Global Fits to Neutrino Properties

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OUTLINE

1. "Standard" three-neutrino oscillations [PRD 63 (2001) 033005]

– *The solar neutrino problem* [PRD 67 (2003) 013011]

– *The atmospheric neutrino problem* [EPJC 26 (2003) 417]

– *Reactor and Accelerator experiments* [PRD 67 (2003) 093003]

– *Global analysis in a three-neutrino scenario* [in preparation]

2. What about LSND? [PRD 64 (2001) 093001], [PLB 518 (2001) 252]

– *Four-neutrino models* [PRD 65 (2003) 093004]

– *Problems of (2+2) and (3+1) models* [NPB 643 (2002) 321]

– *CPT and other alternative solutions* [in preparation]

3. Bounding New Physics with neutrino data

– *Non-standard neutrino-matter interactions* [PRD 65 (2002) 013010]

– *Matter density fluctuations in the Sun* [APJ 588 (2003) L55]

Two-neutrino oscillations: SOLAR data

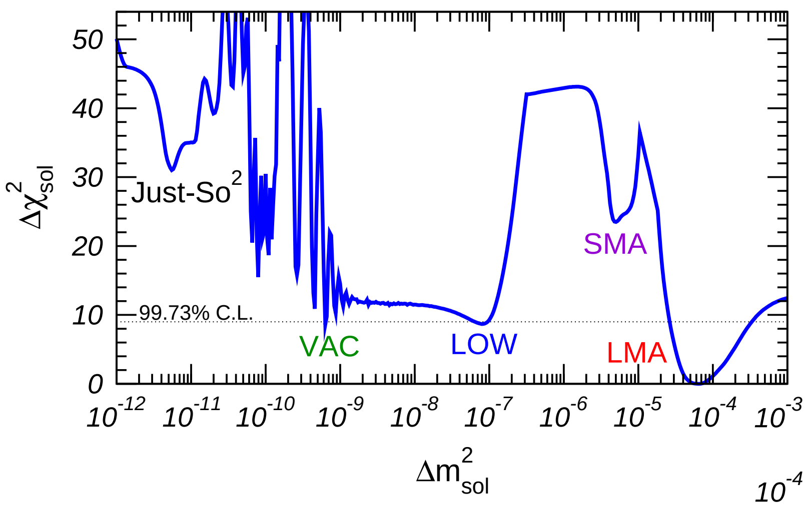
- Equation of motion: **2** parameters:

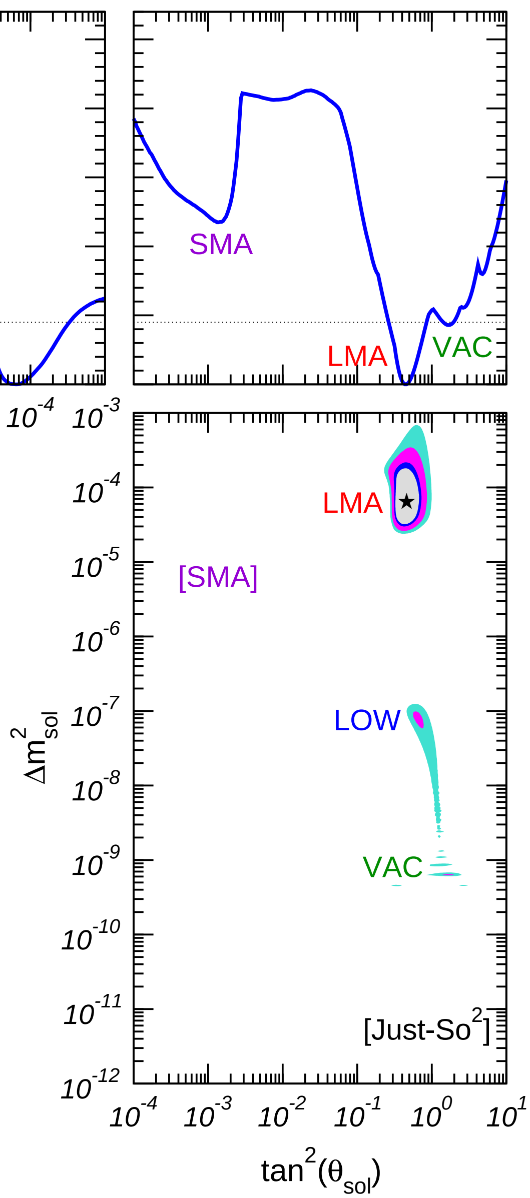
$$i\frac{d\vec{\nu}}{dt} = \mathbf{H}\vec{\nu}; \qquad \mathbf{H} = \mathbf{O}\cdot\mathbf{H}_0^d\cdot\mathbf{O}^\dagger + \mathbf{V};$$

$$\mathbf{H}_0^d = \frac{1}{2E_\nu}\mathbf{diag}\left(0, \Delta m^2\right), \qquad \mathbf{O} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}, \qquad \vec{\nu} = \begin{pmatrix} \nu_e \\ \nu_a \end{pmatrix};$$

$$\mathbf{V} = \pm\,\mathbf{diag}\left(V_e, 0\right), \qquad V_e = \sqrt{2}\,G_F\,N_e\,;$$

- the sign $+$ $(-)$ in the expression of $\mathbf{V}$ refers to neutrinos (antineutrinos).





- exp. data: $3_{\text{rates}} + 44_{\text{SK}} + 34_{\text{SNO}} = \mathbf{81}$;
- parameters: **2** $(\Delta m^2, \theta)$;
- 3σ: $\begin{cases} \tan^2\theta_{\text{SOL}} \in [0.26,\ 0.86], \\ \Delta m^2_{\text{SOL}} \in [2.6,\ 33]\times 10^{-5}\ \text{eV}^2. \end{cases}$

Region	$\tan^2\theta_{\text{SOL}}$	Δm^2_{SOL} [eV^2]	χ^2_{SOL}	GOF
LMA	0.46	6.6×10^{-5}	65.8	86%
LOW	0.66	7.9×10^{-8}	74.4	62%
VAC	1.7	6.3×10^{-10}	74.4	63%
SMA	1.4×10^{-3}	5.0×10^{-6}	89.3	20%
Just-So^2	1.0	5.5×10^{-12}	96.8	8%

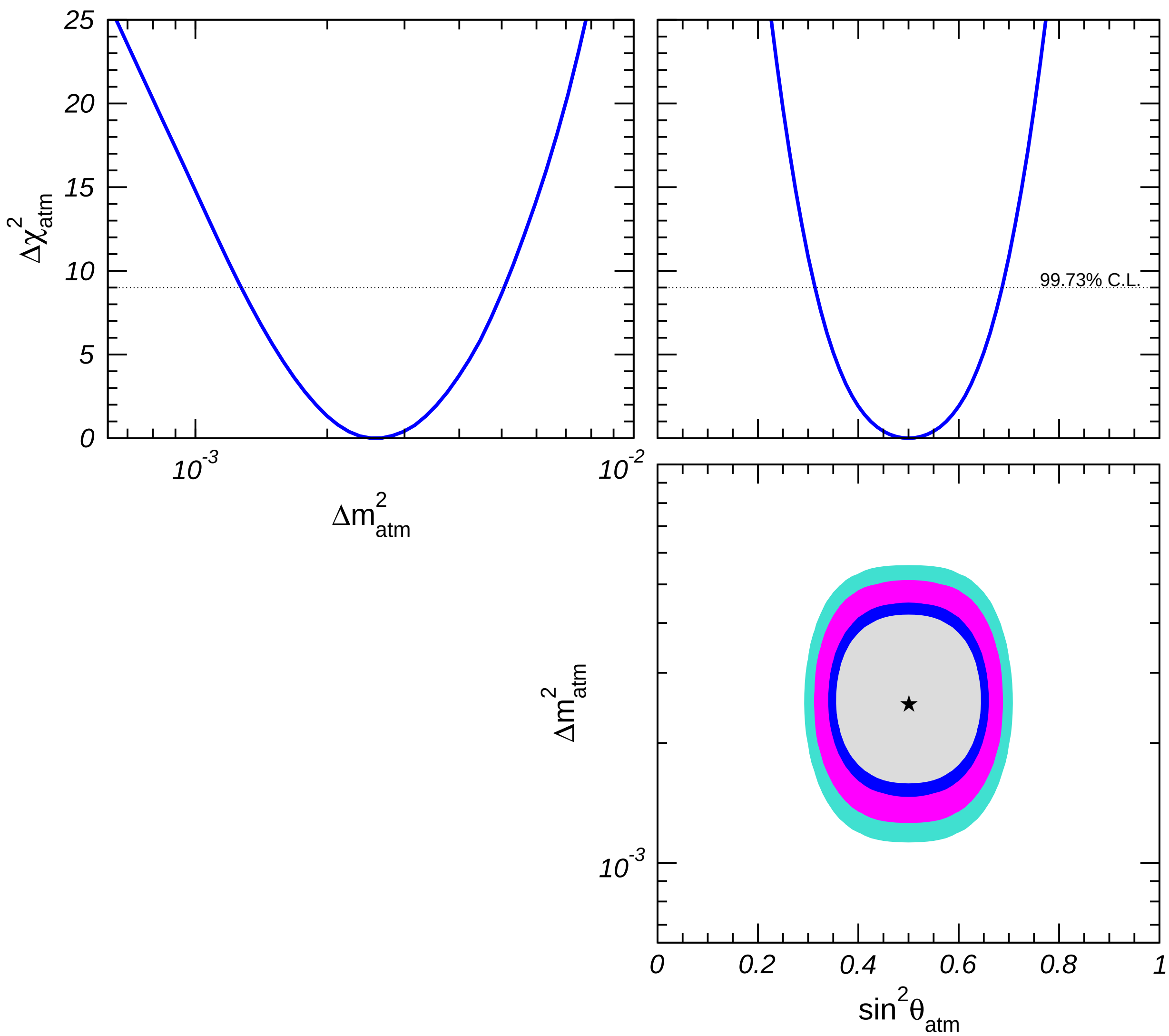
Two-neutrino oscillations: ATMOSPHERIC data

- Equation of motion: **2** parameters:

$$i\frac{d\vec{\nu}}{dt} = \mathbf{H}\vec{\nu}; \qquad \mathbf{H} = \mathbf{O}\cdot\mathbf{H}_0^d\cdot\mathbf{O}^\dagger;$$

$$\mathbf{H}_0^d = \frac{1}{2E_\nu}\mathbf{diag}\left(0, \Delta m^2\right), \qquad \mathbf{O} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}, \qquad \vec{\nu} = \begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix};$$

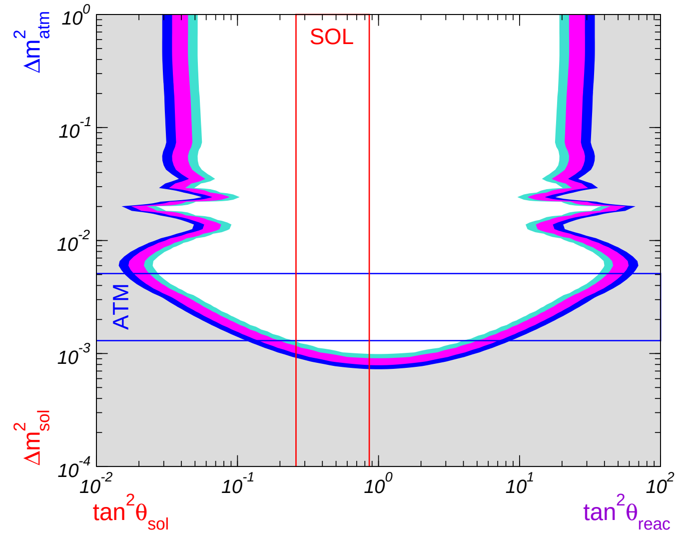
- **NO** matter effects $\Rightarrow$ pure vacuum oscillations;
- exp. data: $20_{\text{SK-Sub}} + 20_{\text{SK-Multi}} + 5_{\text{SK-stop}} + 10_{\text{SK-thru}} + 10_{\text{Macro}} = \mathbf{65}$;
- best fit: $\Delta m^2 = 2.5\times 10^{-3}$ eV^2, $\sin^2\theta = 0.50$, $\chi^2 = 40.2$;
- 3σ ranges: $\begin{cases} \sin^2\theta_{\text{ATM}} \in [0.31,\ 0.69], \\ \Delta m^2_{\text{ATM}} \in [1.3,\ 5.1]\times 10^{-3}\ \text{eV}^2. \end{cases}$



Other neutrino experiments

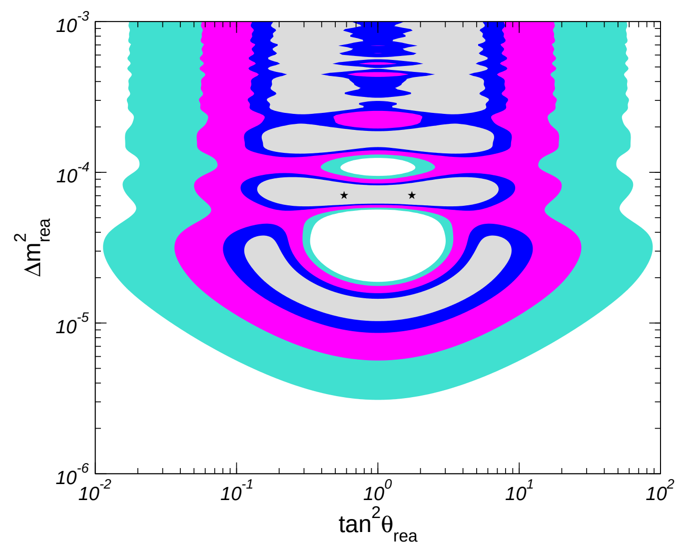
Chooz & Palo Verde (reactor)

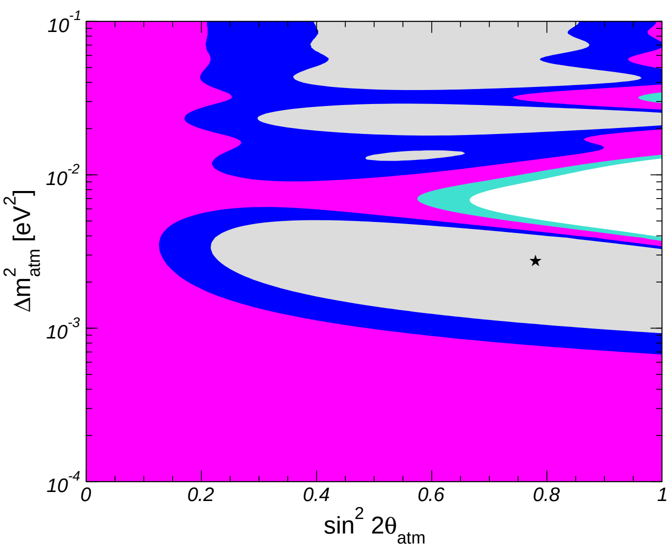
- Bound from *non-observation* of $\bar{\nu}_e$ disappearance (length: $\lesssim 1$ km);
- from solar data: $0.26 \le \tan^2\theta_{\text{SOL}} \le 0.86 \Rightarrow$ **upper** bound on Δm^2_{SOL};
- from atmospheric data: $\Delta m^2_{\text{ATM}} \gtrsim 10^{-3}$ eV^2 $\Rightarrow$ **upper** bound on θ_{REA}.



KamLAND (reactor)

- First *evidence* of $\bar{\nu}_e$ disappearance (average length: ≈ 180 km);
- consistency with solar data: *only LMA region*;
- sensitivity to θ_{REA}: weaker than Chooz.





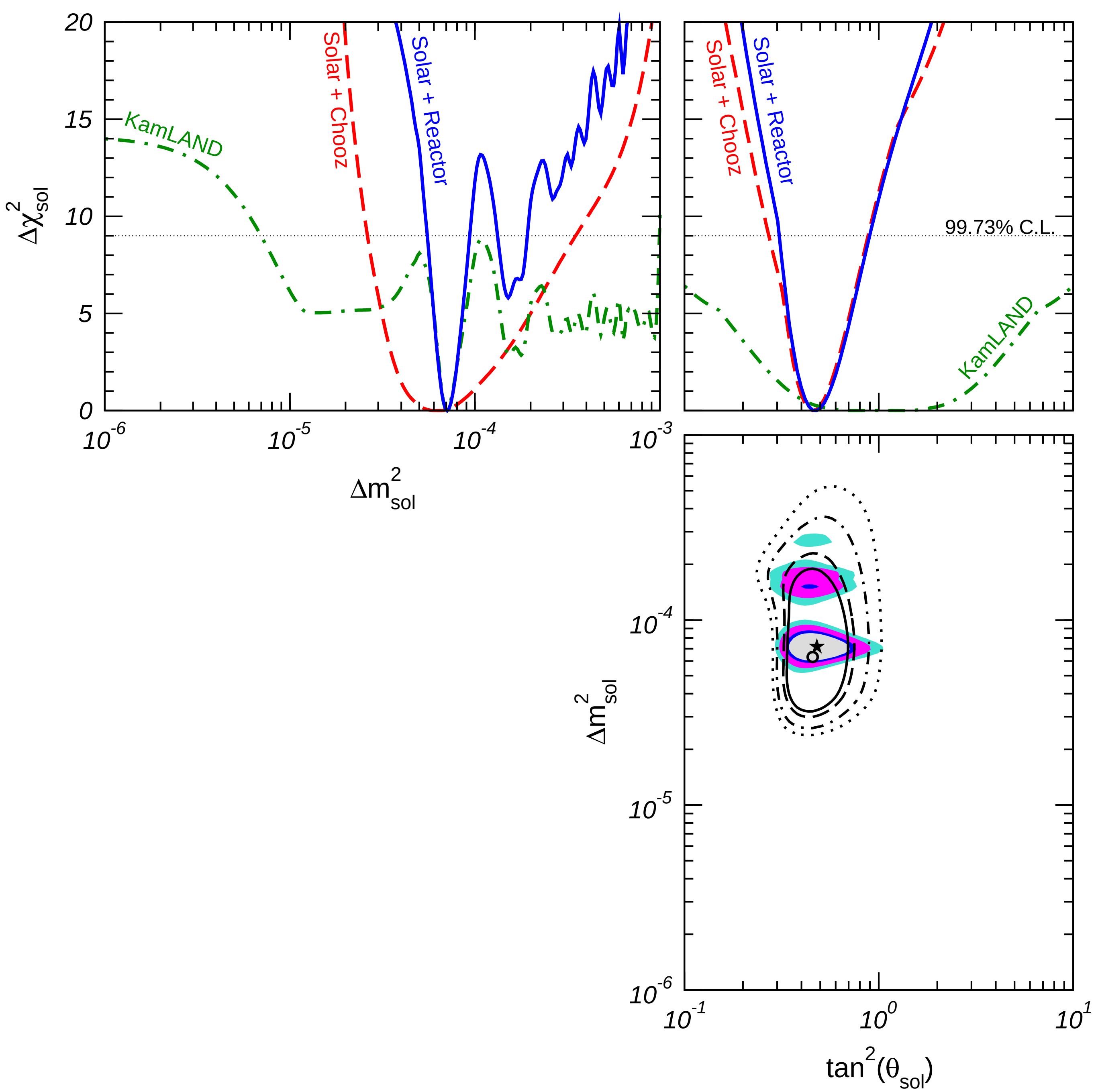
K2K (accelerator)

- *evidence* of ν_μ disappearance (length: ≈ 250 km);
- single-ring μ-like events: 44 expected, 29 observed;

$\Rightarrow$ *fully consistent* with atmospheric data if oscillations are assumed.

Combined analysis of Solar + Chooz + KamLAND data

- KamLAND selects the LMA solution to the solar neutrino problem;
- solar data break the degeneracy $\theta \to (\pi - \theta)$ of reactor experiments;
- 3σ ranges: $\begin{cases} \tan^2\theta_{\text{SOL}} \in [0.31,\ 0.90], \\ \Delta m^2_{\text{SOL}} \in [5.5,\ 9.4] \times 10^{-5}\ \text{eV}^2 \cup [1.3,\ 1.9] \times 10^{-4}\ \text{eV}^2; \end{cases}$
- bound on θ_{SOL} mostly unaffected, bound on Δm^2_{SOL} strongly improved;
- best fit point position dominated by solar data.



Combining Solar with Atmospheric data

- Solar/KamLAND data and Atmospheric data require *two different* mass-squared differences;
- a complete three-neutrino description is needed to accommodate all the experimental results;
- Equation of motion: **5** parameters (neglecting CP violating effects):

$$i\frac{d\vec{\nu}}{dt} = \mathbf{H}\vec{\nu}; \qquad \mathbf{H} = \mathbf{O}\cdot\mathbf{H}_0^d\cdot\mathbf{O}^\dagger + \mathbf{V};$$

$$\mathbf{O} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23} & c_{12}c_{23} - s_{12}s_{13}s_{23} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23} & -c_{12}s_{23} - s_{12}s_{13}c_{23} & c_{13}c_{23} \end{pmatrix}, \qquad \vec{\nu} = \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix};$$

$$\mathbf{H}_0^d = \frac{1}{2E_\nu}\mathbf{diag}\left(-\Delta m_{21}^2, 0, \Delta m_{32}^2\right);$$

$$\mathbf{V} = \mathbf{diag}\left(\pm\sqrt{2}G_F N_e, 0, 0\right);$$

– solar parameters (Δm^2_{SOL}, θ_{SOL}) are identified with (Δm^2_{21}, θ_{12});

– atmospheric parameters (Δm^2_{ATM}, θ_{ATM}) are identified with (Δm^2_{32}, θ_{23});

– the reactor parameter θ_{REA} is identified with θ_{13}.

The hierarchy approximation

- From SOL and ATM data, we have $\Delta m^2_{21} \ll \Delta m^2_{32}$;

Atmospheric analysis

- approximation: $\Delta m^2_{21} \approx 0$;
- θ_{12} cancels out from equations;

⇒ only **3** parameters: Δm^2_{32}, θ_{23}, θ_{13}.

Solar analysis

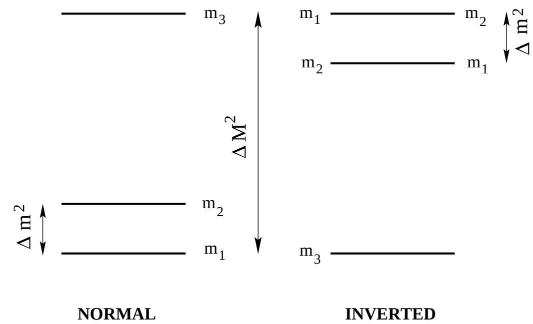
- approximation: $\Delta m^2_{32} \approx \infty$;
- θ_{23} cancels out from P_{ee};

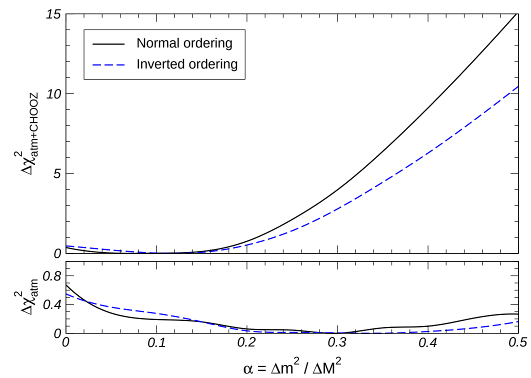
⇒ only **3** parameters: Δm^2_{21}, θ_{12}, θ_{13}.

Beyond the one-mass scale approximation

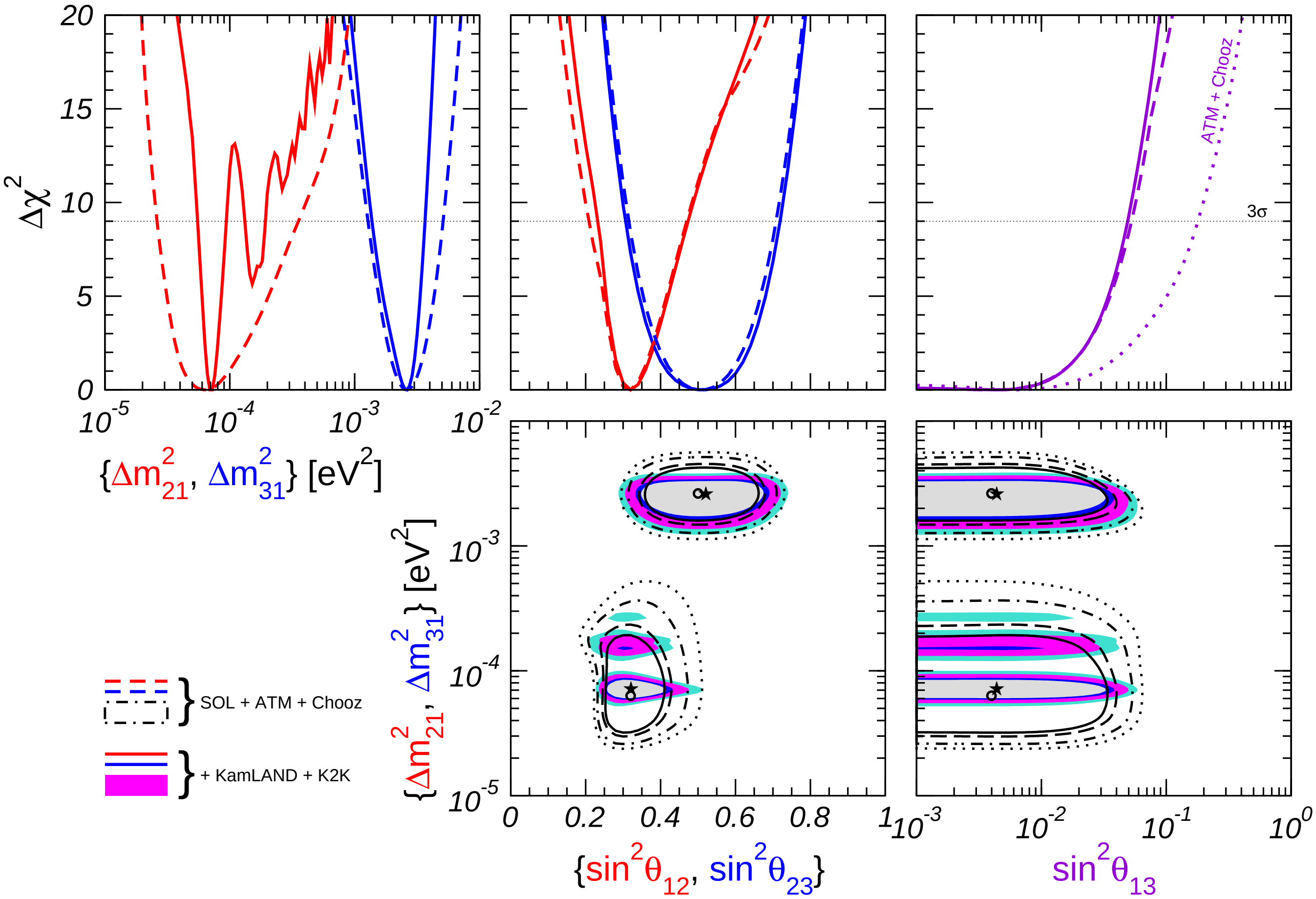
- Mass spectra: **normal** and **inverted**;
- hierarchy parameter: $\alpha = \Delta m^2 / \Delta M^2$;
- present ATM data do not allow to discriminate between normal and inverted hierarchy;
- strongest constraint on α from Chooz;
- no visible effect of finite Δm^2 values on the ATM data analysis;

$\Rightarrow$ the one-mass scale approximation is reliable.

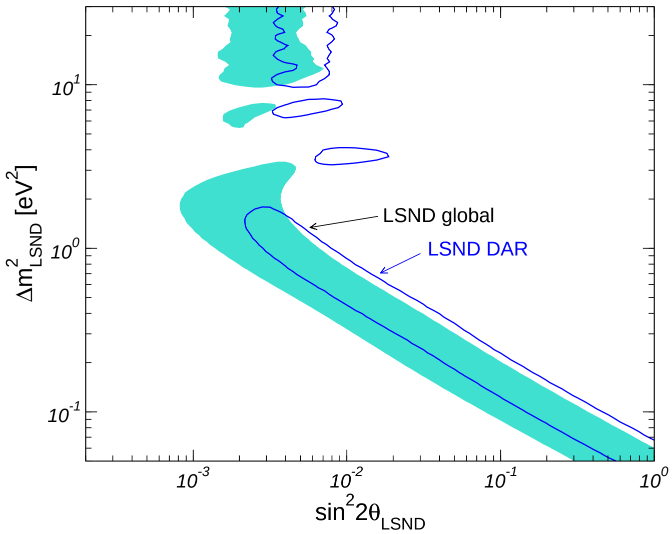




Combined analysis (SOL + ATM + Reactor + K2K)



Beyond the "standard" three-neutrino oscillations



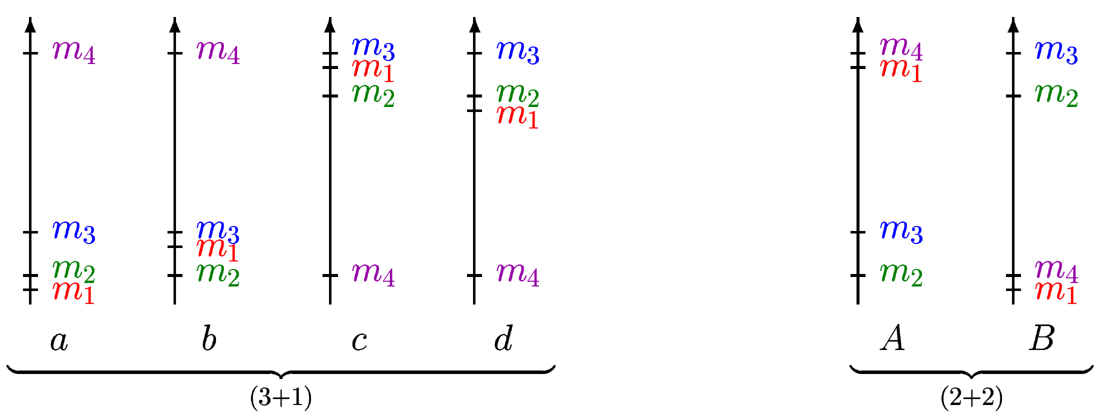
The LSND result

- *evidence* of $\bar{\nu}_\mu \to \bar{\nu}_e$ conversion (length: $\lesssim 100$ m);
- neutrino oscillation interpretation: requires $\Delta m^2 \gtrsim 0.1$ eV^2;

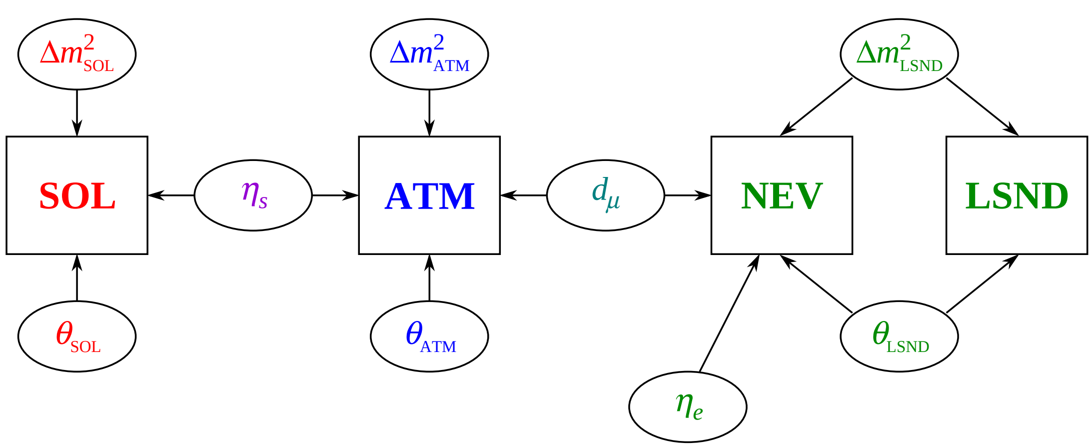
$\Rightarrow$ *incompatible* with solar and atmospheric data in a 3ν scenario.

The simplest solution: adding a neutrino

- the new neutrino must be *sterile* (from LEP measure of Z width);
- Approximation: $\Delta m^2_{SOL} \ll \Delta m^2_{ATM} \ll \Delta m^2_{LSND} \Rightarrow$ 6 different mass schemes:



- different set of experimental data *partially decouple*:



Bounds on sterile neutrino

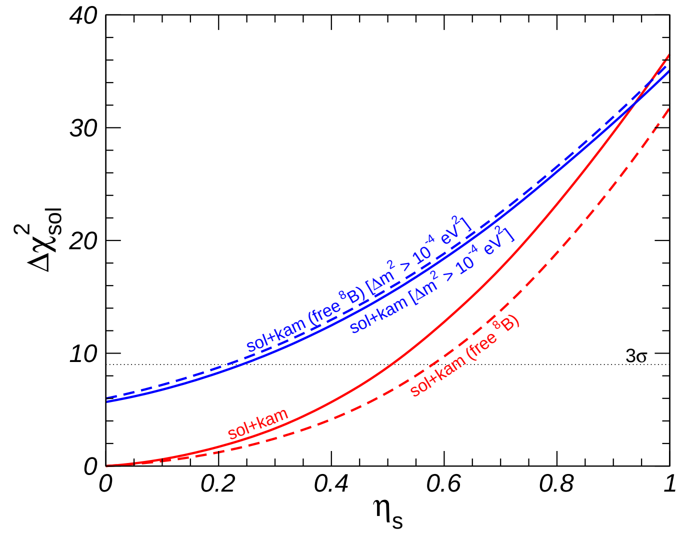
Solar analysis

- fraction of ν_s in solar oscillations: $\eta_s \equiv |U_{s1}|^2 + |U_{s\odot}|^2$;
- **3** parameters: Δm^2_{SOL}, θ_{SOL}, η_s.

⇒ Preferred value: $\eta_s = 0$;

⇒ 3σ: $\begin{cases} \eta_s \leq 0.51 \text{ (boron-fixed)}, \\ \eta_s \leq 0.58 \text{ (boron-free)}; \end{cases}$

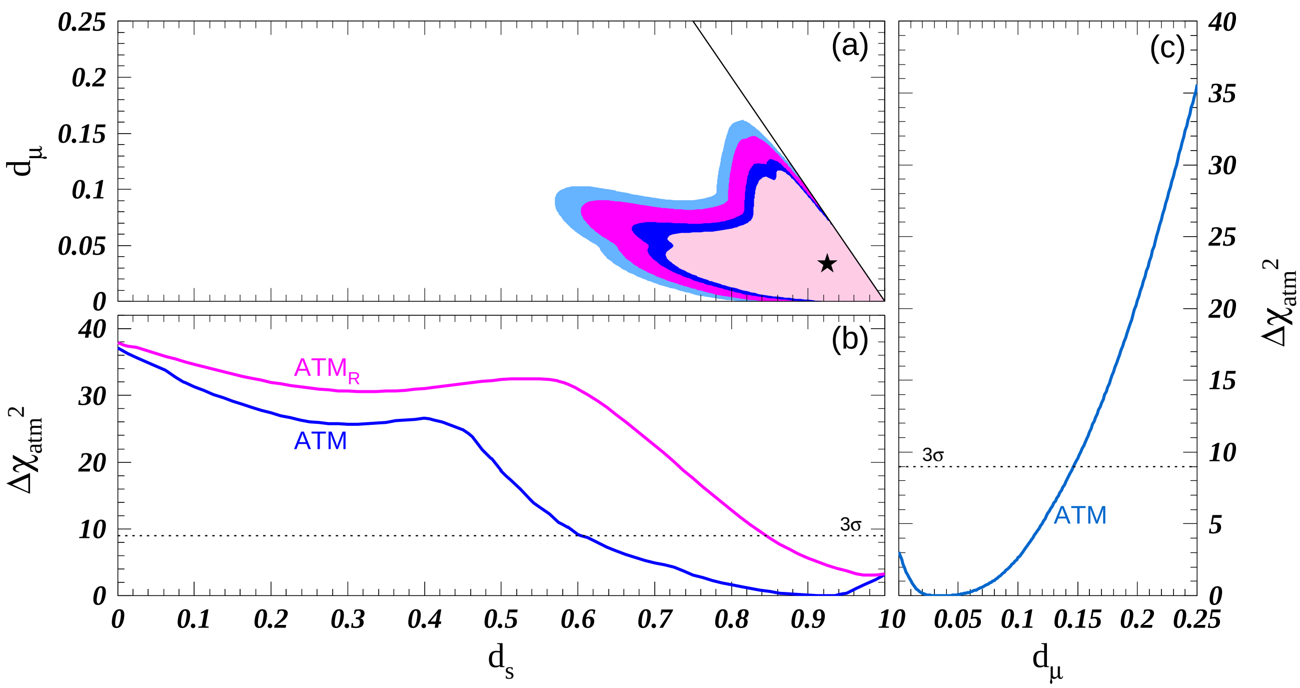
- determination of best-fit Δm^2_{SOL} and θ_{SOL} is unaffected.



Atmospheric analysis

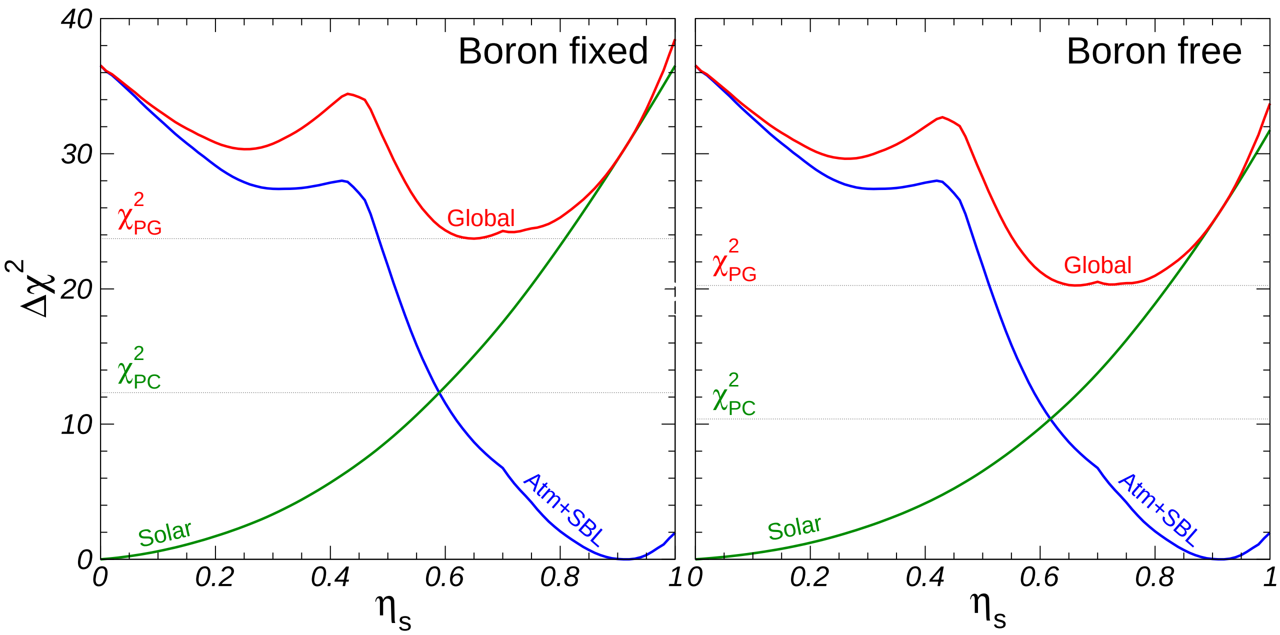
- Fraction of ν_μ in atmospheric oscillations: $1 - d_\mu \equiv |U_{\mu 2}|^2 + |U_{\mu 3}|^2$;
- fraction of ν_s in atmospheric oscillations: $1 - d_s \equiv |U_{s2}|^2 + |U_{s3}|^2$;
- **4** parameters: Δm^2_{ATM}, θ_{ATM}, d_s, d_μ.

⇒ 3σ bounds: $d_s \geq 0.61$ and $d_\mu \leq 0.15$.



Status of four-neutrino oscillations

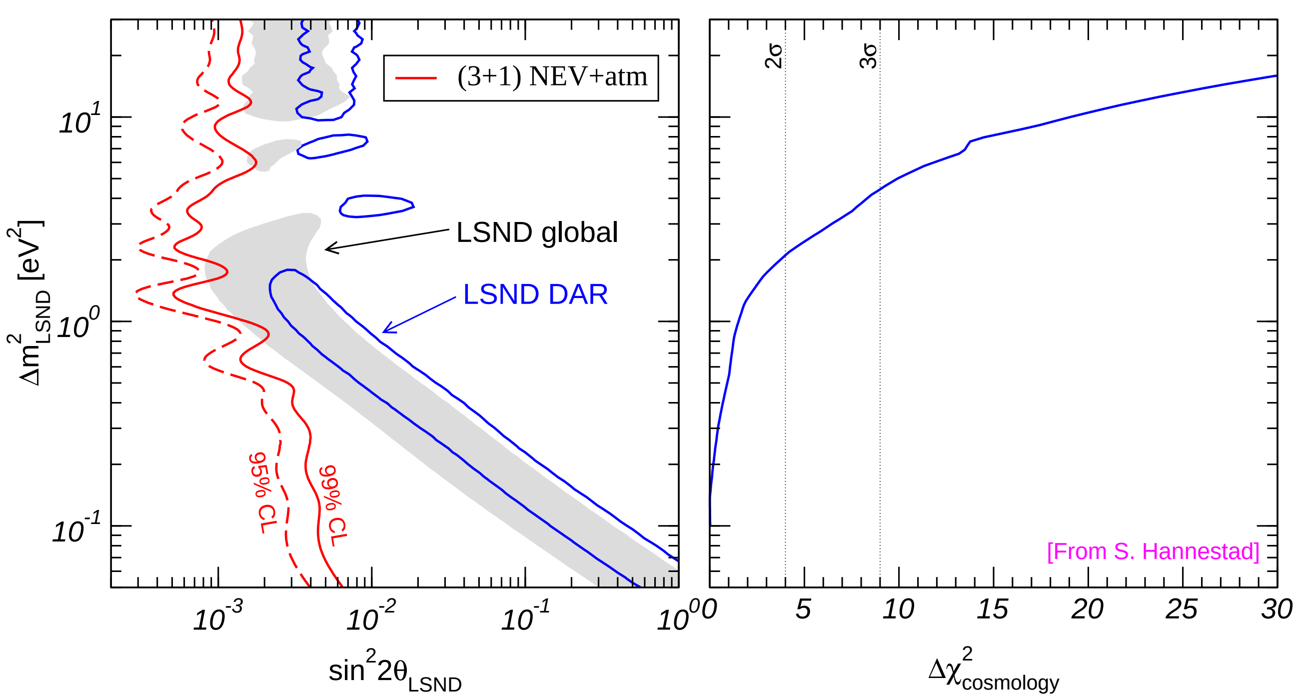
(2+2): ruled out by solar and atmospheric data



$$\begin{cases} \chi^2_{\text{PC}} = 12.3 & (3.5\sigma) \\ \chi^2_{\text{PG}} = 23.7 & (\text{PG} = 1.1 \times 10^{-6}) \end{cases} \qquad \begin{cases} \chi^2_{\text{PC}} = 10.4 & (3.2\sigma) \\ \chi^2_{\text{PG}} = 20.3 & (\text{PG} = 6.8 \times 10^{-6}) \end{cases}$$

[For a rigorous definition of PG, see hep-ph/0304176]

(3+1): strongly disfavored by SBL data



Interpretation of the LSND result

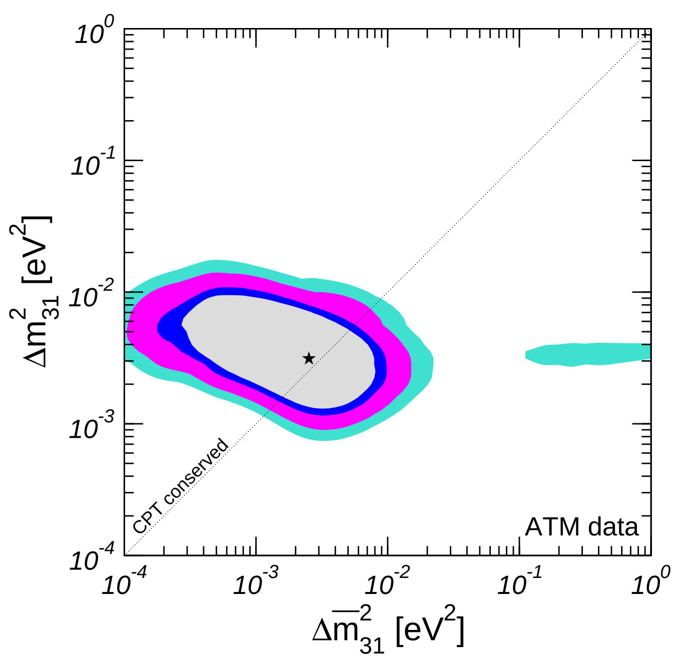
Status of the sterile neutrino solutions

- Both **solar** and **atm** data reject oscillations into a sterile neutrino;
- **(2+2)** models fail to reconcile **solar** and **atmospheric** data;
- **(3+1)** models fail to reconcile **LSND** with other **SBL** experiments;
- the oscillation hypothesis **does NOT provide** a good solution;

$\Rightarrow$ if MiniBooNE confirms LSND, then different mechanisms have to be investigated.

Possible alternatives

- It was noted [Päs, Song, Weiler, hep-ph/0209373] that some of the approximations used in the calculations of (2+2) models may be too restrictive. However, so far an extensive fit has not been performed.
- Also, in a recent paper [Sorel, Conrad, Shaevitz, hep-ph/0305255] a model with **two** sterile neutrinos was considered, and found to fit the data considerably better than (3+1) models.
- A recent analysis of SK **contained** events found that the LSND problem can be explained by assuming CPT violation [Barenboim, Borissov, Lykken, hep-ph/0212116]. However, when also **upgoing-μ** data are included the quality of the fit gets worse [Strumia, hep-ph/0201134v4; Gonzalez-Garcia, MM, Schwetz, in preparation].



Non-standard neutrino-matter interactions

Analysis of atmospheric data

- Simplifying assumption: ν_e decoupled $\Rightarrow$ 2ν oscillations ($\nu_\mu \leftrightarrow \nu_\tau$);
- Equation of motion: **4** parameters:

$$i\frac{d\vec{\nu}}{dt} = \mathbf{H}\vec{\nu}; \qquad \mathbf{H} = \mathbf{O}\cdot\mathbf{H}_0^d\cdot\mathbf{O}^\dagger + \mathbf{V}; \qquad \mathbf{V} = \pm\sqrt{2}G_F N_f(r)\begin{pmatrix} 0 & \varepsilon \\ \varepsilon & \varepsilon' \end{pmatrix};$$

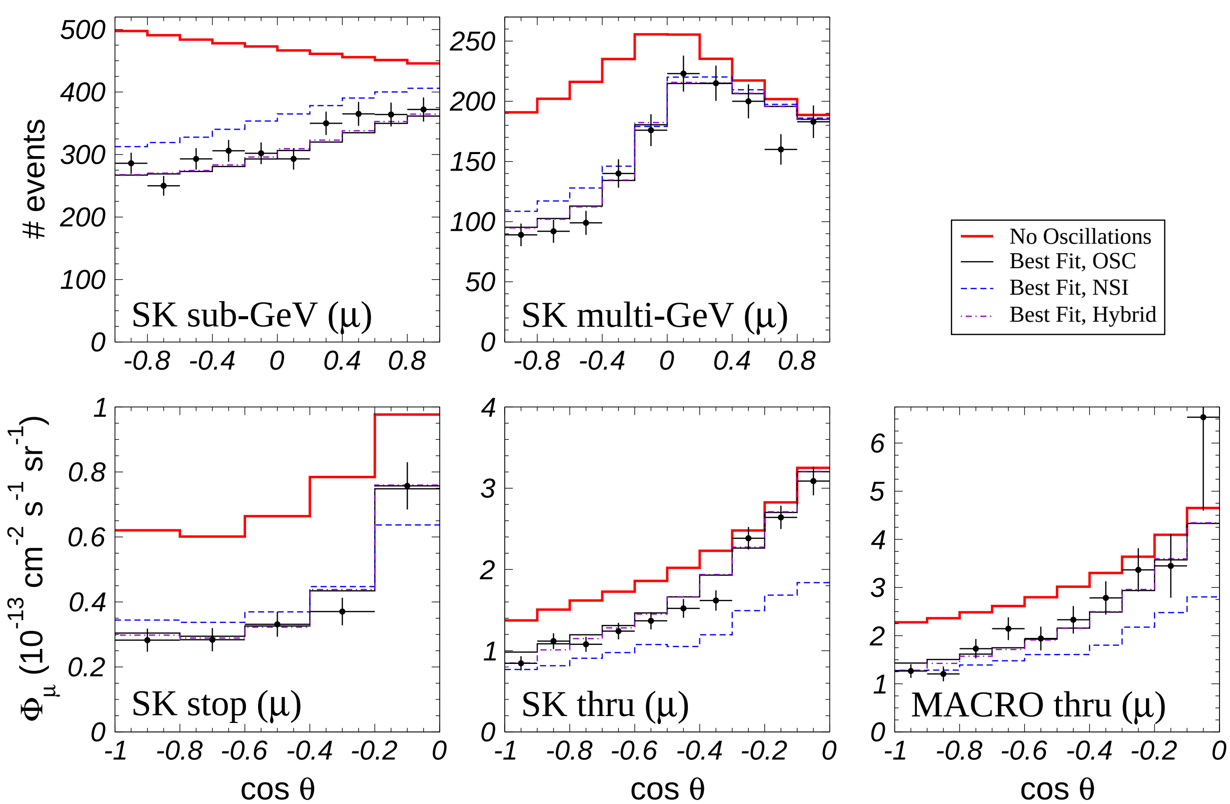
$$\mathbf{H}_0^d = \frac{1}{2E_\nu}\mathbf{diag}\left(0, \Delta m^2\right), \qquad \mathbf{O} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}, \qquad \vec{\nu} = \begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix};$$

- the sign $+$ ($-$) in the expression of $\mathbf{V}$ refers to neutrinos (antineutrinos).

Atmospheric data: zenith distribution

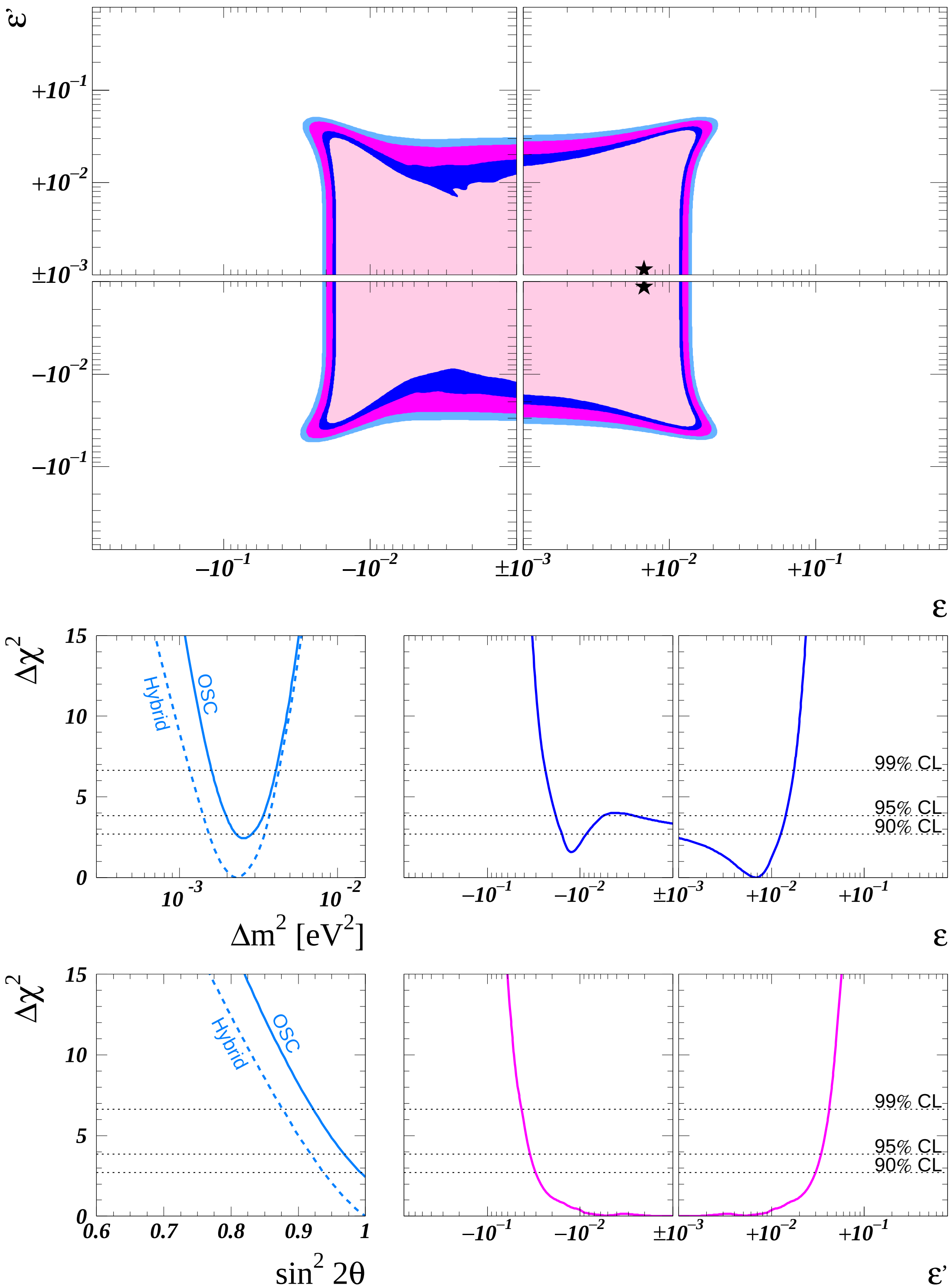
- **Pure oscillations** provide a good explanation of ATM data;
- **Pure NSI** fail to reconcile *contained* and *upgoing-μ* events;

$\Rightarrow$ in an hybrid NSI+OSC scenario, ATM data bound the NSI component.



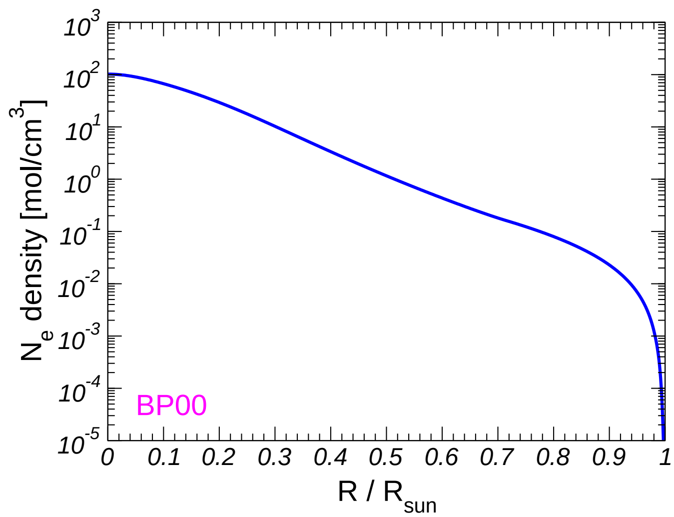
Bound on NSI from atmospheric data

- Δm^2 and θ are not affected by the presence of a NSI component;
- general result (99.73% CL): $-0.03 \leq \varepsilon \leq 0.02$ and $|\varepsilon'| \leq 0.05$.

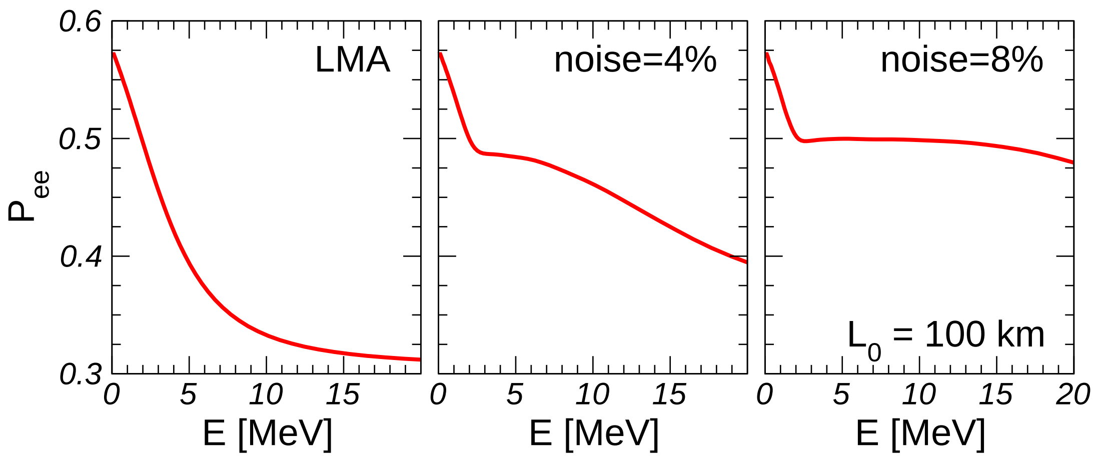


Solar density fluctuations and neutrino oscillations

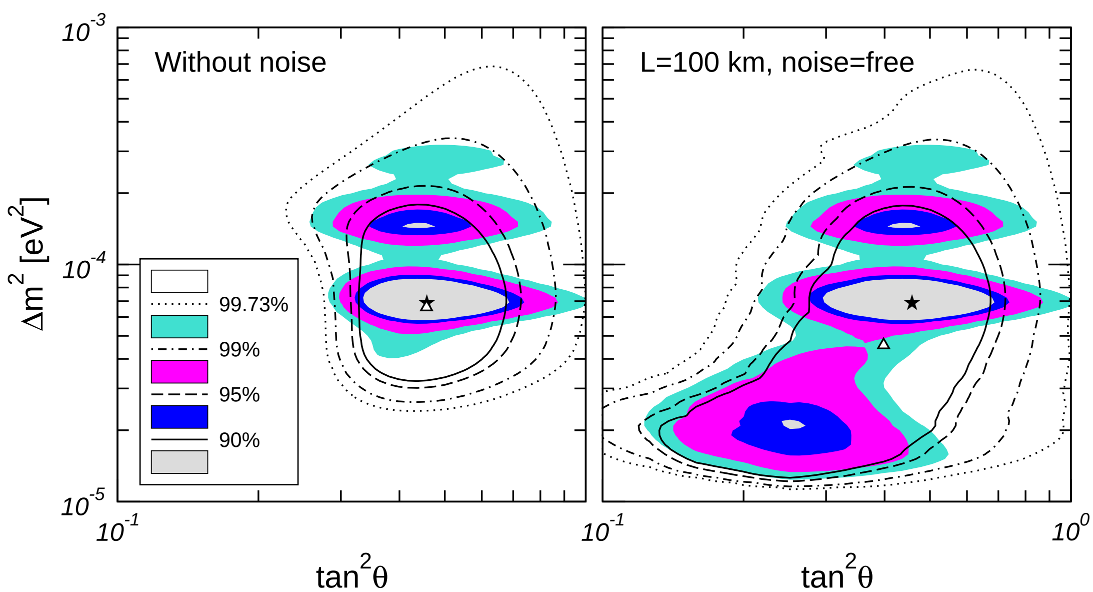
- Helioseismology severely constrains matter density fluctuations in the Sun at scales $\gg 1000$ km;
- at smaller scales, large density fluctuations are permitted;
- such fluctuations can considerably modify the pattern of neutrino oscillations.



- **4** parameters: *oscillation* (Δm^2, θ) and *noise* (L_0, ξ);

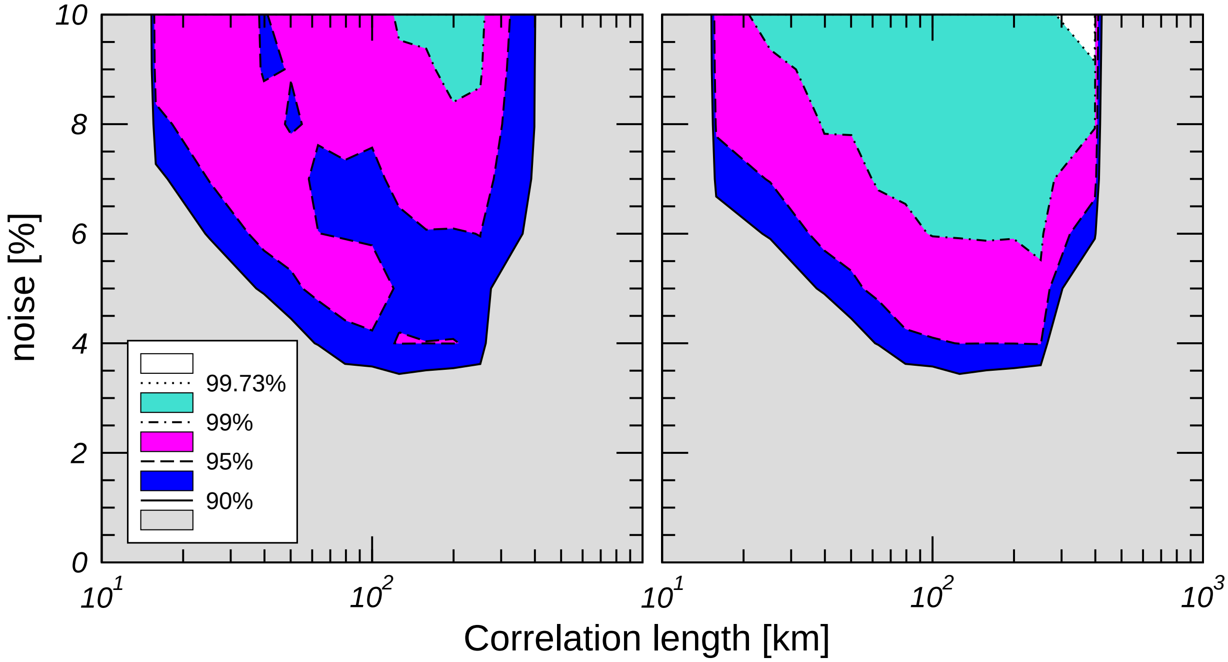


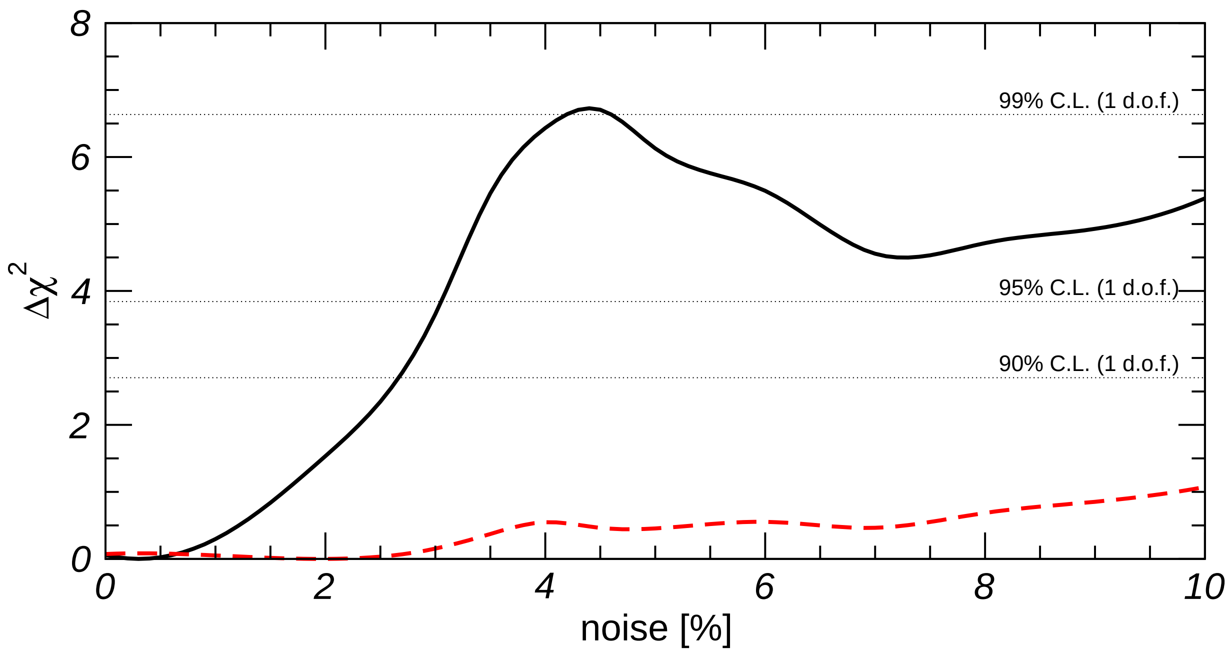
- Impact of *noise* on the determination of *oscillation* parameters:



Solar neutrino data and density fluctuations

- Precise measurements of the neutrino flux coming from the Sun can provide important informations on the presence of matter density fluctuations on scales ≈ 100 km;
- a detailed knowledge of neutrino oscillation parameters is required $\Rightarrow$ future KamLAND data will be essential.





Conclusions

- We have presented analyses of neutrino data in the context:
  - of 2ν oscillations;
  - of 3ν oscillations, combining solar, atmospheric, reactor, K2K data;
  - of 4ν oscillations, including also the LSND result;
  - of models involving non-standard phenomena.

Three-neutrino results

- **Solar**, **Atmospheric**, **reactor** data are perfectly compatible;
- the only solar solution after KamLAND data is LMA, with $\Delta m^2_{\text{SOL}} \approx 7 \times 10^{-5}$ eV^2 and *large but non-maximal* mixing;
- atmospheric & K2K data favor $\Delta m^2_{\text{ATM}} \approx 3 \times 10^{-3}$ eV^2 and maximal mixing;
- reactor data (Chooz) indicate $\theta_{\text{REA}} \approx 0$.

Four-neutrino results

- Both **(3+1)** and **(2+2)** oscillation models fail to explain the LSND result;
- **CPT violation** is also not a viable solution;

$\Rightarrow$ if MiniBooNE confirms LSND, more exotic mechanisms have to be investigated.

Other non-standard mechanisms

- Non-standard neutrino-matter interactions are severely bounded by atmospheric data;
- Neutrino data will be a powerful tool to study matter density fluctuations in the Sun, once the oscillation parameters have been measured.