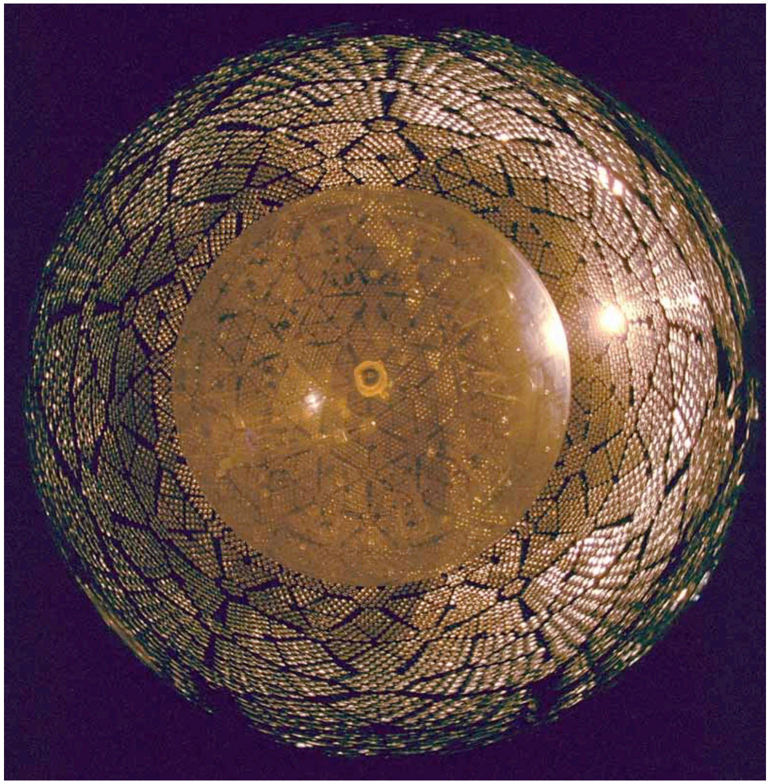
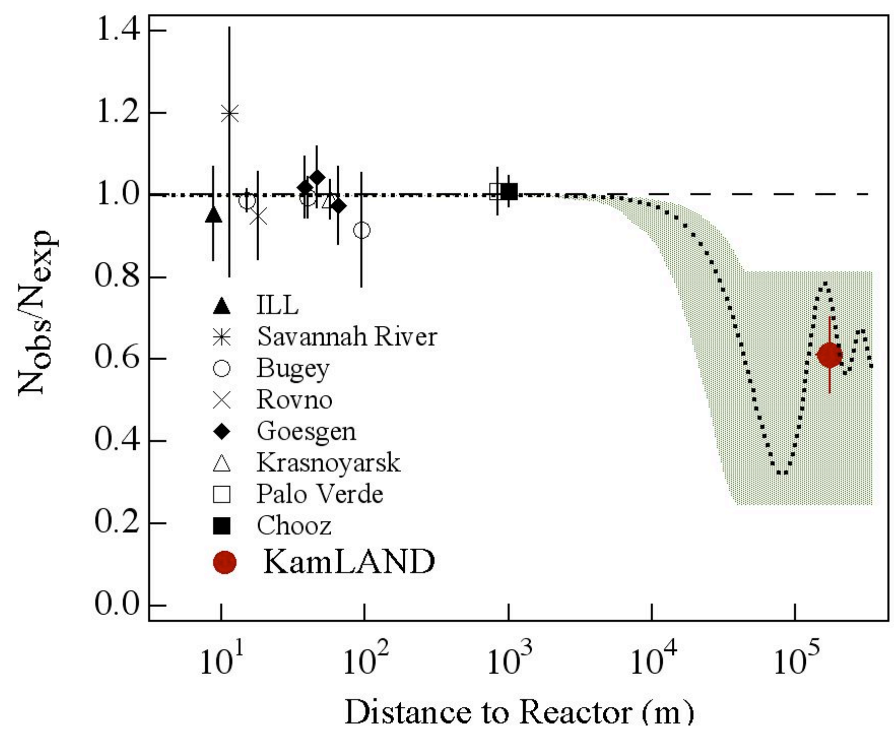
The Resolution to the Solar Neutrino Problem: Evidence for Neutrino Oscillation from SNO and KamLAND





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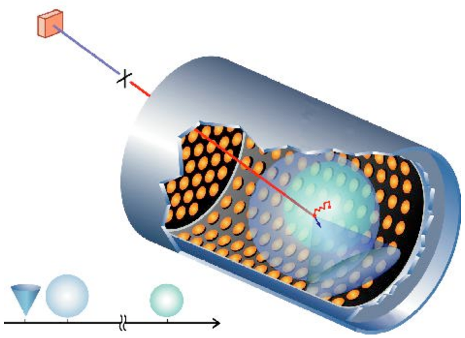
Recent Discoveries in Neutrino Physics

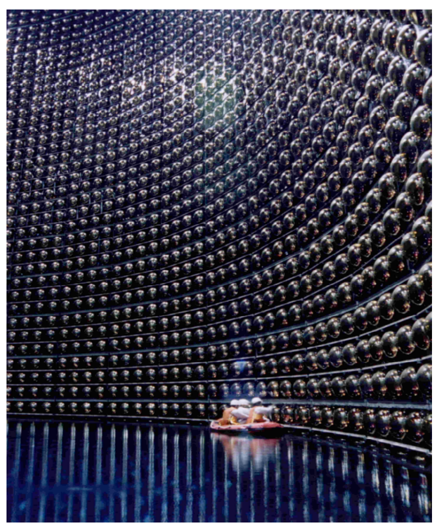
Underground experiments have changed our understanding of neutrinos

- Neutrinos are <u>not massless</u> (mass is small: $m_{\nu_e} < 0.0000059\ m_e$)
- <u>Evidence</u> for neutrino flavor conversion $\nu_e \leftrightarrow \nu_\mu \leftrightarrow \nu_\tau$
- Combination of experimental results show that <u>*neutrinos oscillate*</u>

Different experiments detect transformation of neutrino flavors

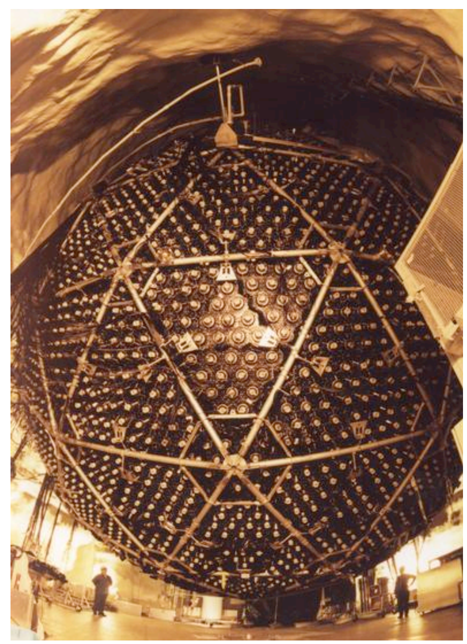
Accelerator ν (LSND)

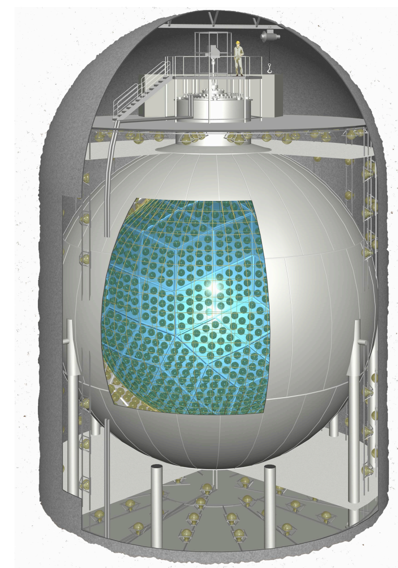




Atmospheric ν (Super-K)

Solar (SNO)

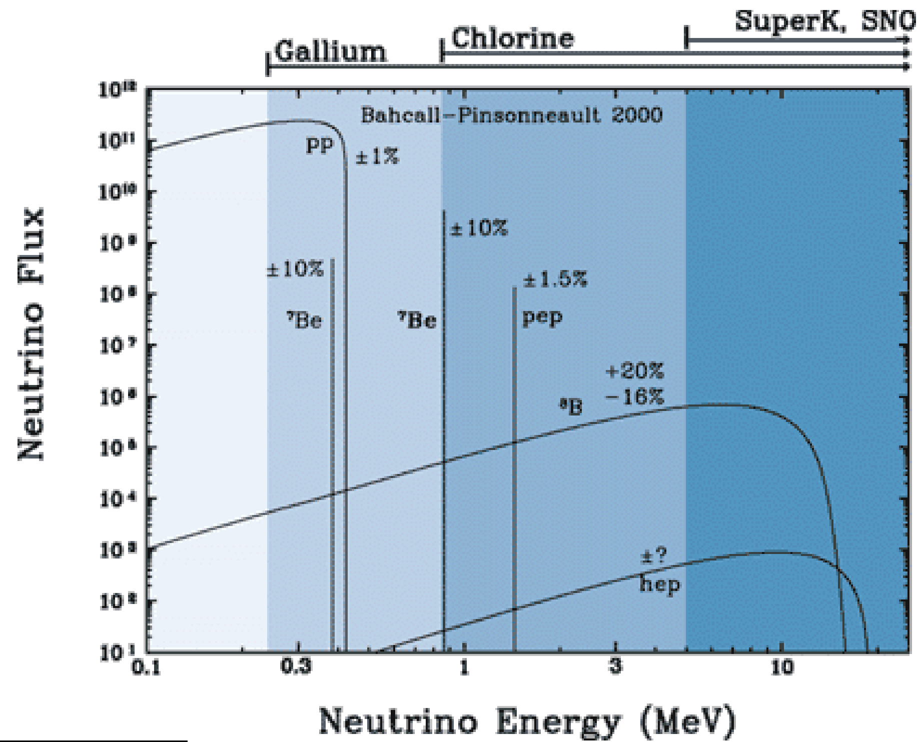




Reactor (KamLAND)

Neutrino Astrophysics

Solar Neutrino Flux Measurements



1960's

- Ray Davis' Chlorine detector
- First Solar Model calculations

For 30 years

CC and ES measurements of solar ν

Experiment	Year	Detection Reaction	Ratio Exp/BP2000
Chlorine (127 t)	1970-1995	$^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-$	0.34 ± 0.03
Kamiokande (680t)	1986-1995	$\nu_x + e^- \rightarrow \nu_x + e^-$	0.54 ± 0.08
SAGE (23 t)	1990-	$^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$	0.55 ± 0.05
Gallex + GNO (12 t)	1991-	$^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$	0.57 ± 0.05
SuperK (22kt)	1996-	$\nu_x + e^- \rightarrow \nu_x + e^-$	$0.451^{+0.017}_{-0.015}$

(CC) $^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-$

$^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$

(ES) $\nu_x + e^- \rightarrow \nu_x + e^-$

⇒ Data are incompatible with standard and non-standard solar models

What is the Solution?

- **Are experiments in error?**

  But all experiments show similar effect.

- **Is astrophysics wrong?**

  Perhaps, but even with all fluxes as free parameters, cannot reproduce the data.

  Data are incompatible with standard and non-standard solar models!
  KMH, Robertson PRL 77:3270 (1996)

- **New neutrino physics such as oscillations?**

  In 1968 Pontecorvo suggests that if lepton number is not conserved, ν_e could change into ν_μ.

  Cl-Ar and Ga detectors are only sensitiv to ν_e, it would appear that the flux was low.

Sudbury Neutrino Observatory

2092 m to Surface (6010 m w.e.)

PMT Support Structure, 17.8 m
9456 20 cm PMTs
~55% coverage within 7 m

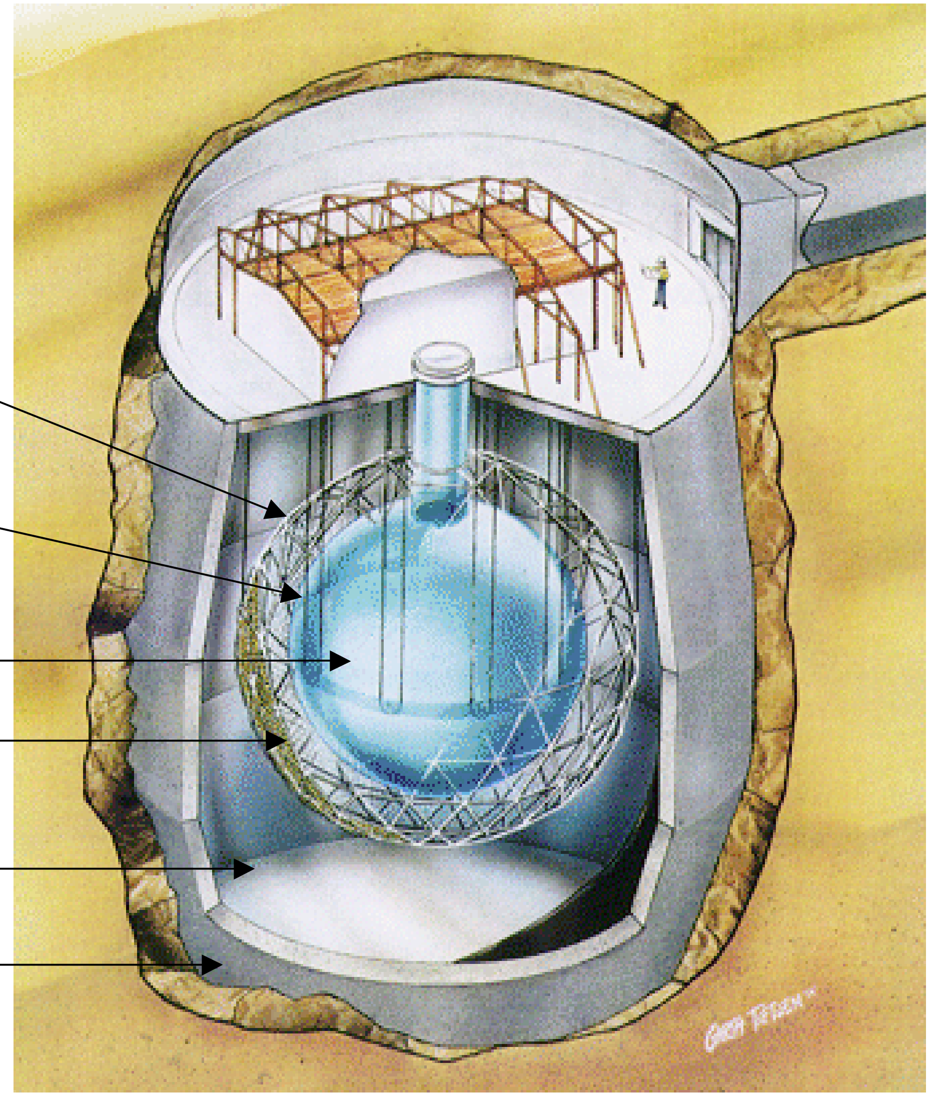
Acrylic Vessel, 12 m diameter

1000 Tonnes D_2O

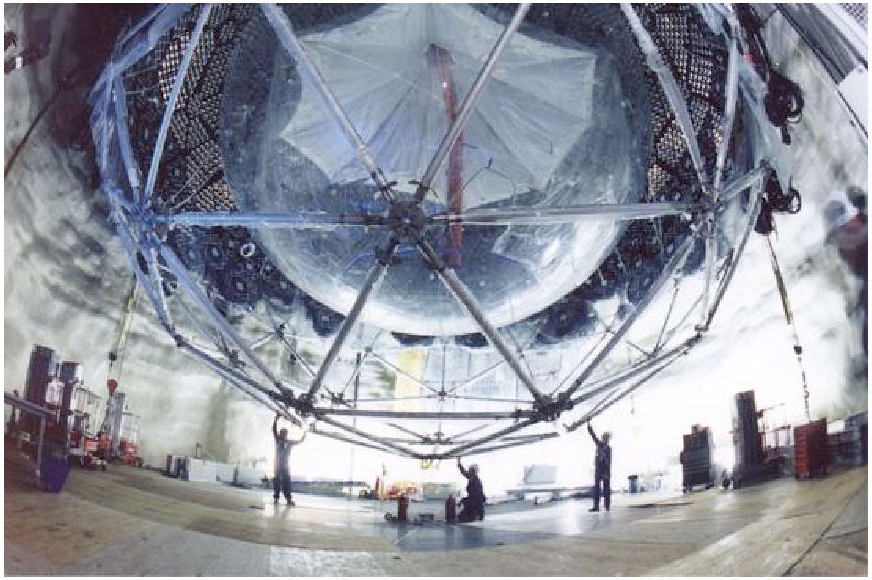
1700 Tonnes H_2O, Inner Shield

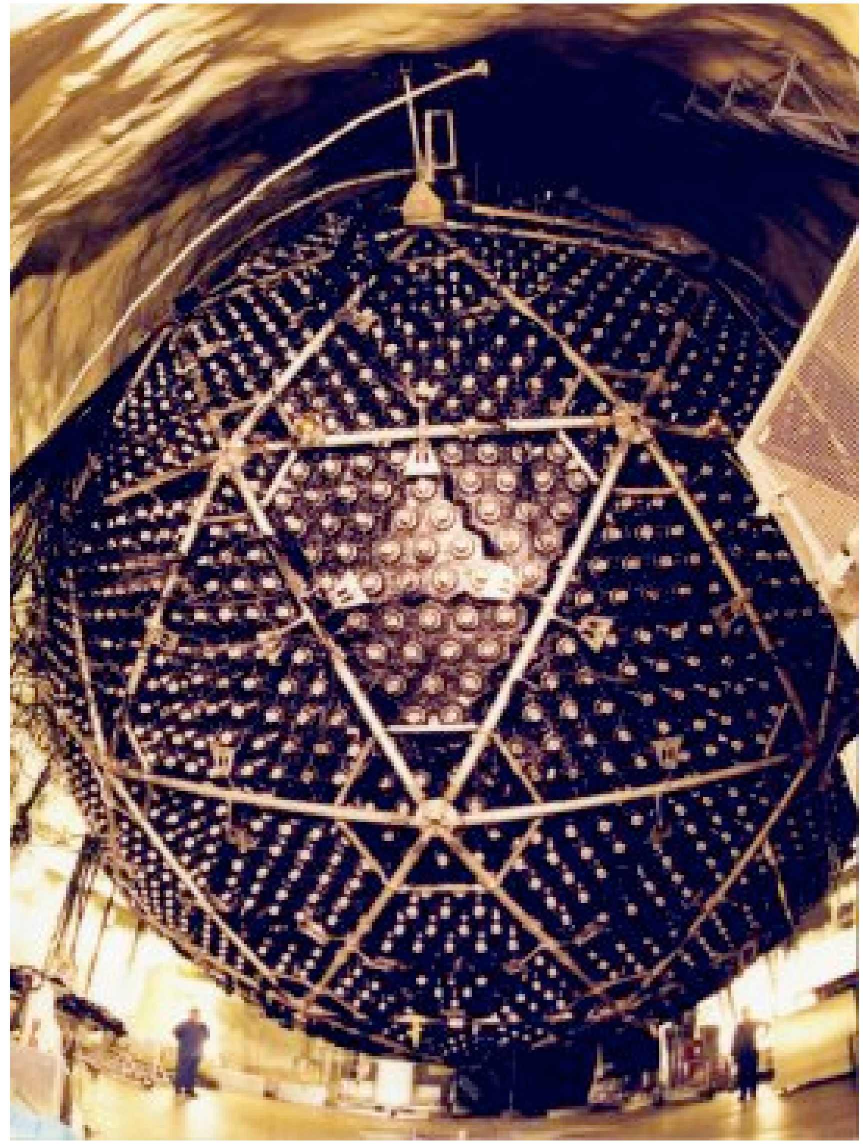
5300 Tonnes H_2O, Outer Shield

Urylon Liner and Radon Seal

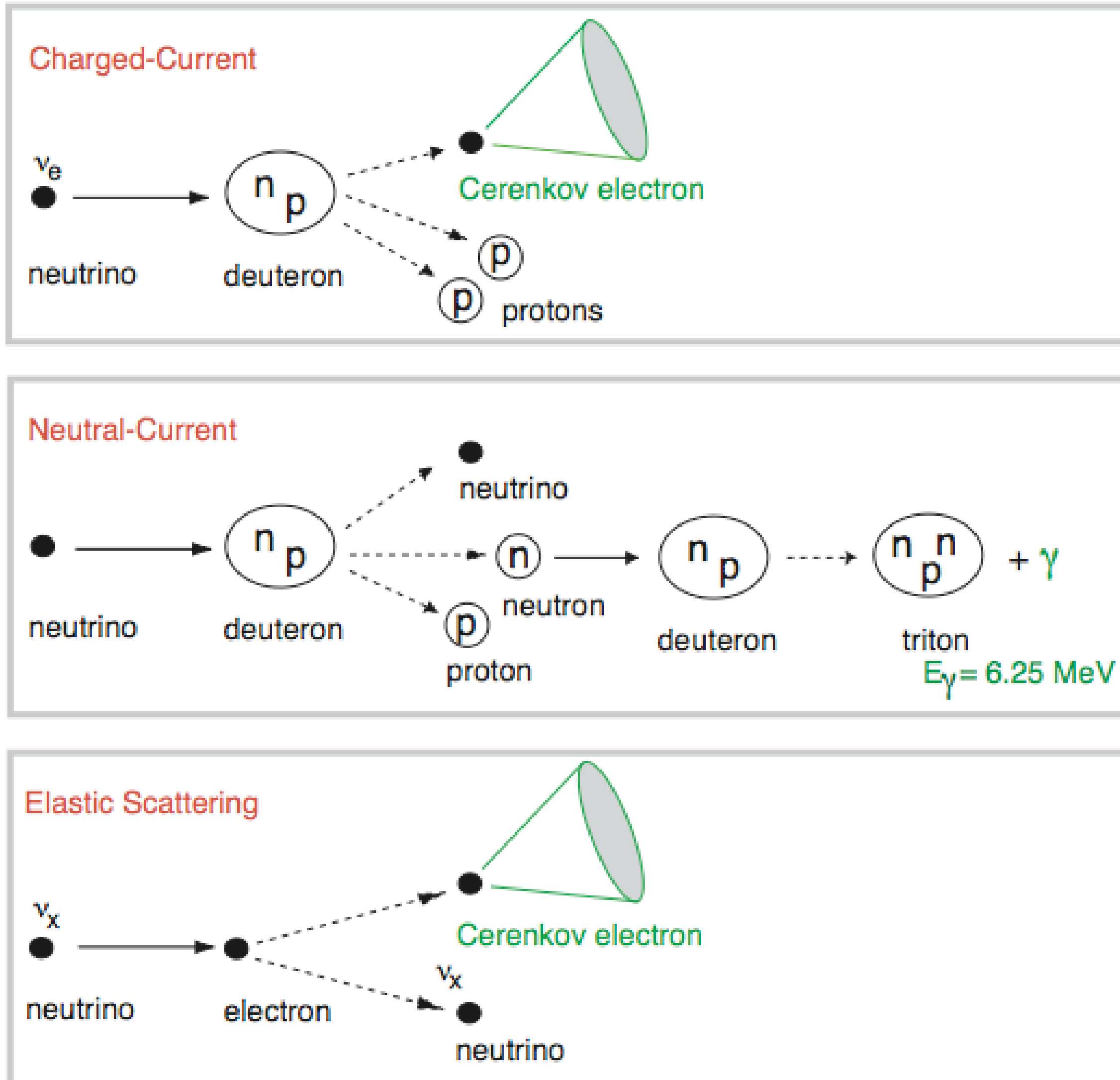


The SNO Detector during Construction





Neutrino Interactions on Deuterium



Neutrino Detection in SNO

Neutrino Interactions in D_2O and H_2O and their Flavor Sensitivity

Charged-Current (CC)
$\nu_e + d \rightarrow e^- + p + p$
$E_{thresh} = 1.4$ MeV

ν_e only
Measurement of energy spectrum

Elastic Scattering (ES)
$\nu_x + e^- \rightarrow \nu_x + e^-$

ν_x, but enhanced for ν_e
Strong directional sensitivity

Neutral-Current (NC)
$\nu_x + d \rightarrow \nu_x + n + p$
$E_{thresh} = 2.2$ MeV

ν_x
Measures total ^8B flux from Sun

Looking for Unexpected Neutrino Flavors

Comparing total flux of solar ^{8}B neutrinos vs pure ν_e flux

CC/NC ratio is a direct signature for flavor transitions

$$\frac{[CC]}{[NC]} = \frac{[\nu_e]}{[\nu_e + \nu_\mu + \nu_\tau]}$$

CC/ES could also show significant effects

$$\frac{[CC]}{[ES]} = \frac{[\nu_e]}{[\nu_e + 0.15(\nu_\mu + \nu_\tau)]}$$

Smoking Gun for Neutrino Flavor Transformation

and Physics Beyond the Standard Model

Beyond the Standard Model: Neutrino Mass and Mixing

Neutrino Flavor Transformation through Oscillations

If neutrinos have mass leptons can mix:

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

Flavor eigenstates are a mixture of mass eigenstates

$$\nu_e = U_{e1}\nu_1 + U_{e2}\nu_2 + U_{e3}\nu_3$$

States evolve with time or distance

$$\nu_e = U_{e1}e^{-iE_1 t}\nu_1 + U_{e2}e^{-iE_2 t}\nu_2 + U_{e3}e^{-iE_3 t}\nu_3$$

Testing the Hypothesis of Neutrino Oscillations

Comparing the solar ν flux at Day and Night

Certain ν oscillation models predict ν regeneration in Earth

$$\frac{[CC]_{DAY}}{[CC]_{NIGHT}} = \frac{[\nu_e]_{DAY}}{[\nu_e]_{NIGHT}} \neq 1$$

$$\frac{[NC]_{DAY}}{[NC]_{NIGHT}} = \frac{[\nu_e + \nu_\mu + \nu_\tau]_{DAY}}{[\nu_e + \nu_\mu + \nu_\tau]_{NIGHT}} \neq 1$$

Smoking Guns for Neutrino Oscillations

Solar Neutrino Physics with SNO

What can we learn from measuring the ^{8}B solar neutrino flux at SNO?

- Total ^{8}B ν flux (NC) vs ν_e flux (CC)

  CC_{SNO}/NC_{SNO} ⇒ **Test of neutrino flavor change**

- Total flux of solar ^{8}B neutrinos

  ⇒ **Test of solar models**

- Diurnal time dependence

  ⇒ **Test of neutrino oscillations**

- Disortions of neutrino energy spectrum

  ⇒ **Test of neutrino oscillations**

Data Flow & Instrumental Background Cuts

Data Flow

Analysis Step	Events
Total Event Triggers	450,188,649
Neutrino Data Triggers	191,312,560
NHIT ≥30 (Analysis Threshold)	10,088,842
Instrumental Background	7,805,238
High Level Cuts	3,418,439
Fiducial Volume Cut	67,343
Energy Threshold	3440
Muon Followers	2981
Invisibles	2928
Candidate Event Set	**2928**

Instrumental Background Removal

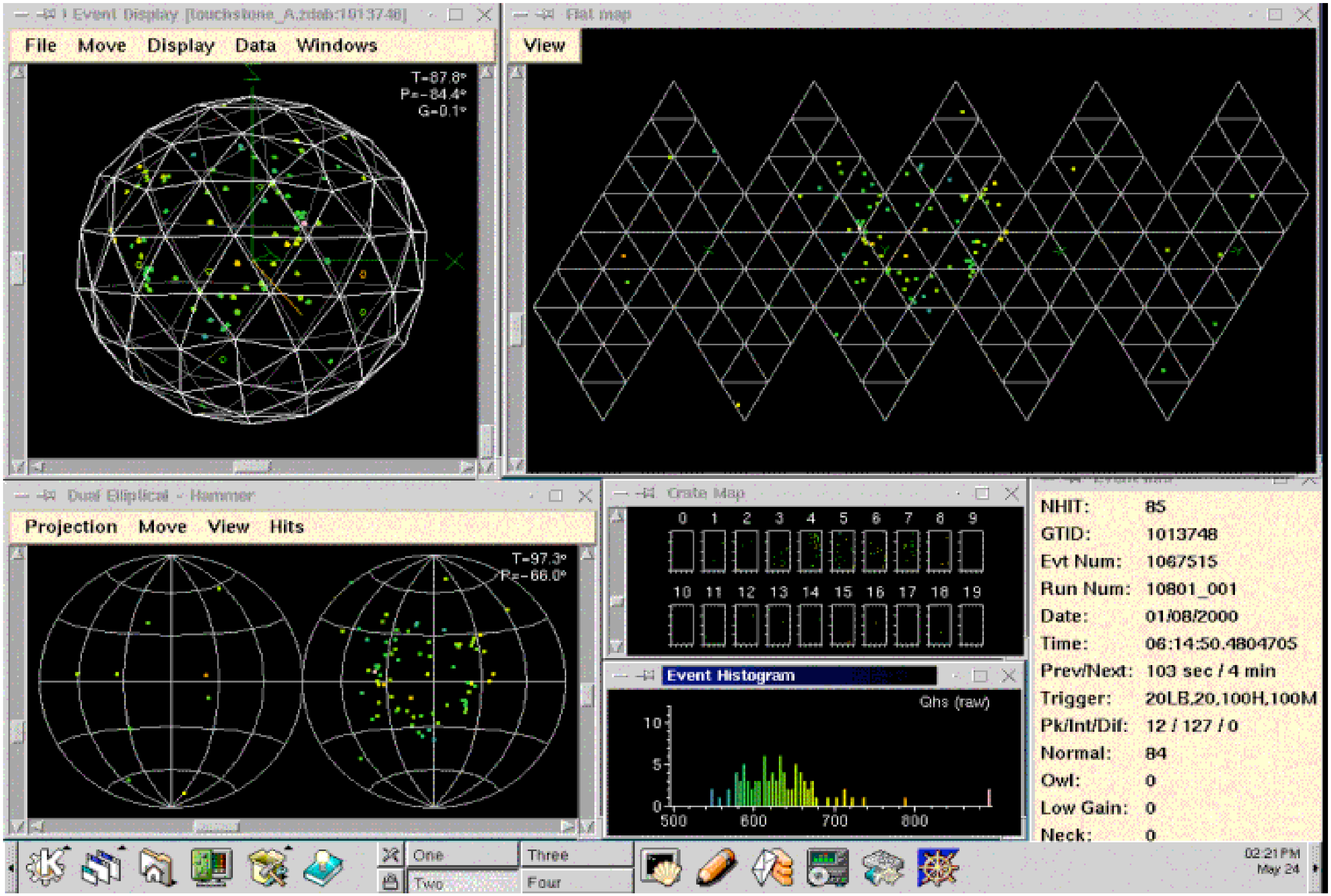
- Charge
- Timing
- PMT hit Geometry
- Event Rate
- PMT Veto Tubes

Cerenkov Nature of Events

- prompt light
- single particle event

Instrumental removal: **Two independent methods**
Signal loss: **0.4±0.3%** within $R_{fit} \leq 550$ cm from ^{16}N, ^{8}Li, and the laser ball
Contamination: limits from bifurcated analyses and hand-scanning

Candidate Neutrino Event

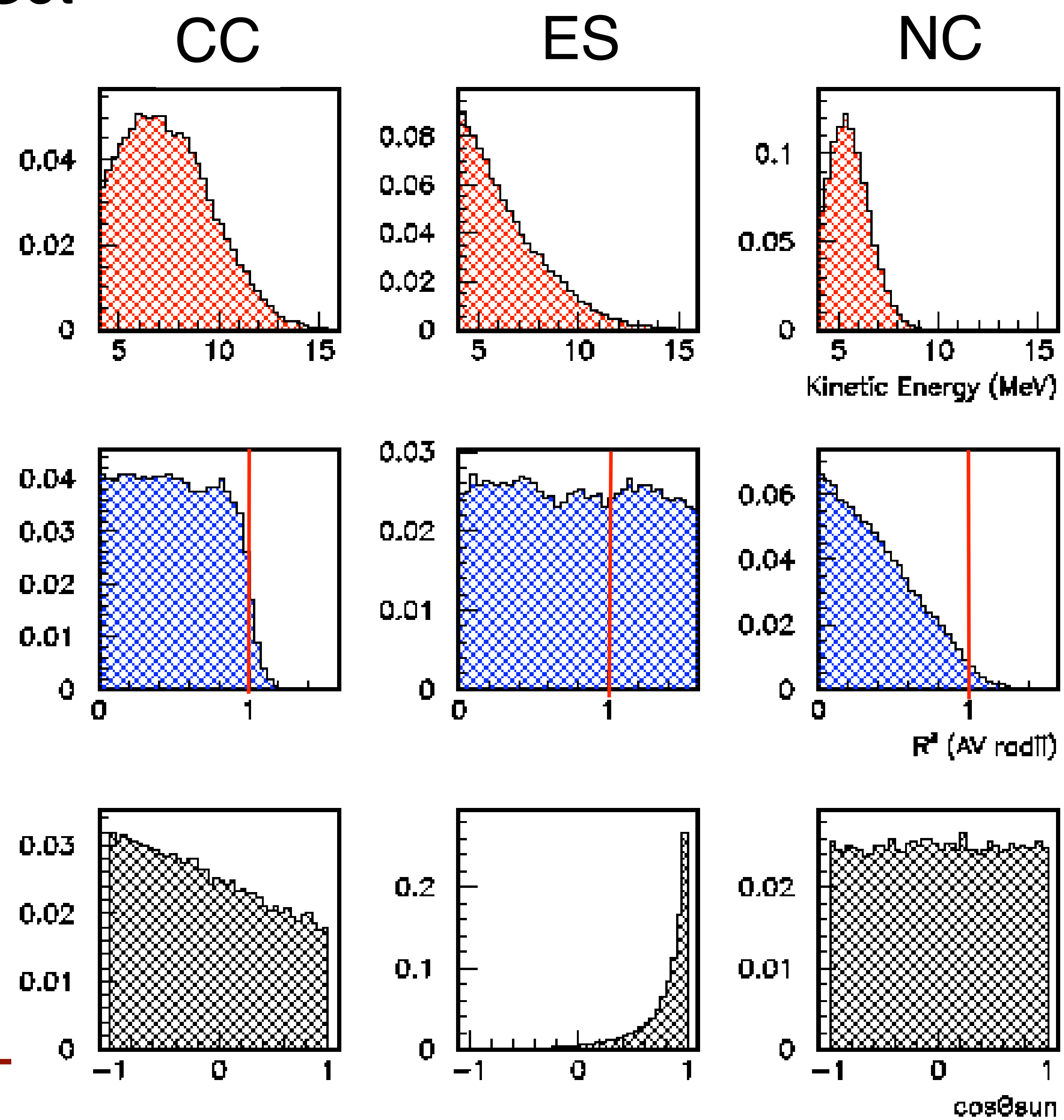


Characteristic Detector Distributions of Candidate Event Set

Energy

Radial

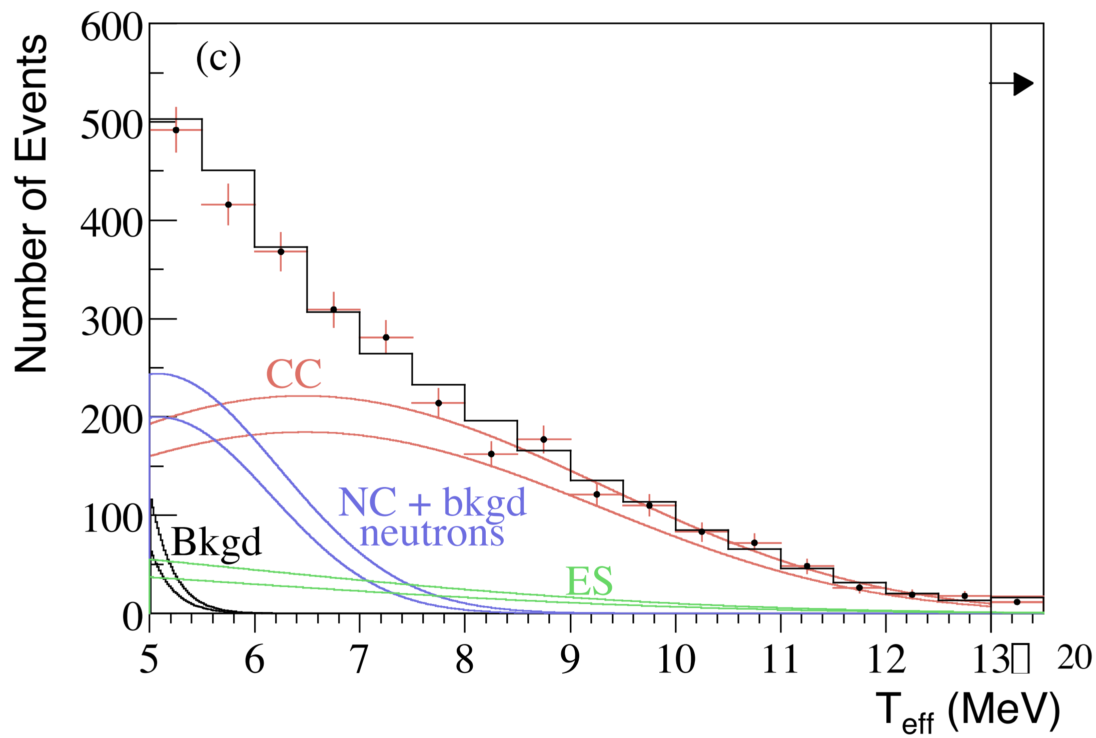
Solar Angle



Neutrino Signal in D_2O Data

Signal Extraction with CC Shape Constraint

CC	1967.7	+61.9 +60.9
NC	576.5	+49.5 +48.9
ES	263.6	+26.4 +25.6



Total Number of Events:	2928
Neutron Bkgd:	78 +12/-12
Cherenkov Bkdg:	45 +18/-12

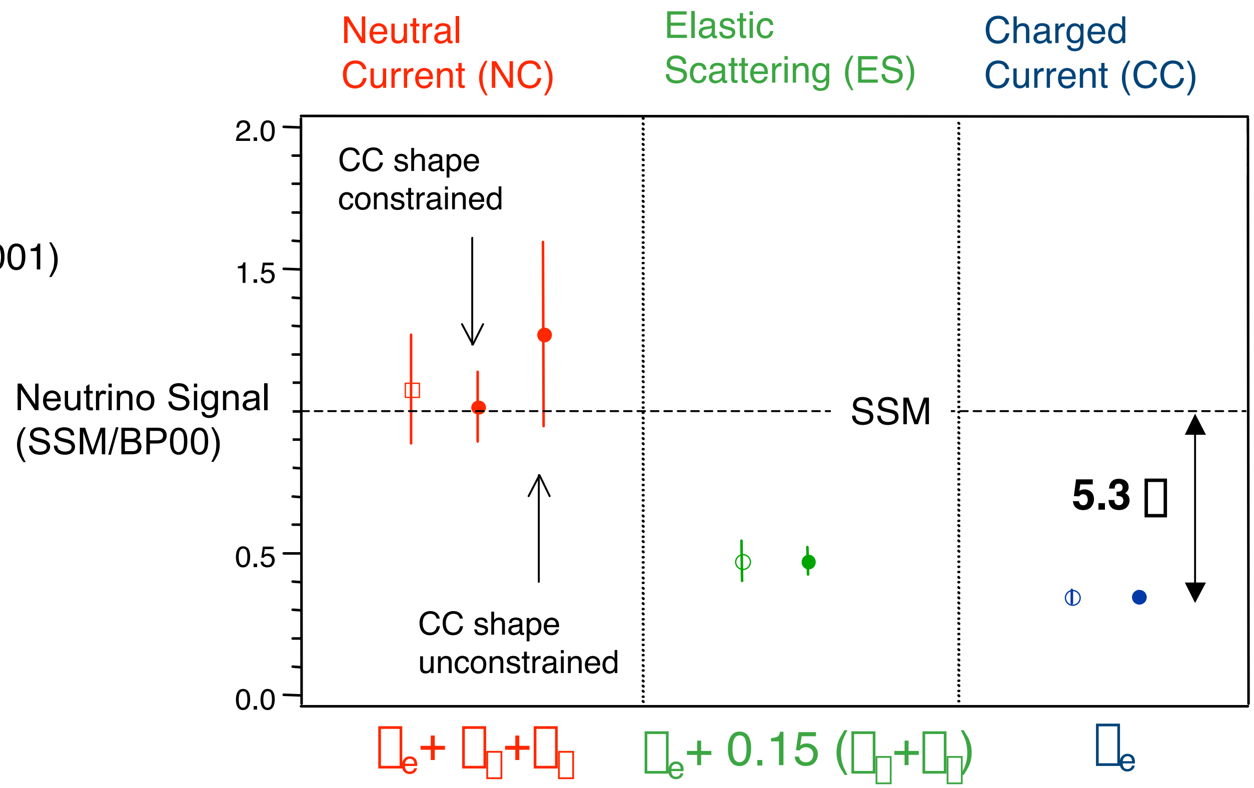
CC Shape Constraint

 No distortion in the ^{8}B energy spectrum
Used to test null hypothesis no flavor change

Solving the Solar Neutrino Problem:
Test of Neutrino Flavor Change & Test of Solar Models

SNO Flux Results

- □ ^8B from $CC_{SNO}+ES_{SK}$ (2001)
- ○ ES_{SNO} (2001)
- ○ CC_{SNO} (2001)
- ● NC_{SNO} (2002)
- ● ES_{SNO} (2002)
- ● CC_{SNO} (2002)



- 2/3 of initial solar ν_e are observed at SNO to be $\nu_{\mu,\tau}$
- Standard Solar Model predictions for total ^8B flux in excellent agreement!

⇒ Null hypothesis (no flavor change) ruled out at 5.3 σ level

⇒ Model-independent evidence for neutrino flavor change

Solar ν Flux at Day and Night

I. Testing the Hypothesis of Neutrino Oscillations
(Evidence for matter effect)

II. Determine Parameters of Oscillation Solution

Certain n oscillation models predict n regeneration in Earth

$$\frac{[CC]_{DAY}}{[CC]_{NIGHT}} = \frac{[\nu_e]_{DAY}}{[\nu_e]_{NIGHT}} \neq 1$$

Neutrino Oscillations

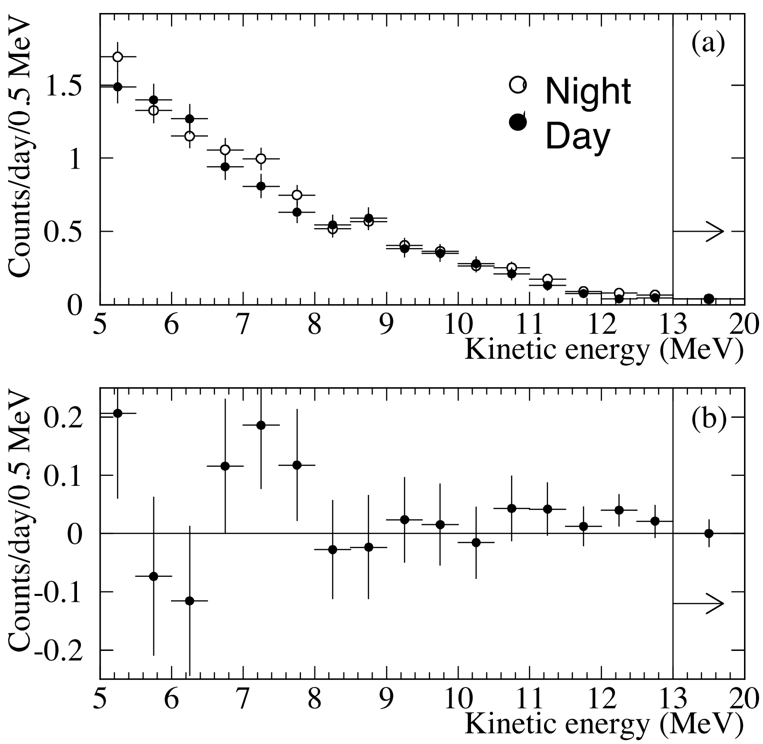
Day/Night Asymmetries of n Flux: $A^{SNO}_{CC} = 14.0 \pm 6.3\%$ $A^{SNO}_{e} = 7.0 \pm 4.9\%$

$A^{SNO}_{NC} = -20.4 \pm 16.9\%$ $A^{SK}_{e} = 5.3 \pm 3.7\%$

Solar Neutrino Flux at Day and Night

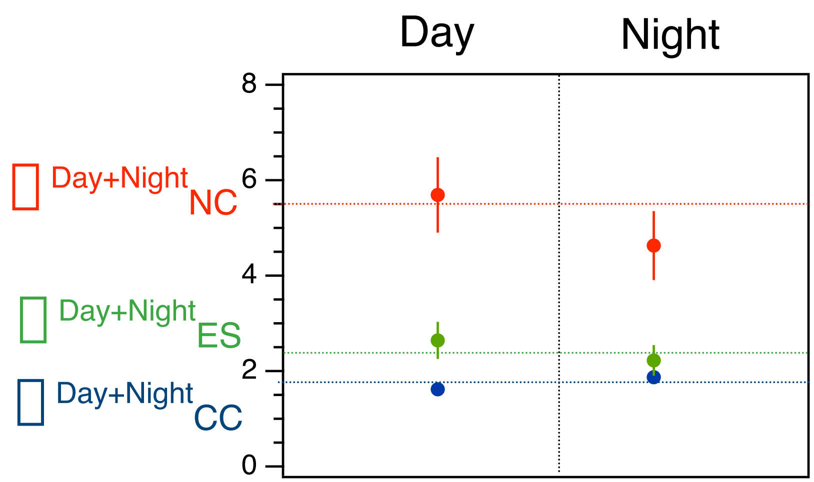
Total Livetime:	306.4 days	Day:	128.5 days
Number of Events:	2928	Night:	177.9 days

Day-Night Energy Spectrum



Day-Night Fluxes

Signal Extraction in □$_{CC}$, □$_{NC}$, □$_{ES}$



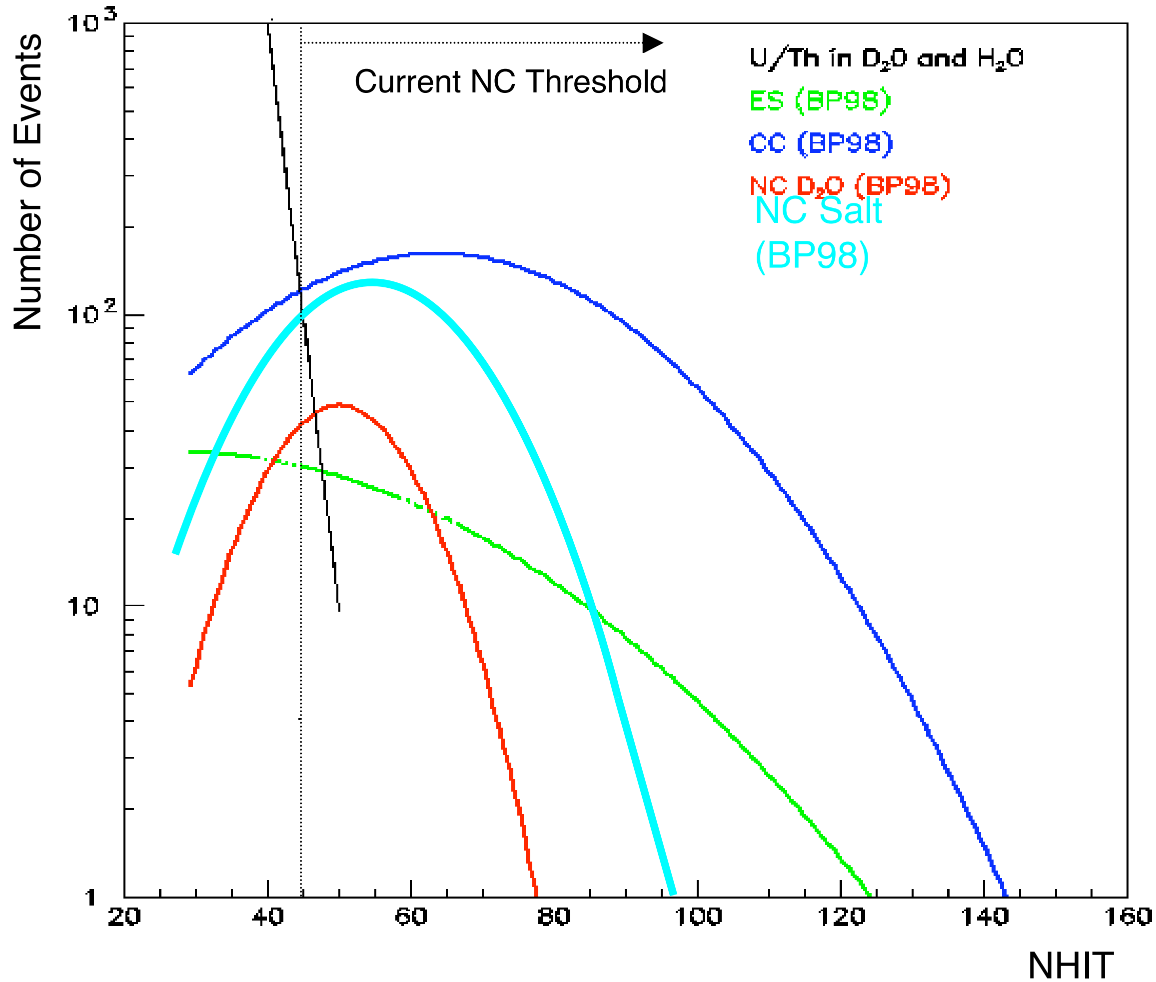
□ in units of x10^{6} cm^{-2} s^{-1}

SNO Phase II - Physics with Salt

Enhanced NC sensitivity
□$_n$~45% above threshold
n+^{35}Cl □ ^{36}Cl+ Σ□

Systematic check of energy scale
E $_{Σ □}$= 8.6 MeV

NC and CC separation by event isotropy



SNO Phase III - Neutral Current Detection via $^3He(n,p)^3H$

Array of ^3He counters

50 Strings on 1-m grid

450 m total active length

Detection Principle

$^2H + \nu_x \rightarrow p + n + \nu_x - 2.22$ MeV (NC)

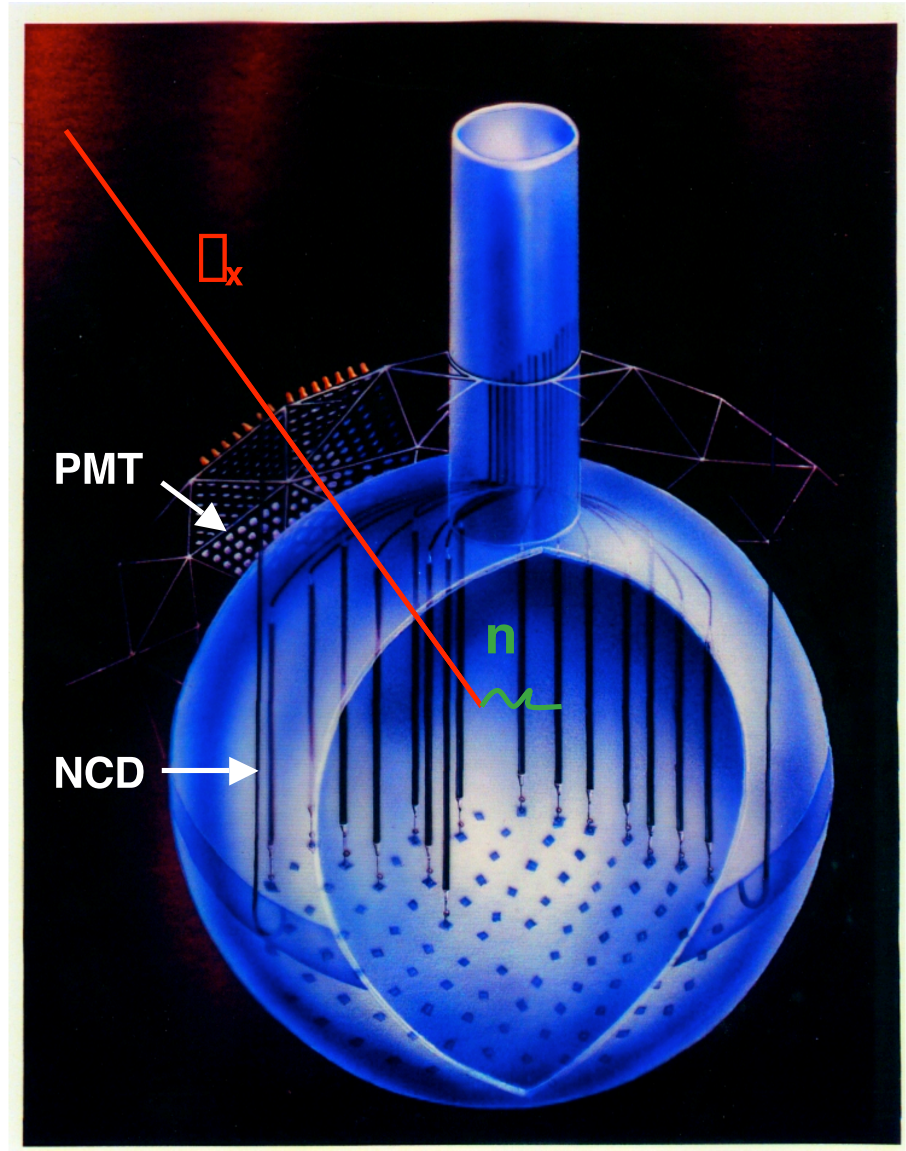
$\searrow\ ^3He + n \rightarrow p + {}^3H$

Physics Motivation

Event-by-event separation. Measure NC and CC in separate data streams.

Different systematic uncertainties than neutron capture on NaCl.

NCD array as active poison.



Oscillation Interpretation of Solar Neutrino Data

Matter Enhanced Oscillations

• explains energy dependence

• effective 2-neutrino mixing

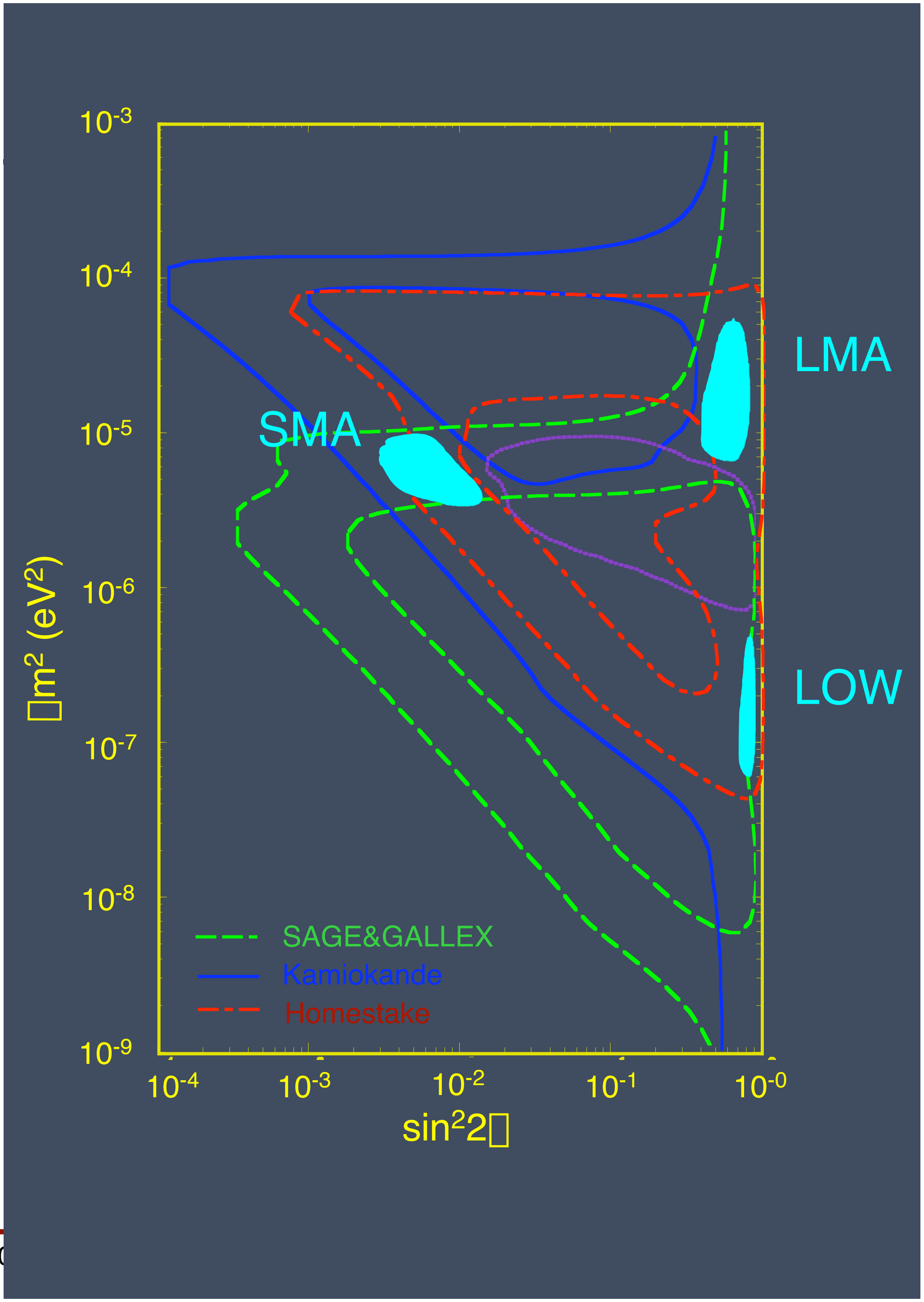
• MSW gives dramatic extension of oscillation sensitivity to potential regions in Δm^2

Chlorine **Homestake**

Gallium **GALLEX/GNO**
SAGE

Water **Super-Kamiokande**

 Several possible oscillation solutions fit the solar data



Solar Neutrinos in the Big Picture

Reactor and Beamstop Neutrinos

□□ □ □s □ □e

Atmospheric and Reactor Neutrinos

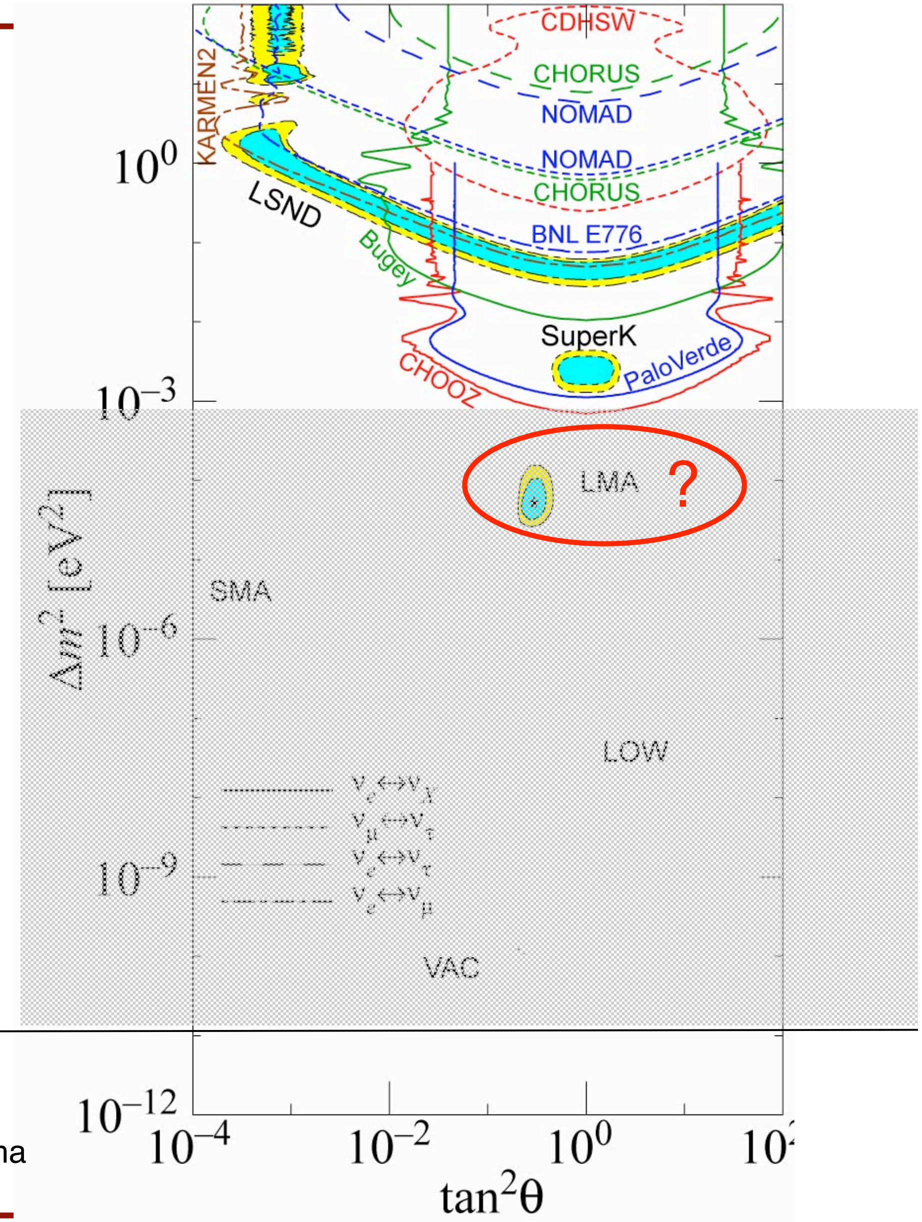
□□ □ □□

Solar and Reactor Neutrinos

□e □ □□,□

Large mixing favored

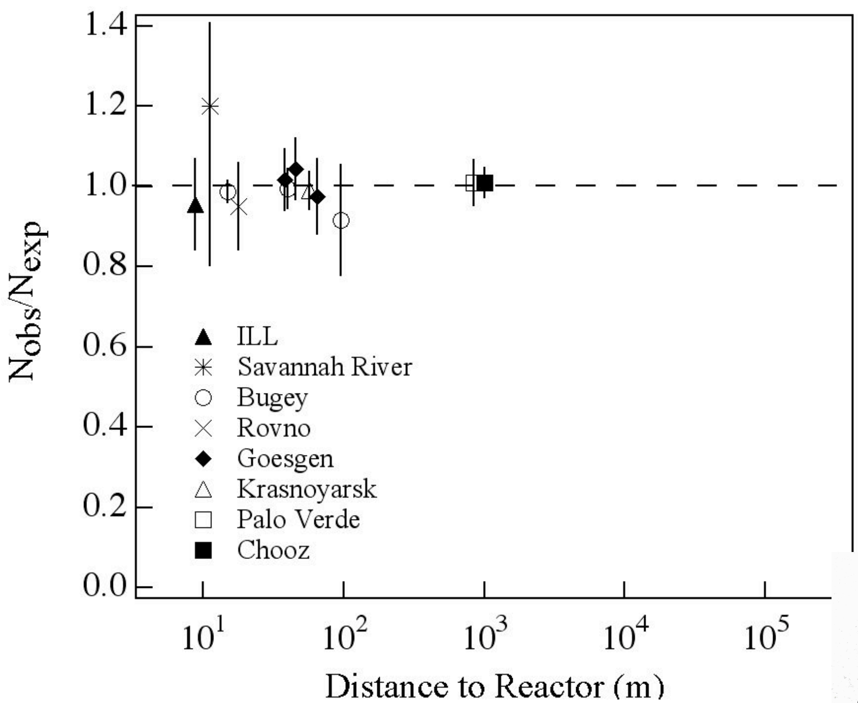
***LMA** solution can be tested with reactor neutrinos*



Status: Summer 2002

Murayama

Search for Neutrino Oscillations with Reactor Neutrinos



50 Years of Reactor Neutrino Physics

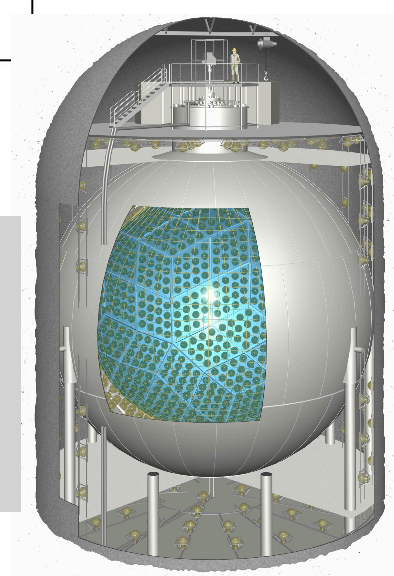
1953 First reactor neutrino experiment

1956 *"Detection of Free Antineutrino",*
F. Reines and C.L. Cowan

 Nobel Prize in 1995

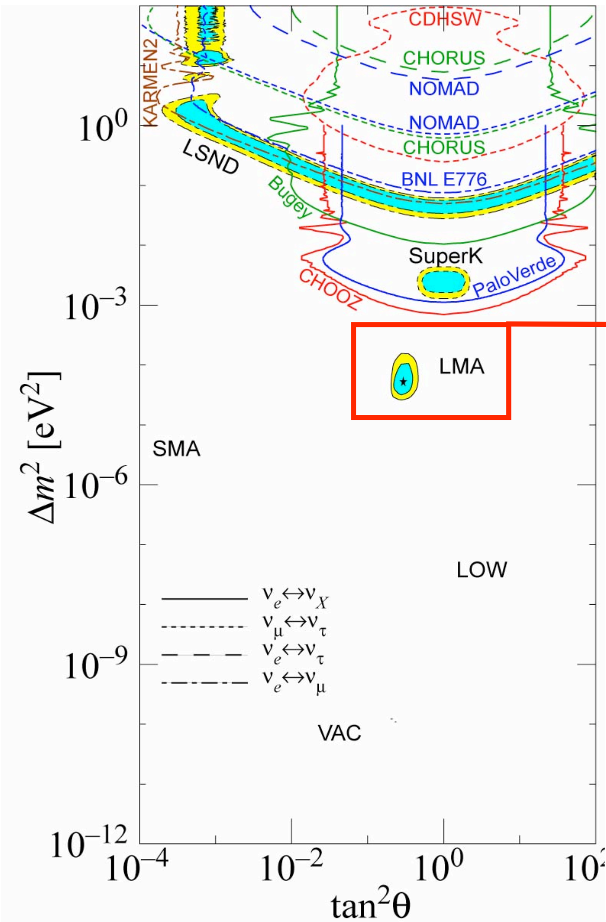
No signature of neutrino oscillations until 2002!

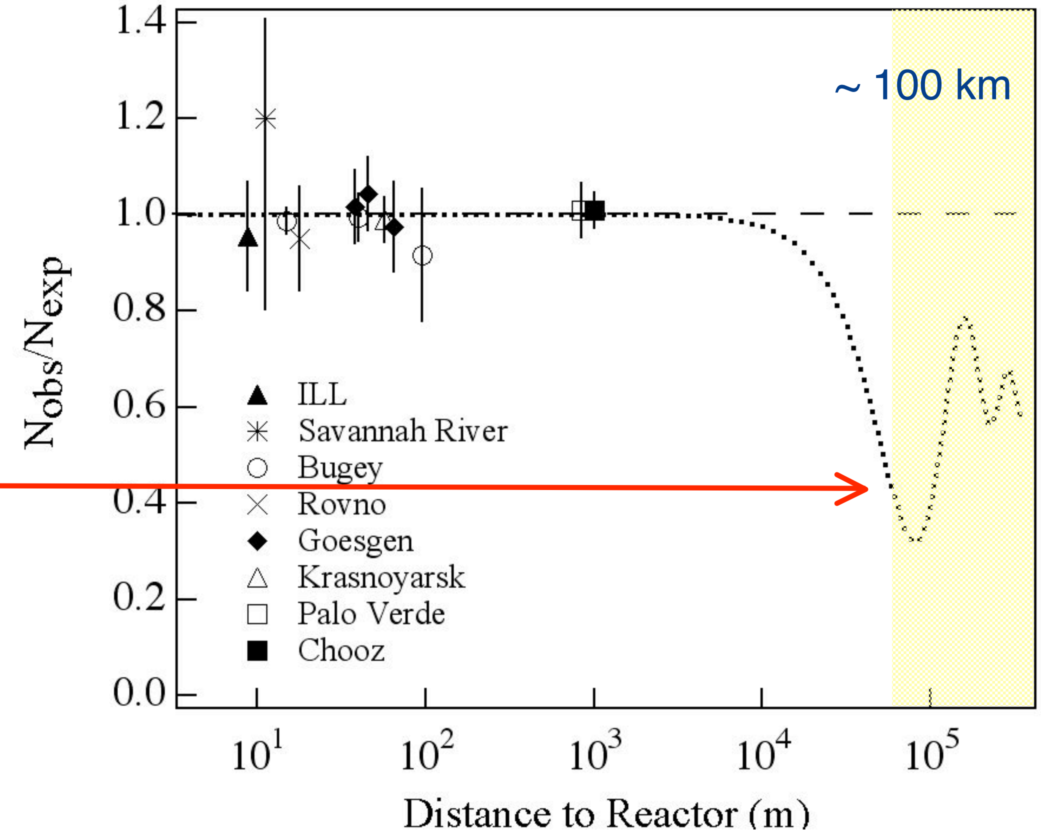
Results from solar experiments suggest study of reactor neutrinos with a baseline of ~ 180 km



LMA Prediction for KamLAND

LMA (large mixing angle) solution favored by *solar experiments*



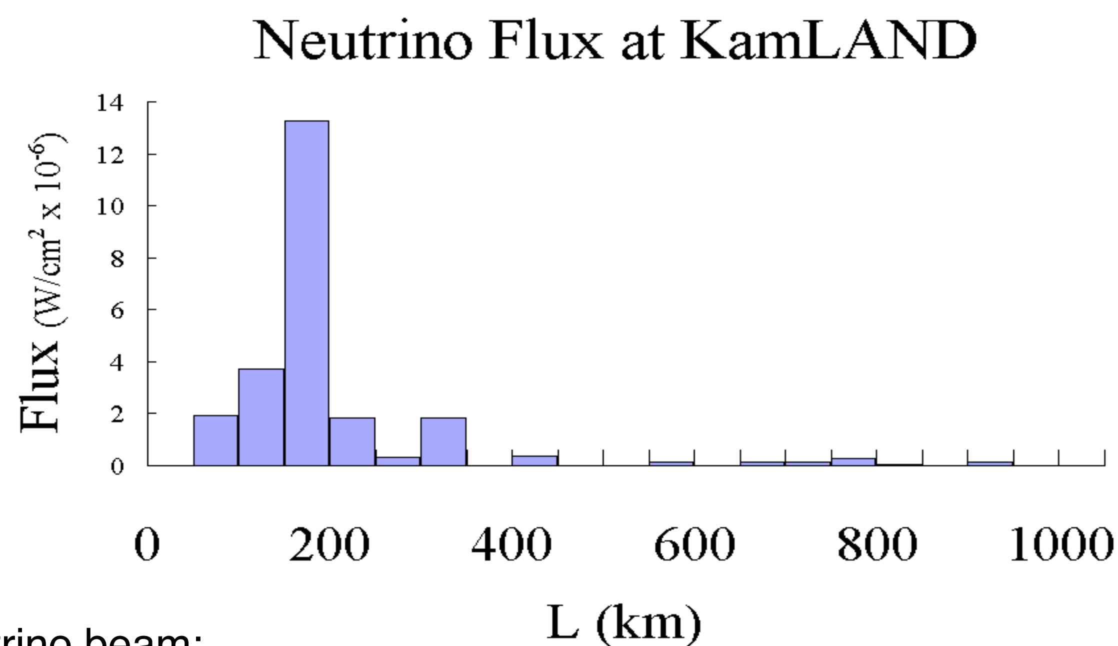


⇒ Signature for disappearance of reactor $\bar{\nu}_e$ in reach at the KamLAND reactor neutrino experiment

Neutrino Flux at KamLAND

Narrow Band of Distances to Neutrino Sources

~79% of flux from distance 138-214 km.
6.7% from one reactor at 88 km.



As by product of our anti-neutrino beam:

20% of world nuclear energy production

4% of world energy production

KamLAND - Kamioka Liquid Scintillator Antineutrino Detector

Uses reactor neutrinos to study ν oscillation with a baseline of L ~ 140-210 km

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

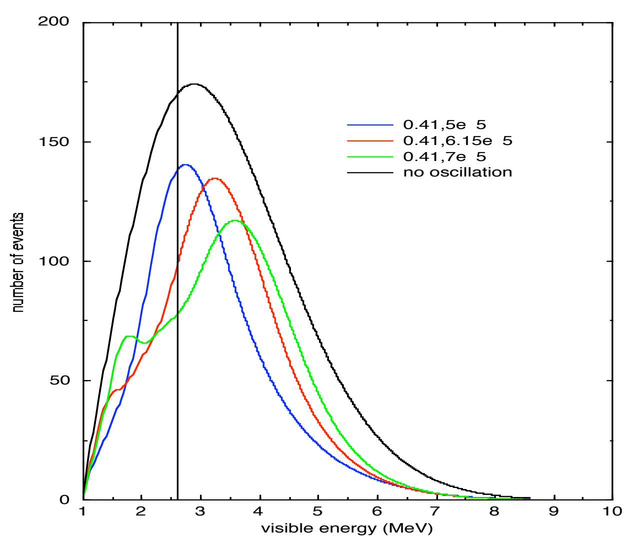
Coincidence:

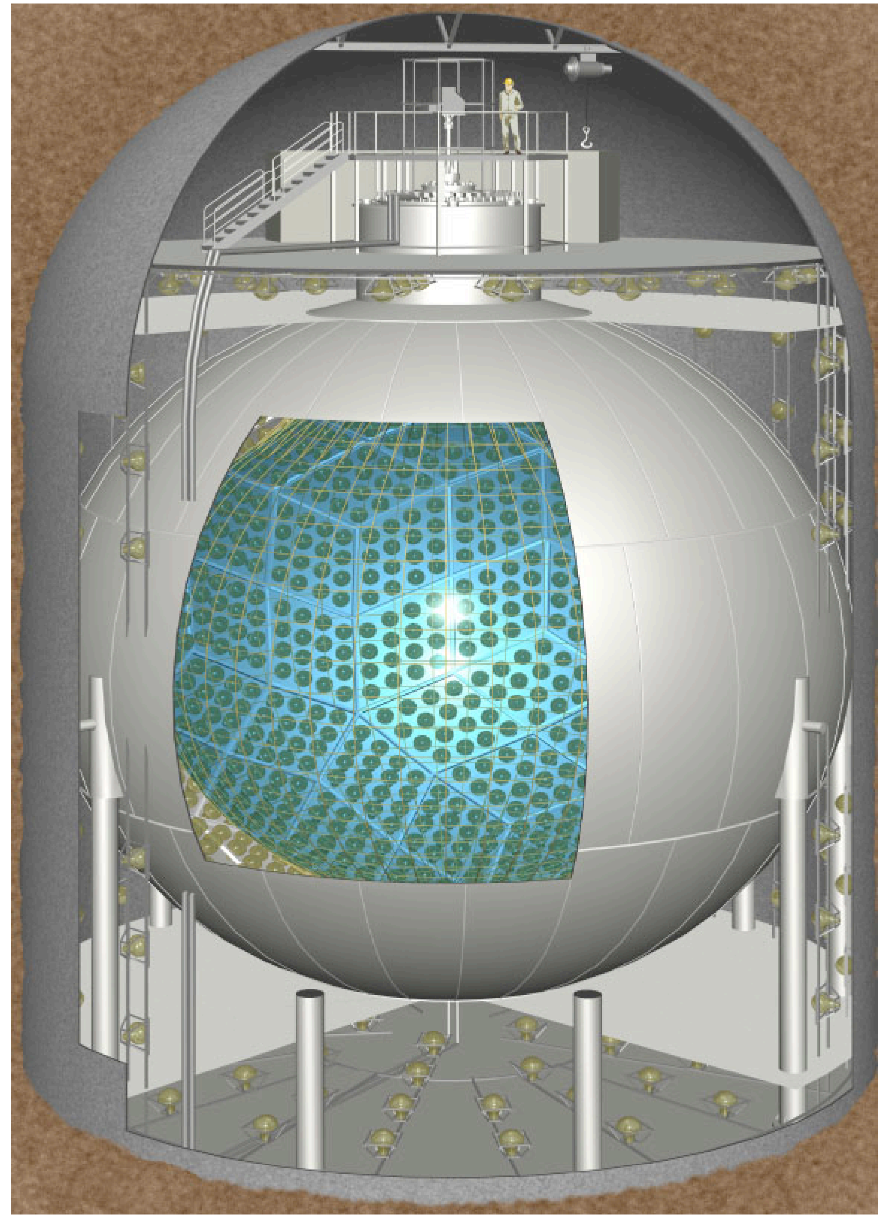
Prompt e^+ annihilation

Delayed n capture, ~ 210 μs capture time

KamLAND studies the disappearance of $\bar{\nu}_e$ and measures

- interaction rate
- energy spectrum





Measuring the ν_e Flux and Energy Spectrum:

Signatures of Neutrino Oscillations at KamLAND

Flux

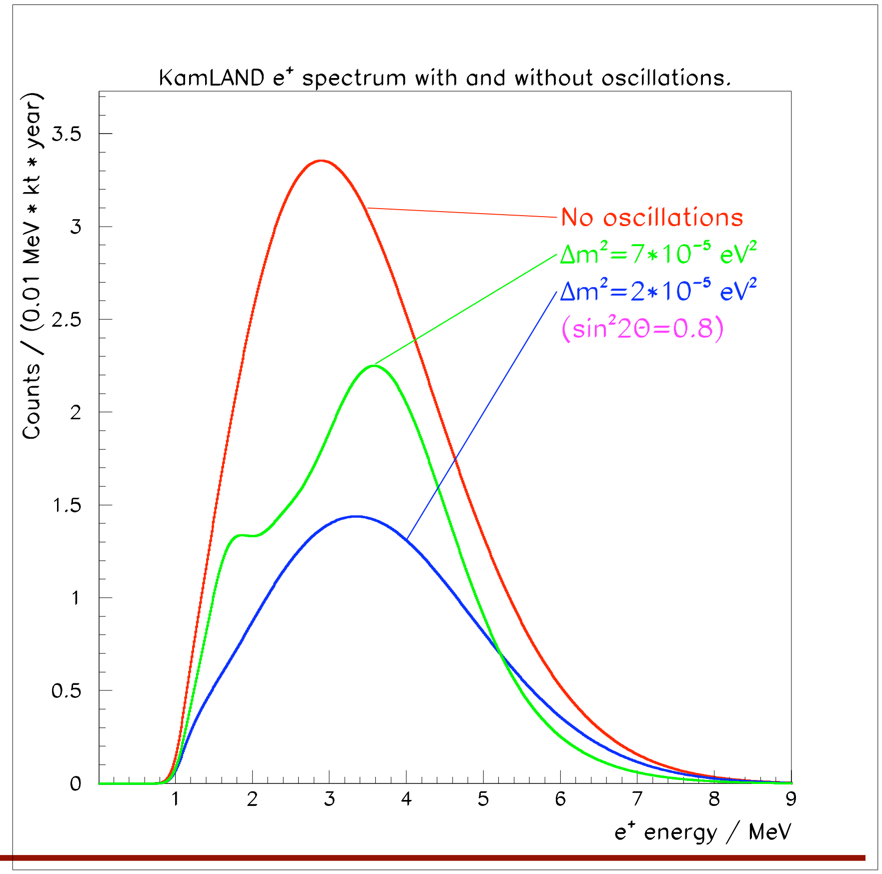
- Up to factor 2 rate reduction depending on Δm^2 and $\sin^2 2\theta$

Reactors at full power:

2 captures /day/kt without oscillations,
need ~1 kt target

Energy Spectrum

- Spectral distortions if ν_e oscillate



KamLAND Neutrino Program

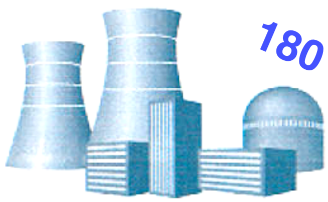
Phase I:

Reactor and Geo Neutrinos

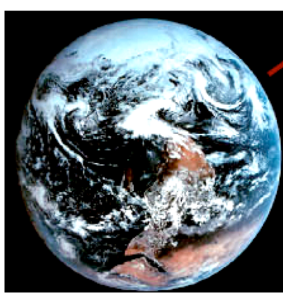
$(E_{th} = 1.8 \text{ MeV})$

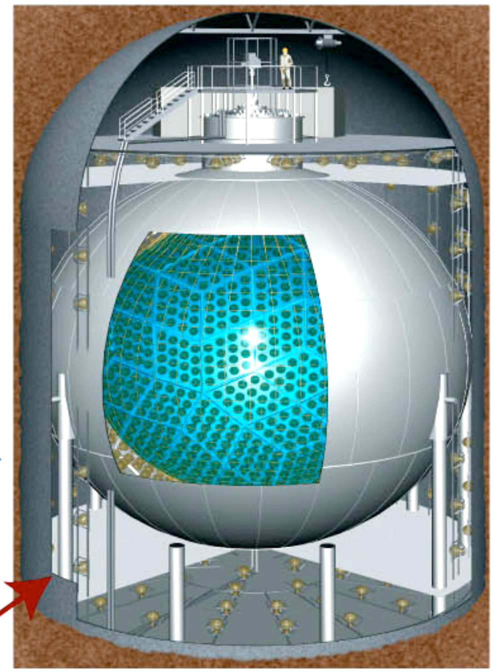
$\bar{\nu}_e + p \rightarrow e^+ + n$

n oscillation search



Terrestrial n detection





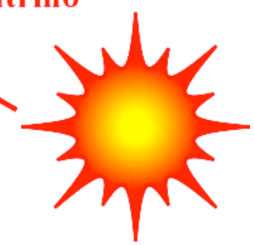
Phase II:

Solar Neutrinos

$(E_{th} = 200 \text{ keV})$

$\nu_e + e^- \rightarrow \nu_e + e^-$

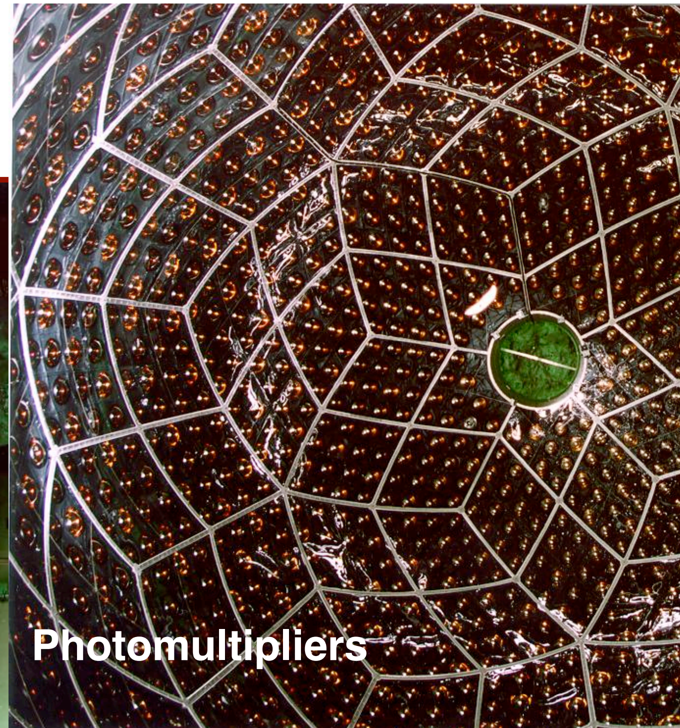
Direct detection of ^{7}Be n

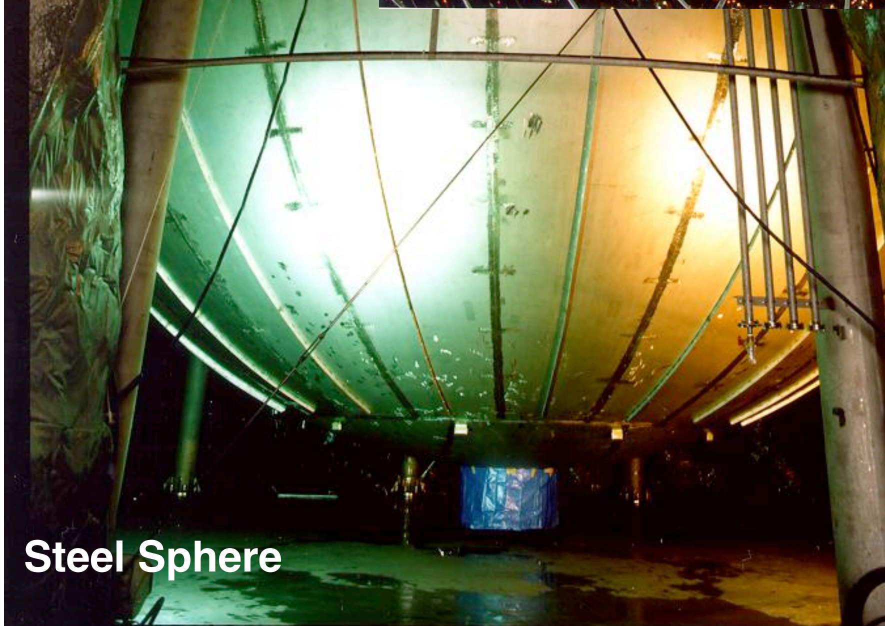


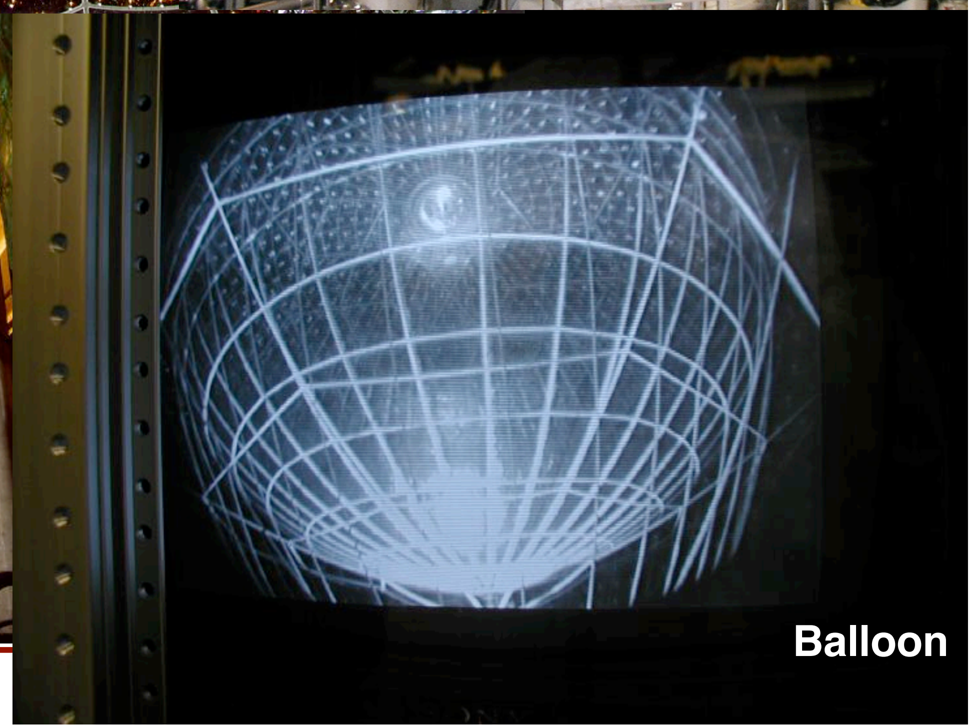
Solar n_e search, supernova detection,

Nucleon decay

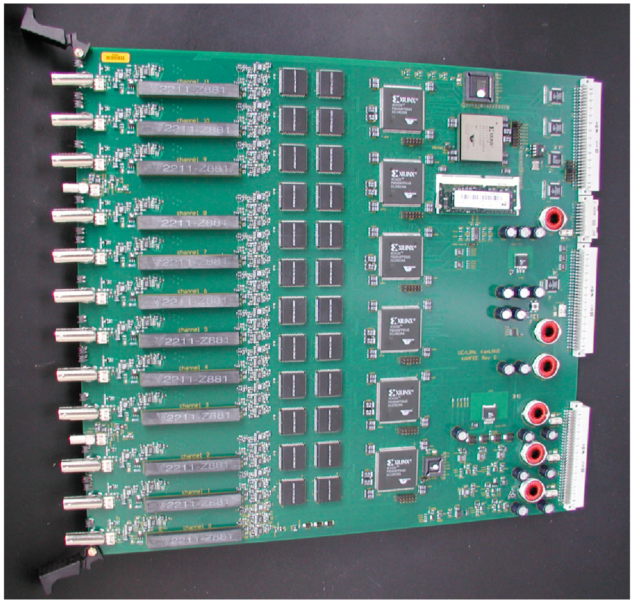
KamLAND





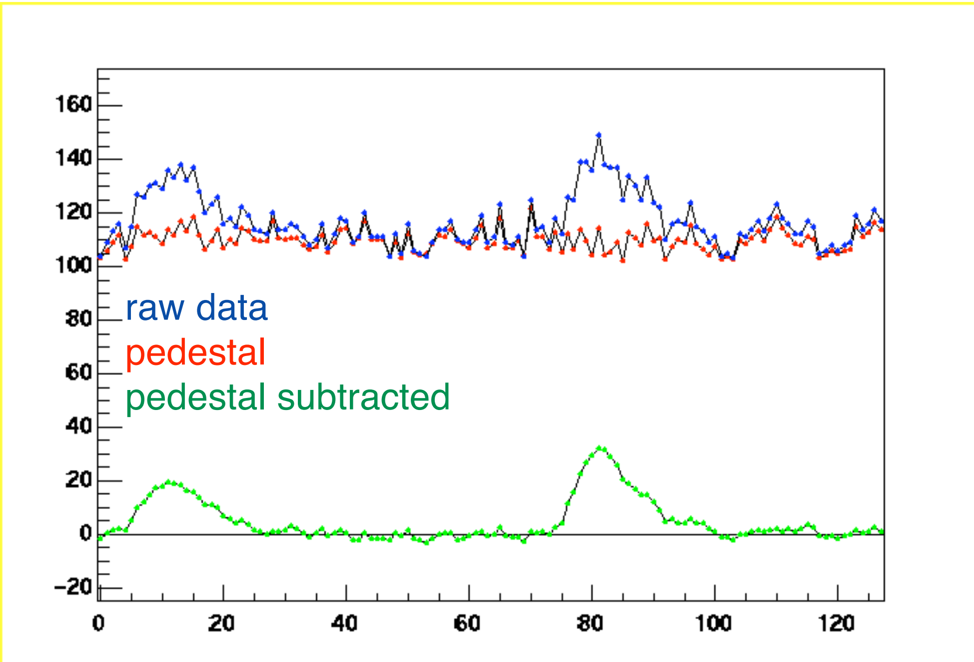


Front End Electronics



Waveforms are recorded using Analogue Transient Waveform Digitizers (ATWDs), allowing multi p.e. resolution

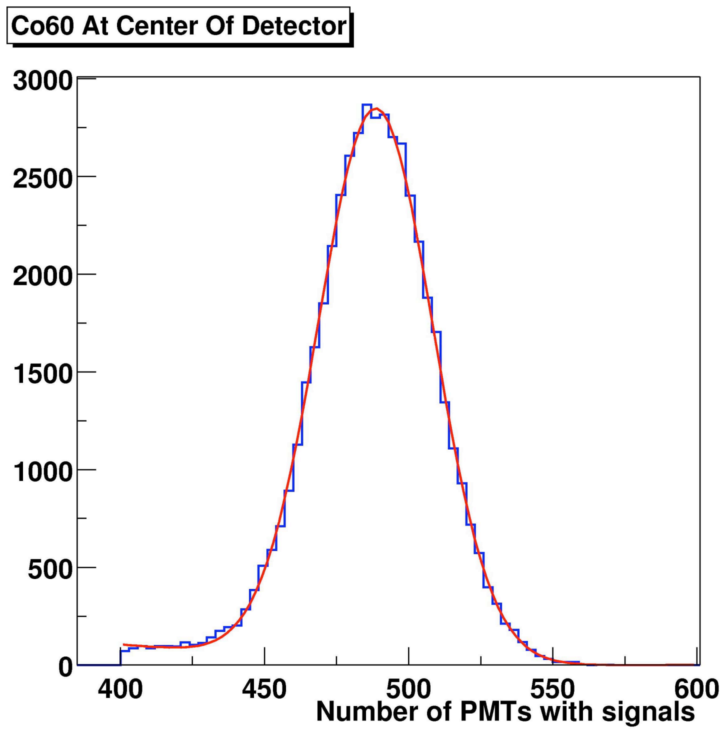
ADC Counts

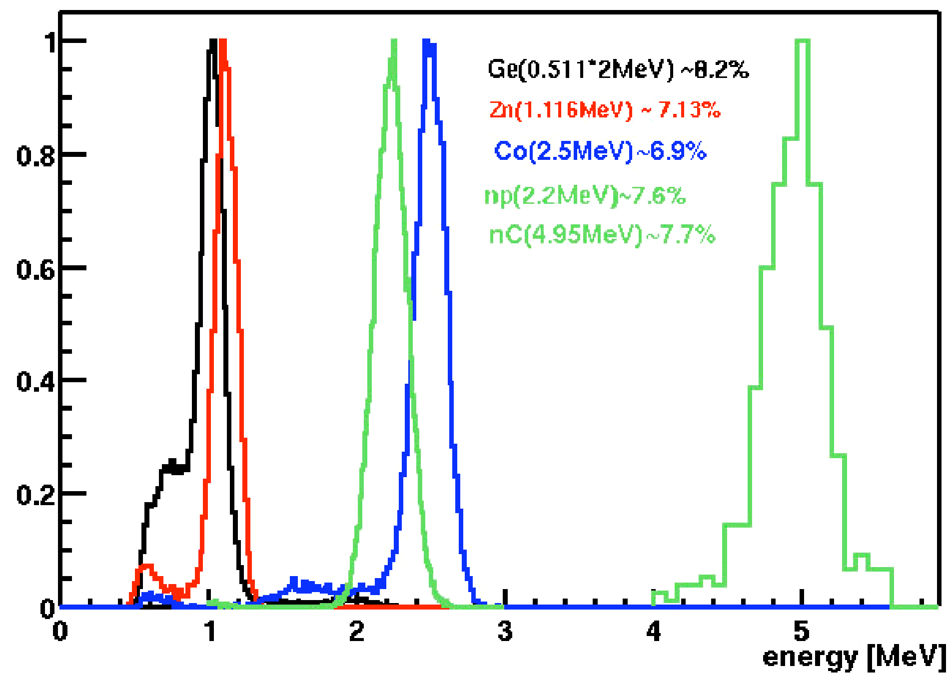


samples (~1.5ns)

- The ATWDs are self launching with a threshold ~1/3 p.e.
- Each PMT is connected to 2 ATWDs, reducing deadtime
- Each ATWD has 3 gains (20, 4, 0.5), allowing a dynamic range of ~1mV- ~1V

Energy Determination & Resolution





^{60}**Co:** 1.173+1.333 MeV

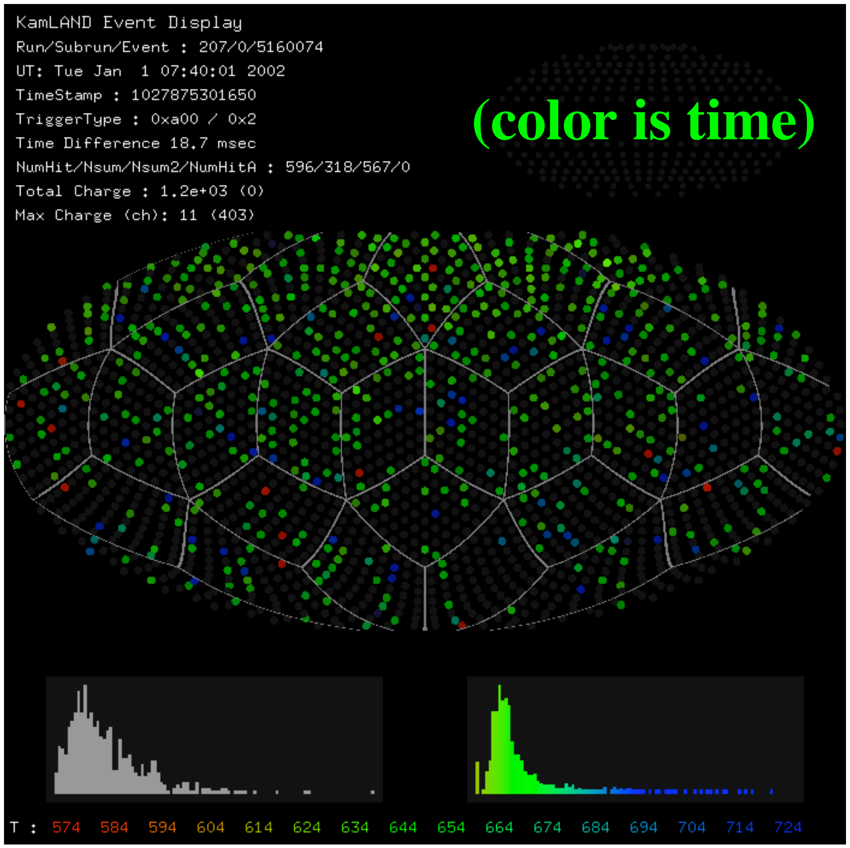
□E_{syst} = 1.91% at 2.6 MeV □ 2.13 % for □$_e$

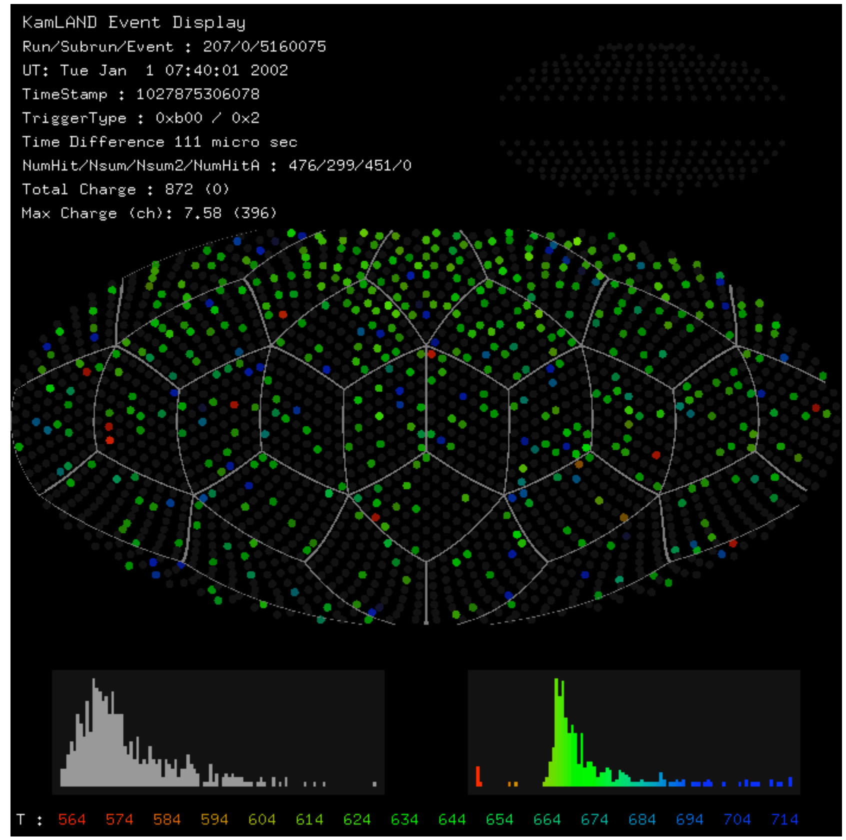
□E/E ~ 7.5% /$\sqrt{E}$

Light yield ~ 300p.e./MeV

Energy varies by < 0.5% within 10 m.

KamLAND Events - Neutrino Candidate



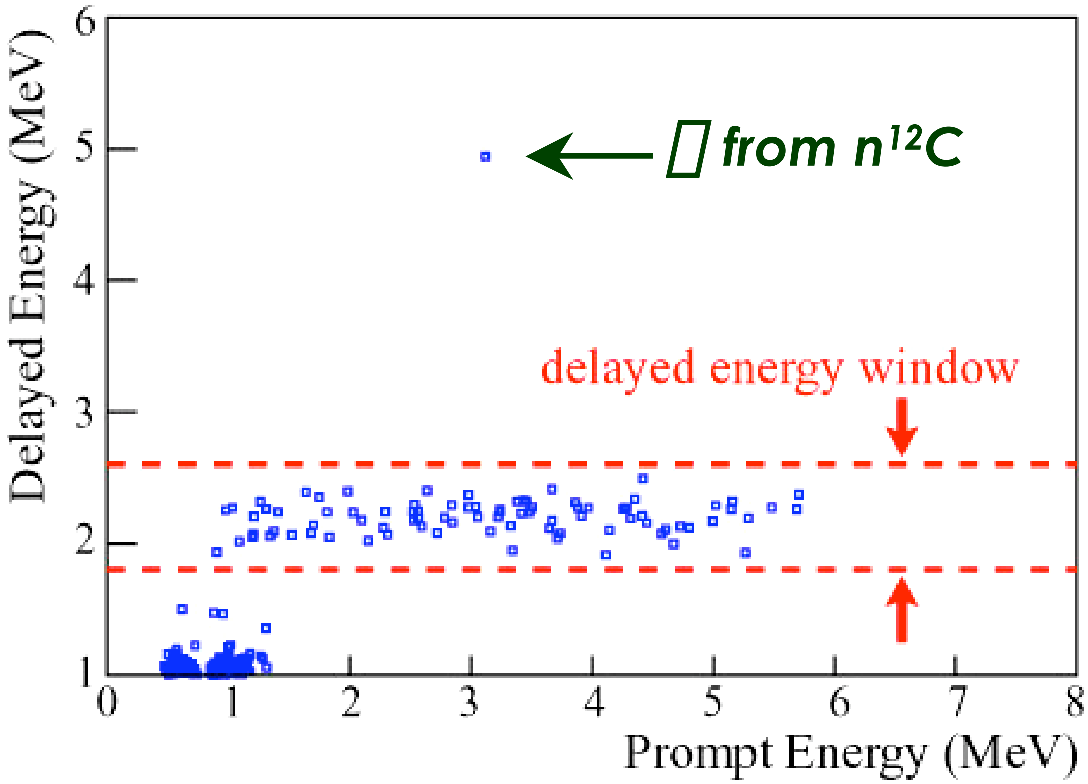


Prompt (e^+) Signal
E = 3.20 MeV

$\Delta t = 111\ \mu s$
$\Delta R = 34$ cm

Delayed (neutron) Signal
E = 2.22 MeV

Prompt and Delayed Energies



Fitted correlation time between prompt and delayed sub-event:

$\Delta t = 188 \pm 23\ \mu s$

⇒ In agreement with expectation for thermal n-capture.

Event Rates at KamLAND

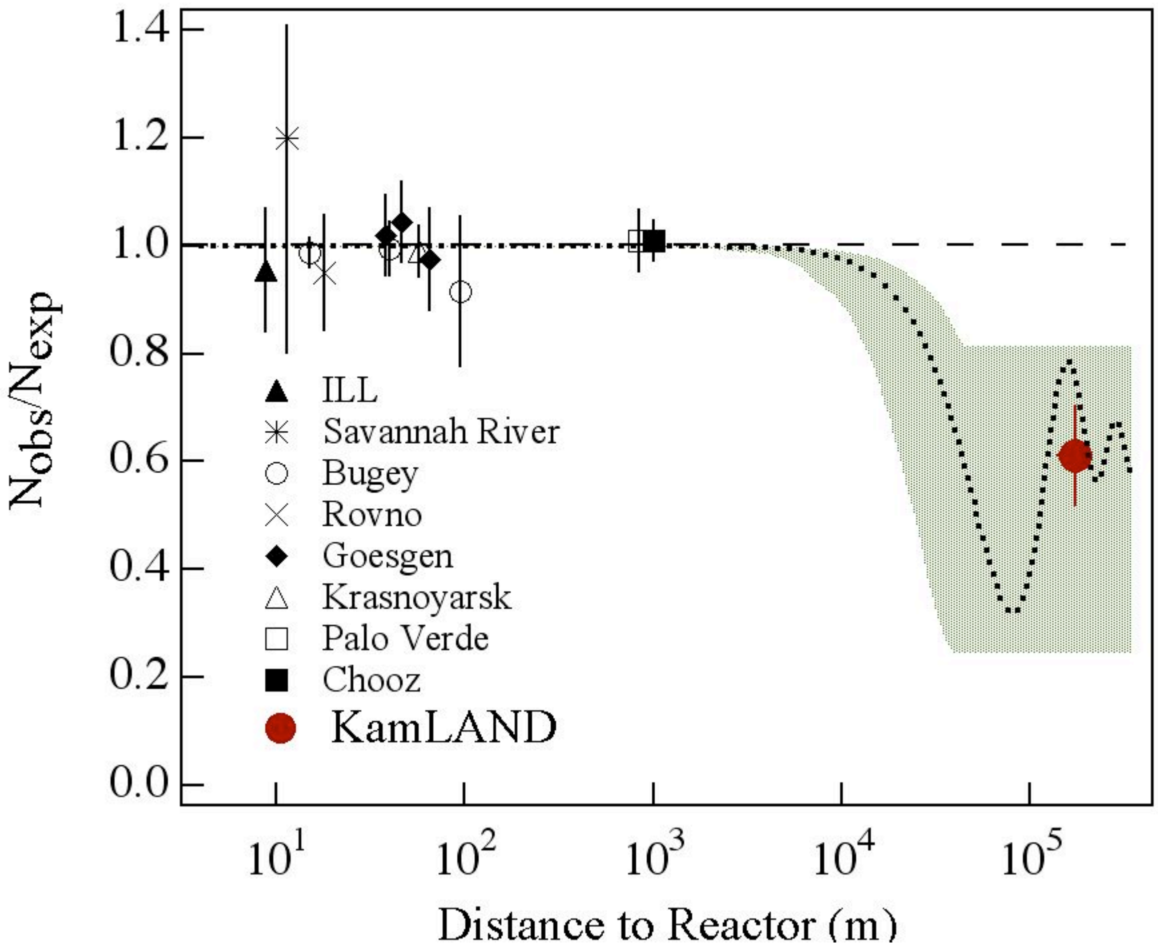
Observed	**54 events** 162 ton•yr, $E_{prompt} > 2.6$ MeV	*Excludes geo-□*
Expected	**86.8 ± 5.6 events**	
Background	1 ± 1 events	
accidental	*0.0086 ± 0.0005*	*Measured: □t_{pd}=0.02-20 s.*
$^{9}Li/^{8}He$	*0.94 ± 0.85*	*Confirmed by □within 3%.*
fast neutron	*< 0.5*	*From observed n signal and known neutron production in rock.*

Evidence for Reactor $\bar{\nu}_e$ Disappearance

$$\frac{N_{obs} - N_{BG}}{N_{expected}} = 0.611 \pm 0.085\ (\text{stat}) \ \pm 0.041\ (\text{syst})$$

Probability that result is consistent with no oscillation hypothesis < 0.05%

Ratio of Measured and No-Oscillation ν_e Flux from Reactor Neutrino Experiments



········· LMA:

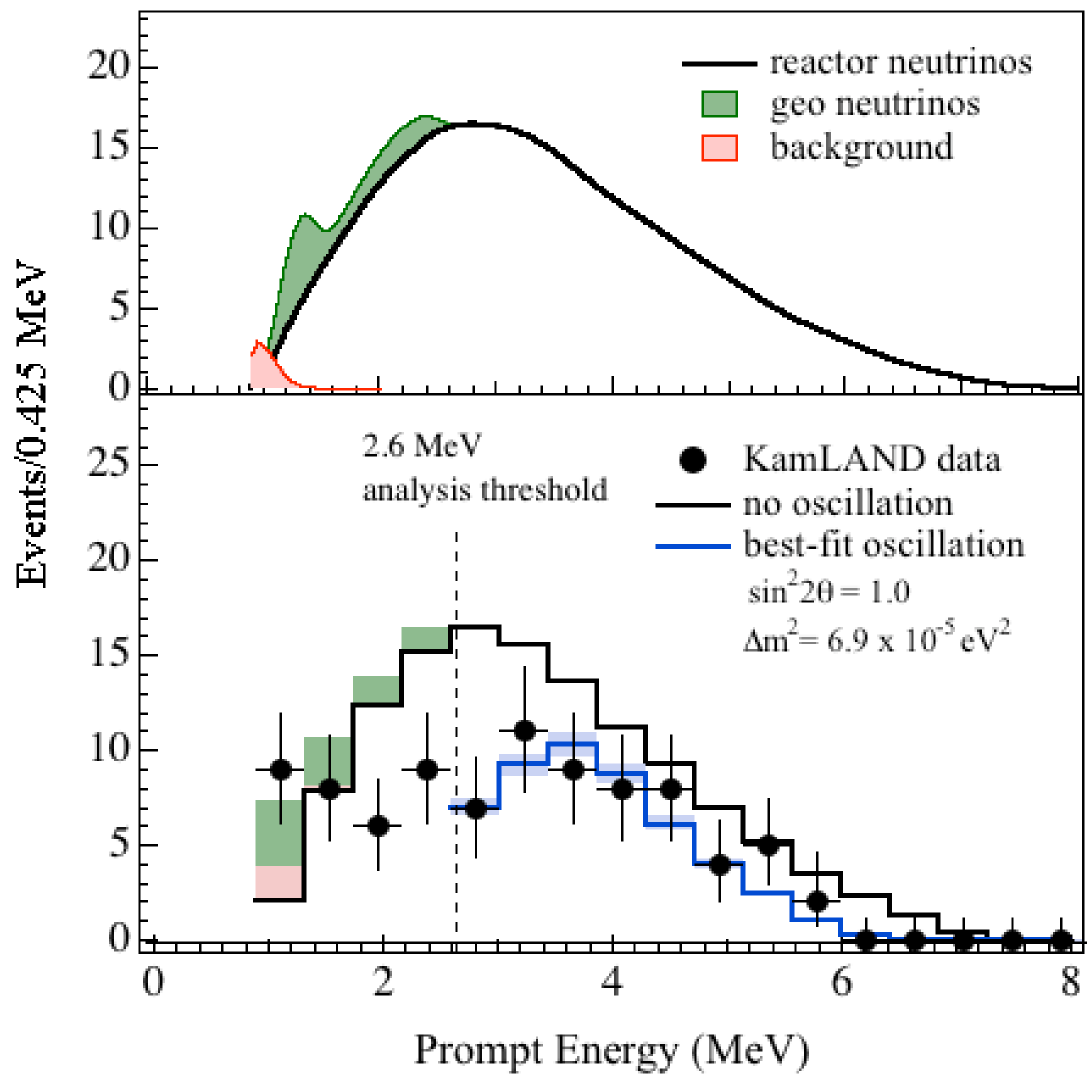
$\Delta m^2 = 5.5 \times 10^{-5}$ eV^2

$\sin^2 2\theta = 0.833$

LMA parameters from: G.Fogli et al., PRD 66, 010001-406, (2002)

Energy Spectrum

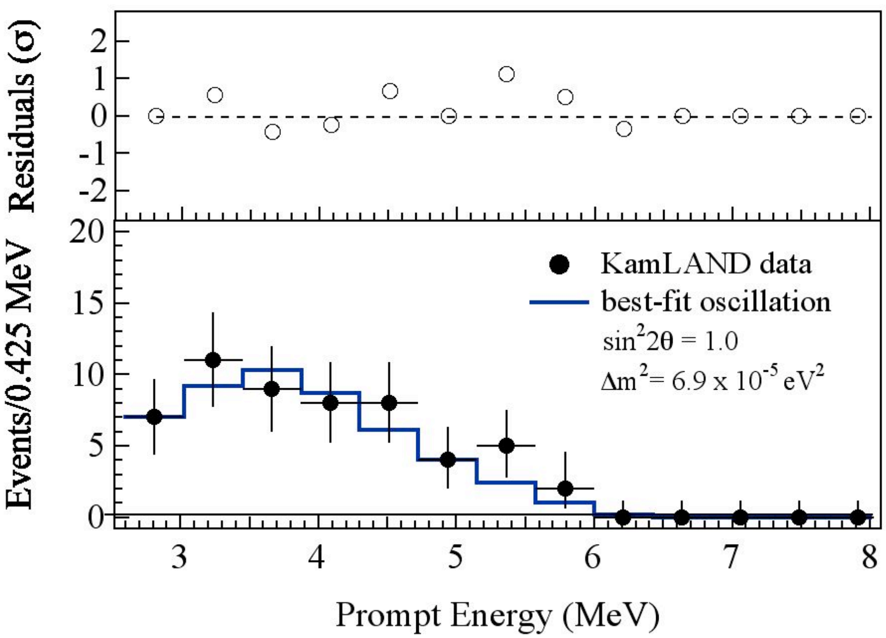
E_{prompt} > 2.6 MeV



Oscillation Solution vs. Suppression of Flux

Do we see a distorted Spectrum?

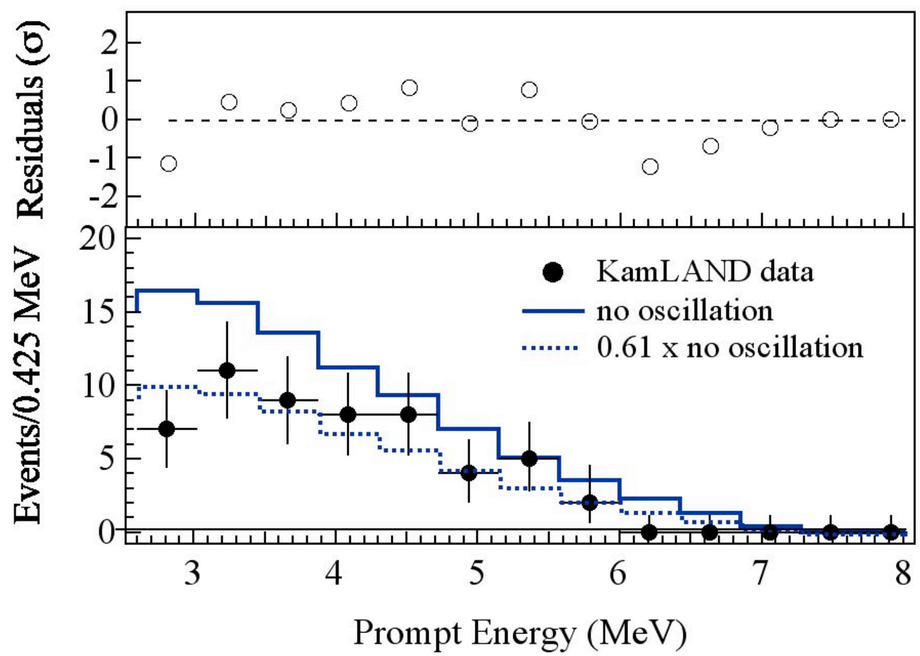
2-ν oscillation: best-fit



$\chi^2{}_{/\,8\ \mathrm{d.o.f}} = 0.31$

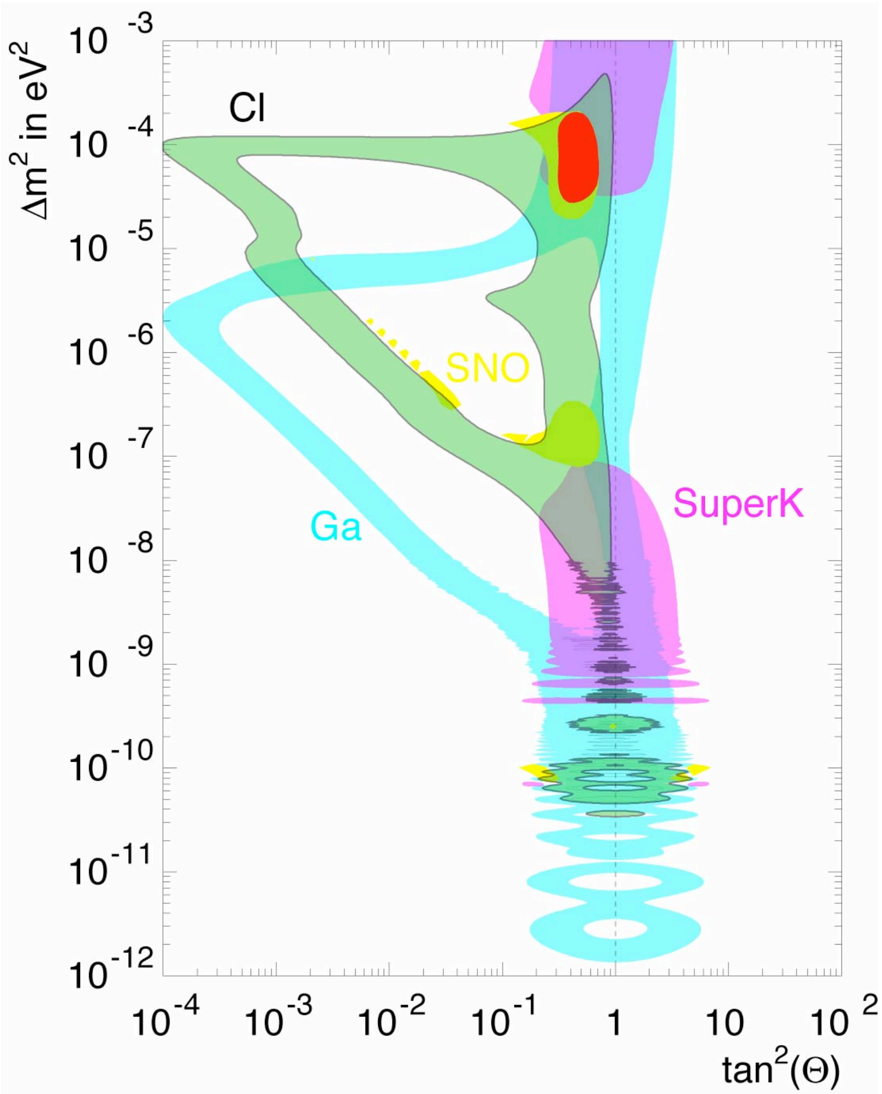
Data and best oscillation fit consistent at 93% C.L.

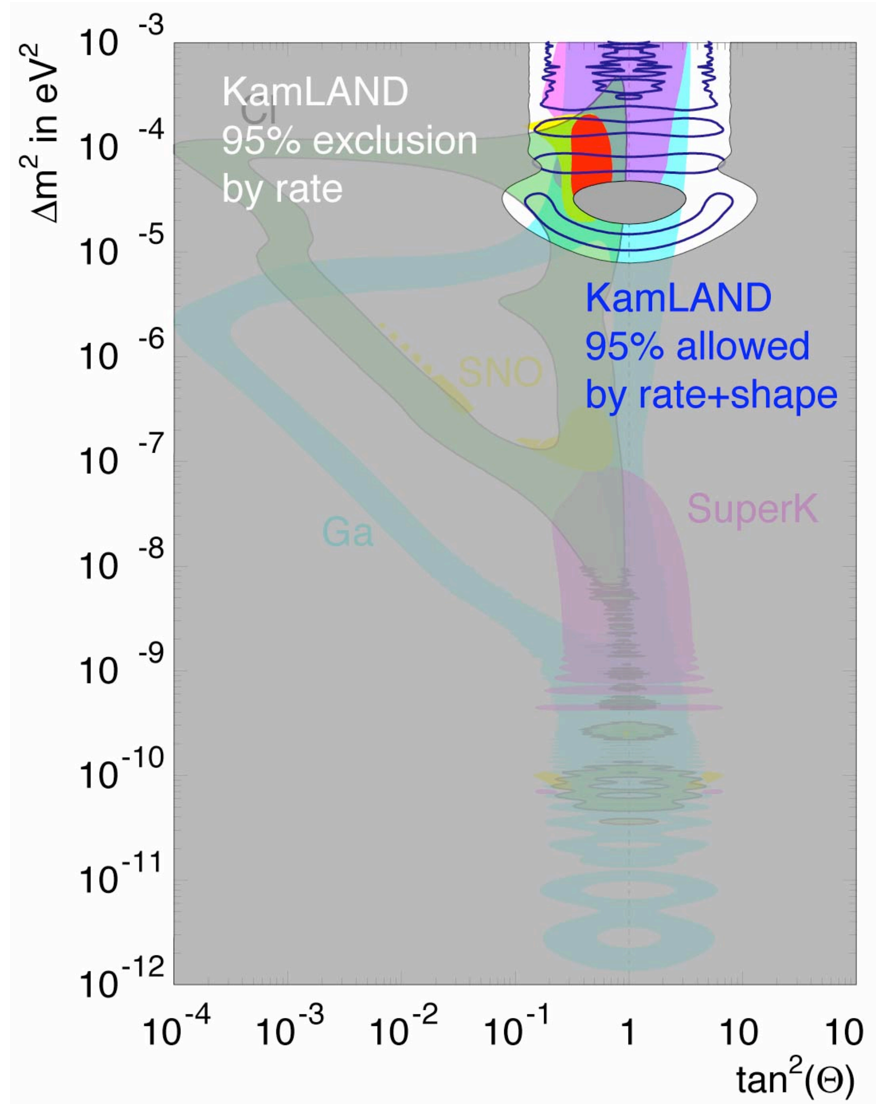
No oscillation, flux suppression



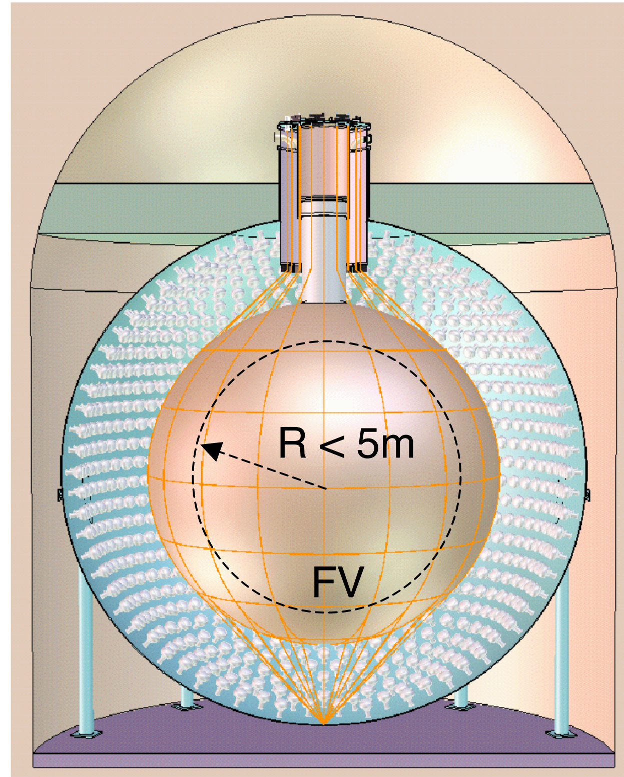
Data and best oscillation fit consistent at 53% C.L. as determined by Monte Carlo

Oscillation Parameters *Before* and *After* KamLAND





Future Improvements



I. Increasing the fiducial volume

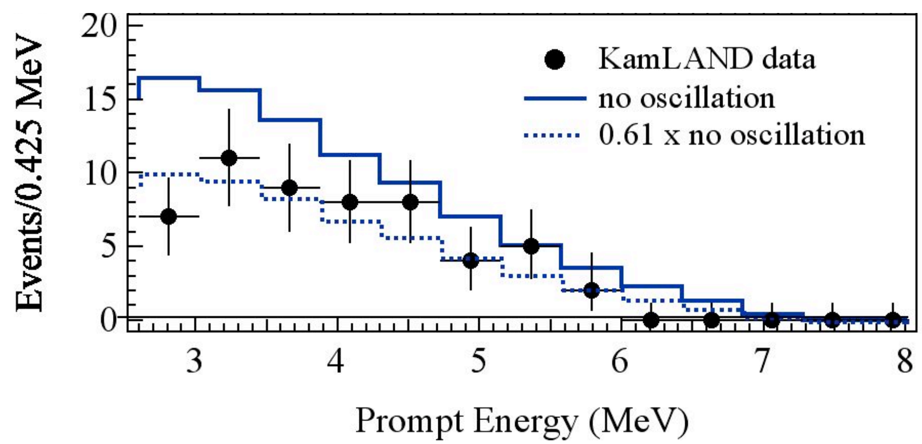
54 $\bar{\nu}_e$ candidate events above 2.6 MeV for R < 5 m
[72] $\bar{\nu}_e$ candidate events for R < 5.5 m

II. Reducing the systematic error

Fiducial volume error	4.6%
Total systematic error	6.4%
⇒ Goal for next analysis	~5-6%

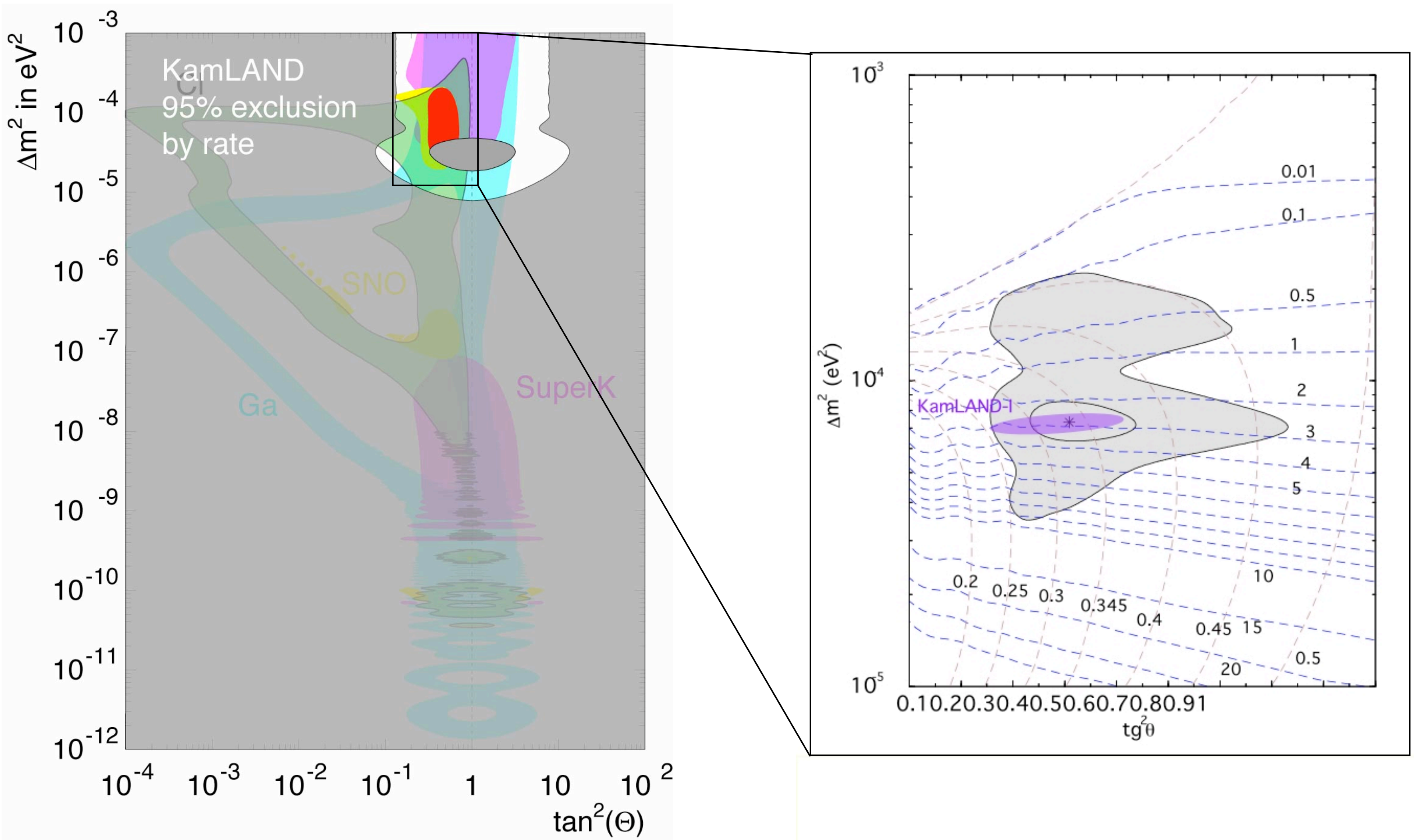
III. Precision measurement of the detector response

⇒ search for spectral distortions as a *unique* signature of neutrino oscillations



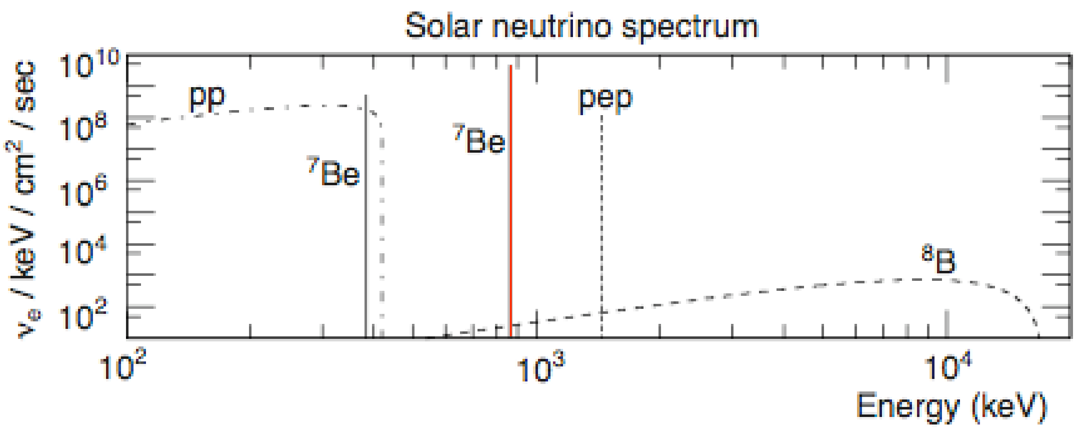
Precision Measurement of Δm^2_{solar} and θ_{12}

Measuring Reactor Neutrinos at KamLAND for 3+ Years

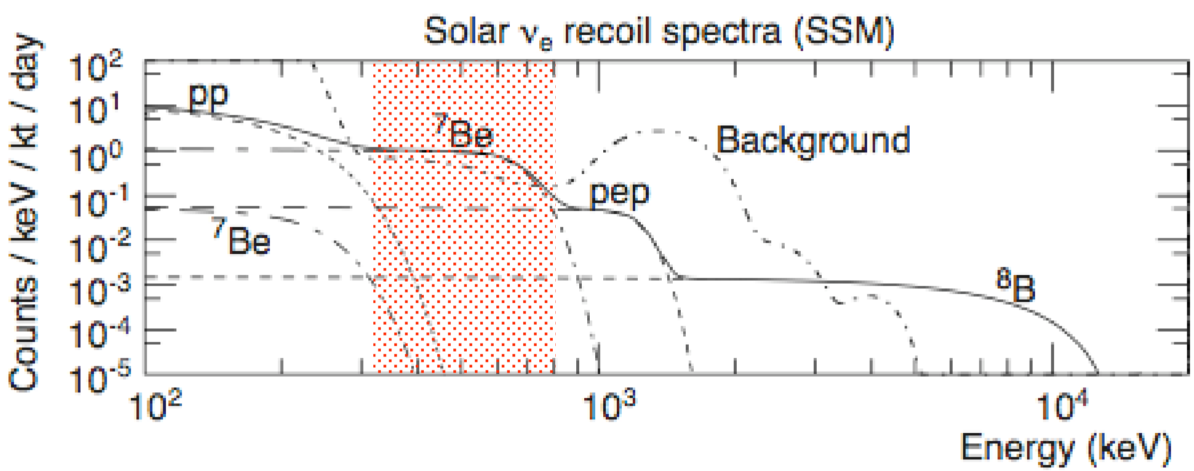


KamLAND-II

The Solar Phase of KamLAND

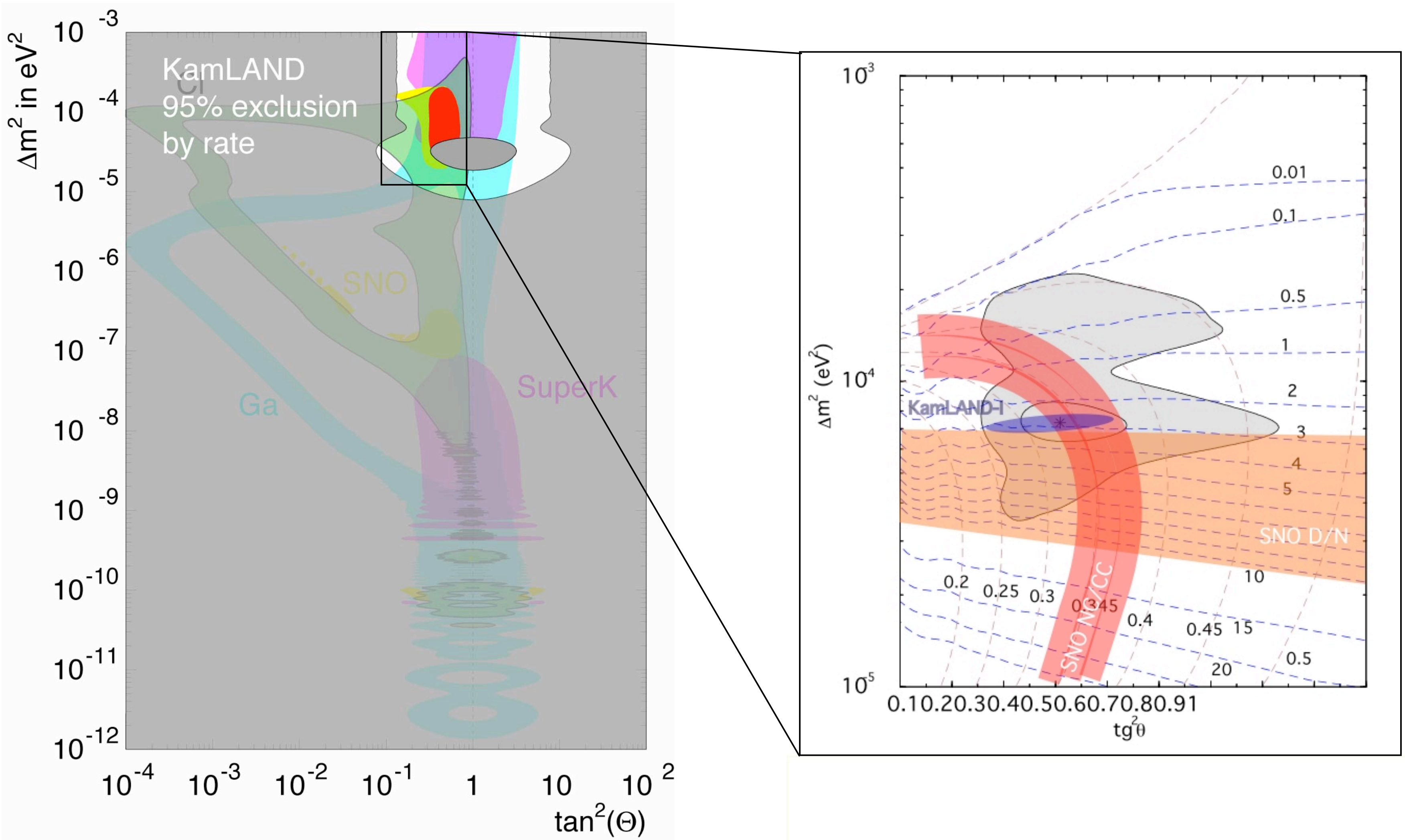


I. Direct detection of solar ^{7}Be n
II. Confirmation of solar model
III. Evidence for oscillation if no spectral signature found



Precision Measurement of □m$^2_{solar}$ and □$_{12}$

Measuring Solar Neutrinos at KamLAND-II and SNO



U_{MNSP} Neutrino Mixing Matrix

MNSP Matrix

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

In 3-ν scheme with Dirac neutrinos: $U_{MNSP} = U_{atm} \cdot U_{e3} \cdot U_{solar}$ δ=CP violating phase

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric ν — reactor and accelerator ν — solar ν + KamLAND

U_{MNSP} Neutrino Mixing Matrix

Mixing Angles

Solar	$\theta_{12} = 30.3°$
Atmospheric	$\theta_{23} = \sim 45°$
Chooz + SK	$\tan^2 \theta_{13} < 0.03$ at 90% CL

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1/\sqrt{2} & 1/\sqrt{2} \\ 0 & -1/\sqrt{2} & 1/\sqrt{2} \end{pmatrix} \times \begin{pmatrix} \sim 1 & 0 & e^{-i\delta_{CP}} \sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}} \sin\theta_{13} & 0 & \sim 1 \end{pmatrix} \times \begin{pmatrix} 0.85 & 0.51 & 0 \\ -0.51 & 0.85 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric ν (SK) — reactor and accelerator ν (Chooz) — solar ν + KamLAND (LMA)

U_{MNSP} Neutrino Mixing Matrix

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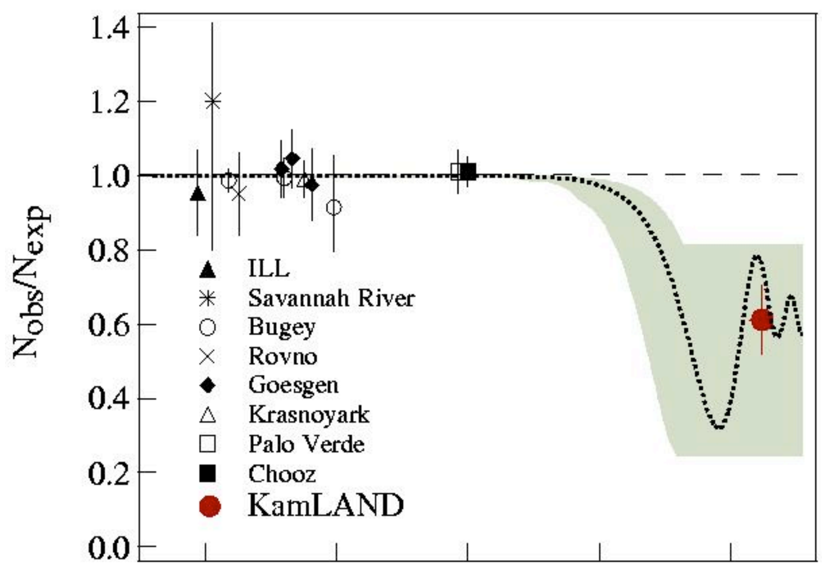
?

atmospheric
(SK)

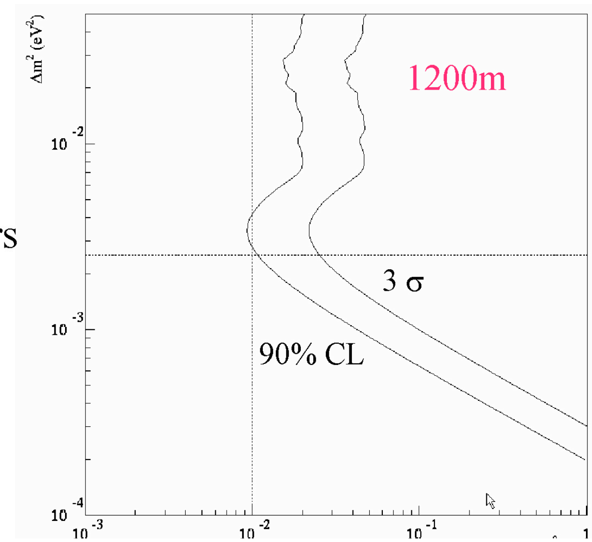
reactor and accelerator
(Chooz)

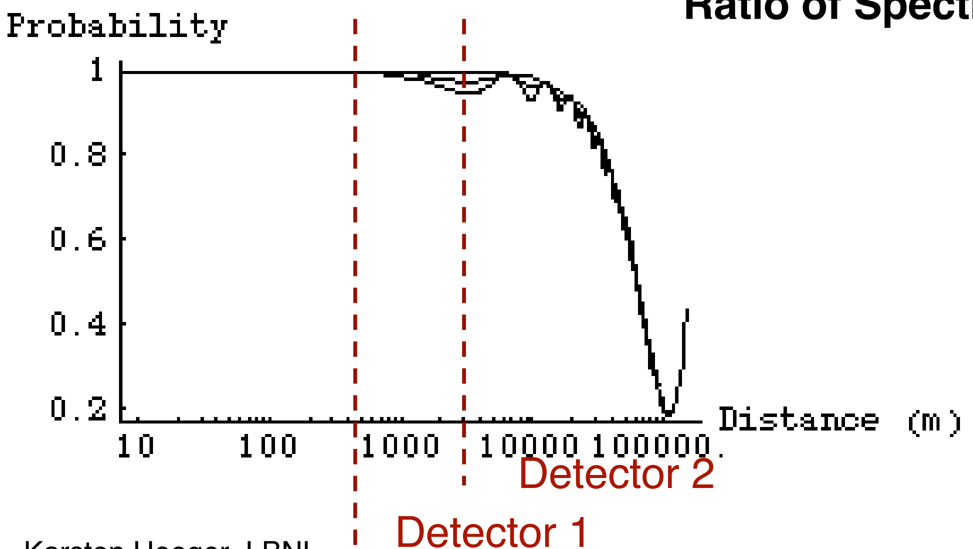
solar
(LMA)

θ_{13} Studies with a Reactor Neutrino Experiment

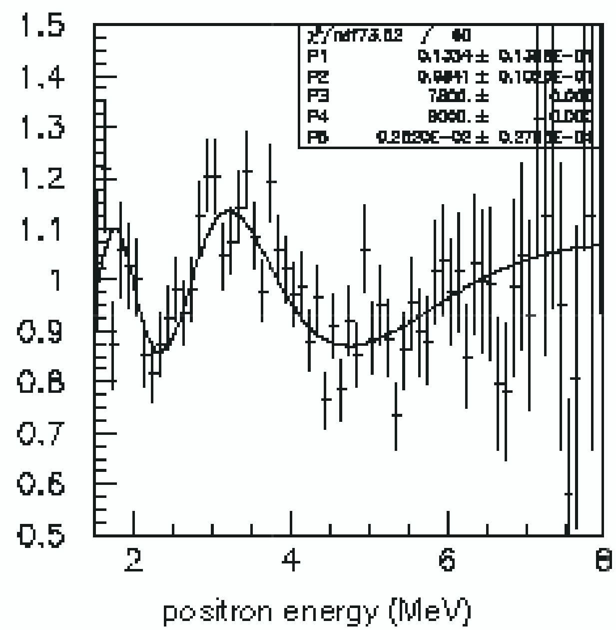


3 yrs





Ratio of Spectra



What has been learned?

- The Solar Neutrino problem was caused

  by new neutrino properties.

- Neutrinos have mass.

- Neutrinos have mixed flavor, and …. they oscillate.

- There is physics beyond the Minimal Standard Model.

- An experimental science...

Outlook

Next steps in neutrino physics...

- Search for direct signs of neutrino oscillation in SNO and KamLAND.
- How many neutrino mass eigenstates?
- What are the sizes and phases of the U_{MNSP} elements?

  Is $U_{e3}=0$? (Is there CP violation for neutrinos?)
- What is the level ordering and hierarchy?
- What are the masses?
- Are neutrinos Dirac or Majorana particles?
- What are the electromagnetic properties (dipole moments)? ...

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