Complementarity of Short-Baseline Neutrino Oscillation Searches with CEvNS

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with Dutta, Gao, Kubik, Mahapatra, Mirabolfathi, Strigari - Phys. Rev. D 94, 093002
+ Dutta, Dent to appear
& Representing the MIνER Collaboration

Please see the excellent review 1803.10661 by
Dentler, Hernandez-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, Schwetz

University of Chicago
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Outline

- Summary of Status of Anomalies:

  There are SEVERAL, generally consistent within “types”, but not obviously consistent with each other globally. See talk by Danny Marfatia for one possible approach – a sterile sector WITH Non-Standard Interactions

- Review of Physics and Analysis:

  Pros and Cons of various experimental approaches to characterizing short-baseline steriles with CEvNS

- Projection of Sensitivity with CEvNS:

  Complementarity of beam and reactor searches

Formalism

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

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

- Transition to self and transition to alternate flavor

$$\begin{aligned} P_{\alpha\alpha} &= 1 - 4|U_{\alpha 4}|^{2}\left(1 - |U_{\alpha 4}|^{2}\right)\sin^{2}\left(\frac{\Delta m_{41}^{2} L}{4E}\right) \\ P_{\alpha\beta} &= 4|U_{\alpha 4}|^{2}|U_{\beta 4}|^{2}\sin^{2}\left(\frac{\Delta m_{41}^{2} L}{4E}\right) \end{aligned}$$

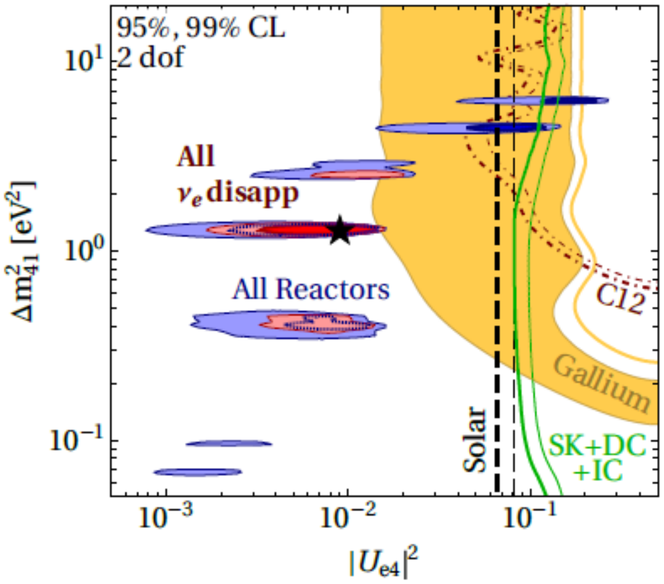
REACTOR and GALLIUM ANOMALIES

- 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

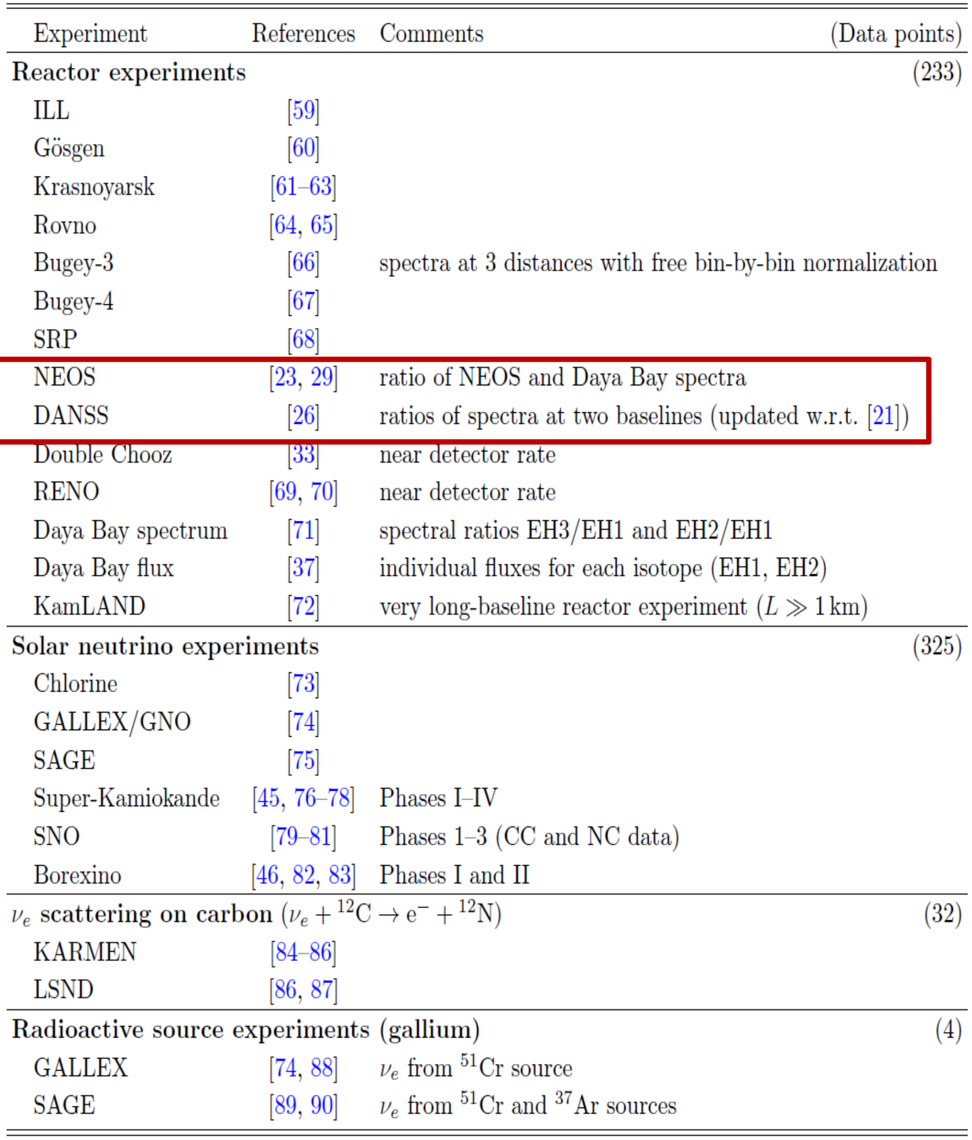
MiniBooNe: $\sin^2 2\theta_{\mu e} \equiv 4|U_{e4}|^2|U_{\mu 4}|^2 .$

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

$$P_{\alpha\beta}^{\rm SBL} = 4|U_{\alpha 4}|^2|U_{\beta 4}|^2\,\sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right). \qquad (\alpha \neq \beta)$$



Dentler, Hernandez-Cabezudo, Kopp, Machado, Maltoni, Schwetz,'18



Experiment	References	Comments	(Data points)
Reactor experiments			(233)
ILL	[59]		
Gösgen	[60]		
Krasnoyarsk	[61–63]		
Rovno	[64, 65]		
Bugey-3	[66]	spectra at 3 distances with free bin-by-bin normalization	
Bugey-4	[67]		
SRP	[68]		
NEOS	[23, 29]	ratio of NEOS and Daya Bay spectra	
DANSS	[26]	ratios of spectra at two baselines (updated w.r.t. [21])	
Double Chooz	[33]	near detector rate	
RENO	[69, 70]	near detector rate	
Daya Bay spectrum	[71]	spectral ratios EH3/EH1 and EH2/EH1	
Daya Bay flux	[37]	individual fluxes for each isotope (EH1, EH2)	
KamLAND	[72]	very long-baseline reactor experiment ($L \gg 1$ km)	
Solar neutrino experiments			(325)
Chlorine	[73]		
GALLEX/GNO	[74]		
SAGE	[75]		
Super-Kamiokande	[45, 76–78]	Phases I–IV	
SNO	[79–81]	Phases 1–3 (CC and NC data)	
Borexino	[46, 82, 83]	Phases I and II	
ν_e scattering on carbon ($\nu_e + {}^{12}\text{C} \to e^- + {}^{12}\text{N}$)			(32)
KARMEN	[84–86]		
LSND	[86, 87]		
Radioactive source experiments (gallium)			(4)
GALLEX	[74, 88]	ν_e from ^{51}Cr source	
SAGE	[89, 90]	ν_e from ^{51}Cr and ^{37}Ar sources	

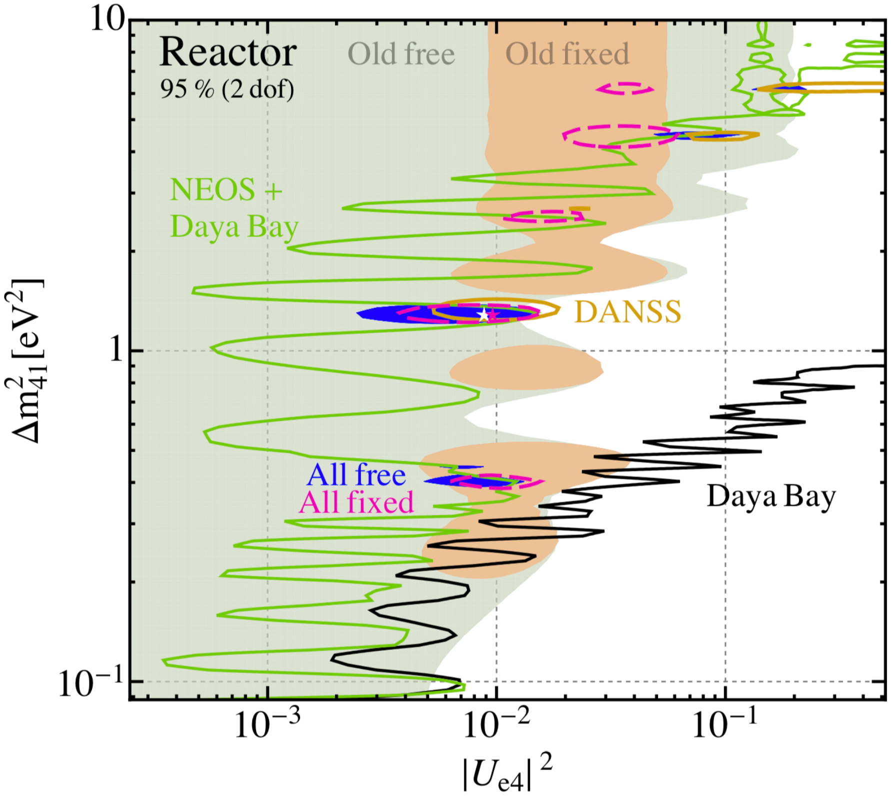
Without reactors,
a larger $|U_{e4}|^2 \sim 5$ - 6×10^{-2} is ok

From Dutta

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)



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.

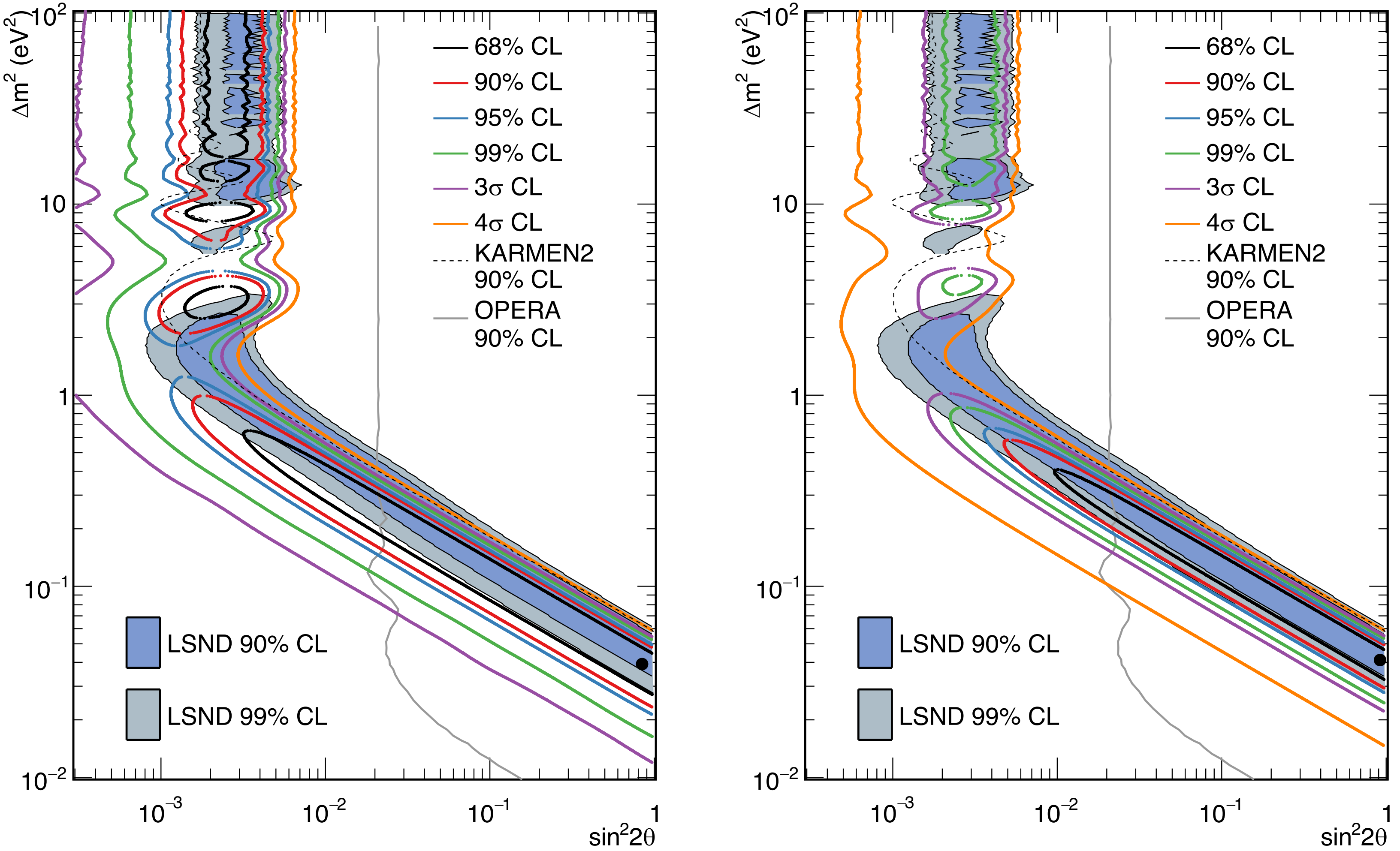
- Two neutrino mu to e oscillation has goodness of fit 20.1%. Background only hypothesis is 5×10^{-7} relative to best fit with $L/E_\nu \approx 1[\mathrm{m/MeV}]$.

- 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

MiniBooNE Results

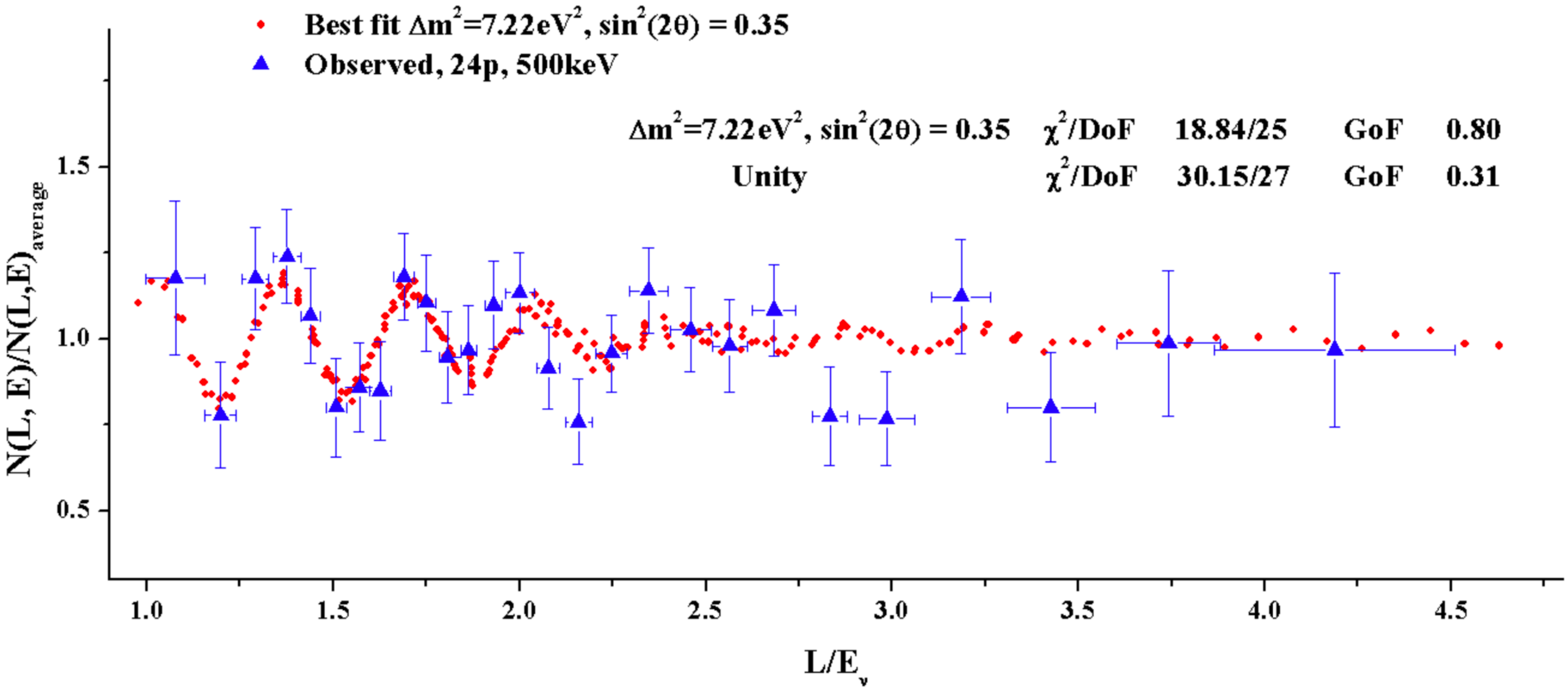
- 1805.12028 Left: Neutrino Mode and Right: Combined with Anti-Neutrino
- Best fit “dot” should not be strongly preferred over regions in contours



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

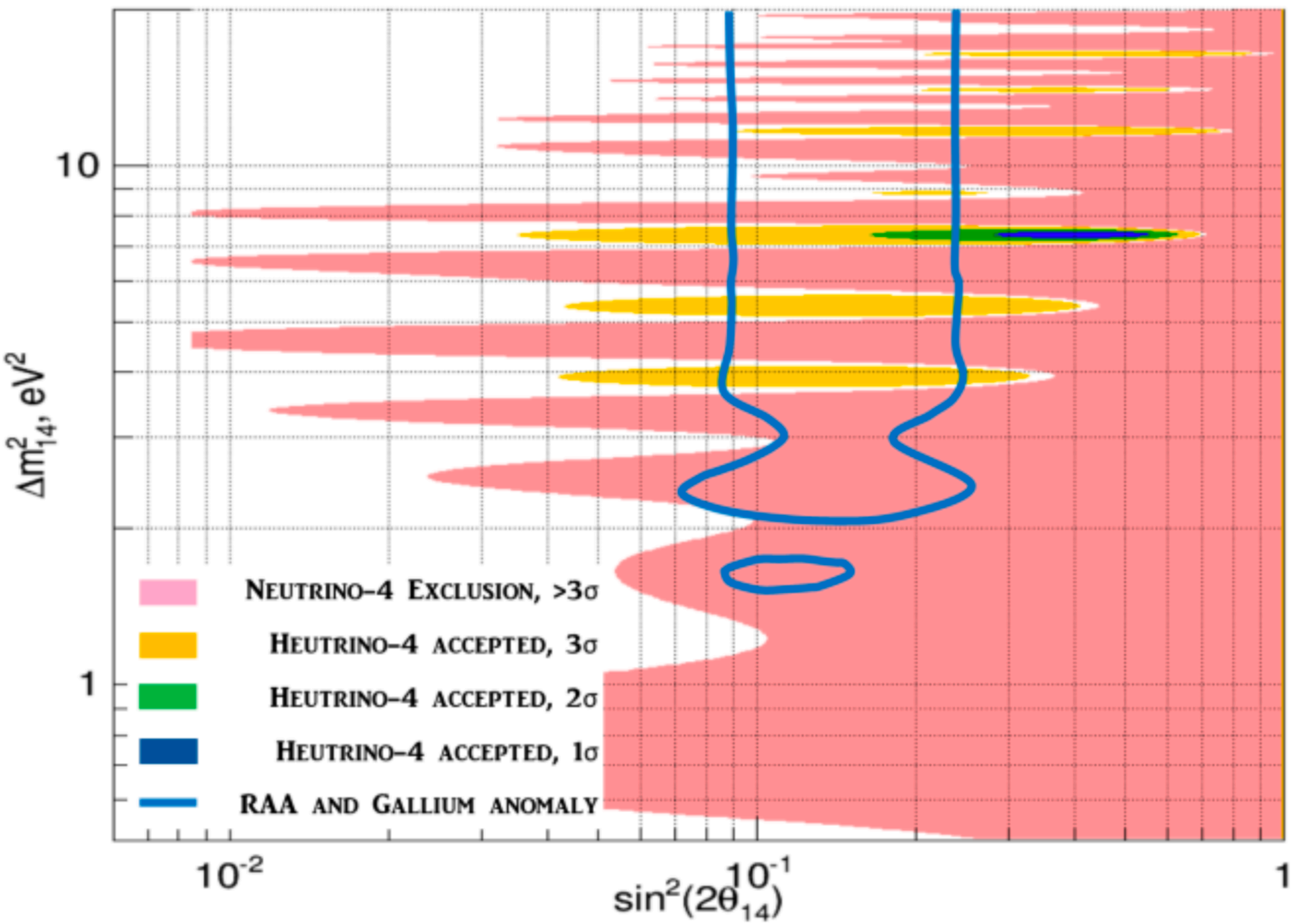
Neutrino 4

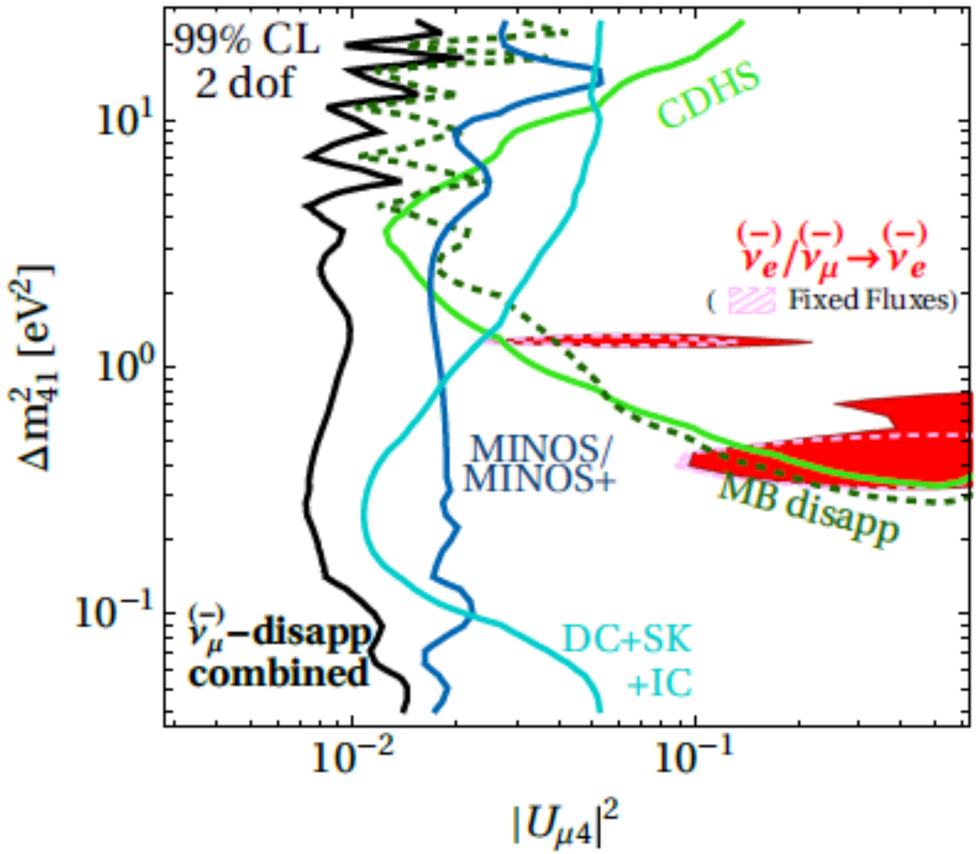


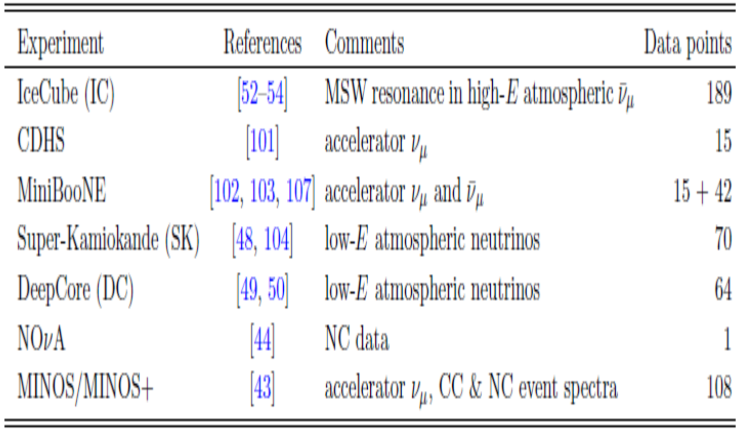
Best fit Δm^2=7.22eV^2, $\sin^2(2\theta)$ = 0.35
Observed, 24p, 500keV
Δm^2=7.22eV^2, $\sin^2(2\theta)$ = 0.35 χ^2/DoF 18.84/25 GoF 0.80
Unity χ^2/DoF 30.15/27 GoF 0.31
$N(L, E)/N(L,E)_{average}$
1.5
1.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
L/E_ν

Neutrino 4

- Yellow, Green, and Blue are increasingly favored







Experiment	References	Comments	Data points
IceCube (IC)	[52–54]	MSW resonance in high-E atmospheric $\bar{\nu}_\mu$	189
CDHS	[101]	accelerator ν_μ	15
MiniBooNE	[102, 103, 107]	accelerator ν_μ and $\bar{\nu}_\mu$	15 + 42
Super-Kamiokande (SK)	[48, 104]	low-E atmospheric neutrinos	70
DeepCore (DC)	[49, 50]	low-E atmospheric neutrinos	64
NOνA	[44]	NC data	1
MINOS/MINOS+	[43]	accelerator ν_μ, CC & NC event spectra	108

Dentler, Harnadex-Cabezudo, Kopp, Machado, Maltoni, Schwetz,'18

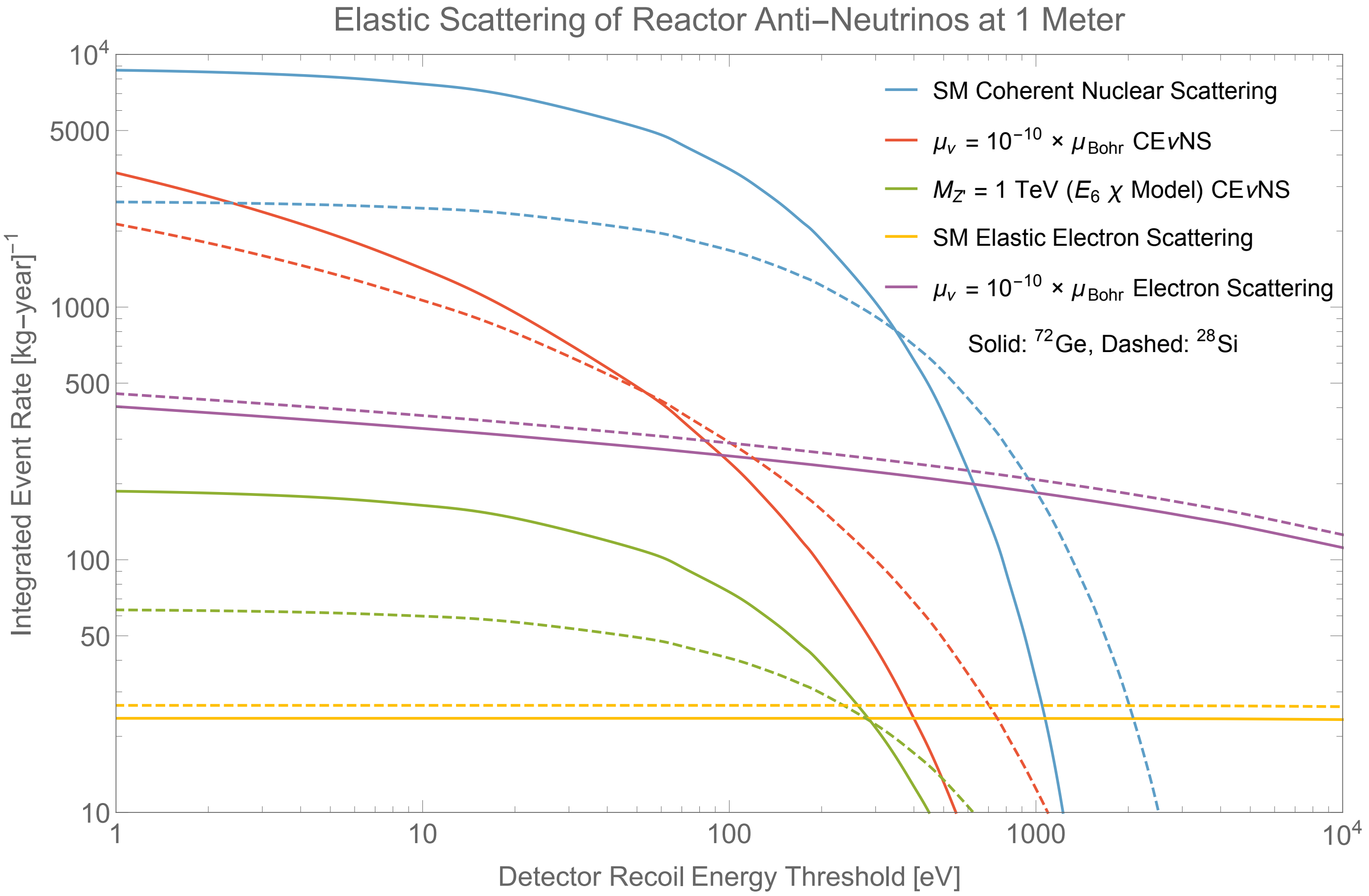
$|U_{\mu 4}|^2 \leq 0.01$

From Dutta

Searching for New Physics with CEvNS

- Large statistics allow precision discrimination
- Can search for new neutral currents, e.g. Z’, NSI – this creates a modification to the RATE only
- Sensitivity is BEST to models that impact also the expected event distribution SHAPE:
- Light mediators, magnetic moment, sterile

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

Oscillation to Sterile 4th Flavor Neutrino

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

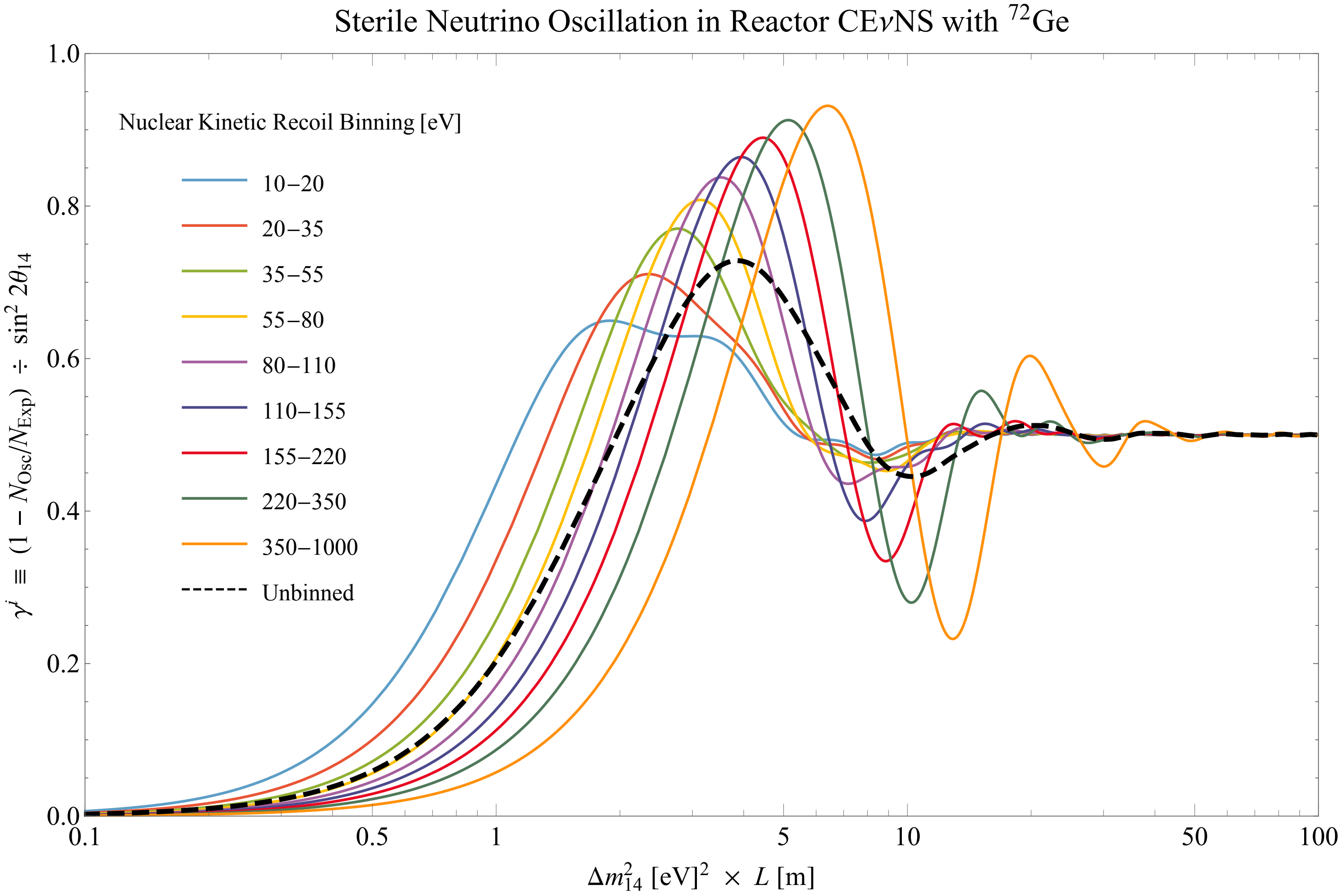
$$\lambda = 4.97\ [\mathrm{m}] \times \left\{\frac{E_\nu}{1\ [\mathrm{MeV}]}\right\} \times \left\{\frac{1\ \mathrm{eV}^2}{\Delta m^2}\right\}$$

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

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

- 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

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

COHERENT at the SNS

- Stopped Positive Pion produces isotropic muon neutrino ν_μ of fixed energy ~ 30 MeV

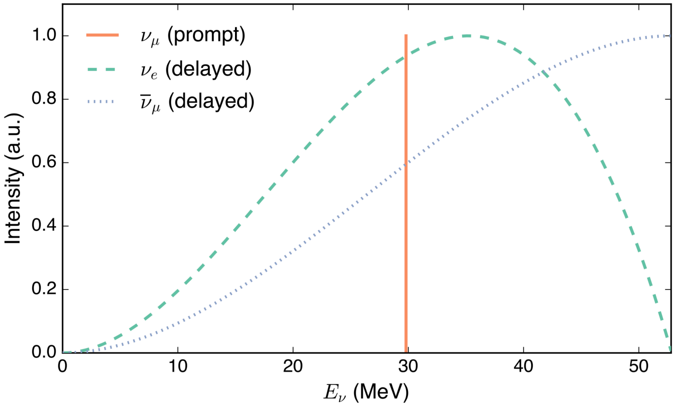
- This is ~ 20X the mean energy of a reactor neutrino

- Subsequently the delayed decay of the μ^+ to $e^+\nu_e\bar{\nu}_\mu$ yields calculable SPECTRA with endpoint energy m_μ (1804.09459). The $\nu_\mu : \nu_e : \bar{\nu}_\mu$ flavors are produced in equal proportion. BUT, for a NR threshold ~ 5 keV, the coherent scattering rates are around 0.2 : 0.3 : 0.5 due to rate enhancement at higher energy.

- INTEGRATED cross section is 20^2 = 400X larger and recoils are similarly more energetic – this is why low threshold is less critical for COHERENT. In principle, it also allows for much more massive detectors.

- Timing information helps with background suppression.

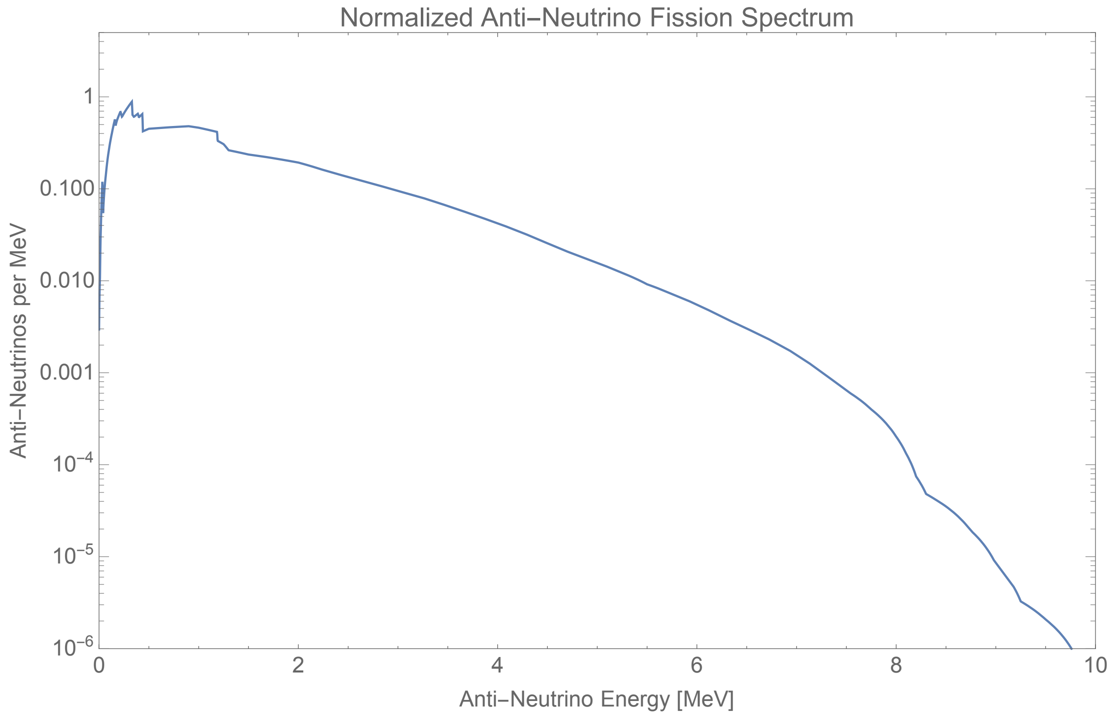
- BUT flux is ~ 10^5 times lower than a reactor.



Coherent Scattering at a Reactor

- Flux is high, (10^{12} – 10^{13} per cm^2 per second) and backgrounds are challenging
- The reactor spectrum is (reasonably) well known.
- Because of the neutral current coherent, scattering detection never resolves flavor.
- Because of the differential cross-section, a given neutrino can produce many different recoils, and the map is NOT INVERTABLE. BUT harder neutrinos will tend to produce harder recoils, so binning in energy is essential.
- On an event-by-event basis one never knows what the neutrino energy was (directional detection would resolve this)

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
- MW reactor delivers flux of 1.5×10^{12}/cm^2/sec @ 1 m (vs. Solar ~ 5×10^{6}/cm^2/sec)

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

Formalism

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

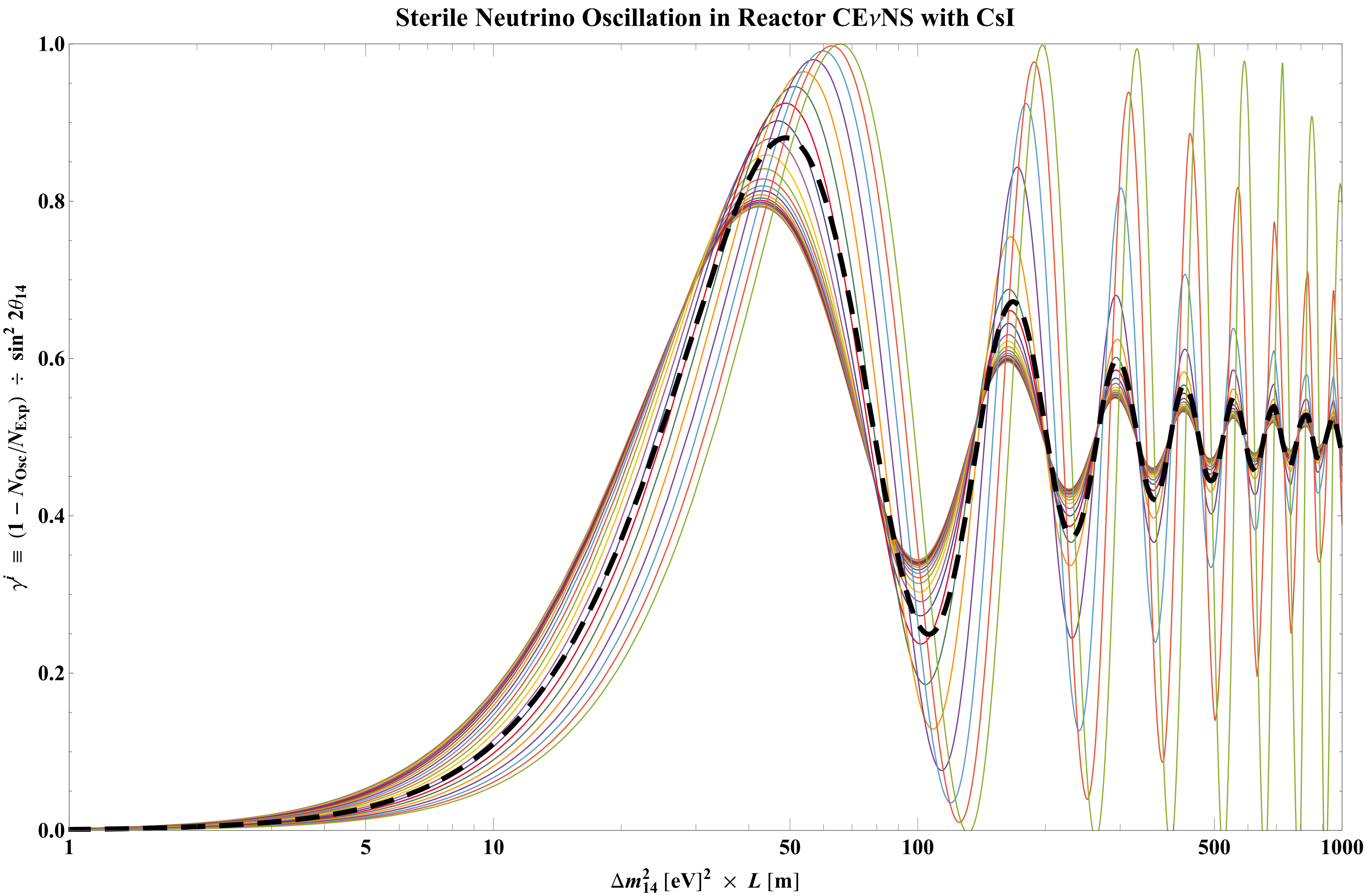
$$P_{\bar{\nu}_e\to\bar{\nu}_e} + P_{\bar{\nu}_e\to\bar{\nu}_\mu} + P_{\bar{\nu}_e\to\bar{\nu}_\tau} = 1 - 4|U_{e4}|^2\left(1 - |U_{e4}|^2 - |U_{\mu4}|^2 - |U_{\tau4}|^2\right)\sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

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

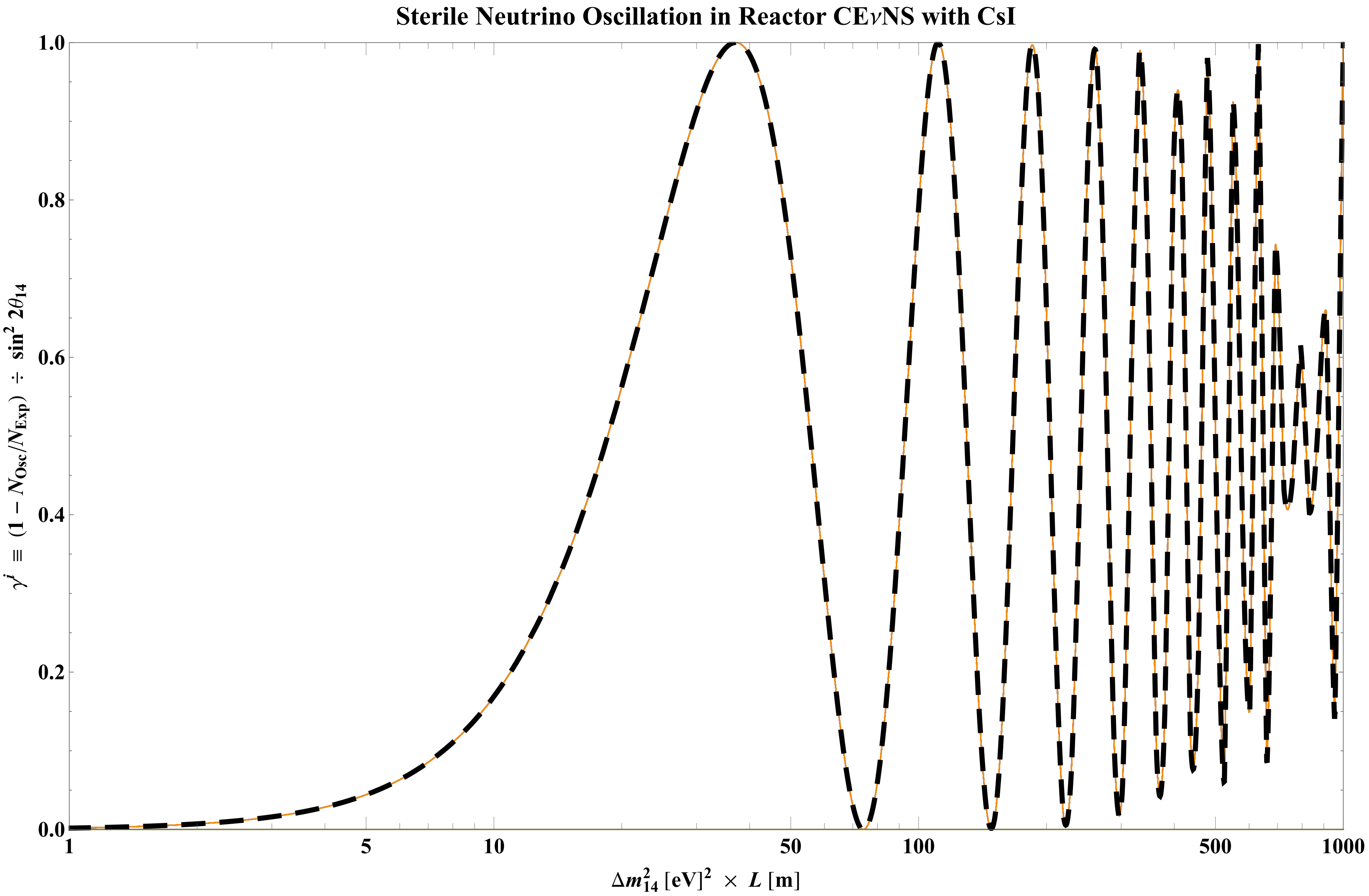
$$\begin{aligned}
P_{\nu_\mu\to\nu_\mu} + P_{\nu_\mu\to\nu_e} + P_{\nu_\mu\to\nu_\tau} &= 1 - 4|U_{\mu4}|^2\left(1 - |U_{e4}|^2 - |U_{\mu4}|^2 - |U_{\tau4}|^2\right)\sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)\\
P_{\bar{\nu}_\mu\to\bar{\nu}_\mu} + P_{\bar{\nu}_\mu\to\bar{\nu}_e} + P_{\bar{\nu}_\mu\to\bar{\nu}_\tau} &= 1 - 4|U_{\mu4}|^2\left(1 - |U_{e4}|^2 - |U_{\mu4}|^2 - |U_{\tau4}|^2\right)\sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)\\
P_{\nu_e\to\nu_e} + P_{\nu_e\to\nu_\mu} + P_{\nu_e\to\nu_\tau} &= 1 - 4|U_{e4}|^2\left(1 - |U_{e4}|^2 - |U_{\mu4}|^2 - |U_{\tau4}|^2\right)\sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)
\end{aligned}$$

$$|U_{e4}|^2 \;\;;\;\; |U_{\mu4}|^2 \;\;;\;\; 1 - |U_{e4}|^2 - |U_{\mu4}|^2 - |U_{\tau4}|^2$$

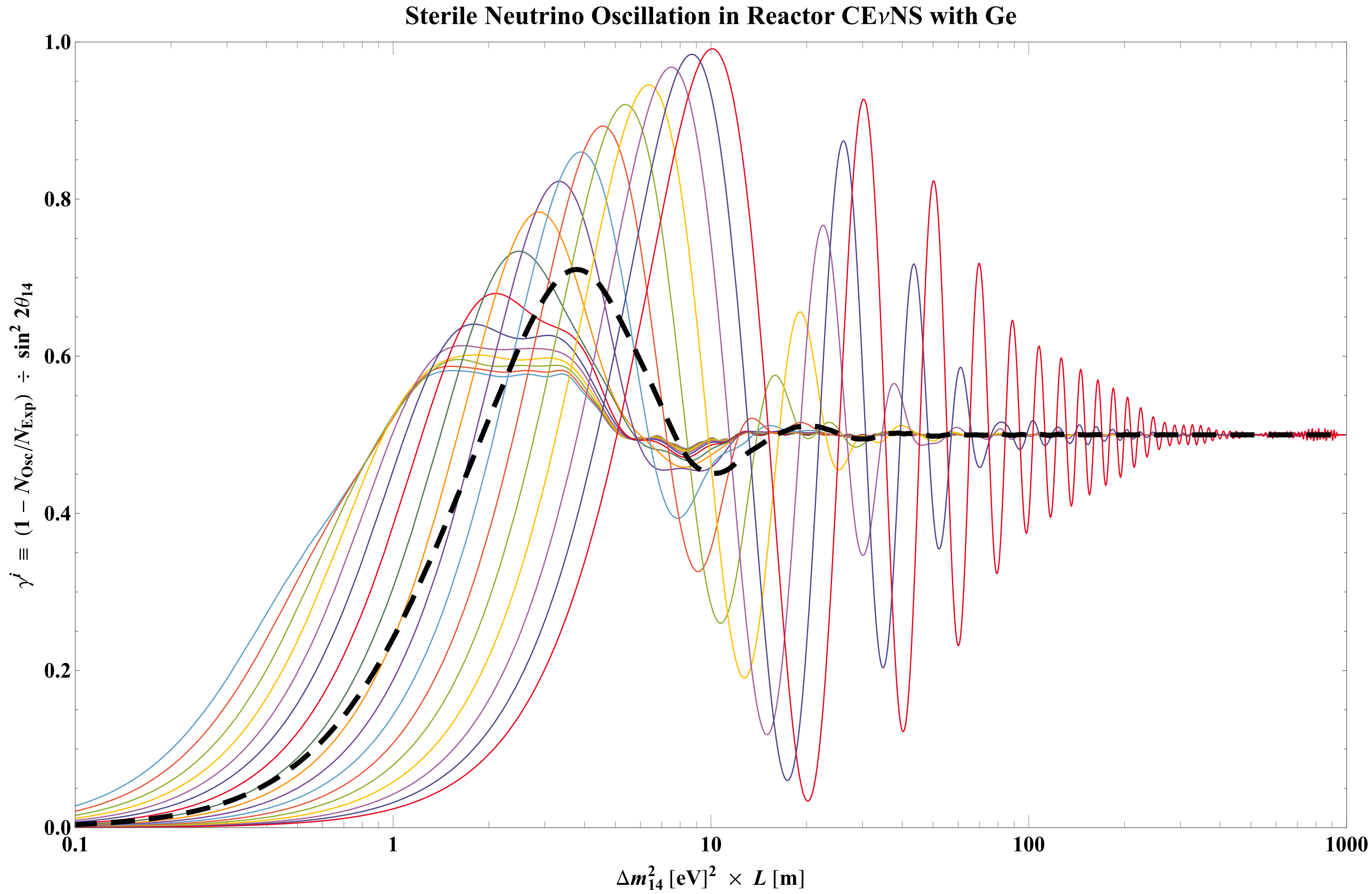
SNS Delayed


Sterile Neutrino Oscillation in Reactor CEνNS with CsI
$\gamma^j \equiv (1 - N_{\mathrm{Osc}}/N_{\mathrm{Exp}}) \div \sin^2 2\theta_{14}$
1.0
0.8
0.6
0.4
0.2
0.0
1
5
10
50
100
500
1000
$\Delta m^2_{14}\,[\mathrm{eV}]^2 \times L\,[\mathrm{m}]$

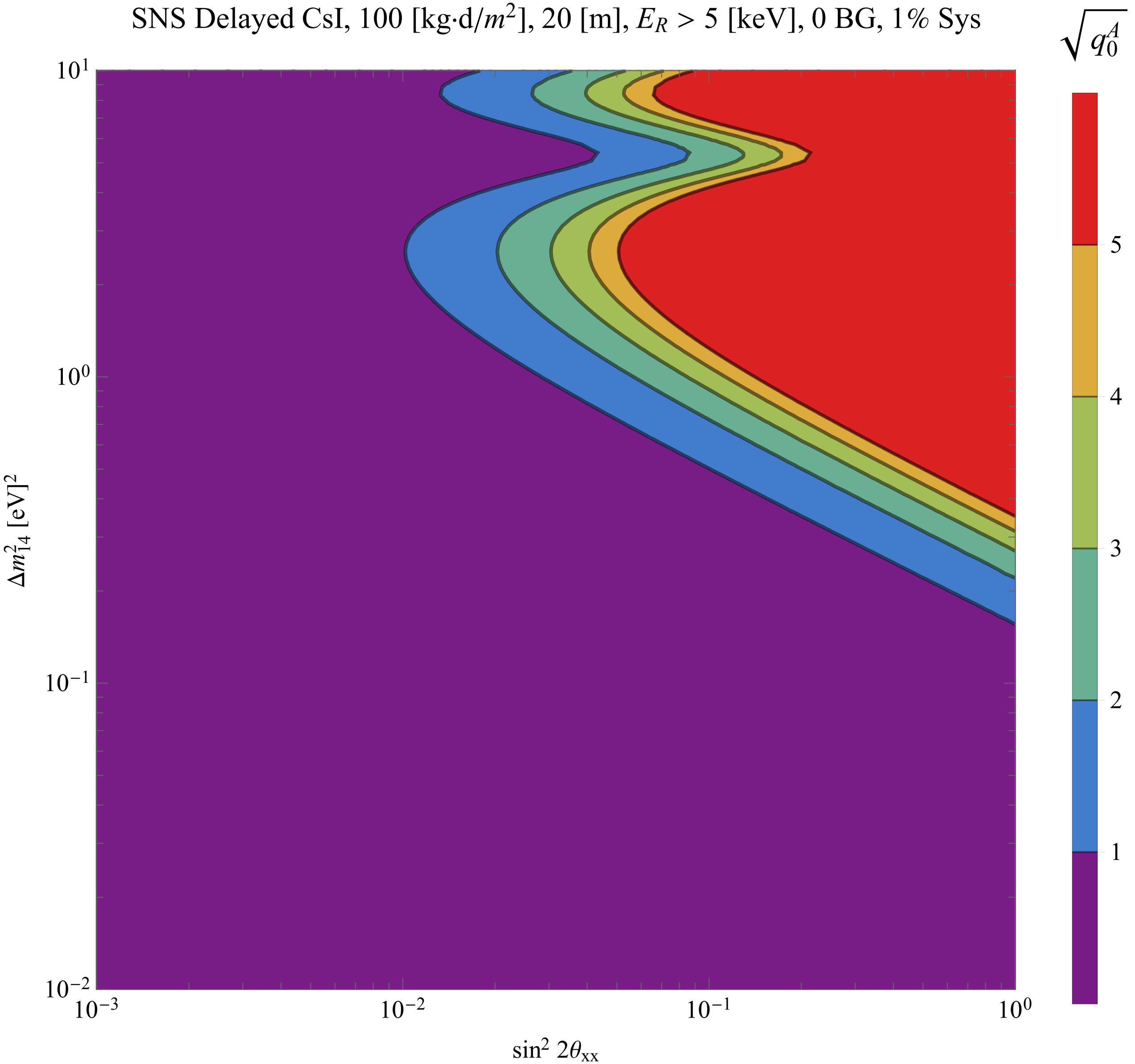
SNS Prompt


Sterile Neutrino Oscillation in Reactor CEνNS with CsI
$\gamma^j \equiv (1 - N_{\mathrm{Osc}}/N_{\mathrm{Exp}}) \div \sin^2 2\theta_{14}$
1.0
0.8
0.6
0.4
0.2
0.0
1
5
10
50
100
500
1000
$\Delta m_{14}^2\,[\mathrm{eV}]^2 \times L\,[\mathrm{m}]$

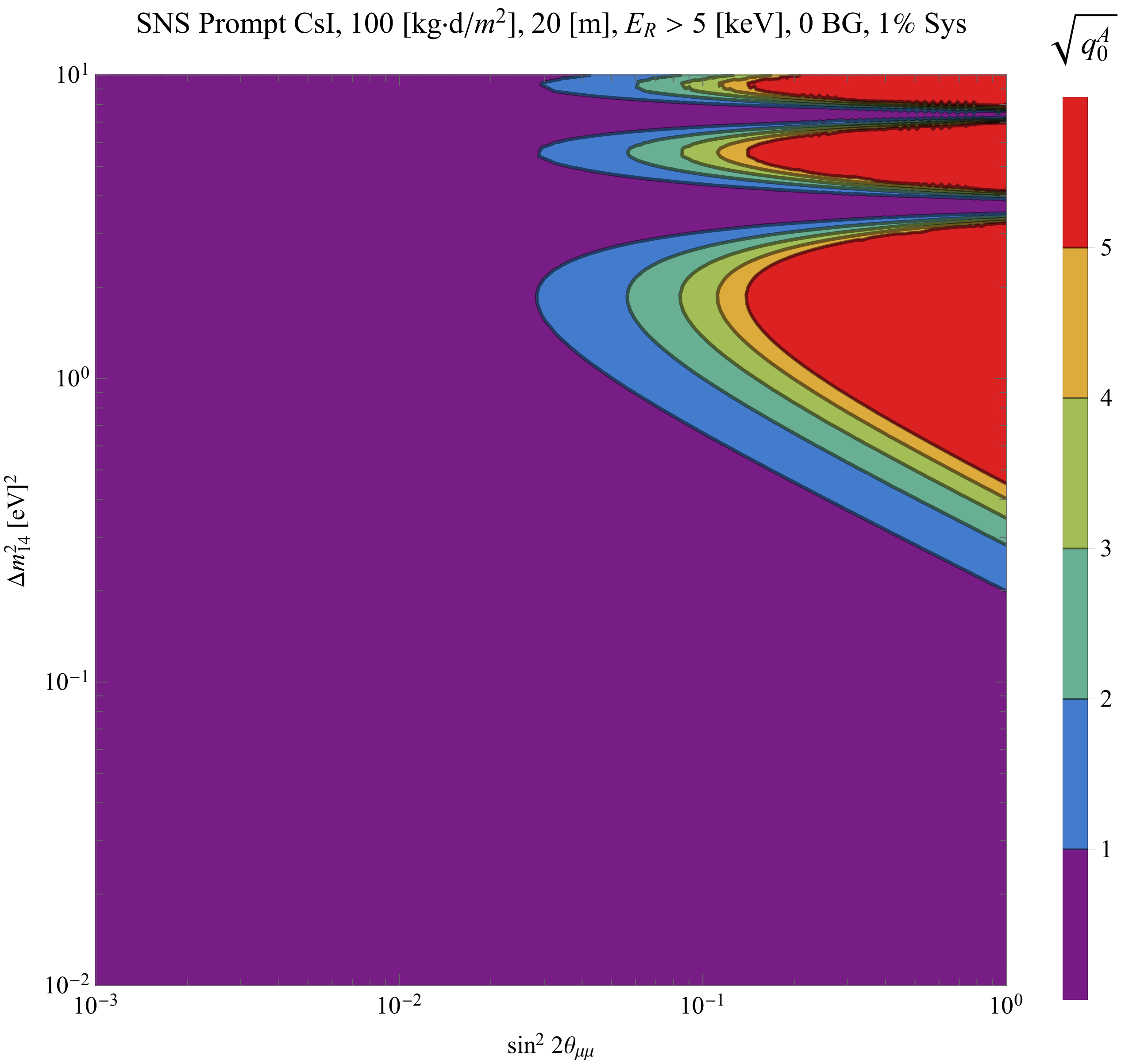
Reactor


Sterile Neutrino Oscillation in Reactor CEνNS with Ge
$\gamma^j \equiv (1 - N_{\text{Osc}}/N_{\text{Exp}}) \div \sin^2 2\theta_{14}$
1.0
0.8
0.6
0.4
0.2
0.0
0.1
1
10
100
1000
$\Delta m^2_{14}\,[\text{eV}]^2 \times L\,[\text{m}]$

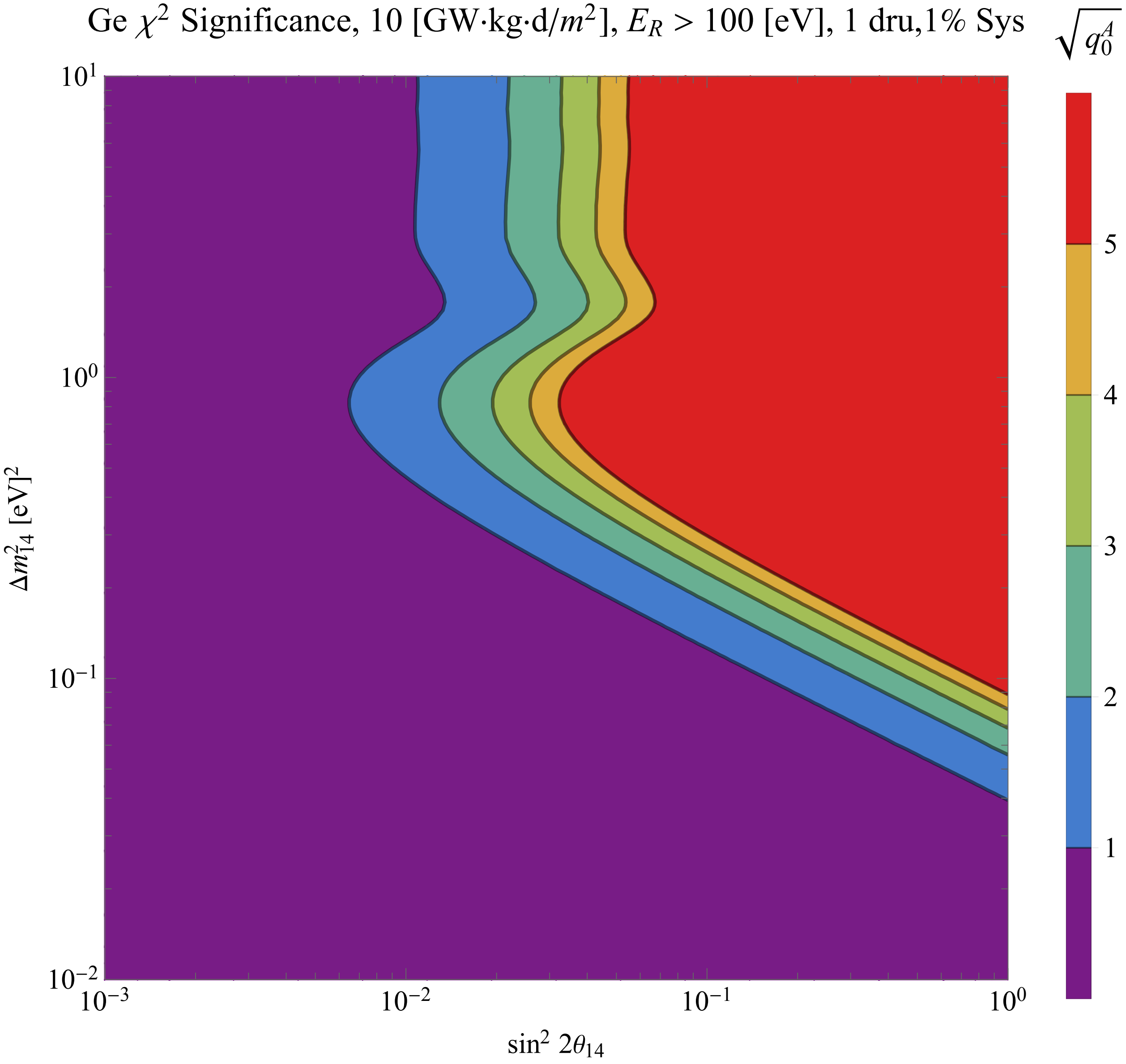
SNS Delayed


SNS Delayed CsI, 100 [kg·d/m^2], 20 [m], $E_R > 5$ [keV], 0 BG, 1% Sys
$\sqrt{q_0^A}$
Δm^2_{14} [eV]^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
10^0
$\sin^2 2\theta_{xx}$
5
4
3
2
1

SNS Prompt


SNS Prompt CsI, 100 [kg·d/m^2], 20 [m], $E_R > 5$ [keV], 0 BG, 1% Sys
$\sqrt{q_0^A}$
10^1
10^0
10^{-1}
10^{-2}
Δm_{14}^2 [eV]^2
10^{-3}
10^{-2}
10^{-1}
10^0
$\sin^2 2\theta_{\mu\mu}$
1
2
3
4
5

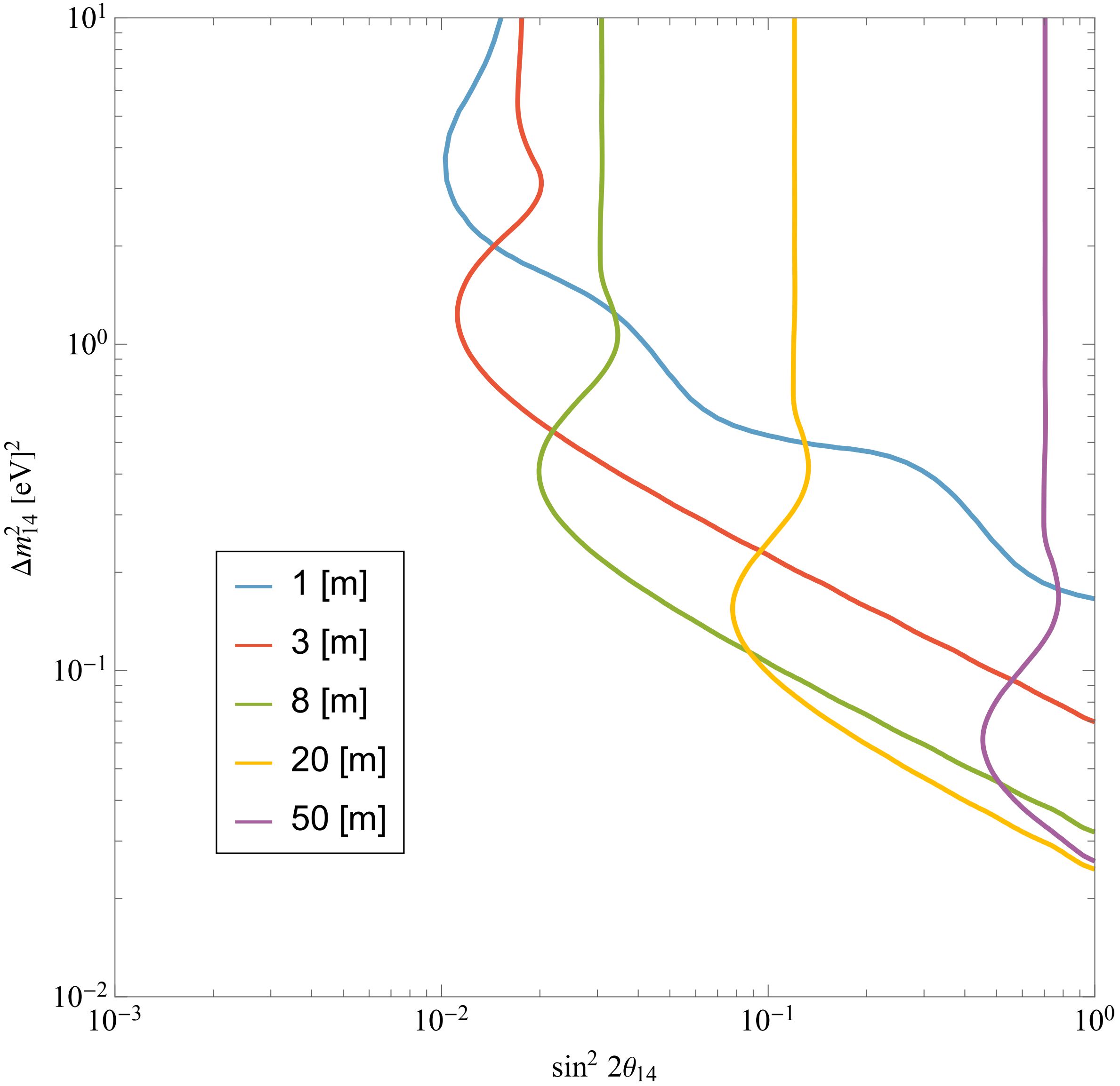
Reactor



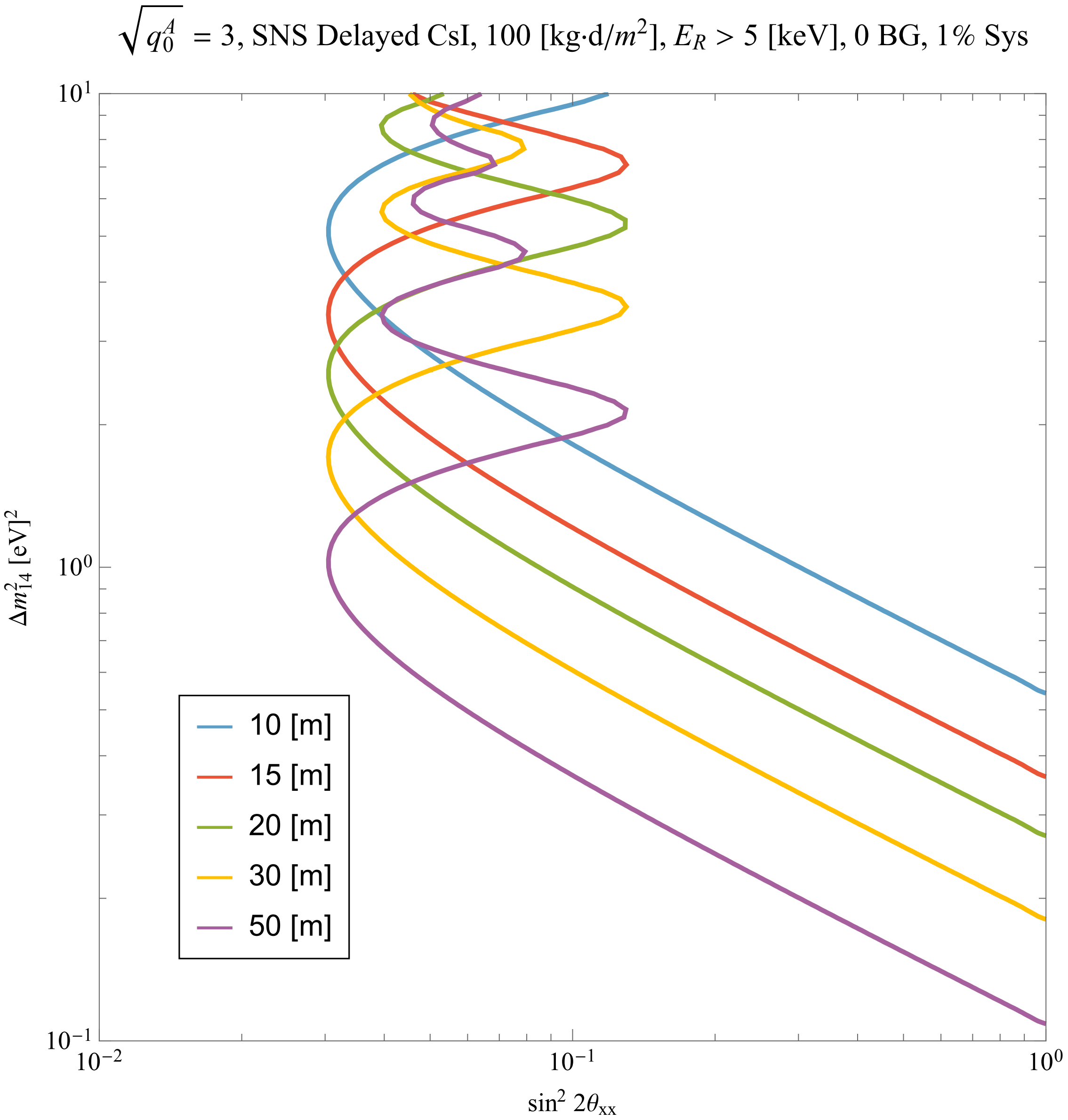
Ge χ^2 Significance, 10 [GW·kg·d/m^2], $E_R > 100$ [eV], 1 dru,1% Sys

Reactor

$\sqrt{q_0^A} = 3$, Ge 10 [GW·kg·d/m^2], $E_R > 40$ [eV], 1 dru,1% Sys

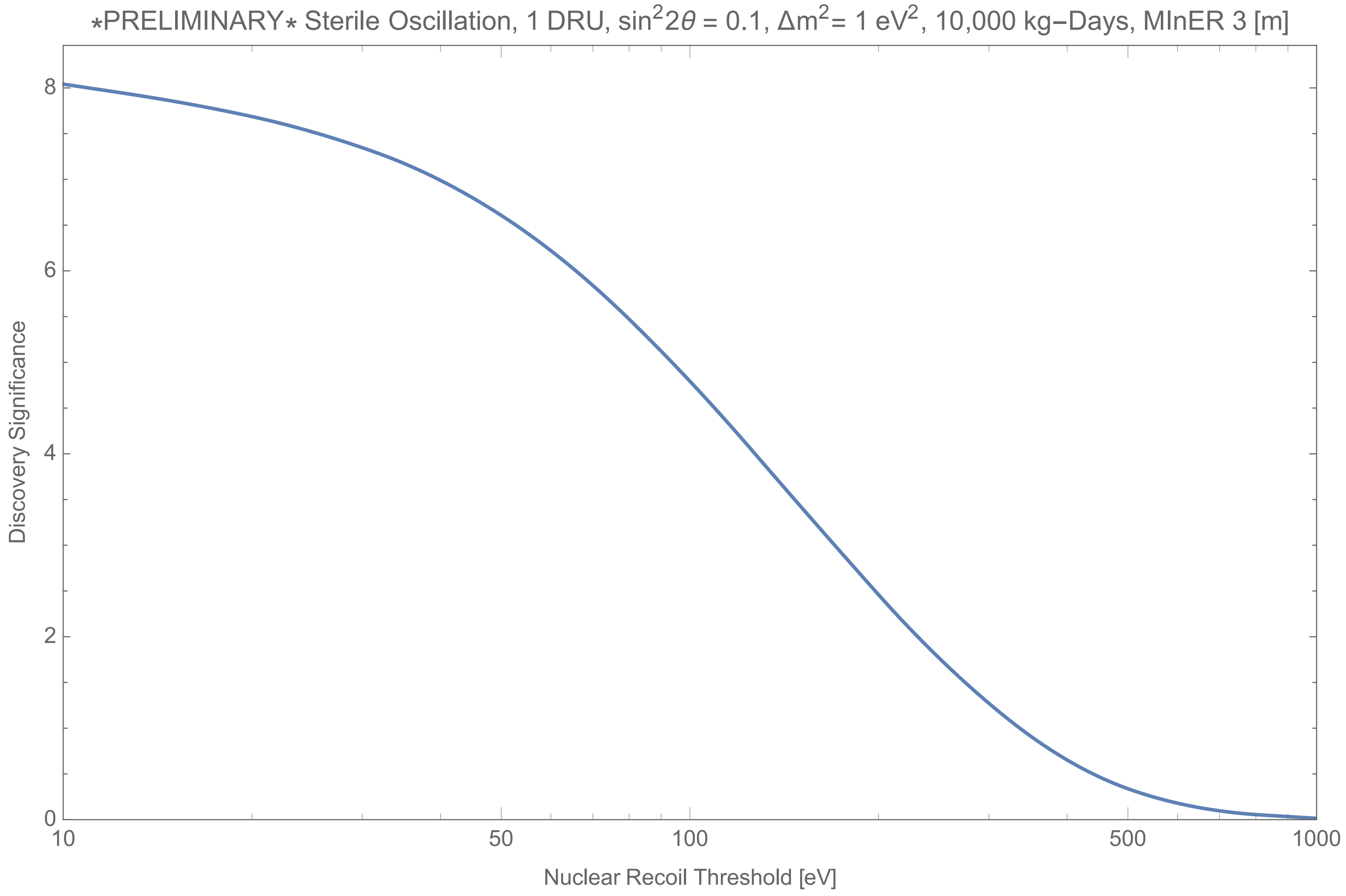


SNS Delayed


$\sqrt{q_0^A} = 3$, SNS Delayed CsI, 100 [kg·d/m^2], $E_R > 5$ [keV], 0 BG, 1% Sys
10^1
10^0
10^{-1}
Δm_{14}^2 [eV]^2
10^{-2}
10^{-1}
10^0
$\sin^2 2\theta_{xx}$
10 [m]
15 [m]
20 [m]
30 [m]
50 [m]

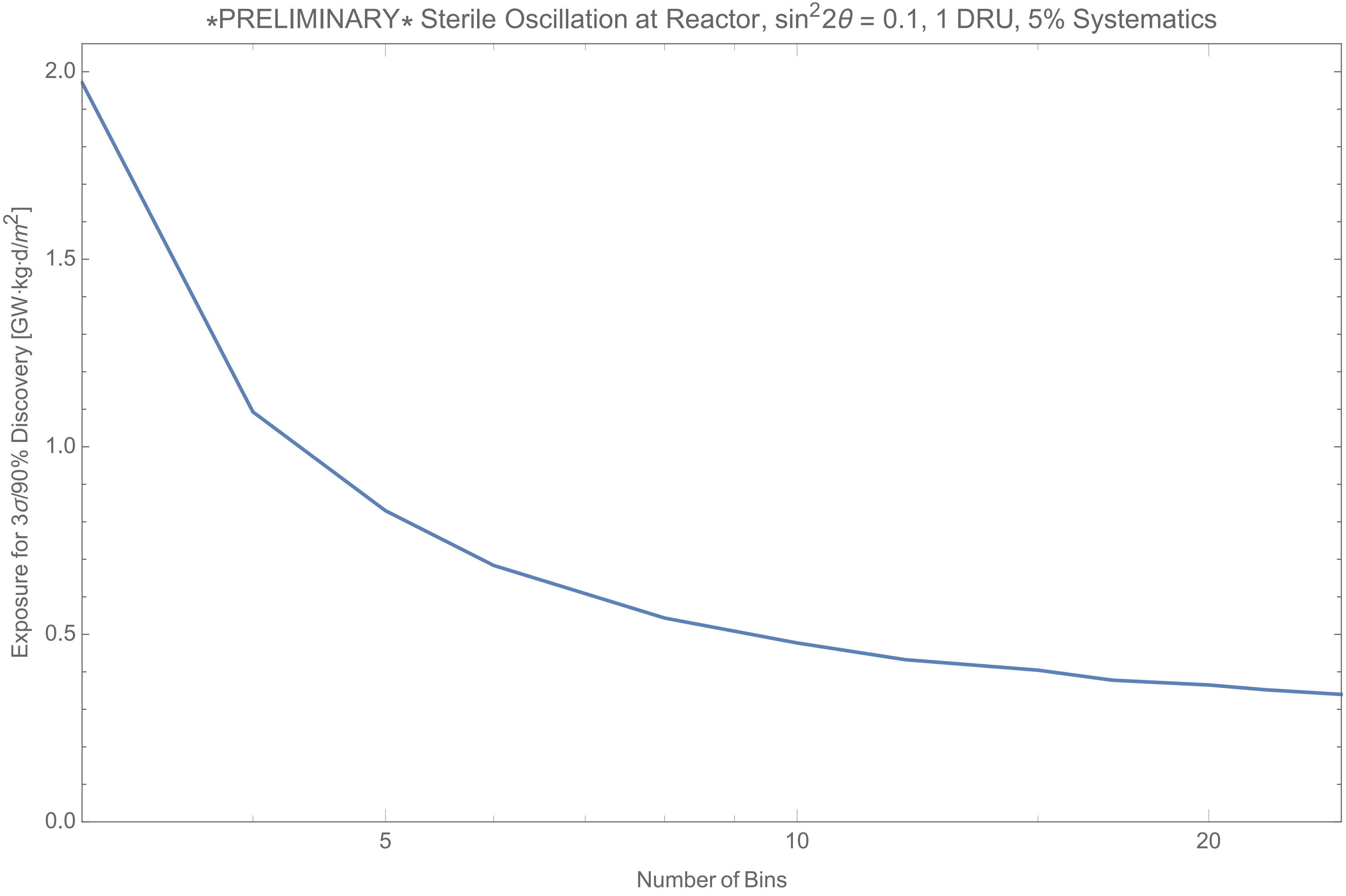
Reactor Threshold

- Low threshold is essential for additional channels



Reactor Binning

- One must bin in order to separate correlated effects



Reactor Systematics

- Large systematics require low thresholds