Signatures of sterile ν mixing in high energy cosmic ν flux

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1. Introduction

Standard framework of 3 flavor ν oscillation

Mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Functions of mixing angles θ_{12}, θ_{23}, θ_{13}, and CP phase δ

Information we have obtained so far:

ν_{solar}+KamLAND (reactor) → $\theta_{12} \cong \frac{\pi}{6}, \Delta m^2_{21} \cong 8 \times 10^{-5} \mathrm{eV}^2$

ν_{atm}+K2K,MINOS(accelerators) → $\theta_{23} \cong \frac{\pi}{4}, |\Delta m^2_{32}| \cong 2.5 \times 10^{-3} \mathrm{eV}^2$

CHOOZ (reactor) → $|\theta_{13}| \leq \sqrt{0.15}/2$

Original motivation for sterile ν

- accelerator ν anomaly: **LSND**

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

$\Delta m^2 \cong O(1)\text{eV}^2$ **??**
$\sin^2 2\theta \cong O(10^{-2})$

$\Delta m^2_{\text{sol}} \sim 10^{-4}\text{eV}^2$

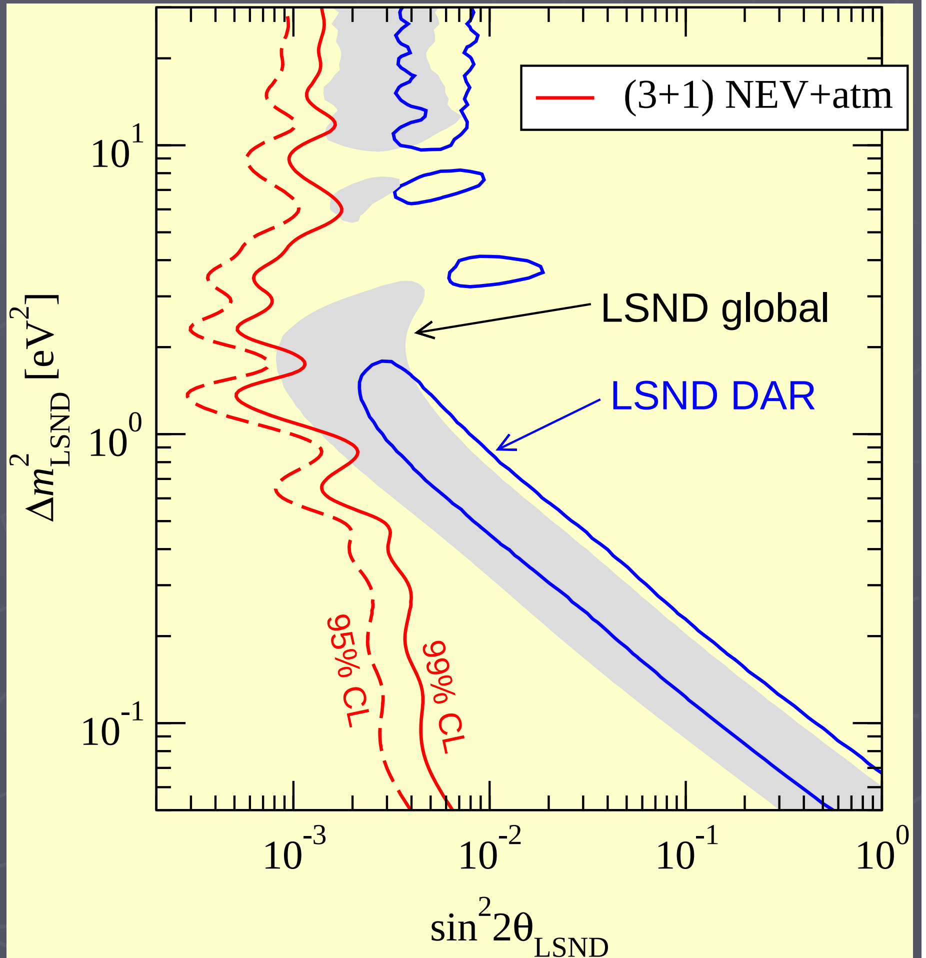
$\Delta m^2_{\text{atm}} \sim 10^{-3}\text{eV}^2$

$\Delta m^2_{\text{LSND}} \sim O(1)\text{eV}^2$

at least one more massive ν eigenstate is required

From LEP any extra ν flavor eigenstate has to be sterile ν (ν_s)

Maltoni et al., hep-ph/0405172

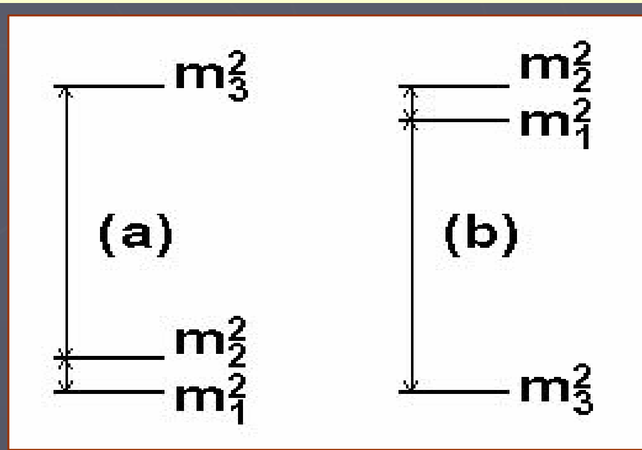


2. N_ν=4 schemes

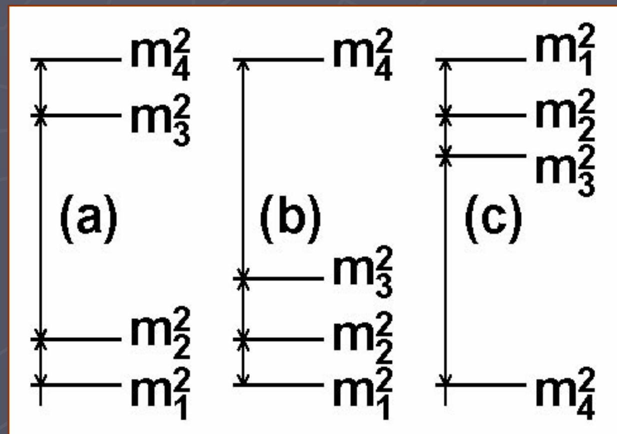
Because of the hierarchy: $\Delta m^2_{sol} << \Delta m^2_{atm} << \Delta m^2_{LSND}$

N_ν =3 schemes can't explain LSND.

$\Delta m^2_{21} = \Delta m^2_{sol}, \Delta m^2_{32} = \Delta m^2_{atm}$



N_ν =4 schemes may be able to explain all.



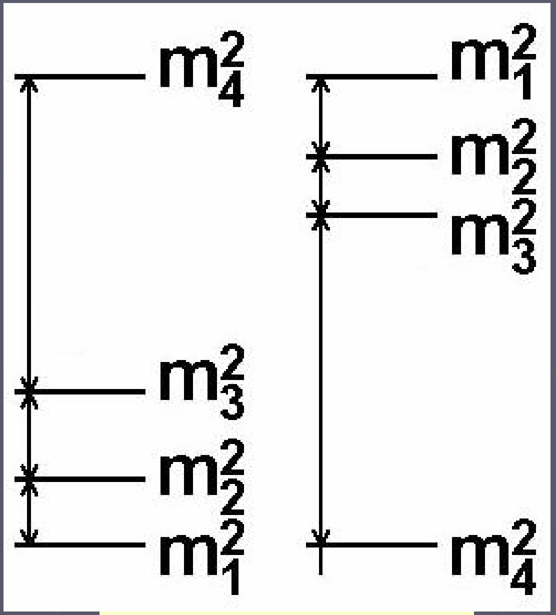
It turns out that it doesn't work.

$\Delta m^2_{21} = \Delta m^2_{sol}, \Delta m^2_{32} = \Delta m^2_{atm}, \Delta m^2_{43} = \Delta m^2_{LSND}$

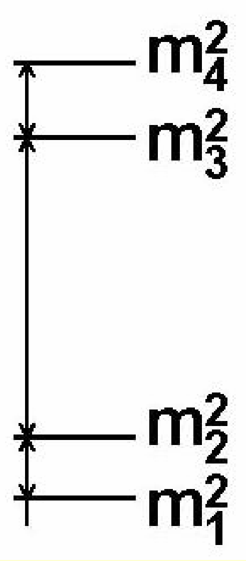
N_ν=4 schemes to explain LSND

scheme	accelerator + reactor	solar + atmospheric
(3+1)	tension	✓
(2+2)	✓	excluded

Any of 4 ν scenarios doesn't work.



(3+1)-scheme



(2+2)-scheme

(2+2)-scheme

$\eta_s \equiv |U_{s1}|^2 + |U_{s2}|^2 \to 0$

$\nu_{atm} : \nu_\mu \to \nu_s (100\%)$

Strongly disfavored by SK ν_{atm} data

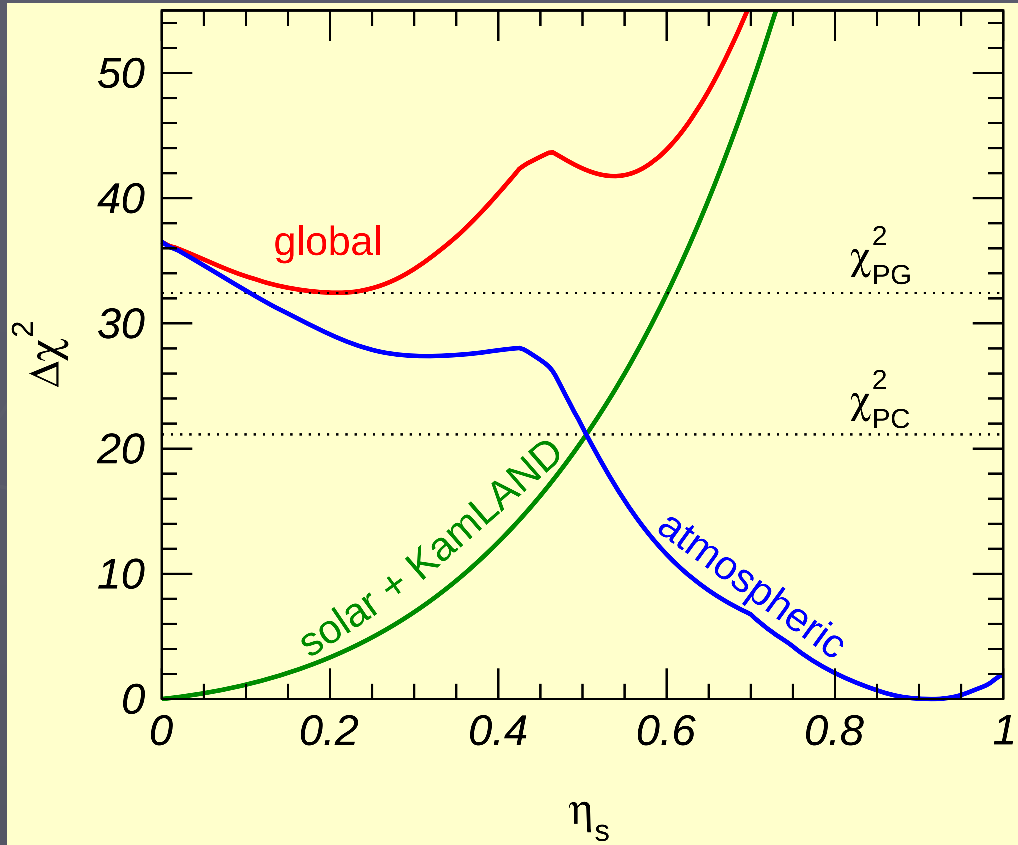
$\eta_s \equiv |U_{s1}|^2 + |U_{s2}|^2 \to 1$

$\nu_{sol} : \nu_e \to \nu_s (100\%)$

Strongly disfavored by SNO ν_{sol} data

For any value of $|U_{s1}|^2 + |U_{s2}|^2$, fit to sol+atm data is bad.

Maltoni et al., hep-ph/0405172



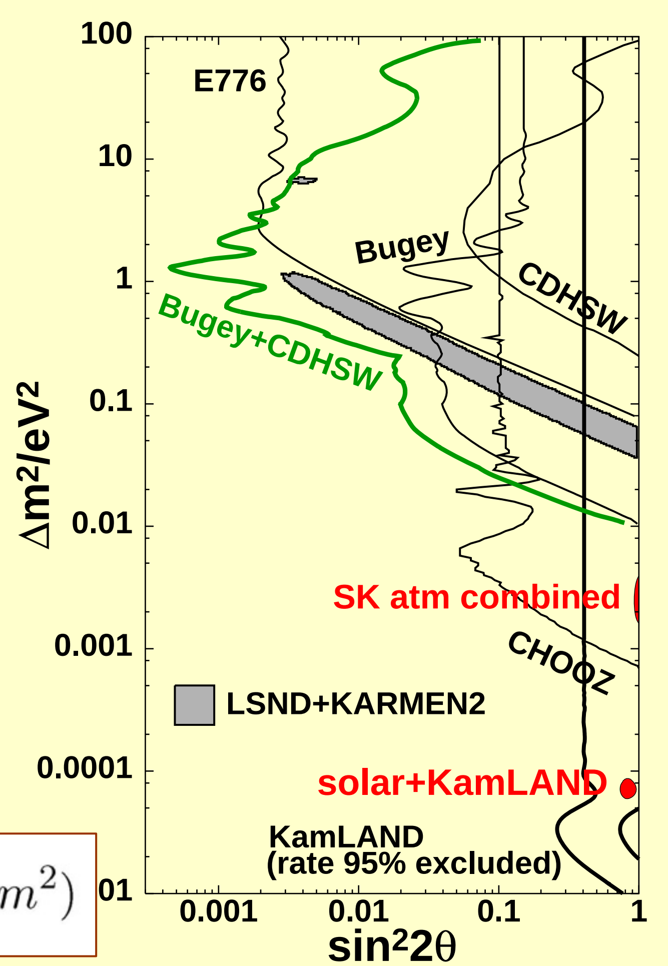
excluded (~5σCL) because it contradicts with ν_{atm} or ν_{solar} :

independent of LSND

(3+1)-scheme (assuming LSND)

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - 4|U_{e4}|^2(1-|U_{e4}|^2)\sin^2(\Delta m^2_{41}L/4E)$$
$$P(\nu_\mu \to \nu_\mu) = 1 - 4|U_{\mu 4}|^2(1-|U_{\mu 4}|^2)\sin^2(\Delta m^2_{41}L/4E)$$
$$P(\bar{\nu}_\mu \to \bar{\nu}_e) = 4|U_{e4}|^2|U_{\mu 4}|^2\sin^2(\Delta m^2_{41}L/4E)$$

$$\sin^2 2\theta_{Bugey} > 4|U_{e4}|^2(1-|U_{e4}|^2) \simeq 4|U_{e4}|^2$$
$$\sin^2 2\theta_{CDHSW} > 4|U_{\mu 4}|^2(1-|U_{\mu 4}|^2) \simeq 4|U_{\mu 4}|^2$$
$$\sin^2 2\theta_{LSND} = 4|U_{e4}|^2|U_{\mu 4}|^2$$



$$\sin^2 2\theta_{\rm LSND}(\Delta m^2) < \frac{1}{4}\sin^2 2\theta_{\rm Bugey}(\Delta m^2)\sin^2 2\theta_{\rm CDHSW}(\Delta m^2)$$

must be satisfied **(Okada-OY'97, Bilenky-Giunti-Grimus '98)**

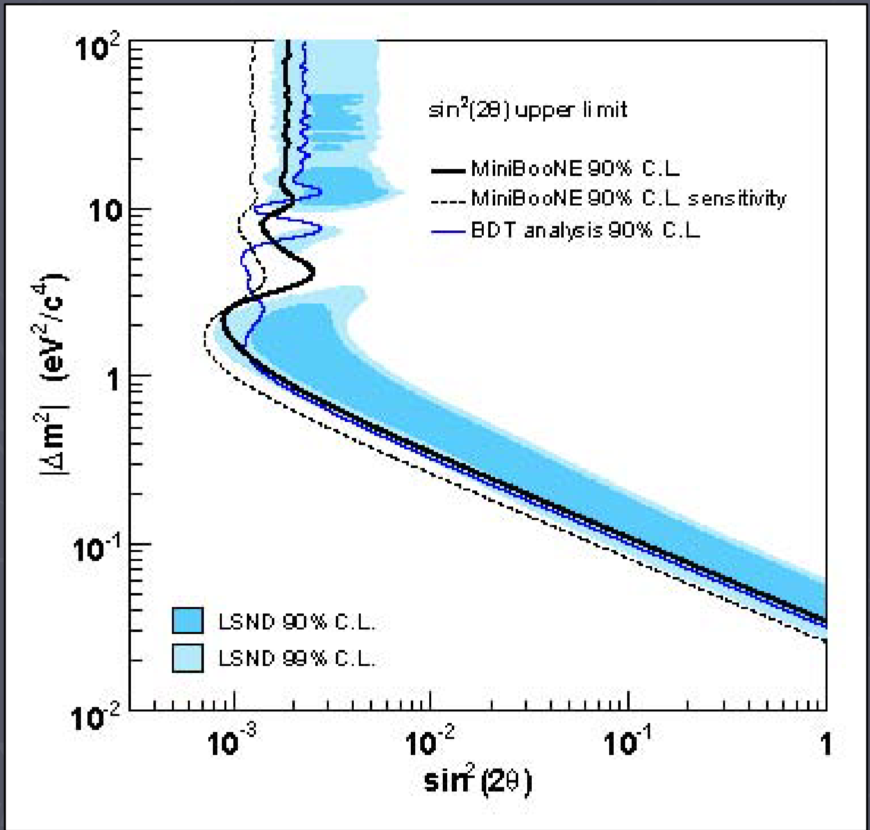
But there is no overlap between **LSND** and left side of **Bugey+CDHSW**

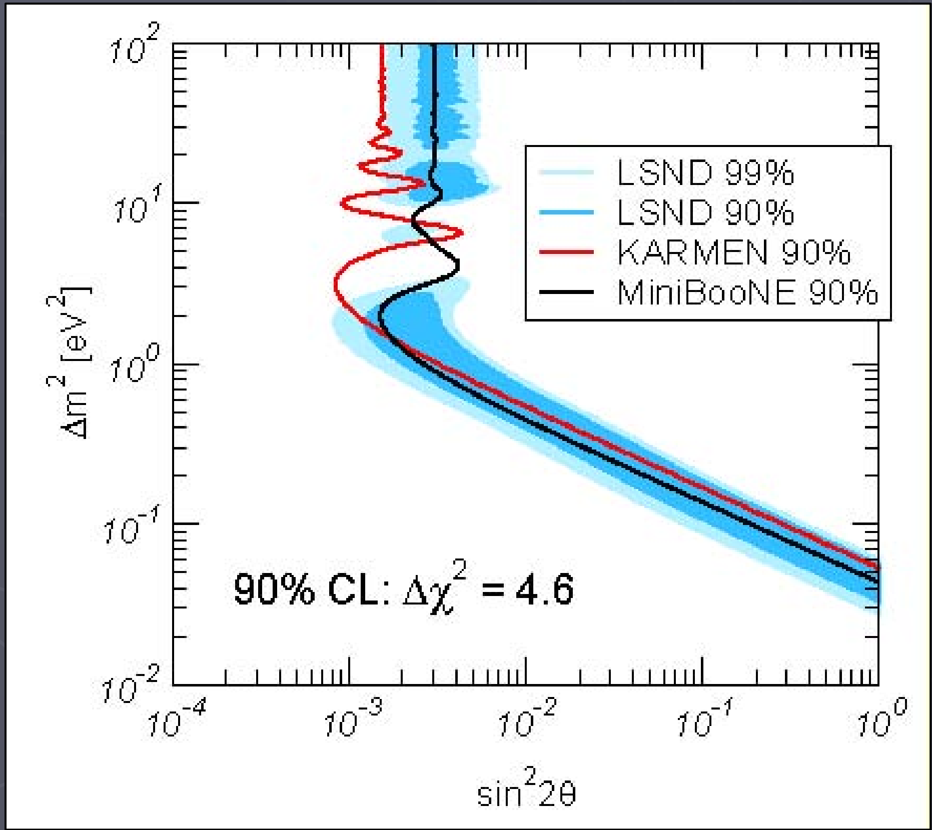
Strongly disfavored (~3σCL) because of the tension between LSND and Bugey+CDHSW (+other negative results)

Moreover, we have negative result from MiniBooNE

$\nu_\mu \rightarrow \nu_e$

The result may not be conclusive but significance got even larger





Schwetz@nufact07

Sterile neutrinos w/o assuming LSND

Without assuming LSND and imposing all the negative constraints, one can still consider consistent (3+1)-scheme.

Why am I still interested in (3+1)-scheme?

The (3+1)-scheme w/o LSND is not motivated by any experimental data, but 4 neutrino schemes offer phenomenologically natural scenario for deviation from 3 flavor unitarity, which may be tested in future neutrino experiments. (cf. B factories)

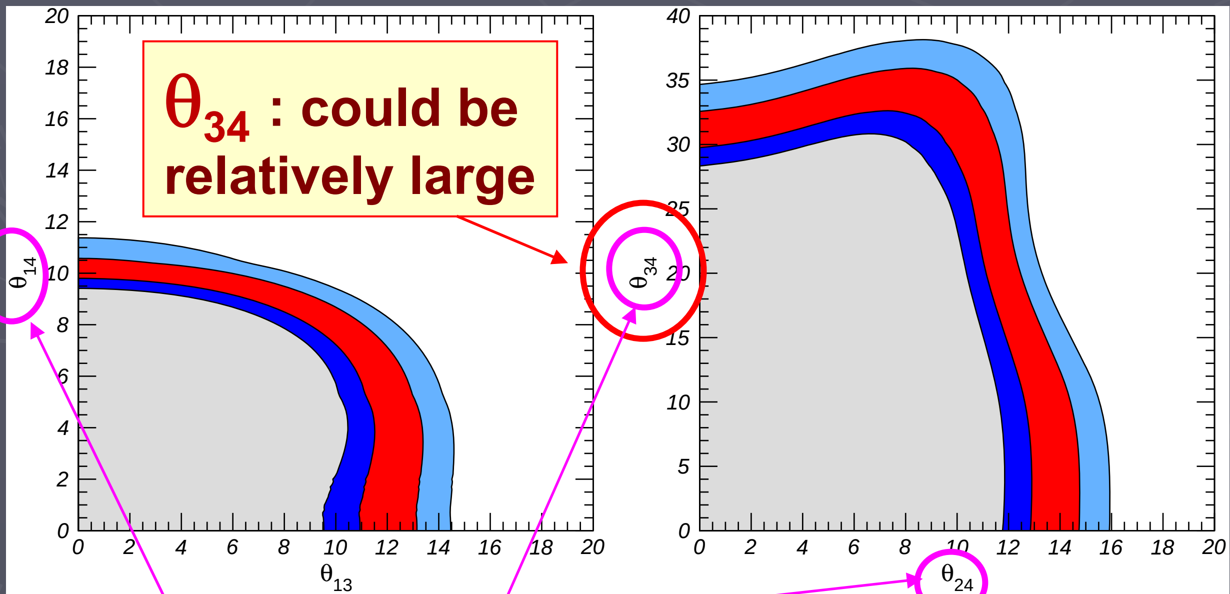
Sterile neutrinos w/o assuming LSND

Donini-Maltoni-Meloni-Migliozzi-Terranova arXiv:0704.0388v2

Without assuming LSND and imposing all the negative constraints one can still consider (3+1)-scheme

$$U = R_{34}(\theta_{34})\ R_{24}(\theta_{24})\ R_{23}(\theta_{23},\ \delta_3)\ R_{14}(\theta_{14})\ R_{13}(\theta_{13},\ \delta_2)\ R_{12}(\theta_{12},\ \delta_1)$$

Constraints by all the negative results give the allowed region



θ_{34} : ratio of $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_s$

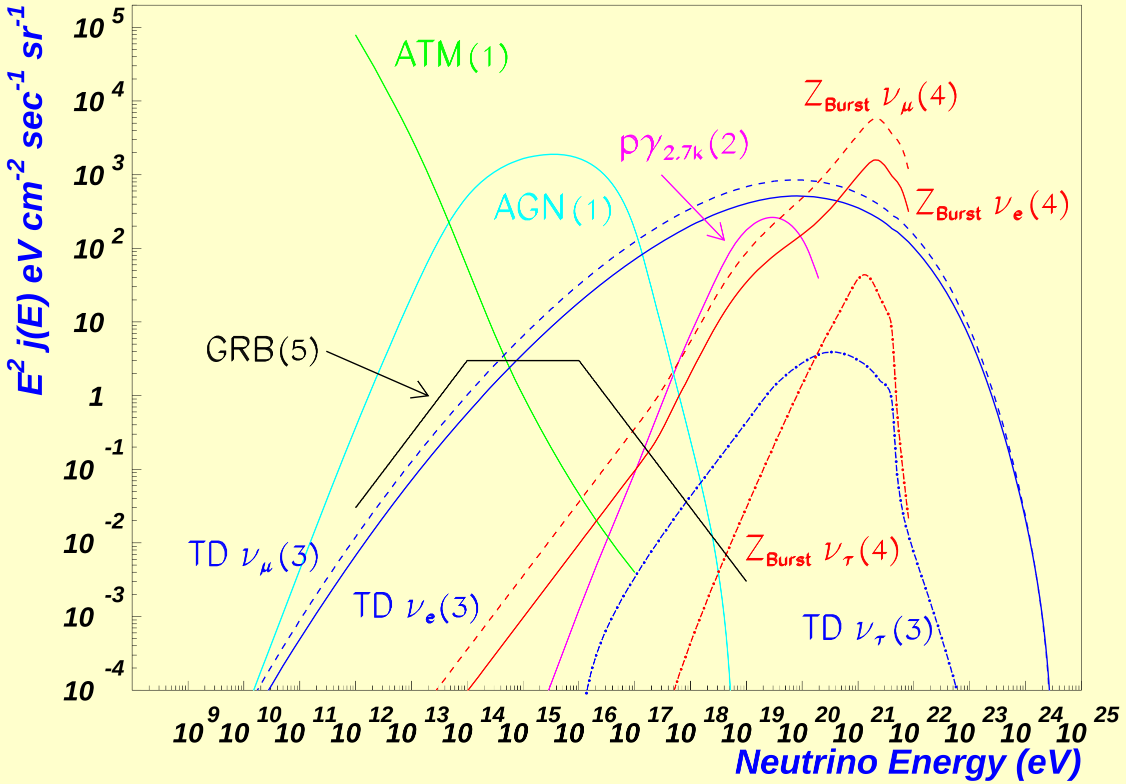
in ν_{atm}

θ_{24} : ratio of $\sin^2(\Delta m^2_{atm} L/4E)$ and $\sin^2(\Delta m^2_{SBL} L/4E)$

θ_{14} , θ_{24} , θ_{34} : angles which appear only in 4ν scenario

3. High energy astrophysical ν

Flux of high energy cosmic ν from Active Galactic Nuclei or Gamma Ray Burst etc.



S/N ratio is expected to be large due to little background of atmospheric ν

- **Precise normalization of flux is not known**

$\rightarrow$ **The ratio of different flavors is important quantity to observe**

- **Initial flux:**

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

$\Rightarrow$ $F^0(\nu_e):F^0(\nu_\mu):F^0(\nu_\tau) \cong 1:2:0$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$
$$\hookrightarrow e^- + \bar{\nu}_e + \nu_\mu$$

- **Observed flux on Earth:**

Due to ν oscillations

$|\theta_{13}|<<1, |\pi/4-\theta_{23}|<<1$ $\Rightarrow$ $F(\nu_e):F(\nu_\mu):F(\nu_\tau) \cong 1:1:1$

Learned, Pakvasa '95

In standard N_ν=3, when L→∞ oscillation probability in vacuum

$$P_{\alpha\beta} = \sum_j |U_{\alpha j}|^2 |U_{\beta j}|^2$$

$$|U_{\alpha j}|^2 \cong \begin{pmatrix} c_{12}^2 & s_{12}^2 & 0 \\ s_{12}^2/2 & c_{12}^2/2 & 1/2 \\ s_{12}^2/2 & c_{12}^2/2 & 1/2 \end{pmatrix}$$

$$F(\nu_e) = F^0(\nu_e)(P_{ee} + 2P_{\mu e}) = F^0(\nu_e)(1\text{-}P_{\tau e} + P_{\mu e}) = 1$$
$$F(\nu_\mu) = F^0(\nu_e)(P_{e\mu} + 2P_{\mu\mu}) = F^0(\nu_e)(1\text{-}P_{\tau\mu} + P_{\mu\mu}) = 1$$
$$F(\nu_\tau) = F^0(\nu_e)(P_{e\tau} + 2P_{\mu\tau}) = F^0(\nu_e)(1\text{-}P_{\tau\tau} + P_{\mu\tau}) = 1$$

$$F(\nu_\alpha) = F^0(\nu_e)P_{e\alpha} + F^0(\nu_\mu)P_{\mu\alpha} = F^0(\nu_e)(P_{e\alpha} + 2P_{\mu\alpha})$$

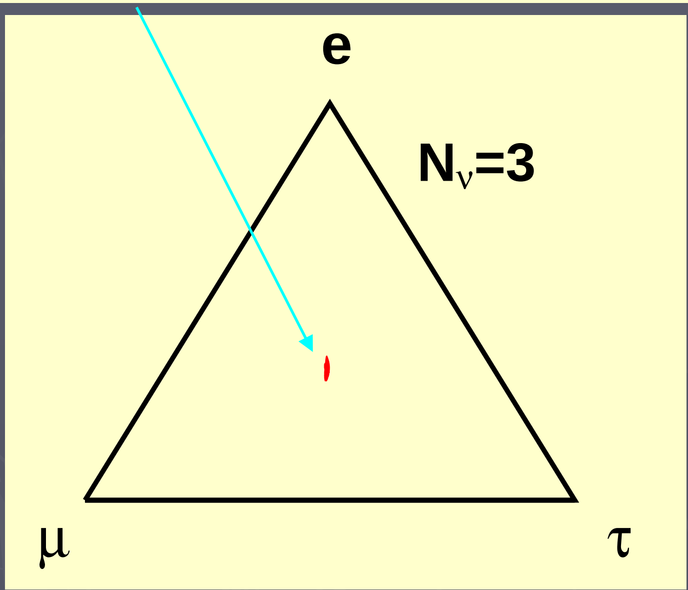
$$P_{e\alpha} + 2P_{\mu\alpha} = (P_{e\alpha} + P_{\mu\alpha}) + P_{\mu\alpha} = 1\text{-}P_{\tau\alpha} + P_{\mu\alpha} = 1$$

CHOOZ+ν_{atm}: $|\theta_{13}|$<<1

ν_{atm}: $|\pi/4 - \theta_{23}|$<<1

Athar-Jezabek-OY '00

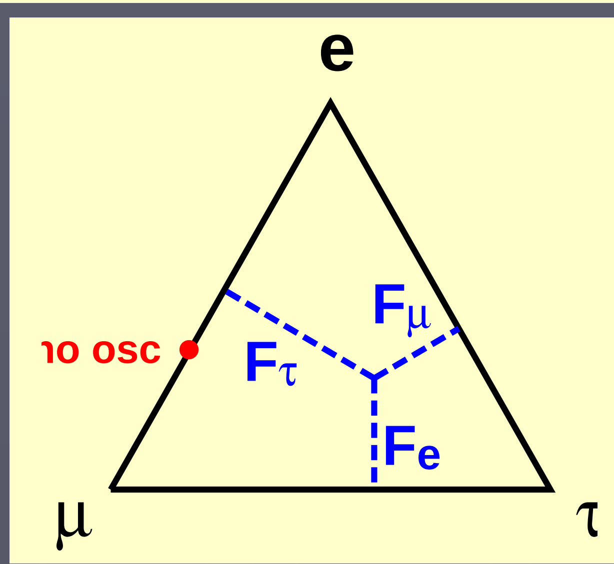
Deviation from 1:1:1 is small for 3 flavor case

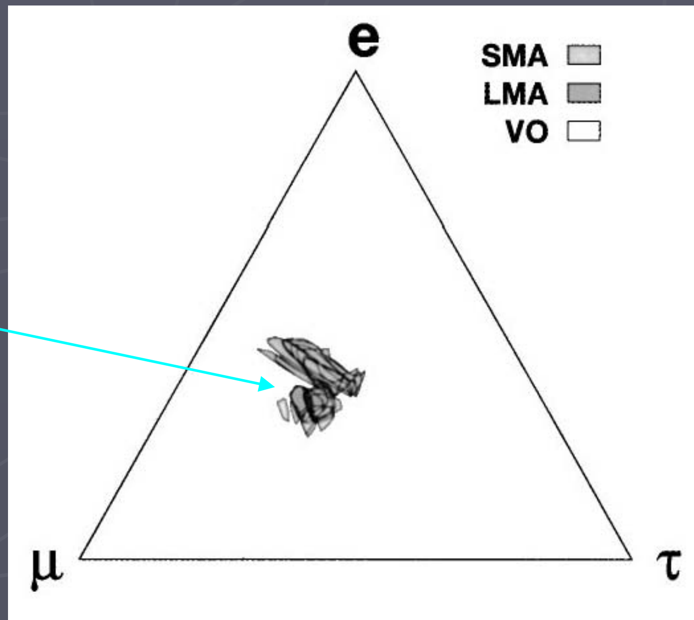


(2+2)-scheme (which was acceptable in '00) gave relatively large deviation

Normalized ratio of active flavors is useful:

$$\widetilde{F}(\nu_\alpha) \equiv \frac{F(\nu_\alpha)}{F(\nu_e) + F(\nu_\mu) + F(\nu_\tau)}$$





A few scenarios to predict deviation from 1:1:1 have been proposed

- **Standard flux + ν decay**

  α:1:1 (α=1.4~6)

  Beacom-Bell-Hooper-Pakvasa-Weiler '03

- **Standard flux + pseudo-Dirac ν**

  α:1:1 (α=2/3~14/9)

  Beacom -Bell-Hooper-Learned-Pakvasa-Weiler'04

- **Electromagnetic energy losses of π & μ**

  α:1:1 (α=1/1.8~1)

  Kashti-Waxman '05

All these scenarios predict $\nu_\mu:\nu_\tau = 1:1$ (as long as $\nu_\mu \leftrightarrow \nu_\tau$ mixing occurs according to the 3 flavor scenario)

Deviation from $\nu_\mu:\nu_\tau = 1:1$ is interesting

4 neutrino scenarios offer such a possibility

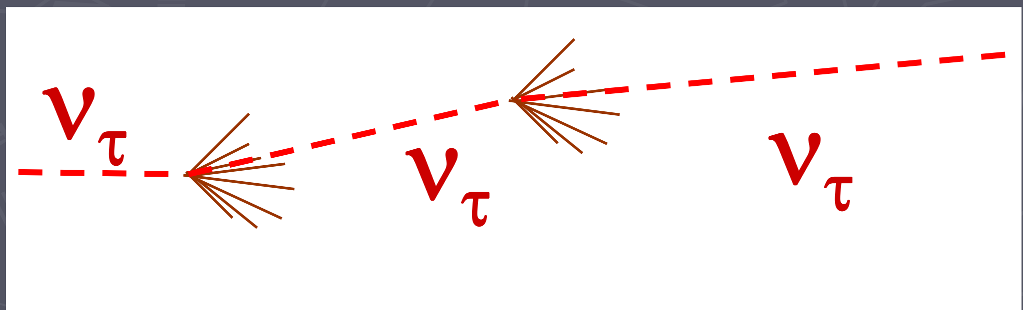
Identification of ν flavors

ν_e : electromagnetic showers

ν_μ : muon tracks

ν_τ : double bang events (E=1-20PeV)

Learned, Pakvasa '95



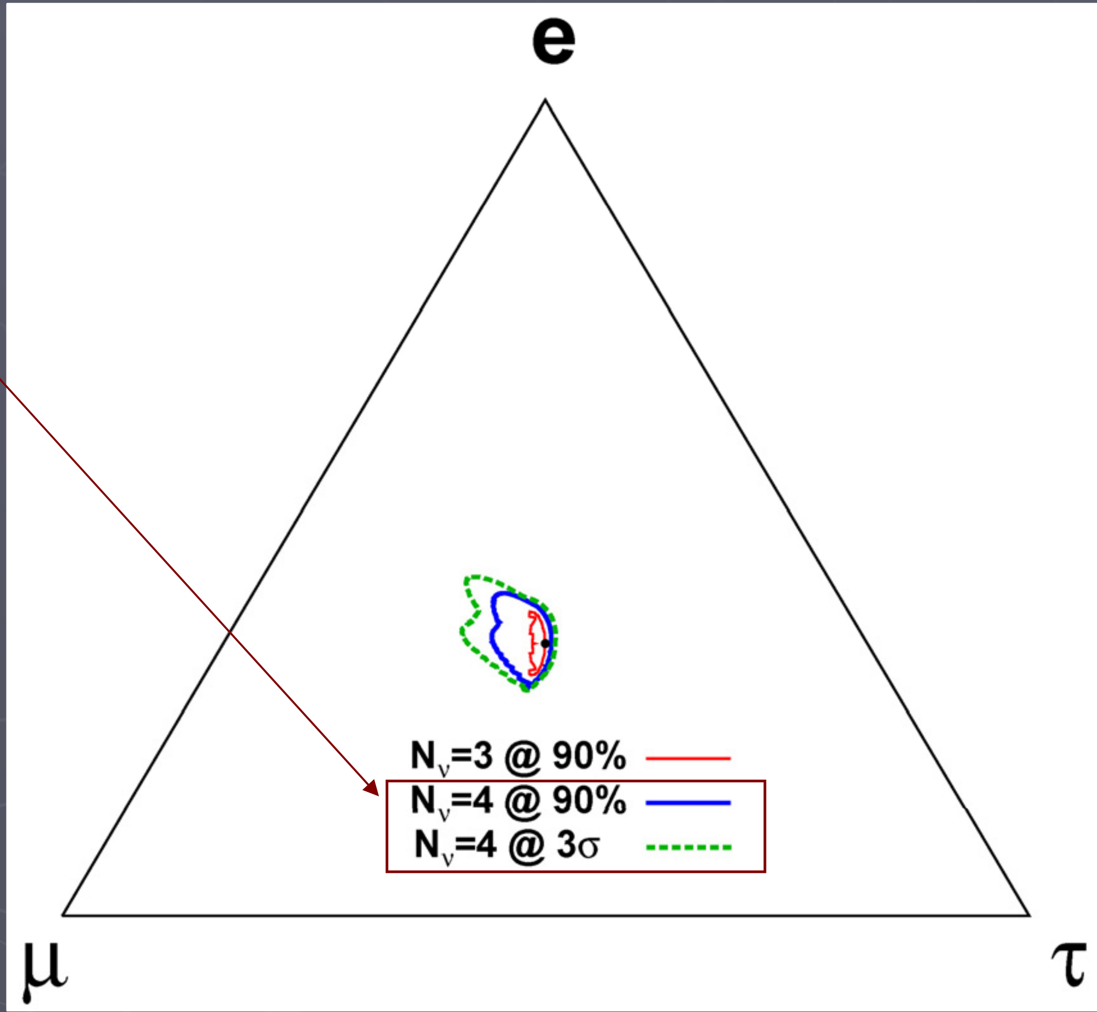
Flavor ratio of ν flux for (3+1)- scheme

Donini-OY ‘07

(3+1)-scheme w/o LSND gives the prediction which could be distinguished from N_ν=3 case

In principle, (3+1)-scheme could be distinguished from the three flavor case

$$\frac{F(\nu_\tau)}{F(\nu_\mu)} = c_{34}^2 \geq 0.67$$



Theoretical uncertainties of original ν flux

Lipari-Lusignoli-Meloni Phys.Rev.D75:123005,2007

For illustrations, they discussed ν flux from GRB using Waxman-Bahcall

- **Proton energy spectrum**

$$N_p(E_p) \propto E_p^{-\alpha}$$

- **Photon number density**

$$n_\gamma(\epsilon) \propto \begin{cases} (\epsilon/\epsilon_b)^{-\beta_1} & \text{for } \epsilon \le \epsilon_b, \\ (\epsilon/\epsilon_b)^{-\beta_2} & \text{for } \epsilon_b < \epsilon < \epsilon_{max} \\ 0 & \text{for } \epsilon \ge \epsilon_{max}, \end{cases}$$

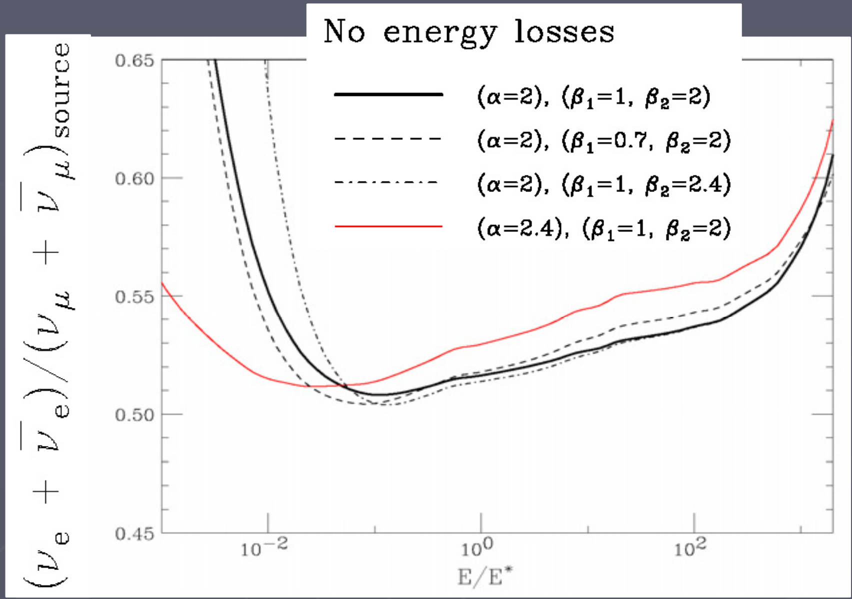
- **Muon energy loss due to synchrotron radiation**

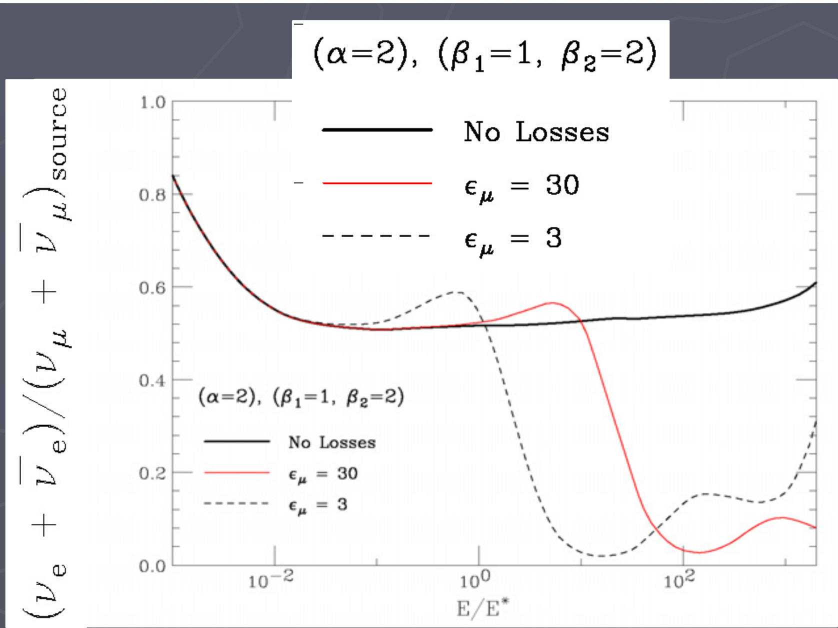
$$\epsilon_\mu = \frac{E^\mu_{syn}}{E^*} = 8.4 \times 10^4 \left(\frac{\text{Gauss}}{B}\right)\left(\frac{\epsilon_b}{\text{KeV}}\right)$$

$$E^* \simeq 6.9 \times 10^{13} (\epsilon_b/\text{KeV})^{-1} \text{eV}$$

: Proton threshold energy for inelastic interactions with γ

- **e:μ=1:2 not necessarily correct**
- **Energy dependence expected**

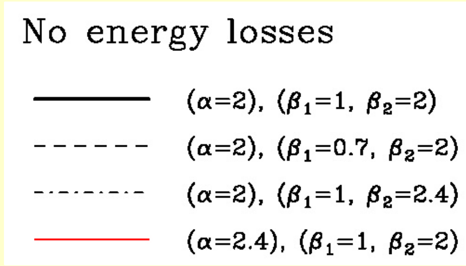




e/μ ratio vs μ/τ ratio & energy spectrum for (3+1)- scheme

Donini-OY '07

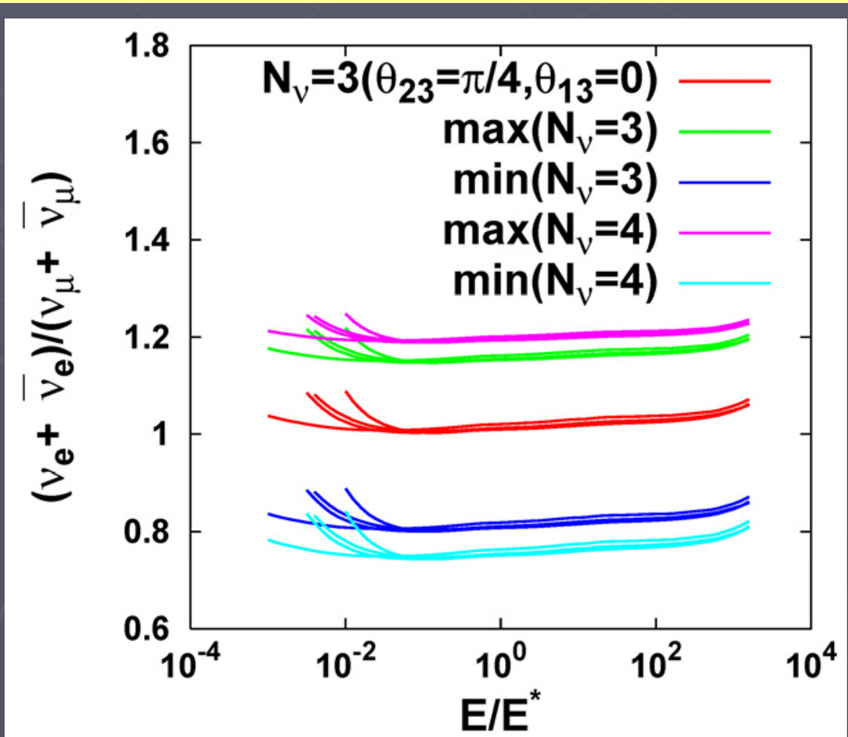
4 curves (energy dependence of p, γ) corresponding to uncertainties by Lipari et al.

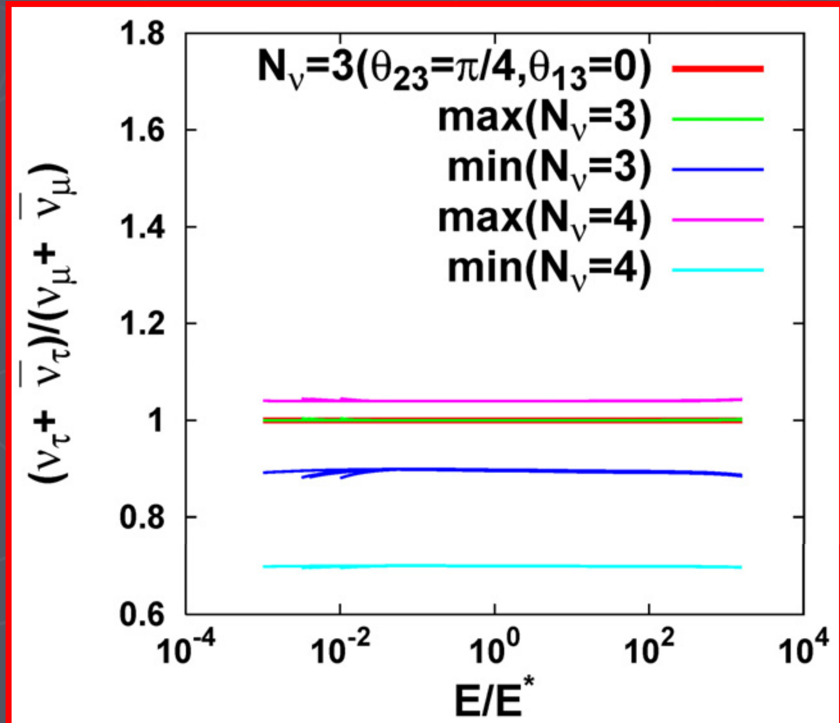


μ/τ ratio is less energy dependent

(to 1st order in small parameters)

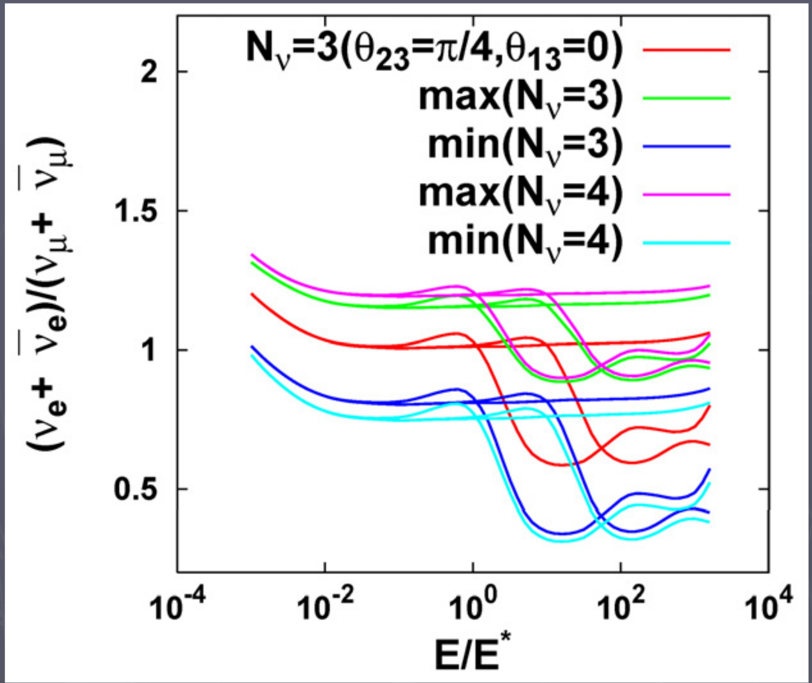
$$F(\nu_\tau)/F(\nu_\mu) = c_{34}^2 \geq 0.67$$

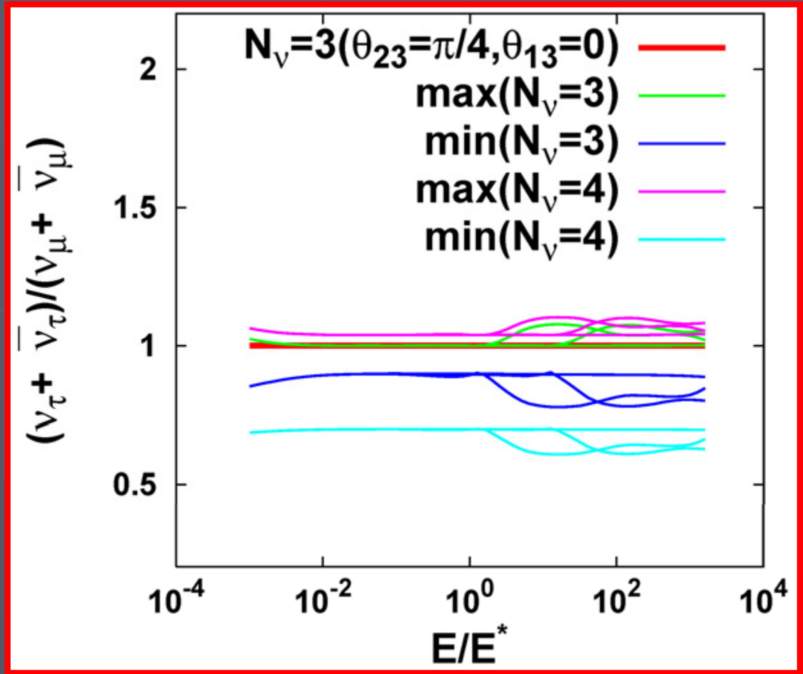




3 curves (muon enery loss) corresponding to uncertainties by Lipari et al.

Donini-OY '07





- **Energy dependence gives us hint on the uncertainties**
- **μ/τ ratio is less energy dependent**

$$F(\nu_\tau)/F(\nu_\mu) = c_{34}^2 \geq 0.67$$

(to 1st order in small parameters)

Statistics of expected events

For a typical galactic source, ten years of running at a km^3 water equivalent detector:

e, μ events ~ O(100)

τ events ~ O(30)

P. Lipari, astro-ph/0605535

$$N_e/N_\mu\ (N_\nu = 3) \simeq 1.0^{+0.14}_{-0.2}(\mathrm{osc})^{+0}_{-0.58}(\mu\ \mathrm{damp}) \pm 0.14(\mathrm{stat})$$
$$N_e/N_\mu\ (N_\nu = 4; \theta_{34} = 35°) \sim 0.75\ {}^{+0}_{-0.4}(\mu\ \mathrm{damp}) \pm 0.11(\mathrm{stat})$$
$$N_\tau/N_\mu\ (N_\nu = 3) \simeq 0.30^{+0}_{-0.03}(\mathrm{osc})^{+0}_{-0.02}(\mu\ \mathrm{damp}) \pm 0.08(\mathrm{stat})$$
$$N_\tau/N_\mu\ (N_\nu = 4; \theta_{34} = 35°) \sim 0.2\ {}^{+0}_{-0.01}(\mu\ \mathrm{damp}) \pm 0.06(\mathrm{stat})$$

μ/τ ratio suffers from theoretical uncertainty less than e/τ ratio, but statistics is not sufficient.

A possible way out:
To increase the detector volume in the future?

4.Conclusions

- (3+1)-scheme without LSND constraint predicts flavor ratio of HE cosmic ν which could be in principle distinguished from 3 flavor case.
- μ/τ ratio suffers relatively less from theoretical uncertainties, and could play an important role to look for signatures of sterile ν.
- Information from energy spectrum could be also important to check theoretical uncertainties.
- Statistics from one source is not sufficient to get signatures of sterile ν, but if we can increase the detector volume in the future, then we may be able to say something about sterile ν.

Backup slides

LSND($\bar{\nu}_\mu \to \bar{\nu}_e$): affirmative

MiniBOONE($\nu_\mu \to \nu_e$): negative

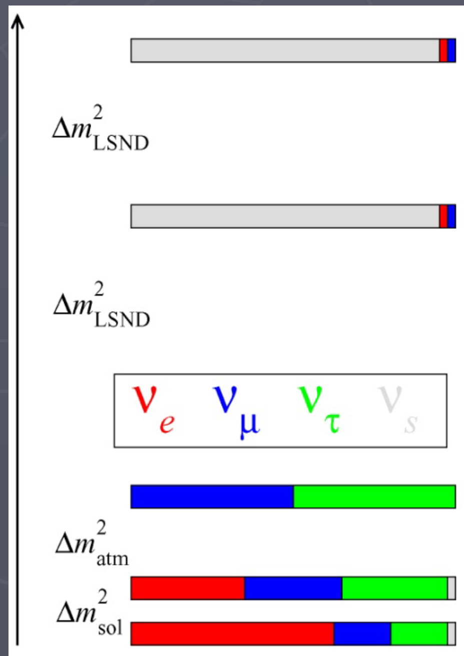
with one more ν_s difference between ν & anti-ν may offer a promising fit

(3+2)-scheme with CP phase δ

$$
\begin{aligned}
P_{\nu_\mu \to \nu_e} &= 4\,|U_{e4}|^2 |U_{\mu 4}|^2 \sin^2\phi_{41} \\
&+ 4\,|U_{e5}|^2 |U_{\mu 5}|^2 \sin^2\phi_{51} \\
&+ 8\,|U_{e4}U_{\mu 4}U_{e5}U_{\mu 5}| \sin\phi_{41} \sin\phi_{51} \cos(\phi_{54} - \delta)
\end{aligned}
$$

with the definitions

$$\phi_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E}, \qquad \delta \equiv \arg\left(U^*_{e4} U_{\mu 4} U_{e5} U^*_{\mu 5}\right).$$



Schwetz-Mangold@nufact07

$\phi_{54}^{best} = 1.64\,\pi$

$\Delta m^2_{41} = 0.89$ eV^2
$\Delta m^2_{51} = 6.49$ eV^2

$\chi^2_{\rm min} = 94.5/(107-7)$

Karagiorgi@nufact07

$\chi^2/ndf = 146.7/156$
gof=69%
$\phi_{54}^{best} = 1.74\,\pi$

- **(3+2)** schemes
  - offer the possiblity of CP violation to reconcile LSND and MiniBooNE,
  - but there is tension between appearance and disappearance data ($3\sigma, 4\sigma$ for MB300)

$\bar{\nu}_e \to \bar{\nu}_e$: Bugey | $\nu_\mu \to \nu_\mu$: CDHSW

So from the global fit, (3+2) is probably not a promising scheme…