Nuclear Physics from COHERENT neutrino-nucleus scattering data

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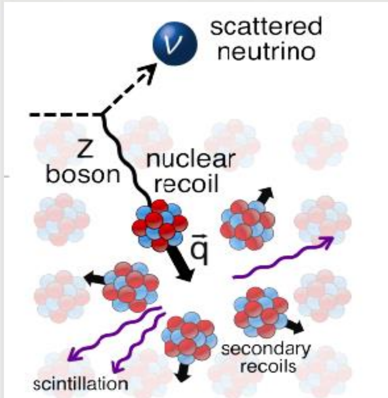
6th Symposium on Neutrinos and Dark Matter in Nuclear Physics (NDM 2018)

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

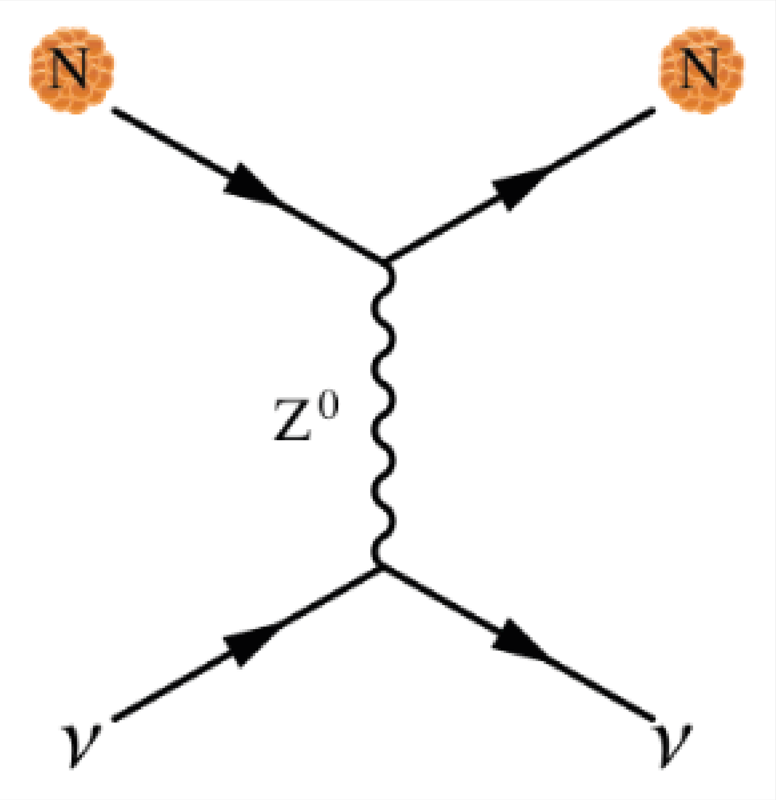
Why coherent?

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

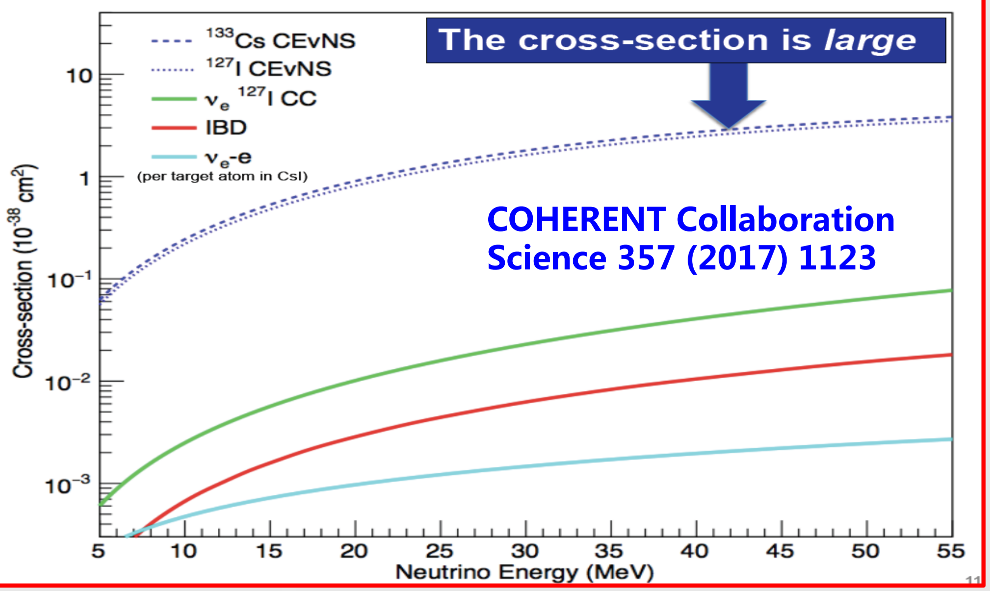
Coherency hold up to ~ 50 MeV

The cross section: within & beyond SM

$$\frac{d\sigma_{\nu\text{-}\mathcal{N}}}{dT}(E,T) \simeq \frac{G_F^2 M}{4\pi}\left(1-\frac{MT}{2E^2}\right) \times \left[N F_N(q^2) - \epsilon Z F_Z(q^2)\right]^2$$

$T_{\max} \simeq 2E^2/M$

$\epsilon = 1 - 4\sin^2\vartheta_W$

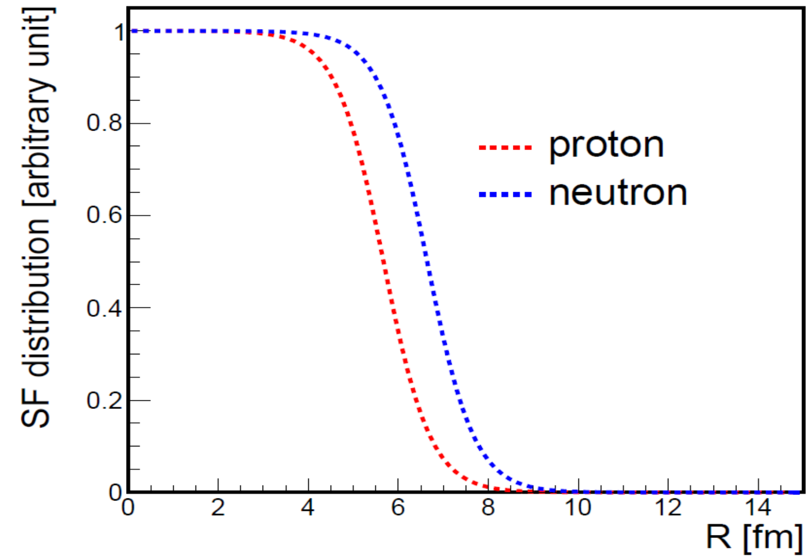


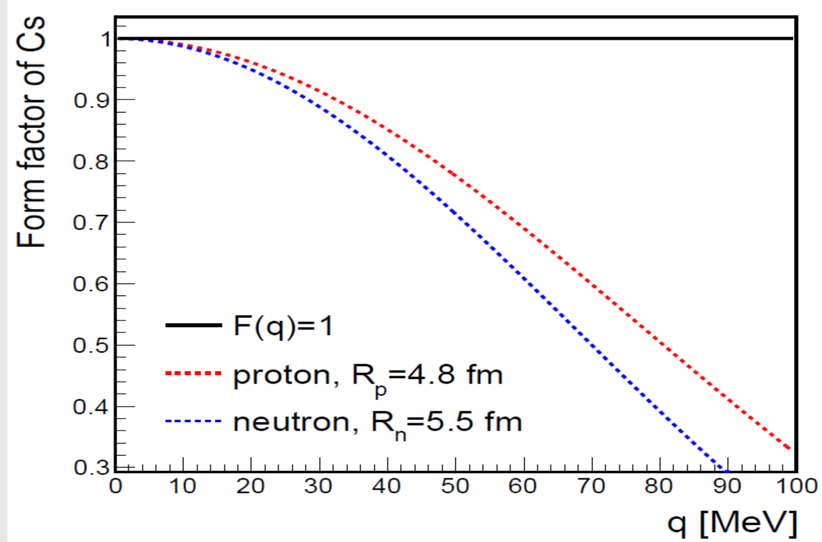
$$\frac{d\sigma}{dT}(E_\nu,T) = \frac{G_F^2 M}{\pi}\left(1-\frac{MT}{2E_\nu^2}\right) \times \left\{\left[F_Z^V(q^2) Z g_V^p + F_N^V(q^2) N g_V^n\right]^2\right\}$$

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

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

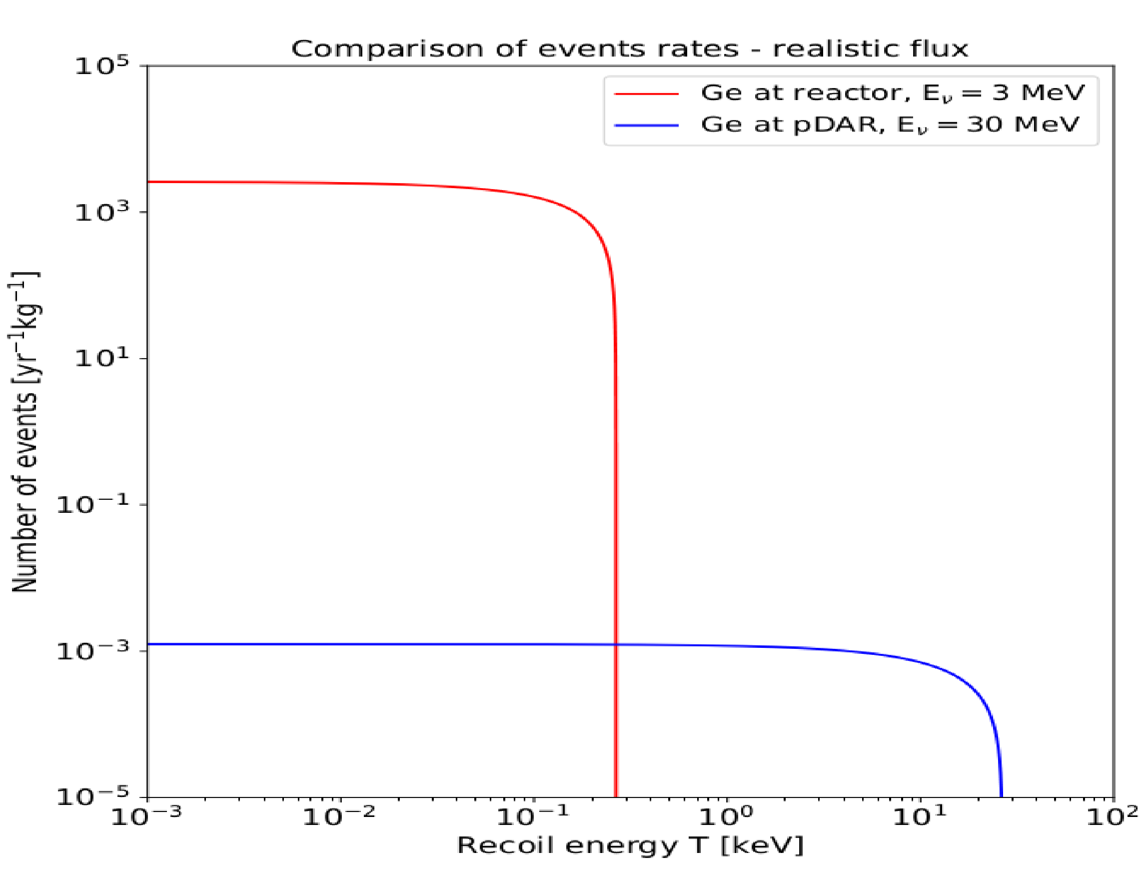
Barranco et. al., JHEP (2005)

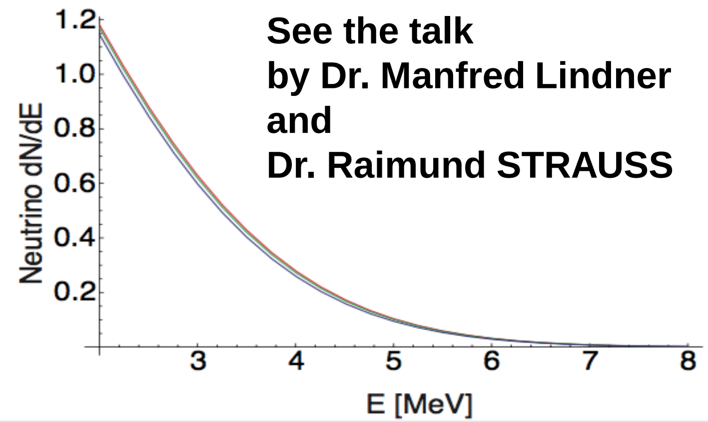




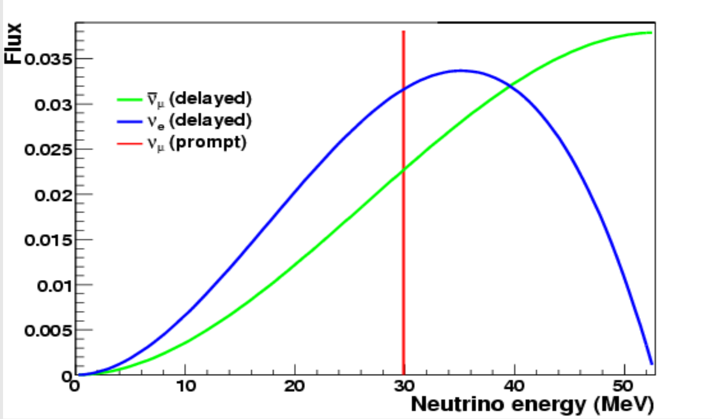
Why difficult?

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





See the talk by Dr. Manfred Lindner and Dr. Raimund STRAUSS



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

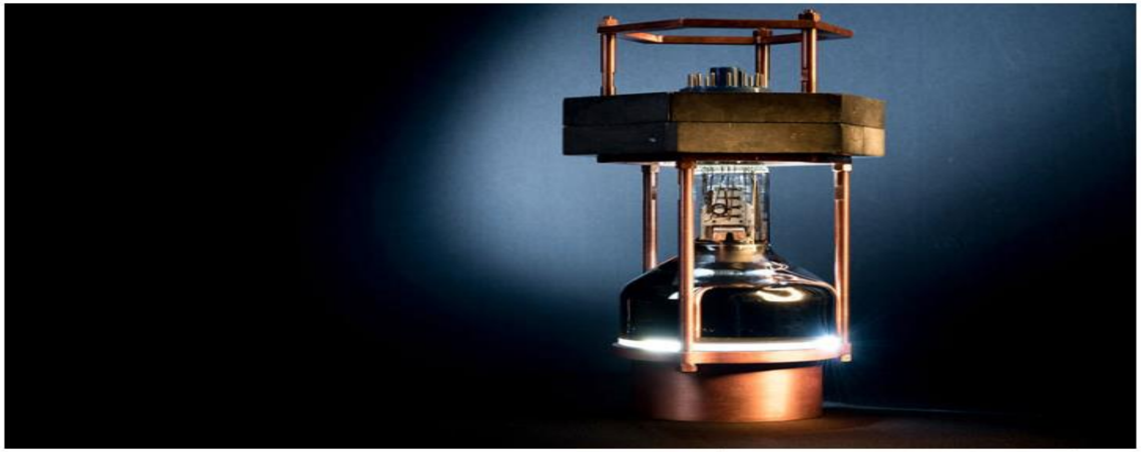
See the talk by Dr. Grayson RICH

PRE 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

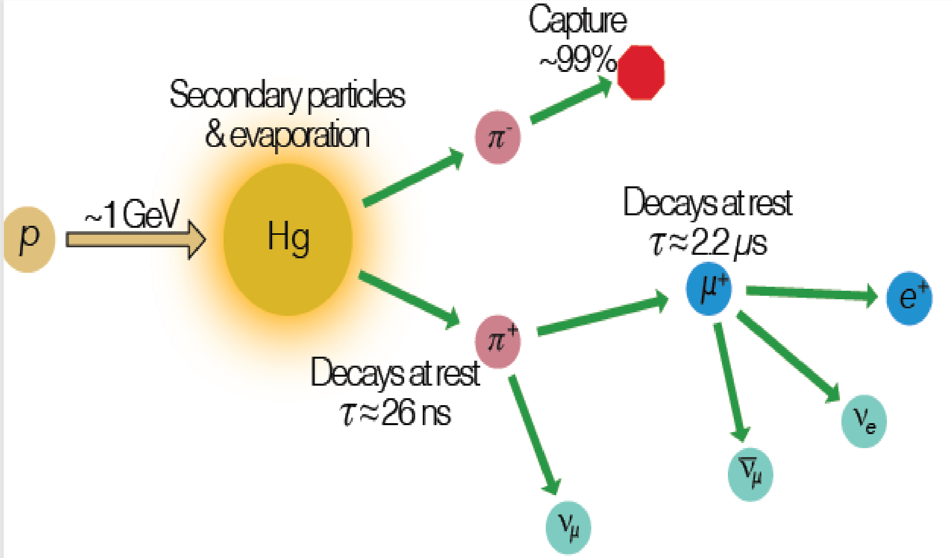
A tiny detector for the shiest particles

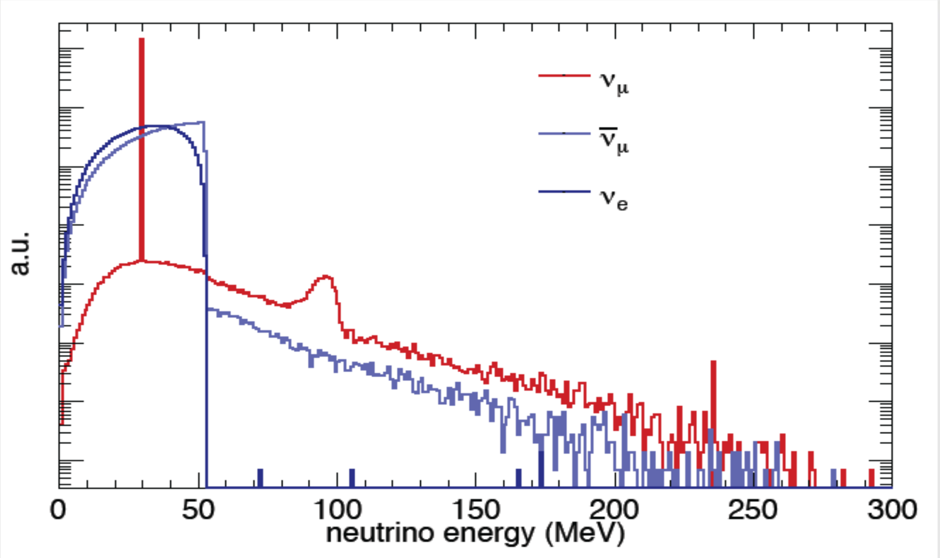


A prototype of a detector that spotted coherent neutrino scattering for the first time. (JEAN LACHAT/UNIVERSITY OF CHICAGO)

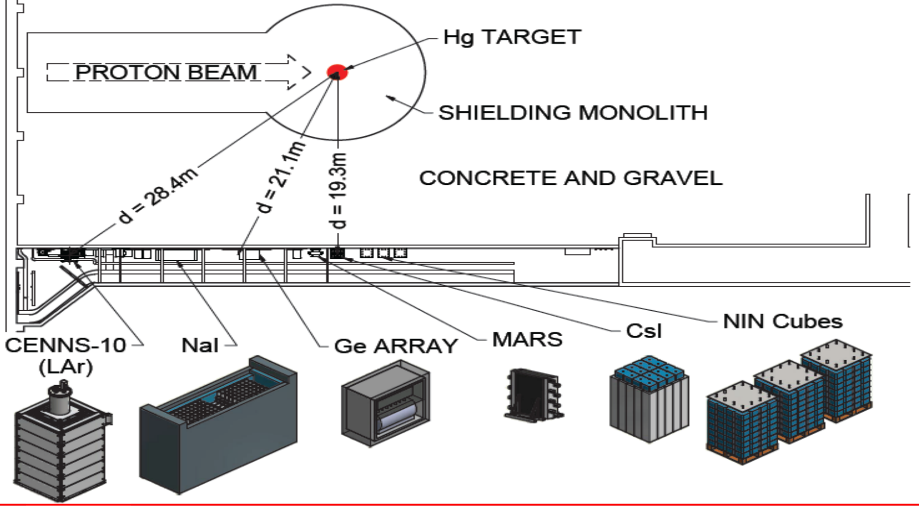
This year, physicists spotted the most elusive subatomic particles, neutrinos, pinging off atomic nuclei in a new way. The achievement fulfilled a 4-decade-long quest, and it didn't require the massive hardware usually used to detect neutrinos. Instead, the researchers pulled off the feat with a portable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

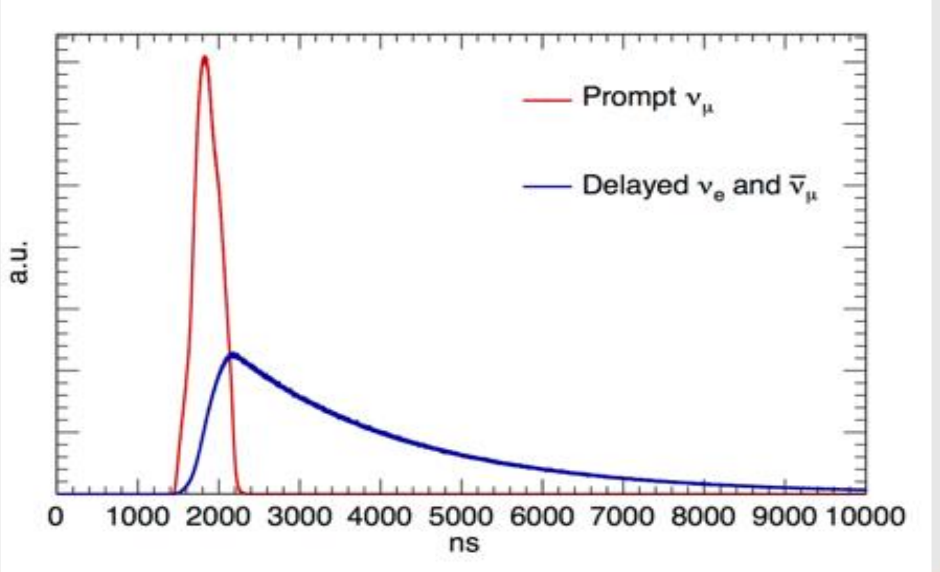
What is "COHERENT"?



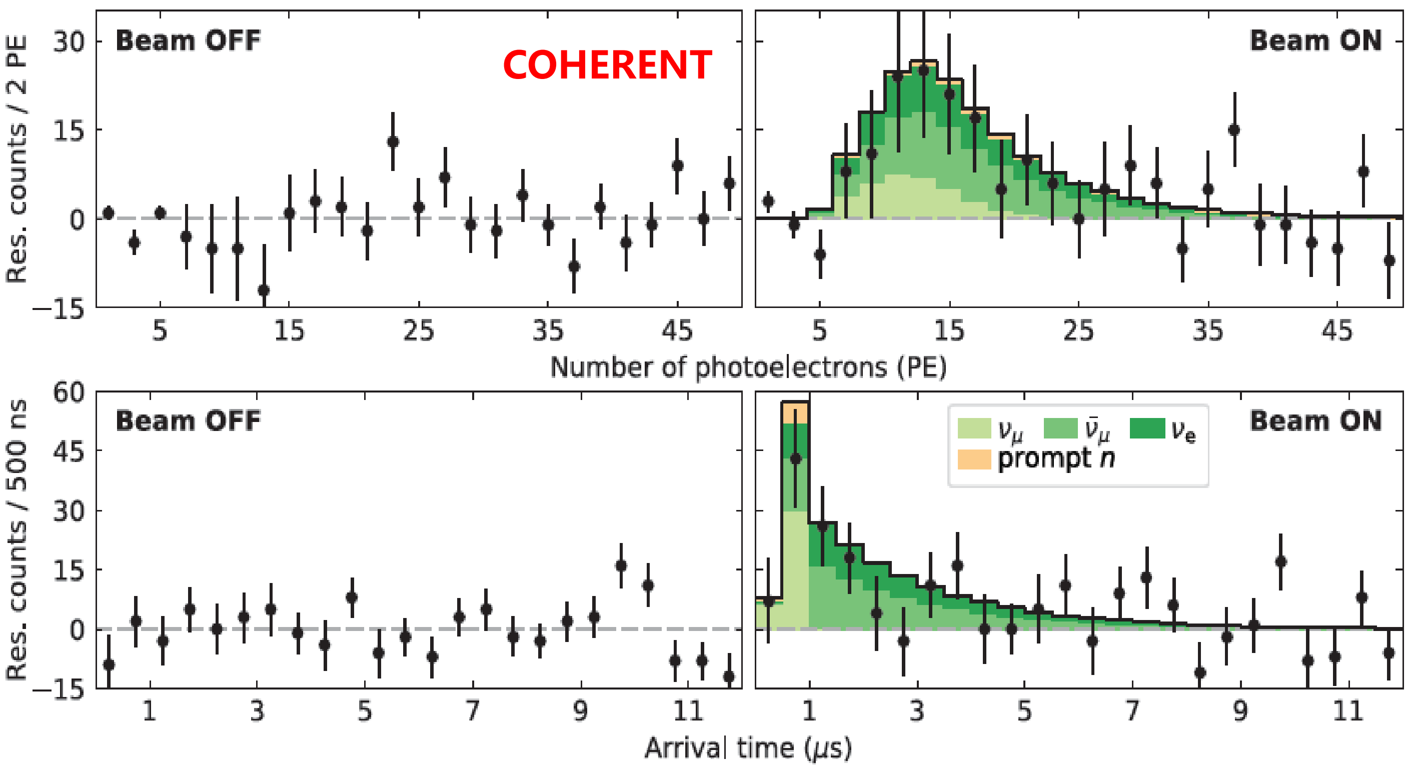


See the talk by **Dr. Grayson RICH**





First observation of CEvNS



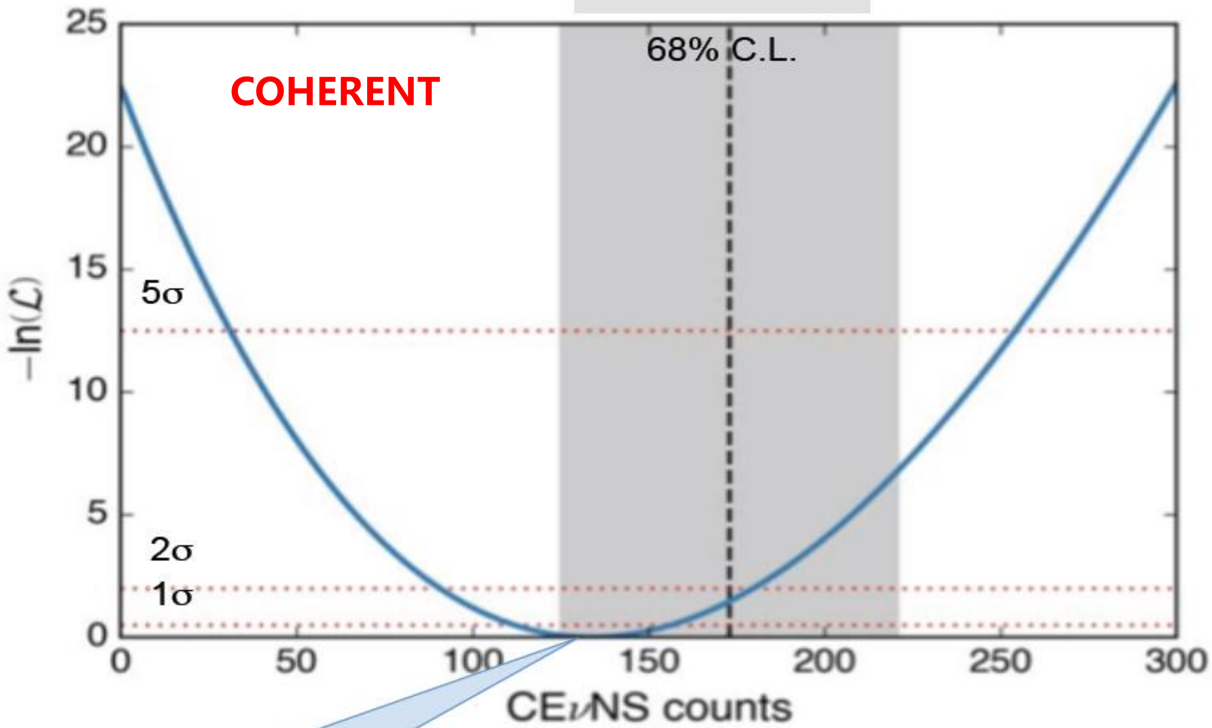
Akimov et al. *Science* Vol 357, Issue 6356 15 September 2017

- 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 the SM prediction

Results of 2D energy, time fit

SM prediction, 173 events



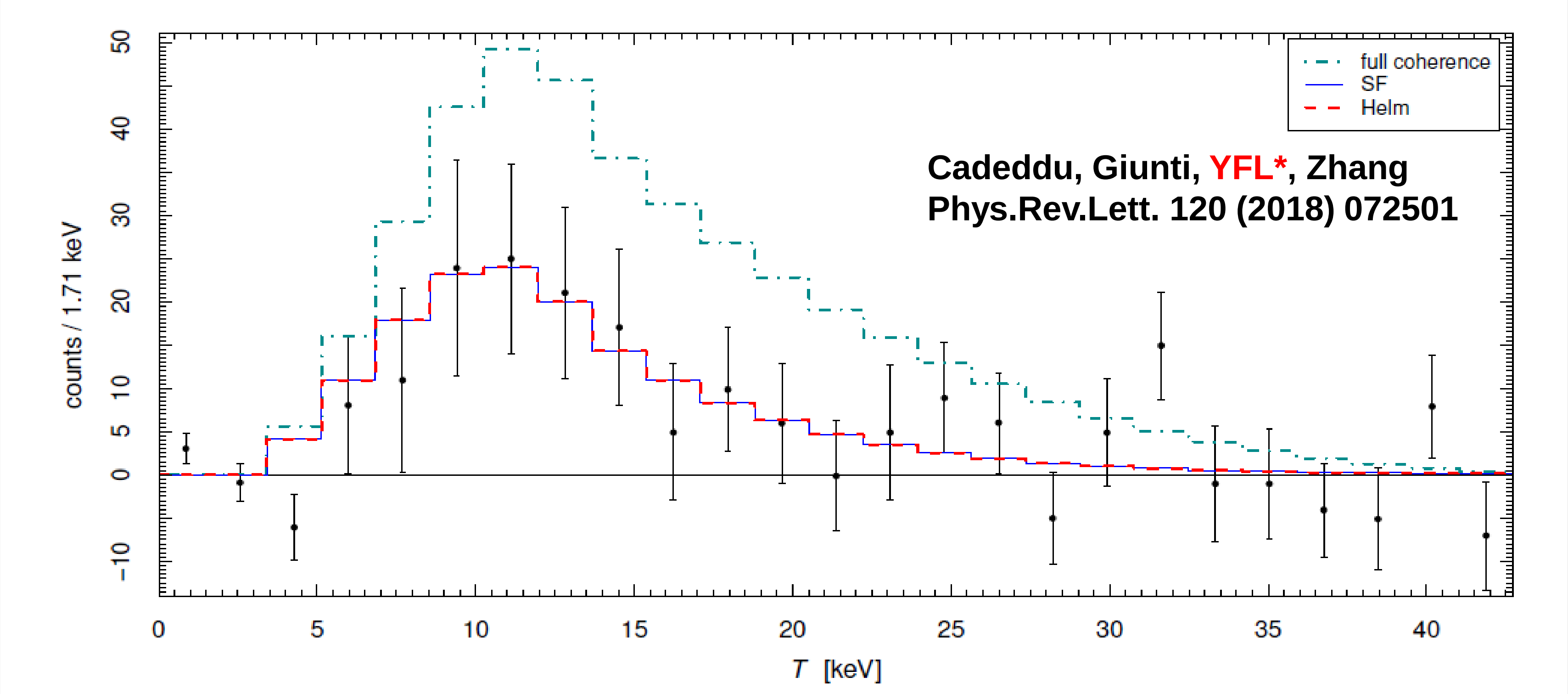
Best fit: **134 ± 22** observed events

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

$$\chi^2 = \sum_{i=4}^{15} \left(\frac{N_i^{\text{exp}} - (1+\alpha)\, N_i^{\text{th}} - (1+\beta)\, B_i}{\sigma_i} \right)^2 + \left(\frac{\alpha}{\sigma_\alpha} \right)^2 + \left(\frac{\beta}{\sigma_\beta} \right)^2 .$$

Signal: 28% **Background: 25%**

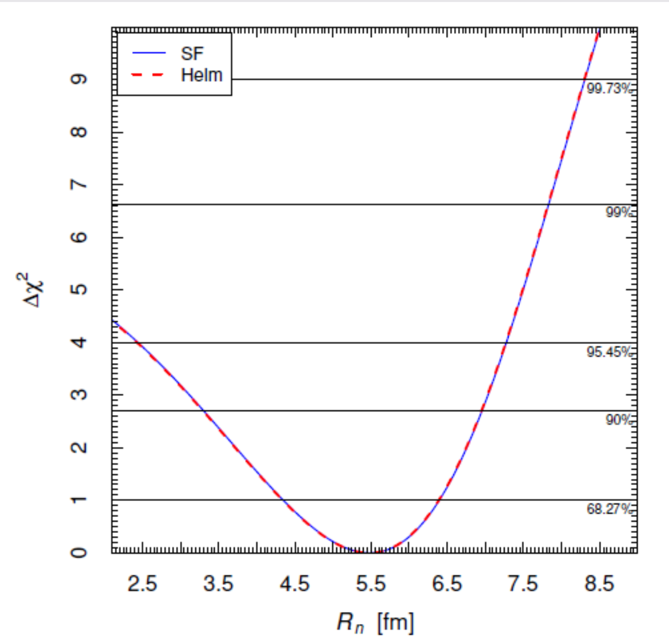
Test of the full coherency

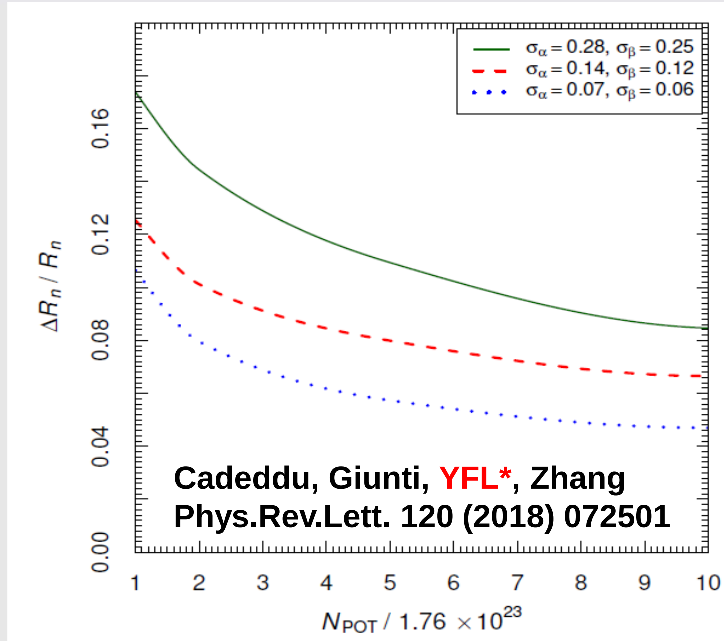


(1) **Full coherence → Fq = Fn =1.**

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

Neutron radius and skin





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

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

→ **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

Question:

(1) How large is the neutron skin?

(2) Possible for higher order moment expansions?
(see 1207.0693)

Why study the neutron radius?

(a) The neutron radius and neutron skin are strongly correlated to the nuclear Equation of State (EOS), the slope of bulk symmetry energy, and other nuclear quantities.

(b) A larger neutron skin would suggest a stiffer EOS and imply a larger neutron star radius, which is related to the gravitational binding energy of core collapse supernovae.

(c) With the first observation of binary neutron star inspiral at Advanced LIGO and Advanced Virgo, one can infer the tidal deformability parameter, which is also related to the neutron star EOS and to the neutron skin.

(d) Information on the nuclear neutron density radius is also important for a precise determination of the background due to coherent elastic neutrino-nucleus scattering in dark matter detectors (e.g., 133Cs and 127I have similar atomic and mass numbers to that of Xenon).

Neutrino charge radius

Neutrino electromagnetic properties and interactions:

$$\Lambda_\lambda(q) = \left(\gamma_\lambda - \frac{q_\lambda \not{q}}{q^2}\right)\left[f_Q(q^2) + f_A(q^2) q^2 \gamma^5\right] - i\sigma_{\lambda\rho} q^\rho \left[f_M(q^2) + i f_E(q^2)\gamma^5\right]$$

charge, anapole, magnetic, and electric neutrino form factors

(1) Electric charge quantization requires neutrinos to be electrically neutral particles

(2) The electrically neutral neutrinos could still have non-trival charge structures: charge radius (see for example 1703.00401)

$$\langle r_\nu^2 \rangle = 6 \left. \frac{d f_Q(q^2)}{dq^2} \right|_{q^2=0}$$

(3) For ultra-relativistic neutrinos, the anapole part only changes a sign because of gamma(5), according to the neutrino chirality.

Neutrino radii for 3-neutrino mixing

Generalize to a 3 x 3 matrix to describe the neutrino radii

For CEνNS:

$$\frac{d\sigma_{\nu_\ell\text{-}\mathcal{N}}}{dT}(E,T) \simeq \frac{G_F^2 M}{\pi}\left(1-\frac{MT}{2E^2}\right)\left\{\left[\left(g_V^p + \tilde{Q}_{\ell\ell}\right) Z F_Z(q^2) + g_V^n N F_N(q^2)\right]^2 + Z^2 F_Z^2(q^2) \sum_{\ell'\neq\ell} |\tilde{Q}_{\ell'\ell}|^2\right\},$$

with

$$g_V^p = \frac{1}{2} - 2\sin^2\vartheta_W, \qquad g_V^n = -\frac{1}{2},$$

$$\tilde{Q}_{\ell\ell'} = \sum_{j,k} U_{\ell j}^* U_{\ell' k} \tilde{Q}_{jk} = \frac{2\sqrt{2}\pi\alpha}{G_F}\left[\frac{(e_\nu)_{\ell\ell'}}{q^2} + \frac{\langle r_\nu^2\rangle_{\ell\ell'}}{6}\right] = 4 m_W^2 \sin^2\vartheta_W \left[\frac{(e_\nu)_{\ell\ell'}}{q^2} + \frac{\langle r_\nu^2\rangle_{\ell\ell'}}{6}\right].$$

Because we do not measure the neutrino final state:

$$\nu_\ell + \mathcal{N} \to \sum_{\ell'} \nu_{\ell'} + \mathcal{N}. \qquad \sin^2\vartheta_W \to \sin^2\vartheta_W - \frac{\sqrt{2}\pi\alpha}{6 G_F}\langle r_\nu^2\rangle_{\ell\ell}.$$

(1) For $\ell' = \ell$, the neutrino charge radii contribution will interfere with the weak interaction process and so they contribute coherently.

(2) For $\ell' \neq \ell$, these channels do not interfere and contribute incoherently.

$$\chi^2 = 2\sum_{i,j=1}^{12}\Bigg[(1+\alpha)\,N_{ij}^{\rm th} + (1+\beta)\,B_{ij} + (1+\gamma)\,\mu_i^{\rm AC}(t_j^{\rm C}) - N_{ij}^{\rm C} + N_{ij}^{\rm C}\ln\left(\frac{N_{ij}^{\rm C}}{(1+\alpha)\,N_{ij}^{\rm th} + (1+\beta)\,B_{ij} + (1+\gamma)\,\mu_i^{\rm AC}(t_j^{\rm C})}\right)\Bigg] + \left(\frac{\alpha}{\sigma_\alpha}\right)^2 + \left(\frac{\beta}{\sigma_\beta}\right)^2 + \left(\frac{\gamma}{\sigma_\gamma}\right)^2,$$

From AC data

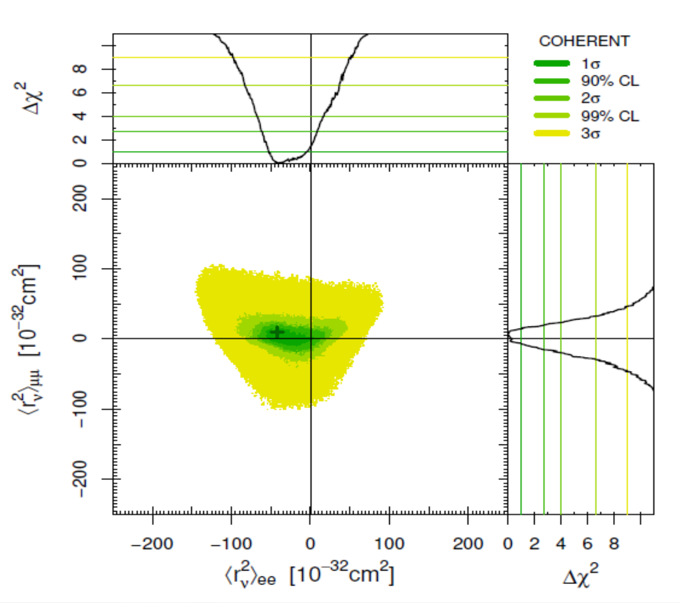
In the new data release: 1804.09459

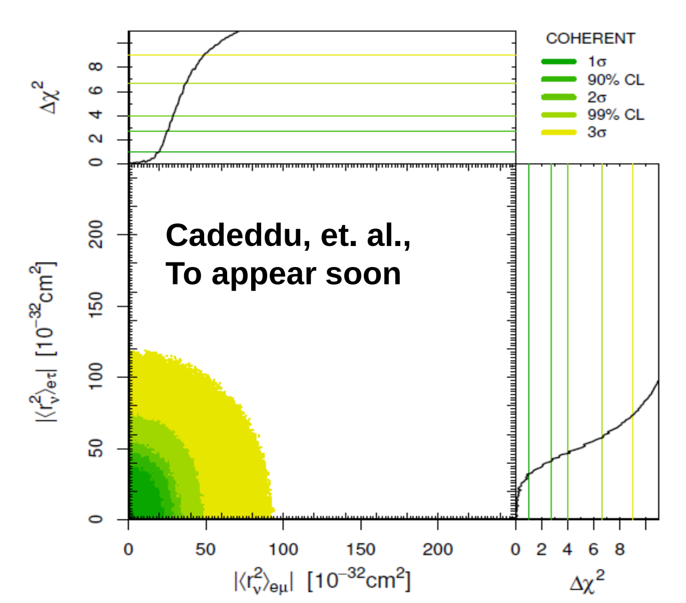
Signal: 28% **Background: 25%**

Neutrino radii Limits

in units of 10^{-32} cm^2.

	Best Fit	1σ	2σ	3σ
$\langle r_\nu^2 \rangle_{ee}$	-42.00	$-52.00 \div -5.00$	$-67.00 \div 16.00$	$-98.00 \div 51.00$
$\langle r_\nu^2 \rangle_{\mu\mu}$	10.00	$-6.00 \div 14.00$	$-19.00 \div 23.00$	$-46.00 \div 46.00$
$\langle r_\nu^2 \rangle_{e\mu}$	2.00	< 20.00	< 28.00	< 48.00
$\langle r_\nu^2 \rangle_{e\tau}$	1.00	< 32.00	< 46.00	< 73.00
$\langle r_\nu^2 \rangle_{\mu\tau}$	1.00	< 22.00	< 33.00	< 56.00





Conclusion:

Up to the size of ~10^{-16} cm, neutrinos are still point-like particles.

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 with high precision.

CEνNS will become an interesting tool for:
neutron form factors and neutrino radii,
tests of SM and new physics

→ very interesting potential of CEνNS

Thanks!

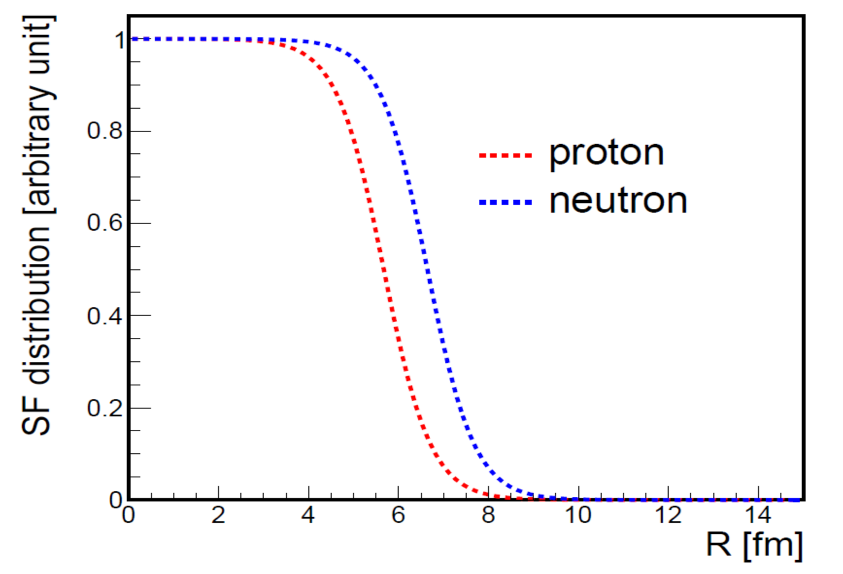
Description of form factors

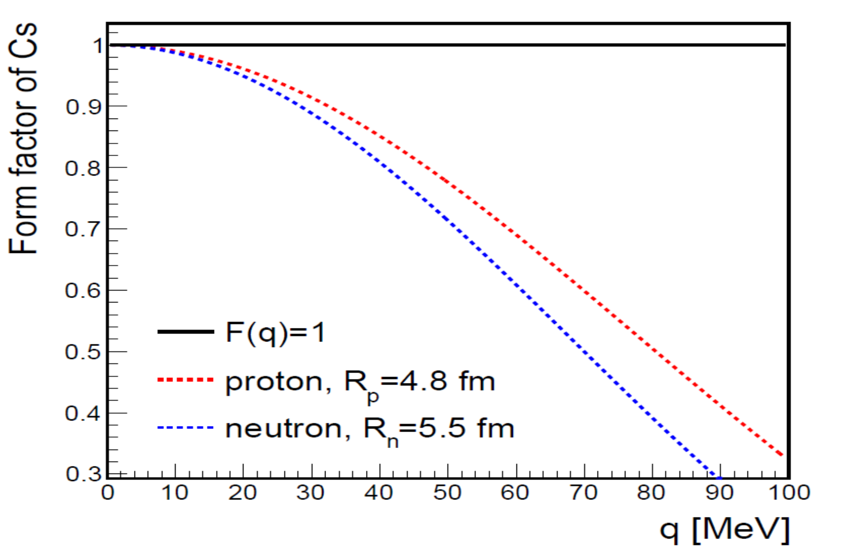
$$\rho_{\mathrm{F}}(r) = \frac{\rho_0}{1 + e^{(r-c)/a}},$$

$$\rho_{\mathrm{SF}}(r) = \rho_{\mathrm{F}}(r) + \rho_{\mathrm{F}}(-r) - 1$$

$$F_Z^{\mathrm{SF}}(q^2) = \frac{3}{qc\left[(qc)^2 + (\pi qa)^2\right]}\left[\frac{\pi qa}{\sinh(\pi qa)}\right] \times \left[\frac{\pi qa \sin(qc)}{\tanh(\pi qa)} - qc\cos(qc)\right].$$

$$F_N^{\mathrm{Helm}}(q^2) = 3\,\frac{j_1(qR_0)}{qR_0}\,e^{-q^2 s^2/2},$$

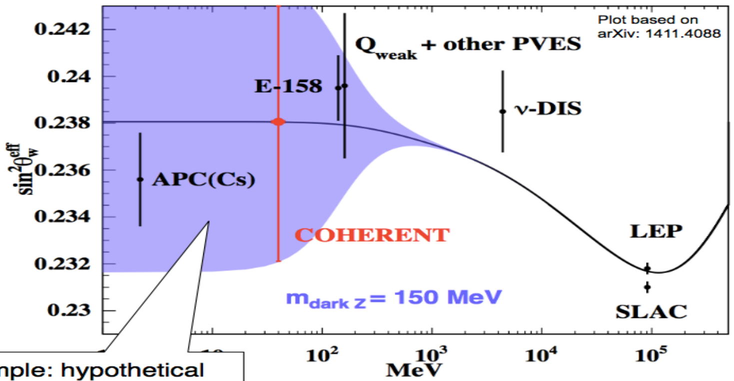




Implication: weak mixing angle

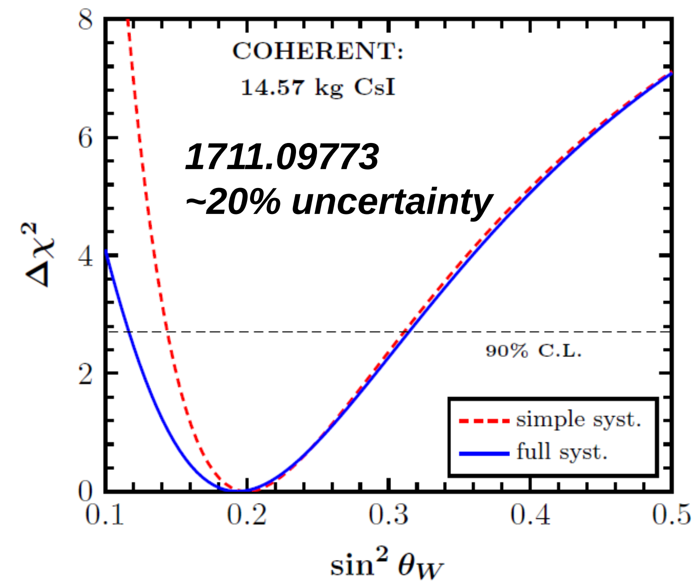
Clean SM prediction for the rate ➔ measure $\sin^2\theta_W$eff ;
deviation probes new physics

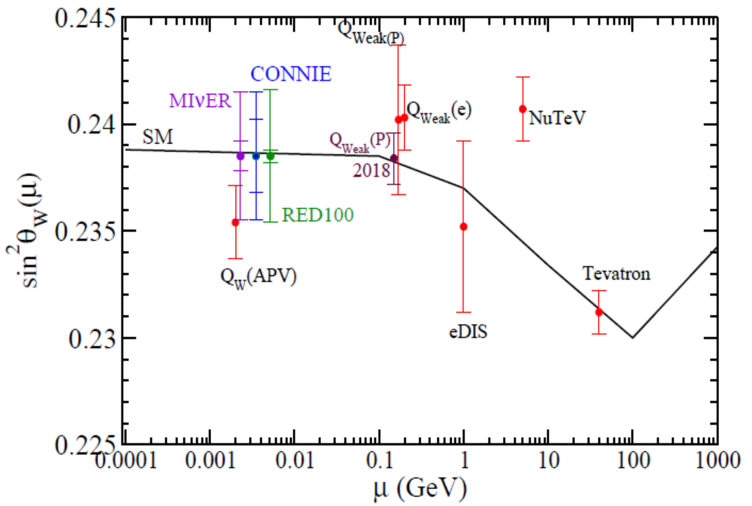
$$\sigma \sim \frac{G_f^2 E^2}{4\pi}\left(N - (1 - 4\sin^2\theta_W)Z\right)^2$$

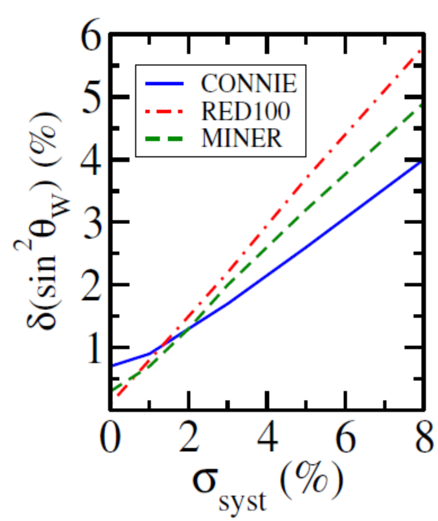


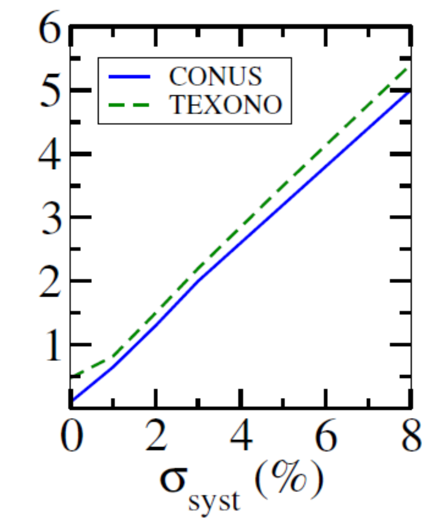
Example: hypothetical dark Z mediator (explanation for g-2 anomaly)

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









Implication: beyond SM (NSI as an example)

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

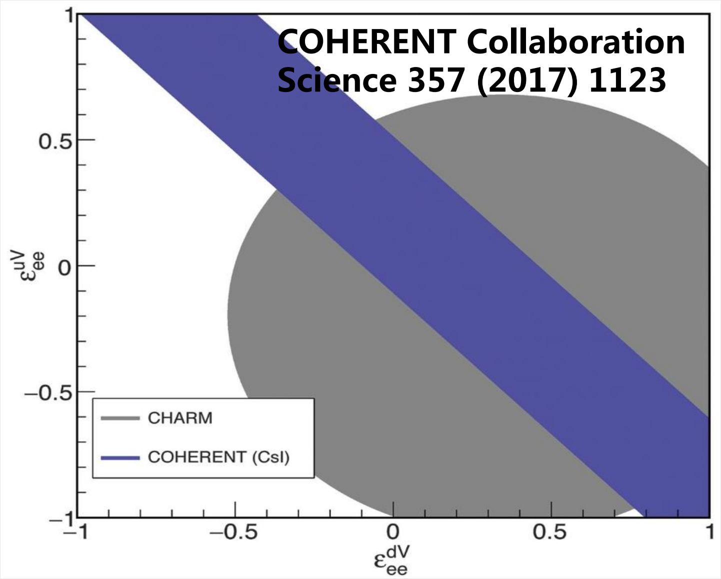
$$\mathcal{L}_{NSI} \simeq \epsilon_{\alpha\beta} 2\sqrt{2} G_F (\bar{\nu}_{L\beta}\, \gamma^\rho\, \nu_{L\alpha})(\bar{f}_L \gamma_\rho f_L)$$

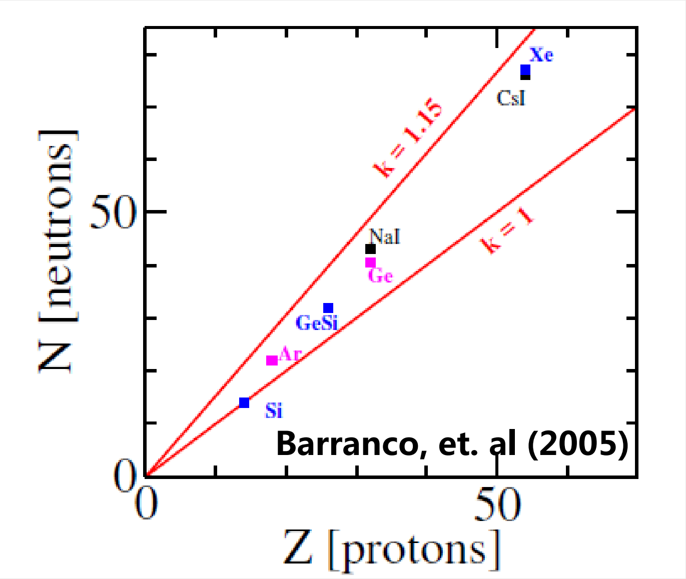
$$|\epsilon| \simeq \frac{M_W^2}{M_{NSI}^2}$$

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

0.01 in epsilon ←→ TeV scale

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





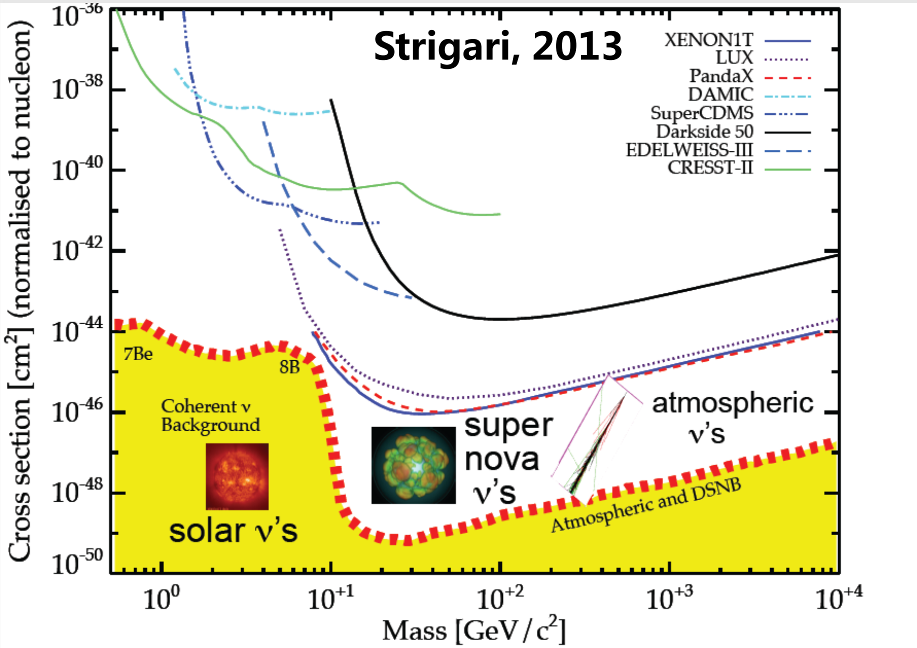
$$G_V = \left[\left(g_V^p + 2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV}\right) Z + \left(g_V^n + \varepsilon_{ee}^{uV} + 2\varepsilon_{ee}^{dV}\right) N\right] F_{nucl}^V(Q^2)$$

Implication: astrophysics

DM connection

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

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

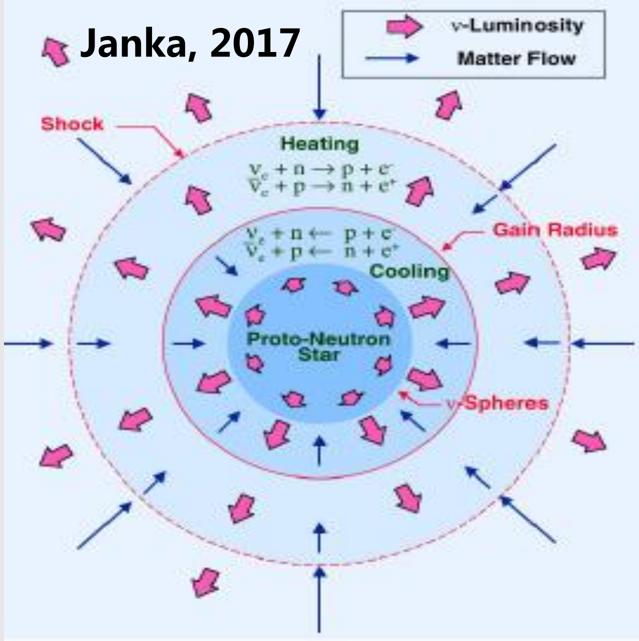


Measure CEvNS to understand nature of background/astro signal

Supernovae

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

2) CEνNS for detecting supernova neutrinos.

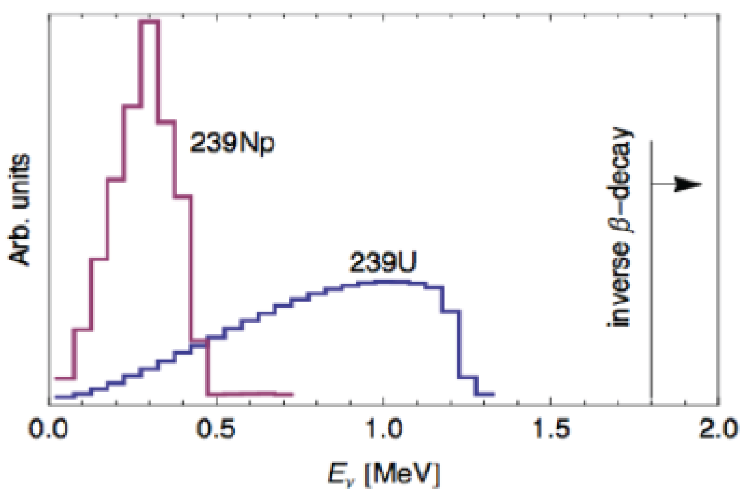


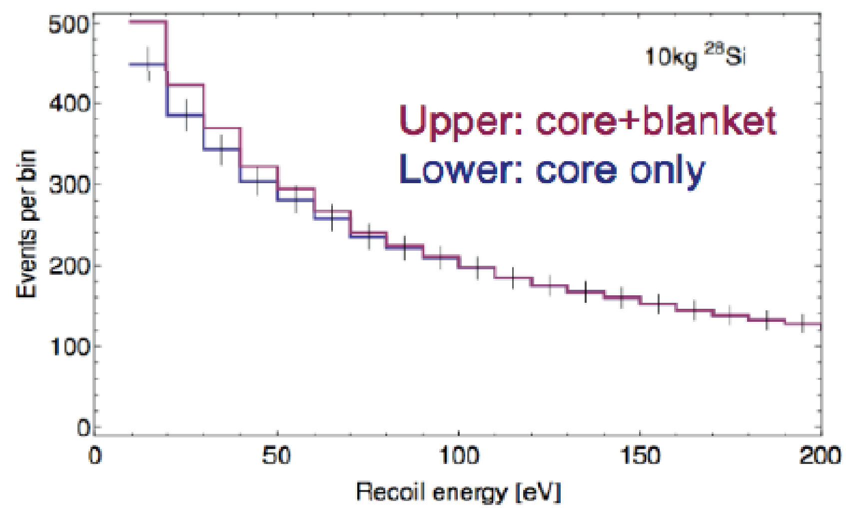
Implication: reactor monitoring

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