From Majorana to LHC
Workshop on the origin of ν mass

ICTP
Trieste, 2/10/13

Light and very light sterile νs

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Outline

Introduction

A critical look to the hints of light sterile νs

From light to very light sterile νs

Conclusions

Introduction

Beyond three neutrino families

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:

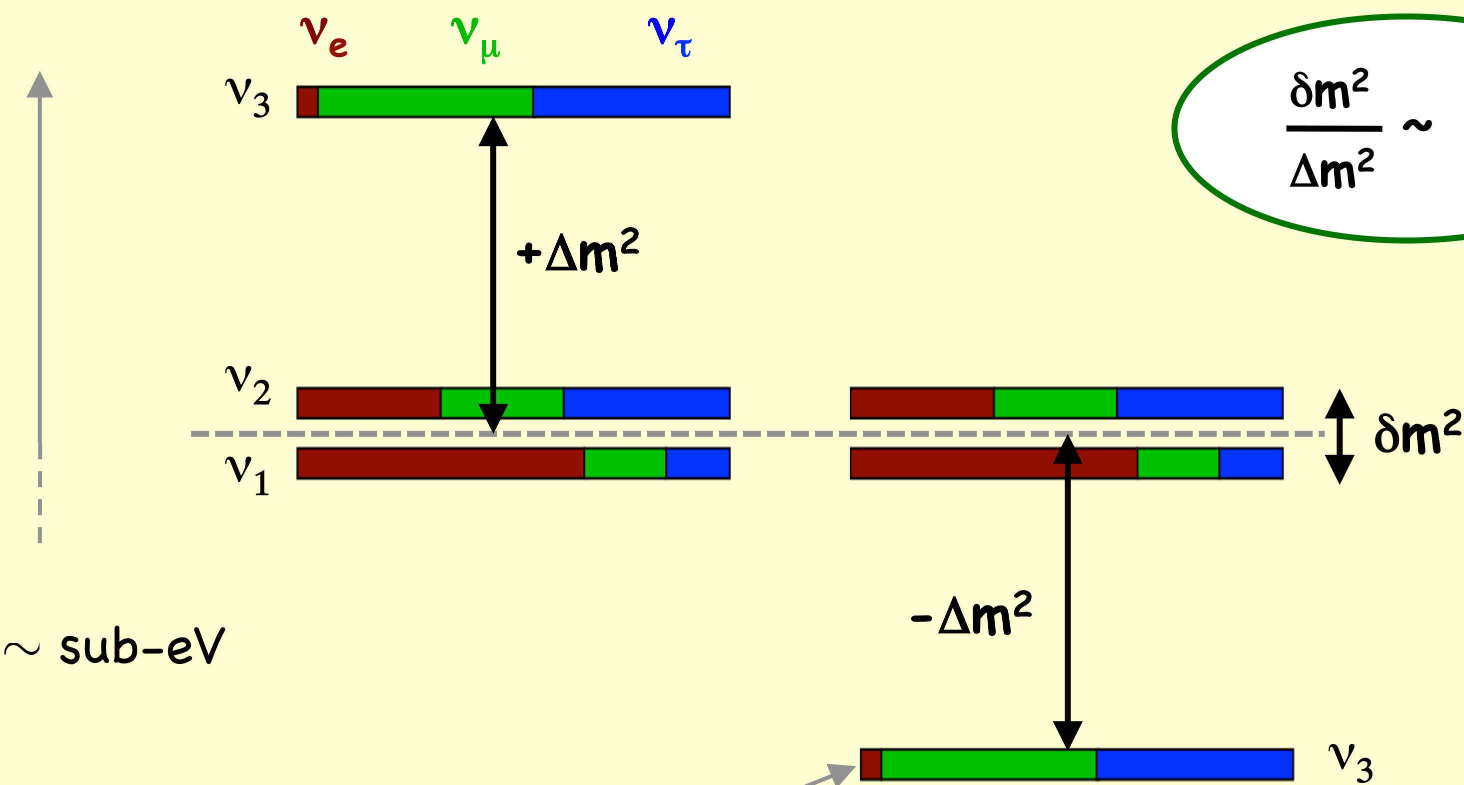
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$s_{23}^2 \sim 0.39$ $\quad$ $s_{13}^2 \sim 0.023$ $\quad$ $s_{12}^2 \sim 0.31$

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

The neutrino mass spectrum

NH or IH ?



$\sum m_i \sim$ sub-eV

$$|U_{e3}|^2 \equiv \sin^2\theta_{13} \simeq 0.025$$

Why go beyond the standard picture?

Experimental hints

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

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

Future data

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 (sub-)eV ν_s's from oscillation phenomenology and cosmology

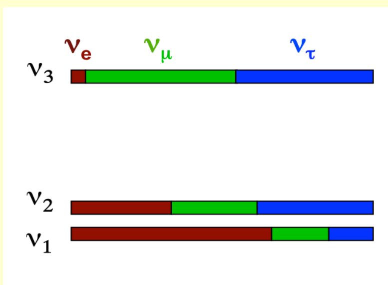
(II) Indications of "warm" dark matter from astrophysical "small-scale" problems (keV ν_s's are a good option)

I will discuss only (sub-)eV ν_s's

The success of the 3ν scheme must be preserved

The 3+1 scheme

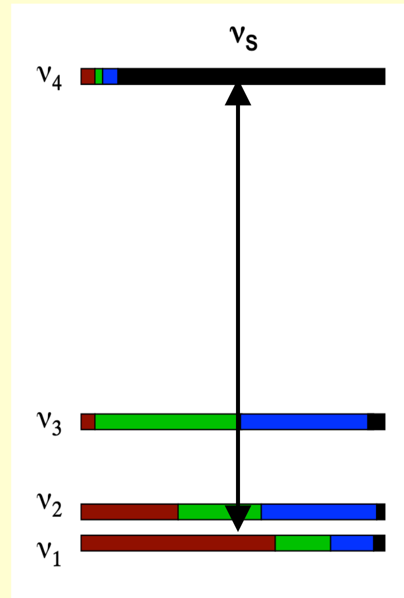
The 4th ν state induces
a small perturbation of
the 3-flavor framework



Δm^2_{atm}

Δm^2_{sol}

$|U_{s4}| \sim 1$



$\Delta m^2_{new} \sim 1 eV^2$

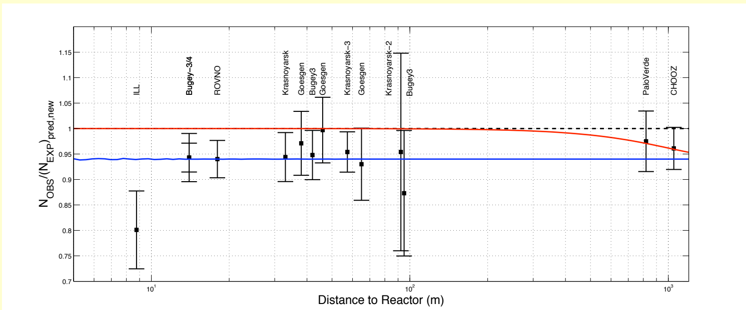
Strong effects are expected in short-baseline (SBL) reactor and accelerator experiments and in cosmology

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

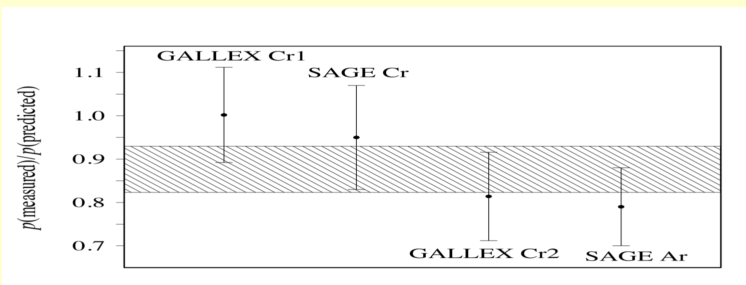
Hints of light (eV) sterile neutrinos

A critical outlook

The reactor and gallium anomalies



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:

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

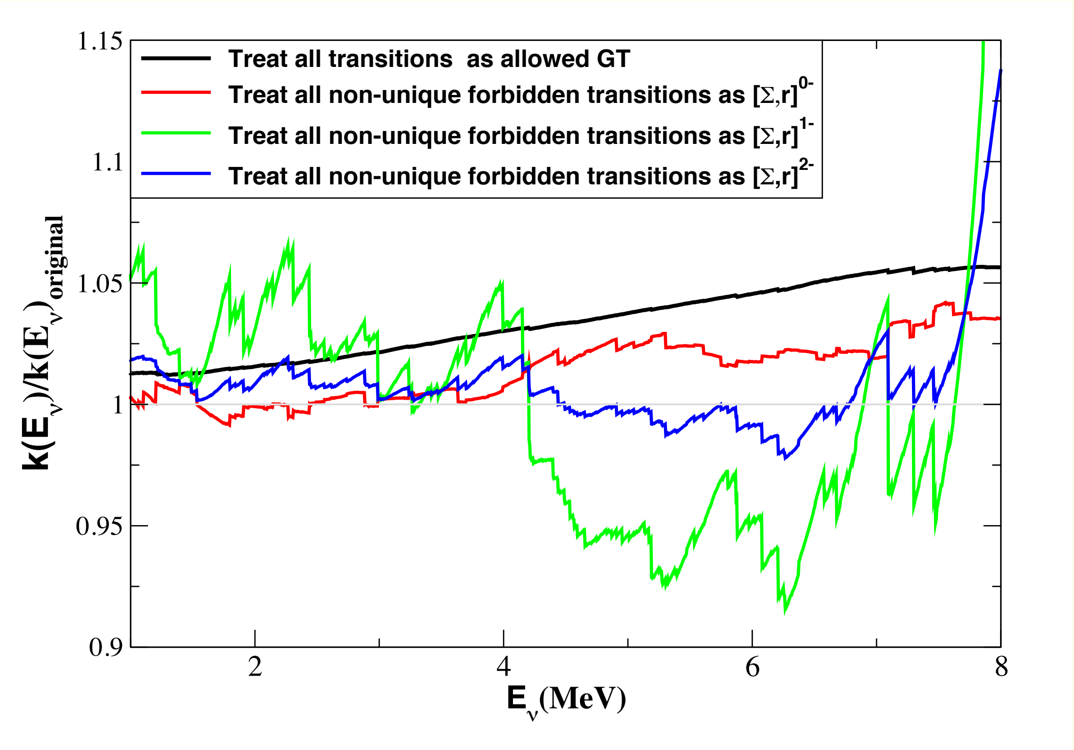
$$\Delta m^2_{sol} \ll \Delta m^2_{atm} \ll \Delta m^2_{new}$$

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

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

One example

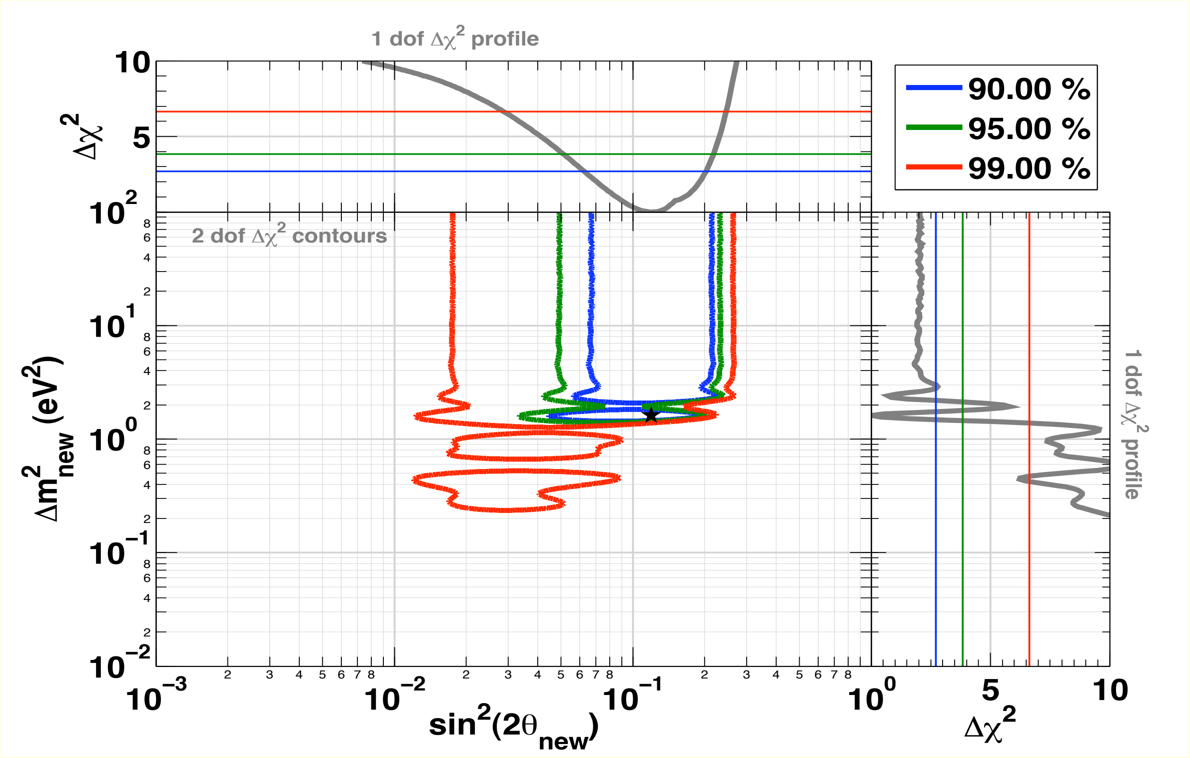
Systematics in reactor spectra may have been underestimated



A.C. Hayes et al arXiv:1309.4146 [nucl-th]

However, if we believe the anomalies point to new physics…

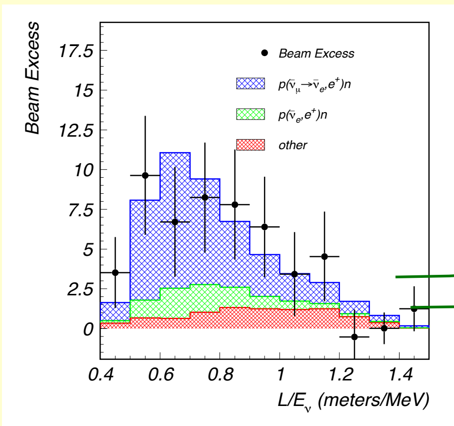
Fitting the anomalies with sterile ν oscillations



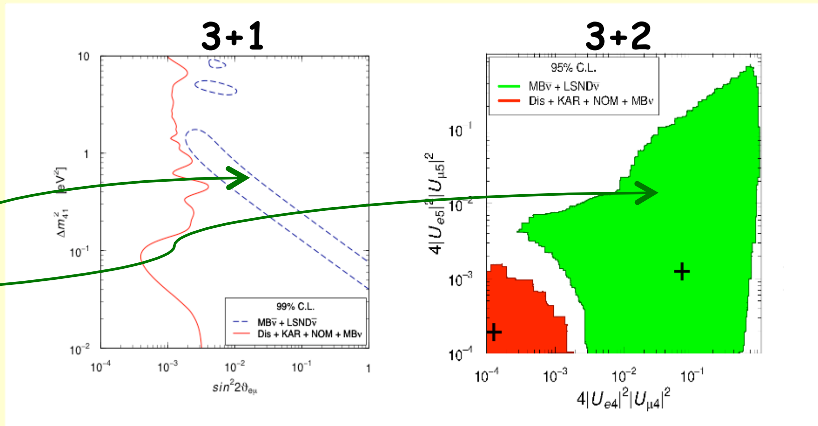
Mention et al., PRD 83 073006 (2011)

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

The SBL accelerator anomaly



LSND, PRL 75 (1995) 2650



Giunti and Laveder, arXiv:1107.1452

Warning:

In tension with disappearance searches:

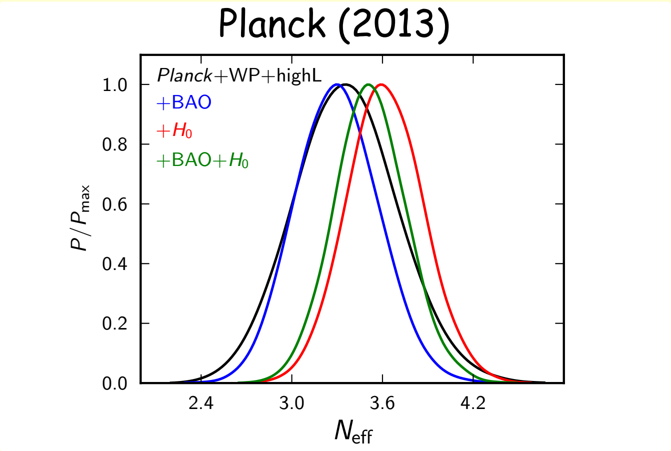
$\nu_\mu \to \nu_e$ positive appearance signal incompatible with joint $\nu_e \to \nu_e$ (positive) & $\nu_\mu \to \nu_\mu$ (negative) searches

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 %

The "dark radiation" anomaly



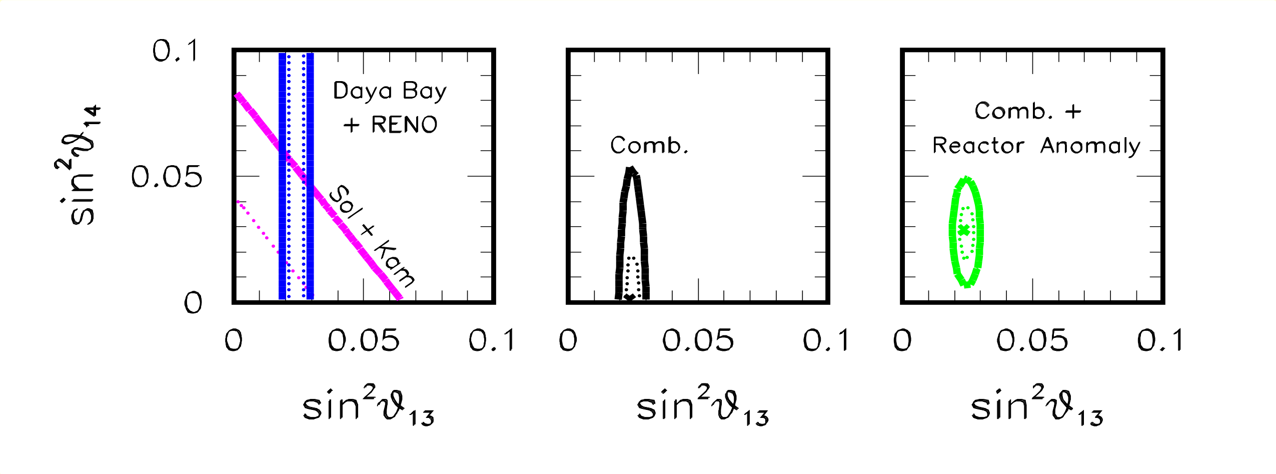
extra relativistic content
~ 2 sigma effect

Warnings:

- ΔN_{eff}>0 driven by tension in H_0 determination (CMB vs Astro)
- $\Delta N_{eff} \in [0, 1]$ requires a mechanism hampering νs thermalization
- N_{eff} is not specific of sterile neutrinos

What "ordinary" data tell us on eV νs?

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



More details in A.P., PRD 83, 113013 (2011); A.P., PRD 85, 077301 (2012)

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

- Bound independent of reactor fluxes (KamLAND only shape)

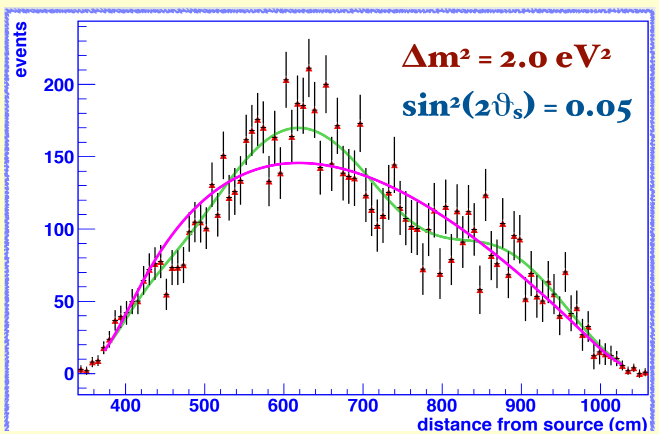
- Combination reduces the indication to the ~ 2σ level

How to shed light onto a confused picture

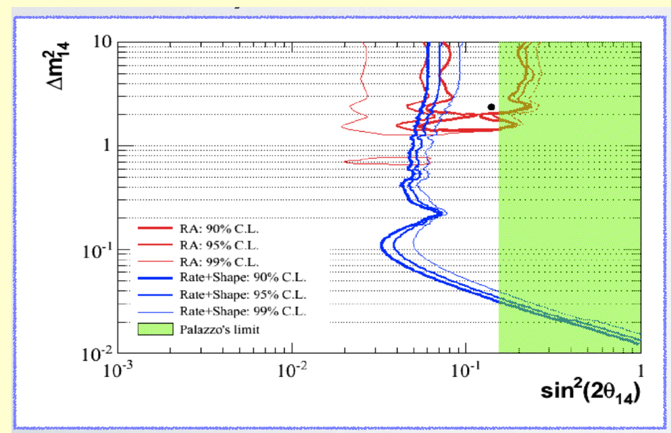
Smoking gun: oscillatory pattern (in energy and/or space)

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

A critical summary on eV sterile neutrinos

Three pieces of data may be interpreted as positive indications

Reactor, gallium, accelerator anomalies (systematics under control?)

Their simultaneous interpretation is problematic due to strong tension among different datasets. This difficulty weakens the case for eV νs

Cosmology tends to disfavor eV sterile neutrinos (more on this later) as it can tolerate only sub-eV masses and ΔN_{eff} smaller than unity

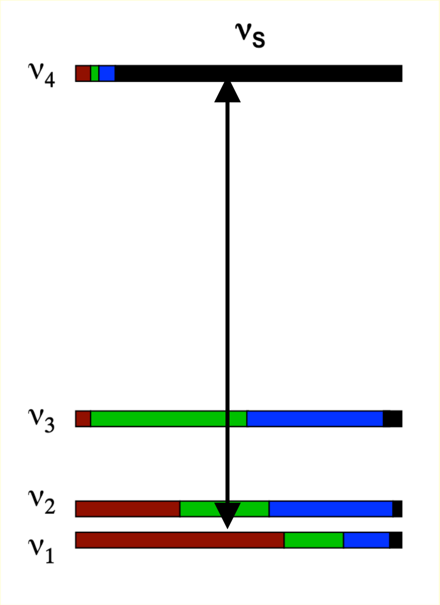
The overall picture is rather confused. The final word will come from new more sensitive experiments, which are under development.

Towards a change of paradigm

From Light to Very Light Sterile νs

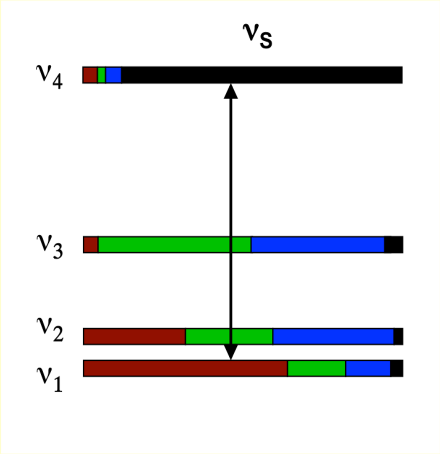
3+1 mass spectrum: Light vs Very Light

Light



$\Delta m^2_{14} \sim 1\ eV^2$

Very Light



$\Delta m^2_{14} \sim [10^{-3} - 10^{-1}]\ eV^2$

Motivations for investigating VLSν's

Theory does not provide solid information on ν_s mass-mixing properties and these should be investigated without prejudice

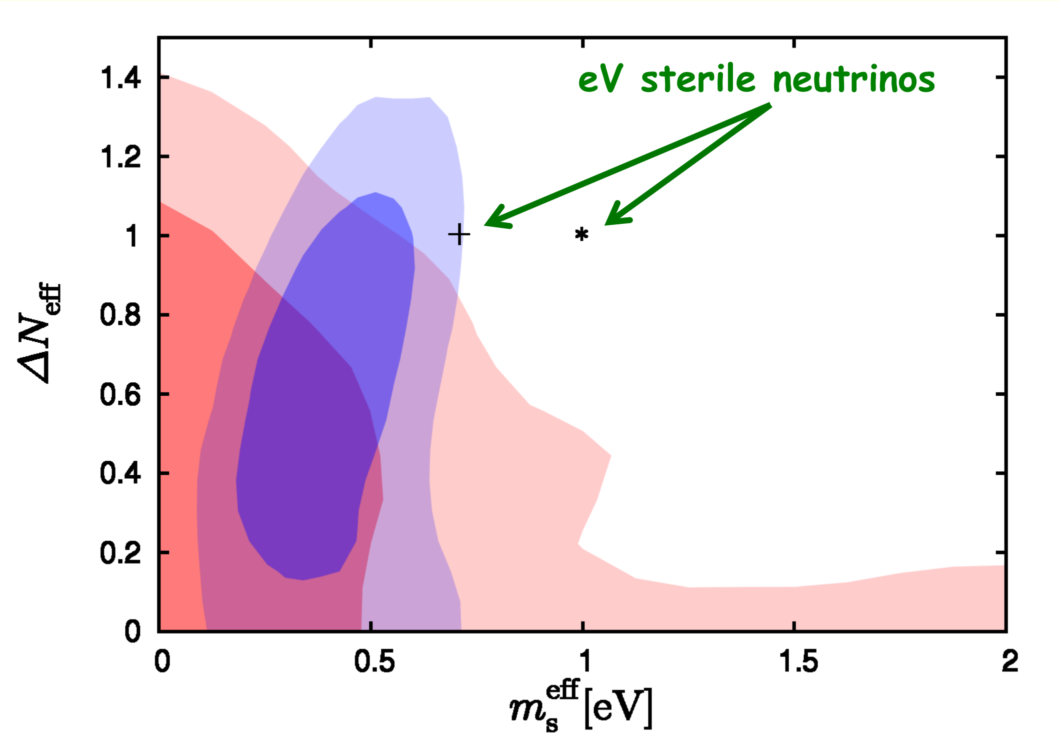
"Classical" eV light sterile neutrinos have several problems

The latest cosmological analyses present anomalous features which can be easily explained by VLSν's (but not by eV νs)

For the first time new reactor experiments, born for other purposes (measure θ_{13}) allow us to probe small values of Δm^2_{14}

New trends in cosmological data

$\Delta N_{eff} \sim 0.6$



$m_\nu \sim 0.4$ eV

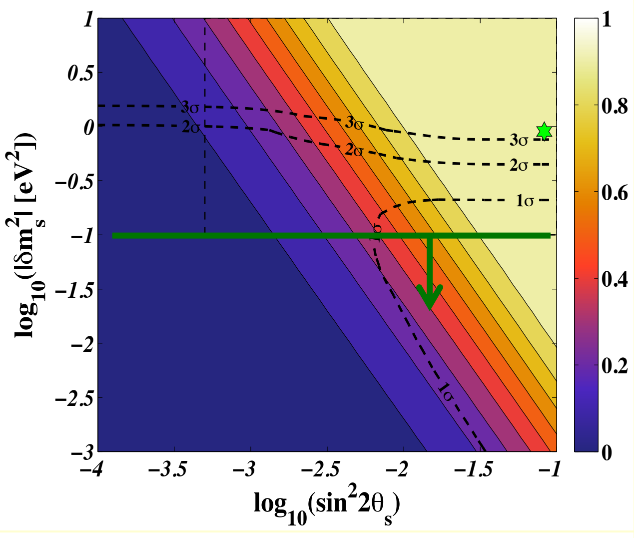
Haman and Hasenkamp [1308.3255 astro-ph]

Similar findings in: Wyman et al. [1307.7715 hep-ph]
Giunti et al. [1309.3192 astro-ph]

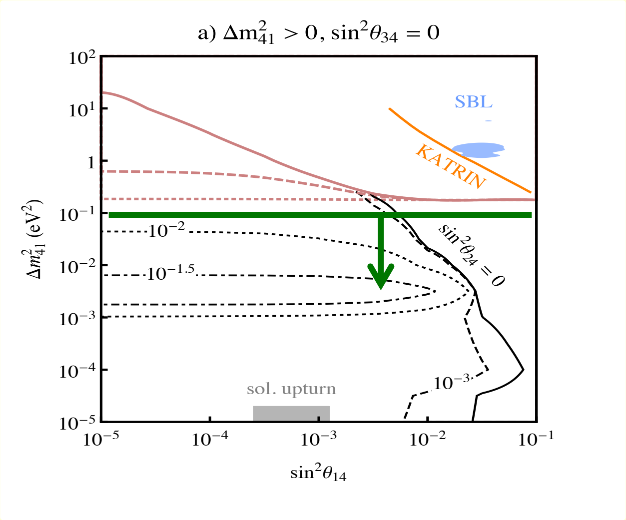
A VLSν provides both features

Contribution to the absolute neutrino mass in the sub-eV range

Partial thermalization for $\Delta m^2_{14} \in [10^{-3}, 10^{-1}]$ eV^2 and $U^2_{e4} < 10^{-2}$



Hannestad et al 1204.5861



Mirizzi et al. 1303.5368

No need to resort to more exotic mechanisms (a sterile ν is already exotic!) such as big lepton asymmetry

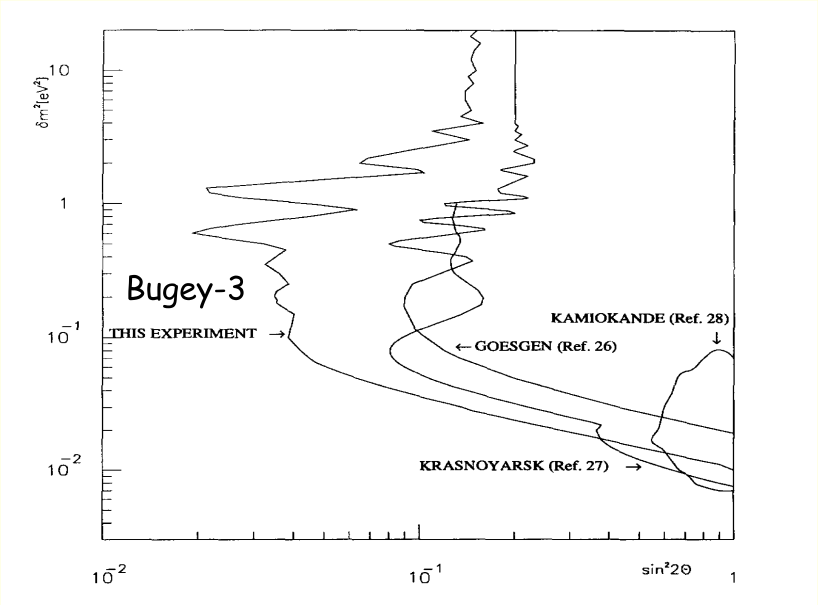
First laboratory constraints on VLSν's from

θ_{13}-sensitive reactor experiments

see A.P. [1308.5880 hep-ph]

Role of reactor experiments in ν_s searches

Reactor experiments are sensitive to the mixing of the sterile neutrinos with the electron neutrino ($|U_{e4}|^2 = \sin^2\theta_{14}$)



Existing constraints limited to Δm^2_{14} > few x 10^{-2} eV^2

Were obtained with baselines O(100 m)

Expected sensitivity of θ_{13}-sensitive experiments to smaller Δm^2_{14}
Baselines of few hundreds meters (near site) to 1-2 km (far site)

4ν formulae valid at reactors

Neglecting terms prop to $|U_{e3}|^2|U_{e4}|^2$ or Δm^2_{sol} we have

$$P_{ee} \simeq 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{13} L}{4E_\nu}\right) - \sin^2 2\theta_{14} \sin^2\left(\frac{\Delta m^2_{14} L}{4E_\nu}\right) .$$

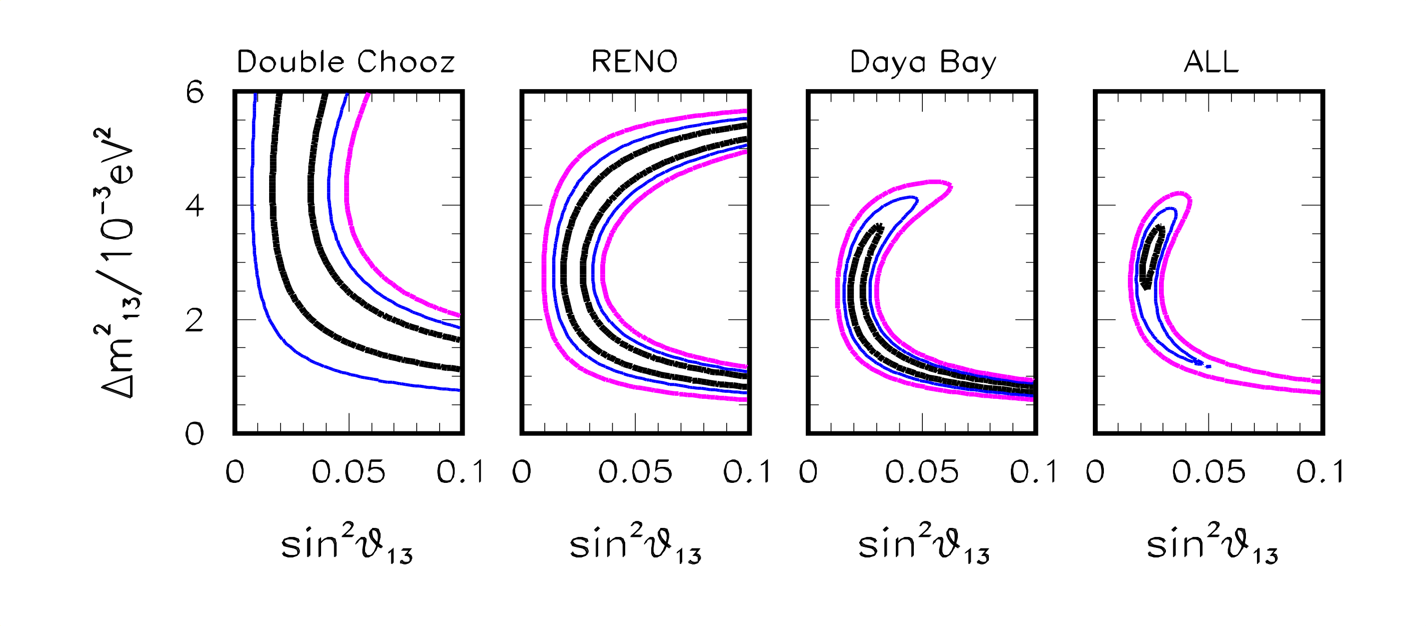
Sizable effects expected both at near and far detectors

$$\frac{\Delta m^2_{14} L}{4E_\nu} \simeq 1.267 \left(\frac{\Delta m^2_{14}}{10^{-2}\ \mathrm{eV}^2}\right) \left(\frac{L}{400\ \mathrm{m}}\right) \left(\frac{4\ \mathrm{MeV}}{E_\nu}\right) .$$

Far/near ratios are expected to provide information on VLSν's

3-flavor analysis (θ_{14}=0)

A.P. [1308.5880 hep-ph]

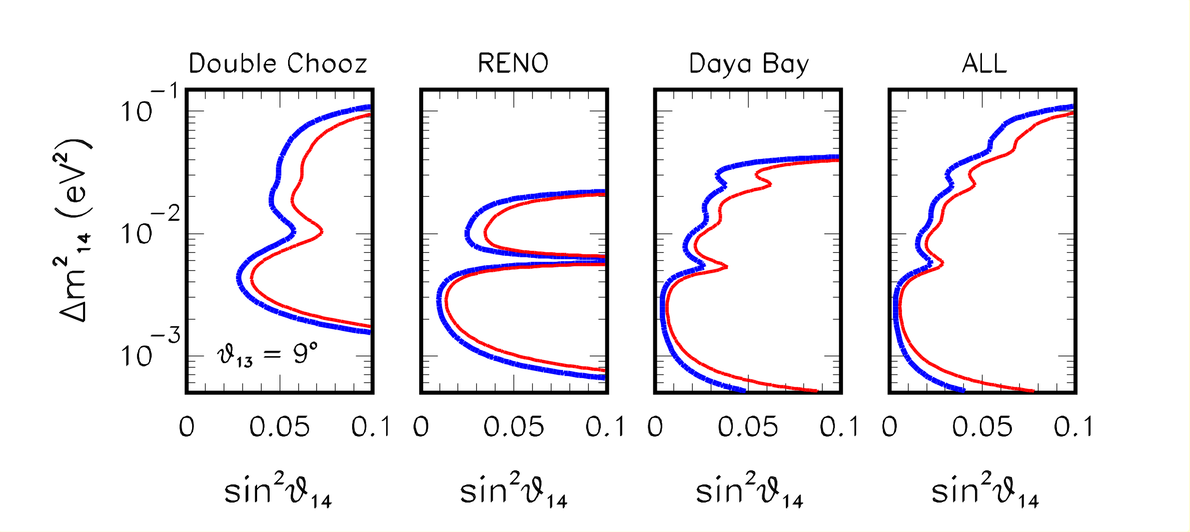


Excellent agreement with the three collaborations

Combination gives θ_{13} at ~10 sigma level $\sin^2\theta_{13}$ = 0.023 +/- 0.002

4-flavor analysis performed at fixed θ_{13}

A.P. [1308.5880 hep-ph]



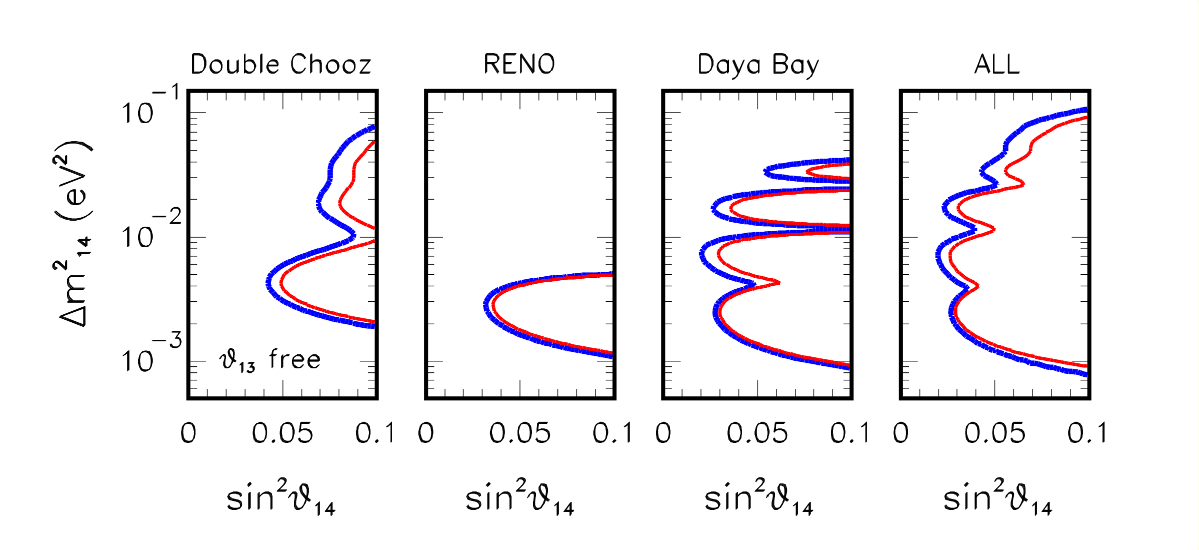
All the three experiments exclude a lobe around the atm. splitting (far site sees the oscillation phase, at near site negligible effects)

All the three experiments exclude a second lobe around 10^{-2} eV^2 (at far site oscillations averaged, near site sees oscillation phase)

D-Chooz used Bugey-4 (15 m) as an anchor, limits up to 10^{-1} eV^2

4-flavor analysis performed for free θ_{13}

A.P. [1308.5880 hep-ph]



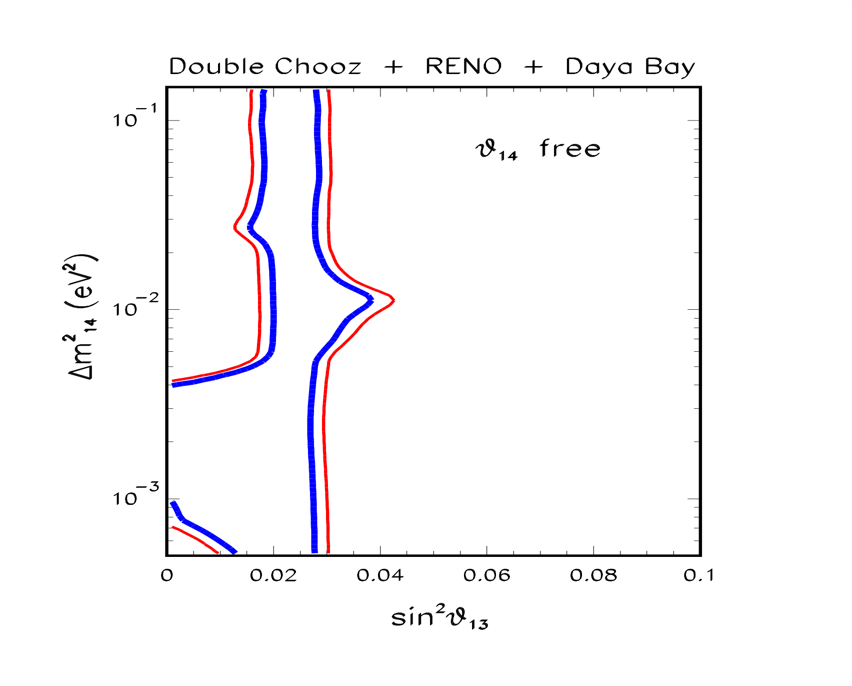
General degradation of sensitivity in all the three experiments

Entire lobes disappear due to strong degeneracies among θ_{13} and θ_{14}

Degradation less severe in:
D-Chooz (Bugey-4 at 15 m as an anchor)
Daya-Bay (additional near/near ratio constrain values > 10^{-2} eV^2)

Noticeable synergy in the global combination

Estimate of θ_{13} in a 4-flavor framework



A.P. [1308.5880 hep-ph]

Standard 3ν estimate is robust provided that Δm^2_{14} > 6 x 10^{-3} eV^2

No lower bound for smaller Δm^2_{14} due to degeneracy of θ_{13} and θ_{14}

However, in this region lower bound by T2K (4ν effects negligible)

Conclusions

Light (eV) sterile neutrinos hinted at by terrestrial experiments but a consistent picture is missing. Final word to new experiments

Very light sterile neutrinos (VLSν's) $\Delta m^2 \sim [10^{-3}\text{-}10^{-1}]$ eV^2 offer an option for cosmo hints (dark radiation and hot-dark-matter)

First constraints on VLSν's obtained with θ_{13}-dedicated experiments

Further information on VLSν's can be gained by spectral analysis and from LBL accelerator experiments and atmospheric neutrinos

Not unreasonable to think that several sterile νs can co-exist and explain some observations: (SBL,eV), solar spectrum (10^{-3} eV), dark radiation (sub-eV), DM (keV), Leptogenesis (TeV), small ν mass (GUT)

ALL MASS SCALES SHOULD BE PROBED WITHOUT PREJUDICES!

Thank you
for
your attention!