# Phenomenology of neutrino
# --- Overview ---

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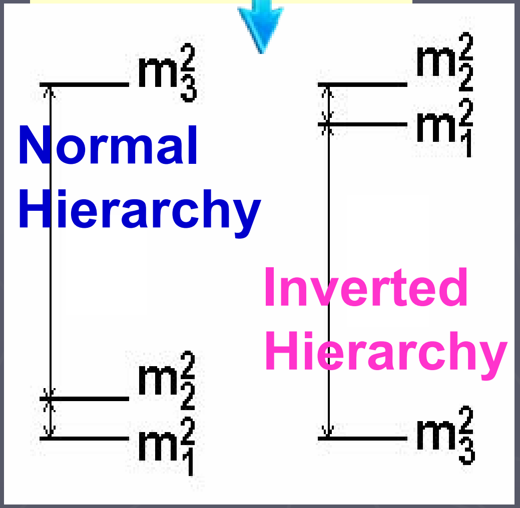
# Contents

# 1. Introduction

## Framework of 3 flavor ν oscillation

Both hierarchy patterns are allowed




**Mixing matrix**

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Functions of mixing angles $\theta_{12}$, $\theta_{23}$, $\theta_{13}$, and CP phase $\delta$

## All 3 mixing angles have been measured (2012):

$\nu_{solar}$+KamLAND (reactor) → $\theta_{12} \cong \frac{\pi}{6}, \Delta m_{21}^2 \cong 8 \times 10^{-5} eV^2$

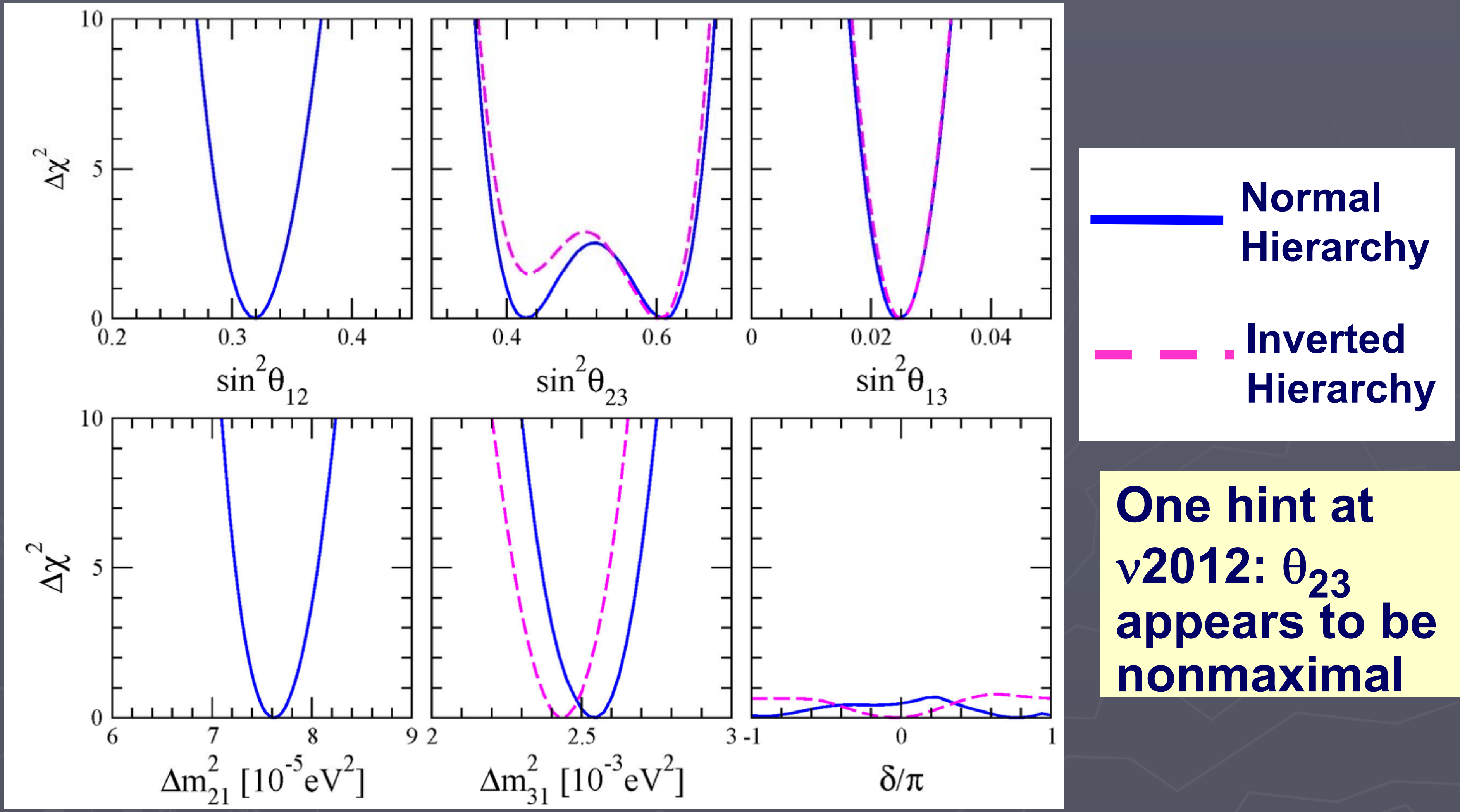
$\nu_{atm}$+K2K,MINOS(accelerators) → $\theta_{23} \cong \frac{\pi}{4}, |\Delta m_{32}^2| \cong 2.5 \times 10^{-3} eV^2$

DCHOOZ+Daya Bay+Reno (reactors), T2K+MINOS, others → $\theta_{13} \cong \pi / 20$

Johnson's talk

Hillairet's talk

# Global analysis




**One hint at $\nu$2012: $\theta_{23}$ appears to be nonmaximal**

**Forero, Tortola, Valle arXiv:1205.4018 (nu2012 data included)**

## A word on theory: Simple theoretical ansatz to predict $\theta_{13}$ successfully

### Anarchy

Hall, Murayama, Weiner, PRL 84 (2000) 2572

$\sin^2 2\theta_{13} \sim 0.1$

$\sin^2 2\theta_{23} \sim 1$

### Quark-lepton complementarity

Minakata, Smirnov, PR D70 (2004) 073009

$\theta_{12} + \theta_C = 45$ deg

→ $\theta_{13} = 8.9$ deg

$\theta_{12} = 35.4$ deg

$\theta_{23} = 42.1$ deg

Dighe, Goswami, Roy
PR D76 (2007) 096005

# Oscillation vs non-oscillation experiments

- **neutrino oscillation**

$$\Delta m^2_{jk} = m^2_j - m^2_k$$

- **neutrinoless double beta decay**

$$m_{ee} = |\Sigma (U_{ej})^2 m_j \exp(i\phi_j)|$$

Majorana phases

- **direct measurement**

$$m_\beta = (\Sigma |U_{ej}|^2 m^2_j)^{1/2}$$

- **cosmology**

$$\Sigma m_j$$

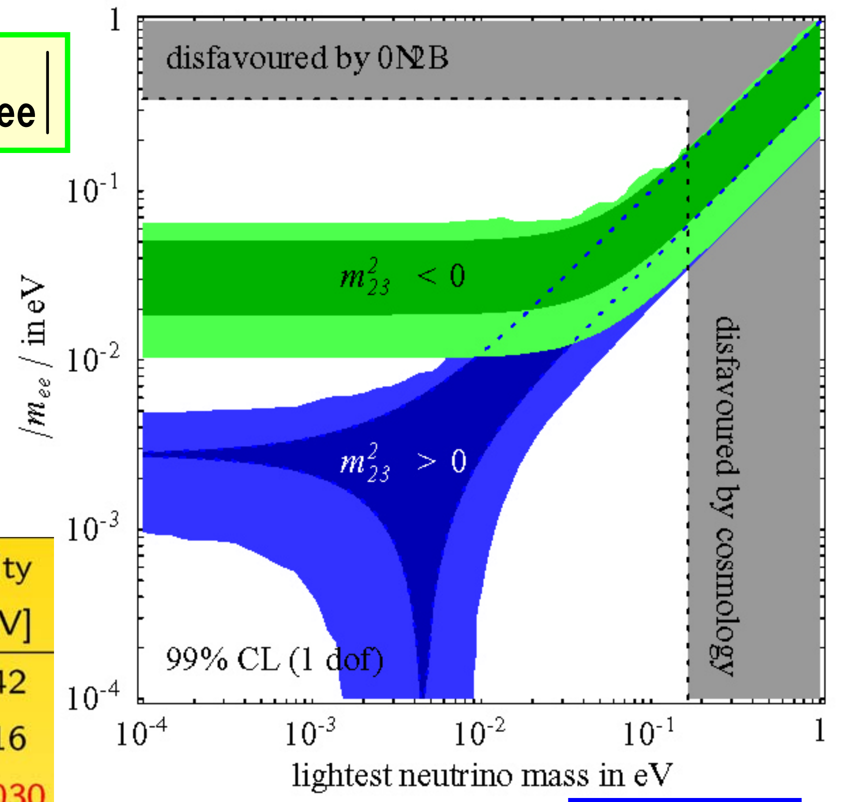
# neutrinoless double beta decay

$m_{ee}=|\Sigma(U_{ej})^2 m_j \exp(i\phi_j)|$

**Rodejohann@NOW2012**

| Experiment | Isotope | Status | Start of data-taking | Sensitivity $\langle m_\nu \rangle$ [eV] |
|---|---|---|---|---|
| GERDA | $^{76}$Ge | running | ~ 2011 | 0.17-0.42 |
| | | in progress | ~ 2012 | 0.06-0.16 |
| | | R&D | ~ 2015 | 0.012-0.030 |
| CUORE | $^{130}$Te | in progress | ~ 2013 | 0.018-0.037 |
| | | | | 0.03-0.066 |
| MAJORANA | $^{76}$Ge | in progress | ~ 2013 | 0.06-0.16 |
| | | R&D | ~ 2015 | 0.012-0.030 |
| EXO | $^{136}$Xe | running | ~ 2011 | 0.073-0.18 |
| | | R&D | ~ 2015 | 0.02-0.05 |
| SuperNEMO | $^{82}$Se | R&D | ~ 2013-15 | 0.04-0.096 |
| KamLAND-Zen | $^{136}$Xe | running | ~ 2011 | 0.03-0.07 |
| | | R&D | ~ 2013-15 | 0.02-0.046 |
| SNO+ | $^{150}$Nd | in progress | ~ 2014 | 0.09-0.18 |

$|m_{ee}|$



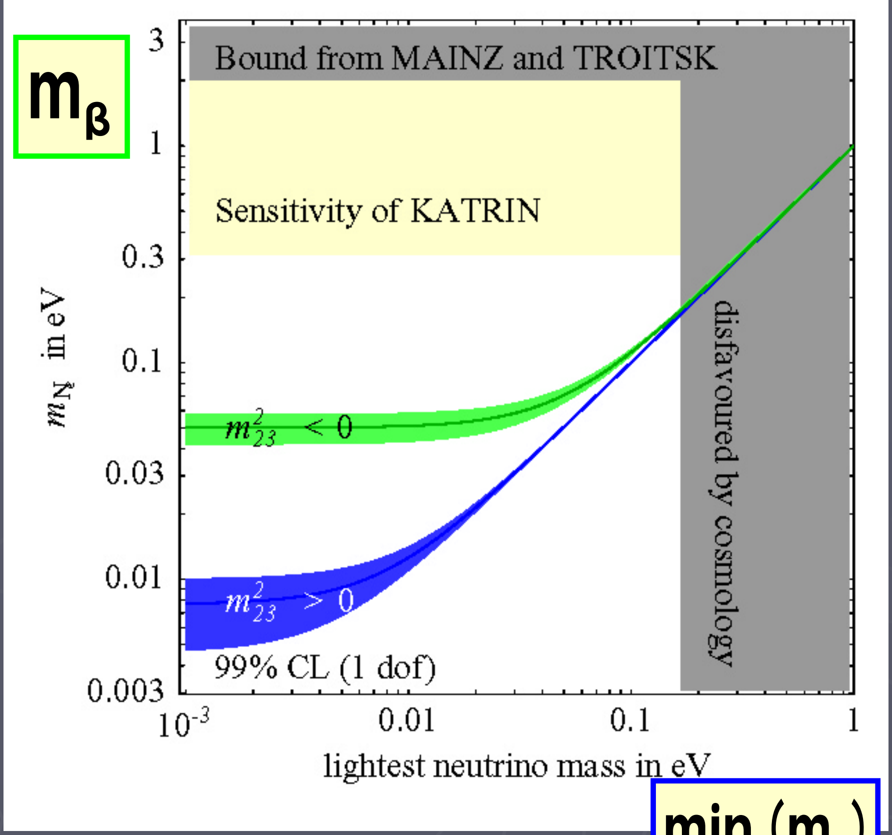

min ($m_j$)

**Strumia-Vissani: hep-ph/0606054**

## direct measurement

$m_\beta=(\Sigma|U_{ej}|^2 m_j^2)^{1/2}$

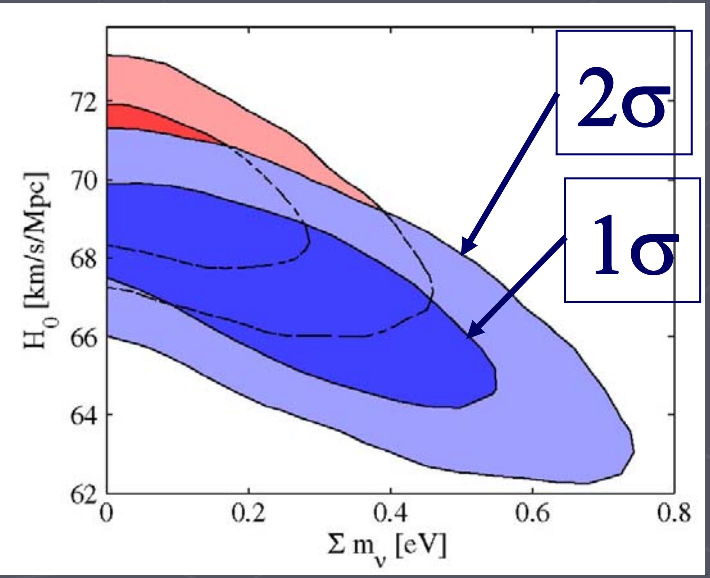
Strumia-Vissani:
hep-ph/0606054




## cosmology

$\Sigma m_j$

Calabrese et al:
PRD86, 043520




$H_0$=73km/c/Mpc

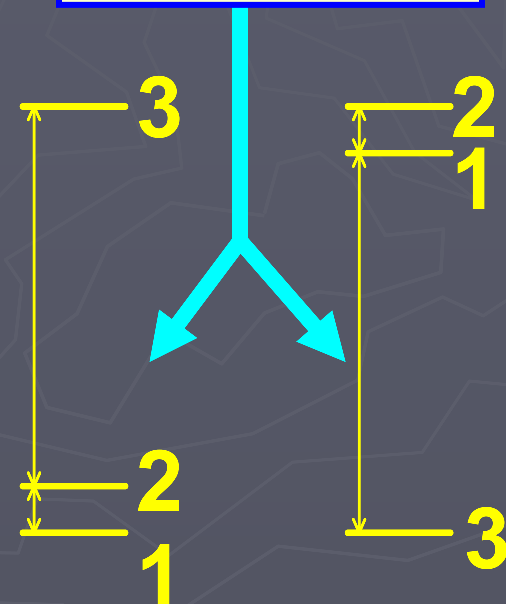
$H_0$=68km/c/Mpc

# 2. Future LBL (Long BaseLine experiments)

$$U=\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \cong \begin{pmatrix} c_{12} & s_{12} & \varepsilon \\ -s_{12}/\sqrt{2} & c_{12}/\sqrt{2} & 1/\sqrt{2} \\ s_{12}/\sqrt{2} & -c_{12}/\sqrt{2} & 1/\sqrt{2} \end{pmatrix}$$

- Both mass hierarchies are allowed

Next task is to measure sign($\Delta m^2_{31}$) , $\pi/4-\theta_{23}$ and $\delta$




normal hierarchy

$\Delta m^2_{32} > 0$

inverted hierarchy

$\Delta m^2_{32} < 0$

Most realistic way to measure sign($\Delta m^2_{31}$) and $\delta$ is Long Base Line experiments by accelerators or reactors

## Future LBL experiments → Rubbia's talk

To measure $\delta$, we need a lot of numbers of events to improve statistical errors → We need **high intensity beam**

**Candidates for high intensity beam in the future:**

- (conventional) superbeam

$$\begin{cases} \pi^+ \to \mu^+ + \nu_\mu & \nu_\mu \to \nu_e \\ \pi^- \to \mu^- + \bar{\nu}_\mu & \bar{\nu}_\mu \to \bar{\nu}_e \end{cases}$$

- neutrino factory

  $\mu$ in a storage ring

$$\begin{cases} \mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu & \nu_e \to \nu_\mu \\ \mu^- \to e^- + \bar{\nu}_e + \nu_\mu & \bar{\nu}_e \to \bar{\nu}_\mu \end{cases}$$

- beta beam

  RI in a storage ring

$$\begin{cases} {}^6_2\mathrm{He} \to {}^6_3\mathrm{Li} + e^- + \bar{\nu}_e & \bar{\nu}_e \to \bar{\nu}_\mu \\ {}^{18}_{10}\mathrm{Ne} \to {}^{18}_9\mathrm{F} + e^+ + \nu_e & \nu_e \to \nu_\mu \end{cases}$$

# Future LBL exp. (under construction / proposed )

- **superbeam**

  T2K phase II (2.2MW+HK(+Okinoshima), E~1GeV, L=295km, 658km)

  NOvA (FNAL→ Ash River (MN), E~2GeV, L=810km)

  LBNE (FNAL→Homestake, E~a few GeV, L=1290km)

  CN2PY (CERN→Pyhasalmi, E~several GeV, L=2300km)

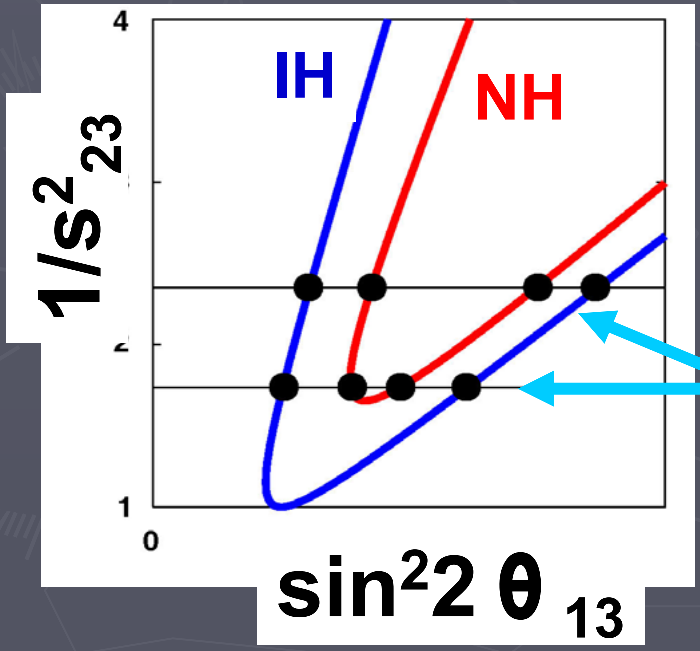
- **neutrino factory** (reference design, $E_\nu$~10GeV, L~2000km)

- **beta beam** ($E_\nu$=0.5-1.5GeV, L~130km)

**Mass Hierarchy [sign($\Delta m^2_{31}$)] may be determined next**

# Parameter degeneracy

**Even if we know $P \equiv P(\nu_\mu \to \nu_e)$ and $\bar{P} \equiv P(\overline{\nu_\mu} \to \overline{\nu_e})$ in a long baseline accelerator experiments with approximately monoenergetic neutrino beam, precise determination of $\theta_{13}$ , $\theta_{23}$ , sign($\Delta m^2_{31}$) and $\delta$ is difficult because of the 8-fold parameter degeneracy.**




**Plots in ($\sin^2 2\theta_{13}$, $1/s^2_{23}$) plane are useful to see 8-fold degeneracy**

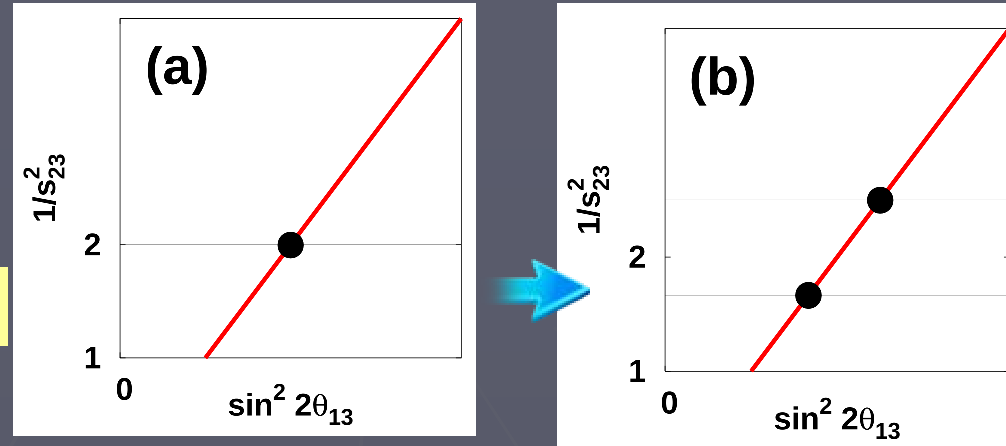
**OY, New J.Phys. 6 (2004) 83**

**Each point has different value of $\delta$.**
**→Parameter degeneracy must be resolved for precise measurements of $\delta$.**

## octant degeneracy

$\theta_{23} \Leftrightarrow \pi/2 - \theta_{23}$

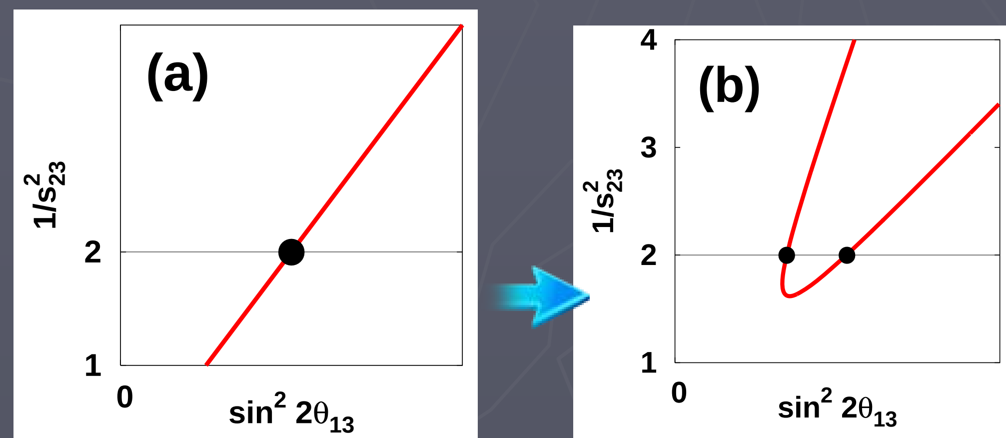
$$(a)\cos 2\theta_{23} = 0 \to (b)\cos 2\theta_{23} \neq 0$$




## intrinsic degeneracy

$(\delta, \theta_{13})$

$$(a)\frac{\Delta m^2_{21}}{|\Delta m^2_{31}|} = 0 \to (b)\frac{\Delta m^2_{21}}{|\Delta m^2_{31}|} \cong \frac{1}{35} \neq 0$$

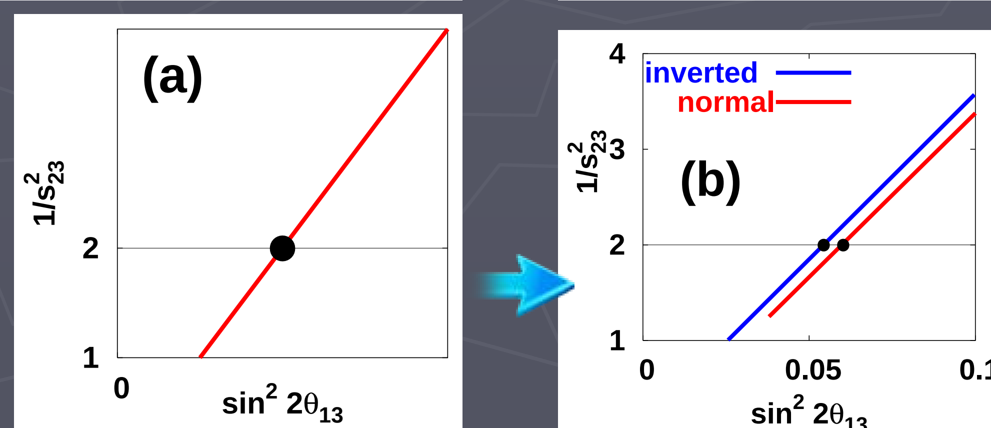



## sign degeneracy

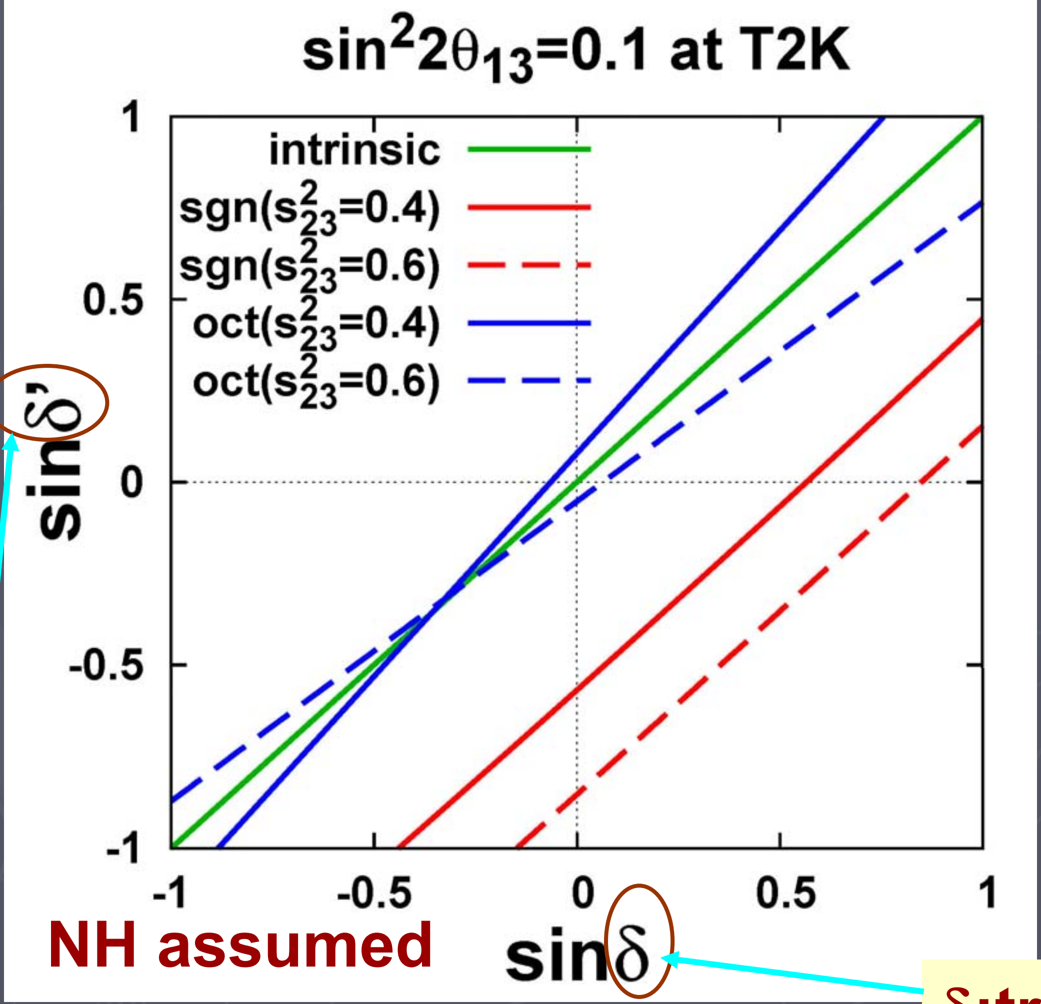
$\Delta m^2_{31} \Leftrightarrow -\Delta m^2_{31}$

$$(a)AL/2 = 0 \to (b)AL/2 \neq 0$$

$$A \equiv \sqrt{2}G_F N_e \cong 1/2000\text{km}$$



**Sign degeneracy is more serious than octant one, because $\sin\delta(\text{sign})=0 \Rightarrow \sin\delta'(\text{sign})=O(1)\neq 0$**



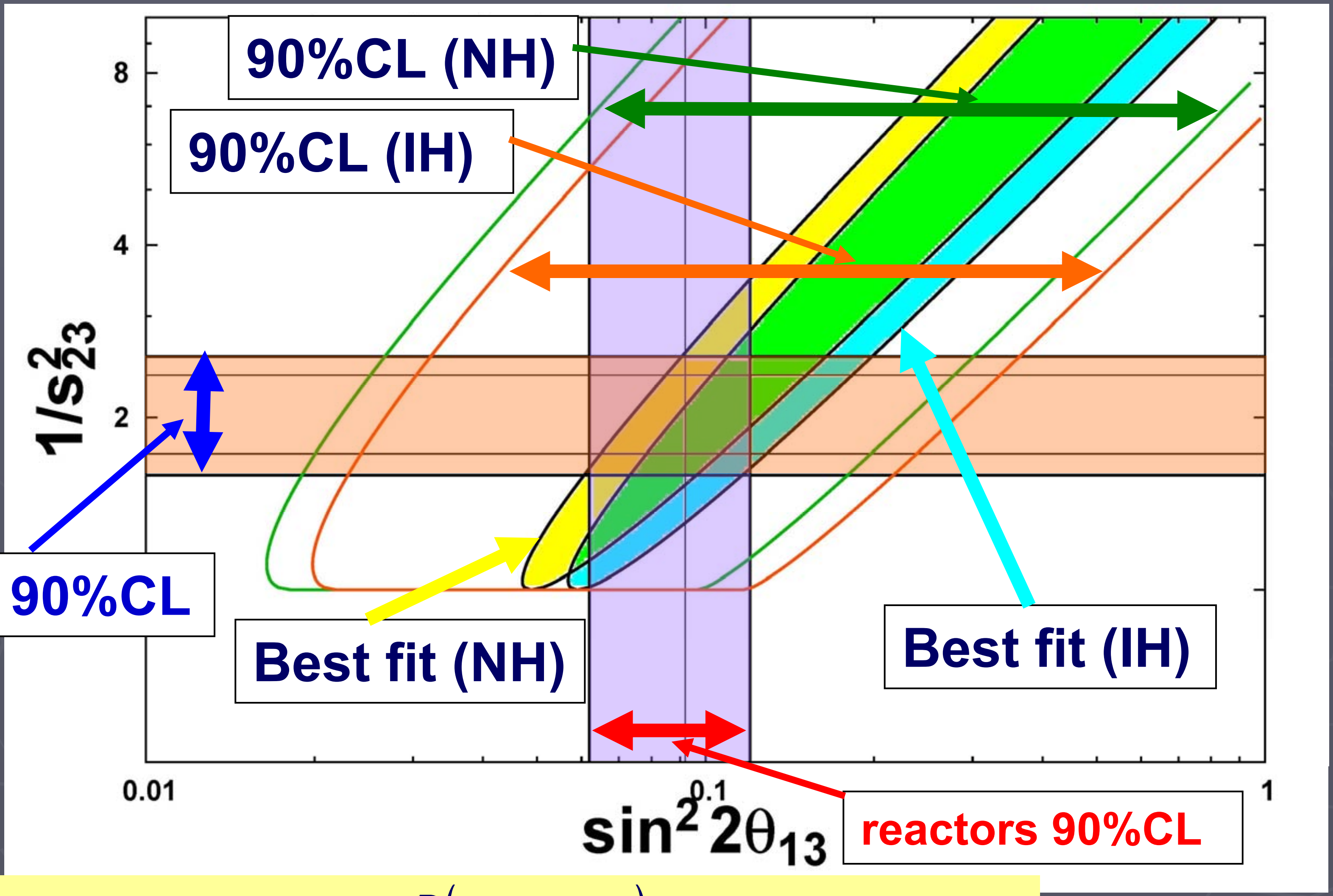

**NB: At T2K $|\Delta m^2_{31}|L/4E=\pi/2 \Rightarrow \sin\delta(\text{intrinsic}) = \sin\delta'(\text{intrinsic})$**

**Resolution of sign degeneracy is important for CP measurement**

**δ: true value**

**δ': prediction w/ wrong ansatz**

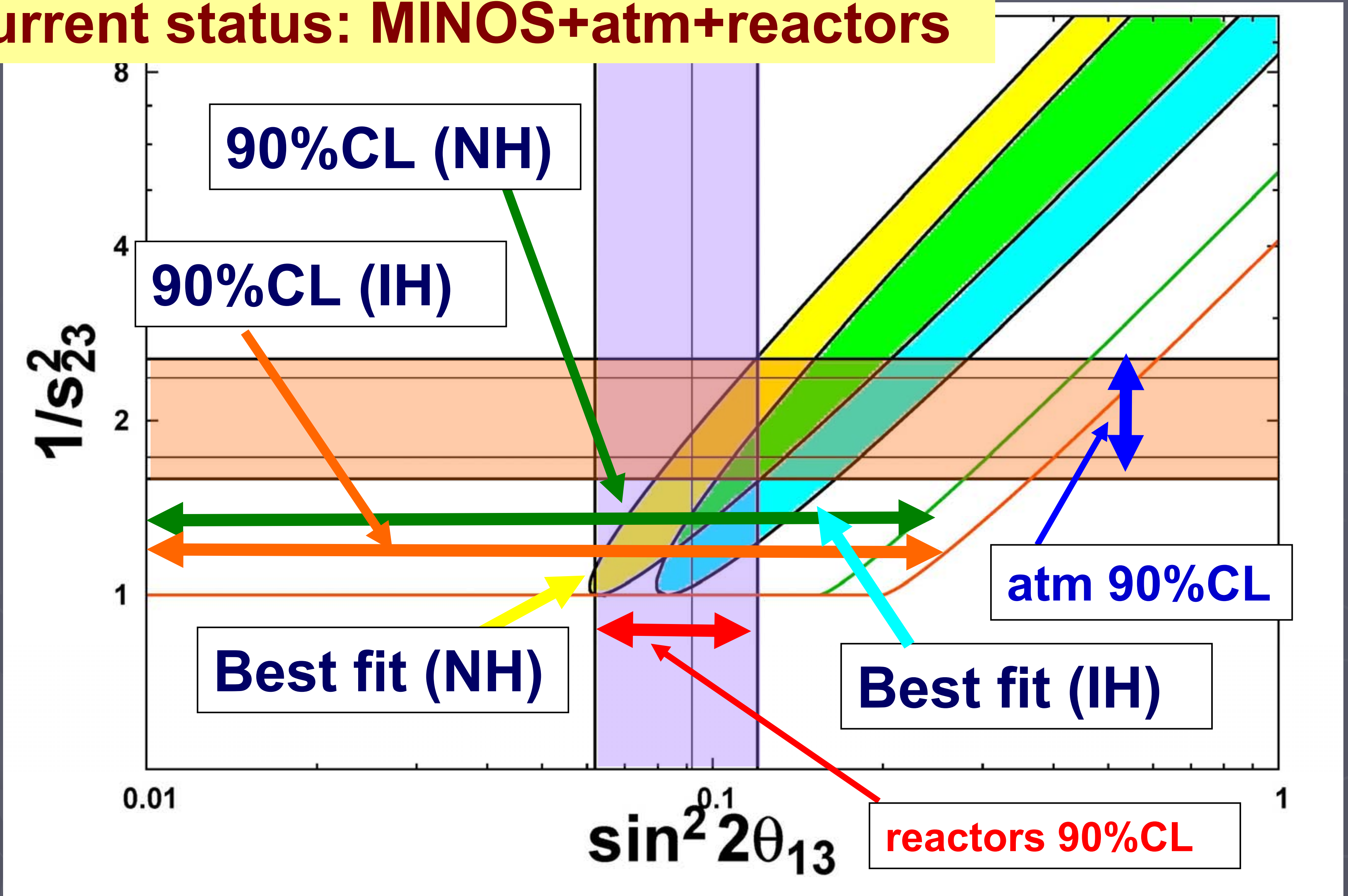
# Current status: T2K+atm+reactors




**Allowed region from $P(\nu_\mu \to \nu_e)$ of T2K at best-fit & 90%CL (w/ Sakashita@ICHEP2012)**

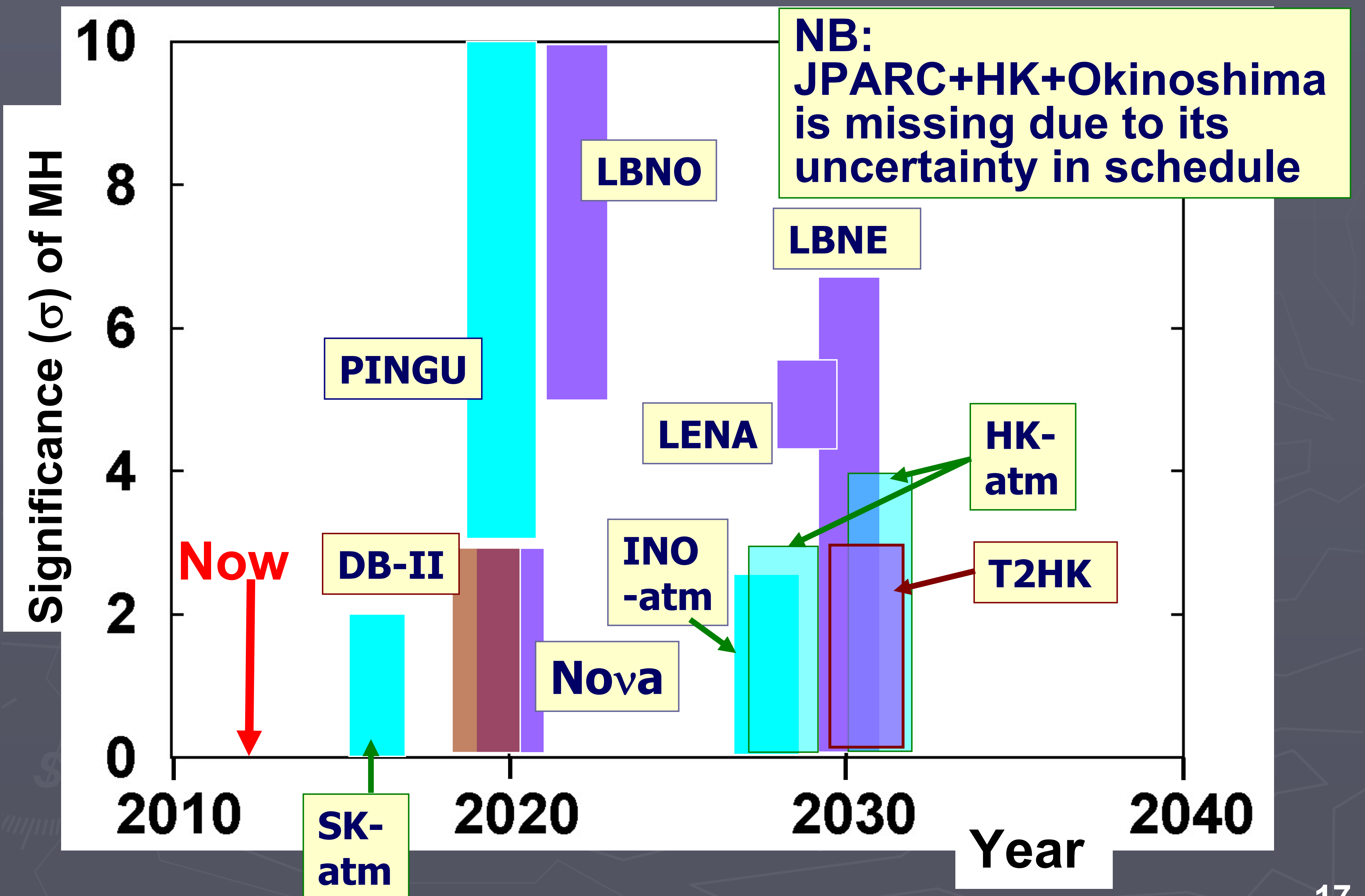
**Error is large→needs more statistics & $P(\overline{\nu_\mu} \to \overline{\nu_e})$ to improve**

# Current status: MINOS+atm+reactors




**Allowed region from $P(\nu_\mu \to \nu_e)$ of MINOS at best-fit & 90%CL (w/ arXiv:1108.0015 data)**

# Future exp. vs Mass Hierarchy



## 3. New Physics & $\nu_\tau$ detection

NP:= Deviation from SM+massive $\nu$

Most of discussions to date are phenomenological

**Motivation: High precision measurements of $\nu$ oscillation in future experiments can be used also to probe physics beyond SM by looking at deviation from SM+massive $\nu$**

$\nu_\tau$ channels: not studied much→There is a plenty of room to probe New Physic

- **MINSIS** (Main Injector Non Standard Interactions Search): Near detectors may enable us to study $\tau$ channels [Para, Madrid $\nu$ NSI Workshop (Dec. 2009)]

- **$\nu$ factory**
  - Higher energy option ($E_\mu$=50GeV, L=3000km) w/ $\tau$ detectors has better sensitivity to NP
  - Unfortunately higher energy option has poor sensitivity to $\delta$ for $\sin^2 2\theta_{13}$ =0.1 [Pinney-OY, 2001]
  - current baseline ($E_\mu$=10GeV, L=2000km) does not have a $\tau$ detector [NF Reference Design], but $\tau$ detector may be included in the future (if physics case is strong)

| | | | |
|---|---|---|---|
| $\nu_e \to \nu_\mu$ | golden channel | $\nu_\mu \to \nu_\mu$ | disappearance channel |
| $\nu_e \to \nu_\tau$ | silver channel | $\nu_\mu \to \nu_\tau$ | discovery channel |

**New physics** which can be probed at a future long baseline neutrino experiments includes:

- NSI at production / detection
- Unitarity Violation 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 at production / detection | × |
| Unitarity Violation due to heavy particles | × |
| Light sterile neutrinos | × |

| Scenarios | Phenomenological bound on deviation of 3 flavor unitarity |
|---|---|
| NSI at production / detection | O(1%) |
| Violation of unitarity due to heavy particles | O(0.1%) |
| Light sterile neutrinos | O(10%) |

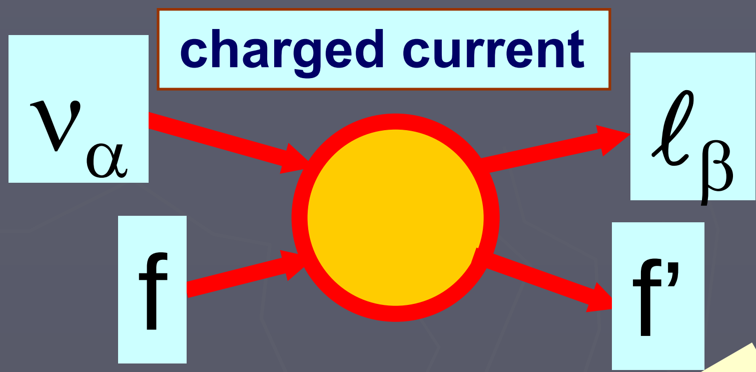
- (Except sterile ν) none of these scenarios has ever been supported experimentally.
- Even if LSND anomaly is excluded in the near future, light sterile ν could be phenomenologically even more promising than others.

# 3-1. NSI at source and detector

Grossman, Phys. Lett. B359, 141 (1995)

**Possible processes with**

$$\mathcal{L}_{\rm eff} = G_F\, \epsilon^{ff'}_{\alpha\beta}\, \bar{\nu}_\alpha \gamma^\rho \ell_\beta \bar{f} \gamma_\rho f'$$




## ● NP at source

$$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu^s_\mu$$

$$\nu^s_e = \nu_e + \epsilon^s_{e\mu} \nu_\mu$$

Effective eigenstate $\equiv U^s$

$$\begin{pmatrix} \nu^s_e \\ \nu^s_\mu \end{pmatrix} = \begin{pmatrix} 1 & \epsilon^s_{e\mu} \\ -\epsilon^s_{e\mu} & 1 \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

**SM: U → NP: $U^sU$**

## ● NP at detector

$$\nu^d_\mu + n \to \mu^- + p$$

$$\nu^d_\mu = \nu_\mu - \epsilon^d_{e\mu} \nu_e$$

Effective eigenstate $\equiv U^d$

$$\begin{pmatrix} \nu^d_e \\ \nu^d_\mu \end{pmatrix} = \begin{pmatrix} 1 & \epsilon^d_{e\mu} \\ -\epsilon^d_{e\mu} & 1 \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

**SM: U → NP: $U^dU$**

# Direct bounds on prod/det NSI

From $\mu$, $\beta$, $\pi$ decays and zero distance oscillations

$$2\sqrt{2}G_F\varepsilon^{ud}_{\alpha\beta}\left(\bar{l}_\beta\gamma^\mu P_L\nu_\alpha\right)\left(\bar{u}\gamma_\mu P_{L,R}d\right) \qquad 2\sqrt{2}G_F\varepsilon^{\mu e}_{\alpha\beta}\left(\bar{\mu}\gamma^\mu P_L\nu_\beta\right)\left(\bar{\nu}_\alpha\gamma_\mu P_L e\right)$$

$$\left|\varepsilon^{ud}\right| < \begin{pmatrix} 0.042 & 0.025 & 0.042 \\ 2.6\cdot 10^{-5} & 0.1 & 0.013 \\ 0.087 & 0.013 & 0.13 \end{pmatrix} \qquad \left|\varepsilon^{\mu e}\right| < \begin{pmatrix} 0.025 & 0.03 & 0.03 \\ 0.025 & 0.03 & 0.03 \\ 0.025 & 0.03 & 0.03 \end{pmatrix}$$

**Bounds ~O($10^{-2}$)**

C. Biggio, M. Blennow and EFM 0907.0097

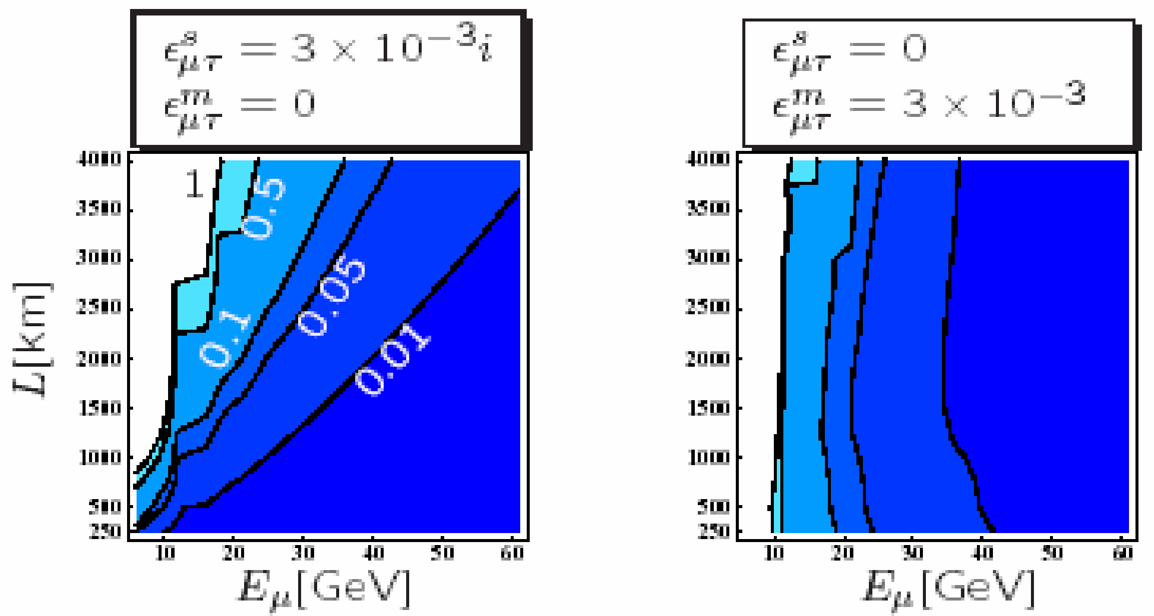
# Sensitivity to $\varepsilon_{\mu\tau}$ at $\nu$ factory

Ota-Sato-Yamashita, PRD65:093015,2002

$\nu_\mu \to \nu_\tau$

$$\left|\varepsilon^{s,m}_{\mu\tau}\right| = 3\times10^{-3}$$

**Required data size in unit of $10^{21}$ $\mu$ × 100kt**




■ The expected sensitivity is $\epsilon \gtrsim \mathcal{O}(10^{-4})$.

Sato: ISS 2nd plenary @ KEK

| | $\epsilon^{s,m}_{e\mu}$ $(\epsilon^s_{\mu e})$ | $\epsilon^{s,m}_{e\tau}$ | $\epsilon^{s,m}_{\mu\tau}$ |
|---|---|---|---|
| $\nu_e \to \nu_\mu$ | △ | △ | × |
| $\nu_\mu \to \nu_\mu$ | × | × | ○ |
| $\nu_e \to \nu_\tau$ | × | ○ | △ |
| $\nu_\mu \to \nu_\tau$ | × | △ | ○ |
| $\nu_\mu \to \nu_e$ | △ | × | × |
| $\nu_e \to \nu_e$ | × | × | × |

# Sensitivity to $\varepsilon_{e\tau}$, $\varepsilon_{\mu\tau}$ at $\nu$ factory

Tang-Winter, Phys.Rev.D80:053001,2009

- Near $\tau$ detector improves sensitivity

| | Without $\nu_\tau$ ND5 | With $\nu_\tau$ ND5 |
|---|---|---|
| $\lvert\epsilon^s_{e\tau}\rvert$ | 0.004 | 0.0007 |
| $\lvert\epsilon^s_{\mu\tau}\rvert$ | 0.4 | 0.0006 |

ND5: mass 2 kton, L=1 km

# 3-2. Violation of unitarity w/o light $\nu_s$
## (Minimal Unitarity Violation)

Antusch, Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon, JHEP0610,084, '06

In generic see-saw models, after integrating out $\nu_R$, the kinetic term gets modified, and unitarity is expected to be violated.

$$L = \frac{1}{2}\left(i\overline{\nu}_\alpha \partial K_{\alpha\beta}\nu_\beta - \overline{\nu}^c{}_\alpha M_{\alpha\beta}\nu_\beta\right) - \frac{g}{\sqrt{2}}\left(W^+_\mu \bar{l}_\alpha \gamma^\mu P_L \nu_\alpha + h.c.\right) + \ldots$$

rescaling $\nu$ →

$$L = \frac{1}{2}\left(i\overline{\nu}_i \partial \nu_i - \overline{\nu}^c{}_i m_{ii}\nu_i\right) - \frac{g}{\sqrt{2}}\left(W^+_\mu \bar{l}_\alpha \gamma^\mu P_L N_{\alpha i}\nu_i\right) + \ldots$$

*N*: non-unitary lepton mixing matrix

# Sensitivity to MUV parameters at ν factory

$N := (1+\eta)U$

- **4kt OPERA-like near detector @100 m**

Antusch et al, JHEP0610,084, '06

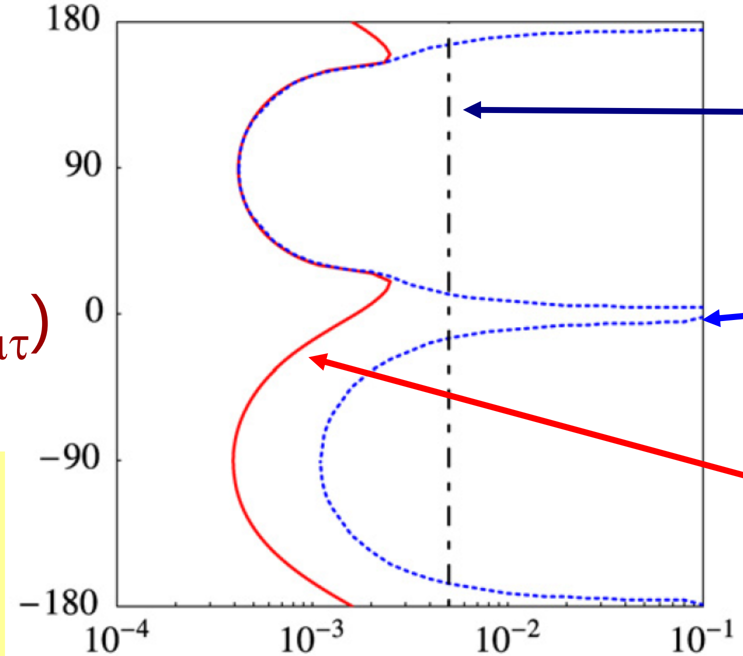
$\nu_\mu \to \nu_\tau$

$|\eta_{\mu\tau}| < 1.3 \times 10^{-3}$ (present: $6.5 \times 10^{-3}$)

- **5kt OPERA-like far detector @130 km**

Fernandez-Martinez et al, PLB649:427,'07

$\nu_\mu \to \nu_\tau$




$\arg(\eta_{\mu\tau})$

$|\eta_{\mu\tau}|$

**Present bound from $\tau \to \mu\gamma$**

**Sensitivity to $\arg(\eta_{\mu\tau})$**

**Sensitivity to $|\eta_{\mu\tau}|$**

**For non-trivial $\arg(\eta_{\mu\tau})$, one order of magnitude improvement for $|\eta_{\mu\tau}|$**

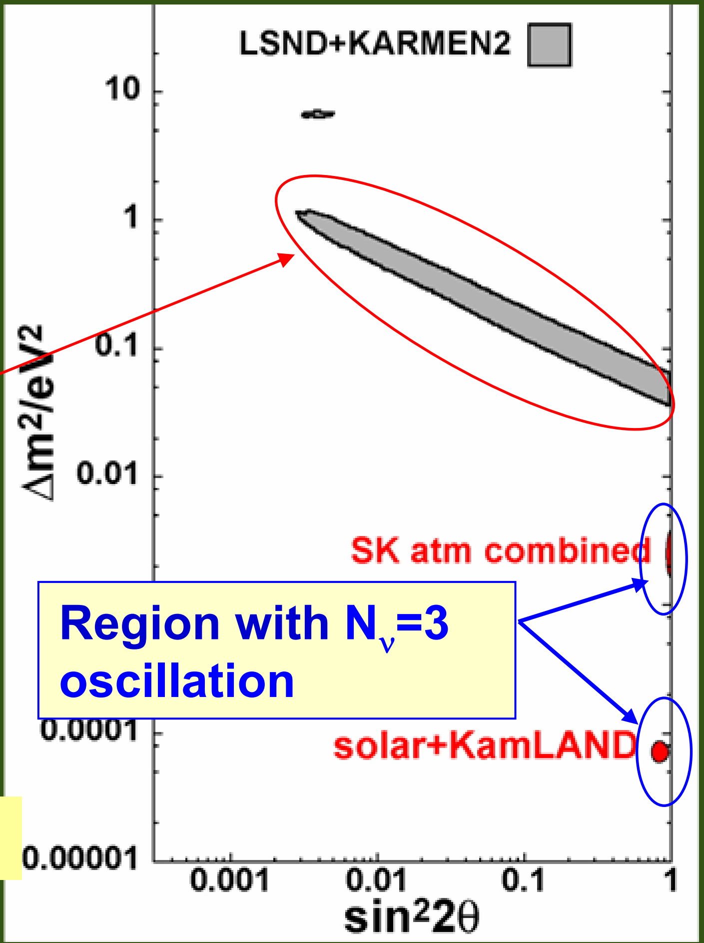
# 3-3. Light sterile neutrinos

- **LNSD experiment (1993-1998@LANL)**

$\bar{\nu}_\mu \to \bar{\nu}_e$

$\Delta m^2 \cong O(1)eV^2, \sin^2 2\theta \cong O(10^{-2})$ **??**

It cannot be explained by $N_\nu$=3 oscillation → LEP data → $N_\nu$=3 active light ν → 4th ν must be sterile

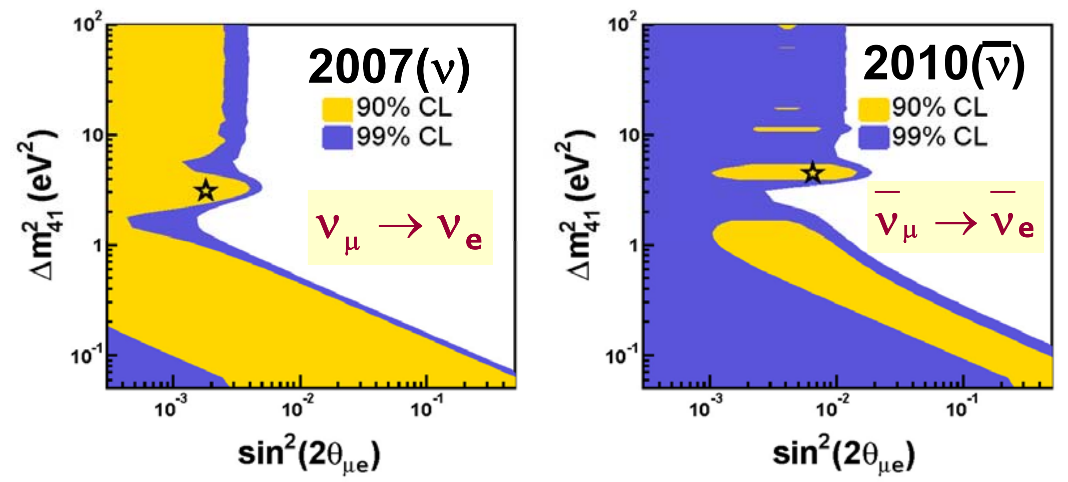



Region with $N_\nu$=3 oscillation

- **MiniBooNE (2002-, FNAL)**

Check of the LSND data

Johnson's talk




2007 (ν)
LSND was wrong!

2010 ($\bar{\nu}$)
LSND was correct?

Seems to be inconclusive

## ● Reactor ν anomaly

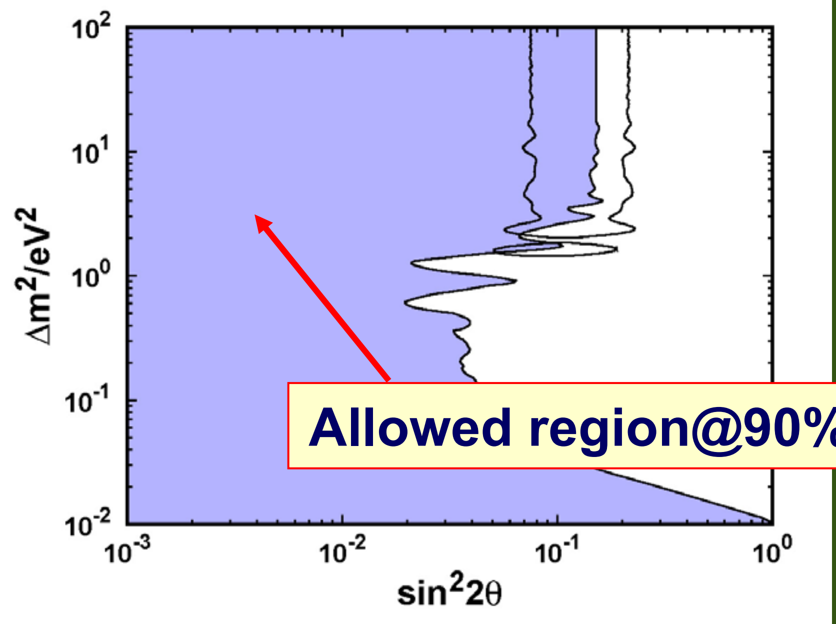
Mention et al, PRD83 (2011) 073006

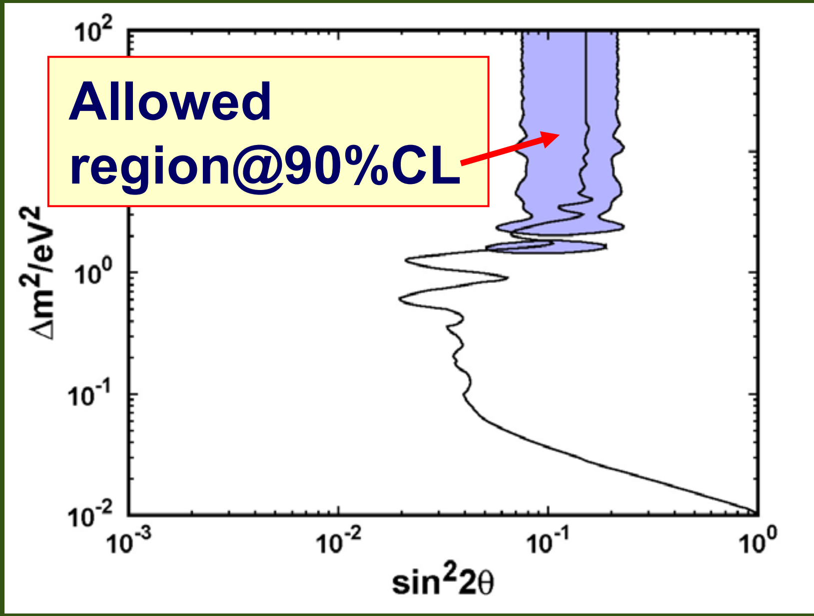
**Recent reevaluation of reactor ν flux suggests affirmative interpretation of $\bar{\nu}_e \to \bar{\nu}_e$ oscillation**

**(new flux)= (old flux) x 1.03**

**Bugey(reactor $\bar{\nu}_e \to \bar{\nu}_e$ ):**
**Negative w/ old flux**

**Bugey(reactor)+etc:**
**Affirmative w/ new flux?**




**No ν oscillation for $\Delta m^2_{41} = O(1)\ eV^2$**

**ν oscillation may exist for $\Delta m^2_{41} = O(1)\ eV^2$**

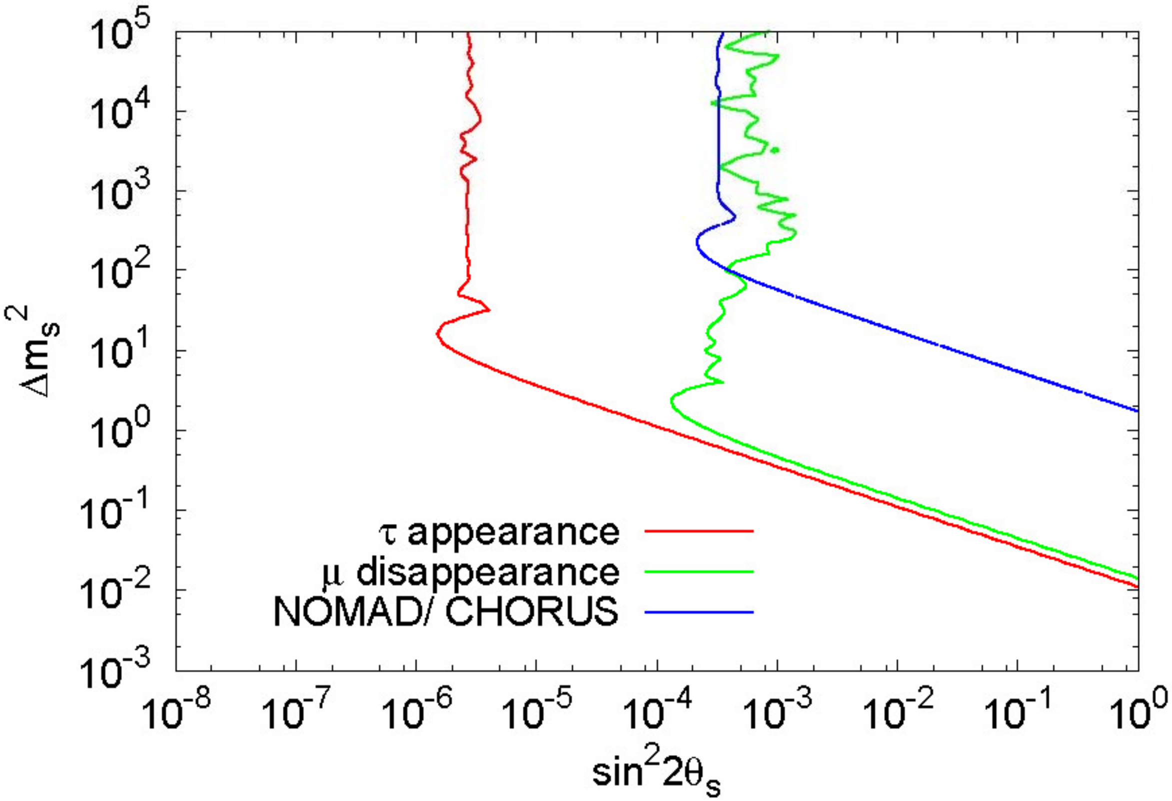
## Sensitivity of LBL to $\nu_s$

## Sensitivity of MINSIS to $\nu_s$

Li@Madrid $\nu$ NSI Workshop

With $\mu$ disappearance, have similar sensitivity to $\sin^2 2\theta_s^{\mu\mu}$ as NOMAD and CHORUS have to $\sin^2 2\theta_s^{\mu\tau}$.

$\tau$ appearance is $\sim$ 100 times more sensitive than $\mu$ disappearance.



# Sensitivity of ν factory to CP violation

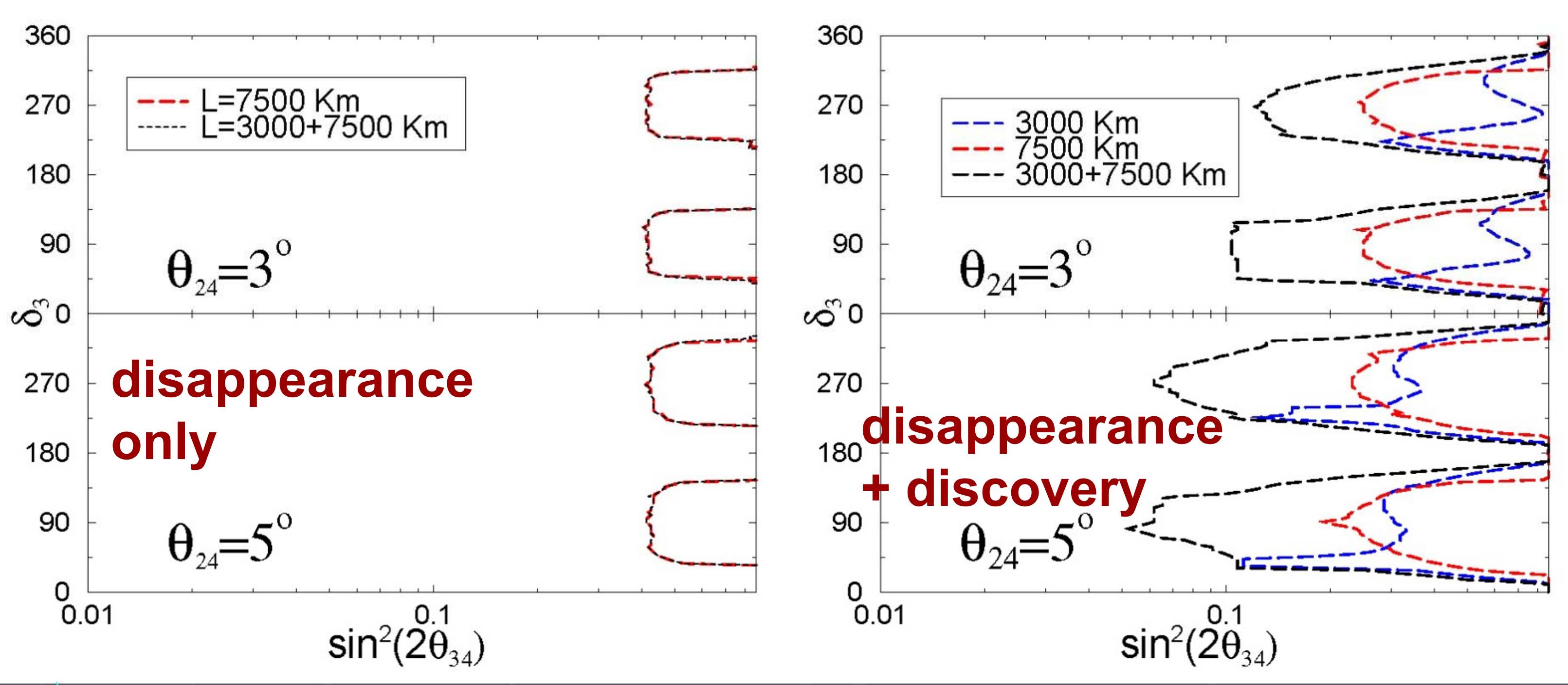
**Potentially the largest CP violation occurs in μ-τ channel:**
**CP violation due to the new CP phase**

$$P(\nu_\mu \to \nu_\tau) - P(\bar{\nu}_\mu \to \bar{\nu}_\tau) = 2 s_{24}\, s_{34} \boxed{\sin\delta_3} \sin(\Delta m^2_{31} L/4E) + \cdots$$

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

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

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




**Discovery channel is crucial to measure the new CP phase**

# 4. Summary (1)

- Three mixing angles have been determined : $\theta_{12} \simeq \pi/6$, $\theta_{23} \simeq \pi/4$, $\theta_{13} \simeq \pi/20$.
- The remaining parameters to be measured are sign($\Delta m^2_{31}$), sign($\theta_{23} - \pi/4$) and $\delta$ .
- To determine $\delta$, parameter degeneracy (particularly of mass hierarchy) must be resolved.
- Accelerator and reactor experiments are expected to determine sign($\Delta m^2_{31}$) and $\delta$ in 10-20 years.

# 4. Summary (2)

- High precision measurements of $\nu$ oscillation in the future experiments will enable us to probe New Physics such as (NSI at production / detection, Violation of unitarity, Schemes with light sterile neutrinos).
- $\tau$ detectors may be placed at NUMI $\nu$ beams or at $\nu$ factory in the future option.
- In absence of 3 flavor unitarity, $\tau$ detectors in principle give us important information on New Physics $\rightarrow$ $\nu_\tau$ detection deserves further study.

# Backup slides

# Global Fits:

**Fogli, Lisi, Marrone, Montanino , Palazzo, Rotunno**
**Phys.Rev. D86 (2012) 013012**
**arXiv:1205.5254**

## Global Fit

**Forero, Tortola, Valle**
**arXiv:1205.4018**

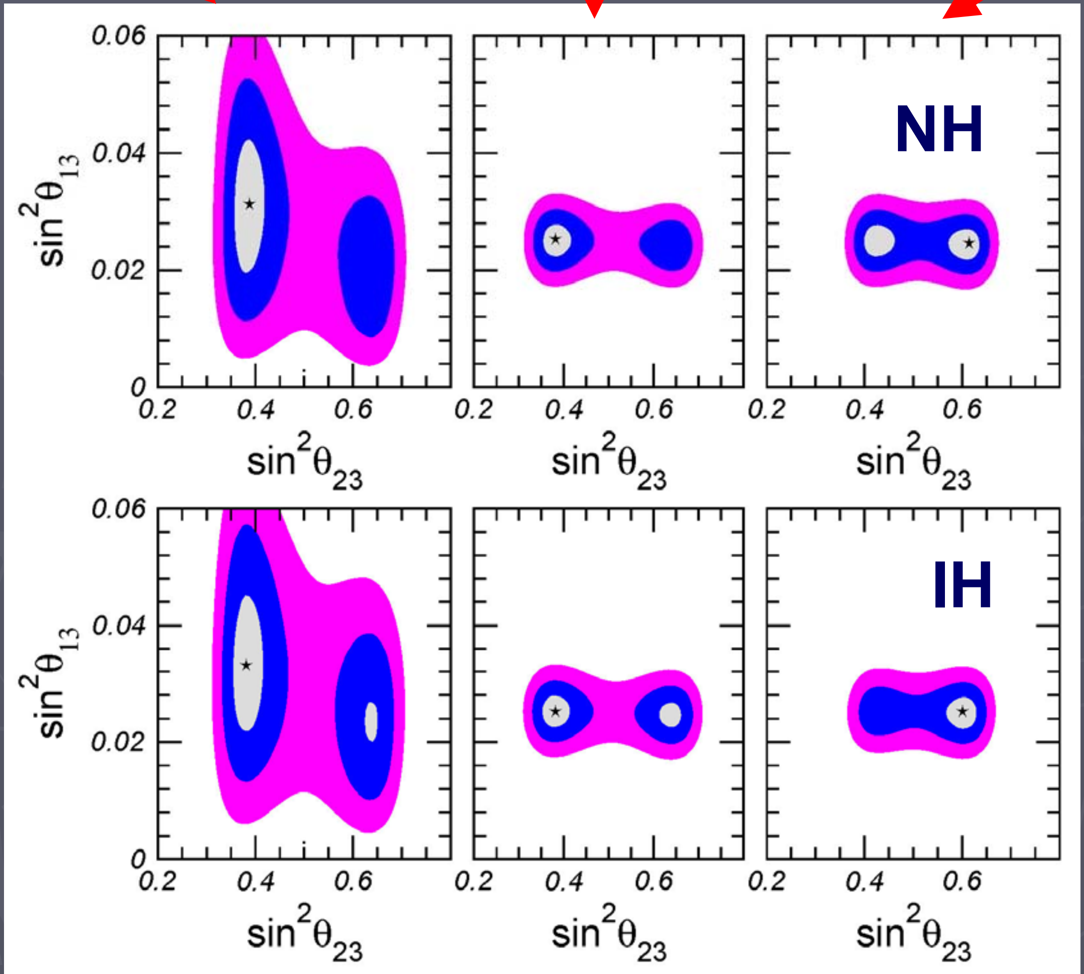
Rotunno '12

| parameter | best fit $\pm 1\sigma$ | best fit $\pm 1\sigma$ |
|---|---|---|
| $\Delta m^2_{21}$ $[10^{-5}\mathrm{eV}^2]$ | $7.62 \pm 0.19$ | $7.54^{+0.26}_{-0.22}$ |
| $\Delta m^2_{31}$ $[10^{-3}\mathrm{eV}^2]$ | $2.53^{+0.08}_{-0.10}$<br>$-(2.40^{+0.10}_{-0.07})$ | $2.43^{+0.07}_{-0.09}$<br>$-(2.42^{+0.07}_{-0.10})$ |
| $\sin^2\theta_{12}$ | $0.320^{+0.015}_{-0.017}$ | $0.307^{+0.018}_{-0.016}$ |
| $\sin^2\theta_{23}$ | $0.49^{+0.08}_{-0.05}$<br>$0.53^{+0.05}_{-0.07}$ | $0.398^{+0.030}_{-0.026}$<br>$0.408^{+0.035}_{-0.030}$ |
| $\sin^2\theta_{13}$ | $0.026^{+0.003}_{-0.004}$<br>$0.027^{+0.003}_{-0.004}$ | $0.0245^{+0.0034}_{-0.0031}$<br>$0.0246^{+0.0034}_{-0.0031}$ |
| $\delta$ | $(0.83^{+0.54}_{-0.64})\,\pi$<br>$0.07\pi$ [a] | $(0.89^{+0.29}_{-0.44})\pi$<br>$(0.90^{+0.32}_{-0.43})\pi$ |

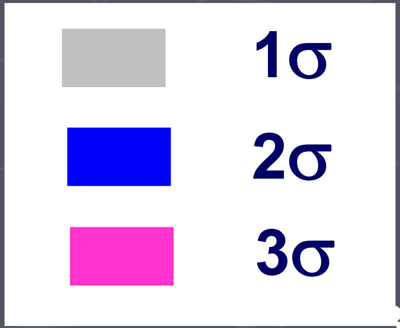
MINOS+T2K +sol+ KL

MINOS+T2K+sol+ KL+DC+DB+RENO

MINOS+T2K+sol+ KL+DC+DB+RENO+atm

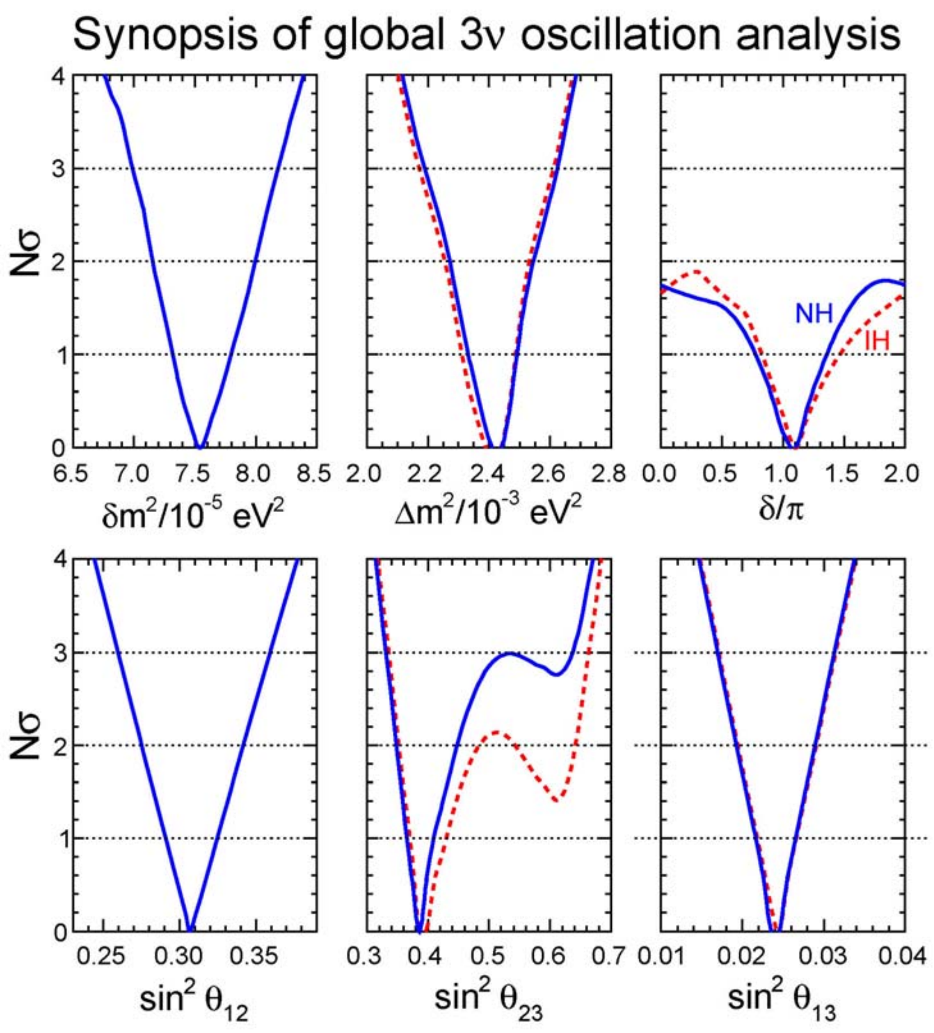



$\pi/4-\theta_{23}<0$ is preferred




Forero, Tortola, Valle arXiv:1205.4018

# Octant of $\theta_{23}$ ($\pi/4 - \theta_{23} > 0$?) appears to be subtle

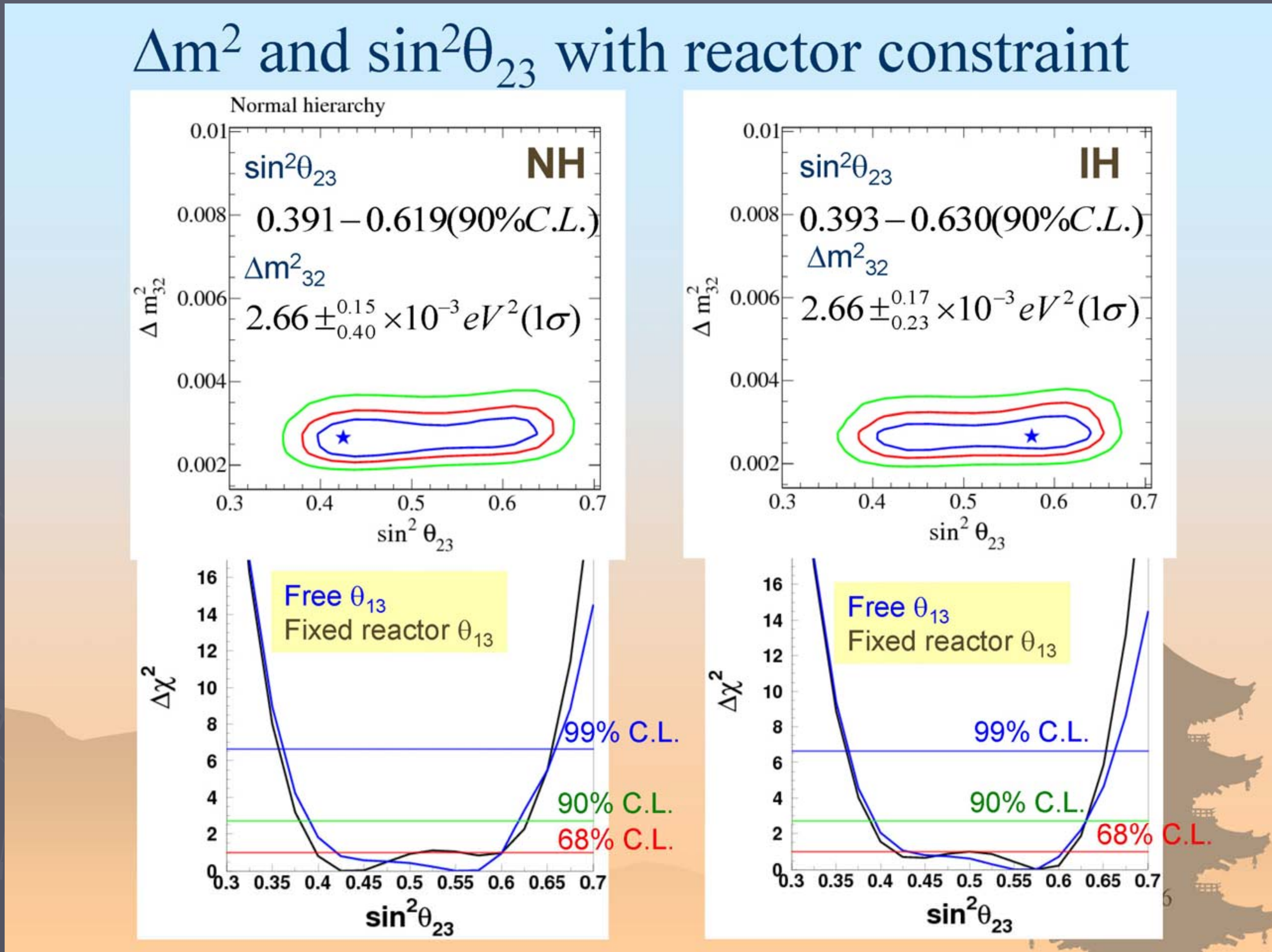



**$\pi/4 - \theta_{23} > 0$ is preferred**

**Fogli, Lisi, Marrone, Montanino , Palazzo, Rotunno**
**Phys.Rev. D86 (2012) 013012 arXiv:1205.5254**

# Info on MH seems necessary

Itow@ν2012

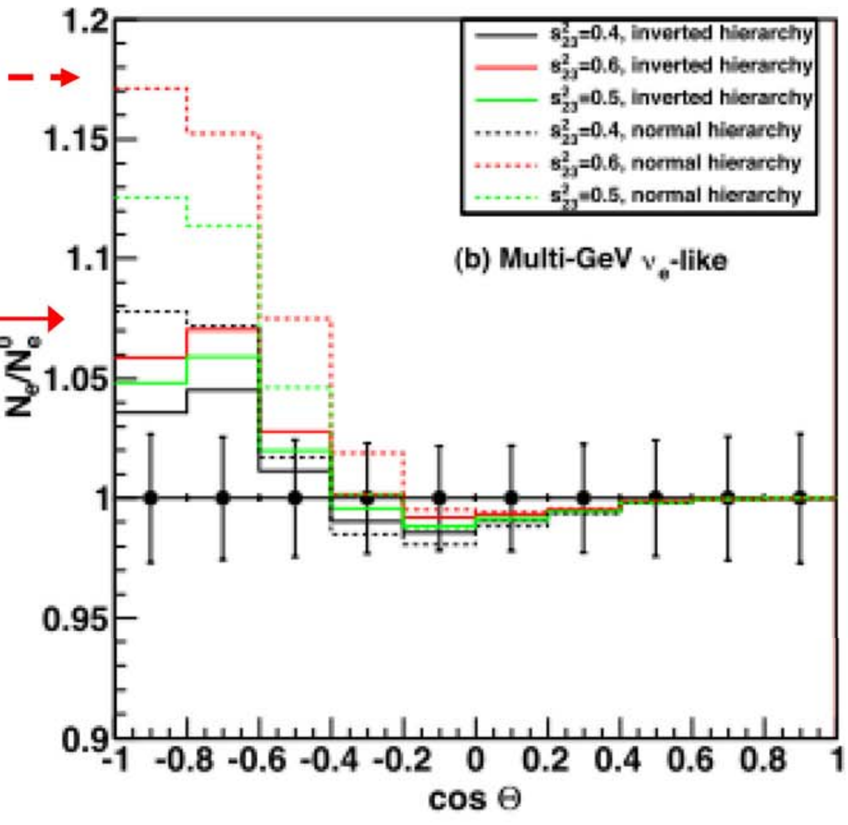


# 3 flavor atmospheric ν oscillations

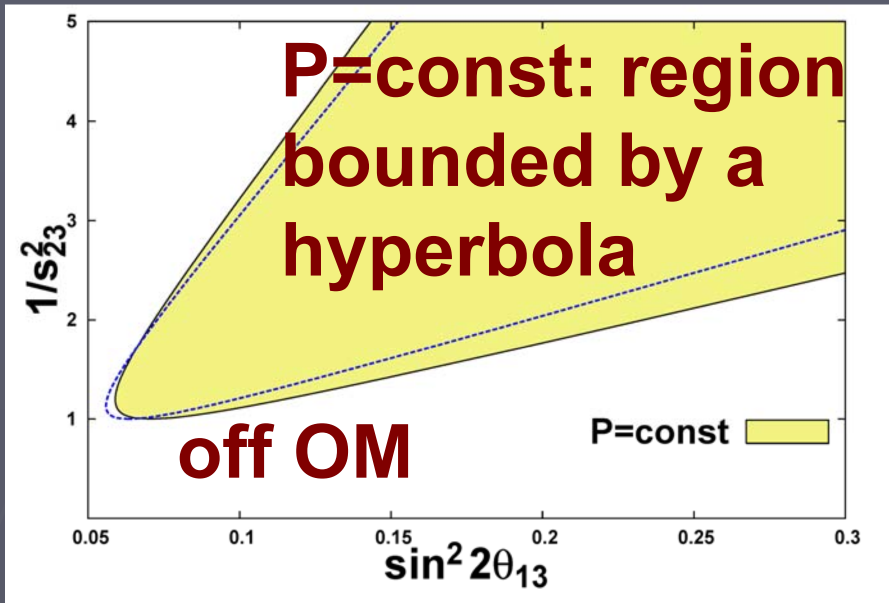
$$\frac{\Phi(\nu_e)}{\Phi_0(\nu_e)} - 1 \approx P_2 \cdot (r \cdot \cos^2\theta_{23} - 1)$$
$$-r \cdot \sin\tilde{\theta}_{13} \cdot \cos^2\tilde{\theta}_{13} \cdot \sin 2\theta_{23} \cdot (\cos\delta \cdot R_2 - \sin\delta \cdot I_2)$$
$$+2\sin^2\tilde{\theta}_{13} \cdot (r \cdot \sin^2\theta_{23} - 1)$$

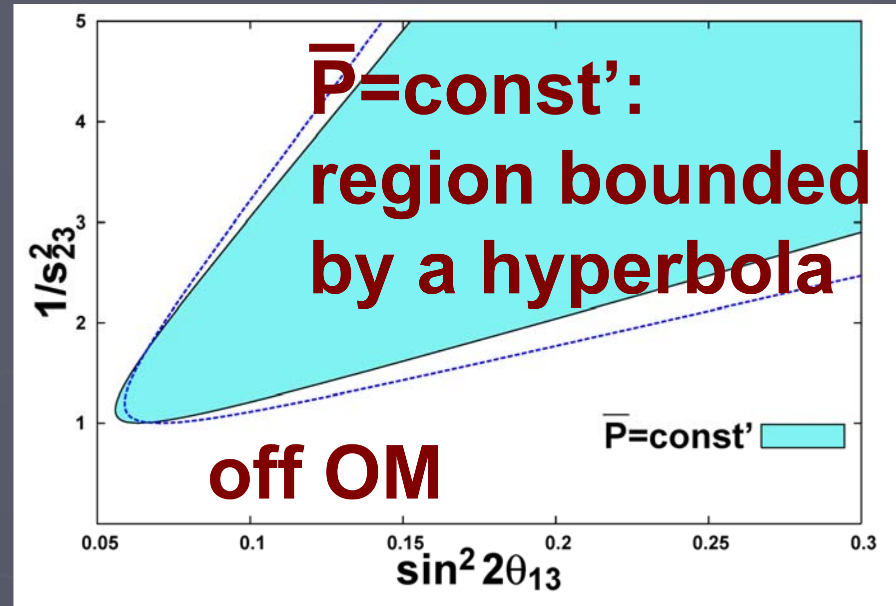
Normal Hierarchy

Inverted Hierarchy

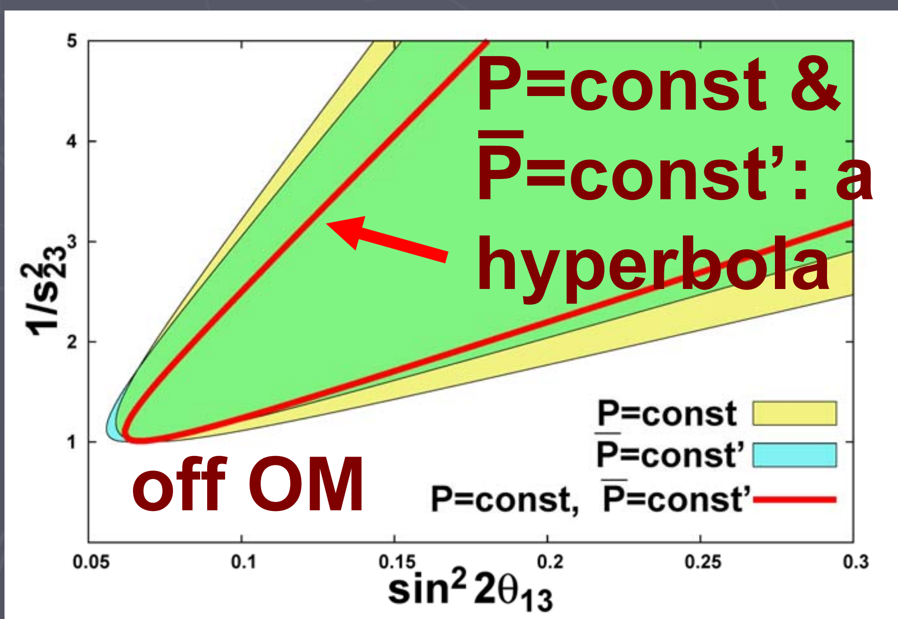


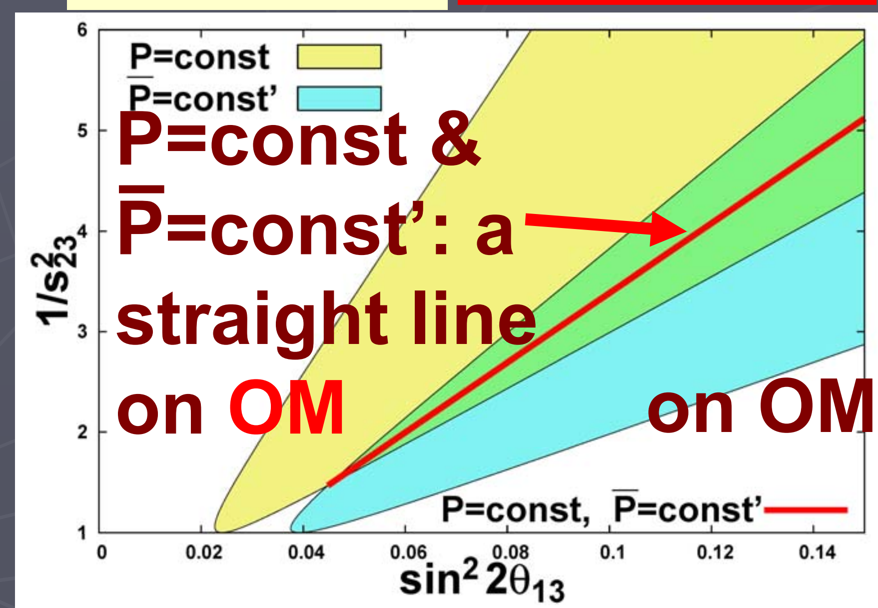

10 years HK (5.6Mt year) = 248year SK




**Oscillation Maximum:** $\Delta \equiv \frac{|\Delta m^2_{31}|L}{4E} = \frac{\pi}{2}$



## Differences in values of CP phases

$\theta_{13}$:= $\theta_{13}$(true), $\theta_{13}$':= $\theta_{13}$(false)

$\delta$:= $\delta$(true), $\delta$':= $\delta$(false)

### sign degeneracy

$$\sin^2 2\theta'_{13} = \sin^2 2\theta_{13} \tan^2 \theta_{23} + \frac{\alpha^2 g^2 \sin^2 2\theta_{12}}{f \bar{f}} (1 - \tan^2 \theta_{23}) \, ,$$

$$\sin 2\theta'_{13} \sin \delta' = \sin 2\theta_{13} \sin \delta + \frac{\alpha g (f - \bar{f}) \sin 2\theta_{12}}{f \bar{f}} \frac{\cot 2\theta_{23}}{\sin \Delta} \, ,$$

### octant degeneracy

$$x'^2 = \frac{x^2 (f^2 + \bar{f}^2 - f \bar{f}) - 2yg(f - \bar{f}) x \sin \delta \sin \Delta}{f \bar{f}} \, ,$$

$$x' \sin \delta' = x \sin \delta \frac{f^2 + \bar{f}^2 - f \bar{f}}{f \bar{f}} - \frac{x^2}{\sin \Delta} \frac{f^2 + \bar{f}^2}{f \bar{f}} \frac{f - \bar{f}}{2yg} \, .$$

Barger Marfatia Whisnant Phys.Rev.D65:073023,2002

# To solve parameter degeneracy, various combinations have been proposed:

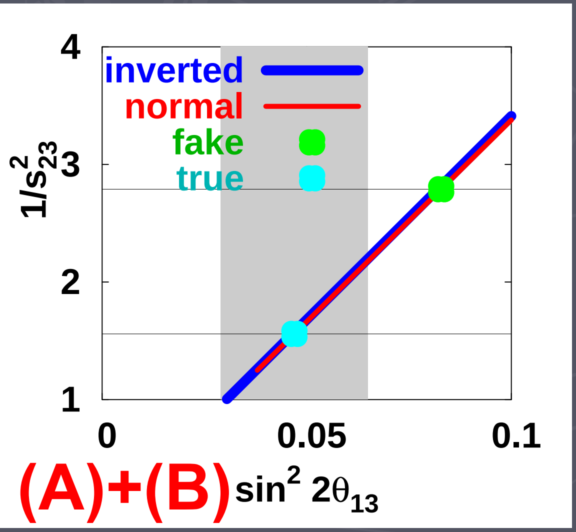
(A) LBL measurement at $|\Delta m^2_{31}|L/4E = \pi/2$

(B) reactor measurement of $\theta_{13}$ $\bar{\nu}_e \to \bar{\nu}_e$

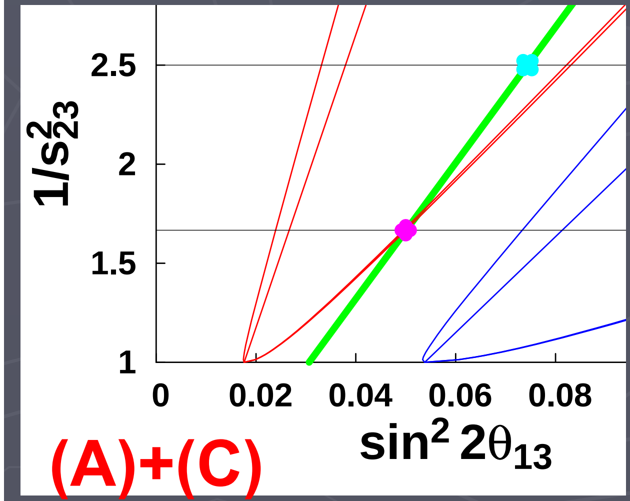
(C) LBL measurement of $\nu_\mu \to \nu_e$ (or $\nu_e \to \nu_\mu$ )

with different L/E (larger L separates NH&IH more)

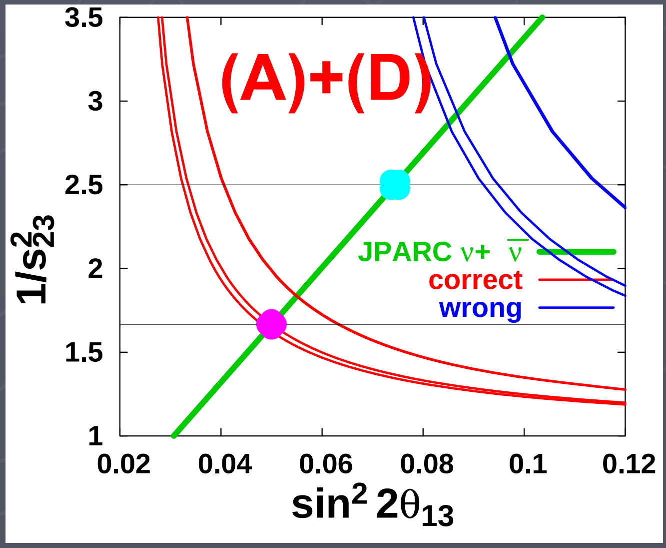
(D) measurement of $\nu_e \to \nu_\tau$ at $\nu$ factory



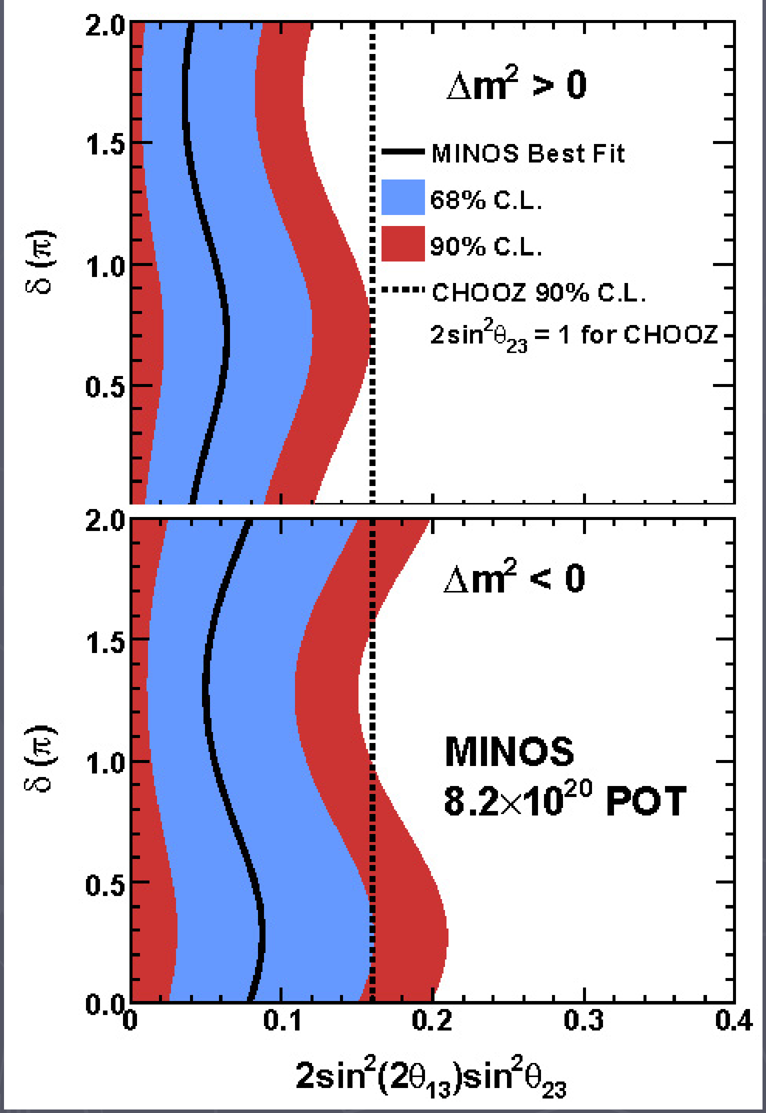

(A)+(B)

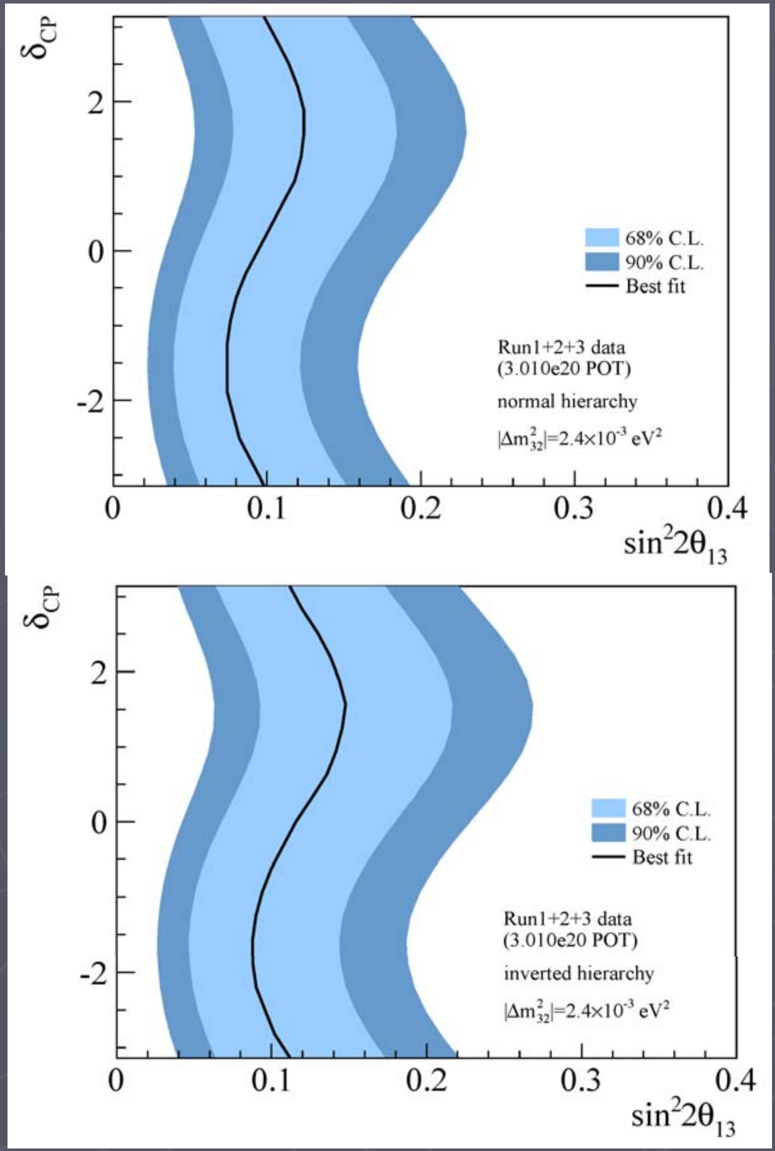



(A)+(C)



# Current status of appearance experiments



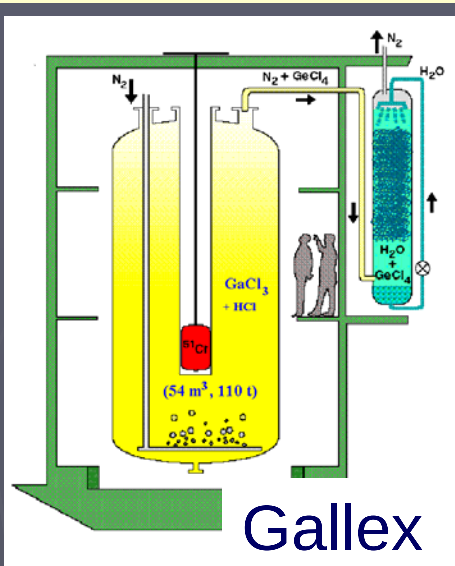




**arXiv:1108.0015**

**Sakashita@ICHEP2012**

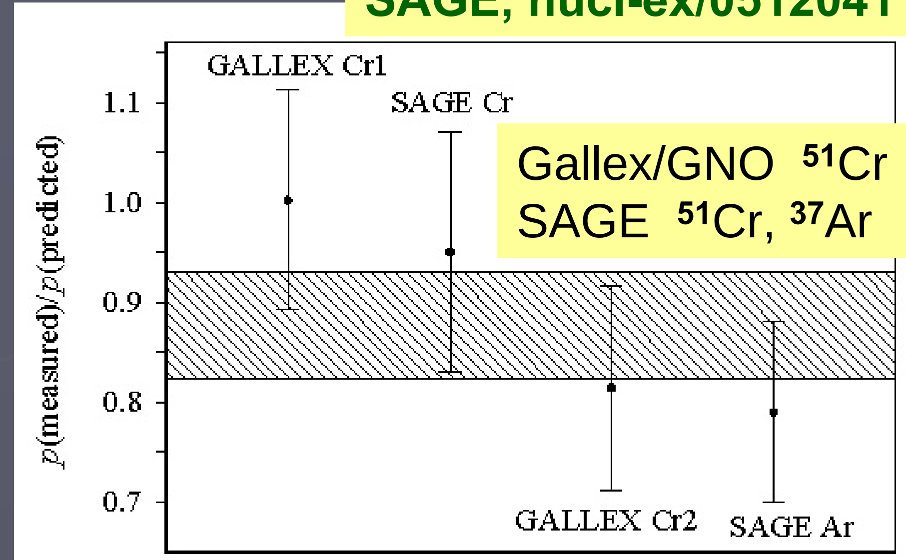
# Gallium anomaly

## Gallium radioactive source experiments



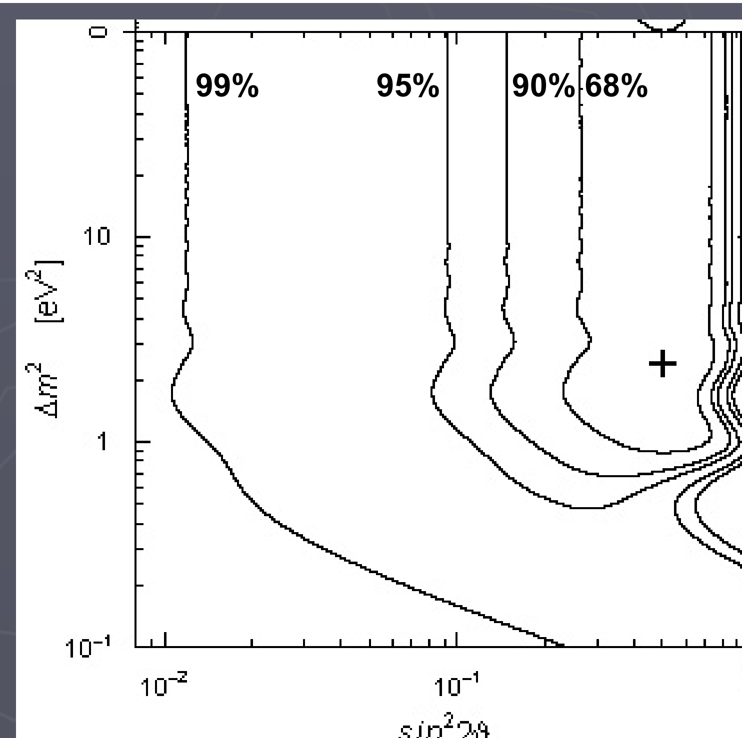


SAGE, nucl-ex/0512041



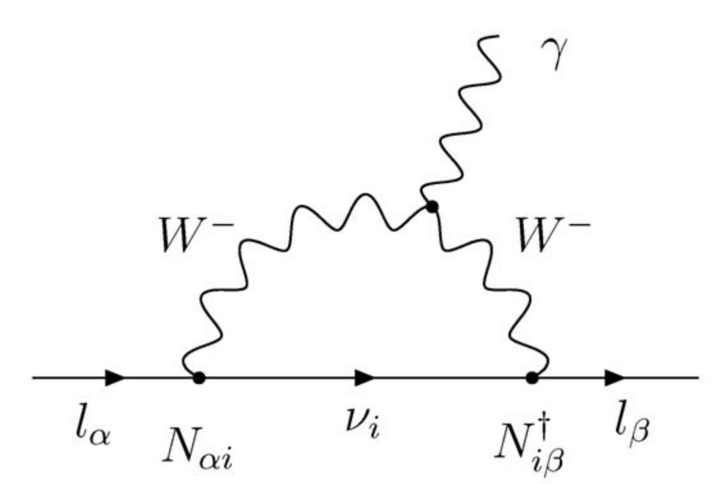

$$R \equiv \frac{\mathrm{p(measured)}}{\mathrm{p(predicted)}} = 0.88 \pm 0.05 (1\sigma)$$

Giunti-Laveder, 1006.3244v3 [hep-ph]




**Results of the Ga radioactive source calibration experiments may be interpreted as an indication of the disappearance of $\nu_e$ due to active-sterile oscillations.**

# Violation of unitarity due to heavy fields (Minimal Unitarity Violation)




**Antusch, Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon, JHEP0610,084, '06**

$$\frac{\Gamma(\ell_\alpha \to \ell_\beta \gamma)}{\Gamma(\ell_\alpha \to \nu_\alpha \ell_\beta \overline{\nu}_\beta)} = \frac{3\alpha}{32\pi} \frac{|\sum_k N_{\alpha k} N^\dagger_{k\beta} F(x_k)|^2}{(NN^\dagger)_{\alpha\alpha}(NN^\dagger)_{\beta\beta}},$$

where $x_k \equiv m_k^2/M_W^2$ with $m_k$ being the masses of the light neutrinos and

$$F(x) \equiv \frac{10 - 43x + 78x^2 - 49x^3 + 4x^4 + 18x^3 \ln x}{3(x-1)^4}.$$

# Violation of unitarity due to heavy fields (Minimal Unitarity Violation)

Antusch, Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon, JHEP0610,084, '06

$F(x) \approx 10/3$, it follows that

$$\frac{\Gamma(\ell_\alpha \to \ell_\beta \gamma)}{\Gamma(\ell_\alpha \to \nu_\alpha \ell_\beta \overline{\nu}_\beta)} = \frac{100\alpha}{96\pi} \frac{|(NN^\dagger)_{\alpha\beta}|^2}{(NN^\dagger)_{\alpha\alpha}(NN^\dagger)_{\beta\beta}},$$

leading to the constraint

$$\frac{|(NN^\dagger)_{\alpha\beta}|^2}{(NN^\dagger)_{\alpha\alpha}(NN^\dagger)_{\beta\beta}} = \frac{\Gamma(\ell_\alpha \to \ell_\beta \gamma)}{\Gamma(\ell_\alpha \to \nu_\alpha \ell_\beta \overline{\nu}_\beta)} \frac{96\pi}{100\alpha}.$$

## Violation of unitarity due to heavy fields (Minimal Unitarity Violation)

Antusch, Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon, JHEP0610,084, '06

## Experimental bound (in 2006)

$$Br(\tau \to \mu\gamma) < 6.8 \cdot 10^{-8} \,,$$
$$Br(\tau \to e\gamma) < 1.1 \cdot 10^{-7} \,,$$
$$Br(\mu \to e\gamma) < 1.2 \cdot 10^{-11}$$

$$Br(\tau \to \nu_\tau \mu \overline{\nu}_\mu) = 0.1736 \pm 0.0006,$$
$$Br(\tau \to \nu_\tau e \overline{\nu}_e) = 0.1784 \pm 0.0006$$
$$Br(\mu \to \nu_\mu e \overline{\nu}_e) \approx 100\%$$

$$\begin{aligned} |(NN^\dagger)_{\mu\tau}|^2 &= (NN^\dagger)_{\mu\mu}(NN^\dagger)_{\tau\tau}\frac{\Gamma(\tau \to \mu\gamma)}{\Gamma(\tau \to \nu_\tau \mu \overline{\nu}_\mu)}\frac{96\pi}{100\alpha} \\ &\simeq \frac{6.8 \cdot 10^{-8}}{0.1736} \cdot \frac{96\pi}{100\alpha} \\ &= 1.6 \times 10^{-4} \end{aligned}$$