

# **Status of neutrino oscillations and sterile neutrinos**

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International Europhysics Conference on High Energy Physics  
Grenoble, Rhône Alpes, France – July 22nd, 2011

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- I. Conventional three-neutrino oscillations**
  - II. The LSND experiment and four-neutrino models**
  - III. MiniBooNE and models with two sterile neutrinos**
- Summary**

## General three-neutrino framework

- Equation of motion: 6 parameters (including CP-violating effects):

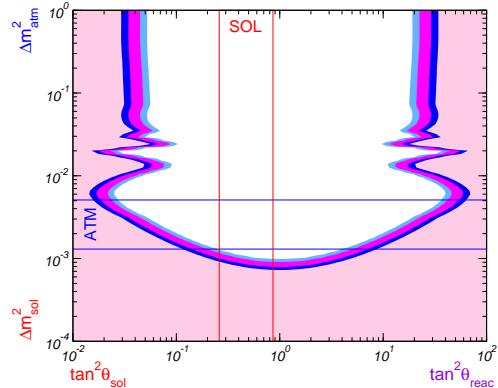
$$i \frac{d\vec{\nu}}{dt} = H \vec{\nu}; \quad H = U_{\text{vac}} \cdot D_{\text{vac}} \cdot U_{\text{vac}}^\dagger \pm V_{\text{mat}};$$

$$U_{\text{vac}} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{\text{CP}}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}, \quad \vec{\nu} = \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix};$$

$$D_{\text{vac}} = \frac{1}{2E_\nu} \text{diag}(0, \Delta m_{21}^2, \Delta m_{31}^2); \quad V_{\text{mat}} = \sqrt{2} G_F N_e \text{diag}(1, 0, 0).$$

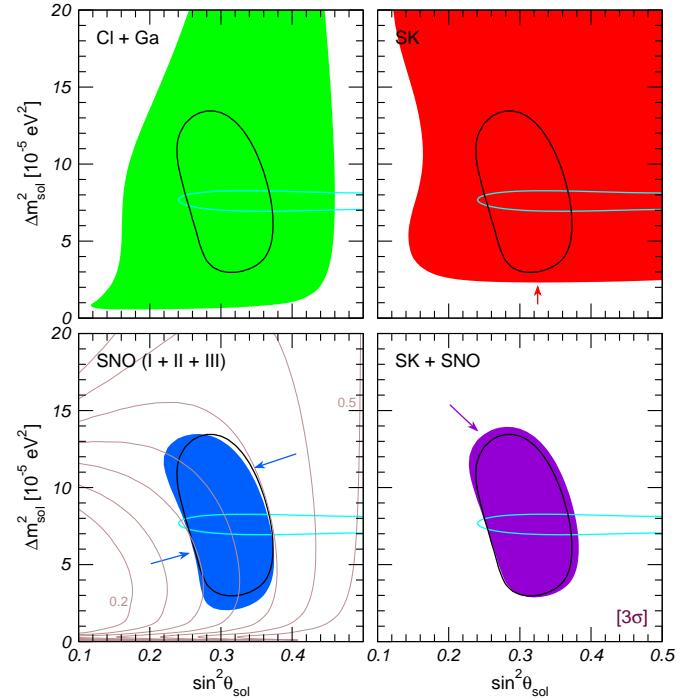
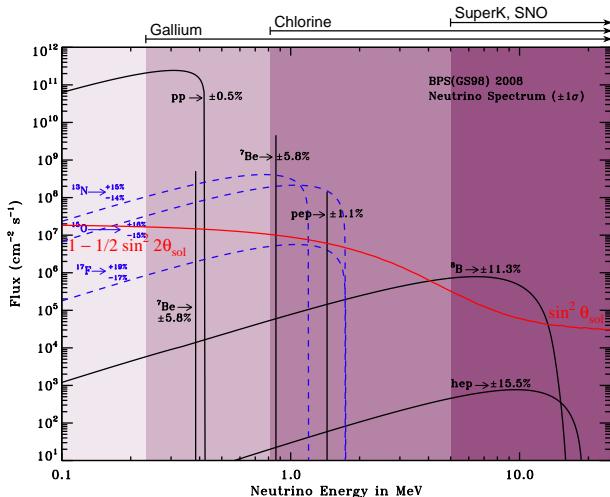
### The hierarchy approximation

- From SOL and ATM data, we have  $\Delta m_{21}^2 \ll \Delta m_{31}^2$ ;
- SOL:**  $\Delta m_{31}^2 \approx \infty \Rightarrow$  only 3 parameters:  $\Delta m_{21}^2, \theta_{12}, \theta_{13}$ ;
- ATM:**  $\Delta m_{21}^2 \approx 0 \Rightarrow$  only 3 parameters:  $\Delta m_{31}^2, \theta_{23}, \theta_{13}$ ;
- CP-violating phase  $\delta_{\text{CP}}$  disappears from equations;
- Chooz limit:  $\theta_{13} \approx 0 \Rightarrow$  SOL and ATM decoupled.



## Solar neutrinos: anatomy of the oscillation solution

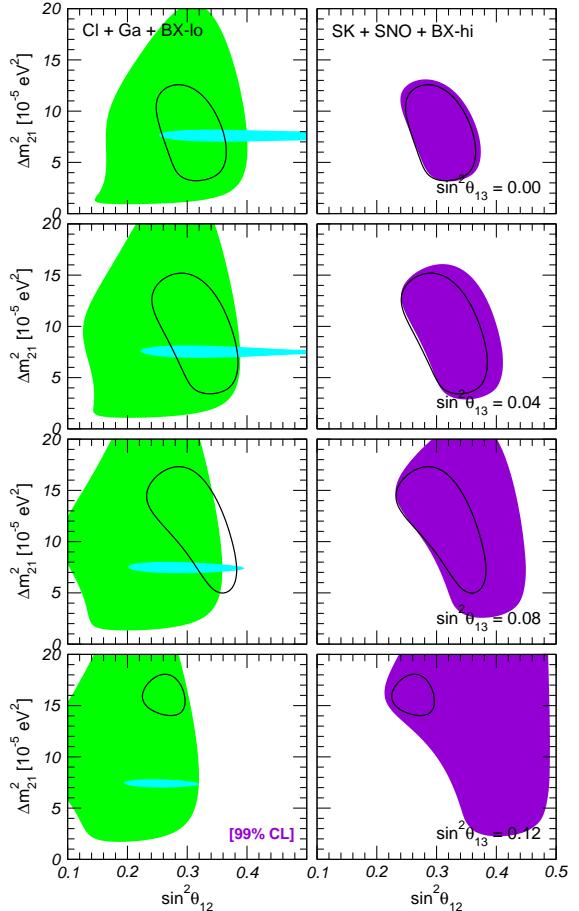
- $\theta_{13} = 0 \Rightarrow i\frac{d\vec{\nu}}{dt} = \left[ \frac{\Delta m_{21}^2}{4E_\nu} \begin{pmatrix} -\cos 2\theta_{12} & \sin 2\theta_{12} \\ \sin 2\theta_{12} & \cos 2\theta_{12} \end{pmatrix} \pm \sqrt{2} G_F \begin{pmatrix} N_e & 0 \\ 0 & 0 \end{pmatrix} \right] \vec{\nu}$ , with  $\vec{\nu} = \begin{pmatrix} \nu_e \\ \nu_a \end{pmatrix}$ ;
- Data:  $\begin{cases} \text{low-E (Cl, Ga): } P_{ee} \approx 1 - \frac{1}{2} \sin^2 2\theta_{12}, \\ \text{high-E (SK, SNO): } P_{ee} \approx \sin^2 \theta_{12}; \end{cases}$
- fit presently dominated by high-E.



# I. Conventional three-neutrino oscillations

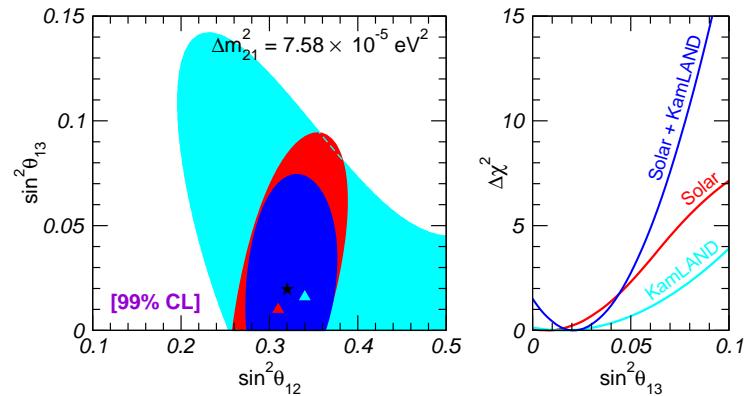
## Bound on $\theta_{13}$ from solar & KamLAND

- $\nu_\mu \equiv \nu_\tau \Rightarrow$  no sensitivity to  $\theta_{23}$  and  $\delta_{CP}$ ;
- $\Delta m_{31}^2 \approx \infty \Rightarrow$  specific  $\Delta m_{31}^2$  value irrelevant;
- $\Rightarrow$  data only depend on  $\Delta m_{21}^2$ ,  $\theta_{12}$  and  $\theta_{13}$ ;
- $P_{ee} \approx \begin{cases} \text{Kam: } \cos^4 \theta_{13} \left(1 - \sin^2 2\theta_{12} \sin^2 \frac{\Delta m_{21}^2 L}{4E}\right), \\ \text{low-E: } \cos^4 \theta_{13} \left(1 - \frac{1}{2} \sin^2 2\theta_{12}\right), \\ \text{high-E: } \cos^4 \theta_{13} \sin^2 \theta_{12}; \end{cases}$
- as  $\theta_{13}$  increases,  $\cos^4 \theta_{13}$  decreases and:
  - KamLAND and low-E data favor **smaller**  $\theta_{12}$ ;
  - high-E data favor **larger**  $\theta_{12}$  and  $\Delta m_{21}^2$ ;
  - Kam fit gets worse as osc. are suppressed;
- synergy between **solar** and **KamLAND** data: as  $\theta_{13}$  increases,  $\Delta m_{21}^2$ :  $\begin{cases} \text{increases in solar data;} \\ \text{remains stable in KamLAND;} \end{cases}$  hence, a tension appear.



## Hint for non-zero $\theta_{13}$ in solar and KamLAND data

- For  $\theta_{13} = 0$ , we have  $\sin^2 \theta_{12} = \begin{cases} 0.30 & \text{from Solar data} \\ 0.36 & \text{from KamLAND data} \end{cases} \Rightarrow$  a tension appear;
- as we have just seen, when  $\theta_{13}$  increases:
  - solar region slightly moves to larger  $\theta_{12}$  (high-E data dominate over low-E ones);
  - KamLAND region definitely shifts to smaller  $\theta_{12}$ ;
- therefore, a non-zero value of  $\theta_{13}$  reduces the tension between solar and KamLAND data [1, 2];
- new SNO-III data favor smaller  $\phi_{CC}/\phi_{NC} \Rightarrow$  smaller  $\theta_{12}$  from solar  $\Rightarrow$  tension with KamLAND is increased  $\Rightarrow$  larger  $\theta_{13}$  is preferred.

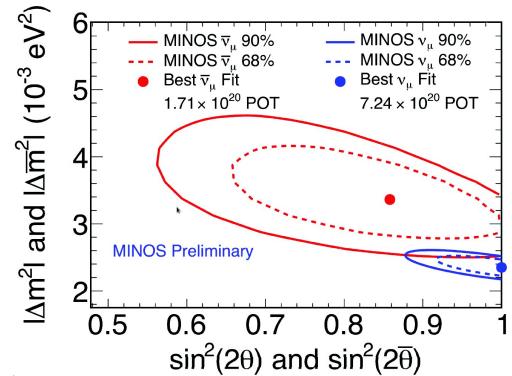
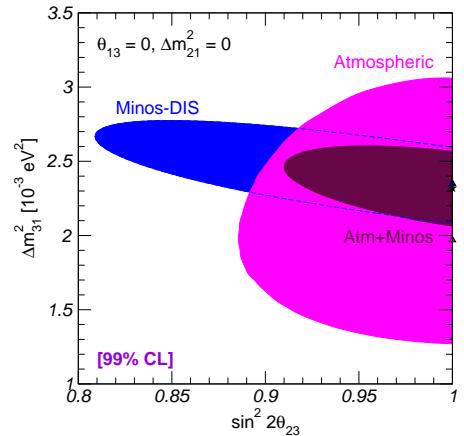
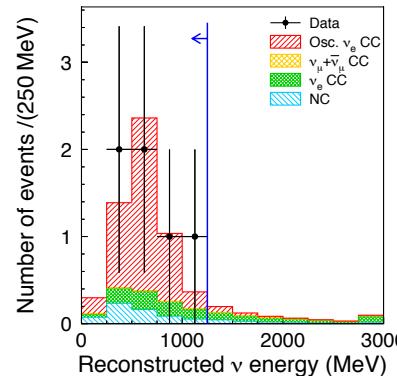
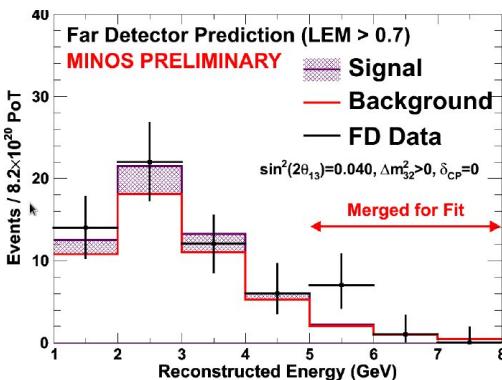


[1] G.L. Fogli *et al.*, Phys. Rev. Lett. **101** (2008) 141801 [[arXiv:0806.2649](https://arxiv.org/abs/0806.2649)].

[2] T. Schwetz, M.A. Tortola, J.W.F. Valle, New J. Phys. **10** (2008) 113011 [[arXiv:0808.2016](https://arxiv.org/abs/0808.2016)].

## Atmospheric sector: the $\Delta m_{21}^2 = 0$ limit

- $\Delta m_{31}^2$  is now determined by Minos-DIS ( $\nu_\mu$ ) data;
- $\theta_{23}$  still dominated by atmospheric data;
- $\theta_{13}$  mainly bounded by Chooz, with small atm contribution;
- hints of non-zero  $\theta_{13}$  in  $\nu_e$  appearance data, from Minos ( $1.6\sigma$ ) [→ Holin's talk] and T2K ( $2.5\sigma$ ) [→ Giganti's talk];
- some tension ( $2.4\sigma$ ) between Minos disappearance  $\nu_\mu$  and  $\bar{\nu}_\mu$  data [→ Holin's talk].

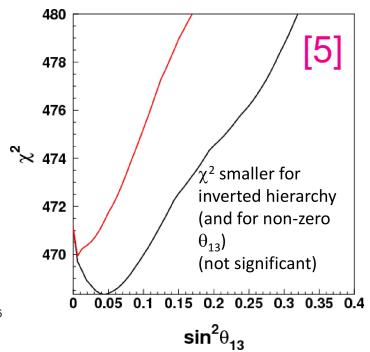
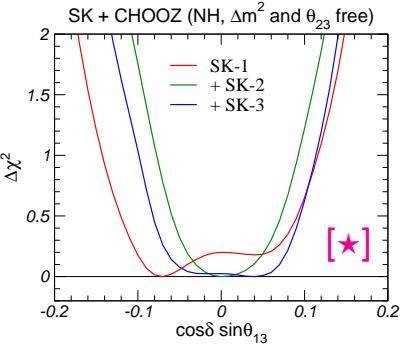
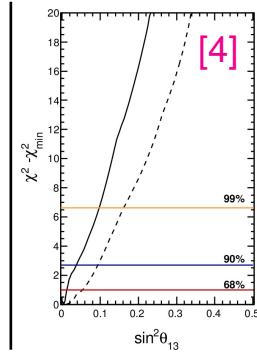
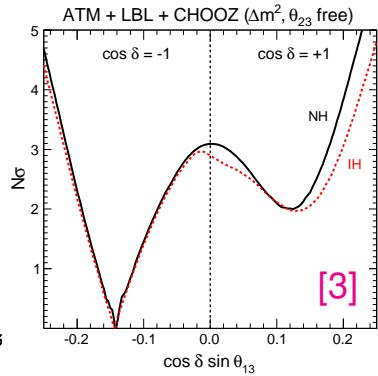
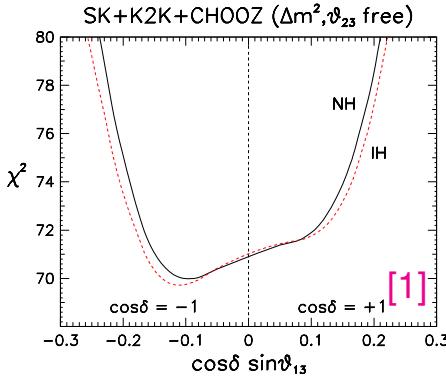


# I. Conventional three-neutrino oscillations

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## $\theta_{13}$ from SK atmospheric data

- Hint of non-zero  $\theta_{13}$  in SK atmospheric data [1, 3];
- no such hint (or very weak one) from our simulation [ $\star$ ];
- ★ details of the simulation very important  $\Rightarrow$  SK has final word;
- SK confirms  $\theta_{13} = 0$  [4] but crucial  $\Delta m_{21}^2$  effects are neglected;
- preliminary full  $3\nu$  fit [5] suggests weak deviations for IH only.



[1] G.L. Fogli *et al.*, Phys. Rev. Lett. **101** (2008) 141801 [[arXiv:0806.2649](https://arxiv.org/abs/0806.2649)].

[3] G.L. Fogli, E. Lisi, A. Marrone, A. Palazzo, A.M. Rotunno, [arXiv:1106.6028](https://arxiv.org/abs/1106.6028).

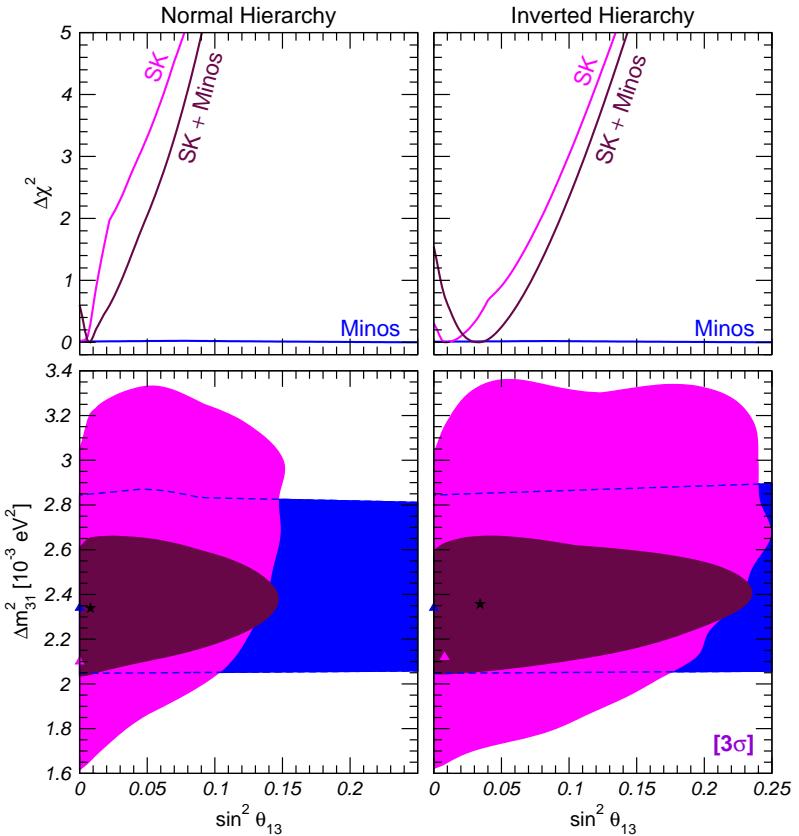
[4] R. Wendell *et al.* [SK Collaboration], Phys. Rev. **D81** (2010) 092004 [[arXiv:1002.3471](https://arxiv.org/abs/1002.3471)].

[5] T. Kajita, talk presented at NOW 2010, 7/09/2010.

# I. Conventional three-neutrino oscillations

## $\theta_{13}$ from SK + Minos data

- For  $\theta_{13} = 0$  we have:  
$$\Delta m_{31}^2 = \begin{cases} 2.10 \times 10^{-3} \text{ eV}^2 [\text{SK}], \\ 2.36 \times 10^{-3} \text{ eV}^2 [\text{Minos}]; \end{cases}$$
- hence there is some tension between SK and Minos-DIS data;
- as  $\theta_{13}$  increases:
  - SK region shifts to larger  $\Delta m_{31}^2$ ;
  - Minos-DIS region does not move;
- therefore, a non-zero value of  $\theta_{13}$  reduces the tension between SK and Minos-DIS data [6, 7];
- effect is particularly relevant for IH.

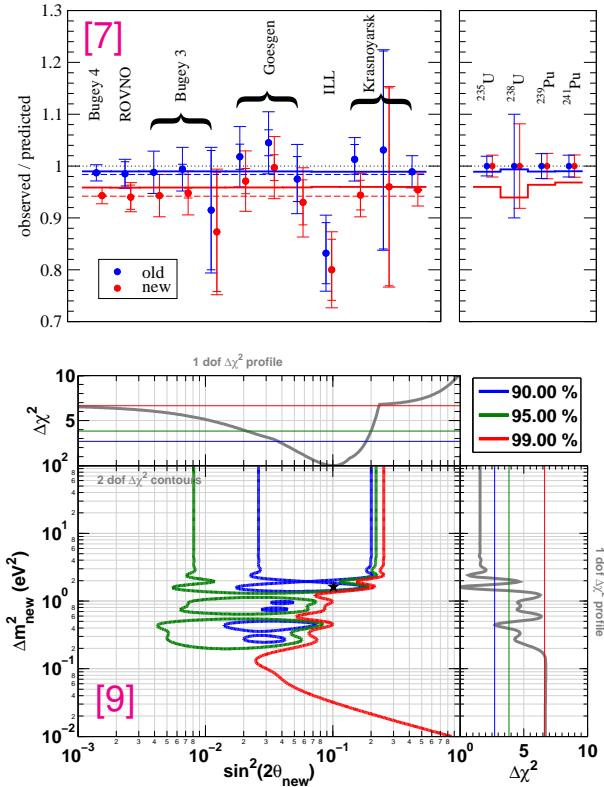


[6] M. C. Gonzalez-Garcia, M. Maltoni, J. Salvado, JHEP 04 (2010) 056 [[arXiv:1001.4524](https://arxiv.org/abs/1001.4524)].

[7] T. Schwetz, M. Tortola, J.W.F. Valle, New J. Phys. 13 (2011) 063004 [[arXiv:1103.0734](https://arxiv.org/abs/1103.0734)].

## The reactor neutrino anomaly

- In [8] the reactor  $\bar{\nu}$  fluxes has been reevaluated;
- the new calculation results in a small increase of the flux by about **3.5%** [→ Lasserre's talk];
- hence, **all** reactor experiments finding **no evidence** are actually **observing a deficit**;
- this deficit **could** be interpreted as being due to neutrino oscillations **but** requires  $\Delta m^2 \gtrsim 1 \text{ eV}^2$ ;
- if used within  $3\nu$  models, Chooz favor  $\theta_{13} \neq 0$  **but** deficit of **other** SBL experiments unexplained;
- consistent approach [7]: fit also reactor fluxes (within errors) including **all** reactor data;
- this way “old” and “new” fluxes equivalent for  $\theta_{13}$ .



[7] T. Schwetz, M. Tortola, J.W.F. Valle, New J. Phys. **13** (2011) 063004 [[arXiv:1103.0734](https://arxiv.org/abs/1103.0734)].

[8] T.A. Mueller *et al.*, Phys. Rev. **C83** (2011) 054615 [[arXiv:1101.2663](https://arxiv.org/abs/1101.2663)].

[9] G. Mention *et al.*, Phys. Rev. **D83** (2011) 073006 [[arXiv:1101.2755](https://arxiv.org/abs/1101.2755)].

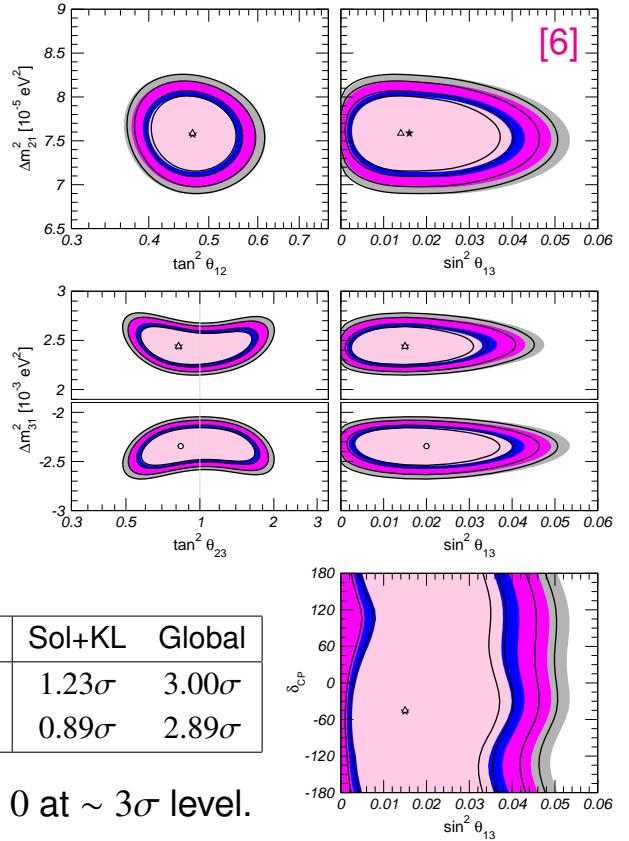
## Neutrino oscillations: where we are

- Global 6-parameter fit (including  $\delta_{CP}$ ):
  - **Solar**: Cl + Ga + SK-I + SNO-Ieta (I+II) + SNO-III + BX-low + BX-high;
  - **Atmospheric**: SK-I + SK-II + SK-III;
  - **Reactor**: Chooz + KamLAND;
  - **Accelerator**: K2K + Minos-DIS + Minos-APP + T2K;
- BPS09(GS): best-fit and  $1\sigma$  ( $3\sigma$ ):
 
$$\theta_{12} = 34.4 \pm 1.0 \begin{pmatrix} +3.3 \\ -2.9 \end{pmatrix}, \quad \Delta m_{21}^2 = 7.58 \pm 0.20 \begin{pmatrix} +0.59 \\ -0.61 \end{pmatrix} \times 10^{-5} \text{ eV}^2,$$

$$\theta_{23} = 42.1 \begin{pmatrix} +6.5 \\ -2.6 \end{pmatrix} \begin{pmatrix} +11.9 \\ -6.5 \end{pmatrix}, \quad \Delta m_{31}^2 = \begin{cases} -2.34 \pm 0.09 \begin{pmatrix} +0.26 \\ -0.29 \end{pmatrix} \times 10^{-3} \text{ eV}^2, \\ +2.44 \pm 0.09 \begin{pmatrix} +0.29 \\ -0.25 \end{pmatrix} \times 10^{-3} \text{ eV}^2, \end{cases}$$

$$\theta_{13} = 7.4 \begin{pmatrix} +2.3 \\ -2.0 \end{pmatrix} (\leq 12.8), \quad \delta_{CP} = -45 \begin{pmatrix} +75 \\ -100 \end{pmatrix} (\text{any});$$
- BPS09(AGSS): as above except:
 
$$\theta_{12} = 34.4 \pm 1.0 \begin{pmatrix} +3.2 \\ -2.8 \end{pmatrix}, \quad \theta_{13} = 6.9 \begin{pmatrix} +2.3 \\ -1.8 \end{pmatrix} (\leq 12.4);$$
- Fogli *et al.* [3]:  $\sin^2 \theta_{13} = 0.021 \pm 0.007$ , with  $\theta_{13} > 0$  at  $\sim 3\sigma$  level.

Solar model	Sol+KL	Global
BPS09(GS)	$1.23\sigma$	$3.00\sigma$
BPS09(AGSS)	$0.89\sigma$	$2.89\sigma$



[3] G.L. Fogli, E. Lisi, A. Marrone, A. Palazzo, A.M. Rotunno, arXiv:1106.6028.

[6] M. C. Gonzalez-Garcia, M. Maltoni, J. Salvado, JHEP 04 (2010) 056 [arXiv:1001.4524], updated.

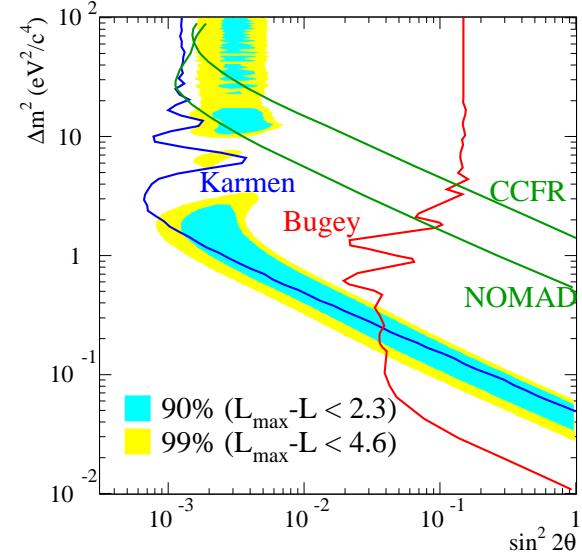
### The LSND problem

- LSND observed  $\bar{\nu}_e$  appearance in a  $\bar{\nu}_\mu$  beam ( $E_\nu \sim 30$  MeV,  $L \simeq 35$  m);
- Karmen did not confirm the claim, but couldn't fully exclude it either;
- the signal is compatible with  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  oscillations provided that  $\Delta m^2 \gtrsim 0.1$  eV $^2$ ;
- on the other hand, other data give (at  $3\sigma$ ):

$$\Delta m_{\text{SOL}}^2 \simeq 7.6 \pm 0.6 \times 10^{-5} \text{ eV}^2,$$

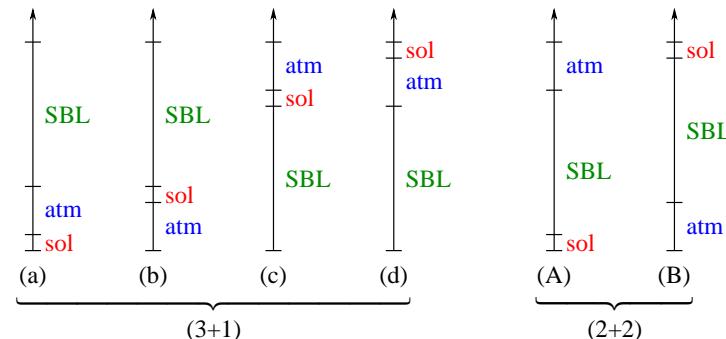
$$|\Delta m_{\text{ATM}}^2| \simeq 2.4 \pm 0.4 \times 10^{-3} \text{ eV}^2;$$

- in order to explain LSND with mass-induced neutrino oscillations one needs *at least one more* neutrino mass eigenstate;
- **WARNING:** having enough  $\Delta m^2$  is not enough. To make sure that the model works, one has to check explicitly that all the experiments can be fitted simultaneously.

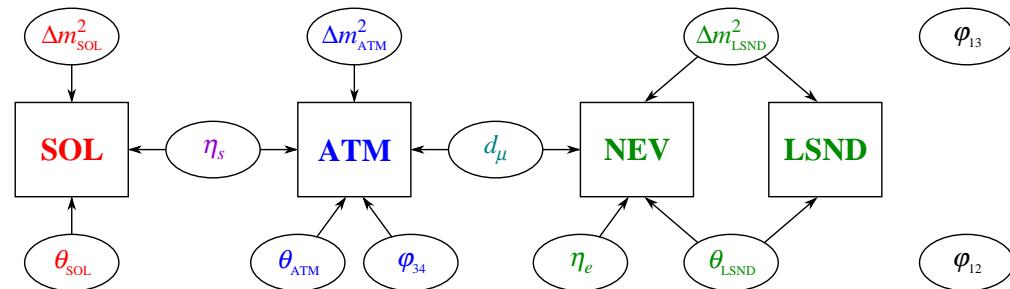


### Four neutrino mass models

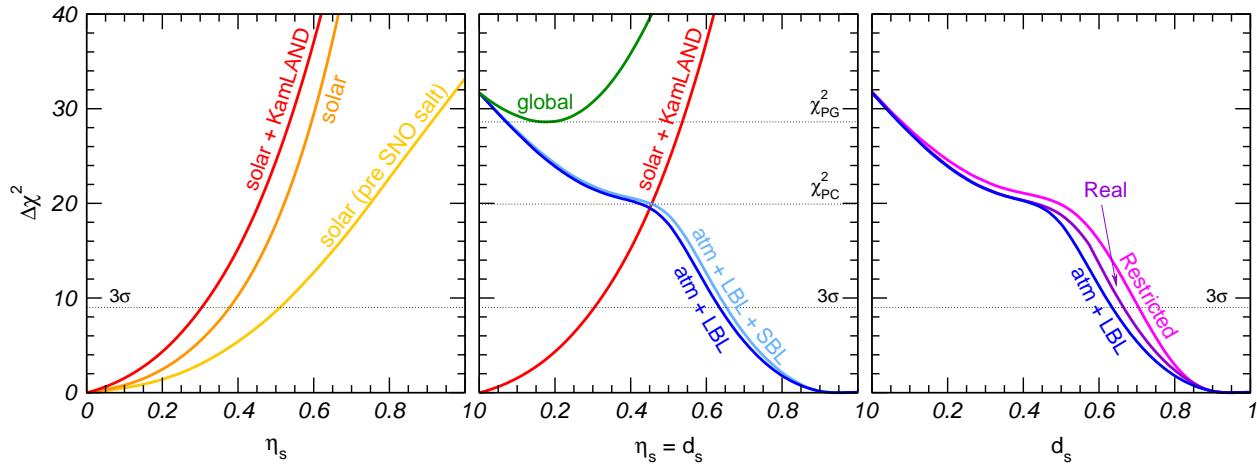
- Approximation:  $\Delta m_{\text{sol}}^2 \ll \Delta m_{\text{ATM}}^2 \ll \Delta m_{\text{LSND}}^2 \Rightarrow$  6 different mass schemes:



- Total: 3  $\Delta m^2$ , 6 angles, 3 phases. Different set of experimental data *partially decouple*:



(2+2): ruled out by solar and atmospheric data



- in (2+2) models, fractions of  $\nu_s$  in **solar** ( $\eta_s$ ) and **atmos** ( $1 - d_s$ ) add to one  $\Rightarrow \boxed{\eta_s = d_s}$ ;
- $3\sigma$  allowed regions  $\eta_s \leq 0.31$  (solar) and  $d_s \geq 0.63$  (atmos) do not overlap; superposition occurs only above  $4.5\sigma$  ( $\chi^2_{\text{PC}} = 19.9$ );
- the  $\chi^2$  increase from the combination of **solar** and **atmos** data is  $\chi^2_{\text{PG}} = 28.6$  (1 dof), corresponding to a PG =  $9 \times 10^{-8}$  [10].

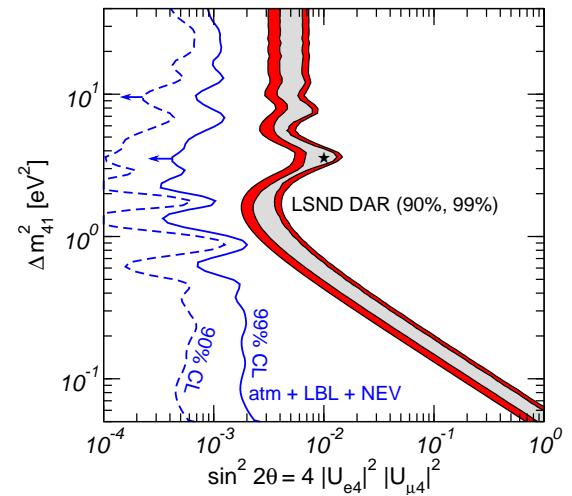
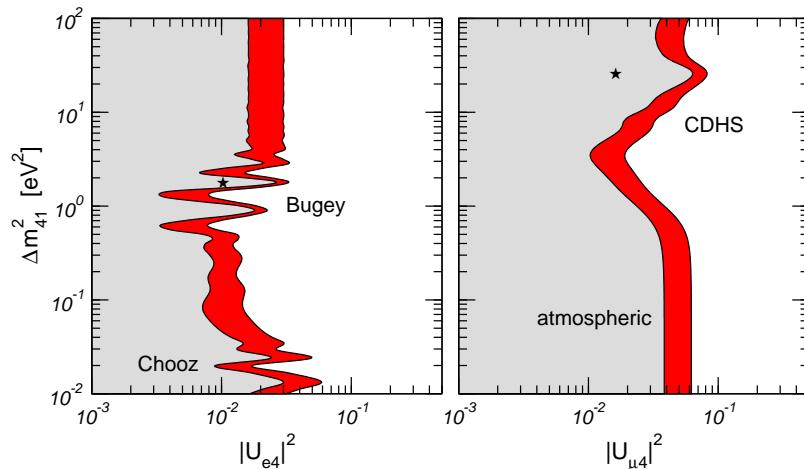
[10] M. Maltoni, T. Schwetz, M.A. Tortola, J.W.F. Valle, Nucl. Phys. **B643** (2002) 321 [hep-ph/0207157].

### (3+1): tension between LSND and short-baseline data

- In (3+1) schemes the SBL *appearance* probability is effectively  $2\nu$  oscillations:

$$P_{\mu e} = \sin^2 2\theta \sin^2 \frac{\Delta m_{41}^2 L}{4E}, \quad \sin^2 2\theta = 4 |U_{e4}|^2 |U_{\mu 4}|^2;$$

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

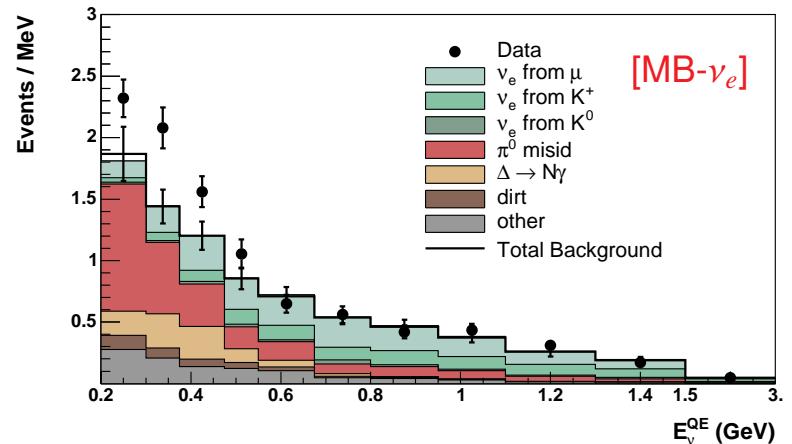
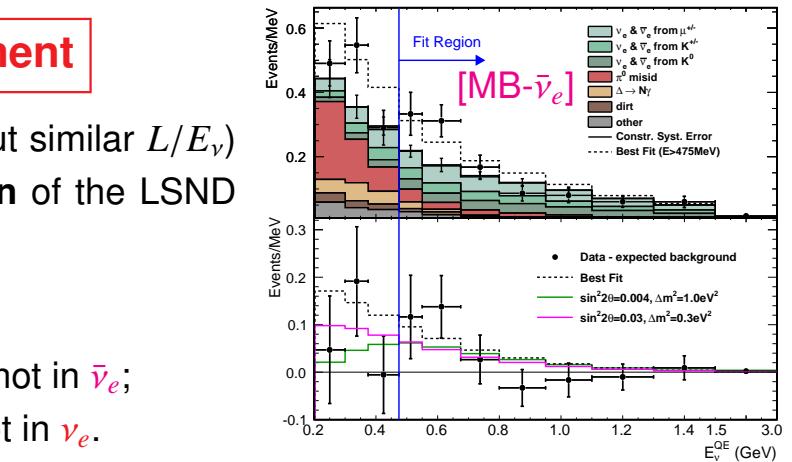
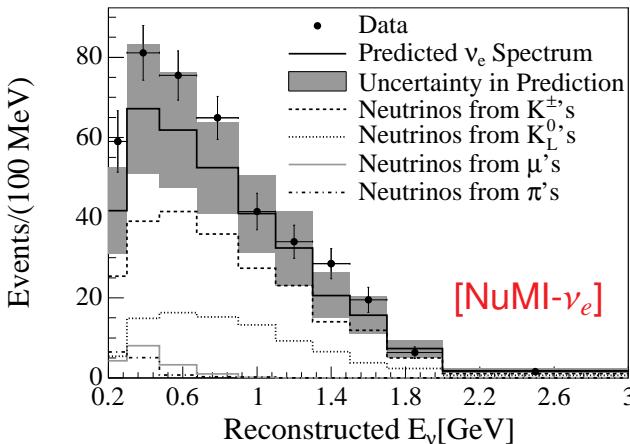


- LSND is in conflict [10]:
  - with other *appearance* experiments (Karmen & Nomad);
  - with all *disappearance* exp's.

[10] M. Maltoni, T. Schwetz, M.A. Tortola, J.W.F. Valle, Nucl. Phys. **B643** (2002) 321 [[hep-ph/0207157](https://arxiv.org/abs/hep-ph/0207157)].

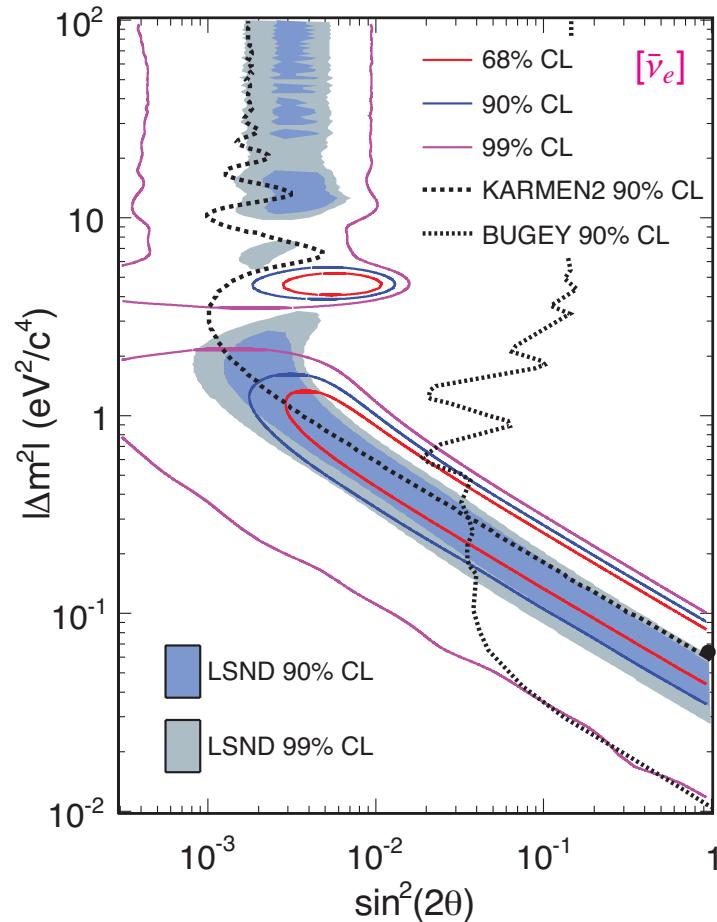
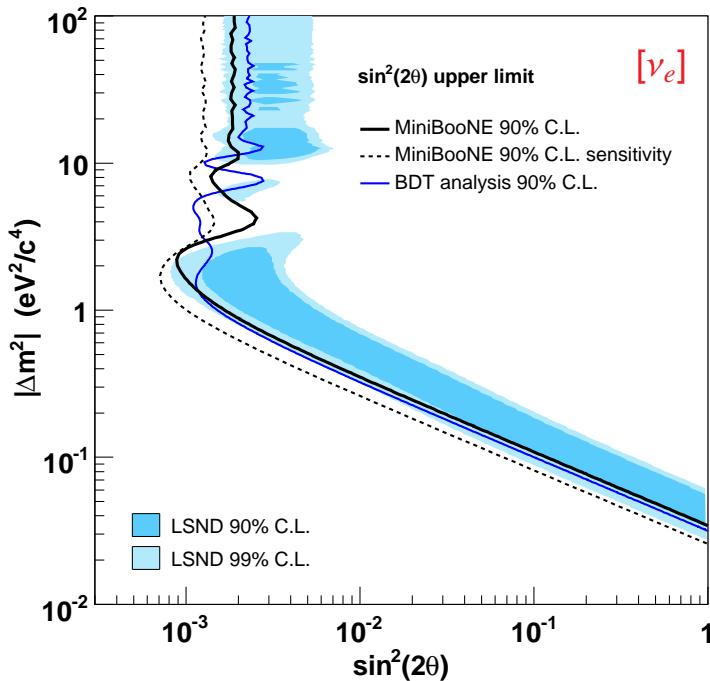
### The MiniBooNE experiment

- $E_\nu$  and  $L$  very different from LSND (but similar  $L/E_\nu$ )  
 ⇒ can check **the oscillation solution** of the LSND problem, **not** the signal itself;
- very peculiar results:
  - strong low-energy excess in  $\nu_e$ , but not in  $\bar{\nu}_e$ ;
  - mild mid-energy excess in  $\bar{\nu}_e$ , but not in  $\nu_e$ .



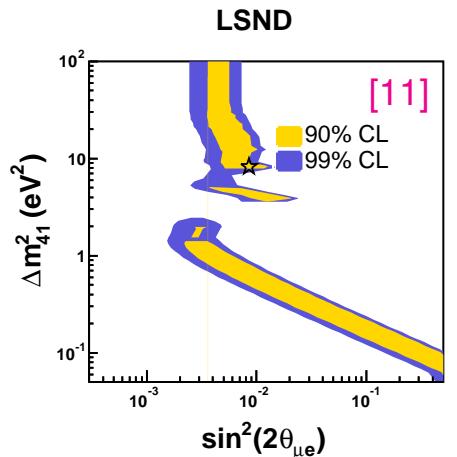
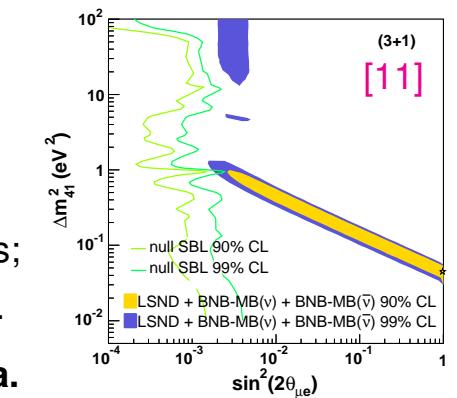
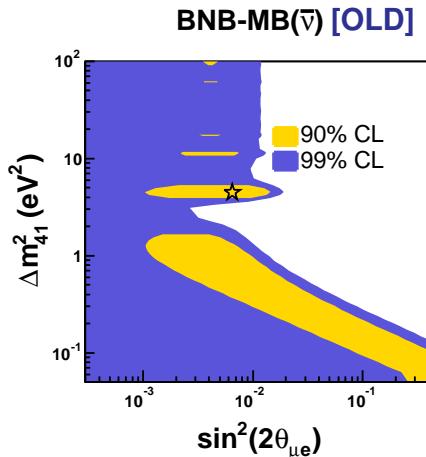
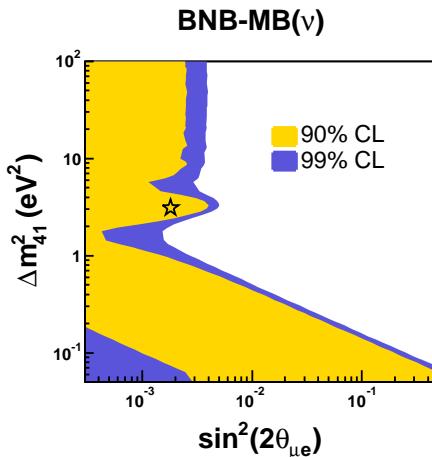
### LSND vs MiniBooNE in (3+1)

- $\nu_e$ : no signal  $\Rightarrow$  excludes LSND;
- $\bar{\nu}_e$ : signal  $\Rightarrow$  confirms LSND.



### Status of (3+1) models after MiniBooNE

- (3+1) four-neutrino schemes fail because:
    - can't reconcile *appearance* and *disappearance* data;
    - can't explain the different  $\nu_e$  (MB) and  $\bar{\nu}_e$  (LSND) results;
    - can't account for the low-energy  $\nu_e$  event excess in MB.
- ⇒ (3+1) models are ruled out as explanation of SBL data.



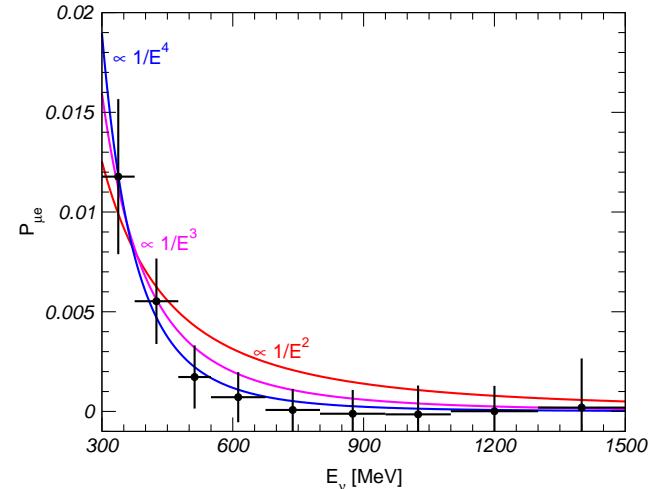
[11] G. Karagiorgi *et al.*, Phys. Rev. D80 (2009) 073001 [[arXiv:0906.1997](https://arxiv.org/abs/0906.1997)].

## Explaining the MiniBooNE excess with two sterile neutrinos

- With *one* extra sterile neutrino,  $m_4$ :

$$P_{\mu e}^{4\nu} = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2 \phi_{41} \quad \text{with} \quad \phi_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E};$$

- for large energy  $P_{\mu e}^{4\nu}$  drops as  $1/E^2$ ;
  - however, the low-energy MB excess is much sharper ( $\sim 1/E^4$ );
- $\Rightarrow$  it is not possible to account for the MB excess with only one extra sterile neutrino.



- On the other hand, with *two* extra neutrinos,  $m_4$  and  $m_5$ :

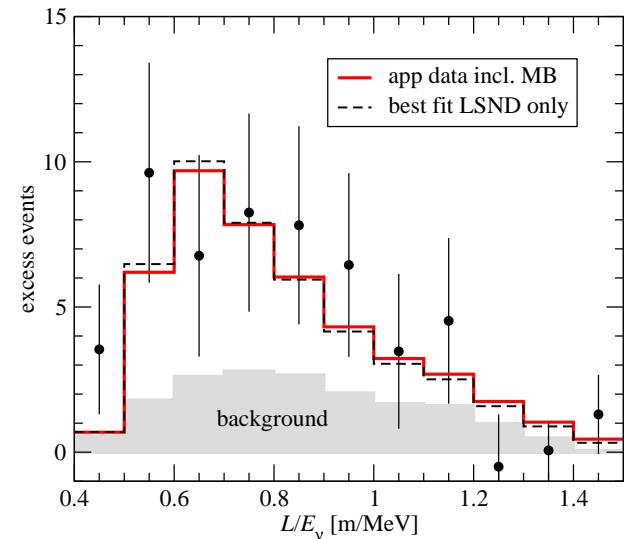
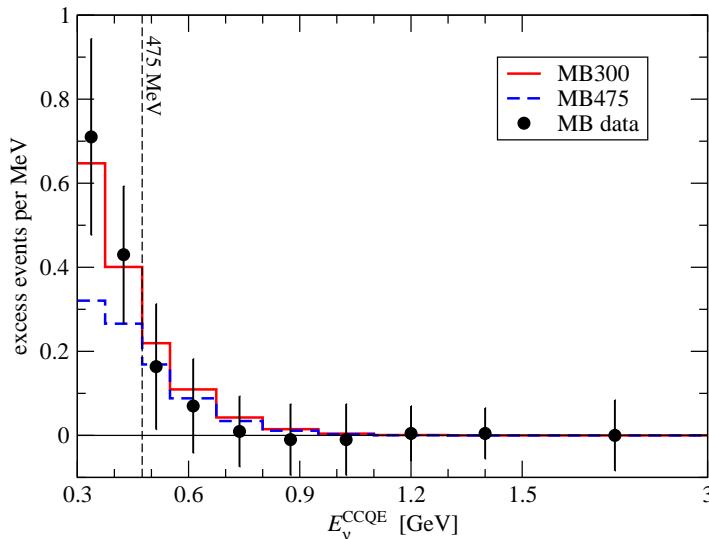
$$P_{\mu e}^{5\nu} = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2 \phi_{41} + 4|U_{e5}|^2|U_{\mu 5}|^2 \sin^2 \phi_{51} + 8|U_{e4} U_{e5} U_{\mu 4} U_{\mu 5}| \sin \phi_{41} \sin \phi_{51} \cos(\phi_{54} - \delta);$$

- terms of order  $1/E^2$  cancel if  $\delta = \pi$  and  $|U_{e4} U_{\mu 4}| \Delta m_{41}^2 = |U_{e5} U_{\mu 5}| \Delta m_{51}^2$ ;

$\Rightarrow$  with two extra sterile states it is possible to fit the MB low-energy excess [12].

[12] M. Maltoni, T. Schwetz, Phys. Rev. D76 (2007) 093005 [arXiv:0705.0107].

## Reconciling MiniBooNE and LSND in (3+2) models

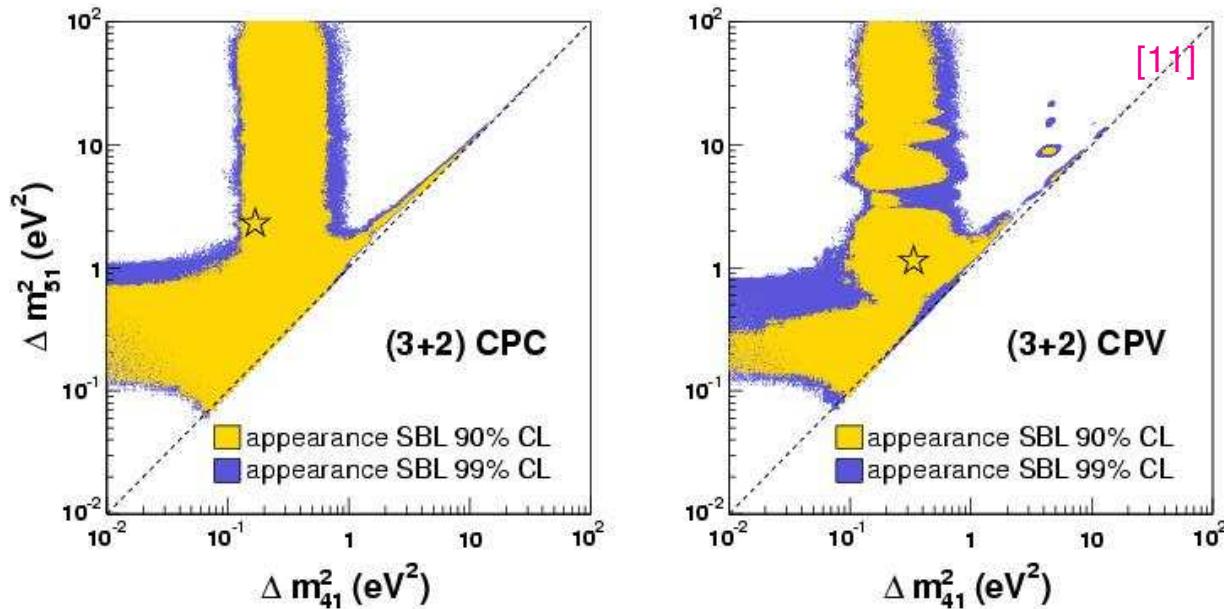


- Trick: use the CP phase  $\delta = \arg(U_{e4}^* U_{\mu 4} U_{e5} U_{\mu 5}^*)$  to differentiate  $\nu$  (MB) from  $\bar{\nu}$  (LSND):  

$$P_{\mu e}^{5\nu} = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2 \phi_{41} + 4|U_{e5}|^2|U_{\mu 5}|^2 \sin^2 \phi_{51} + 8|U_{e4} U_{e5} U_{\mu 4} U_{\mu 5}| \sin \phi_{41} \sin \phi_{51} \cos(\phi_{54} - \delta);$$
- note that  $\delta = \pi + \epsilon$  and  $|U_{e4} U_{\mu 4}| \Delta m_{41}^2 \approx |U_{e5} U_{\mu 5}| \Delta m_{51}^2$  to suppress MB probability [12].

[12] M. Maltoni, T. Schwetz, Phys. Rev. D76 (2007) 093005 [arXiv:0705.0107].

Fitting all appearance data in (3+2) models



data set	$ U_{e4}U_{\mu 4} $	$\Delta m_{41}^2$	$ U_{e5}U_{\mu 5} $	$\Delta m_{51}^2$	$\delta$	$\chi^2_{\min}/\text{dof}$	gof
appearance (CPC)	0.12	0.18	0.006	2.31	–	95.8/86	22%
appearance (CPV)	0.080	0.39	0.029	1.10	$1.1\pi$	82.5/85	56%

NOTE: data taken from Ref. [11], which uses old MB- $\bar{\nu}$  data.

[11] G. Karagiorgi *et al.*, Phys. Rev. D80 (2009) 073001 [[arXiv:0906.1997](https://arxiv.org/abs/0906.1997)].

#### The doom of disappearance data

- As for (3+1) models, disappearance data imply bounds on  $|U_{ei}|^2$  and  $|U_{\mu i}|^2$  ( $i = 4, 5$ );
- these bounds are in conflict with the large values of  $|U_{ei}U_{\mu i}|$  required by appearance data;
- again, a tension between APP and DIS arises:

$$\chi^2_{PG} = 17.5 \text{ (4 dof)} \Rightarrow PG = 1.5 \times 10^{-3} \text{ [no MB];}$$

$$\chi^2_{PG} = 17.2 \text{ (4 dof)} \Rightarrow PG = 1.8 \times 10^{-3} \text{ [MB475];}$$

$$\chi^2_{PG} = 25.1 \text{ (4 dof)} \Rightarrow PG = 4.8 \times 10^{-5} \text{ [MB300];}$$

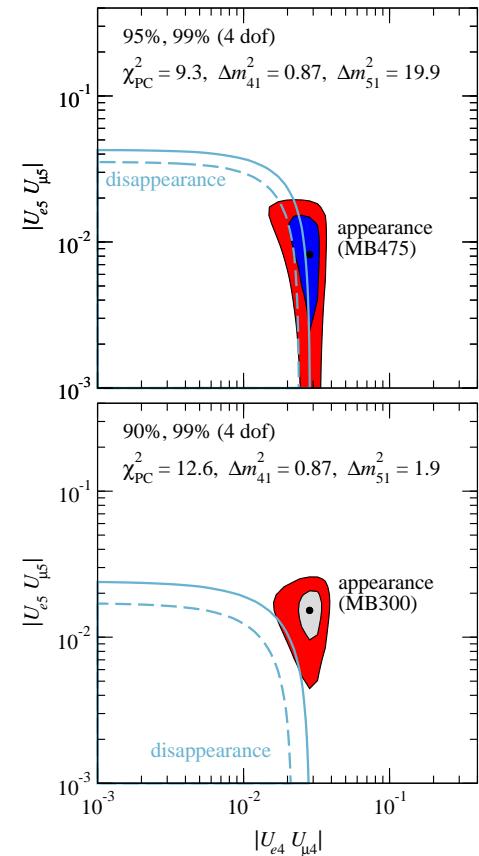
- alternatively, compare LSND and NEV as in (3+1):

$$\chi^2_{PG} = 19.6 \text{ (5 dof)} \Rightarrow PG = 1.5 \times 10^{-3} \text{ [before MB];}$$

$$\chi^2_{PG} = 21.2 \text{ (5 dof)} \Rightarrow PG = 7.4 \times 10^{-4} \text{ [after MB].}$$

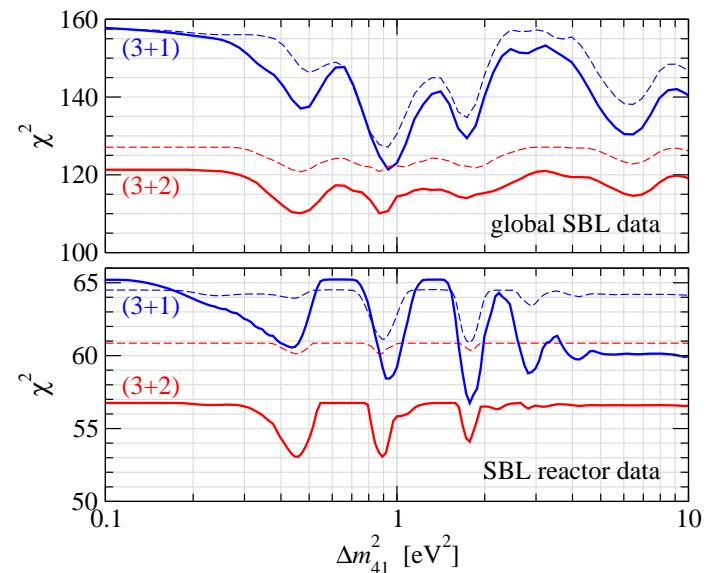
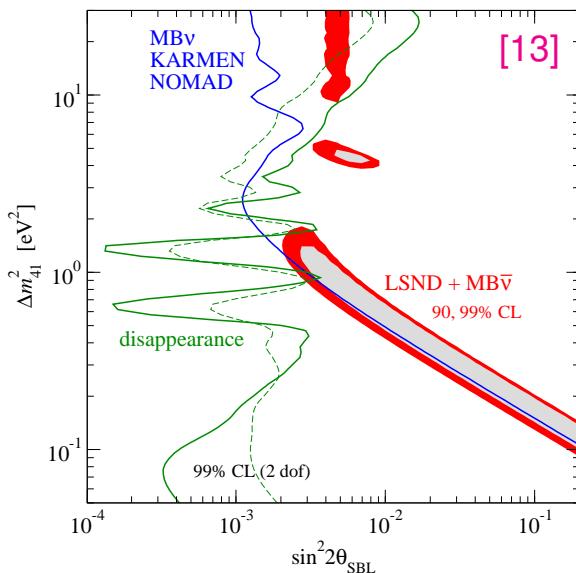
⇒ Conclusion: (3+2) models fail exactly as (3+1) [12].

[12] M. Maltoni, T. Schwetz, Phys. Rev. D76 (2007) 093005 [arXiv:0705.0107].



#### Impact of the new reactor fluxes

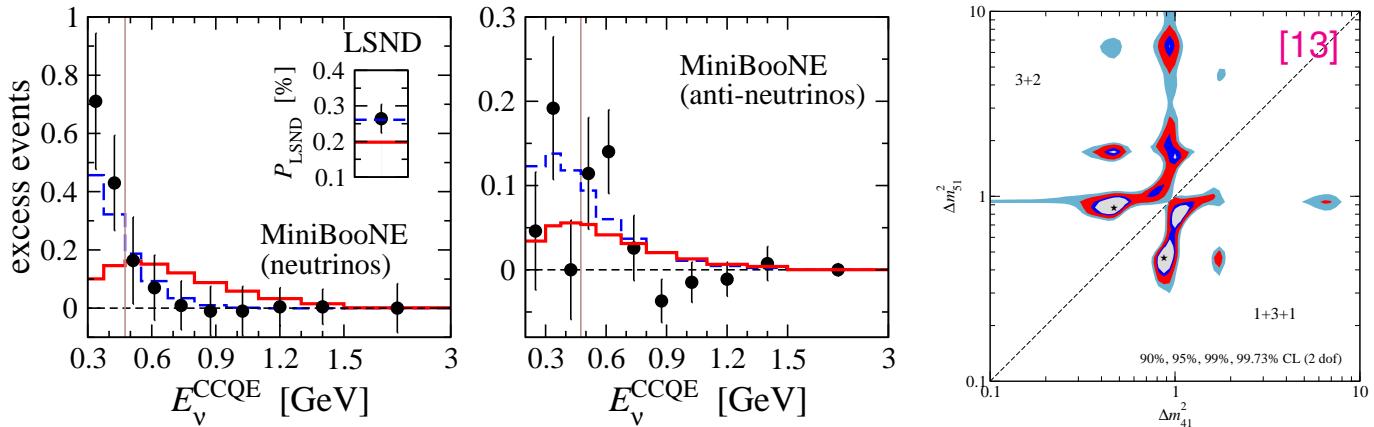
- (3+1)models:  $\chi^2_{\text{PG}}/\text{dof} = 24.2/2 \rightarrow 21.5/2$  for **LSND + MB( $\bar{\nu}$ )** vs **NEV** ( $\Delta\chi^2_{\text{PG}} = 2.7$ );
- (3+2) models:  $\left\{ \begin{array}{l} \chi^2_{\text{PG}}/\text{dof} = 25.1/5 \rightarrow 19.9/5 \text{ for LSND + MB}(\bar{\nu}) \text{ vs NEV } (\Delta\chi^2_{\text{PG}} = 5.2); \\ \chi^2_{\text{PG}}/\text{dof} = 19.4/4 \rightarrow 14.7/4 \text{ for APP vs DIS } (\Delta\chi^2_{\text{PG}} = 4.7). \end{array} \right.$



[13] J. Kopp, M. Maltoni, T. Schwetz, to appear in PRL [arXiv:1103.4570].

#### Status of (3+2) models with the new reactor fluxes

- (3+2) models experience substantial improvement, but tension with **disappearance** data remains considerably strong: PG=0.53%;
- situation becomes more critical if the **MiniBooNE low-E excess** is included, since larger mixing angles are required;
- (1+3+1) works slightly better, but has stronger problems with **cosmology** since the sum of neutrino masses ( $\sum m_\nu$ ) is larger.



[13] J. Kopp, M. Maltoni, T. Schwetz, to appear in PRL [arXiv:1103.4570].

- Most of the present data from **solar**, **atmospheric**, **reactor** and **accelerator** experiments are well explained by the  $3\nu$  oscillation hypothesis;
- the “hint” for non-zero  $\theta_{13}$  has now reached the  $3\sigma$  **level**, summing up various contributions from **solar+KamLAND**, **atmospheric+Minos-DIS**, **Minos-APP** and **T2K**;

⇒ **the three-neutrino scenario is robust and provide a good description of most data.**

- Yet, a few experiments exhibit deviations from theis “new” standard  $3\nu$  scenario:
  - LSND observed an excess of  $\bar{\nu}_e$  events in a  $\bar{\nu}_\mu$  beam;
  - MiniBooNE confirms this high-E excess in  $\bar{\nu}$  mode, but not in  $\nu$  mode;
  - MiniBooNE observes a low-E excess in  $\nu$  mode, but not in  $\bar{\nu}$  mode;
  - new fission  $\bar{\nu}$  fluxes suggests that **all** SBL **reactor** experiments are observing a deficit;
- however, these “hints” for sterile neutrinos are **not** in agreement among them:
  - MiniBooNE asymmetry in  $\nu/\bar{\nu}$  requires CP violation, hence at least **two sterile  $\nu$ 's**;
  - (3+2) models reconcile **APP** data, but **DIS** ones still show tension;
  - new **reactor** fluxes reduce tension with **DIS** data, but **not** for MB low-E excess;

⇒ **we are still quite far from the solution of the LSND puzzle!**