Status of light sterile neutrino oscillation fits

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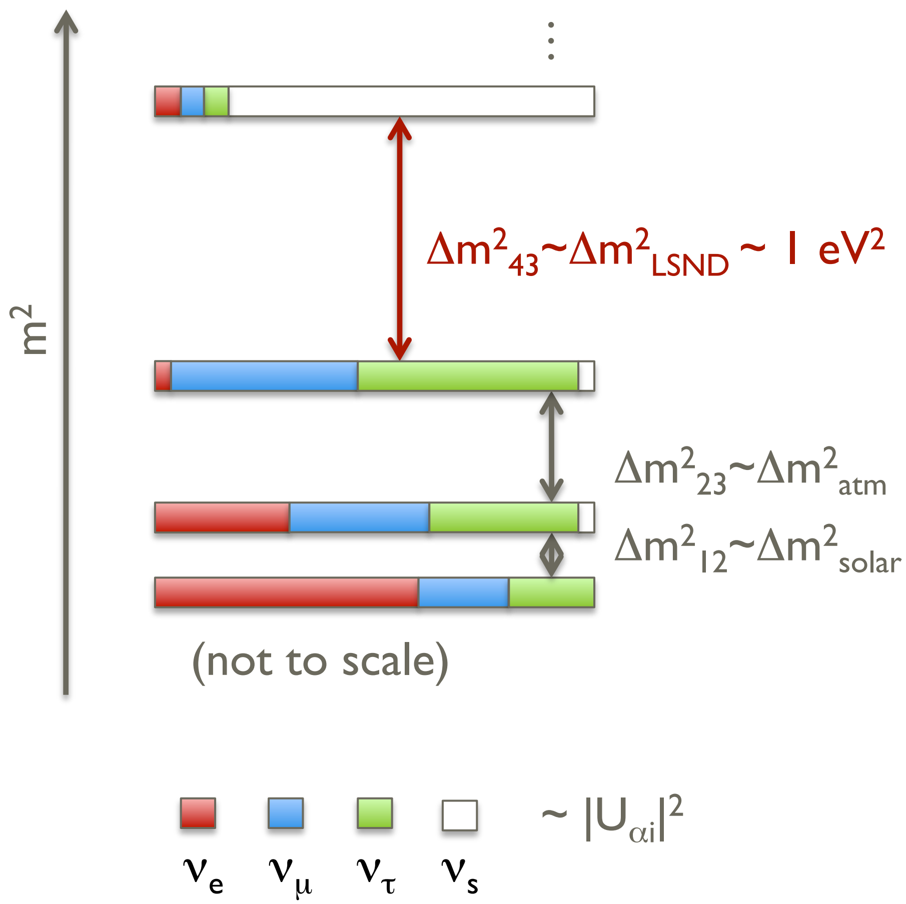
Outline

- Light sterile neutrino oscillations
- Constraints from neutrino oscillation experiments
- Global fits status as of May 2010 [PRD 80, 073001 (2009)]
- Current status given
  - MiniBooNE antineutrino excess
  - Reactor antineutrino anomaly
- Near-future constraints

New results, PRELIMINARY

Light sterile neutrino oscillations

3 active + n sterile neutrino states



Recipe:

- Oscillation probability derivation assumptions (E>>m, unitarity) are still valid
- Summation over 3+n mass eigenstates; only 3 active flavor states (associated with production and detection)
- Approximations/assumptions:
  - $m_{4,\ldots} >> m_{1,2,3} \sim 0 \rightarrow$ (n+1)-neutrino approx.
  - only e, μ flavors at production/detection

E.g., (3+1):

Disppearance probability:

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2 x_{41}$$

$$\sin^2 2\theta_{ee} \equiv 4U_{e4}^2(1 - U_{e4}^2)$$

$$\sin^2 2\theta_{\mu\mu} \equiv 4U_{\mu 4}^2(1 - U_{\mu 4}^2)$$

$$x_{ji} \equiv 1.27\Delta m_{ji}^2 L/E$$

Appearance probability:

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta_{\alpha\beta} \sin^2 x_{41}$$

$$\sin^2 2\theta_{\mu e} \equiv 4U_{e4}^2 U_{\mu 4}^2$$

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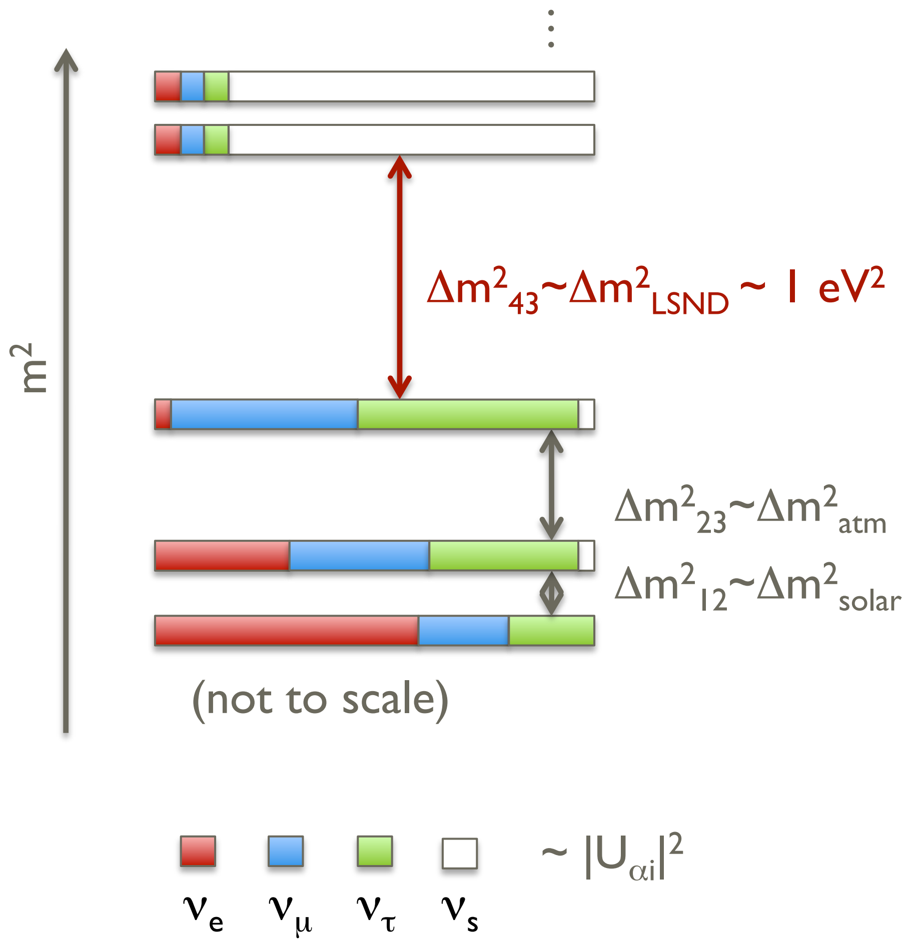

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E.g., (3+2):

Disppearance probability:

$$P(\nu_\alpha \to \nu_\alpha) = 1 - 4[(1 - |U_{\alpha 4}|^2 - |U_{\alpha 5}|^2) \cdot (|U_{\alpha 4}|^2 \sin^2 x_{41} + |U_{\alpha 5}|^2 \sin^2 x_{51}) + |U_{\alpha 4}|^2 |U_{\alpha 5}|^2 \sin^2 x_{54}]$$

Appearance probability:

$$P(\nu_\alpha \to \nu_{\beta \neq \alpha}) = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2 \sin^2 x_{41} + 4|U_{\alpha 5}|^2 |U_{\beta 5}|^2 \sin^2 x_{51} + 8|U_{\alpha 5}||U_{\beta 5}||U_{\alpha 4}||U_{\beta 4}| \sin x_{41} \sin x_{51} \cos(x_{54} - \phi_{45})$$

CPV phase

Constraints from short-baseline experiments

- Why "short-baseline" (SBL)?
  - "Short-baseline" is relative to neutrino energy: L/E
  - E.g., appearance oscillation probability:
    (two-neutrino approximation)

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta_{\alpha\beta} \sin^2(1.27\ \Delta m^2\ L[km]/E[GeV]\ )$$

Typical L/E (solar, atm oscillations): ~ $10^{2\text{-}4}$ km/GeV

For higher Δm^2 ~1 eV^2, we need L/E~1 km/GeV
→ decrease L to O(10-1000 m)

Constraints from short-baseline experiments

- Appearance and disappearance constraints

LSND	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	CCFR	$\nu_\mu \rightarrow \nu_\mu$
MiniBooNE(ν)	$\nu_\mu \rightarrow \nu_e$	CDHS	$\nu_\mu \rightarrow \nu_\mu$
MiniBooNE($\bar{\nu}$)	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	**Bugey**	$\bar{\nu}_e \rightarrow \bar{\nu}_e$
NuMI at MiniBooNE	$\nu_\mu \rightarrow \nu_e$	**CHOOZ**	$\bar{\nu}_e \rightarrow \bar{\nu}_e$
KARMEN	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	atmospheric	$\nu_\mu \rightarrow \nu_\mu$
NOMAD	$\nu_\mu \rightarrow \nu_e$		

$\nu_e \rightarrow$ access to $|U_{ei}|$
$\nu_\mu \rightarrow$ access to $|U_{\mu i}|$

PRD 80, 073001 (2009) [hep-ph/0906.1997v3]

Positive vs. null results

- Appearance and disappearance constraints

Excess:
LSND
MiniBooNE($\bar{\nu}$)

No excess:
KARMEN
NOMAD

No deficit:
CCFR
CDHS
Bugey
CHOOZ
atmospheric

Excess?:
NuMI at MiniBooNE (small)
MiniBooNE(ν) (low E)

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"Signal hints come primarily from **antineutrino** datasets"

PRD 80, 073001 (2009) [hep-ph/0906.1997v3]

Global fits as of end of May 2010
Ref.: PRD 80, 073001 (2009) [hep-ph/0906.1997v3]

(3+1) results:

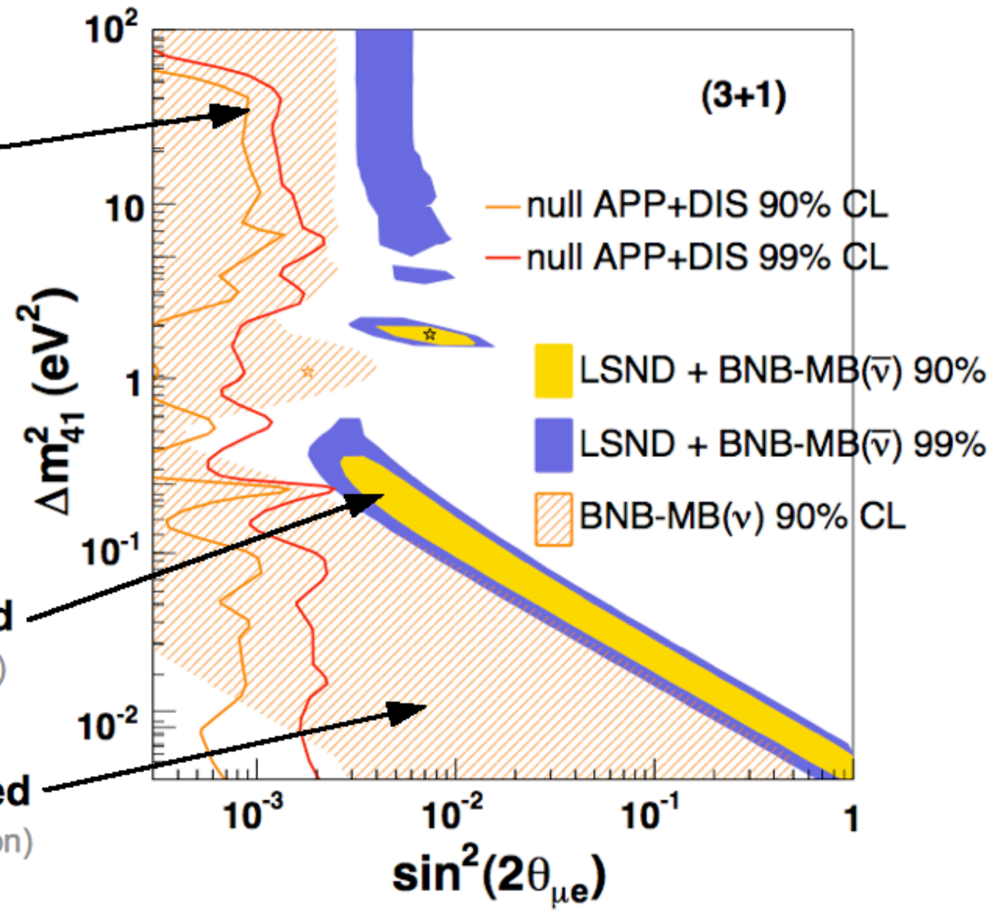
Compatibility of all SBL+atm datasets: 0.11%
(3+1) CP-conserving scenario essentially RULED OUT

Combined **exclusion limits from null** atmospheric ν_μ disappearance and null short-baseline experiments:

Bugey and Chooz: $\bar{\nu}_e$ disappearance
CCFR, CDHS: ν_μ disappearance
NOMAD, NuMI-MiniBooNE $\nu_\mu \to \nu_e$ appearance
KARMEN: $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance

Joint **LSND+MiniBooNE($\bar{\nu}$)* allowed**
(compatible at 49%)

MiniBooNE(ν) allowed
(including low E region)



Global fits as of end of May 2010
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(3+2) results:

- Because of differences in size and L/E for neutrino vs. antineutrino observed excesses, there has been particular interest in (3+2) fits with CP violation

- However, fit results quite discouraging
  - Large $|U_{ei}||U_{\mu i}|$ preferred by appearance data opposed by disappearance (null) constraints
  - No significant difference in CPC vs. CPV fit quality
  - Neutrino/antineutrino incompatibilty

Datasets	CPV χ^2-prob	CPC χ^2-prob	CPV compat.
MiniBooNE(ν)+ MiniBooNE($\bar{\nu}$)+LSND (90% closed contours)	53%	13%	86%
MiniBooNE(ν)+MiniBooNE($\bar{\nu}$)+LSND+ NUMI+KARMEN+NOMAD (appearance)	56%	22%	74%
all SBL+atm	54%	52%	7%
appearance vs disappearance			0.004%
neutrino vs antineutrino			0.06%
ν	62%		43%
$\bar{\nu}$	88%		80%

Global fits as of end of May 2010
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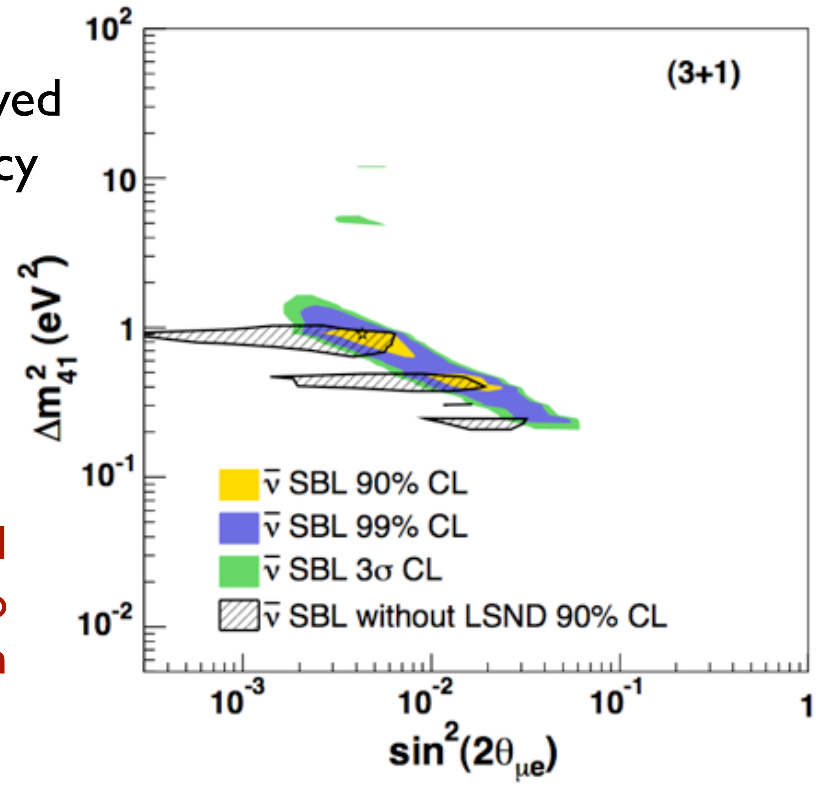
[Back to (3+1) results:]

- However, antineutrino data alone showed high compatibility (30%) and consistency with two-neutrino oscillations

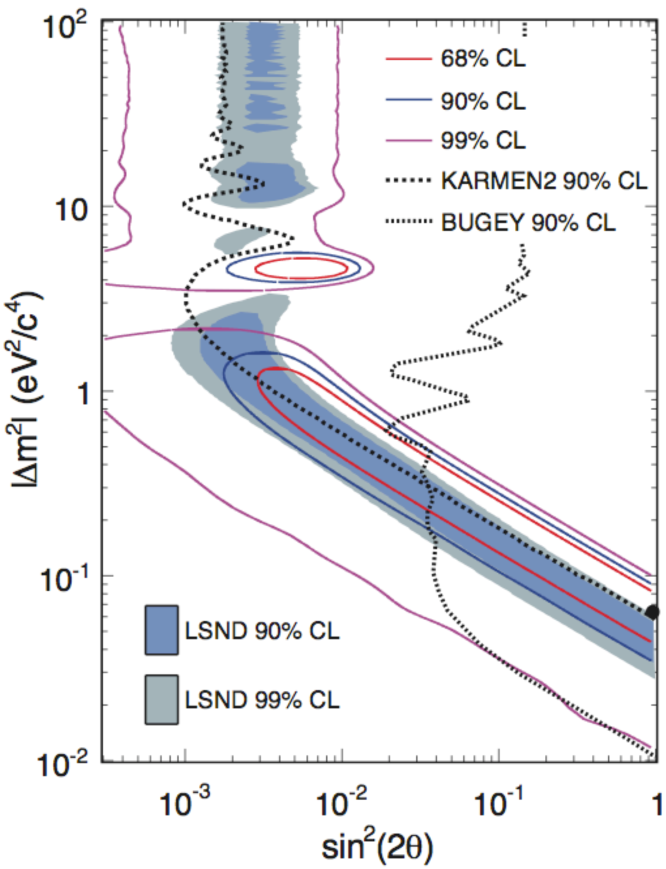


Oscillation hypothesis favored at >3σ in a two-neutrino oscillation approximation

- Why? Antineutrino disappearance data only constrain $|U_{e4}|$; $|U_{\mu4}|$ remains unconstrained in these fits, and can be large enough to accommodate observed appearance signals in MiniBooNE($\bar{\nu}$) and LSND:

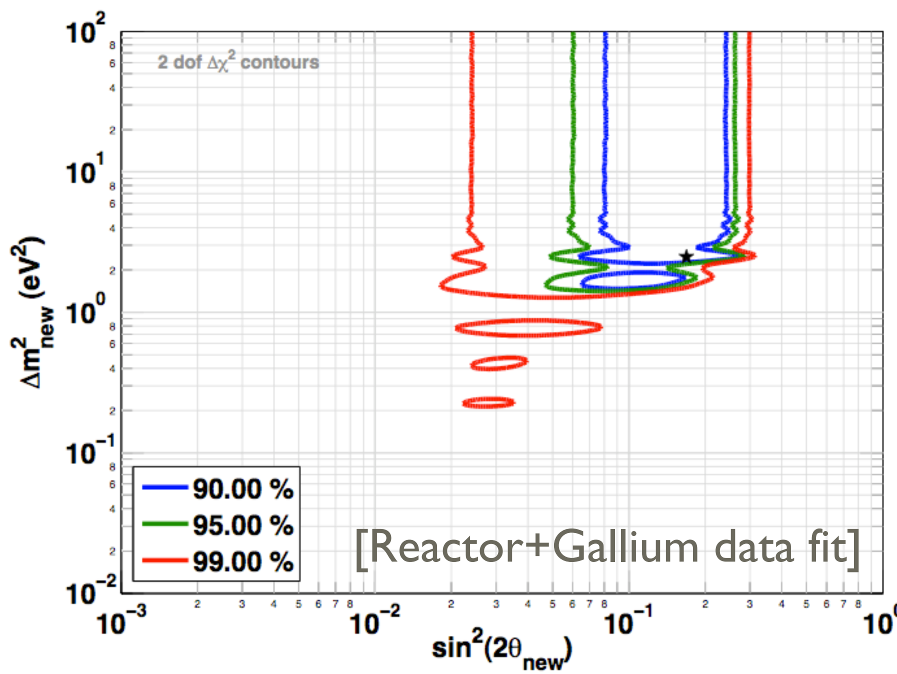
best-fit $\sin^2 2\theta_{\mu\mu}$= 35% (large!!! …what can we learn from MINOS ν_μ disappearance?)

Recent developments: MiniBooNE antineutrino excess and reactor antineutrino anomaly



MiniBooNE Collab., PhysRevLett.105.181801

G. Mention et al., hep-ex/1101.2755



Recent developments: MiniBooNE antineutrino excess and reactor antineutrino anomaly

- MiniBooNE antineutrino result:

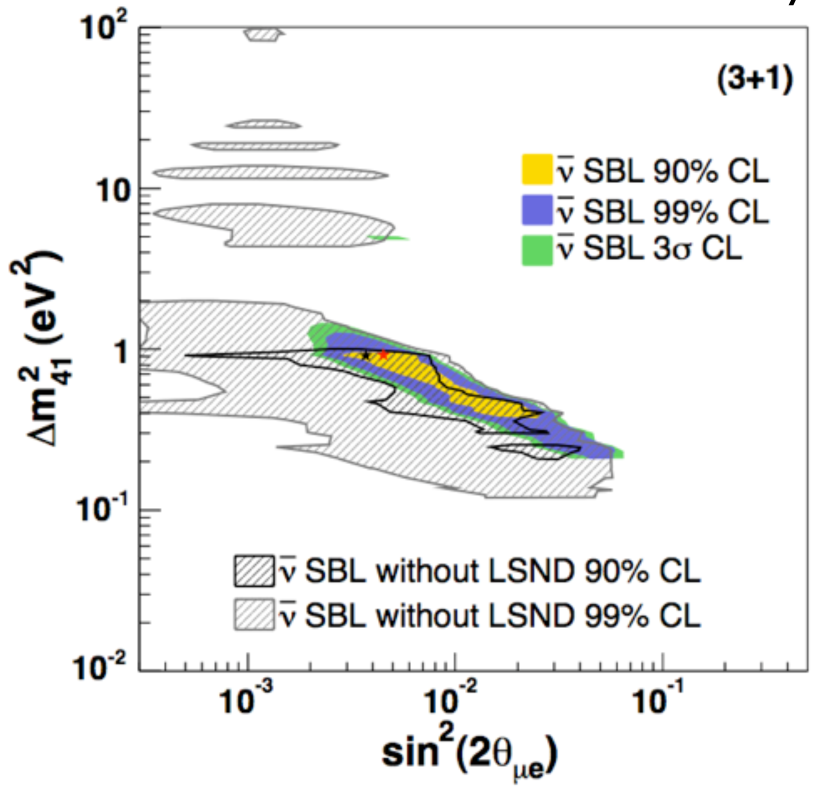
  Brought fits to a "deadend."

  Simultaneous fit to neutrinos and antineutrinos does not work: no way to reconcile with constraints from SBL+atm disappearance experiments

all SBL+atm	(3+1) compat.	: 0.04%
	(3+2) CPV	: 3%

Has already led to consideration of (effectively) CPT-violating models…

[CPT? Inclusion of latest MiniBooNE antineutrino data to antineutrino-only fit]



Recent developments: MiniBooNE antineutrino excess and reactor antineutrino anomaly

- Reactor antineutrino anomaly:

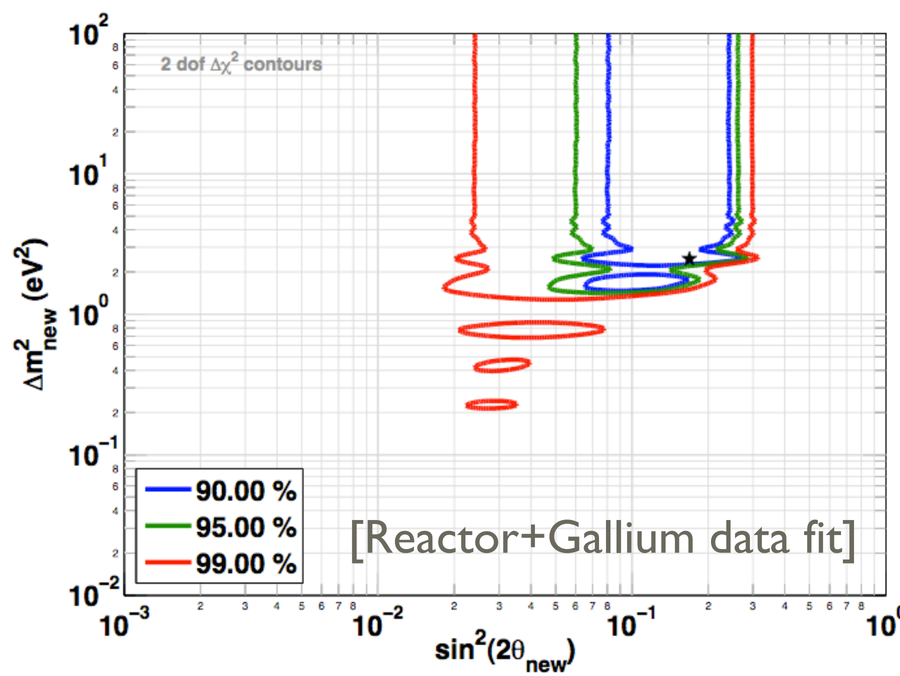
A glimpse of hope for sterile neutrinos?

G. Mention et al., hep-ex/1101.2755

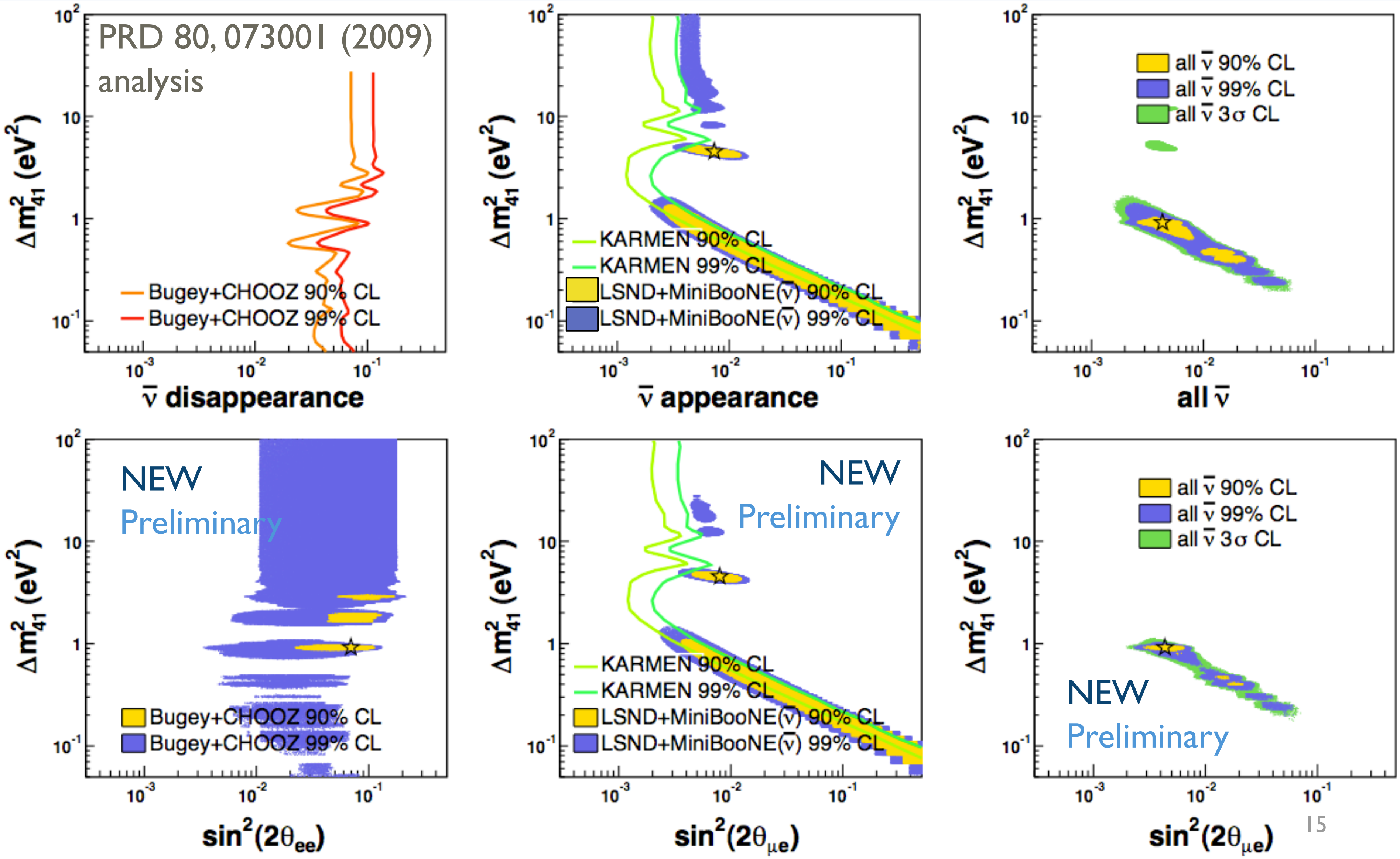
Reactor (mainly antineutrino) spectra show deficits at the level of ~3% →

Possible interpretation: Disappearance due to new (fourth) neutrino mass state,

$\Delta m^2_{41} \sim 2$ eV^2
$\sin^2 2\theta_{ee} \sim 0.16$



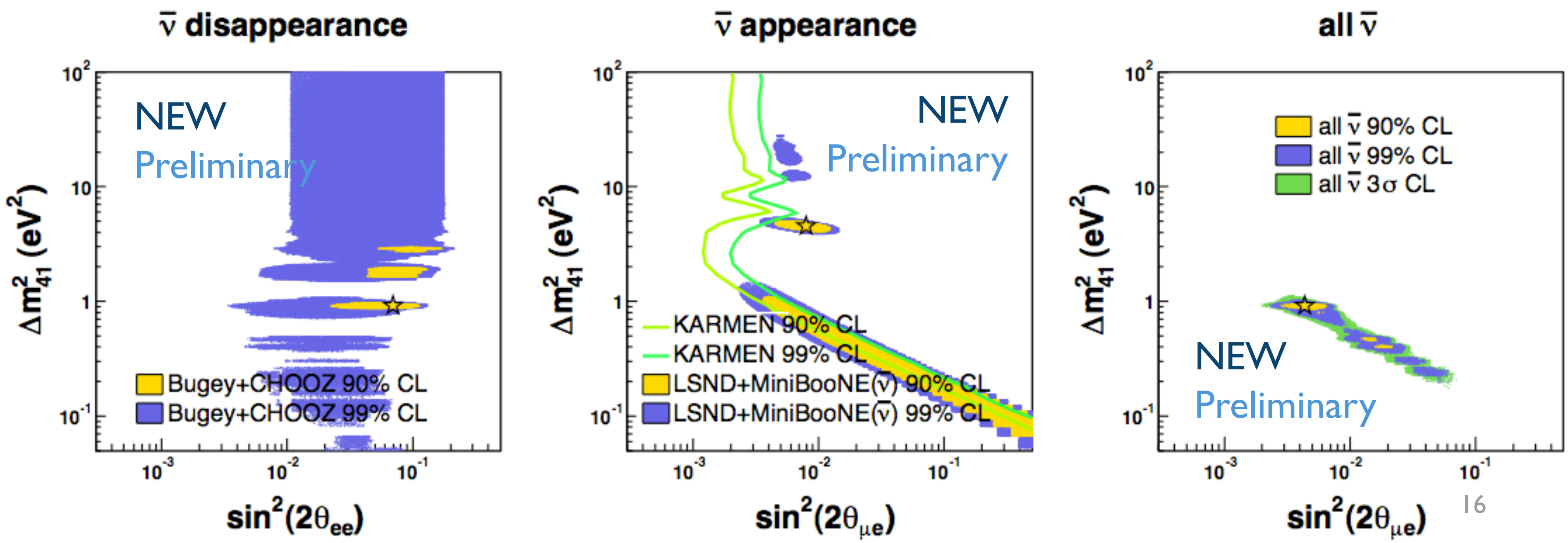
Updated fits: (3+1), antineutrino-only



Updated fits: (3+1), antineutrino-only

Now, reactor data from CHOOZ and Bugey yield allowed parameters at >99% CL rather than limits to $\sin^2 2\theta_{ee}$

Antineutrino SBL compatibility: 22% (reduction due to MiniBooNE($\bar{\nu}$))



Updated fits: (3+2)

PRELIMINARY

Dataset	CP	χ^2 (ndf)	gof	Δm^2_{41}	Δm^2_{51}	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	$\lvert U_{e5}\rvert$	$\lvert U_{\mu 5}\rvert$	ϕ_{45}
all SBL+ atm	**CPC**	186.1 (193)	62%	0.92	23.8	0.13	0.13	0.083	0.14	0
	CPV	182.6 (192)	67%	0.92	26.6	0.14	0.14	0.077	0.15	1.7π
all SBL+ atm	**CPC**	191.5 (193)	52%	0.92	24.0	0.12	0.14	0.070	0.14	0
	CPV	189.3 (192)	54%	0.92	26.5	0.13	0.13	0.078	0.15	1.7π

OLD: PRD 80 073001 (2009)

NEW: includes updated MiniBooNE antineutrino appearance dataset, and new reactor flux predictions

Best fit parameters essentially unchanged. Small improvements in χ^2.

Change in χ^2 OLD→NEW — CPC: 5.4/0 dof; CPV: 6.7/0 dof

Change in χ^2 CPC→CPV — NEW: 3.5/1 dof; OLD: 2.2/1 dof

Compatibility among all SBL+atm: 7% → 6% (decrease is due to MiniBooNE($\bar{\nu}$))

Status of light sterile neutrino oscillations given recent developments

- Almost all hints consistent with light sterile neutrino oscillations come from antineutrino experiments…

- However, especially with the addition of the latest MiniBooNE antineutrino results, mass and mixing parameters allowed by antineutrino datasets <u>found in conflict</u> with constraints from neutrino experiments, even after invoking the possibility of CP violation.

  The <u>new reactor flux spectra reduce some of the tension</u> seen previously between neutrino and antineutrino data in CP violating sterile neutrino oscillation fits…

Promising for "New Physics" supporters… but not the end of the story.

Near-future constraints/signals(?)

- MiniBooNE, plans to more than double antineutrino statistics (relative to most recent result) — End of run in March 2012
- MicroBooNE (LArTPC), can resolve the low energy excess seen in MiniBooNE as electron-like (e.g. sterile neutrinos) or photon-like (something else) — CD1 approved; commissioning in 2013
- Joint MiniBooNE/SciBooNE $\bar{\nu}_\mu$ disappearance search — Analysis in progress
- MINOS $\bar{\nu}_\mu$ disappearance — Preliminary results
- IceCube/DeepCore, atmospheric neutrino high-Δm^2 oscillation search (covers the range $0.001 < L/E < 100$ km/GeV)
- Other ideas: two LArTPC at CERN-PS, BooNE, two LArTPC at BNB, OscSNS,…

Conclusions

- Several anomalies seen, consistent independently and jointly with high-Δm^2 oscillations

- MiniBooNE recent antineutrino results (Neutrino2010) and reactor flux re-analysis strengthens the case for light sterile neutrino oscillations…

- If light sterile neutrino oscillations are realized in nature,
  - Huge implications for particle physics!
  - Given current indications, they would provide a unique opportunity for measurements of CP violation in the lepton sector → huge implications for our understanding of the universe!