地球の物質密度測定を使った MSW理論のテスト

"Testing MSW theory by Determination of Earth Matter Density"

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第20回「宇宙ニュートリノ」研究会
2007年2月20日 @ 宇宙線研究所

研究会テーマ

ニュートリノで探る

non-standard physics

“standard physics” is *standard* ?

neutrino oscillation

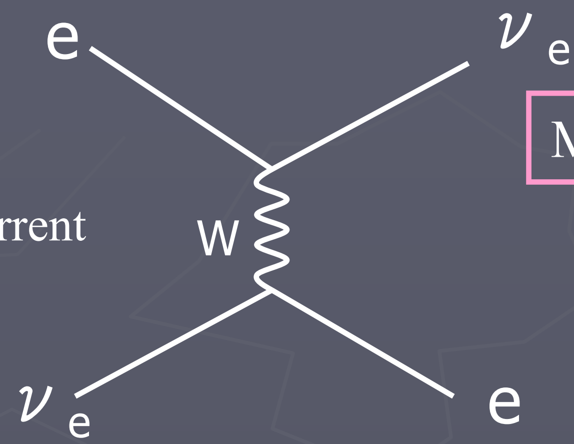
in vacuum

$$i\frac{\partial}{\partial t}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U\begin{pmatrix}0 & 0 & 0\\ 0 & \frac{\Delta m^2_{21}}{2E} & 0\\ 0 & 0 & \frac{\Delta m^2_{31}}{2E}\end{pmatrix}U^{-1}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

$$\begin{pmatrix}c_{12}c_{13} & c_{13}s_{12} & e^{-i\delta}s_{13}\\ -c_{23}s_{12}-e^{i\delta}c_{12}s_{13}s_{23} & c_{12}c_{23}-e^{i\delta}s_{12}s_{13}s_{23} & c_{13}s_{23}\\ s_{12}s_{23}-e^{i\delta}c_{12}c_{23}s_{13} & -e^{i\delta}c_{23}s_{12}s_{13}-c_{12}s_{23} & c_{13}c_{23}\end{pmatrix}$$

$$s_{ij}\equiv\sin\theta_{ij},\, c_{ij}\equiv\cos\theta_{ij}$$

standard interaction theory



charged current

Mikheev-Smirnov-Wolfenstein

MSW effect

charged current interaction with electron

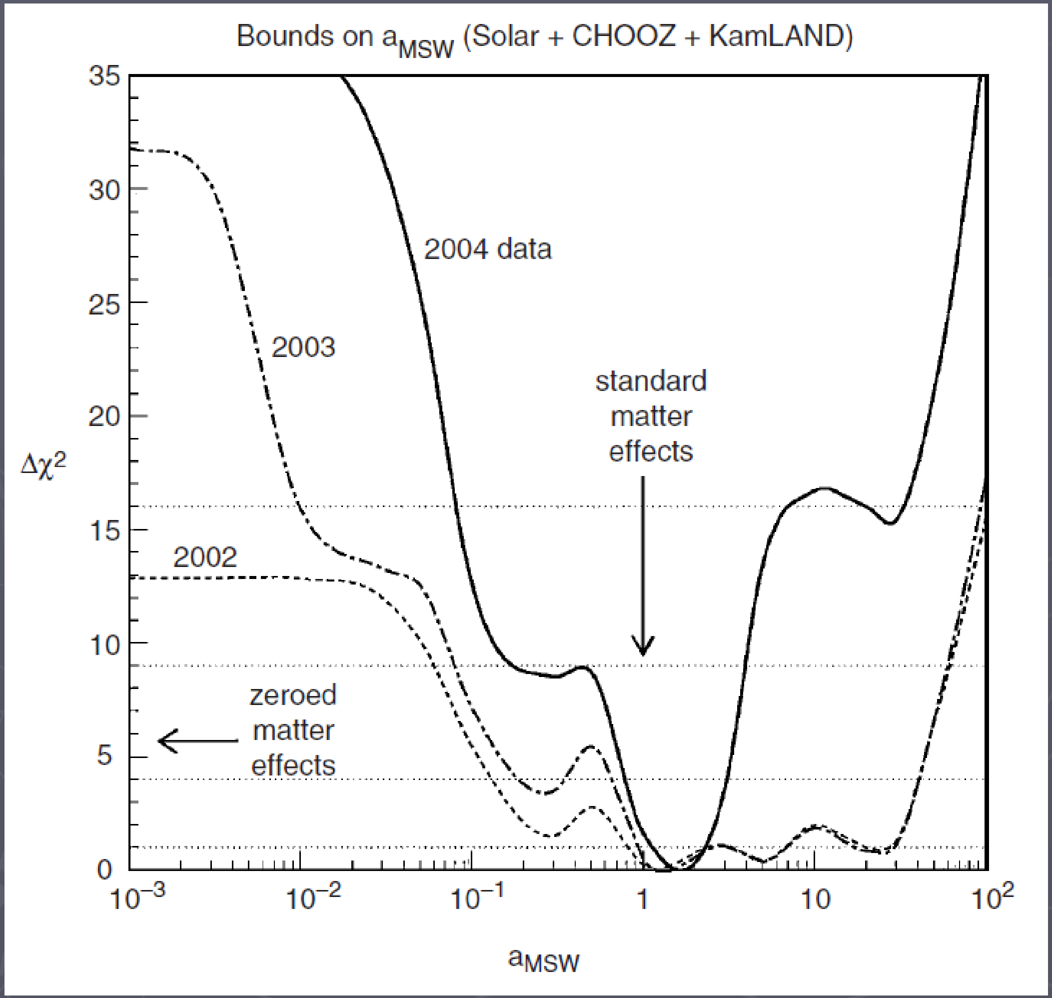
$$i\frac{\partial}{\partial t}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \left\{ U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} \end{pmatrix} U^{-1} + \begin{pmatrix} \sqrt{2}G_F N_e & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \right\} \begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

electron number density

neutrino oscillations are modified

in matter

Evidence for the MSW effect



Gianluigi Fogli, Eligio Lisi

"Evidence for the MSW effect"

New J.Phys.6:139,2004.

$$V = a_{MSW} \times V_{standard}$$
$$= a_{MSW}\sqrt{2}G_F N_e$$

a_{MSW}=1 for standard

a factor of ~2 uncertainty (at 2σ)

Testing MSW theory

in neutrino factory

more precision

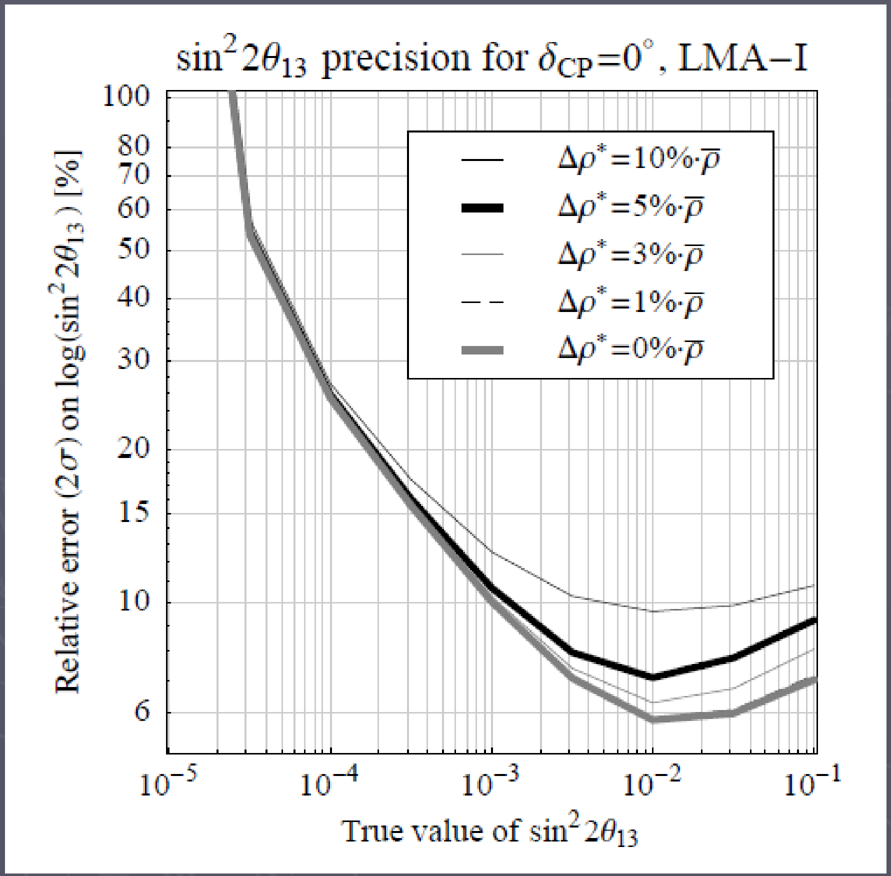
Original Motivation

We want to determine the Earth Matter Density

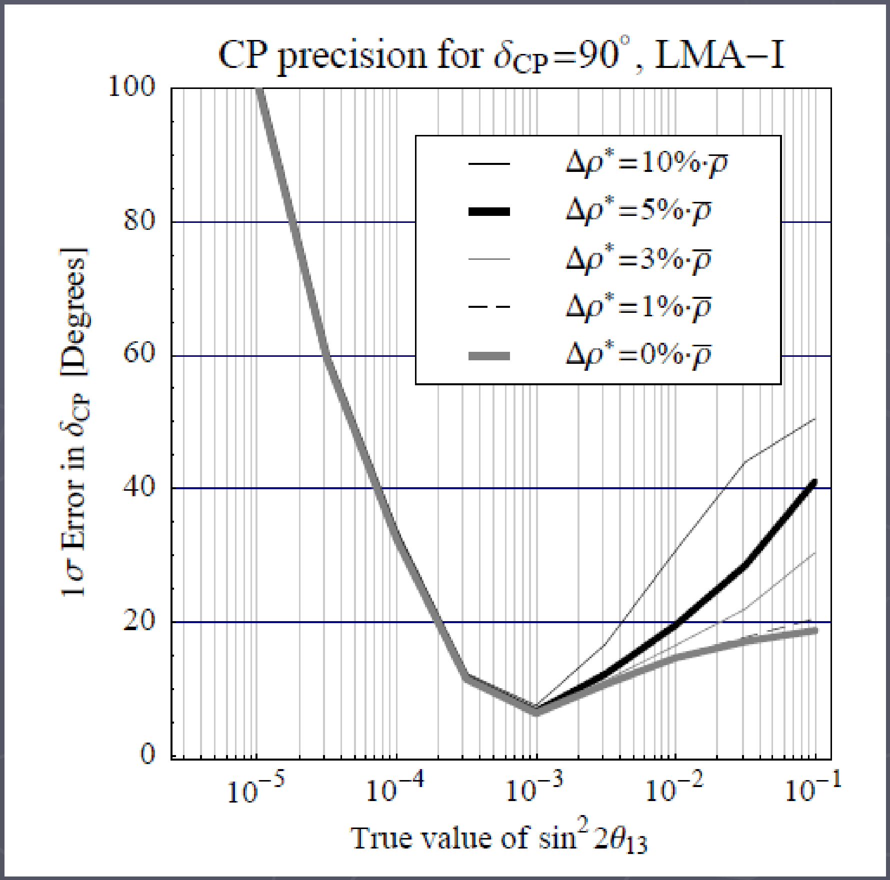
in Neutrino Factory

Effect of matter density uncertainties

on $\sin^2 2\theta_{13}$



on CP δ



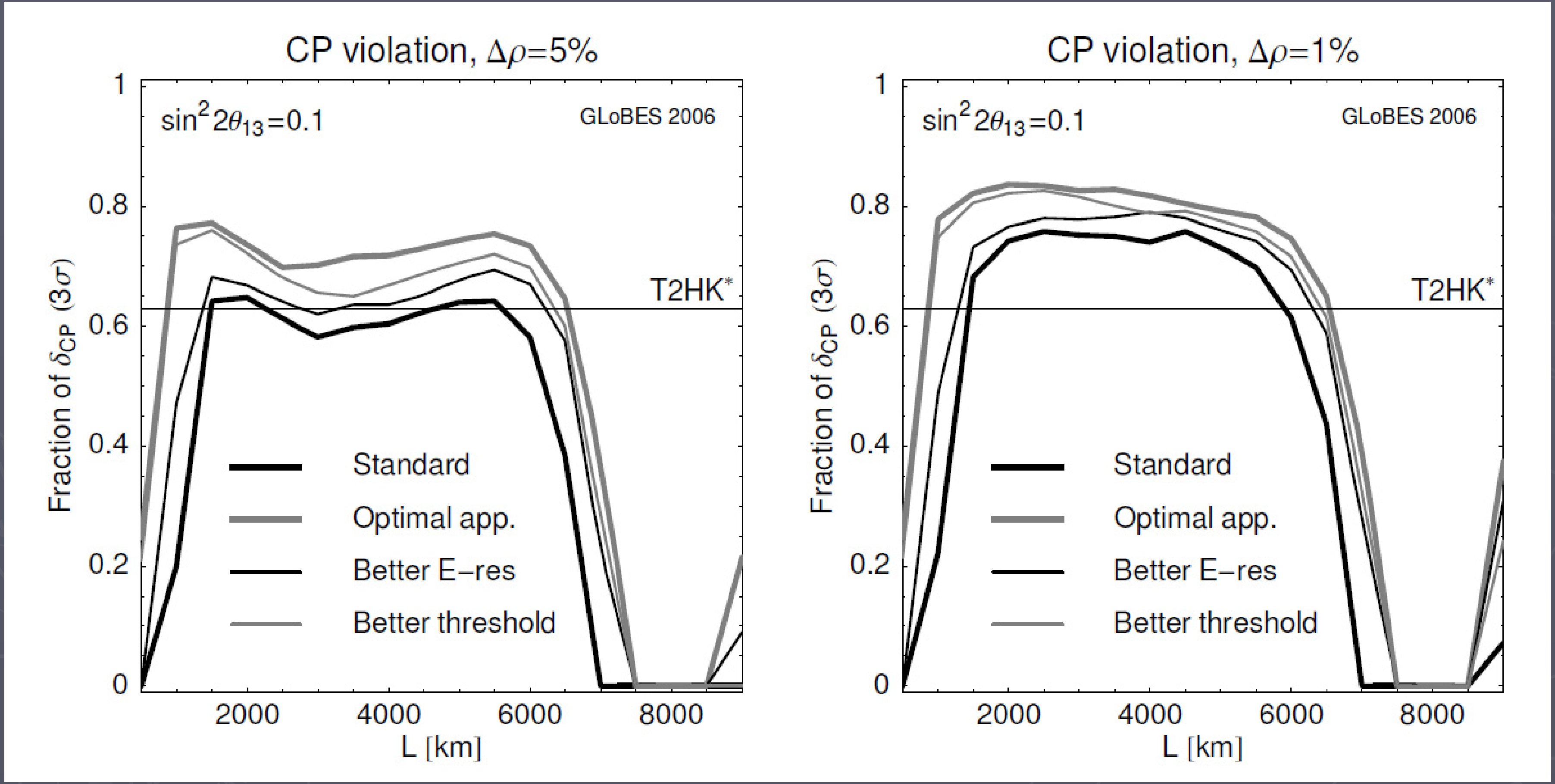
Tommy Ohlsson , Walter Winter

"The role of matter density uncertainties in the analysis of future neutrino factory experiments"

Phys.Rev.D68:073007,2003

Effect of matter density uncertainties

on sensitivity to CP violation



P. Huber , M. Lindner , M. Rolinec , W. Winter

"Optimization of a neutrino factory oscillation experiment "

Phys.Rev.D74:073003,2006

Determination of Earth Matter Density

(highly precise)

↓

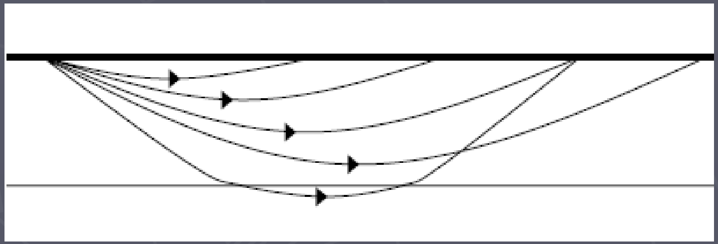
Test of MSW theory

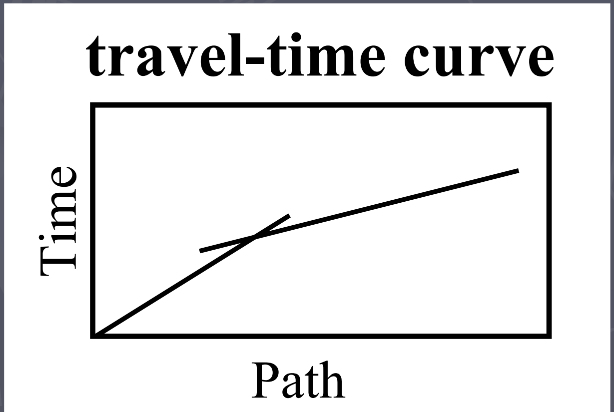
(compare with geographic data)

Earth Structure by Geophysics

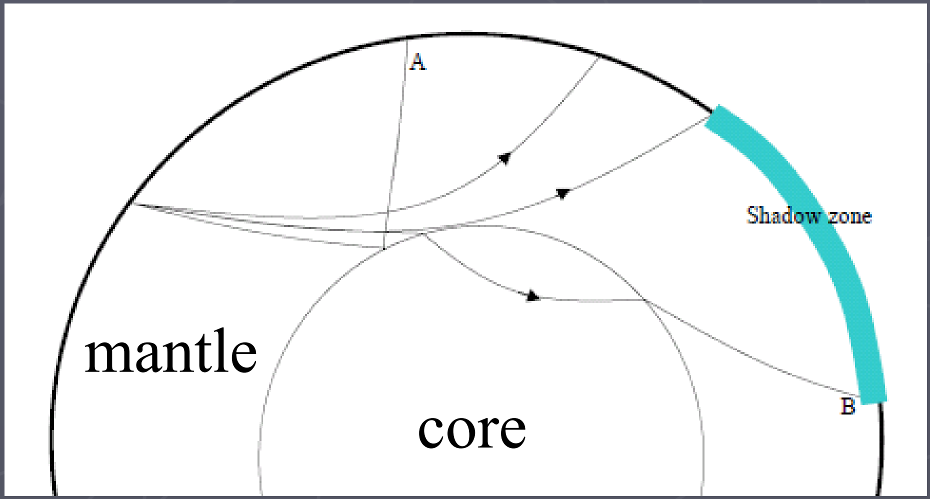
Seismic waves tell us about Earth

Mohorovičić discontinuity





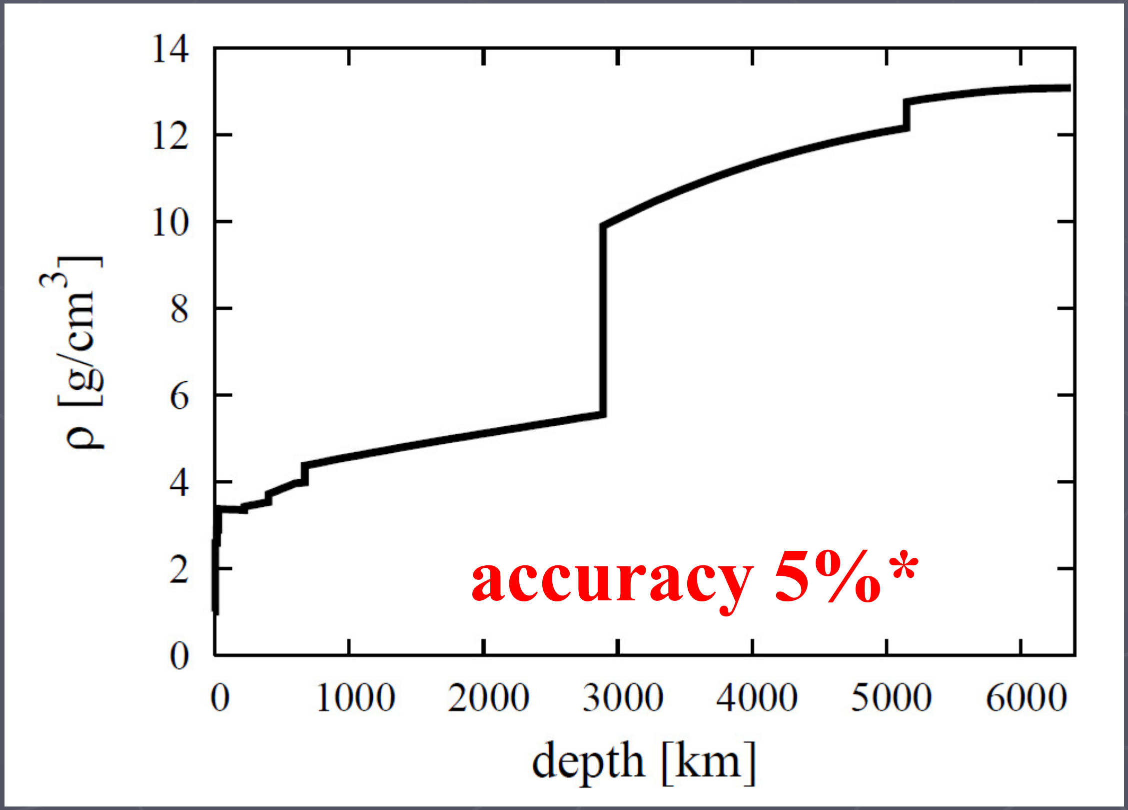
Core-Mantle boundary



Density Profile

seismic +

free vibration by massive earthquake & inertia moment etc.



isotropic PREM

A. M. Dziewonski , D. L. Anderson
"Preliminary reference Earth model"
Phys.Earth. Planet. Inter. 25, 4, 297, (1981)

* Robert Geller , Tatsuhiko Hara
"Geophysical aspects of very long baseline neutrino experiments"
Nucl.Instrum.Meth.A503:187-191,2001

focus on

Neutrino Factory

NF have potential for determination of density

(very long baseline & $\nu_e \rightarrow \nu_\mu$ channel)

$\nu_e \to \nu_\mu$ (appearance) in matter

$$P(\nu_e \to \nu_\mu) = X_\pm \sin^2 2\theta_{13} + Y_\pm \sin 2\theta_{13} \cos(\pm\delta - \Delta_{31}) + P_{sol}$$

$$X_\pm = s_{23}^2 \left(\frac{\Delta_{31} \sin(aL \mp \Delta_{31})}{aL \mp \Delta_{31}} \right)^2$$

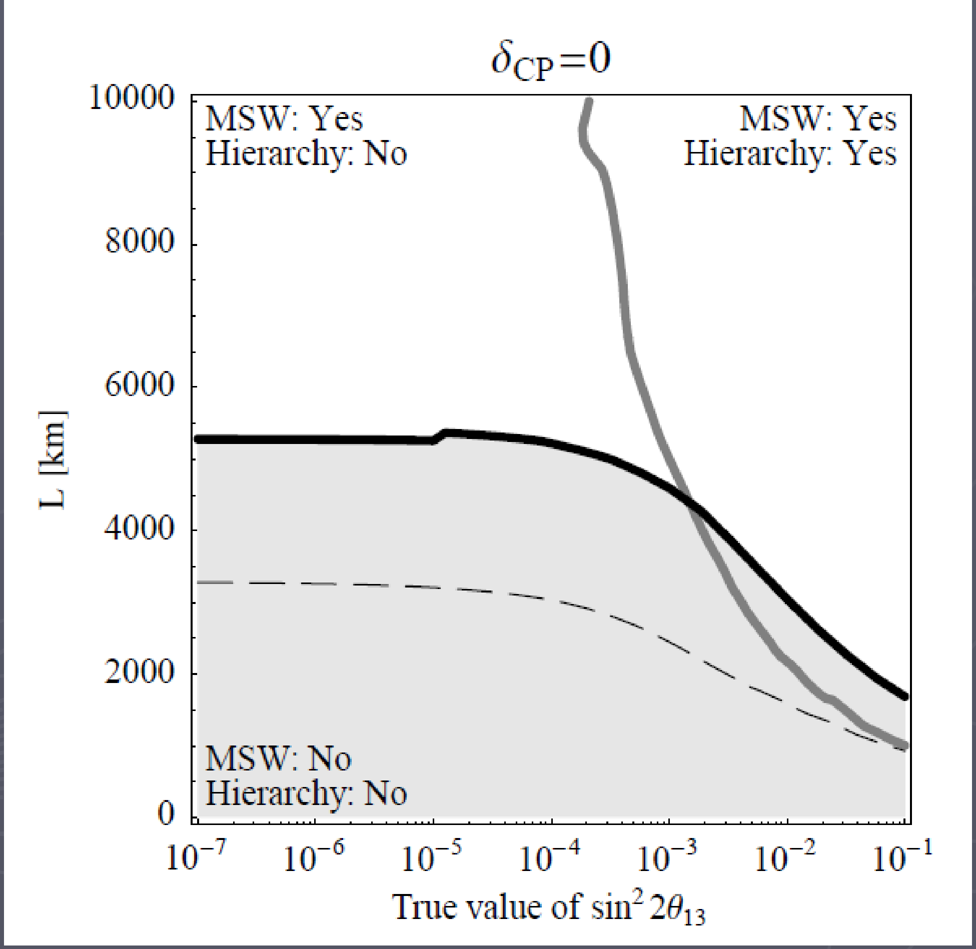
$$Y_\pm = \sin 2\theta_{12} \sin 2\theta_{23} \left(\frac{\Delta_{31} \sin(aL \mp \Delta_{31})}{aL \mp \Delta_{31}} \right) \left(\frac{\Delta_{21} \sin(aL)}{aL} \right)$$

$$P_{sol} = c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{21} \sin(aL)}{aL} \right)^2$$

$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E}$$

$$a = \frac{G_F Y_e}{\sqrt{2} m_N} \rho$$

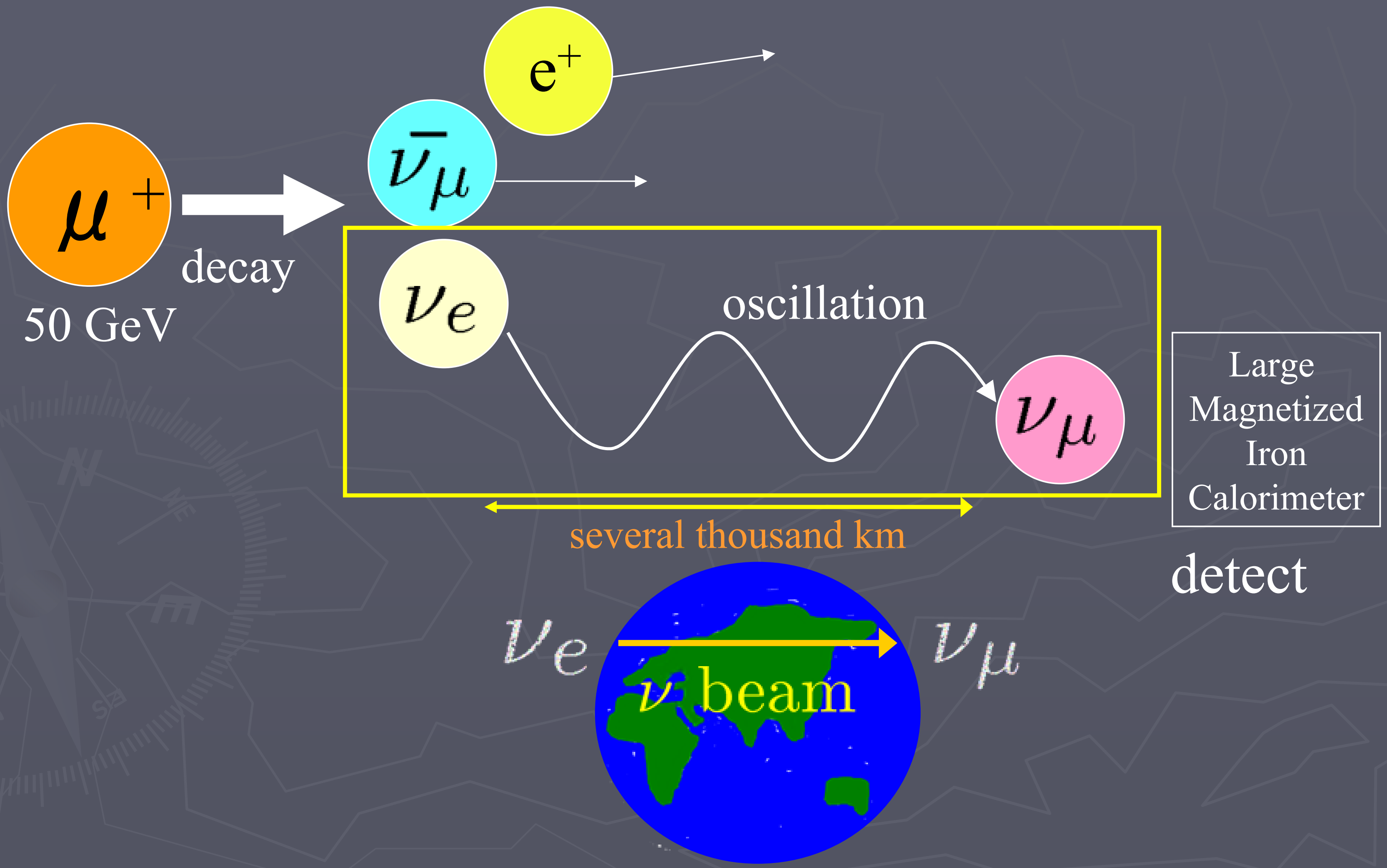
Direct test of MSW in neutrino factory



MSW effect≠0 (5σ)

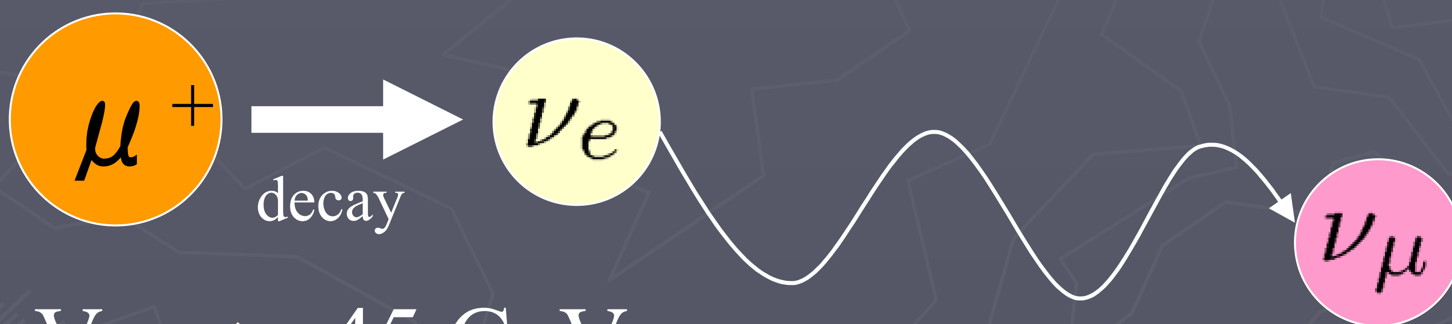
Walter Winter
"Direct test of the MSW effect by the solar appearance term in beam experiments"
Phys.Lett.B613:67-73,2005.

neutrino factory



First Step (Which distance is better?)

tune a muon energy



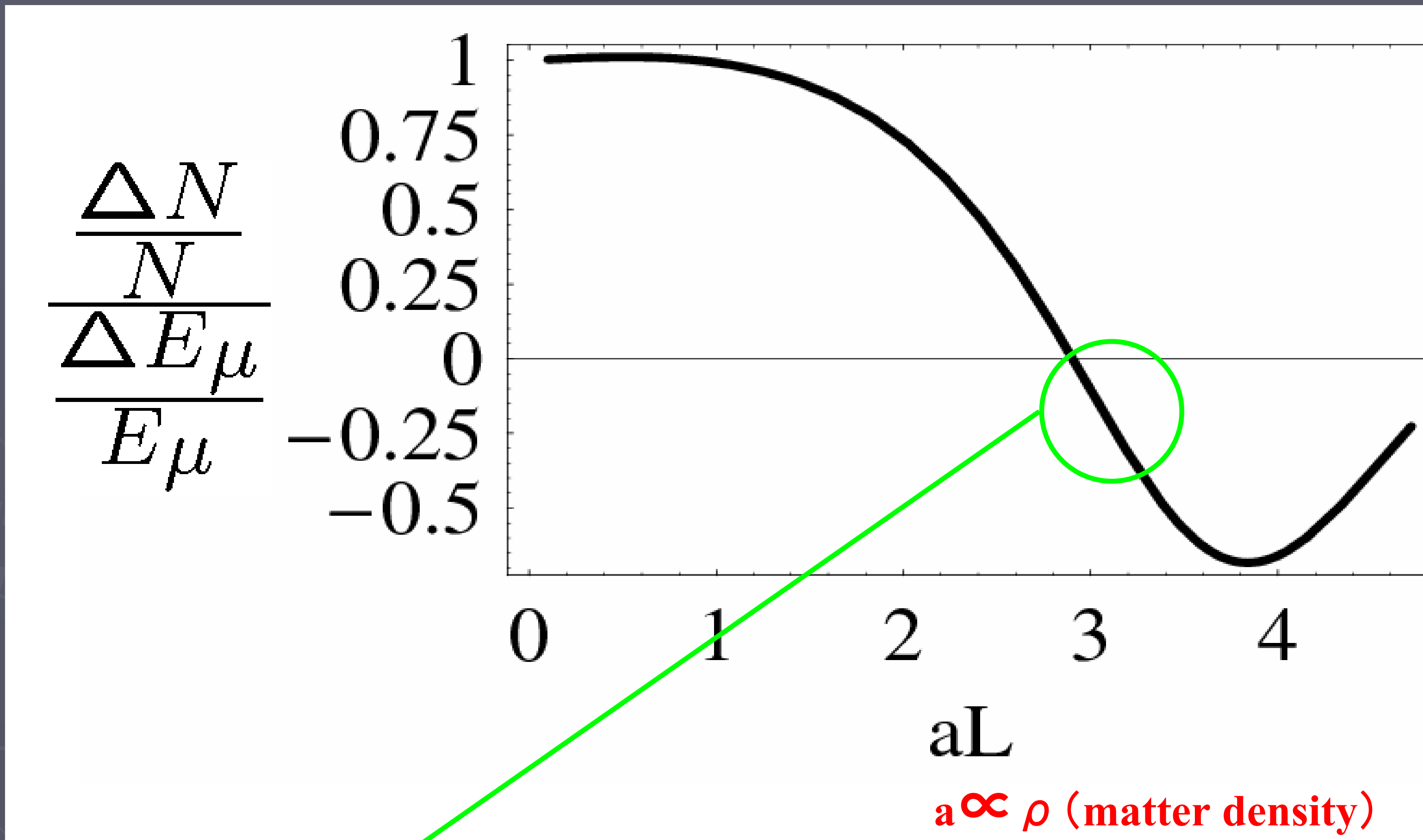
50 GeV $\longrightarrow$ 45 GeV

2 years   2 years

(energy scan)

New Information
variation of event number

Energy Scan



aL=π　large gradient

→strong response to density change

Good determination

$$aL = \pi$$

(a = const × matter density)

special distance

(Magic Baseline)

$$\left(a = \frac{G_F Y_e}{\sqrt{2} m_N} \rho \right)$$

L=7500 km

Magic Baseline（aL＝π）

L=7500 km

$$P(\nu_e \to \nu_\mu) = X_\pm \sin^2 2\theta_{13}$$
$$+ Y_\pm \sin 2\theta_{13} \cos(\pm\delta - \Delta_{31}) + P_{sol}$$

$$X_\pm = s_{23}^2 \left(\frac{\Delta_{31} \sin(aL \mp \Delta_{31})}{aL \mp \Delta_{31}} \right)^2$$

$$Y_\pm = \sin 2\theta_{12} \sin 2\theta_{23} \left(\frac{\Delta_{31} \sin(aL \mp \Delta_{31})}{aL \mp \Delta_{31}} \right) \left(\frac{\Delta_{21} \sin(aL)}{aL} \right)$$

$$P_{sol} = c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{21} \sin(aL)}{aL} \right)^2$$

vanish at aL＝π

→ measure θ_{13} independently of CP δ

of course matter density!

analysis

at Magic BL

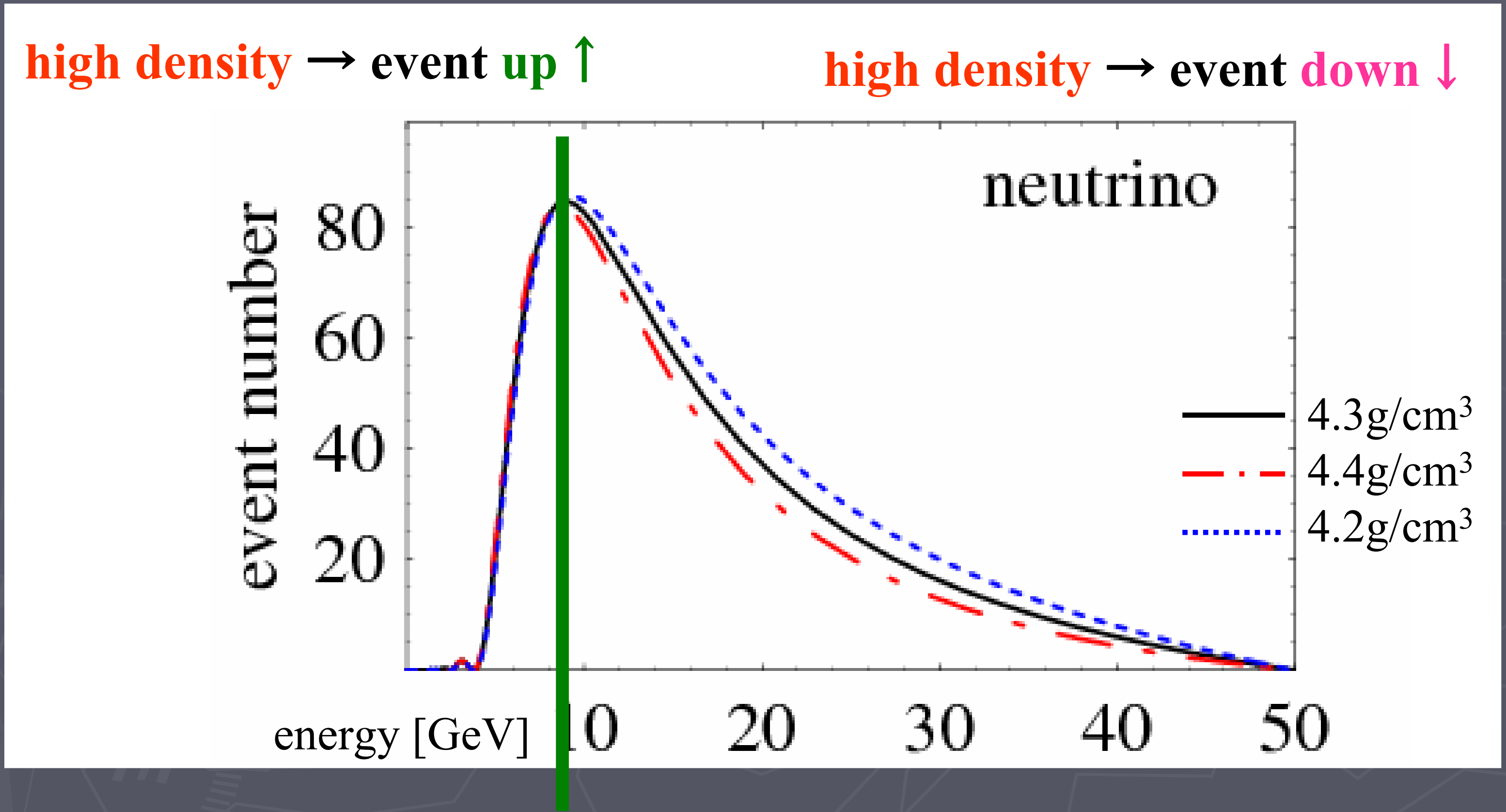
$$P(\nu_e \to \nu_\mu) = s_{23}^2 \left(\frac{\Delta_{31} \sin(aL \mp \Delta_{31})}{aL \mp \Delta_{31}} \right)^2 \sin^2 2\theta_{13}$$

event number scale depending on θ_{13}

↓

note energy spectra

analysis



low energy ⇔ high energy

opposite response of density change

critical energy

response of density change

$aL = \pi \;\rightarrow\; \pi + \varepsilon$

$$\delta P = 2 s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{31} \sin(\pi \mp \Delta_{31})}{\pi \mp \Delta_{31}} \right)^2 \times \left[\mp \cot(\Delta_{31}) - \frac{1}{\pi \mp \Delta_{31}} \right] \epsilon$$

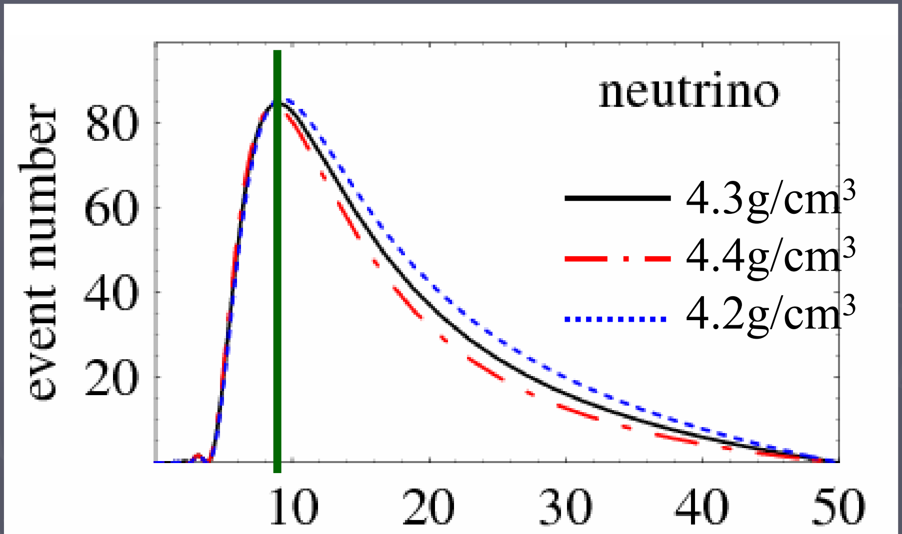
$$\Delta_{31} = \frac{\Delta m_{31}^2 L}{4E}$$

critical energy E_C

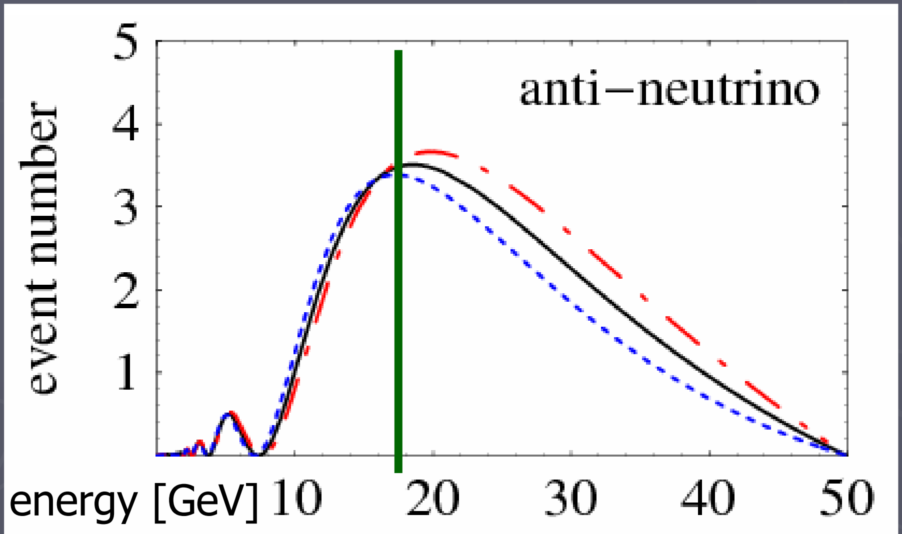
normal hierarchy	$\delta P > 0 \; (E < E_C)$
neutrino channel	$\delta P < 0 \; (E > E_C)$

response of density change

neutrino



anti-neutrino



(low E : event few & high E : event large)
→low density

(low E : event large & high E : event few)
→high density

(low E : event large & high E : event few)
→high density

(low E : event few & high E : event large)
→low density

low-high energy 2 bin analysis

analysis

chi-square test

$$\Delta\chi^2 \equiv \min_{\alpha's} \sum_{a=\nu,\bar{\nu}} \left[\sum_{i=1,2} \left\{ \frac{\left(N_{ai}^{obs} - (1+\alpha_i+\alpha_a+\alpha)N_{ai}^{exp}\right)^2}{N_{ai}^{exp} + \sigma_{ai}^2 (N_{ai}^{exp})^2} + \frac{\alpha_i^2}{\sigma_i^2} \right\} + \frac{\alpha_a^2}{\sigma_a^2} \right] + \frac{\alpha^2}{\sigma_{corr}^2}$$

N_1 : event number of low energy bin

N_2 : event number of high energy bin

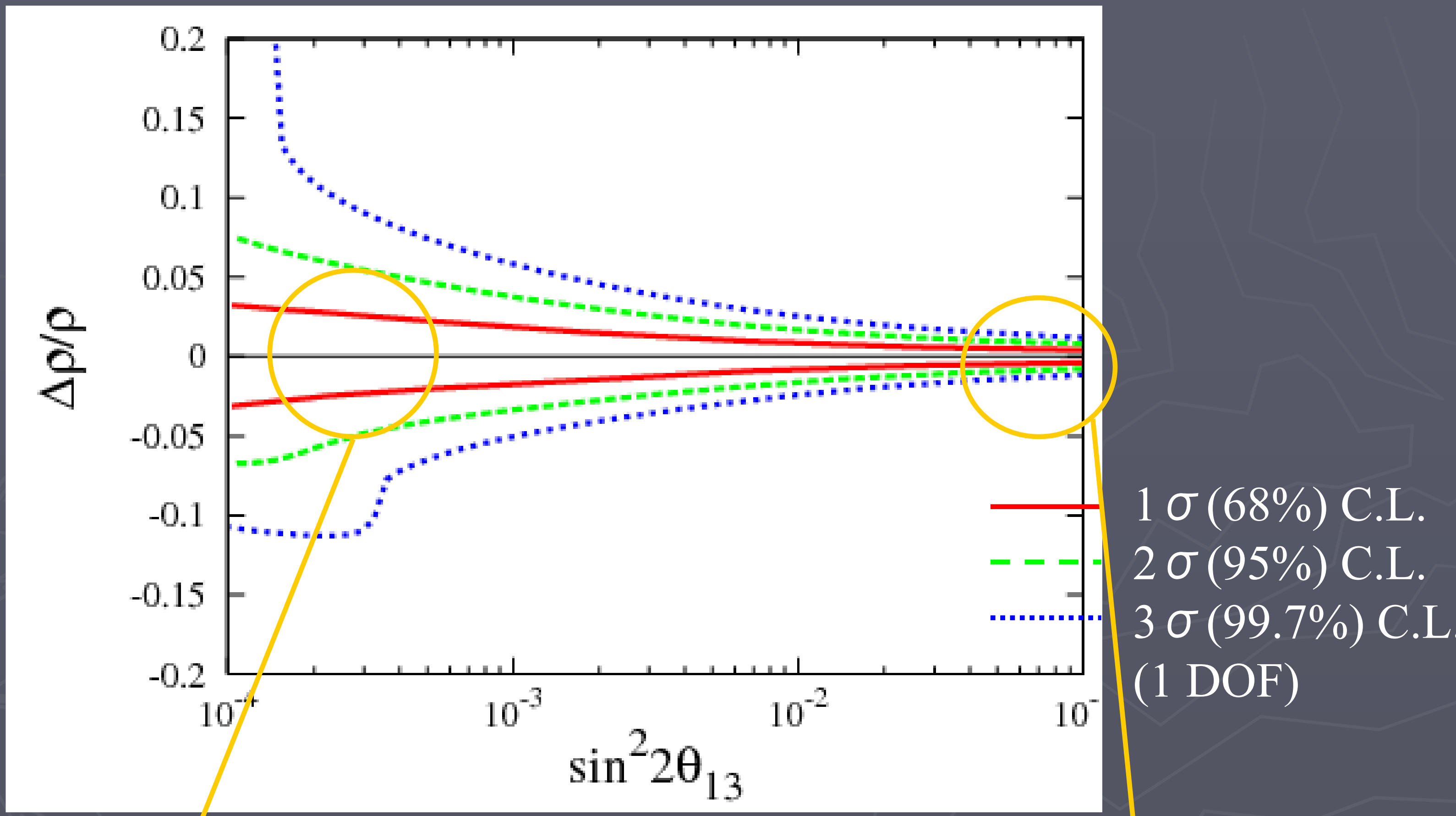
σ : systematic error

$\sigma_{corr} = \sigma_a = \sigma_i = 2\%$, $\sigma_{ai} = 1\%$

fit θ_{13} and ρ

result

accuracy of matter density $\Delta\rho / \rho$



a few (<5) % (1 σ)

1% ! (3 σ)

Magic Baseline（aL= π ）

L=7500 km

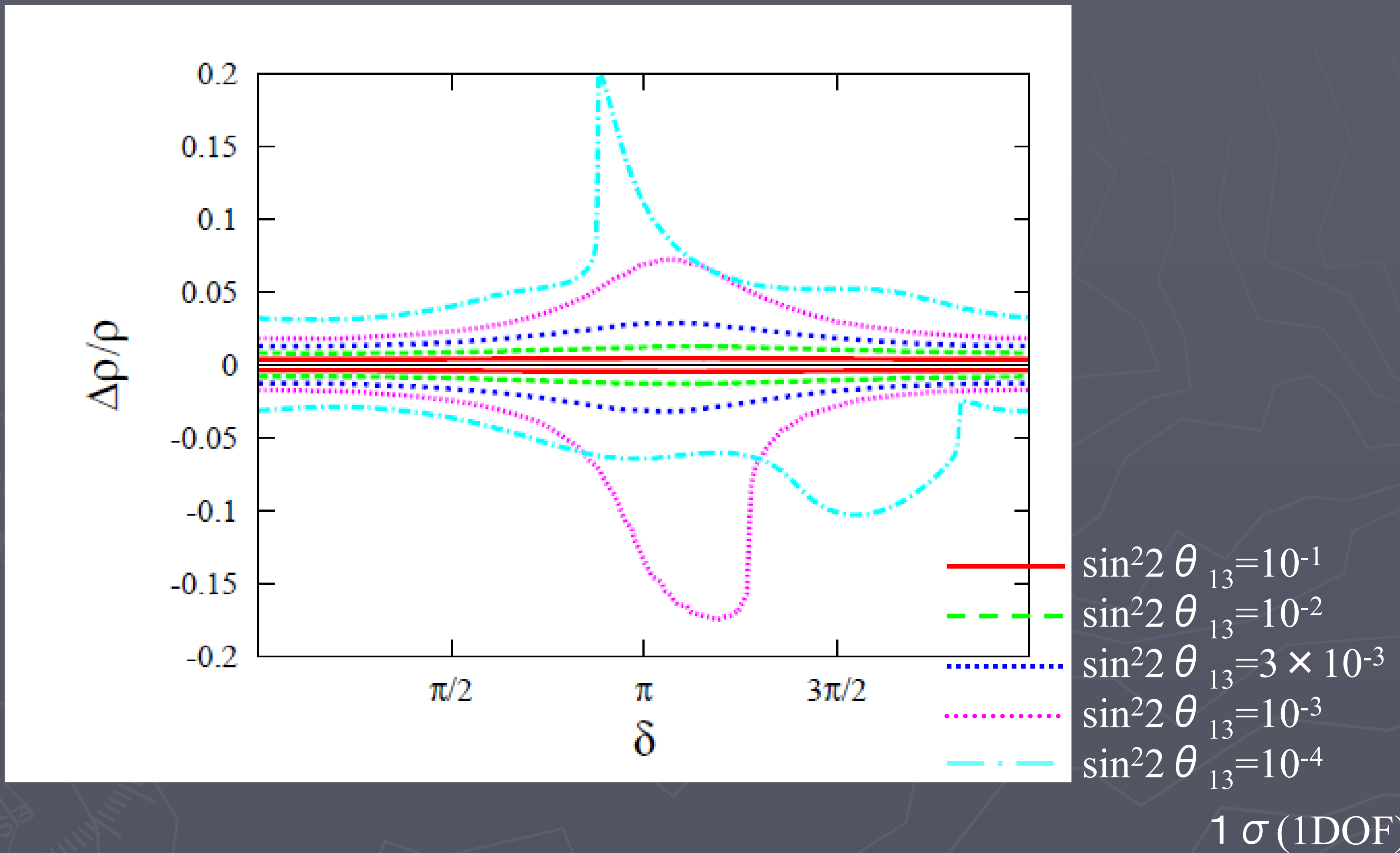
$$P(\nu_e \to \nu_\mu) = X_\pm \sin^2 2\theta_{13}$$

$$\cancel{+Y_\pm \sin 2\theta_{13} \cos(\pm\delta - \Delta_{31}) + P_{sol}}$$

→It was independently of CP δ

But…

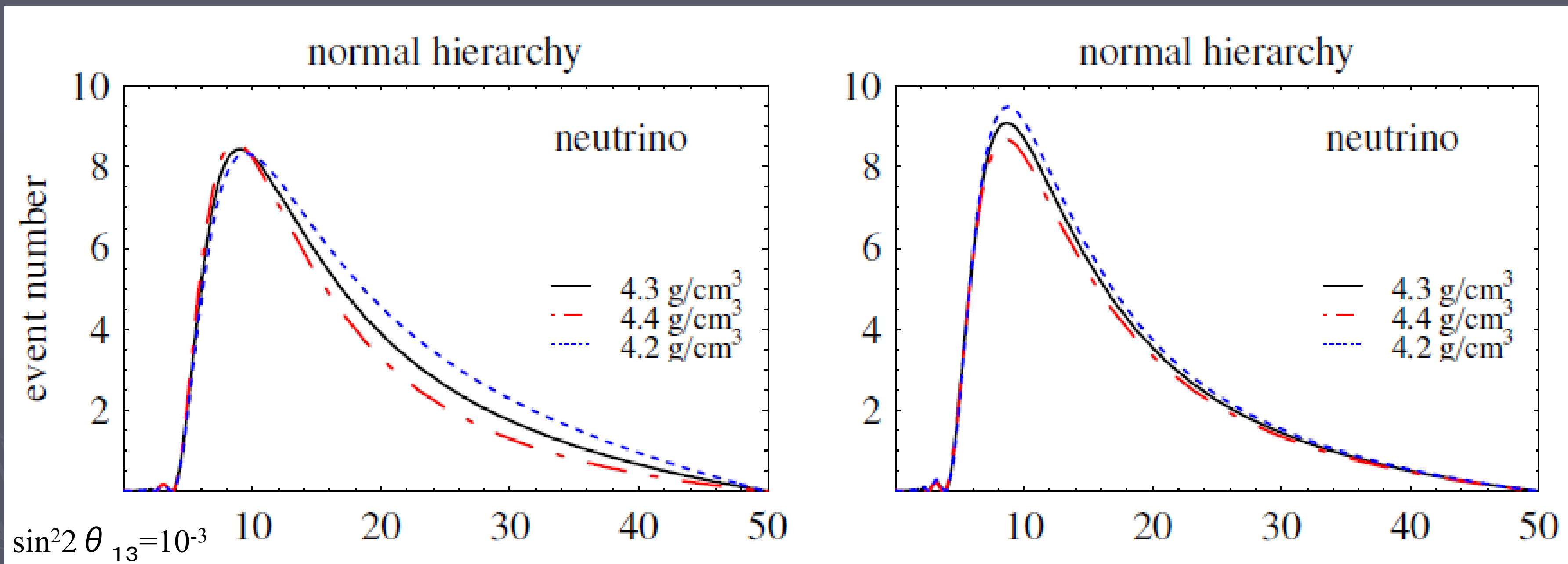
δ dependence



if θ_{13} is small ($\sin^2 2\theta_{13}<10^{-3}$),
accuracy of matter density get worse depending on δ

δ dependence

(small θ_{13})



$\delta = 0$ $\delta = 7\pi/6$

oscillation probability change is small

δ dependence

response of density change

aL = $\pi \longrightarrow \pi + \varepsilon$

$$\delta P(\nu_e \to \nu_\mu) = -\epsilon A \left[\pm \cos(\delta \mp \Delta_{31}) + B \sin 2\theta_{13} \right]$$

If θ_{13} is small
canceled out!

poor response to density change

↓

enlarged error in $\Delta \rho / \rho$

summary

- very precise determination of ρ at Magic BL
- large θ_{13} $\rightarrow$ 1 % (3 σ)
- small θ_{13} $\rightarrow$ < 5 % (1 σ)

MSW theory 200 % (2 σ) accuracy → 10 % ?

in future…

- Analysis with density profile
- New Physics search !