Summary of WG1 (Theoretical Part)

Convenors:
P. Hernández, M. Messier, O. Yasuda

NuFact06, 30 August 2006 @UCI

Theoretical discussions on ν masses

Murayama: How can we test seesaw experimentally?
Ma: Lepton family symmetries for neutrino masses and mixing
Harrison: Democracy in Neutrino Oscillations: Magic/S3 Group Mixing and its Derivatives

Dark matter

Kusenko: Opening a new window for warm dark matter
Cirelli: Spectra of neutrinos from dark matter annihilations

New physics

Friedland: Two modes of searching for new ν int. at MINOS
Biggio: Unitarity of the leptonic mixing matrix
Ota: Discovery reach for non-standard interactions in a ν Factory
Okamura: Matter Effect on ν osc. from violation of universality in ν NC Int.

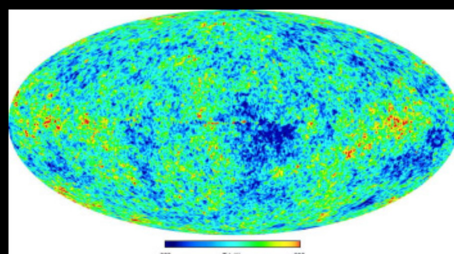
New proposals

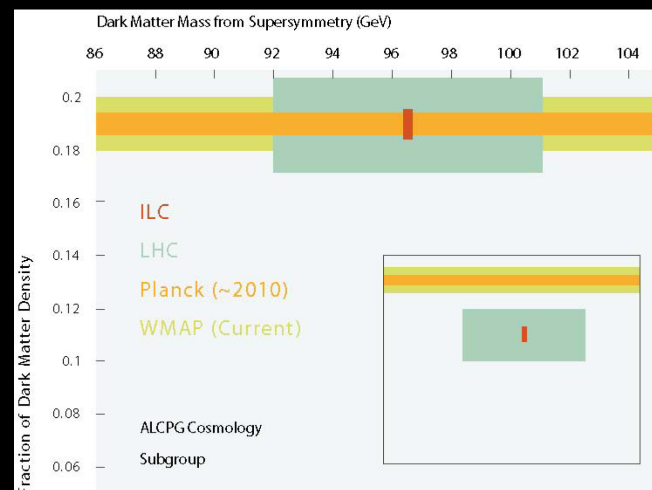
Takamura: Maximal CP phase effect & θ_{13} screening in long baseline ν exp.
Zukanovich Funchal: Determining ν mass hierarchy by precision measurements in disappearance exp.

How can we test seesaw experimentally? (Murayama)

A scenario to "establish" seesaw

- Next generation experiments discover neutrinoless double beta decay
- $0\nu\beta\beta$ leaves the possibility for *R*-parity violation
- Consistency between cosmology, dark matter detection, and LHC/ILC will remove the concern





$$\Omega_M = \frac{0.756(n+1)x_f^{n+1}}{g^{1/2}\sigma_{ann}M_{Pl}^{\ 3}}\frac{3s_0}{8\pi H_0^2} \approx \frac{\alpha^2/(TeV)^2}{\sigma_{ann}}$$

High precision needed to know the scale Λ

Lepton family symmetries for neutrino masses and mixing (Ma)

$$U \simeq \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -1/\sqrt{6} & 1/\sqrt{3} & -1/\sqrt{2} \\ -1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$$ [Harrison/ Perkins/Scott (2002)]

Tetrahedral Symmetry A_4

class	n	h	χ_1	$\chi_{1'}$	$\chi_{1''}$	χ_3
C_1	1	1	1	1	1	3
C_2	4	3	1	ω	ω^2	0
C_3	4	3	1	ω^2	ω	0
C_4	3	2	1	1	1	–1

With the application of the non-Abelian discrete symmetry A_4, a plausible theoretical understanding of the HPS form of the neutrino mixing matrix has been achieved.

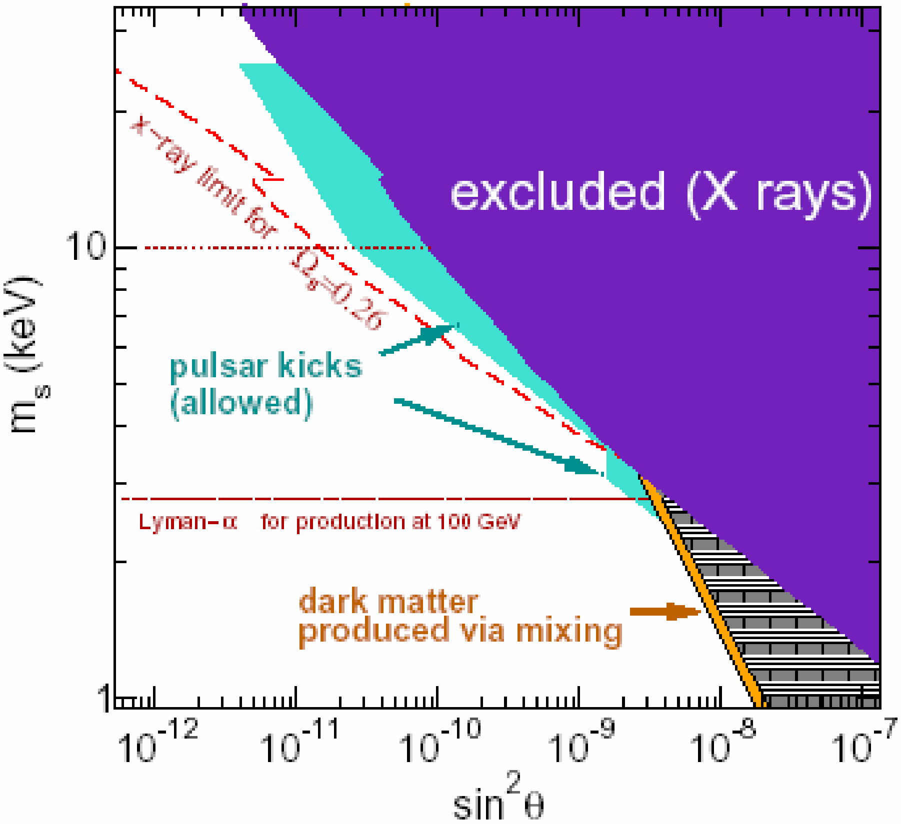
Democracy in Neutrino Oscillations: Magic/S3 Group Mixing and its Derivatives (Harrison)

Democracy Symmetry $\Longleftrightarrow$ S3 Group property $\Longleftrightarrow$ Magic property $\Longleftrightarrow$ At least one trimaximally mixed mass eigenstate: $\frac{1}{\sqrt{3}}(1,1,1)$

THE FOUR CONDITIONS ARE ALL EQUIVALENT!

H_ν Constraint(s)	Extra Symms.	Given Name	U_{MNS} Constraint(s)
$y = z$	$\mu - \tau^*$	Tri-χ maximal, XZZ(A)	$\mathrm{Re}(U_{e3}) = 0$
$d = 0$	CP	Tri-ϕ maximal, XZZ(B)	$\mathrm{Im}(U_{e3}) = 0$
$y = z$ and $d = 0$	$\mu - \tau^*$ and CP	Tri-bimaximal mixing	$U_{e3} = 0$
$y = z = 0$	$\mu - \tau^*$	Simplest mass matrix	$\mathrm{Re}(U_{e3}) = 0$ and $\mathrm{Im}(U_{e3}) = \sqrt{\frac{2}{3}}\sqrt{\frac{\Delta m^2_{\mathrm{sol}}}{\Delta m^2_{\mathrm{atm}}}}$
$d = 0$ and $f(x, y, z, a_0) = 0$	CP	Friedberg-Lee model	$\mathrm{Im}(U_{e3}) = 0$ and $\mathrm{Re}(U_{e3}) \simeq \frac{1}{2\sqrt{2}}\frac{\Delta m^2_{\mathrm{sol}}}{\Delta m^2_{\mathrm{atm}}}$
$d = z = 0$	CP	Simplest Real mass matrix	$\mathrm{Im}(U_{e3}) = 0$ and $\mathrm{Re}(U_{e3}) \simeq \frac{1}{\sqrt{3}}\frac{\Delta m^2_{\mathrm{sol}}}{\Delta m^2_{\mathrm{atm}}}$

Opening a new window for warm dark matter (Kusenko)



- Sterile neutrinos with mass in the keV range can be dark matter
- The same sterile neutrinos can explain the pulsar kicks and can play a role in star formation and reionization.
- Sterile dark matter can be warm or cold, depending on the production mechanism and on values of the parameters.

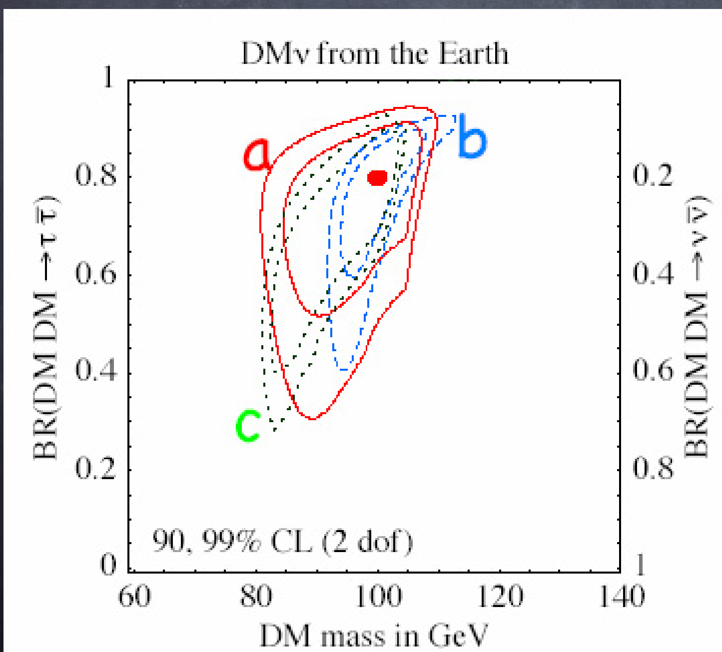
Spectra of neutrinos from dark matter annihilations (Cirelli)

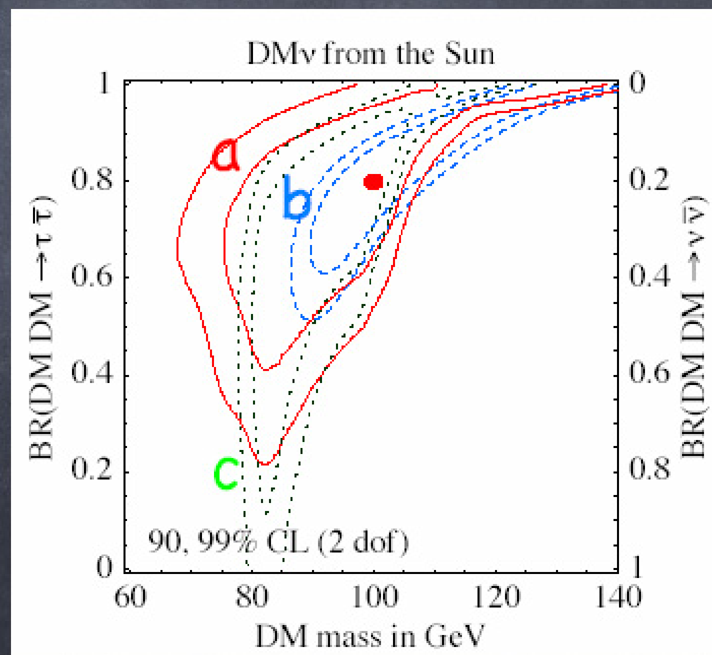
DM in Sun and in Earth → ν from Sun and Earth

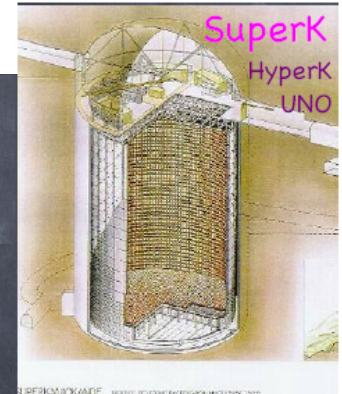
ν from DM carry precious insight on the properties of DM.

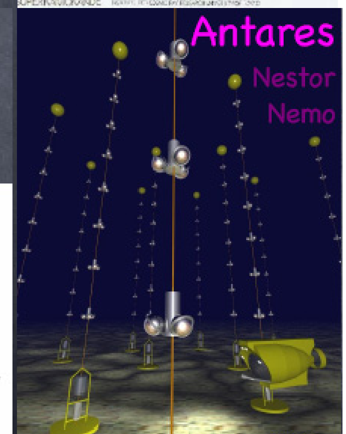
We have the formalism to compute spectra, including everything.

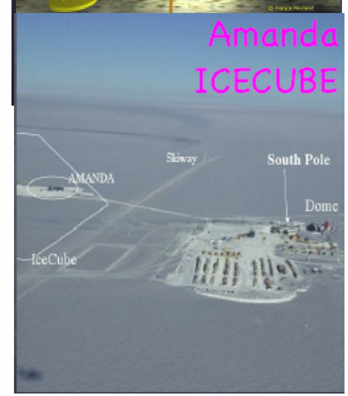
a) 100 contained muons or
b) 1000 thru-going muons or
c) 300 shower events





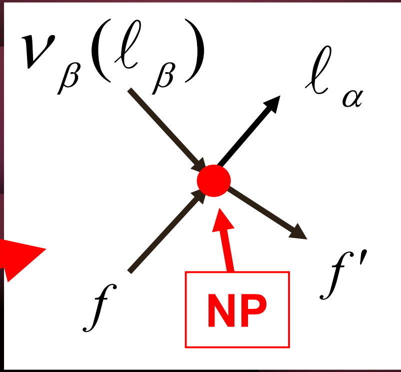




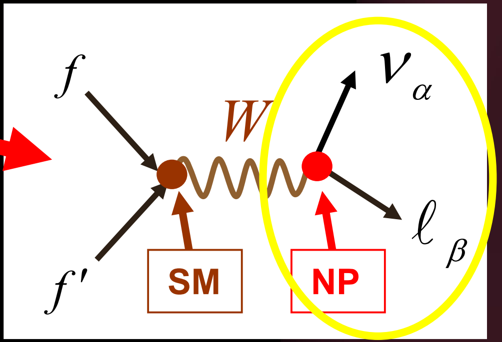


New Physics involving charged leptons

If either of the particles with flavor α and β in the NP interaction is charged lepton, then



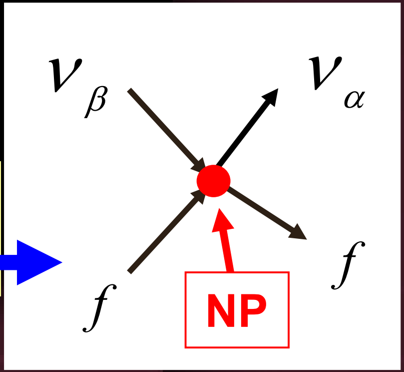
- **New Physics at source and detector**
- **Discussions on 3 flavor unitarity w/o light ν_s : Biggio**



New Physics involving charged leptons

If the particles with flavor α and β in the NP interaction are both neutrinos, then

- **New Physics in propagation (matter effect): Friedland, Ota, Okamura**

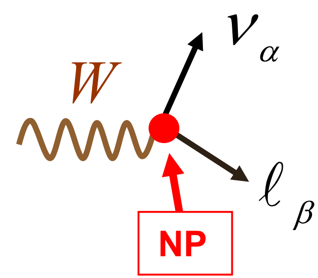


$$\begin{pmatrix} A & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \Rightarrow A\begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\tau\mu} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\tau\mu} & \varepsilon_{\tau\tau} \end{pmatrix}$$

Unitarity of the leptonic mixing matrix (Biggio)

$U \to N$ (non-unitary)

$NN^\dagger - 1$: deviation from unitarity



minimal non-unitary model

$$|NN^\dagger| \approx \begin{pmatrix} 1.002 \pm 0.005 & < 7.2 \cdot 10^{-5} & < 1.6 \cdot 10^{-2} \\ < 7.2 \cdot 10^{-5} & 1.003 \pm 0.005 & < 1.3 \cdot 10^{-2} \\ < 1.6 \cdot 10^{-2} & < 1.3 \cdot 10^{-2} & 1.003 \pm 0.005 \end{pmatrix}$$

mostly from rare decays

In the future…

Rare leptons decays (present)

- $\mu \to e\gamma$ $\quad (NN^\dagger)_{e\mu} < 7.2 \cdot 10^{-5}$

$\sim 10^{-7}$ **NUFACT**

- $\tau \to e\gamma$ $\quad (NN^\dagger)_{e\tau} < 0.016$
- $\tau \to \mu\gamma$ $\quad (NN^\dagger)_{\mu\tau} < 0.013$

ZERO-DISTANCE EFFECT

40Kt Iron calorimeter @ NUFACT

- $\nu_e \to \nu_\mu$ $\quad (NN^\dagger)_{e\mu} < 2.3 \cdot 10^{-4}$

4Kt emulsion cloud chamber @ NUFACT

- $\nu_e \to \nu_\tau$ $\quad (NN^\dagger)_{e\tau} < 2.9 \cdot 10^{-3}$
- $\nu_\mu \to \nu_\tau$ $\quad (NN^\dagger)_{\mu\tau} < 2.6 \cdot 10^{-3}$

Two modes of searching for new ν int. at MINOS (Friedland)

- The best-fit region shifts to smaller θ and larger Δm^2:

$\epsilon_{e\tau} = 0, \epsilon_{\tau\tau} = 0;$

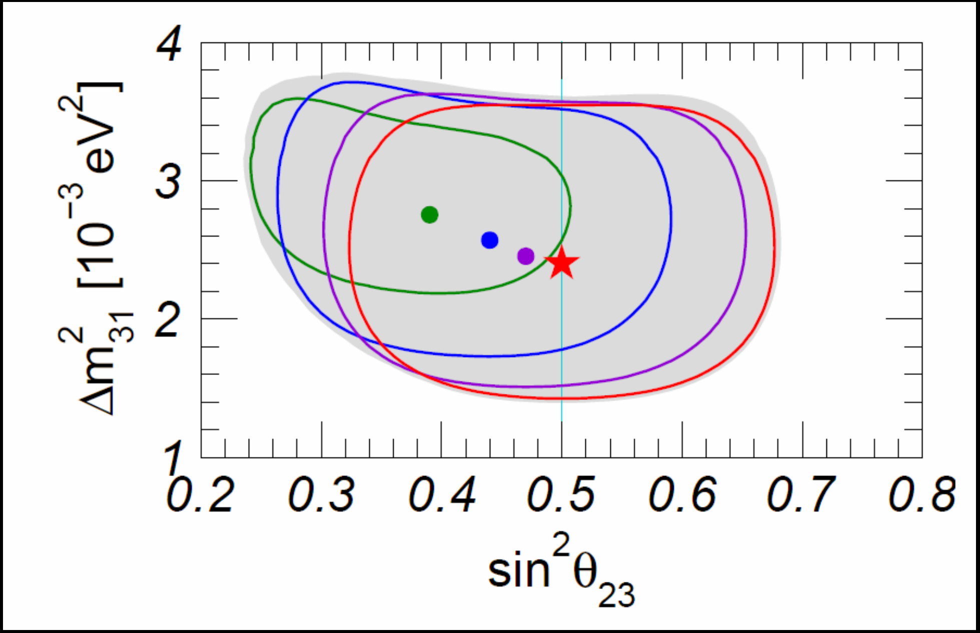
$\epsilon_{e\tau} = 0.30, \epsilon_{\tau\tau} = 0.106;$

$\epsilon_{e\tau} = 0.60, \epsilon_{\tau\tau} = 0.424;$

$\epsilon_{e\tau} = 0.90, \epsilon_{\tau\tau} = 0.953.$

Phys.Rev.D70 111301, (2004)

$$A \begin{pmatrix} 1+\epsilon_{ee} & 0 & \epsilon_{e\tau} \\ 0 & 0 & 0 \\ \epsilon_{e\tau} & 0 & \epsilon_{\tau\tau} \end{pmatrix}$$



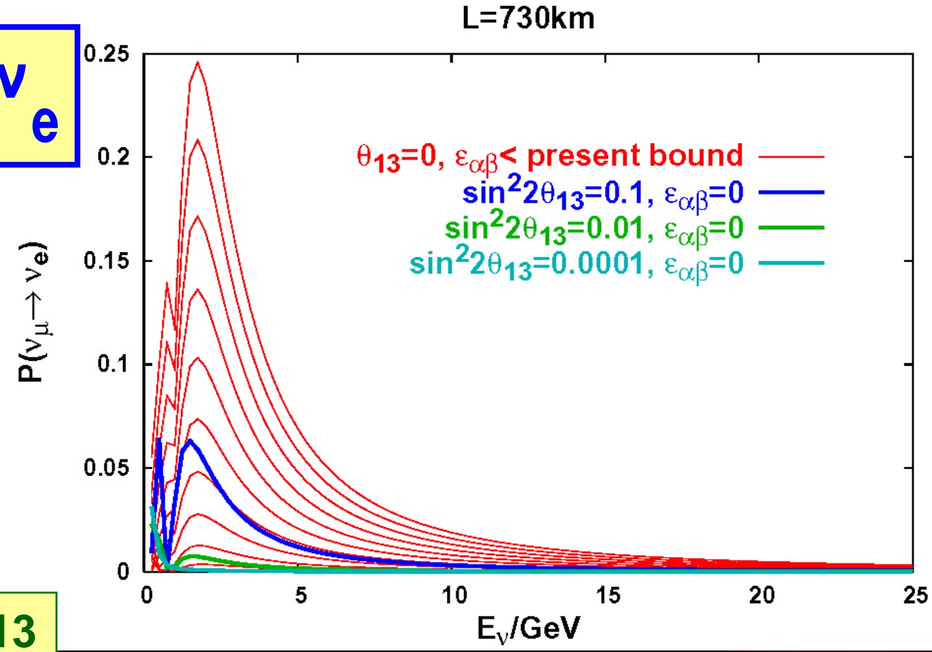
➡ measurement of $\nu_\mu \to \nu_\mu$ mode @ MINOS

measurement of $\nu_\mu \to \nu_e$ mode @ MINOS

$$\nu_\mu \xrightarrow{\Delta_{23},\theta_{23}} \nu_\tau \xrightarrow{\epsilon_{e\tau}} \nu_e .$$

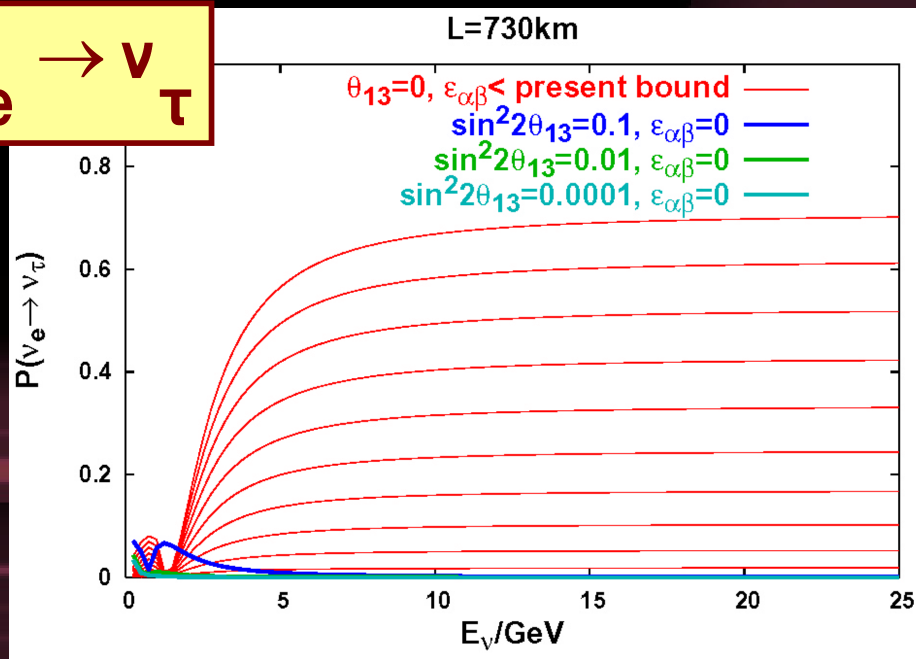
MINOS (ν_e appearance) $\nu_\mu \to \nu_e$

$$A\begin{pmatrix} 1+\epsilon_{ee} & 0 & \epsilon_{e\tau} \\ 0 & 0 & 0 \\ \epsilon_{e\tau} & 0 & \epsilon_{\tau\tau} \end{pmatrix}$$



Kitazawa, Sugiyama, OY, hep-ph/0606013

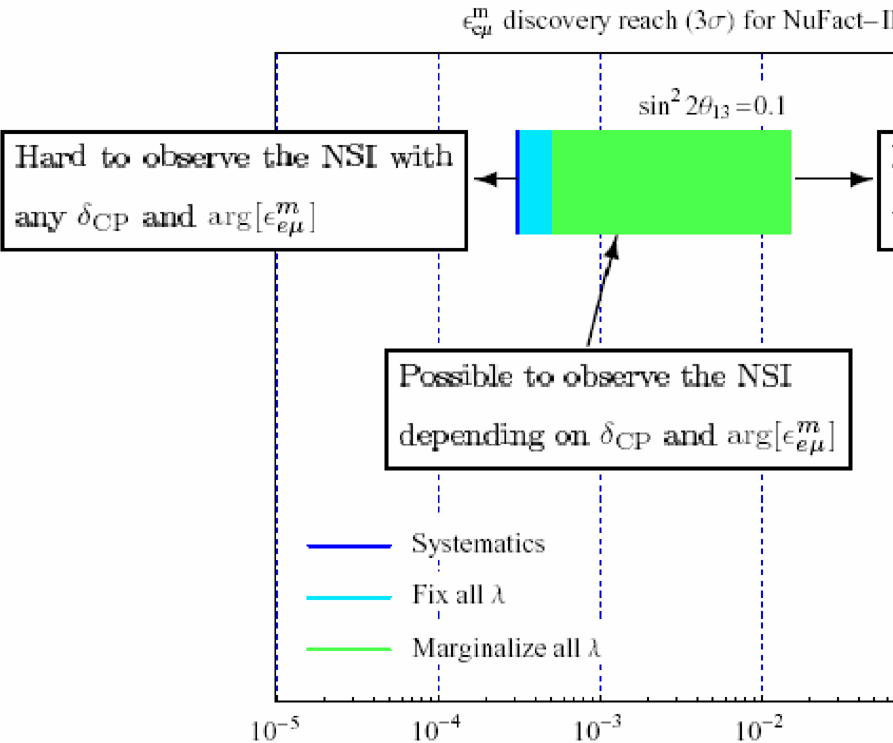
ν factory (silver channel) $\nu_e \to \nu_\tau$



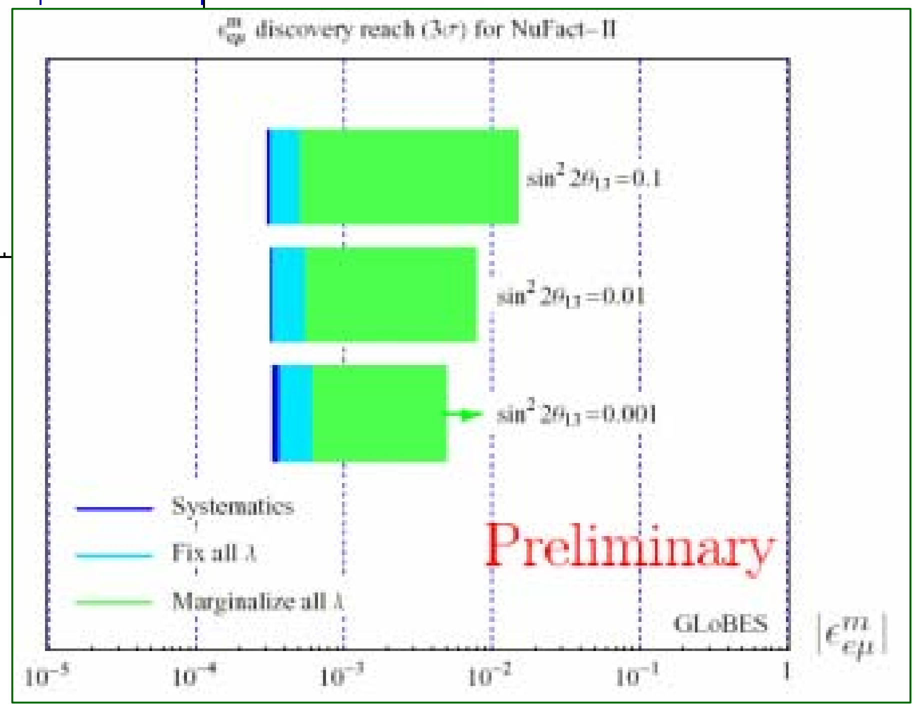
Existence of $\varepsilon_{\alpha\beta}$~O(1) predicts signals potentially larger than standard scenario in appearance channel of MINOS and future LBL

Discovery Reach for Non-Standard Interactions in a ν Factory (Ota)

$$A\begin{pmatrix} 1 & \varepsilon_{e\mu} & 0 \\ \varepsilon^*_{e\mu} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$



Study on $\varepsilon_{e\mu}$ in propagation taking into account both $\mathrm{Re}(\varepsilon_{e\mu})$ and $\mathrm{Im}(\varepsilon_{e\mu})$



Matter Effect on ν oscillation from violation of universality in ν NC Int. (Okamura)

$$A\begin{pmatrix} 1+\varepsilon_{ee} & 0 & 0 \\ 0 & \varepsilon_{\mu\mu} & 0 \\ 0 & 0 & \varepsilon_{\tau\tau} \end{pmatrix}$$

We investigated the matter effect on neutrino oscillation from universality violation in neutral current interactions.

The violation effects	normal	inverted
mixing angle	θ_{12}	θ_{23}
oscillation probability (L=9,120 km, 17GeV)	$\sin^2(2\theta_{23}) = 0.92$	
	☺ ☺ ☺ ☺	☺ ☺ ☺ ☺
	$\sin^2(2\theta_{23}) = 1$ (best fit)	
	×	

➢ **This result is highly sensitive to the value of $\sin^2(2\theta_{23})$**

Fermilab ⇒ Hyper-Kamiokande

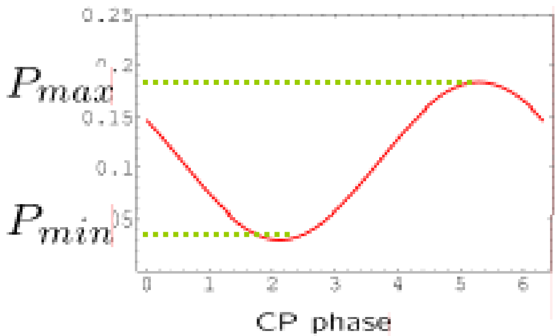
➢ **If $\sin^2(2\theta_{23})$ is NOT too close to 1,**
we may be able to either observe this effect, or impose a much tighter constraint on universality violation than that from CHARM and CHARMII.

Maximal CP phase effect & θ_{13} screening in long baseline ν exp. (Takamura)

Inequality (I)

$$P(\nu_e \to \nu_\mu) = A\cos\delta + B\sin\delta + C$$

Max and Min of probability



CP phase effect

$$P(\nu_e \to \nu_\mu) = \sqrt{A^2+B^2}\sin(\delta+\alpha) + C$$

$$P_{max} = \sqrt{A^2+B^2} + C$$
$$P_{min} = \sqrt{A^2+B^2} - C$$

New index for CP phase effect

$$I_{CP} = \frac{P_{max} - P_{min}}{P_{max} + P_{min}}$$

$$I_{CP} = \frac{\sqrt{A^2+B^2}}{C}$$

Applications

(1) Easy understanding of magic baseline phenomenon

(2) Easy understanding of $P_{\mu e}$~0 for δ=135° at T2K

Determining n mass hierarchy by precision measurements in disappearance exp. (Zukanovich Funchal)

- The sign of $|\Delta m^2_{31}| - |\Delta m^2_{32}|$ can be restated in a transparent way by introducing the effective mass squared differences $\Delta m^2(ee)$ and $\Delta m^2(\mu\mu)$
- The mass hierarchy is normal (inverted) if $|\Delta m^2(ee)| - |\Delta m^2(\mu\mu)|$ is positive (negative)
- By comparing $\Delta m^2(ee)$ and $\Delta m^2(\mu\mu)$ measured in ν_e and ν_μ disappearance modes, in principle, it is possible to determine the neutrino mass hierarchy at $>$ 95% CL for $0.3\,\pi \lesssim \delta \lesssim 1.7\,\pi$

$$1 - P(\nu_\alpha \to \nu_\alpha) \equiv sin^2 2\theta_{\alpha\alpha}\, sin^2 \left(\frac{\Delta m^2_{\alpha\alpha}}{4E} L\right)$$

$$+\,\mathcal{O}((\Delta m^2_{21} L/4E)^2)$$

$$\begin{aligned}\Delta_{e\mu} &= |\Delta m^2(ee)| - |\Delta m^2(\mu\mu)| = (|\Delta m^2_{31}| - |\Delta m^2_{32}|)\cos 2\theta_{12} \\ &= \pm \Delta m^2_{21} \cos 2\theta_{12}\end{aligned}$$

$\Delta m^2(\mu\mu)$ T2K-I: $\frac{\delta|\Delta m^2(\mu\mu)|}{|\Delta m^2(\mu\mu)|} \sim 2\%$

$\Delta m^2(ee)$ ${}^3H \to \bar{\nu}_e + {}^3He + \text{orbital } e^-$

Raghavan hep-ph/0511191, hep-ph/061079

(Mössbauer Effect) $\delta \frac{\delta|\Delta m^2(ee)|}{|\Delta m^2(ee)|} = 0.6 \times (0.05/\sin^2 2\theta_{13})\%$

Future problems toward nufact07

After the 1 year work of ISS, there are still a lot of problems to be worked out:

- **Quantitative discussions on measuring θ_{13} and effects of new physics and/or non-unitarity (correlations of errors, degeneracies, dependence on the beam energy and the baseline, etc.)**
- **Distinction between the new physics effects (e.g., 4-fermi interactions vs. non-unitarity from modification in the kinetic term)**
- **Predictions of various models on deviation from SM+massive ν**
- **many more .....**