Neutrino oscillation update: Hints for θ_{13} and eV sterile neutrinos

GDR neutrino, Annecy, 28 Nov 2011

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Outline

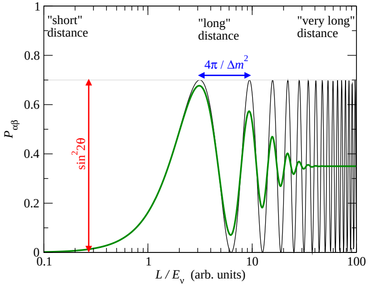
Neutrino oscillations

... require that there is

- mixing in the lepton sector, and
- neutrinos have non-degenerate masses.

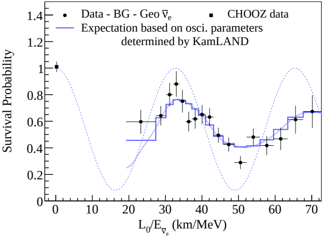
Two-flavour vacuum oscillations:

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}, \qquad P = \sin^2 2\theta \, \sin^2 \frac{\Delta m^2 L}{4E_\nu}$$



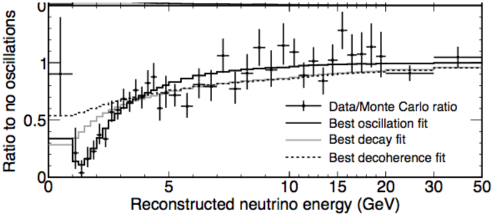
Neutrinos oscillate!

KamLAND ($\bar{\nu}_e \to \bar{\nu}_e$)



$>5\sigma$ evidence for spectral distortion

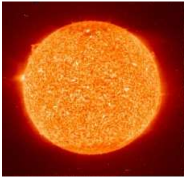
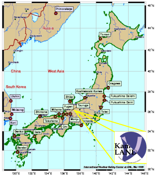
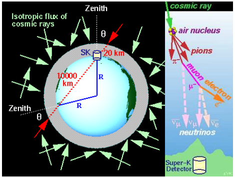
MINOS ($\nu_\mu \to \nu_\mu$)



$$P_{\text{survival}} \approx 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4}\frac{L}{E_\nu}\right)$$

Global data on neutrino oscillations

from various neutrino sources and
vastly different energy and distance scales:

sun	reactors	atmosphere	accelerators
			
Homestake,SAGE,GALLEX SuperK, SNO, Borexino	KamLAND, CHOOZ	SuperKamiokande	K2K, MINOS, T2K

- global data fits nicely with the 3 neutrinos from the SM
- a few "anomalies" at 2-3 σ: LSND, MiniBooNE, reactor anomaly, no LMA MSW up-turn of solar neutrino spectrum

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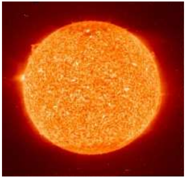	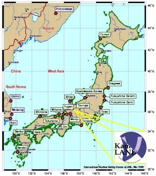	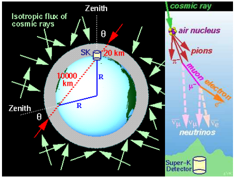	
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- global data fits nicely with the 3 neutrinos from the SM
- a few "anomalies" at 2-3 σ: LSND, MiniBooNE, reactor anomaly, no LMA MSW up-turn of solar neutrino spectrum
- OPERA result on super-luminal neutrinos?? 100+ cites

Outline

3-flavour oscillation parameters

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

3-flavour oscillation parameters

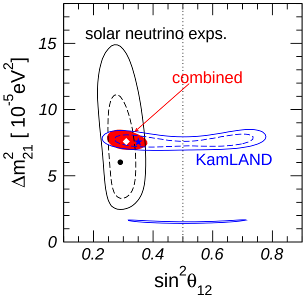
$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\Delta m^2_{31}\text{: atmos+LBL(dis)}} \underbrace{\begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix}}_{\Delta m^2_{31}\text{: Chooz+LBL(app)}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\Delta m^2_{21}\text{: solar+KamLAND}}$$

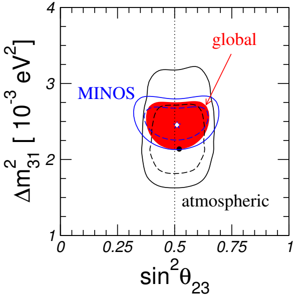
3-flavour effects are suppressed: $\Delta m^2_{21} \ll \Delta m^2_{31}$ and $\theta_{13} \ll 1$ ($U_{e3} = s_{13} e^{-i\delta}$)

$\Rightarrow$ dominant oscillations are well described by effective two-flavour oscillations

$\Rightarrow$ CP-violation is suppressed by θ_{13} and $\Delta m^2_{21}/\Delta m^2_{31}$

The dominanting oscillation modes

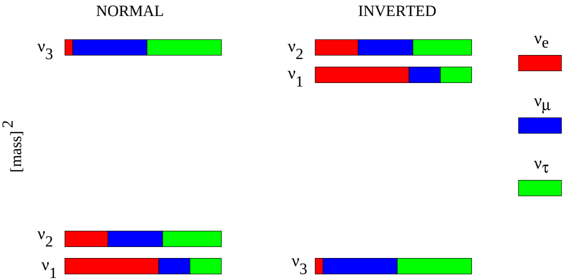




$\sin^2\theta_{12} \approx 0.3$ $\sin^2\theta_{23} \approx 0.5$

$$\frac{\Delta m^2_{21}}{\Delta m^2_{31}} \approx \frac{1}{30}$$

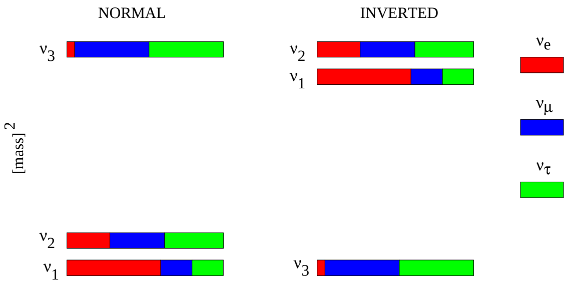
Neutrino mass spectra and mixing



$\Delta m^2_{31} > 0$ $\Delta m^2_{31} < 0$

- ν_1 is dominantely ν_e (non-maximal but large θ_{12})
  close to equal mixing of ν_μ and ν_τ ($\theta_{23} \approx 45^\circ$)
- we know the sign of Δm^2_{21} (matter effect in sun) but not of Δm^2_{31}
- we do not know yet the ν_e component of ν_3 (θ_{13})

Effects of θ_{13}



1. transitions of ν_e involving Δm^2_{31}:
   1.1 $\bar{\nu}_e$ disappearance at reactors with $L \simeq 1$ km
   1.2 $\nu_\mu \to \nu_e$ transitions at accelerator experiments
2. subleading effects in solar/KamLAND/atmospheric oscillations

Measuring θ_{13}

two complementary approaches towards θ_{13}:

- $\bar{\nu}_e \to \bar{\nu}_e$ disappearance reactor experiments:
  CHOOZ, Double Chooz, Daya Bay, RENO

- long-baseline accelerator experiments looking for
  $\nu_\mu \to \nu_e$ appearance: **MINOS, T2K, NOvA**

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  "clean" measurement of θ_{13}:

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E_\nu} + \mathcal{O}\left(\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right)^2$$

  $\Rightarrow$ bring stat. and syst. errors below % level

- long-baseline accelerator experiments looking for
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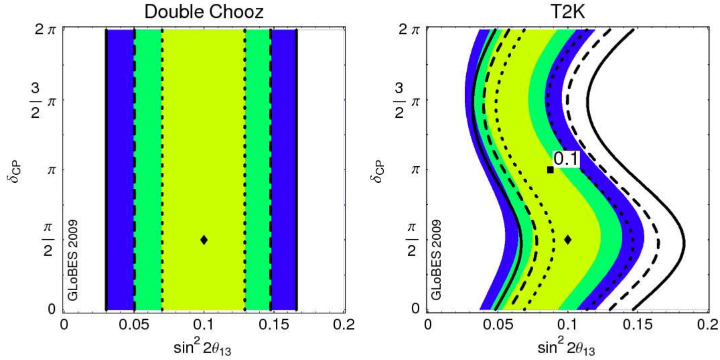
- long-baseline accelerator experiments looking for
  $\nu_\mu \rightarrow \nu_e$ appearance: **MINOS, T2K, NOvA**
  $P_{\mu e}$ is a complicated function of all 3-flavour parameters
  θ_{13} is correlated with other parameters (CP-phase δ, sign of Δm^2_{31})

Reactor vs Beam

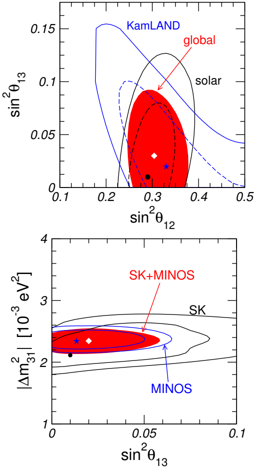
assume $\sin^2 2\theta_{13} = 0.1$, $\delta = \pi/2$

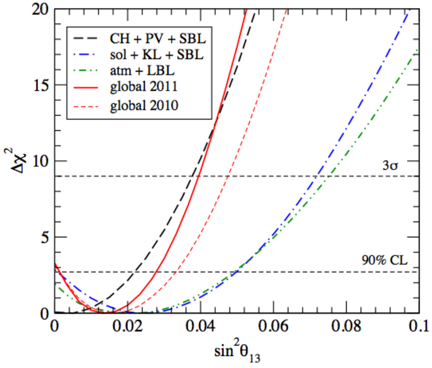


fake data! Huber et al, 2004, 2009,...

θ_{13} till June 2011

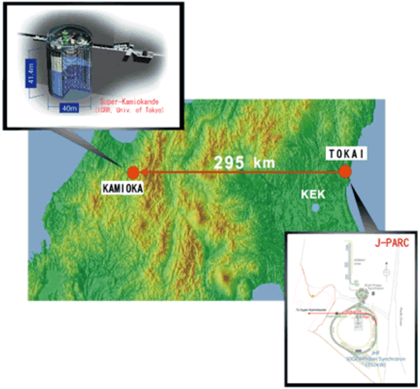
$\sin^2\theta_{13} \lesssim 0.04$ (3σ) from global data (dominated by CHOOZ)
$\theta_{13} > 0$ @ 1.8σ from slight tension between solar/KamL and MINOS/SK





TS, Tortola, Valle, 08, 1103; Fogli et al, 08;
Gonzalez-Garcia, Maltoni, Salvado, 10

T2K data on $\nu_\mu \to \nu_e$ appearance



search for $\nu_\mu \to \nu_e$ oscillations with $L = 295$ km and $E_\nu \simeq 0.7$ GeV

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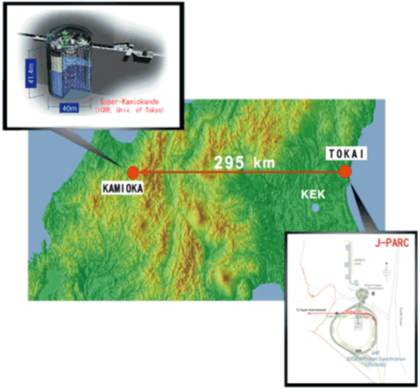
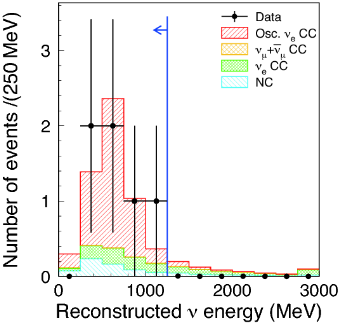


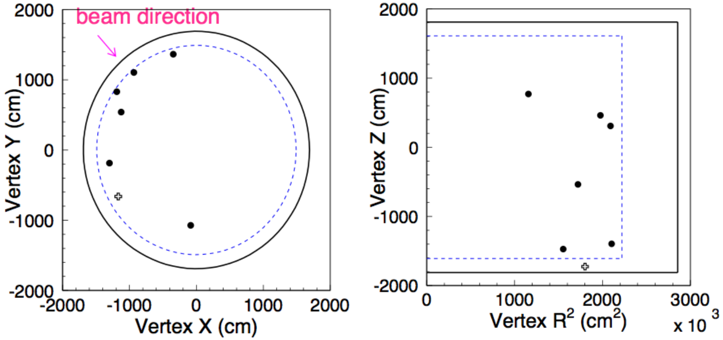


K. Abe et al., 1106.2822

search for $\nu_\mu \to \nu_e$ oscillations
with $L = 295$ km and
$E_\nu \simeq 0.7$ GeV

6 events obs
1.5 ± 0.3 expected for $\theta_{13} = 0$
2.5σ indication for $\theta_{13} > 0$

Vertex distribution of T2K ν_e events

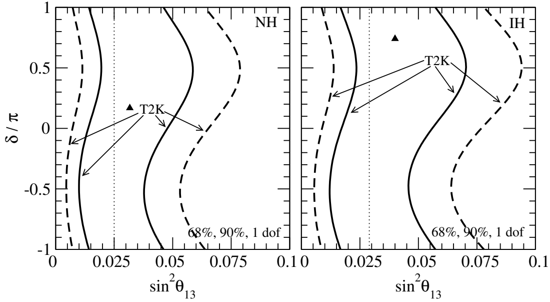


prob to obtain 6 events in front half of detector: $1/2^6 = 1/64 \approx 0.015$
this is approximately the probablity of $\theta_{13} = 0$

K.S. test of R^2 distribution gives $p = 0.03$ (2.2σ)

Recent data on $\nu_\mu \to \nu_e$ appearance

- T2K: 6 events obs (1.5 ± 0.3 expected for $\theta_{13} = 0$)
  2.5σ indication for $\theta_{13} > 0$ T2K, 1106.2822



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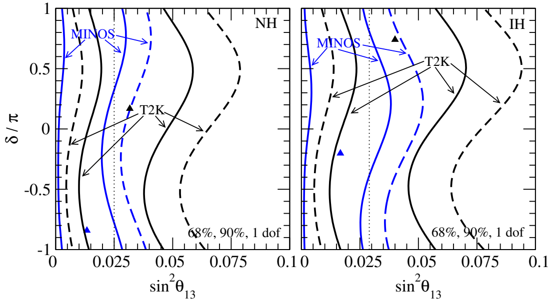
- MINOS: 62 events obs ($49.6 \pm 7.0 \pm 2.7$ expected for $\theta_{13} = 0$)
  consistent with $\theta_{13} = 0$ MINOS, 1108.0015



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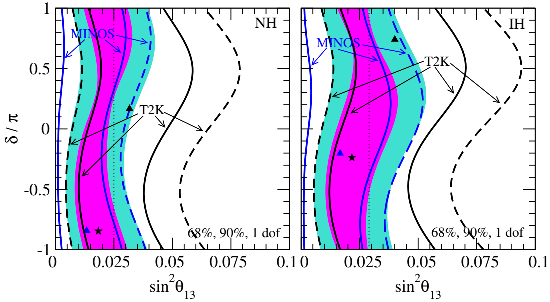
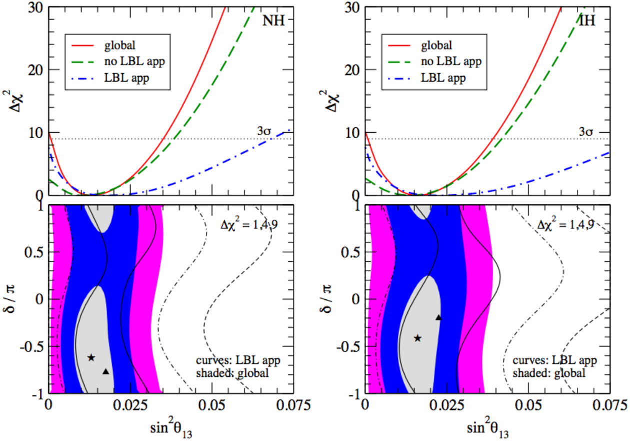


Global data on θ_{13} TS, Tortola, Valle, 1108.1376



$$\sin^2\theta_{13} = 0.013^{+0.007}_{-0.005} \qquad \sin^2\theta_{13} = 0.016^{+0.008}_{-0.006}$$

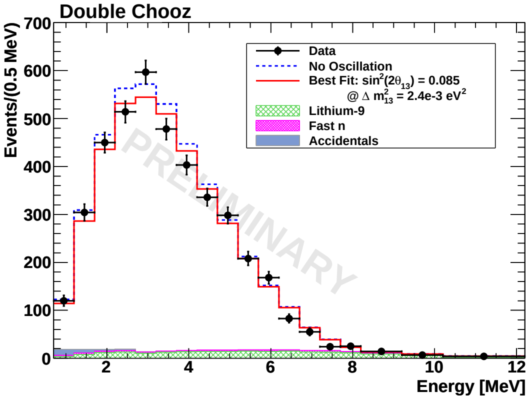
$$\theta_{13} = 0: \ \Delta\chi^2 = 10.1\,(3.2\sigma)$$

similar results by Fogli et al, 1106.6028; Maltoni @ EPS11

Preliminary results from Double Chooz

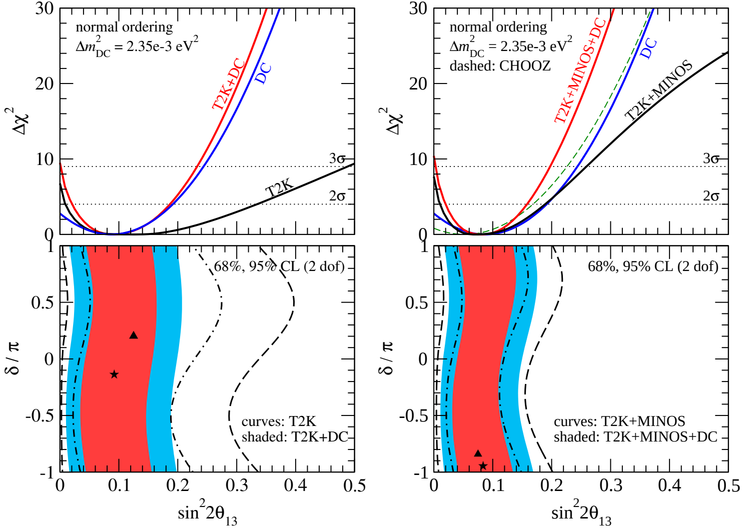
H. deKerret, talk @ LowNu, Korea, 11 Nov 2011

data from April 13 to Sept 18 (101.5 days)



$$\sin^2 2\theta_{13} = 0.085 \pm 0.029(\text{stat}) \pm 0.042(\text{syst}) \qquad (> 0 \,@\, 1.7\sigma)$$

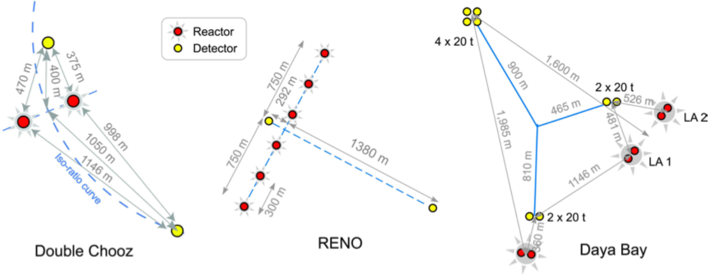
Preliminary results from Double Chooz



$\theta_{13} = 0$ excluded at 3σ

Upcoming experiments searching for θ_{13}

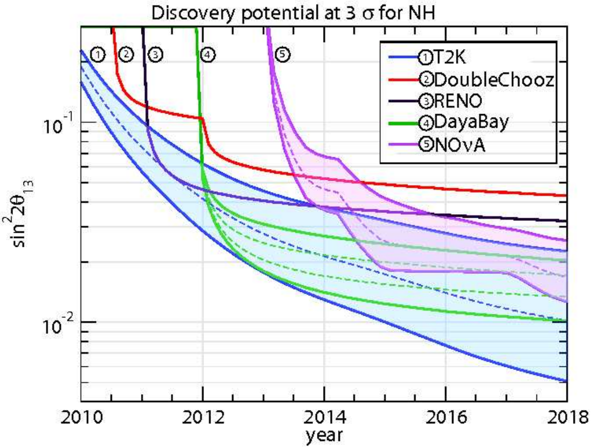
- $\bar{\nu}_e \to \bar{\nu}_e$ disappearance reactor experiments:



- long-baseline accelerator experiments looking for $\nu_\mu \to \nu_e$ appearance:
  T2K: $E_\nu \simeq 0.7$ GeV, $L \approx 295$ km, off-axis 2.5°
  NOvA: $E_\nu \simeq 2$ GeV, $L \approx 810$ km, off-axis 0.8°

Near term prospects for θ_{13}

upcoming reactor and accelerator experiments



Mezzetto, TS, 10

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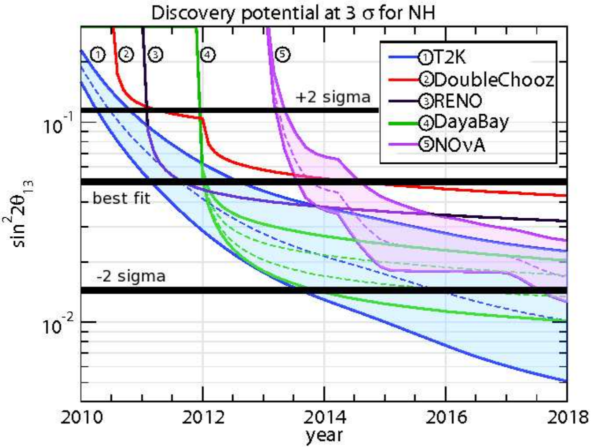


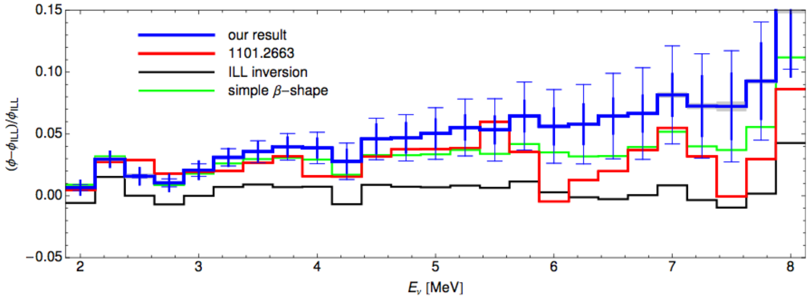
Mezzetto, TS, 10

Outline

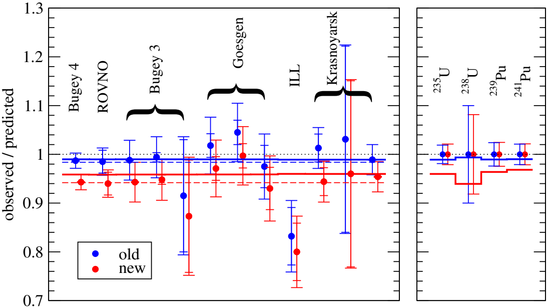
New reactor flux calculations

- to predict the $\bar{\nu}_e$ flux from nuclear reactors one has to convert the measured e^- spectra from ^{235}U, ^{239}Pu, ^{241}Pu into neutrino spectra

  Schreckenbach et al., 82, 85, 89
- recent improved calculation Mueller et al., 1101.2663 yields $\sim$ 3% higher fluxes
- confirmed by independent calculation P. Huber, 1106.0687



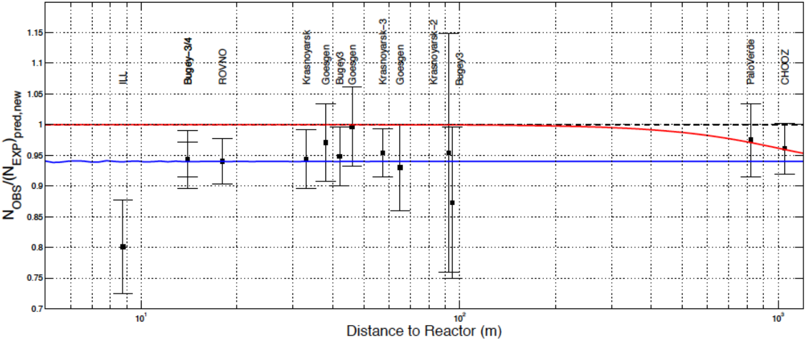
New reactor flux calculations



- $\chi^2 = 8.1(13.0)/12$ dof for old (new) fluxes $\Rightarrow$ still acceptable fit within errors (P-value: 37%)
- flux free analysis: $f = 0.942 \pm 0.024$, $f = 1$ disfavored with $\Delta\chi^2 = 6.2$ (2.5σ)

New reactor fluxes and reactor data

Mention et al., 1101.2755



- non-zero θ_{13} can reduce flux at $L \gtrsim 1$ km but not shorter baselines
- sterile neutrino with $\Delta m^2 \sim 1\,\text{eV}^2$ can account for rate reduction at $L \gtrsim 10 - 100$ m
- systematic error or problem with new calculations?

Dependence of θ_{13} from global fit on SBL reactor data

- new fluxes and including SBL reactors in fit ("default analysis")

$$\sin^2\theta_{13} = 0.013^{+0.007}_{-0.005}\,, \quad \Delta\chi^2 = 10.1\,(3.2\sigma) \qquad \text{(NH)}$$
$$\sin^2\theta_{13} = 0.016^{+0.008}_{-0.006}\,, \quad \Delta\chi^2 = 10.1\,(3.2\sigma) \qquad \text{(IH)}$$

- new fluxes not including SBL reactors in fit

$$\sin^2\theta_{13} = 0.022 \pm 0.008\,, \quad \Delta\chi^2 = 13.5\,(3.7\sigma) \quad \text{(NH)}$$
$$\sin^2\theta_{13} = 0.026 \pm 0.009\,, \quad \Delta\chi^2 = 15.2\,(3.9\sigma) \quad \text{(IH)}$$

- including SBL reactors but allow free flux normalization

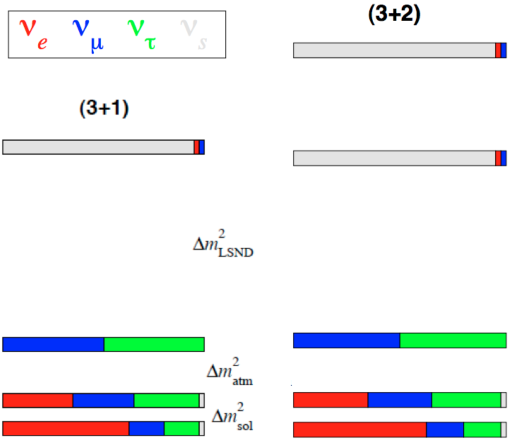
$$\sin^2\theta_{13} = 0.011^{+0.007}_{-0.004}\,, \quad \Delta\chi^2 = 7.7\,(2.8\sigma) \quad \text{(NH)}$$
$$\sin^2\theta_{13} = 0.014^{+0.007}_{-0.006}\,, \quad \Delta\chi^2 = 8.4\,(2.9\sigma) \quad \text{(IH)}$$

Outline

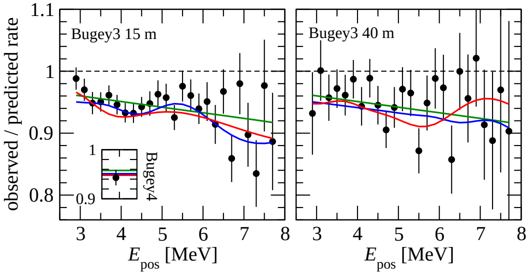
Sterile neutrinos at the eV scale

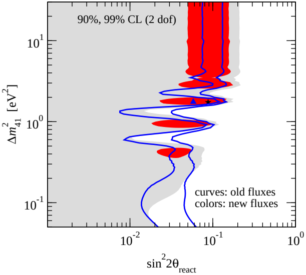
Sterile neutrinos are generic in models for neutrino mass (though typically at much higher scales).

Why not assume that some of them have masses at the eV scale?



Reactor data and sterile neutrinos





	Δm^2_{41} [eV^2]	$\lvert U_{e4}\rvert$	Δm^2_{51} [eV^2]	$\lvert U_{e5}\rvert$	$\Delta\chi^2$(no osc)
3+1	1.78	0.151			8.5 (98% CL 2 dof)
3+2	0.46	0.108	0.89	0.124	12.1 (98% CL 4 dof)

- bounds on $U_{e4,5}$ become “preferred regions” with new reactor fluxes

Mention et al., 11; Kopp, Maltoni, TS, 11

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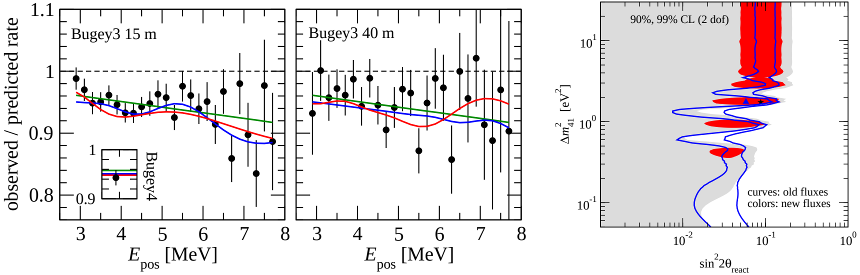

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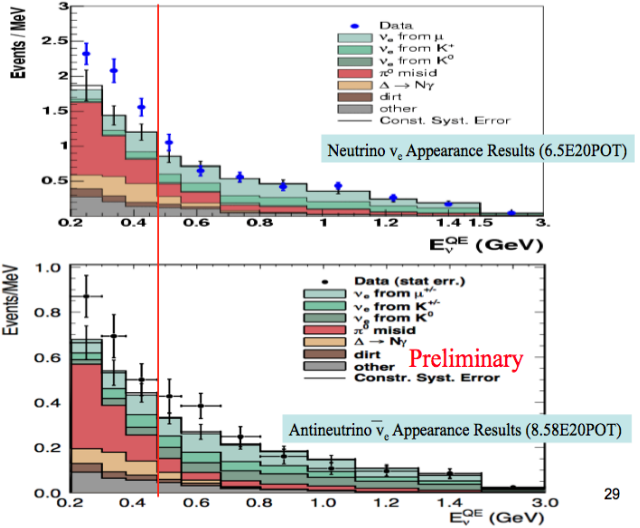
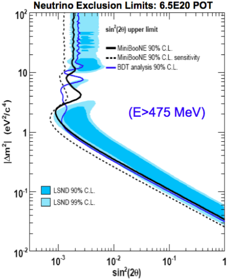
- bounds on $U_{e4,5}$ become "preferred regions" with new reactor fluxes
  Mention et al., 11; Kopp, Maltoni, TS, 11
- hint for $U_{e4} > 0$ from callibration data in gallium solar ν exps ("Gallium anomaly") Acero, Giunti, Laveder, 07;Giunti, Laveder, 10

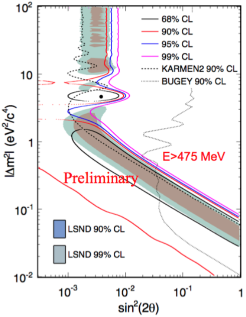
More hints for eV neutrinos from $\nu_\mu \to \nu_e$ searches

- 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
- KARMEN $\bar{\nu}_\mu \to \bar{\nu}_e$, tight constraint on LSND region
  (slightly smaller L/E than LSND)
- MiniBooNE $\nu_\mu \to \nu_e$
  $E > 475$ MeV: no excess, $E < 475$ MeV: $\sim 3\sigma$ excess
- MiniBooNE $\bar{\nu}_\mu \to \bar{\nu}_e$, inconclusive
  consistent with MBν as well as with LSND in 2ν framework

Latest MiniBooNE results Z. Djurcic @ NuFact11







Can we fit all this in a 3+1 (or 3+n) scheme

3+1 $\nu_\mu \to \nu_e$ appearance

$$P_{\mu e} = \sin^2 2\theta_{\rm app} \sin^2 \frac{\Delta m^2_{41} L}{4E} \qquad \sin^2 2\theta_{\rm app} = 4|U_{e4}|^2|U_{\mu 4}|^2$$

3+1 ν_e and ν_μ disappearance

$$P_{\alpha\alpha} = 1 - \sin^2 2\theta_{\rm dis} \sin^2 \frac{\Delta m^2_{41} L}{4E} \qquad \sin^2 2\theta_{\rm dis} = 4|U_{\alpha 4}|^2(1 - |U_{\alpha 4}|^2)$$

3+1: constraints from ν_e (ν_μ) disappearance experiments on U_{e4} ($U_{\mu 4}$) imply that appearance mixing angle is quadratically suppressed

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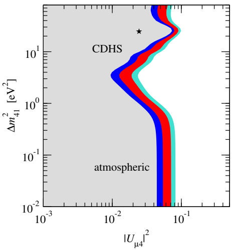
3+1: constraints from ν_e (ν_μ) disappearance experiments on U_{e4} ($U_{\mu 4}$) imply that appearance mixing angle is quadratically suppressed

3+2: phase $\delta \equiv \arg \left(U^*_{e4} U_{\mu 4} U_{e5} U^*_{\mu 5} \right) \to$ CP violation

Karagiorgi et al. 06; Maltoni, TS 07

BUT: constrain $|U_{ei}|$ and $|U_{\mu i}|$ ($i = 4, 5$) from disappearance to be reconciled with appearance amplitudes $|U_{ei} U_{\mu i}|$

Limits on $U_{\mu 4}$



- ν_μ disappearance CDHS
- atmospheric neutrinos Bilenky, Giunti, Grimus, TS 99; Maltoni, TS, Valle 01

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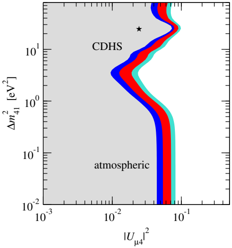

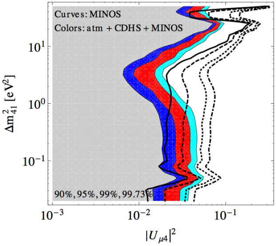

Kopp, Maltoni, TS, in prep

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- MINOS NC data 1001.0336, 1104.3922

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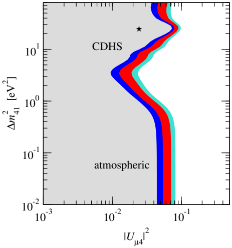

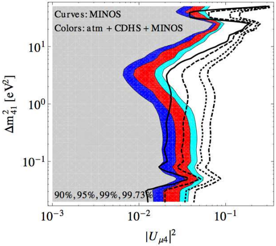

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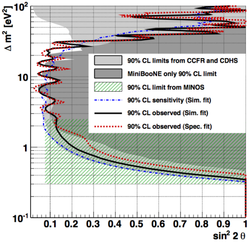
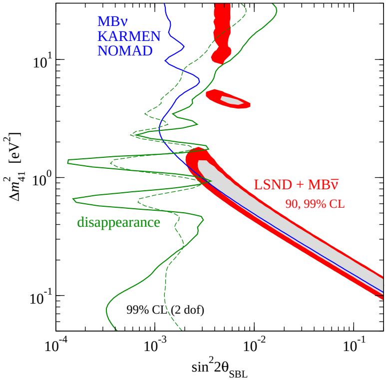


MiniBooNE, 1106.5685

$\sin^2 2\theta = 4|U^2_{\mu 4}|(1 - |U^2_{\mu 4}|)$

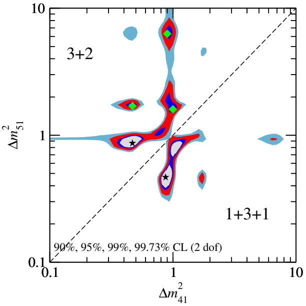
- ν_μ disappearance CDHS
- atmospheric neutrinos Bilenky, Giunti, Grimus, TS 99; Maltoni, TS, Valle 01
- MINOS NC data 1001.0336, 1104.3922
- additional constraints from MiniB $\nu_\mu(\bar{\nu}_\mu)$ at $\Delta m^2 \gtrsim 1$ eV^2

3+1 global fit



- no CP violation → LSND+MB$\bar{\nu}$ versus MBν
- despite relaxed constraints on U_{e4} no improvement of global 3+1 fit
- LSND+MB$\bar{\nu}$ versus rest: $\chi^2_{PG} = 21.5(24.2)$ for new (old) flux
  → compatibility of less than 10^{-5}

3+2 global fit Kopp, Maltoni, TS, PRL 11

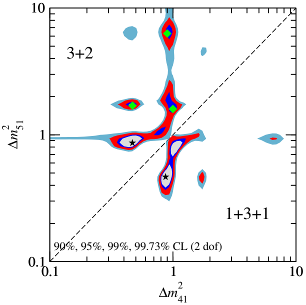


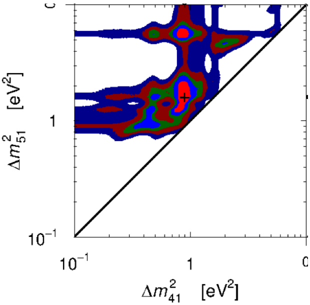
some improvement in the fit:

- $\Delta\chi^{2\text{(old vs new fluxes)}}_{3+2} = 11.1$
- $\Delta\chi^2$ (3+1 vs 3+2) = 11.2 (97.6% CL, 4 dof)
  6.3 for old flux

	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	$\chi^2/130$
3+2	0.47	0.128	0.165	0.87	0.138	0.148	1.64	110.1
3+2'	0.47	0.117	0.201	1.70	0.151	0.101	1.39	114.4
3+2'	1.00	0.133	0.163	1.60	0.122	0.079	1.48	114.4
3+2'	0.90	0.123	0.163	6.30	0.135	0.091	1.67	115.0
1+3+1	0.47	0.129	0.154	0.87	0.142	0.163	0.35	106.1

3+2 global fit Kopp, Maltoni, TS, PRL 11





Giunti, Laveder, 1109.4033

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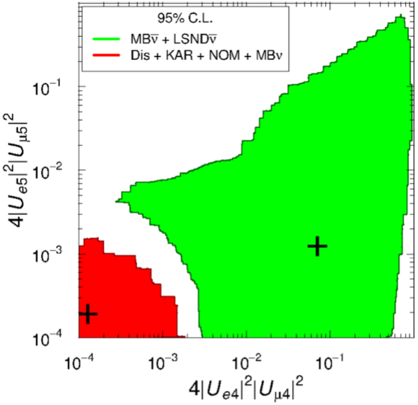
GL:	0.90	0.130	0.134	1.60	0.130	0.080	1.52	92/100

There is severe tension in the 3+2 fit



Giunti, Laveder, 1109.4033

There is severe tension in the 3+2 fit

	LSND+MB($\bar{\nu}$) vs rest		appearance vs disapp.	
	old	new	old	new
$\chi^2_{\rm PG}$/dof	25.1/5	19.9/5	19.9/4	14.7/4
PG	10^{-4}	0.13%	5×10^{-4}	0.53%
adding MINOS NC Kopp, Maltoni, TS, work in prep.				
$\chi^2_{\rm PG}$/dof	30.0/5	24.8/5	24.7/4	19.5/4
PG	10^{-5}	10^{-4}	5×10^{-5}	6×10^{-4}

- explanation of appearance signal requires U_{ei} and $U_{\mu i}$ $(i = 4, 5)$
- no hint for oscillations seen in ν_μ disappearance
  $\Rightarrow$ constraints on $U_{\mu i}$ in tension with signals
- MINOS NC data makes compatibility worse by one order of magnitude
- MB low-E excess cannot be explained when disap. data are included

Summary sterile global fit

- If we assume that the 3+n oscillation scenario is correct at least one of the experiments is "mis-interpreted".
- If we neglect LSND, there is still the hint for ν_e disappearance from the reactor anomaly and maybe Gallium
(less solid, relies on complicated theoretical calculations, uncertainties difficult to estimate)
- If we stick to LSND, probably we have to discard more than one experiment (several experiments constrain ν_μ disappearance)

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eV sterile neutrinos and cosmology

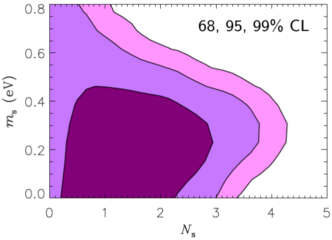
- CMB, SDSS, HST: prefer some extra radiation, but limit on HDM excludes two eV-scale neutrinos

- BBN: $N_s < 1.2$ (95% CL)

  Mangano, Serpico, 1103.1261

  $\rightarrow$ PLANCK!

Hamann et al., 1006.5276



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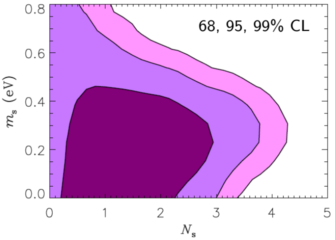

If those eV-scale sterile neutrinos were confirmed on Earth we would need a

substantial modification of standard cosmology

e.g. extra rel. dof, large lepton number, weared DE eq. of state,...

Elgaroy, Kristiansen, 1104.0704, Hamann, Hannestad, Raffelt, Wong, 1108.4136

More exotic ideas

- 3-neutrinos and CPT violation Murayama, Yanagida 01; Barenboim, Borissov, Lykken 02; Gonzalez-Garcia, Maltoni, TS 03
- 4-neutrinos and CPT violation Barger, Marfatia, Whisnant 03
- Exotic muon-decay Babu, Pakvasa 02
- CPT viol. quantum decoherence Barenboim, Mavromatos 04
- Lorentz violation Kostelecky et al., 04, 06; Gouvea, Grossman 06
- mass varying ν Kaplan,Nelson,Weiner 04; Zurek 04; Barger,Marfatia,Whisnant 05
- shortcuts of sterile νs in extra dim Paes, Pakvasa, Weiler 05
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most of these ideas involve sterile neutrinos

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most of these ideas have problems with some data

Many ideas to test eV sterile neutrinos

- radioactive source experiments (e.g., in Borexino, SNO+) Cribier et al, 1107.2335; Garvin et al, 1006.2103; Vergados, Novikov, 1006.3862; Grieb, Link, Raghavan, hep-ph/0611178,...
- several ideas at FNAL (MINOS+, MicroBooNE, MiniBooNE extensions, very-low-E NuFact) B. Louis @ NuFact11
- ICARUS at CERN PS C. Rubbia et al. 0909.0355
- experiments with ∼100 kW proton synchrotrons Conrad, Shaevitz 09; Huber, Agarwalla 10; Agarwalla, Conrad, Shaevitz, 11
- signatures in IceCube (Deep Core) Nunokawa, Peres, Zukanovich, hep-ph/0302039; Coubey, 0709.1937; Razzaque, Smirnov, 1104.1390

Many ideas to test eV sterile neutrinos

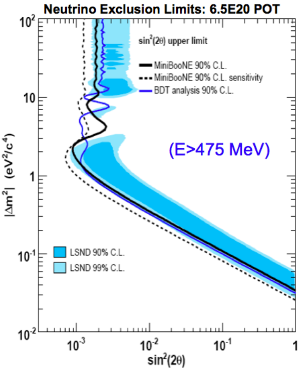
2011 sterile neutrino workshops:

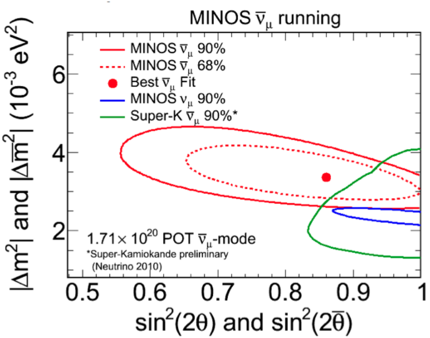
- LNGS, Italy, May 2011
- FNAL, USA, May 2011
- Virginia Tech, Blacksburg, USA, Sept 2011

White paper on sterile neutrinos is in preparation:
http://cnp.phys.vt.edu/white_paper/

Personal comment

two examples for regions in disagreement at 90% CL:





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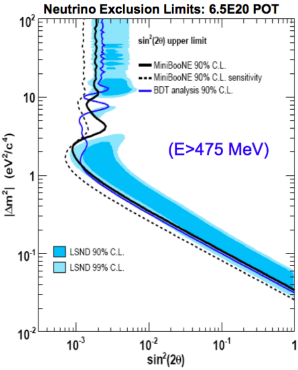

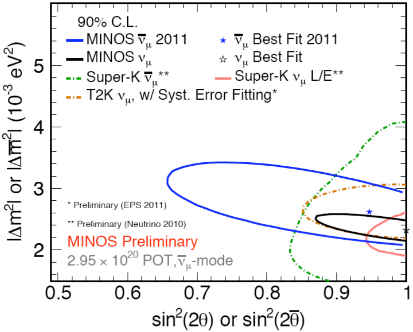

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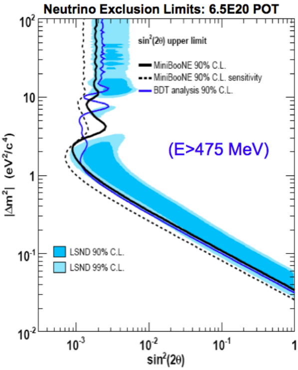

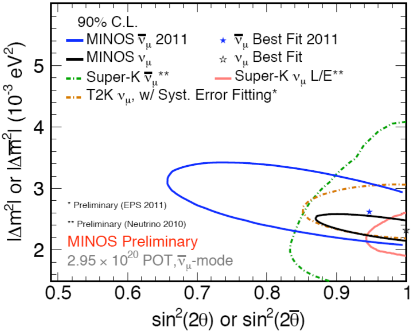

We need to solve the question of sterile neutrinos **conclusively**!

Outline

Conclusions

- the bulk of data on neutrino oscillations is fitted perfectly within the three-flavour framework, and we have evidence for oscillatory behaviour of the survival probablility as function of neutrino energy
- recent T2K results on ν_e appearance combined with the rest of the data or with prelim. DoubleChooz results lead to a hint for $\theta_{13} > 0$ at about 3σ – will be tested very soon by up-coming experiments
- there are intriguing hints for sterile neutrinos at the eV scale: LSND, reactor anomaly, Gallium anomaly, cosmology? BUT: no consistent picture has emerged sofar

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  LSND, reactor anomaly, Gallium anomaly, cosmology?
  BUT: no consistent picture has emerged sofar

Thank you for your attention!

3-flavour oscillation parameters TS, Tortola, Valle, 1108.1376

	best fit $\pm 1\sigma$	3σ range	prec@3σ	
$\frac{\Delta m^2_{21}}{10^{-5}\text{eV}^2}$	$7.59^{+0.20}_{-0.18}$	7.09–8.19	7%	KamLAND
$\frac{\Delta m^2_{31}}{10^{-3}\text{eV}^2}$	$2.50^{+0.09}_{-0.16}$ $-(2.40^{+0.08}_{-0.09})$	$2.14 - 2.76$ $-(2.13 - 2.67)$	12%	MINOS
$\sin^2\theta_{12}$	$0.312^{+0.017}_{-0.015}$	0.27–0.36	14%	SNO
$\sin^2\theta_{23}$	$0.52^{+0.06}_{-0.07}$ 0.52 ± 0.06	0.39–0.64	24%	SuperK
$\sin^2\theta_{13}$	$0.013^{+0.007}_{-0.005}$ $0.016^{+0.008}_{-0.006}$	0.001–0.035 0.001–0.039	120%	T2K + global data
δ	$\left(-0.61^{+0.75}_{-0.65}\right)\pi$ $\left(-0.41^{+0.65}_{-0.70}\right)\pi$	$0 - 2\pi$	–	

upper: normal hierarchy, lower: inverted hierarchy

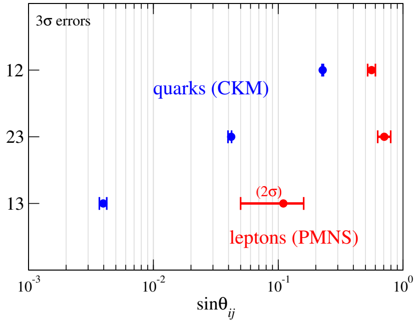
CKM versus PMNS

Quark mixing:

$$U_{CKM} = \begin{pmatrix} 1 & \epsilon & \epsilon \\ \epsilon & 1 & \epsilon \\ \epsilon & \epsilon & 1 \end{pmatrix}$$

Lepton mixing:

$$U_{PMNS} = \frac{1}{\sqrt{3}} \begin{pmatrix} \mathcal{O}(1) & \mathcal{O}(1) & \epsilon \\ \mathcal{O}(1) & \mathcal{O}(1) & \mathcal{O}(1) \\ \mathcal{O}(1) & \mathcal{O}(1) & \mathcal{O}(1) \end{pmatrix}$$



Symmetry versus anarchy?

Are lepton mixing angles "special"?

Example: Tri-bimaximal mixing: Harrison, Perkins, Scott, hep-ph/0202074

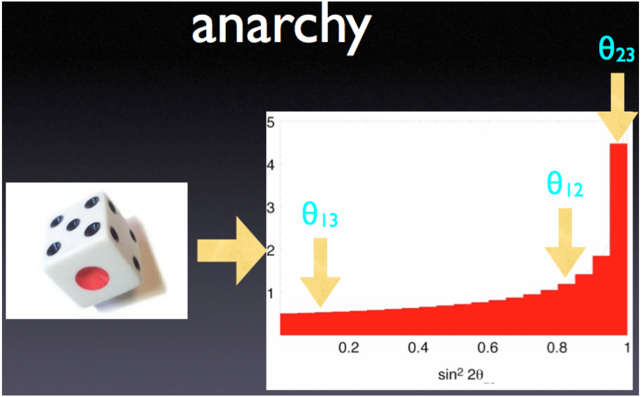
$$U_{TBM} = \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \\ 1/\sqrt{6} & -1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$$

Since June, $\mathcal{O}(50)$ papers appeared on arXiv claiming that large θ_{13} is consistent with tri-bimaximal mixing or similar flavour symmetries.

To me it is not clear whether these models remain attractive if θ_{13} is large.

Symmetry versus anarchy?

Maybe the mixing angles are just random numbers? Murayama et al.



3+1 + NSI Akhmedov, TS 10

assume

- a 4th neutrino with $\Delta m^2_{41} \sim 1$ eV^2
- a new type of CC-like interaction

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2} G_F \sum_{\alpha,\beta} \varepsilon^{ff'}_{\alpha\beta} (\bar{f} P_{L,R} \gamma^\mu f')(\bar{l}_\alpha P_L \gamma_\mu \nu_\beta) + h.c.$$

f, f' fermions depending on production or detection process

(NC-like NSI will have no relevant effect in short-baseline experiments since matter effect is very small)

3+1 + NSI

- zero-distance effects and CPV (NSI-oscillation interference)
- can decouple LSND/KARMEN from the rest:

	source	detection
LSND/KARMEN	μ decay	ν-nucl CC (e)
MiniB/NOMAD	π decay	ν-nucl CC (e)
CDHS (atm)	π decay	ν-nucl CC (μ)
Bugey/Chooz	ν-nucl CC (e)	ν-nucl CC (e)

$|\alpha_{\mu e}^{\rm LK}|, |\beta_{\mu e}^{\rm LK}|, \delta^{\rm LK}$, $\alpha_e, \alpha_\mu, |\beta_{\mu e}|, \delta$, Δm^2_{41}

$\rightarrow$ 8 parameters (7 for 3+2 osc)

3+1 + NSI

- $\chi^2_{(3+1)\mathrm{osc}} - \chi^2_{(3+1)\mathrm{NSI}} = 18.5(5\ \mathrm{dof}) \quad \rightarrow \quad 99.76\%$ CL
  appearance versus disappearance: PG compatibility of 15%

- $|U_{e4}| \approx 0.116$, $|U_{\mu 4}| \approx 0.205$ (more freedom from new react flux)
  $|\varepsilon^{ud}_{\mu s}| \approx 0.05$, $|\varepsilon^{ud}_{e\mu}| \approx 0.011$, $|\varepsilon^{e\nu}_{\mu s}| \approx 0.03$, $|\varepsilon^{e\nu}_{\mu e}| \approx 0.01$
  strength of new interactions at the level of few % compared to G_F
  in agreement with bounds Biggio, Blennow, Fernandez-Martinez, 0907.0097

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3+1 + NSI

- $\chi^2_{(3+1)\text{osc}} - \chi^2_{(3+1)\text{NSI}} = 18.5(5\text{ dof}) \quad \rightarrow \quad$ 99.76% CL
  appearance versus disappearance: PG compatibility of 15%

- $|U_{e4}| \approx 0.116$, $|U_{\mu 4}| \approx 0.205$ (more freedom from new react flux)
  $|\varepsilon^{ud}_{\mu s}| \approx 0.05$, $|\varepsilon^{ud}_{e\mu}| \approx 0.011$, $|\varepsilon^{e\nu}_{\mu s}| \approx 0.03$, $|\varepsilon^{e\nu}_{\mu e}| \approx 0.01$
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Energy dependent quantum decoherence Farzan, TS, Smirnov 07

- no sterile neutrino needed
- postulate quantum-decoherence of the mass states $\Rightarrow$ damping of the interference terms in the oscillation probabilities.
- damping affects only oscillations with Δm^2_{31} and rapidly decreases with the neutrino energy
- reconcile LSND signal with MBν and other null-result exps.
- standard explanations of solar, atmos, KamL, MINOS not affected
- LSND signal controlled by the 1-3 mixing: $0.0014 < \sin^2\theta_{13} < 0.034$
- comparison of near and far measurements at reactors: null-result positive signal for θ_{13} in long-baseline accelerator experiments
- seems to be consistent with reactor anomaly!