26th Rencontres de Blois

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Phenomenology of light sterile νs

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Outline

Beyond three neutrino families

Phenomenology of eV sterile vs

From eV to sub-eV sterile neutrinos

Conclusions

Beyond three neutrino families

Many extensions of the SM involve sterile neutrinos, i.e. singlets of the SM gauge group

ν_s's have been investigated at several E scales:

- GUT, see-saw models of ν mass, leptogenesis
- TeV, production at LHC and impact on EWPOs
- keV, dark matter candidates
- ✓ eV, anomalies in SBL oscillation experiments
- ✓ sub-eV, θ_{13} reactors and solar neutrinos

"Light ν_s"

Wide interest in the scientific community

arXiv:1204.5379v1 [hep-ph] 18 Apr 2012

Light Sterile Neutrinos: A White Paper

K. N. Abazajian[a],[1] M. A. Acero,[2] S. K. Agarwalla,[3] A. A. Aguilar-Arevalo,[2] C. H. Albright,[4,5] S. Antusch,[6] C. A. Argüelles,[7] A. B. Balantekin,[8] G. Barenboim[a],[3] V. Barger,[8] P. Bernardini,[9] F. Bezrukov,[10] O. E. Bjaelde,[11] S. A. Bogacz,[12] N. S. Bowden,[13] A. Boyarsky,[14] A. Bravar,[15] D. Bravo Berguño,[16] S. J. Brice,[5] A. D. Bross,[5] B. Caccianiga,[17] F. Cavanna,[18,19] E. J. Chun,[20] B. T. Cleveland,[21] A. P. Collin,[22] P. Coloma,[16] J. M. Conrad,[23] M. Cribier,[22] A. S. Cucoanes,[24] J. C. D'Olivo,[2] S. Das,[25] A. de Gouvêa,[26] A. V. Derbin,[27] R. Dharmapalan,[28] J. S. Diaz,[29] X. J. Ding,[16] Z. Djurcic,[30] A. Donini,[31,3] D. Duchesneau,[32] H. Ejiri,[33] S. R. Elliott,[34] D. J. Ernst,[35] A. Esmaili,[36] J. J. Evans,[37,38] E. Fernandez-Martinez,[39] E. Figueroa-Feliciano,[23] B. T. Fleming[a],[18] J. A. Formaggio[a],[23] D. Franco,[40] J. Gaffiot,[22] R. Gandhi,[41] Y. Gao,[42] G. T. Garvey,[34] V. N. Gavrin,[43] P. Ghoshal,[41] D. Gibin,[44] C. Giunti,[45] S. N. Gninenko,[43] V. V. Gorbachev,[43] D. S. Gorbunov,[43] R. Guenette,[18] A. Guglielmi,[44] F. Halzen,[46,8] J. Hamann,[11] S. Hannestad,[11] W. Haxton,[47,48] K. M. Heeger,[8] R. Henning,[49,50] P. Hernandez,[3] P. Huber[b],[16] W. Huelsnitz,[34,51] A. Ianni,[52] T. V. Ibragimova,[43] Y. Karadzhov,[15] G. Karagiorgi,[53] G. Keefer,[13] Y. D. Kim,[54] J. Kopp[a],[5] V. N. Kornoukhov,[55] A. Kusenko,[56,57] P. Kyberd,[58] P. Langacker,[59] Th. Lasserre[a],[22,40] M. Laveder,[60] A. Letourneau,[22] D. Lhuillier,[22] Y. F. Li,[61] M. Lindner,[62] J. M. Link[b],[16] B. L. Littlejohn,[8] P. Lombardi,[17] K. Long,[63] J. Lopez-Pavon,[64] W. C. Louis[a],[34] L. Ludhova,[17] J. D. Lykken,[5] P. A. N. Machado,[65,66] M. Maltoni,[31] W. A. Mann,[67] D. Marfatia,[68] C. Mariani,[53,16] V. A. Matveev,[43,69] N. E. Mavromatos,[70,39] A. Melchiorri,[71] D. Meloni,[72] O. Mena,[3] G. Mention,[22] A. Merle,[73] E. Meroni,[17] M. Mezzetto,[44] G. B. Mills,[34] D. Minic,[16] L. Miramonti,[17] D. Mohapatra,[16] R. N. Mohapatra,[51] C. Montanari,[74] Y. Mori,[75] Th. A. Mueller,[76] H. P. Mumm,[77] V. Muratova,[27] A. E. Nelson,[78] J. S. Nico,[77] E. Noah,[15] J. Nowak,[79] O. Yu. Smirnov,[69] M. Obolensky,[40] S. Pakvasa,[80] O. Palamara,[18,52] M. Pallavicini,[81] S. Pascoli,[82] L. Patrizii,[83] Z. Pavlovic,[34] O. L. G. Peres,[36] H. Pessard,[32] F. Pietropaolo,[44] M. L. Pitt,[16] M. Popovic,[5] J. Pradler,[84] G. Ranucci,[17] H. Ray,[85] S. Razzaque,[86] B. Rebel,[5] R. G. H. Robertson,[87,78] W. Rodejohann[a],[62] S. D. Rountree,[16] C. Rubbia,[39,52] O. Ruchayskiy,[39] P. R. Sala,[17] K. Scholberg,[88] T. Schwetz[a],[62] M. H. Shaevitz,[53] M. Shaposhnikov,[89] R. Shrock,[90] S. Simone,[91] M. Skorokhvatov,[92] M. Sorel,[3] A. Sousa,[93] D. N. Spergel,[94] J. Spitz,[23] L. Stanco,[44] I. Stancu,[28] A. Suzuki,[95] T. Takeuchi,[16] I. Tamborra,[96] J. Tang,[97,98] G. Testera,[81] X. C. Tian,[99] A. Tonazzo,[40] C. D. Tunnell,[100] R. G. Van de Water,[34] L. Verde,[101] E. P. Veretenkin,[43] C. Vignoli,[52] M. Vivier,[22] R. B. Vogelaar,[16] M. O. Wascko,[63] J. F. Wilkerson,[49,102] W. Winter,[97] Y. Y. Y. Wong[a],[25] T. T. Yanagida,[57] O. Yasuda,[103] M. Yeh,[104] F. Yermia,[24] Z. W. Yokley,[16] G. P. Zeller,[5] L. Zhan,[61] and H. Zhang[62]

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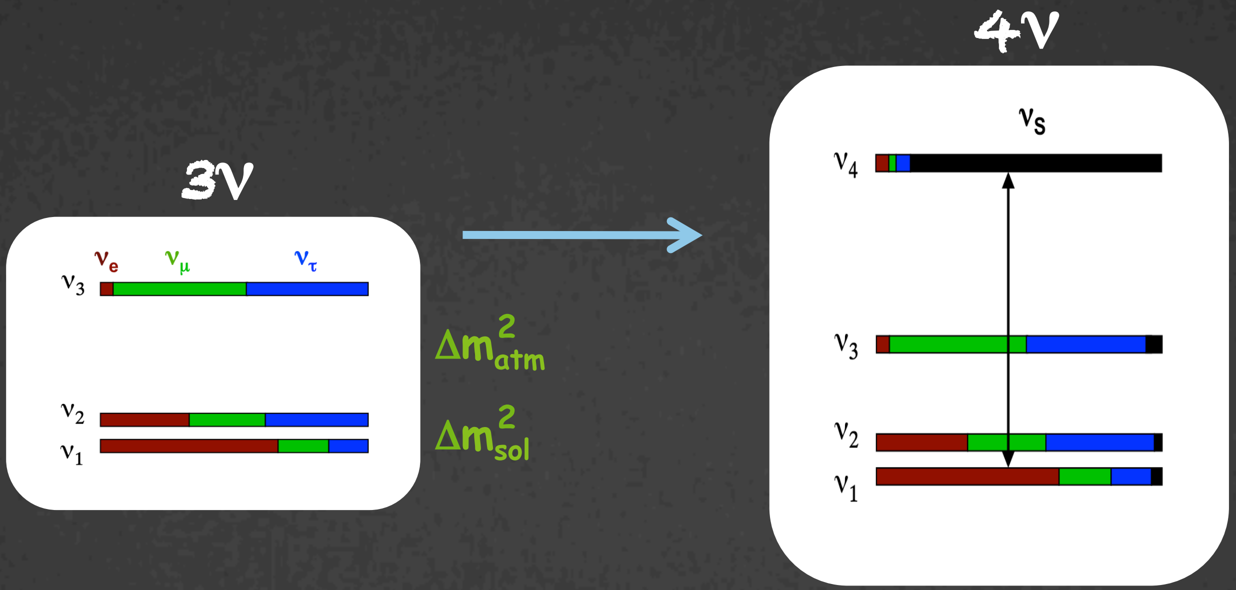
Introducing a light sterile neutrino



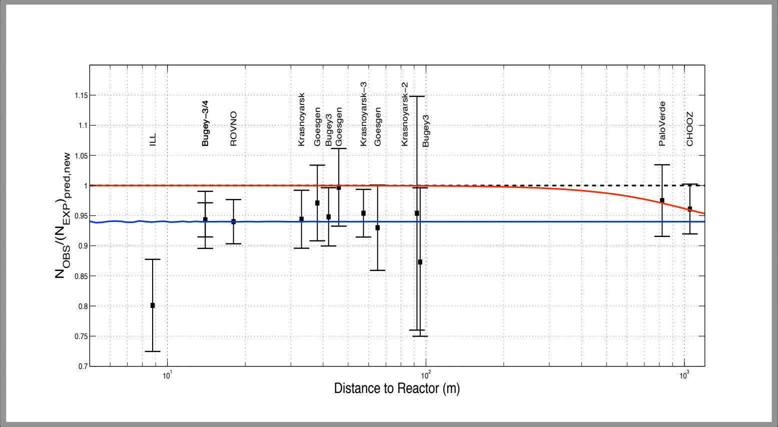
$|U_{s4}| \sim 1$

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

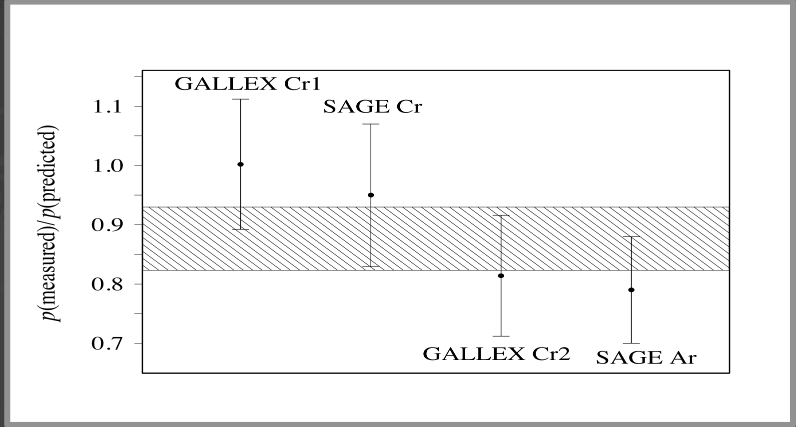
Small mixing of active flavors with the 4th state

The reactor and gallium anomalies

(unexplained ν_e disappearance)



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

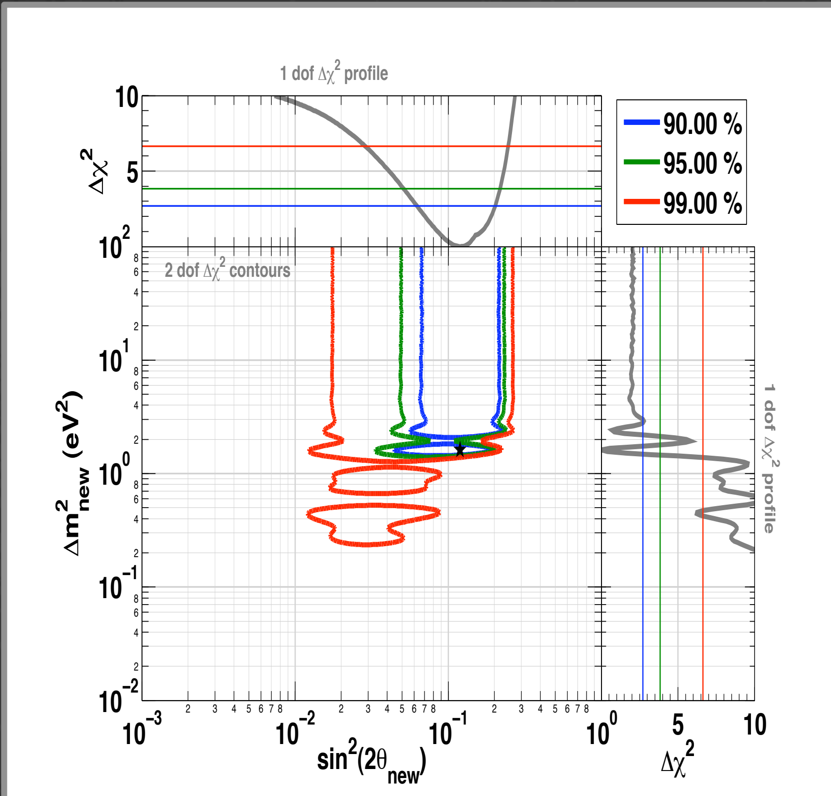


SAGE coll., PRC 73 (2006) 045805

Warning: both are mere normalization issues

The culprit may be in hidden systematics

Fitting the SBL ν_e anomalies



Mention et al., PRD 83 073006 (2011)

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:

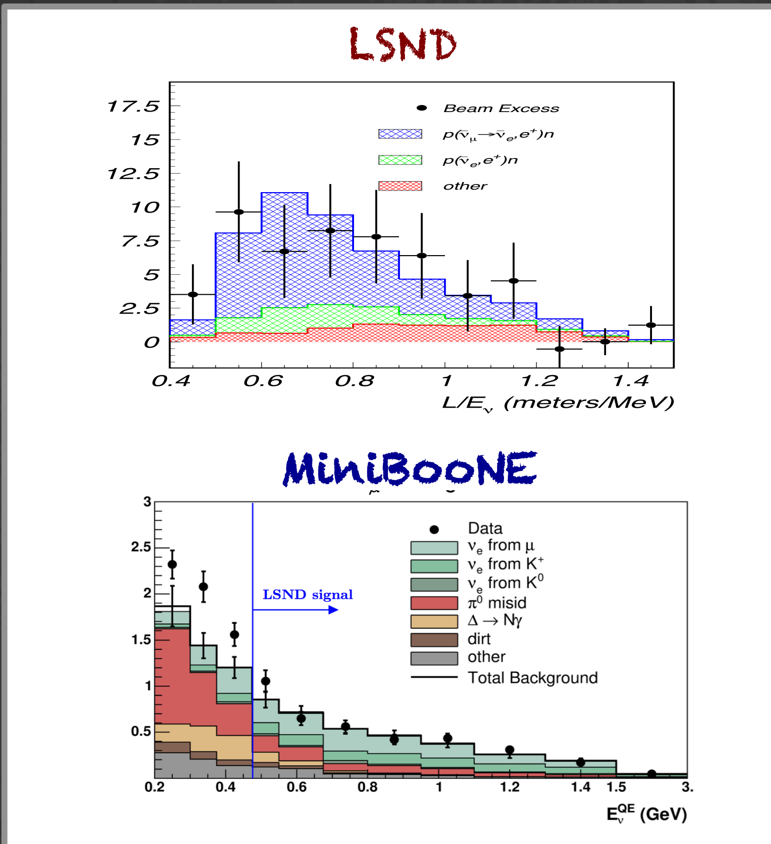
$$P_{ee} = 1 - 4 \sum_{j>k} U^2_{ej} U^2_{ek} \sin^2 \frac{\Delta m^2_{jk} L}{4E}$$

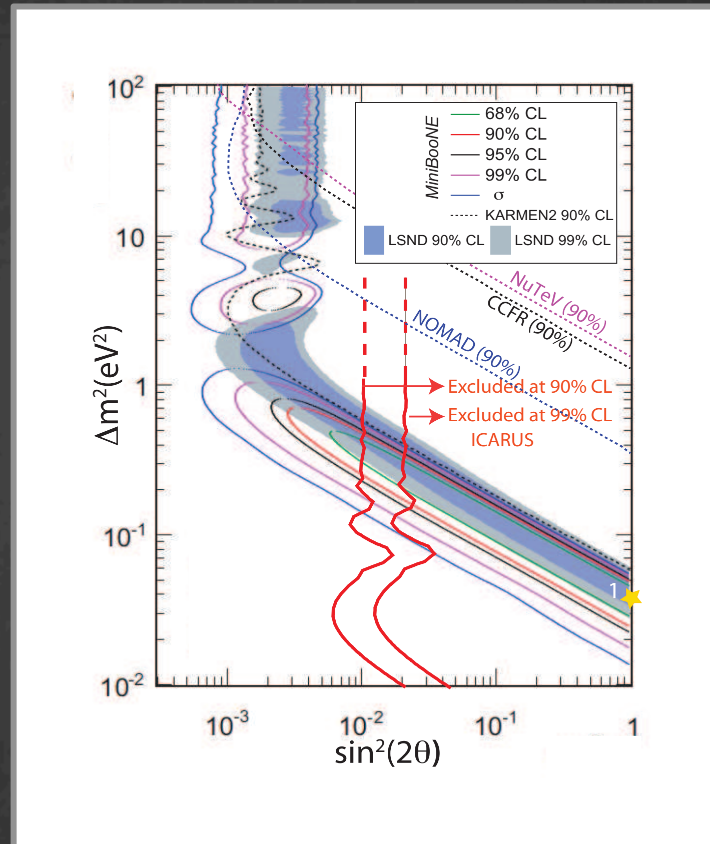
$$\Delta m^2_{sol} \ll \Delta m^2_{atm} \ll \Delta m^2_{new}$$

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

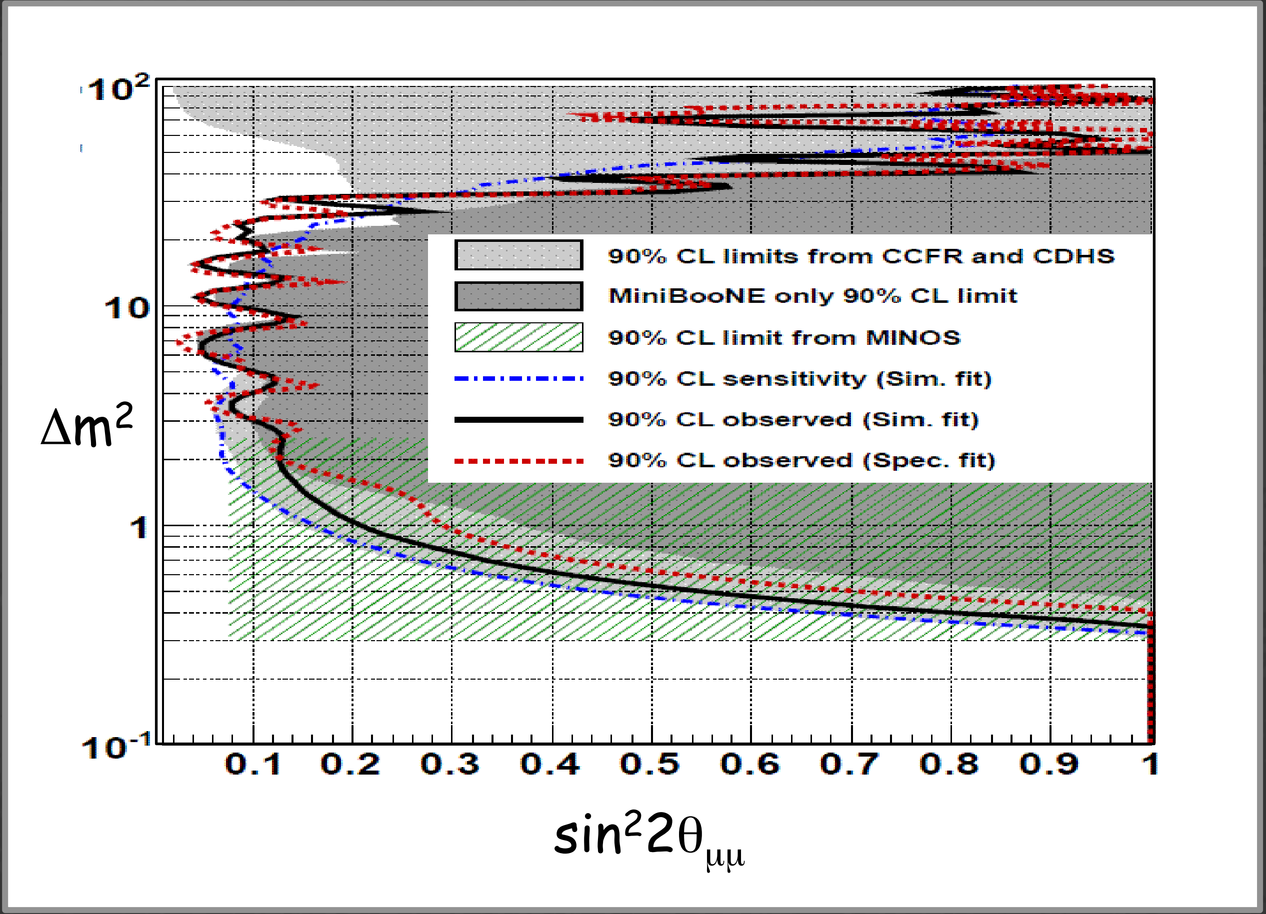
The SBL accelerator anomalies

(unexplained ν_e appearance in a ν_μ beam)



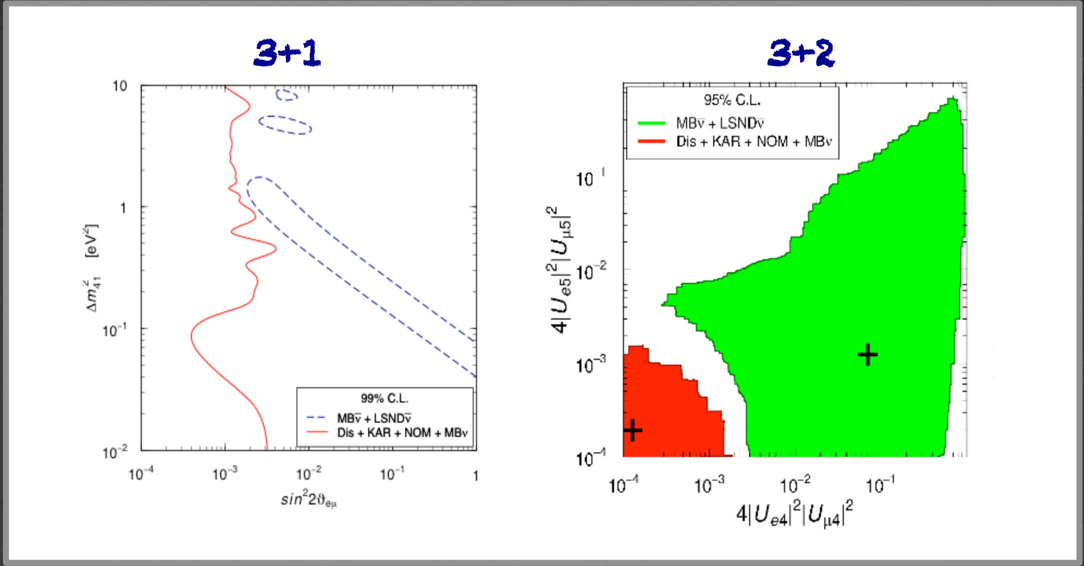


No anomaly in ν_μ disappearance



only upper bounds (till now)

Tension in all ν_s models



Giunti & Laveder

arXiv:1107.1452

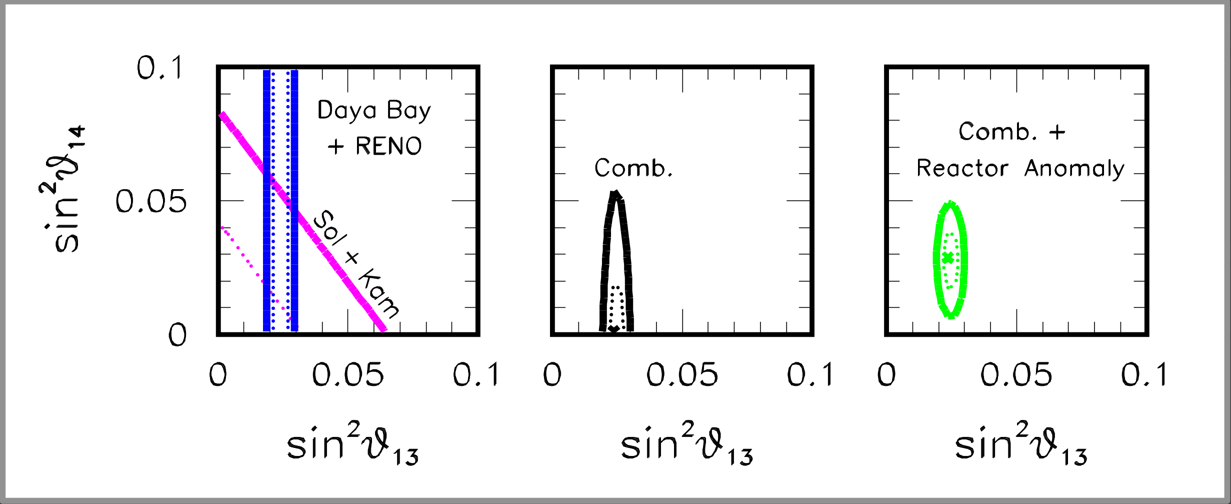
$\nu_\mu \to \nu_e$ positive
$\nu_e \to \nu_e$ positive
$\nu_\mu \to \nu_\mu$ negative

$|U_{e4}||U_{\mu 4}| > 0$
$|U_{e4}| > 0$
$|U_{\mu 4}| \sim 0$

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

What non-SBL exp tell us on ν_ss ?

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

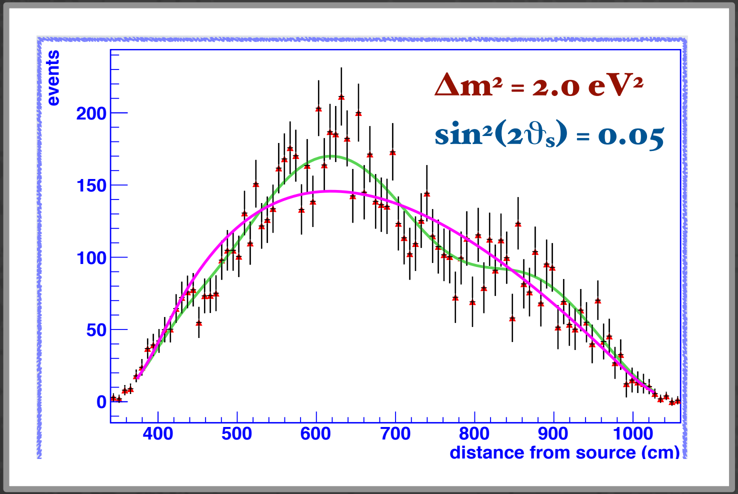


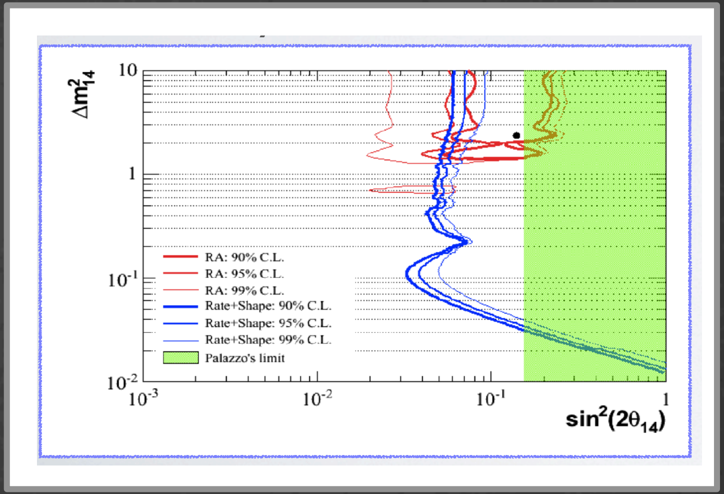
- Solar + LBL reactors: $\boxed{\sin^2\theta_{14} < 0.04 \quad (90\% \text{ C.L.})}$
- Bound indep. of reactor fluxes (KamLAND only shape)
- Combination reduces the indication to the ~ 2σ level

How to shed light onto a confused picture

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

A promising option: ν source close or inside Borexino



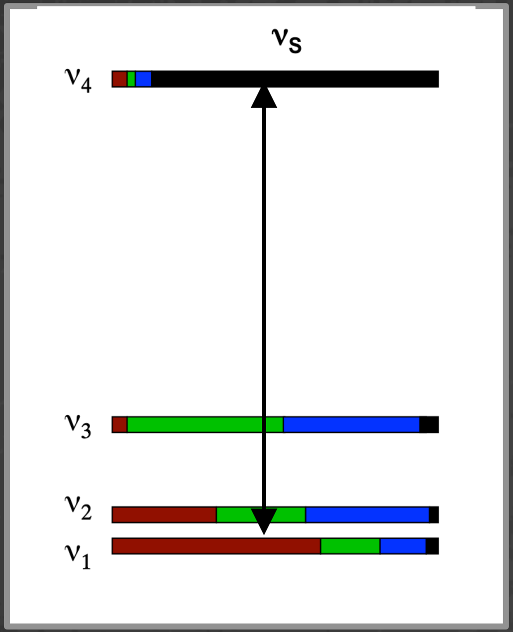


M. Pallavicini @ Neutrino 2012

Several other projects under scrutiny

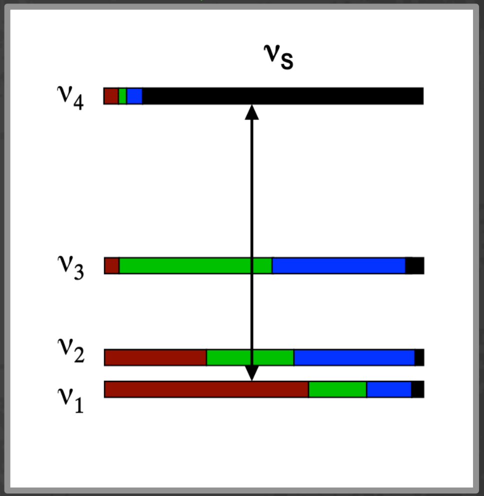
From light to very light sterile νs

Light



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

Very Light



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

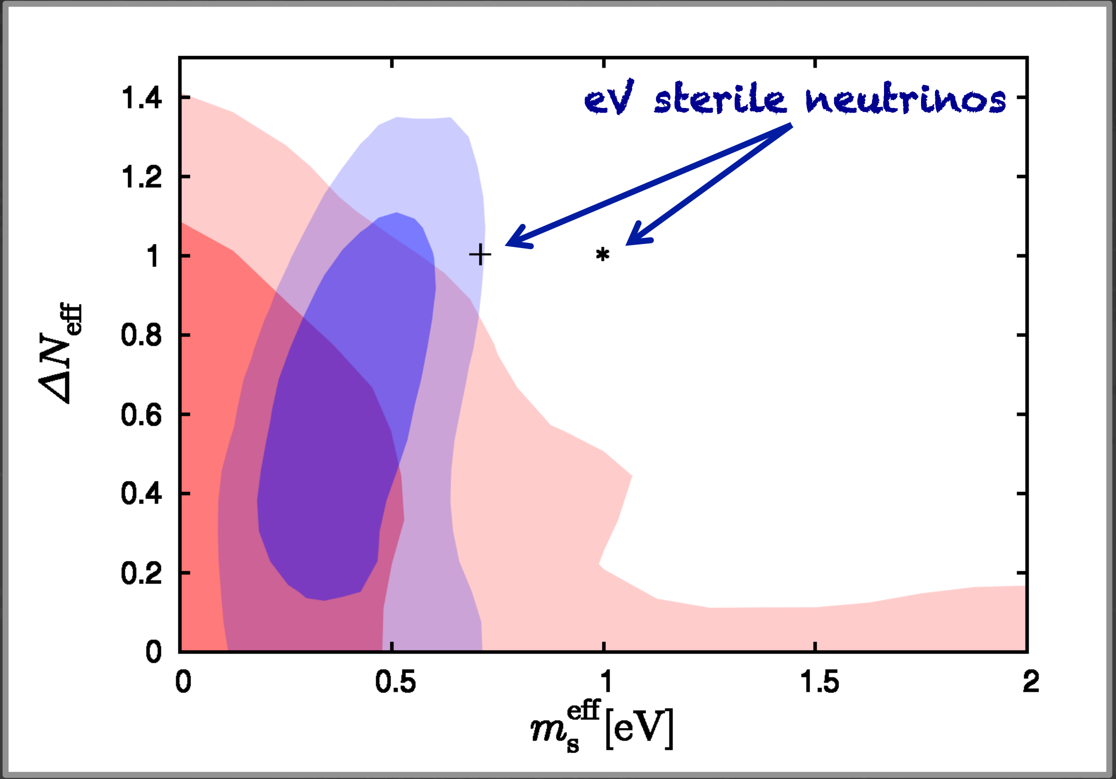
Motivations for investigating VLSν's

Theory does not provide info on ν_s mass-mixing which should be investigated without prejudice

Cosmology presents anomalous features which can be easily explained by VLSν's (but not by eV νs)

For the first time new experiments, born for other purposes (to measure θ_{13}) can probe sub-eV masses

New trends in cosmological data



ΔN_{eff} ~ 0.6

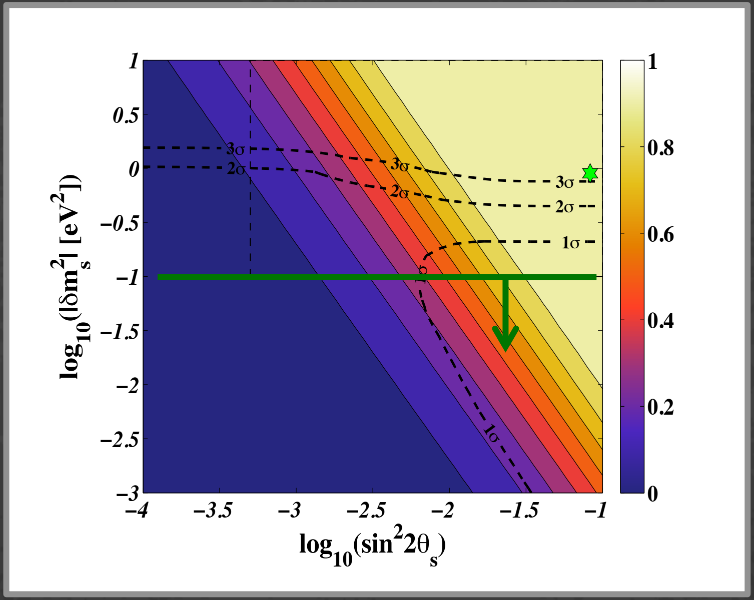
m_ν ~ 0.4 eV

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 ν mass in the sub-eV range
- Only partial thermalization ($N_{eff} < 1$)

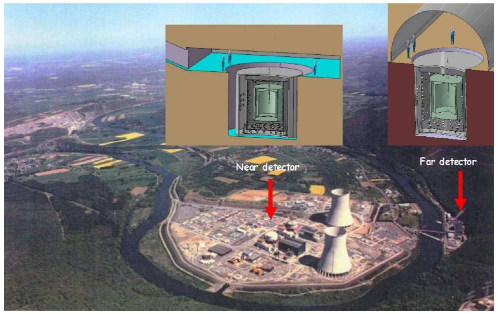


Hannestad et al 1204.5861

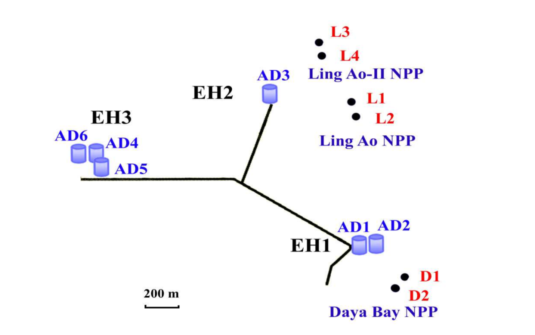
No need to resort to more exotic mechanisms such as big lepton asymmetry or self-interactions

Studying VLSνs with θ_{13} experiments

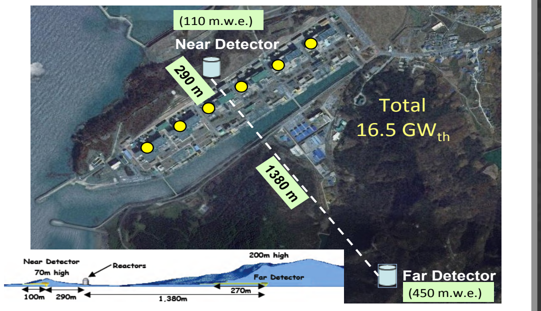
Double CHOOZ



Daya Bay



RENO



Observed far/near deficit implies $\theta_{13} > 0$

$$P_{ee} \simeq 1 - 4|U_{e3}|^2(1 - |U_{e3}|^2)\sin^2\frac{\Delta m^2_{13} L}{4E}$$

$$4|U_{e3}|^2(1 - |U_{e3}|^2) \equiv \sin^2 2\theta_{13}$$

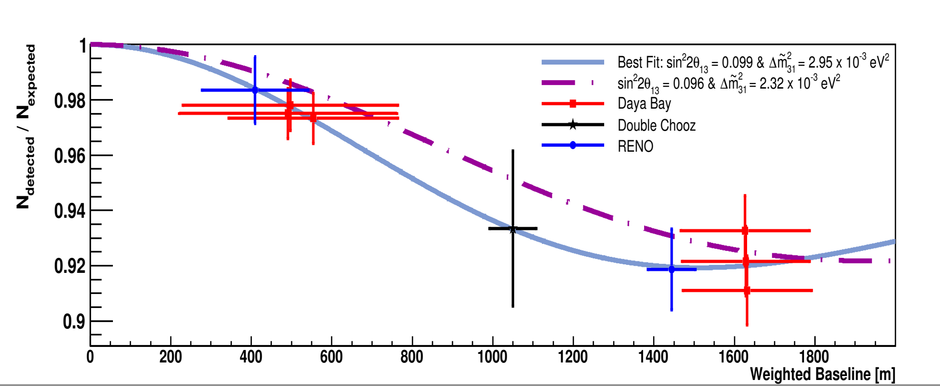


Figure from Bezerra et al. Phys Lett. B 725 (2013) 271

4ν formulae valid at reactors

Neglecting terms $\propto |U_{e3}|^2|U_{e4}|^2$ or $\propto \Delta m^2_{sol}$ 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 site

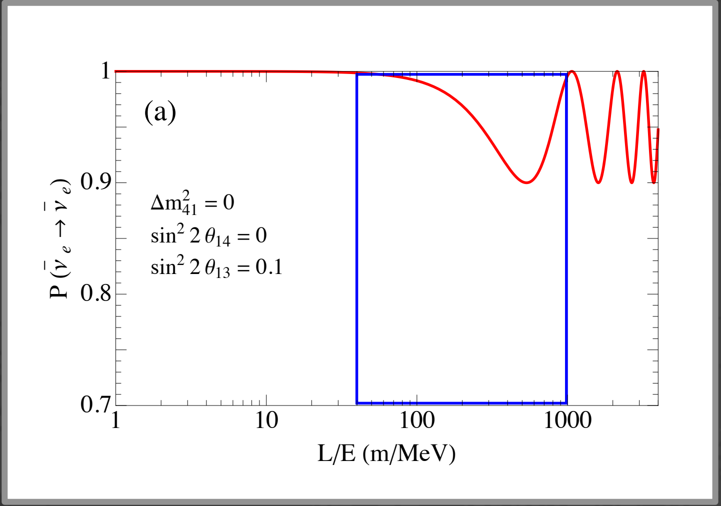
$$\frac{\Delta m^2_{14} L}{4E_\nu} \simeq 1.267 \left(\frac{\Delta m^2_{14}}{10^{-2}\ \mathrm{eV}^2}\right)\left(\frac{L}{400\ \mathrm{m}}\right)\left(\frac{4\ \mathrm{MeV}}{E_\nu}\right)$$

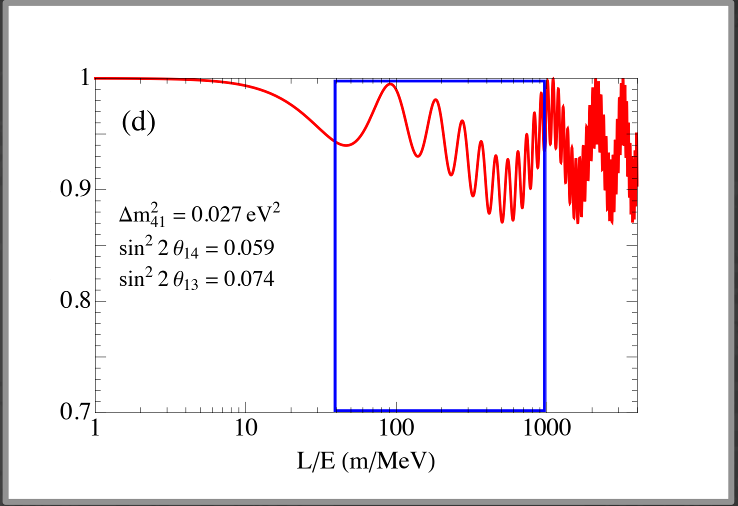
Far/near ratios expected to give info on VLSν's

Numerical examples

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

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

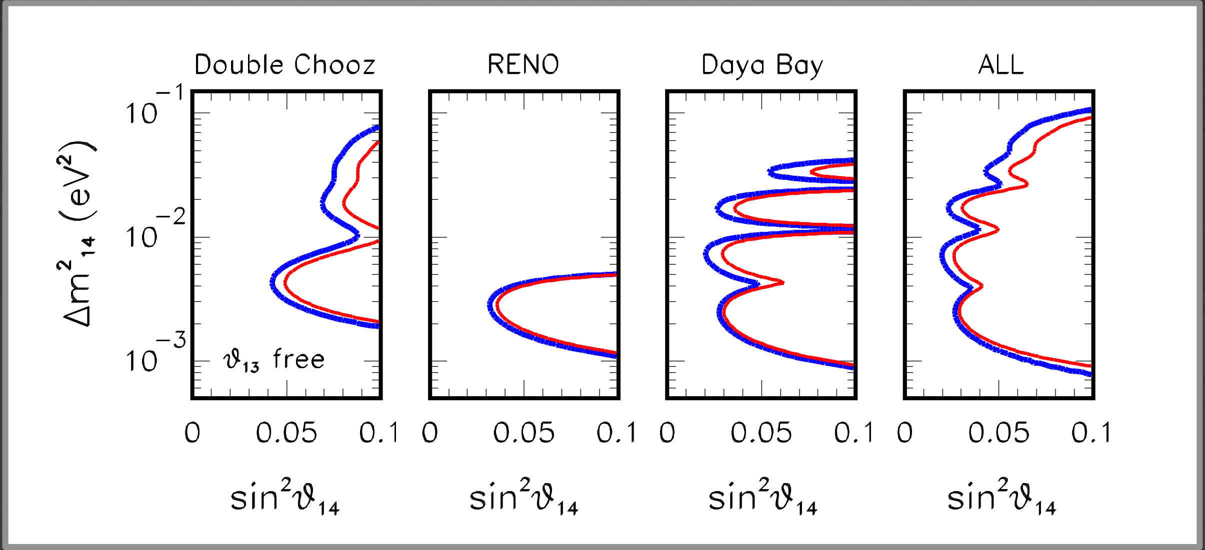




Figures from Esmaili et al., Phys. Rev. D 88, 073012 (2013)

Far/near ratios are expected to give info on VLSνs

4-flavor analysis performed for free θ_{13}

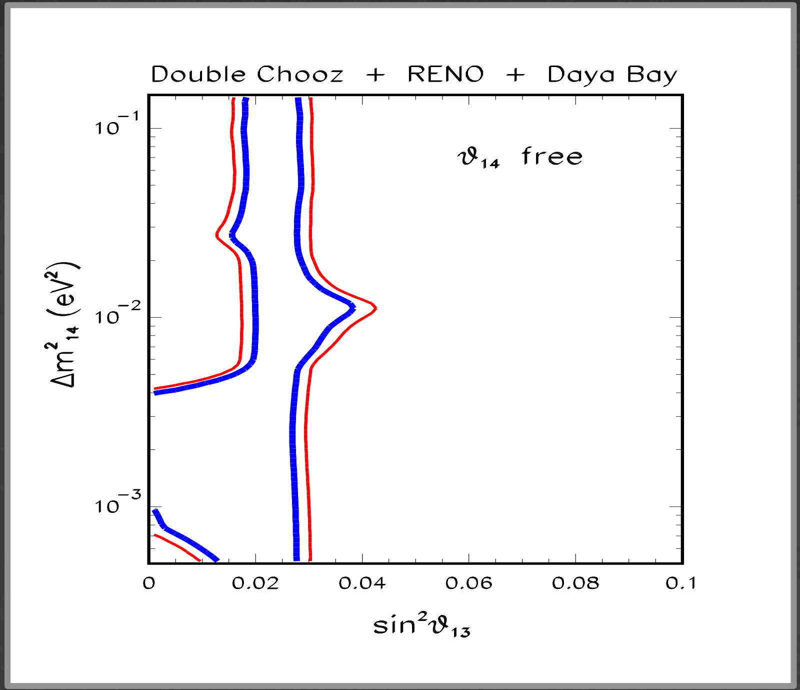


A.P. JHEP 1310, 172 (2013) [1308.5880 hep-ph]

Each experiment excludes a different region

Synergy in the global combination

Estimate of θ_{13} in a 4ν framework



A.P. JHEP 1310, 172 (2013) [1308.5880 hep-ph]

3ν estimate robust provided that $\Delta m^2_{14} > 6 \times 10^{-3}$ eV^2

No lower bound for smaller Δm^2_{14} (θ_{13}-θ_{14} degeneracy)

However, in this region lower bound by T2K

Summary

- Possible indications of eV sterile neutrinos
- Global interpretation problematic (app/dis tension)
- Hint from cosmology also is difficult to explain
- VLSν's with $\Delta m^2 \sim [10^{-3} - 10^{-1}]$ eV ^{2} offer an option for cosmo hints (dark rad. and hot-dark-matter)
- New information on eV/sub-eV νs indispensable

What if a ν_s were discovered?

First concrete extension of the SM; will need scrutiny
Properties beyond m & θ? Self interactions & with DM ?

Subleading effcts expected in osc. phenomenology.
NMH & CPV sensitivities altered. New CPV phases.

Impact in cosmology (radiation and hot dark matter)

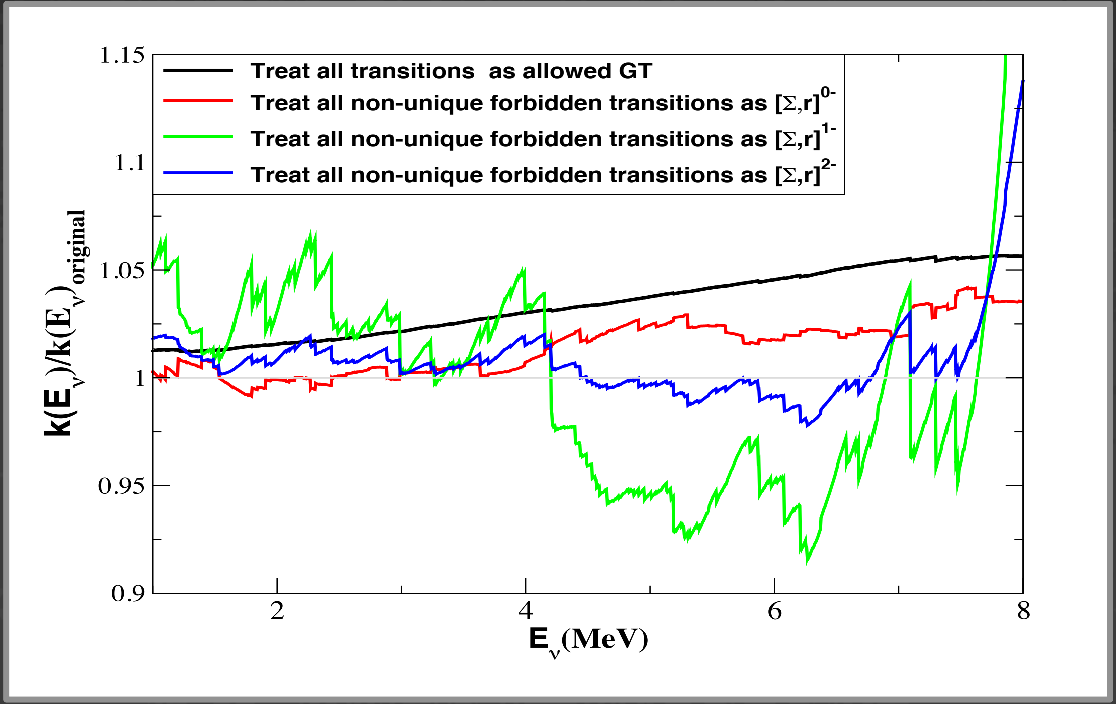
Impact in astrophysics (supernova explosion)

It will be natural to think that several ν_s may exist and explain other observations: DM (keV), baryon asymmetry via leptogenesis and small ν mass (GUT), etc ...

Thank you for your attention!

Backup slides

Are systematics under control?



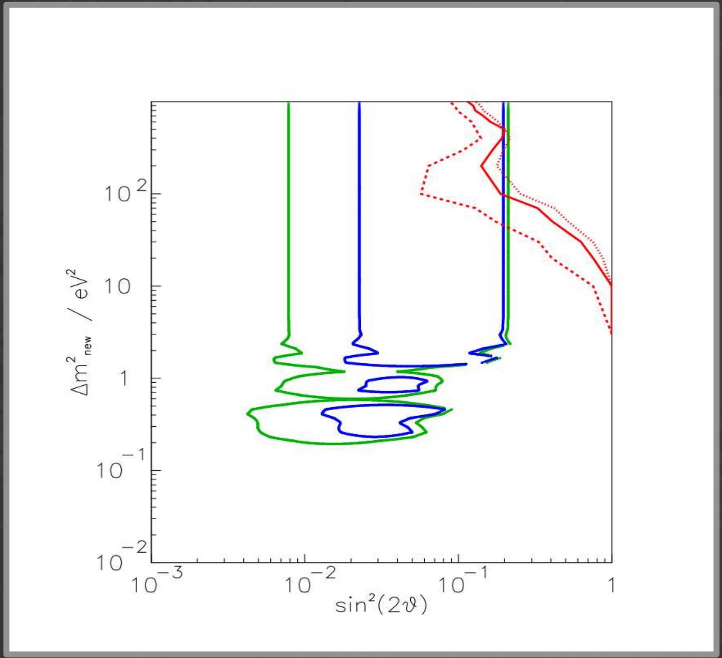
A.C. Hayes et al. arXiv:1309.4146 [nucl-th]

Systematics in reactor spectra may have been underestimated

Impact of a light sterile neutrino in β-decay

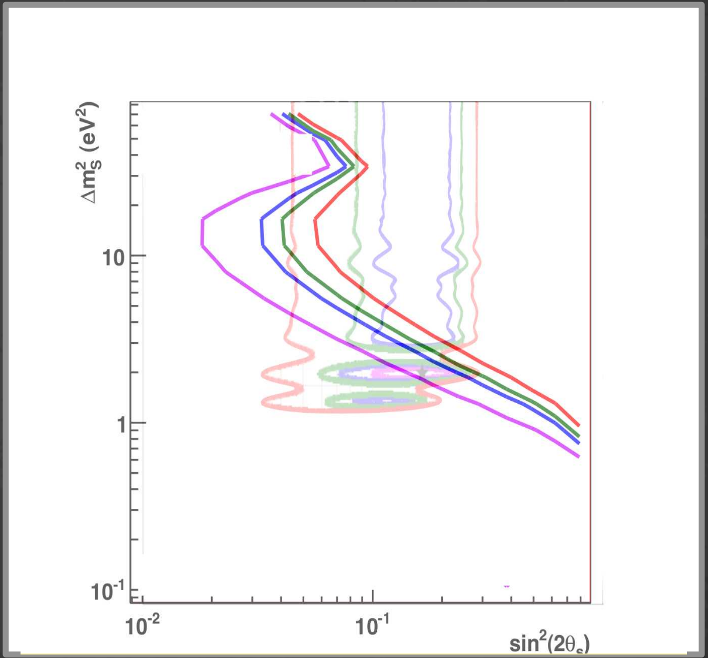
$$m_\beta = \sqrt{\sum |U_{ei}|^2 m_i^2} \;\; = \left|c_{12}^2 c_{13}^2 c_{14}^2 m_1^2 + s_{12}^2 c_{13}^2 c_{14}^2 m_2^2 + s_{13}^2 c_{14}^2 m_3^2 + s_{14}^2 m_4^2\right|^{1/2}$$

Present: Mainz



Kraus et al., arXiv:1105.1326

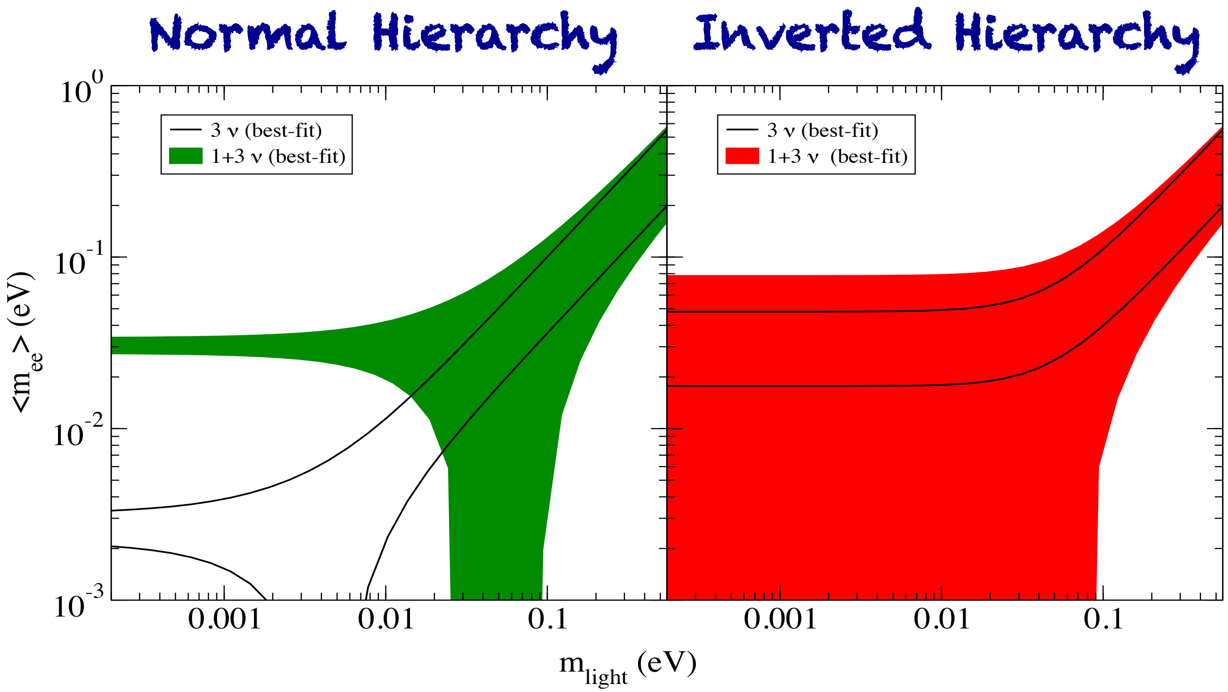
Future: KATRIN



Formaggio & Barrett, arXiv:1105.1326

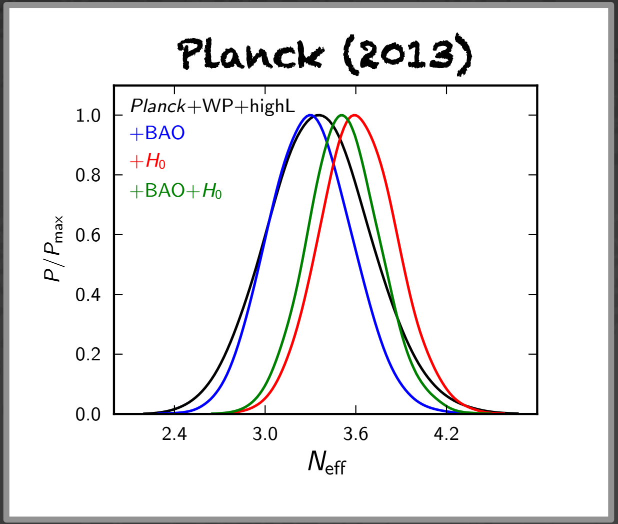
Impact of a light sterile in 0ν2β-decay

$$m_{\beta\beta} = \left| \sum U_{ei}^2 m_i \right| = \left| c_{12}^2 c_{13}^2 c_{14}^2 m_1 + s_{12}^2 c_{13}^2 c_{14}^2 m_2 e^{i\alpha} + s_{13}^2 c_{14}^2 m_3 e^{i\beta} + s_{14}^2 m_4 e^{i\gamma} \right|$$



Barry, Rodejohann, Zhang, arXiv:1105.3911

What cosmology tells us?



Extra relativistic content
~ 2 sigma effect

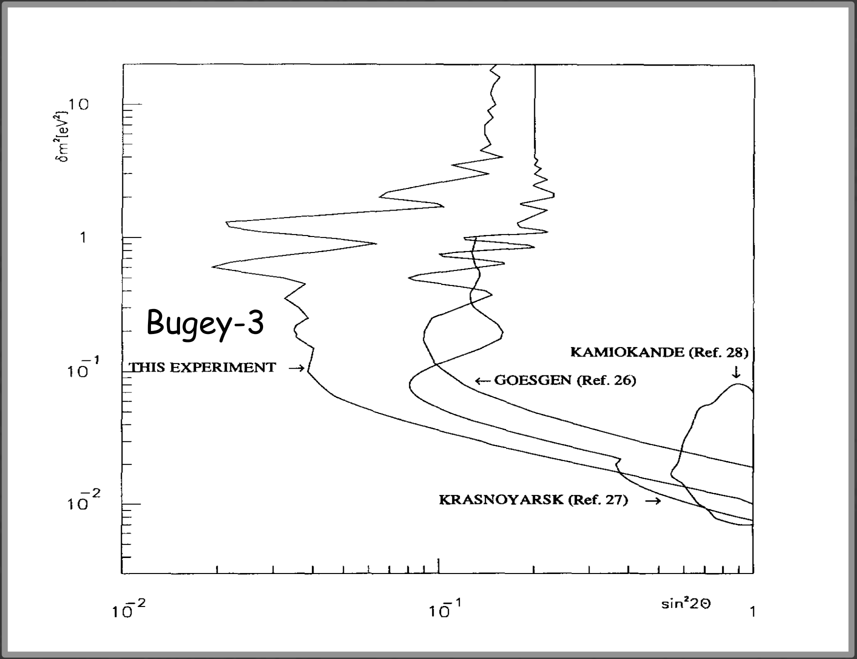
"Dark radiation"

Warnings:

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

Role of reactor experiments in ν_s searches

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

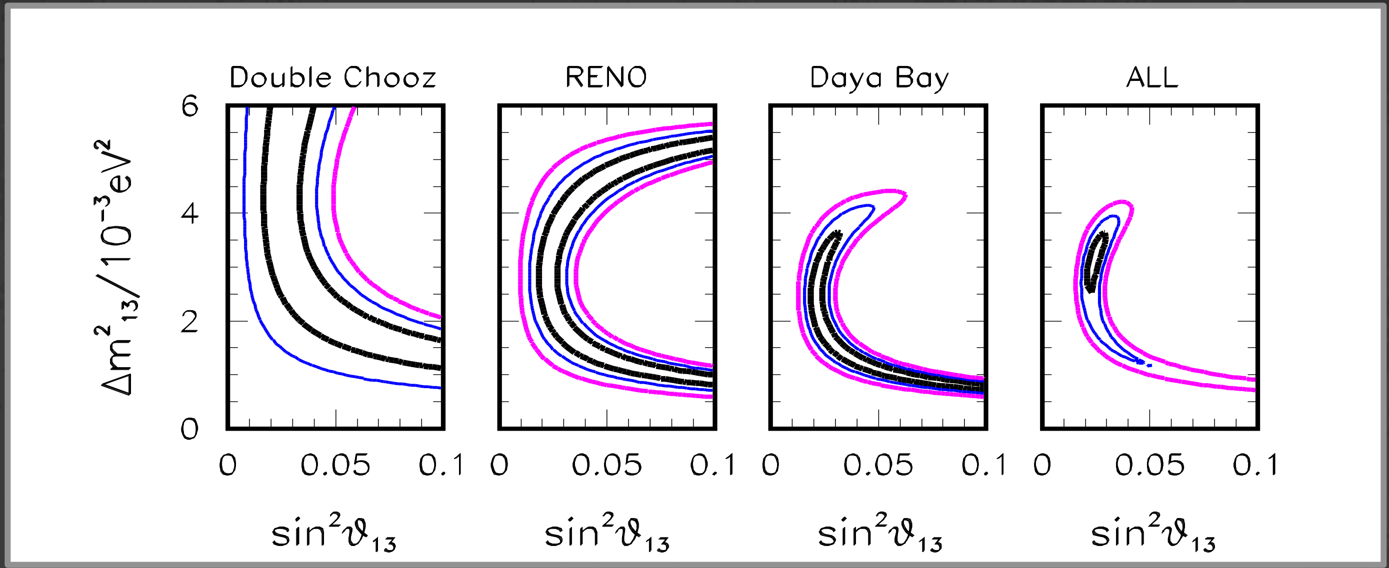


Existing constraints limited to Δm^2_{14} > few x 10^{-2} eV^2

Obtained with baselines < 100 m

New experiments with longer baselines are now operating and make it possible to probe smaller values of Δm^2_{14}

3-flavor analysis (θ_{14}=0)



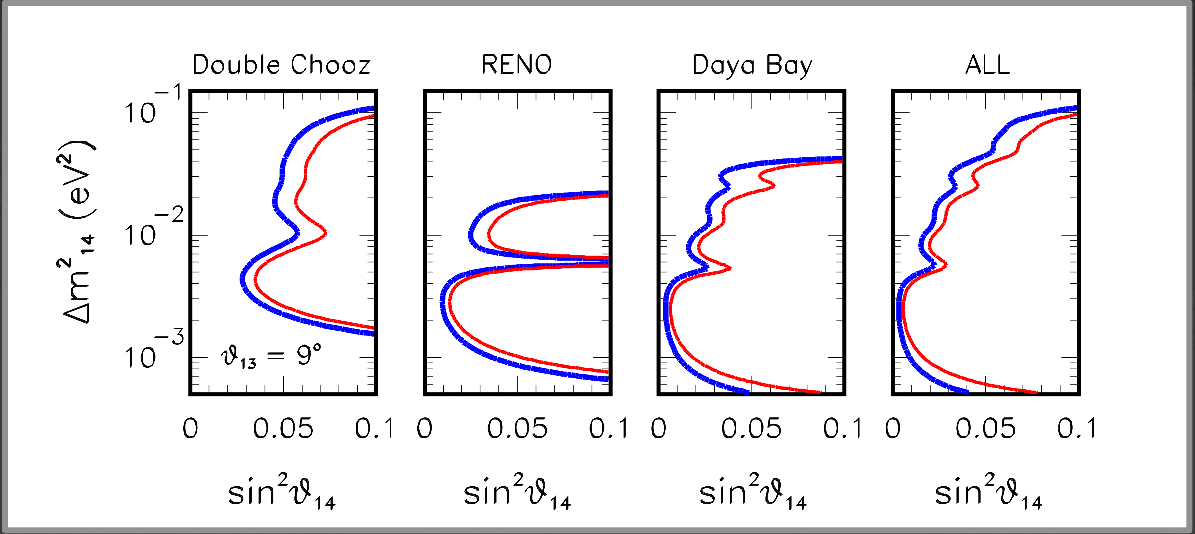
A.P. JHEP 1310, 172 (2013) [1308.5880 hep-ph]

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. JHEP 1310, 172 (2013) [1308.5880 hep-ph]

All 3 experiments exclude a lobe around the atm. splitting
(far site sees the osc. phase, at near site negligible effects)

All 3 experiments exclude a second lobe around 10^{-2} eV^2
(at far site averaged osc., near site sees oscillation phase)