DPG-Frühjahrstagung Dresden, 5/3/2013

Exploring new physics with solar νs

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Outline

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

2) Intermezzo
Why so much attention on one angle?

3) Beyond three neutrino families
Solar νs as a probe of new sterile states

Introduction

The 3ν mass-mixing properties

The PMNS mixing matrix

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i}|\nu_i\rangle$$

$$U = O_{23}\Gamma_\delta O_{13}\Gamma^\dagger_\delta O_{12}$$

$$\Gamma_\delta = \mathrm{diag}(1, 1, e^{+i\delta})$$

$$\delta \in [0, 2\pi]$$

Dirac CP-violating phase δ

U is non-real if δ ≠ (0, π)

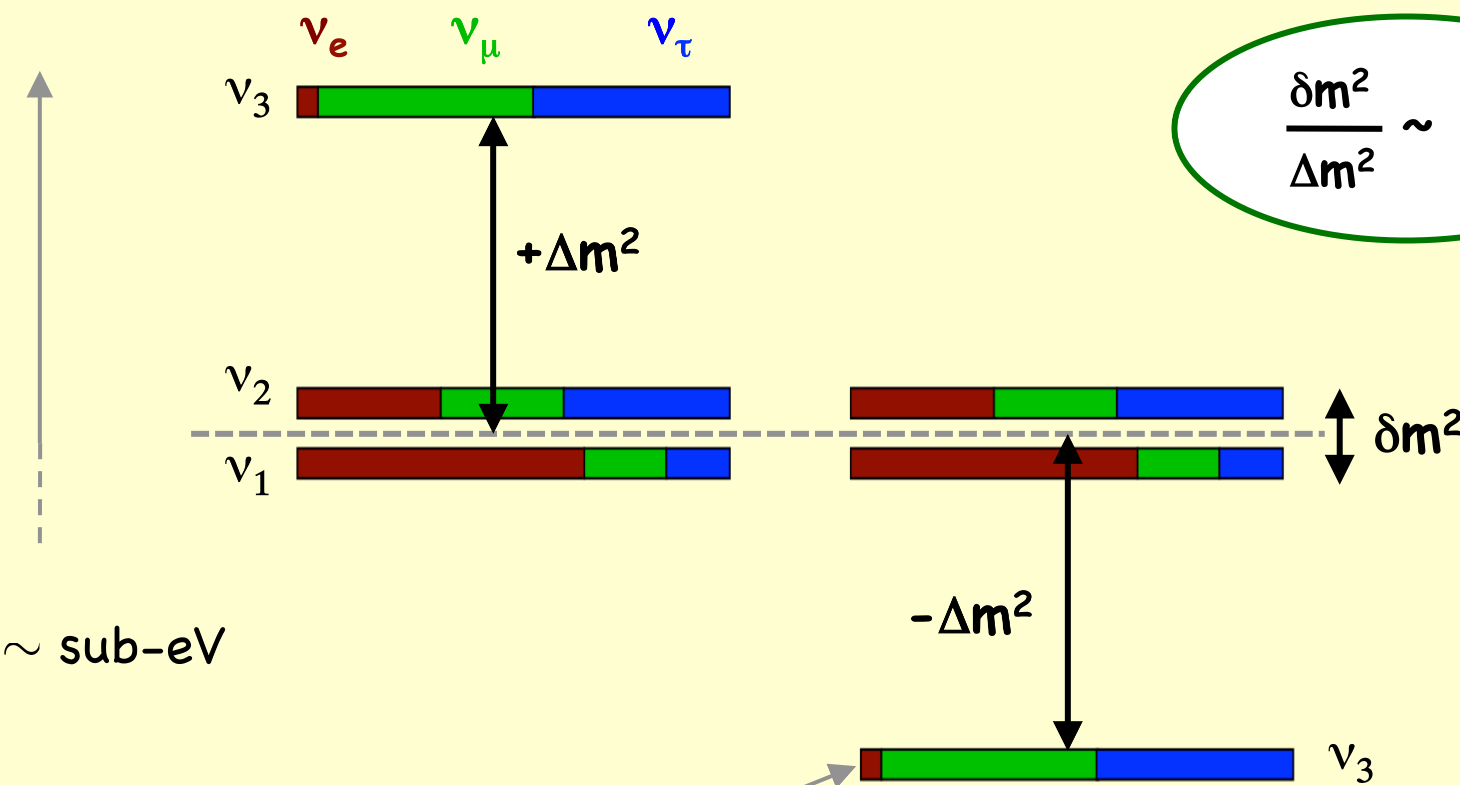
Explicit form: $$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$s_{23}^2 \sim 0.39$ $s_{13}^2 \sim 0.024$ $s_{12}^2 \sim 0.31$

$\theta_{23} \sim 39°$ $\theta_{13} \sim 9°$ $\theta_{12} \sim 34°$

The neutrino mass spectrum

NH or IH ?



$$\frac{\delta m^2}{\Delta m^2} \sim 0.03$$

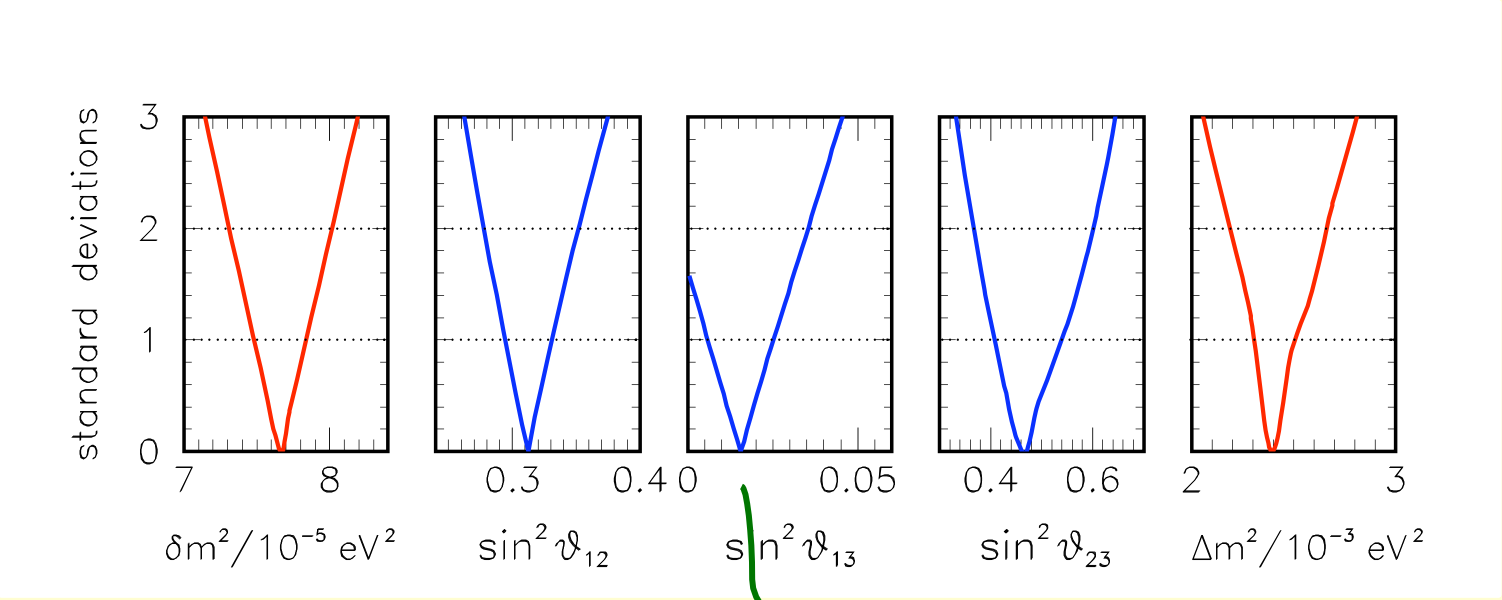
$\sum m_i \sim$ sub-eV

$|U_{e3}|^2 \equiv \sin^2\theta_{13} \simeq 0.024$

θ_{13} is non-zero and relatively large

Solar νs as harbingers of the discovery

2008: First indication of $\theta_{13}>0$

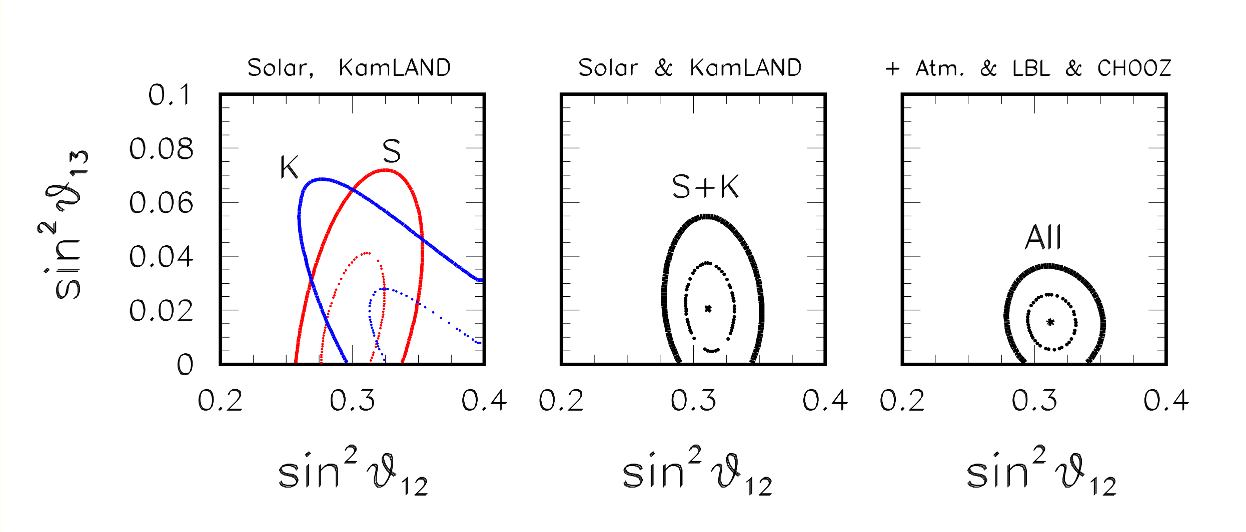


preference for $\theta_{13}>0$

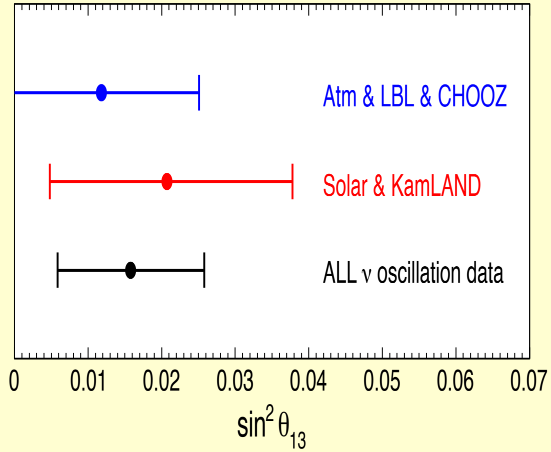
The global analysis provided a preference for θ_{13} > 0 at 90% C.L.

Fogli, Lisi, Marrone, A.P, Rotunnno, PRL 101, 141801 (2008)

Indication came from two independent hints



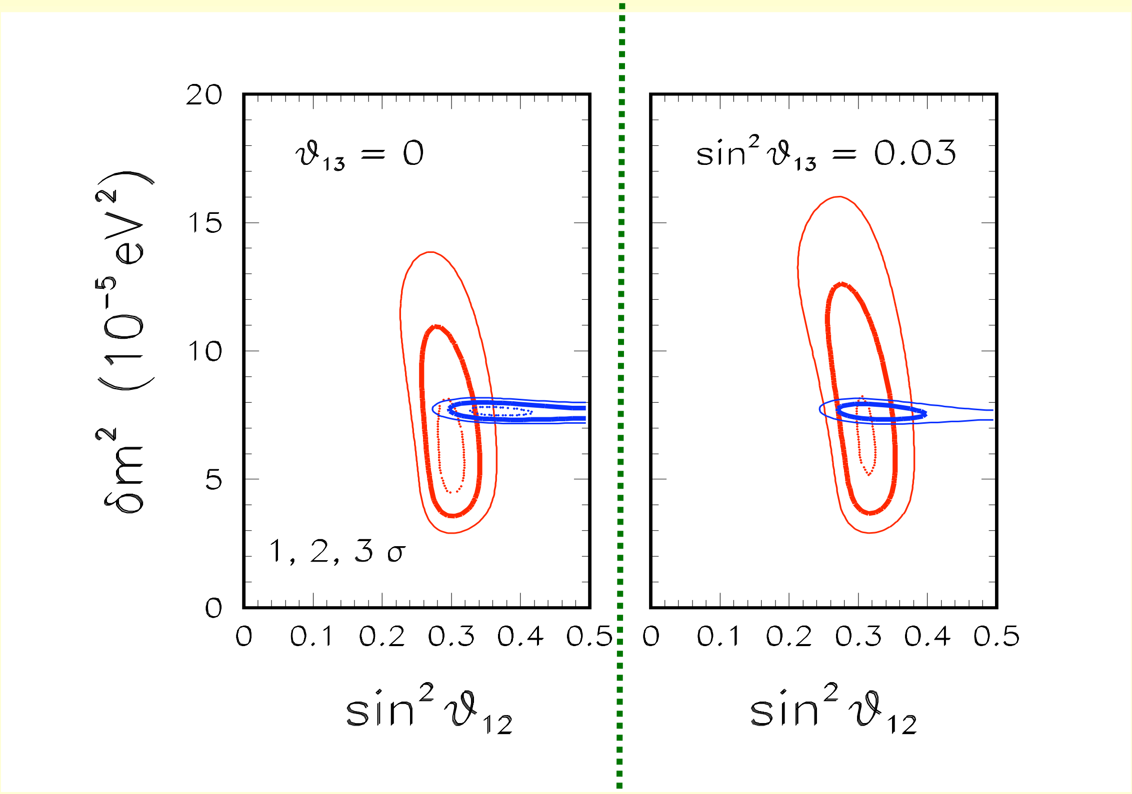
Fogli, Lisi, Marrone, A.P., Rotunno, Phys. Rev. Lett. 101, 141201 (2008)



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

Role of solar and KamLAND crucial

$\theta_{13} = 0$



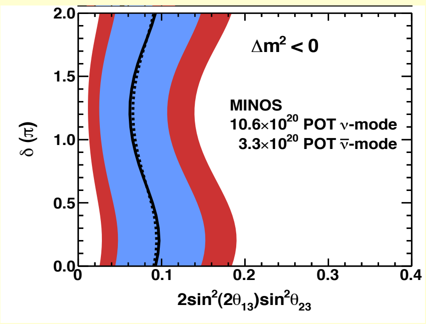
$\theta_{13} > 0$

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

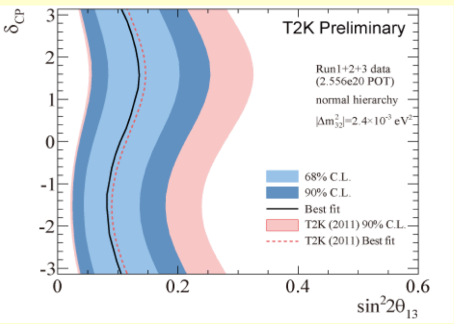
Indication irrefutably confirmed in 2012

(θ_{13} non-zero at the ten sigma level, $\theta_{13} \sim 9^{\circ}$)

MINOS

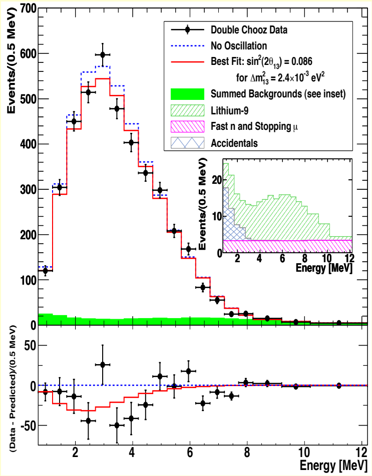


T2K

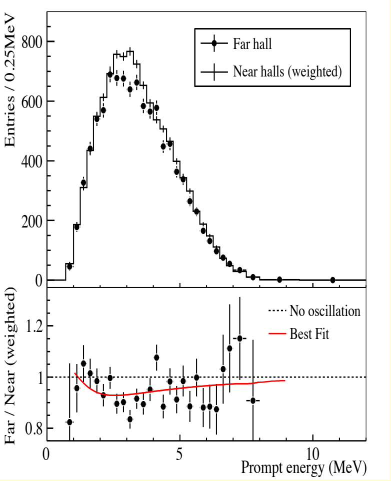


Accelerator experiments

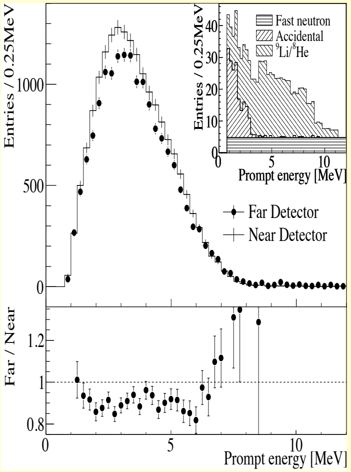
Double-CHOOZ



Daya Bay



RENO



Reactor experiments

Intermezzo

Why so much attention on one angle?

$\theta_{13}>0$: precondition for leptonic CPV

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

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

In the standard parameterization the expression of J is:

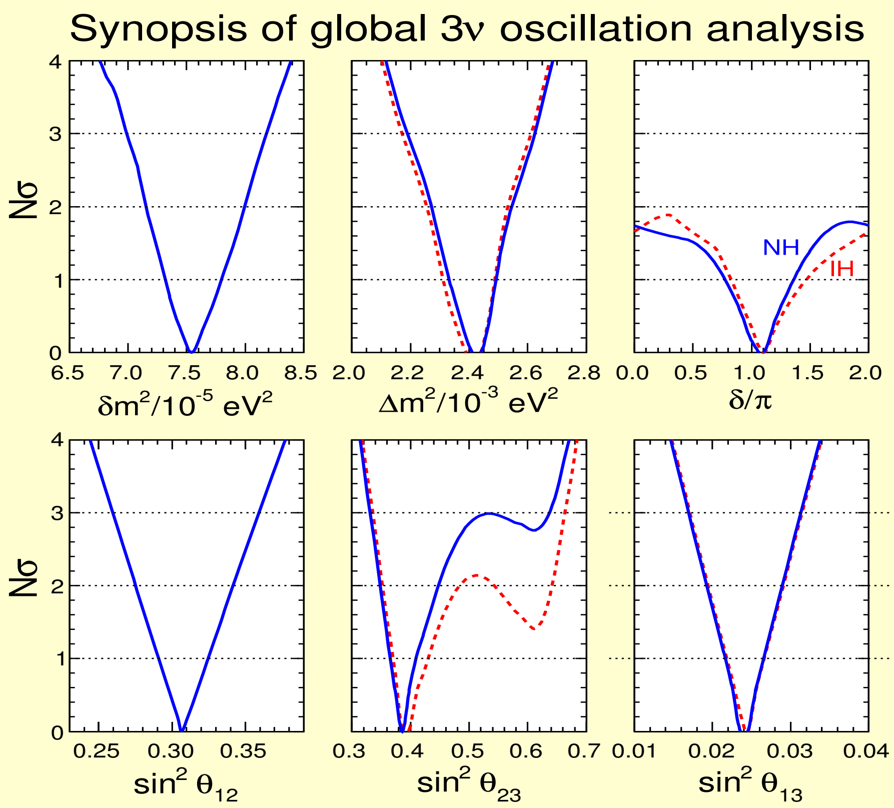
$$J = \frac{1}{8} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos\theta_{13} \sin\delta$$

Only if all three $\theta_{ij} \neq 0$ the CP symmetry can be violated

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| may be as large as 3×10^{-2} : it will depend on δ …

… first information about δ



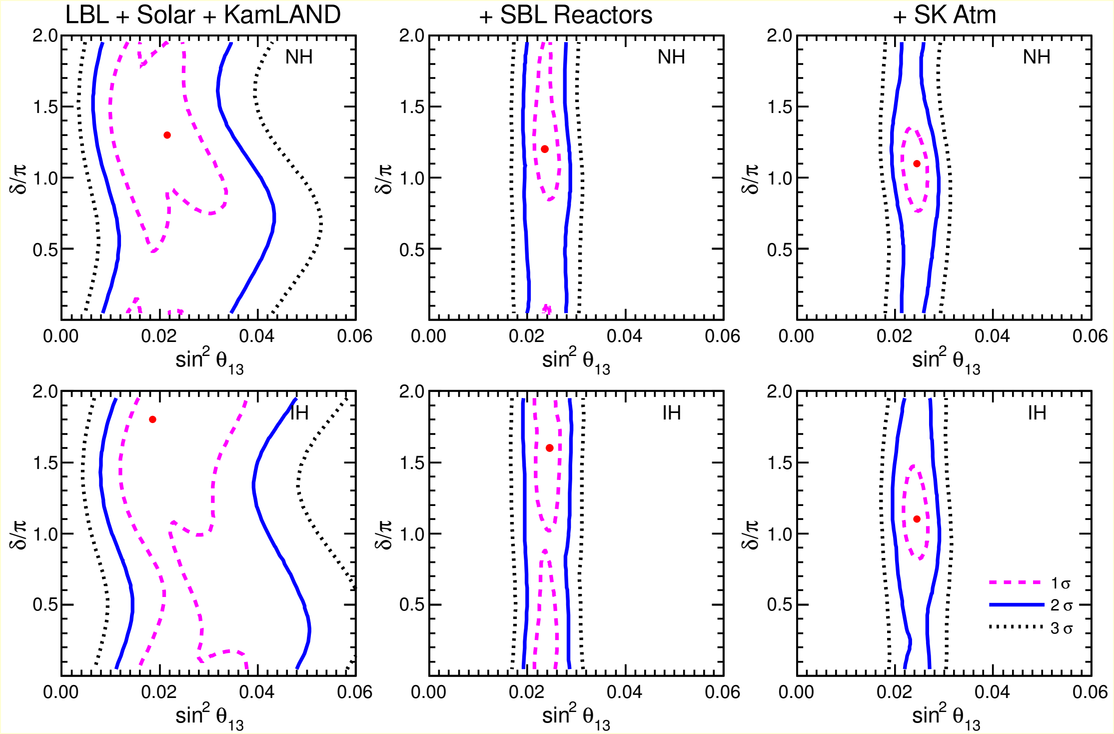
Hint of $\delta \sim \pi$

Indication of non-maximal θ_{23} ($\theta_{23} < \pi/4$)

No sensitivity to mass hierarchy

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

Where the hint of $\delta \sim \pi$ come from?



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

LBL are almost insensitive to δ

Weak sensitivity emerges once reactors fix θ_{13}

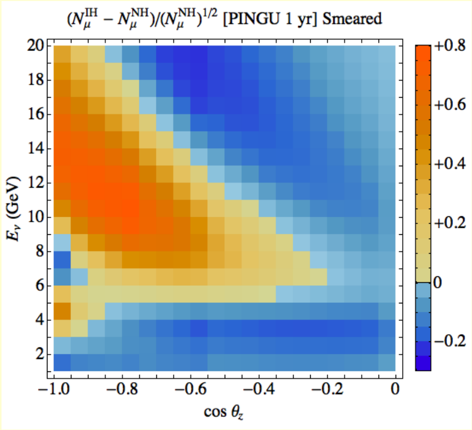
Atm. enhance sensitivity

Global hint of $\delta \sim \pi$ emerges

If $\delta \sim \pi$ confirmed it would indicate U ~ real and a small J
… and a long and difficult way towards CPV observation!

θ_{13}>0: opportunity to determine νMH

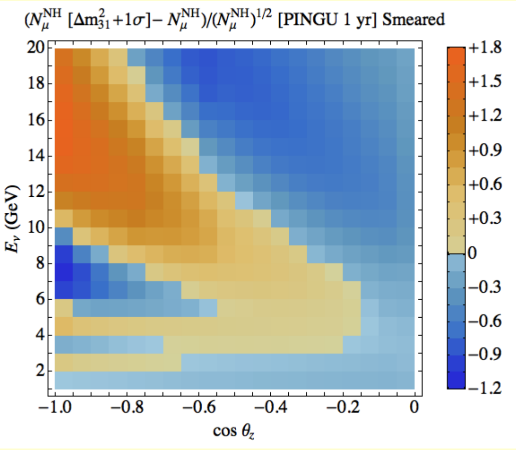
PINGU @ IceCube is a promising option



Akhmedov et al 1205.7071 hep-ph

For θ_{13} >0 one expects an interference between the MSW matter potential felt by atm. νs traversing the earth and $\pm\Delta m^2$

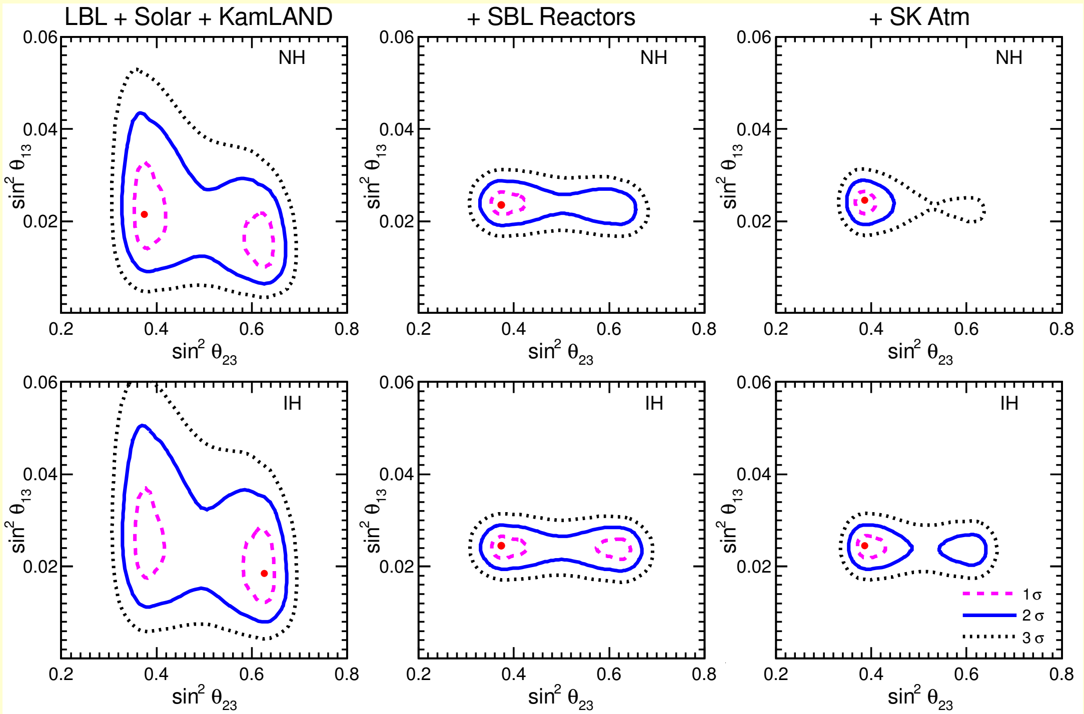
Signature in the energy/zenith-angle dist.



However, degeneracies exist due to uncertainties on mass-mixing parameters, which can partly mimic the signature

Several sensitivity studies under way both by the IceCube collab. and other groups

Precise knowledge of θ_{13} important for θ_{23}



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

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

due to synergy of reactor, accelerator and atmospheric data

Beyond three neutrino families?

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 are showing up

New data expected

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

Why introduce new light ν species?

A few anomalies seem to point towards sterile neutrino species ν_s's [singlets of U(1)xSU(2)]

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

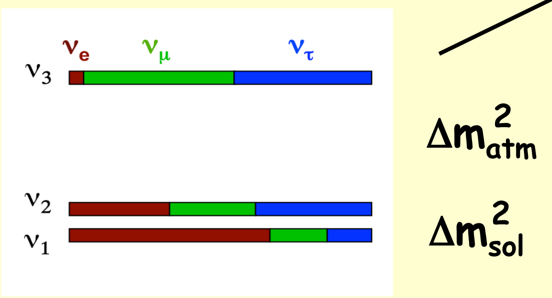
(II) Indications of "warm" dark matter from astrophysical "small-scale" problems (keV ν_s's are a good option)

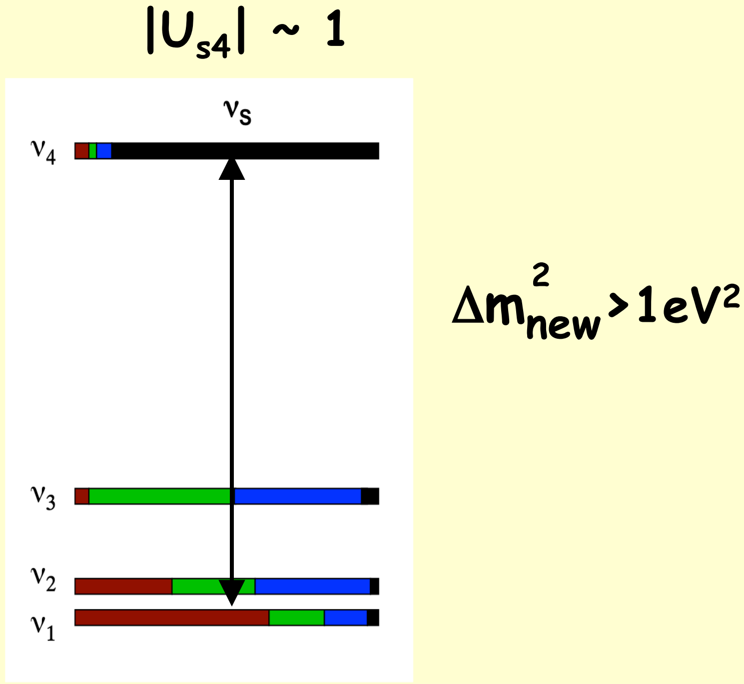
I will discuss only eV ν_s's

The success of the 3ν scheme must be preserved

The 3+1 scheme

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



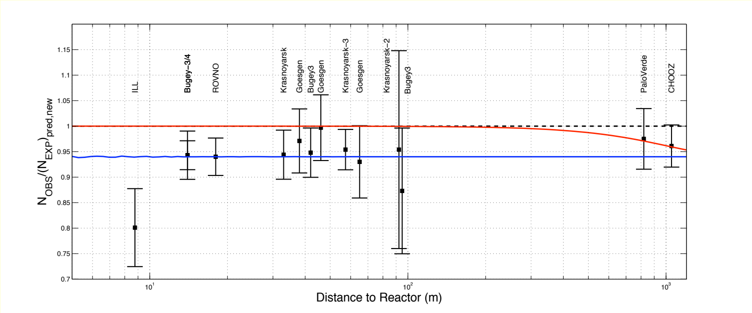


Leading effects are expected in short-baseline (SBL) reactor and accelerator experiments and in cosmology

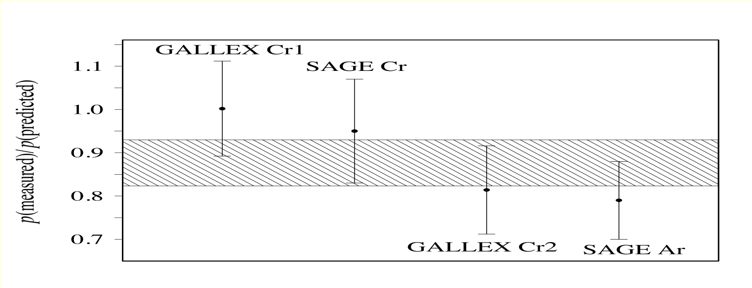
Subleading effects expected in "ordinary" data (solar, atm., LBL-react, LBL-accel.) used in the 3ν fits

I) The reactor and gallium anomalies

(SBL $\nu_e \rightarrow \nu_e$ disappearance)



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:

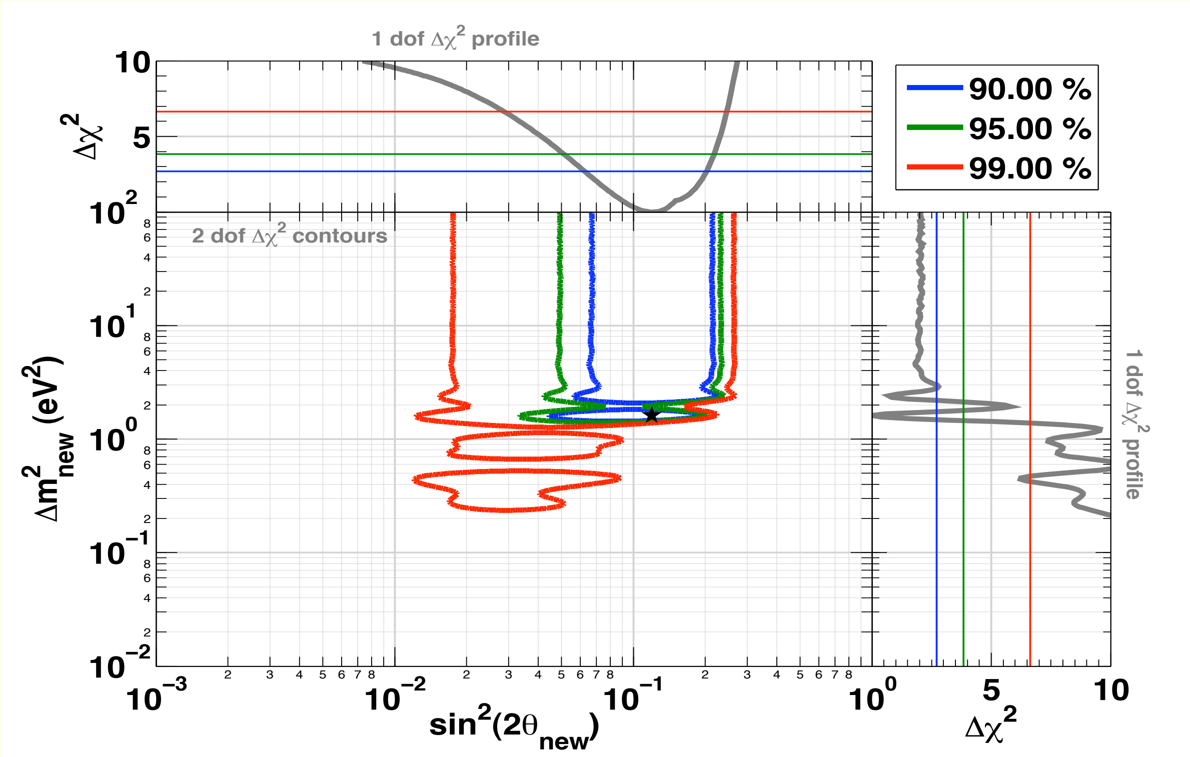
$$P_{ee} = 1 - 4 \sum_{j>k} U^2_{ej} U^2_{ek} \sin^2 \frac{\Delta m^2_{jk} L}{4E}$$

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

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

Warning: both are mere total rate issues
The culprit may be hidden in systematics

Fitting them to sterile ν oscillations

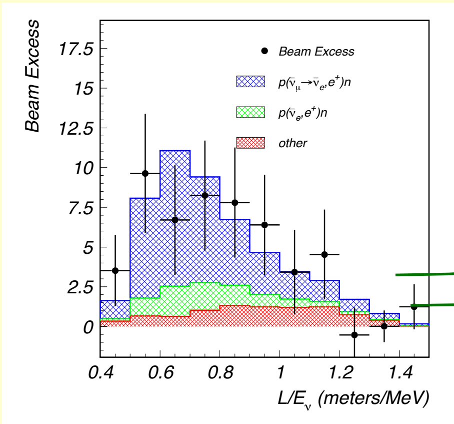


Mention et al., PRD 83 073006 (2011)

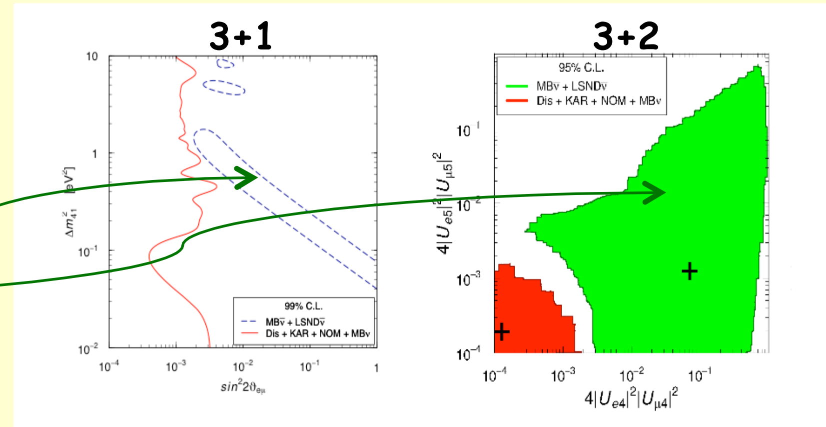
$$\sin^2 2\theta_{new} \simeq 0.1 \qquad\qquad \Delta m^2_{new} \gtrsim 1\ \mathrm{eV}^2$$

II) The accelerator anomaly

(SBL $\nu_\mu \rightarrow \nu_e$ appearance)



LSND, PRL 75 (1995) 2650



Giunti and Laveder, arXiv:1107.1452

Warning:

In tension with disappearance searches:

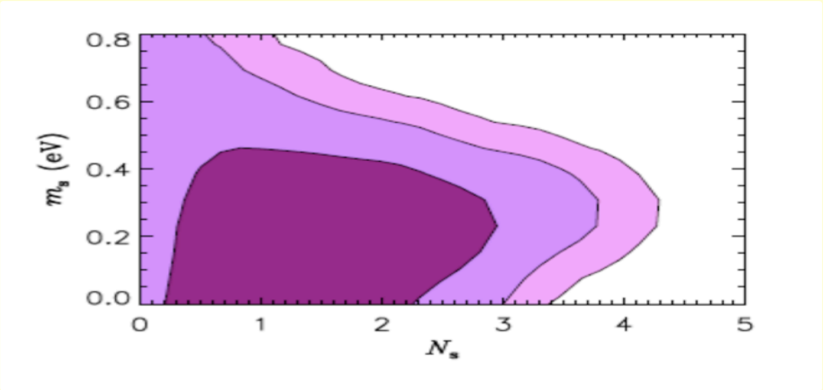
ν_μ->ν_e positive appearance signal incompatible with joint ν_e->ν_e (positive) & ν_μ->ν_μ (negative) searches

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 %

III) The "dark radiation" anomaly



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

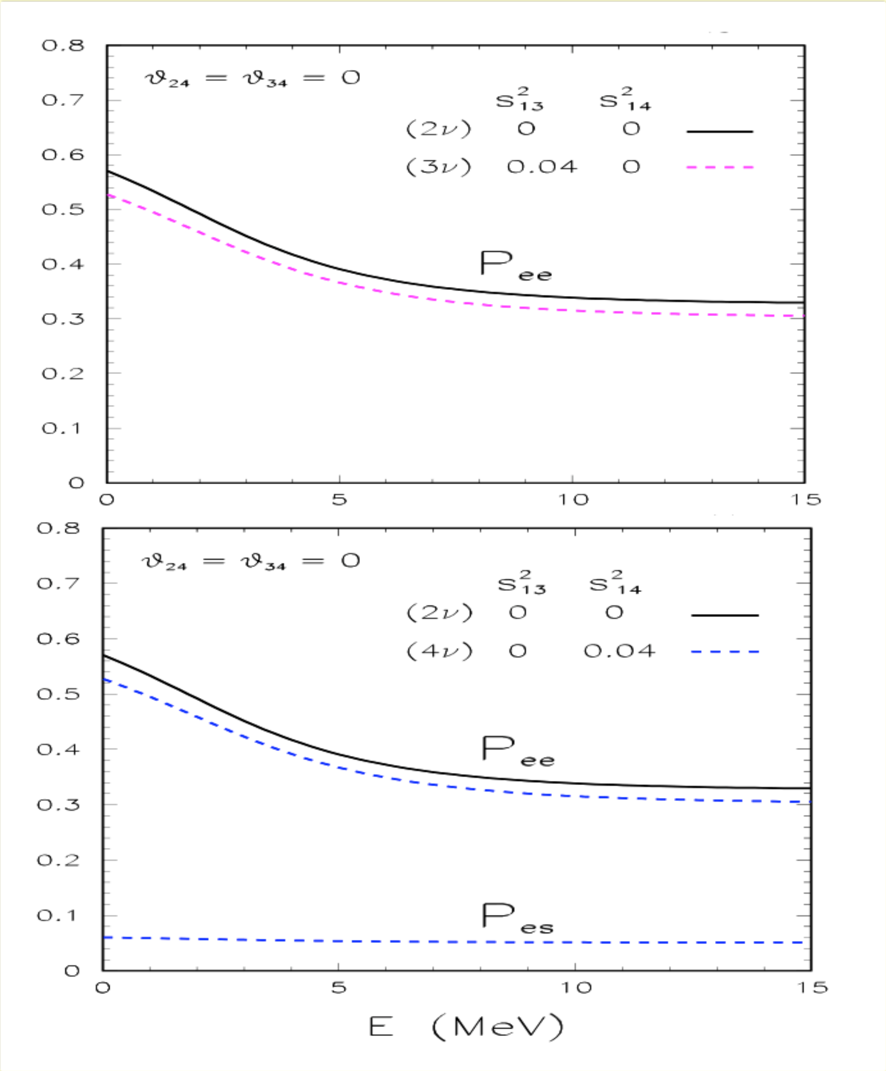
[Hamann et al., PRL 105, 181301 (2010)]

Warnings:

- **eV masses acceptable only abandoning standard ΛCDM**
- **N_s>1 at BBN strongly disfavored** (Mangano & Serpico PLB 701, 296, 2011)
- **N_s is not specific of sterile neutrinos**

What the solar ν data can tell us?

Solar νs are sensitive to ν_s oscillations



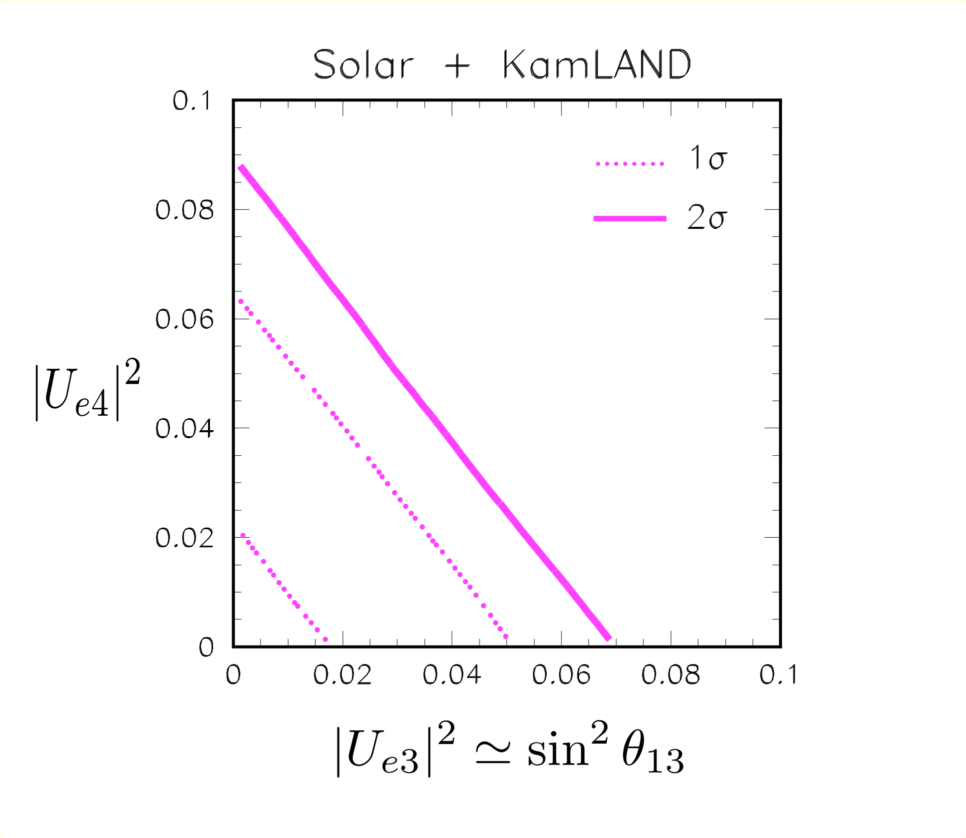
$\theta_{13} \neq 0$ $\theta_{14} = 0$ **(3ν)**

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

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

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

… and constrain the electron neutrino mixing



Complete degeneracy
U_{e3}-U_{e4} indistinguishable

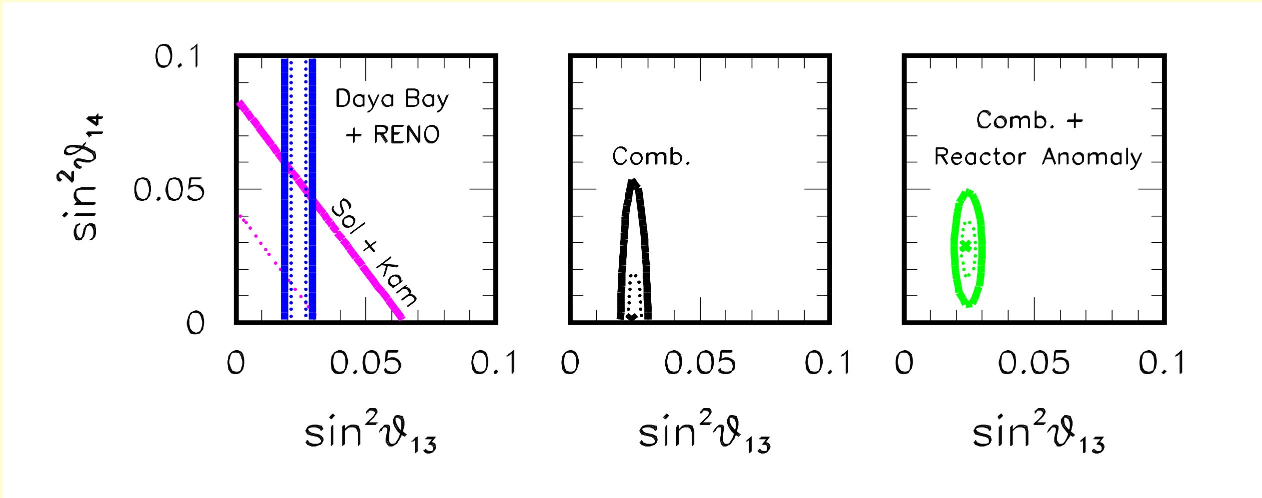
Robust upper bound
on the combination
~ $|U_{e3}|^2 + |U_{e4}|^2$

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]

Interplay of solar and reactor experiments

A.P., Invited Review for Mod. Phys. Lett. A 28, 1330004 (2013)



- **Solar** + **LBL reactors** ⟶ $\sin^2\theta_{14} < 0.04 \quad (90\% \text{ C.L.})$

- **Bound is not incompatible with the SBL reactor anomaly**

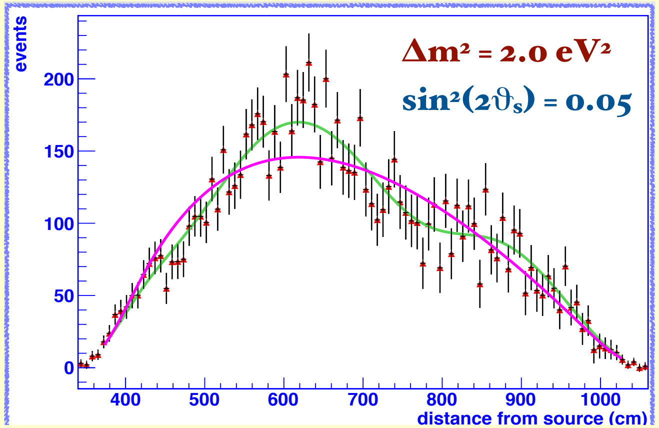
- **It makes sense to perform a combination, which reduces the indication for sterile neutrinos to the ~2.5 σ level**

How to discover/rule out sterile neutrinos

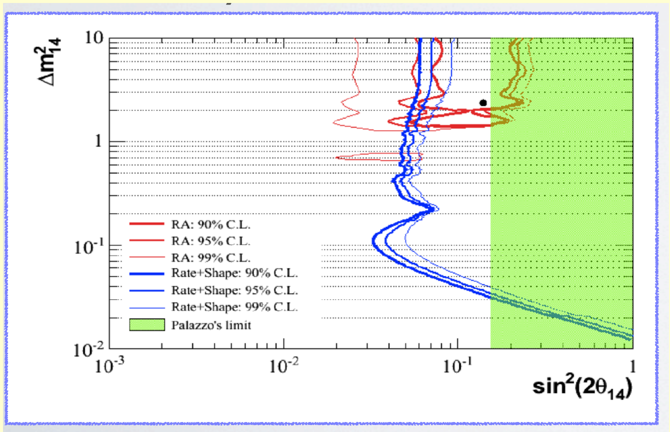
Smoking gun: oscillatory pattern (in energy and/or space)

A promising option: ν source close or inside Borexino

External ^{51}Cr source



M. Pallavicini @ Neutrino 2012



M. Pallavicini @ Neutrino 2012

Several other projects under scrutiny

Summary

- Solar νs harbingers of the discovery of $\theta_{13} > 0$
- This discovery opens the way to CPV and νMH
- First information on CPV phase ($\delta \sim \pi$) & $\theta_{23} < \pi/4$
- A few anomalies suggest new light sterile νs
- The phenomenological picture is rather confused
- New experiments indispensable to settle the issue

Conclusion

A unique moment for neutrino physics!

This is the right time to strengthen our effort to:

1) Complete the understanding of the standard 3ν framework

2) Explore and hopefully discover new ν properties

Kairos (καιρός)

It is our task to exploit the propitious moment (kairos)!

Thank you
for
your attention!