Reactor measurements of θ_{13} and complementarity to LBL experiments

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I. Introduction

Oscillation parameters in N_ν=3 framework

$$
\begin{array}{ll}
(\Delta m^2_{21},\ \theta_{12}) & \leftarrow \nu_\odot\text{+KamLAND} \\
(|\Delta m^2_{32}|,\ \theta_{23}) & \leftarrow \nu_{\rm atm} \\
(\theta_{13},\ \mathrm{sign}(\Delta m^2_{32}),\ \delta) & \leftarrow \mathrm{unknown}
\end{array}
$$

As a first step toward the measurement of CP violation, we need to know the magnitude of θ_{13}.

There are two complementary methods so far:

	degeneracy	sensitivity to $\sin^2 2\theta_{13}$
LBL	some	$\mathcal{O}(10^{-3})$
reactor	none	$\mathcal{O}(10^{-2})$

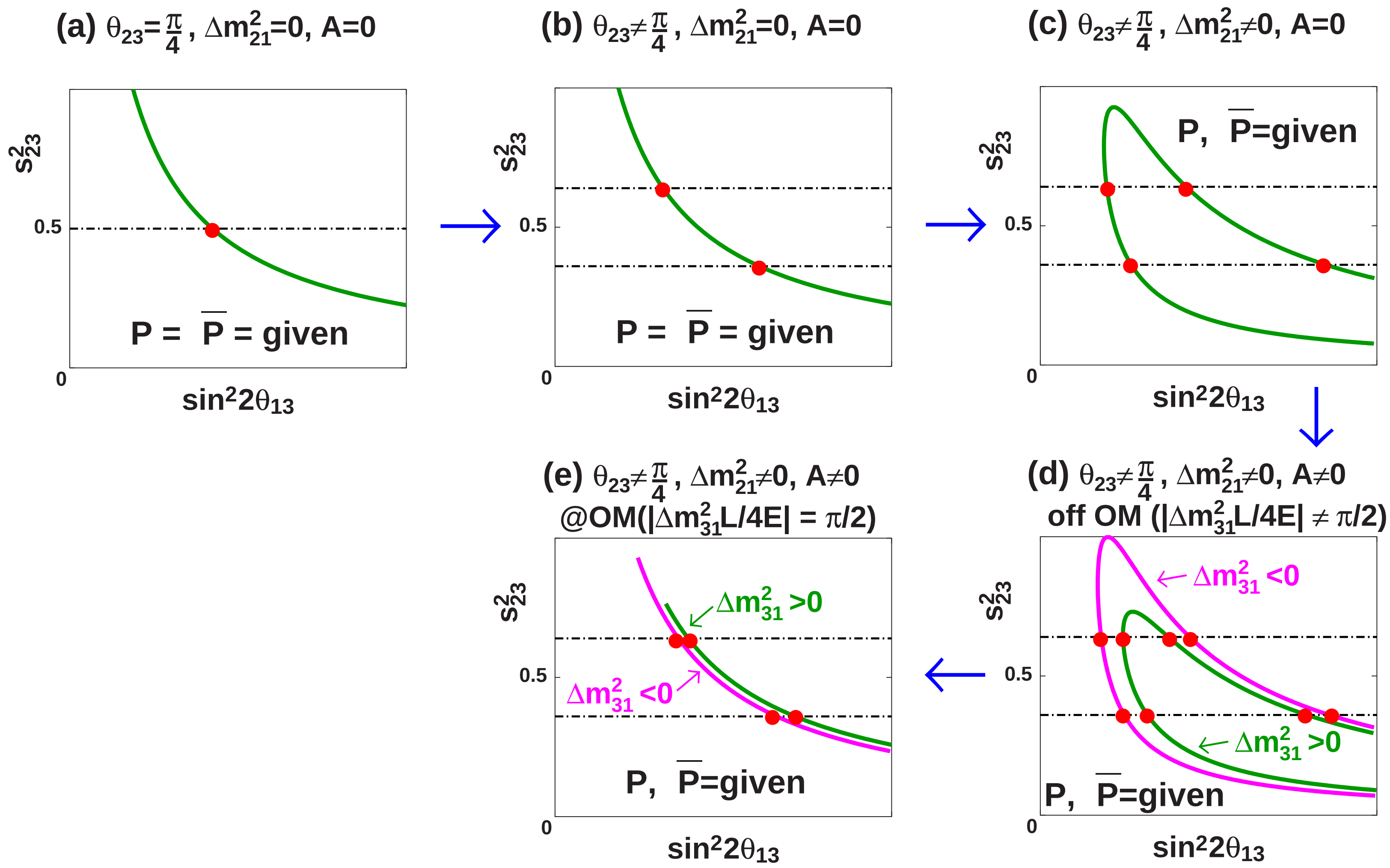
II. Parameter degeneracies

Even if we know $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ in a long baseline accelerator experiment with an approximately monoenergetic neutrino beam, precise determination of θ_{13}, sign of Δm^2_{31} and δ is difficult because of the 8-fold parameter degeneracy.

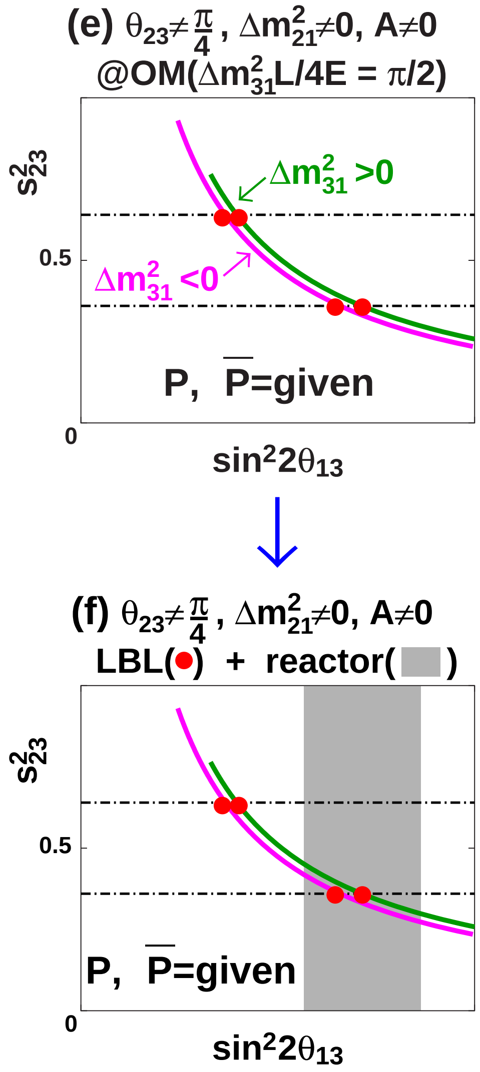
- intrinsic (θ_{13}, δ) degeneracy
- $\Delta m^2_{31} \leftrightarrow -\Delta m^2_{31}$ degeneracy
- $\theta_{23} \leftrightarrow \pi/2 - \theta_{23}$ degeneracy

$\longrightarrow$ talks by Minakata, Sugiyama, Whisnant,
Donini, Migliozzi, Winter

The 8-fold degeneracy is lifted as the small parameters $\cos^2 2\theta_{23}$, $|\Delta m^2_{21}/\Delta m^2_{31}|$, AL $(A \equiv \sqrt{2} G_F N_e)$ are switched on:



III. Measurement of θ_{13} by reactors



Measurement of θ_{13} by reactors is free of ambiguities from θ_{23}, δ, θ_{12}, Δm^2_{21}, A:

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

($|\Delta m^2_{31}| \leftarrow \nu_{\mathrm{atm}}$, MINOS, or JHF–I)

Therefore,

a long baseline accelerator experiment
$+$
a reactor measurements of θ_{13}

may enable us to resolve the degeneracy.

Experimental conditions for θ_{13} (Suekane-san)

Optimization of baseline

SK $\nu_{\rm atm}$ result: $|\Delta m^2_{31}| \simeq 2.5 \times 10^{-3}$eV^2

$$\int F(E)\sigma(E)\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)dE = \max$$

$\longrightarrow$ $L \simeq$1.7km

$\longrightarrow$ $N_\nu \sim$150/yr/target-ton/GW$_{\rm th}$

1% stat. error/yr (necessary to improve the CHOOZ bound)

$\longrightarrow$ $M_{\rm target} \cdot P_{\rm reactor}$=70 t·GW$_{\rm th}$

Kashiwazaki-Kariwa NPP (24.3 GW$_{\rm th}$)

$\longrightarrow$ $M_{\rm target} \sim$ 5 tons (=just CHOOZ size)

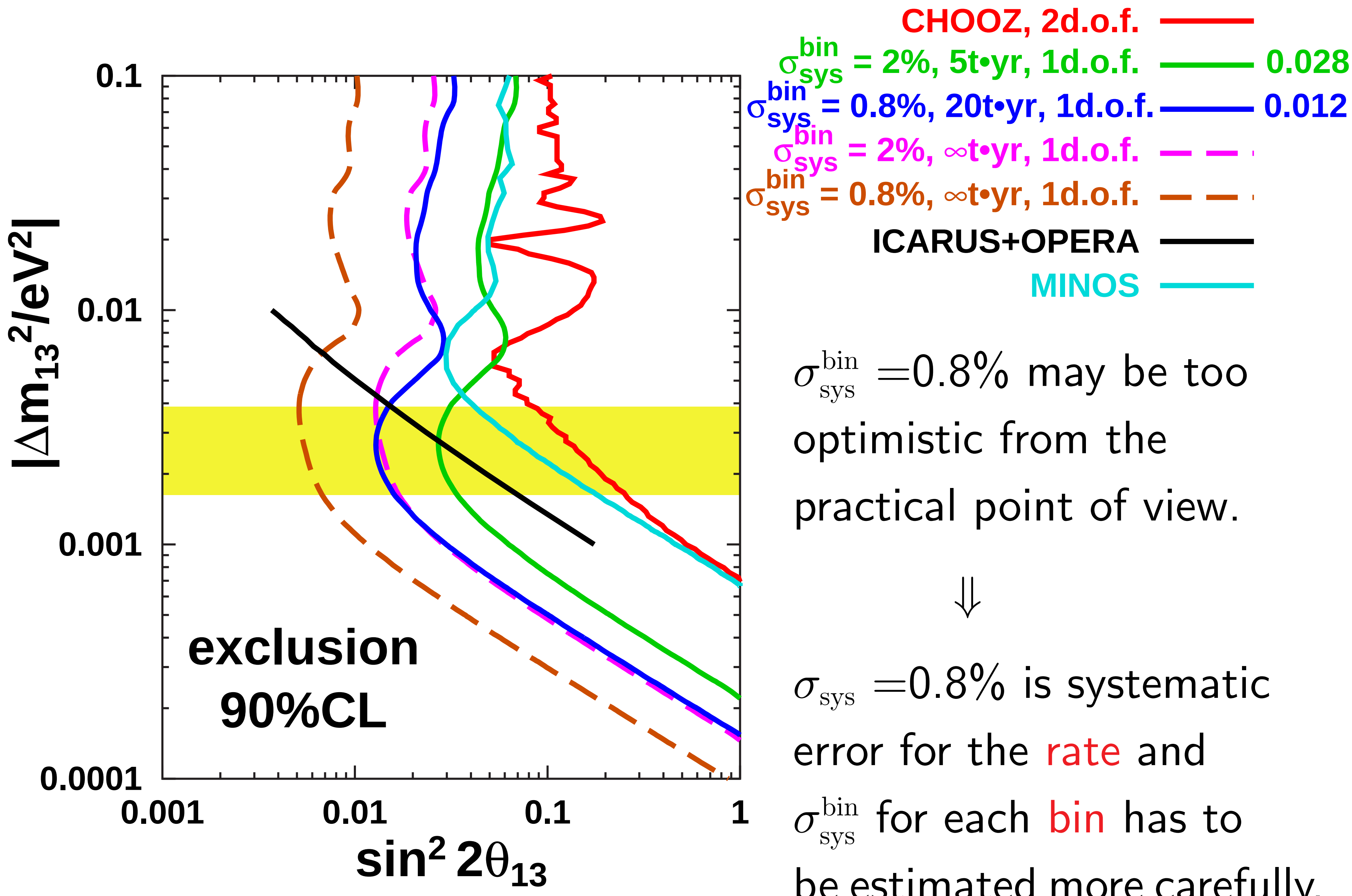
Systematic errors can be reduced by detectors at two baselines:

Bugey	absolute	relative	rel./abs.
flux	2.8%	0.0%	0
number of protons	1.9%	0.6%	0.32
solid angle	0.5%	0.5%	1
detection efficiency	3.5%	1.7%	0.49
total	4.9%	2.0%	

CHOOZ–like	absolute	relative (expected)	rel./abs.
flux	2.1%	0.0%	0
number of protons	0.8%	0.3%	0.38
detection efficiency	1.5%	0.7%	0.47
total	2.7%	0.8%	

Here we assume:

- $24.3\,\mathrm{GW}_{\mathrm{th}}$
- 80% operation efficiency
- 70% detection efficiency
- baselines L_1=0.3km and L_2=1.7km
  - (1.7km: optimum for $|\Delta m^2_{31}| = 2.5 \times 10^{-3}$eV^2)
  - (Two detectors are necessary to reduce systematic error.)
- energy spectrum: 14 bins of 0.5MeV
- systematic error $\sigma^{\mathrm{bin}}_{\mathrm{sys}}$ & data size D (two cases):
  - ($\sigma^{\mathrm{bin}}_{\mathrm{sys}}$, D) =(2%, 5 t·yr) or (0.8%, 20 t·yr)



$\sigma_{\rm sys}^{\rm bin} = 0.8\%$ may be too optimistic from the practical point of view.

$\Downarrow$

$\sigma_{\rm sys} = 0.8\%$ is systematic error for the rate and $\sigma_{\rm sys}^{\rm bin}$ for each bin has to be estimated more carefully.

With out the knowledge on the the relative systematic error $\sigma_{\rm sys}^{\rm bin}$ for each bin, we assume that $\sigma_{\rm sys}^{\rm bin}$ is distributed equally into bins,

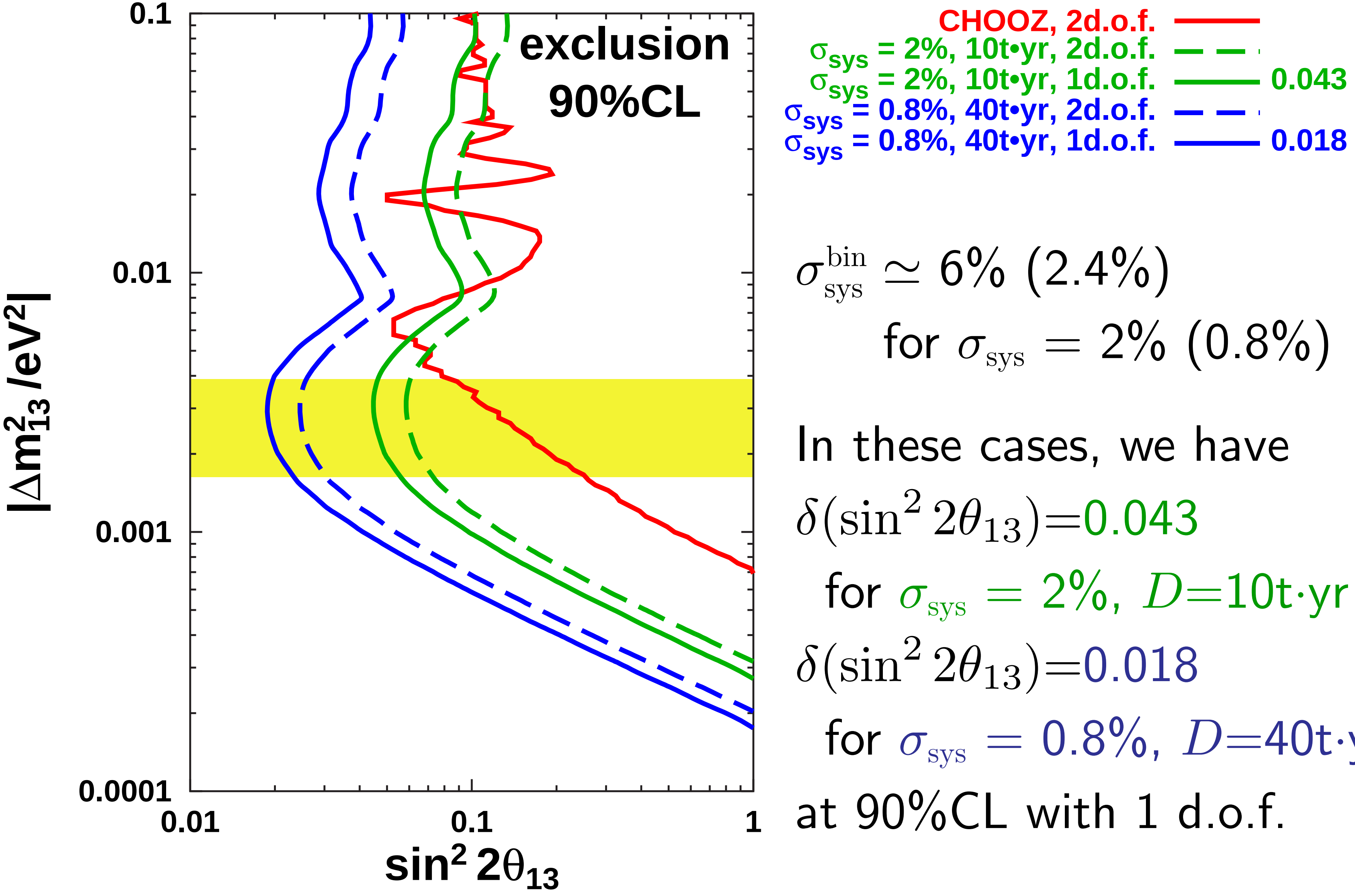
$$(\sigma_{\rm sys}^{\rm bin})_i = \sigma_{\rm sys}^{\rm bin}$$

and is estimated from the relative systematic error $\sigma_{\rm sys}$ for the total number of events by

$$\sigma_{\rm sys}^2 (N_{\rm tot}(L_2))^2 = \sum_i (\sigma_{\rm sys}^{\rm bin})_i^2 (N_i(L_2))^2 = (\sigma_{\rm sys}^{\rm bin})^2 \sum_i (N_i(L_2))^2,$$

$$(\sigma_{\rm sys}^{\rm bin})^2 = \sigma_{\rm sys}^2 \frac{(N_{\rm tot}(L_2))^2}{\sum_i (N_i(L_2))^2} \simeq (2.4\%)^2$$

CHOOZ–like	relative (expected)
total	$\sigma_{\rm sys}$=0.8%
for bins	$\sigma_{\rm sys}^{\rm bin}$=2.4%



$\sigma_{\rm sys}^{\rm bin} \simeq$ 6% (2.4%)

for $\sigma_{\rm sys} =$ 2% (0.8%)

In these cases, we have

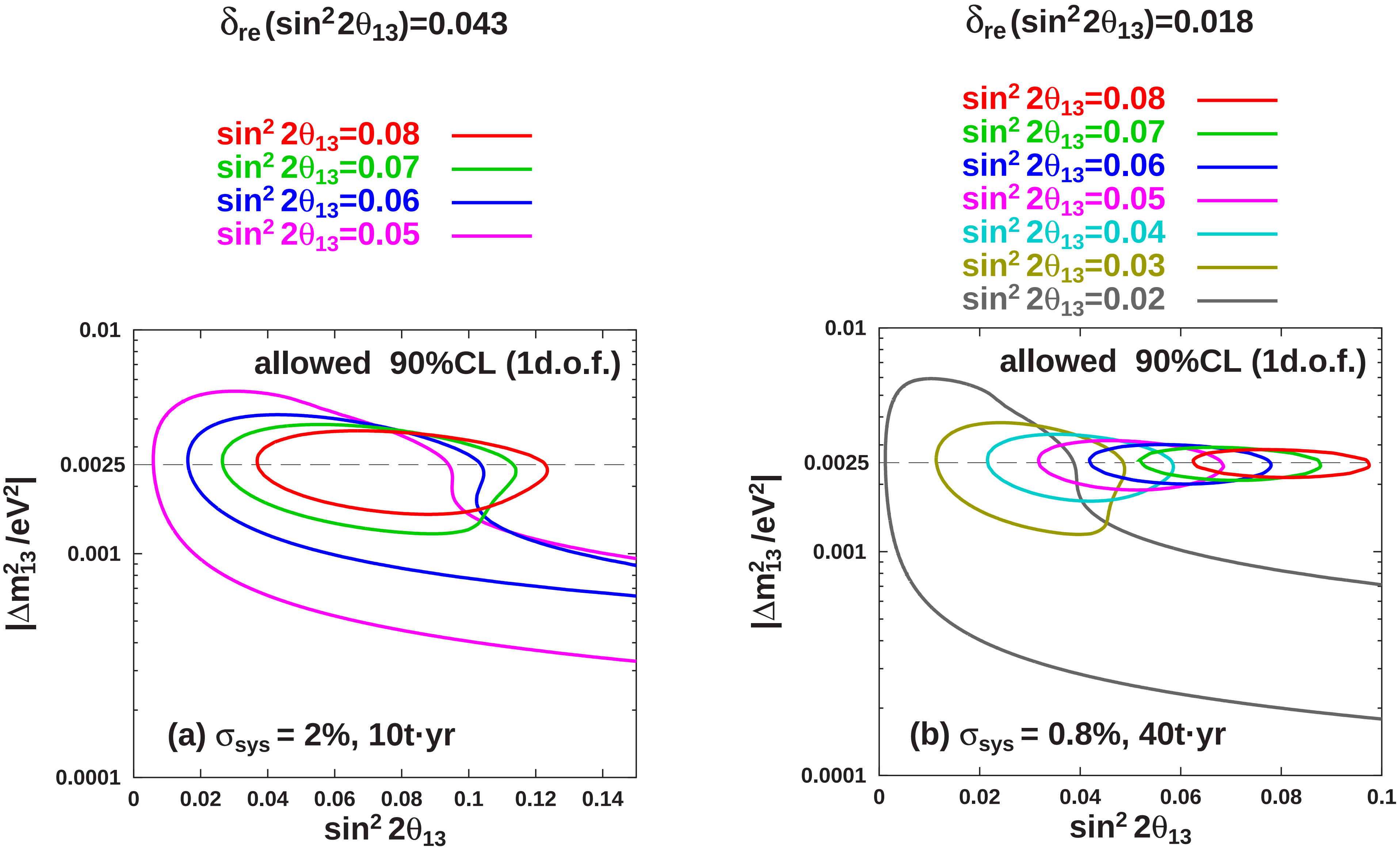
$\delta(\sin^2 2\theta_{13})$=0.043

for $\sigma_{\rm sys} =$ 2%, D=10t·yr

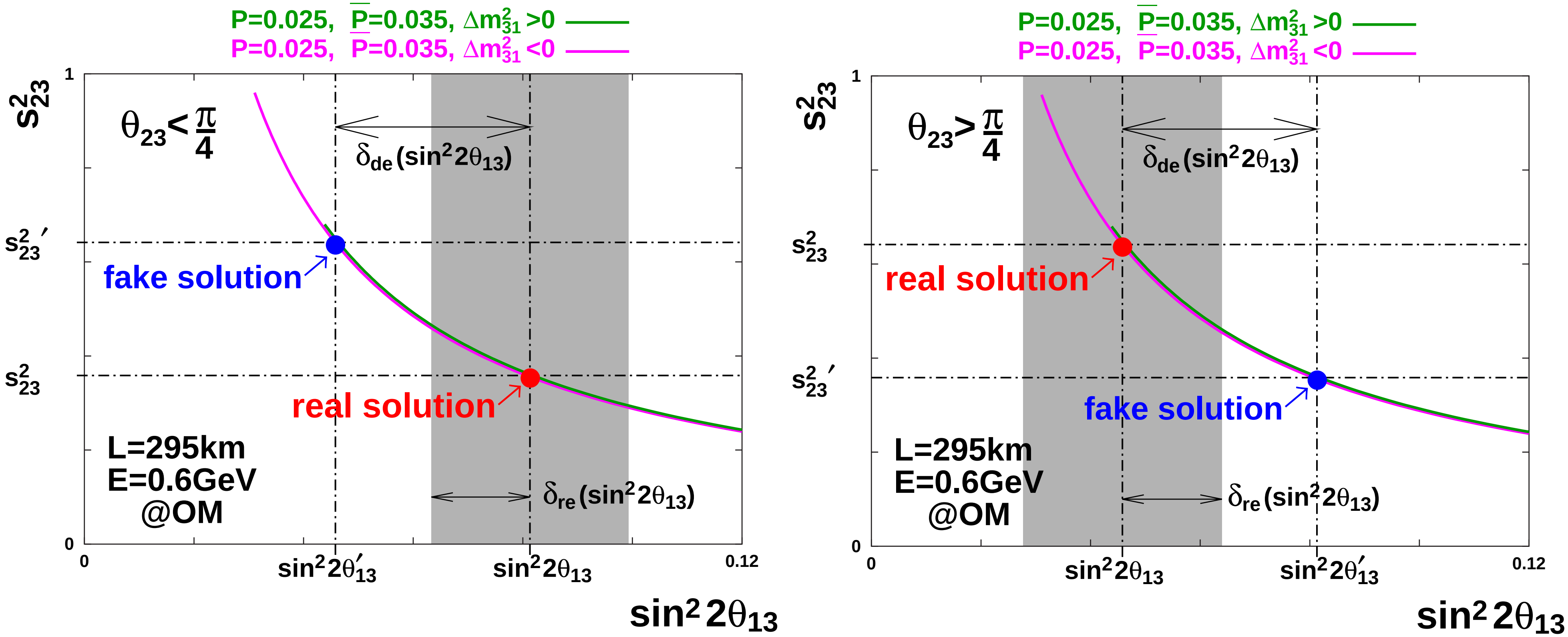
$\delta(\sin^2 2\theta_{13})$=0.018

for $\sigma_{\rm sys} =$ 0.8%, D=40t·yr

at 90%CL with 1 d.o.f.



δre (sin² 2θ13)=0.043
sin² 2θ13=0.08
sin² 2θ13=0.07
sin² 2θ13=0.06
sin² 2θ13=0.05
allowed 90%CL (1d.o.f.)
0.01
0.0025
0.001
0.0001
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
|Δm²13 /eV²|
sin² 2θ13
(a) σsys = 2%, 10t·yr
δre (sin² 2θ13)=0.018
sin² 2θ13=0.08
sin² 2θ13=0.07
sin² 2θ13=0.06
sin² 2θ13=0.05
sin² 2θ13=0.04
sin² 2θ13=0.03
sin² 2θ13=0.02
allowed 90%CL (1d.o.f.)
0.01
0.0025
0.001
0.0001
0
0.02
0.04
0.06
0.08
0.1
|Δm²13 /eV²|
sin² 2θ13
(b) σsys = 0.8%, 40t·yr



The ambiguity due to the parameter degeneracy by the LBL accelerator experiment alone can be resolved by reactor measurements of θ_{13} if $\delta_{\rm re}(\sin^2 2\theta_{13}) < \delta_{\rm de}(\sin^2 2\theta_{13})$.

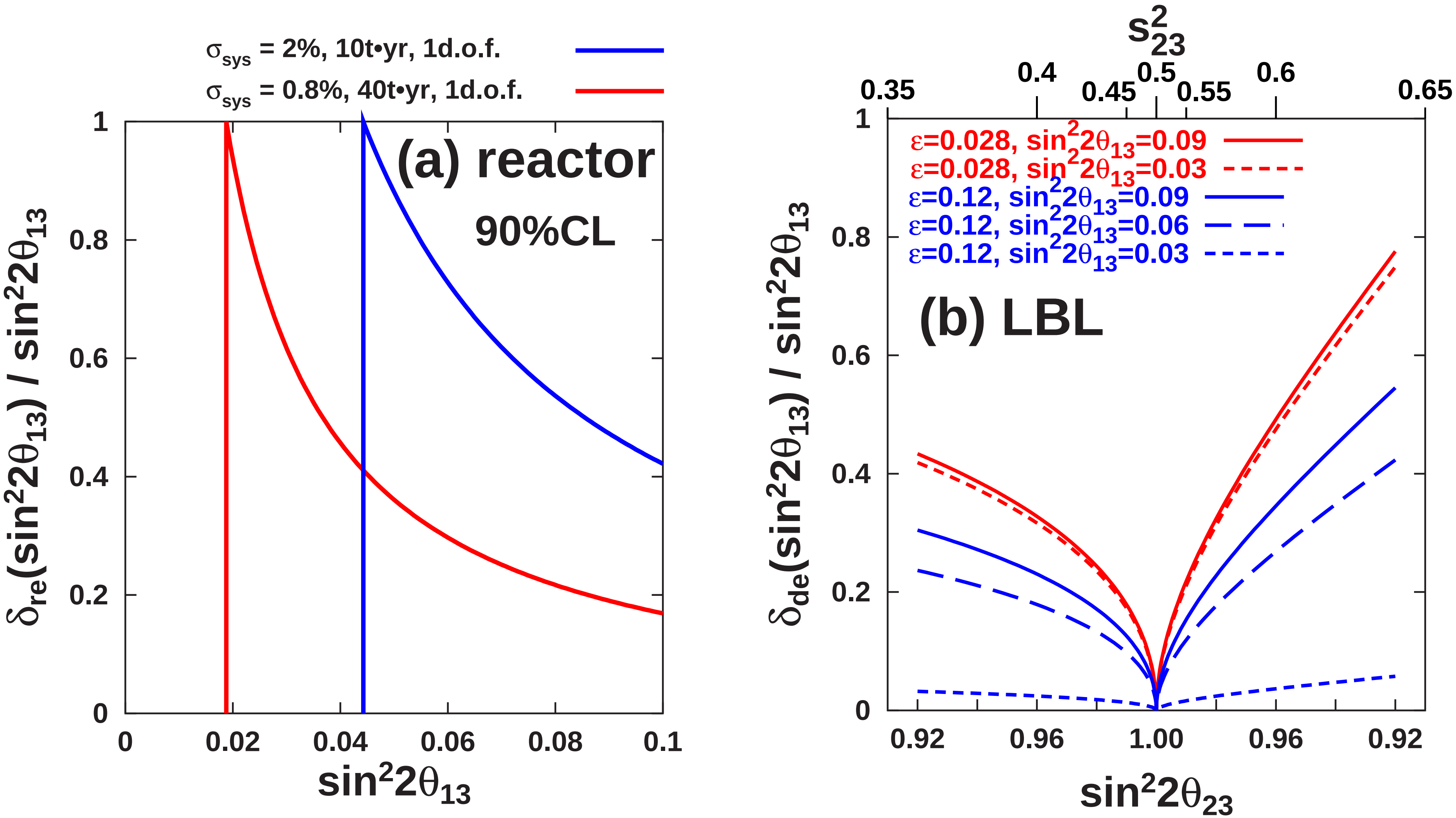
$$\delta_{\rm re}(\sin^2 2\theta_{13}) = 0.043$$
for $\sigma_{\rm sys} = 2\%$

$$\delta_{\rm re}(\sin^2 2\theta_{13}) = 0.018$$
for $\sigma_{\rm sys} = 0.8\%$

$$\delta_{\rm de}(\sin^2 2\theta_{13})/\sin^2 2\theta_{13} = |1-\tan^2\theta_{23}|\left(1+\frac{\mathcal{O}(1)\epsilon^2}{\sin^2 2\theta_{13}}\right)$$

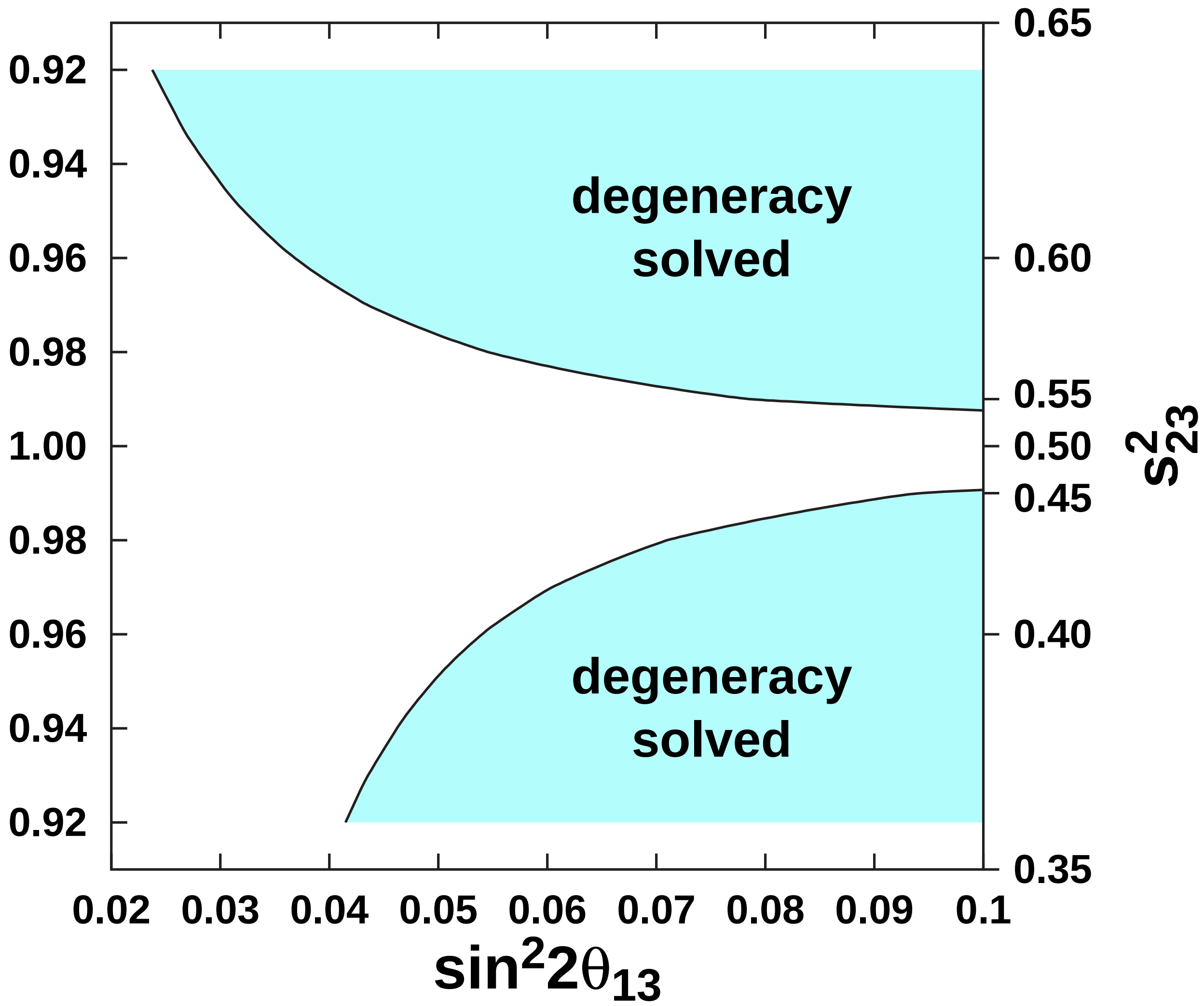
$$\epsilon \equiv \left|\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right| \simeq \frac{1}{35}\ \text{(best fit)}$$

$\simeq 0.12$ (worst case @90%CL)



The region where $\delta_{\rm re}(\sin^2 2\theta_{13}) < \delta_{\rm de}(\sin^2 2\theta_{13})$ is satisfied.
Error in the LBL experiment is not taken into account here.

$\rightarrow$ Sugiyama's talk with the errors of JHF



IV. Idea of a measurement of θ_{13} at Kashiwazaki-Kariwa NPP

Working group so far

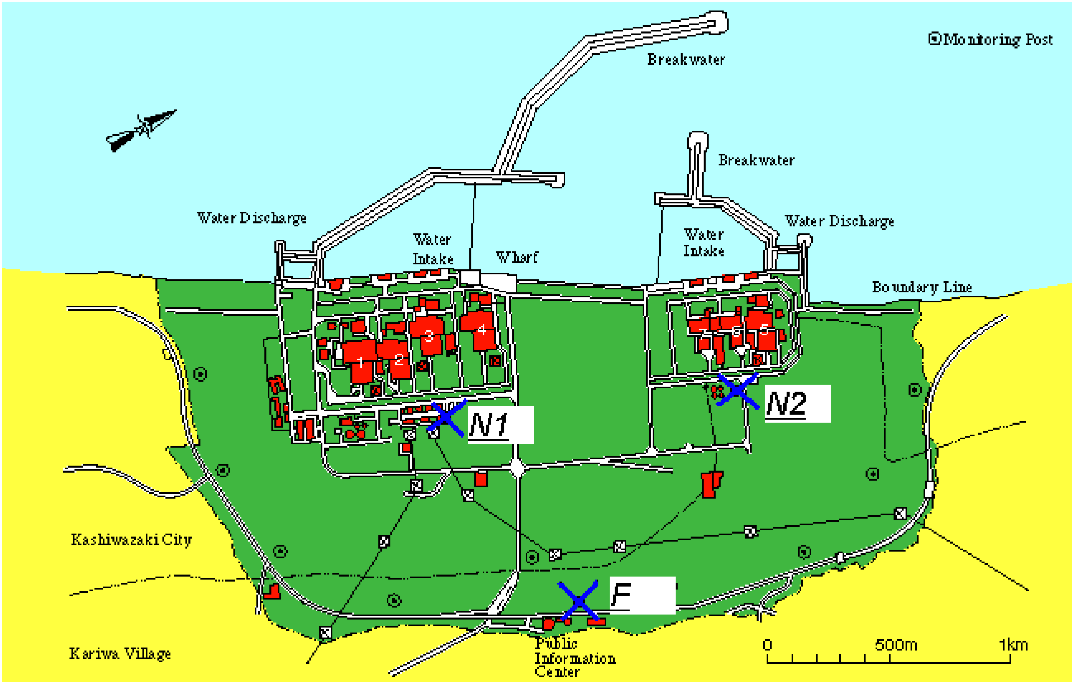
F. Suekane, K. Inoue, T. Araki, K. Jongok (Tohoku Univ.)
H. Minakata, H. Sugiyama, O.Y. (TMU)

- Optimization on baseline

$$\int F(E)\sigma(E)\sin^2\left(\frac{\Delta m^2_{31}L_2}{4E}\right)dE = \max$$

in principle gives the optimal baseline L_2=1.7km, but we have to compromise with the longest possible baseline in the Kashiwazaki-Kariwa NPP site: L_2=1.3km.

Kashiwazaki-Kariwa Nuclear Power Plant

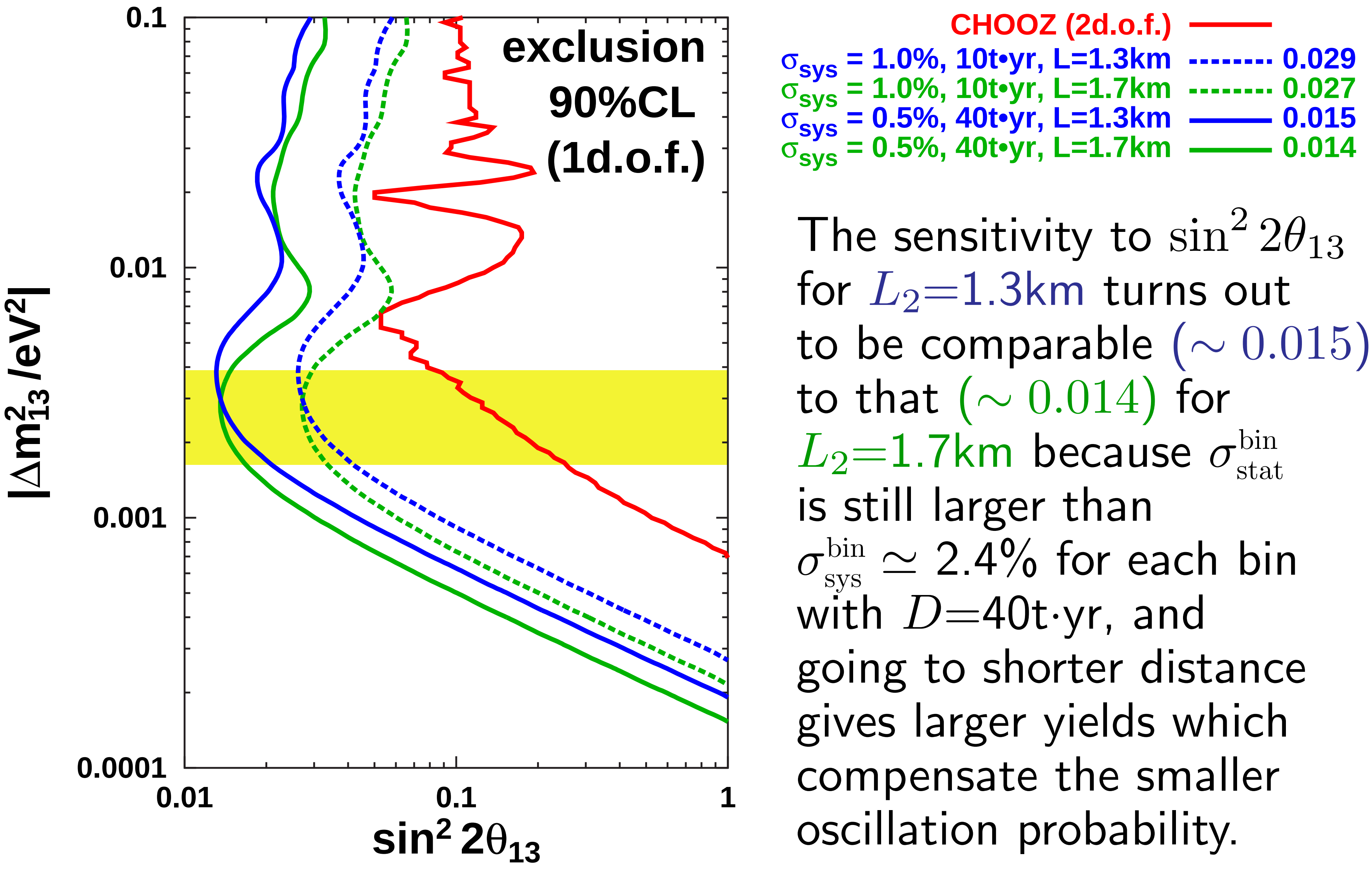


Two near detectors are necessary:

N1: Near detector I (L=0.35km, 70m deep)

N2: Near detector II (L=0.3km, 70m deep)

F: Far detector (L=1.3km, 200m deep)



The sensitivity to $\sin^2 2\theta_{13}$ for L_2=1.3km turns out to be comparable (~ 0.015) to that (~ 0.014) for L_2=1.7km because $\sigma^{\rm bin}_{\rm stat}$ is still larger than $\sigma^{\rm bin}_{\rm sys} \simeq 2.4\%$ for each bin with D=40t·yr, and going to shorter distance gives larger yields which compensate the smaller oscillation probability.

V. Summary

• Measurements of θ_{13} by reactors are free of ambiguities of the parameter degeneracy, and may enable us to resolve the ambiguity which occurs in the LBL experiment if $\sin^2 2\theta_{13}$ and $\cos^2 2\theta_{23}$ are both large.

• Sensitivity to $\sin^2 2\theta_{13} \gtrsim 0.02$ (0.05) is obtained with a 24.3 $\mathrm{GW_{th}}$ reactor, $D = 40$ (10) t·yr and $\sigma_{\rm sys} = 0.8\%$ (2%).

• At Kashiwazaki-Kariwa NPP with L_2=1.3km, similar sensitivity can be obtained for $D = 40$ t·yr and $\sigma_{\rm sys} = 0.5\%$.