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

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Coral Gables Conference on High Energy Physics and Cosmology

Dec. 21, 2003

Happy birthday, Paul!

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Ref:

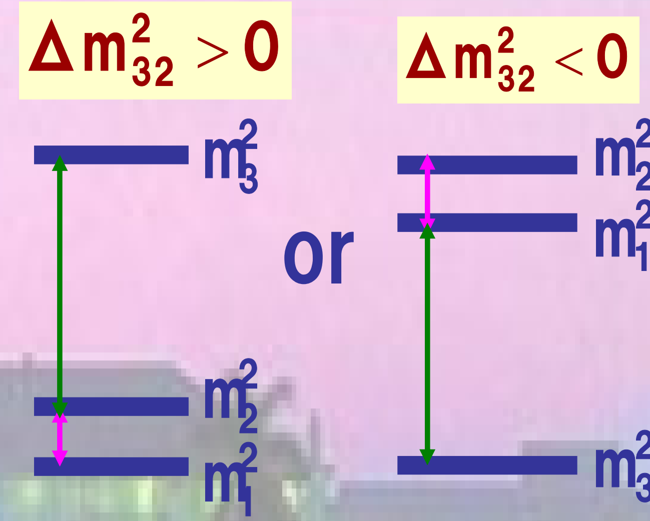
2.,3. H. Minakata, H. Sugiyama, O.Y., F. Suekane, K. Inoue, Phys.Rev.D68:033017,2003;
H. Sugiyama, O.Y., F. Suekane, G.A. Horton-Smith, to appear

4. H. Sugiyama, O.Y., to appear

1. Introduction

ν oscillation

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$



- solar ν・KamLAND
  ⇒ $\Delta m^2_{21} = 7\times10^{-5}$eV, $\sin^2 2\theta_{12} \cong 0.9$
- atmospheric ν・K2K
  ⇒ $|\Delta m^2_{32}| = 2\times10^{-3}$eV^2, $\sin^2 2\theta_{23} \cong 1.0$
- CHOOZ
  ⇒ $\sin^2 2\theta_{13} < 0.2$

Next things to determine: θ_{13} and δ (CP phase)

Naïve argument on measurement of θ_{13}

$$P(\nu_\mu \to \nu_e) \cong s^2_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right) + \text{corrections}$$

θ_{13} can be deduced

Naïve argument on measurement of δ

$$P(\nu_\mu \to \nu_e) - P(\overline{\nu_\mu} \to \overline{\nu_e}) = 2J \sin\left(\frac{\Delta m^2_{21} L}{4E}\right) \sin\left(\frac{\Delta m^2_{32} L}{4E}\right) \sin\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

$$J \equiv \sin\delta \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23}$$

δ can be deduced

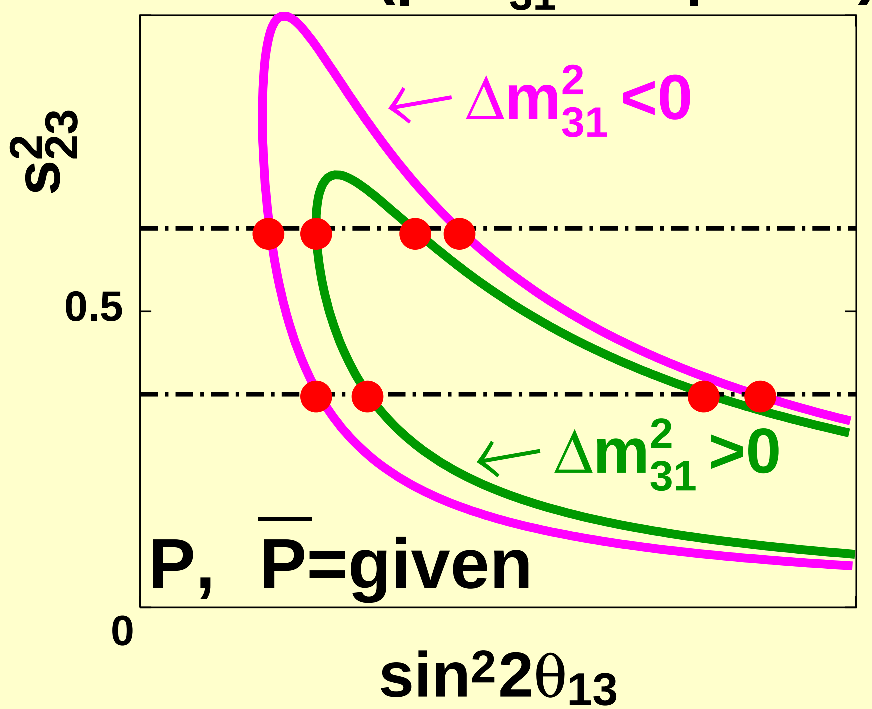
2. Parameter degeneracy

Even if we know $P(\nu_\mu \to \nu_e)$ and $P(\overline{\nu_\mu} \to \overline{\nu_e})$ in a long baseline accelerator experiments with approximately monoenergetic neutrino beam, precise determination of θ_{13}, sign(Δm^2_{32}) and δ is difficult because of the 8-fold parameter degeneracy.

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

8-fold degeneracy

off OM ($|\Delta m^2_{31} L/4E| \neq \pi/2$)



Matter effect:

$$\frac{\Delta m^2 L}{4E} \rightarrow \frac{L}{2}\left[\left(\frac{\Delta m^2}{2E}\cos 2\theta \mp A\right)^2 + \left(\frac{\Delta m^2}{2E}\sin 2\theta\right)^2\right]^{1/2} \quad \text{for} \begin{pmatrix}\nu \\ \overline{\nu}\end{pmatrix}$$

$$A \equiv \sqrt{2} G_F N_e \cong (2000\text{km})^{-1} \bullet (\rho / 2.7\text{g} \cdot \text{cm}^{-3})$$

→ not significant for L～300km

Resolution of the degeneracy

- A long baseline accelerator experiment at **O**scillation **M**aximum:

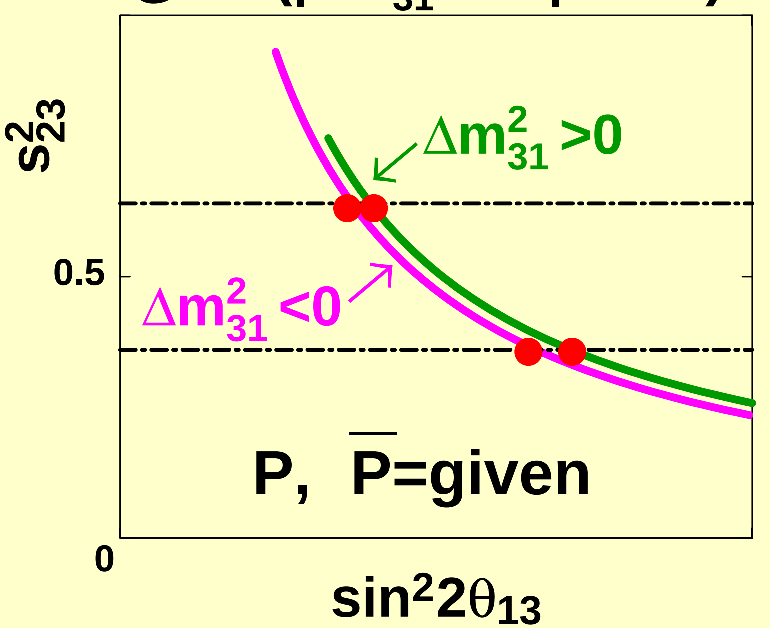
$$\left|\frac{\Delta m^2_{31} L}{4E}\right| = \frac{\pi}{2}$$

+

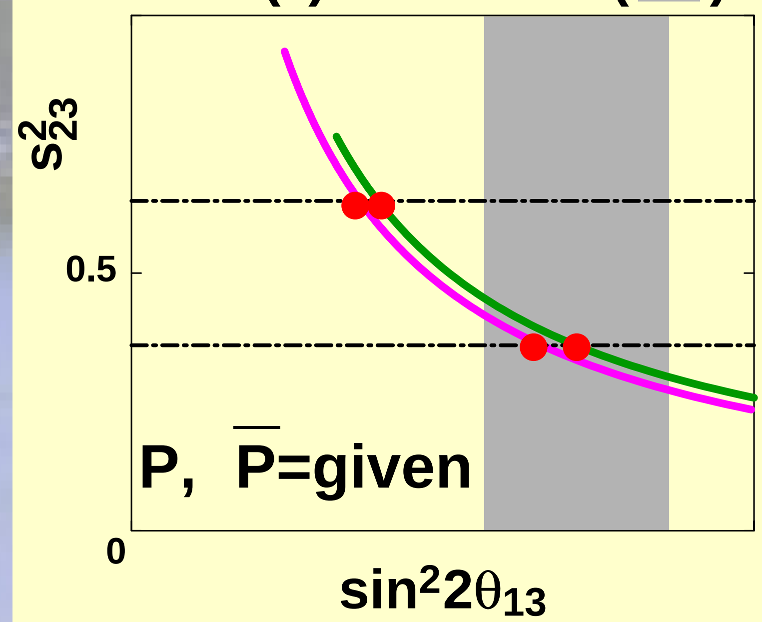
- A reactor measurement of θ_{13}:

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

@OM($|\Delta m^2_{31} L/4E| = \pi/2$)



LBL(●) + reactor(▬)



3. KAShiwazaki-KAriwa plan (KASKA)

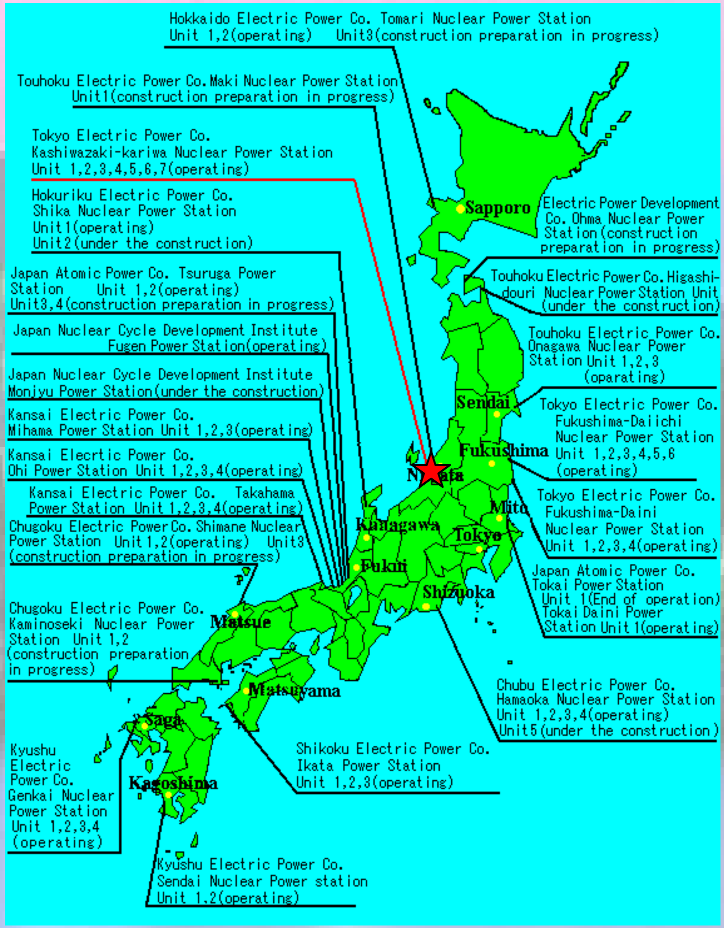
kaska = faint or very little (in Japanese)

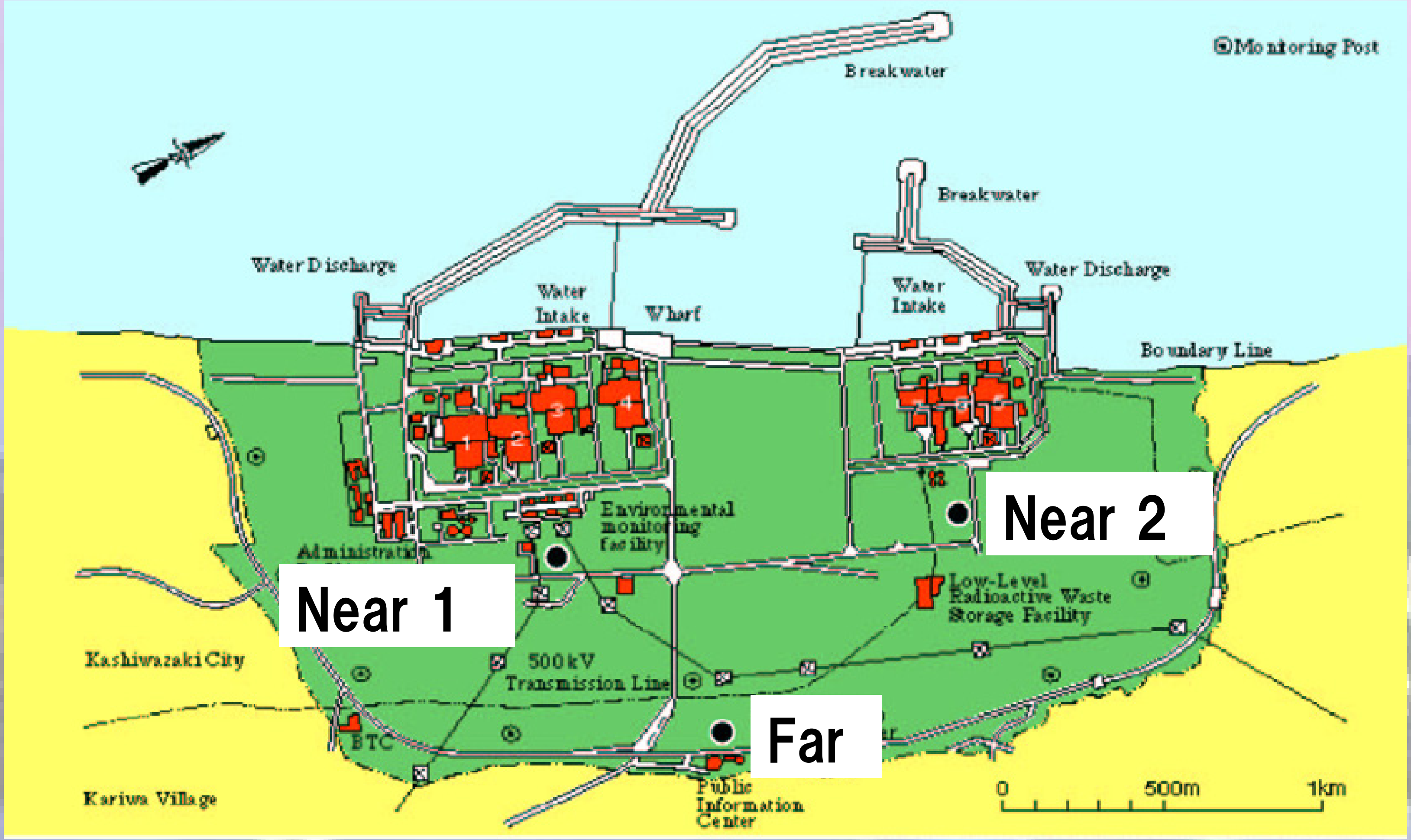
Kashiwazaki-Kariwa nuclear power plant (in Niigata pref.)

24 GW_{th}: the largest in the world

Collaborators so far:

- Tohoku U. (2)
- Niigata U. (4)
- Tokyo Met. U. (3)
- Tokyo Inst. Tech. (1)
- Rikkyo U. (1)

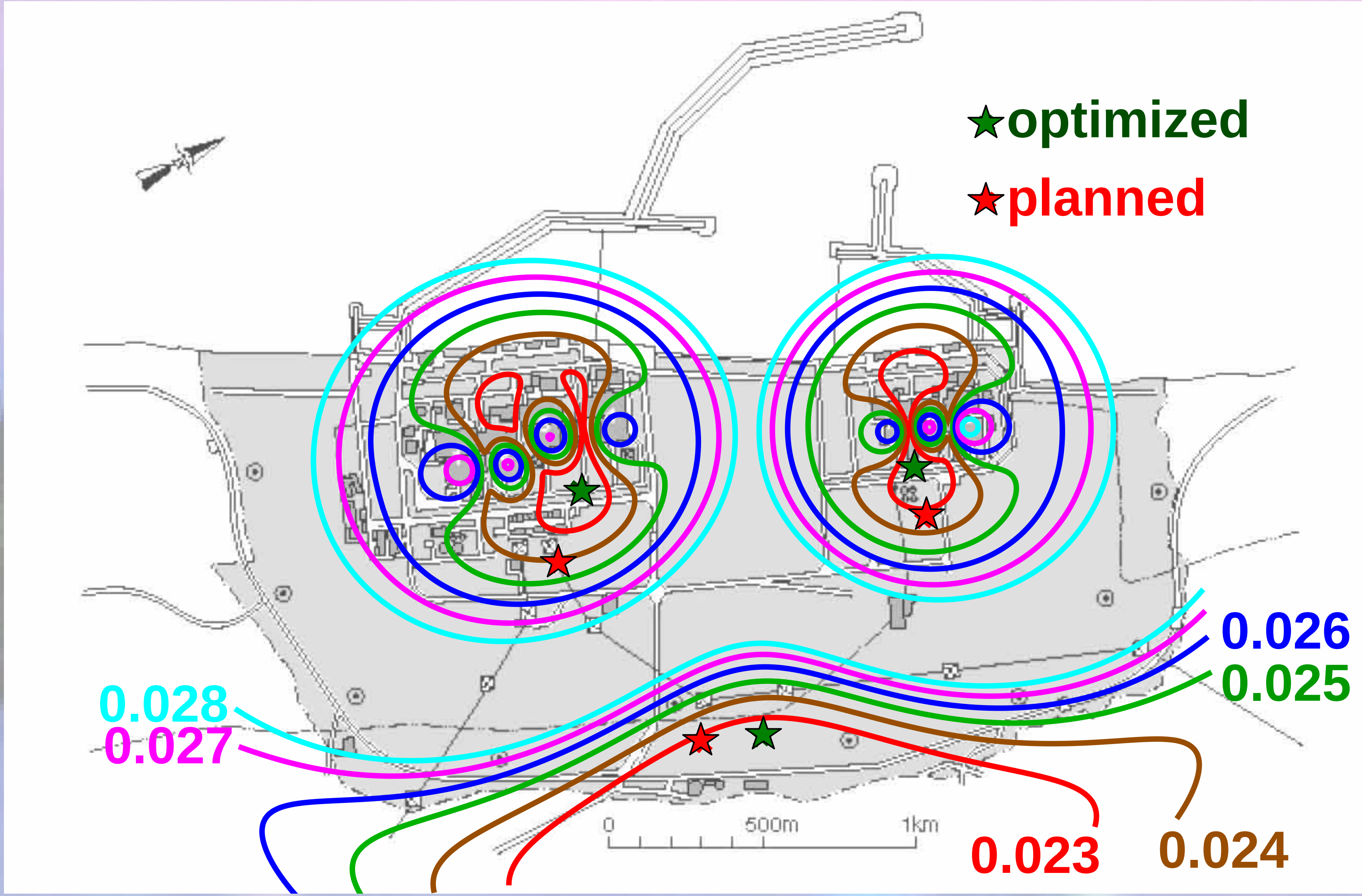




To cancel the correlated error, more than 1 detector is required.

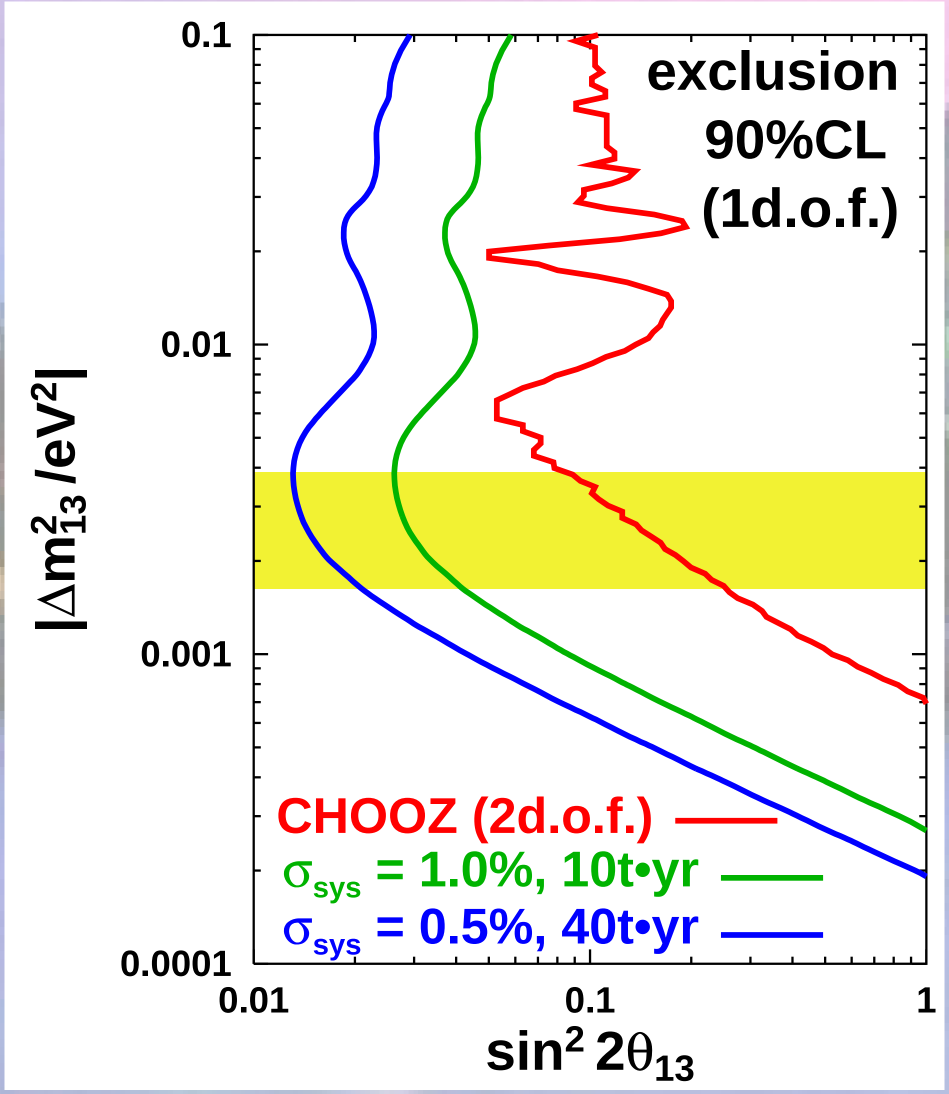
7reactors+3detectors→ sensitivity of $\sin^2 2\theta_{13} \cong 0.02$

L_{far}=1.3km, L_{near}~0.4km



contour plot of $\sin^2 2\theta_{13}$ with 20 ton•yr, σ_{sys}=0.6%

Sensitivity to $\sin^2 2\theta_{13}$ at KASKA



- Sensitivity at JPARC ($\sin^2 2\theta_{13} \sim 10^{-3}$) is far better but reactor experiments are complementary.
- Although KASKA consists of multiple reactors, extra ambiguity does not arise.

4. Lower bound on sensitivity to $\sin^2 2\theta_{13}$ in reactor experiments and possibility of its improvement

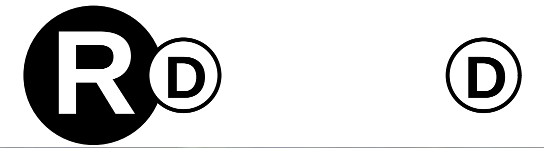
I will discuss systematic limit:

$$\left(\sin^2 2\theta_{13}\right)_{\text{sensitivity}} \geq \left(\sin^2 2\theta_{13}\right)^{\text{sys only}}_{\text{limit}}$$

$$(\text{equality when } \#(\text{events}) \to \infty)$$

- case with 1 reactor + 2 detectors

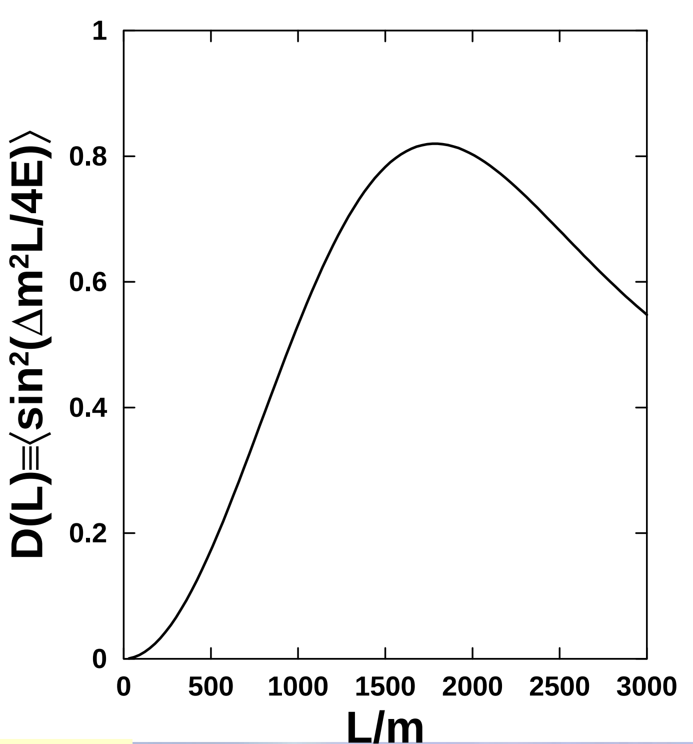
$$\left(\sin^2 2\theta_{13}\right)^{\text{sys only}}_{\text{limit}} \simeq \frac{\sqrt{2.7}\sqrt{2}\,\sigma_u}{D(L_{far}) - D(L_{near})}$$



where σ_u: uncorrelated systematic error,

$$D(L) \equiv \left\langle \sin^2\left(\frac{\Delta m^2 L}{4E}\right)\right\rangle \equiv \frac{\int dE\,\sigma(E)\,f(E)\,\varepsilon(E)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)}{\int dE\,\sigma(E)\,f(E)\,\varepsilon(E)}$$

$$\left(\sin^2 2\theta_{13}\right)^{\text{sys only}}_{\text{limit}}$$
$$\cong \frac{\sqrt{2.7}\sqrt{2}\,\sigma_u}{D(L_{far}) - D(L_{near})}$$
$$\geq \frac{\sqrt{2.7}\sqrt{2}\,\sigma_u}{0.8} \quad (\text{equality}: L_{far} = 1.8\text{km},\ L_{near} = 0\text{km})$$
$$= 2.8\,\sigma_u$$
$$= 0.017 \quad (\text{if } \sigma_u = 0.6\%)$$



→ With 1 reactor + 2 detectors, sensitivity cannot be better than 0.017!

σ_u=0.6%: extrapolation from Bugey+CHOOZ

(σ_u<0.6% seems to be hard to achieve.)

● case with N reactors + (N+1) detectors

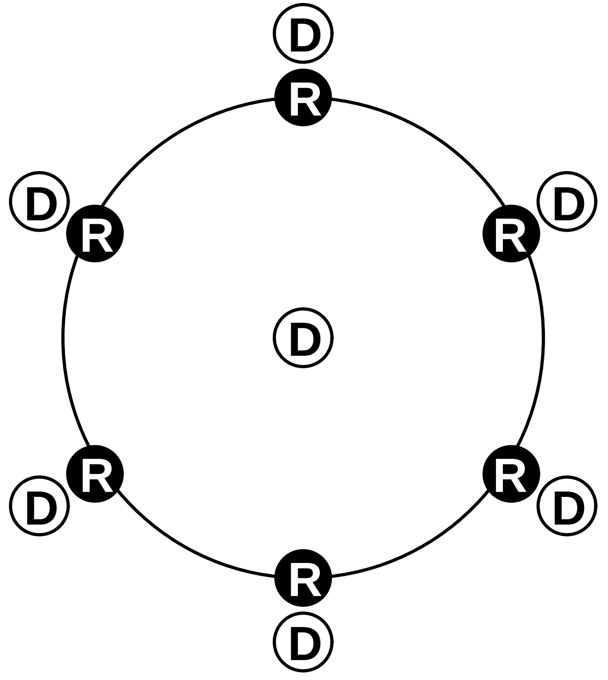
$$\left(\sin^2 2\theta_{13}\right)^{\text{sys only}}_{\text{limit}}$$

$$\cong \frac{\sqrt{2.7}\sqrt{1+1/N}\,\sigma_u}{D(L_{far})-D(L_{near})}$$

$$\geq \frac{\sqrt{2.7}\sqrt{1+1/N}\,\sigma_u}{0.8} \quad (\text{equality}: L_{far}=1.8\text{km},\ L_{near}=0\text{km})$$

$$=2.0\,\sigma_u \quad (\text{if } N>>1)$$

$$=0.012 \quad (\text{if } \sigma_u=0.6\%)$$



→ **With N reactor + (N+1) detectors, sensitivity cannot be better than 0.012!**

Possible way to improve sensitivity (theorist's personal speculation)

If one puts n near detectors and n far detectors with the same σ_u, then theoretically sensitivity becomes:

$$\min\left(\sin^2 2\theta_{13}\right)^{\text{sys only}}_{\text{limit}} = 2.8\,\sigma_u$$

$$\min\left(\sin^2 2\theta_{13}\right)^{\text{sys only}}_{\text{limit}} = 2.8\sqrt{\frac{1}{n}}\,\sigma_u$$

Assumption: σ_u is independent of n. (Is it correct?)

Conclusion

- 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.

- Sensitivity to $\sin^2 2\theta_{13} \sim 0.02$ is obtained with a 24.3 GW_{th} reactor, 40 t•yr, σ_{sys}= 0.6% (KASKA). This is close to the naïve lower bound of $\left(\sin^2 2\theta_{13}\right)^{\text{sys only}}_{\text{limit}}$.

- Sensitivity may be improved by increasing the numbers of near and far detectors.
→ Dependence of σ_u on the numbers has to be carefully studied.