Reactor anomaly, θ_{13}, and sterile neutrinos

Neutrino Telescopes 2011

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Outline

- The reactor anomaly

  refer to previous talk

- Implications for θ_{13}

  TS, Tortola, Valle, 1103.0734

- Sterile neutrinos

  Kopp, Maltoni, TS, 1103.xxx

- Summary and outlook

Outline

The reactor anomaly

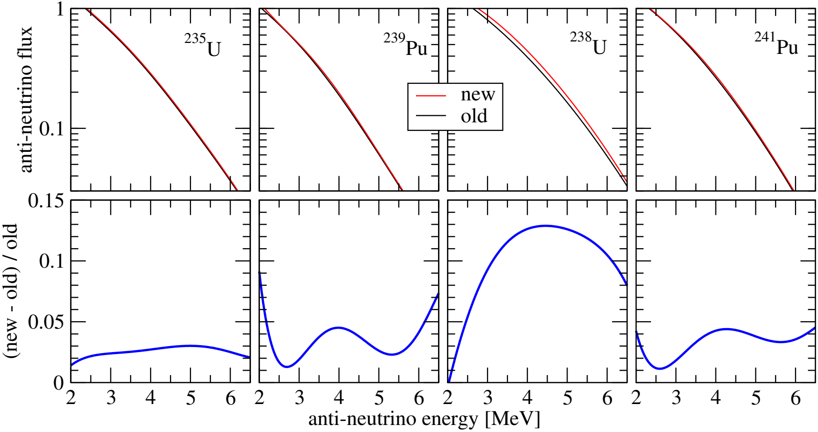
θ_{13}

Sterile neutrinos

Summary and outlook

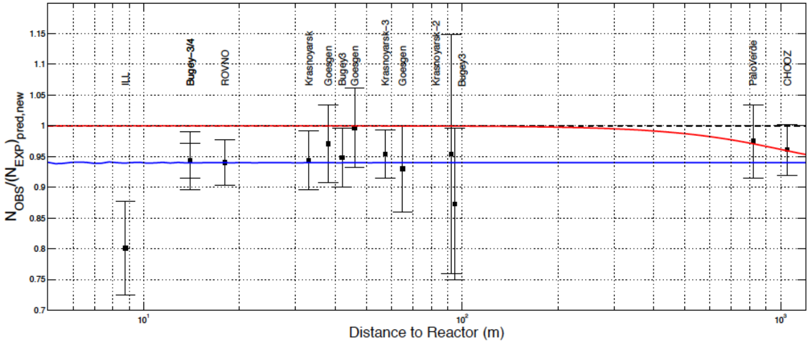
New reactor anti-neutrino flux predictions

"new" fluxes Mueller et al., 1101.2663 compared to "old" fluxes Schreckenbach et al., 82, 85, 89



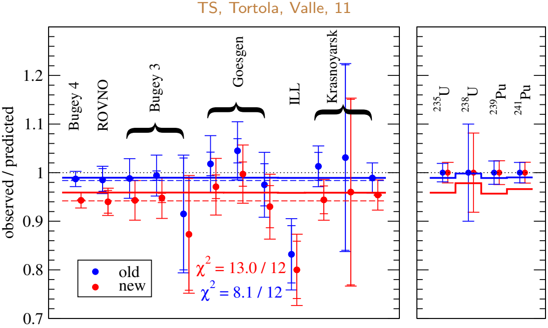
New reactor fluxes and reactor data

Mention et al., 1101.2755, talk by T. Lasserre



are we seeing θ_{13}, sterile neutrinos, or just a systematic error?

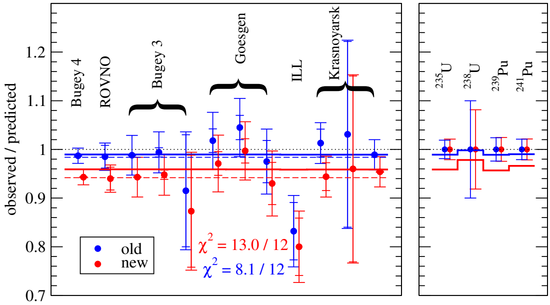
New reactor fluxes and SBL reactor data



- still very good fit (within quoted uncertainties): P-value 37%
- flux free analysis (dashed lines)
  old flux best fit: $f = 0.984$ ($f = 1$ within 1 σ)
  new flux best fit: $f = 0.942$ ($f = 1$: $\Delta\chi^2 = 6.2 \to 2.5\sigma$)
- sterile neutrino with $\Delta m^2 \gtrsim 1$ eV^2: $f \to \frac{1}{2}\sin^2 2\theta$

New reactor fluxes and SBL reactor data

TS, Tortola, Valle, 11



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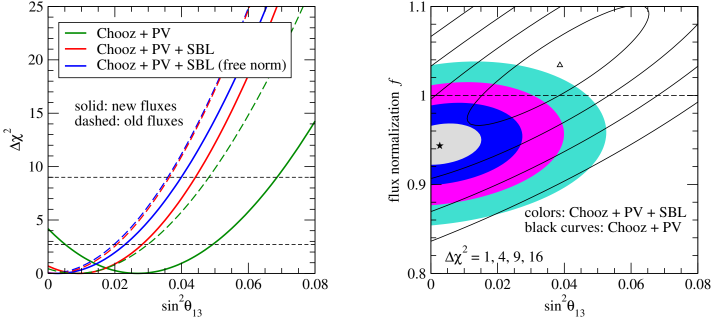
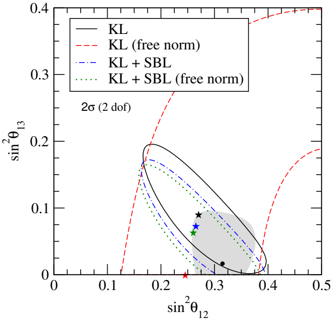
Outline

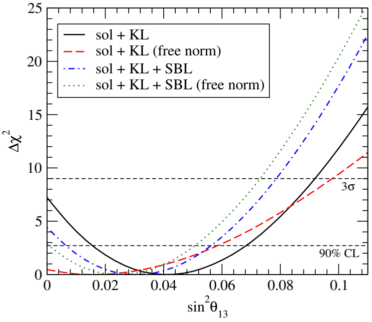
Reactor data and θ_{13}



- using only CHOOZ and Palo Verde leads to a hint for $\theta_{13} > 0$ at 2σ
- if SBL data are included the hint disappears and limits become similar with old and new fluxes

Solar and KamLAND data and θ_{13}





- KamLAND prefers a non-zero θ_{13}
- solar + KamLAND + SBL react:
  $\sin^2\theta_{13} = 0.030^{+0.015}_{-0.016}$, $\Delta\chi^2(\sin^2\theta_{13} = 0) = 4.4$ (2.1σ)

  old fluxes: $\Delta\chi^2(\sin^2\theta_{13} = 0) = 2.2$

Atmospheric and MINOS data

- MINOS $\nu_\mu \to \nu_e$ appearance data: $(7 \times 10^{20}$ pot)
  54 electron neutrino events, $49.1 \pm 7.0 \pm 2.7$ expected (0.7σ)
- SK I+II+II SK Coll, 1002.3471: $\Delta\chi^2(\sin^2\theta_{13} = 0) = 0(0.3)$ for NH (IH)

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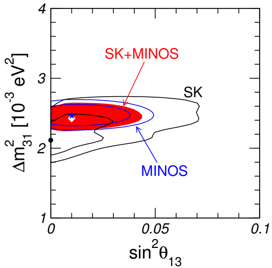
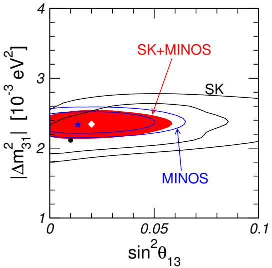
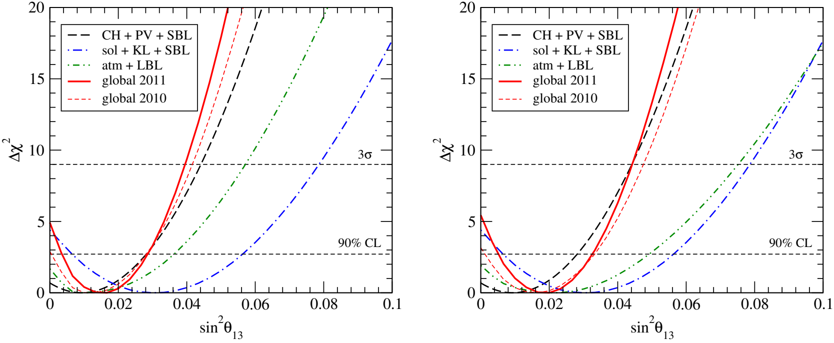
- but there is a $\sim 1\sigma$ hint from SK + MINOS combined:





$\Delta\chi^2(\theta_{13} = 0) = 1.6(1.9)$ for NH (IH)

Global data on θ_{13}



	$\sin^2\theta_{13}$	$\Delta\chi^2(\theta_{13}=0)$	3σ bound
NH	$0.017^{+0.007}_{-0.009}$	4.9 (2.2σ)	0.040
IH	$0.020^{+0.008}_{-0.009}$	5.4 (2.3σ)	0.044

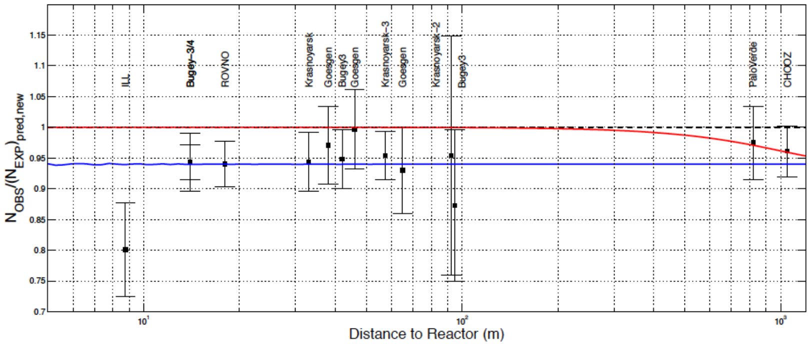
θ_{13} depends on SBL reactor treatment

	$\sin^2\theta_{13}$	$\Delta\chi^2(\theta_{13}=0)$	3σ bound
solar + KamLAND + SBL	$0.030^{+0.015}_{-0.016}$	4.4 (2.1σ)	0.079
Chooz + Palo Verde + SBL	$0.009^{+0.012}_{-0.011}$	0.7 (0.8σ)	0.044
atmospheric + MINOS	$0.010^{+0.016}_{-0.008}$ $0.020^{+0.018}_{-0.015}$	1.7 (1.3σ) 1.9 (1.4σ)	0.057 0.075
atmos + MINOS + solar	$0.013^{+0.014}_{-0.009}$ $0.020^{+0.015}_{-0.012}$	2.3 (1.5σ) 2.7 (1.6σ)	0.053 0.065
global with SBL	$0.017^{+0.007}_{-0.009}$ $0.020^{+0.008}_{-0.009}$	4.9 (2.2σ) 5.4 (2.3σ)	0.040 0.044
global with SBL (free norm)	$0.010^{+0.009}_{-0.006}$ $0.013^{+0.010}_{-0.007}$	3.1 (1.8σ) 3.3 (1.8σ)	0.036 0.041
global w/o SBL	$0.023^{+0.010}_{-0.008}$ 0.030 ± 0.010	9.0 (3.0σ) 10.3 (3.2σ)	0.052 0.058
global w/o SBL (old fluxes)	$0.012^{+0.010}_{-0.007}$ 0.017 ± 0.010	2.9 (1.7σ) 3.2 (1.8σ)	0.042 0.048

Outline

New reactor fluxes and sterile neutrinos

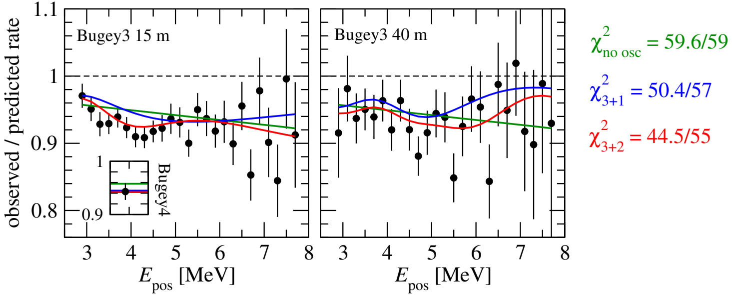
Mention et al., 1101.2755, talk by T. Lasserre



oscillations with $\Delta m^2 \sim 1$ eV^2 may account for disappearance at baselines $L \lesssim 100$ m

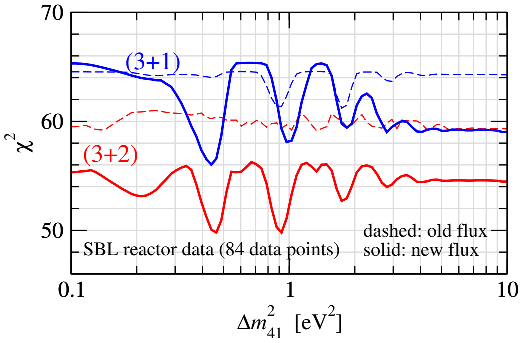
3+1 and 3+2 best fit to SBL reactor data

fitting reactor data by adding one or two sterile neutrinos



	Δm^2_{41} [eV^2]	$\lvert U_{e4}\rvert$	Δm^2_{51} [eV^2]	$\lvert U_{e5}\rvert$
$(3+1)$	0.45	0.117		
$(3+2)$	0.46	0.115	0.93	0.115

3+1 and 3+2 fit to SBL reactor data



- preference for sterile neutrino oscillations
- $\Delta\chi^2(3+1/\text{no-osc}) = 9.3 \to 99\%$ CL (2 dof)
- $\Delta\chi^2(3+2/\text{no-osc}) = 15.4 \to 99.6\%$ CL (4 dof)
- old flux: $\Delta\chi^2 = 3.3(5.4)$ for 3+1 (3+2)

$\nu_\mu \to \nu_e$ data at the $E/L \sim 1$ eV^2 scale

- LSND $\bar\nu_\mu \to \bar\nu_e$, $87.9 \pm 22.4 \pm 6.0$ excess events
  $P = (0.264 \pm 0.067 \pm 0.045)\% \sim 3.8\sigma$ away from zero
- MiniBooNE $\bar\nu_\mu \to \bar\nu_e$, $\sim 2\sigma$ excess
  consistent with LSND in 2ν framework
- MiniBooNE $\nu_\mu \to \nu_e$
  $E > 475$: no excess, $E < 475$: $\sim 3\sigma$ excess talk by G. Mills
- KARMEN $\bar\nu_\mu \to \bar\nu_e$, tight constraint on LSND region
  (slightly smaller L/E than LSND)

3+1 oscillations

In 3+1 schemes the appearance probability at short-baselines is effectively 2-ν oscillations:

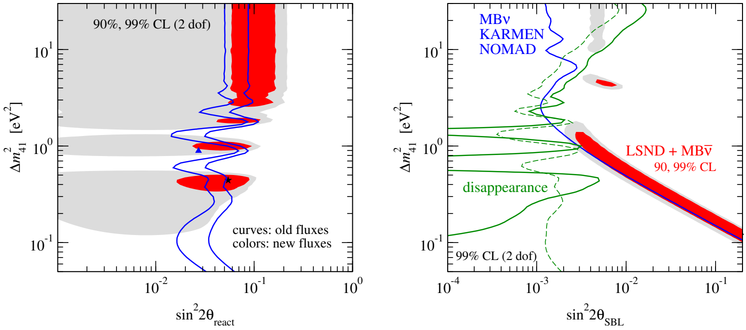
$$P_{\mu e} = \sin^2 2\theta_{\rm SBL} \sin^2 \frac{\Delta m^2_{41} L}{4E}$$

with

$$\sin^2 2\theta_{\rm SBL} = 4|U_{e4}|^2 |U_{\mu 4}|^2$$

- no CP violation
- constraints from ν_e (ν_μ) disappearance experiments on U_{e4} ($U_{\mu 4}$)

3+1 global



despite relaxed constraints from reactors on U_{e4}
no improvement of global 3+1 fit

3+2 appearance probability

$$
\begin{aligned}
P_{\nu_\mu \to \nu_e} &= 4\,|U_{e4}|^2 |U_{\mu 4}|^2 \sin^2\phi_{41} \\
&+ 4\,|U_{e5}|^2 |U_{\mu 5}|^2 \sin^2\phi_{51} \\
&+ 8\,|U_{e4} U_{\mu 4} U_{e5} U_{\mu 5}| \sin\phi_{41} \sin\phi_{51} \cos(\phi_{54} - \delta)
\end{aligned}
$$

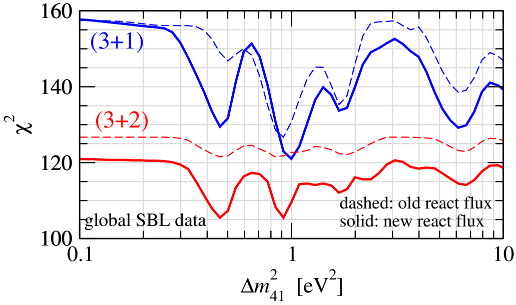
with the definitions

$$
\phi_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E}\,, \qquad \delta \equiv \arg\left(U^*_{e4} U_{\mu 4} U_{e5} U^*_{\mu 5}\right)
$$

- 3+2 osc. include the possibility of CP violation Karagiorgi 07
  remember: MiniBooNE: neutrinos, LSND: anti-neutrinos
- good fit to appearance exps (even MB low-E) Maltoni, TS 07

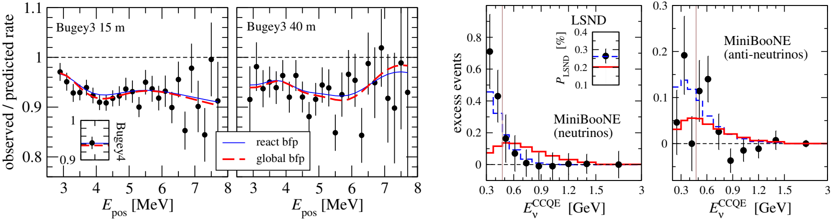
3+2 global fit

Δm^2_{41}	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	Δm^2_{51}	$\lvert U_{e5}\rvert$	$\lvert U_{\mu 5}\rvert$	δ/π	χ^2/dof
0.47	0.131	0.170	0.93	0.135	0.142	1.62	105.9/130



- $\Delta\chi^2$ (old vs new fluxes) = 15.5
- $\Delta\chi^2$ (3+1 vs 3+2) = 14.1 (99.3% CL, 4 dof)

3+2 best fit point



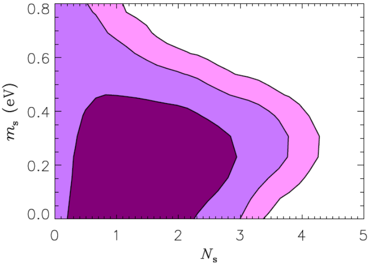
$\Delta\chi^2$ between global bfp and app/disapp separate bfp:

LSND	MB$\bar{\nu}$	MBν	KAR	React	CDHS	Atmos
1.2	2.9	2.5	1.5	0.9	2.4	2.3

Kopp, Maltoni, TS, 1103.xxxx

Other signatures of sterile neutrinos

- checked solar/KamLAND fit: U_{e4}, U_{e5} similar effect as U_{e3}
- MINOS NC 1001.0336 analysis may give additional constraints
- Deficit in radioactive source experiments at Gallium exps C. Giunti
- Cosmology:



CMB, SDSS, HST
Hamann et al., 1006.5276

talk by A. Melchiorri

- BBN: $N_s < 1.2$ (95% CL) Mangano, Serpico, 1103.1261

Outline

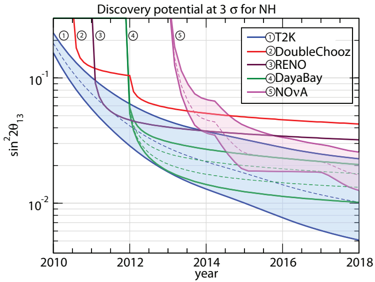
Summary

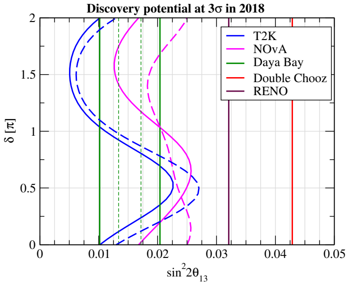
- slightly ambiguous status of θ_{13} due to new reactor fluxes:
  $\sin^2\theta_{13} = 0.1 - 0.3$ with hints for $\theta_{13} > 0$ at $1.8 - 3.2\sigma$

- intriguing accumulation of hints for eV-scale sterile neutrinos (LSND/MiniBooNE/reactor/Gallium)
  3+2 model with two eV-scale neutrinos gives good fit to global data

Outlook θ_{13}

Huber, Lindner, TS, Winter, 09; Mezzetto, TS, 10





width beams: dependence on CP phase, DayaBay: syst. uncert. 0.18% - 0.6%

- one order of magnitude improvement within $\sim$ 5 years talks in next session
- can disentangle θ_{13} from effects of sterile neutrinos by near-far comparison (reactors: cancel flux uncert. + sterile ν, beams: predict background from ND to avoid effects of sterile ν - check L/E!)

Outlook sterile neutrinos

how can we clarify the issue of eV-scale neutrinos?

- radioactive source experiments

  Garvin et al, 1006.2103; Vergados, Novikov, 1006.3862; Grieb, Link, Raghavan, hep-ph/0611178;...

- new experiment at CERN talk by C. Rubbia
- LSND-like experiment at stopped pion source (ESS) talk by H. Wacklin
- look for ν_μ disappearance at the eV^2 scale
- signatures in IceCube (Deep Core)? S. Coubey, 0709.1937
- etc