Bounds on θ_{13} & θ_{14} from low energy neutrino data

Antonio Palazzo

MAX-PLANCK-GESELLSCHAFT

MARIE CURIE ACTIONS

SEVENTH FRAMEWORK PROGRAMME

Max-Planck-Institut für Physik (Munich)

Outline

1) Solar νs as harbingers of non-zero θ_{13}

2) Solar νs as a probe of sterile neutrinos

3) Solar νs as a probe of the MSW dynamics

Tightly interconnected topics, as we will see …

Solar νs as harbingers of non-zero θ_{13}

Why a non-zero θ_{13} is so important

$$J = \Im[U_{\mu 3} U_{e2} U^*_{\mu 2} U^*_{e3}]$$

The Jarlskog invariant J gives a parameterization-independent measure of the CP violation induced by the complexity of U

In the standard parameterization the expression of J is:

$$J = \frac{1}{8} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos\theta_{13} \sin\delta$$

Only if all three $\theta_{ij} \neq 0$ we can have CP violation

quark-sector: $J_{CKM} \sim 3 \times 10^{-5}$, much smaller than $|J|_{max} = \frac{1}{6\sqrt{3}} \sim 0.1$

lepton-sector: $|J|$ <u>may</u> be as large as 3×10^{-2} (it will depend on δ)

Historical result established by CHOOZ in 1998

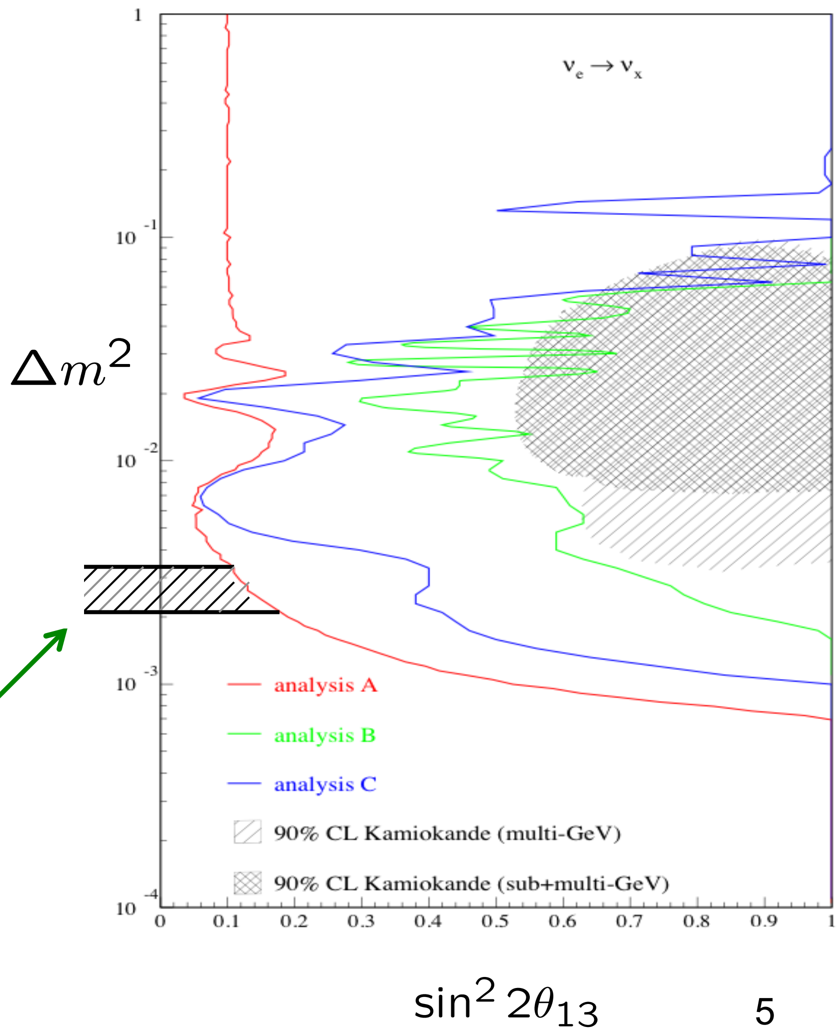
$$P_{ee}^{\text{osc}} = 1 - 4U_{e3}^2(1 - U_{e3}^2)\sin^2\left(\frac{\Delta m^2}{4E}L\right)$$

$$P_{ee}^{\text{exp}} \simeq 1 \qquad U_{e3}^2 = \sin^2\theta_{13}$$

Exclusion plot in the $(\Delta m^2, \theta_{13})$ plane

Δm^2 scale **now** set with precision by Atm +LBL

CHOOZ exclusion plot



...since then...

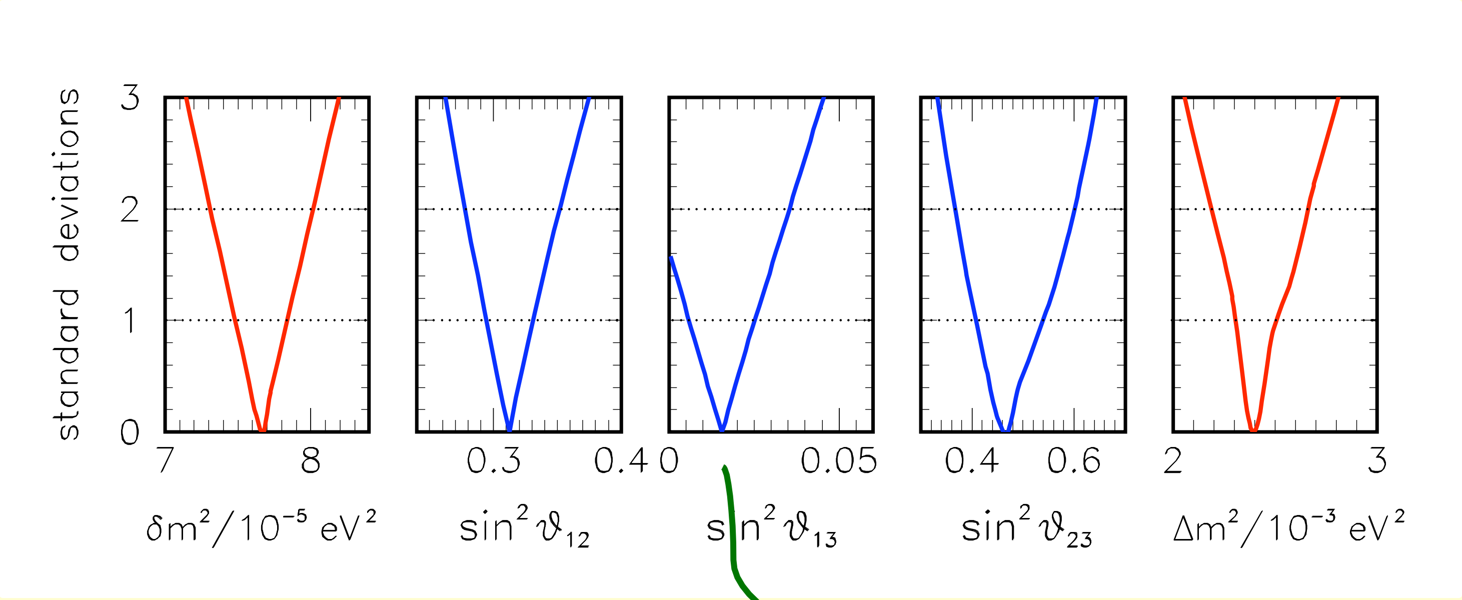
The 3ν global analyses have played an increasingly relevant role in pinning down θ_{13}, constantly improving their sensitivity.

They have first corroborated (atm. analyses) and then strengthened (sol+Kam analyses) the CHOOZ upper limit.

Hence, in 2008 it was not surprising that they started to be competitive, reaching values of θ_{13} below the CHOOZ limit.

What instead – pleasantly - surprised us was that, for the first time, the analyses pointed towards a non-zero value of this parameter…

2008: Global 3ν analysis



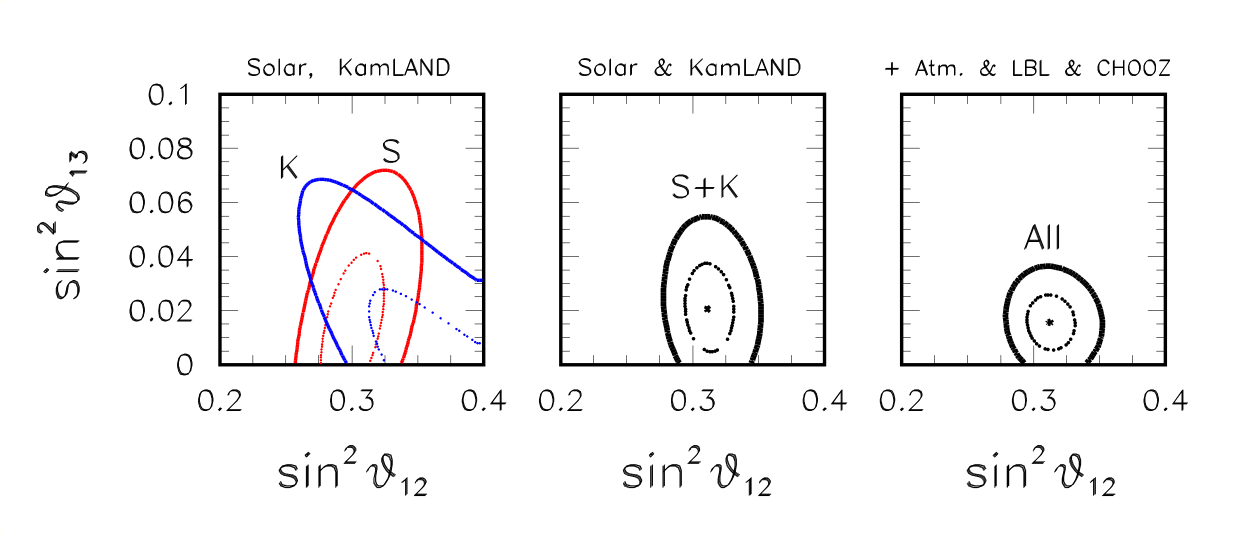
preference for $\theta_{13}>0$

The global analysis provided a preference for θ_{13} > 0 at 90% C.L.

Fogli, Lisi, Marrone, A.P, Rotunnno,

PRL 101, 141801 (2008), arXiv:0806.2649, hep-ph.

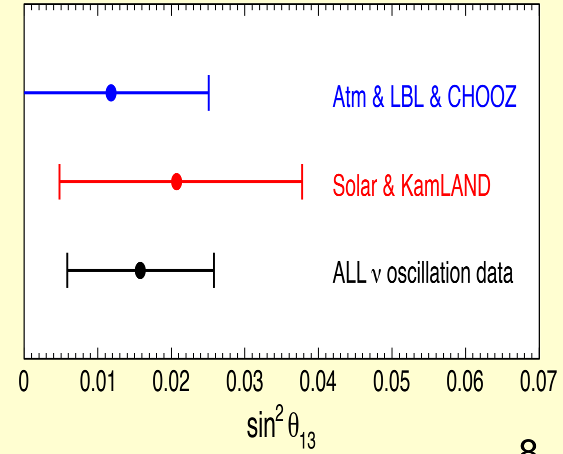
2008: First indication of non-zero θ_{13}



Fogli, Lisi, Marrone, A.P., Rotunno, Phys. Rev. Lett. 101, 141201 (2008)

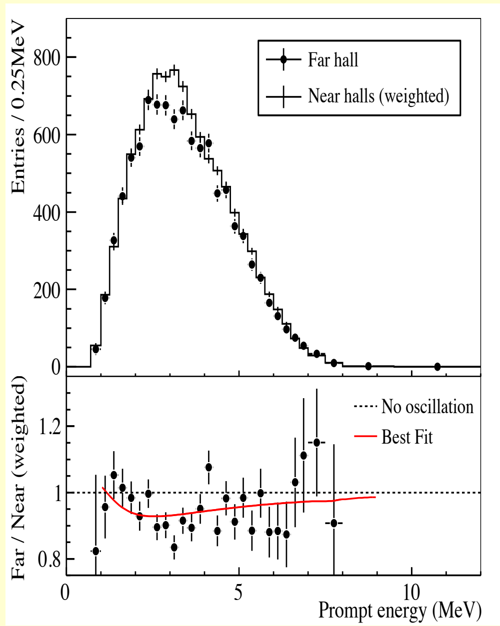
Two independent hints came from solar and atmospheric sectors:

$\sin^2\theta_{13} \sim 0.016$

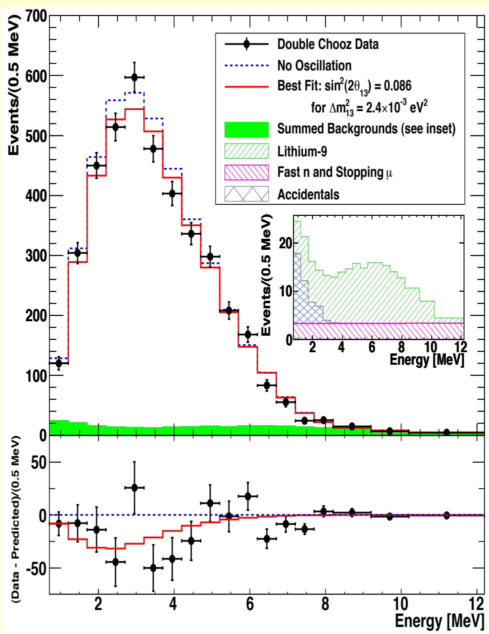


Indication irrefutably confirmed in 2012

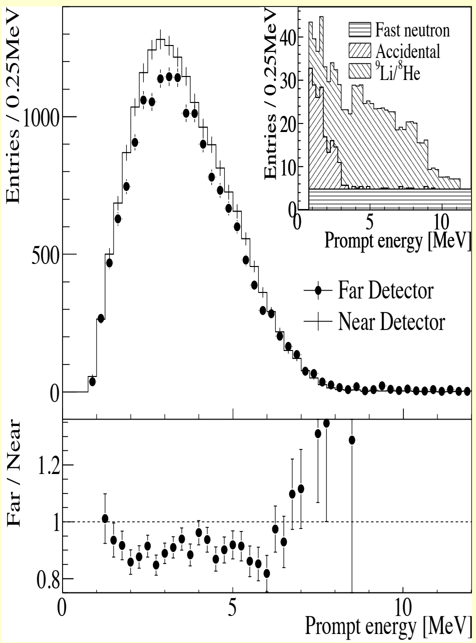
Daya Bay



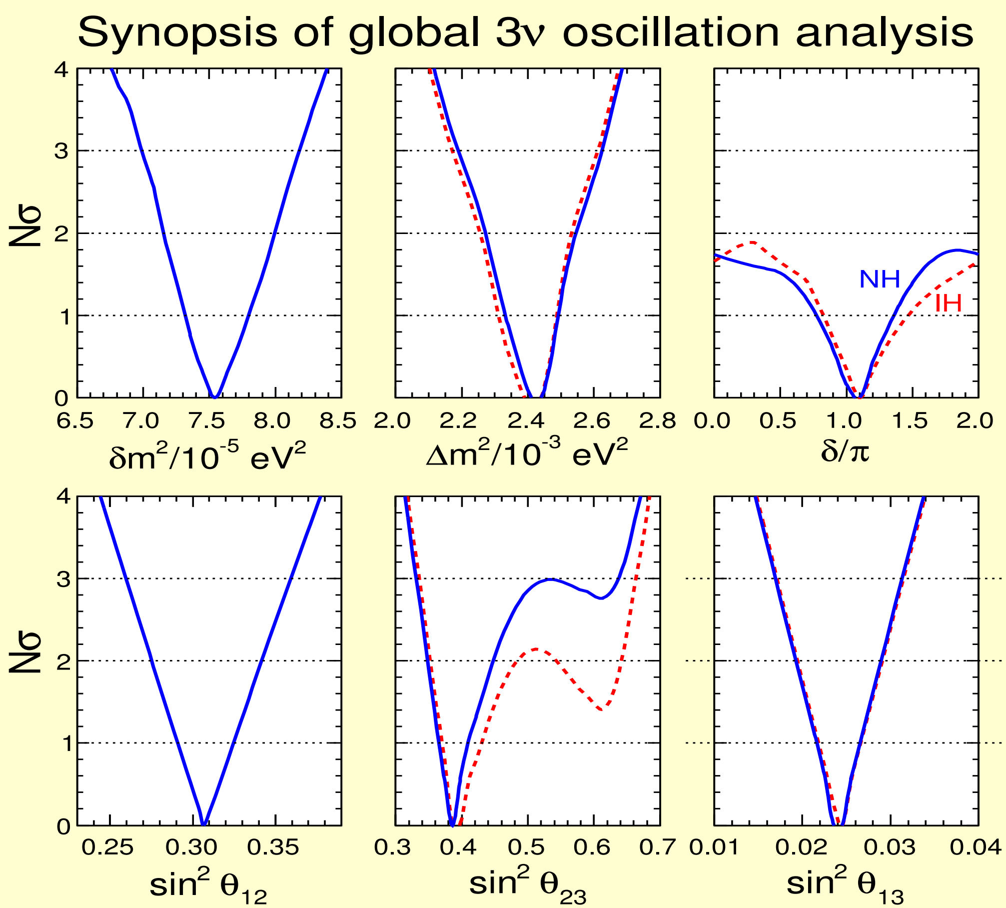
Double-CHOOZ



Reno



Parameter estimates as of June 2012



θ_{13} non-zero at 8σ

$\sim 2\sigma$ indication of non-maximal θ_{23} ($\theta_{23} < \pi/4$)

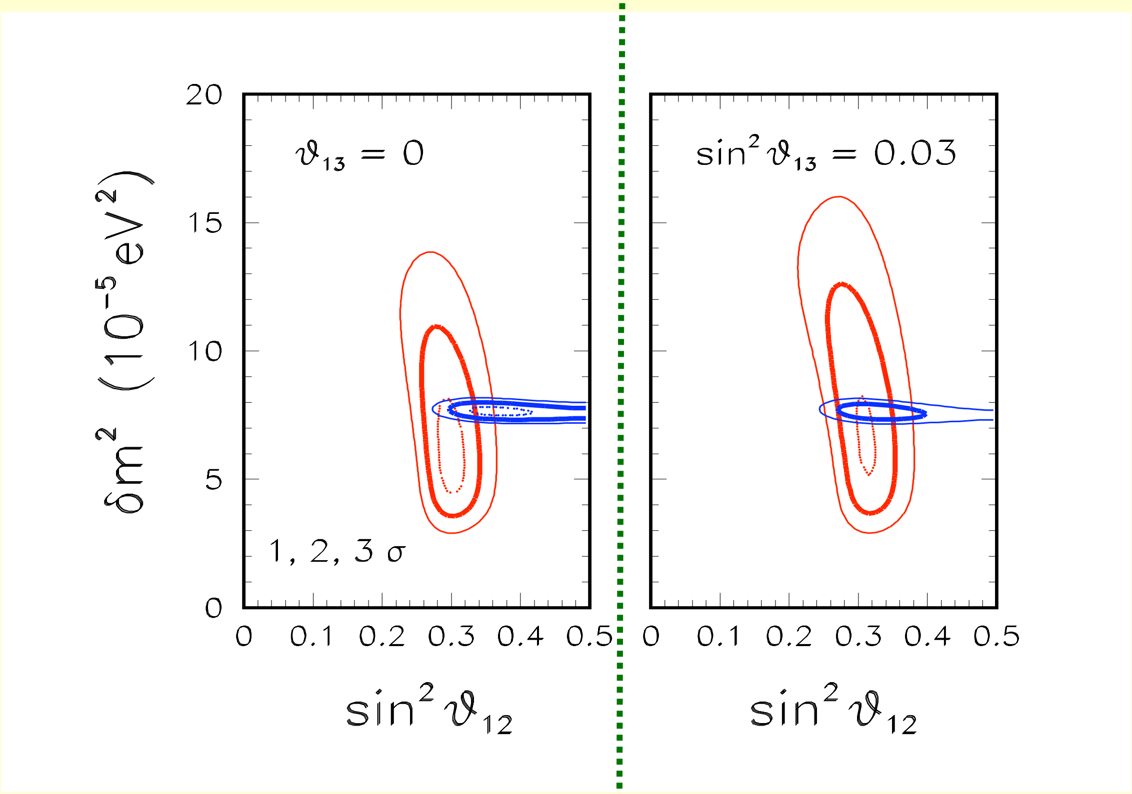
Hint of $\delta \sim \pi$

no sensitivity to mass hierarchy

Fogli, lisi, Marrone, Montanino, A.P., Rotunno, PRD 86 013012 (2012)
(includes Neutrino 2012 results)

A closer look to the solar hint of $\theta_{13}>0$ shows that it emerged from a delicate interplay of solar and KamLAND

$\theta_{13} = 0$



$\theta_{13} > 0$

Solar νs are thus a very precise machine and we can trust it also when searching for non-standard physics!

Beyond the standard 3ν paradigm

Exploring new neutrino properties

Why go beyond the standard 3ν picture?

Theory

Many extensions of the SM point towards new ν properties (interactions, new states,…)

Acquired knowledge

Precision on standard parameters enhances the sensitivity to any kind of perturbation

Experimental hints

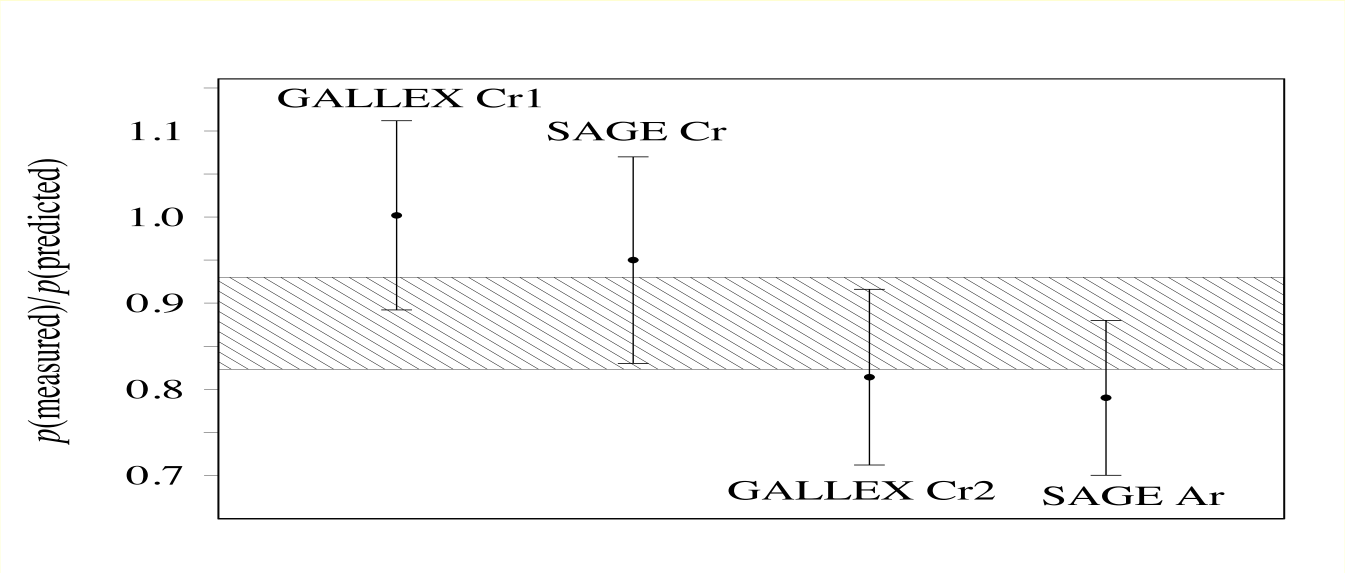
Although the 3ν scheme explains most of the data an increasing number of anomalies is showing up

Future data

A rich plan of new experiments will allow us to explore and chart unknown territories

The hints of light sterile neutrinos

Hint #1: The Gallium calibration anomaly

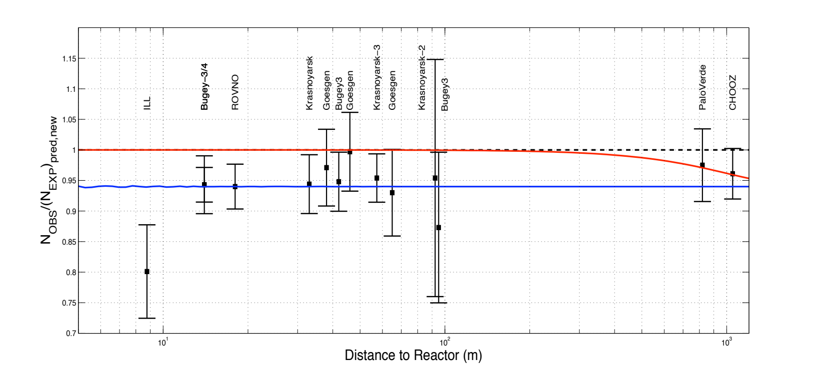


SAGE coll., PRC 73 (2006) 045805

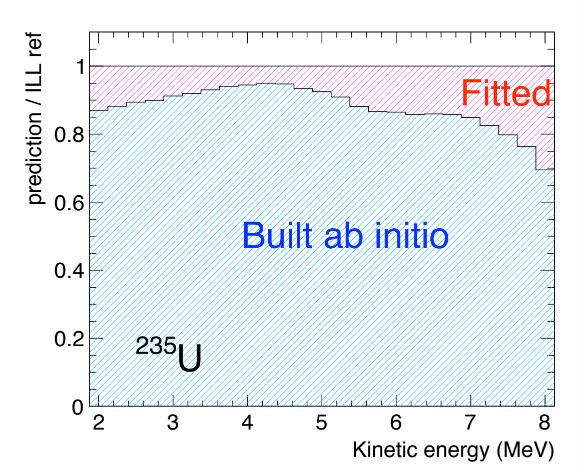
Deficit observed in calibration performed with radioactive sources

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)

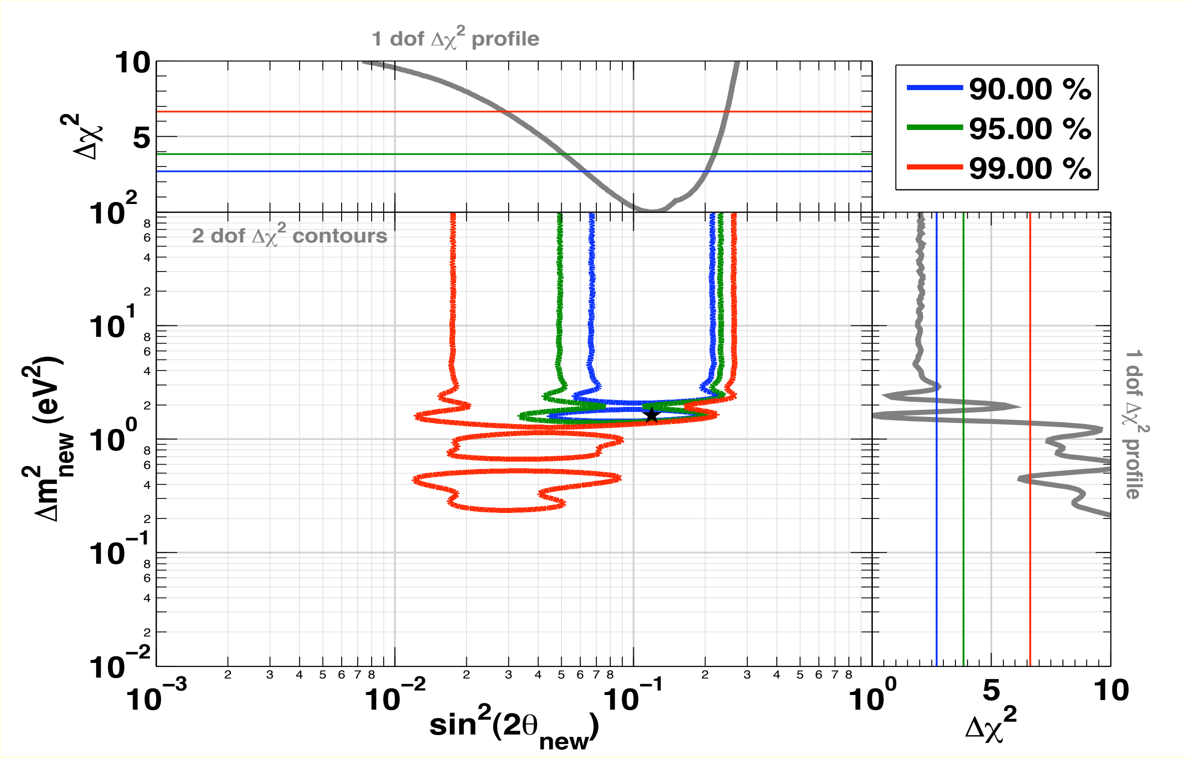


Mueller et al., PRC 83 054615 (2011)
Huber, PRC 84 024617 (2011)

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)

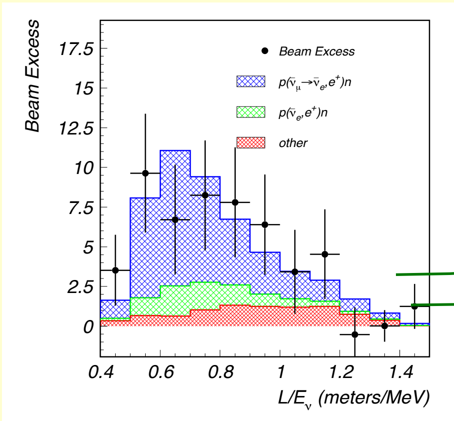
Fitting the short-distance ν_e-disappearance



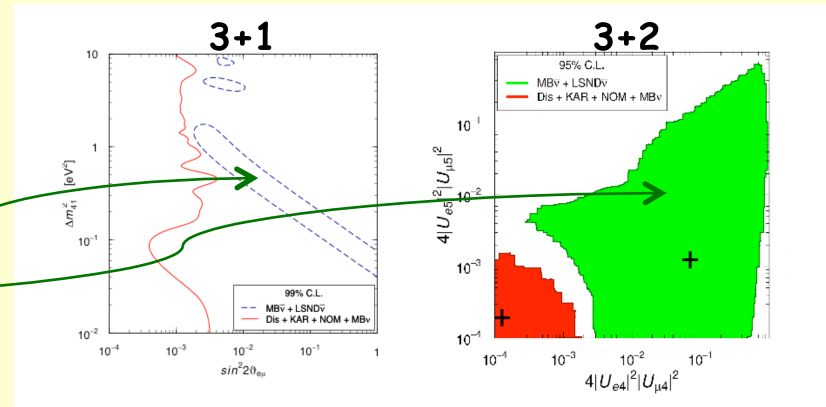
Mention et al., PRD 83 073006 (2011)

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

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:**

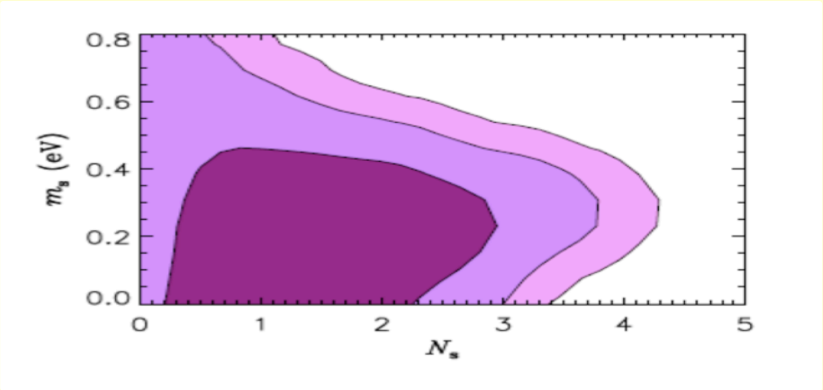
$\nu_\mu \to \nu_e$ positive appearance signal incompatible with joint $\nu_e \to \nu_e$ (positive) & $\nu_\mu \to \nu_\mu$ (negative) searches

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)]

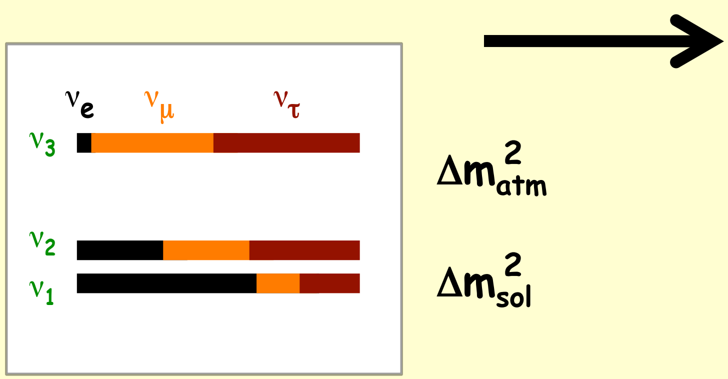
Warnings:

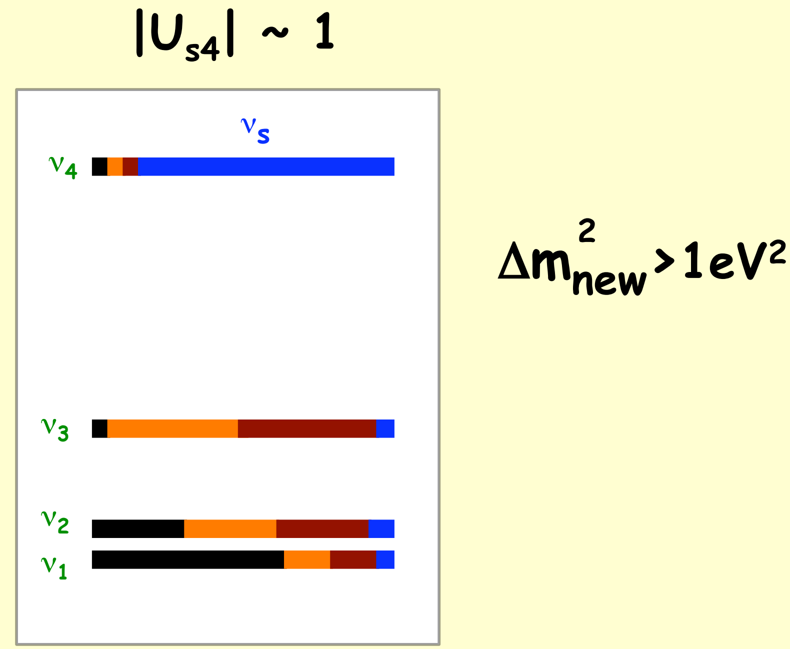
- **eV masses acceptable only abandoning standard ΛCDM**
  (Kristiansen & Elgaroy arXiv:1104.0704 , Hamann et al. arXiv:1108.4136)
- **N_s>1 at BBN strongly disfavored** (Mangano & Serpico PLB 701, 296, 2011)
- **N_s is not specific of ν_s**
  (new light particles, decay of dark matter particles, quintessence, …)

Can we get some information on ν_s from the solar neutrino sector?

The 3+1 scheme:

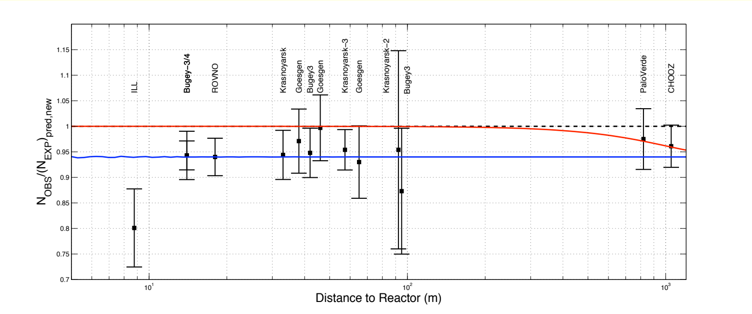
The 4th ν state induces a small perturbation of the 3-flavor framework



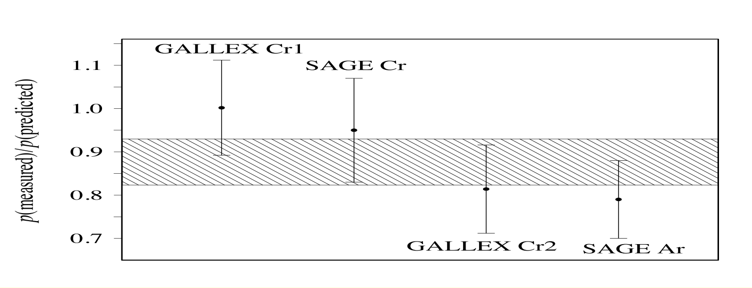


From the "point of view" of the solar doublet (ν_1, ν_2) we expect similar sensitivity to U_{e3} & U_{e4}

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:

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

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

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

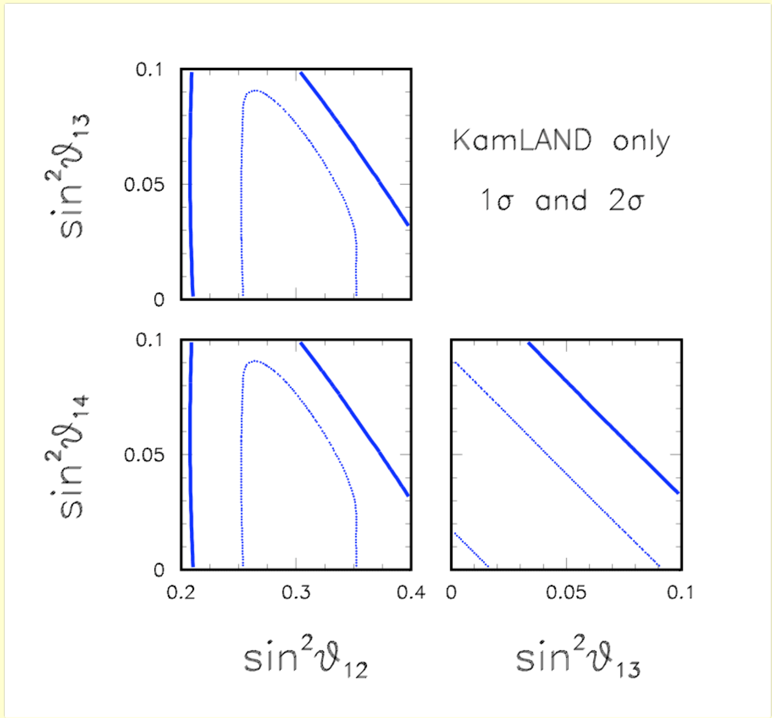
$$\Delta m_{sol}^2 \ll \Delta m_{atm}^2 \ll \Delta m_{new}^2$$

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

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

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

Formally equivalent to NSI
(see later)

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

New MSW dynamical corrections induced by the 4th state are smaller than 1% and too small to be observable (see later).

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)

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

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

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

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

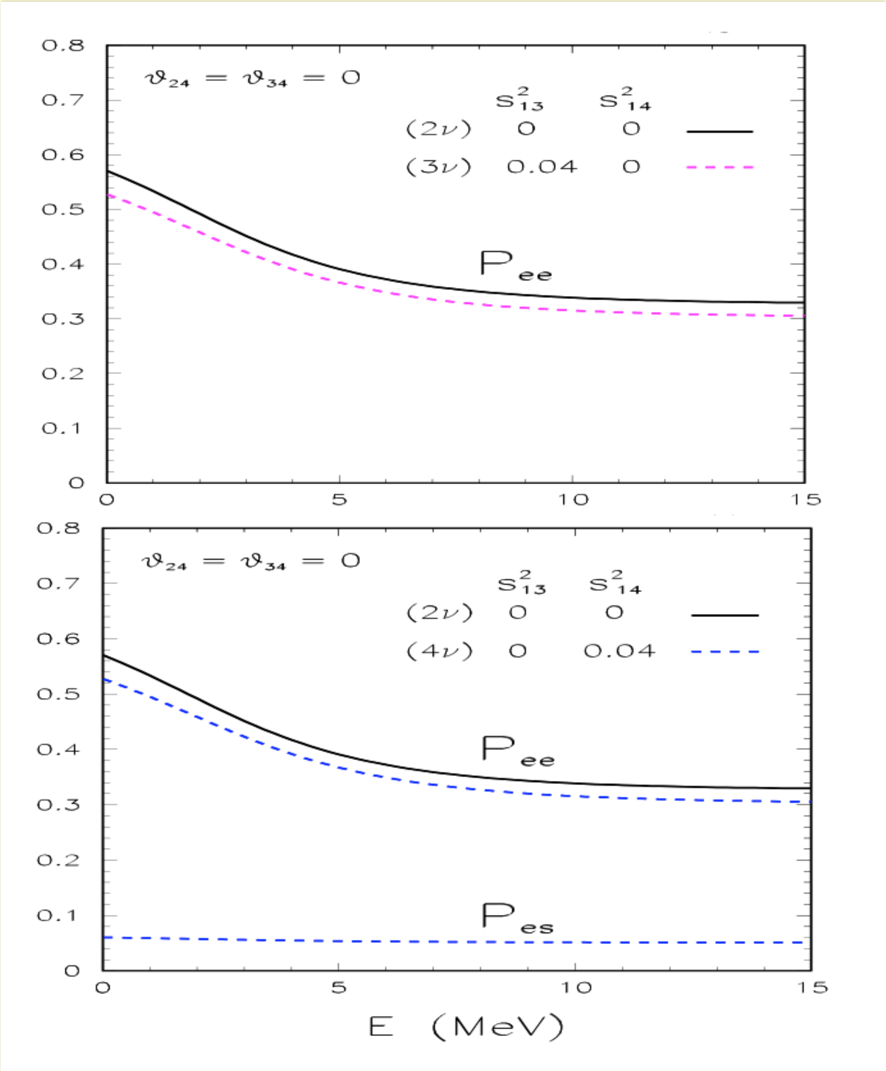
$$\left.\begin{aligned} U_{s1}^2 &= s_{14}^2 c_{13}^2 c_{12}^2 \\ U_{s2}^2 &= s_{14}^2 c_{13}^2 s_{12}^2 \end{aligned}\right\} \sim s_{14}^2$$

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

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

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

Solar ν: Two simple limit cases



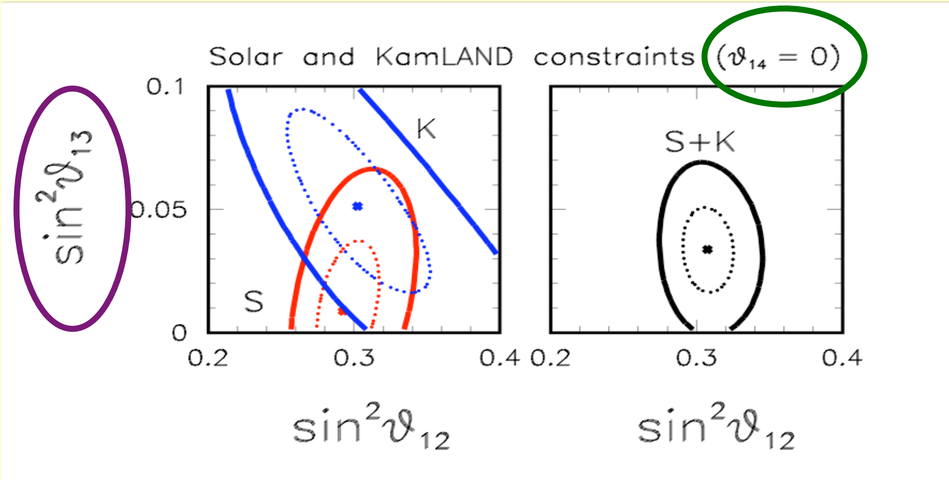
$\theta_{13} \neq 0$ $\theta_{14} = 0$ (3ν)

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

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

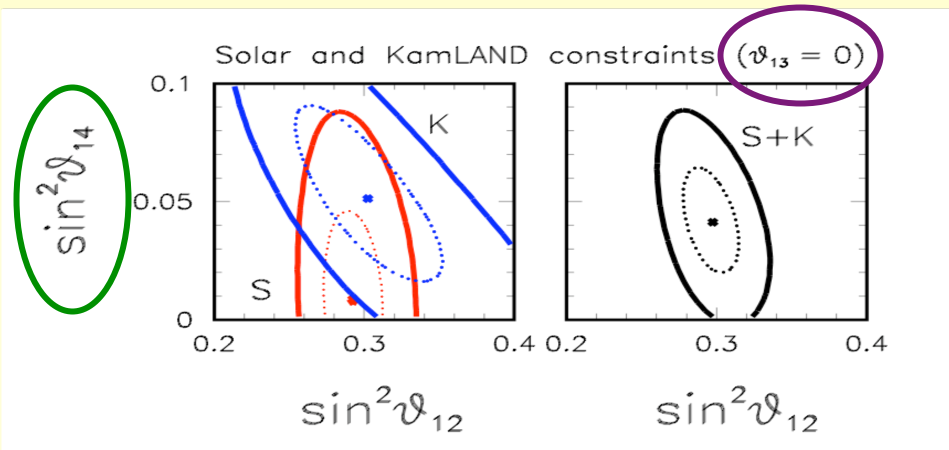
$$\begin{cases} P_{ee} = c_{14}^4 P_{ee}^{2\nu}\Big|_{V \to V c_{14}^2} + s_{14}^4 \\ P_{es} \simeq s_{14}^2 P_{ee}^{2\nu}\Big|_{V \to V c_{14}^2} + s_{14}^2 \end{cases}$$

$(\theta_{13},\theta_{12})$ 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)

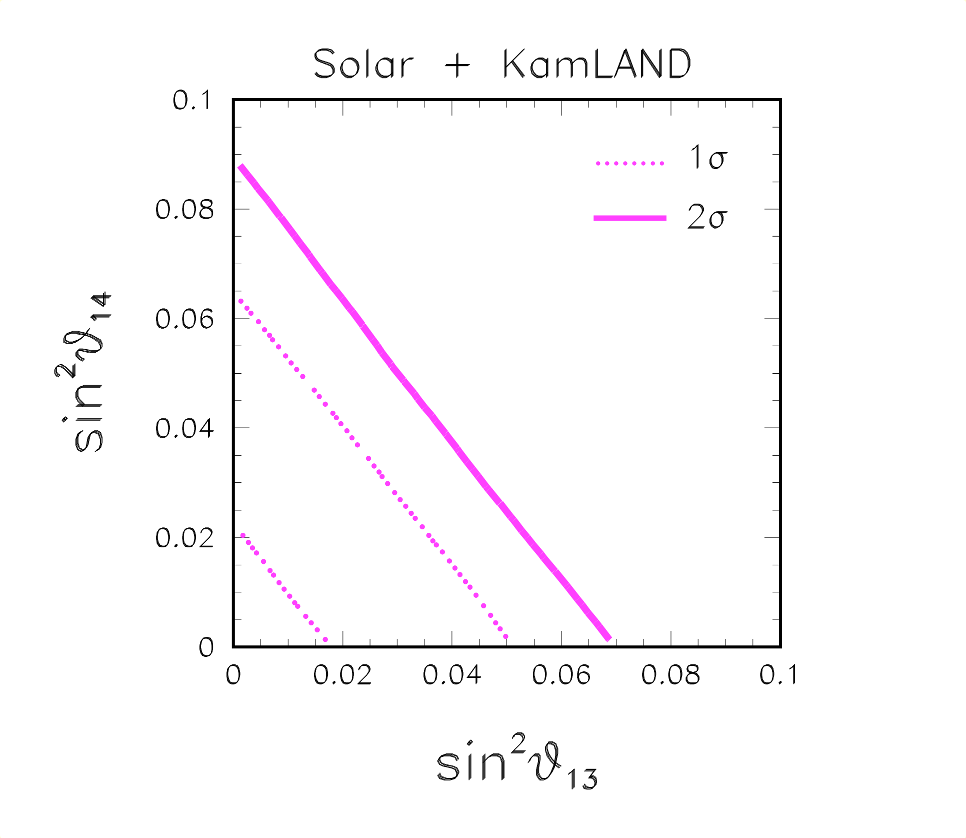


But unfortunately only small differences among 3ν and 4ν

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



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

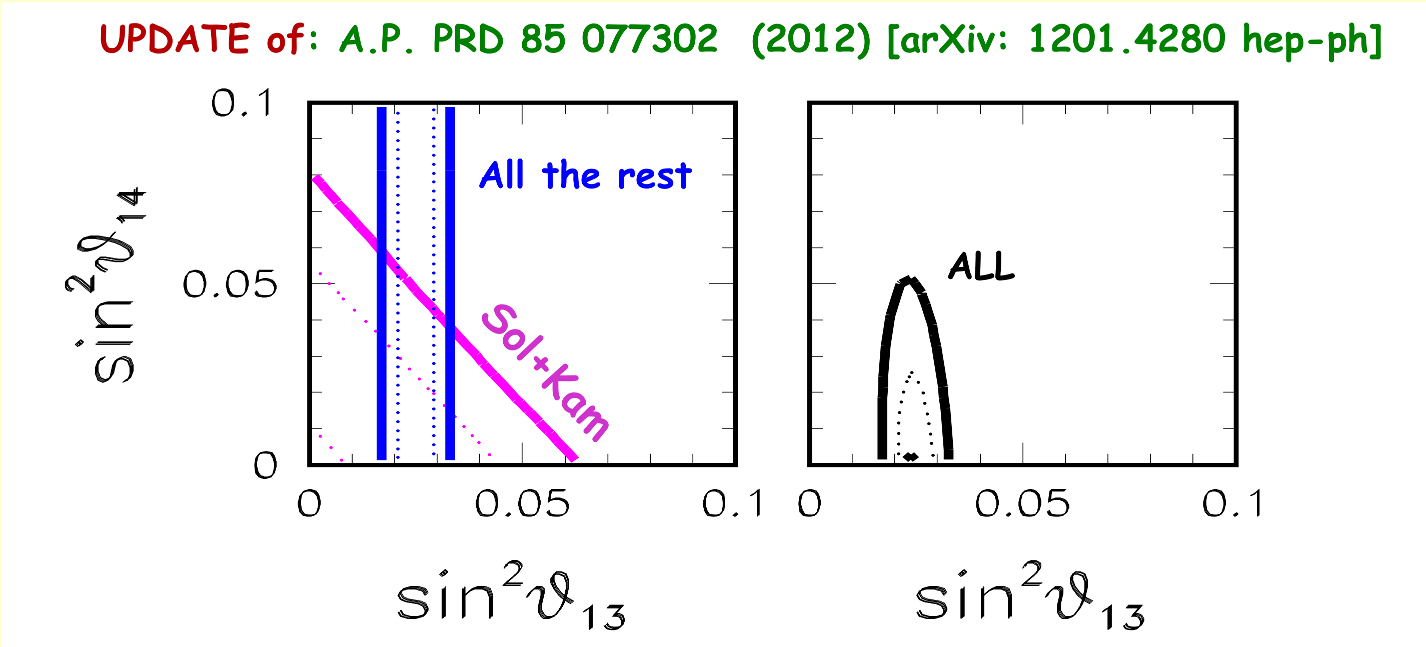
Solar sector essentially sensitive to ~ $U_{e3}^2 + U_{e4}^2$

Hint 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

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

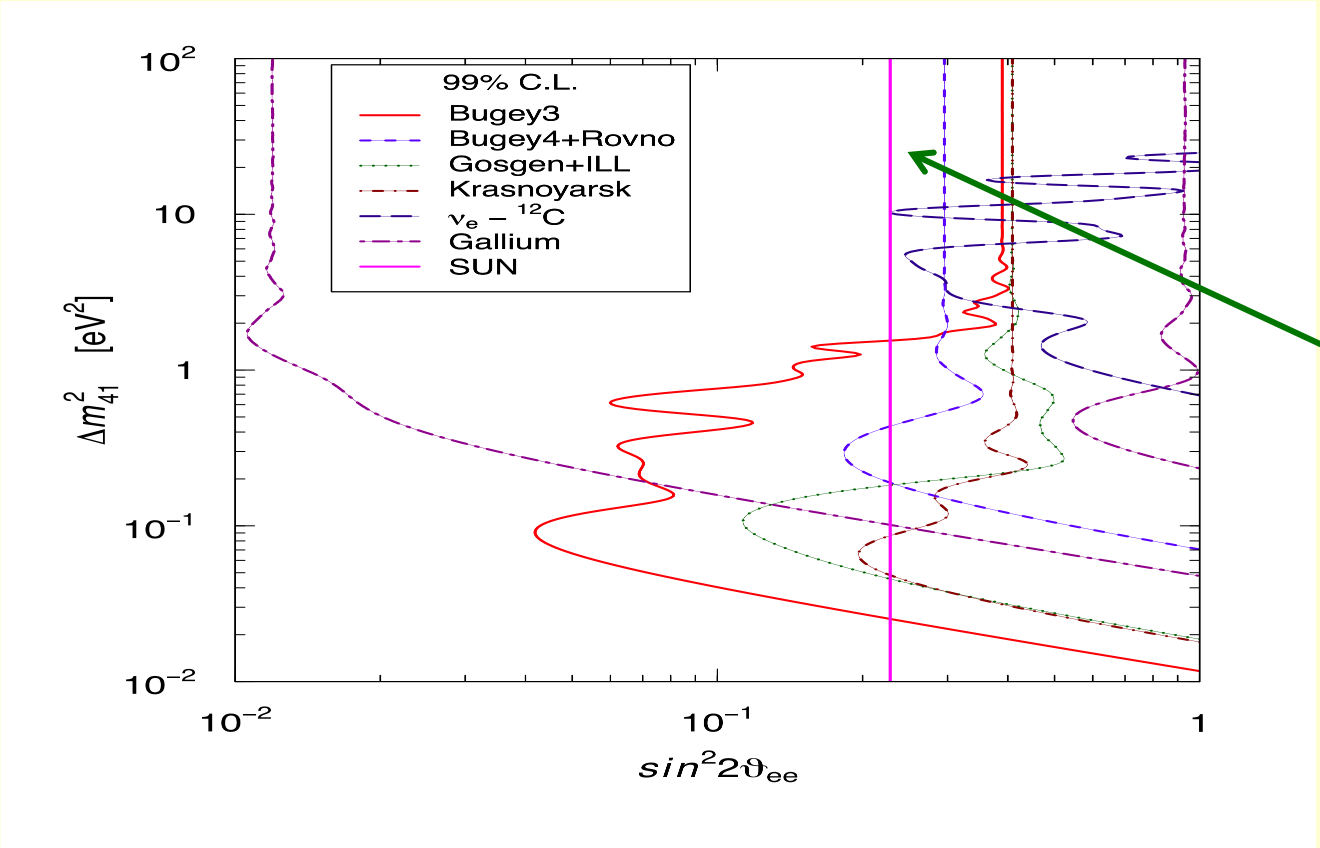
Evidence of θ_{13}>0 kills preference of θ_{14}>0



- Upper limit → $\sin^2\theta_{14} < 0.04$ (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 Δm^2_{14}> 1eV^2

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



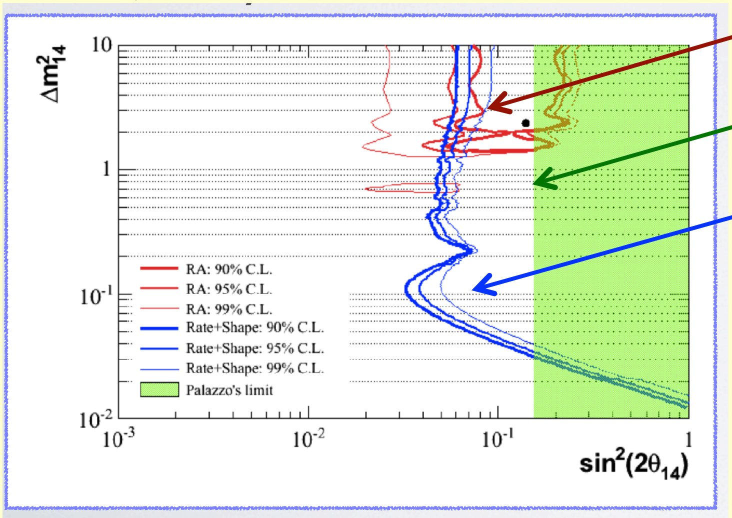
solar bound

Talk by C. Giunti @ νTURN 2012

How to go below the solar upper limit

Make use of a ν source close to a Borexino-like detector

Talk by M. Pallavicini @ Neutrino 2012



Identified by reactor anomaly

Solar upper limit

Borexino sensitivity

The "Borexino Kairos"

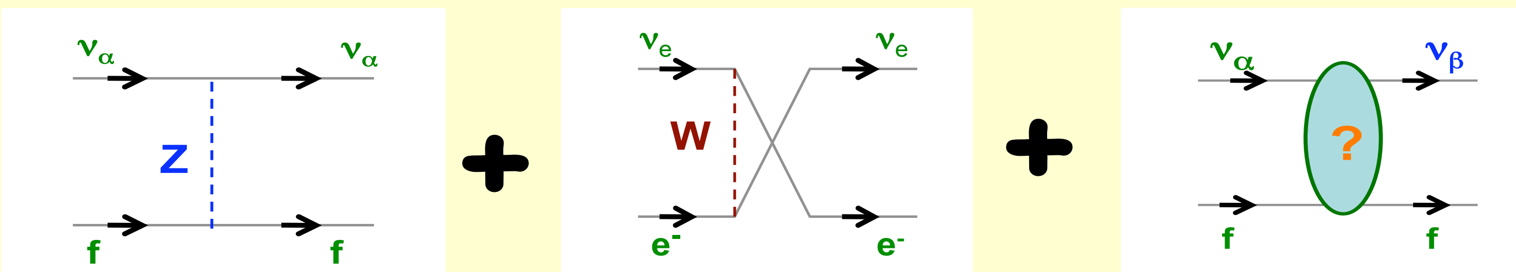
This is the right (and fleeting) moment (kairos) for Borexino to exploit its unique potential!

Kairos (καιρός)

Solar νs as a probe of non-standard MSW dynamics

Coherent forward scattering in the presence of NSI : pictorial view

NC CC NC



Standard interaction terms **NSI term(s)**

NSI described by an effective four-fermions operator

$$\mathrm{O}_{\alpha\beta}^{\mathrm{NSI}} \sim \overline{\nu}_\alpha \nu_\beta \overline{f} f$$

$(\alpha, \beta) = e, \mu, \tau$

$f \equiv (e, u, d)$

Coherent forward scattering in the presence of NSI : math. view

Evolution in the flavor basis:

$$i\,\frac{d}{dx}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = H\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

H contains three terms:

$$H = H_{\rm kin} + H^{\rm std}_{\rm dyn} + H^{\rm NSI}_{\rm dyn}$$

Kinematics

$$H_{\rm kin} = U\begin{pmatrix}-\delta k/2 & 0 & 0\\ 0 & +\delta k/2 & 0\\ 0 & 0 & k/2\end{pmatrix}U^\dagger$$

$$\delta k = \delta m^2/2E$$

$$k = m^2/2E$$

Standard MSW dynamics

$$H^{\rm std}_{\rm dyn} = {\rm diag}(V,\,0,\,0)$$

$$V(x) = \sqrt{2}G_F N_e(x)$$

Non-standard dynamics

$$(H^{\rm NSI}_{\rm dyn})_{\alpha\beta} = \sqrt{2}\,G_F\,N_f(x)\epsilon_{\alpha\beta}$$

Reduction to an effective two flavor dynamics

One mass scale approximation: $\Delta m^2 \to \infty$

$$P_{ee} = c_{13}^4 P_{ee}^{\rm eff} + s_{13}^4$$

survival probability

$$i\,\frac{d}{dx}\begin{pmatrix}\nu_e\\ \nu_a\end{pmatrix} = H^{\rm eff}\begin{pmatrix}\nu_e\\ \nu_a\end{pmatrix}$$

effective evolution

$$H^{\rm eff} = V(x)\begin{pmatrix}c_{13}^2 & 0\\ 0 & 0\end{pmatrix} + \sqrt{2}G_f N_d(x)\begin{pmatrix}0 & \varepsilon\\ \varepsilon & \varepsilon'\end{pmatrix}$$

Formally similar to 4ν effects

For $\theta_{13} = 0$:

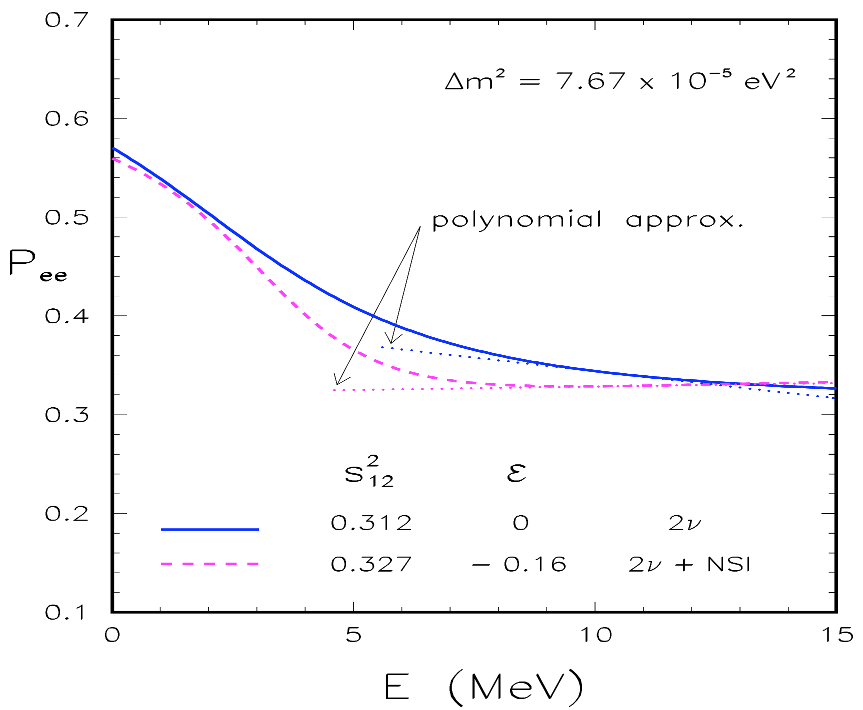
$$\varepsilon = -\varepsilon_{e\mu}c_{23} - \varepsilon_{e\tau}s_{23}$$

$$\varepsilon' = -2\varepsilon_{\mu\tau}s_{23}c_{23}$$

$\varepsilon_{\mu\tau}$ ~ 0 (strong bounds from atmospheric ν)

Parameter space: $[\delta m^2, \theta_{12}, \varepsilon]$

Impact of NSI on the solar spectrum



A.P, PRD 83, 101701 (2011) (Rapid Communications)

$$\epsilon = -0.16$$

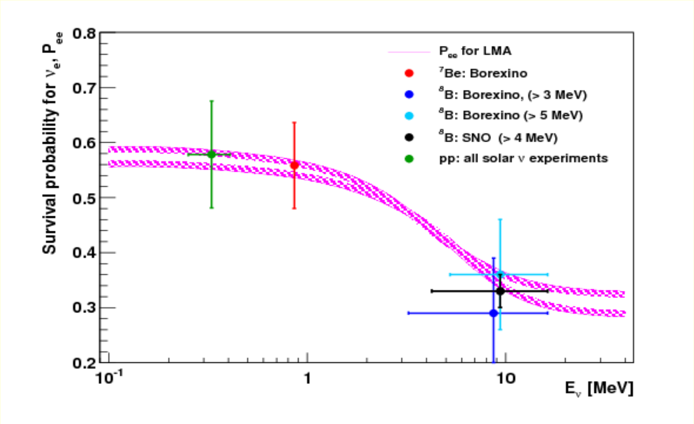
$$(\epsilon_{e\tau} = +0.23)$$

for interaction with d-quark

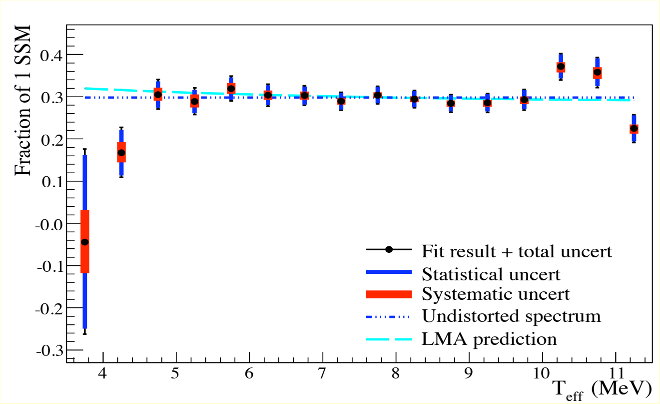
NSI with a size of ~10% are needed to produce appreciable effects:
4ν effects induced by sterile neutrinos (~1%) are thus unobservable

NSIs can help to explain the anomalous spectrum behavior

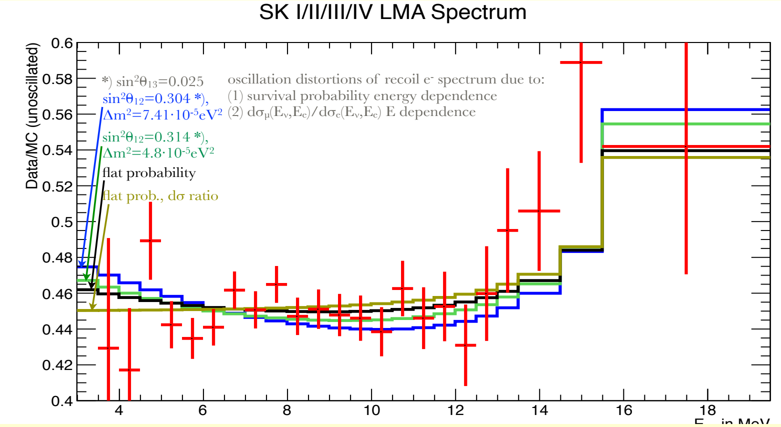
BOREXINO



SNO



SK



This hypothesis can be tested quantitatively

The response functions of SK, SNO, Borexino are centered around E_0 = 10 MeV, where they have maximal sensitivity

Assuming a regular behavior for the survival probability we can parameterize its high energy behavior as a second order polynomial

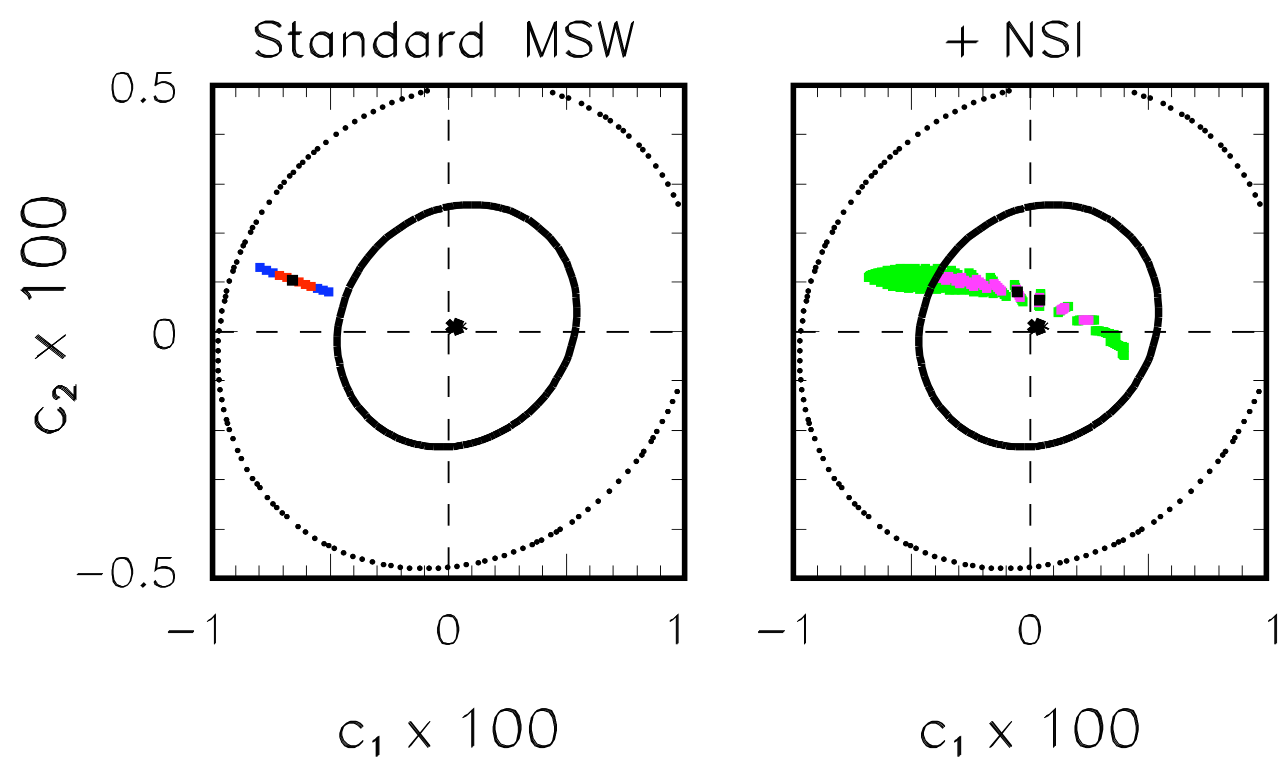
$$P_{ee} = c_0 + c_1 (E-E_0) + c_2 (E-E_0)^2$$

It is then possible to:

1) Extract the coefficients from the combination of all the experiments sensitive to the high-energy neutrinos.

2) Check where a given theor. model (standard MSW,+NSI, etc.) "lives" in the space of the coefficients c_i's.

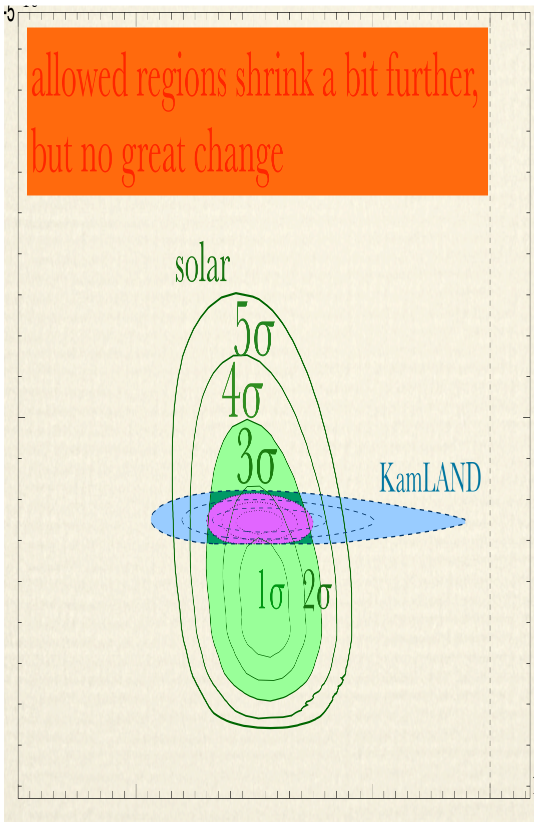
Constraints on [c1,c2]

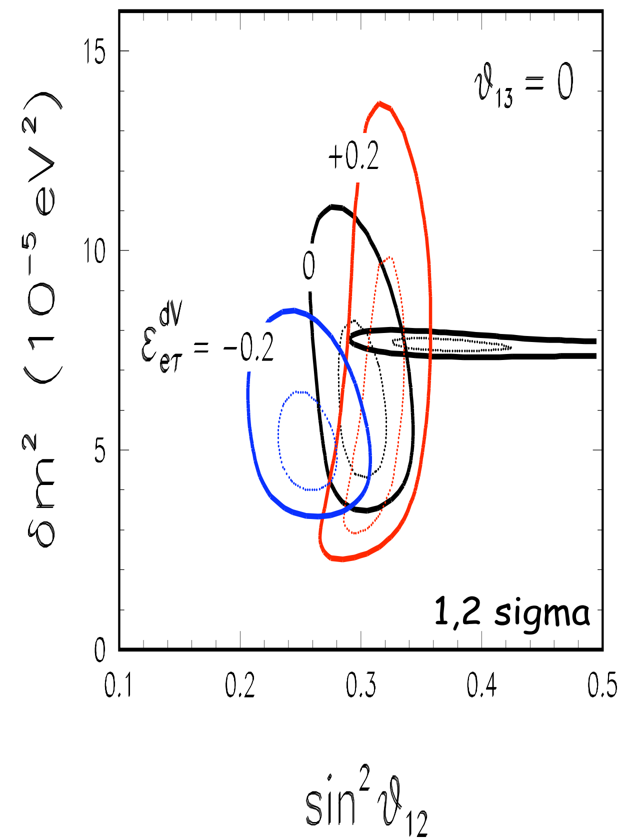


A.P, PRD 83, 101701 (2011) (Rapid Communications) arXiv:1101.3875

NSI gains a $\Delta\chi^2$ ~ -2.0 from better description of the spectrum

NSI can also alleviate tension in δm^2 determinations





M. Smy @ Neutrino 2012

A.P. and J.W.F. Valle, PRD 80, 091301 (2009)

Summary

- Solar νs gave the first indication of non-zero θ_{13} and constitute a precision-machine usable to test new physics.

- An important example is provided by sterile νs, now at the center of intense investigation. Taking into account that θ_{13}>0, the solar sector enables us to establish:

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

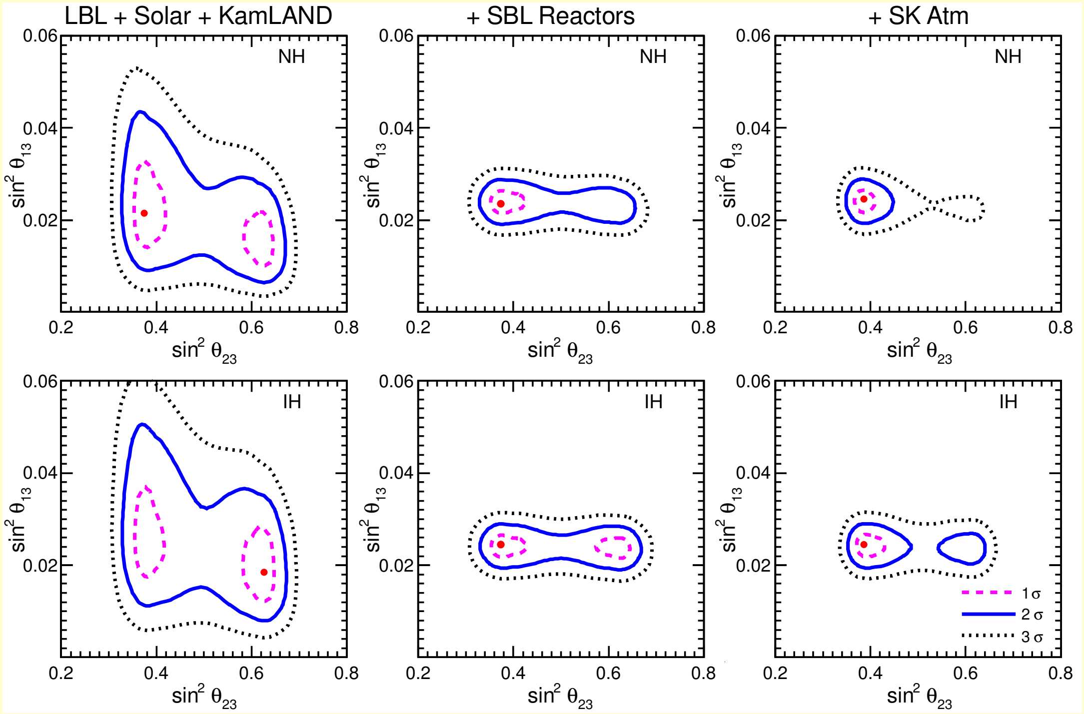
- A second example is given by NSI. The current analyses show NSI may help in explaining two emergent anomalies.

- New experiments are indispensable to settle both issues.

Thank you
for
your attention!

Spares

How the indication of $\theta_{23}<\pi/4$ emerges



LBL introduce:
- θ_{23}-θ_{13} anticorrelation
- prefer. non-maximal θ_{23}
- weak octant asymmetry

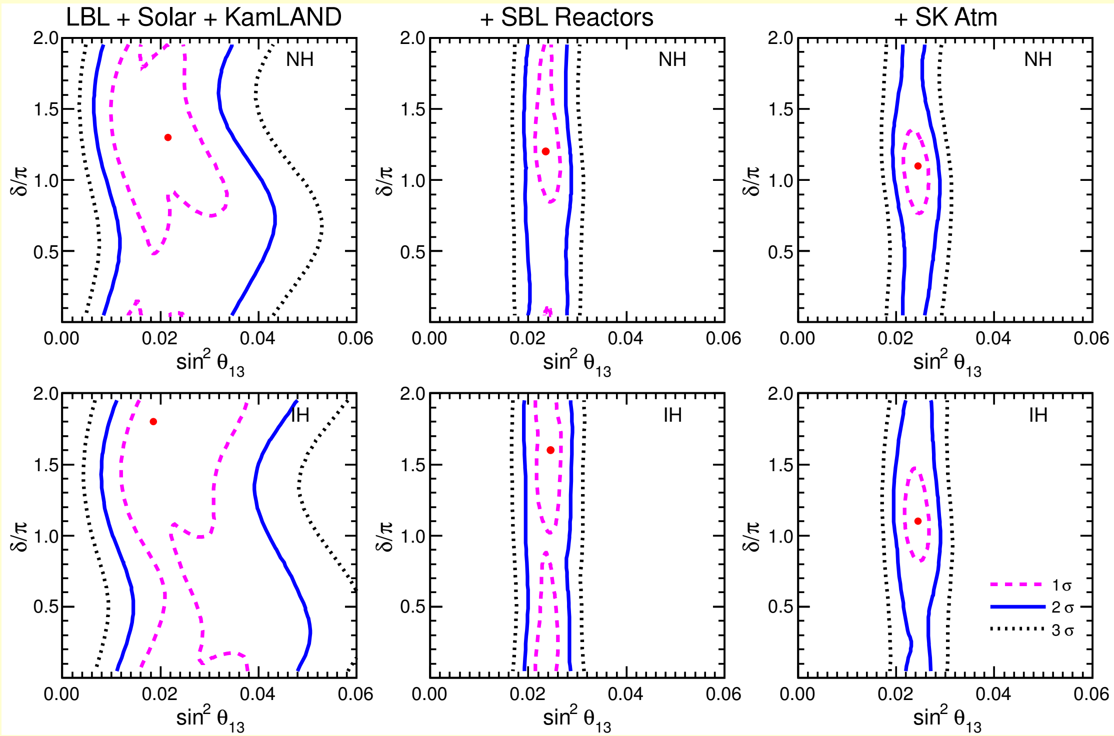
Once reactors fix θ_{13} the octant asymmetry is enhanced

Atm. further enhance octant asymmetry

Global indication of $\theta_{23}<\pi/4$ emerges

Fogli, lisi, Marrone, Montanino, A.P., Rotunno, PRD 86 013012 (2012)
(includes Neutrino 2012 results)

First information about δ



LBL are almost insensitive to δ

Weak sensitivity emerges once reactors fix θ_{13}

Atm. enhance sensitivity

Global hint of δ ~ π emerges

Fogli, lisi, Marrone, Montanino, A.P., Rotunno, PRD 86 013012 (2012)
(includes Neutrino 2012 results)

If δ ~ π confirmed it would indicate U ~ real and a small J
… and a long and difficult way towards CPV observation!