Implication of upper bound on m_ν and N_ν from WMAP

- review -

S. Kaneko (Niigata Univ.)
金子 悟　　新潟大学

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Implications of $\sum m_\nu < 0.7\,\text{eV}$, $N_\nu < 3.4$ for

1. LSND
2. Neutrinoless Double-β Decay
3. Leptogenesis

Summary in pre-WMAP and post-WMAP

$$\sum_i m_i < 0.71\,\text{eV} \quad \text{and} \quad N_\nu^{\text{eff}} < 3.4$$

1. LSND

Introducing 1 sterile neutrino ($N_\nu = 4$),

(2+2) : excluded by solar and atmospheric data @ 3.4σ.

(3+1) : excluded by SBL and atmospheric data @ 95%C.L.

$$\Downarrow$$

(2+2) and (3+1) are excluded by WMAP

$N_\nu = 4$ is excluded by WMAP+BBN

2. Neutrinoless Double-β Decay

$0\nu\beta\beta$ experiment : $\langle m \rangle_{\beta\beta} \leq (0.35 - 1.24)$ eV

$$\Downarrow$$

WMAP : $\langle m \rangle_{\beta\beta} \leq 0.23\,\text{eV}$

3. Leptogenesis

η_{WMAP} + Leptogenesis $\rightarrow \sum m_\nu < 0.35\,\text{eV}$

This is stable with respect to change of η_{obs}.

ref.) Direct measurement

Tritium β decay : $m_{\nu_e} < 2.2$ eV [Mainz('01)]

$\pi \rightarrow \mu^+ \nu_\mu$: $m_{\nu_\mu} < 190$ KeV [PDG('02)]

$\tau^- \rightarrow n\pi\nu_\tau$: $m_{\nu_\tau} < 18.2$ MeV [PDG('02)]

1. LSND

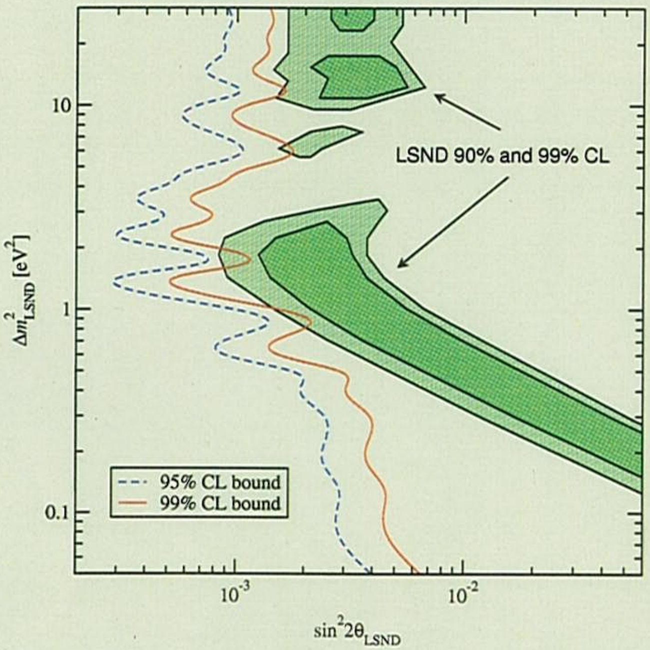
M.Maltoni, T.Schwetz, M.A.Tortola and J.W.Valle, hep-ph/0209368
A.Pierce and H.Murayama, hep-ph/0302131

Liquid Scintillator Neutrino Detector experiment :

$\pi^+ \to \mu^+ \nu_\mu, \quad \mu^+ \to e^+ \nu_e \bar{\nu}_\mu, \quad \bar{\nu}_\mu \to \bar{\nu}_e$ ($\bar{\nu}_e$ appearance)

L = 30m

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) \quad = \quad (0.264 \pm 0.067 \pm 0.045) \ @ \ 3.3\sigma$$



$\Delta m^2_{\mathsf{LSND}} \simeq 1.2$ eV^2,

$\sin^2 2\theta_{\mathsf{LSND}} \simeq 3 \times 10^{-3}$.

[LSND('01)]

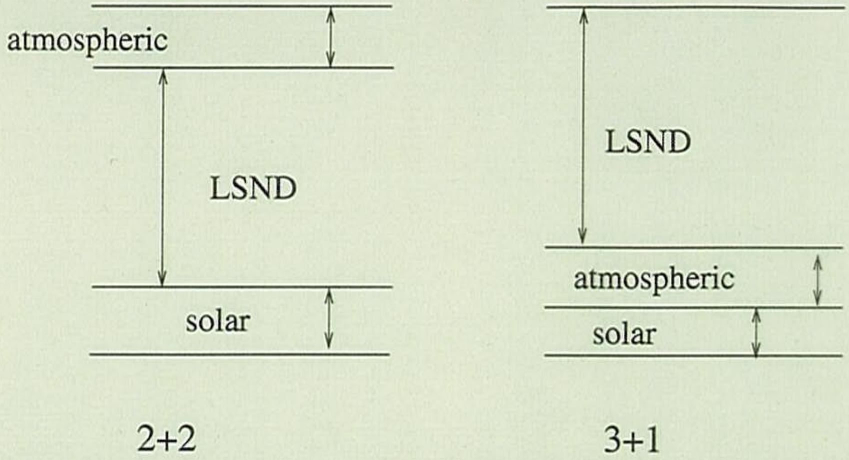
We already have $\Delta m^2_{\mathsf{sol}} \sim 10^{-5}$ eV^2 and $\Delta m^2_{\mathsf{atm}} \sim 10^{-3}$ eV^2.

Sterile neutrino (gauge singlet) is required : $N_\nu \geq 4$.

($N_\nu^{\mathsf{active}} = 2.994 \pm 0.012$ [LEP, PDG('02)])

LSND data ($N_\nu = 4$) in Pre-WMAP

ref.) O.Yasuda san's talk at Niigata.



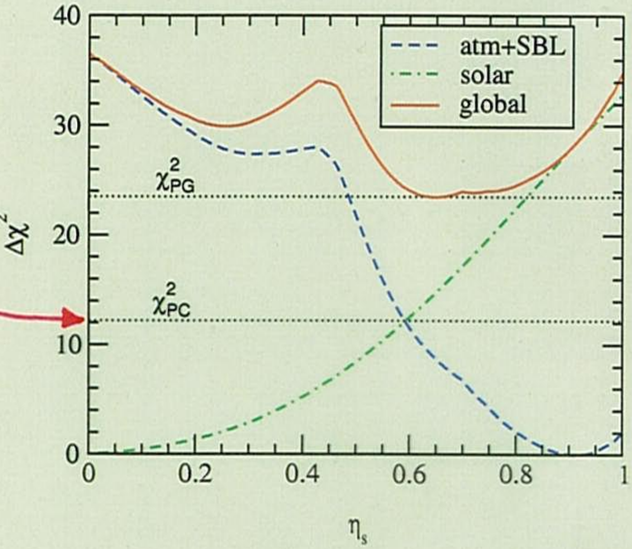
(2+2) is excluded by solar and atmospheric data @ 3.4σ.

$\eta_s \equiv |U_{s1}|^2 + |U_{s2}|^2$

solar: $\nu_e \to \sqrt{\eta_s}\nu_s + \sqrt{1-\eta_s}\nu_{\mu,\tau}$

atm: $\nu_\mu \to \sqrt{1-\eta_s}\nu_s - \sqrt{\eta_s}\nu_\tau$

M.Maltoni, T.Schwetz, M.A.Tortola and J.W.Valle, hep-ph/0209368

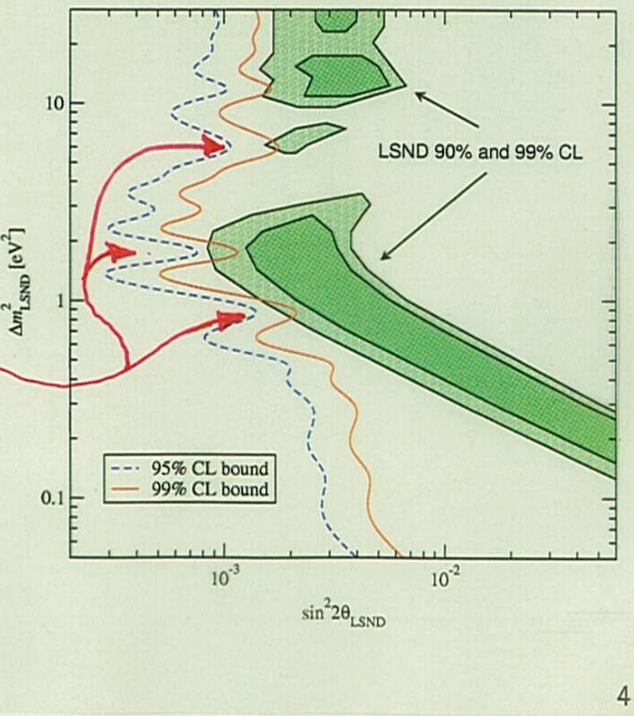


(3+1) is excluded by other short baseline and atmospheric data @ 95%C.L..

Bugey, CDHS, KARMEN, NOMAD + CHOOZ

marginaly allowed @ 99%C.L.

M.Maltoni, T.Schwetz and J.W.Valle, hep-ph/0107150

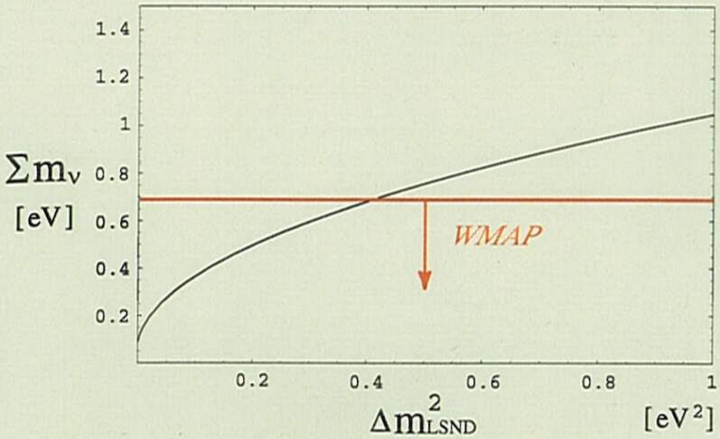


$\Delta m^2_{\mathrm{LSND}}$ in post-WMAP

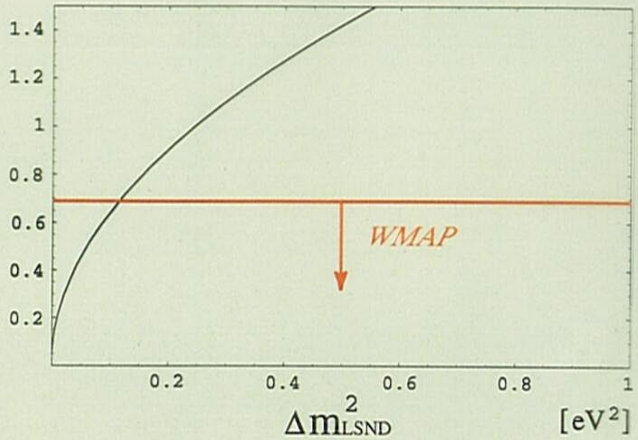
$$\sum m_\nu < 0.7\,\mathrm{eV}$$

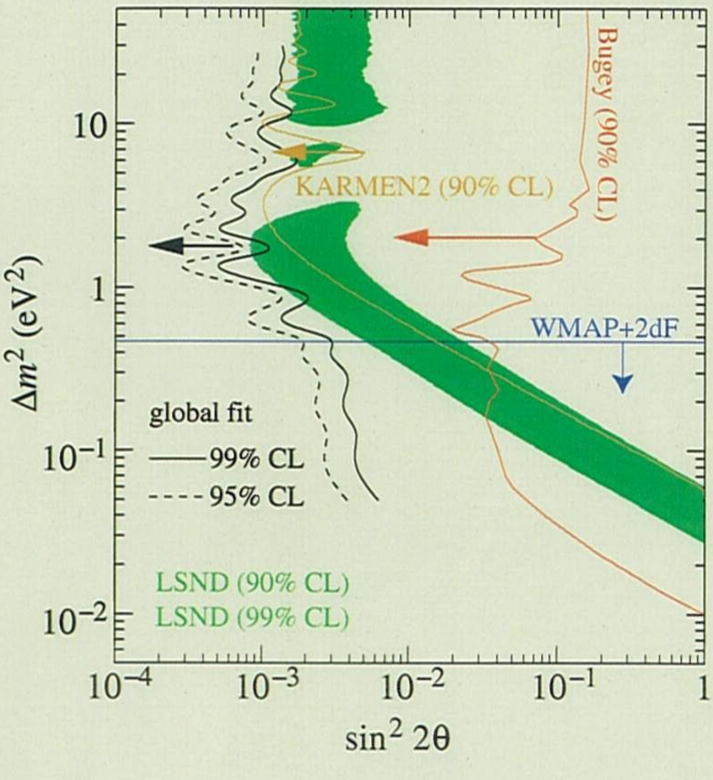
best fit : Δm^2_{sol}, Δm^2_{atm}

(3+1)



(2+2)





LSND : $\Delta m^2 \geq 0.8\ \mathrm{eV}^2$

$\Updownarrow$

WMAP :

$(3+1)\ :\ \Delta m^2 \leq 0.4\ \mathrm{eV}^2$

$(2+2)\ :\ \Delta m^2 \leq 0.1\ \mathrm{eV}^2$

1 sterile : (3+1) and (2+2) are excluded by WMAP.

A.Pierce and H.Murayama, hep-ph/0302131

MiniBooNE experiment will check it.

N_ν in pre-WMAP

N_ν in Big-Bang Nucleosynthesis (BBN)

for a review, A.D.Dolgov('02)

$Y_P + \eta$ ← BBN + measurement of D, ^{3}He, ^{4}He, ^{7}Li

$Y_P + \eta$ ← CMB measurement of $\Omega_b h^2$

⇓ BBN

bound on N_ν

deta are in confusion

Y_p : Primordial abundance of ^{4}He

η : Baryon to photon ratio

N_ν has wide allowed region.

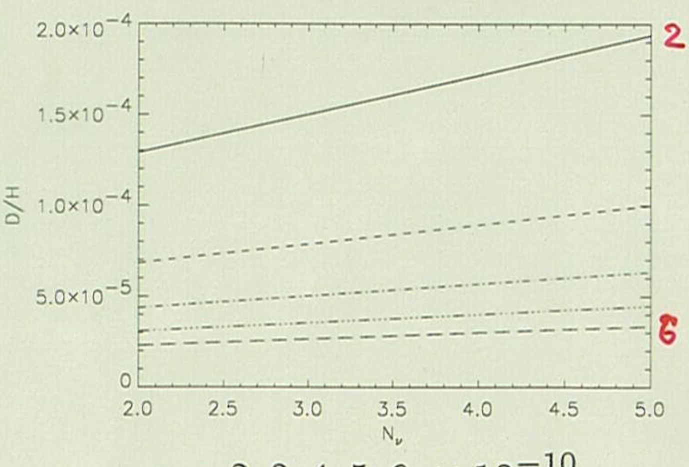
$N_\nu^{\rm eff} < 3.4$ @ 2σ — K.A.Olive et al. ('00)

$N_\nu^{\rm eff} < 4$ — E.Lisi et al. ('99)

$N_\nu^{\rm eff} \leq 4.9$ @ 95%C.L. (^{7}Li data only) — K.A.Olive et al. ('99)

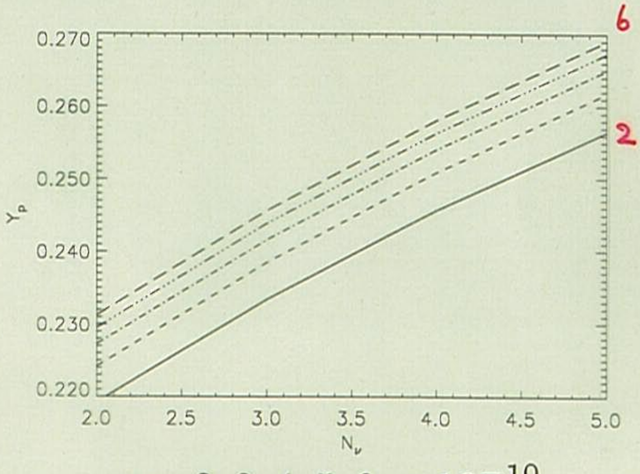
$N_\nu = 4$ is still allowed.

N_ν - Deutron/Hydrogen



$\eta = 2, 3, 4, 5, 6 \times 10^{-10}$

N_ν - Y_p



$\eta = 2, 3, 4, 5, 6 \times 10^{-10}$

N_ν in post-WMAP

$Y_P + \eta$ ← BBN + measurement of D, ^{3}He, ^{4}He, ^{7}Li

← CMB measurement of $\Omega_b h^2$ by WMAP

⇓ BBN

bound on N_ν

WMAP: $\eta = (6.2 - 6.9) \times 10^{-10}$

cf.) $\eta_{CMB} = (5.2 - 7.1) \times 10^{-10}$ [BOOMerANG,DASI('02)]

$\eta_{BBN} = (5.1 - 6.7) \times 10^{-10}$

$Y_P = 0.249 + 0.013(N_\nu^{eff} - 3)$ ← best-fit of η

In-put ↑

$Y_p = 0.238 \pm 0.002 \pm 0.005$ Particle Data Group ('02)

Taking higher value of Y_P & additional systematic error :

$Y_p = 0.244 \pm 0.002 \pm 0.005$

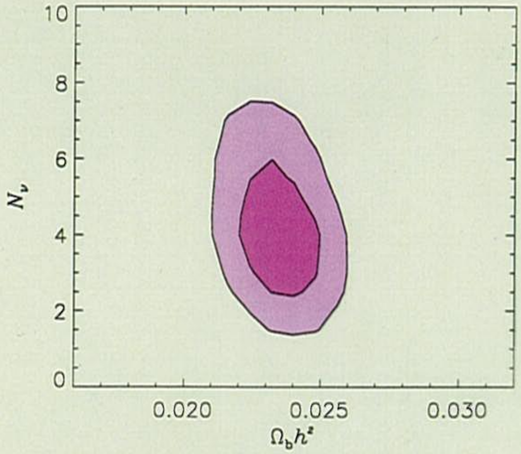
A.Pierce and H.Murayama, hep-ph/0302131

PDG : $N_\nu^{eff} < 3.0$ @ 95% C.L.

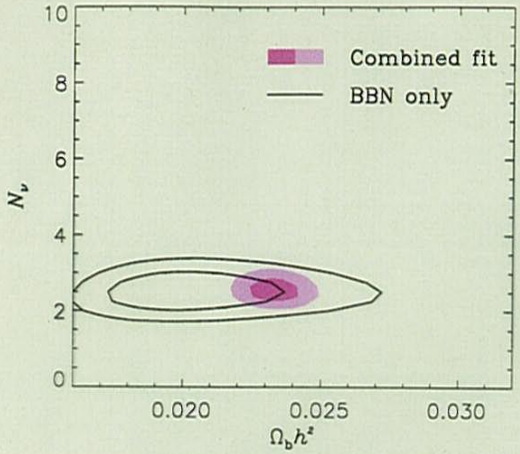
PM : $N_\nu^{eff} < 3.4$ @ 95% C.L.

$N_\nu = 4$ is excluded by BBN+WMAP.

Power of BBN



WMAP+2dF+HST+SNI-a



WMAP+2dF+HST+SNI-a+BBN

S. Hannested, hep-astro/0303076

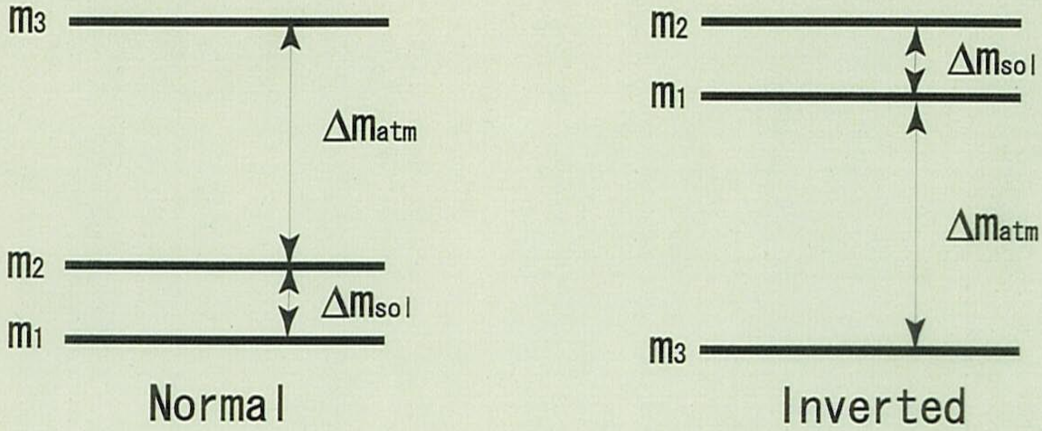
2. Neutrinoless Double-β Decay Constraints

H. Minakata and H. Sugiyama, hep-ph/0212240
G.Bhattacharyya, H.Päs, L.Song, T.J. Weiler, hep-ph/0302191
F.R. Joaquim, hep-ph/0304276

Three Majorana Neutrinos Mixing Scheme (set up)

$$M_\nu = U_{\mathsf{MNS}} \times \mathrm{diag}(m_1,\ m_2 e^{i\beta},\ m_3 e^{i\gamma}) \times U^T_{\mathsf{MNS}}\ ,$$

$$U_{\mathsf{MNS}} = U_{\mathsf{MNS}}(\theta_{12}, \theta_{23}, \theta_{13}, \delta)$$



Normal	Inverted
$m_1 \equiv m_1$	$m_1 = \sqrt{m_3^2 + \Delta m^2_{\mathsf{atm}}}$
$m_2 = \sqrt{m_1^2 + \Delta m^2_{\mathsf{sol}}}$	$m_2 = \sqrt{m_3^2 + \Delta m^2_{\mathsf{atm}} + \Delta m^2_{\mathsf{sol}}}$
$m_3 = \sqrt{m_1^2 + \Delta m^2_{\mathsf{sol}} + \Delta m^2_{\mathsf{atm}}}$	$m_3 \equiv m_3$

Atmospheric :

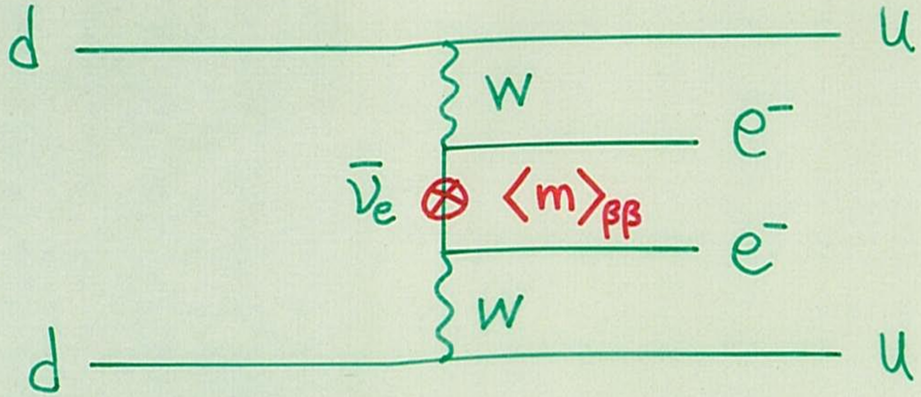
$$\sin^2 2\theta_{\mathsf{atm}} \geq 0.92,\ \ \Delta m^2_{\mathsf{atm}} = (1.5 \sim 3.9) \times 10^{-3}\mathrm{eV}^2$$

KamLAND+Solar :

$$\tan^2 \theta_{\mathsf{sol}} = 0.33 \sim 0.67,\ \ \Delta m^2_{\mathsf{sol}} = (6 \sim 8.5) \times 10^{-5}\mathrm{eV}^2$$

CHOOZ : $\sin^2 \theta_{\mathsf{CHOOZ}} \leq 0.03$

$$(A, Z) \to (A, Z+2) + e^- + e^-$$



Neutrinoless double-β decay "observable"

$$\begin{aligned} \langle m \rangle_{\beta\beta} &\equiv \left| \sum_{i=1}^{3} m_i U_{ei}^2 \right| \\ &= \left| m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{2i\beta} + m_3 s_{13}^2 e^{-2i\delta} e^{2i\gamma} \right| \end{aligned}$$

$s_{ij} \equiv \sin\theta_{ij}, \; c_{ij} \equiv \cos\theta_{ij}$

Experimental bounds

$\langle m \rangle_{\beta\beta} \leq (0.35 - 1.24)$ eV [Heidelberg-Moscow ('01-a)]
$\langle m \rangle_{\beta\beta} \leq (0.33 - 1.35)$ eV [IGEX ('02)]

"Evidence"
$\langle m \rangle_{\beta\beta} = (0.11 - 0.56)$ eV [Heidelberg-Moscow ('01-b)]

Normal

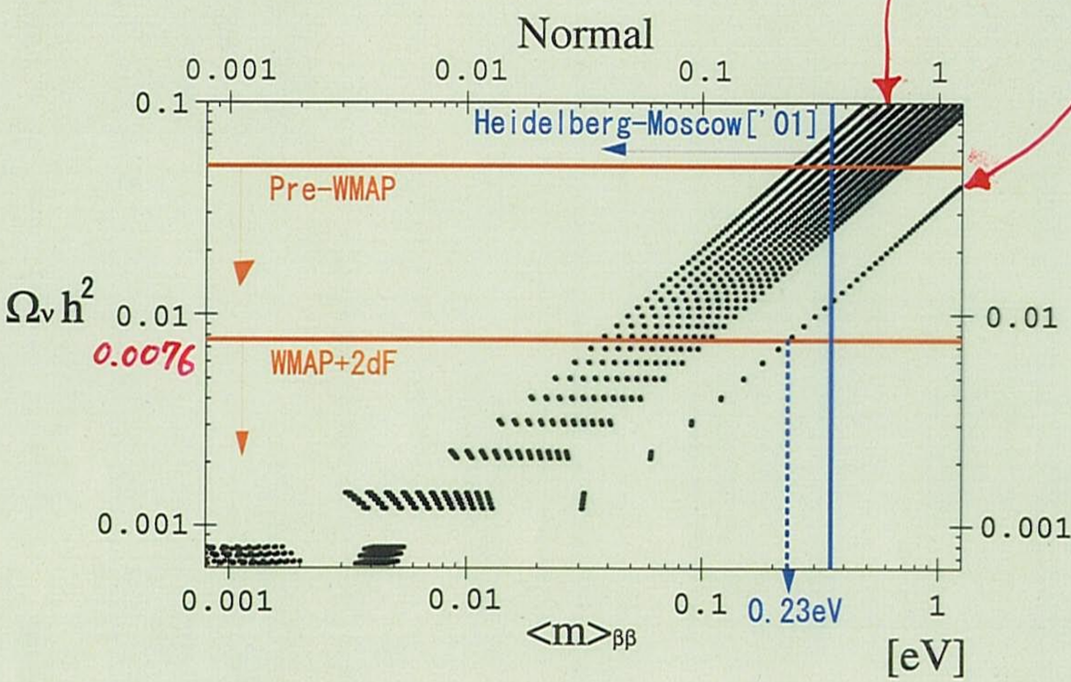
H. Minakata and H. Sugiyama, hep-ph/0212240

$s_{13} \leq s^2_{\mathrm{CH}} \equiv 0.03$

$$\langle m \rangle_{\beta\beta} \leq (m_1 c^2_{12} + m_2 s^2_{12}) c^2_{\mathrm{CH}} + m_3 s^2_{\mathrm{CH}} \quad : \text{upper bound}$$

$$\langle m \rangle_{\beta\beta} \geq |m_1 c^2_{12} - m_2 s^2_{12}| c^2_{\mathrm{CH}} - m_3 s^2_{\mathrm{CH}} \quad : \text{lower bound}$$

post-WMAP



$$\Omega_\nu h^2 = (m_1 + m_2 + m_3)/91.5\,\mathrm{eV}$$

$$\langle m \rangle_{\beta\beta} \leq 0.23\,\mathrm{eV}$$

$\langle m \rangle_{\beta\beta} = 0.23\,\mathrm{eV} \;\rightarrow\; m_1 = 0.23\,\mathrm{eV}$ quasi-degenerate !

$m_2 = 0.23159\,\mathrm{eV}$

$m_3 = 0.235682\,\mathrm{eV}$

Inverted

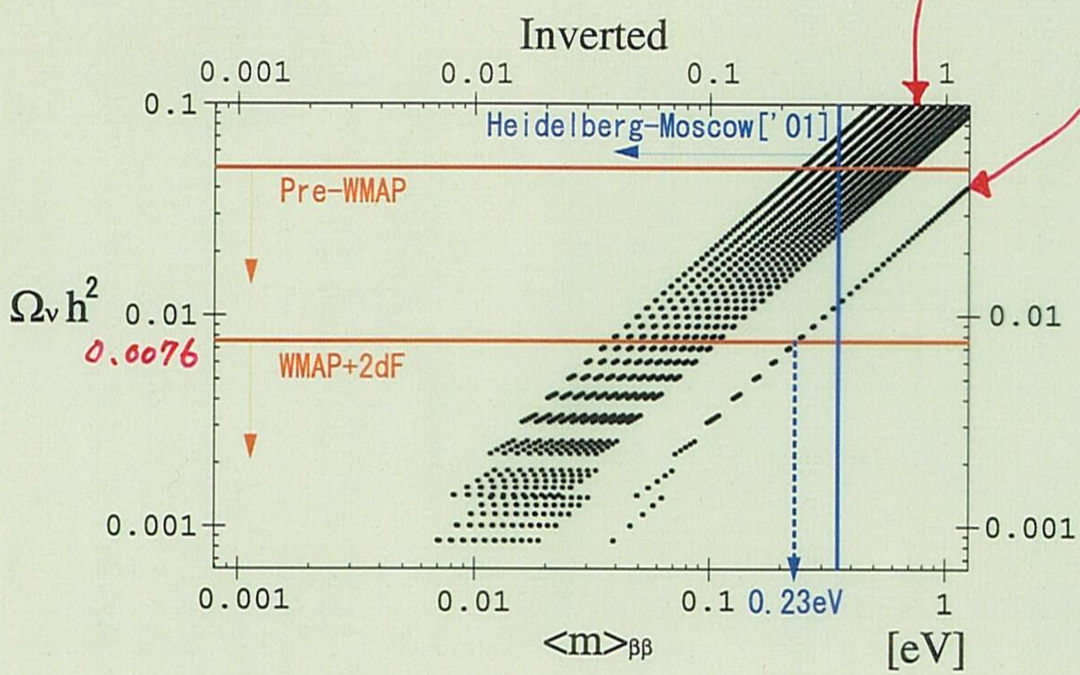
H. Minakata and H. Sugiyama, hep-ph/0212240

$s_{13} \leq s^2_{\rm CH} \equiv 0.03$

$$\langle m \rangle_{\beta\beta} \leq m_1 c^2_{12} + m_2 s^2_{12} \quad \text{: upper bound}$$

$$\langle m \rangle_{\beta\beta} \geq |m_1 c^2_{12} - m_2 s^2_{12}| c^2_{\rm CH} - m_3 s^2_{\rm CH} \quad \text{: lower bound}$$

post-WMAP



$$\Omega_\nu h^2 = (m_1 + m_2 + m_3)/91.5\,\text{eV}$$

$$\langle m \rangle_{\beta\beta} \leq 0.23\,\text{eV}$$

$$\langle m \rangle_{\beta\beta} = 0.23\,\text{eV} \quad \rightarrow \quad m_1 = 0.235372\,\text{eV}$$

quasi-degenerate !

$$m_2 = 0.235527\,\text{eV}$$

$$m_3 = 0.23\,\text{eV}$$

$\langle m \rangle_{\beta\beta} \leq 0.23\,\text{eV}$ for Normal and Inverted

Implication for the recent "evidence"

$0.11 < \langle m \rangle_{\beta\beta} < 0.56$ eV @95% C.L. (best fit : 0.39 eV)

⇓ $\pm 50\%$ uncertainty of nuclear matrix element,

$0.05 < \langle m \rangle_{\beta\beta} < 0.84$ eV @95% C.L. (best fit : 0.39 eV)

[H.V.Klapdor-Kleingrothaus et al.('02)]

This best fit value exceeds the WMAP bound.
If one consider the "evidence", $0.05 \leq \langle m \rangle_{\beta\beta} \leq 0.23$ eV.

Implication for the future experiments

Future neutrinoless double-β decay searches must have the sensitivity in the region $\langle m \rangle_{\beta\beta} < 0.2$ eV.

Experiment	Nucleus	Sensitivity $T^{0\nu}_{1/2}$ [yr]	Sensitivity $\langle m \rangle_{\beta\beta}$ [eV]
NEMO 3	^{100}Mo	4×10^{24}	5.6×10^{-1}
COBRA	^{130}Te	1×10^{24}	2.4×10^{-1}
CUORICINO	^{130}Te	1.5×10^{25}	1.9×10^{-1}
XMASS	^{136}Xe	3.3×10^{26}	9×10^{-2}
CAMEO	^{116}Cd	1×10^{26}	6.9×10^{-2}
EXO	^{136}Xe	8×10^{26}	5.2×10^{-2}
MOON	^{100}Mo	1×10^{27}	3.6×10^{-2}
CUORE	^{130}Te	7×10^{26}	2.7×10^{-2}
Majorana	^{76}Ge	4×10^{27}	2.5×10^{-2}
GEM	^{76}Ge	7×10^{27}	1.8×10^{-2}
GENIUS	^{76}Ge	1×10^{28}	1.5×10^{-2}

3. Leptogenesis

Standard Model : $B+L$ is violated and $B-L$ is conserved by sphaleron process.

$\Rightarrow$ Baryogenesis requires violation of $B-L$

Leptogenesis : SM + right-handed Majorana neutrino N_R
[M.Fukugita, T.Yanagida ('86)]

$$\mathcal{L} = Y\bar{\ell}HN_R + \frac{1}{2}M_R\overline{N}_R^c N_R + \text{h.c.}$$

Light neutrino masses is generated by see-saw mechanism :

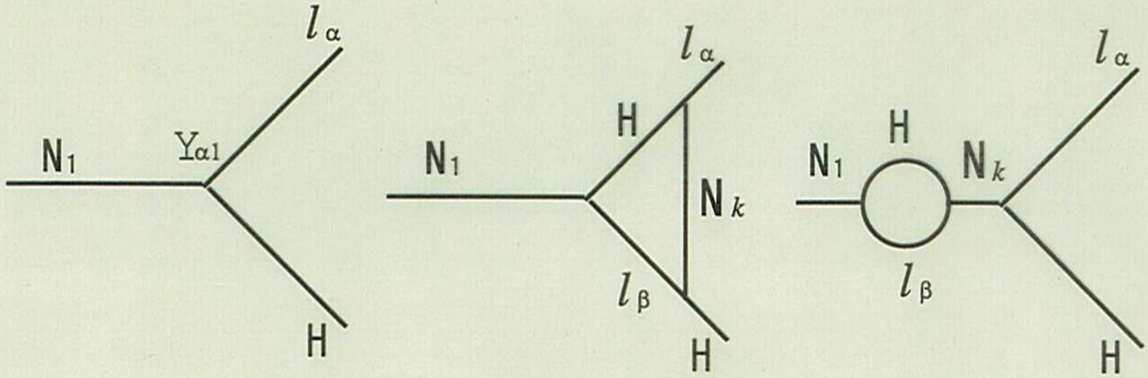
$$m_\nu = -m_D M_R^{-1} m_D^T$$

Dirac mass : $m_D = Yv \quad (v \equiv \langle H \rangle)$

Natural assumption : $v \ll M_R$

Neutrino mixing : $U^\dagger m_\nu U = -diag(m_1, m_2, m_3)$

Lepton asymmetry ($B-L$ violation) is generated by N_R decay:



Bound on m_ν from Leptogenesis

[Buchmüller, Di Bari, Plümacher('02)]

$\eta_{\rm th}^{\rm max} \geq \eta_{\rm obs}^{\rm min} \Rightarrow$ upper bound on m_ν

Leptogenesis bound is stable with respect to change of $\eta_{\rm obs}$.

Maximal CP asymmetry : $\epsilon_1^{\rm max}$

$\eta_{\rm th}^{\rm max}$ is a function of $\epsilon_1^{\rm max}$: $\eta_{\rm th} \propto \epsilon_1 \Rightarrow \eta_{\rm th}^{\rm max}(\epsilon_1^{\rm max})$

$$\epsilon_1 \equiv \frac{\Gamma(N_1 \to \ell + H) - \Gamma(\overline{N}_1 \to \bar{\ell} + \overline{H})}{\Gamma(N_1 \to \ell + H) + \Gamma(\overline{N}_1 \to \bar{\ell} + \overline{H})}$$

$$\simeq \frac{3}{16\pi}\frac{M_1}{v^2}\sum_{i\neq 1}\frac{\Delta m_{i1}^2}{m_i}\frac{Im(\widetilde{Y}_{i1}^2)}{(\widetilde{Y}^\dagger\widetilde{Y})_{11}}, \quad \widetilde{Y} \equiv U^\dagger Y$$

$$= \frac{3}{16\pi}\frac{M_1}{v^2}\left(\frac{\Delta m_{21}^2}{m_2}y_2 + \frac{\Delta m_{31}^2}{m_3}y_3\right), \quad \frac{\widetilde{Y}_{i1}^2}{(\widetilde{Y}^\dagger\widetilde{Y})_{11}} \equiv x_i + iy_i$$

$\Rightarrow$ ϵ_1 is a function of neutrino masses !

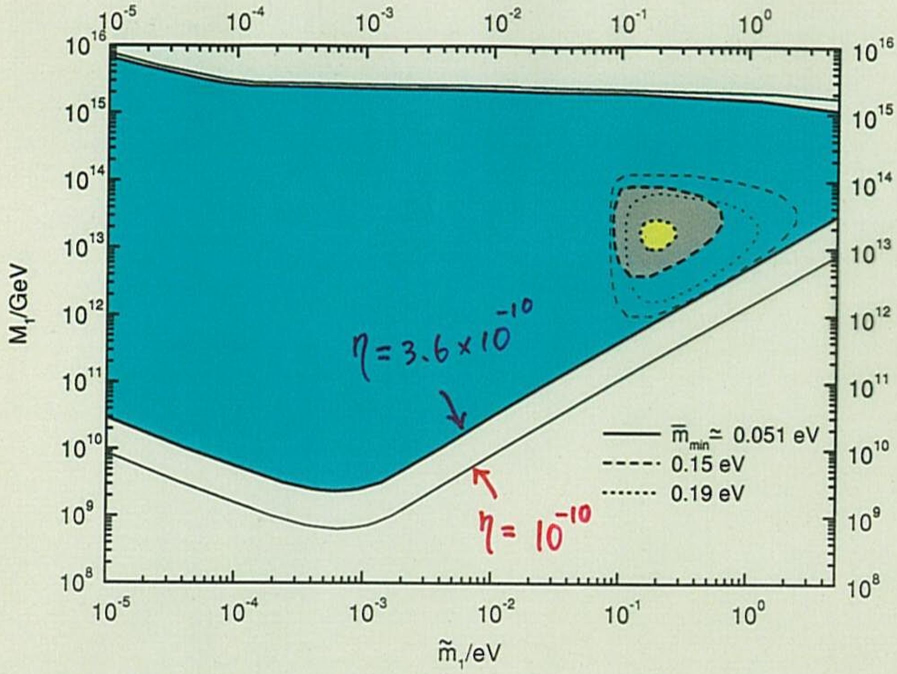
$\sum_i |x + iy_i| = 1$ and taking $x_2 = x_3 = y_2 = 0$,

$$\epsilon_1^{\rm max} = \frac{3}{16\pi}\frac{M_1 m_3}{v^2}\left[1 - \frac{m_1}{m_3} + \left(1 + \frac{m_3^2 - m_1^2}{\widetilde{m}_1^2}\right)^{\frac{1}{2}}\right],$$

$$\widetilde{m}_1 \equiv \frac{v^2(Y^\dagger Y)_{11}}{M_1}, \quad \overline{m} \equiv \sqrt{m_1^2 + m_2^2 + m_3^2}, \quad M_1$$

$$\epsilon_1^{\rm max} = \epsilon_1^{\rm max}(\widetilde{m}, \overline{m}, M_1)$$

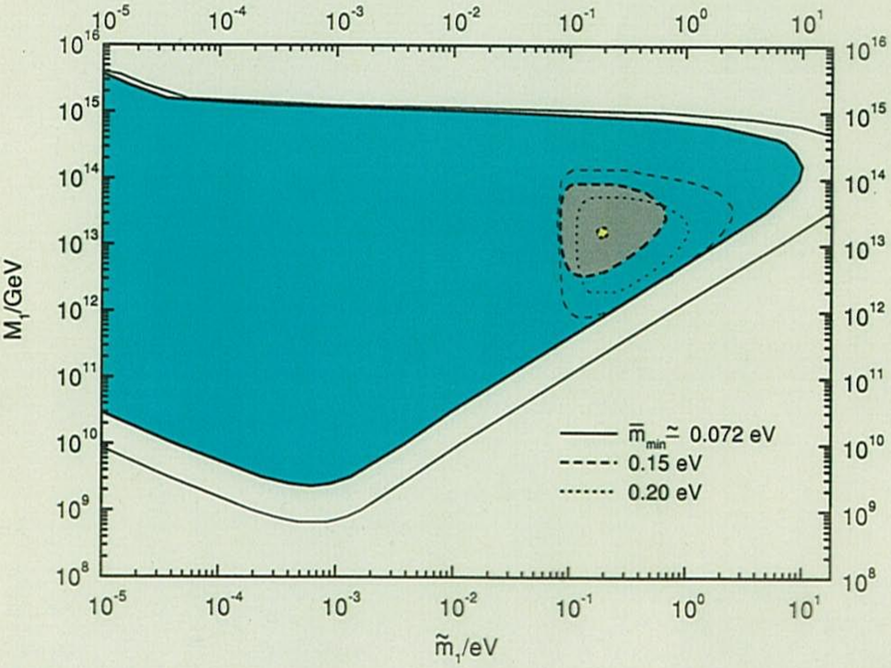
Normal



m̄ ≡ √(m1² + m2² + m

$$\overline{m} < 0.20\,\mathrm{eV} \;\Rightarrow\; m_1, m_2 < 0.11\,\mathrm{eV},\; m_3 < 0.12\,\mathrm{eV}$$

Inverted



$$\overline{m} < 0.21\,\mathrm{eV} \;\Rightarrow\; m_1 < 0.11\,\mathrm{eV},\; m_2, m_3 < 0.12\,\mathrm{eV}$$

$\sum m_\nu < 0.35\,\mathrm{eV}$ is required for Baryogenesis.

Buchmüller, Di Bari, Plümacher('02)

$$\eta_{\text{WMAP}} + \text{Leptogenesis} \rightarrow \sum m_\nu < 0.35\,\text{eV}$$

$$(\Omega_\nu h^2)_{\text{WMAP+2dF}} \rightarrow \sum m_\nu < 0.7\ \text{eV}$$

This is stable with respect to change of η_{obs}.

Summary

WMAP : $\sum_i m_i < 0.71\,\text{eV}$ and $N_\nu^{\text{eff}} < 3.4$

1. LSND

(3+1) and (2+2) are excluded by WMAP.
$N_\nu = 4$ are excluded by WMAP+BBN.

2. Neutrinoless Double Beta Decay

$\langle m \rangle_{\beta\beta} \leq 0.23\,\text{eV}$ is obtained.
If one condider the "evidence", $0.05 \leq \langle m \rangle_{\beta\beta} \leq 0.23\,\text{eV}$.

3. Leptogenesis

Taking η_{WMAP} and Leptogenesis, we have $\sum m_\nu < 0.35\,\text{eV}$.
This is stable with respect to change of η_{obs}.