KamLAND

Kamioka Liquid scintillator Anti-Neutrino Detector

The KamLAND[1] Reactor Neutrino Experiment

Testing the Solar Neutrino Anomaly in a Terrestrial Experiment

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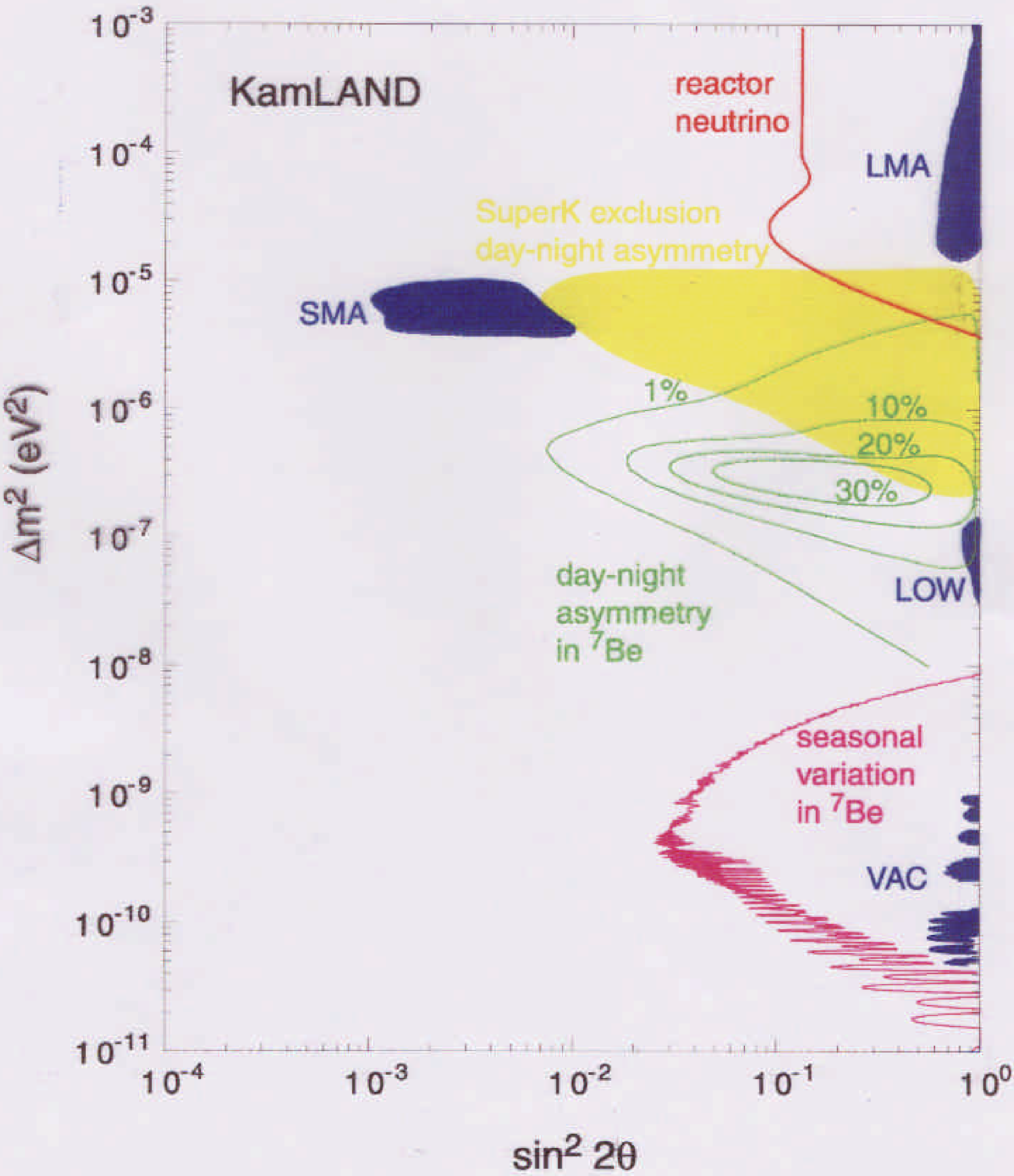
University of Alabama

for the KamLAND Collaboration

Neutrino 2000, Sudbury

[1]Supported by the Japanese Minstry of Science and Education and US Department of Energy

Sensitivity to Solar Neutrino Solutions



Solar Model independent Test of Solar Parameter Space

For massive and mixed Neutrinos probability P to find ν_ℓ as $\nu_{\ell'}$ after travelling distance L given through:

$$P(\nu_\ell \to \nu_{\ell'}) = sin^2 2\theta \cdot sin^2 \frac{1.27 \cdot \Delta m^2(eV^2) \cdot L(m)}{E(MeV)}$$

Matter enhanced solar Neutrino oscillations (**Small and Large Mixing Angle Solution**) $\Delta m^2 \approx 2 \cdot 10^{-5}$ eV^2.

$\rightarrow$ Use low energy Neutrinos to perform oscillation test at reasonable distance to source.

Assume CP conservation in Lepton sector $\rightarrow$ oscillation probability the same for particles and anti-particles. $\rightarrow$ Use low energy reactor anti-Neutrinos.

$\langle E_{\overline{\nu}_e} \rangle \approx 4$ MeV $\rightarrow P$ becomes maximal at $L \approx 250$ km.

BUT appearance of ν_μ and ν_τ energetically forbidden $\rightarrow$ disappearance search.

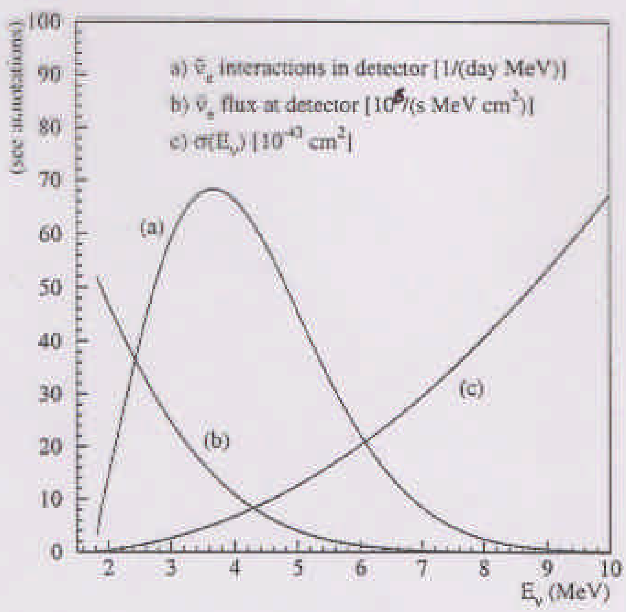
Perform disappearance search by comparing expected to measured event rate $\rightarrow$ statistically limited mixing angle sensitivity. $\rightarrow$ Only sensitive to Large Mixing Angle Solution.

Nuclear Reactors as Neutrino Sources

Intense and well understood source of $\overline{\nu}_e$. Typical neutrino luminosity of P_{therm}=3.8 GW reactor: $6 \cdot 10^{20}$ s^{-1}.

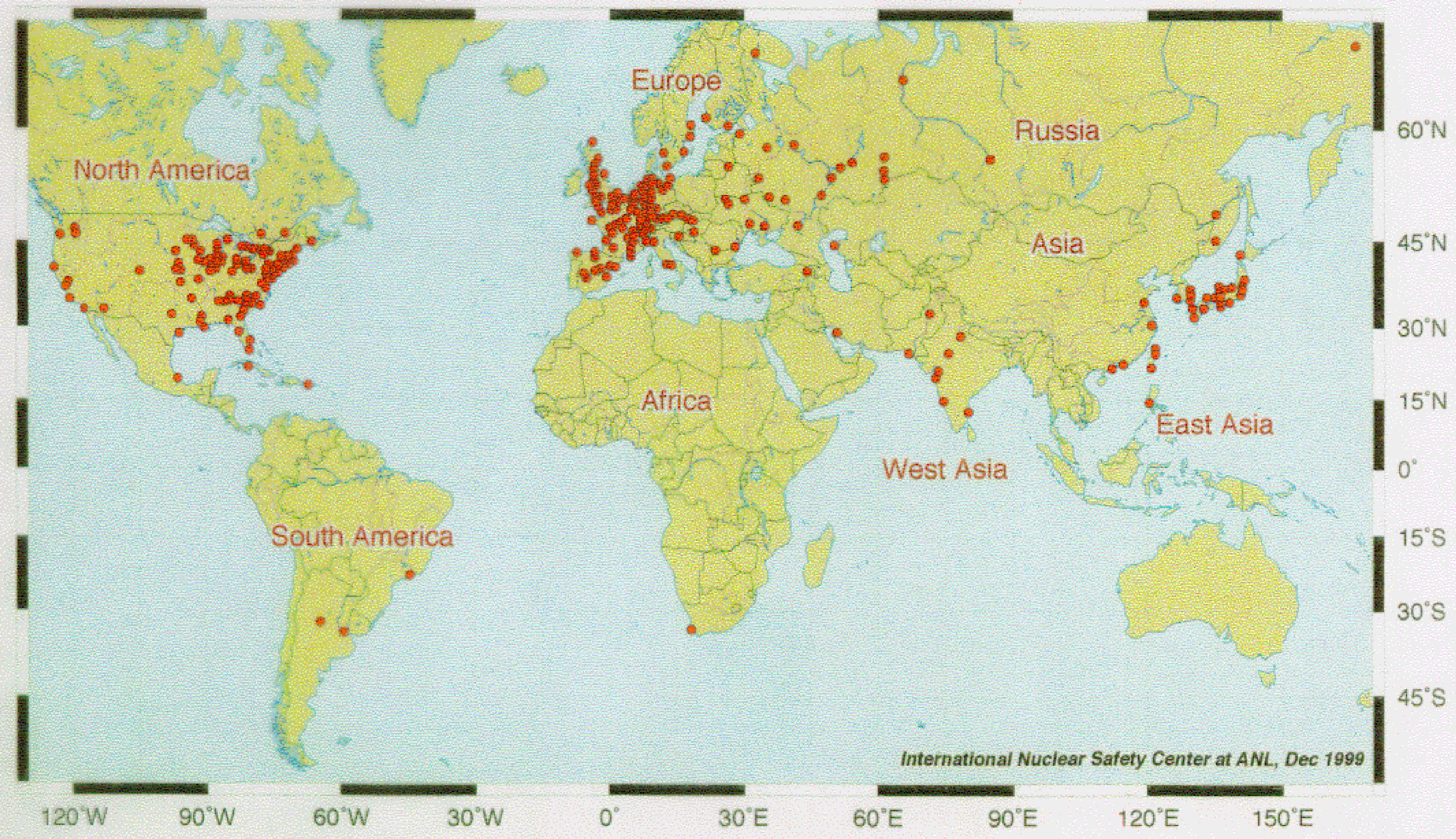
Neutrinos emitted in β-decay of unstable fission fragments. Spectrum can be reliably calculted from known thermal power and fuel composition. Short baseline experiments find 2% agreement.

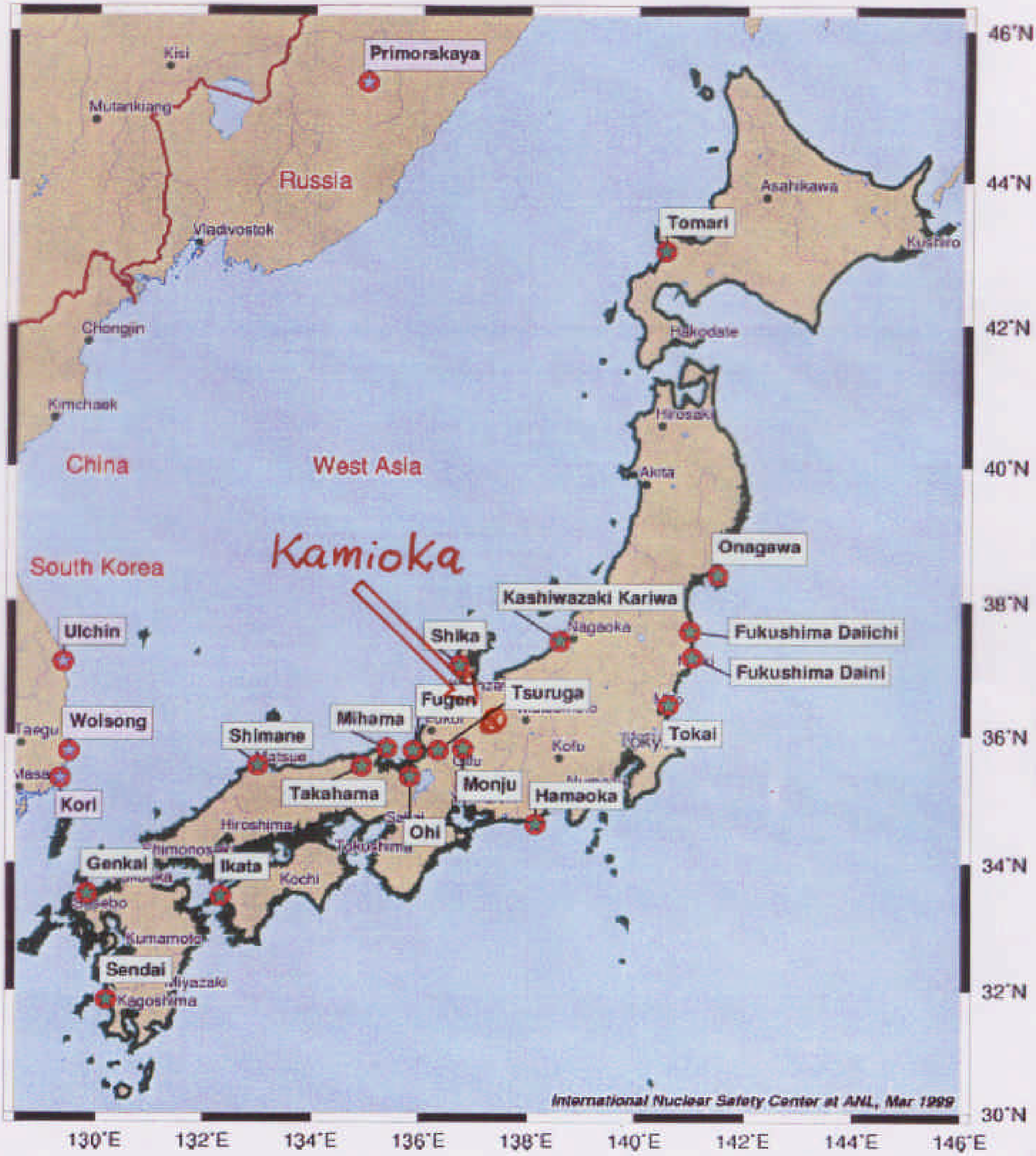
→ **Disappearance search doesn't need near detector**



Detector backgrond can be inferred directly from reactor power modulation or bank swapping.

$\overline{\nu}_e$-flux at Kamioka very small due to large distance. Many reactors contribute.


Europe
Russia
North America
Asia
Africa
East Asia
West Asia
South America
International Nuclear Safety Center at ANL, Dec 1999
60°N
45°N
30°N
15°N
0°
15°S
30°S
45°S
120°W
90°W
60°W
30°W
0°
30°E
60°E
90°E
120°E
150°E


Primorskaya
Kisi
Mutankiang
Russia
Vladivostok
Chongjin
Kimchaek
China
West Asia
South Korea
Kamioka
Ulchin
Wolsong
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Kori
Shimane
Matsue
Mihama
Fugen
Tsuruga
Shika
Takahama
Monju
Ohi
Hamaoka
Kashiwazaki Kariwa
Nagaoka
Onagawa
Fukushima Daiichi
Fukushima Daini
Tokai
Kofu
Tomari
Asahikawa
Kushiro
Hakodate
Hirosaki
Akita
Hiroshima
Tokushima
Kochi
Genkai
Ikata
Sasebo
Kumamoto
Sendai
Miyazaki
Kagoshima
International Nuclear Safety Center at ANL, Mar 1999
46°N
44°N
42°N
40°N
38°N
36°N
34°N
32°N
30°N
130°E
132°E
134°E
136°E
138°E
140°E
142°E
144°E
146°E

Calculated $\overline{\nu}_e$ flux in Kamioka

Reactor	Distance (km)	Blocks	P_{therm} (GW)	Flux ($\overline{\nu}_e$ / cm^{2}s)	e^+ rate (year^{-1})	Accum. yield
Kashiwazaki	160.0	7	24.58	$4.25 \cdot 10^5$	348.1	0.316
Ohi	179.5	4	13.69	$1.88 \cdot 10^5$	154.0	0.455
Takahama	190.6	4	10.20	$1.24 \cdot 10^5$	101.8	0.548
Shiga	80.6	1	1.59	$1.08 \cdot 10^5$	88.8	0.628
Tsuruga	138.6	2	4.49	$1.03 \cdot 10^5$	84.7	0.705
Mihama	145.4	3	4.93	$1.03 \cdot 10^5$	84.5	0.782
Hamaoka	214.0	4	10.62	$1.03 \cdot 10^5$	84.1	0.858
Fukushima-1	344.0	6	14.20	$5.3 \cdot 10^4$	43.5	0.898
Fukushima-2	344.0	4	13.17	$4.9 \cdot 10^4$	40.3	0.934
Tokai-II	294.6	1	3.29	$1.7 \cdot 10^4$	13.7	0.946
Shimane	414.0	2	3.82	$9.9 \cdot 10^3$	8.1	0.954
Onagawa	430.2	2	4.09	$9.8 \cdot 10^3$	8.0	0.961
Ikata	561.2	3	5.96	$8.4 \cdot 10^3$	6.9	0.967
Genkai	755.4	4	6.72	$5.2 \cdot 10^3$	4.3	0.971
Sendai	824.1	2	5.32	$3.5 \cdot 10^3$	2.8	0.974
Tomari	783.5	2	3.30	$2.4 \cdot 10^3$	2.0	0.976
Ulchin	750	4	11.2	$8.8 \cdot 10^3$	7.2	0.982
Yonggwang	940	6	16.8	$8.4 \cdot 10^3$	6.9	0.988
Kori	700	4	8.9	$8.0 \cdot 10^3$	6.6	0.994
Wolsong	690	4	8.1	$7.5 \cdot 10^3$	6.2	1.000
Total		69	174.97	$1.34 \cdot 10^6$	1102.5	

→ Baseline is limted: 85.3% of signal from baseline **140-344 km**.

Takes about 1.4% of total world power production (∼12800 GW[1])

or 21.9% of world nuclear power (800 GW) to do experiment!

[1] According to the Energy Information Administration of DoE

Piepke - 07

KamLAND

KEK
Taniguchi, Takashi

Miyagi Gakuin Women's University
Chikamatsu, Takeshi

Tohoku University
Enomoto, Sanshiro; Furuno, Koichiro; Glenn Horton-Smith; Hanada, Hiromitsu; Hatakeyama, Syuichiro; Ikeda, Haruo; Inoue, Kunio; Ishihara, Kenji; Itoh, Tomoki; Iwamoto, Toshiyuki; Kinoshita, Hidenobu; Koga, Masayuki; Mitsui, Tadao; Nakajima, Minoru; Nakajima, Takashi, Nakamura, Kengo; Ogawa, Hiroshi; Oki, Kazuhiro; Shirai, Junpei; Suekane, Fumihiko; Suzuki, Atsuto; Tagashira, Kenji; Tajima, Osamu; Takayama, Tomoaki; Tamae, Kyoko; Watanabe, Hideki

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P.Alivisatos

Physics Department and Lawrence Berkeley National Laboratory
R.N.Cahn, Y.D.Chan, X.Chen, S.J.Freedman, B.K.Fujikawa, K.T.Lesko, K.-B.Luk, Hitoshi Murayama, D.R.Nygren, C.E.Okada, A.W.Poon, H.M.Sreiner

California Institute of Technology
K.B.Lee, R.D.McKeown, V.Novikov, P.Vogel

Drexel University
C.E.Lane, R.Steinberg

University of Hawaii
John G.Learned, Shigenobu Matsuno, Sandip Pakvasa

Louisiana State University
B.-K.Kim, R.C.Svoboda

University of New Mexico
Byron D.Dieterle, Steve Riley, Chilton Gregory

Oak Ridge National Laboratory
C.Britton, W.Bryan, S.Frank, A.Wintenberg, J.Wolker

Stanford University
Giorgio Gratta, Haw-Ling Liew, Lester Miller, N.Sleepz, H.Tanaka, D.Tracy, Yi-Fang Wang

University of Tennessee
Steve Berridge, William Bugg, Hans Cohn, Yuri Efremenko, Ed Hart, Yuri Kamyshkov

Duke University
Ludwig De Braeckeleer, Chee Liang Hoe, Michael Hornish, Hugon Karwowski, Jason Messimore, Kengo Nakamura, Neal Simmons, Werner Tornow

North Carolina State University
Christopher Gould, Diane Markoff, Ryan Rohm

Detection Reaction

At low neutrino energies detection cross sections **very small**.

Use inverse beta decay offering "high" cross section:
$\sigma = 6 \cdot 10^{-43}\ \mathrm{cm}^2/\mathrm{fission}$.

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

Low threshold $E_{th} = M_n - M_p + M_e^+ = 1.8$ MeV.

Cross section well understood. No nuclear matrix element needed can use measured ft-value of neutron decay. To lowest order given as:

$$\begin{aligned}\frac{d\sigma}{dE_{\overline{\nu}_e}} &= \frac{c}{f \cdot \tau_n} \cdot p_{e^+} \cdot E_{e^+} \\ &= \frac{c}{f \cdot \tau_n} \cdot [E_{\overline{\nu}_e} - (M_n - M_p)] \cdot \sqrt{[E_{\overline{\nu}_e} - (M_n - M_p)]^2 - M_{e^+}}\end{aligned}$$

Because $M_p \gg M_e^+ \rightarrow$ small neutron recoil:

$$E_{\overline{\nu}_e} = E_e^+ + M_e^+ + M_n - M_p + \mathcal{O}\left(\frac{E_{\overline{\nu}_e}}{M_n}\right)$$

Measures the $\overline{\nu}_e$ folded with cross section.

Oscillation Signature

Energy range of reactor $\overline{\nu}_e$ 2-8 MeV $\rightarrow$ within range of radioactivity.

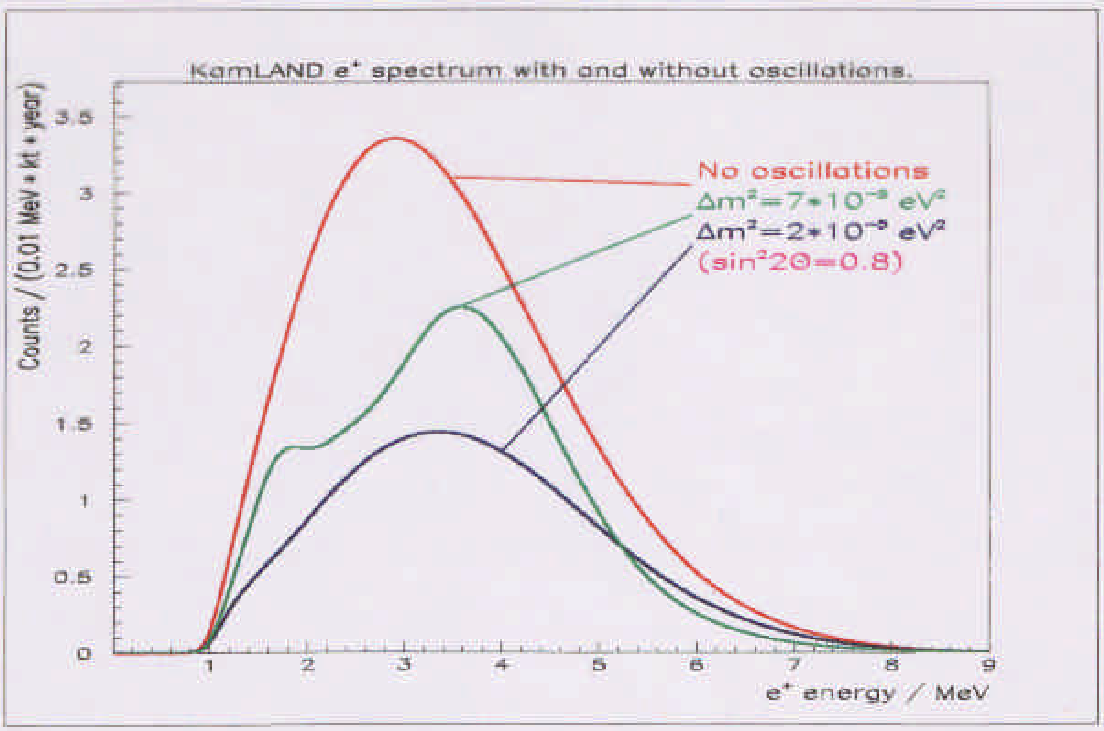
$$\overline{\nu}_e + p \rightarrow e^+ + n$$

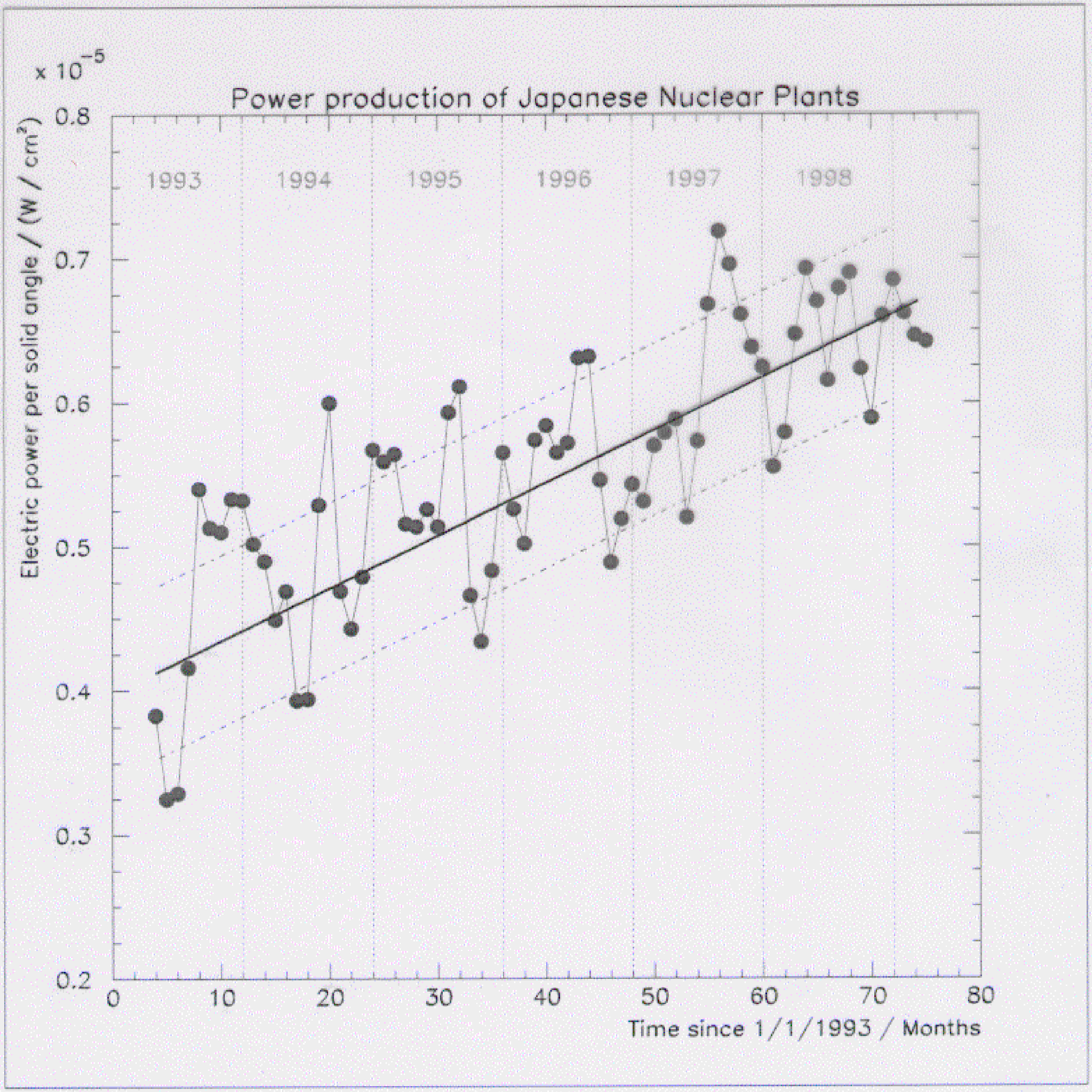
Use 1000 tons of liquid scintillator as target and detector. Measures energy of e^+ (plus M_e). Expected reaction rate at Kamioka: 2 / day.

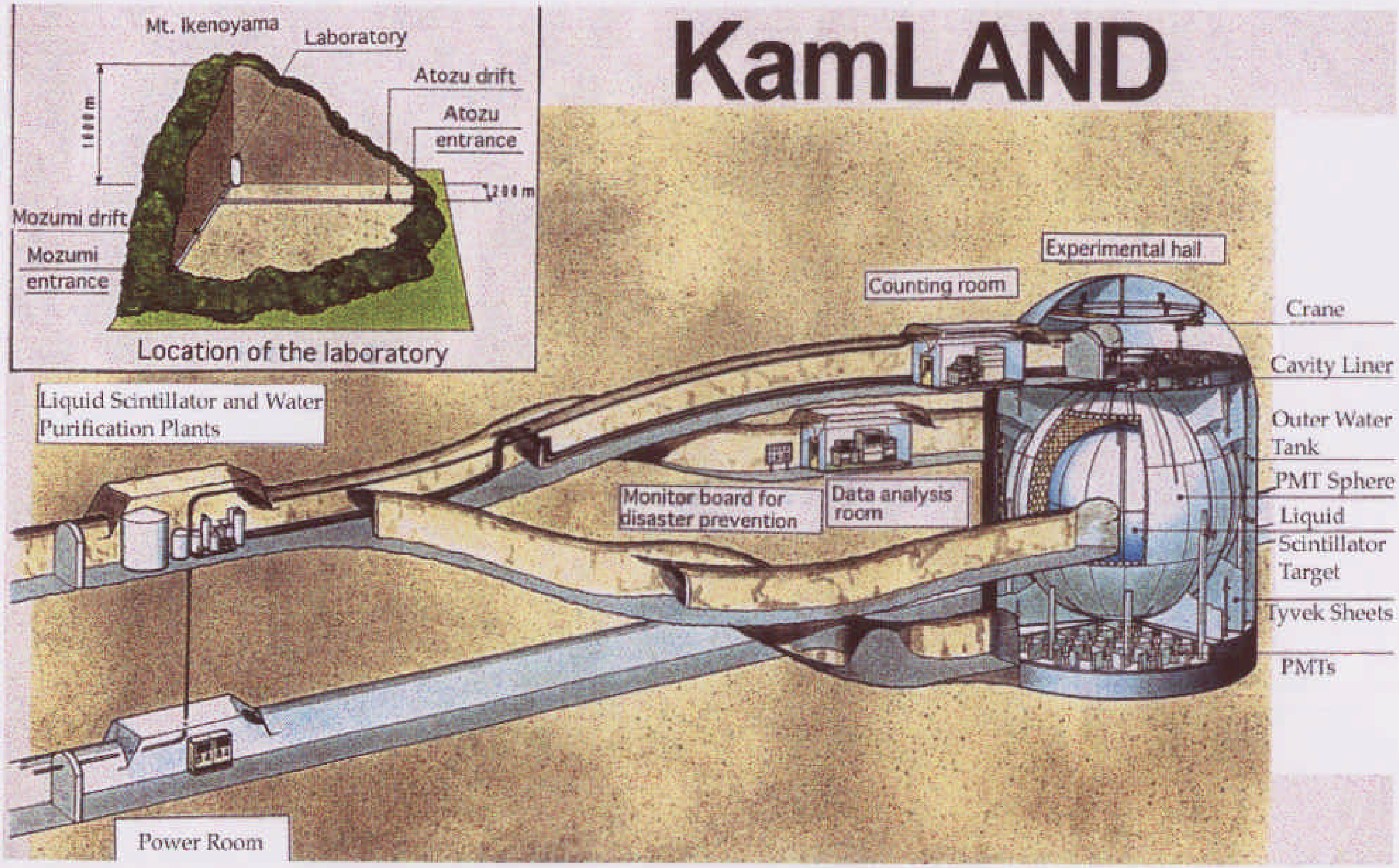
Reaction neutron ($E_{kin} \approx 10$ keV) moderated and captured on proton. $p + n \rightarrow d + \gamma_{2.2MeV}$, capture time $\tau = 170 \quad \mu s$.

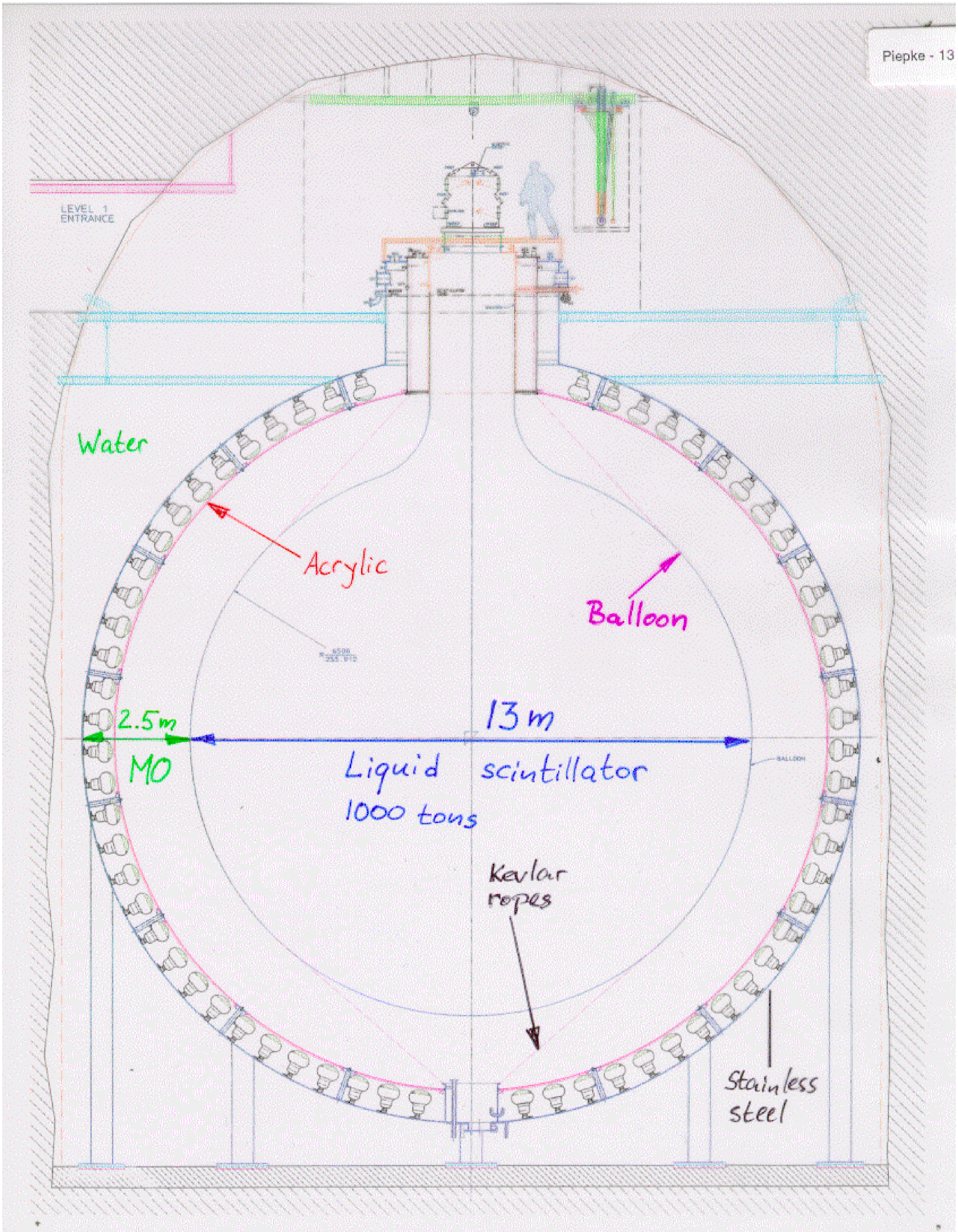
Delayed temporal and spatial coincidence defines neutrino signal. **Crucial to suppress background**. Measured e^+-spectrum Y:

$$Y(E_{\overline{\nu}_e}, L, t, \Delta m^2, sin^2 2\theta) = N(\overline{\nu}_e, t) \cdot \sigma(\overline{\nu}_e) \cdot [1 - sin^2 2\theta \cdot sin^2 \frac{1.27 \Delta m^2 L}{E_{\overline{\nu}_e}}]$$




Power production of Japanese Nuclear Plants
x 10^-5
Electric power per solid angle / (W / cm²)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
1993
1994
1995
1996
1997
1998
0
10
20
30
40
50
60
70
80
Time since 1/1/1993 / Months


KamLAND
Mt. Ikenoyama
Laboratory
Atozu drift
Atozu
entrance
Mozumi drift
Mozumi
entrance
Location of the laboratory
Liquid Scintillator and Water
Purification Plants
Experimental hall
Counting room
Crane
Cavity Liner
Outer Water
Tank
PMT Sphere
Liquid
Scintillator
Target
Tyvek Sheets
PMTs
Monitor board for
disaster prevention
Data analysis
room
Power Room


LEVEL 1
ENTRANCE
Water
Acrylic
Balloon
2.5m
13m
MO
Liquid scintillator
1000 tons
Kevlar ropes
Stainless steel
BALLOON

Detector parameters

- 1000 tons of scintillator

  20% trimethylbenzene

  + 80% paraffin

  + 1.5 g/l PPO $\quad$ AL ≈ 10 m @ 400 nm

- 1500 tons buffer

  33% iso-paraffin

  + 67% paraffin $\Rightarrow \frac{\rho_{SCINT}}{\rho_{BUF}} = 1.015$

Balloon from composite film

Nylon/EVOH[5]/Nylon → low Rn permeability

Scintillator and buffer purification through water stripping + N_2 purging

$U/Th < 10^{-13}$ g/g (MS)

1300 17" Hamamatsu photo multipliers (10 ns) 22% coverage

plus 600 20" PMT from Kamiokande

→ 36%

⇒ Resolution : 150 p.e./MeV

200 20" in OD

Analog **T**ransient **W**aveform **D**igitizer as front end electronics "digital scope" for every channel. Double chips and buffering → dead time less ~ 1 kHz

Supernova promote PSD

Backgrounds

$\overline{\nu}_e$-flux in Kamioka is factor 5700 smaller than in Palo Verde.

Needs a **large** detector, with **very low** background.

Use a homogenuous detector.

- Correlated background due to neutrons created by cosmic ray muons in lab walls and detector are suppressed by going deep underground (2700 mw.e.). Use massive passive shield and cosmic ray veto. Cosmic μ-flux in Kamioka is about $6.5 \cdot 10^4$ times smaller than in Palo Verde.
- Random background due to radioactivity accidentally satisfying energy, temporal and spatial event cuts are avoided by building the detector from low activity materials. The scintillator needs to have U/Th concentrations below 10^{-14} g/g.

Reactor $\bar{\nu}_e$

Detector simulation using :

GEANT (geometry, materials, em-interactions)

FLUKA (hadronic interactions)

GCALOR (neutron transport)

Correlated background

Fast n recoil followed by capture.

Dominant component n produced through μ-spallation in lab. walls (no veto tag).

Random background

Natural radioactivity

Cosmogenic activities (negligible)

Cuts identifying correlation

Energy:

Prompt energy $1\,\text{MeV} \leq E_p \leq 10\,\text{MeV}$
Delayed energy $1.8\,\text{MeV} \leq E_d \leq 2.7\,\text{MeV}$ $(\pm 3\cdot\sigma)$

Time : $10 - 500\,\mu s$

Space : $r \leq 1\,m$

Correlated background

6000 n/day in 1 m rock shell.
(Yield : $4\cdot10^{-4}\,\frac{n\cdot cm^2}{g\cdot\mu}$; $\varrho = 2.7\,g/cm^3$ @ 2700 mw.e.)

n-transport through MC : 1.8 n-induced recoil signals in 1 kt scint. and day.

Above cuts : 0.05 events per 1 kt scint. and day. Main reduction through cut on prompt energy.
Reminder : ν_e-signal 2.2 /day

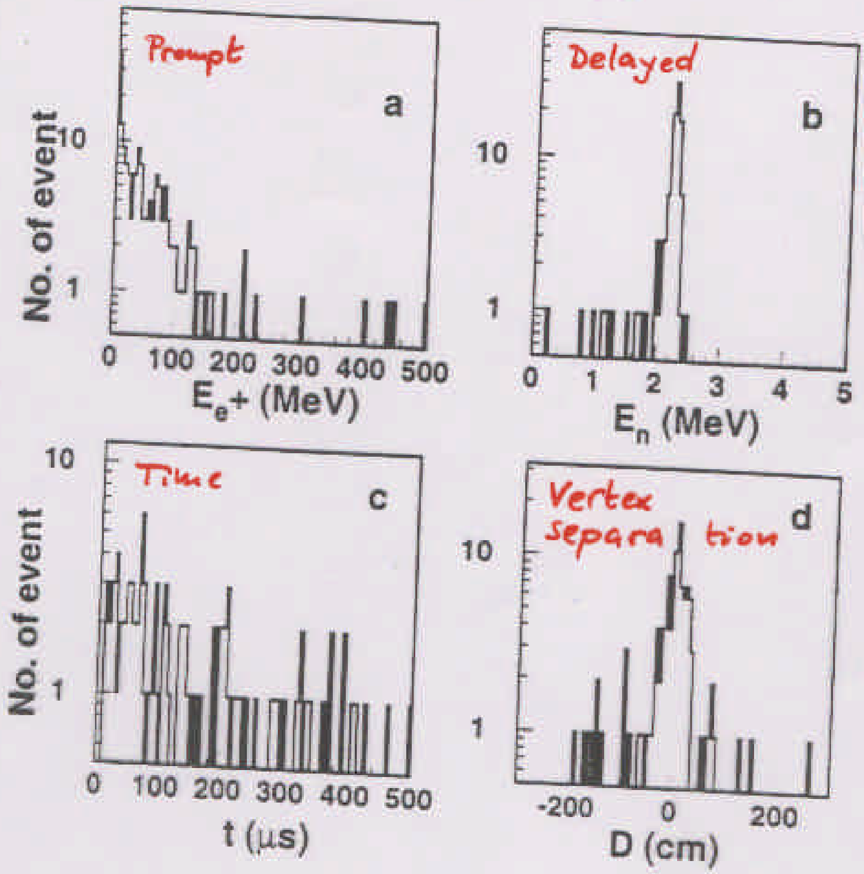
Random background:

Measure together with $\bar{\nu}_e$-signal using correlation times between prompt and delayed signal beyond n-capture time.

→ Flexible electronics.

Although not trivial (scintillator purity U/Th 10^{-14} g/g) reactor experiment seems feasible.

Spallation n



- n produced in lab. walls (6000/day @ ≤1 m).
- E spectrum power law.
- Neutron has to penetrate ≥ 3 m passive shield, parent μ misses veto. → 0.05 events/day passing $\bar{\nu}_e$-cuts. μ-capture small.

Background from Natural Radioactivity

Energy threshold = 1 MeV

Material	Mass (tons)	Isotope	Purity (ppb)	1 kton back. (Hz)	600 ton back. (Hz)
Scint.	1000	^{238}U	10^{-7} (5)	0.003	0.002
		^{232}Th	10^{-7} (5)	0.001	0.0005
		^{40}K	10^{-7} (5)	0.004	0.002
		radon	1 μBq/m^3	0.002	0.001
Buffer Oil	1523	^{238}U	10^{-5}	0.003	0.0
		^{232}Th	10^{-5}	0.001	0.0
		^{40}K	10^{-5}	0.009	0.0
		radon	10 mBq/m^3	0.030	0.0
Steel Tank	31	^{238}U	1	0.001	0.0
		^{232}Th	1	0.004	0.0
		^{40}K	1	0.010	0.0
		^{60}Co	10^{-9}	0.005	0.0
PMT	7.2	^{238}U	400	0.503	0.003
		^{232}Th	300	0.137	0.0004
		^{40}K	180	0.046	0.0002
Rock	627	^{238}U	73000	0.199	0.001
		^{232}Th	200000	0.059	0.0002
		^{40}K	4600	0	0
Total				1.02	<0.012

Scint 10^{-5} 1.86

Main cosmogenic backgrounds

Isotopes	Lifetime (s)	cross section (mb)	No. day^{-1}	background day^{-1}	Borexino CERN meas.
^{12}B	0.02	30 [56]	< 1700	< 1700	
^{11}C	1218	28.7 [55]	< 1700	< 1700	1020
^{10}C	19.3	1.1 [55]	< 65	< 65	
^{10}Be	1.5×10^6 y	2.5 [55]	<150	0	
^{7}Be	53.28 d	7.1 [55]	<409	<40	25

Rate of μ through det. : $0.37\ s^{-1}$

μ-spallation:

$$^{12}C + \gamma \longrightarrow {}^{11}C + n$$

$$^{12}C + \gamma \longrightarrow {}^{10}C + 2n$$

$$^{12}C + \gamma \longrightarrow {}^{11}B + p$$

$$^{12}C + \gamma \longrightarrow {}^{10}B + np$$

n-spallation:

$$N + n \longrightarrow N' + h$$

$h = \gamma, \alpha, \pi$ (FLUKA)

μ-capture:

$$^{12}C + \mu^- \longrightarrow {}^{12}B^* + \nu_\mu$$

Total Background for Reactor Neutrinos

Singles:

$$E > 1 \text{ MeV}$$

Doubles:

$$E_{prompt} > 1 \text{ MeV}$$

$$E_{delayed} > 1 \text{ MeV}$$

$$T_{delayed-prompt} < 550\ \mu s$$

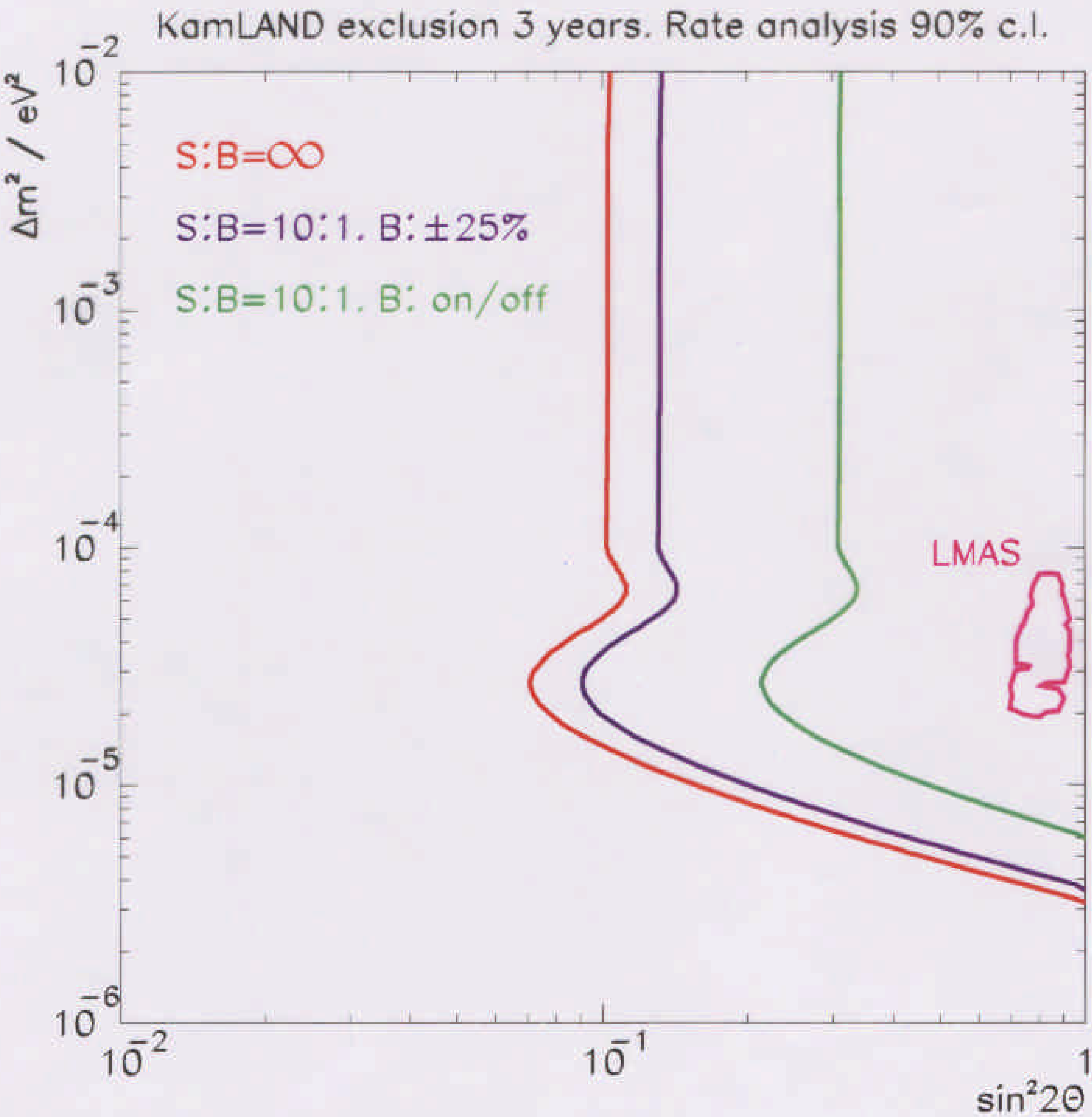
Backgrounds for singles	1 kton back.	600 ton back.
neutrons from muon spallation	2.0 day^{-1}	1.2 day^{-1}
activation from n capture	0 day^{-1}	0 day^{-1}
activation from n spallation	<1800 day^{-1}	<1200 day^{-1}
activation from μ capture	0 day^{-1}	0 day^{-1}
activation from μ spallation	< 1800 day^{-1}	< 1200 day^{-1}
Natural radioactivity	1.02 Hz	<0.012 Hz
Backgrounds for doubles		
Cosmic muons induces neutrons	0.05 day^{-1}	0.03 day^{-1}
Natural radioactivity (random)	0.05 day^{-1}	0.00 day^{-1}
Natural radioactivity (correlated)	0.00 day^{-1}	0.00 day^{-1}

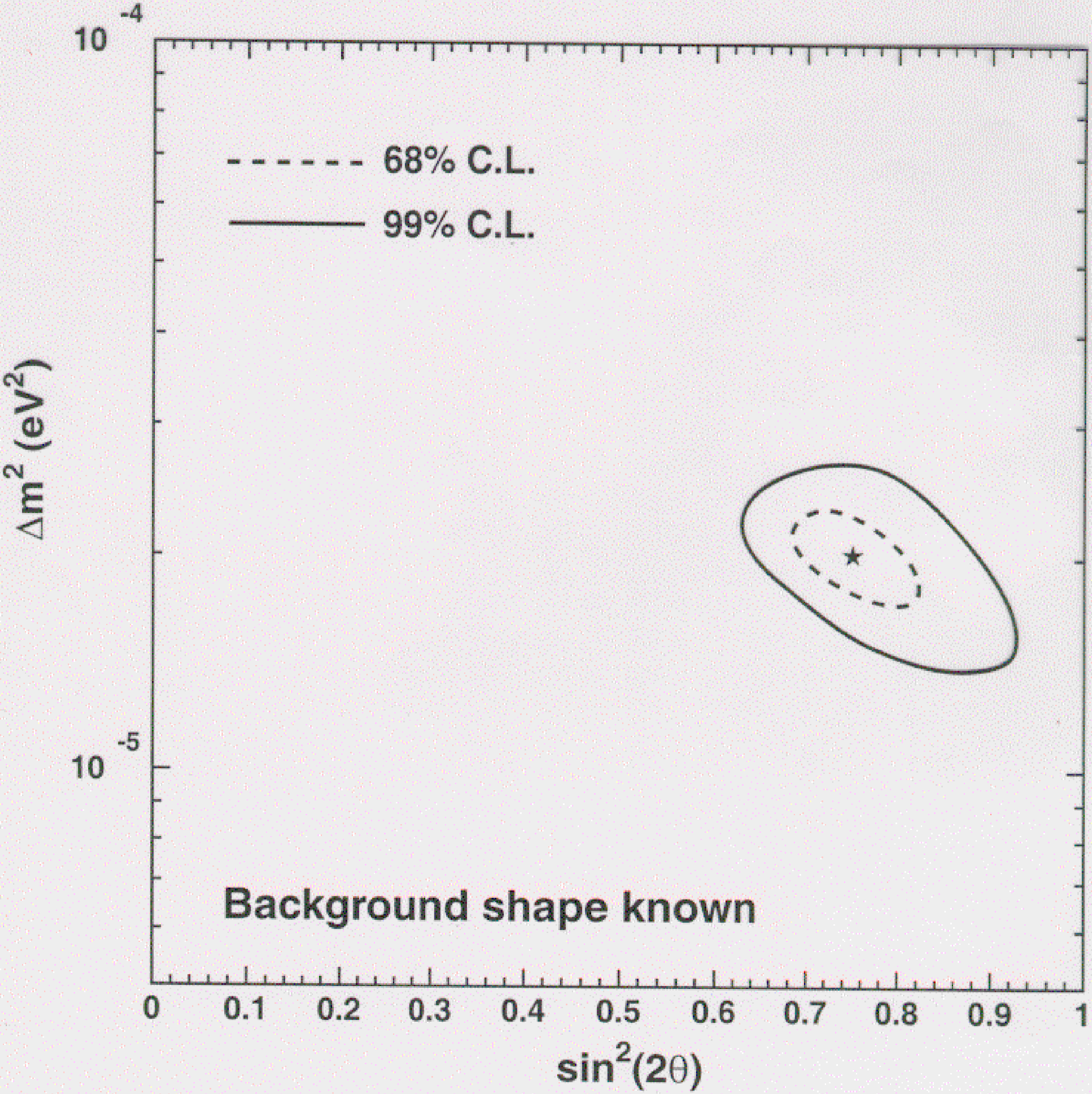
Total background 0.1 day^{-1}

$\bar{\nu}_e$ - signal 2 day^{-1}

For U/Th : 10^{-14} g/g Singles 1 kton 1.86 Hz

→ Random coincidence rate : 0.15 day^{-1}


KamLAND exclusion 3 years. Rate analysis 90% c.l.
Δm² / eV²
S:B=∞
S:B=10:1. B:±25%
S:B=10:1. B: on/off
LMAS
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻¹
1
sin²2Θ



10^-4
10^-5
68% C.L.
99% C.L.
Δm^2 (eV^2)
Background shape known
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
sin^2(2θ)

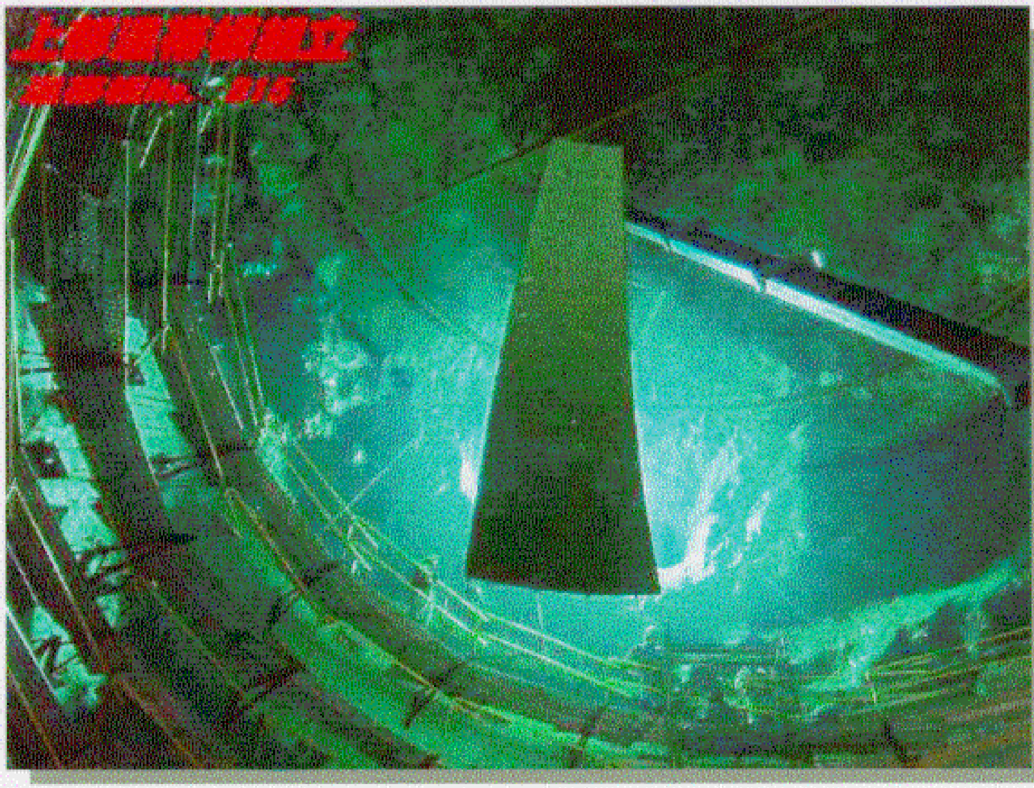
Status of KamLAND

- Steel sphere build and in place.
- Water, scintillator and buffer purification facilities under construction.
- Deployment test of full size balloon successfully completed.
- All phototubes delivered, tested and, calibrated. Kamiokande PMTs refurbished.
- Electronics under development.
- Calibration devices (LEDs, Laser flasher, CCD cameras, radioactive sources plus deployment systems) under development.

Schedule

- June 2000: start of PMT installation.
- October 2000: start scintillator filling.
- Spring 2001: start data taking.

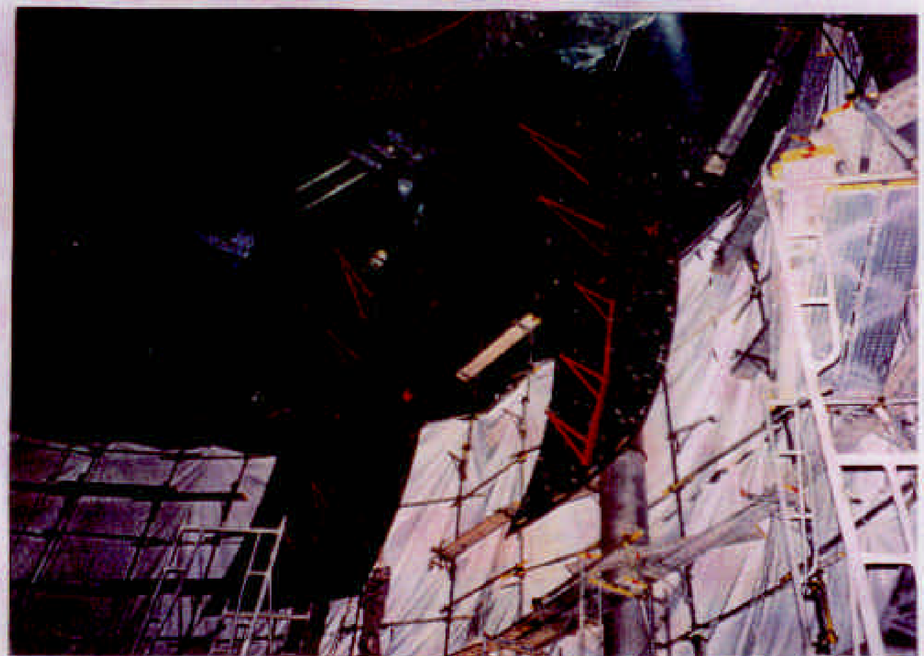
KamLAND October 14, 1999



写真名前.jtd

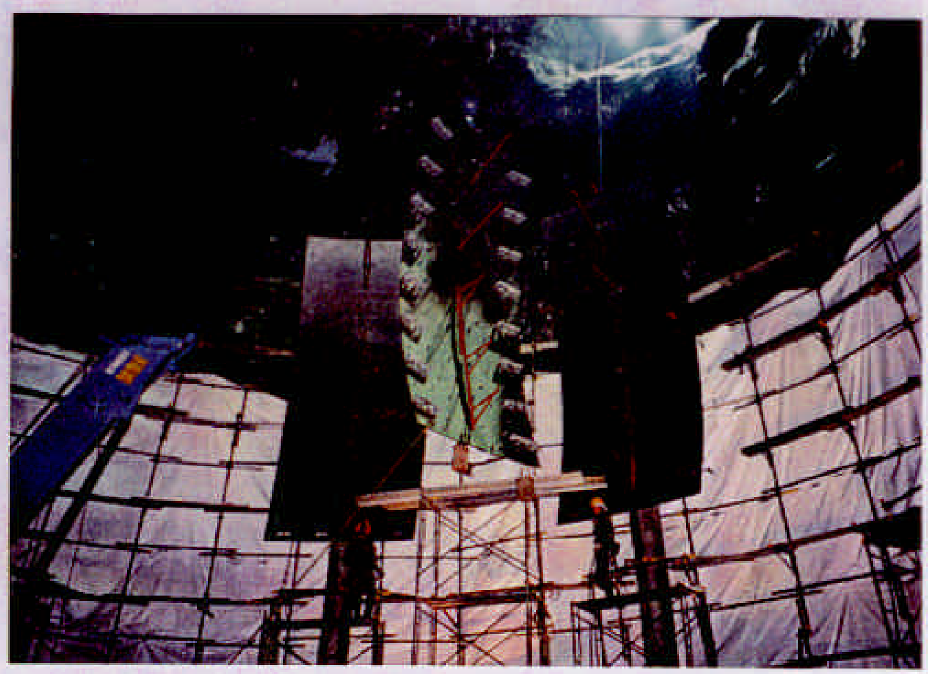
赤道板（Ｃ１３）

吊り込み・組立



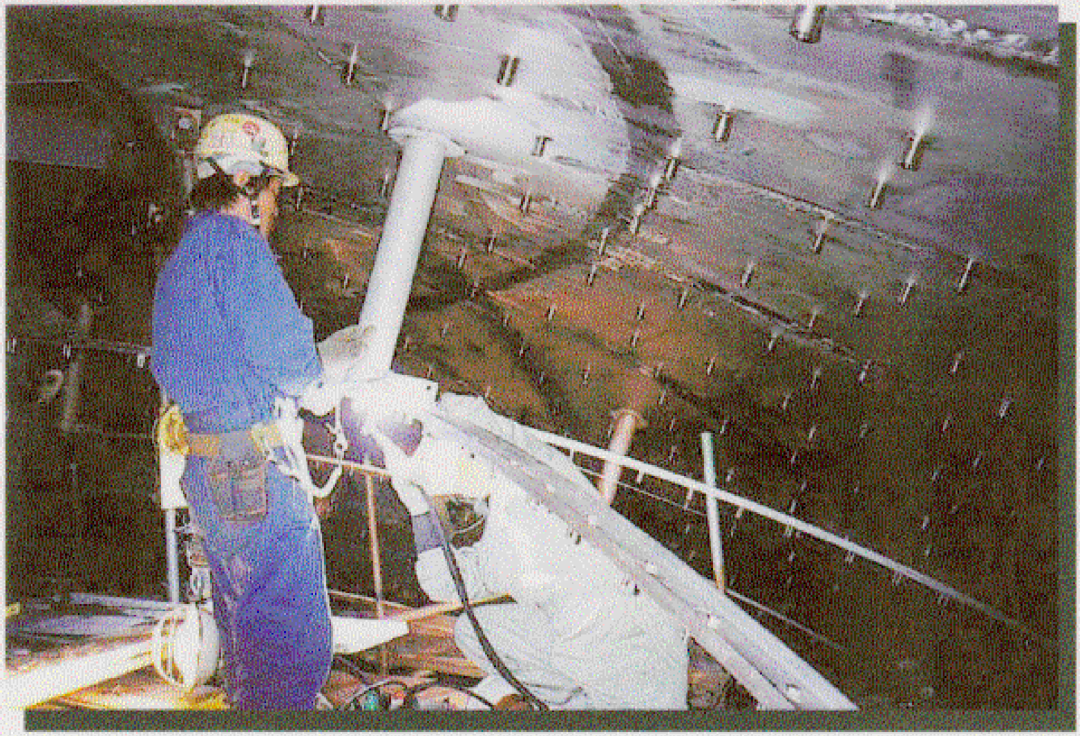
赤道板（Ｃ１４）

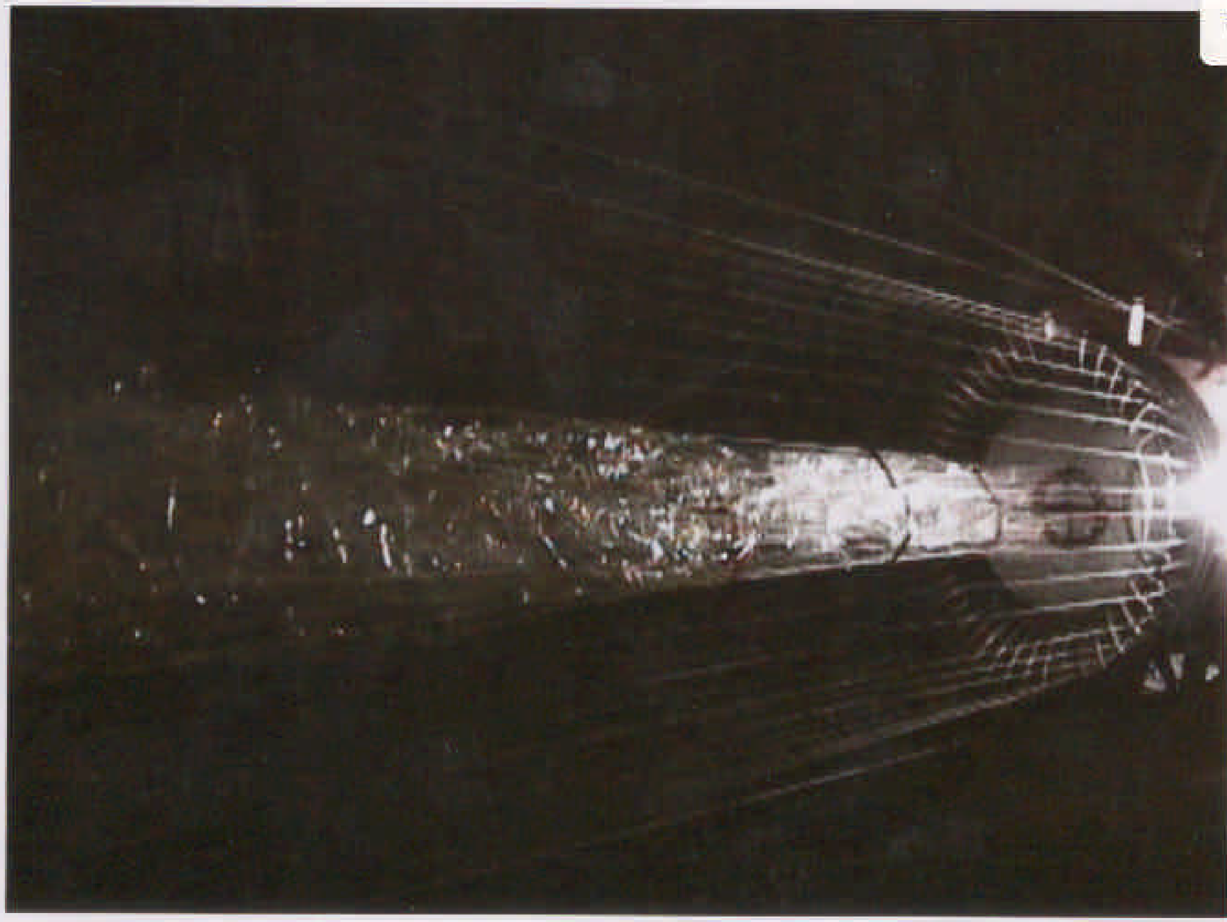
吊り込み・組立



KamLAND November 11, 1999

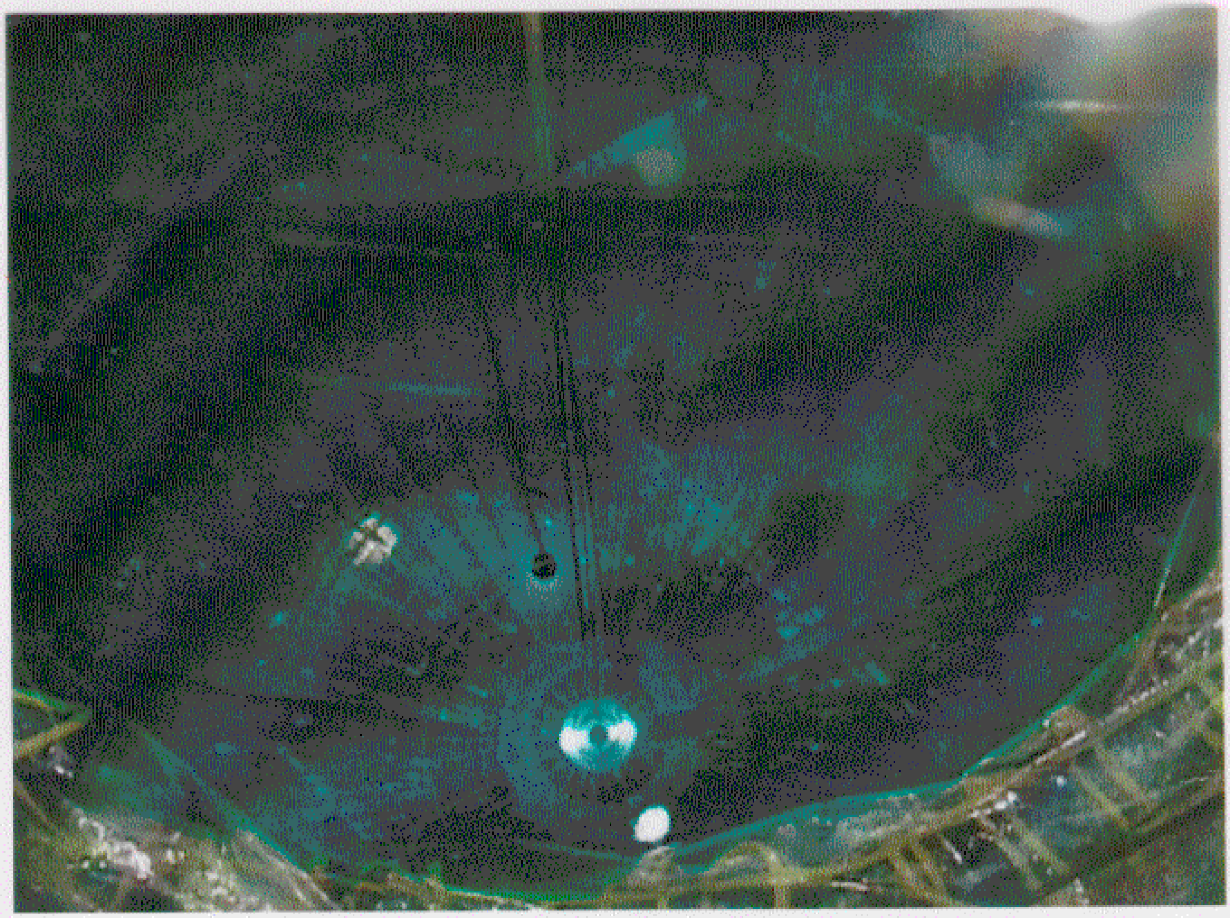
Kamland March 8, 2000





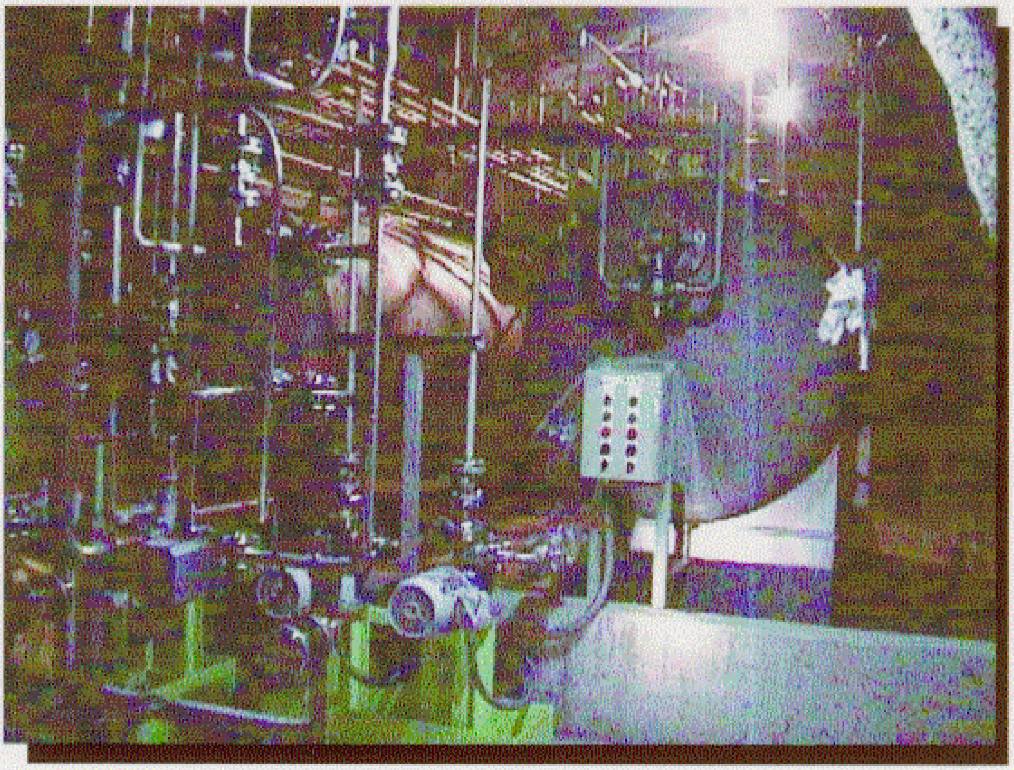
Balloon pulled up.

Piepke - 31




1605

KamLAND June 9, 1999



Other Physics Opportunities at KamLAND

- Detection of low energy solar ^{7}Be neutrinos through $\nu_e + e^- \rightarrow \nu_e + e^-$
- Detection of a gallactic supernova. Neutral current interaction in ^{12}C
- Detection of terrestrial anti-neutrinos to constrain U/Th of earth
- Search for double beta decay

Alternative uses of KamLAND can be worked out while the reactor neutrino data is taken.

Detector is build in a way as not to preclude a later up-grade for solar neutrino detection (acrylic Rn shield, construction material selection, clean room in dome).

Other unexpected findings?

Conclusion

- A strong US-Japanese collaboration is in place to build and perform the experiment.
- The KamLAND experiment is fully funded through the Japanese Ministry of Science and Education and the US DoE.
- Detector construction is well under way with data taking expected to start next year.
- We believe that KamLAND will be able to provide convincing proof or disproof of the Large Mixing Angle Solution to the solar neutrino problem which will be completely indepent of our understanding of the suns interior within 1 to 2 years of data taking.
- The experience gained during the reactor neutrino data taking might allow us to address a wealth of other physics issues.