KEK Physics Seminar

(Language: English)

November 4th(Tue) 16:00 ~ 17:00

Room345 in the 4th Building

Future Reactor Neutrino Experiment after KamLAND

Fumihiko Suekane (Tohoku Univ.)

abstract: KamLAND has observed disappearance of the reactor anti-electron neutrinos, in 2002. The most natural explanation of the deficit is the neutrino oscillation which is driven by ¥theta_12 and ¥Delta m^2_12. The next important step in neutrino physics after the KamLAND is to measure the last mixing angle ¥theta_13. A new reactor neutrino experiment is planned to measure pure ¥theta_13 using Kashiwazaki-Kariwa multi-reactor complex. The speaker describes the importance of the reactor ¥theta_13 measurement and this reactor neutrino project after short description of the KamLAND results.

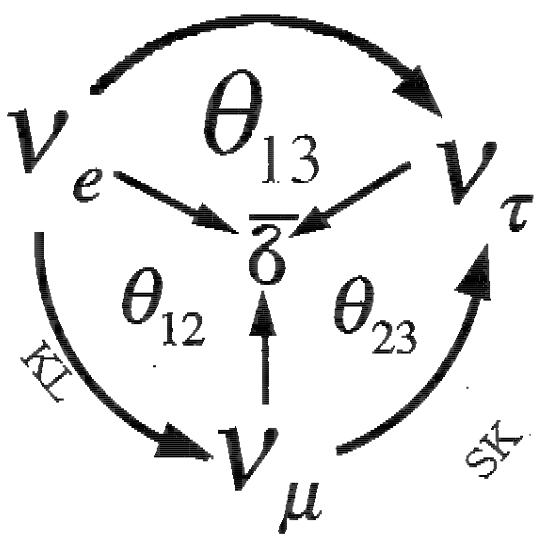
Past presentations are archived at our home page of http://seminar.kek.jp/physics/

Organisers: T. Komatsubara and I. Adachi

2003.10.21

Future Reactor Neutrino Experiments after the KamLAND

Kashiwazaki-
Kariwa



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@KEK Physics Seminar

2003.11.04

Contents

* KamLAND result and
Status of ν physics

* Significance of
Reactor θ_{13} Measurement

* The Kashiwazki-Kariwa Project
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- Sensitivity

* Status of the K-K Project

* World Activities on Reactor θ_{13}

* Summary

KamLAND Result and status of ν physics

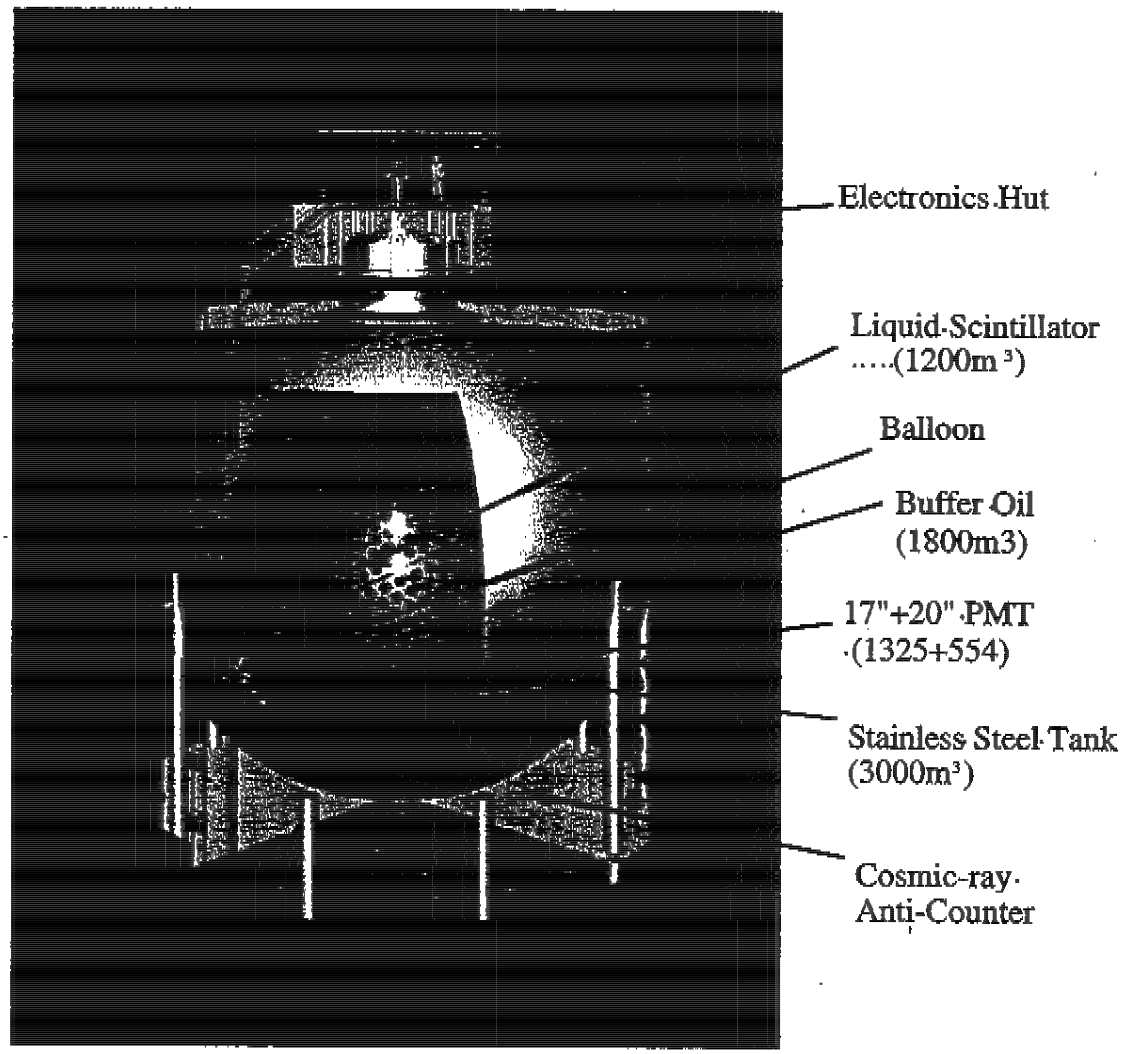
KamLAND

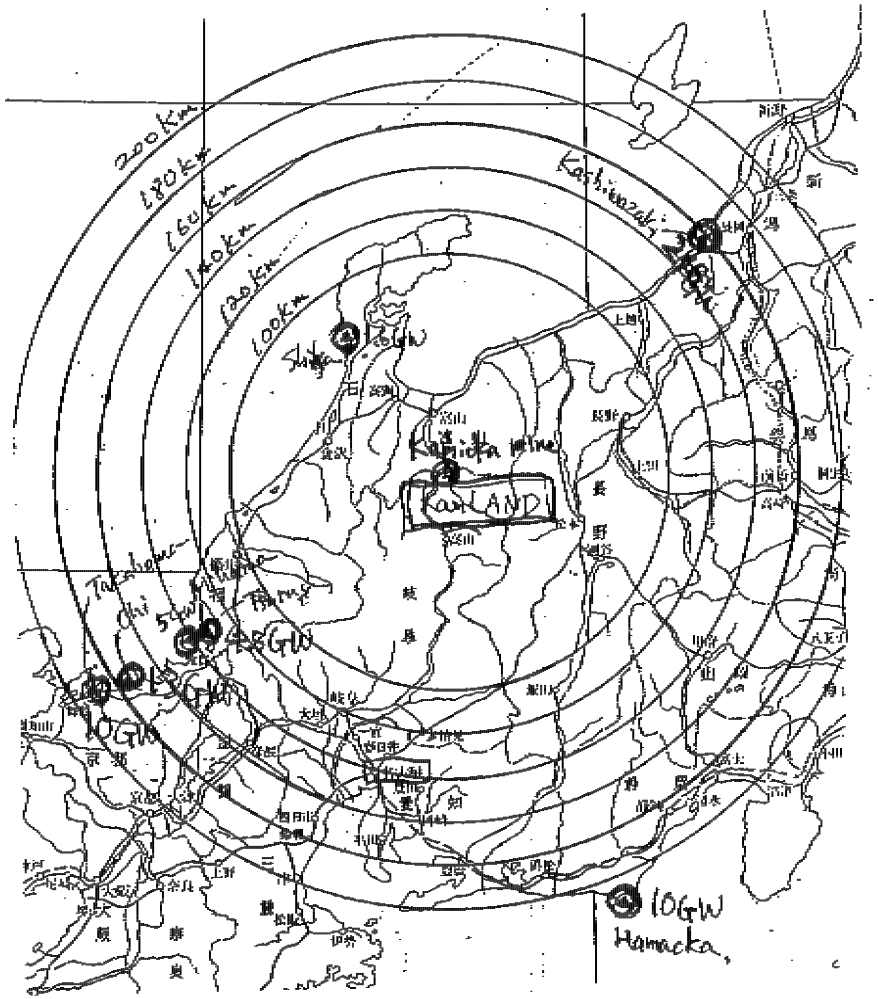
(Kamioka Liquid Scintillator Anti-Neutrino Detector)

||

Long (L~180km) Baseline

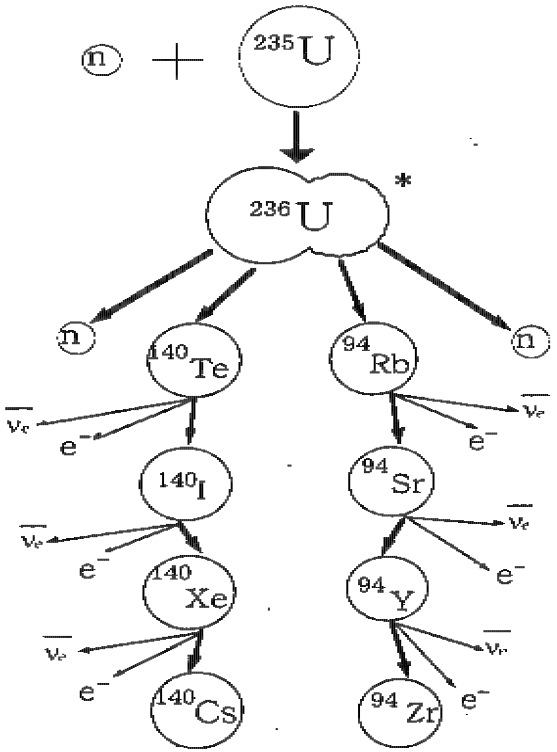
Reacotor $\bar{\nu}_e$ (E~4MeV) experiment





$\bar{\nu}_e$ Generation in Reactor

(an example)



$E_\nu \sim$ a few MeV

$\sim$6 $\bar{\nu}e$/fission & Q$\sim$200MeV/fission

(-> N_A/15min/GWe)

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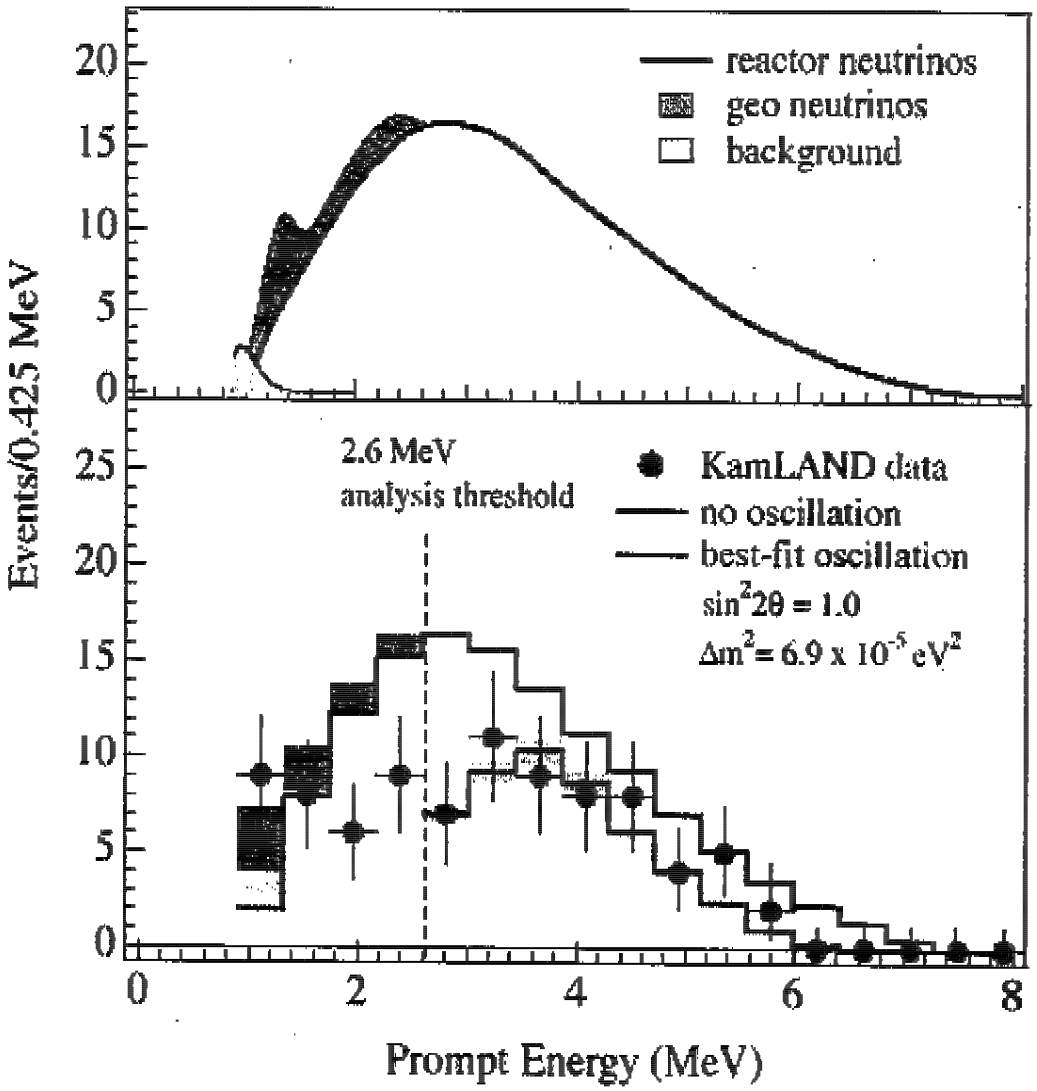
KamLAND Data



(38.9 ± 9.4)% of Deficit (99.95%CL)

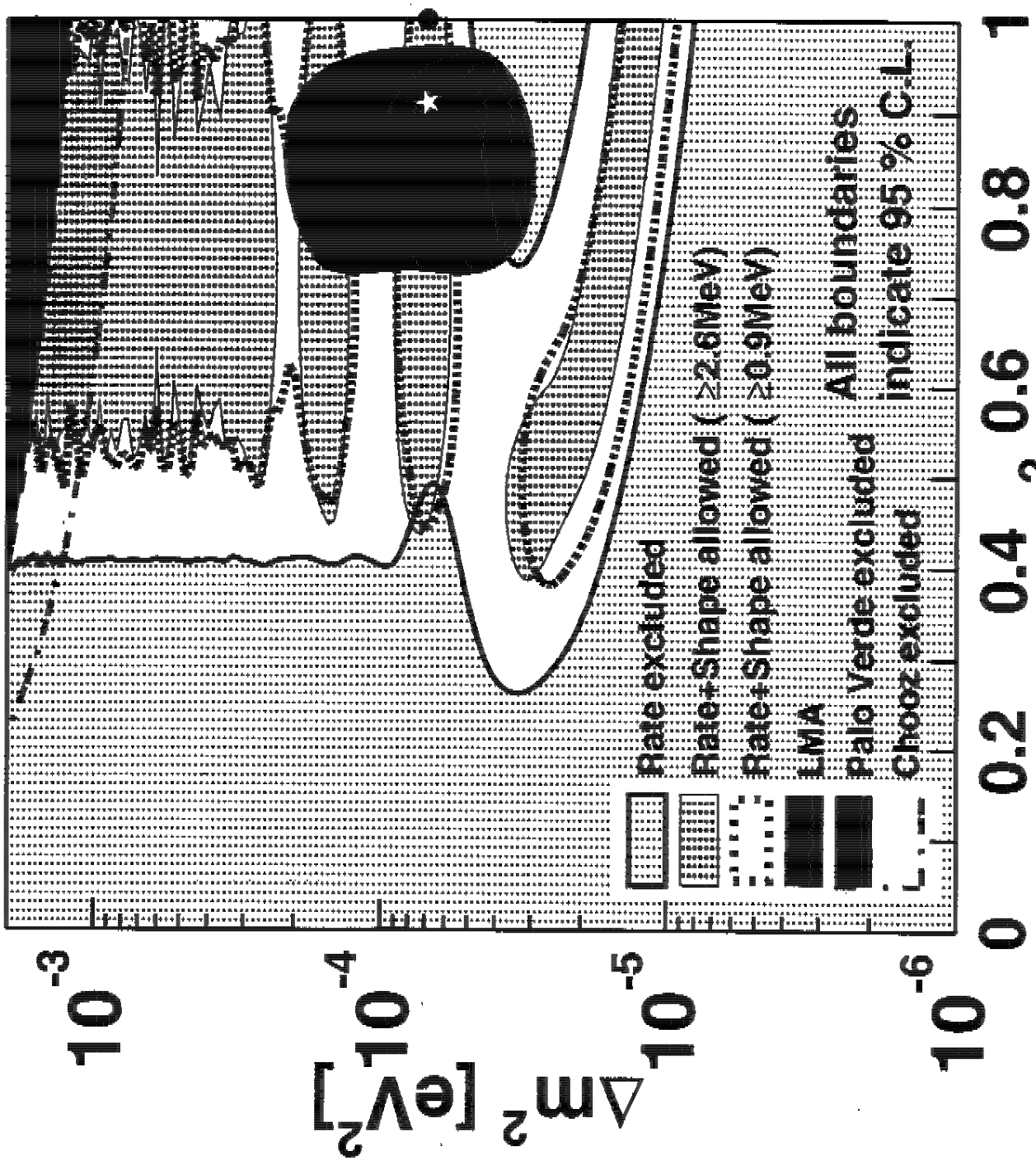
Best Oscillation Fit

⇓

$\sin^2 2\theta = 1.0,\ \Delta m^2_{12} = 6.9 \times 10^{-5} eV^2$

&

Only LMA is consistent with this result


Rate excluded
Rate+Shape allowed (< 2.6MeV)
Rate+Shape allowed (< 0.9MeV)
LMA
Palo Verde excluded
Chooz excluded
All boundaries indicate 95 % C.L.
Δm^2 [eV^2]
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0
0.2
0.4
0.6
0.8
1
$\sin^2 2\theta$

KamLAND showed $\sin^2 2\theta_{12}$ and Δm^2_{12} are not so small.

$\Downarrow$

(1) Leptonic CP violation δ_l may be detectable in the future Long Base Line Accelerator (LBLA) experiments. Because CP asymmetry may be large:

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

$$\approx \frac{\Delta m^2_{12} \sin 2\theta_{12}}{\Delta m^2_{13} \sin \theta_{13}} \sin \delta_l > 0.12 \sin \delta_l$$

(@ oscillation maximum; $\sin^2 \frac{\Delta m^2_{23} L}{4E} = 1$)

<== ν people

(NO HOPE for SMA, LOW or VAC solution.)

(2) After the KamLAND

SK+K2K: $\nu_\mu \to \nu_\mu$

KamLAND, CHOOZ: $\bar{\nu}_e \to \bar{\nu}_e$ (limit)

Solar neutrino experiments: $\nu_e \to \nu_e$

$\Downarrow$

Magnitudes of the MNS matrix elements have been roughly determined.

$$|U_{MNS}| \sim \begin{pmatrix} 0.7 & 0.7 & \sin\theta_{13}e^{i\delta_l} \\ 0.5 & 0.5 & 0.7 \\ 0.5 & 0.5 & 0.7 \end{pmatrix}$$

$\sin^2 2\theta_{13} < 0.15$ (CHOOZ),

δ_l: totally unknown

$\Downarrow$

The next important step is to measure finite θ_{13} value

&

lead to δ_l measurement.

Importances of θ_{13} measurement

(1) It is an elementary parameters. The value of θ_{13} may become a key point when builing an unified theory of elementary particles because it is small with respect to other neutrino mixing elements being large.

(2) The detetability of the leptonic CP violantion δ_l in future LBLA experiments depend on θ_{13} and it provides a guideline when designing those experiments which cost \$B.

(3) It is necessary to know θ_{13} to precisely measure θ_{12} from KamLAND measurement. Because KamLAND measurement is actually

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

θ_{13} Experiment

Long Base Line Accelerator Experiment

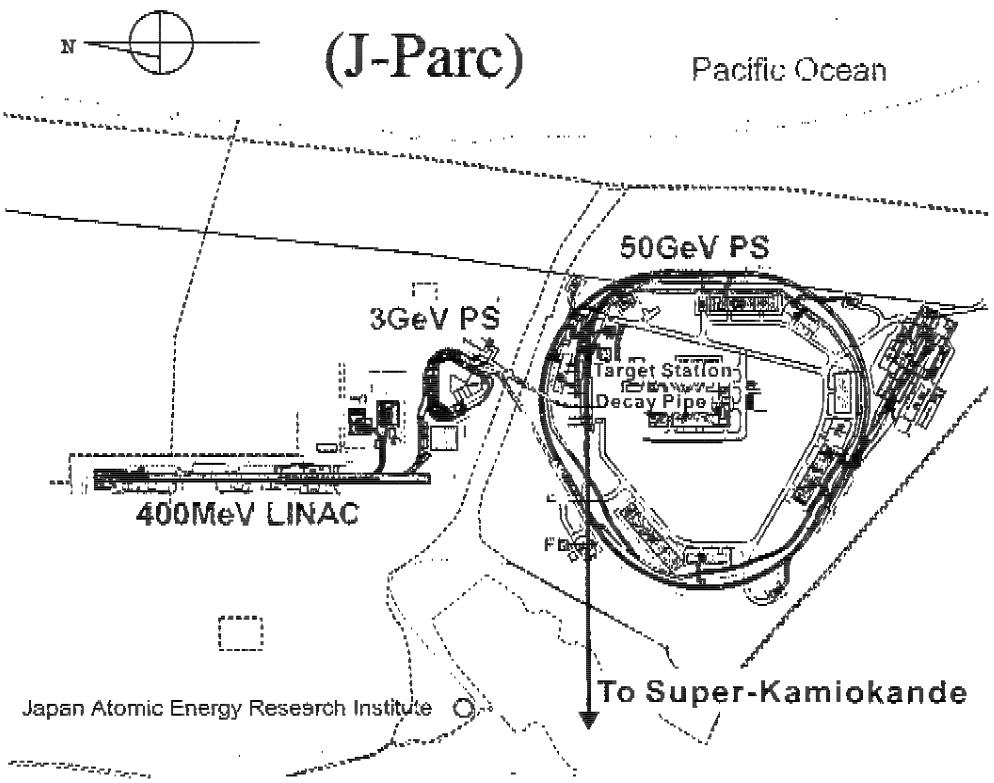
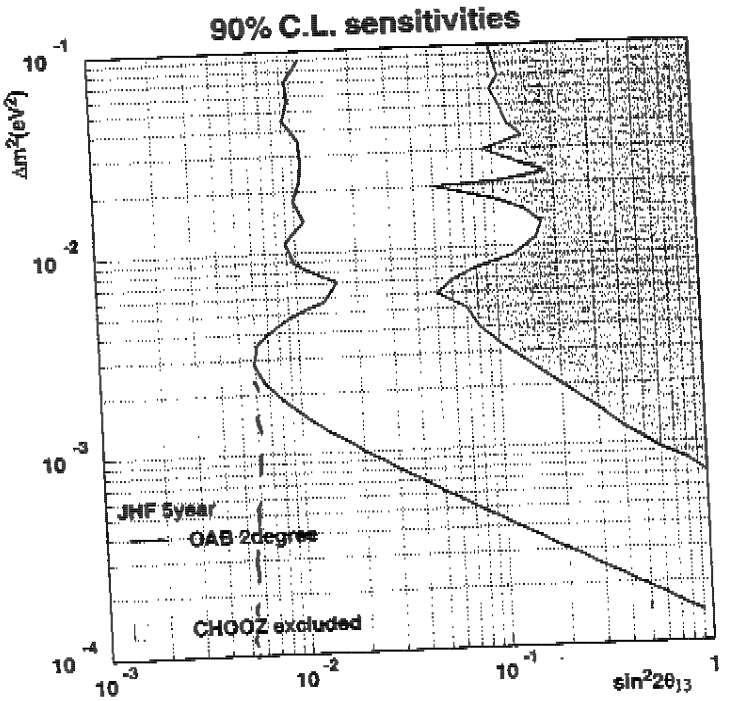


Figure 1: Layout of JHF.

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{13} \sin^2 \theta_{23} + 2nd\ term$$



C.ccf

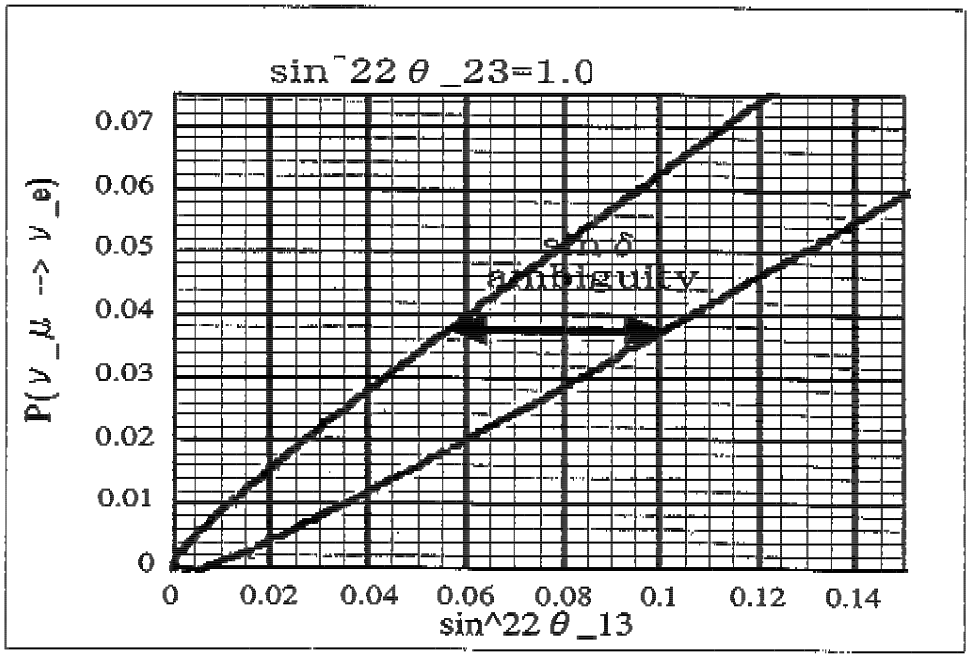
However, the KamLand result also shows ambiguities in $\sin^2 2\theta_{13}$ determination in the near future LBLA experiments is not so small:

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{13} \sin^2 \theta_{23}$$

$$- \frac{\pi}{2} \frac{\Delta m^2_{12} \sin 2\theta_{12}}{\Delta m^2_{23}} \sin 2\theta_{13} \sin 2\theta_{23} \sin \delta$$

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

Because $\sin 2\theta_{13}$ sensitivity of ~0.1 is aimed at in the next LBLA experiment, the 2nd term is not negligible now.



Moreover if θ_{23} degenerarcy is taken into account, the ambiguity beocmes worse,

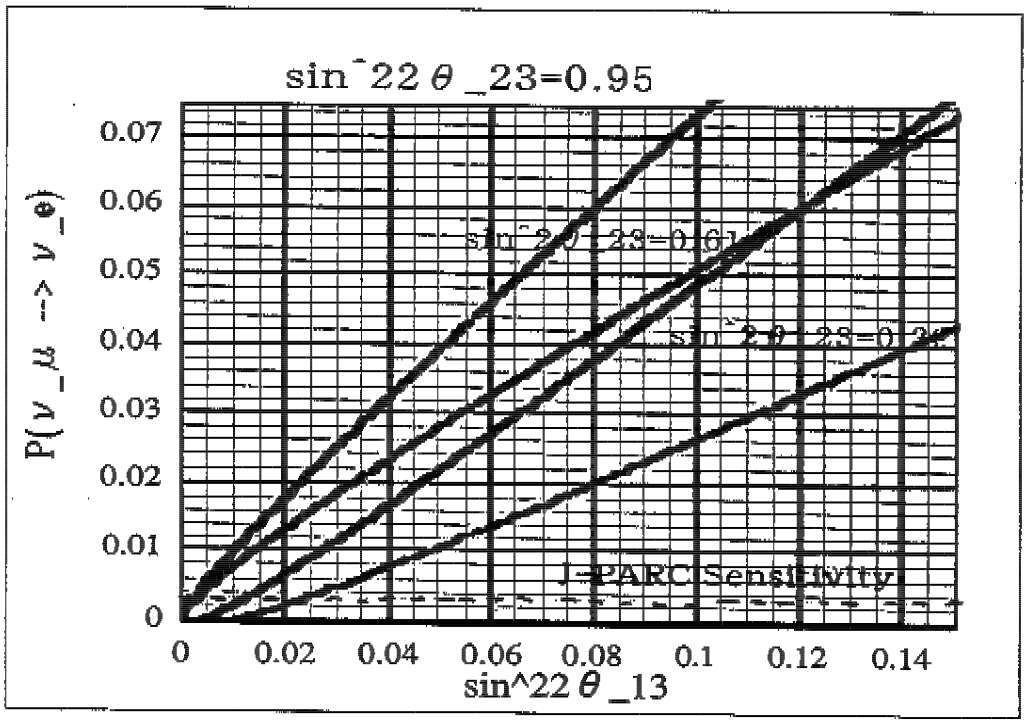
(θ_{23}degenerarcy: At a given $\sin^2 2\theta_{23}$, there are $2\ \sin^2\theta_{23}$ solutions.)

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

measured by $\nu_m \to \nu_m$ to be large.

$\sin^2 2\theta_{23}$=0.95 $\Rightarrow$ $\sin^2\theta_{23}$=0.39 or 0.61

$$P\left(\nu_\mu \to \nu_e\right) = \sin^2 2\theta_{13}\sin^2\theta_{23} + \text{2nd term}$$



Why Reactor θ_{13} Measurement?

- It is a pure $\sin^2 2\theta_{13}$ measurement

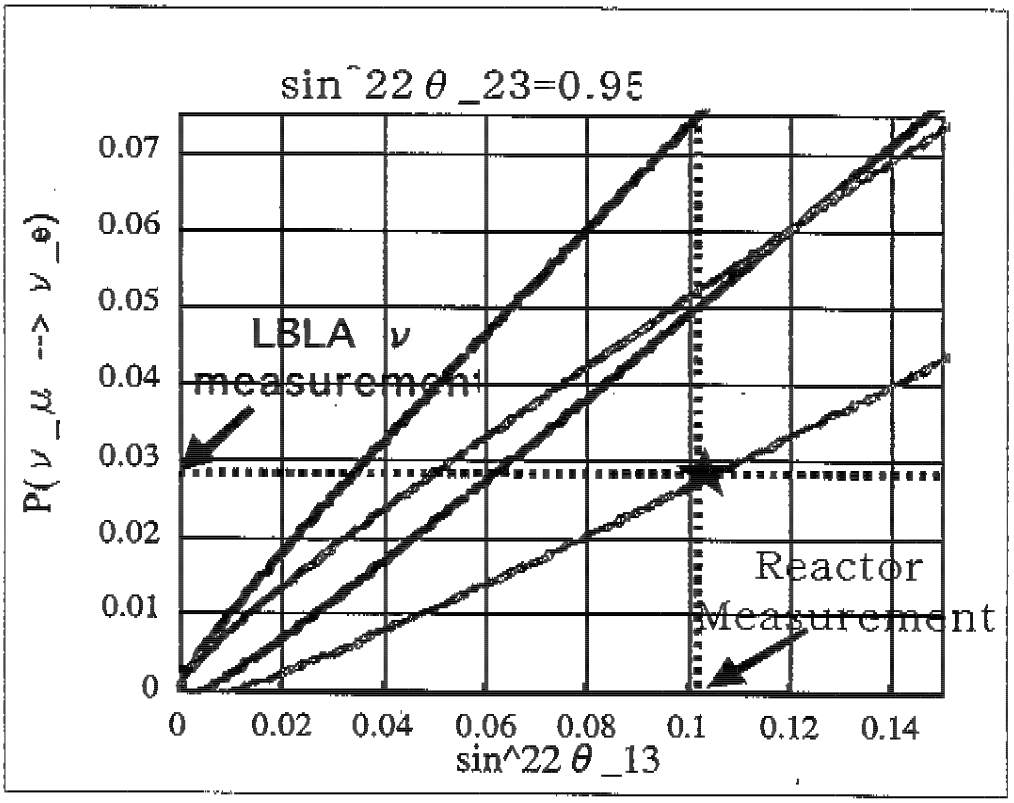
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{13} L}{4E}$$

&

- Complementary with LBLA experiments.

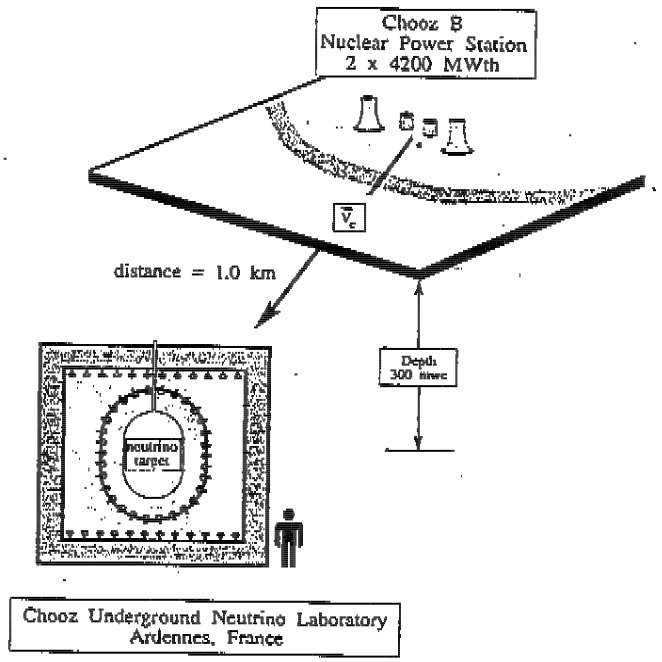
By Combining LBLA (ν mode)and reactor data, it may be possible to solve θ_{23} degeneracy and indicate non-0 δ_l.

(Minakata et al. hep-ph/0211111& 0309323, Huber et al. hep-ph/0303232)



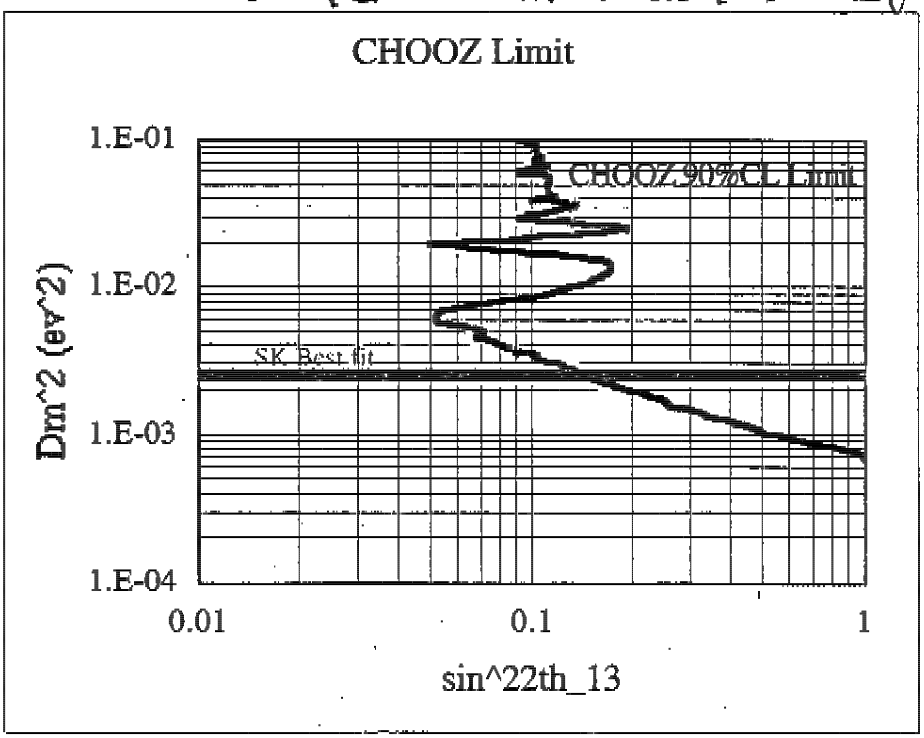
(A Lucky Case)

Current θ_{13} Limit by CHOOZ experiment



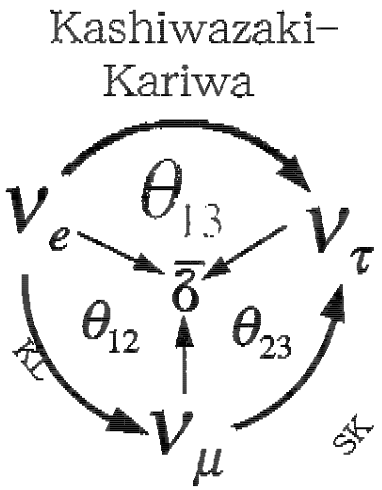
$$\sin^2 2\theta_{13} < 0.15 \ @\Delta m^2 \approx 2.5\times10^{-3} eV^2$$

$< 0.2 \quad \Delta m^2 \approx 2.0 \times 10^{-3}$ eV^2



So we got together to improve the reactor θ_{13} sensitivity significantly:

The Kashiwazaki-Kariwa Project.



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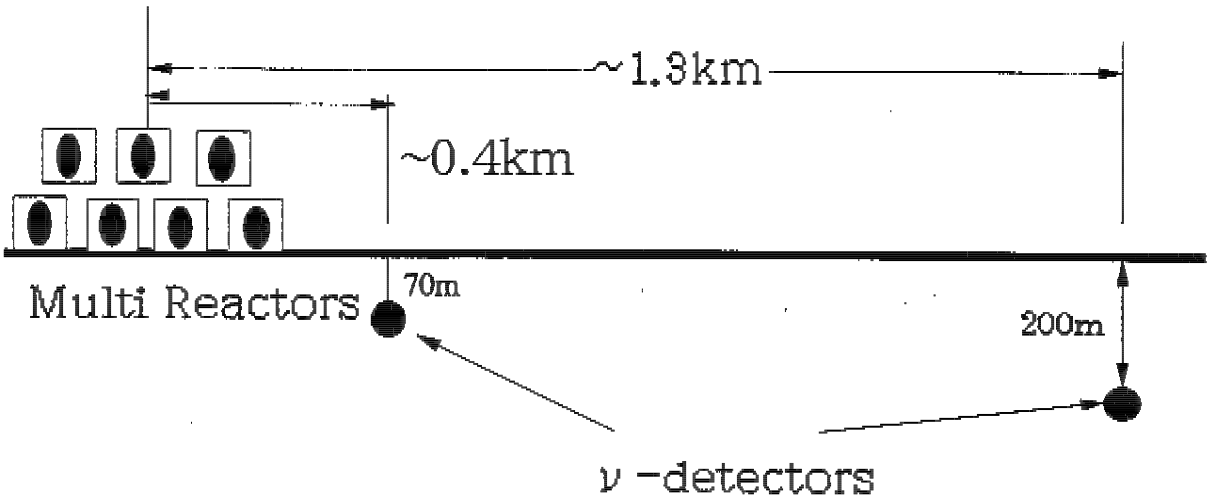
How to improve sensitivity over CHOOZ



Multi Detectors → Cancel Systematics

Multi Reactors → Gain Statistics & S/N

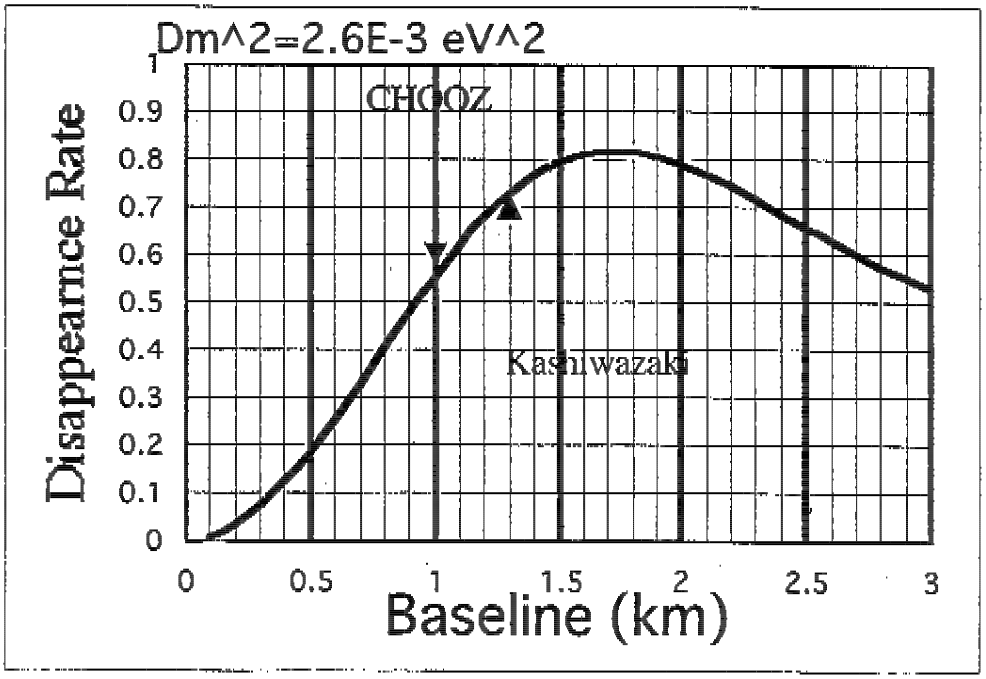
Deeper underground → Less BKG

No Rate Sensitive Cuts → Less Systematics

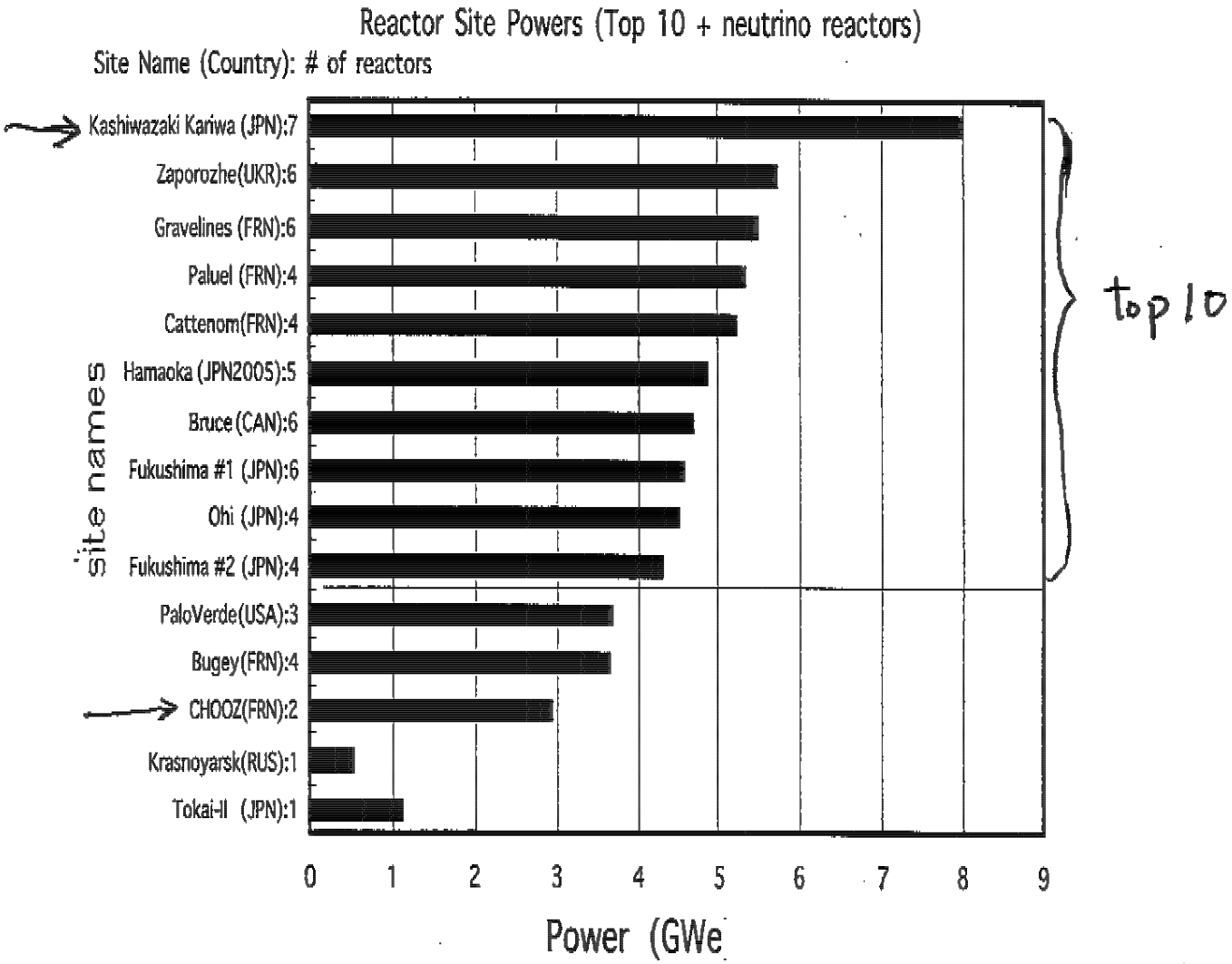
Higher Gd Contents → Less Systematics

&

Longer Baseline Larger Oscillation



Nuclear Powers



Kashiwazaki-Kariwa NPP ($24.3GW_{th}$)

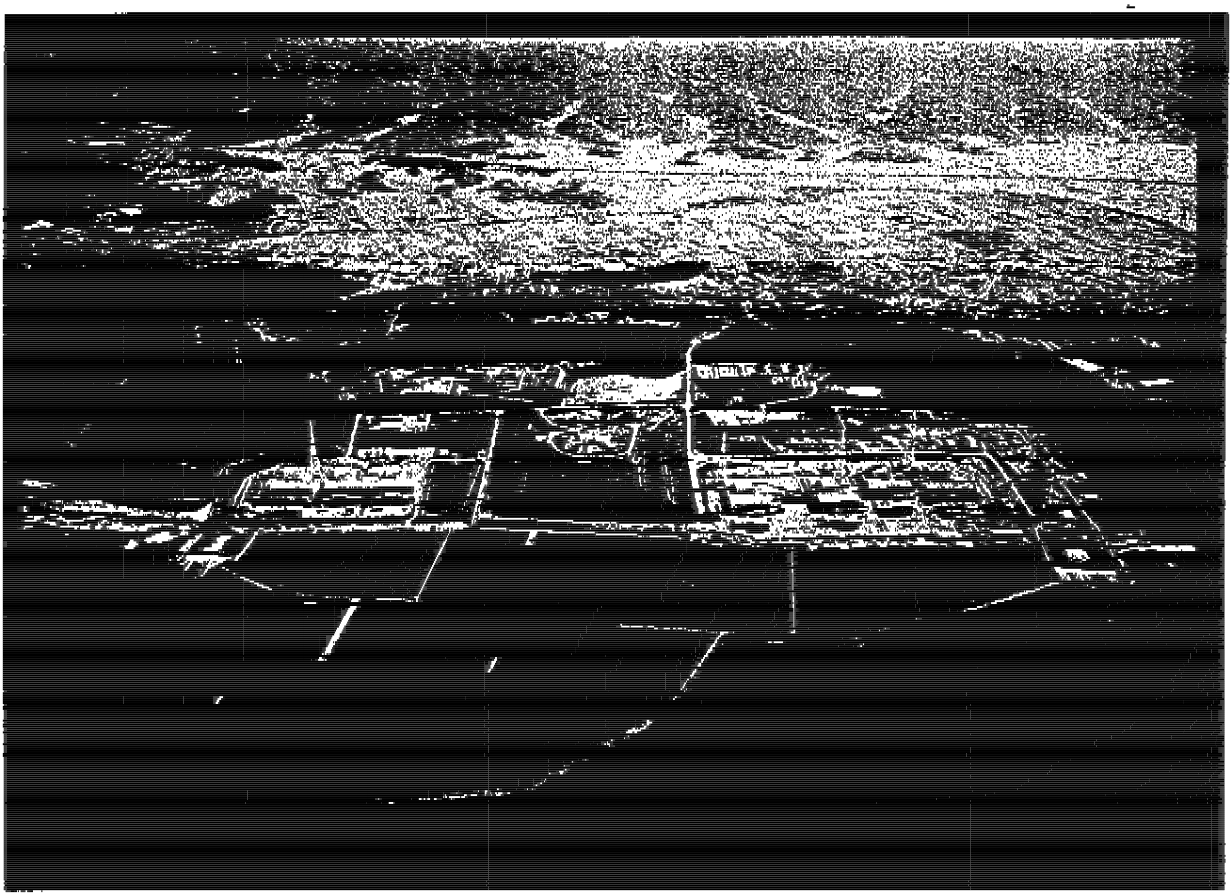
⇓

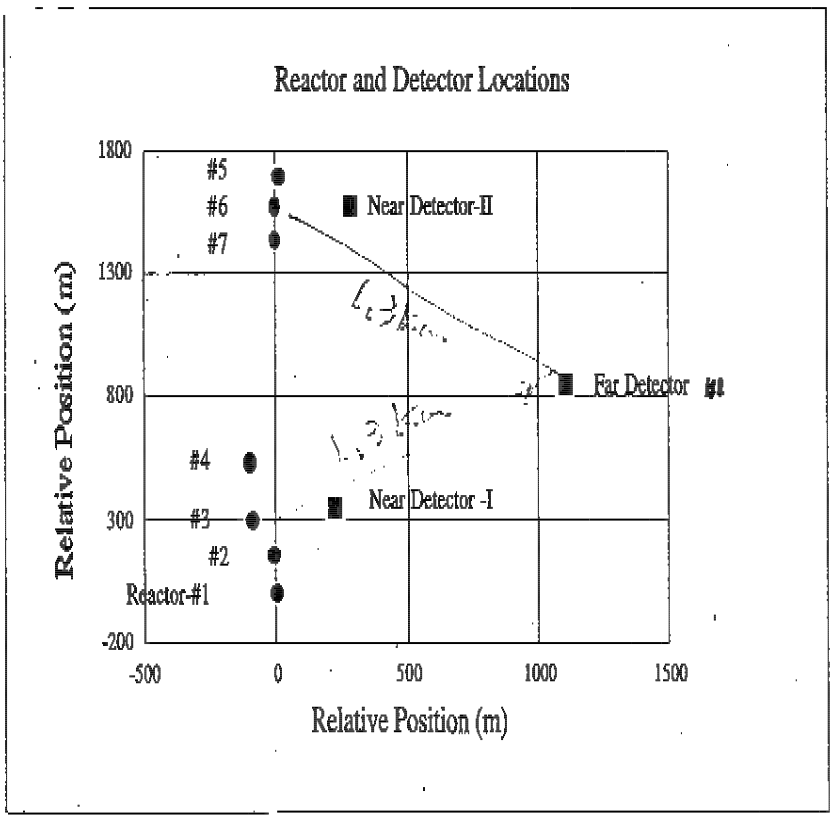
The Most Powerful Nuclear Power Plant in the World.

$N_\nu = 40,000/2$ years/8.5ton ==> σ_{stat}=0.5%

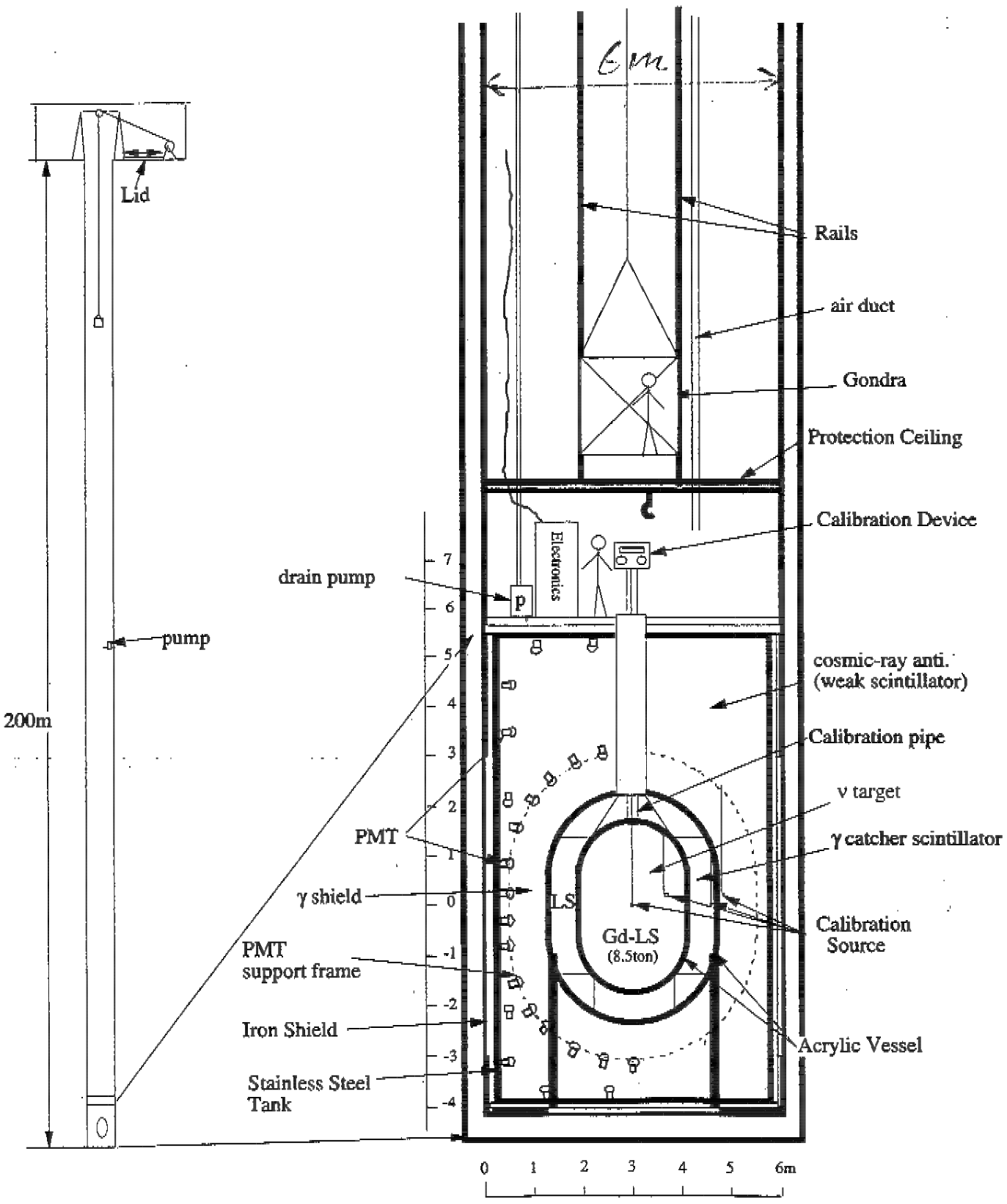
(2.7% CHOOZ)

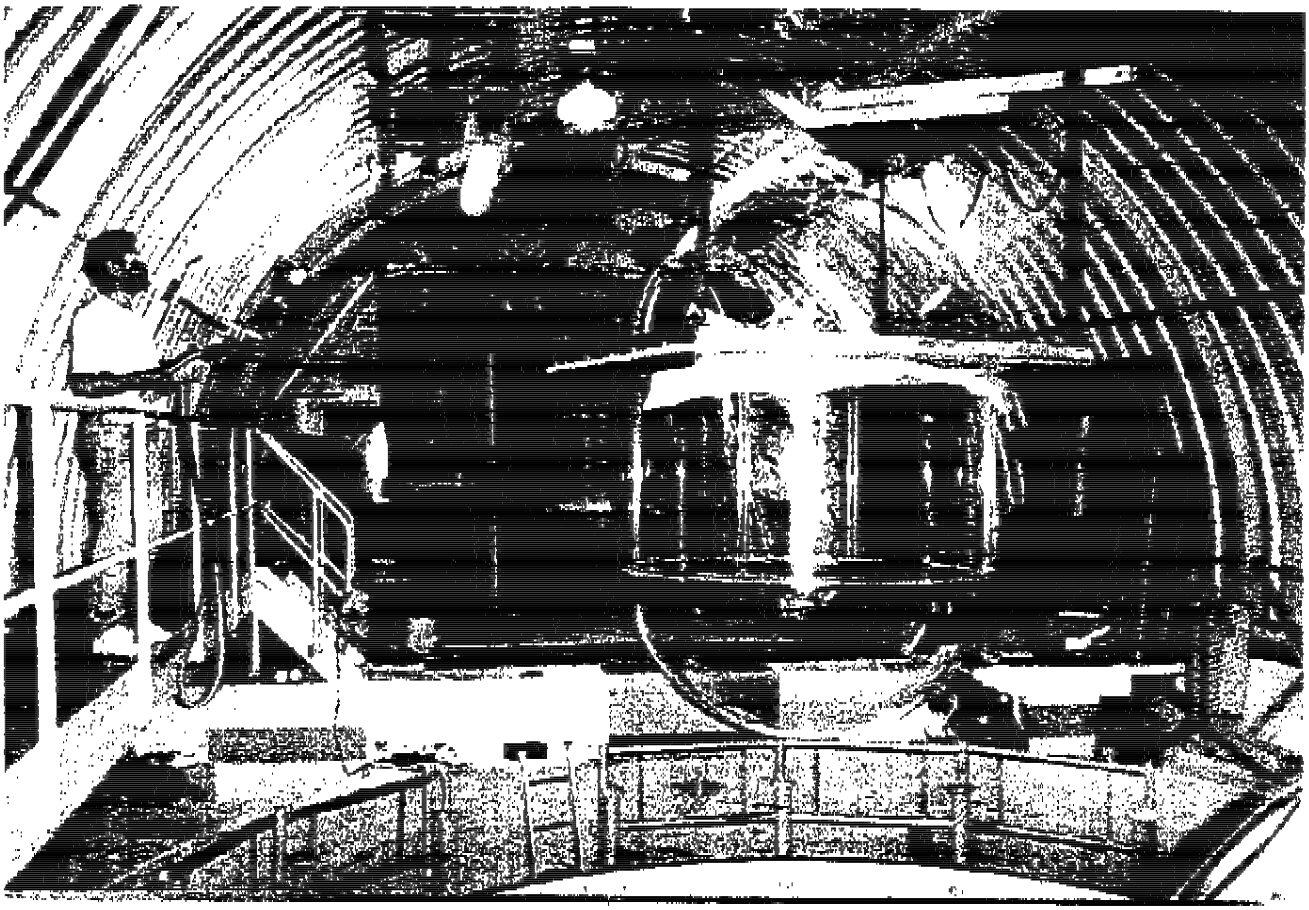
Kashiwazaki site



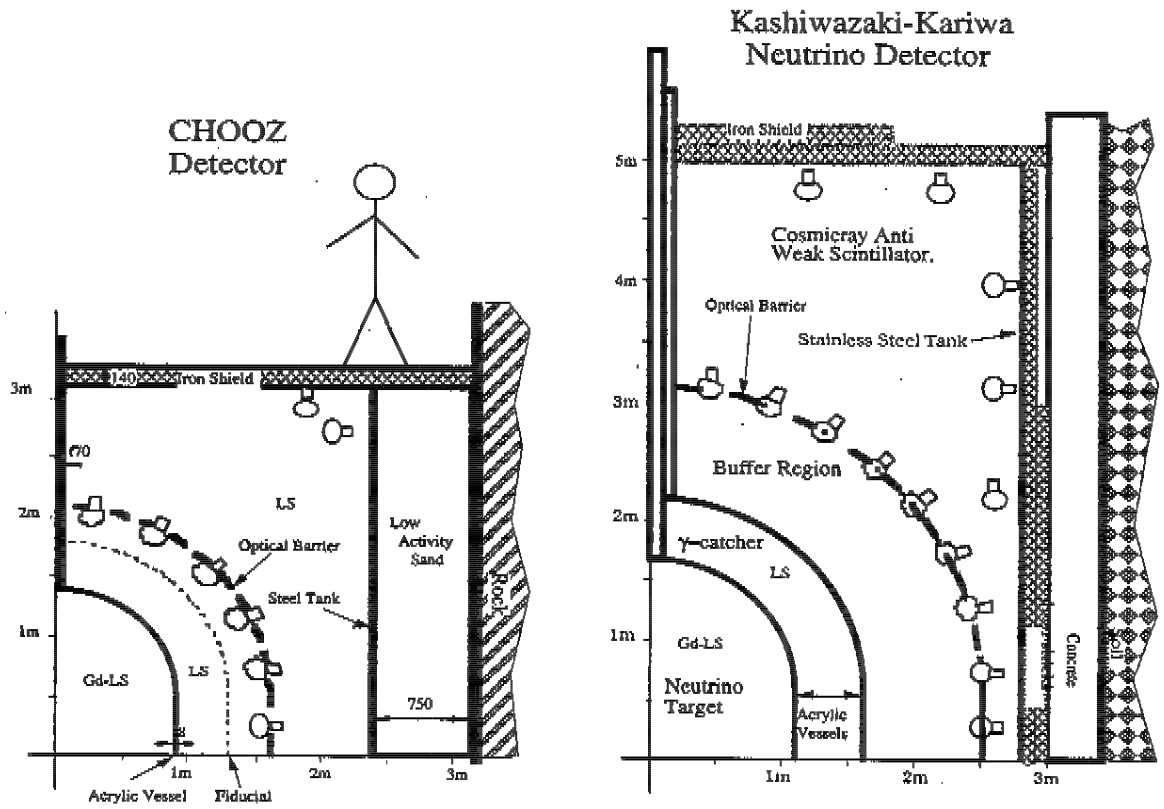


shafe hole & Detector





CHOOZ Acrylic Container



Improvements from CHOOZ

(1) γ-ray shield

==> Significnatly reduce sigle rate

(2) Thicker Buffer Oil

==> Reduce neutron & rock γ background

(3) High Gd Concentration(0.15%)

==> neutron absorption rate is high

==> Less systematics associate with efficiency

(4) Cosmic-anti = weak scintillator

==> Improve cosmic ray tagging efficiency.

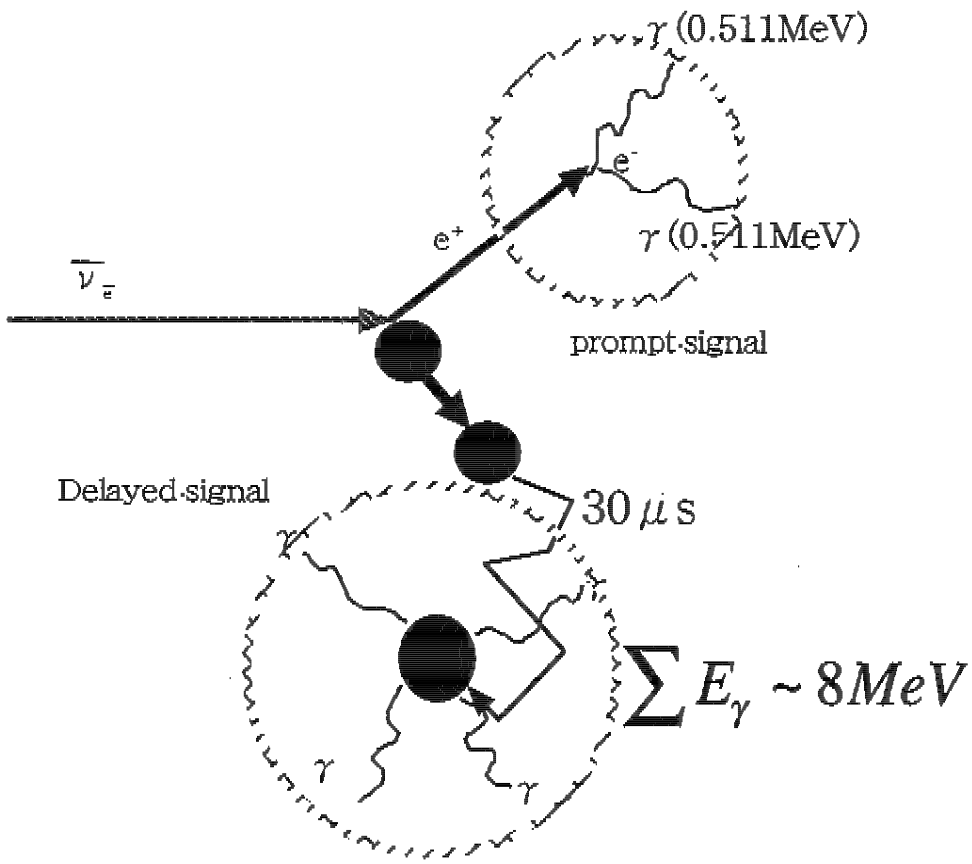
Principle of $\bar{\nu}_e$ Detection

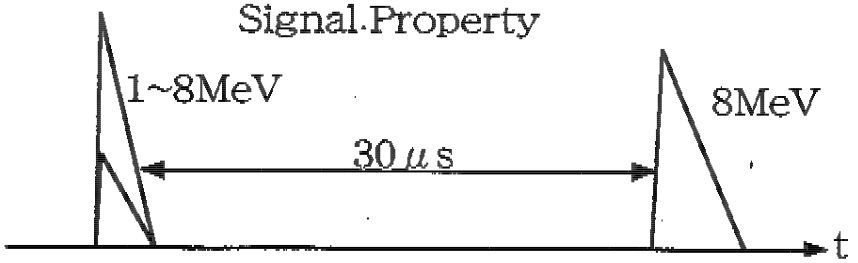
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Then

$$e^+ + e^- \rightarrow 2\gamma(2 \times 0.511 MeV)$$

$$n + Gd \rightarrow Gd' + \gamma' s\left(\sum E_\gamma \sim 8MeV\right)$$





Gd: • largest n absorption crossection
• large γray Energy (natural BKG < 5MeV)

Gd-LS stability in acrylic container

Palo Verde
hep-ex/0003022 v1

μ=(350cm → 311cm)/year

↳ a few years ⇒ ok

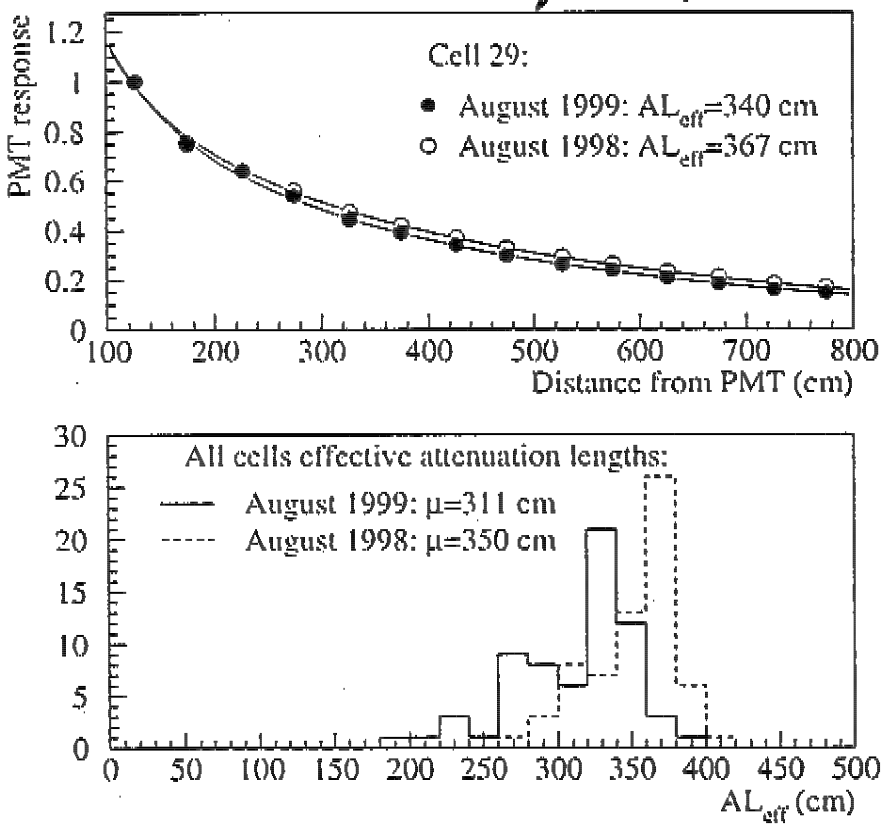
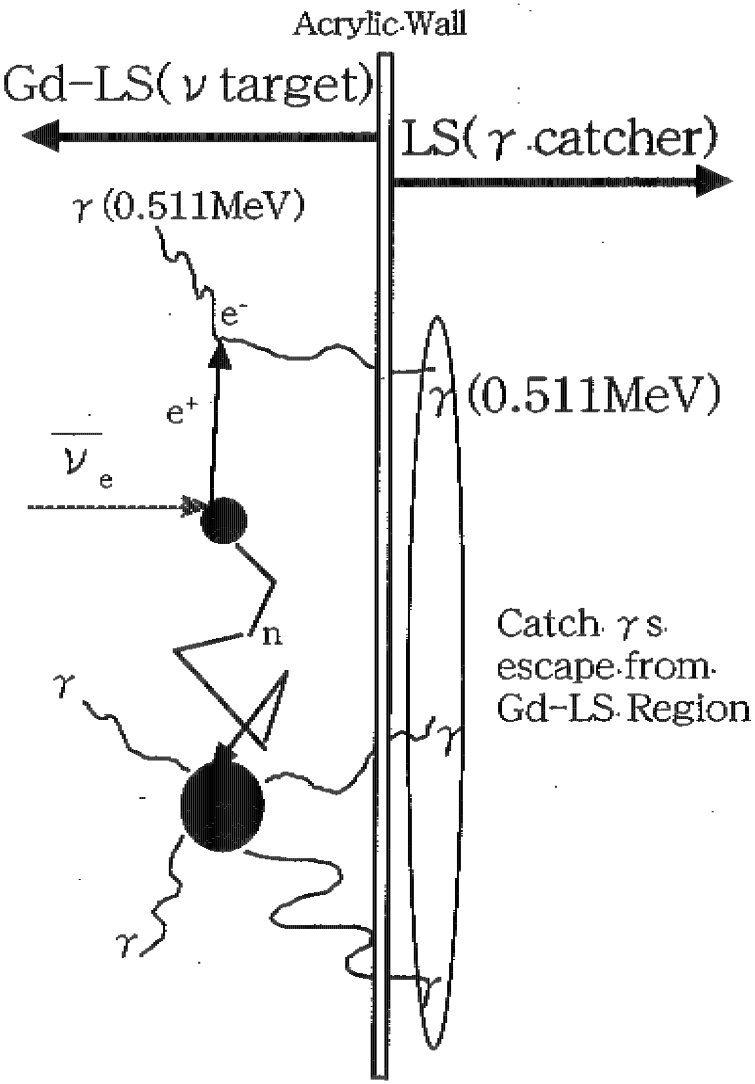
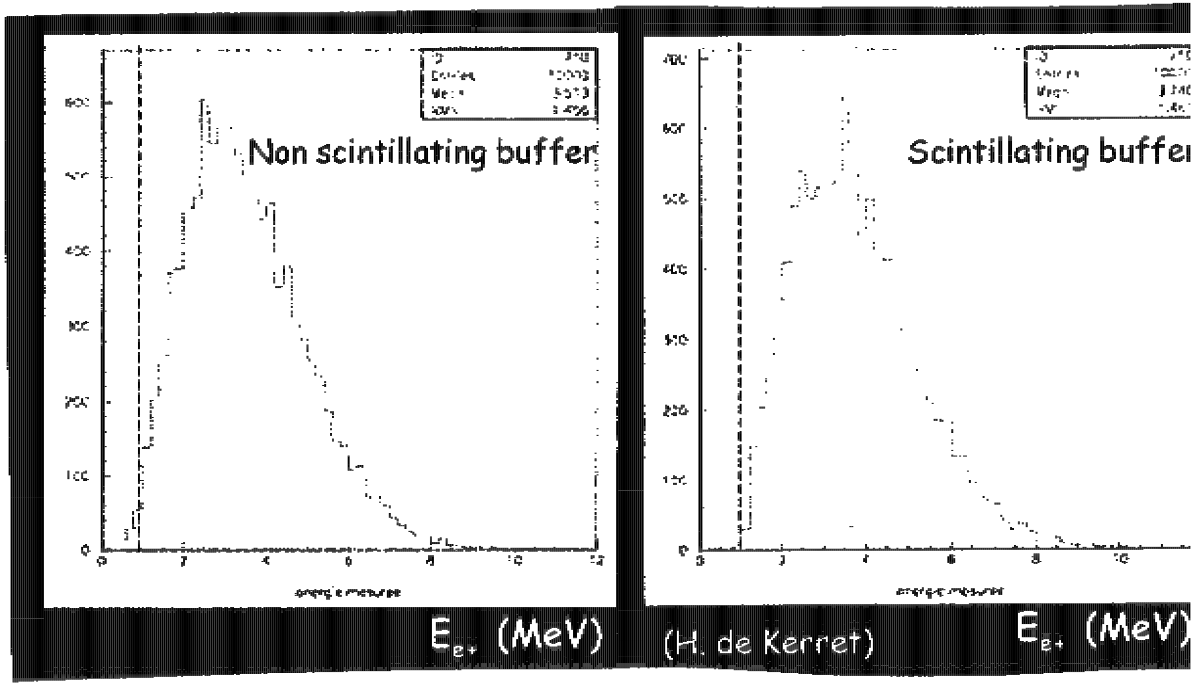


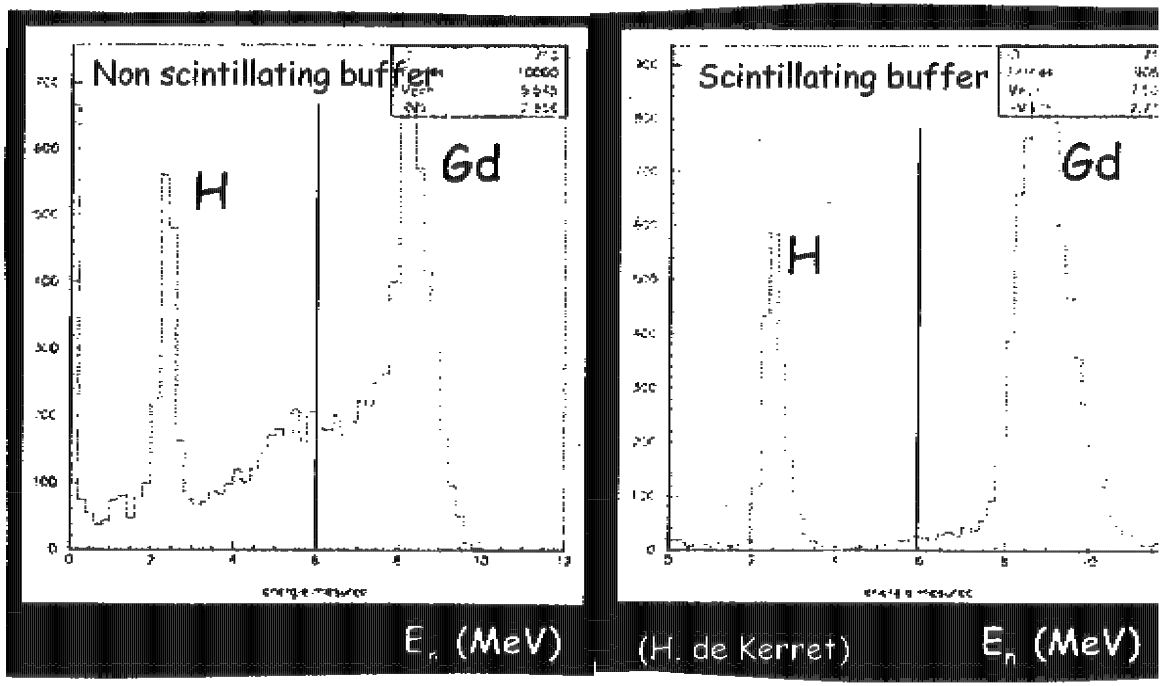
FIG. 6. Effect of aging on Gd loaded scintillator. Top: ^{228}Th Compton edge position at seven different longitudinal locations along a typical cell. The two curves are from calibrations taken a year apart. The curves are normalized at the location nearest to the PMT. Bottom: Effective attenuation lengths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

Puropose of the γ-catcher region



Catch γ s escape from Gd-LS Region





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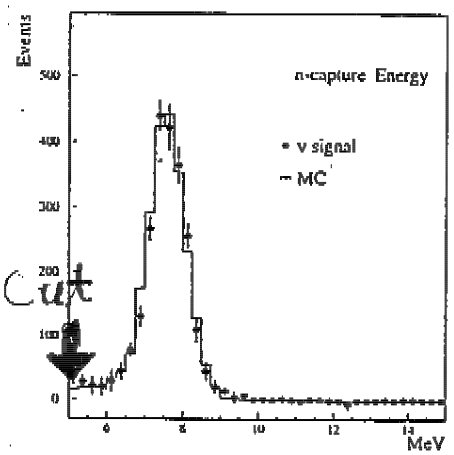
rate insensitive

Event Selection

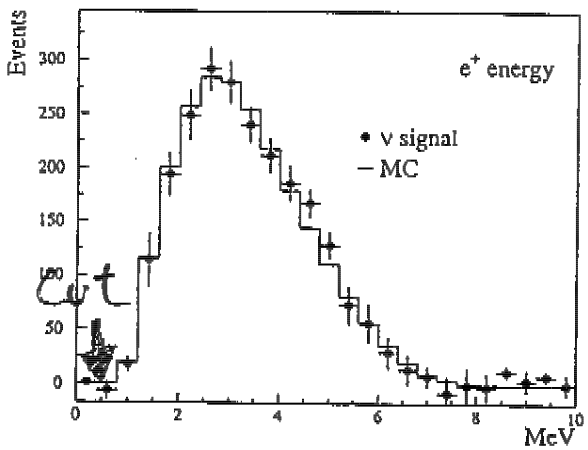
(1) $E_{delay} > 5MeV$ ($\varepsilon \sim 97\%$, $\delta\varepsilon_{relative} < 0.5\%$)



Cut

CHOOZ data

(2) $E_{prompt} > 0.5MeV$ ($\varepsilon > 99\%$, $\delta\varepsilon_{rel.} = O(0.1\%)$)



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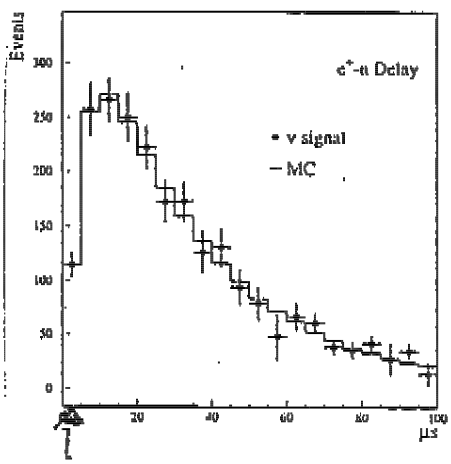
CHOOZ data

(3) $1\mu s < \Delta t < 150\mu s$ ($\varepsilon \sim 97\%$, $\delta\varepsilon_{rel.} < 0.5\%$)



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CHOOZ data

Event Selection Efficiency & Relative Error

Selection	chooz	Kashiwazaki (0.15%Gd)
(1) n Capture energy	94.6±0.4	97±<0.4%
(2) e^+ Energy	97.8±0.8	>99±O(0.1%)
(3) e^+–n time difference	93.7±0.4	97±<0.4%
e^+–Geode distance	99.9±0.1	–
n Capture	84.6±1.0	89±<0.5%
n-geode distance	98.4±0.3	–
e^+–n distance	98.4±0.3	–
n multiplicity	97.4±0.5	–
Combined	69.8±1.5	83±<0.76%
# of protons	±0.8	±<0.3
Total error	±1.7%	± <0.82%

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Baseline Ratio difference effect

Yes, the baselines are different for Kashiwazaki 7 reaqctors case.

But the uncertainty from the fact is very small because,

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

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

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

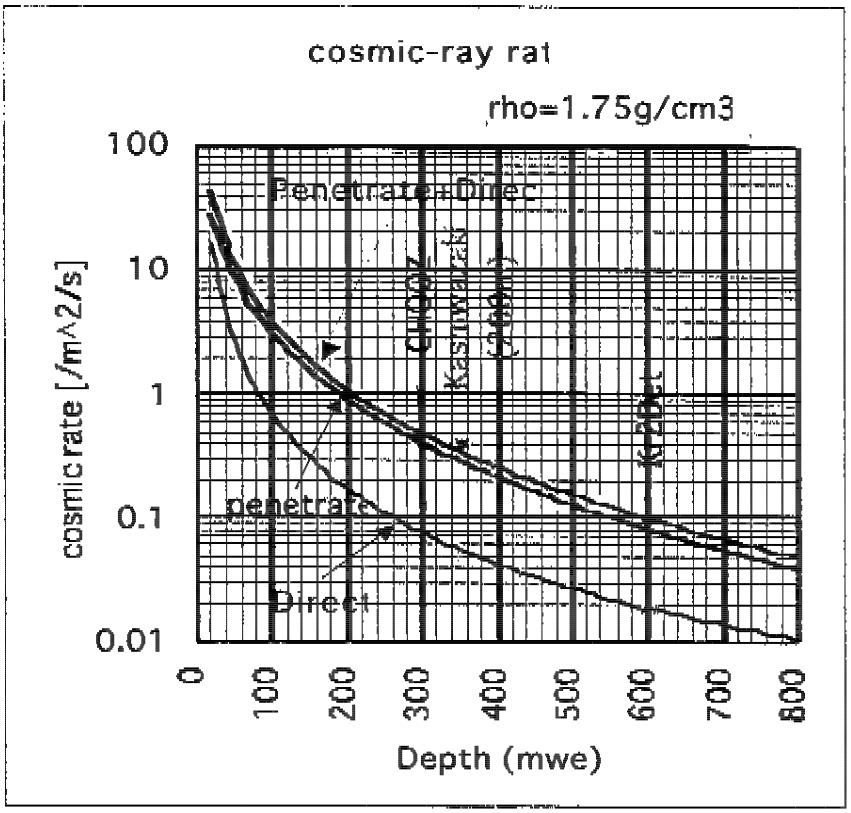
where, P is the reactor operating power and $\delta P^{un-corr.}$ is un-correlated error of P (<2%).

R_r is the ratio of squred baseline between reactor and near/far detectors.

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

Background

Over burden = 350mwe



μ rate $=0.35/m^2/s$

(direct $\mu \ll$ penetrate μ)

&

ν flux$=14.4GW/km^2$

⇩

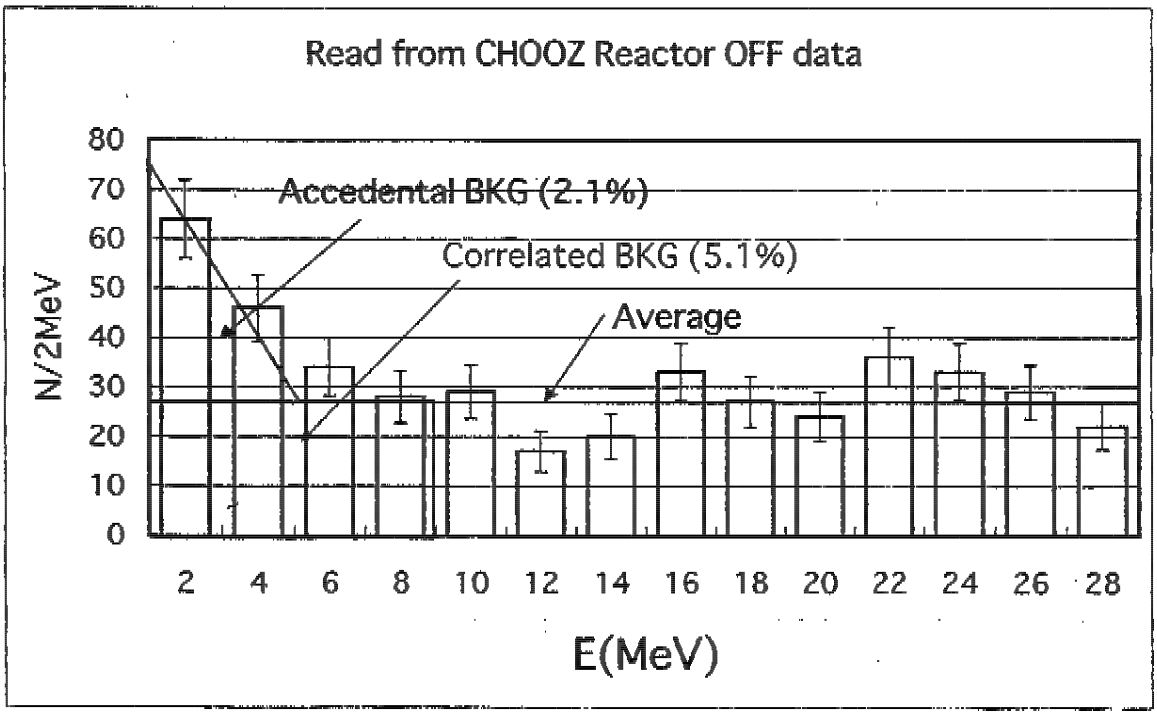
μ / ν ratio $=(8.4/14.4)\times(0.35/0.4)$

$=0.51$ of CHOOZ

Fast Neutron

5.1%(chooz)×0.51(μ / ν ratio)
×$(5/8.5)^{2/3}$(surface/volume ratio)
×$e^{(-20cm/30cm)}$(Additional Oil shield)
~0.9%

Can be estimated from
* >11MeV & <1MeV event rate



* position dependence of event
* Tagged muon

Error~20% (2×of CHOOZ)

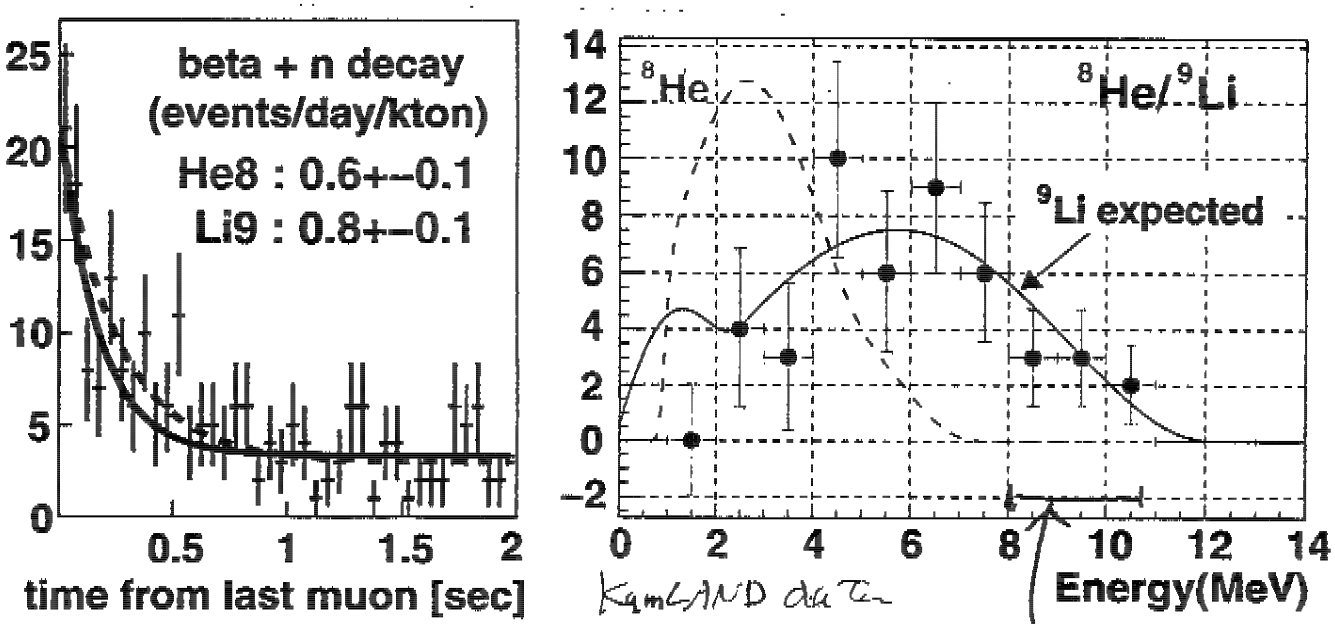
⇓

BKG~(0.9±0.2)%

Correlated Spallation (^{9}Li, ^{8}He)

KamLAND shows ^{9}Li is dominate.

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



(from thesis of Tajima.)

$\sigma(\mu\ (190\mathrm{GeV}) + {}^{12}\mathrm{C} \rightarrow ({}^9\mathrm{Li} + {}^8\mathrm{He})) = 2.12\,\mu\mathrm{b}$

(T.Hagner et al., Astropart. Phys. 14, 33(2000))

⇩

BKG rate =0.41/day (0.4%)

Estimation can be done by using event rate
at 8MeV<E<11MeV
and dt-dx distibution to the last muon
Error of estimation ~ 50%

⇩

BKG=(0.4±0.2)%

Correlated BackGround Summary

Note: μ / ν ratio is 1/2 of CHOOZ & 1/20 of KamLAND

Source	rate	Comment
Fast Neutron	$<(0.9\pm0.2)\%$	* 20cm thicker BO. * (30) can be estimated from >11MeV events.
Spallation	$(0.4\pm0.2)\%$	* $\overline{\sigma}$ (^{9}Li)=0.78 μ b, β -n branch=48% * estimated from 8MeV<E<11MeV * Gd spallation is assumed to be negligible (#Gd/#C~1.4×10^{-4})
Total	$<(1.3\pm0.3)\%$	

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Accidental Back Ground

Positron window(>0.7MeV)

Source	Generation	single rate	Comment
Rock	10MHz	<1Hz	110cm thick BO+Fe(15cm)
PMT Glass	1KHz	8Hz	80cm thick BO, 20% Solid Angle
Gd-LS	-	1.1Hz	Mostly from Gd (CHOOZ data)
Acrylic Vessels	-	1.0Hz	KamLAND Acrylic
		<11Hz	

Neutron window (>6MeV)

For CHOOZ case, Rn=45/h (mostly from low energy tail) and Re=65Hz.

For K-K, Rn<45/h×11Hz/65Hz=7.6/h

Accidental rate <11Hz×7.6/h×150 μs<0.3/day (0.3%)

(can precisely estimated by off timing coincidence.)

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Systematic Uncertainty Total

	CHOOZ	Kashiwazaki-Kariwa
Efficiency	1.5%	<0.76%
N_p	0.8%	<0.3%
Detector total	1.7%	<0.82%
neutrino flux and σ ($\sigma \times f_\nu$)	2.1%	O(0.1%)
Baseline difference	0%	0.2%
Event rate total	2.1%	0.2%
BKG Substraction		0.3%
Grand Total	2.7%	<0.9%

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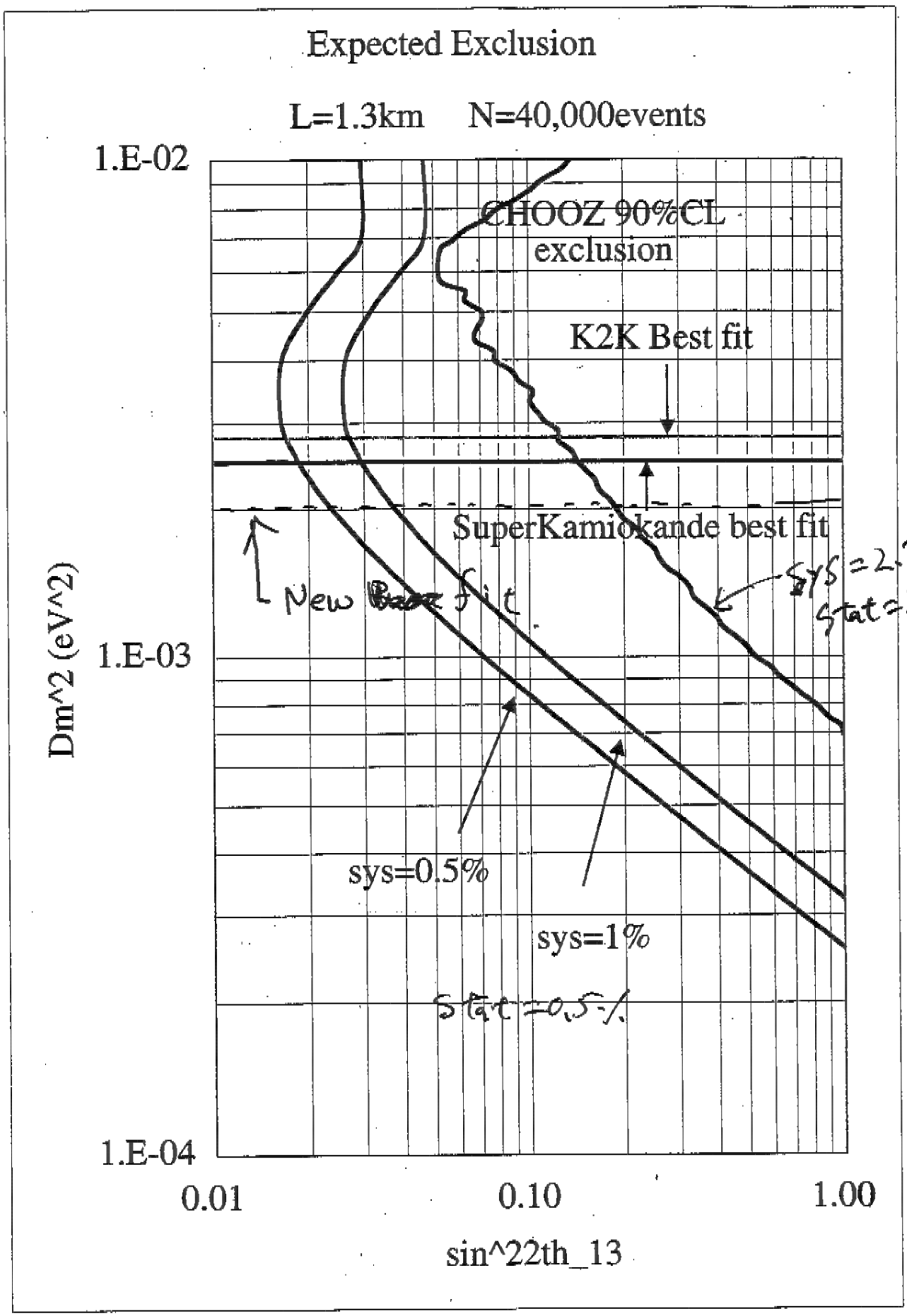
Expected Exclusion
L=1.3km N=40,000events
1.E-02
1.E-03
1.E-04
Dm^2 (eV^2)
CHOOZ 90%CL
exclusion
K2K Best fit
SuperKamiokande best fit
New Best fit
sys=2.7%
stat=2.6%
sys=0.5%
sys=1%
stat=0.5%
0.01
0.10
1.00
sin^22th_13

positive case (90% CL)

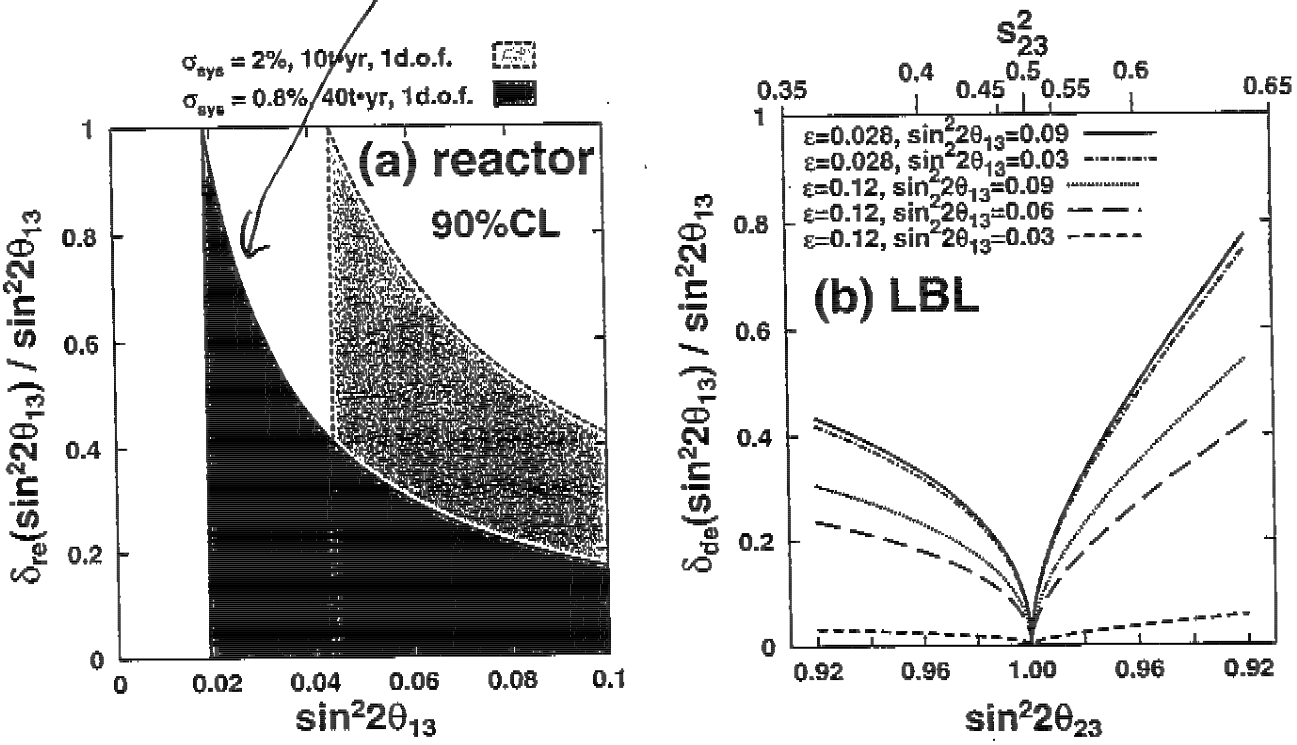

FIG. 6: (a) The normalized error at 90 % CL in the reactor measurement of θ_{13} is given for $\sigma_{\rm sys}$=2 %, 10 t·yr (d.o.f.=1, $\delta_{\rm re}(\sin^2 2\theta_{13}) = 0.043$) and for $\sigma_{\rm sys}$=0.8 %, 40 t·yr (d.o.f.=1, $\delta_{\rm re}(\sin^2 2\theta_{13}) = 0.018$), respectively. Notice that the degrees of freedom becomes 1 once the value of $|\Delta m^2_{31}|$ is known from JHF.
(b) The fractional difference $\delta_{\rm de}(\sin^2 2\theta_{13})/\sin^2 2\theta_{13}$ due to the degeneracy is plotted as a function of $\sin^2 2\theta_{23}$. Here, $\delta_{\rm de}(\sin^2 2\theta_{13}) \equiv |\sin^2 2\theta'_{13} - \sin^2 2\theta_{13}|$ stands for the difference between the true solution $\sin^2 2\theta_{13}$ and the fake one $\sin^2 2\theta'_{13}$, and $\epsilon \equiv \Delta m^2_{21}/|\Delta m^2_{31}|$; $\epsilon = 6.9\times10^{-5}\,{\rm eV}^2/2.5\times10^{-3}\,{\rm eV}^2 = 0.028$ is for the best fit and an extreme case with $\epsilon = 1.9\times10^{-4}\,{\rm eV}^2/1.6\times10^{-3}\,{\rm eV}^2 = 0.12$, which is allowed at 90 % CL (atmospheric) or 95 % CL (solar), is also shown for illustration. The horizontal axis is suitably defined so that it is linear in $\sin^2 2\theta_{23}$, where the left half is for $\theta_{23} < \pi/4$ whereas the right half is for $\theta_{23} > \pi/4$. The solar mixing angle is taken as $\tan^2\theta_{12} = 0.38$. $\sin^2 2\theta_{23} \geq 0.92$ has to be satisfied due to the constraint from the Super-Kamiokande atmospheric neutrino data. If the value of $\cos^2 2\theta_{23}$ is large enough, the value of $\delta_{\rm de}(\sin^2 2\theta_{13})/\sin^2 2\theta_{13}$ increases and lies outside of the normalized error of the reactor experiment, then the reactor result may resolve the θ_{23} ambiguity.

Solving Power of θ_{23} Degeneracy

(Minakata et al. hep-ph/0211111)

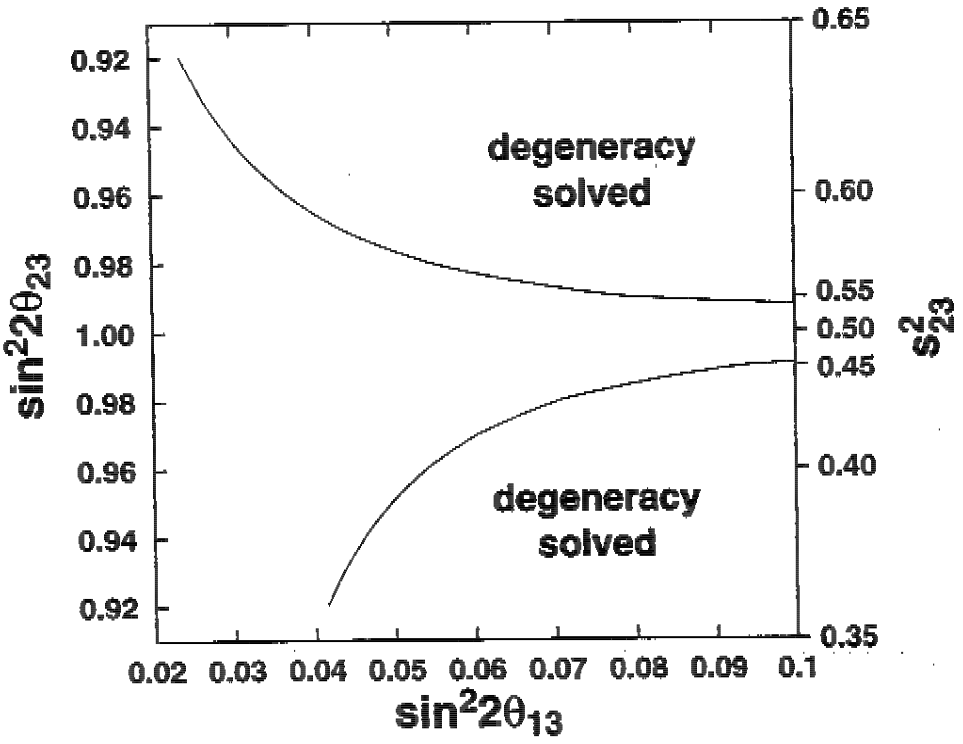

FIG. 7: The shadowed area stands for the region in which $\delta_{\rm re}(\sin^2 2\theta_{13}) < \delta_{\rm dc}(\sin^2 2\theta_{13})$ is satisfied for $\sigma_{\rm sys}$=0.8 %, 40 t·yr, d.o.f.=1 and for the best fit values of the solar and atmospheric oscillation parameters. In this shadowed region, the (θ_{13}, θ_{23}) degeneracy may be solved. The vertical axis is the same as the horizontal axis of Fig. 6(b).

Expandability
(Kashiwazaki-Kariwa Phase-II)

Because the Kashiwazaki-Kariwa Nuclear Power Plant is the most powerful reactor complex in the world, there are opportunities to expand the experiment in the future.

For example,

(1) Explore CP violation δ_l, combining with JPARC->Hyper Kamiokande ν mode data. (100ton LS target will be necessary)
(Minakata et al. hep-ph/0309323).

(2) Precise $\sin^2 2\theta_{12}$ measurement by placing far detector at optimum base line (~60km). (Sado gold mine?)

(3) Search for sterile neutrinos with very near (~a few 10m) detectors.

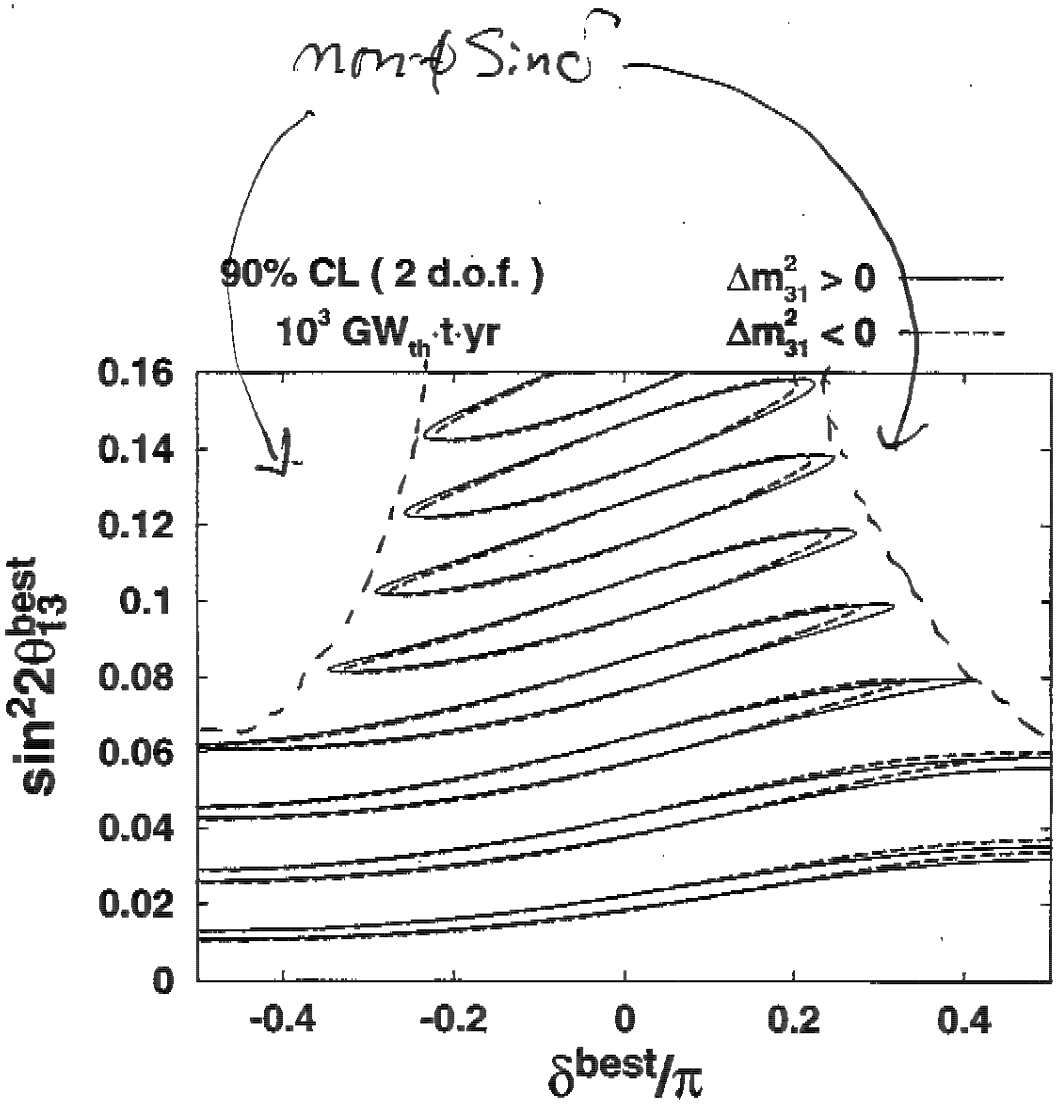

FIG. 3: The contours consistent with CP conservation at 90% CL ($\Delta\chi^2_{CP} = 4.6$) for the inverted mass hierarchy $\Delta m^2_{31} < 0$ (indicated by dashed line) are compared to those of the normal mass hierarchy, $\Delta m^2_{31} > 0$ (indicated by solid lines). The case of 10^3 GW$_{th}$ · ton · year exposure is shown because the difference is roughly equal or less prominent in the other two cases presented in Fig. 2.

Status of the Project

(1) Conceptual design of the experiment is almost complete. Now we are asking for detector R&D money and boring money to Kakenhi.

(2) Negotiation with Tokyo Electric Company for site use has been very successful. The final detector locations are almost determined based on the land usage in the site.

(3) Research on the digging method has been going on with Tokyo Electric Company. We have already received a quotation.

(4) We will host the next international workshop on the reactor θ_{13} experiment at Niigata university in March 2004. There will be a tour to Kashiwzaki- Kariwa Nuclear Power Plant.

30/20,21,22

Mile Stones

Year	Kashiwazaki	Other
2003	R&D	
2004	R&D	
2005	R&D	MINOS/OPERA start
2006	Detector Construction	
2007	Detector Construction	
2008	Detector Construction	
	Start Data Taking	
2009	1st result (10K events;)	J-Park start ?
2010	result(40K events)	MINOS/OPERA Result
2011	K-K Phase-II (?)	
2012		
2013		
2014		JHF ν mode final result

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Activities in the World

	Reactor	Power	Baseline	Overburden	Target mass	Detector Config.
JPN	Kashiwazaki-Kariwa	24.3GW	1.3km	350mwe	8.5ton	2near+1far
EU	CHOOZ-II	8.4GW	1.1km	300mwe	20ton	1near +1far
RUS	Krasnoyarsk	1.6GW	1.0km	600mwe	50ton	1near+1far
USA	DiabloCanyon	6.2GW	0.8~2km	600mwe	50~100ton	movable

Dedicated Workshops

2003.5	University of Alabama (USA)	Done
2003.10	Munich Technical Institute (Germany)	Done
2004.3	Niigata Uuniversity (Japan)	In Preparation
2004.6	Paris (French)	(with ν 2004)

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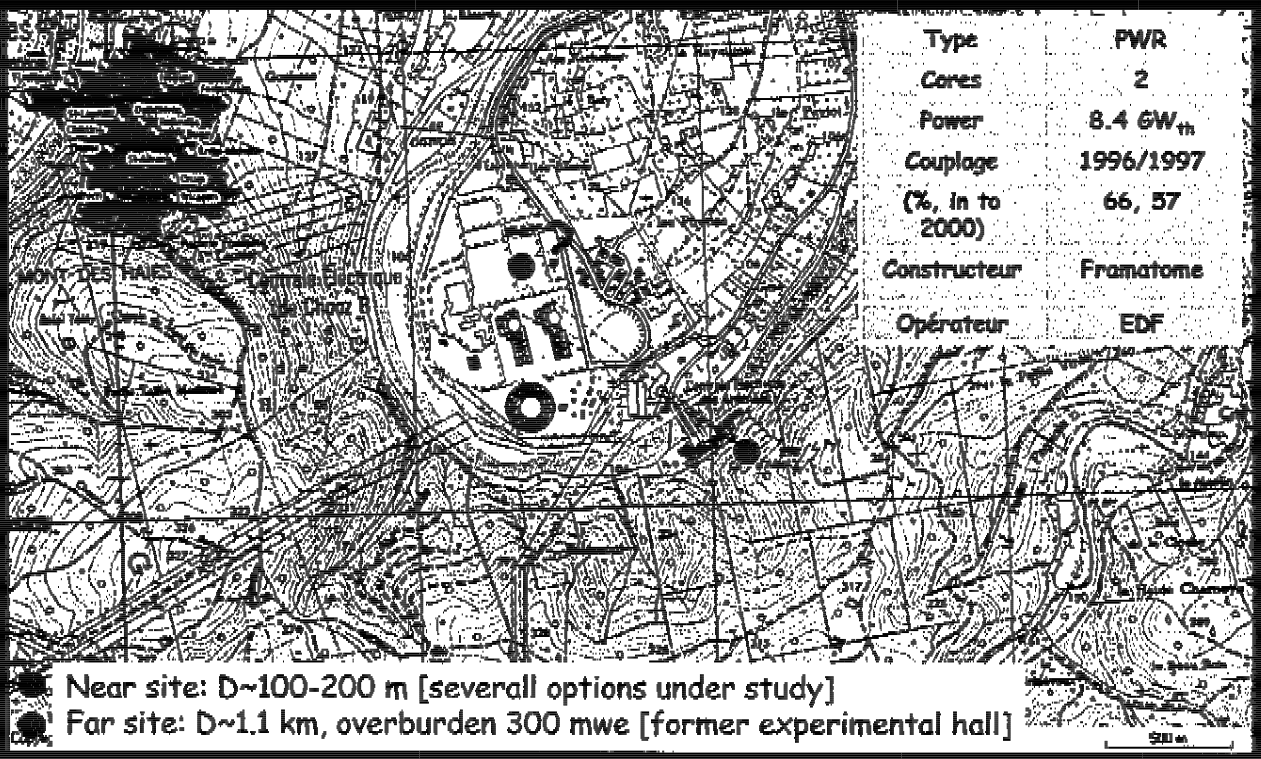
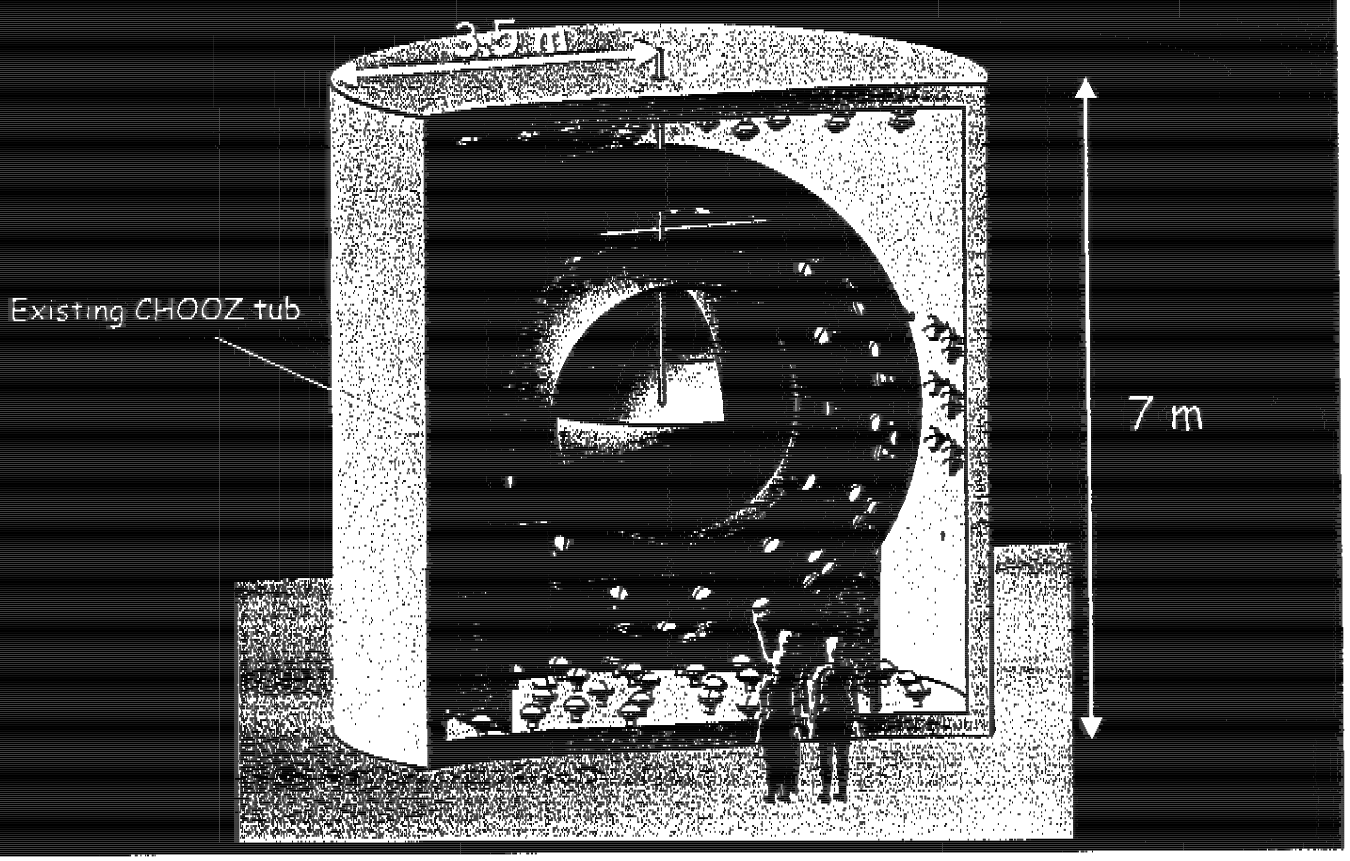
The Chooz site



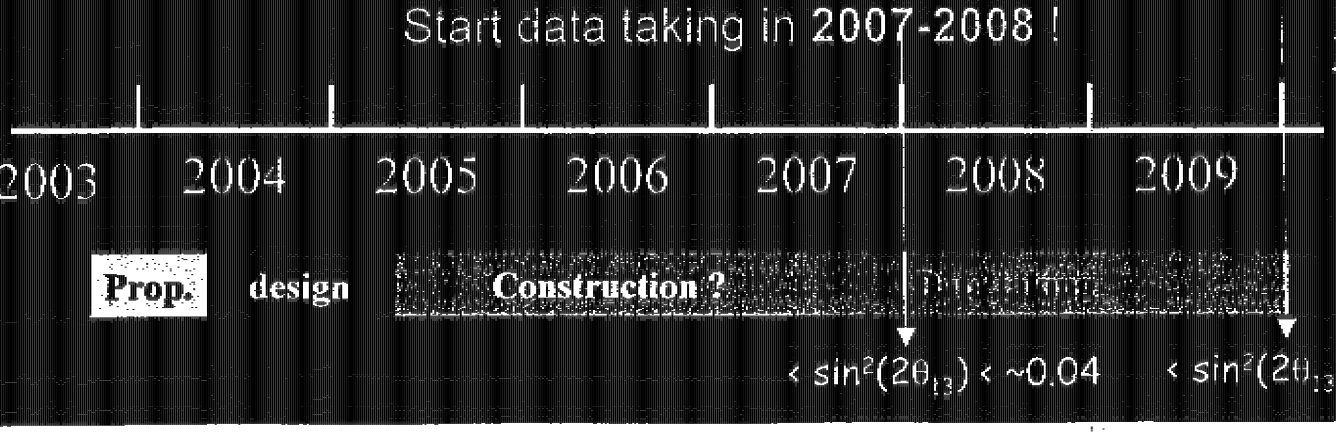
- Positive signs from EDF for reusing the former CHOOZ site. Near site → civil engineering
- 2x11.5 tons, D1=100-200m, D2=1050m. Sensitivity: 3 years → $\sin^2(2\theta_{13}) < \sim 0.03$

CHOOZ-Far detector



Summary & outlook

- ✓ Strong support for the EDF power company to do a 2nd experiment @CHOOZ !
  Reactor potential @CHOOZ: $\sin^2(2\theta_{13})<\sim 0.03$, 90% C.L.
  Current limint: CHOOZ : $\sin^2(2\theta_{13})<0.2$ → discovery potential !
- ✓ Technology / design well known (Chooz, Borexino, KamLAND, ...)
  → few R&D needed : Gd loading (stability) + material compatibility
  → R&D in Saclay : material compatibility + mechanical constraints + scint. tests
- ✓ Case under study: French ν target vessels & German scintillator (MPIK)
- ✓ Experiment cost @CHOOZ:
  2 x 11.5 tons. cost detectors <10 Meuros. (+ Civil engineering)
- ✓ Our Goal @CHOOZ: Construction starts in 2005 (+ civil engineering)
  Start data taking in **2007-2008** !



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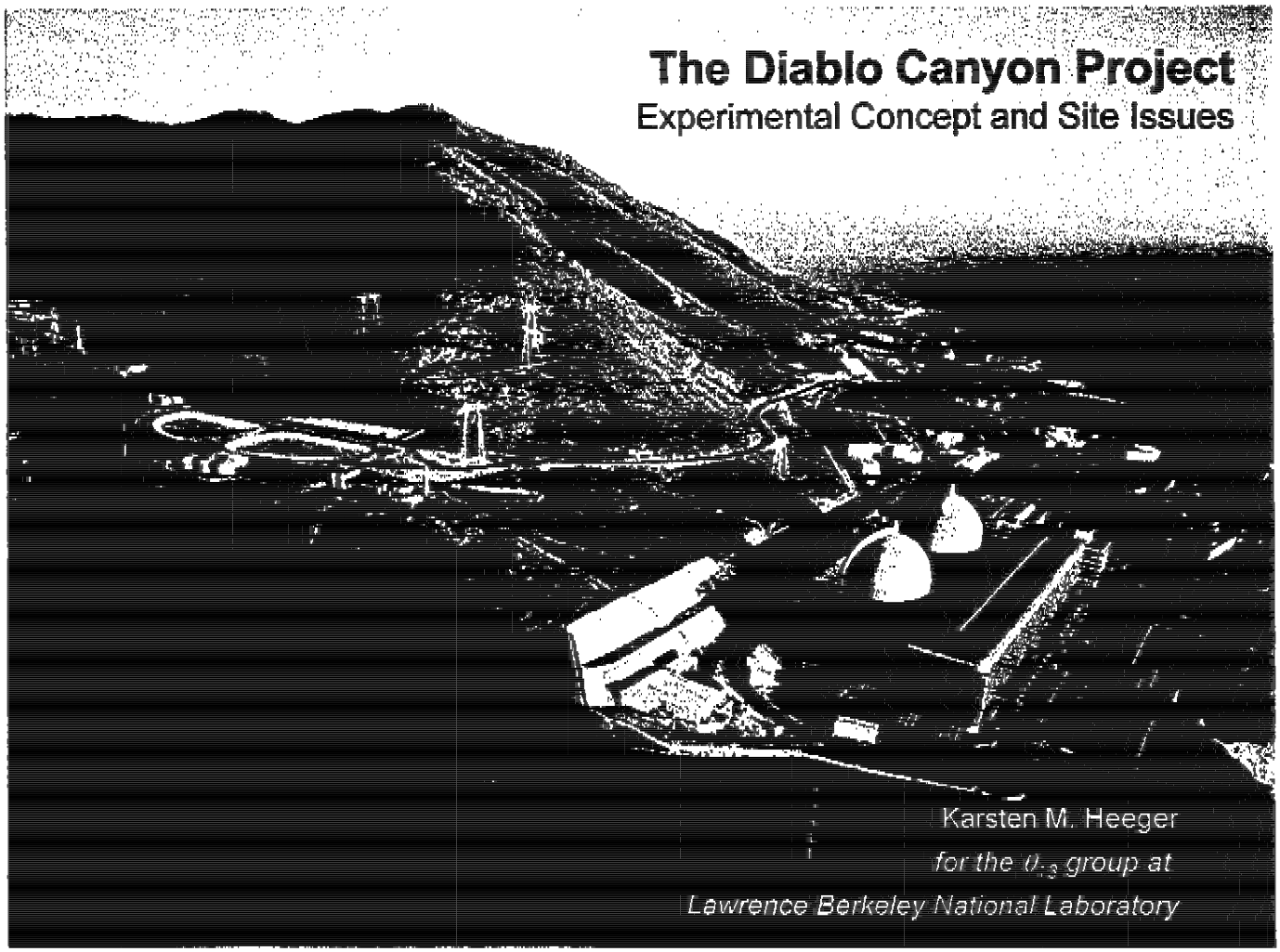
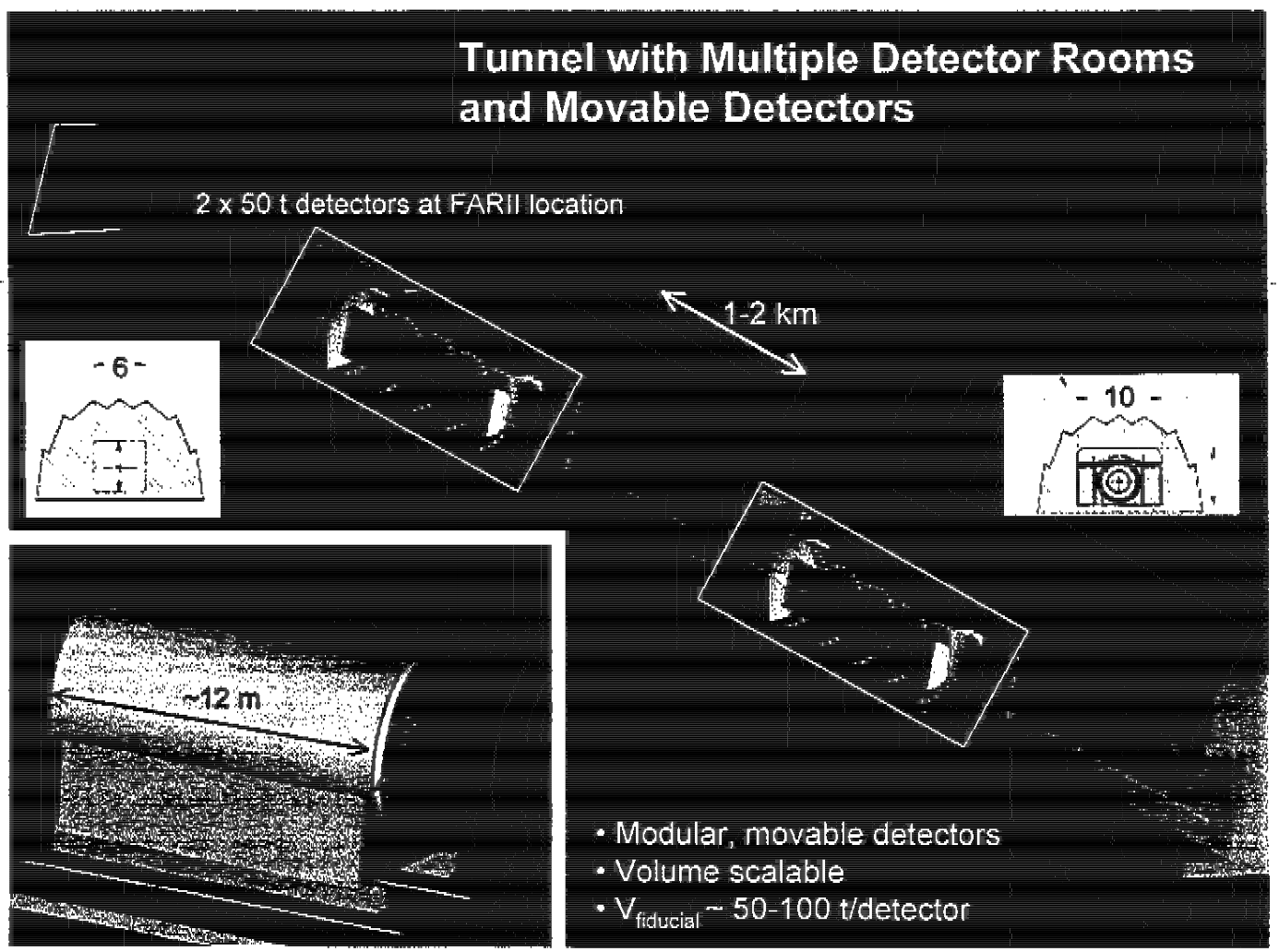
The Diablo Canyon Project

Experimental Concept and Site Issues



Karsten M. Heeger
for the θ_{13} group at
Lawrence Berkeley National Laboratory

Tunnel with Multiple Detector Rooms and Movable Detectors



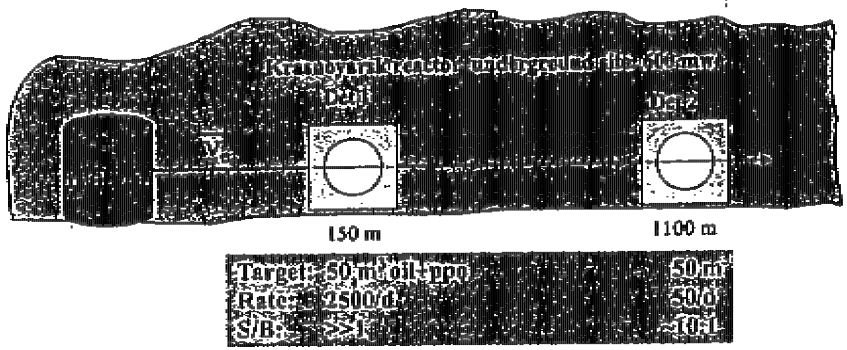
Kr2Det proposal to search for U_{e3}

We plan to use two identical detectors (far and near) at

1100 m and ~150 m from the reactor at ~ 600 m.w.e. depth.

Target masses: ~ 50 t of mineral oil scintillator (5% of the KamLAND's mass).

Detector design: KamLAND in miniature



Ratio of the measured positron energy spectra should be energy independent in no oscillation case. $R = S_{far} / S_{near}$ = const

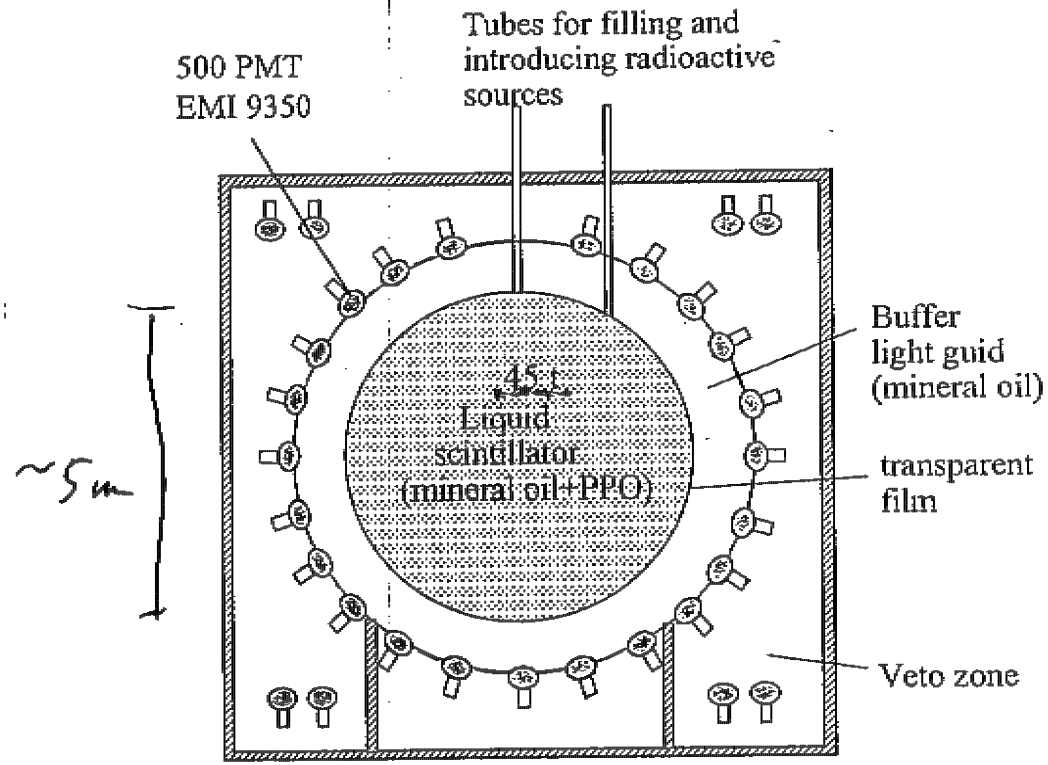
Deviation from a constant value is analyzed for oscillations.

The method of analysis is purely relative:

The results do not require exact knowledge of the reactor power, neutrino flux and the energy spectrum, detection efficiencies and target proton numbers…

Sendai 2002

Scheme of the detector



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Summary

(1) Reactor measurement of $\sin^2 2\theta_{13}$ is very important bacause;

* It is pure $\sin^2 2\theta_{13}$ measurement.
* It is Complimentary to LBLA experiment.

(2) By using the most giant nuclear power plant and 3 identical detectors placed at appropriate location and depth, $\sin^2 2\theta_{13}$ sensitivity of ~0.02(90%CL) is possible, which is 7 times better than the current CHOOZ limit.

(3) The Kashiwazaki-Kariwa project is realistic.

* CHOOZ+Paloverde+KamLAND technology is enough.
* The cost is not high if compared with LBLA.
* It can go quickly once started and can catch up with LBLA.

(4) We seriously lack of man-power.

<u>Serious collaborators are welcome.</u>

(Woule like to join? Please contact to one of the collaborators.)