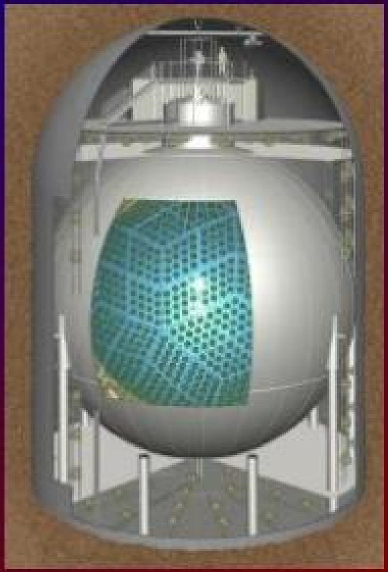
Reactor Neutrinos — **Kam**LAND and beyond

$\bar{\nu}_e$



Yoshi Uchida

Imperial College London

Overview

Introduction to Reactor Antineutrino Experiments

KamLAND Reactor Results

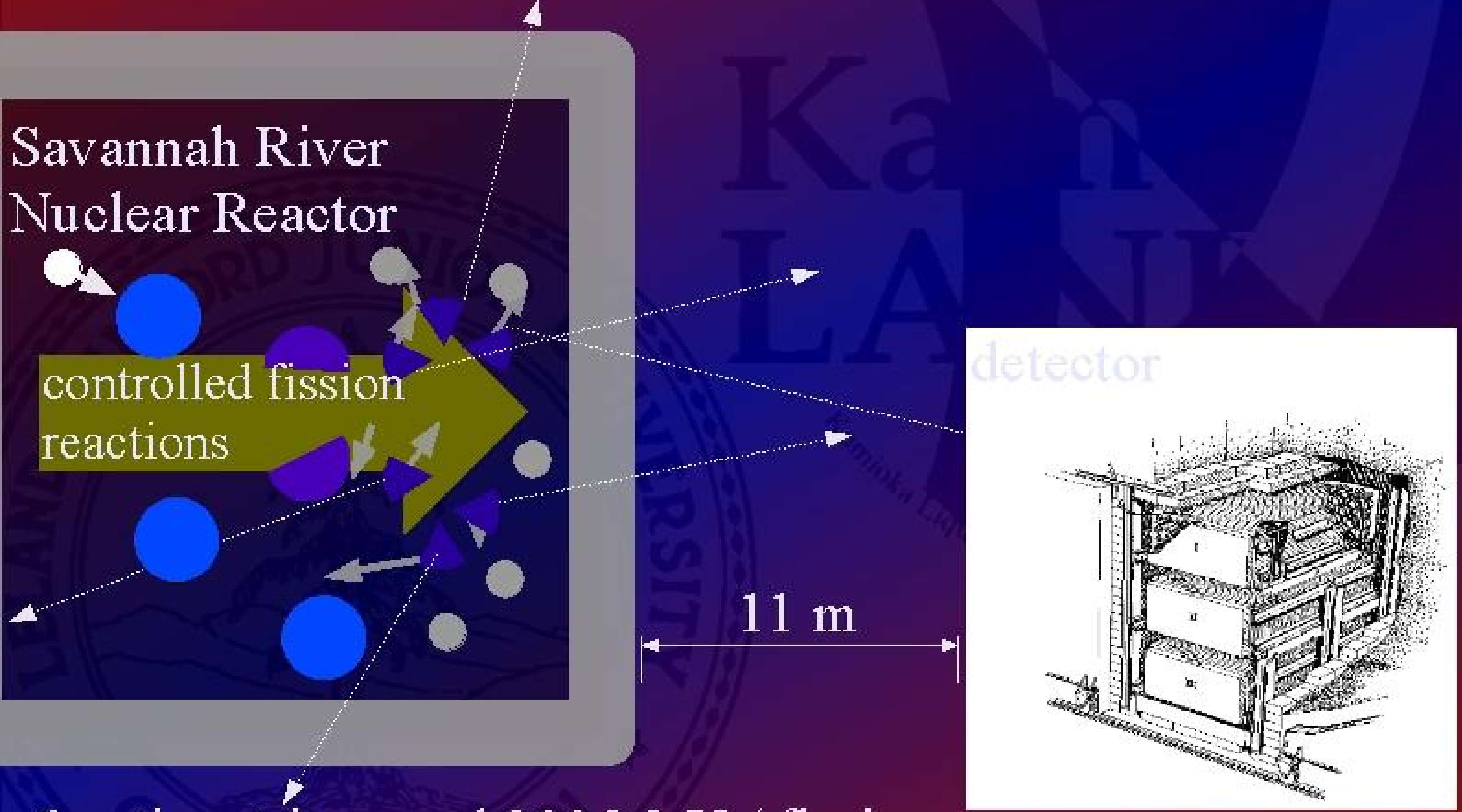
Future Reactor Antineutrino Physics

Non-Reactor Physics at KamLAND

(cf. Gratta, Oberauer at Neutrino 2004)

The First Reactor Antineutrino Experiment

1956 Discovery of the Neutrino by Reines and Cowan



Savannah River Nuclear Reactor

controlled fission reactions

detector

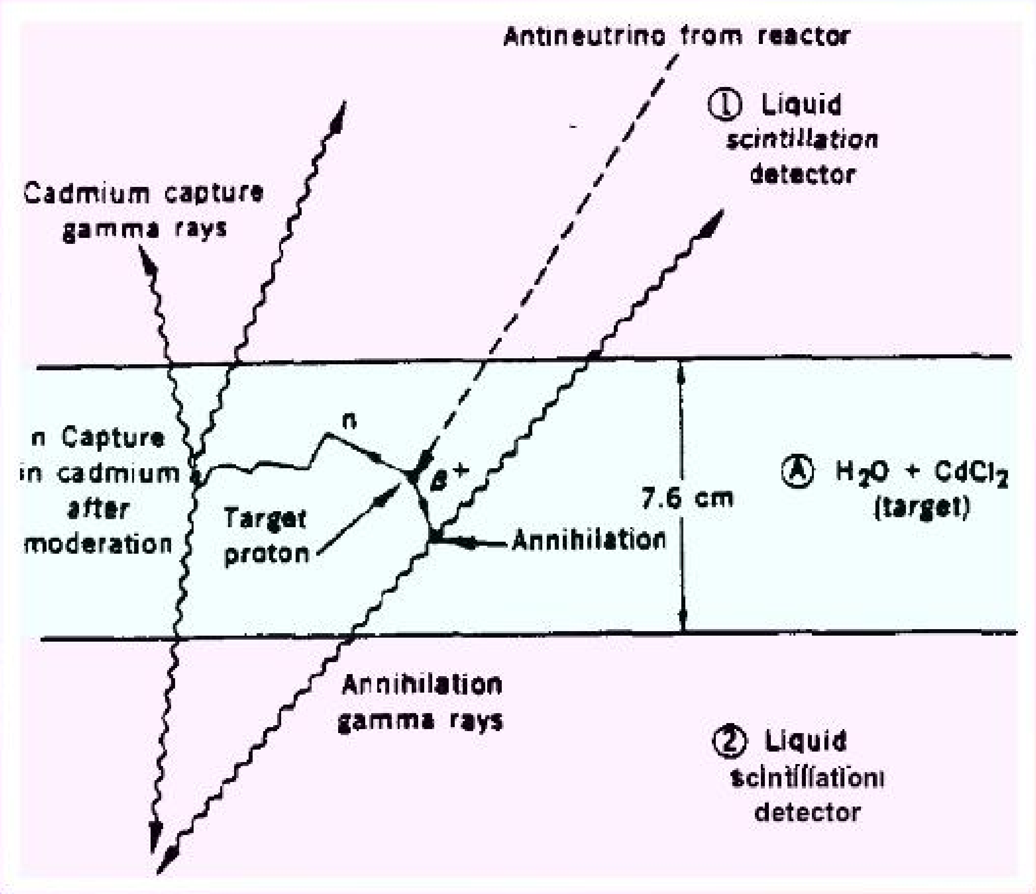
11 m

6 antineutrinos and 200 MeV / fission

The First Reactor Antineutrino Experiment

1956 Discovery of the Neutrino by Reines and Cowan

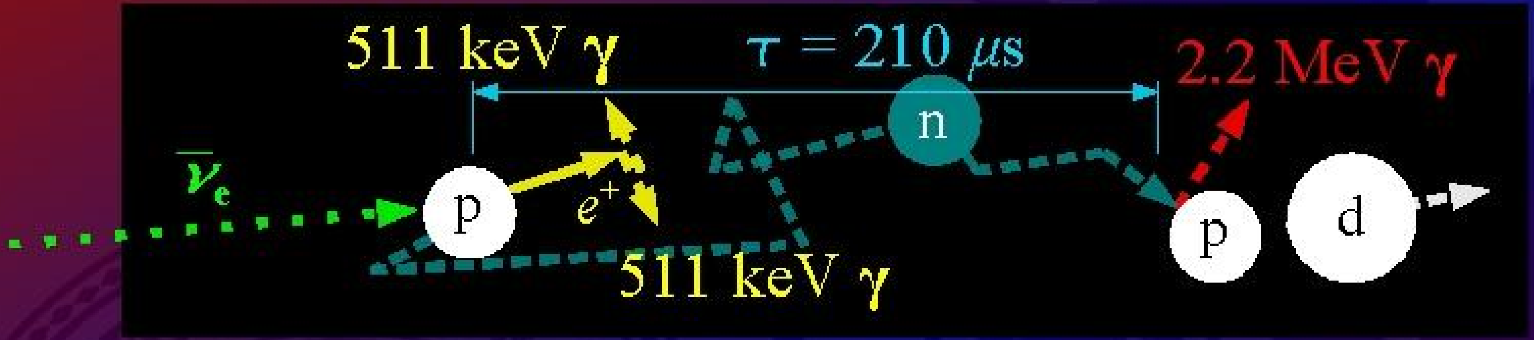
Detection Method



"Giant" detector with 1400 litres of the newly developed liquid scintillator

Antineutrino Signature in Scintillator

Antineutrino interactions leave distinctive 2-part signature

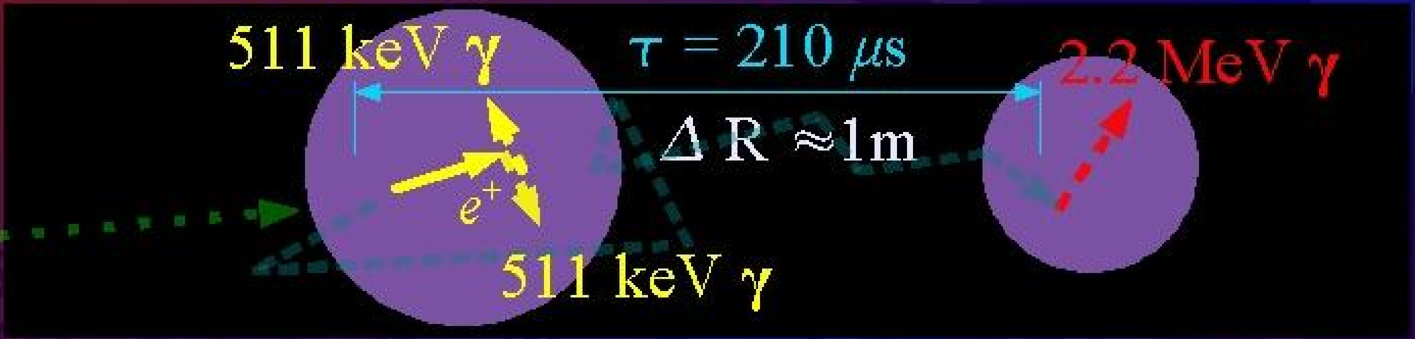


1. Prompt Part:
   positron with $E_{e^+} \simeq E_{\nu_e} - (M_n - M_p) - M_{e^+}$
   & two **511 keV photons**
2. Delayed Part:
   2.2 MeV photon from neutron capture on p,
   capture $\tau \approx 210\ \mu s$

Delayed-coincidence signature allows high-purity tagging of low-rate antineutrino signal (KamLAND trigger: 30 Hz)

Antineutrino Signature in Scintillator

Antineutrino interactions leave distinctive 2-part signature

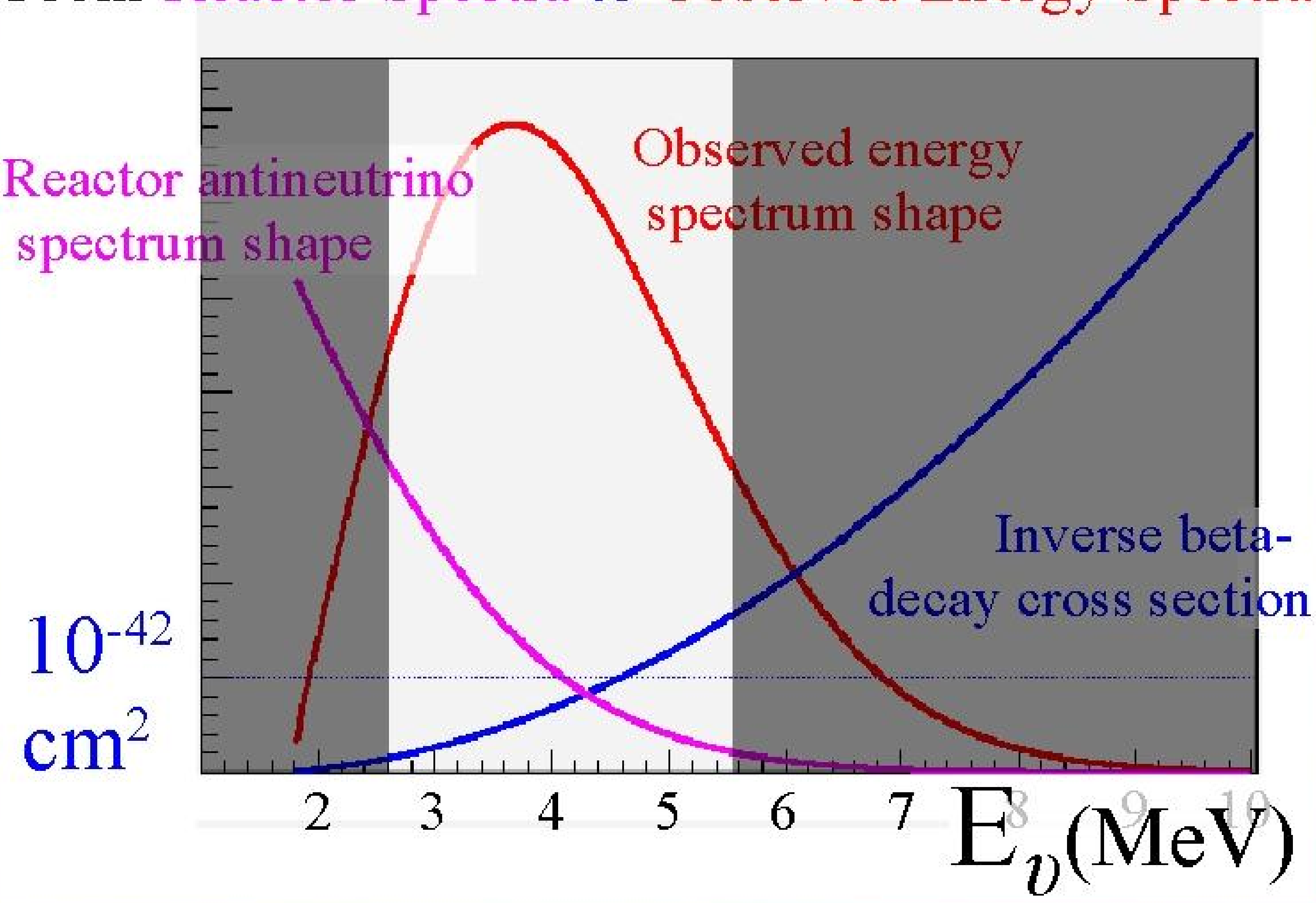


1. Prompt Part:
   positron with $E_{e^+} \simeq E_{\nu_e} - (M_n - M_p) - M_{e^+}$
   & two **511 keV photons**
2. Delayed Part:
   2.2 MeV photon from neutron capture on p,
   capture $\tau \approx 210\ \mu s$

Experiment-dependent,
eg. with Gd, Cd loading

Delayed-coincidence signature allows high-purity tagging of low-rate antineutrino signal (KamLAND trigger: 30 Hz)

From Reactor Spectra to Observed Energy Spectra



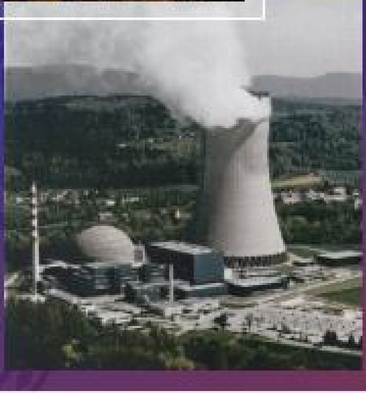
Reactor Antineutrino Oscillation Searches

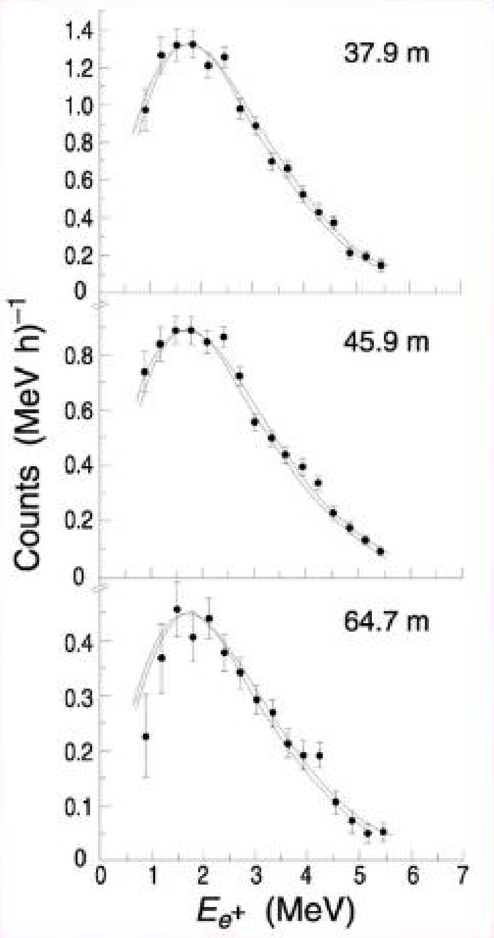
Baselines up to 1 km →
no deficits / oscillations:

Goesgen

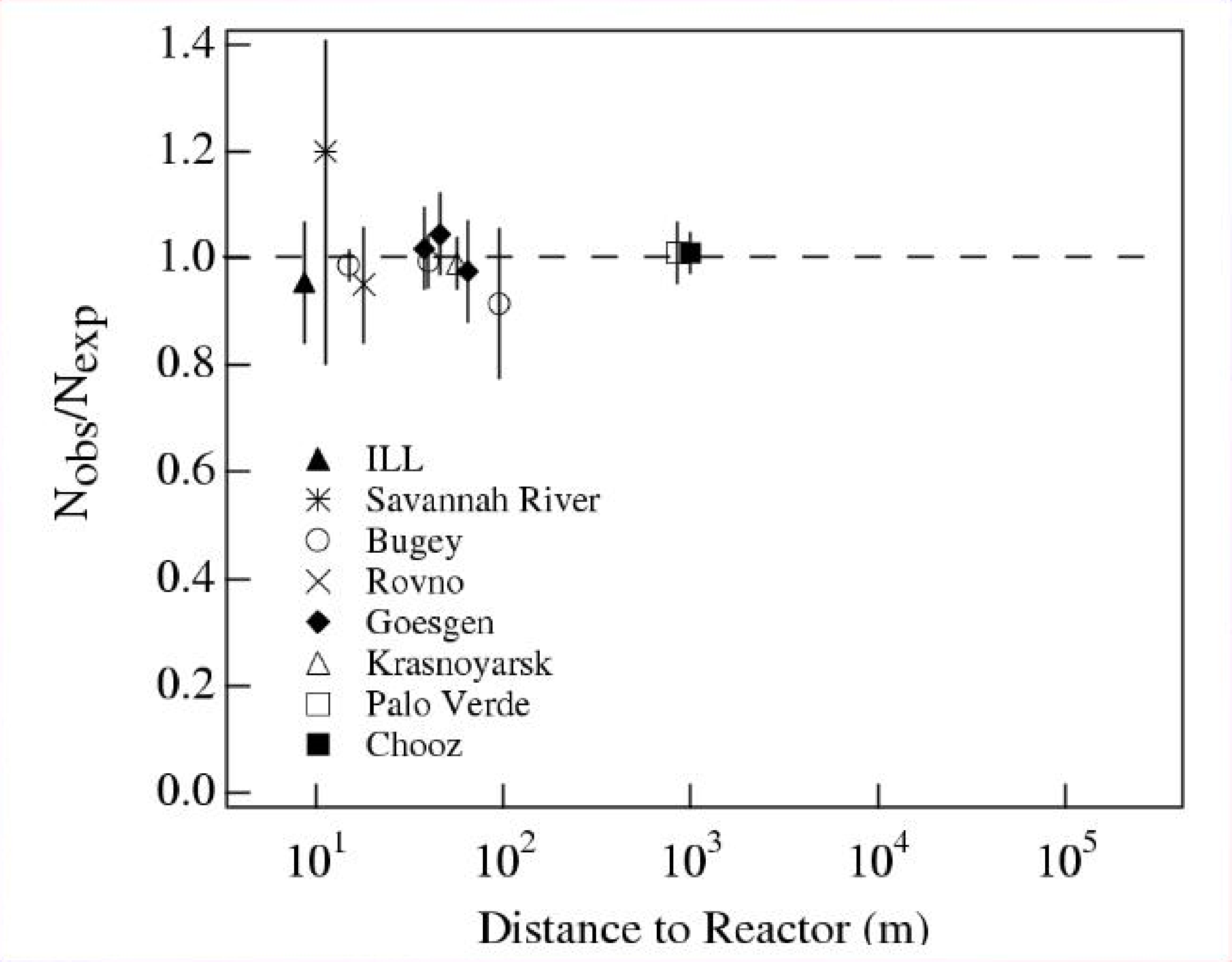
Chooz

Palo Verde





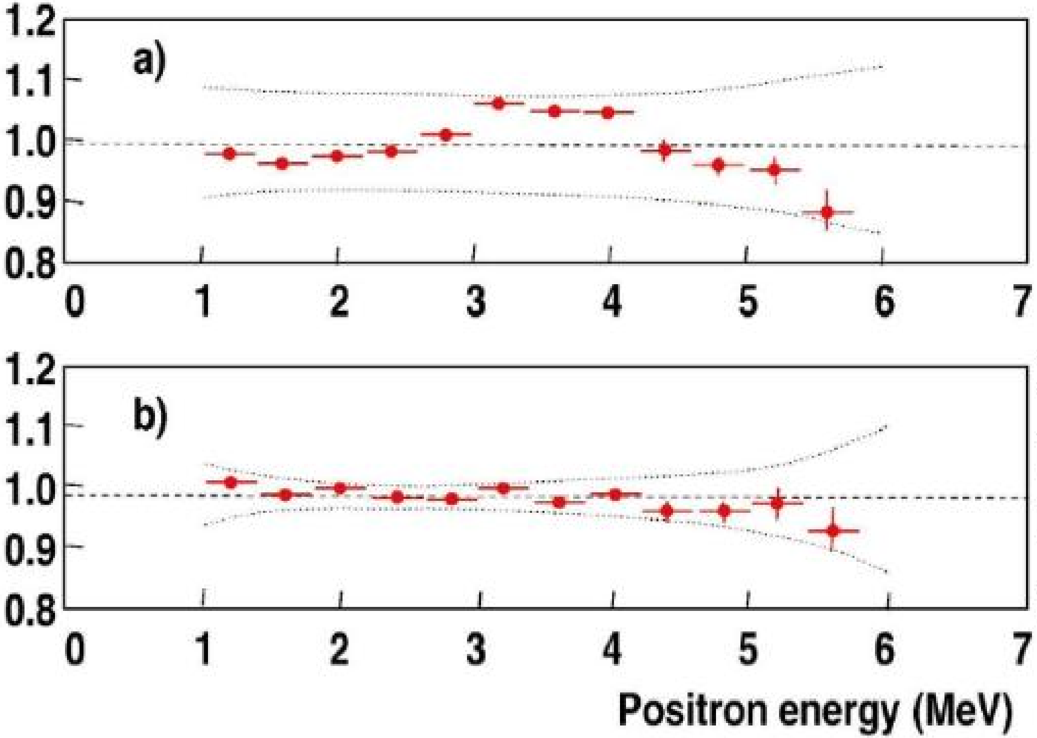
Reactor Antineutrino Oscillation Searches



Bugey

Short baseline, high statistics (0.15 M evts) allowed detailed study of reactor and detection characteristics

Measured/Expected Ratio



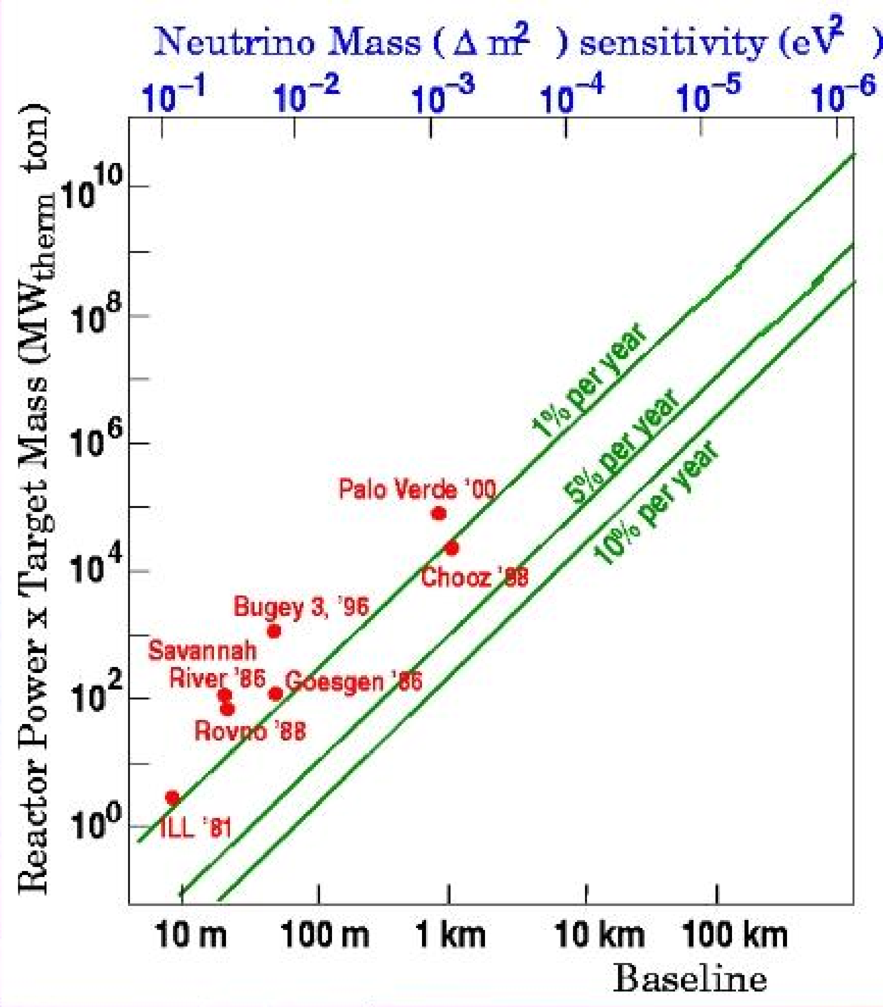
Simple Calculation

Best Prediction using beta spectra and calculations

Probing Oscillations with Reactor Antineutrinos

Reactor Flux & Detector Size v. Baselines —

Experimental Sensitivity to Δm^2



$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2(2\theta_{12}) \times \sin^2\left(1.27\,\Delta m^2_{12}(\mathrm{eV}^2)\,\frac{L(\mathrm{m})}{4(\mathrm{MeV})}\right)$$

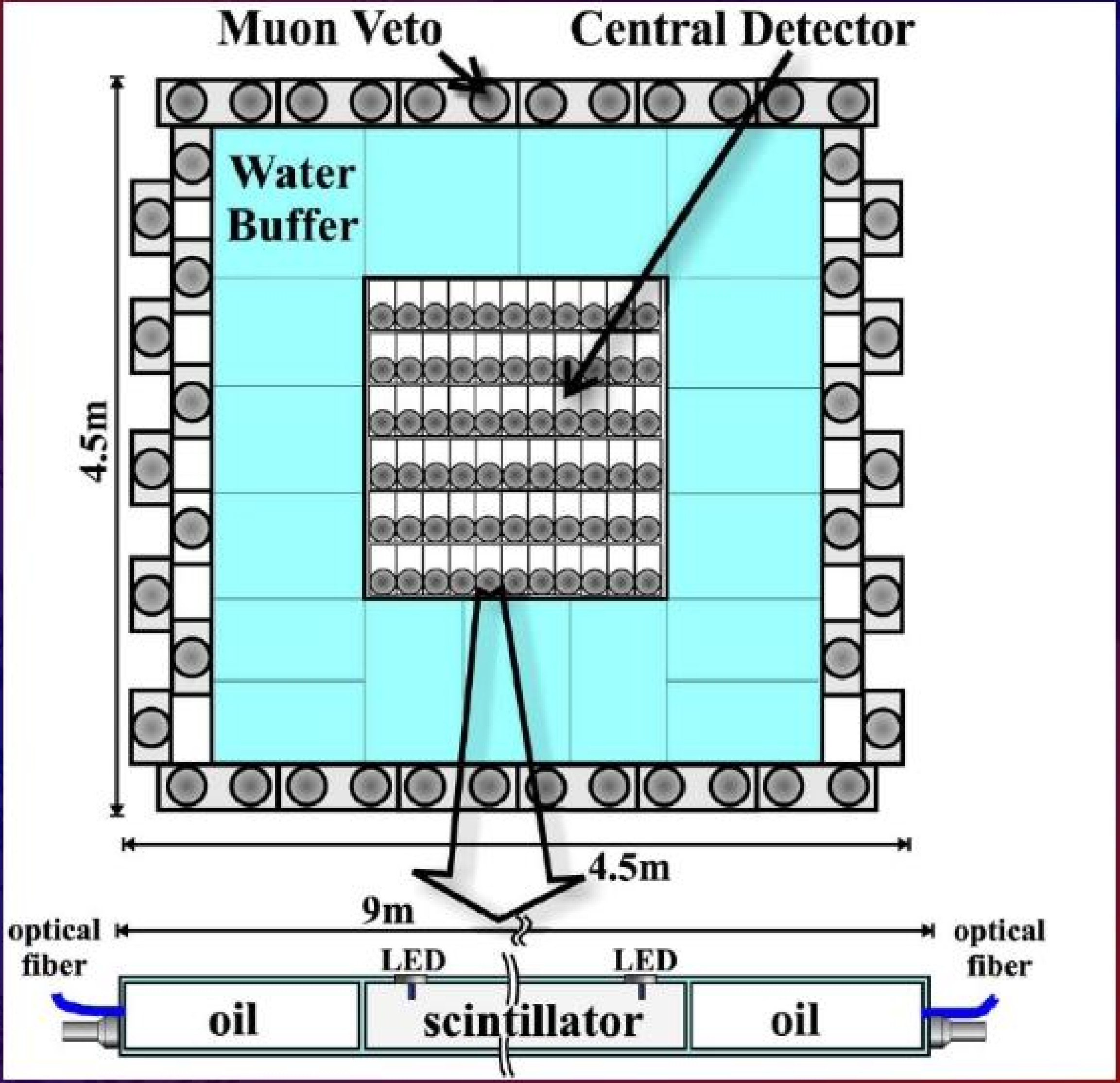
Yoshi.Uchida@imperial.ac.uk

Palo Verde

32 m.w.e.
11.6 GW

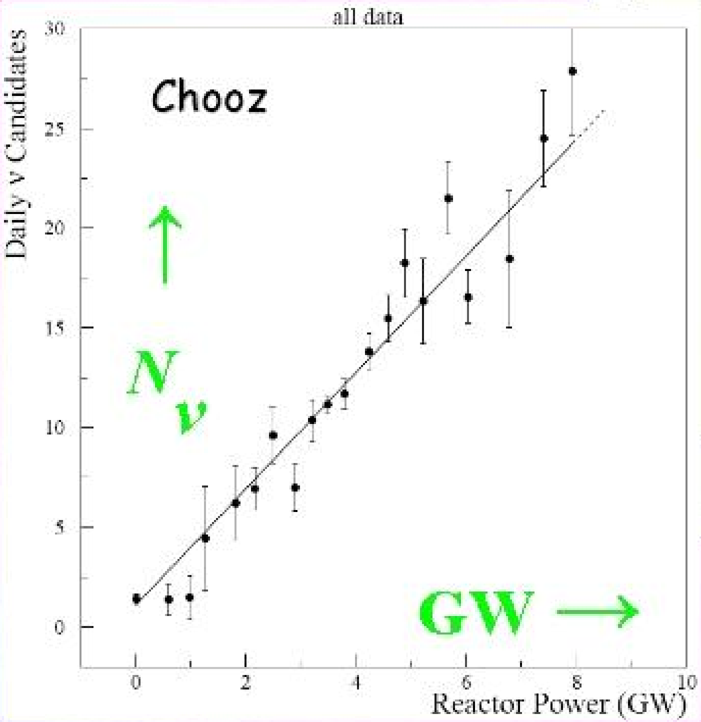
890m and
750m

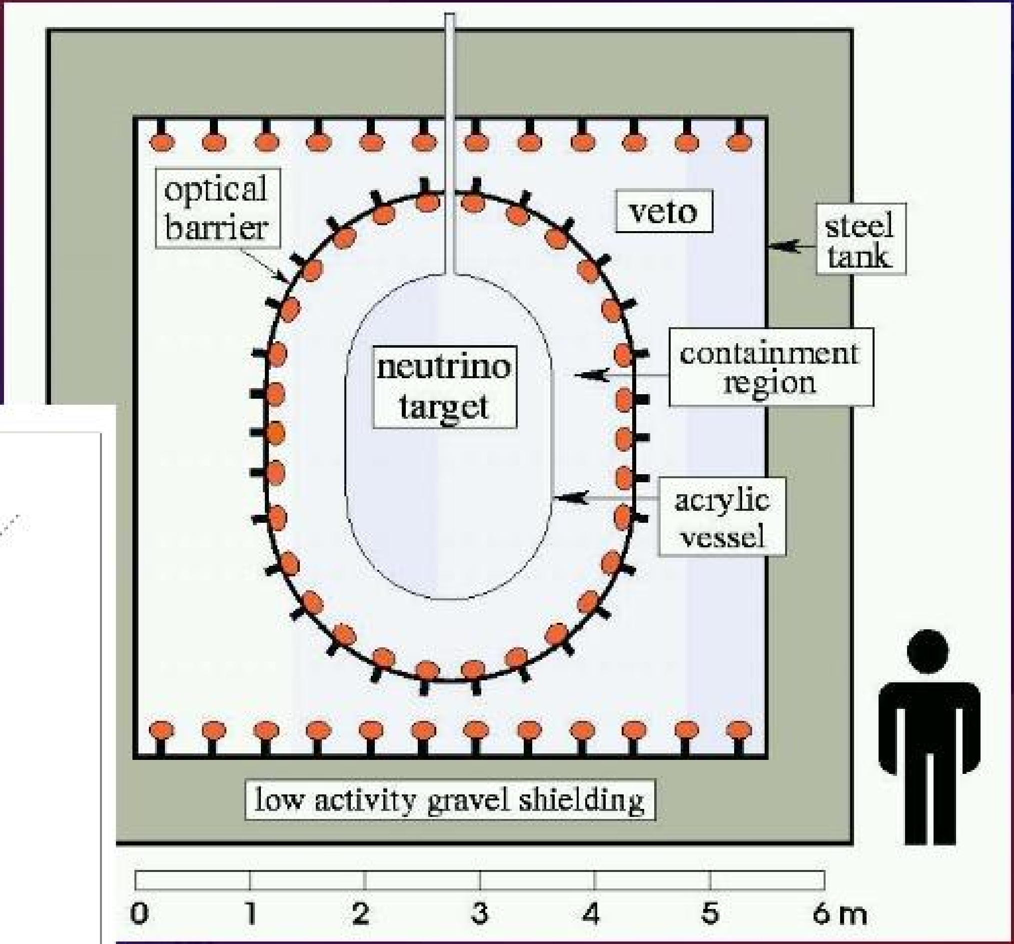
50 evts/day



Chooz

300 m.w.e.
8.5 GW
1115m and 998m
25 evts/day





12 t GW y --
Ran during reactor turn-on

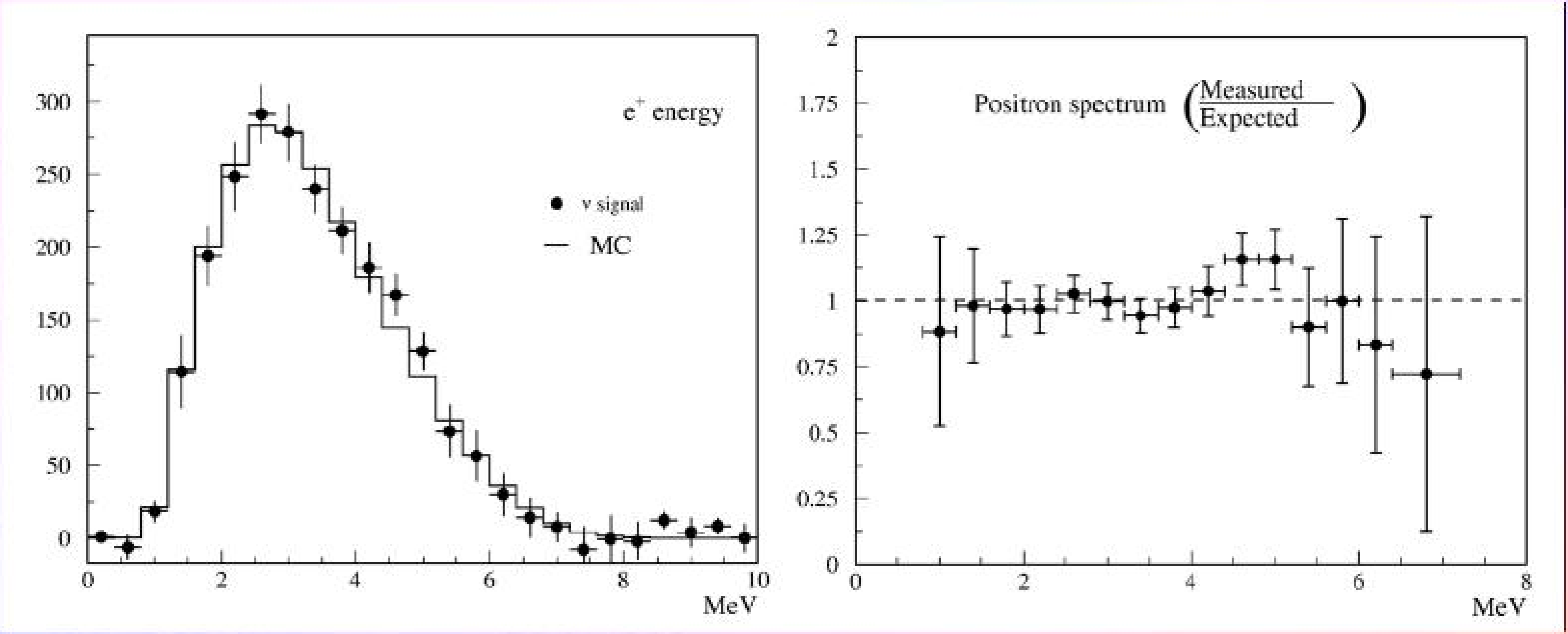
Yoshi.Uchida@imperial.ac.uk

Chooz and Palo Verde

Looked for reactor antineutrino disappearance at ≈1 km

Δm^2 corresponds to atmospheric neutrinos

Should see deficit if atm. effects due to $\nu_\mu \longrightarrow \nu_e$



Yoshi.Uchida@imperial.ac.uk

Chooz and Palo Verde

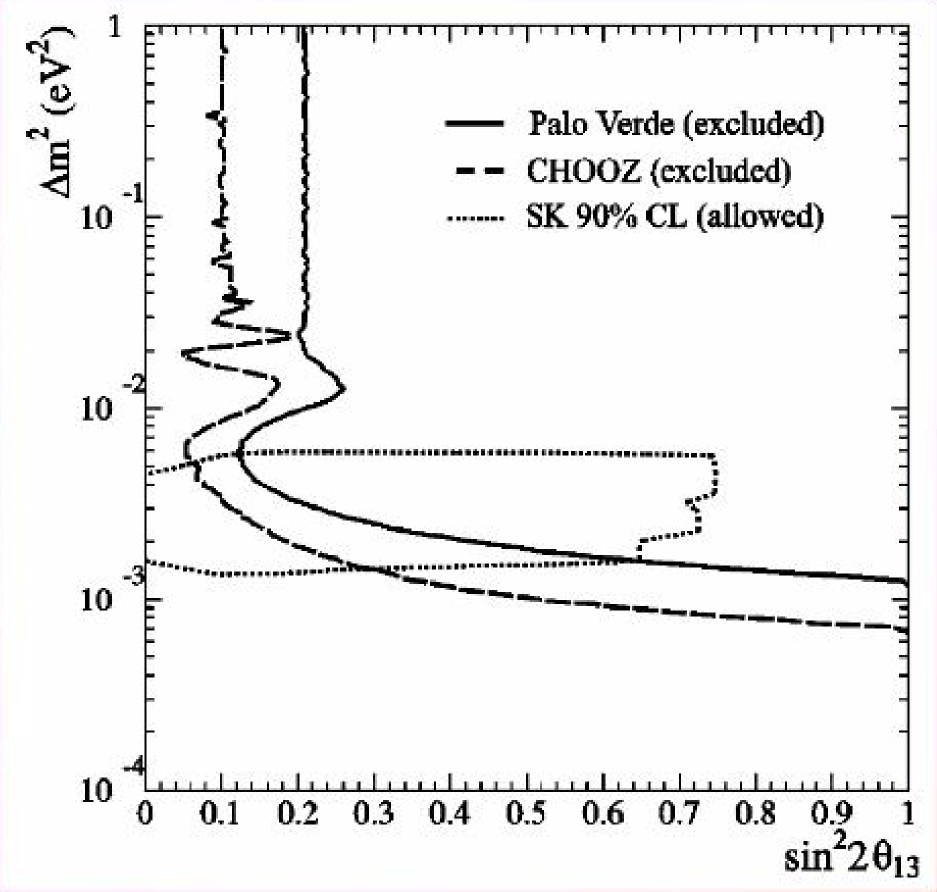
$$P(\bar{\nu}_e \to \bar{\nu}_e) \cong 1 - \sin^2 2\theta_{13} \sin^2(\frac{\Delta m^2_{atm} L}{4E}) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2(\frac{\Delta m^2_{12} L}{4E})$$

No significant deficit

→ limit on θ_{13}

Next generation
1 km baseline
reactor experiments
poised to “measure” θ_{13}

...but in the meantime....



Location – Kamioka, Japan

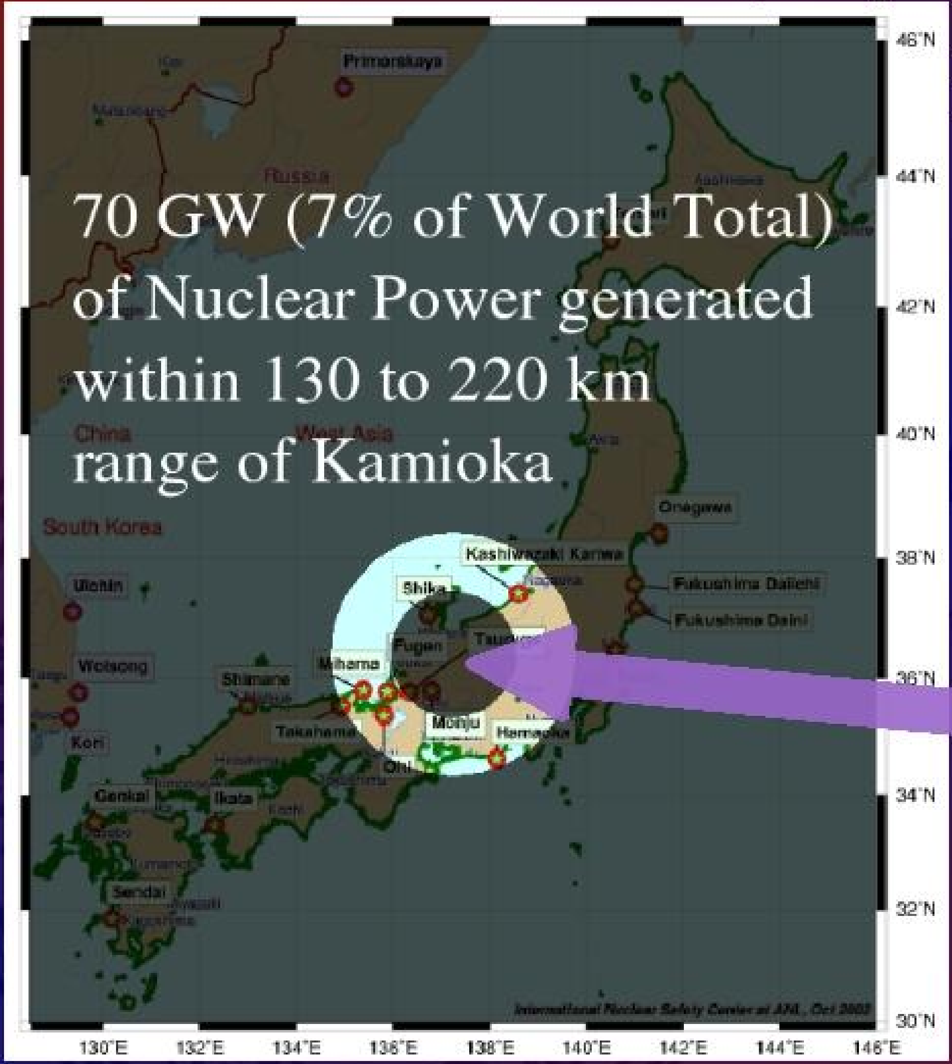
Former site of Kamiokande detector, in Kamioka Pb/Zn mine

KamLAND

Kamioka Liquid scintillator Anti Neutrino Detector

Yoshi.Uchida@imperial.ac.uk

Location – Kamioka, Japan



70 GW (7% of World Total) of Nuclear Power generated within 130 to 220 km range of Kamioka

Former site of **Kamiokande** detector, **in Kamioka Pb/Zn mine**

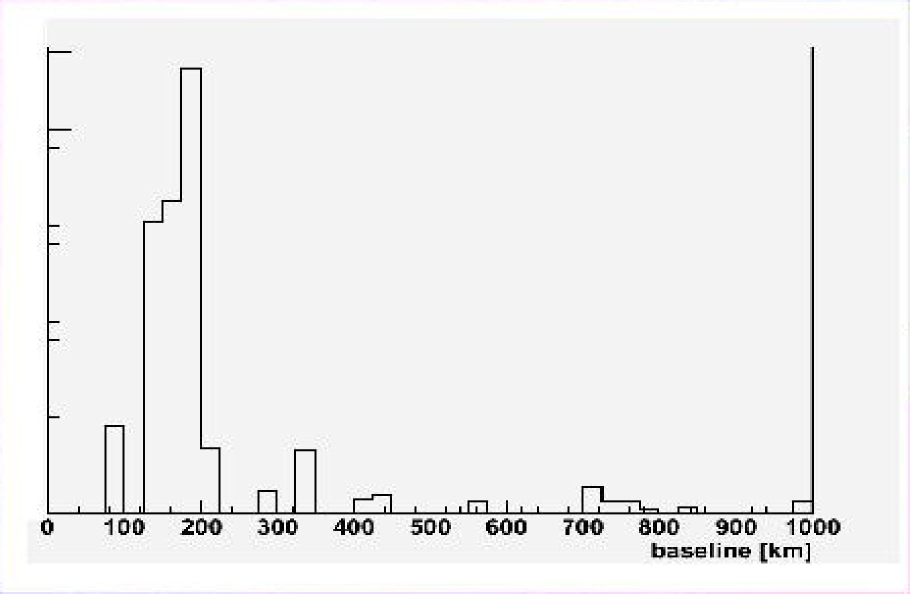
KamLAND

Kamioka Liquid scintillator Anti Neutrino Detector

Yoshi.Uchida@imperial.ac.uk

Location
– Reactor Fluxes

86% of antineutrinos from 180 ±35 km baselines



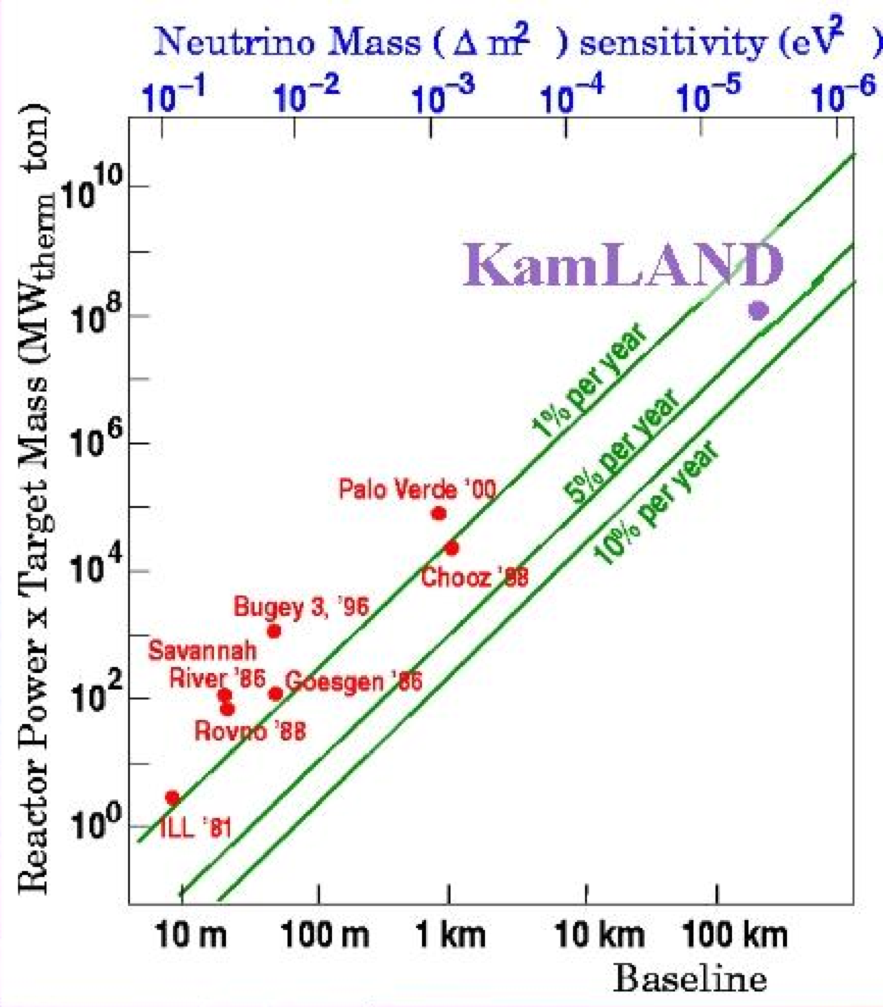
Site	Distance (km)	# of cores	P(ther.) (GW)	flux $(\bar{\nu}\ cm^{-2}s^{-1})$
Japan				
Kashiwazaki	160.0	7	24.6	4.25×10^{5}
Ohi	179.5	4	13.7	1.88×10^{5}
Takahama	190.6	4	10.2	1.24×10^{5}
Hamaoka	214.0	4	10.6	1.03×10^{5}
Tsuruga	138.6	2	4.5	1.03×10^{5}
Shiga	80.6	1	1.6	1.08×10^{5}
Mihama	145.4	3	4.9	1.03×10^{5}
Fukushima-1	344.0	6	14.2	5.3×10^{4}
Fukushima-2	344.0	4	13.2	4.9×10^{4}
Tokai-II	294.6	1	3.3	1.7×10^{4}
Shimane	414.0	2	3.8	9.9×10^{3}
Onagawa	430.2	2	4.8	9.8×10^{3}
Ikata	561.2	3	6.0	8.4×10^{3}
Genkai	755.4	4	6.7	5.3×10^{3}
Sendai	824.1	2	3.3	3.5×10^{3}
Tomari	783.5	2	5.3	2.4×10^{3}
Korea				
Ulchin	~750	4	11.2	8.8×10^{3}
Wolsong	~690	4	8.1	7.5×10^{3}
Yonggwang	~940	6	16.8	8.4×10^{3}
Kori	~700	4	8.9	8.0×10^{3}
Total		69	175.7	1.34×10^{6}

Yoshi.Uchida@imperial.ac.uk

Probing Oscillations with Reactor Antineutrinos

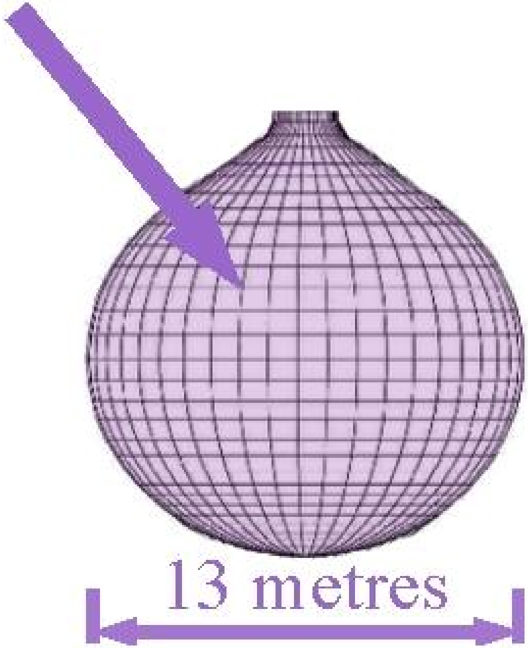
Reactor Flux & Detector Size v. Baselines —

Experimental Sensitivity to Δm^2



$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2(2\theta_{12}) \times \sin^2\left(1.27\,\Delta m^2_{12}(\mathrm{eV}^2)\frac{L(\mathrm{m})}{4(\mathrm{MeV})}\right)$$

KamLAND

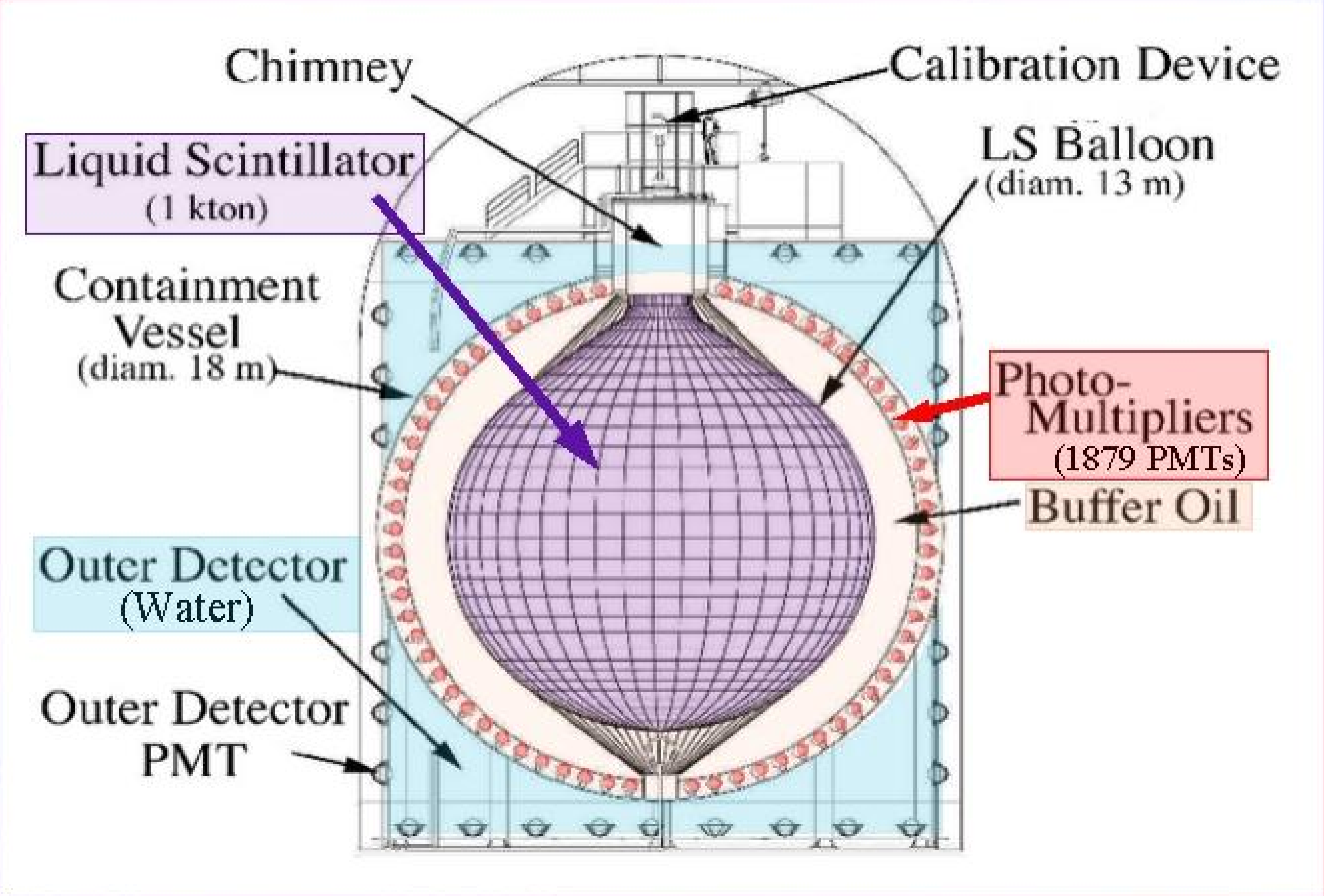


1000 tonnes of Liquid Scintillator

13 metres

Yoshi.Uchida@imperial.ac.uk

The **Kam**ioka **L**iquid Scintillator **A**nti-**N**eutrino **D**etector



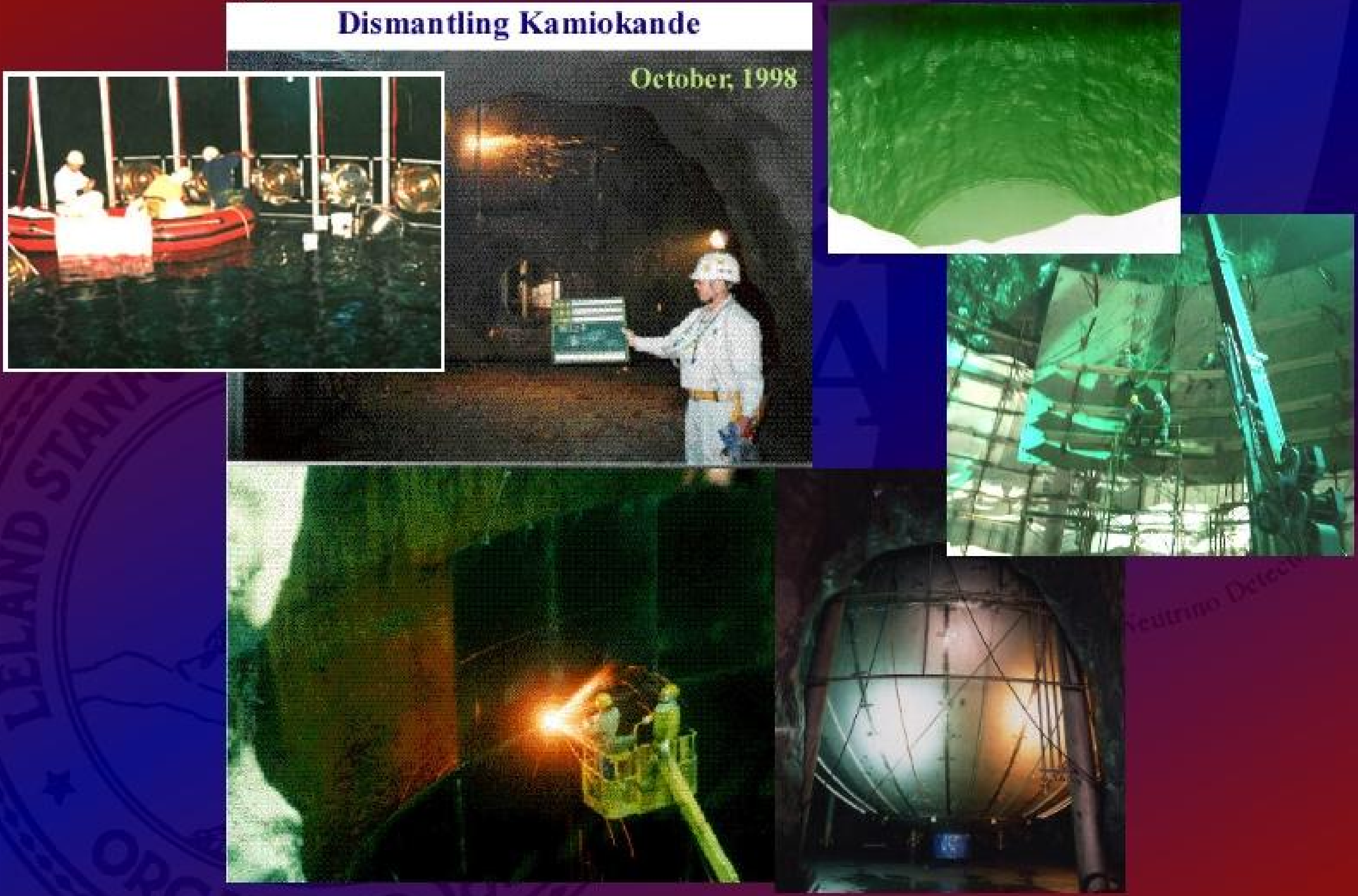
Yoshi.Uchida@imperial.ac.uk

KamLAND Site

1 km (2700 m water equiv.)
underground in
Kamioka Mine, Japan

Yoshi.Uchida@imperial.ac.uk

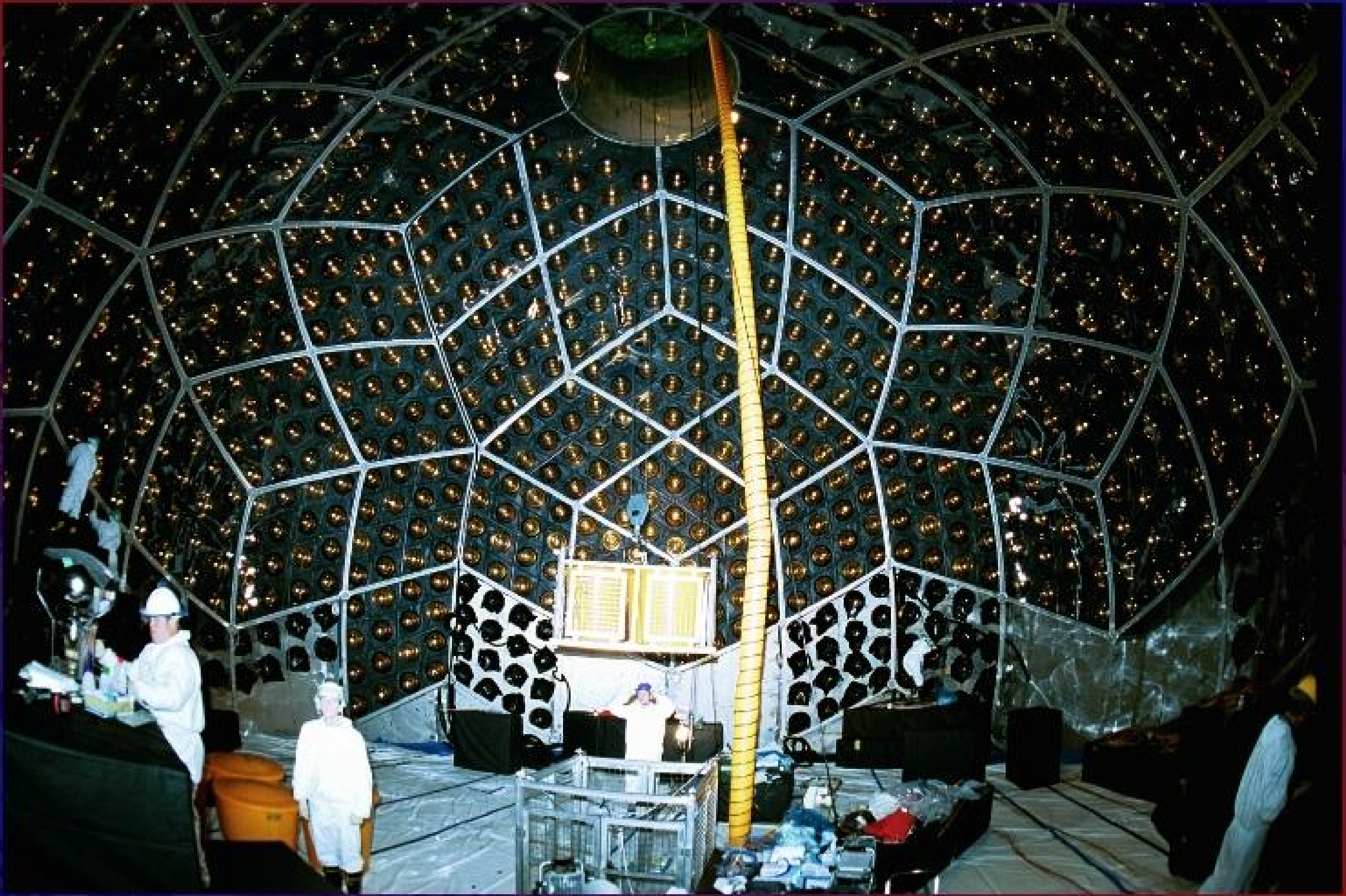
Site Preparation / Tank Installation



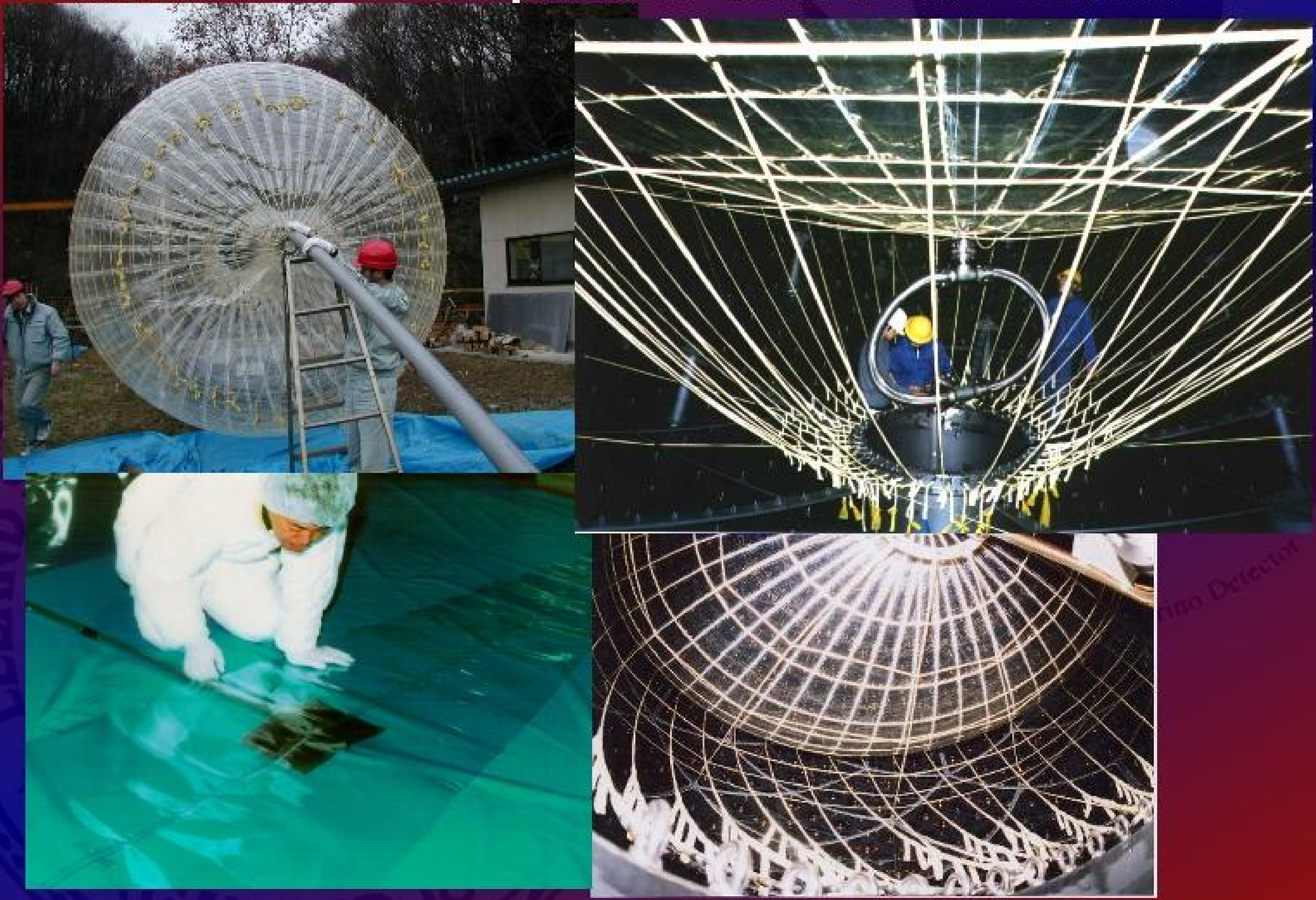
Dismantling Kamiokande

October, 1998

Construction: PMT Installation



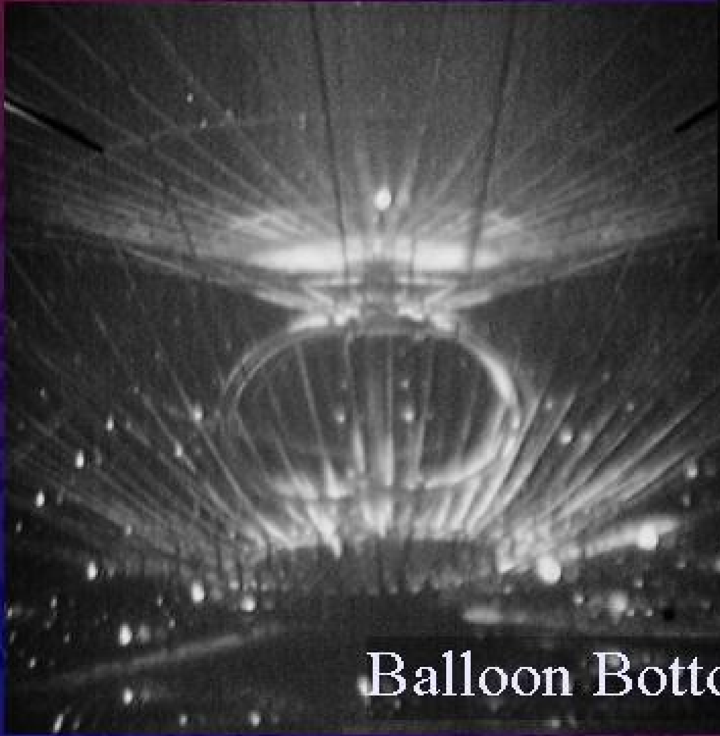
Balloon Development and Installation



The Balloon

(Internal CCD Images)

Balloon Top



Balloon Bottom

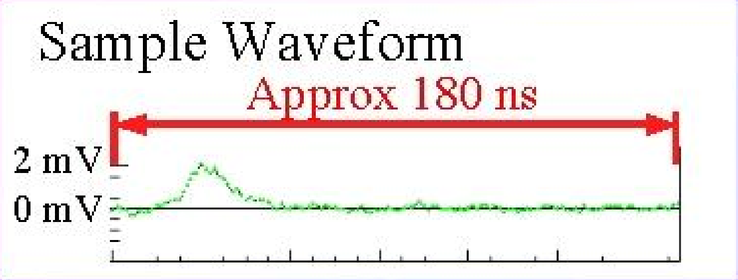
Yoshi.Uchida@imperial.ac.uk

Construction: Detector Filling

Yoshi.Uchida@imperial.ac.uk

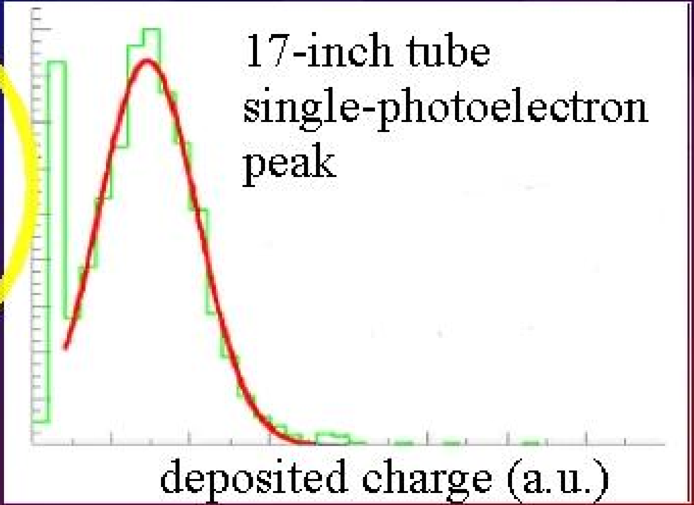
Photomultiplier Tubes

PMTs: convert photon striking its surface into an signal recordable by Front-End Electronics



1325 17-inch tubes — specially designed for KamLAND with exceptional timing/charge resolution (22% coverage)

554 20-inch tubes — from Kamiokande (12% coverage)



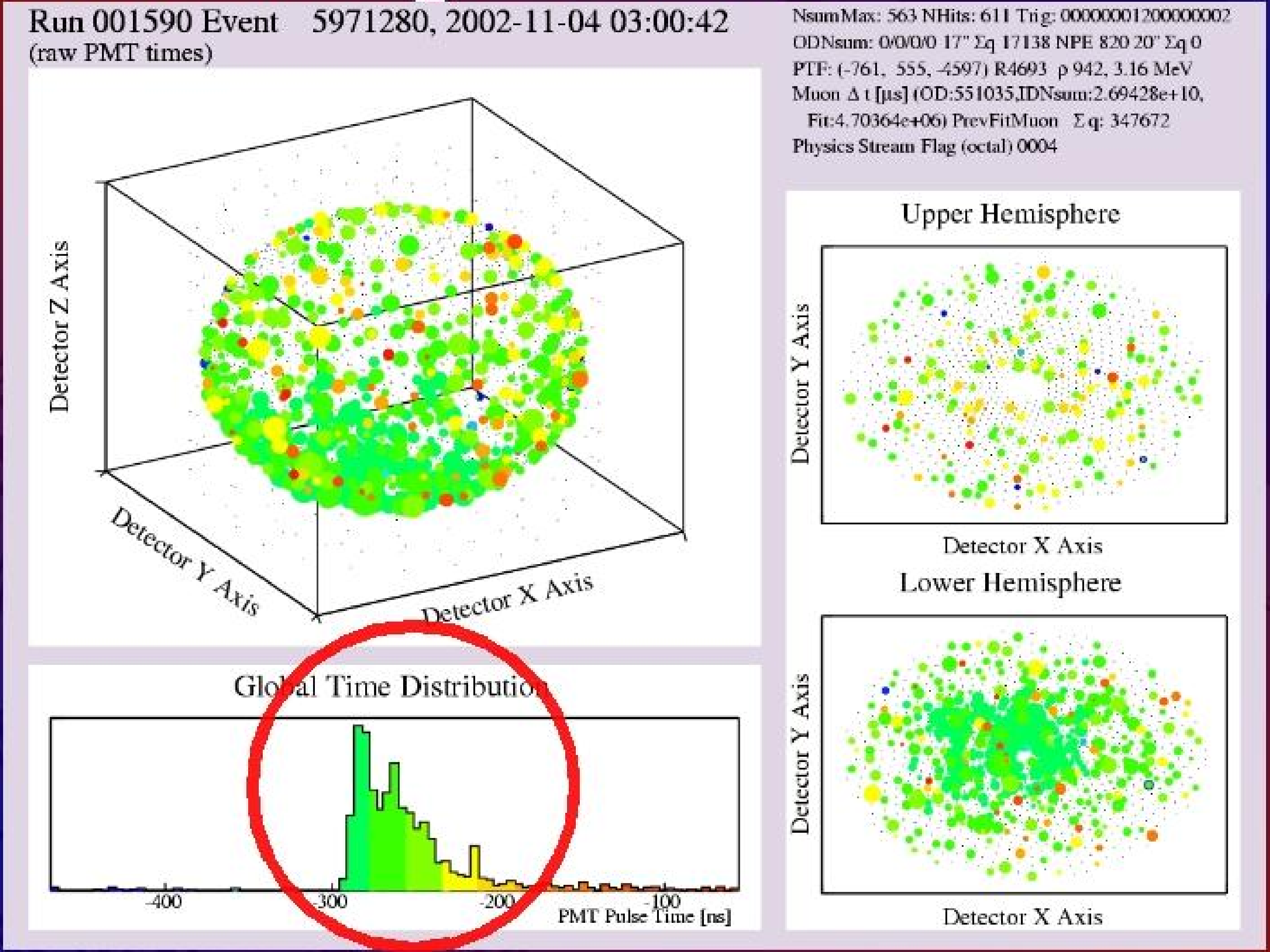
Yoshi.Uchida@imperial.ac.uk

KamLAND Timeline

Autumn 1998	Dismantling of Kamiokande
1999	Enlargement of cavern, tank installation
Summer 2000	PMT installation
Winter 2000 – 01	Veto counter installation
Feb – Apr 2001	Balloon insertion, inflation and tests
Apr – Sep 2001	Plumbing and Filling of Scintillator and Buffer
Aug – Sep 2001	Engineering runs with MACRO
Sep 2001	Electronics/Trigger/DAQ integration
End Sep 2001	First test data taking
Jan 22, 2002	**Data taking commences**
Dec 2002	**First Reactor Results** (145 days)
Oct 2003	**“Higher Energy Antineutrino” Results**
Jun 2004	**Second Reactor Results** (515 days)

Yoshi.Uchida@imperial.ac.uk

Scintillation Light Detection

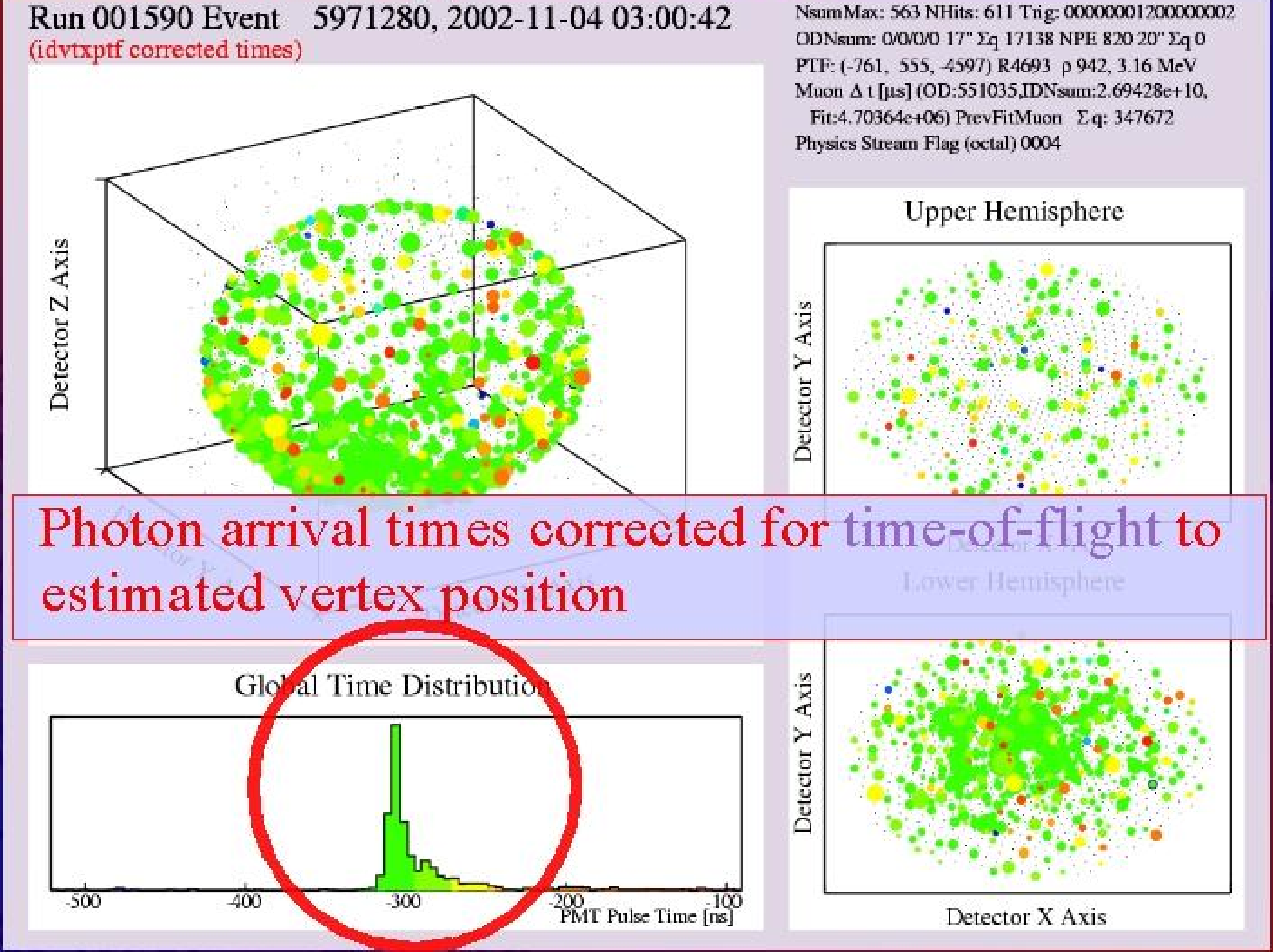


Run 001590 Event 5971280, 2002-11-04 03:00:42
(raw PMT times)

NsumMax: 563 NHits: 611 Trig: 00000001200000002
ODNsum: 0/0/0/0 17" Σq 17138 NPE 820 20" Σq 0
PTF: (-761, 555, -4597) R4693 ρ 942, 3.16 MeV
Muon Δ t [μs] (OD:551035,IDNsum:2.69428e+10,
Fit:4.70364e+06) PrevFitMuon Σ q: 347672
Physics Stream Flag (octal) 0004

Yoshi.Uchida@imperial.ac.uk

Scintillation Light Detection



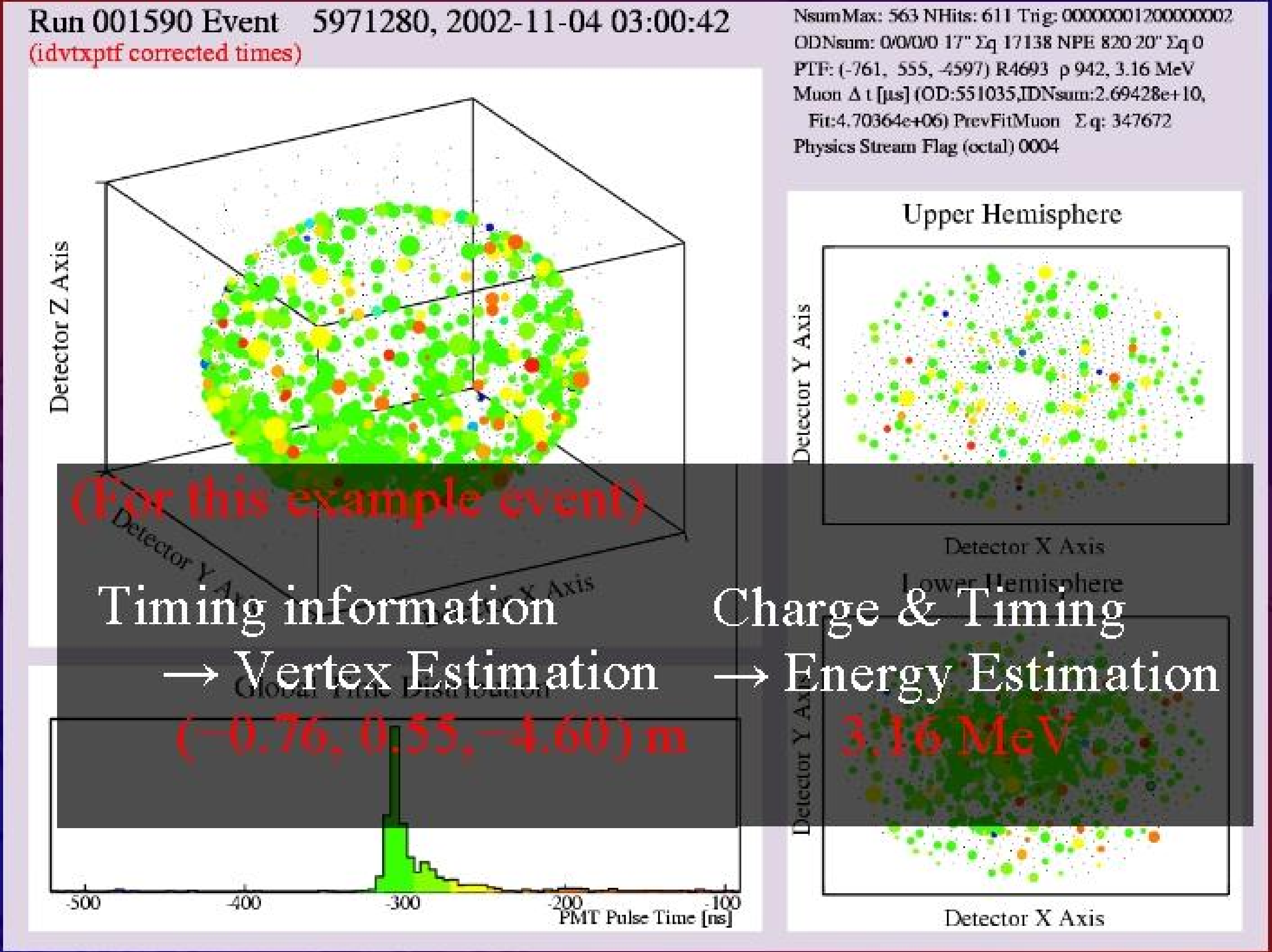
Run 001590 Event 5971280, 2002-11-04 03:00:42
(idvtxptf corrected times)

```
NsumMax: 563 NHits: 611 Trig: 00000001200000002
ODNsum: 0/0/0/0 17" Σq 17138 NPE 820 20" Σq 0
PTF: (-761, 555, -4597) R4693  ρ 942, 3.16 MeV
Muon Δ t [μs] (OD:551035,IDNsum:2.69428e+10,
  Fit:4.70364e+06) PrevFitMuon   Σq: 347672
Physics Stream Flag (octal) 0004
```

Photon arrival times corrected for time-of-flight to estimated vertex position

Yoshi.Uchida@imperial.ac.uk

Event Reconstruction



Run 001590 Event 5971280, 2002-11-04 03:00:42

(idvtxptf corrected times)

NsumMax: 563 NHits: 611 Trig: 0000000120000002
ODNsum: 0/0/0/0 17" Σq 17138 NPE 820 20" Σq 0
PTF: (-761, 555, -4597) R4693 ρ 942, 3.16 MeV
Muon Δ t [μs] (OD:551035,IDNsum:2.69428e+10,
Fit:4.70364e+06) PrevFitMuon Σq: 347672
Physics Stream Flag (octal) 0004

(For this example event)

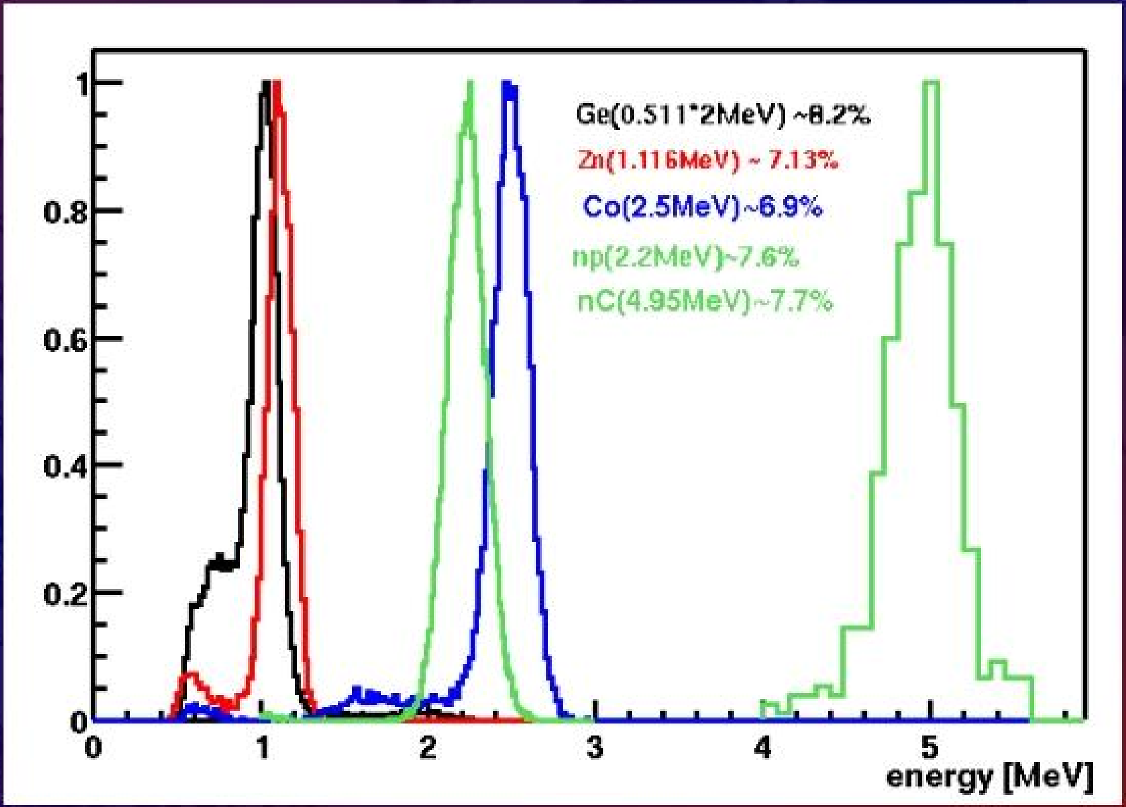
Timing information
→ Vertex Estimation
(−0.76, 0.55, −4.60) m

Charge & Timing
→ Energy Estimation
3.16 MeV

Yoshi.Uchida@imperial.ac.uk

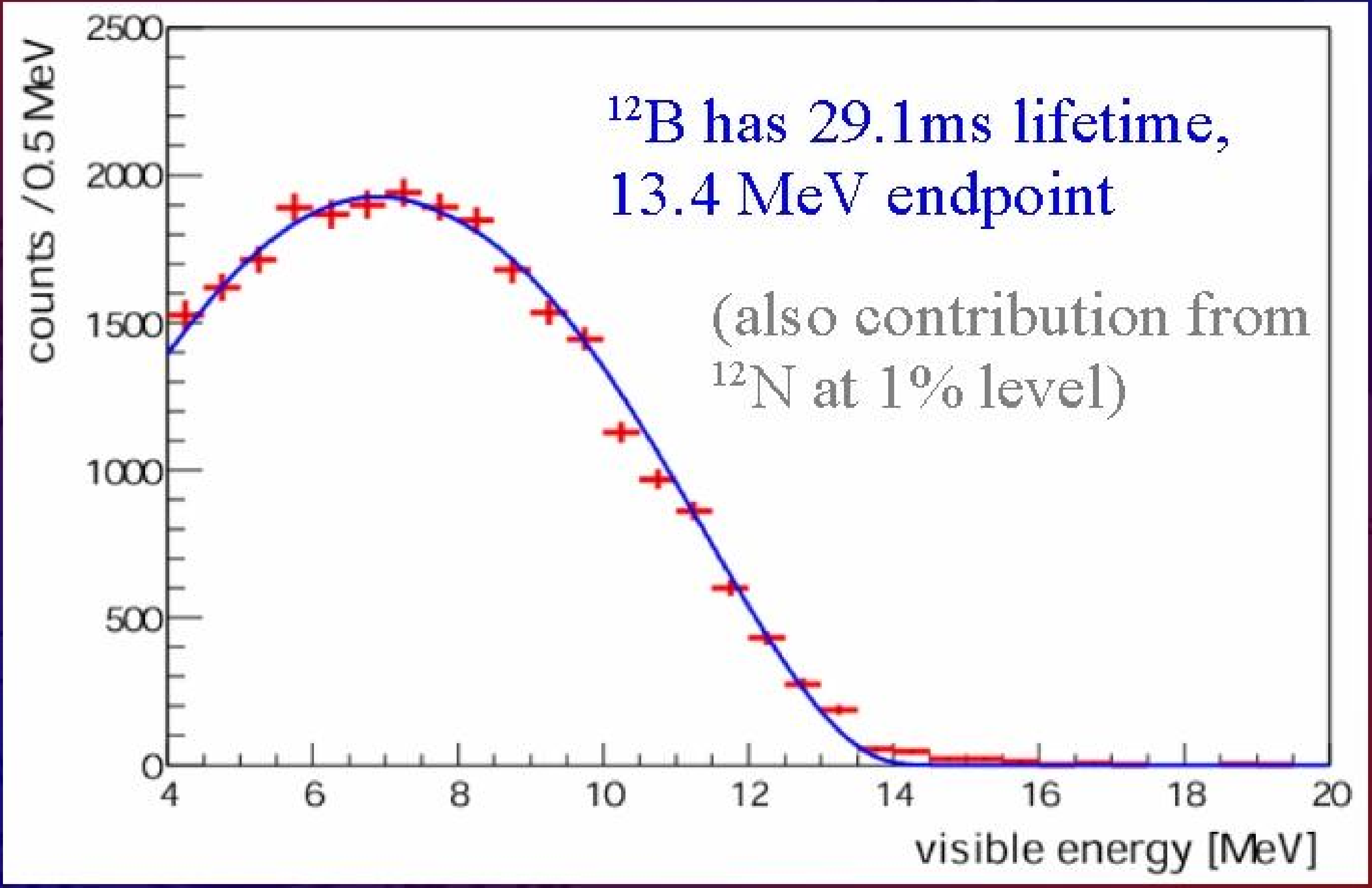
Calibrations

Radioactive gamma sources inserted in detector to calibrate energy and position reconstruction



Yoshi.Uchida@imperial.ac.uk

Energy Reconstruction With Cosmogenics



^{12}B has 29.1ms lifetime, 13.4 MeV endpoint

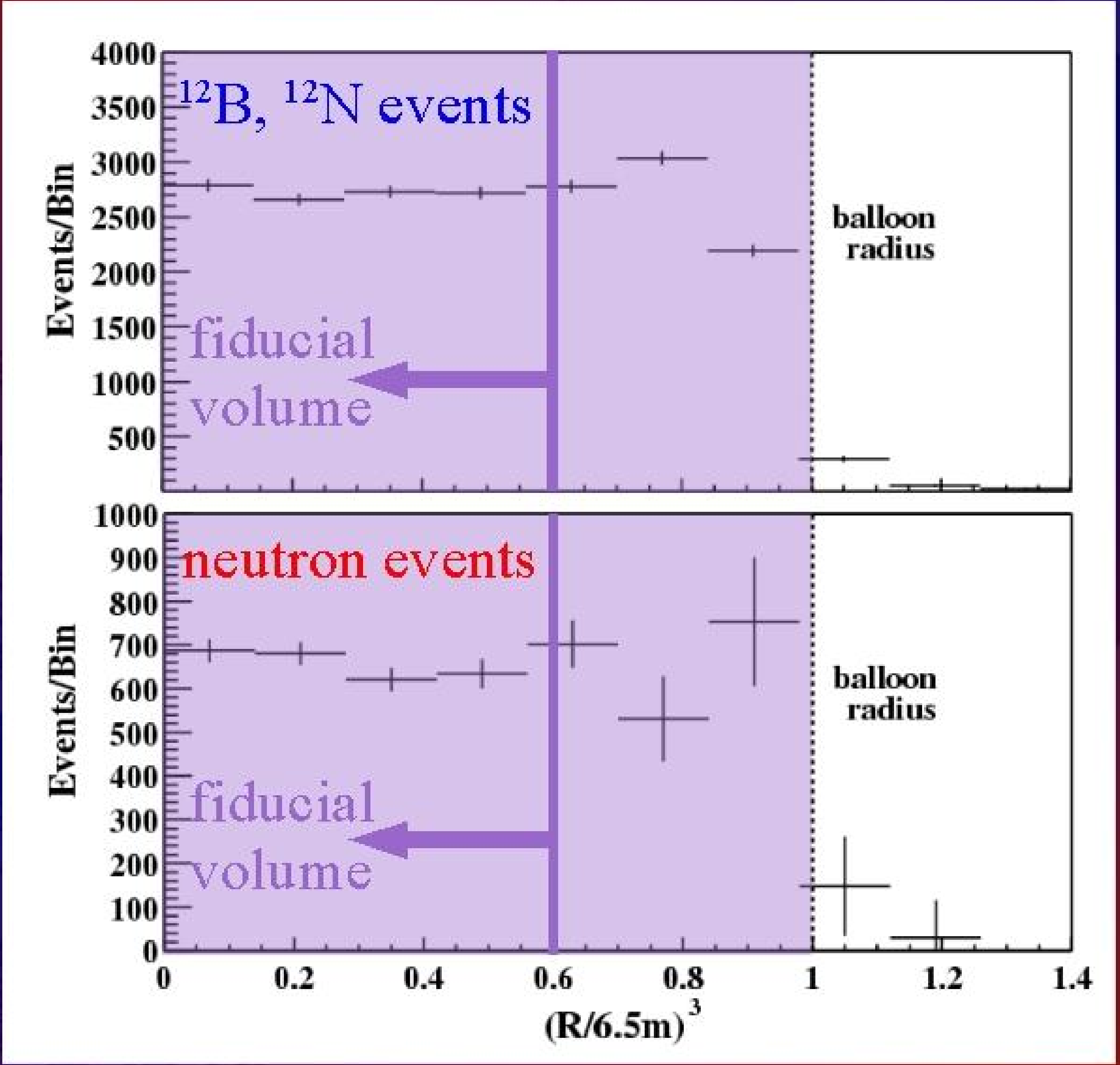
(also contribution from ^{12}N at 1% level)

Yoshi.Uchida@imperial.ac.uk

Fiducial Volume Estimation

1 muon / 3 seconds

Use full cosmogenic statistics to provide uniformly distributed sample



Spallation Cuts

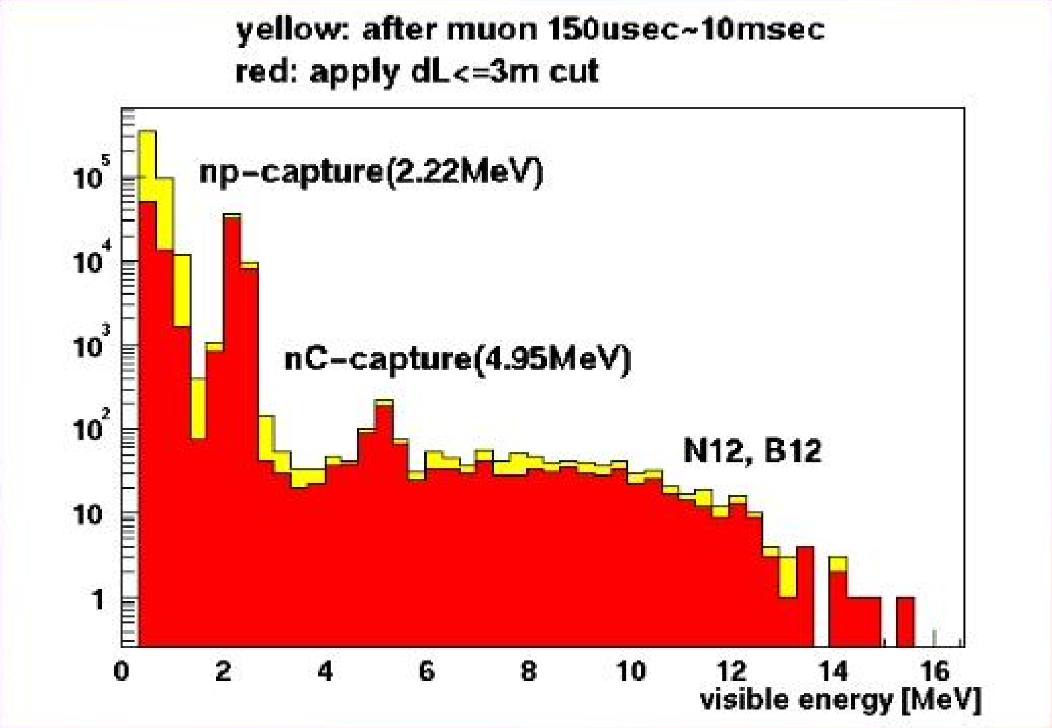
Muons leave neutrons which can fake the signal

- Veto **entire detector** for 2 ms after all muons

Muons can also leave longer lived (100+ msec) neutron emitters

Veto **3 m cylinder** around all muons for 2 seconds

- For high-energy (> 3 GeV) muons, veto **entire detector** for 2 seconds



First Results Analysis Summary (Dec 2002)

145.1 days of data (162 ton·yrs)

- Fiducial volume R=5m; error estimation from data
- Source calibrations along central axis
- Only 17” PMTs used: 22% coverage
- Energy resolution 7.3% at 1 MeV
- Low backgrounds (< 1 event)
- Showed spectrum down to 0.9 MeV prompt energy

Yoshi.Uchida@imperial.ac.uk

KamLAND should see

86.8 ± 5.6

(0.94 ± 0.85 background)

events if all antineutrinos travel to KamLAND from reactors without loss

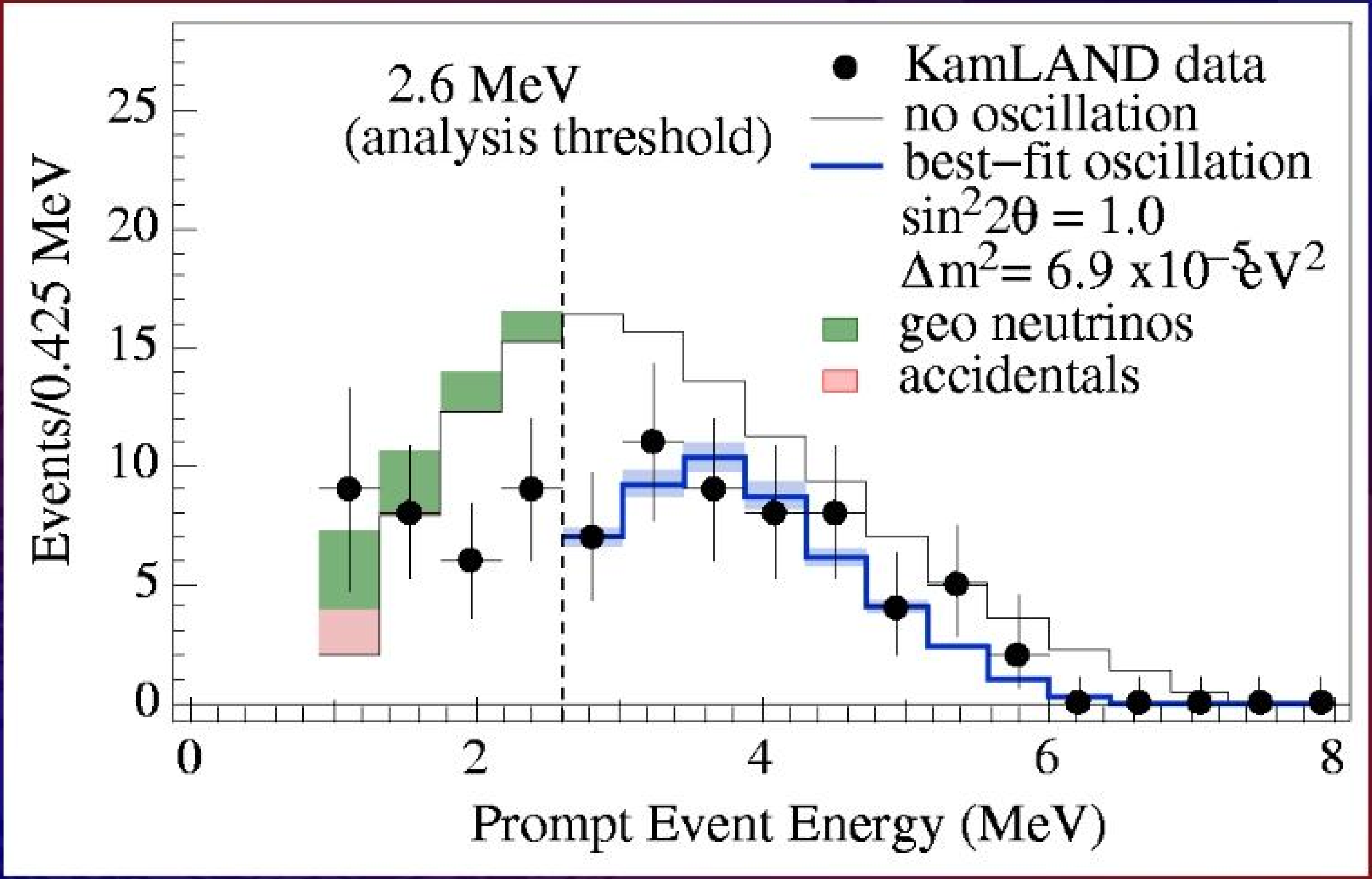
---

54

events observed

Yoshi.Uchida@imperial.ac.uk

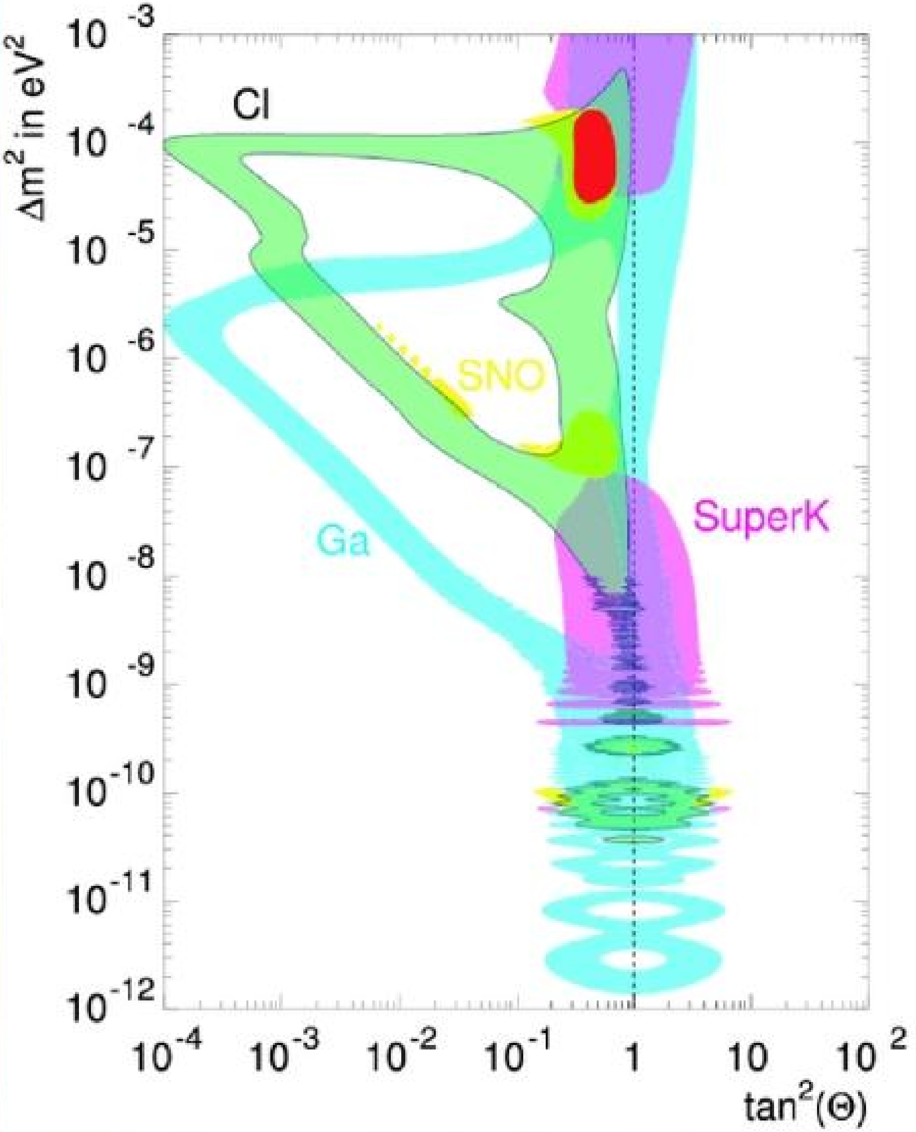
Antineutrino Candidate Energy Spectrum



Solar Results

(circa 2002)

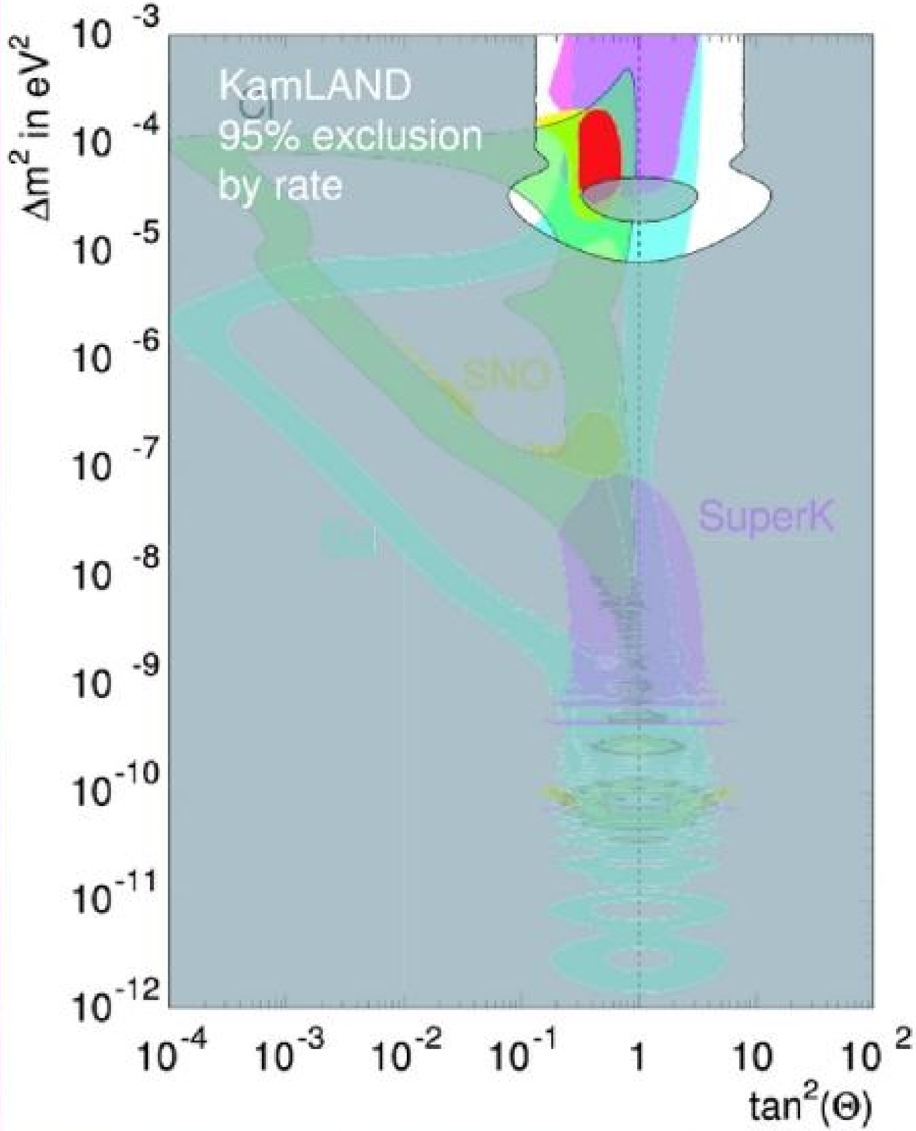
Plot on Δm^2 v. θ *assuming* oscillations and solar matter effects



Yoshi.Uchida@imperial.ac.uk

Solar Results
(circa 2002)
& KamLAND

Plot on Δm^2 v. θ *assuming* oscillations and solar matter effects

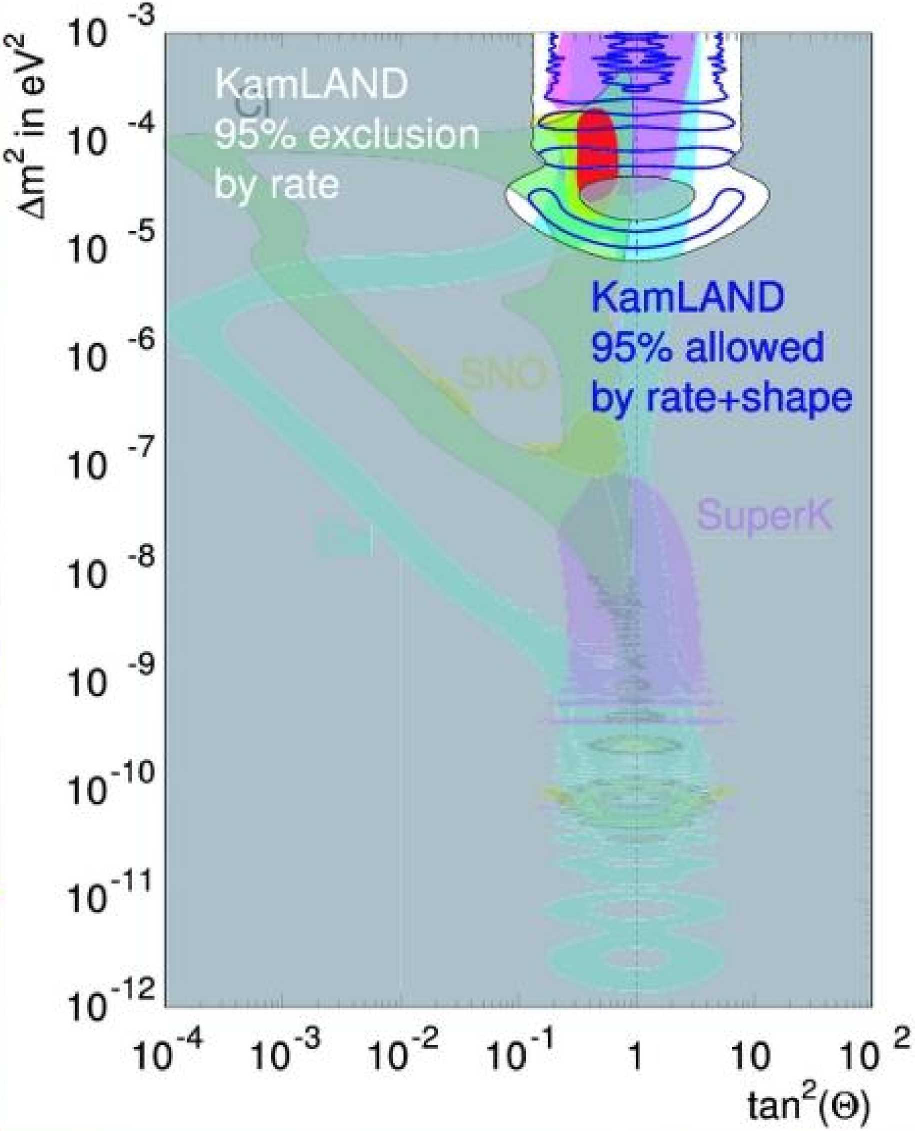


Yoshi.Uchida@imperial.ac.uk

Solar Results
(circa 2002)
& KamLAND

Solar LMA:
Neutrinos with
Sun – Earth baseline
+ Matter Effects in Sun

KamLAND:
Antineutrinos with
180 km baseline ("tuned"
to Δm^2 at 10^{-5} eV^2)
+ Vacuum Oscillations



Second Reactor Results Analysis Summary

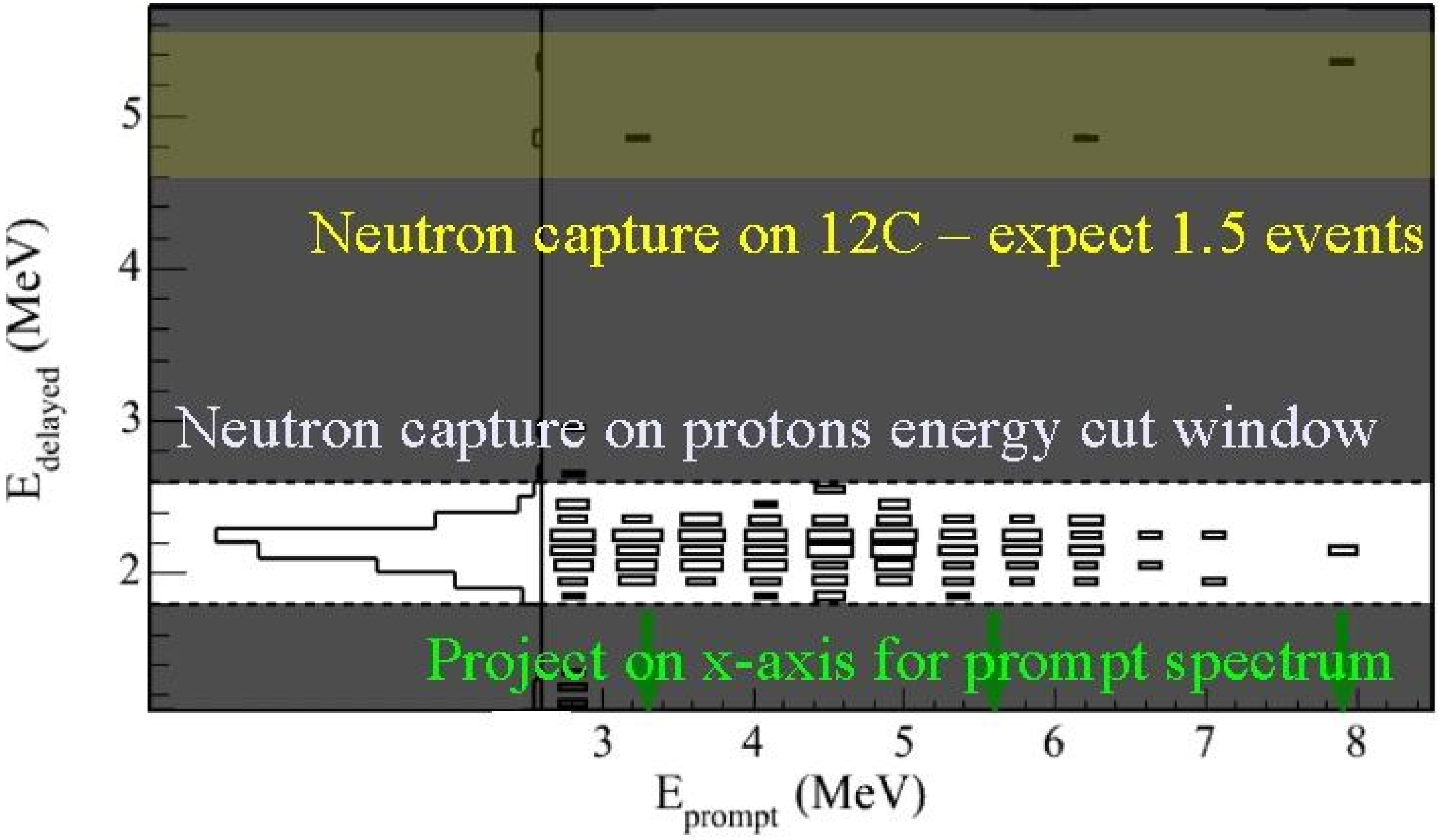
515.1 days of data (766.3 ton·yrs)

- Fiducial volume increased to R=5.5m
- Source calibrations along central axis
- All PMTs used: 34% coverage
- Energy resolution 6.2% at 1 MeV
- Slightly higher backgrounds
- Only report events above 2.6 MeV prompt energy

Yoshi.Uchida@imperial.ac.uk

Prompt/Delayed Event Energies

After fiducial, delayed – prompt $\{\Delta t, \Delta x\}$, & spallation cuts:



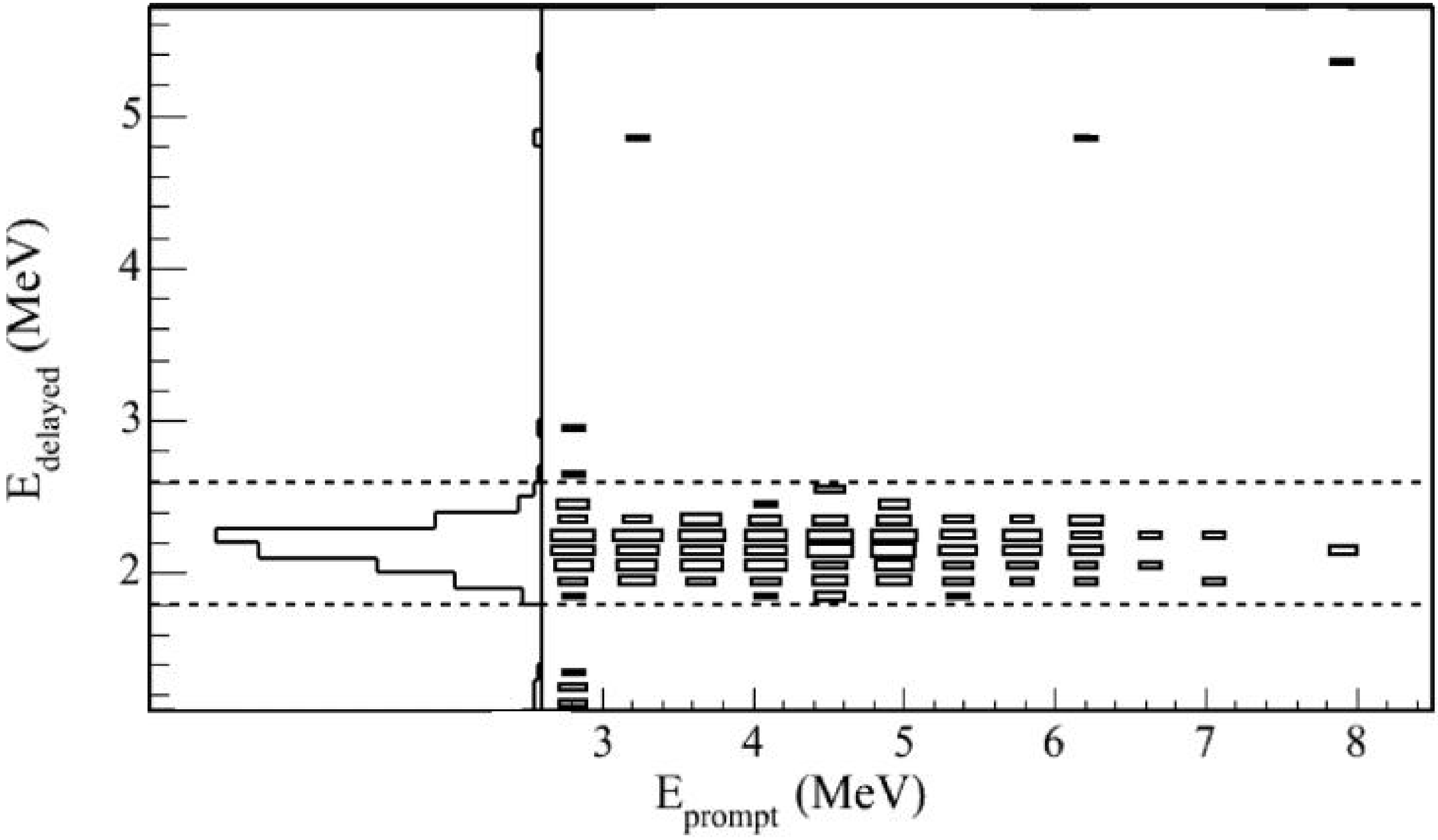
Neutron capture on 12C – expect 1.5 events

Neutron capture on protons energy cut window

Project on x-axis for prompt spectrum

Prompt/Delayed Event Energies

After fiducial, delayed – prompt $\{\Delta t, \Delta x\}$, & spallation cuts:



Systematic Uncertainties

Estimated Contributions to the Systematic Uncertainty (%):

Total Scintillator Mass	2.1
Fiducial mass ratio	4.2
Energy threshold	2.3
Efficiency of cuts	1.6
Live time	0.1
Reactor power	2.1
Fuel composition	1.0
Time lag	0.0
Antineutrino spectra	2.5
$\overline{\nu}_e$ - p cross section	0.2
Total systematic error	6.5 %

KamLAND would see

365 ± 24

(7.5 ± 1.3 background)

events if all antineutrinos travel to KamLAND from reactors without loss

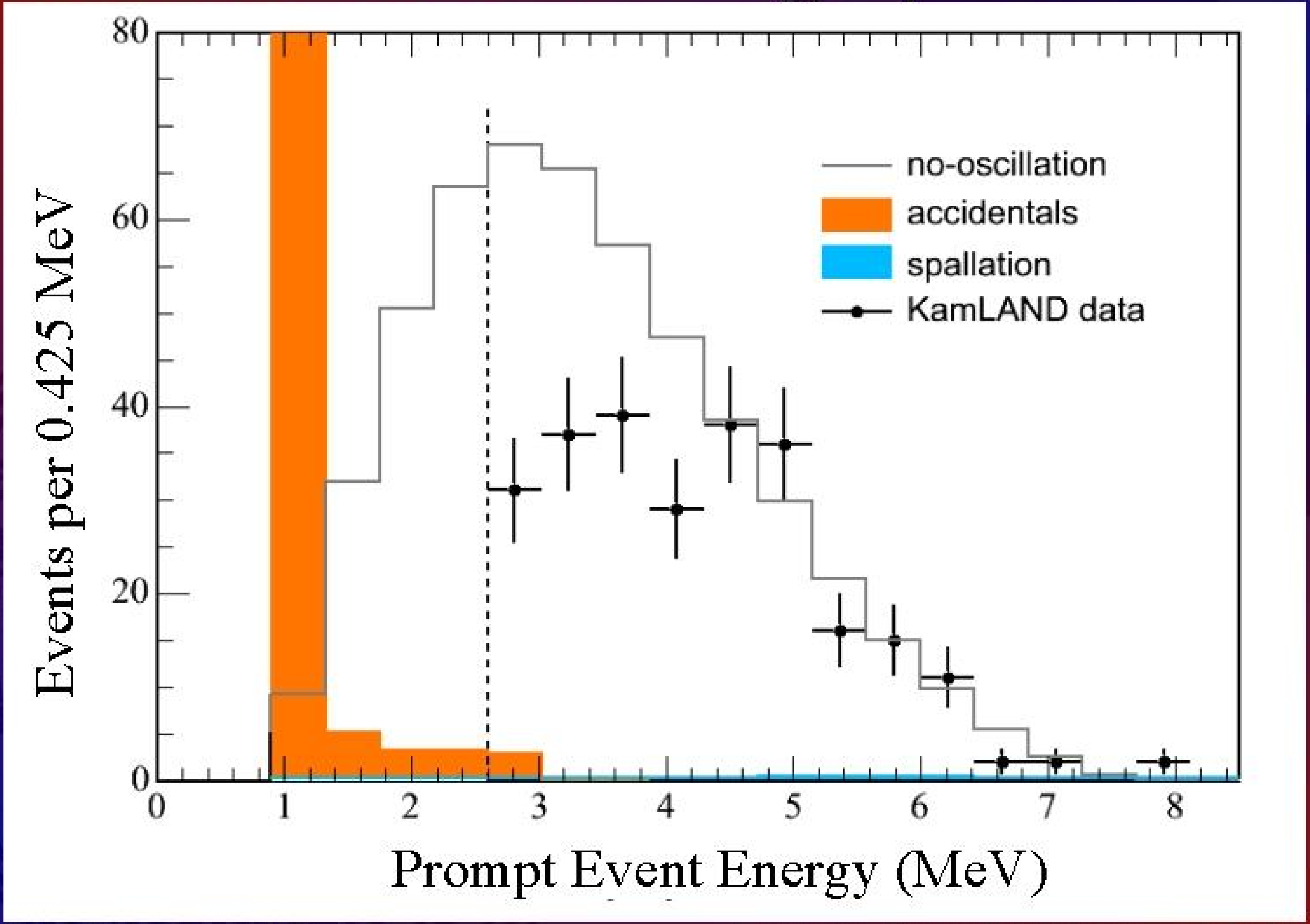
258

events observed

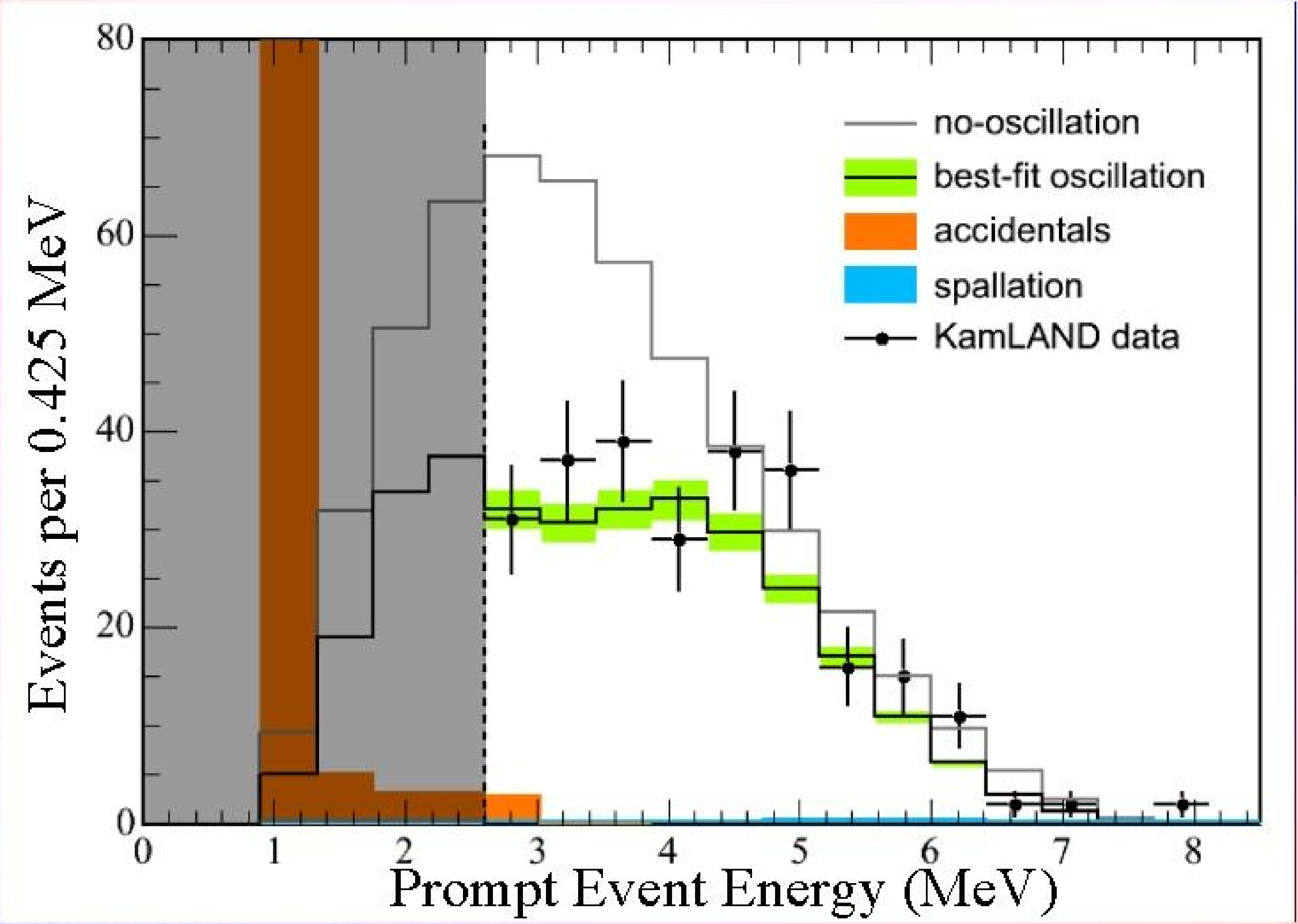
Inconsistent with inverse-square propagation at 99.995%
(but actual ratio not a physically meaningful number)

Yoshi.Uchida@imperial.ac.uk

Antineutrino Candidate Energy Spectrum



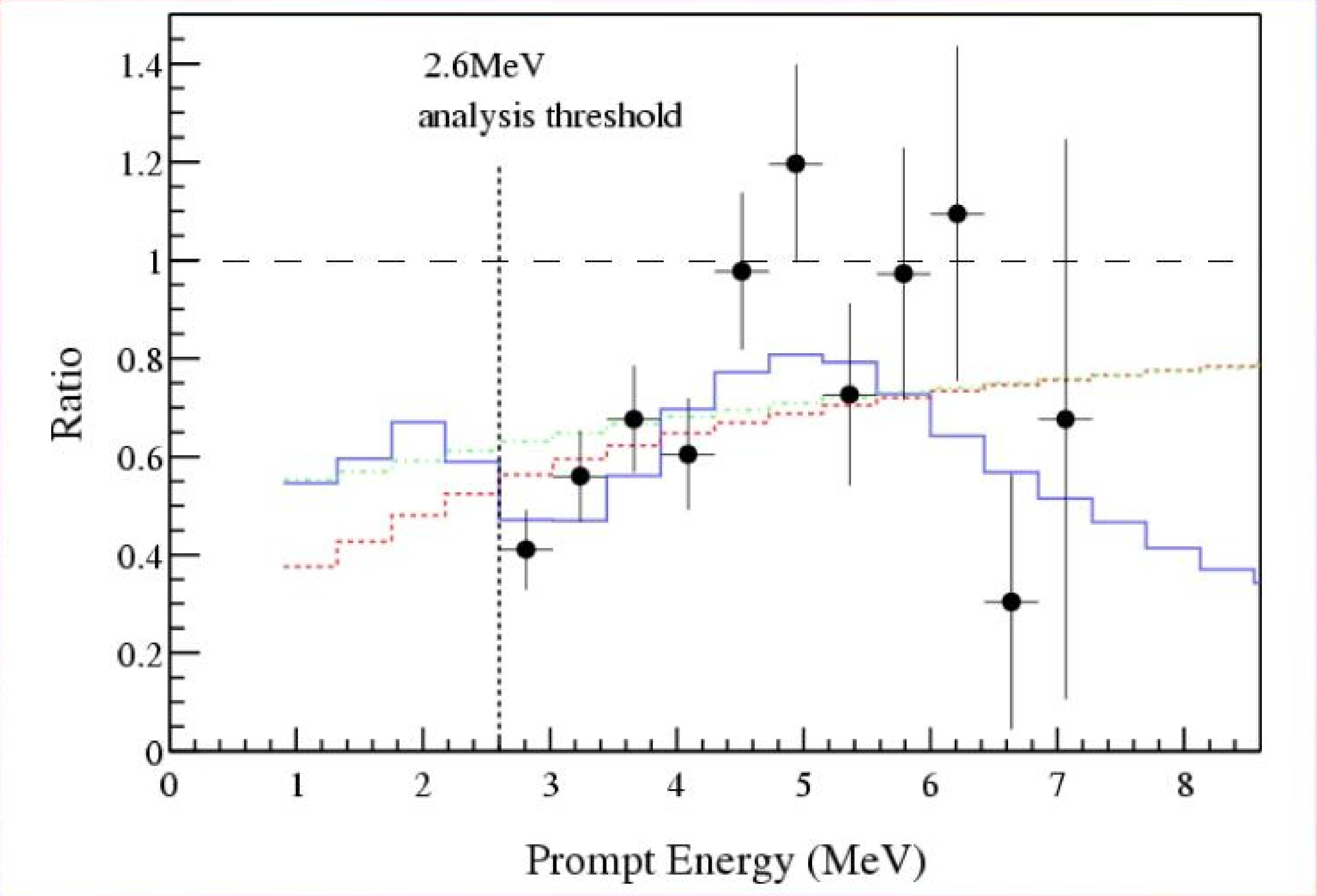
Antineutrino Candidate Energy Spectrum



Yoshi.Uchida@imperial.ac.uk

Benasque Centre for Science — July 2004

Measured/No-Oscillations Ratio Spectrum

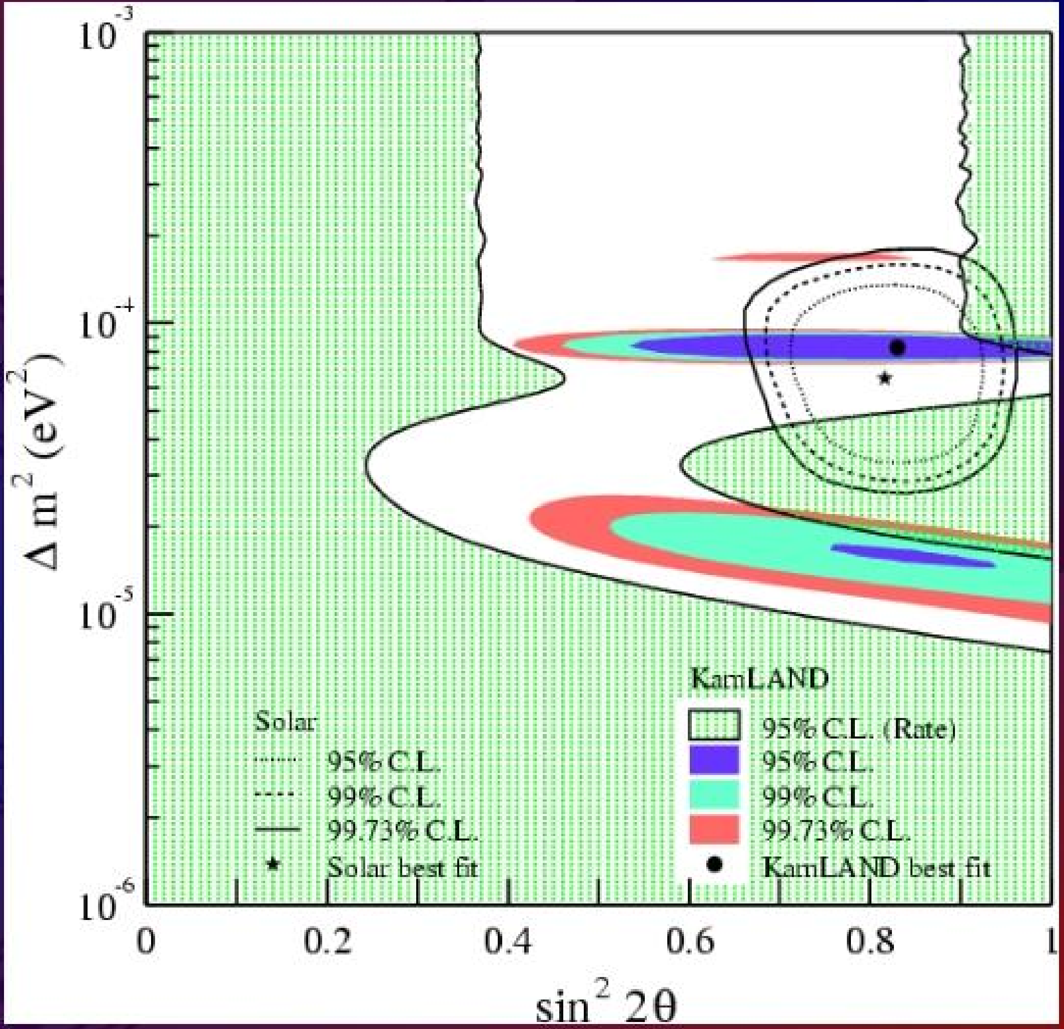


KamLAND 2004 Shape and Rate

Best fit:

$\Delta m^2 = 8.3\ 10^{-5}\ \mathrm{eV}^2$

$\sin^2 2\theta = 0.83$



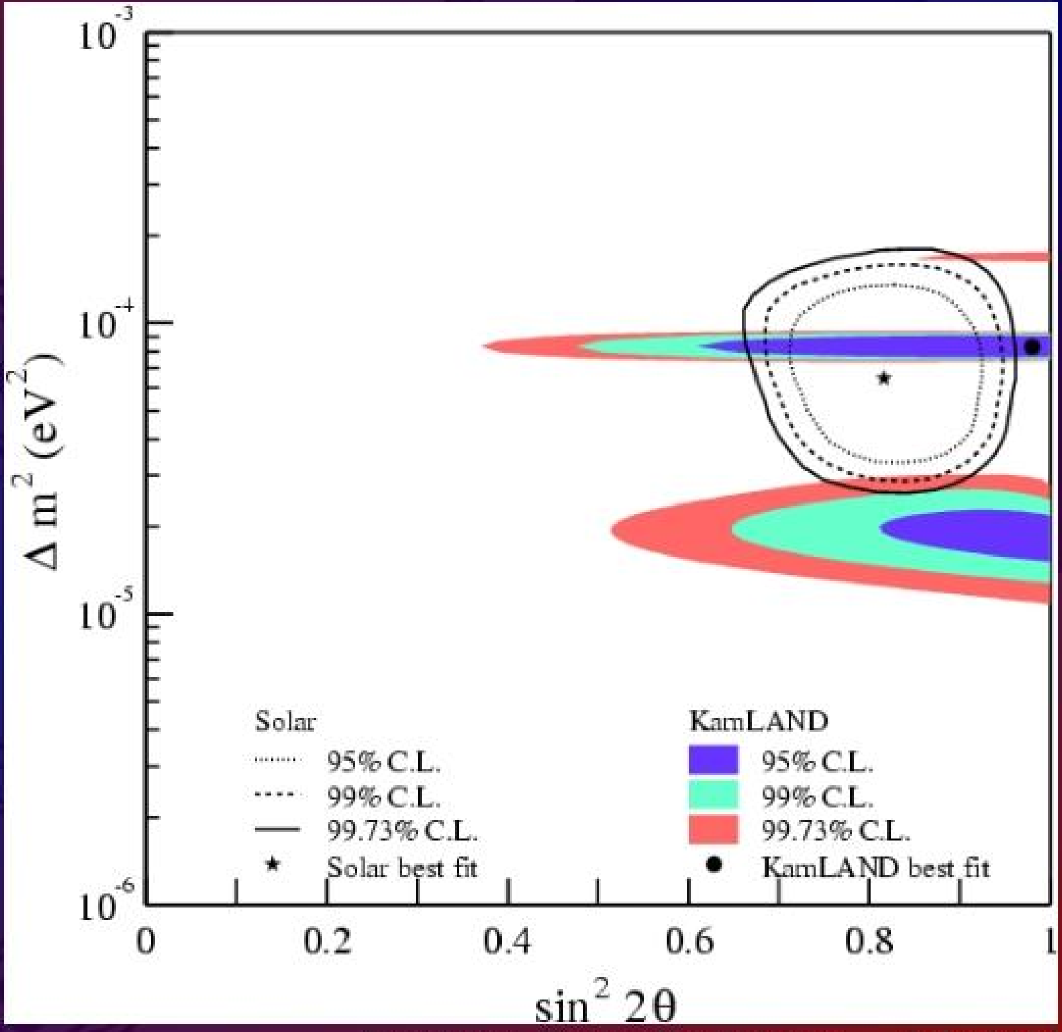
Yoshi.Uchida@imperial.ac.uk

KamLAND 2004 Shape Only

Best fit:

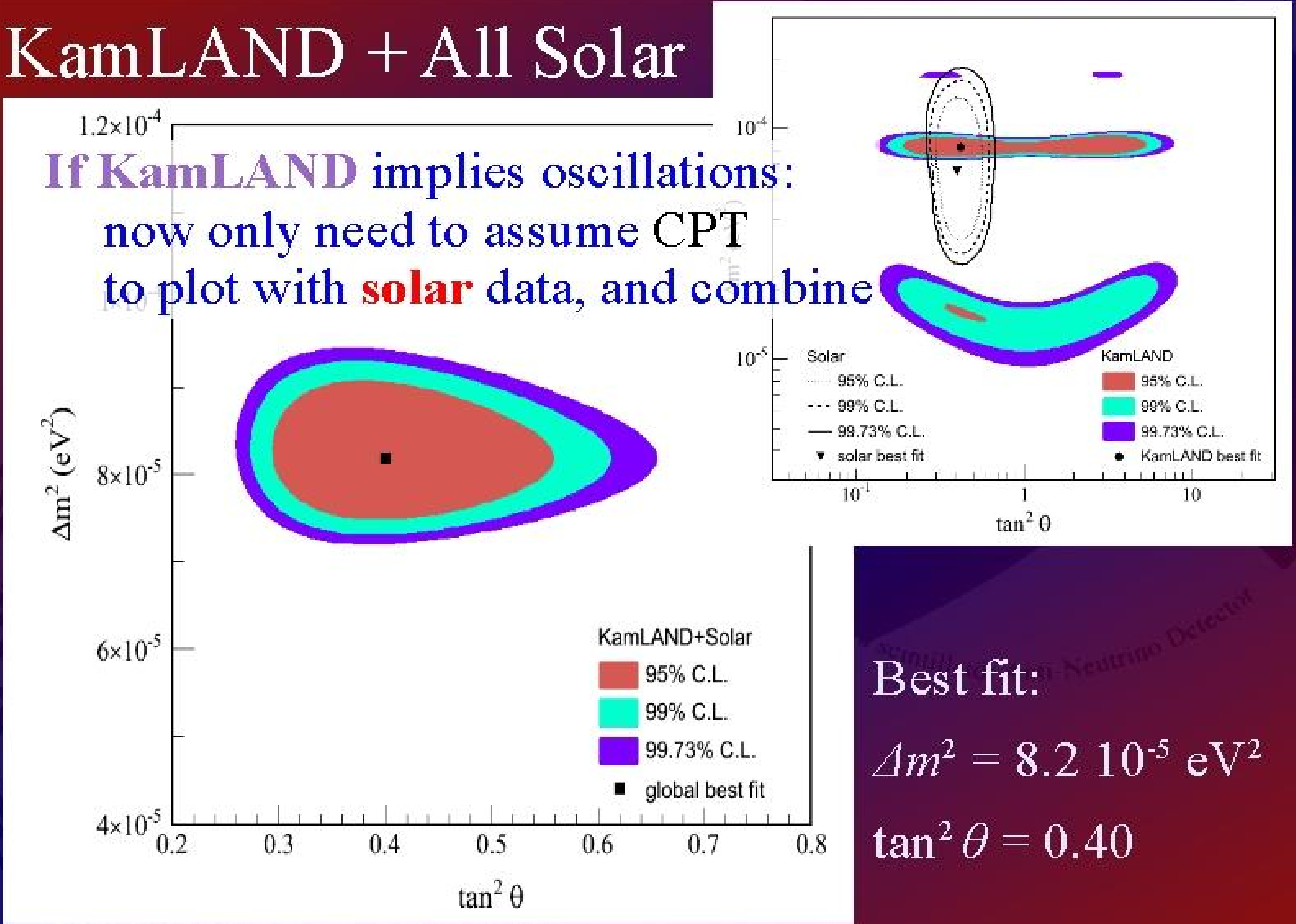
$\Delta m^2 = 8.3\ 10^{-5}\ \mathrm{eV}^2$

$\sin^2 2\theta = 0.98$



Yoshi.Uchida@imperial.ac.uk

KamLAND + All Solar



If KamLAND implies oscillations:

now only need to assume CPT
to plot with **solar** data, and combine

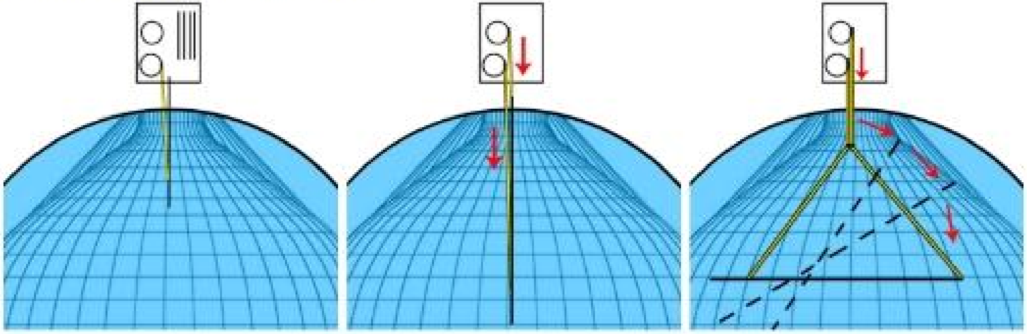
Best fit:

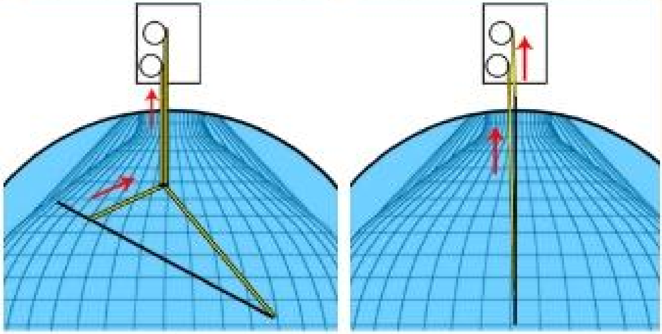
$\Delta m^2 = 8.2\ 10^{-5}\ \mathrm{eV}^2$

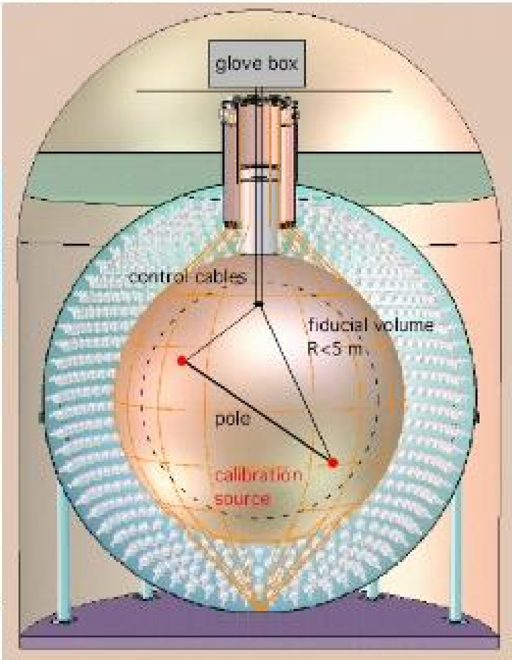
$\tan^2\theta = 0.40$

KamLAND Off-Axis Calibration

Calibration throughout entire detector volume







Fiducial volume:
$R < 5$ m

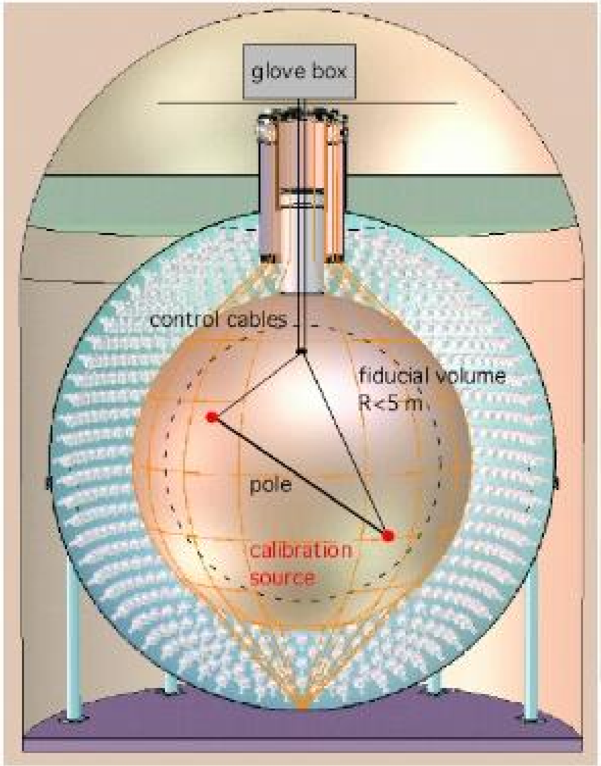
$\Delta R_{FV} = 5$ cm
$\rightarrow \Delta V = 3\%$

Position Dependence of Detector Response

Event energy $E(r,\theta,\phi)$
Vertex reconstruction $R_{fit}(r,\theta,\phi)$

KamLAND Off-Axis Calibration

Prototype Test



The KamLAND Collaboration

T. Araki,[1] K. Eguchi,[1] S. Enomoto,[1] K. Furuno,[1] K. Ichimura,[1] H. Ikeda,[1] K. Inoue,[1] K. Ishihara,[1,*] T. Iwamoto,[1,†]
T. Kawashima,[1] Y. Kishimoto,[1] M. Koga,[1] Y. Koseki,[1] T. Maeda,[1] T. Mitsui,[1] M. Motoki,[1] K. Nakajima,[1] H. Ogawa,[1]
K. Owada,[1] J.-S. Ricol,[1] I. Shimizu,[1] J. Shirai,[1] F. Suekane,[1] A. Suzuki,[1] K. Tada,[1] O. Tajima,[1] K. Tamae,[1] Y. Tsuda,[1]
H. Watanabe,[1] J. Busenitz,[2] T. Classen,[2] Z. Djurcic,[2] G. Keefer,[2] K. McKinny,[2] D.-M. Mei,[2,‡] A. Piepke,[2] E. Yakushev,[2]
B.E. Berger,[3] Y.D. Chan,[3] M.P. Decowski,[3] D.A. Dwyer,[3] S.J. Freedman,[3] Y. Fu,[3] B.K. Fujikawa,[3] J. Goldman,[3]
F. Gray,[3] K.M. Heeger,[3] K.T. Lesko,[3] K.-B. Luk,[3] H. Murayama,[3,§] A.W.P. Poon,[3] H.M. Steiner,[3] L.A. Winslow,[3]
G.A. Horton-Smith,[4] C. Mauger,[4] R.D. McKeown,[4] P. Vogel,[4] C.E. Lane,[5] T. Miletic,[5] P.W. Gorham,[6] G. Guillian,[6]
J.G. Learned,[6] J. Maricic,[6] S. Matsuno,[6] S. Pakvasa,[6] S. Dazeley,[7] S. Hatakeyama,[7] A. Rojas,[7] R. Svoboda,[7]
B.D. Dieterle,[8] J. Detwiler,[9] G. Gratta,[9] K. Ishii,[9] N. Tolich,[9] Y. Uchida,[9,¶] M. Batygov,[10] W. Bugg,[10] Y. Efremenko,[10]
Y. Kamyshkov,[10] A. Kozlov,[10] Y. Nakamura,[10] C.R. Gould,[11] H.J. Karwowski,[11] D.M. Markoff,[11] J.A. Messimore,[11]
K. Nakamura,[11] R.M. Rohm,[11] W. Tornow,[11] R. Wendell,[11] A.R. Young,[11] M.-J. Chen,[12] Y.-F. Wang,[12] and F. Piquemal[13]

[1] *Research Center for Neutrino Science, Tohoku University, Sendai 980-8578, Japan*
[2] *Department of Physics and Astronomy, University of Alabama, Tuscaloosa, Alabama 35487, USA*
[3] *Physics Department, University of California at Berkeley and*
Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
[4] *W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125, USA*
[5] *Physics Department, Drexel University, Philadelphia, Pennsylvania 19104, USA*
[6] *Department of Physics and Astronomy, University of Hawaii at Manoa, Honolulu, Hawaii 96822, USA*
[7] *Department of Physics and Astronomy, Louisiana State University, Baton Rouge, Louisiana 70803, USA*
[8] *Physics Department, University of New Mexico, Albuquerque, New Mexico 87131, USA*
[9] *Physics Department, Stanford University, Stanford, California 94305, USA*
[10] *Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996, USA*
[11] *Triangle Universities Nuclear Laboratory, Durham, North Carolina 27708, USA and*
Physics Departments at Duke University, North Carolina State University, and the University of North Carolina at Chapel Hill
[12] *Institute of High Energy Physics, Beijing 100039, People's Republic of China*
[13] *CEN Bordeaux-Gradignan, IN2P3-CNRS and University Bordeaux I, F-33175 Gradignan Cedex, France*

Back to θ_{13}….

In three-neutrino mixing picture, θ_{12} and θ_{23} very large

but only an upper limit on θ_{13} of 11° or 0.16 in $\sin^2 2\theta_{13}$ (90% C.L.)

If finite (ie. $\sin^2 2\theta_{13} \approx 0.01$ or bigger), we can go ahead and measure CP violation using future accelerators

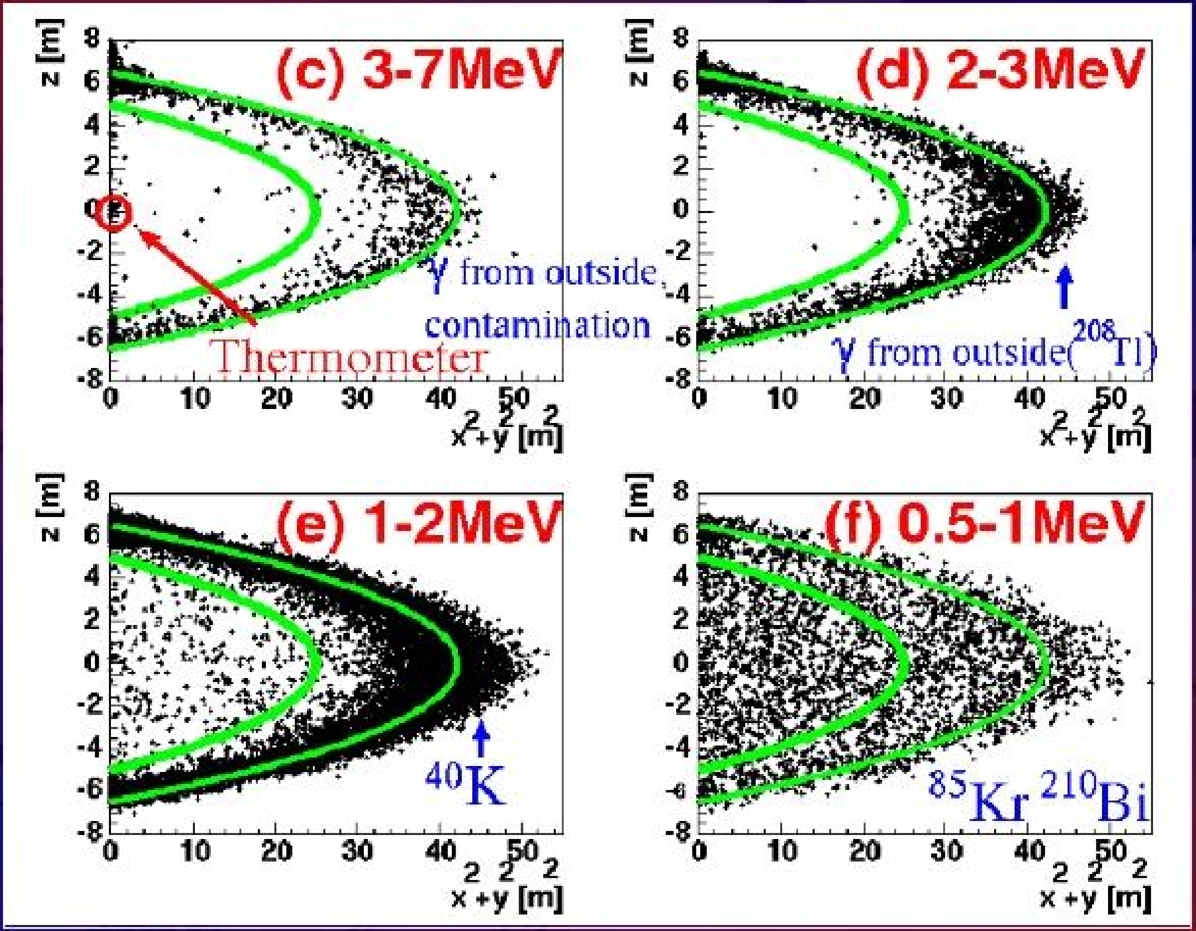
↓

Large global effort underway to build a ultra-high precision 1 km baseline reactor experiment to determine size of θ_{13}

Oberauer, Neutrino 2004

Yoshi.Uchida@imperial.ac.uk

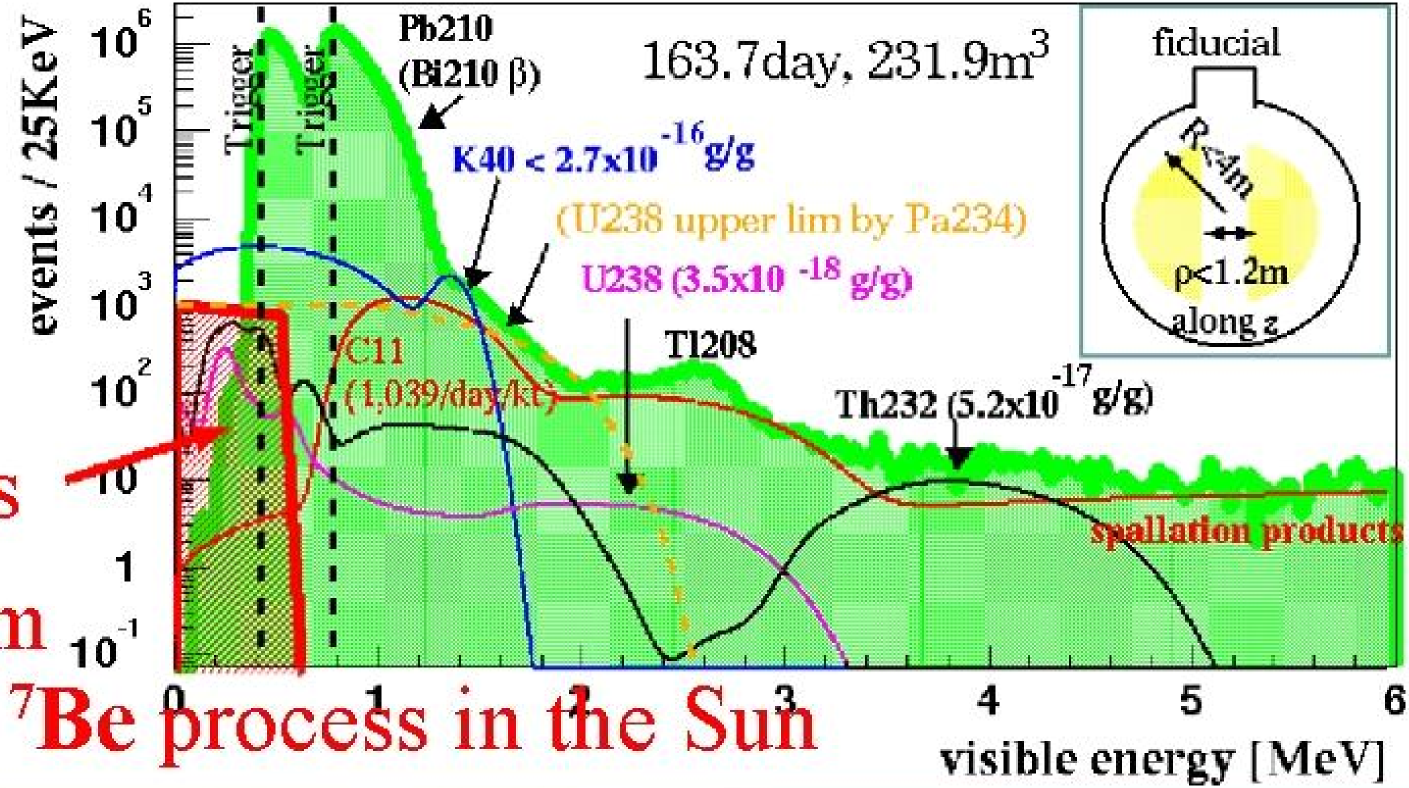
Singles Backgrounds in Detector



7Be Neutrinos: 0.6 MeV and below

Yoshi.Uchida@imperial.ac.uk

Present Backgrounds Energy Spectrum



ν_e's from the ^{7}**Be** process in the Sun

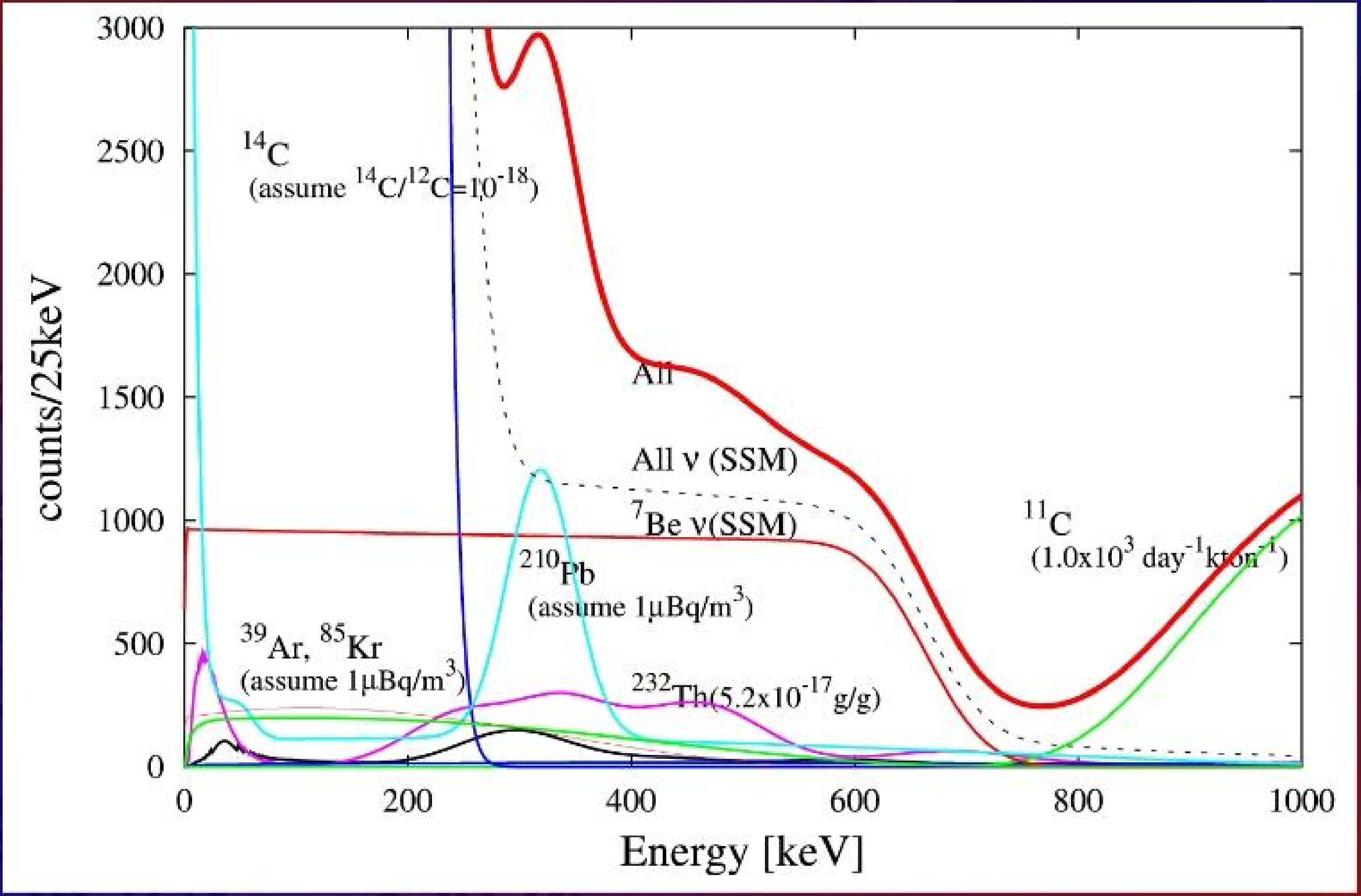
Backgrounds: Status and Goals

Background	now	goal
$^{238}\mathrm{U}$(by Bi-Po)	$3.5 \times 10^{-18}\mathrm{g/g}$	**OK!!**
$^{238}\mathrm{U}$(by $^{234}\mathrm{Pa}$)	$\mathbf{O}(10^{-17}\mathrm{g/g})$(Max.)	$10^{-18}\mathrm{g/g}$
$^{232}\mathrm{Th}$ (by Bi-Po)	$5.2 \times 10^{-17}\mathrm{g/g}$	**OK!!**
$^{40}\mathrm{K}$	$2.7 \times 10^{-16}\mathrm{g/g}$(max.)	$< 10^{-18}\mathrm{g/g}$
$^{210}\mathrm{Pb}$	$\sim 10^{-20}\mathrm{g/g}$	$5 \times 10^{-25}\mathrm{g/g} \sim 1\mu\mathrm{Bq/m^3}$
$^{85}\mathrm{Kr}, {}^{39}\mathrm{Ar}$	$^{85}\mathrm{Kr} = 0.7\mathrm{Bq/m^3}$	$1\mu\mathrm{Bq/m^3}$
$^{222}\mathrm{Rn}$ (after purification)	$^{238}\mathrm{U} = 3.5 \times 10^{-18}\mathrm{g/g}$ $= 3.3 \times 10^{-8}\mathrm{Bq/m^3}$	**OK!!** $(1\mu\mathrm{Bq/m^3})$
$^{222}\mathrm{Rn}$ (during purification)		$1\mathrm{mBq/m^3}$ $^{210}\mathrm{Pb} = 0.5\mu\mathrm{Bq/m^3}$ after decay

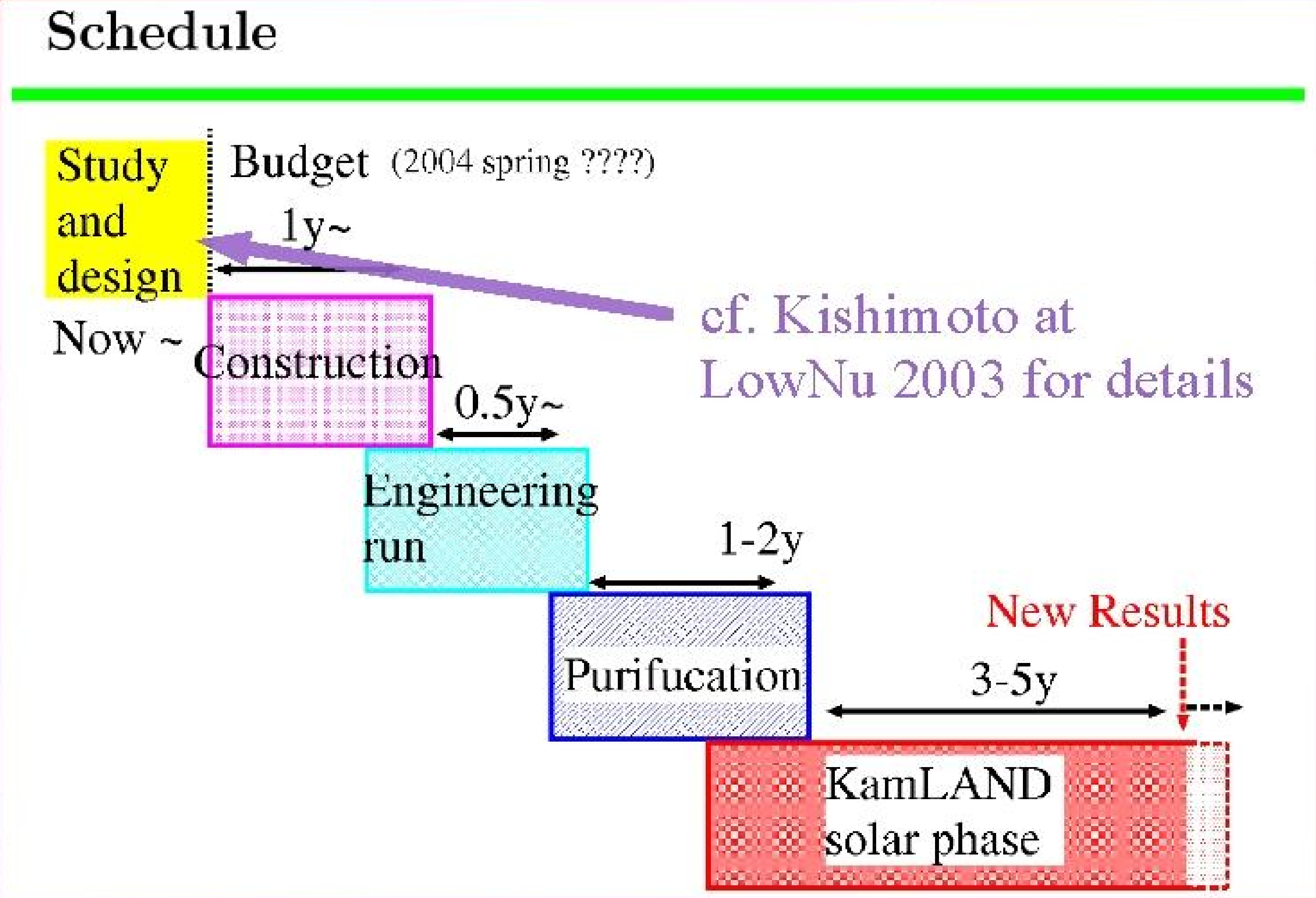
Solar Phase studies from Y. Kishimoto (Tohoku)

Yoshi.Uchida@imperial.ac.uk

Singles Distributions After Purification



Possible Timeframe



Schedule

Study and design

Budget (2004 spring ????)

1y~

Now ~

Construction

0.5y~

Engineering run

1-2y

Purifucation

3-5y

New Results

KamLAND solar phase

cf. Kishimoto at LowNu 2003 for details

Yoshi.Uchida@imperial.ac.uk

KamLAND ^{7}Be Solar Neutrino Phase

Currently undergoing R&D

New purification facility construction possible soon

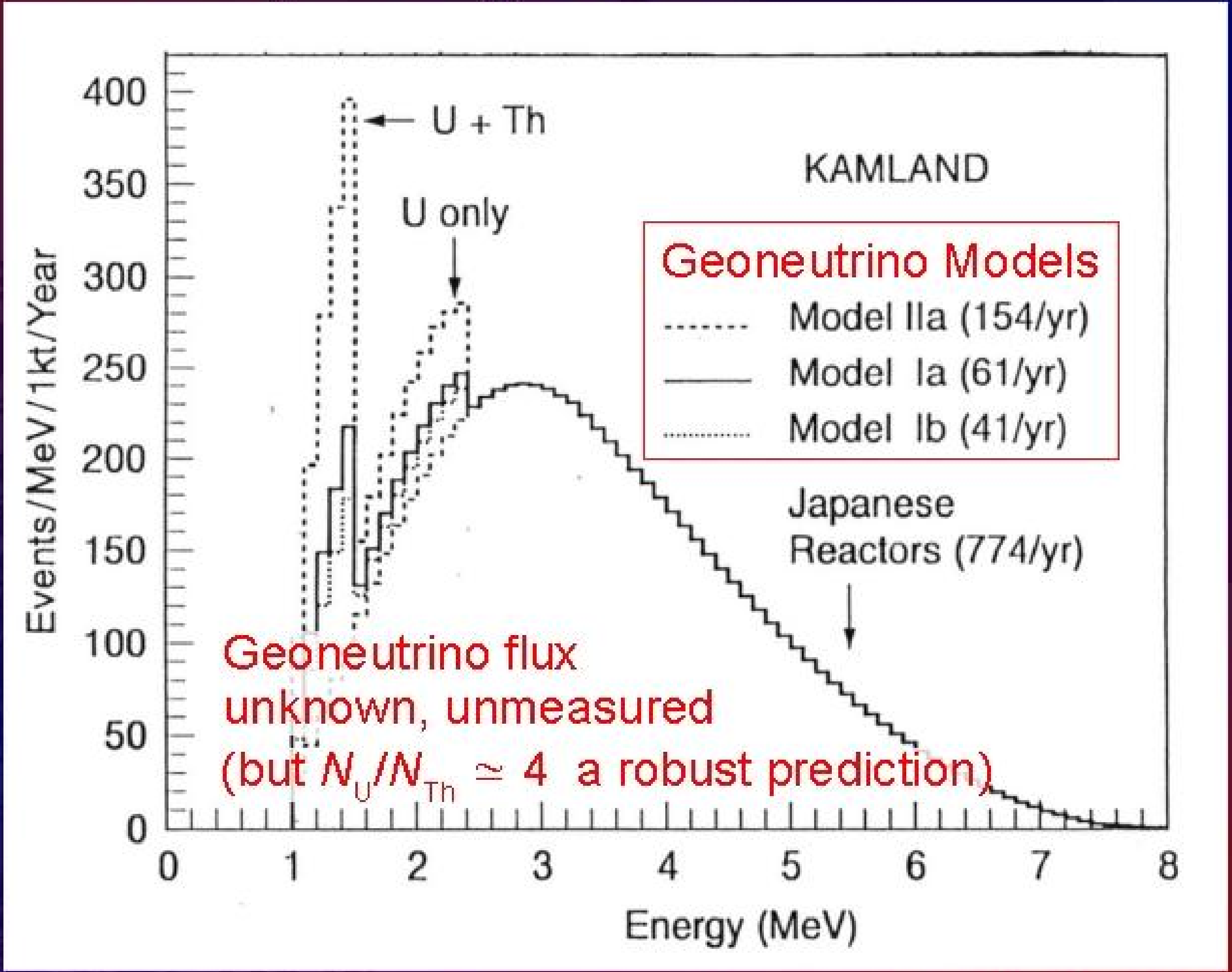
Purification possible in a few years

Results in 5 to 7 years?

Funded in June in Japan as a 5 year project '04 – '09

Antineutrino Signal Spectra

Expected spectra for Reactor and Geothermal antineutrino events

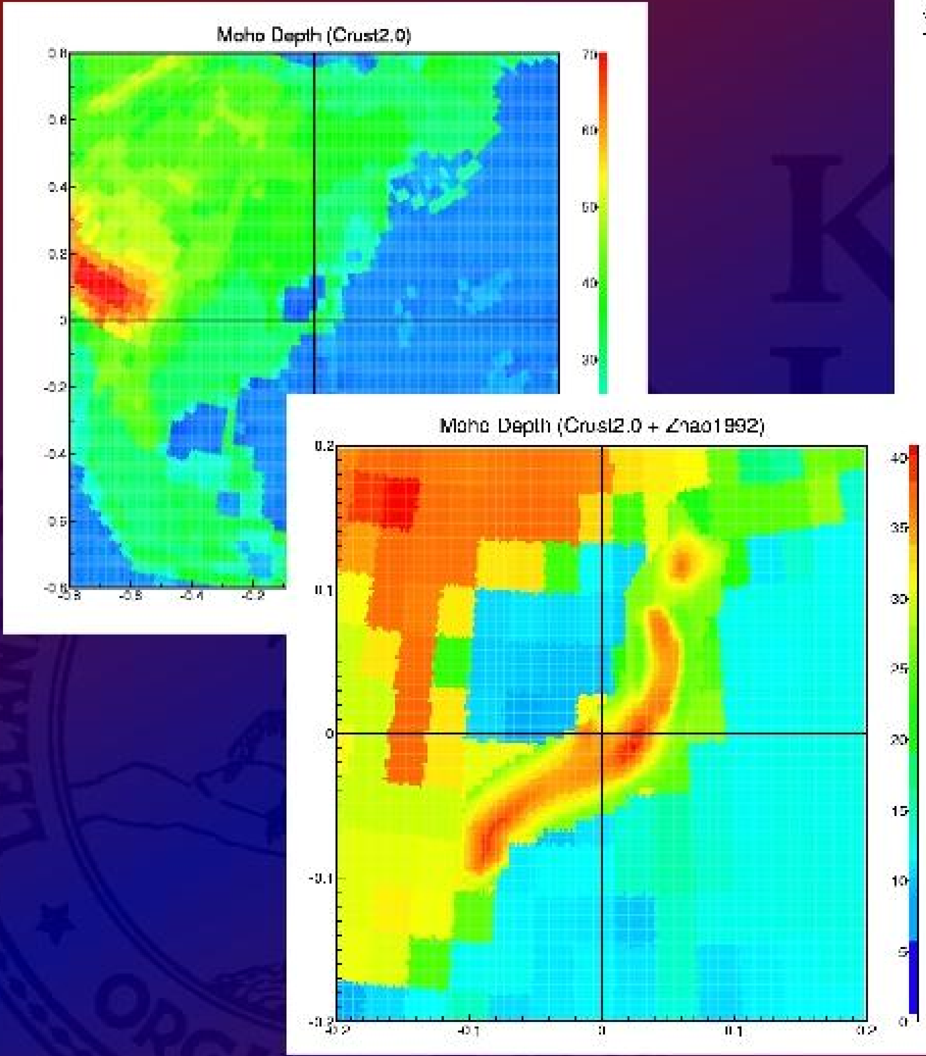


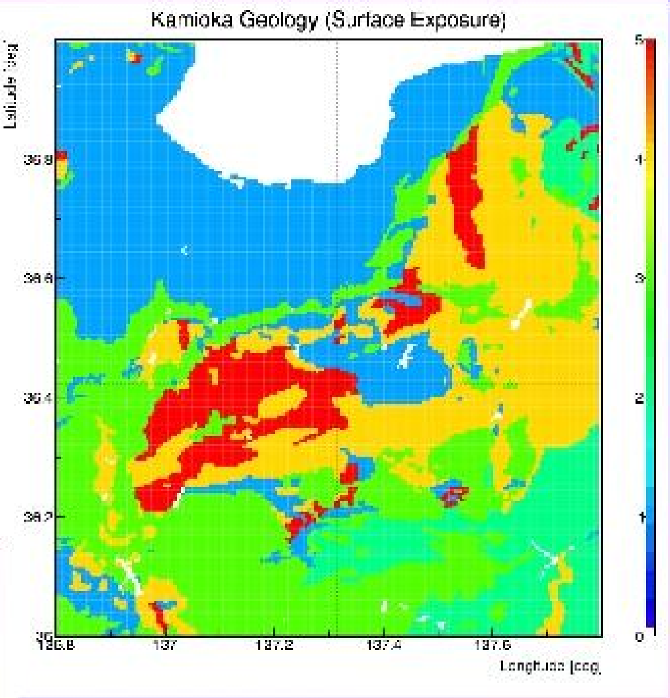
Geoneutrino flux unknown, unmeasured (but $N_U/N_{Th} \simeq 4$ a robust prediction)

cf. Raghavan, Phys. Rev. Lett. **80**, 635, (1998)

Yoshi.Uchida@imperial.ac.uk

Other Earth Models



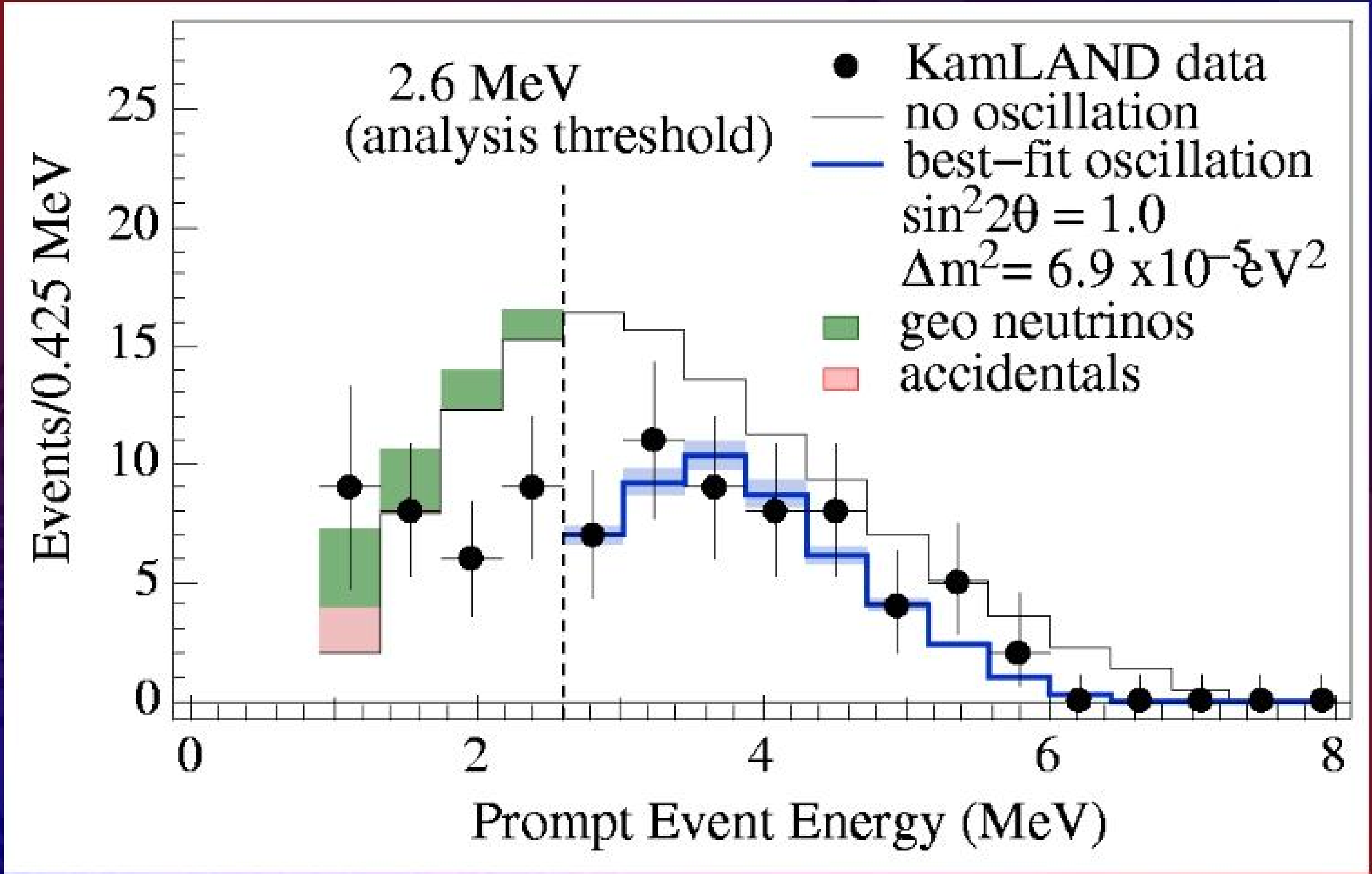


S, Enomoto

http://www.awa.tohoku.ac.jp/~sanshiro/neutrino/NeutrinoGeophysics/

Yoshi.Uchida@imperial.ac.uk

2002 Energy Spectrum



Yoshi.Uchida@imperial.ac.uk

Geoneutrinos

- First clear observation of geoneutrinos forthcoming
- Much ongoing work on geoneutrino predictions
- N_U/N_{Th} a good test parameter
- Discrimination between models possible with high statistics

Supernovae

Last SN observed through neutrinos: SN1987A

Galactic SN: ~10 second bursts of mixture of ν's, every few decades:

Important to be sensitive to this mixture globally

At KamLAND:

a few hundred $\overline{\nu}_e$ inverse beta-decay events

- $\nu_e + {}^{12}C \rightarrow {}^{12}N$
- NC excitation of ^{12}C: 15.11 MeV γ
- ES of protons (with background reduction)

Dedicated SN trigger and DAQ mode in operation, and undergoing improvement

cf. P. Vogel [nucl-th/0305003]

Conclusions

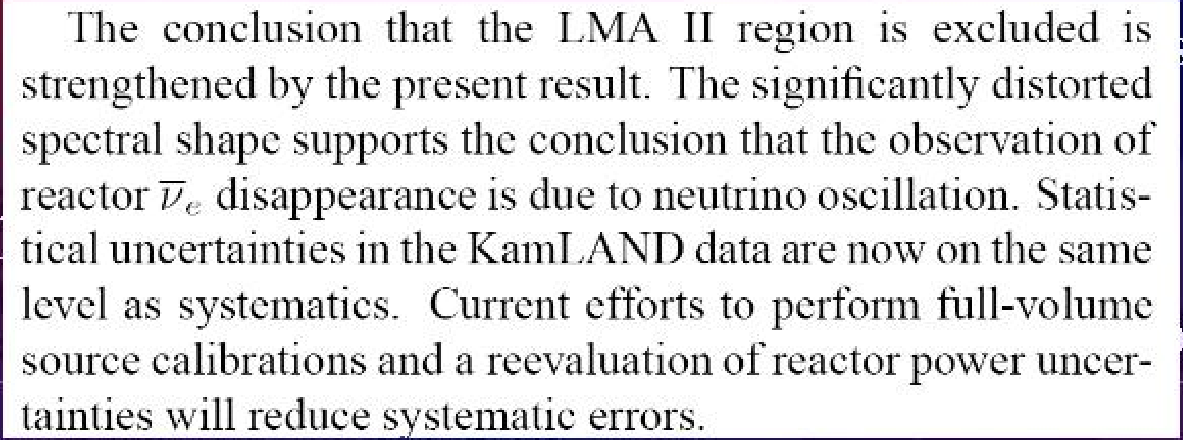
KamLAND Reactor Results

stics

Clear S

More p

vae?



The conclusion that the LMA II region is excluded is strengthened by the present result. The significantly distorted spectral shape supports the conclusion that the observation of reactor $\overline{\nu}_e$ disappearance is due to neutrino oscillation. Statistical uncertainties in the KamLAND data are now on the same level as systematics. Current efforts to perform full-volume source calibrations and a reevaluation of reactor power uncertainties will reduce systematic errors.

Next step – High precision 1 km baseline measurement

Reactor antineutrino physics, from discoveries to precision measurements, still going strong, and revealing neutrino sector secrets that are complementary to those from solar, atmospheric and accelerator programmes

Yoshi.Uchida@imperial.ac.uk