idm2008

Neutrino oscillation update

Thomas Schwetz-Mangold

CERN

10-yr anniversary of neutrino oscillations

VOLUME 81, NUMBER 8 PHYSICAL REVIEW LETTERS 24 AUGUST 1998

Evidence for Oscillation of Atmospheric Neutrinos

Y. Fukuda,[1] T. Hayakawa,[1] E. Ichihara,[1] K. Inoue,[1] K. Ishihara,[1] H. Ishino,[1] Y. Itow,[1] T. Kajita,[1] J. Kameda,[1] S. Kasuga,[1] K. Kobayashi,[1] Y. Kobayashi,[1] Y. Koshio,[1] M. Miura,[1] M. Nakahata,[1] S. Nakayama,[1] A. Okada,[1] K. Okumura,[1] N. Sakurai,[1] M. Shiozawa,[1] Y. Suzuki,[1] Y. Takeuchi,[1] Y. Totsuka,[1] S. Yamada,[1] M. Earl,[2] A. Habig,[2] E. Kearns,[2] M.D. Messier,[2] K. Scholberg,[2] J.L. Stone,[2] L.R. Sulak,[2] C.W. Walter,[2] M. Goldhaber,[3] T. Barszczxak,[4] D. Casper,[4] W. Gajewski,[4] P.G. Halverson,[4,*] J. Hsu,[4] W.R. Kropp,[4] L.R. Price,[4] F. Reines,[4] M. Smy,[4] H.W. Sobel,[4] M.R. Vagins,[4] K.S. Ganezer,[5] W.E. Keig,[5] R.W. Ellsworth,[6] S. Tasaka,[7] J.W. Flanagan,[8,†] A. Kibayashi,[8] J.G. Learned,[8] S. Matsuno,[8] V.J. Stenger,[8] D. Takemori,[8] T. Ishii,[9] J. Kanzaki,[9] T. Kobayashi,[9] S. Mine,[9] K. Nakamura,[9] K. Nishikawa,[9] Y. Oyama,[9] A. Sakai,[9] M. Sakuda,[9] O. Sasaki,[9] S. Echigo,[10] M. Kohama,[10] A.T. Suzuki,[10] T.J. Haines,[11,4] E. Blaufuss,[12] B.K. Kim,[12] R. Sanford,[12] R. Svoboda,[12] M.L. Chen,[13] Z. Conner,[13,‡] J.A. Goodman,[13] G.W. Sullivan,[13] J. Hill,[14] C.K. Jung,[14] K. Martens,[14] C. Mauger,[14] C. McGrew,[14] E. Sharkey,[14] B. Viren,[14] C. Yanagisawa,[14] W. Doki,[15] K. Miyano,[15] H. Okazawa,[15] C. Saji,[15] M. Takahata,[15] Y. Nagashima,[16] M. Takita,[16] T. Yamaguchi,[16] M. Yoshida,[16] S.B. Kim,[17] M. Etoh,[18] K. Fujita,[18] A. Hasegawa,[18] T. Hasegawa,[18] S. Hatakeyama,[18] T. Iwamoto,[18] M. Koga,[18] T. Maruyama,[18] H. Ogawa,[18] J. Shirai,[18] A. Suzuki,[18] F. Tsushima,[18] M. Koshiba,[19] M. Nemoto,[20] K. Nishijima,[20] T. Futagami,[21] Y. Hayato,[21,§] Y. Kanaya,[21] K. Kaneyuki,[21] Y. Watanabe,[21] D. Kielczewska,[22,4] R.A. Doyle,[23] J.S. George,[23] A.L. Stachyra,[23] L.L. Wai,[23,‖] R.J. Wilkes,[23] and K.K. Young[23]
(Super-Kamiokande Collaboration)

3000+ citations

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

  some brief comments on exotic proposals

Global data and three-neutrino oscillations

Maltoni, TS, Tortola, Valle, hep-ph/0309130, hep-ph/0405172

TS, Tortola, Valle, 0808.2016

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

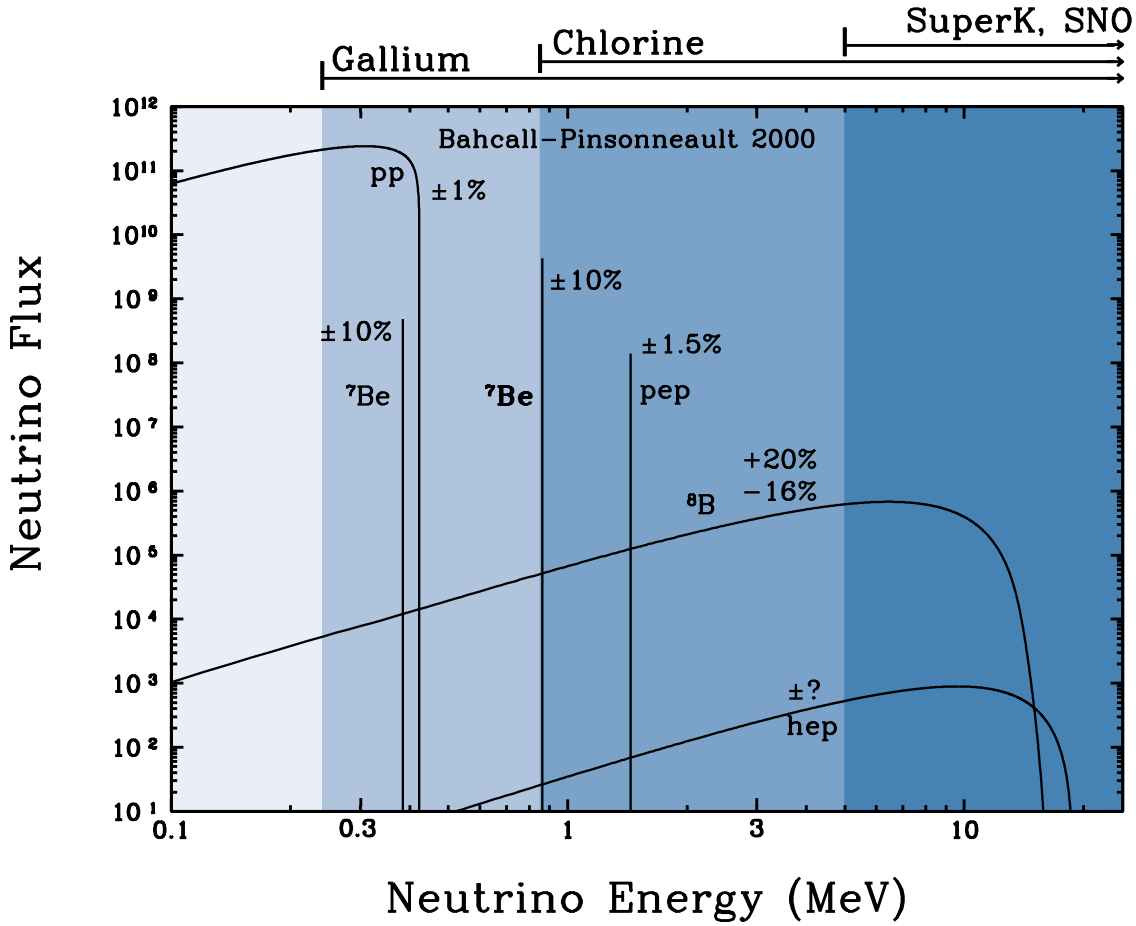
The “solar” parameters Δm^2_{21}, θ_{12}

Δm^2_{31} $\qquad\qquad\qquad\qquad$ Δm^2_{21}

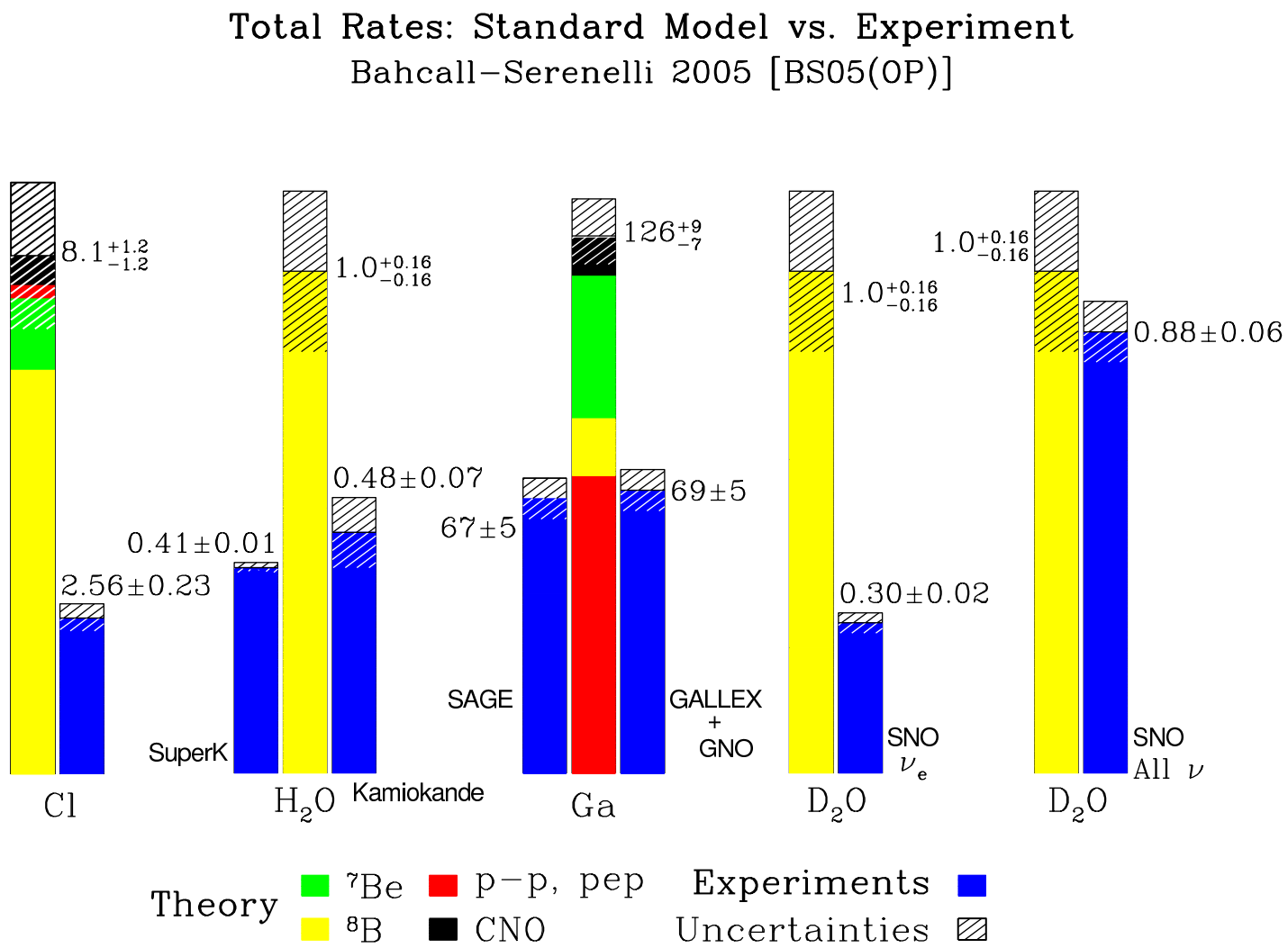
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric+LBL $\qquad\qquad$ Chooz $\qquad\qquad$ solar+KamLAND

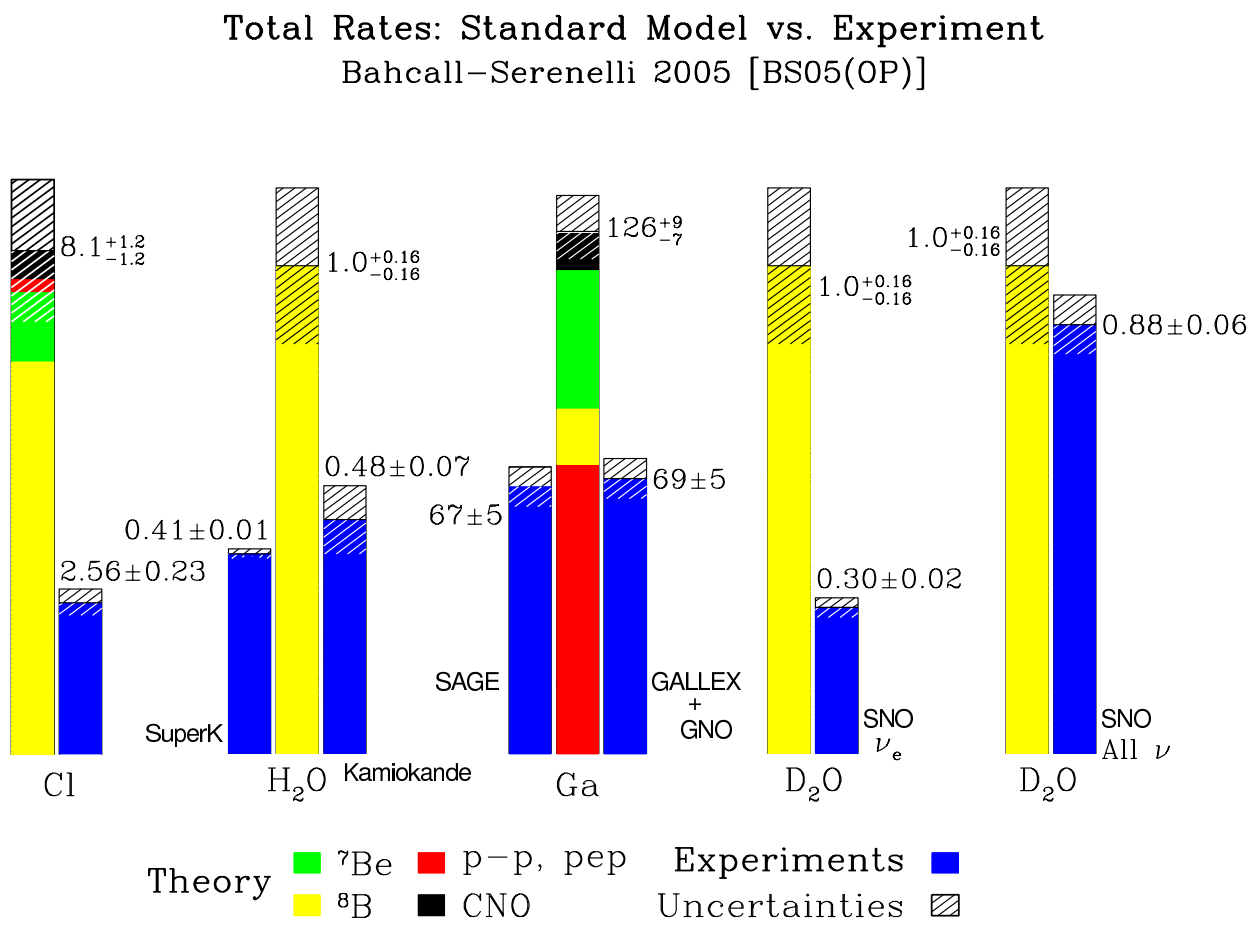
The solar neutrino flux



Solar neutrino experiments



Solar neutrino experiments



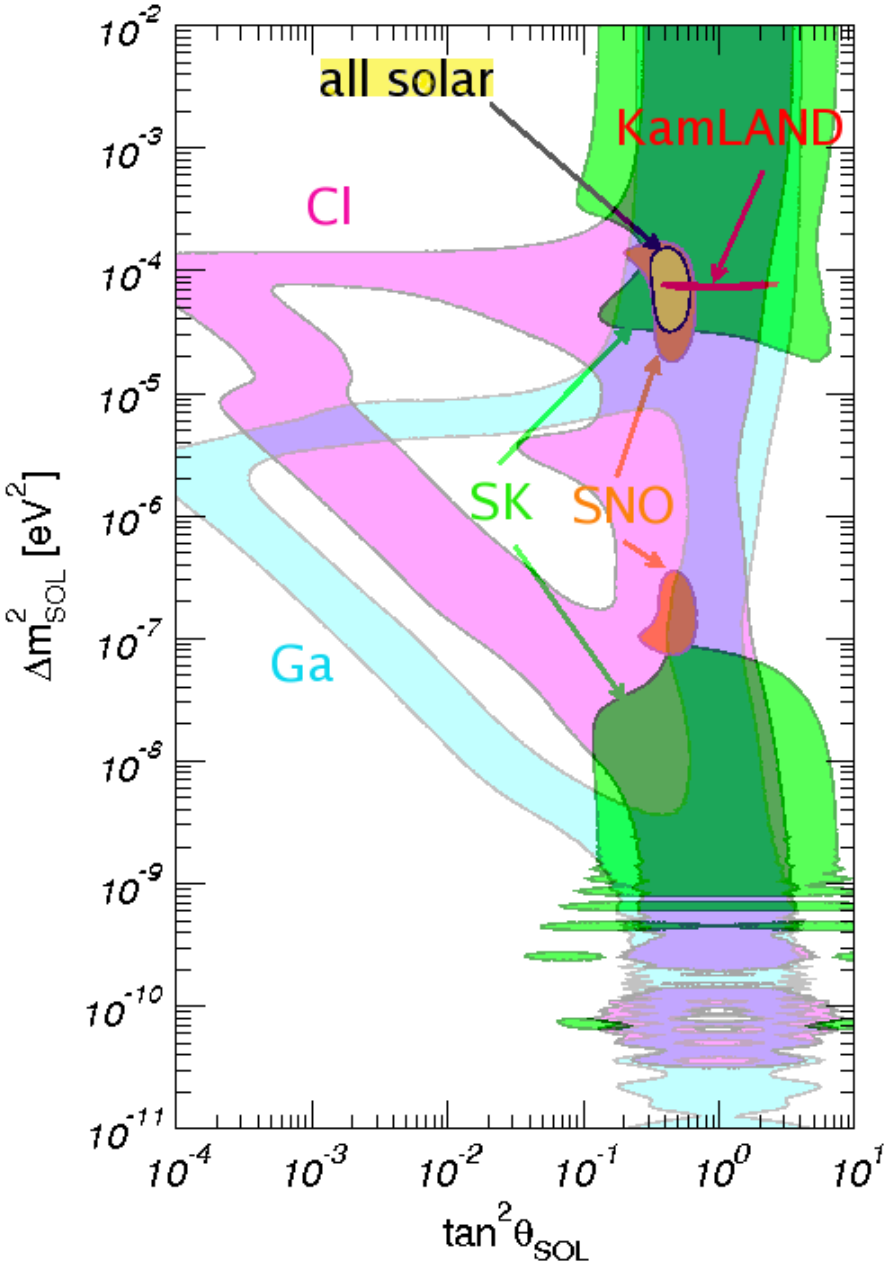
SNO:

$$\nu_e + d \rightarrow p + p + e^-$$
$$\nu_x + d \rightarrow p + n + \nu_x$$

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

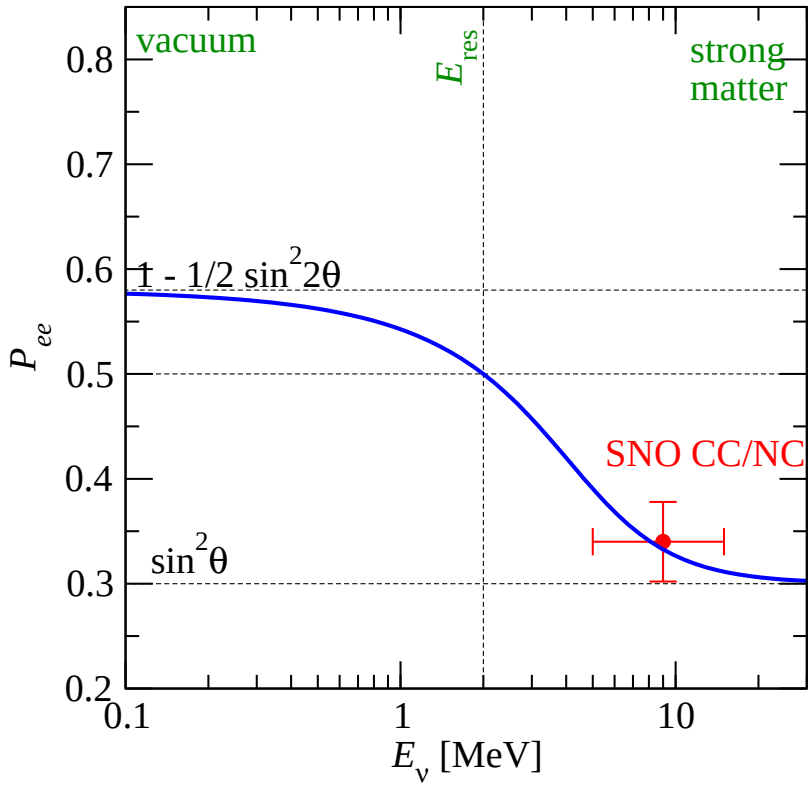
7σ evidence for a non-zero $\nu_{\mu,\tau}$ flux from the sun

’Solar’ parameters



The LMA-MSW solution

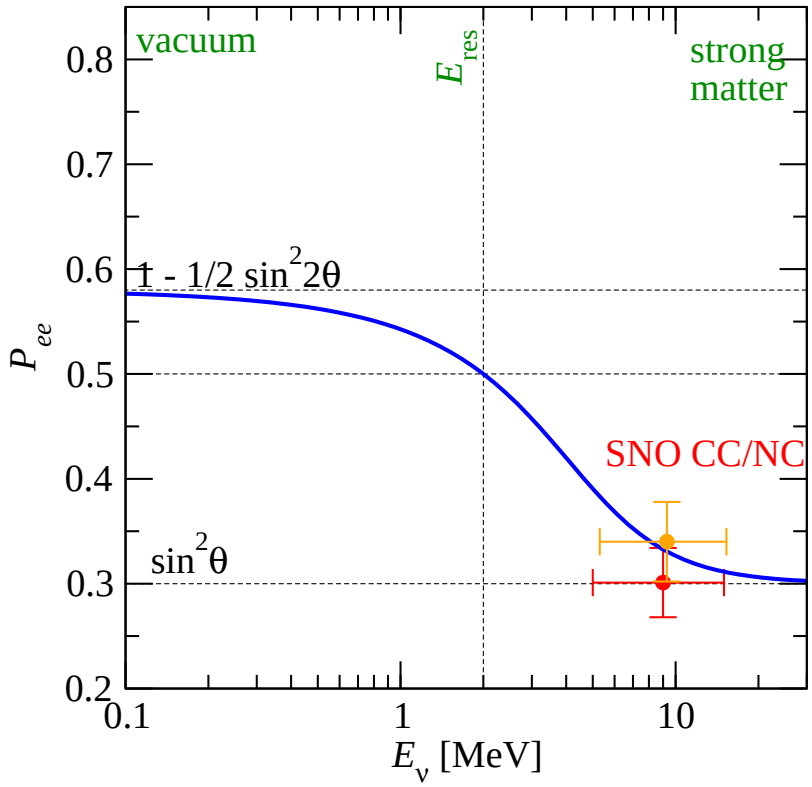
adiabatic evolution of the neutrino state from the center of the sun to the surface

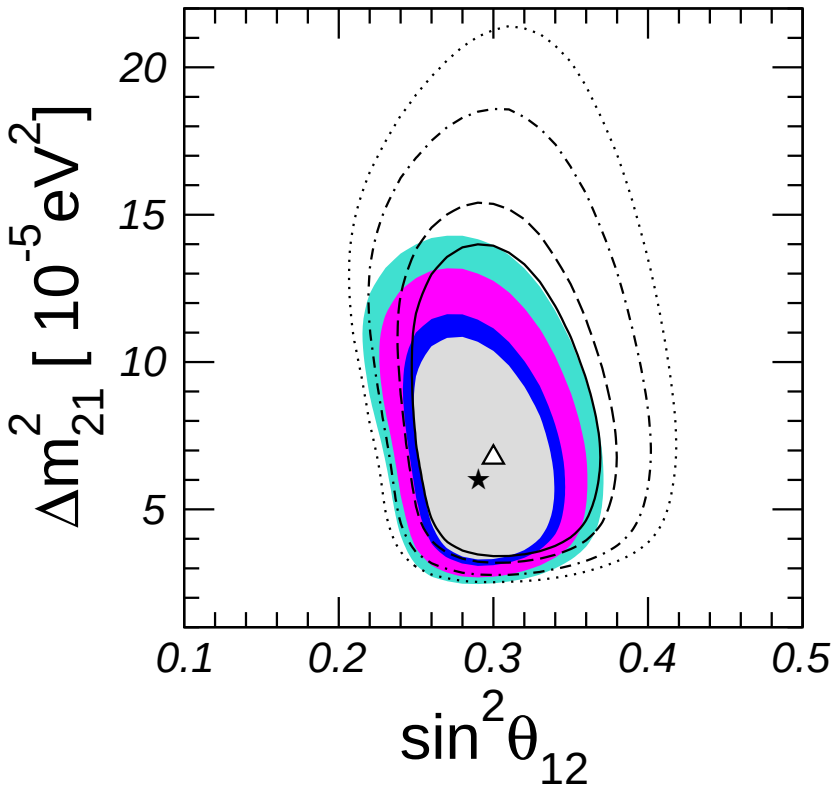


SNO CC/NC: constraint on $\sin^2\theta_{12}$, evidence for MSW effect

The LMA-MSW solution

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

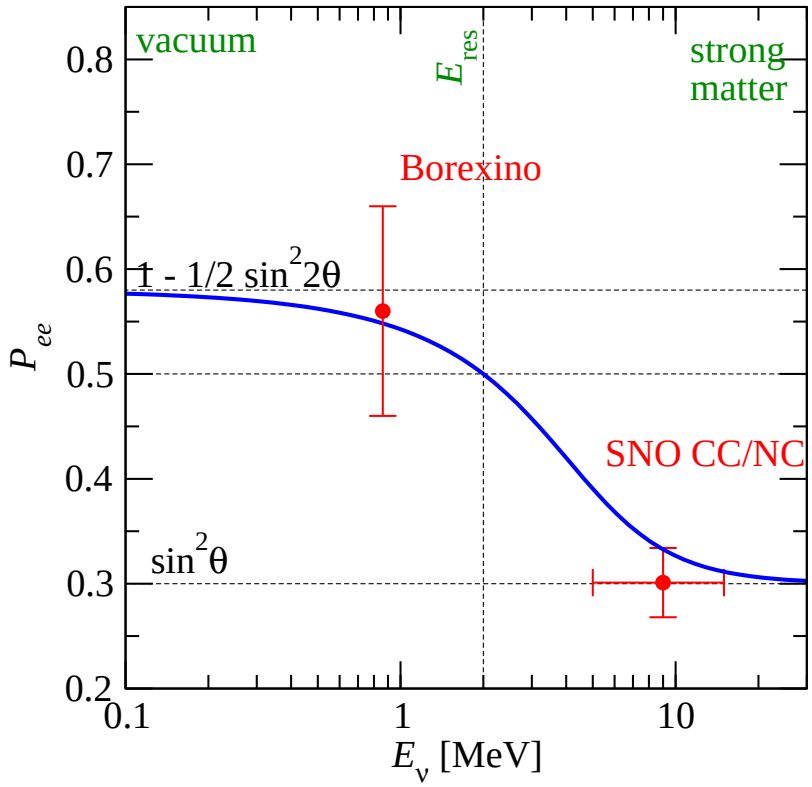


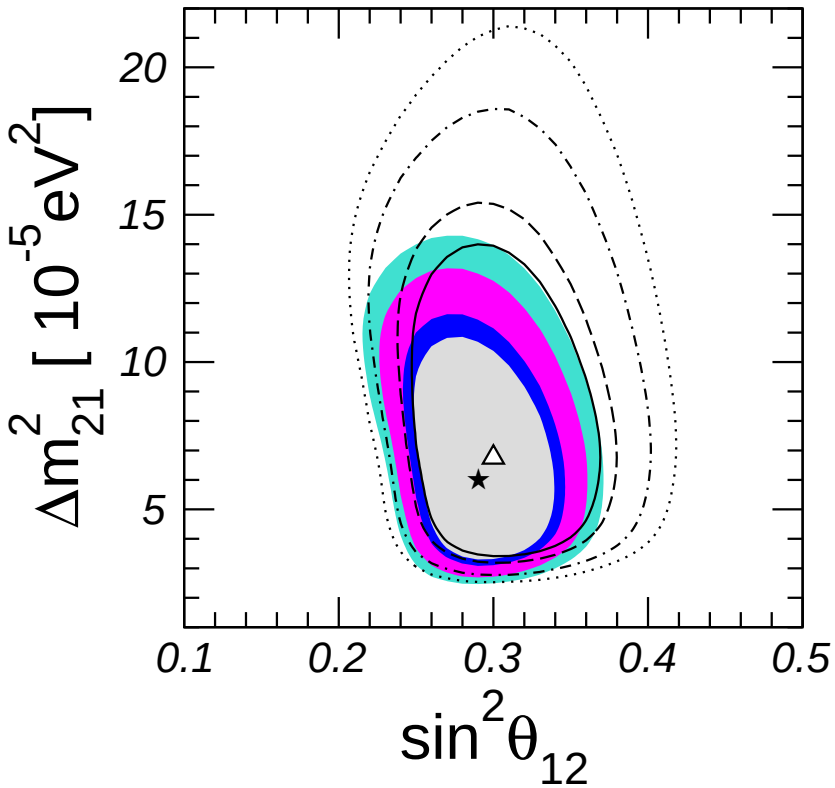


$$(\phi_{CC}/\phi_{NC})_{\rm salt} = 0.340 \pm 0.038 \rightarrow (\phi_{CC}/\phi_{NC})_{\rm NCD} = 0.301 \pm 0.033$$

The LMA-MSW solution

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

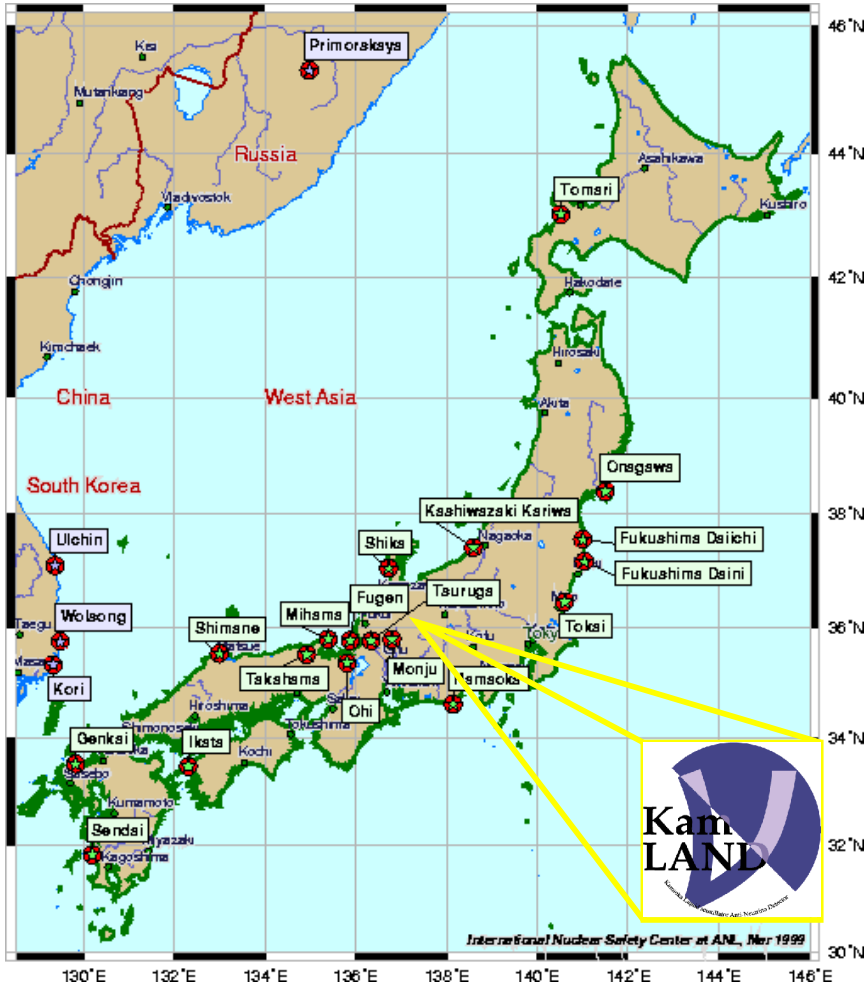




BOREXINO: measurment of the Be7 neutrino line at 0.862 MeV

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

Data released 2007:

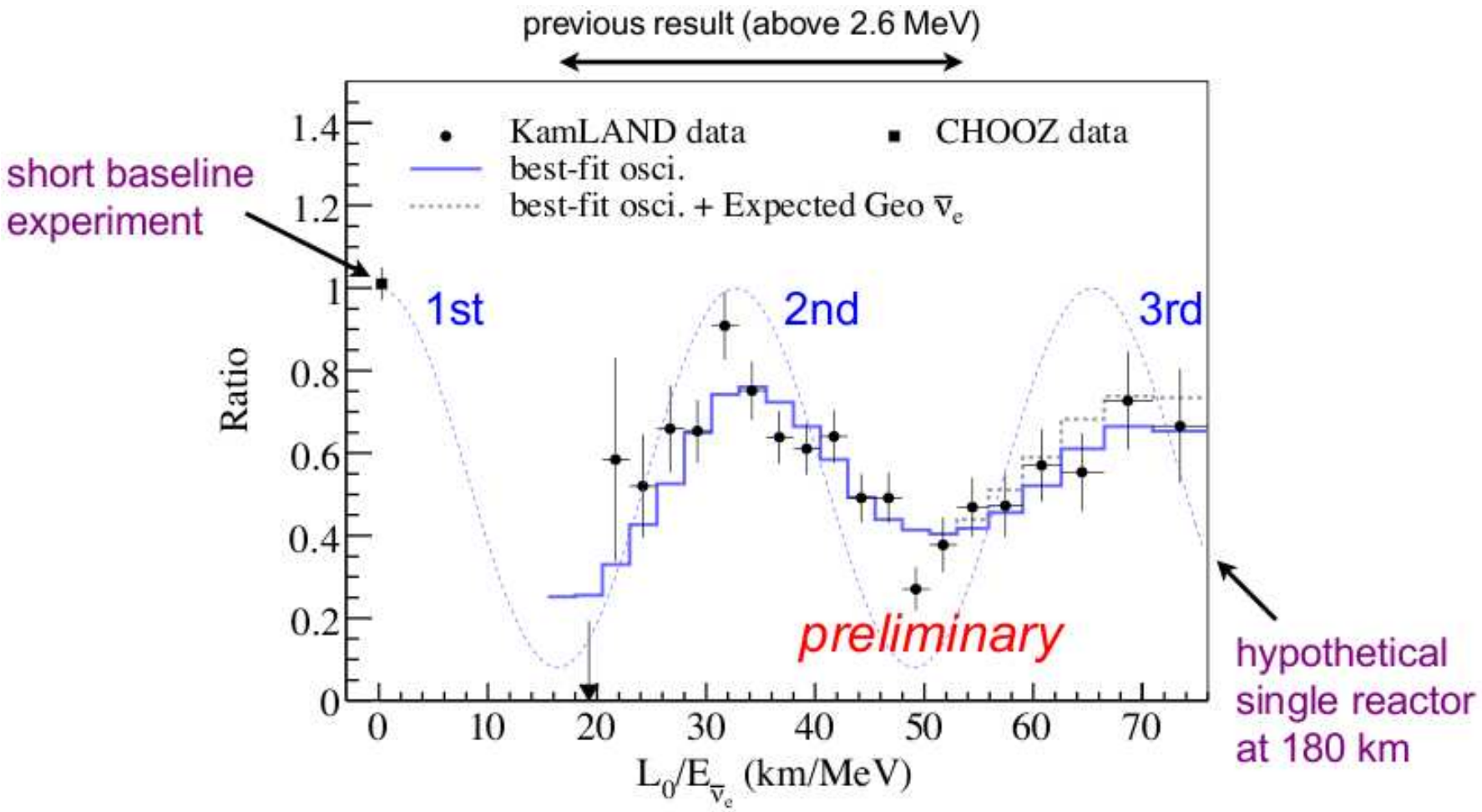
- 2881 ton yr data
  4 times more than previous 2004 data
- reduced syst. error due to full volume calibration from 4.7% to 1.8%
  dominating error for Δm^2 determination is now the uncertainty on the energy scale of 1.5%

observed number of events above 2.6 MeV: 985

expectation without oscillations:

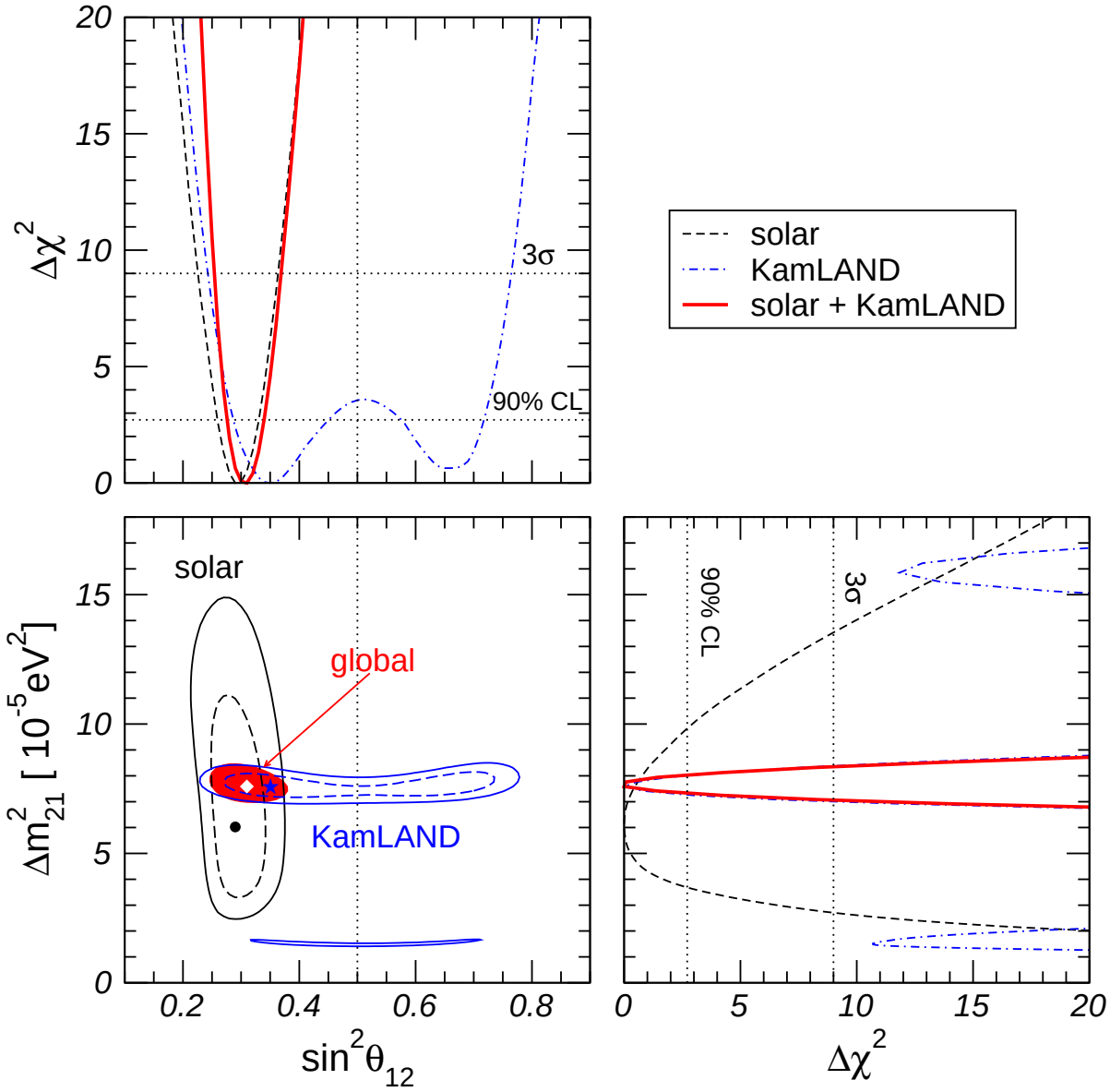
1550 reactor neutrino events + 63 background

The KamLAND energy spectrum



evidence for oscillations in $1/E_\nu$

KamLAND vs solar data



$$\sin^2\theta_{12} = 0.304^{+0.022}_{-0.016}\,, \qquad \Delta m^2_{21} = 7.65^{+0.23}_{-0.20} \times 10^{-5}\,\mathrm{eV}^2$$

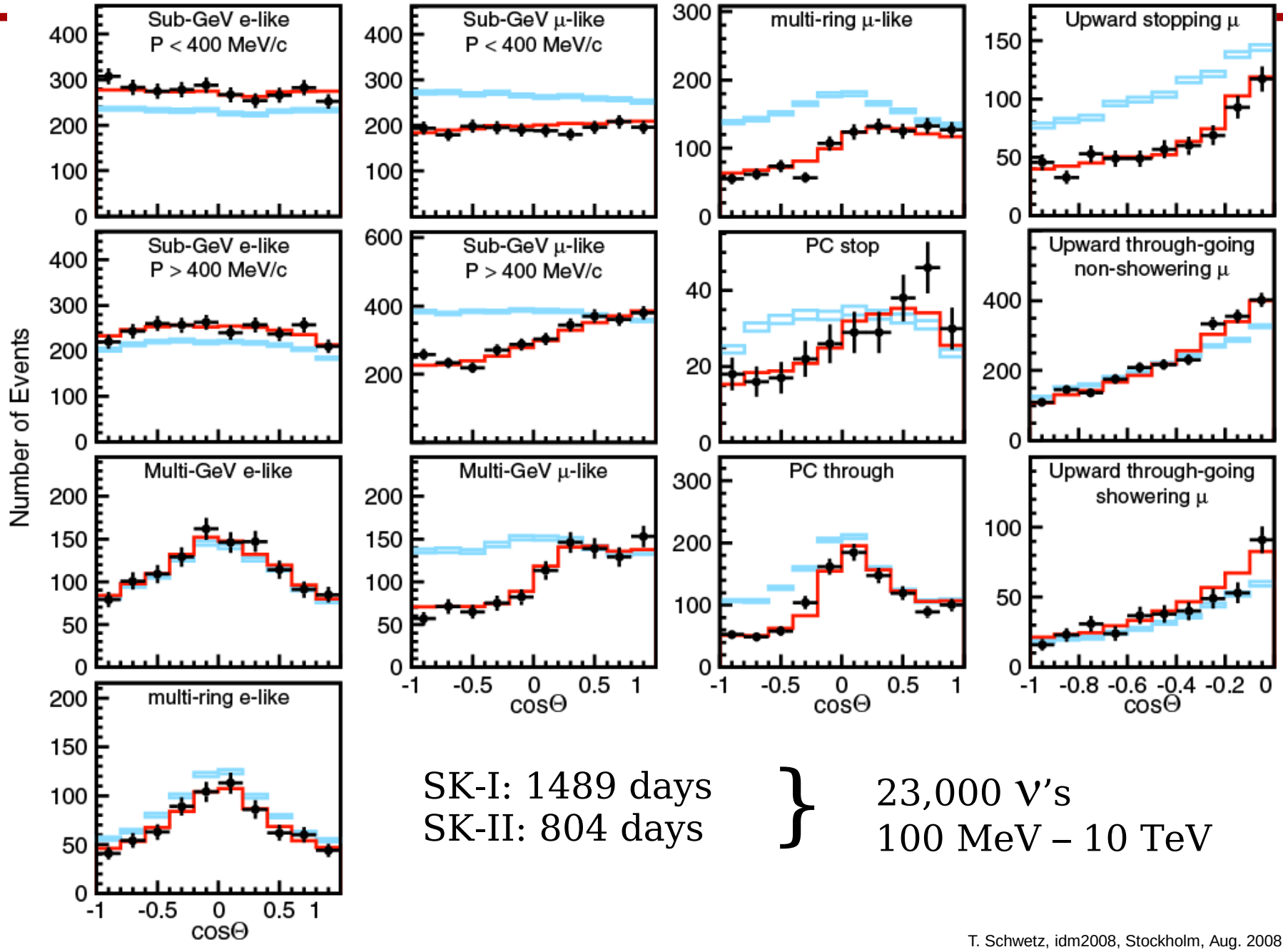
The “atmospheric” parameters Δm^2_{31}, θ_{23}

Δm^2_{31} $\qquad\qquad\qquad\qquad$ Δm^2_{21}

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

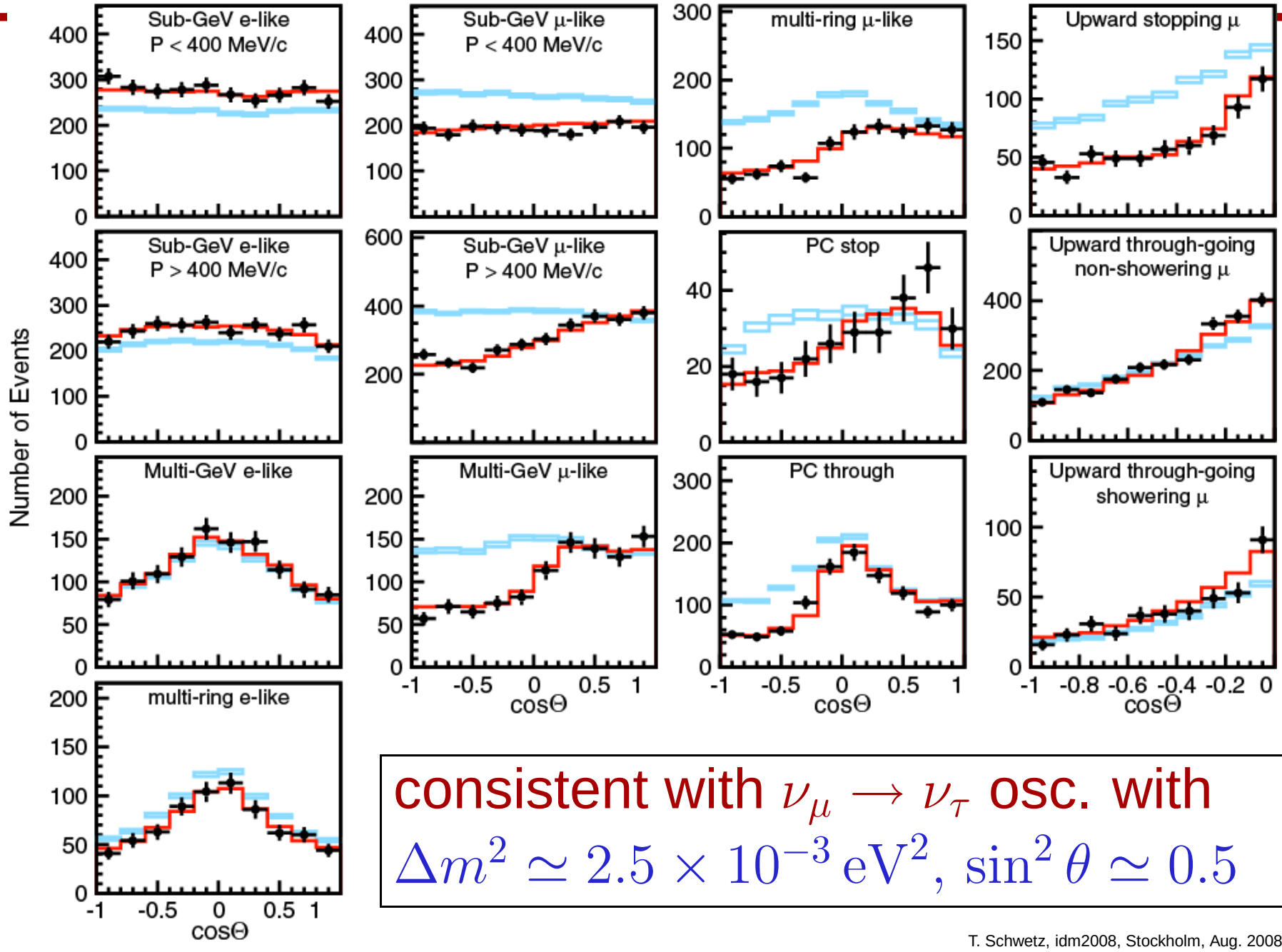
atmospheric+LBL $\qquad$ Chooz $\qquad$ solar+KamLAND

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

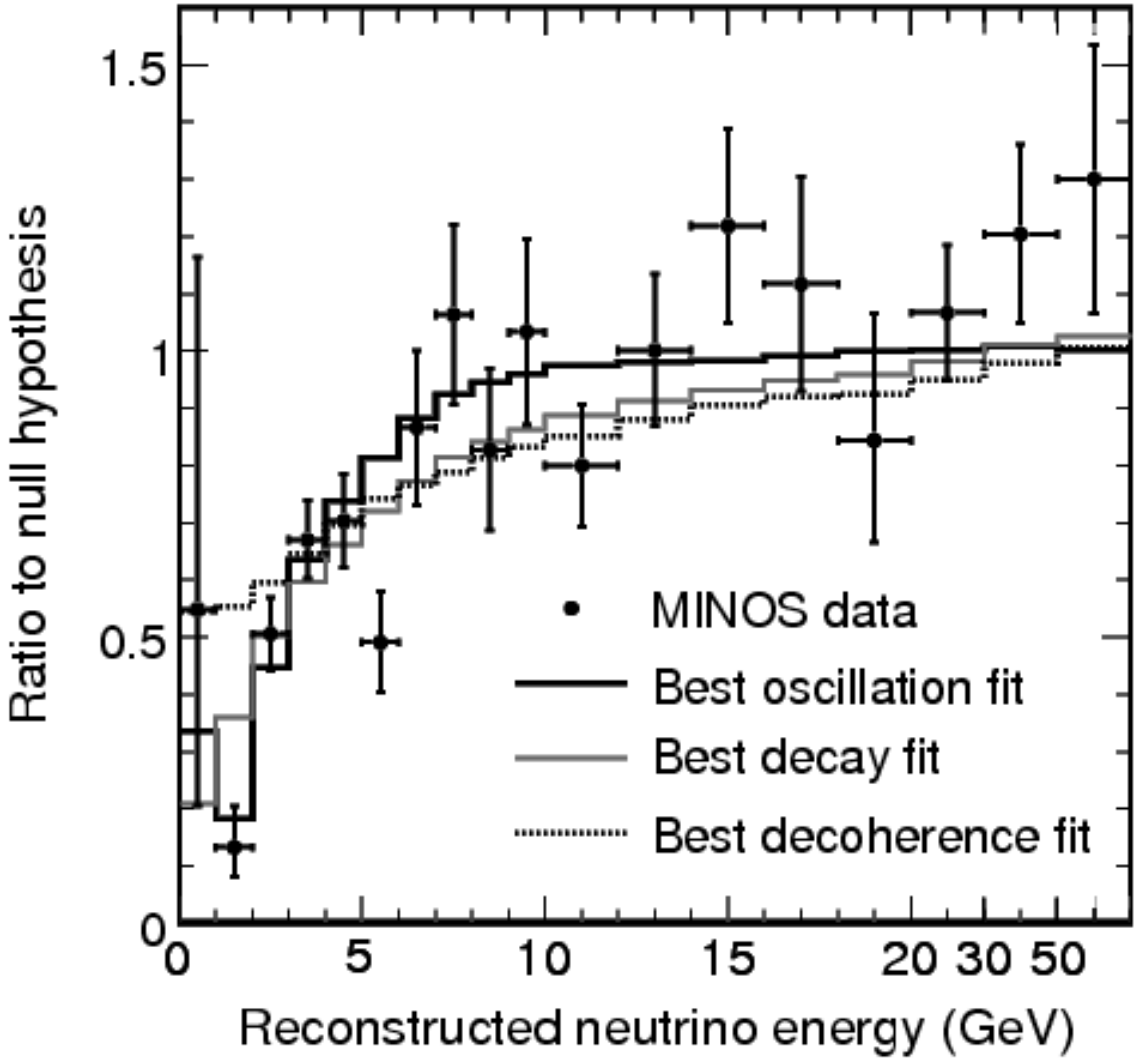
first generation of LBL experiments
($\nu_\mu \rightarrow \nu_\mu$ disappearance)

Long-baseline experiments

first generation of LBL experiments
($\nu_\mu \to \nu_\mu$ disappearance)

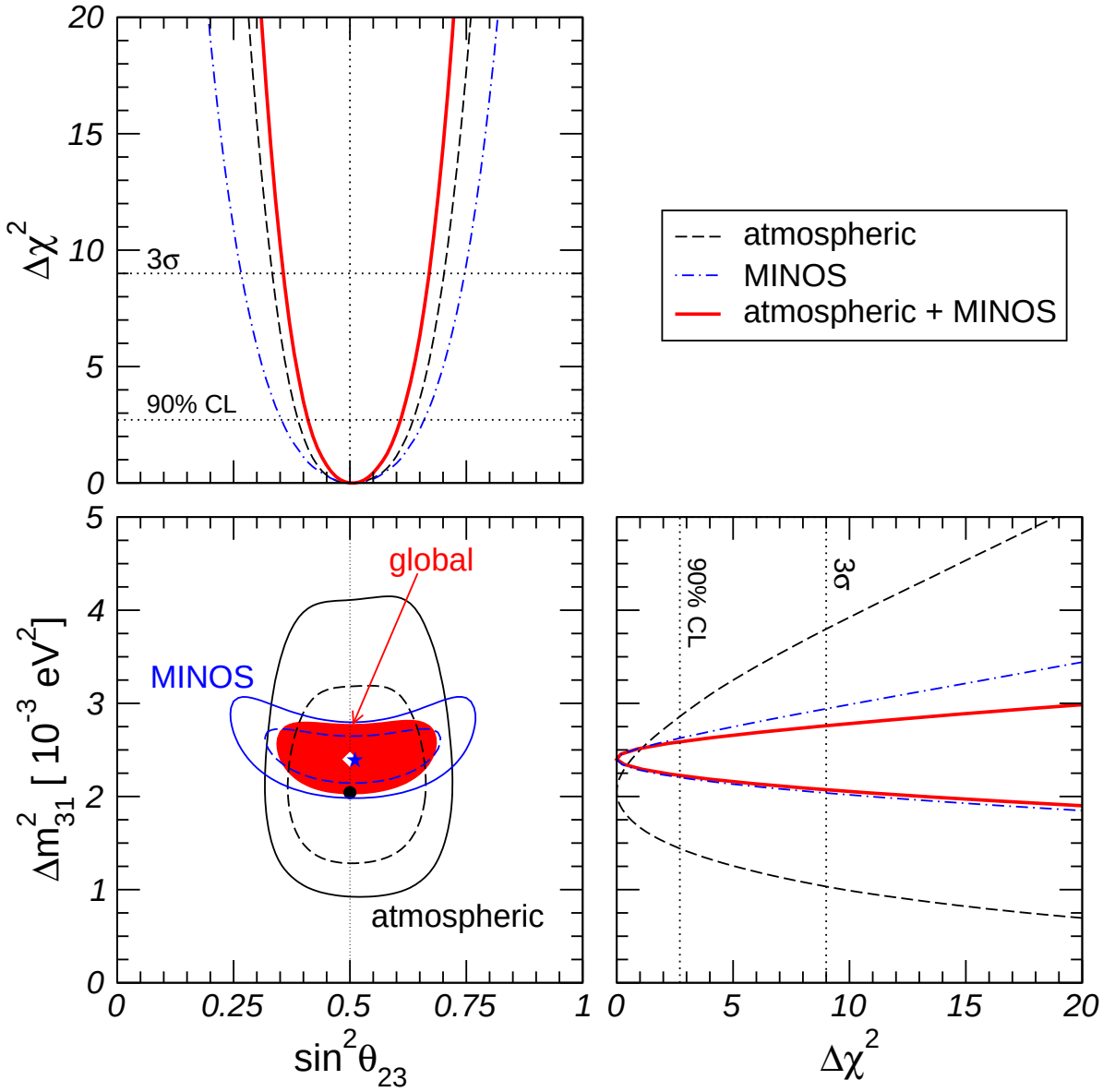
	K2K	MINOS
source	KEK	Fermilab
detector	Super-K	Soudan
baseline	250 km	735 km
neutrino energy	1.3 GeV	3 GeV
E_ν/L [eV^2]	5.2×10^{-3}	4.1×10^{-3}
obs. events	112	848
expect. w/o osc.	$158.1^{+9.2}_{-8.6}$	1065 ± 60

MINOS energy spectrum



arxiv:0806.2237, 3.4×10^{20} pot

Super-K + K2K + MINOS



$$\sin^2\theta_{23} = 0.50^{+0.07}_{-0.06}\,, \qquad |\Delta m^2_{31}| = 2.40^{+0.12}_{-0.11} \times 10^{-3}\,\mathrm{eV}^2$$

The status of θ_{13}

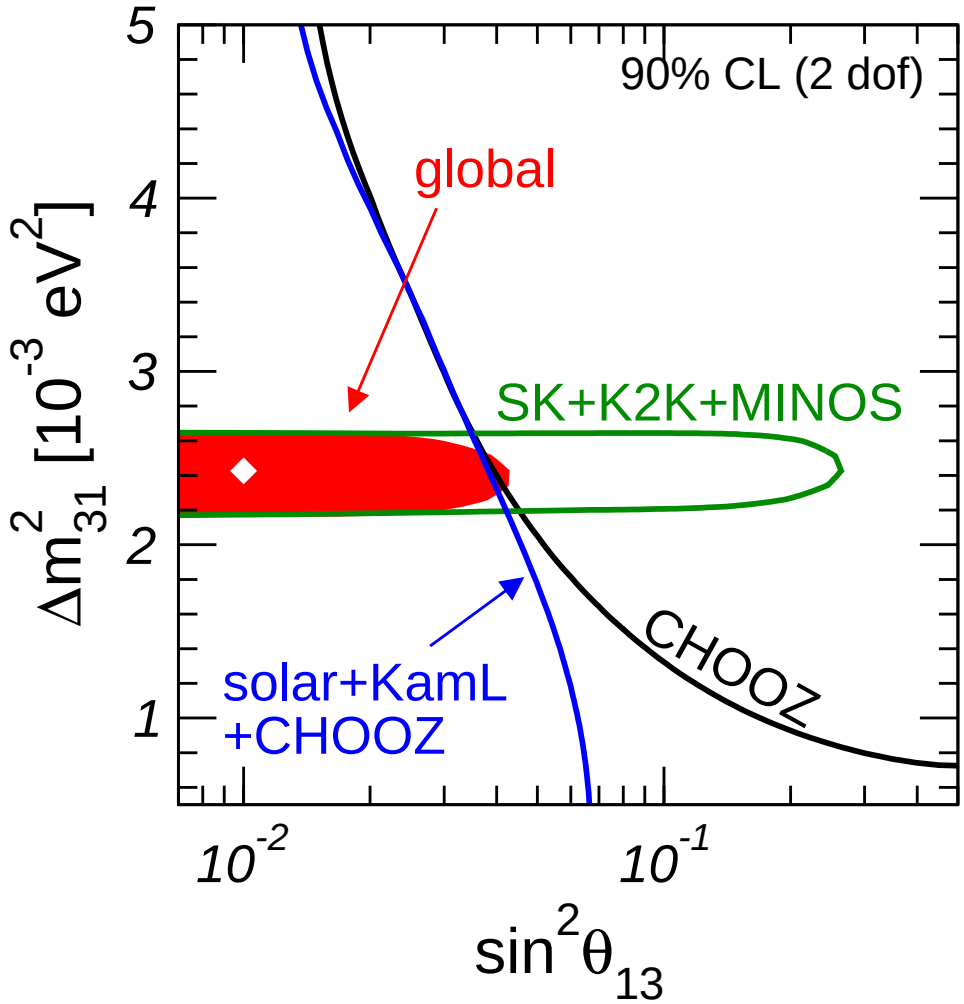
Δm^2_{31} $\qquad$ Δm^2_{21}

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

atmospheric+LBL $\qquad$ Chooz $\qquad$ solar+KamLAND

The bound on θ_{13}

global data: $\sin^2\theta_{13} < 0.035\,(0.056)$ at 90% CL (3σ)



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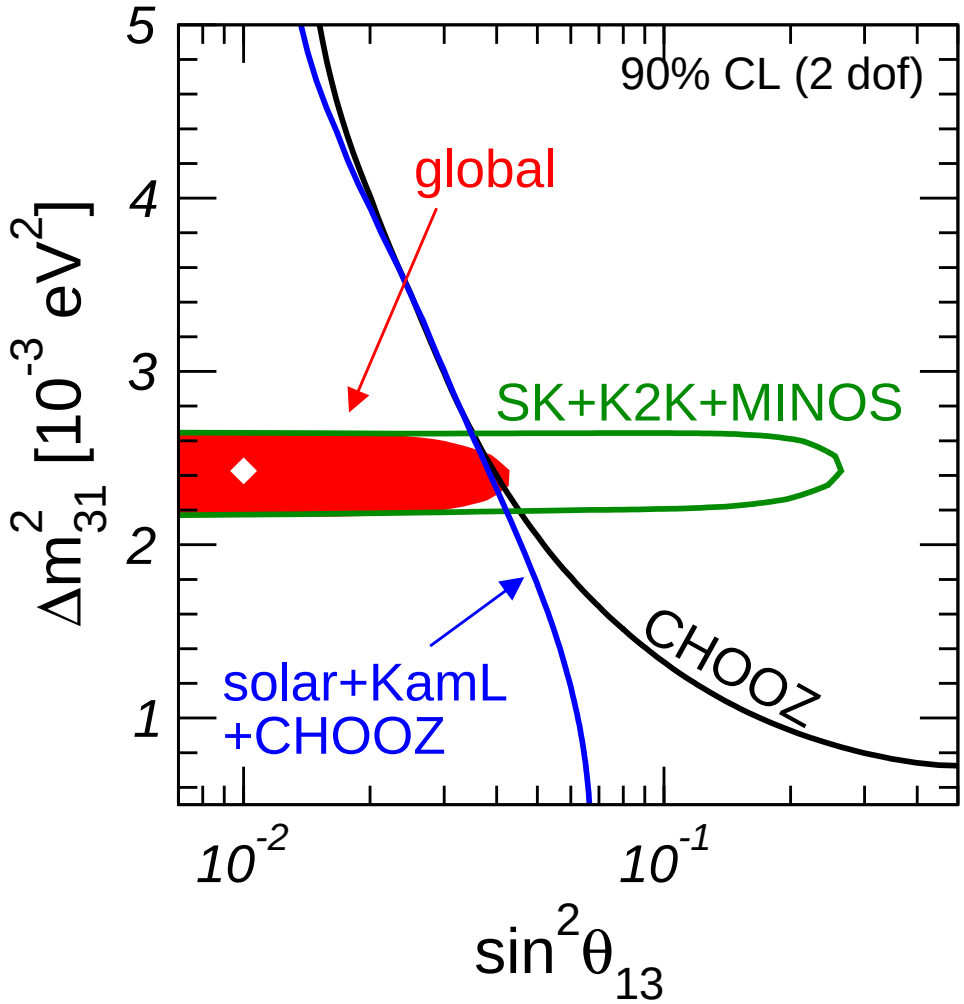
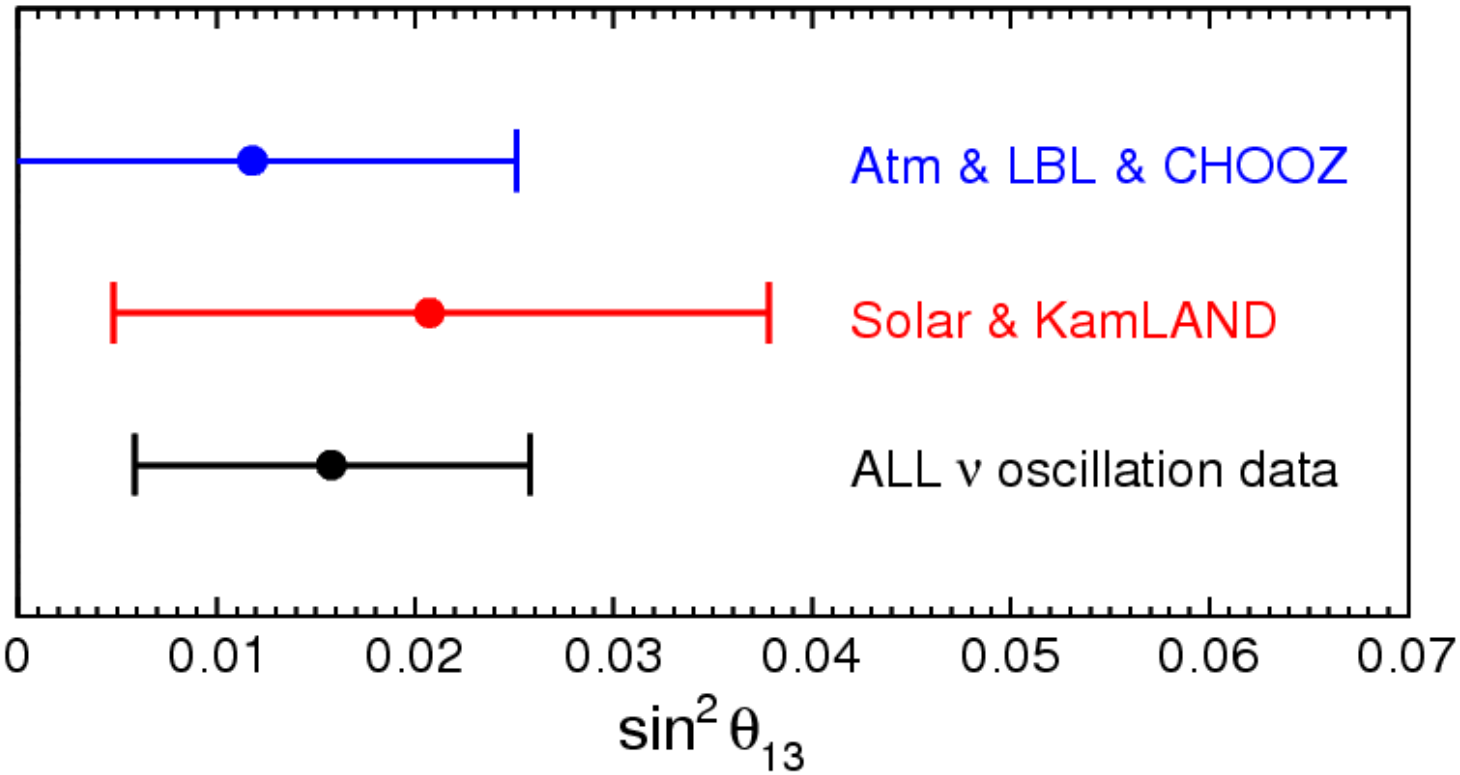


$$\sin\theta_{13} = |U_{e3}| < 0.237\,(3\sigma) \quad \leftrightarrow \quad |V_{us}| = 0.2257 \pm 0.0021$$

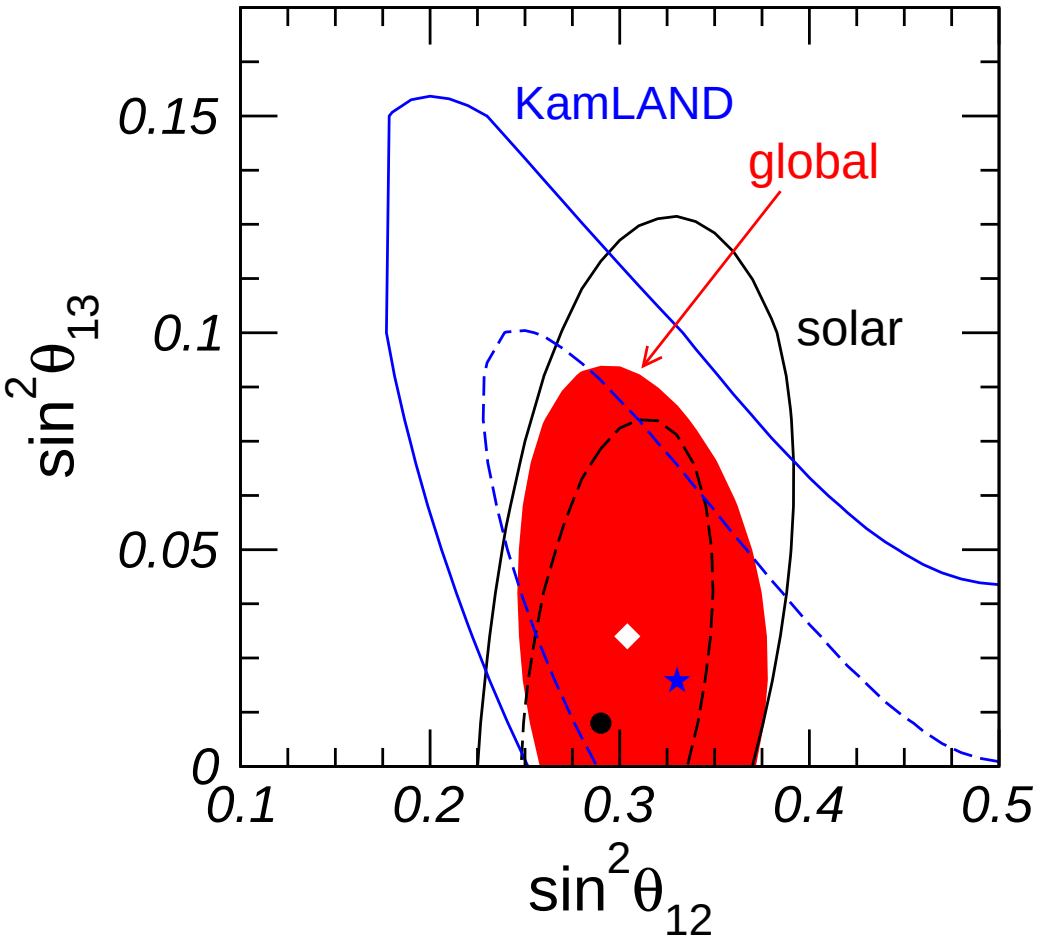
Hint for non-zero θ_{13}?



$$\sin^2\theta_{13} = 0.016 \pm 0.01 \quad (1\sigma)$$

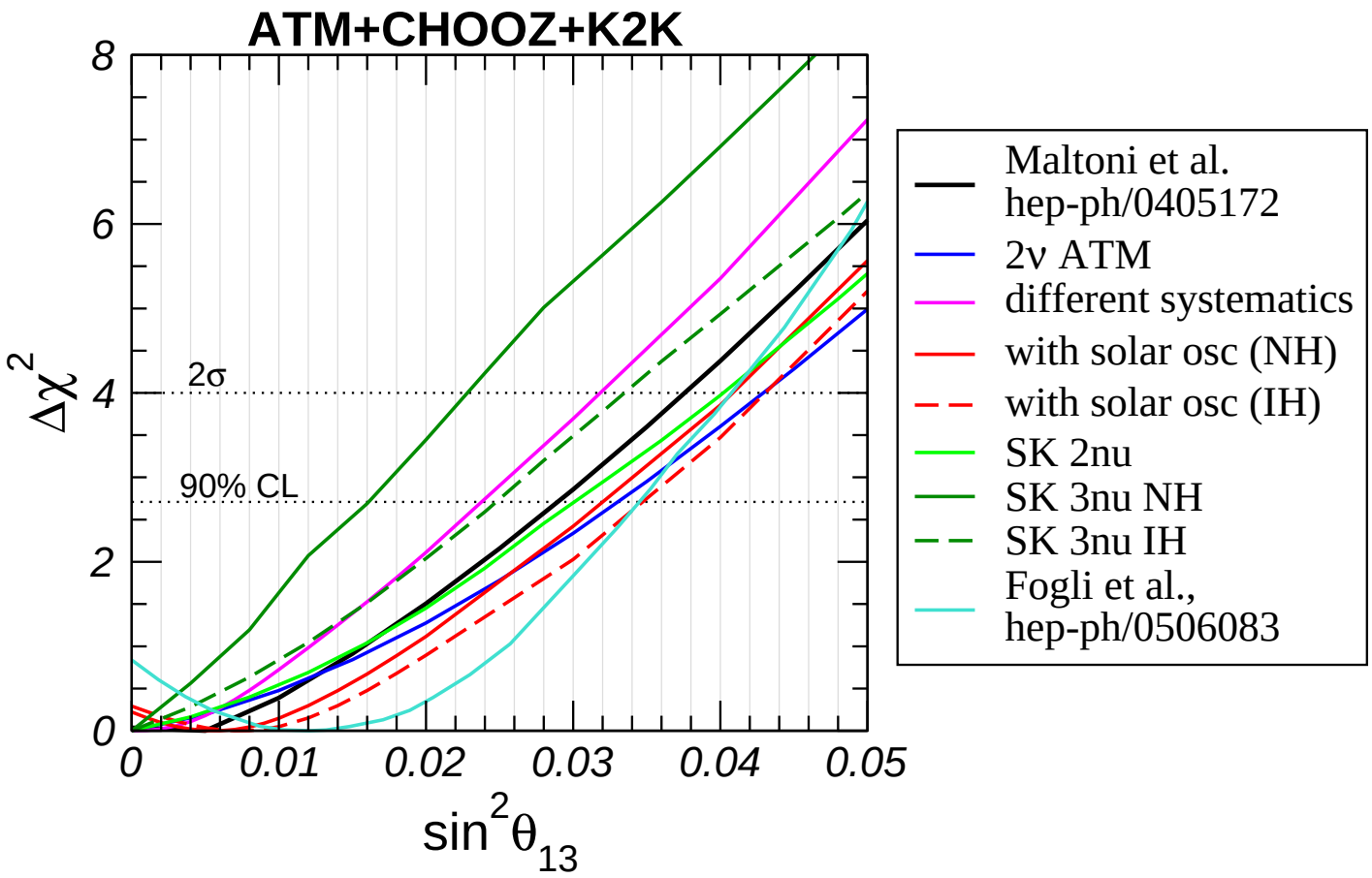
Fogli, Lisi, Marrone, Palazzo, Rotunno, arxiv:0806.2649

Hint from solar + KamLAND data



solar + KamLAND: $\sin^2\theta_{13} = 0.03 > 0$ at 1.5σ

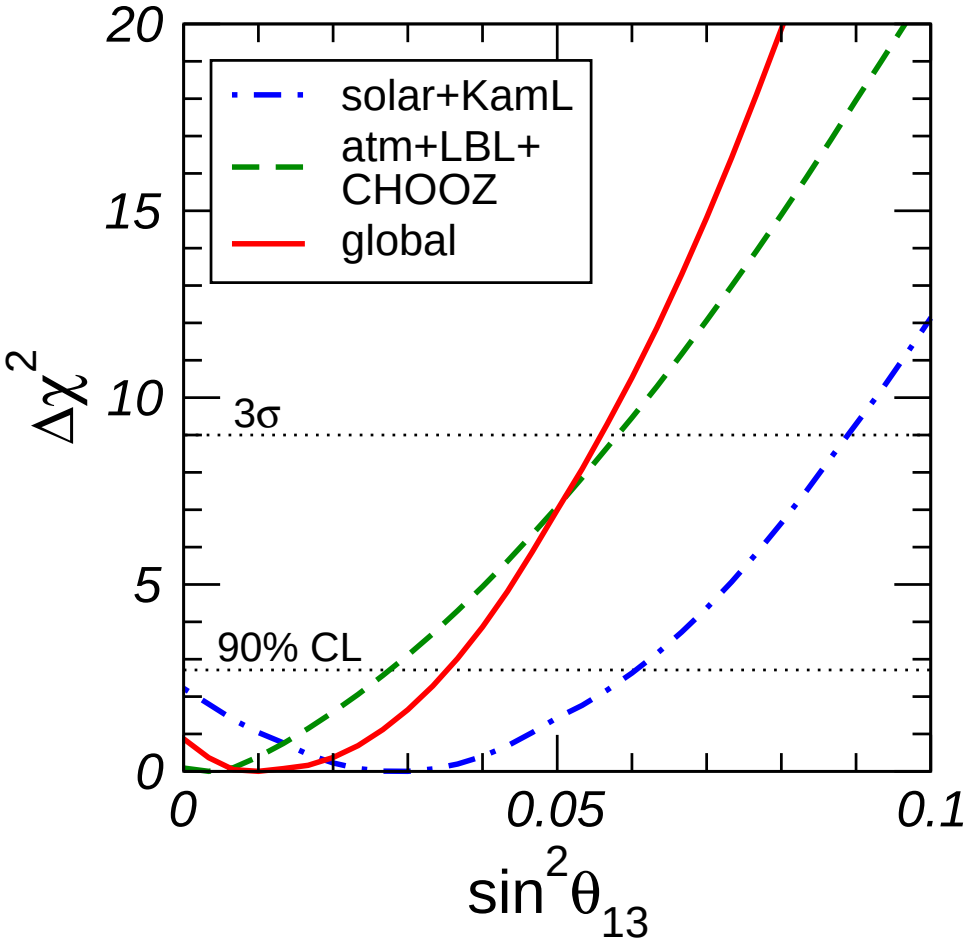
Hint from atmospheric data??



my talk in this room at SNOW2006; thanks to Michele Maltoni

"hint" from atmospheric data depends on subtle effects not well understood

No hint from global data?



global: $\sin^2\theta_{13} = 0.01^{+0.016}_{-0.011}$ (0.9σ)

TS, Tortola, Valle, 08

Summary 3-flavour oscillation parameters

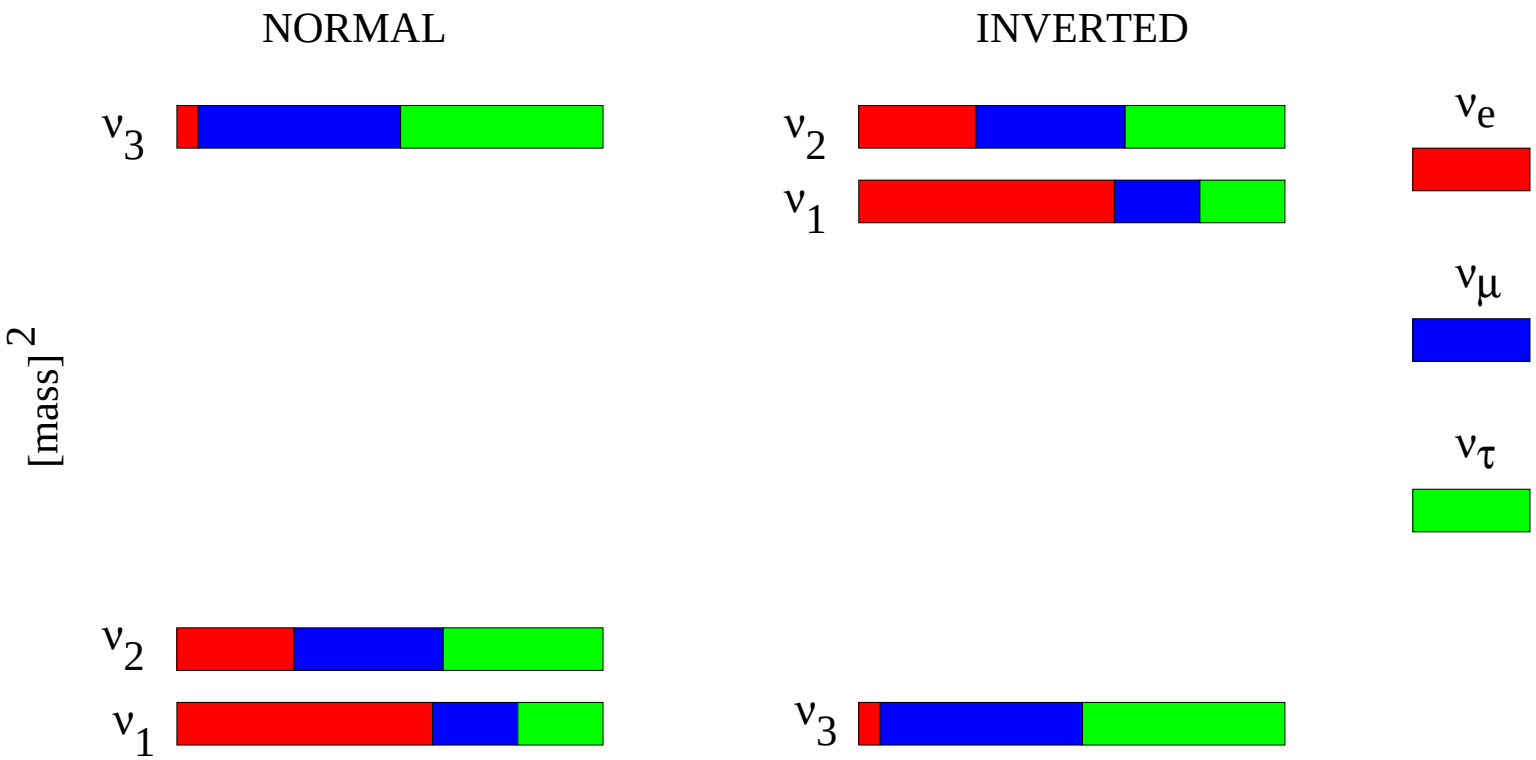
3-flavour oscillation parameters

	bf $\pm 1\sigma$	acc. @ 3σ	
Δm^2_{21}	$(7.65^{+0.23}_{-0.20})\,10^{-5}\,\mathrm{eV}^2$	(8%)	KamLAND
$\sin^2\theta_{12}$	$0.304^{+0.022}_{-0.016}$	(19%)	SNO
$\lvert\Delta m^2_{31}\rvert$	$(2.40^{+0.12}_{-0.11})\,10^{-3}\,\mathrm{eV}^2$	(14%)	MINOS
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	(30%)	SK atm
$\sin^2\theta_{13} < 0.056$ @ 3σ			CHOOZ

TS, Tortola, Valle, 0808.2016

Three flavour osc. parameters summary

two possibilities for the neutrino mass spectrum



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

3-flavour oscillation outlook

- Upcoming oscillation experiments:

  Reactor: Double-Chooz, Daya Bay, RENO
  Accelerator: T2K, NoVA

  Sensitivity to $\sin^2\theta_{13} \gtrsim 0.0025$ (factor 10)

3-flavour oscillation outlook

- Upcoming oscillation experiments:

  Reactor: Double-Chooz, Daya Bay, RENO
  Accelerator: T2K, NoVA

  Sensitivity to $\sin^2\theta_{13} \gtrsim 0.0025$ (factor 10)

- Long-term future:

  Superbeams, Betabeams, Neutrino Factory

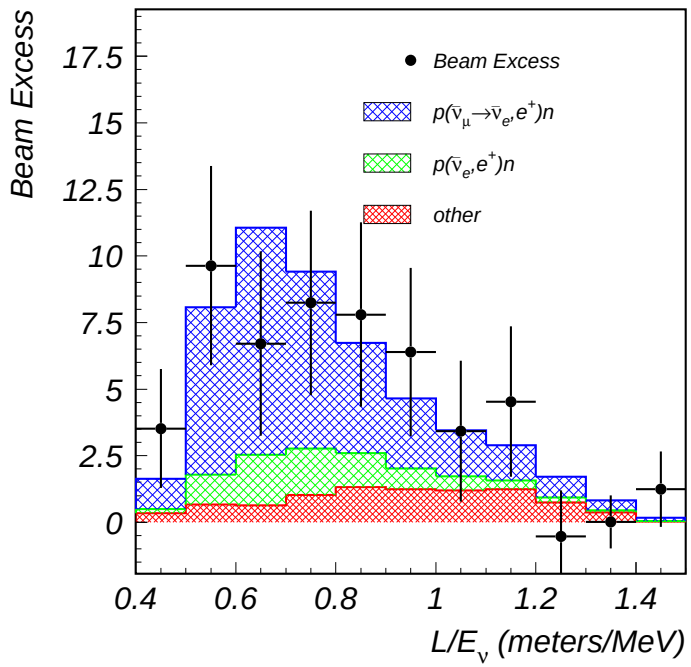
  CP-violation, neutrino mass hierarchy

The LSND puzzle and MiniBooNE results

Maltoni, TS, 0705.0107

The LSND signal

$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu \xrightarrow{\text{oscillations}} \bar{\nu}_e$$



$L \simeq$ 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

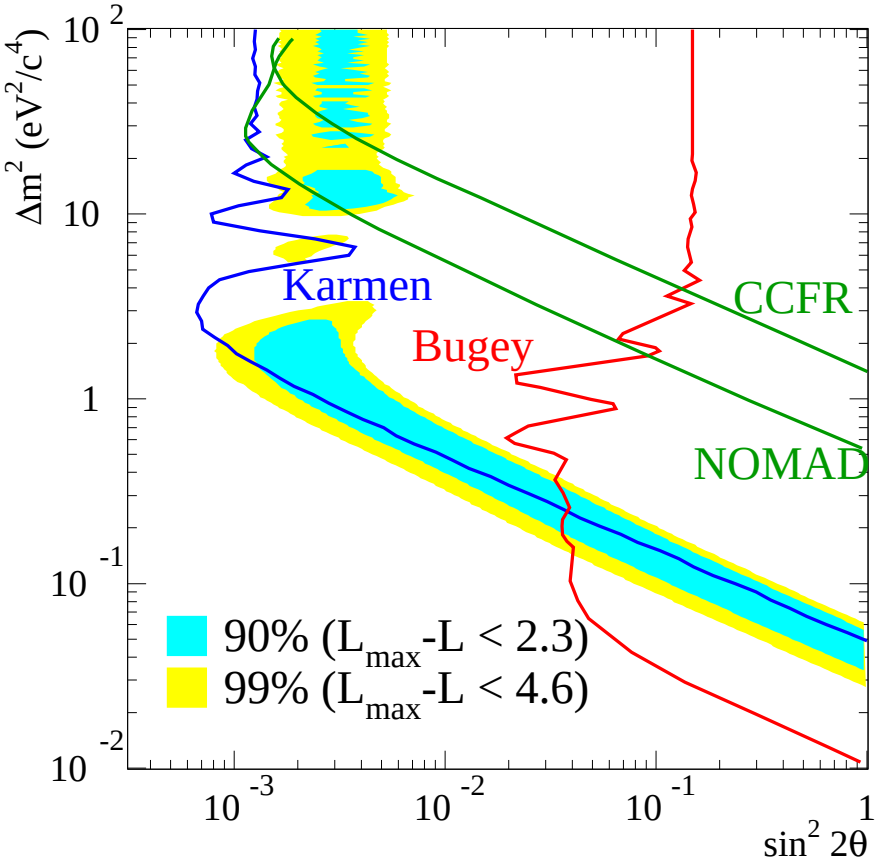
$P = (0.264 \pm 0.067 \pm 0.045)\%$

$\sim 3.3\sigma$ 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

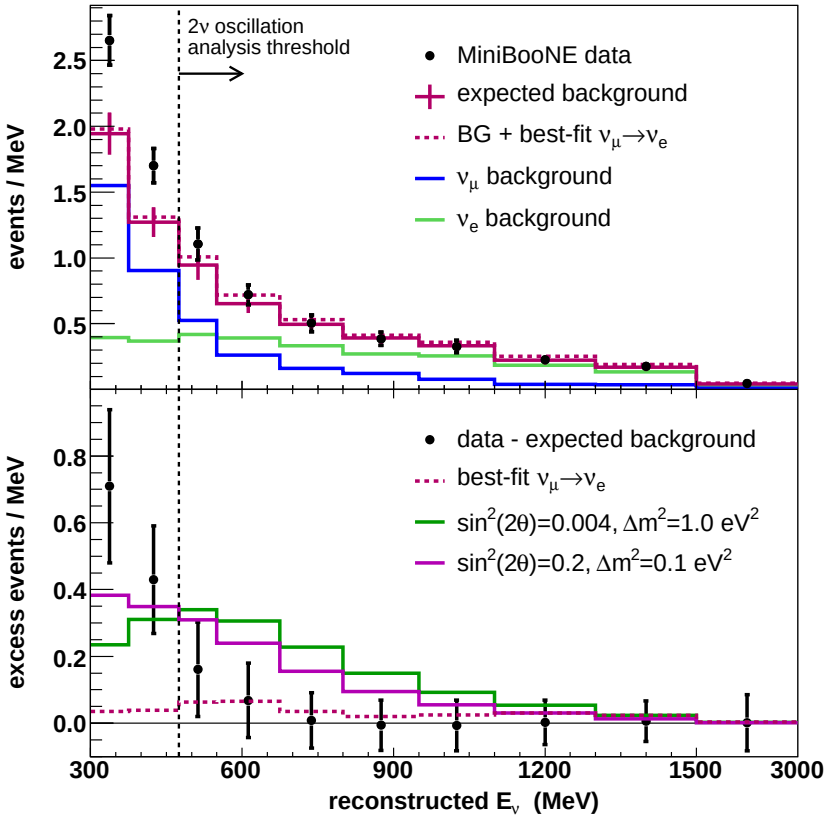
	LSND	MiniBooNE
energy	30 MeV	500 MeV
baseline	30 m	500 m
	same L/E_ν value	
channel	$\overline{\nu}_\mu \longrightarrow \overline{\nu}_e$	$\nu_\mu \longrightarrow \nu_e$

MiniBooNE results, April 2007

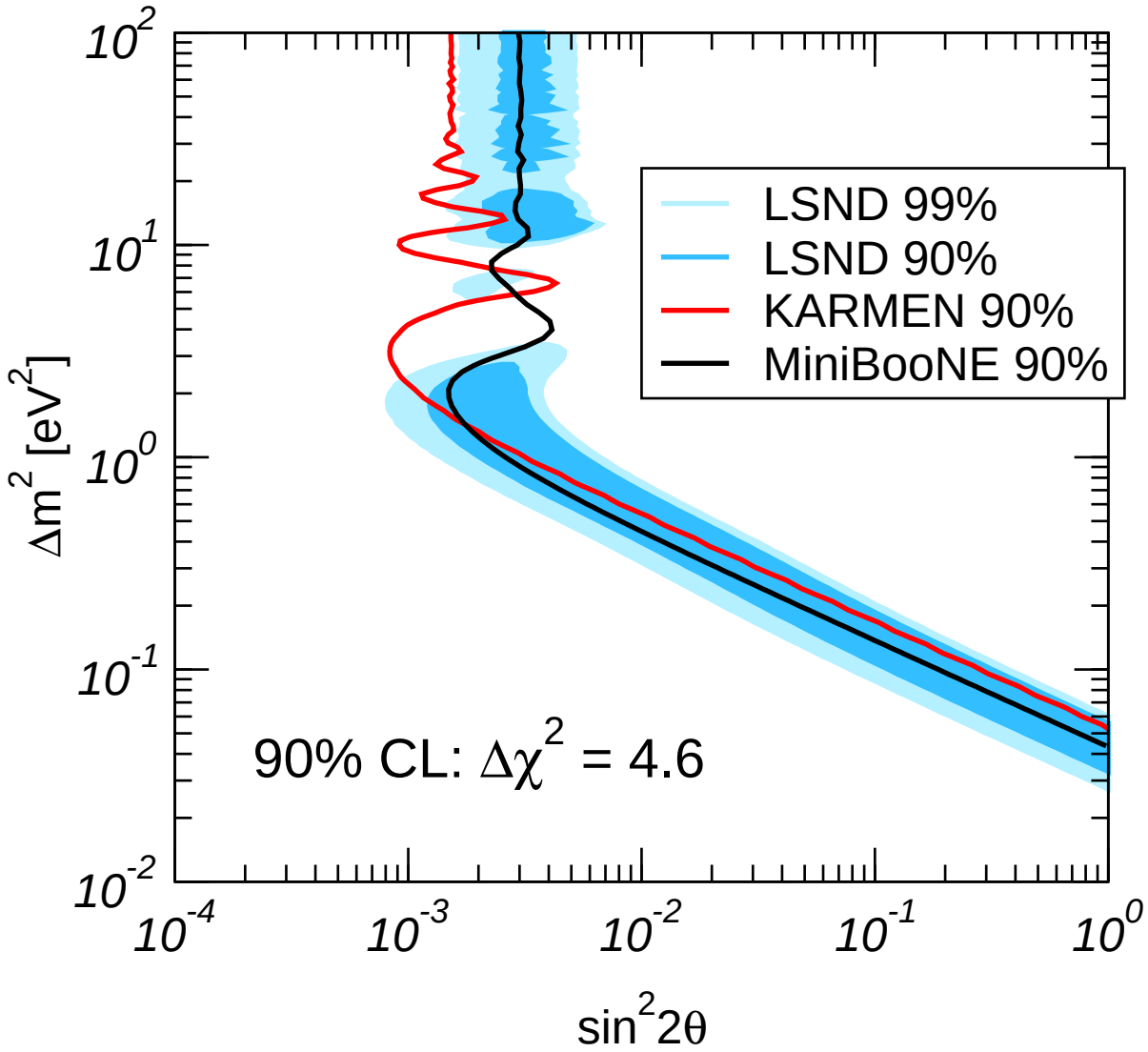
obs. events minus background:

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

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

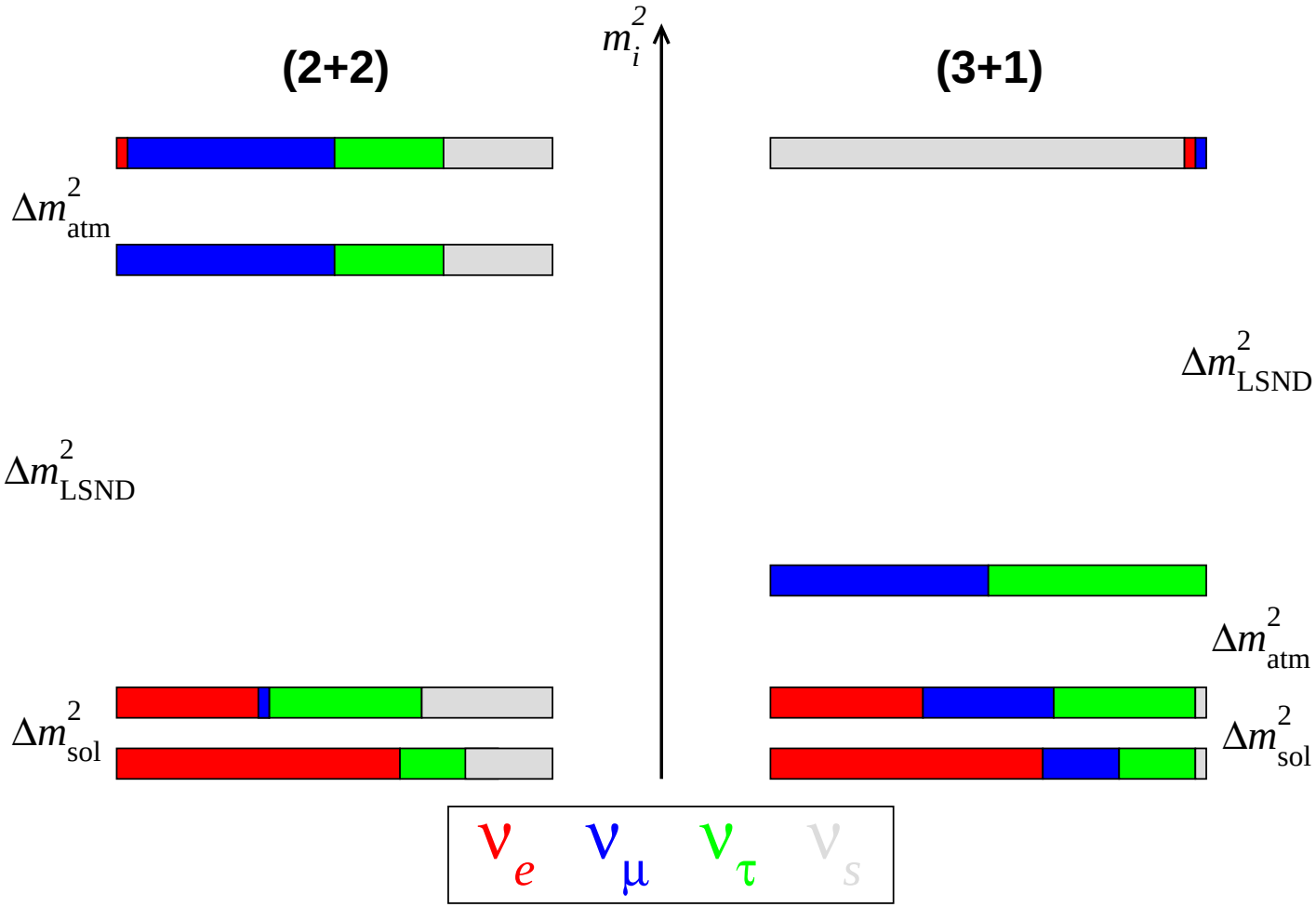


The MiniBooNE 2-neutrino limit



Adding a sterile neutrino

4-neutrino mass schemes:



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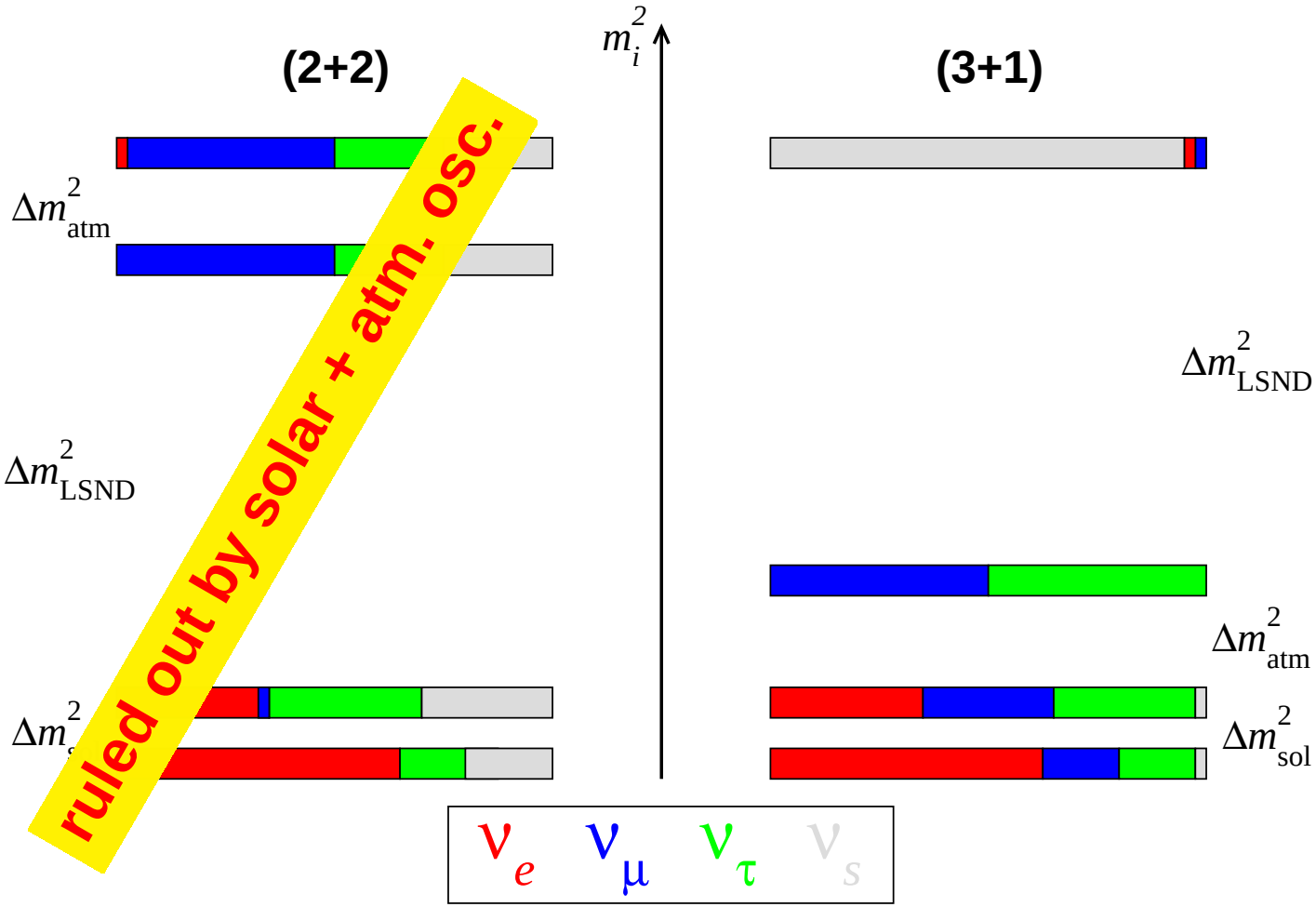


MB vs LSND in (3+1)

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

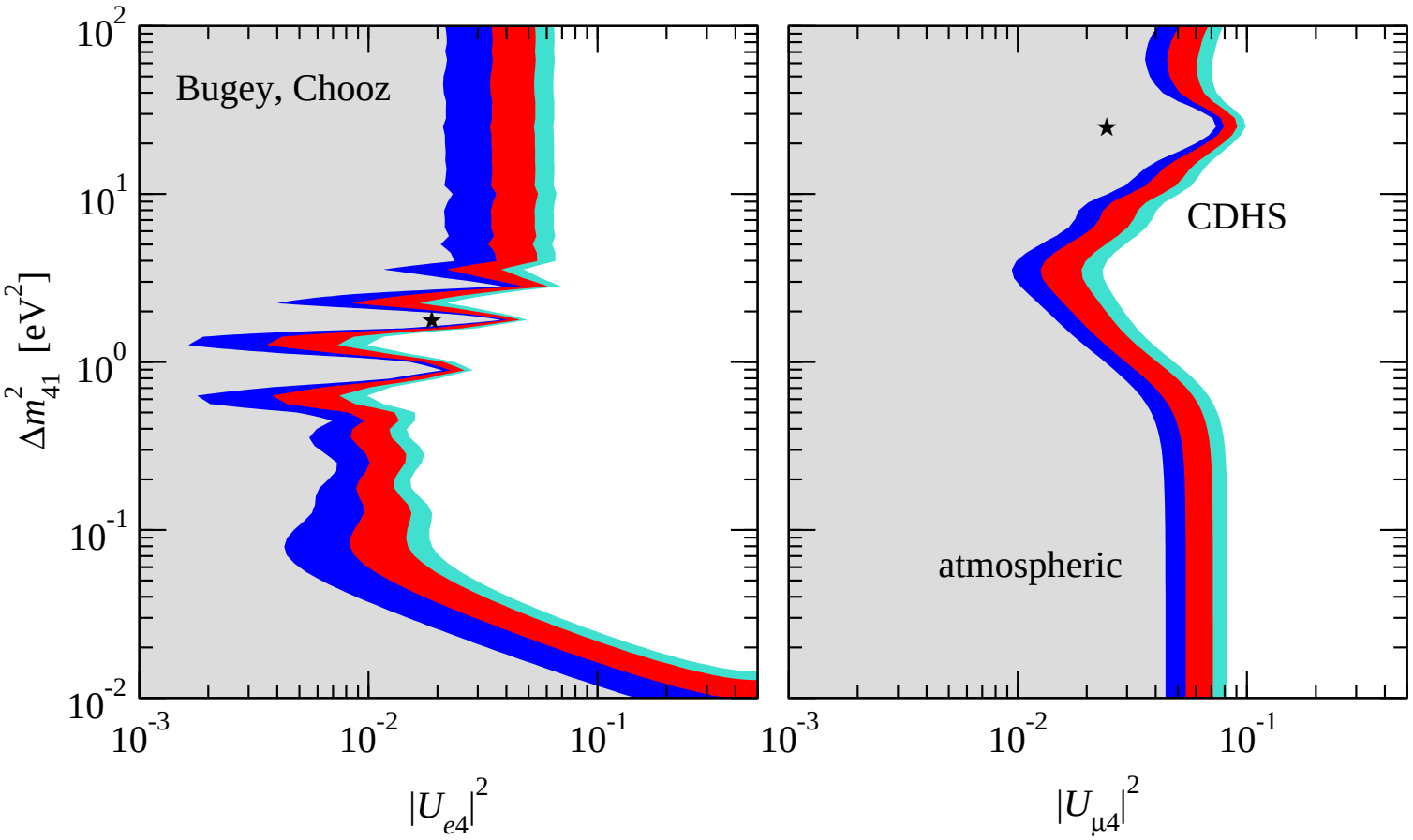
$$\sin^2 2\theta_{\rm SBL} = 4|U_{e4}|^2|U_{\mu 4}|^2$$

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

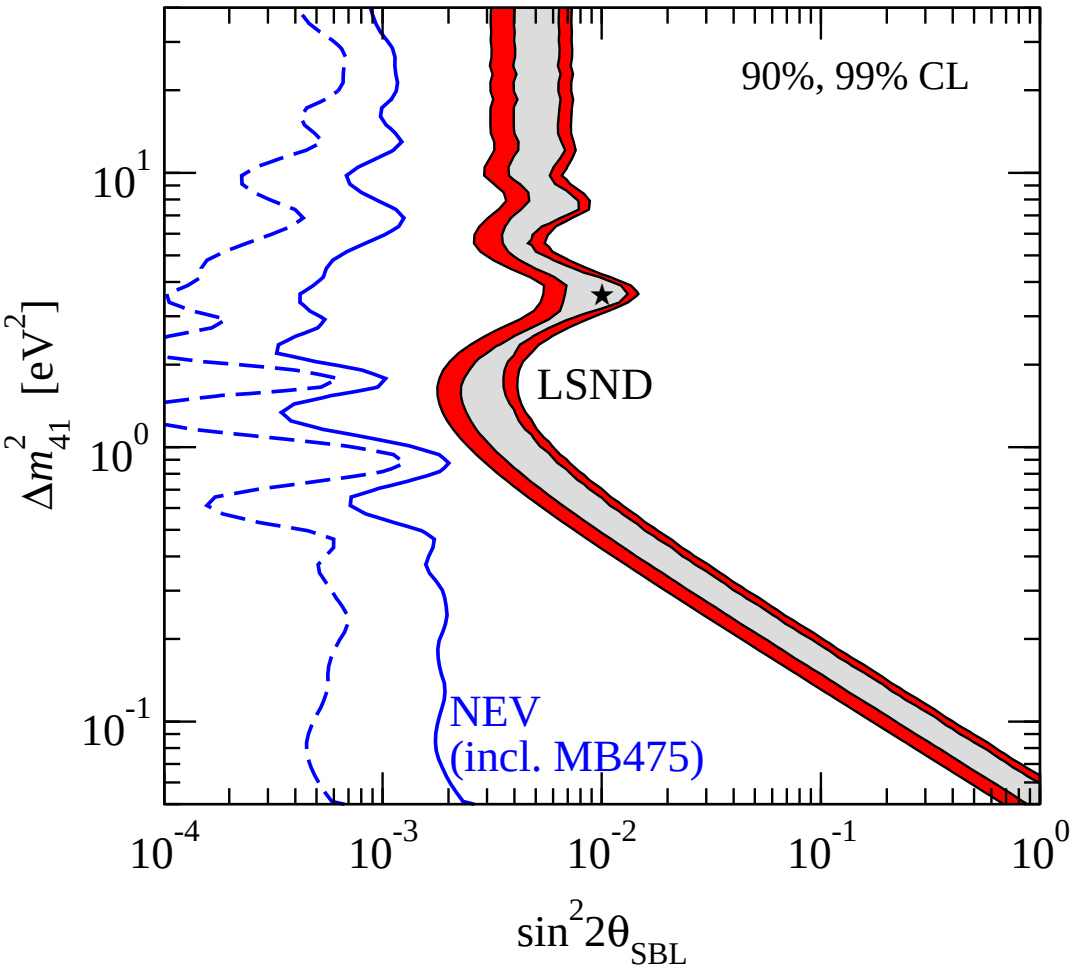
Appearance vs disappearance in (3+1)

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

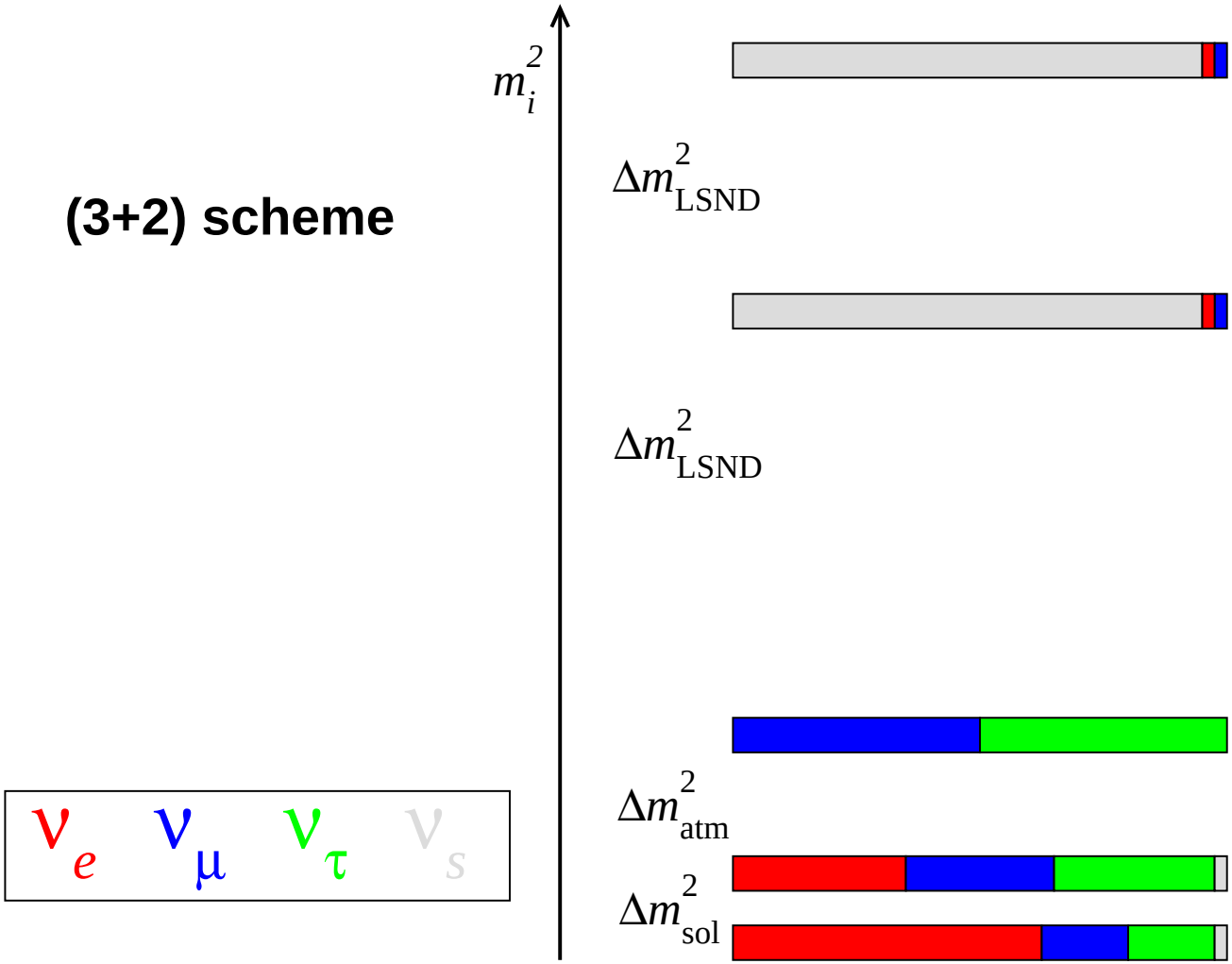
MB incl.:
$\chi^2_{\rm PG} = 24.7\,(2\,{\rm dof})$

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

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

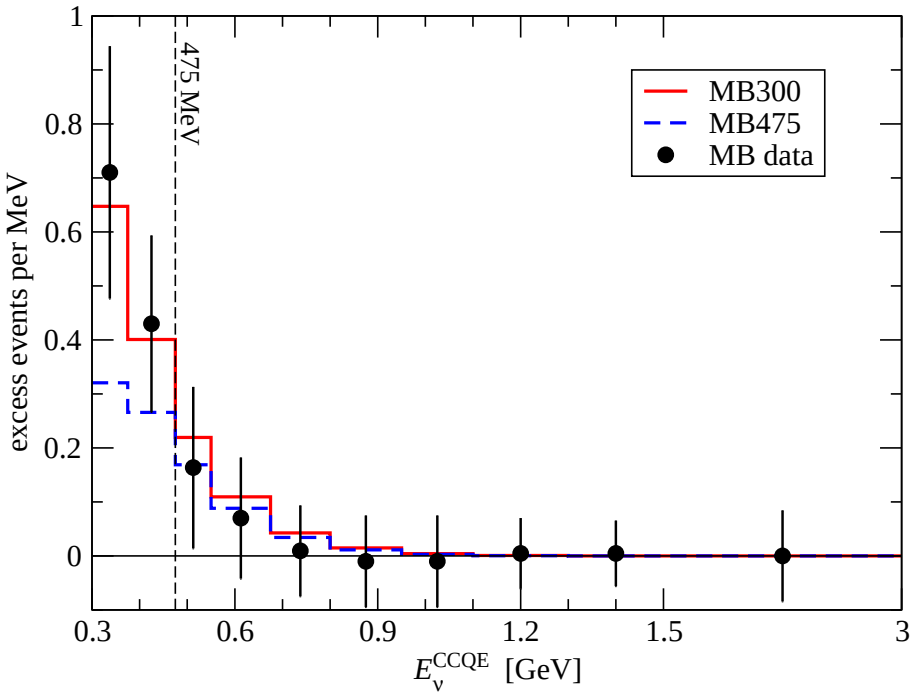
(3+2) osc. include the possibility of CP violation!

remember: MiniBooNE: neutrinos, LSND: anti-neutrinos

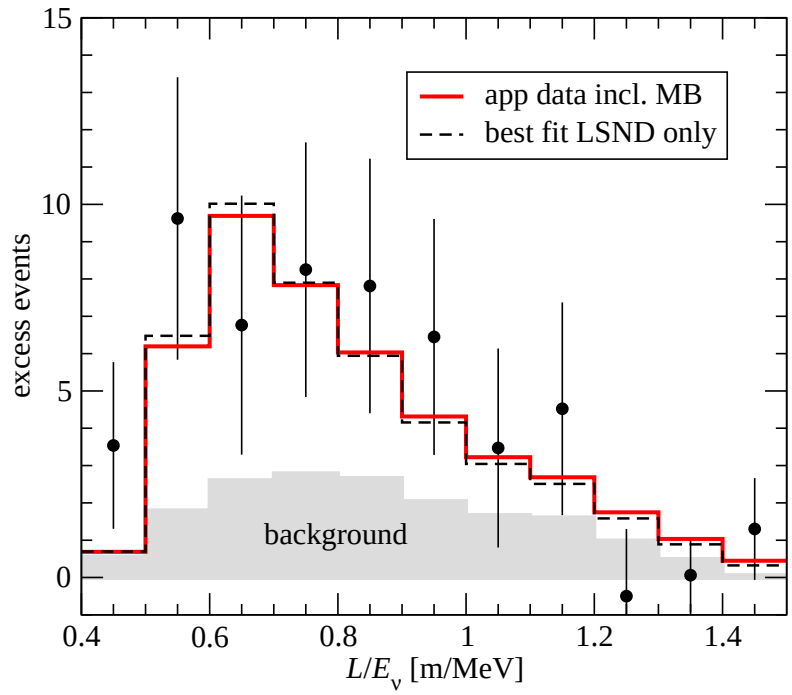
(3+2) appearance data

best fit point spectra:

MiniBooNE



LSND



Perfect fit to appearance data:

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

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

(3+2) disappearance data

what about the disappearance data?

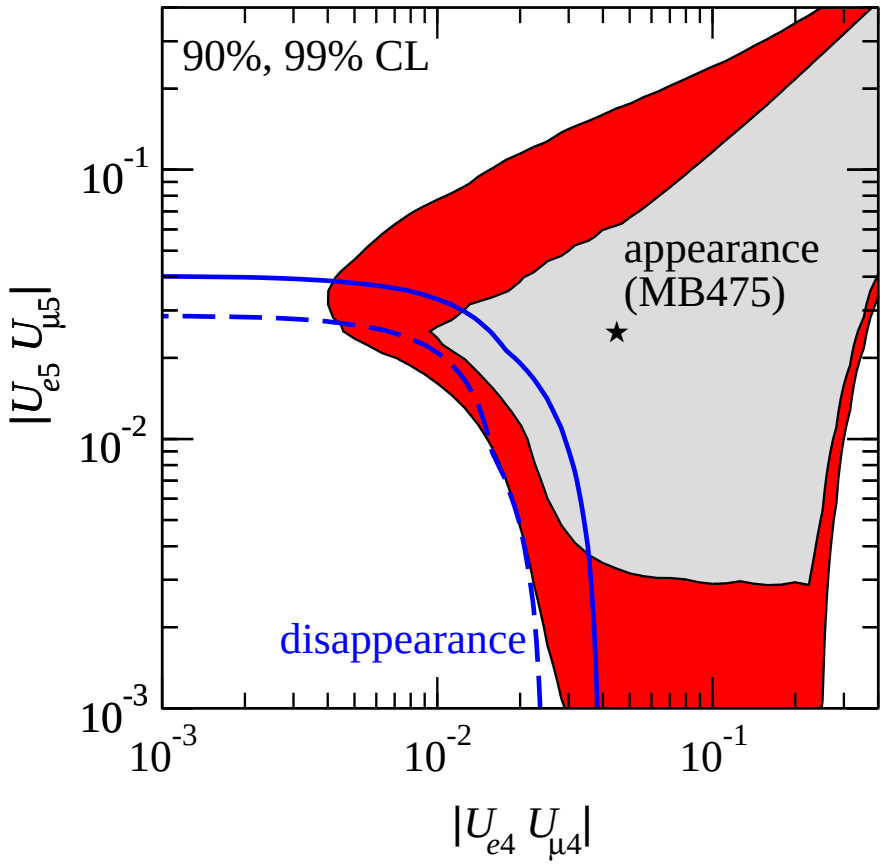
$$
\begin{aligned}
P_{\nu_\alpha \to \nu_\alpha} &= 1 - 4\left(1 - \sum_{i=4,5} |U_{\alpha i}|^2\right) \sum_{i=4,5} |U_{\alpha i}|^2 \sin^2 \phi_{i1} \\
&- 4\,|U_{\alpha 4}|^2 |U_{\alpha 5}|^2 \sin^2 \phi_{54}
\end{aligned}
$$

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

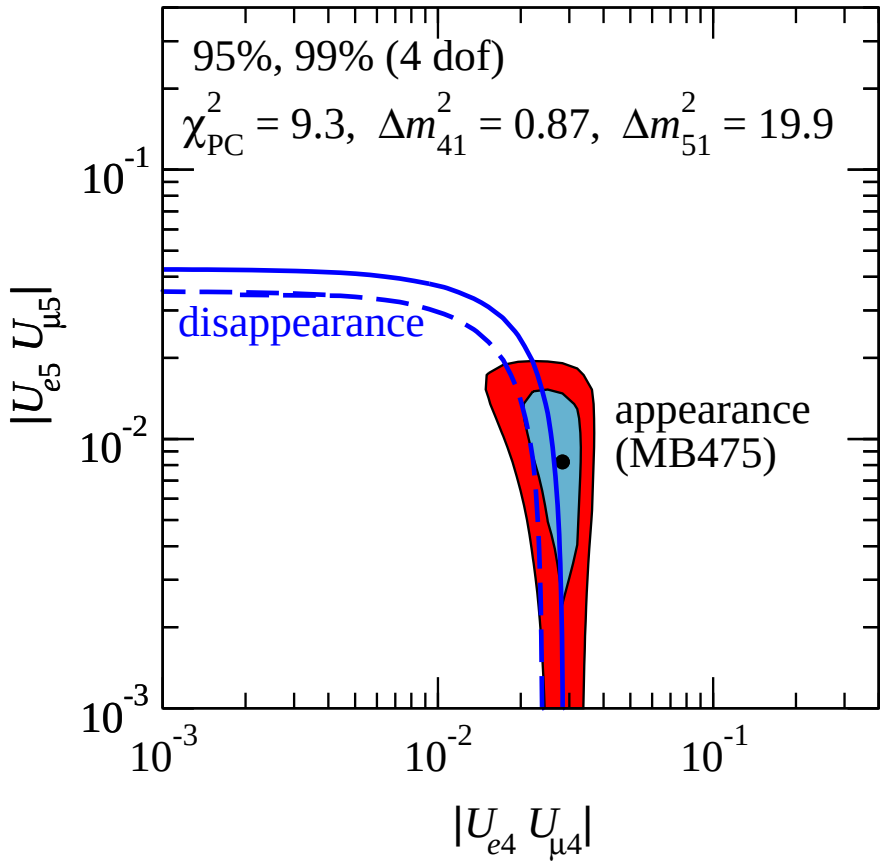
to be reconciled with appearance amplitudes $|U_{ei} U_{\mu i}|$

(3+2) app vs disap

projection



section



(3+2) global

testing consistency of disappearance and appearance data:

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

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

inconsistency at about 3.1σ

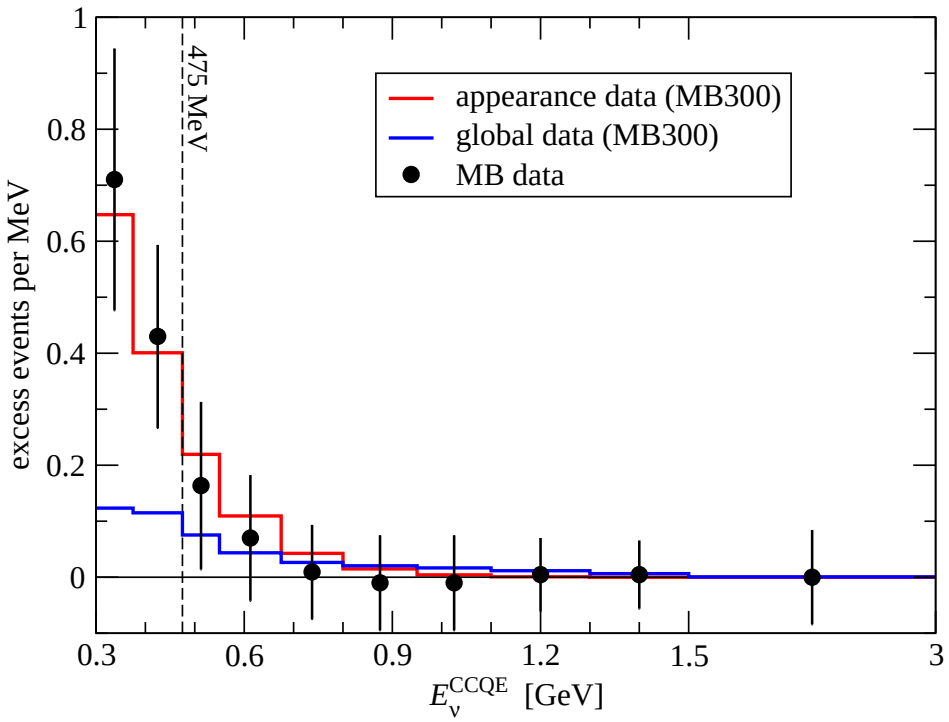
parameters in common $|U_{e4}U_{\mu 4}|, |U_{e5}U_{\mu 5}|, \Delta m^2_{41}, \Delta m^2_{51}$

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

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



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

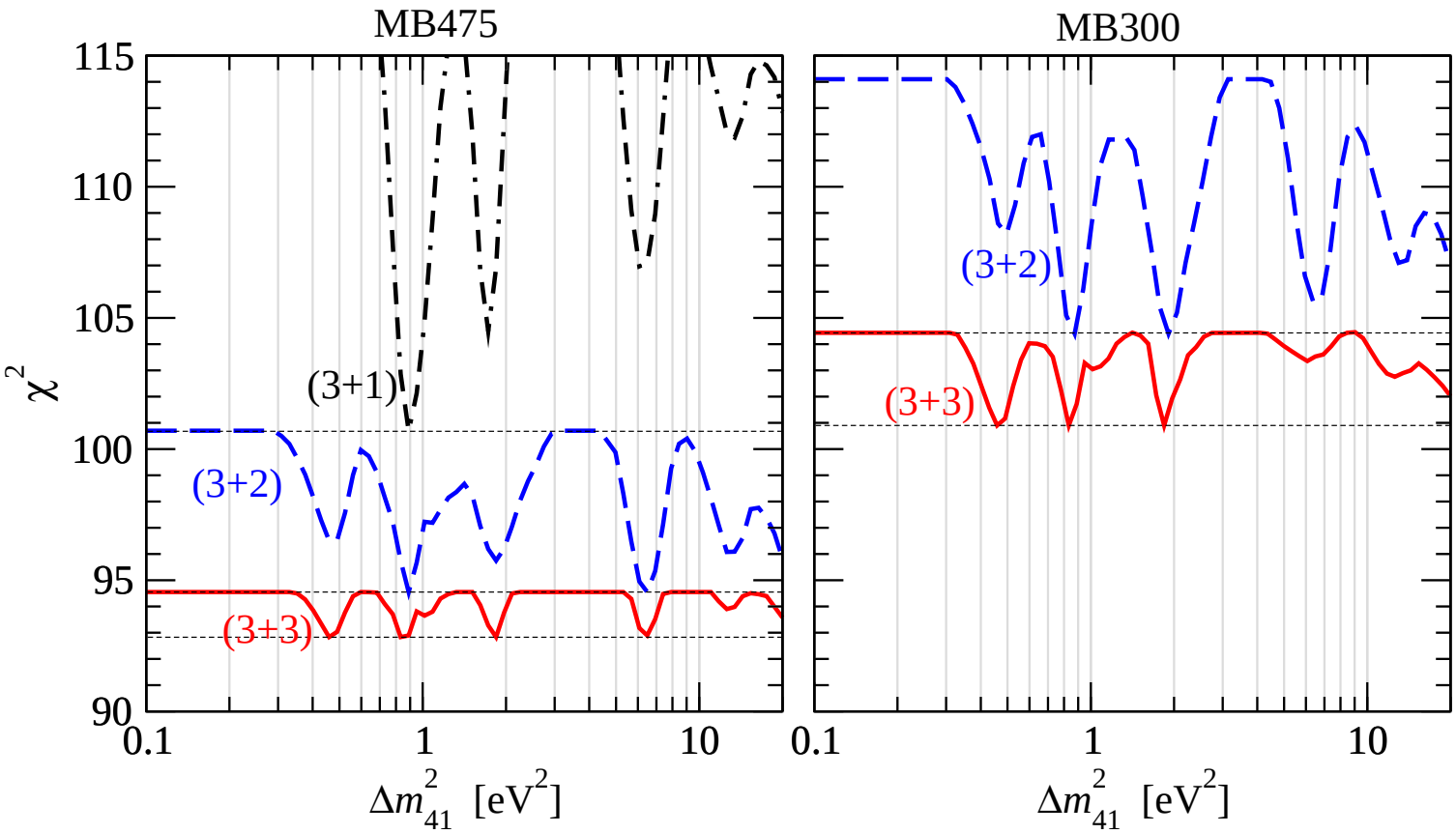
$$\chi^2_{\mathrm{MB475}} = 94.5/(107-7)$$

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

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

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%

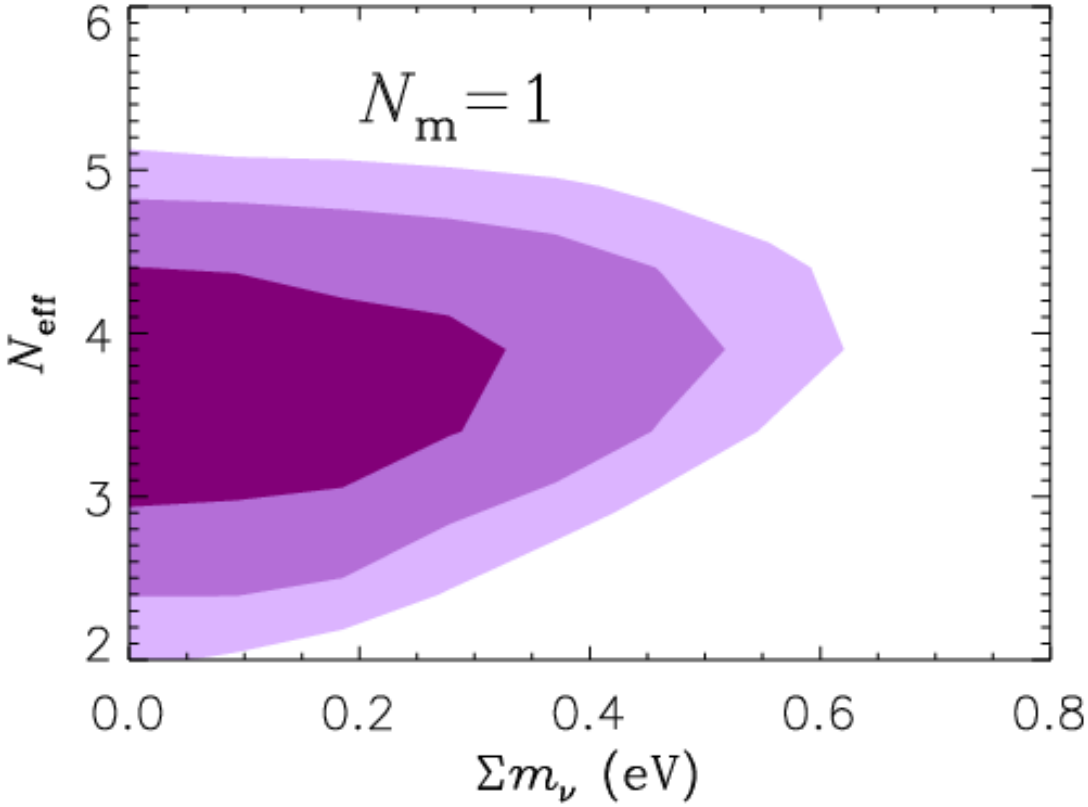
All these sterile neutrino schemes

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

Sterile neutrino oscillations - outlook

- CPV is being tested by MiniBooNE anti-neutrino data (problem of statistics?)
- the problem of (3+s) schemes heavily relies on SBL disappearance experiments
  Bugey ($\bar{\nu}_e$ reactor) and CDHS (ν_μ accelerator)
- could be worth to look for disappearance at the $\Delta m^2 \sim 1\,\mathrm{eV}^2$ scale at future reactor or LBL experiments (near detectors)
- 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

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
  Kostelecky, Mews, 04; Gouvea, Grossman, 06; Katori, Kostelecky, Tayloe, 06
- mass varying neutrinos
  Kaplan, Nelson, Weiner 04; Zurek 04; Barger, Marfatia, Whisnant 05
- shortcuts of sterile neutrinos in extra dimensions
  Paes, Pakvasa, Weiler 05
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  Farzan, Schwetz, Smirnov, 08

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KamLAND+atmospheric antineutrino data

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KARMEN, TWIST

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CDHS+atmospheric data?

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Quantum decoherence

$$\frac{d\rho}{dt} = -i[H, \rho] - \mathcal{D}[\rho]$$

Quantum decoherence

$$\frac{d\rho}{dt} = -i[H, \rho] - \mathcal{D}[\rho]$$

assume a special form for $\mathcal{D}[\rho]$:

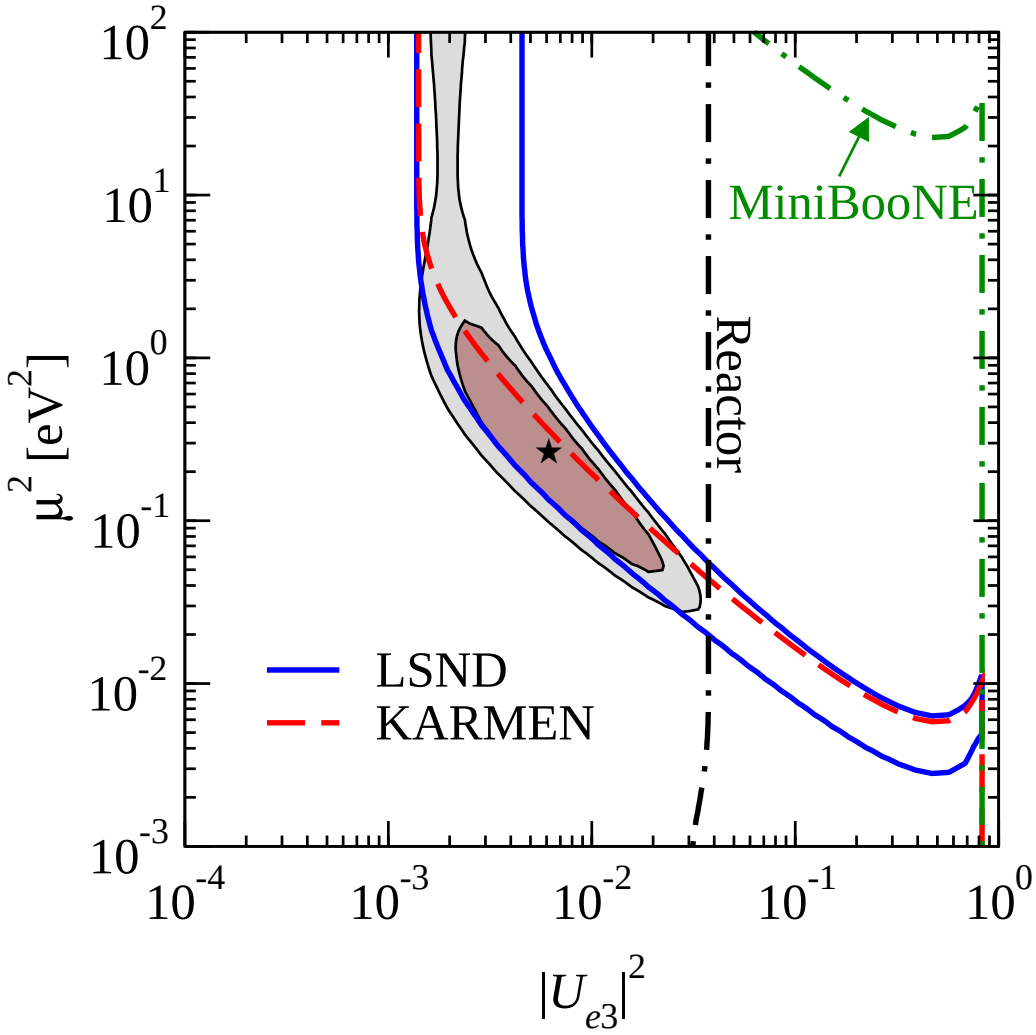
Farzan, TS, Smirnov, 08

- only ν_3 is affected by decoherence
  (1-2 oscillations in solar + KamLAND not affected)
- decoherence is suppressed for high energies:

$$\gamma \propto E_\nu^{-4}$$

LSND (40 MeV), MiniBooNE, CDHS, NOMAD ($\gtrsim$ GeV)

LSND and decoherence



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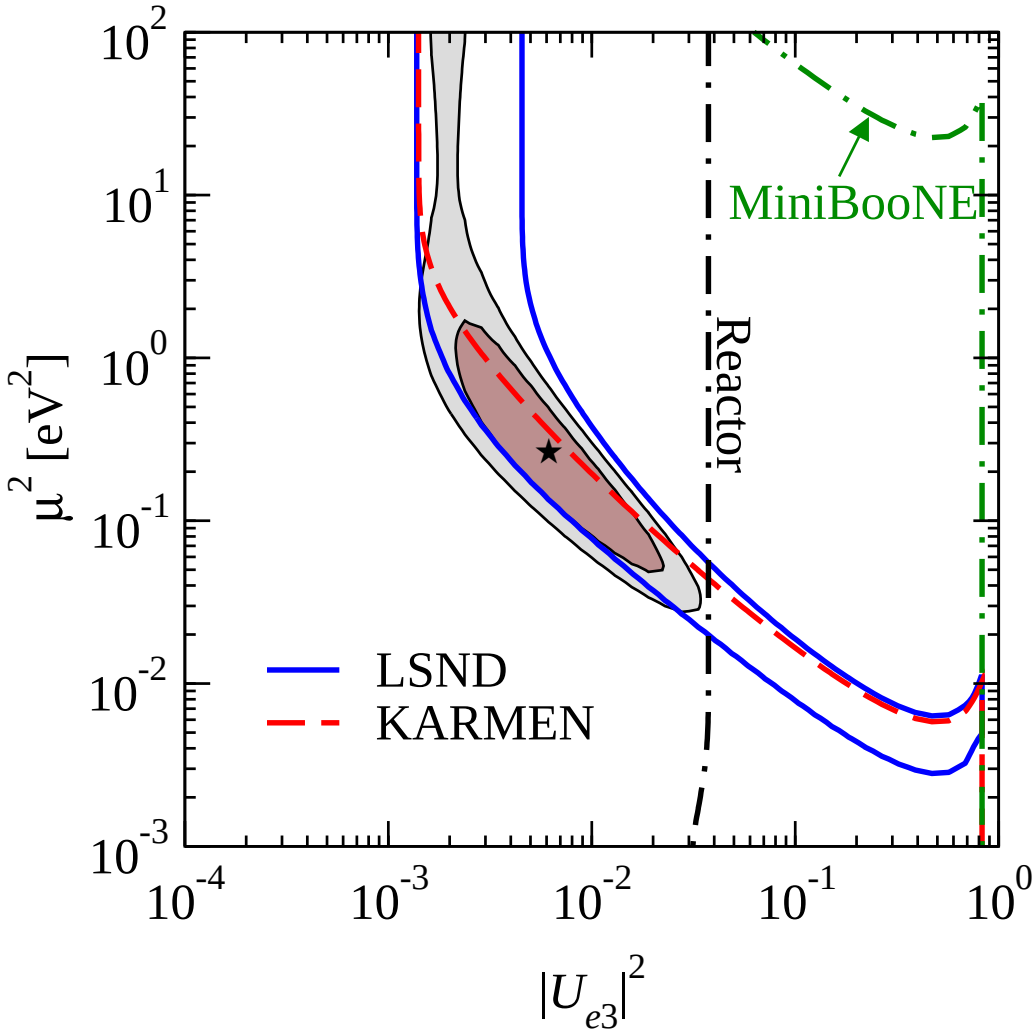


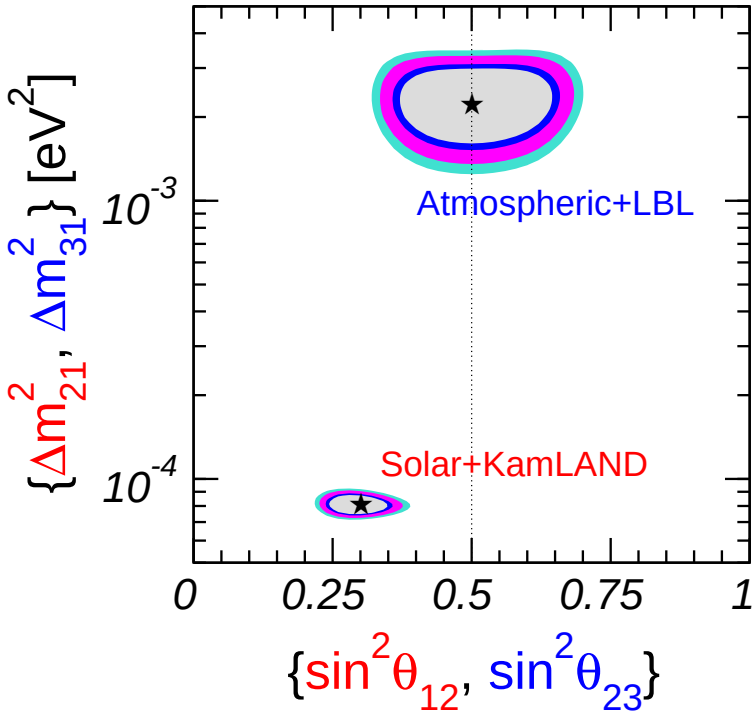
Predictions:

- LSND signal is related to θ_{13}
- positive signal for θ_{13} at T2K (GeV) but no signal at reactor experiments (MeV energies)

Summary

Summary

3-nu oscillations:



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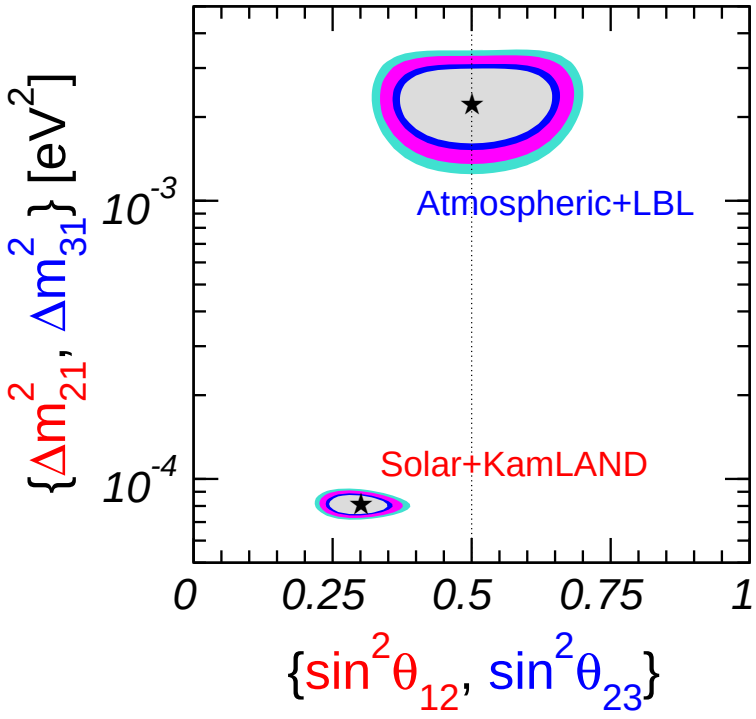

LSND/MiniBooNE issue:

- **(3+1)**: strongly disfavoured
- **(3+2)**: LSND and MB consistent

  but: severe tension in the global fit
- many exotic “solutions” fail

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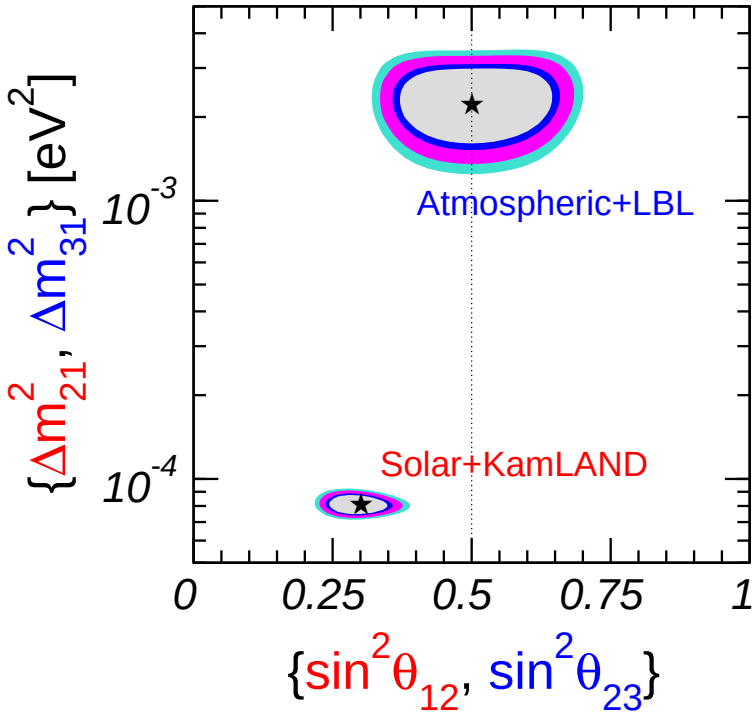

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Thanks for your attention!