An Overview of Neutrino Floor Analysis and Application in the Search for Dark Matter & Coherent Scattering
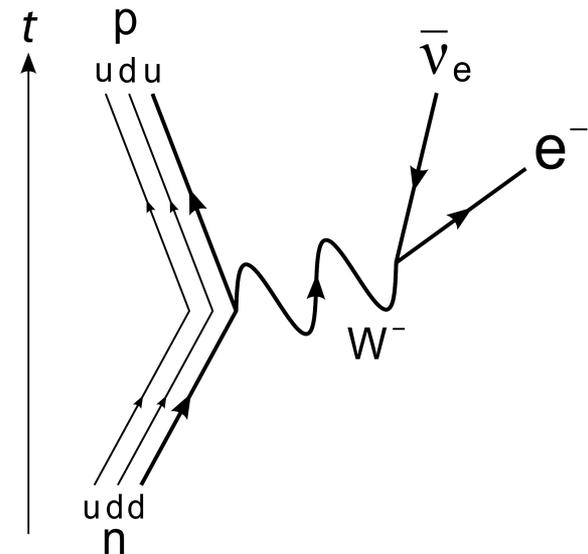
Matthew Breeding & Derek Johnson
Sam Houston State University

With Joel Walker, Dutta, Gao, Kubik, Mahapatra, Mirabolfath, Strigari
Phys. Rev. D 93, 013015 (2016), Phys. Rev. D 94, 093002 (2016)
+ Dent, Newstead, Liao, 1612.06350
& Representing the MIνER Collaboration

Pheno, Pittsburgh PA
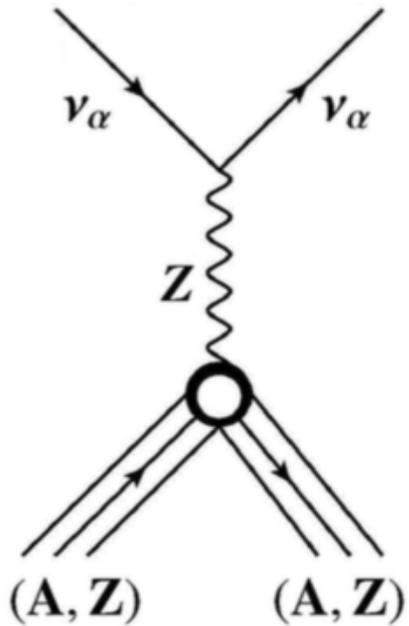May 9, 2017

Weak Interactions

- Neutrinos have no electromagnetic or "color" charge, but do have "weak" charge
- The "Weak Nuclear Force" is mediated by exchange of W/Z Bosons, with mass ~ 80/90 times the proton mass
- Trillions of neutrinos (mostly from the Sun, but also Supernovae & atmospheric interactions with cosmic rays) pass through your body each second – most zip through the Earth with no interaction
- The heaviness of these particles makes it unlikely that low energy particles will able to exchange them ("Off Shell") – This is what makes the weak force weak

Neutrino Detection

- The Ray Davis experiment used neutrinos to convert neutrons into protons while emitting an electron. The decay of the Argon via gamma ray was detected. Threshold was 0.8 MeV (A proton has ~ 1 GeV of mass-energy)

- Gallium to Germanium detectors use the same process, but extend down to 0.2 MeV

- Anti-neutrinos can also convert protons to neutrons, emitting a positron. Two flashes of light come from the positron annihilation and later the neutron capture. This scenario has a larger cross section, but a higher threshold of 1.8 MeV

- All of the prior are "Charged Current" (W Boson) and require kilo-ton scale targets in order to resolve the signal.

- We want to study "Neutral Current" (Z Boson) scattering, which is both elastic and coherent

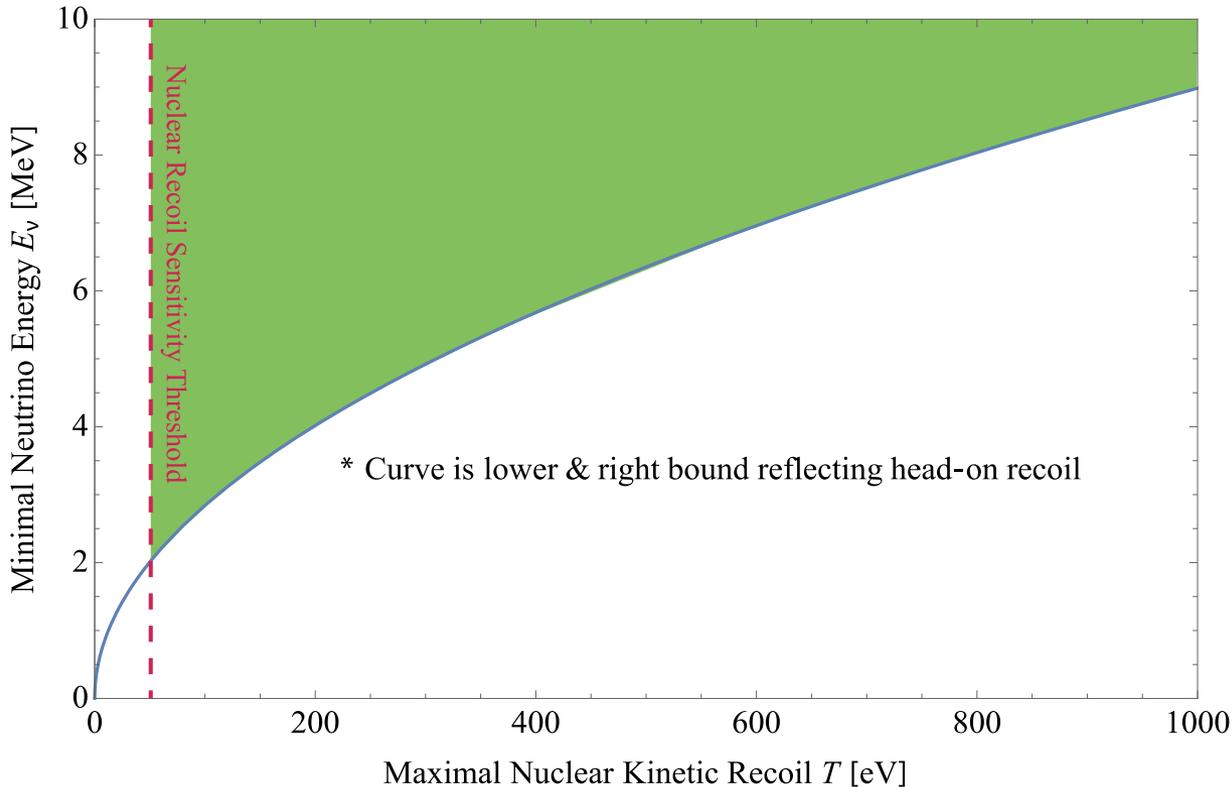# New Search: Coherent Elastic Neutrino Nucleus Scattering (CEvNS) via Z-boson

- SM scattering is Z-boson exchange (neutral current)
- Extremely weak, elastic collision
- New physics may alter the rate and coupling
- Interested in seeing as signal
- Momentum transfer deBroglie wavelength should be larger than the Nucleus

Energy vs. Recoil Integration Region
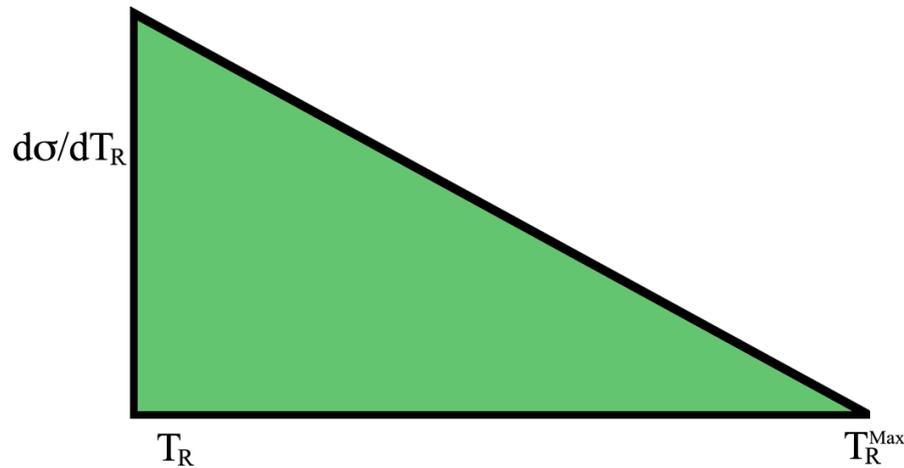
Neutrino Energy vs. ^{72}Ge Nuclear Recoil

Minimal Neutrino Energy E_ν [MeV] (vertical axis, 0 to 10)

Nuclear Recoil Sensitivity Threshold

* Curve is lower & right bound reflecting head-on recoil

Maximal Nuclear Kinetic Recoil T [eV] (horizontal axis, 0 to 1000)

$T \leq \dfrac{2E_\nu^2}{2E_\nu + M}$: Solution for maximal kinetic recoil $(1 - \cos\theta$ for other angles$)$

$E_\nu \geq \dfrac{1}{2}\left(T + \sqrt{2MT + T^2}\right)$: Inversion for minimal incident neutrino energy

$Q \leq \dfrac{2E_\nu(E_\nu + M)}{2E_\nu + M}$: Solution for maximal momentum transfer
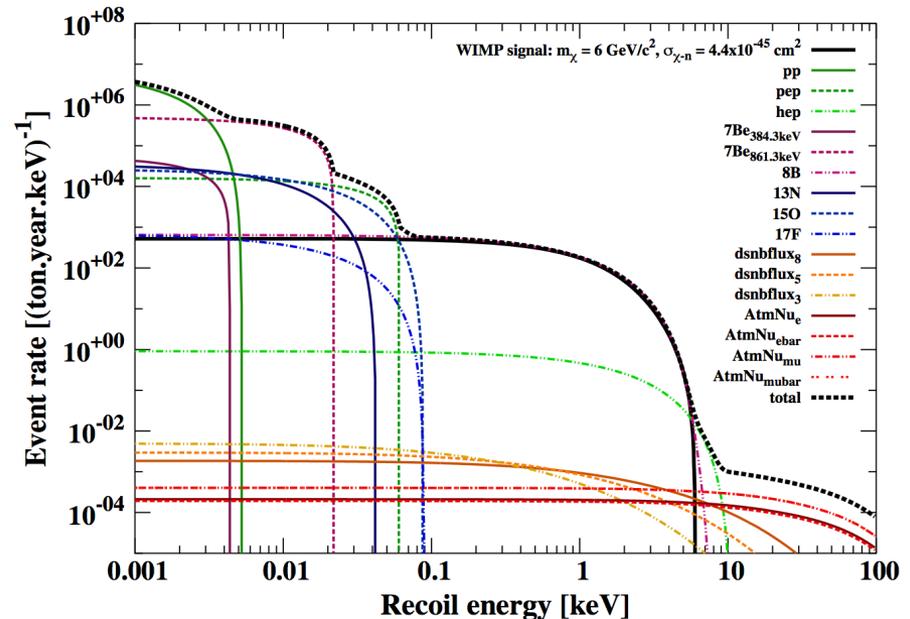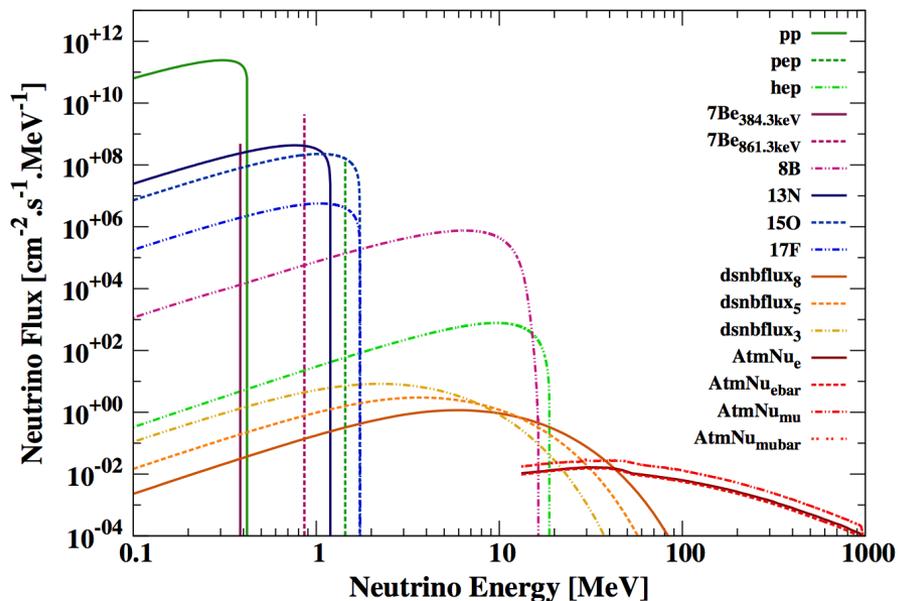
Cross Section in Leading Vector Limit

- Leading dependence is $\frac{d\sigma}{dT_R} \propto 1 - MT_R/2E_\nu^2 \sim 1 - T_R/T_R^{Max}$

- Interpolates between large cross section at zero recoil & zero cross section at cutoff

- $\sigma \propto \int_0^{T_R^{Max}} \left(1 - \frac{T}{T_R^{Max}}\right) dT_R = \frac{T_R^{Max}}{2} \propto \frac{E_\nu^2}{M}$

- The cross section, like max. recoil, is proportional to square of neutrino energy
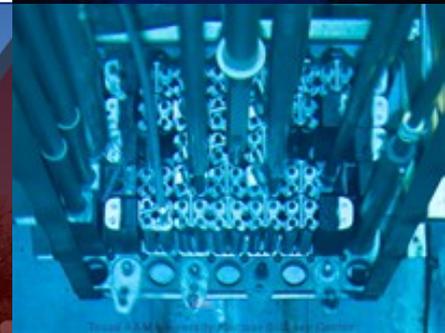
Solar Fluxes & CEvNS Rates

- The Coherent Enhancement can lead to appreciable interaction rates, which are concentrated in a narrow energy band (less BG)

- BUT the HEAVY nucleus recoils very softly – you need tremendous low energy detection sensitivity

- The large Solar fluxes are for lower energy neutrinos, which deposit even LESS energy in the detector!
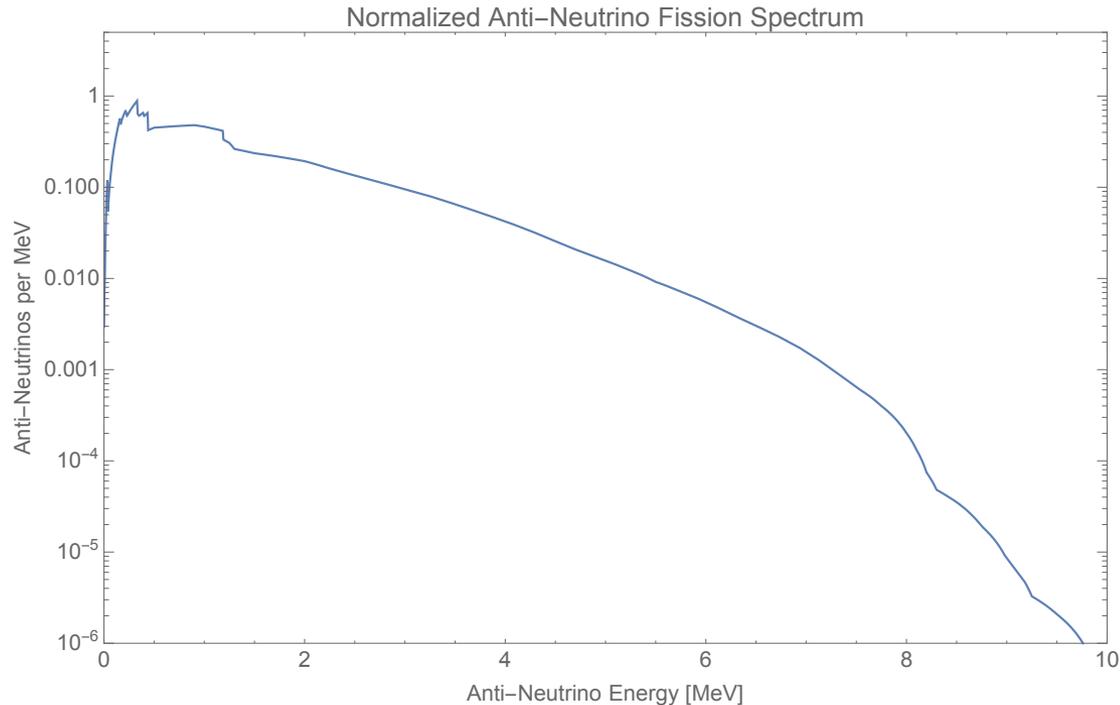
Strigari, et al., 1408.3581

Possible Solution: Reactor Neutrino Source

- A nuclear reactor is a tremendous source of neutrinos with very large (potentially ~ 20X larger than the largest Solar component) flux, and reasonably high energy (easier to detect)

- Close to a nuclear reactor, we must REALLY begin to worry about controlling backgrounds

- We will use the same detectors employed for ultra-quiet dark matter searches a mile underground, but place them instead in this new ultra-intense radiation zone

- We will try to observed the process presenting the "Neutrino Floor" Dark Matter background on purpose, for the first time
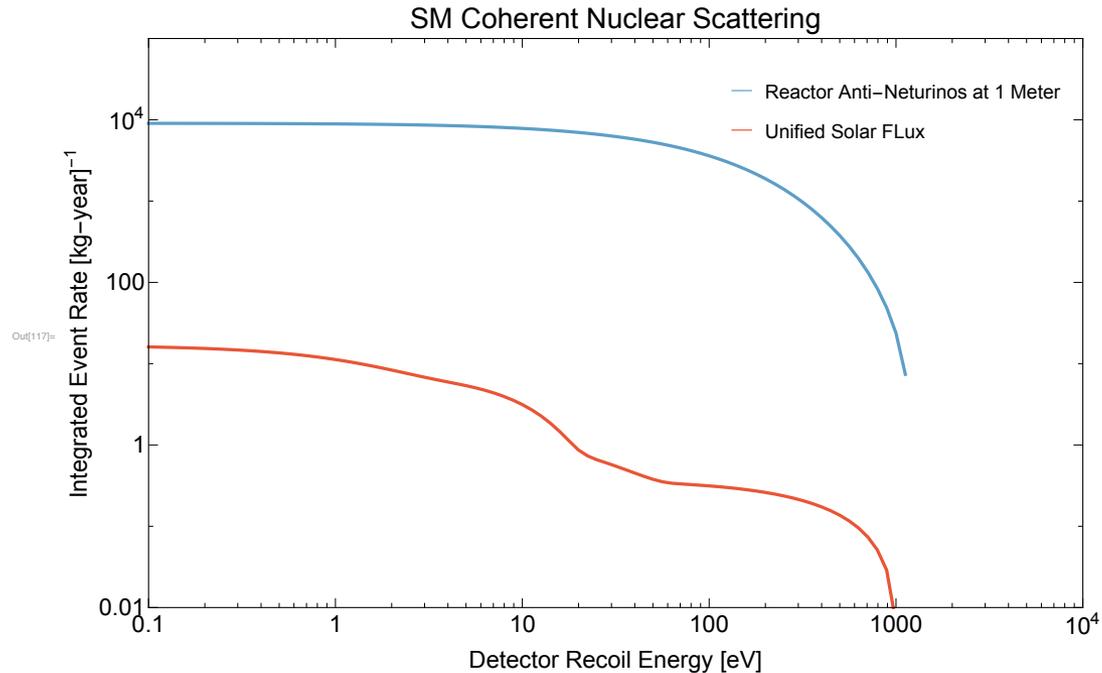
Operating Since 1961

Adapted From: Sean M. McDeavitt

Reactor Anti-Neutrino Source

Normalized Anti−Neutrino Fission Spectrum

- ^{235}U yields a thermal energy of 202 MeV per fission
- Neutrino yield in cascade is 6.14 with 1.5 MeV mean energy
- If reactor power is known, then the neutrino flux is known
- Spectrum is experimental (Schreckenbach et al.) above 2 MeV
- Below inverse β threshold, spectrum is theoretical (Kopeiken)
- Coherency of scattering is naturally well-maintained
- MW reactor delivers flux of 1.5×10^{12}/cm²/sec @ 1 m (vs. Solar ~ 5×10^6/cm²/sec)
- Shielding expected to optimize $S/\sqrt{S+B}$ at 2-3 m

Integrated Event Rate

SM Coherent Nuclear Scattering

Out[117]=

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

- 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

Shielding & Background Control

- A moderator (e.g. water) can be used to convert the fast neutron flux to a thermal flux after which the predominantly thermal spectrum can be shielded using a thermal neutron absorber such as boron, cadmium or gadolinium.

- It is possible to reduce the backgrounds adequately with the reactor core as close as ~2-3 meters

- Can get additional handles on background by using secondary iZIP detectors (higher threshold but good electron/nuclear discrimination), measurements of reactor on/off, observation of background scaling with distance (experiment stays put while reactor core is moved, etc.

MIνER Experimental Summary

- Primary detectors are of the High Voltage CDMSLite variety
- Dark matter searches target ~ zero background hideaways ~ 1 mile underground
- We are planning to set up 1-3 m from a MW nuclear reactor
- This provides tremendous flux (5-6 orders of magnitude above Solar ^8B)
- The "neutrino floor" is our target, via coherent nuclear scattering
- Excellent shielding design is essential to controlling gammas and neutrons
- Statistics can be huge, allowing for a BSM neutrino sector laboratory

Experimental Efforts in Progress

- Physical preparation of experimental cavity adjacent to the reactor source
- Measurement of in-situ neutron and gamma background rates
- Simulation & calibration of background rate and shape in Geant4
- Establishment of optimized shielding scenario
- Securing of dilution refrigerator & testing for suitability to intended use
- Ongoing development of ultra-low threshold solid-state detectors

Connection to WIMPs

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

Bolometric Detection of Neutrinos

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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 (< 0.41 MeV) 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).
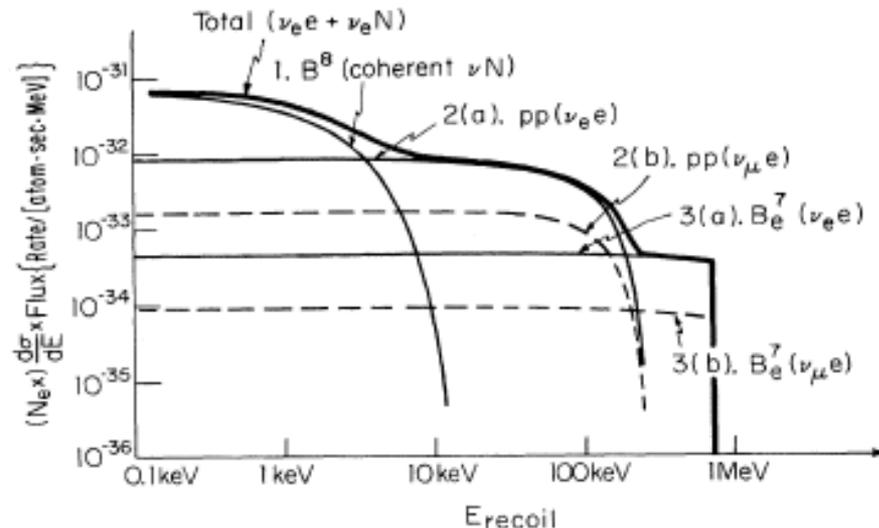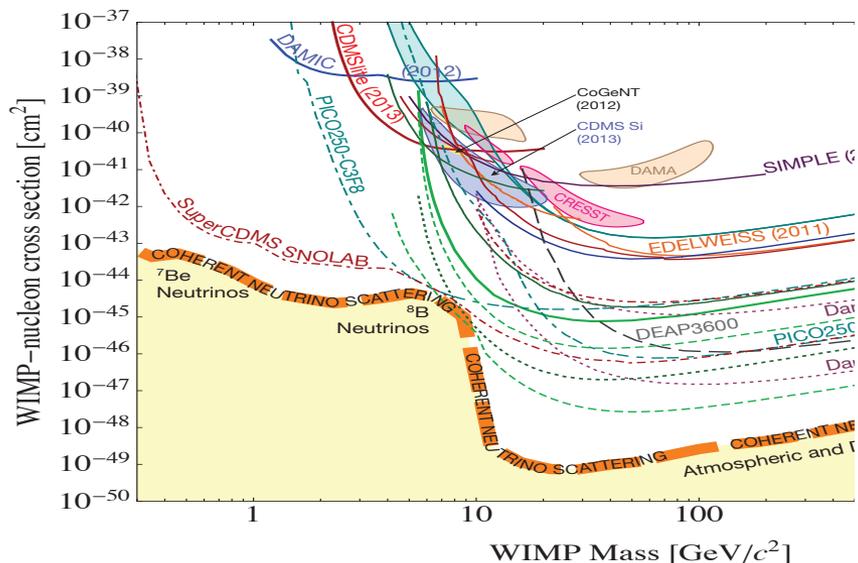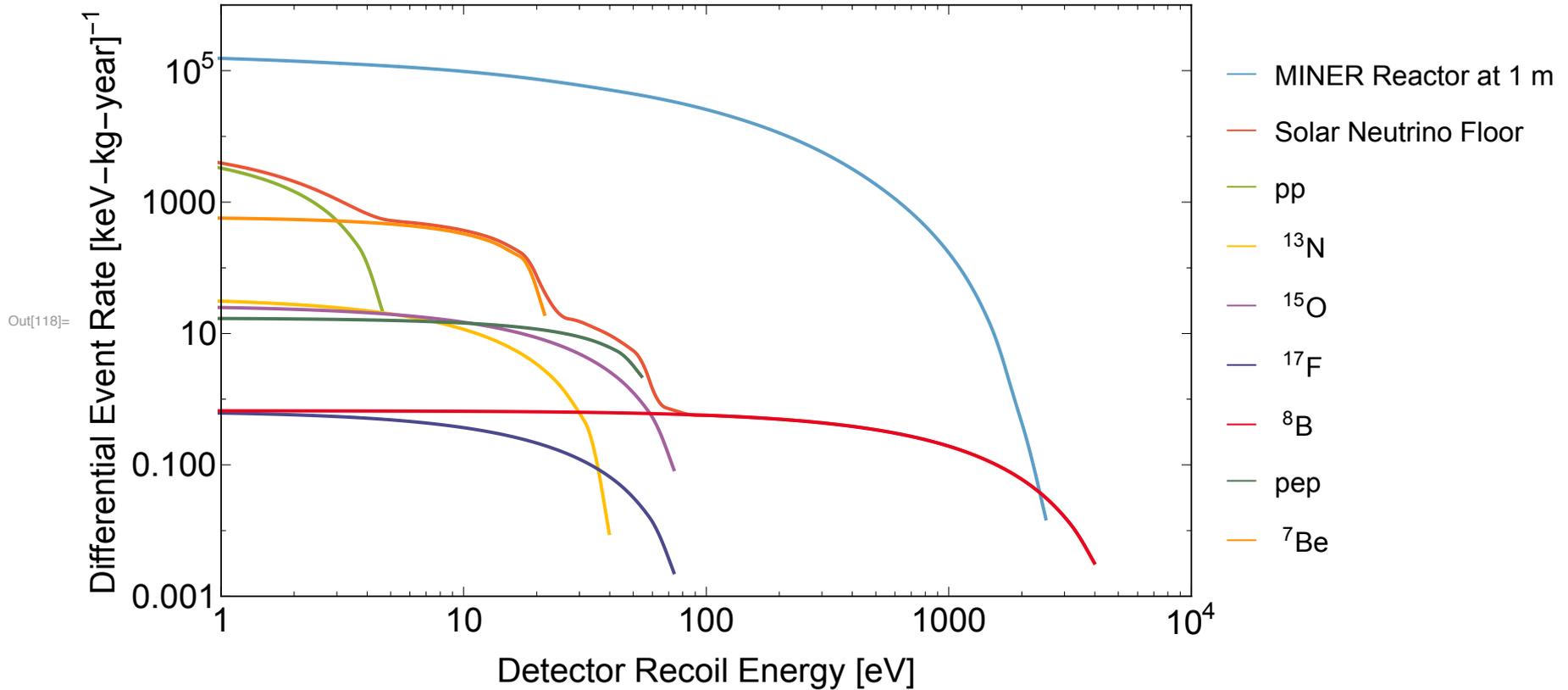

FIG. 1. Event rate vs recoil energy for solar-ν spectra.
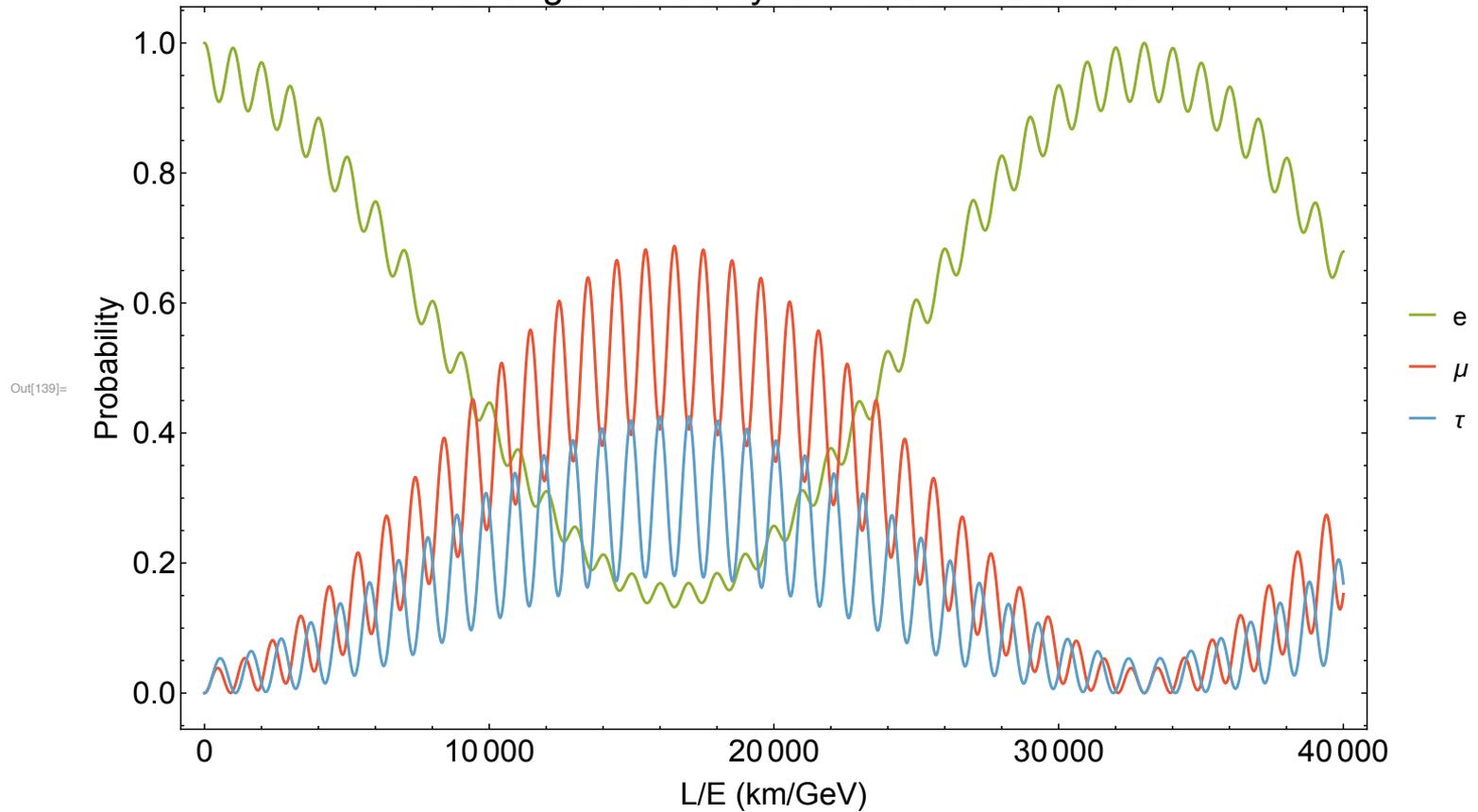
Same low threshold detector challenges for SuperCDMS and CNS . . Precisely measuring this process may aid the search for dark matter below the neutrino floor. *From: Rupak Mahapatra*

SM Coherent Nuclear Scattering Differential Event Rate

- MIνER project solves the energy/flux problem by allowing close proximity to neutrino source
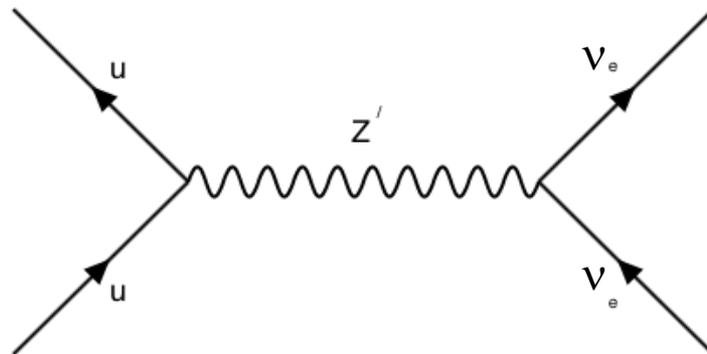
Flavor Change Probability for Electron Neutrinos

$$P_{\alpha \to \beta} = \delta_{\alpha\beta} - 4 \sum_{i>j} \text{Re}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2 \left(\frac{\Delta m_{ij}^2 L}{4E} \right)$$

$$+ 2 \sum_{i>j} \text{Im}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin \left(\frac{\Delta m_{ij}^2 L}{2E} \right)$$
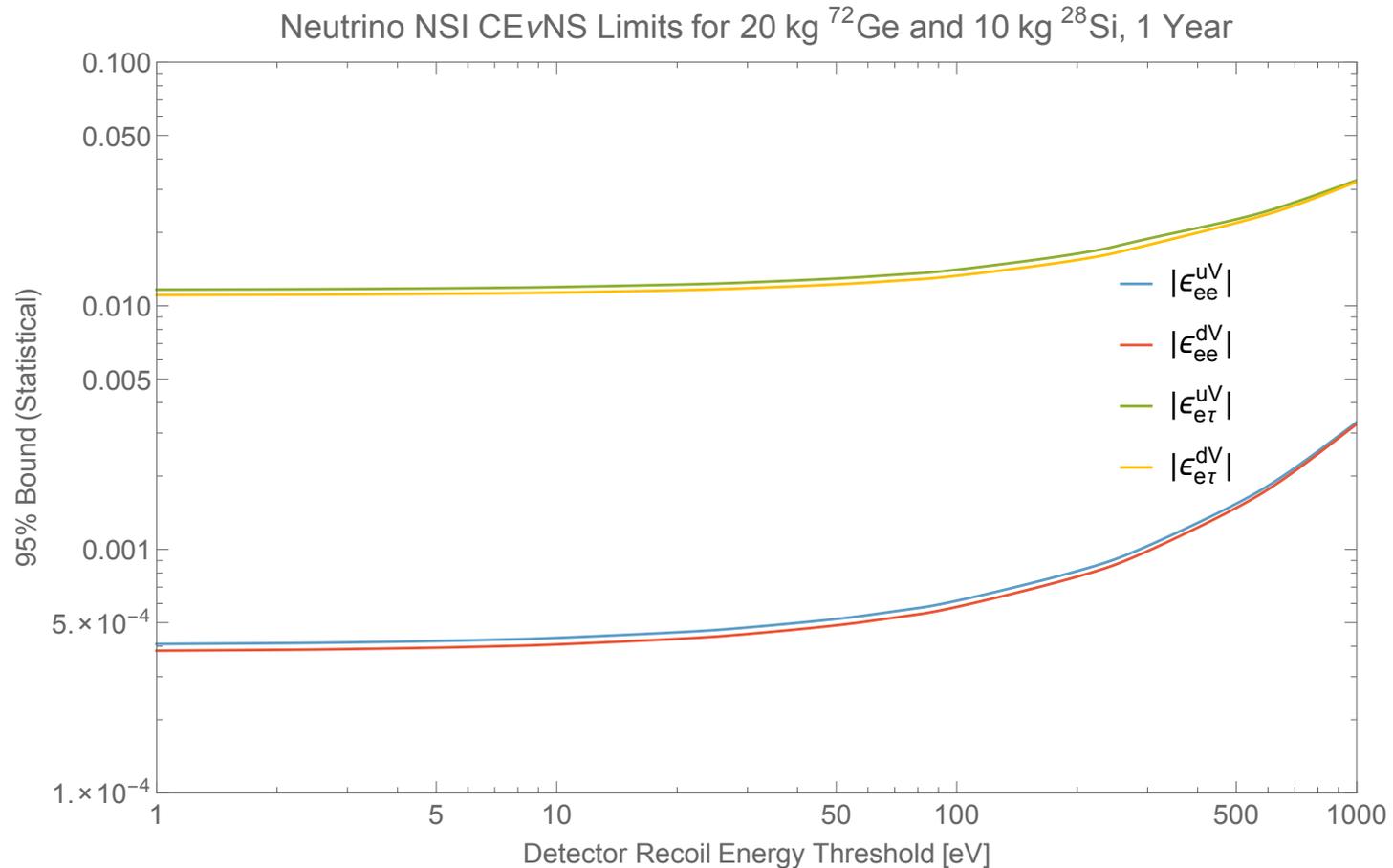
- New experimental results can be surprising, point to new physics

Z Prime Boson

- complimentary search to colliders, dilepton res and precise mass

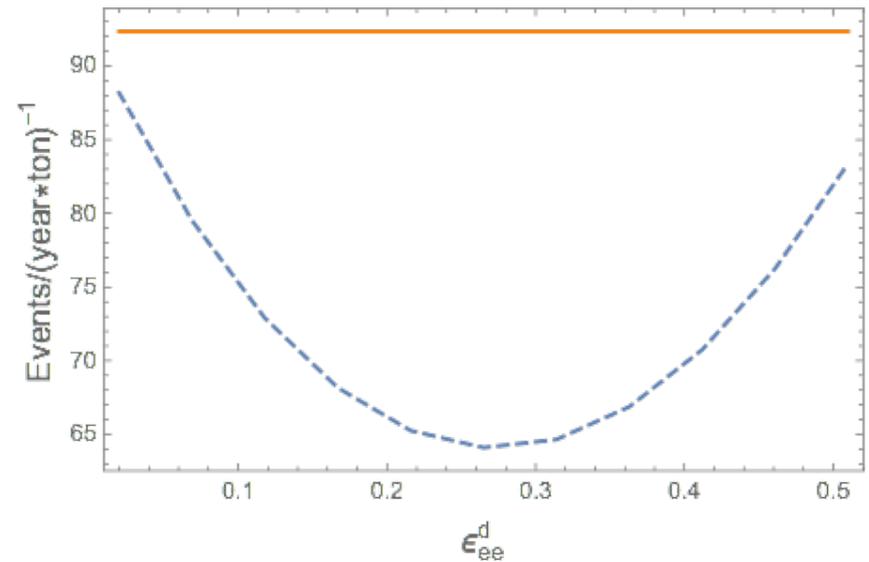- enhancement in event rate

- characterize isospin

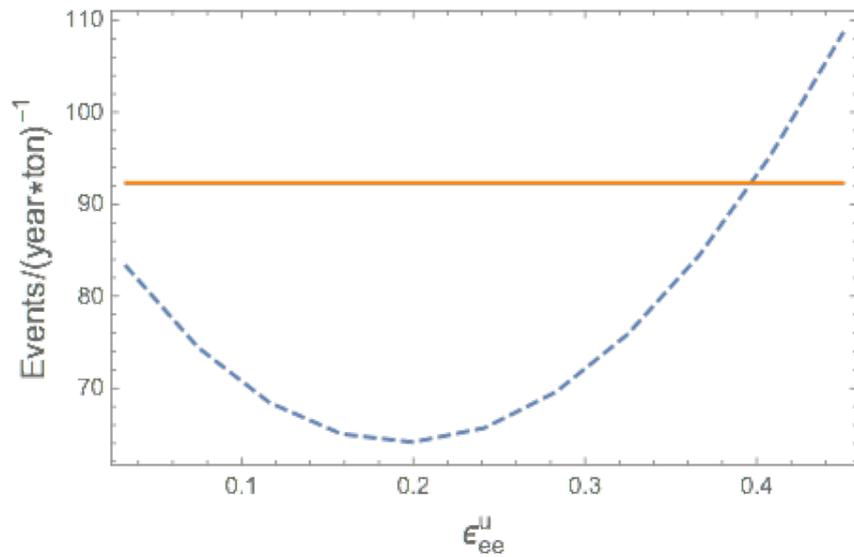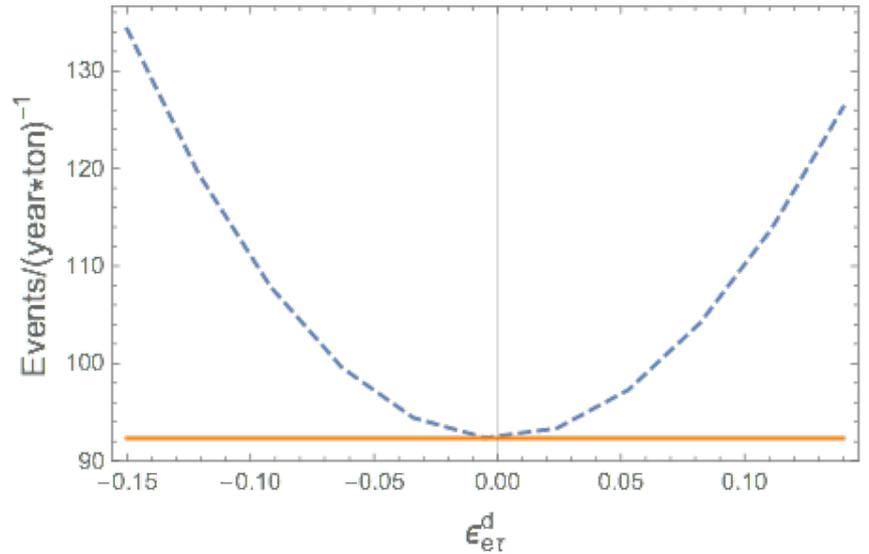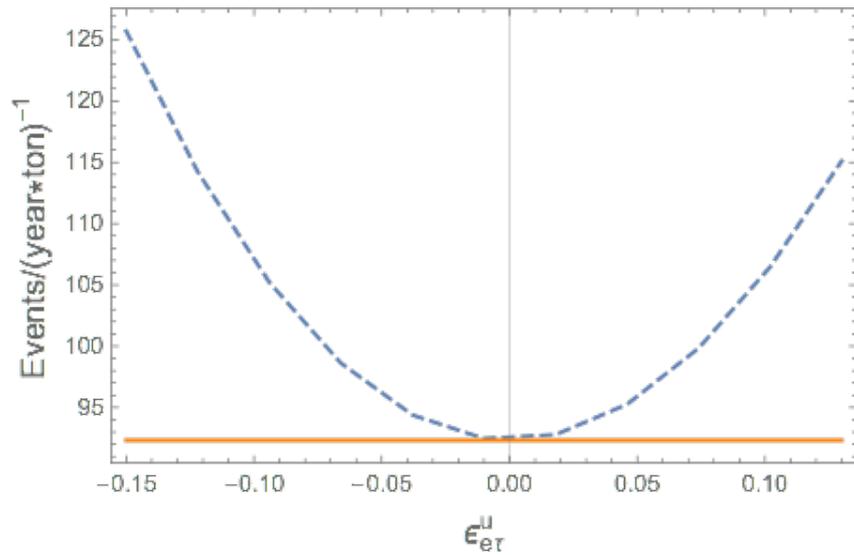- SM CS doesn't interact w/ protons

Sensitivity to Non-Standard Interactions

Neutrino NSI CEνNS Limits for 20 kg ^{72}Ge and 10 kg ^{28}Si, 1 Year

- Flavor-diagonal NSI statistical bounds are world competitive ~ 5×10^{-4} (1 year, 30 kg)
- Flavor-mixed (e/μ, e/τ) terms are not competitive, due to lack of SM cross-term boost
- Statistical bounds on flavor-diagonal NSI scale as a square-root of mass × time × flux

NSI effects on event rates of nuclear recoils

From: Shu Liao

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
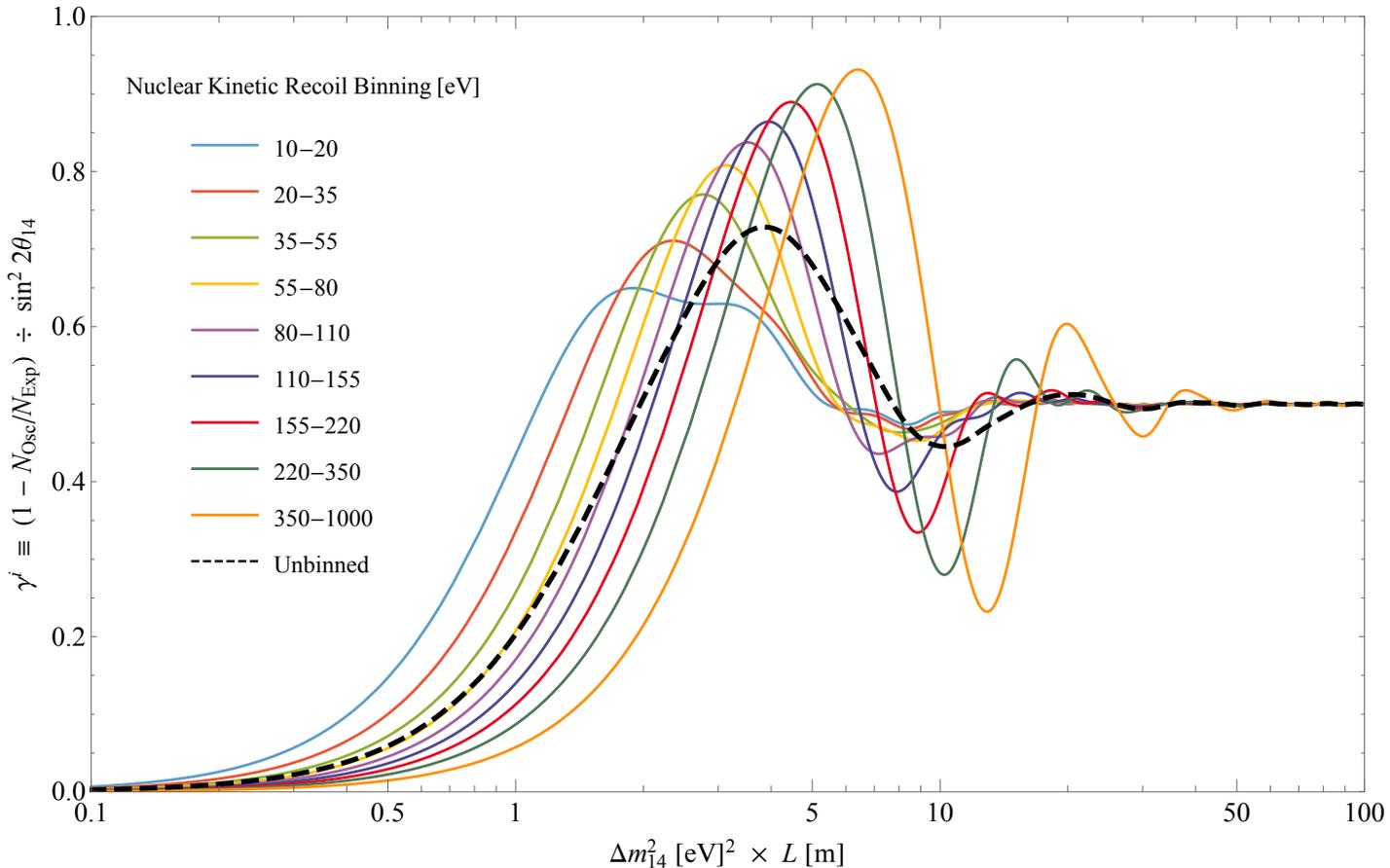- Could enhance event rate

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

For Example, See:
- Dent et al. 1612.06350
- Boehm et al. J.Phys.G30:279-286,2004
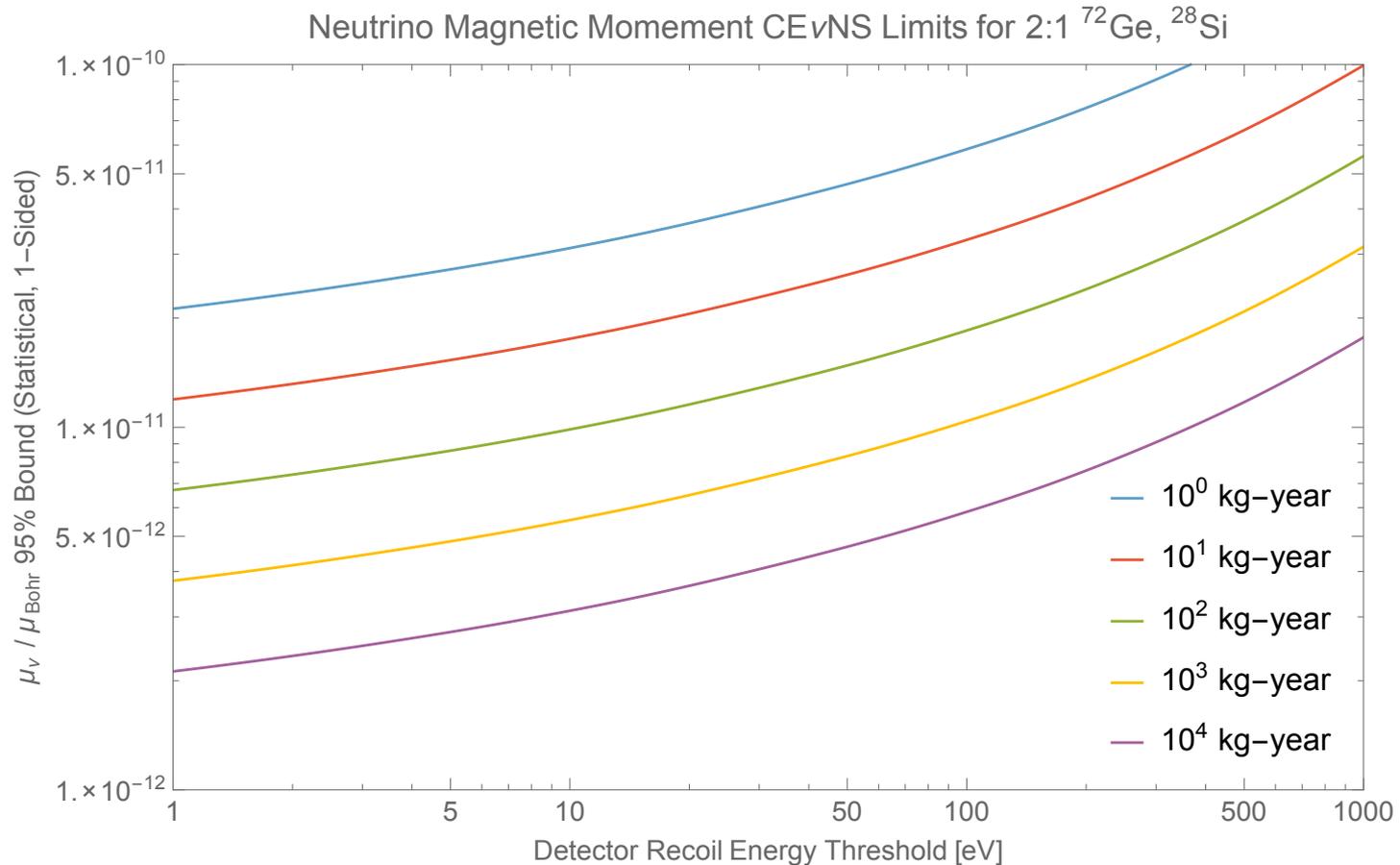- Cerdeno et al. 1604.01025
- Feng et. Al 1604.07411

Depletion via Oscillation

Sterile Neutrino Oscillation in Reactor CEνNS with ^{72}Ge

- 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

Sensitivity to Neutrino Magnetic Moment

Neutrino Magnetic Momement CEνNS Limits for 2:1 ^{72}Ge, ^{28}Si

- Low thresholds required to observe nucleus - neutrino magnetic moment scattering
- Early statistical bounds are (terrestrial) world competitive ~ 10^{-11} Bohr units (1 year, 30 kg)
- Statistical bounds on μ_ν scale inversely as a fourth-root of mass $\times$ time $\times$ flux

Summary

- MINER as a reactor neutrino experiment
- Search for coherent scattering
- Non standard physics in neutrino sector
- Neutrinos as future dark matter background