Coherent neutrino scattering

Evgeny Akhmedov

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Plan of the lecture

- Coherent elastic neutrino-nucleus scattering and its first observation
- Why is CEvNS interesting? What can we learn?
- Can one achieve coherent neutrino scattering on macroscopic scales?
- How can we improve theoretical description of CEvNS?

Many interesting talks on CEvNS: Workshop “The Magnificent CEvNS”, Chicago, Now. 2-2, 2018.
Slides of the talks at https://kicp-workshops.uchicago.edu/2018-CEvNS/program.php

Coherent elastic neutrino-nucleus scattering

NC – mediated neutrino-nucleus scattering:

$$\nu + A \to \nu + A$$

Incoherent scattering – Probabilities of scattering on individual nucleons add:

$\diamondsuit$ $\sigma \propto (\#$ of scatterers$)$

Coherent scattering on nucleus as a whole – Amplitudes of scattering on individual nucleons add

$\diamondsuit$ $\sigma \propto (\#$ of scatterers$)^2$

Significant increase of the cross sections (but requires small momentum transfer, $q \lesssim R^{-1}$)

(D.Z. Freedman, 1974)

Coherent neutrino nucleus scattering: Predictions & Implications

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)

If there is a weak neutral current, then the elastic scattering process $\nu + A \to \nu + A$ should have a sharp coherent forward peak just as $e + A \to e + A$ does. Experiments to observe this peak can give important information on the isospin structure of the neutral current. The experiments are very difficult, although the estimated cross sections (about 10^{-38} cm^2 on carbon) are favorable. The coherent cross sections (in contrast to incoherent) are almost energy-independent. Therefore, energies as low as 100 MeV may be suitable. Quasi-coherent nuclear excitation processes $\nu + A \to \nu + A^*$ provide possible tests of the conservation of the weak neutral current. Because of strong coherent effects at very low energies, the nuclear elastic scattering process may be important in inhibiting cooling by neutrino emission in stellar collapse and neutron stars.

- Implications for neutrino transport in supernovae
- Large cross section important for understanding how neutrinos emerge from supernovae

THE WEAK NEUTRAL CURRENT AND ITS EFFECTS IN STELLAR COLLAPSE

Daniel Z. Freedman
Institute for Theoretical Physics, State University of New York at Stony Brook, Stony Brook, New York 11790

David N. Schramm[1] *and David L. Tubbs*[2]
Enrico Fermi Institute (LASR), University of Chicago, Chicago, Illinois 60637

NC-induced neutrino-nucleus scattering: flavour blind.

$$\diamondsuit \quad \left[\frac{d\sigma_{\nu A}}{d\Omega}\right]_{\rm coh} \simeq \frac{G_F^2}{16\pi^2} E_\nu^2 [Z(4\sin^2\theta_W - 1) + N]^2 \, (1 + \cos\theta) |F(\vec{q}^{\,2})|^2$$

$F(\vec{q}^{\,2})$ is nuclear formfactor:

$$F_{N(Z)}(\vec{q}^{\,2}) = \frac{1}{N(Z)} \int d^3x \rho_{N(Z)}(\vec{x}) e^{i\vec{q}\vec{x}}, \qquad \vec{q} = \vec{k} - \vec{k}'.$$

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For $q \ll R^{-1} \quad \Rightarrow \quad F(\vec{q}^{\,2}) = 1, \quad \left[d\sigma_{\nu A}/d\Omega\right]_{\rm coh} \propto N^2$.

For $q \gg R^{-1}$: $\quad F(\vec{q}^{\,2}) \ll 1$.

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By Heisenberg uncertainty relation: for $q \lesssim R^{-1}$ the uncertainty of the coordinate of the sctatterer $\delta x \gtrsim R \quad \Rightarrow$ it is in principle impossible to find out on which nucleon the neutrino has scattered. Also: neutrino waves scattered off different nucleons of the nucleus are in phase with each other.

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The necessary conditions for coherent scattering!

CEvNS: nuclear recoil

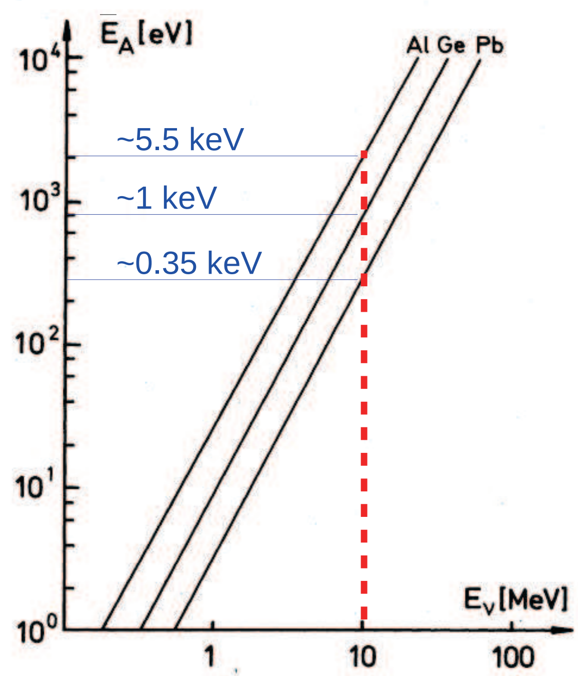
Nuclear recoil energy:

- Observable of CEvNS process: recoil energy of struck nucleus
- No threshold (like for inverse beta-decay, IBD)
- Scaling of nuclear recoil energy:

$$E_{rec}^{max} = \frac{2 \cdot E_\nu^2}{m_n \cdot A + 2 \cdot E_\nu} \approx \frac{2 \cdot E_\nu^2}{m_n \cdot A}$$

with: - m_n: nucleon mass; ≈939 MeV/c^2
- A: atomic number; A=N+Z

$$\langle E_{rec} \rangle = \frac{2}{3} \cdot \frac{E_\nu^2}{m_n \cdot A}$$



A.Drukier, L.Stodolsky, Phys.Rev.D 30 (1984) 11

→ **push-pull situation**: $\sigma_{\nu A}^{tot} \propto \mathbf{N}^2$ vs. $E_{rec} \propto \frac{1}{(N+Z)}$

→ low recoil energy responsible for CEvNS not been detected so far

$$R \simeq 1.2 \text{ fm } A^{1/3}; \quad A \sim 130 \quad \Rightarrow \quad R^{-1} \sim 30 \text{ MeV}.$$

Recoil energy of the nucleus:

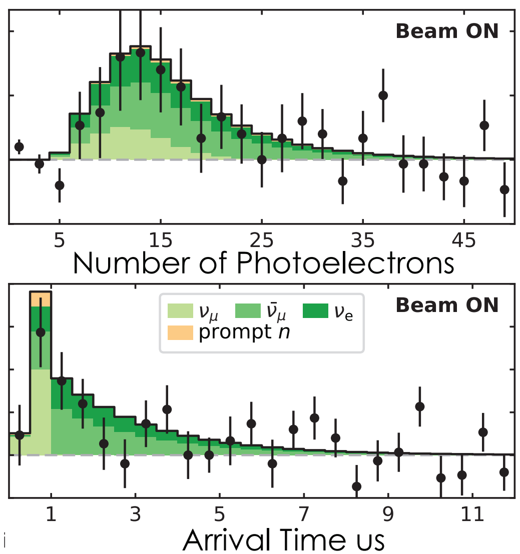
$$E_{rec} \simeq \frac{\vec{q}^{\,2}}{2M_A}, \qquad E_{rec}^{max} = \frac{2E_\nu^2}{M_A + 2E_\nu} \simeq \frac{2E_\nu^2}{M_A}.$$

For $q \sim 30$ MeV: $E_{rec} \sim 5$ keV.

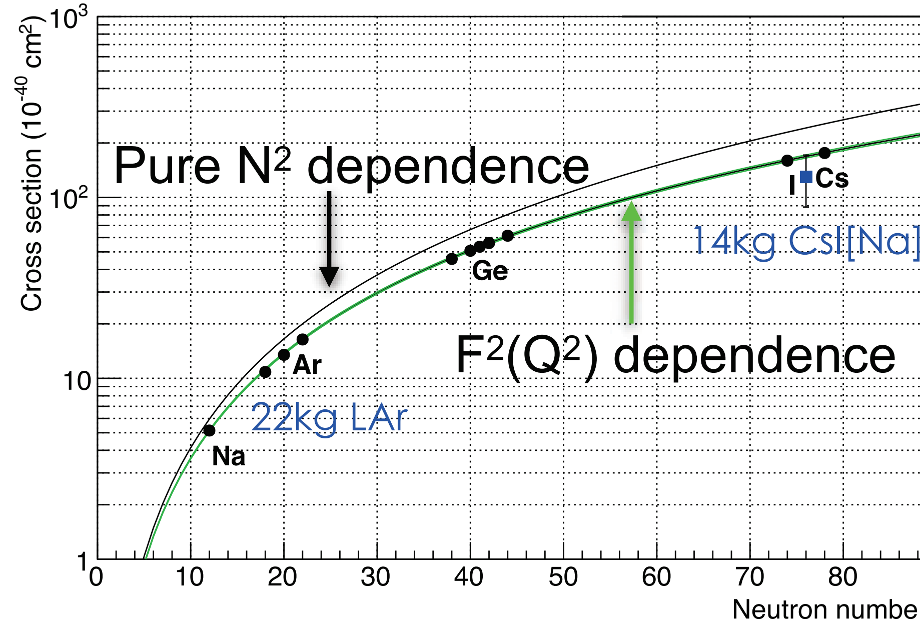
Need to detect very low recoil energies $\Rightarrow$ requires

- Very low detection thresholds
- Low backgrounds
- Intense neutrino fluxes

First Observation of CEvNS



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



First light detectors deployed to measure neutron-squared dependence. (Na, Ge in 2019)

High precision measurements enable the full potential of CEvNS scientific impact.

OAK RIDGE National Laboratory Jason Newby, Magnificent CEvNS Workshop 2018

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COHERENT experiment

Neutrino energies: $E_\nu \sim 16 - 53\ \mathrm{MeV}$. Nuclear recoil energy: keV - scale.

# of events expected (SM): 173 $\pm$ 48

# of events detected: 134 $\pm$ 22

"We report a 6.7 sigma significance for an excess of events, that agrees with the standard model prediction to within 1 sigma"
$\sim 2 \times 10^{23}$ POT; $\sigma \sim 10^{-38}$ cm^2.

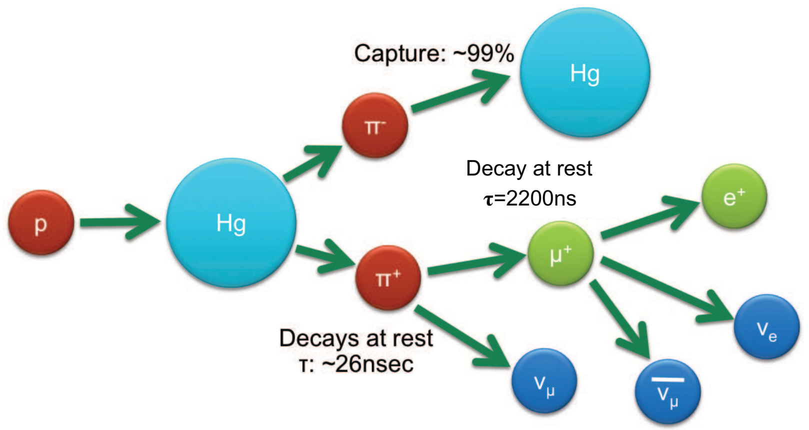
D. Akimov et al., Science 10.1126/science.aao0990 (2017).

Systematic Uncertainties of the CEvNS observation

Uncertainties on CsI signal and background predictions	
Event selection (signal acceptance)	5%
Form Factor	5%
Neutrino Flux	10%
Quenching factor	25%
Total uncertainty on signal	**28%**

All uncertainties except neutrino flux are detector specific and could be much less for other technologies

SNS produces pions via π decay at rest

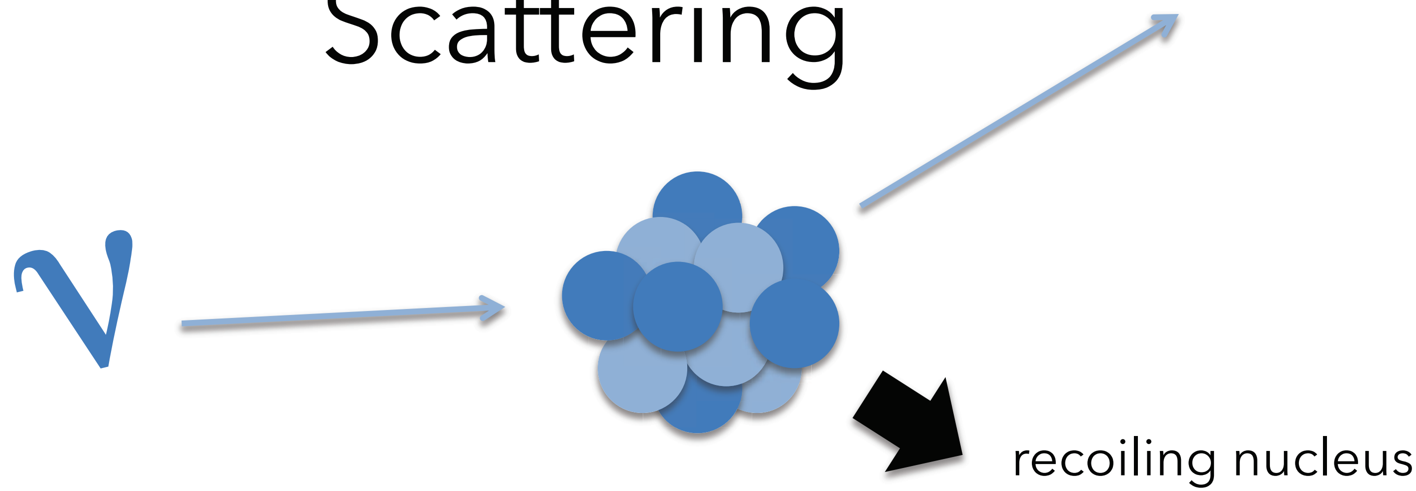


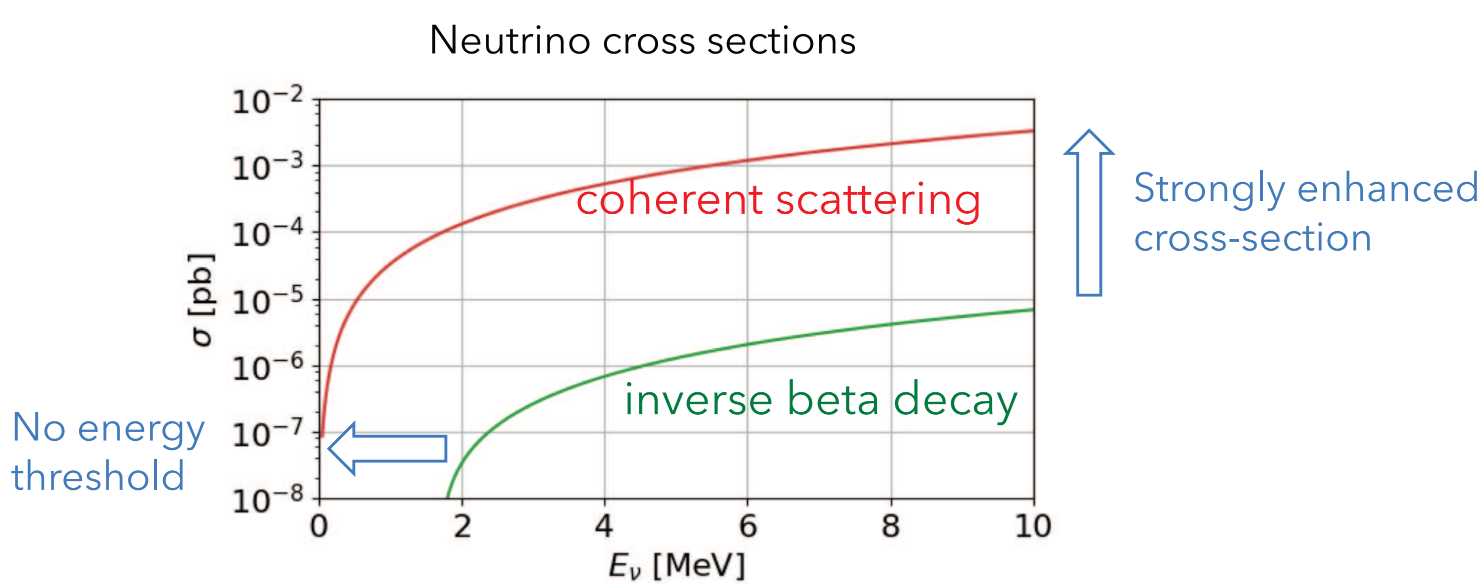
- Largest uncertainty is pion production from p+Hg
- 10% discrepancy between Bertini and LAHET calculations

To unlock high precision CEvNS program, we need to calibrate SNS neutrino flux

8 Oak Ridge National Laboratory Jason Newby, Magnificent CEvNS Workshop 2018

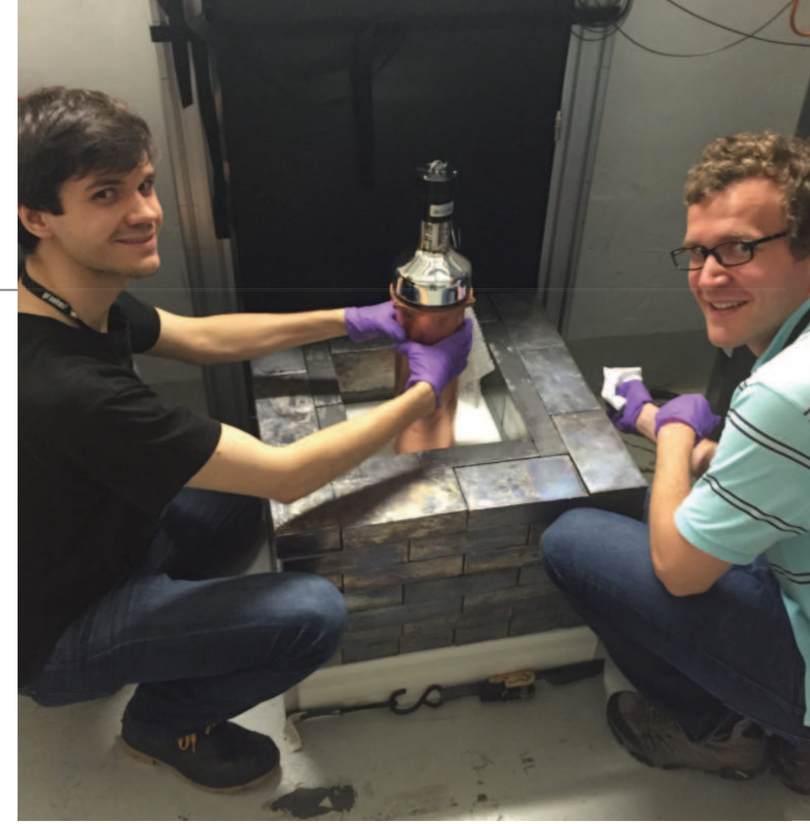
Coherent Neutrino-Nucleus Scattering

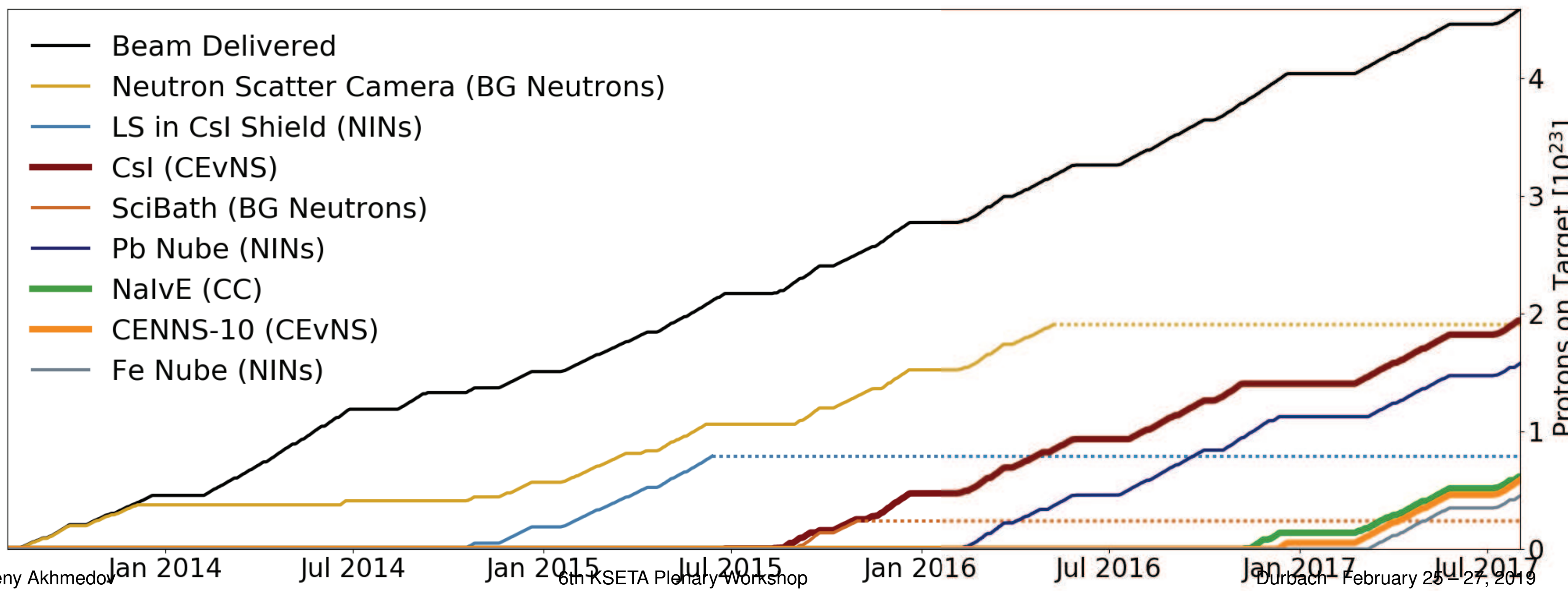




A hand-held neutrino detector

- 14.6 kg low-background CsI[Na] detector deployed to a basement location of the SNS in the summer of 2015
- ~ 2×10^{23} POT delivered and recorded since CsI began taking data





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Why is CEvNS interesting?

- Large cross sections – small detectors
- Very clean SM predictions for cross sections – sensitivity to NSI
- Sensitivity to μ_ν and $\langle r_\nu^2 \rangle$
- Possibility to measure $\sin^2\theta_W$ at low energies
- Masurements of neutron formfactors (nuclear structure)
- Nuclear reactor monitoring (non-proliferation)
- Precision flavor-independent neutrino flux measurements for oscillation experiments
- Sterile neutrino searches
- Energy transport in SNe
- SN neutrino detection
- Input for DM direct detection (neutrino floor)
- Detection of solar neutrinos

Why is CEvNS interesting?

Many experiments planned or under way – CONUS, TEXONO, Ricochet, Connie, ν-cleus, RED100, MINER, νGEN, ...

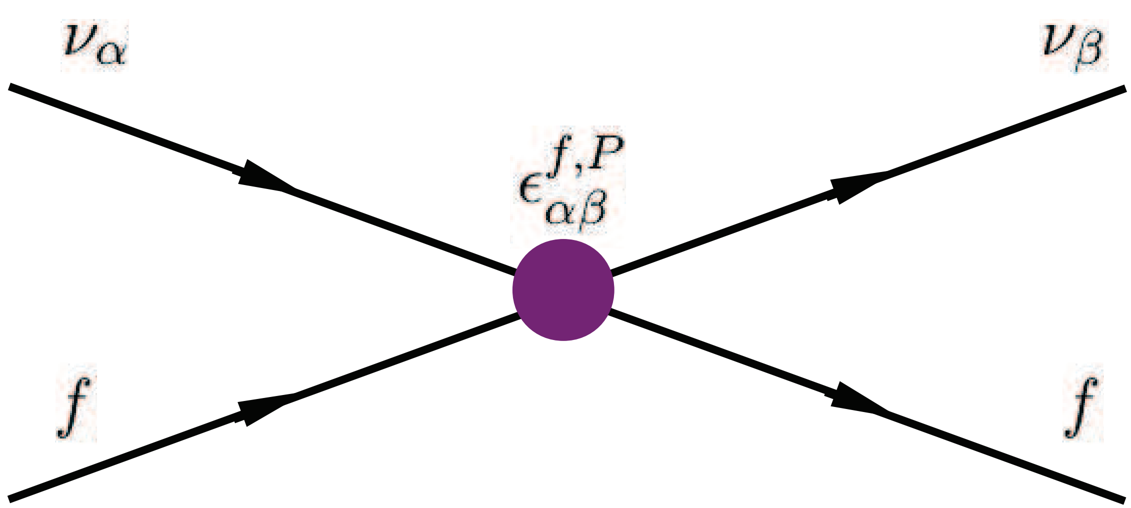
Many theoretical studies

A very active field!

NSI parameterization

P. Coloma. P.B. Denton, M.C. Gonzalez-Garcia, M. Maltoni, T. Schwetz,
”Curtailing the Dark Side in Non-Standard Neutrino Interactions”, arXiv:1701.04828

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \epsilon_{\alpha\beta}^{f,P} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P f)$$



Assuming heavy NSI mediators

CEvNS cross section and NSI

J. Barranco, O.G. Miranda, T.I. Rashba,
"Probing new physics with coherent neutrino scattering off nuclei", arXiv:hep-ph/0508299

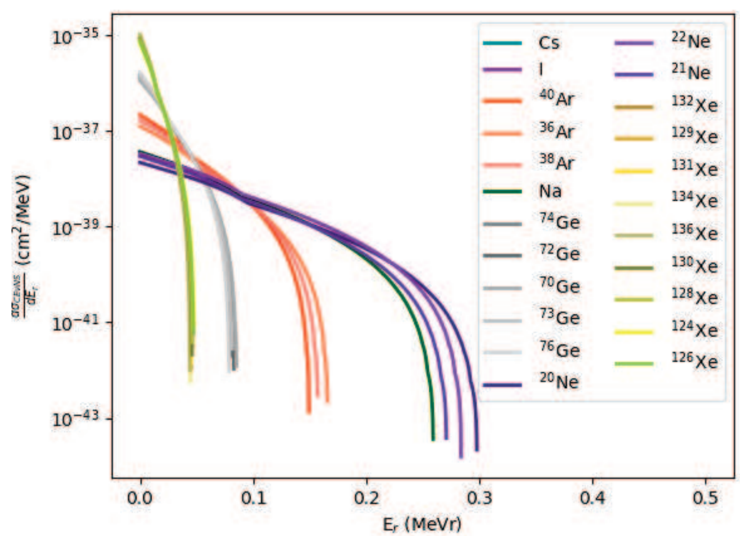
$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{2\pi} F^2(Q) \left[(G_V + G_A)^2 + (G_V - G_A)^2 \left(1 - \frac{T}{E_\nu}\right)^2 - (G_V^2 - G_A^2)\frac{MT}{E_\nu^2} \right]$$

$$G_V = (g_V^p + \boxed{2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV}})Z + (g_V^n + \boxed{\varepsilon_{ee}^{uV} + 2\varepsilon_{ee}^{dV}})N$$

NSI terms

$$G_A = (g_A^p + 2\varepsilon_{ee}^{uA} + \varepsilon_{ee}^{dA})(Z_+ - Z_-) + (g_A^n + \varepsilon_{ee}^{uA} + 2\varepsilon_{ee}^{dA})(N_+ - N_-) \approx 0$$

- Modification = $\frac{\sigma(\varepsilon)}{\sigma^{SM}}$



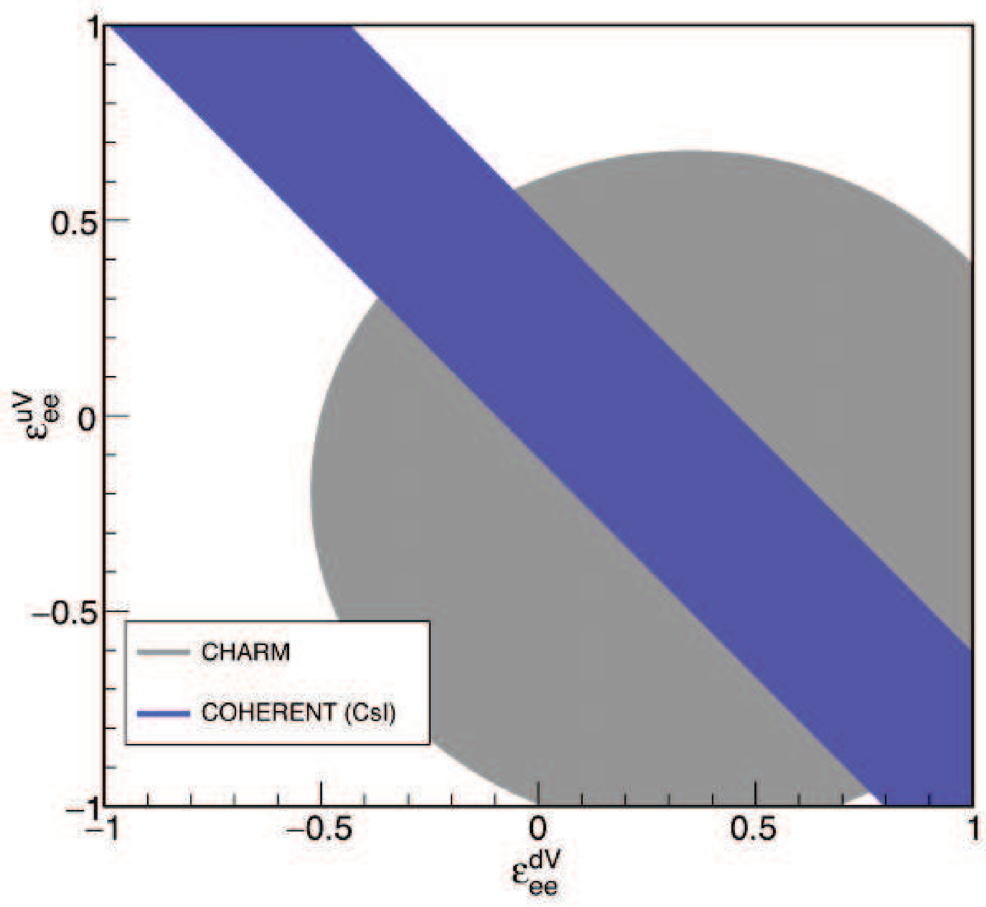
SM diff σ weighted by piDAR spectra

Magnificent CEvNS 2018/11/02 Gleb Sinev, Duke Constraining NSI with Multiple Targets 10

D. Akimov, J.B. Albert, P. An, et al.,
”Observation of Coherent Elastic Neutrino-Nucleus Scattering”, arXiv:1708.01294

COHERENT NSI constraint

- August 2017 result
- 14.6 kg CsI[Na]
- ~2 years running
  - 308.1 live-days
- Events
  - 134 ± 22 observed
  - 173 ± 48 predicted



Why straight lines for SM rate?

J. Barranco, O.G. Miranda, T.I. Rashba,
"Probing new physics with coherent neutrino scattering off nuclei", arXiv:hep-ph/0508299

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

$$G_V = (g_V^p + 2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV})Z + (g_V^n + \varepsilon_{ee}^{uV} + 2\varepsilon_{ee}^{dV})N \qquad G_A \approx 0$$

SM rate: $G_V^{SM} = g_V^p Z + g_V^n N$

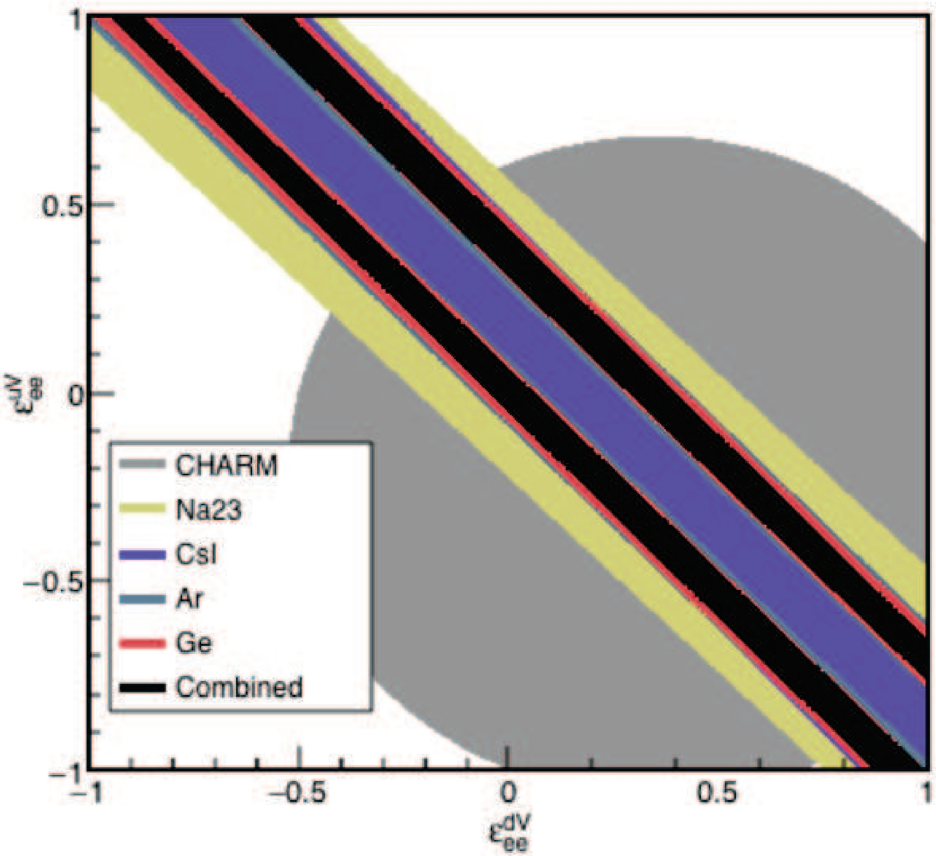
$$\frac{d\sigma^{SM}}{dT} = \frac{d\sigma}{dT}(G_V^{SM}) \quad \rightarrow \quad {G_V^{SM}}^2 = G_V^2$$

$$(g_V^p + 2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV})Z + (g_V^n + \varepsilon_{ee}^{uV} + 2\varepsilon_{ee}^{dV})N = \pm (g_V^p Z + g_V^n N)$$

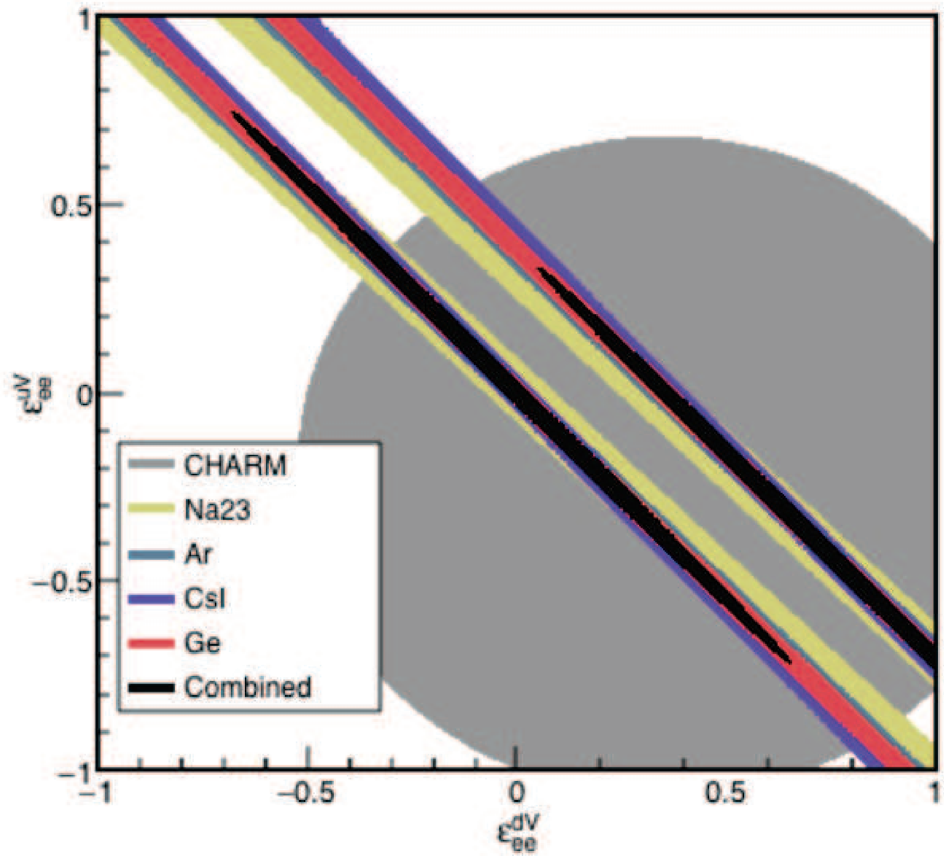
Generating two straight lines in NSI-coupling space with SM rate

Future COHERENT NSI constraints

after ~3 years



reduced systematical, negligible statistical errors



D. Akimov, J.B. Albert, P. An, et al., ”COHERENT 2018 at the Spallation Neutron Source”, arXiv:1803.09183

Including magnetic moment scattering

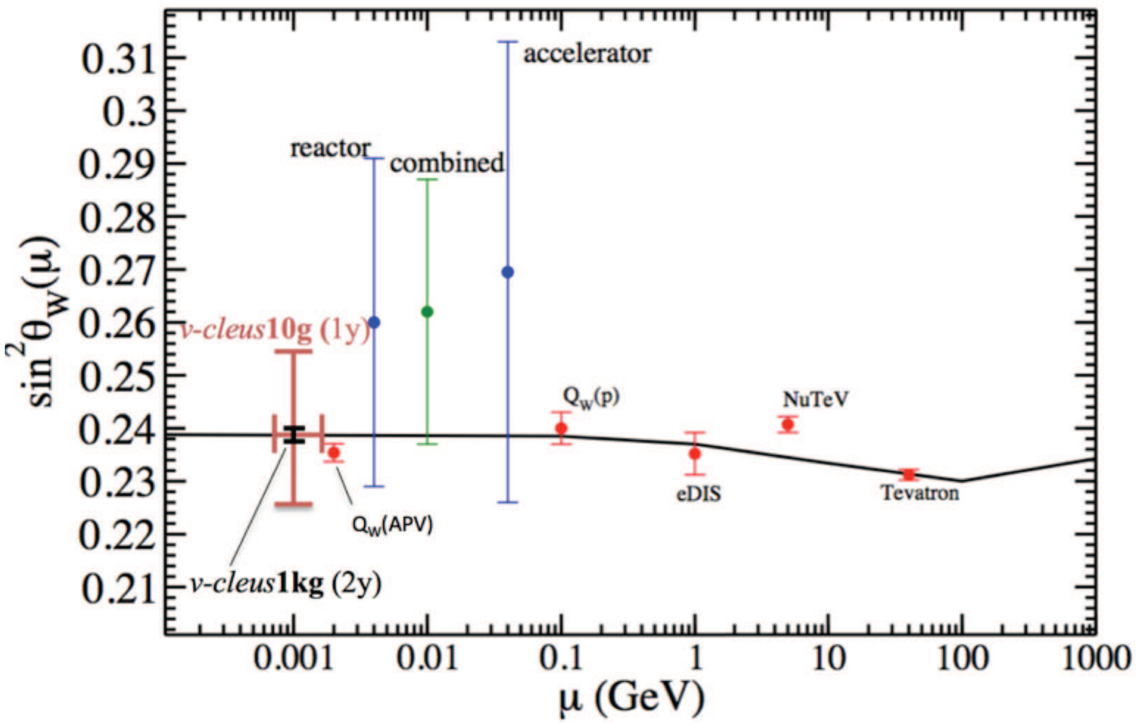
$$\frac{d\sigma}{dT} = \frac{G_F^2}{8\pi} M \left[2 - \frac{2T}{T_{max}} + \left(\frac{T}{E}\right)^2\right] Q_W^2 [F_Z(Q^2)]^2 + \frac{\pi\alpha^2\mu_{\rm eff}^2 Z^2}{m_e^2}\left[\frac{1}{T} - \frac{1}{E}\right][F_\gamma(Q^2)]^2$$

$$\mu_{\rm eff}^2 = \sum_i \left|\sum_j U_{(e\,{\rm or}\,\mu)j}\; e^{-iE_jL}\mu_{ji}\right|^2$$

Note that this is a different combination at CEνNS than what is measured at reactors or solar neutrino experiments!

Weinberg Angle

"Running" of Weinberg Angle



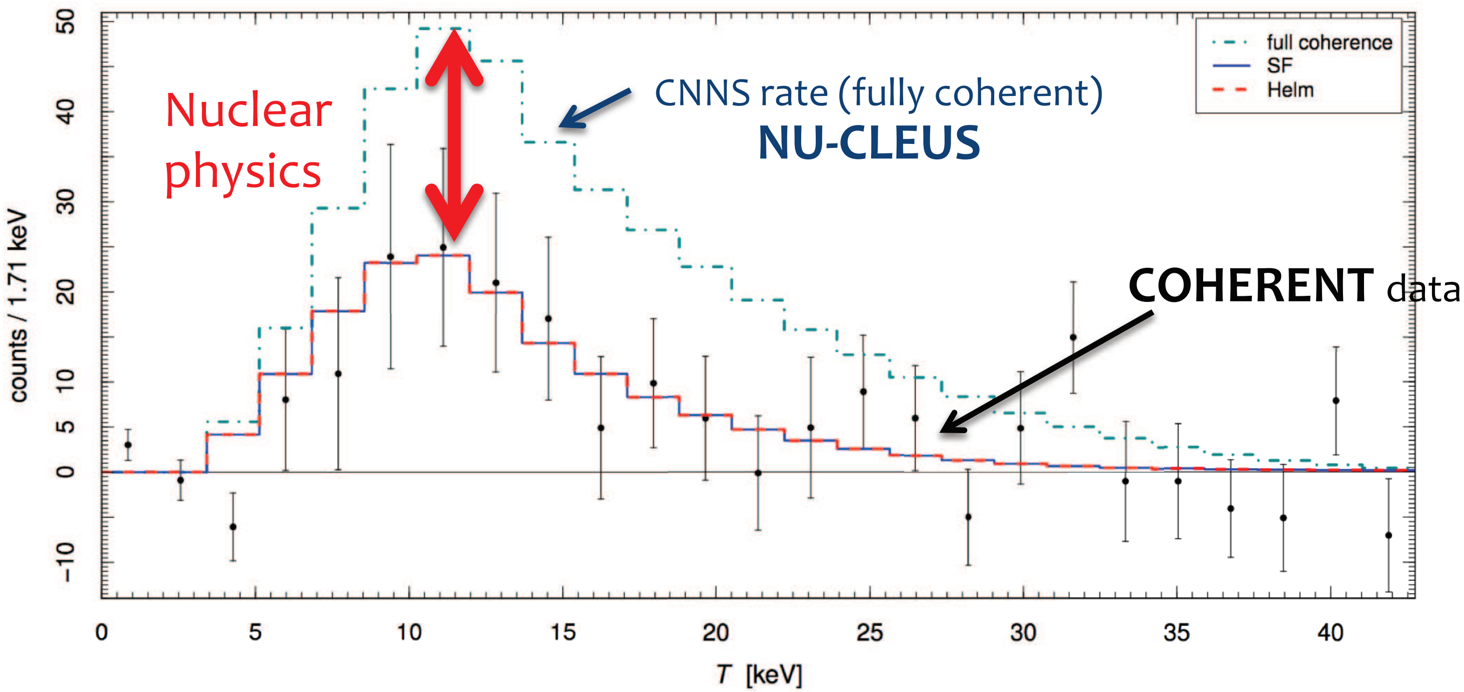
$$\left(\frac{d\sigma}{dE}\right)_{\nu_\alpha A} = \frac{G_F^2 M}{\pi} F^2(2ME)\left[1 - \frac{ME}{2k^2}\right] \times$$
$$\{[Z(g_V^p + 2\varepsilon_{\alpha\alpha}^{uV} + \varepsilon_{\alpha\alpha}^{dV}) + N(g_V^n + \varepsilon_{\alpha\alpha}^{uV} + 2\varepsilon_{\alpha\alpha}^{dV})]^2$$

With $g_V^p = (\frac{1}{2} - 2\sin^2\theta_W)$ and $g_V^n = -\frac{1}{2}$

First determination of the Weinberg angle at q = 1MeV/c after 2-3 weeks of measurement with 10g!

Nuclear physics: Neutron rms

Phys. Rev. Lett. **120** 071501, arXiv:1710.02730



$$R_n = 5.5^{+0.9}_{-1.1}\,\text{fm.} \qquad \Delta R_{np} \simeq 0.7^{+0.9}_{-1.1}\,\text{fm.}$$

Evaluation of the form factors (Other effective methods)

The Helm form factor can be estimated from effective expressions like

$$F_Z(\mathbf{q}^2) = \frac{3 j_1(|\mathbf{q}| R_0)}{|\mathbf{q}| R_0} \exp\left[-\frac{1}{2}(|\mathbf{q}| s)^2\right] ,$$

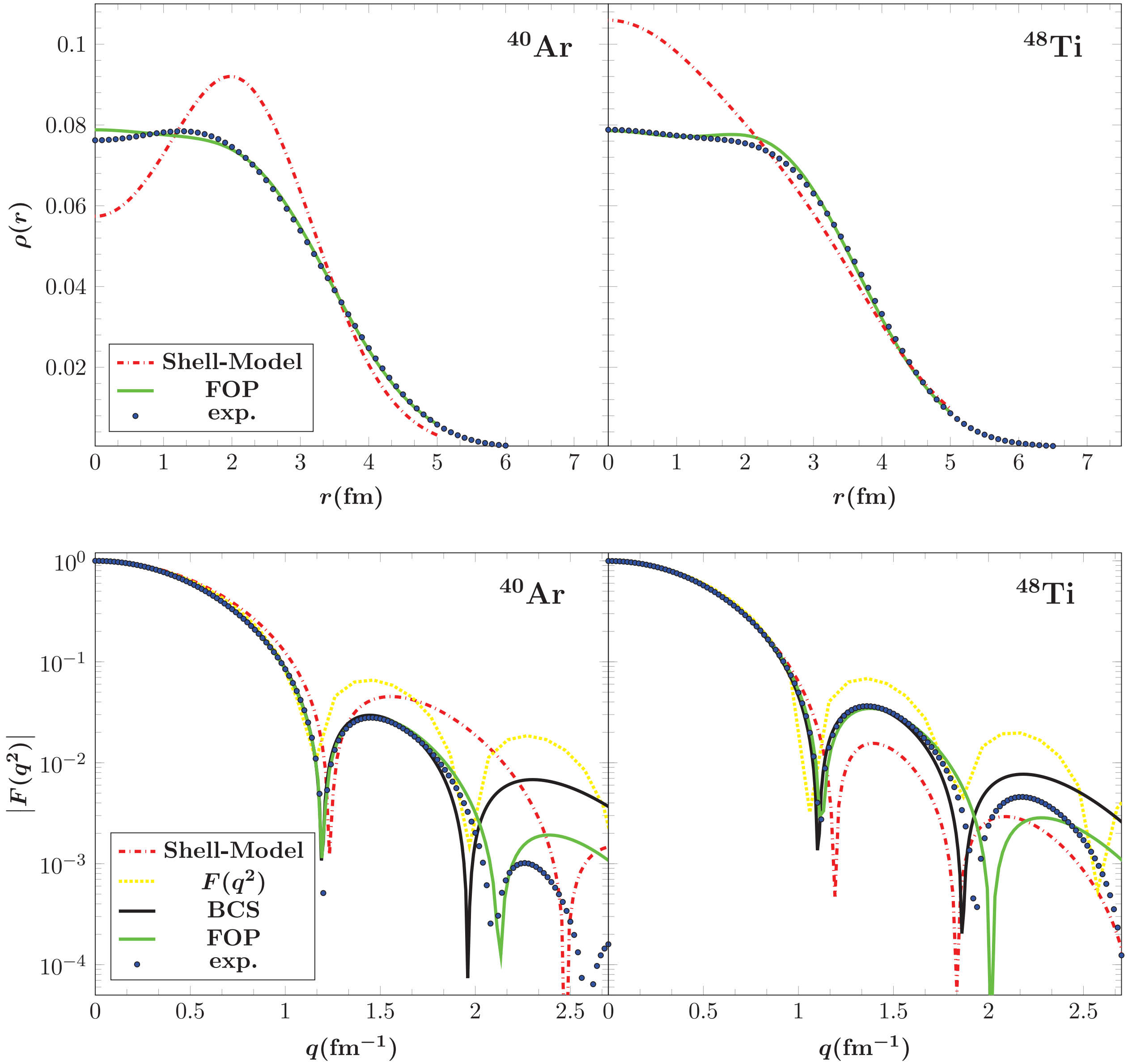
J. Engel, Phys.Lett. **B 264** (1991) 114

- $j_1(x)$ is the known first-order Spherical-Bessel function and $R_0^2 = R^2 - 5s^2$,
- R radius of the nucleus
- s surface thickness of the nucleus (of the order of $0.5\,\mathrm{fm}$).

The radius parameter is usually given from the semi-empirical formula $R = 1.2\,A^{1/3}\,\mathrm{fm}$.

Comparison of the nuclear methods

D.K. Papoulias and T.S. Kosmas, Adv.High Energy Phys. **2015** (2015) 763648

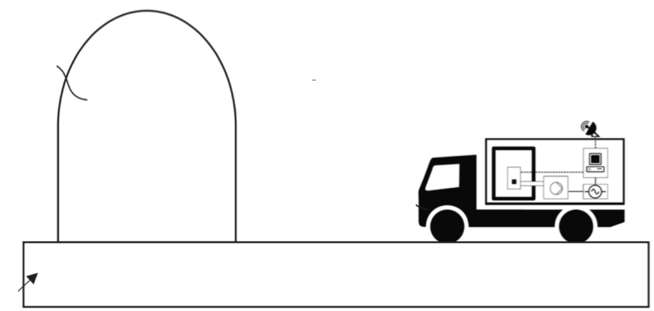


Application of NU-CLEUS Technology

Mobile cryogenic detector

Use neutrinos to monitor nuclear reactors

Surveillance of power plants world-wide



IAEA
International Atomic Energy Agency
Atoms for Peace

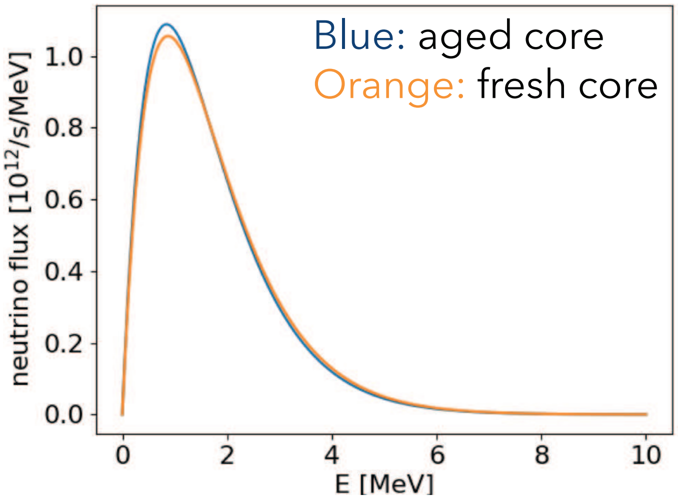
Nuclear non-proliferation

e.g. Phys. Rev. Lett. 113, 042503 (2014)

Nuclear Non-Proliferation

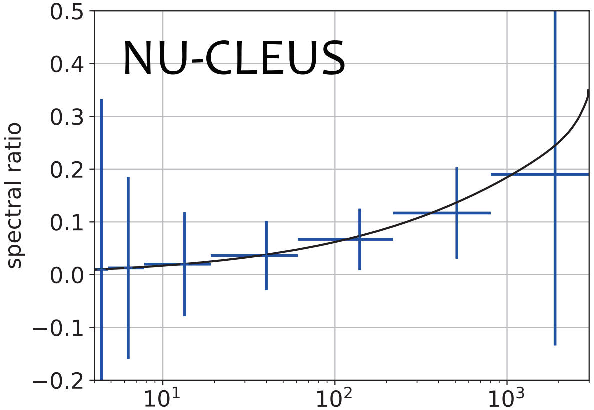
http://www.lefigaro.fr/assets/pdf/AIEA-neutrino.pdf

Fuel content modifies antineutrino spectrum



Following the scenario of
Phys. Rev. Lett. 113, 042503 (2014)

<u>At 40m distance:</u>
Significance for diversion of fuel elements after 8 days (90%conf.)

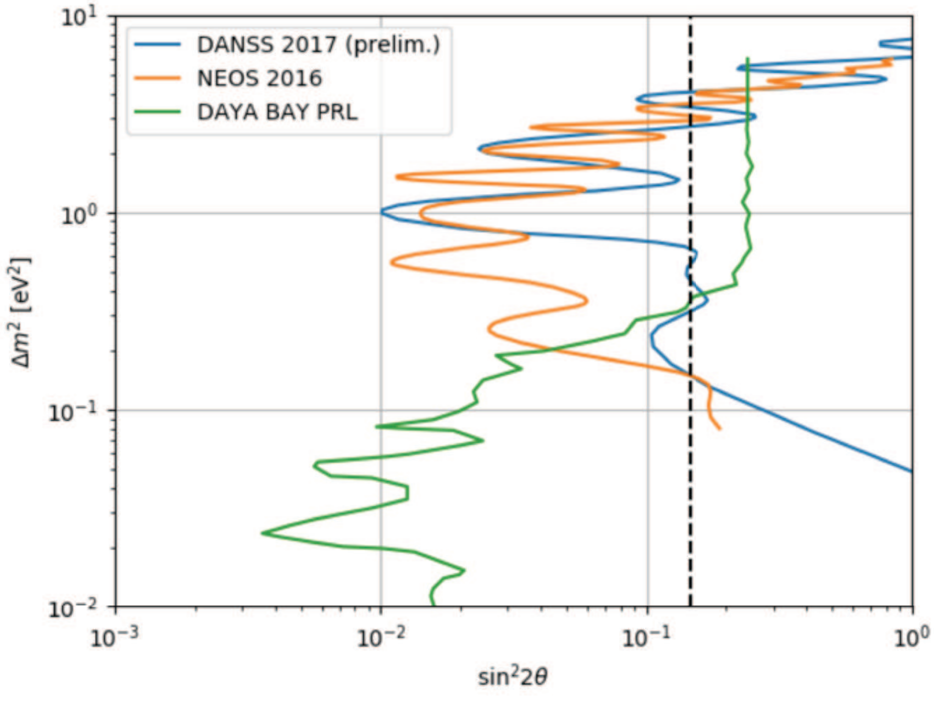


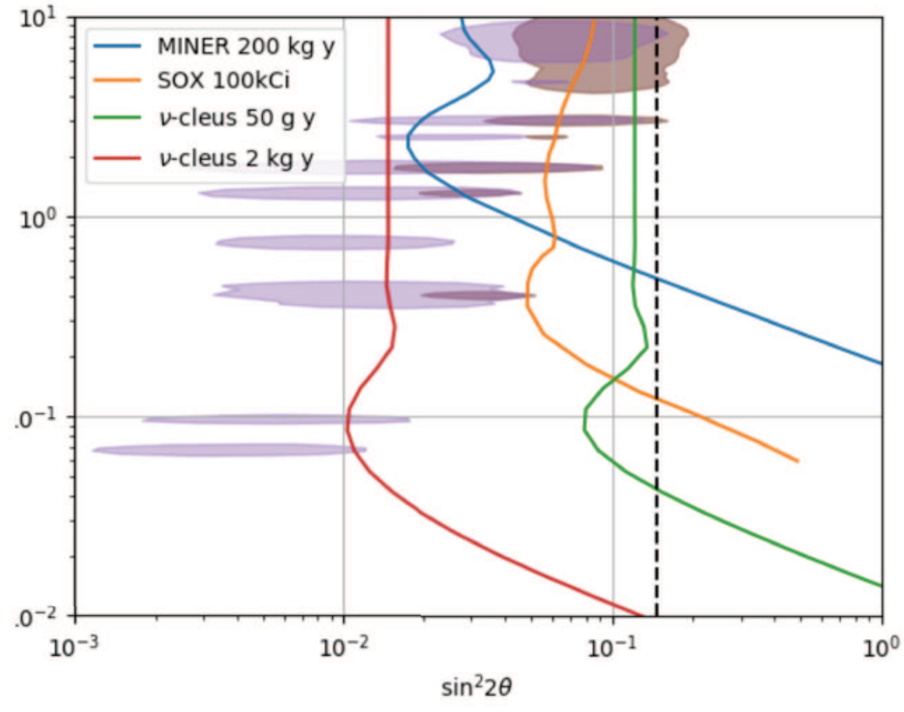
Sensitivity Study on Sterile Neutrinos

3+1 neutrino model: $P_{e\to s} = 1 - \sin^2(2\theta_{14}) \sin^2\left(1.27 \frac{\Delta m_{14}^2 d}{E_\nu}\right)$ for $\frac{\Delta m_{14}^2 d}{E_\nu}$ in units of $\left[\frac{\text{eV}^2\text{m}}{\text{MeV}}\right]$

Oscillation maximum at reactor: $d[\text{m}] \approx 4 / \Delta m_{14}^2\,[\text{eV}^2]$

→ Extend searches to lower Δm_{14}^2

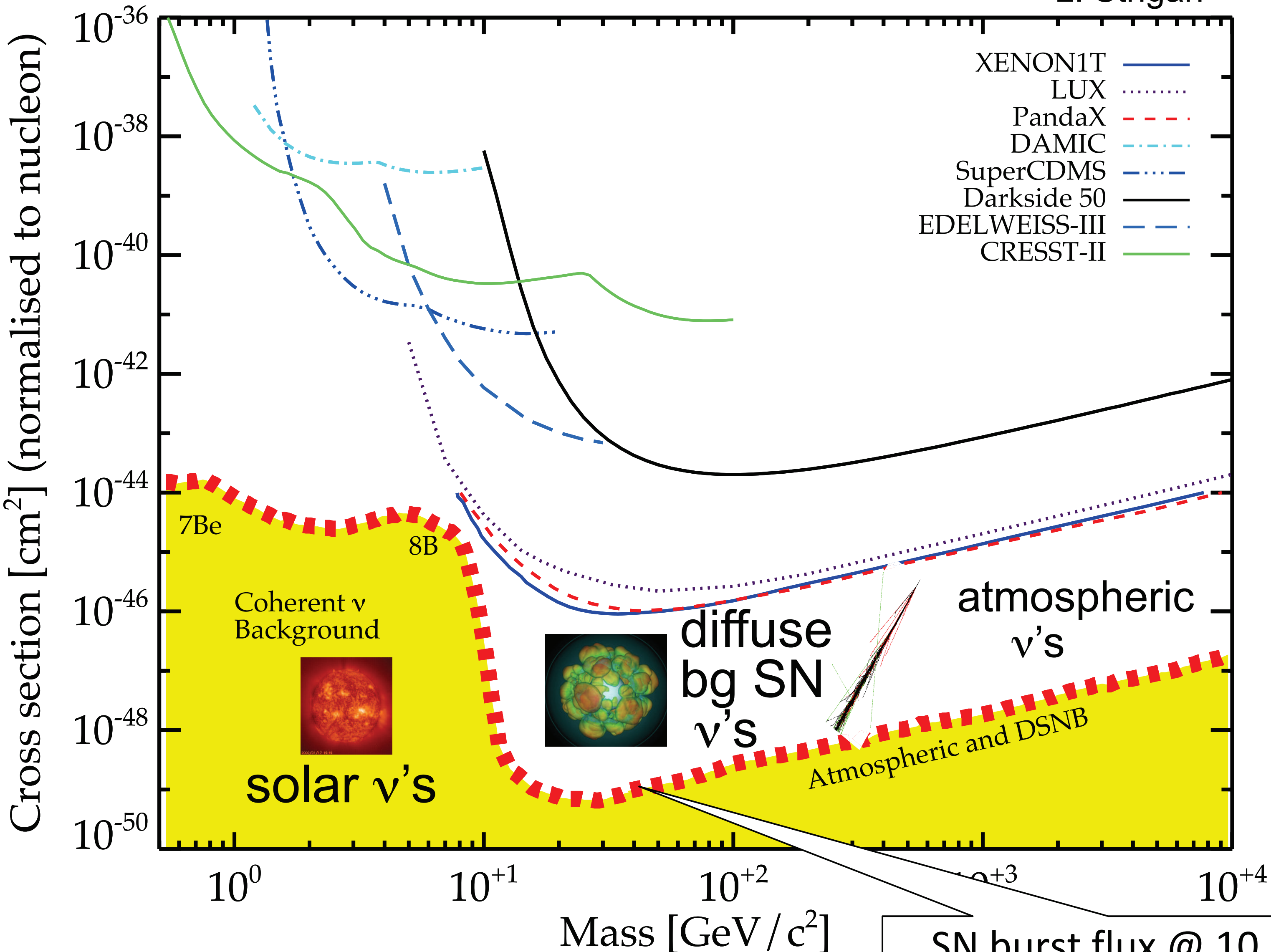




The so-called "**neutrino floor**" for DM experiments

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

L. Strigari

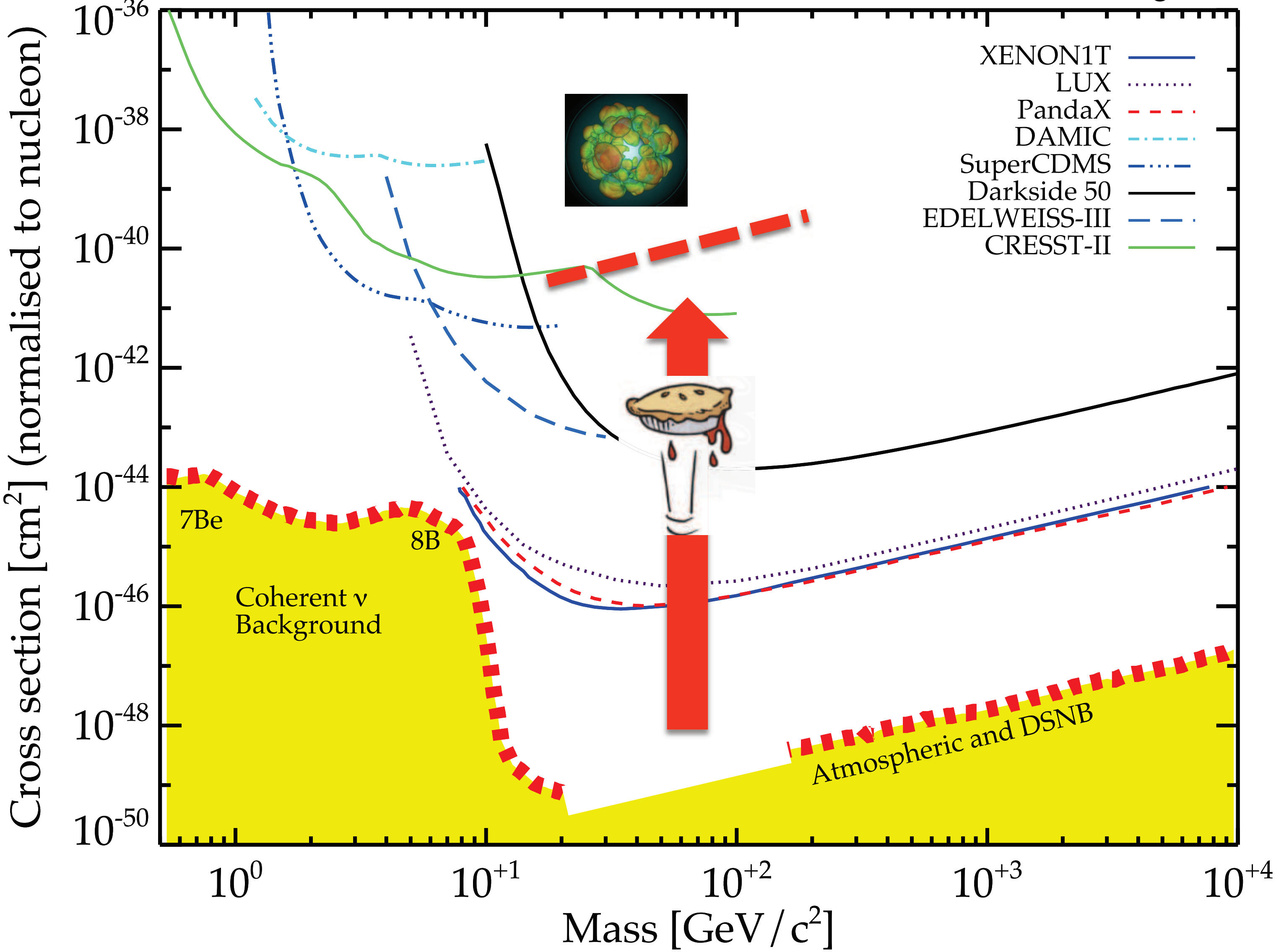


SN burst flux @ 10 kpc is 9-10 orders of magnitude greater than DSNB flux

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



Coherence on larger scales?

Can one have coherence on larger scales?

◇ Coherent neutrino scattering on atoms:

- Advantages – larger number of particles (larger σ)
- CC scattering on electrons contributes – sensitivity to neutrino oscillations!
- Disadvantage: smaller q required $\Rightarrow$ much smaller recoil energies.

For $A \sim 100$:

$$|\vec{q}| \lesssim (\text{a few } a_B)^{-1} \sim 1\,\text{keV} \quad \Rightarrow$$

$$E_{rec} \simeq \frac{\vec{q}^{\,2}}{2m_A} \sim 10^{-5}\,\text{eV}$$

$\sim$ 6 – 8 orders of magnitude below currently achieved sensitivity.

◇ Can one have (at least in principle) macroscopic coherence?

Elastic ν scattering on macroscopic bodies

- Forget first about problems with detection. What could one gain due to coherence?

Elastic ν scattering on macroscopic bodies

- ♢ Forget first about problems with detection. What could one gain due to coherence?

Simple estimate: consider a target of linear size $\sim$ 1 cm and mass ~ 1 g. For coherent scattering one needs $|\vec{q}| \lesssim q_0 \sim (1\ \mathrm{cm})^{-1} \sim 10^{-5}\ \mathrm{eV}$. Gain: large number of particles in the coherent volume $N \propto 1/q_0^3$.

Elastic ν scattering on macroscopic bodies

◇ Forget first about problems with detection. What could one gain due to coherence?

Simple estimate: consider a target of linear size $\sim$ 1 cm and mass ~ 1 g. For coherent scattering one needs $|\vec{q}| \lesssim q_0 \sim (1\ \mathrm{cm})^{-1} \sim 10^{-5}\ \mathrm{eV}$. Gain: large number of particles in the coherent volume $N \propto 1/q_0^3$.

For $E_\nu \gg q_0 \sim 10^{-5}\ \mathrm{eV}$ small q $\Rightarrow$ nearly forward ν scattering:

$$\vec{q}^{\,2} = 2E_\nu^2(1 - \cos\theta)$$

$\Rightarrow$ by limiting $\vec{q}^{\,2} < q_0^2$ we constrain the solid angle;

$$\sigma_0 \simeq \frac{G_F^2}{\pi} E_\nu^2 \quad \longrightarrow \quad \frac{G_F^2}{2\pi^2} q_0^2 .$$

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Net enhancement factor $\propto 1/q_0 \propto N^{1/3}$ $\Rightarrow$

$$\sigma_{tot} \propto N^{4/3}, \quad \text{not} \quad N^2 .$$

Still for $N \sim N_A \simeq 6\times 10^{23}$ a significant enhancement!

Elastic ν scattering on macroscopic bodies

The problem: detection.

Momentum transfers $|\vec{q}| \lesssim q_0 \sim 10^{-5}$ eV to achieve a (1 cm)^3 - scale coherence would mean, for a 1 g target,

$$E_{rec} \simeq \frac{q_0^2}{2M_{tot}} \sim 10^{-43}\ \mathrm{eV}\,!$$

Leaving aside other problems, measuring such small E_{rec} would require energy resolution δE at least of the same order.
But: By time-energy uncertainty relation this would require the measurement time

$$\delta t \sim (\delta E)^{-1} \sim 10^{27}\ \mathrm{sec}$$

– 10 orders of maginutude larger than t_U !

$\Rightarrow$ New ideas are necessary.

Ways around?

One problem: what is detected are typically scintillations and ionization caused by the recoiling target particles that are $\propto E_{rec}$.

$$E_{rec} \simeq \frac{\vec{q}^{\,2}}{2M_{tot}} \ll |\vec{q}|.$$

Can one make use of the recoil momentum $|\vec{q}|$ rather than E_{rec}?

An attempt – Experiments of J. Weber in the 1980s: torsion balance expts.; sapfire crystal. Sources: solar neutrinos; reactor neutrinos; radioactive source.

Combined 2 interesting ideas:

- Force = momentum transfer per unit time $\Rightarrow$ force impinged by neutrinos on the crystal is directly related to $\vec{q}$ rather than to E_{rec}.
- For small enough E_{rec} Mössbauer-type scattering is possible.

Elastic neutrino scattering on crystals

The idea: if the expected recoil energy of individual target atoms $E_R \simeq \frac{\vec{q}^{\,2}}{2m_A}$ is small compared to $T_{\rm Debye} \sim 10~{\rm keV}$, the recoil is given to the crystal as a whole (like in Mössbauer experiments).

Recoil-free fraction

$$f \simeq \exp\left\{-\frac{E_R}{T_D}\left(\frac{3}{2}+\frac{\pi^2 T^2}{T_D^2}\right)\right\}$$

is close to 1 for "would-be" recoil energies $E_R \ll T_D$ – easily satisfied even for $q \sim E_\nu$ as large as a few×(10 MeV).

Individual atoms (or nuclei) do not experience any recoil and so are not tagged. Coherence may occur at macroscopic level!

Positive results claimed, in agreement with the proposed theoretical model. Force exerted on the crystal: $\sim 10^{-5}~{\rm dyn}$.

Weber's approach – criticism

Criticised from several viewpoints

- Ho, 1986: Approach excluded by expts. on neutron scattering on crystals
- Bertsch & Austin, 1986: Excluded by expts. on γ-ray scattering on crystals
- Franson & Jacobs, 1992; McHugh & Keyser, 1993: more sensitive torsion balance experiments with neutrinos – no signal observed
- Criticisms of Weber's theoretical model:
  - Casella, 1986
  - Butler, 1987
  - Smith, 1987
  - Lipkin, 1987 r
  - Trammell & Hannon, 1987
  - Aharonov, Avignone, Casher & Nussinov, 1987

$\Rightarrow$ Cross section oversestimated by $\sim$ 24 orders of magnitude

What was wrong?

Absence of recoil of the individual nuclei is necessary for macroscopic coherence, but not sufficient: It is also necessary that the neutrino waves scattered from different nuclei be in phase with each other.

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For scattering on many centers $\mathcal{A} \propto$ structure factor $F(\vec{q})$,

$$\mathcal{A} \propto F(\vec{k}-\vec{k}\,') = \sum_i e^{i(\vec{k}-\vec{k}\,')\vec{r}_i}, \qquad \sigma \propto |F(\vec{k}-\vec{k}\,')|^2.$$

[N.B.: If one writes the density of scatterers as $\rho(\vec{x}) = \sum_i \delta^3(\vec{x}-\vec{x}_i)$, factor F takes the familiar form $F(\vec{q}) = \int d^3x \rho(\vec{x}) e^{i\vec{q}\vec{x}}$].

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Now,

$$|F(\vec{q})|^2 \;=\; \sum_{i,j} e^{i\vec{q}(\vec{r}_i-\vec{r}_j)}.$$

In general, for $q\max\{|\vec{r}_i-\vec{r}_j|\} \simeq qL \ll 1$ one has $|F(\vec{q})|^2 \;\simeq\; \sum_{i,j} 1 = N^2$; in the opposite case $qL \gg 1$ only diagonal terms in the sum contribute, $|F(\vec{q})|^2 \;=\; N$.

What was wrong – contd.

For Weber's expts. the condition $|\vec{q}| < L^{-1} \sim 10^{-5}$ eV was violated (only much weaker cond. $|\vec{q}| < (2m_A T_D)^{1/2} \sim 50\ \mathrm{MeV}$ was met).

Crystals are a special case. $|\vec{q}|$ need not be very small! For

$$\vec{q}(\vec{r}_i - \vec{r}_j) = 2\pi n$$

– constructive interference, $d\sigma \propto N^2$. $\Leftrightarrow$ Bragg condition:

$$2d \sin\theta = n\lambda$$

(d is interplanar distance, $\lambda = 2\pi/k$).

But: Bragg maxima lead to $d\sigma \propto N^2$ only in very narrow cones with $\Delta\Omega \propto N^{-2/3}$ and for energy intervals $\Delta E \propto N^{-1/3}$. When integrated over Ω and E_ν lead to the usual $\sigma \propto N$ dependence.

Need a different idea.

A possibility:

Radiative neutrino scattering

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

Photon energy ω_γ can be as large as the neutrino momentum transfer (not E_{rec} of the target particle, which can even be zero)! No need to detect tiny recoils.

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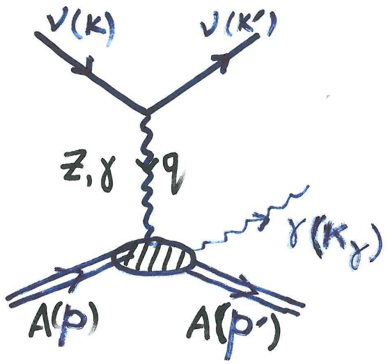
Another possibility – bremsstrahlung on free electrons, $\nu + e \to \nu + e + \gamma$. First considered by Lee and Sirlin (1964) and then by many other people. In all but two papers – also not in connection with macroscopic coherence.

Radiative ν-atom scatt. with $\omega \gtrsim \omega_{\rm char}$



ν + A → ν + A + γ

Energy-momentum conservation:

$$p + k = p' + k' + k_\gamma$$

EA, G. Arcadi, M. Lindner and S. Vogl, JHEP 1810 (2018) 045 [arXiv:1806.10962]

The structure factor:

$$F(\vec{k} - \vec{k}') = \sum_i e^{i(\vec{k}-\vec{k}')\vec{r}_i} \longrightarrow \sum_i e^{i(\vec{k}-\vec{k}'-\vec{k}_\gamma)\vec{r}_i}$$

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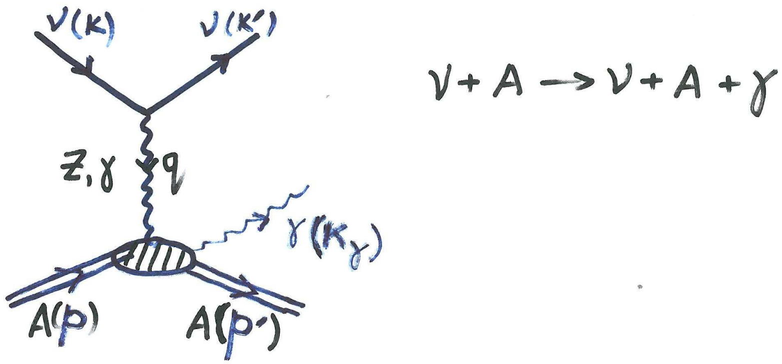

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♢ Coherence at macroscopic scales requires $|\vec{k} - \vec{k}' - \vec{k}_\gamma|L \ll 1$, (not $|\vec{k} - \vec{k}'|L \ll 1$!) $\Rightarrow$ all scattered waves in phase w/ each other.

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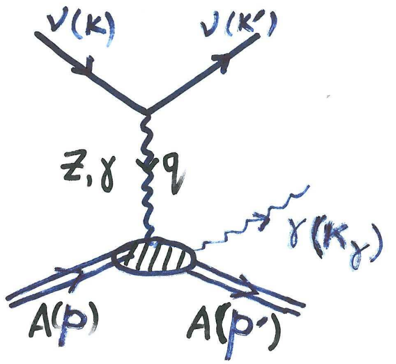

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From momentum conservation: recoil momentum

$$\vec{p}\,' = (\vec{k}-\vec{k}\,') - \vec{k}_\gamma$$

$\Rightarrow$ very small $\vec{k}-\vec{k}\,'-\vec{k}_\gamma$ also means very small $|\vec{p}\,'|$ – exactly what is needed for the process to be coherent!

Advantages:

- The energy of detected photons ω_γ can in principle be as large as momentum transfer to electrons from neutrinos $|\vec{k}-\vec{k}\,'|$.
- Neither $|\vec{k}-\vec{k}\,'|$ nor ω_γ need be small to ensure macroscopic coherence – only their difference needs. For $\omega_\gamma \sim \omega \gg \omega_{at}$ no ω^4 suppression.

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The price to pay:

- Phase-space volume gets severely constrained: $\vec{k}_\gamma$ nearly equals $\vec{k} - \vec{k}\,'$,

$$|\vec{p}\,'| = |\vec{k} - \vec{k}' - \vec{k}_\gamma| < p_0 \lesssim L^{-1}.$$

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Can the increase due to macroscopic coherence compensate for the suppression of the elementary cross section σ_0?

Rad. ν scatt. mediated by weak CC and NC

I. Without constraining $|\vec{p}\,'|$:

$$\sigma_w \simeq \frac{G_F^2 g_V^2 e^2}{(2\pi)^3} \frac{16}{9} \frac{E_\nu^4}{m_e^2}.$$

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Cross section scales as p_0^4: a factor p_0^3 from the phase space with the electron recoil momentum constrained by $|\vec{p}\,'| \le p_0$, another p_0 from the squared modulus of the transition amplitude.

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$$\sigma_{tot} \propto p_0^4 \cdot \frac{1}{p_0^3} = p_0$$

– decreases with p_0. Suppression of σ_{tot} instead of enhancement!

Radiative ν-e scattering and μ_ν

Kinematic enhancement in the case of μ_ν-mediated radiative $\nu - e$ scattering.

$$\sigma_m(\omega_\gamma > \omega_0) \simeq \frac{\mu_\nu^2 e^4}{(2\pi)^3} \frac{1}{m_e^2} \cdot \frac{4}{3} \omega^2 \ln(\omega/\omega_0)\,.$$

For $|\vec{p}\,'| \leq p_0$, to leading order in p_0

$$\sigma_m(\omega_\gamma > \omega_0) \simeq \frac{\mu_\nu^2 \alpha^2}{\pi} \frac{1}{m_e^2} \cdot \frac{1}{3} \frac{p_0^3}{\omega_0}\,.$$

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$$\sigma_{tot} \propto p_0^3 \cdot \frac{1}{p_0^3} = const. \quad (\text{for} \quad L^{-1} \lesssim p_0 \ll E_\nu, \, \omega_\gamma, \, E_\nu - \omega_\gamma) \,.$$

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For μ_ν-induced radiative νe scattering: Macroscopic coherence gives advantage over the elastic scattering only for $T \gtrsim 100\ \mathrm{keV}$.

But: it may allow detection of very low-E neutrinos ($\sim 10\ \mathrm{eV}$ – $10\ \mathrm{keV}$).

No enhancement of neutrino detection by huge factors.

We need a different idea!

Current theoretical activities

- CEvNS sensitivity to non-standard neutrino properties (NSI, electromagn. properties)
- Sensitivity to sterile neutrinos
- Implications for DM detection
- New detection mechanisms and techniques

But: Even theoretical calculations of the standard cross CEvNS sections need to be improved. Most theoretical formulas based on simplified approaches:

– Neglect axial-vector contributions or use simplified formulas
– Do not describe coherent and incoherent contributions in a unified way
– Use the common nuclear formfactor for N and Z

Sufficiently good approximations for first studies but need to be improved when precision measurements are needed!

Coherent *vs.* incoherent scattering

In the fully coherent limit

$$q \ll R^{-1}\,, \qquad F(\vec{q}^{\,2}) \to 1\,, \qquad \sigma_{tot} \propto N^2\,.$$

In the fully incoherent limit

$$q \gg R^{-1}\,, \qquad \sigma_{tot} \propto N\,,$$

which requires

$$|F(\vec{q}^{\,2})| \to 1/\sqrt{N}\,.$$

But with the usual definition of the formfactors, for $q \to \infty$

$$|F(\vec{q}^{\,2})| \to 0\,, \quad \text{not} \quad \to 1/\sqrt{N}\,.$$

No unified description of coherent and incoherent limits.

G_A contribution

For non-relativistic targets are due to spin-spin interaction:

$$\propto \; \vec{s}_\nu \cdot \vec{S}_T \;=\; s_\nu^- S_T^+ \;+\; s_\nu^+ S_T^- \;+\; s_{\nu z} S_{Tz} \qquad \left(s^\pm = \frac{1}{\sqrt{2}}(s_x \pm i s_y)\right)$$

$S_{Tz} \;\propto\; (N_\uparrow - N_\downarrow)$, $(Z_\uparrow - Z_\downarrow)$ – typically small compared to the total number of nucleons $\Rightarrow$ the G_A contribution is subleading. Still should in general be included if $\vec{J} \neq 0$!

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The issue still to be clarified.

A lot of interesting things yet to be done —

We are just in the beginning of the road!