PARTICLE PHYSICS PROSPECTS OF COHERENT NEUTRINO SCATTERING

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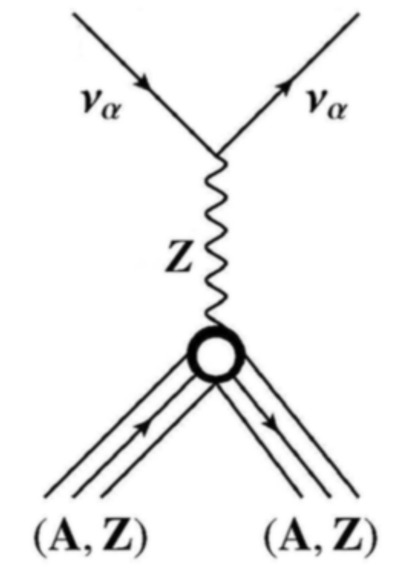
Sam Houston State University
Prospects of Neutrino Physics
Kavli IPMU, April 8-12, 2019

with Dent, Dutta, Gao, Kubik, Liao, Mahapatra, Mirabolfathi, Newstead & Strigari
Phys. Rev. D 93, 13015, Phys. Rev. D 94, 093002, 1612.06350, 1705.00661, 1711.03521
Including slides from "The Magnificent CEvNS" — KICP, Nov. 18 — as credited

COVERAGE

- Coherent Elastic Neutrino-Nucleus Scattering (CEvNS) — Review of Underlying Physics Process
- Summary of Modes of New Physics Visible to CEvNS
- Comparison & Complementarity of CEvNS Searches
- Summary of Discovery & Exclusion Prospects

WHAT IS CEVNS?



(1502.02928)

- T-Channel flavor-inclusive neutral-current scattering
- Small momentum exchange (long wavelength) limit implies that nuclear structure is unresolved
- Summing prior to squaring in the amplitude leads to quadratic (rather than linear) scaling with N
- By "accident" (Weinberg angle) neutrons contribute about ten times more than protons
- CEvNS is a future background "Neutrino Floor" to DM searches

History: Connection to WIMPs

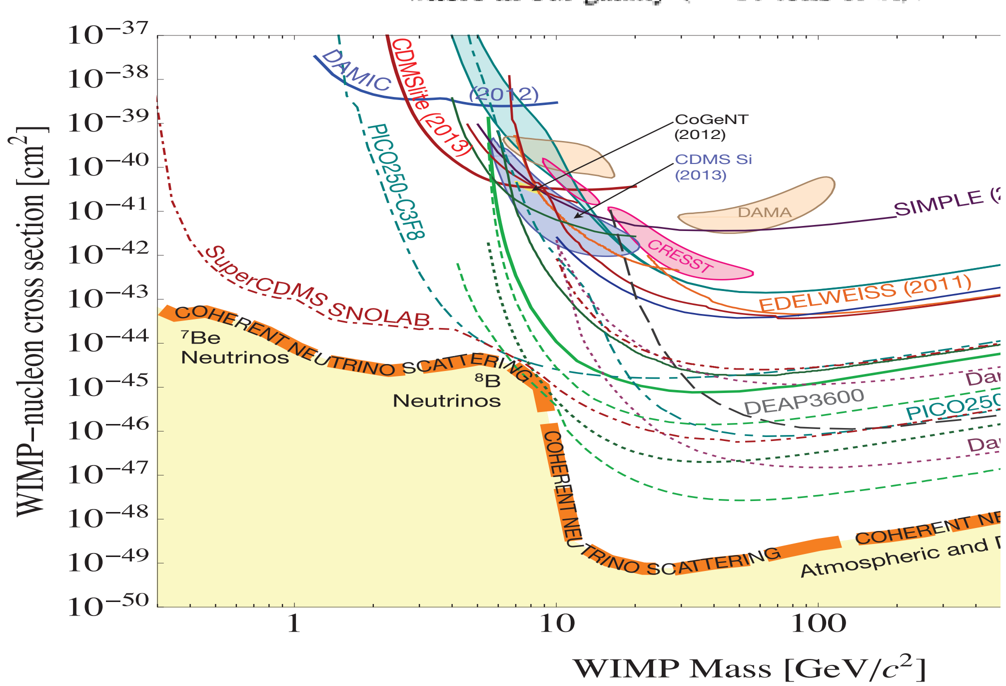
Coherent scattering of neutrinos and WIMP search have the same technological pursuit

VOLUME 55, NUMBER 1 PHYSICAL REVIEW LETTERS 1 JULY 1985

Bolometric Detection of Neutrinos

Blas Cabrera, Lawrence M. Krauss, and Frank Wilczek
Department of Physics, Stanford University, Stanford, California 94305
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 01238
Institute for Theoretical Physics, University of California, Santa Barbara, California 93106
(Received 14 December 1984)

Elastic neutrino scattering off electrons in crystalline silicon at 1–10 mK results in measurable temperature changes in macroscopic amounts of material, even for low-energy (< 0.41MeV) *pp* ν's from the sun. We propose new detectors for bolometric measurement of low-energy ν interactions, including coherent nuclear elastic scattering. A new and more sensitive search for oscillations of reactor antineutrinos is practical (~ 100 kg of Si), and would lay the groundwork for a more ambitious measurement of the spectrum of *pp*, ^{7}Be, and ^{8}B solar ν's, and supernovae anywhere in our galaxy (~ 10 tons of Si).



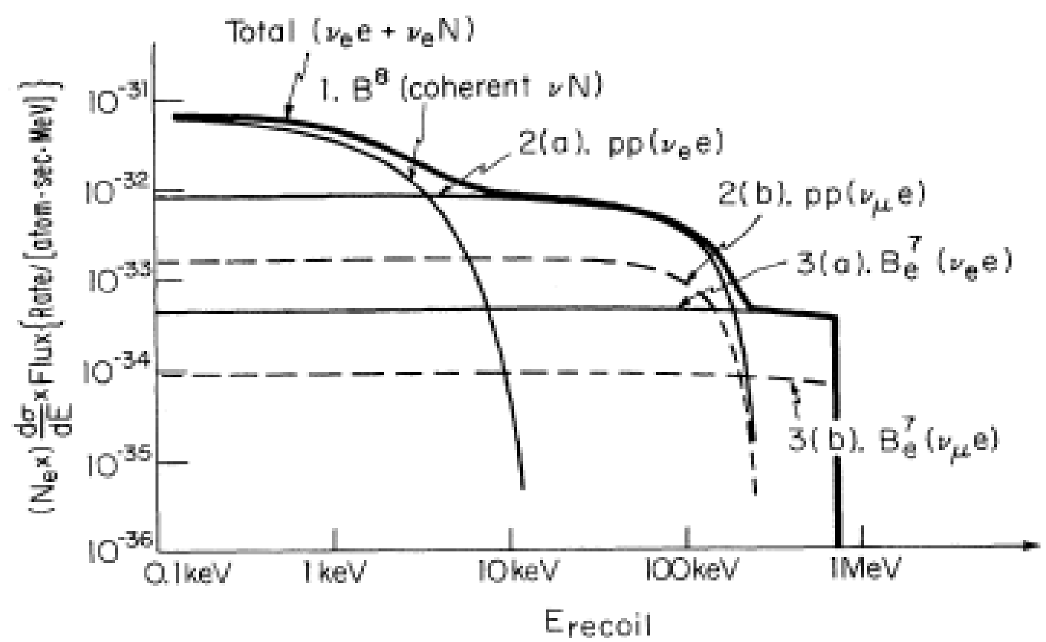


FIG. 1. Event rate vs recoil energy for solar-ν spectra.

Same low threshold detector challenges for SuperCDMS and CNS . . Precisely measuring this process may aid the search for dark matter below the neutrino floor. *From: Rupak Mahapatra*

2018 DISCOVERY BY COHERENT (OAKRIDGE SNS)

- The initial observation by COHERENT was based on around 135 events over about 18 months
- Rejection of null hypothesis (something rather than nothing) approached 7-sigma
- Compatible with the SM, offset by around 1.5-sigma
- Signal characterization requires much more statistics

Discovery: August 2017 by COHERENT™

Science REPORTS

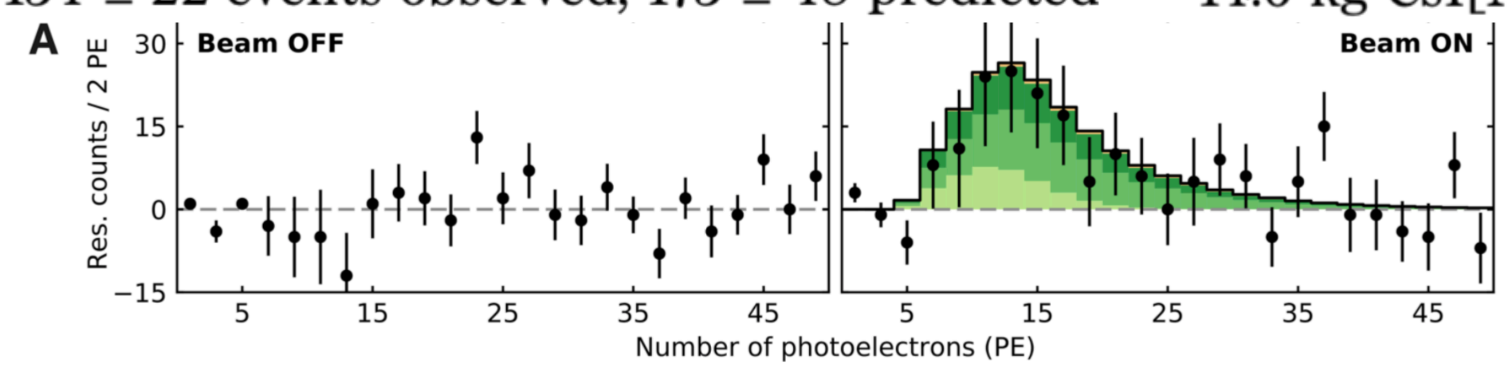
Cite as: D. Akimov *et al.*, *Science* 10.1126/science.aao0990 (2017).

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. Bolozdynya,[2] B. Cabrera-Palmer,[8] M. Cervantes,[5] J. I. Collar,[9]* R. J. Cooper,[10] R. L. Cooper,[11,12] C. Cuesta,[13]† D. J. Dean,[14] J. A. Detwiler,[13] A. Eberhardt,[13] Y. Efremenko,[6,14] S. R. Elliott,[12] E. M. Erkela,[13] L. Fabris,[14] M. Febbraro,[14] N. E. Fields,[9]‡ W. Fox,[3] Z. Fu,[13] A. Galindo-Uribarri,[14] M. P. Green,[4,14,15] M. Hai,[9]§ M. R. Heath,[3] S. Hedges,[4,5] D. Hornback,[14] T. W. Hossbach,[16] E. B. Iverson,[14] L. J. Kaufman,[3]|| S. Ki,[4,5] S. R. Klein,[10] A. Khromov,[2] A. Konovalov,[1,2,17] M. Kremer,[4] A. Kumpan,[2] C. Leadbetter,[4] L. Li,[4,5] W. Lu,[14] K. Mann,[4,15] D. M. Markoff,[4,7] K. Miller,[4,5] H. Moreno,[11] P. E. Mueller,[14] J. Newby,[14] J. L. Orrell,[16] C. T. Overman,[16] D. S. Parno,[13]¶ S. Penttila,[14] G. Perumpilly,[9] H. Ray,[18] J. Raybern,[5] D. Reyna,[8] G. C. Rich,[4,14,19] D. Rimal,[18] D. Rudik,[1,2] K. Scholberg,[5] B. J. Scholz,[9] G. Sinev,[5] W. M. Snow,[3] V. Sosnovtsev,[2] A. Shakirov,[2] S. Suchyta,[10] B. Suh,[4,5,14] R. Tayloe,[3] R. T. Thornton,[3] I. Tolstukhin,[3] J. Vanderwerp,[3] R. L. Varner,[14] C. J. Virtue,[20] Z. Wan,[4] J. Yoo,[21] C.-H. Yu,[14] A. Zawada,[4] J. Zettlemoyer,[3] A. M. Zderic,[13] COHERENT Collaboration#

The coherent elastic scattering of neutrinos off nuclei has eluded detection for four decades, even though its predicted cross-section is the largest by far of all low-energy neutrino couplings. This mode of interaction provides new opportunities to study neutrino properties, and leads to a miniaturization of detector size, with potential technological applications. We observe this process at a 6.7-sigma confidence level, using a low-background, 14.6-kg CsI[Na] scintillator exposed to the neutrino emissions from the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory. Characteristic signatures in energy and time, predicted by the Standard Model for this process, are observed in high signal-to-background conditions. Improved constraints on non-standard neutrino interactions with quarks are derived from this initial dataset.

134 ± 22 events observed, 173 ± 48 predicted 14.6 kg CsI[Na]



KEY CEVNS PHYSICS CHARACTERISTICS

- Cross-section scales as E_ν^2 (proportional to G_F^2)
- Maximum recoil is suppressed by nuclear mass

$$T_{\text{Max}} = 2E_\nu^2/M_N$$

- Event rate falls linearly with recoil up to cutoff

$$d\sigma/dT \propto 1 - T/T_{\text{Max}}$$

- “Squeezing” recoil into a narrow bandwidth enhances the visibility over background below T_{Max}

Differential Cross Section

$$\frac{d\sigma}{dT_{\mathrm{R}}} = \frac{G_F^2 M}{2\pi}\left[(q_V + q_A)^2 + (q_V - q_A)^2\left(1 - \frac{T_{\mathrm{R}}}{E_\nu}\right)^2 - (q_V^2 - q_A^2)\frac{MT_{\mathrm{R}}}{E_\nu^2}\right]$$

- Neutrino is pure left-handed, and its charge has been factored out: $q_{V,A}$ are the target
- Cross section applies to nuclear scattering and the electron cloud
- Sum over quark content of all nucleons prior to squaring amplitude: Coherency Boost
- Sum over electrons after squaring amplitude: Linear not quadratic enhancement

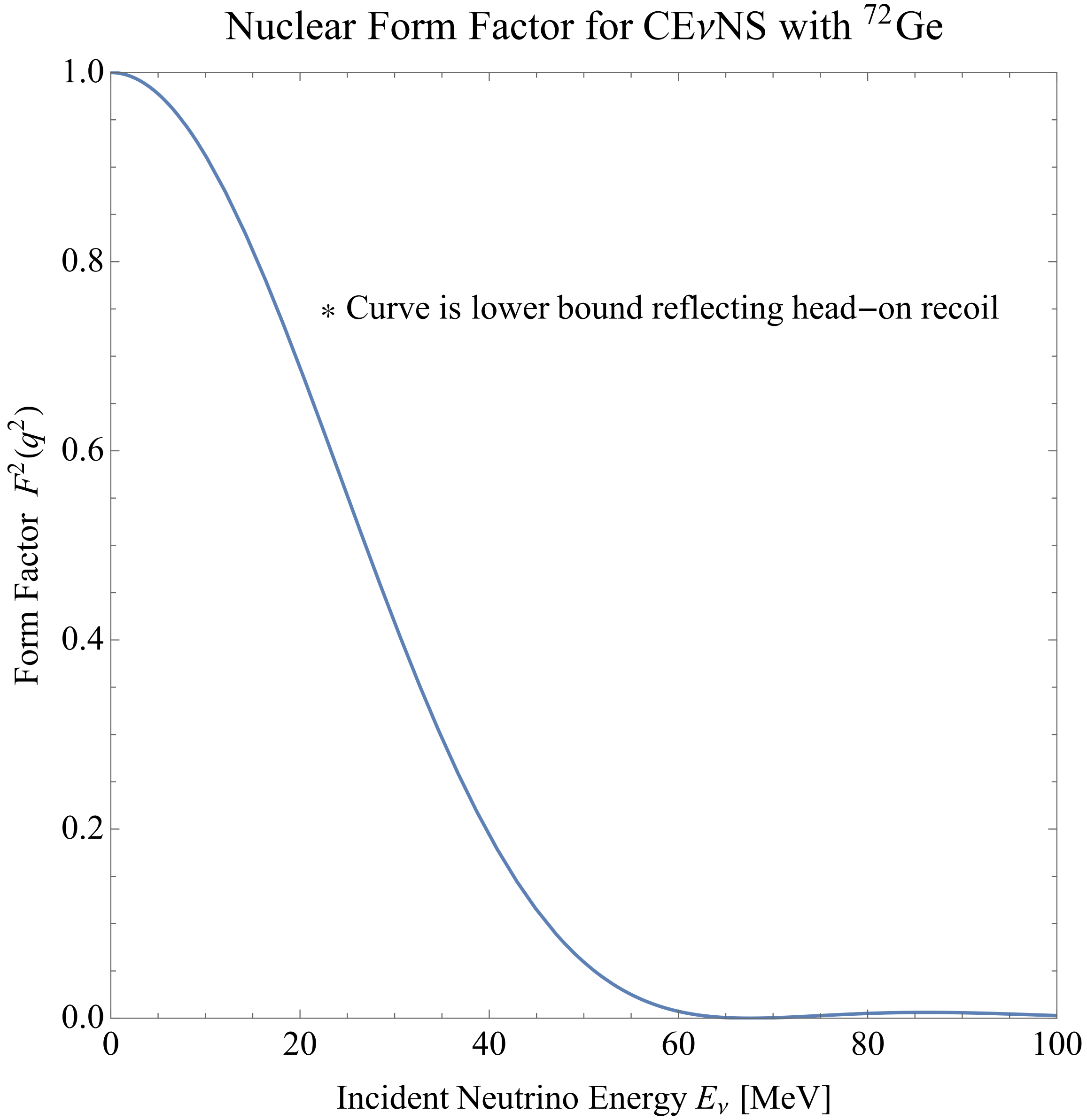
- This introduces factors of (Z,N) for the vector charges
- Likewise, factors of $(Z^+ - Z^-,\, N^+ - N^-)$ for the axial charges (sub-dominant)
- ^{72}Ge has 2 extra spin up neutrons, and a deficit of 2 spin up protons
- ^{28}Si is spin zero for both protons and neutrons independently

Integrated Event Rate

$$N_{\mathrm{Exp}}^{i,n} = \phi_0 \times T_n \times \frac{L_0^2}{L_n^2} \times \frac{M_{\mathrm{Det}}}{M} \times \int_{E_\nu^{\mathrm{min}}(E_{\mathrm{R}}^{i\downarrow})}^{\infty} dE_\nu \, \lambda(E_\nu) \int_{E_{\mathrm{R}}^{i\downarrow}}^{\min\{E_{\mathrm{R}}^{i\uparrow}, E_{\mathrm{R}}^{\mathrm{max}}(E_\nu)\}} dE_{\mathrm{R}} \, \frac{d\sigma}{dE_{\mathrm{R}}}(E_\nu, E_{\mathrm{R}})$$

- Integrate in the physical region over recoils and over the normalized E_ν spectrum
- Result is proportional to flux, time, and mass, and inversely so to distance-square
- Form factor $F^2(q^2)$ is suppressed (assumed equal to unity)
- For MeV order neutrinos, an ultra-low detection threshold is vital
- Note “area” is from the interaction cross section – NOT the physical detector dimension

Maintaining Coherency



$$F(q^2) = \frac{3 j_1(qR_0)}{qR_0} e^{-(qs)^2/2} \quad \text{(Engel PLB 1991)}$$

Nuclear form factor is Fourier Transform of ground state mass density

$R \simeq 1.2\, A^{1/3}$ [fm] : Semi-empirical nuclear radius

$S \simeq 0.5$ [fm] : Surface thickness parameter

$R_0 \equiv \sqrt{R^2 - 5S^2}$: Effective radius of constant density

- Momentum transfer deBroglie wavelength should be larger than the Nucleus
- The reactor experiments do NOT have to worry about nuclear physics
- The accelerator experiments ARE sensitive to nuclear physics effects

PATHS TO SIGNAL VISIBILITY

- Boost neutrino energy to boost the recoil deposition

AND/OR

- Build extremely sensitive (low threshold) detectors

SIMILARITY TO DARK MATTER SEARCHES

- The CDMS-styled Ge and Si detectors built for light dark matter are perfect for application to CEvNS

- Especially, the “CDMS-Lite” HIGH-VOLTAGE detectors (ionization is converted to phonons) can reach the required low 100’s of eV threshold target

- Various N/Z ratios provide a window into isospin effects, i.e. differential coupling to up/down quarks

A NEW WINDOW ON NEW PHYSICS

- Although discovery of CEvNS has taken a long time, the process is NOT RARE
- Under the right conditions, with the right technology, the signal rate can be ENORMOUS
- For example: the event rate at 1m from a 1MW reactor with 1kg of Ge at 10eV threshold is ONE per HOUR
- High statistics give a precision window on BSM physics

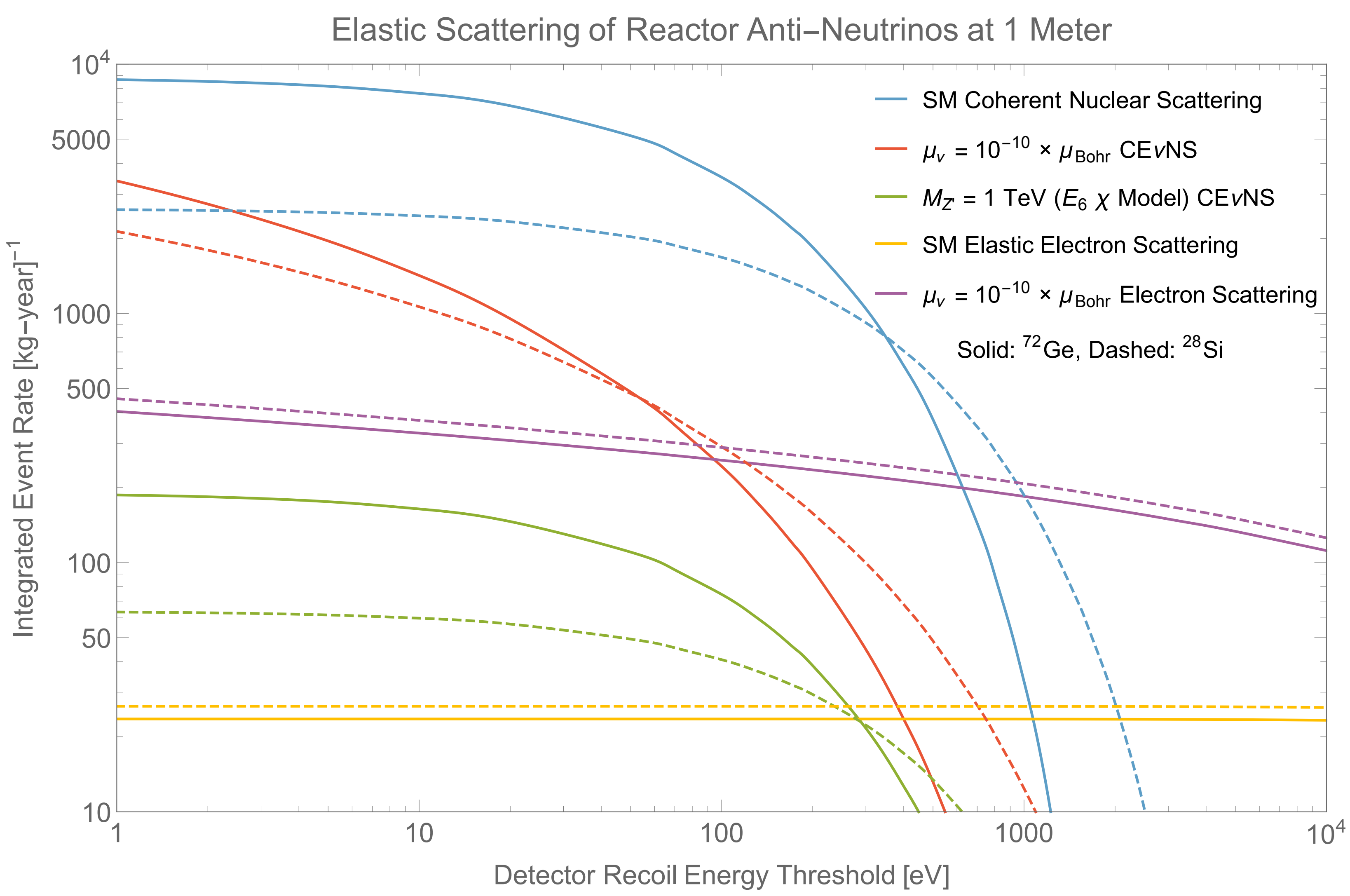
PATHS TO HIGH STATISTICS

- Use a nuclear reactor for high flux

AND/OR

- Build much larger detectors

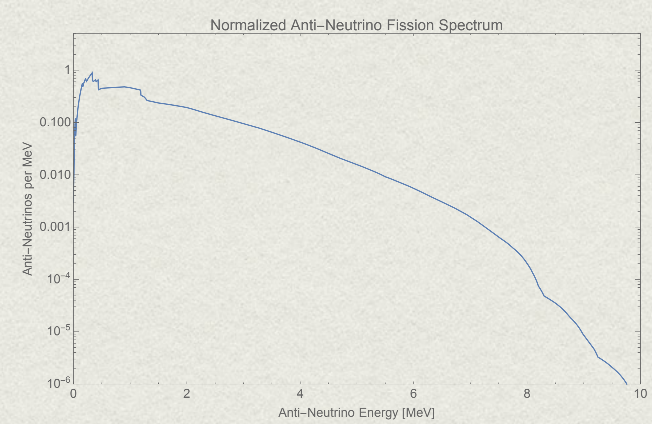
SM & BSM Event Rates



- Huge event rates of ~ 1/kg/hour are possible in the SM
- The signal region stands out b/c of narrow bandwidth and coherency enhancement
- For BSM physics look to distinguish rate, shape, and Si Vs. Ge

PROS & CONS OF REACTOR SOURCES

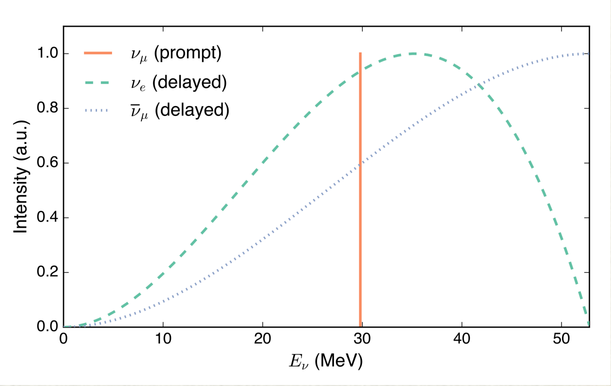
- Flux can be extraordinary (10^{12-13} per cm^2 per s)
- Backgrounds (neutrons/gammas) can be tough
- Mean energy is ~ 1.5 MeV (need ~ 100 eV threshold) — spectrum is measured but not monochromatic
- Flavor is single-valued and known ($\overline{\nu}_e$)



- Nuclear form factor is ignorable (full coherence)

PROS & CONS OF STOPPED PION SOURCES

- Energy can exceed 30 MeV (enhances rate)
- Recoils are hard — scintillators are sufficient
- Flavors are mixed (prompt ν_μ and delayed $\bar{\nu}_\mu / \nu_e$)
- Pulsed timing helps reduce backgrounds



- Coherency is partial, leading to large uncertainties (but one can measure the form factor)

WHERE CAN CEVNS OFFER THE BEST SENSITIVITY?

- But, looking for new physics on top of the SM CEvNS signal can be very challenging
- Systematic rate uncertainties are tied to source power, nuclear form factor, the Weinberg angle, detector calibration, etc.
- New physics will be more visible if it non-trivially alters the recoil spectrum SHAPE or non-trivially depends on source flavor or target isospin

HEAVY POINTLIKE MEDIATORS (Z-PRIME)

- A heavier Z-like mediator can contribute to CEvNS
- The propagator $g^2/M_{Z'}^2$ suppresses the contribution
- Leading contributions are in the cross-term with the SM (the pure new physics contributions are $\propto M_{Z'}^{-4}$)
- The real problem is that this only RESCALES the SM
- Can't compete with LHC dilepton limits (~4TeV), which would also directly pinpoint the mass scale of a discovery

Modification of of SM Charges

$$Q_{SM}(i) \Rightarrow Q_{SM}(i) + Q_{\rm BSM}(i) \times \left\{ Q_{\rm BSM}(\nu)/Q_{\rm SM}(\nu) \times (g' \cos\theta_W/g)^2 \times (M_Z/M_{Z'})^2 \right\}$$

- SM charges, couplings, and masses are cancelled and replaced
- E_6 is GUT normalized: $(g'/g)^2 = 5/3 \tan^2\theta_W$
- For *B-L*, (g'/g) is unconstrained
- For the sequential SM $g' \cos\theta_w/g$ = 1

- New physics appears in charge-squared cross terms with SM at leading order
- This implies that the event rate declines as $M_{Z'}^{-2}$, rather than $M_{Z'}^{-4}$

Quark and lepton neutral current charges in the SM and various extensions.

	Q_{SM}	$\sqrt{40}\, Q^{\chi}_{E_6}$	$\sqrt{24}\, Q^{\psi}_{E_6}$	Q_{B-L}
u_L	$\frac{1}{2} - \frac{2}{3}\sin^2\theta_W$	-1	1	$\frac{1}{3}$
d_L	$-\frac{1}{2} + \frac{1}{3}\sin^2\theta_W$	-1	1	$\frac{1}{3}$
u_R	$-\frac{2}{3}\sin^2\theta_W$	1	-1	$\frac{1}{3}$
d_R	$\frac{1}{3}\sin^2\theta_W$	-3	-1	$\frac{1}{3}$
ν_L	$\frac{1}{2}$	3	1	-1
e_L	$-\frac{1}{2} + \sin^2\theta_W$	3	1	-1
e_R	$\sin^2\theta_W$	1	-1	-1

Cancellation of Systematics in Ge, Si

$$\xi \equiv \frac{E_{\mathrm{Ge}} / B_{\mathrm{Ge}} - 1}{E_{\mathrm{Si}} / B_{\mathrm{Si}} - 1} = \frac{S_{\mathrm{Ge}} / B_{\mathrm{Ge}}}{S_{\mathrm{Si}} / B_{\mathrm{Si}}}$$

$$\zeta \equiv \frac{E_{\mathrm{Ge}}}{B_{\mathrm{Ge}}} - \frac{E_{\mathrm{Si}}}{B_{\mathrm{Si}}} = \frac{S_{\mathrm{Ge}}}{B_{\mathrm{Ge}}} - \frac{S_{\mathrm{Si}}}{B_{\mathrm{Si}}}$$

- *E, B, S=E-B* are experimental total, expected SM background, and BSM signal
- Leading correlated systematic errors in Ge, Si cancel in these observables
- ξ is insensitive to scale, but readily discriminates mode of new physics

	SM	E_6	$B-L$	μ_ν
ξ	1.0	0.89	0.86	0.43

- ζ alternatively retains sensitivity to the *Z*-prime scale
- Residual percentile errors are calculable in closed form

$$\frac{\sigma_\xi}{\xi} = \sqrt{\frac{B_{\mathrm{Ge}}}{S_{\mathrm{Ge}}^2} + \frac{B_{\mathrm{Si}}}{S_{\mathrm{Si}}^2}} \quad ; \quad \sigma_\zeta = \sqrt{\frac{1}{B_{\mathrm{Ge}}} + \frac{1}{B_{\mathrm{Si}}}}$$

LIGHT MILLI-CHARGED MEDIATORS

- New physics mediators that are very light cannot be ruled out experimentally if the coupling is also weak
- For light mediators the momentum exchange is not negligible in the propagator $g^2/(2TM_N + m_{z'}^2)$
- Colliders have NOTHING to say about this, because large momentum exchange suppresses the effect
- Also, non-trivial dependence of the effective charge on the recoil kinematics characteristically alters the SPECTRUM
- The effect can be largest at the softest recoils: CEvNS is well suited

Probing Light Mediators

- To avoid bounds, new forces must be weak and/or short ranged
- New forces are motivated by mixing of dark sector with visible
- Light mediators will enhance the scattering rate for low momentum transfer
- To escape bounds, lighter mediators must be more weakly coupled

$$[g_v, g_a] \Rightarrow [(g_v + \delta_{X,e}), \pm (g_a + \delta_{X,e})] + \frac{g_{\nu,Z'}\, g_{X,Z'}}{\sqrt{2}G_F\,(2E_R\, m_X + M_{Z'}^2)} \times [\cos\alpha, \pm \sin\alpha]$$

For Example, See:

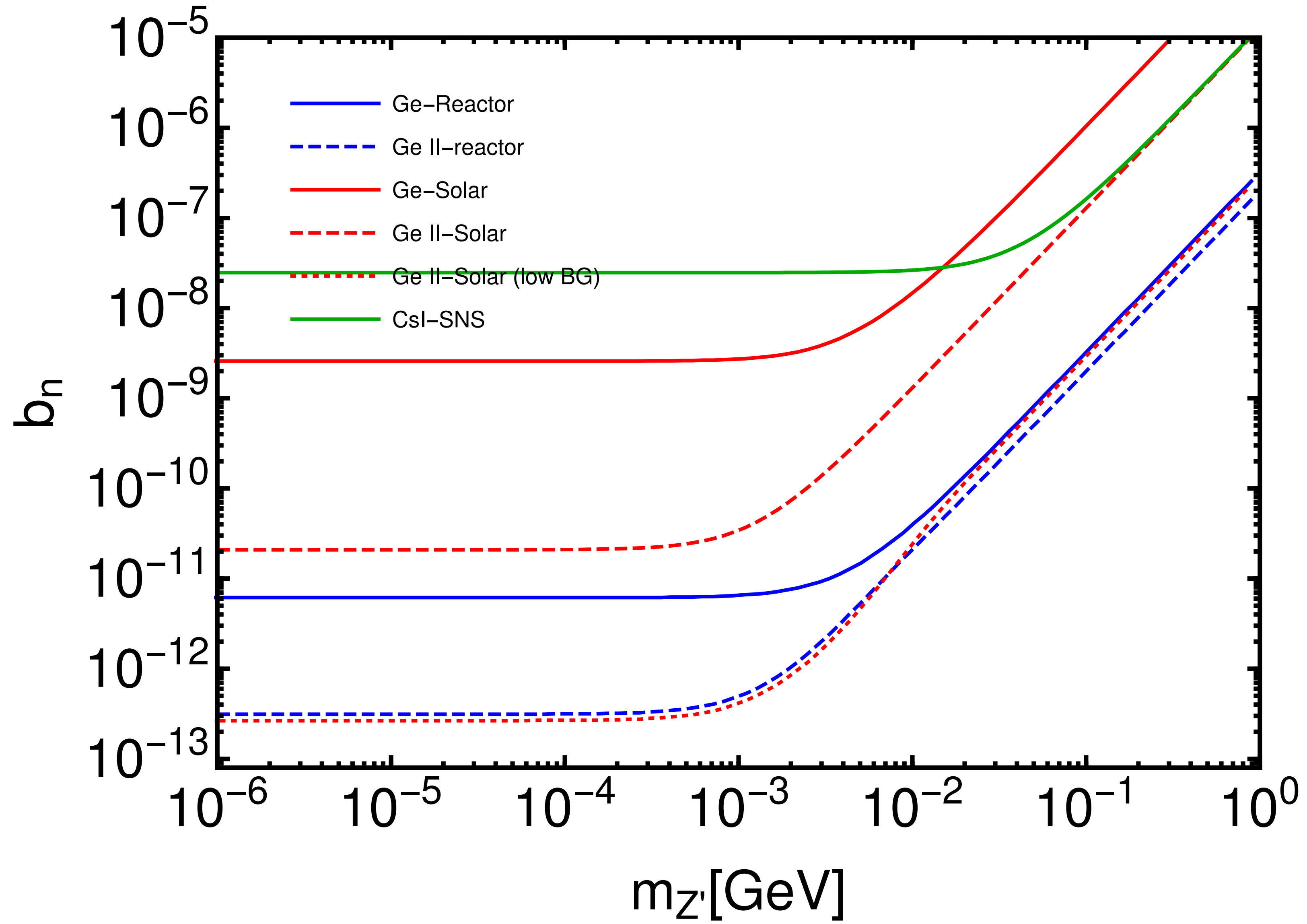
- Dent et al. 1612.06350 (our work)
- Boehm et al. J.Phys.G30:279-286,2004
- Cerdeno et al. 1604.01025
- Feng et. Al 1604.07411

Light Mediator Differential Cross-Sections

Mediator	$\mathcal{L}$	$d\sigma_e/dE_R - d\sigma_e^{\rm SM}/dE_R$	$d\sigma_N/dE_R - d\sigma_N^{\rm SM}/dE_R$
Scalar	$(g_{\nu,\phi}\,\phi\bar{\nu}_R\nu_L + h.c.) + \phi\bar{\ell}g_{\ell,s}\ell + \phi\bar{q}g_{q,s}q$	$\frac{g_{\nu,\phi}^2 g_{e,s}^2 E_R m_e^2}{4\pi E_\nu^2\left(2E_R m_e + m_\phi^2\right)^2}$	$\frac{Q_s'^2 m_N^2 E_R}{2\pi E_\nu^2\left(2E_R m_N + m_\phi^2\right)^2}$
Pseudoscalar	$(g_{\nu,\phi}\,\phi\bar{\nu}_R\nu_L + h.c.) - i\gamma^5\phi\bar{\ell}g_{\ell,p}\ell - i\gamma^5\phi\bar{q}g_{q,p}q$	$\frac{g_{\nu,\phi}^2 g_{e,p}^2 E_R^2 m_e}{8\pi E_\nu^2\left(2E_R m_e + m_\phi^2\right)^2}$	0
Vector	$g_{\nu,Z'}Z'_\mu\bar{\nu}_L\gamma^\mu\nu_L + Z'_\mu\bar{\ell}\gamma^\mu g_{\ell,v}\ell + Z'_\mu\bar{q}\gamma^\mu g_{q,v}q$	$\frac{2\sqrt{2}G_F m_e g_v g_{\nu,Z'} g_{e,v}}{\pi\left(2E_R m_e + m_{Z'}^2\right)} + \frac{m_e g_{\nu,Z'}^2 g_{e,v}^2}{2\pi\left(2E_R m_e + m_{Z'}^2\right)^2}$	$-\frac{G_F m_N Q_v Q_v'(2E_\nu^2 - E_R m_N)}{2\sqrt{2}\pi E_\nu^2\left(2E_R m_N + m_{Z'}^2\right)} + \frac{Q_v'^2 m_N(2E_\nu^2 - E_R m_N)}{4\pi E_\nu^2\left(2E_R m_N + m_{Z'}^2\right)^2}$
Axial Vector	$g_{\nu,Z'}Z'_\mu\bar{\nu}_L\gamma^\mu\nu_L - Z'_\mu\bar{\ell}\gamma^\mu g_{\ell,a}\gamma^5\ell - Z'_\mu\bar{q}\gamma^\mu g_{q,a}\gamma^5 q$	$\frac{2\sqrt{2}G_F m_e g_a g_{e,a} g_{\nu,Z'}}{\pi\left(2E_R m_e + m_{Z'}^2\right)} + \frac{m_e g_{\nu,Z'}^2 g_{e,a}^2}{2\pi\left(2E_R m_e + m_{Z'}^2\right)^2}$	$\frac{G_F m_N Q_a Q_a'(2E_\nu^2 + m_N E_R)}{2\sqrt{2}\pi E_\nu^2\left(2E_R m_N + m_{Z'}^2\right)} - \frac{G_F m_N Q_v Q_a' E_\nu E_R}{\sqrt{2}\pi E_\nu^2\left(2E_R m_N + m_{Z'}^2\right)} + \frac{Q_a'^2 m_N(2E_\nu^2 + E_R m_N)}{4\pi E_\nu^2\left(2E_R m_N + m_{Z'}^2\right)^2}$

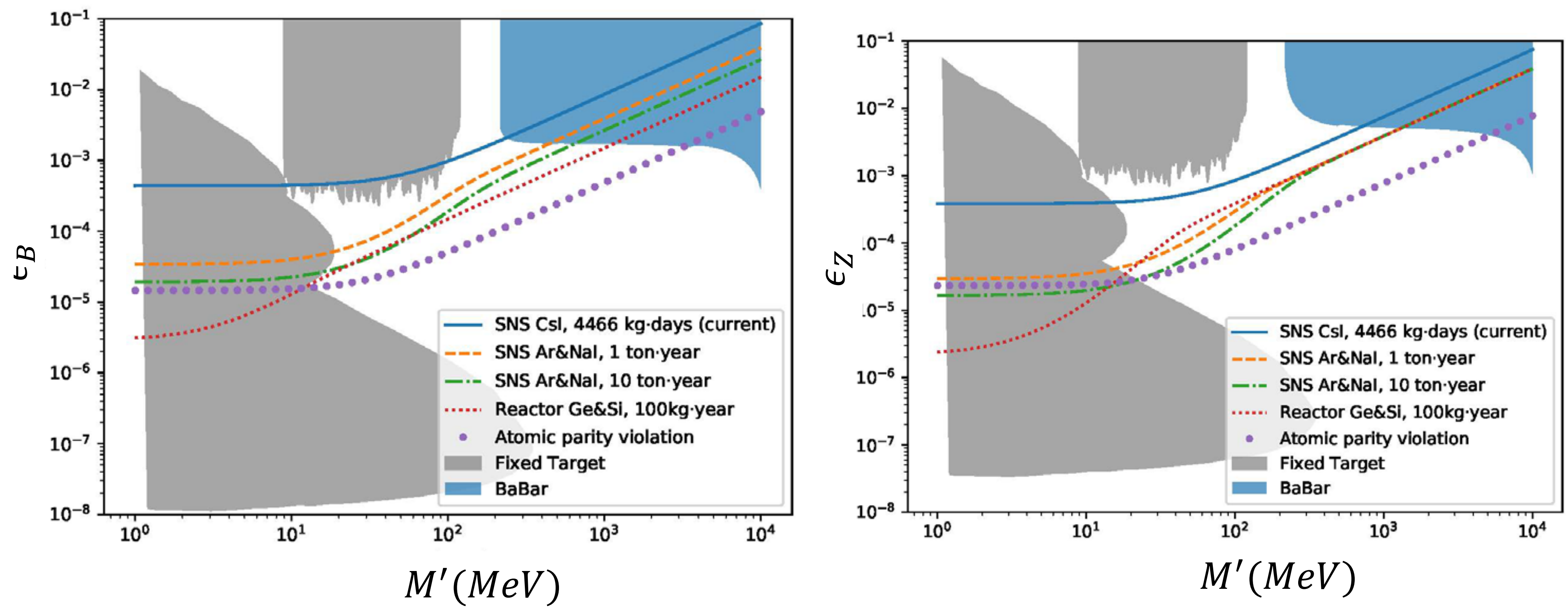
- Cerdeno et al. 1604.01025
- Electron recoils are independent of the source energy E_ν at leading order
- There is ehancement for soft recoils (low momentum transfer)
- For the nuclear case, the large M_N means recoils will be much softer & harder to see
- The electrons have an advantage over the coherent enhancement in some cases

Light Mediator Nuclear Coupling Discovery Reach



The solid blue line is 10,000 kg days in Ge with 100 dru BG and 100 eV threshold
b_n is the effective product of the mediator coupling to the neutrino/nucleon

Kinetic mixing



Abdullah, Dent, Dutta, Liao, Kane, Strigari,'18

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B. Dutta — The Magnificent CEvNS '18

NON-STANDARD INTERACTIONS (NSI)

- The so-called “NSI” represent an effective field theory-like approach to possible contact interactions
- The parameter space is large, and impossible to uniquely constrain with current data
- Complementarity of sources & targets is essential to characterization of this space — gives CEvNS an edge

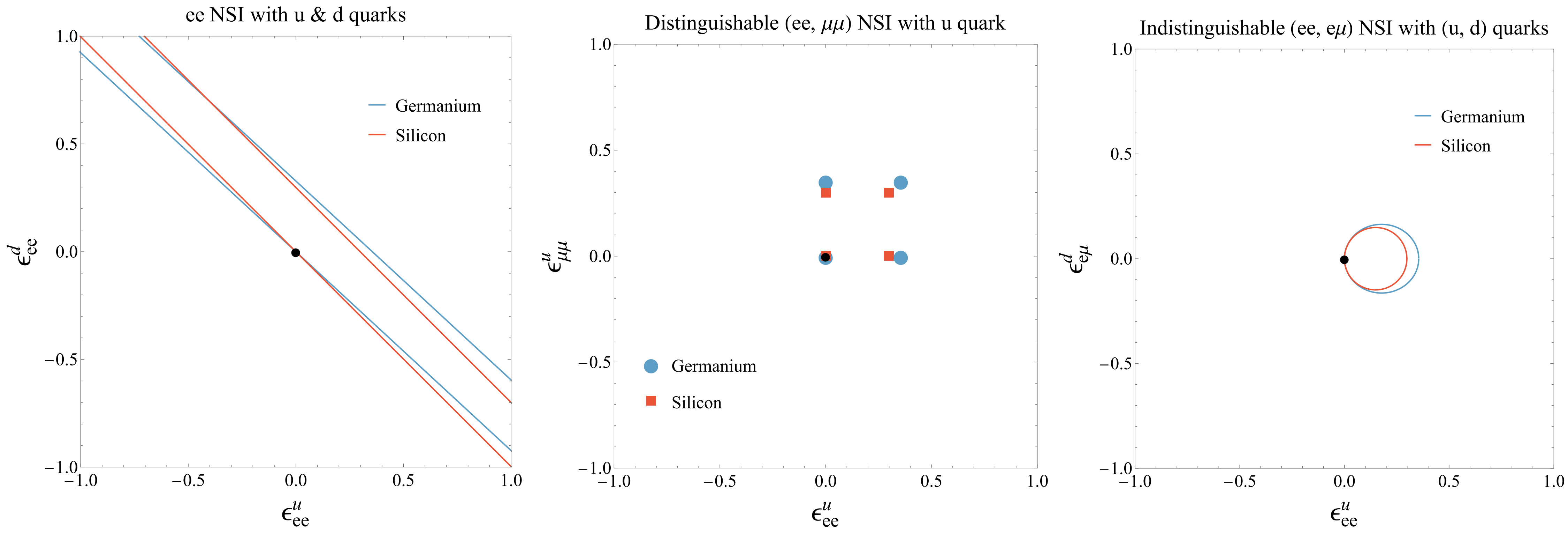
Complementarity of Reactor & Accelerator Data for Constraining NSI

$$Q_V^2 \equiv \left[Z(g_p^V + 2\epsilon_{\alpha\alpha}^{uV} + \epsilon_{\alpha\alpha}^{d}) + N(g_n^V + \epsilon_{\alpha\alpha}^{uV} + 2\epsilon_{\alpha\alpha}^{d})\right]^2$$
$$+ \sum_{\alpha\neq\beta}\left[Z(2\epsilon_{\alpha\beta}^{uV} + \epsilon_{\alpha\beta}^{d}V) + N(\epsilon_{\alpha\beta}^{uV} + 2\epsilon_{\alpha\beta}^{dV})\right]^2$$

- 1711.03521 Dent, Dutta, Laio, Newstead, Strigari, JWW
- The effective vector charge-square has many degeneracies
- NSI coefficients with identical final states interfere: linear relation
- NSI coefficents with different final states sum in quadrature: elliptical relation
- COHERENT is sensitive to muon flavor in addition to electron
- Reactors provide large flux and high statistics for electron flavor constraint

- We are not including “Matter Effect” oscillation data – (further complementarity)
- These experiments are sensitive only to differences in flavor diagonal terms
- They probe zero momentum transfer (even “light” mediators are pointlike)
- They cannot distinguish up-type from down-type couplings

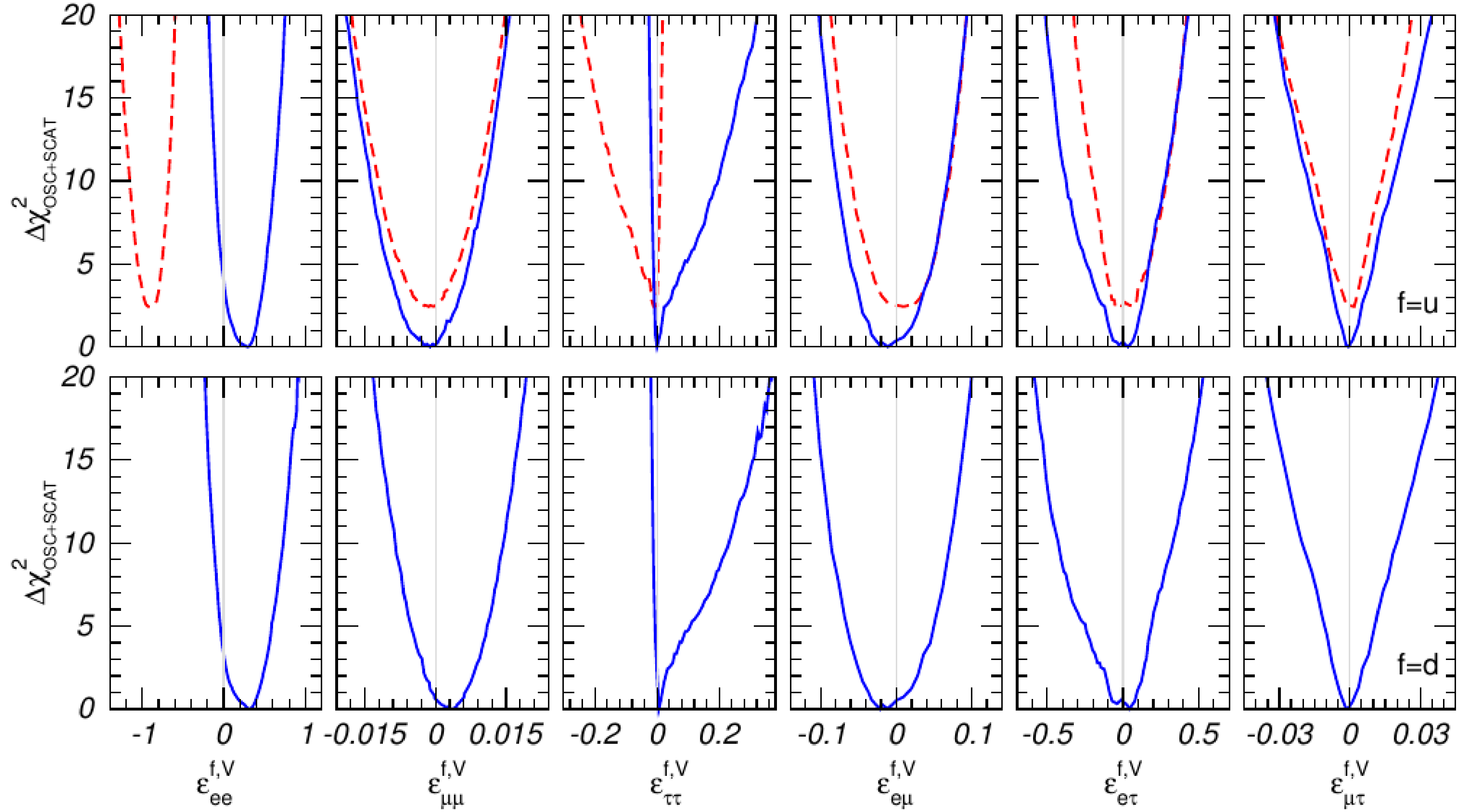
Examples of Degeneracy with 2 Terms



- 1711.03521 Dent, Dutta, Laio, Newstead, Strigari, JWW
- The degeneracy-lifting effect of multiple target materials is exhibited for Si and Ge
- NSI contributions interfere within a single amplitude (left)
- As a sum of squares, with flavor contributions distinguishable (middle)
- As a sum of squares, with flavor contributions indistinguishable (right)

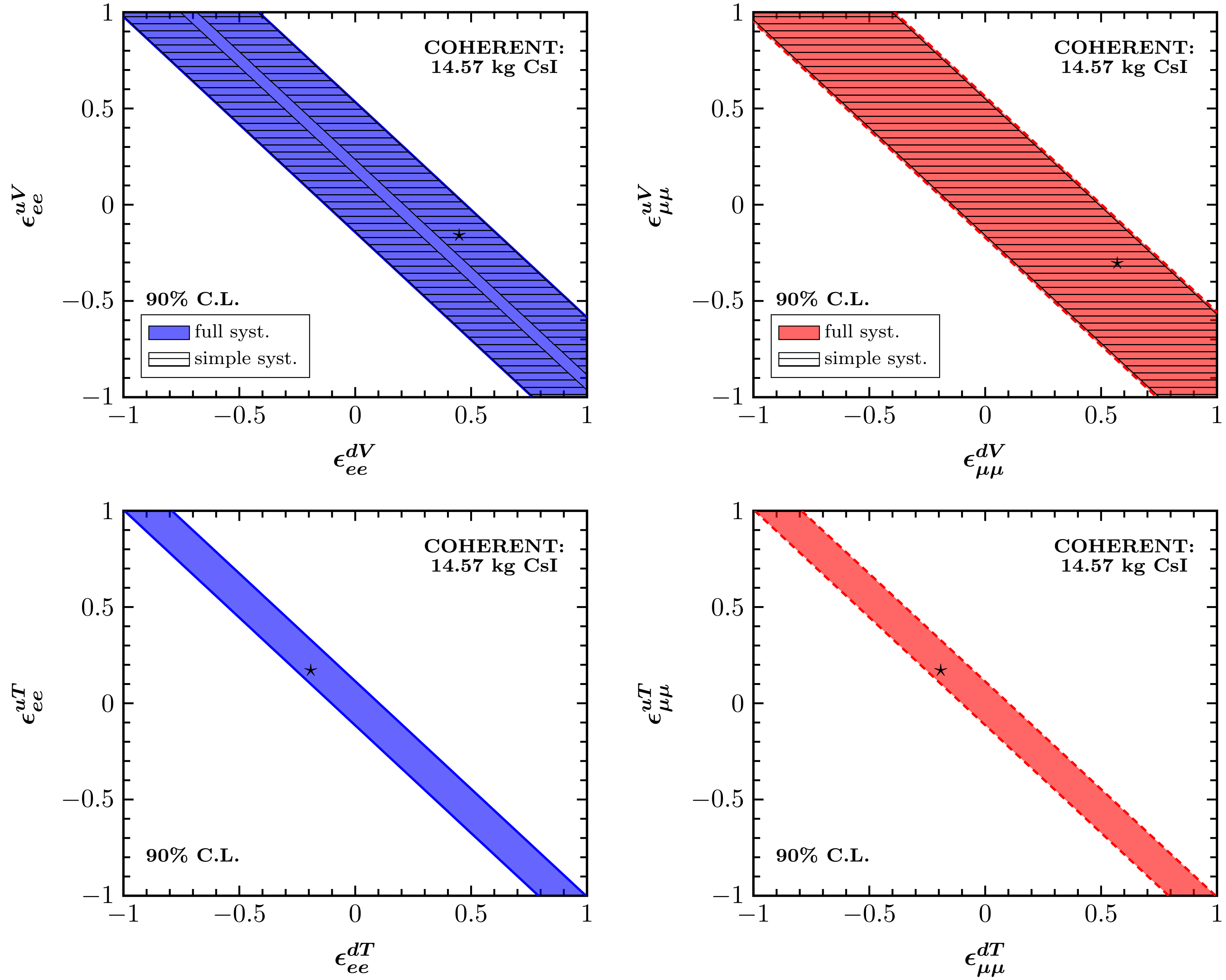
Pre-COHERENT NSI limits

From oscillation experiments + CHARM + NuTeV



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

Analysis of the COHERENT data: NSI (2 param.)



D.K. Papoulias and T.S. Kosmas, Phys.Rev. **D97** (2018) 033003

interesting accelerator-reactor complementarity in CEvNS: Dent et al., PRD 97 (2018) 035009

Constraints

Coherent Elastic Neutrino-Nucleus Scattering

Sensitivity to new physics
- The case of NSI
- Constraints
- The NGI case
- Constraints from oscillations
- Parameter space scenarios
- One-parameter analysis
- Vector -vs- SM+vector

Summary

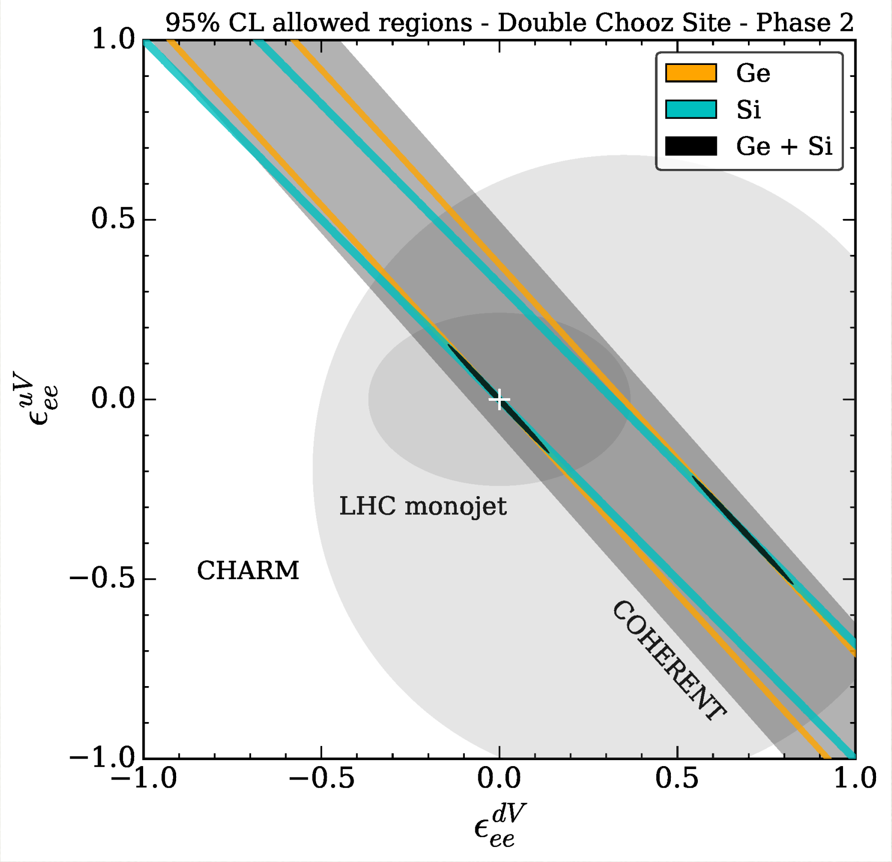
COHERENT data has been used to constraint NSI contributions to the CEνNS

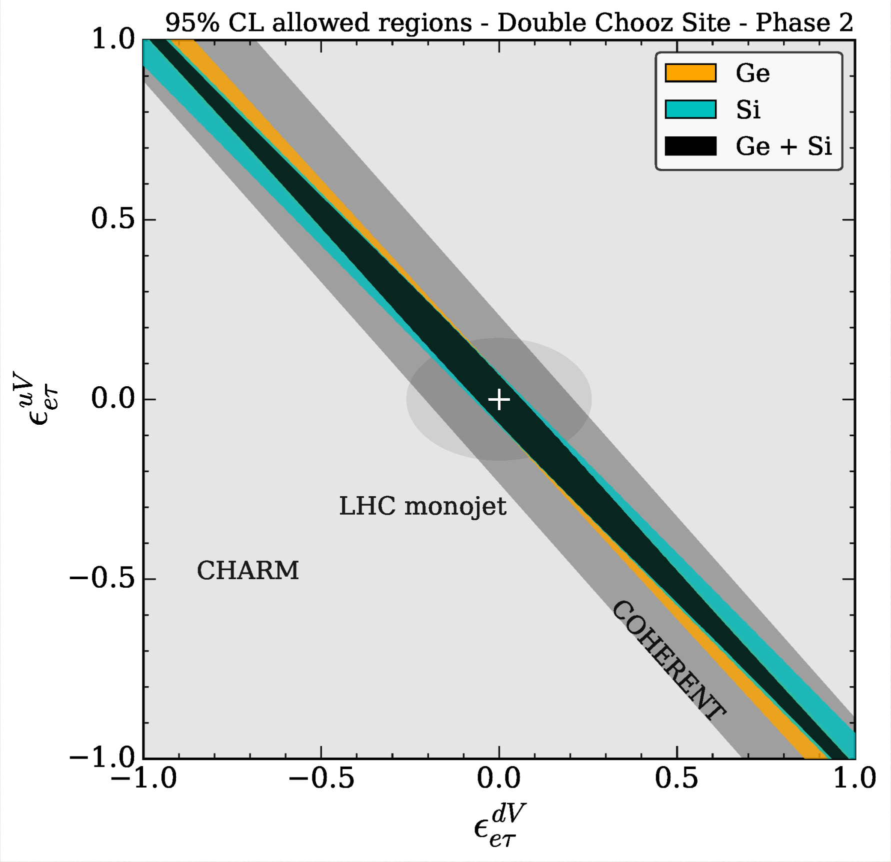
Gonzalez-Garcia et. al, 2017

J. Liao & D. Marfatia, 2017

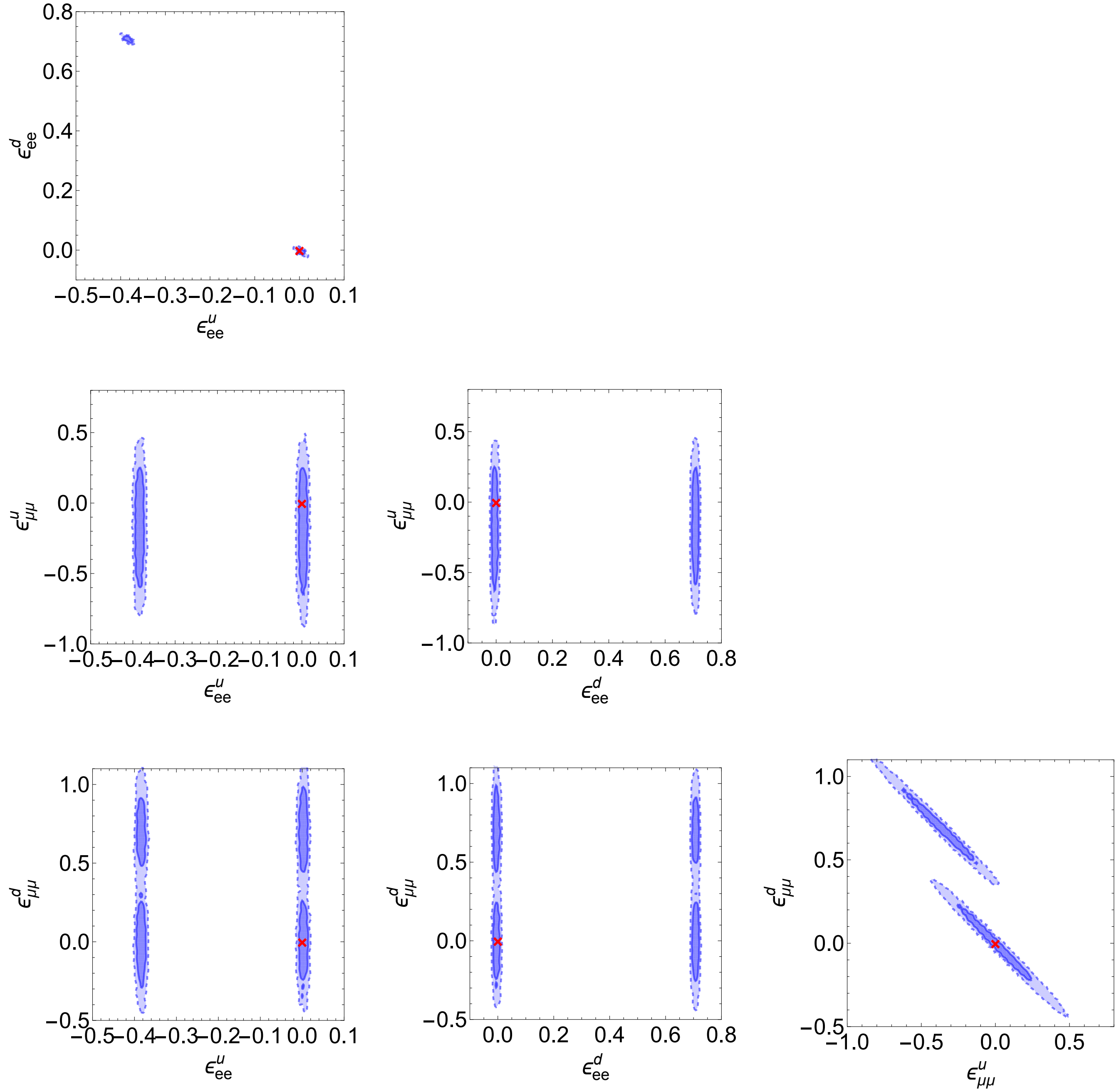
Kosmas et. al, 2018

Billard et. al, 2018



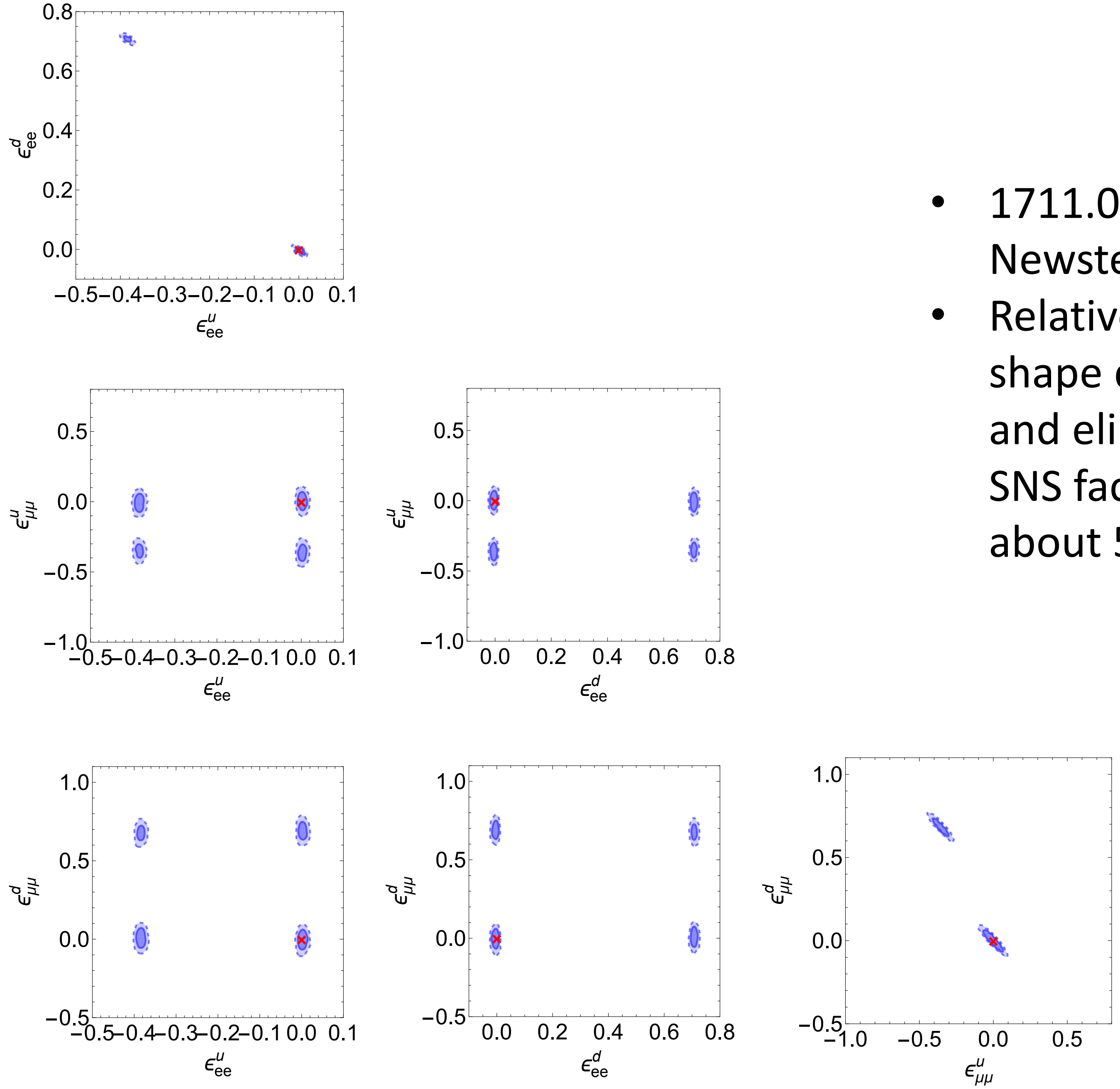


Breaking Degeneracy with 4 Terms



- 1711.03521 Dent, Dutta, Laio, Newstead, Strigari, JWW
- Multiple target materials PLUS reactor/accelerator combination can break a four-fold degeneracy
- Discrete reflection symmetries (squares) persist; X is SM
- Posterior probabilities are projected using Bayesian MultiNest framework
- Contours are 68% and 95% credible regions
- We marginalize over background and flux uncertainties
- 1 GW, 20 m, 10^4 kg-d, 100 eV
- 1 ton-y SNS, 2 keV NaI, 30 keV Ar

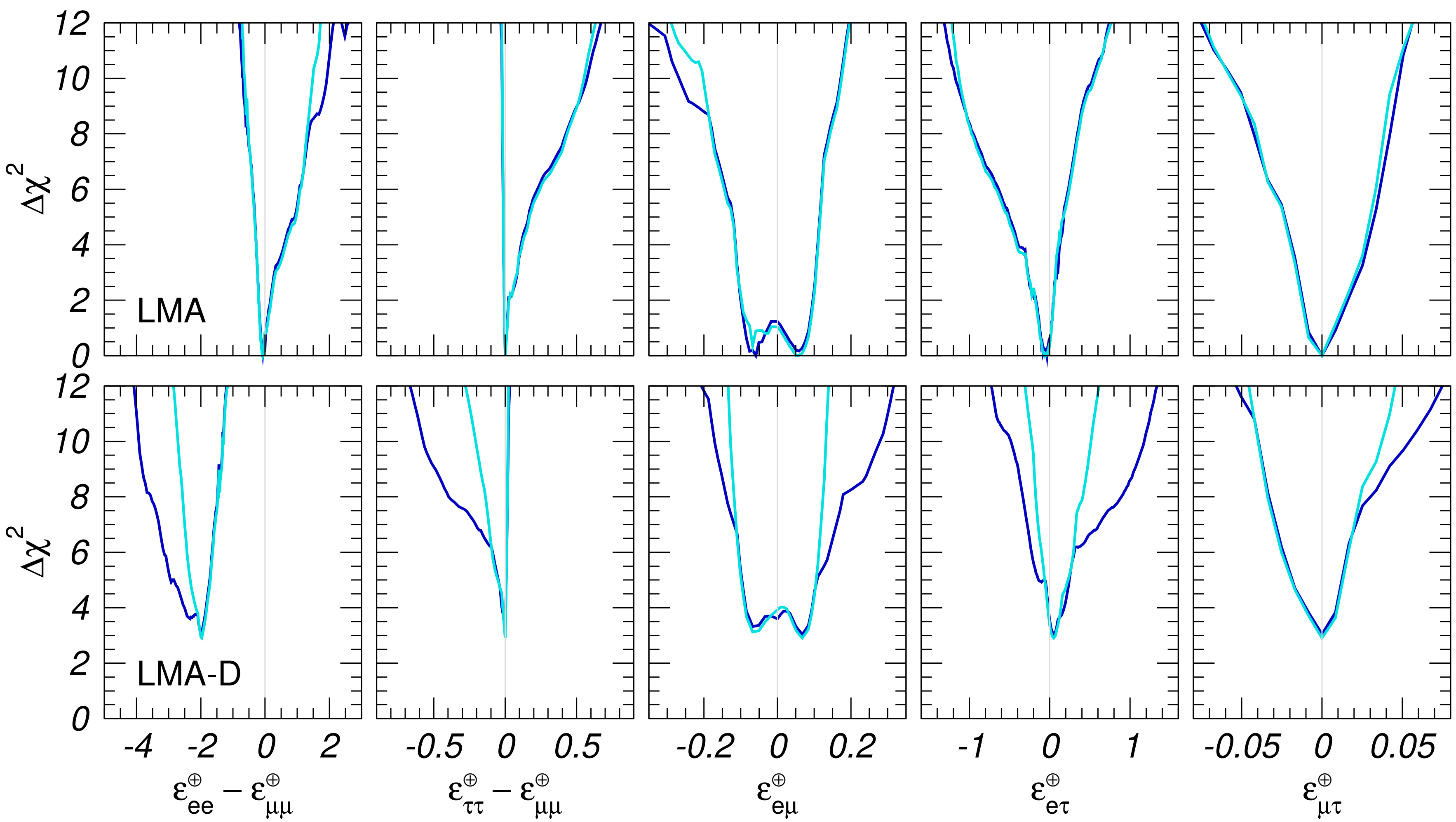
Breaking Degeneracy with 4 Terms



- 1711.03521 Dent, Dutta, Laio, Newstead, Strigari, JWW
- Relative to prior figure, recoil shape data (via spectral binning) and elimination of BG for the SNS facilitate local precision of about 5% in Fermi units

Combined analysis of oscillation and COHERENT

- Non-diagonal couplings are also reduced.



SHORT BASELINE STERILE NEUTRINO OSCILLATION

- A sterile neutrino intrinsically alters the recoil spectrum as a function of E_ν and L

- This SHAPE discrimination on top of rate effects is critical for 1: Discovery (separation from null hypothesis of SM CEvNS) and 2: Characterization (isolation of preferred mixing and mass scale)

- You don't have to believe in sterile neutrinos to appreciate the importance of probing $E_\nu/L \simeq \mathrm{eV}^2$

REACTOR and GALLIUM ANOMALIES

- Nuclear reactors produce $\bar{\nu}_e$ flavor states; effect of steriles is *disappearance*
- The "REACTOR ANOMALY": There is a global ~ 3σ flux deficit relative to the theoretical expectation. This is amplified by recent reevaluation of the theory (Huber / Mueller et. al 1101.2663 & 1106.0687). Observed/Expected is ~ 94%
- Radiactive source experiments with Gallium (GALLEX and SAGE – 0711.4222 & 1006.3244) likewise show a flux deficit.
- There is an observed "bump" in the reactor spectrum near 5 MeV (1610.04326)
- Daya Bay (1704.02276) has used time evolution of the fuel composition to break down flux contributions. There is a suggestion that the anomaly is associated with ^{235}U, while ^{239}Pu is consistent. This would disfavor a sterile interpretation. However, there is some disagreement on methodolgoy (1510.08948)
- Dentler et. al (1709.04294) find goodness of fit 73% with free flux normalizations vs. 18% with fixed flux plus sterile $\Delta m^2 \sim \mathrm{eV}^2$.
- However, DANSS and NEOS prefer sterile to flux rescaling. This weakens the global preference. Including time-dependence of decay chains and neutron capture on fission productsr reduces Daya Bay's preference below 2σ – P. Huber

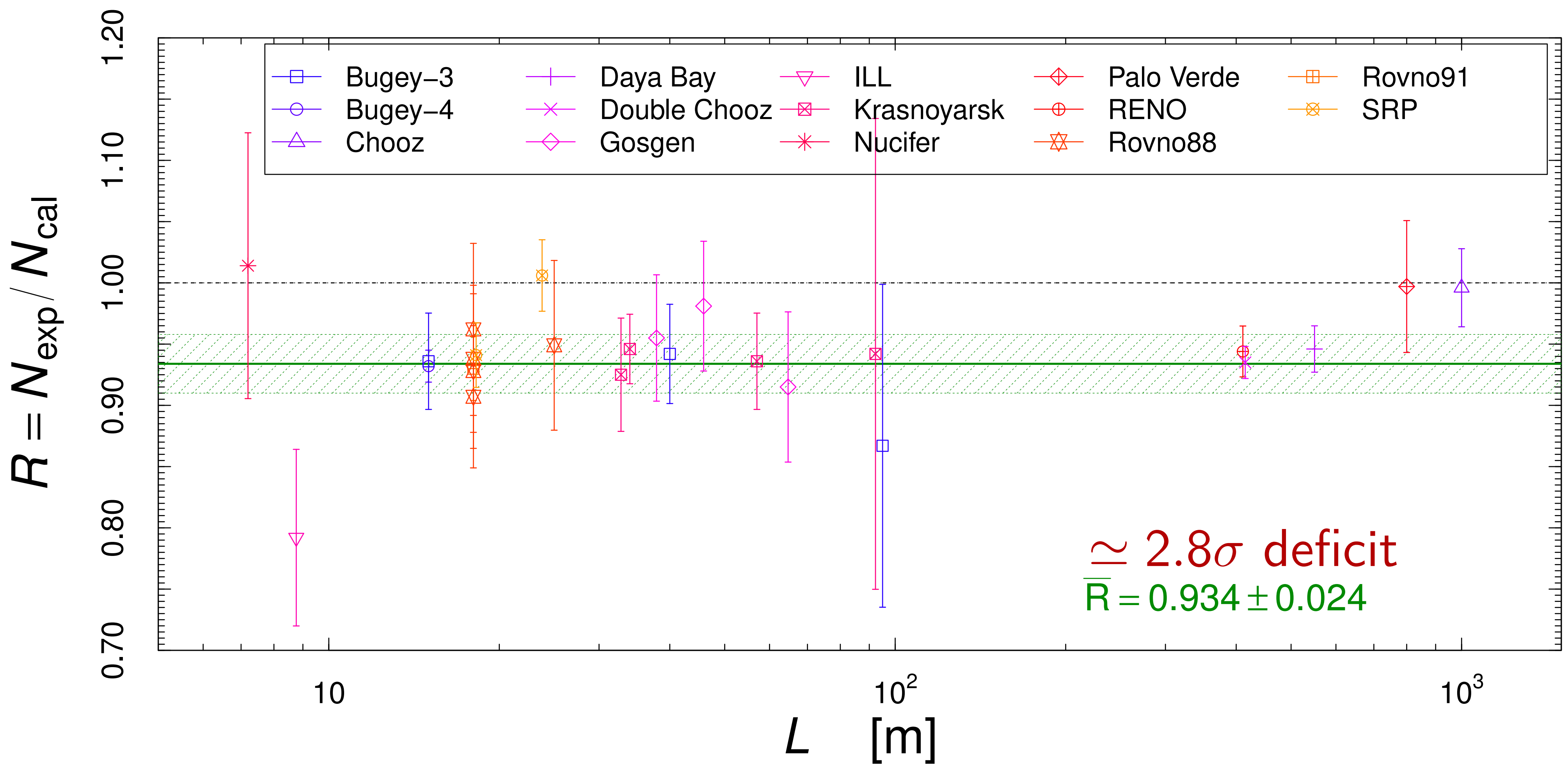
Reactor Antineutrino Anomaly (RAA)

[PRD 83 (2011) 073006]

2011: new reactor $\bar{\nu}_e$ fluxes by Huber and Mueller+ (HM)

[Huber, PRC 84 (2011) 024617] [Mueller et al., PRC 83 (2011) 054615]

Previous reactor rates evaluated with new fluxes ⇒ deficit



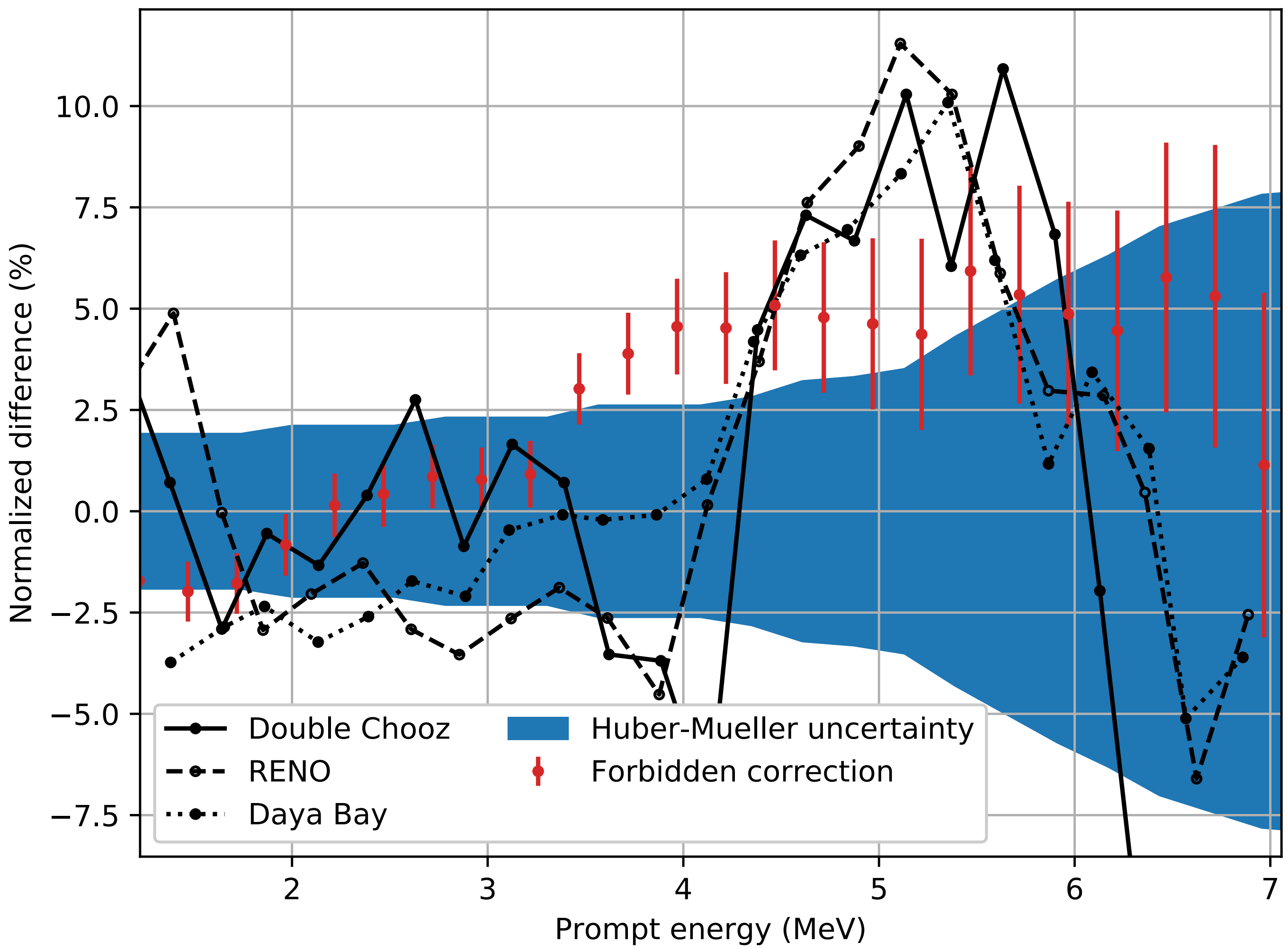
Suppression at detector due to active-sterile oscillations?

Results from the analyses including the β spectra

Taking into account the (first-forbidden) decays of

^{86}Br(0^+), ^{86}Br(2^+), ^{87}Se, ^{88}Rb, ^{89}Br($3/2^+$), ^{89}Br($5/2^+$), ^{90}Rb, ^{91}Kr($5/2^-$), ^{91}Kr($3/2^-$), ^{92}Rb, ^{92}Y, ^{93}Rb, ^{94}Y(0^+), ^{94}Y(0^+), ^{95}Rb($7/2^+$), ^{95}Rb($3/2^+$), ^{95}Sr, ^{96}Y, ^{97}Y, ^{98}Y, ^{133}Sn, ^{134m}Sb(6^+), ^{134m}Sb(6^+?), ^{135}Te, ^{136m}I, ^{137}I, ^{138}I, ^{139}Xe, ^{140}Cs, ^{142}Cs

decreases the $\bar{\nu}$ flux by some 5% !



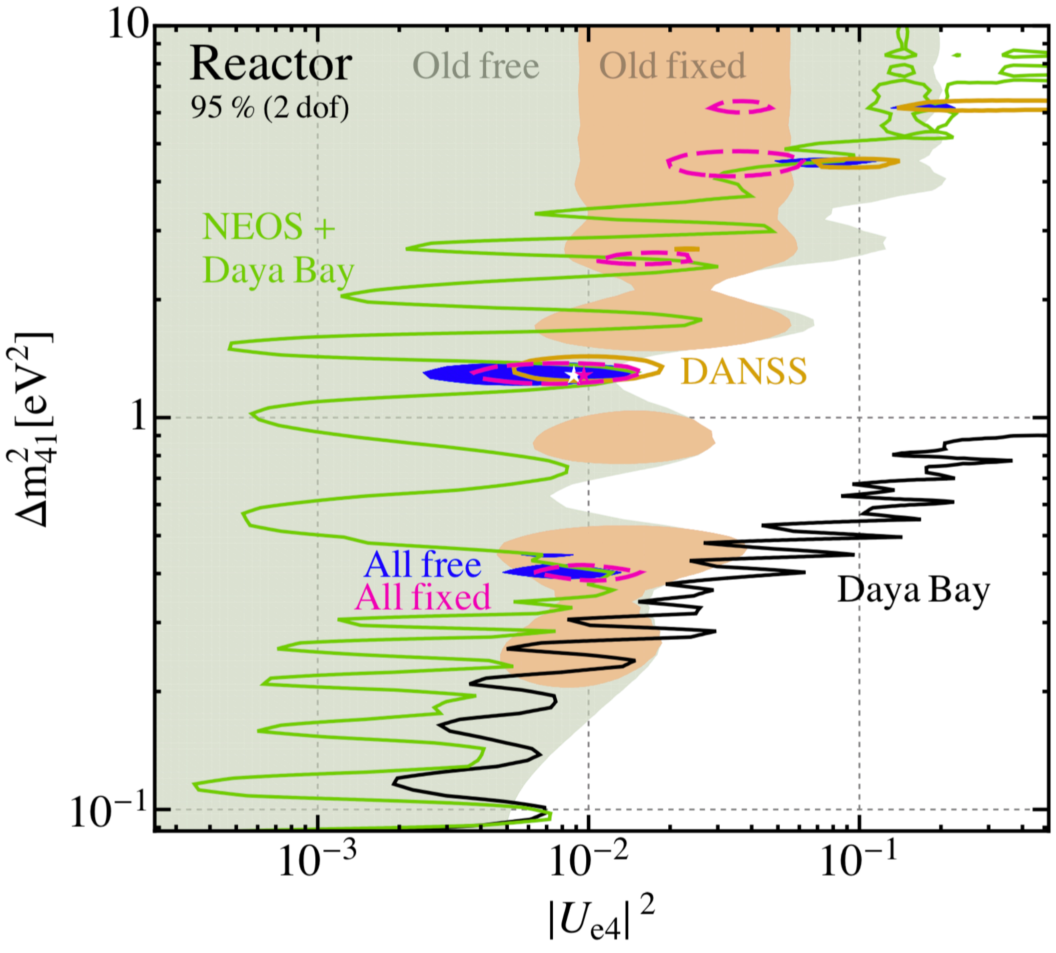
The spectral sholder appears due to forbidden spectral corrections !

See: L. Hayen, J. Kostensalo, N. Severijns, J.Suhonen, First-forbidden transitions in reactor antineutrino spectra, Phys. Rev. C 99 (2019) 031301(R)

Daya Bay DANSS and NEOS

- Newer (1607.01174, 1610.0534, 1606.02896) reactor analyses take RATIOS of observations at different baselines in order to REMOVE dependence upon the flux normalization and intrinsic spectral shape.

- Inclusion of a sterile improves the fit at the level of 3σ (1803.10661)



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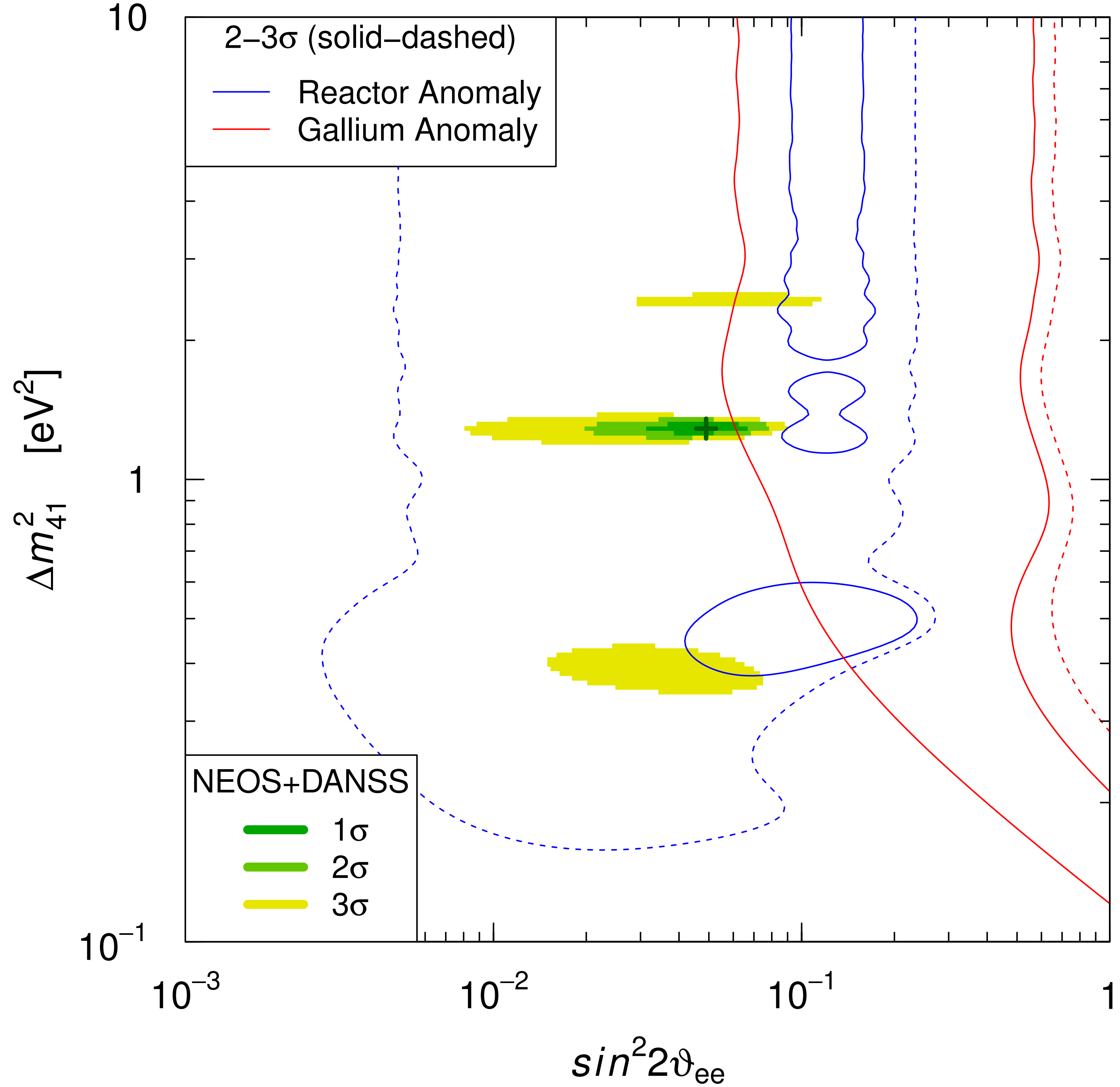
Model-independent fit of $\overset{(-)}{\nu}_e$ DIS

[SG et al., PLB 782 (2018) 13]

DANSS + NEOS + RAA + Gallium



DANSS + NEOS do not agree with Gallium and RAA

LSND and MiniBooNE

- At MiniBooNE, 8 GeV protons from FNAL Booster strike a Be target. Magnetically focused charged pions produce ν_μ or $\bar{\nu}_\mu$ beams. Detector is 818 tons of mineral oil at ~ 540 m baseline. Detection is flavor-sensitive CCQE off electrons. Neutrino energies are around 500 MeV. (1805.12028)
- Around 10^{21} protons on target
- There is 4.8σ evidence of an excess of electron neutrino appearance.
- Two neutrino mu to e oscillation has goodness of fit 20.1%. Background only hypothesis is $5{\times}10^{-7}$ relative to best fit with $L/E_\nu \approx 1[\mathrm{m/MeV}]$.
- This is MUCH too short for standard neutrino oscillation to be responsible. BUT – the transition could occur *through* a sterile.
- In combination with results form the prior similar LSND experiments at Los Alamos (which is compatible) the significance is 6.1σ

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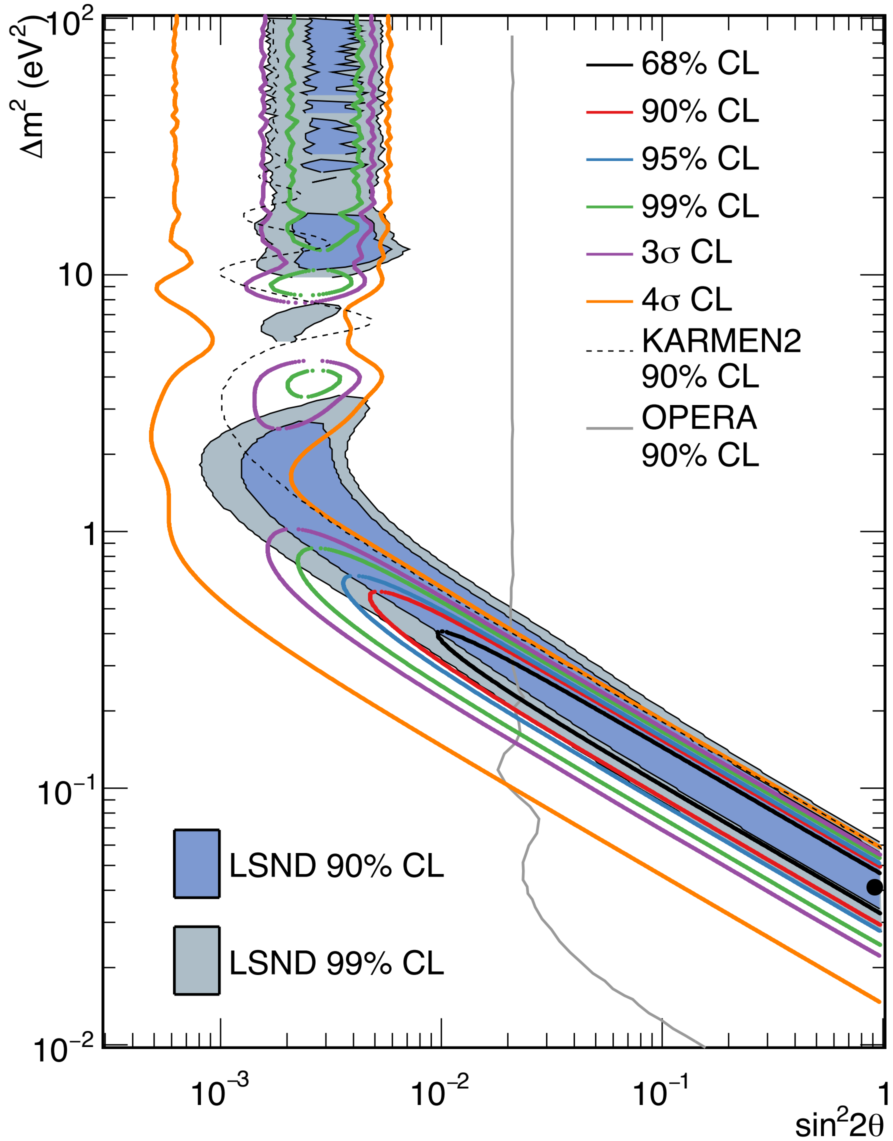
MiniBooNE

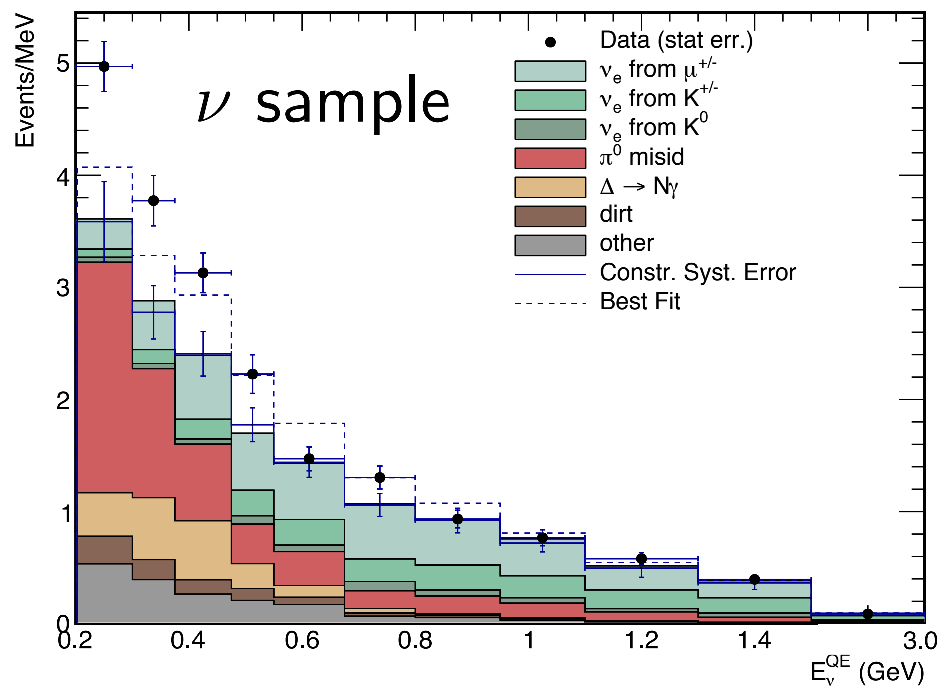
[arxiv:1805.12028]

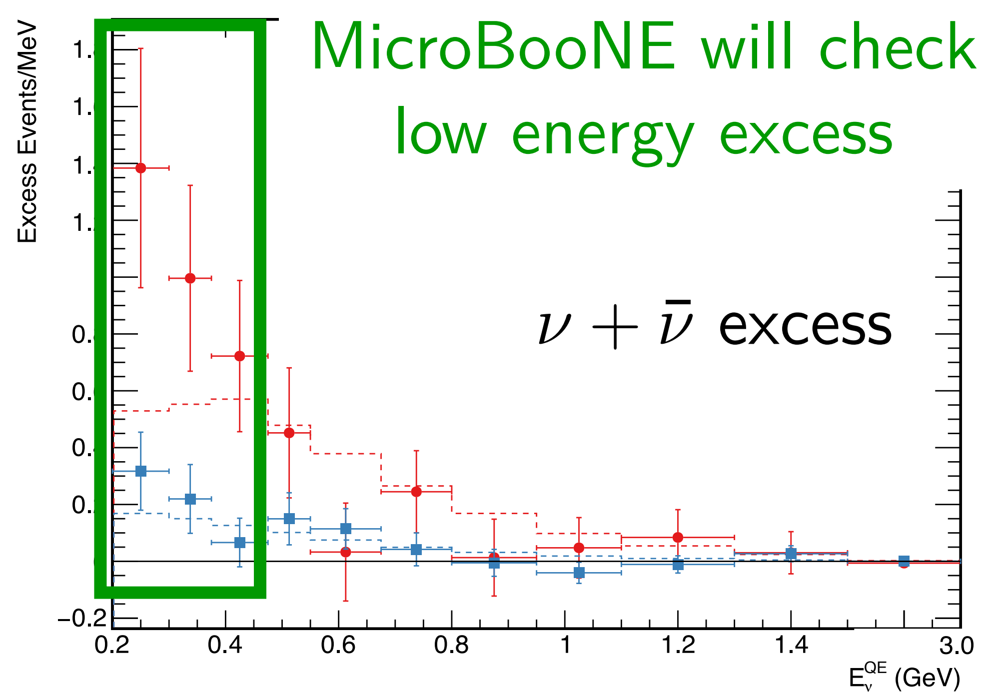
purpose: check LSND signal

$L \simeq 541$ m, 200 MeV $\leq E \lesssim$ 3 GeV

no money, no near detector

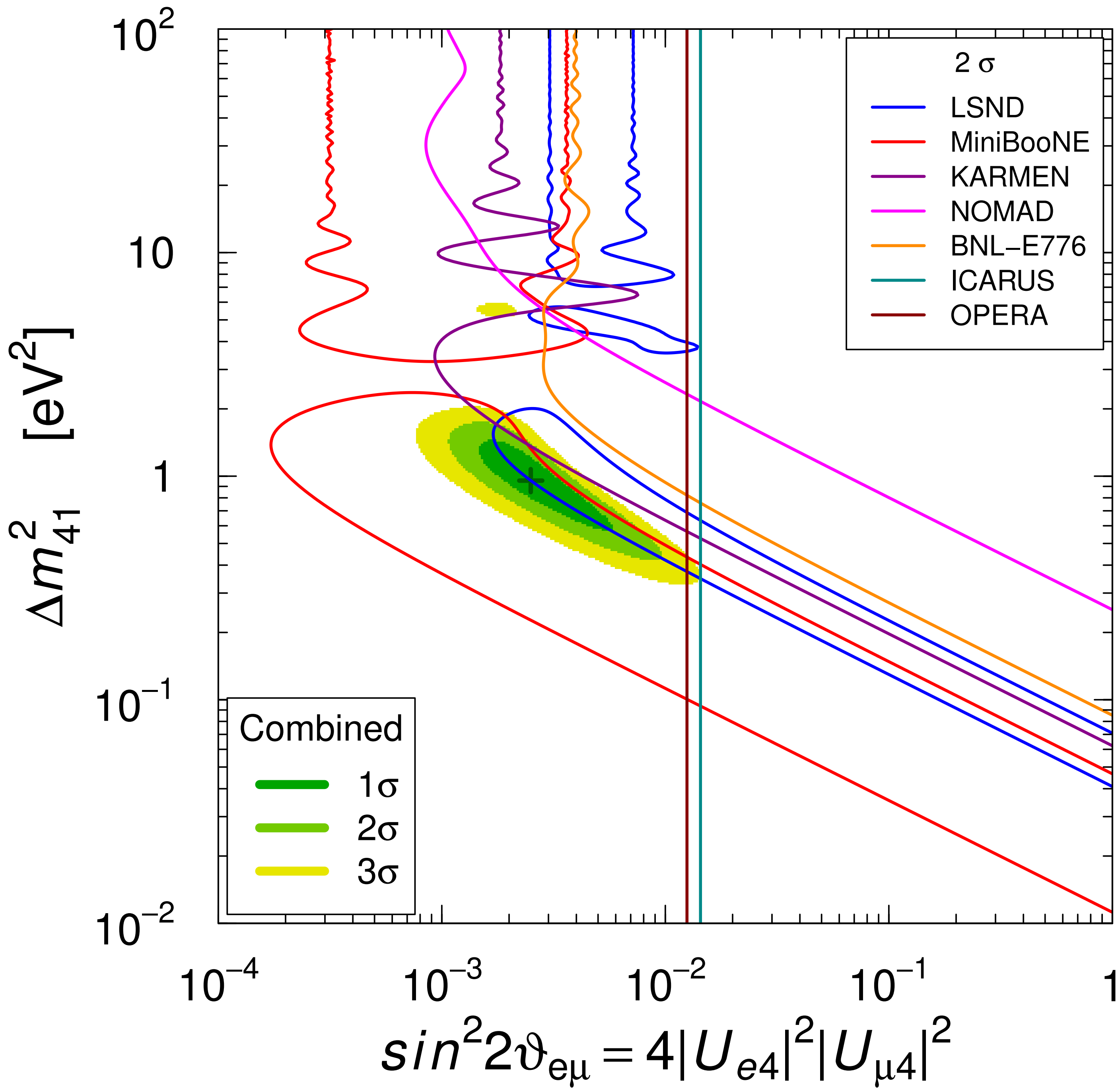






Global fit of $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ APP

[SG+, preliminary]



ICARUS and OPERA exclude MiniBooNE best fit

LSND and MiniBooNE only partially in agreement

KARMEN cuts part of LSND region

Oscillation to Sterile 4th Flavor Neutrino

$$P_{(\alpha\to\beta)} = \sin^2\left[2\theta\right] \times \sin^2\left[\frac{\Delta m^2 L}{4E_\nu}\right]$$

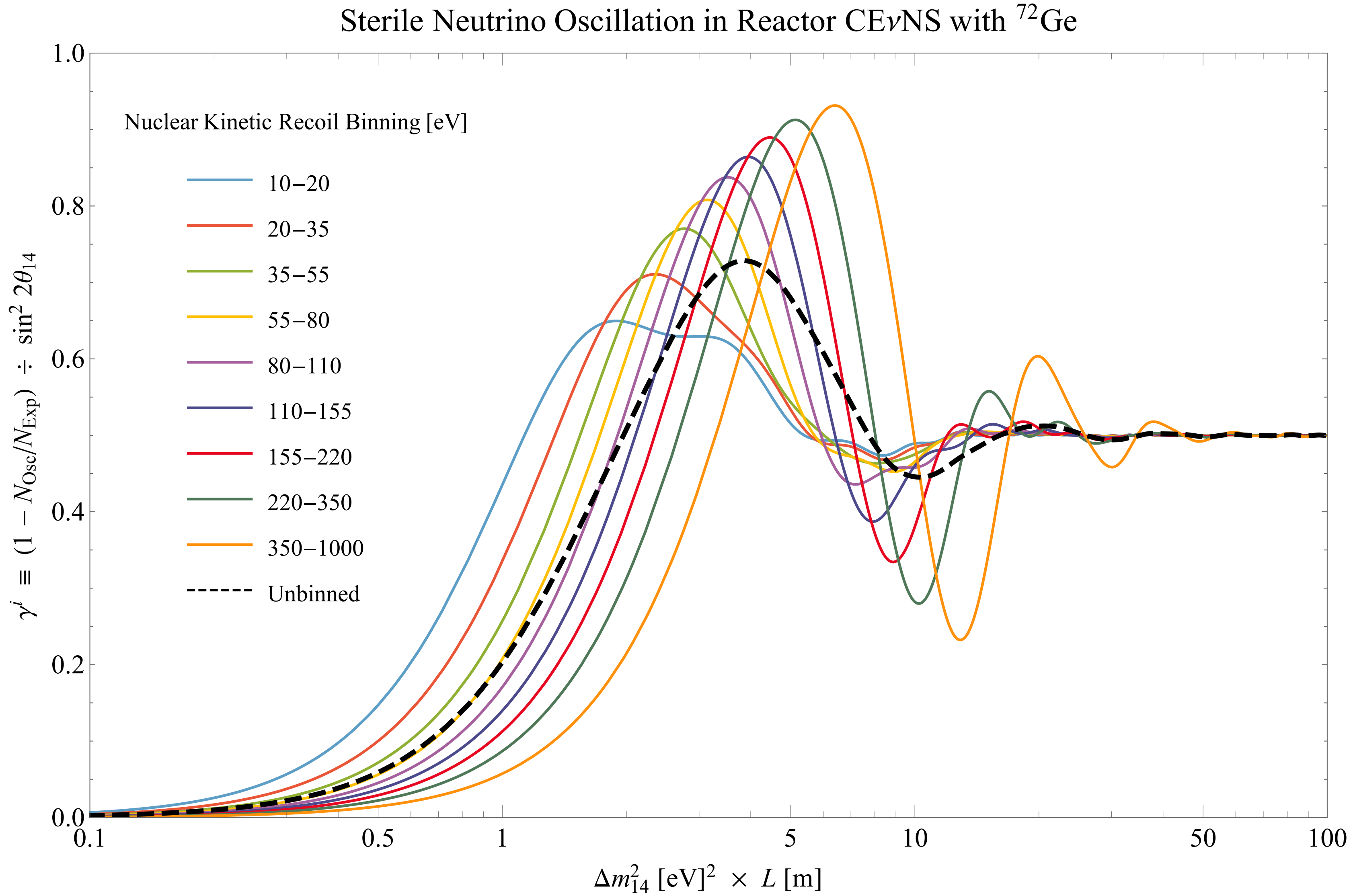
$$\lambda = 4.97\ [\mathrm{m}] \times \left\{\frac{E_\nu}{1\ [\mathrm{MeV}]}\right\} \times \left\{\frac{1\ \mathrm{eV}^2}{\Delta m^2}\right\}$$

$$\gamma_i(\Delta m^2_{14} L) \ \equiv\ \frac{1\ -\ (N^i_{\mathrm{Osc}}/N^i_{\mathrm{Exp}})}{\sin^2 2\theta_{14}}$$

$$\gamma_i(\Delta m^2_{14} L)\ =\ \left\langle \sin^2\left[\frac{\Delta m^2_{14} L}{4E_\nu}\right]\right\rangle_{E_\nu}\ \equiv\ \iint dE_\nu\, d\sigma\, \lambda \times \sin^2\left[\frac{\Delta m^2_{14} L}{4E_\nu}\right]\ \div\ \iint dE_\nu\, d\sigma\, \lambda$$

- Probability for oscillation depends on mixing (amplitude) and mass gap (phase)
- For the region of interest, an experimental baseline on the order of meters is relevant
- Dimensionless scale-invariant basis functions encapsulate all aspects of theory
- Neutrino anomalies exist in radioactive source (GALLEX,SAGE), solar (Solar + KamLAND), and short-baseline accelerator (LSND, MiniBooNE) experiments

Depletion via Oscillation



- Larger values in the vertical correspond to greater depletion via oscillation
- Universal curve bases are rescaled (vert.) by mixing amplitude and (horiz.) mass gap
- Bins are selected for approximately equivalent population event rates
- Even with a fixed length scale, multiple energy samples give sensitivity to oscillation
- Oscillation decoheres over multiple cycles & with mixing in the neutrino energy

Formalism

- At the matrix element level: Sum over intermediate states and square the amplitude

$$P_{\alpha\beta} = \sum_{j,k=1}^{4} U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k} \exp\left(-i \frac{\Delta m^2_{jk} L}{2E}\right)$$

- Transition to self and transition to alternate flavor

$$P_{\alpha\alpha} = 1 - 4|U_{\alpha 4}|^2 \left(1 - |U_{\alpha 4}|^2\right) \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$P_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2 \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

Formalism

- CEvNS Neutral current touches all flavors – use unitarity at reactors

$$P_{\bar{\nu}_e \to \bar{\nu}_e} + P_{\bar{\nu}_e \to \bar{\nu}_\mu} + P_{\bar{\nu}_e \to \bar{\nu}_\tau} = 1 - 4|U_{e4}|^2 \left(1 - |U_{e4}|^2 - |U_{\mu 4}|^2 - |U_{\tau 4}|^2\right) \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

- And at the SNS beamline. If we idealize prompt and delayed as separate experiments we can solve the system.

$$P_{\nu_\mu \to \nu_\mu} + P_{\nu_\mu \to \nu_e} + P_{\nu_\mu \to \nu_\tau} = 1 - 4|U_{\mu 4}|^2 \left(1 - |U_{e4}|^2 - |U_{\mu 4}|^2 - |U_{\tau 4}|^2\right) \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

$$P_{\bar{\nu}_\mu \to \bar{\nu}_\mu} + P_{\bar{\nu}_\mu \to \bar{\nu}_e} + P_{\bar{\nu}_\mu \to \bar{\nu}_\tau} = 1 - 4|U_{\mu 4}|^2 \left(1 - |U_{e4}|^2 - |U_{\mu 4}|^2 - |U_{\tau 4}|^2\right) \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

$$P_{\nu_e \to \nu_e} + P_{\nu_e \to \nu_\mu} + P_{\nu_e \to \nu_\tau} = 1 - 4|U_{e4}|^2 \left(1 - |U_{e4}|^2 - |U_{\mu 4}|^2 - |U_{\tau 4}|^2\right) \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

$$|U_{e4}|^2 \;\; ; \;\; |U_{\mu 4}|^2 \;\; ; \;\; 1 - |U_{e4}|^2 - |U_{\mu 4}|^2 - |U_{\tau 4}|^2$$

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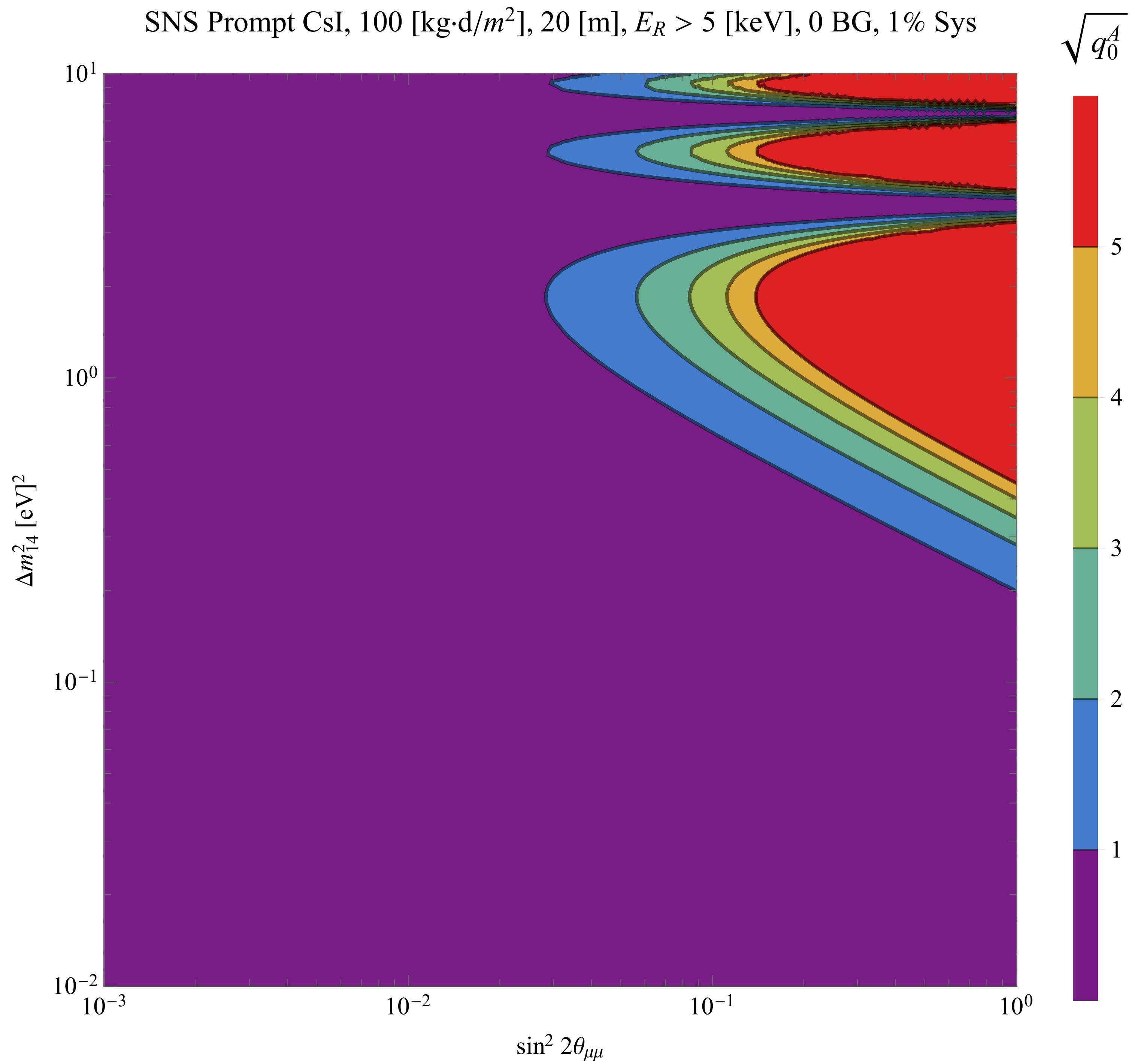
SNS Prompt



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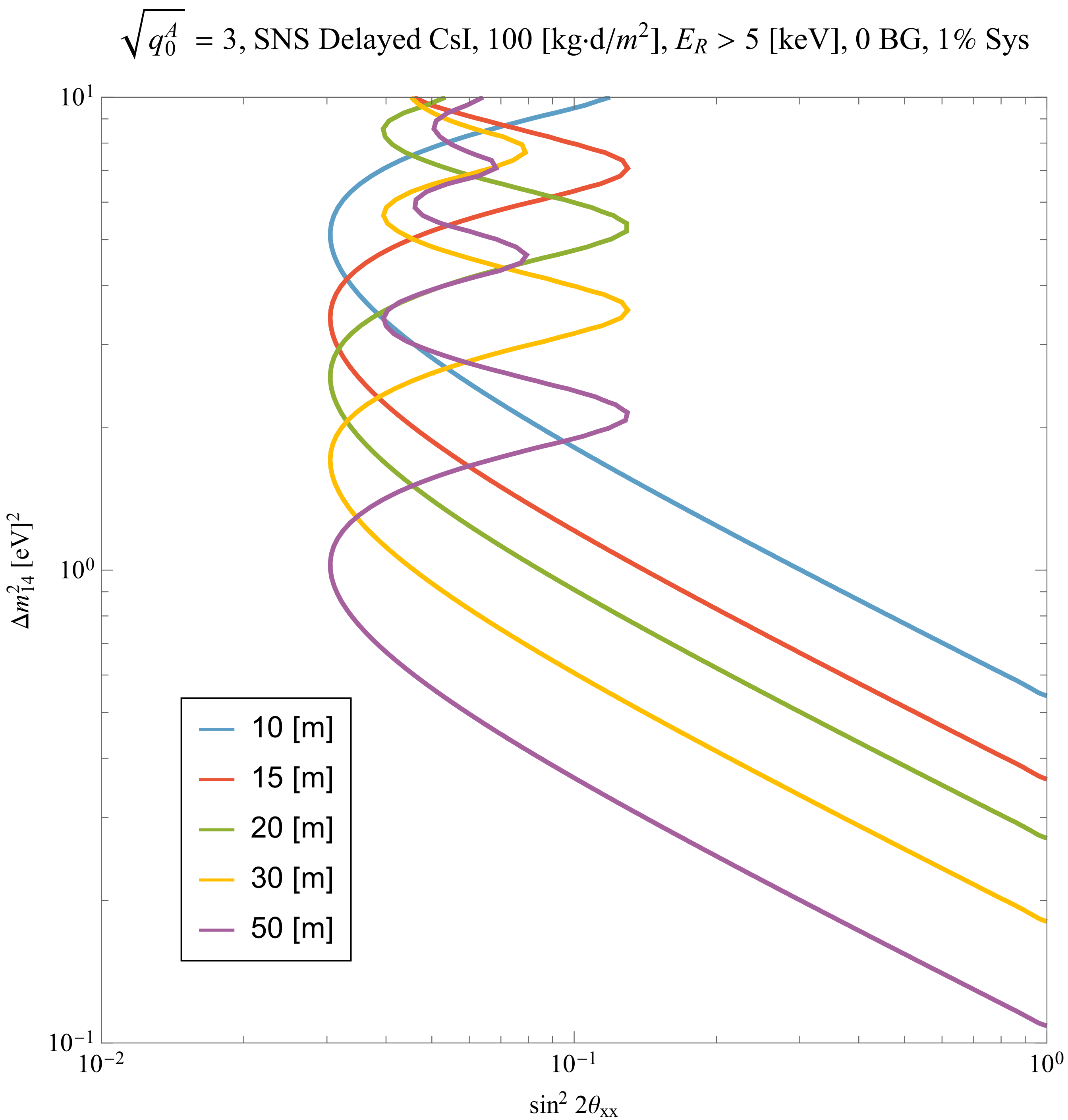
SNS Delayed



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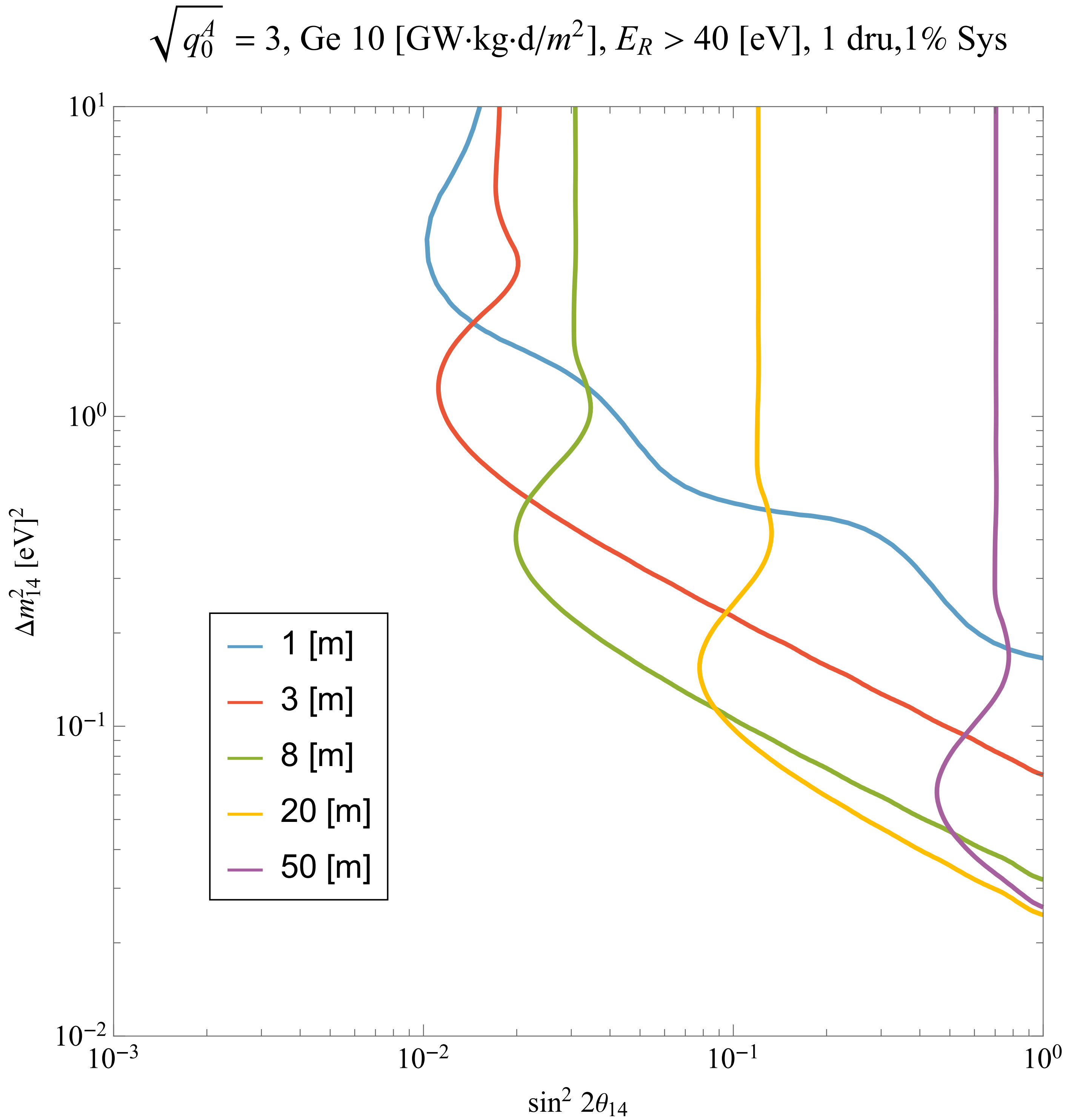
Reactor


$\sqrt{q_0^A} = 3$, Ge 10 [GW·kg·d/m^2], $E_R > 40$ [eV], 1 dru,1% Sys
10^1
10^0
10^{-1}
10^{-2}
Δm^2_{14} [eV]^2
1 [m]
3 [m]
8 [m]
20 [m]
50 [m]
10^{-3}
10^{-2}
10^{-1}
10^0
$\sin^2 2\theta_{14}$

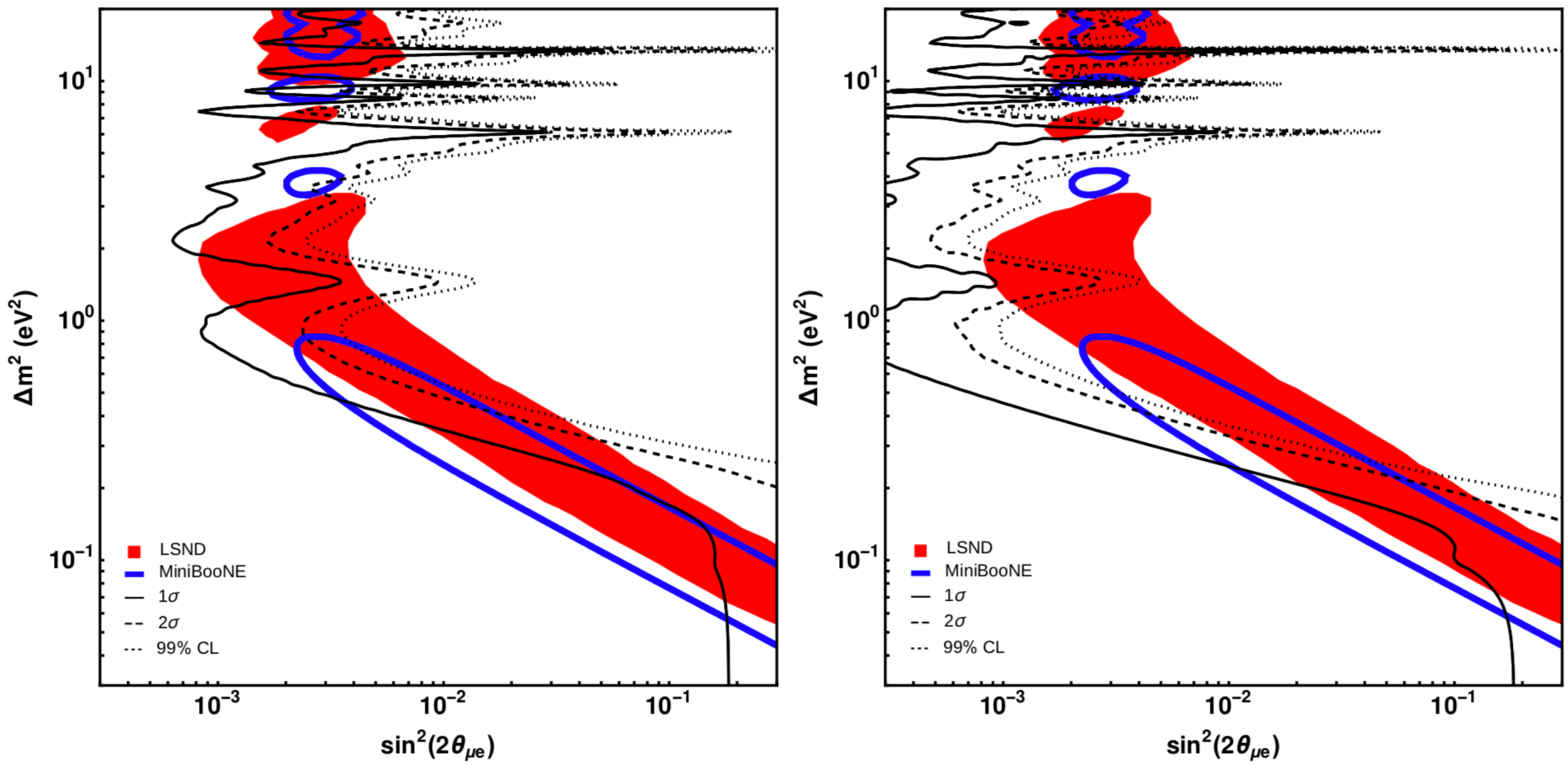


FIG. 2. The projected constraints on the sterile neutrino parameter space for a 100 kg CsI detector and source that generates 4×10^{23} protons on target per year with an energy of 1 GeV, after collecting data for a total of 3 years (left) or 10 years (right). In each case, we have assumed that the detector was located at a distance of 20 meters from the source during the first half of the exposure, and at a distance of 40 meters during the second half. These constraints are compared to the regions that could potentially account for the LSND [1] and MiniBooNE [2] anomalies (at the 99% confidence level).

Blanco, Hooper, Machado 1901.08094

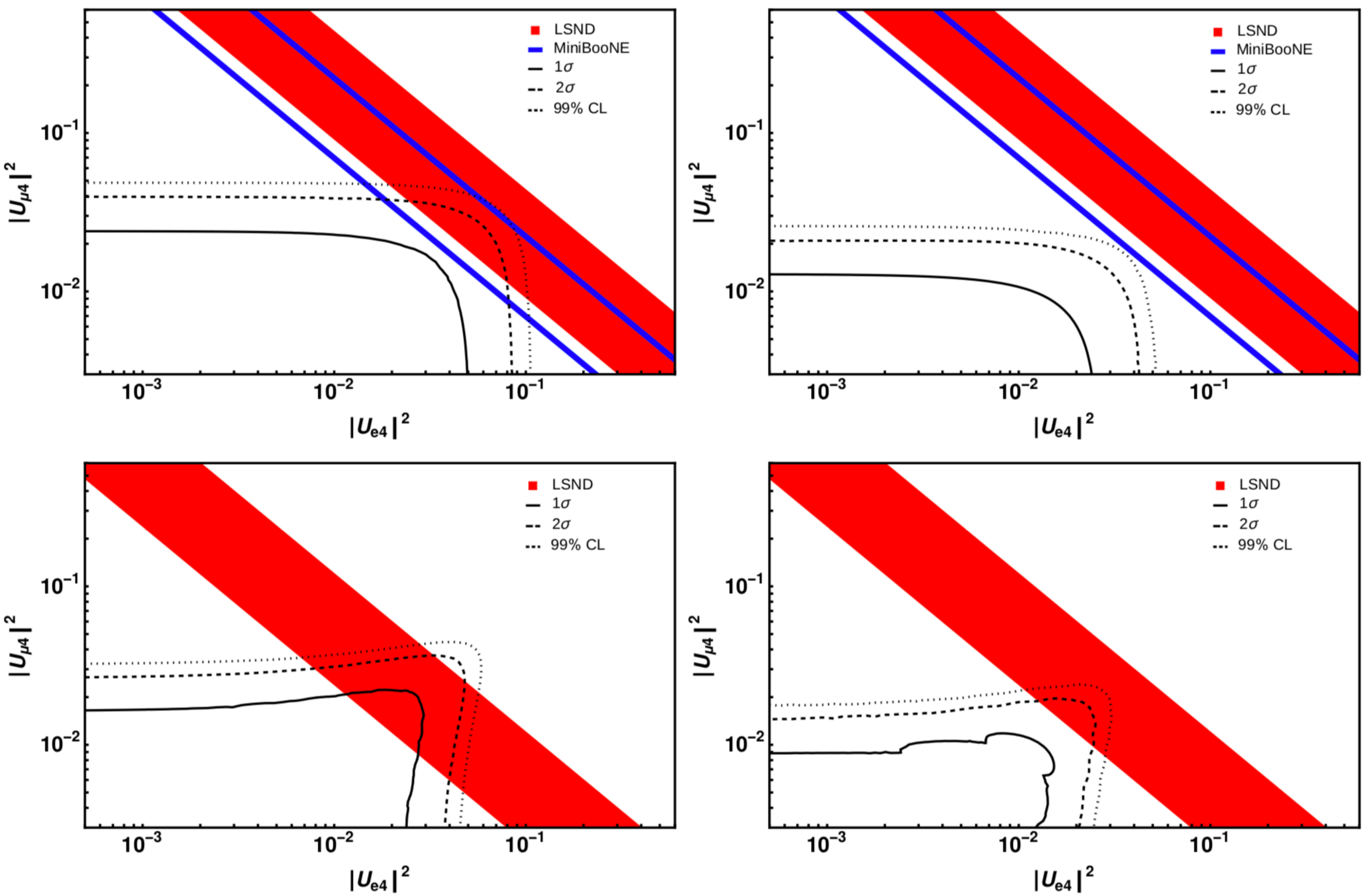


FIG. 3. As in Fig. 2, but in terms of the $|U_{\mu 4}|^2$ vs $|U_{e4}|^2$ parameter space, for the choice of either $\Delta m^2 = 0.55$ eV^2 (upper frames) or $\Delta m^2 = 1.3$ eV^2 (lower frames). Again, the left (right) frames are after collecting data for 3 (10) years. These constraints are compared to the regions that could potentially account for the LSND [1] and MiniBooNE [2] anomalies (at the 99% confidence level).

Blanco, Hooper, Machado 1901.08094

FORWARD SCATTERING (THE MATTER EFFECT)

- Forward scattering (optical theorem) occurs at zero momentum transfer
- Even “light mediators” induce contact operators here
- Relevant to probing Solar & Terrestrial structure
- Relevant to Supernova detonation

Nonstandard interactions in matter

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_F \sum_{\alpha,\beta,\mathfrak{f},C} \epsilon_{\alpha\beta}^{\mathfrak{f}C} \left[\overline{\nu}_\alpha \gamma^\rho P_L \nu_\beta\right] \left[\overline{\mathfrak{f}} \gamma_\rho P_C \mathfrak{f}\right]$$

$$\alpha, \beta = e, \mu, \tau, \quad C = L, R, \quad \mathfrak{f} = u, d, e$$

$$V = 2\sqrt{2}G_F N_e E \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} e^{i\phi_{e\mu}} & \epsilon_{e\tau} e^{i\phi_{e\tau}} \\ \epsilon_{e\mu} e^{-i\phi_{e\mu}} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} e^{i\phi_{\mu\tau}} \\ \epsilon_{e\tau} e^{-i\phi_{e\tau}} & \epsilon_{\mu\tau} e^{-i\phi_{\mu\tau}} & \epsilon_{\tau\tau} \end{pmatrix}$$

Vector interaction relevant for propagation:

$$\epsilon_{\alpha\beta}^{\mathfrak{f}} \equiv \epsilon_{\alpha\beta}^{\mathfrak{f}L} + \epsilon_{\alpha\beta}^{\mathfrak{f}R} \quad \Longrightarrow \quad \epsilon_{\alpha\beta} e^{i\phi_{\alpha\beta}} \equiv \sum_{\mathfrak{f}} \epsilon_{\alpha\beta}^{\mathfrak{f}} \frac{N_{\mathfrak{f}}}{N_e}$$

On earth $N_u = N_d = 3N_e$

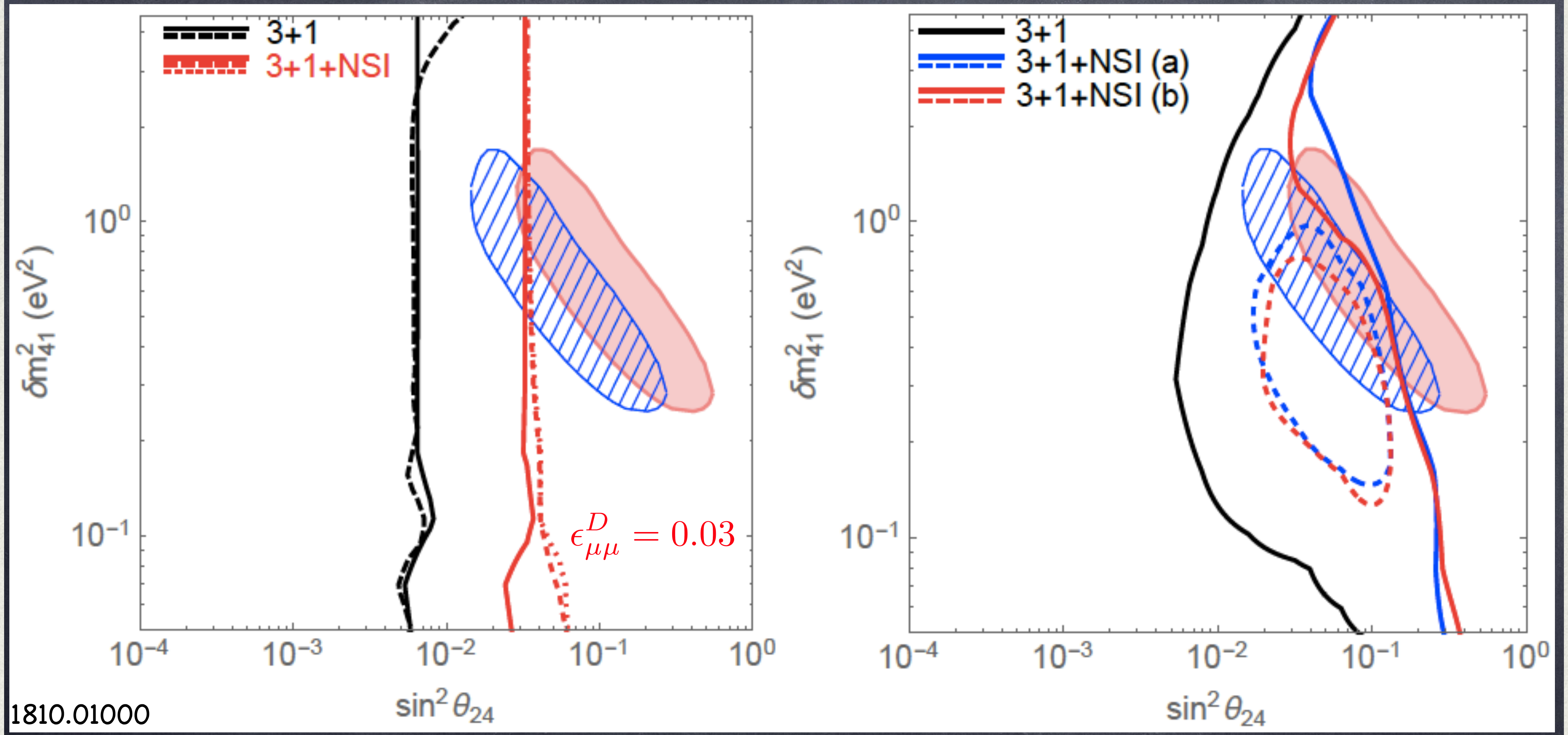
3+1 oscillations with CC and NC NSI

$$\tilde{P}(\nu_\alpha^S \to \nu_\beta^D) = \left| \left[(1+\epsilon^D)^T e^{-iHL} (1+\epsilon^S)^T \right]_{\beta\alpha} \right|^2$$

$$H = \frac{1}{2E} \left[V \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & \delta m_{21}^2 & 0 & 0 \\ 0 & 0 & \delta m_{31}^2 & 0 \\ 0 & 0 & 0 & \delta m_{41}^2 \end{pmatrix} V^\dagger + V_\mathrm{m} \right]$$

$$V_m = 2\sqrt{2} G_F N_e E \begin{pmatrix} 1+\epsilon_{ee}^m & \epsilon_{e\mu}^m & \epsilon_{e\tau}^m & \epsilon_{es}^m \\ \epsilon_{e\mu}^{m*} & \epsilon_{\mu\mu}^m & \epsilon_{\mu\tau}^m & \epsilon_{\mu s}^m \\ \epsilon_{e\tau}^{m*} & \epsilon_{\mu\tau}^{m*} & \epsilon_{\tau\tau}^m & \epsilon_{\tau s}^m \\ \epsilon_{es}^{m*} & \epsilon_{\mu s}^{m*} & \epsilon_{\tau s}^{m*} & \kappa+\epsilon_{ss}^m \end{pmatrix}$$

$$\kappa = \frac{N_n}{2N_e} \simeq 0.5$$



$$(a) \quad |\epsilon^m_{\tau\tau}| < 6\,, \quad |\epsilon^m_{\mu\mu} - \epsilon^m_{\tau\tau}| < 0.5$$

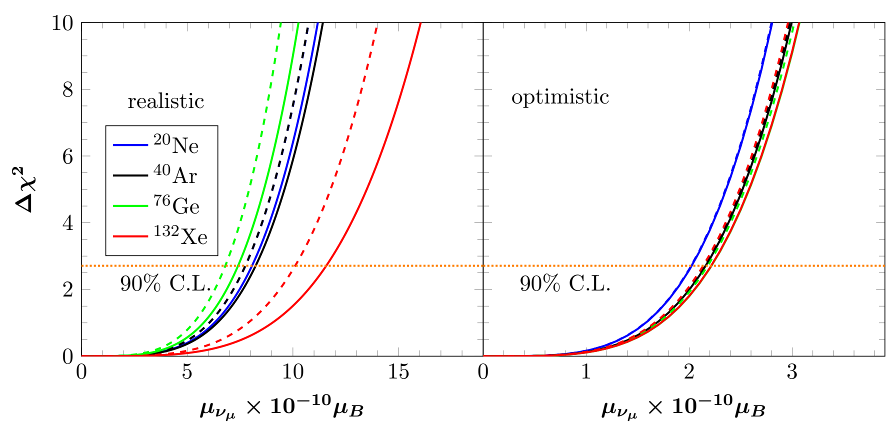
$$(b) \quad |\epsilon^m_{ss}| < 6\,, \quad |\epsilon^m_{\tau\tau}| < 0.5\,, \quad |\epsilon^m_{\mu\mu} - \epsilon^m_{\tau\tau}| < 0.5$$

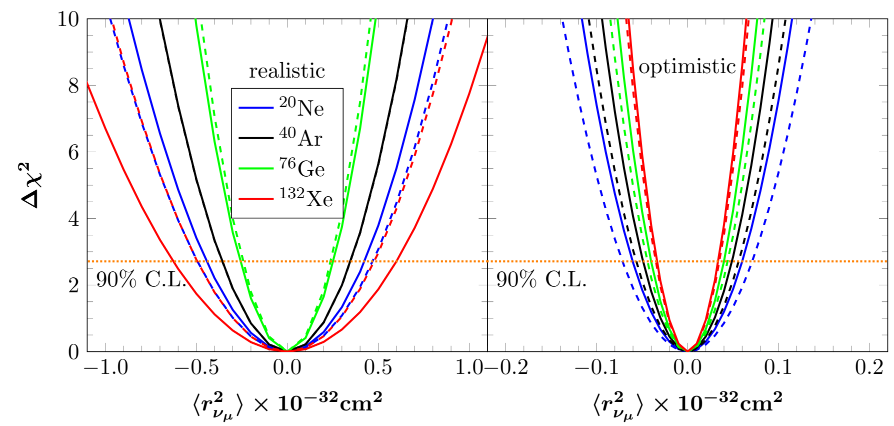
MAJORANA NEUTRINO MAGNETIC MOMENT

- Nuclear magnetic moment scattering cross-section has sharp inverse energy scaling behavior
- This gives a unique spectral shape visible at low energy to CEvNS
- However, the effect remains weak & CEvNS is unlikely to set the most stringent bounds on μ
- Discrimination from standard CEvNS is difficult

Electromagnetic neutrino properties @ COHERENT (future)

T.S. Kosmas, O.G. Miranda, D.K. Papoulias, M. Tortola, J.W.F. Valle, Phys. Rev. **D92** (2015) 013011





- **neutrino magnetic moment**
- $\mu_{\nu_\mu}(10^{-10}\mu_B)$
- **neutrino charge radius**
- $\sin^2\theta_W \to \sin^2\overline{\theta_W} + \frac{\sqrt{2}\pi a_{\mathrm{EM}}}{3G_F}\langle r^2_{\nu_\alpha}\rangle$

Nucleus	^{20}Ne	^{40}Ar	^{76}Ge	^{132}Xe
μ_{ν_μ}	9.09 [2.31]	9.30 [2.47]	8.37 [2.54]	12.94 [2.54]
$\mu_{\bar{\nu}_\mu}$	10.28 [2.53]	10.46 [2.69]	9.39 [2.75]	14.96 [2.74]
μ_{ν_e}	10.22 [2.44]	10.55 [2.60]	9.46 [2.68]	15.20 [2.68]
$\mu_{\nu_\mu}^{\mathrm{comb}}$	8.07 [2.02]	8.24 [2.16]	7.41 [2.22]	11.58 [2.21]

improved sensitivity from combined data of the prompt and delayed beams

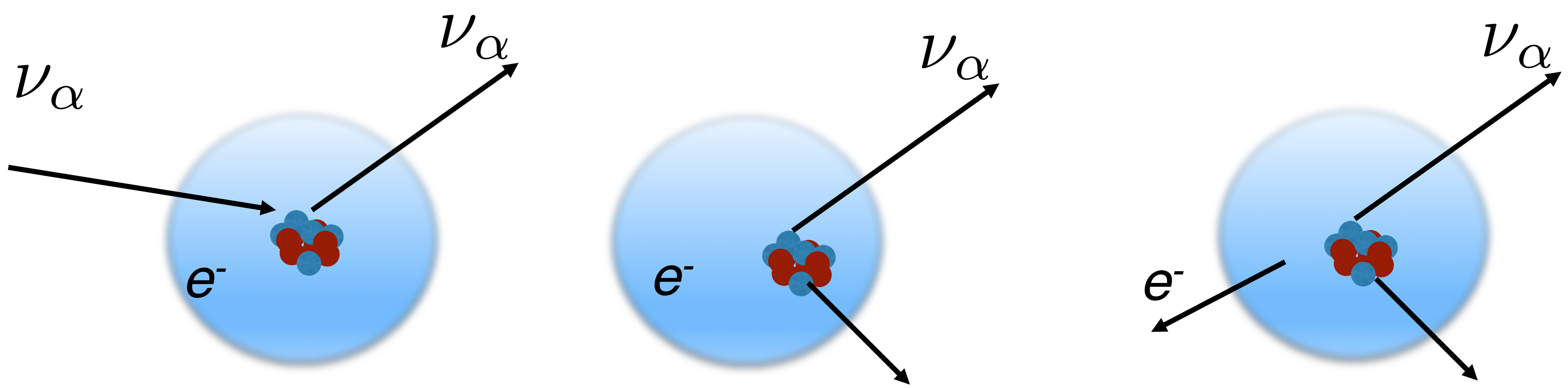
OTHER EFFECTS

- Bremsstrahlung radiation could create a signal for very soft recoils below threshold
- The Migdal Effect is ionization and excitation of electrons via relative nuclear displacement/impulse

The Migdal Effect

A.B.Migdal, J.Phys. USSR (1941), Landau & Lifschitz, QM Sec.41

Ionization and excitation of electron states from the relative momentum arising when the nucleus is given an impulse.



Proposed for dark matter detection years ago, and recently revisited in more detail. M. Ibe, W. Nakano, Y. Shoji, and K. Suzuki, JHEP (2018) 1707.07258

M.Dolan, F.Kahlhoefer, and C.McCabe, PRL(2018) 1711.09906 (above figure adapted from this paper)

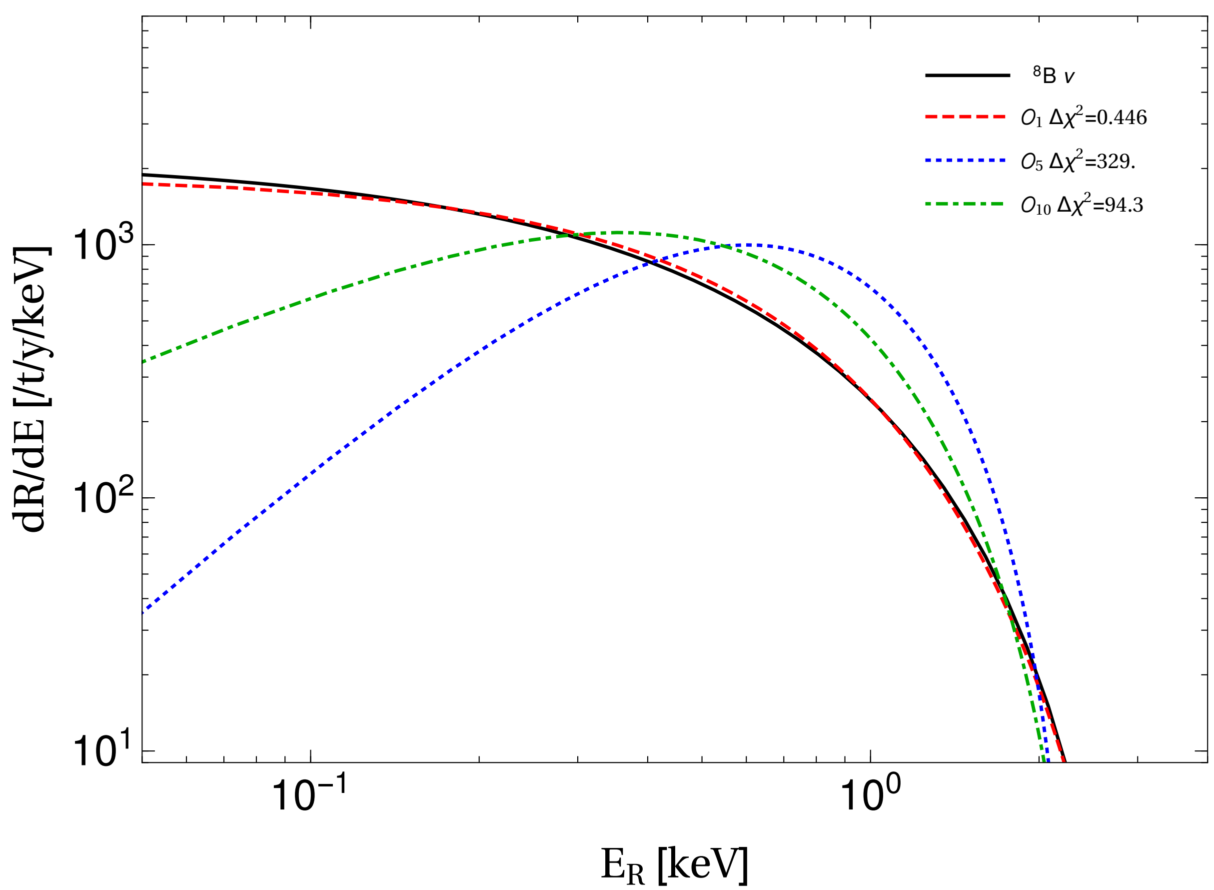
Does *not* suffer from the same suppression as brem.

Beyond standard formalism: non-relativistic EFT

- Heavy mediators

$\mathcal{O}_1$	$1_\chi 1_N$	SI
$\mathcal{O}_2$	$(v^\perp)^2$	
$\mathcal{O}_3$	$i\vec{S}_N \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$	
$\mathcal{O}_4$	$\vec{S}_\chi \cdot \vec{S}_N$	SD
$\mathcal{O}_5$	$i\vec{S}_\chi \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$	
$\mathcal{O}_6$	$(\frac{\vec{q}}{m_N} \cdot \vec{S}_N)(\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi)$	
$\mathcal{O}_7$	$\vec{S}_N \cdot \vec{v}^\perp$	
$\mathcal{O}_8$	$\vec{S}_\chi \cdot \vec{v}^\perp$	
$\mathcal{O}_9$	$i\vec{S}_\chi \cdot (\vec{S}_N \times \frac{\vec{q}}{m_N})$	
$\mathcal{O}_{10}$	$i\frac{\vec{q}}{m_N} \cdot \vec{S}_N$	
$\mathcal{O}_{11}$	$i\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi$	
$\mathcal{O}_{12}$	$\vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^\perp)$	
$\mathcal{O}_{13}$	$i(\vec{S}_\chi \cdot \vec{v}^\perp)(\frac{\vec{q}}{m_N} \cdot \vec{S}_N)$	
$\mathcal{O}_{14}$	$i(\vec{S}_N \cdot \vec{v}^\perp)(\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi)$	
$\mathcal{O}_{15}$	$-(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})\left((\vec{S}_N \times \vec{v}^\perp) \cdot \frac{\vec{q}}{m_N}\right)$	

Fan, Reece, Wang, 2010; Fitzpatrick et al. 2012; Anand et al. 2014

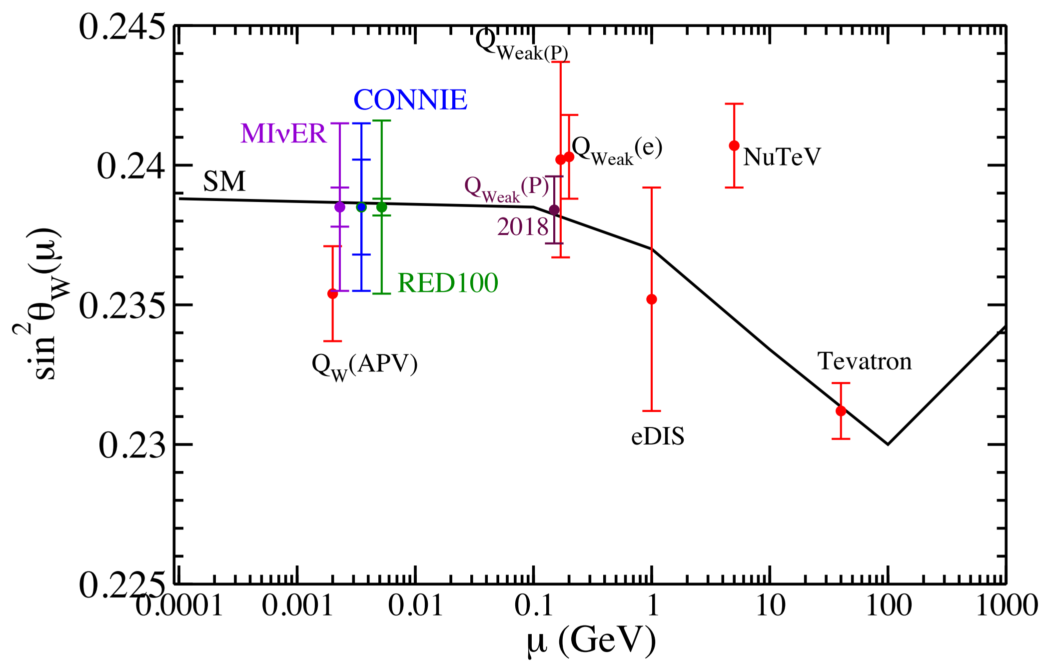


Dent, Dutta, Newstead, Strigari, PRD 2016

MEASUREMENTS OF INTEREST

- The Weinberg angle at low momentum exchange
- The nuclear form factor moments
- The role of axial (spin-dependent) couplings

expectations for $\sin^2 \theta_W$



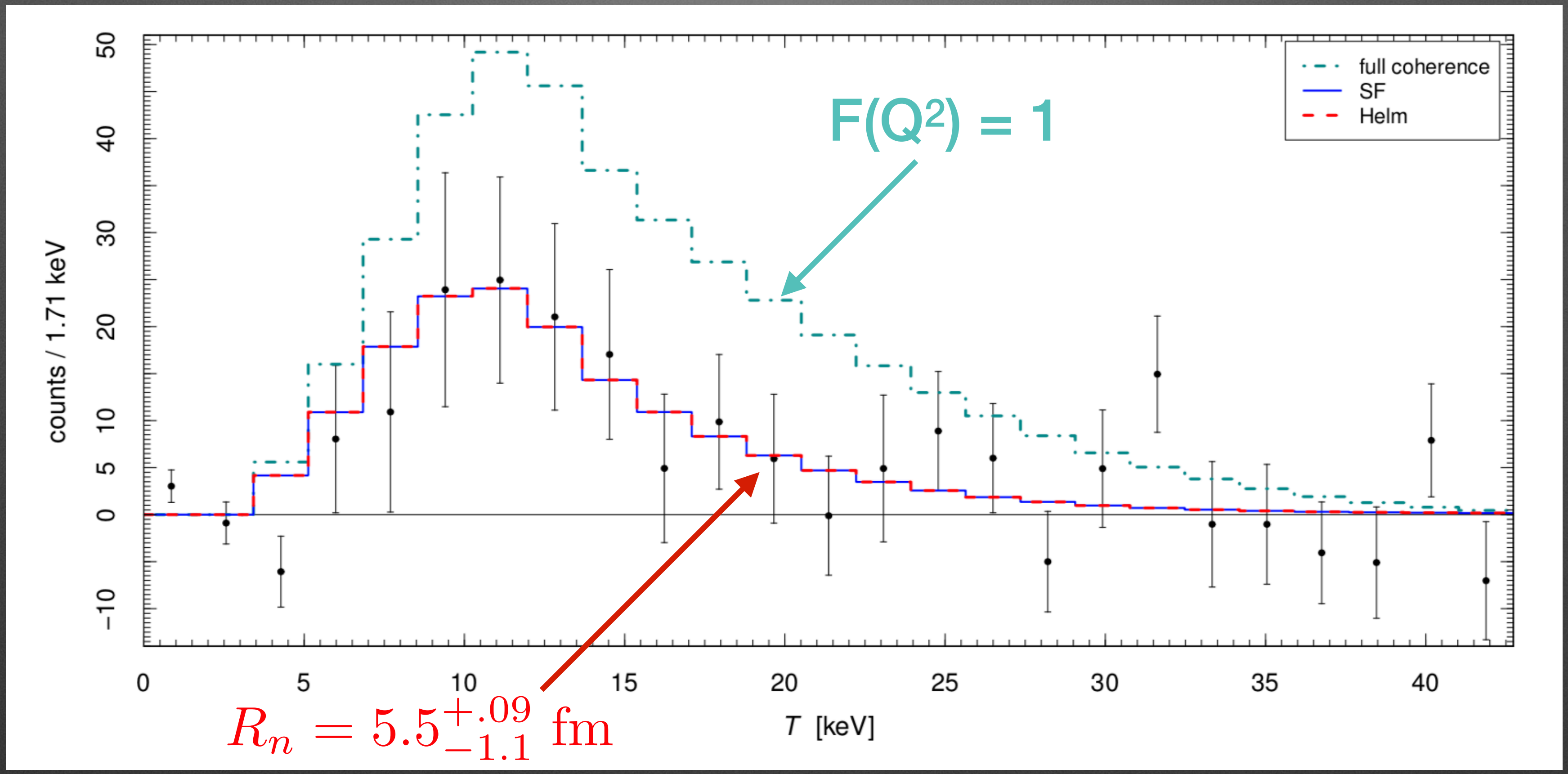
Canas et al. Phys. Lett. B **784**, 159 (2018)

D. Androic et al., Nature **557** 207 (2018)

C. Patrignani et al., Chin. Phys. C **40** 100001 (2016)

For the current constraint from COHERENT see D. K. Papoulias and T. Kosmas Phys.Rev. D97 (2018) no.3, 033003

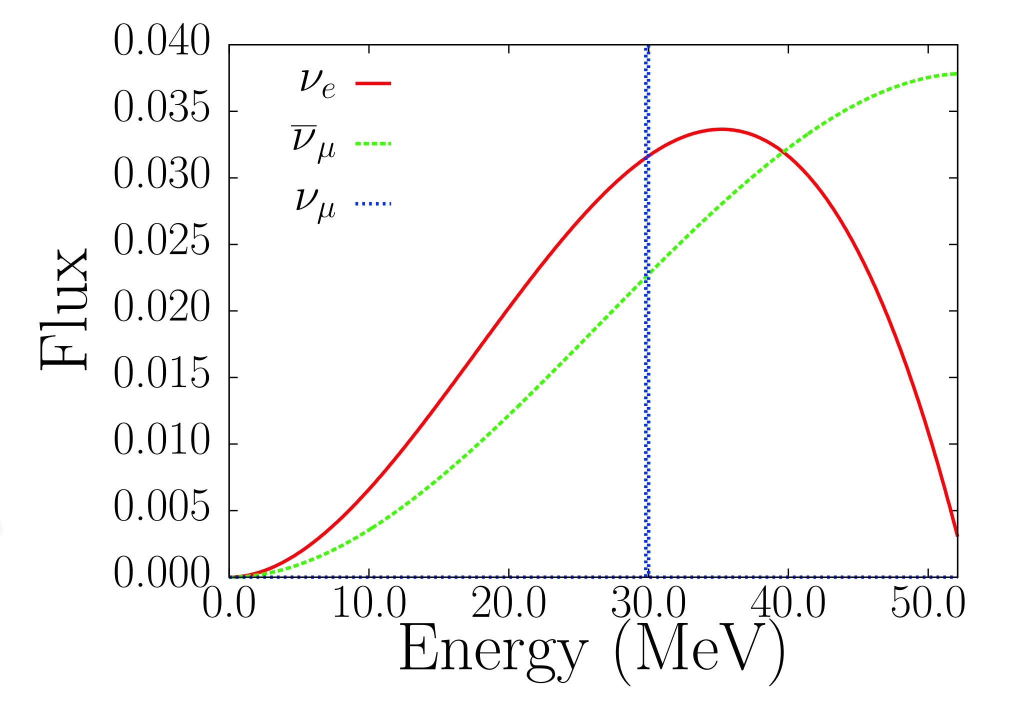
COHERENT Data



- χ² minimization including some systematic uncertainties gives a best fit of $R_n = 5.5^{+.09}_{-1.1}$ fm

Neutrino Source

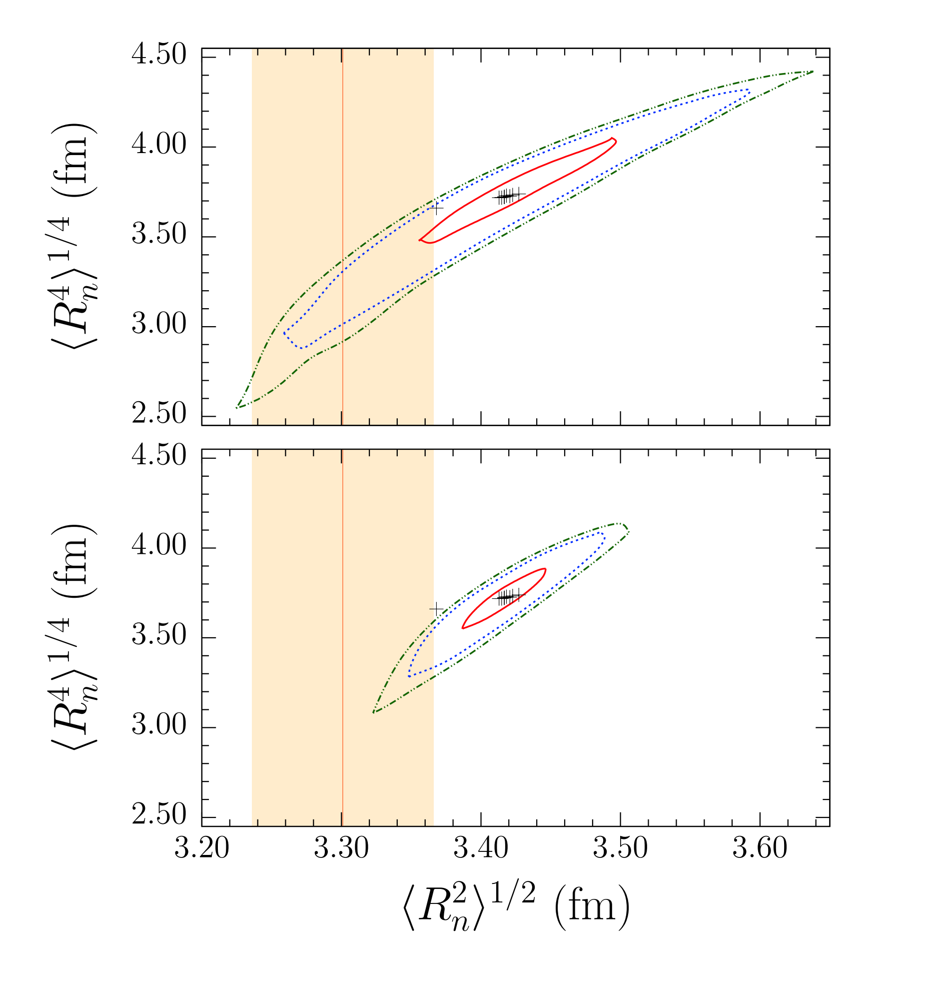
- Assume a stopped pion source
- Since the scattering is low energy and low Q, we can Taylor expand the form factor



$$F(Q^2) = N\left(1 - \frac{Q^2}{3!}\langle R_n^2\rangle + \frac{Q^4}{5!}\langle R_n^4\rangle - \frac{Q^6}{7!}\langle R_n^6\rangle + \cdots\right)$$

$$\langle R_n^k\rangle = \frac{\int \rho_n r^k d^3r}{\int \rho_n d^3r}$$

Results



- 3.5 tonne ^{40}Ar detector
  - RMS radius to 5%
  - Fourth moment to 20%
- 1.5 tonne Ge detector
  - Effective RMS radius to 5%
  - Effective fourth moment to 15%
- 300 kg Xe detector
  - Effective RMS radius to 5%
  - Effective fourth moment to 7%
- Knowing L_ν reduces uncertainty

Figure from **K. M. Patton**, J. Engel, G. C. McLaughlin and N. Schunck, *Phys. Rev. C* **86**, 024612 (2012).

Role of Axial (Spin Dependent) Couplings

- The multipole expansion of hadronic currents gives a consistent way to account for the non-point like nature of the nucleus
- Can be extended to include higher order effects (will affect vector rate too), and inelastic (incoherent) scattering
- I find that the axial cross section is smaller than previously suggested, and may be irrelevant for CevENs experiments
- Complete analysis in progress.. stay tuned

CEVNS VERSUS INVERSE BETA DECAY (IBD)

- The CEvNS cross-section is much larger, allowing for much lighter and more compact detectors
- CEvNS is not limited by the 1.8 MeV IBD threshold — for example, it can monitor reactor breeding neutrinos
- IBD positron annihilation plus neutron-capture gamma limit background and fully reconstruct E_ν
- CEvNS could reconstruct E_ν with directional detection

Neutron Capture Antineutrino Bump

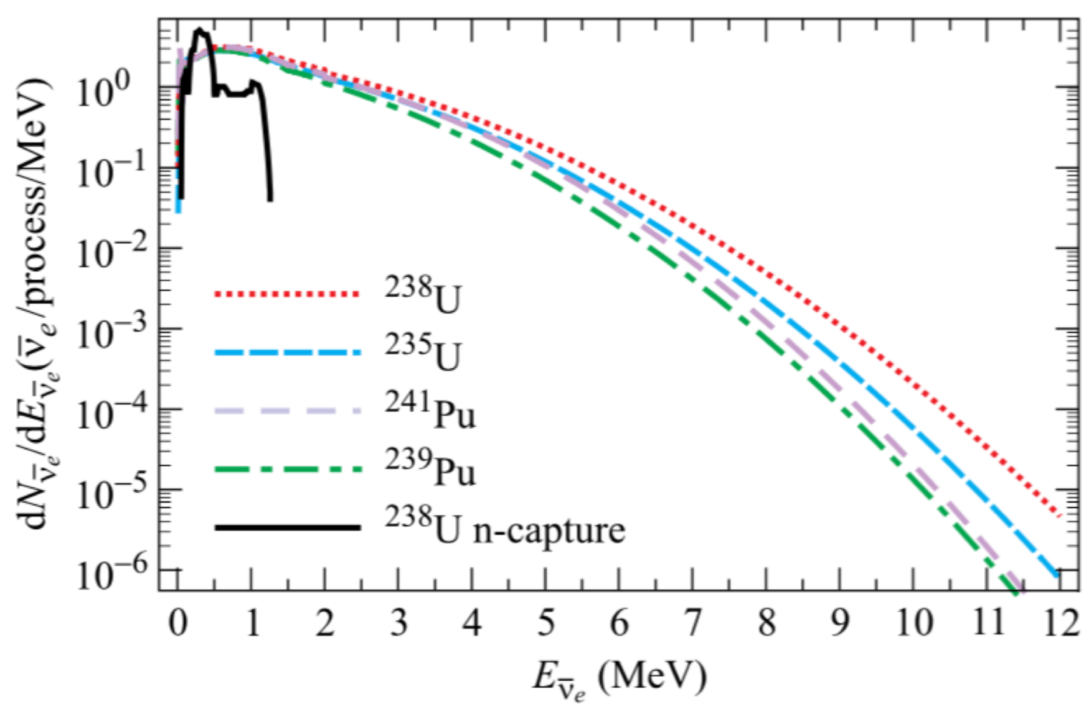


Image: Fernandez Moroni, PRD 91, 072001 (2015).
Note spectrum is for a thermal (not fast) reactor.

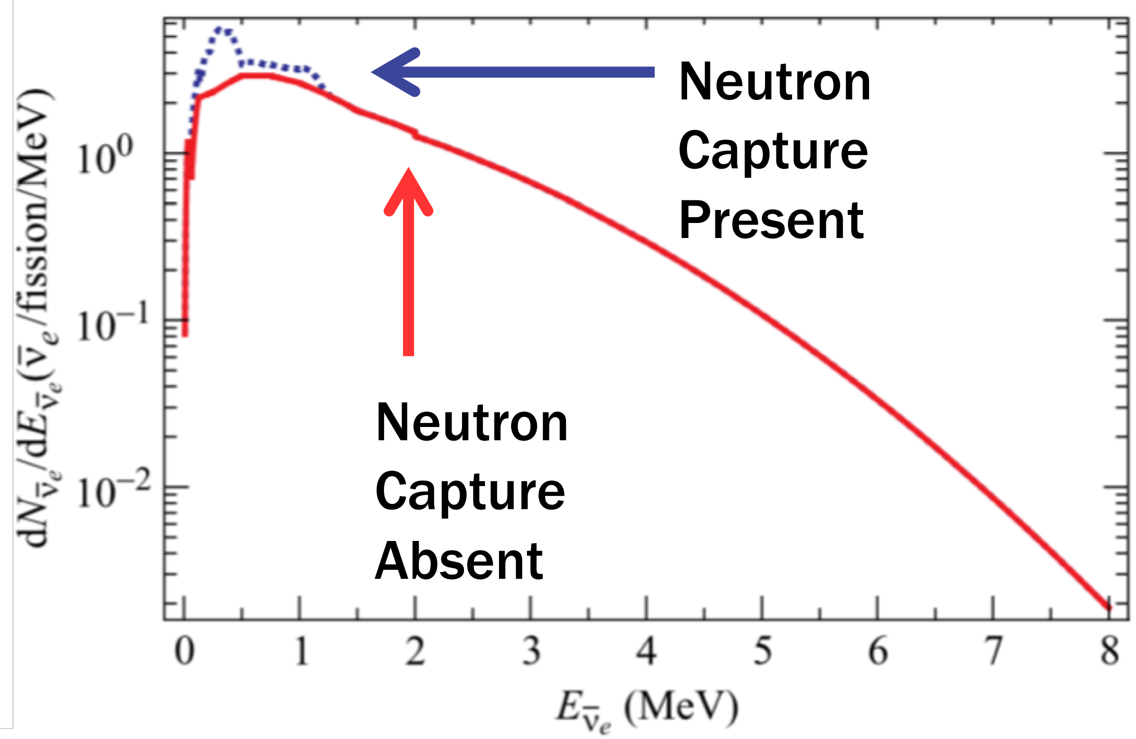


Image: Fernandez Moroni, PRD 91, 072001 (2015).
Note spectrum is for a thermal (not fast) reactor.

6 electron antineutrinos emitted per fission with energy < 12 MeV

2 electron antineutrinos emitted per capture with energy < 1.3 MeV

Low energy bump signals neutron capture.
If a blanket is present this bump will be significant.

Proof of Principle: 2016

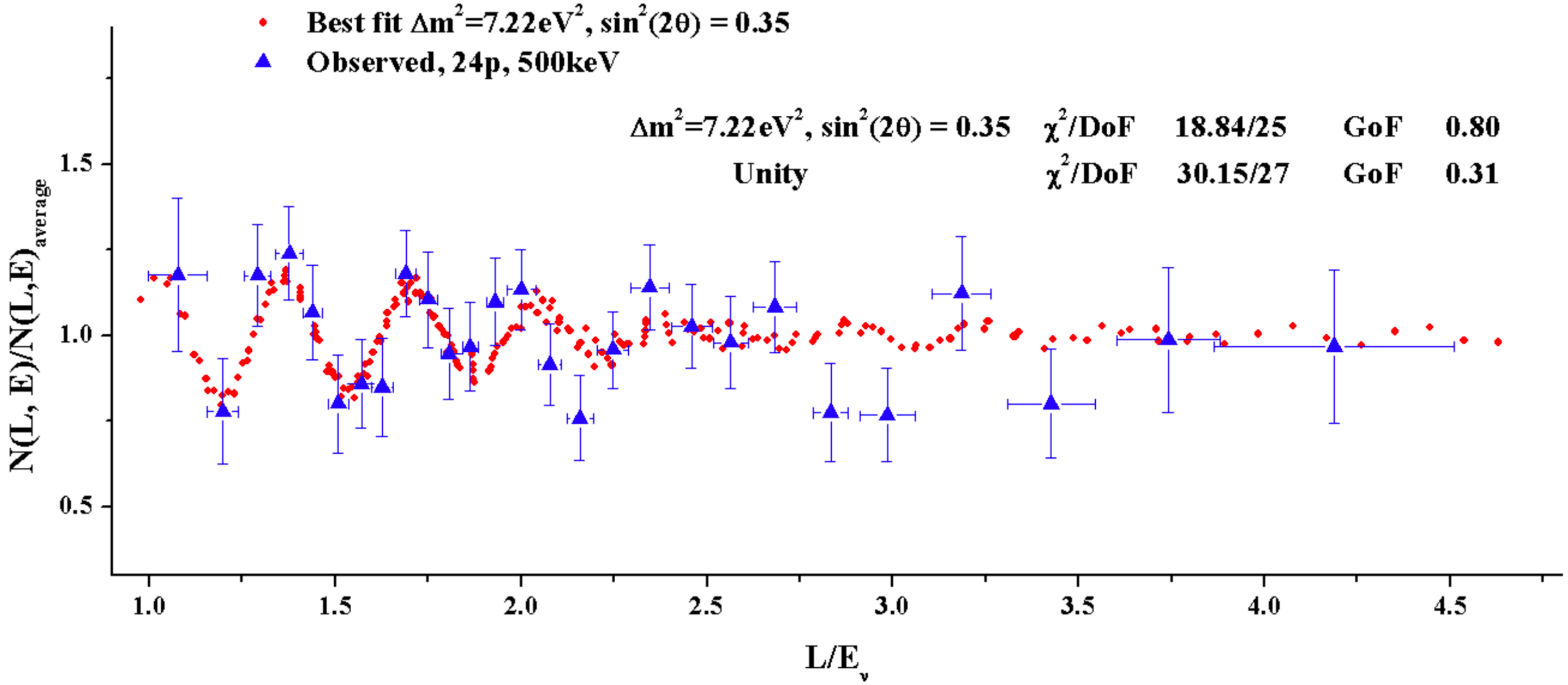
- Can detect the presence of a breeding blanket at a PFBR-type fast reactor at 95% confidence level within 90 days using a 36-kg ^{28}Si CEvNS detector with a threshold of 30 eV[1]
- R&D on silicon-based charge coupled devices (CCDs) suggests detector masses of 17-kg with 20 eV threshold are possible[2]

[1] Cogswell and Huber, Sci. & Global Security 24 (2016);
[2] G. Fernandez Moroni, J. Estrada, E. E. Paolini, et al., Phys. Rev. D 91, 072001 (2015)

Neutrino 4

- Hosted at a megawatt research reactor in Russia. 95% ^{235}U. 480 live days.
- Baseline is 6-12 meters. Core is compact and detector is segmented.
- Gadolineum-doped liquid scintillator with 1.8 m^3 detects neutrinos via inverse beta decay ($\bar{\nu}_e + p \rightarrow e^+ + \mathrm{n}$).
- Analysis uses RATIOS of events and plots in L/E_ν to extract oscillation without dependence upon normalization of flux.
- Claim 3σ preference for oscillation. NOTE: this is a DELTA χ^2. The no-oscillation hypothesis is a reasonably good fit. This is NOT a 3σ exclusion of the SM.
- The IBD detection FULLY RECONSTRUCTS the neutrino energy – this allows for "coherency" of the oscillation over many cycles, with deep cuts as a function of Δm^2. It is also flavor sensitive.
- But, the cross-section is very low compared to coherent scattering

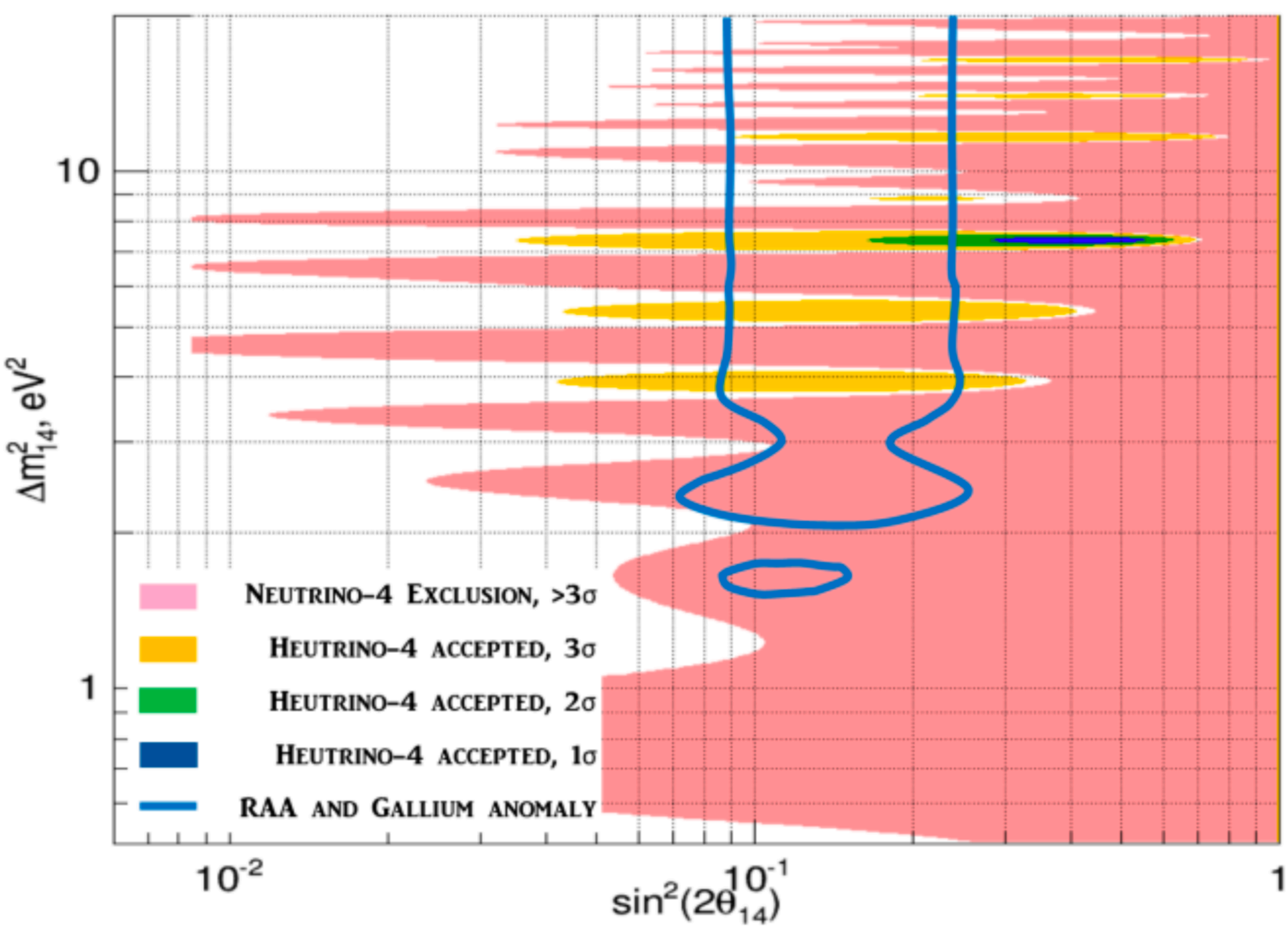
Neutrino 4



Best fit Δm²=7.22eV², sin²(2θ) = 0.35
Observed, 24p, 500keV
Δm²=7.22eV², sin²(2θ) = 0.35 χ²/DoF 18.84/25 GoF 0.80
Unity χ²/DoF 30.15/27 GoF 0.31
N(L, E)/N(L,E)average
1.5
1.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
L/Eν

Neutrino 4

- Yellow, Green, and Blue are increasingly favored



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SUMMARY

- Coherent Neutrino-Nucleus Scattering is observed
- With high statistics this is a new channel for probing BSM physics of several varieties
- CEvNS will be most effective where the SHAPE of the recoil spectrum is characteristically affected
- Reactors & beam experiments are complementary, especially with distinct target nuclei

THANK YOU

Sam Houston State University

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