First Results from KamLAND

Evidence for Reactor Anti-neutrino Disappearance

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KamLAND: Evidence for Neutrino Oscillations
$\nu_e$ are abundant by-products of nuclear fusion in the sun

\[ p + p \rightarrow ^2H + e^+ + \nu_e + 0.42\text{MeV} \]

"pp" 99.75%

\[ p + e^- + p \rightarrow ^2H + \nu_e + 1.44\text{MeV} \]

"pep" 0.25%

\[ ^2H + p \rightarrow ^3He + \gamma + 5.49 \text{MeV} \]

"hep" 2.4x10^-5

86%

\[ ^3He + ^3He \rightarrow \alpha + 2p + 12.86\text{MeV} \]

14%

\[ ^3He + \alpha \rightarrow ^7Be + \gamma + 1.59\text{MeV} \]

\[ ^3He + p \rightarrow \alpha + e^+ + \nu_e \]

"7Be" 99.89%

\[ ^7Be + e^- \rightarrow ^7Li + \gamma + \nu_e + 0.8617\text{MeV} \]

0.11%

\[ ^7Be + p \rightarrow ^8B + \gamma + 0.14\text{MeV} \]

"8B" 0.11%

\[ ^8B \rightarrow ^8Be + e^+ + \nu_e + 14.6\text{MeV} \]

\[ ^7Li + p \rightarrow \alpha + \alpha + 17.35\text{MeV} \]

\[ ^8Be \rightarrow \alpha + \alpha + 3\text{MeV} \]
Ray Davis Jr.
Physics Nobel Prize 2002
Homestake Mine, Lead SD
1400 m underground

615 tons of perchloroethilene
\((C_2Cl_4)\)

2.2*10^{30} \text{ atoms of } ^{37}\text{Cl}
^{36}\text{Ar or }^{38}\text{Ar added to the fluid as carrier gas}

Data taken continuously since 1967 (!)
3 types of experiments detecting solar neutrinos

- **Chlorine**: $^{37}\text{Cl} + \nu_e = ^{37}\text{Ar} + e^-$
  1 exp running >30 yrs (US)

- **Gallium**: $^{71}\text{Ga} + \nu_e = ^{71}\text{Ge} + e^-$
  3 exp (Russia, Italy)

- **Cerenkov**: $e^- + \nu_e = e^- + \nu_e$
  3 exp (Japan, Canada)
Conclusion:

- We detect $n_s$! : nuclear fusion powers the sun
- The sun is still shining (this is not trivial: it takes ~ 1Myr for a photon to emerge from the sun)

The sun imaged with neutrinos (courtesy R. Svoboda and the SK collab.)
Conclusion:

We do not see enough vs !

- do we understand the sun well enough ?

- are ννs playing tricks ?

"It starts to be really interesting ! It would be nice if all this will end with something unexpected from the point of view of particle physics. Unfortunately it will not be easy to demonstrate this, even if nature works this way..."  B.Pontecorvo, 1972
\[ \nu_x + e^- \rightarrow \nu_x + e^- \]
\[ \nu_e + e^- \rightarrow \nu_e + e^- \]
sensitive to a \( \nu_e, \nu_x \) mix

\[ \nu_e + ^2 H \rightarrow \nu_x + p + n \]
equally sensitive to all neutrinos

\[ \nu_e + ^2 H \rightarrow p + p + e^- \]
sensitive to \( \nu_e \) only
If $m_\nu$ is non-zero then leptons could behave like quarks.

The weak interaction eigenstate $|\nu_j\rangle$ is a superposition of mass eigenstates $|\nu_j\rangle = \sum_j U_{jl} |\nu_l\rangle$

$U_{jl}$ is a $3 \times 3$ unitary matrix (like the CKM matrix for quarks).

What propagates is the mass eigenstate $|\nu_l\rangle$.

$$|\nu_l(t)\rangle = e^{-i(E_l t - p_i L)} |\nu_l(0)\rangle \approx e^{-i(m_j^2/2E)L} |\nu_l(0)\rangle$$

What is produced and detected is $|\nu_j\rangle$.

Assuming

$$E_i = E >> m_i \quad p_i >> m_i$$
\[ |\nu_j\rangle \equiv \sum_l U_{lj} e^{-i(m^2_l/2E) L} |\nu_l\rangle \equiv \sum_{j'} \sum_l U_{lj} e^{-i(m^2_l/2E) L} U^*_{j'j} |\nu_{j'}\rangle \]

...that is neutrinos “acquire” components from other flavors as they propagate.

We can define a “transition probability”

\[ P(\nu_{j'} \rightarrow \nu_j, L) = \left| \sum_l U_{lj} U^*_{j'j} e^{-i(m^2_l/2E) L} \right|^2 \]

...a periodic function of the baseline \( L \)
For 2 flavors this simplifies:

\[
U = \begin{pmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta
\end{pmatrix}
\]

Only one mixing parameter \( \theta \)

\[
P(\nu_e \rightarrow \nu_\mu, L) = \sin^2 2\theta \sin^2 \frac{1.3 \Delta m^2 L}{E}
\]

Neutrino oscillations \( m_\nu \neq 0 \)
If the correct interpretation is that neutrinos oscillate, only two solutions are compatible with all solar data.
All of this is very interesting…

…but wouldn’t it be great if we could reproduce it with artificial means?
Nuclear reactors are very intense sources of $\nu_e$ deriving from beta-decay of the neutron-rich fission fragments.

$N_1$ and $N_2$ still have too many neutrons and decay:

$$N_2 \rightarrow N_3 + e^- + \nu_e$$

Look for a deficit of $\bar{\nu}_e$ at a distance $L$. 

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KamLAND: Evidence for Neutrino Oscillations
Fred Reines preparing a reactor anti-neutrino detector (circa 1953)
Complementary properties of Reactors and Accelerators

$E_\nu \sim \text{few MeV}$

- Can probe very small $\Delta m^2$
- Disappearance only $\rightarrow$ fair $\sin^2 2\theta$ sensitivity
- $4\pi$ source $\rightarrow$ detector mass grows with $L^2$

$E_\nu \sim \text{few GeV}$

- Good mass sensitivity requires very large $L$
- Appearance possible (produce $\mu$ and $\tau$)
- "Collimated" beam

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KamLAND: Evidence for Neutrino Oscillations
Example: $^{235}\text{U}$ fission

$^{235}_{92}\text{U} + n \rightarrow X_1 + X_2 + 2n$

stable nuclei with $A$
most likely from fission

$^{94}_{40}\text{Zr}$ $^{140}_{58}\text{Ce}$

together these have
98 protons and
136 neutrons

so, on average 6 $n$ have to
decay to 6 $p$ to reach stable matter
Power/commercial reactors are generally used since only requirement is to have large power

\[ 200\text{MeV} / \text{fission} \]
\[ 6\overline{\nu}_e / \text{fission} \]

A typical large power reactor produces \( 3\ \text{GW}_{\text{thermal}} \) and \( 6 \cdot 10^{20} \) antineutrinos/s

the Chooz plant in France
>99.9% of $\bar{\nu}$ are produced by fissions in $^{235}\text{U}, ^{238}\text{U}, ^{239}\text{Pu}, ^{241}\text{Pu}$.

contribution $<10^{-3}$ not taken into account for neutrino flux calculations

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

$\tau \approx 200 \mu s$

$p + n \rightarrow d + \gamma(2.2 \text{ MeV})$

\[
E_{\bar{\nu}} \approx E_{e^+} + E_n + (M_n - M_p) + m_{e^+}
\]

$\nu$ det. at low energy is tricky: beware of backgrounds!

Event tagging by delayed coincidence in energy, time and space

$\gamma 2200 \text{ keV}$

$\gamma 511 \text{ keV}$

$\gamma 511 \text{ keV}$

$\approx 10^{-40} \text{ keV}$

$\nu_{\text{measurement}}$

1000 ton Scint.
The $\bar{\nu}_e$ energy spectrum

Neutrinos with $E < 1.8$ MeV are not detected

So in practice only $\sim 1.5$ neutrinos/fission can be detected above threshold
...disappearance experiments...
how well do we know the flux and spectrum?

The 200 MeV/fission part:

Thermal power is routinely measured by the reactor operator in order to adjust the reactor to the highest licensed power.

Economics push the error on this to 0.6-0.7%
how well do we know the flux and spectrum?

The $6 \bar{\nu}/$fission part:

Anti-neutrino spectra from $^{235}\text{U}$, $^{239}\text{Pu}$ and $^{241}\text{Pu}$ fission can be derived from $\beta^-$ spectroscopy

This is not entirely trivial as there are very many fission branches and then many possible $\beta$ decays for each branch

The $\bar{\nu}$ yield from $^{238}\text{U}$ derives from fast-neutron fission and could not be measured in the papers above.

...but one can also calculate the $\bar{\nu}$ yield from first principles.

Errors of about 10% are typical in these calculations that have to include ~1000 channels.

So, $^{238}\text{U}$ that contributes about 11% to the total yield, introduces a total error of about 1%.
All these techniques can be cross-checked using precise $\bar{\nu}$ spectra measured at short baseline reactor experiments.
Of course the use of short baseline experiments to check normalization implies no oscillations, as it can be directly checked in cases where the baseline was varied.
An experiment relevant for solar neutrinos will have ~100 km baseline and hence will need a huge detector and a "huge source".
Need to think regionally: large concentration of nuclear power plants exist in Europe, eastern US and Japan.
~1 km high
Mt Ikenoyama
KamLAND: the ultimate reactor neutrino oscillation experiment

- 1 kton liq. Scint. Detector in the Kamioka cavern
- ~1300 17” fast PMTs
- ~700 20” large area PMTs
- 30% photocathode coverage
- H₂O Cerenkov veto counter
- Multi-hit deadtime-less electronics
- $\Delta m^2$ sensitivity $7 \times 10^{-6}$ eV²
  - LMA-MSW solution within reach on the earth!
## KamLAND: Evidence for Neutrino Oscillations

Baseline is limited: 85.3% of signal has 140 km < L < 344 km

### Site Table

<table>
<thead>
<tr>
<th>Site</th>
<th>Distance (km)</th>
<th># of cores</th>
<th>P(ther.) (GW)</th>
<th>Flux ($\bar{\nu}$ cm$^{-2}$ s$^{-1}$)</th>
<th>Signal ($\bar{\nu}$/yr)</th>
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<td>Japan</td>
<td></td>
<td></td>
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<tr>
<td>Kashiwazaki</td>
<td>160.0</td>
<td>7</td>
<td>24.6</td>
<td>4.25x10$^5$</td>
<td>348.1</td>
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<td>Ohi</td>
<td>179.5</td>
<td>4</td>
<td>13.7</td>
<td>1.88x10$^5$</td>
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<td>Takahama</td>
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<td>Genkai</td>
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<td>Sendai</td>
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<td>Tomari</td>
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<td>5.3</td>
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<td>Ulchinn</td>
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<td>~940</td>
<td>6</td>
<td>16.8</td>
<td>8.4x10$^3$</td>
<td>6.9</td>
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<tr>
<td>Kori</td>
<td>~700</td>
<td>4</td>
<td>8.9</td>
<td>8.0x10$^3$</td>
<td>6.6</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>69</strong></td>
<td><strong>175.7</strong></td>
<td><strong>1.34x10^6</strong></td>
<td><strong>1102</strong></td>
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</tr>
</tbody>
</table>

### Neutrino Flux at KamLAND

![Neutrino Flux at KamLAND](image-url)
The total electric power produced “as a by-product” of the vs is:

• ∼60 GW or...
• ∼4% of the world’s manmade power or...
• ∼20% of the world’s nuclear power

Total expected signal from reactors in 1 kton:

≈2 ev/day

Expected S/N ratio ≈ 20
@ 10^{-14} U, Th, ^{40}K contamination in the scintillator
Power flux at KamLAND (10^{-6} W/cm^2)

Time after Apr 1993 (month)

Since reactors produce $\bar{\nu}_e$ while the sun produces $\nu_e$, the equivalence of solar neutrino oscillations with what can be observed with the KamLAND reactor experiment rests on the validity of CPT.

An unexpected oscillation pattern in KamLAND could be an indication of CPT violation.
KamLAND: neutrino physics on a shinkansen

- Summer 2000: PMT installation
- Winter 2000-01: Veto counter installation
- Feb 2001: Balloon insertion
- Mar-Apr 2001: Balloon inflation and test
- Apr-May 2001: Plumbing for fill
- Jun-Sept 2001: Fill MO and LS
- Sept 2001: FEE/DAQ/Trigger int. (LBL)
- end Sept 2001: First data taking with FEE
- Jan 22, 2002: Begin Data Taking
- Dec 6, 2002: First Physics Paper (hep-ex/0212021)

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KamLAND: Evidence for Neutrino Oscillations
Cleaning the KamLAND sphere (Summer 2000)
Installing 17" and 20" PMTs in KamLAND (Summer 2000)
The completed detector, looking up
Scintillator is a blend of 20% pseudocumene and 80% dodecane

Different density paraffines are used to tune the density of buffer to 0.995 of that of the scintillator

PPO concentration is 1.5 g/l of the final scint.

During blending the liquids are pre-purified.
KamLAND Event Display
Run/Subrun/Event: 110/0/1907
UT: Sat Feb 23 15:16:54 2002
TimeStamp: 3416793063
TriggerType: 0x7210 / 0x2
Time Difference: 10.1 msec
NumHit/Nsum/Nsum2/NumHitA: 1315/199/1327/77
Total Charge: 9.02e+05 (1.17e+03)
Max Charge (ch): 3.54e+03 (210)

through-going muon

color is pulseheight

all tubes illuminated
KamLAND Event Display
Run/Subrun/Event : 110/0/19244
UT: Sat Feb 23 15:25:11 2002
TimeStamp : 13052924536
TriggerType : 0x3a10 / 0x2
Time Difference 28.3 msec
NumHit/Nsum/Nsum2/NumHitA : 1317/264/1322/46
Total Charge : 3.21e+05 (465)
Max Charge (ch): 2.22e+03 (640)
KamLAND Event Display
Run/Subrun/Event: 110/0/91185
UT: Sat Feb 23 15:57:50 2002
TimeStamp: 53000002993
TriggerType: 0xb00 / 0x2
Time Difference: 925 nsec
NumHit/Nsum/Nsum2/NumHitA: 585/466/1071/0
Total Charge: 4.12e+03 (0)
Max Charge (ch): 38.7 (210)

...decaying into a Michel electron
Corner-clipper muon:

Cherenkov ring in the buffer but no scintillation activity
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KamLAND: Evidence for Neutrino Oscillations

Anti-Neutrino Candidate

Prompt Signal

$E = 3.20$ MeV

$\Delta t = 111$ $\mu$s

$\Delta R = 34$ cm

Delayed Signal

$E = 2.22$ MeV
The data set

Used for this analysis:
Mar 4 – Oct 6, 2002
Total 145.1 days

370 M triggers
Triggering KamLAND

- Single ch. ATWD threshold 1/3 p.e. (0.5 mV)
- Correlated (antineutrino):
  - prompt \( > \sim 0.7 \text{MeV} \)
  - del’d (1 ms) \( \sim 0.4 \text{ MeV} \)
- Prescaled singles \( > \sim 0.4 \text{ MeV} \)
- Trigger data readout for all singles \( > \sim 0.4 \text{ MeV} \)
- (Supernova “burst trigger”)

*Approximate energy, exact energy value depends on location in the detector
The position of an energy deposit is found by time of arrival of light to the different PMTs.

Timing calibration was done using a dye laser (\(\lambda = 500\) nm)

- single p.e. events before
- and after correction

\[\sigma = 1.98\text{ ns}\]
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KamLAND: Evidence for Neutrino Oscillations

Position Reconstruction Uncertainty Along the Vertical Axis

\[ ^{68}\text{Ge} : 1.012 \text{ MeV (}\gamma + \gamma\text{)} \quad ^{65}\text{Zn} : 1.116 \text{ MeV (}\gamma\text{)} \]
\[ ^{60}\text{Co} : 2.506 \text{ MeV (}\gamma + \gamma\text{)} \quad \text{AmBe : 2.20, 4.40, 7.6 MeV (}\gamma\text{)} \]
$\Delta E/E \approx 7.5\% / \sqrt{E}$, Light Yield: 260 p.e./MeV
Autoradiography of KamLAND

$^{238}\text{U} : ^{214}\text{Bi} \to ^{214}\text{Po} \to ^{210}\text{Pb}$

$\beta + \gamma$
$E = 3.27 \text{ MeV}$
$\tau = 28.7 \text{ min.}$

$\alpha$
$E = 7.69 \text{ MeV}$
$\tau = 237 \mu\text{s}$

Top flange and chimney region
Central thermometer
Balloon
Bottom flange and plumbing

$^{214}\text{Bi Vertex Distribution}$
Correlations can be used to quantitatively measure scintillator contaminations:

\[
\text{Correlations can be used to quantitatively measure scintillator contaminations:}
\]

\[
\text{214Bi - 214Po - 210Pb Signal}
\]

\[
\begin{align*}
\text{prompt} & \quad \beta + \gamma \\
\text{delayed} & \quad \alpha
\end{align*}
\]

\[
\Delta T = |t_{\text{prompt}} - t_{\text{delayed}}|
\]

\[
\tau = 222.7 \pm 7.4 \mu s
\]

\[
\tau (\text{214Po:} \alpha) = 237 \mu s
\]

\[
\text{238U} = (3.5 \pm 0.5) \times 10^{-18} \text{ g/g}
\]
KamLAND is probably the lowest radioactivity environment on Earth!
μ-Induced Neutrons & Spallation-$^{12}\text{B}/^{12}\text{N}$
are both a background and a calibration source

yellow: after muon 150usec~10msec
red: apply dL<=3m cut

np-capture(2.22MeV)
nC-capture(4.95MeV)

visible energy [MeV]
In particular neutrons & $^{12}$B/$^{12}$N are the best tool to establish the fiducial volume

$$R_{fid} = 6.5 \text{ m}$$
$$R_{fid} = 5 \text{ m}$$
$$\Delta V_{fid}/V_{fid} = 4.6\%$$

Fiducial mass 408 ton (out of 1000)
Selecting anti-neutrinos

- $0.5 \mu s < \Delta T_{e-n} < 660 \mu s$
- $\Delta R_{e-n} < 1.6 m$
- $1.8 \text{ MeV} < E_n < 2.6 \text{ MeV}$

Tagging efficiency 78.3%

- $R < 5 \text{ m}$
- thermometer cut $[x^2+y^2>(1.2m)^2]$ 3.46x10^{31} free protons

- $E_e > 2.6 \text{ MeV}$

- 2 s veto for showering $\mu$ $(E>3\text{GeV})$
- 2 s veto in a $R = 3 \text{ m}$ tube along all $\mu$

Dead-time 11.4%
All cuts applied BUT the one on delayed energy

$\gamma$ from $n^{12}C$

delayed energy window

Prompt Energy (MeV)

Delayed Energy (MeV)
## Estimated Systematic Uncertainties

<table>
<thead>
<tr>
<th>Parameter</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total LS mass</td>
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<tr>
<td>Fiducial mass ratio</td>
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<td>Energy threshold</td>
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<td>Selection cuts</td>
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<td>Live time</td>
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<td>Reactor power</td>
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<td>Fuel composition</td>
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<td>Time lag</td>
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<td>$\nu_e$ spectra</td>
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<tr>
<td>Cross section</td>
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Total systematic error 6.4 %
Time Dependence of Reactor Power and Signals

2002

Number of events

Thermal power flux (MW/cm²)

Mar  Apr  May  Jun  Jul  Aug  Sep

0  5  10  15  20  25

0  0.05  0.1  0.15  0.2  0.25  0.3  0.35  0.4

x10^{-10}
### Observed Event Rates with $E_{\text{prompt}} > 2.6$ MeV

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>Data</strong></td>
<td>54 events</td>
</tr>
<tr>
<td><strong>Expected</strong></td>
<td>86.8 ± 5.6 events</td>
</tr>
<tr>
<td><strong>Total Background</strong></td>
<td>0.95 ± 0.99 events</td>
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</table>

- **accidental**: $0.0086 ± 0.0005$
- **$^9\text{Li}/^8\text{He}$**: $0.94 ± 0.85$
- **fast neutron**: $< 0.5$
Evidence for Reactor $\bar{\nu}_e$ Disappearance

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

Inconsistent with $1/R^2$ flux dependence at 99.95 % C.L. for $E_\nu > 3.4$ MeV
After 30 years of work reactor neutrinos finally are unmasked!
December 2002

KamLAND: Evidence for Neutrino Oscillations

Events/0.425 MeV

2.6 MeV (analysis)

- KamLAND data
- no oscillation
- best-fit oscillation

\[ \sin^2 2\theta = 1.0 \]
\[ \Delta m^2 = 6.9 \times 10^{-5} \text{ eV}^2 \]

Almost background free measurement!

Shape prefers deformation

...but...

Scaled no-osc. shape compat. at 53% CL

\[ \rightarrow \text{need more data for this} \]
Fit to Oscillations for $E_{\text{prompt}} > 2.6$ MeV

Best fit:

$\Delta m^2 = 6.9 \times 10^{-5}$ eV$^2$

$\sin^2 2\theta = 1.0$
A number (5 as of this morning) of phenomenological papers have appeared on the LANL server even before our preprint.
December 2002
KamLAND: Evidence for Neutrino Oscillations

Almost background free measurement!

Shape prefers deformation

...but...

Scaled no-osc. shape compat. at 53% CL
→ need more data for this
Fix background but float geo-neutrinos in the fit

Best fit:
\[ \Delta m^2 = 6.9 \times 10^{-5} \text{ eV}^2 \]
\[ \sin^2 2\theta = 0.91 \]

Resulting geo-neutrinos
4 events for \(^{238}\text{U}\)
5 events for \(^{232}\text{Th}\)
...still compatible with all sensible geophysical models at 95% CL
Conclusions:

KamLAND observes a >4 sigma deficit of reactor anti-neutrinos

Assuming that CPT is conserved the interpretation of this result in terms of oscillations is smack in the middle of the LMA-MSW solution:

The solar neutrino puzzle is now completely understood: we can reproduce it on Earth!

We can move on and use neutrinos to do solar physics!

More precision data on oscillation and many other phenomena is on the way... stay tuned!