Decaying Sterile Neutrinos at MicroBooNE

In collaboration with Matheus Hostert and Kevin Kelly. arXiv:2405.XXXXX

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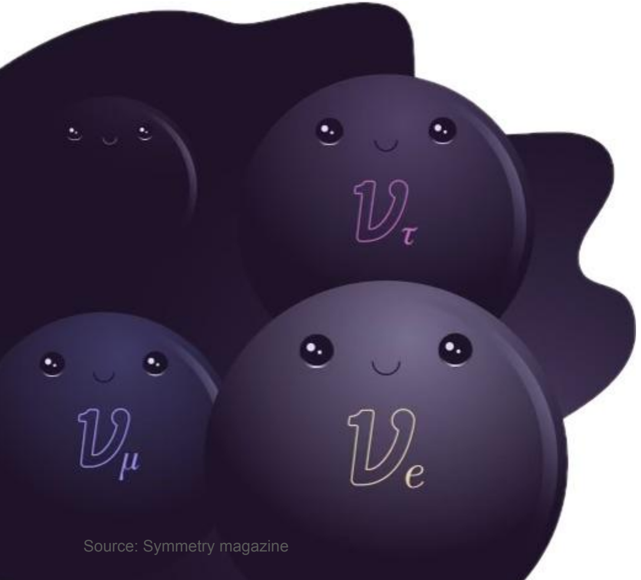
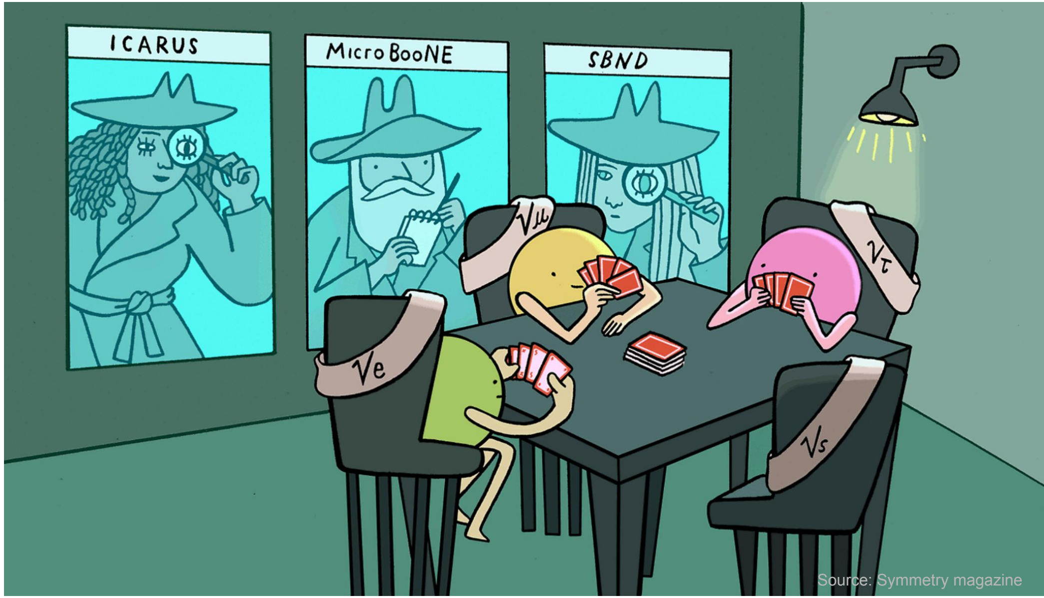


Source: Symmetry magazine

Outlines

- Why sterile neutrino?
- Decaying sterile neutrino
- Formalism
- Event rates
- Oscillation fits
- Decay fits
- Conclusion



Sterile neutrinos (3+1)

As an explanation for SBL anomalies

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

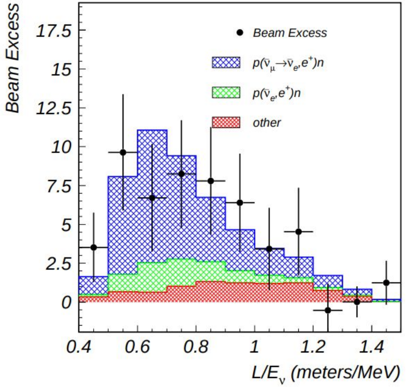
A sterile neutrino only participates in oscillation.

However, significant tension remains

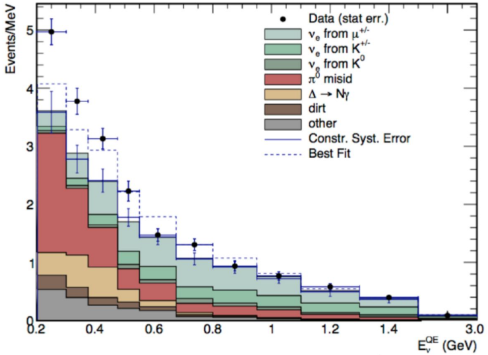
A simple 3+1 model is not enough

This motivates us to go beyond oscillations

LSND 3.8σ



MiniBooNE 4.8σ

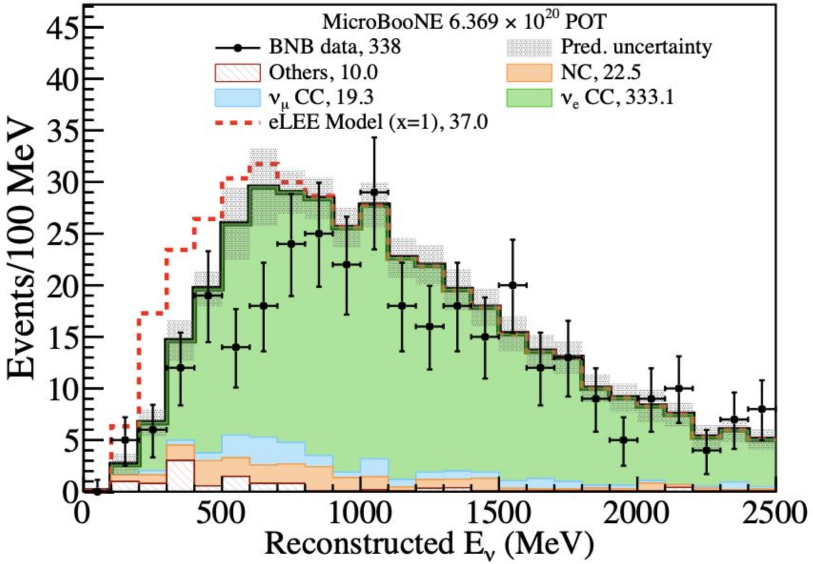


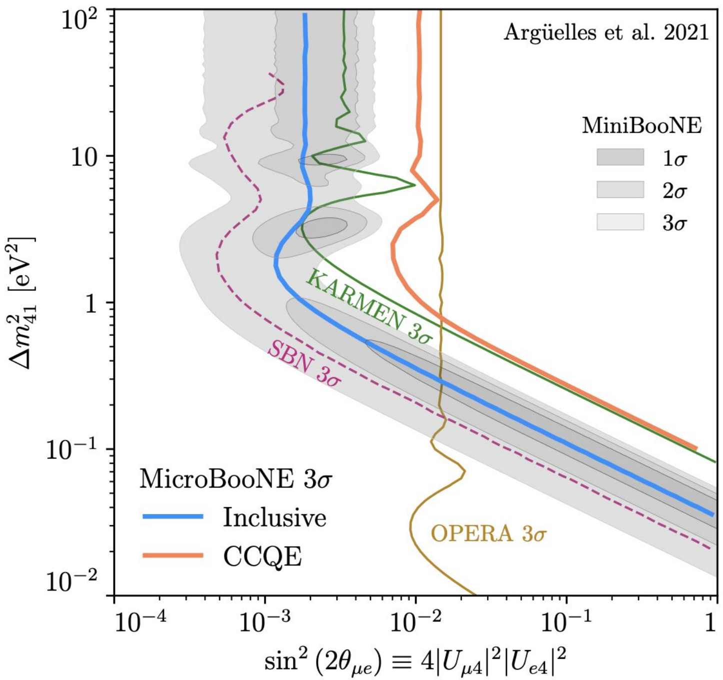
MicroBooNE

C. A. Arguelles, I. Esteban, M. Hostert, K. J. Kelly, J. Kopp, P. A. N. Machado, I.Martinez-Soler, and Y. F. arXiv: 2111.10359

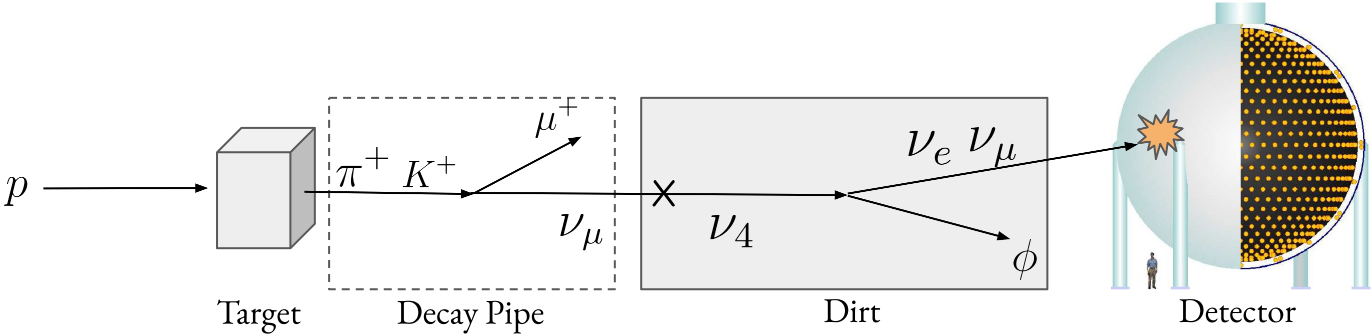
No Excess?

arXiv: 2110.14054





Decaying sterile neutrinos (3+1+decay)

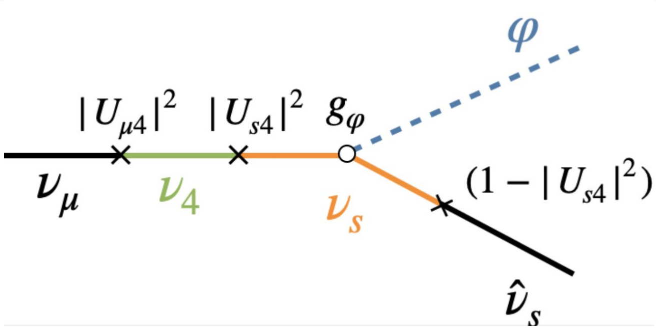


MiniBooNE excess is interpreted as the active neutrinos from sterile decay product.

ν_e appearance signal is only suppressed by the square of the mixing, not 4th power in the oscillation case ($4|U_{\mu4}|^2|U_{e4}|^2$). Therefore, smaller $U_{\mu4}$ is allowed, evading limits from ν_μ disappearance.

Decaying sterile neutrinos (3+1+decay)

$$-\mathcal{L} \supset g_\phi \overline{\nu_s} \nu_s \phi + \sum_{\alpha,\beta} m_{\alpha\beta} \overline{\nu}_\alpha \nu_\beta$$



Decay width:

$$\Gamma^{(\mathrm{I})}_{\nu_4} = \Gamma_{\nu_4 \to \hat{\nu}_s \phi} = |U_{s4}|^2 (1 - |U_{s4}|^2) \frac{g_\phi^2}{16\pi} \frac{m_4^2}{E_4}$$

Normalized active states:

$$|\hat{\nu}_s\rangle = \frac{\sum_{i=1}^{3} U^*_{fi} |\nu_i\rangle}{\left(\sum_{k=1}^{3} |U_{fk}|^2\right)^{1/2}}$$

Decaying sterile neutrinos (3+1+decay)

ν_β flux from a ν_α source:

$$\Phi_{\nu_\beta}(L, E_\nu) = \int_{E_4^{\min}}^{\infty} dE_4 \Phi_{\nu_\alpha}(L=0, E_4) P_{\alpha\beta}(L, E_4, E_\nu)$$

$$P_{\alpha\beta} = P_{\alpha\beta}^{\text{dec}} S_{\alpha\beta}^{\text{dec}} + P_{\alpha\beta}^{\text{osc}}$$

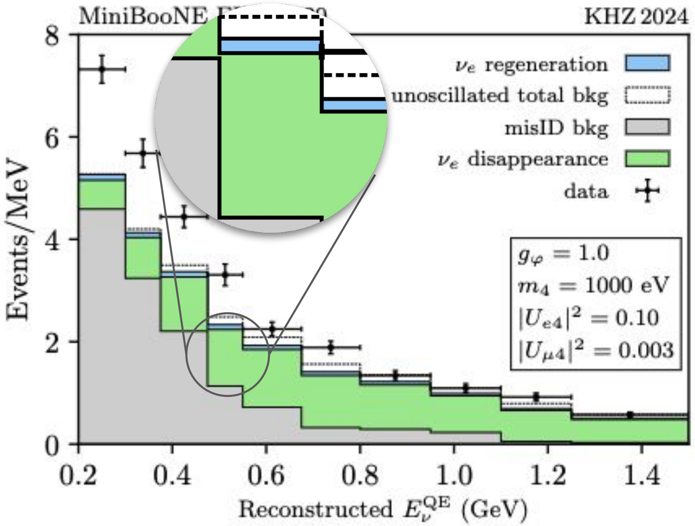
$P_{\alpha\beta}^{\text{osc}}$: ν_4 that is yet to decay at baseline L produces ν_e through oscillation.

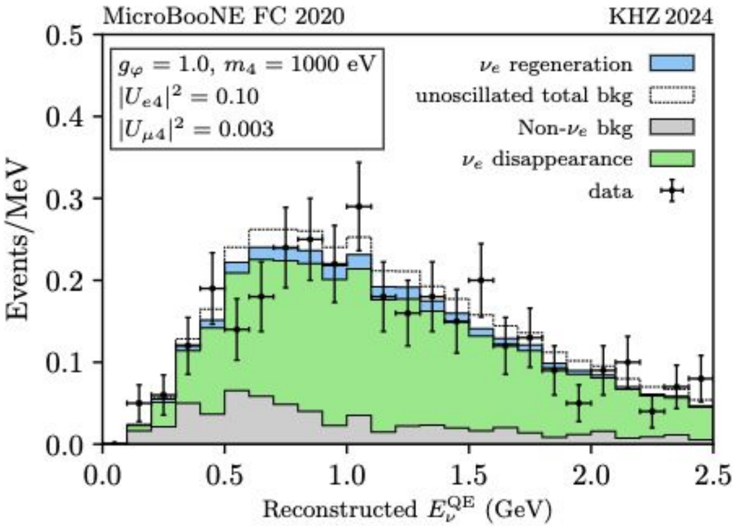
$P_{\alpha\beta}^{\text{dec}} S^{\text{dec}}$: ν_4 that decays into active states.

For helicity-conserving decays, $S_{\alpha\beta}^{\text{dec}}(E_4, E_\nu) = \frac{1}{\Gamma_{\nu_4}} \frac{d\Gamma_{\nu_4 \to \nu\phi}}{dE_\nu} = \frac{E_\nu}{E_4}$

Disappearance of the intrinsic ν_e

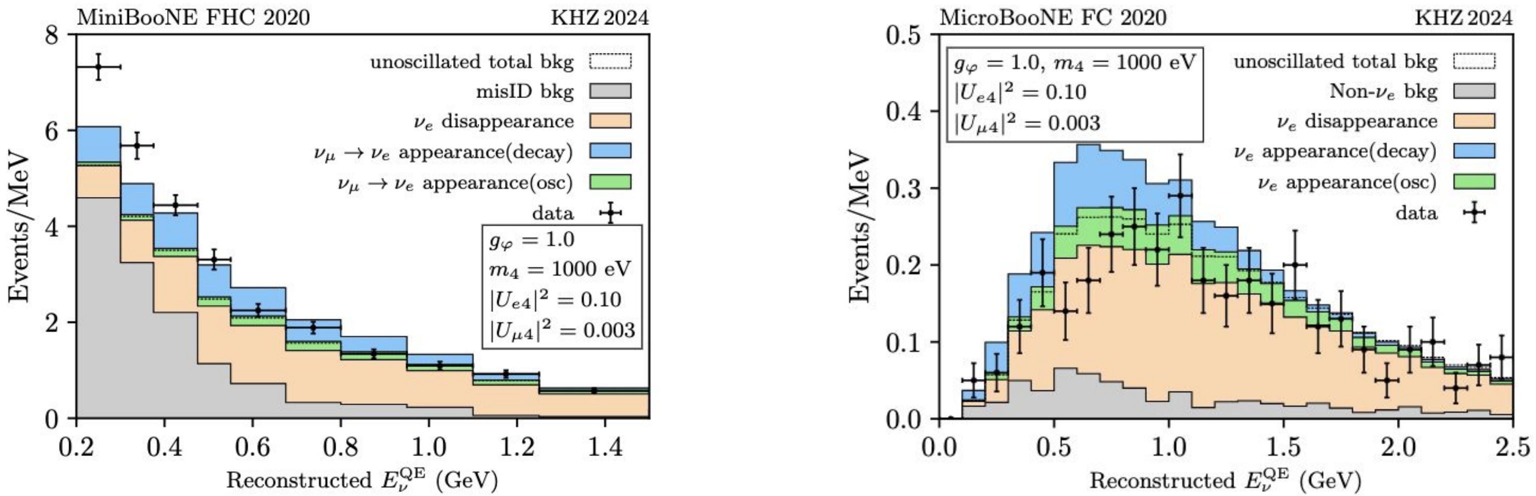
$$P_{ee} = P_{ee}^{\rm dec} S_{ee}^{\rm dec} + P_{ee}^{\rm osc}$$





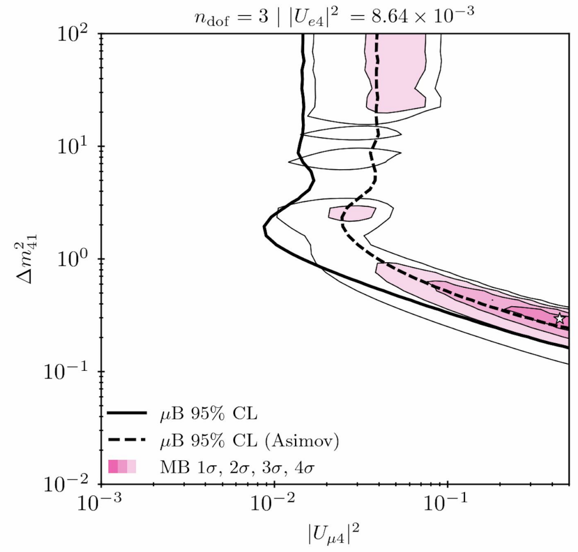
$\nu_\mu \to \nu_e$ Appearance signal

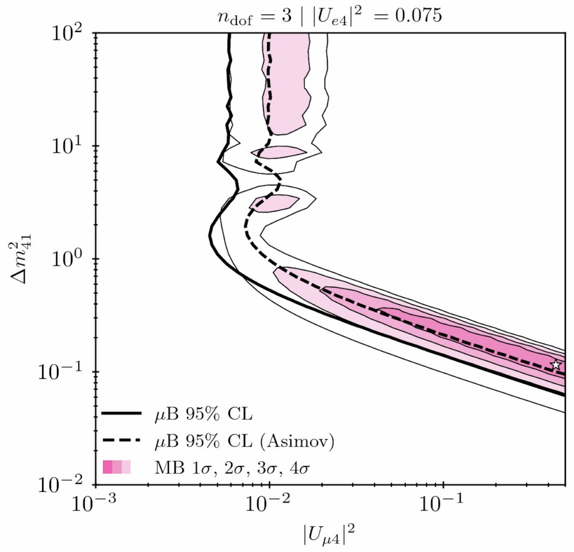
$$P_{\mu e} = P_{\mu e}^{\rm dec} S_{\mu e}^{\rm dec} + P_{\mu e}^{\rm osc}$$

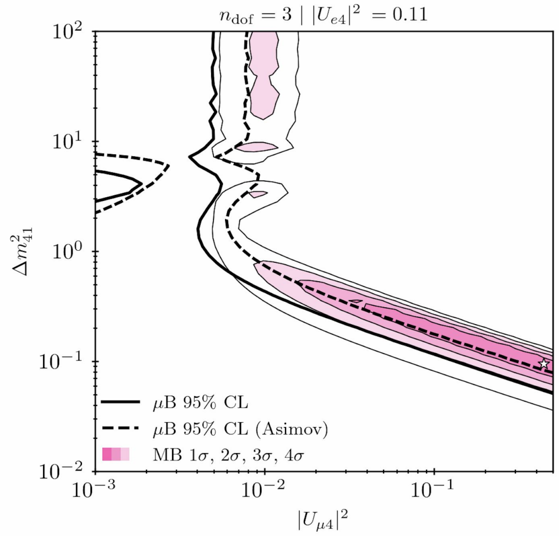


MiniBooNE favors decay because of the low energy events from decay. Although there is some penalty from detector efficiency, cross section and the helicity-conserving factor.

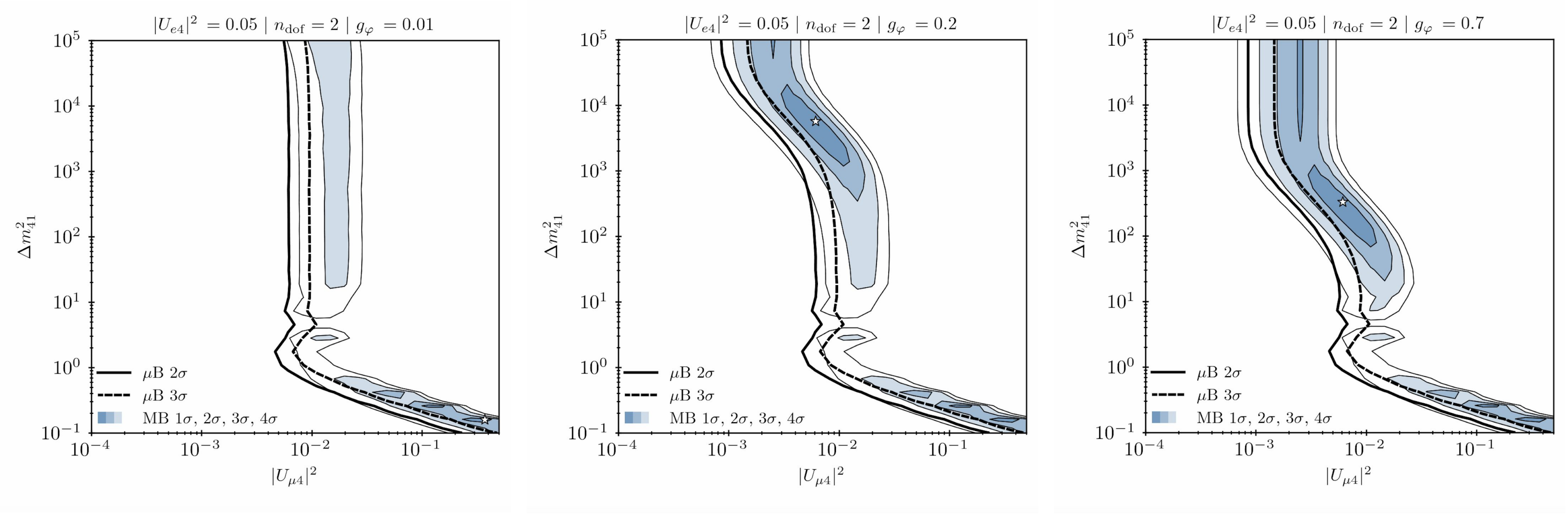
Oscillation Fits – varying $|U_{e4}|^2$



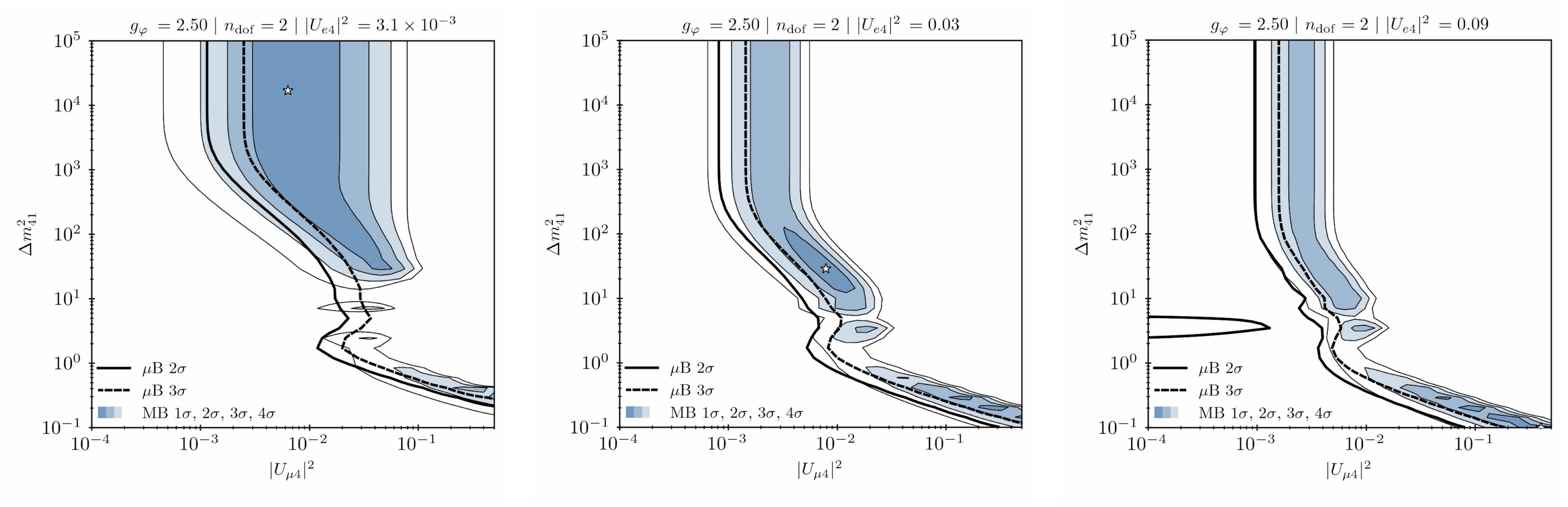




Decay Fits – varying coupling



Decay Fits – varying $|U_{e4}|^2$



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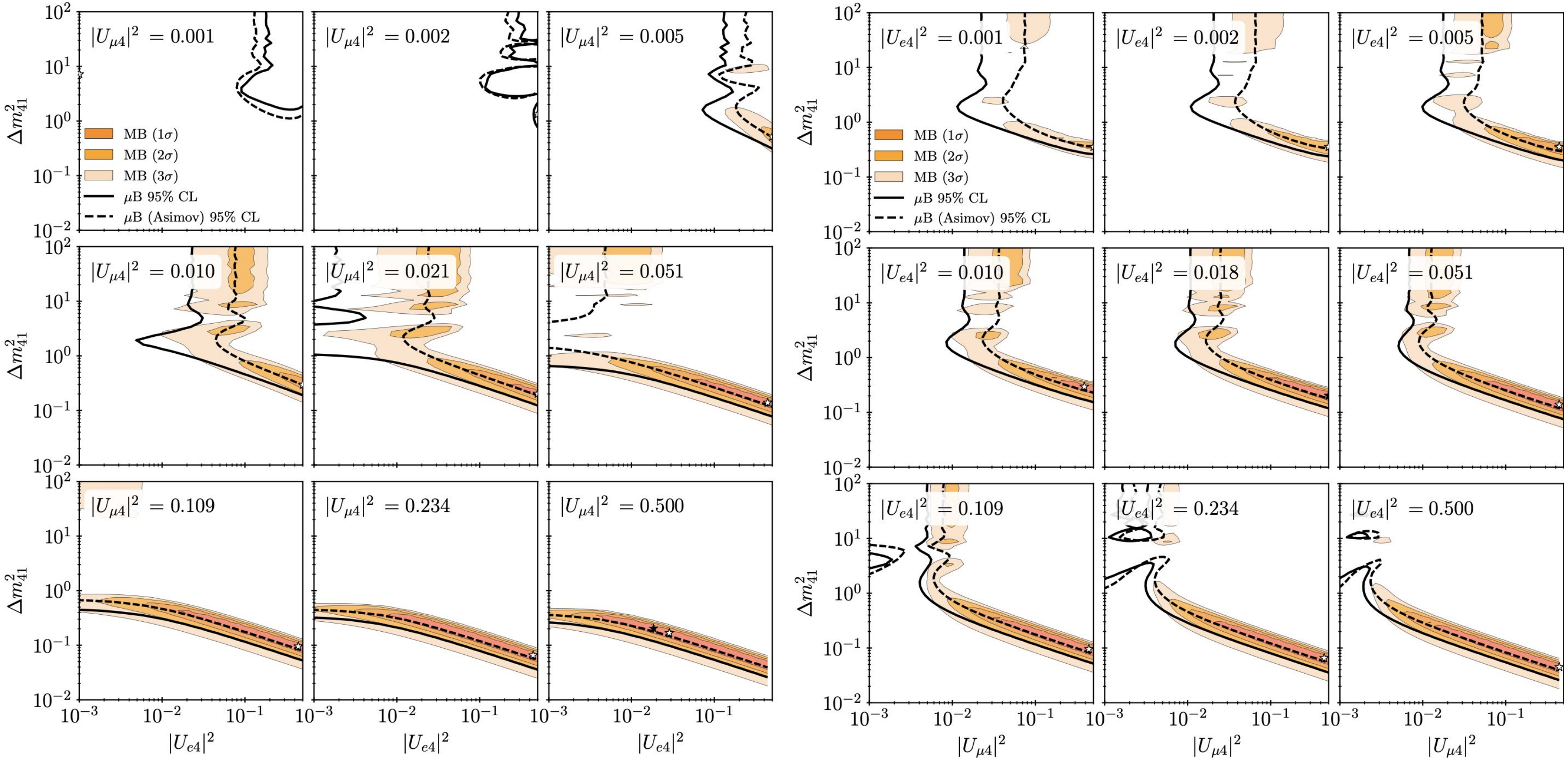
Conclusion

- The minimal 3+1 model is not enough to reconcile all the anomalies.
- Decaying sterile neutrinos predicts LEE at MiniBooNE and fits better.
- We present the first comprehensive fit to MicroBooNE, accounting for disappearance, energy loss, etc.
- Decaying sterile solution to MiniBooNE is ruled out by MicroBooNE at more than 95% CL.
- In principle it can also explain the BEST anomaly.

Backup – 3+1 slices



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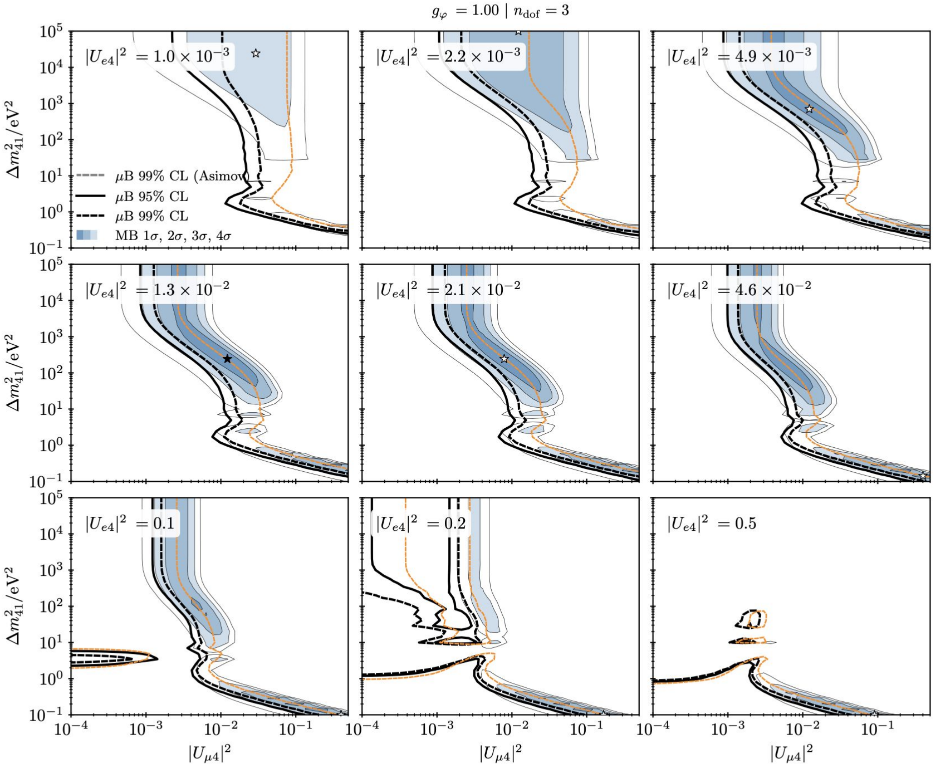
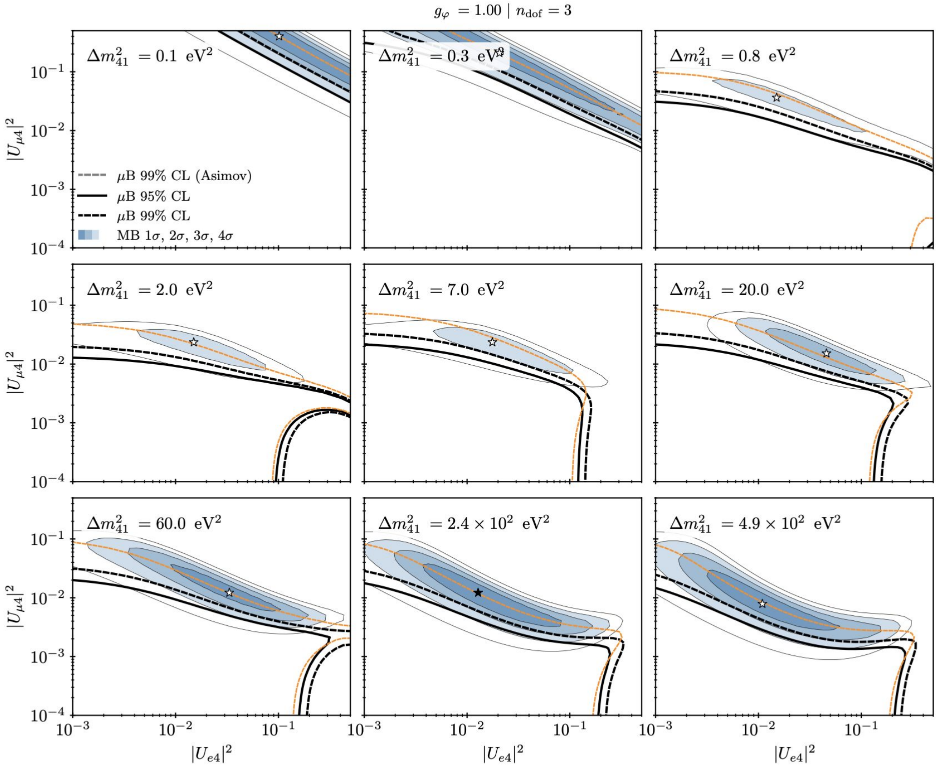
Backup – 3+1+decay slices





Oscillation probability, best-fits

$$P_{\alpha\beta} = P^{\rm dec}_{\alpha\beta} S^{\rm dec}_{\alpha\beta} + P^{\rm osc}_{\alpha\beta}$$

$$P^{\rm osc}_{\alpha\beta}(L, E_\nu) = \delta_{\alpha\beta} - 2\delta_{\alpha\beta}|U_{\alpha 4}U_{\beta 4}| \left[1 - e^{-\frac{L}{2L_{\rm dec}}} \cos\left(\pi \frac{L}{L_{\rm osc}}\right)\right] + |U_{\alpha 4}U_{\beta 4}|^2 \left[1 - 2e^{-\frac{L}{2L_{\rm dec}}} \cos\left(\pi \frac{L}{L_{\rm osc}}\right) + e^{-\frac{L}{L_{\rm dec}}}\right]$$

$$P^{\rm dec}_{\alpha\beta}(L, E_4, E_\nu) = |U_{\alpha 4}|^2 \frac{|\langle \hat{\nu}_s \mid \nu_\beta \rangle|^2}{|\langle \hat{\nu}_s \mid \hat{\nu}_s \rangle|^2} \left(1 - e^{-\frac{L}{L_{\rm dec}}}\right)$$

New Physics Model	$\|U_{e4}\|^2$	$\|U_{\mu 4}\|^2$	g_φ or g_e	Δm^2_{41}	$p^{\rm val}_{\rm MB}$	$\chi^2_{\mu \rm B} - \chi^2_{\mu \rm B,Null}$
Decay model (I)	0.21	0.15	3	0.1 eV^2	36%	35
	0.19	0.17	2.5 (fixed)	0.1 eV^2	39%	22
	0.013	0.012	1.0 (fixed)	2.4×10^2 eV^2	38%	25