Phenomenology of Light Sterile Neutrinos

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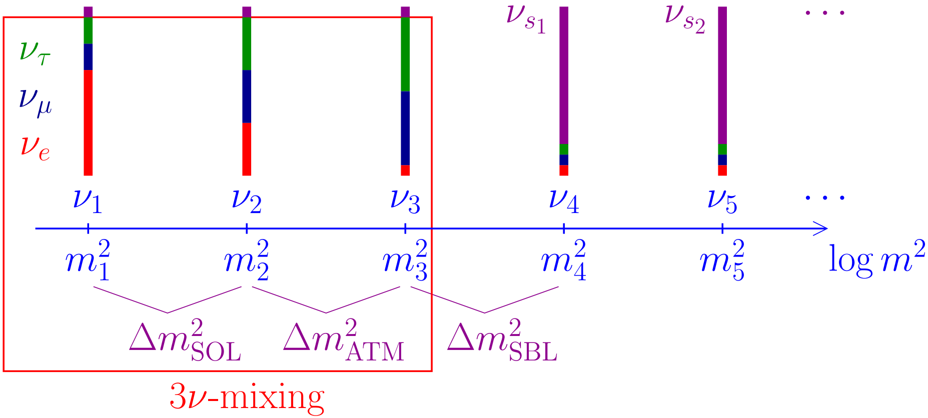
Seoul, Korea

17 June 2013

Three-Neutrino Mixing Paradigm

Solar $\nu_e \to \nu_\mu, \nu_\tau$	SNO, BOREXino; Super-Kamiokande; GALLEX/GNO, SAGE; Homestake, Kamiokande	$\Delta m^2_{\text{S}} \simeq 7.6 \times 10^{-5}\,\text{eV}^2$, $\sin^2\vartheta_{\text{S}} \simeq 0.30$
VLBL Reactor $\bar{\nu}_e$ disappearance	(KamLAND)	
Atmospheric $\nu_\mu \to \nu_\tau$	Super-Kamiokande; Kamiokande, IMB; MACRO, Soudan-2	$\Delta m^2_{\text{A}} \simeq 2.4 \times 10^{-3}\,\text{eV}^2$, $\sin^2\vartheta_{\text{A}} \simeq 0.50$
LBL Accelerator ν_μ disappearance	(K2K, MINOS, T2K)	
LBL Accelerator $\nu_\mu \to \nu_\tau$	(Opera)	
LBL Accelerator $\nu_\mu \to \nu_e$	(T2K, MINOS)	Δm^2_{A}, $\sin^2\vartheta_{13} \simeq 0.023$
LBL Reactor $\bar{\nu}_e$ disappearance	Daya Bay, RENO; Double Chooz	

Beyond Three-Neutrino Mixing



Sterile Neutrinos from Physics Beyond the SM

- Neutrinos are special in the Standard Model: the only neutral fermions

- In extensions of SM neutrinos can mix with non-SM fermions

- SM: $L_L = \begin{pmatrix} \nu_L \\ \ell_L \end{pmatrix}$ $\qquad \widetilde{\Phi} = i\sigma_2 \, \Phi^* = \begin{pmatrix} \phi^0 \\ \phi^- \end{pmatrix} \xrightarrow[\text{Breaking}]{\text{Symmetry}} \begin{pmatrix} v/\sqrt{2} \\ 0 \end{pmatrix}$

- SM singlet $\overline{L_L}\widetilde{\Phi}$ can couple to new singlet chiral fermion field f_R related to physics beyond the SM $[Y(\overline{L_L}) = +1, \; Y(\widetilde{\Phi}) = -1]$

- Known examples: light ν_R, SUSY, new symmetries, extra dimensions, mirror world, ... [see http://www.nu.to.infn.it/Sterile_Neutrinos/]

- Dirac mass term $\sim \overline{L_L}\widetilde{\Phi} f_R \quad + \quad$ Majorana mass term $\sim \overline{f_R^c} f_R$

- Diagonalization of mass matrix $\Longrightarrow$ massive Majorana neutrinos

- f_R is often called Right-Handed Neutrino: $f_R \to \nu_R$

Light Sterile Neutrinos

- Light anti-ν_R are called sterile neutrinos

$$\nu_R^c \to \nu_{sL} \qquad \text{(left-handed)}$$

- Sterile means no standard model interactions
- Active neutrinos $(\nu_e, \nu_\mu, \nu_\tau)$ can oscillate into light sterile neutrinos (ν_s)
- Observables:
  - Disappearance of active neutrinos (neutral current deficit)
  - Indirect evidence through combined fit of data (current indication)
- Short-baseline anomalies + 3ν-mixing:

$$\begin{array}{ccccc} & \Delta m^2_{21} \ll & |\Delta m^2_{31}| \ll & |\Delta m^2_{41}| \leq & \ldots \\ \nu_1 & \nu_2 & \nu_3 & \nu_4 & \ldots \\ \nu_e & \nu_\mu & \nu_\tau & \nu_{s_1} & \ldots \end{array}$$

- In this talk I consider sterile neutrinos with mass scale $\sim 1\,\text{eV}$ in light of short-baseline Reactor Anomaly, Gallium Anomaly, LSND, MiniBooNE.

- Other possibilities (not incompatible):

  - Very light sterile neutrinos with mass scale $\ll 1\,\text{eV}$: important for solar neutrino phenomenology

    [Das, Pulido, Picariello, PRD 79 (2009) 073010]
    [de Holanda, Smirnov, PRD 83 (2011) 113011]

  - Heavy sterile neutrinos with mass scale $\gg 1\,\text{eV}$: could be Warm Dark Matter

    [Kusenko, Phys. Rept. 481 (2009) 1]
    [Boyarsky, Ruchayskiy, Shaposhnikov, Ann. Rev. Nucl. Part. Sci. 59 (2009) 191]
    [Drewes, arXiv:1303.6912]

Effective SBL Oscillation Probabilities in 3+1 Schemes

$$P_{\nu_\alpha \to \nu_\beta} = \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) \qquad \sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

No CP Violation!

$$P_{\nu_\alpha \to \nu_\alpha} = 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) \qquad \sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 \left(1 - |U_{\alpha 4}|^2\right)$$

Perturbation of 3ν Mixing

$$|U_{e4}|^2 \ll 1 \,, \quad |U_{\mu 4}|^2 \ll 1 \,, \quad |U_{\tau 4}|^2 \ll 1 \,, \quad |U_{s4}|^2 \simeq 1$$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

SBL (fourth column)

$$\sin^2 2\vartheta_{\alpha\alpha} \ll 1$$

$$\Downarrow$$

$$|U_{\alpha 4}|^2 \simeq \frac{\sin^2 2\vartheta_{\alpha\alpha}}{4}$$

Effective SBL Oscillation Probabilities in 3+2 Schemes

$$\phi_{kj} = \Delta m^2_{kj} L / 4E$$

$$\eta = \arg[U^*_{e4} U_{\mu4} U_{e5} U^*_{\mu5}]$$

$$P_{\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e} = 4|U_{e4}|^2|U_{\mu4}|^2 \sin^2\phi_{41} + 4|U_{e5}|^2|U_{\mu5}|^2 \sin^2\phi_{51} + 8|U_{\mu4}U_{e4}U_{\mu5}U_{e5}| \sin\phi_{41} \sin\phi_{51} \cos(\phi_{54} \overset{(+)}{-} \eta)$$

$$P_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} = 1 - 4(1 - |U_{\alpha4}|^2 - |U_{\alpha5}|^2)(|U_{\alpha4}|^2 \sin^2\phi_{41} + |U_{\alpha5}|^2 \sin^2\phi_{51}) - 4|U_{\alpha4}|^2|U_{\alpha5}|^2 \sin^2\phi_{54}$$

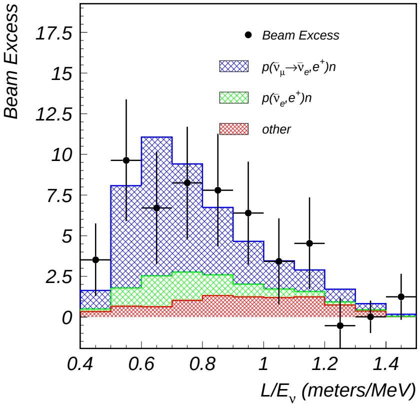
[Sorel, Conrad, Shaevitz, PRD 70 (2004) 073004; Maltoni, Schwetz, PRD 76 (2007) 093005; Karagiorgi et al, PRD 80 (2009) 073001; Kopp, Maltoni, Schwetz, PRL 107 (2011) 091801; Giunti, Laveder, PRD 84 (2011) 073008; Donini et al, JHEP 07 (2012) 161; Conrad, Ignarra, Karagiorgi, Shaevitz, Spitz, AHEP 2013 (2013) 163897; Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050]

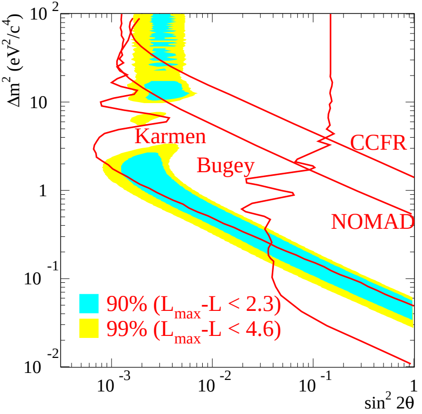
- Good: CP violation
- Bad: 4 more parameters: $\underbrace{\Delta m^2_{41}, |U_{e4}|^2, |U_{\mu4}|^2}_{3+1}, \Delta m^2_{51}, |U_{e5}|^2, |U_{\mu5}|^2, \eta$

LSND

[PRL 75 (1995) 2650; PRC 54 (1996) 2685; PRL 77 (1996) 3082; PRD 64 (2001) 112007]

$\bar{\nu}_\mu \to \bar{\nu}_e$ $\quad L \simeq 30\,\text{m}$ $\quad 20\,\text{MeV} \le E \le 200\,\text{MeV}$



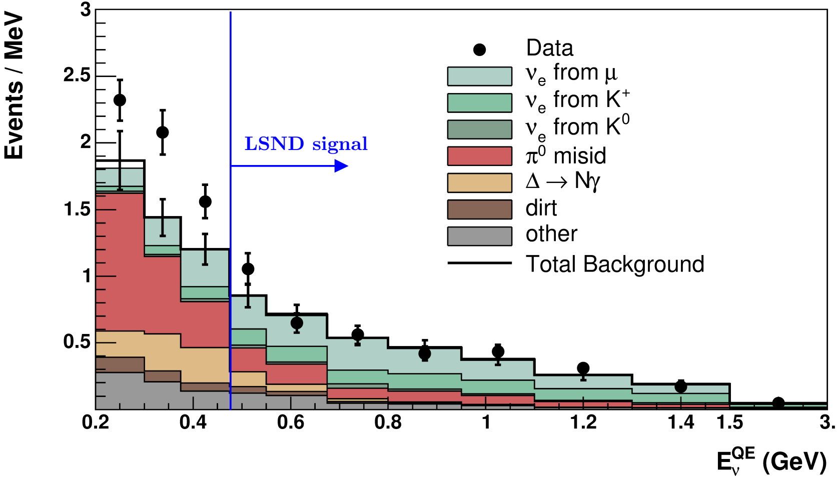


3.8σ excess $\quad \Delta m^2_{\text{LSND}} \gtrsim 0.2\,\text{eV}^2 \quad (\gg \Delta m^2_{\text{A}} \gg \Delta m^2_{\text{S}})$

MiniBooNE Neutrinos - 2008

[PRL 102 (2009) 101802, arXiv:0812.2243]

$\nu_\mu \to \nu_e$ $\quad L \simeq 541\,\mathrm{m}$ $\quad 200\,\mathrm{MeV} \leq E \lesssim 3\,\mathrm{GeV}$

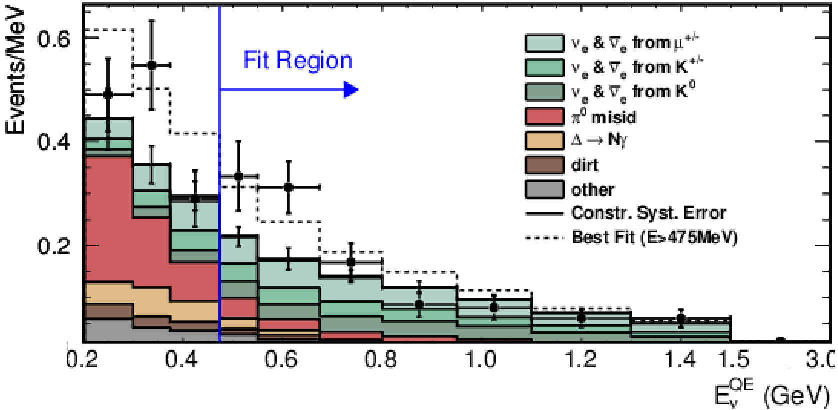


- no $\nu_\mu \to \nu_e$ signal corresponding to LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ signal ($E > 475\,\mathrm{MeV}$)
- low-energy anomaly

MiniBooNE Antineutrinos - 2010

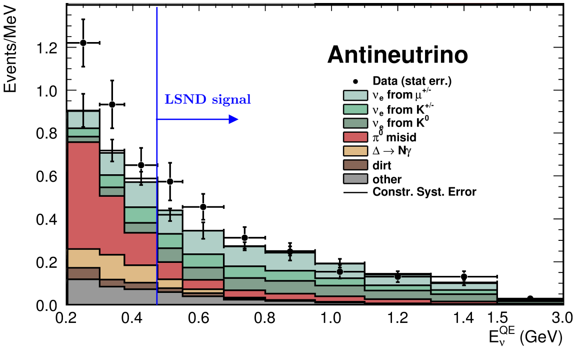
[PRL 105 (2010) 181801, arXiv:1007.1150]

$\bar{\nu}_\mu \to \bar{\nu}_e$ $L \simeq 541\,\text{m}$ $200\,\text{MeV} \leq E \lesssim 3\,\text{GeV}$



- agreement with LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ signal ($E > 475\,\text{MeV}$)
- similar L/E but different L and E $\Longrightarrow$ oscillations
- CP violation?

MiniBooNE $\bar{\nu}$ - Neutrino 2012 - 6 June



		1st half			2nd half	
	data	mc	excess	data	mc	excess
200-475	119	100.5±14.3	18.5 (1.3s)	138	100.0±14.1	38 (2.7s)
475-1250	120	99.1±14.0	20.9 (1.5s)	101	103.1±14.4	-2.2 (-0.2s)

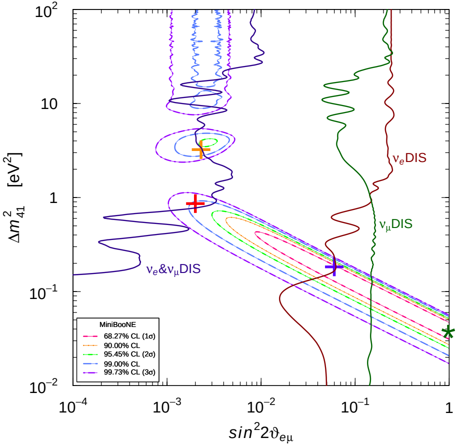
? agreement with LSND signal ? CP violation ?

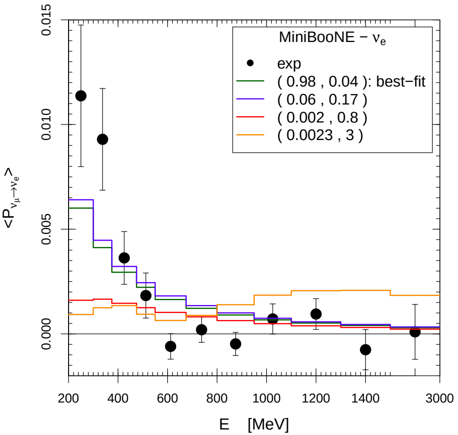
? nevertheless, claim of evidence of oscillations of ν and $\bar{\nu}$?

? mainly from low-energy excess (contradiction with 2009 ν-data paper) ?

[arXiv:1207.4809, duplicated in arXiv:1303.2588 → PRL 110 (2013) 161801]

MiniBooNE ν and $\bar{\nu}$ - arXiv:1207.4809





- Fit of low-energy excess is marginal for $\Delta m^2_{41} \lesssim 0.4\,\text{eV}^2$
- No fit of low-energy excess for realistic $\Delta m^2_{41} \gtrsim 0.8\,\text{eV}^2$
- Neutrino energy reconstruction problem?

[Martini, Ericson, Chanfray, PRD 85 (2012) 093012]

Reactor Electron Antineutrino Anomaly

[Mention et al, PRD 83 (2011) 073006]

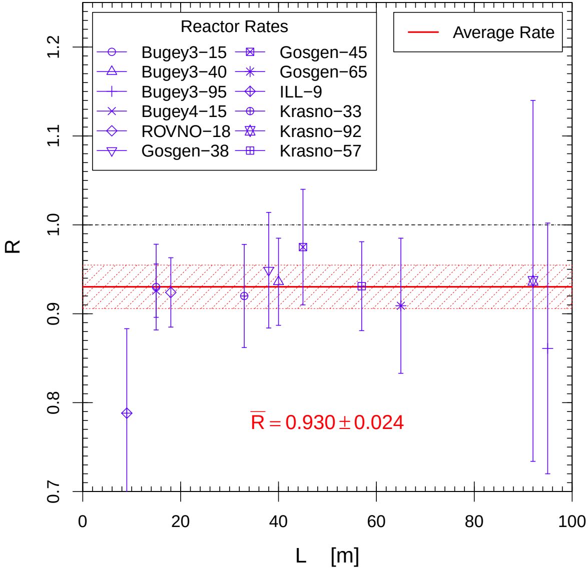
[update in White Paper, arXiv:1204.5379]

new reactor $\bar{\nu}_e$ fluxes

[Mueller et al, PRC 83 (2011) 054615]

[Huber, PRC 84 (2011) 024617]

2.8σ anomaly



Gallium Anomaly

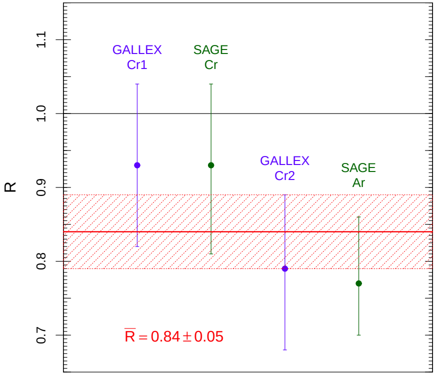
Gallium Radioactive Source Experiments: GALLEX and SAGE

Detection Process: $\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$

ν_e Sources: $e^- + {}^{51}\text{Cr} \to {}^{51}\text{V} + \nu_e$ $\qquad e^- + {}^{37}\text{Ar} \to {}^{37}\text{Cl} + \nu_e$

Anomaly supported by new ${}^{71}\text{Ga}({}^{3}\text{He}, {}^{3}\text{H}){}^{71}\text{Ge}$ cross section measurement

[Frekers et al., PLB 706 (2011) 134]



$E \sim 0.7\,\text{MeV}$

$\langle L \rangle_{\text{GALLEX}} = 1.9\,\text{m}$

$\langle L \rangle_{\text{SAGE}} = 0.6\,\text{m}$

2.9σ anomaly

3+1 SBL ν_e and $\bar{\nu}_e$ Survival Probability

$$P_{\overset{(-)}{\nu_e} \to \overset{(-)}{\nu_e}} = 1 - \sin^2 2\vartheta_{ee} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$\sin^2 2\vartheta_{ee} = 4|U_{e4}|^2 \left(1 - |U_{e4}|^2\right)$$

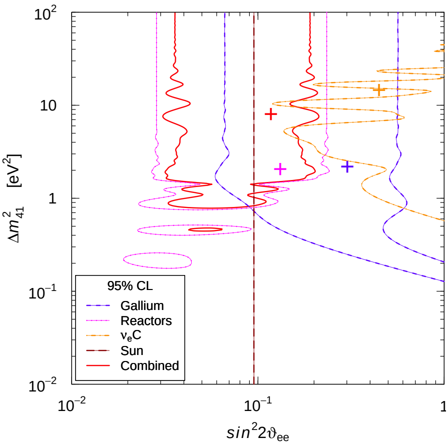
standard parameterization

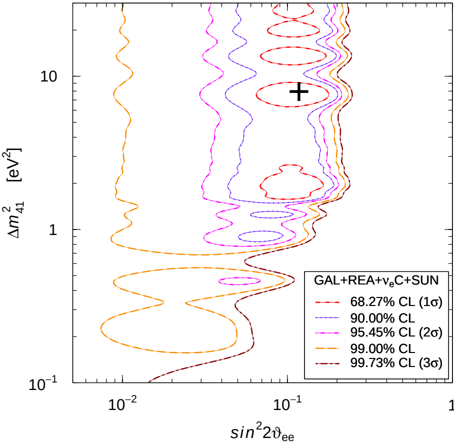
$$U_{e1} = c_{12} c_{13} c_{14} \quad U_{e2} = s_{12} c_{13} c_{14} \quad U_{e3} = s_{13} c_{14} e^{-i\delta_{13}} \quad U_{e4} = s_{14} e^{-i\delta_{14}}$$

$$\sin^2 2\vartheta_{ee} = \sin^2 2\vartheta_{14}$$

Global ν_e and $\bar{\nu}_e$ Disappearance

[Giunti, Laveder, Y.F. Li, Q.Y. Liu, H.W. Long, PRD 86 (2012) 113014]





$\nu_e + {}^{12}C \to {}^{12}N_{g.s.} + e^-$

KARMEN + LSND

[Conrad, Shaevitz, PRD 85 (2012) 013017]

[Giunti, Laveder, PLB 706 (2011) 200]

solar ν_e + KamLAND $\bar{\nu}_e$ + ϑ_{13}

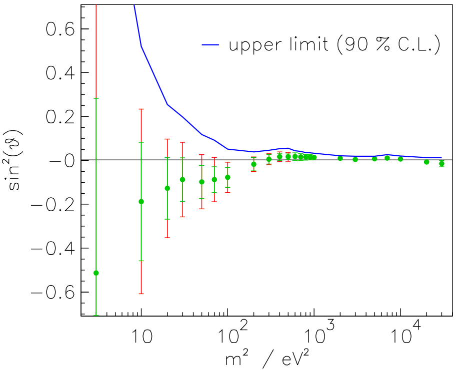
[Giunti, Li, PRD 80 (2009) 113007]

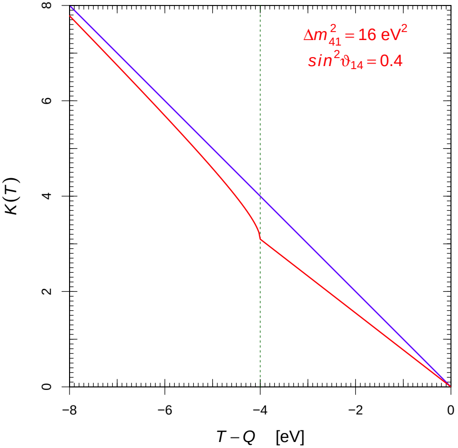
[Palazzo, PRD 83 (2011) 113013]

[Palazzo, PRD 85 (2012) 077301]

Mainz Limit on m_4^2

[Kraus, Singer, Valerius, Weinheimer, arXiv:1210.4194]

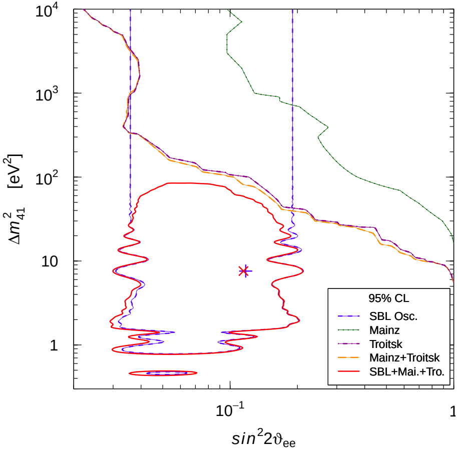


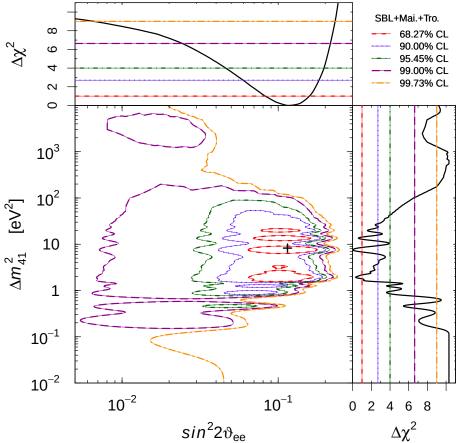


$$m_4 \gg m_1, m_2, m_3 \quad \Longrightarrow \quad \Delta m^2_{41} \equiv m_4^2 - m_1^2 \simeq m_4^2$$

Troitsk: Surprising Much Better Limit on m_4^2

[Belesev, Berlev, Geraskin, Golubev, Likhovid, Nozik, Pantuev, Parfenov, Skasyrskaya, arXiv:1211.7193]

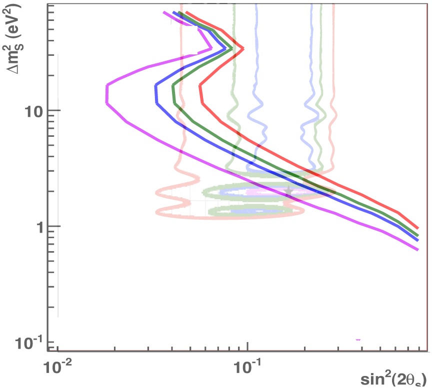




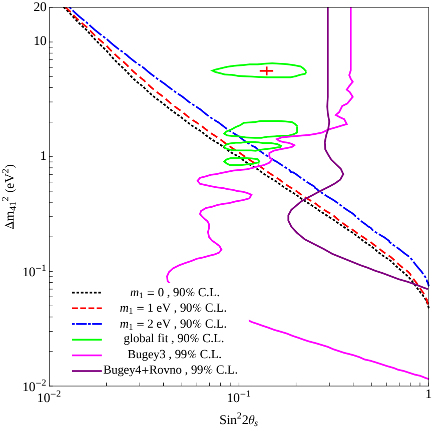
$$2\sigma: \quad 0.85 \lesssim \Delta m^2_{41} \lesssim 43\,\text{eV}^2 \quad \Longrightarrow \quad 6\,\text{cm} \lesssim \frac{L^{\text{OSC}}_{41}}{E\,[\text{MeV}]} \lesssim 3\,\text{m}$$

[Giunti, Laveder, Y.F. Li, H.W. Long, PRD 87 (2013) 013004]

KATRIN Sensitivity



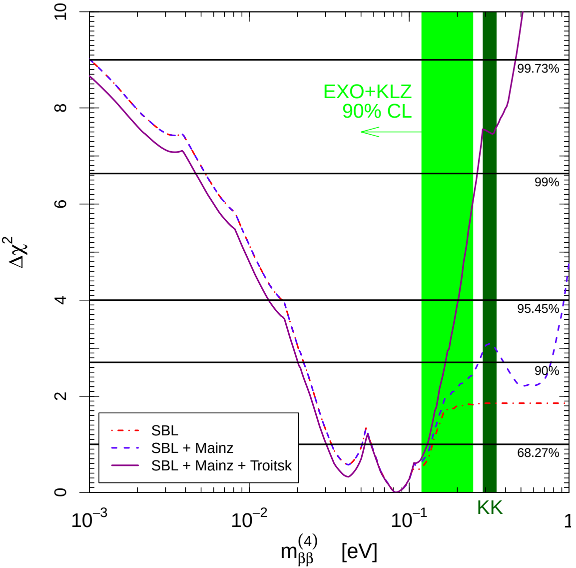
[Formaggio, Barrett, PLB 706 (2011) 68]



[Esmaili, Peres, PRD 85 (2012) 117301]

[see also Sejersen Riis, Hannestad, JCAP (2011) 1475; Sejersen Riis, Hannestad, Weinheimer, PRC 84 (2011) 045503]

Neutrinoless Double-β Decay



$$|m_{\beta\beta}| = \left|\sum_{k=1}^{4} U_{ek}^2\, m_k\right|$$

$$m_{\beta\beta}^{(4)} = |U_{e4}|^2 \sqrt{\Delta m_{41}^2}$$

caveat:

possible cancellation with $m_{\beta\beta}^{(3\nu-IH)}$

[Barry et al, JHEP 07 (2011) 091]

[Li, Liu, PLB 706 (2012) 406]

[Rodejohann, JPG 39 (2012) 124008]

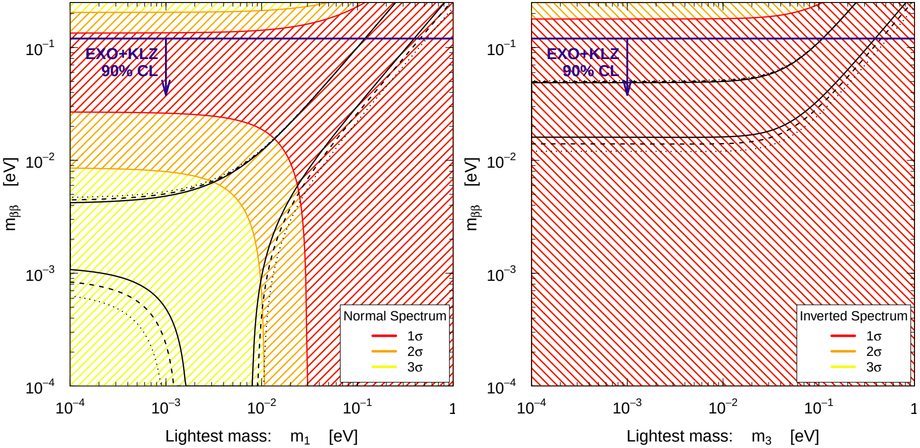
Cancellation with $m_{\beta\beta}^{(\text{light})}$?

[Barry, Rodejohann, Zhang, JHEP 07 (2011) 091]; Li, Liu, PLB 706 (2012) 406; Rodejohann, JPG 39 (2012) 124008]

$$m_{\beta\beta}^{(\text{light})} = \left| \sum_{k=1}^{3} U_{ek}^2 \, m_k \right| \qquad m_{\beta\beta}^{(4)} = |U_{e4}|^2 \sqrt{\Delta m_{41}^2}$$

$$m_{\beta\beta} = m_{\beta\beta}^{(\text{light})} + e^{i\alpha_4} m_{\beta\beta}^{(4)} \qquad m_{\beta\beta}^{(4)} \gtrsim 10^{-2}\,\text{eV}$$

- **Normal Hierarchy:** $m_{\beta\beta}^{(\text{light})} \lesssim 4.5 \times 10^{-3}\,\text{eV}$ (95% CL)
  no cancellation is possible
- **Inverted Hierarchy:** $1.4 \times 10^{-2} \lesssim m_{\beta\beta}^{(\text{light})} \lesssim 5.0 \times 10^{-2}\,\text{eV}$ (95% CL)
  cancellation is possible
- **Quasi-Degenerate:** $m_{\beta\beta}^{(\text{light})} \gtrsim 5.0 \times 10^{-2}\,\text{eV}$ cancellation is possible

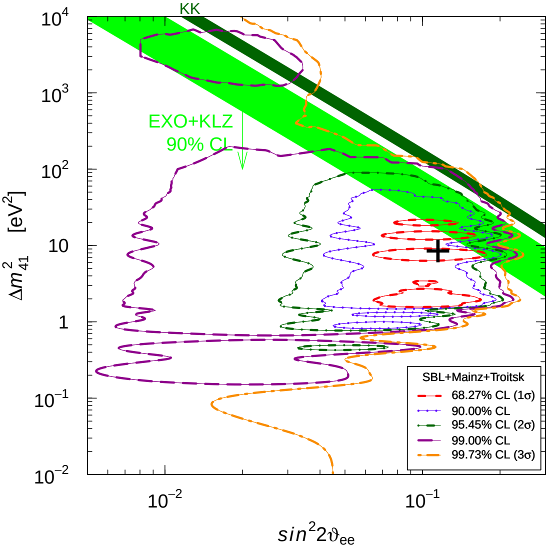


EXO+KLZ
90% CL
Normal Spectrum
1σ
2σ
3σ
$m_{\beta\beta}$ [eV]
Lightest mass: m_1 [eV]
EXO+KLZ
90% CL
Inverted Spectrum
1σ
2σ
3σ
$m_{\beta\beta}$ [eV]
Lightest mass: m_3 [eV]

Assumption: no cancellation

$$m_{\beta\beta} \geq m_{\beta\beta}^{(4)}$$
$$= |U_{e4}|^2 \sqrt{\Delta m_{41}^2}$$

$$\Delta m_{41}^2 = \left(\frac{m_{\beta\beta}^{(4)}}{|U_{e4}|^2} \right)^2$$
$$\leq \left(\frac{m_{\beta\beta}}{|U_{e4}|^2} \right)^2$$



3+1: Appearance vs Disappearance

- ν_e disappearance experiments:

$$\sin^2 2\vartheta_{ee} = 4|U_{e4}|^2 \left(1 - |U_{e4}|^2\right) \simeq 4|U_{e4}|^2$$

- ν_μ disappearance experiments:

$$\sin^2 2\vartheta_{\mu\mu} = 4|U_{\mu4}|^2 \left(1 - |U_{\mu4}|^2\right) \simeq 4|U_{\mu4}|^2$$

- $\nu_\mu \to \nu_e$ experiments:

$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2 \simeq \frac{1}{4} \sin^2 2\vartheta_{ee} \sin^2 2\vartheta_{\mu\mu}$$

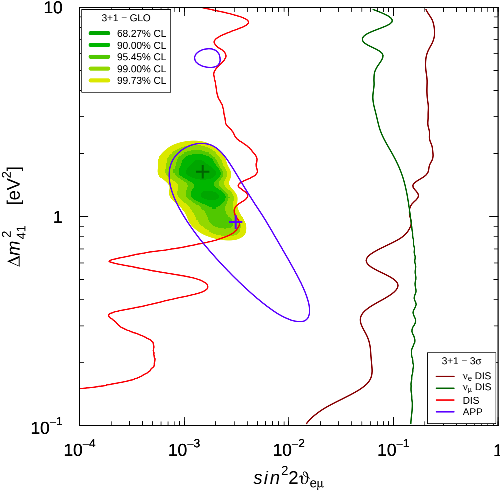
- Upper bounds on $\sin^2 2\vartheta_{ee}$ and $\sin^2 2\vartheta_{\mu\mu} \Longrightarrow$ strong limit on $\sin^2 2\vartheta_{e\mu}$

[Okada, Yasuda, Int. J. Mod. Phys. A12 (1997) 3669-3694]

[Bilenky, Giunti, Grimus, Eur. Phys. J. C1 (1998) 247]

3+1 Global Fit

[Giunti, Laveder, Y.F. Li, H.W. Long, in preparation (2013)]



No Osc. GoF = 1%

3+1 GoF = 33%

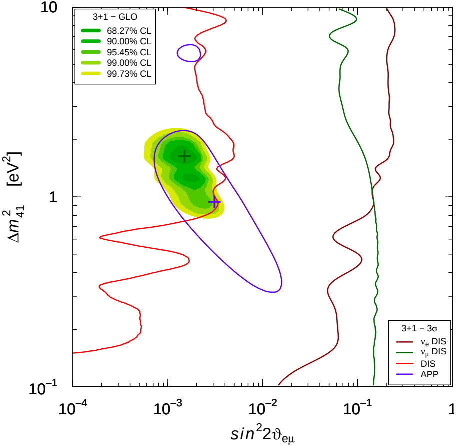
PGoF = 10%

- APP $\nu_\mu \to \nu_e$ & $\bar{\nu}_\mu \to \bar{\nu}_e$: LSND (Y), MiniBooNE (?), OPERA (N), ICARUS (N), KARMEN (N), NOMAD (N), BNL-E776 (N)
- DIS ν_e & $\bar{\nu}_e$: Reactors (Y), Gallium (Y), ν_eC (N), Solar (N)
- DIS ν_μ & $\bar{\nu}_\mu$: CDHSW (N), MINOS (N), Atmospheric (N), MiniBooNE/SciBooNE (N)

[see also Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050]

MiniBooNE Impact on SBL Oscillations?

with MiniBooNE

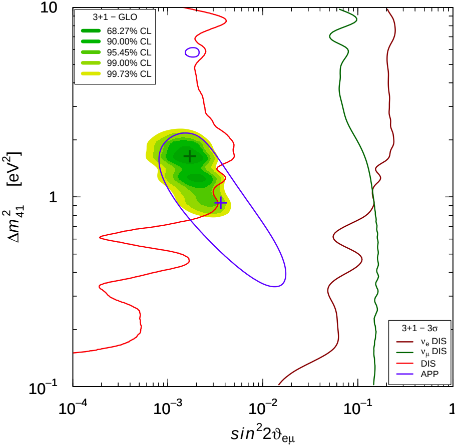


No Osc. GoF = 1%

3+1 GoF = 33%

PGoF = 10%

without MiniBooNE



No Osc. GoF = 0.4%

3+1 GoF = 22%

PGoF = 5%

3+2

- 3+2 is preferred to 3+1 only if
  - there is evidence of two peaks of the probability corresponding to two Δm^2's

    or
  - there is CP-violating difference of $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ transitions

- 2008 ν + 2010 $\bar{\nu}$ MiniBooNE data indicated ν–$\bar{\nu}$ difference

  $\Downarrow$

  reasonable and useful to consider 3+2

- ν–$\bar{\nu}$ difference almost disappeared with 2012 $\bar{\nu}$ data

- Okkam razor: 3+1 is enough!

Cosmology

- N_s = number of thermalized sterile neutrinos (not necessarily integer)

- CMB+LSS in ΛCDM: $N_s = 1.3 \pm 0.9$ $m_s < 0.66\,\text{eV}$ (95% C.L.)

  [Hamann, Hannestad, Raffelt, Tamborra, Wong, PRL 105 (2010) 181301]

  $$N_s = 1.61 \pm 0.92 \qquad m_s < 0.70\,\text{eV} \quad (95\%\ \text{C.L.})$$

  [Giusarma, Corsi, Archidiacono, de Putter, Melchiorri, Mena, Pandolfi, PRD 83 (2011) 115023]

- BBN: $\begin{cases} N_s \leq 1 \text{ at } 95\%\ \text{C.L.} \\ N_s = 0.0 \pm 0.5 \end{cases}$ [Mangano, Serpico, PLB 701 (2011) 296] [Pettini, Cooke, arXiv:1205.3785]

- CMB+LSS+BBN in ΛCDM: $N_s = 0.85^{+0.39}_{-0.56}$ (95% C.L.)

  [Hamann, Hannestad, Raffelt, Wong, JCAP 1109 (2011) 034]

- Standard ΛCDM in 2012: 3+1 allowed, 3+2 disfavored

Recent CMB Measurements

- highL South Pole Telescope (SPT) [arXiv:1212.6267]

  $N_{\text{eff}} = 3.62 \pm 0.48$ (WMAP7+SPT)
  $N_{\text{eff}} = 3.71 \pm 0.35$ (WMAP7+SPT+BAO+HST)

- highL Atacama Cosmology Telescope (ACT) [arXiv:1301.0824]

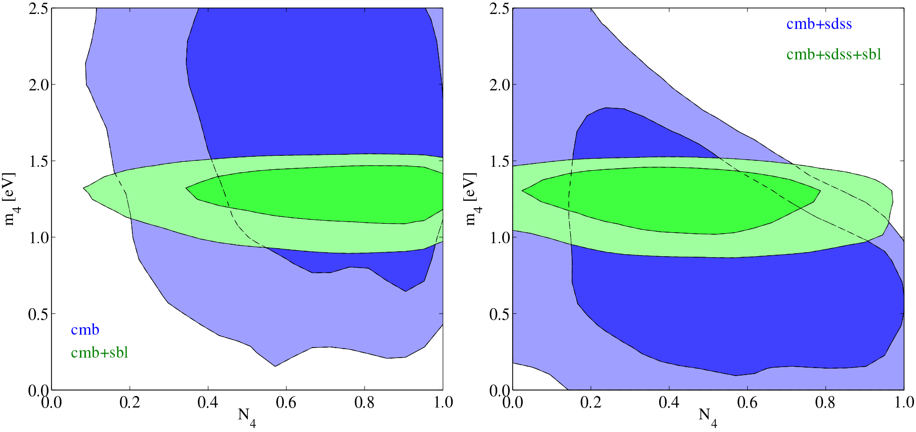
  $N_{\text{eff}} = 2.79 \pm 0.56$ (WMAP7+ACT)
  $N_{\text{eff}} = 3.50 \pm 0.42$ (WMAP7+ACT+BAO+HST)

- Planck [arXiv:1303.5076]

  $N_{\text{eff}} = 3.36^{+0.68}_{-0.64}$ (95%; Planck+WMAP9+highL)
  $N_{\text{eff}} = 3.30^{+0.54}_{-0.51}$ (95%; Planck+WMAP9+highL+BAO)
  $N_{\text{eff}} = 3.52^{+0.48}_{-0.45}$ (95%; Planck+WMAP9+highL+BAO+HST)

Pre-Planck Oscillation + Cosmology Fit

[Archidiacono, Fornengo, Giunti, Hannestad, Melchiorri, arXiv:1302.6720]

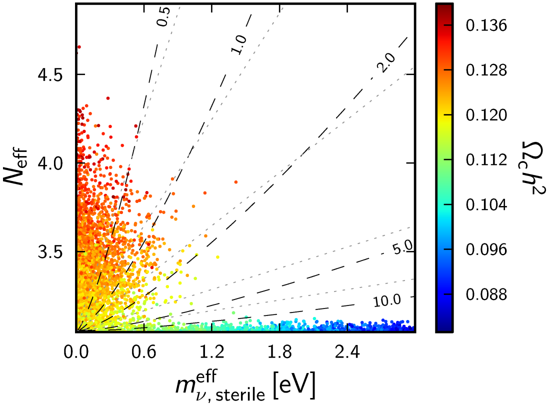


- Mass Hierarchy: $m_4 \gg m_3, m_2, m_1 \quad \Longrightarrow \quad m_4 \simeq \sqrt{\Delta m^2_{41}}$
- $m_4 = 1.23 \pm 0.13\,\text{eV}^2$
- $N_4 < 0.83$ (95% Bayesian CL)

Planck

[arXiv:1303.5076]

$N_{\text{eff}} < 3.80 \qquad m_{\nu,\text{sterile}}^{\text{eff}} < 0.42 \qquad (95\%; \text{CMB} + \text{BAO})$



- $m_{\nu,\text{sterile}}^{\text{eff}} \equiv 94.1 \omega_{\nu_4}$ eV
- Thermally distributed:

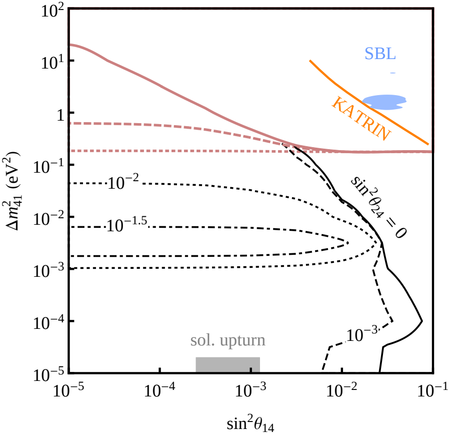
$$m_{\nu,\text{sterile}}^{\text{eff}} = \left(\frac{T_s}{T_\nu} \right)^3 m_4 = (\Delta N_{\text{eff}})^{3/4} m_4$$

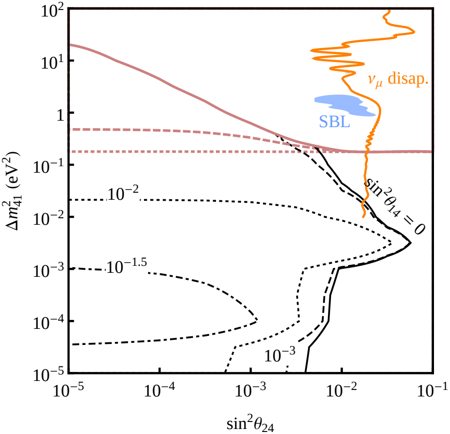
- Dodelson-Widrow:

$$m_{\nu,\text{sterile}}^{\text{eff}} = \chi_s m_4$$

Standard Cosmological Scenario Mixing Bounds

[Mirizzi, Mangano, Saviano, Borriello, Giunti, Miele, Pisanti, arXiv:1303.5368]





Non-standard mechanis for partial thermalization of ν_s is needed

Large primordial neutrino asymmetry?

[Hannestad, Tamborra, Tram, JCAP 1207 (2012) 025; Mirizzi, Saviano, Miele, Serpico, PRD 86 (2012) 053009; Saviano, Mirizzi, Pisanti, Serpico, Mangano, Miele, PRD 87 (2013) 073006]

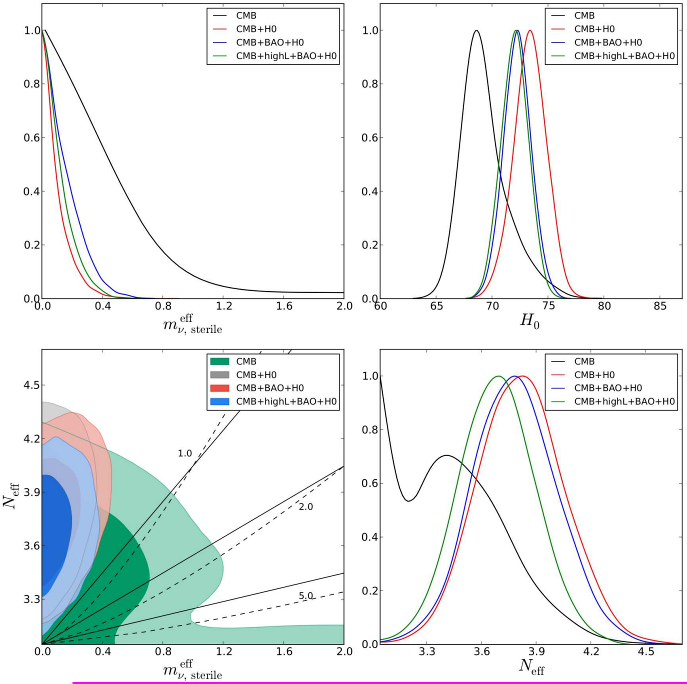
CMB + H_0

[Gariazzo, Giunti, Laveder, in preparation (2013)]

$$H_0 = \left\{ \begin{array}{ll} 67.4 \pm 1.4 & \text{Planck} \\ 70.0 \pm 2.2 & \text{WMAP-9} \\ 73.8 \pm 2.4 & \text{Cepheids+SNIa} \\ 74.3 \pm 2.6 & \text{Carnegie HP} \\ 78.7 \pm 4.5 & \text{COSMOGRAIL} \end{array} \right\} [\text{km}\,\text{s}^{-1}\text{Mpc}^{-1}]$$

Gaussian Prior: $H_0 = 74.7 \pm 1.6\,\text{km}\,\text{s}^{-1}\text{Mpc}^{-1}$

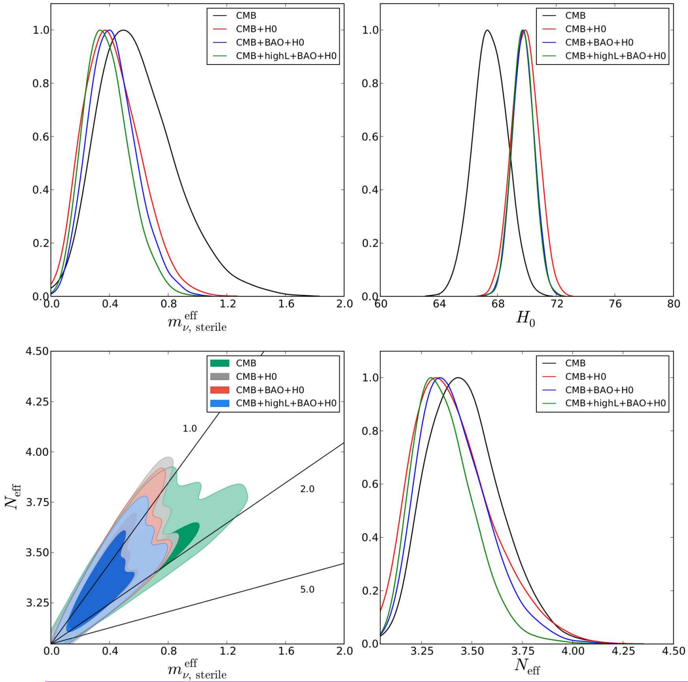
weighted average of Cepheids+SNIa, Carnegie HP, COSMOGRAIL



$3.16 < N_{\mathrm{eff}} < 4.24 \quad (99\%)$

$m_{\nu,\mathrm{sterile}}^{\mathrm{eff}} < 0.41\,\mathrm{eV} \quad (99\%)$

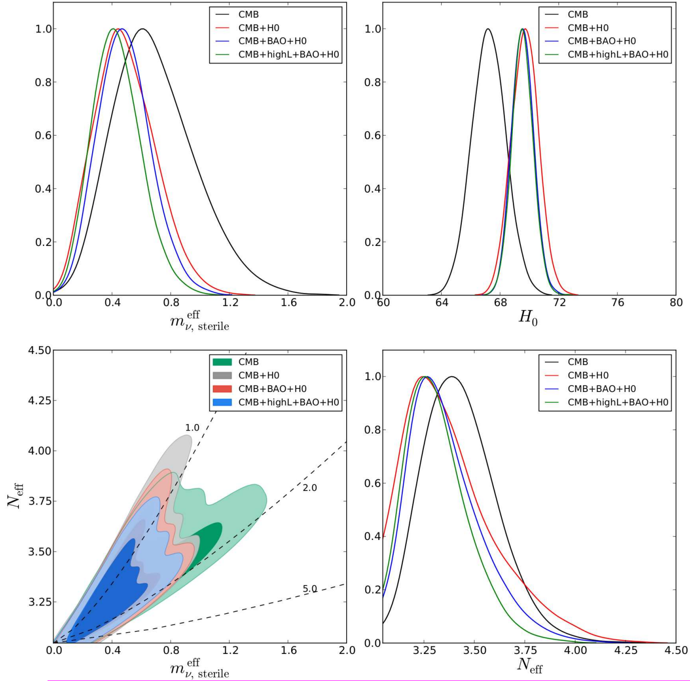
SBL Prior - Dodelson-Widrow



$N_{\mathrm{eff}} < 3.80$ (99%)

$0.042 < m_{\nu,\mathrm{sterile}}^{\mathrm{eff}} < 0.81\,\mathrm{eV}$ (99%)

SBL Prior - Thermal



$N_{\mathrm{eff}} < 3.79 \quad (99\%)$

$0.049 < m_{\nu,\mathrm{sterile}}^{\mathrm{eff}} < 0.90\,\mathrm{eV} \quad (99\%)$

Conclusions

- Short-Baseline ν_e and $\bar{\nu}_e$ 3+1 Disappearance:
  - Reactor $\bar{\nu}_e$ anomaly is alive and exciting
  - Gallium ν_e anomaly strengthened by new cross-section measurements
  - Many promising projects to test short-baseline ν_e and $\bar{\nu}_e$ disappearance in a few years with reactors and radioactive sources
  - Independent tests through effect of m_4 in β-decay and $(\beta\beta)_{0\nu}$-decay
- Short-Baseline $\bar{\nu}_\mu \to \bar{\nu}_e$ LSND Signal:
  - MiniBooNE experiment has been inconclusive
  - If $|U_{e4}| > 0$ why not $|U_{\mu 4}| > 0$? $\Longrightarrow$ Maybe LSND luckily observed a fluctuation of a small $\bar{\nu}_\mu \to \bar{\nu}_e$ transition probability with amplitude $\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu 4}|^2$, which has not been seen by other appearance experiments
  - Better experiments are needed to check LSND signal
- Cosmology:
  - Tension between Planck H_0 and direct mesaurements
  - $N_{\text{eff}} = 4$ is not excluded (CMB + HigL + BAO + H_0)
  - Strong constraints on mass: $m_{\nu,\text{sterile}}^{\text{eff}} < 0.41\,\text{eV}$ $\quad$ (99%)
  - Cosmology + SBL: $m_4 \simeq \Delta m_{41}^2 \simeq 1\,\text{eV}^2$ and $N_{\text{eff}} < 3.8$ $\quad$ (99%)
  - Mechanis for partial thermalization of ν_s is needed (large primordial neutrino asymmetry, ...)