NOW 2012 Conca Specchiulla, 14/09/2012

Low-energy sterile neutrinos: Theory

Antonio Palazzo

Excellence Cluster 'Universe' (TUM)

Outline

Introduction

Hints of light sterile ν's

Theoretical framework

The 3+1 scheme and the MSW effect

Phenomenological implications

Testing sterile ν's with solar sector data

Conclusions

INTRODUCTION

Hints of light sterile ν's

Why introduce new light ν species?

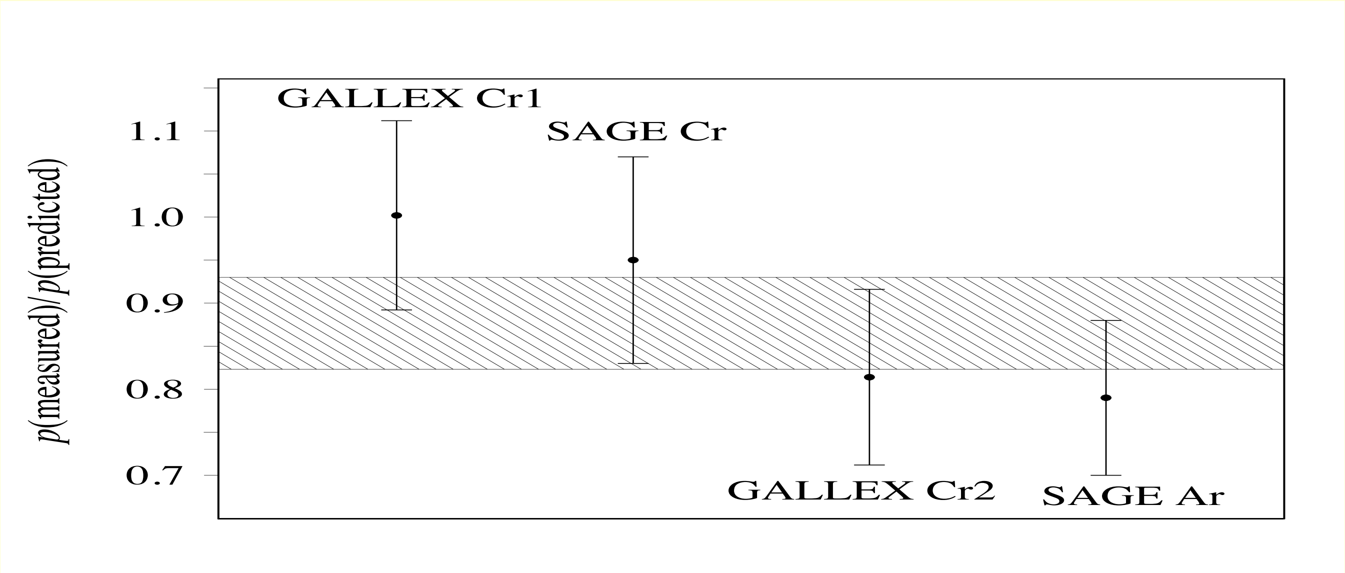
No compelling theoretical reason but several experimental anomalies seem to point in this direction

(I) Accumulating hints of eV ν_s's from oscillation phenomenology and cosmology

(II) Indications of "warm" dark matter from astrophysical "small-scale" problems (keV ν_s's are a good option)

I will discuss only eV ν_s's

Hint #1: The Gallium calibration anomaly

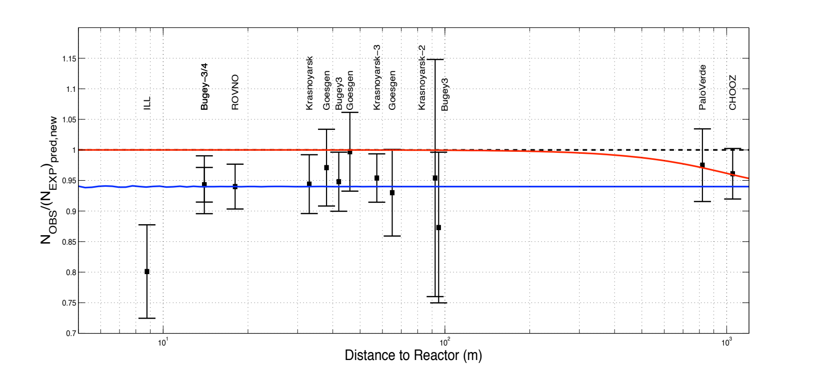


SAGE coll., PRC 73 (2006) 045805

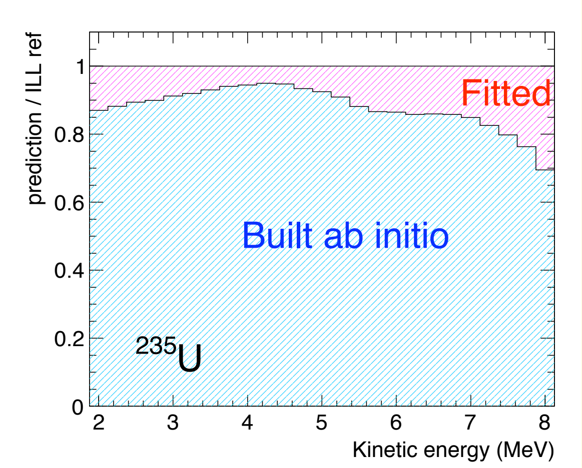
Deficit observed in calibration performed with radioactive sources

But it could be due to overestimate of $\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$ cross section

Hint #2: The reactor antineutrino anomaly



Mention et al., PRD 83 073006 (2011)

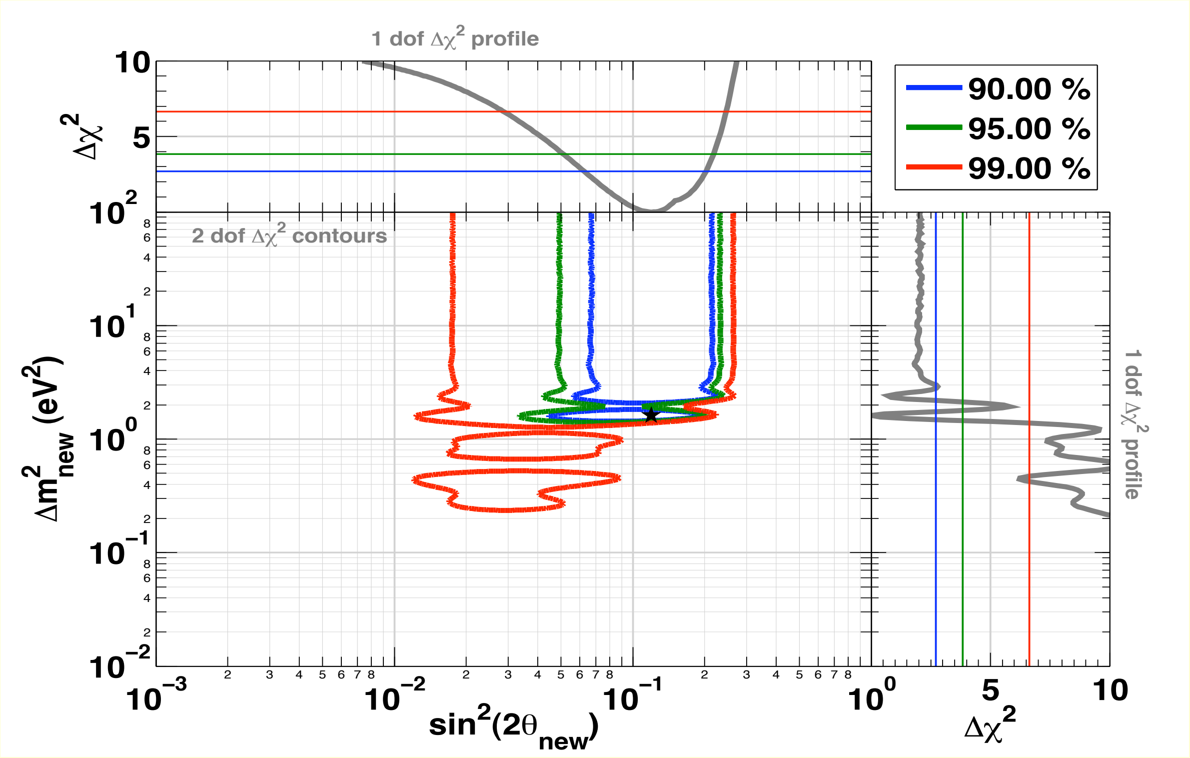


Mueller et al., PRC 83 054615 (2011)
Huber, PRC 84 024617 (2011)

With new reactor fluxes deficit of all the short-baseline reactor measurements

But new calculations, like older ones, are still anchored to (one single) β-spectrum experiment (ILL)

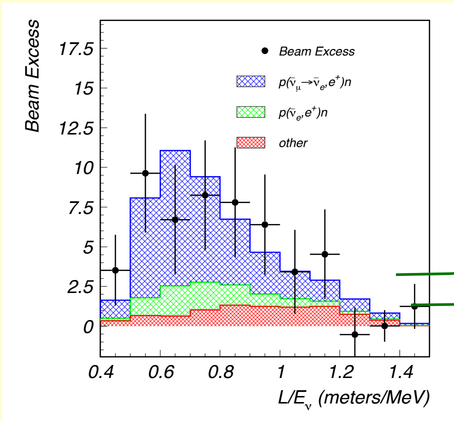
Fitting the short-distance ν_e-disappearance



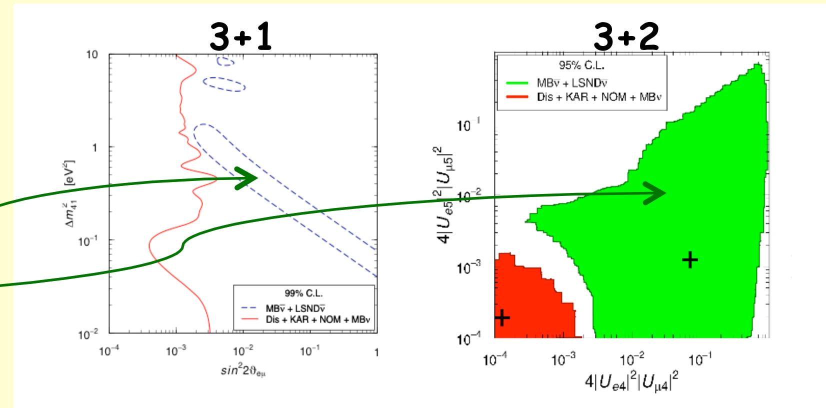
Mention et al., PRD 83 073006 (2011)

$$\sin^2 2\theta_{new} \simeq 0.1 \qquad\qquad \Delta m^2_{new} \gtrsim 1 \text{ eV}^2$$

Hint #3: Anomalous short-distance ν_e-appearance



LSND, PRL 75 (1995) 2650



Giunti and Laveder, arXiv:1107.1452

Warning: **In tension with disappearance searches:**

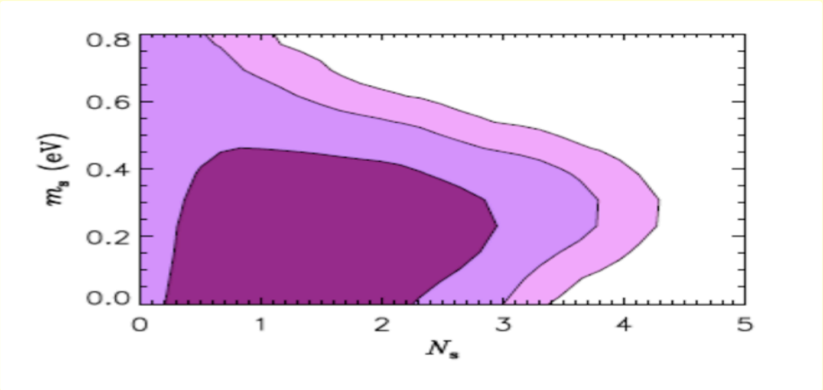
$\nu_\mu \to \nu_e$ positive appearance signal incompatible with joint $\nu_e \to \nu_e$ (positive) & $\nu_\mu \to \nu_\mu$ (negative) searches

Theory:

$$\sin^2 2\theta_{e\mu} \simeq \frac{1}{4}\sin^2 2\theta_{ee}\,\sin^2 2\theta_{\mu\mu} \simeq 4|U_{e4}|^2|U_{\mu4}|^2$$

Experiments: ~ few ‰ ~ 0.1 < few %

Hint #4: Cosmology favors extra radiation



CMB + LSS tend to prefer extra relativistic content ~ 2 sigma effect

[Hamann et al., PRL 105, 181301 (2010)]

Warnings:

- **eV masses acceptable only abandoning standard ΛCDM**
  (Kristiansen & Elgaroy arXiv:1104.0704 , Hamann et al. arXiv:1108.4136)

- **N_s>1 at BBN strongly disfavored** (Mangano & Serpico PLB 701, 296, 2011)

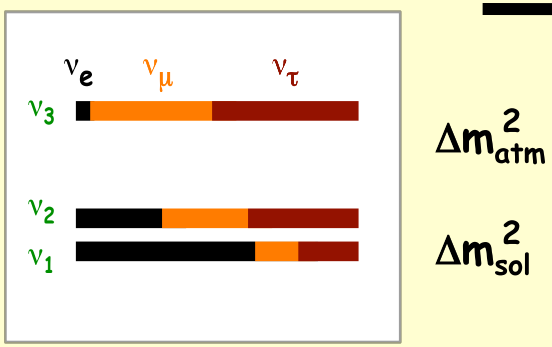
- **N_s is not specific of ν_s**
  (new light particles, decay of dark matter particles, quintessence, …)

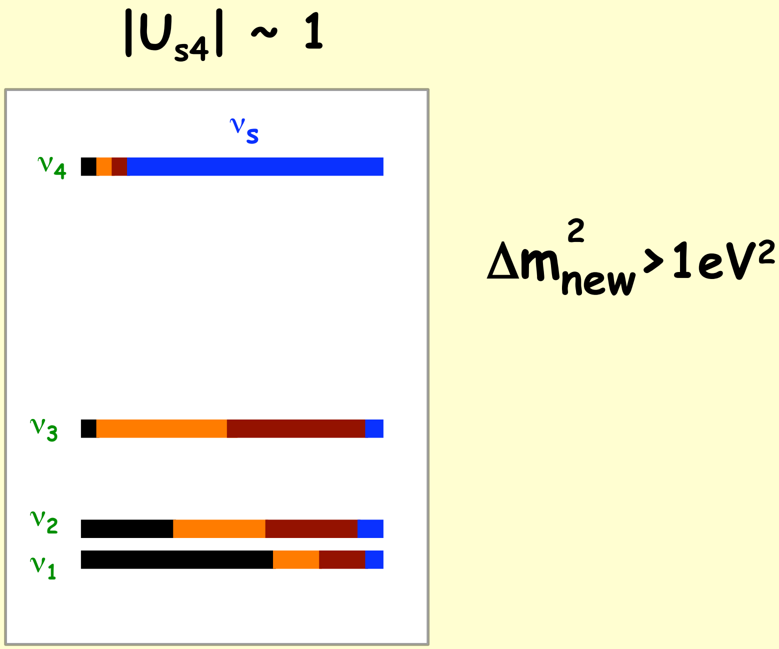
THEORETICAL FRAMEWORK

The 3+1 scheme and the MSW mechanism

The 3+1 scheme:

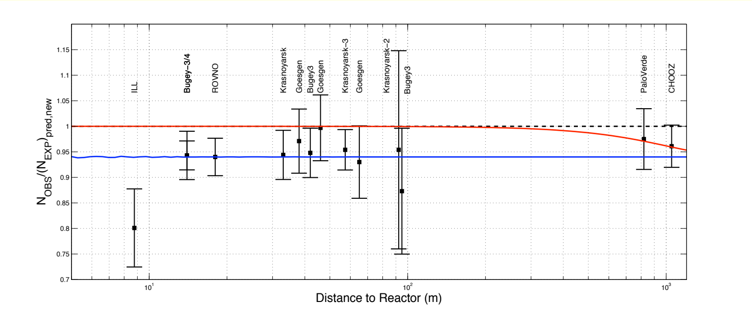
The 4^{th} ν state induces a small perturbation of the 3-flavor framework



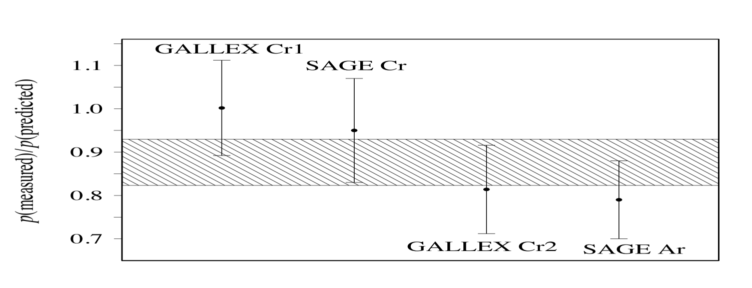


From the "point of view" of the solar doublet (ν_1, ν_2) we expect similar sensitivity to U_{e3} & U_{e4}

VSBL ν_e disappearance in a 3+1 scheme



Mention et al. arXiv:1101:2755 [hep-ex]



SAGE coll., PRC 73 (2006) 045805

In a 2ν framework:

$$P_{ee} \simeq 1 - \sin^2 2\theta_{new} \sin^2 \frac{\Delta m^2_{new} L}{4E}$$

$$\sin^2 2\theta_{new} \simeq 0.17 \pm 0.1 \ (95\%)$$

In a 3+1 scheme:

$$P_{ee} = 1 - 4 \sum_{j>k} U^2_{ej} U^2_{ek} \sin^2 \frac{\Delta m^2_{jk} L}{4E}$$

$$\Delta m^2_{sol} \ll \Delta m^2_{atm} \ll \Delta m^2_{new}$$

$$\sin^2 \theta_{new} \simeq U^2_{e4} = \sin^2 \theta_{14}$$

3+1 scheme has several consequences: solar, atm, react., accel.

We will focus on the implications for Solar (S) & KamLAND (K)

LBL ν_e disappearance in a 3+1 scheme

$$P_{ee} = 1 - 4 \sum_{j>k} U_{ej}^2 U_{ek}^2 \sin^2 \frac{\Delta m_{jk}^2 L}{4E}$$

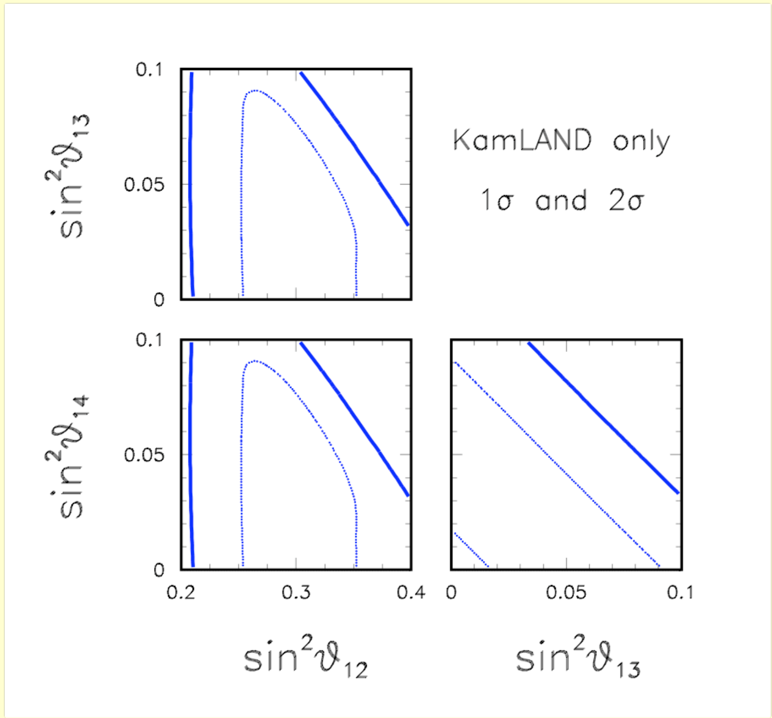
$$\Delta m_{sol}^2 \ll \Delta m_{atm}^2 \ll \Delta m_{new}^2$$

Δm^2_{atm}, Δm^2_{new} -driven osc. averaged

$$P_{ee} = (1 - U_{e3}^2 - U_{e4}^2)^2 P_{ee}^{2\nu} + U_{e3}^4 + U_{e4}^4$$

$$U_{e3}^2 = c_{14}^2 s_{13}^2 \qquad U_{e4}^2 = s_{14}^2$$

KamLAND



Exact degeneracy between U_{e3} and U_{e4}

Solar ν MSW effect in a 3+1 scheme

$$i\,\frac{d}{dx}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix} = H\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix} \qquad H = UKU^T + V(x)$$

$$K = \frac{1}{2E}\mathrm{diag}(k_1,\, k_2,\, k_3,\, k_4) \qquad k_i = \frac{m_i^2}{2E}$$

wavenumbers in vacuum

Useful to write the mixing matrix as*: $U = R_{23}\, S\, R_{13}\, R_{12}$ $\qquad S = R_{24}\, R_{34}\, R_{14}$

$\theta_{14}=\theta_{24}=\theta_{34}=0$ --> $S = I$ --> 3-flavor case

$$V = \mathrm{diag}(V_{CC},\, 0,\, 0,\, -V_{NC})$$

MSW potential

$$V_{CC} = \sqrt{2}\,G_F\,N_e \qquad V_{NC} = \frac{1}{2}\sqrt{2}\,G_F\,N_n$$

* We assume U to be real but in general it can be complex due to CP phases

Change of basis: $\nu' = (R_{23}\, S\, R_{13})^T\, \nu = A^T \nu = R_{12} U^T$

In the new basis: $H' = A^T H A = R_{12} K R_{12}^T + R_{13}^T S^T V S R_{13}$

At zeroth order in:

$\dfrac{V}{k_{atm}}$ and $\dfrac{V}{k_{new}}$

$$H' \simeq \left(\begin{array}{c|cc} H'_{2\nu} & & \\ \hline & k_3 & \\ & & k_4 \end{array} \right)$$

The 3rd & 4th state evolve independently from the 1st & 2nd

The dynamics reduces to that of a 2x2 system

Diagonalization of the Hamiltonian

The 2x2 Hamiltonian is diagonalized by a 1-2 rotation

$$\tilde{R}_{12}^T H'_{2\nu} \tilde{R}_{12} = diag(\tilde{k}_1, \tilde{k}_2)$$

which defines the solar mixing angle in matter

$$\tilde{\theta}_{12}(x)$$

wavenumbers in matter

$$\tilde{k}_i$$

The starting Hamiltonian is then diagonalized by

$$\tilde{U} = A\tilde{R}_{12}$$
$$\tilde{U}^T H \tilde{U} = diag(\tilde{k}_1, \tilde{k}_2, k_3, k_4)$$

For ν_3 and ν_4 (averaged) vacuum-like propagation

The 2x2 Hamiltonian: $H'_{2\nu} = H'^{\,\mathrm{kin}}_{2\nu} + H'^{\,\mathrm{dyn}}_{2\nu}$

$$H'^{\mathrm{kin}}_{2\nu} = \begin{pmatrix} c_{12} & s_{12} \\ -s_{12} & c_{12} \end{pmatrix} \begin{pmatrix} -k_{sol}/2 & 0 \\ 0 & k_{sol}/2 \end{pmatrix} \begin{pmatrix} c_{12} & -s_{12} \\ s_{12} & c_{12} \end{pmatrix} \qquad k_{sol} = \frac{m_2^2 - m_1^2}{2E}$$

$$H'^{\mathrm{dyn}}_{2\nu} = V_{CC}(x) \begin{pmatrix} \gamma^2 + r(x)\,\alpha^2 & r(x)\,\alpha\beta \\ r(x)\,\alpha\beta & r(x)\,\beta^2 \end{pmatrix}^{*} \qquad r(x) = \frac{V_{NC}(x)}{V_{CC}(x)}$$

$$\begin{cases} \alpha^2 + \beta^2 = U_{s1}^2 + U_{s2}^2 \\ \gamma^2 = 1 - (U_{e3}^2 + U_{e4}^2) \end{cases} \qquad \begin{cases} \alpha = c_{24}c_{34}c_{13}s_{14} - s_{34}s_{13} \\ \beta = s_{24}c_{34} \\ \gamma = c_{13}c_{14} \end{cases}$$

All the dynamical effects induced by the 4th (and 3rd) state are 2nd order in the s_{ij}: small deviations from the standard MSW.

But important new kinematical effects are present …

* A.P. PRD 83 113013 (2011) [arXiv: 1105.1705 hep-ph]

For adiabatic propagation (valid for small deviations around the LMA)

$$P_{ee} = \sum_{i=1}^{4} U_{ei}^2 \tilde{U}_{ei}^2 = U_{e1}^2 \tilde{U}_{e1}^2 + U_{e2}^2 \tilde{U}_{e2}^2 + U_{e3}^4 + U_{e4}^4$$

$$P_{es} = \sum_{i=1}^{4} U_{si}^2 \tilde{U}_{ei}^2 = U_{s1}^2 \tilde{U}_{e1}^2 + U_{s2}^2 \tilde{U}_{e2}^2 + U_{s3}^2 U_{e3}^2 + U_{s4}^2 U_{e4}^2$$

Expressions for U_{ei}'s (always valid)

$$\left.\begin{array}{l} U_{e1}^2 = c_{14}^2 c_{13}^2 c_{12}^2 \\ U_{e2}^2 = c_{14}^2 c_{13}^2 s_{12}^2 \end{array}\right\} \sim 1 - s_{14}^2 - s_{13}^2$$

$$U_{e3}^2 = c_{14}^2 s_{13}^2 \quad \sim s_{13}^2$$

$$U_{e4}^2 = s_{14}^2$$

Expressions for U_{si}'s valid for $\theta_{24} = \theta_{34} = 0$

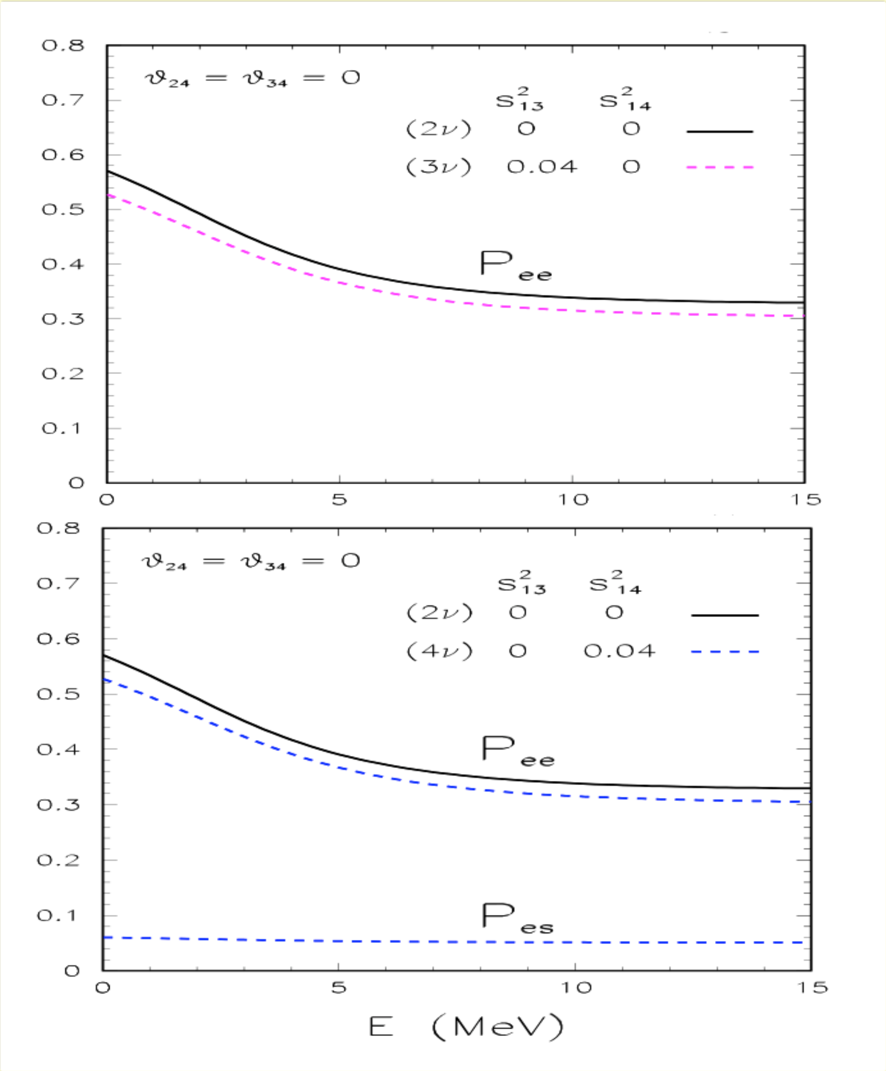
$$\left.\begin{array}{l} U_{s1}^2 = s_{14}^2 c_{13}^2 c_{12}^2 \\ U_{s2}^2 = s_{14}^2 c_{13}^2 s_{12}^2 \end{array}\right\} \sim s_{14}^2$$

$$U_{s3}^2 = s_{14}^2 s_{13}^2 \quad \sim 0$$

$$U_{s4}^2 = c_{14}^2 c_{13}^2 \quad \sim 1 - s_{14}^2$$

The elements of $\tilde{U}$ are obtained replacing θ_{12} with $\tilde{\theta}_{12}$ calculated in the production point (near the sun center)

Two simple limit cases



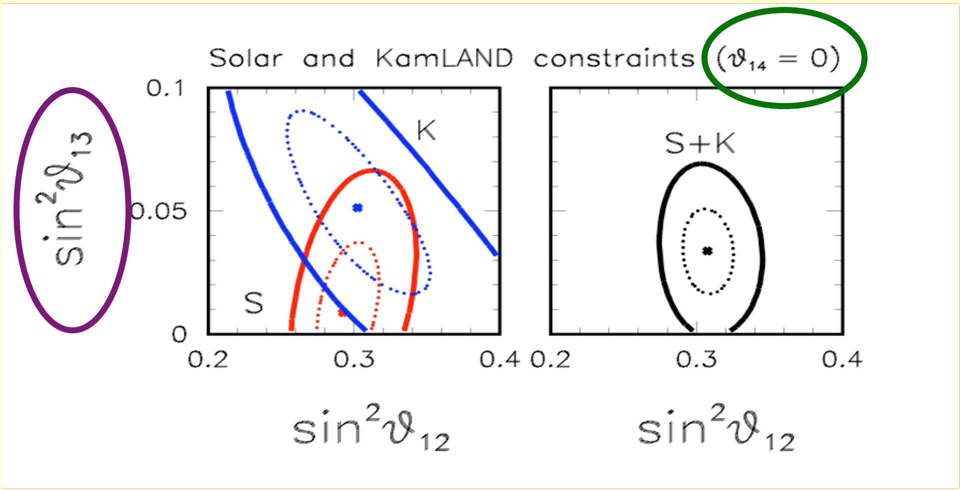
$\theta_{13} \neq 0 \quad \theta_{14} = 0 \quad (3\nu)$

$$\begin{cases} P_{ee} = c_{13}^4 P_{ee}^{2\nu}\Big|_{V \to V c_{13}^2} + s_{13}^4 \\ P_{es} = 0 \end{cases}$$

$\theta_{13} = 0 \quad \theta_{14} \neq 0 \quad (4\nu)$

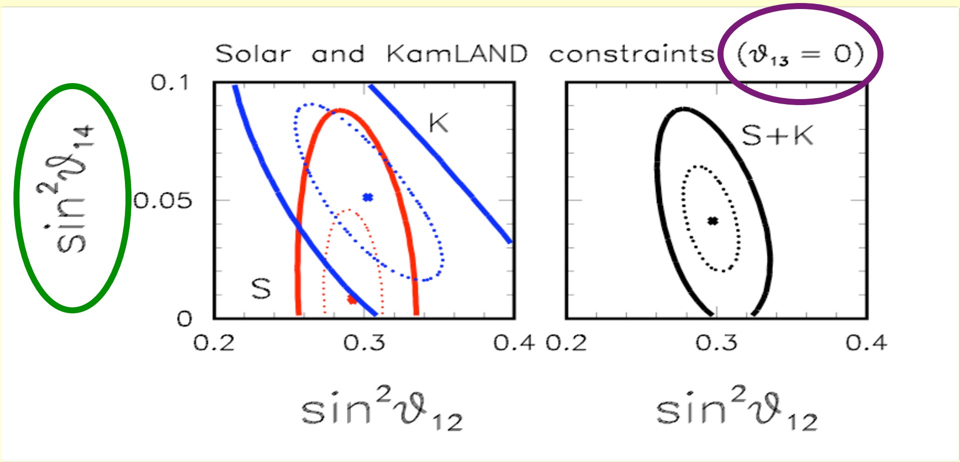
$$\begin{cases} P_{ee} = c_{14}^4 P_{ee}^{2\nu}\Big|_{V \to V c_{14}^2} + s_{14}^4 \\ P_{es} \simeq s_{14}^2 P_{ee}^{2\nu}\Big|_{V \to V c_{14}^2} + s_{14}^2 \end{cases}$$

$(\theta_{13},\theta_{12})$ vs $(\theta_{14},\theta_{12})$ constraints



$$\begin{cases} CC \sim \Phi_B\, P_{ee} \\ NC \sim \Phi_B\, (1-P_{es}) \\ ES \sim \Phi_B\, (P_{ee} + 0.15\, P_{ea}) \end{cases}$$

Solar ν sensitive to Pes
CC/NC (SNO) & ES (SK)

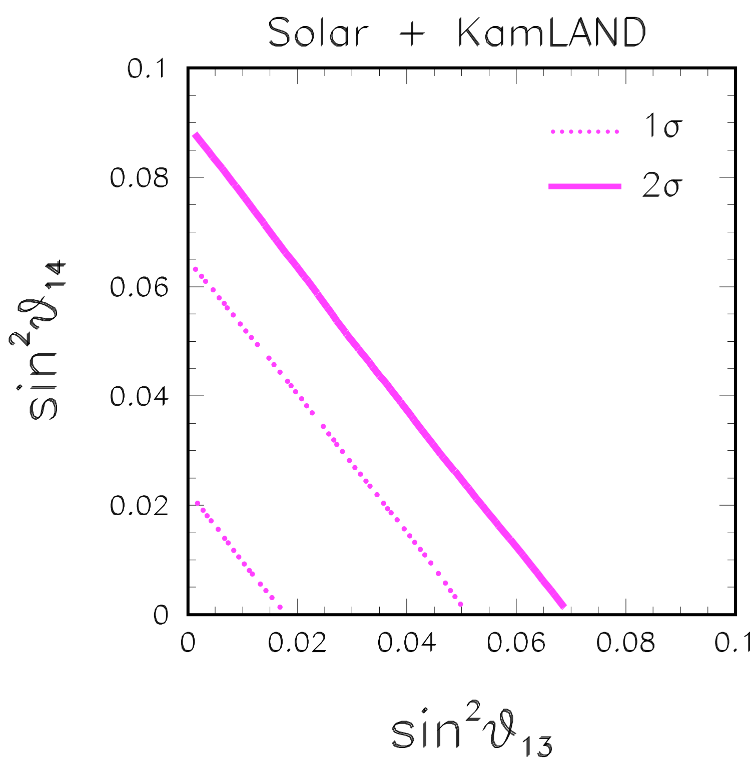


But unfortunately only small differences among 3ν and 4ν

We expect a degeneracy among θ_{13} and θ_{14}

A.P. PRD 83 113013 (2011) [arXiv: 1105.1705 hep-ph]

$(\theta_{13},\theta_{14})$ constraints



A.P. PRD 83 113013 (2011) [arXiv: 1105.1705 hep-ph]

Complete degeneracy
θ_{13}-θ_{14} indistinguishable

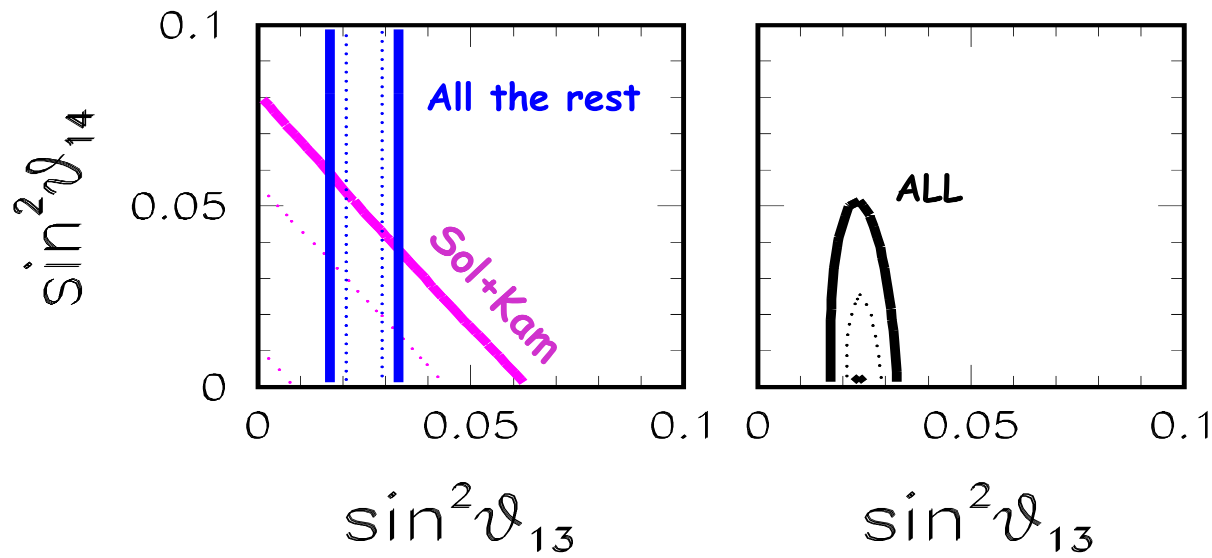
Solar sector essentially sensitive to ~ $U_{e3}^2 + U_{e4}^2$

Preference for ν_e mixing with states others than (ν_1,ν_2)

Different probes are necessary to determine if ν_e mixes with ν_3 or ν_4

Evidence of θ_{13}>0 kills preference of θ_{14}>0

UPDATE of: A.P. PRD 85 077302 (2012) [arXiv: 1201.4280 hep-ph]



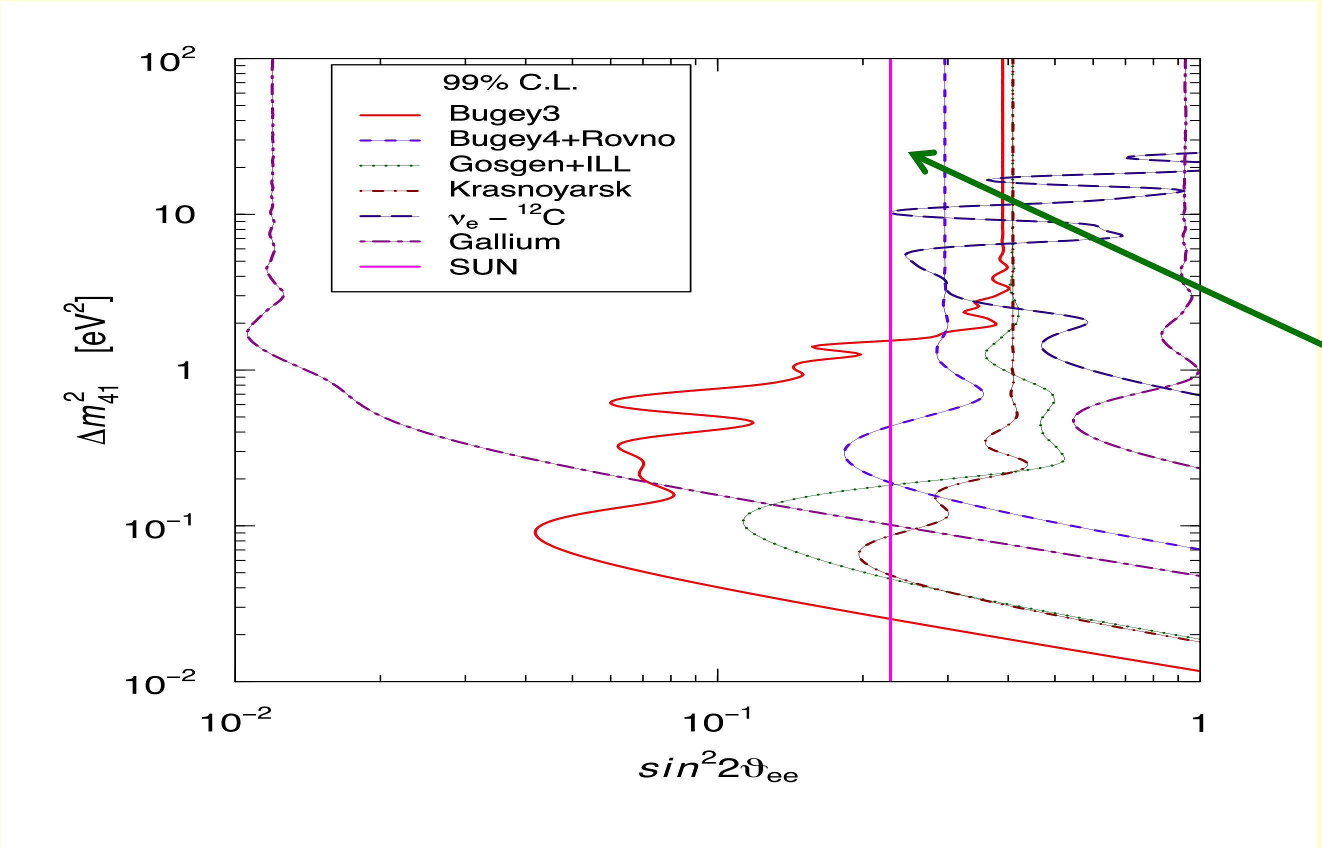
- Upper limit $\longrightarrow$ $\sin^2\theta_{14} < 0.04$ (90% C.L.)

- KamLAND, only spectral shape included:
  limit is independent of reactor flux estimates

- θ_{13} estimate independent of θ_{14}

Solar bound is the most stringent one for $\Delta m^2_{14} > 1 eV^2$

Compilation of all the existing limits on θ_{14} (= θ_{ee})



Our bound

Talk by C. Giunti @ νTURN 2012

Summary

- Several pieces of data, taken separately, point towards ν_s

- However, taken together, the same results do not converge towards a consistent theoretical picture.

- Restricting the attention to the low-energy experiments: the data indicate ν_e mix with new sterile state(s) ($U_{e4} \neq 0$).

- In this context the solar sector can be exploited (with the evidence of $\theta_{13}>0$) to corner the putative admixture:

$$U_{e4}^2 < 0.04 \quad (90\% \text{ C.L.})$$

independent of the reactor fluxes' estimates.

- New experiments should be able to probe this region.