Neutrino Horizons in the 21$^{\rm st}$ Century

Status of neutrino oscillations

Thomas Schwetz-Mangold

CERN

Outline

- Global fit to present oscillation data in the three-neutrino framework
  impact of new data from the last 12 months
- LSND puzzle in the light of MiniBooNE results
  the fate of sterile neutrino oscillation schemes

Global data and three-neutrino oscillations

Maltoni, TS, Tortola, Valle, hep-ph/0405172 v6; TS, 0710.5027

Neutrino oscillation experiments

natural neutrino sources:

- solar neutrinos
  Homestake, SAGE+GNO, Super-K, SNO, Borexino
- atmospheric neutrinos
  Super-Kamiokande

artificial neutrino sources:

- reactor neutrinos
  Chooz (1 km), KamLAND (180 km)
- long-baseline accelerator experiments
  K2K (250 km), MINOS (735 km)

3-flavour oscillation parameters

$$\Delta m^2_{31} \qquad\qquad\qquad\qquad \Delta m^2_{21}$$

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

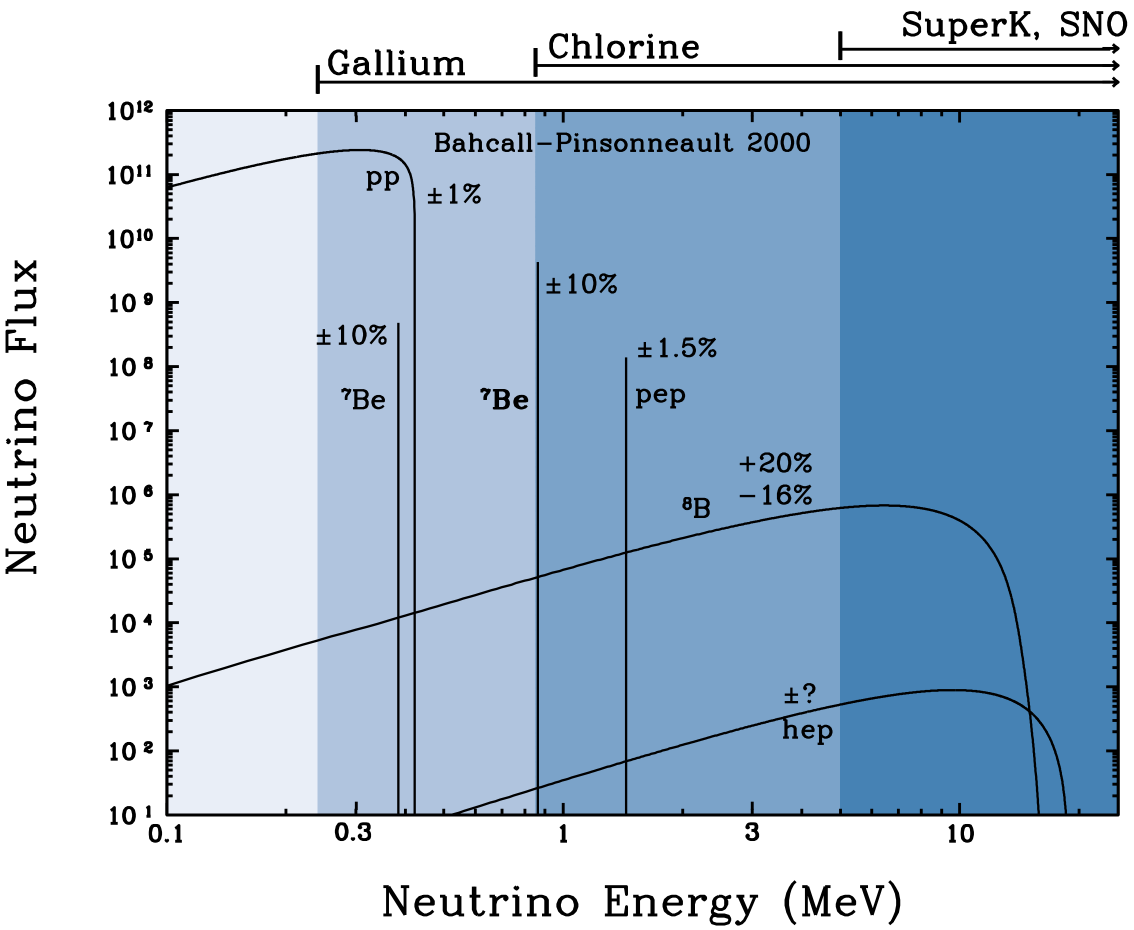
atmospheric+LBL — Chooz — solar+KamLAND

3-flavour effects are suppressed because $\Delta m^2_{21} \ll |\Delta m^2_{31}|$ and $\theta_{13} \ll 1$

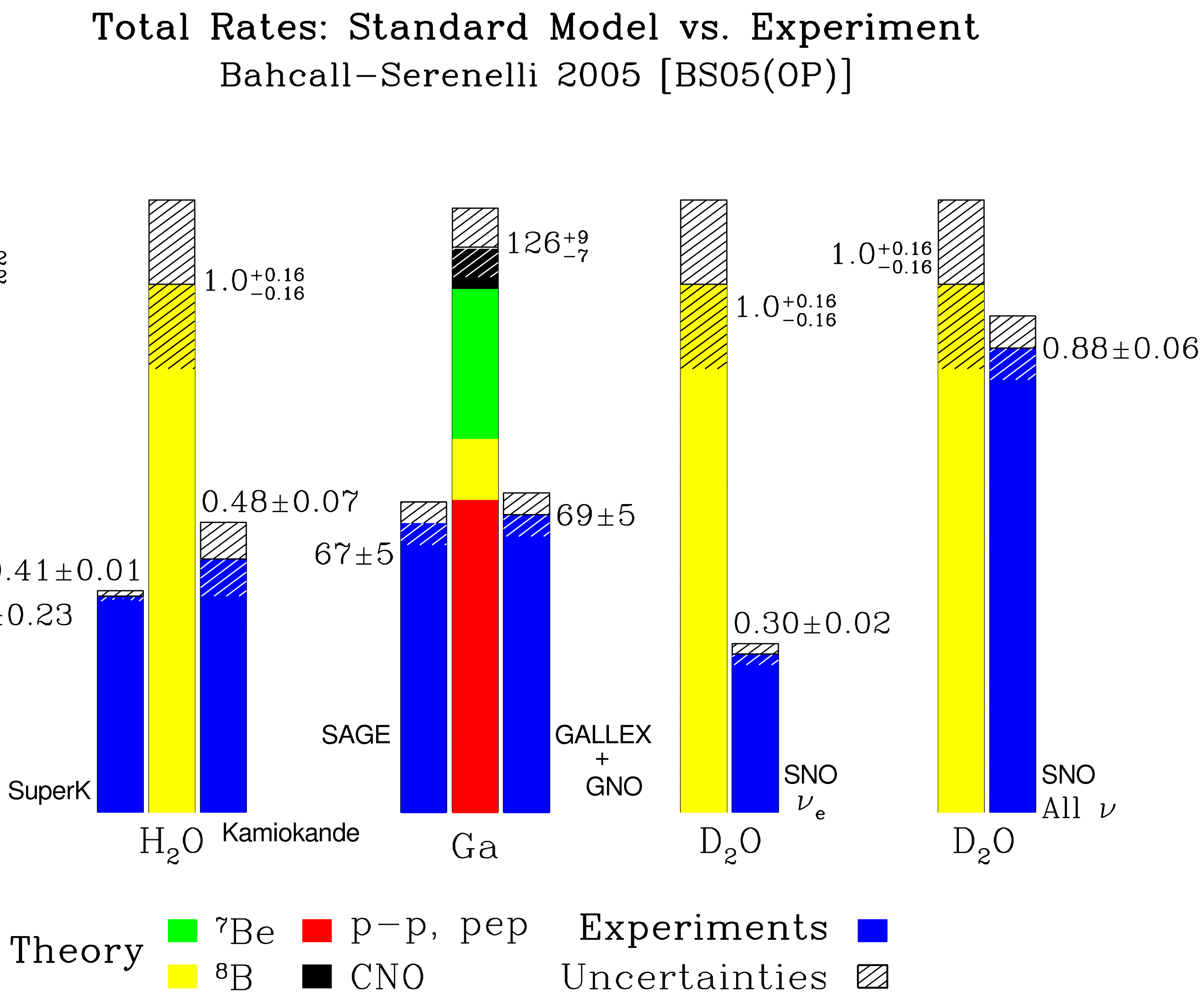
$\Rightarrow$ dominant oscillations are well described by effective two-flavour oscillations

The “solar” parameters Δm^2_{21}, θ_{12}

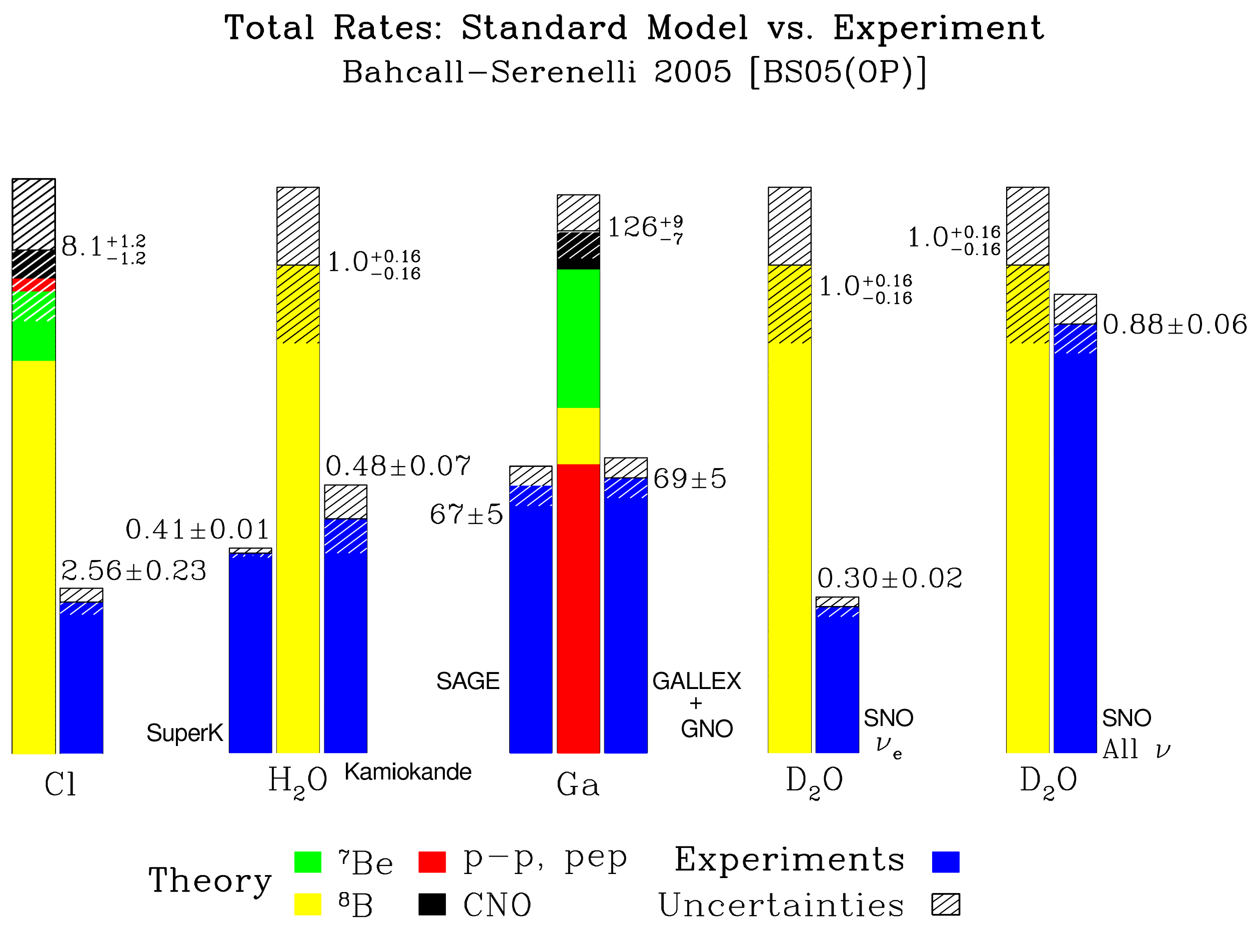
The solar neutrino flux



Solar neutrino experiments



Solar neutrino experiments

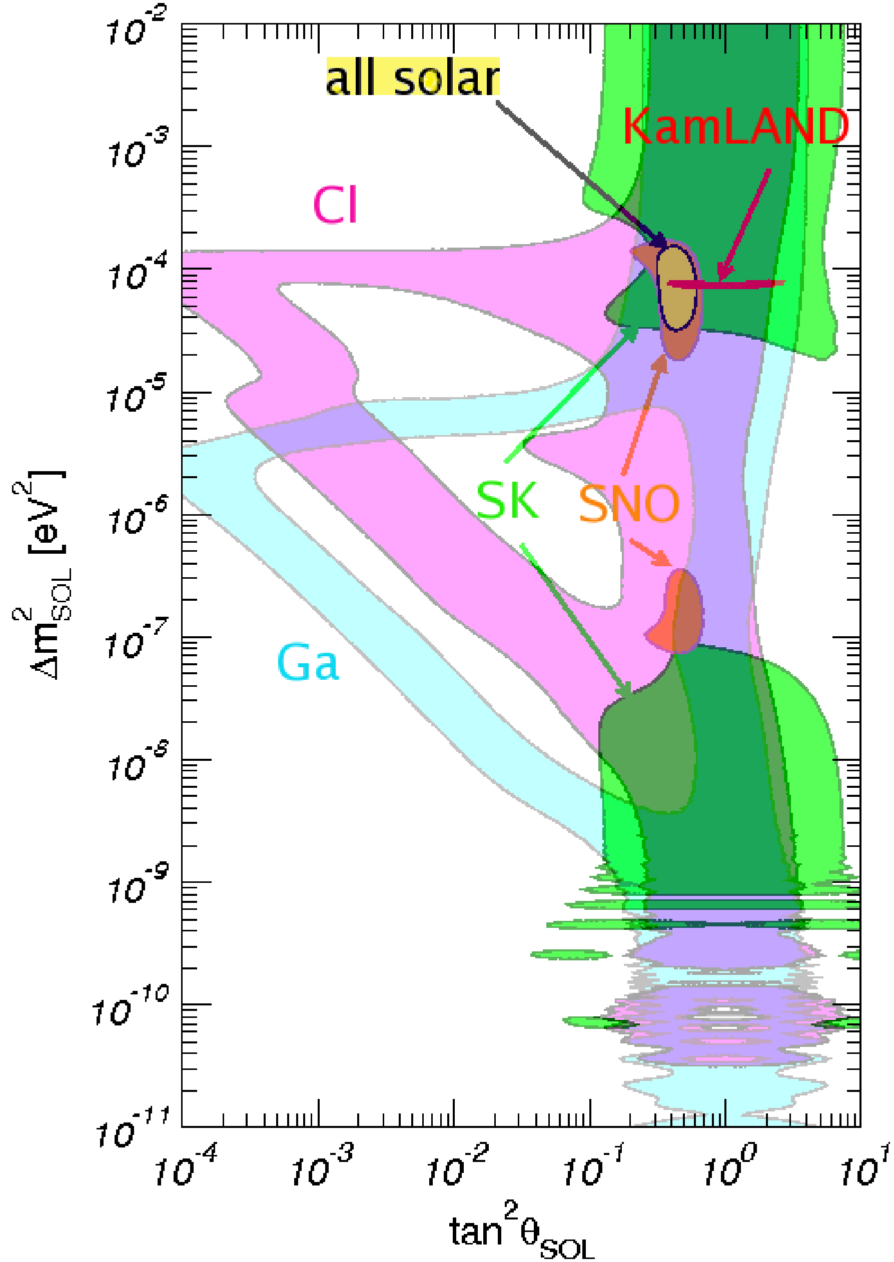


SNO: $$\nu_e + d \longrightarrow p + p + e^- \qquad \nu_x + d \longrightarrow p + n + \nu_x$$

$$\frac{\phi_{CC}}{\phi_{NC}} = 0.340 \pm 0.023 \pm 0.030$$

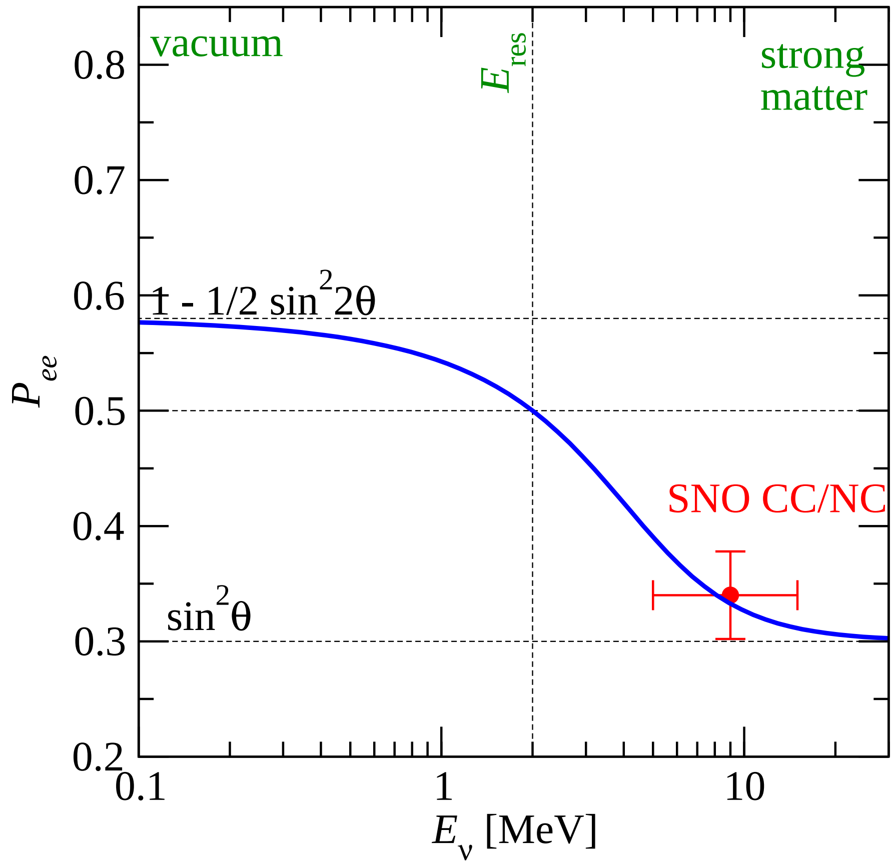
7σ evidence for a non-zero $\nu_{\mu,\tau}$ flux from the sun

’Solar’ parameters



The LMA-MSW solution

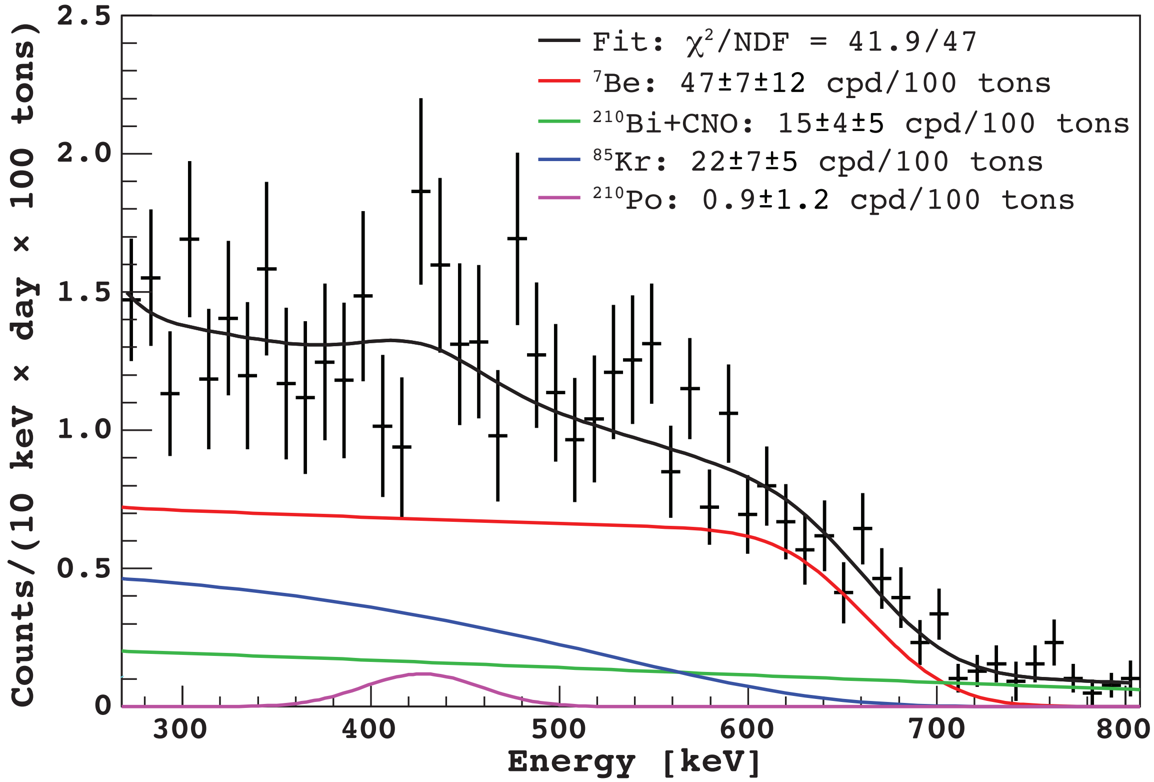
adiabatic evolution of the neutrino state from the center of the sun to the surface



First data from Borexino

0708.2251 [astro-ph] measurment of the Be7 neutrino line at 0.862 MeV by $e\nu \to e\nu$ scattering $(\Rightarrow)$

47 ± 7(stat) $\pm\, 12$(sys) ev/(day x 100t), without osc.: 75 ± 4



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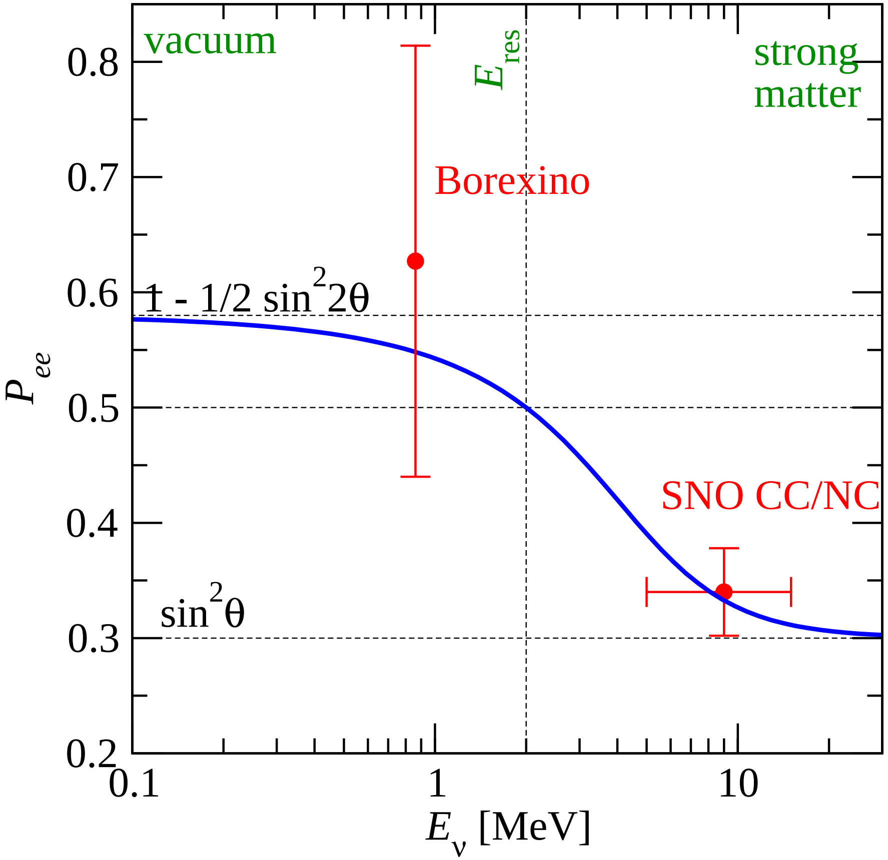
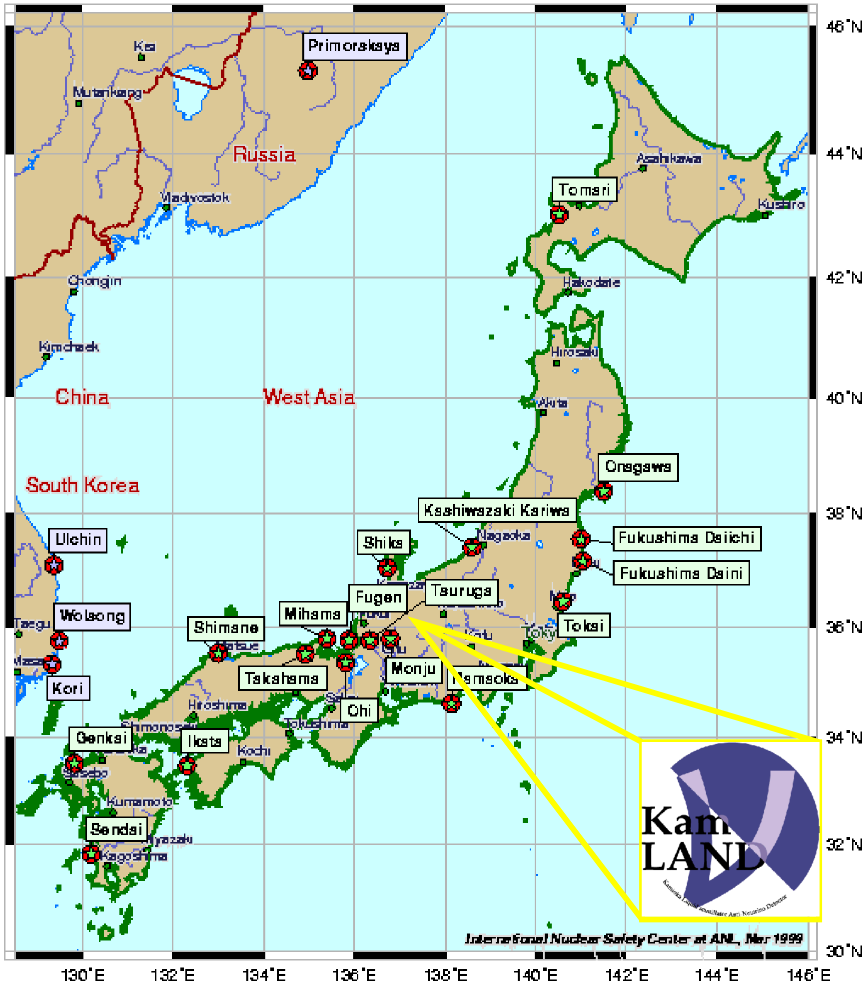


The KamLAND reactor neutrino experiment

Kamioka Liquid scinitillator Anti-Neutrino Detector



detection of $\bar{\nu}_e$ produced in surrounding nuclear power plants

70 GW of nuclear power (7% of world total) is generated at a distance 175 ± 30 km from Kamioka

KamLAND update

New data released this summer:

- 2881 ton yr data

  4 times more than previous 2004 data

- reduced syst. error due to full volume calibration from 4.7% to 1.8%

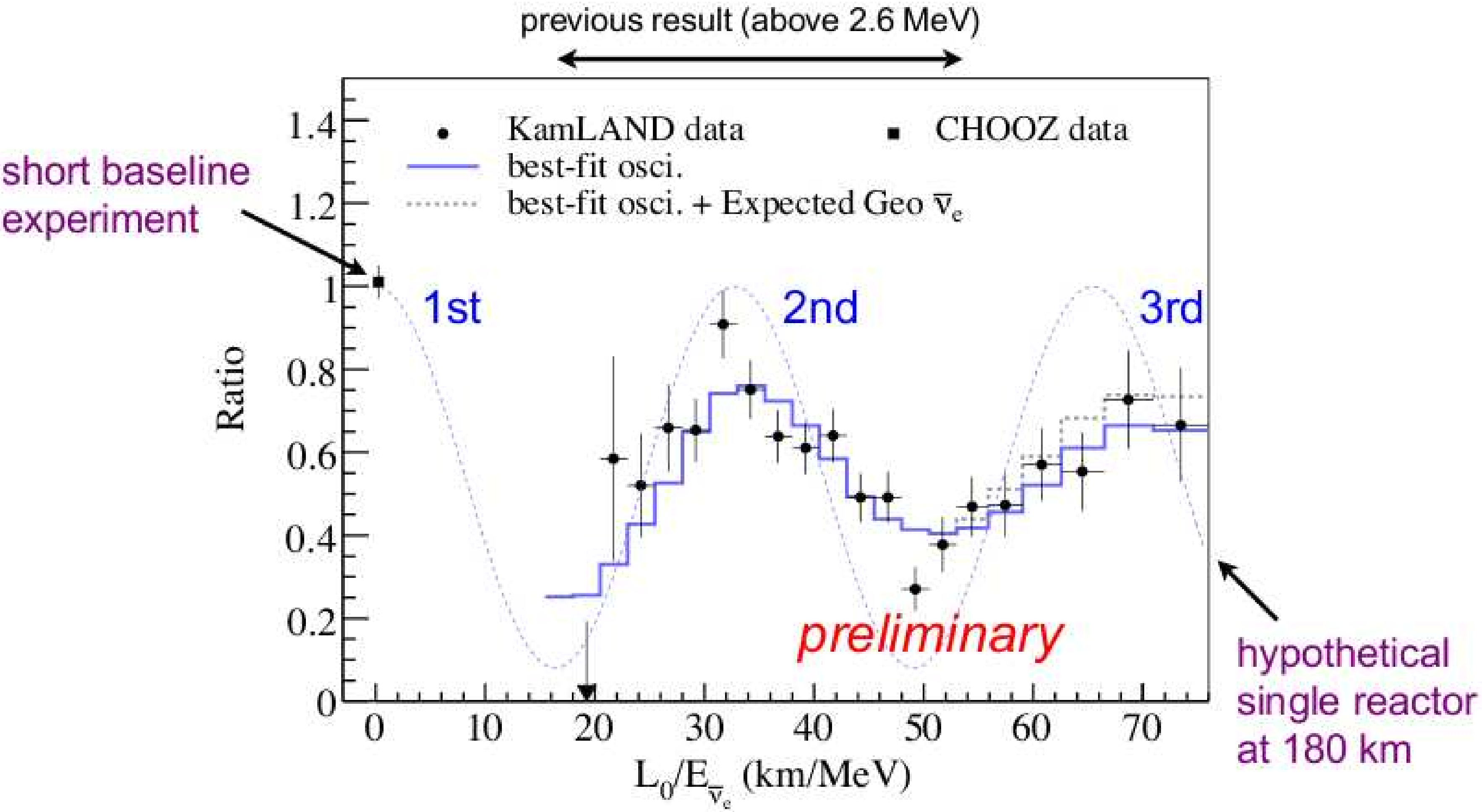
  dominating error for Δm^2 determination is now the uncertainty on the energy scale of 1.5%

observed number of events: 985

expectation without oscillations:

1550 reactor neutrino events + 63 background

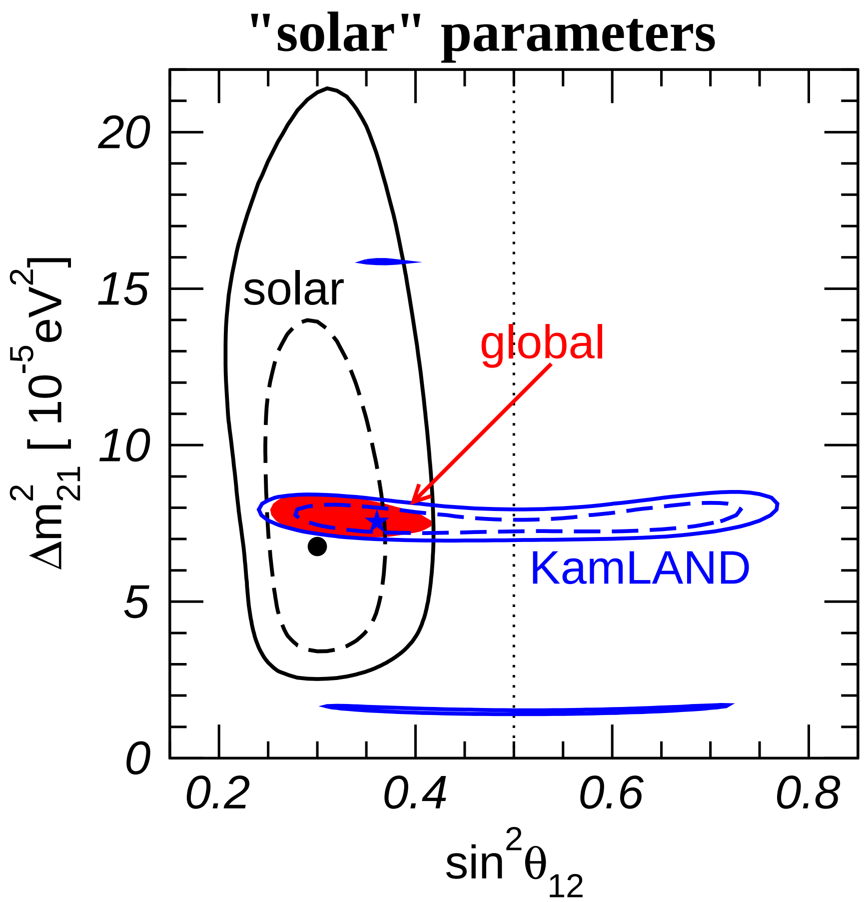
The KamLAND energy spectrum



evidence for oscillations in $1/E_\nu$

KamLAND vs solar data

90% and 99.73% CL contours



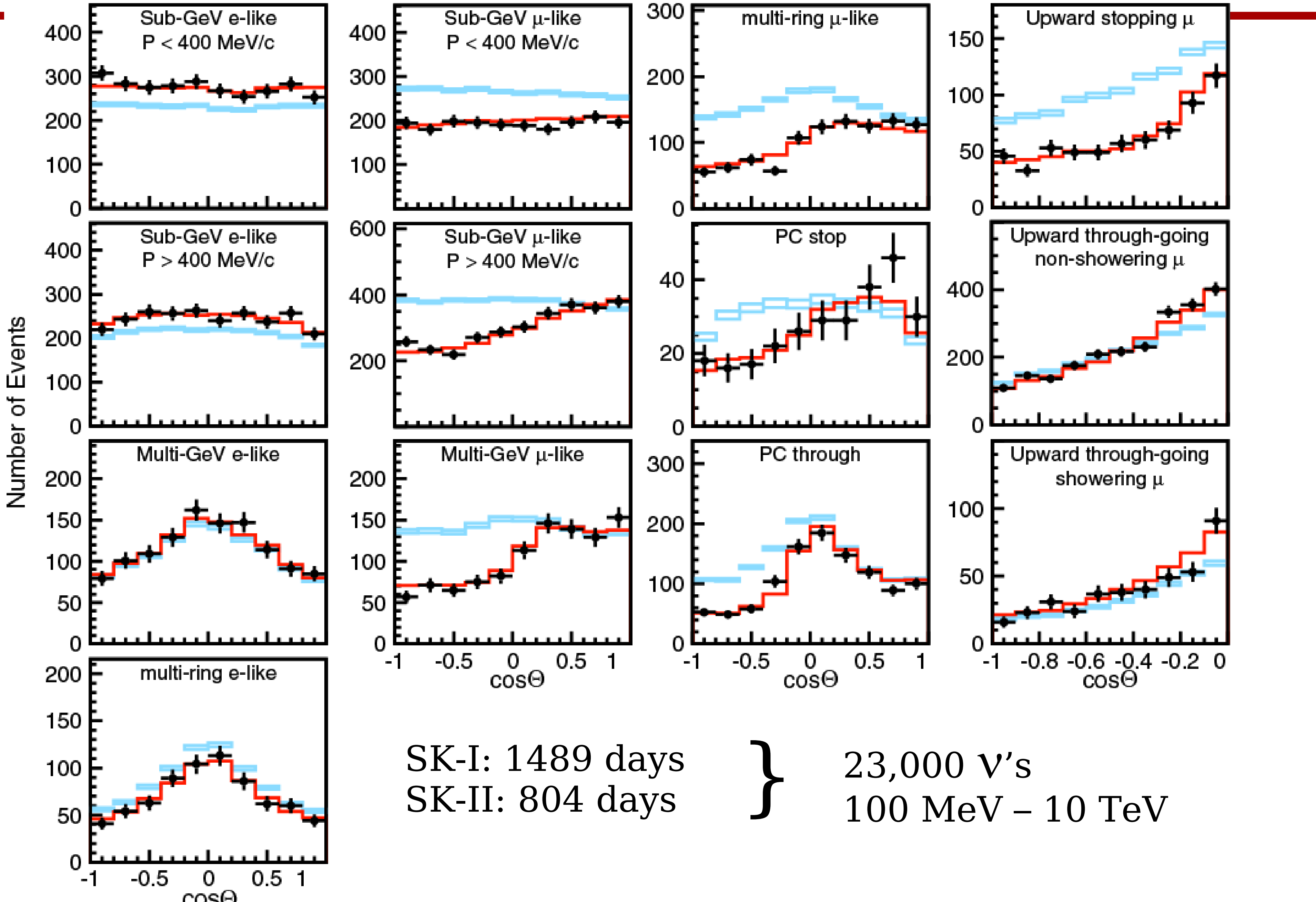
Δm^2_{21}: measured by KamLAND

$\sin^2\theta_{12}$: measured by SNO

$$\Delta m^2_{21} = 7.6 \pm 0.20 \times 10^{-5}\,\mathrm{eV}^2,\ \sin^2\theta_{12} = 0.32 \pm 0.023$$

The “atmospheric” parameters Δm^2_{31}, θ_{23}

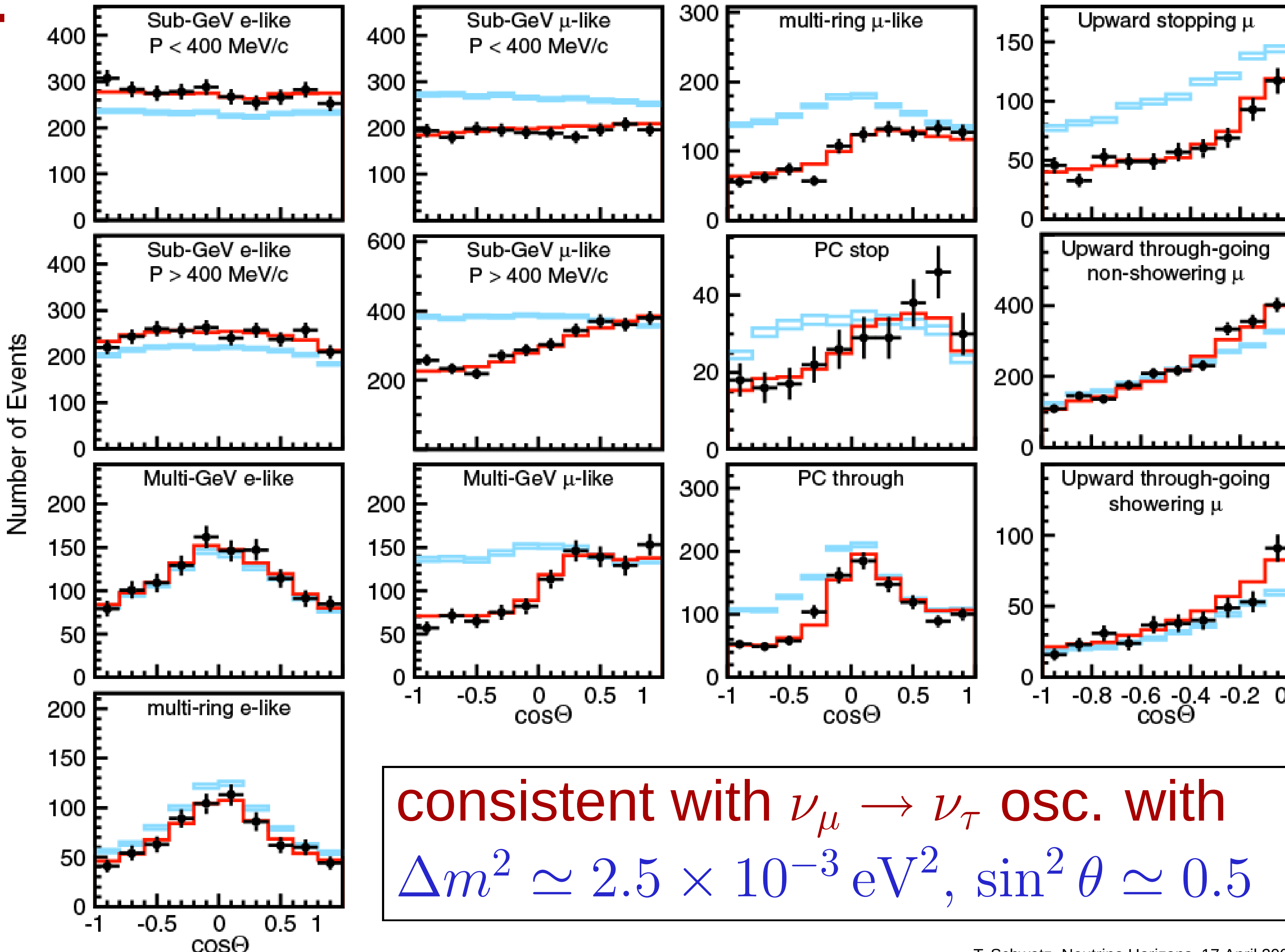
Super-K atmospheric neutrino data



SK-I: 1489 days
SK-II: 804 days

} 23,000 ν's
100 MeV – 10 TeV

Super-K atmospheric neutrino data



consistent with $\nu_\mu \to \nu_\tau$ osc. with

$\Delta m^2 \simeq 2.5 \times 10^{-3}\,\mathrm{eV}^2,\ \sin^2\theta \simeq 0.5$

Long-baseline experiments

first generation of LBL experiments
(ν_μ-disappearance)

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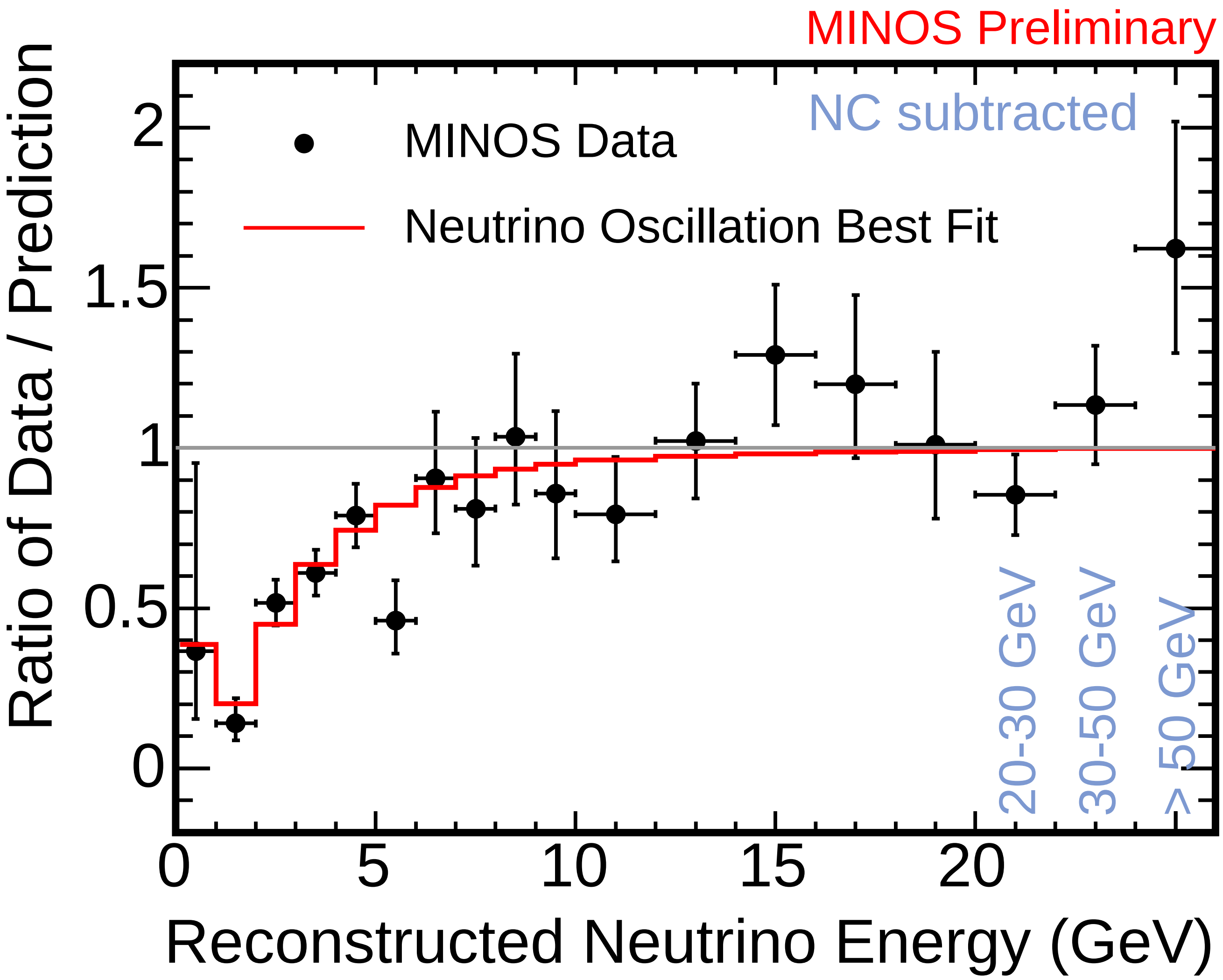
(ν_μ-disappearance)

	K2K	MINOS
source	KEK	Fermilab
detector	Super-K	Soudan
baseline	250 km	735 km
neutrino energy	1.3 GeV	3 GeV
E_ν/L [eV^2]	5.2×10^{-3}	4.1×10^{-3}
obs. events	112	563
expect. w/o osc.	$158.1^{+9.2}_{-8.6}$	738 ± 30

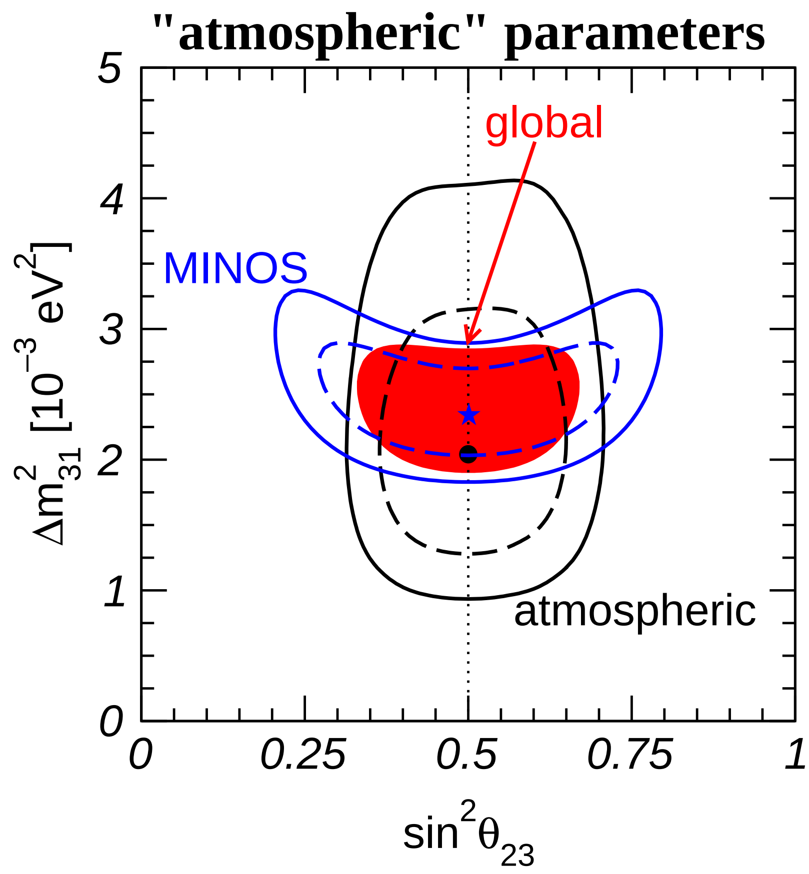
MINOS energy spectrum



arxiv:0708.1495, 2.5×10^{20} pot

Super-K + K2K + MINOS

90%, 99.73% CL regions



$$\Delta m^2_{31} = 2.4 \pm 0.15 \times 10^{-3}\,\mathrm{eV}^2,\ \sin^2\theta_{23} = 0.50 \pm 0.063$$

The bound on θ_{13}

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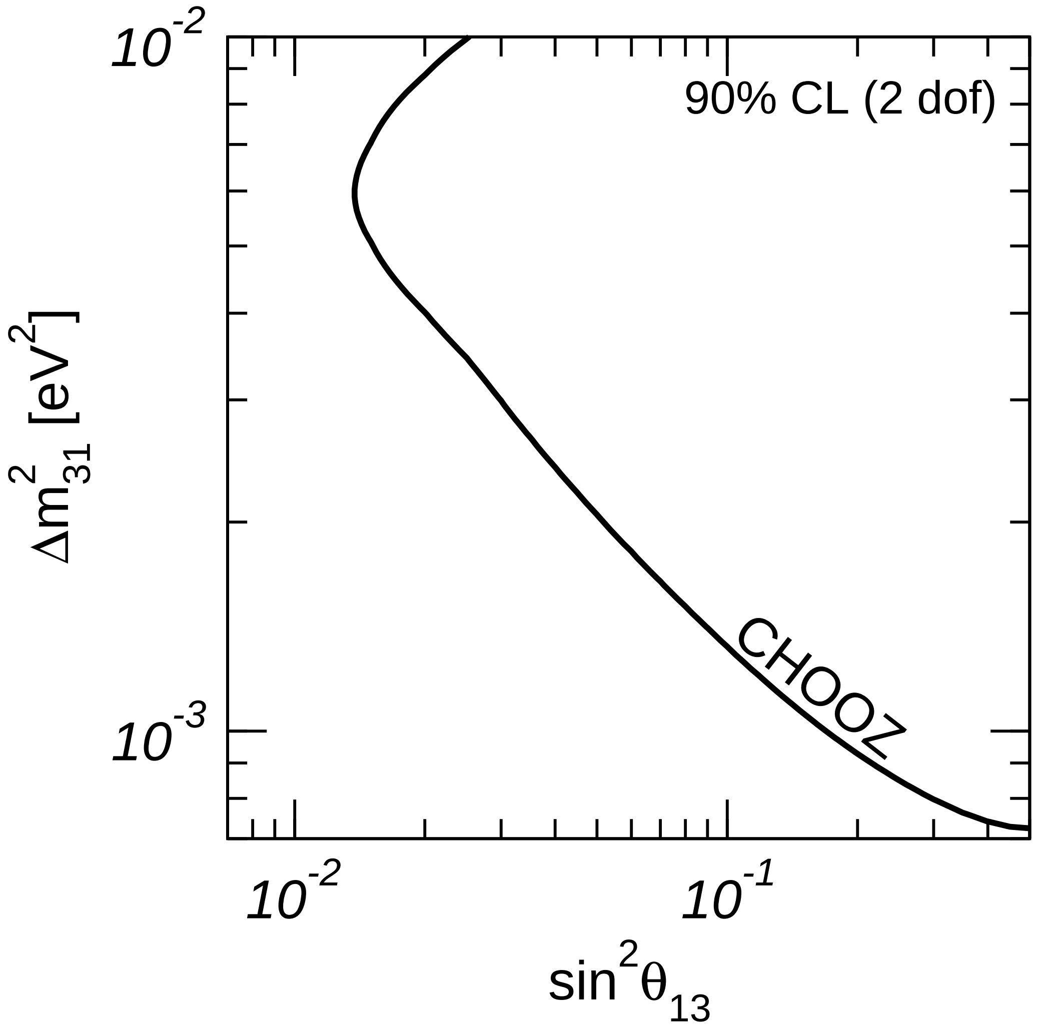
The bound on θ_{13} emerges from an interplay of the global data



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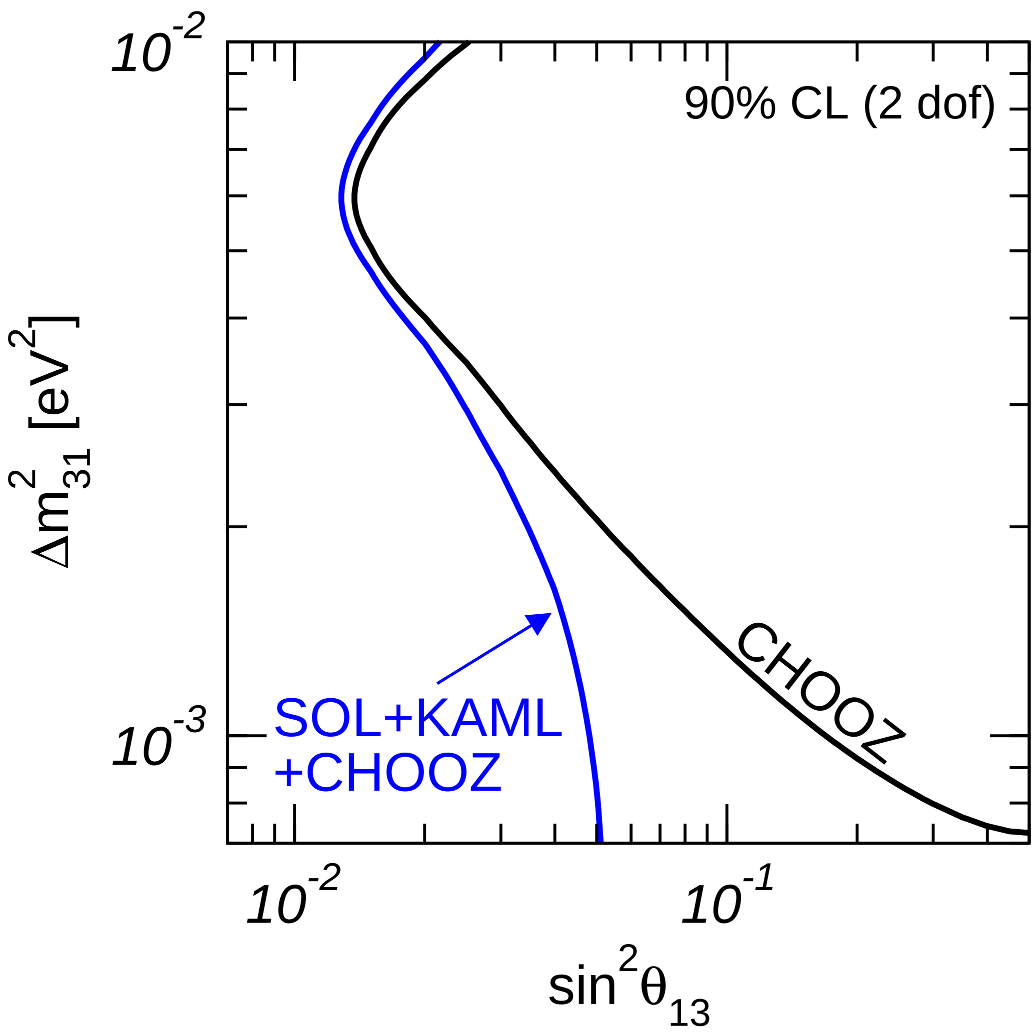

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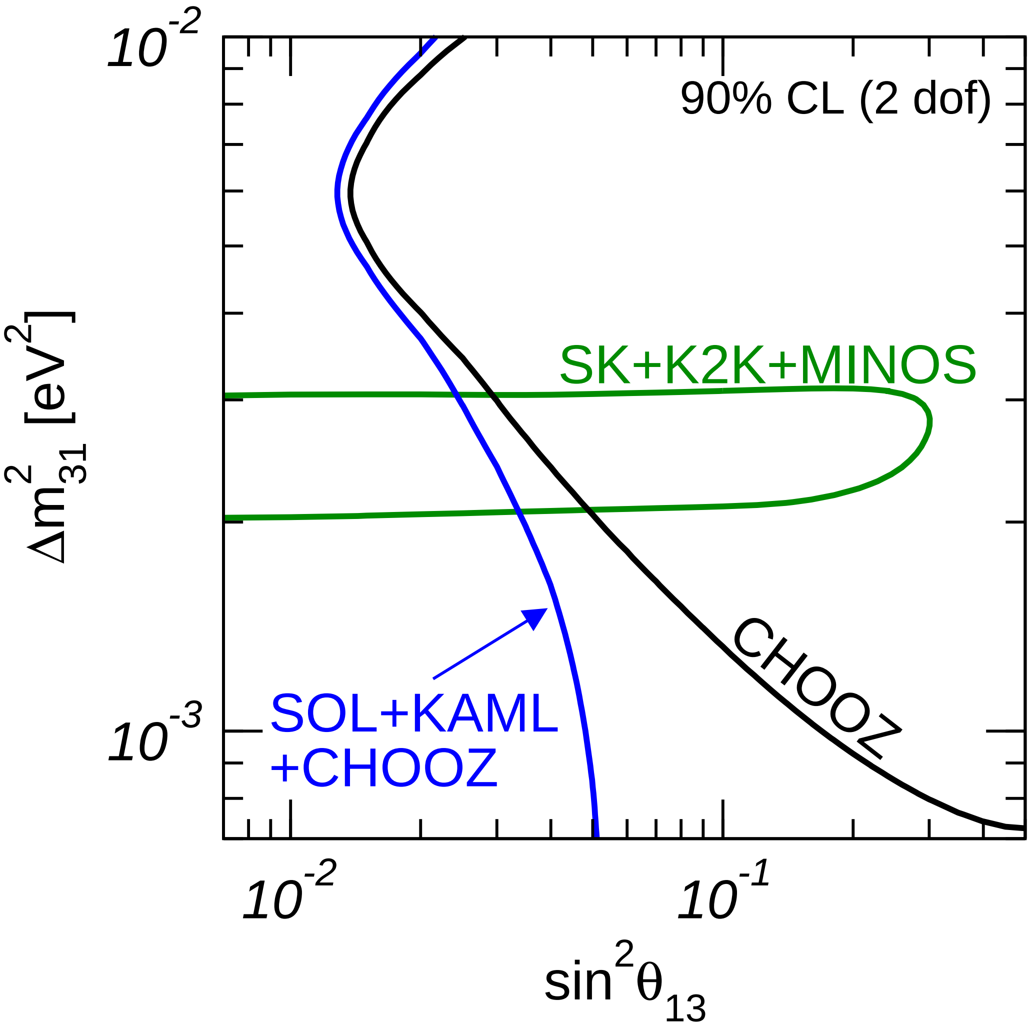
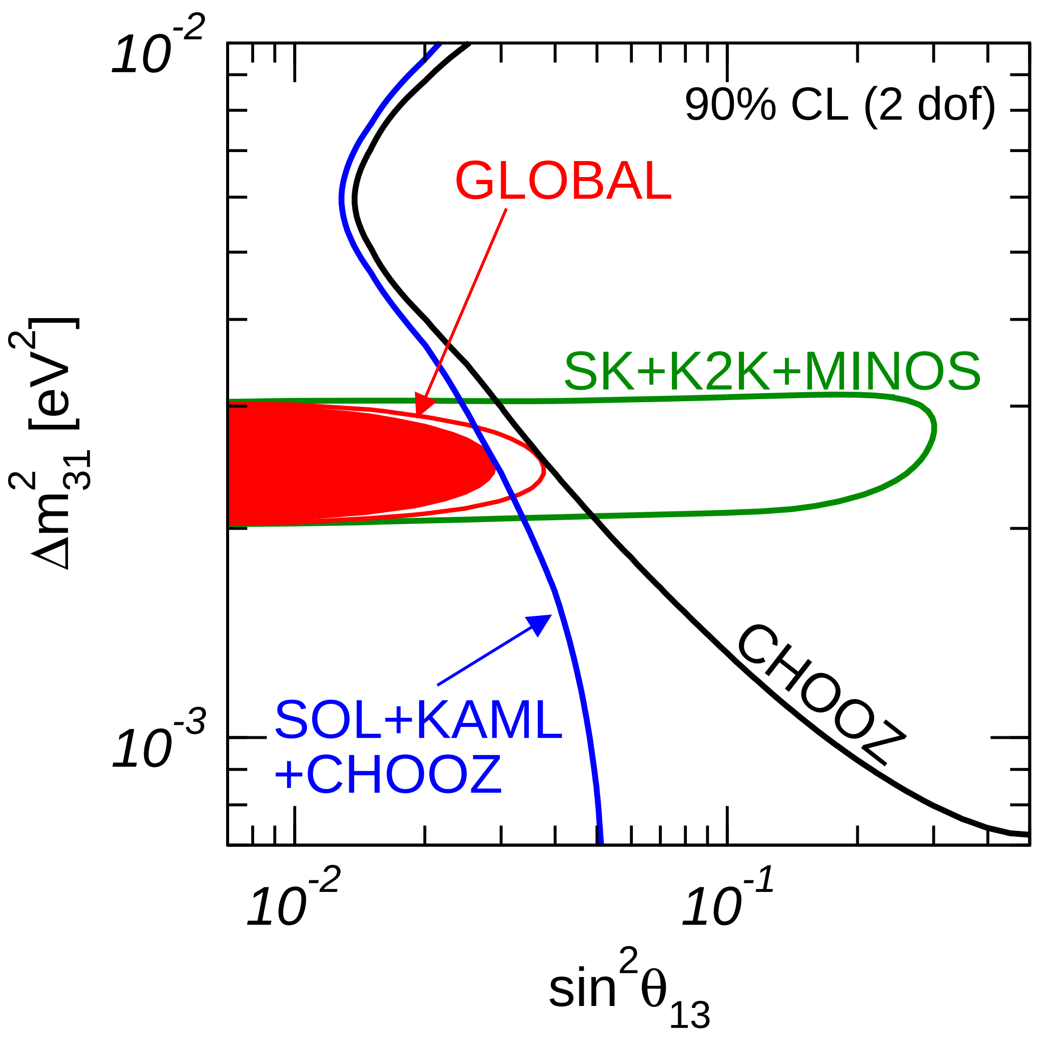


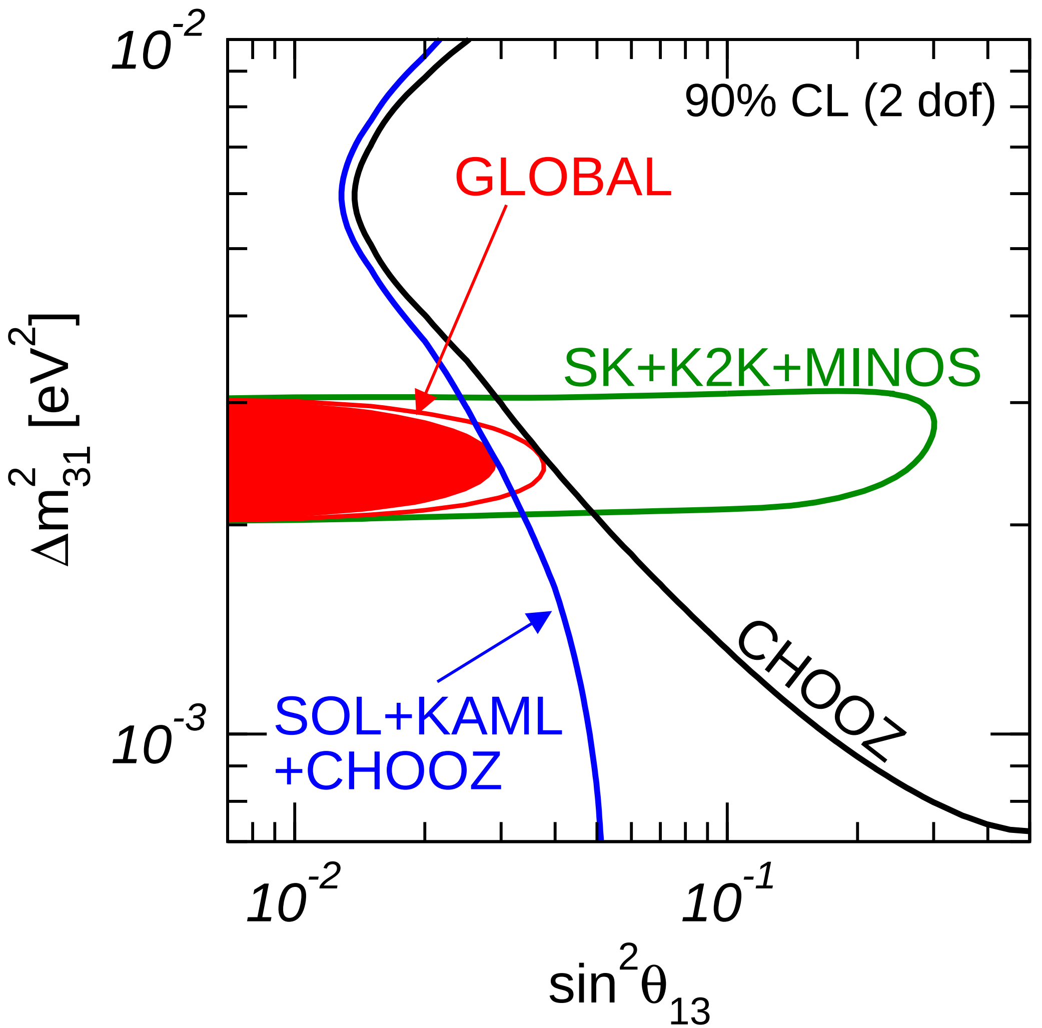
The bound on θ_{13}

global data: $\sin^2\theta_{13} < 0.05$ at 3σ



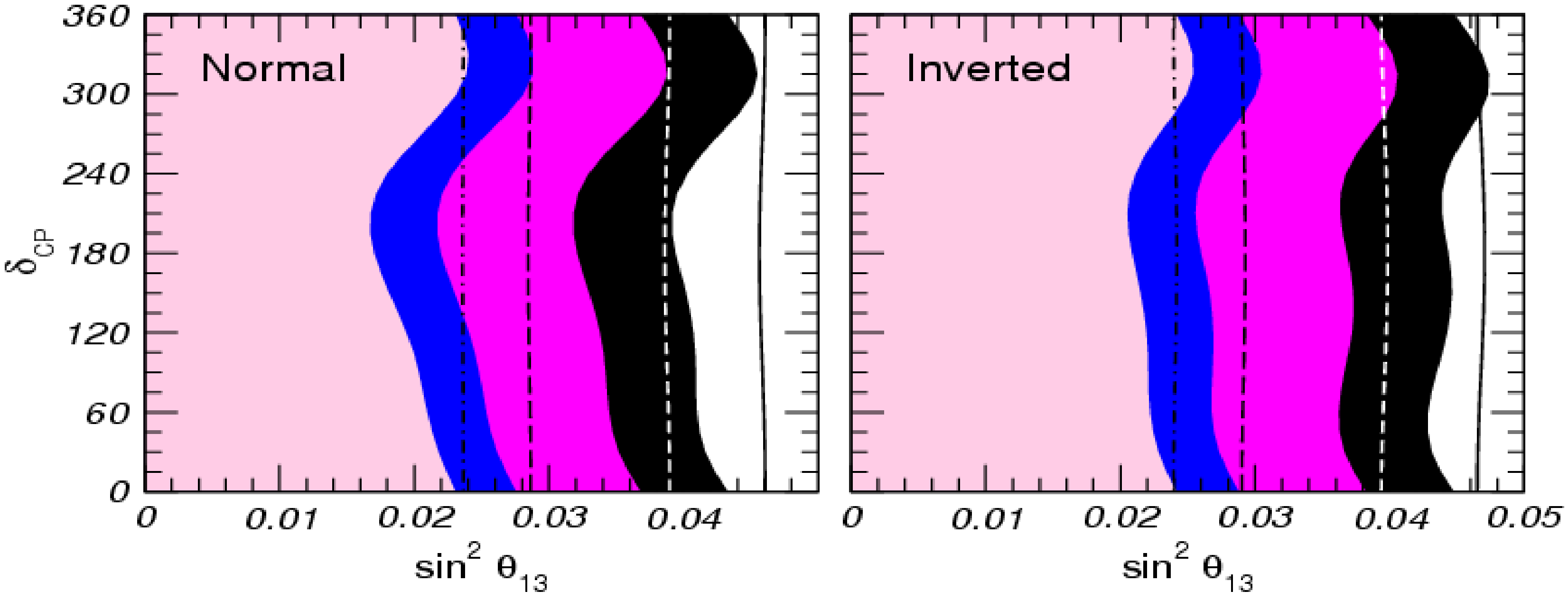
The bound on θ_{13}

$$\sin\theta_{13} = |U_{e3}| < 0.224\,(3\sigma) \quad \leftrightarrow \quad |V_{us}| = 0.2257 \pm 0.0021$$



Three flavour effects in present data

bound on θ_{13} depends on $\delta_{\rm CP}$ and on hierarchy:
(atmospheric data)



Gonzalez-Garcia, Maltoni, 0704.1800

Summary 3-flavour oscillation parameters

3-flavour oscillation parameters

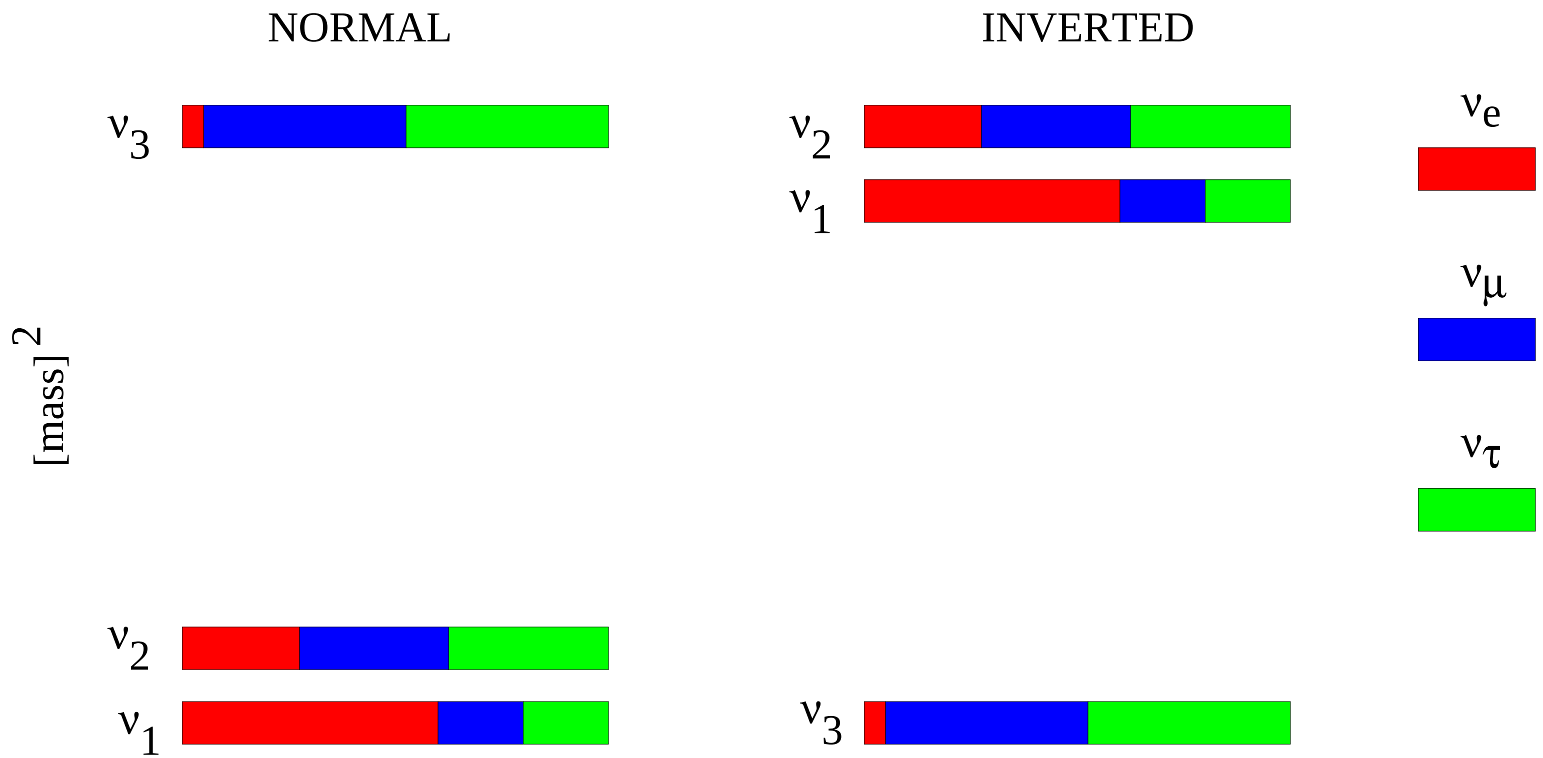
	bf $\pm 1\sigma$	acc. $@\, 3\sigma$	
Δm^2_{21}	$(7.6 \pm 0.2)\, 10^{-5}\, \mathrm{eV}^2$	(8%)	KamLAND
$\sin^2\theta_{12}$	0.32 ± 0.023	(22%)	SNO
$\lvert\Delta m^2_{31}\rvert$	$(2.4 \pm 0.15)\, 10^{-3}\, \mathrm{eV}^2$	(17%)	MINOS
$\sin^2\theta_{23}$	0.50 ± 0.063	(33%)	SK atm

$\sin^2\theta_{13} < 0.05 \; @\, 3\sigma$ CHOOZ

Maltoni, TS, Tortola, Valle, hep-ph/0405172 v6; TS, 0710.5027

Three flavour osc. parameters summary

two possibilities for the neutrino mass spectrum



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

3-flavour oscillations

Open questions:

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- Increase the precision on sol and atm params (e.g. Is θ_{23} exactly 45°?)

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- Increase the precision on sol and atm params (e.g. Is θ_{23} exactly 45°?)
- How small is θ_{13}?
- What is the value of the CP phase δ?
- Type of the neutrino mass ordering (sign of Δm^2_{31})

3-flavour oscillations

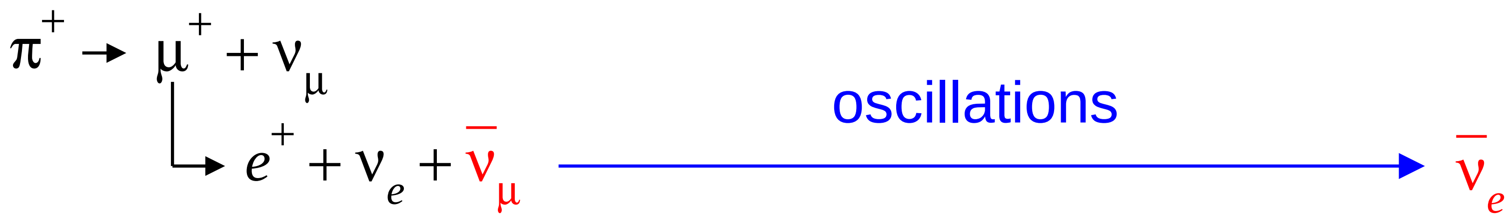
Open questions:

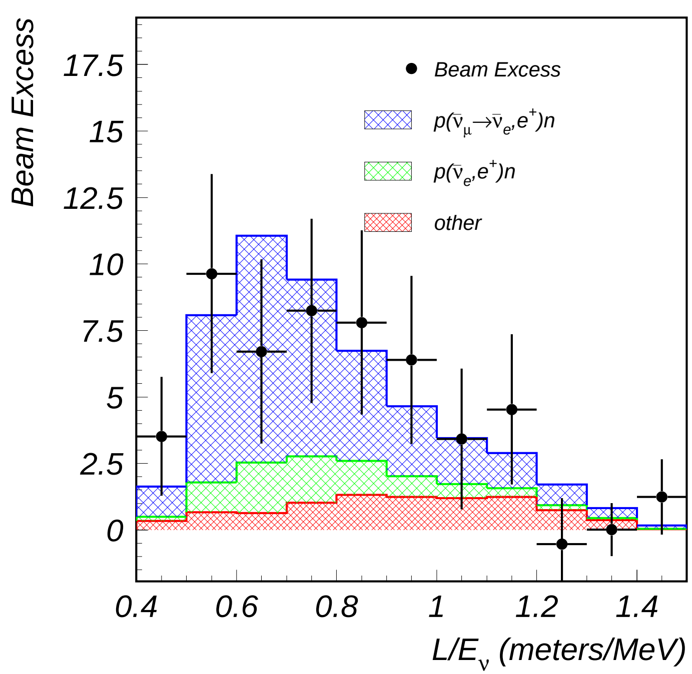
- Increase the precision on sol and atm params (e.g. Is θ_{23} exactly $45°$?)
- How small is θ_{13}?
- What is the value of the CP phase δ?
- Type of the neutrino mass ordering (sign of Δm^2_{31})
- Is this basic picture correct?
  LSND hint?
  non-standard effects beyond oscillations?

The LSND puzzle and MiniBooNE results

Maltoni, TS, 0705.0107

The LSND signal





$L \simeq$ 35 m

evidence for $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$ oscillations

A. Aguilar *et al.*, PRD 64 (2001) 112007

$87.9 \pm 22.4 \pm 6.0$ excess events

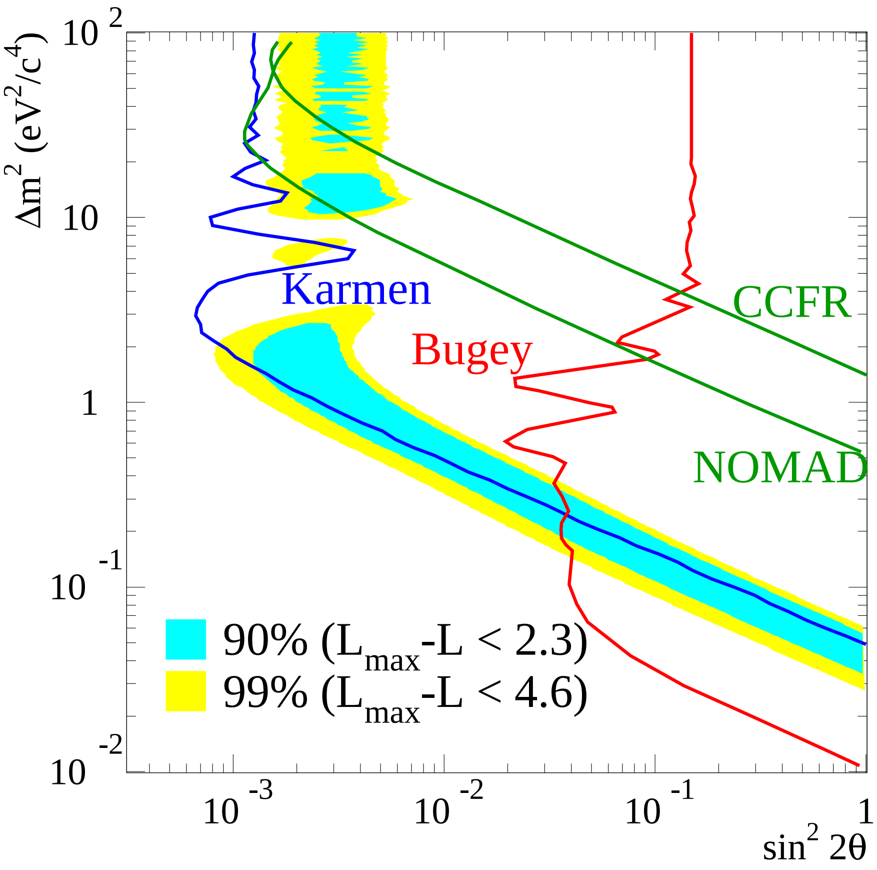
$P = (0.264 \pm 0.067 \pm 0.045)\%$

$\sim 3.3\sigma$ away from zero

Oscillation interpretation of LSND

the problem:

$\Delta m^2 \sim$ eV^2 not consistent with solar (8×10^{-5}) and atmospheric (3×10^{-3}) mass splittings for three neutrinos!



Check LSND with MiniBooNE

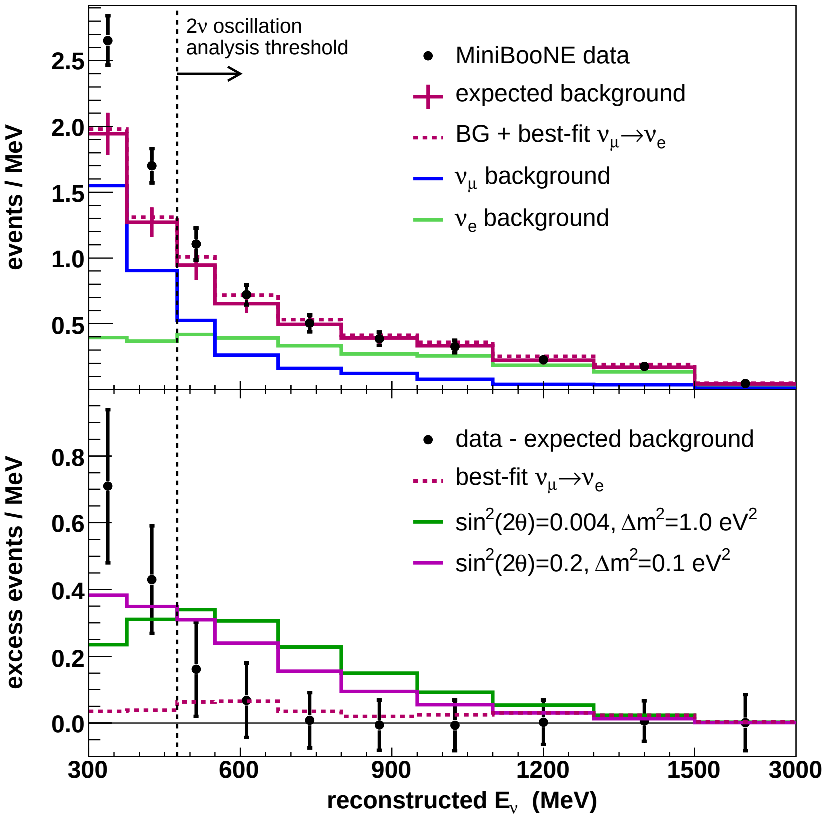
	LSND	MiniBooNE
energy	30 MeV	500 MeV
baseline	30 m	500 m
	same L/E_ν value	
channel	$\overline{\nu}_\mu \longrightarrow \overline{\nu}_e$	$\nu_\mu \longrightarrow \nu_e$

MiniBooNE results, April 2007

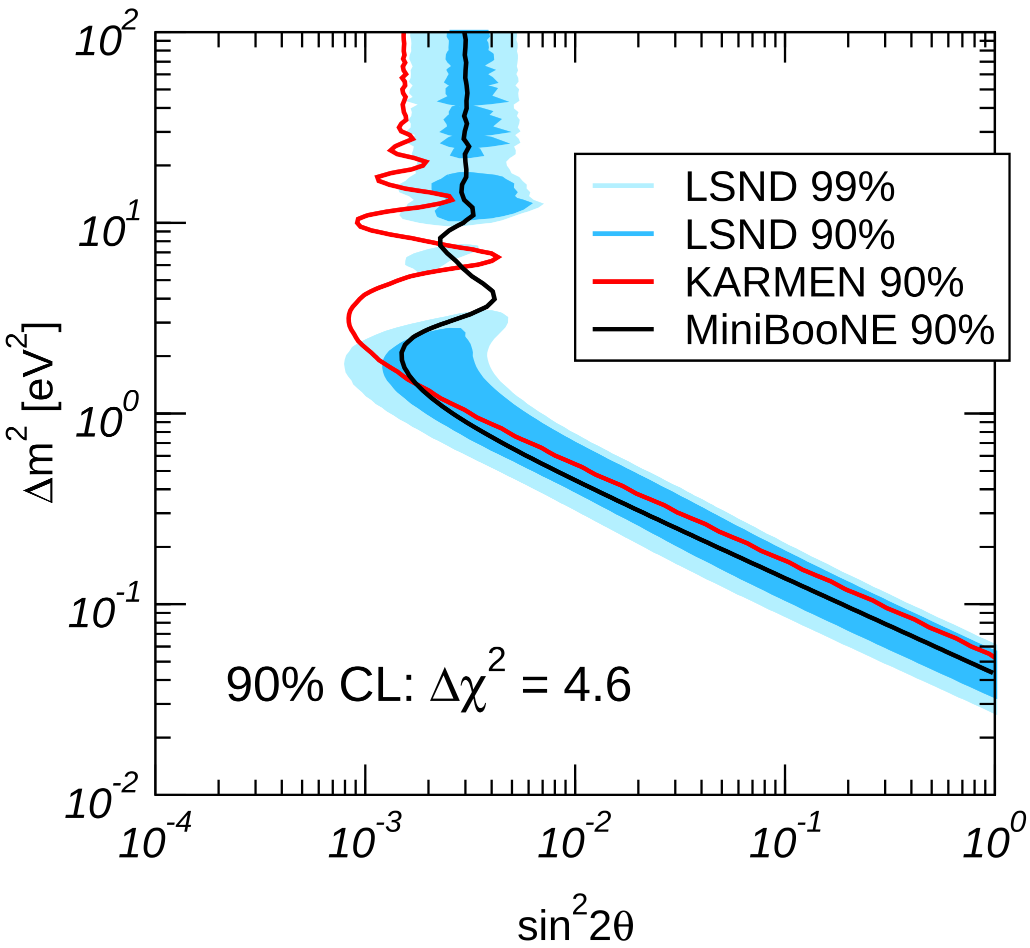
obs. events minus background:

$475 < E_\nu^{\rm QE} < 1250\,{\rm MeV}$:
$22 \pm 19 \pm 35$ events
(consistent with zero)

$300 < E_\nu^{\rm QE} < 475\,{\rm MeV}$:
$96 \pm 17 \pm 20$ events
(excess at 3.6σ)



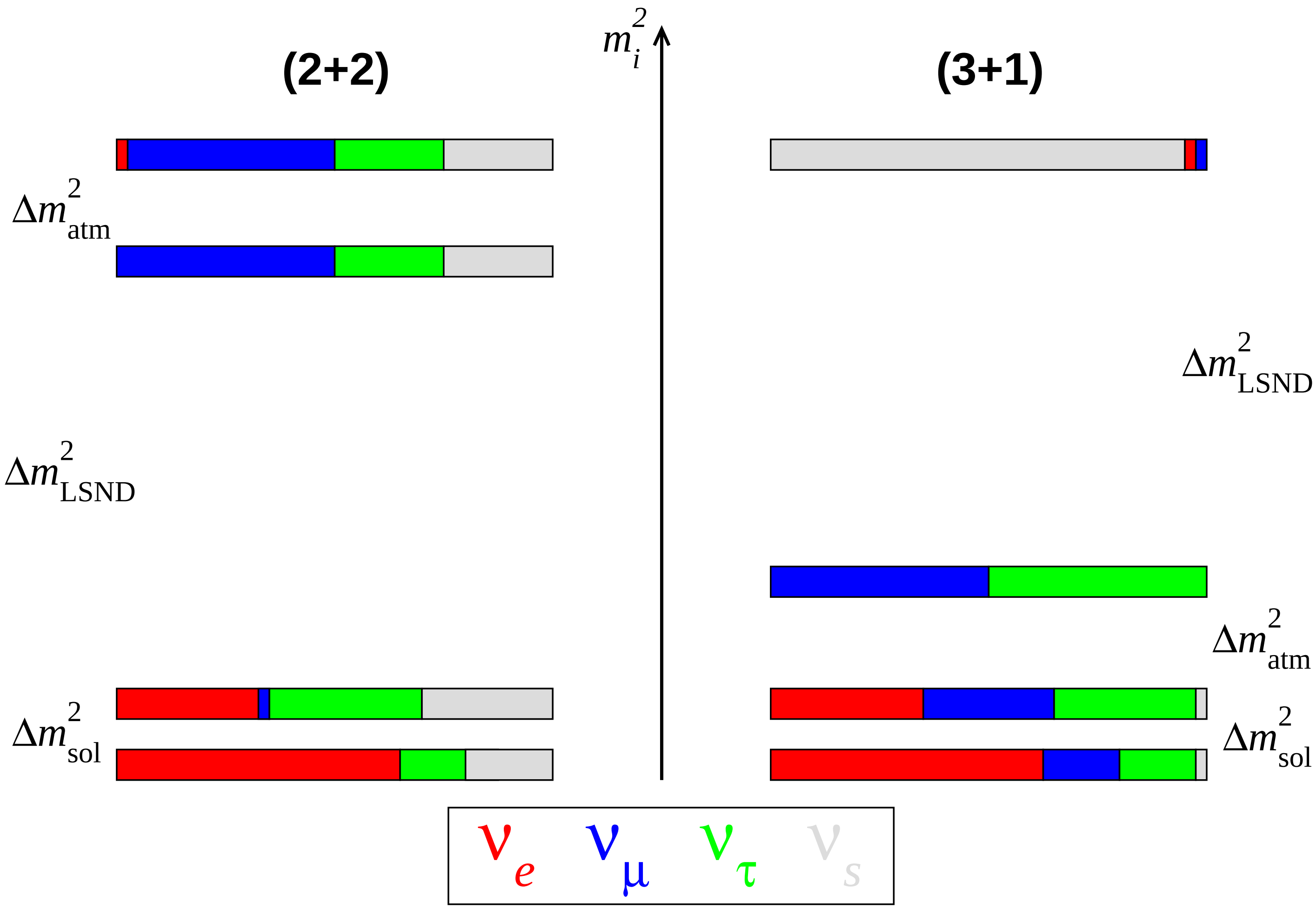
The MiniBooNE 2-neutrino limit



In the 2-neutrino framework MiniBooNE and LSND are incompatible at the 98% CL Aguilar-Arevalo et al., PRL08

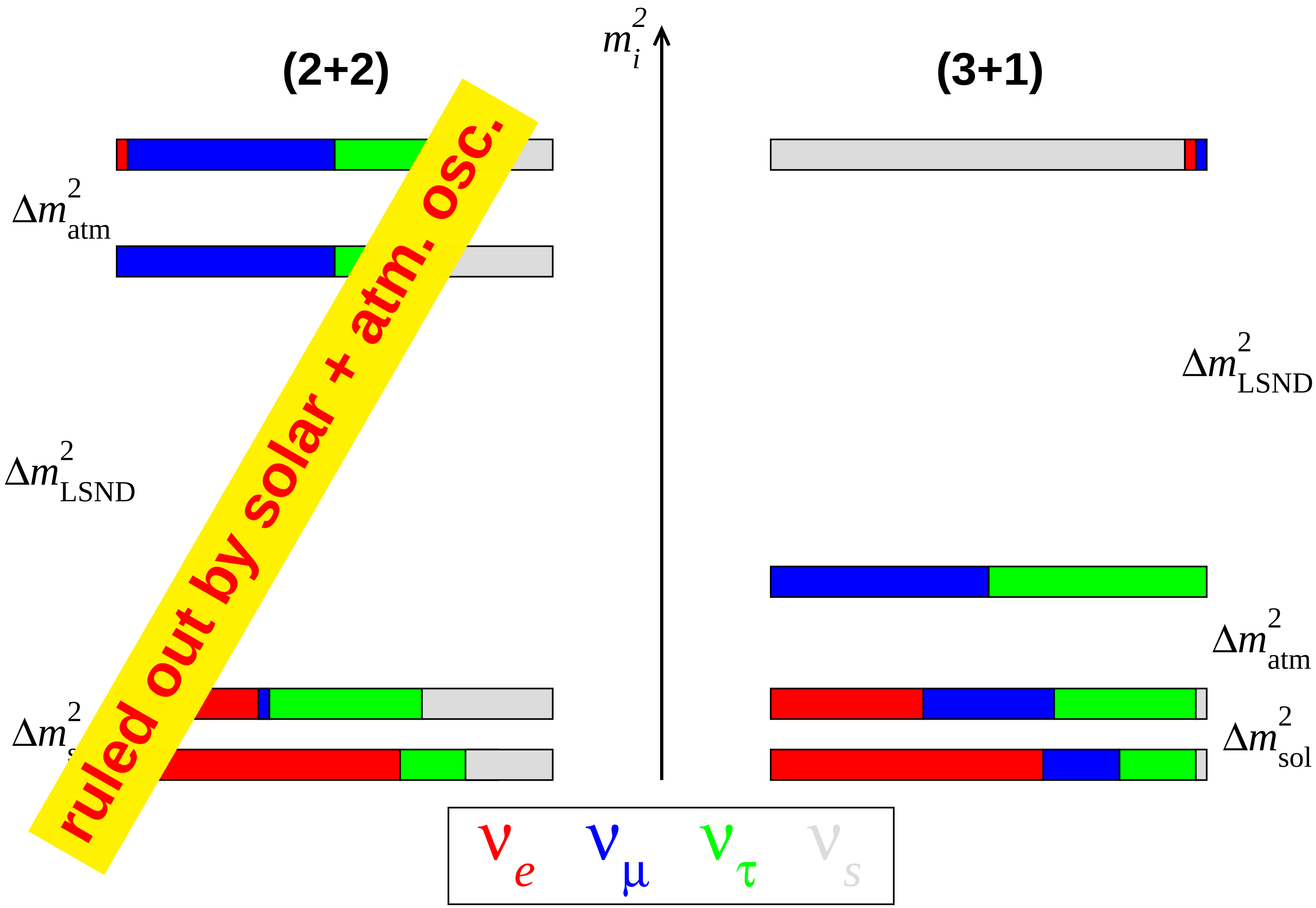
Adding a sterile neutrino

4-neutrino mass schemes:



Adding a sterile neutrino

4-neutrino mass schemes:



MB vs LSND in (3+1)

In (3+1) schemes the SBL appearance probability is effectively 2-ν oscillations:

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

with

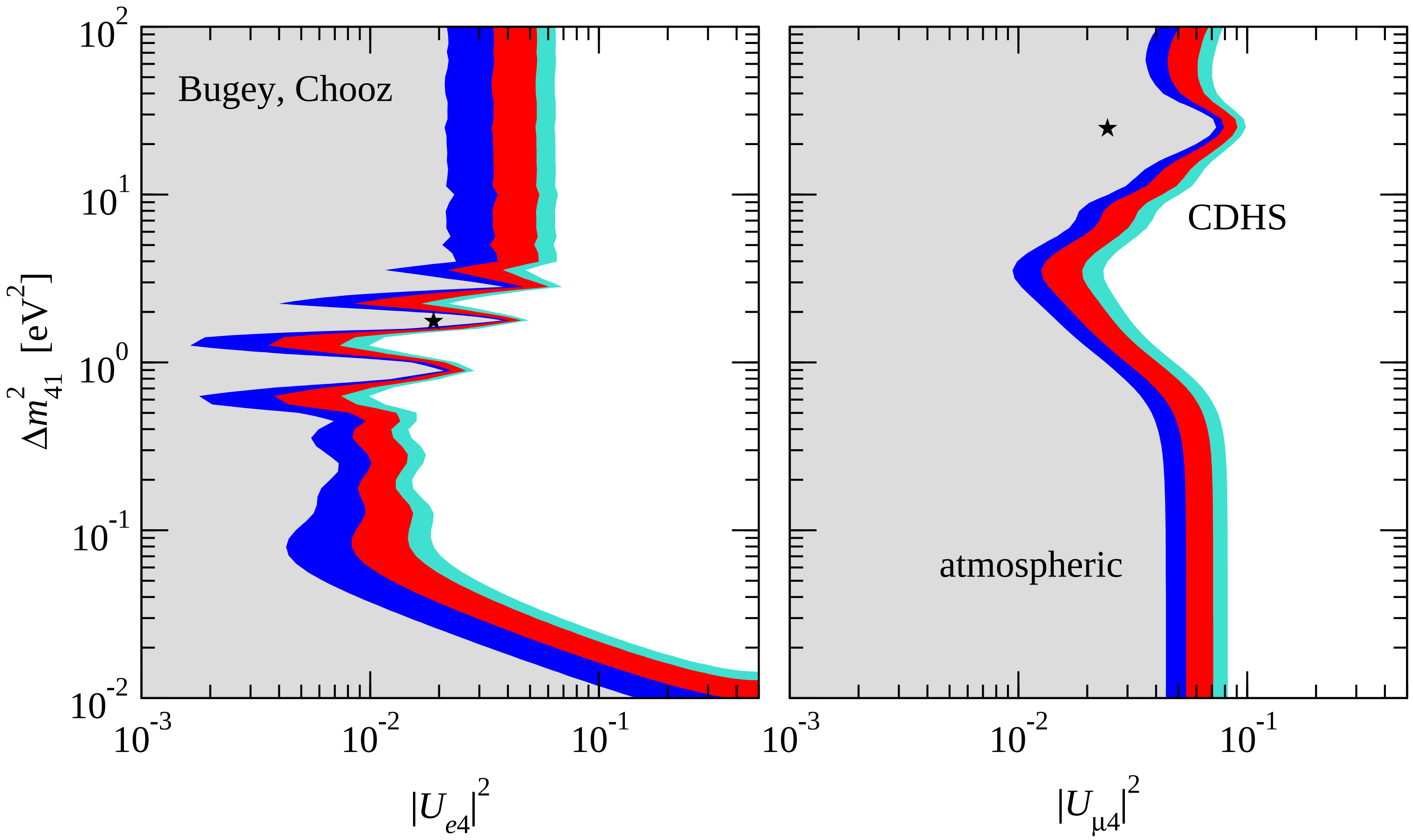
$$\sin^2 2\theta_{\rm SBL} = 4|U_{e4}|^2|U_{\mu 4}|^2$$

LSND / MiniBooNE inconsistency is the same as in the 2-flavour analysis presented by the MiniBooNE collaboration (98% CL)

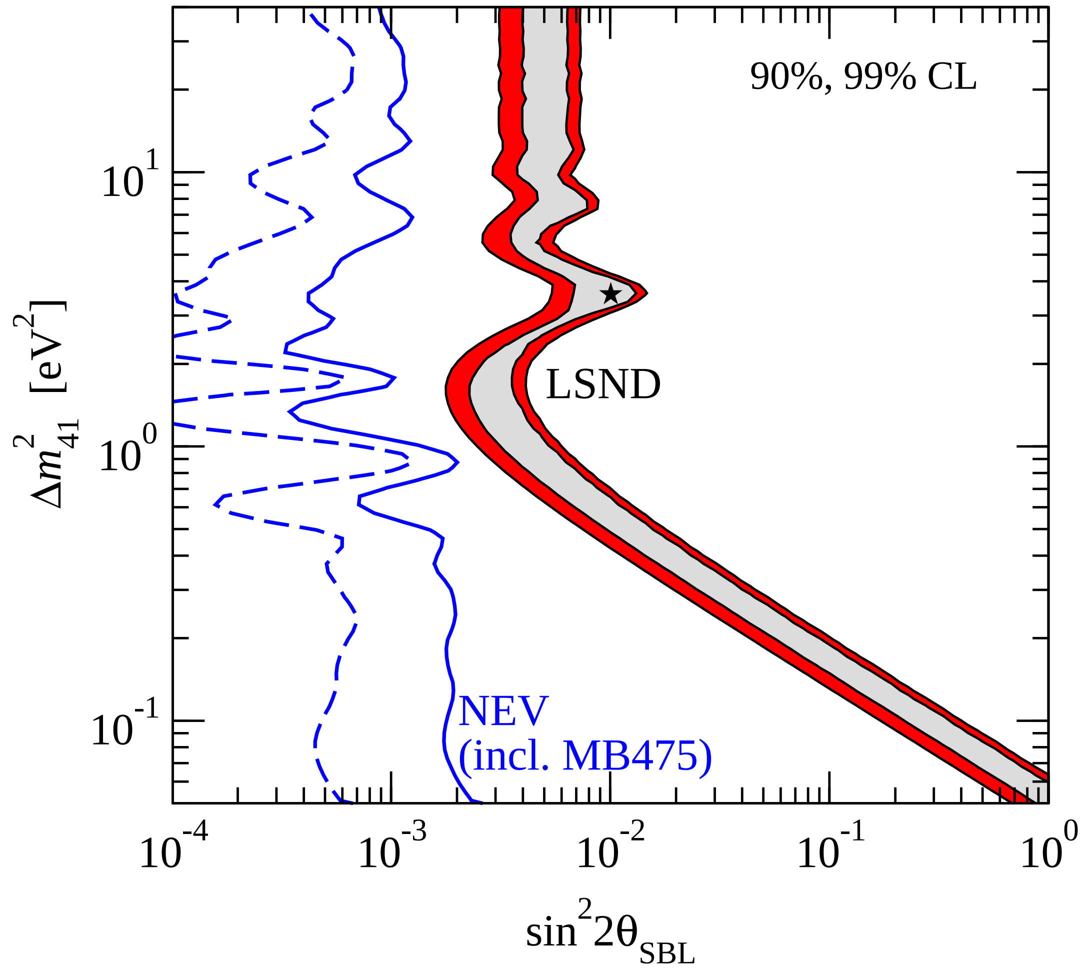
Appearance vs disappearance in (3+1)

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

disappearance experiments bound $|U_{e4}|^2$ and $|U_{\mu 4}|^2$



(3+1) global



before MB:
$\chi^2_{\rm PG} = 20.9\,(2\,\rm dof)$

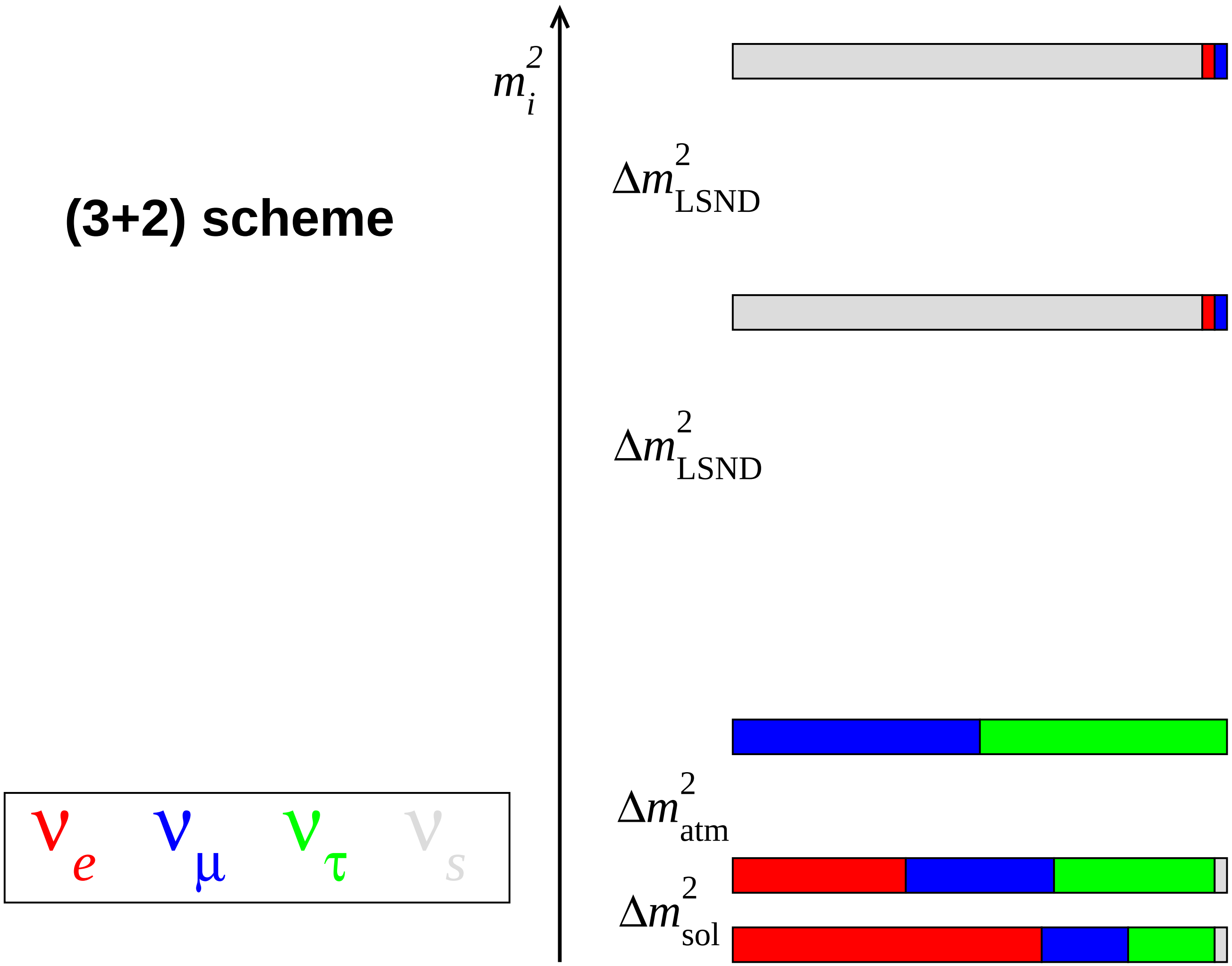
MB incl.:
$\chi^2_{\rm PG} = 24.7\,(2\,\rm dof)$

disagreement at about 4σ

More sterile neutrinos?

5-neutrino oscillations

(3+2) scheme



Sorel, Conrad, Shaevitz, hep-ph/0305255

(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

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

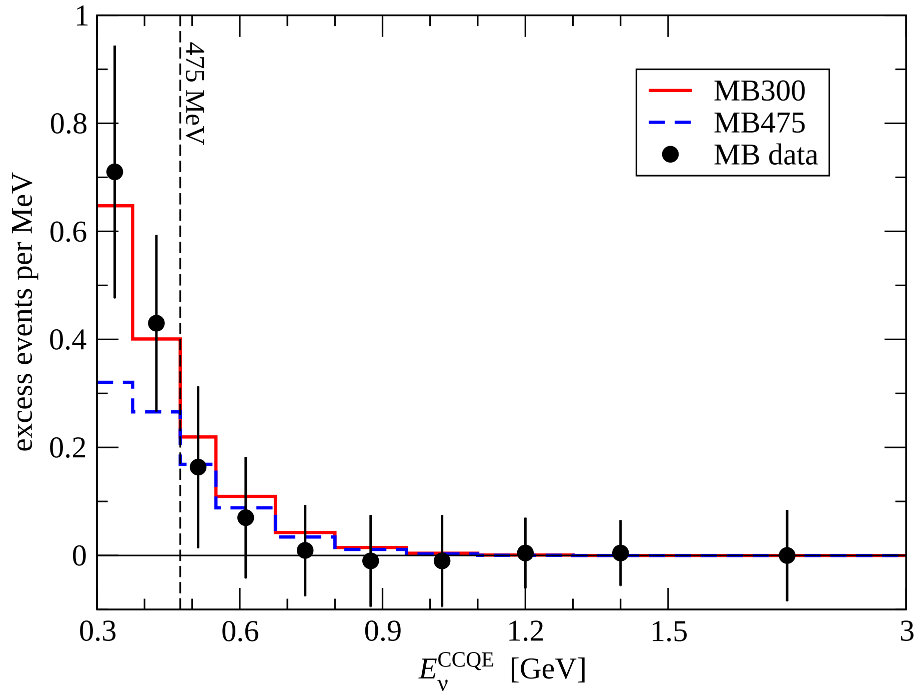
(3+2) osc. include the possibility of CP violation!

remember: MiniBooNE: neutrinos, LSND: anti-neutrinos

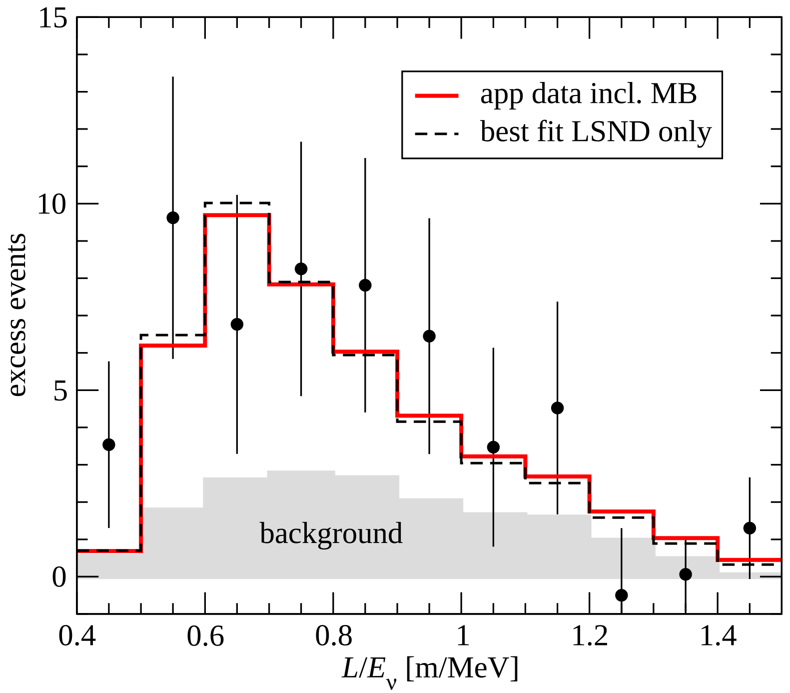
(3+2) appearance data

best fit point spectra:

MiniBooNE



LSND



Perfect fit to appearance data:

w/o MB low energy excess: $\chi^2_{\min} = 16.9/(29-5)$

with MB low energy excess: $\chi^2_{\min} = 18.5/(31-5)$

(3+2) disappearance data

what about the disappearance data?

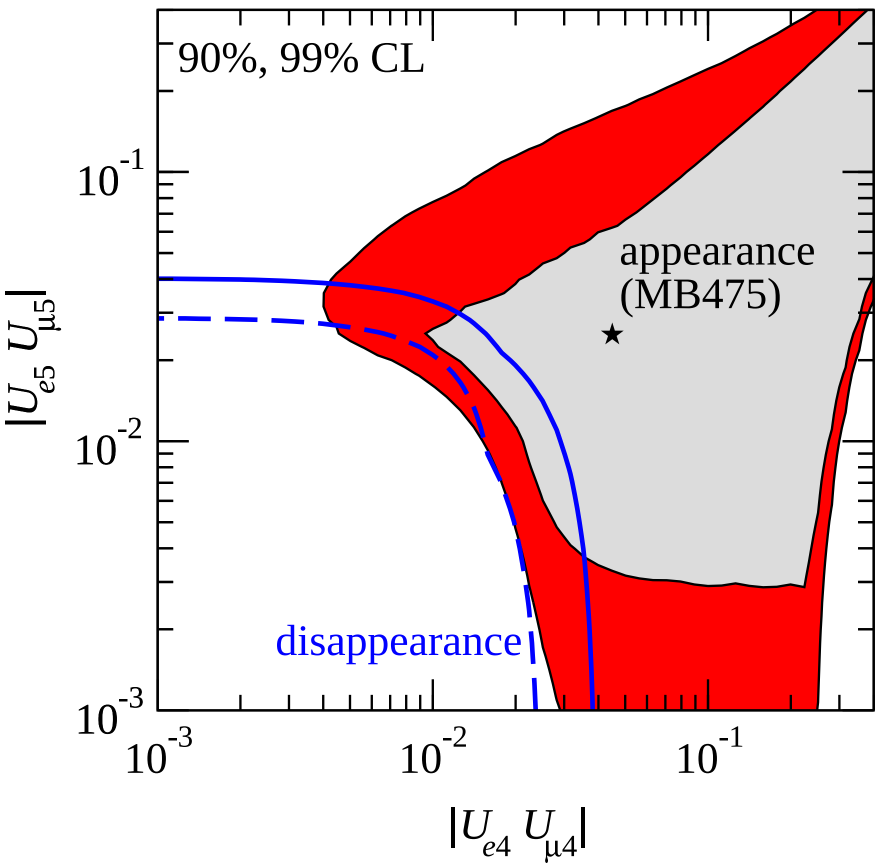
$$P_{\nu_\alpha\to\nu_\alpha} = 1 - 4\left(1 - \sum_{i=4,5} |U_{\alpha i}|^2\right) \sum_{i=4,5} |U_{\alpha i}|^2 \sin^2\phi_{i1}$$
$$- \; 4\,|U_{\alpha 4}|^2 |U_{\alpha 5}|^2 \sin^2\phi_{54}$$

$\Rightarrow$ bound $|U_{ei}|$ and $|U_{\mu i}|$ ($i = 4, 5$), similar as in (3+1)

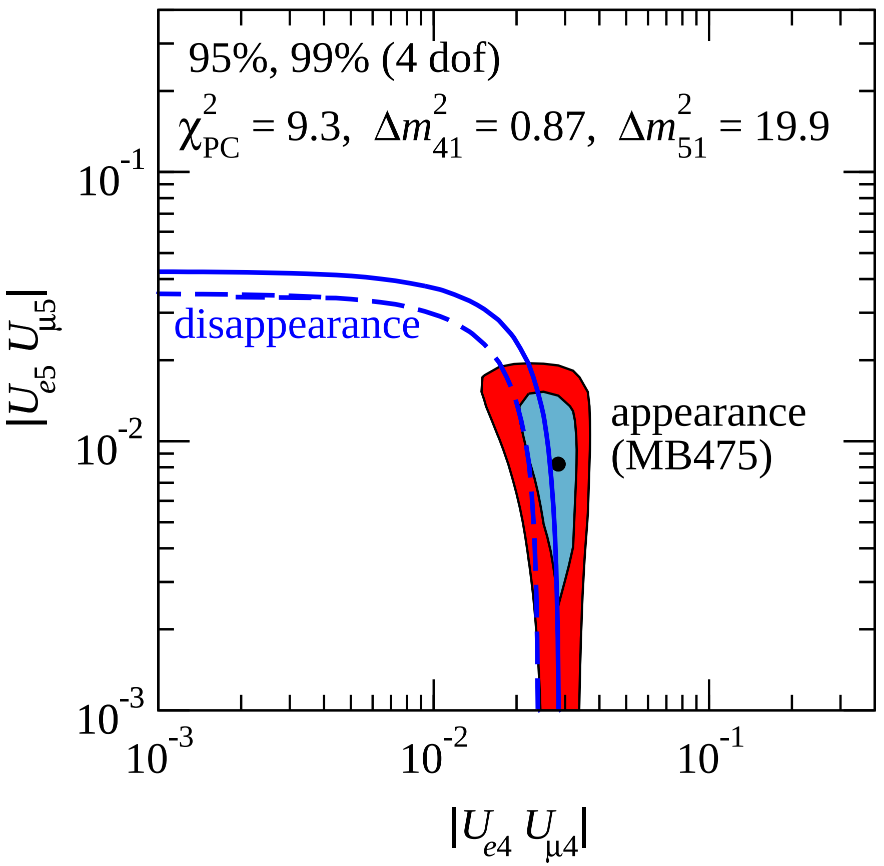
to be reconciled with appearance amplitudes $|U_{ei}U_{\mu i}|$

(3+2) app vs disap

projection



section



(3+2) global

testing consistency of disappearance and appearance data:

$$\chi^2_{\mathrm{PG}} = 17.2\,(4\,\mathrm{dof}) \qquad \mathrm{PG} = 0.18\%$$

(without MB: $\chi^2_{\mathrm{PG}} = 17.5$)

inconsistency at about 3.1σ

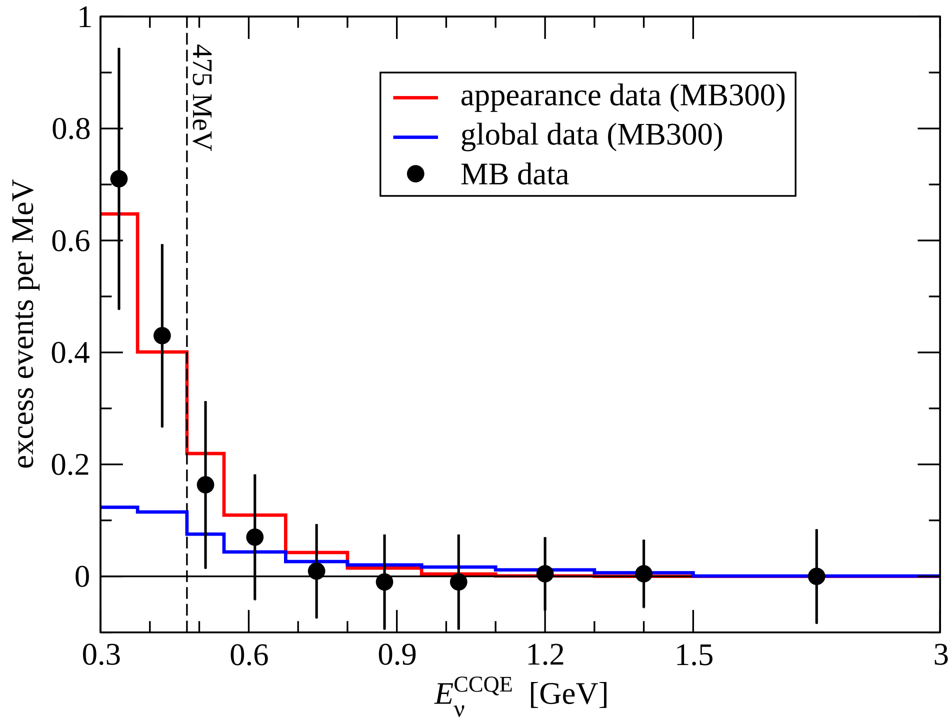
parameters in common $|U_{e4}U_{\mu4}|, |U_{e5}U_{\mu5}|, \Delta m^2_{41}, \Delta m^2_{51}$

best fit: $\Delta m^2_{41} = 0.9$ eV^2, $\Delta m^2_{51} = 6.5$ eV^2, $\chi^2_{\mathrm{min}} = 94.5/(107-7)$

$\chi^2_{\text{min, global (3+1)}} - \chi^2_{\text{min, global (3+2)}} = 6.1/4$ dof (81% CL)

the low energy MB excess in the (3+2) fit

the MB low energy excess is not reproduced at the global best fit point:



$$\chi^2_{\rm MB300} = 104.4/(109-7)$$

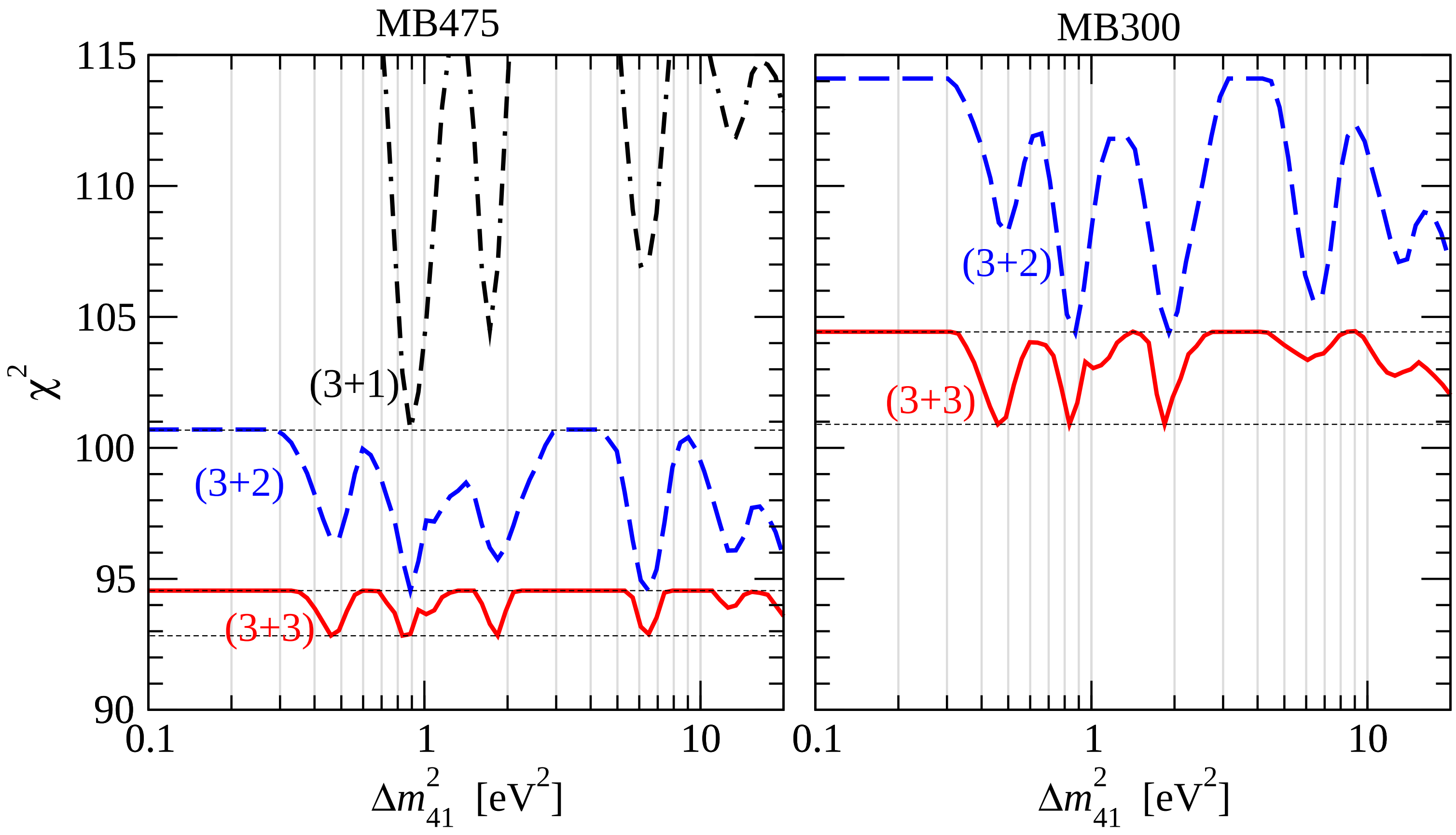
$$\chi^2_{\rm MB475} = 94.5/(107-7)$$

$$\chi^2_{\rm PG} = 25.1/4$$

$$\mathrm{PG} = 4.8 \times 10^{-5}\ (4\sigma)$$

adding another sterile: (3+3)

(3+3) global fit



	Δm^2_{41}	Δm^2_{51}	Δm^2_{61}	$\chi^2_{\rm min}$	$\chi^2_{(3+2)} - \chi^2_{(3+3)}$	CL
MB475	0.46	0.83	1.84	92.8	$1.7/4$	20%
MB300	0.46	0.83	1.84	100.9	$3.5/4$	52%

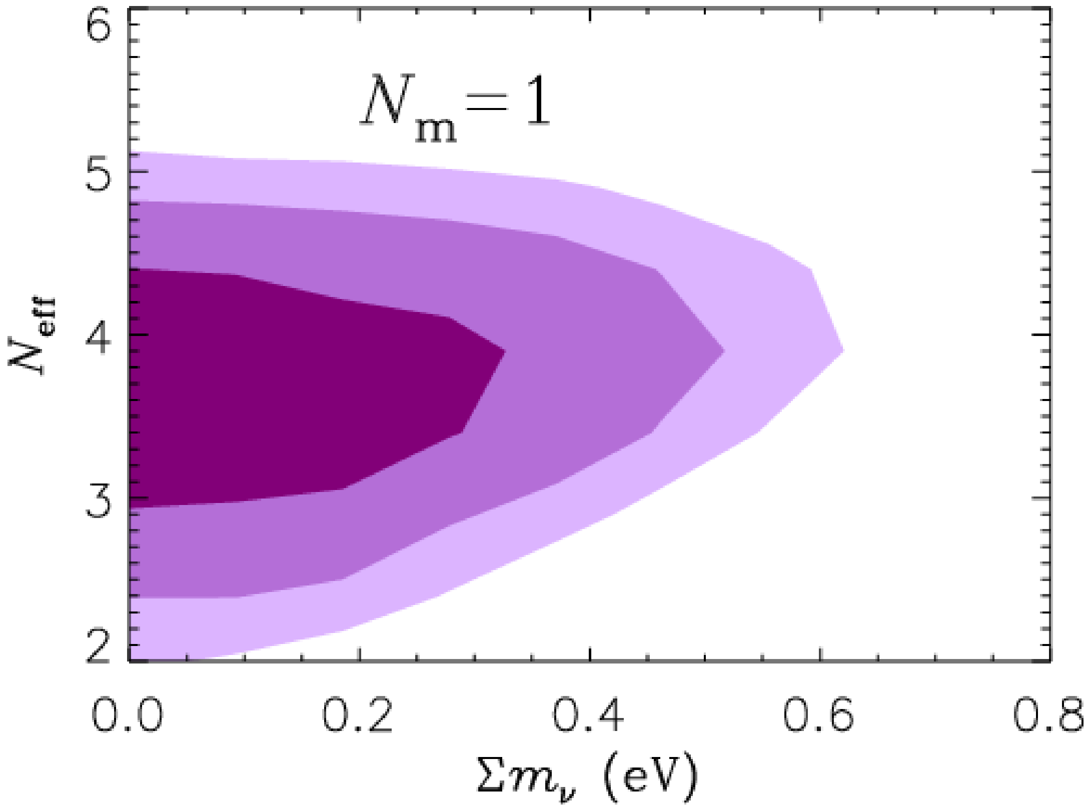
All these sterile neutrino schemes

have problems with cosmology

- sterile states contribute to the relativistic degrees of freedom (CMB, BBN)
- conflict with bound on the sum of neutrino masses from various cosmological data sets (LSS)

Cosmology

SN Ia, LSS (2dF, SDSS), BAO, CMB (WMAP, BOOMERANG)



68%, 95%, 99% CL

Hannestad, Raffelt, astro-ph/0607101

More ’exotic’ proposals

More exotic proposals

- 3-neutrinos and CPT violation Murayama, Yanagida 01; Barenboim, Borissov, Lykken 02; Gonzalez-Garcia, Maltoni, Schwetz 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
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- sterile neutrinos with $\Delta m^2 \sim 1\,\mathrm{eV}^2$ might lead to large effects for high energy atmospheric neutrinos in IceCube S. Choubey, 0709.1937

Summary

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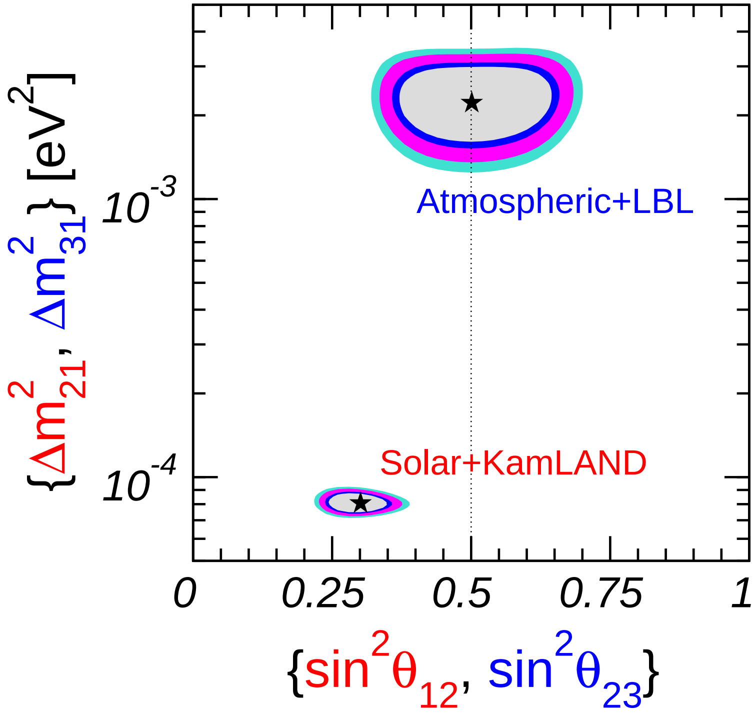

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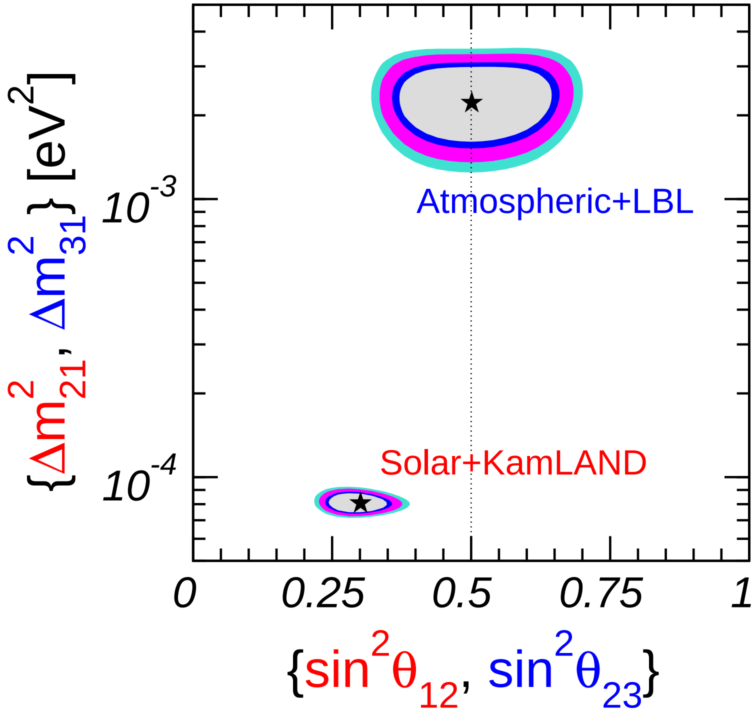

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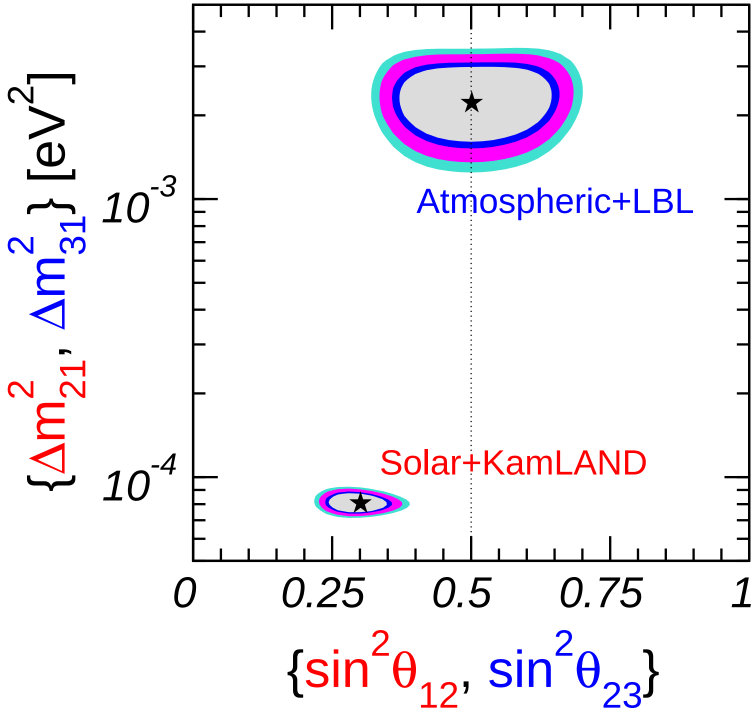

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Thanks for your attention!