ν oscillation in high energy cosmic ν

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1. Status of ν oscillation

1.1 $N_\nu = 3$: $\nu_{atm} + \nu_{solar}$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \cong \begin{pmatrix} c_{12} & s_{12} & \varepsilon \\ -s_{12}/\sqrt{2} & c_{12}/\sqrt{2} & 1/\sqrt{2} \\ s_{12}/\sqrt{2} & -c_{12}/\sqrt{2} & 1/\sqrt{2} \end{pmatrix}$$

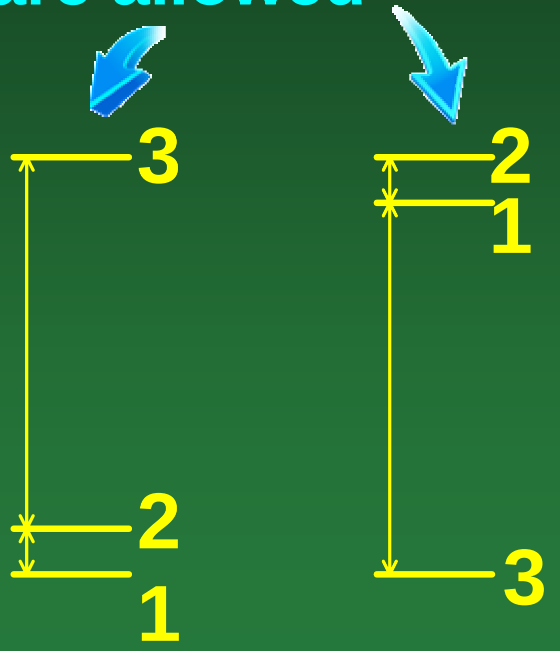
Both hierarchies are allowed

$$\theta_{12} \cong \pi / 6$$

$$|\varepsilon| \le \sqrt{0.1}/2$$

$$\Delta m_{21}^2 = 7 \times 10^{-5} eV^2$$

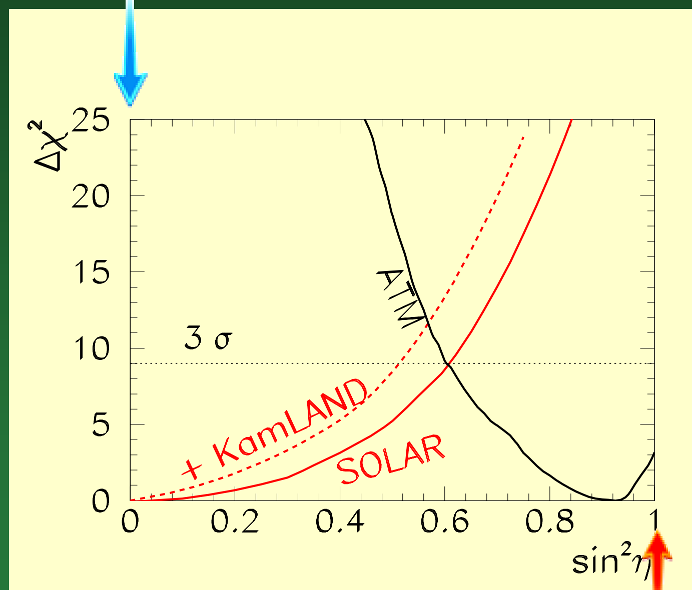
$$|\Delta m_{32}^2| = 3 \times 10^{-3} eV^2$$



1.2 $N_\nu = 4 : \nu_{atm} + \nu_{solar} + \nu_{LSND}$

(1) (2+2)-scheme: almost excluded (>3.4σ) because it contradicts either ν_{atm} or ν_{solar}

$\nu_{atm} : \nu_\mu \leftrightarrow \nu_s$



$\nu_{solar} : \nu_e \leftrightarrow \nu_s$

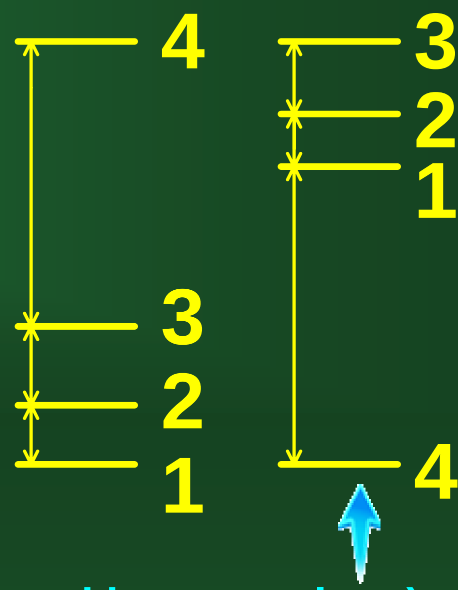
(2) (3+1)-scheme

- Tension (~95%CL) with

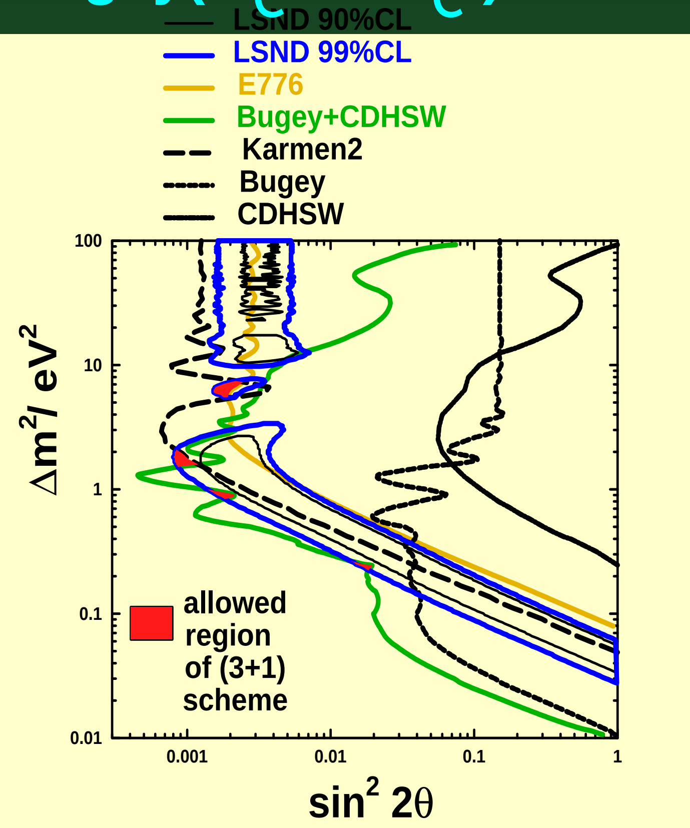
LSND ($\overline{\nu}_\mu \rightarrow \overline{\nu}_e$)

or

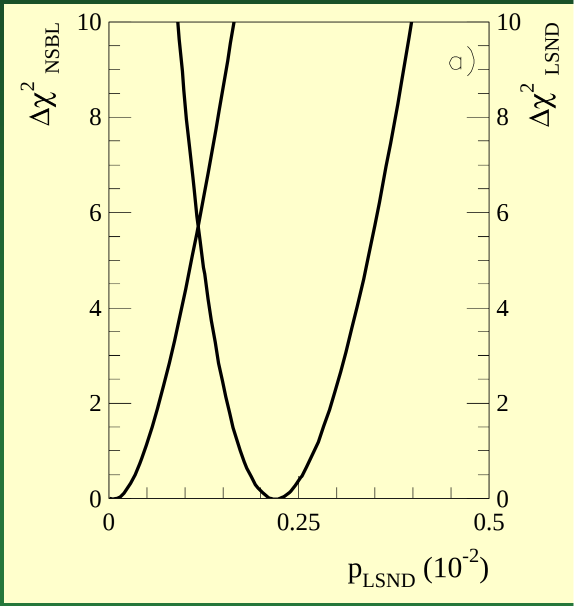
Bugey($\overline{\nu}_e \rightarrow \overline{\nu}_e$)+CDHSW($\nu_\mu \rightarrow \nu_\mu$)



(Presumably disfavored by cosmology)



$$p_{LSND} \equiv \langle P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e) \rangle_{LSND}$$



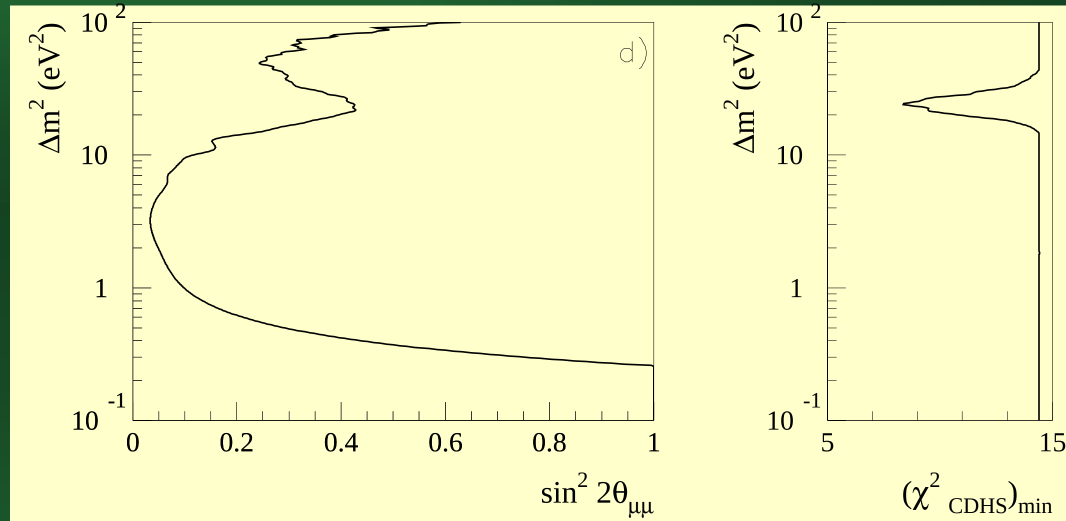
comment on (3+1)-scheme

Taking advantage of artifacts of statistics:

CDHSW($\nu_\mu \to \nu_\mu$)

Local minimum of

χ^2 at Δm^2 20 eV^2



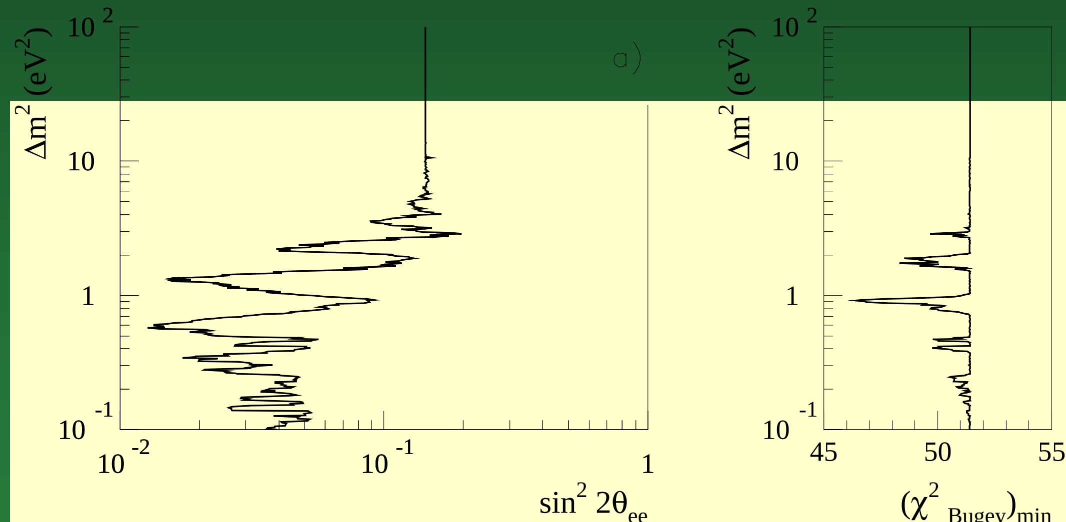
Bugey($\bar{\nu}_e \to \bar{\nu}_e$)

Local minima of

χ^2 at

Δm^2 0.45,0.9,

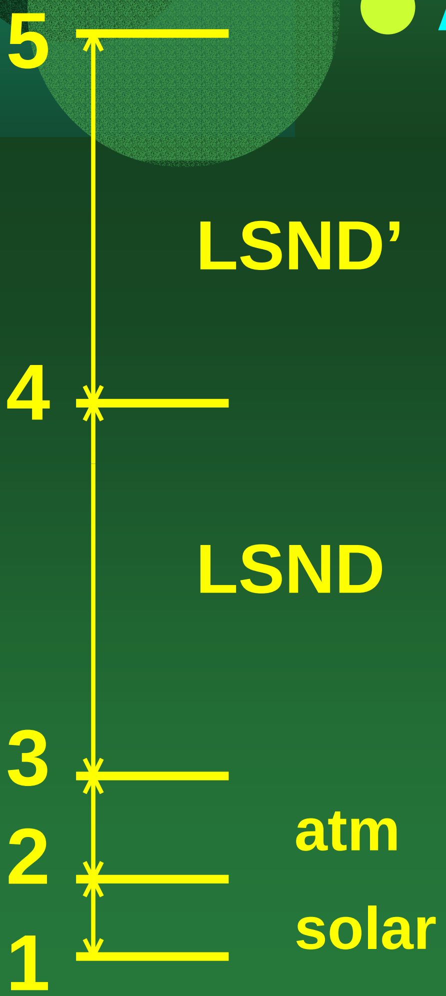
1.6,1.7 eV^2

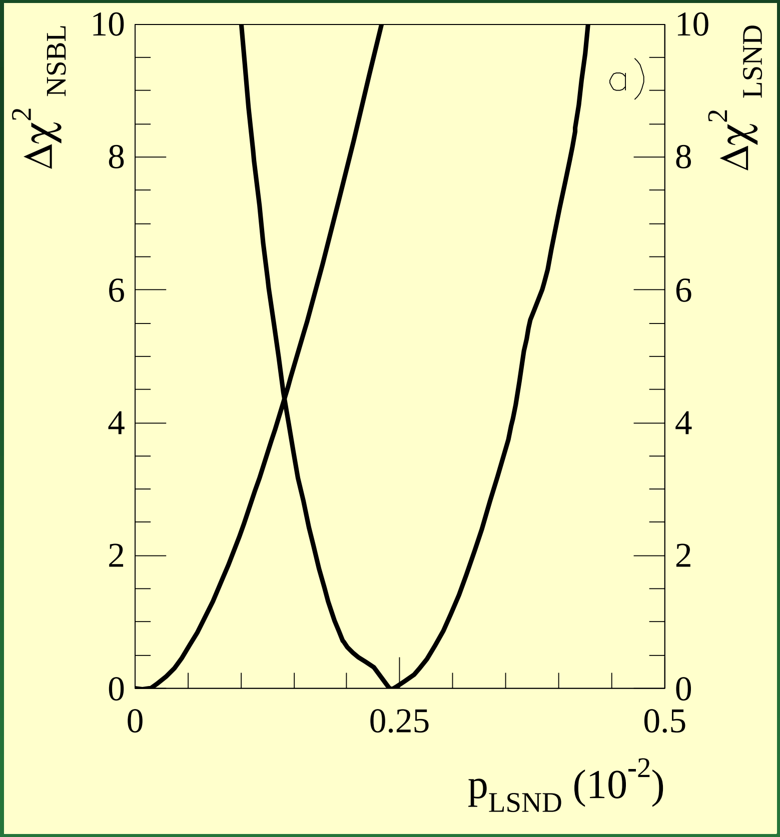


1.3 $N_\nu = 5$ (3+2) : $\nu_{atm} + \nu_{solar} + \nu_{LSND}$

Sorel et al. **hep-ph/0305255**

- **Allowed at 55%CL**

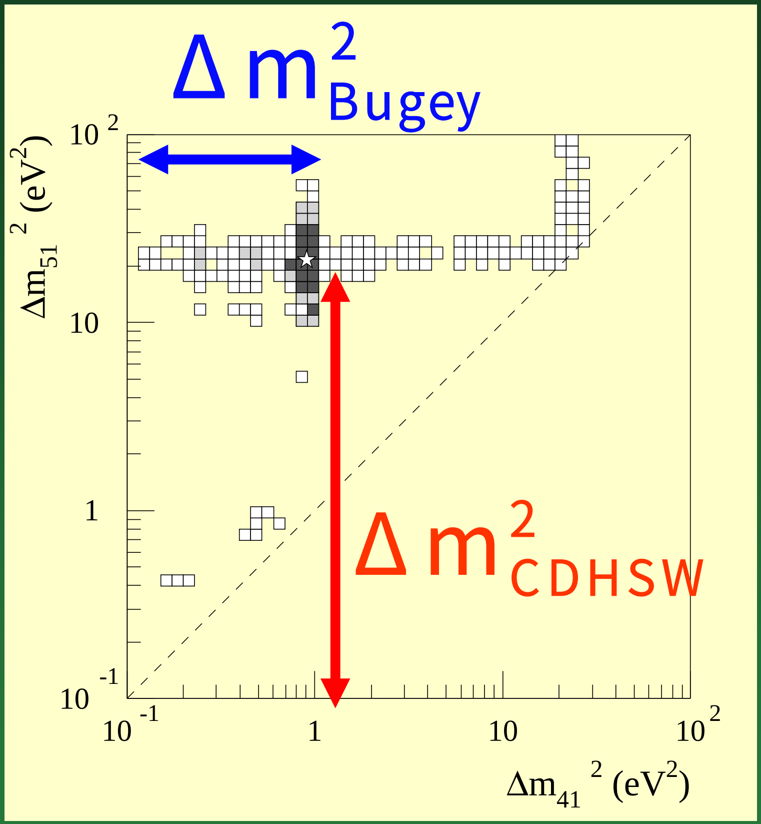


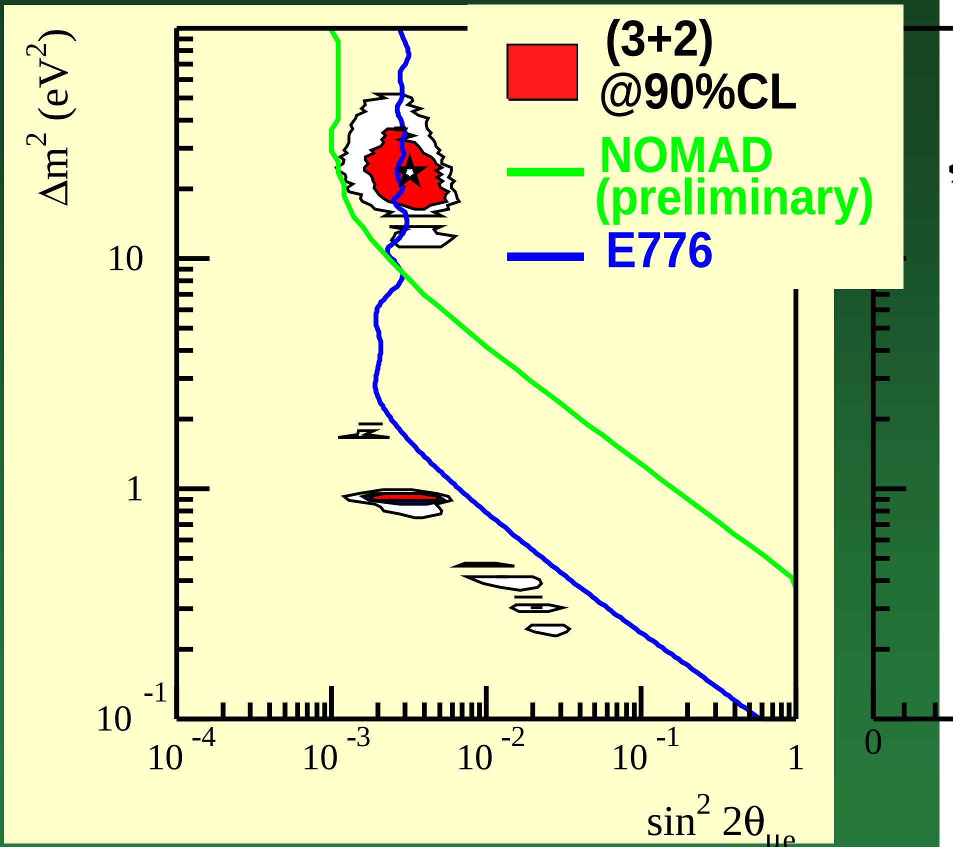


$$p_{LSND} \equiv \langle P(\overline{\nu}_\mu \to \overline{\nu}_e) \rangle_{LSND}$$

comments on (3+2)

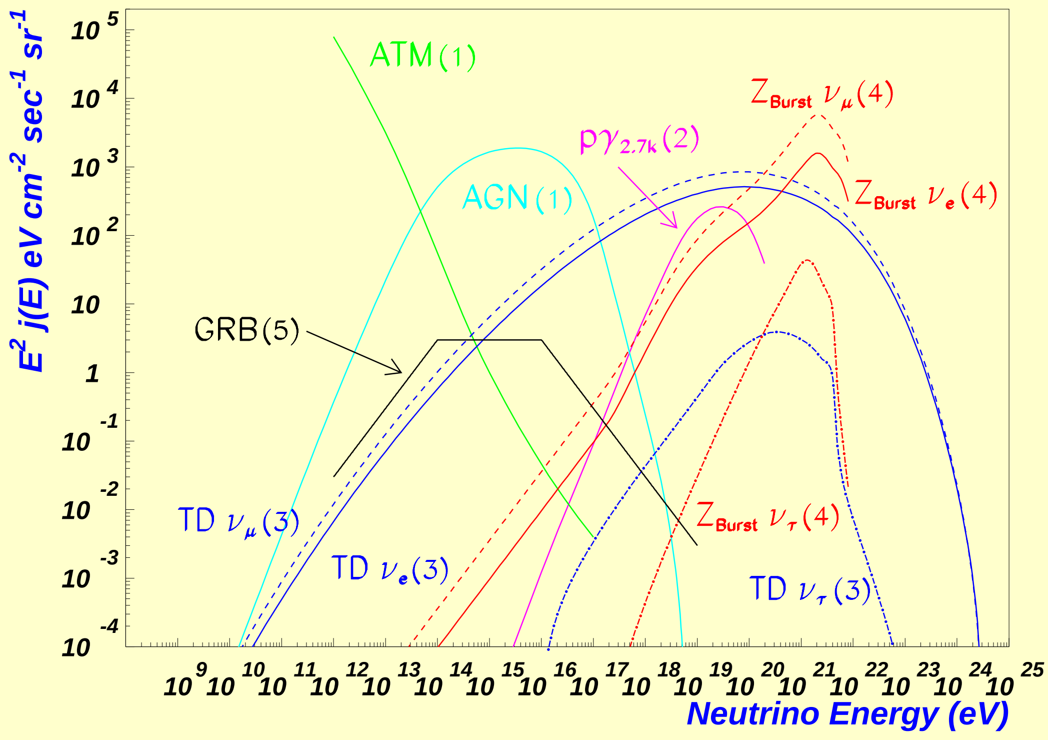
- Taking advantage of artifacts of statistics
- near the boundary of allowed region of E776 and possibly outside of allowed region of preliminary result of NOMAD (V. Valuev, HEP 2001)





2.Effects of ν oscillation on high energy cosmic ν

2.1 Flux of high energy cosmic ν



2.2 ν flux

- **Triangle representation of flux:**

  Precise normalization is not known

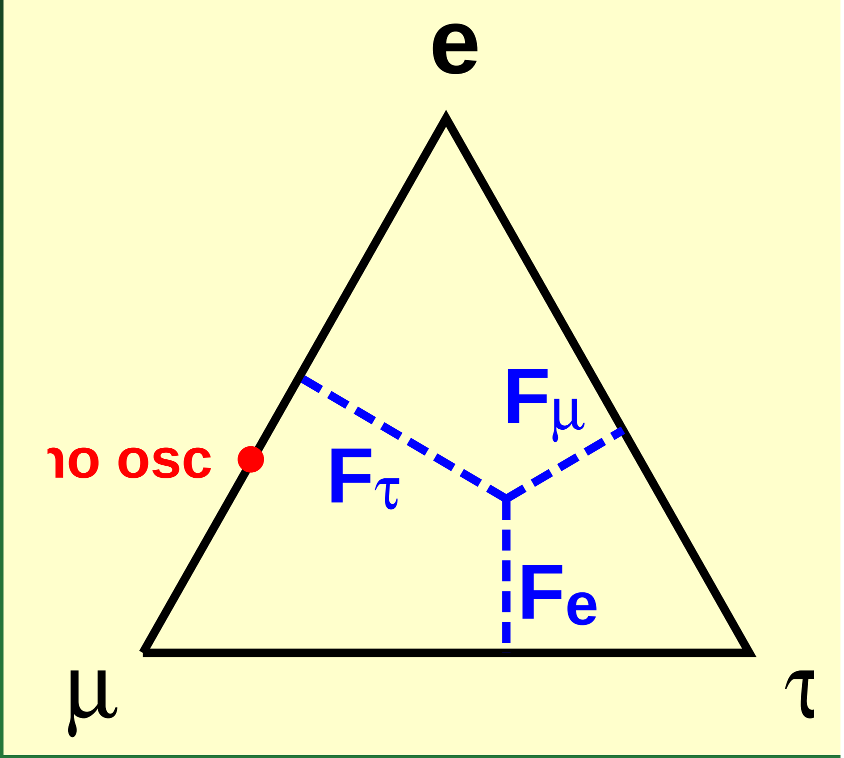
  → **the ratio of different flavors is important quantity to observe**

- **Initial flux:**

Just like in ν_{atm}, the source of ν is π decay

→ $F^0(\nu_e):F^0(\nu_\mu):F^0(\nu_\tau)$

$\simeq 1:2:0$



2.3 $N_\nu=3$

Learned, Pakvasa '95

In standard $N_\nu=3$, when $L\to\infty$

$$P(\nu_e\leftrightarrow\nu_e)\cong 1-\frac{1}{2}\sin^2 2\theta_{solar}$$

$$P(\nu_e\leftrightarrow\nu_\mu)\cong P(\nu_e\leftrightarrow\nu_\tau)\cong \frac{1}{4}\sin^2 2\theta_{solar}$$

$$P(\nu_\mu\leftrightarrow\nu_\mu)\cong P(\nu_\mu\leftrightarrow\nu_\tau)\cong \frac{1}{2}-\frac{1}{8}\sin^2 2\theta_{solar}$$

$$F(\nu_e)=1\cdot(1-\frac{1}{2}\sin^2 2\theta_{solar})+2\cdot\frac{1}{4}\sin^2 2\theta_{solar}=1$$

$$F(\nu_\mu)=1\cdot\frac{1}{4}\sin^2 2\theta_{solar}+2\cdot(\frac{1}{2}-\frac{1}{8}\sin^2 2\theta_{solar})=1$$

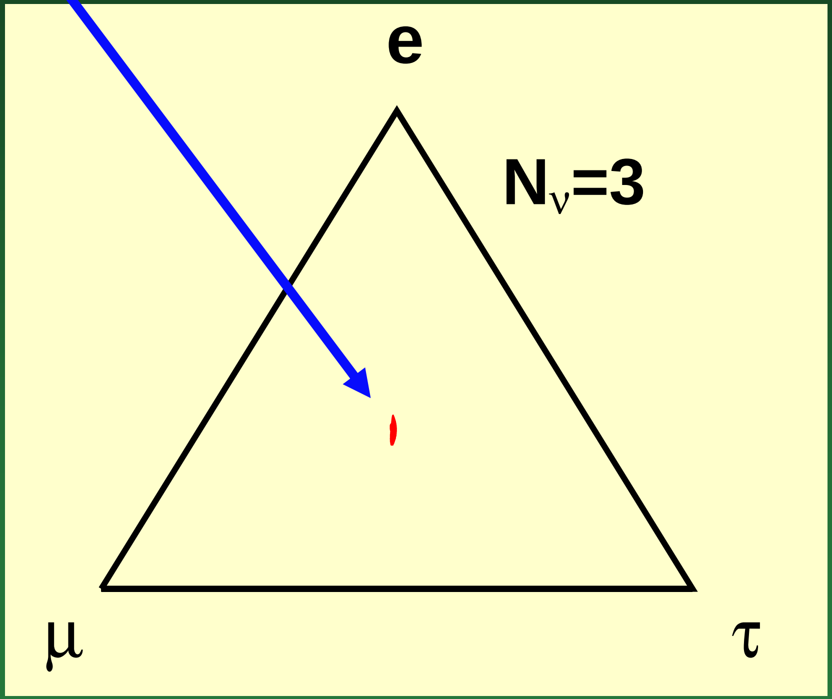
$$F(\nu_\tau)=1\cdot\frac{1}{4}\sin^2 2\theta_{solar}+2\cdot(\frac{1}{2}-\frac{1}{8}\sin^2 2\theta_{solar})=1$$

CHOOZ+ ν_{atm}: $|\theta_{13}| \ll 1$

ν_{atm}: $|\pi/4 - \theta_{23}| \ll 1$

↓

Deviation from 1:1:1 is small



2.3 Standard flux+ ν decay

Beacom et al. **PRL90:181301,2003**

Assume 2-body decay for simplicity:

$$\nu_\alpha \to \nu_\beta + \mathrm{Majoron}$$

$$F(\nu_\alpha) = \sum_{i\beta} F^0(\nu_\beta)|U_{\beta i}|^2 |U_{\alpha i}|^2 e^{-L/\tau_i}$$

$$\to \sum_{i(\mathrm{stable})\,\beta} F^0(\nu_\beta)|U_{\beta i}|^2 |U_{\alpha i}|^2$$

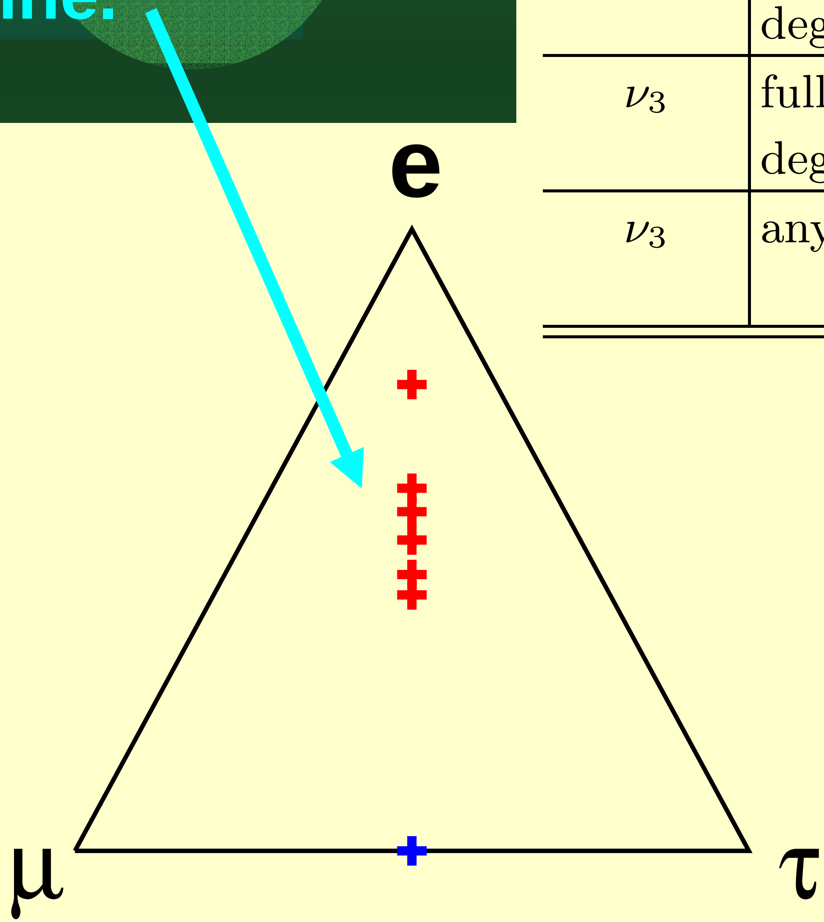
$|U_{\mu j}|$ $|U_{\tau j}|$ ⟶ $F(\nu_\mu)$ $F(\nu_\tau)$

Only the ratio of $F(\nu_e)$ could be different

Because θ_{23} $\pi/4$, all the predictions lie on the mid line.

TABLE I: Flavor ratios for various decay scenarios.

Unstable	Daughters	Branchings	$\phi_{\nu_e} : \phi_{\nu_\mu} : \phi_{\nu_\tau}$
ν_2, ν_3	anything	irrelevant	$6 : 1 : 1$
ν_3	sterile	irrelevant	$2 : 1 : 1$
ν_3	full energy degraded ($\alpha = 2$)	$B_{3\to 2} = 1$	$1.4 : 1 : 1$ $1.6 : 1 : 1$
ν_3	full energy degraded ($\alpha = 2$)	$B_{3\to 1} = 1$	$2.8 : 1 : 1$ $2.4 : 1 : 1$
ν_3	anything	$B_{3\to 1} = 0.5$ $B_{3\to 2} = 0.5$	$2 : 1 : 1$



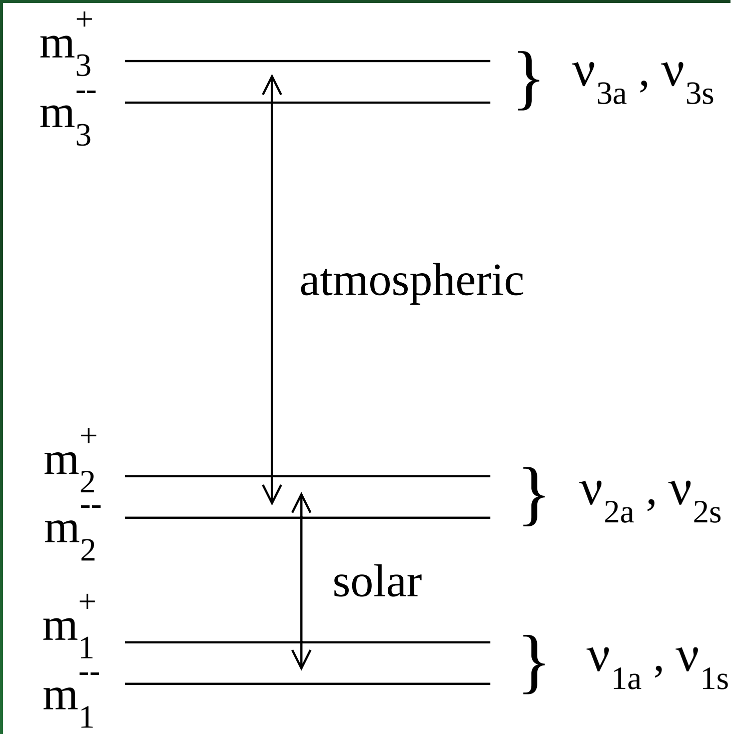
+: normal hierarchy

+: inverted hierarchy

2.4 Standard flux + pseudo-Dirac ν

Beacom et al. **hep-ph/0307151**

$$\begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix} \qquad |m_L|, |m_R| \ll |m_D|$$



$$|\delta m^2| \cong |2m_D(m_L + m_R)|$$

$$< 10^{-11} eV^2 \ll \Delta m^2_{solar}$$

$$F(\nu_\beta) = \sum_\alpha F^0(\nu_\alpha) \sum_{j=1}^{3} |U_{\alpha j}|^2 |U_{\beta j}|^2$$

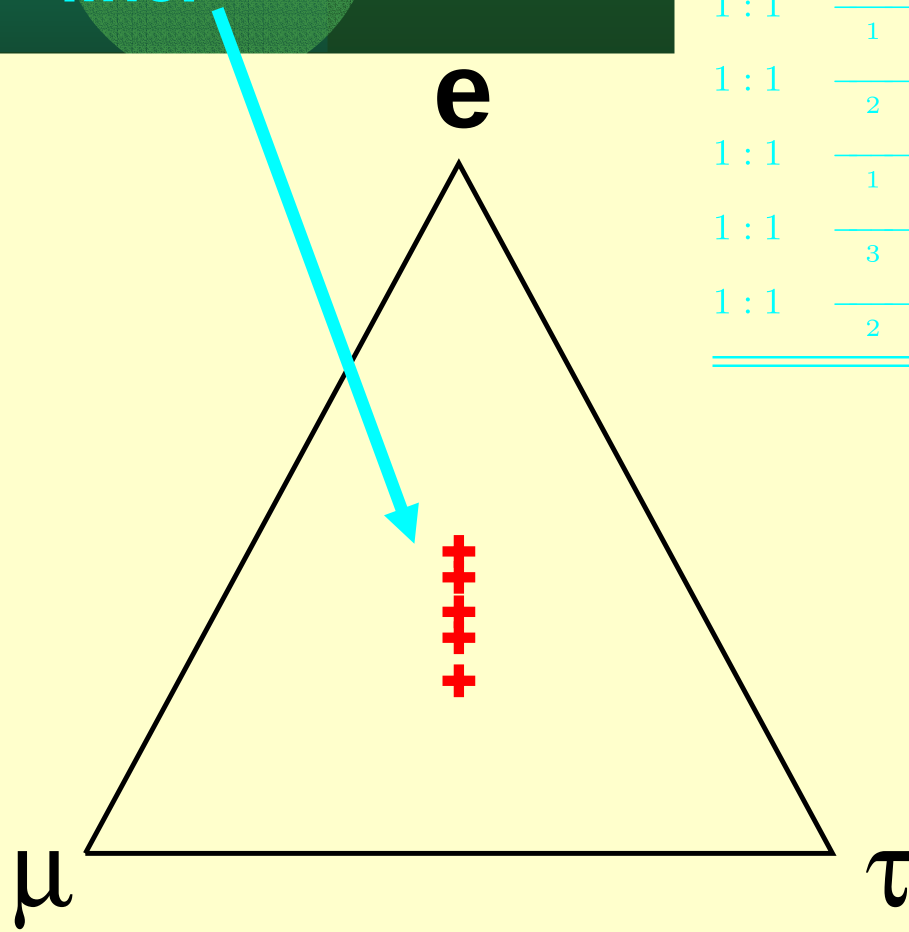
$$\times \left[1 - \sin^2\left(\frac{\delta m_j^2 L}{4E} \right) \right]$$

This may be 0 or ½, depending on $L \ll E/\delta m^2$ or $L \gg E/\delta m^2$

Because θ_{23} π/4, all the predictions lie on the mid line.

TABLE I: Flavor ratios $\nu_e : \nu_\mu$ for various scenarios. The numbers j under the arrows denote the pseudo-Dirac splittings, δm_j^2, which become accessible as L/E increases. Oscillation averaging is assumed after each transition j. We have used $\theta_{\rm atm} = 45°$, $\theta_{\rm solar} = 30°$, and $U_{e3} = 0$.

1 : 1	$\xrightarrow[3]{}$	4/3 : 1	$\xrightarrow[2,3]{}$	14/9 : 1	$\xrightarrow[1,2,3]{}$	1 : 1
1 : 1	$\xrightarrow[1]{}$	2/3 : 1	$\xrightarrow[1,2]{}$	2/3 : 1	$\xrightarrow[1,2,3]{}$	1 : 1
1 : 1	$\xrightarrow[2]{}$	14/13 : 1	$\xrightarrow[2,3]{}$	14/9 : 1	$\xrightarrow[1,2,3]{}$	1 : 1
1 : 1	$\xrightarrow[1]{}$	2/3 : 1	$\xrightarrow[1,3]{}$	10/11 : 1	$\xrightarrow[1,2,3]{}$	1 : 1
1 : 1	$\xrightarrow[3]{}$	4/3 : 1	$\xrightarrow[1,3]{}$	10/11 : 1	$\xrightarrow[1,2,3]{}$	1 : 1
1 : 1	$\xrightarrow[2]{}$	14/13 : 1	$\xrightarrow[1,2]{}$	2/3 : 1	$\xrightarrow[1,2,3]{}$	1 : 1



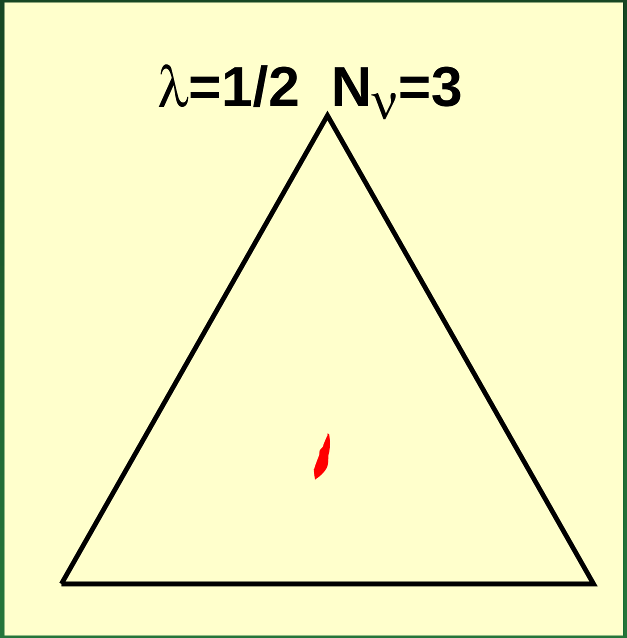
Observation of cosmic ν is the only known way to probe $\Delta m^2 \ll 10^{-10} eV^2$

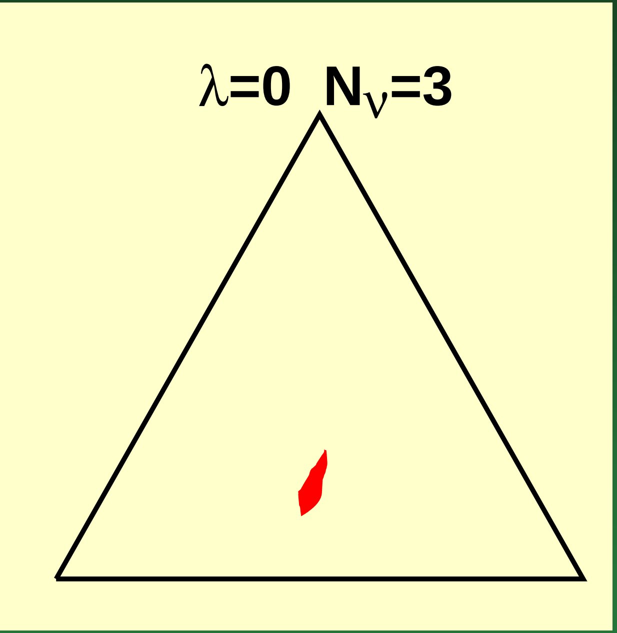
2.5 Non-standard flux + N_ν=3

Assume hypothetically

$$F^0(\nu_e):F^0(\nu_\mu):F^0(\nu_\tau)=\frac{\lambda}{3}:1-\frac{\lambda}{3}:0$$

Then even prediction with N_ν=3 is distinct from the standard case:





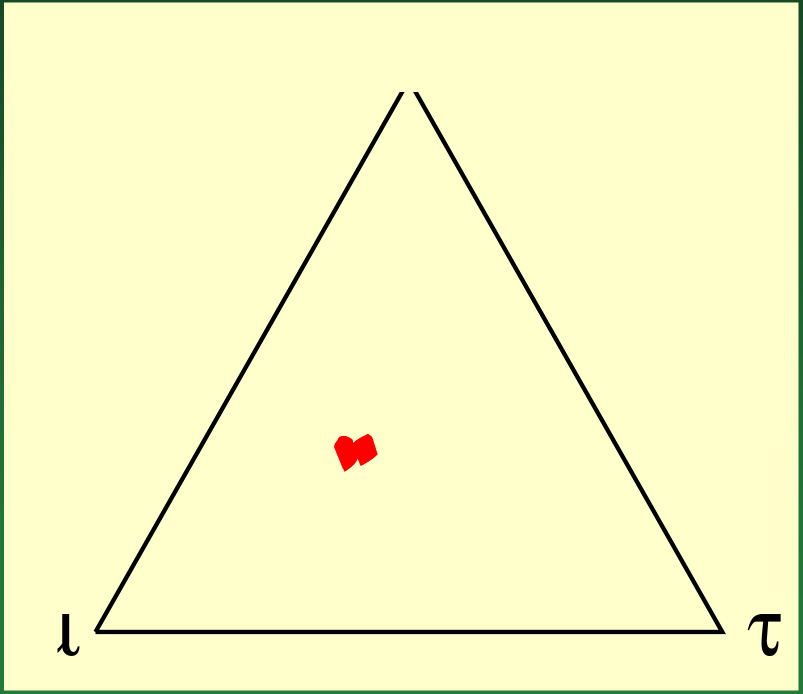
2.6 sterile ν scenarios

To have deviation from midline ($F(\nu_\mu)=F(\nu_\tau)$), (2+2)-like sterile ν scenario may be necessary.

(∵ some fraction of $\nu_\mu \rightarrow \nu_s$ in (2+2))

(3+1)- and (3+2)-schemes give almost the same prediction as $N_\nu=3$

Even though (2+2)-scheme is now disfavored, it may be worth taking a look:



3.Conclusions

- If $F_0(\nu_e)$: $F_0(\nu_\mu)$: $F_0(\nu_\tau)$=1:2:0, then N_ν=3 scenario predicts

  $F(\nu_e)$: $F(\nu_\mu)$: $F(\nu_\tau)$=1:1:1.
- There are scenarios (ν decay, pseudo-Dirac ν) which have predictions quite different from 1:1:1.
- If the initial flux is not 1:2:0, then observed flux would be also different from 1:1:1.
- To have deviation from $F(\nu_\mu)$: $F(\nu_\tau)$=1:1, some exotic scenario, such as (2+2)-sterile scheme, seems to be necessary.