Terrestrial solar-scale neutrino oscillations

小石川植物園にて

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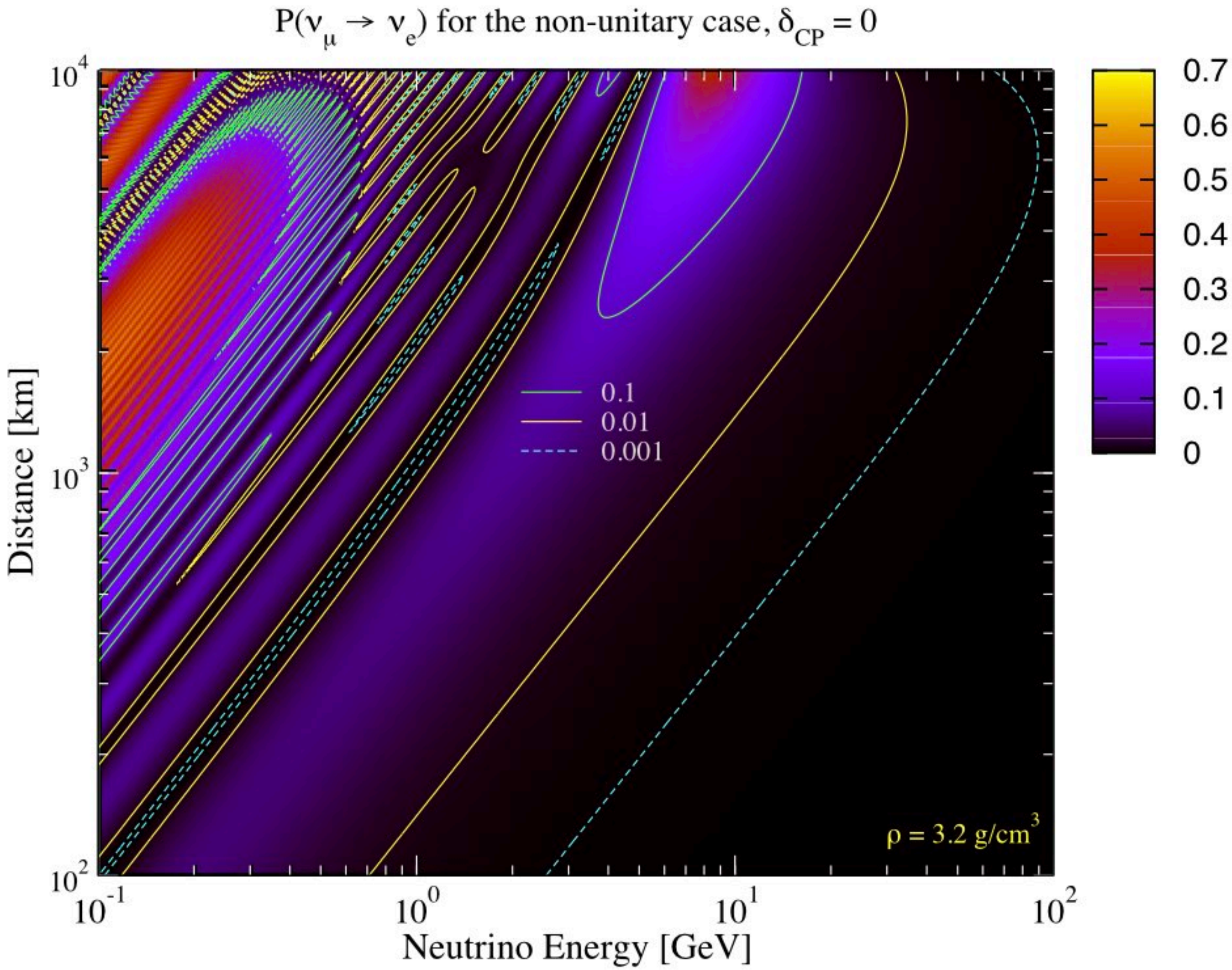
Partly based on Ivan Martinez-Soler, HM

My talk is meant to
be a pedagogical talk,
not for the experts…

Solar-scale oscillation is large on our planet

Let’s utilize it !



How to utilize terrestrial solar-scale oscillation ?

- E=100 – 500 MeV, L=1000 – 5000 km, solar scale oscillation is large
- Possibility to use it for precision measurement of parameters?
- Low energy atmospheric neutrinos
- Accelerator LBL neutrinos (JPARC beam to HKK)? → See next slide
- What is the characteristics of such low energy Nu?

T2HKK: Hyper-K in Korea

T2hkk white paper@PTEP

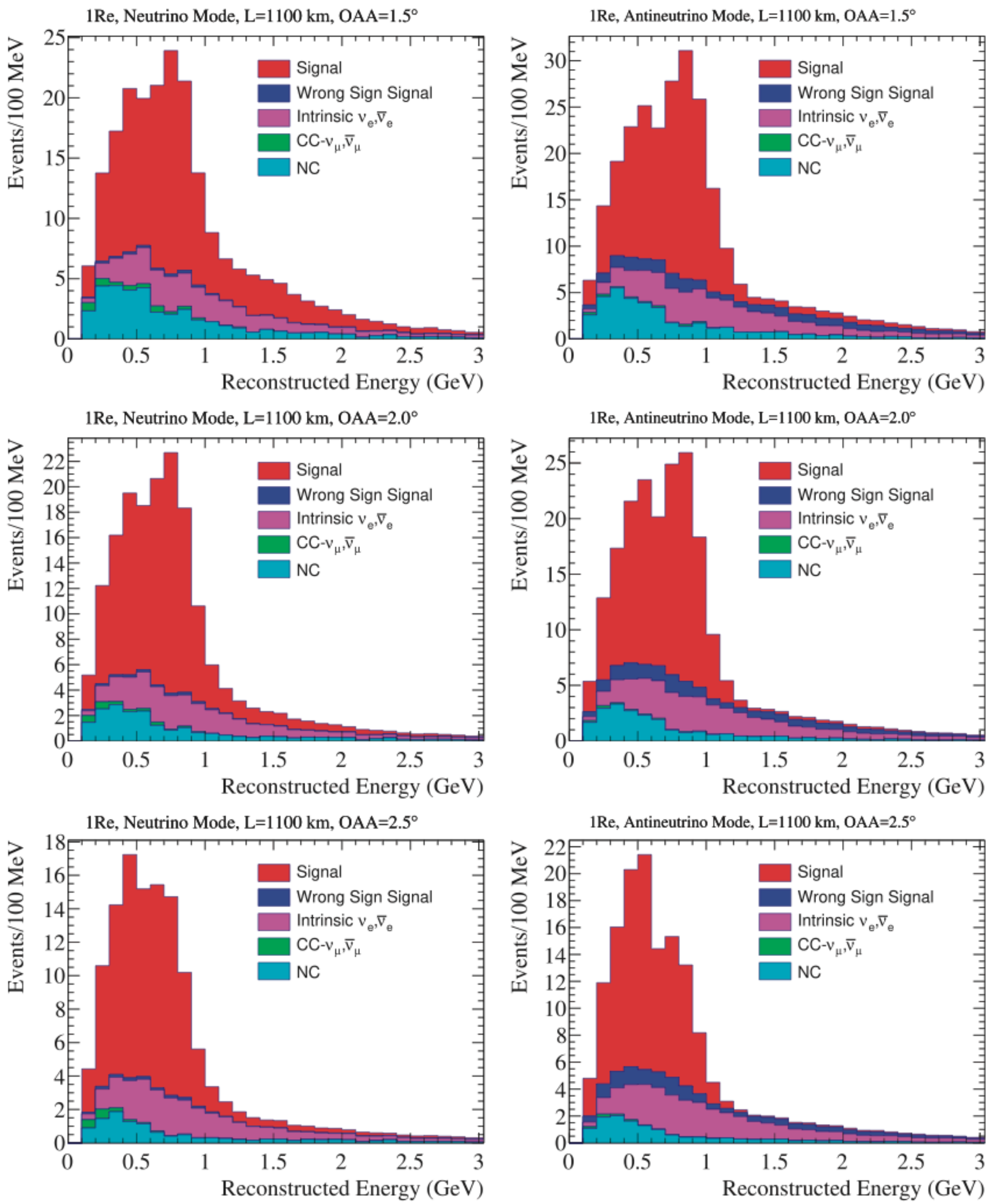


Fig. 13. Predicted 1R*e* candidate rates for neutrino mode (left) and antineutrino mode (right) with the detector at a 1.5° (top), 2.0° (middle), or 2.5° (bottom) off-axis angle. The oscillation parameters are set to $\delta_{CP} = 0$, $\Delta m^2_{32} = 2.5 \times 10^{-3}$ eV^2 (normal mass ordering), $\sin^2\theta_{23} = 0.5$, $\sin^2\theta_{13} = 0.0219$.

Physics of low energy neutrinos

CP violation is > 10 times larger in solar scale oscillation

To show the point, let us look at the CP odd $\sin\delta$ term in $P(\nu_\mu \to \nu_e)$ in vacuum.[9] It takes the form as

$$
\begin{aligned}
&-8 J_r \sin\delta \sin\left(\frac{\Delta_{21} x}{2}\right) \sin\left(\frac{\Delta_{31} x}{2}\right) \sin\left(\frac{\Delta_{32} x}{2}\right) \\
&\approx -8 J_r \sin\delta \sin\left(\frac{\Delta_{21} x}{2}\right) \sin^2\left(\frac{\Delta_{31} x}{2}\right) \qquad (5.6)
\end{aligned}
$$

$$J_r \equiv c_{23} s_{23} c_{13}^2 s_{13} c_\varphi s_\varphi . \qquad \Delta_{ji} \equiv \frac{\Delta m_{ji}^2}{2E},$$

Ivan Martinez-Soler, HM, to appear

- In usual LBL at atm. oscillation maximum, $\Delta_{21}L/2 = \Delta m^2_{21}L/4E = \sim \Delta m^2_{21}/\Delta m^2_{31} = 1/30$
- ➡ CPV is doubly suppressed, but not in solar maximum

L=1000 – 2000 km tunnel in the earth?

- Looks expensive…
- Lets formulate simple approximation by which we can calculate everything very easily
- Key parameters:

$$\frac{a}{\Delta m^2_{21}} = 0.609 \left(\frac{\Delta m^2_{21}}{7.5 \times 10^{-5}\ \mathrm{eV}^2} \right)^{-1} \left(\frac{\rho}{3.0\,\mathrm{g/cm}^3} \right) \left(\frac{E}{200\ \mathrm{MeV}} \right) \sim \mathcal{O}(1),$$

$$A_{\exp} \equiv c_{13} s_{13} \left| \frac{a}{\Delta m^2_{31}} \right| = 2.78 \times 10^{-3} \left(\frac{\Delta m^2_{31}}{2.4 \times 10^{-3}\ \mathrm{eV}^2} \right)^{-1} \left(\frac{\rho}{3.0\,\mathrm{g/cm}^3} \right) \left(\frac{E}{200\ \mathrm{MeV}} \right)$$

← Effective expansion parameter

solar resonance perturbation theory

Ivan Martinez-Soler, HM, to appear

Solar resonance perturbation theory: 1 p summary

$$\check{H} = (U_{23}U_{13})^{\dagger} H U_{23}U_{13} = U_{12} \begin{bmatrix} 0 & 0 & 0 \\ 0 & \Delta_{21} & 0 \\ 0 & 0 & \Delta_{31} \end{bmatrix} U_{12}^{\dagger} + U_{13}^{\dagger} \begin{bmatrix} \Delta_a & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} U_{13} \qquad \Delta_{ji} \equiv \frac{\Delta m_{ji}^2}{2E}, \qquad \Delta_a \equiv \frac{a}{2E}.$$

$$\check{H}_0 = \begin{bmatrix} s_{12}^2\Delta_{21} + c_{13}^2\Delta_a & c_{12}s_{12}\Delta_{21} & 0 \\ c_{12}s_{12}\Delta_{21} & c_{12}^2\Delta_{21} & 0 \\ 0 & 0 & \Delta_{31} + s_{13}^2\Delta_a \end{bmatrix} \qquad \check{H}_1 = \begin{bmatrix} 0 & 0 & c_{13}s_{13}\Delta_a \\ 0 & 0 & 0 \\ c_{13}s_{13}\Delta_a & 0 & 0 \end{bmatrix}$$

"hat" basis

$$\hat{H} = U_{\varphi}^{\dagger} \check{H} U_{\varphi} \qquad U_{\varphi} = \begin{bmatrix} \cos\varphi & \sin\varphi & 0 \\ -\sin\varphi & \cos\varphi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Only one nontrivial feature!!

$$\hat{H}_0 = \begin{bmatrix} h_1 & 0 & 0 \\ 0 & h_2 & 0 \\ 0 & 0 & h_3 \end{bmatrix}, \qquad \hat{H}_1 = \begin{bmatrix} 0 & 0 & c_{\varphi}c_{13}s_{13}\Delta_a \\ 0 & 0 & s_{\varphi}c_{13}s_{13}\Delta_a \\ c_{\varphi}c_{13}s_{13}\Delta_a & s_{\varphi}c_{13}s_{13}\Delta_a & 0 \end{bmatrix}$$

$$\hat{S}(x) = e^{-i\hat{H}_0 x}\Omega(x)$$

$$= \begin{bmatrix} e^{-ih_1x} & 0 & c_{\varphi}c_{13}s_{13}\frac{\Delta_a}{h_3-h_1}\left\{e^{-ih_3x} - e^{-ih_1x}\right\} \\ 0 & e^{-ih_2x} & s_{\varphi}c_{13}s_{13}\frac{\Delta_a}{h_3-h_2}\left\{e^{-ih_3x} - e^{-ih_2x}\right\} \\ c_{\varphi}c_{13}s_{13}\frac{\Delta_a}{h_3-h_1}\left\{e^{-ih_3x} - e^{-ih_1x}\right\} & s_{\varphi}c_{13}s_{13}\frac{\Delta_a}{h_3-h_2}\left\{e^{-ih_3x} - e^{-ih_2x}\right\} & e^{-ih_3x} \end{bmatrix}$$

Flavor basis S matrix

$$S = (U_{23}U_{13}U_{\varphi})\,\hat{S}\,(U_{23}U_{13}U_{\varphi})^{\dagger}.$$

$P(\nu_\mu \rightarrow \nu_e)$: zeroth order

$$P(\nu_\mu \to \nu_e)^{(0)} = c_{23}^2 c_{13}^2 \sin^2 2\varphi \sin^2 \frac{(h_2 - h_1)x}{2}$$
$$+ s_{23}^2 \sin^2 2\theta_{13} \left[c_\varphi^2 \sin^2 \frac{(h_3 - h_1)x}{2} + s_\varphi^2 \sin^2 \frac{(h_3 - h_2)x}{2} - c_\varphi^2 s_\varphi^2 \sin^2 \frac{(h_2 - h_1)x}{2} \right]$$
$$+ 4 J_{mr} \cos\delta \left\{ \cos 2\varphi \sin^2 \frac{(h_2 - h_1)x}{2} - \sin^2 \frac{(h_3 - h_2)x}{2} + \sin^2 \frac{(h_3 - h_1)x}{2} \right\}$$
$$+ 8 J_{mr} \sin\delta \sin \frac{(h_3 - h_2)x}{2} \sin \frac{(h_2 - h_1)x}{2} \sin \frac{(h_1 - h_3)x}{2}.$$

$$J_{mr} \equiv c_{23} s_{23} c_{13}^2 s_{13} c_\varphi s_\varphi = J_r \left[\left(\cos 2\theta_{12} - c_{13}^2 r_a \right)^2 + \sin^2 2\theta_{12} \right]^{-1/2}$$

$$J_r \equiv c_{23} s_{23} c_{13}^2 s_{13} c_\varphi s_\varphi.$$

$P(\nu_\mu \rightarrow \nu_e)$: zeroth order—averaged over atmospheric oscillations

$$
\begin{aligned}
P(\nu_\mu \to \nu_e)^{(0)} &= c_{23}^2 c_{13}^2 \sin^2 2\varphi \sin^2 \frac{(h_2-h_1)x}{2} \\
&+ s_{23}^2 \sin^2 2\theta_{13}\left[c_\varphi^2 \sin^2 \frac{(h_3-h_1)x}{2} + s_\varphi^2 \sin^2 \frac{(h_3-h_2)x}{2} - c_\varphi^2 s_\varphi^2 \sin^2 \frac{(h_2-h_1)x}{2}\right] \\
&+ 4J_{mr}\cos\delta\left\{\cos 2\varphi \sin^2 \frac{(h_2-h_1)x}{2} - \sin^2 \frac{(h_3-h_2)x}{2} + \sin^2 \frac{(h_3-h_1)x}{2}\right\} \\
&+ 8J_{mr}\sin\delta \sin \frac{(h_3-h_2)x}{2} \sin \frac{(h_2-h_1)x}{2} \sin \frac{(h_1-h_3)x}{2}.
\end{aligned}
$$

→

$$
\begin{aligned}
\left\langle P(\nu_\mu \to \nu_e)^{(0)} \right\rangle &= \frac{1}{2} s_{23}^2 \sin^2 2\theta_{13} + c_{13}^2 \sin^2 2\varphi \left(c_{23}^2 - s_{23}^2 s_{13}^2\right) \sin^2 \frac{(h_2-h_1)x}{2} \\
&+ 4J_{mr}\cos\delta \cos 2\varphi \sin^2 \frac{(h_2-h_1)x}{2} - 2J_{mr}\sin\delta \sin(h_2-h_1)x.
\end{aligned}
$$

$$
J_{mr} \equiv c_{23} s_{23} c_{13}^2 s_{13} c_\varphi s_\varphi = J_r \left[\left(\cos 2\theta_{12} - c_{13}^2 r_a\right)^2 + \sin^2 2\theta_{12}\right]^{-1/2}
$$

CP violation at solar resonance

$$\left\langle P(\nu_\mu \to \nu_e)^{(0)} \right\rangle = \frac{1}{2} s_{23}^2 \sin^2 2\theta_{13} + c_{13}^2 \sin^2 2\varphi \left(c_{23}^2 - s_{23}^2 s_{13}^2\right) \sin^2 \frac{(h_2 - h_1)x}{2}$$

$$+ 4J_{mr} \cos\delta \cos 2\varphi \sin^2 \frac{(h_2 - h_1)x}{2} - 2J_{mr} \sin\delta \sin(h_2 - h_1)x.$$

$$(h_2 - h_1)x = \pi/2.$$

$\sin 2\theta_{12} = 0.9248$, $J_r \equiv c_{23} s_{23} c_{13}^2 s_{13} c_{12} s_{12} = 0.03339$, and $J_{mr} = J_r / \sin 2\theta_{12} = 0.03611$.

→

the magnitude of the $\sin\delta$ term at the solar resonance is given by

$$2J_{mr} = J_r / \sin 2\theta_{12} = 0.0722$$

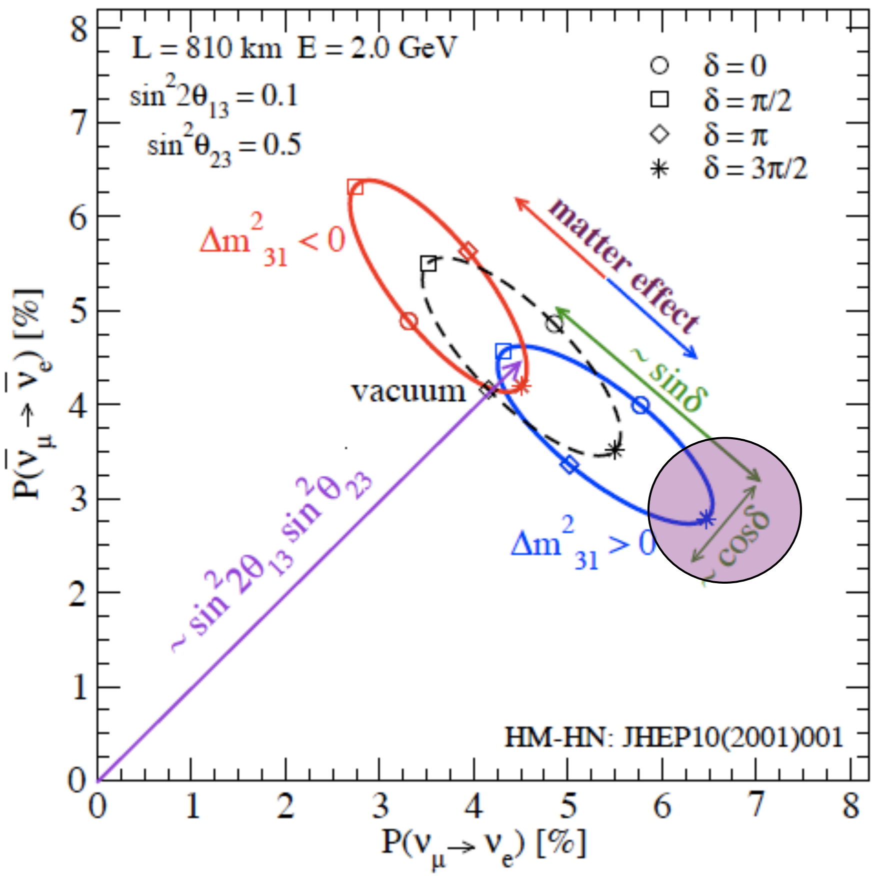
LBL in vacuum

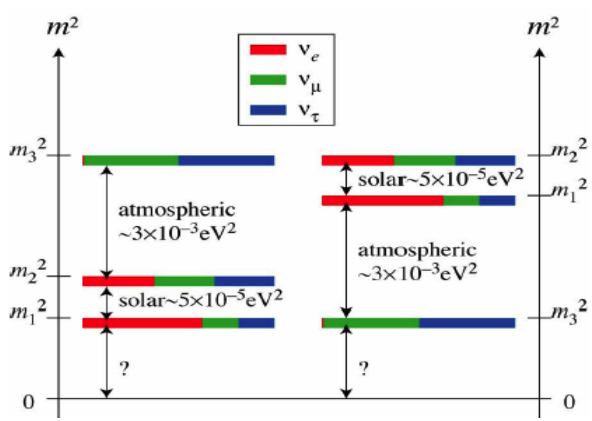
$$8\epsilon J_r \simeq 0.0089,$$

12 times larger

δ=3π/2 (or –π/2) implies that we are at the tip of the ellipse → the best case for NOvA

P-\bar{P} bi-probability diagram, proposed by HM-H.Nunokawa, JHEP 2001



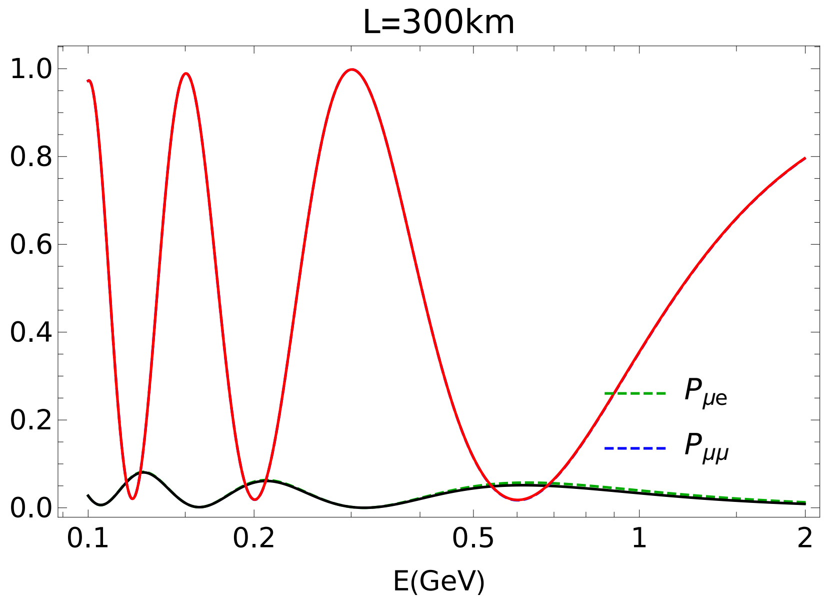


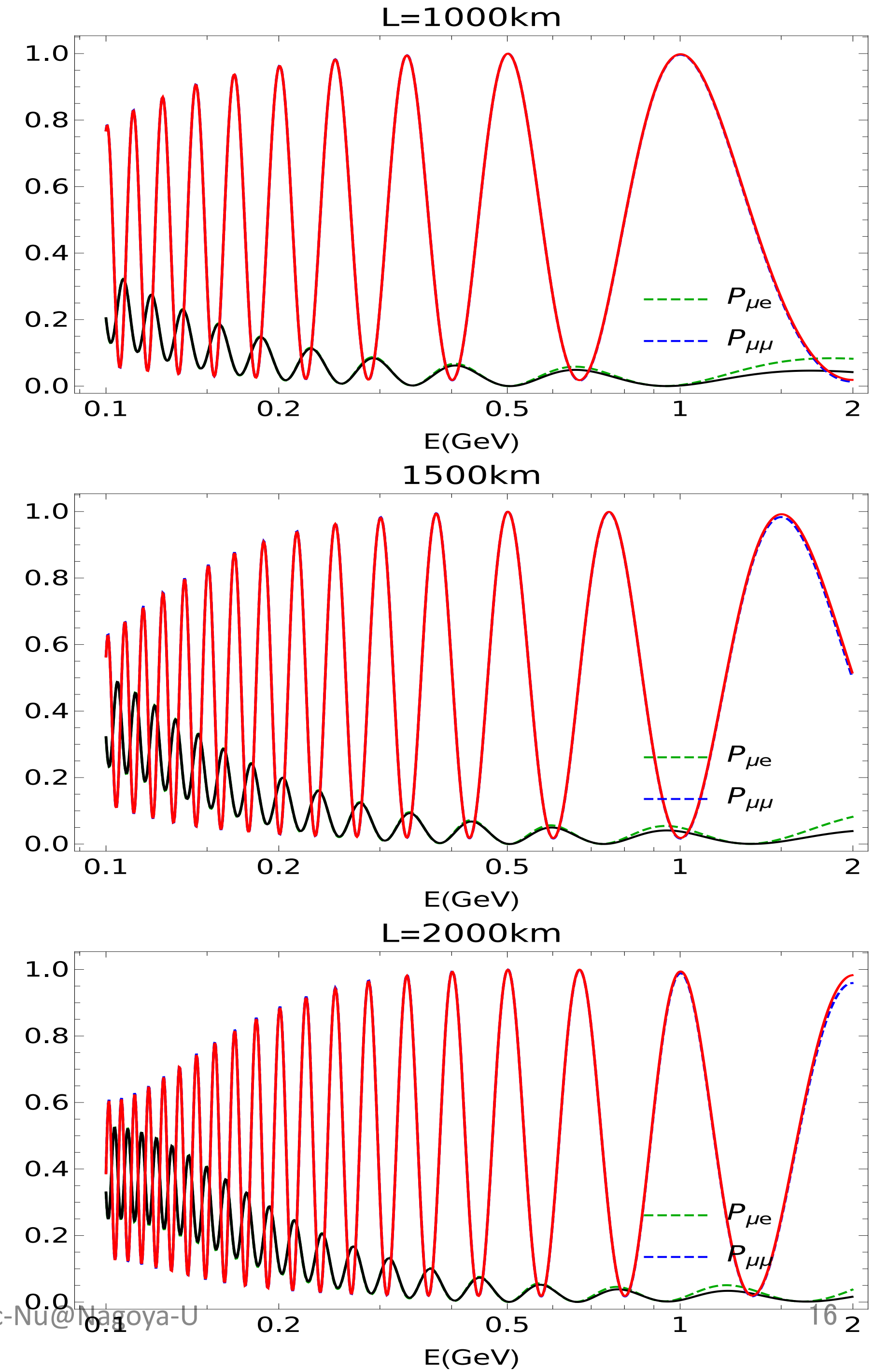
Sign of Δm^2_{31} distinguishes normal vs inverted mass ordering

δ and sign Δm^2_{31} couple because (Δm^2_{31} → − Δm^2_{31} , δ →π-δ) symmetry in vacuum (JHEP 2001)

How accurate is the formula?

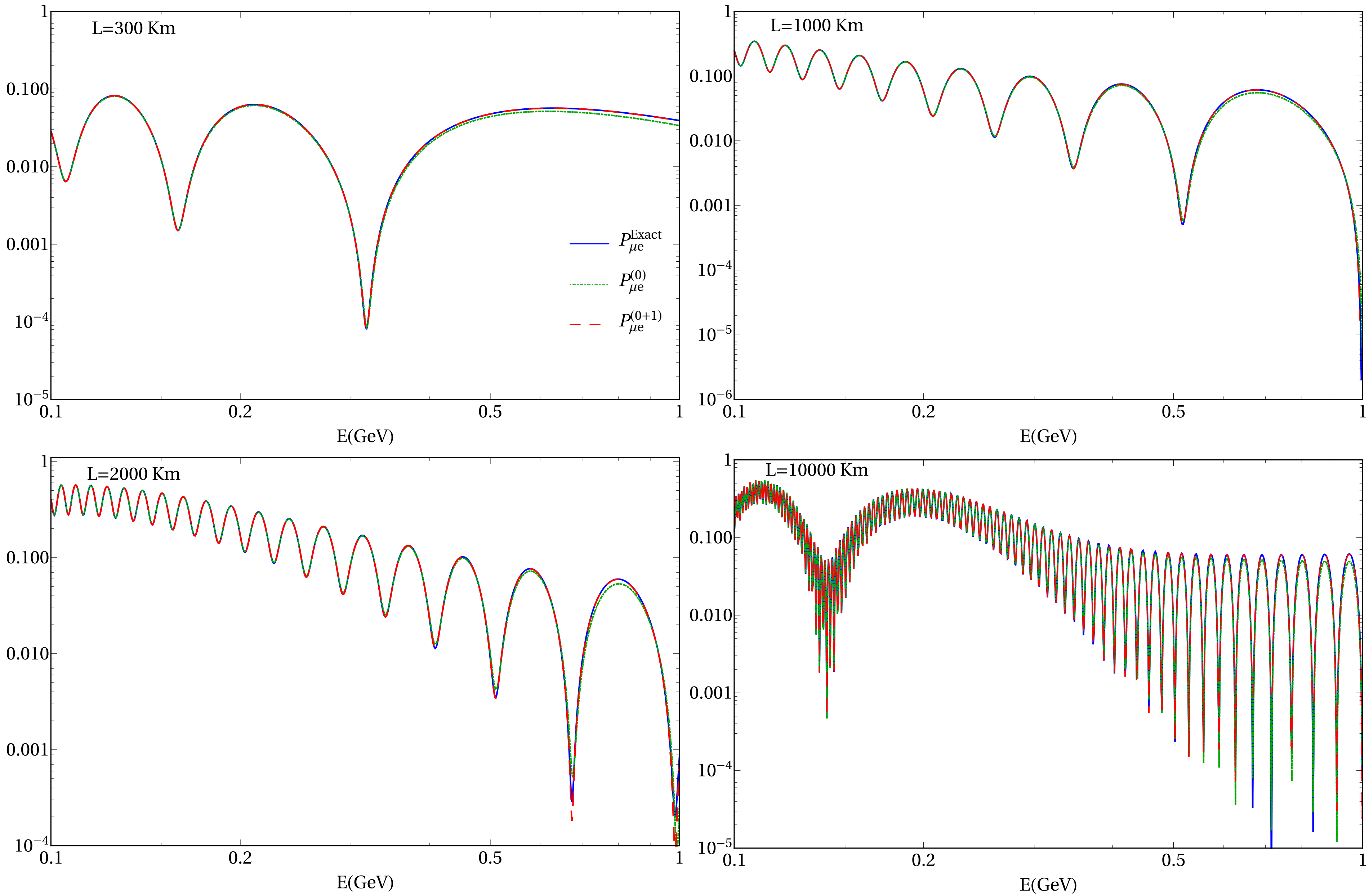
How accurate is the formula? (leading order)





Works even for T2K !!

Ivan Martinez-Soler, HM, to appear


L=300 Km
L=1000 Km
L=2000 Km
L=10000 Km
$P_{\mu e}^{\rm Exact}$
$P_{\mu e}^{(0)}$
$P_{\mu e}^{(0+1)}$
E(GeV)
E(GeV)
E(GeV)
E(GeV)

Physics with low-energy atmospheric neutrinos

Atmospheric neutrinos at low energies

- low-energy atmospheric neutrinos

→ very interesting option for parameter measurement

- Because of many large detectors in construction or planned

→ Hyper-K, DUNE, JUNO, IceCube-Gen2/PINGU and KM3NeT-ORCA …

- Main oscillation term in $P_{\mu e} \sim c_{23}^2$ (unlike conventional LBL $\sim s_{23}^2$)

→ good for θ_{23} degeneracy

Extensive works done, see below, but not became a majority?...

[25] O. L. G. Peres and A. Y. Smirnov, "Atmospheric neutrinos: LMA oscillations, U(e3) induced interference and CP violation," Nucl. Phys. B **680** (2004) 479 doi:10.1016/j.nuclphysb.2003.12.017 [hep-ph/0309312].

[26] O. L. G. Peres and A. Y. Smirnov, "Oscillations of very low energy atmospheric neutrinos," Phys. Rev. D **79** (2009) 113002 doi:10.1103/PhysRevD.79.113002 [arXiv:0903.5323 [hep-ph]].

[27] E. K. Akhmedov, M. Maltoni and A. Y. Smirnov, "Neutrino oscillograms of the Earth: Effects of 1-2 mixing and CP-violation," JHEP **0806**, 072 (2008) doi:10.1088/1126-6708/2008/06/072 [arXiv:0804.1466 [hep-ph]].

[28] S. Razzaque and A. Y. Smirnov, "Super-PINGU for measurement of the leptonic CP-phase with atmospheric neutrinos," JHEP **1505** (2015) 139 doi:10.1007/JHEP05(2015)139 [arXiv:1406.1407 [hep-ph]].

May be more...

To do physics with low-energy atmospheric neutrinos

- Okumura-san says: the limiting factor is "systematic errors too large" (>~ 20%)
- What are the systematic errors?
- Neutrino flux and cross sections (very bread & butter…)
- Honda-san says: to improve flux prediction, measure atmospheric muon flux at 500 MeV – 1.5 GeV
- How? HAWK?, ALPACA?, GRAPES-3?

100 MeV atmospheric neutrinos?

- JUNO: atmospheric neutrino detection in liquid scintillatior ??

  → e-μ separation?, Directionality?, Energy resolution?

- DUNE: atmospheric neutrino detection in liquid Ar?
- How Gd helps

Conclusion

- low-energy atmospheric neutrinos

→ very interesting target experimentally (even for theorists)

- Physics is very simple: CP phase dependent terms ~> 10 times larger than conventional LBL
- Main oscillation term in $P_{\mu e} \sim c_{23}^2$ ($\sim s_{23}^2$ in conventional LBL)
- Experimentally challenging:

→ Control systematic error: flux and σ

→ new detection scheme: JUNO, DUNE, SKGd

P(ν_μ → ν_e): first order

$$
\begin{aligned}
&P(\nu_e \to \nu_\mu)^{(1)} \\
&= 4c_{13}^2 s_{13}^2 c_\varphi^2 \frac{\Delta_a}{h_3 - h_1} \Bigg[\left\{ s_{23}^2 \cos 2\theta_{13}(1 + c_\varphi^2) - c_{23}^2 s_\varphi^2 \right\} \sin^2 \frac{(h_3 - h_1)x}{2} \\
&- s_\varphi^2 \left(c_{23}^2 + s_{23}^2 \cos 2\theta_{13} \right) \left\{ \sin^2 \frac{(h_2 - h_1)x}{2} - \sin^2 \frac{(h_3 - h_2)x}{2} \right\} \Bigg] \\
&+ 4c_{13}^2 s_{13}^2 s_\varphi^2 \frac{\Delta_a}{h_3 - h_2} \Bigg[\left\{ s_{23}^2 \cos 2\theta_{13}(1 + s_\varphi^2) - c_{23}^2 c_\varphi^2 \right\} \sin^2 \frac{(h_3 - h_2)x}{2} \\
&- c_\varphi^2 \left(c_{23}^2 + s_{23}^2 \cos 2\theta_{13} \right) \left\{ \sin^2 \frac{(h_2 - h_1)x}{2} - \sin^2 \frac{(h_3 - h_1)x}{2} \right\} \Bigg] \\
&+ 4J_{mr} \cos\delta \frac{\Delta_a}{h_3 - h_1} \Bigg[\left\{ \cos 2\theta_{13} c_\varphi^2 - s_{13}^2 (1 + c_\varphi^2) \right\} \sin^2 \frac{(h_3 - h_1)x}{2} \\
&+ \left(\cos 2\theta_{13} c_\varphi^2 + s_{13}^2 s_\varphi^2 \right) \left\{ \sin^2 \frac{(h_2 - h_1)x}{2} - \sin^2 \frac{(h_3 - h_2)x}{2} \right\} \Bigg] \\
&- 4J_{mr} \cos\delta \frac{\Delta_a}{h_3 - h_2} \Bigg[\left\{ \cos 2\theta_{13} s_\varphi^2 - s_{13}^2 (1 + s_\varphi^2) \right\} \sin^2 \frac{(h_3 - h_2)x}{2} \\
&+ \left(\cos 2\theta_{13} s_\varphi^2 + s_{13}^2 c_\varphi^2 \right) \left\{ \sin^2 \frac{(h_2 - h_1)x}{2} - \sin^2 \frac{(h_3 - h_1)x}{2} \right\} \Bigg] \\
&+ 8J_{mr} \sin\delta \left(s_{13}^2 - c_{13}^2 c_\varphi^2 \right) \frac{\Delta_a}{h_3 - h_1} \sin \frac{(h_3 - h_2)x}{2} \sin \frac{(h_2 - h_1)x}{2} \sin \frac{(h_1 - h_3)x}{2} \\
&+ 8J_{mr} \sin\delta \left(s_{13}^2 - c_{13}^2 s_\varphi^2 \right) \frac{\Delta_a}{h_3 - h_2} \sin \frac{(h_3 - h_2)x}{2} \sin \frac{(h_2 - h_1)x}{2} \sin \frac{(h_1 - h_3)x}{2}
\end{aligned}
$$

$$
J_{mr} \equiv c_{23} s_{23} c_{13}^2 s_{13} c_\varphi s_\varphi = J_r \left[\left(\cos 2\theta_{12} - c_{13}^2 r_a \right)^2 + \sin^2 2\theta_{12} \right]^{-1/2}
$$