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

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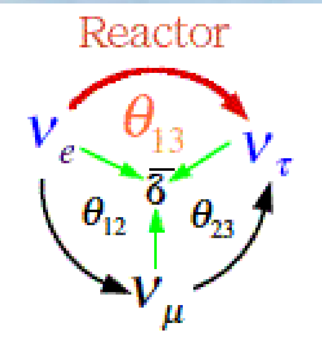

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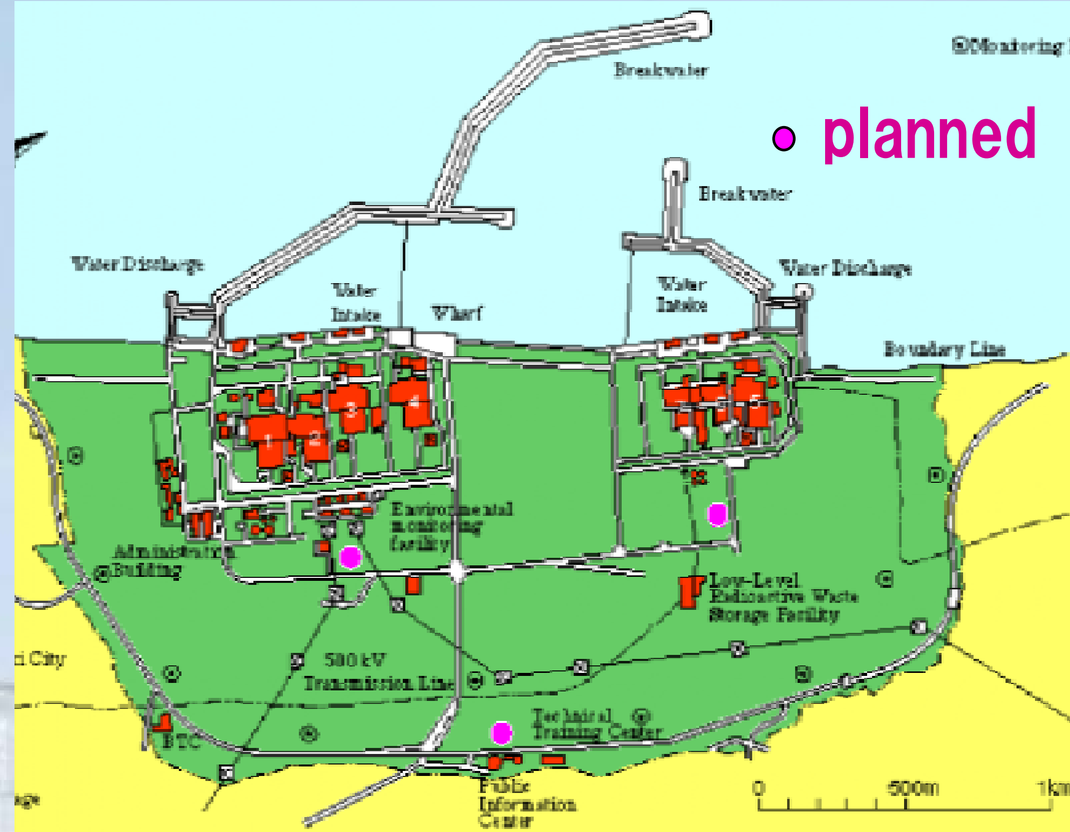
1. Introduction



The locations of the detectors in the KASKA project are planned as indicated in the figure.

One has to make sure that these locations are close to the optimum.

Assumptions throughout this talk:

- Identical systematic errors in KASKA

from detectors	σ_c	correlated	～1.6%
	σ_u	uncorrelated	～0.6%
from reactors	$\sigma_c^{(r)}$	correlated	～2.5%
	$\sigma_u^{(r)}$	uncorrelated	～2.3%

The sensitivity to $\sin^2 2\theta_{13}$ only σ_u depends on to a good approximation.

- The present analysis is rate only.
- The sensitivity is defined @90%CL.

How sensitivity to $\sin^2 2\theta_{13}$ is obtained @90%CL

$$\chi^2 = \min_{\alpha's}\left\{\sum_{i=1}^{3}\left[\frac{M^i - T^i\left(1+\alpha_c+\alpha_c^{(r)}+\sum_{a=1}^{7}\left(\frac{T_a^i}{T^i}\right)\alpha_{ua}^{(r)}\right)}{T^i\sigma_u}\right]^2 + \left(\frac{\alpha_c}{\sigma_c}\right)^2 + \left(\frac{\alpha_c^{(r)}}{\sigma_c^{(r)}}\right)^2 + \sum_{a=1}^{7}\left(\frac{\alpha_{ua}^{(r)}}{\sigma_u^{(r)}}\right)^2\right\}$$

M^i: measured # (events), T^i: theoretical # (events)

$$T^i = \sum_{a=1}^{7} T_a^i, \quad M^i = \sum_{a=1}^{7} M_a^i$$

$i=1,2,3$ (detectors) ; $a=1,\ldots,7$ (reactors)

$$M_a^i = \int \varepsilon(E)\,\sigma(E)\,f_a(E)\,P(E;L_{ia})\,dE$$

$$T_a^i = \int \varepsilon(E)\,\sigma(E)\,f_a(E)\,dE$$

contribution from a-th reactor to yield at i-th detector w/ and w/o osc.

$$2.7 = \chi^2\Big|_{90\%CL} = \text{const}\times\sin^4 2\theta_{13} \Rightarrow \sin^2 2\theta_{13} = \sqrt{\frac{2.7}{\text{const}}}$$

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

(1) Dependence on positions of detectors

1. Obtain the optimized positions of the three detectors.

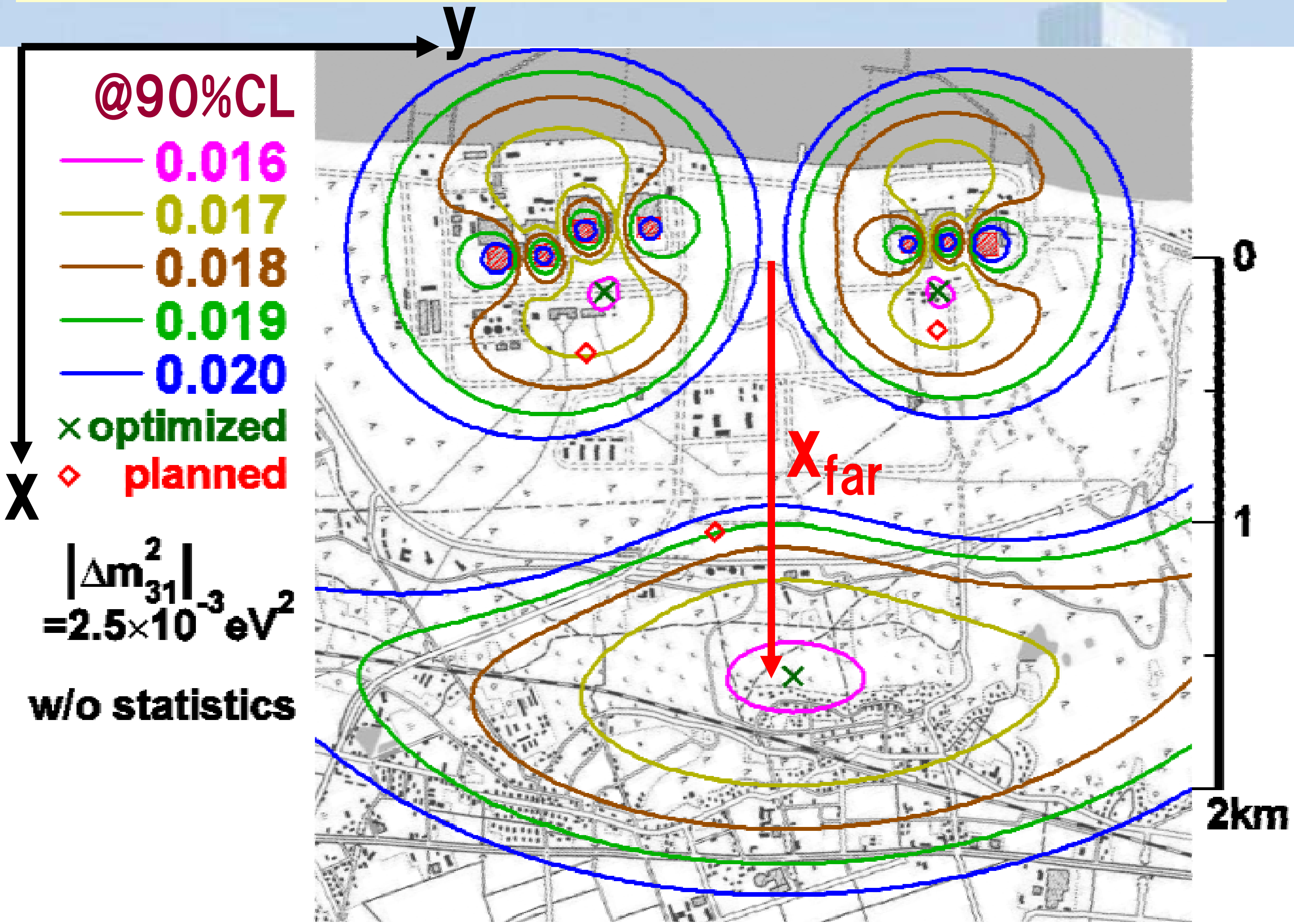
2. Vary the position of one detectors while keeping the other two in the optimized locations.

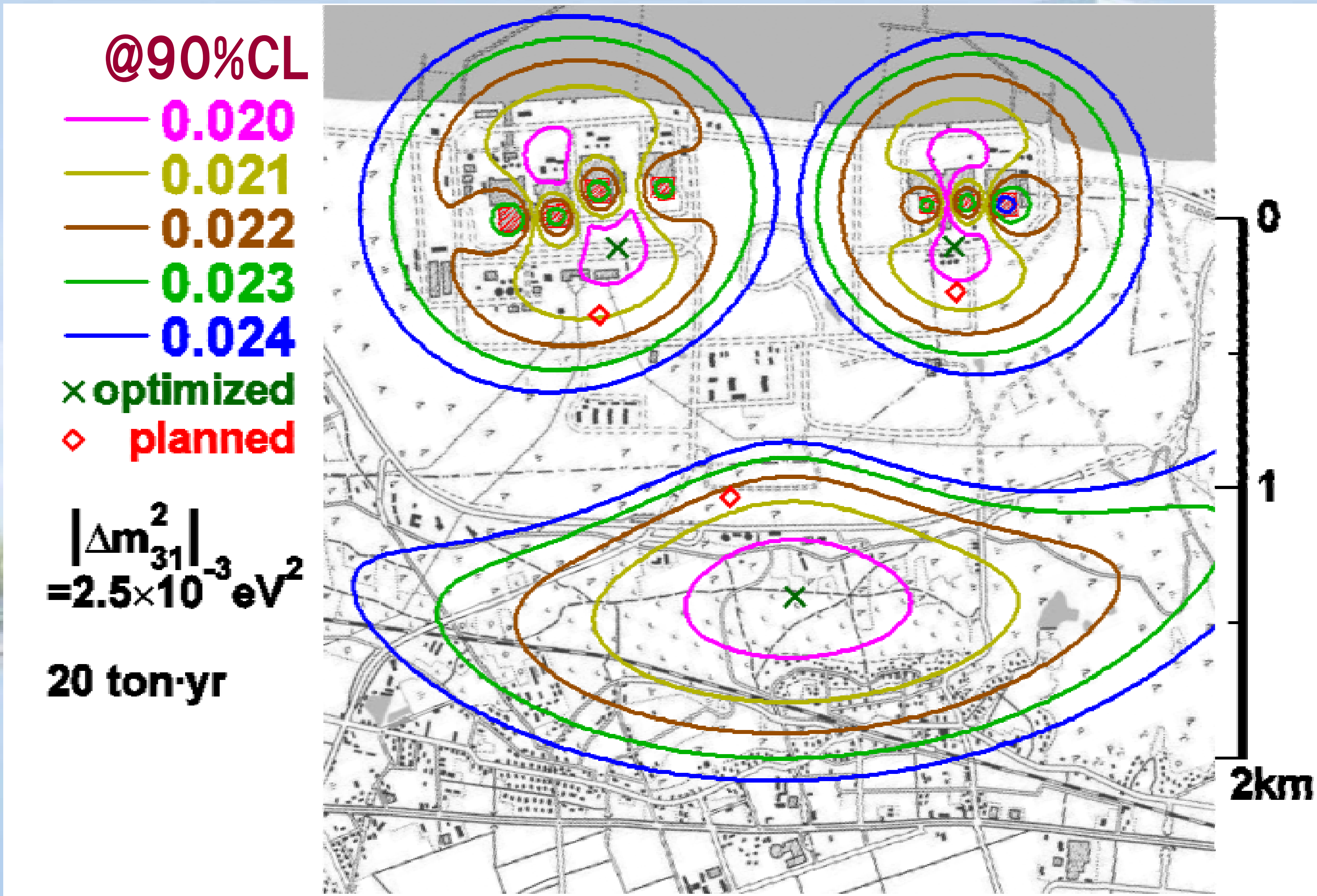
3. Combine each contour of the sensitivity to $\sin^2 2\theta_{13}$ in one figure for ∞ton・yr and 20ton・yr.

(2) Dependence on data size

Obtain sensitivity to $\sin^2 2\theta_{13}$ for various data size assuming the optimized positions of the detectors.

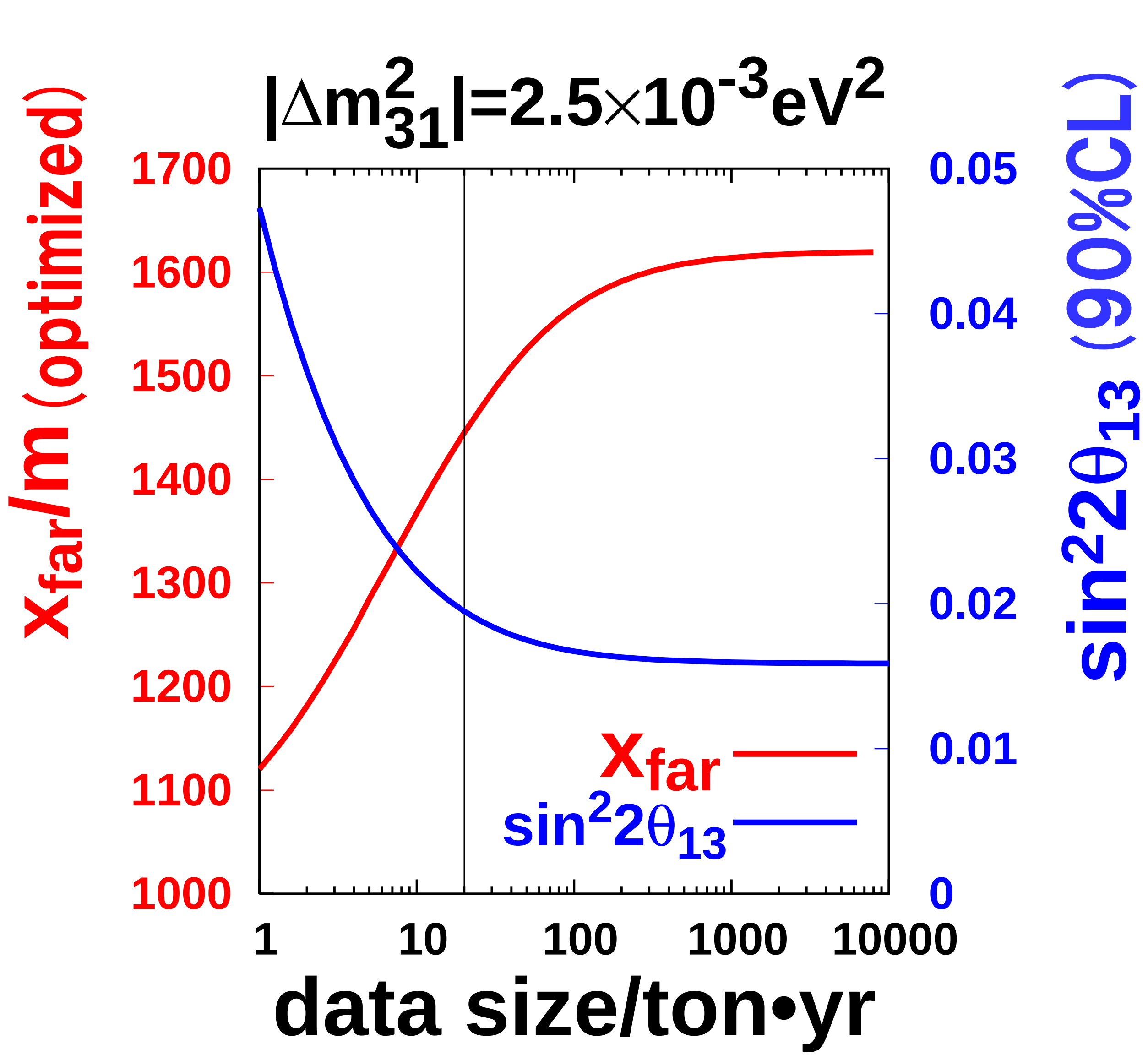
(1) Dependence on positions of detectors





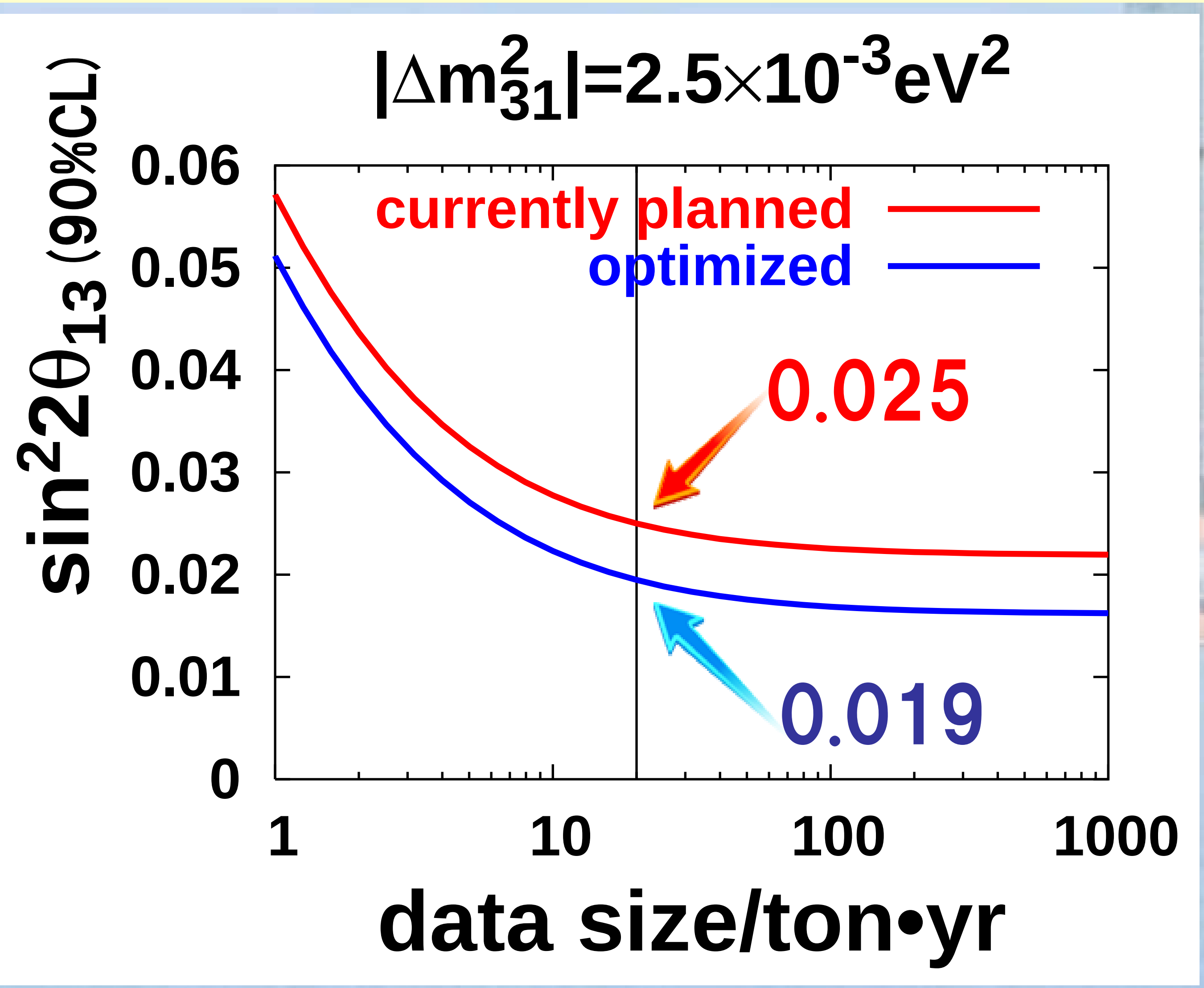
@90%CL
0.020
0.021
0.022
0.023
0.024
× optimized
◇ planned
$|\Delta m^2_{31}|$
$=2.5\times10^{-3}\,eV^2$
20 ton·yr
0
1
2km

(2) Dependence on data size

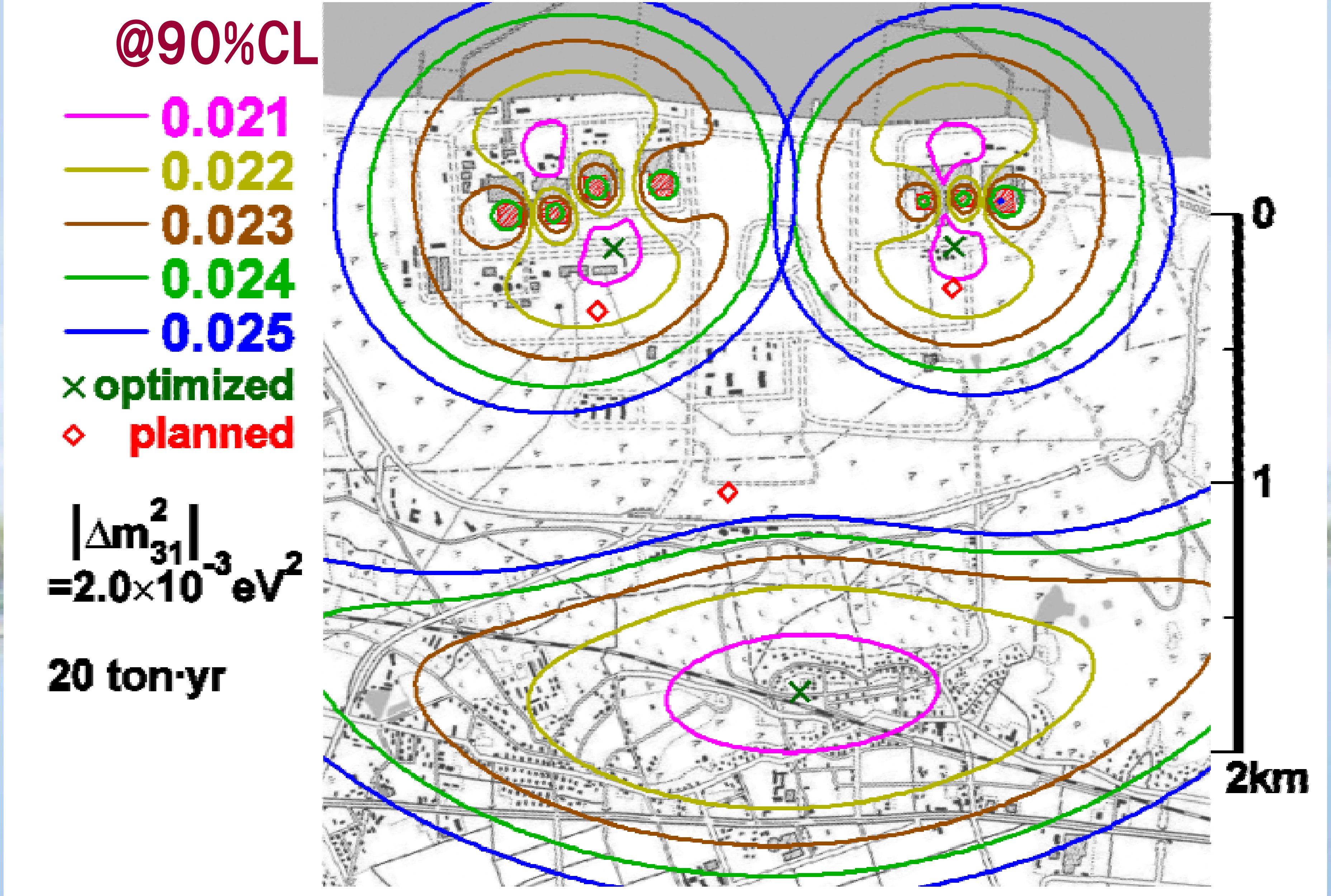


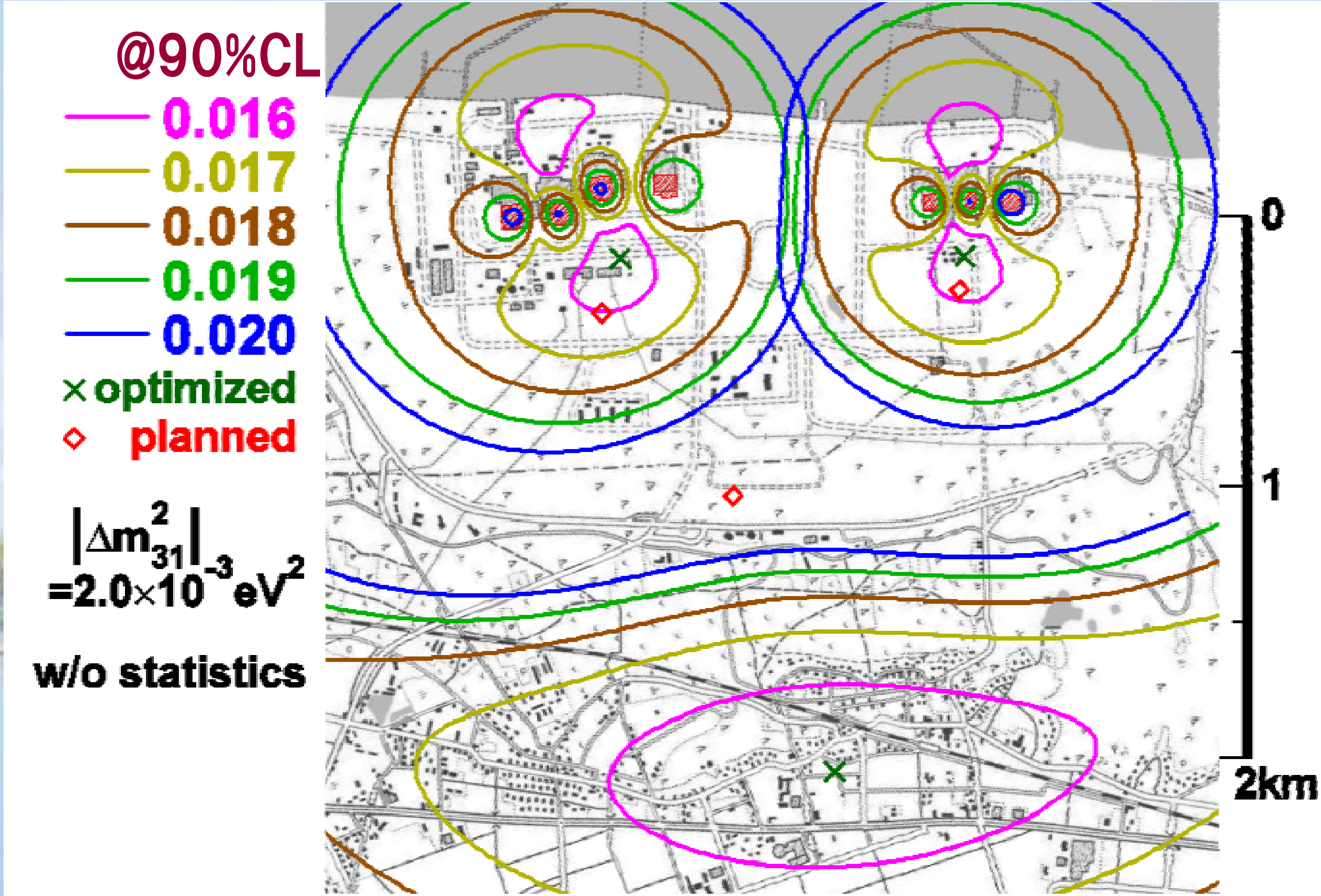
Sensitivity is obtained assuming the optimized positions of the three detectors for each value of data size.

Sensitivity to $\sin^2 2\theta_{13}$ with the planned and optimized locations of the detectors

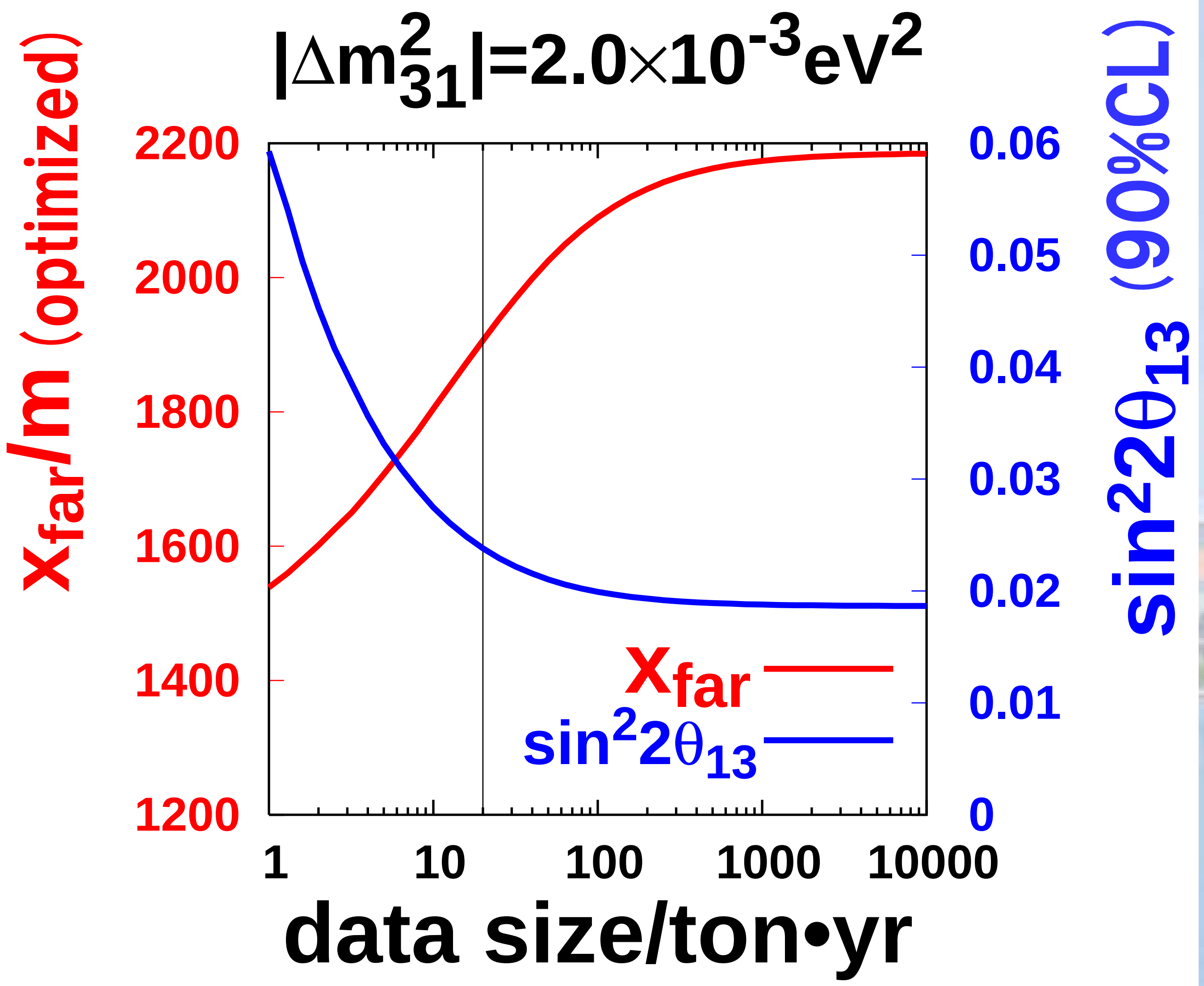


If Δm^2_{31}=2.0×10^{-3}eV^2, the situation changes:

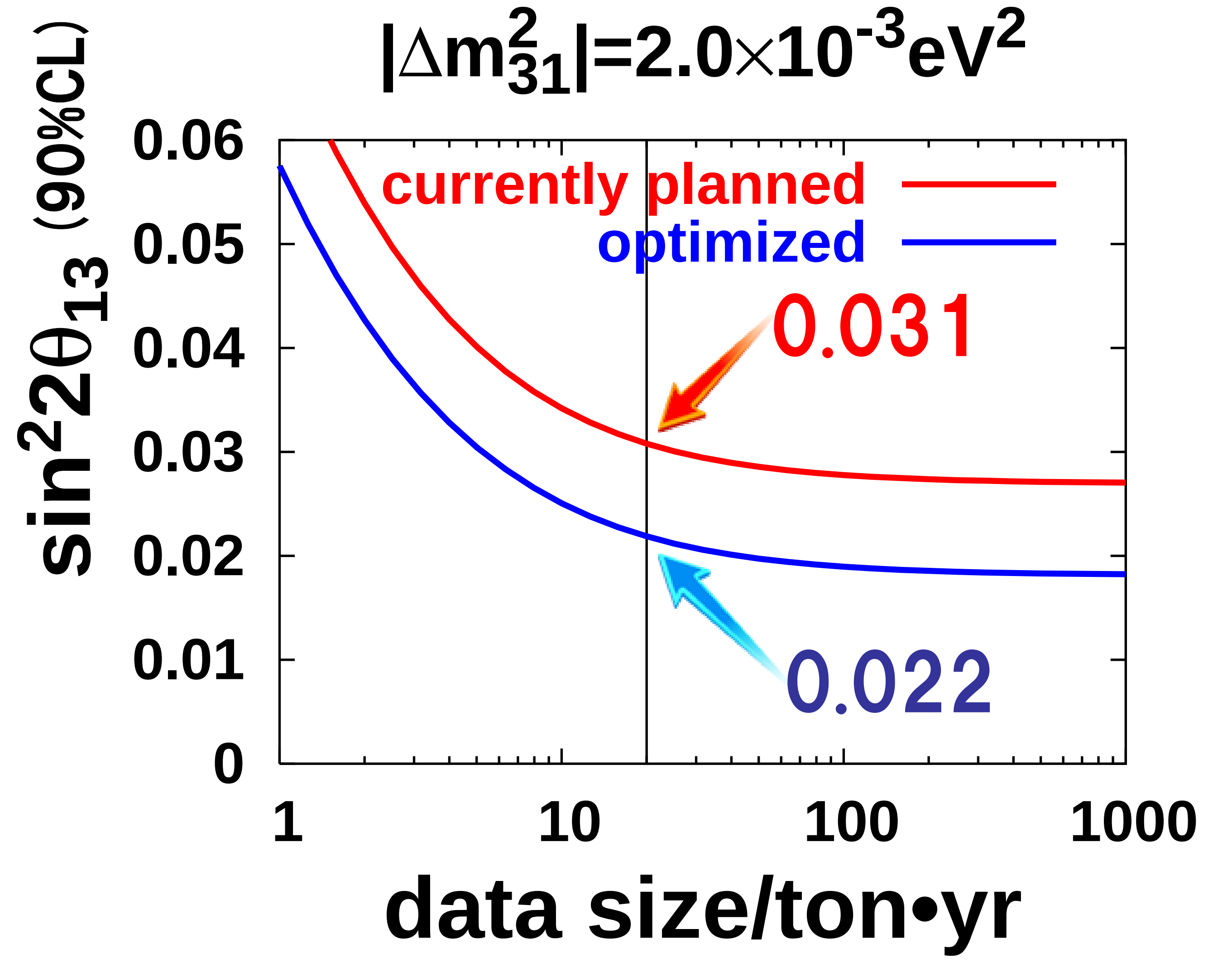




@90%CL
0.016
0.017
0.018
0.019
0.020
× optimized
◇ planned
$|\Delta m^2_{31}|$
$=2.0\times10^{-3}\,eV^2$
w/o statistics
0
1
2km



Sensitivity is obtained assuming the optimized positions of the three detectors.



$|\Delta m^2_{31}|=2.0\times10^{-3}eV^2$
$\sin^2 2\theta_{13}$ (90%CL)
0.06
0.05
0.04
0.03
0.02
0.01
0
currently planned
optimized
0.031
0.022
1
10
100
1000
data size/ton•yr

3. Comparison between KASKA and lower bound on sensitivity to $\sin^2 2\theta_{13}$ in reactor experiments

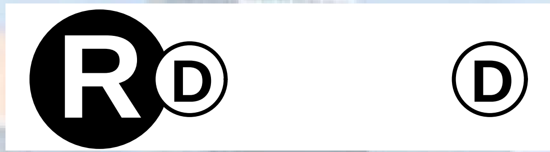
(1) lower bound on sensitivity to $\sin^2 2\theta_{13}$

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



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

@90%CL
rate only

where σ_u: uncorrelated systematic error

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

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

@90%CL

rate only

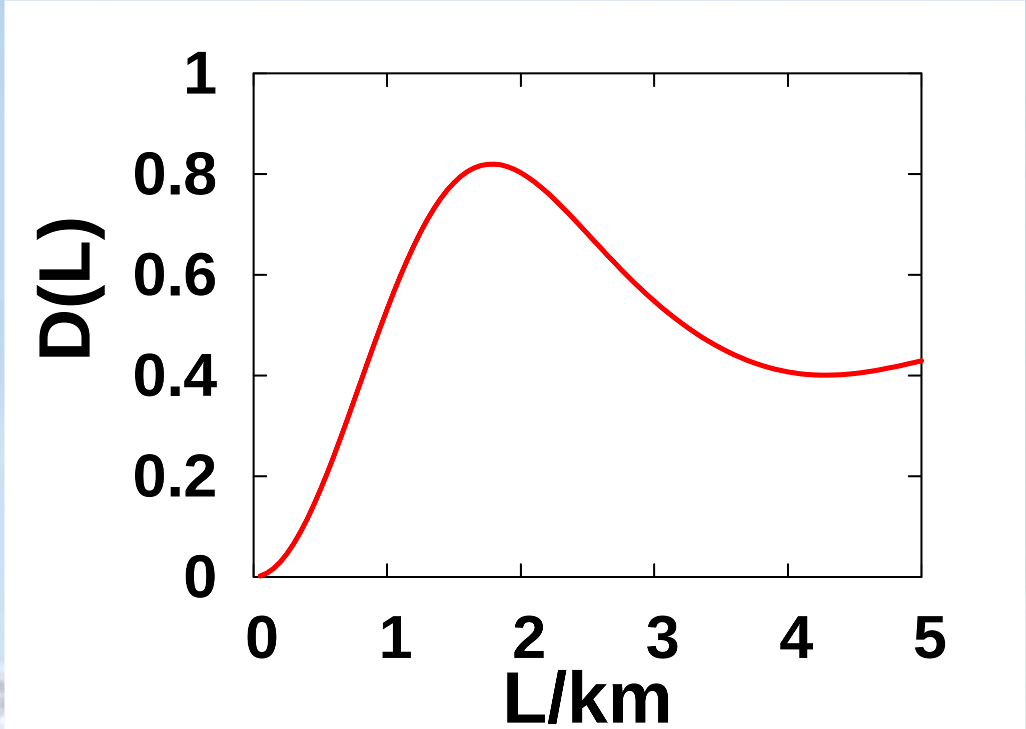
$$\cong \frac{\sqrt{2.7}\sqrt{2}\,\sigma_u}{D(L_{far}) - D(L_{near})}$$

$$\geq \frac{\sqrt{2.7}\sqrt{2}\,\sigma_u}{0.8}$$

equality : $\left\{\begin{array}{l} L_{far} = 1.8\text{km} \\ L_{near} = 0\text{km} \end{array}\right\}$

$$= 2.8\,\sigma_u$$

$$= 0.017 \quad (\text{if } \sigma_u = 0.6\%)$$



→With 1reactor + 2detectors
sensitivity @90%CL cannot be better than 0.017!

KASKA (~0.016) is not so bad!

σ_u=0.6%: extrapolation from Bugey+CHOOZ

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

(2) 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:

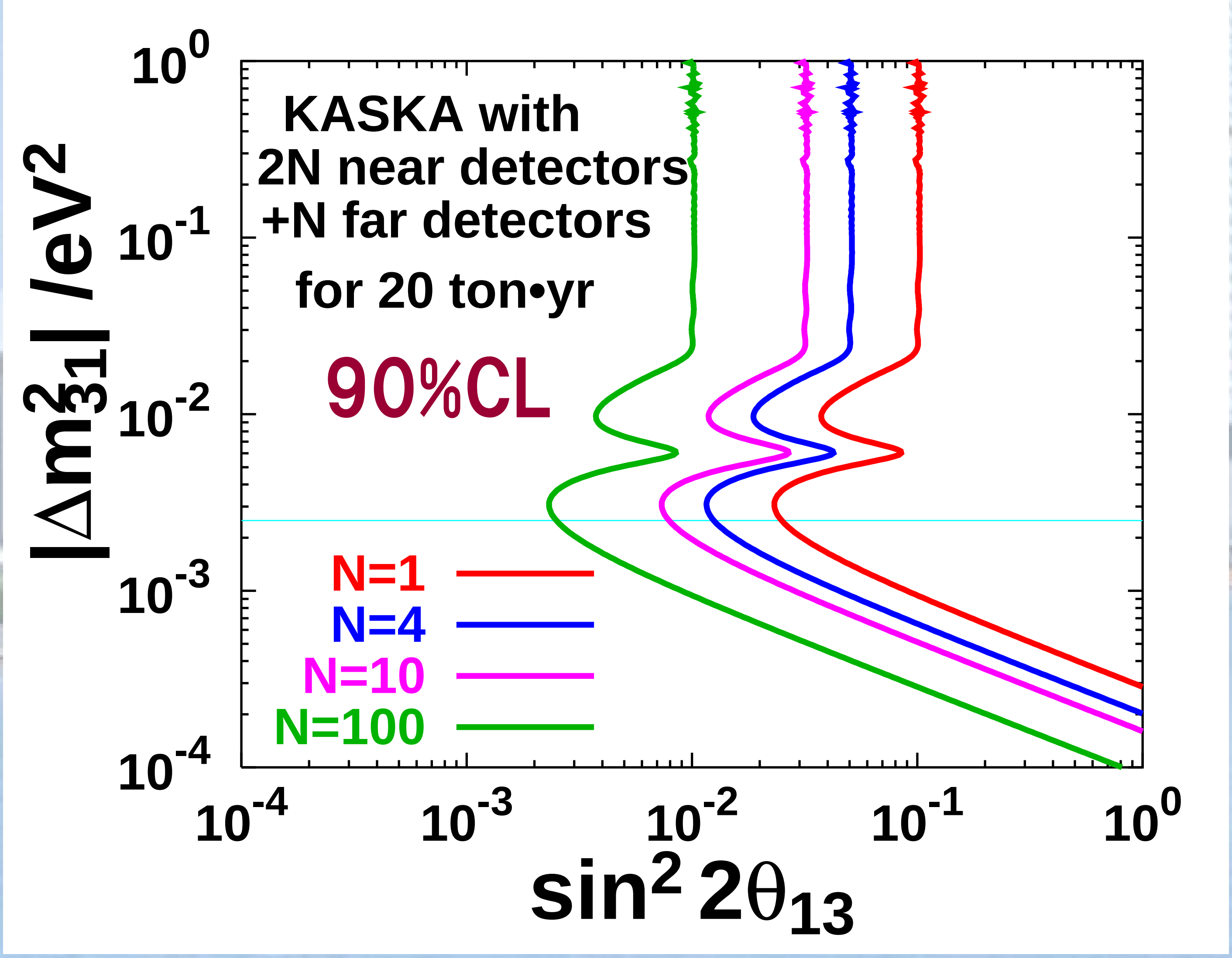
$$\min_{L_f, L_n} \left(\sin^2 2\theta_{13}\right)^{\text{sys only}}_{\text{limit}} = 2.8\,\sigma_u \quad \text{@90\%CL}$$

$$\min_{L_f, L_n} \left(\sin^2 2\theta_{13}\right)^{\text{sys only}}_{\text{limit}} = 2.8\sqrt{\frac{1}{N}}\,\sigma_u \quad \text{@90\%CL}$$

$$\chi^2 \Rightarrow N\chi^2$$

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

Here is what a theorist would get by putting 3N detectors at KASKA:



4.Conclusion

Part I

- At KASKA the following sensitivity is obtained with 20 t・yr, σ_u= 0.6% @90%CL (rate only) :

$\sin^2 2\theta_{13}$ ~0.025, x_{far}=1.1km (in the campus)

$\sin^2 2\theta_{13}$ ~0.019, x_{far}=1.4km (outside the campus)

Part II

- If σ_u is fixed, then sensitivity to $\sin^2 2\theta_{13}$ has a lower bound @90%CL (rate only):

$$\min(\sin^2 2\theta_{13}) \cong 2.8\,\sigma_u \quad \text{(one reactor case)}$$
$$\geq 0.017 \quad (\sigma_u = 0.6\%)$$

The sensitivity of KASKA (∼0.02) is not far from this bound.

- Sensitivity may be improved by increasing the numbers of near and far detectors, or by combining the reactor experiments all over the world.

→ Dependence of σ_u on the numbers has to be carefully studied.

Appendix

Proof of lower bound

$$\chi^2 = \frac{\left(y^f - y^n\right)^2}{2\sigma_u^2} + \frac{\left(y^f + y^n\right)^2}{2\sigma_u^2 + 4\left[\sigma_c^2 + (\sigma_c^{(r)})^2 + (\sigma_u^{(r)})^2\right]}$$

$$\cong \frac{\left(y^f - y^n\right)^2}{2\sigma_u^2} = \frac{\left(D(L_f) - D(L_n)\right)^2}{2\sigma_u^2}\sin^2 2\theta_{13}$$

$$y^n \equiv \frac{M^n - T^n}{T^n} = -\sin^2 2\theta_{13} D(L_n),$$

$$y^f \equiv \frac{M^f - T^f}{T^f} = -\sin^2 2\theta_{13} D(L_f)$$

M: measured

T: theoretical

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

$$\chi^2\Big|_{90\%CL} = 2.7 \quad \Rightarrow \quad \sin^2 2\theta_{13} \cong \frac{\sqrt{2.7}\sqrt{2}\,\sigma_u}{D(L_f) - D(L_n)}$$

case with M reactors + (M+1) detectors

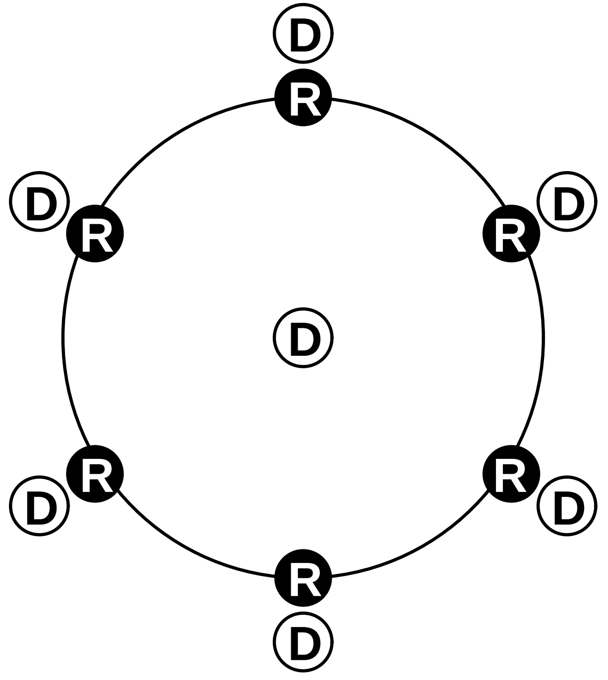
$$\left(\sin^2 2\theta_{13}\right)^{\text{sys only}}_{\text{limit}}$$ @90%CL (rate only)

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

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

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

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



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