

# New interactions: past and future experiments

Michele Maltoni

Departamento de Física Teórica & Instituto de Física Teórica  
Universidad Autónoma de Madrid

Neutrino 2008, Christchurch, New Zealand – May 27, 2008

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## I. Non-standard interactions with matter

Violation of fundamental principles

## II. Models with extra sterile neutrinos

Neutrino magnetic moment

Long-range leptonic forces

## III. Neutrino decay and decoherence

Mass-varying neutrinos

Summary

...

## Lagrangian formalism

- Effective low-energy Lagrangian for **standard** neutrino interactions with matter:

$$\mathcal{L}_{\text{SM}}^{\text{eff}} = -2\sqrt{2}G_F \sum_{\beta} ([\bar{\nu}_{\beta} \gamma_{\mu} L \ell_{\beta}] [\bar{f} \gamma^{\mu} L f'] + \text{h.c.}) - 2\sqrt{2}G_F \sum_{P,\beta} g_P^f [\bar{\nu}_{\beta} \gamma_{\mu} L \nu_{\beta}] [\bar{f} \gamma^{\mu} P f]$$

where  $P \in \{L, R\}$ ,  $(f, f')$  form an  $SU(2)$  doublet, and  $g_P^f$  is the  $Z$  coupling to fermion  $f$ :

$$\begin{aligned} g_L^v &= \frac{1}{2}, & g_L^{\ell} &= \sin^2 \theta_W - \frac{1}{2}, & g_L^u &= -\frac{2}{3} \sin^2 \theta_W + \frac{1}{2}, & g_L^d &= \frac{1}{3} \sin^2 \theta_W - \frac{1}{2}, \\ g_R^v &= 0, & g_R^{\ell} &= \sin^2 \theta_W, & g_R^u &= -\frac{2}{3} \sin^2 \theta_W, & g_R^d &= \frac{1}{3} \sin^2 \theta_W; \end{aligned}$$

- here we consider **NC-like non-standard** neutrino-matter described by:

$$\mathcal{L}_{\text{NSI}}^{\text{eff}} = -2\sqrt{2}G_F \sum_{P,\alpha,\beta} \epsilon_{\alpha\beta}^{fP} [\bar{\nu}_{\alpha} \gamma_{\mu} L \nu_{\beta}] [\bar{f} \gamma^{\mu} P f];$$

note that  $\epsilon_{\alpha\beta}^{fP}$  is Hermitian;

- for convenience, we also define the **vector** component  $\epsilon_{\alpha\beta}^{fV} = \epsilon_{\alpha\beta}^{fL} + \epsilon_{\alpha\beta}^{fR}$ .

### Bounds from non-oscillation experiments (Flavor Conserving)

$-0.03 < \varepsilon_{ee}^{eL} < 0.08$	$0.004 < \varepsilon_{ee}^{eR} < 0.15$	$\nu_e e \rightarrow \nu e$ $\bar{\nu}_e e \rightarrow \bar{\nu} e$	LSND Reactors	good	[1, 2]
$-1 < \varepsilon_{ee}^{uL} < 0.3$	$-0.4 < \varepsilon_{ee}^{uR} < 0.7$	$\nu_e q \rightarrow \nu q$	CHARM	mild	[3]
$-0.3 < \varepsilon_{ee}^{dL} < 0.3$	$-0.6 < \varepsilon_{ee}^{dR} < 0.5$	$\nu_e q \rightarrow \nu q$	CHARM	mild	[3]
$ \varepsilon_{\mu\mu}^{eL}  < 0.03$	$ \varepsilon_{\mu\mu}^{eR}  < 0.03$	$\nu_\mu e \rightarrow \nu e$	CHARM II	good	[1, 3]
$ \varepsilon_{\mu\mu}^{uL}  < 0.003$	$-0.008 < \varepsilon_{\mu\mu}^{uR} < 0.003$	$\nu_\mu q \rightarrow \nu q$	NuTeV	strong	[3]
$ \varepsilon_{\mu\mu}^{dL}  < 0.003$	$-0.008 < \varepsilon_{\mu\mu}^{dR} < 0.015$	$\nu_\mu q \rightarrow \nu q$	NuTeV	strong	[3]
$-0.5 < \varepsilon_{\tau\tau}^{eL} < 0.2$	$-0.3 < \varepsilon_{\tau\tau}^{eR} < 0.4$	$e^+ e^- \rightarrow \nu \bar{\nu} \gamma$	LEP	mild	[1, 4]
$ \varepsilon_{\tau\tau}^{uL}  < 1.4$	$ \varepsilon_{\tau\tau}^{uR}  < 3$	rad. corrections	$\tau$ decay	poor	[3]
$ \varepsilon_{\tau\tau}^{dL}  < 1.1$	$ \varepsilon_{\tau\tau}^{dR}  < 6$	rad. corrections	$\tau$ decay	poor	[3]

(limits at 90% CL varying *one parameter at a time*)

[1] J. Barranco *et al.*, arXiv:0711.0698.

[2] J. Barranco *et al.*, Phys. Rev. **D73** (2006) 113001 [hep-ph/0512195].

[3] S. Davidson *et al.*, JHEP **03** (2003) 011 [hep-ph/0302093].

[4] Z. Berezhiani and A. Rossi, Phys. Lett. **B535** (2002) 207 [hep-ph/0111137].

## Bounds from non-oscillation experiments (Flavor Changing)

$ \varepsilon_{e\mu}^{eL}  < 0.0005$	$ \varepsilon_{e\mu}^{eR}  < 0.0005$	rad. corrections	$\mu \rightarrow 3e$	strong	[3]
$ \varepsilon_{e\mu}^{uL}  < 0.0008$	$ \varepsilon_{e\mu}^{uR}  < 0.0008$	rad. corrections	$Ti\mu \rightarrow Tie$	strong	[3]
$ \varepsilon_{e\mu}^{dL}  < 0.0008$	$ \varepsilon_{e\mu}^{dR}  < 0.0008$	rad. corrections	$Ti\mu \rightarrow Tie$	strong	[3]
$ \varepsilon_{e\tau}^{eL}  < 0.33$	$ \varepsilon_{e\tau}^{eR}  < 0.28$	$\nu_e e \rightarrow \nu e$	LEP+LSND+Rea	mild	[1, 4]
$ \varepsilon_{e\tau}^{uL}  < 0.5$	$ \varepsilon_{e\tau}^{uR}  < 0.5$	$\nu_e q \rightarrow \nu q$	CHARM	mild	[3]
$ \varepsilon_{e\tau}^{dL}  < 0.5$	$ \varepsilon_{e\tau}^{dR}  < 0.5$	$\nu_e q \rightarrow \nu q$	CHARM	mild	[3]
$ \varepsilon_{\mu\tau}^{eL}  < 0.1$	$ \varepsilon_{\mu\tau}^{eR}  < 0.1$	$\nu_\mu e \rightarrow \nu e$	CHARM II	good	[1, 3]
$ \varepsilon_{\mu\tau}^{uL}  < 0.05$	$ \varepsilon_{\mu\tau}^{uR}  < 0.05$	$\nu_\mu q \rightarrow \nu q$	NuTeV	good	[3]
$ \varepsilon_{\mu\tau}^{dL}  < 0.05$	$ \varepsilon_{\mu\tau}^{dR}  < 0.05$	$\nu_\mu q \rightarrow \nu q$	NuTeV	good	[3]

(limits at 90% CL varying *one parameter at a time*)

**WARNING: bounds become weaker when correlations among parameters are included!**

[1] J. Barranco *et al.*, arXiv:0711.0698.

[3] S. Davidson *et al.*, JHEP **03** (2003) 011 [hep-ph/0302093].

[4] Z. Berezhiani and A. Rossi, Phys. Lett. **B535** (2002) 207 [hep-ph/0111137].

## NSI and neutrino oscillations

- Equation of motion: **lots** of parameters:

$$i \frac{d\vec{v}}{dt} = H \vec{v}; \quad H = U \cdot H_0^d \cdot U^\dagger + V_{\text{SM}} + V_{\text{NSI}}; \quad H_0^d = \frac{1}{2E_\nu} \text{diag} \left( 0, \Delta m_{21}^2, \Delta m_{31}^2 \right);$$

$$U = \begin{pmatrix} c_{12} c_{13} & s_{12} c_{13} & s_{13} e^{-i\delta_{\text{CP}}} \\ -s_{12} c_{23} - c_{12} s_{13} s_{23} e^{i\delta_{\text{CP}}} & c_{12} c_{23} - s_{12} s_{13} s_{23} e^{i\delta_{\text{CP}}} & c_{13} s_{23} \\ s_{12} s_{23} - c_{12} s_{13} c_{23} e^{i\delta_{\text{CP}}} & -c_{12} s_{23} - s_{12} s_{13} c_{23} e^{i\delta_{\text{CP}}} & c_{13} c_{23} \end{pmatrix}, \quad \vec{v} = \begin{pmatrix} v_e \\ v_\mu \\ v_\tau \end{pmatrix};$$

$$V_{\text{SM}} = \pm \sqrt{2} G_F N_e \text{diag} (1, 0, 0); \quad V_{\text{NSI}} = \pm \sqrt{2} G_F N_e \sum_f \frac{N_f}{N_e} \begin{pmatrix} \epsilon_{ee}^{fV} & \epsilon_{e\mu}^{fV} & \epsilon_{e\tau}^{fV} \\ \epsilon_{e\mu}^{fV*} & \epsilon_{\mu\mu}^{fV} & \epsilon_{\mu\tau}^{fV} \\ \epsilon_{e\tau}^{fV*} & \epsilon_{\mu\tau}^{fV*} & \epsilon_{\tau\tau}^{fV} \end{pmatrix};$$

- note that only the **vector** couplings  $\epsilon_{\alpha\beta}^{fV} = \epsilon_{\alpha\beta}^{fL} + \epsilon_{\alpha\beta}^{fR}$  appear in propagation;
- however, **NC-like** NSI can affect **detection** (e.g.,  $\nu e \rightarrow \nu e$  elastic scattering);
- ★ too much parameters  $\Rightarrow$  only partial analyses so far...

## Solar neutrinos

- As in the SM case, solar neutrinos can be reduced to an effective 2ν problem [5]:

$$i \frac{d\vec{v}}{dt} = \left[ \frac{\Delta m_{21}^2}{4E_\nu} \begin{pmatrix} -\cos 2\theta_{12} & \sin 2\theta_{12} \\ \sin 2\theta_{12} & \cos 2\theta_{12} \end{pmatrix} \pm \sqrt{2} G_F N_e(r) \begin{pmatrix} c_{13}^2 & 0 \\ 0 & 0 \end{pmatrix} \pm \sqrt{2} G_F N_f(r) \begin{pmatrix} 0 & \epsilon_f \\ \epsilon_f & \epsilon'_f \end{pmatrix} \right] \vec{v},$$

$$\vec{v} = \begin{pmatrix} v_e \\ v_a \end{pmatrix}, \quad \begin{cases} \epsilon_f = c_{13}(\epsilon_{e\mu}^{fV} c_{23} - \epsilon_{e\tau}^{fV} s_{23}) - s_{13}[\epsilon_{\mu\tau}^{fV}(c_{23}^2 - s_{23}^2) + (\epsilon_{\mu\mu}^{fV} - \epsilon_{\tau\tau}^{fV})c_{23}s_{23}], \\ \epsilon'_f = \epsilon_{\mu\mu}^{fV} c_{23}^2 + \epsilon_{\tau\tau}^{fV} s_{23}^2 - \epsilon_{ee}^{fV} - 2\epsilon_{\mu\tau}^{fV} c_{23}s_{23} + 2s_{13}c_{13}(\epsilon_{e\tau}^{fV} c_{23} + \epsilon_{e\mu}^{fV} s_{23}) \\ \quad - s_{13}^2(\epsilon_{\tau\tau}^{fV} c_{23}^2 + \epsilon_{\mu\mu}^{fV} s_{23}^2 - \epsilon_{ee}^{fV} + 2\epsilon_{\mu\tau}^{fV} s_{23}c_{23}) \end{cases}$$

(neglecting for simplicity  $\delta_{CP}$  and the complex phases in  $\epsilon_{\alpha\beta}^{fV}$ );

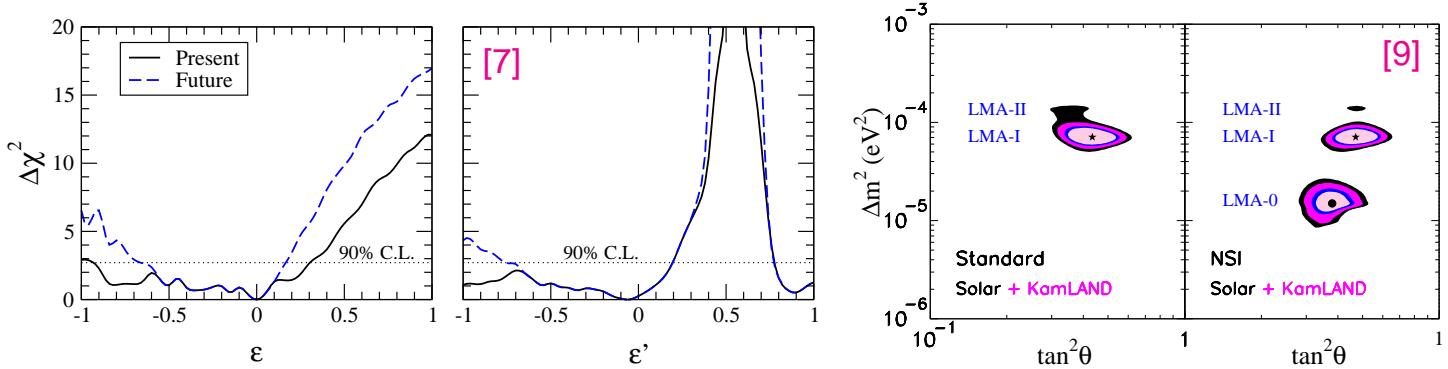
- Analyses in the literature [5, 6] focus on  $f = \{u, d\}$ , because (1) bounds on  $\epsilon_{\alpha\beta}^{qV}$  are weaker, and (2) for  $f = e$  SK detection is also affected by NSI.
- pre-Borexino solar data *can be perfectly fitted* by NSI only (i.e.,  $\Delta m_{21}^2 = 0$ );
- however, KamLAND requires  $\Delta m_{21}^2 \Rightarrow$  pure NSI solution no longer interesting.

[5] M. Guzzo *et al.*, Nucl. Phys. **B629** (2002) 479 [[hep-ph/0112310](#)].

[6] A. M. Gago *et al.*, Phys. Rev. **D65** (2002) 073012 [[hep-ph/0112060](#)].

## Solar neutrinos with both oscillations and NSI

- Solar LMA solution is **unstable** with respect to the introduction of NSI [7, 8, 9];
- KamLAND is insensitive to NSI  $\Rightarrow$  it determines  $\Delta m_{21}^2$ ;
- bounds on  $\varepsilon_q$  and  $\varepsilon'_q$  from combined Solar+KamLAND analysis are very weak.



[7] O. G. Miranda, M. A. Tortola, and J. W. F. Valle, JHEP **10** (2006) 008 [hep-ph/0406280].

[8] M. M. Guzzo, P. C. de Holanda, and O. L. G. Peres, Phys. Lett. **B591** (2004) 1 [hep-ph/0403134].

[9] A. Friedland, C. Lunardini, and C. Pena-Garay, Phys. Lett. **B594** (2004) 347 [hep-ph/0402266].

## Atmospheric neutrinos: the $\nu_\mu - \nu_\tau$ channel

- We consider NSI in the  $\mu - \tau$  sector [10] (note that  $\epsilon_{\mu\mu}^{fV} \approx 0$  from LAB data):

$$i \frac{d\vec{v}}{dt} = \left[ \frac{\Delta m_{31}^2}{4E_\nu} \begin{pmatrix} -\cos 2\theta_{23} & \sin 2\theta_{23} \\ \sin 2\theta_{23} & \cos 2\theta_{23} \end{pmatrix} \pm \sqrt{2} G_F N_f(r) \begin{pmatrix} 0 & \epsilon_{\mu\tau}^{fV} \\ \epsilon_{\mu\tau}^{fV*} & \epsilon_{\tau\tau}^{fV} \end{pmatrix} \right] \vec{v}, \quad \vec{v} = \begin{pmatrix} v_\mu \\ v_\tau \end{pmatrix};$$

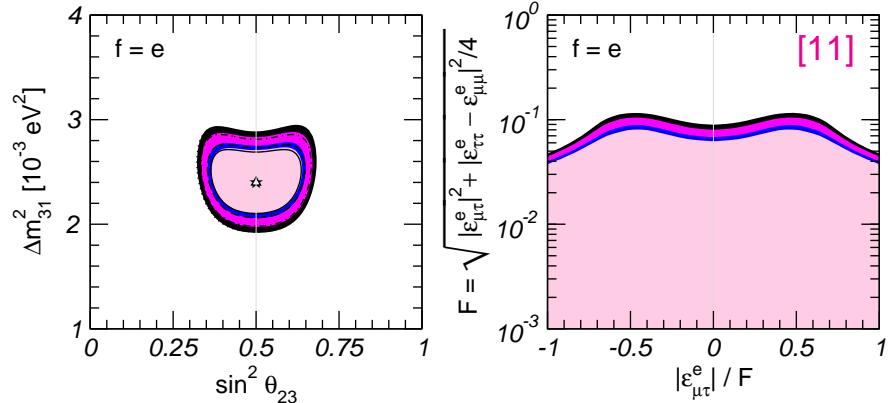
- determination of **oscillation parameters is very stable**;

- 90% ( $3\sigma$ ) bounds on NSI [11]:

$$(e) \begin{cases} |\epsilon_{\mu\tau}^{eV}| \leq 0.038 \text{ (0.058)}, \\ |\epsilon_{\tau\tau}^{eV}| \leq 0.12 \text{ (0.19)}; \end{cases}$$

$$(u) \begin{cases} |\epsilon_{\mu\tau}^{uV}| \leq 0.012 \text{ (0.019)}, \\ |\epsilon_{\tau\tau}^{uV}| \leq 0.039 \text{ (0.061)}; \end{cases}$$

$$(d) \begin{cases} |\epsilon_{\mu\tau}^{dV}| \leq 0.012 \text{ (0.019)}, \\ |\epsilon_{\tau\tau}^{dV}| \leq 0.038 \text{ (0.060)}; \end{cases}$$



- Bounds on  $\epsilon_{\tau\tau}^{fV}$  are much stronger than LAB ones.

[10] N. Fornengo *et al.*, Phys. Rev. **D65** (2002) 013010 [[hep-ph/0108043](#)].

[11] M. C. Gonzalez-Garcia and M. Maltoni, Phys. Rept. **460** (2008) 1 [[arXiv:0704.1800](#)].

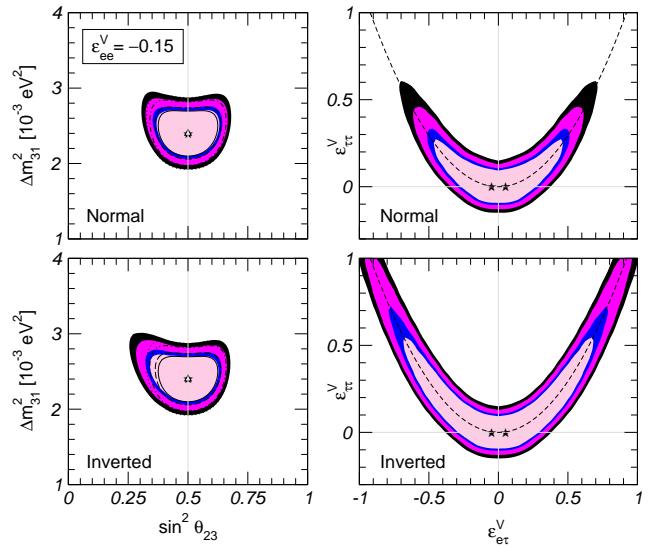
## Atmospheric $\nu$ : the $\nu_e - \nu_\tau$ channel

- Let us now turn to the  $e - \tau$  sector [12, 13, 14]:

$$V_{\text{NSI}} = \begin{pmatrix} \varepsilon_{ee}^V & 0 & \varepsilon_{e\tau}^V \\ 0 & 0 & 0 \\ \varepsilon_{e\tau}^V & 0 & \varepsilon_{\tau\tau}^V \end{pmatrix} \quad \varepsilon_{\alpha\beta}^V \equiv \sum_f \frac{N_f}{N_e} \varepsilon_{\alpha\beta}^{fV} \approx \varepsilon_{\alpha\beta}^{eV} + 3\varepsilon_{\alpha\beta}^{uV} + 3\varepsilon_{\alpha\beta}^{dV}$$

- a dramatic cancellation [12] occurs along the parabola  $(1 + \varepsilon_{ee}^V) \varepsilon_{\tau\tau}^V = |\varepsilon_{e\tau}^V|^2$ ;
  - determination of osc. parameters **is still stable**;
  - but the previous bound on  $\varepsilon_{\tau\tau}^V$  no longer applies;
  - however, the  $\perp$  bound is still strong;
- ⇒ Correlations among different  $\varepsilon_{\alpha\beta}^V$  can have very important consequences!

$$\oplus \begin{cases} N_u/N_e = 3.137 \text{ (core)}, 3.012 \text{ (mantle)} \\ N_d/N_e = 3.274 \text{ (core)}, 3.024 \text{ (mantle)} \end{cases}$$



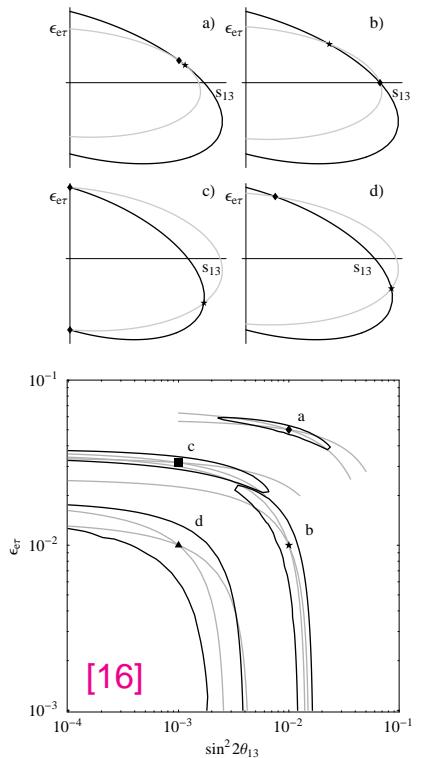
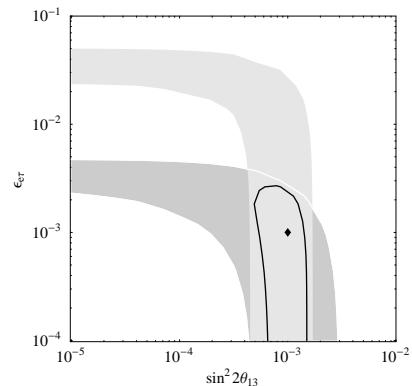
[12] A. Friedland, C. Lunardini, and M. Maltoni, Phys. Rev. **D70** (2004) 111301 [hep-ph/0408264].

[13] A. Friedland and C. Lunardini, Phys. Rev. **D72** (2005) 053009 [hep-ph/0506143].

[14] A. Friedland and C. Lunardini, Phys. Rev. **D74** (2006) 033012 [hep-ph/0606101].

## Future experiments: degeneracies at $\nu$ factories

- Neutrino factories data will provide complementary information to atmospheric neutrinos [15];
- however, in a  $\nu$ -factory critical degeneracies may arise between **NSI** and **oscillation** parameters;
- in particular, NSI may spoil the sensitivity to  $\theta_{13}$  of a neutrino factory [16, 17];
- the situation somewhat improves if data from two different baselines are combined [16].



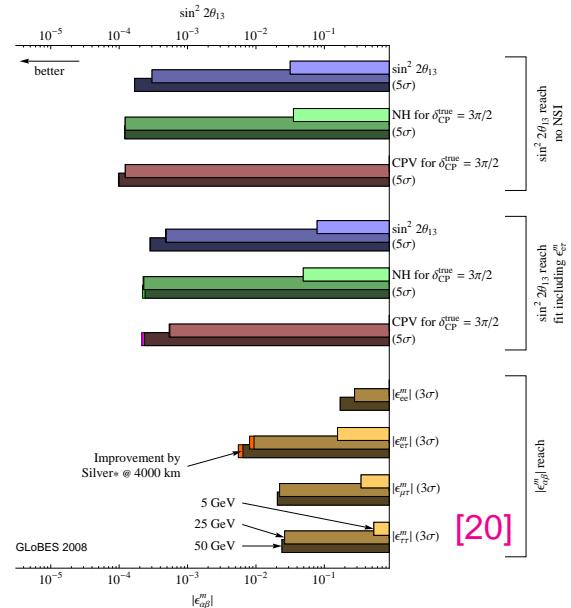
[15] P. Huber and J. W. F. Valle, Phys. Lett. **B523** (2001) 151 [hep-ph/0108193].

[16] P. Huber, T. Schwetz, and J. W. F. Valle, Phys. Rev. Lett. **88** (2002) 101804 [hep-ph/0111224].

[17] P. Huber, T. Schwetz, and J. W. F. Valle, Phys. Rev. **D66** (2002) 013006 [hep-ph/0202048].

## NSI at $\nu$ factories: recent studies

- **Single baseline** (3000 km) [18]: the correlation between  $\arg(\epsilon_{e\mu}^V)$  and  $\delta_{CP}$  is crucial. Sensitivity to  $|\epsilon_{e\tau}^V|$  is considerably worse than to  $|\epsilon_{e\mu}^V|$ ;
- **Two baselines** (3000–4000 & 7000–7500 km):
  - degeneracies solved: NSI don't spoil  $\theta_{13}$  and  $\delta_{CP}$  [19];
  - sensitivities:  $|\epsilon_{e\tau}^V| \lesssim O(10^{-3})$  and  $|\epsilon_{e\mu}^V| \lesssim O(10^{-4})$ , independently of  $\theta_{13}$  [19];
  - energy: performances drop for  $E_\mu < 25$  GeV [20];
  - $\nu_\mu \rightarrow \nu_\mu$  important to resolve degeneracies [20];
  - in contrast,  $\nu_e \rightarrow \nu_\tau$  contributes very little [20].



[18] J. Kopp, M. Lindner, and T. Ota, Phys. Rev. D76 (2007) 013001 [[hep-ph/0702269](#)].

[19] N. C. Ribeiro *et al.*, JHEP 12 (2007) 002 [[arXiv:0709.1980](#)].

[20] J. Kopp, T. Ota, and W. Winter, [arXiv:0804.2261](#).

## Forthcoming facilities

- **Borexino**: precise measurement of the  ${}^7\text{Be}$  line can have a strong impact on NSI [21];
- **MINOS** (future): degeneracy with  $\varepsilon_{e\tau}^V$  spoils sensitivity to  $\theta_{13}$ . External input on either parameter helps measuring the other [22];
- **OPERA**: data sample is too small to gain sensitivity to  $\varepsilon_{e\tau}^V$  and  $\varepsilon_{\tau\tau}^V$ , even if combined with MINOS and Double-CHOOZ [23]. However, it may help in the determination of  $\varepsilon_{\mu\tau}^V$  [24];
- **Coherent  $v$  scattering**: very sensitive to NSI interactions with quarks; present limits on  $\varepsilon_{ee}^{qV}$  and  $\varepsilon_{e\tau}^{qV}$  could be improved dramatically [25, 26].

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[21] Z. Berezhiani, R. S. Raghavan, and A. Rossi, Nucl. Phys. **B638** (2002) 62 [hep-ph/0111138].

[22] M. Blennow, T. Ohlsson, and J. Skrotzki, Phys. Lett. **B660** (2008) 522 [hep-ph/0702059].

[23] A. Esteban-Pretel, J. W. F. Valle, and P. Huber, arXiv:0803.1790.

[24] M. Blennow *et al.*, arXiv:0804.2744.

[25] J. Barranco, O. G. Miranda, and T. I. Rashba, JHEP **12** (2005) 021 [hep-ph/0508299].

[26] J. Barranco, O. G. Miranda, and T. I. Rashba, Phys. Rev. **D76** (2007) 073008 [hep-ph/0702175].

## Other long-term facilities

- **T2KK**: good sensitivity to  $\varepsilon_{\mu\tau}^V$  [27] (analysis restricted to the  $\mu - \tau$  sector only);
- $\beta\text{B}$ : also affected by degeneracies between  $\varepsilon_{\alpha\beta}^V$  and  $\theta_{13}$  [28].
- **Reactors+superbeams**: widely complementary, since reactors are insensitive to  $\varepsilon_{\alpha\beta}^V$ , hence determine  $\theta_{13}$  irrespectively of NSI [29].

### Warning

- In this talk we have focused only on **neutral-current NSI**. If NSI are considered also for **charged-current interactions**, so far neglected in most phenomenological studies, the problem of degeneracies may become more serious [17, 18, 29].

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[17] P. Huber, T. Schwetz, and J. W. F. Valle, Phys. Rev. **D66** (2002) 013006 [[hep-ph/0202048](#)].

[18] J. Kopp, M. Lindner, and T. Ota, Phys. Rev. **D76** (2007) 013001 [[hep-ph/0702269](#)].

[27] N. C. Ribeiro *et al.*, Phys. Rev. **D77** (2008) 073007 [[arXiv:0712.4314](#)].

[28] R. Adhikari, S. K. Agarwalla, and A. Raychaudhuri, Phys. Lett. **B642** (2006) 111 [[hep-ph/0608034](#)].

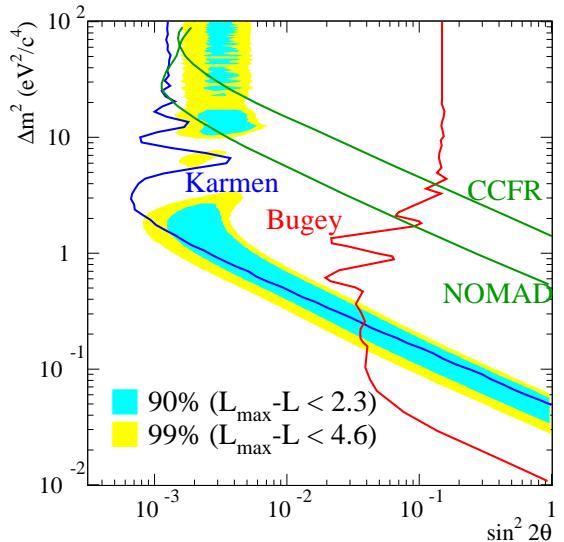
[29] J. Kopp, M. Lindner, T. Ota, and J. Sato, Phys. Rev. **D77** (2008) 013007 [[arXiv:0708.0152](#)].

### The LSND problem

- LSND observed  $\bar{\nu}_e$  appearance in a  $\bar{\nu}_\mu$  beam ( $E_\nu \sim 30$  MeV,  $L \simeq 35$  m);
- the signal is compatible with  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  oscillations provided that  $\Delta m^2 \gtrsim 0.1$  eV<sup>2</sup>;
- on the other hand, other data give (at  $3\sigma$ ): [11]

$$\Delta m_{\text{SOL}}^2 = 7.67^{+0.67}_{-0.61} \times 10^{-5} \text{ eV}^2,$$

$$\Delta m_{\text{ATM}}^2 = \begin{cases} -2.37^{+0.43}_{-0.46} \times 10^{-3} \text{ eV}^2 & (\text{IH}), \\ +2.46^{+0.47}_{-0.42} \times 10^{-3} \text{ eV}^2 & (\text{NH}); \end{cases}$$

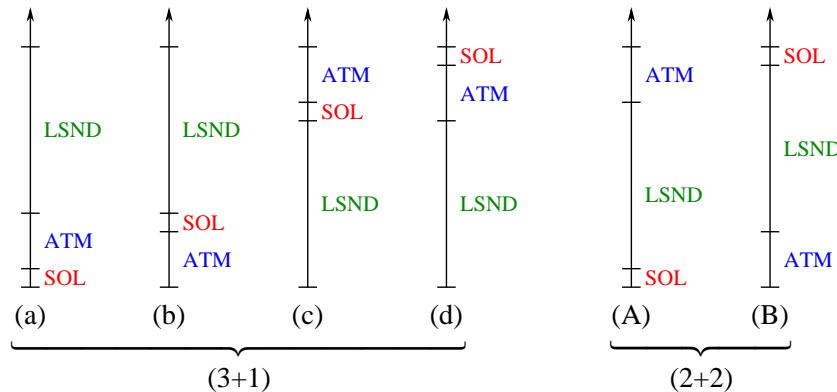


- in order to explain LSND with mass-induced neutrino oscillations one needs *at least one more* neutrino mass eigenstate.
- These new states must be **sterile** in order not to spoil the  $Z$  width measurement.

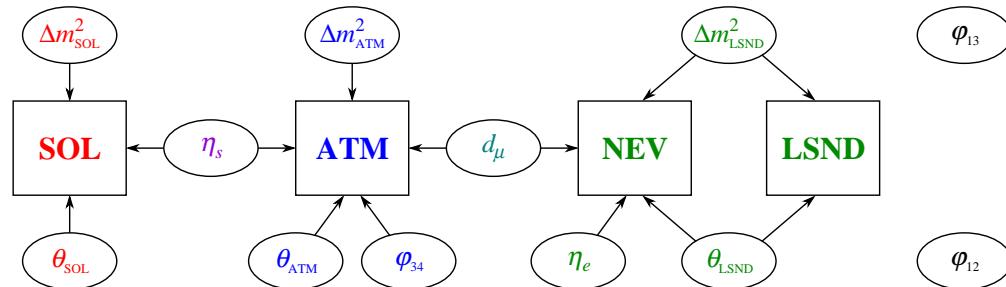
[11] M. C. Gonzalez-Garcia and M. Maltoni, Phys. Rept. **460** (2008) 1 [arXiv:0704.1800].

### Four neutrino mass models

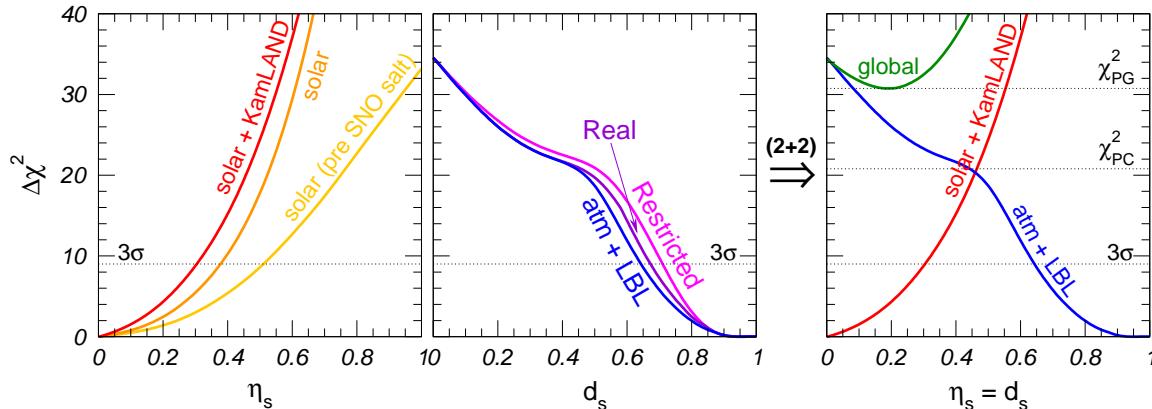
- Approximation:  $\Delta m_{\text{SOL}}^2 \ll \Delta m_{\text{ATM}}^2 \ll \Delta m_{\text{LSND}}^2 \Rightarrow$  6 different mass schemes:



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

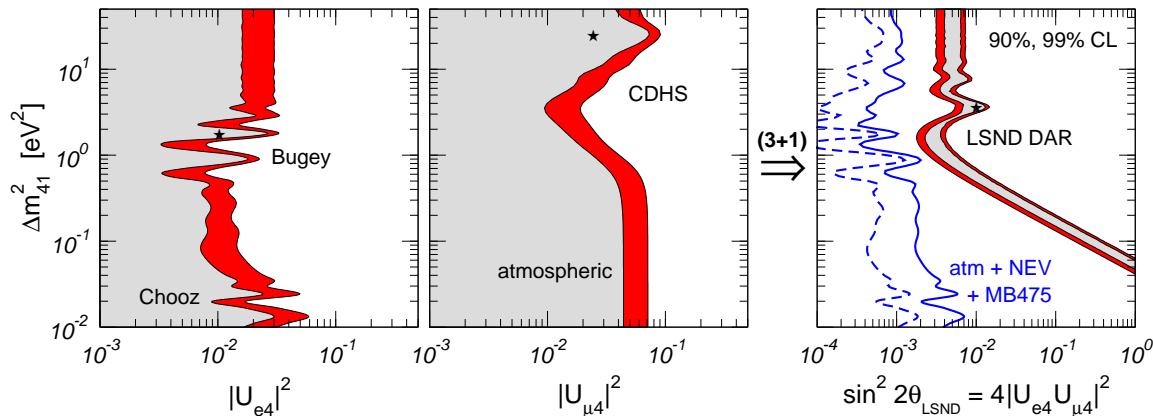


(2+2): ruled out by solar and atmospheric data



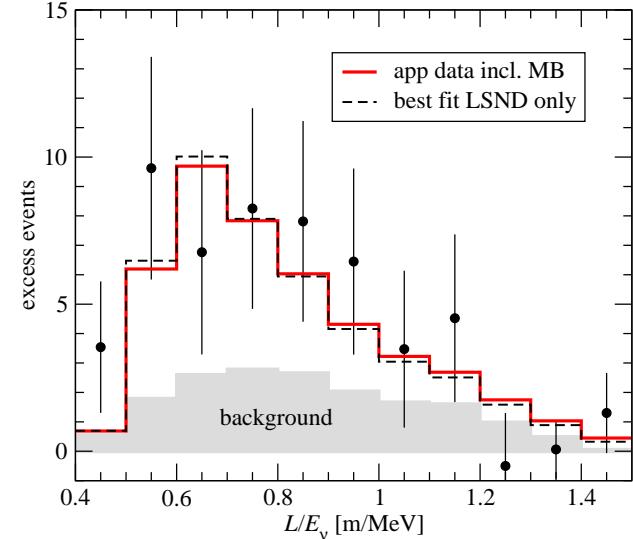
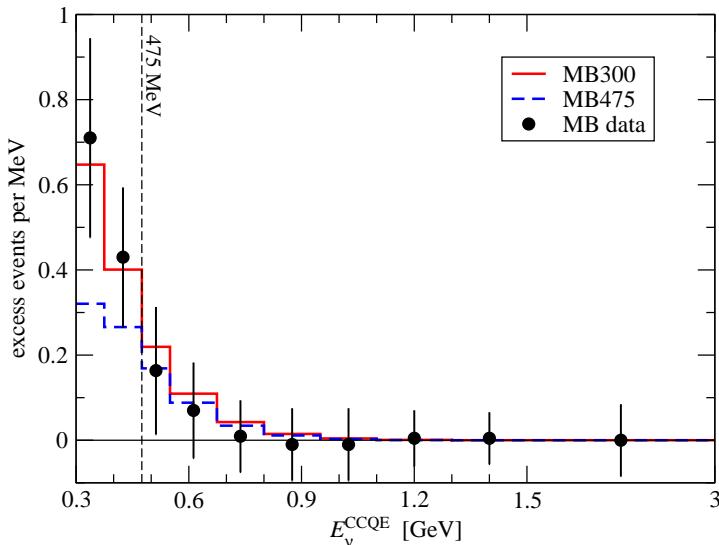
- in (2+2) models, the fractions of  $\nu_s$  in **solar** ( $\eta_s$ ) and **atmospheric** ( $1 - d_s$ ) oscillations add to one  $\Rightarrow \boxed{\eta_s = d_s}$ ;
- $3\sigma$  allowed regions  $\eta_s \leq 0.31$  (solar) and  $d_s \geq 0.64$  (atmospheric) do not overlap; superposition occurs only above  $4.6\sigma$  ( $\chi^2_{PC} = 20.8$ );
- the  $\chi^2$  increase due to the combination of **solar** and **atmospheric** data is  $\chi^2_{PG} = 30.7$  (1 dof), corresponding to a  $PG = 3 \times 10^{-8}$ .

(3+1): ruled out by short-baseline data



- In (3+1) schemes, the SBL *appearance* probability is  $P_{\mu e}^{4\nu} = 4 |U_{e4} U_{\mu 4}|^2 \sin^2 \phi_{41}$ ;
  - *disappearance* experiments put upper bounds on  $|U_{e4}|^2$  and  $|U_{\mu 4}|^2$ ;
  - LSND is in conflict:  $\left\{ \begin{array}{l} \text{with other } \textcolor{red}{\text{appearance}} \text{ experiments (Karmen, Nomad, MiniBooNE);} \\ \text{with } \textcolor{red}{\text{disappearance}} \text{ experiments;} \end{array} \right.$
  - quantitatively:  $\chi^2_{\text{PG}} = 24.8$  (4 dof)  $\Rightarrow \text{PG} = 6 \times 10^{-5}$ ;
- ⇒ Conclusion: four-neutrino models cannot explain LSND.

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

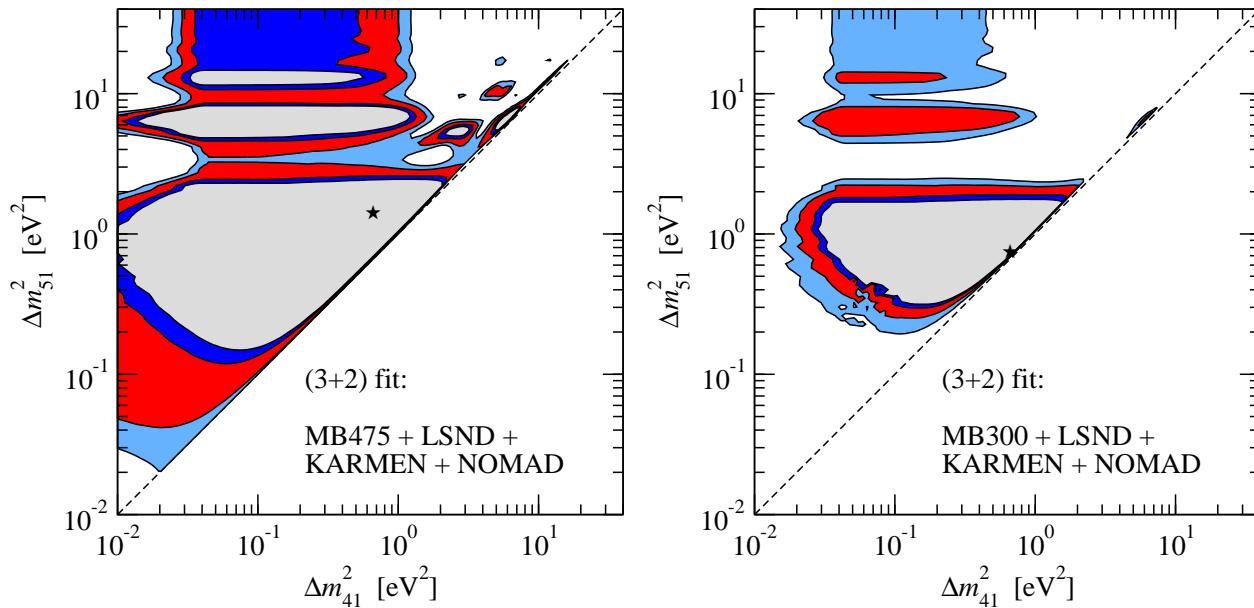


- **Trick:** use the CP phase  $\delta = \arg(U_{e4}^* U_{\mu 4} U_{e5} U_{\mu 5}^*)$  to differentiate  $v$  (MB) from  $\bar{v}$  (LSND) [30]:  

$$P_{\mu e}^{5v} = 4|U_{e4} U_{\mu 4}|^2 \sin^2 \phi_{41} + 4|U_{e5} U_{\mu 5}|^2 \sin^2 \phi_{51} + 8|U_{e4} U_{e5} U_{\mu 4} U_{\mu 5}| \sin \phi_{41} \sin \phi_{51} \cos(\phi_{54} - \delta);$$
- **Also:**  $\delta = \pi + \epsilon$  and  $|U_{e4} U_{\mu 4}| \Delta m_{41}^2 \approx |U_{e5} U_{\mu 5}| \Delta m_{51}^2$  suppress MB probability.

[30] M. Maltoni and 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 (MB475)	0.044	0.66	0.022	1.44	$1.12\pi$	$16.9/(29 - 5)$	85%
appearance (MB300)	0.31	0.66	0.27	0.76	$1.01\pi$	$18.5/(31 - 5)$	85%

### 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:

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

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

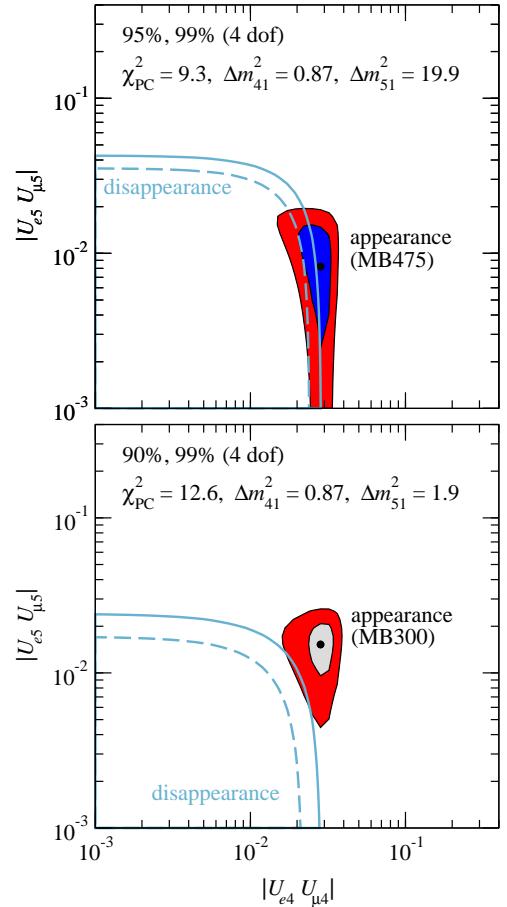
$$\chi^2_{\text{PG}} = 25.1 \text{ (4 dof)} \Rightarrow \text{PG} = 4.8 \times 10^{-5} \text{ [MB300];}$$

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

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

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

⇒ Conclusion: (3+2) models fail exactly as (3+1) do.



### Adding a third sterile neutrino: (3+3) models

- Improvements:

–  $(3+1) \rightarrow (3+2)$  [MB475]:

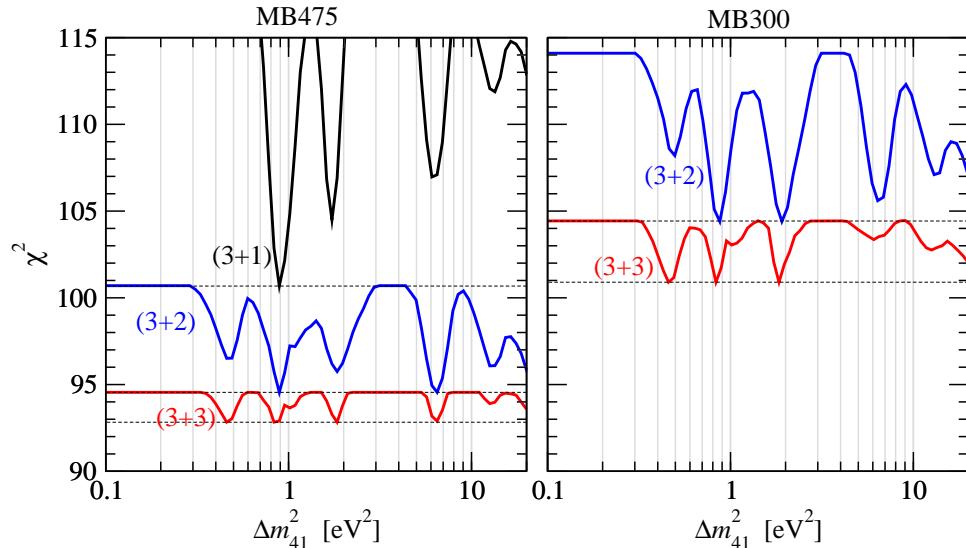
$$\Delta\chi^2 = 6.1/4 \text{ dof (81% CL)}$$

–  $(3+2) \rightarrow (3+3)$  [MB475]:

$$\Delta\chi^2 = 1.7/4 \text{ dof (21% CL)}$$

–  $(3+2) \rightarrow (3+3)$  [MB300]:

$$\Delta\chi^2 = 3.5/4 \text{ dof (52% CL)}$$



- (3+3) models do not offer qualitatively new effects with respect to (3+2) models; in particular, the improvement in  $\chi^2$  is very modest [30].

⇒ In brief: it is not possible to explain LSND with sterile neutrinos.

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

### Sterile neutrinos: what next?

- Once LSND is dropped, there is no reason to make any assumption on the mass of the sterile states. However, this general case has been considered only in a very few works [31, 32, 33];
- most of the works performed so far still assume **heavy** sterile neutrinos, in the context of Opera [34], of future  $\nu$  factories [35, 36, 37, 38], and of neutrino telescopes [39, 40].

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- [31] P. C. de Holanda and A. Y. Smirnov, Phys. Rev. **D69** (2004) 113002 [hep-ph/0307266].
  - [32] V. Barger, S. Geer, and K. Whisnant, New J. Phys. **6** (2004) 135 [hep-ph/0407140].
  - [33] M. Cirelli, G. Marandella, A. Strumia, and F. Vissani, Nucl. Phys. **B708** (2005) 215–267 [hep-ph/0403158].
  - [34] A. Donini, M. Maltoni, D. Meloni, P. Migliozzi, and F. Terranova, JHEP **12** (2007) 013 [arXiv:0704.0388].
  - [35] V. D. Barger, S. Geer, R. Raja, and K. Whisnant, Phys. Rev. **D63** (2001) 033002 [hep-ph/0007181].
  - [36] A. Donini, M. B. Gavela, P. Hernandez, and S. Rigolin, hep-ph/0007283.
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  - [38] A. Dighe and S. Ray, Phys. Rev. **D76** (2007) 113001 [arXiv:0709.0383].
  - [39] R. L. Awasthi and S. Choubey, Phys. Rev. **D76** (2007) 113002 [arXiv:0706.0399].
  - [40] S. Choubey, JHEP **12** (2007) 014 [arXiv:0709.1937].

## Neutrino decay

- Two phenomenologically situations:

- (1)  $\nu_i \rightarrow \bar{\nu}_j + X$ : the decay products include one (or more) detectable neutrinos. A **theoretical model** is needed to fix the **energy distribution** of the daughter neutrino(s);
- (2)  $\nu_i \rightarrow X$ : the decay products are completely invisible. The process is completely described by the **neutrino lifetime**  $\tau_i$ .

- We will discuss mainly Case (2).
- Neglecting possible interference effects [41] between oscillations and decay:

$$i\frac{d\vec{\nu}}{dt} = H_0 \vec{\nu}; \quad H_0 = U \cdot \left[ H_0^d - i\Gamma_0^d \right] \cdot U^\dagger; \quad U \text{ as usual};$$

$$H_0^d = \frac{1}{2E_\nu} \text{diag} \left( 0, \Delta m_{21}^2, \Delta m_{31}^2 \right); \quad \Gamma_0^d = \frac{1}{2E_\nu} \text{diag} \left( \frac{m_1}{\tau_1}, \frac{m_2}{\tau_2}, \frac{m_3}{\tau_3} \right);$$

- analyses performed so far are restricted to 2ν scenarios.

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[41] M. Lindner, T. Ohlsson, and W. Winter, Nucl. Phys. **B607** (2001) 326 [[hep-ph/0103170](https://arxiv.org/abs/hep-ph/0103170)].

## Neutrino decoherence

- **Origin:** finite-size neutrino wave-packet, averaging due to finite detector resolution, neutrino interactions with space-time “foam”, ...
- **Approach:** use density-matrix formalism:  $\frac{d\rho}{dt} = -i[H, \rho] - \mathcal{D}[\rho]$ ;
- most conservative assumptions on  $\mathcal{D}[\rho]$ :
  - complete positivity  $\Rightarrow$  Lindblad form:  $\mathcal{D}[\rho] = \sum_{\ell} \{\rho, D_{\ell} D_{\ell}^{\dagger}\} - 2D_{\ell}\rho D_{\ell}^{\dagger}$ ;
  - unitarity & increase of Von Neumann entropy  $[-\text{Tr}(\rho \ln \rho)] \Rightarrow D_{\ell} = D_{\ell}^{\dagger}$ ;
  - conservation of energy in vacuum  $\Rightarrow [H_0, D_{\ell}] = 0$ ;

lead to  $\mathcal{D}[\rho] = \sum_{\ell} [D_{\ell}, [D_{\ell}, \rho]]$ , with  $D_{\ell} = \text{diag}(d_{\ell 1}, \dots, d_{\ell n})$  in the vacuum mass basis;

- in this case the evolution equation (in vacuum) can be solved analytically. For  $n$  neutrinos there are  $n(n-1)/2$  new parameters,  $\gamma_{ji} = \sum_{\ell} (d_{\ell j} - d_{\ell i})^2$ , in addition to the usual ones;
- note that  $\gamma_{ji}$  can depend on the neutrino energy:  $\gamma_{ji} = \gamma_{ji}(E_{\nu})$ .

### Decay of solar neutrinos

- Since Sun-Earth distance  $\gg$  solar radius,  $\nu$  decay inside the Sun can be neglected;
- $\nu_1$  is usually assumed to be stable. Also, present bounds on  $\theta_{13}$  show that  $\nu_3$  mixes very little with  $\nu_e$ . Hence solar data imply limits on  $\nu_2$  lifetime;
- $\nu$  decay produces **(A)** model-independent  $\nu_2$  disappearance, and **(B)** model-dependent  $\bar{\nu}_1$  appearance. The mean  $\bar{\nu}_1$  energy is higher for quasi-degenerate masses [42];
- limits on  $\nu_2$  disappearance have been studied in [43, 44]. The strongest limit is  $\tau_2/m_2 > 8.7 \times 10^{-5}$  s/eV (99% CL) [44]. This bound may not hold for quasi-degenerate masses [42];
- limits on solar  $\bar{\nu}_e$  appearance have been set by KamLAND [45] and by SNO [46], giving  $\tau_2/m_2 > 0.067$  (0.0011) s/eV for quasi-degenerate (hierarchical) masses [45].

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[42] J. F. Beacom and N. F. Bell, Phys. Rev. **D65** (2002) 113009 [[hep-ph/0204111](#)].

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[44] A. Bandyopadhyay, S. Choubey, and S. Goswami, Phys. Lett. **B555** (2003) 33–42 [[hep-ph/0204173](#)].

[45] KamLAND Collaboration, K. Eguchi *et al.*, Phys. Rev. Lett. **92** (2004) 071301 [[hep-ex/0310047](#)].

[46] SNO Collaboration, B. Aharmim *et al.*, Phys. Rev. **D70** (2004) 093014 [[hep-ex/0407029](#)].

## Decoherence in solar and reactor neutrinos

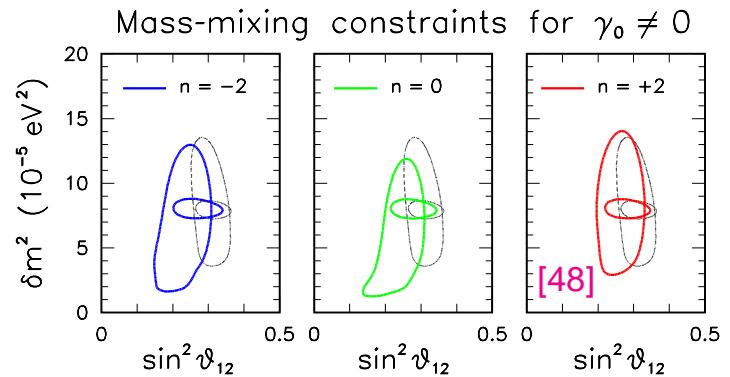
- In the  $2\nu$  limit, the explicit formula for the survival probability in vacuum is:

$$P_{\text{surv}} = 1 - \frac{1}{2} \sin^2(2\theta) \left[ 1 - e^{-\gamma L} \cos \left( \frac{\Delta m^2 L}{2E_\nu} \right) \right]. \quad \text{We assume } \gamma(E_\nu) = \kappa_n \left( \frac{E_\nu}{\text{GeV}} \right)^n;$$

- this formula properly describes decoherence effects in KamLAND [47]. In contrast, for solar neutrinos matter effects cannot be neglected [48];
- combined solar+KamLAND analysis [48]:

95% CL: 
$$\begin{cases} \kappa_{-2}^{\text{sol}} < 8.1 \times 10^{-29} \text{ GeV}, \\ \kappa_{-1}^{\text{sol}} < 7.8 \times 10^{-27} \text{ GeV}, \\ \kappa_0^{\text{sol}} < 6.7 \times 10^{-25} \text{ GeV}, \\ \kappa_{+1}^{\text{sol}} < 5.8 \times 10^{-23} \text{ GeV}, \\ \kappa_{+2}^{\text{sol}} < 4.7 \times 10^{-21} \text{ GeV}; \end{cases}$$

- determination of solar parameters is reasonably stable.

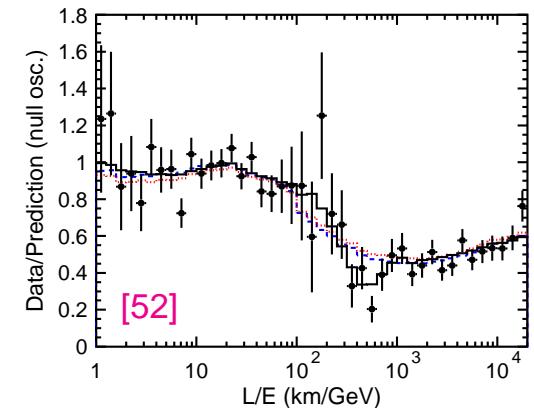


[47] T. Schwetz, Phys. Lett. **B577** (2003) 120–128 [[hep-ph/0308003](#)].

[48] G. L. Fogli *et al.*, Phys. Rev. **D76** (2007) 033006 [[arXiv:0704.2568](#)].

## Pure decay and decoherence in atmospheric neutrinos

- Focus on effective  $2\nu$  oscillations in the  $\mu - \tau$  sector;
- a  $2\nu$  pure decoherence solution ( $\kappa_{-1}^{\text{atm}} = 1.2 \times 10^{-21}$  GeV) to the ATM problem was first proposed in [49], and later found to be disfavored – although not excluded [50];
- similarly, a pure  $\nu_3$  decay solution to the ATM problem was proposed in [51] (note that from solar data  $\nu_1$  and  $\nu_2$  are stable for atmospheric  $L/E$ );
- a more recent analysis of SK-I data ruled out both possibilities at more than  $3\sigma$  [52];
- hence we will focus on combined osc+decay and osc+decoherence analysis.



[49] E. Lisi, A. Marrone, and D. Montanino, Phys. Rev. Lett. **85** (2000) 1166–1169 [[hep-ph/0002053](#)].

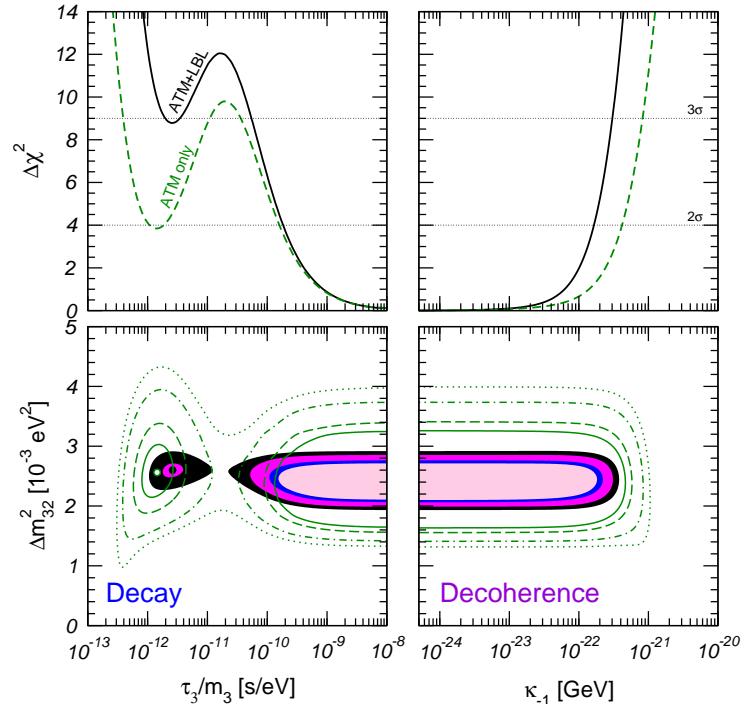
[50] G. L. Fogli *et al.*, Phys. Rev. **D67** (2003) 093006 [[hep-ph/0303064](#)].

[51] V. D. Barger *et al.*, Phys. Lett. **B462** (1999) 109–114 [[hep-ph/9907421](#)].

[52] Super-Kamiokande Collaboration, Y. Ashie *et al.*, Phys. Rev. Lett. **93** (2004) 101801 [[hep-ex/0404034](#)].

#### Present bounds on decay and decoherence from ATM+LBL data

- First osc+decoh analysis reported in [49];
- pure decay and pure decoherence fits now excluded, in agreement with SK;
- an alternative oscill+decay solution with  $\tau_3/m_3 \simeq 2.6 \times 10^{-12}$  s/eV gives a good fit to ATM data, but is ruled out by LBL [53];
- 90% CL:  $\tau_3/m_3 > 2.9 \times 10^{-10}$  s/eV;
- 90% CL:  $\left\{ \begin{array}{l} \kappa_{-2}^{\text{atm}} < 1.9 \times 10^{-22} \text{ GeV}, \\ \kappa_{-1}^{\text{atm}} < 1.2 \times 10^{-22} \text{ GeV}, \\ \kappa_0^{\text{atm}} < 2.7 \times 10^{-24} \text{ GeV}, \\ \kappa_{+1}^{\text{atm}} < 3.8 \times 10^{-27} \text{ GeV}, \\ \kappa_{+2}^{\text{atm}} < 2.4 \times 10^{-30} \text{ GeV}; \end{array} \right.$
- determination of osc. parameters stable.



[49] E. Lisi, A. Marrone, and D. Montanino, Phys. Rev. Lett. **85** (2000) 1166–1169 [hep-ph/0002053].

[53] M. C. Gonzalez-Garcia and M. Maltoni, Phys. Lett. **B** (in press) [arXiv:0802.3699].

## Explaining LSND with decoherence

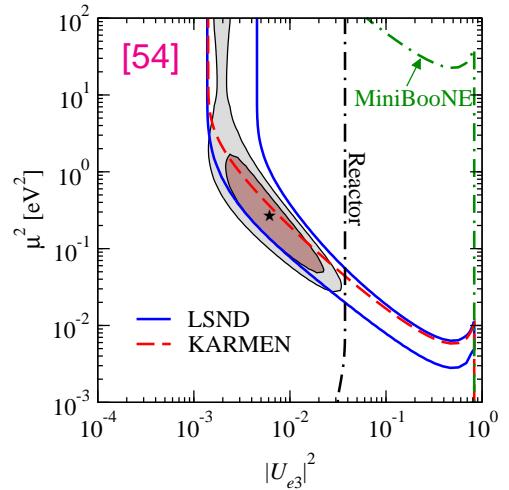
- Recent suggestion [54]: 3ν oscillations + decoherence, with  $\gamma_{21} = 0$ ,  $\gamma_{31} = \gamma_{32} = \gamma$  and  $\gamma(E) = \kappa_{-4}(E_\nu/\text{GeV})^{-4}$ ;
- only 1 new parameter. Probabilities:

$$P_{\mu e}(\gamma, L) = P_{e \mu}(\gamma, L) = 2|U_{\mu 3}|^2 |U_{e 3}|^2 [1 - e^{-\gamma L} \cos(\Delta_{31}L)] ,$$

$$P_{ee}(\gamma, L) = 1 - 2|U_{e 3}|^2 (1 - |U_{e 3}|^2) [1 - e^{-\gamma L} \cos(\Delta_{31}L)] ,$$

$$P_{\mu \mu}(\gamma, L) = 1 - 2|U_{\mu 3}|^2 (1 - |U_{\mu 3}|^2) [1 - e^{-\gamma L} \cos(\Delta_{31}L)] ;$$

- Best fit:  $\kappa_{-4}^{\text{atm}} = 1.7 \times 10^{-23} \text{ GeV}$ ;
- Explicit prediction:  $\sin^2 \theta_{13} > (2.6 \pm 0.8) \times 10^{-3}$ ;
- Other possibilities: decay + sterile neutrinos [55], decoherence + CPT-violation [56], decoherence with unusual  $L$  dependence [57], ...



[54] Y. Farzan, T. Schwetz, and A. Y. Smirnov, arXiv:0805.2098.

[55] S. Palomares-Ruiz, S. Pascoli, and T. Schwetz, JHEP **09** (2005) 048 [hep-ph/0505216].

[56] G. Barenboim and N. E. Mavromatos, JHEP **01** (2005) 034 [hep-ph/0404014].

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## Decay and decoherence at future facilities

- Damping effects at future reactors and  $\nu$ -factories have been discussed in [58]. Results:
  - **decay** scenarios can easily be recognized at a  $\nu$  factory;
  - **decoherence** effects can fake the determination of  $\theta_{13}$  by reactor experiments;
  - the sensitivity of a  $\nu$  factory to **decoherence** depends on the shape of  $\gamma(E_\nu)$ ;
- the sensitivity to **decoherence** of near-future accelerator experiments CNGS and T2K is discussed in [59]. It is shown that the bounds on  $\kappa_n^{\text{atm}}$  which can be put by these experiments are comparable to those derived with atmospheric neutrinos;
- similar results hold for T2KK configuration [27], which in the context of **decoherence** models it is shown to be systematically better than the separate Kamioka-only and Korea-only configurations.

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[27] N. C. Ribeiro *et al.*, Phys. Rev. **D77** (2008) 073007 [[arXiv:0712.4314](https://arxiv.org/abs/0712.4314)].

[58] M. Blennow, T. Ohlsson, and W. Winter, JHEP **06** (2005) 049 [[hep-ph/0502147](https://arxiv.org/abs/hep-ph/0502147)].

[59] N. E. Mavromatos *et al.*, Phys. Rev. **D77** (2008) 053014 [[arXiv:0801.0872](https://arxiv.org/abs/0801.0872)].

## Decay and decoherence at neutrino telescopes

- The impact of  $\nu$  decay on high-energy neutrinos has been discussed in a number of papers (see, e.g., [60, 61, 62, 63] and references therein). In particular:
  - due to the extremely long distance traveled by astrophysical neutrinos, the sensitivity to decay effects is many orders of magnitude larger than “terrestrial” experiments;
  - neutrino decay can break the  $1 : 1 : 1$  flavor ratio expected from a  $\pi$ -decay source, hence opening the possibility to measure oscillation parameters at  $\nu$  telescopes;
- Under our restrictive assumptions, decoherence is indistinguishable from averaged oscillations. However, more general scenarios may exhibit unique signatures [64, 65].

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[60] J. F. Beacom *et al.*, Phys. Rev. Lett. **90** (2003) 181301 [[hep-ph/0211305](#)].

[61] J. F. Beacom *et al.*, Phys. Rev. **D69** (2004) 017303 [[hep-ph/0309267](#)].

[62] D. Meloni and T. Ohlsson, Phys. Rev. **D75** (2007) 125017 [[hep-ph/0612279](#)].

[63] M. Maltoni and W. Winter, [arXiv:0803.2050](#).

[64] D. Hooper, D. Morgan, and E. Winstanley, Phys. Lett. **B609** (2005) 206–211 [[hep-ph/0410094](#)].

[65] L. A. Anchordoqui *et al.*, Phys. Rev. **D72** (2005) 065019 [[hep-ph/0506168](#)].

## Non-standard interactions with matter

- present bounds on NSI parameters are affected by strong degeneracies;
- these degeneracies may spoil the sensitivity to  $\theta_{13}$  of future LBL experiments;
- for  $\nu$  factories, the problem can be solved by combining data from two different baselines.

## Models with extra sterile neutrinos

- four-neutrino models fail to reconcile LSND with MiniBooNE;
- five-neutrino models avoid this problem, but severe tension with disapp. data spoil the fit;
- six-neutrino models does not add any qualitatively new feature to the 5v case.

## Neutrino decay and decoherence

- We have reviewed the present limits on neutrino decay and decoherence parameters;
- future reactor and accelerator facilities can further constraint these parameters;
- presence of  $\nu$  decay can enhance the sensitivity of  $\nu$  telescopes to oscillation parameters.

**Thank you for your attention!**