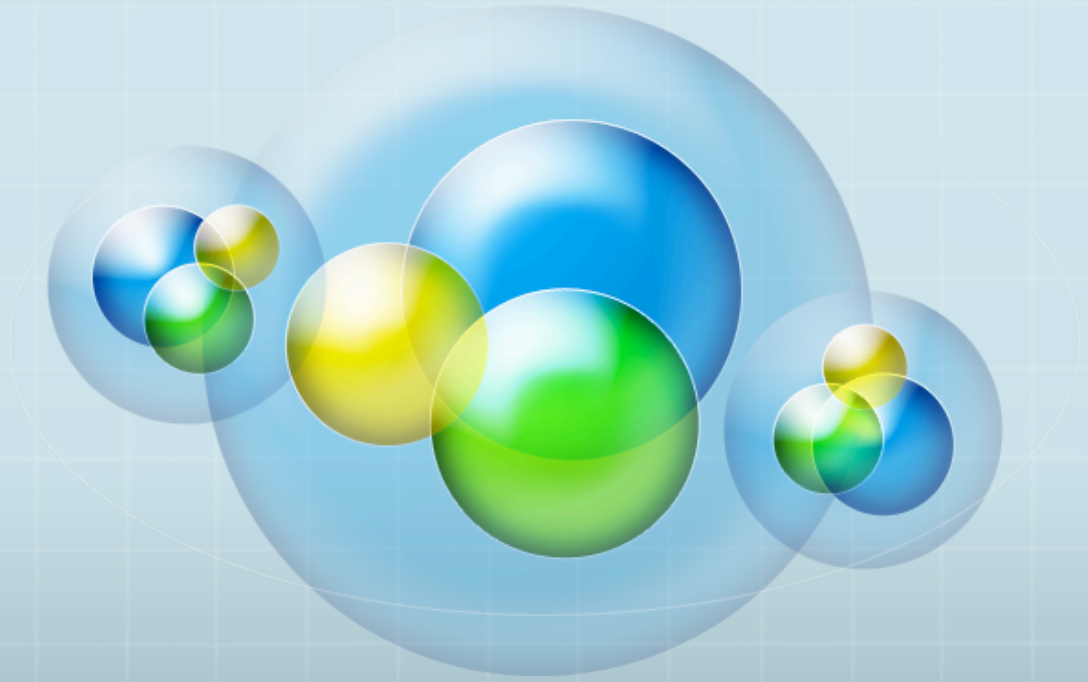


Theories of light sterile neutrinos

JiJi Fan
Princeton University

work with P. Langacker, 1201.6662 (hep-ph) JHEP, 2012

Outline

- Sterile neutrino basics: SM singlet lepton present in most m_ν models

  Masses *anywhere* from sub-eV to $M_p \sim 10^{18}$ GeV

- This talk: eV-scale light sterile neutrinos
- Motivations
  a. Terrestrial hints: LSND, MiniBooNE, reactor
  b. Cosmological Hints: CMB, LSS and others
- Mini – seesaw mechanism
  a. Mini – seesaw from high dimensional operators
  b. Mixing parameters and phenomenology
- Modified 3+1 scheme

Sterile neutrino preliminaries

- **Active neutrino:**

  in SU(2) doublet with a charged lepton – normal weak interactions

$$\nu_L \leftrightarrow \nu_R^c \quad \text{by CP}$$

- **Sterile neutrino:**

  SU(2) singlet; no interactions except by mixing, Higgs or BSM

$$N_R \leftrightarrow N_L^c \quad \text{by CP}$$

Neutrino mass terms

- **Dirac mass:**

Connects two distinct Weyl spinors (active to sterile)

$$m_D(\bar{\nu}_L \nu_R + \bar{\nu}_R \nu_L) = m_D \bar{\nu}_D \nu_D$$

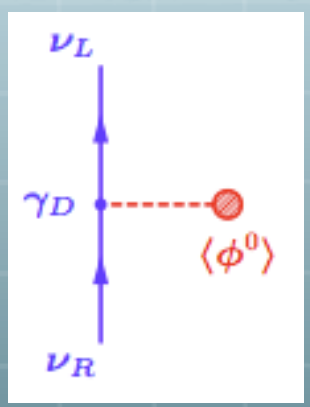
Dirac field:
4 component

$$\nu_D \equiv \nu_L + \nu_R$$

$$\Delta L = 0$$

$$\Delta t_L^3 = \pm \frac{1}{2} \rightarrow \text{Higgs doublet}$$

$$Why\ small?$$



High-dimensional operators

Majorana mass: connects Weyl spinor with itself

$$\frac{m_T}{2}(\bar{\nu}_L \nu_R^c + \bar{\nu}_R^c \nu_L) = \frac{m_T}{2}\bar{\nu}_M \nu_M (active)$$

$$\frac{m_S}{2}(\bar{N}_L^c N_R + \bar{N}_R N_L^c) = \frac{m_S}{2}\bar{N}_M N_M \, (sterile)$$

Majorana fields: 2 components

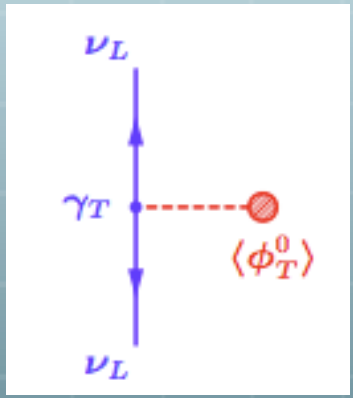
$$\nu_M \equiv \nu_L + \nu_R^c = \nu_M^c$$

$$N_M \equiv N_L^c + N_R = N_M^c$$

$$\Delta L = \pm 2$$

$$active : \Delta t_L^3 = \pm 1 \rightarrow$$ Higgs triplet

$$sterile : \Delta t_L^3 = \pm 0 \rightarrow$$ Bare mass or singlet



The smallness of all the masses could be explained by higher dimensional operators

Short baseline anomalies

- LSND/MiniBooNE anti-neutrino data suggest $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$

oscillations ($\Delta m^2 \sim eV^2$)

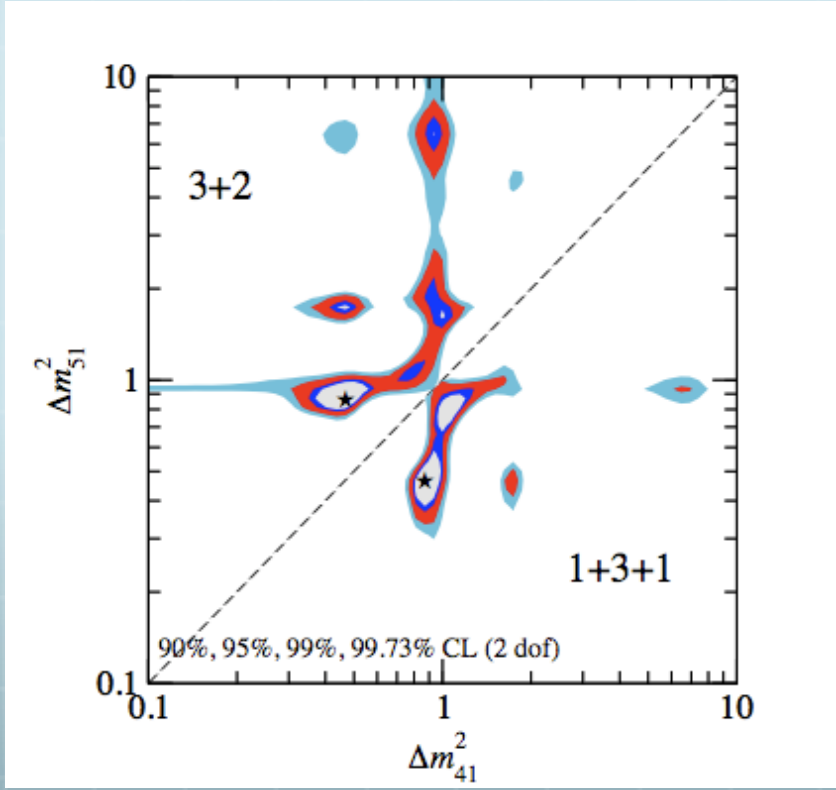
- The non-observation of $\nu_\mu \longrightarrow \nu_e$

  suggests CP violation: more than 1 sterile neutrino; simplest scenario 3+2 schemes (or 3+1+large effective CP violation or alternative scenarios)

- Global 3+2/3+1 fits: (Kopp, Maltoni and Schwetz '11; Giunti and Laveder '11)

  New reactor flux analysis improves consistency (Mention, Fechner, Lasserre, Mueller, Lhuilier '11)

  3 active neutrinos +2 sterile neutrinos gives a reasonable fit.



$$\delta \equiv \arg\left(\frac{U_{e5}U^*_{\mu 5}}{U_{e4}U^*_{\mu 4}}\right)$$

	Δm^2_{41}	Δm^2_{51}	$\lvert U_{e4}\rvert$	$\lvert U_{e5}\rvert$	$\lvert U_{\mu 4}\rvert$	$\lvert U_{\mu 5}\rvert$	δ/π	χ^2/dof
KMS	0.47	0.87	0.128	0.138	0.165	0.148	1.64	110.1/130
GL	0.90	1.60	0.13	0.13	0.13	0.08	1.52	91.6/100

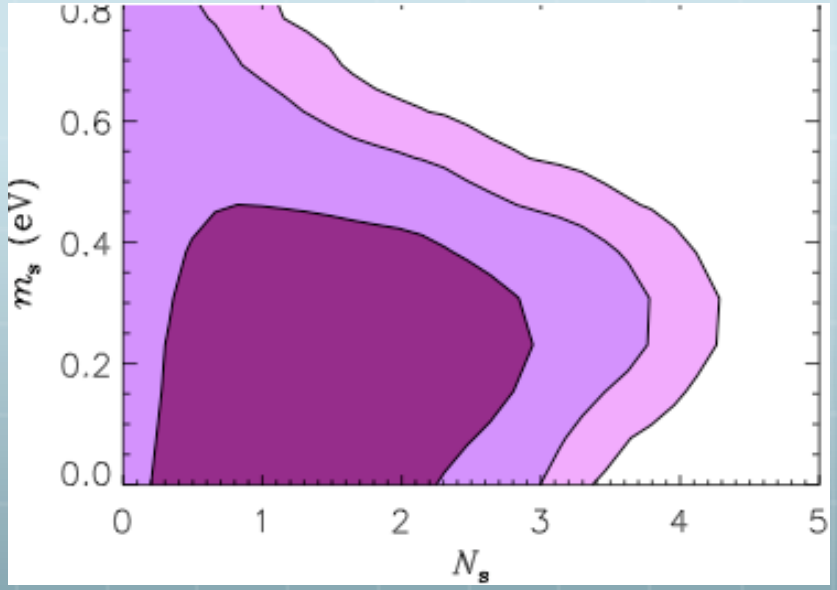
eV scale sterile neutrinos

large mixing ~ 0.1

large CP violation phase

Cosmological Hints

CMB and others: allow or weakly favor $N_s \sim 1 - 2$ sterile neutrinos



Hamann, Hannestad, Raffelt, Tamborra, Wong '10 ;

3+2 scheme: $m_s < 0.45$ eV at 95% C. L.

However, $m_s \sim$ eV is not favored within ΛCDM;
Besides, BBN requires: $N_s < 1.26$ at 95% C.L.
Yet bounds weakened by allowing additional radiation, $w < -1$

Hamann, Hannestad, Raffelt, Wong '11 ;

Neutrino mixing models

3×3 3×n n: # of sterile neutrino

$$-\mathcal{L} = \frac{1}{2}\left(\bar{\nu}_L^0 \;\; \bar{N}_L^{0c}\right)\begin{pmatrix} M_T & M_D \\ M_D^T & M_S \end{pmatrix}\begin{pmatrix} \nu_R^{0c} \\ N_R^0 \end{pmatrix}$$

n×n

$$M_T: \quad |\Delta L| = 2 \quad |\Delta t_L^3| = 1 \quad Majorana$$

$$M_D: \quad |\Delta L| = 0 \quad |\Delta t_L^3| = \frac{1}{2} \quad Dirac$$

$$M_S: \quad |\Delta L| = 2 \quad |\Delta t_L^3| = 0 \quad Majorana$$

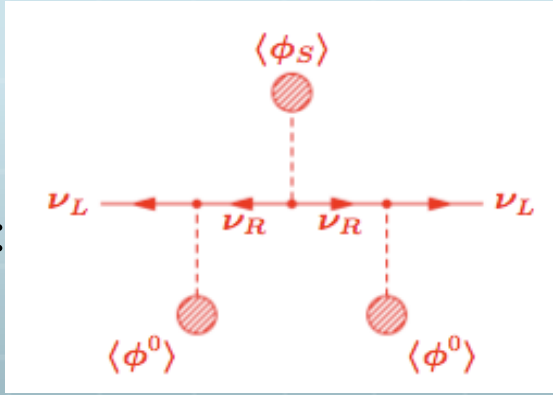
Interesting limits: Majorana (M_D = 0); Dirac (M_T = M_s = 0) **NO active-sterile mixing!**

- **Seesaw mechansim (minimal or Type 1 seesaw) $M_s >> M_D, M_T$**

For example: GUT seesaw

$$\gamma_D H_u L N + M_s N N$$

$\mathcal{O}(1)$



$$M_T = 0, M_D = \mathcal{O}(m_t), M_S = \mathcal{O}(10^{15}\,\mathrm{GeV}):$$

$$|m_1| \sim M_D^2/M_S \sim 0.01\,\mathrm{eV}$$

$$\theta \sim M_D/M_s \sim 10^{-13}$$

Light sector is essentially active while heavy sterile decouples

Heavy sterile neutrino decouples at low energy $(H_u L)^2/M_s$

Heavy sterile neutrino decays ➔ leptogenesis

- **So far no limit gives rise to a big enough active/sterile mixing to explain short baseline anomalies**
- **We need: small M_s and M_D (and/or small M_T)**

$$\begin{pmatrix} M_T & M_D \\ M_D^T & M_S \end{pmatrix} = \begin{pmatrix} \mathcal{O}(0.01) & \mathcal{O}(0.1) \\ \mathcal{O}(0.1) & \mathcal{O}(1) \end{pmatrix}$$

$$\theta \sim M_D/M_s \sim 0.1$$

$$m_1 \sim M_D^2/M_s \sim 0.01\mathrm{eV}$$

$$m_2 \sim M_s \sim \mathrm{eV}$$

Gouvea, '05;
Gouvea, Jenkins and Vasudevan '06;

Mini See-saw

Mechanism for small masses

$$\gamma_D H_u L N + M_s N N$$

$$\begin{pmatrix} M_T & M_D \\ M_D^T & M_S \end{pmatrix} = \begin{pmatrix} \mathcal{O}(0.01) & \mathcal{O}(0.1) \\ \mathcal{O}(0.1) & \mathcal{O}(1) \end{pmatrix}$$

$$\gamma_D \sim 10^{-12}$$

$$M_s \sim 10^{-27} M_{planck}$$

Parameters tuned or generated by dynamics

Mechanisms for small neutrino mass parameters:

Geometric suppression: wavefunction overlaps in large (or warped) extra dimensions; sterile neutrinos in the bulk while SM confines to the brane.

$$M_D \sim \frac{v M_F}{M_{Planck}} \sim 0.1\,\mathrm{eV}\,\frac{M_F}{10^3\,\mathrm{TeV}}$$

fundamental gravitational scale in 4+δ dimensions

Arkani-Hamed, Dimopoulos, Dvali and March-Russell '98; Dienes, Dudas, Gherghetta '98

Stringy mechansims: mass terms exponentially suppressed by non-perturbative instanton effects (e.g. D-brane instantons);
No known reason to get small correlated M_D, M_s at the same time.

Blumenhagen, Cvetic, Kachru and Weigand '09; Langacker '11

High-dimensional operators (HDO) Langacker '98

The effect of ordinary seesaw is to introduce a high-dimensional operator in the low energy theory which is suppressed by a large scale;

Additional symmetries (global, gauge, discrete) may lead to highly suppressed leading operators

S: SM singlet with a VEV

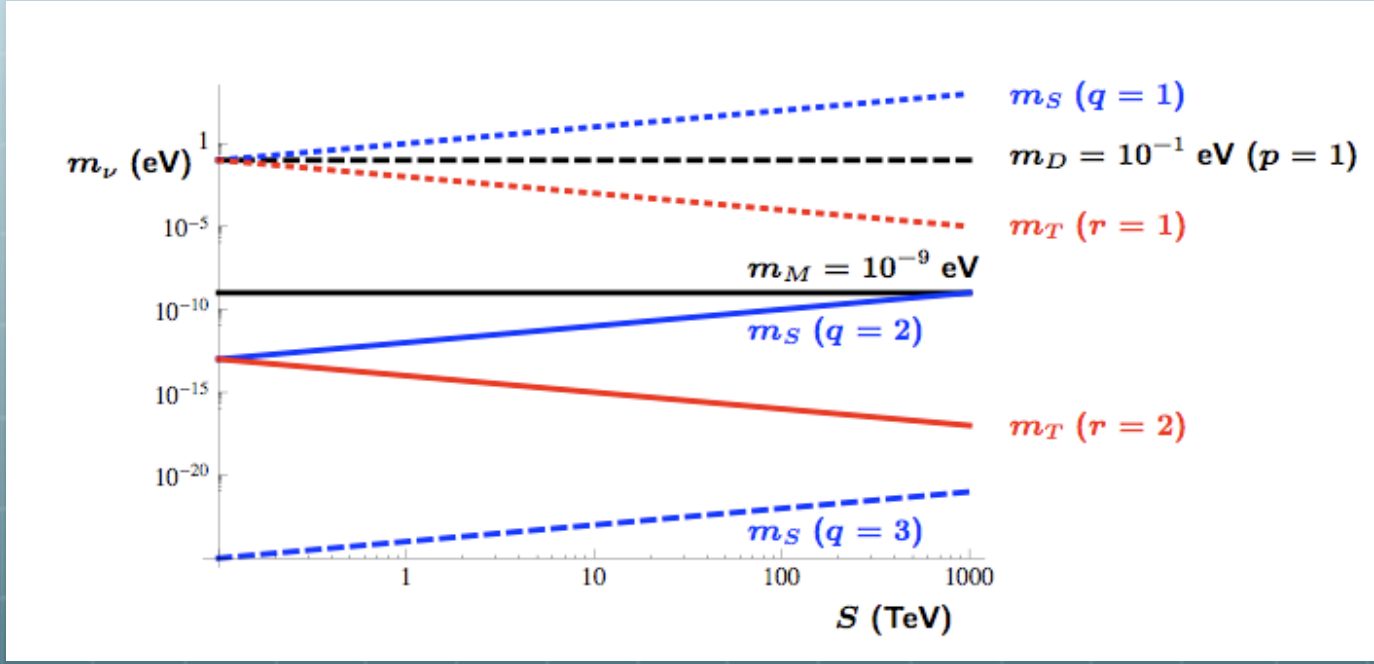
$$\mathcal{L} \supset \frac{\boxed{S}^p}{M^p} L H_u N_R, \frac{\boxed{S}^{q+1}}{M^q} N_R N_R, \frac{\boxed{S}^{r-1}}{M^r} (L H_u)^2$$

p, q ≥ 0 and r ≥ 1 : lowest dimensions allowed by the symmetries;
S^p/M^q : shorthand for $S_1 S_2 \ldots S_p / (M_1 M_2 \ldots M_q)$

$$\mathcal{L} \supset \frac{S^p}{M^p} L H_u N_R, \frac{S^{q+1}}{M^q} N_R N_R, \frac{S^{r-1}}{M^r} (L H_u)^2$$

HDO mini-seesaw p=q=1, r=1, <S> ~ TeV, M ~ M_{GUT}

$$\boxed{\mathcal{L} \supset \frac{S}{M} L H_u N_R, \frac{S^2}{M} N N, \frac{1}{M} (L H_u)^2}$$



Active-sterile mixing parameters

So far we see qualitatively that 3+2 schemes may be accommodated into mini-seesaw ;
But we want to be more quantitative. In particular, we want to address:

a. What is the minimal set of parameters that characterize mini-seesaw ?
b. How well could they explain the data?

In the limit, M_T =0, the active neutrino mass is generated purely via seesaw, the active-sterile mixing parameters are fixed by the active/sterile neutrino masses up to an orthogonal complex matrix;

in other words, the minimal mini-seesaw (M_T =0) relies on a more constraining parameter set

M_T = 0, n sterile neutrinos, 3-n massless active neutrinos;
n=1 Normal hierarchy; n=2 Normal/Inverted hierarchy

seesaw tells: $m_\nu = M_D M_S^{-1} M_D^T = DD^T$

$$D = M_D M_S^{-1/2} \text{ is a } (3 \times n)\text{-dimensional complex matrix}$$

$$m_\nu = A_L^\nu m_d A_L^{\nu T} = LL^T \qquad L \equiv A_L^\nu m_d^{1/2}.$$

PMNS matrix diagonal matrix of light neutrino masses

$$A_L^\nu = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\rho} \\ 0 & 1 & 0 \\ -s_{13}e^{i\rho} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \Phi,$$

$$\Phi = \mathrm{Diag}(e^{i\alpha_1}, e^{i\alpha_2}, e^{i\alpha_3})$$

α_i: Two independent at most

The most general solution: $D = LR(z_k)$; $R(z_k)$: orthorgonal n×n complex matrix

M_T = 0, n sterile neutrinos, 3-n massless active neutrinos;
n=1 Normal hierarchy; n=2 Inverted hierarchy

$$m_\nu = M_D M_S^{-1} M_D^T = DD^T,$$

$$m_\nu = A_L^\nu m_d A_L^{\nu T} = LL^T$$

PMNS matrix diagonal matrix of light neutrino masses

The most general solution: $D = LR(z_k)$, $R(z_k)$: orthorgonal n×n complex matrix

seesaw tells: $U = iM_D M_S^{-1} = iDM_S^{-1/2} = iA_L^\nu R(z_k) m_d^{1/2} M_s^{-1/2}$

$$n = 1, \quad U_{\alpha 4} = i\frac{M_D^{\alpha 4}}{M_4} = \pm i A_L^{\nu\alpha 3}\sqrt{\frac{m_3}{M_4}}, \quad \alpha = e, \mu, \tau.$$

$A^{\nu e3}$ small, $|U_{e4}| << 0.1$

n > 1

$$\boxed{U_{\alpha i} = i\frac{M_D^{\alpha i}}{M_i} = iA_L^{\nu\alpha j}\sqrt{m_j}\,R_{ji}\,\frac{1}{\sqrt{M_i}}},$$

$$\alpha = e, \mu, \tau;\ j = 1, \cdots, n;\ i = 4, \cdots, 3+n$$

n=2

NH: hard to get large enough U_{e4}, U_{e5};

IH: 1 massless active neutrino; a complex angle z;

$$R(z) = \begin{pmatrix} \cos z & \sin z \\ -\sin z & \cos z \end{pmatrix}$$

n = 2, IH, one massless active neutrino, choose $m_3 = 0$; thus $\alpha_3 = 0$

$$\boxed{U_{\alpha i} = i\frac{M_D^{\alpha i}}{M_i} = iA_L^{\nu\alpha j}\sqrt{m_j}\,R_{ji}\,\frac{1}{\sqrt{M_i}}},$$

$$\alpha = e, \mu, \tau;\ j = 1, 2;\ i = 4, 5$$

5 real free parameters:

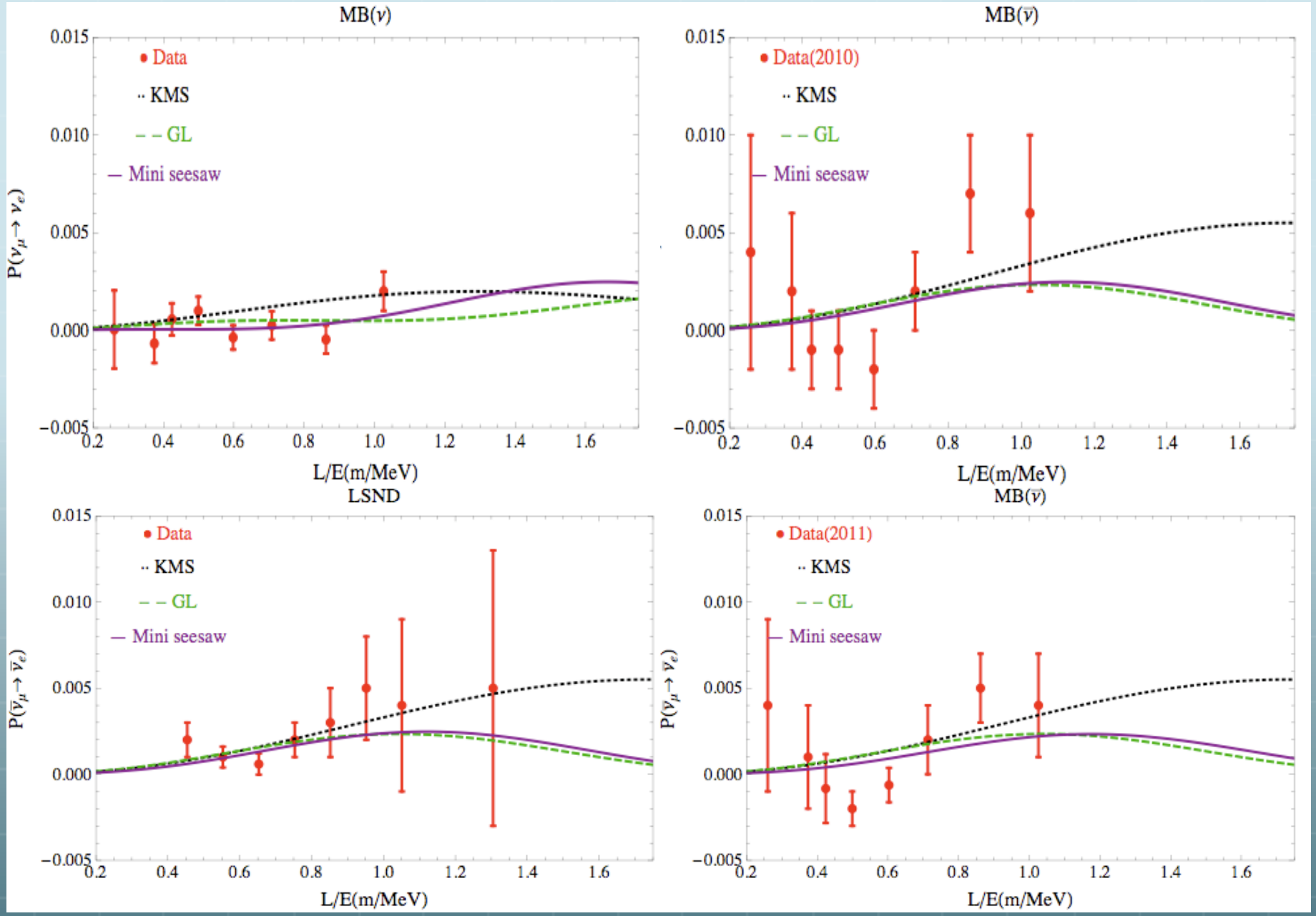
α_2 , complex angle z, two sterile neutrino masses: M_4, M_5

6 complex $U_{\alpha i}$, M_4, M_5 (6 |U|, M4, M5, δ in global fits)

$$\boxed{U_{\alpha i} = i\frac{M_D^{\alpha i}}{M_i} = iA_L^{\nu\alpha j}\sqrt{m_j}\,R_{ji}\,\frac{1}{\sqrt{M_i}}},$$

$$\alpha = e, \mu, \tau;\ j = 1, 2;\ i = 4, 5$$

	z	α_2	Δm^2_{41}	Δm^2_{51}	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	$\lvert U_{e5}\rvert$	$\lvert U_{\mu 5}\rvert$	δ/π	χ^2/dof
MMS(2010)	$0.39\ e^{-i0.53\pi}$	2.01	0.89	1.78	0.15	0.15	0.07	0.15	1.25	18.6/19
MMS(2011)	$0.38\ e^{-i0.54\pi}$	1.92	0.89	1.76	015	0.15	0.07	0.15	1.21	24.3/19
KMS			0.47	0.87	0.128	0.165	0.138	0.148	1.64	110.1/130
GL			0.90	1.60	0.13	0.13	0.13	0.08	1.52	91.6/100


MB(ν)
Data
KMS
GL
Mini seesaw
P(ν_μ → ν_e)
L/E(m/MeV)
MB(ν̄)
Data(2010)
KMS
GL
Mini seesaw
L/E(m/MeV)
LSND
Data
KMS
GL
Mini seesaw
P(ν̄_μ → ν̄_e)
L/E(m/MeV)
MB(ν̄)
Data(2011)
KMS
GL
Mini seesaw
P(ν_μ → ν_e)
L/E(m/MeV)

Constraints on the sterile masses

tritium decay $$m_\beta^2 \equiv \sum_i |\mathcal{A}_{ei}|^2 m_i^2$$

neutrinoless double β decay $$m_{\beta\beta} \equiv \sum_i (\mathcal{A}_{ei})^2 m_i = (M_T)_{11}$$

Cosmology $$\Sigma = \sum_{i=4}^{5} |M_i|$$

	3+2 (eV)	3+2 MSS (eV)	EXP (eV)
m_β	~ 0.2	0.18	$(1-2) \to 0.2$
$m_{\beta\beta}$	$0-0.08$	0	$(0.2-0.7) \to (0.01-0.03)$
Σ	~ 2	2.4	$(0.5-1) \to (0.05-0.1)$

Cosmologically 3+2 schemes with 2 eV scale steriles are not favored;

Some (highly speculative/creative) loopholes:

Nonzero chemical potential

Kang, Steigman '92; Foot and Volkas '95; Foot, Thomson and Volkas '95; Abazajian, Bell, Fuller and Wong '04 ….

$$\frac{n}{p} = \exp\left(-\frac{m_n - m_p}{T} - \xi\right)$$

Time-dependent neutrino mass

Fardon, Nelson, Weiner '03; Kaplan, Nelson, Weiner '04

$$M_S^z = (1+z)^n M_s$$

Late-time phase transitions to suppress the sterile masses and mixings until after they decouple

Chacko, Hall, Oliver and Perelstein '04;

Modified 3+1 schemes

Modify 3+1 scheme by introducing an "effective" large CP violation phase (effective non-unitary transition matrix)

3 + 1 light sterile + 1 **Heavy** sterile neutrino: Nelson '10

1 light sterile: mass splitting ~ O(eV)
1 heavy sterile: mass splitting >> 10 eV, oscillation length averaged over

Reduction of phase space

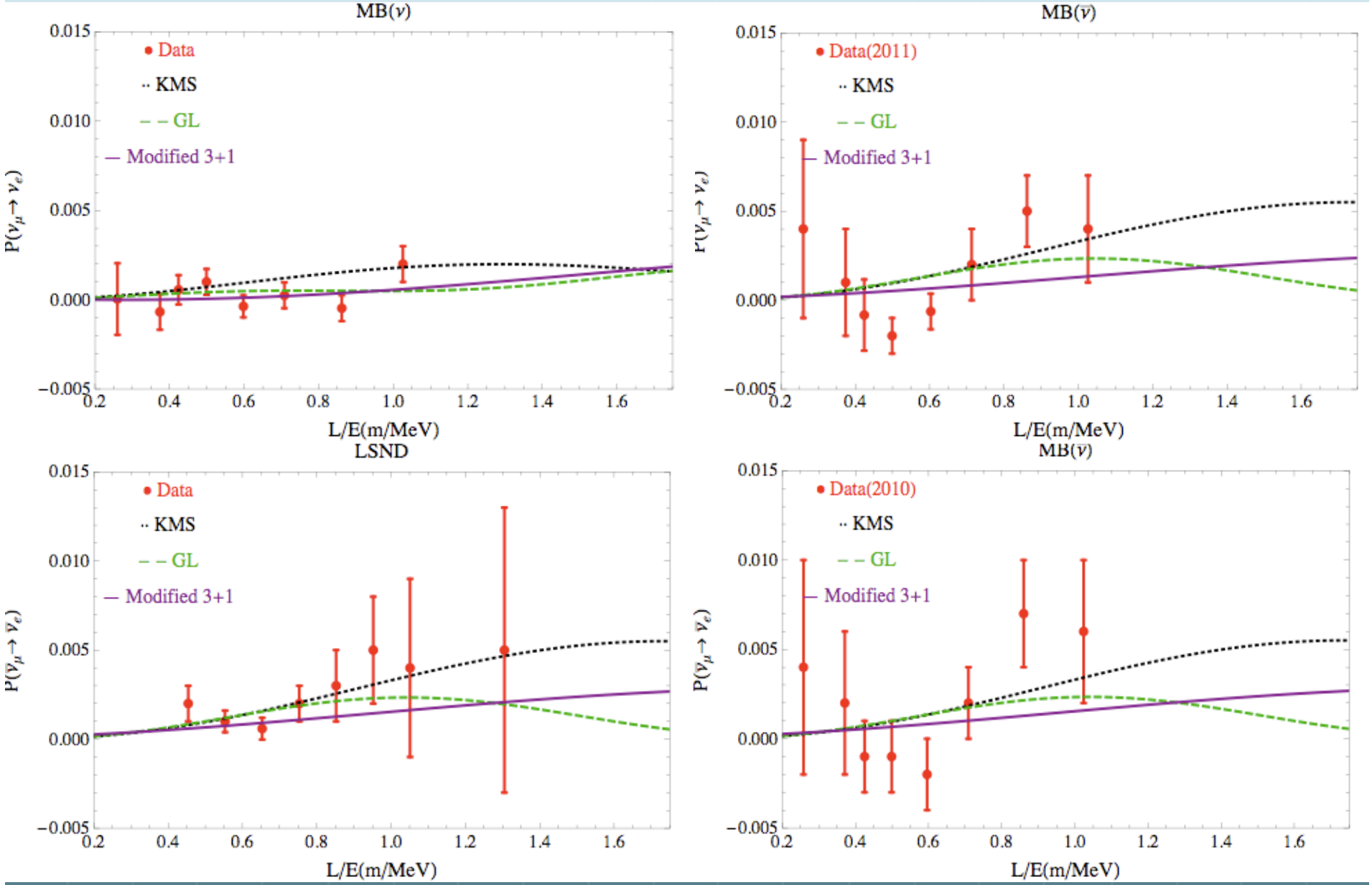
$$P_{\nu_\mu(\bar{\nu}_\mu)\to\nu_e(\bar{\nu}_e)} = \sin^2 2\theta_{\mu e} \sin^2 (x_{41} \pm \beta) + \kappa$$

$$\kappa = |U_{\mu 4}|^2 |U_{e4}|^2 \left\{ (1-r)^2 + a\left[(1-r)^2 + 4r\sin^2\beta\right] \right\}$$

$$r \equiv \left| U^*_{\mu 4} U_{e4} + U^*_{\mu 5} U_{e5} \right| / \left| U^*_{\mu 4} U_{e4} \right|$$

$$\beta \equiv \frac{1}{2} \tan^{-1} \left(\frac{\sin\phi |U_{e5}||U_{\mu 5}|}{|U_{e4}||U_{\mu 4}| + \cos\phi |U_{e5}||U_{\mu 5}|} \right)$$

When a=0, where the heavy sterile is not produced at all, still non-trivial effect on oscillation !!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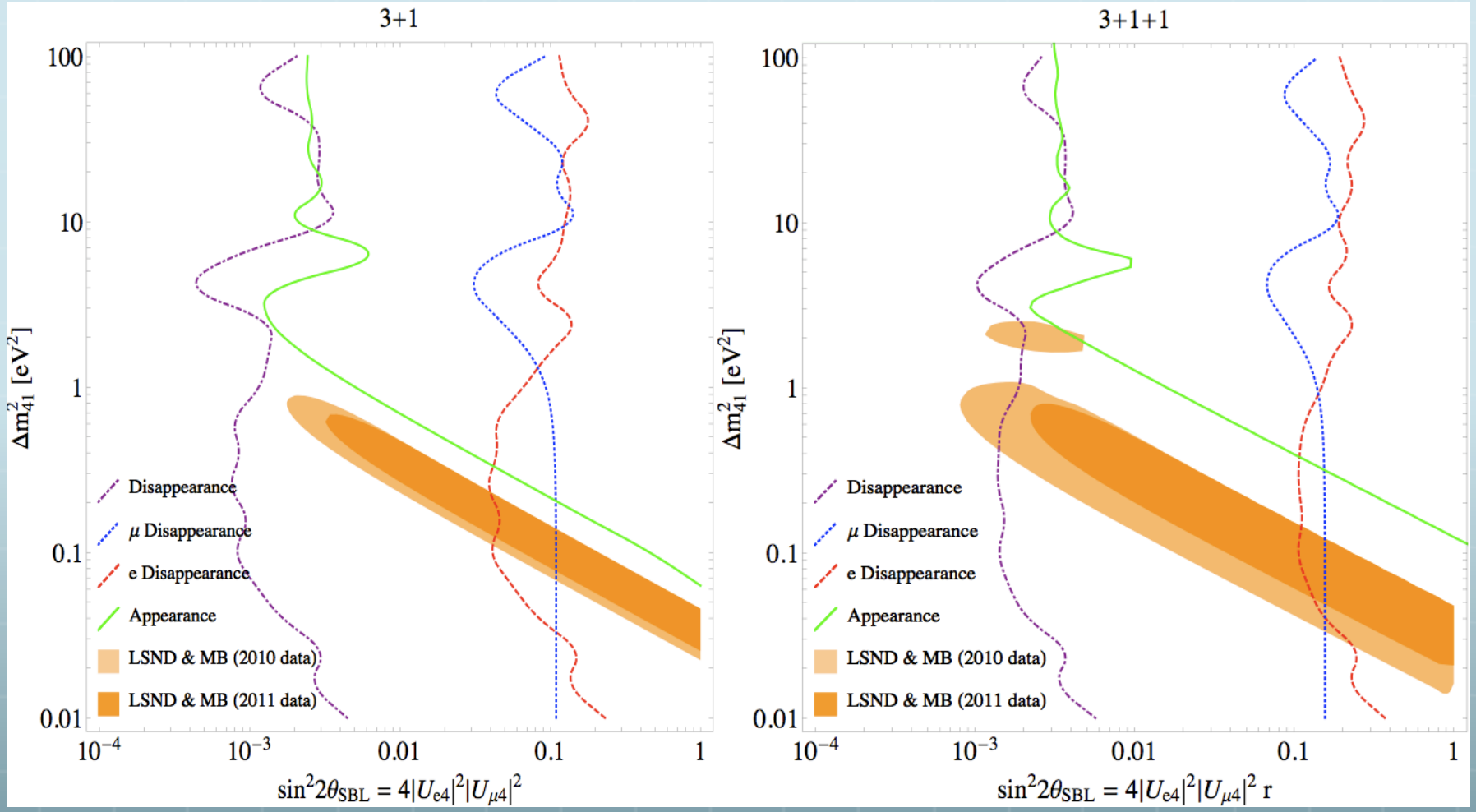
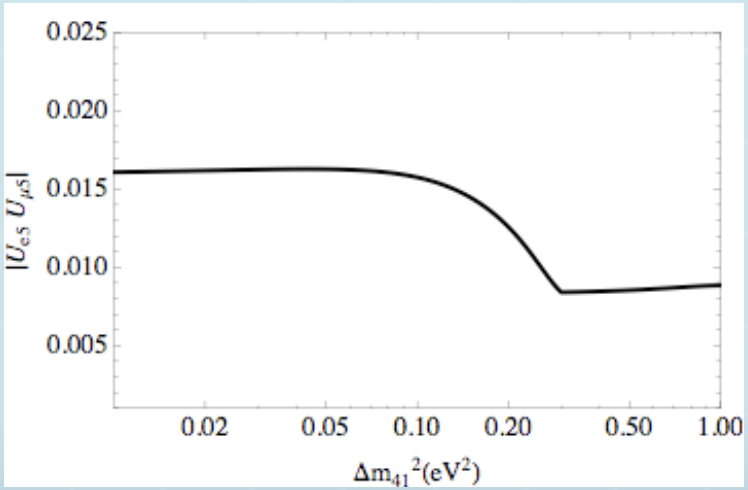
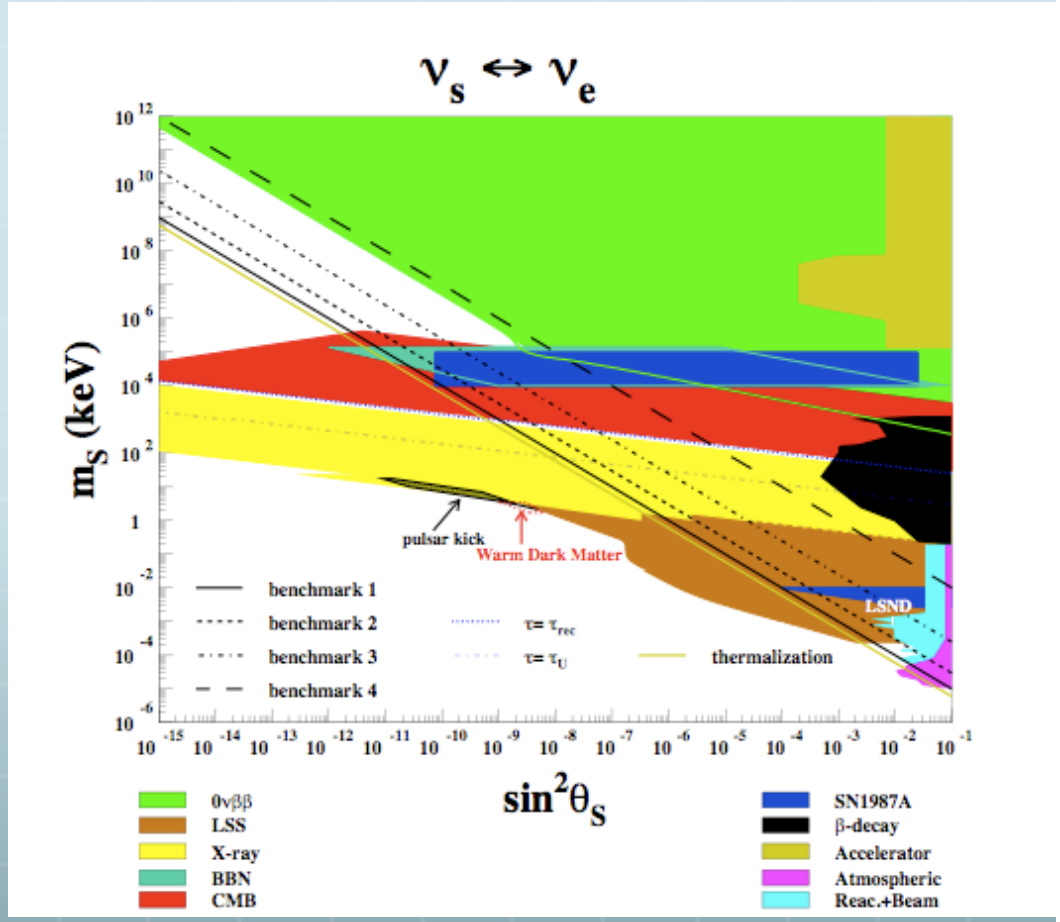


Kuflik, McDermott and Zurek '12

- Apparently this scenario may be more consistent with cosmological observations as it only has one light d.o.f at low energy
- However, ..





The heavy sterile has a mixing comparable to the mixing of the light sterile, which is large !!

Smirnov and Funchal, '06

Limited allowed region ~ GeV ! (unless modify cosmological history)

Conclusion

- Quite a few short baseline/cosmological anomalies that point towards the same direction;
- We may not believe it but it is definitely worth exploring!
- On the cosmological ground, PLANCK will tell us next year N_{eff} with an error ~ 0.2.
- This talk focus on 3+2 schemes and mini-seesaw mechanism
- There are quite a few alternatives; more studies are always welcomed!