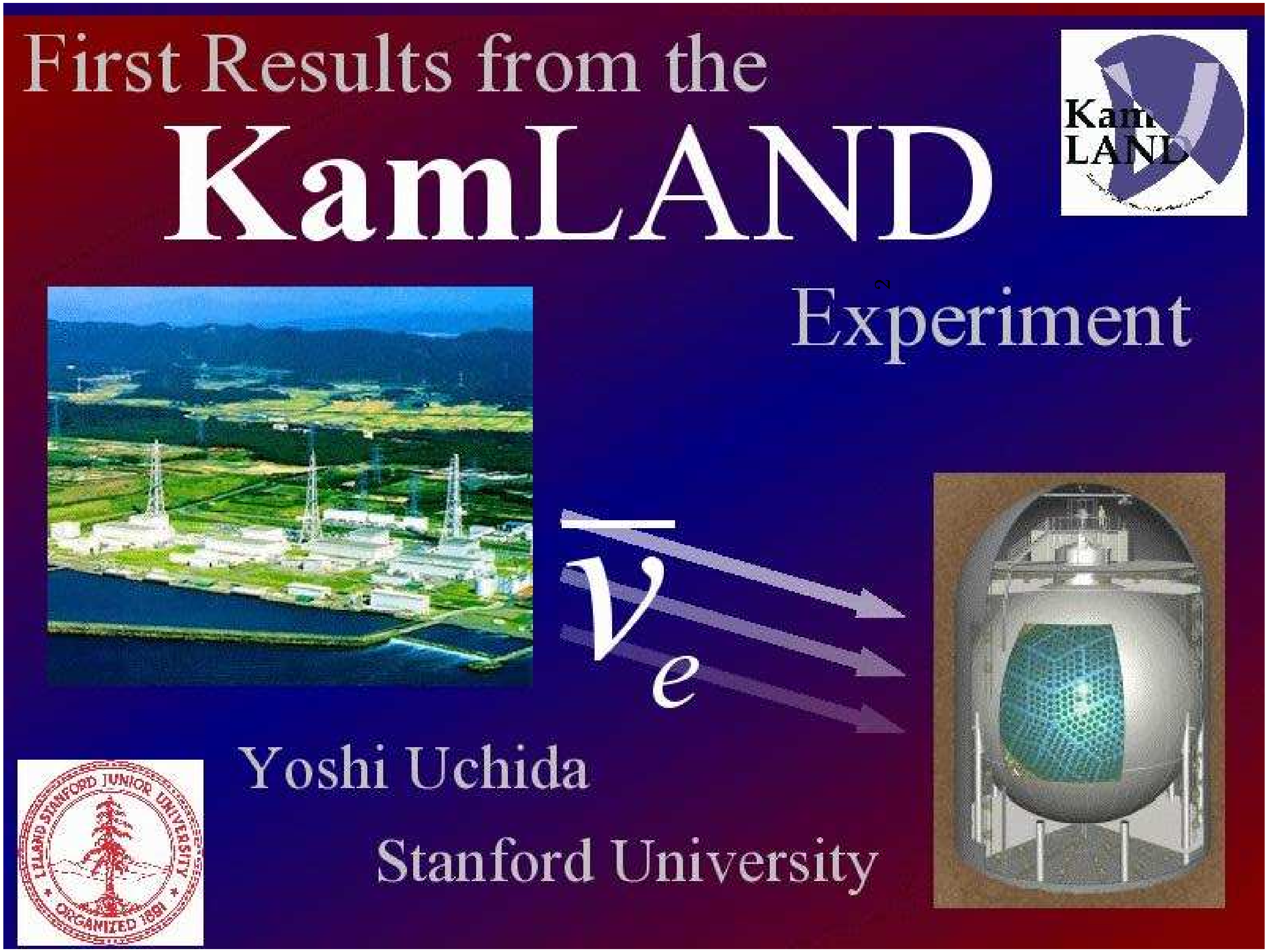


First Results from the KamLAND Experiment

$\bar{\nu}_e$

Yoshi Uchida

Stanford University

Overview

- The Solar Neutrino Problem
- Neutrino Oscillations
- Reactor Neutrinos
- The KamLAND Experiment
  - What it does
  - How it works
  - Its construction
  - Data analysis and results
- Conclusions and Prospects

Solar Neutrino Experiments

Very briefly...

- **Chlorine** (Homestake[†] '68 –'97)
  - Chemical, ν_e Total Rate only
- **Gallium** (SAGE '90 –, Gallex/GNO '91 –)
  - Chemical, ν_e Total Rate only, very low energy threshold
- **Water** (Kamiokande[‡] '88 – , SuperK '96 –)
  - Real-time ν_e Rate, Directionality
- **Heavy Water** (SNO '99 –)
  - Real-time ν_e , ν_X Rate, Directionality, Distinguishes Neutrino Types

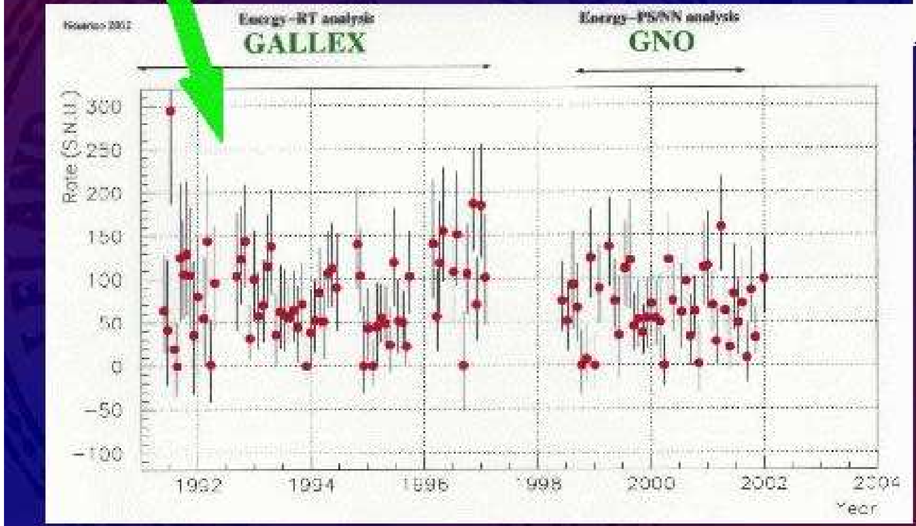
2002 Physics Nobel Prize Awarded to

Ray Davis[†] and Masatoshi Koshiba[‡]

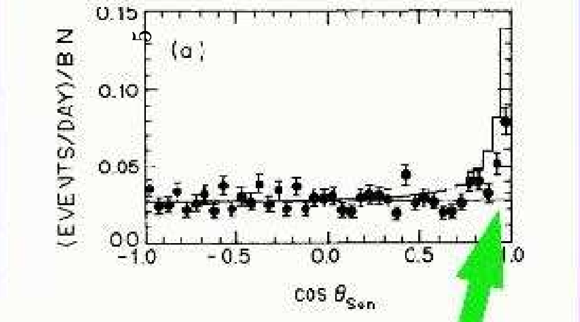
Solar Neutrino Experiments

Some examples of the reported results

Gallium detector solar neutrino rate measurements

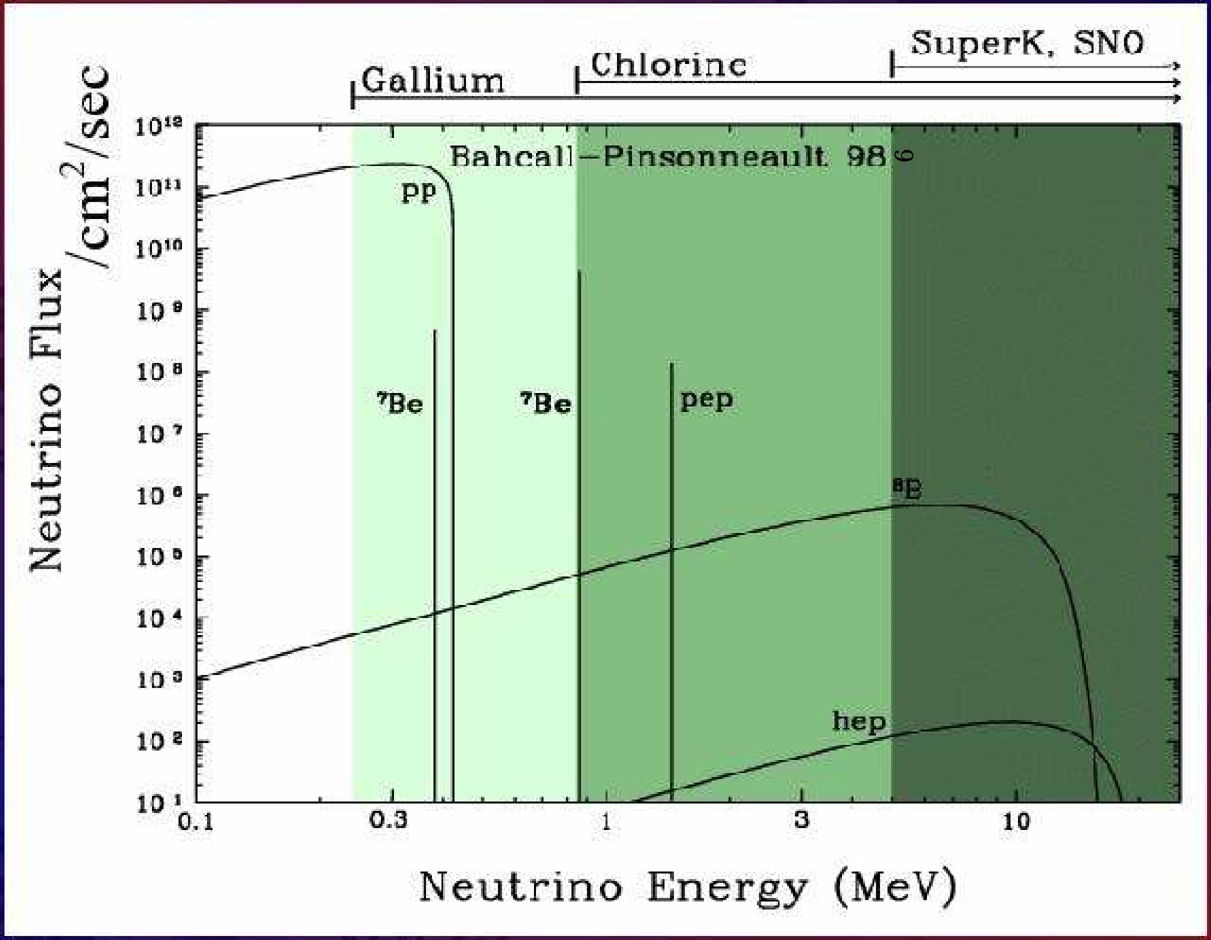


Kamiokande II



Real-time detection rate higher for neutrinos arriving from direction of Sun

Solar Standard Model Predictions



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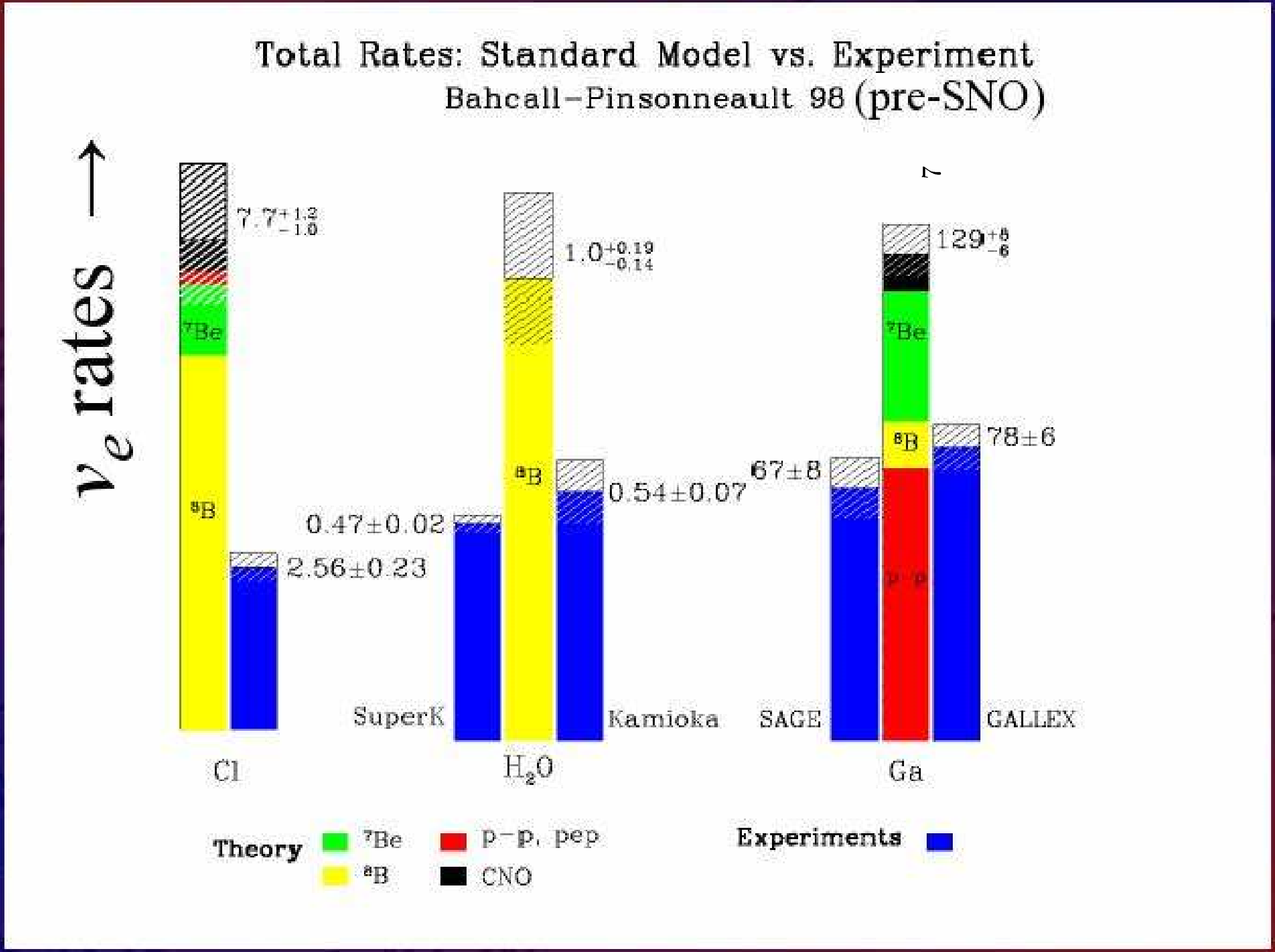
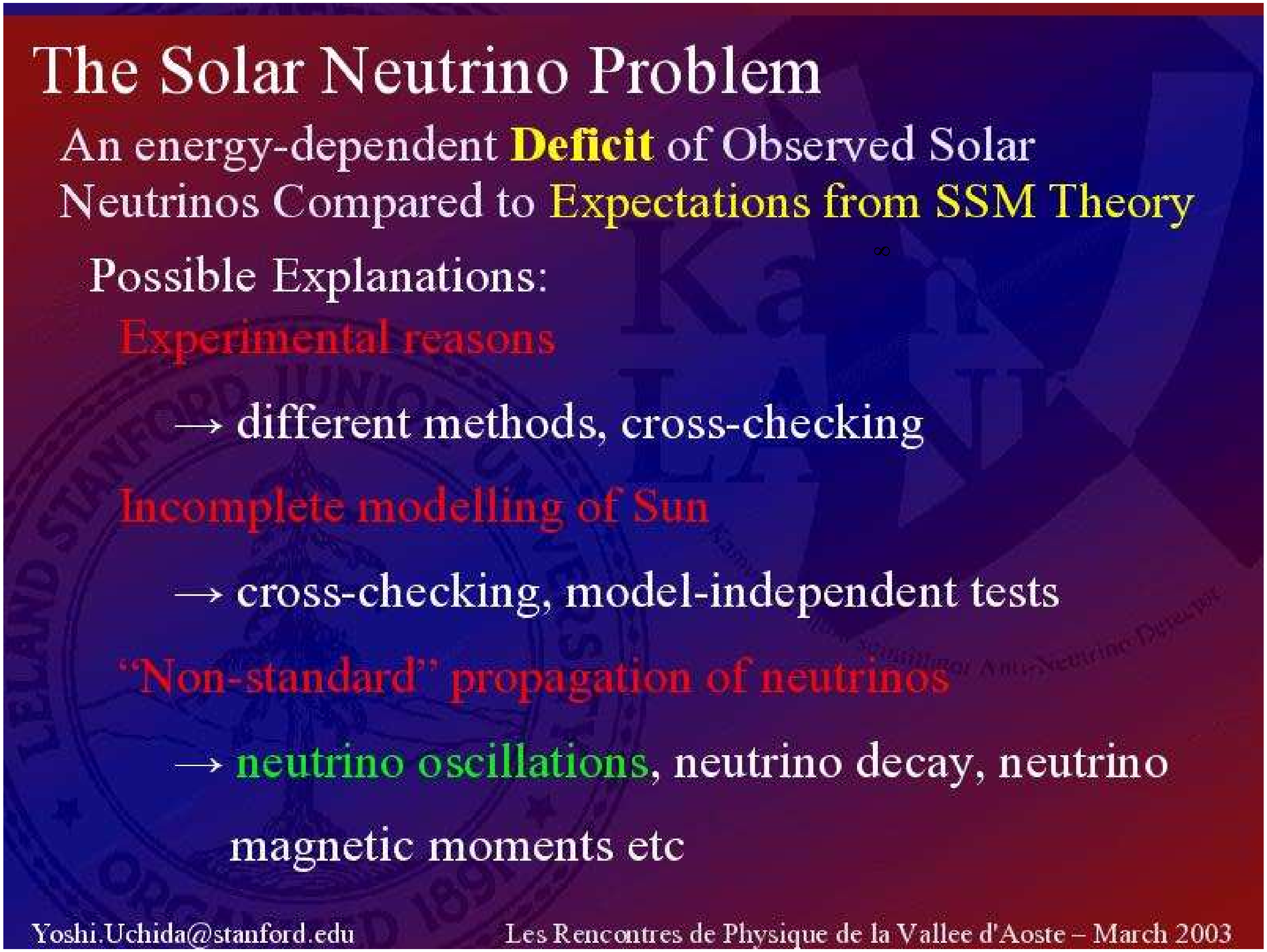
The Solar Neutrino Problem





The Solar Neutrino Problem

An energy-dependent **Deficit** of Observed Solar Neutrinos Compared to Expectations from SSM Theory

Possible Explanations:

Experimental reasons

→ different methods, cross-checking

Incomplete modelling of Sun

→ cross-checking, model-independent tests

"Non-standard" propagation of neutrinos

→ neutrino oscillations, neutrino decay, neutrino magnetic moments etc

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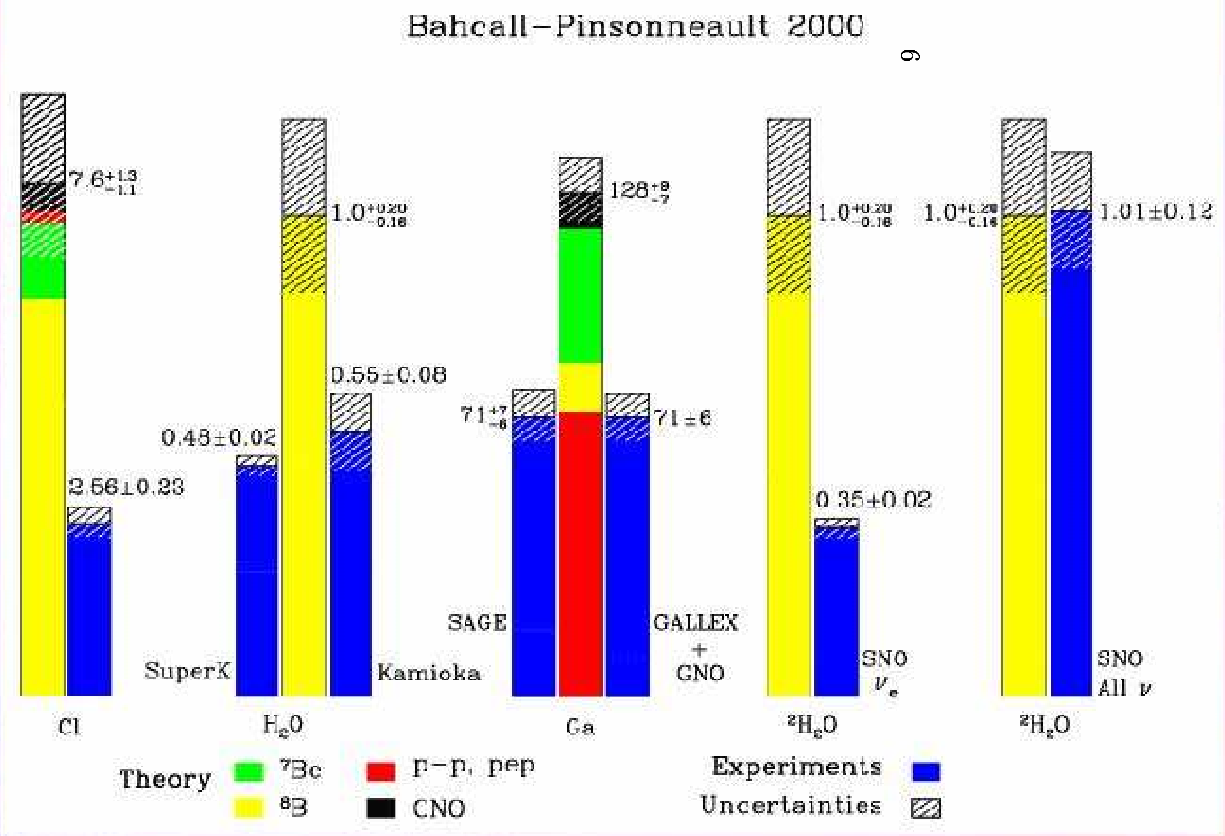
Latest Solar Neutrino Results

SNO (Sudbury Neutrino Observatory) results released 2001, 2002



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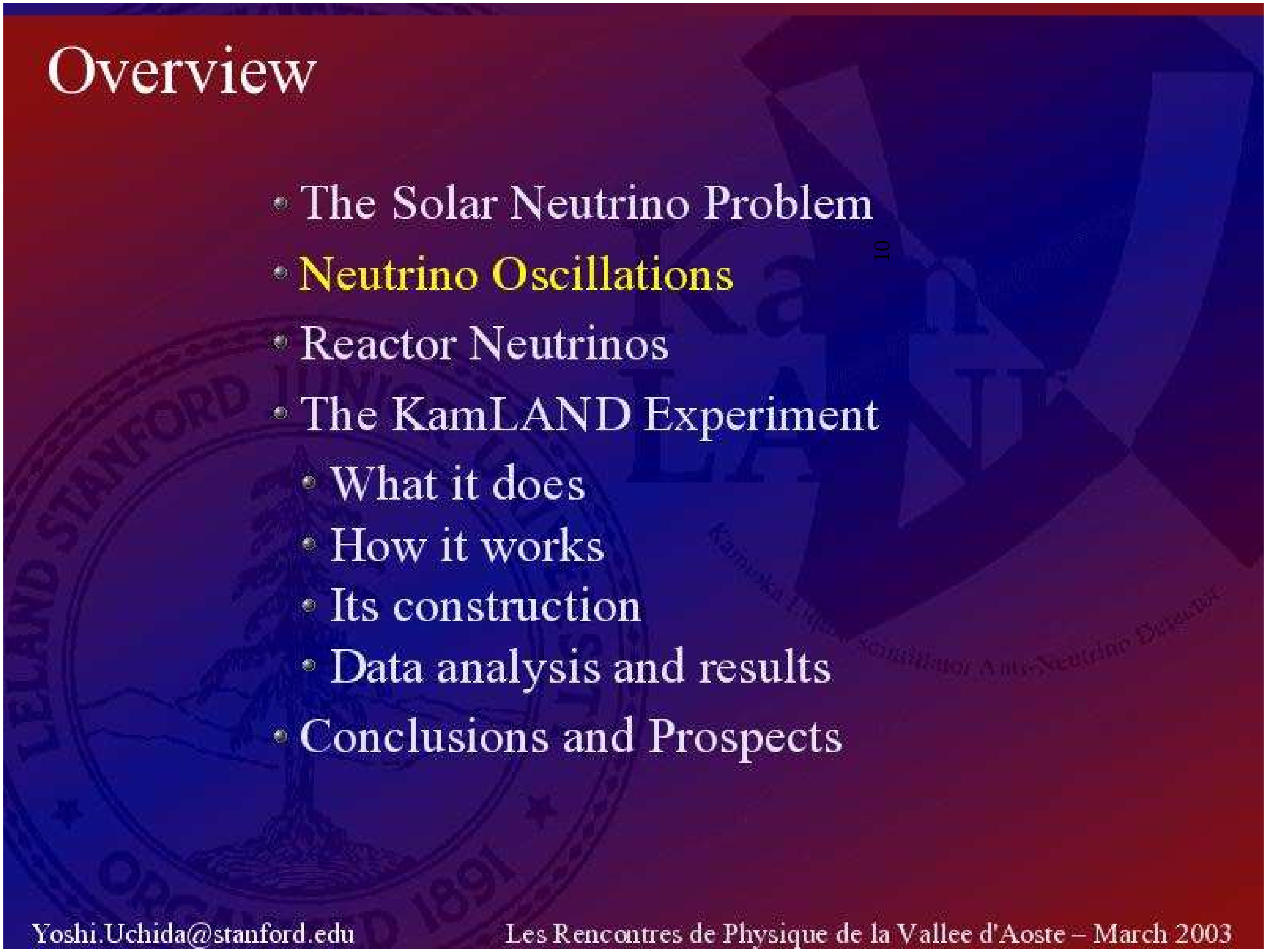

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Neutrino Mass ↔ Oscillations/Mixing

In Quantum Mechanics:

Neutrino creation/destruction: e, μ, τ eigenstates

Neutrino propagation: m_1, m_2, m_3 mass eigenstates

If $m_i \neq m_j$, interference in propagation can occur, causing different mixtures of the e, μ, τ eigenstates before and after propagation, as a function of $\Delta m_{ij}^2 = m_i^2 - m_j^2$

---

nb. Formally similar to $K^0 \leftrightarrow \overline{K}^0$ oscillations

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Neutrino Mixing in Vacuum and Matter

The two-generation mixing equation with commonly-used units inserted:

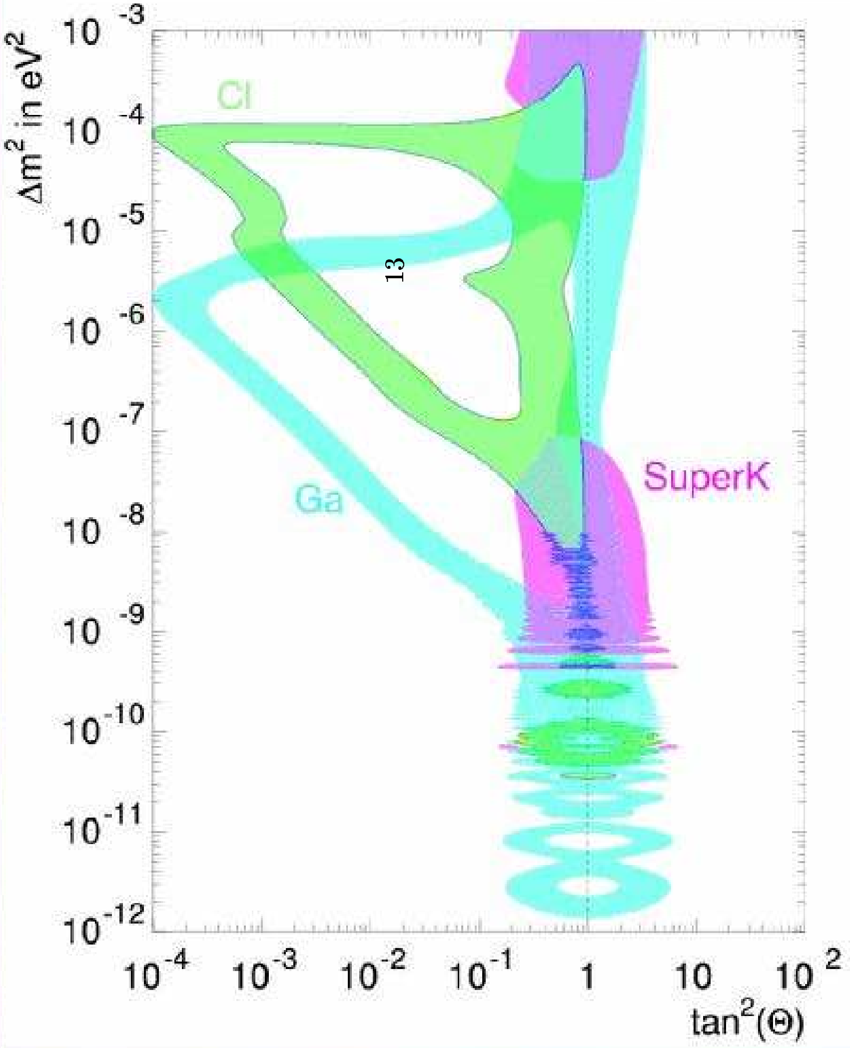
$$P(\nu_e \to \nu_e) = 1 - \sin^2(2\theta_{12}) \times \sin^2\left(1.27\,\Delta m^2_{12}(\mathrm{eV}^2)\,\frac{L(\mathrm{m})}{E(\mathrm{MeV})}\right)$$

For reactor experiments including KamLAND, this vacuum approximation valid

In matter (electrons and nucleons), oscillations can be enhanced (MSW effect), modifying above equation

Solar Experiment Oscillation Solutions

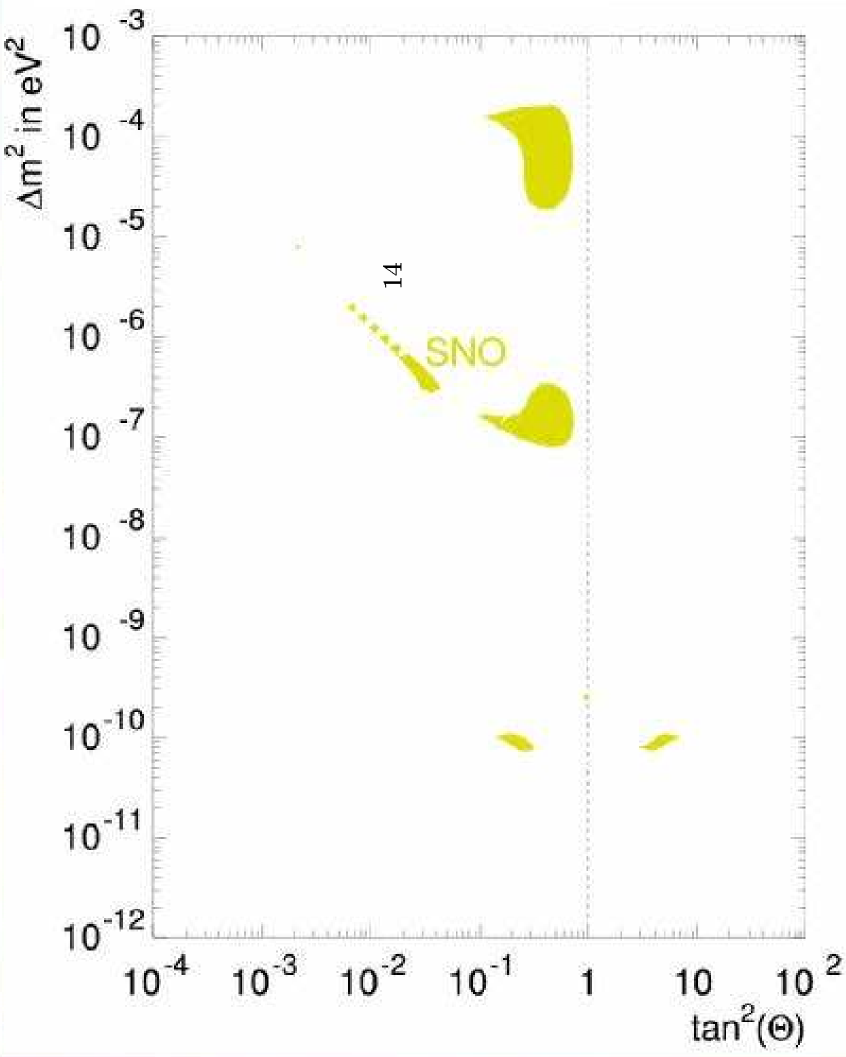
95% Allowed Regions



Adapted from Smy, Murayama

Solar Experiment Oscillation Solutions

95% Allowed Regions



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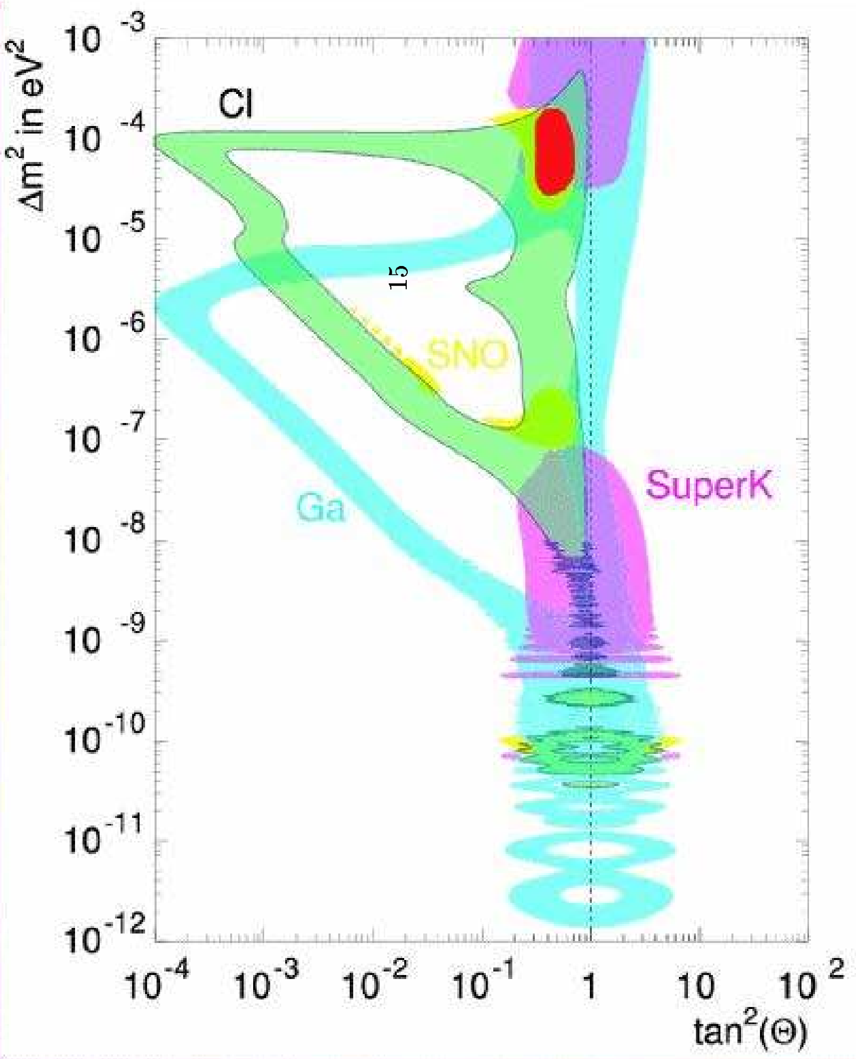
Solar Experiment Oscillation Solutions

95% Allowed Regions



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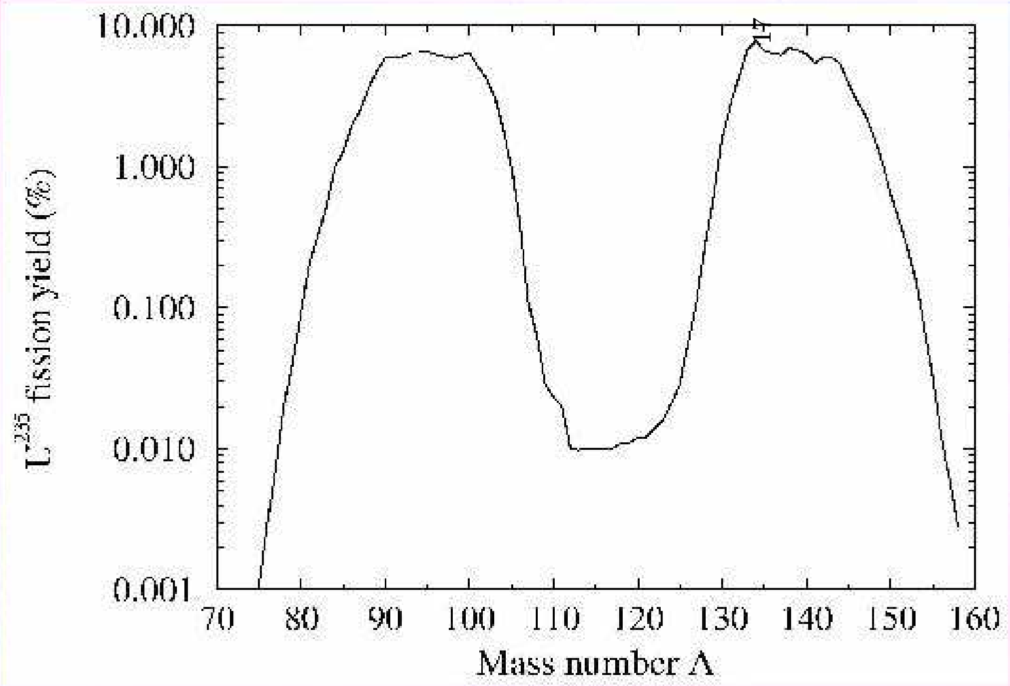
Antineutrinos from Reactors

Nuclear reactors operate by causing controlled fission chain-reactions of heavy radioactive elements

eg. ^{235}U:



The product isotopes are unstable and beta decay, producing antineutrinos ($N' \rightarrow N'' + e^- + \overline{\nu}_e$)

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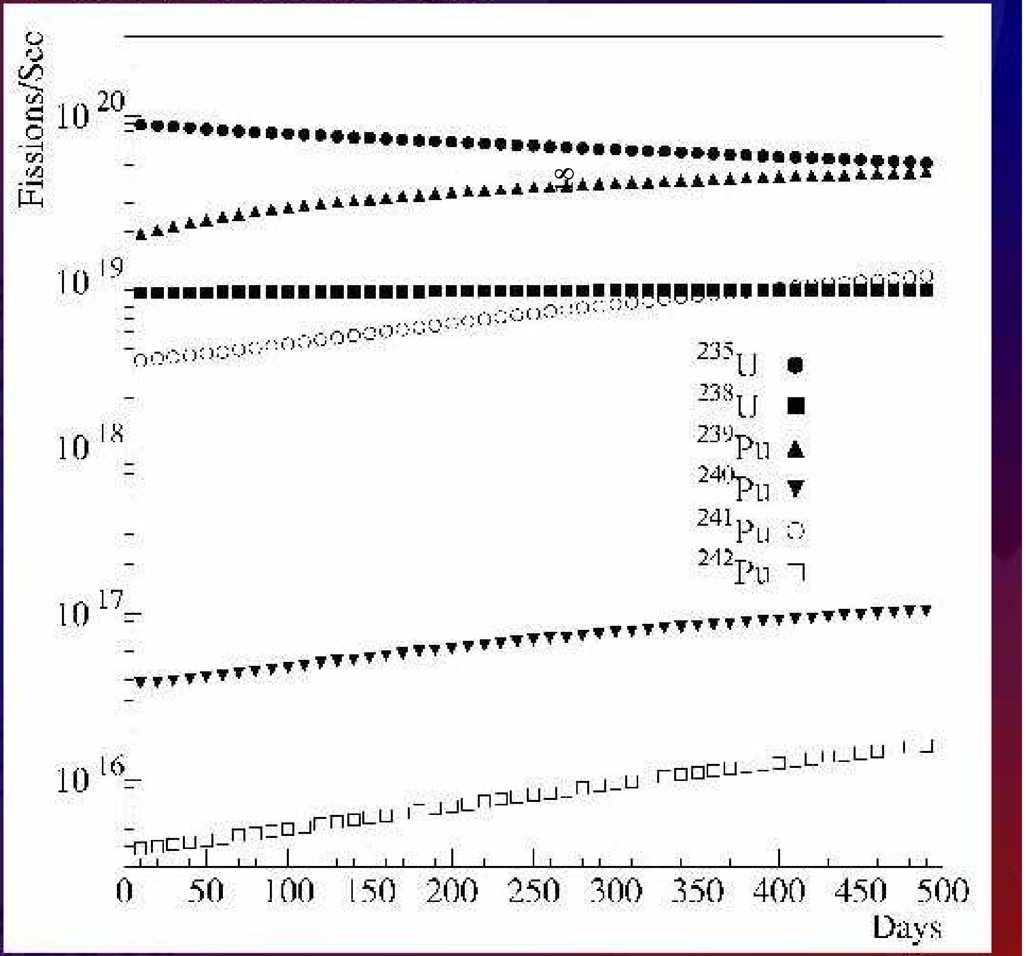
Antineutrinos from Reactors

Fuel composition evolution over time



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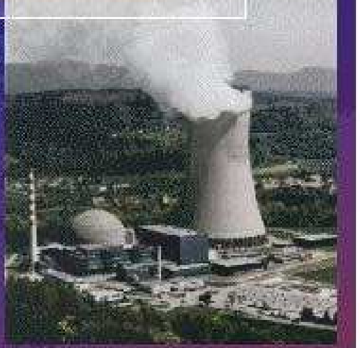
Reactor Antineutrino Oscillation Searches

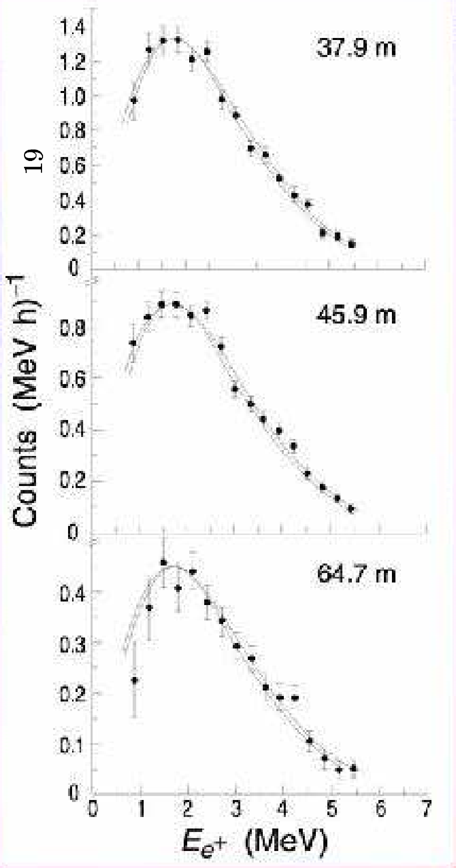
Shorter baseline reactor experiments showed **no deficits / oscillations**:

Chooz

Goesgen

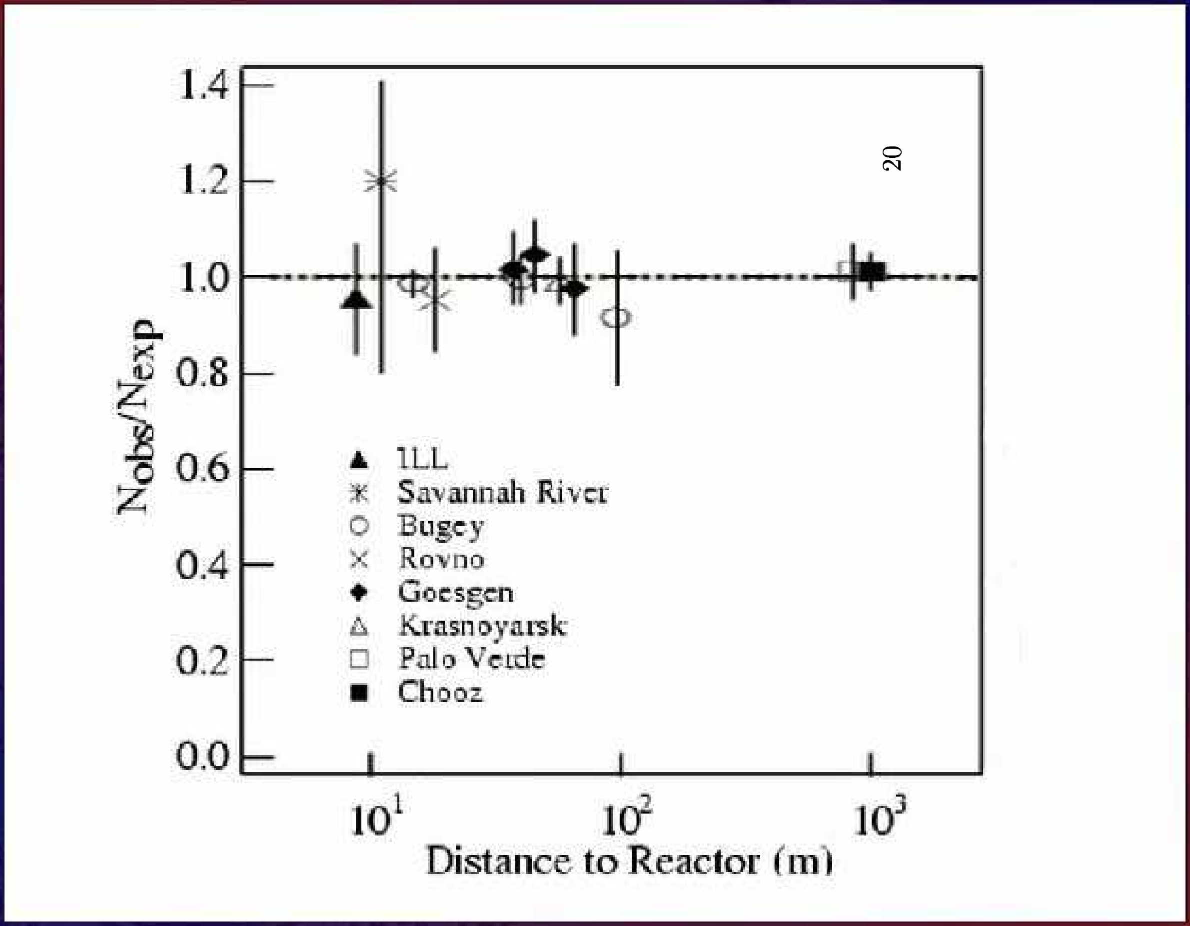


Palo Verde



➜ Now give precise knowledge of antineutrino production

Reactor Antineutrino Oscillation Searches



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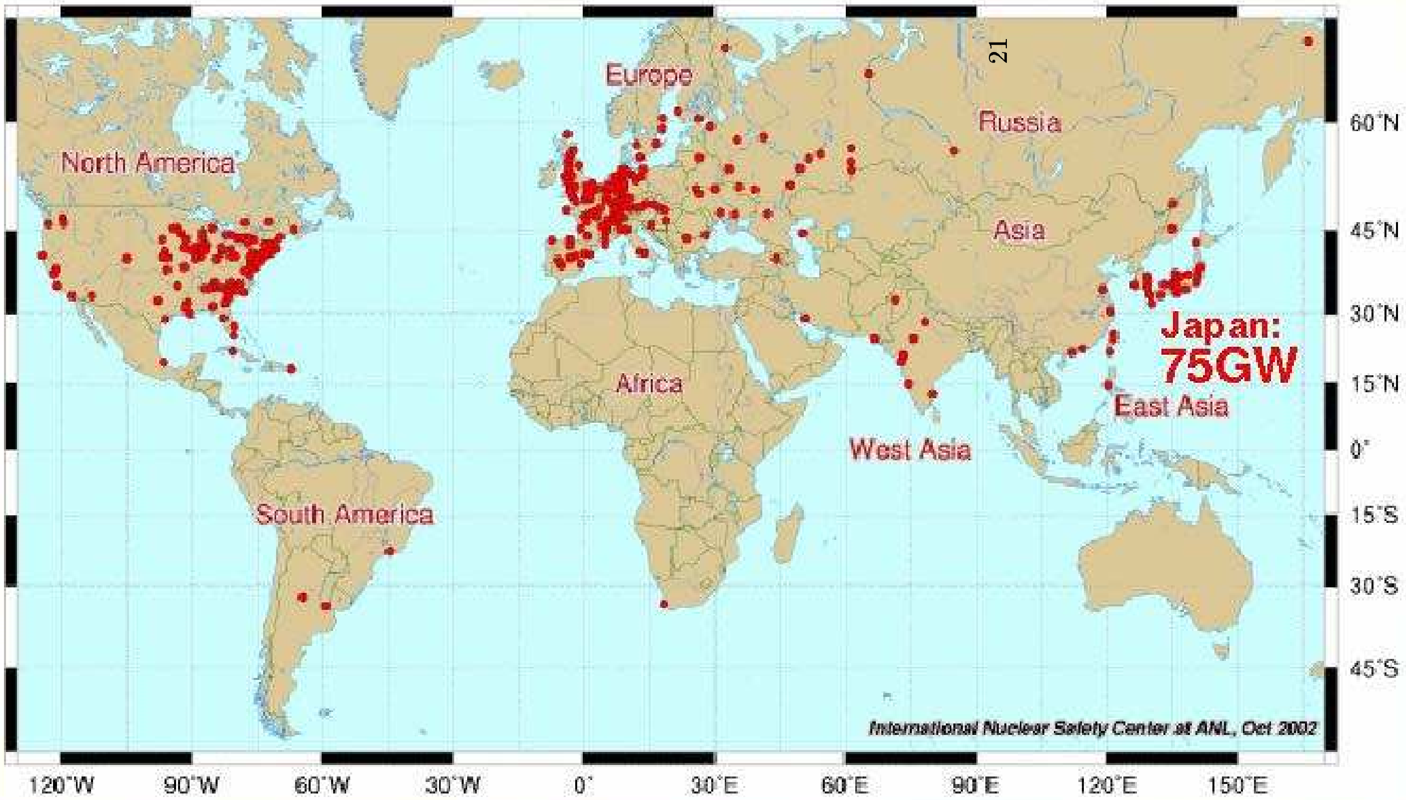
Nuclear Reactors Around The World

1/5 of Worldwide Nuclear Power Generated in Japan



International Nuclear Safety Center at ANL, Oct 2002

Location – Kamioka, Japan

Former site of **Kamiokande** detector, **1 km below surface** in **Kamioka Pb/Zn mine** (infrastructure and support already in place)

KamLAND

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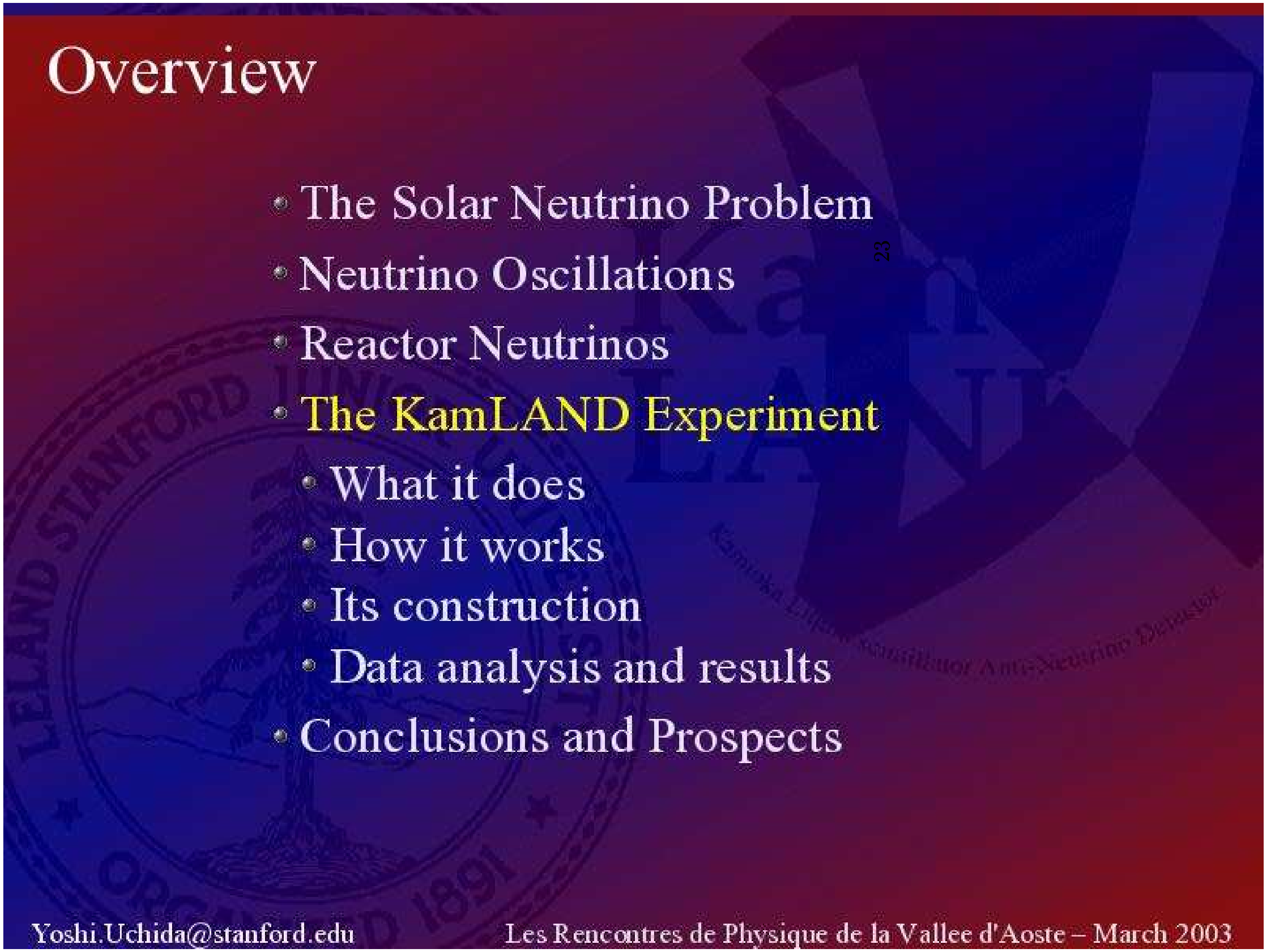

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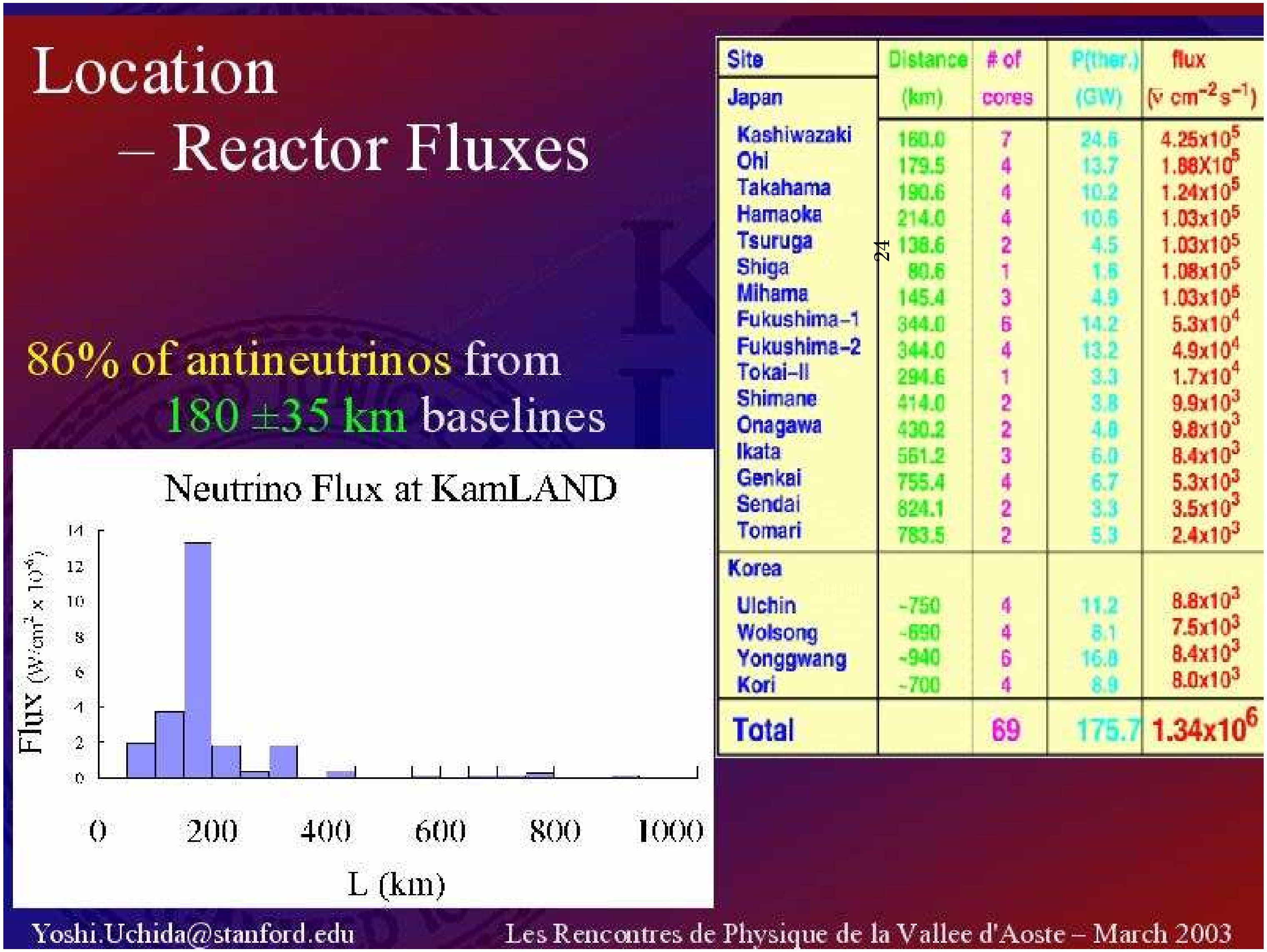


Location

– Reactor Fluxes

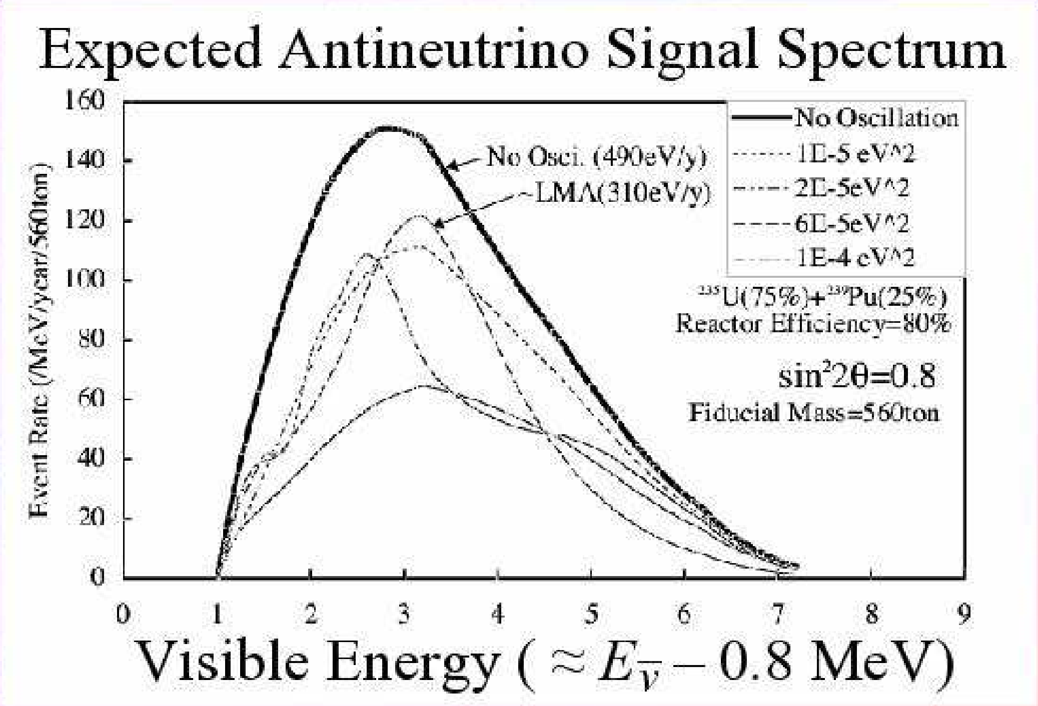
86% of antineutrinos from 180 ±35 km baselines

Neutrino Flux at KamLAND

Site	Distance (km)	# of cores	P(ther.) (GW)	flux ($\bar{\nu}$ cm^{-2}s^{-1})
Japan				
Kashiwazaki	160.0	7	24.6	4.25x10^5
Ohi	179.5	4	13.7	1.88X10^5
Takahama	190.6	4	10.2	1.24x10^5
Hamaoka	214.0	4	10.6	1.03x10^5
Tsuruga	138.6	2	4.5	1.03x10^5
Shiga	80.6	1	1.6	1.08x10^5
Mihama	145.4	3	4.9	1.03x10^5
Fukushima-1	344.0	6	14.2	5.3x10^4
Fukushima-2	344.0	4	13.2	4.9x10^4
Tokai-II	294.6	1	3.3	1.7x10^4
Shimane	414.0	2	3.8	9.9x10^3
Onagawa	430.2	2	4.8	9.8x10^3
Ikata	561.2	3	6.0	8.4x10^3
Genkai	755.4	4	6.7	5.3x10^3
Sendai	824.1	2	3.3	3.5x10^3
Tomari	783.5	2	5.3	2.4x10^3
Korea				
Ulchin	~750	4	11.2	8.8x10^3
Wolsong	~690	4	8.1	7.5x10^3
Yonggwang	~940	6	16.8	8.4x10^3
Kori	~700	4	8.9	8.0x10^3
Total		69	175.7	1.34x10^6

Oscillation Searches at KamLAND

$$P(\nu_e \to \nu_e) = 1 - \sin^2(2\theta_{12}) \times \sin^2\left(1.27\,\Delta m^2_{12}(\mathrm{eV}^2)\,\frac{180000(\mathrm{m})}{E(\mathrm{MeV})}\right)$$


Expected Antineutrino Signal Spectrum

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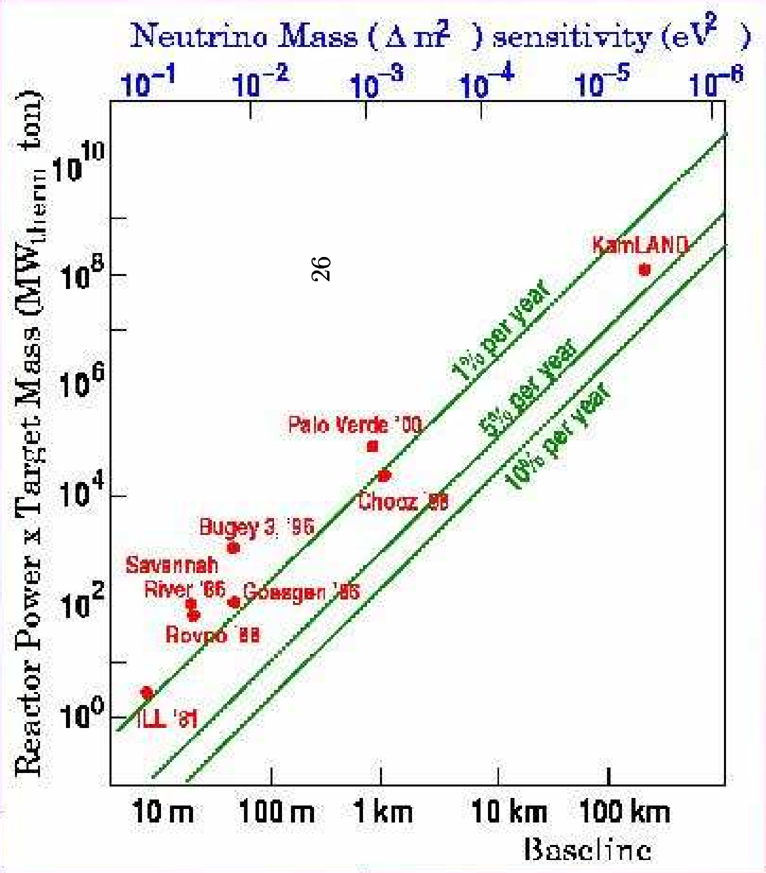
Probing the Solar Neutrino Problem with KamLAND

Reactor Flux & Detector Size v. Baselines — Experimental Sensitivity to Δm^2



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

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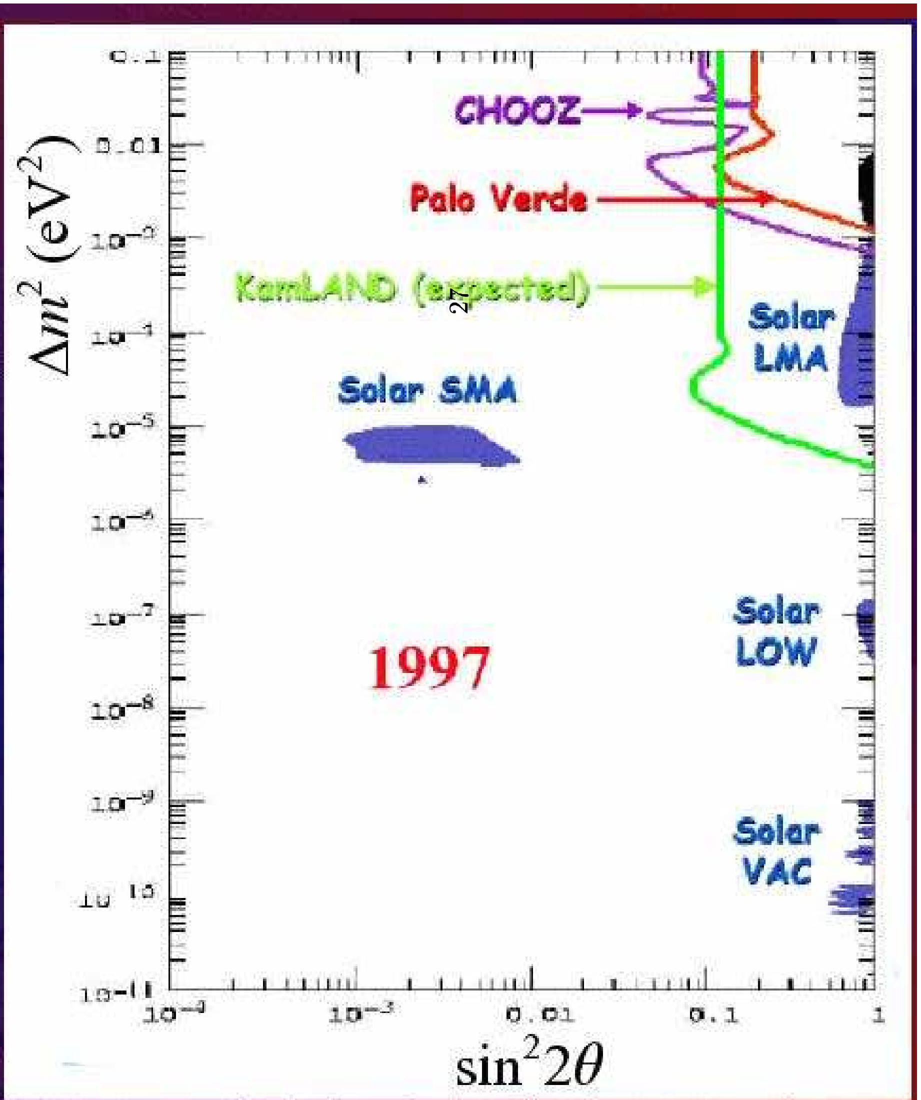
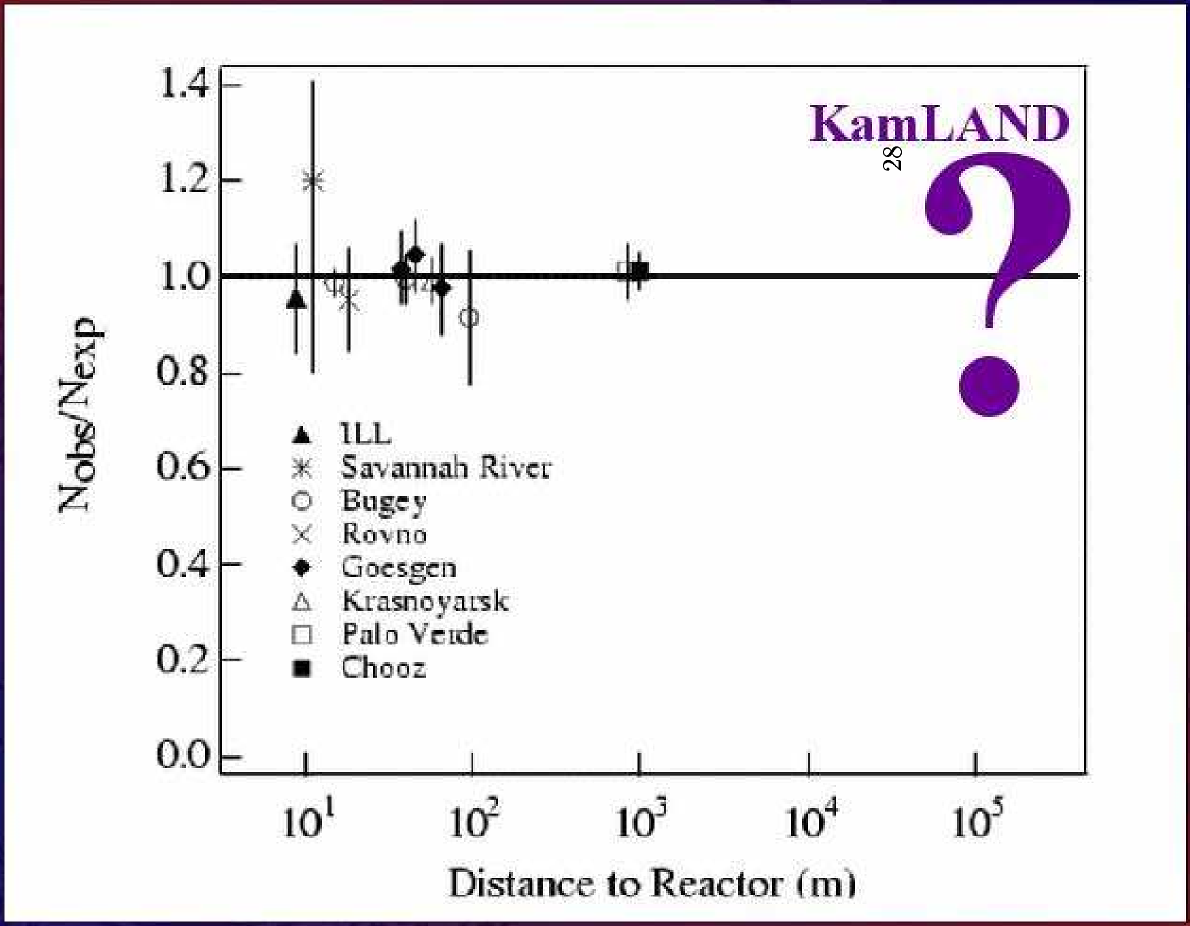
Les Rencontres de Physique de la Vallee d'Aoste – March 2003

Probing the Solar Neutrino Problem with KamLAND

"KamLAND tests the MSW LMA solution to the Solar Neutrino Problem, in a ***laboratory*** environment"



Reactor Antineutrino Oscillation Searches



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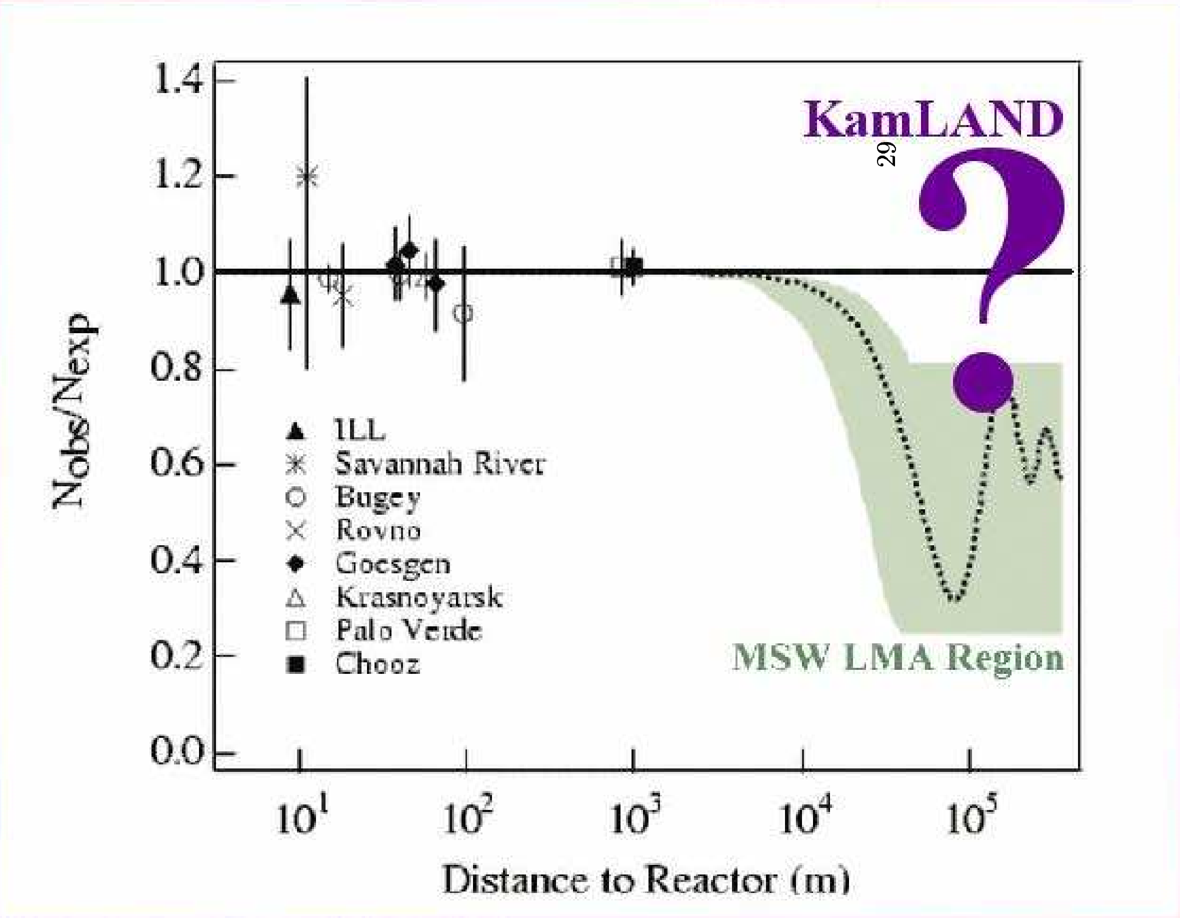
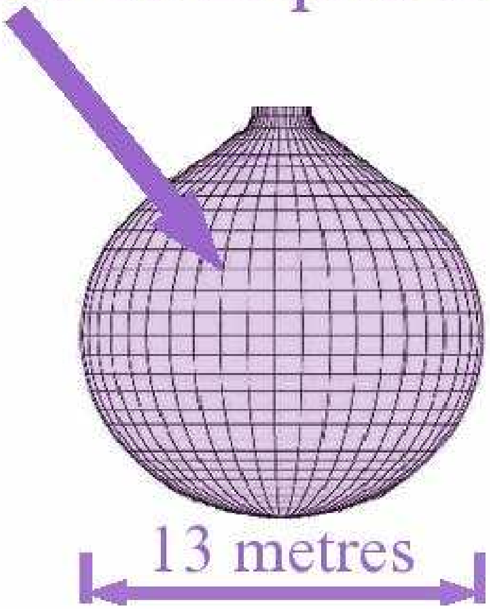
Reactor Antineutrino Oscillation Searches



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

1000 tonnes of Liquid Scintillator



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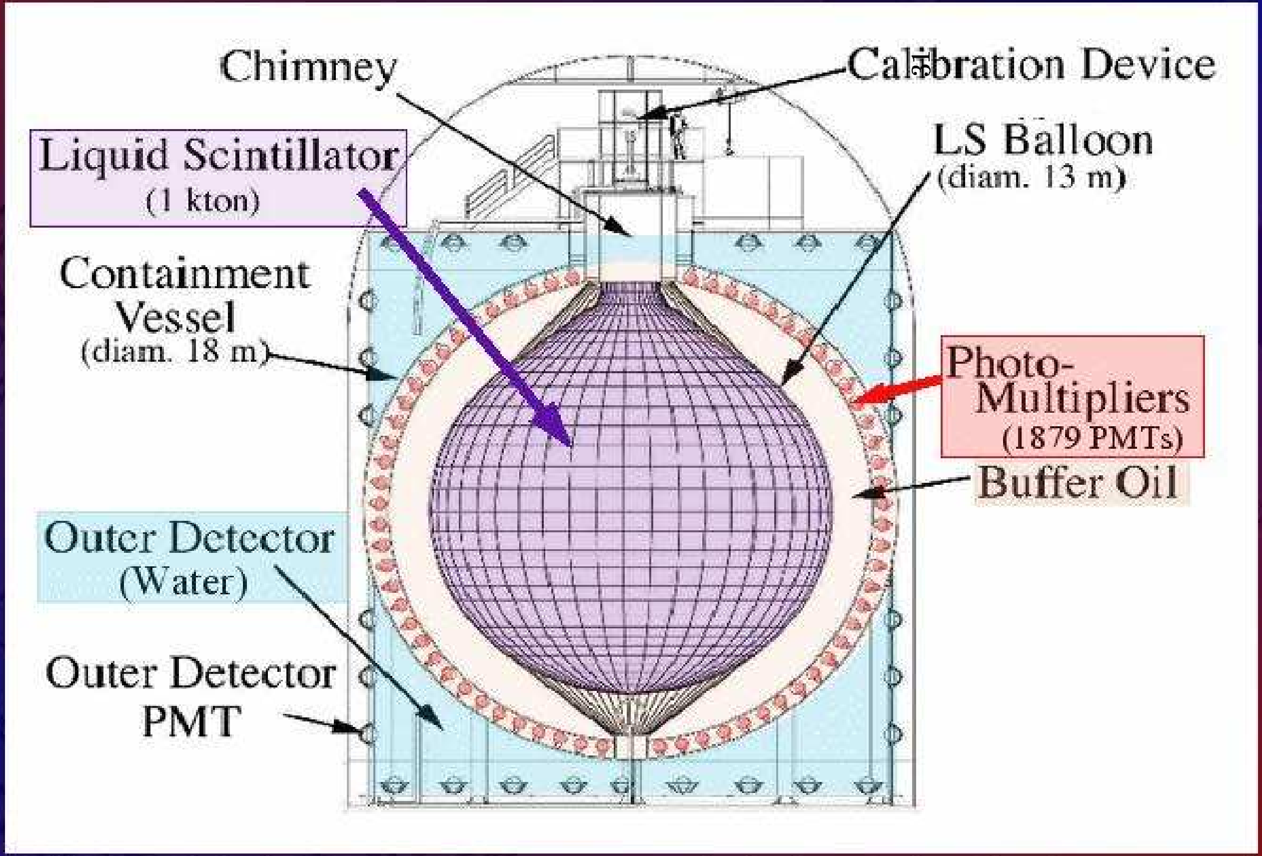
The **Kam**ioka **L**iquid Scintillator **A**nti-**N**eutrino **D**etector



Chimney

Calibration Device

Liquid Scintillator
(1 kton)

LS Balloon
(diam. 13 m)

Containment
Vessel
(diam. 18 m)

Photo-
Multipliers
(1879 PMTs)

Buffer Oil

Outer Detector
(Water)

Outer Detector
PMT

Liquid Scintillator and Buffer Oil

LS Composition: 80% docecane
20% pseudocumene
1.52 g/litre PPO

Buffer Oil: dodecane and isoparaffin mixed for density 0.04% lower than LS

- Purification by water extraction, nitrogen bubbling
- → PPO prepurification allowed very low backgrounds
- High transparency
- 300 photoelectrons in PMTs per MeV

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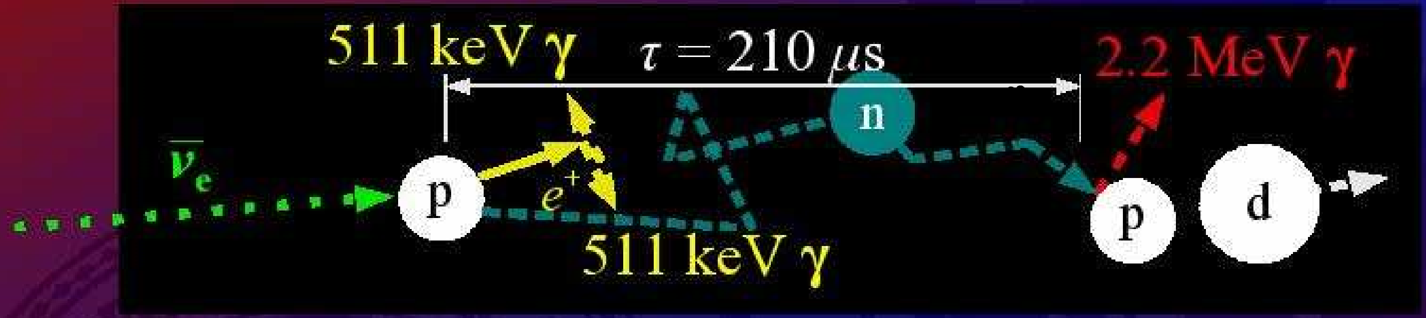
Antineutrino Signature

Antineutrino interactions leave a distinctive 2-part signature



1. Prompt Part:
   positron with $E_{e^+} \approx E_{\overline{\nu}_e} - (M_n - M_p) - M_{e^+}$
   & 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 (trigger rate: 30 Hz)

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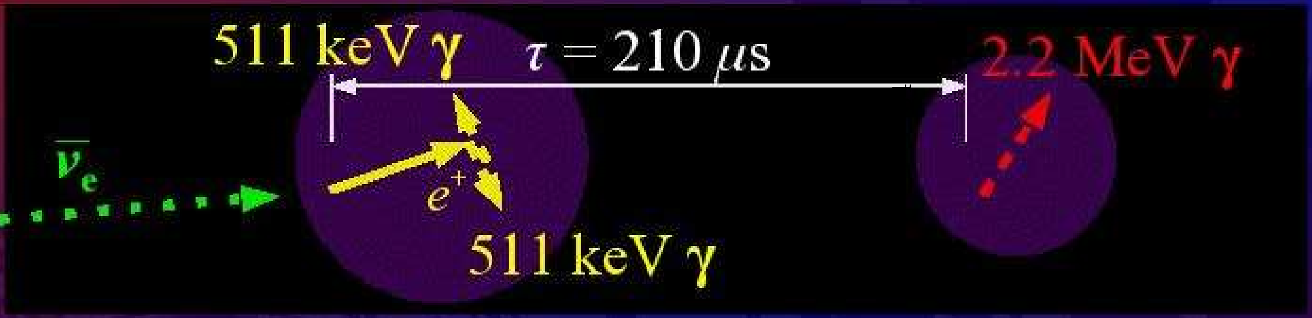

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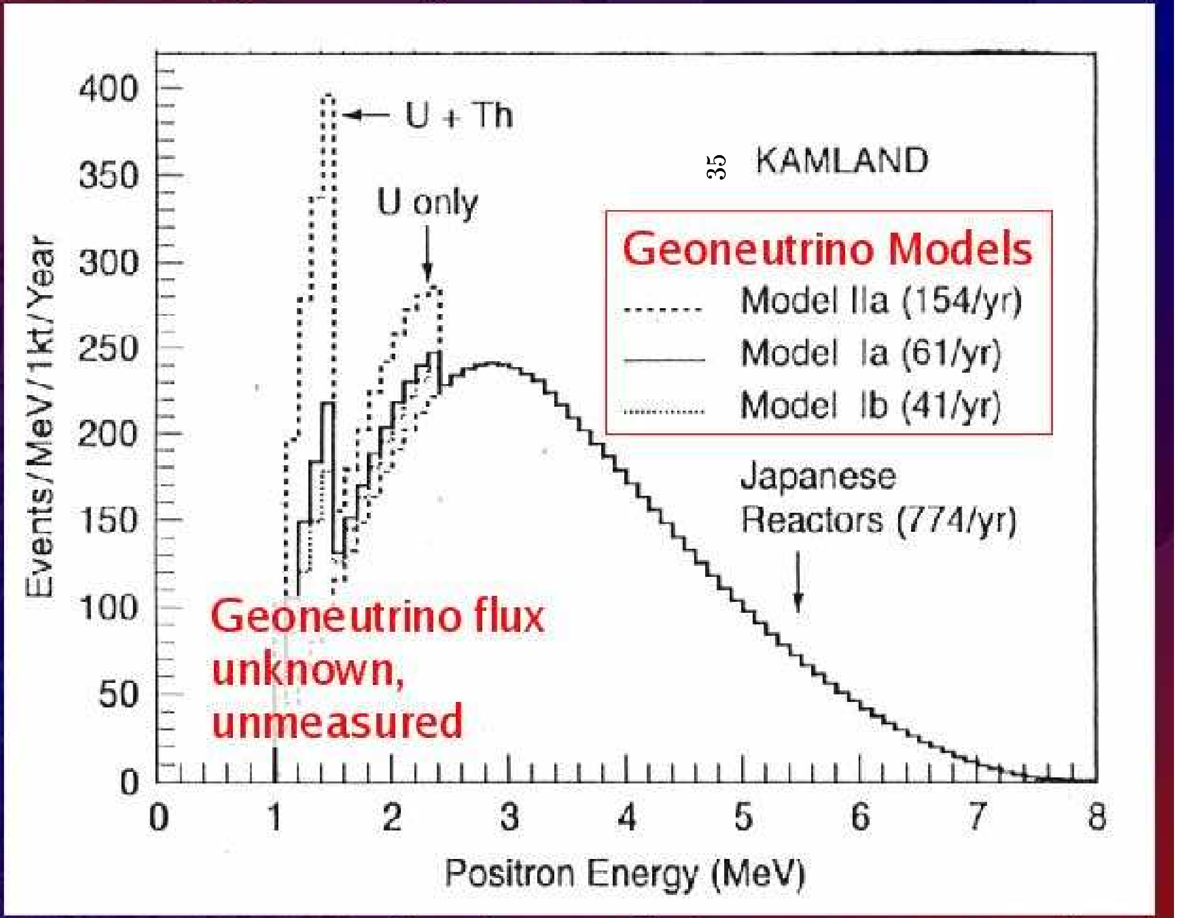
Antineutrino Signal Spectra

Expected spectra for Reactor and Geothermal antineutrino events



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

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KamLAND Fundamentals

- Location: Kamioka, Japan, under ~1 km of rock
- ~180 km average baseline from Japanese Nuclear Reactors (probing of MSW LMA solution to solar neutrino problem)
- ~1000 tonnes of Ultra-Pure Liquid Scintillator
- ~2 m of inactive Buffer Oil
- 1,325 fast 17-inch diameter PMTs
- 30 Hz average total trigger rate
- Muon rate in entire detector: 1 every 3 seconds
- Outer Detector Muon Veto (active water shield)
- Japan – United States – People's Republic of China Collaboration

The KamLAND Collaboration

*Research Center for Neutrino Science, **Tohoku University***, Japan

K. Eguchi, S. Enomoto, K. Furuno, J. Goldman, H. Hanada, H. Ikeda, K. Ikeda, K. Inoue, K. Ishihara, W. Itoh, T. Iwamoto, T. Kawaguchi, T. Kawashima, H. Kinoshita, Y. Kishimoto, M. Koga, Y. Koseki, T. Maeda, T. Mitsui, M. Motoki, K. Nakajima, M. Nakajima, T. Nakajima, H. Ogawa, K. Owada, T. Sakabe, I. Shimizu, J. Shirai, F. Suekane, A. Suzuki, K. Tada, O. Tajima, T. Takayama, K. Tamae, H. Watanabe

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*Department of Physics and Astronomy, **University of Tennessee***, USA

M. Batygov, W. Bugg, H. Cohn, Y. Efremenko, Y. Kamyshkov, A. Kozlov, Y. Nakamura

Triangle Universities Nuclear Laboratory, and ***Physics Departments at Duke University, North Carolina State University***, and the ***University of North Carolina at Chapel Hill***, USA

L. De Braeckeleer, C.R. Gould, H.J. Karwowski, D.M. Markoff, J.A. Messimore, K. Nakamura, R.M. Rohm, W. Tornow, A.R. Young

Institute of High Energy Physics, People's Republic of China

Y-F. Wang

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 – May 2001	Plumbing for filling
Jun – Sep 2001	Filling with LS and Buffer
Aug – Sep 2001	Engineering runs with MACRO electronics
Sep 2001	F.E. Electronics/Trigger/DAQ integration
end Sep 2001	First test data taking
Jan 22, 2002	Data taking commences
6 Dec 2002	**First Results Submitted to Phys. Rev. Lett.**

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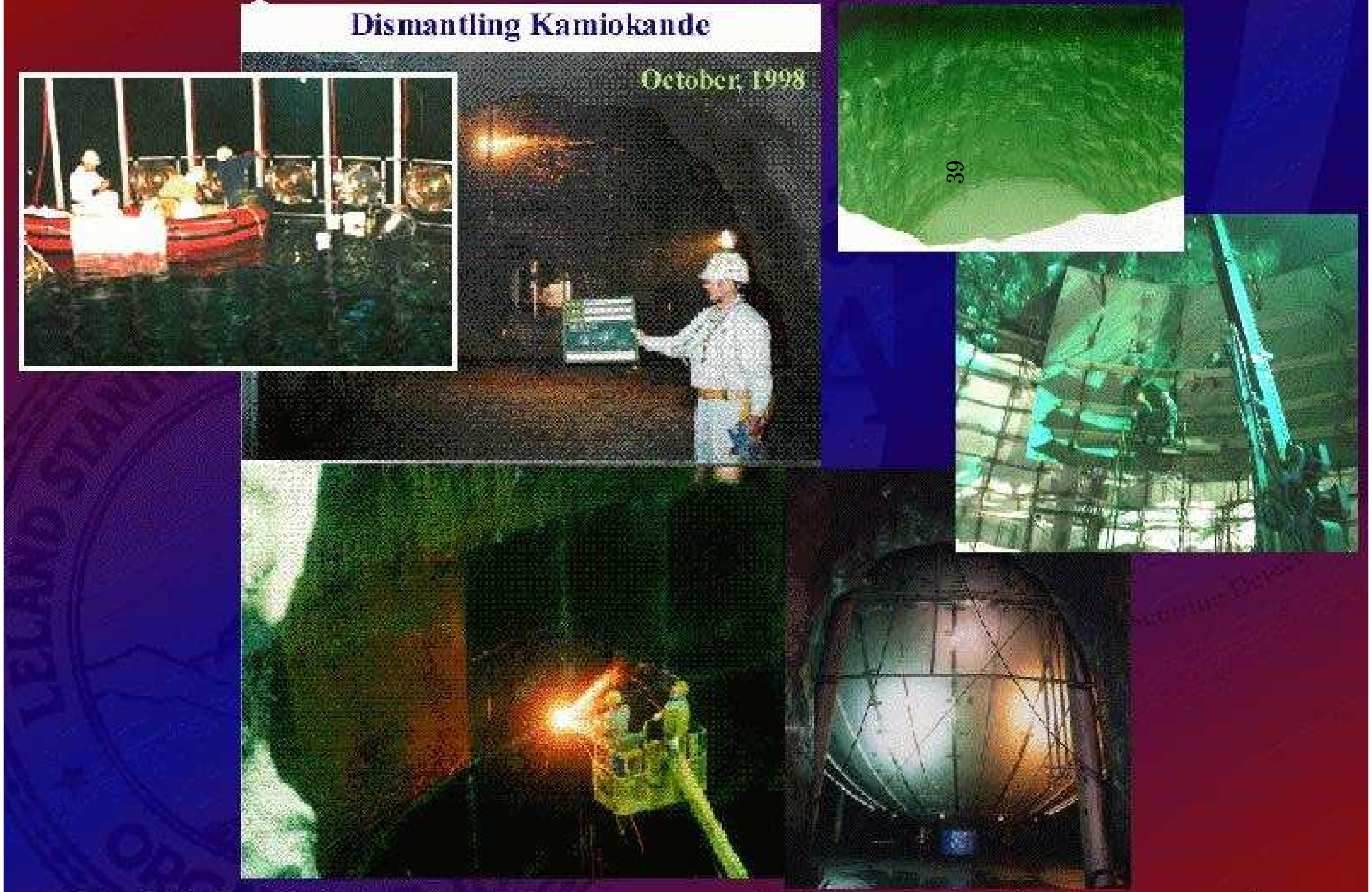
Site Preparation / Tank Installation



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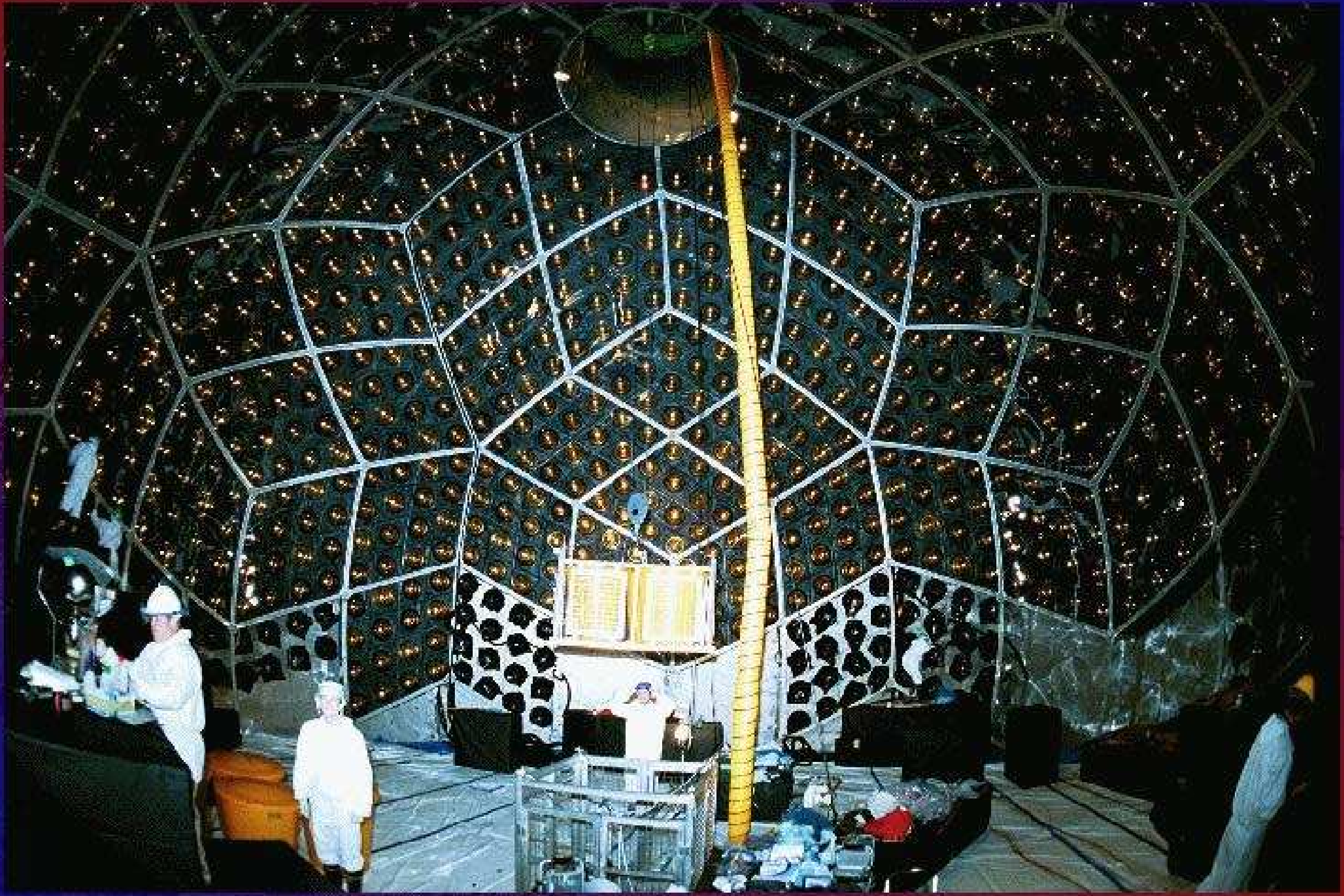
Construction: PMT Installation



Construction: PMT Installation

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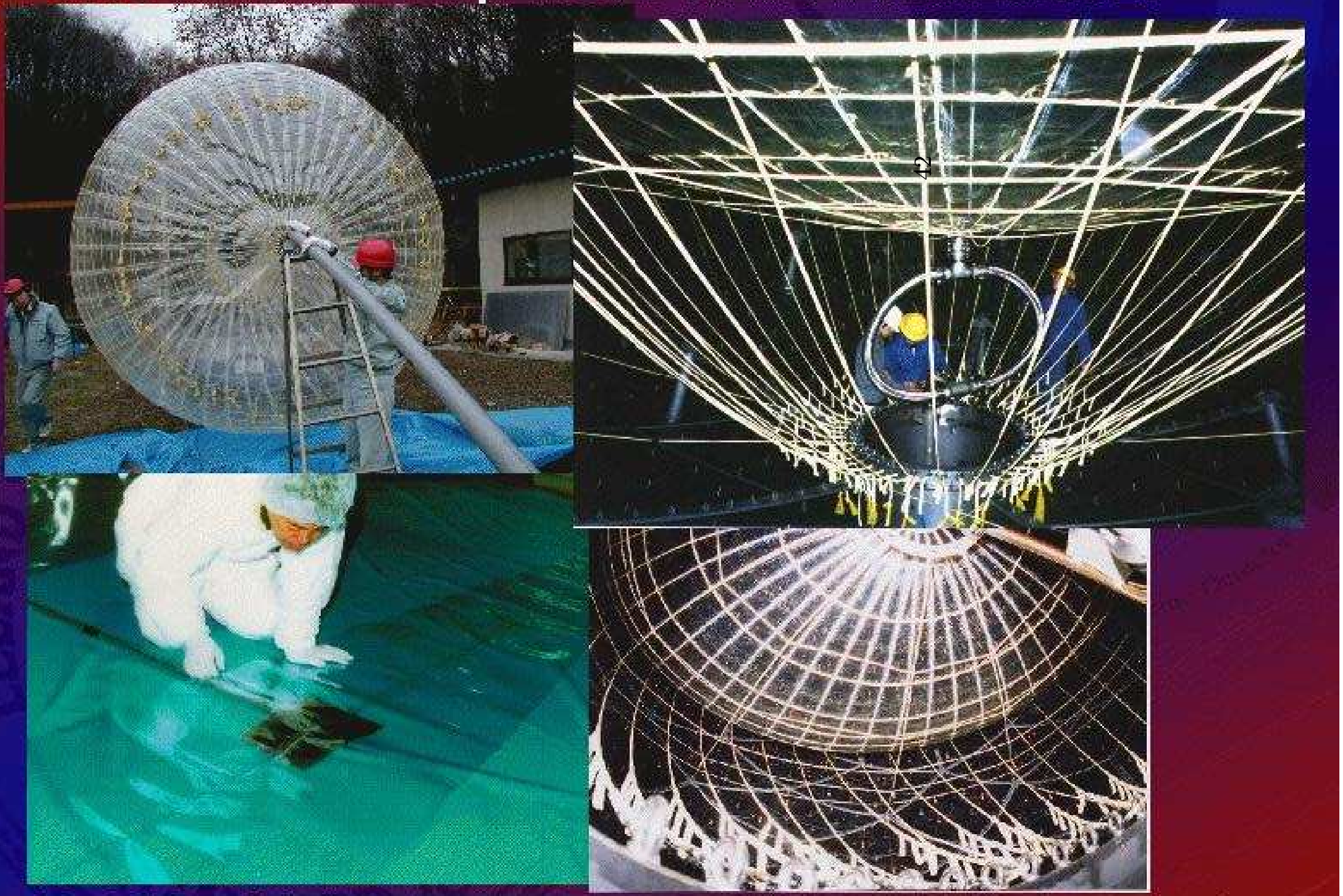
Balloon Development and Installation



Construction: Detector Filling

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Construction: Balloon Filling

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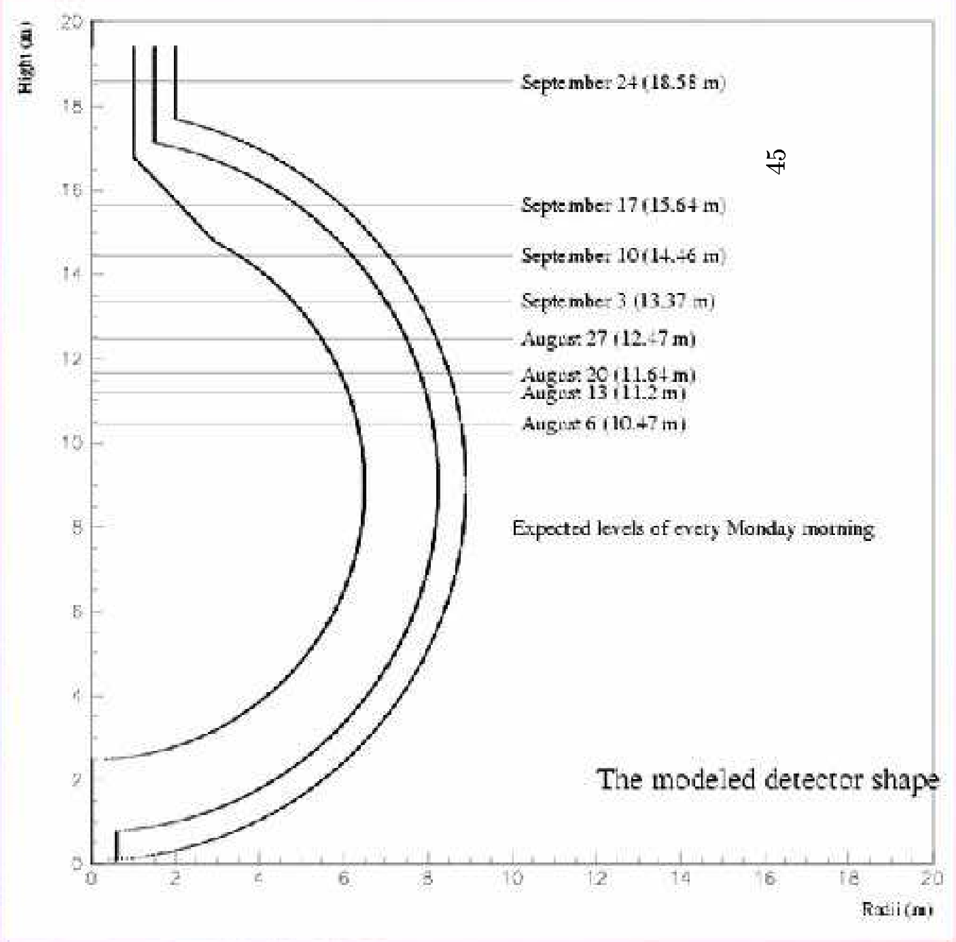
Construction: Balloon Filling



The modeled detector shape

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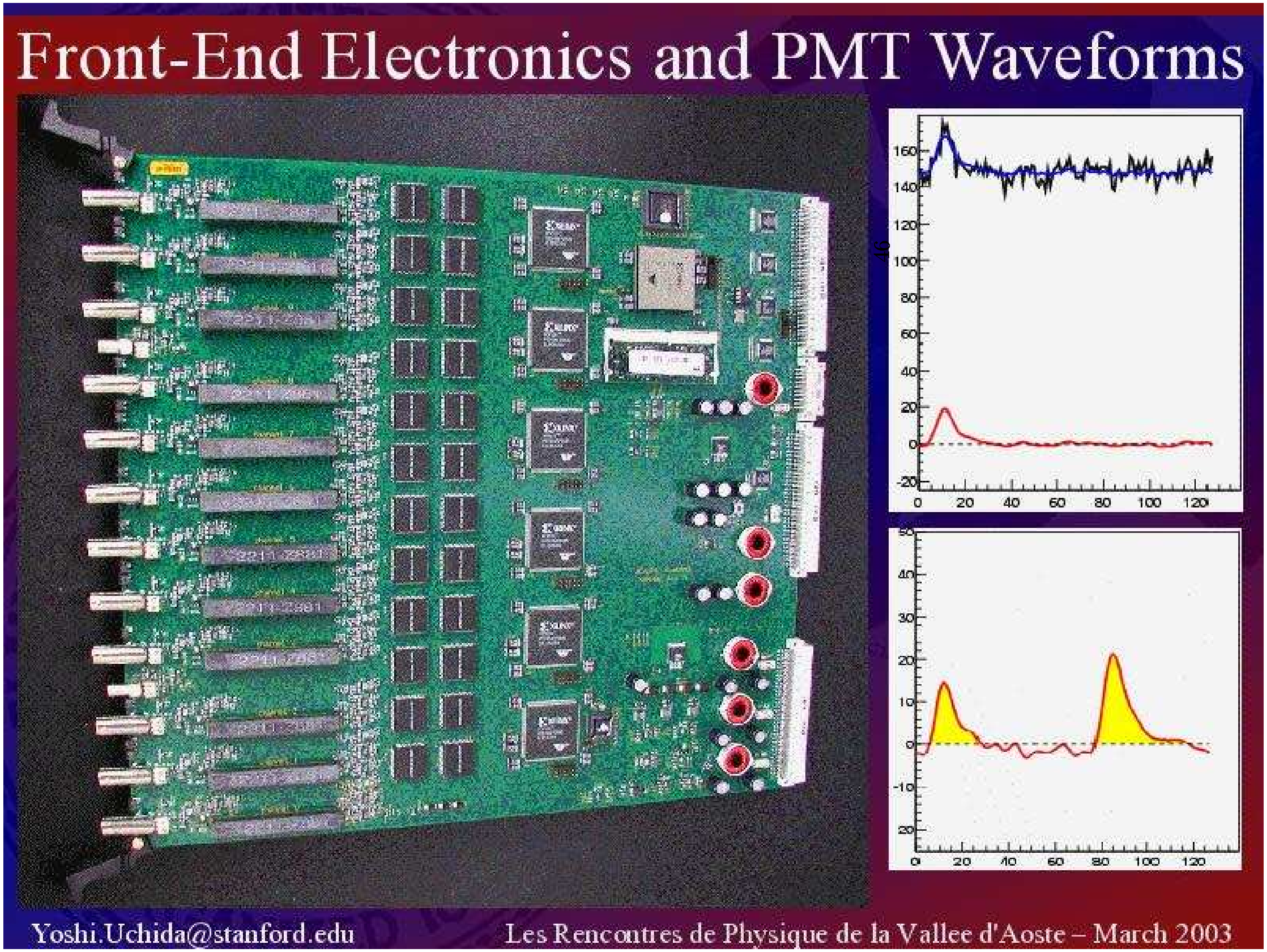

Front-End Electronics and PMT Waveforms

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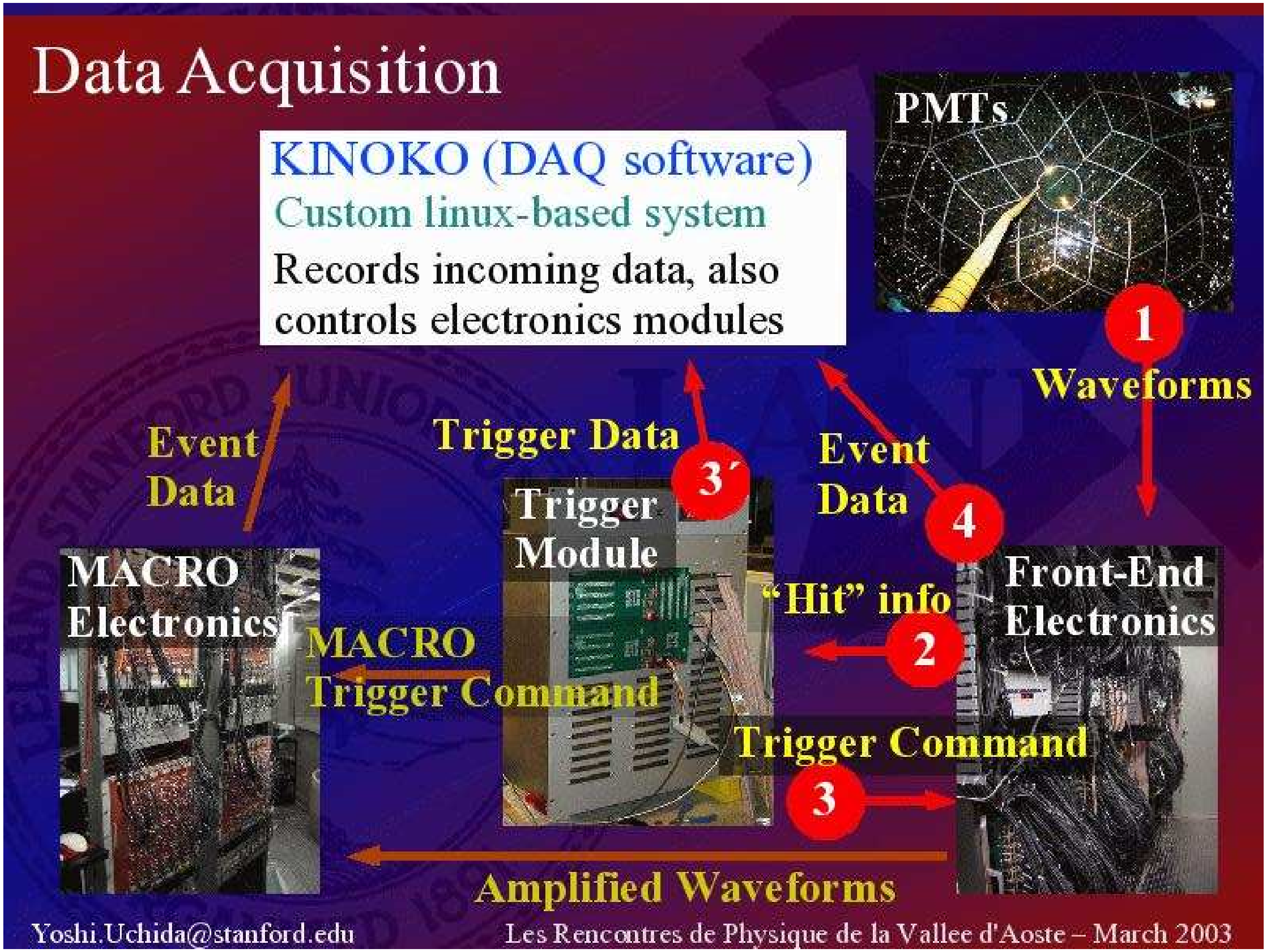
Les Rencontres de Physique de la Vallee d'Aoste – March 2003

Data Acquisition



KINOKO (DAQ software)

Custom linux-based system

Records incoming data, also controls electronics modules

PMTs

1 Waveforms

Front-End Electronics

2 "Hit" info

Trigger Module

3 Trigger Command

3´ Trigger Data

4 Event Data

MACRO Trigger Command

MACRO Electronics

Event Data

Amplified Waveforms

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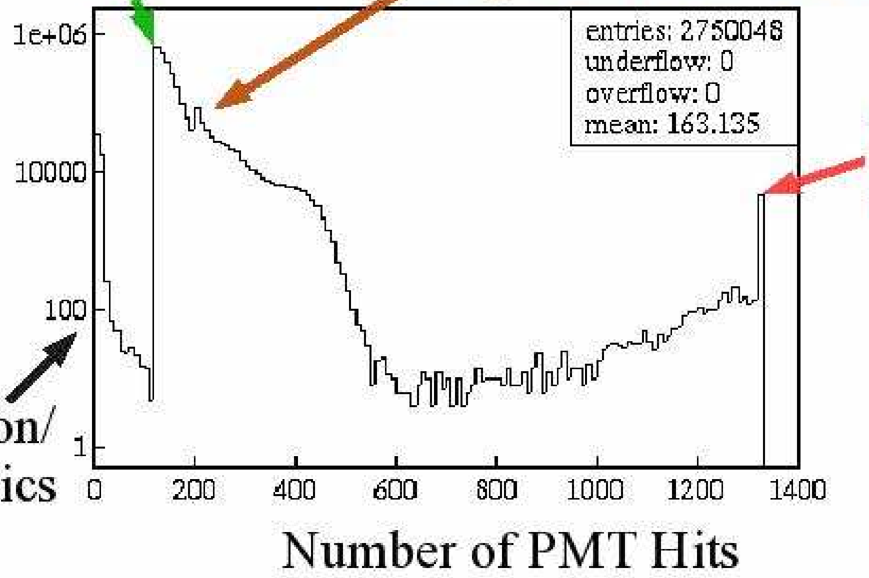
PMT Hit Information

The trigger uses "hit" information from the front-end electronics, which is simply the number of PMTs that have seen a pulse greater than 1/3 of a single photoelectron



Coincidence, prescaled, & trigger record threshold (120 tubes hit)

Singles threshold: 200 tubes hit

Muons (all tubes hit)

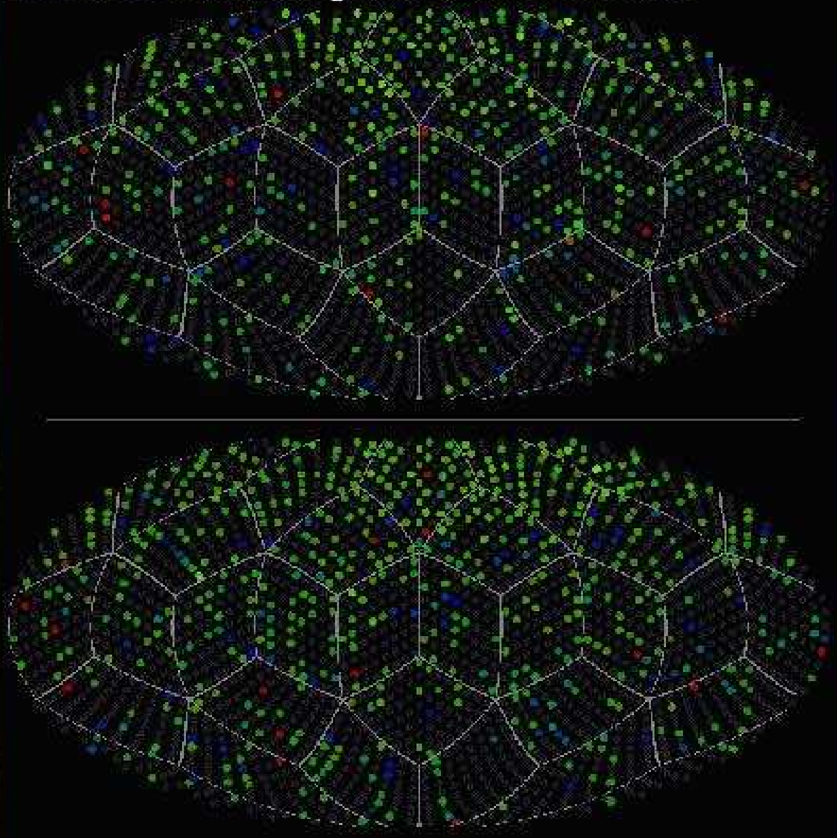
Calibration/ non-physics events

Trigger looks every 25 ns over the previous 125 ns

Event Reconstruction

Example event displays

Colour coded for photon arrival times



Events of interest have energies of several MeV

PMTs see

≈300 photons/MeV

Photon arrival times used to determine vertex positions, and charges and distributions used to estimate event energies

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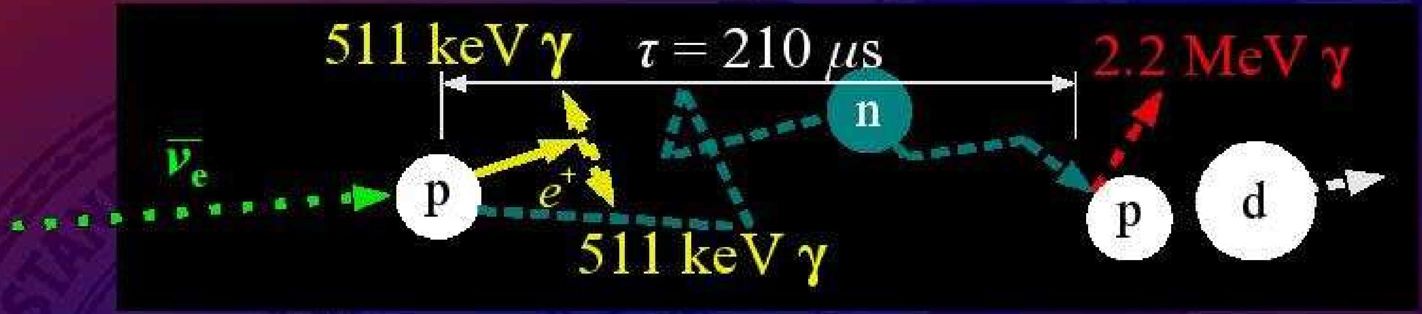
Signal Cuts

Spherical Fiducial Volume: $R < 5$ m

Central Axis Cut: $\rho > 1.2$ m



Time Correlation: $0.5\ \mu s < \Delta T < 660\ \mu s$

Vertex Correlation: $\Delta x < 1.6$ m

Delayed Event Energy: $1.8\ \text{MeV} < E_{\text{delayed}} < 2.6\ \text{MeV}$

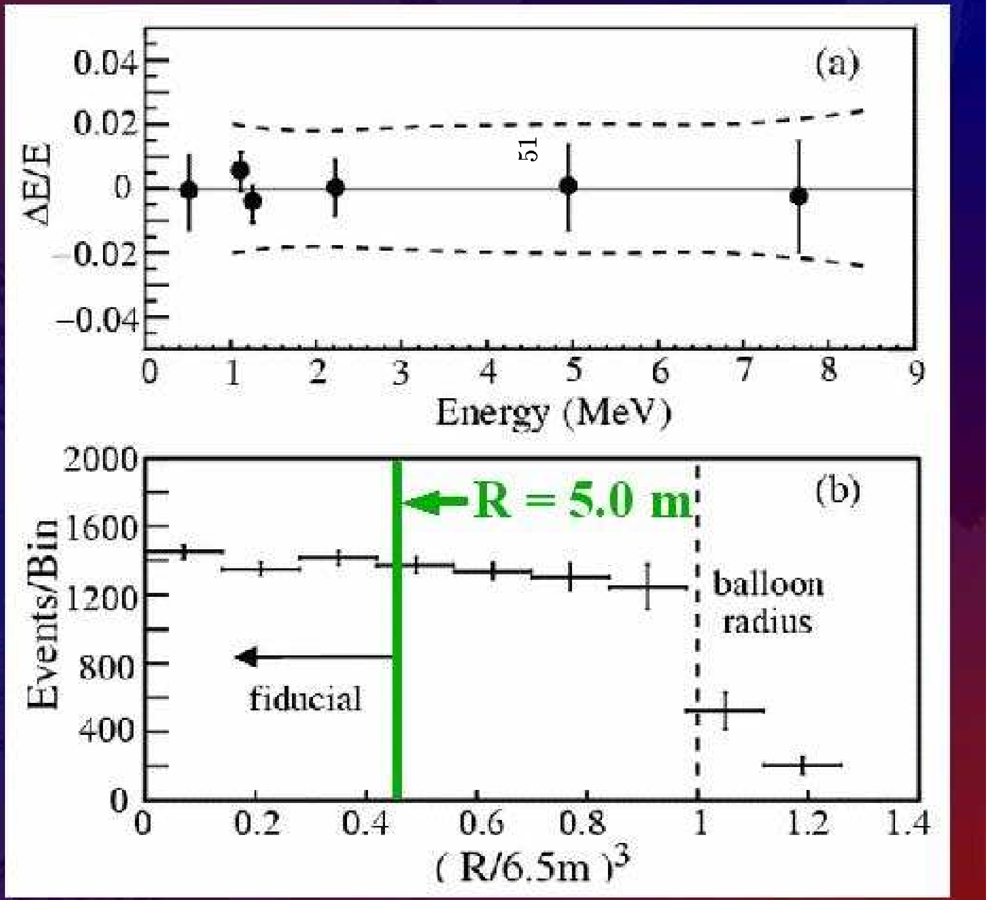
Total Signal Efficiency: 78.3 ± 1.6 %

Reconstruction Performance

Energy estimation linearity from radioactive source calibrations

$\sigma = 7.5\ \% / \sqrt{E\ (\text{MeV})}$

R = 5.0 m radius fiducial volume estimation from spallation neutron uniformity



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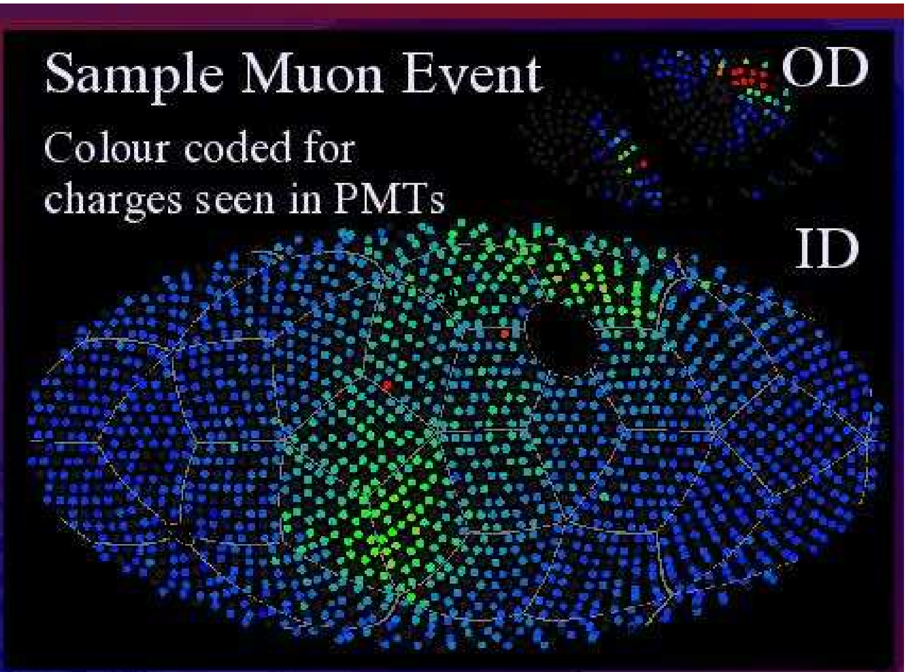
Muon Reconstruction

Muons saturate detector, leave 'track' as opposed to 'vertex'

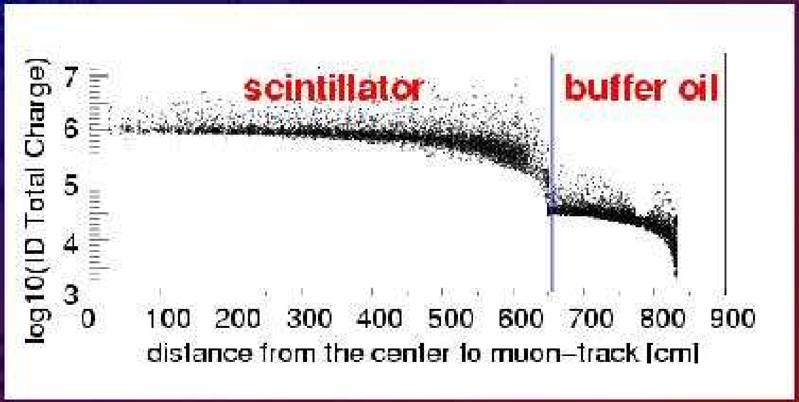
→ Different reconstruction requirements from low energy vertex events



Sample Muon Event

Colour coded for charges seen in PMTs

Reconstruction performance:



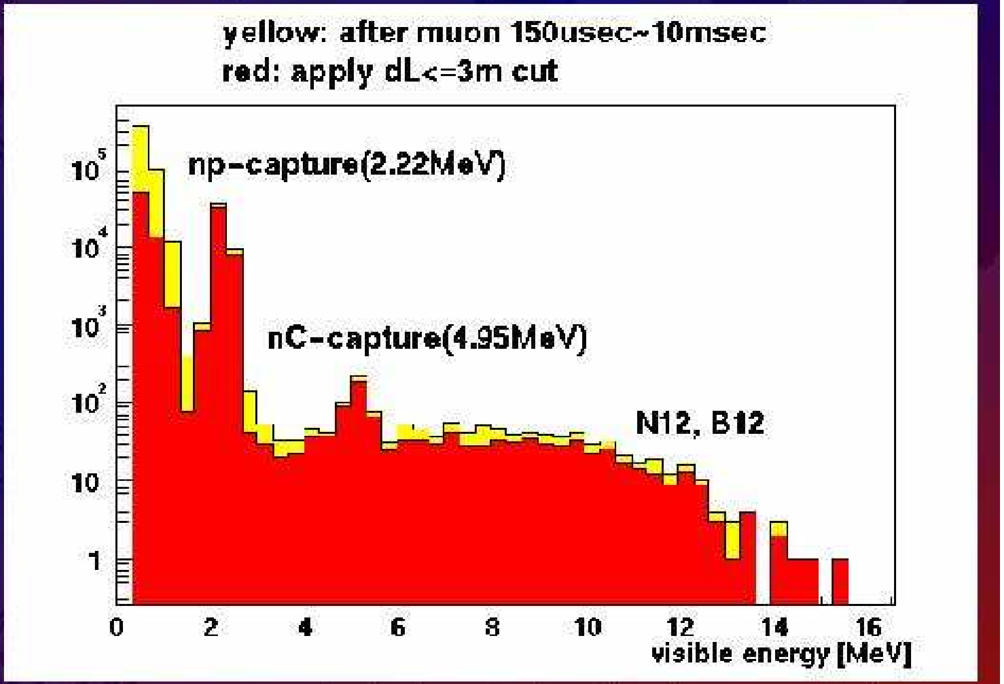
Spallation Cuts

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



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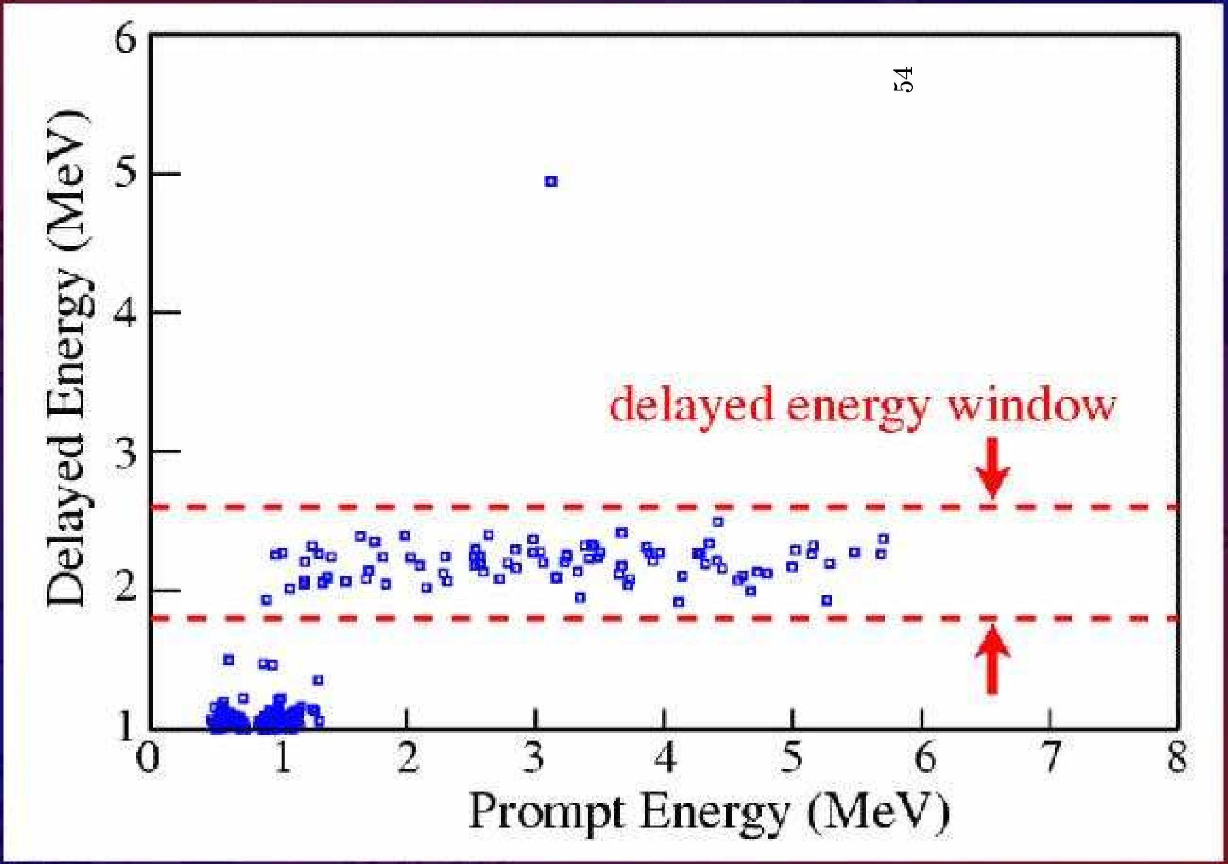
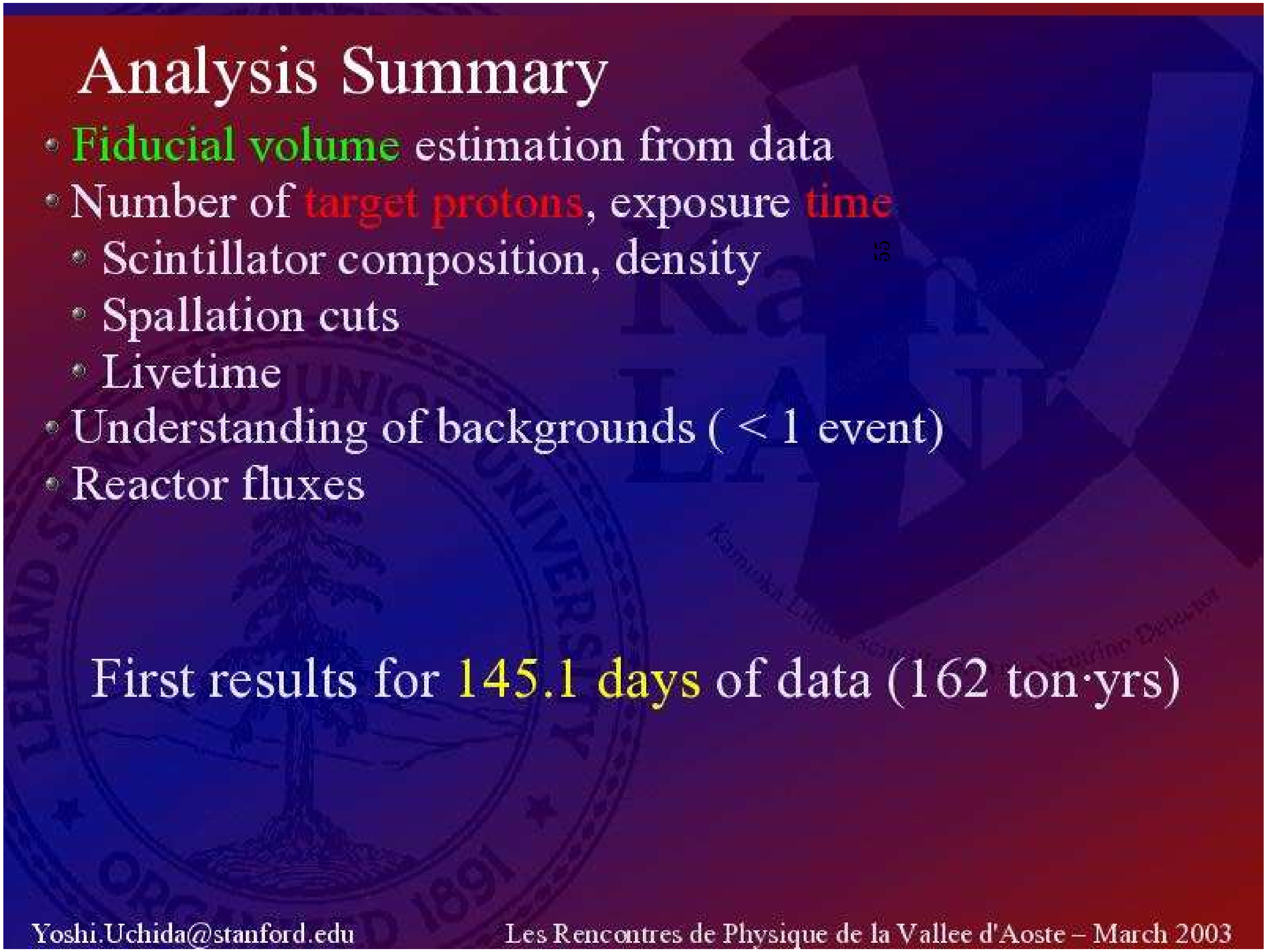
Prompt/Delayed Event Energies

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





Analysis Summary

- Fiducial volume estimation from data
- Number of target protons, exposure time
  - Scintillator composition, density
  - Spallation cuts
  - Livetime
- Understanding of backgrounds (< 1 event)
- Reactor fluxes

First results for 145.1 days of data (162 ton·yrs)

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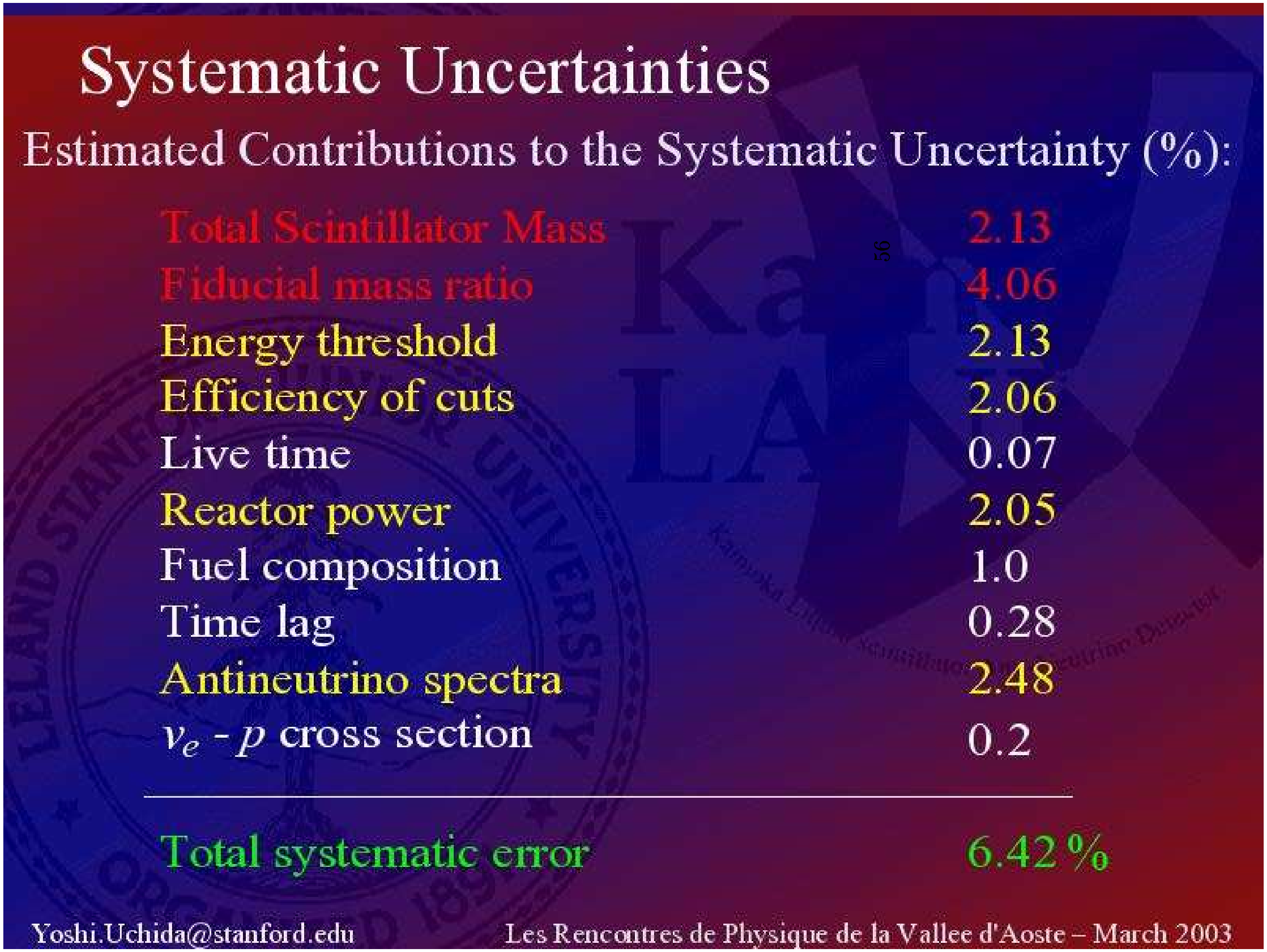

Systematic Uncertainties

Estimated Contributions to the Systematic Uncertainty (%):

Total Scintillator Mass	2.13
Fiducial mass ratio	4.06
Energy threshold	2.13
Efficiency of cuts	2.06
Live time	0.07
Reactor power	2.05
Fuel composition	1.0
Time lag	0.28
Antineutrino spectra	2.48
ν_e - p cross section	0.2
Total systematic error	6.42 %

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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

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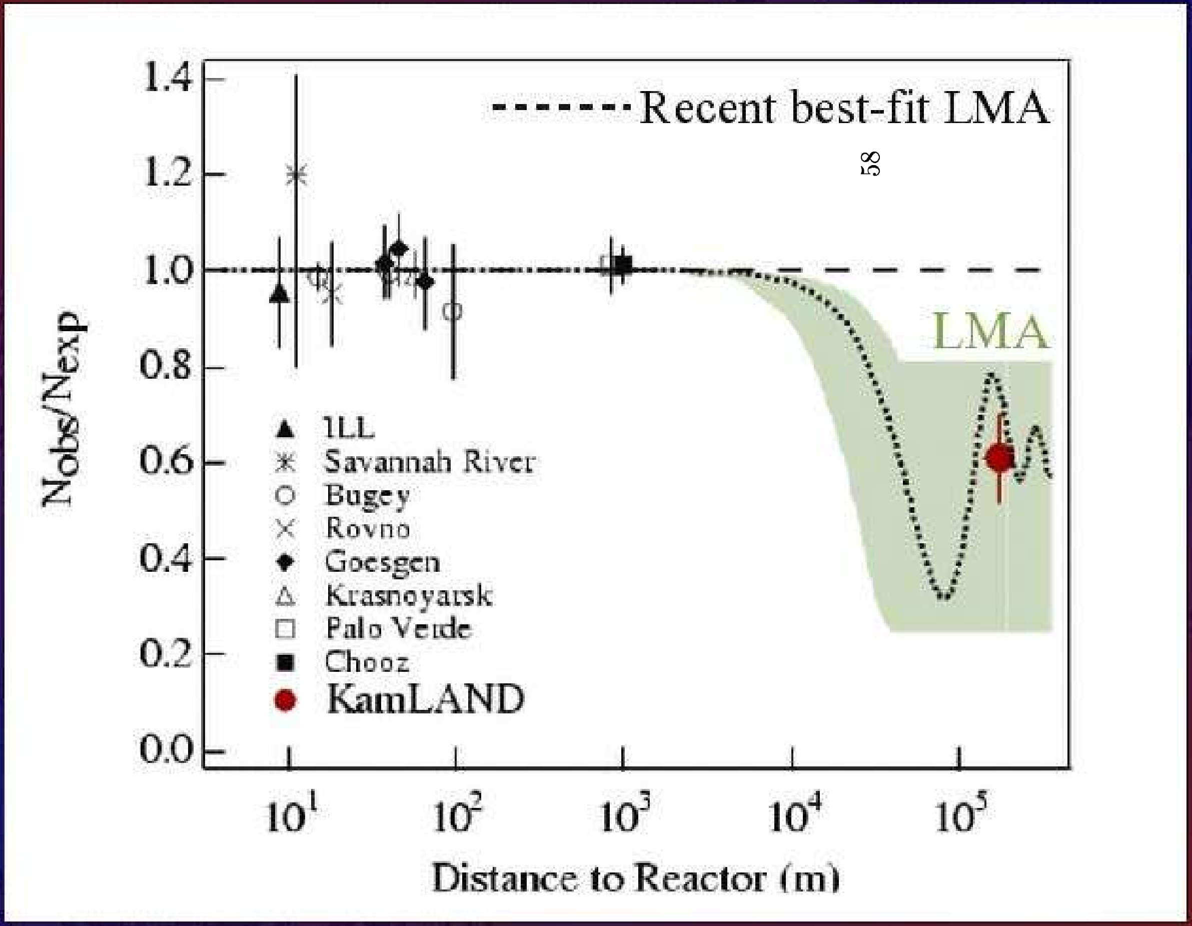
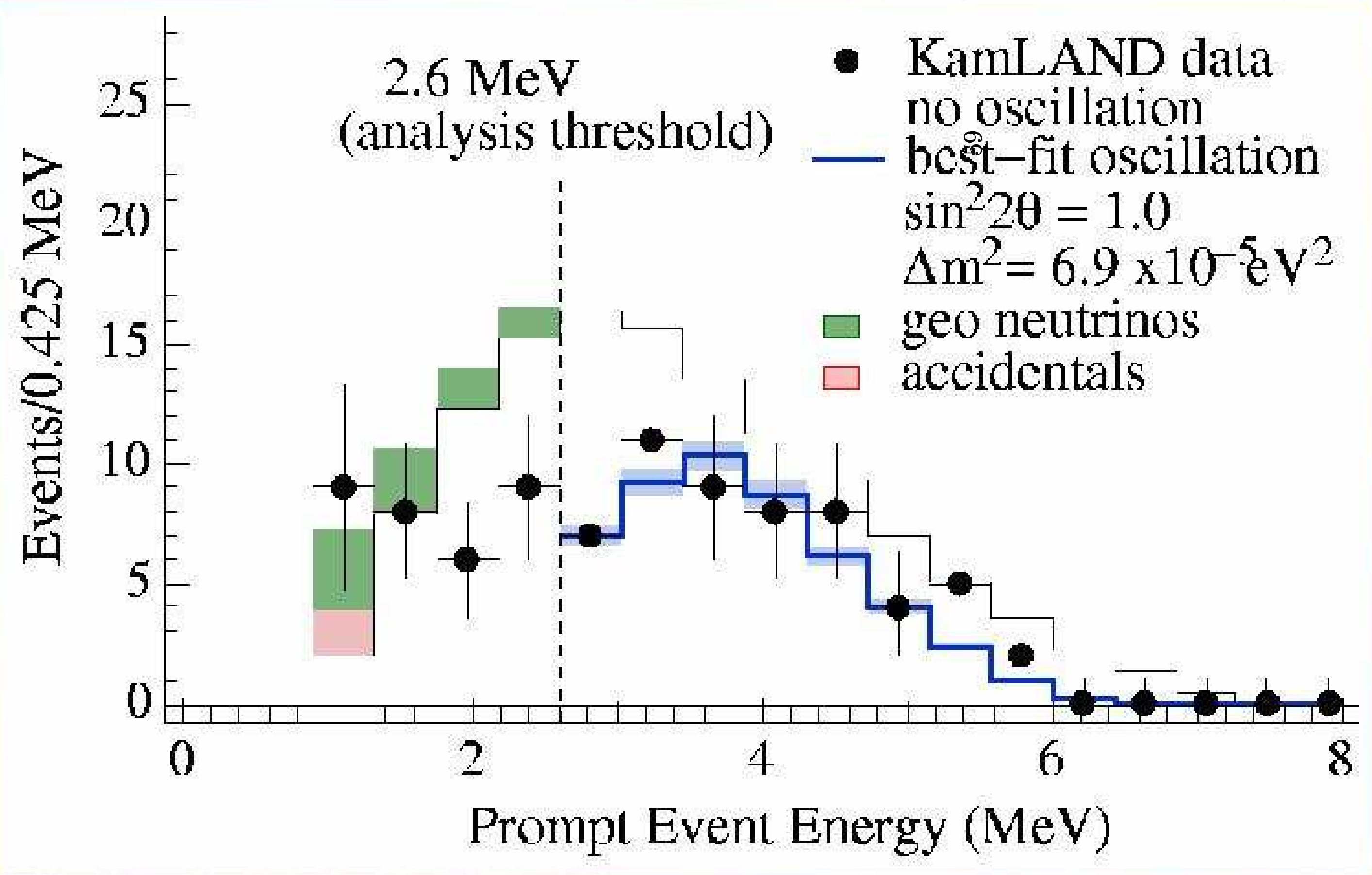
Measured Antineutrino Event Rate



Antineutrino Candidate Energy Spectrum

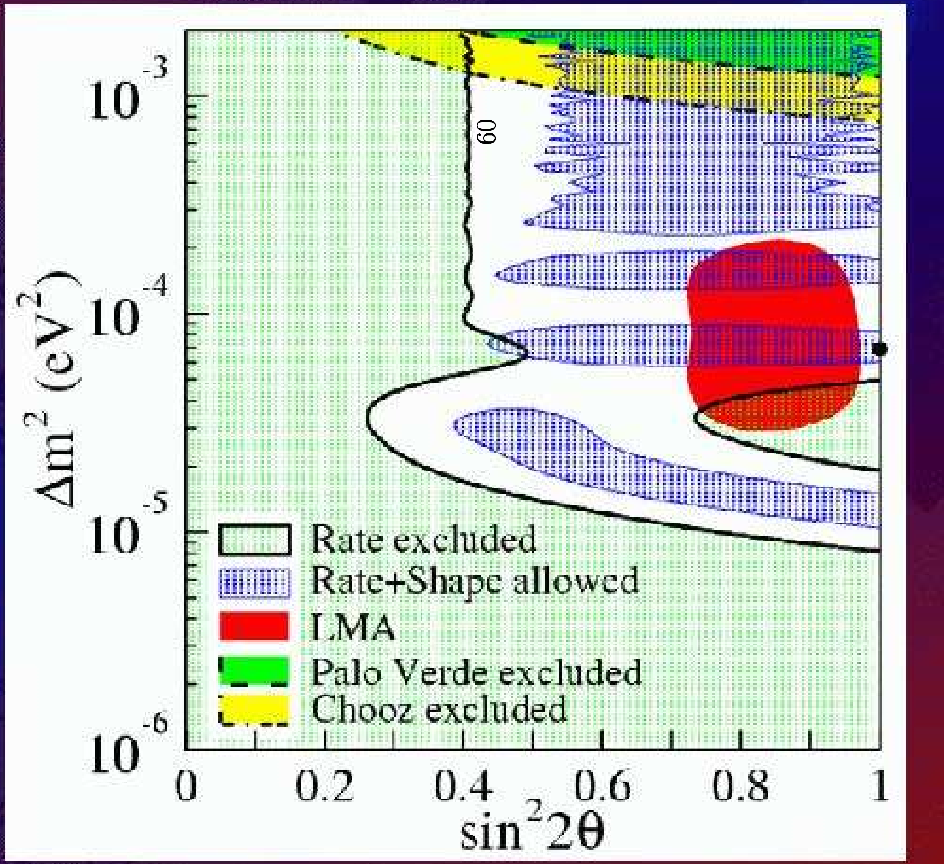


Two-Generation Oscillation Hypothesis

- 95% Confidence Level regions

"Rate" = number of events

"Shape" = energy spectrum



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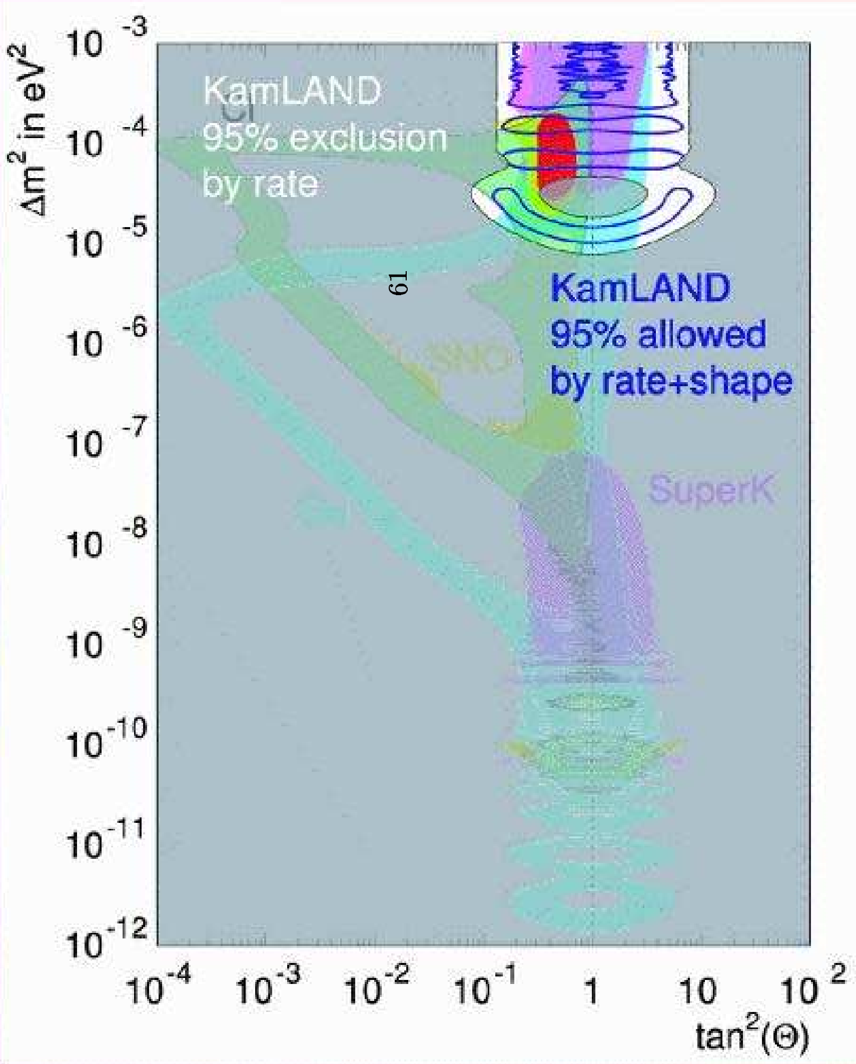
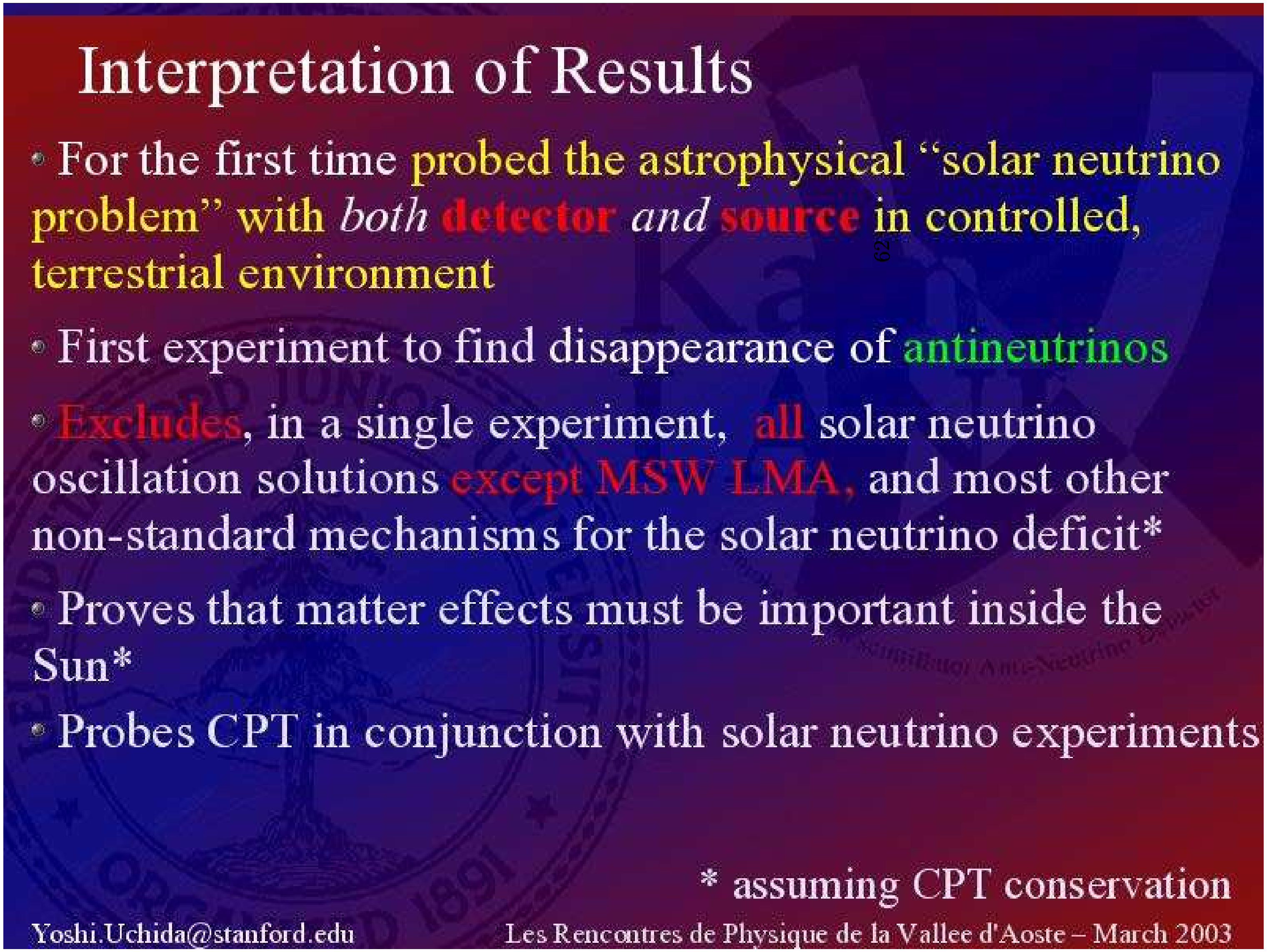
Comparison with Solar Results

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

KamLAND:
Antineutrinos with
180 km baseline
+ Vacuum Oscillations





Interpretation of Results

- For the first time probed the astrophysical "solar neutrino problem" with *both* **detector** *and* **source** in controlled, terrestrial environment
- First experiment to find disappearance of antineutrinos
- Excludes, in a single experiment, all solar neutrino oscillation solutions except MSW LMA, and most other non-standard mechanisms for the solar neutrino deficit*
- Proves that matter effects must be important inside the Sun*
- Probes CPT in conjunction with solar neutrino experiments

* assuming CPT conservation

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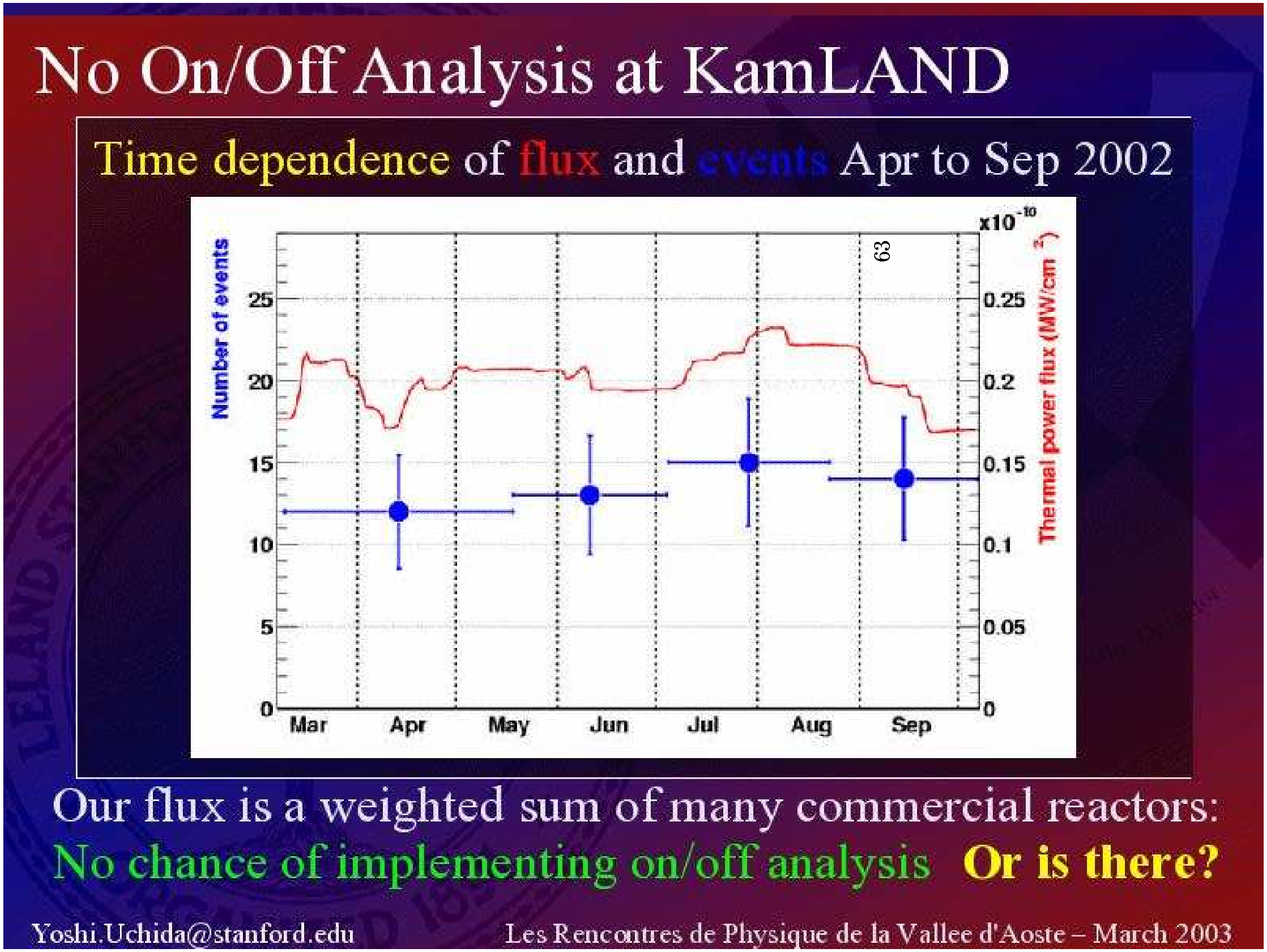

No On/Off Analysis at KamLAND

Time dependence of flux and events Apr to Sep 2002

Our flux is a weighted sum of many commercial reactors:

No chance of implementing on/off analysis **Or is there?**

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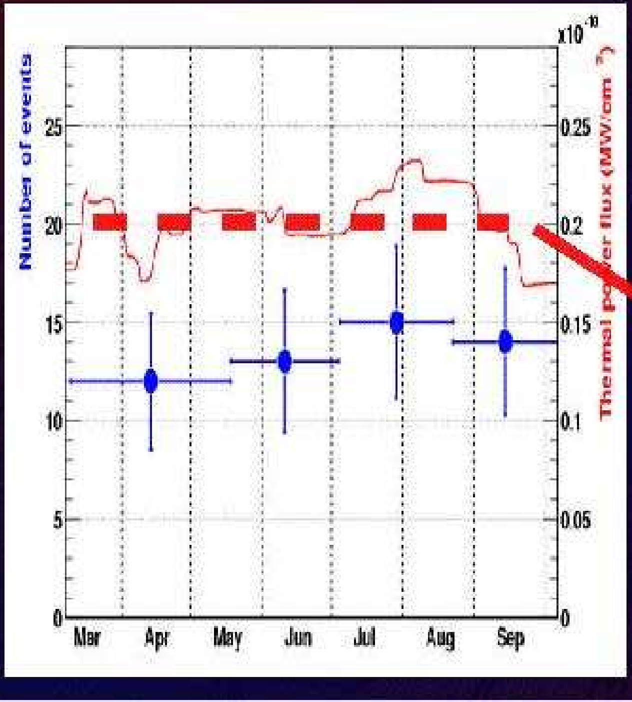
Future On/Off Analysis at KamLAND



Projected fluxes
for 2003

Down to 50% April 2003
(all Kashiwazaki Kariwa
cores off)

Issues at Japanese reactors: multiple simultaneous core shutdowns this spring → Effective On/Off at KamLAND

Conclusions and Prospects

- Unique very long baseline reactor antineutrino experiment
- More statistics will pinpoint mixing parameters
- Expected 50% reduction in reactor flux during 2003
- Precision “laboratory” study of neutrinos to improve understanding of astrophysical neutrino observations
- First experimental study of geoneutrinos
- Always on look-out for Supernovae
- Direct measurement of low energy solar neutrinos in possible future phase