Sensitivity to Z-prime, neutrino magnetic moment, and oscillation with a sterile fourth generation neutrino from ultra-low threshold neutrino-nucleus coherent scattering

Joel W. Walker
Sam Houston State University

with Dutta, Gao, Mahapatra, Mirabolfath, Strigari, Gao
(1508.07981, 1511.02834)
& Representing the MIνER Collaboration

PHENO
University of Pittsburgh
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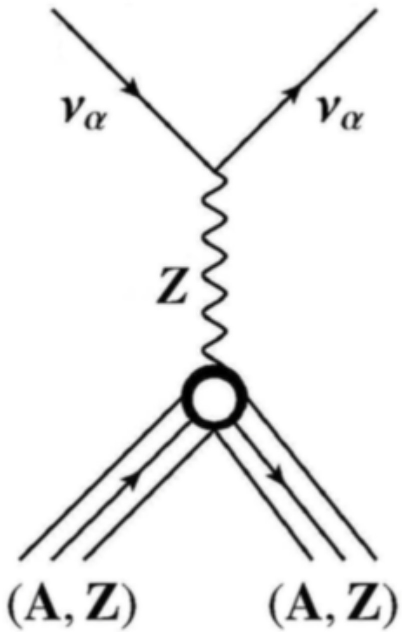
MIνER Experimental Personnel

- Texas A&M: Mahapatra, Mirabolfath, Harris, Webb, Agnolet, Teizer, Rogachev, McDeavitt, Kubik, Jastram
- University of Texas: Lang, Flanagan
- Minnesota: Mandic
- Fukui, Japan: Tamagawa-san, Nakajima-san, Ogawa-san
- South Dakota: Sander
- NISER: Badangas
- + Others

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

Elastic Neutrino Scattering via *Z*-boson



(1502.02928)

- SM scattering is t-channel *Z*-boson exchange
- Contributions from nuclear and electron scattering
- New physics diagrams may alter the rate and coupling
- With 1 target nucleus search for deviations in the rate
- With 2 or more nuclei search for deviations in the coupling

Scattering Kinematics

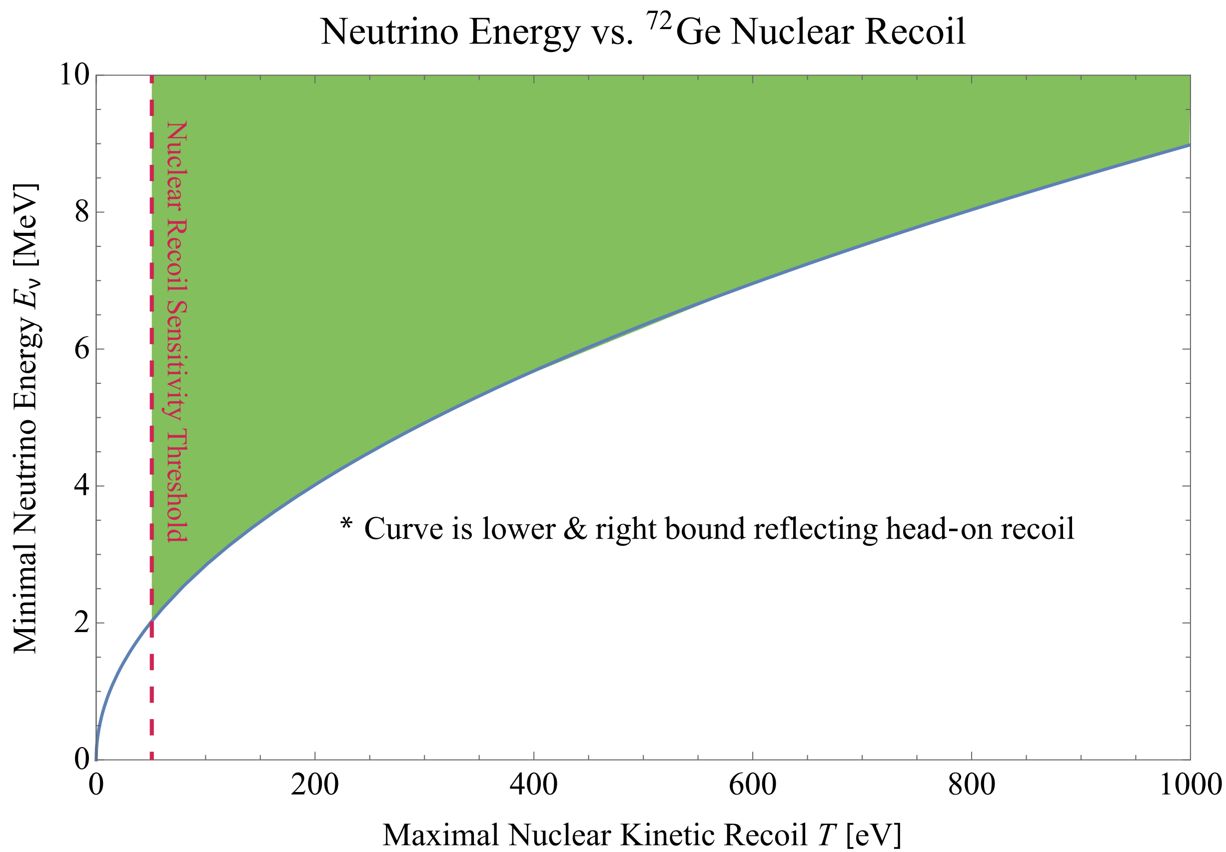
$P_i \equiv E_\nu$ is incoming neutrino energy
$-P_f$ is recoiling neutrino energy
T is the kinetic recoil of nuclear mass M

$P_i - P_f = Q$: Momentum conservation
$M + P_i = M + T - P_f$: Energy conservation
$(M + T)^2 - Q^2 = M^2$: Mass shell condition

$(M + T)^2 - (2E_\nu - T)^2 = M^2$: Combination of prior

- Considering recoil of heavy stationary nucleus from massless particle
- Threshold calculation is in the limit of head-on collision
- Cross section accounts for distribution of glancing blows in phase space
- Only a very small fraction of incoming energy is transferred
- MeV scale neutrino energies are downgraded to eV scale recoils

Energy vs. Recoil Integration Region

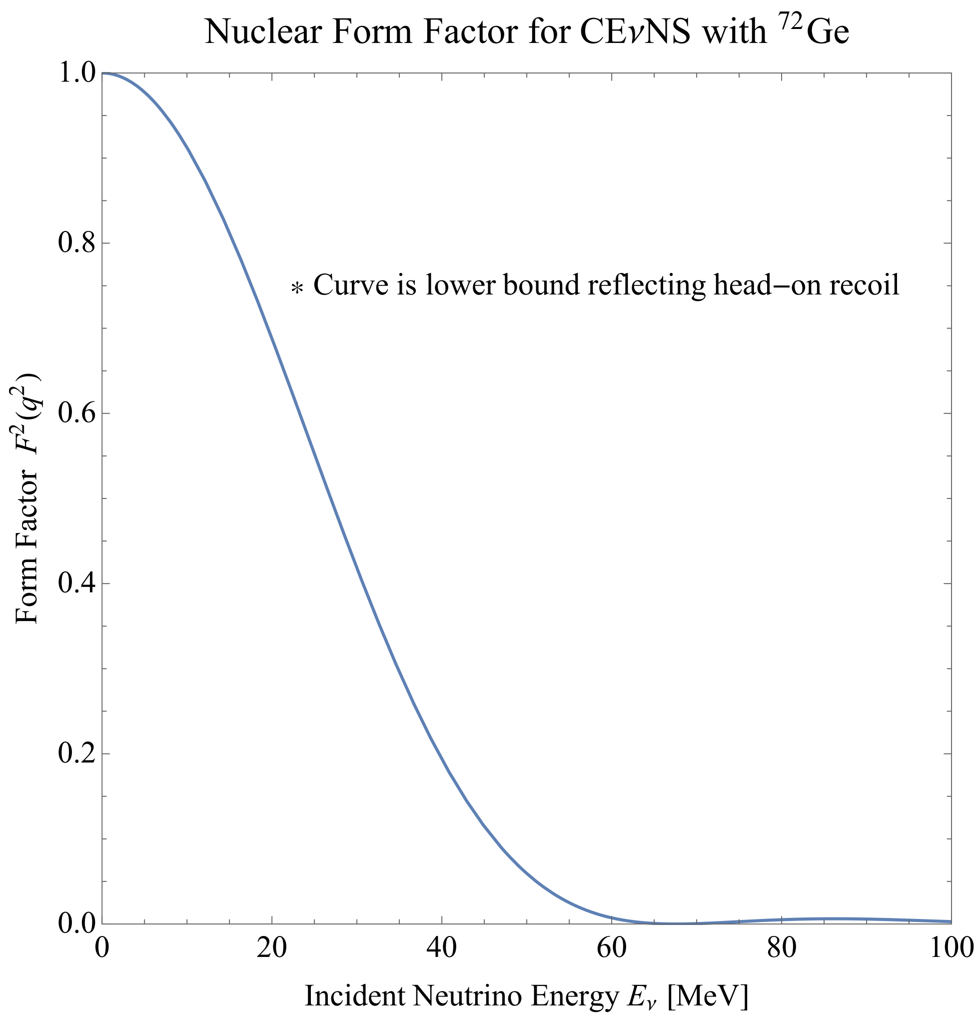


$T \leq \frac{2E_\nu^2}{2E_\nu + M}$: Solution for maximal kinetic recoil

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

$Q \leq \frac{2E_\nu(E_\nu + M)}{2E_\nu + M}$: Solution for maximal momentum transfer

Maintaining Coherency

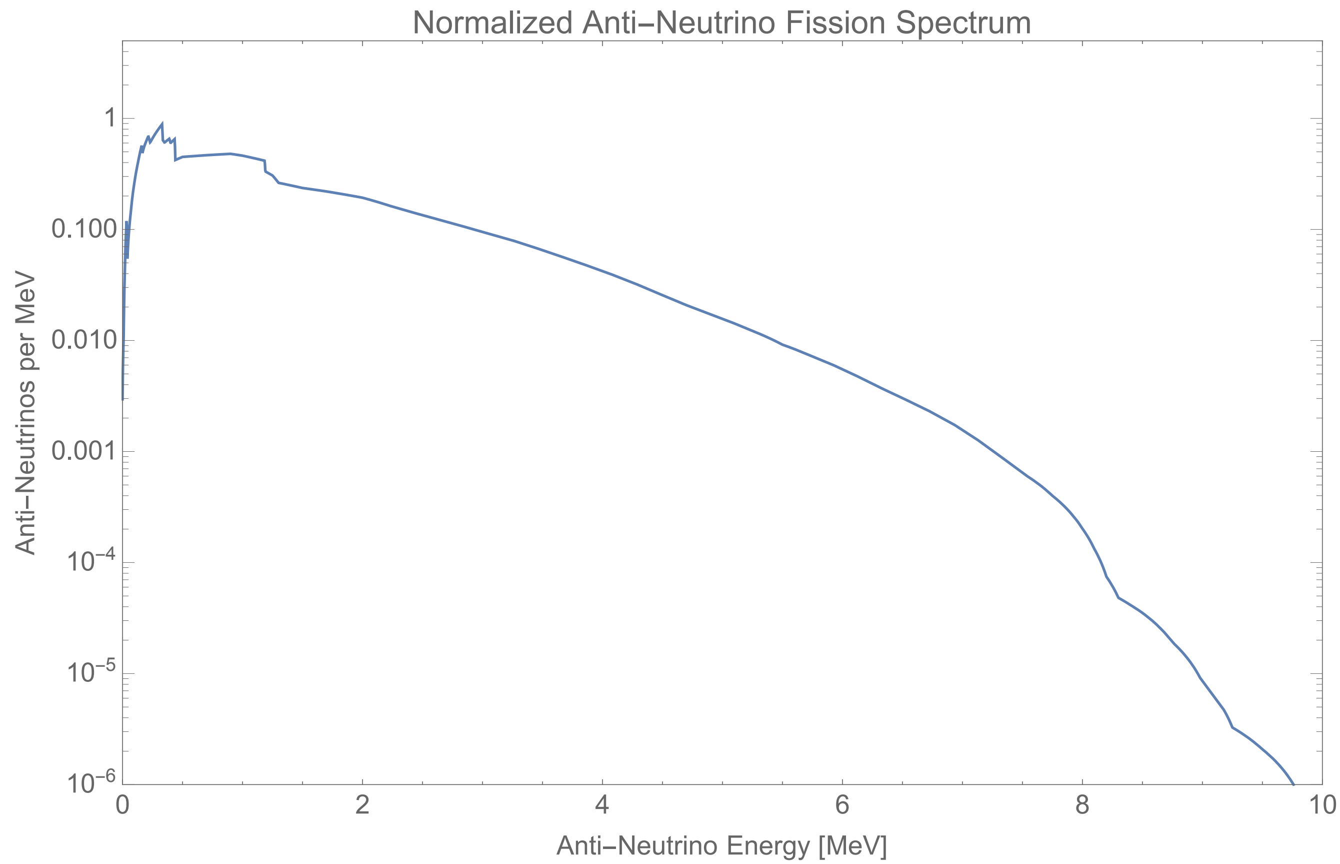


$$F(q^2) = \frac{3j_1(qR_0)}{qR_0} e^{-(qs)^2/2}$$ (Engel PLB 1991)

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

Reactor Anti-Neutrino Source



- ^{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

Assignment of SM Charges

- g and g' are the $SU(2)_L \times U(1)_Y$ coupling constants
- Coupling to neutral current Z is $g/\cos\theta_W$, where $\tan\theta_W = g'/g$, and $e = g\sin\theta_W$
- Neutral Z-boson current charge operator is $T_3 - Q\,\sin^2\theta_W$
- Effective dimension six coupling (Fermi) $G_F = \sqrt{2}g^2/8M_W^2$, where $M_W = M_Z\cos\theta_W$
- Vector $q_V = q_L + q_R$ and Axial $q_V = q_L - q_R$ mix chiralities
- For anti-neutrino scattering, relative sign flip between q_V and q_A for parity

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 (3.5% boost)
- ^{28}Si is spin zero for both protons and neutrons independently

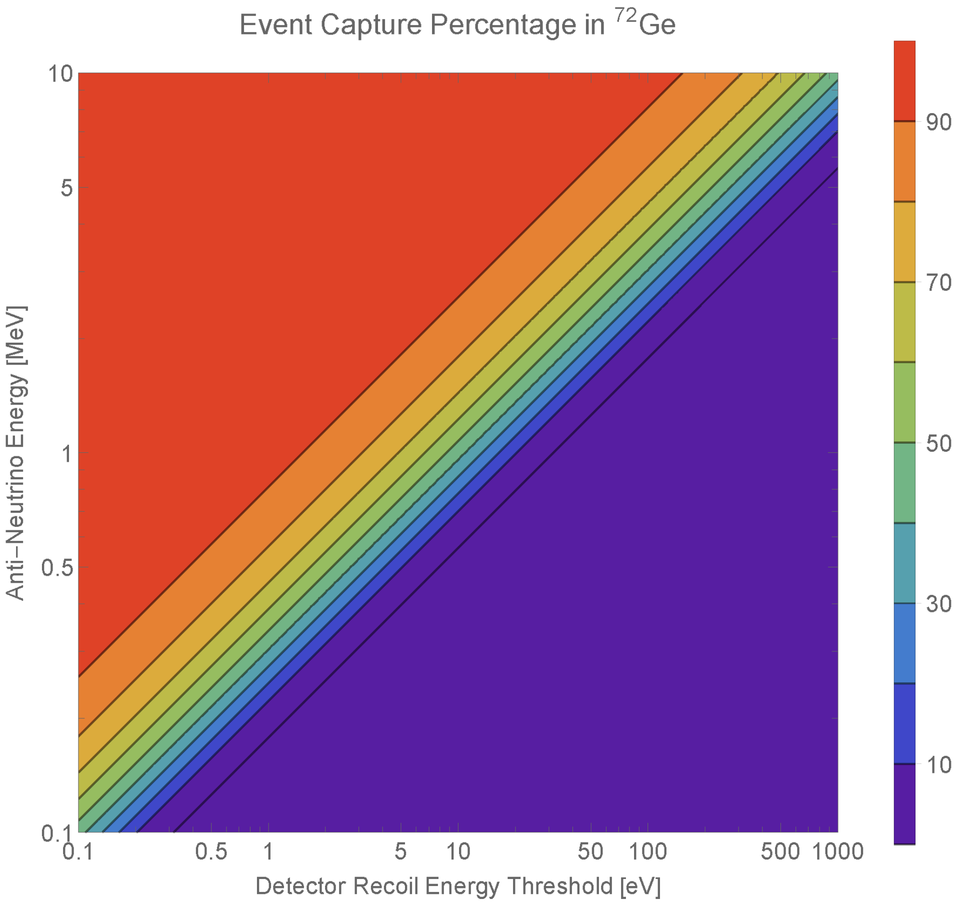
- In the pure-vector limit, the leading dependence is $1 - MT_R/2E_\nu^2$
- Interpolates between large cross section at zero recoil & zero cross section at cutoff

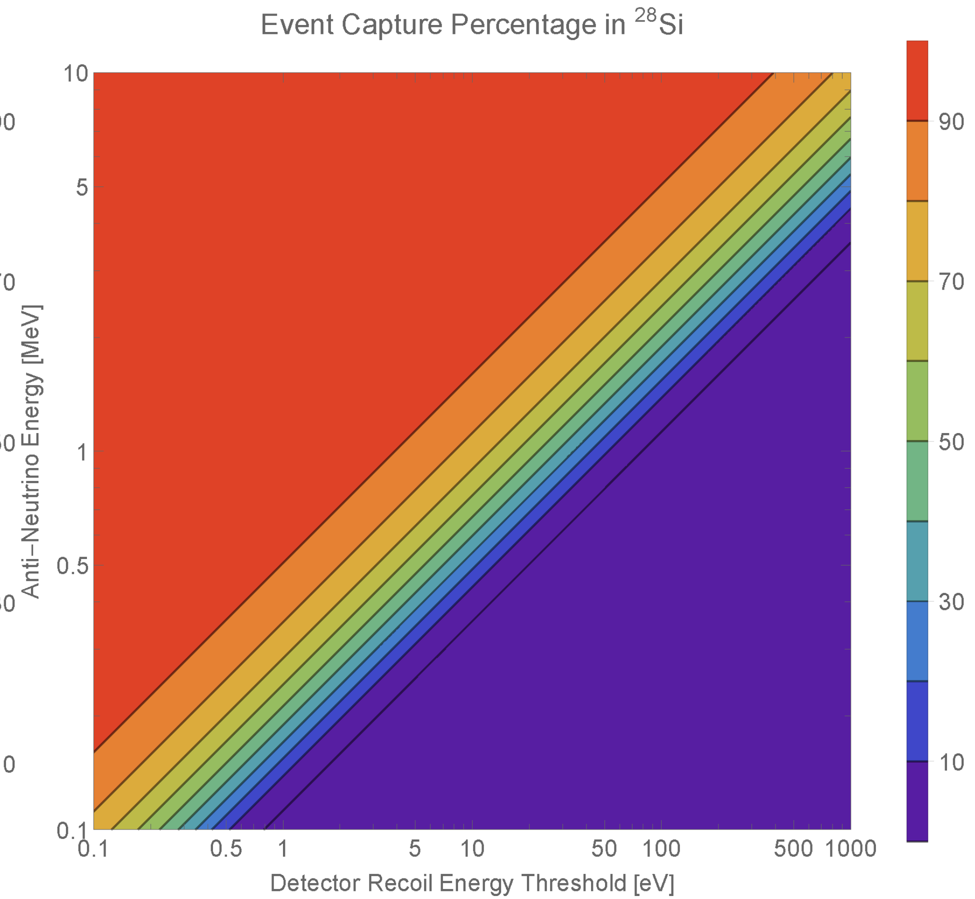
Integrated Event Rate

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

- 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

Threshold vs. Neutrino Energy





- To capture ½ of neutrinos at mean energy of 1.5 MeV, threshold is 20 eV (Ge) or 50 eV (Si)

Z-prime Models

- A *Z*-prime is a heavy neutral analog of the *Z*-boson
- They are expected relics of local *U(1)* symmetries broken at higher energies
- Such symmetries emerge naturally in various string and GUT constructions
- Typical *Z*-prime benchmark models are:

- The E_6 GUT models.
- Coupling is fixed by symmetry
- Charge operator is continuous $Q_{E6} = \cos\beta\, Q_{E6}^{\chi} + \sin\beta\, Q_{E6}^{\psi}$ [admixture of 2 $U(1)$'s]

- The *B-L* Baryon-minus-Lepton number models
- Coupling is arbitrary. We will study $g' = 0.2$ and $g' = 0.4$

- The Sequential Standard Model
- Couplings are identical to SM, but particle is heavier

- LHC looks for Z' via structures in the dilepton invariant mass distribution
- At LHC 13/14 projected 95% Z' limits are ~ 4-6 TeV (Gershtein et al. Snowmass 2013)
- Solid state detectors fare better at large coupling (parton lumin. is mass suppressed)
- SS detectors are not directly sensitive to scale, but can distinguish mode (^{72}Ge vs. ^{28}Si)
- SS detectors can probe scale with high statistics and control of systematics

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

Magnetic Moment Scattering

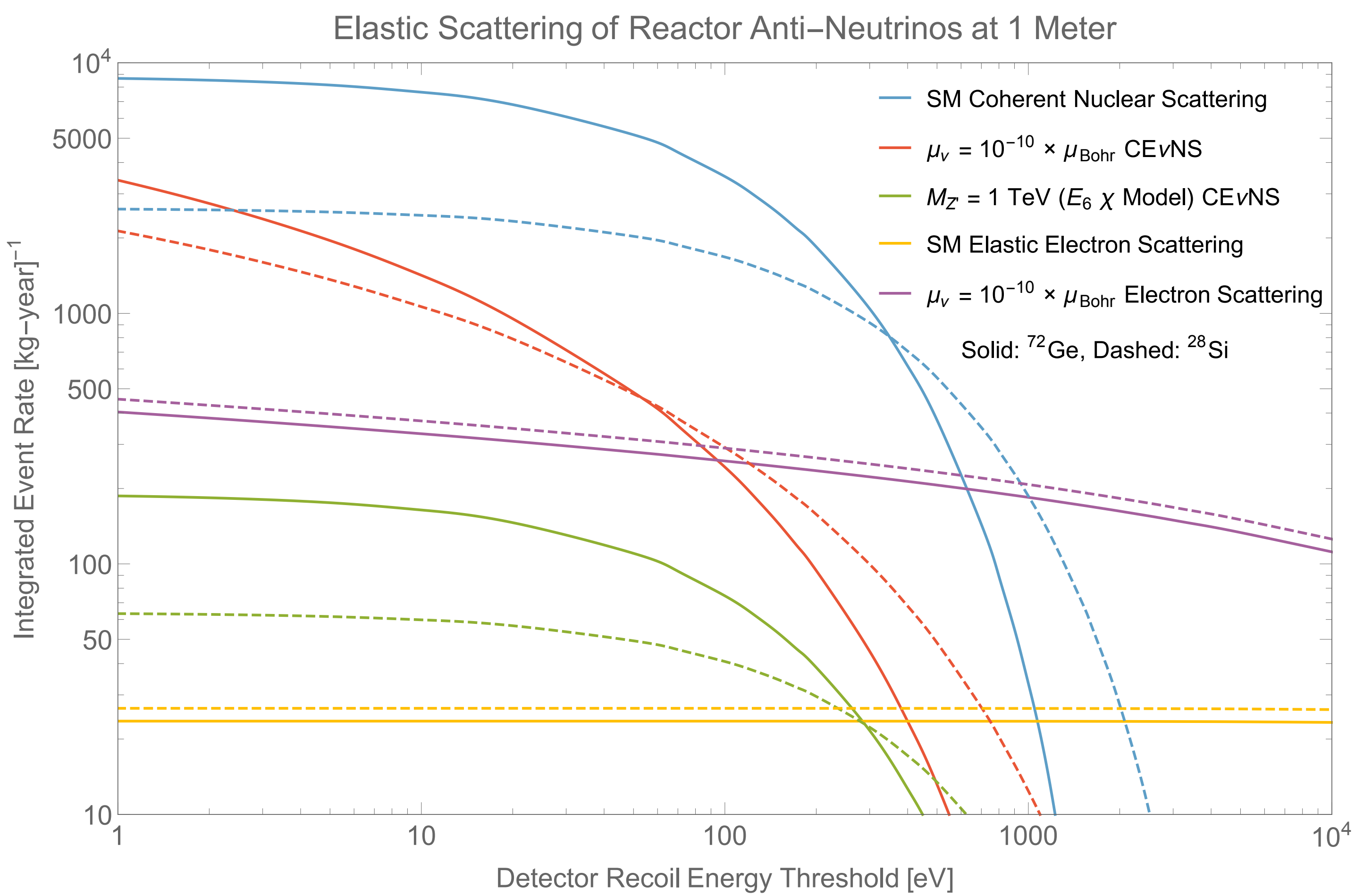
$$\left.\frac{d\sigma}{dT_{\rm R}}\right|_{\mu_\nu} = \frac{\pi\alpha^2\mu_\nu^2}{m_e^2}\left[\frac{1-T_{\rm R}/E_\nu}{T_{\rm R}} + \frac{T_{\rm R}}{4E_\nu^2}\right]$$

- Magnetic moment of neutrino in units of Bohr magneton $\mu_{\text{Bohr}} = e/2m_e$
- This supplements the main cross-section as a simple sum
- In the nucleus, only protons couple (contrast to CEνNS where neutrons are vital)
- This allows for efficient discrimination of mode in ^{72}Ge vs. ^{28}Si

- The second term is applicable to nuclear scattering, but not the electron cloud
- There is another term (not shown) for nuclei with odd *A*
- (Vogel, Engel PRD 1989)

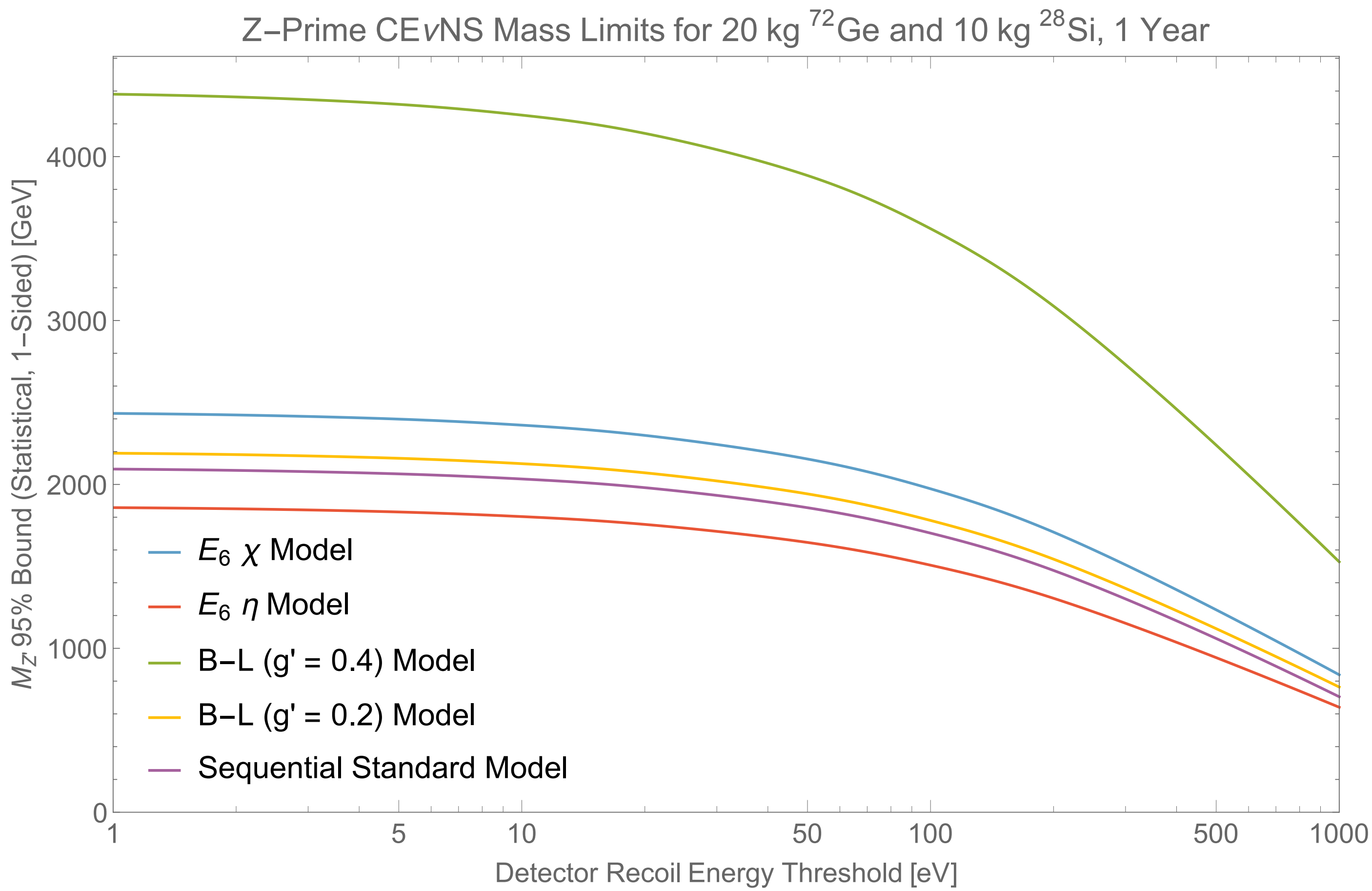
- Current limits on Majorana μ_ν are on the order 10^{-11} (terrestrial) and 10^{-12} (astro)

Components of Elastic Scattering



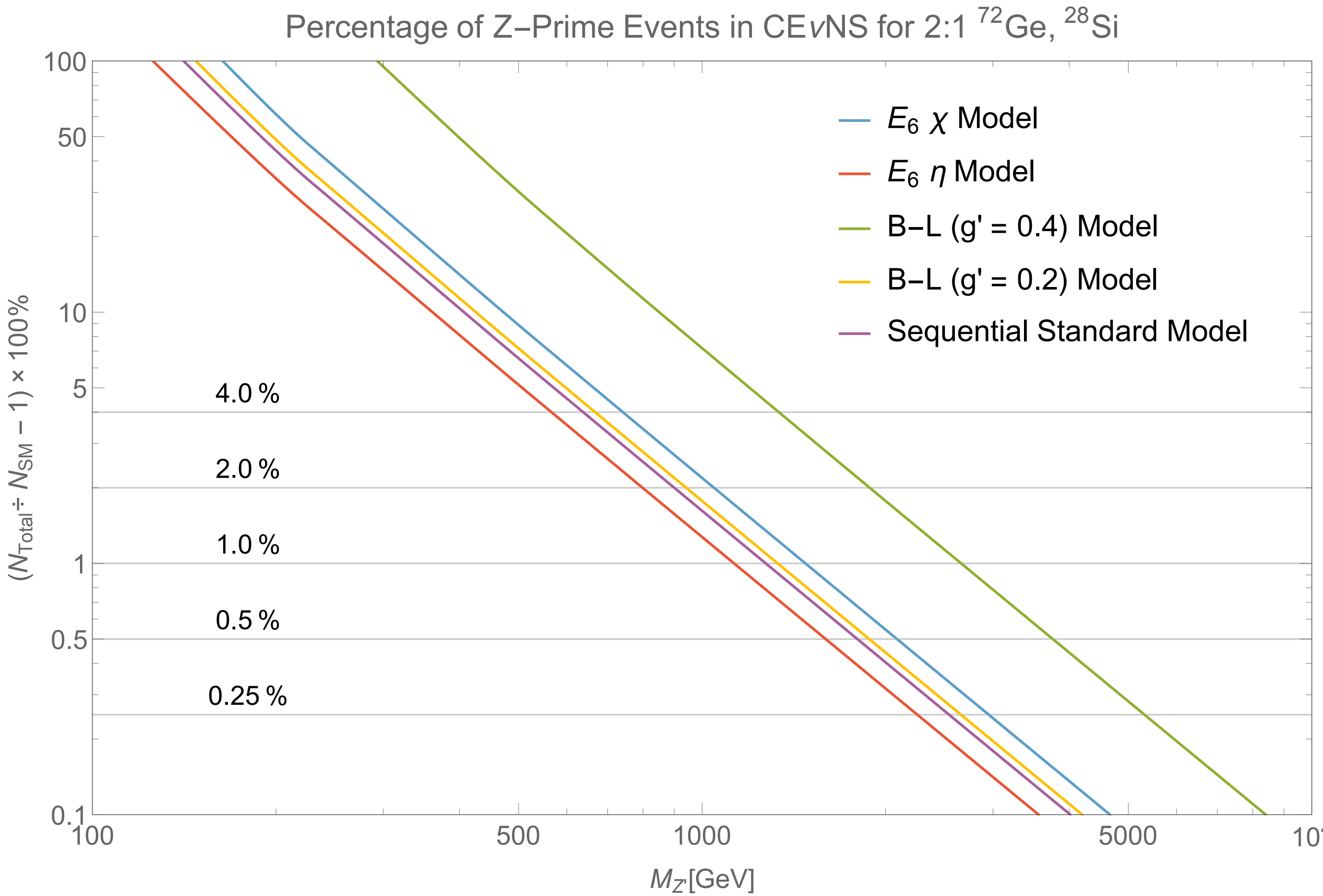
- Coherency boosts nuclear cross section, but large mass implies low recoil thresholds
- Yellow & purple electron recoil terms are smaller, but dominate at high threshold
- Nucleus - neutrino magnetic moment scattering (red) benefits most at low thresholds
- μ_ν scattering is absolutely larger in the nucleus, but fractionally larger for electrons

Sensitivity to Z’ Mass



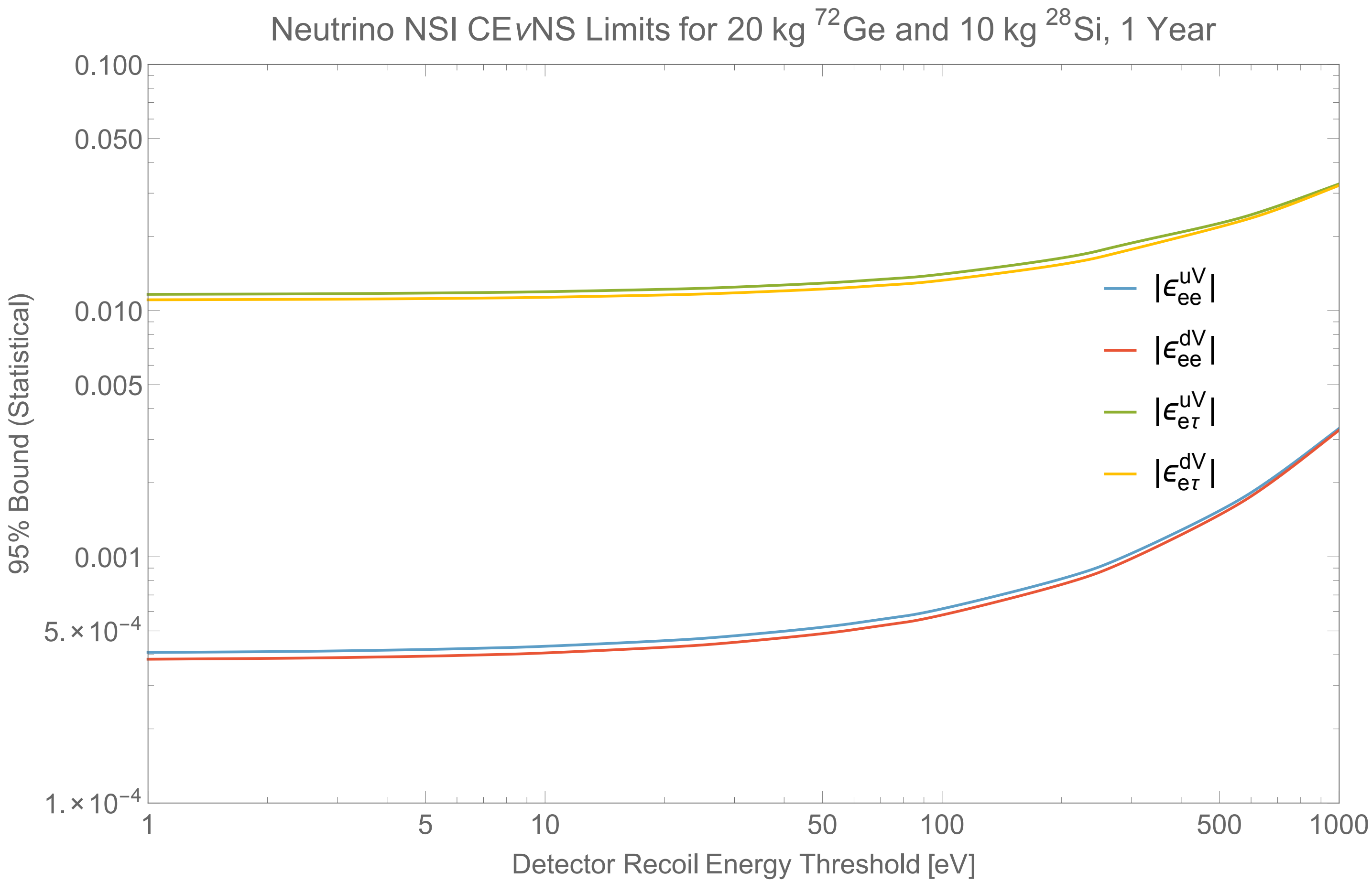
- Early statistical bounds are world competitive at ~ 2-4 TeV range (1 year, 30 kg)
- Phase II bounds on mass of Z’ scale as a fourth-root of mass × time × flux
- LHC 14 has projected future reach of 5-6 TeV for 300/fb integrated luminosity
- Various models couple distinctly to *n*,*p*, so that Si vs. Ge rates can distinguish

Impact of Systematic Errors



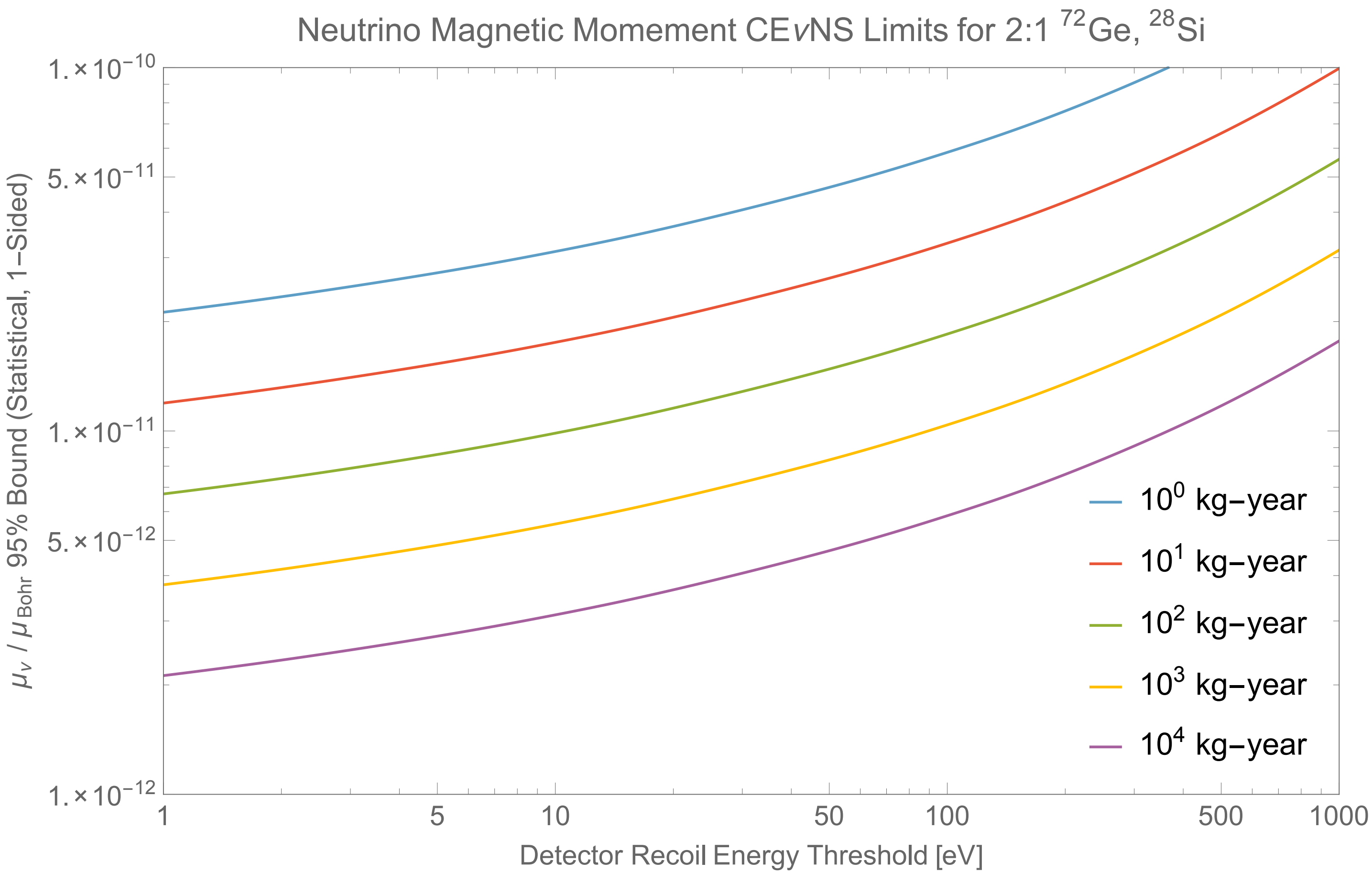
- Baseline uncertainty in reactor anti-neutrino flux is ~ 2%, limiting mass resolution
- This is more damaging in the large mass / long exposure limit (low stat. error)
- Differential measurement of Si vs. Ge cancels systematics and elevates ceiling

Sensitivity to Non-Standard Interactions



- 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

Sensitivity to Neutrino Magnetic Moment



- 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 × time × flux

Cancellation of Systematics in Ge, Si

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

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

- *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

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

Long-Term, High-Mass Detector Reach

kg-years	$M_{Z'}(E_6, \chi)$	$M_{Z'}(B-L, g'=0.4)$	$\mu_\nu/\mu_{\mathrm{Bohr}}$
12	$(1.9, 1.9, 1.6)$	$(3.5, 3.4, 2.8)$	$(1.1, 1.7, 3.1) \times 10^{-11}$
5×10^3	$(8.7, 8.5, 7.1)$	$(16, 15, 13)$	$(2.5, 3.7, 7.0) \times 10^{-12}$
1×10^5	$(18, 18, 15)$	$(33, 32, 27)$	$(1.2, 1.8, 3.3) \times 10^{-12}$

- Statistical projections are for (1 year, 12 kg), or (5 year, 1,000 kg), or (10 year, 10,000 kg)
- Systematics are comparable to statistical errors in first phase, but dominate in latter
- Parenthesis compare (1,10,100) eV detector recoil thresholds
- Ultra-low eV-scale thresholds present greatest benefit to magnetic moment searches
- Z-prime masses are in TeV units

Oscillation to Sterile 4th Flavor Neutrino

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

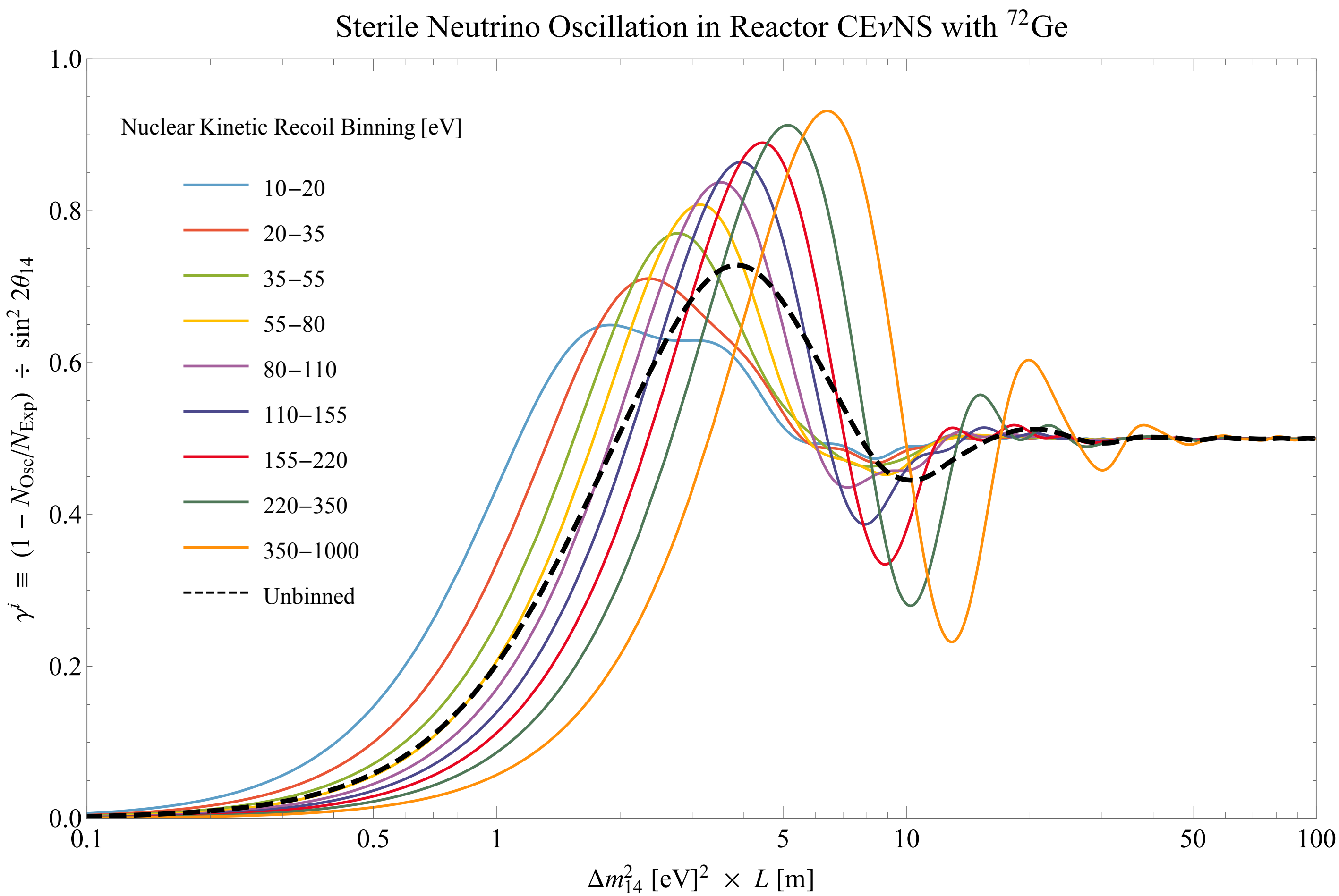
$$\lambda = 4.97\ [\mathrm{m}] \times \left\{\frac{E_\nu}{1\ [\mathrm{MeV}]}\right\} \times \left\{\frac{1\ \mathrm{eV}^2}{\Delta m^2}\right\}$$

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

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

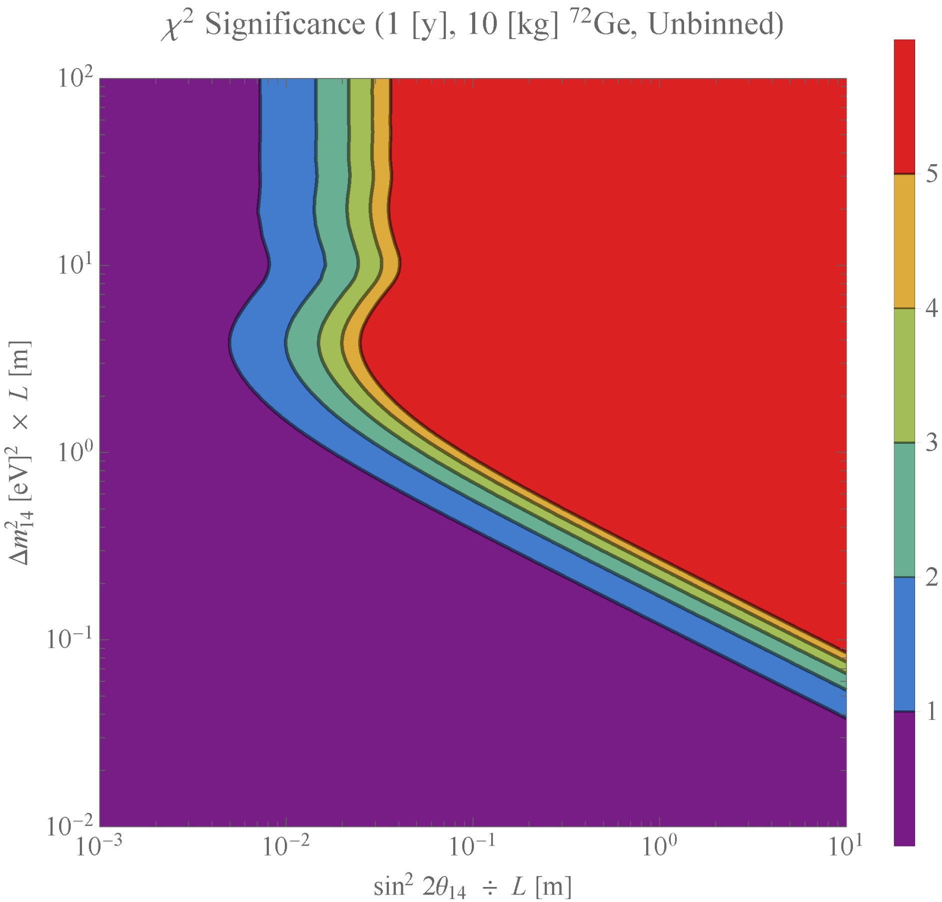
- Probability for oscillation depends on mixing (amplitude) and mass gap (phase)
- For the region of interest, an experimental baseline on the order of meters is relevant
- Dimensionless scale-invariant basis functions encapsulate all aspects of theory
- Neutrino anomalies exist in radioactive source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

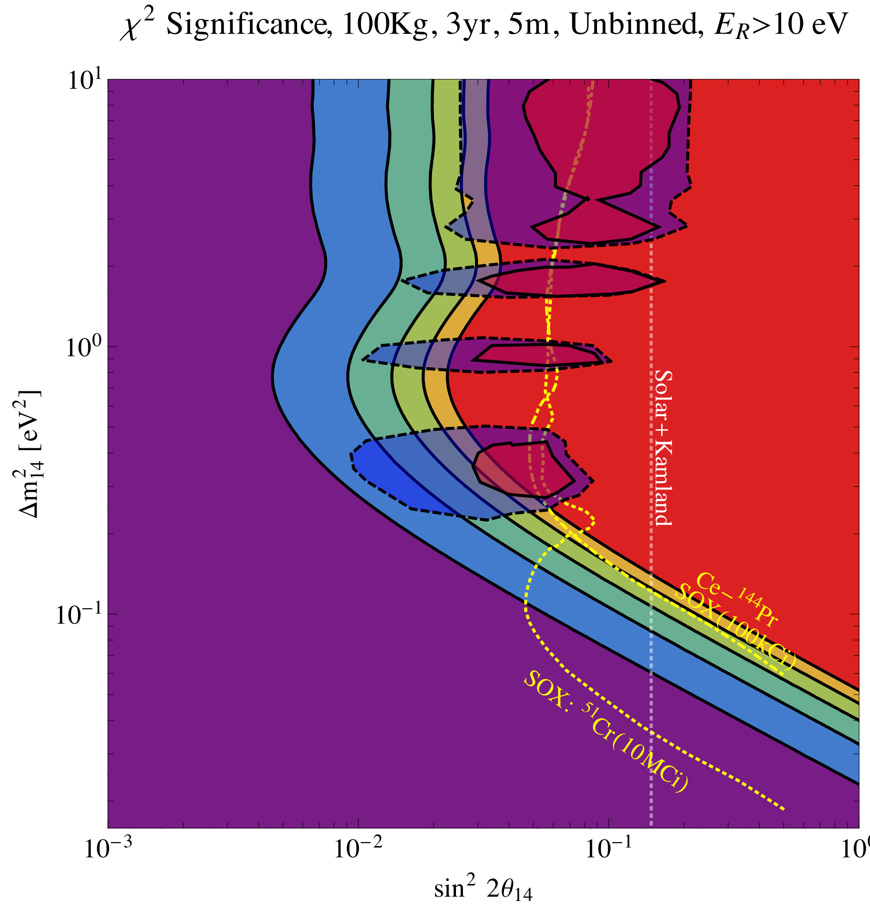
Depletion via Oscillation



- 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

Projected Sensitivity to Oscillation





- Left: Projected scale-invariant sensitivity, in the statistics-only limit, with unbinned data
- Naively, sensitive to $\Delta m^2 \sim 1\ \mathrm{eV}^2$ for $\sin^2 2\theta \sim 10^{-2}$ or $\Delta m^2 \sim 0.1\ \mathrm{eV}^2$ at unit amplitude
- Right: Global fits to reactor and gallium anomalies are superimposed
- Additionally, SOX and Solar+Kamland limits are compared

Template fitting to Oscillation Shape

$$\mathcal{P}_i \equiv \mathcal{P}(N^i_{\text{Obs}}) = \exp\left\{-\frac{\left[N^i_{\text{Obs}} - \alpha N^i_{\text{Osc}}\right]^2}{\sigma_i^2}\right\}$$

$$\widetilde{\mathcal{L}_B} = \sum_{i=1}^{B} \frac{\left[N^i_{\text{Obs}} - \alpha N^i_{\text{Osc}}\right]^2}{\sigma_i^2}$$

$$\sum_{i=1}^{B} \frac{\left[N^i_{\text{Obs}} - \alpha\, N^i_{\text{Exp}} \times \{1 - \widehat{s}\,\gamma_i\}\right] \times N^i_{\text{Exp}} \times \{1 - \widehat{s}\,\gamma_i\}}{\sigma_i^2} = 0$$

$$\Delta^{i,n}_{\text{Obs}} \equiv \frac{N^{i,n}_{\text{Obs}}}{\langle N^i_{\text{Obs}}\rangle} - 1$$

$$\Delta^{i,n}_{\text{Osc}} \equiv \widehat{s} \times \left\{\frac{1 - 2\,\gamma_{i,n}}{2 - \widehat{s}}\right\}$$

$$\widetilde{\mathcal{L}^i_2} = \langle N^i_{\text{Obs}}\rangle \times \sum_{n=0}^{N} \left\{\Delta^{i,n}_{\text{Obs}} - \Delta^{i,n}_{\text{Osc}}\right\}^2$$

$$\widetilde{\mathcal{L}^i_0} = \sum_{n=0}^{N} \frac{\left\{N^{i,n}_{\text{Obs}} - \langle N^i_{\text{Obs}}\rangle\right\}^2}{\langle N^i_{\text{Obs}}\rangle} = (N+1) \times \frac{\sigma_i^2}{\langle N^i_{\text{Obs}}\rangle} \geq (N+1)$$

$$\widetilde{\mathcal{L}^i_2} \leq \widetilde{\mathcal{L}^i_0} - \text{CDF}^{-1}\big(\chi^2_2, 1-p\big)/2$$

$$p = 1 - \text{CDF}\big(\,\chi^2_2,\, 2 \times \left[\widetilde{\mathcal{L}^i_0} - \widetilde{\mathcal{L}^i_2}\right]\big)$$

$$\mathfrak{N} = \sqrt{\text{CDF}^{-1}\big(\chi^2_1, 1-p\big)}$$

- Quantify goodness-of-fit for the oscillation template to data vs. null hypothesis
- Uncertainty in reactor normalization & leading systematic errors cancel out
- Physical motion of reactor core may be correlated with energy behavior at fixed baseline

Summary

- Coherent Neutrino Scattering is a challenging observation, requiring low recoil threshold
- If CEνNS is observed with high statistics and BG control, it is a lab for new physics
- This will be more sensitive in many cases to the mode of new physics than the scale
- A leading handle for Z-prime may be differential observation of multiple nuclei
- For neutrino μ, the shape of the recoil spectrum & low thresholds also may help a lot
- For oscillation, the key will be multiple baselines and/or energy bin observations