Sterile neutrinos and near detectors at a neutrino factory

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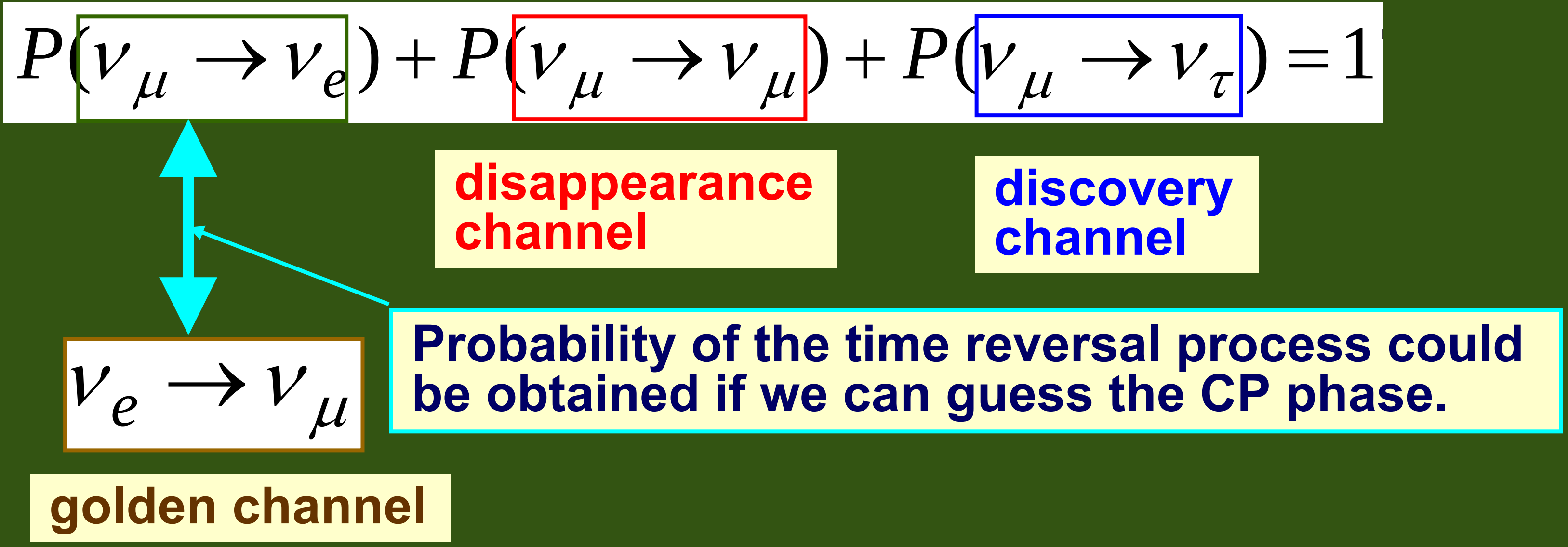
1. Introduction

Motivation for research on New Physics and τ detection

- Just like at B factories, high precision measurements of ν oscillation in future experiments will allow us to probe physics beyond SM by looking at deviation from SM+massive ν.
- If θ_{13} turns out to be large, search for new physics and test of unitarity will be even more important subjects at ν factory. (cf. $\sin^2\theta_{13}=0.02\pm0.01@1\sigma$, Fogli et al, arXiv:0905.3549 [hep-ph])

- If 3 flavor unitarity is guaranteed, then roughly speaking, we could guess (discovery) from (golden) + (disappearance) at ν factory from 3 flavor unitarity:



$$P(\boxed{\nu_\mu \to \nu_e}) + P(\boxed{\nu_\mu \to \nu_\mu}) + P(\boxed{\nu_\mu \to \nu_\tau}) = 1$$

disappearance channel

discovery channel

$$\boxed{\nu_e \to \nu_\mu}$$

golden channel

Probability of the time reversal process could be obtained if we can guess the CP phase.

- Intuitively, therefore, τ detection is supposed to be important to test New Physics which violates unitarity.

→ Quantitative estimate is necessary to draw conclusions.

New physics which can be probed at a neutrino factory includes:

- Non standard interactions in propagation
- Non standard interactions at production / detection
- Violation of unitarity due to heavy particles
- Schemes with light sterile neutrinos

$$\sum_{\beta=e,\mu,\tau} P(\nu_\alpha \to \nu_\beta) = 1$$

Scenarios	3 flavor unitarity
NSI in propagation	✓
NSI at production / detection	✗
Violation of unitarity due to heavy particles	✗
Light sterile neutrinos	✗

Scenarios	Phenomenological bound on deviation of unitarity
NSI at production / detection	O(0.1%)
Violation of unitarity due to heavy particles	O(0.1%)
Light sterile neutrinos	O(10%)

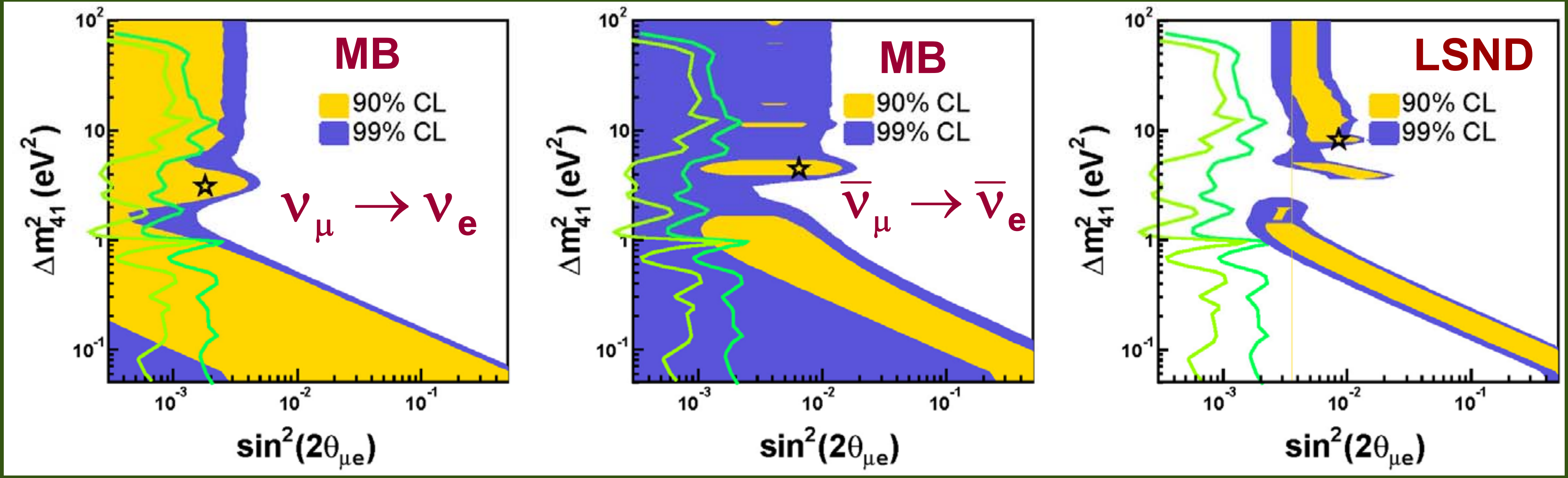
◆ (Except sterile ν) none of these scenarios has ever been supported experimentally.

◆ To encourage experimentalists, one should adopt the most optimistic scenario.

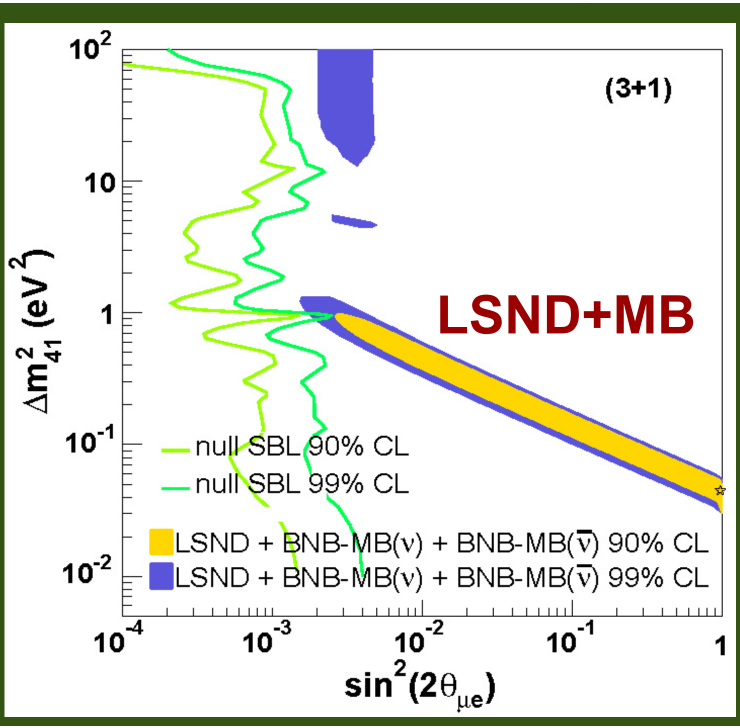
→ Even if LSND anomaly is excluded in the near future, light sterile ν could be phenomenologically even more promising than others!

Recent status of LSND: Check by MiniBooNE

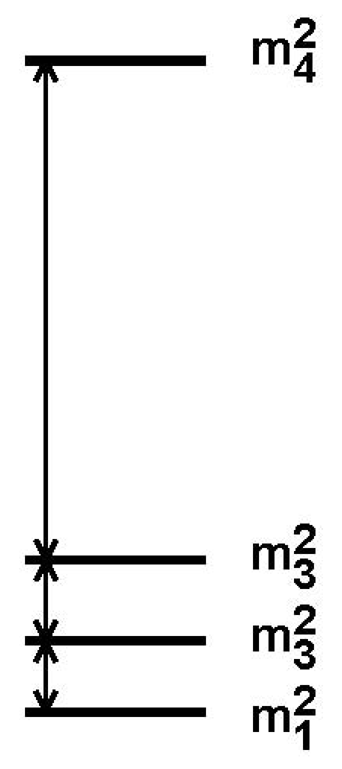
Karagiorgi et al,
Phys.Rev.D80:073001,2009



- **Neither MiniBooNE (ν or $\bar{\nu}$) nor disappearance results (CDHSW+Bugey+atm) excludes LSND at 4σ.**



2. Light sterile neutrinos



(3+1)-scheme w/ LSND: the situation is unclear, but it's worth checking it

(3+1)-scheme w/o LSND: still a possible scenario, provided that the mixing angles satisfy all the constraints of the negative results

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

$$U = R_{34}(\theta_{34},\, 0)\; R_{24}(\theta_{24},\, 0)\; R_{23}(\theta_{23},\, \delta_3)\; R_{14}(\theta_{14},\, 0)\; R_{13}(\theta_{13},\, \delta_2)\; R_{12}(\theta_{12},\, \delta_1)$$

θ_{34} : ratio of $\nu_\mu \leftrightarrow \nu_\tau$ and $\nu_\mu \leftrightarrow \nu_s$ in ν_{atm}

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

θ_{14} : mixing angle in ν_{reactor} at L=O(10m)

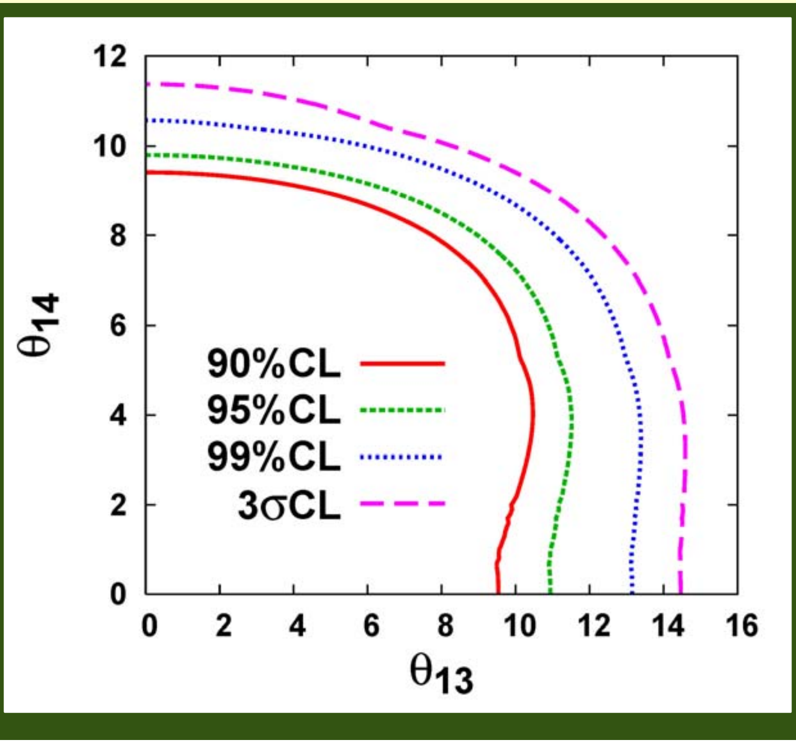
Constraints from ν_{atm} and SBL

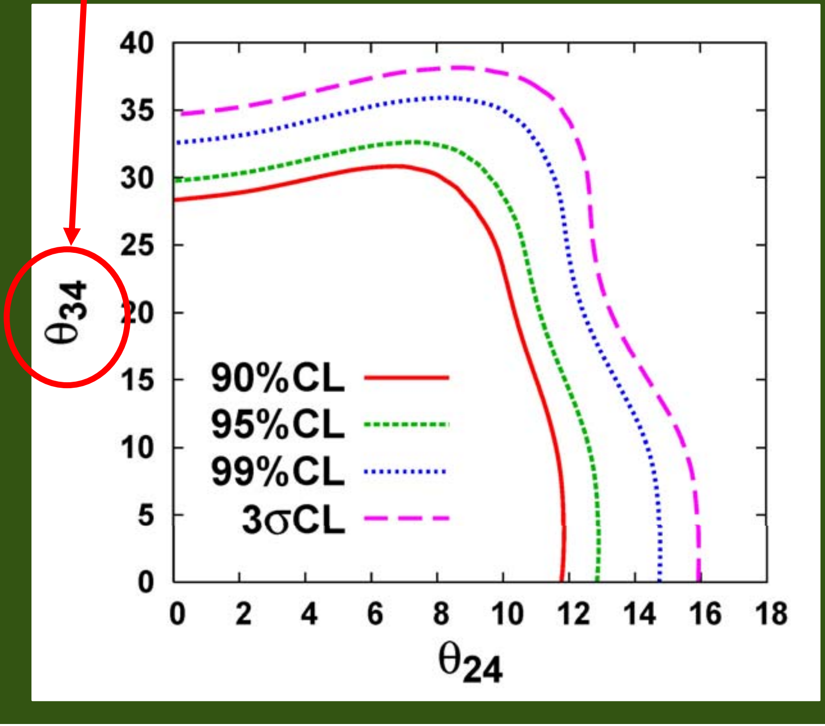
Donini-Maltoni-Meloni-Migliozzi-Terranova, JHEP 0712:013,'07

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

Assumption on rapid oscillations in ν_{atm}: $\Delta m^2_{41} > 0.1\ \mathrm{eV}^2$

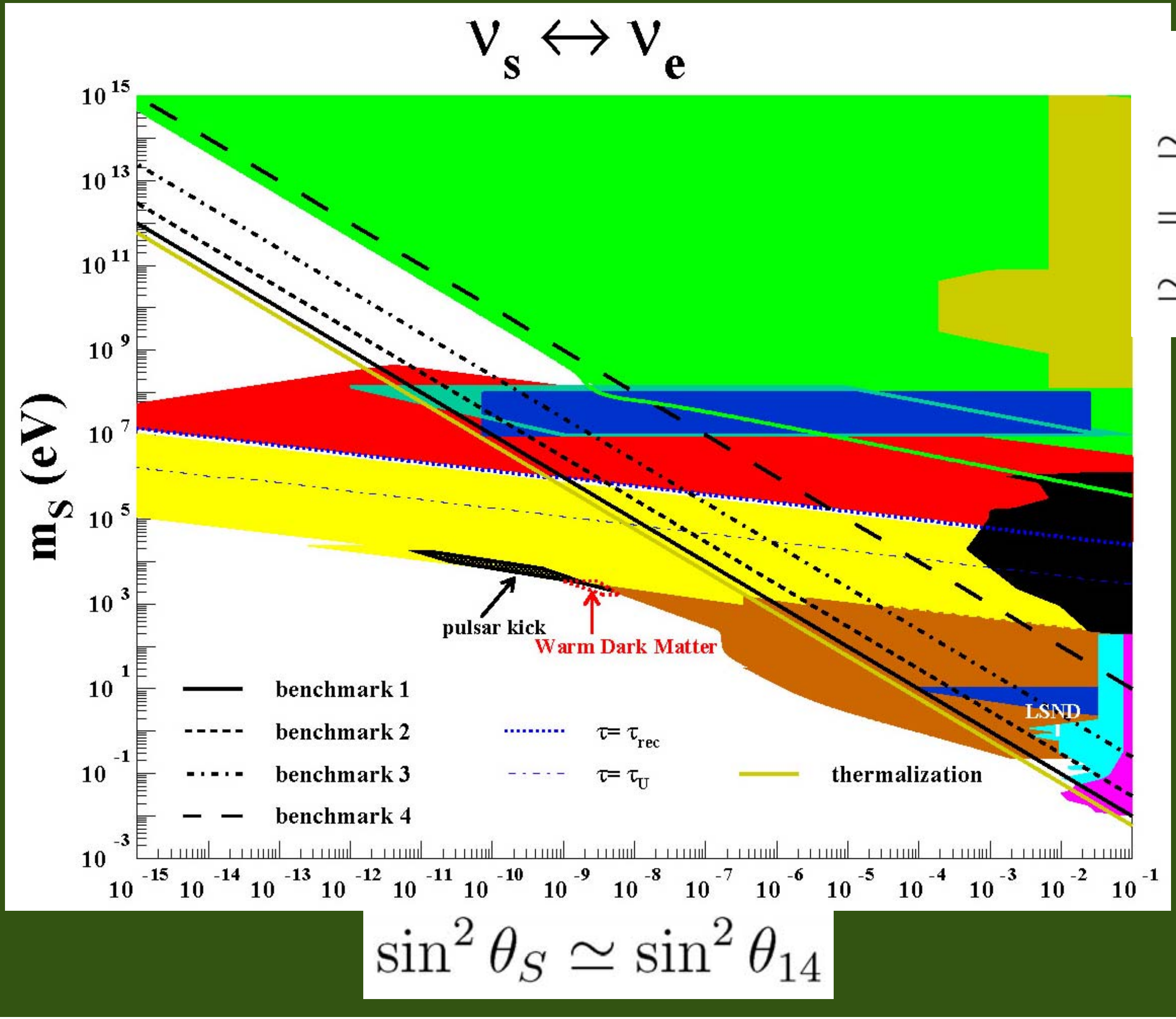
θ_{34} : could be relatively large





Cosmological constraints on light sterile neutrinos (s⇔e)

Smirnov & Zukanovich -Funchal, Phys.Rev.D74:013001,2006



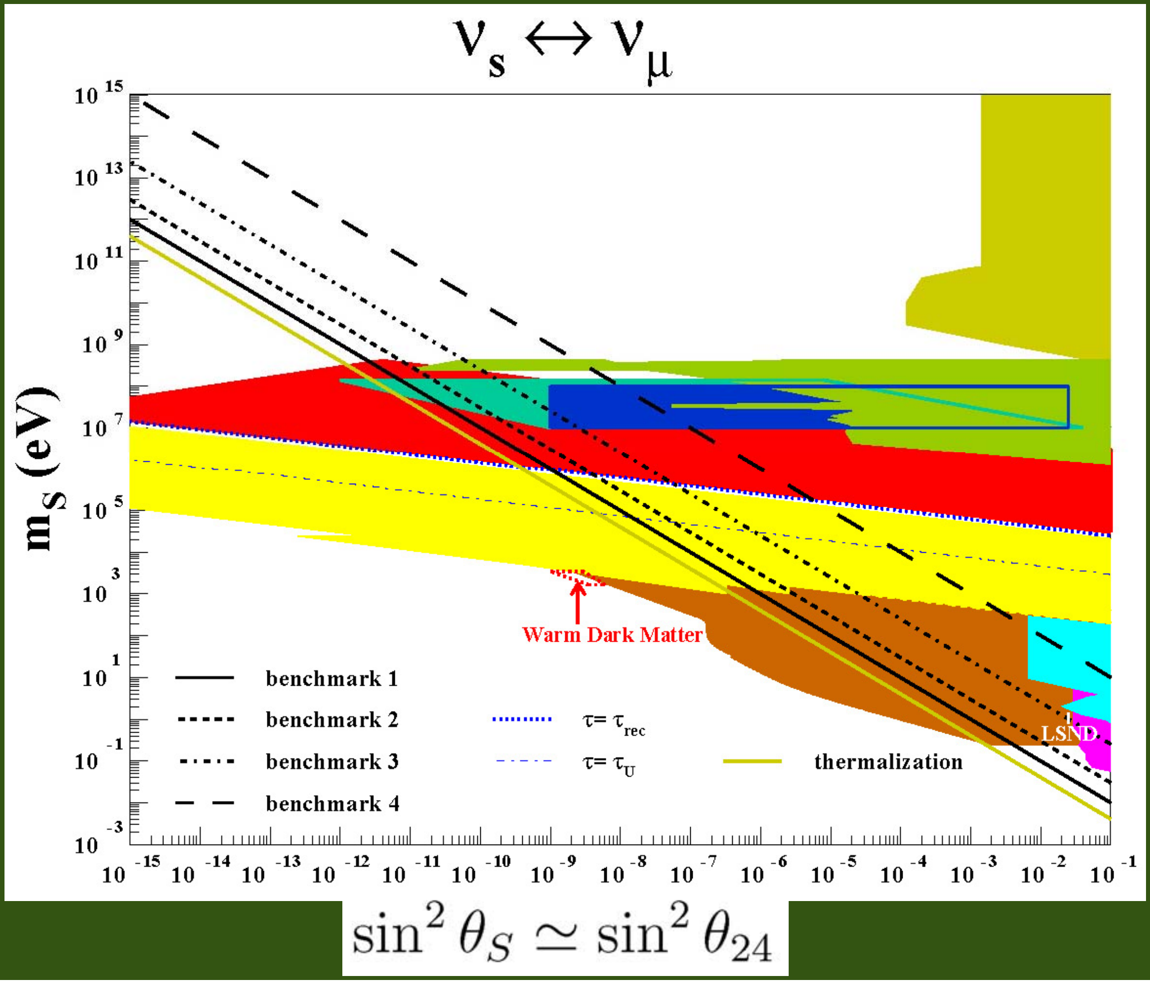
$$
\begin{aligned}
& P(\nu_e \to \nu_s) \\
\simeq \; & 4|U_{e4}U_{s4}|^2 \sin^2(\Delta m_{41}^2 L/4E) \\
= \; & c_{24}^2 c_{34}^2 \sin^2 2\theta_{14} \sin^2(\Delta m_{41}^2 L/4E) \\
\simeq \; & \sin^2 2\theta_{14} \sin^2(\Delta m_{41}^2 L/4E)
\end{aligned}
$$

- 🟩 0νββ
- 🟫 LSS
- 🟨 X-ray
- ▨ BBN
- 🟥 CMB

- 🟦 SN1987A
- ⬛ β-decay
- 🟨 Accelerator
- 🟪 Atmospheric
- ▨ Reac.+Beam

Cosmological constraints on light sterile neutrinos (s⇔μ)

Smirnov & Zukanovich -Funchal, Phys.Rev.D74:013001,2006



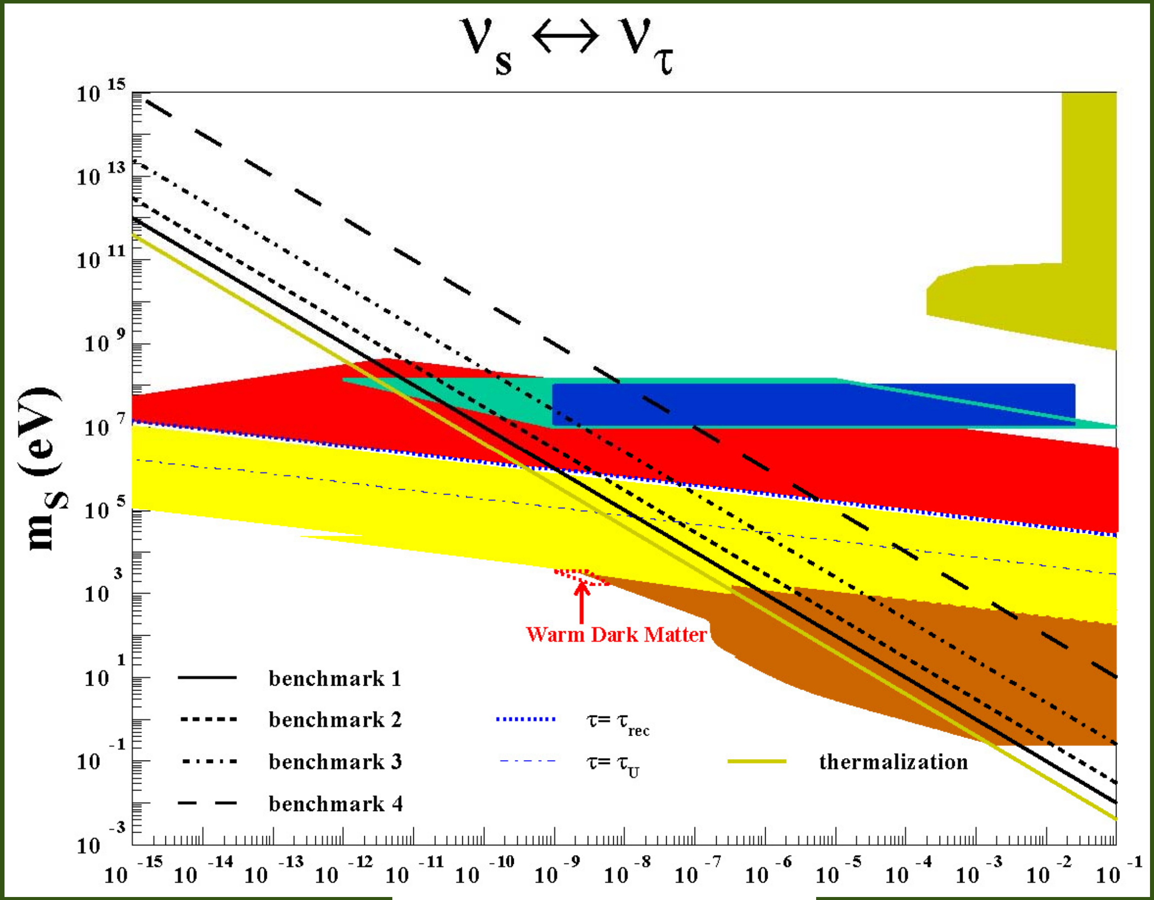
$$
\begin{aligned}
& P(\nu_\mu \to \nu_s) \\
\simeq \;& 4|U_{\mu 4}U_{s4}|^2 \sin^2(\Delta m_{41}^2 L/4E) \\
= \;& c_{14}^4 c_{34}^2 \sin^2 2\theta_{24} \sin^2(\Delta m_{41}^2 L/4E) \\
\simeq \;& \sin^2 2\theta_{24} \sin^2(\Delta m_{41}^2 L/4E)
\end{aligned}
$$

🟫 **LSS**
🟨 **X-ray**
🟩 **BBN**
🟥 **CMB**

🟦 **SN1987A**
🟨 **Accelerator**
🟩 **Decays**
🟪 **Atmospheric**
🟦 **Beam**

Cosmological constraints on light sterile neutrinos (s⇔τ)

Smirnov & Zukanovich -Funchal, Phys.Rev.D74:013001,2006



$$\sin^2\theta_S \simeq \sin^2\theta_{34}$$

$$\begin{aligned} & P(\nu_\tau \to \nu_s) \\ \simeq\ & 4|U_{\tau 4}U_{s4}|^2 \sin^2(\Delta m^2_{41} L/4E) \\ =\ & c^4_{24} \sin^2 2\theta_{34} \sin^2(\Delta m^2_{41} L/4E) \\ \simeq\ & \sin^2 2\theta_{34} \sin^2(\Delta m^2_{41} L/4E) \end{aligned}$$

🟧 LSS
🟨 X-ray
🟩 BBN
🟥 CMB

🟦 SN1987A
🟨 Accelerator

NB: Constraints from LSS, X-ray, BBN, CMB may be avoided if some suppression mechanism (e.g., lepton asymmetry) exists

In that case

θ_{14} : major constraints from ν_{atm} & SBL

for Δm^2_{41} : <10^5 eV^2

θ_{24}, θ_{34} : major constraints from ν_{atm} & SBL

for Δm^2_{41} : <10^{14} eV^2

Hence there may be some room for sterile neutrino mixings for these values of Δm^2_{41}.

3. Sensitivity to θ_{14}, θ_{24}, θ_{34} at ν factory with a near detector

Donini, Meloni, Eur.Phys.J.C22:179-186,2001

2×10^{20} μ^- ‘s/yr × 5 yrs, E_μ = 20GeV

10kton MIND @ L = 40 Km + 1ton ECC @ L = 1 Km

efficiency=0.5 for μ, 0.35 for τ

statistical errors + BG (w/o systematic errors)

golden

$$P(\nu_e \to \nu_\mu) \;=\; 4c_{24}^2 c_{34}^4 s_{14}^2 s_{24}^2 \,\sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

sensitivity to $s^2_{14}\, s^2_{24}$

silver

$$P(\nu_e \to \nu_\tau) \;=\; 4c_{24}^2 c_{34}^2 s_{14}^2 s_{34}^2 \,\sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

sensitivity to $s^2_{14}\, s^2_{34}$

discovery

$$P(\nu_\mu \to \nu_\tau) \;=\; 4c_{34}^2 s_{24}^2 s_{34}^2 \,\sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

sensitivity to $s^2_{24}\, s^2_{34}$

disappearance

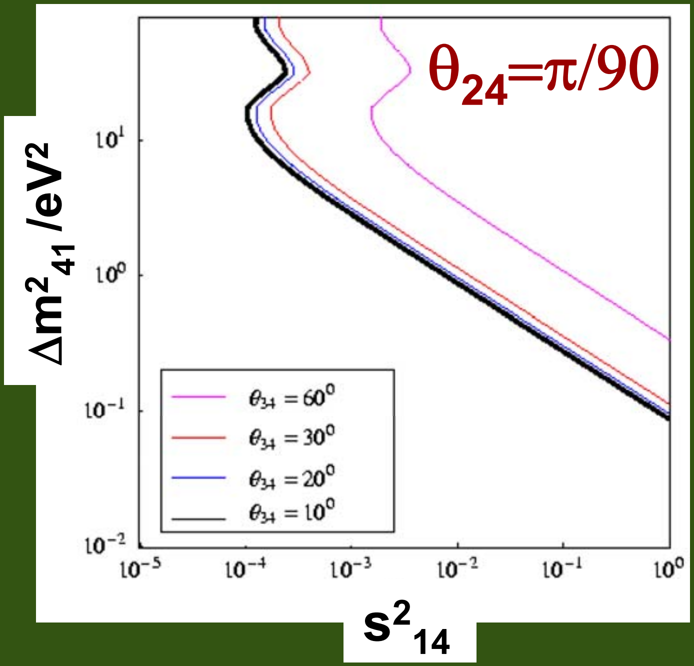
$$P(\nu_\mu \to \nu_\mu) \;=\; 1 - 4c_{34}^2 s_{24}^2 (1 - c_{34}^2 s_{24}^2) \,\sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

sensitivity to s^2_{24}

Donini, Meloni, Eur.Phys.J.C22:179-186,2001

golden

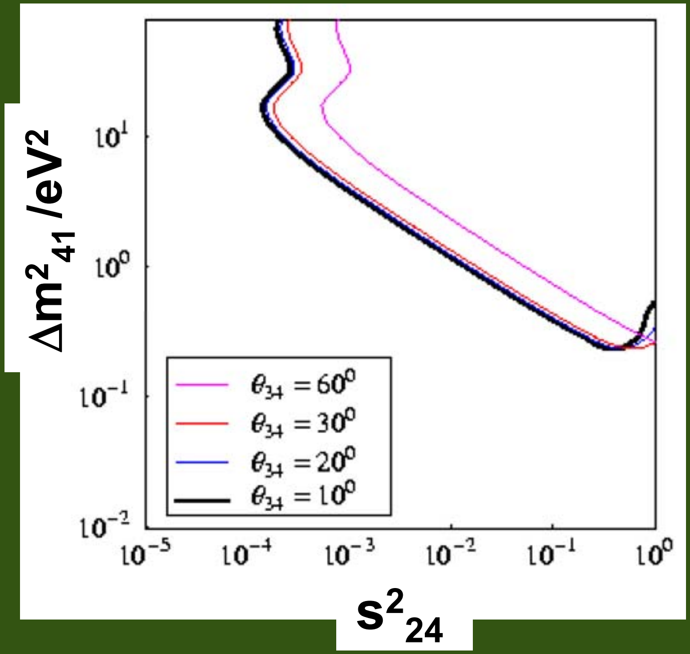
$$P(\nu_e \to \nu_\mu) \;=\; 4c_{24}^2 c_{34}^4 s_{14}^2 s_{24}^2 \,\sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$



$4|U_{e4}U_{\mu4}|^2 > 1.4\text{x}10^{-7}$

disappearance

$$\begin{aligned} &P(\nu_\mu \to \nu_\mu) \\ &= \; 1 - 4c_{34}^2 s_{24}^2 (1 - c_{34}^2 s_{24}^2) \,\sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right) \end{aligned}$$



$4|U_{\mu4}|^2 > 5.3\text{x}10^{-4}$

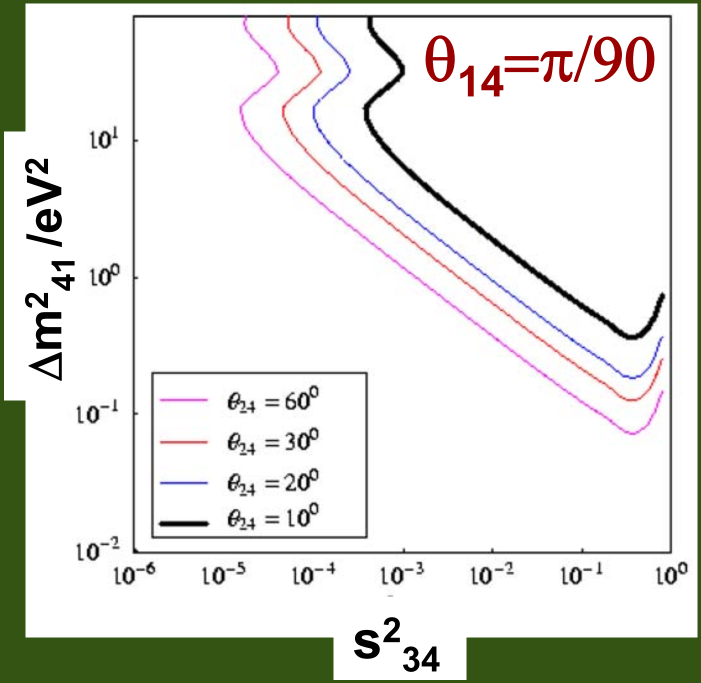
Donini, Meloni, Eur.Phys.J.C22:179-186,2001

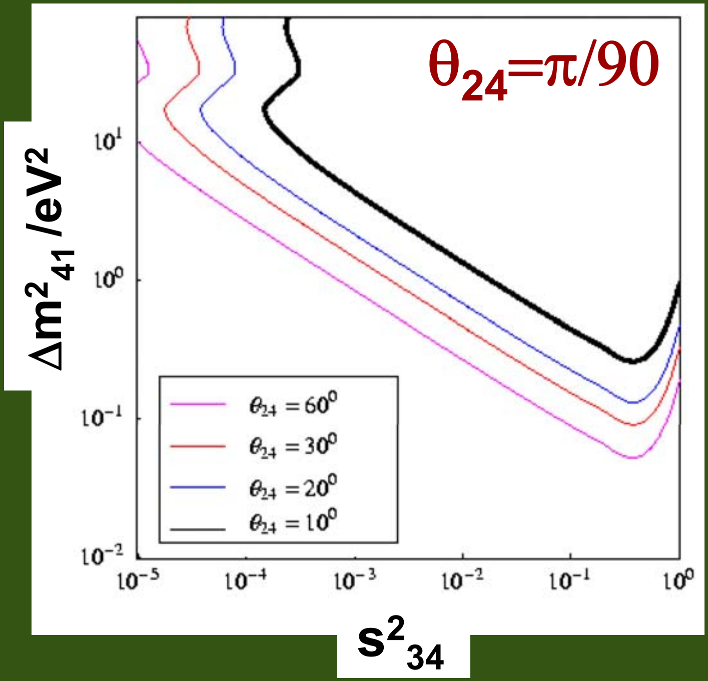
silver

discovery

$$P(\nu_e \to \nu_\tau) = 4c_{24}^2 c_{34}^2 s_{14}^2 s_{34}^2 \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

$$P(\nu_\mu \to \nu_\tau) = 4c_{34}^2 s_{24}^2 s_{34}^2 \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$





$4|U_{e4}U_{\tau4}|^2 > 4.8\text{x}10^{-5}$

$4|U_{\mu4}U_{\tau4}|^2 > 1.8\text{x}10^{-5}$

4. Sensitivity to θ_{14}, θ_{24}, θ_{34} at ν factory with far detectors

Donini et al, JHEP 0908:041,2009

5×10^{20} $\mu^-+\mu^+$'s/yr × 4 yrs
(E_μ/GeV, L/km)= (50,3000+7500) or (20, 4000+7500)
50kton MIND + 4kton MECC

Results for E_μ=20GeV case are shown below for a fair comparison

statistical errors + systematic errors + BG

efficiency ∼ 0.7 for μ, ∼0.65 for τ

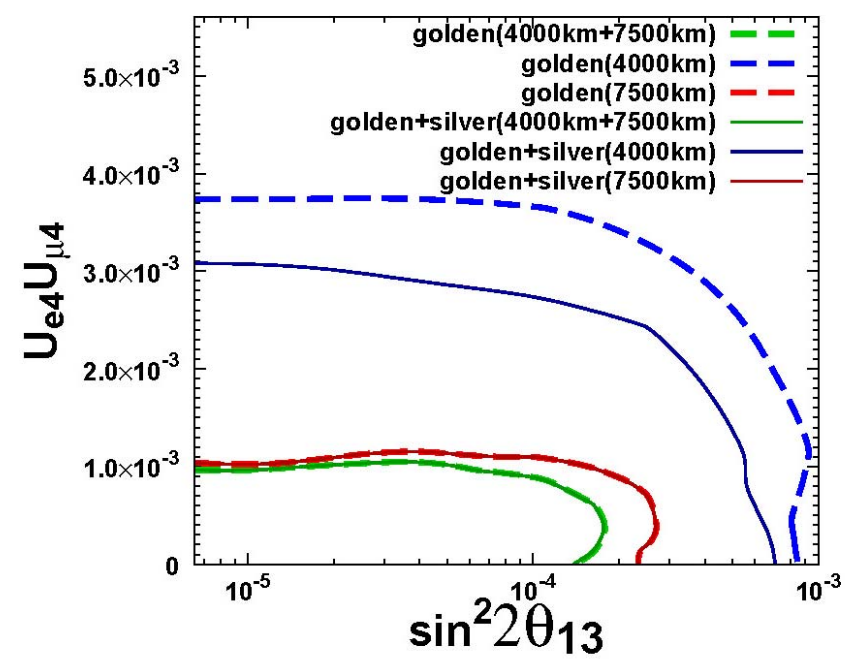
NB. Magnetized Emulsion Cloud Chamber (MECC)
active target: iron
$\tau\to\mu$ decay + $\tau\to e$ decay + $\tau\to$hadron decay are used

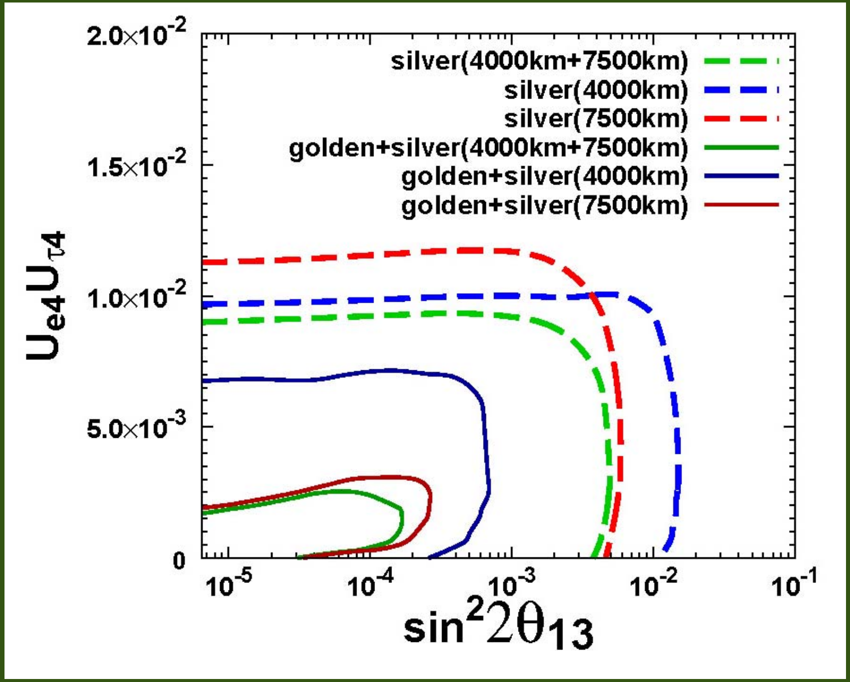
golden + silver

Donini et al, JHEP 0908:041,2009

$$P(\nu_e \to \nu_\mu) = 4\mathrm{Re}\left[U_{e3}U^*_{\mu 3}(U^*_{e3}U_{\mu 3} + \boxed{U^*_{e4}U_{\mu 4}})\right] \sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) + \cdots$$

$$P(\nu_e \to \nu_\tau) = 4\mathrm{Re}\left[U_{e3}U^*_{\tau 3}(U^*_{e3}U_{\tau 3} + \boxed{U^*_{e4}U_{\tau 4}})\right] \sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) + \cdots$$





$4|U_{e4}U_{\mu 4}|^2 > 5.8\times10^{-6}$

$4|U_{e4}U_{\tau 4}|^2 > 3.8\times10^{-5}$

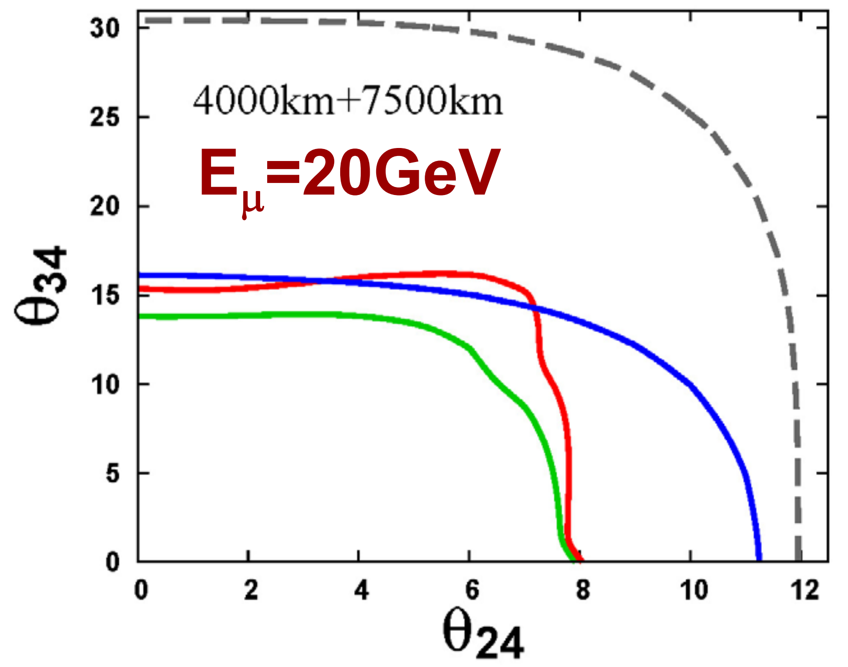
disappearance + discovery

Donini et al, JHEP 0908:041,2009

$$P(\nu_\mu \to \nu_\mu) = 1 - 4|U_{\mu 3}|^2(1 - |U_{\mu 3}|^2 - \boxed{|U_{\mu 4}|^2}) \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + \cdots$$

$$P(\nu_\mu \to \nu_\tau) = 4\mathrm{Re}\left[U_{\mu 3}U^*_{\tau 3}(U^*_{\mu 3}U_{\tau 3} + \boxed{U^*_{\mu 4}U_{\tau 4}})\right] \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + \cdots$$

--- current — disappearance — discovery — combined



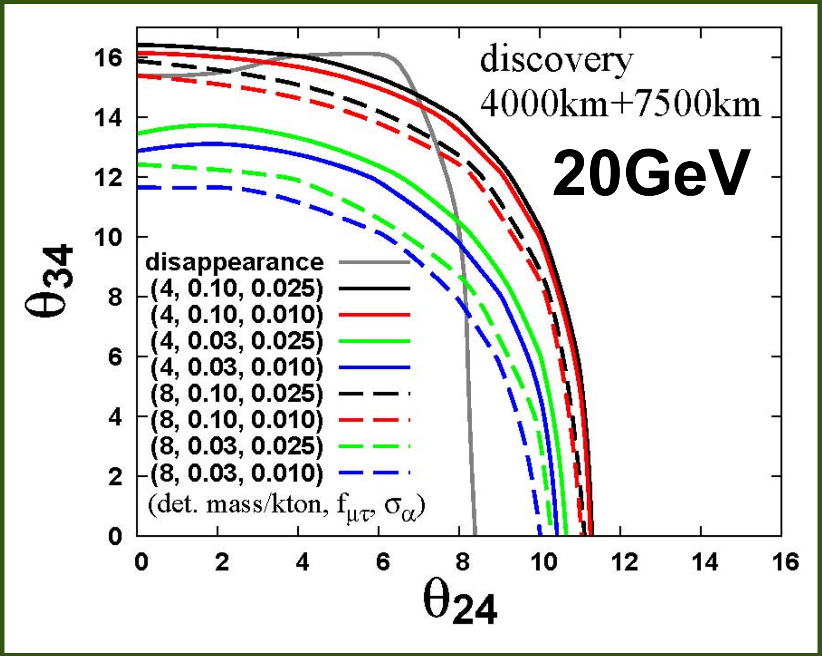
$4|U_{\mu 4}|^2 > 7.6\mathrm{x}10^{-2}$

$4|U_{\mu 4}U_{\tau 4}|^2 > 1.9\mathrm{x}10^{-3}$

- **Byproduct of the near detectors: improvement of systematic errors at far detectors**

Dependence of sensitivity on systematic errors

Donini et al, JHEP 0908:041,2009



In previous page, $f_{\mu\tau}$=10%, σ_α=2.5% (black solid lines above) was assumed

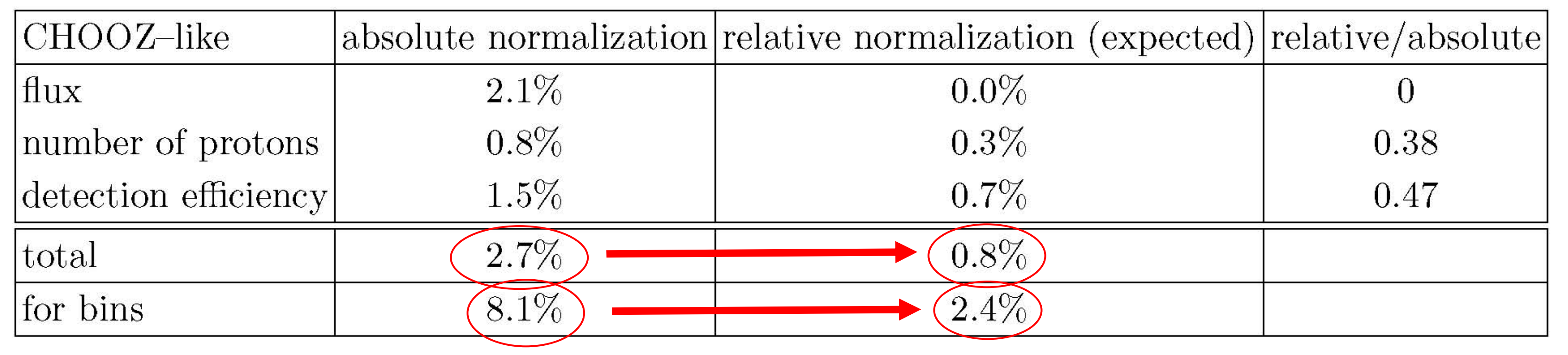
$f_{\mu\tau}$: uncorrelated bin-to-bin systematic error (error in detection efficiency in each bin etc.)

σ_α : correlated systematic error (error in detector volume etc.)

By placing a near τ detector, systematic errors could be reduced

cf. Reduction of systematic errors in the 2 detector complex at reactor experiments

**Minakata et al.,
Phys.Rev.D68:033017,2003**



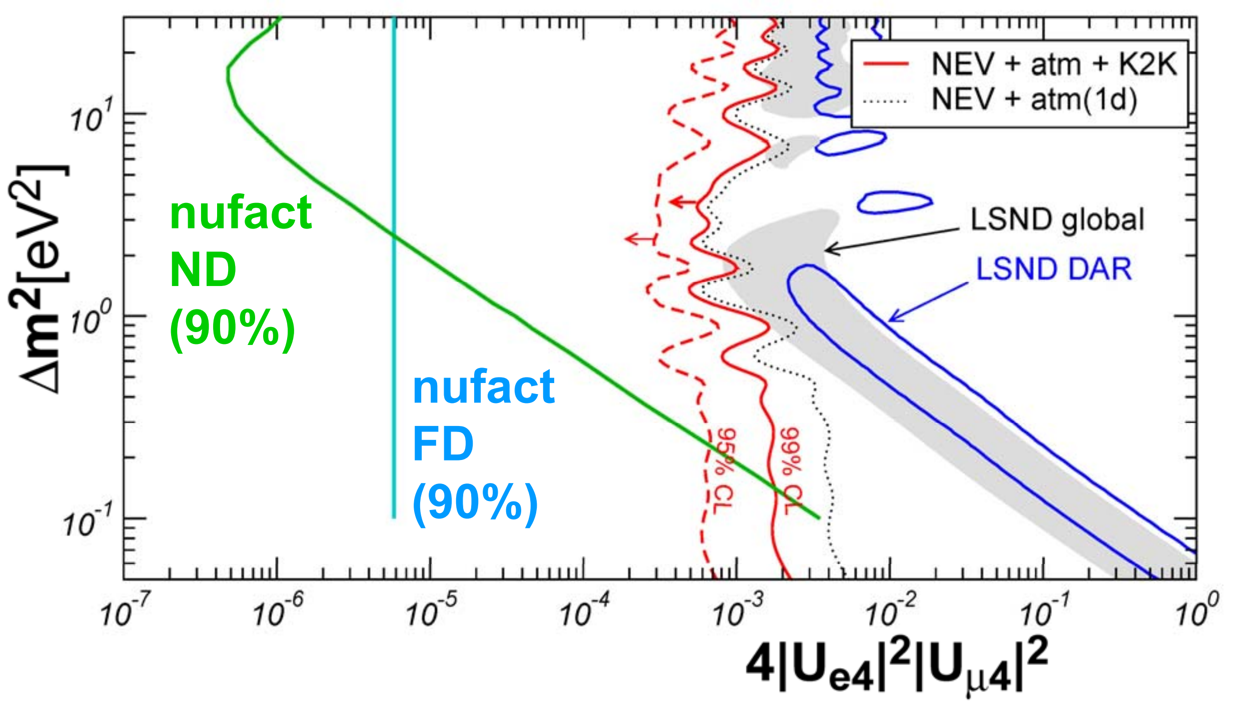
CHOOZ–like	absolute normalization	relative normalization (expected)	relative/absolute
flux	2.1%	0.0%	0
number of protons	0.8%	0.3%	0.38
detection efficiency	1.5%	0.7%	0.47
total	2.7%	0.8%	
for bins	8.1%	2.4%	

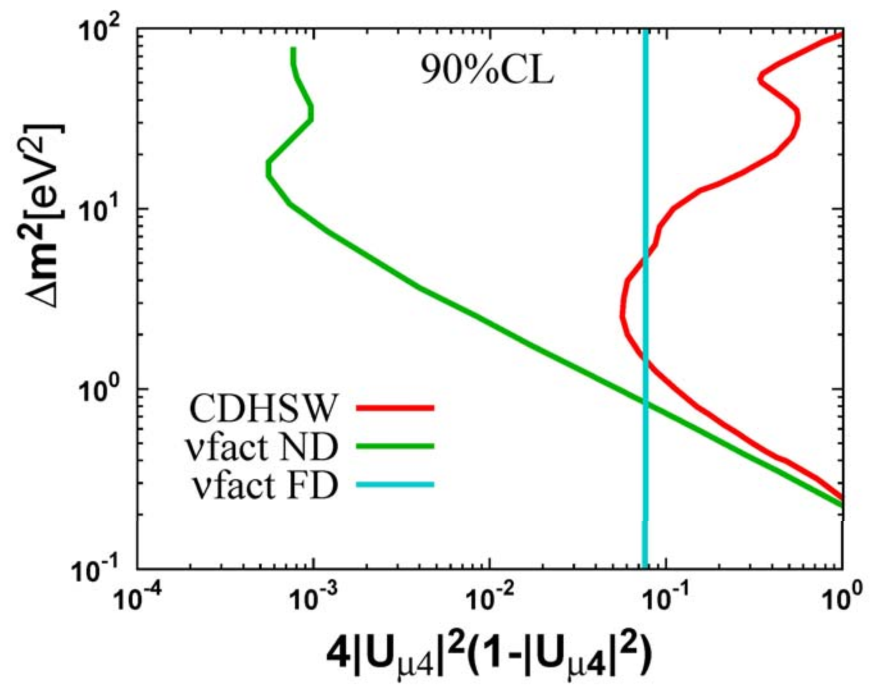
2.6 Summary

- In most cases sensitivity to the sterile mixings is better at a near detector (@Oscillation Maximum) than at far detectors. (Notice the absence of the systematic errors in the analysis of ND. → Further study is necessary.)

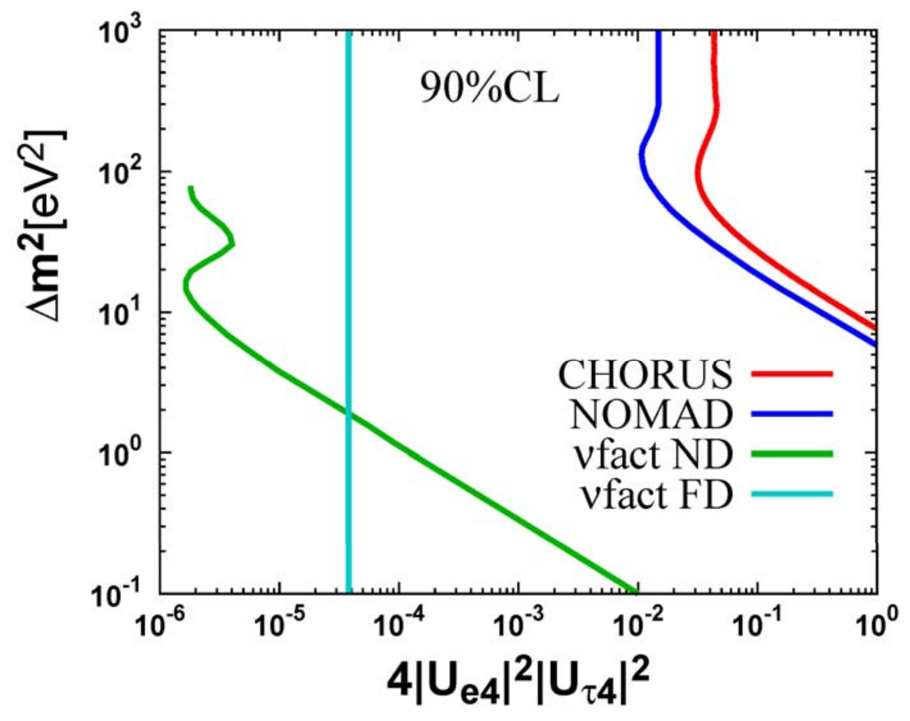
	near@Osc.Max	far
$4\lvert U_{e4}U_{\mu 4}\rvert^2$	$1.4\mathrm{x}10^{-7}$	$5.8\mathrm{x}10^{-6}$
$4\lvert U_{e4}U_{\tau 4}\rvert^2$	$4.8\mathrm{x}10^{-5}$	$3.8\mathrm{x}10^{-5}$
$4\lvert U_{\mu 4}\rvert^2$	$5.3\mathrm{x}10^{-4}$	$7.6\mathrm{x}10^{-2}$
$4\lvert U_{\mu 4}U_{\tau 4}\rvert^2$	$1.8\mathrm{x}10^{-5}$	$1.9\mathrm{x}10^{-3}$

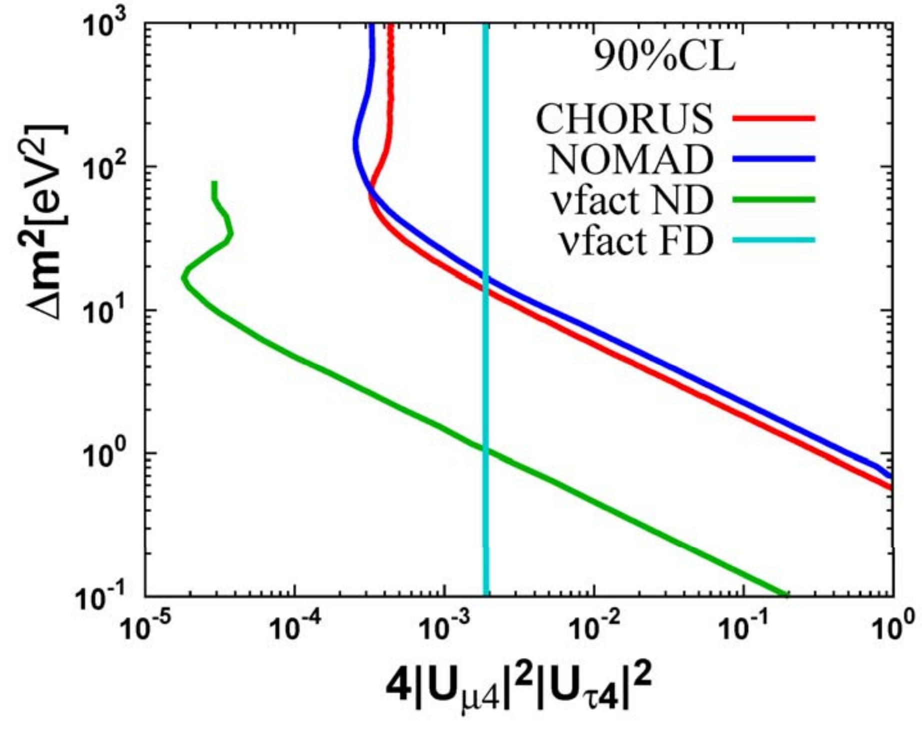
Sensitivity to the sterile mixings at ND & FD is very good compared to the present bound.
→ It could serve as a severe test of LSND/MiniBooNE.





- **Sensitivity to $4|U_{e4}U_{\tau4}|^2$ & $4|U_{\mu4}U_{\tau4}|^2$: improvement over the present bound by one order of magnitude**





- Sensitivity to Δm^2_{41} :

  FD: insensitive

  ND: sensitive but some fine tuning required

→ ND & very near detector are necessary.

→ To cover the region $\Delta m^2_{41} \sim O(1\text{eV}^2)$, L ~O(10km)

- To measure the new CP phase due to sterile neutrinos, discovery channel at far detectors is crucial. → ND & FD are complementary in the study of sterile neutrinos at a ν factory.

- Near τ detectors are useful not only to improve sensitivity to sterile neutrino mixings by themselves, but also to reduce the systematic errors of the far τ detectors.

In answering Belen's questions on τ-ND (1)

- Is it worth the trouble to develop such a "tau-sensitive" detector?

  Yes, since it doesn't cost much, it's worth putting a tau ND.
- Is it doable?

  The analysis on ND has to be done again, but presumably it is.
- How good results one can get?

  We can improve sensitivity to $4|U_{e4}U_{\mu4}|^2$ ($4|U_{e4}U_{\tau4}|^2$, $4|U_{\mu4}U_{\tau4}|^2$) by 2 (4, 1) orders of magnitude.
- If we only improve a limit - will anybody care?

  At least I do. The neutrino factory would give a limit independent of cosmology.

  As for $4|U_{e4}U_{\mu4}|^2$, by putting a MIND, we can exclude LSND by 4 orders of magnitude. Presumably it is possible only with a neutrino factory.

In answering Belen's questions on τ-ND (2)

- For instance, for your chosen physics goal or subject, what sensitivity would be required to be worth physics-wise? eμ: Both ND & FD w/ assumed σ_{sys} will test LSND. eτ or $\mu\tau$: W/o particular physics model, typically improvement by one order of magnitude is one goal.
- And what are the optimal characteristics of the detector? MECC seem to be the best so far as a τ detector to have better efficiency.
- How does it compare with respect to physics reach with other future planned detectors? Complementarity? Liquid argon TPC could be alternative. → Further study is required.
- For what other beams is it appropriate or possible?
  Superbeam: ν_τ contamination
  β beam: Energy is too low to produce τ .

Backup slides

- τ detection is potentially advantage of ν factory:

- Detection of large number of τ's is possible at ν factory
- No ν_τ contamination at a neutrino factory (cf. super-beam, [Van de Vyver-Zucchelli, NIM A385:91,1997])

- τ channels in 3 family model are not so useful:

- (golden) @4000km+7500km is better than (silver)+(golden) @4000km to solve intrinsic degeneracy [ISS report]
- (disappearance) is better than (discovery) to measure atmospheric parameters [Donini, 0th IDS mtg@CERN]

$\nu_e \rightarrow \nu_\mu$ golden channel

$\nu_\mu \rightarrow \nu_\mu$ disappearance channel

$\nu_e \rightarrow \nu_\tau$ silver channel

$\nu_\mu \rightarrow \nu_\tau$ discovery channel

τ detectors

- **Emulsion Cloud Chamber (ECC)**

  Prototype: the OPERA detector at the CNGS
  active target: lead
  spectrometers to measure the charge
  only τ→μ decay is used: detection efficiency∼O(5%)

→Proposal of Magnetized Emulsion Cloud Chamber (MECC)

active target: iron
τ→μ decay + τ→e decay + τ→hadron decay are used:

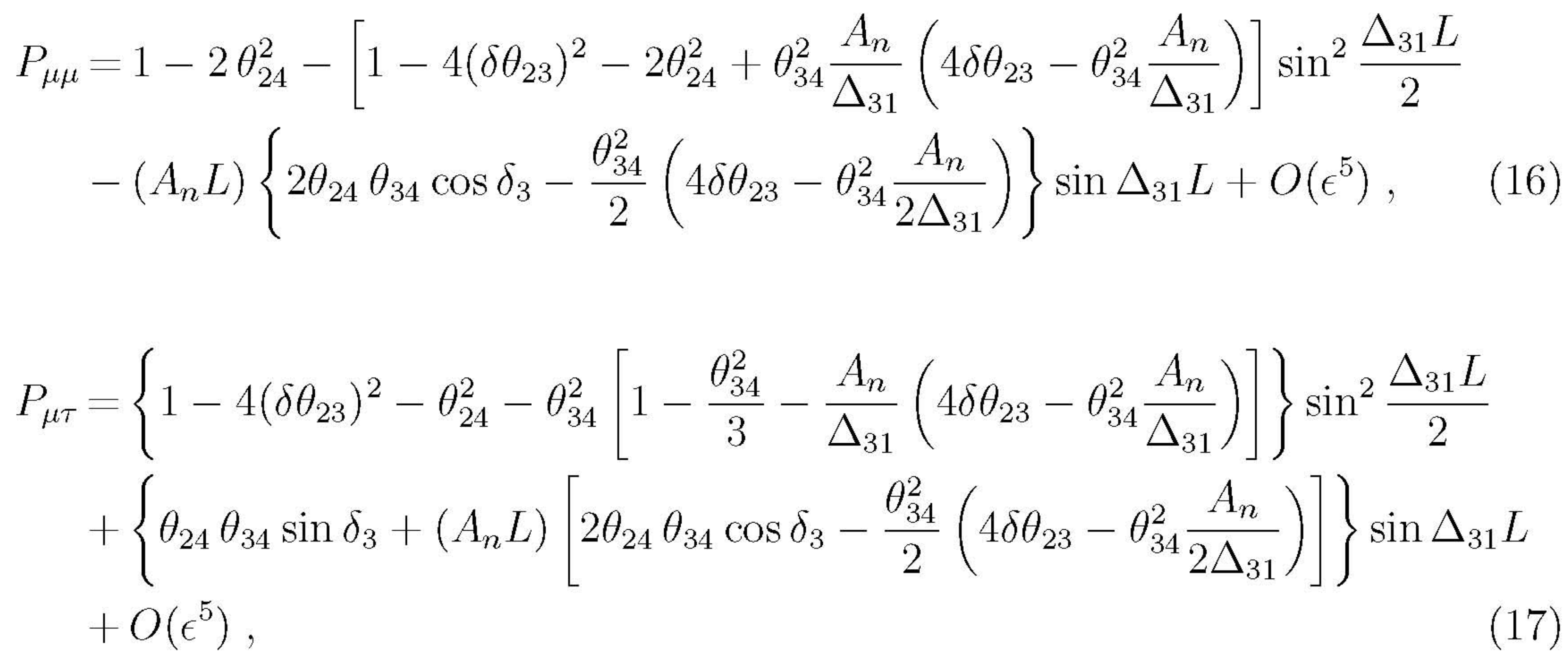
detection efficiency∼O(25%)

- **Liquid Argon TPC (LAr-TPC)**

  Prototype: the ICARUS T600 at the CNGS

Oscillation probability in (3+1)-scheme

Donini, Fuki, Lopez-Pavon, Meloni, Yasuda, JHEP 0908:041,2009

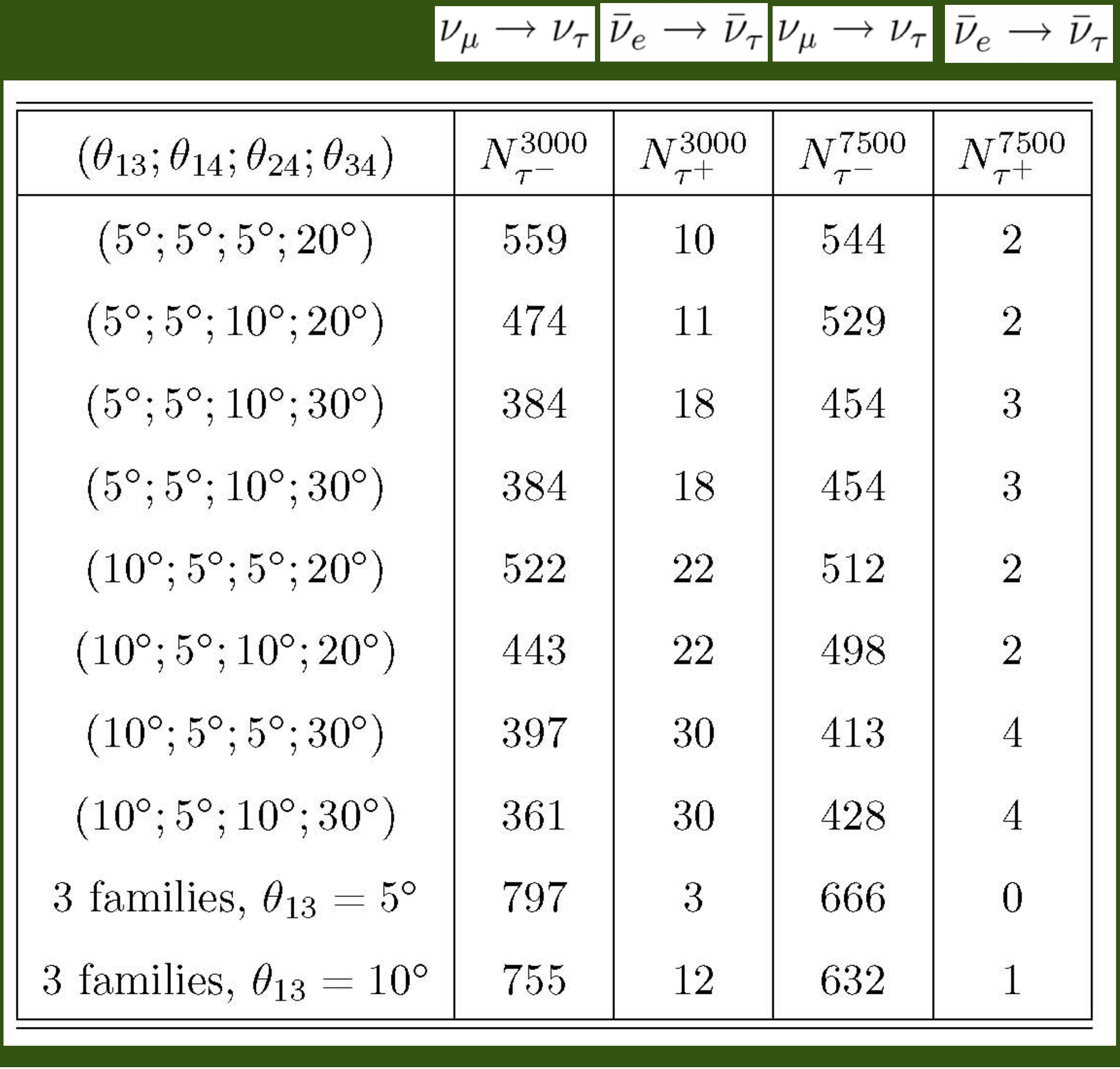


$$\begin{aligned} P_{\mu\mu} = {} & 1 - 2\,\theta_{24}^2 - \left[1 - 4(\delta\theta_{23})^2 - 2\theta_{24}^2 + \theta_{34}^2\frac{A_n}{\Delta_{31}}\left(4\delta\theta_{23} - \theta_{34}^2\frac{A_n}{\Delta_{31}}\right)\right]\sin^2\frac{\Delta_{31}L}{2} \\ & - (A_nL)\left\{2\theta_{24}\,\theta_{34}\cos\delta_3 - \frac{\theta_{34}^2}{2}\left(4\delta\theta_{23} - \theta_{34}^2\frac{A_n}{2\Delta_{31}}\right)\right\}\sin\Delta_{31}L + O(\epsilon^5)\ , \end{aligned} \tag{16}$$

$$\begin{aligned} P_{\mu\tau} = {} & \left\{1 - 4(\delta\theta_{23})^2 - \theta_{24}^2 - \theta_{34}^2\left[1 - \frac{\theta_{34}^2}{3} - \frac{A_n}{\Delta_{31}}\left(4\delta\theta_{23} - \theta_{34}^2\frac{A_n}{\Delta_{31}}\right)\right]\right\}\sin^2\frac{\Delta_{31}L}{2} \\ & + \left\{\theta_{24}\,\theta_{34}\sin\delta_3 + (A_nL)\left[2\theta_{24}\,\theta_{34}\cos\delta_3 - \frac{\theta_{34}^2}{2}\left(4\delta\theta_{23} - \theta_{34}^2\frac{A_n}{2\Delta_{31}}\right)\right]\right\}\sin\Delta_{31}L \\ & + O(\epsilon^5)\ , \end{aligned} \tag{17}$$

Numbers of events in (3+1)-scheme

Donini, Fuki, Lopez-Pavon, Meloni, Yasuda, JHEP 0908:041,2009

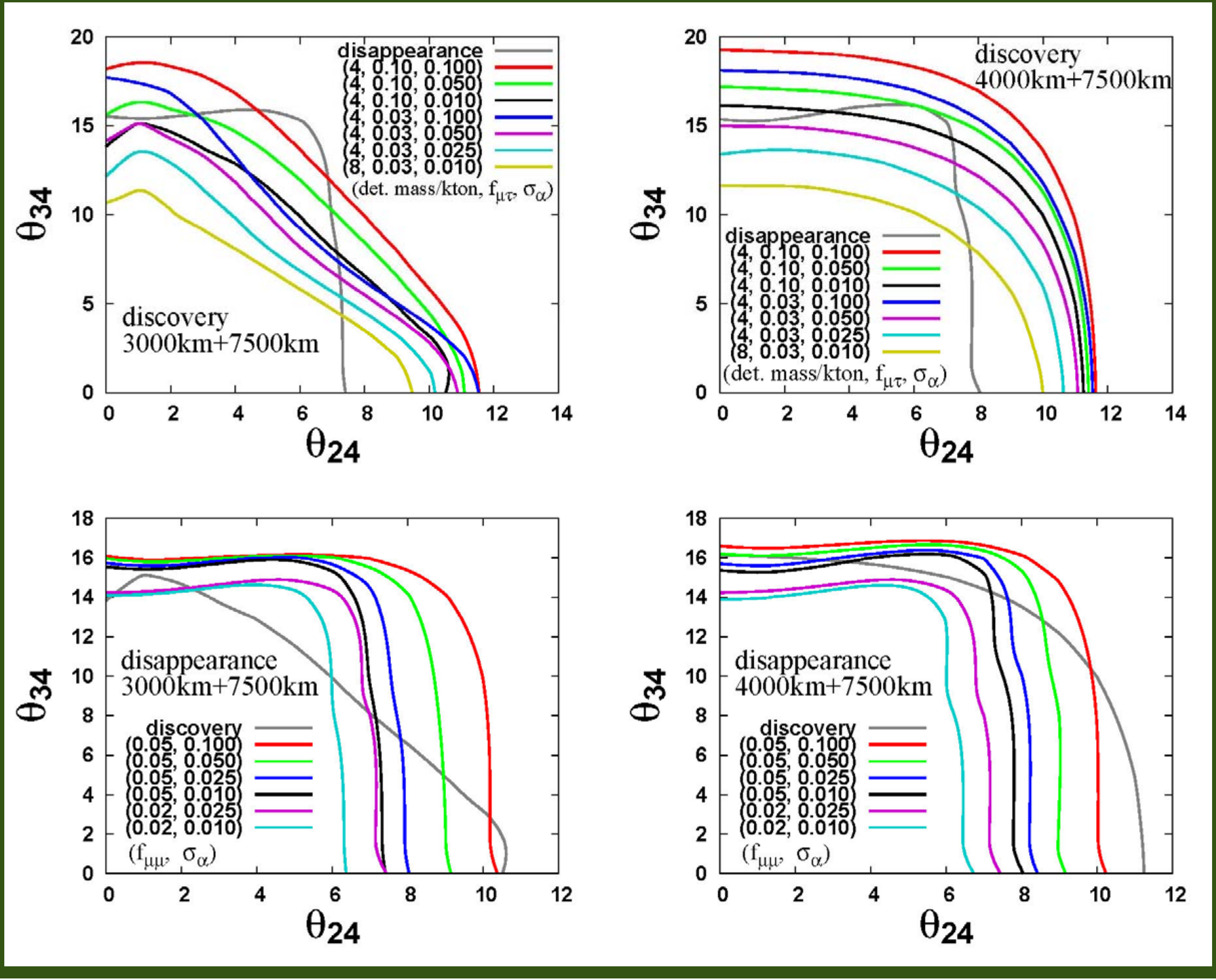


	$\nu_\mu \to \nu_\tau$	$\bar{\nu}_e \to \bar{\nu}_\tau$	$\nu_\mu \to \nu_\tau$	$\bar{\nu}_e \to \bar{\nu}_\tau$
$(\theta_{13};\theta_{14};\theta_{24};\theta_{34})$	$N^{3000}_{\tau^-}$	$N^{3000}_{\tau^+}$	$N^{7500}_{\tau^-}$	$N^{7500}_{\tau^+}$
$(5^\circ;5^\circ;5^\circ;20^\circ)$	559	10	544	2
$(5^\circ;5^\circ;10^\circ;20^\circ)$	474	11	529	2
$(5^\circ;5^\circ;10^\circ;30^\circ)$	384	18	454	3
$(5^\circ;5^\circ;10^\circ;30^\circ)$	384	18	454	3
$(10^\circ;5^\circ;5^\circ;20^\circ)$	522	22	512	2
$(10^\circ;5^\circ;10^\circ;20^\circ)$	443	22	498	2
$(10^\circ;5^\circ;5^\circ;30^\circ)$	397	30	413	4
$(10^\circ;5^\circ;10^\circ;30^\circ)$	361	30	428	4
3 families, $\theta_{13} = 5^\circ$	797	3	666	0
3 families, $\theta_{13} = 10^\circ$	755	12	632	1

Number of events
2×10^{20} flux
1 year
1 Kton MECC
perfect efficiency

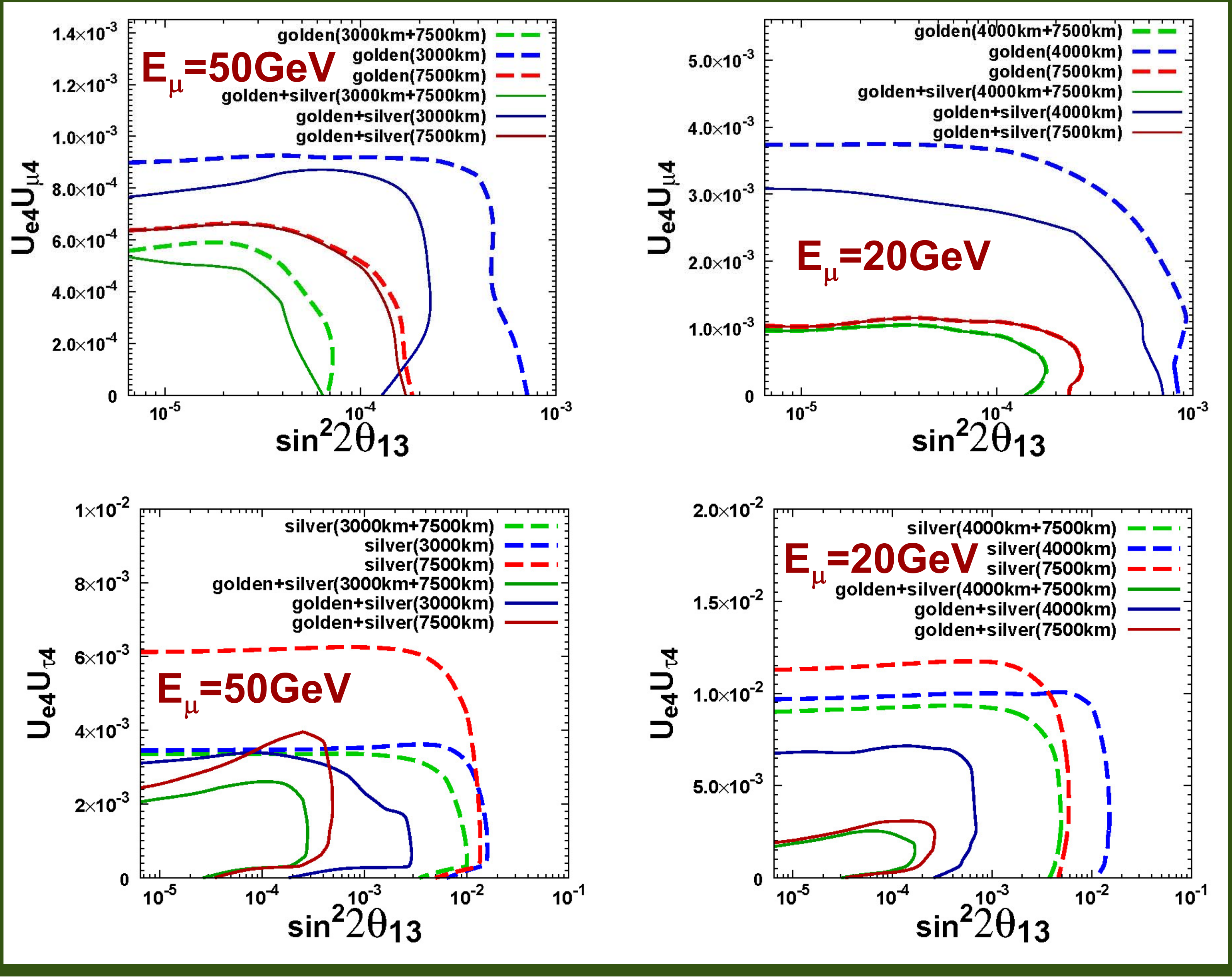
Dependence of sensitivity on systematic errors in (3+1)-scheme

Donini, Fuki, Lopez-Pavon, Meloni, Yasuda, JHEP 0908:041,2009

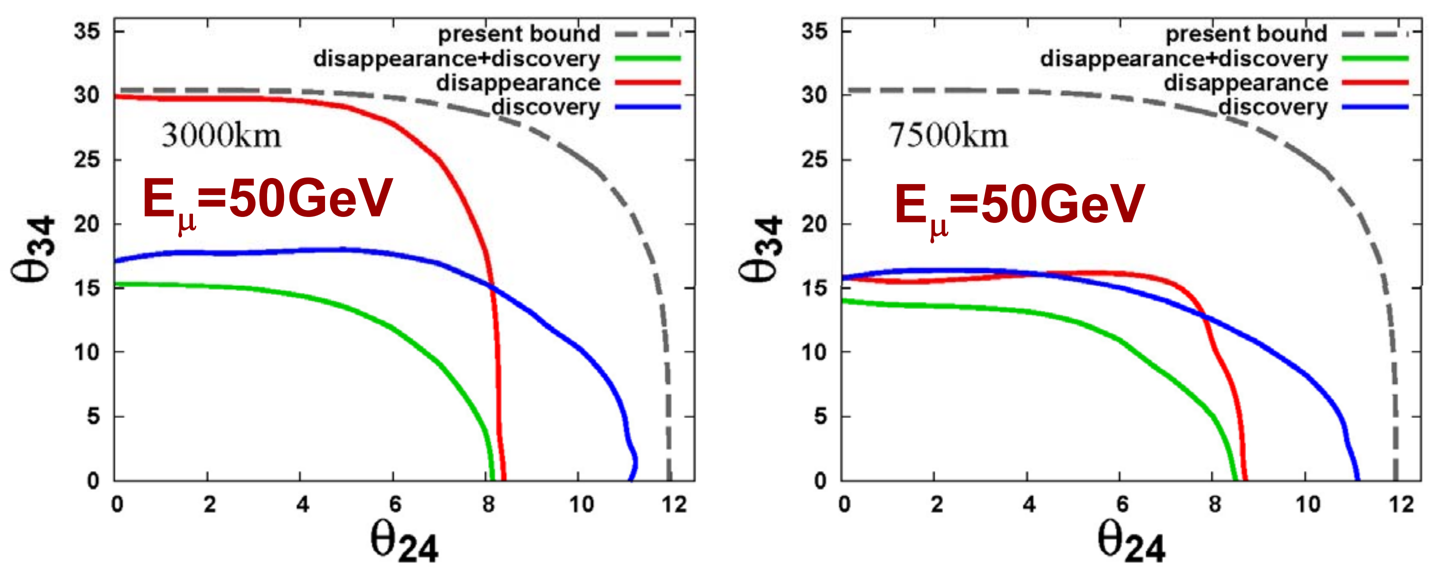


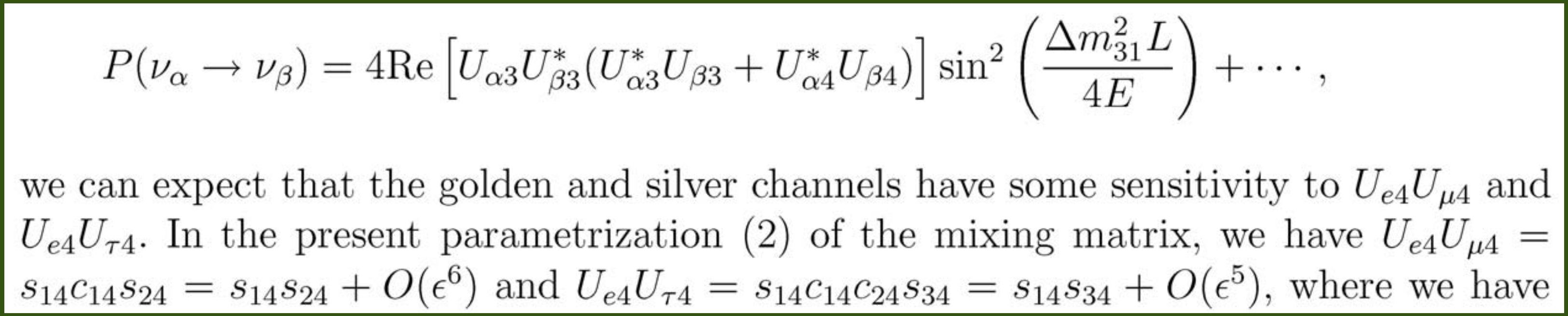
Sensitivity to $U_{e4}U_{\mu4}$ & $U_{e4}U_{\tau4}$

Donini, Fuki, Lopez-Pavon, Meloni, Yasuda, JHEP 0908:041,2009



Donini, Fuki, Lopez-Pavon, Meloni, Yasuda, JHEP 0908:041,2009



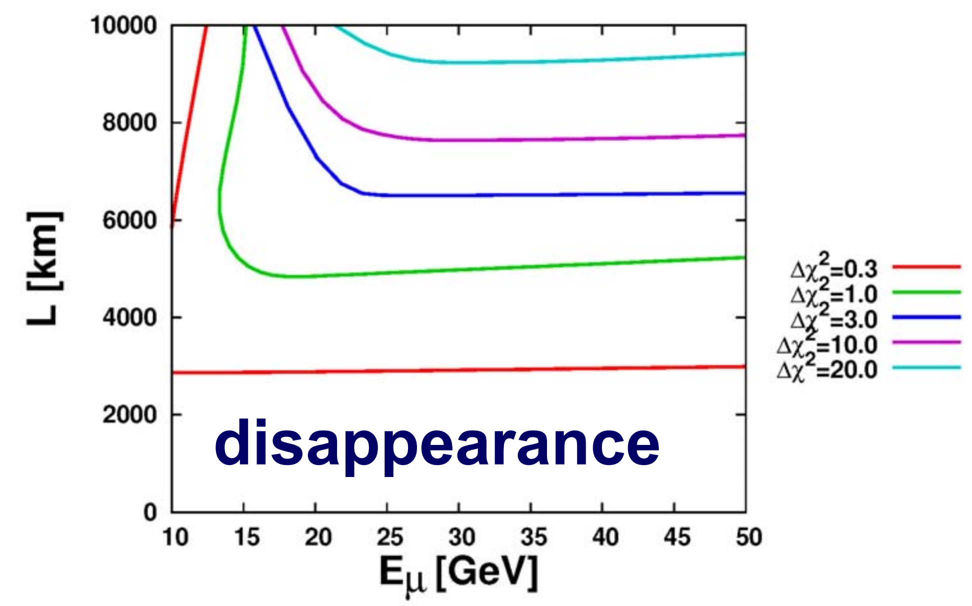


$$P(\nu_\alpha \to \nu_\beta) = 4\mathrm{Re}\left[U_{\alpha 3}U^*_{\beta 3}(U^*_{\alpha 3}U_{\beta 3} + U^*_{\alpha 4}U_{\beta 4})\right]\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) + \cdots ,$$

we can expect that the golden and silver channels have some sensitivity to $U_{e4}U_{\mu 4}$ and $U_{e4}U_{\tau 4}$. In the present parametrization (2) of the mixing matrix, we have $U_{e4}U_{\mu 4} = s_{14}c_{14}s_{24} = s_{14}s_{24} + O(\epsilon^6)$ and $U_{e4}U_{\tau 4} = s_{14}c_{14}c_{24}s_{34} = s_{14}s_{34} + O(\epsilon^5)$, where we have

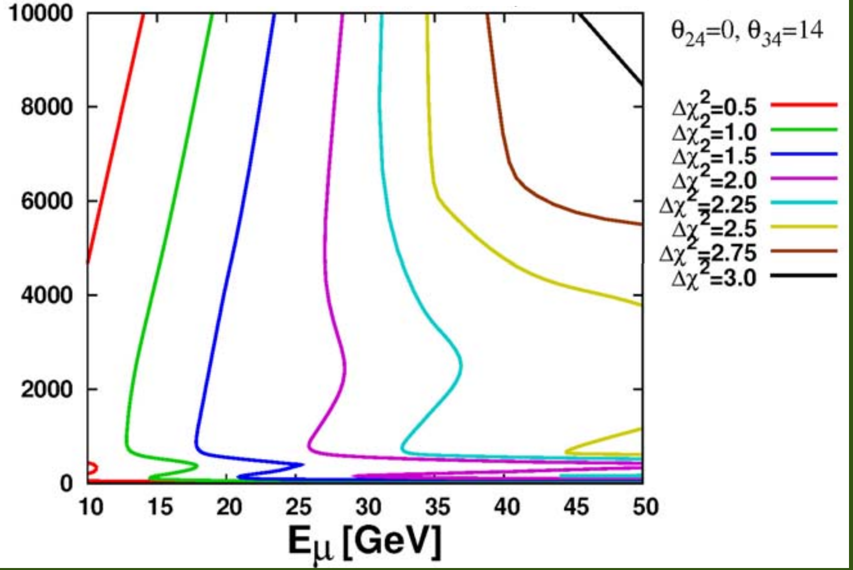
Which τ detector is less important, @3000km or @7500km ?

Contour plot of significance for signal with θ_{24}=0, θ_{34}=14



disappearance

discovery



For 50GeV (20GeV), L=3000km (L=4000km) performs (slightly) poor. This is also the case w/ disappearance.

➡ One @7500km seems better in most cases