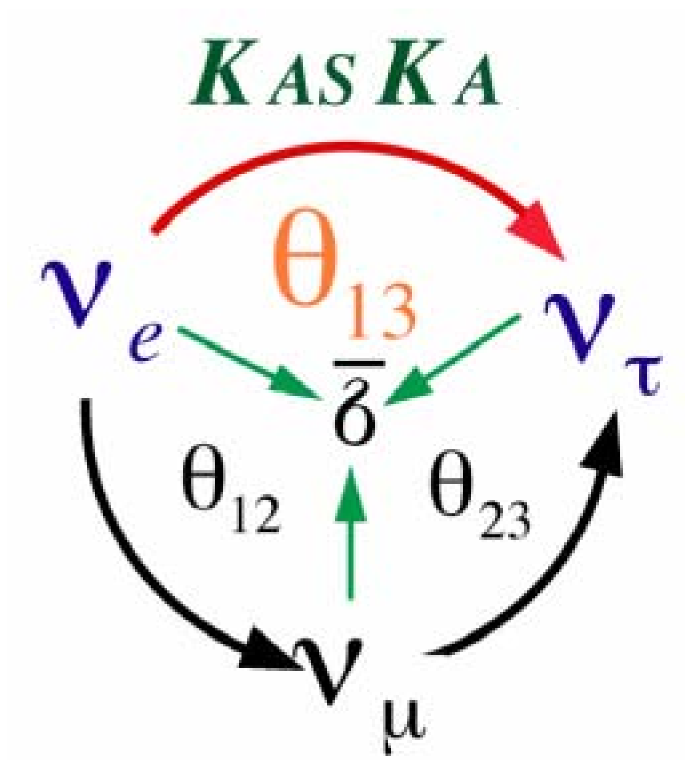
KASKA (微)
The Reactor θ_{13} Project in Japan



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The *KASKA* Project Members

Neutrino Experiment at
*Kas*hiwazaki-*Ka*riwa Nuclear Power Plant

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Contents

Neutrino Mixings

Maki-Nakagawa-Sakata Matrix

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

$\nu_e, \nu_\mu, \nu_\tau :$ flavor eigenstates.

$\nu_1, \nu_2, \nu_3 :$ mass eigenstates of $m = m_1, m_2, m_3$.

c.f. KM Matrix $\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & U_{us} & U_{ub} \\ U_{cd} & U_{cs} & U_{cb} \\ U_{td} & U_{ts} & U_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$

Neutrino Oscillation

If flavor eigen states and mass eigen states mix,

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

The ν_e state at t=0,

$$\phi(0) = \nu_e = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$

Becomes, after time *t*,

$$\phi(t) = \cos\theta|\nu_1\rangle e^{-iE_1 t} + \sin\theta|\nu_2\rangle e^{-iE_2 t}$$

$$= \left(\cos^2\theta e^{-iE_1 t} + \sin^2\theta e^{-iE_2 t}\right)|\nu_e\rangle + \sin\theta\cos\theta\left(e^{-iE_2 t} - e^{-iE_1 t}\right)|\nu_\mu\rangle$$

(a little bit cheated)

Then the survival probability after traveling L is,

$$P_{\nu_e \to \nu_e} = |\langle \nu_e | \phi(t)\rangle|^2 = 1 - \sin^2 2\theta \sin^2 \frac{(E_2 - E_1)t}{2}$$

$$\to 1 - sin^2 2\theta sin^2 \frac{\Delta m^2 L}{4E_\nu}$$

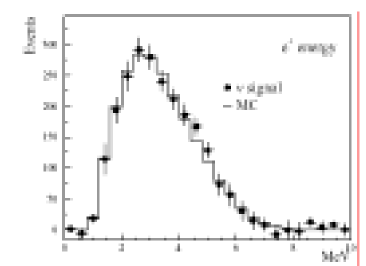
Measurement of Neutrino Oscillation $\Rightarrow \Delta m^2, \theta$

3 flavor oscillations

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}1&0&0\\0&c_{23}&s_{23}\\0&-s_{23}&c_{23}\end{pmatrix}\begin{pmatrix}c_{13}&0&s_{13}e^{i\delta}\\0&1&0\\-s_{13}e^{-i\delta}&0&c_{13}\end{pmatrix}\begin{pmatrix}c_{12}&s_{12}&0\\-s_{12}&c_{12}&0\\0&0&1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

CHOOZ

$\sin^2 2\theta_{13} < 0.2$



ν_e → ν_τ

KamLAND, Solar

$\Delta m^2_{12} \sim 7\times 10^{-5} eV^2$

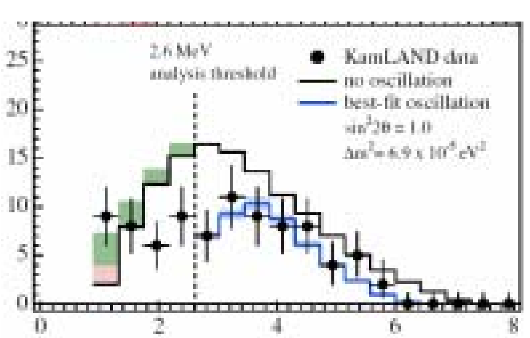
$\sin^2 2\theta_{12} \sim 1$

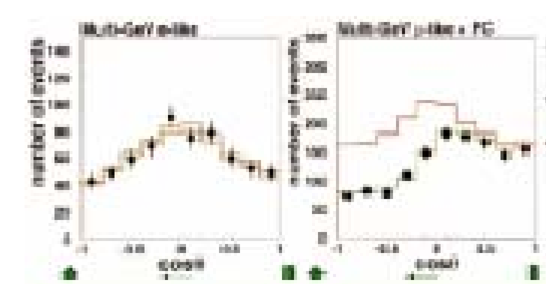
SK, K2K

$\Delta m^2_{23} \sim 2\times 10^{-3} eV^2$

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

ν_μ





Currently Known MNS Matrix

Magnitudes of the MNS matrix elements
have been roughly determined.

$$|U_{MNS}| \sim \begin{pmatrix} 0.7 & 0.7 & <0.2 \\ 0.5 & 0.5 & 0.7 \\ 0.5 & 0.5 & 0.7 \end{pmatrix}$$

$\sin\theta_{13} e^{i\delta_l}$

$\sin\theta_{13} < 0.2$,
δ_l: totally unknown

The next important step is to
measure finite θ_{13} value or to set stringent upper limit.

(δ_l measurement takes some more time)

Importance of θ_{13} measurement-I

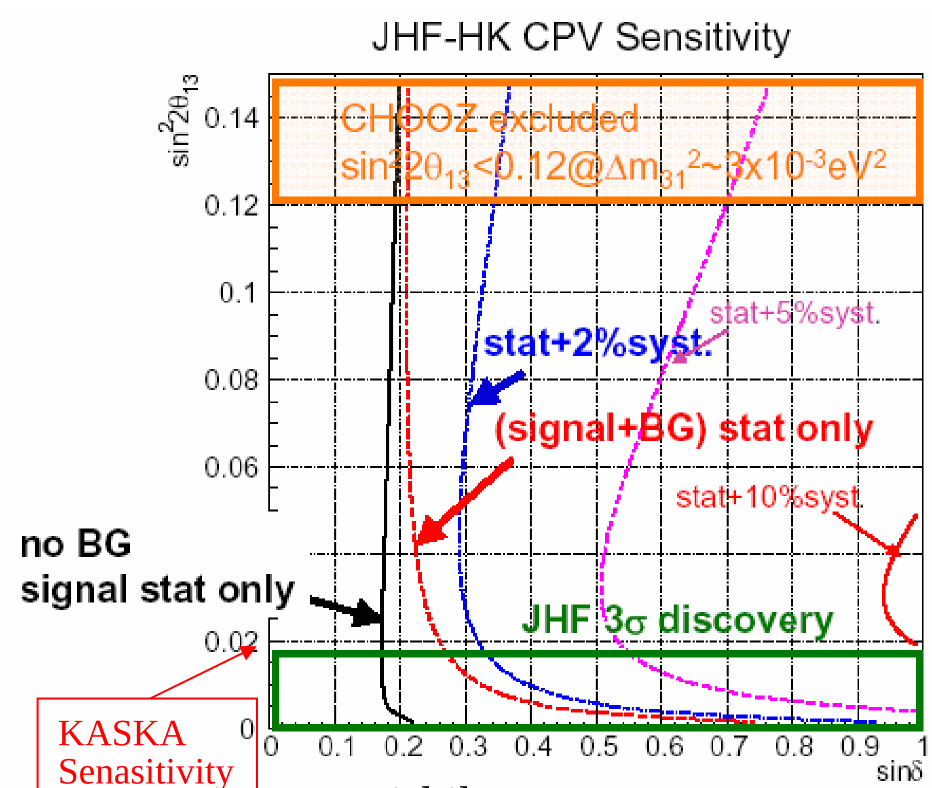
- It is an elementary parameter.

- It is small compared to other mixing parameters.
  $\sin^2 2\theta_{13} < 0.2$, $\sin^2 2\theta_{12} \sim 1$, $\sin^2 2\theta_{23} \sim 1$

=> θ_{13} value may play a key role when building the unified theory.

Importance of θ_{13} measurement-II

δ_l detectability



K.Nishikawa

θ_{13} controls δ_l detectability in future experiments and it provides a guideline when designing such experiments which cost $B.

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)}$$

$$\approx \frac{\Delta m_{12}^2}{\Delta m_{13}^2} \frac{\sin 2\theta_{12}}{\sin \theta_{13}} \sin \delta_l \sim \frac{0.04}{\sin \theta_{13}} \sin \delta_l$$

Too large θ_{13} => small asymmetry

Too small θ_{13} => small statistics

Importance of θ_{13} measurement-III

Improvement of KamLAND θ_{12} Accuracy

Precise θ_{13} to measurement improves θ_{12} accuracy by KamLAND because KamLAND measurement is actually

$$P_{KL}(\bar{\nu}_e \to \bar{\nu}_{x\neq e}) = \cos^4\theta_{13} \times \left(1 - \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2_{12} L}{4E}\right)$$

$$\Rightarrow \sin^2 2\theta_{12} \sim \sin^2 2\theta_{KL} - 0.8\sin^2 2\theta_{13}$$

$$\sin^2 2\theta_{13} < 0.2(90\%CL) \quad \to \delta\sin^2 2\theta_{12} \sim 0.1 \quad Now$$

$$\delta\sin^2 2\theta_{13} = 0.02(90\%CL) \to \delta\sin^2 2\theta_{12} \sim 0.01$$

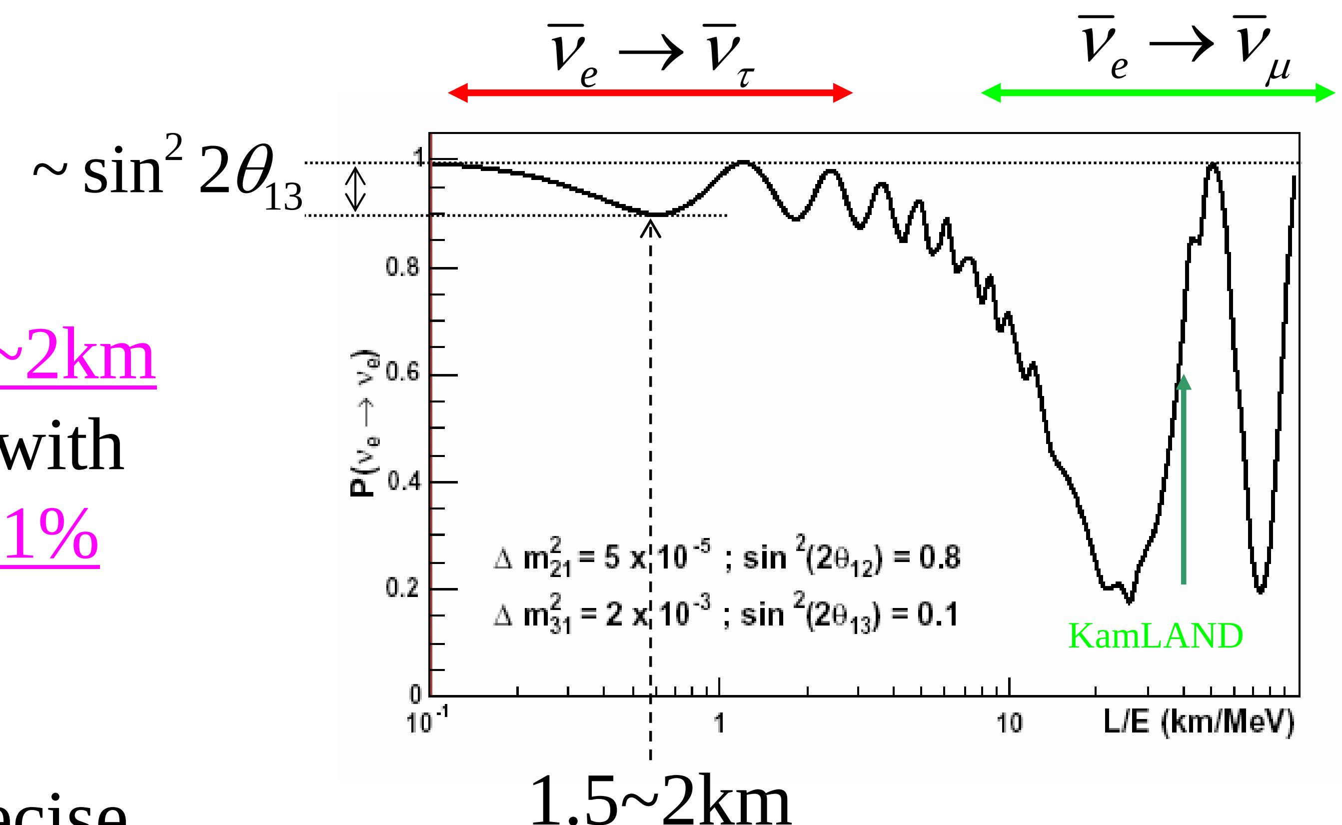
($\delta\sin^2 2\theta_{KL}$~0.1 in the future)

How to measure θ_{13} by reactor neutrinos

Baseline 1~2km
ν_e deficit with accuray~1%

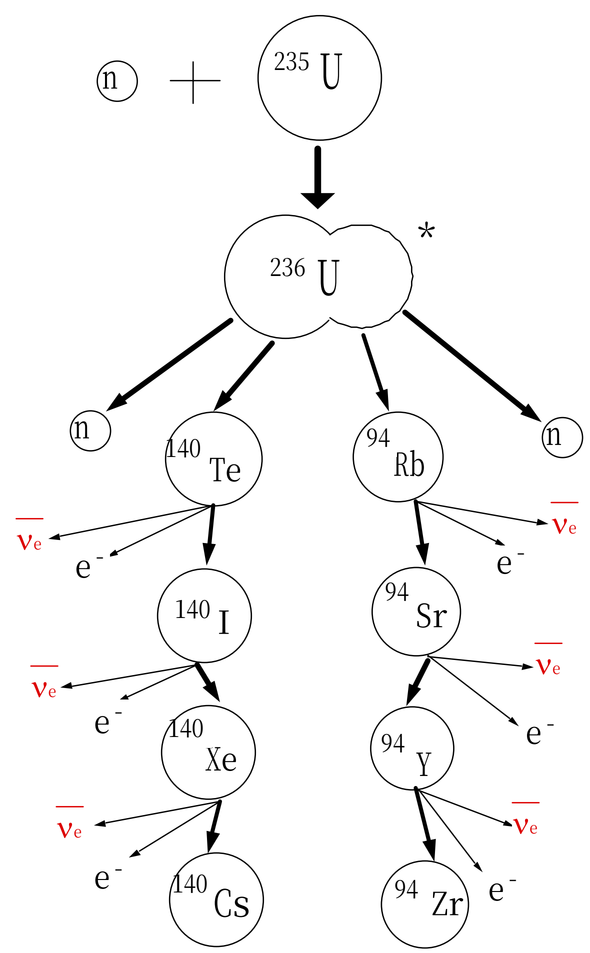
↓

Pure & Precise
$\sin^2 2\theta_{13}$ Measurement

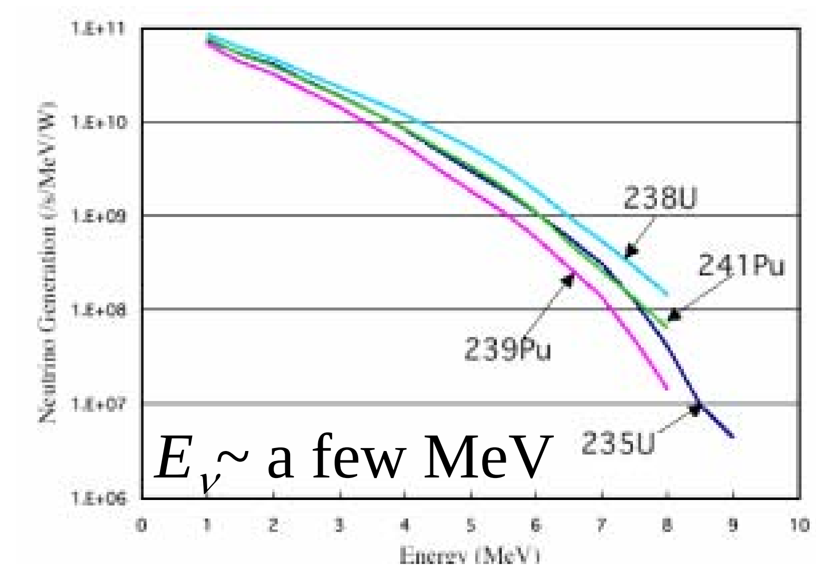


$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{13} L}{4E}$$

Reactor Neutrino



Neutrino Spectra



~6ν/fission & ~200MeV/fission

$$\Downarrow$$

$$\sim 6 \times 10^{20}\, \overline{\nu}_e / s / reactor$$

$$\sigma_{flux} \sim 2\%$$

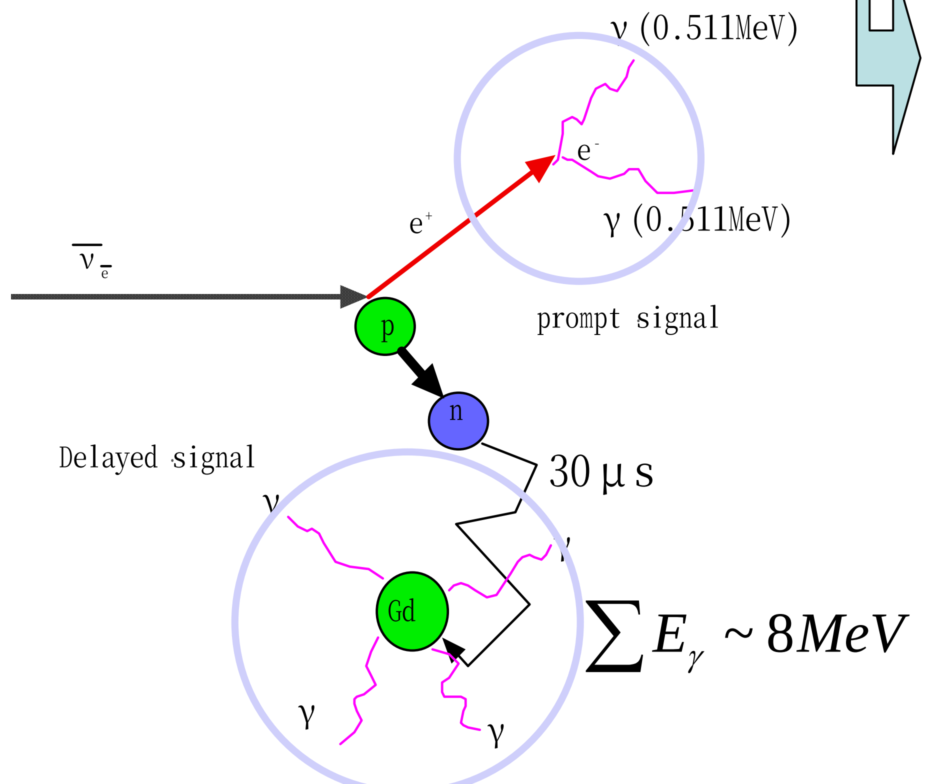
$\overline{\nu}_e$ Detection

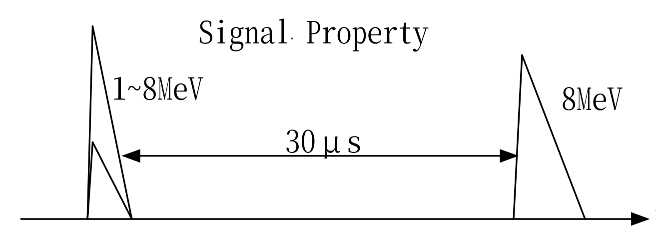
$$\bar{\nu}_e + p \to n + e^+$$

$$e^+ + e^- \to 2\gamma$$

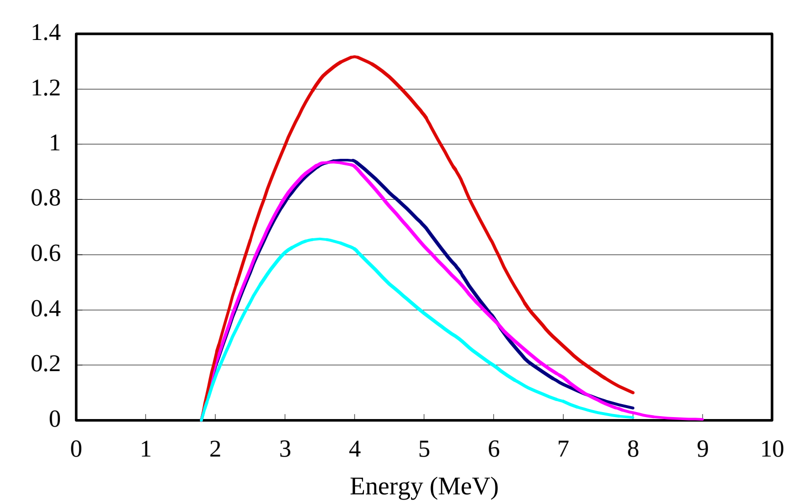
$$\left(E_\nu - 0.8MeV\right)$$

$$n + Gd \to Gd' + \gamma s\left(\sum E = 8MeV\right)$$





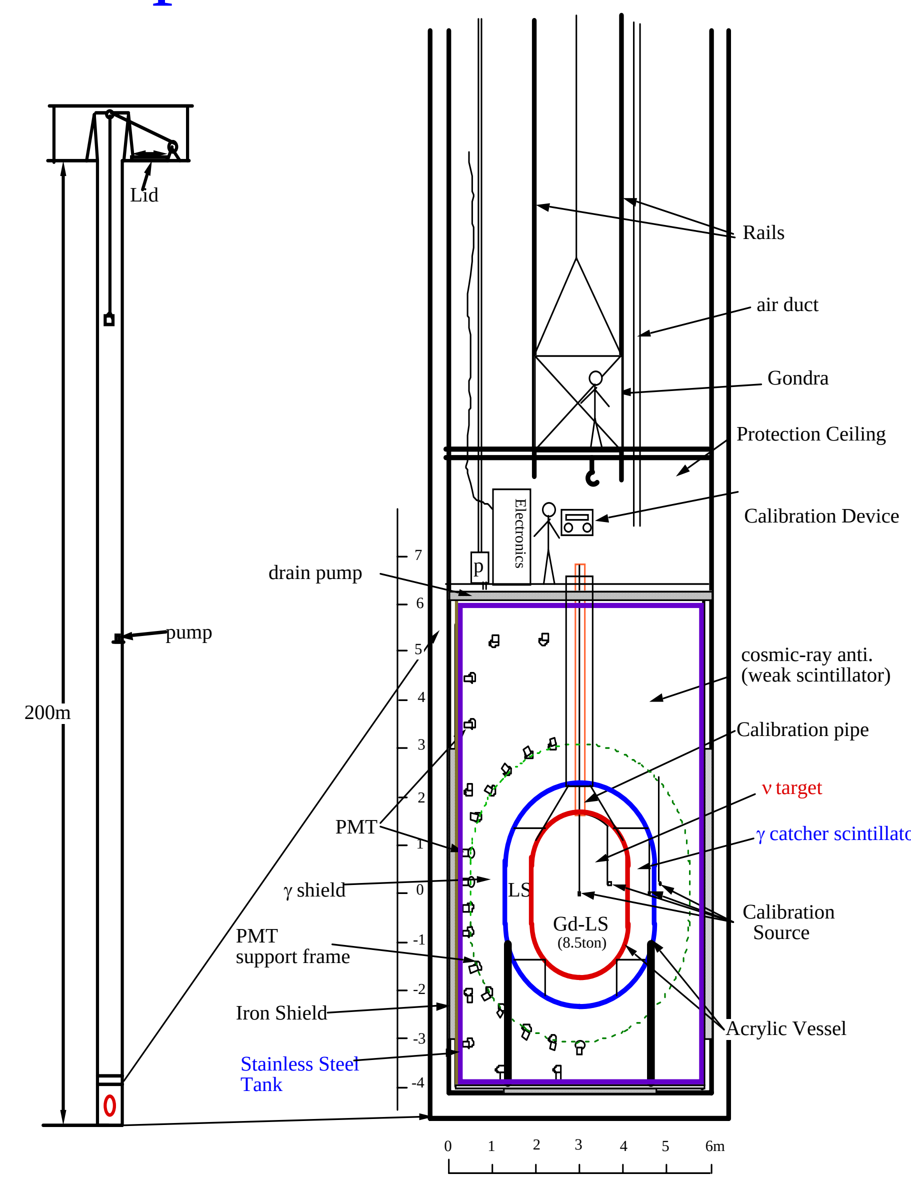
Neutrino Detection Rate per Power Generation



The KASKA Experiment

Kashiwazaki-Kariwa
Nuclear Power Plant

Baseline=1.3~1.8km
Target Mass~8ton
Overburden=350~450mwe
Event rate=100~50/day



Accelerator θ_{13} Measurement
(J-PARC)

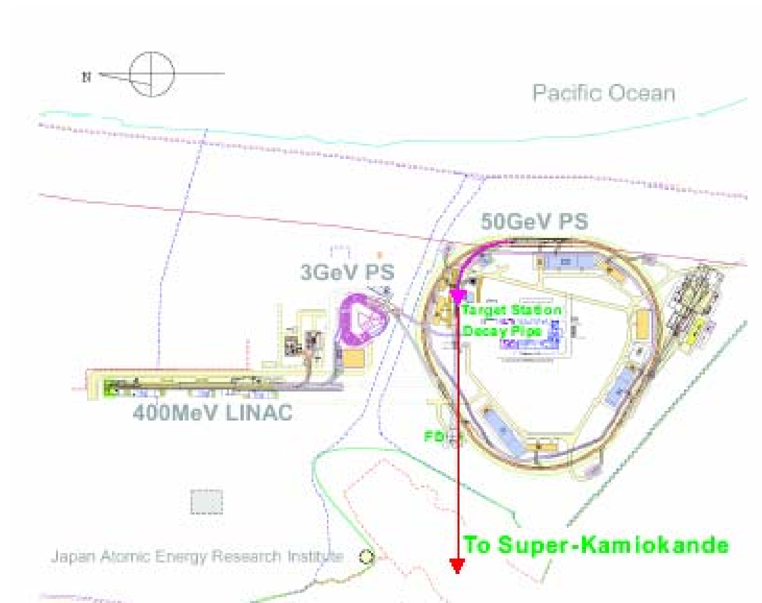
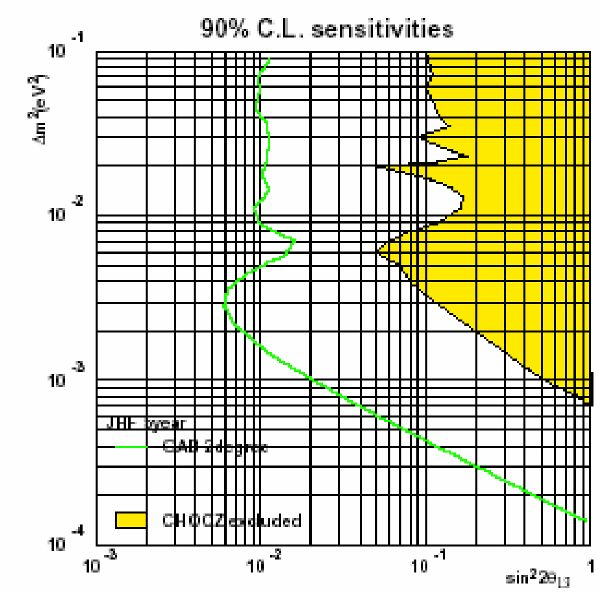


Figure 1: Layout of JHF.



$$P(\nu_\mu \to \nu_e) \sim \frac{1}{2}\sin^2 2\theta_{13}$$

Sensitivity: $\sin^2 2\theta_{13} > 0.006 \ @ \Delta m^2 = 3\times 10^{-3} eV$

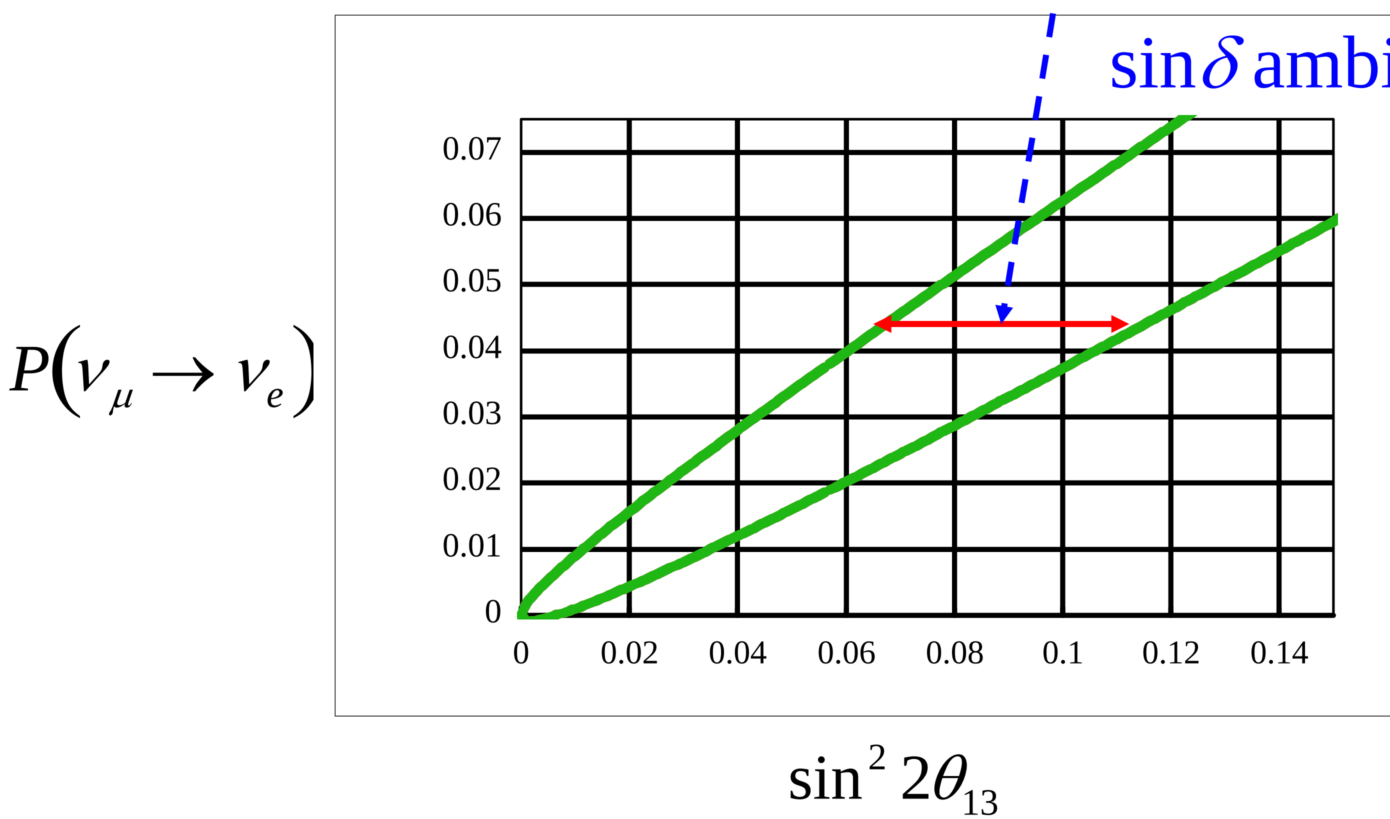
However,

Ambiguity in $\sin^2 2\theta_{13}$ Determination-I

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{13} \sin^2 \theta_{23} - \frac{\pi}{2} \frac{\Delta m^2_{12} \sin 2\theta_{12}}{\Delta m^2_{23}} \sin 2\theta_{13} \sin 2\theta_{23} \sin \delta$$

$$\sim \frac{1}{2} \sin^2 2\theta_{13} \left(1 \pm \frac{0.08}{\sin 2\theta_{13}} \sin \delta \right)$$

$\sin\delta$ ambiguity



Ambiguity in $\sin^2 2\theta_{13}$ Determination-II

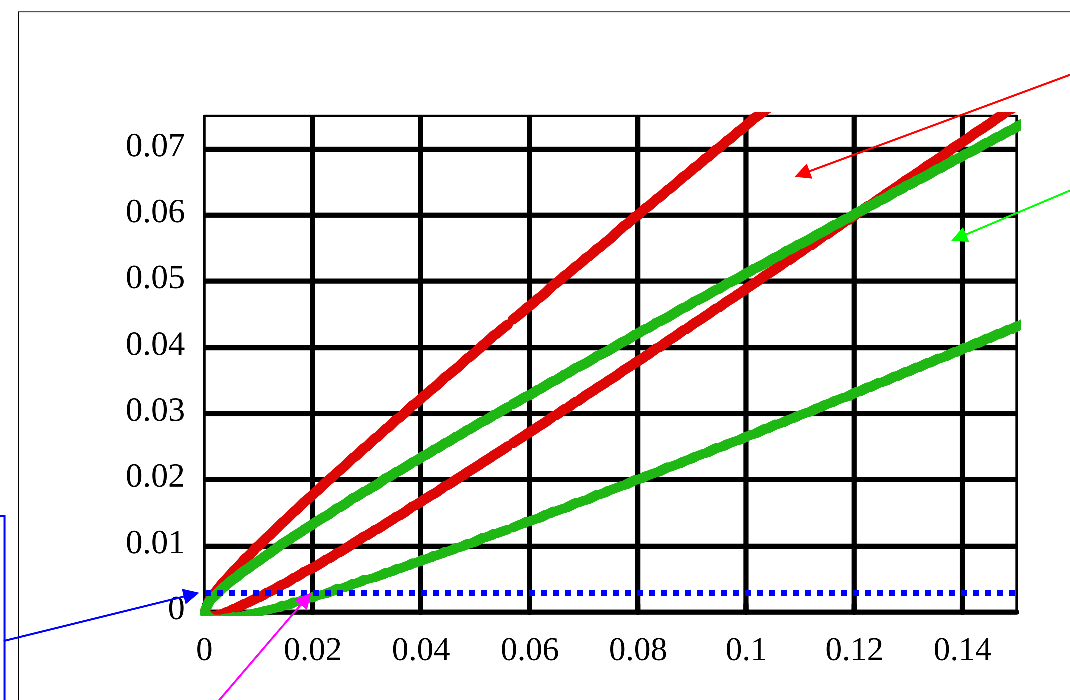
$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{13} \sin^2\theta_{23} - \frac{\pi}{2}\frac{\Delta m_{12}^2 \sin 2\theta_{12}}{\Delta m_{23}^2} \sin 2\theta_{13} \sin 2\theta_{23} \sin\delta$$

$$\sin^2 2\theta_{13} \frac{1}{2}\left(1 \pm \sqrt{1 - \sin^2 2\theta_{23}}\right)$$

$$\sin^2 2\theta_{23} = 0.95$$

$$\sin^2\theta_{23} = \begin{cases} 0.61 \\ 0.39 \end{cases}$$

$P(\nu_\mu \to \nu_e)$



J-PARC Limit

$\sin^2 2\theta_{13} \sim 0.02$

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

Complementarity of Reactor-Accelerator Meas.

Reactor Measurement= Pure $\sin^2 2\theta_{13}$ measurement

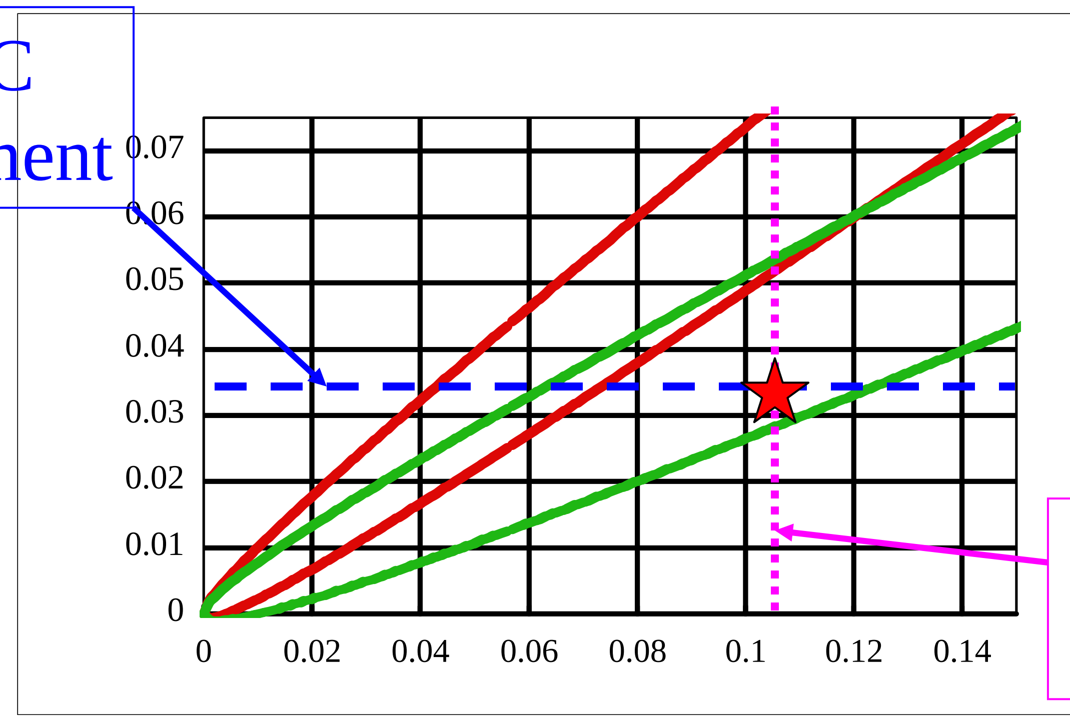
Reactor-Accelerator combination
=> a lot of physics potential

* Answer to θ_{23} degeneracy

$$\sin^2\theta_{23} = \begin{cases} \sout{0.61} \\ 0.39 \end{cases}$$

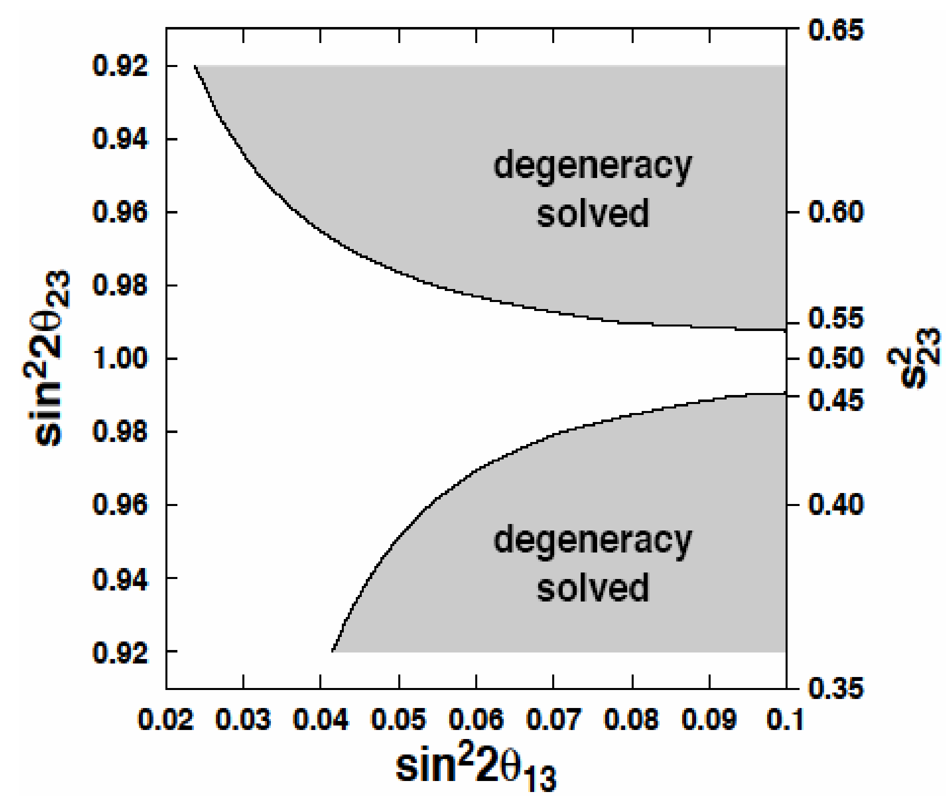
* If accuracy is good enough
=> $|\sin\delta_l|$

$P(\nu_\mu \to \nu_e)$



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

Solving Potential of θ_{23} degeneracy



H.Minakata, et. al. hep-ph/0211111

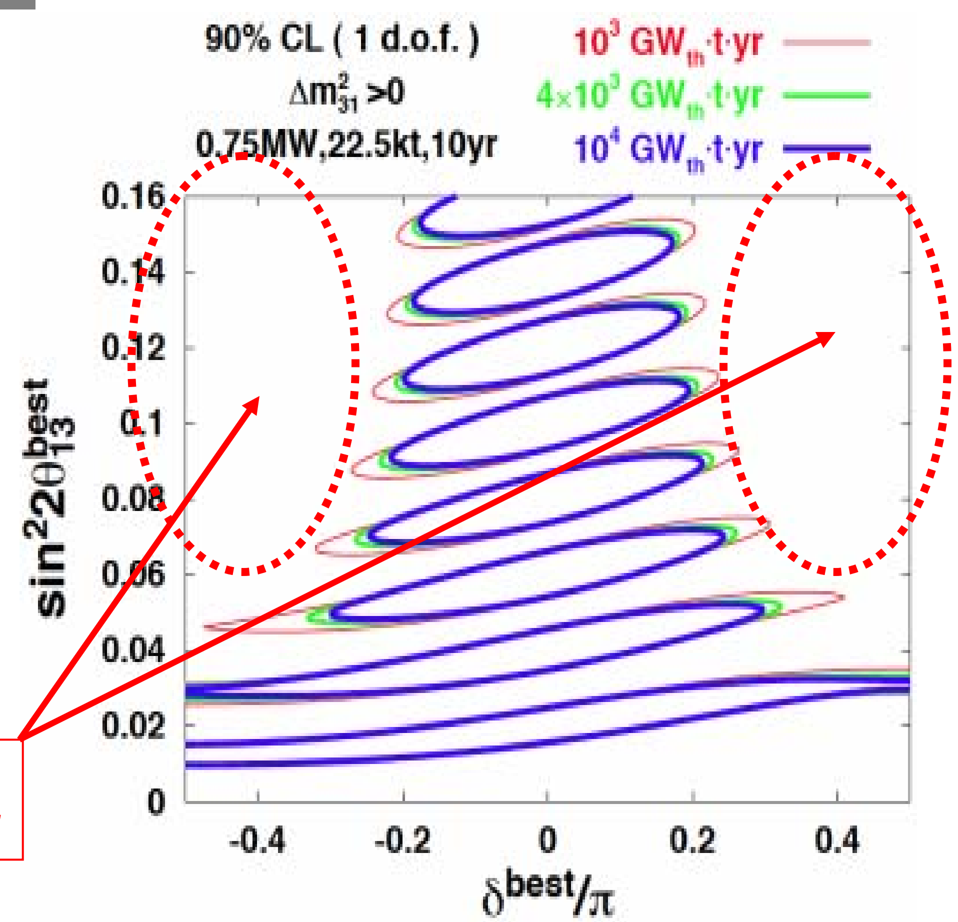
Detection Potential of non-0 δ_l

In the case of "C-evaluation" by the HK review committee

$$\sin\delta = \frac{P(\nu_\mu \to \nu_e) - P_{solar} - X_\pm s_{13}^2}{\mp Y_\pm s_{13}}$$

- JPARC-SK neutrino mode, 10 years (0.75 MW & 22.5 kton, s/bg accounted)
- 50 ton detectors @KASKA-II (1-10 years)

the only way to detect CPV without HK?



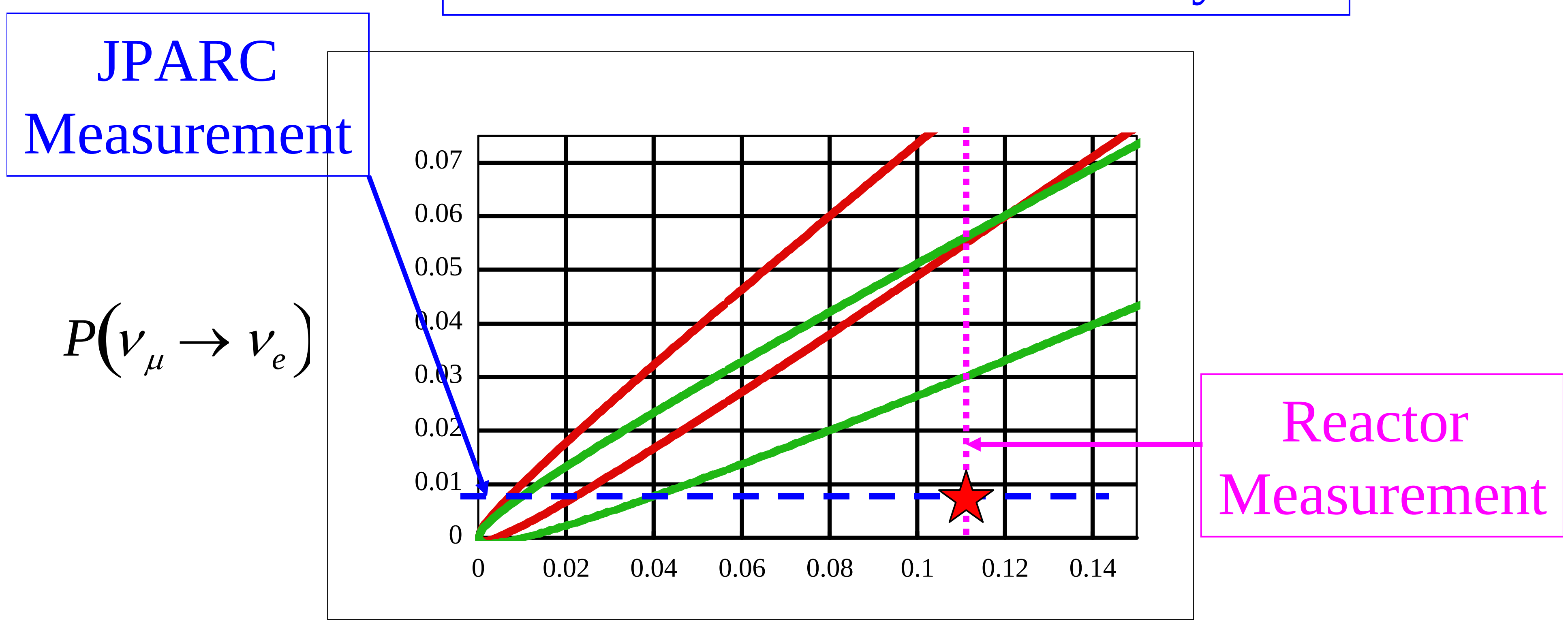
Detection area of non-0 δ_l

(modified from H.Minakata's presentation)

... And New Physics

$P(\nu_\mu \to \nu_e)$ and $P(\nu_e \to \nu_e)$ are related based on the extended standard model.

If this is the case ==> New Physics!

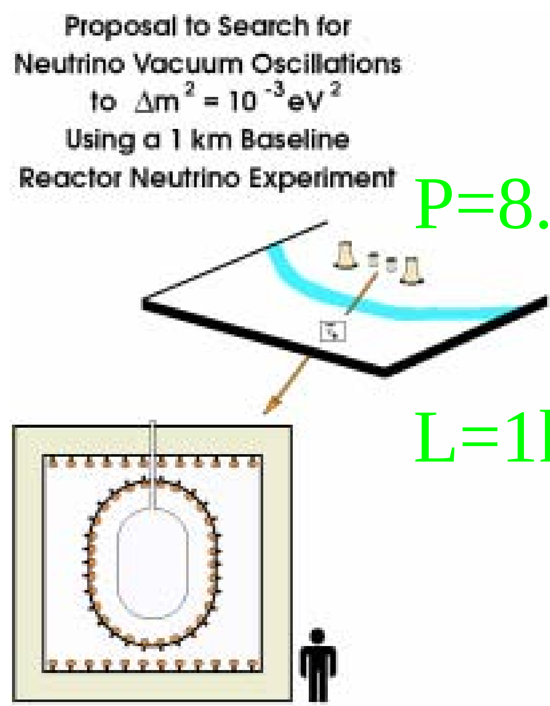


$P(\nu_\mu \to \nu_e)$

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

How to Improve from CHOOZ Limit

CHOOZ Facts

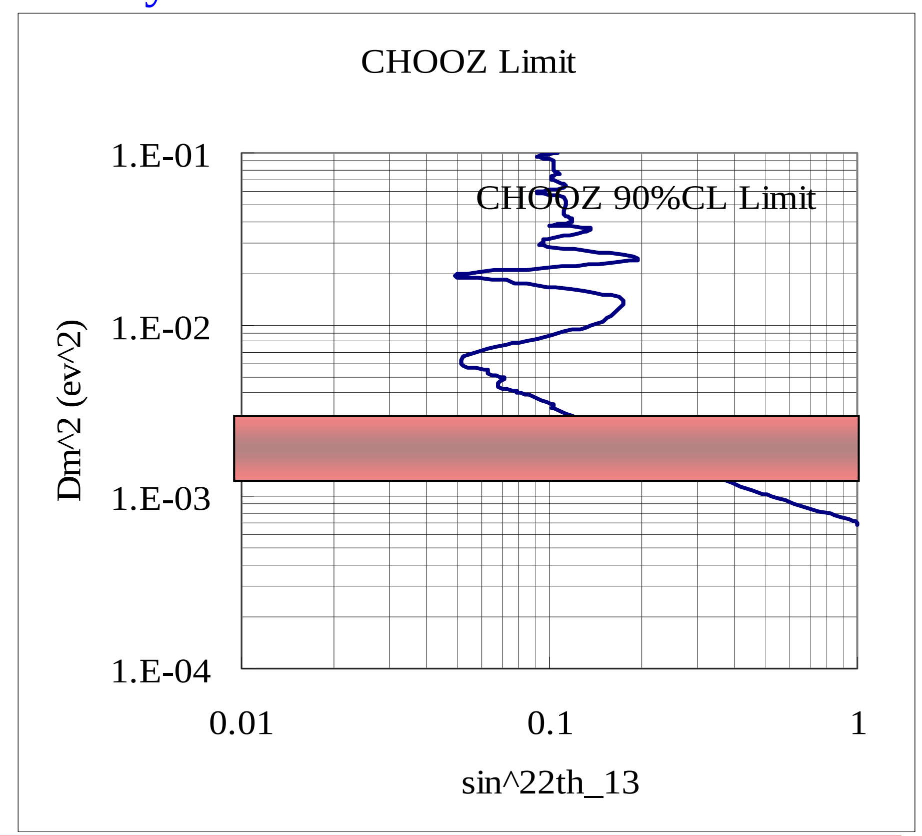


P=8.4GWth

L=1km

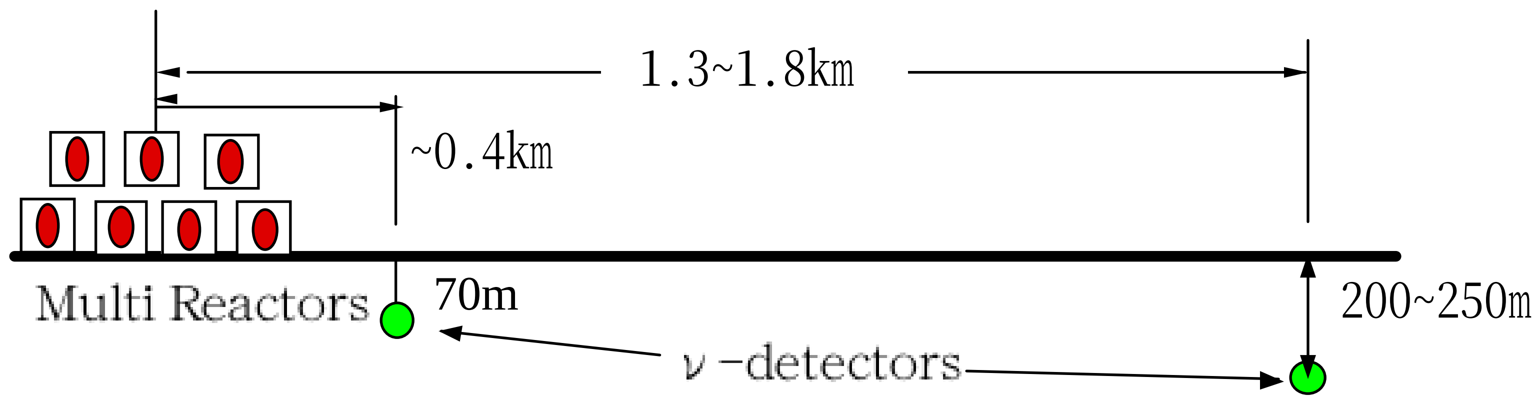
M=5ton

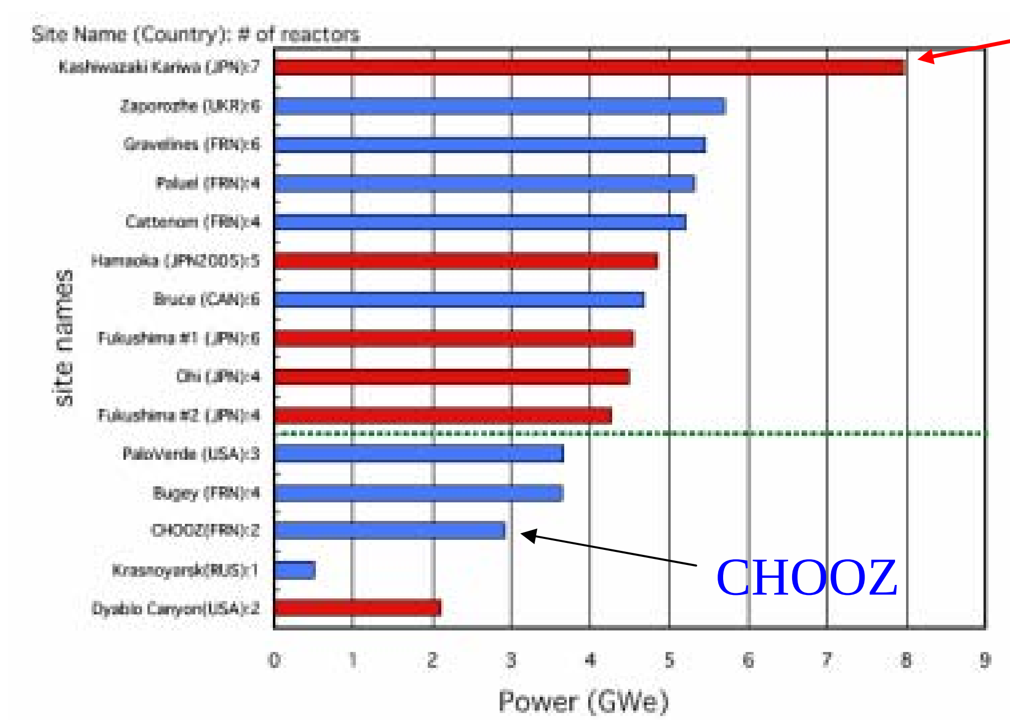
$\sigma_{sys.}$=2.8%, $\sigma_{stat.}$ =2.7%



$\sin^2 2\theta_{13} < 0.2$ @ $\Delta m^2 = 2*10^{-3}$ eV^2

How to Improve from CHOOZ Limit



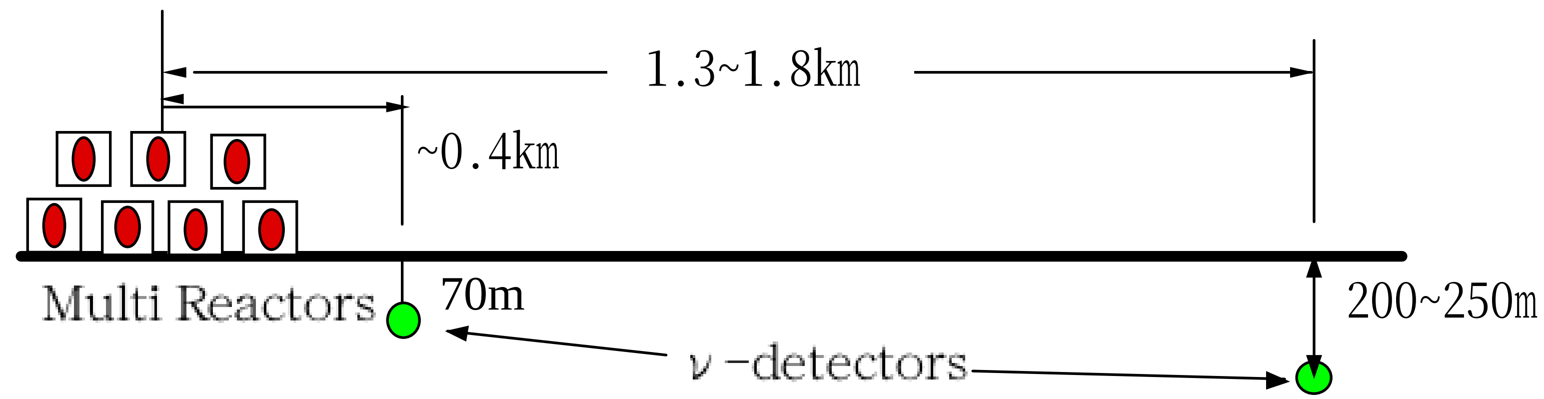


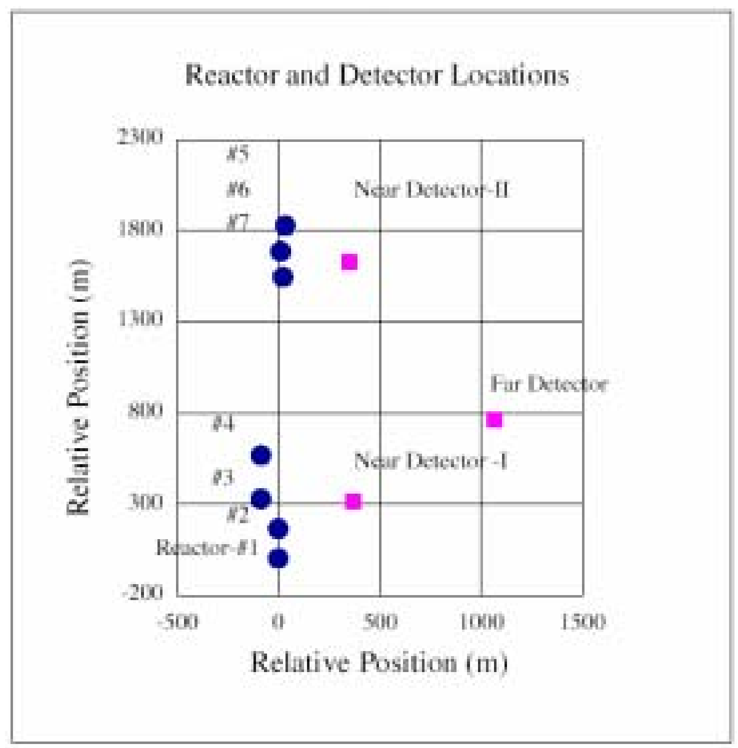
Kashiwazaki-Kariwa;
The World's Most Powerful
Nuclear Power Plant
Pth=24.3GW

Powerful Reactors
+ Larger Detector(8ton)
=> Gain Statistics & S/N

$\sigma_{stat.}$=0.5% in 2~3 years

How to Improve from CHOOZ Limit



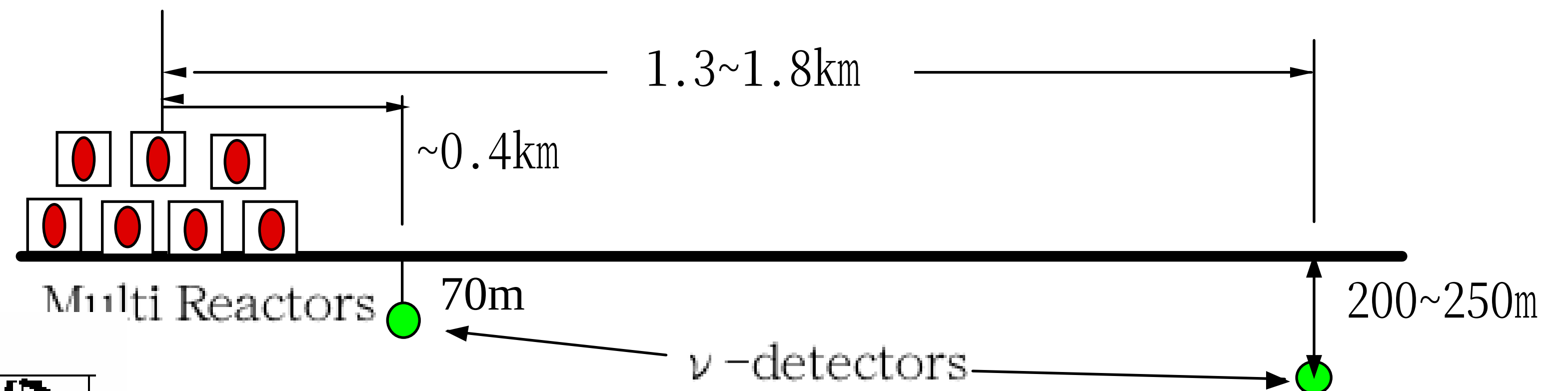


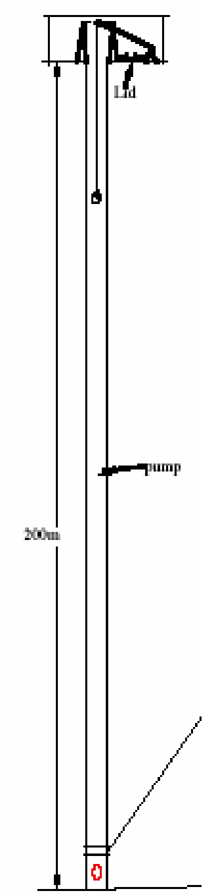
2 near + 1 far detectors

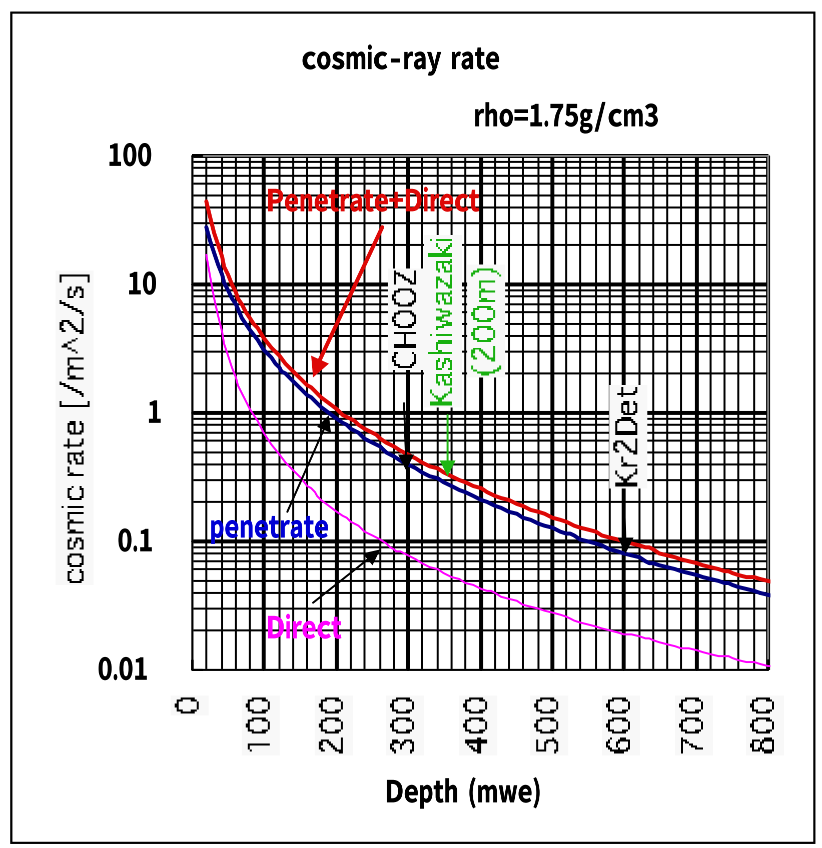
Identical Multi Detectors
=> Cancel Systematics

* ν flux (2% --> 0.2%)
* detector efficiency (1.5% --> <1%)

How to Improve from CHOOZ Limit





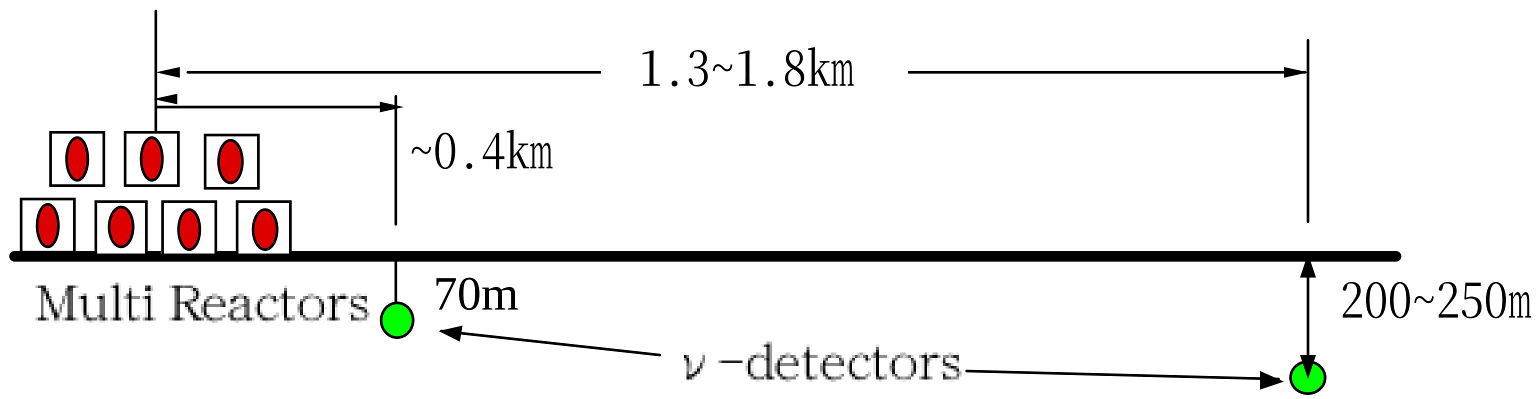


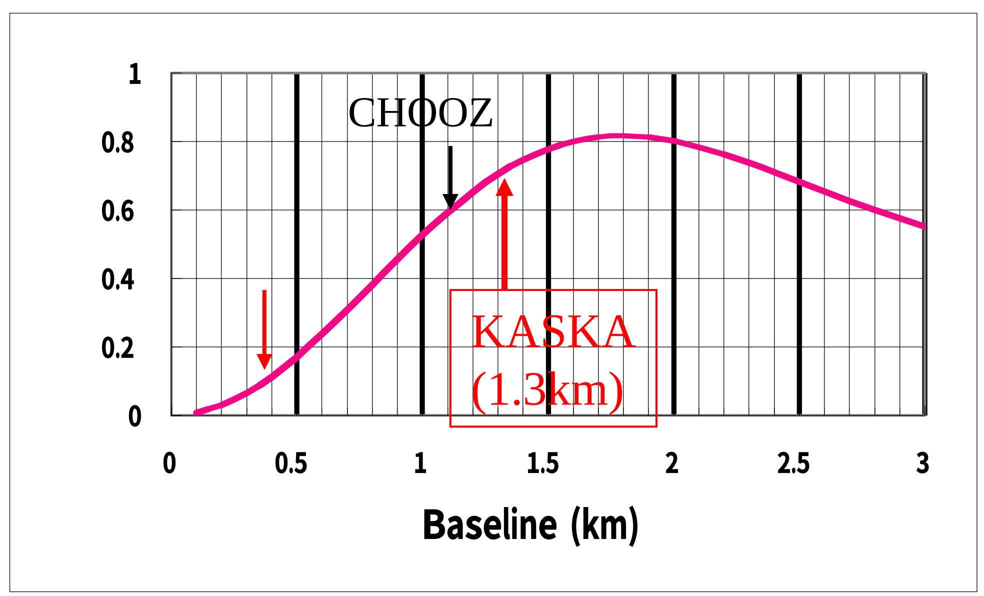
Deeper underground
=> Less BKG

μ /ν ratio =1/2 of CHOOZ

Shaft Hole
=> can put detector
wherever we want.

How to Improve from CHOOZ Limit

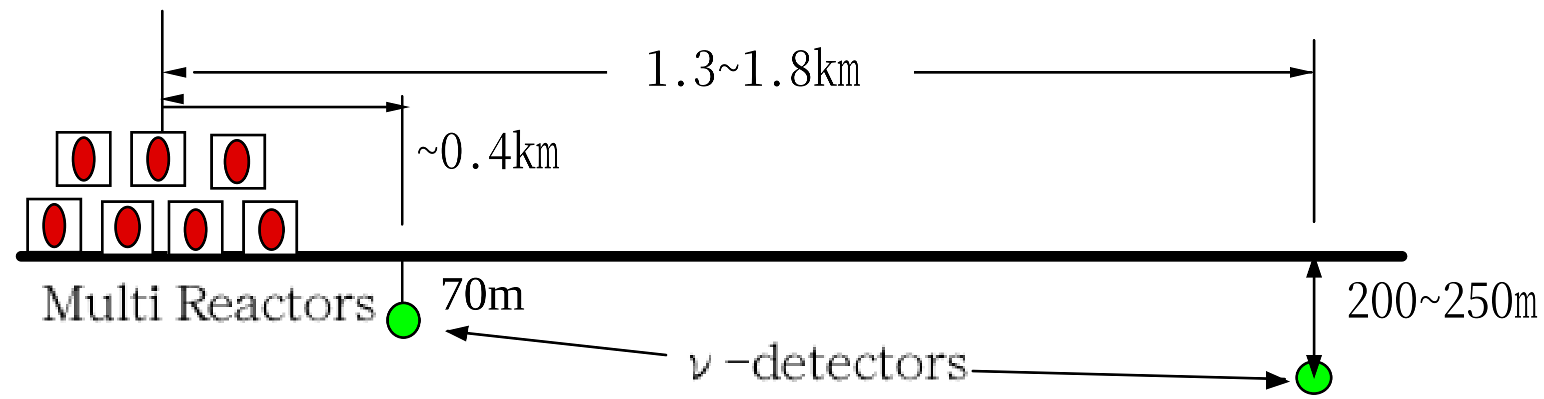


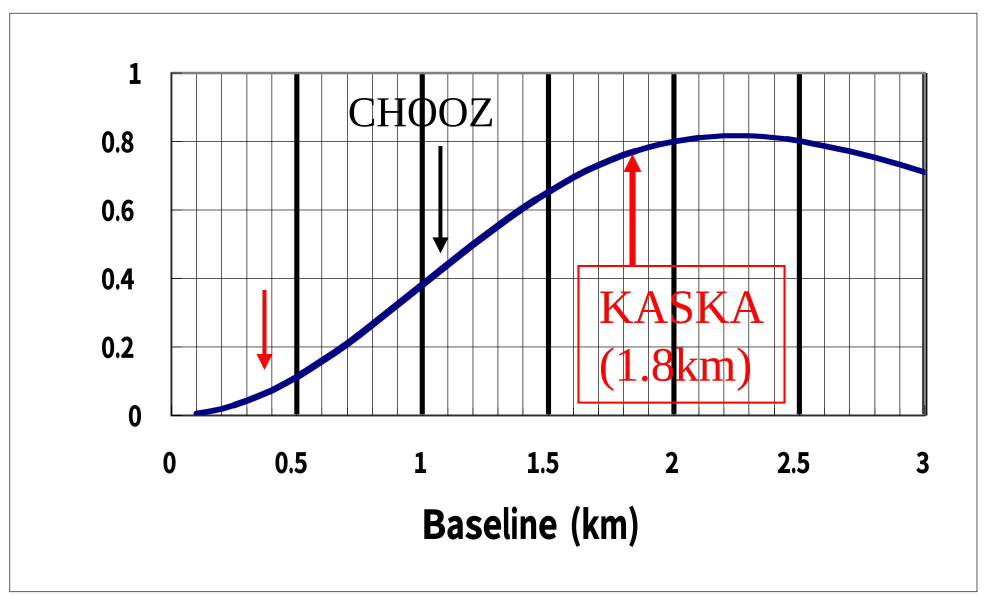


Longer Baseline
=> Larger Oscillation

KASKA1.3 if $\Delta m^2 \sim 2.5 * 10^{-3} eV^2$

How to Improve from CHOOZ Linit





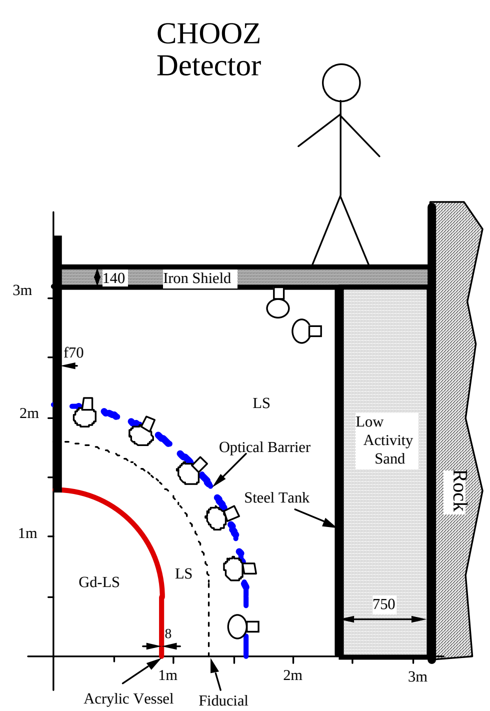
KASKA1.8 if $\Delta m^2 \sim 2.0 * 10^{-3} eV^2$

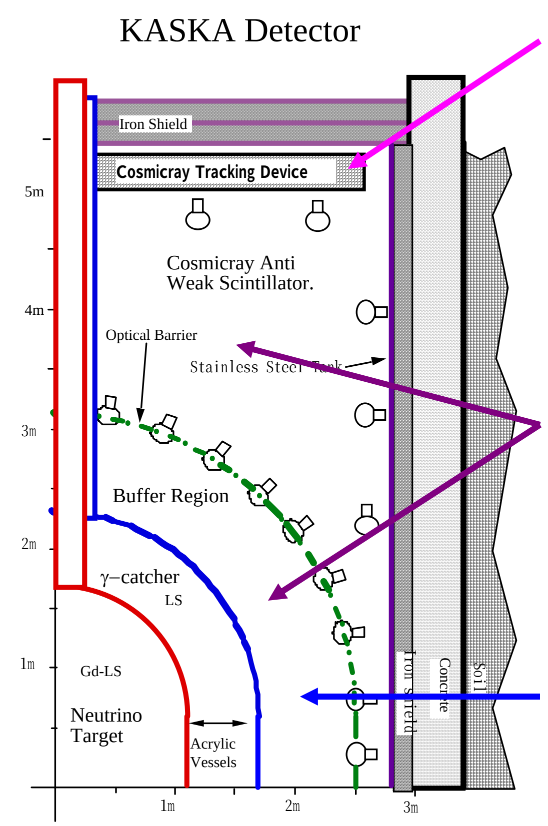
Longer Baseline
=> Larger Oscillation

Detector=same
depth=+50m
Data taking 2yrs=>3yrs

How to Improve from CHOOZ Limit

Detector Improvements



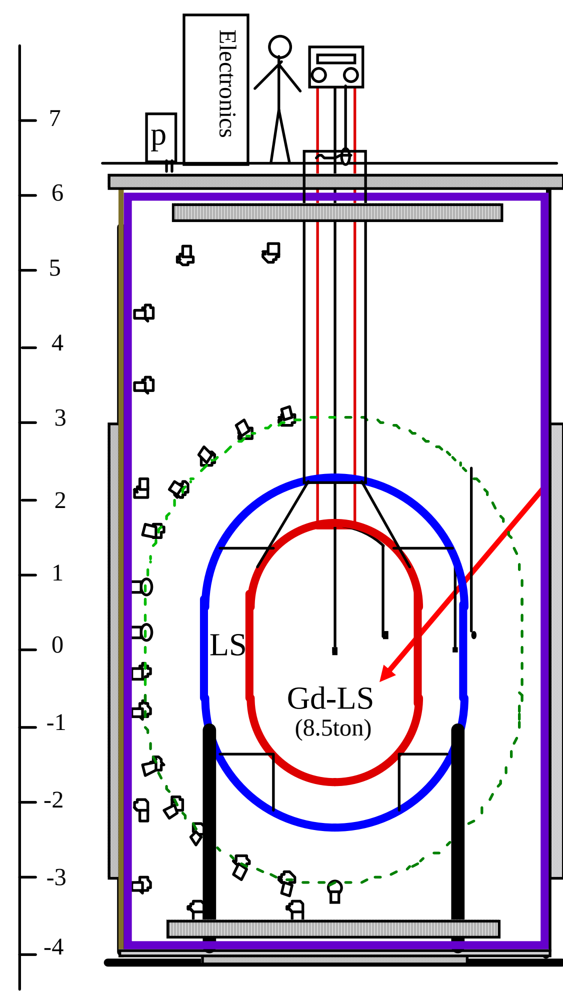


*** Cosmicray tracking device**
==> Measure cosmic-ray associated BKG

*** Thicker Buffer Oil**
==> Reduce neutron & rock γ background

*** γ -ray shield**
==> Significantly reduce single rate.

Detector



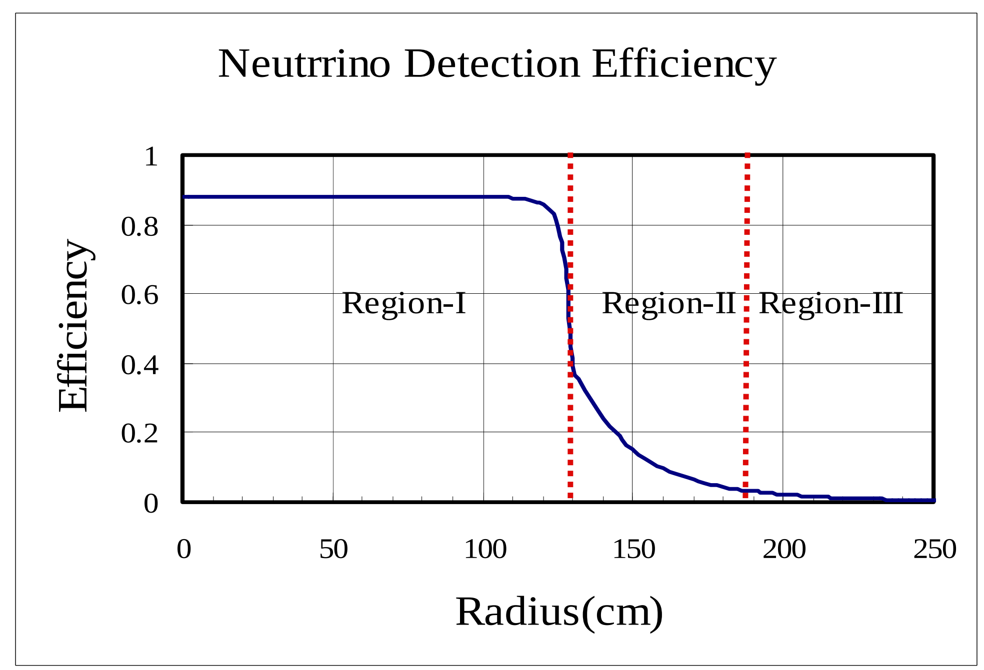
•Neutrino Target [Region-I]:

Gd Loaded Liquid Scintillator

Gd (~0.1%)+ PC(~30%) + n-paraffin (~70%)

M=8ton (r~1.3m)

Contained in Acrylic Vessel



Acrylic Vessel

CHOOZ Vessel

$\times 1.6 = KASKA$

Detector

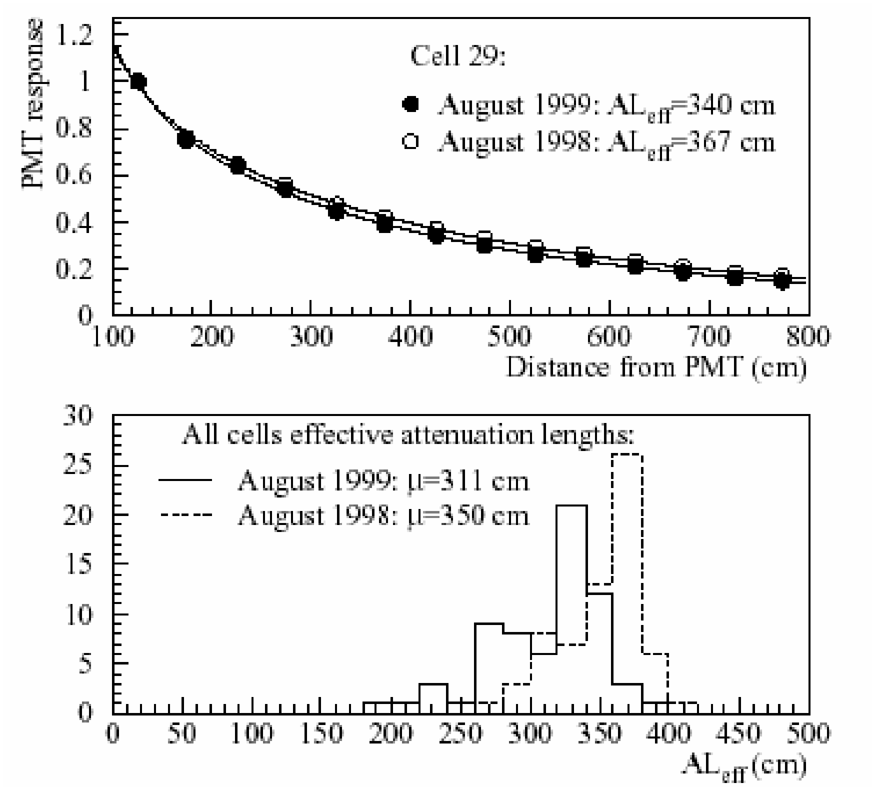


FIG. 6. Effect of aging on Gd loaded scintillator. Top: ^{228}Th Compton edge position at seven different longitudinal locations along a typical cell. The two curves are from calibrations taken a year apart. The curves are normalized at the location nearest to the PMT. Bottom: Effective attenuation lengths for all 66 cells from the two calibrations.

PaloVerde Hep-ex/0003022

Stability of Gd Loaded Liquid Scintialltor

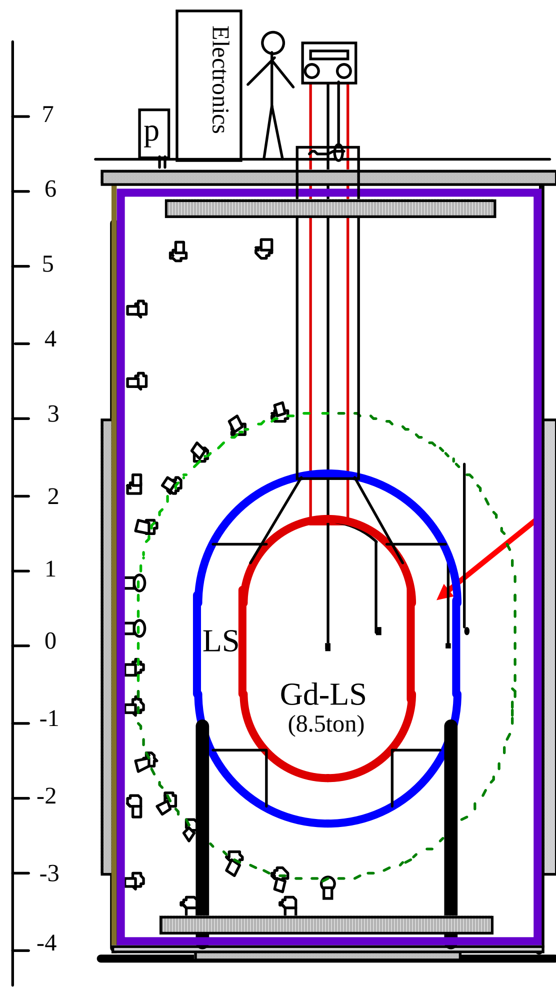
PaloVerde Type:
gadolinium 2-ethylhexanoate
$Gd(CH_3(CH_2)_3CH(C_2H_5)CO_2)_3$-$xH_20$
(Note CHOOZ LS = $Gd(NO_3)_3$)

$$\Delta\lambda = -0.4 m / year$$

OK for 2~3 years

(R&D of better Gd-LS will take place)

Detector

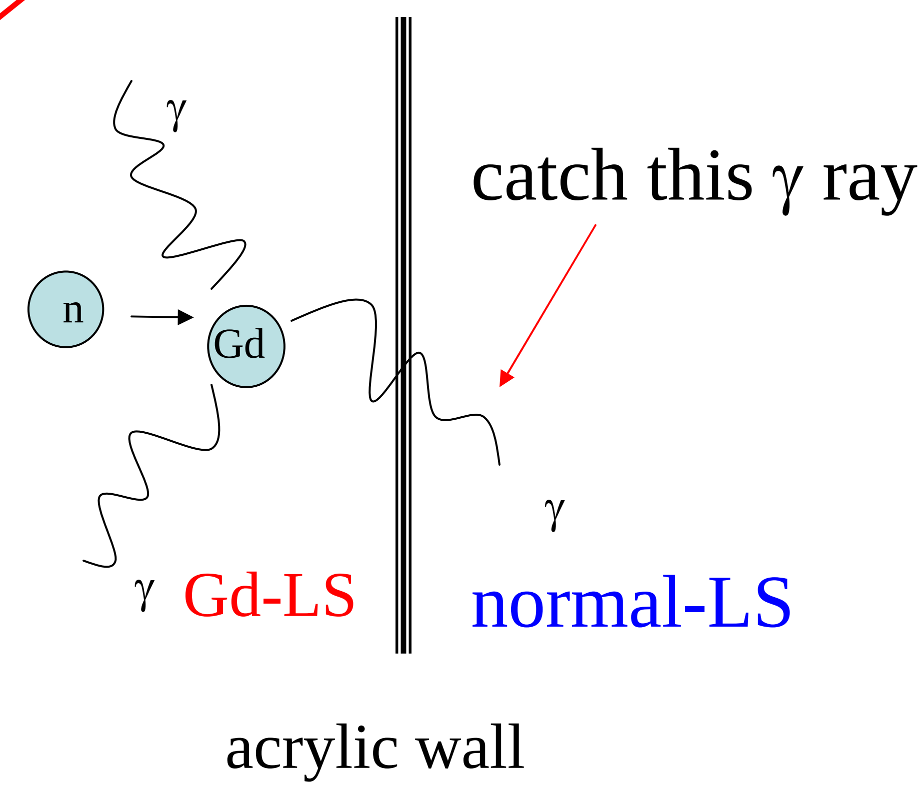


* γ catcher [Region-II]:

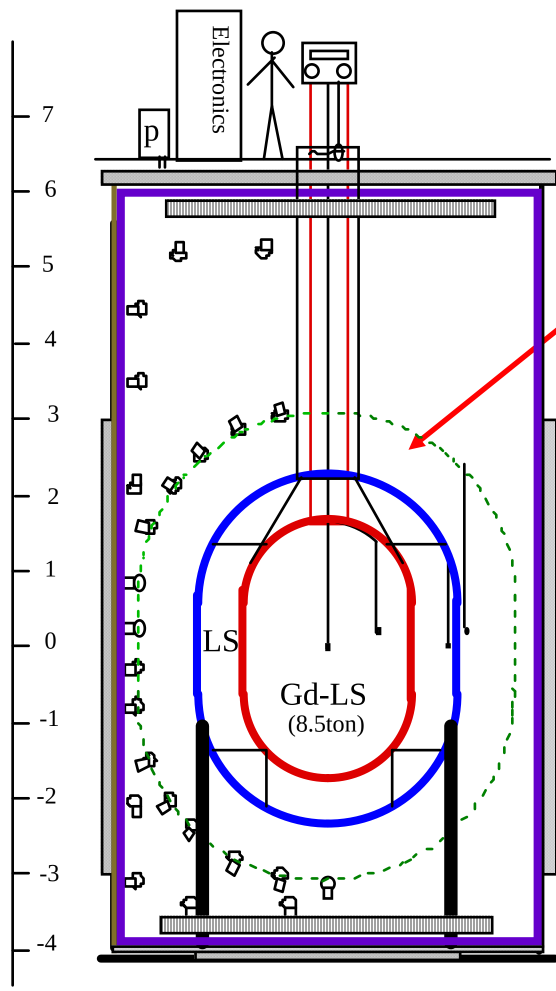
Liquid Scintillator (No Gd)

Thickness 50~60cm

Contained in Acrylic Vessel



Detector

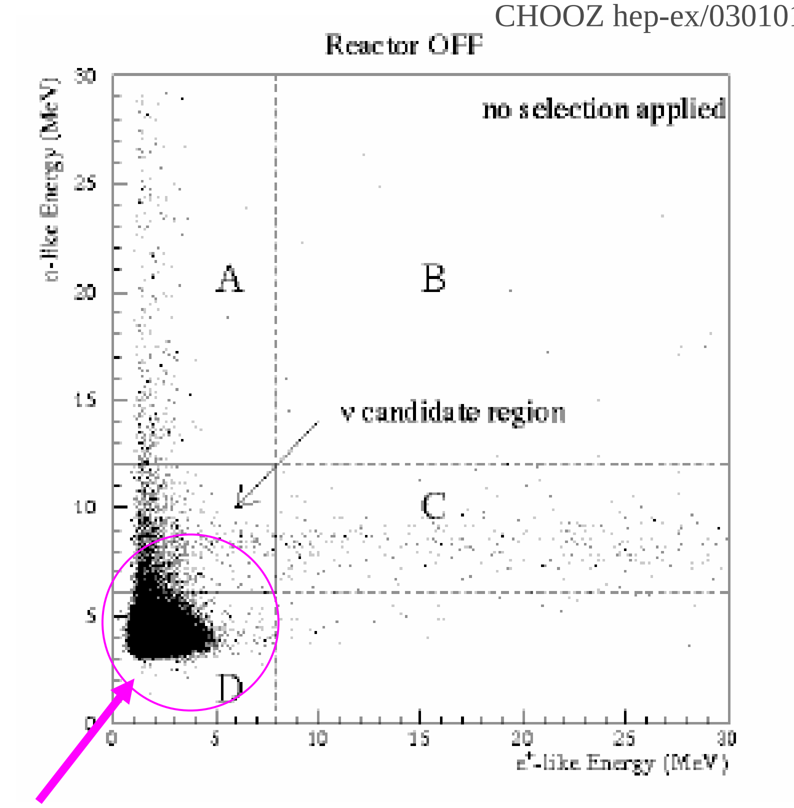


* <u>Inner Buffer(γ-shield) [Region-III]:</u>

Thickness 80~90cm

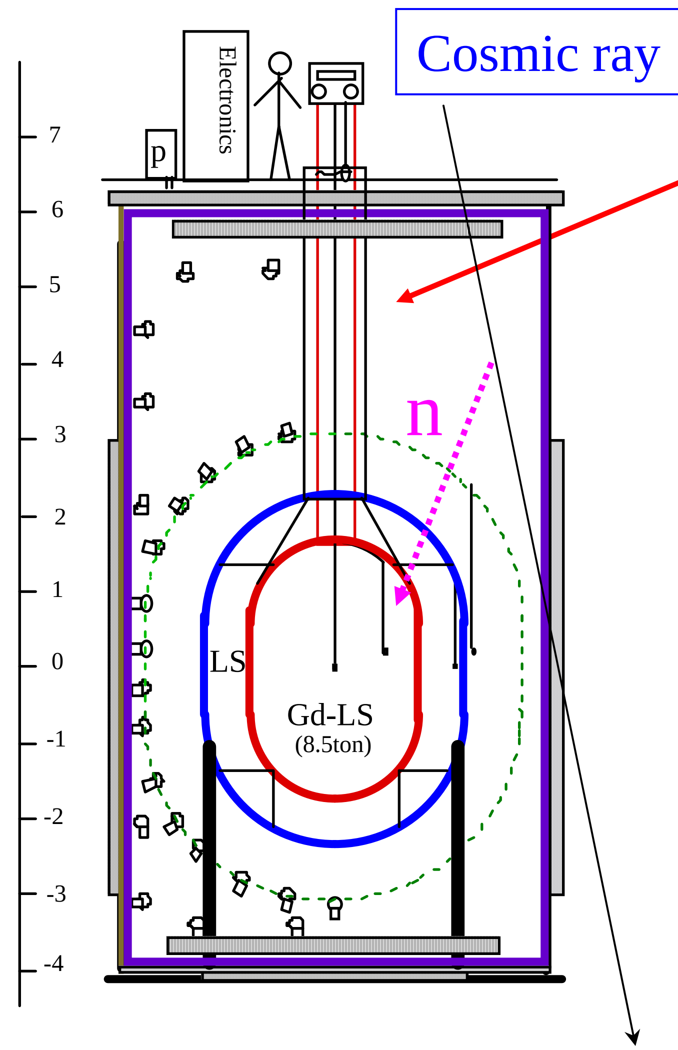
This is to shield γ rays from PMT glass

CHOOZ hep-ex/0301017 v1



Reduce this BKG significantly

Detector



* Outer Buffer(cosmic-anti) [Region-IV]:

Weak Scintillator

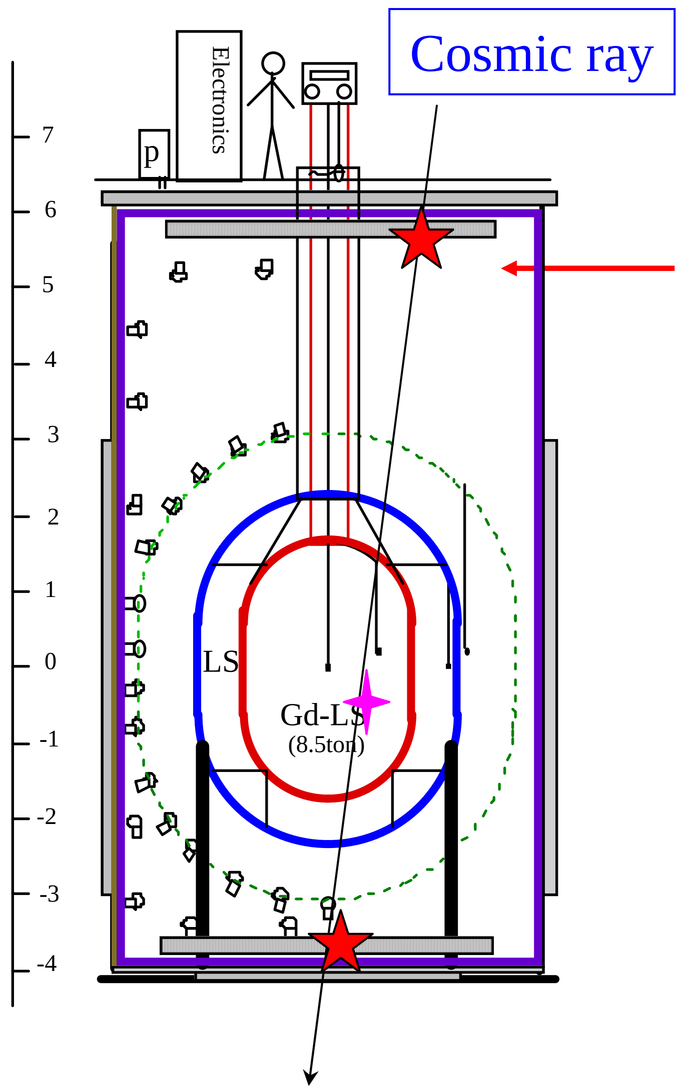
V~150m3

This is to veto cosmic rays.

~10Hz for far detector

~100Hz for near detectors

Detector



* Cosmic ray tracking device

σ~10cm

To estimate spallation BKG

$\mu + {}^{12}C \Rightarrow \mu + {}^{9}Li + 3p$

${}^{9}Li$ (260ms)=> ${}^{8}Be + e^{-} + n$

Correlated BKG

Why we believe systematic error can be <1%

e^+ signal selection

(1) $E_{prompot} > 0.7MeV$

CHOOZ
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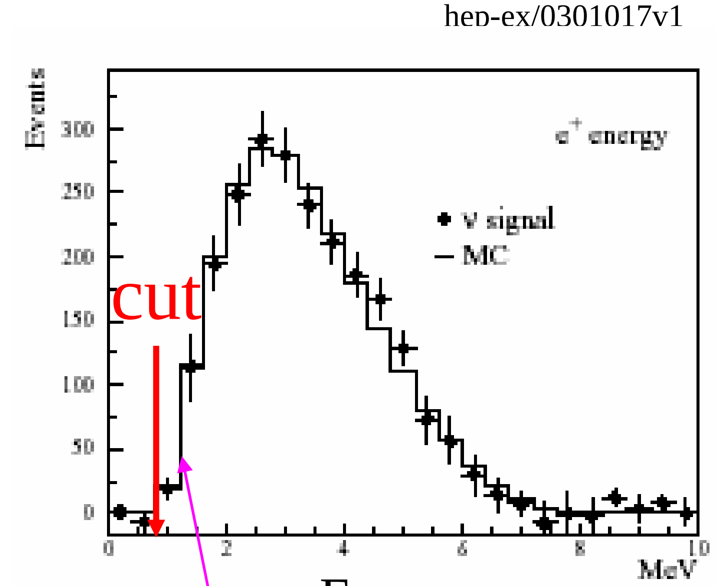


E_{prompt}

$e^+ + e^-$ => 1.02MeV
Natural Threshold

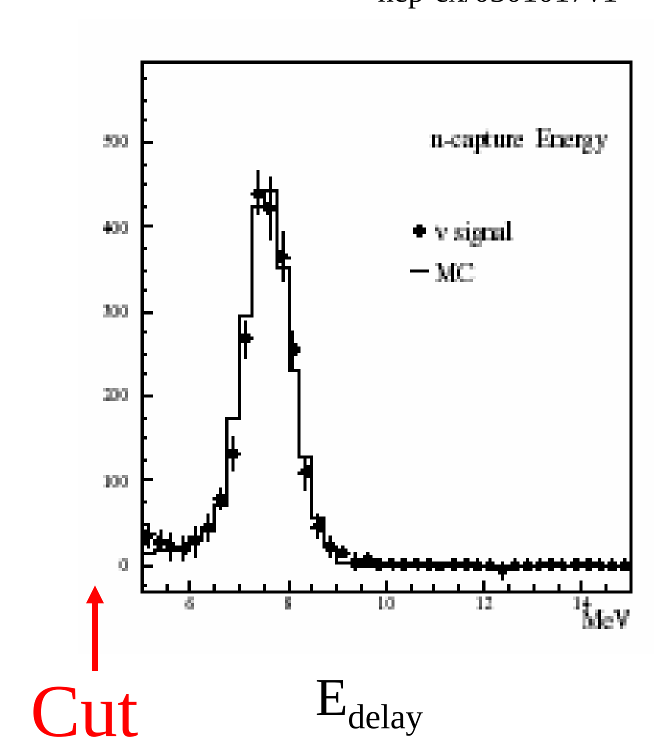
$\varepsilon > 99\%$,
$\delta\varepsilon_{relative} \sim O(0.1\%)$

Why we believe systematic error can be <1%

n signal selection

(2) $E_{delayed} > 4MeV$

CHOOZ
hep-ex/0301017v1



E_{delay}

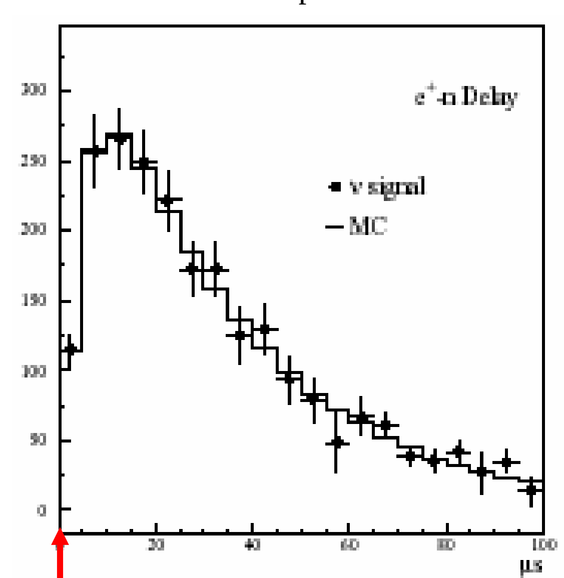
$\varepsilon > 97\%$,
$\delta\varepsilon_{relative} < 0.5\%$

Why we believe systematic error can be <1%

Timing Correlation Cut

(3) $2\mu s < \Delta t_{prompt\text{-}delayed} < 500\mu s$

CHOOZ
hep-ex/0301017v1



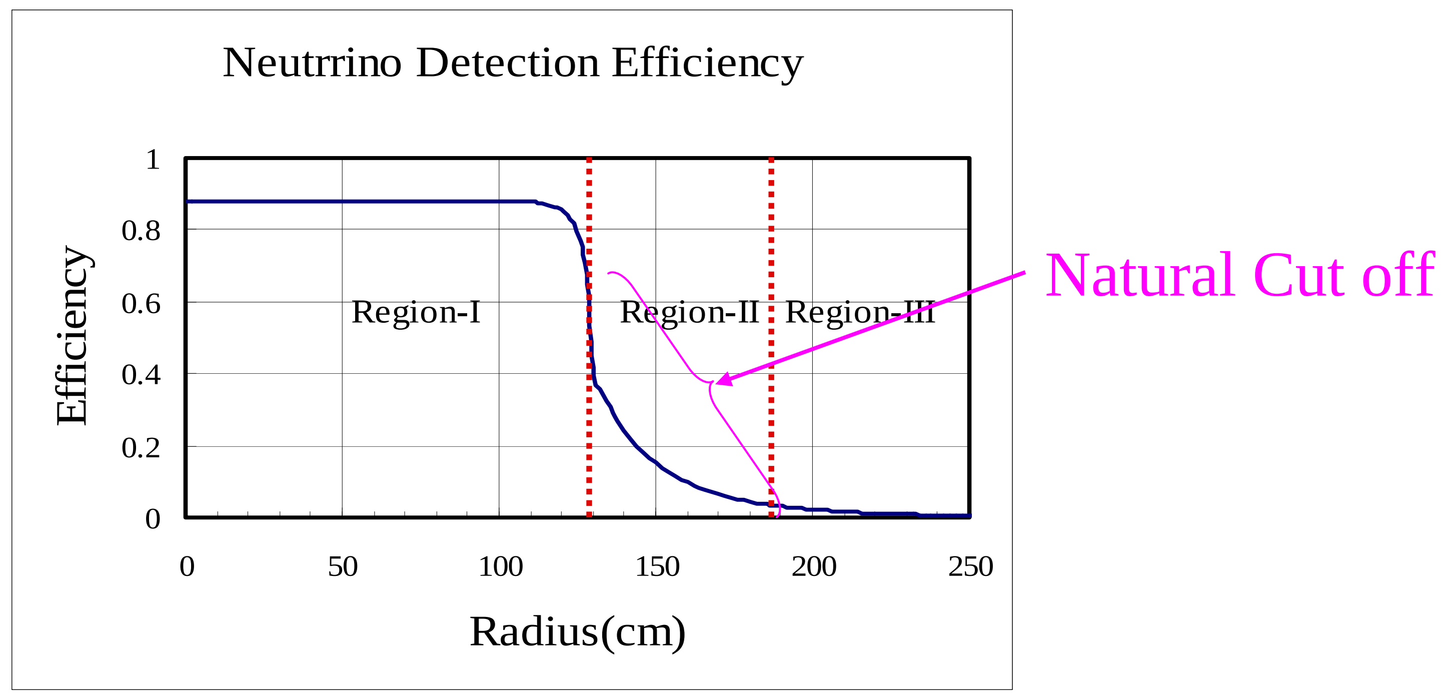
Δt

Cut

$\varepsilon > 98\%$,
$\delta\varepsilon_{relative} < 0.3\%$

Why we believe
systematic error can be <1%

There is no fiducial cut.

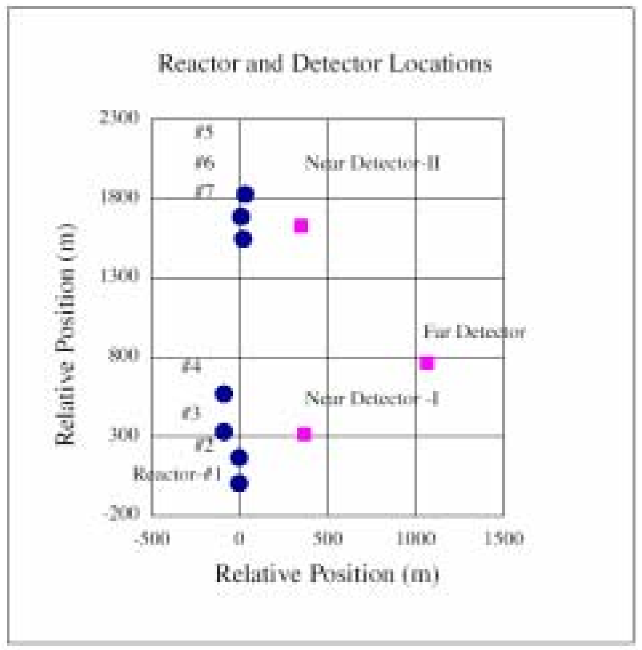


Main Uncertainty

<= Relative Mass Difference of Gd-LS

Volume measurement => <0.5%

Uncertainties of Neutrino Flux



(1) The correlated error cancels out regardless the baseline difference.

(2) The uncorrelated error reduces to the factor of the standard deviation of the squared baseline difference ratio.

$$\frac{\delta f_\nu}{f_\nu} \sim \left(\frac{\delta P^{un-corr.}}{P}\right) \times \sqrt{\frac{1}{7}\sum_r \left(1 - \frac{R_r}{\langle R \rangle}\right)^2}$$ <0.2%

P : the reactor operating power and $\delta P^{\text{un-corr}}$ is un-correlated error of P (<2%).

R_r : the ratio of squared baseline between reactor and near/far detectors.

$$R_r = \frac{L^2_{r,far}}{L^2_{r,near}}$$

BackGround-I

Accidental BKG

(E>0.7MeV)

Soil: <1Hz with >100cm oil+15cmFe

PMT: ~5Hz with 80cm shield

Gd-LS ~1Hz (CHOOZ Gd)

Acrylic ~1Hz

==================================

Total <10Hz

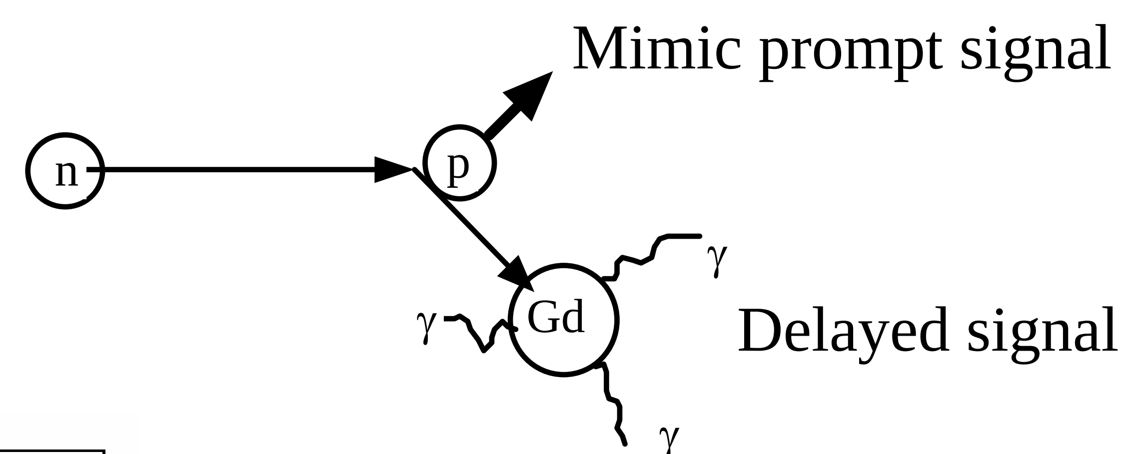
(f_n <$2*10^{-3}$Hz)

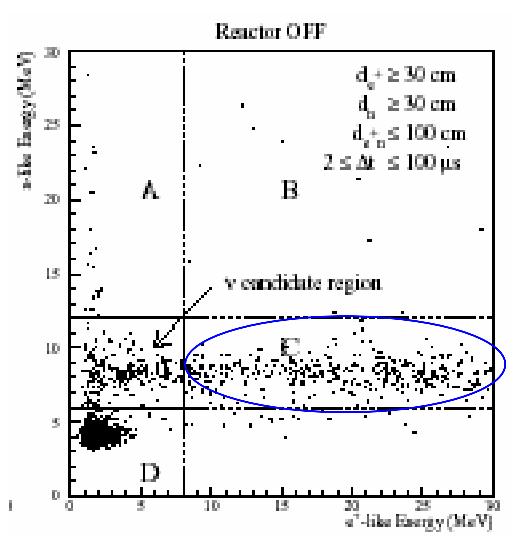
Accidental BKG<1%

& can precisely estimated by shifting coincidence window.

BackGround-II

Fast Neutron





CHOOZ
hep-ex/0301017v1

n backgrounds have flat distribution

Extrapolating Events Rate @>13MeV,

n BKG $\sim (1 \pm 0.2)\%$

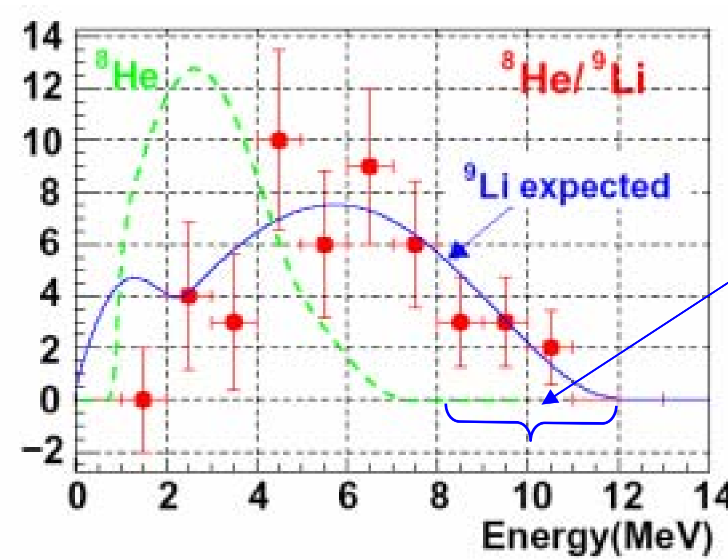
(CHOOZ Case $(5 \pm 0.5)\%$)

BackGround-III

Spallation

$\mu + {}^{12}C \dashrightarrow {}^{9}Li + X$

${}^{9}Li \dashrightarrow {}^{8}Be + \beta(13MeV) + n$, (τ=0.26s, Br=48%)



KamLAND Data
O.Tajima Thesis

Estimation can be done by using event rate at 8MeV<E<11MeV & dt-dx distribution to the last muon.

Error of estimation ~ 50%

⇓

Spallation BKG ~ $(0.4 \pm 0.2)\%$

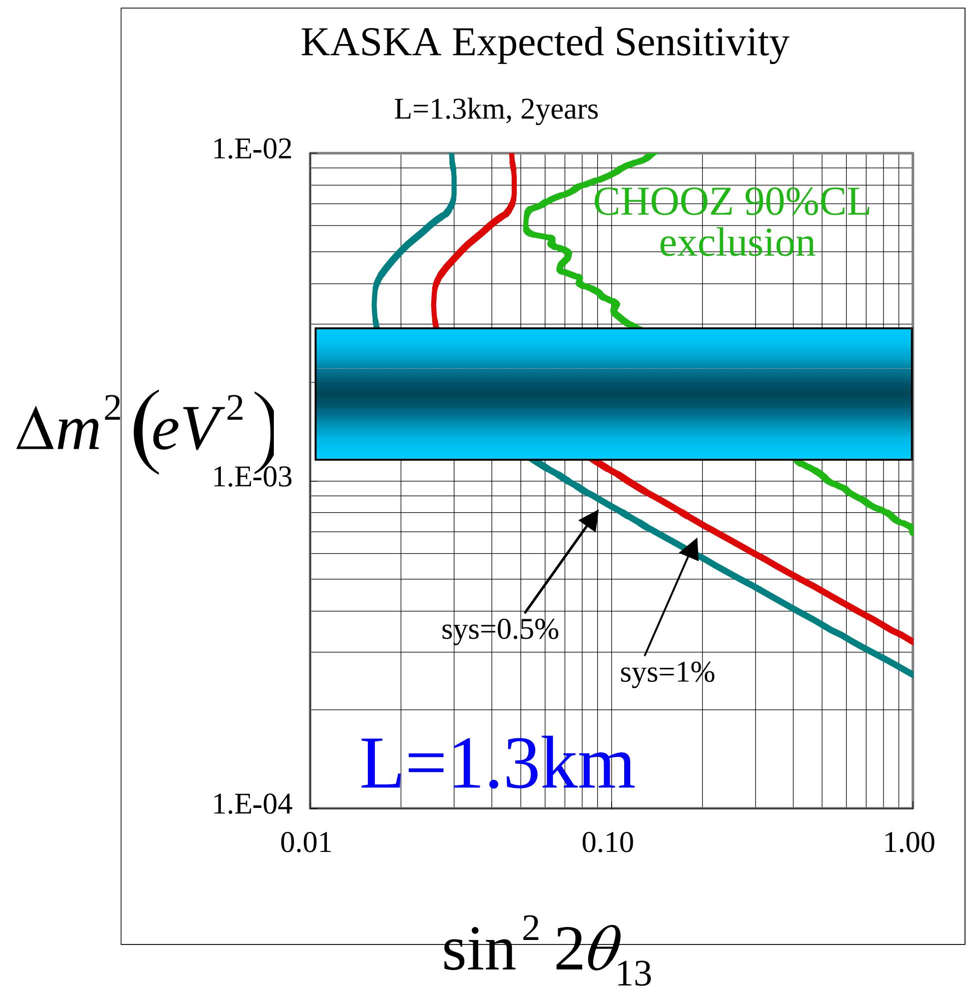
(This BKG was too small to be seen by CHOOZ)

Errors

Statistic Error: 1.3km ==> 0.5%/2years
1.8km ==> 0.6%/3years

Systematic Error: Detector Associated <1%
Flux Associated ~0.2%
=====================
Total <1%

Errors and Expected Sensitivity



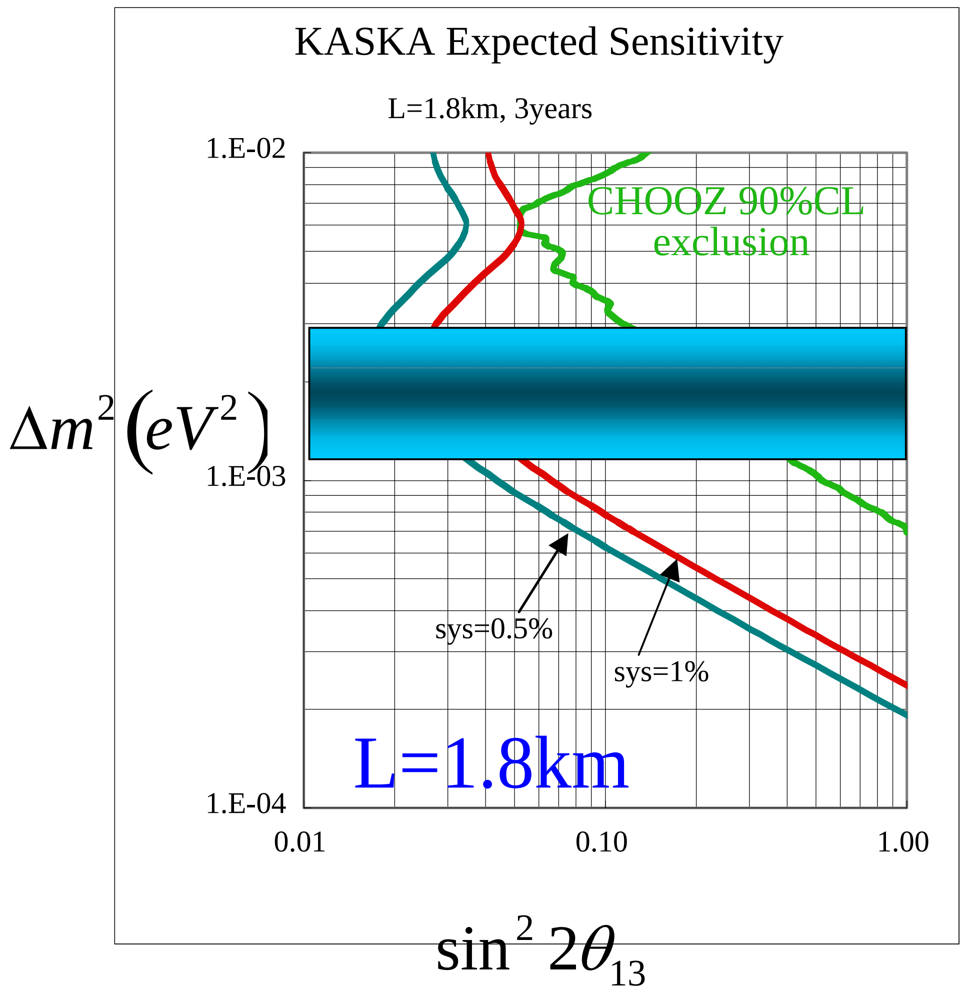
σ_{sys} <1% (CHOOZ 2.7%)

σ_{stat}~0.5% (CHOOZ 2.8%)

5~10 times better sensitivity than CHOOZ

& Comparable to Accelerator θ_{13} sensitivity.

Errors and Expected Sensitivity



σ_{sys} <1% (CHOOZ 2.7%)

σ_{stat}~0.5% (CHOOZ 2.8%)

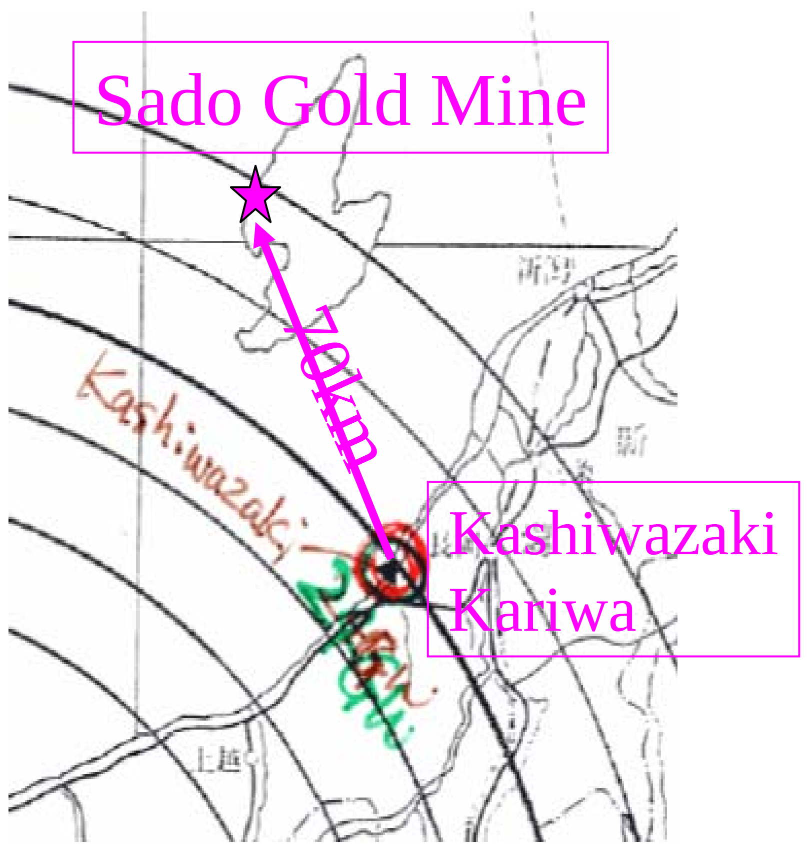
5~10 times better sensitivity

than CHOOZ

& Comparable to Accelerator θ_{13} sensitivity.

Possible Extension??

(1) KASKA-II: 50ton @ Optimized Baseline
to Look for non-0 δ_l with J-PARC??



(2) KASKA as a front detector
for optimized θ_{12} detector??

Oscillation Max~70km

KASKA=front detector
+KamLAND Scale Detector
in Sado Gold Mine

=> $\delta \sin^2 2\theta_{12} < 0.04$ (1σ)

Status of the Project

(1) Conceptual design of the experiment is almost complete. Asking for detector R&D money to some funding agencies.

(2) Negotiation with Electric Company for site use has been very successful. Briefing to the local government was also successful.

(4) We will host the Next International Workshop on the Reactor θ_{13} Experiment at Niigata in March 20-22, 2004.
http://www.hep.sc.niigata-u.ac.jp/~neutrino/workshop/

Workshop Poster

Dedicated to Reactor θ_{13}

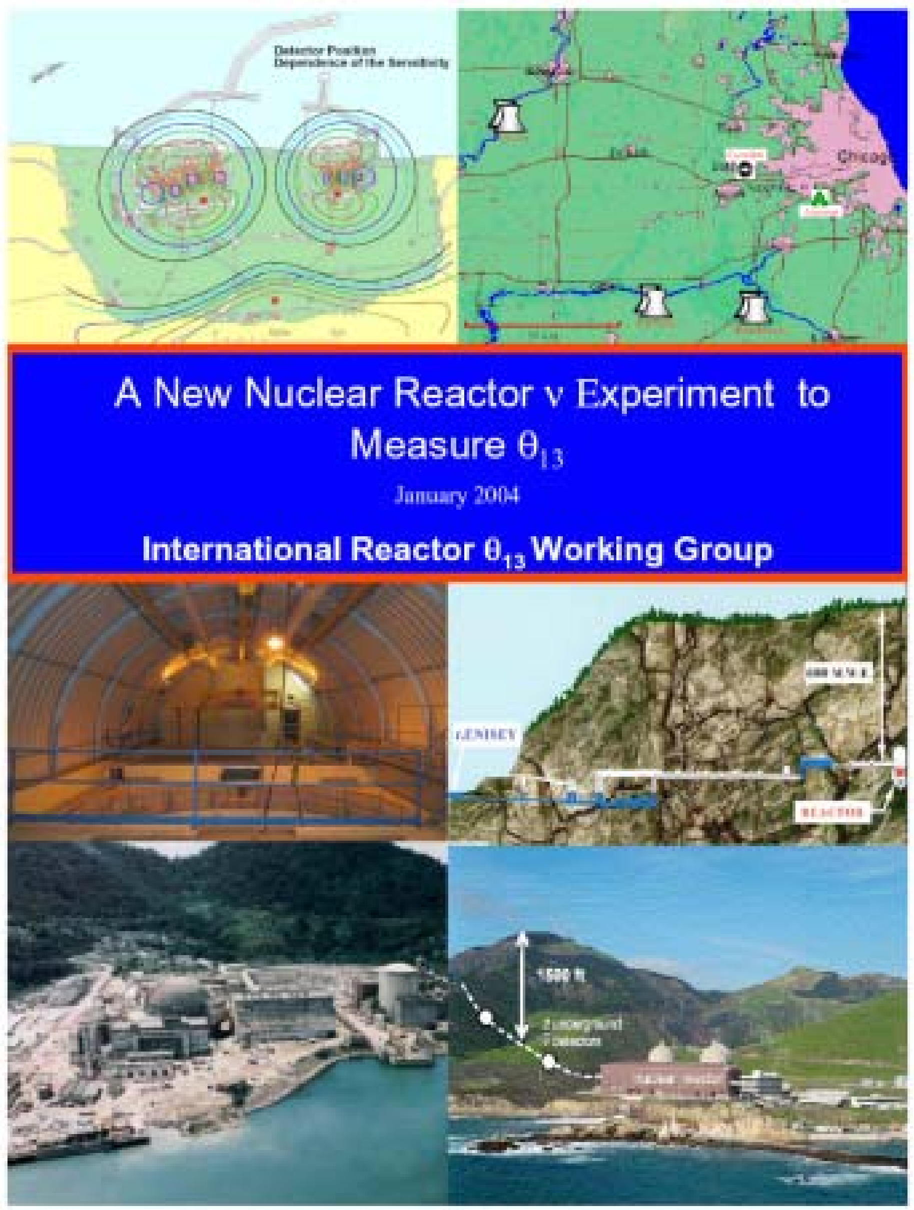
Kashiwazaki-Kariwa
NPP Tour Takes Place.

Interested participants are welcome.

Possible Schedule (my hope)

2002: KASKA Group was formed
2003: Conceptual Design
Investigation of Site Availability
2004: Detector R&D
2005: Detector R&D
2006: Start Construction
2007: Construction Continues
2008: Start Data Taking
2009: Initial Result
2010:
2011,or 2012: Final Result

World Activities



White Paper (Jan. ‘04) p167

(http://www.hep.anl.gov/minos/reactor13/white.html)

International Reactor θ_{13} Working Group:

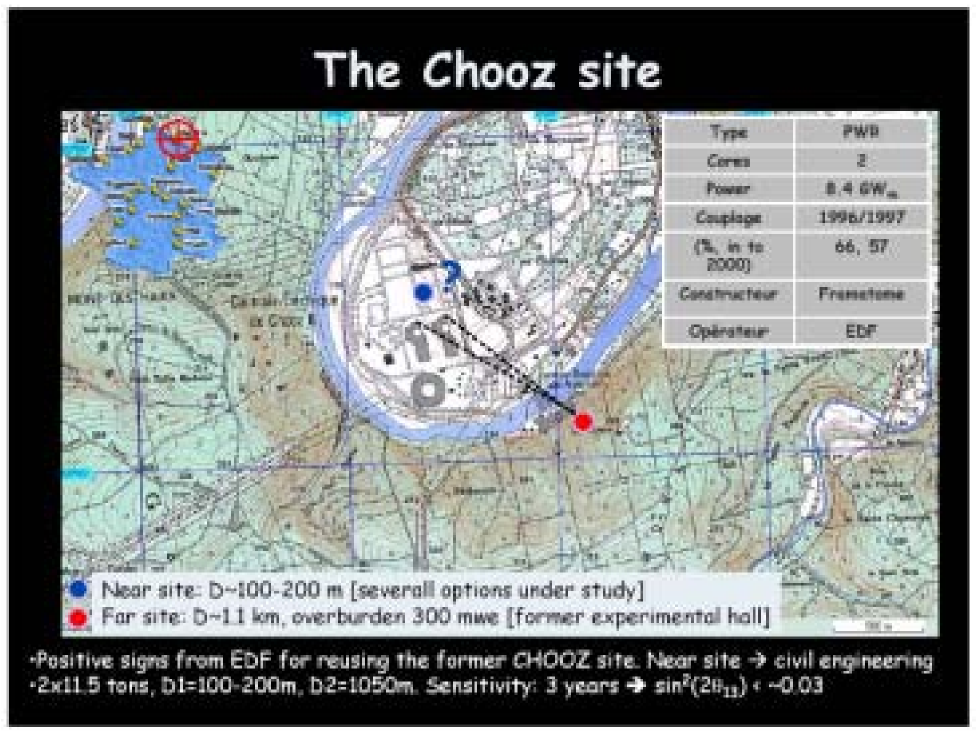
125 people,
40 Institutions,
from
Japan, USA, Europe,
Russia, China, Brazil

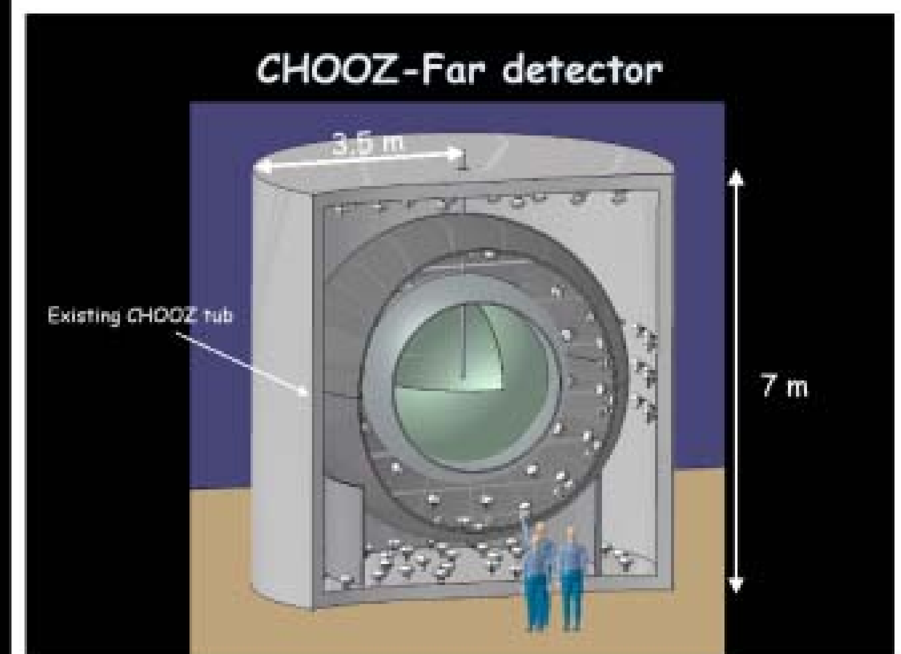
World of Proposed Reactor Neutrino Experiments

(....like baby bamboos after the rain)

by K.Heeger

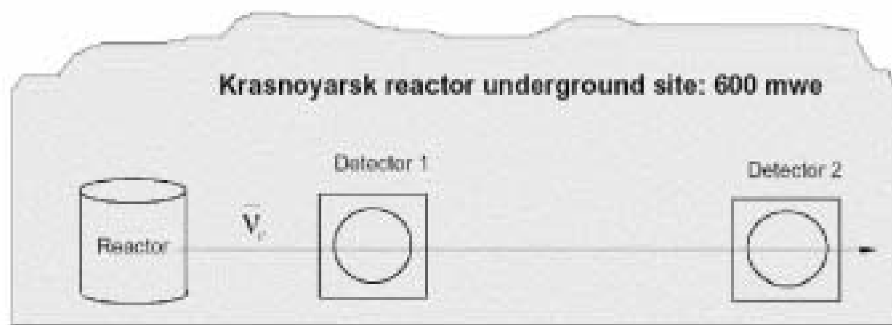
Double CHOOZ (French)



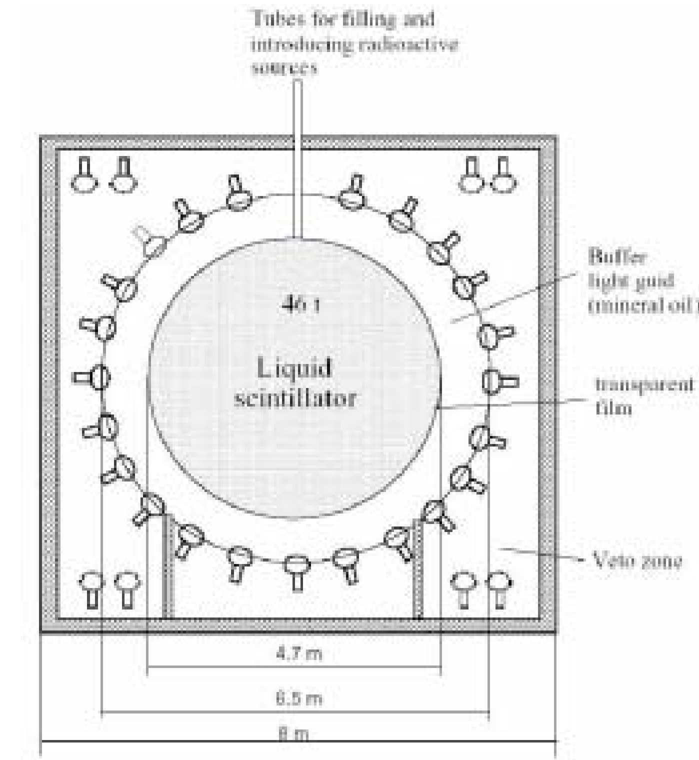


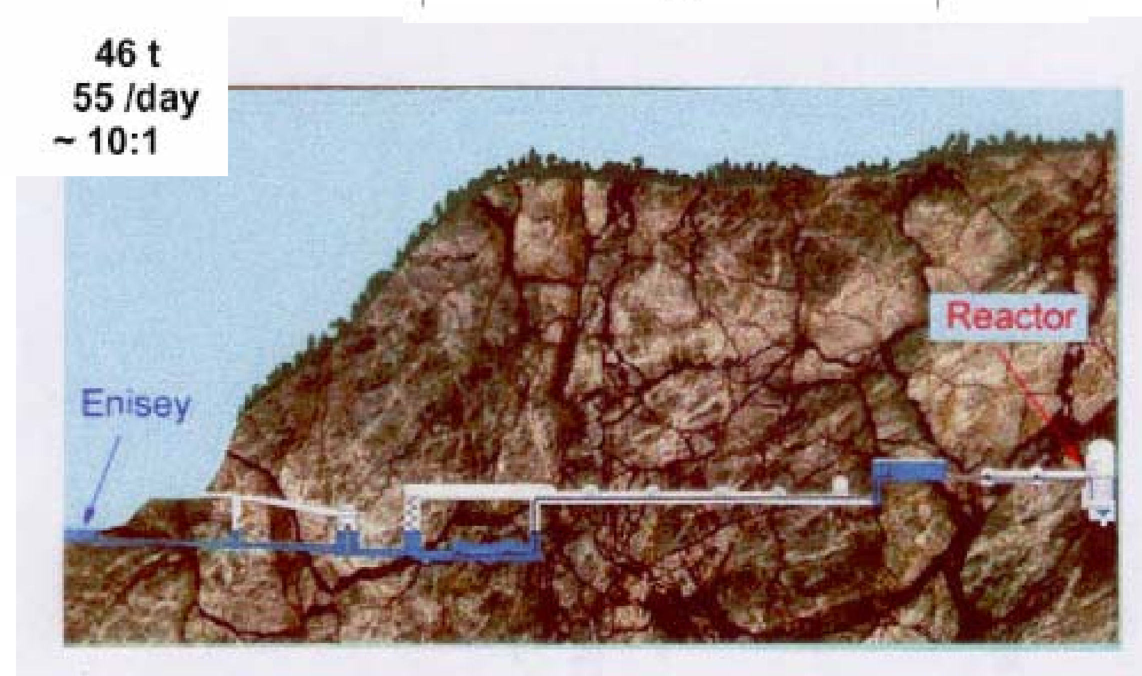
P=8.4GW, L=1.1km, M=20ton

Kr2Det (Russia)



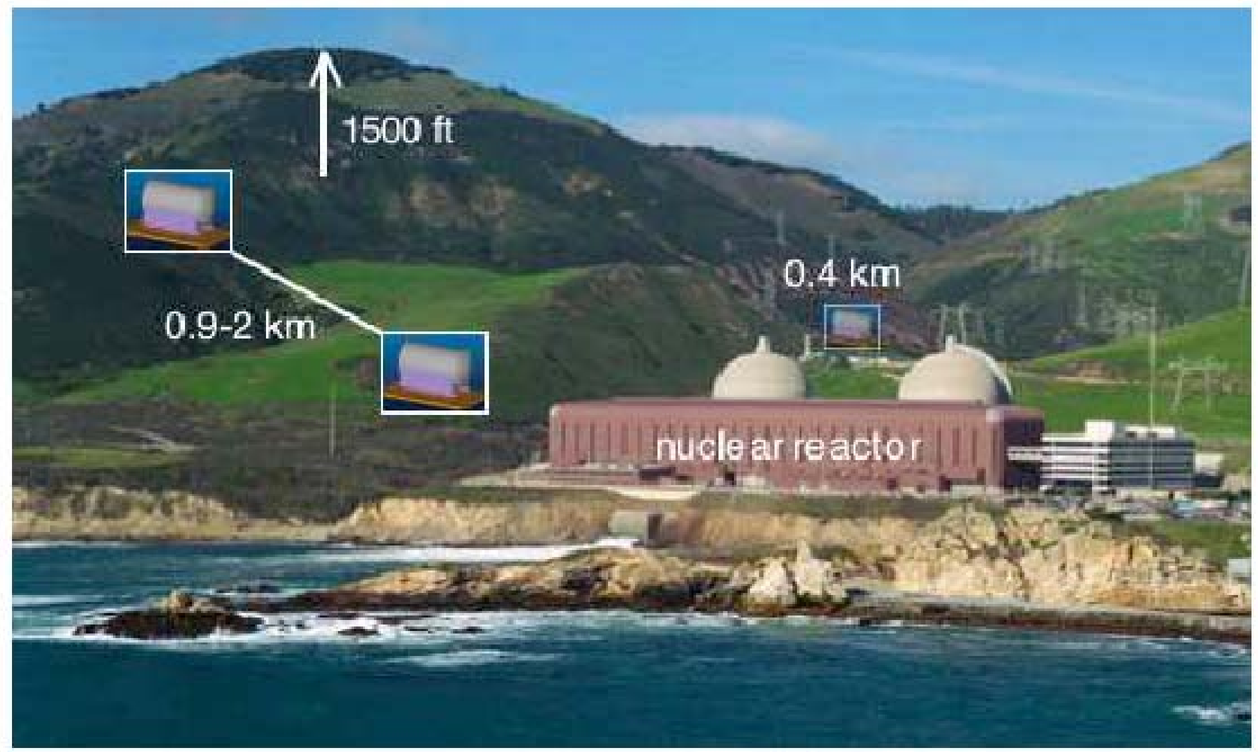
	115 m	1000 m
Target:	46 t	46 t
Rate:	4200/day	55 /day
S:B	>>1	~ 10:1





P=1.6GW,
L=1km,
M=50ton

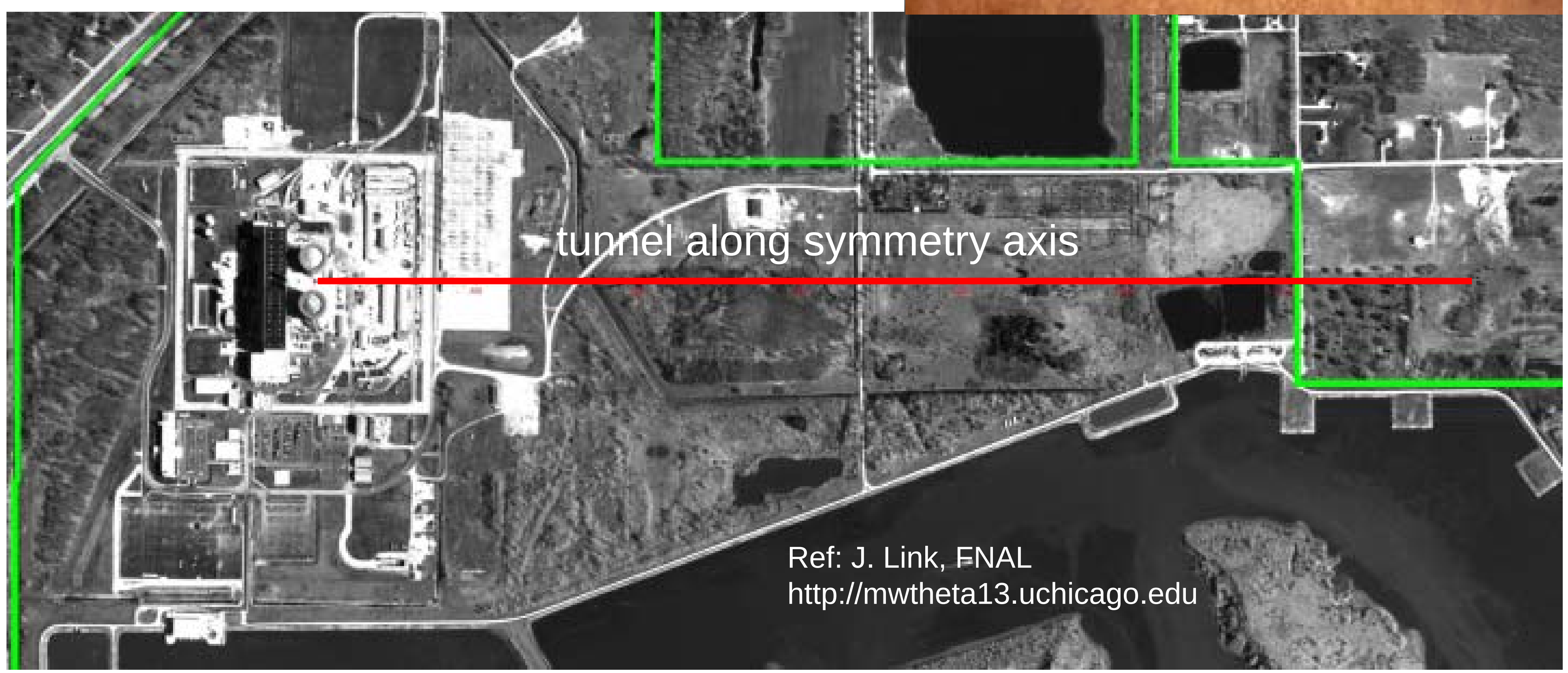
Diablo Canyon (USA)



P=6.2GW, L=0.9~2, M=50~100t

Braidwood, Il (USA)

Reactor	6.5 GW_{th}
Near Detector	200 m
Far Detector	1500 m (1800 m)

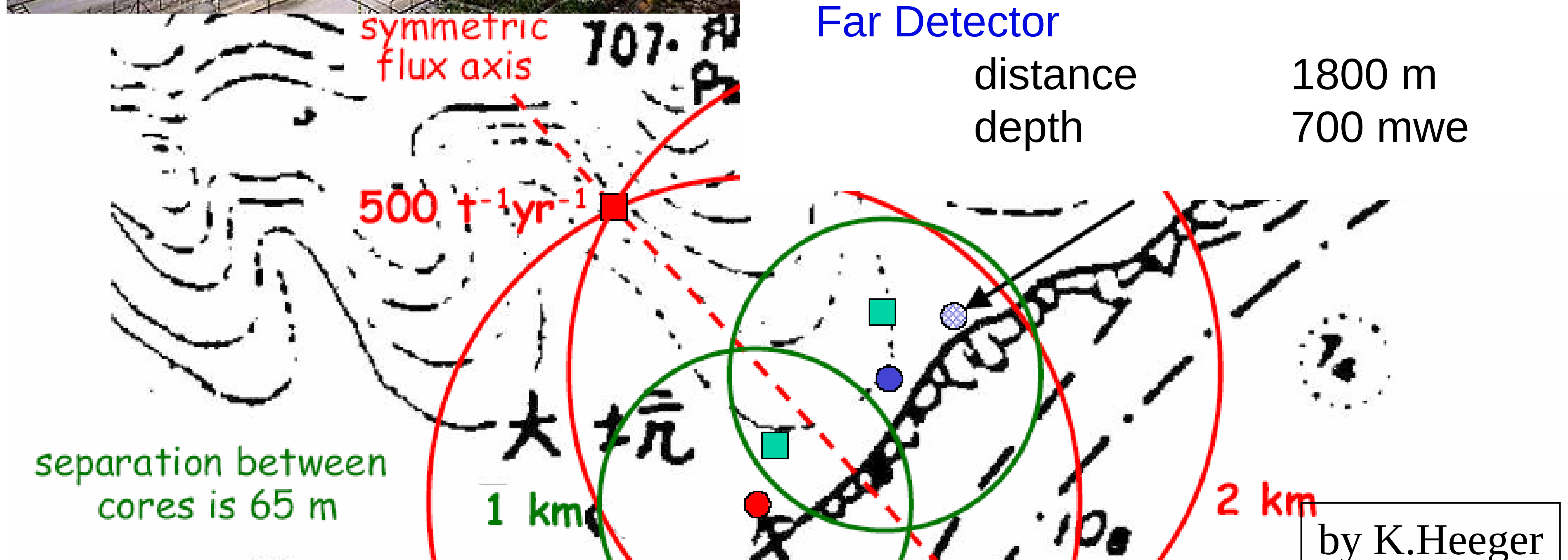


by K.Heeger

Daya Bay, (China)

My assumptions ….

Reactor	11.6 GW
Near Detectors	
distance	~ 300 m
depth	~100 mwe
Far Detector	
distance	1800 m
depth	700 mwe



by K.Heeger

Angra dos Reis, Brazil

Reactor
– Primary 4.1 GW reactor
– Secondary 1.5 GW reactor
(mostly off, may be decommisioned

Far Detector
– 1.3 km baseline
– 200-250 m granite overburden (600-700mwe)

Near Detector
– 300-350 m baseline
– 20m granite overburden (~60 mwe)

Ref: D. Reyna, ANL
theta13 white paper

by K.Heeger

Summary

(1) Reactor measurement of $\sin^2 2\theta_{13}$ is very important because;
 * It is pure $\sin^2 2\theta_{13}$ measurement.
 * It is complimentary to accelerator experiments.
 And there are many such project in the world.

(2) By using the most powerful nuclear power plant and 3 identical detectors, $\sin^2 2\theta_{13}$ sensitivity of ~0.02 (90%CL) is possible in 2~3 years operation, which is 5~10 times better than the CHOOZ limit.

(3) The KASKA project is realistic.
 * KamLAND+CHOOZ+PaloVerde technologies are enough.
 * The cost is not high if compared with accelerator based experiments.
 * It can go quickly once started and can catch up with accelerator experiment.

(4) We are lacking man-power.

Serious collaborators are welcome.