COMPLEMENTARITY OF SHORT-BASELINE NEUTRINO OSCILLATION SEARCHES WITH CEVNS

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The Magnificent CEvNS
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MIÑER

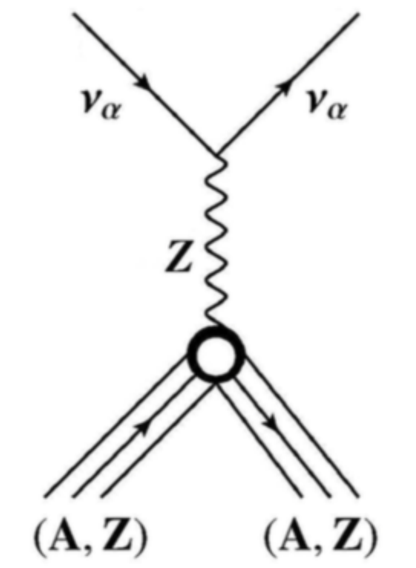
with Dent, Dutta, Strigari

see reviews 1803.10661, 1906.01739,
by Dentler, Hernandez-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, Schwetz,
and by Böser, Buck, Giunti, Lesgourgues, Ludhova, Mertens, Schukraft, Wurm

BIG PICTURE QUESTIONS

- What modes of New Physics are Visible to CEvNS?
- Where are there overlapping hints of Anomalies?
- Where does CEvNS have a natural advantage?
- How can approaches to CEvNS complement each other, as well as other neutrino detection techniques?

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

KEY CEVNS PHYSICS CHARACTERISTICS

- Cross-section scales as E_ν^2 (proportional to G_F^2)

- Maximum recoil is suppressed by nuclear mass
$$T_\mathrm{Max} = 2E_\nu^2/M_N$$
- Event rate falls linearly with recoil up to cutoff
$$d\sigma/dT \propto 1 - T/T_\mathrm{Max}$$
- “Squeezing” recoil into a narrow bandwidth enhances the visibility over background below T_Max

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

PATHS TO SIGNAL VISIBILITY

- Boost neutrino energy to boost the recoil deposition

AND/OR

- Build extremely sensitive (low threshold) detectors

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

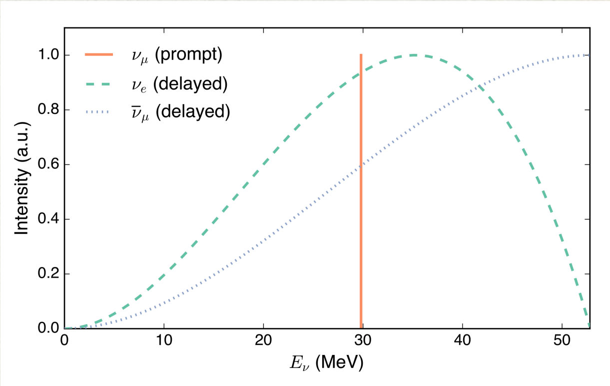
- Use a nuclear reactor for high flux

AND/OR

- Build much larger detectors

PROS & CONS OF STOPPED PION SOURCES

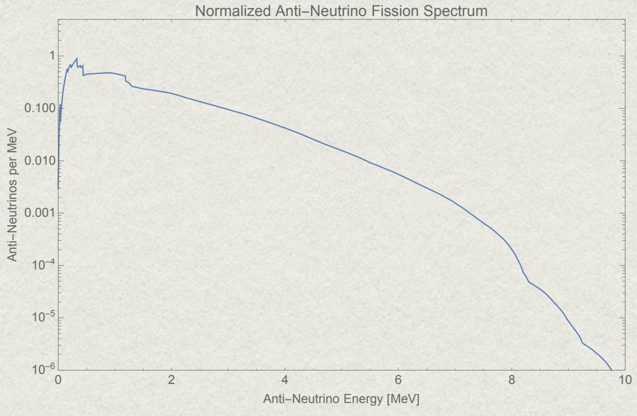
- Energy can exceed 30 MeV (enhances rate)
- Recoils are hard — scintillators are sufficient
- Flavors are mixed (prompt ν_μ and delayed $\bar{\nu}_\mu / \nu_e$)
- Pulsed timing helps reduce backgrounds



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

PROS & CONS OF REACTOR SOURCES

- Flux can be extraordinary ($10^{12\text{-}13}$ 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)



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

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

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

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

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 $E_\nu / L \simeq \mathrm{eV}^2$

INCOMPLETE SURVEY OF CONSTRAINTS & ANOMALIES

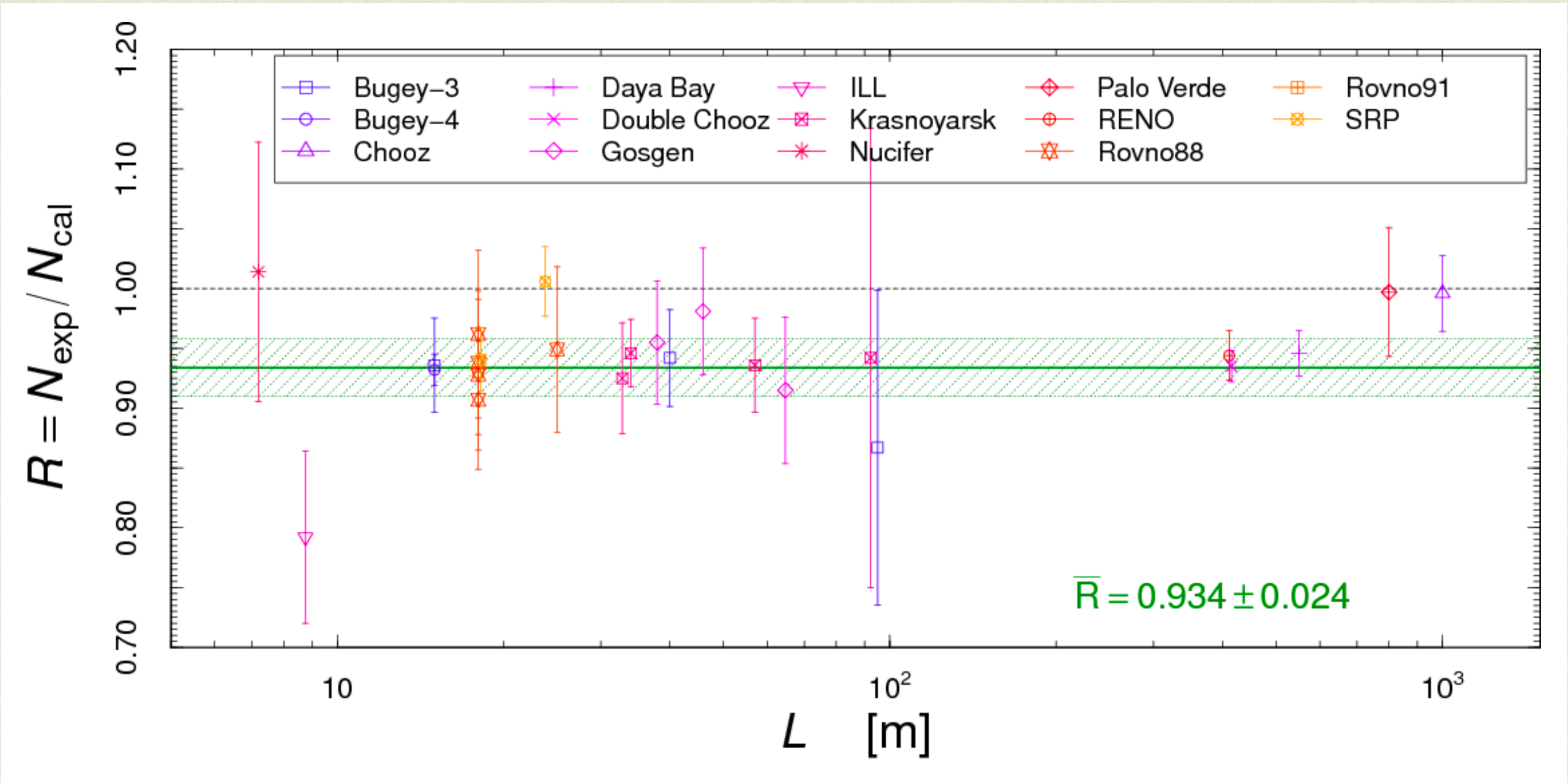
- There are several anomalies across generations of experiments — they are generally "consistent" within "types" but in tension across types (in 3+1 analysis)
- Cosmology disfavors ~eV steriles via N_{eff} / BBN
- REGARDLESS of interpretation, more data is needed

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

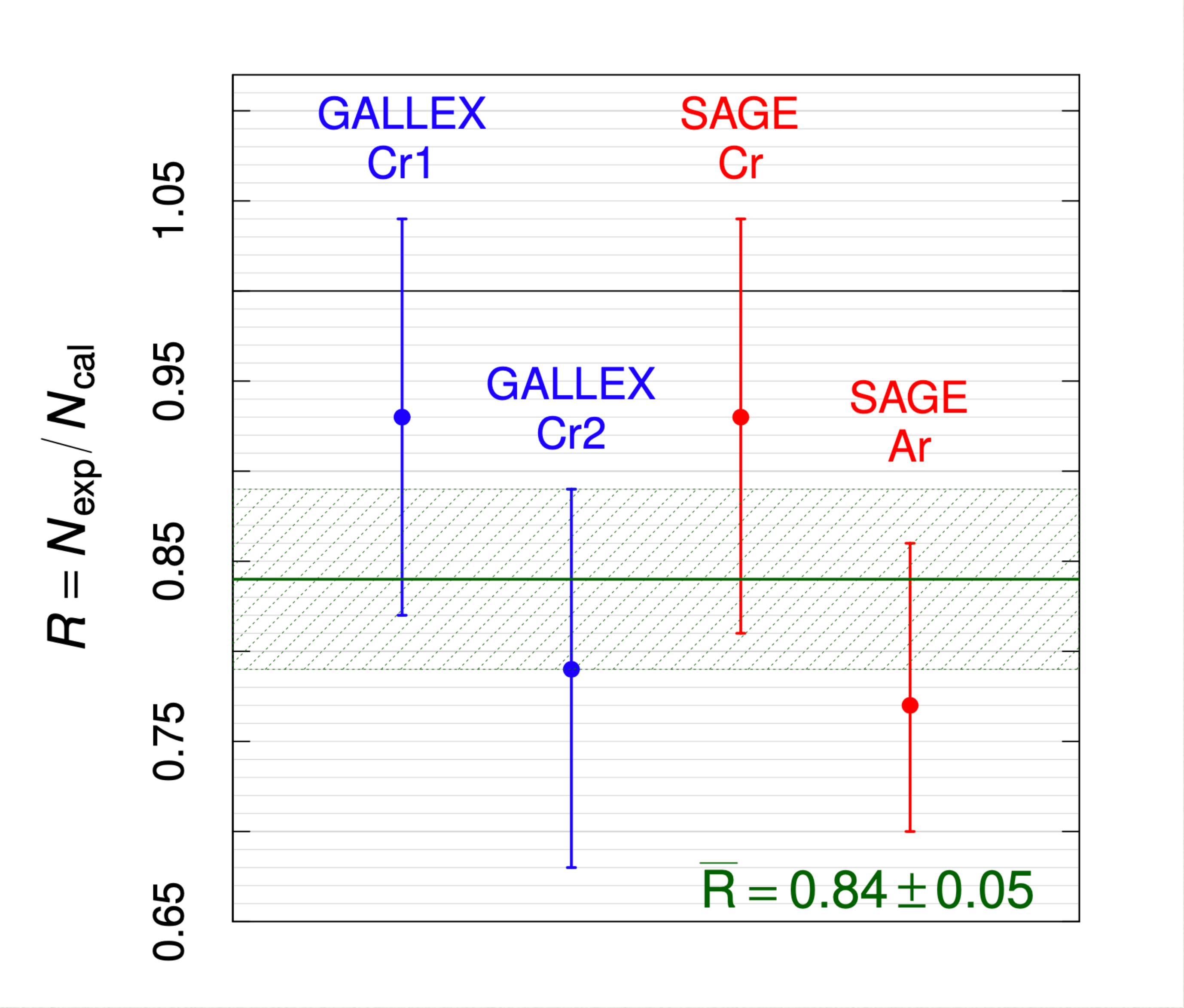
49

REACTOR RATE ANOMALY



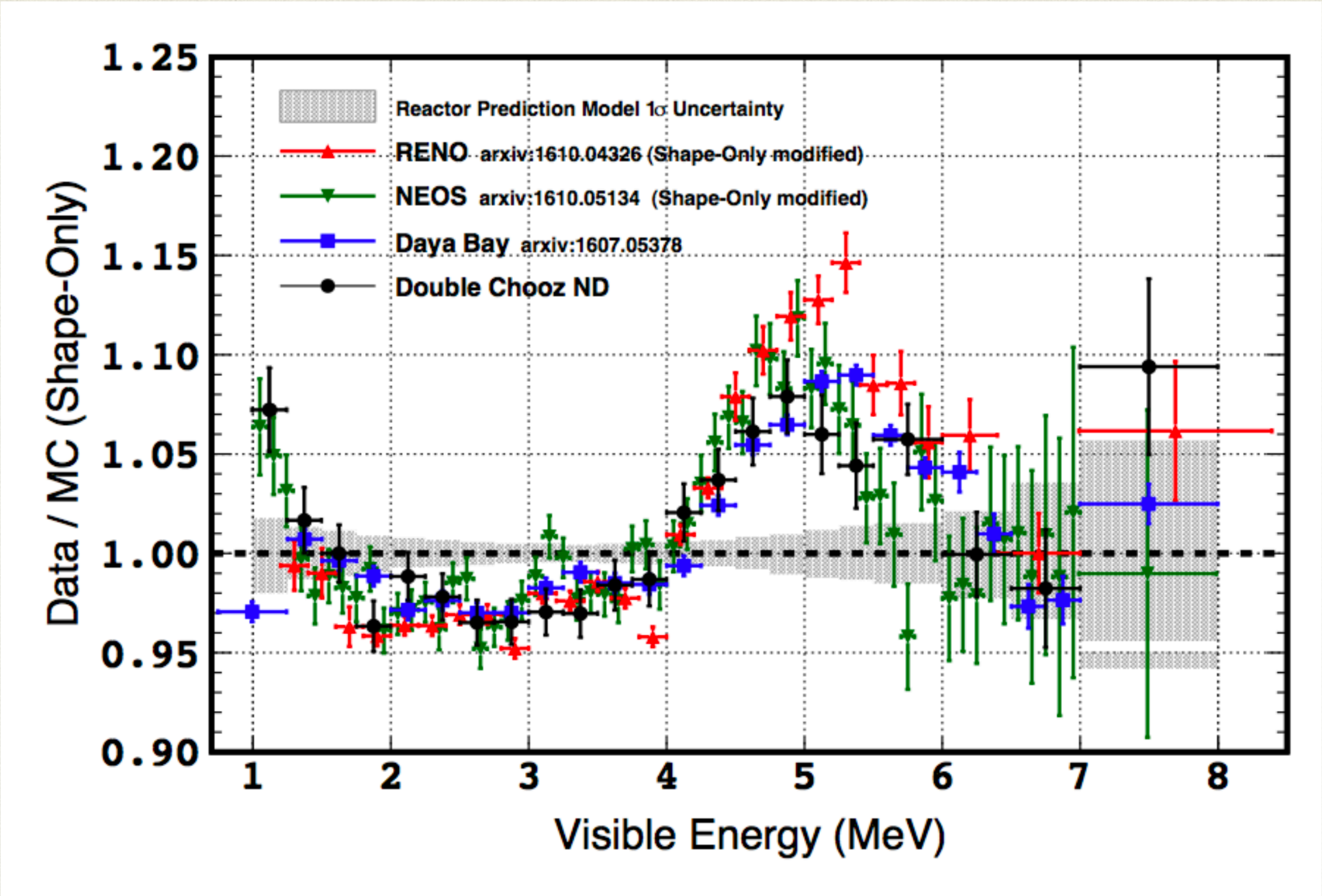
Gariazo et al. 1703.00860

RADIOACTIVE SOURCE RATE ANOMALY



Gariazo et al. 1507.08204+

NORMALIZED DATA/ PREDICTION



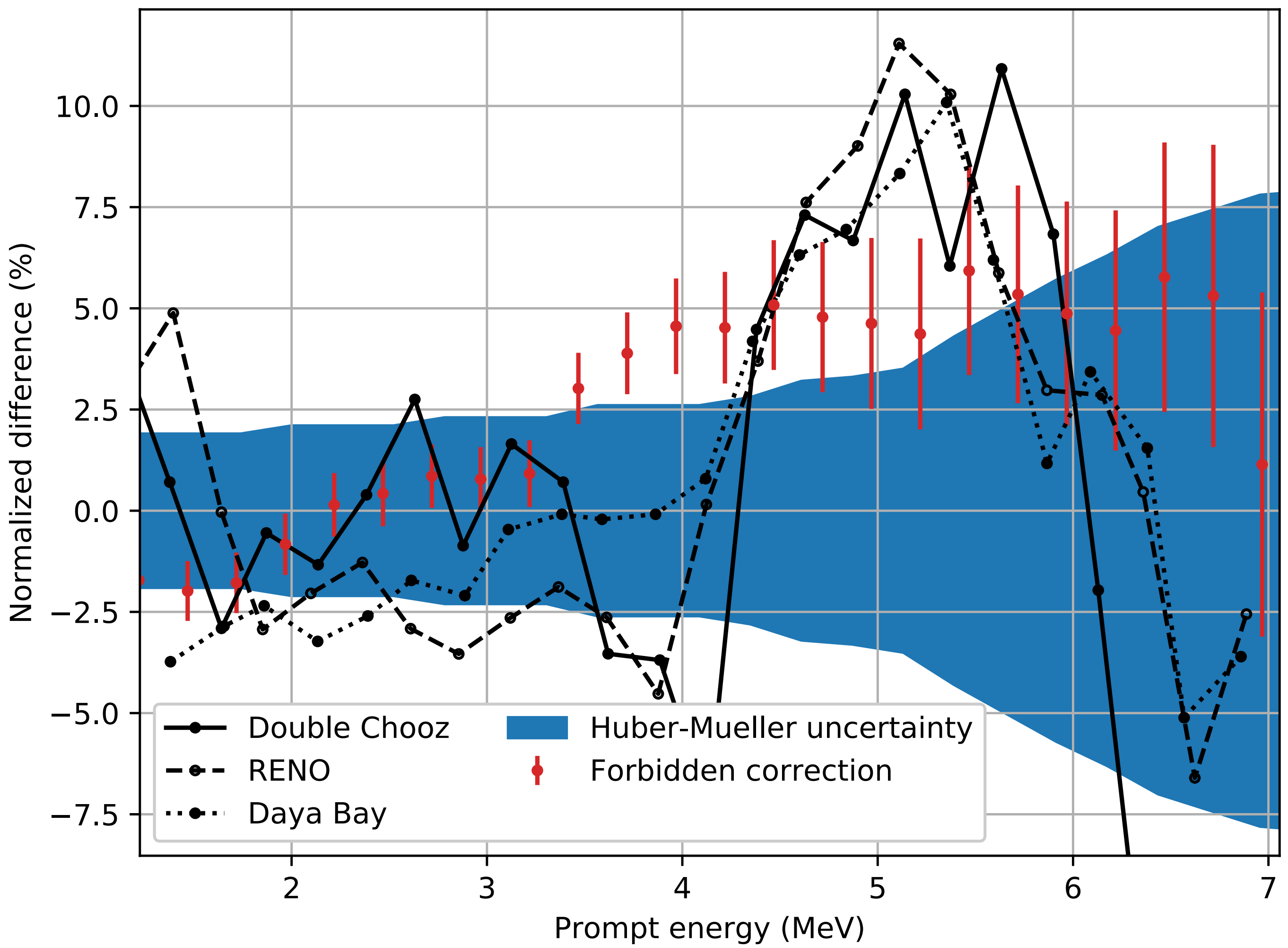
via 1906.01739

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

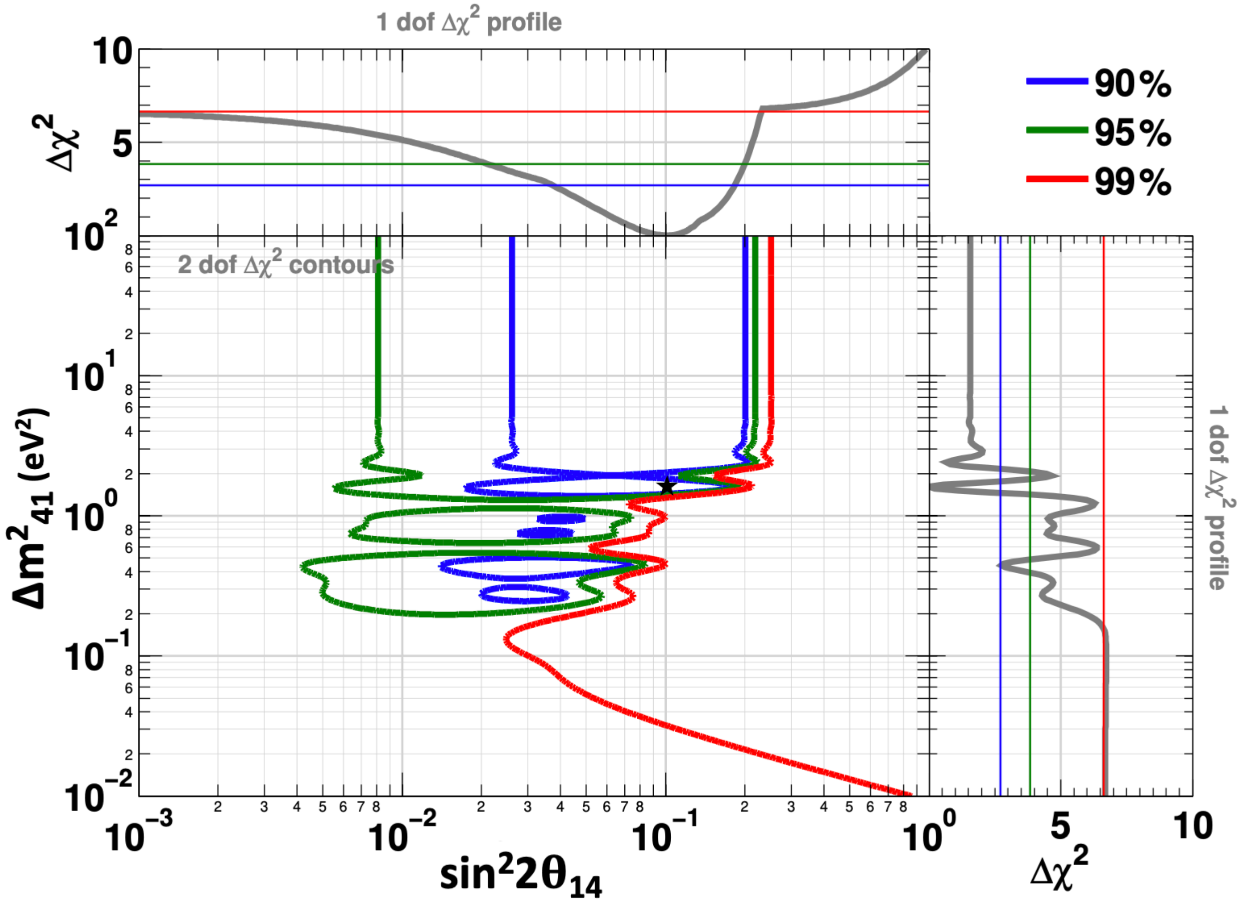
decreases the $\bar{\nu}$ flux by some 5% !



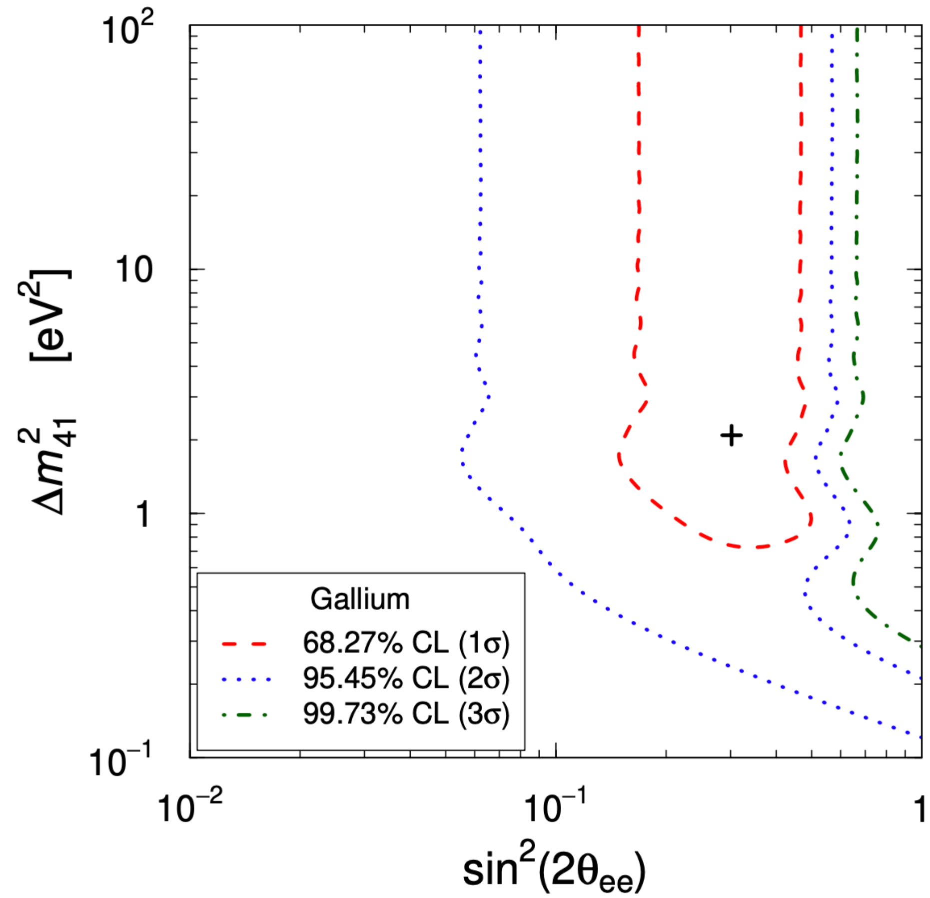
The spectral sholder appears due to forbidden spectral corrections !

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

REACTOR/GALLIUM FITS



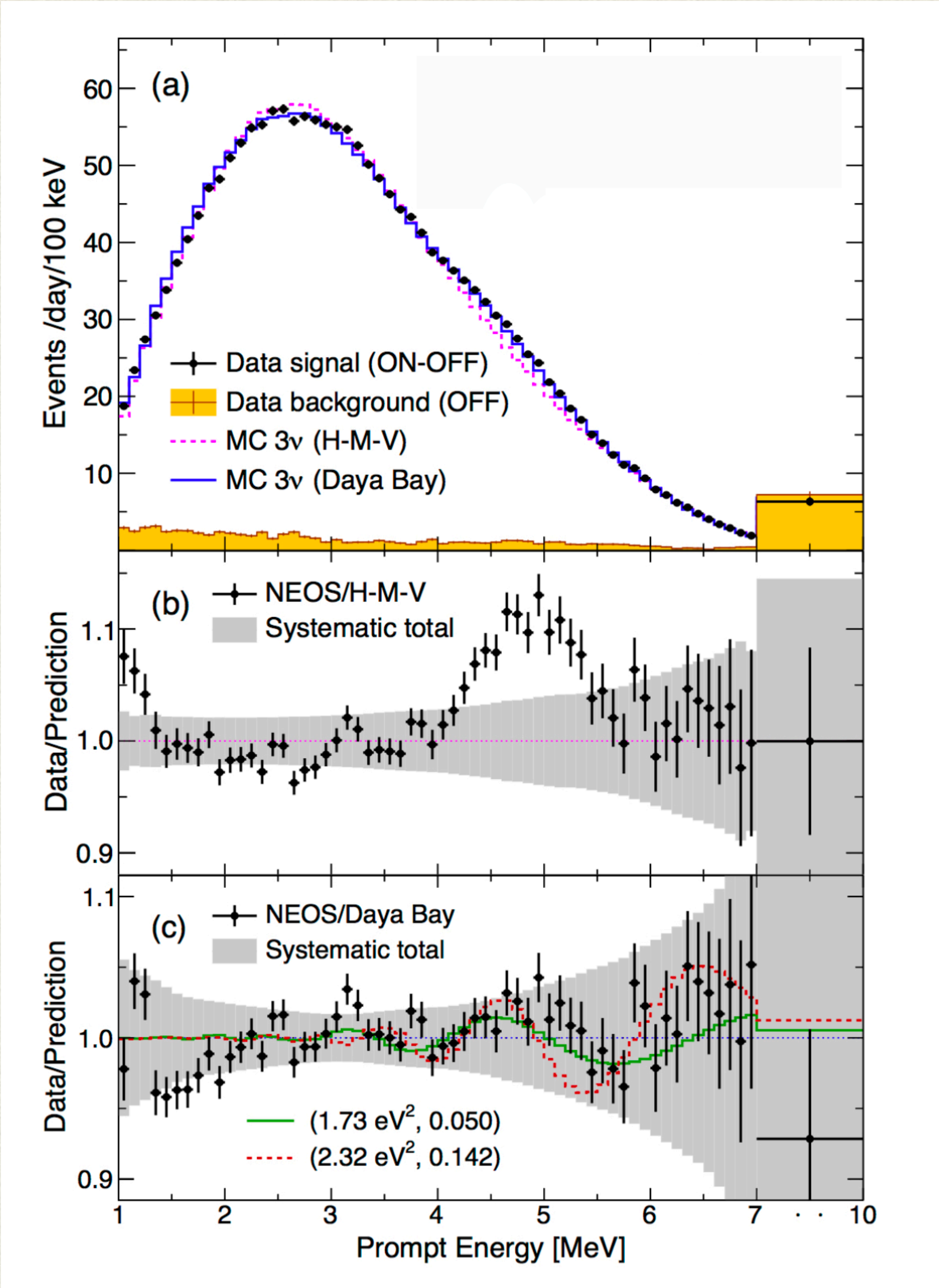
(a) The reactor anomaly [66].

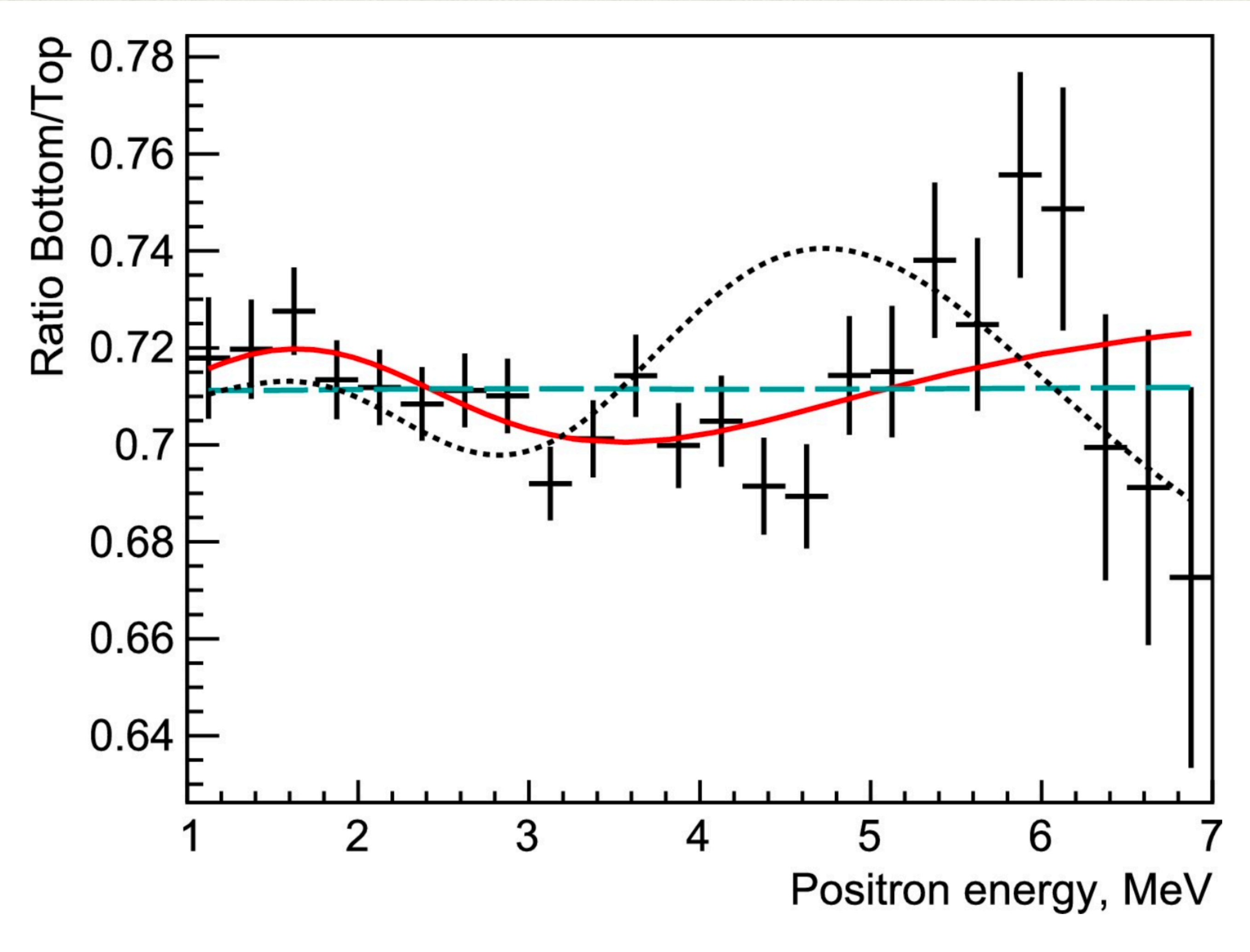


(b) The gallium anomaly [111].

via 1906.01739

NEOS AND DANSS



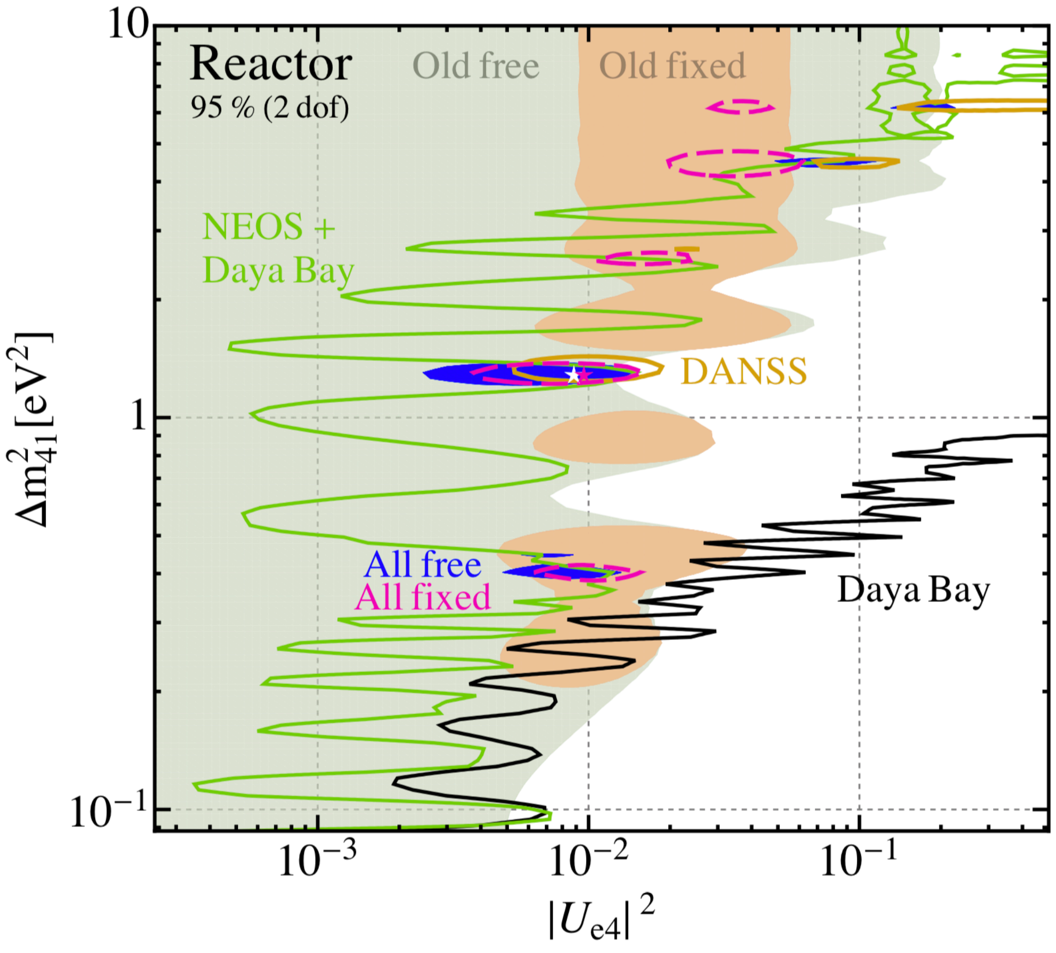


via 1906.01739

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)

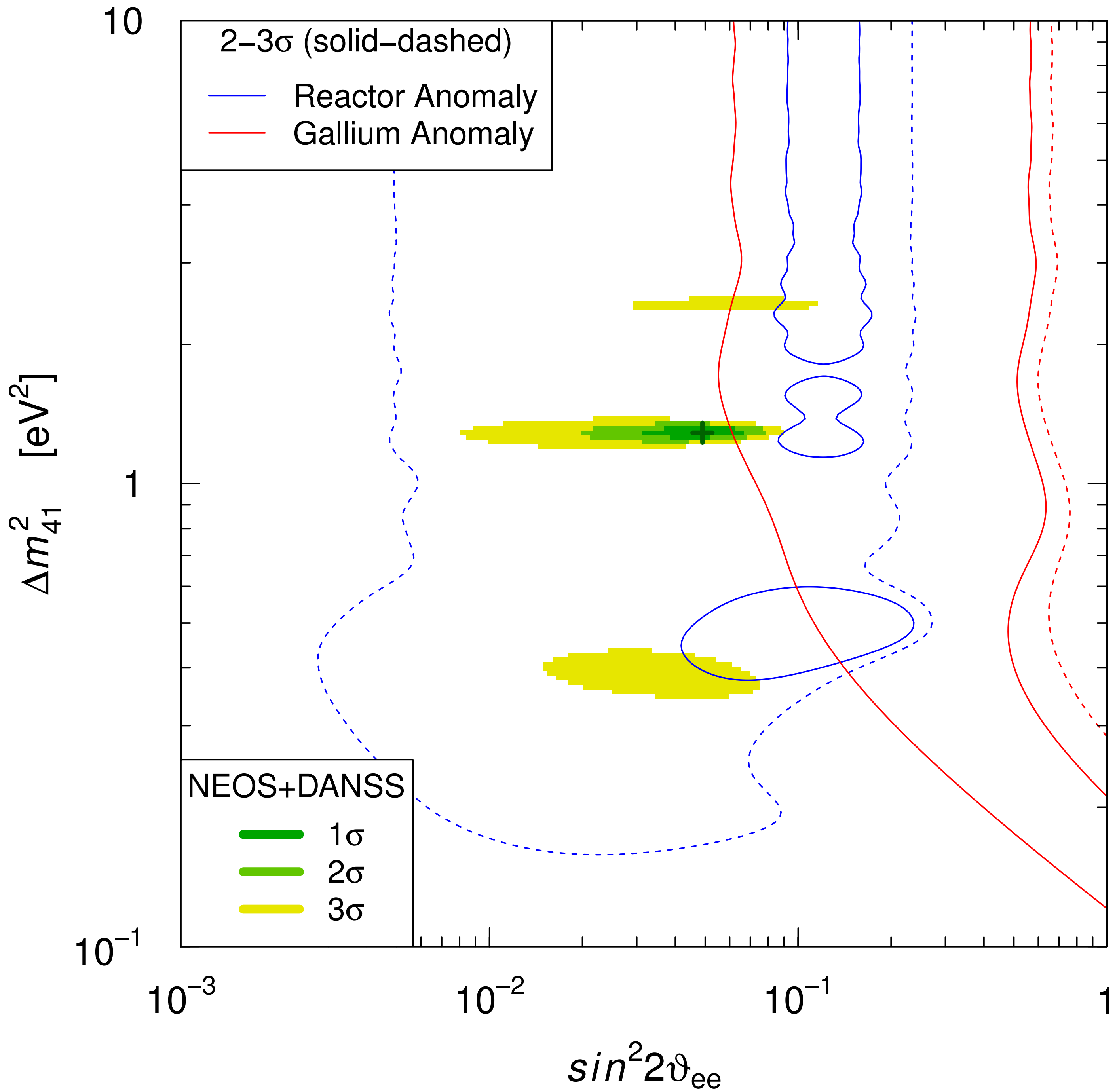


50

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

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

DANSS + NEOS + RAA + Gallium



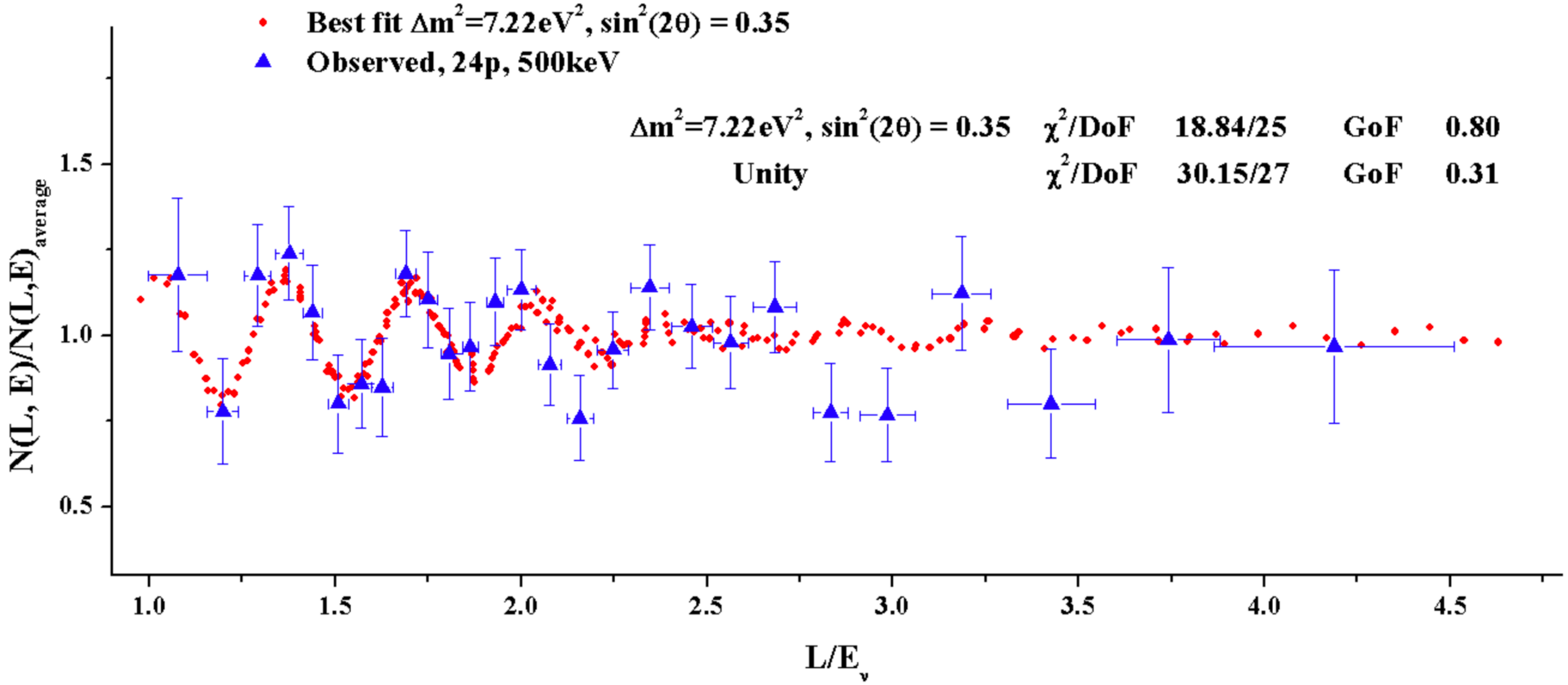
DANSS + NEOS
do not agree with
Gallium and RAA

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

56

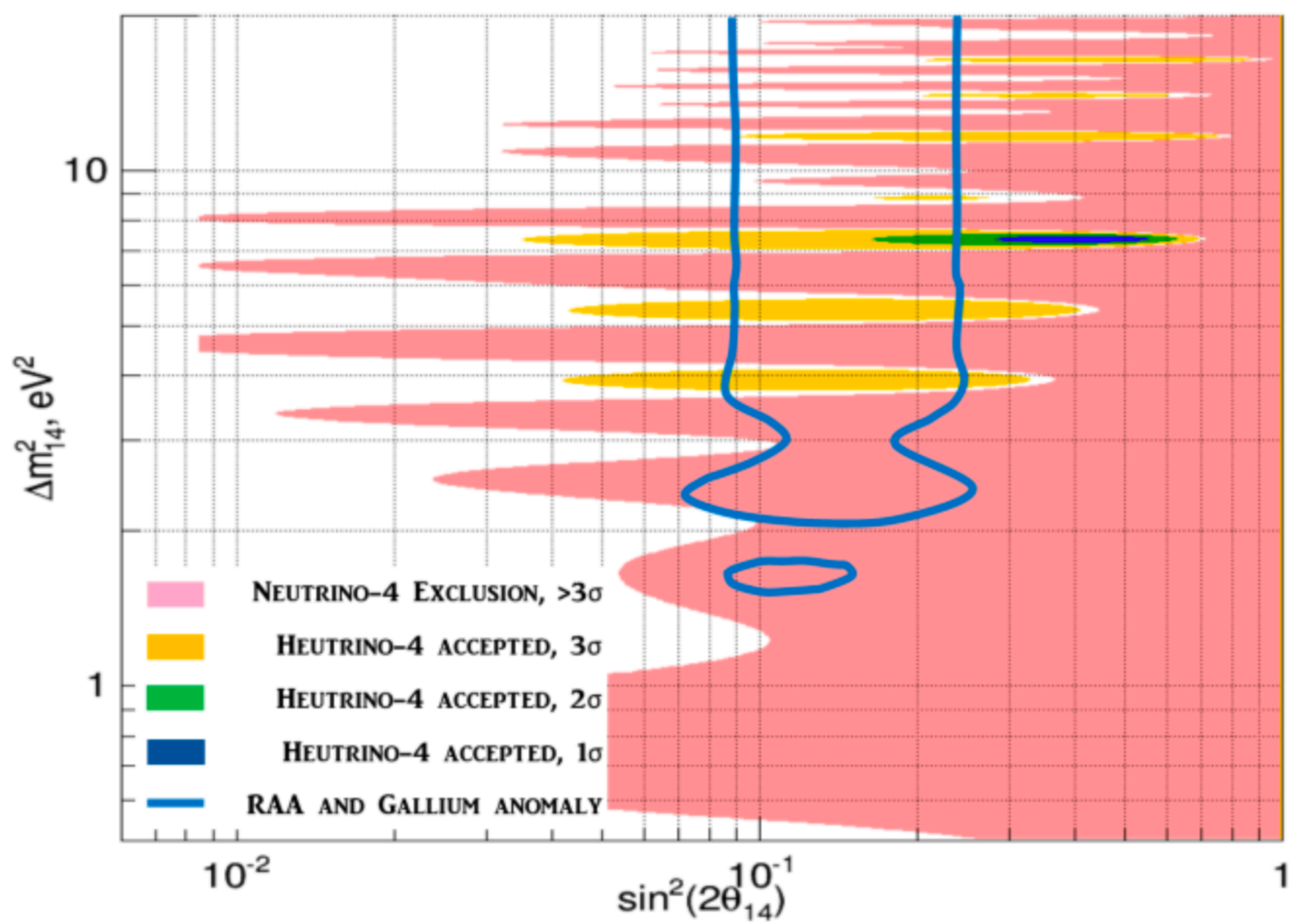
Neutrino 4



57

Neutrino 4

- Yellow, Green, and Blue are increasingly favored



58

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

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.

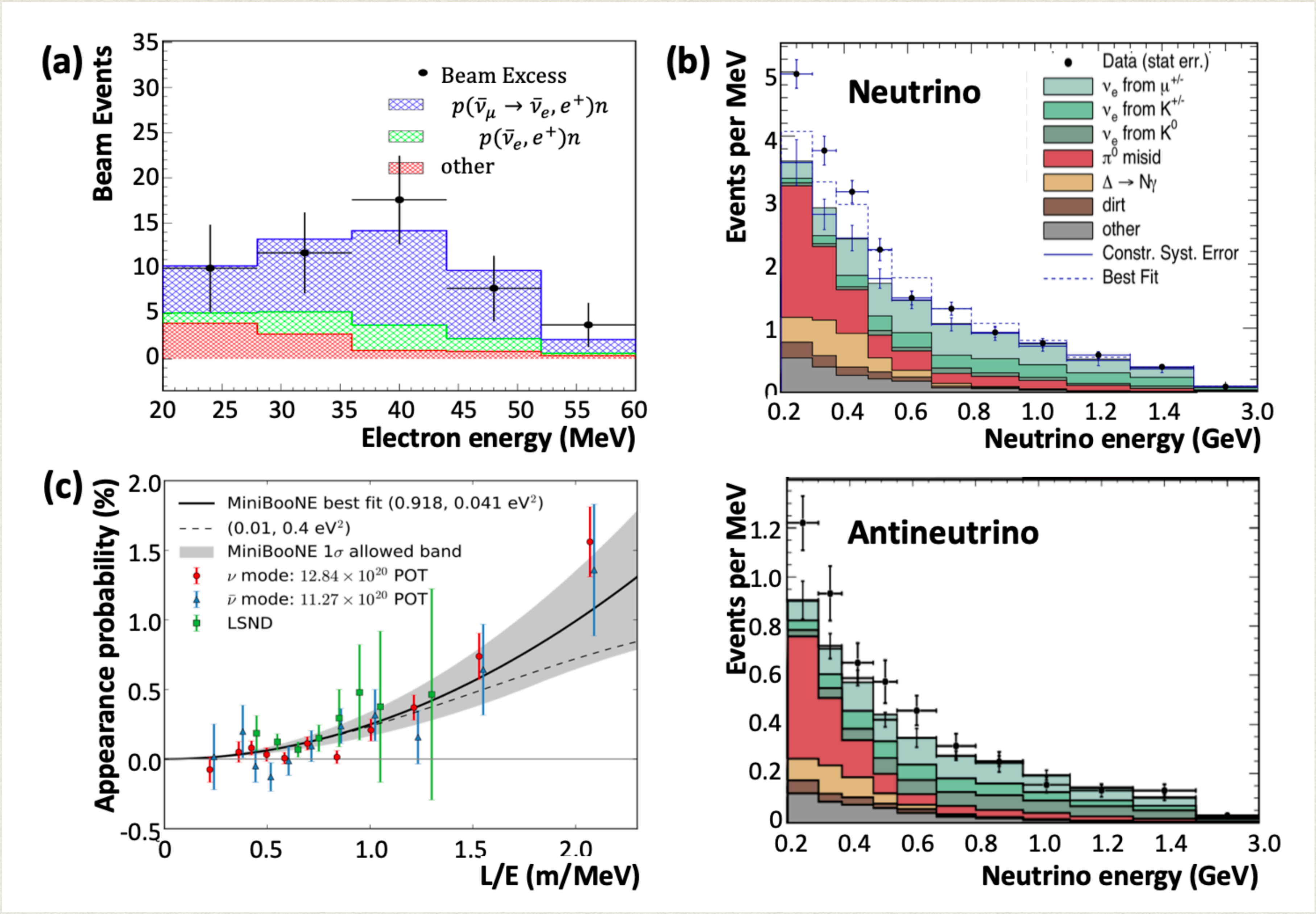
- Two neutrino mu to e oscillation has goodness of fit 20.1%. Background only hypothesis is $5{\times}10^{-7}$ relative to best fit with $L/E_\nu \approx 1[\mathrm{m/MeV}]$.

- 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

53

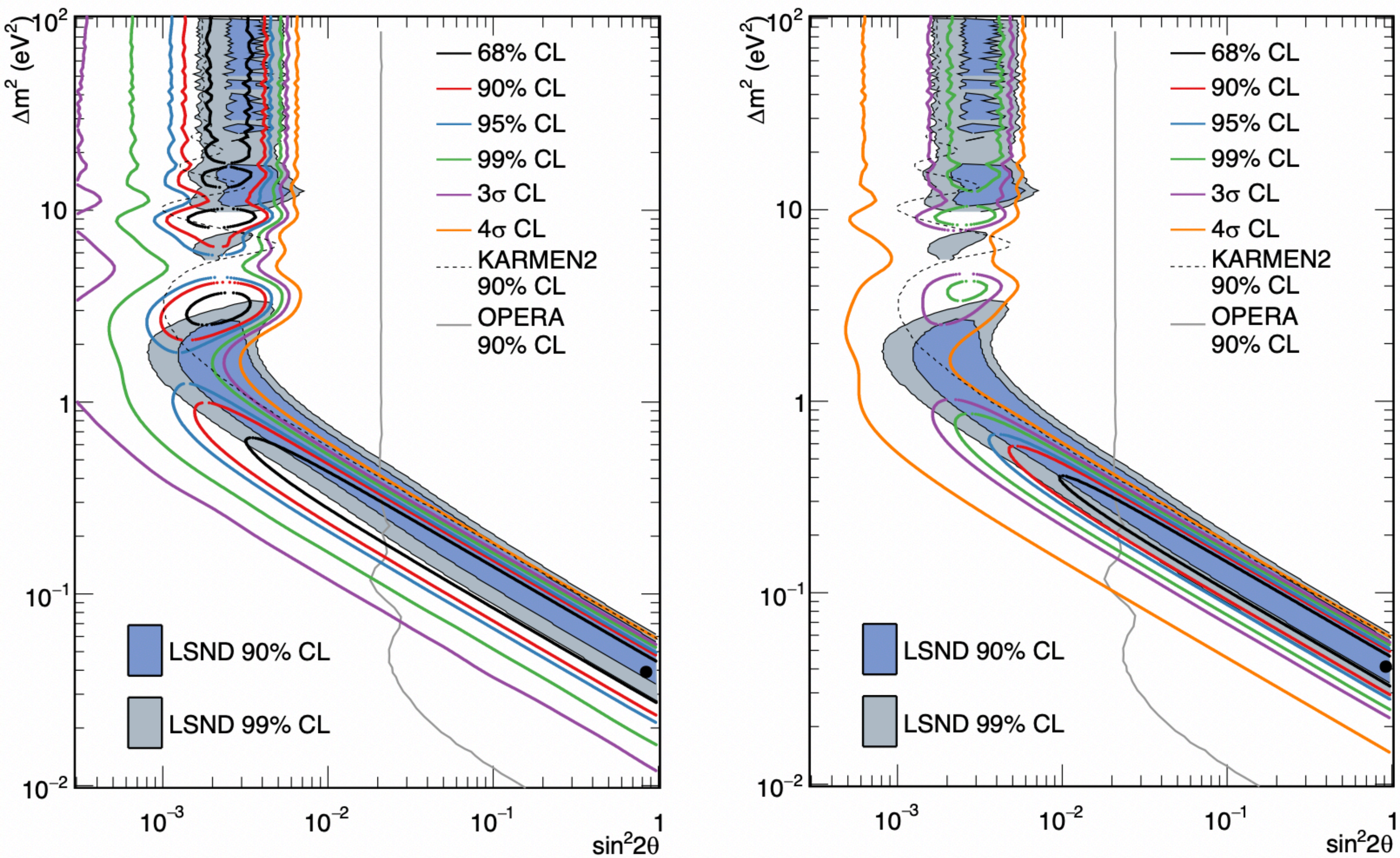
MINIBOONE/LSND



via 1906.01739

MINIBOONE/LSND FITS

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



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

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

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

48

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.

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

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

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

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

Oscillation to Sterile 4th Flavor Neutrino

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

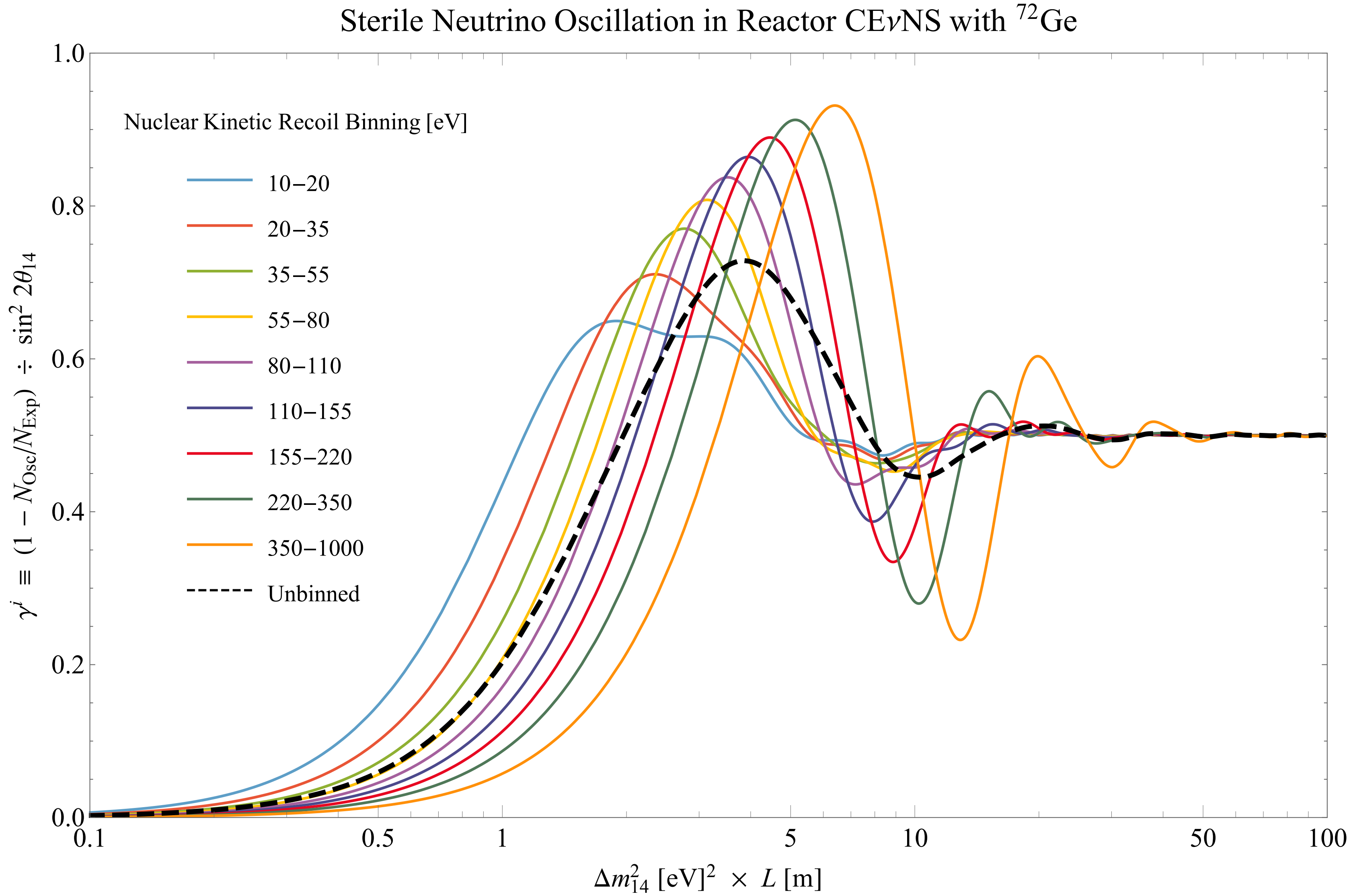
$$\lambda = 4.97\ [\mathrm{m}] \times \left\{\frac{E_\nu}{1\ [\mathrm{MeV}]}\right\} \times \left\{\frac{1\ \mathrm{eV}^2}{\Delta m^2}\right\}$$

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

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

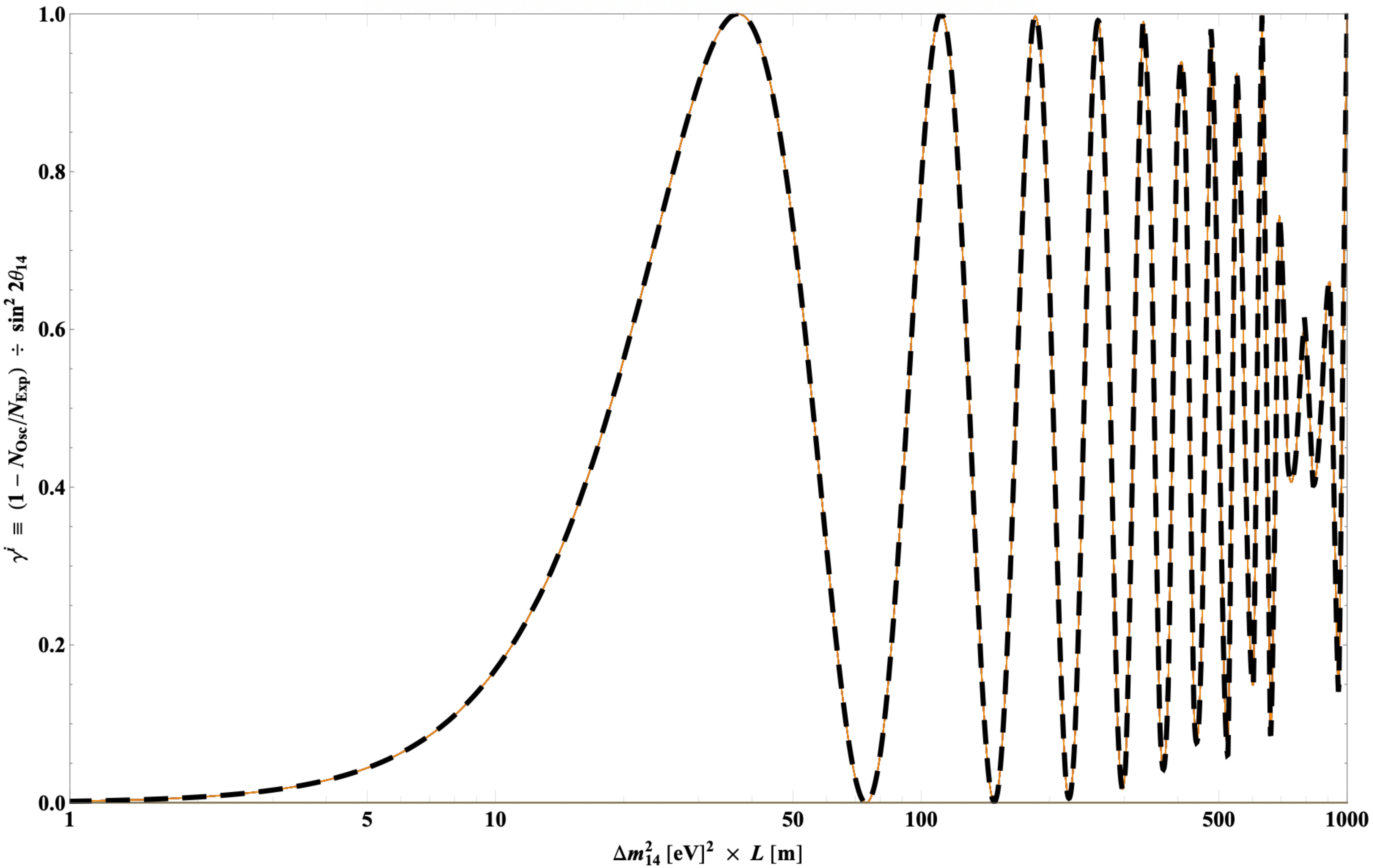
- Probability for oscillation depends on mixing (amplitude) and mass gap (phase)
- For the region of interest, an experimental baseline on the order of meters is relevant
- Dimensionless scale-invariant basis functions encapsulate all aspects of theory
- Neutrino anomalies exist in radioactive source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

Depletion via Oscillation



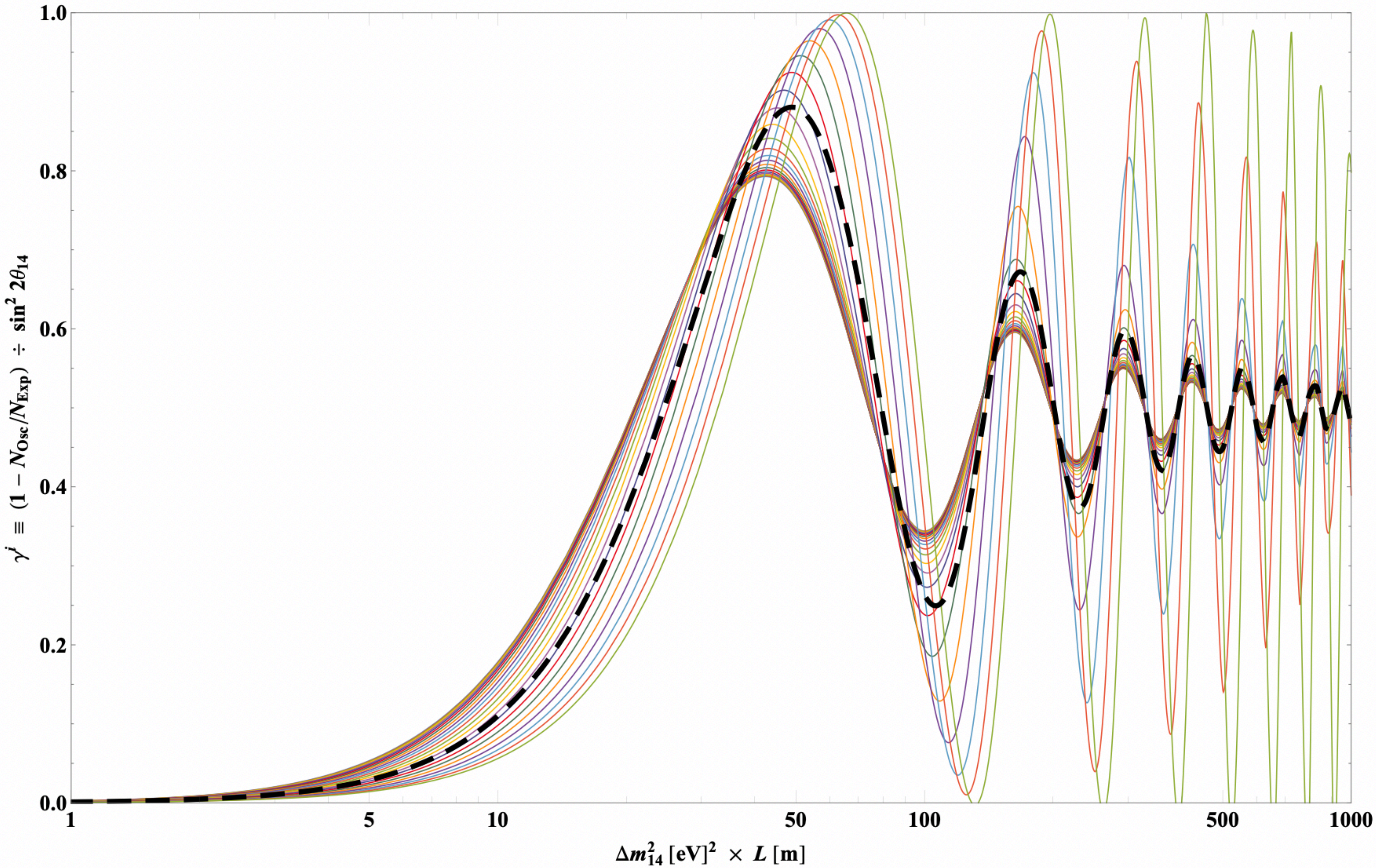
- Larger values in the vertical correspond to greater depletion via oscillation
- Universal curve bases are rescaled (vert.) by mixing amplitude and (horiz.) mass gap
- Bins are selected for approximately equivalent population event rates
- Even with a fixed length scale, multiple energy samples give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

SNS Prompt



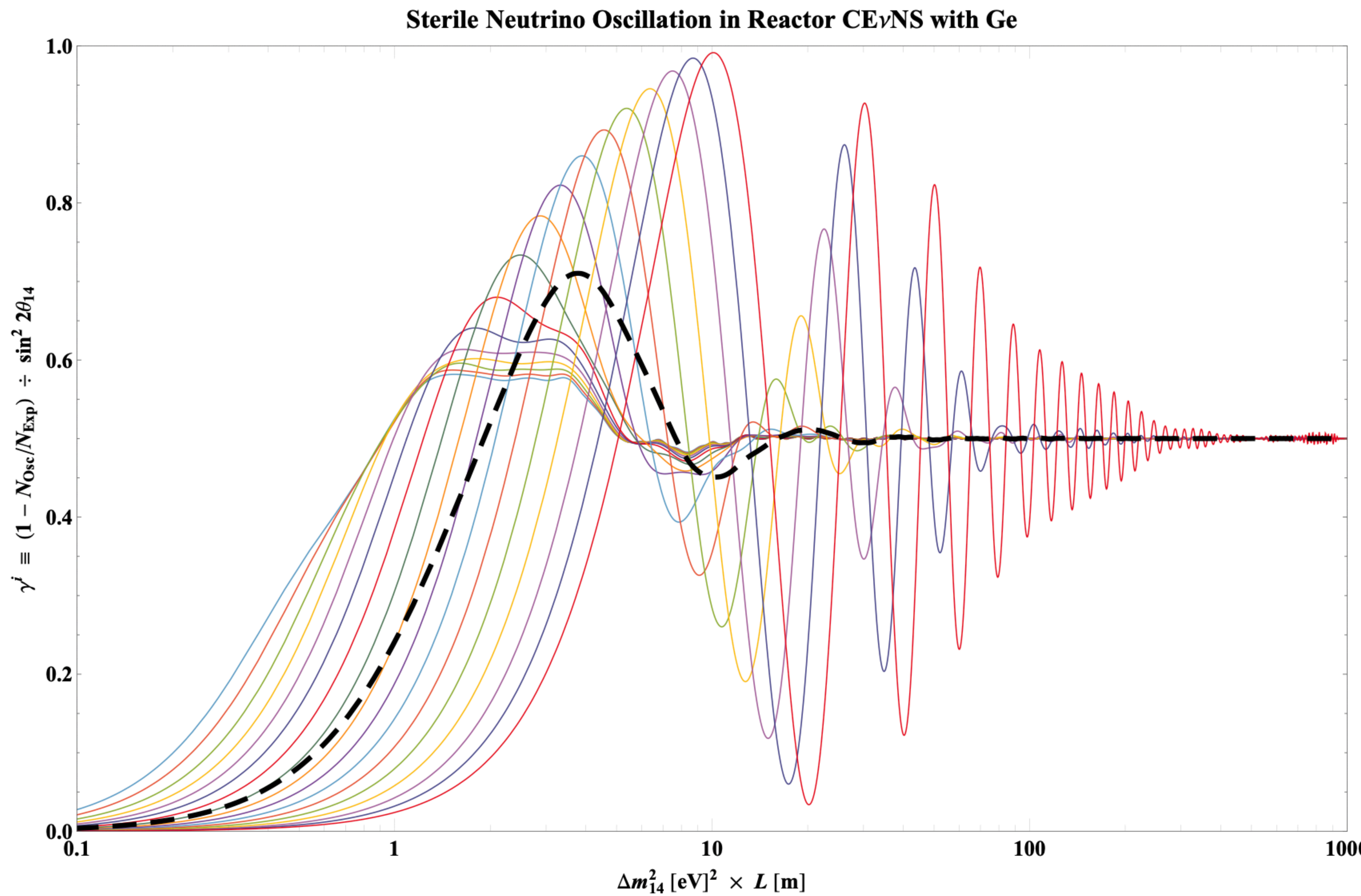
1.0
0.8
0.6
0.4
0.2
0.0
$\gamma^j \equiv (1 - N_{Osc}/N_{Exp}) \div \sin^2 2\theta_{14}$
1
5
10
50
100
500
1000
$\Delta m^2_{14}\,[\mathrm{eV}]^2 \times L\,[\mathrm{m}]$

SNS Delayed



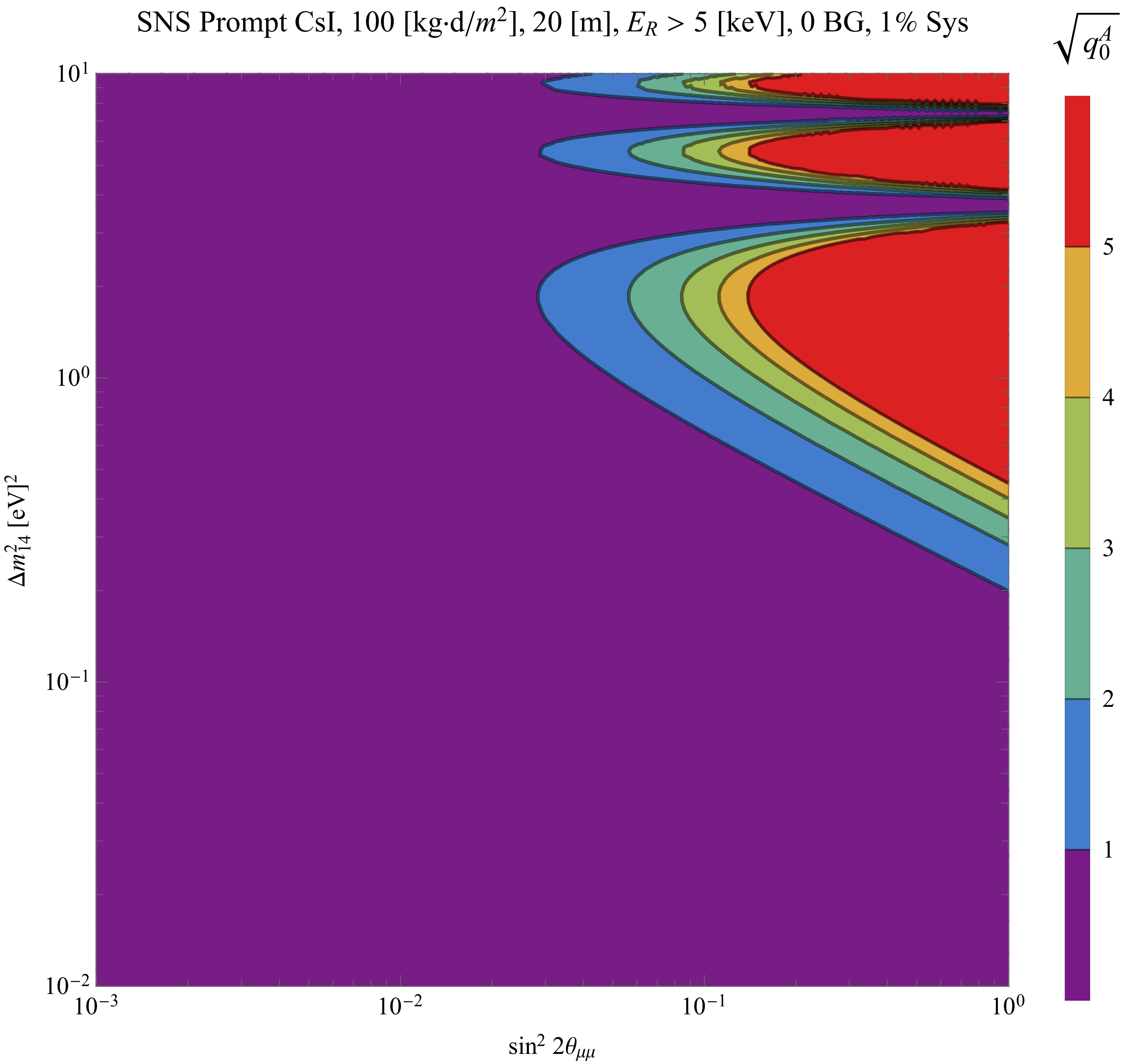
1.0
0.8
0.6
0.4
0.2
0.0
$\gamma^j \equiv (1 - N_{\mathrm{Osc}}/N_{\mathrm{Exp}}) \div \sin^2 2\theta_{14}$
1
5
10
50
100
500
1000
$\Delta m^2_{14}\,[\mathrm{eV}]^2 \times L\,[\mathrm{m}]$

Reactor



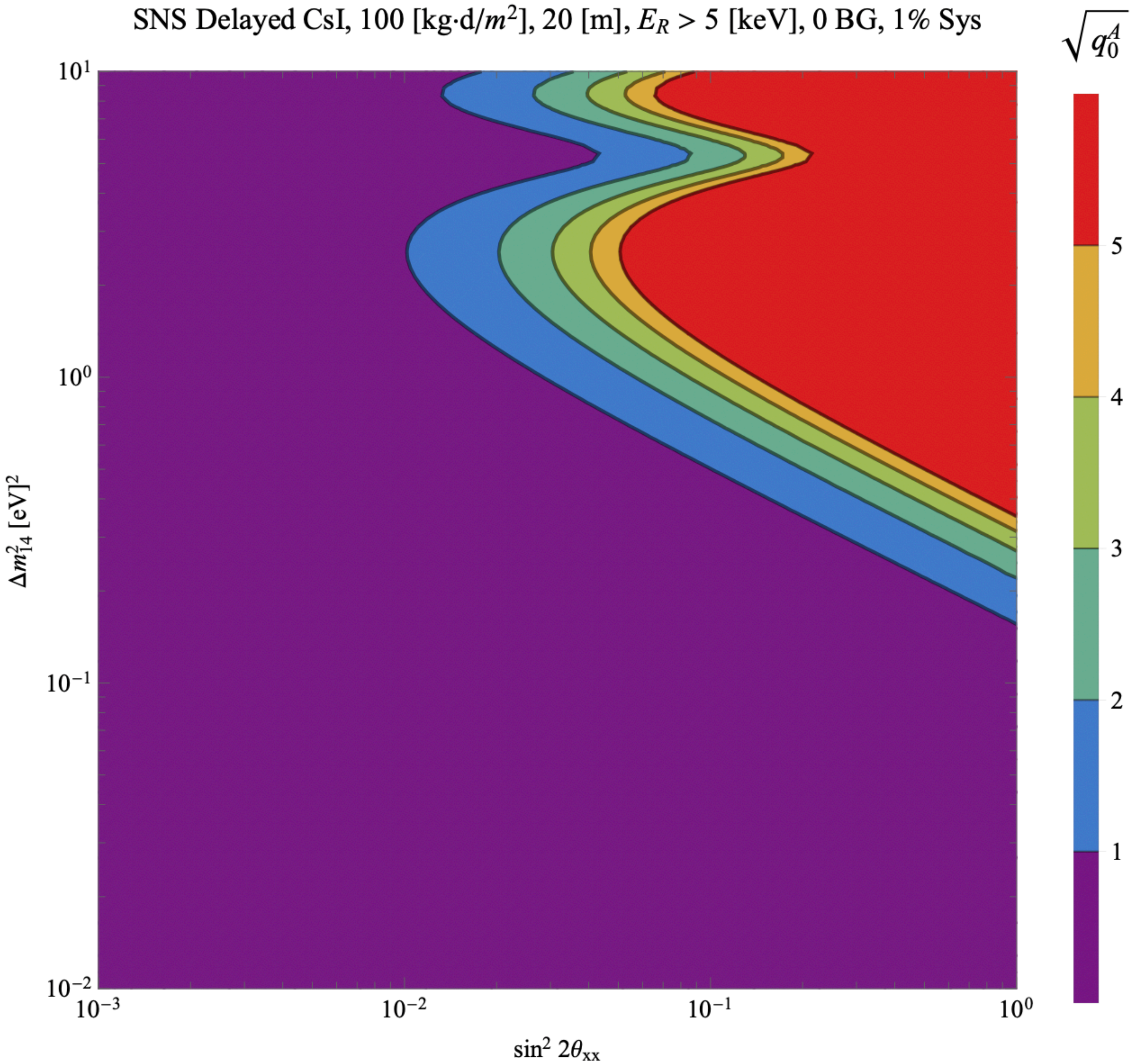
Sterile Neutrino Oscillation in Reactor CEνNS with Ge
$\gamma^j \equiv (1 - N_{Osc}/N_{Exp}) \div \sin^2 2\theta_{14}$
1.0
0.8
0.6
0.4
0.2
0.0
0.1
1
10
100
1000
$\Delta m^2_{14}\,[\mathrm{eV}]^2 \times L\,[\mathrm{m}]$

SNS Prompt



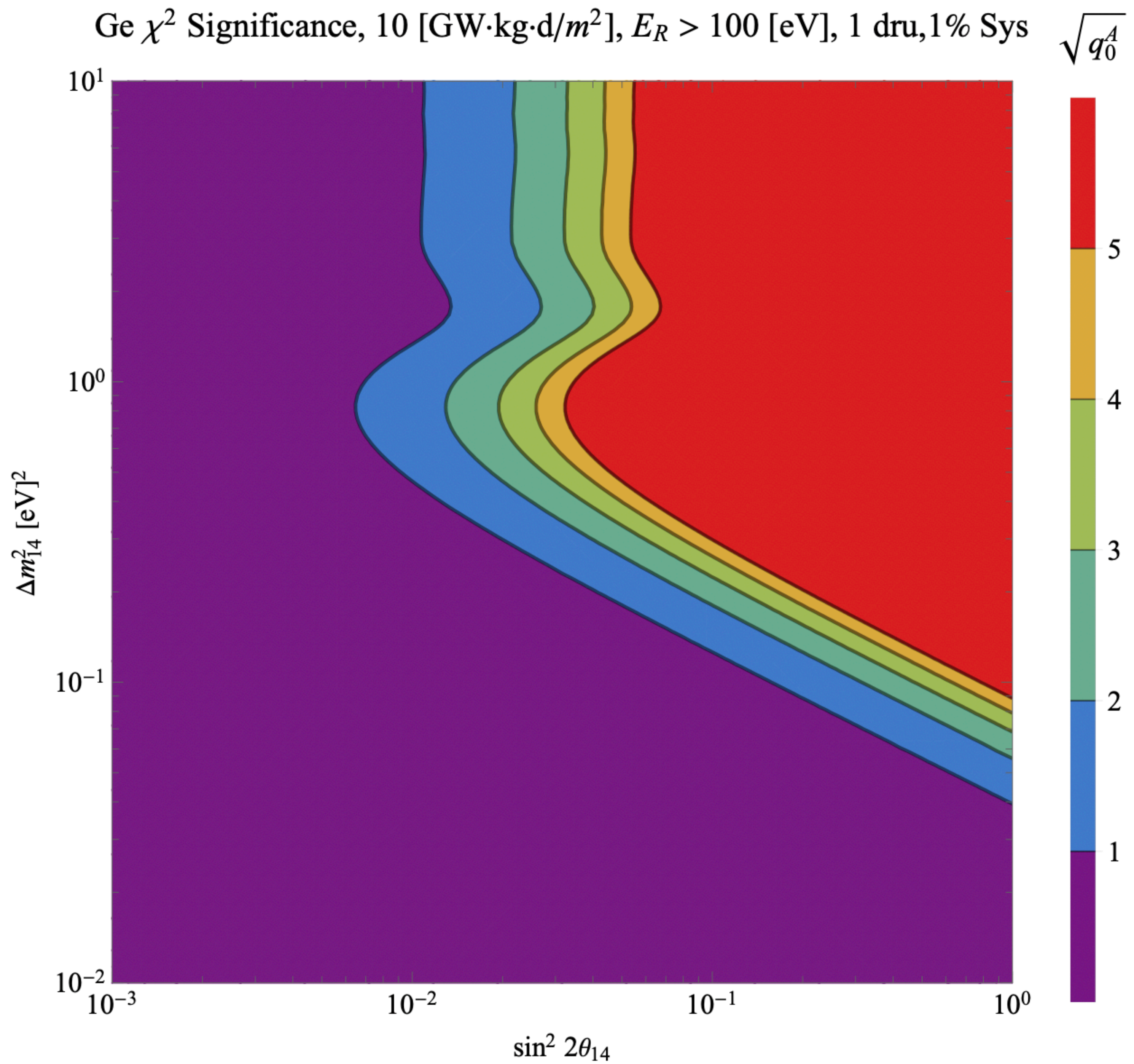
67

SNS Delayed



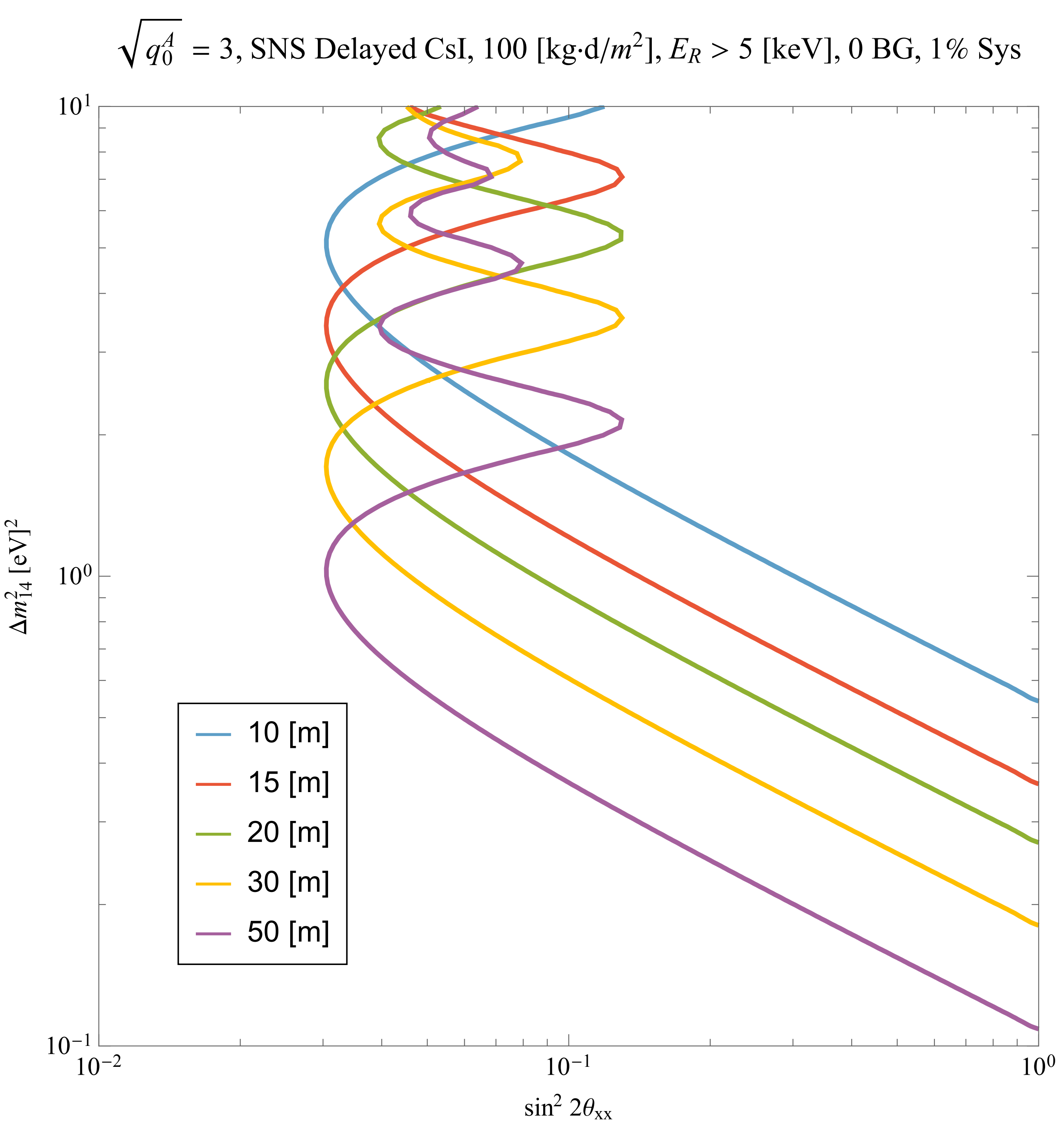
SNS Delayed CsI, 100 [kg·d/m^2], 20 [m], E_R > 5 [keV], 0 BG, 1% Sys
$\sqrt{q_0^A}$
Δm_{14}^2 [eV]^2
$\sin^2 2\theta_{xx}$
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
1
2
3
4
5

Reactor



Ge χ^2 Significance, 10 [GW·kg·d/m^2], E_R > 100 [eV], 1 dru,1% Sys
$\sqrt{q_0^A}$
10^1
10^0
10^{-1}
10^{-2}
Δm^2_{14} [eV]^2
10^{-3}
10^{-2}
10^{-1}
10^0
$\sin^2 2\theta_{14}$
1
2
3
4
5

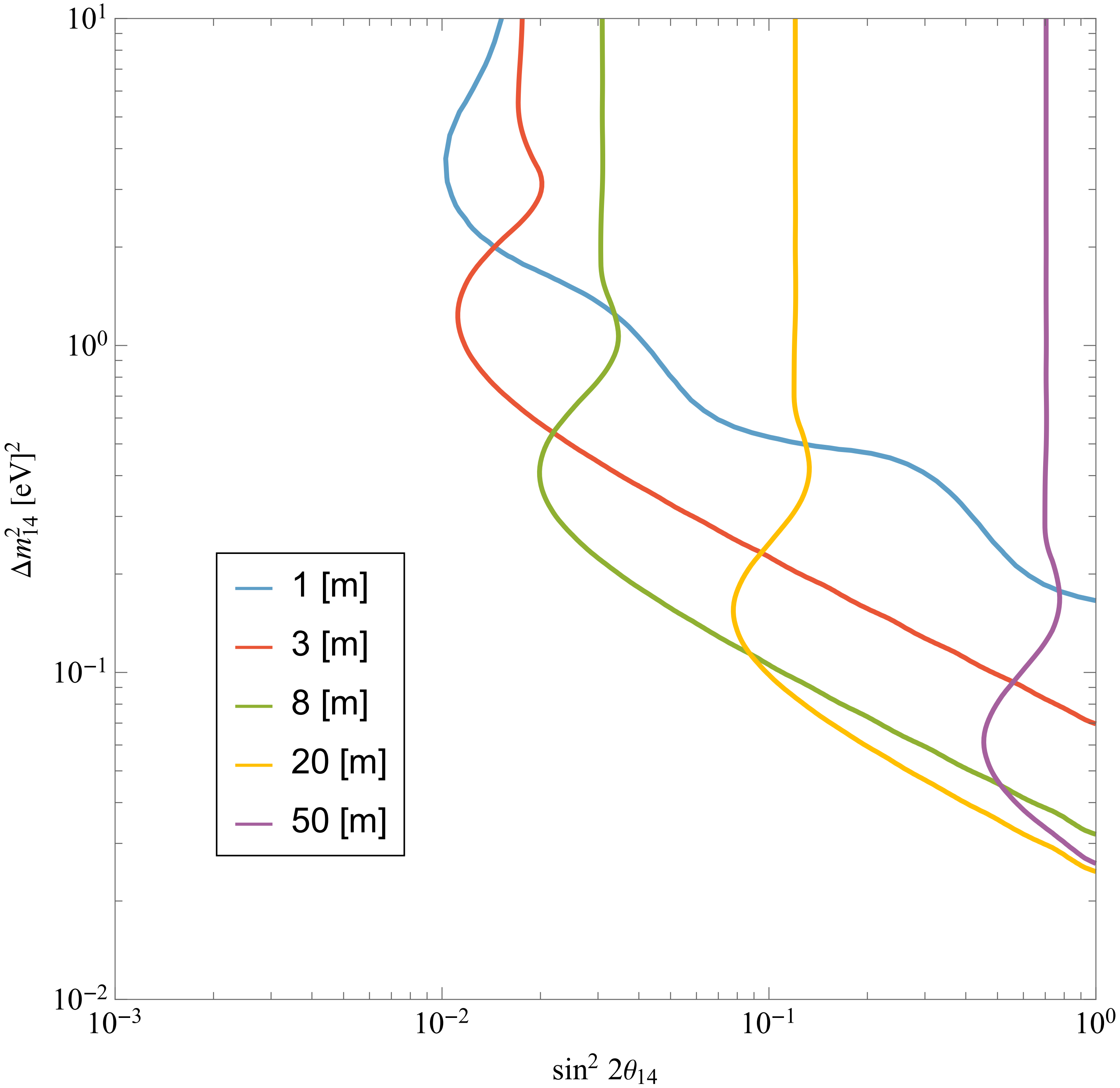
SNS Delayed



69

Reactor

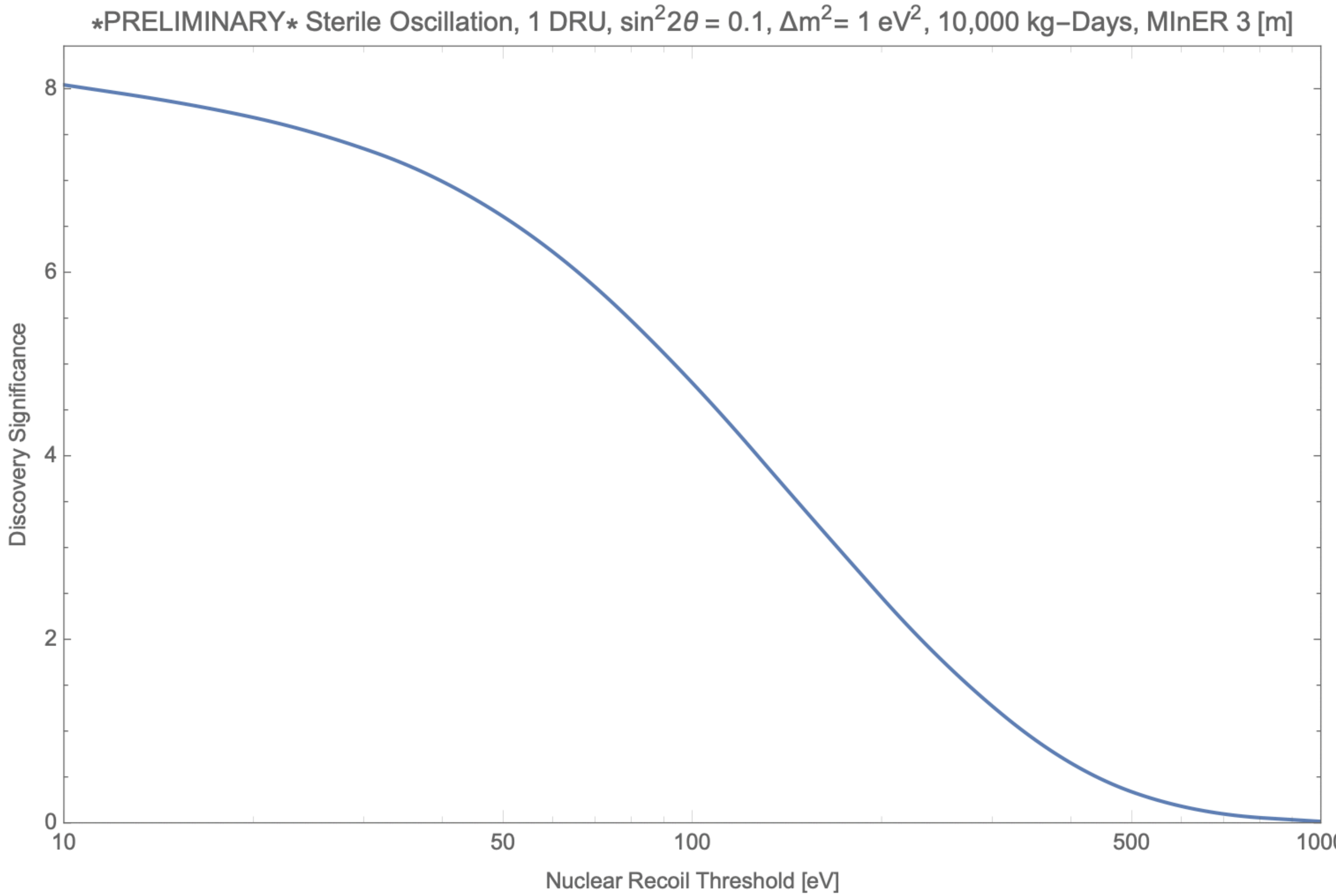
$\sqrt{q_0^A} = 3$, Ge 10 [GW·kg·d/m^2], $E_R > 40$ [eV], 1 dru,1% Sys



68

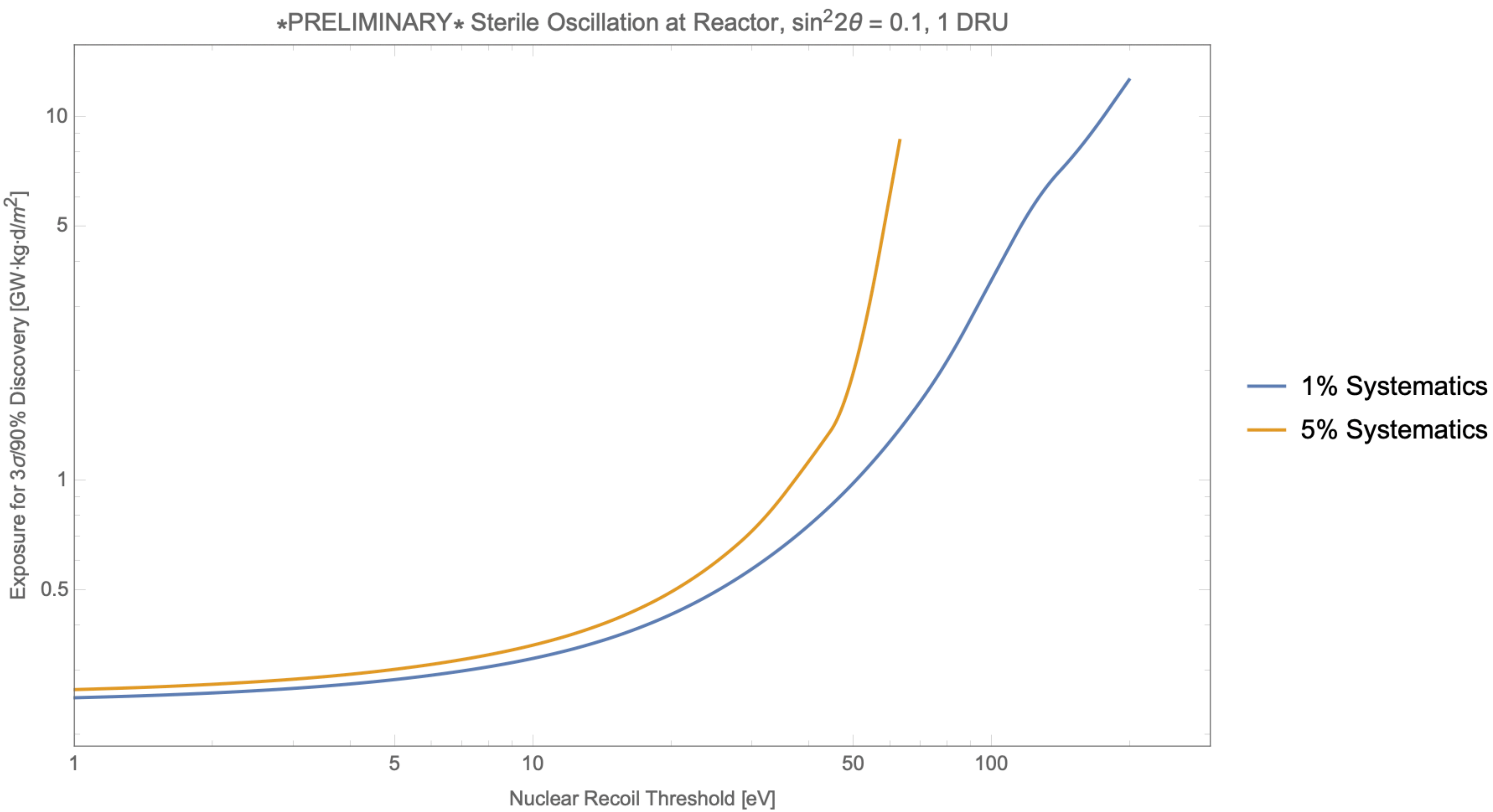
Reactor Threshold

- Low threshold is essential for additional channels



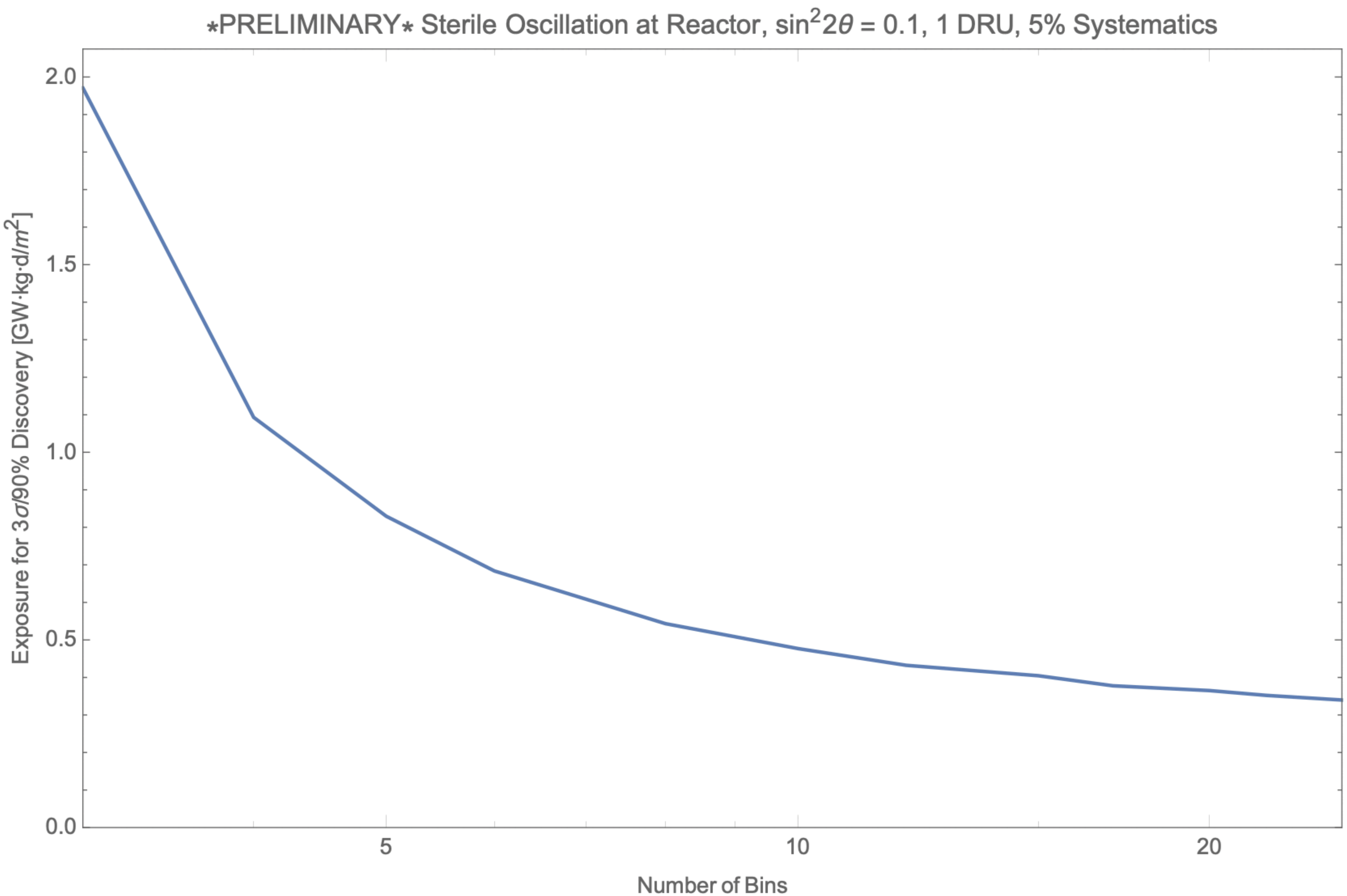
Reactor Systematics

- Large systematics require low thresholds



Reactor Binning

- One must bin in order to separate correlated effects



SUMMARY

- Coherent Neutrino-Nucleus Scattering is observed — with high statistics this can probe BSM physics of several varieties
- CEvNS will be most effective where the SHAPE of the recoil spectrum is characteristically affected
- Searches for a short-baseline eV-scale sterile are motivated by anomalies & leverage the systemic advantages of CEvNS
- Reactors & beam experiments are complementary, especially with distinct target nuclei

THANK YOU

Sam Houston State University

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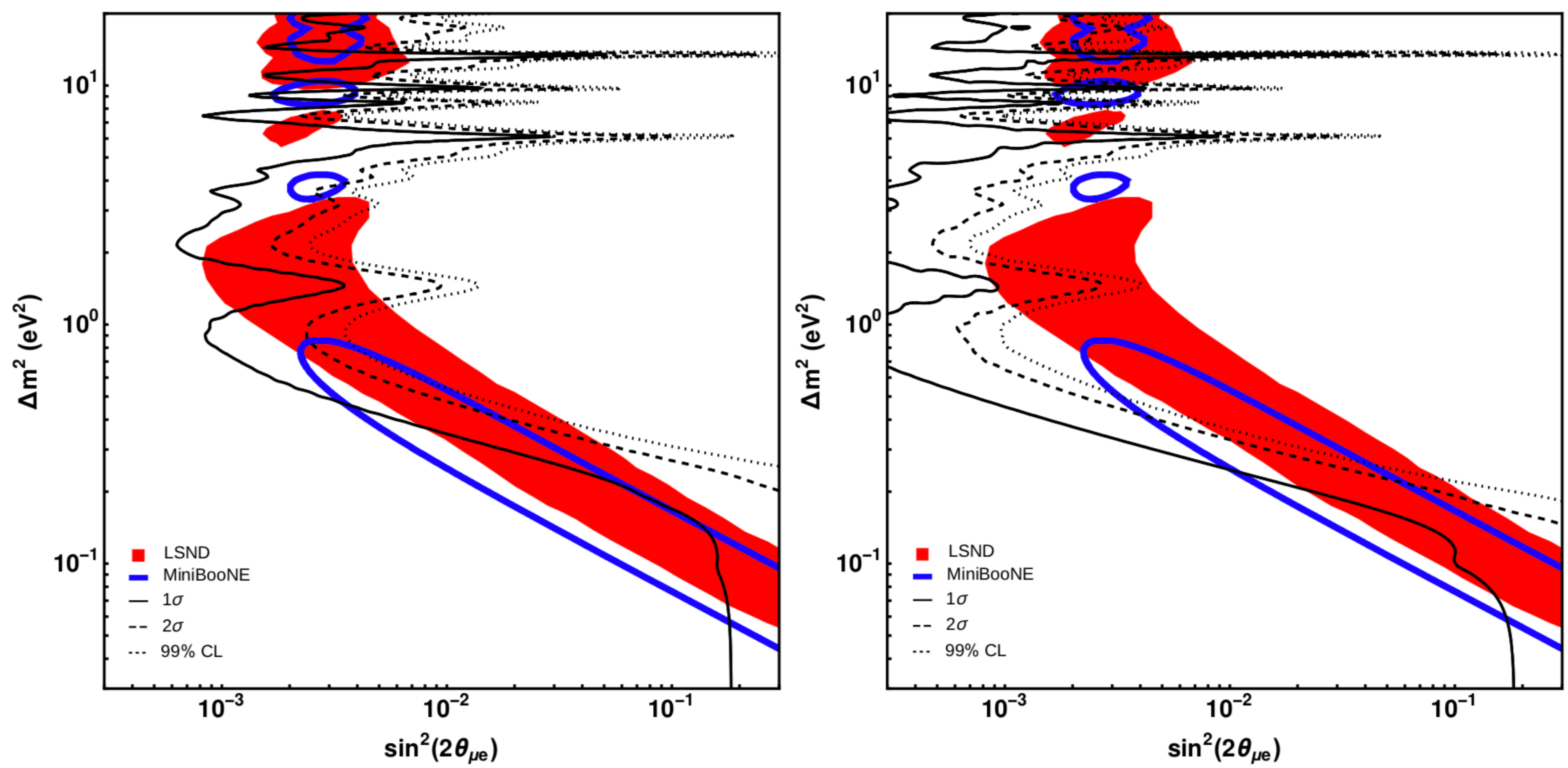

FIG. 2. The projected constraints on the sterile neutrino parameter space for a 100 kg CsI detector and source that generates 4×10^{23} protons on target per year with an energy of 1 GeV, after collecting data for a total of 3 years (left) or 10 years (right). In each case, we have assumed that the detector 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