Title: Quasi-sterile neutrinos from dark sectors

Speakers: Daniele Alves

Series: Particle Physics

Date: March 15, 2022 - 1:00 PM

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Abstract: Quasi-sterile neutrinos are a natural consequence of dark sectors interacting with the Standard Model (SM) sector via neutrino- and vector-portals. Essentially, quasi-sterile neutrinos are light dark sector fermions with two generic properties: (i) they mix with the active neutrinos of the SM, and (ii) they are charged under a vector mediator that couples feebly to SM matter. Various interesting phenomenological consequences result from this class of particles. In this talk, I will discuss one such consequence: new, beyond the SM matter effects that can alter in-medium neutrino oscillations. In particular, for special windows of energy and matter densities, active neutrinos can resonantly oscillate into sterile neutrinos. I will discuss how this feature could be exploited to build a quasi-sterile neutrino model that can explain the MiniBooNE and LSND anomalies, while remaining compatible with observations from long-baseline reactor- and accelerator-based neutrino experiments. I will also discuss the implications to this model from the recent MicroBooNE results, and, time permitting, from solar neutrino measurements.

Zoom Link: https://pitp.zoom.us/j/95362454210?pwd=RzNCeDRkMjJXb2xNbHNkcEc1ZTdkUT09

Quasi-Sterile Neutrinos from Dark Sectors

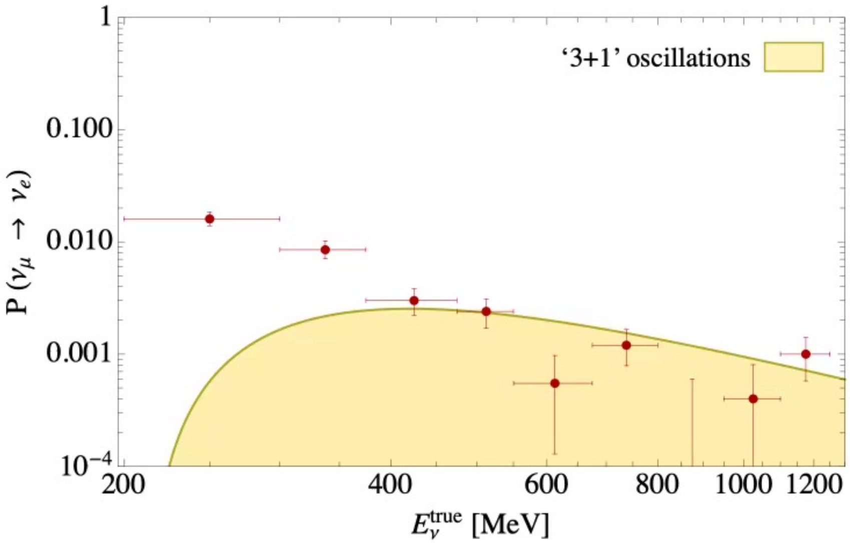
I. BSM Matter Effects in Neutrino Oscillations and the Short-Baseline Anomalies

Daniele S. M. Alves
LANL

Based on arXiv: 2201.00876 w/ Bill Louis and Patrick deNiverville
(and work in progress)

Particle Physics Seminar, Perimeter Institute, March 15th, 2022

The MiniBooNE Low Energy Excess



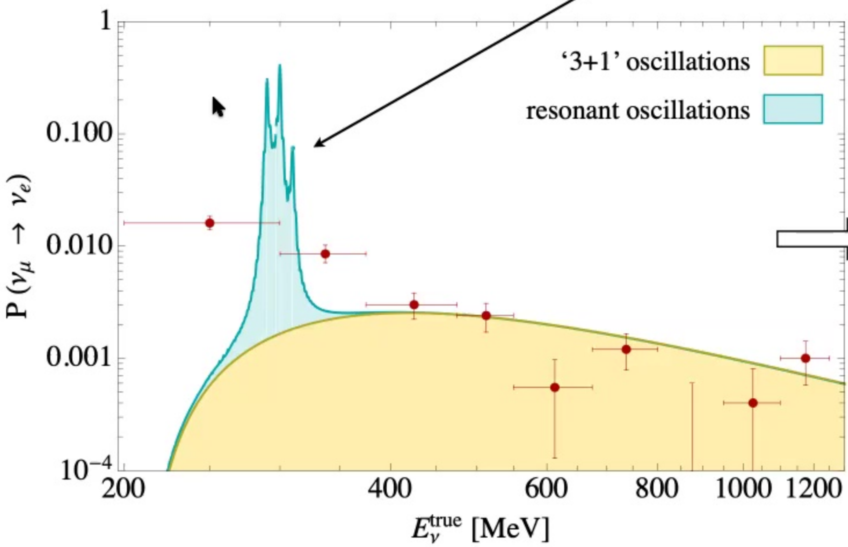
* data points assume $E_\nu^{true} \approx E_\nu^{CCQE}$, therefore this should be taken as a qualitative depiction of the excess

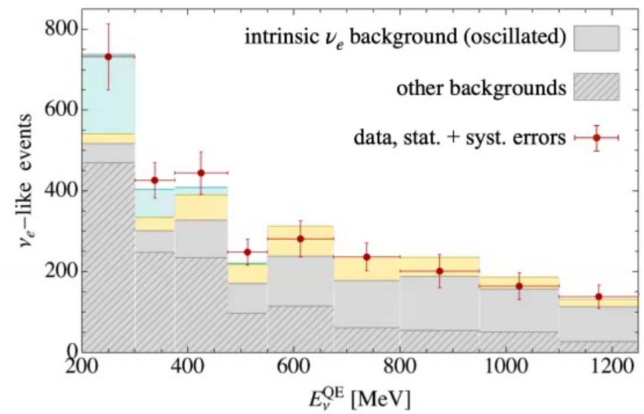
The MiniBooNE appearance data is compatible with the ‘3+1’ sterile neutrino interpretation of the LSND excess in the mid-to-high energy range, $E_\nu \gtrsim 400$ MeV, but an excess at lower energies $E_\nu \lesssim 400$ MeV persists

Unaccounted backgrounds or systematics? Or genuine BSM signal?

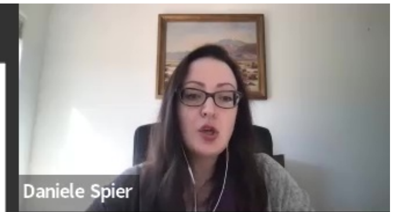
Resonant Neutrino Oscillations?

Previously considered by: Karagiorgi, Shaevitz, Conrad (2012)
Pas, Weiler, *et al.* (2005, 2020)
Asaadi *et al.* (2017)





Excellent fit to MiniBooNE data



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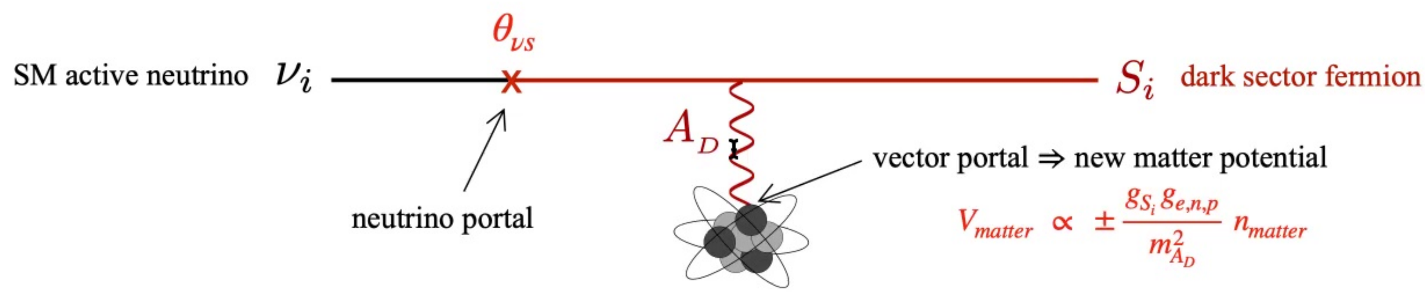
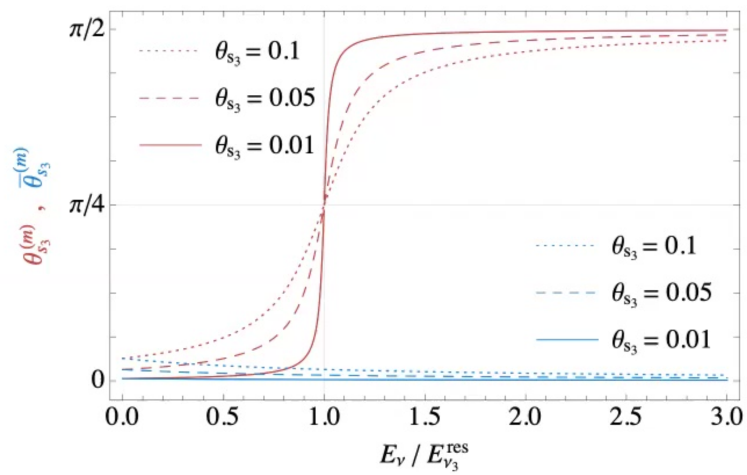
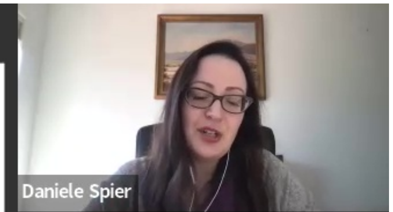
Quasi-Sterile Neutrinos and New Matter Effects



New matter potential acting on quasi-sterile neutrino induces resonant active-to-sterile oscillations when the energy and matter potential satisfy the relation:

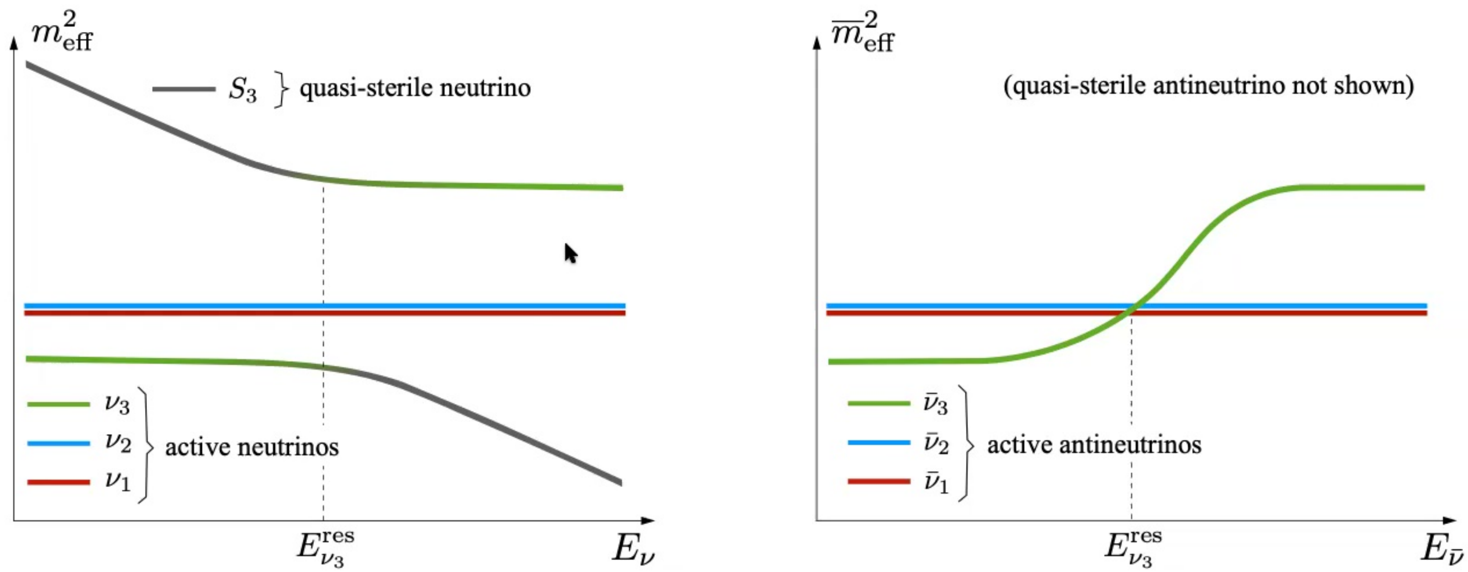
$$E_\nu^{res} = \frac{\delta M^2_{\nu s} \cos(2\theta_{\nu s})}{2\, V_{matter}}$$





Quasi-Sterile Neutrinos and New Matter Effects (toy model)

Effectively, the matter potential alters the propagation eigenstates and their oscillation phases



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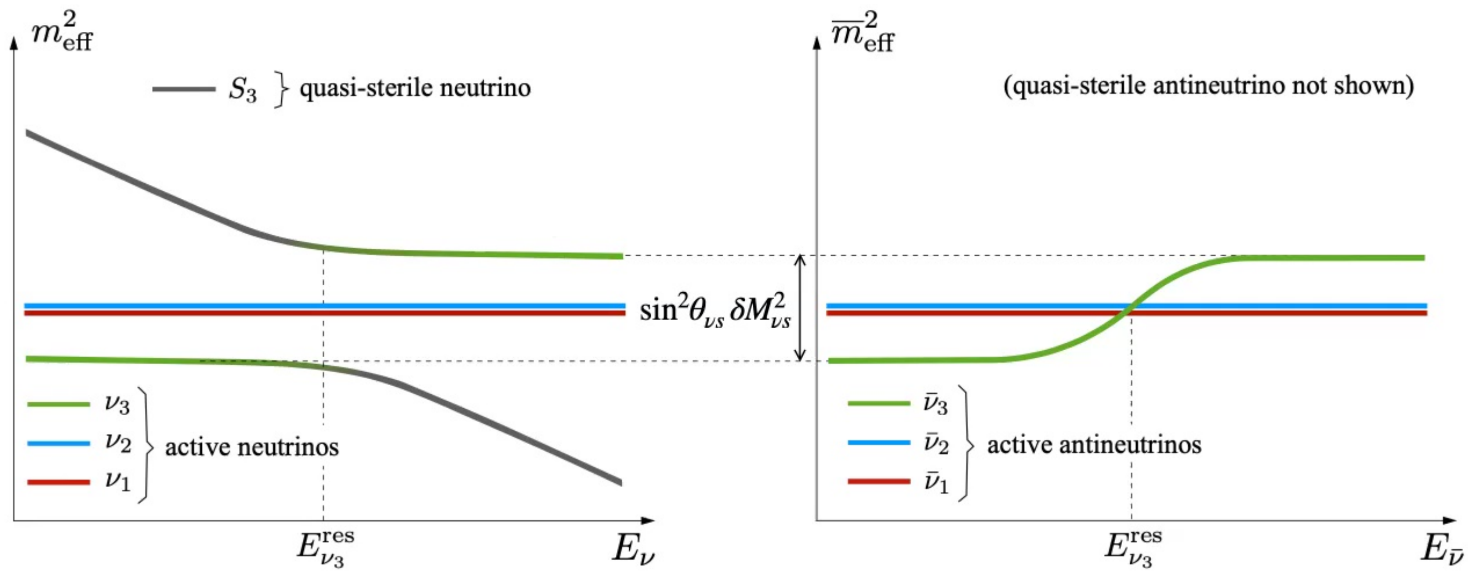
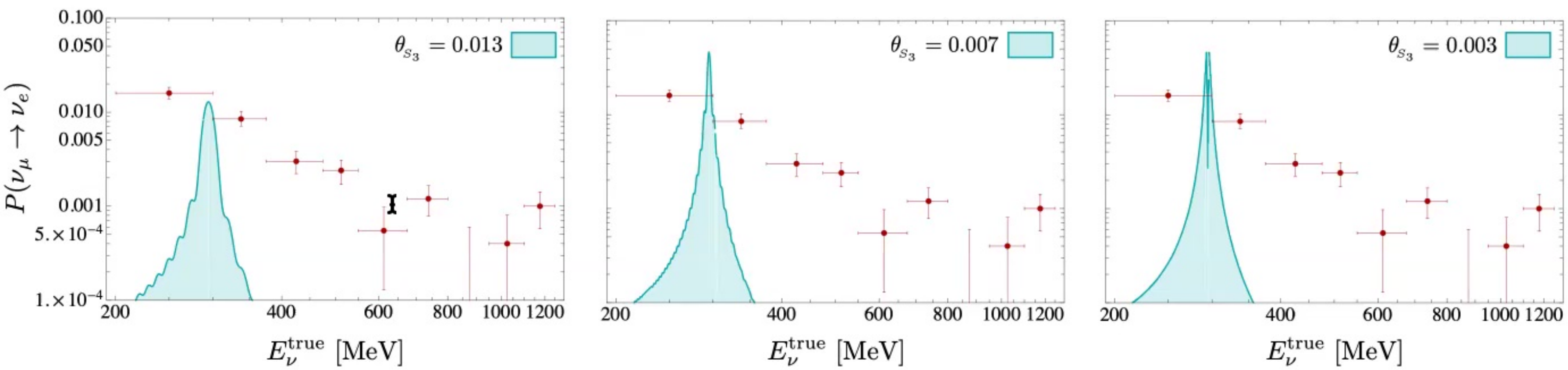


In order to preserve the active neutrino spectrum at high energies, we need:

$\sin^2\theta_{\nu s}\,\delta M^2_{\nu s} \sim 2\,\delta m^2_{32}$ $\Rightarrow$ this constrains the resonance region to be very narrow

Features of a very narrow resonance peak (toy model)

decreasing $\theta_{\nu s}$



- width of resonance is nearly independent of $\theta_{\nu s}$
- resonance peak is saturated at $P(\nu_\mu \to \nu_e)_{\rm max} = 4\,|U_{e3}|^2\,|U_{\mu 3}|^2$ once the active-sterile mixing angle $\theta_{\nu s}$ is below a critical value $\theta_{\nu s}^{\rm min}$

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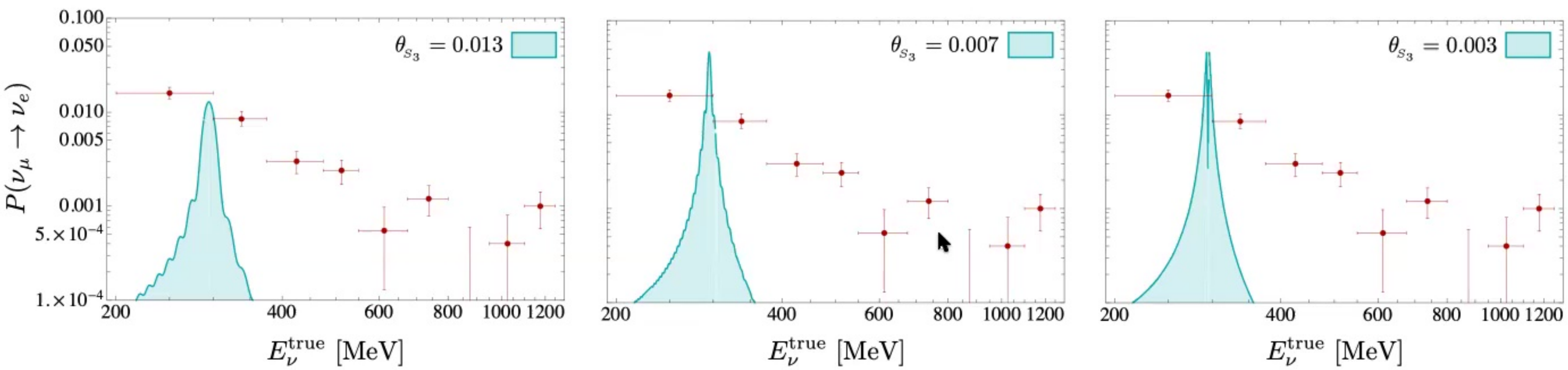

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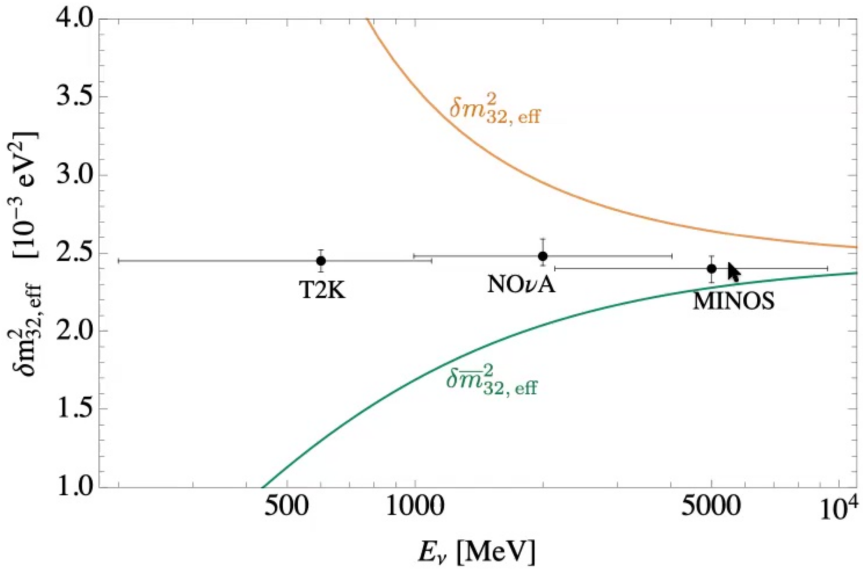

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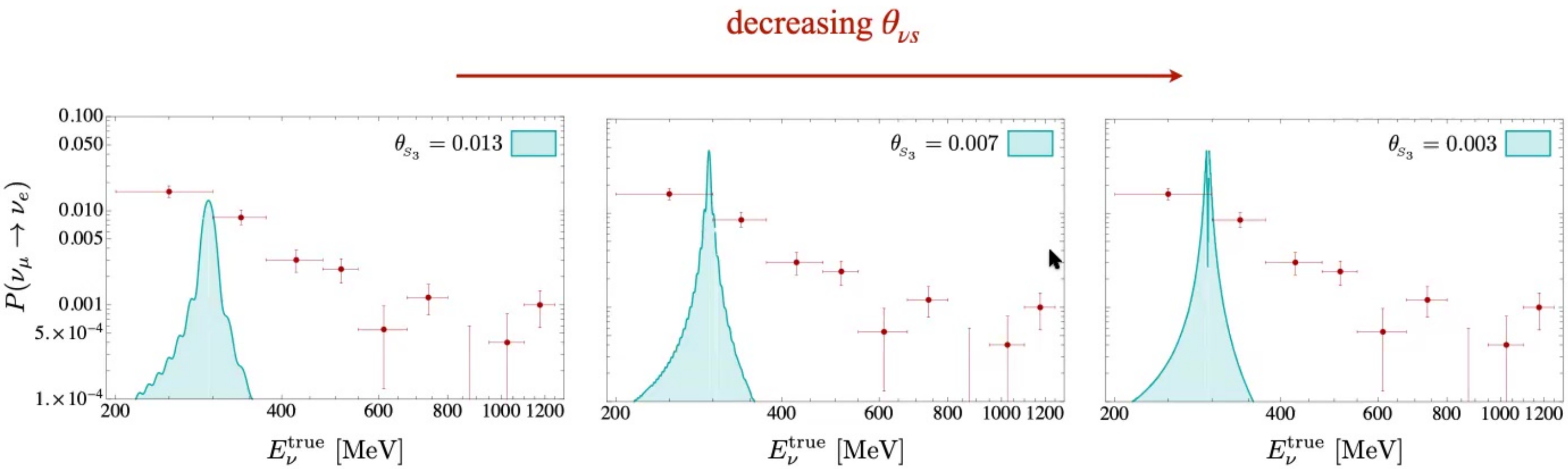

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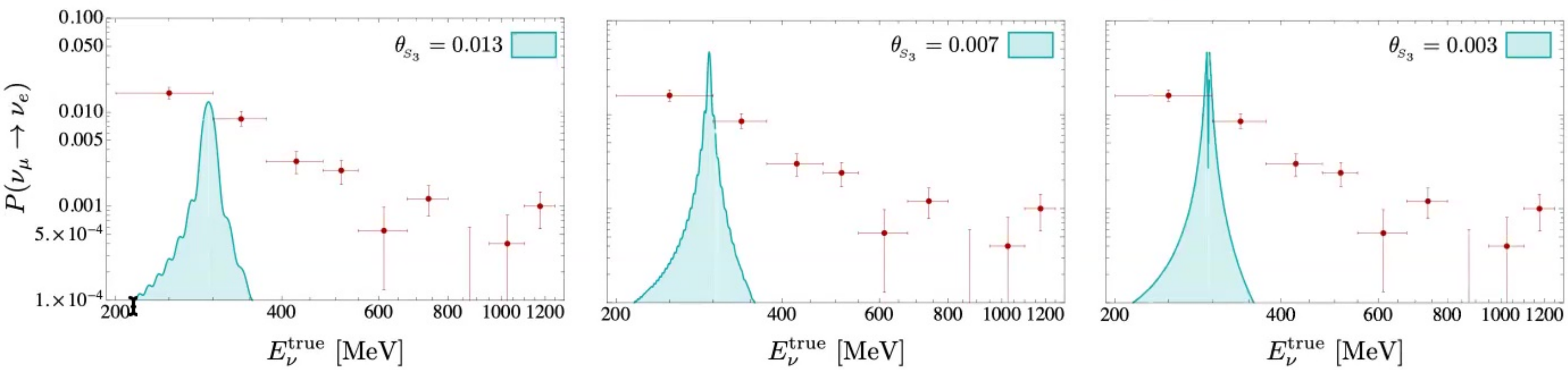

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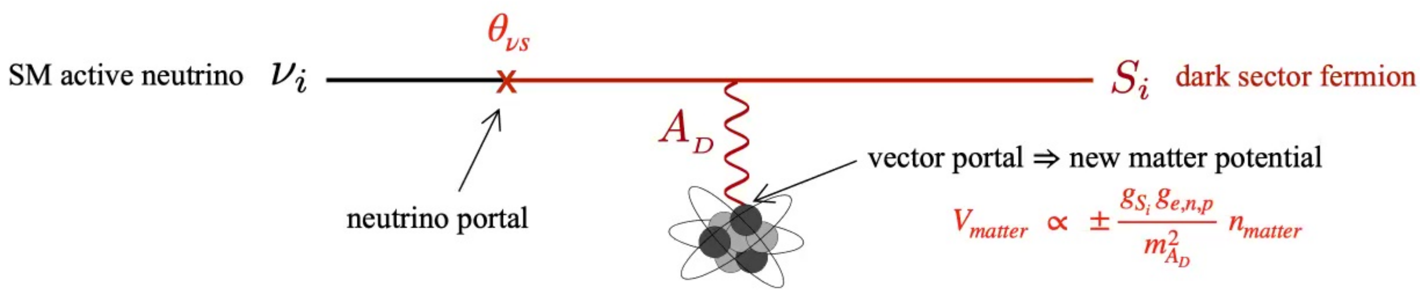

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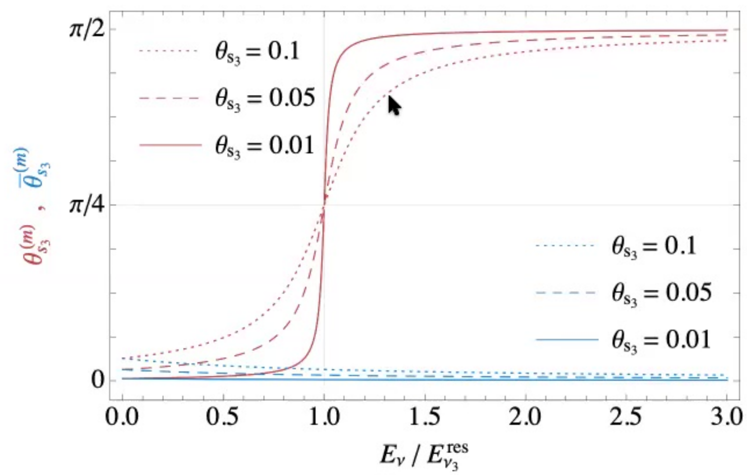

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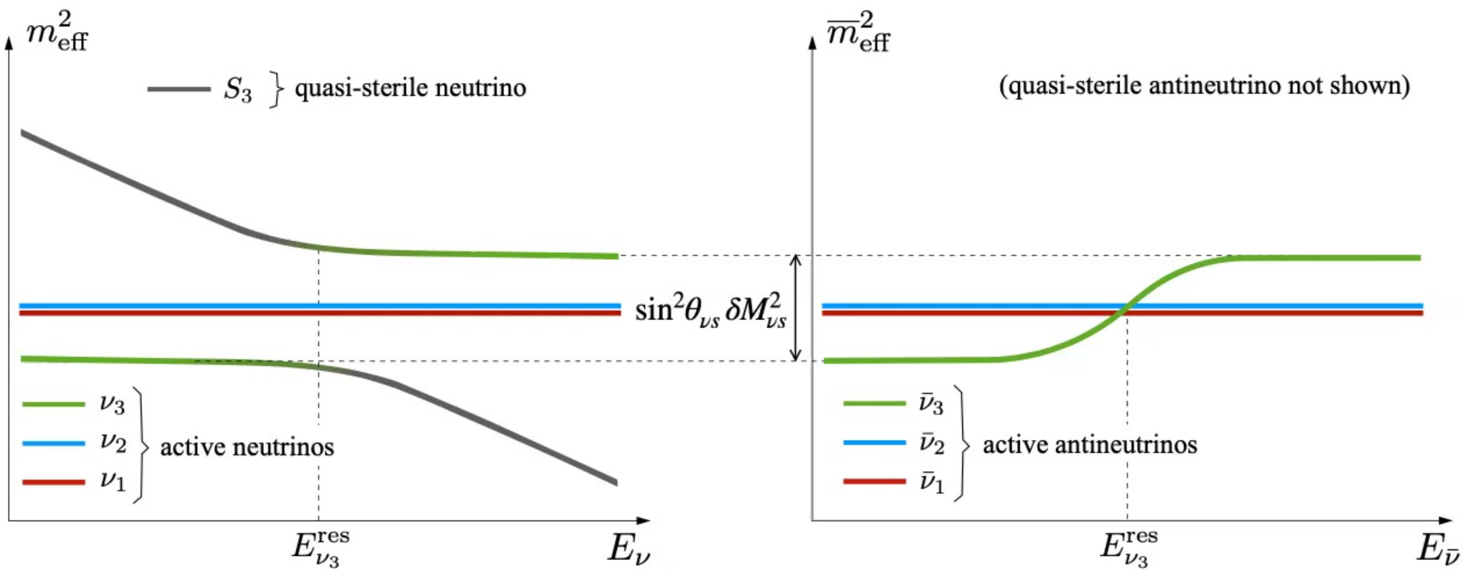

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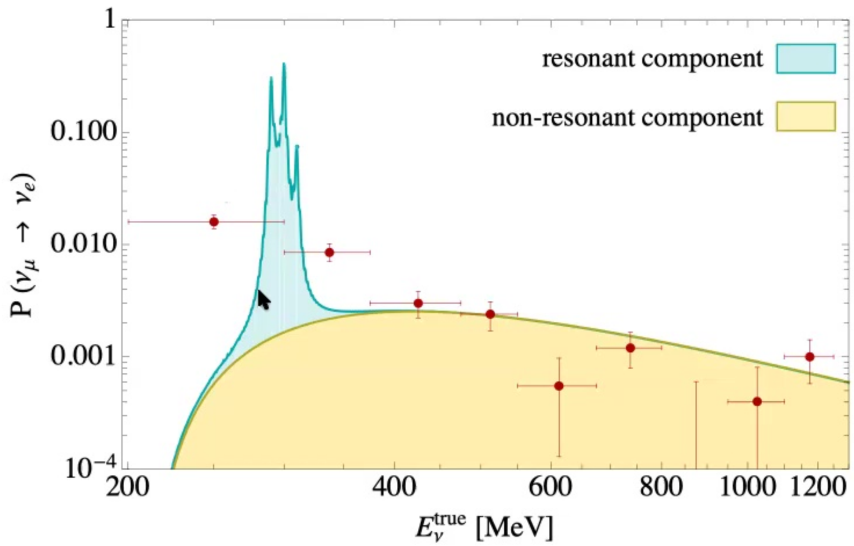
A 'Triple-Resonance' Model



1. Augment the quasi-sterile sector to 3 states (the participation of all three active neutrino species increases the strength of the resonance region)

2. Add a 'vanilla' 3+1 sterile neutrino to induce off-resonance $\nu_\mu \to \nu_e$ oscillations (and also explain $\bar{\nu}_\mu \to \bar{\nu}_e$ and $\bar{\nu}_e \not\to \bar{\nu}_e$ anomalies)

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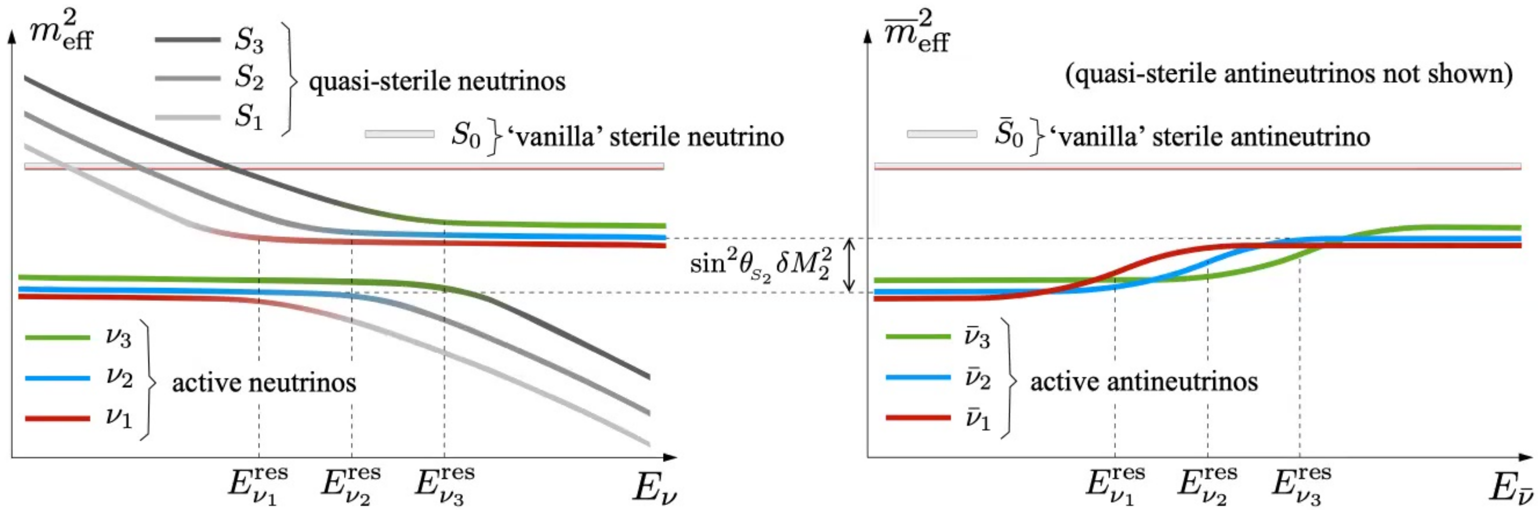

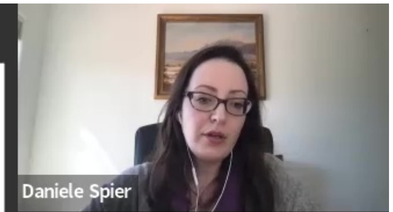

3. Bring the three resonant energies close together to avoid large distortions of the active mass spectrum

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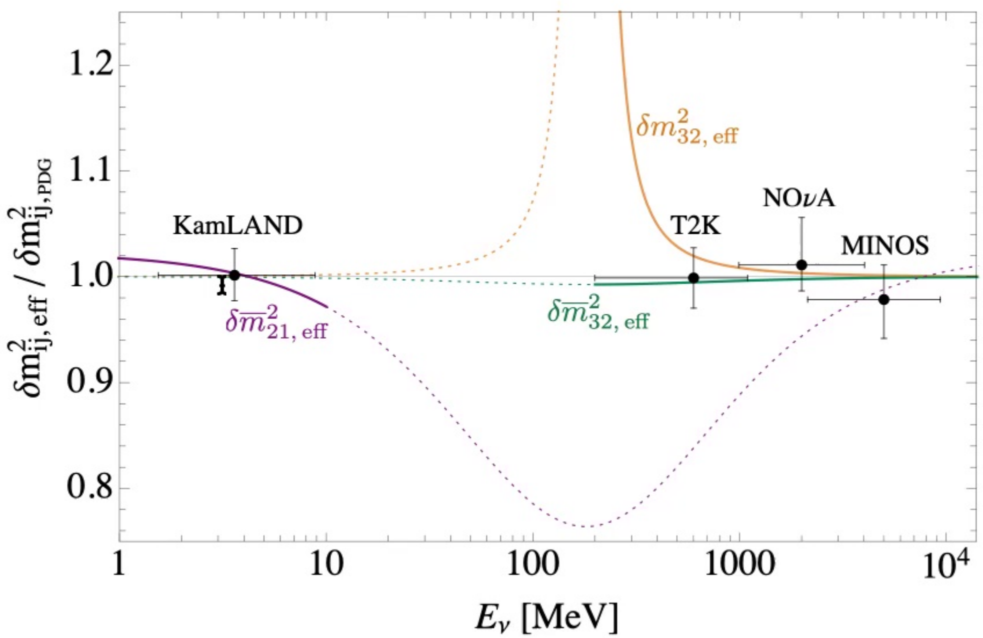
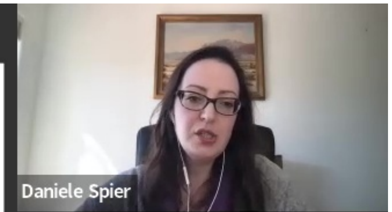




3. Bring the three resonant energies close together to avoid large distortions of the active mass spectrum

Because the resonant energy depends on the medium density,

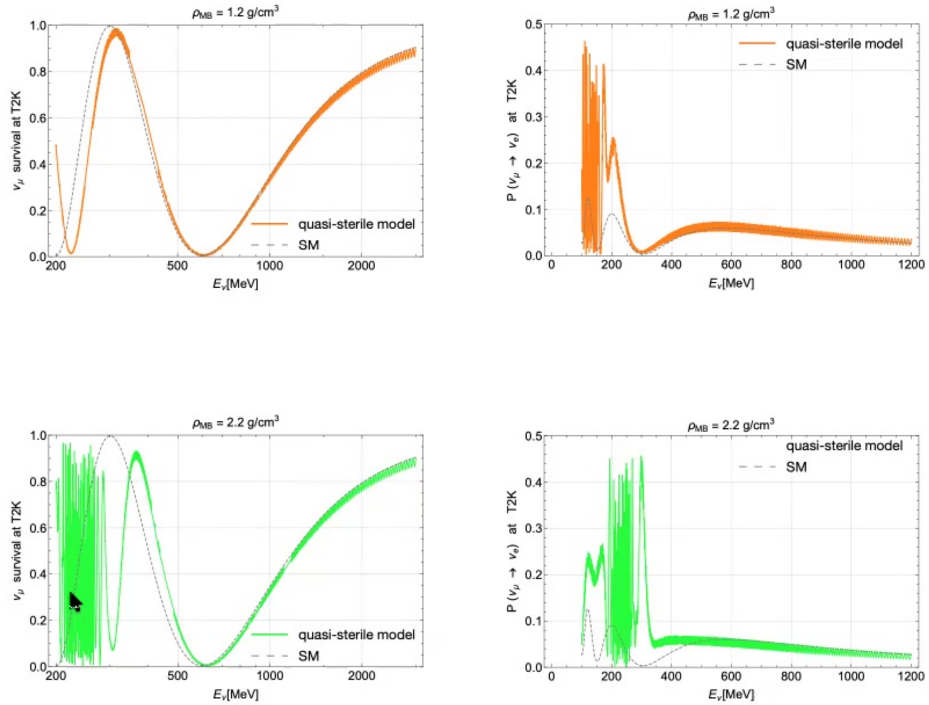
$$E_\nu^{res} = \frac{\delta M_{\nu s}^2 \cos 2\theta_{\nu s}}{2\, V_{matter}} \sim \frac{1}{\rho_{matter}},$$

the resonant energy at long-baselines is lower than at short baselines.
e.g.,

$$E_\nu^{\rm res}\big|_{\rm T2K} = E_\nu^{\rm res}\big|_{\rm MB} \frac{\rho_{\rm MB}}{\rho_{\rm T2K}}$$

$$\approx E_\nu^{\rm res}\big|_{\rm MB} \frac{[1.6-2.2]\ {\rm g/cm^3}}{2.6\ {\rm g/cm^3}}$$

$$\approx [180-250]\ {\rm MeV}$$



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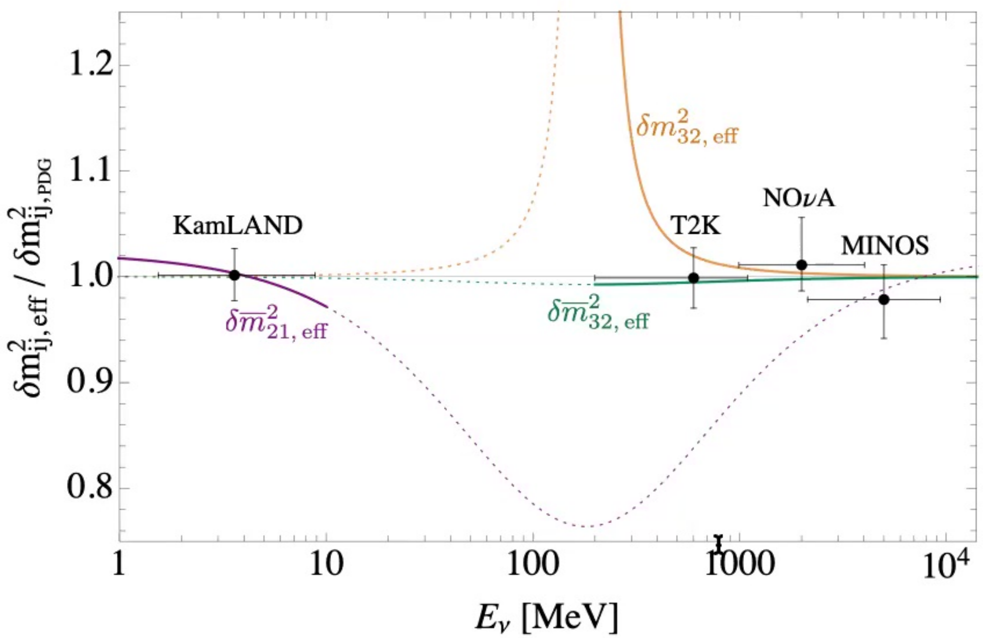

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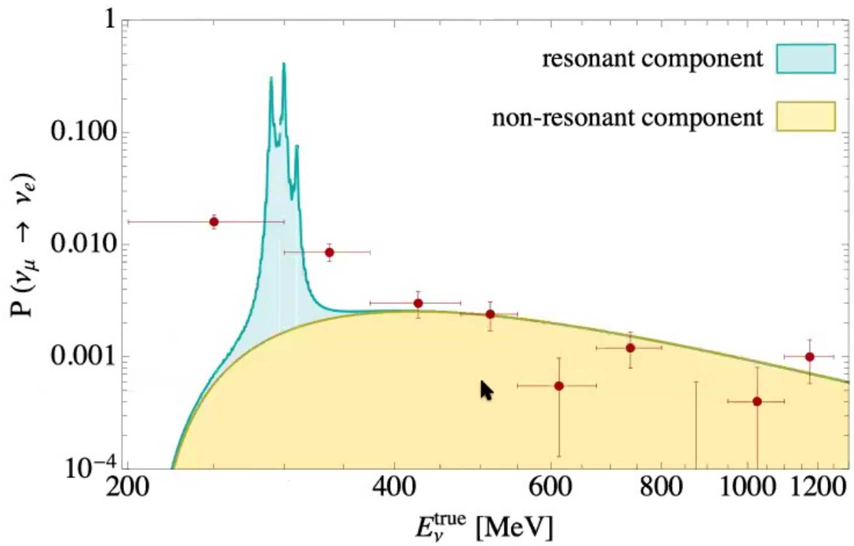

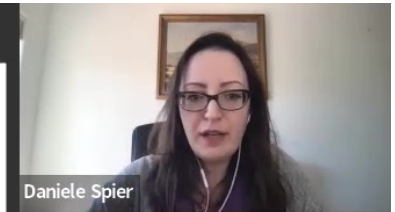

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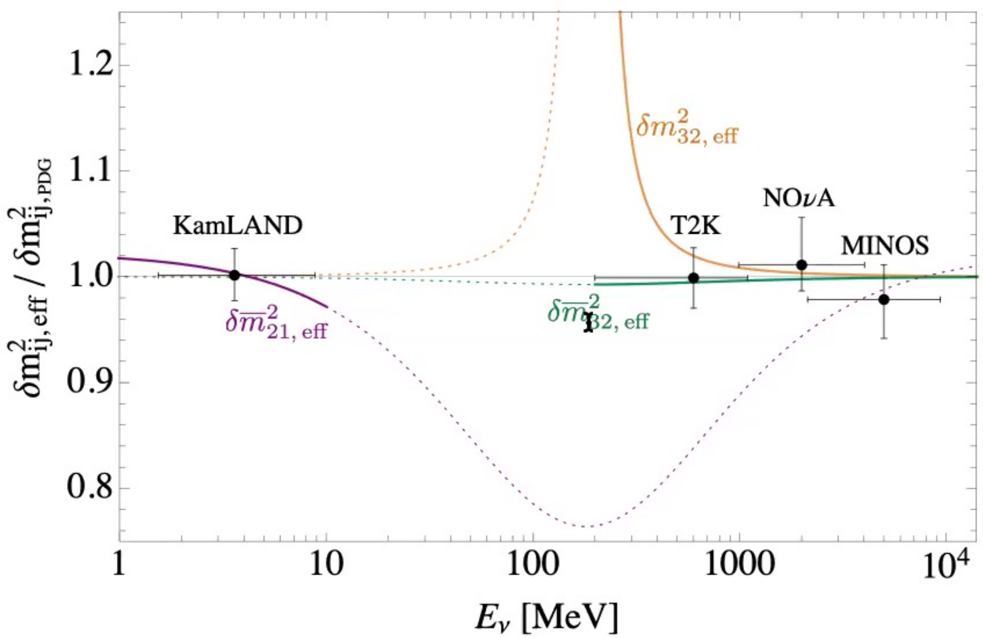

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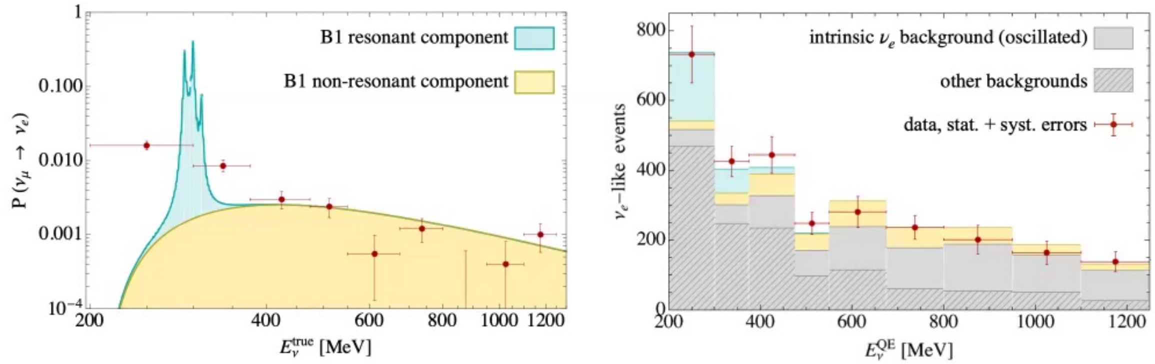
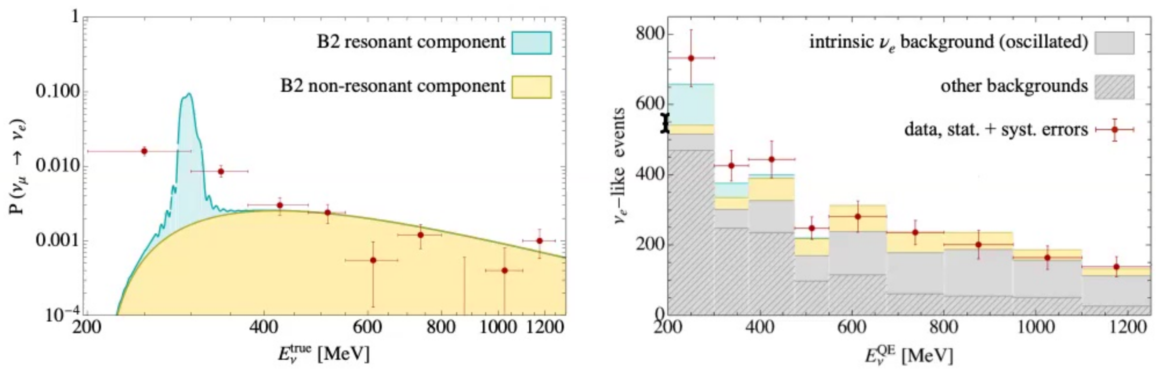
Two illustrative benchmarks

B1:

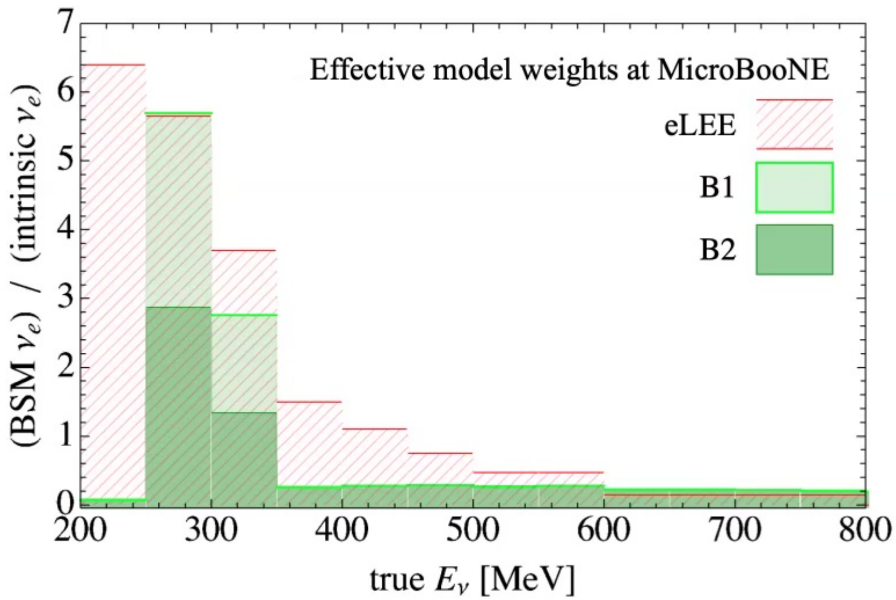


B2:



Compatibility with the recent MicroBooNE results

The flux ratio (BSM ν_e)/(intrinsic ν_e) differs significantly between the quasi-sterile models and the "eLEE" empirical model considered in the MicroBooNE analyses



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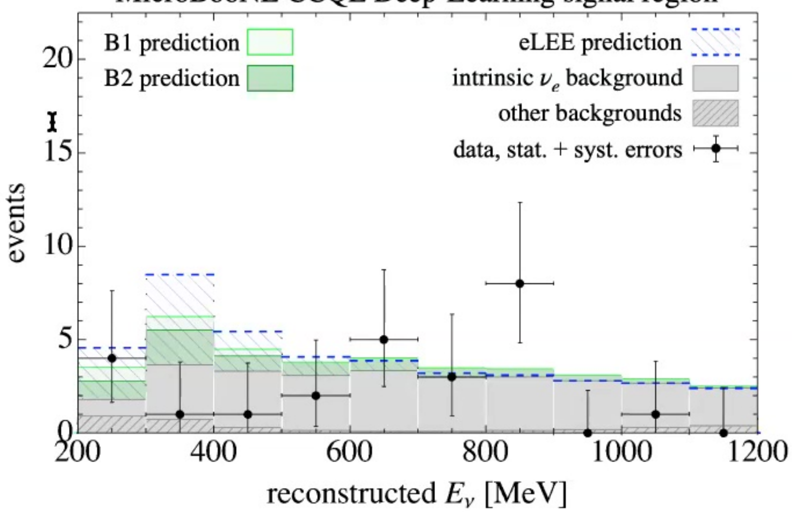
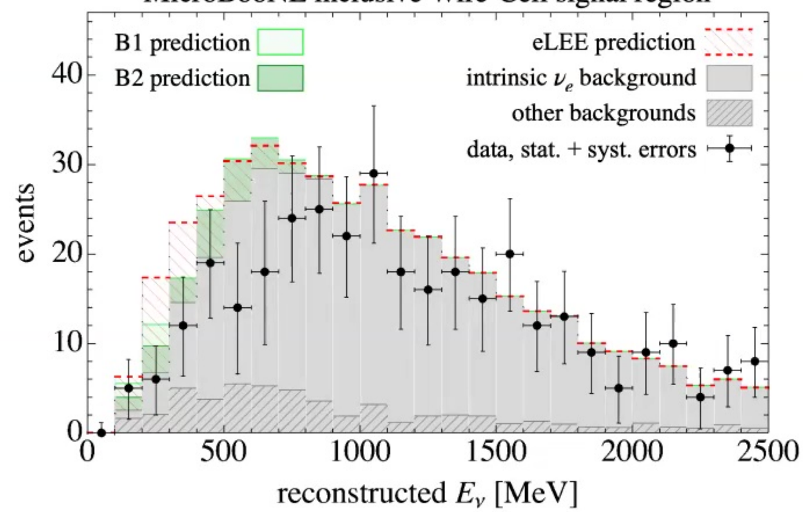
Expected rates at MicroBooNE from quasi-sterile model are *likely* compatible with (although not favored by) the recent MicroBooNE results

(p-values cannot be calculated without the proper covariance matrix, which cannot be built using current information in the public data releases)

MicroBooNE CCQE Deep-Learning signal region



MicroBooNE inclusive Wire-Cell signal region



Challenges to this quasi-sterile neutrino model

(with some work in progress)

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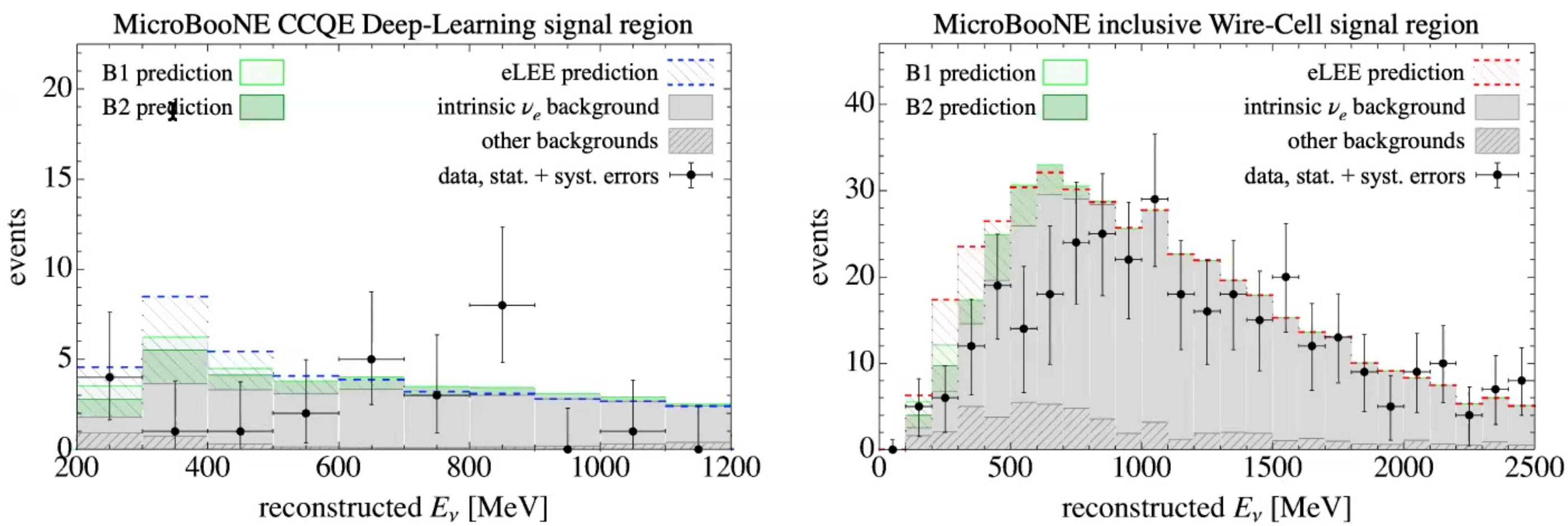

Matheus Hostert

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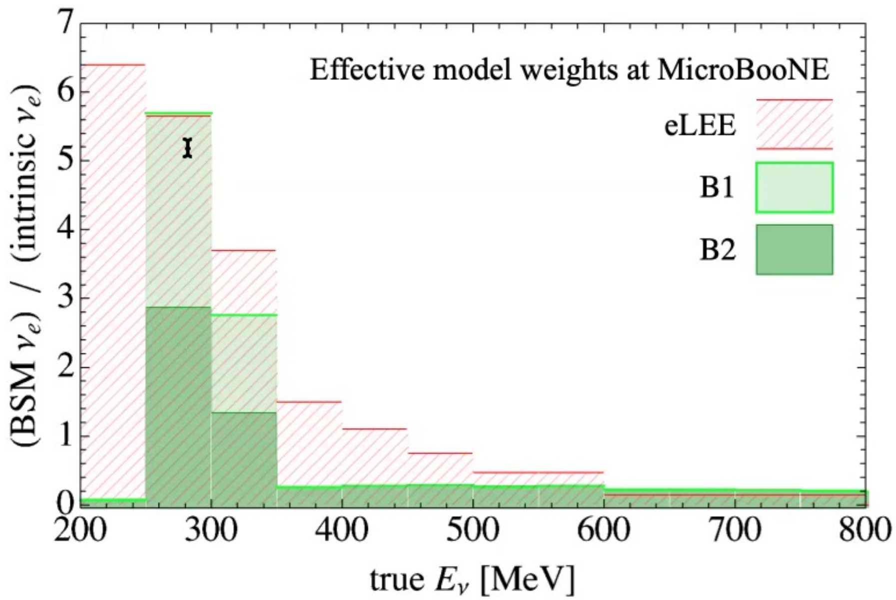

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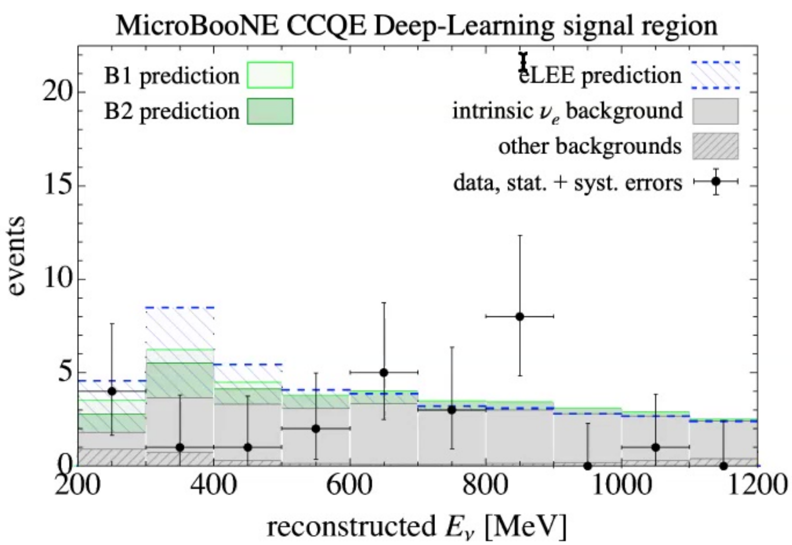
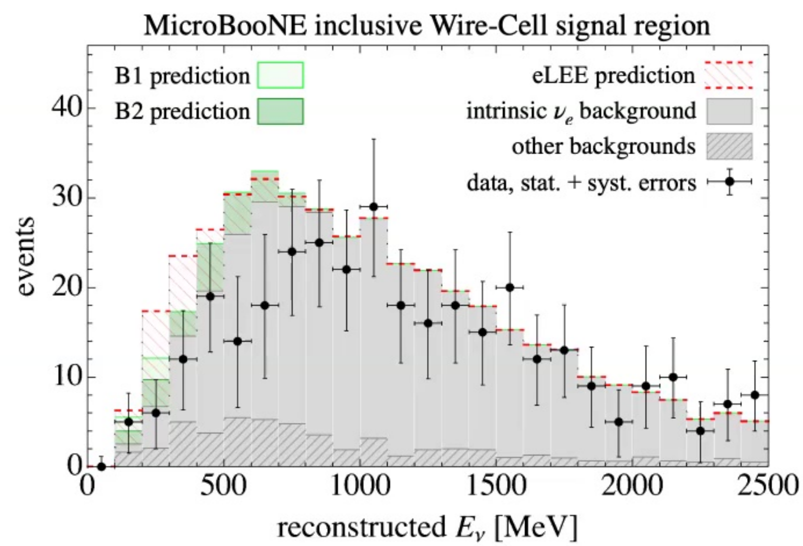
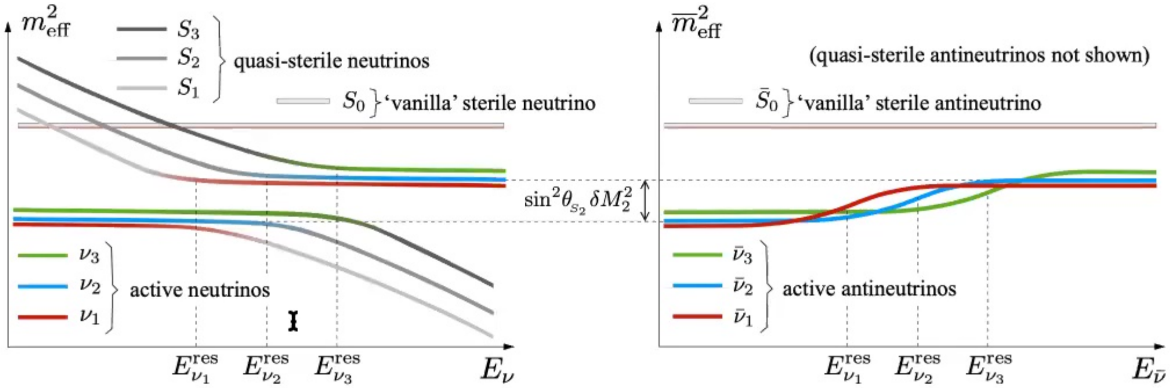




Challenges to this quasi-sterile neutrino model

(with some work in progress)

Challenges to this model: 1. tuning of active-quasisterile mixing



The matter-induced distortion of the active neutrino spectrum requires

(i) alignment with the Yukawa basis, and

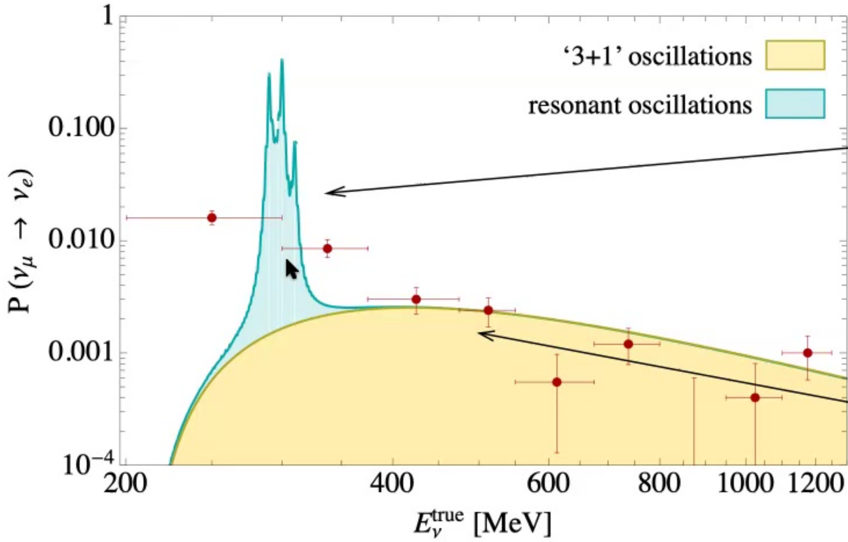
(ii) the same high energy shift for all three species to within ~5%, *i.e.*,

$$\sin^2\theta_{S_1}\,\delta M_1^2 \;\approx\; \sin^2\theta_{S_2}\,\delta M_2^2 \;\approx\; \sin^2\theta_{S_3}\,\delta M_3^2 \;\approx\; \mathcal{O}(1-10)\times|\delta m^2_{32}|$$

Could be the result of *ad hoc* fine-tuning, or some global symmetry in the Yukawa sector:

$$m_i^{(\rm mix)} \;\approx\; \sin\theta_{S_i}\,M_i$$

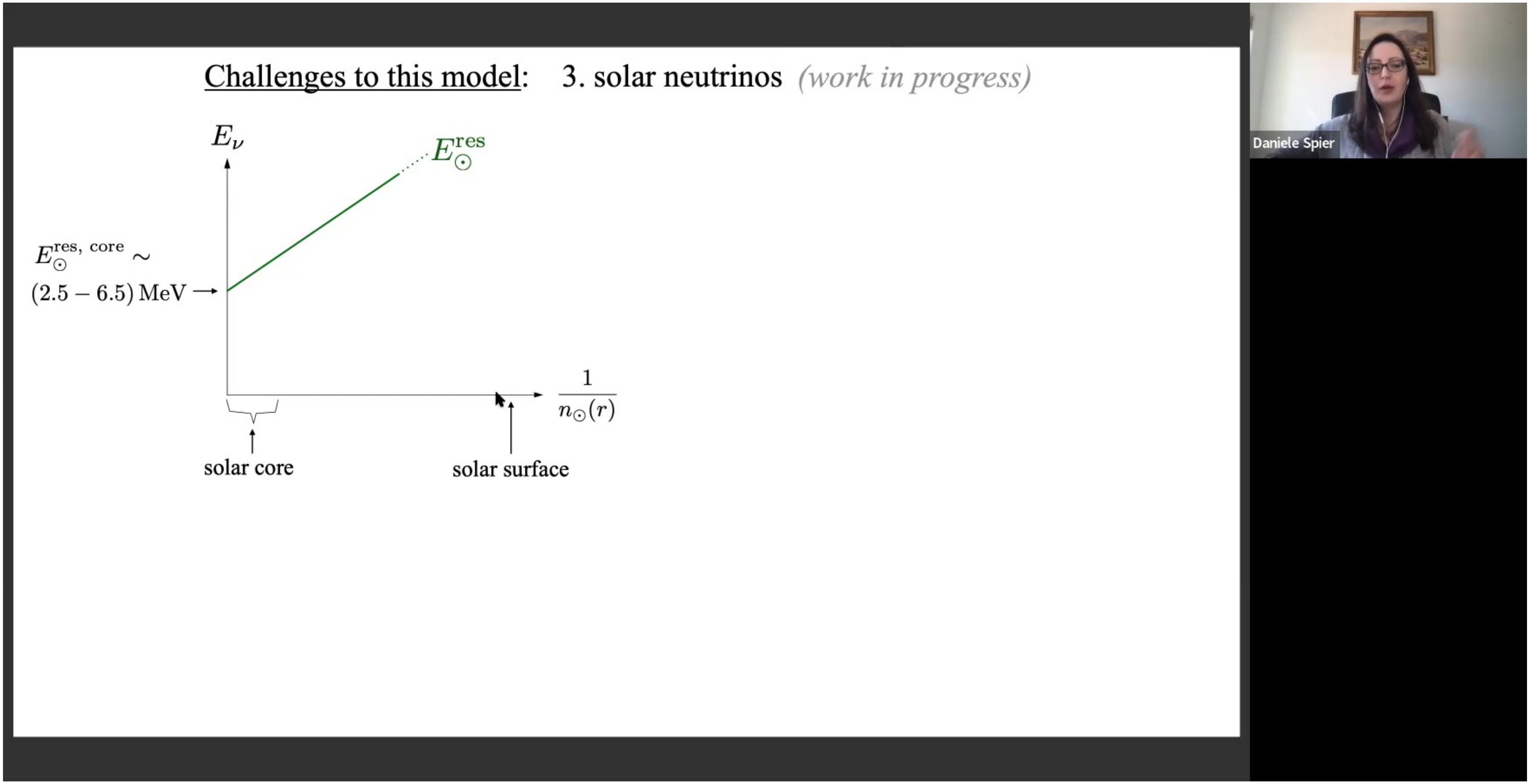
Challenges to this model: 2. the MiniBooNE excess coincidence



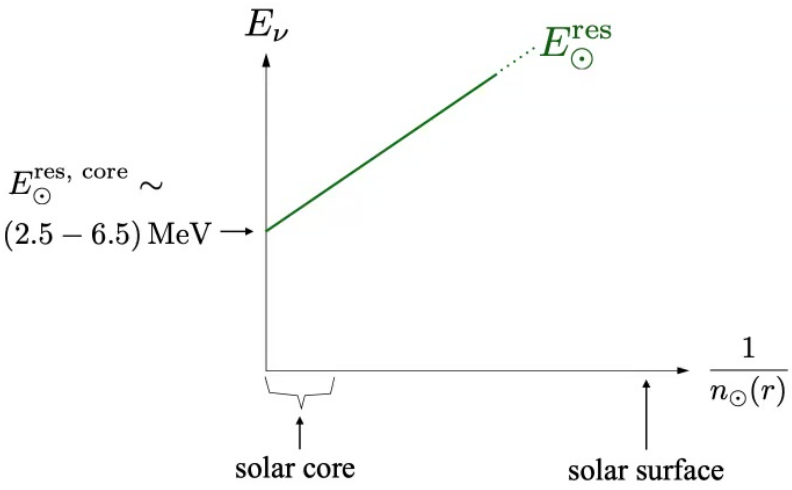
depends on active-quasi-sterile mass splitting and matter potential (mediator's mass and couplings, matter density along MB's beam-line)

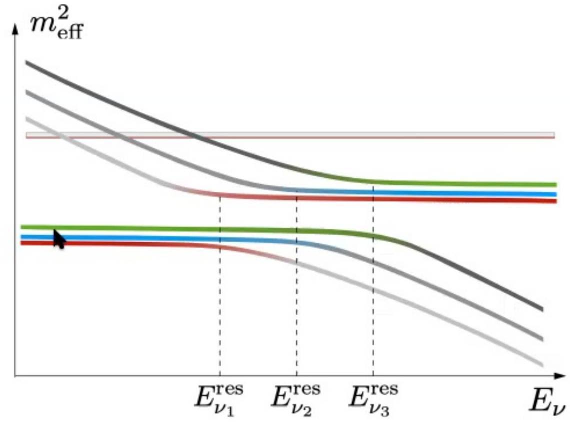
depends on active-'vanilla'-sterile mass splitting and mixing angle

MiniBooNE excess coincidence: the resonant and non-resonant mechanisms, which are unrelated, happen to produce $\nu_\mu \to \nu_e$ excesses at MiniBooNE in the same energy window.


Challenges to this model: 3. solar neutrinos (work in progress)
E_ν
$E_\odot^{\rm res}$
$E_\odot^{\rm res,\ core} \sim$
$(2.5 - 6.5)\,{\rm MeV}$
$\frac{1}{n_\odot(r)}$
solar core
solar surface
Daniele Spier

Challenges to this model: 3. solar neutrinos *(work in progress)*





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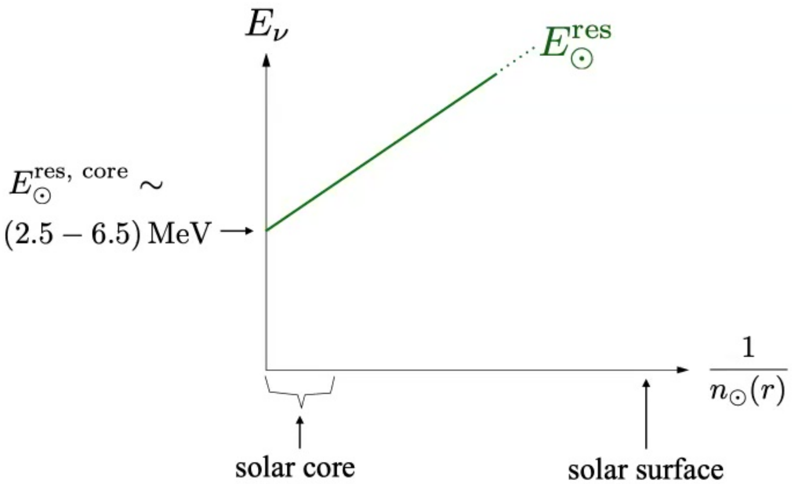

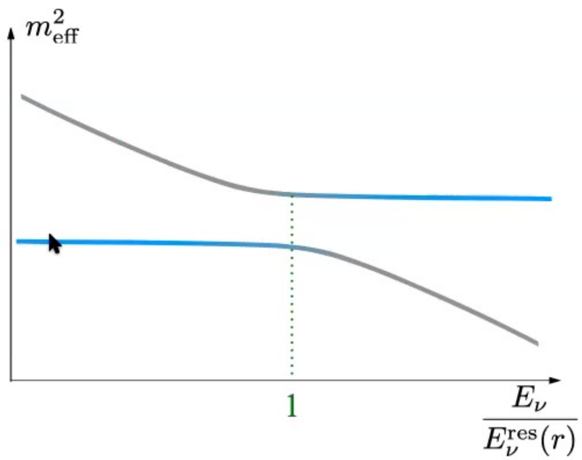

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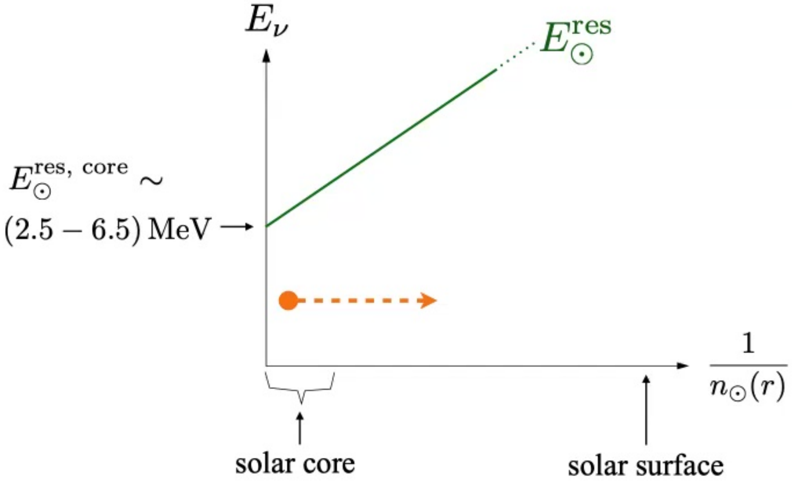

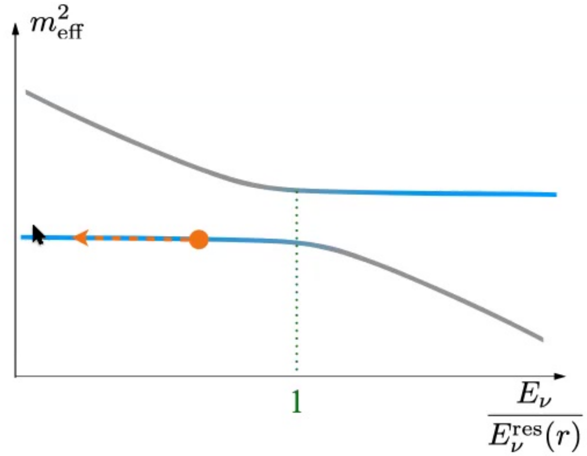

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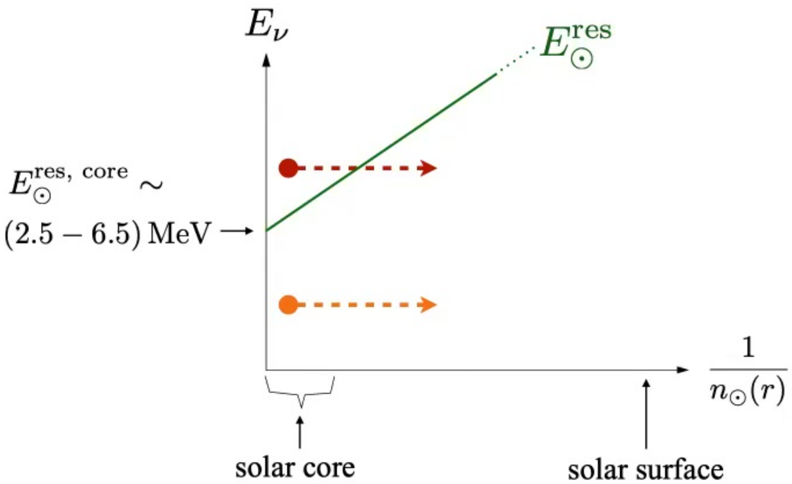
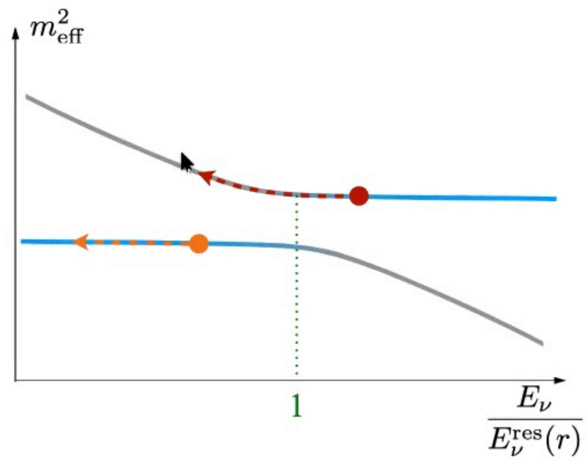


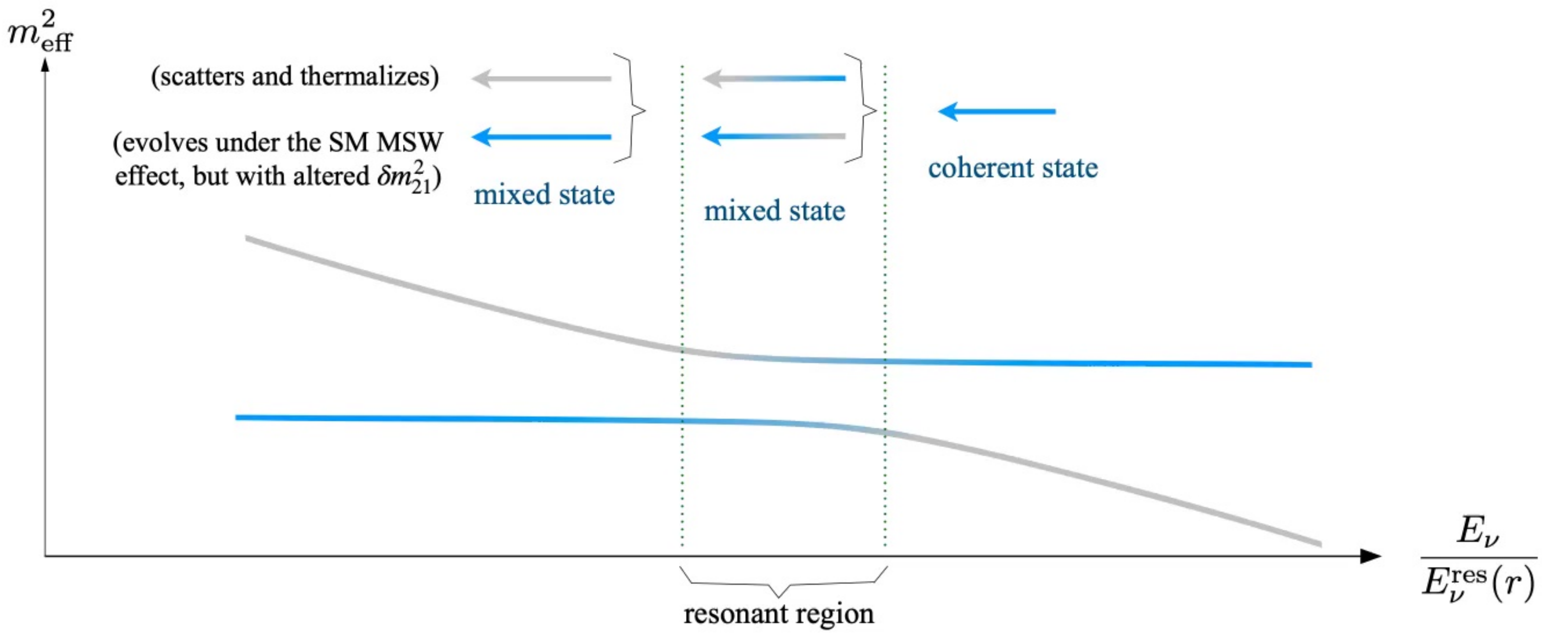


If adiabaticity and coherence are preserved during the solar neutrinos' propagation through the sun, then all active neutrinos with $E_\nu > E_\odot^{\text{res, core}}$ will convert to quasi-sterile neutrinos $\Rightarrow$ *ruled-out*

Challenges to this model: 3. solar neutrinos *(work in progress)*

Possible mechanism to avoid this scenario:

Decoherence of active and quasi-sterile states during resonant region crossing due to the short mean-free-path of quasi-sterile component in the solar medium



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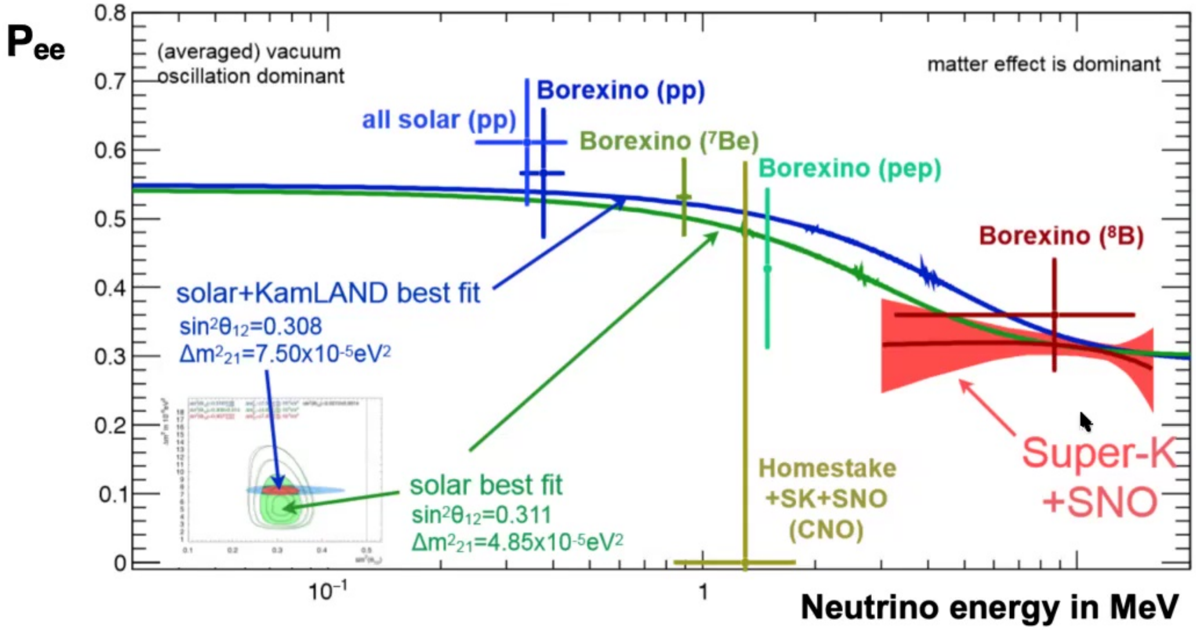
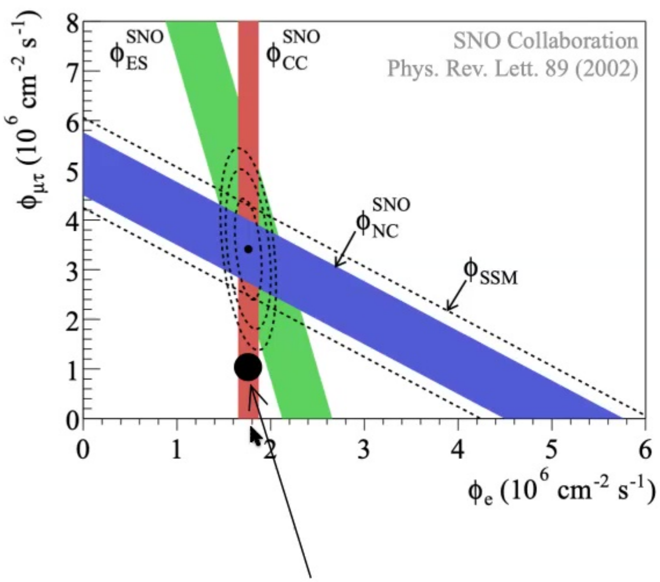


Challenges to this model: 3. solar neutrinos *(work in progress)*

One more issue: SNO has measured solar neutrino NC scattering via $\nu + D \rightarrow n + p + \nu$



Naively expected from quasi-sterile model due to loss of ^{8}B solar neutrino flux

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dark vector mediator contribution to
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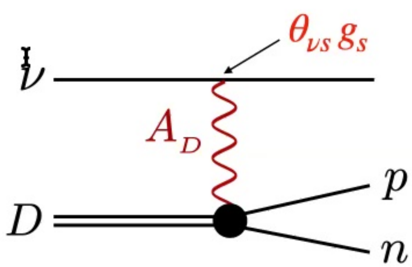
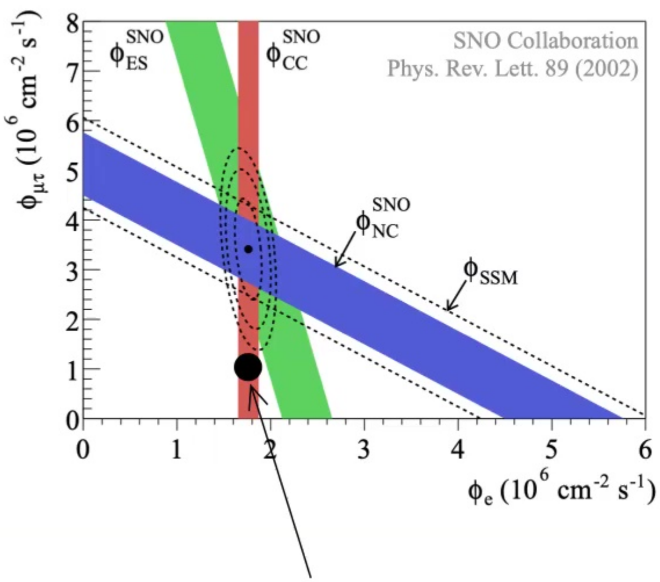
$$\sigma_{\rm NC}^{\rm BSM} \sim (0.3 - 1) \times \sigma_{\rm NC}^{\rm SM}\Big|_{E_\nu \sim \mathcal{O}(\rm MeV)}$$

$$\sim \mathcal{O}(10^{-45}\,{\rm cm}^2)$$





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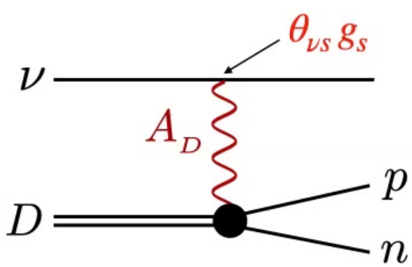

How viable is this possibility?

1. Need consistent dark mediator completion

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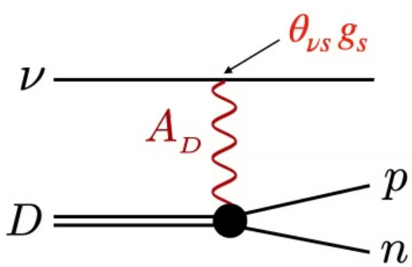

How viable is this possibility?

1. Need consistent dark mediator completion
2. BSM contribution to $\nu - N$ neutral scattering of $O(10^{-45}\,{\rm cm}^2)$ only significant in the low energy range of $E_\nu \lesssim O(10\,{\rm MeV})$
3. In the low energy range* of $E_\nu \lesssim \mathcal{O}(10\,{\rm MeV})$, the only measurements of this cross section were made by reactor experiments, $\bar{\nu}_e + D \to p + n + \bar{\nu}_e$, (Savannah River, ROVNO, Krasnoyarsk, Bugey) with ~20% precision

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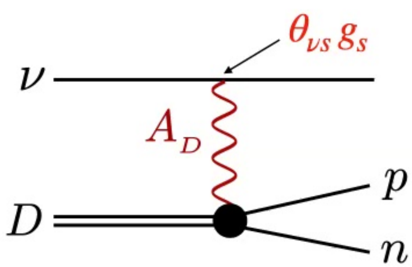

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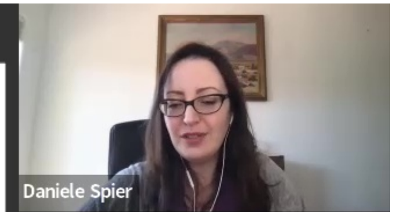
⇒ Significant tension with SNO NC measurements; existence of viable model is not likely.



Challenges to this model

1. tuning of active-quasi-sterile mixing
2. the MiniBooNE excess coincidence
3. solar neutrinos

Take away:

These challenges are significant obstacles to the viability of quasi-sterile neutrino models explaining the MiniBooNE low energy excess

However, they provide a good illustration of how generic consequences of light dark sectors, such as neutrino+vector portals, can be non-trivially constrained by neutrino data, since generically such models lead to:

- significant distortions of the active neutrino mixing and mass spectrum, even in energy regimes far away from the resonance region
- New matter effects, and therefore non-trivial implications for solar neutrinos