MANCHESTER
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STATUS OF GLOBAL FITS TO STERILE NEUTRINOS

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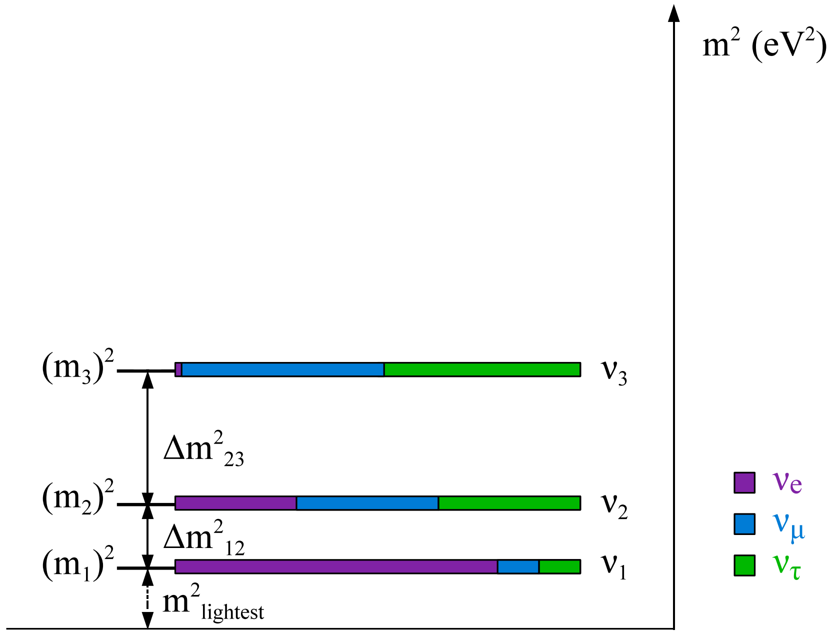
(Light) sterile neutrinos: Framework

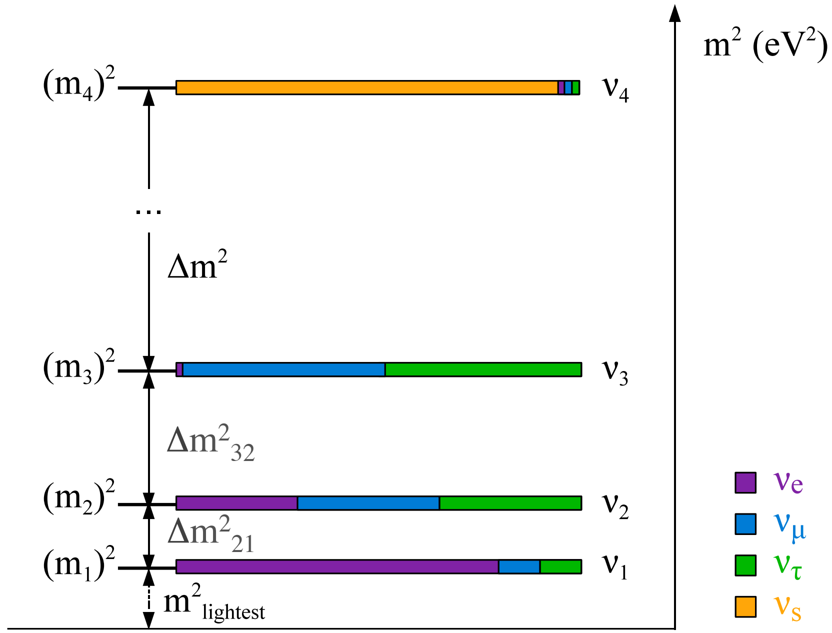
- Phenomenology framework: e.g. 3+1

Three neutrinos:
(e.g. NORMAL hierarchy)



"just 3"

With sterile neutrinos:

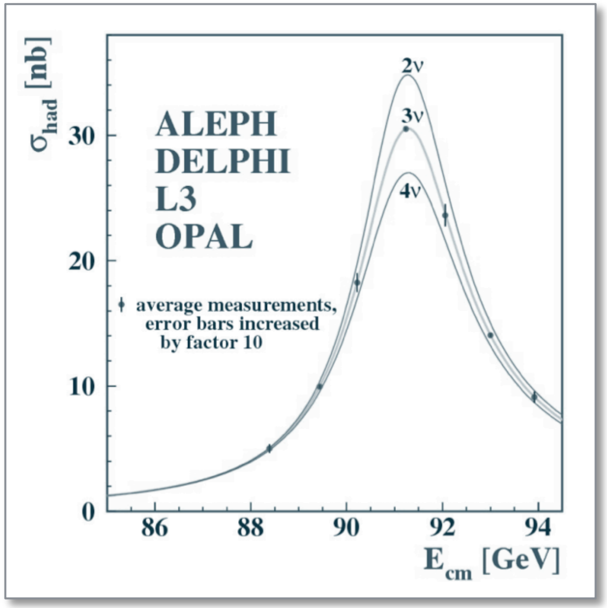


"3+1"

(Light) sterile neutrinos: Framework

- Phenomenology framework: e.g. 3+1

ν_4 is light enough ($<m_Z/2$) to be produced in **Z decay**



$$\Gamma_{\nu\bar{\nu}} = \sum_{i,j} \Gamma[Z \to \nu_i \bar{\nu}_j]$$

$$= \sum_{i,j} \sum_{\alpha}^{active} U^*_{\alpha i} U_{\alpha j} \sum_{\beta}^{active} U_{\beta i} U^*_{\beta j}$$

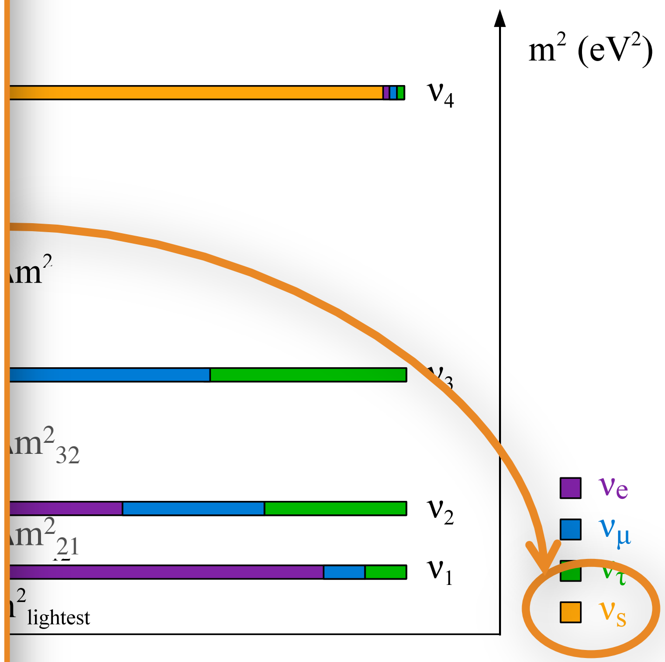
$$= \sum_{\alpha,\beta} \delta_{\alpha\beta}\delta_{\alpha\beta} = \sum_{\alpha=1}^{3} 1 = 3$$

$$N_\nu = \frac{\Gamma_{inv}}{\Gamma_\ell} \left(\frac{\Gamma_\ell}{\Gamma_\nu}\right)_{SM}$$

[Phys. Reports 427, 257 (2006)]

→ ν_s **does not couple to the Z ("sterile")**

terile neutrinos:



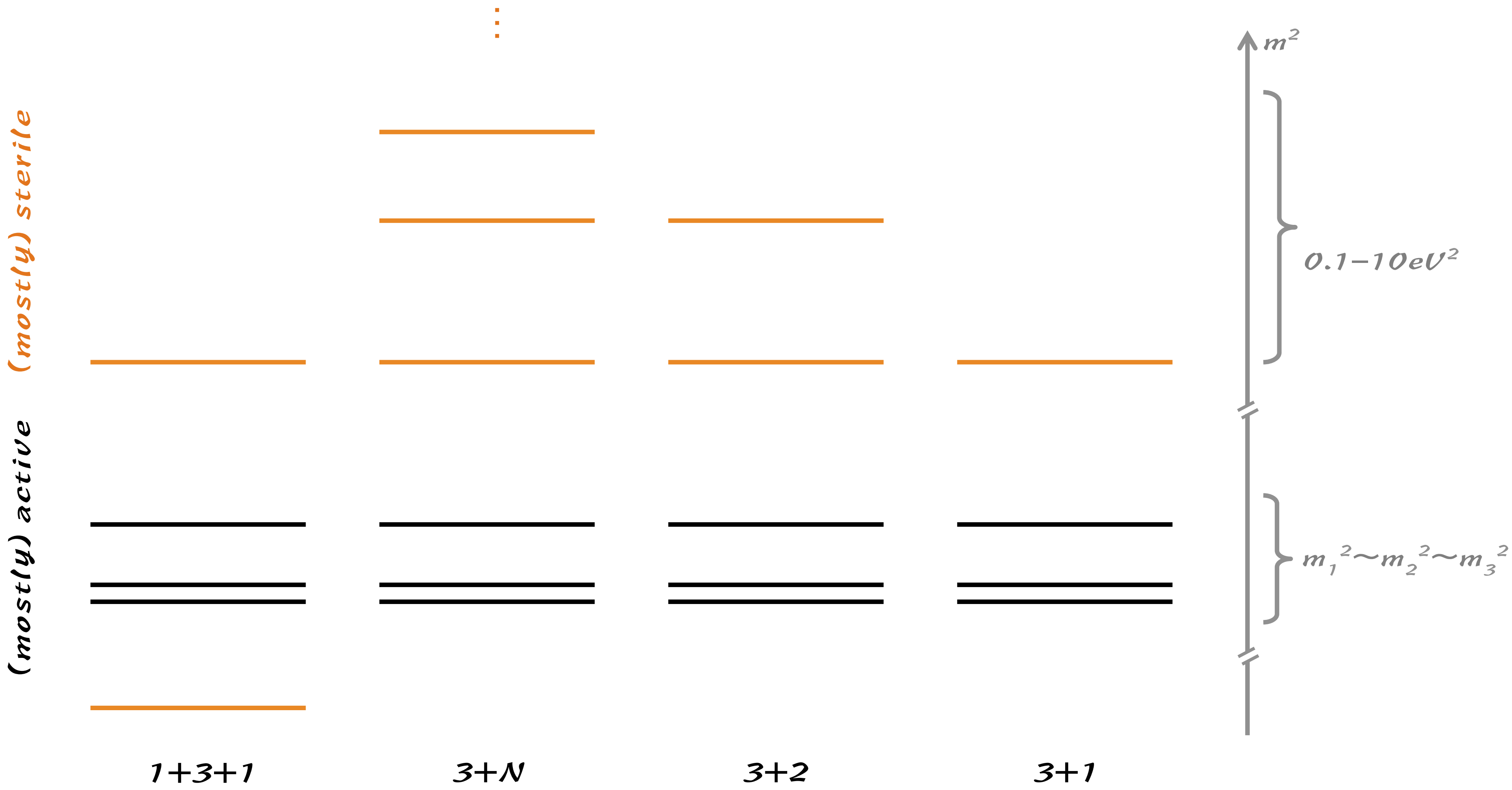
"3+1"

(Light) sterile neutrinos: Framework

- Mixing framework extended
  - 3x3 → (3+N)x(3+N) unitary mixing matrix
  - New CP phases
  - Matter effect must now account for lack of NC potential for ν_s
- More complex L/E signatures
  - Oscillations at "short baselines" ($\Delta m^2 \sim 1\ eV^2$ → L/E ~ 1km/GeV)
  - Additional matter effect resonances?
  - Additional parameter degeneracies at long baselines
- (Not in this talk:) Implications for early universe, astrophysical neutrino measurements, neutrinoless double beta decay…; opportunities for complementary measurements/constraints under certain assumptions

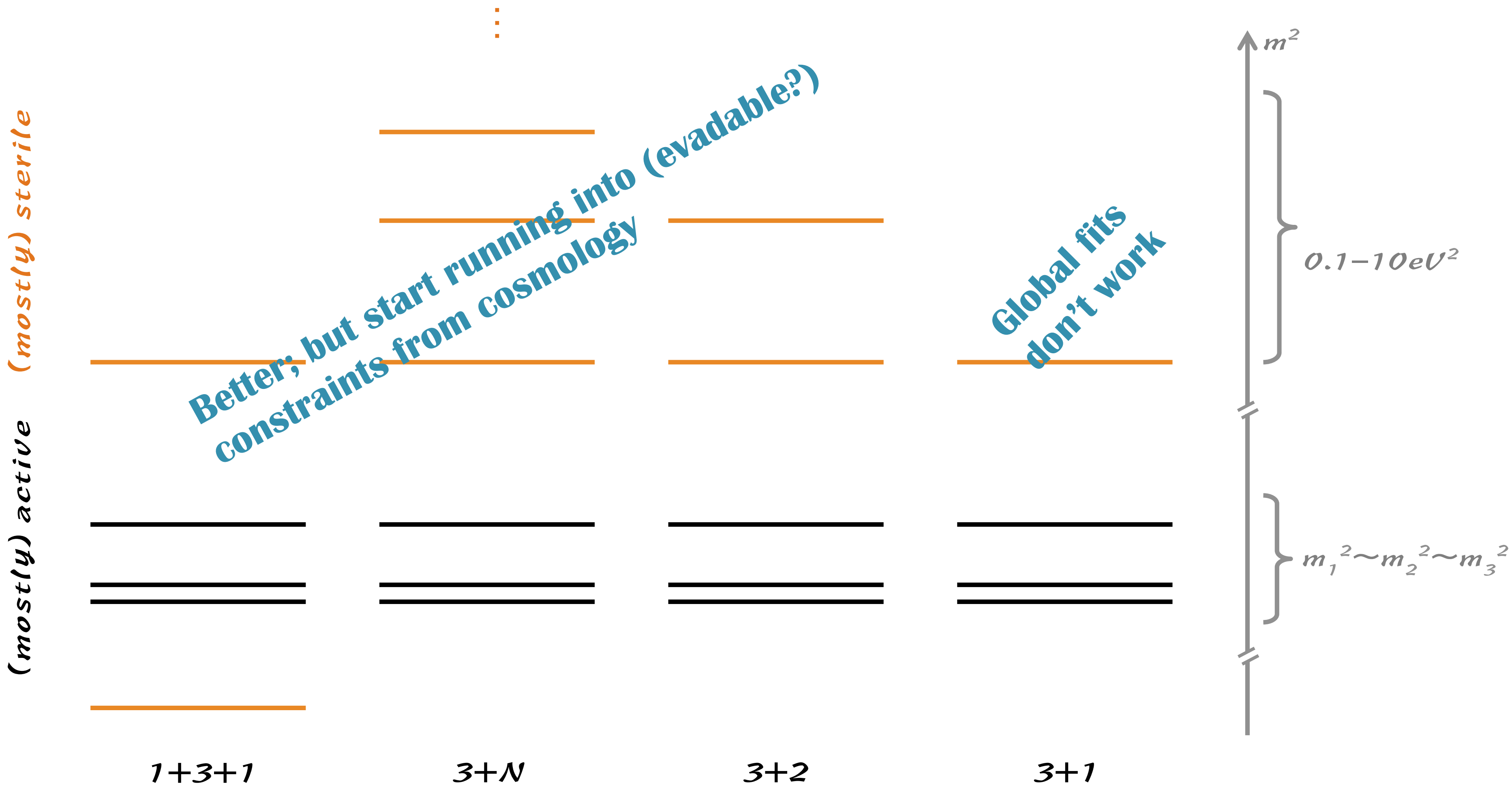
(Light) sterile neutrinos: Framework

- Phenomenology framework: e.g. 3+1, 3+2, 3+N, 1+3+1, …



(Light) sterile neutrinos: Framework

- Phenomenology framework: e.g. 3+1, 3+2, 3+N, 1+3+1, …



(Light) sterile neutrinos: Sources of constraints

- Constraints through oscillation signatures and unitarity
  - Best/direct: L/E-dependent oscillations at "short baselines". Can neglect contributions from solar and atmospheric oscillations ($\Delta m^2_{21} \sim \Delta m^2_{31} \sim \Delta m^2_{32} \sim 0$).

    E.g. 3+2:

$$P^{\mathrm{SBL},3+2}_{\nu_\alpha\to\nu_\beta} = 4\,|U_{\alpha4}|^2|U_{\beta4}|^2\,\sin^2\phi_{41} + 4\,|U_{\alpha5}|^2|U_{\beta5}|^2\,\sin^2\phi_{51} + 8\,|U_{\alpha4}U_{\beta4}U_{\alpha5}U_{\beta5}|\,\sin\phi_{41}\sin\phi_{51}\cos(\phi_{54}-\gamma_{\alpha\beta})\,,$$

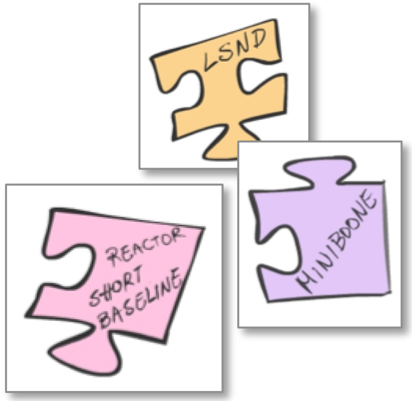
$$P^{\mathrm{SBL},3+2}_{\nu_\alpha\to\nu_\alpha} = 1 - 4\left(1-\sum_{i=4,5}|U_{\alpha i}|^2\right)\sum_{i=4,5}|U_{\alpha i}|^2\,\sin^2\phi_{i1} - 4\,|U_{\alpha4}|^2|U_{\alpha5}|^2\,\sin^2\phi_{54}\,.$$

$$\phi_{ij} \equiv \frac{\Delta m^2_{ij}L}{4E}\,, \qquad \gamma_{\alpha\beta} \equiv \arg\left(I_{\alpha\beta54}\right)\,, \qquad I_{\alpha\beta ij} \equiv U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\,.$$

$$\gamma_{\alpha\beta} \to -\gamma_{\alpha\beta} \quad \text{(neutrinos} \rightarrow \text{antineutrinos)}$$

  - Also:
    Flavor-dependent normalization effects at large L/E ($\sin^2(1.27\Delta m^2 L/E) \rightarrow ½$)
    Modified oscillations + matter effect at long baselines ($\Delta m^2_{21} \sim 0$)

(Light) sterile neutrinos: Motivation



~1-4 σ

- Experimental hints/evidence/anomalies
  - LSND ($\bar{\nu}_\mu \to \bar{\nu}_e$ at L/E ~ 1 km/GeV)
  - MiniBooNE ($\bar{\nu}_\mu \to \bar{\nu}_e$ and $\nu_\mu \to \nu_e$ at L/E ~ 1 km/GeV)
  - Radioactive source calibration measurements at Gallium experiments ($\nu_e \to \nu_{\not{e}}$ at L/E <~ 1 km/GeV)
  - Reactor (<100 m) short-baseline experiments?* ($\bar{\nu}_e \to \bar{\nu}_{\not{e}}$ at L/E ~ 1 km/GeV)

- Can naturally accommodate light sterile neutrinos in theoretical frameworks of neutrino mass

- Interesting, rich phenomenology

***Based on re-evaluation of absolute reactor neutrino fluxes. Interpretation as sterile neutrino oscillations is premature due to poorly understood flux systematic effects. Included here as a "best case scenario".**

(Light) sterile neutrinos: Recent global fit results

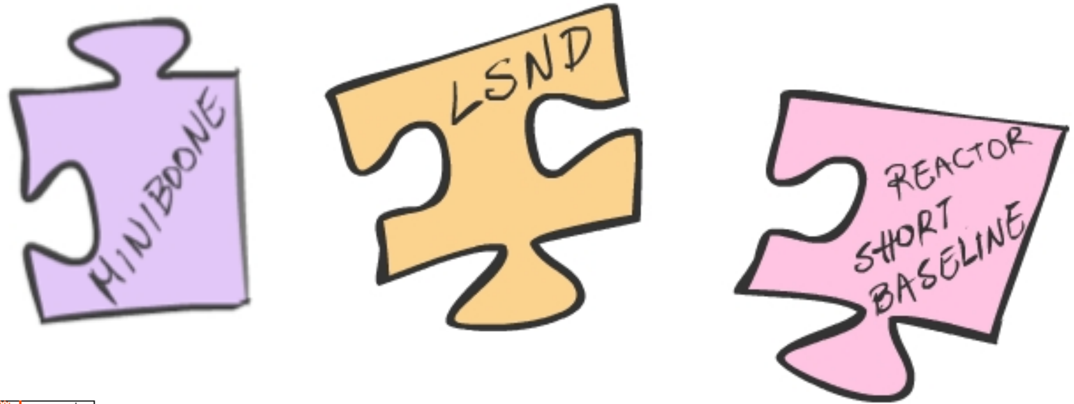
- This talk samples from past global fit analyses
  - [1] J. Kopp, P. A.N. Machado, M. Maltoni, T. Schwetz (arxiv:1303.3011)
  - [2] J. M. Conrad, C. M. Ignarra, G. K., M. H. Shaevitz, J. Spitz (arxiv:1207.4765)
  - (Apologies to others)

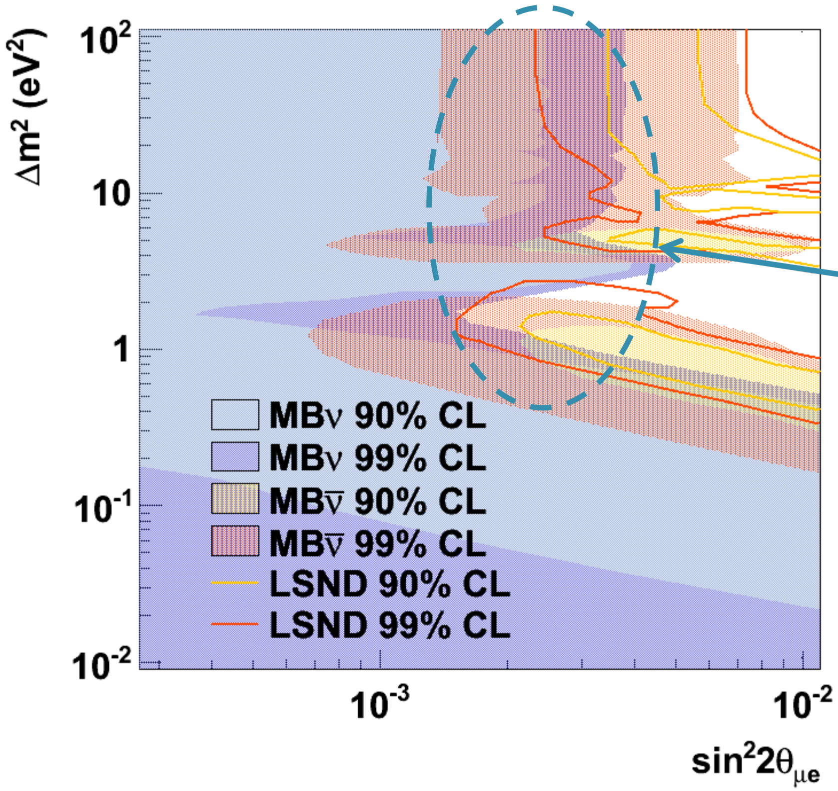
- Qualitative results of above global fit analyses are in agreement

- Some (small) quantitative differences… but see "caveats"

- Reactor anomaly arbitrarily assumed to be real; if the anomaly goes away, situation is slightly worse (constraints from both ν_e and ν_μ disappearance)

Q1: Can all three signatures be explained by a simple (3+1) sterile neutrino hypothesis?





Reactor short-baseline consistent with these values

A: *Yes...*

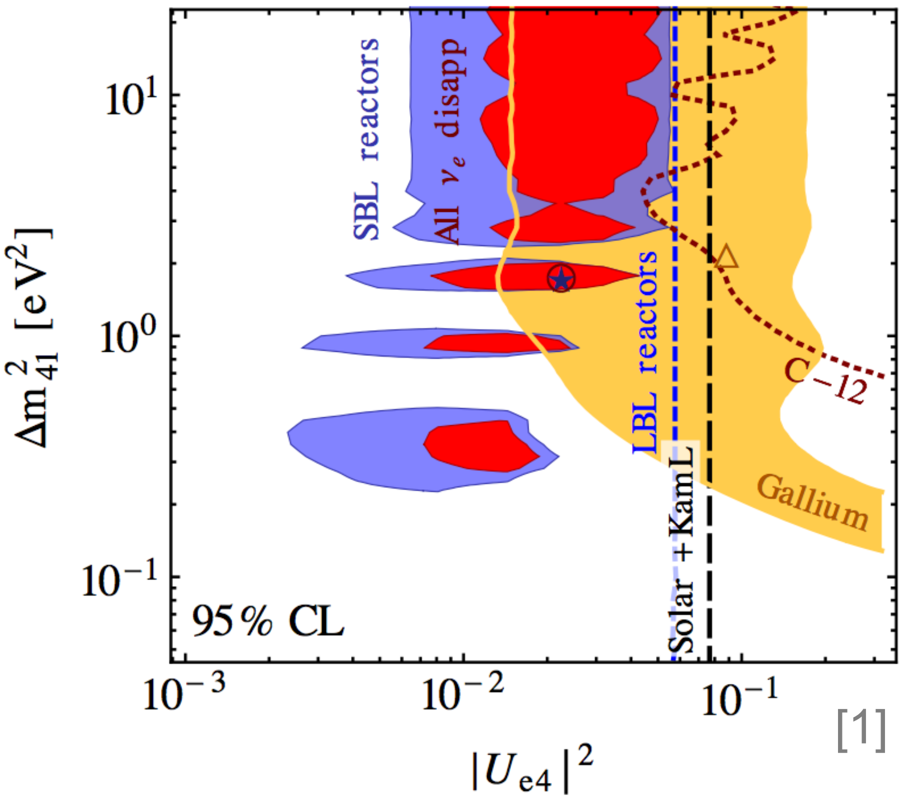
ν_e disappearance constraints: 3+1

- Bounds from reactor long-baseline and Solar+Kamland experiments as well as ν_e-C cross section measurements provide minimal constraints

- θ_{13} value from reactor long-baseline measurements insensitive to reactor anomaly

- ν_e disappearance data are consistent under 3+1

- No significant improvement from 3+1 to 3+2

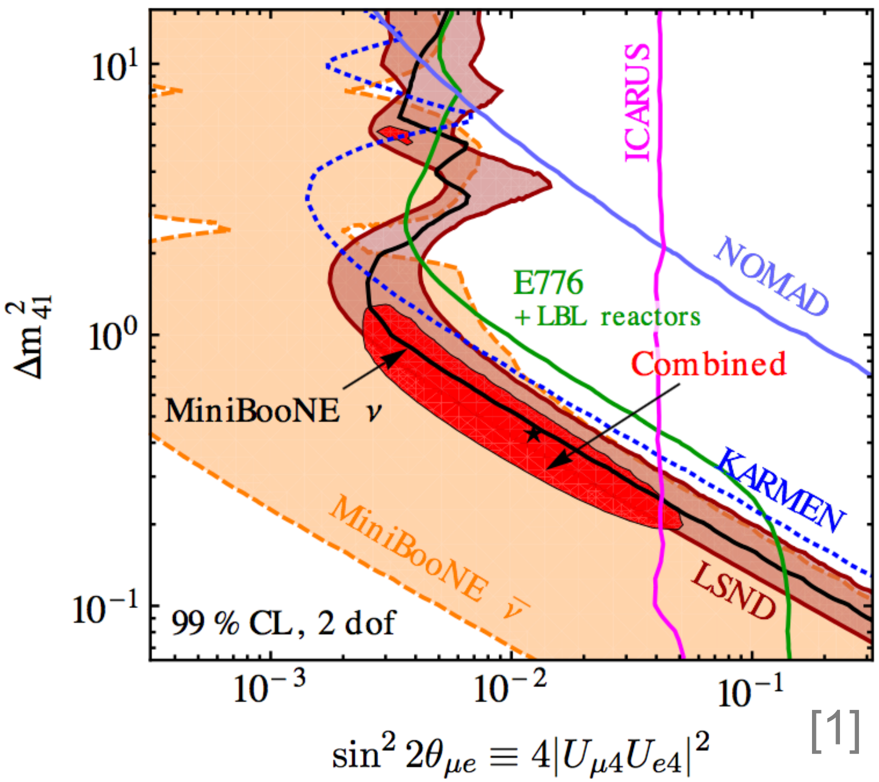


[1]

ν_e appearance constraints: 3+1

- Some tension due to MiniBooNE neutrino mode results (upper bound)
- KARMEN constrains much of the higher Δm^2 space
- ICARUS constrains the lower Δm^2 range

- ν_e appearance data are consistent under 3+1
- Significant improvement in going to 3+2, due to CP violation

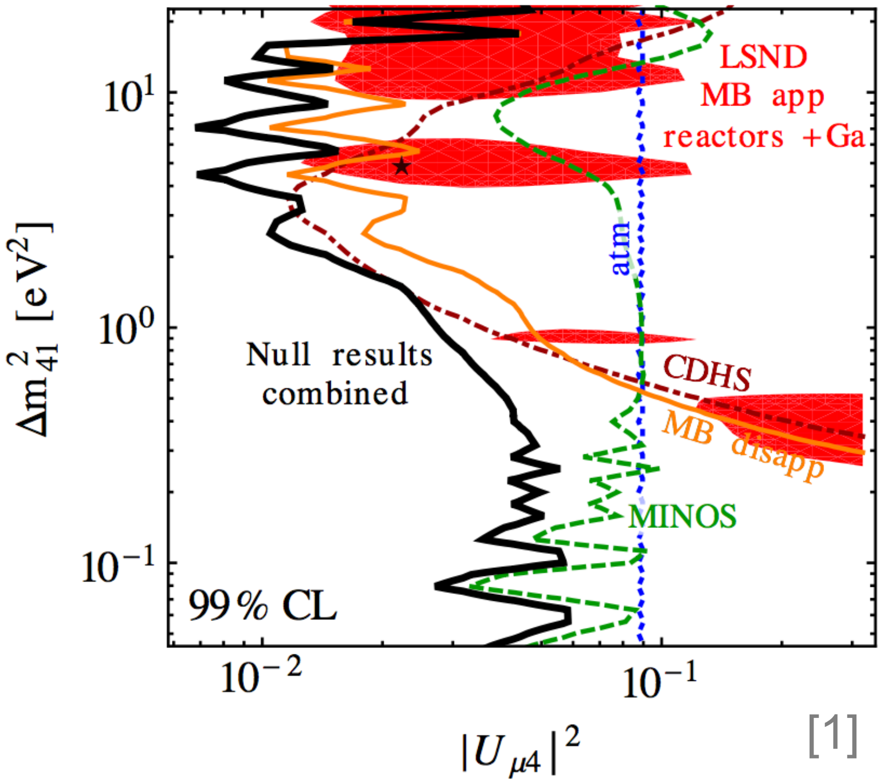


[1]

ν_μ disappearance constraints: 3+1

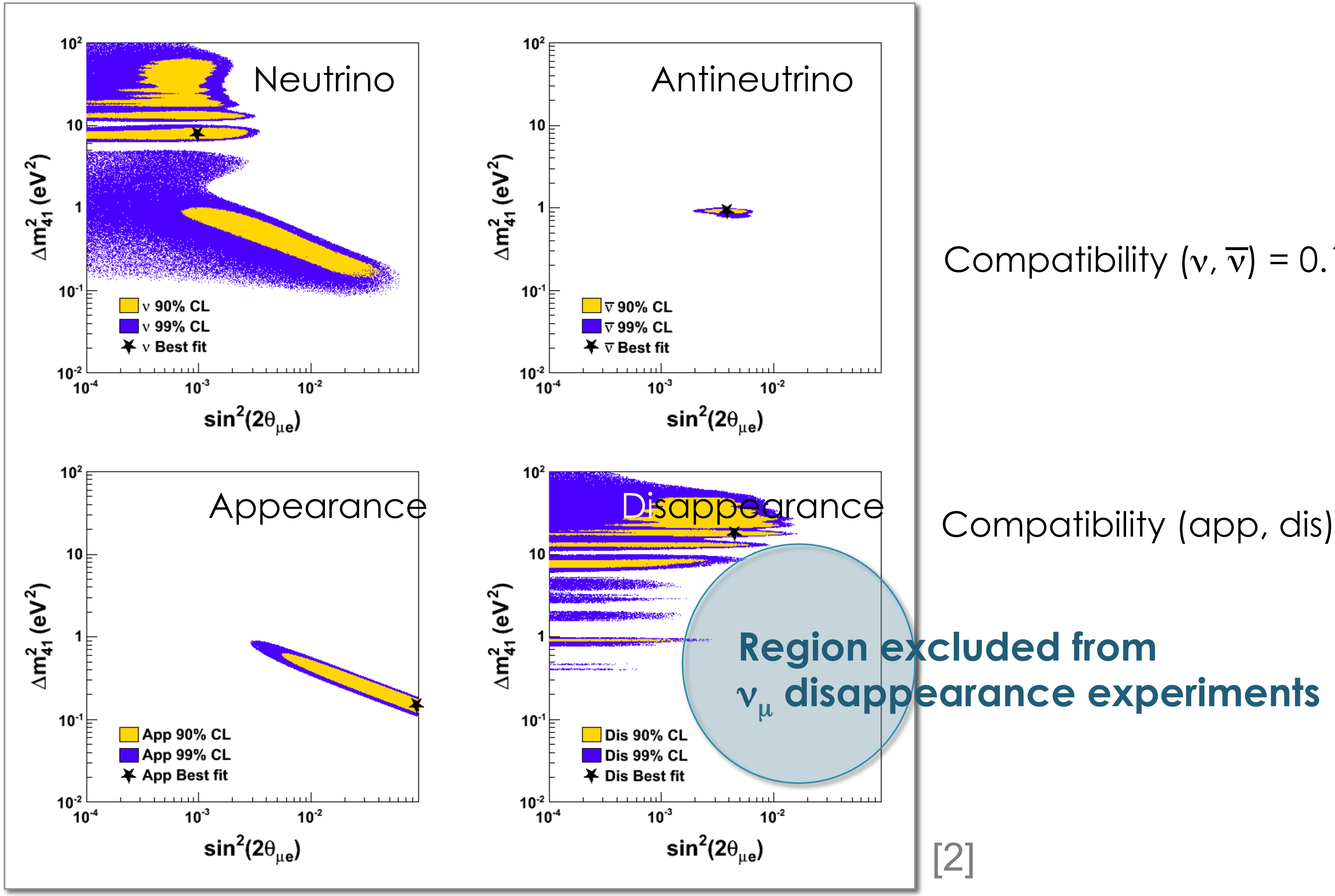
- No signals evident in ν_μ disappearance searches
- CDHS and MiniBooNE constrain much of the higher Δm^2 space
- MINOS and atmospheric results constrain the lower Δm^2 range

- Much of the phase-space jointly preferred by ν_e appearance and disappearance data sets is strongly disfavored by (lack of) ν_μ disappearance
- Tension persists in 3+2, 1+3+1



[1]

(3+1) Global fits



Compatibility (ν, $\bar{\nu}$) = 0.14%

Compatibility (app, dis) = 0.013%

[2]

(3+1) Global fits: Summary

- All "signal" experiments consistent under 3+1, though some tension from lack of high-energy excess in MiniBooNE in neutrino mode
- Appearance experiments and disappearance experiments incompatible under 3+1, due to lack of ν_μ disappearance; appearance amplitude quadratically suppressed by disappearance amplitude

$$\sin^2 2\theta_{\mu e} \approx \frac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}$$

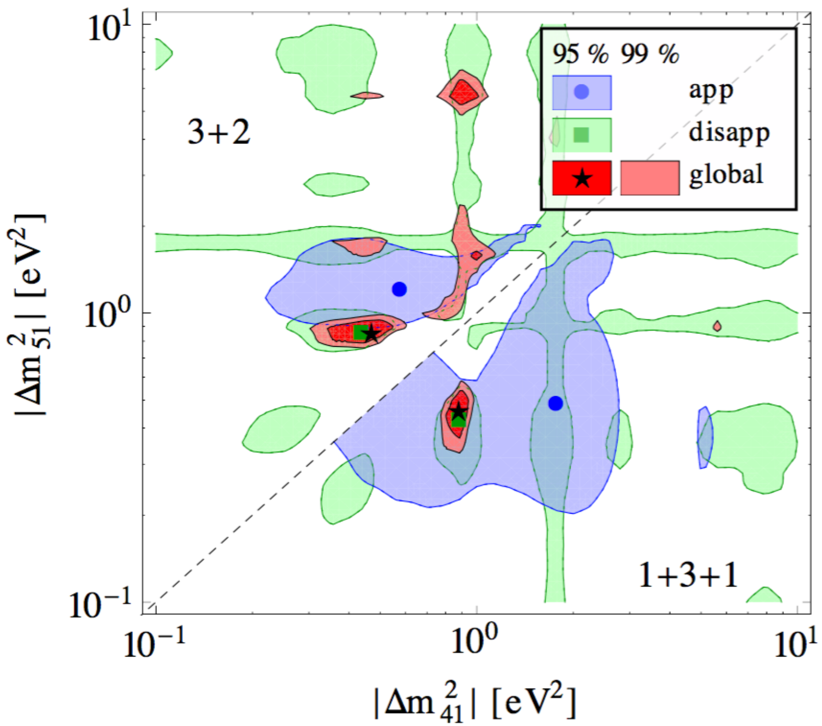
- Also, incompatibilities among neutrino and antineutrino experiments

(3+2) and (1+3+1) Global fits

	$\chi^2_{min}/\mathrm{dof}$	GOF	χ^2_{PG}/dof	PG	$\chi^2_{app,glob}$	$\Delta\chi^2_{app}$	$\chi^2_{dis,glob}$	$\Delta\chi^2_{dis}$
3+1	712/(689 − 9)	19%	18.0/2	1.2×10^{-4}	95.8/68	7.9	616/621	10.1
3+2	701/(689 − 14)	23%	25.8/4	3.4×10^{-5}	92.4/68	19.7	609/621	6.1
1+3+1	694/(689 − 14)	30%	16.8/4	2.1×10^{-3}	82.4/68	7.8	611/621	9.0

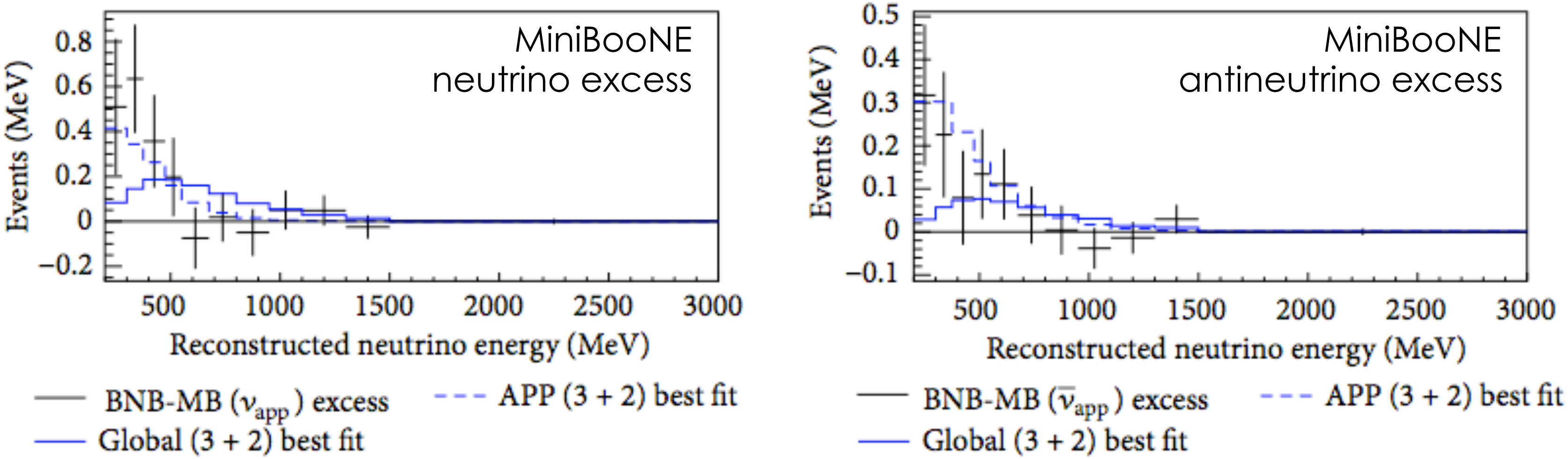
[1]

- Extending the fits to two Δm^2 and one CP phase **worsens compatibility**
- Appearance-only data fit to 3+2 and 1+3+1 significantly better over 3+1, but global fit still cannot accommodate MiniBooNE neutrino mode signal



E.g. (3+2) Global fits

(3+2) global best fit



[2]

(3+2) with CP violation cannot explain
MiniBooNE low E excess, unless
we discard disappearance constraints.

(3+2) and (1+3+1) Global fits

	χ^2_{min}/dof	GOF	χ^2_{PG}/dof	PG	$\chi^2_{app,glob}$	$\Delta\chi^2_{app}$	$\chi^2_{dis,glob}$	$\Delta\chi^2_{dis}$
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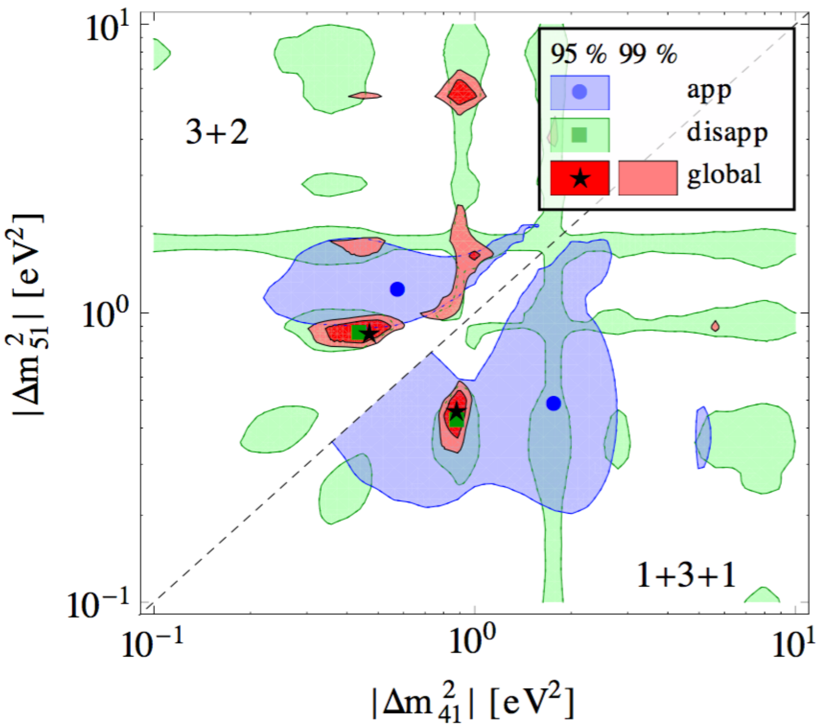
- Extending the fits to two Δm^2 and one CP phase **worsens compatibility**
- Appearance-only data fit to 3+2 and 1+3+1 significantly better over 3+1, but global fit still cannot accommodate MiniBooNE neutrino mode signal
- Tension persists between appearance and disappearance (overlap in projected space, not multi-dimensional space)



Caveats

- How do we quantify **compatibility**?
- A measure of **how well the parameter regions** preferred by different subsets of data **overlap**

$$\chi^2_{PG} = \chi^2_{min,all} - \sum \chi^2_{min,i}$$

compatibility, PG = prob(χ^2_{PG}, ndf$_{PG}$)

- Unlike a χ^2 test, the PG test avoids the problem that a possible disagreement between data sets becomes diluted by data points which are insensitive to the fit

[Maltoni & Schwetz, 2003]

- But, effect of nuisance parameters? [Collin, WIN'15]
  e.g., scaling background normalization can have an effect on ndf_{PG}

- While instructive and useful in understanding the interplay of signals and null results, the reliability of the PG test for providing meaningful quantitative statements must be carefully validated!

(Light) sterile neutrinos: Moving forward

- Need an unambiguous solution.
  This requires (probably multiple) definitive measurements.
  - Appearance and disappearance
  - Shape (L/E) information

- Experimental searches must carefully account for
  - Simultaneous appearance and disappearance effects
  - Neutrino energy reconstruction effects due to cross-section modeling uncertainties

- Global fits must carefully quantify (in)compatibilities

- As we advance toward precision measurements of the tree-neutrino model (e.g. at long-baselines), we must be aware of underlying assumptions.
  See, e.g., added parameter degeneracies in CPV measurements due to sterile neutrinos [Kayser; Gandhi, Masud, Prakash]

Summary

- The existing landscape of observed SBL signals and null signatures is difficult to interpret as (3+N) sterile neutrino oscillations
- Awaiting new, definitive experimental results and/or new theoretical models
- Improving quantitative descriptions of global fits is a pressing issue