Fitting the short-baseline anomalies

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The 4th neutrino – U Chicago, May 19, 2012

Fermilab

Outline

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Theoretical motivation for sterile neutrinos

- Standard Model singlet fermions are a very generic feature of "new physics" models
  - Leftovers of extended gauge multiplets (e.g. GUT multiplets) (typically heavy)
  - Dark matter (keV ... TeV or above)
- Neutrino–singlet mixing is one of the allowed "portals" between the SM and a hidden sector.
- SM singlet fermions can live at any mass scale
  - Here: Focus on $\mathcal{O}(\text{eV})$ sterile neutrinos (accessible to oscillation experiments)
  - Motivated experimentally
- Typical Lagrangian:

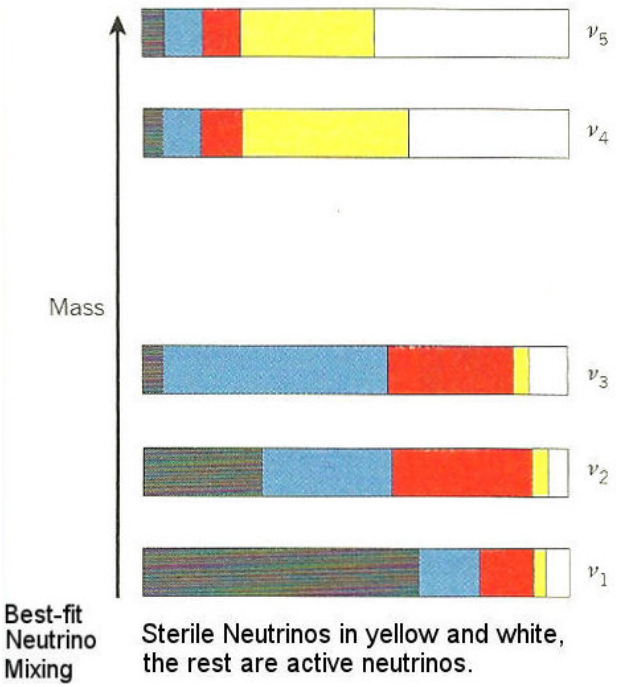
$$\mathcal{L}_{\text{mass}} \supset Y_\nu \, \bar{L} H^* N_R + m_s \, \bar{\nu}_s N_R + \frac{1}{2} M \, \overline{N_R^c} N_R + h.c.$$

$\Rightarrow$ mass mixing between active and sterile neutrinos

Signatures in oscillation experiments

- Disappearance of active neutrinos (e.g. $\nu_e \to \nu_s$ oscillations)
- Anomalous transitions Appearance among active neutrinos (e.g. $\nu_\mu \to \nu_s \to \nu_e$)
- Oscillation length $L^{\rm osc} = 4\pi E/\Delta m^2_{41}$ different from SM expectation (typically shorter)

Notation: $\Delta m^2_{jk} = m^2_j - m^2_k$; $m_{4,5}$: mostly sterile, $m_{1,2,3}$: mostly active



Sterile neutrino oscillations

Idea:

- Introduce extra neutrino flavor ν_s, mixing with the active ones
- Appearance searches (KARMEN, NOMAD, MiniBooNE ...) constrain $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_s \to \overset{(-)}{\nu}_e, \overset{(-)}{\nu}_\tau$
- Disappearance searches (reactors, CDHS, MINOS ...) constrain $\overset{(-)}{\nu}_e, \overset{(-)}{\nu}_\mu \to \bar{\nu}_s$
- $\bar{\nu}_e \to \bar{\nu}_s$ oscillations explain reactor anomaly
- $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_s \to \overset{(-)}{\nu}_e$ oscillations explain LSND + MiniBooNE $\bar{\nu}$

Outline

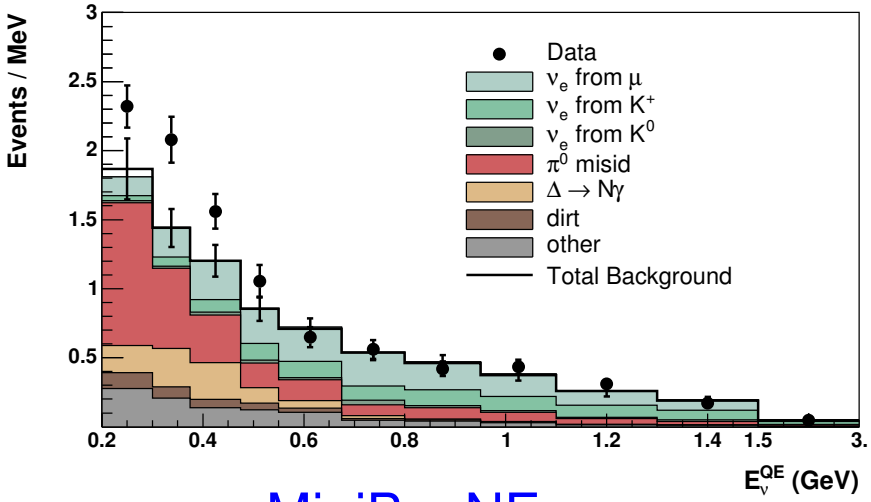
Our fitting procedure

- Atmospheric neutrinos: Eight classes of events: Sub-GeV e, μ ($p < 400$ GeV/c), Sub-GeV e, μ ($p > 400$ GeV/c), Multi-GeV e, μ, Upward stopping μ, upward throughgoing μ, 10 zenith angle bins each
- MINOS: Include NC and CC disappearance search
  (based on 1001.0336 and Neutrino 2010 talk by P. Vahle)
- Reactor experiments: Bugey 3 (incl. spectrum), Bugey 4, Chooz (incl. spectrum), Goesgen 1–3, ILL, Krasnoyarsk 1–3, Palo Verde, Rovno
- SBL ν_e appearance experiments: LSND, KARMEN, MiniBooNE (ν (2010) and $\bar{\nu}$ data, consider only $E > 475$ MeV, i.e. low-E excess in ν_e sample not included)
- Gallium anomaly not included
- SBL ν_μ disappearance experiments: CDHS, NOMAD
- All codes reproduce the individual fits from the respective experiments.

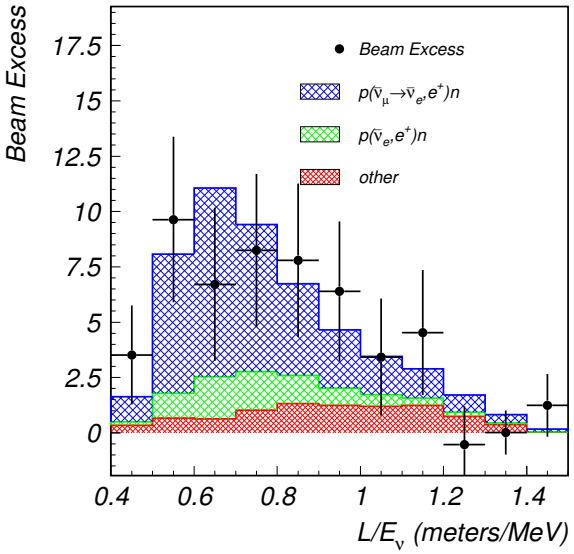
JK Maltoni Schwetz 1103.4570 and work in progress

LSND and MiniBooNE

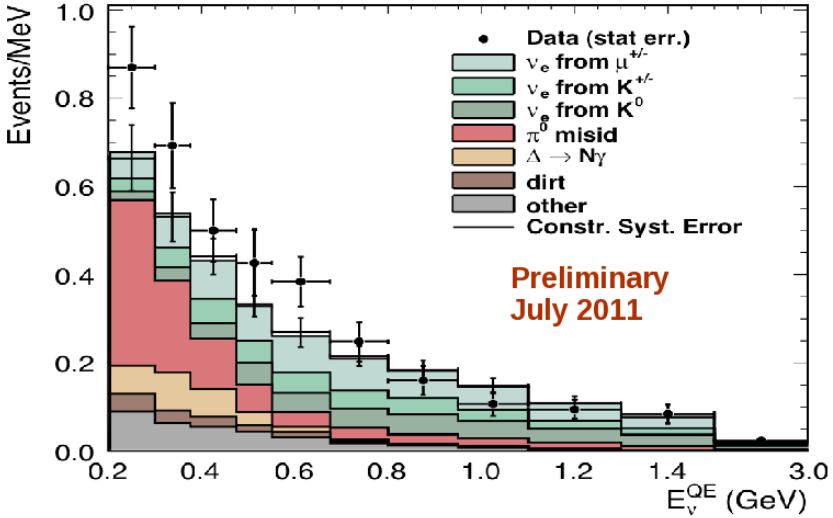
- LSND:
  - $\bar{\nu}_e$ appearance in $\bar{\nu}_\mu$ beam from stopped pion source (3σ)
- MiniBooNE:
  - No significant ν_e or $\bar{\nu}_e$ excess in the LSND-preferred region
  - but $\bar{\nu}_e$ consistent with LSND
  - Low-E excess not understood



MiniBooNE ν_e



LSND $\bar{\nu}_e$



MiniBooNE $\bar{\nu}_e$

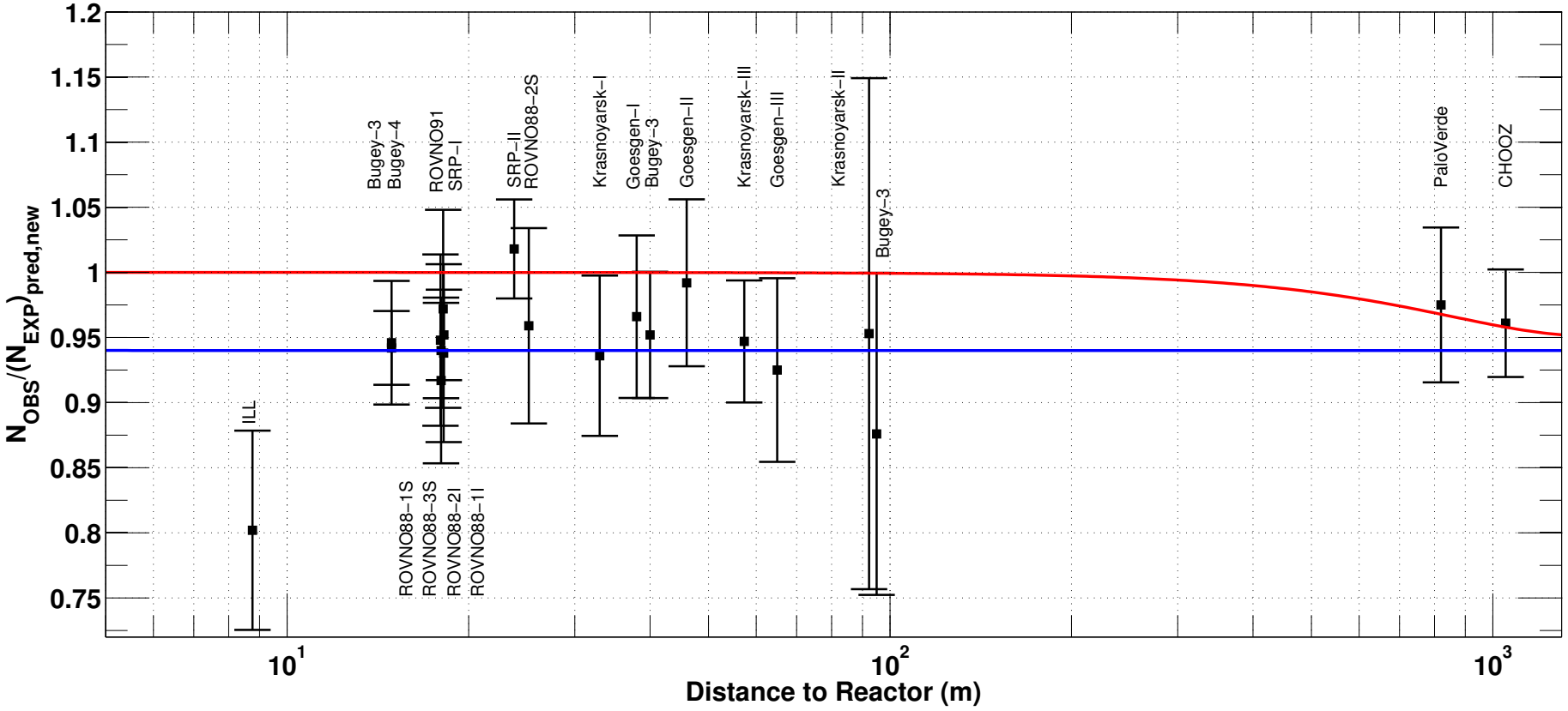
The reactor anomaly

- Recent reevaluation of expected reactor $\bar{\nu}_e$ flux is $\sim 3.5\%$ higher than previous prediction Mueller et al. arXiv:1101.2663, confirmed by P. Huber arXiv:1106.0687
- Method: Use measured β-spectra from ^{238}U, ^{235}U, ^{241}Pu fission at ILL and convert to $\bar{\nu}_e$ spectrum (for single β-decay: $E_\nu = Q - E_e$)
- Problem: Requires knowledge of Q-values for all contributing decays. $\rightarrow$ take from nuclear databases where available, fit to data otherwise
- Cross check:
  - Simulate mock e^- spectra using few well-understood β-decays
  - Reconstruct $\bar{\nu}_e$ spectrum using old method: Result is 3% too low
  - Reconstruct $\bar{\nu}_e$ spectrum using new method: Result is exact.
- Possible problem: Poorly understood effects in nuclei with large log ft

Huber arXiv:1106.0687

The reactor anomaly

- Have short-baseline reactor experiments observed a $\bar{\nu}_e$ deficit?



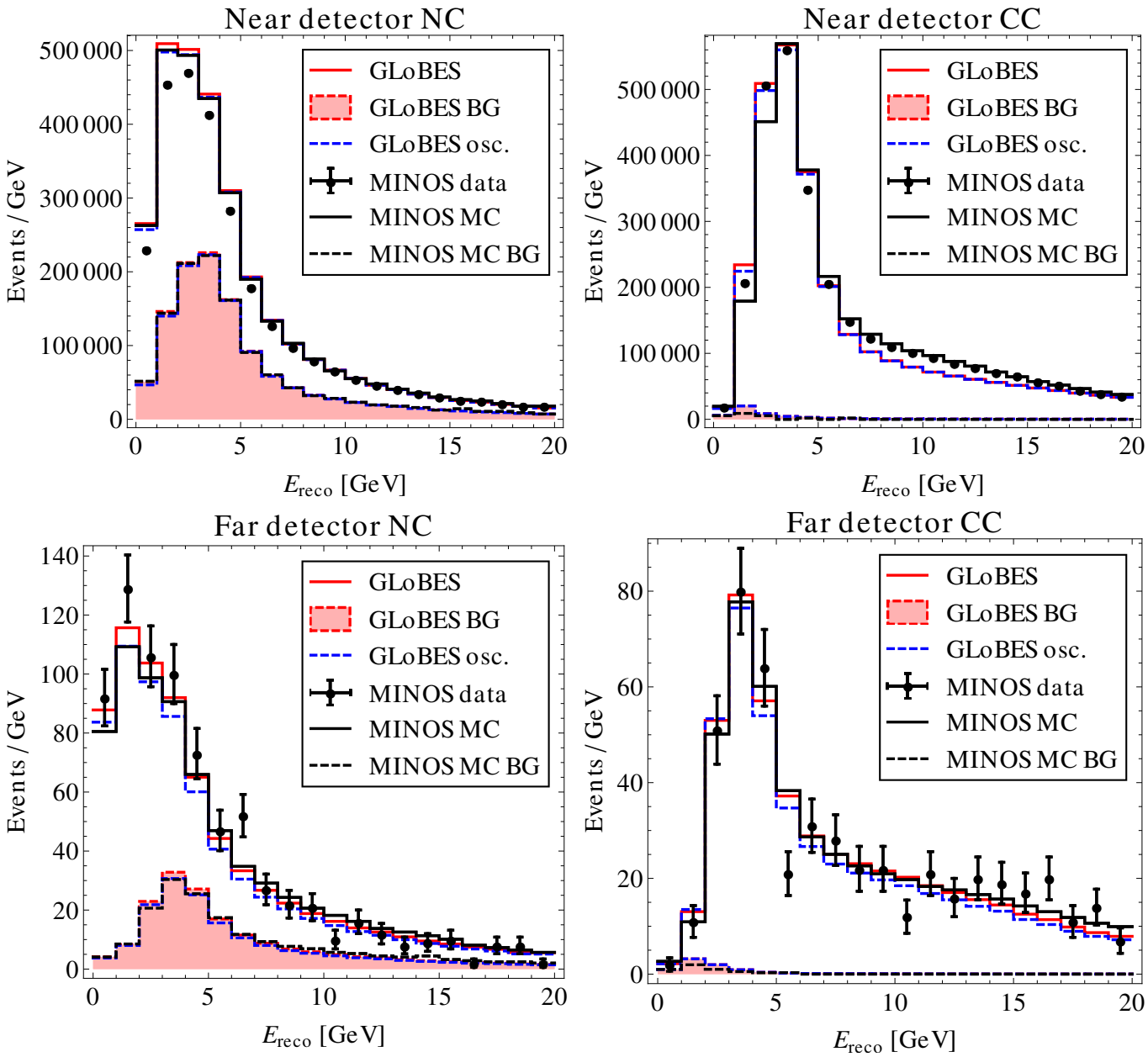
Mention et al. arXiv:1101.2755

red = old reactor $\bar{\nu}_e$ flux prediction
blue = new reactor $\bar{\nu}_e$ flux prediction

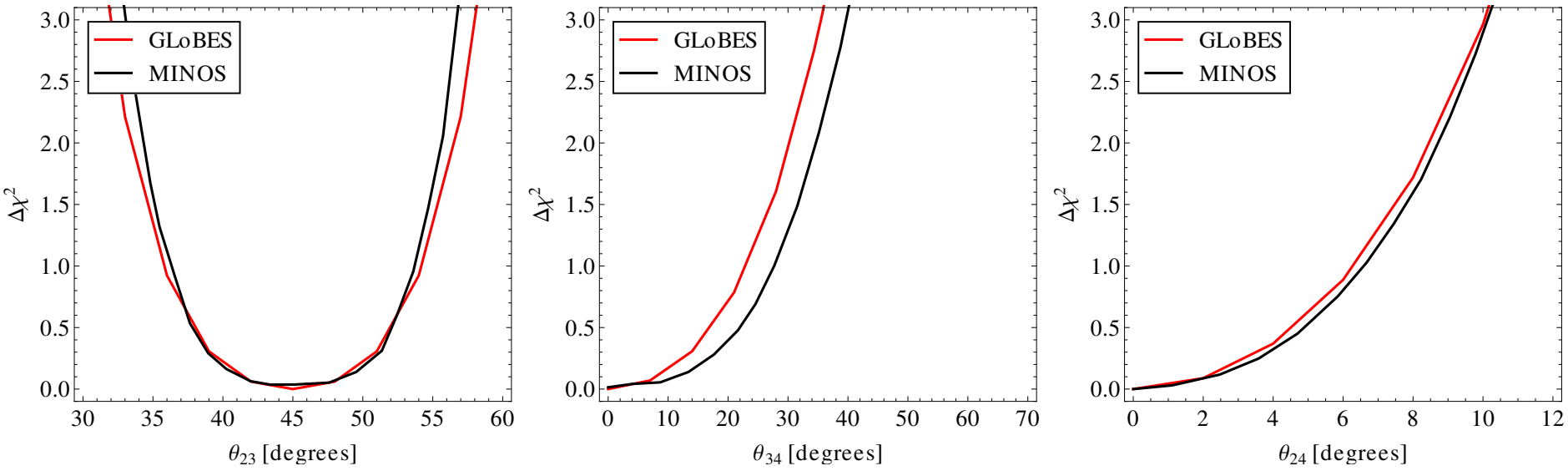
MINOS NC disappearance search

- Based on arXiv:1001.0336 and data shown at Neutrino 2010
- GLoBES simulation
- NC data:
  - Use spectra and detector response functions based on MINOS MC (courtesy Alex Sousa)
- CC data:
  - NuMI fluxes courtesy Mary Bishai
  - Backgrounds and efficiencies based on published results
- Systematic uncertainties:
  - Based on published numbers, but simplified treatment
  - Some fudging in CC channel

MINOS NC disappearance search (2)



MINOS NC disappearance search (3)

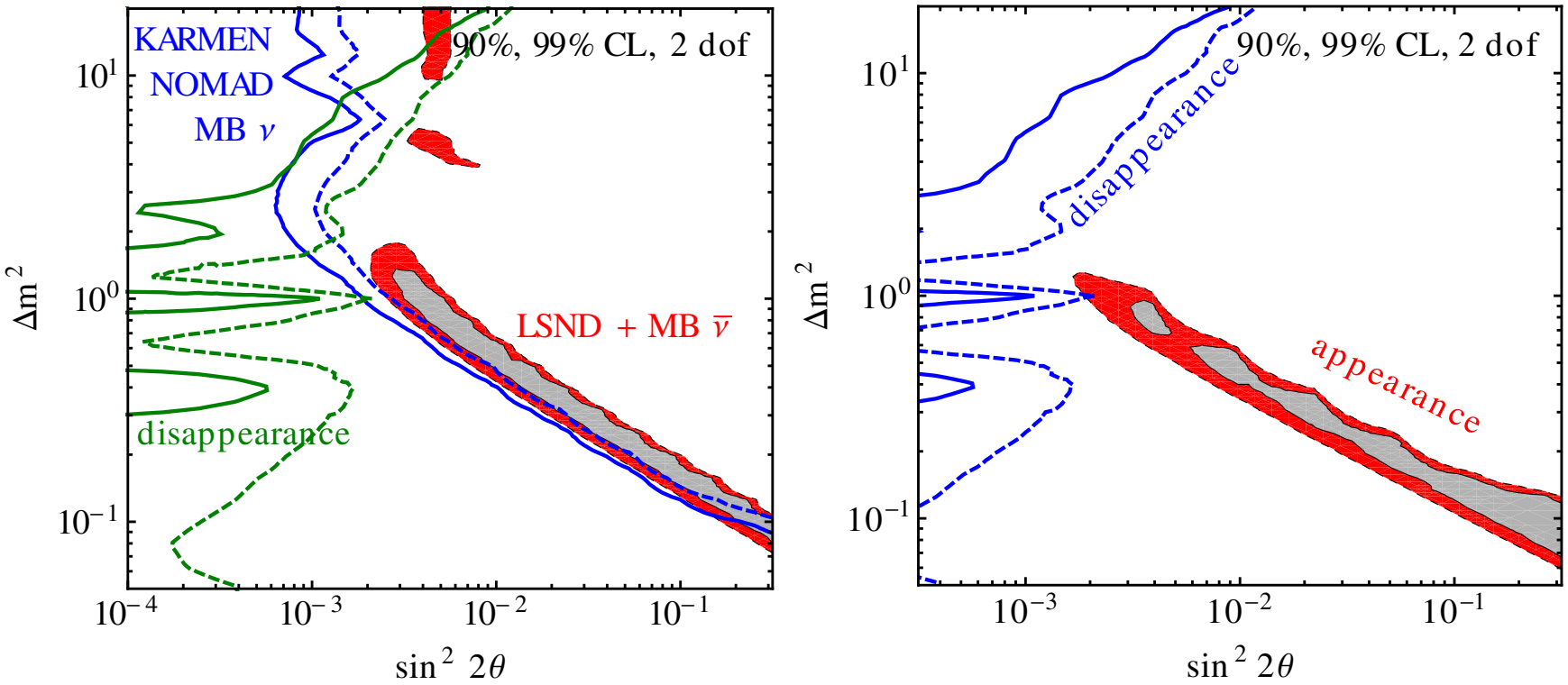


Outline

A 3+1 model: 3 active neutrinos + 1 sterile neutrino

- Short baseline: Standard oscillations ineffective (Δm^2_{21}, Δm^2_{31} too small)
- Add extra (sterile) neutrino
- Fit shows: 3+1 neutrino scheme does not work well

JK Maltoni Schwetz 1103.4570 and work in progress
see also Giunti Laveder 1107.1452 and 1109.4033; Mention et al. 1101.2755; Karagiorgi et al. 0906.1997 and 1110.3735



"disappearance" = SBL reactors, CDHS, atmospheric ν, MINOS

θ = effective mixing angle for $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_s \to \overset{(-)}{\nu}_e$ oscillations

Global fit in a 4-flavor scheme

	$\lvert\Delta m^2_{41}\rvert$	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	χ^2/dof
STD				287.6/256
3+1	0.48	0.14	0.23	255.5/252

	LSND+MB($\bar{\nu}$) vs rest		appearance vs disapp.	
	old	new	old	new
$\chi^2_{\mathrm{PG},3+1}$/dof	27.3/2	25.8/2	15.7/2	14.2/2
PG_{3+1}	1.2×10^{-6}	2.5×10^{-6}	3.9×10^{-4}	8.2×10^{-4}

Parameter goodness of fit: Test compatibility of 2 data sets by comparing global $\chi^2_{\min}$ to $\chi^2_{\min}$ for separate fits

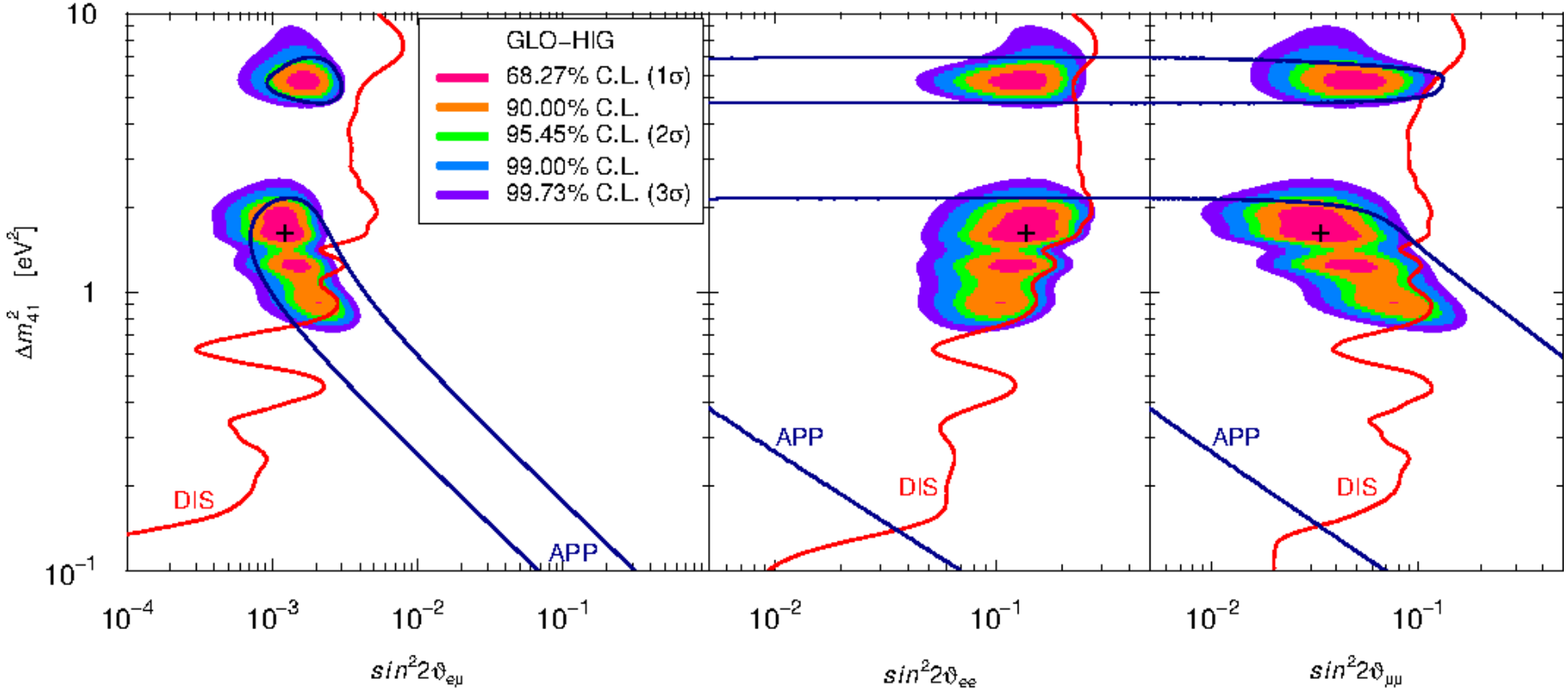
The Giunti–Laveder fit

Includes the following data sets:

- $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ appearance data:
  - LSND
  - MiniBooNE
  - KARMEN
  - NOMAD
- ν_μ disappearance data:
  - CDHS
  - MINOS bound on $|U_{\mu 4}|$
- $\bar{\nu}_e$ disappearance data:
  - Short baseline reactor experiments
  - KamLAND bound on $|U_{e4}|$
  - Gallium anomaly
- ν_e disappearance data:
  - ν_e–^{12}C CC scattering in KARMEN and LSND

Giunti Laveder arXiv:1111.1069

The Giunti–Laveder fit (2)



APP/DIS curves: 3σ C.L.

Parameter goodness of fit (APP vs. DIS): 3×10^{-3}

Giunti Laveder arXiv:1111.1069

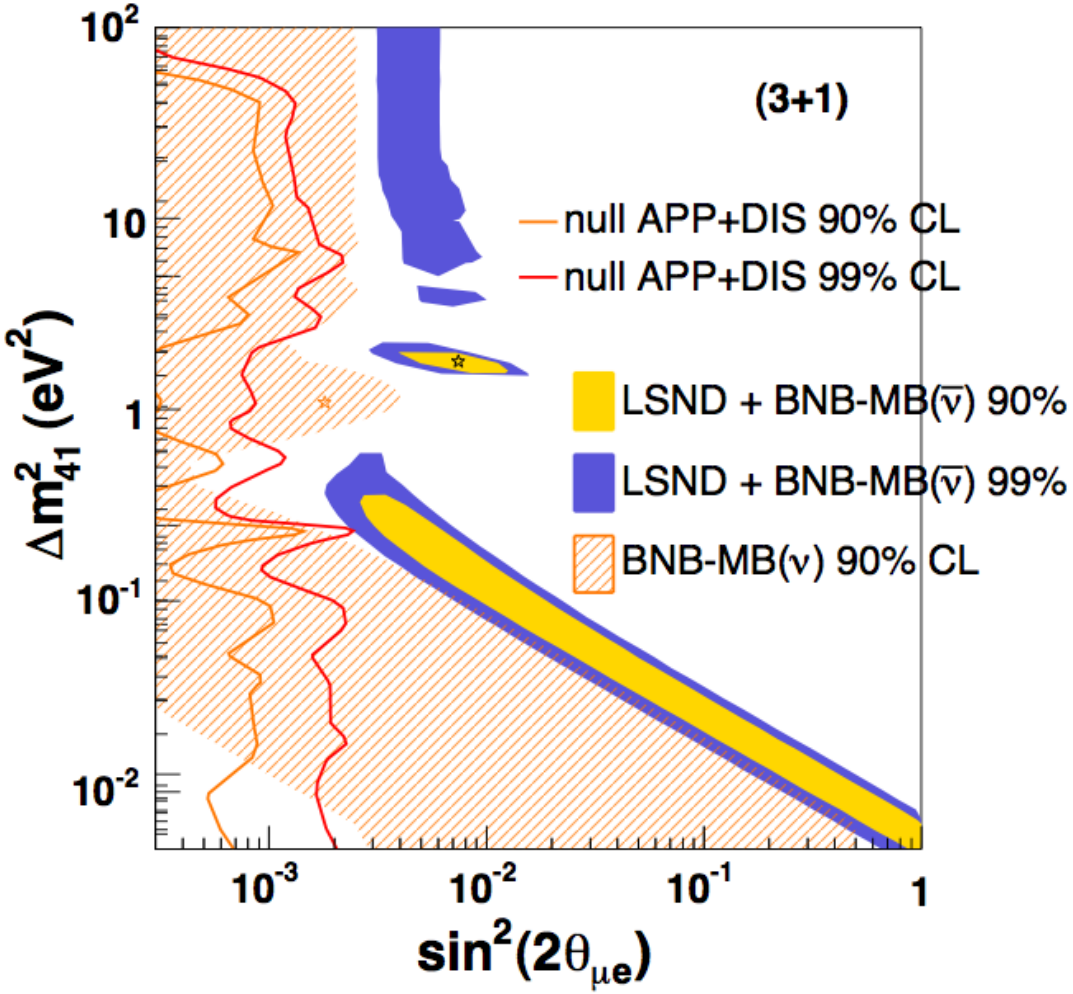
The Karagiorgi et al. fit

Includes the following data sets:

- $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ appearance data:
  - LSND
  - MiniBooNE
  - KARMEN
  - NOMAD
- ν_μ disappearance data:
  - CDHS
  - CCFR84
- $\bar{\nu}_e$ disappearance data:
  - Short baseline reactor experiments

Karagiorgi arXiv:1110.3735, Karagiorgi Djurcic Conrad Shaevitz Sorel arXiv:0906.1997

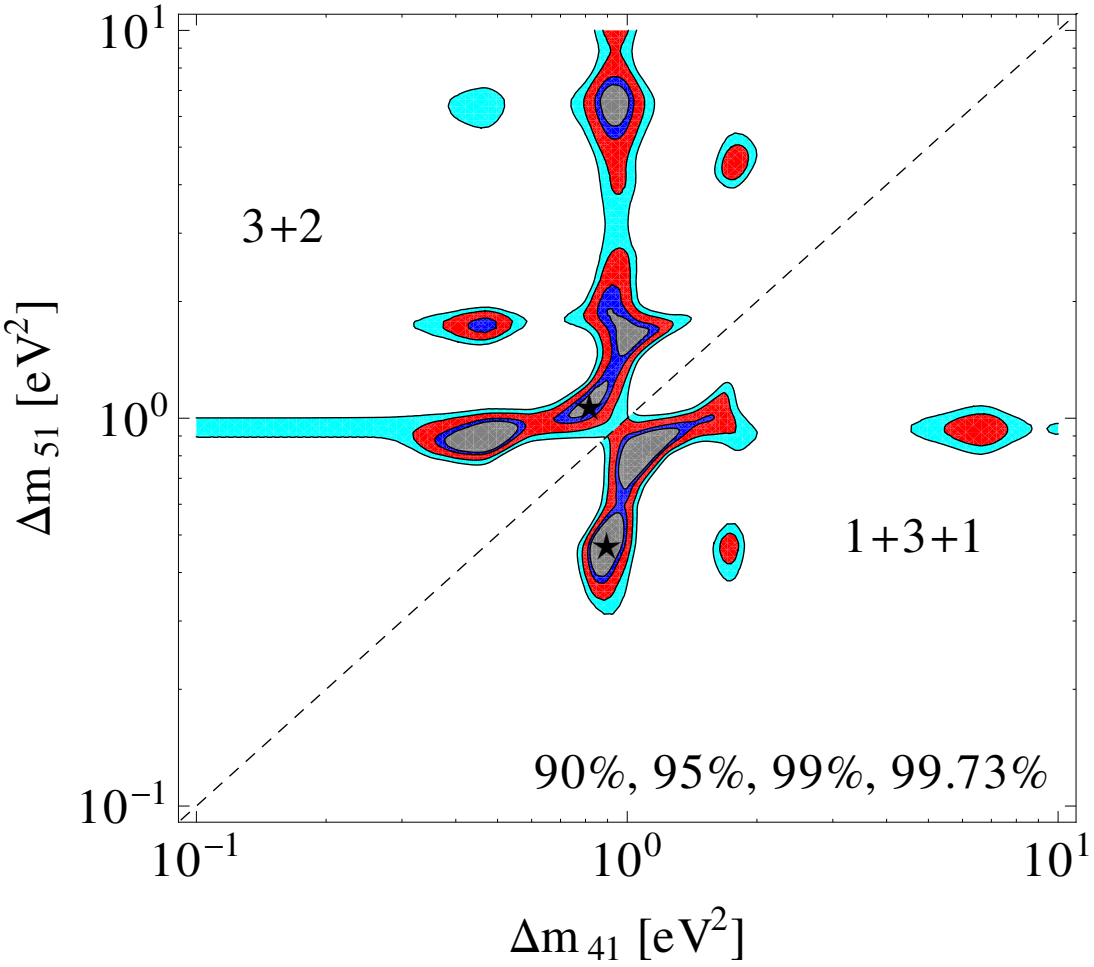
The Karagiorgi et al. fit (2)



Karagiorgi arXiv:1110.3735, Karagiorgi Djurcic Conrad Shaevitz Sorel arXiv:0906.1997

Global fit in a 5-flavor scheme

Check if more than one sterile neutrino improves the fit:



JK Maltoni Schwetz 1103.4570 and work in progress

Global fit in a 5-flavor scheme (2)

	$\lvert\Delta m^2_{41}\rvert$	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	$\lvert\Delta m^2_{51}\rvert$	$\lvert U_{e5}\rvert$	$\lvert U_{\mu 5}\rvert$	δ/π	χ^2/dof
STD								287.6/256
3+1	0.48	0.14	0.23					255.5/252
3+2	1.10	0.14	0.11	0.82	0.13	0.12	-0.31	245.2/247
1+3+1	0.48	0.13	0.12	0.90	0.15	0.15	0.62	241.6/247

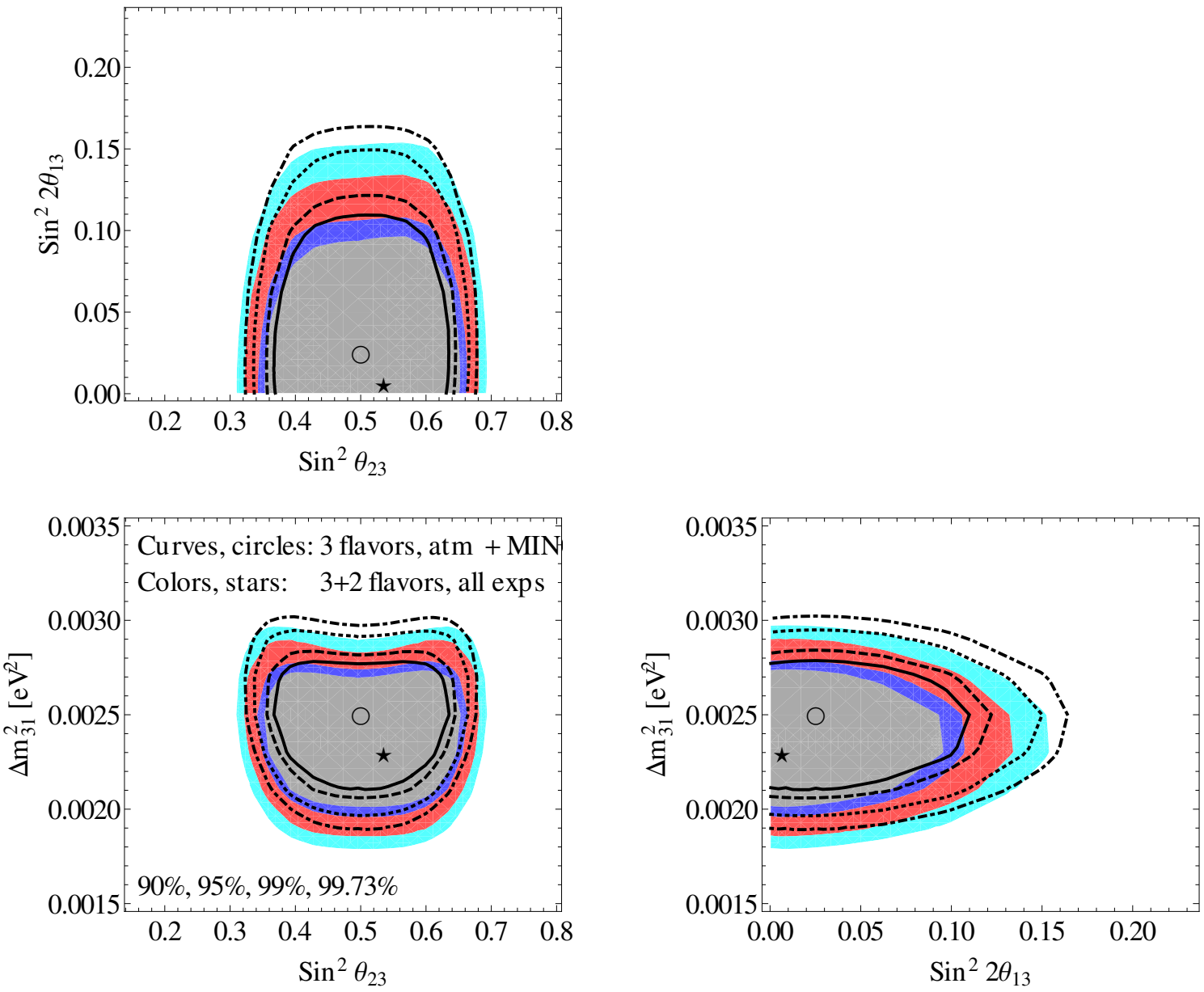
	LSND+MB($\bar{\nu}$) vs rest		appearance vs disapp.	
	old	new	old	new
$\chi^2_{\mathrm{PG},3+1}$/dof	27.3/2	25.8/2	15.7/2	14.2/2
PG_{3+1}	1.2×10^{-6}	2.5×10^{-6}	3.9×10^{-4}	8.2×10^{-4}
$\chi^2_{\mathrm{PG},3+2}$/dof	30.0/5	24.8/5	24.7/4	19.5/4
PG_{3+2}	1.5×10^{-5}	1.5×10^{-4}	5.7×10^{-5}	6.1×10^{-4}
$\chi^2_{\mathrm{PG},1+3+1}$/dof	24.9/5	21.2/5	19.6/4	10.7/4
PG_{1+3+1}	1.5×10^{-4}	7.5×10^{-4}	6.0×10^{-3}	3.1×10^{-2}

Parameter goodness of fit: Test compatibility of 2 data sets by comparing global $\chi^2_{\min}$ to $\chi^2_{\min}$ for separate fits

Does removing *one* experiment relax the tension?

Removing ...	LSND+MB($\bar{\nu}$) vs rest		appearance vs disapp.	
	PG_{3+1}	PG_{3+2}	PG_{3+1}	PG_{3+2}
KARMEN	1.2×10^{-5}	6.2×10^{-4}	8.1×10^{-4}	1.0×10^{-3}
NOMAD	2.6×10^{-6}	1.5×10^{-4}	7.7×10^{-4}	6.1×10^{-4}
MB ν	2.2×10^{-5}	5.1×10^{-4}	1.7×10^{-4}	3.7×10^{-4}
MB $\bar{\nu}$	2.9×10^{-6}	2.0×10^{-3}	1.9×10^{-3}	4.5×10^{-3}
LSND	2.3×10^{-2}	2.1×10^{-2}	2.0×10^{-1}	5.8×10^{-2}
Reactors	4.4×10^{-4}	7.9×10^{-2}	1.3×10^{-1}	2.9×10^{-1}
CDHS	1.2×10^{-5}	3.7×10^{-4}	3.6×10^{-3}	1.5×10^{-3}
Atmospheric	8.1×10^{-6}	6.9×10^{-5}	1.2×10^{-4}	2.3×10^{-4}
MINOS	1.4×10^{-5}	1.1×10^{-3}	4.1×10^{-3}	4.7×10^{-3}

Impact on standard oscillation parameters



Outline

Relation between appearance and disappearance

$3+1$ neutrinos

At large baseline ($L \gg 4\pi E/\Delta m^2_{41}$, but $L \ll 4\pi E/\Delta m^2_{31}$

$$P_{ee} = 1 - 2|U_{e4}|^2(1 - |U_{e4}|^2)$$
$$P_{\mu\mu} = 1 - 2|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2)$$
$$P_{e\mu} = 2|U_{e4}|^2|U_{\mu 4}|^2$$

It follows

$$2P_{e\mu} \simeq (1 - P_{ee})(1 - P_{\mu\mu})$$

In the $3+1$ case, at large enough baseline, there is a one-to-one relation between the appearance and disappearance probabilities.

Relation between appearance and disappearance

$3+2$ neutrinos

At large baseline ($L \gg 4\pi E/\Delta m^2_{41}$, but $L \ll 4\pi E/\Delta m^2_{31}$

$$P_{ee} = 1 - 2\left[|U_{e4}|^2(1-|U_{e4}|^2) + |U_{e5}|^2(1-|U_{e5}|^2) - |U_{e4}|^2|U_{e5}|^2\right]$$

$$P_{\mu\mu} = 1 - 2\left[|U_{\mu4}|^2(1-|U_{\mu4}|^2) + |U_{\mu5}|^2(1-|U_{\mu5}|^2) - |U_{\mu4}|^2|U_{\mu5}|^2\right]$$

$$P_{e\mu} = 2\left[|U_{e4}|^2|U_{\mu4}|^2 + |U_{\mu4}|^2|U_{\mu5}|^2 + \mathrm{Re}(U^*_{e4}U_{\mu4}U_{e5}U^*_{\mu5})\right]$$

Relation between appearance and disappearance

$3+2$ neutrinos

At large baseline ($L \gg 4\pi E/\Delta m^2_{41}$, but $L \ll 4\pi E/\Delta m^2_{31}$

$$P_{ee} = 1 - 2\left[|U_{e4}|^2(1-|U_{e4}|^2) + |U_{e5}|^2(1-|U_{e5}|^2) - |U_{e4}|^2|U_{e5}|^2\right]$$

$$P_{\mu\mu} = 1 - 2\left[|U_{\mu 4}|^2(1-|U_{\mu 4}|^2) + |U_{\mu 5}|^2(1-|U_{\mu 5}|^2) - |U_{\mu 4}|^2|U_{\mu 5}|^2\right]$$

$$P_{e\mu} = 2\left[|U_{e4}|^2|U_{\mu 4}|^2 + |U_{\mu 4}|^2|U_{\mu 5}|^2 + \mathrm{Re}(U^*_{e4}U_{\mu 4}U_{e5}U^*_{\mu 5})\right]$$

It follows

$$\begin{aligned} 2P_{e\mu} &\simeq (1-P_{ee})(1-P_{\mu\mu}) \\ &\quad + 4\left[\mathrm{Re}(U^*_{e4}U_{\mu 4}U_{e5}U^*_{\mu 5}) + 4|U_{e4}|^2|U_{\mu 5}|^2 + 4|U_{e5}|^2|U_{\mu 4}|^2\right] \\ &= (1-P_{ee})(1-P_{\mu\mu}) - 2\left[|U_{e4}|^2|U_{\mu 5}|^2 + |U_{e5}|^2|U_{\mu 4}|^2\right] \\ &\quad - 2\left|U_{e4}U_{\mu 5} - U_{e5}U_{\mu 4}\right|^2 \end{aligned}$$

Relation between appearance and disappearance

$3+2$ neutrinos

At large baseline ($L \gg 4\pi E/\Delta m^2_{41}$, but $L \ll 4\pi E/\Delta m^2_{31}$

$$P_{ee} = 1 - 2\left[|U_{e4}|^2(1-|U_{e4}|^2) + |U_{e5}|^2(1-|U_{e5}|^2) - |U_{e4}|^2|U_{e5}|^2\right]$$

$$P_{\mu\mu} = 1 - 2\left[|U_{\mu4}|^2(1-|U_{\mu4}|^2) + |U_{\mu5}|^2(1-|U_{\mu5}|^2) - |U_{\mu4}|^2|U_{\mu5}|^2\right]$$

$$P_{e\mu} = 2\left[|U_{e4}|^2|U_{\mu4}|^2 + |U_{\mu4}|^2|U_{\mu5}|^2 + \mathrm{Re}(U^*_{e4}U_{\mu4}U_{e5}U^*_{\mu5})\right]$$

It follows

$$2P_{e\mu} \leq (1-P_{ee})(1-P_{\mu\mu})$$

Unlike in the $3+1$ case, for $3+2$ models, there is NO one-to-one relation between the appearance and disappearance probabilities.

However, there is an inequality, which can be used to set meaningful constraints.

Outline

Global fits — take home message

Substantial tension in the global fit.

- Is one (or all) of the positive results not due to neutrino oscillations?
- Are some of the null results wrong?

  (one being wrong is not enough!)
- Are there more than 2 sterile flavors?
- Are there sterile neutrinos plus something else?

Thank you!