SOLAR NEUTRINOS
Solar neutrinos

**The pp-chain**

- $p+p \rightarrow d + e^+ + \nu_e$
  - 99.75%
- $p + e^+ + p \rightarrow d + \nu_e$
  - 0.25%

$D + p \rightarrow ^3\text{He} + \gamma$

$^3\text{He} + ^3\text{He} \rightarrow ^4\text{He} + 2p$

$3^{\text{He}} + 4^{\text{He}} \rightarrow 7^{\text{Be}} + \gamma$

$3^{\text{He}} + p \rightarrow 4^{\text{He}} + e^+ + \nu_e$

$e^- + 7^{\text{Be}} \rightarrow 7\text{Li} + \nu_e$

$p + 7\text{Li} \rightarrow 2^{4}\text{He}$

$8^{\text{B}} \rightarrow 8^{\text{Be}} + e^+ + \nu_e$

Solar spectrum

Nuclear burning in the sun produce Heat, Luminosity and Neutrinos

- **pp neutrinos** < 0.4 MeV
- **Beryllium neutrinos** 0.86 MeV
  - Monochromatic since 2 body decay
  - 2 keV width due to sun temperature
- **Boron neutrinos** < 15 MeV
- **Standard Solar Model (SSM)**
How many?

- **Basic reaction:**
  \[ 4p \rightarrow \text{He}^4 + 2e^+ + 2\nu_e \]

- The \(2e^+\) annihilate with \(2e^-\) producing PHOTONS
  --> Electromagnetic energy.

- **How much?**  
  \[ Q = 4m_p - M_{\text{He}} - E(2\nu_e) \approx 26.1 \text{ MeV} \]

- **Sun luminosity:**  
  \[ L_0 = 3.846 \times 10^{26} \text{ W} = 2.4 \times 10^{39} \text{ MeV.s}^{-1} \]

- **Rate of neutrino emission:**  
  \[ 2 \times (L_0/Q) = 1.8 \times 10^{38} \text{ s}^{-1} \]

- **Flux on Earth** at \(1.5 \times 10^8\) km:  
  \[ 6.4 \times 10^{10} \text{ cm}^{-2} \text{ s}^{-1} \]
How fast?

- **How fast do they reach us:** \( \frac{(1.5 \times 10^8 \text{km})}{(3 \times 10^5 \text{km.s}^{-1})} = 500 \text{ secs.} \)

- **Where do they come from?**
  - Mostly from the core of the sun.

  ![Graph showing Neutrino Production](image)

  \( R_0 = 700 \text{ 000 km} \)

  That’s where most of the photons are also produced.

  But because of repeated interactions they take

  **1 million years to exit and reach us!**
How do we detect them?

Two methods:

- **Radiochemical:** Use a capture reaction in a large detector mass

  \[ \nu_e + (A,Z) \rightarrow e^- + (A,Z+1) \]

  Every few weeks collect the \( A(Z+1) \) produced.

- **Real - time:**

  Observe a solar neutrino interaction electronically as it happens.
HOW DO WE DETECT THEM?

TWO ways to detect them: RADIOCHEMICAL and REAL TIME.

RADIOCHEMICAL

- Use capture reaction

  \[ \nu_e + (A, Z) \rightarrow e^- + (A, Z + 1) \]

- Chemically extract the few atoms of \((A, Z + 1)\) produced and mix with a gas. Only \(\sim 1\) ATOM/DAY is produced!

<table>
<thead>
<tr>
<th>Location</th>
<th>HOMESTAKE</th>
<th>GALLEX</th>
<th>SAGE</th>
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</thead>
<tbody>
<tr>
<td>Material</td>
<td>(C_2\text{Cl}_4)</td>
<td>Gallium (Solution)</td>
<td>Gallium (Metallic)</td>
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<tr>
<td>Initial Isotope</td>
<td>(^{37}\text{Cl})</td>
<td>(^{71}\text{Ga})</td>
<td>(^{71}\text{Ga})</td>
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<tr>
<td>Detected Isotope</td>
<td>(^{37}\text{Ar})</td>
<td>(^{71}\text{Ge})</td>
<td>(^{71}\text{Ge})</td>
</tr>
<tr>
<td>Mass (tonnes)</td>
<td>615.0</td>
<td>30.3</td>
<td>57.0</td>
</tr>
<tr>
<td>Threshold</td>
<td>0.814 MeV</td>
<td>0.233 MeV</td>
<td>0.233 MeV</td>
</tr>
</tbody>
</table>

Be, B  pp, Be, B
Gallex

Calibration source

$^{51}$Cr

$\text{GaCl}_3 + \text{HCl}$

(54 m$^3$, 110 t)

$\text{N}_2$

$\text{N}_2 + \text{GeCl}_4$

$\text{H}_2\text{O}$

$\text{N}_2$

$\text{H}_2\text{O} + \text{GeCl}_4$
Extraction

- Chemically extract the few atoms of \((A,Z+1)\) produced.
- Mix with a gas.
- Fill proportional tubes with gas.
- Detect **X-rays** produced through the capture reaction
  \[
  e^- + (A,Z+1) \rightarrow (A,Z) + \nu_e
  \]
- Count how many atoms are present
- Even with ~ tons of detector mass
- ~ 1 ATOM/DAY
Solar Neutrino Unit (SNU): 1 capture/ $10^{36}$ nuclei
Real time detection

Detect them event by event as they occur
Electronic means

SuperKamiokande (same detector as for atmospheric neutrinos)
Water ($\text{H}_2\text{O}$)

Sudbury Neutrino Observatory (SNO)
Heavy water ($\text{D}_2\text{O}$)
ν Scattering in water

Can occur either on **electrons**    Or    on **nucleons**

Elastic scattering on electrons (ES)
$$\nu + e \rightarrow \nu + e$$
Can occur through:

- **Charged Current**
  - Sensitive to $$\phi(\nu_e)$$ only
  - (Not enough energy to produce a muon or a tau)

- **Neutral Current**
  - Sensitive to flux from all flavours, $$\phi(\nu_e, \nu_\mu, \nu_\tau)$$

But $$\sigma_e / \sigma_{\mu\tau} = 0.154$$ for ES

Result: **ES 6 times more likely for $$\nu_e$$ as for $$\nu_\mu, \nu_\tau$$**
Scattering on Heavy water

How about scattering on nucleons?

- **Charged Current (CC) reactions on nucleons**
  \[ \nu_e + n \rightarrow p + e^- \]  
  At quark level \[ \nu_e + d \rightarrow u + e^- \]
  Sensitive ONLY to \( \phi(\nu_e) \), the flux of \( \nu_e \)
  Not enough energy to produce a muon or a tau

- **Neutral Current (NC) reactions on nucleons**
  \[ \nu_x + n \rightarrow n + \nu_x \]
  Sensitive to flux from ALL flavours, \( \phi(\nu_e, \nu_\mu, \nu_\tau) \)

In WATER, neutrons only in oxygen.
To break up the oxygen atom requires **15 MeV**: Not available.
These reactions energetically impossible: they do **NOT** occur.
But if we replace water by HEAVY WATER: \( D_2O \),
Then it only takes **2.2 MeV** to break up the deuteron. **Possible.**
Very important: it provides a reaction (NC) that is sensitive to **ALL flavours**
Reconstruction

- Threshold \( \sim 5 \text{ MeV} \): sensitive to Boron \( \nu \)'s only.

- From the time of arrival of the pulses at the phototubes the direction of the electron can be deduced.

- The electron direction is related to the neutrino direction.

- Can confirm that they come from the sun.
SK-I: $^8$B Solar Neutrino Flux
(Scattering on electrons in water)

$^8$B flux = $2.35 \pm 0.02 \pm 0.08 \times 10^6$/cm$^2$/s

Data / SSM$_{BP2004}$ = $0.406 \pm 0.004$ (stat.) $+0.014 -0.013$ (syst.)

Data / SSM$_{BP2000}$ = $0.465 \pm 0.005$ (stat.) $+0.016 -0.015$ (syst.)
Solar $\nu$ energy spectrum

- Standard solar model
- SK data
A (SK) neutrino picture of the sun!

Taken underground.....
Suppression relative to Standard Solar Model

Suppression relative to Standard Solar Model is observed in all experiments.

Is it due to a misunderstanding as to how the sun “works”? Standard solar model. Or are the neutrinos “disappearing”? Why is the suppression not the same at all energies?

Largest suppression seems to be at Be ν: 0.865 MeV
How many Be neutrinos?

**Suppressions**
- $x_{pp} = pp \nu$’s suppression
- $x_{Be} = $ Beryllium $\nu$’s suppression
- $x_B = $ Boron $\nu$’s suppression

3 equations and 3 unknowns:

- $69.6 \times x_{pp} + 34.4 \times x_{Be} + 12.4 \times x_b + 12.6 = 68.0 \text{ SNU}$
- $1.2 \times x_{Be} + 5.9 \times x_b + 0.6 = 2.60 \text{ SNU}$
- $1.0 \times x_b = 0.48 \text{ SNU}$

- $x_{pp} = 1.07$
- $x_{Be} = -0.73 \quad \text{No Beryllium!}$
- $x_b = 0.47$
But Boron, which gives Boron $\nu$’s, is produced by the very Reaction that produces Be $\nu$’s. So how can Be $\nu$’s be suppressed MORE than the Boron $\nu$’s?
Is there Beryllium in the sun?

Helioseismology

- **Study of MOTION and BRIGHTNESS variations** in the SURFACE of the sun

- **MOTION** is measured by Doppler shifts of spectral lines.
- Can measure velocities to 15 cm. s\(^{-1}\).
  Corresponding to 10\(^{-4}\) of the spectral line width.
- Deduce INTERNAL STRUCTURE and ROTATION.
- Analyse Doppler and Intensity images.
- Fourier analyse amplitudes as a function of TIME.
- Each Fourier component corresponds to a TYPE of wave.
- Each TYPE of wave penetrates to a CHARACTERISTICS radius.
- Frequency of oscillation affected by SOUND speed in material it traverses.
- Deduce SPEED as a function of radius.
- Deduce MATERIAL composition.
- Compare to MODELS
Solar Modes
Helioseismology results

Be lowered by 1σ.

Lowering the Be content of the sun enough to explain the lack of Be ν’s would result in big effects on Helioseismology which are NOT observed.

Very good agreement between data and Standard Solar Model predictions.
Gallex chrome source calibration

If the Be is in the sun, are we sensitive to Be ν’s?
SAGE and GALLEX check their detectors by irradiating them with a Radioactive chromium source that emits neutrinos of the same energy as the Beryllium neutrinos of the sun.

\(^7\text{Be}: 90\% \text{ at } 0.86 \text{ MeV} \ldots 10\% \text{ at } 0.38 \text{ MeV}
\(^{51}\text{Cr} 90\% \text{ at } 0.75 \text{ MeV} \ldots 10\% \text{ at } 0.43 \text{ MeV}

Extract in same way as for solar exposure
Calculate rate from cross section calculation and known activity of source

Measured rate / Expected rate:

- GALLEX = 0.93 ± 0.07
- SAGE = 0.97 ± 0.12

Lack of Beryllium neutrinos not due to problems with detector.
Sudbury Neutrino Observatory (SNO)

- 1000 tons of heavy water ($\text{D}_2\text{O}$)
- In sphere 12m in diameter
- 9438 photomultipliers
- 2039m below surface to reduce cosmic ray flux (70 muons/day)
SNO Detection reactions

Neutral current reaction

Charged current reaction
SNO flux formulae

\[ \Phi_{ES} = \Phi_e + 0.154 \Phi_{\mu\tau} \]

\[ \Phi_{NC} = \Phi_e + \Phi_{\mu\tau} \]

\[ \Phi_{CC} = \Phi_e \]

\[ \Phi_{\mu\tau} = \Phi_\mu + \Phi_\tau \]
SNO (Heavy water): Sensitive to CC, NC, ES. Calculate flux from each.

$\Phi_{CC} = 1.68^{+0.06}_{-0.06} (stat.)^{+0.08}_{-0.09} (sys.) \times 10^6 \text{ cm}^{-2} \text{s}^{-1}$  \[\nu_e\text{ only}\]

$\Phi_{ES} = 2.35^{+0.22}_{-0.22} (stat.)^{+0.15}_{-0.15} (sys.) \times 10^6 \text{ cm}^{-2} \text{s}^{-1}$  \[\nu_e\text{ mostly}\]

$\Phi_{NC} = 4.94^{+0.21}_{-0.21} (stat.)^{+0.38}_{-0.34} (sys.) \times 10^6 \text{ cm}^{-2} \text{s}^{-1}$  \[\nu_e, \nu_\mu, \nu_\tau\]

$\Phi_{BP04} = 5.82 \pm 1.34 \times 10^6 \text{ cm}^{-2} \text{s}^{-1}$

Using ALL neutrinos
Fully Consistent with Standard Solar Model

Flavor content of solar flux.

Neutrinos DO NOT disappear. They just Change Flavour!
How do we explain their metamorphosis?

Are they oscillating between the Sun and the Earth in vacuum? If so 2 possibilities:

- We are at the first or second maximum of oscillations: **JUST SO**.
  But then since this is just **so precisely** the distance to observe an oscillation, the effect should change as a function of the month. Due to the 3% eccentricity of the Earth orbit.

**It does**. But just enough to account for the reduced detector solid angle ($1/R^2$).

**No extra oscillation effect**
How do we explain their metamorphosis?

Are they oscillating between the Sun and the Earth?

Other possibility:

- We are far into the oscillation, but then for a large number of oscillations to have occurred, the oscillation length must be small. Smaller than the diameter of the Sun (1.4 x 10^6 km).

So depending on where the neutrinos have been produced in the Sun, we can be at either a **MAXIMUM** or a **MINIMUM**.

The effect just averages over the Δm^2 term

\[
P_{\alpha\beta}(t) = \sin^2 2\theta \sin^2 1.27 \frac{L(m)}{E(\text{MeV})} \Delta m^2 (\text{eV}^2)
\]

To \(1/2\) sin^2 2\(\theta\)

Independent of energy. Unlike what we see.
Matter effects: Mikheyev-Smirnov-Wolfenstein

At low energy, only elastic processes important: Inelastic can be neglected.

In forward scattering:

\[ V \text{W} = \sqrt{2} G_F N_e \quad N_e = \text{density of electrons in matter} \]

\[ V \text{W} = -\sqrt{2} G_F N_e \quad \text{for antineutrinos. Changes sign.} \]
Matter effects

Since the extra potential is JUST for $\nu_e$’s we have to work in FLAVOUR basis and not MASS

\[
H_M = H_{vac} + \mathbf{V}_w \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \nu_e \nu_\mu + \mathbf{V}_z \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \nu_e \nu_\mu
\]

\[
H_M = H_{vac} + \frac{\mathbf{V}_w}{2} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} + \frac{\mathbf{V}_w}{2} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}
\]

\[
H_M = \frac{\Delta m^2}{4E} \begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix} + \frac{\mathbf{V}_w}{2} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}
\]
Vacuum oscillations in Flavour basis

**Derivation of** $H_{\text{vac}}$

\[
\frac{i}{\text{d}t} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} = \begin{pmatrix} E_1 & 0 \\ 0 & E_2 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} + \begin{pmatrix} m_1^2/2p & 0 \\ 0 & m_2^2/2p \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}
\]

\[
\frac{i}{\text{d}t} \begin{pmatrix} \nu_e \cos \theta - \nu_\mu \sin \theta \\ \nu_e \sin \theta + \nu_\mu \cos \theta \end{pmatrix} = \begin{pmatrix} m_1^2/2p & 0 \\ 0 & m_2^2/2p \end{pmatrix} \begin{pmatrix} \nu_e \cos \theta - \nu_\mu \sin \theta \\ \nu_e \sin \theta + \nu_\mu \cos \theta \end{pmatrix}
\]

\[
\frac{i}{\text{d}t} (\nu_e \cos \theta - \nu_\mu \sin \theta) = \frac{m_1^2}{2p} (\nu_e \cos \theta - \nu_\mu \sin \theta) \quad \text{(A)}
\]

\[
\frac{i}{\text{d}t} (\nu_e \sin \theta + \nu_\mu \cos \theta) = \frac{m_2^2}{2p} (\nu_e \sin \theta + \nu_\mu \cos \theta) \quad \text{(B)}
\]

**A** $\times \cos \theta + **B**$ $\times \sin \theta \quad \text{and} \quad **B** \times \cos \theta - **A** \times \sin \theta
Flavour basis II

\[ A \times \cos \theta + B \times \sin \theta \]

\[ \begin{align*}
    i \frac{d}{dt} (\nu_e) &= \left[ \frac{\Delta m^2}{4p} (-\cos 2\theta) + \frac{m_1^2 + m_2^2}{4p} \right] \nu_e - \frac{\Delta m^2}{4p} \sin 2\theta \nu_\mu \\
    i \frac{d}{dt} (\nu_\mu) &= \frac{\Delta m^2}{4p} (\sin 2\theta) \nu_e + \left[ \frac{\Delta m^2}{4p} \cos 2\theta + \frac{m_1^2 + m_2^2}{4p} \right] \nu_\mu \\
    i \frac{d}{dt} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} &= \left[ \frac{m_1^2 + m_2^2}{4p} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \frac{\Delta m^2}{4p} \begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix} \right] \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}
\end{align*} \]

Neglect Unity matrix term and \( p \sim E \)
Matter effects

\[ H_M = H_{\text{vac}} + V_w \left( \begin{array}{cc} 1 & 0 \\ 0 & 0 \end{array} \right) \nu_e + V_z \left( \begin{array}{cc} 1 & 0 \\ 0 & 1 \end{array} \right) \nu_\mu \]

\[ H_M = H_{\text{vac}} + \frac{V_w}{2} \left( \begin{array}{cc} 1 & 0 \\ 0 & -1 \end{array} \right) \]

\[ H_M = \frac{\Delta m^2}{4E} \left( \begin{array}{cc} \cos2\theta & \sin2\theta \\ \sin2\theta & \cos2\theta \end{array} \right) + \frac{V_w}{2} \left( \begin{array}{cc} 1 & 0 \\ 0 & -1 \end{array} \right) \]

\[ V_w = \sqrt{2} \ G_F \ N_e \quad N_e = \text{density of electrons in matter} \]
\[ V_w = -\sqrt{2} \ G_F \ N_e \quad \text{for antineutrinos. Changes sign.} \]
Matter effects

\[ x = \frac{V_W/2}{\Delta m^2/4E} = \frac{2\sqrt{2}G_F N_e E}{\Delta m^2} \]

\[ H_M = \frac{\Delta m^2}{4E} \begin{pmatrix} -(\cos 2\theta - x) & \sin 2\theta \\ \sin 2\theta & \cos 2\theta - x \end{pmatrix} \]

Defining:

\[ \cos 2\theta_M = \frac{-(\cos 2\theta - x)}{\sqrt{(\cos 2\theta - x)^2 + \sin^2 2\theta}} \quad \sin 2\theta_M = \frac{\sin 2\theta}{\sqrt{(\cos 2\theta - x)^2 + \sin^2 2\theta}} \]

\[ H_M = \frac{\Delta m^2}{4E} \begin{pmatrix} -\cos 2\theta_M & \sin 2\theta_M \\ \sin 2\theta_M & \cos 2\theta_M \end{pmatrix} \]

with:

\[ \Delta m^2_M = \Delta m^2 \sqrt{(\cos 2\theta - x)^2 + \sin^2 2\theta} \]

Same structure as in vacuum with \( \theta \longrightarrow \theta_M, \Delta m^2 \longrightarrow \Delta m^2_M \)
Oscillations in matter MSW

\[ |\nu_e> = \cos \theta_m |\nu_1> + \sin \theta_m |\nu_2> \quad \text{and} \quad |\nu_\mu> = -\sin \theta_m |\nu_1> + \cos \theta_m |\nu_2> \]

\[ |\nu_1> = \cos \theta_m |\nu_e> - \sin \theta_m |\nu_\mu> \quad \text{and} \quad |\nu_2> = \sin \theta_m |\nu_e> + \cos \theta_m |\nu_\mu> \]
Consequences (Earth)

- Travelling through the earth, away from the very dense core, the density is constant.

- The oscillation probability is just modified to use $\theta_M$

  $$P_{\alpha\beta}(t) = \sin^2 2\theta_M \sin^2 1.27 \frac{L(m)}{E(MeV)} \Delta m_M^2 (eV^2)$$

$V_W$ changes sign for antineutrinos: $x$ changes sign $\rightarrow \theta_M \neq \theta_M$

Matter effects introduce an asymmetry between neutrinos and antineutrinos.

But NOT related to CP violation.

When searching for CP violation this has to be taken into account.
Consequences (Earth)

- $V_W$ changes sign for antineutrinos: $x$ changes sign $\Rightarrow \theta_M \neq \theta_M$
- $x$ also changes sign when $\Delta m^2$ changes sign: with the mass hierarchy ($m_1^2$ smaller or larger than $m_2^2$?).
- $(\cos 2\theta - x)$ term is affected $\Rightarrow A$ is same as $x$
Consequences (Sun)

\[
\sin 2\theta_M = \frac{\sin 2\theta}{\sqrt{(\cos 2\theta - x)^2 + \sin^2 2\theta}}
\]

**IF** \( \cos 2\theta = x = (2\sqrt{2} \ G_F \ N_e \ E) / \Delta m^2 = 1.5 \times 10^{-13} \ (Z/A) \ E \rho \) then even if \( \theta \) (vacuum) is very small

\( \sin 2\theta_M = 1 \implies \theta_M = \pi/4 \implies \text{MAXIMAL mixing.} \)

Note: this condition depends on the **ENERGY** and the **MATTER DENSITY**.

Electron neutrinos of a **PARTICULAR** energy, can traverse a region of the sun with just the right density to be at resonance \( \implies \) oscillate to other type.

Explanation for the extra suppression of the Beryllium neutrinos?
Possible solutions

Based on flux of SK, Homestake, and Gallium experiments

Four possible solutions.

Flux independent analysis:

SK measured zenith angle dependence of solar flux:

Affected by matter in Earth.

Grey area disfavoured

JUST SO and most of SMA Excluded.

LMA and LOW left.
KamLAND

Detect neutrinos emitted by the Japanese power reactors in a detector located in the Kamioka mine at an average distance of 189km from the reactors.
What should they see?

\[ P_{\alpha\beta}(t) = \sin^2 2\theta_{\text{sol}} \sin^2 1.27 \frac{L(m)}{E(\text{MeV})} \Delta m^2 (\text{eV}^2) \]

\[ 1.27 \times (180 \times 1000 \text{m}) \times (8 \times 10^{-5} \text{eV}^2)/(-3\text{MeV}) = 3.9 \pi/2 \]

They should see an energy-averaged oscillation.
KamLAND detector

1 kton of liquid scintillator
Correlation with known reactor flux

They REALLY see reactor neutrinos
KamLAND results

Expectation for
No oscillation

Best fit for
oscillation

Definite suppression: first confirmation of solar disappearance with man-made neutrinos
Reactor results

KamLAND average suppression: first observation of reactor antineutrinos disappearance
KAMLAND: Oscillation fit.

KamLAND can do better than an average suppression:

Assume an average distance of 180km and plot L/E;

Clear oscillation pattern
Solar suppression confirmed by KAMLAND:

\[ \Delta m^2 = (7.9 \pm 0.4/-0.3) \times 10^{-5} \text{ ev}^2 \]
\[ \sin^2 \theta = 0.30 \pm 0.04/-0.025 \]

KamLAND + Solar
Completely consistent
LMA solution only one.
No HOLE at the beryllium neutrino energy: just a smooth suppression.
How do we explain this?
For the accepted solar solution:
\[ \cos 2\theta = 0.43 \] and \( (2\sqrt{2} G_F N_e E) \) is always smaller \( (1.5 \times 10^{-5} E) \)
even for the highest solar density and the highest Boron neutrino energy \( \sim 15 \text{ MeV} \).
So no resonance.
MSW

\[ H_M = H_{\text{vac}} + \mathbf{V}_W \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \nu_e + \mathbf{V}_Z \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \nu_\mu \]

\[ H_M = \frac{\Delta m^2_{\text{sol}}}{4E} \begin{pmatrix} -\cos 2\theta_{\text{sol}} & \sin 2\theta_{\text{sol}} \\ \sin 2\theta_{\text{sol}} & \cos 2\theta_{\text{sol}} \end{pmatrix} + \sqrt{2G_F N_e} \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \]

In the core of the sun \((\sqrt{2} G_F N_e E) = 0.75 \times 10^{-5} \text{ eV}^2/\text{MeV}\)

For the LMA and typical Boron energy \(\Delta m^2_{\text{sol}}/4E = 8 \times 10^{-5}/(4 \times 8 \text{ MeV}) = 0.25 \times 10^{-5}\)

So the interaction term dominates. \(\nu_e\) is an eigen state of \(H\). No off-diagonal terms.

\[ \sin 2\theta_M = \frac{\sin 2\theta}{\sqrt{(\cos 2\theta - x)^2 + \sin^2 2\theta}} \]

\[ x = (2\sqrt{2} G_F N_e E)/\Delta m^2 \text{ is large.} \]

\[ \sin 2\theta_M \sim 0 \quad 2\theta_M = \pi \]

\[ \theta_M = \pi/2 \quad \cos \theta_M = 0, \sin \theta_M = 1 \]

\[ |\nu_e\rangle = \cos \theta_m |\nu_1\rangle + \sin \theta_m |\nu_2\rangle = \text{Pure } |\nu_2\rangle \text{ state} \]
Oscillations in matter MSW: Boron $\nu$

- The $\nu_e$ is then in a pure $\nu_2$ state. $|\nu_e> = \cos \theta_m |\nu_1> + \sin \theta_m |\nu_2>$$$
- As it propagates out of the sun, the density drops.
- The density decreases slowly, adiabatically. This gives time to the $\nu_e$ to oscillate to $\nu_\mu$.
- The $\nu_\mu$ content increases.
- But at a decreased density, $\theta_m$ decreases and the description of a pure $\nu_2$ has an increased $\nu_\mu$ content. $|\nu_2> = \sin \theta_m |\nu_e> + \cos \theta_m |\nu_\mu>$

- So this increased $\nu_\mu$ content means a pure $\nu_2$ is retained all the way out of the sun.
- It remains a $\nu_2$ all the way to Earth.
- No oscillations possible: there is just ONE mass state, $\nu_2$ at the exit from the sun.
- Once it reaches the earth $\theta = \theta_v$ and the $\nu_2$ will interact according to

$$|\nu_2> = \sin \theta_{\text{vac}} |\nu_e> + \cos \theta_{\text{vac}} |\nu_\mu>$$

$$P(\text{to interact as a } \nu_e) = \sin^2 \theta_{\text{vac}}$$
pp $\nu$ Oscillations

For the pp neutrinos, the other end of the spectrum at $\sim 0.2$ MeV,

The vacuum term dominates.

The $\nu_e$ will oscillate away to $\nu_\mu$, $\nu_\tau$ with a probability governed by $\theta_{\text{vac}} = \theta_{\text{sol}}$.

$$P_{\alpha\beta}(t) = \sin^2 2\theta_{\text{sol}} \sin^2 1.27 \frac{L(m)}{E(\text{MeV})} \Delta m^2 (\text{eV}^2)$$

There will be about $10^7$ oscillations between the sun and the earth. A small change in energy or point of production in the sun, will change this number. And will change whether the $\nu$ will be a $\nu_e$ or have oscillated to a $\nu_\mu$, $\nu_\tau$.

So the probability that it will have oscillated will be just $(1/2) \sin^2 \theta_{\text{sol}}$

And the survival probability will be: $1 - (1/2) \sin^2 \theta_{\text{sol}}$
So what kind of oscillations are these?

- At low energy: just vacuum oscillations.
- AT high energy the interaction term dominates and we have a non-resonant MSW

Smooth variation between the two.

- So what about the increased suppression around the Be neutrinos? (the hole in the spectrum)
- Possibly a wrong measurement at Homestake.
- Be neutrinos will be measured by Borexino
TESTING

LMA
Borexino

• **PURPOSE:**
  
  - Investigate the region of the $^7\text{Be}$ (862 keV) line.
  - Was Homestake right?

• **METHOD:**
  
  - 300 tons of organic scintillator
  - Use scattering on electrons
  - $\nu + e \rightarrow \nu + e$
  - Measure electron energy spectrum
Borexino rates

- Must set very low threshold in event acceptance
- This is difficult because of radioactive contaminants such as $^{14}\text{C}$ in the scintillator.
- In 270-800 keV e-recoil energy window Expect
  - $75 \pm 4$ events / (day.100tons) if SSM right and no oscillations
  - $49 \pm 4$ if LMA.
- First results: $47 \pm 7\text{(stat)} \pm 12\text{(syst)}$

- KamLAND will also attempt to increase the purity of its scintillator to address the Be line solar neutrinos.
Boron spectrum distortion

- **SuperK** is working to reduce its threshold to be able to track the Boron spectrum down to 4 MeV.
- This should lead to a 10% reduction of the suppression
- From 0.4 to 0.45.

![Graph showing Boron spectrum distortion](image)
Summary and status
3-family oscillation matrix
(Pontecorvo, Maki, Nakagawa, Sakata)

\[ S = \sin \theta \quad c = \cos \theta \]

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= \begin{pmatrix}
c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{i\delta} \\
-s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{13}e^{-i\delta} \\
s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & c_{23}c_{13}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

- \( \delta \): CP violation phase.

- \( \theta_{12} \): drives SOLAR oscillations: \( \sin^2 \theta_{12} = 0.32 \pm 0.05 \) (\( \pm 16\% \))

- \( \theta_{23} \): drives ATMOSPHERIC oscillations: \( \sin^2 \theta_{23} = 0.50 \pm 0.13 \) (\( \pm 18\% \))

- \( \theta_{13} \): the MISSING link! \( \sin^2 \theta_{13} < 0.033 \) Set by a reactor experiment: CHOOZ.
Present status of the mixing matrix

The quark mixing matrix

- is mostly diagonal
- Has a definite hierarchy
- Is Symmetrical

Why is the neutrino matrix so different?

- Terms are of the same order
- Except for one
- No definite hierarchy
Angles and their meanings

- **sin² θ₁₃**: Amount of $ν_e$ in $ν_3$: $U_{e3}ν_e + U_{μ3}ν_μ + U_{τ3}ν_τ$

  $s_{13}e^{-iδ} ν_e + s_{23}c_{13}ν_μ + c_{23}c_{13}ν_τ \quad \longrightarrow \quad s_{13}^2$

- **tan² θ₁₂**: Ratio of $ν_e$ in $ν_2$ to $ν_e$ in $ν_1$ $|U_{e2}|^2/|U_{e1}|^2$

  $= s_{12}^2/c_{12}^2$ $0.32/0.68 < 1$ So more in $ν_1$

- **tan² θ₂₃**: Ratio $ν_μ$ to $ν_τ$ in $ν_3$. If $θ_{23}=π/4$ Maximal mixing equal amounts.
Mass hierarchy

Sign of $\Delta m^2_{23}$

Normal Hierarchy

$\Delta m_{23}^2 = 2.4 \times 10^{-3}$ eV$^2$

$\Delta m_{12}^2 = 7.6 \times 10^{-5}$ eV$^2$

Inverted Hierarchy

$\Delta m_{12}^2 = 7.6 \times 10^{-5}$ eV$^2$

$\Delta m_{23}^2 = 2.4 \times 10^{-3}$ eV$^2$

Oscillations only tell us about **Differences** in masses
Not the **Absolute** mass scale: Direct measurements or Double $\beta$ decay
Absolute $\nu$ Masses

**Normal Hierarchy**

$\nu_e$  $\nu_\mu$  $\nu_\tau$

$m_3$ [0.058]

$m_2$ [0.009]

$m_1$ [0.0]

**Inverted Hierarchy**

$\nu_e$  $\nu_\mu$  $\nu_\tau$

$m_2$ [0.050]

$m_1$ [0.049]

$m_3$ [0.0]

We DO have a **LOWER LIMIT** on at least one neutrino: $(2.4 \times 10^{-3})^{1/2} > 0.05$ eV
Every observation fits this scenario

EXCEPT……..