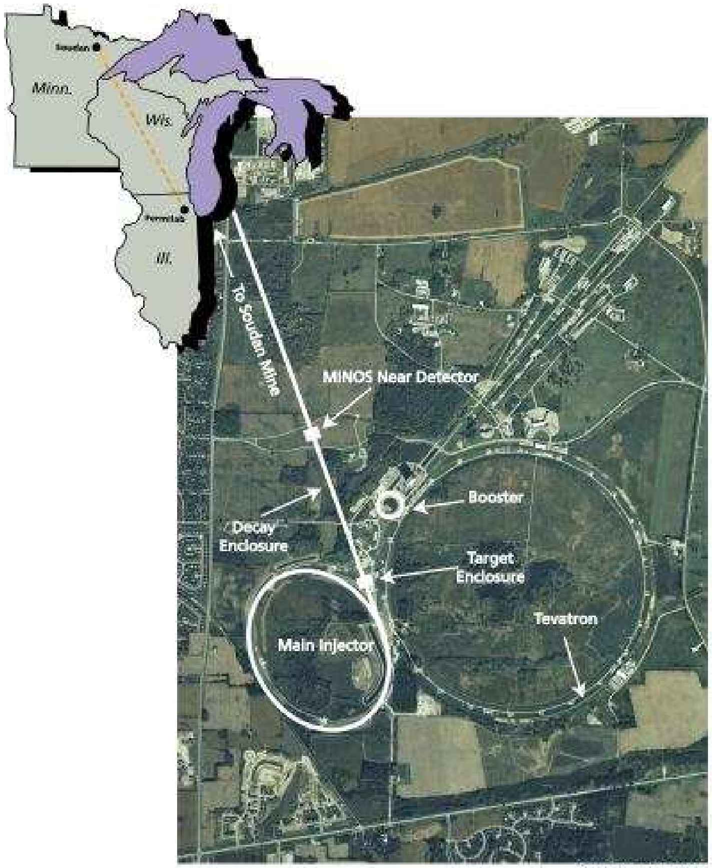
# Long-Range Lepton Flavor Interactions and Neutrino Oscillations

[with H. Davoudiasl and W. Marciano (arXiv:1102.5352)]

Hye-Sung Lee

(Brookhaven National Lab)

PHENO 2011



©FERMILAB #98-1321D

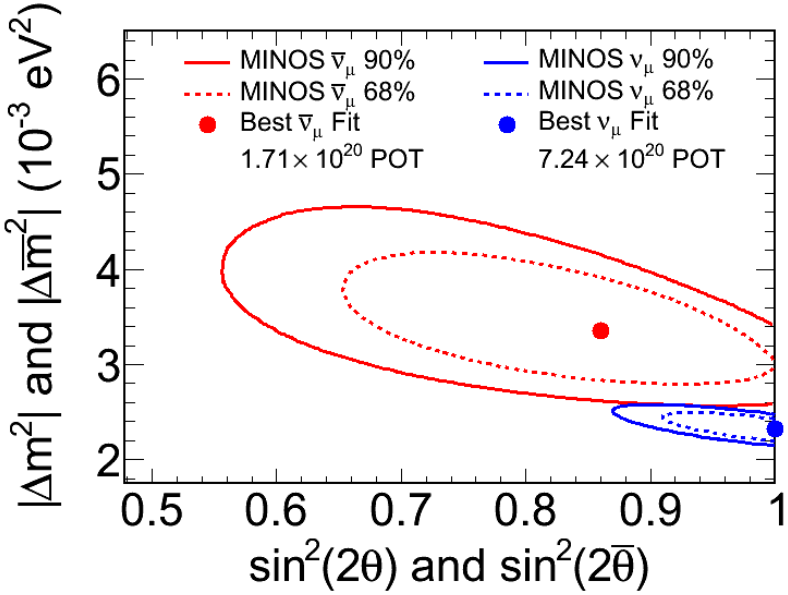
## Goal of this talk

MINOS $\nu_\mu$ and $\bar{\nu}_\mu$ disappearance experiments.

($L = 735\ \mathrm{km}$, $E_\nu \sim \mathrm{GeV}$ scale)

$$\begin{array}{ccc} \nu & & \bar{\nu} \\ |\Delta m^2| & < & |\Delta \bar{m}^2| \\ \sin^2(2\theta) & > & \sin^2(2\bar{\theta}) \end{array}$$

[MINOS Collaboration] arXiv:1104.0344



Likely due to statistics ($N_\nu \sim 2000$, $N_{\bar{\nu}} \sim 100$). Yet, it could be a hint of New Physics that can affect $\nu$ oscillation (differently for $\nu$ and $\bar{\nu}$).

In this talk, we go over a possible explanation and discuss its implications for other $\nu$ experiments.

## Outline

- Long-Range Interaction & $\nu$ oscillation
- Implication for atmospheric $\nu$ at IceCube DeepCore (ongoing)
- Implication for Future Long Baseline $\nu$ experiments

## What type of New Physics?

$$H = H_{\text{vac}} + H_{\text{SM}}$$
$$H_{\text{SM}} = V_W(1,0,0) + V_Z(1,1,1)$$

with $V_W = \sqrt{2} G_F n_e, V_Z = -\frac{G_F}{\sqrt{2}} n_n$

Flavor-universal potential (such as $Z$ boson effect) is irrelevant to $\nu$ flavor oscillation.

We will consider a Lepton Flavor Long-Range Interaction (LRI):

(i) lepton flavor-dependent $U(1)'$, (ii) almost massless gauge boson $Z'$.

$$H_{\text{LRI}} = V_{Z'}(Q_e, Q_\mu, Q_\tau)$$

(No sterile $\nu$, No CPT violation, etc.)

## Related works

Some related works prior to our study : LRI effects on $\nu$ oscillation, MINOS anomaly explanation with new interaction, etc. Joshipura, Mohanty (2003); Gonzalez-Garcia, Holanda, Masso, Funchal (2006); Bandyopadhyay, Dighe, Joshipura (2006); Engelhardt, Nelson, Walsh (2010); Mann, Cherdack, Musial, Kafka (2010); Kopp, Machado, Parke (2010); Heeck, Rodejohann (2010); $\cdots$

## Effective $\nu_\mu$ survival probability in 2-flavor ($\nu_\mu - \nu_\tau$) oscillation

Joshipura, Mohanty (2003)

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\tilde{\theta}_{23}) \sin^2\left(\frac{\Delta\tilde{m}^2_{23} L}{4E_\nu}\right)$$

with effective mass splitting and mixing angle under New Potential

$$\begin{aligned} \Delta\tilde{m}^2_{23} &= \Delta m^2_{23}\sqrt{[\xi - \cos(2\theta_{23})]^2 + \sin^2(2\theta_{23})} \\ \sin^2(2\tilde{\theta}_{23}) &= \sin^2(2\theta_{23}) / \left([\xi - \cos(2\theta_{23})]^2 + \sin^2(2\theta_{23})\right) \end{aligned}$$

$$\xi \equiv -\frac{2W_\tau E_\nu}{\Delta m^2_{23}}, \quad W_\tau = Q_\tau V_{Z'} \ (\text{potential energy})$$

(In analogy of the standard matter effect in $\nu_e$ oscillation: $\xi = \frac{2\sqrt{2}G_F n_e E_\nu}{\Delta m^2}$)

$\xi$ flips sign for $\bar{\nu}$ causing different effects on $\nu$ and $\bar{\nu}$ unless $\sin^2(2\theta_{23})=1$.

## LRI should be extremely weak

T.D. Lee & C.N. Yang (1955): LRI gets constraints from Eötvös-type expt.

$\alpha' < 10^{-47}$ (baryons), $\alpha' < 10^{-49}$ (leptons) Okun, Dolgov (1990's)

LRI needs large (astronomical) source to have sizable effects.

We assume $m_{Z'} \lesssim 1/AU \sim 10^{-18}\,\mathrm{eV}$ to include the Sun (but not much smaller).

## $U(1)'$ charge

$$Q = a_0(B - L) + a_1(L_e - L_\mu) + a_2(L_e - L_\tau) + a_3(L_\mu - L_\tau)$$

: a linear combination of anomaly-free gauge symmetries

We choose $Q = (B - L) + (L_\mu - L_\tau) = B - L_e - 2L_\tau$.

$$H_{\mathrm{LRI}} = V_{Z'}(-1, 0, -2)$$

(Neutrons in the Sun and the Earth are the source of New Potential.

Flavor-dependent charges affect $\nu$ oscillation.)

## Astronomical source of New Potential

$$\text{Sun } (\odot) \quad \longleftarrow r \longrightarrow \quad \text{Earth } (\oplus)$$

$$(N_n^{\odot} = 1.7 \times 10^{56}) \qquad\qquad (N_n^{\oplus} = 1.8 \times 10^{51})$$

$$V_{Z'} = \alpha' \left( \frac{N_n^{\odot}}{r} + \frac{N_n^{\oplus}}{R_{\oplus}} \right) = (2.2 \times 10^{-12}\,\mathrm{eV}) \times \left(\frac{\alpha'}{10^{-50}}\right) \times \left(\frac{AU}{r} + 0.25\right)$$
$$\sim \mathcal{O}(10^{-12}\,\mathrm{eV}) \times (\alpha'/10^{-50})$$

(1) Since the MINOS $\nu$ oscillation is relevant to $\frac{\Delta m_{23}^2}{E_\nu} \sim \mathcal{O}(10^{-12}\,\mathrm{eV})$, LRI with $\mathcal{O}(\alpha') \sim 10^{-50}$ level can affect MINOS experiments.

(In other words, $\nu$ oscillation is a good probe of an extremely weak LRI.)

(2) Annual modulation in New Potential due to $r = (1.47 \sim 1.52) \times 10^8 \mathrm{km}$

## Our fit to MINOS data

$$\begin{aligned} \Delta m^2_{23} &= 2.4 \times 10^{-3}\,\mathrm{eV}^2 \\ \sin^2(2\theta_{23}) &= 0.9 \\ \alpha' &= 1.0 \times 10^{-52} \qquad (\text{or } W_\tau = 5.6 \times 10^{-14}\,\mathrm{eV}) \end{aligned}$$

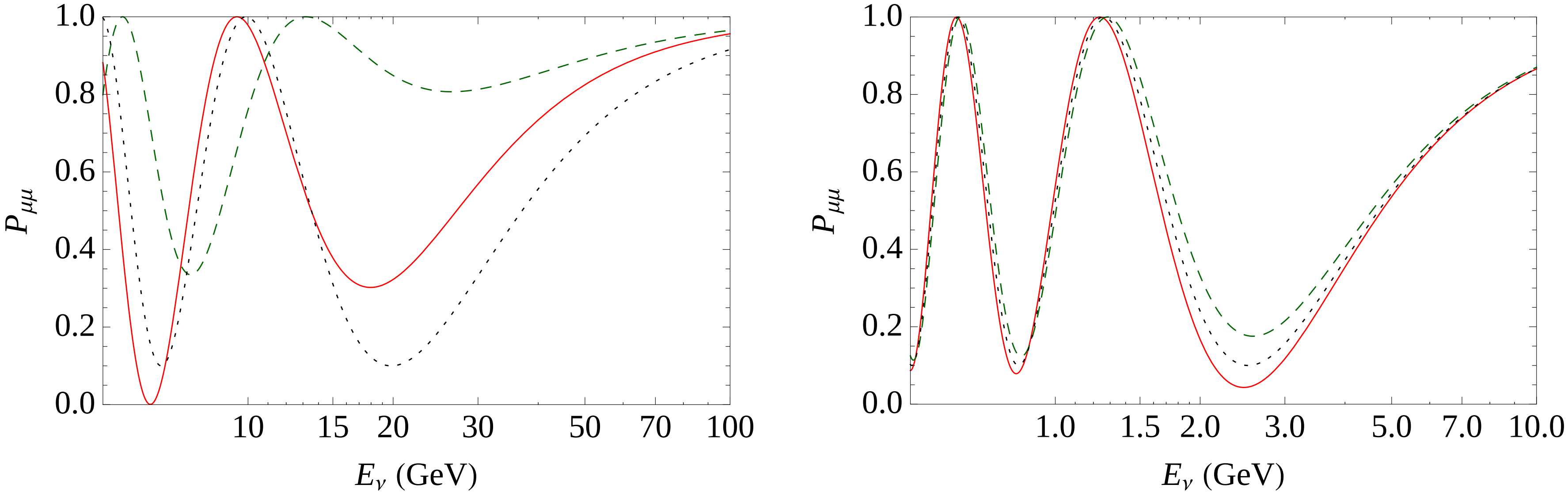
($\alpha' \lesssim 5 \times 10^{-52}$ at $3\sigma$ level))

Using simplified MINOS data from Kopp, Machado, Parke (2010).

Not ruled out by solar+KamLAND $\nu$ and atmospheric $\nu$ data.

Note: The best-fit does not really improve MINOS data fitting, but we take it a motivated benchmarking point to explore other experiments to test the LRI idea.

# Where are good places to test LRI?



[$L = 2 \times 6400\ \mathrm{km}$ (DeepCore)]    [$L = 1300\ \mathrm{km}$ (Future LBNE)]

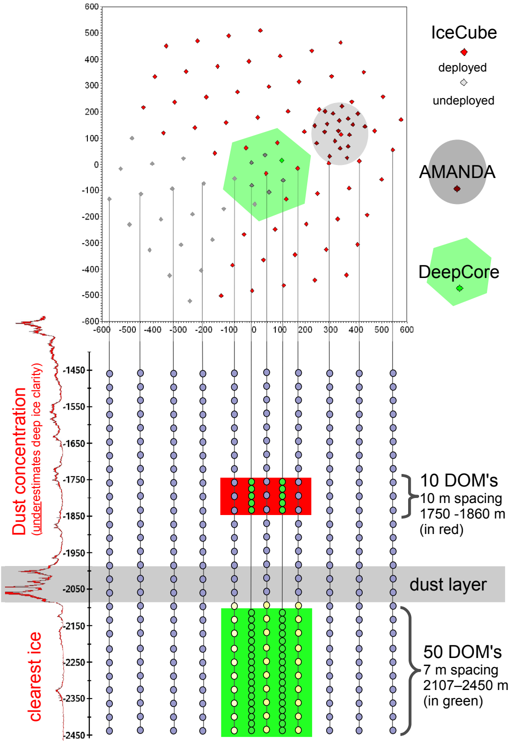
(for MINOS best-fit values)

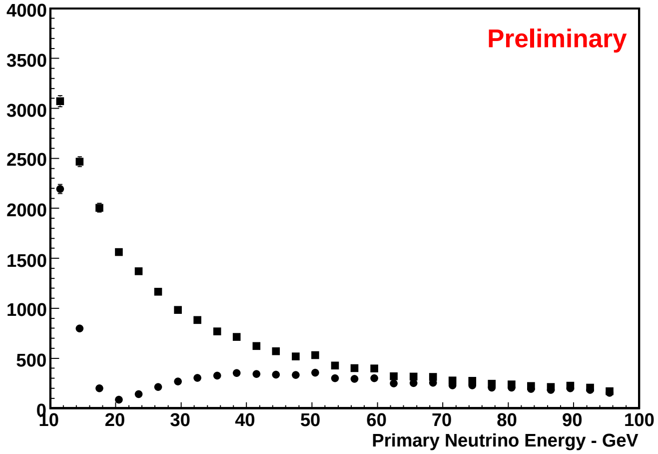
LRI effects on $\nu$ oscillation are energy-dependent.

The effects on $\nu$ (red solid) and $\bar{\nu}$ (green dashed) are different.

$\nu$ and $\bar{\nu}$ are the same in standard oscillation (black dotted).

# DeepCore at IceCube





[Atm $\nu_\mu$ disappearance at DeepCore (simulation)]

C. Wiebusch [IceCube Collaboration] (arXiv:0907.2263)

DeepCore: 6 additional densely instrumented strings + 7 IceCube strings.

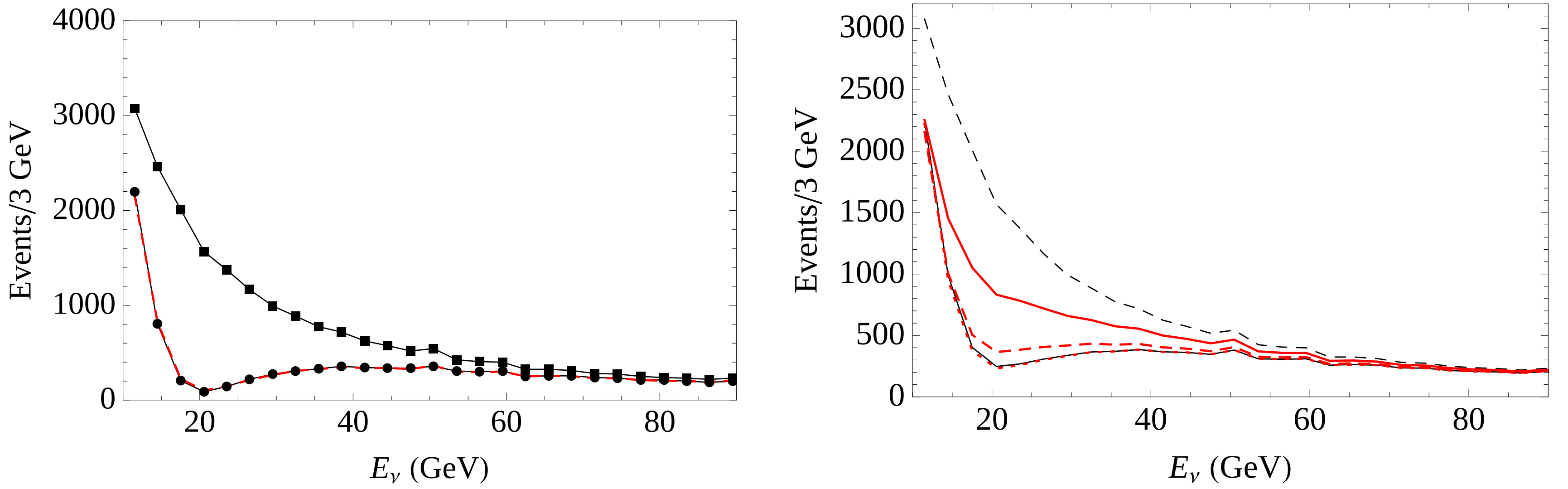
Recently commissioned. Running and taking data now.

$\mathcal{O}(10^5)$ $\nu_{\mathrm{atm}}$ / year in $1 \lesssim E_\nu \lesssim 100\ \mathrm{GeV}$ triggered.

Complementary to IceCube (optimized for $E_\nu \gtrsim 10\ \mathrm{TeV}$).

(G. Giordano's talk: Precise measurement of $\nu_{\mathrm{atm}}$ property at DC is possible.)

# LRI effects on atmospheric $\nu_\mu$ at DeepCore



[reproduction of standard oscillation]
(with different input values)

[for MINOS best-fit]

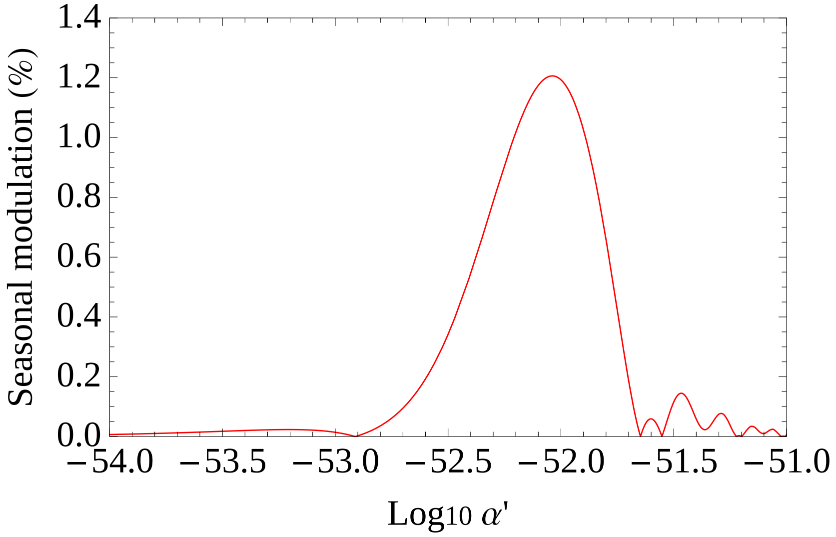
We assume $\nu : \bar{\nu} = 2 : 1$, isotropic flux, zenith angle $0.7\pi \lesssim \phi \leq \pi$.

Red solid: $\alpha' = 1.0 \times 10^{-52}$ (MINOS best-fit)

(Red dashed: $\alpha' = 0.5 \times 10^{-52}$, Red dotted: $\alpha' = 0.1 \times 10^{-52}$)

→ LRI effect on atmospheric $\nu_\mu$ can be quite distinct at DeepCore.

# Annual modulation at DeepCore (due to Sun-Earth distance variation)



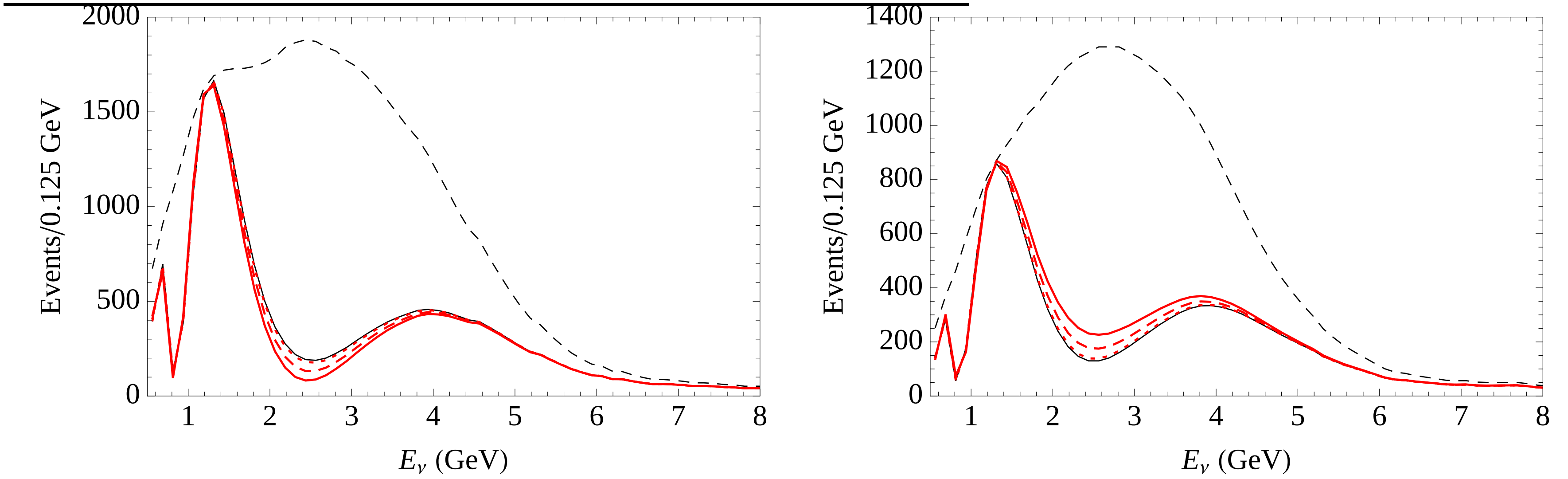
Annual modulation $\left|\frac{N_a - N_p}{N_a + N_p}\right|$ in atmospheric $\nu_\mu$ at DeepCore.

($15 < E_\nu < 30\ \mathrm{GeV}$, 120 days for each season, for uniform flux).

MINOS best-fit ($\alpha' = 10^{-52}$): Total 2700 events (1 year). $1.2\%$ seasonal variation.

$\longrightarrow$ Annual modulation at DeepCore can point the solar origin of New Potential.

# Future Long Baseline $\nu$ Experiment (DUSEL)



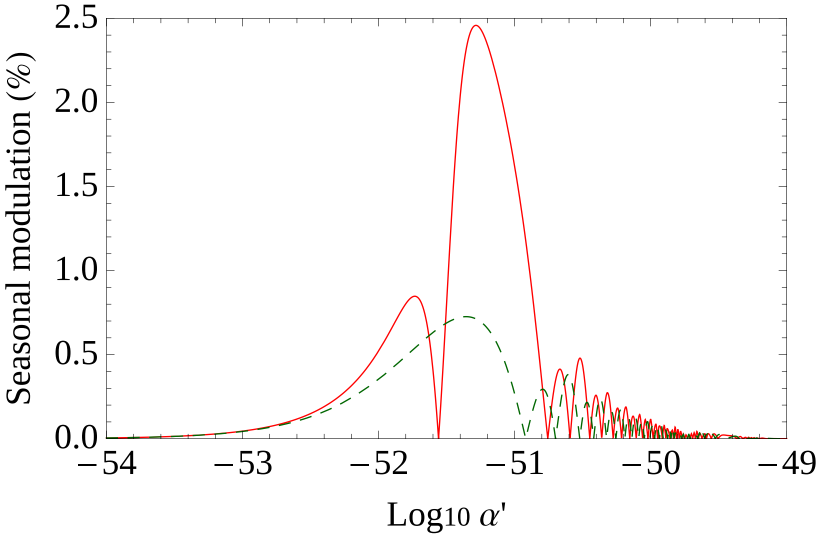
[$\nu_\mu$ disappearance] [$\bar{\nu}_\mu$ disappearance]

- $L = 1300\ \mathrm{km}$, $200\ \mathrm{kton}$ Water Cherenkov detector
- 5-years run unoscillated beam profile from M. Diwan's talk at DURA annual meeting (2010)

MINOS best-fit (red solid): For $E_\nu \sim \mathcal{O}(\mathrm{GeV})$, $\nu_\mu$ has less events ($\bar{\nu}_\mu$ has more events) than the standard oscillation (solid black).

$\longrightarrow$ DUSEL can tell the different LRI effects on $\nu$ and $\bar{\nu}$.

# Annual modulation at DUSEL



Annual modulation $\left|\frac{N_a - N_p}{N_a + N_p}\right|$ for accelerator $\nu_\mu$ at Long Baseline.

($2 < E_\nu < 3\ \mathrm{GeV}$, 180 days for each season, for uniform flux).

MINOS best-fit ($\alpha' = 10^{-52}$): Total 1100 ($\nu_\mu$), 2100 ($\bar{\nu}_\mu$) events (5 years) with $0.5\%$, $0.4\%$ seasonal variation.

(We may need enhanced capability to see annual modulation at DUSEL.)

## Summary

1. MINOS data (difference in $\nu_\mu$ and $\bar{\nu}_\mu$): a possible hint for New Physics which distinguishes $\nu$ and $\bar{\nu}$.
2. Lepton Flavor LRI with $\alpha' \sim 10^{-52}$ is a possibility. ($\nu$ oscillation is sensitive to Lepton Flavor LRI.)
3. IceCube DeepCore (ongoing expt.): can test LRI possibility. Annual modulation (percent-level) can point solar origin of New Potential.
4. DUSEL (future expt.): can tell difference of LRI effects on $\nu$ and $\bar{\nu}$.

## Backup Slide (Other constraints)

MINOS best-fit: $\alpha' = 1.0 \times 10^{-52}$, $W_\tau = 5.6 \times 10^{-14}\,\mathrm{eV}$

(1) Solar+KamLAND $\nu$ data:

$\alpha' \lesssim 5 \times 10^{-52}$ (at $3\sigma$)

Gonzalez-Garcia, Holanda, Masso, Funchal (2006); Bandyopadhyay, Dighe, Joshipura (2006)

(2) Atmospheric $\nu$ data (Super-Kamiokande):

$W_\tau = \epsilon_{\tau\tau}\sqrt{2}G_F n_e$. $\epsilon_{\tau\tau} \lesssim 0.2$ (at 95% CL)

Friedland, Lunardini, Maltoni (2004)

It depends on $n_e$ (electron number density).

In the core ($R \lesssim 3400\,\mathrm{km}$): $n_e \approx 12\,\mathrm{g/cm}^3$ ($W_\tau \lesssim 9 \times 10^{-14}\,\mathrm{eV}$)

In the mantle ($R \gtrsim 3400\,\mathrm{km}$): $n_e \approx 5\,\mathrm{g/cm}^3$ ($W_\tau \lesssim 4 \times 10^{-14}\,\mathrm{eV}$)