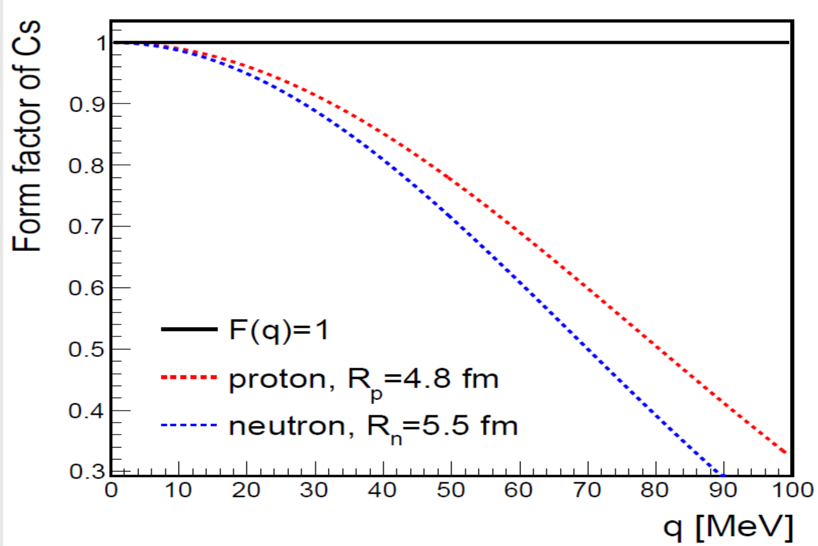


$$\frac{d\sigma}{dT}(E_\nu,T) = \frac{G_F^2 M}{\pi}\left(1-\frac{MT}{2E_\nu^2}\right) \times \left\{\left[F_Z^V(q^2) Z g_V^p + F_N^V(q^2) N g_V^n\right]^2\right\}$$

$$g_V^p = \rho_{\nu N}^{\mathrm{NC}}\left(\frac{1}{2} - 2\hat{\kappa}_{\nu N}\hat{s}_Z^2\right) + 2\lambda^{uL} + 2\lambda^{uR} + \lambda^{dL} + \lambda^{dR}$$

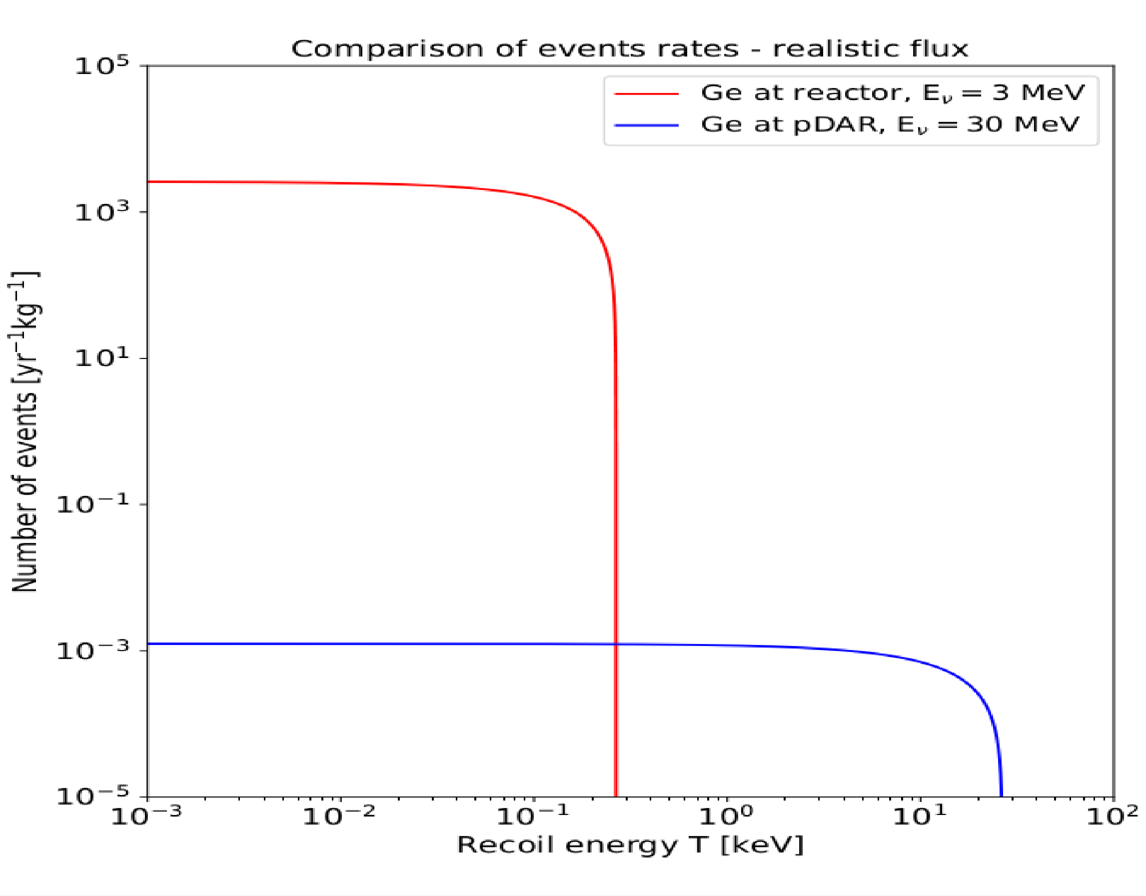
$$g_V^n = -\frac{1}{2}\rho_{\nu N}^{\mathrm{NC}} + \lambda^{uL} + \lambda^{uR} + 2\lambda^{dL} + 2\lambda^{dR}$$

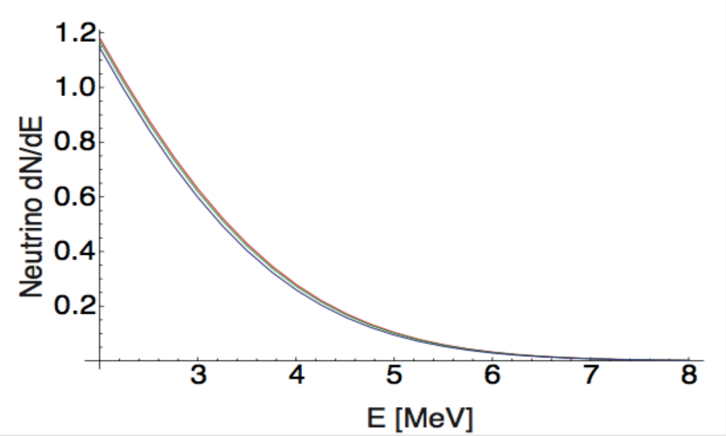


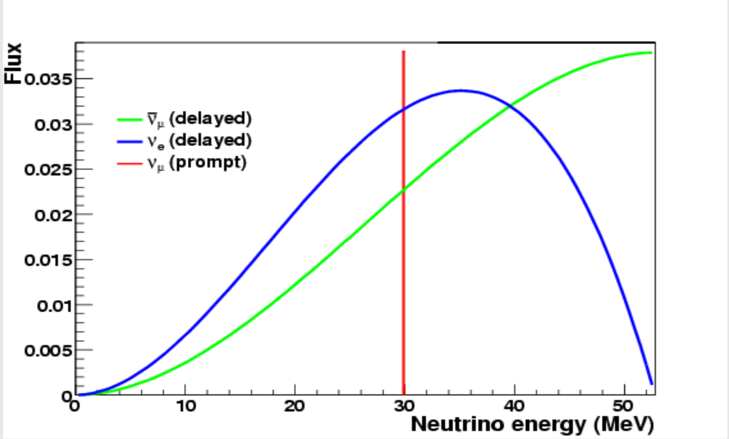


Why difficult?

(1) the only experimental signature: nuclear recoils
(2) tiny nuclear recoil energies







First detection in 2017

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

Science

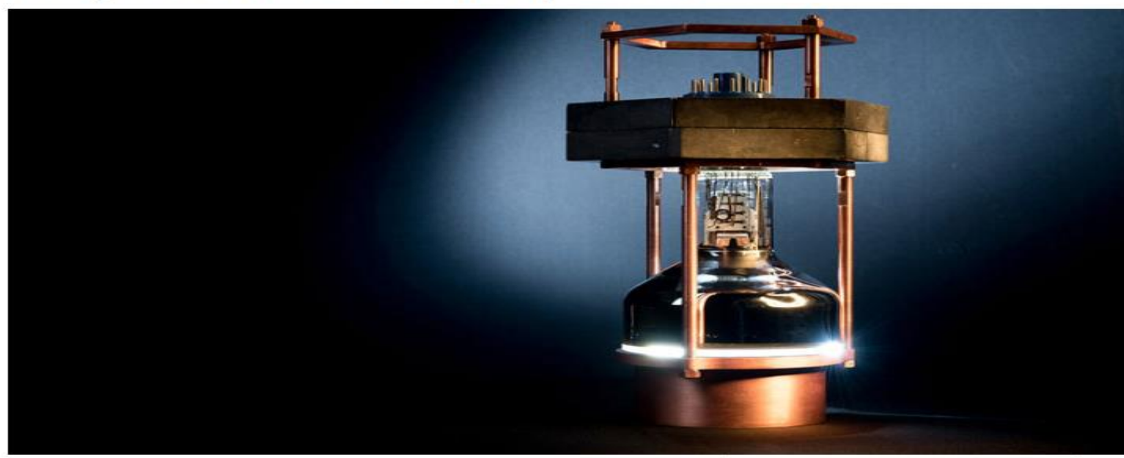
2017 BREAKTHROUGH OF THE YEAR

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

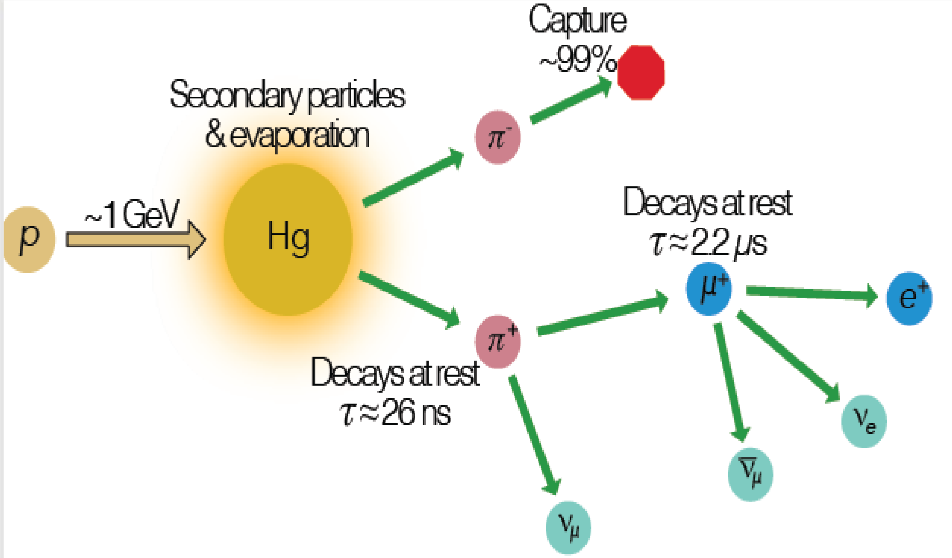
A tiny detector for the shiest particles

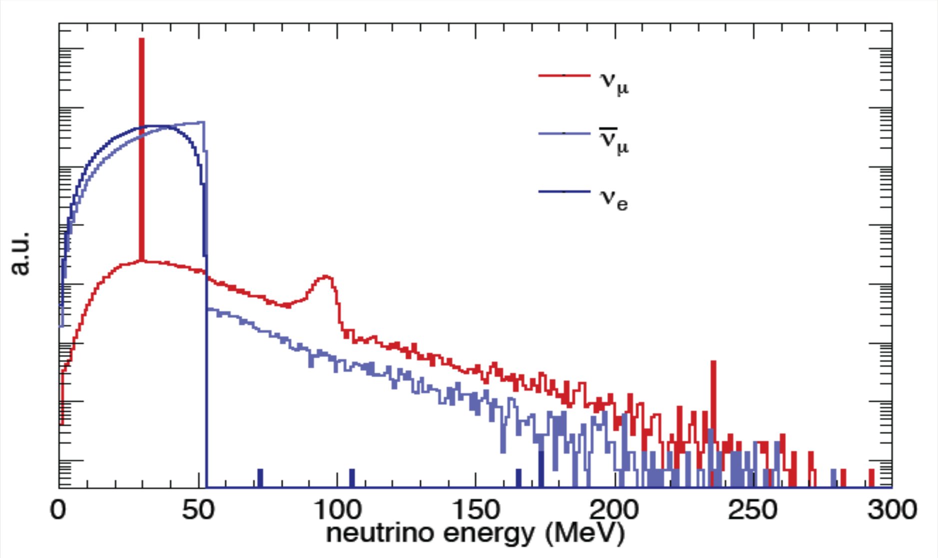


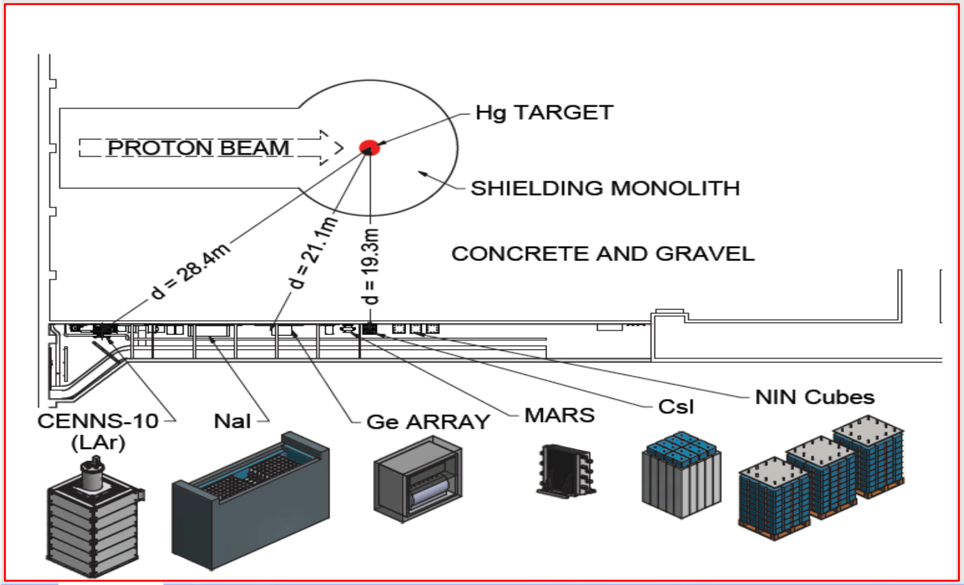
A prototype of a detector that spotted coherent neutrino scattering for the first time. (JEAN LACHAT/UNIVERSITY OF CHICAGO)

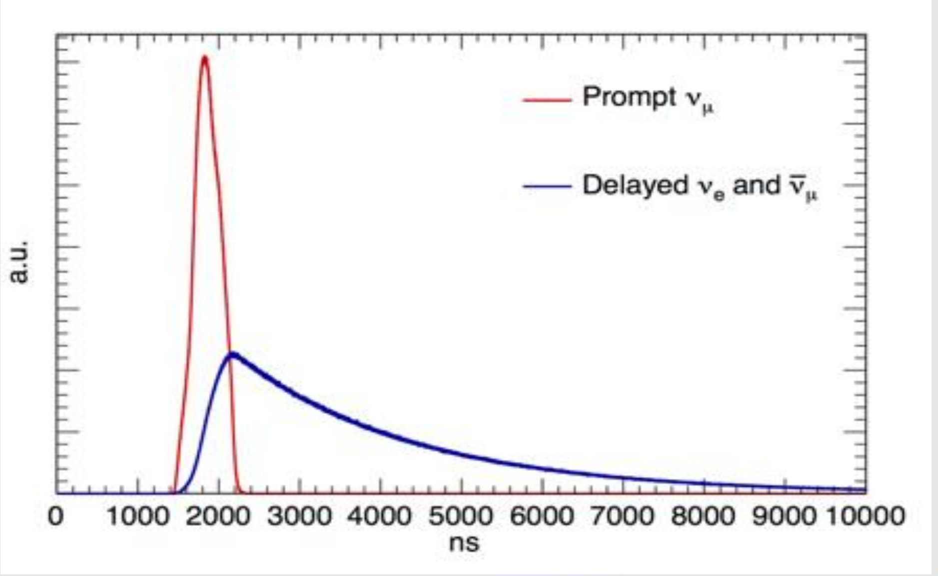
This year, physicists spotted the most elusive subatomic particles, neutrinos, pinging off atomic nuclei in a new way. The achievement fulfilled a 4-decade-long quest, and it didn't require the massive hardware usually used to detect neutrinos. Instead, the researchers pulled off the feat with a portable detector that weighs about as much as a microwave oven.

What is “COHERENT”？

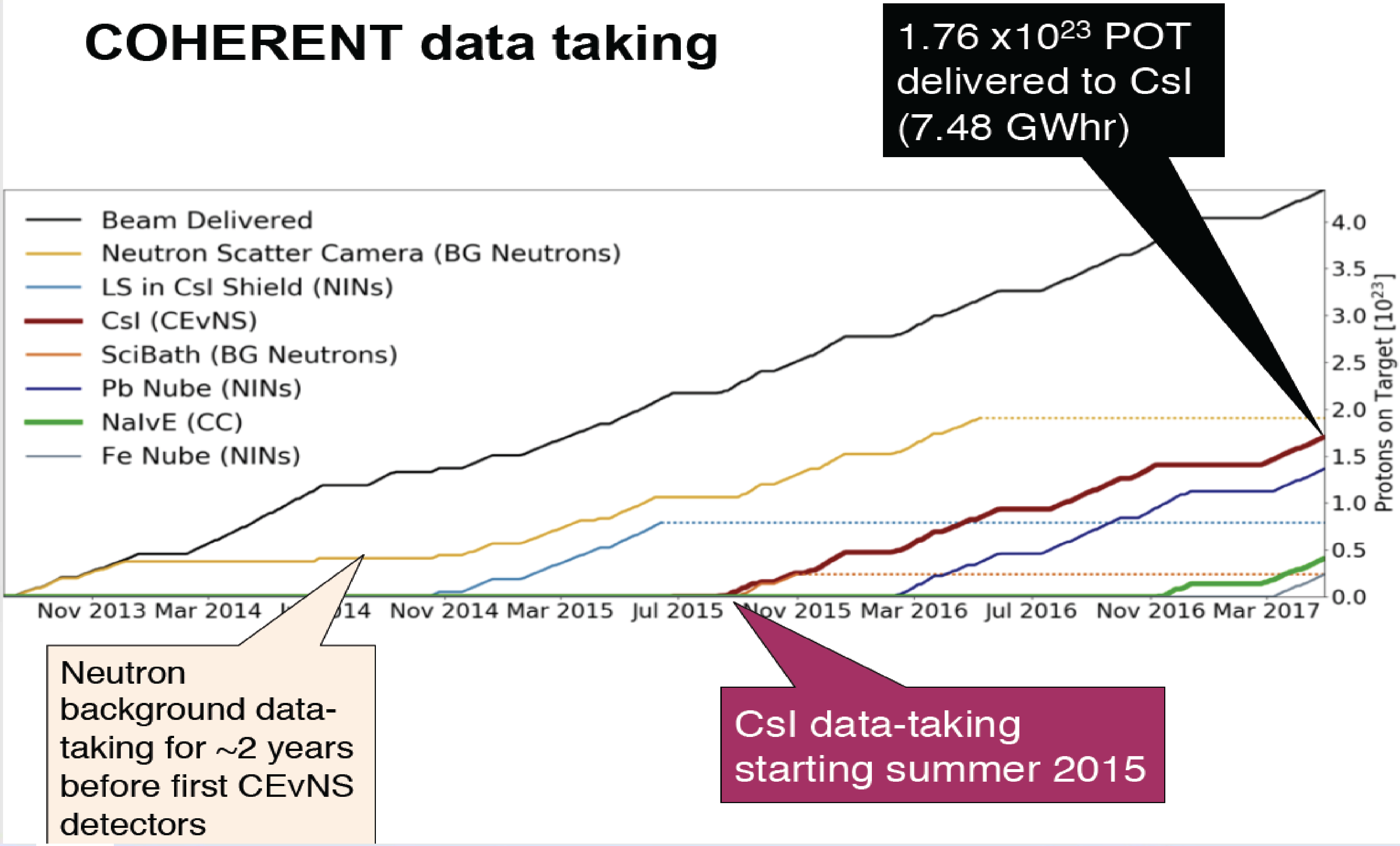




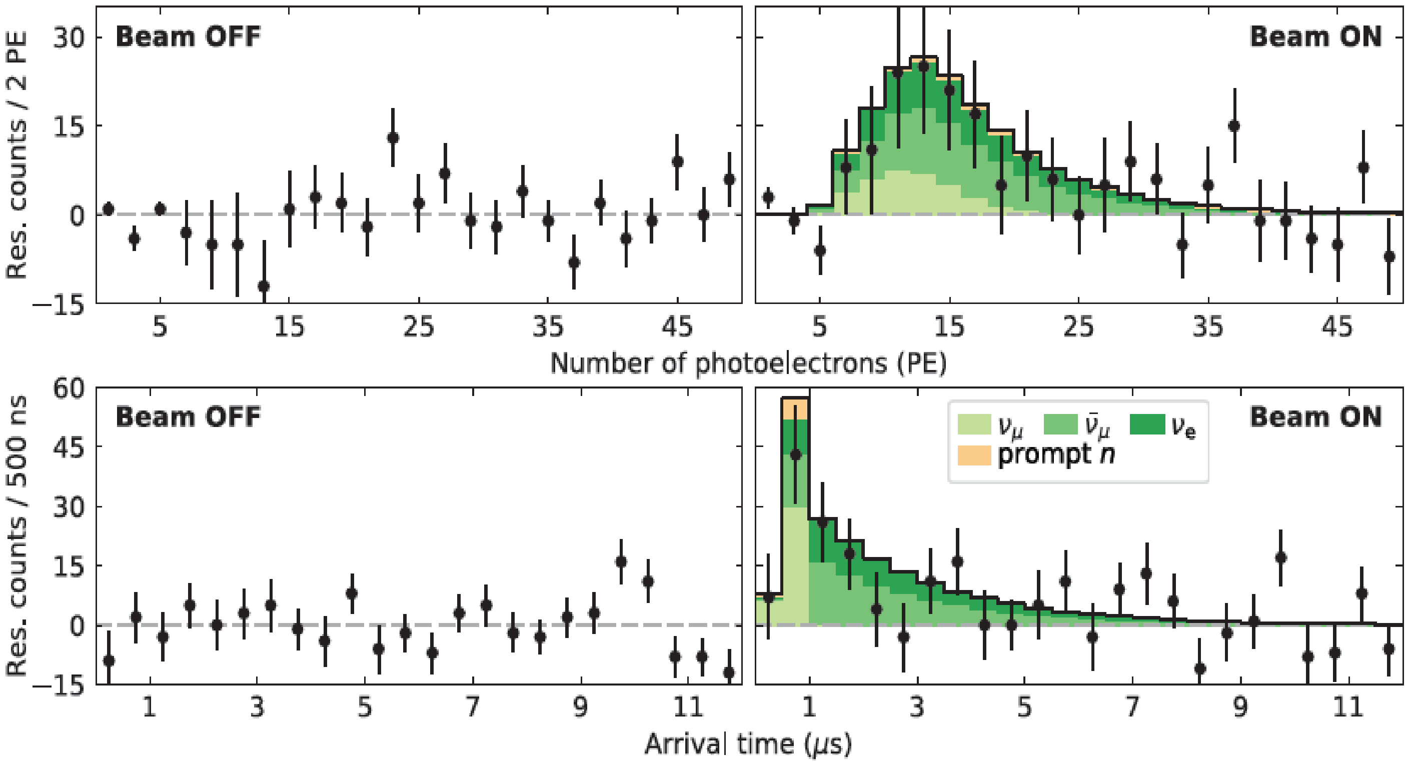




First light with CsI (Na)



First observation of CEvNS



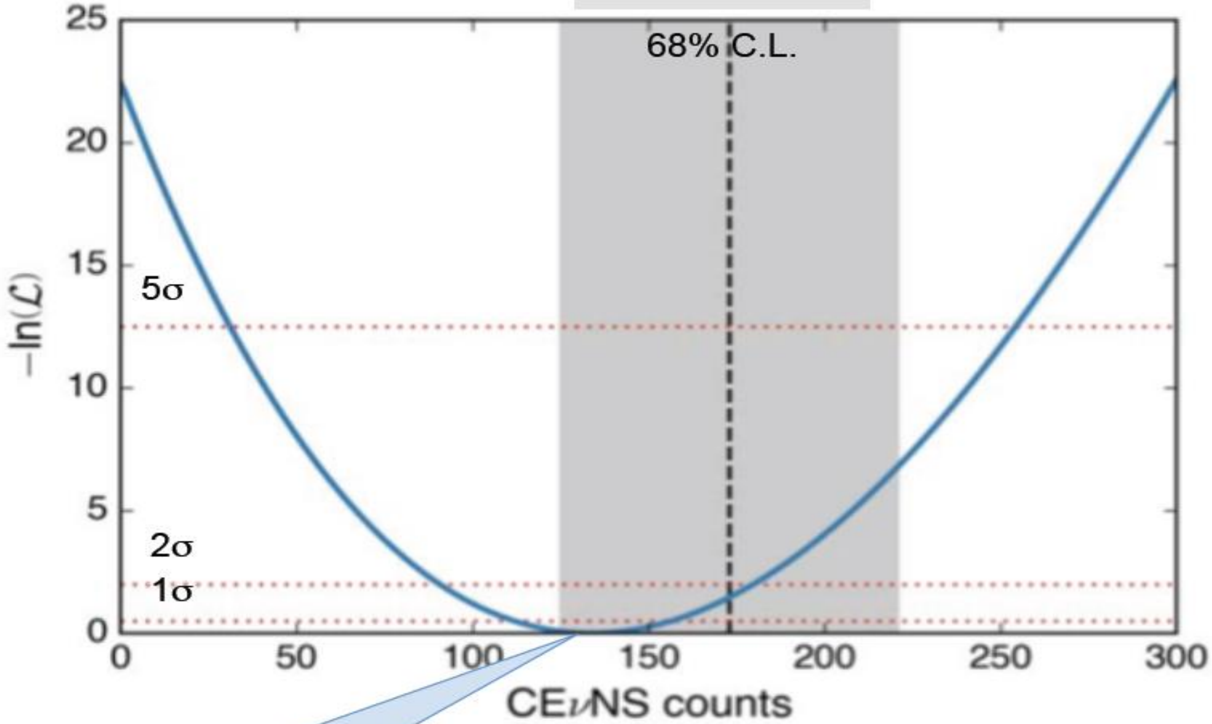
Akimov et al. *Science*
Vol 357, Issue 6356
15 September 2017

- Data are beam coincident and anti-coincident residuals during SNS operation, “On”, and during SNS shutdown periods, “Off”.
- Excess in light yield and timing distributions only for Beam on.

Comparison with SM

Results of 2D energy, time fit

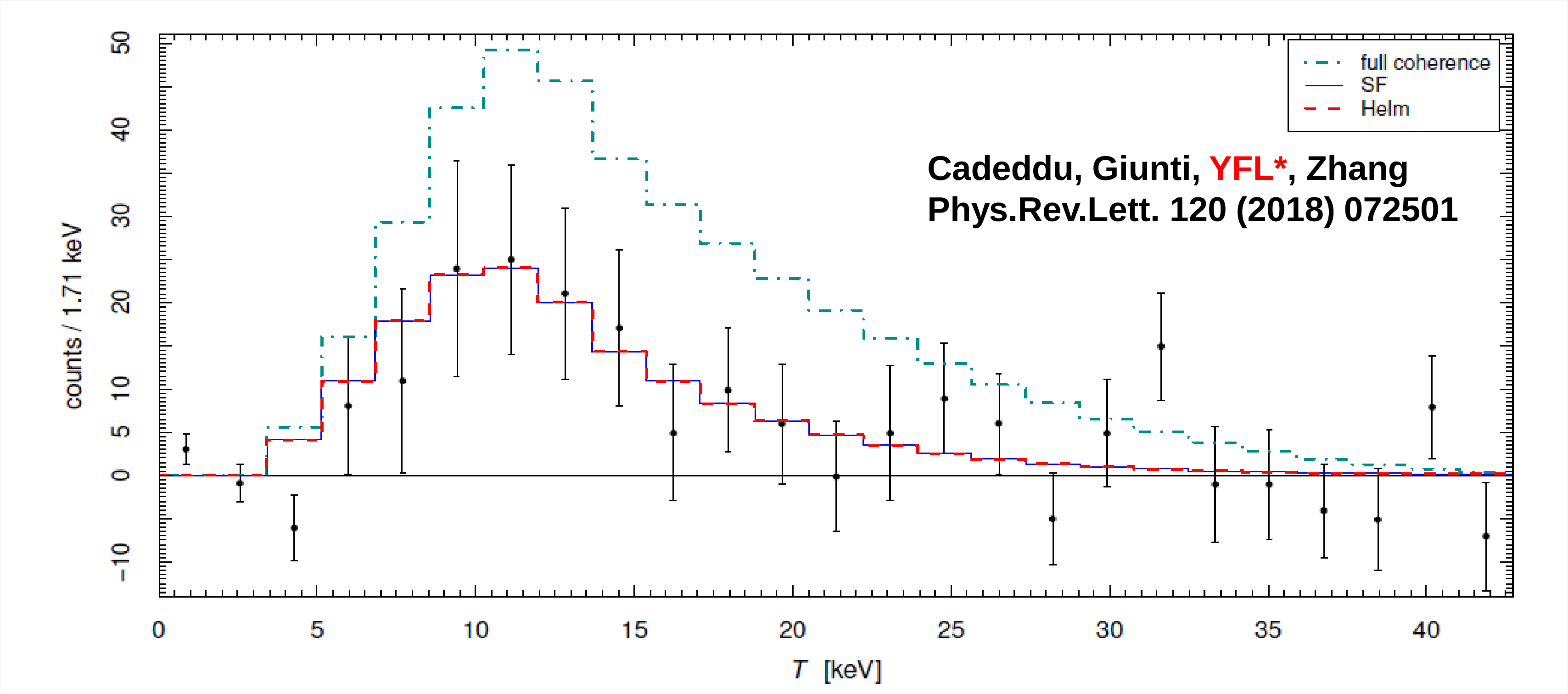
SM prediction, 173 events



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

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

Implication-1: test of the coherency



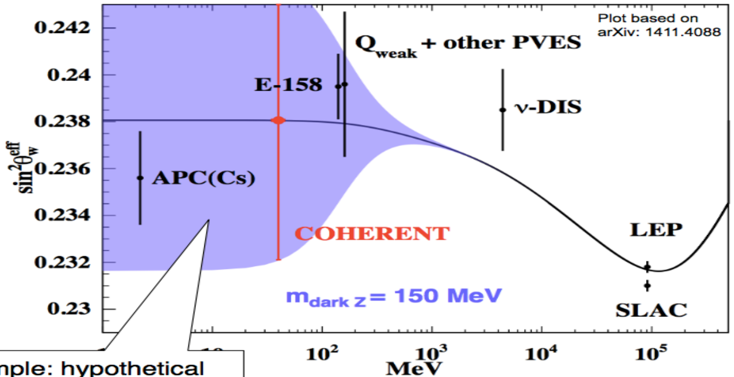
(1) Full coherence → Fq = Fn =1.

(2) COHERENT data show 2.3-sigma evidence of the nuclear structure suppression of the full coherence.

Implication-2: weak mixing angle

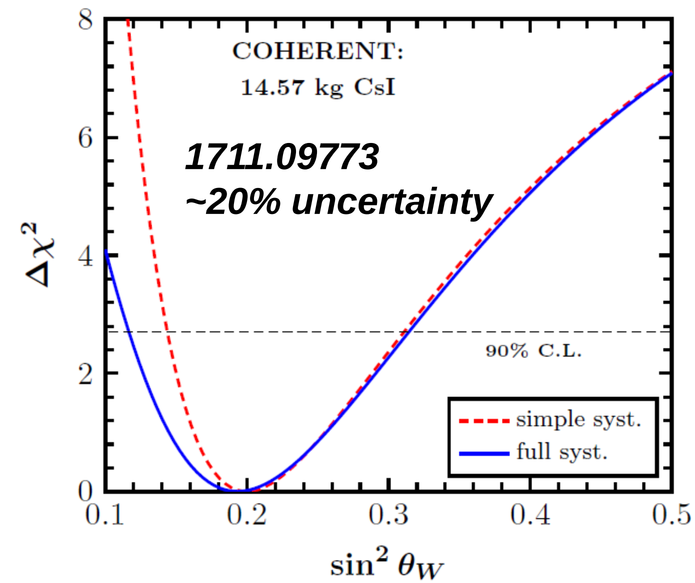
Clean SM prediction for the rate ➔ measure $\sin^2\theta_W$eff ;
deviation probes new physics

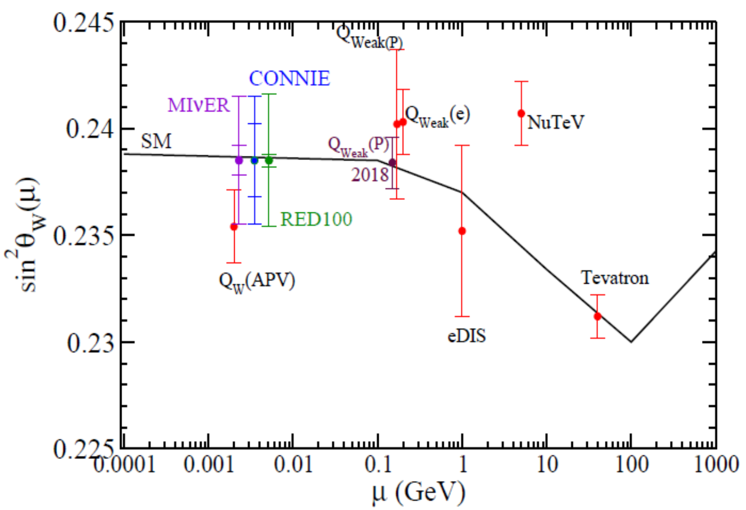
$$\sigma \sim \frac{G_f^2 E^2}{4\pi}(N-(1-4\sin^2\theta_W)Z)^2$$

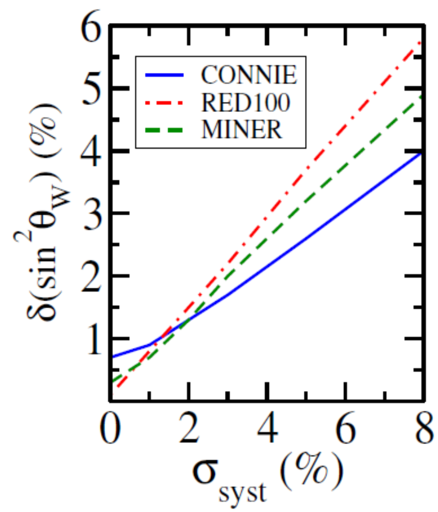


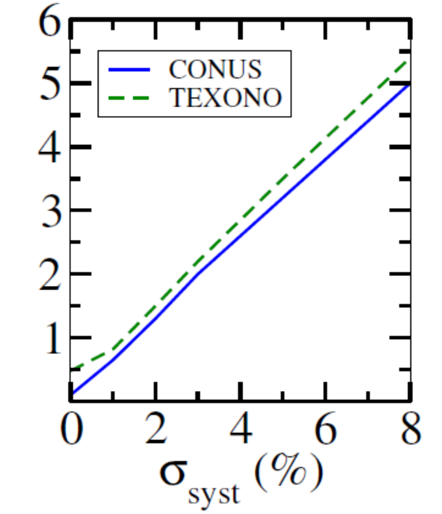
Example: hypothetical dark Z mediator (explanation for g-2 anomaly)

CEvNS sensitivity is @ low Q; need sub-percent precision to compete w/ electron scattering & APV, but **new channel**









Implication-3: beyond SM (NSI as an example)

Neutrino (new) Non-Standard Interactions(NSIs) ←→ new physics at high scales, which are integrated out

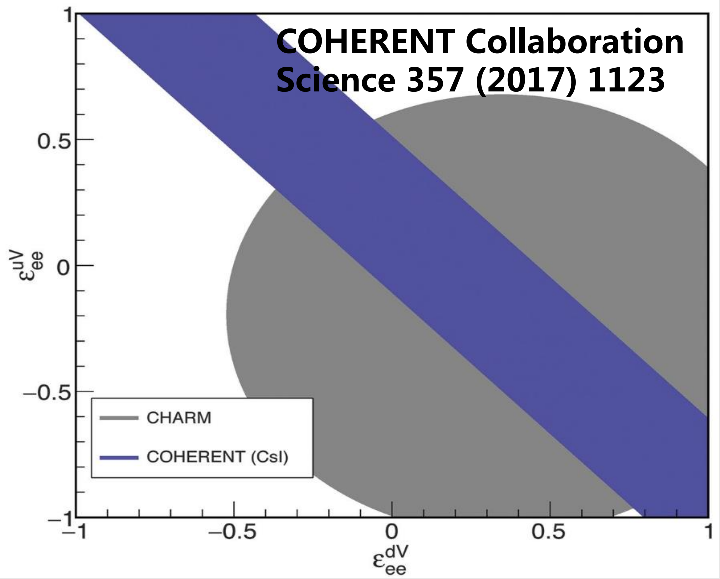
$$\mathcal{L}_{NSI} \simeq \epsilon_{\alpha\beta} 2\sqrt{2} G_F (\bar{\nu}_{L\beta}\, \gamma^\rho\, \nu_{L\alpha})(\bar{f}_L \gamma_\rho f_L)$$

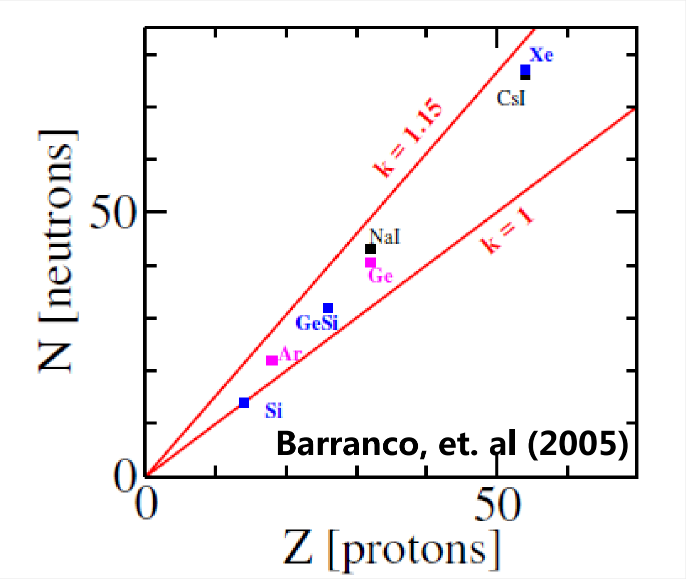
$$|\epsilon| \simeq \frac{M_W^2}{M_{NSI}^2}$$

Complementary method with others, Competitive method to test the TeV scale

0.01 in epsilon ←→ TeV scale

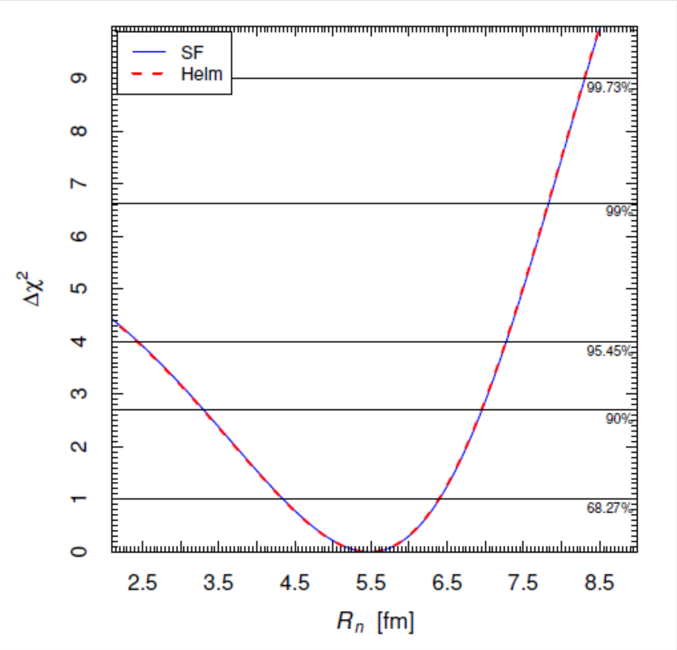
$$k = (Z + 2N)/(2Z + N)$$

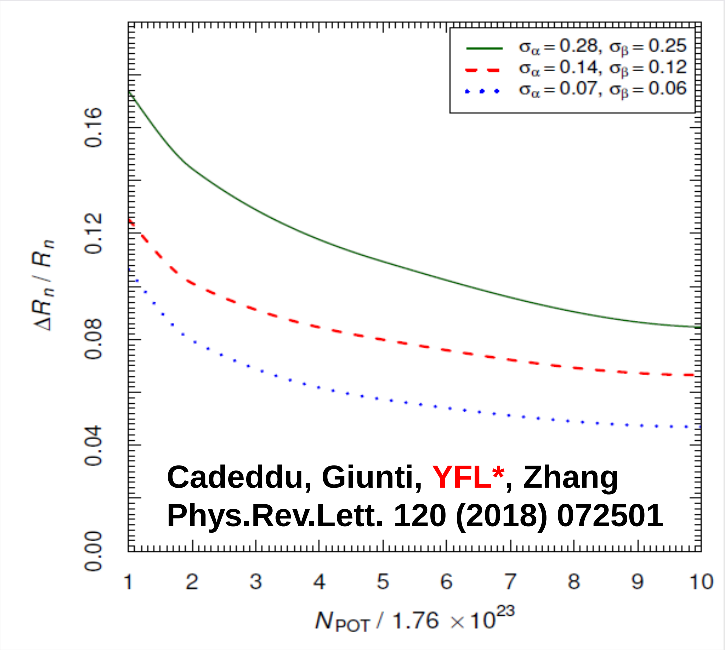




$$G_V = \left[\left(g_V^p + 2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV}\right) Z + \left(g_V^n + \varepsilon_{ee}^{uV} + 2\varepsilon_{ee}^{dV}\right) N\right] F_{nucl}^V(Q^2)$$

Implication-4: neutron radius





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

$$\Delta R_{np} \simeq 0.7^{+0.9}_{-1.1}\ \text{fm}.$$

→ **Neutron skin**

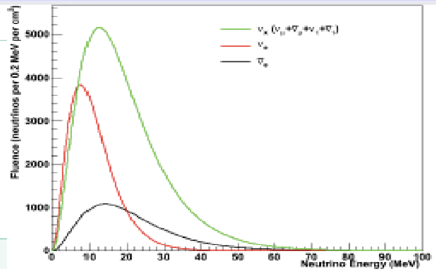
Model	^{133}Cs			^{127}I			CsI		
	R_p	R_n	$R_n - R_p$	R_p	R_n	$R_n - R_p$	R_p	R_n	$R_n - R_p$
SHF SkM* [20]	4.76	4.90	0.13	4.71	4.84	0.13	4.73	4.86	0.13
SHF SkP [21]	4.79	4.91	0.12	4.72	4.84	0.12	4.75	4.87	0.12
SHF SkI4 [22]	4.73	4.88	0.15	4.67	4.81	0.14	4.70	4.83	0.14
SHF Sly4 [23]	4.78	4.90	0.13	4.71	4.84	0.13	4.73	4.87	0.13
SHF UNEDF1 [24]	4.76	4.90	0.15	4.68	4.83	0.15	4.71	4.87	0.15
RMF NL-SH [25]	4.74	4.93	0.19	4.68	4.86	0.19	4.71	4.89	0.18
RMF NL3 [26]	4.75	4.95	0.21	4.69	4.89	0.20	4.72	4.92	0.20
RMF NL-Z2 [27]	4.79	5.01	0.22	4.73	4.94	0.21	4.76	4.97	0.21

Implication for neutron star:

A larger neutron skin would suggest a stiffer EOS and imply a larger neutron star radius, and then a smaller gravitational binding energy.

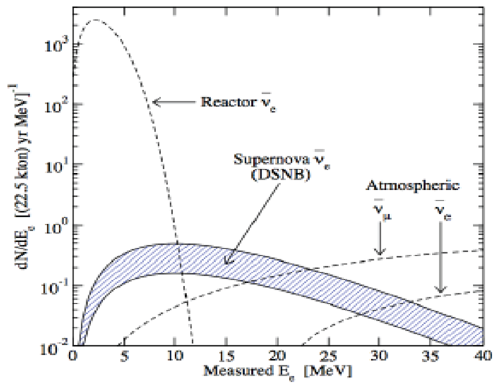
Implication-5: detection of natural sources

Supernova burst neutrinos



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

Supernova relic neutrinos

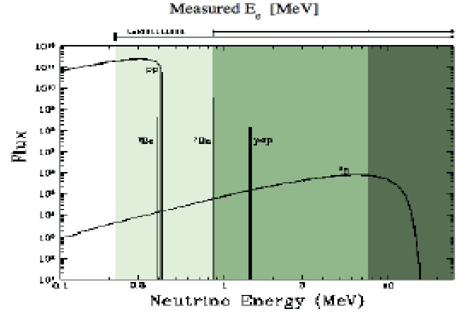


All flavors, low flux

Atmospheric neutrinos

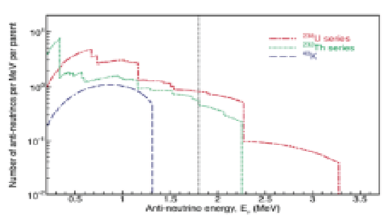
Some component at low energy

Solar neutrinos



Most flux below 1 MeV

Geoneutrinos



Very low energy

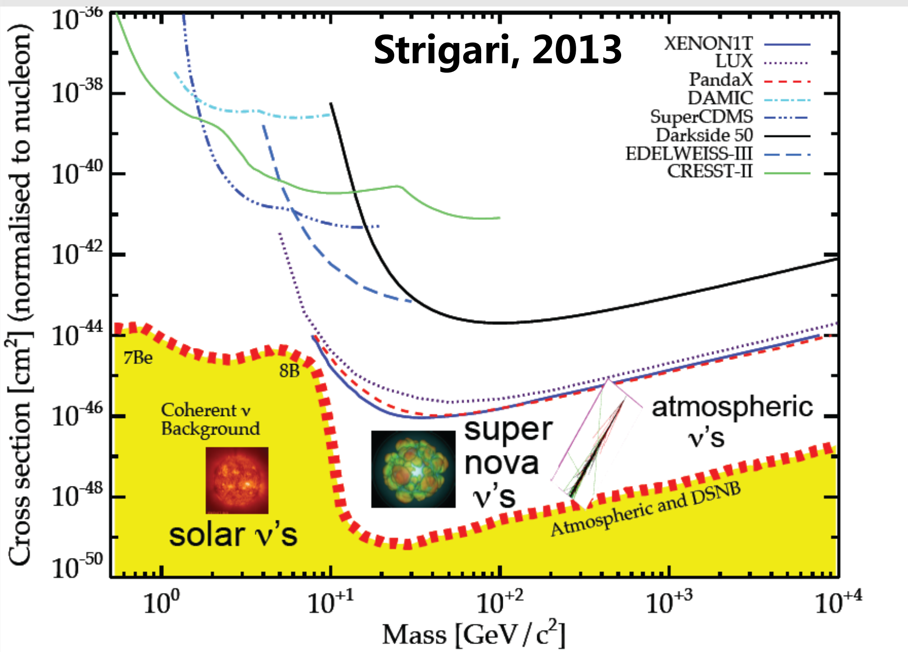
CEvNS eventually seen in DM expts

Implication-6: astrophysics

DM connection

1) DM experiments assume coherent DM scattering: test of CEνNS

2) Neutrino floor of direct DM experiments *IS* the CEνNS signal

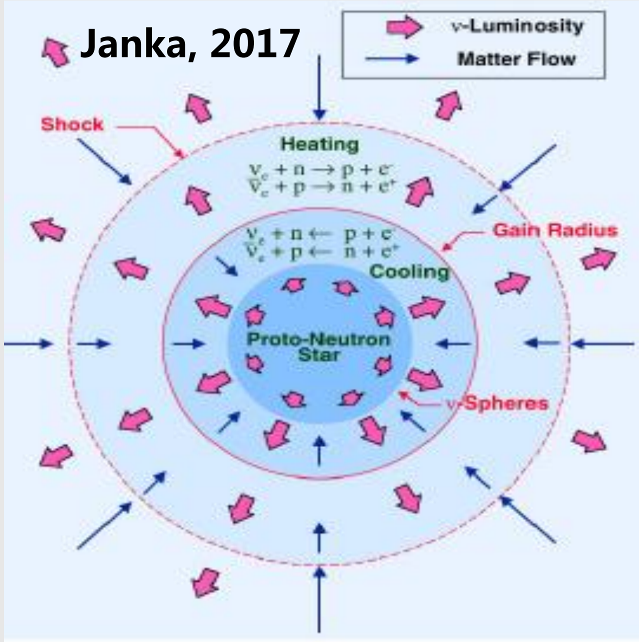


Measure CEvNS to understand nature of background/astro signal

Supernovae

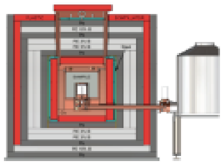
1) CEνNS in Fe+Ni shells influence momentum transport: opaqueness

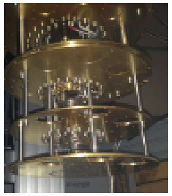
2) CEνNS for detecting supernova neutrinos.

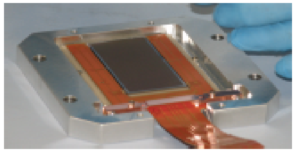


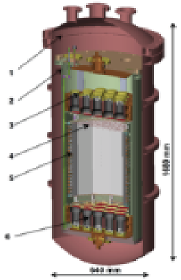
Outlook: proposals of reactors

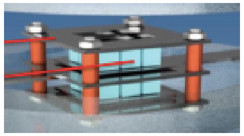
Experiment	Technology	Location
CONUS	HPGe	Germany
Ricochet	Ge, Zn bolometers	France
CONNIE	Si CCDs	Brazil
RED	LXe dual phase	Russia
Nu-Cleus	Cryogenic $CaWO_4$, Al_2O_3 calorimeter array	Europe
MINER	Ge iZIP detectors	USA











TEXONO (Ge, Taiwan), nu-Gen (Ge, Russia)

Novel low-background, low-threshold technologies

Outlook: first indication?

First rate analysis

Definition of cuts from reactor OFF time:
- energy scale calibration
- quality cuts (noise/spurious event red.)
- conservative ROI for CEνNS window
  (individual for every detector)

Definition of efficiencies:
- active volume: (96+-2)%
- muon AC ind. trg. Efficiency: (98+-1)%
- threshold trg. Efficiency
  (individual for every detector)

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 → Some systematics still under study

(*) Including stat. uncertainty and above efficiencies

→ **Observed excess of events is consistent with expected CEνNS signal range**

Summary

CEνNS:

(a) large cross section, but tiny recoils, α N^2
(b) accessible w/ low-energy threshold detectors , plus intensive neutrino sources.

After 43 years, first measurement by COHERENT CsI[Na] at the SNS.
Near future: measurements with different targets in SNS, and possible detection with reactors.

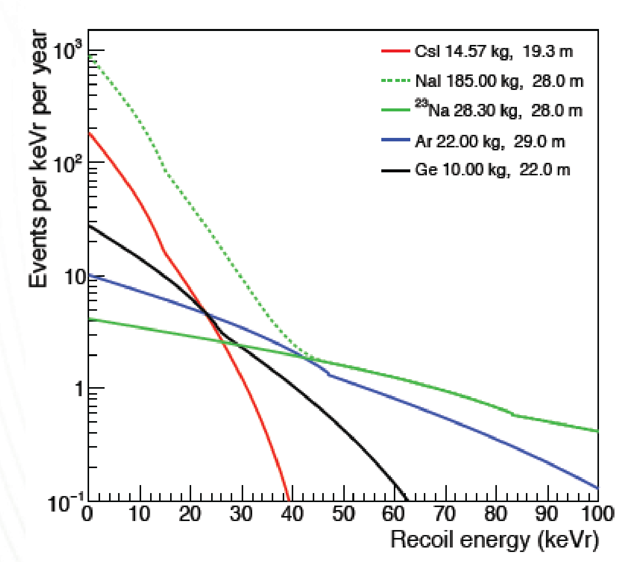
CEνNS will become an interesting tool for:
tests of SM and new physics, neutron form factors, supernova dynamics, DM neutrino floor, reactor monitoring.

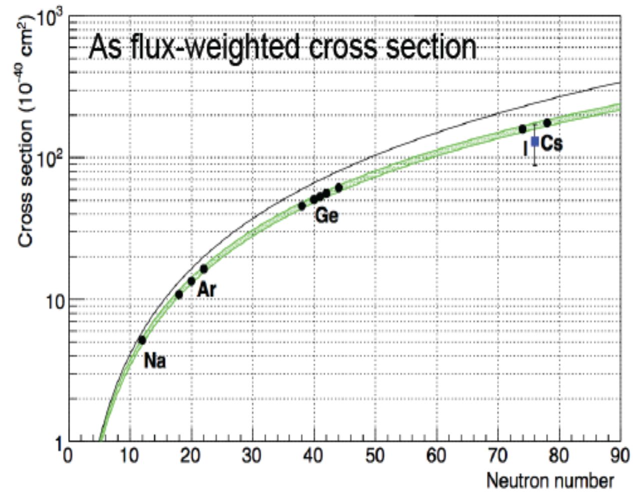
→ very interesting potential of CEνNS

Thanks!

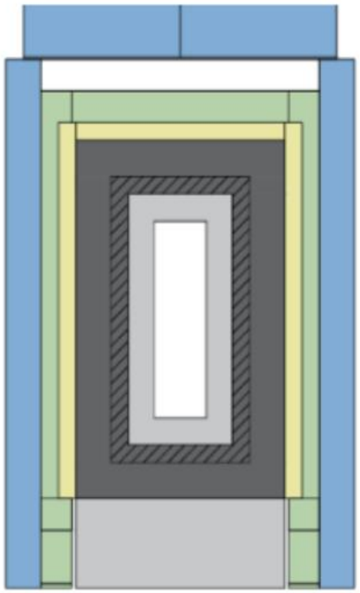
COHERENT CEνNS Detectors

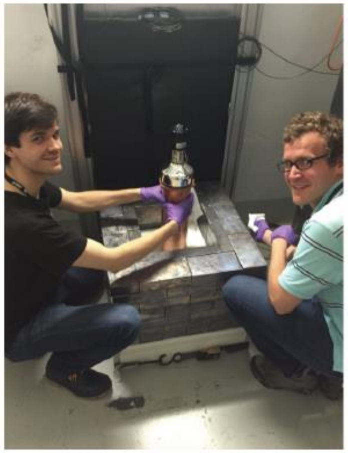
Nuclear Target	Technology	Mass (kg)	Target Distance (m)	Recoil threshold (keVr)
CsI[Na]	Scintillating Crystal	14	20	6.5
Ge	HPGe PPC	10	22	5
LAr	Single-phase	28	29	20
NaI[Tl]	Scintillating Crystal	185*/2000	28	13





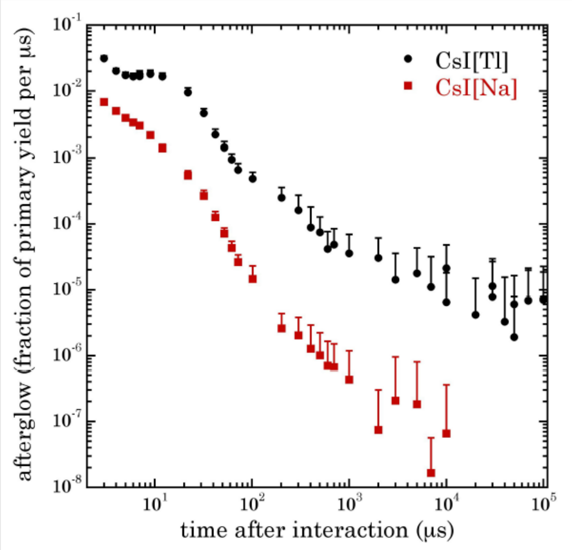
CsI (Na) detector



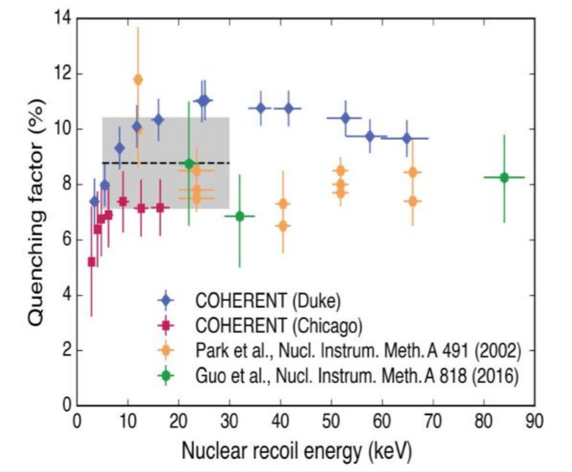


A hand-held detector!

Almost wrapped up...



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



Why CsI (Na)?

Large N^2 →large cross section.

Cs and I surround Xe in Periodic Table.

Na-doping can reduce afterglow

High light yield

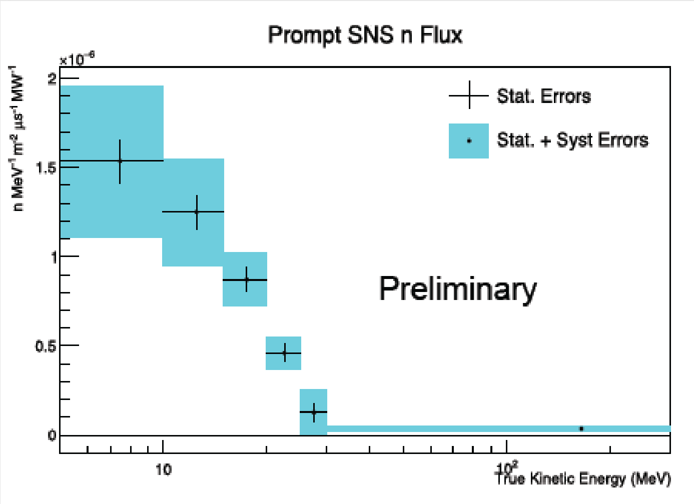
Background

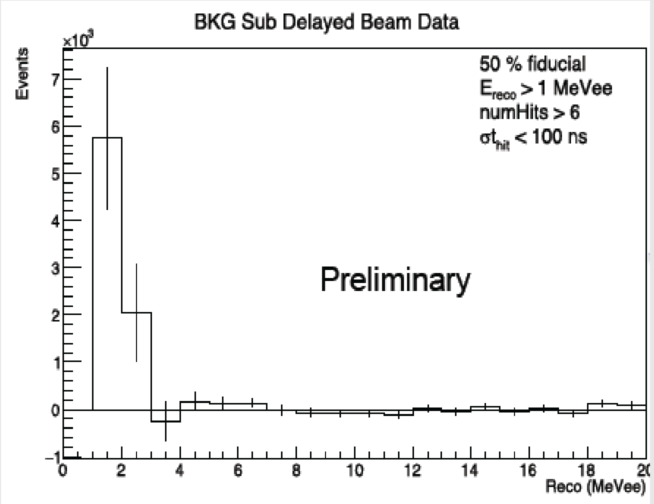
(1) Steady-state backgrounds can be measured off-beam-pulse

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

(2) In-time backgrounds must be carefully characterized

- two neutron detectors for fast neutrons
- neutrino induced neutrons (NIN) blocked by HDPE, and cross section is measured by NIN tubes





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

1n, 2n emission

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

1n, 2n, γ emission

Summary tables

Signal, background, and uncertainty summary numbers

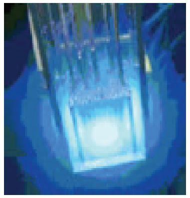
$6 \leq PE \leq 30,\ 0 \leq t \leq 6000$ ns

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 (Quenching factor)

Reactor vs stopped-pion for CEνNS

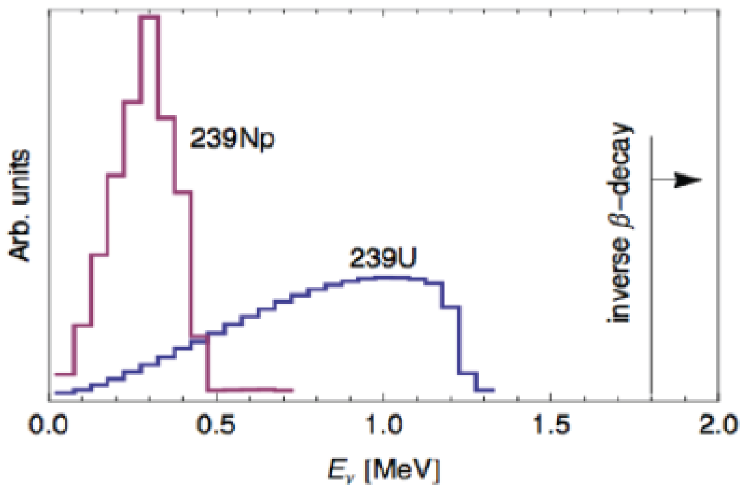
Source	Flux/ ν's per s	Flavor	Energy	Pros	Cons
Reactor 	2e20 per GW	nuebar	few MeV	• huge flux	• lower xscn • require very low threshold • CW
Stopped pion 	1e15	numu/ nue/ nuebar	0-50 MeV	• higher xscn • higher energy recoils • pulsed beam for bg rejection • multiple flavors	• lower flux • potential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

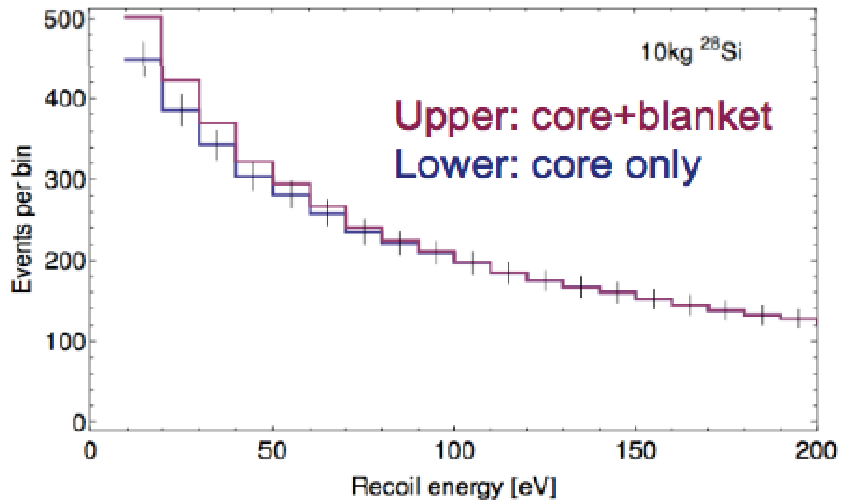
Implication-7: reactor monitoring

Plutonium breeder blanket in a reactor has neutrino spectral signature

$$^{238}\mathrm{U} + n \rightarrow {}^{239}\mathrm{U} \xrightarrow{\beta} {}^{239}\mathrm{Np} \xrightarrow{\beta} {}^{239}\mathrm{Pu}$$

Huber 2015





ν spectrum is below IBD threshold

➔ accessible with CEνNS, but require low recoil energy threshold

additional sensor close to core: monitoring of burn-up and cool-down