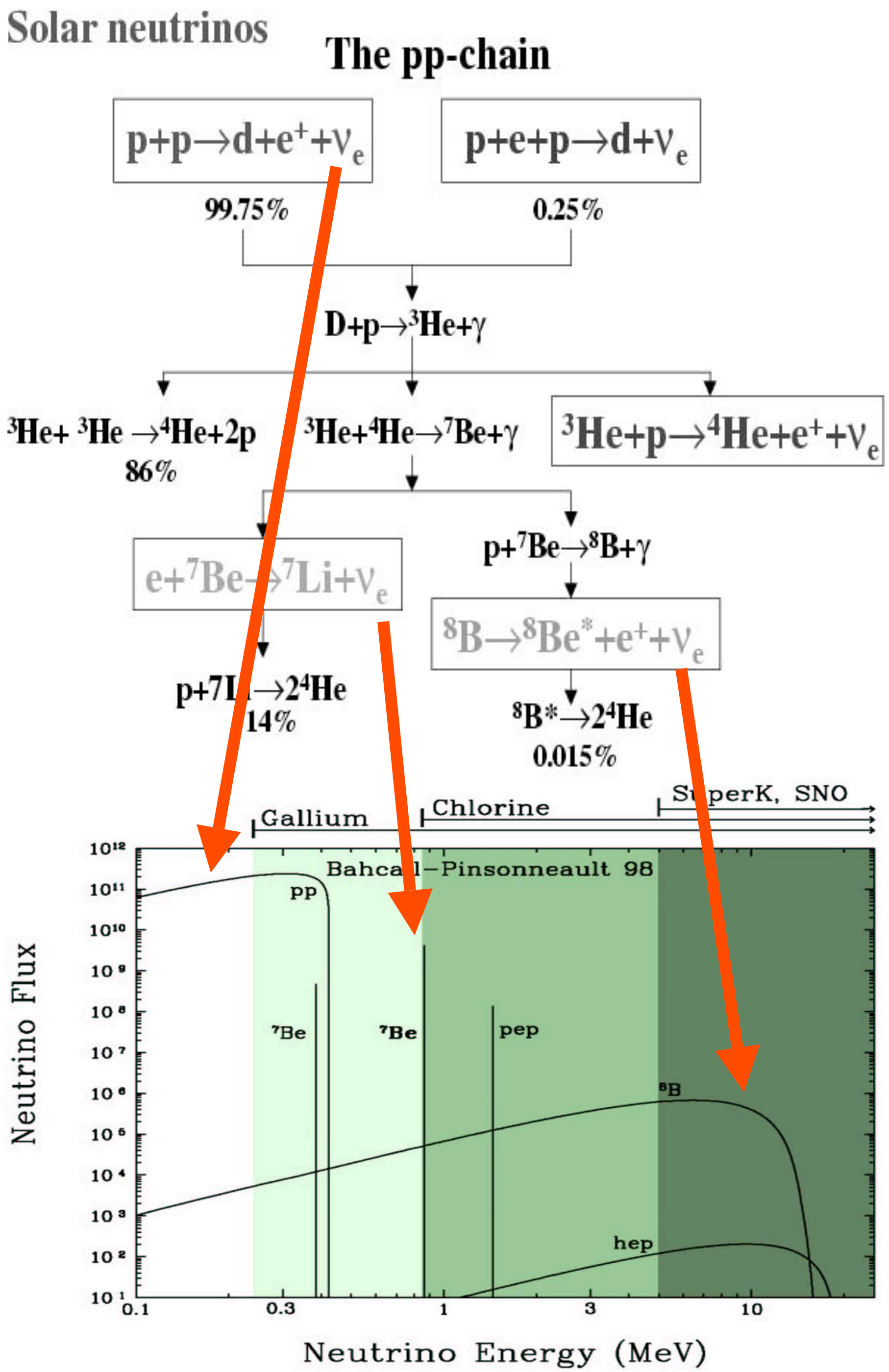
SOLAR NEUTRINOS



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:**

  $$4p \dashrightarrow He^4 + 2e^+ + 2\,\nu_e$$

- The $2e^+$ annihilate with 2 e^- producing PHOTONS

  --> Electromagnetic energy.

- **How much?** $Q = 4m_p - M_{He} - E(2\nu_e) \sim 26.1$ MeV

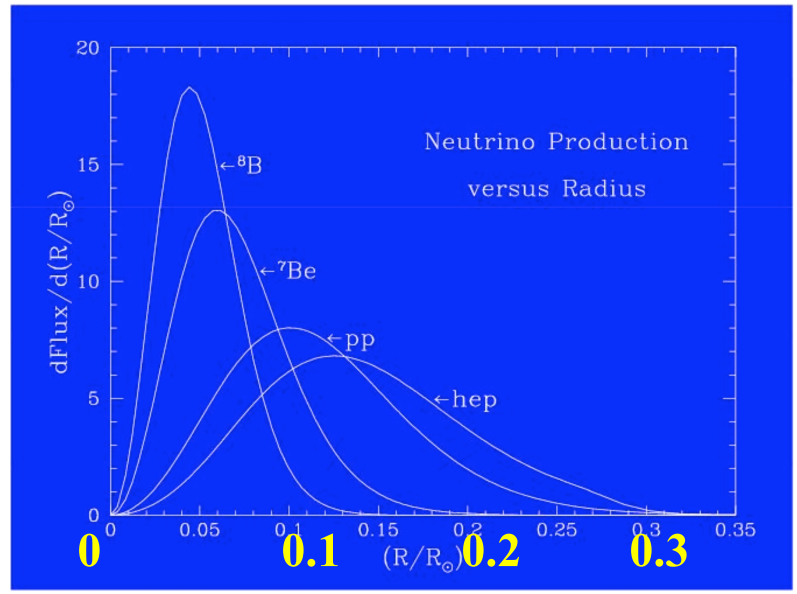
- **Sun luminosity**: $L_0 = 3.846 \times 10^{26}$ W $= 2.4 \times 10^{39}$ MeV.s^{-1}

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

- **Flux on Earth** at 1.5×10^8km: 6.4×10^{10} cm^{-2} s^{-1}

How fast?

- **How fast do they reach us:** $(1.5 \times 10^8 km)/(3 \times 10^5 km.s^{-1}) = 500$ secs.
- **Where do they come from?**



(R/R_0)

- Mostly from the core of the sun.

R_0 = 700 000km

- 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

  $$\nu_e + (A,Z) \dashrightarrow e^- + (A,Z+1)$$

  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

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

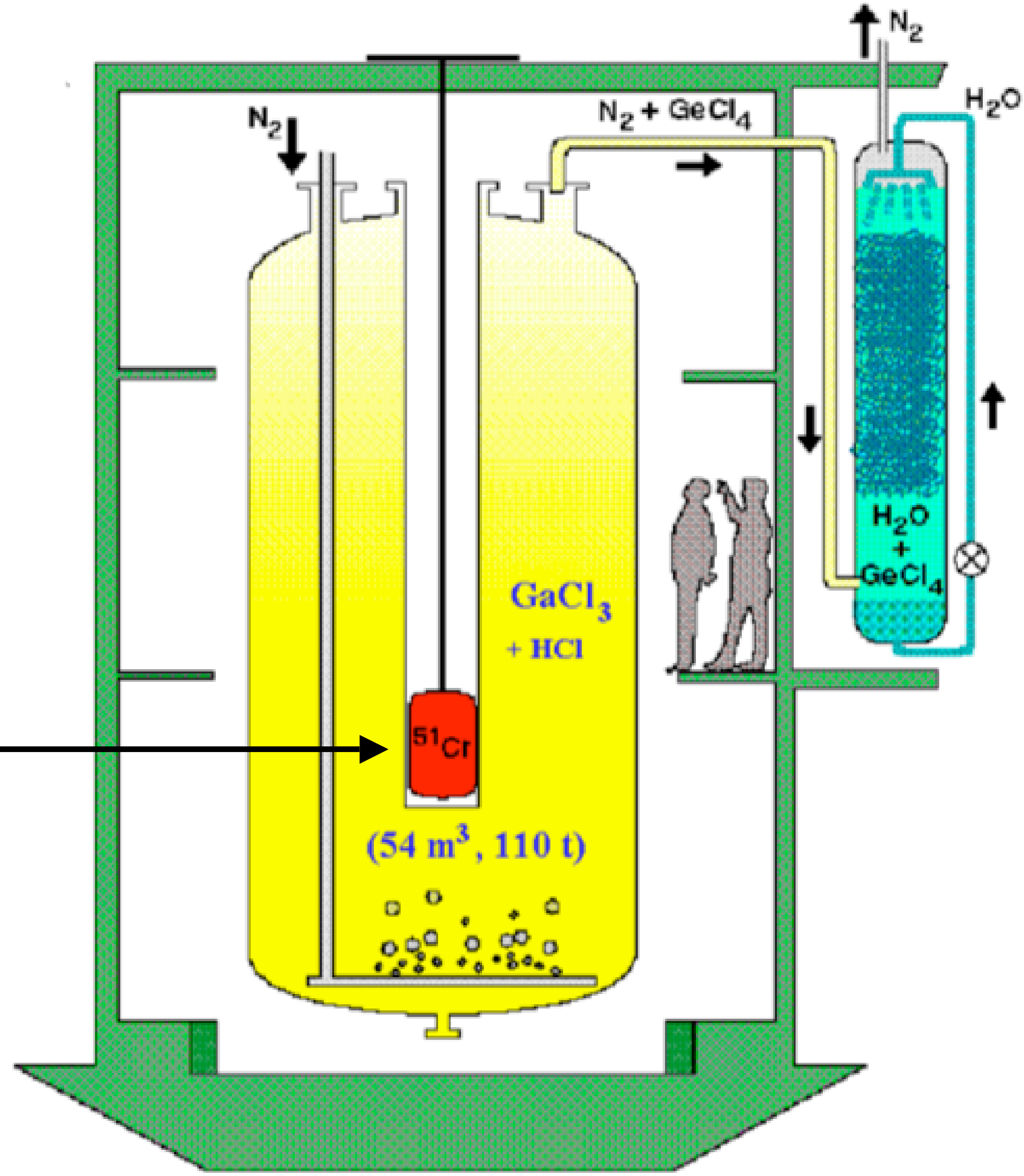
- Chemically extract the few atoms of $(A, Z+1)$ produced and mix with a gas. Only $\sim$ 1 ATOM/DAY is produced !

	HOMESTAKE	GALLEX	SAGE
Location	South Dakota	Gran Sasso	Baksan Mine
Material	C_2Cl_4	Gallium (Solution)	Gallium (Metallic)
Initial Isotope	^{37}Cl	^{71}Ga	^{71}Ga
Detected Isotope	^{37}Ar	^{71}Ge	^{71}Ge
Mass (tonnes)	615.0	30.3	57.0
Threshold	0.814 MeV	0.233 MeV	0.233 MeV

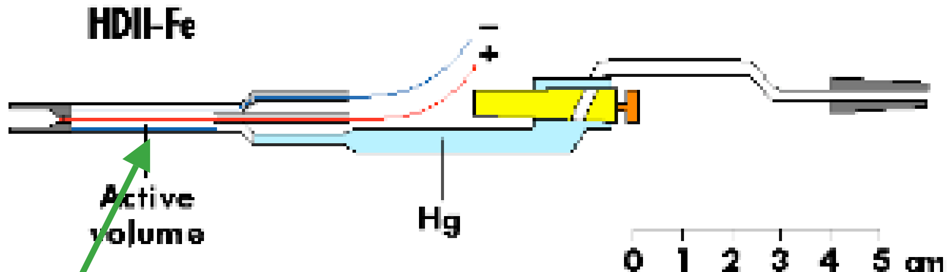
Be, B **pp, Be, B**

Gallex

Calibration source



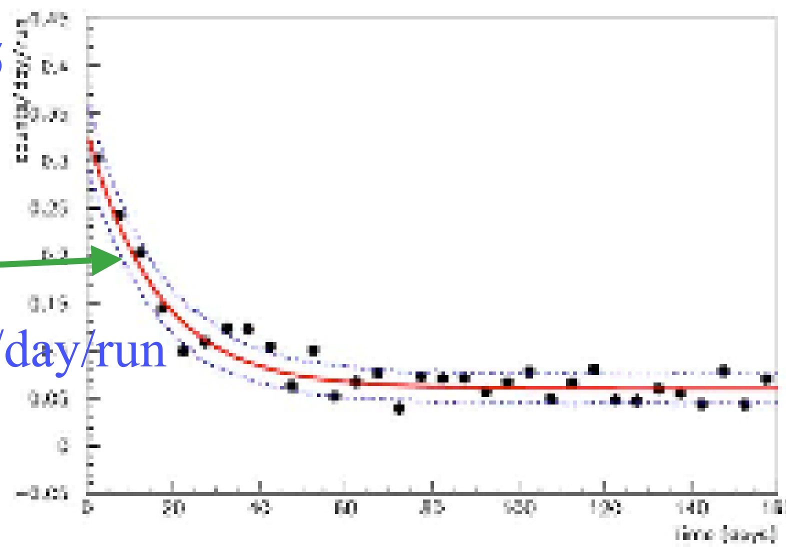
Extraction



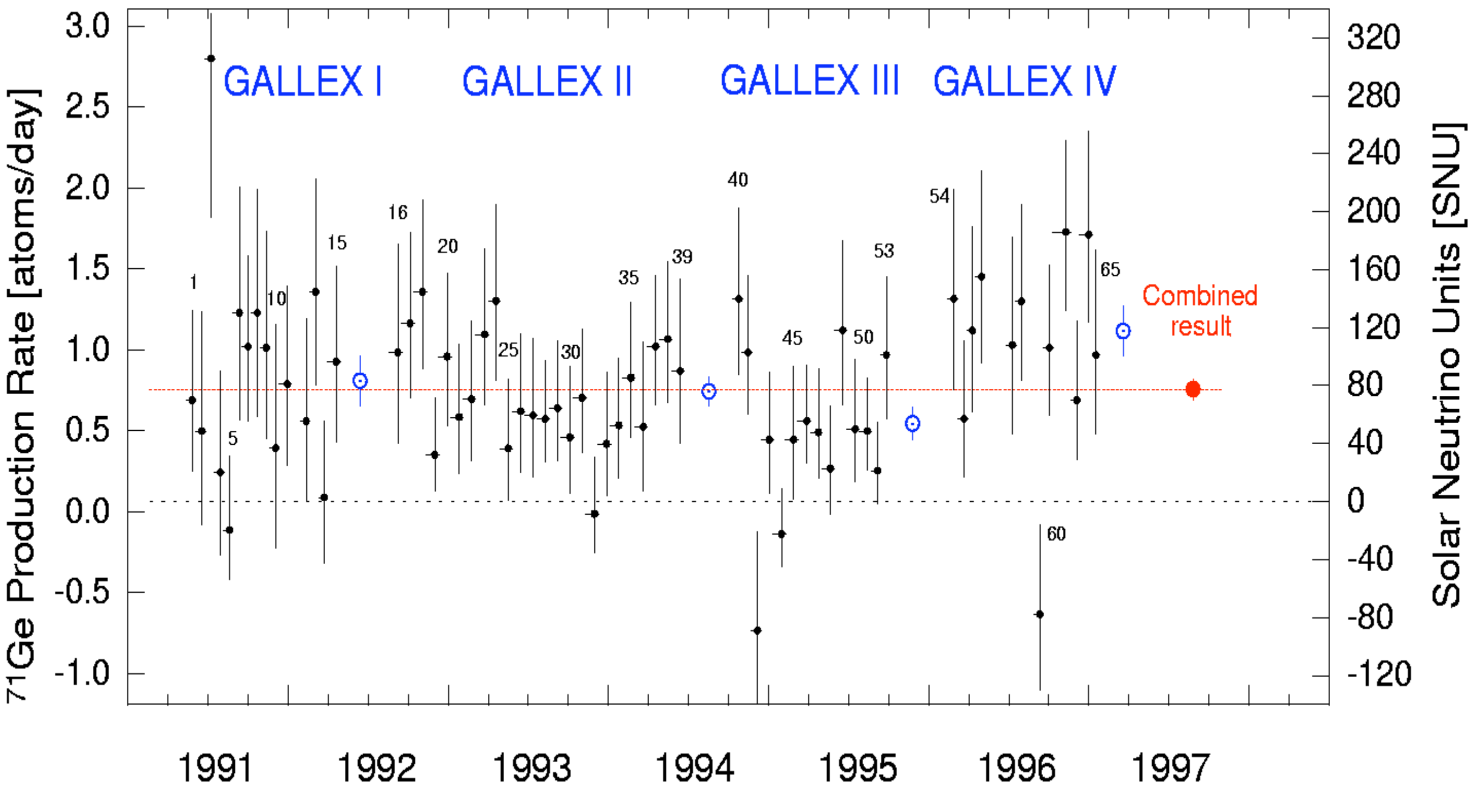
- Chemically extract the few atoms of (A,Z+1) produced.
- Mix with a gas.
- Fill proportional tubes with gas.
- Detect **X-rays** produced through the capture reaction

  $e^- + (A,Z+1) \dashrightarrow (A,Z) + \nu_e$

- Count how many atoms are present
- Even with ~ tons of detector mass
- ~ 1 ATOM/DAY



Gallex



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)

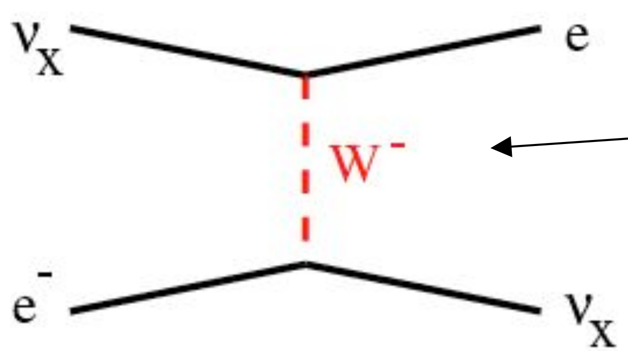
Water (H_2O)

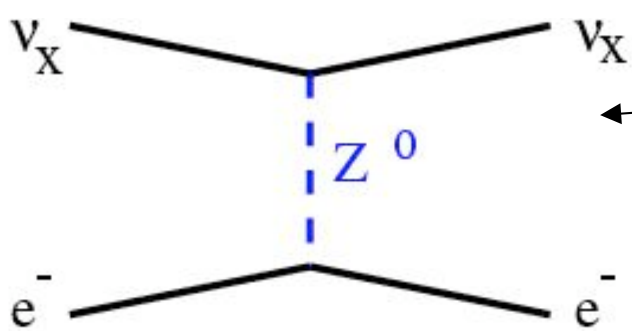
Sudbury Neutrino Observatory (SNO)

Heavy water (D_2O)

ν Scattering in water

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





Elastic scattering on electrons (ES)

$\nu + e \dashrightarrow \nu + e$

Can occur through:

Charged Current

Sensitive to **$\phi(\nu_e)$** only

(Not enough energy to produce

A muon or a tau)

Or

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 ν_e as for ν_μ, ν_τ**

ν Scattering on Heavy water

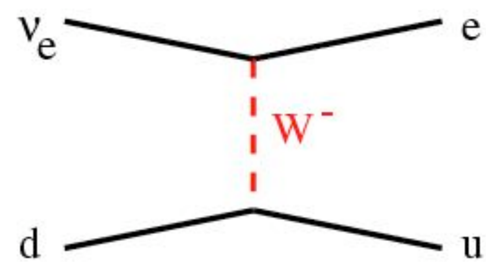
How about scattering on nucleons ?

- 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 ν_e

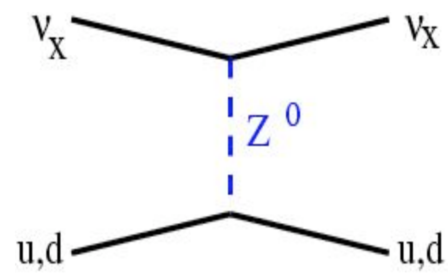
Not enough energy to produce a muon or a tau



- 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**$_2$O,
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**

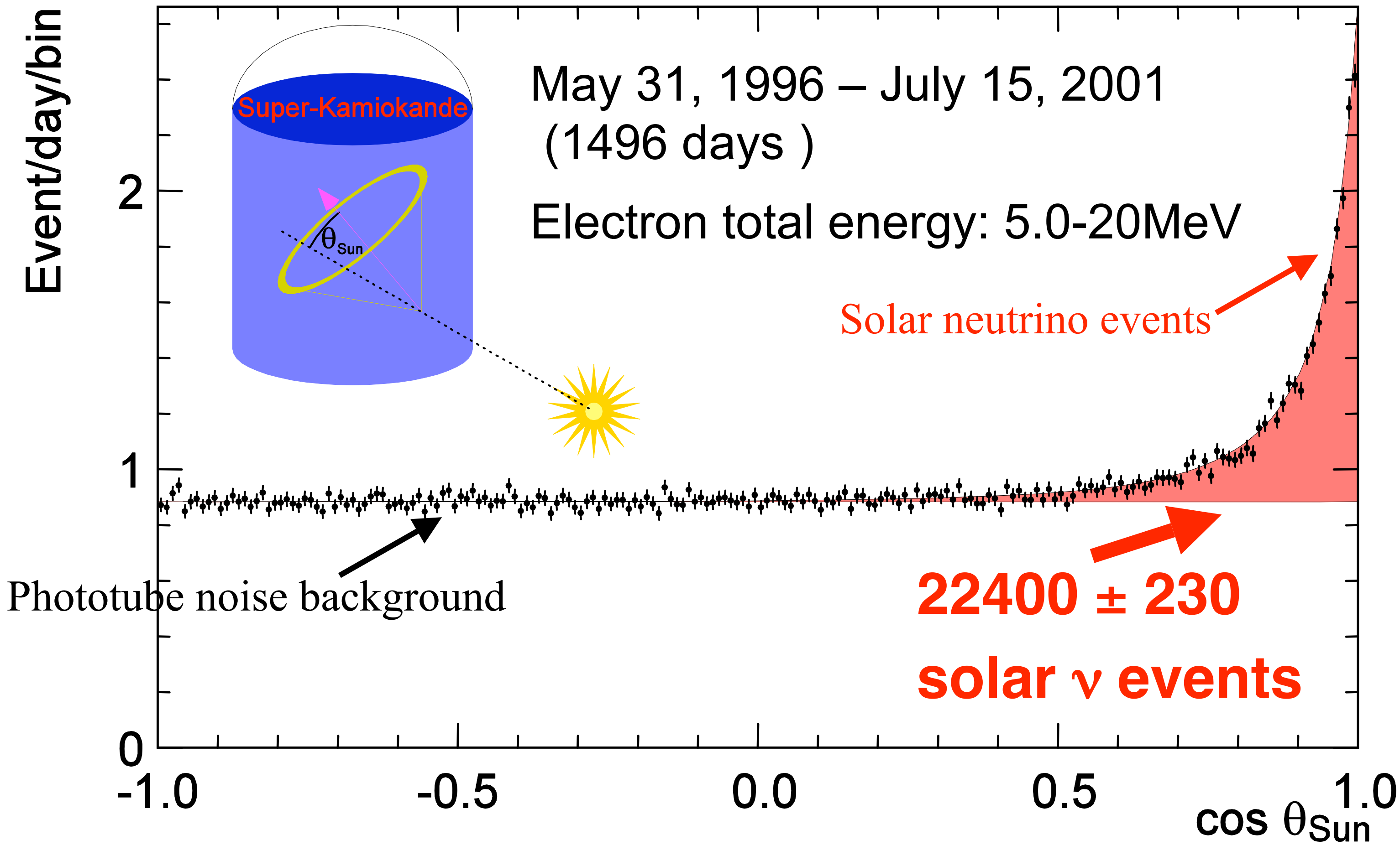
Reconstruction

- Threshold ~ 5 MeV: sensitive to **Boron ν'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.

PLB539 (2002) 179

SK-I: ^{8}B Solar Neutrino Flux

(Scattering on electrons in water)

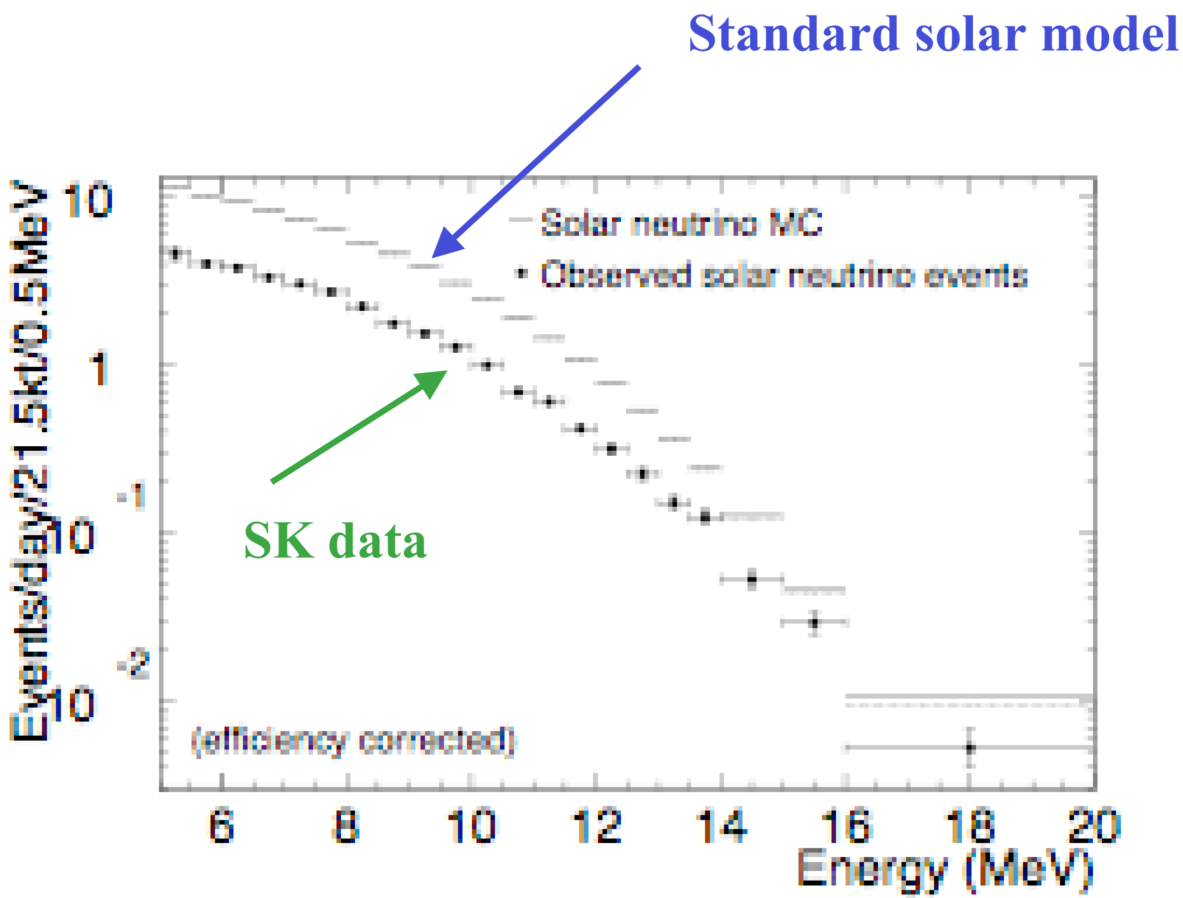


^{8}B flux = 2.35 ± 0.02 ± 0.08 [x10^{6}/cm^{2}/s]

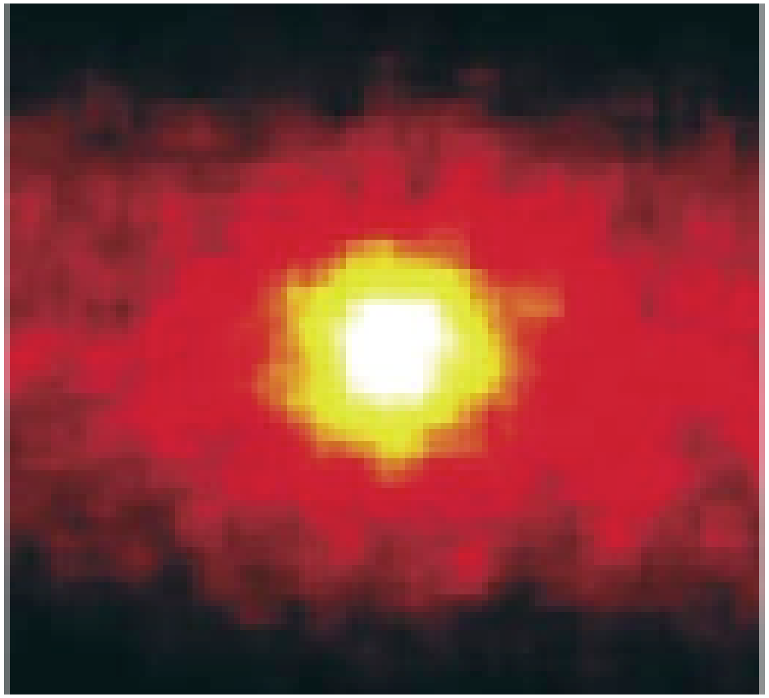
Data / SSM_{BP2004} = 0.406 ±0.004(stat.) +0.014 -0.013 (syst.)

Data / SSM_{BP2000} = 0.465 ±0.005(stat.) +0.016 -0.015 (syst.)

Solar ν energy spectrum



A (SK) neutrino picture of the sun !

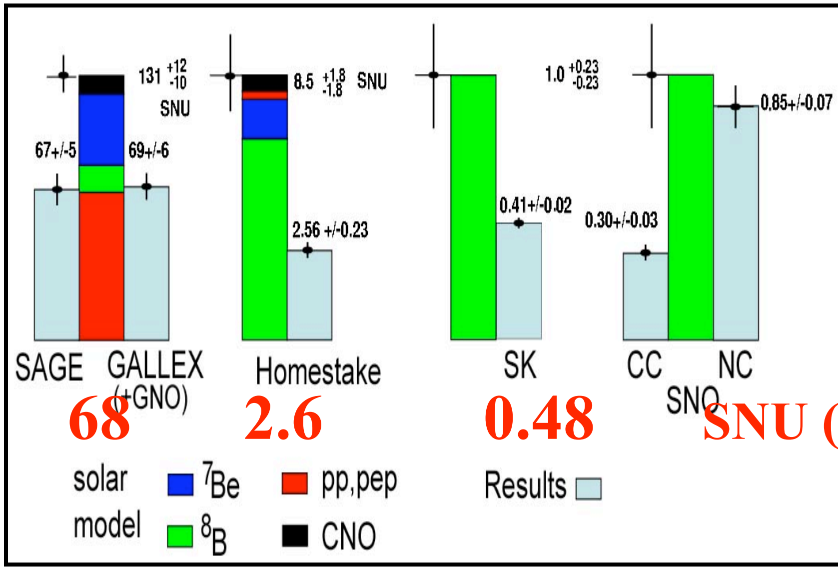


Taken underground…..

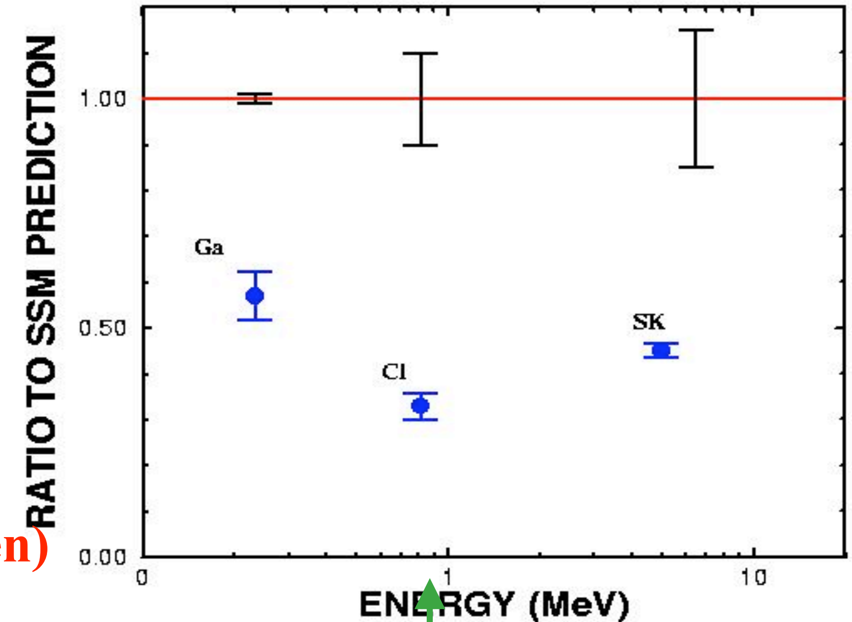
Suppression relative to Standard Solar Model

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

131 8.5 1.0 SNU (expect)



68 2.6 0.48 SNU (seen)



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?

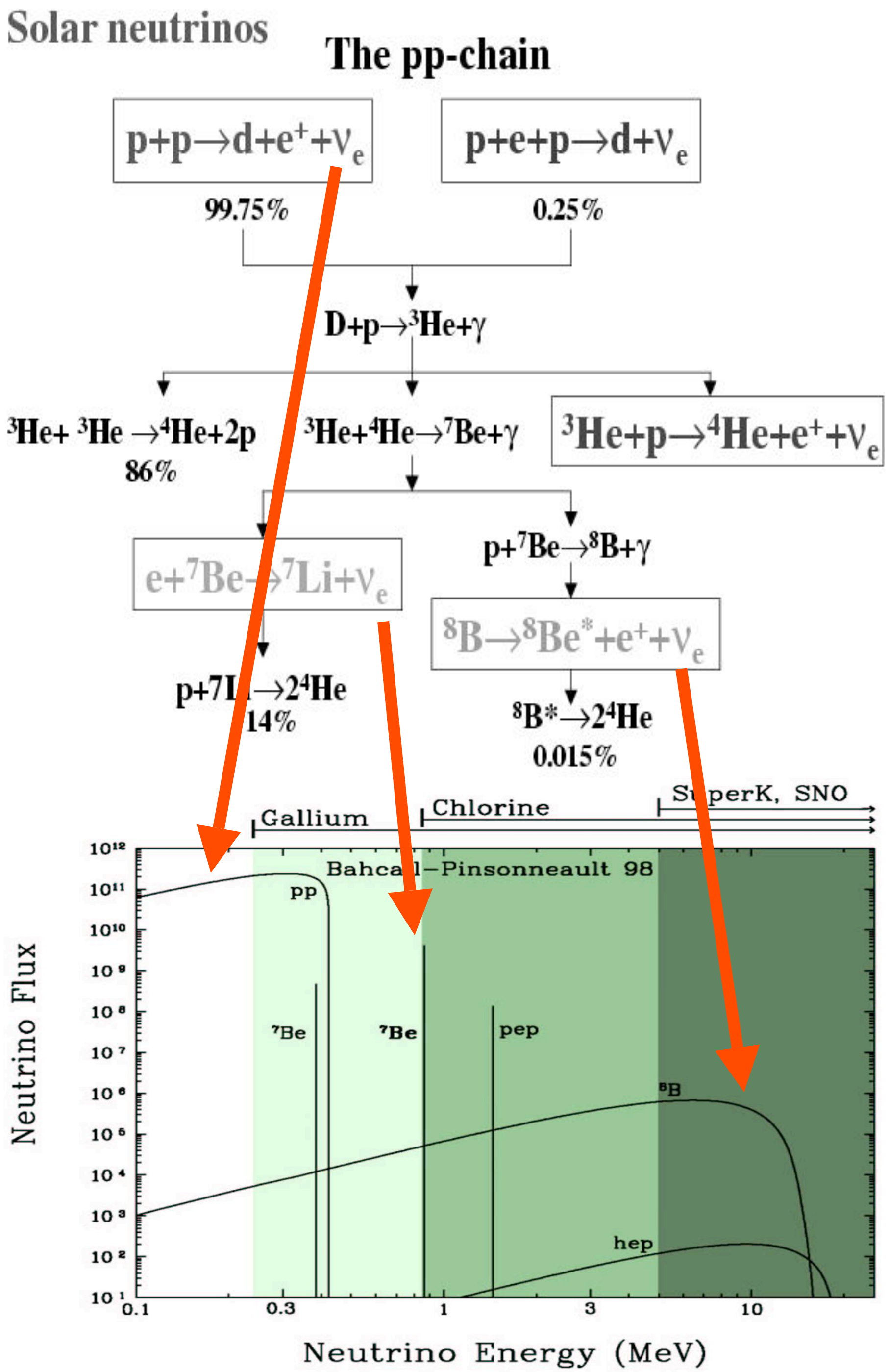
Suppressions

- x_{pp} = pp ν's suppression
- x_{Be} = Beryllium ν's suppression
- x_B = Boron ν's suppression

3 equations and 3 unknowns:

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

- $x_{pp} = 1.07$
- $x_{Be} =$ **-0.73** **No Beryllium !**
- $X_b = 0.47$



Solar spectrum

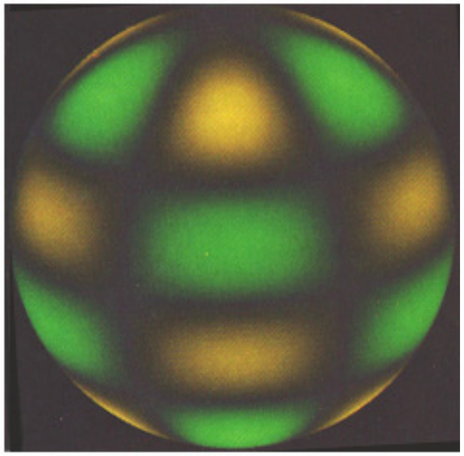
- But Boron, which gives **Boron ν's**, Is produced by the very Reaction that produces **Be ν's**.
- So how can **Be ν's** be suppressed MORE than the **Boron ν's**?

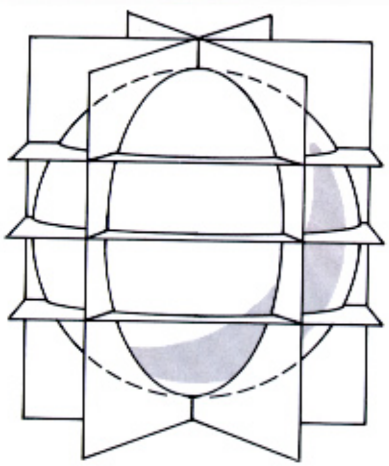
Is there Beryllium in the sun? Helioseismology

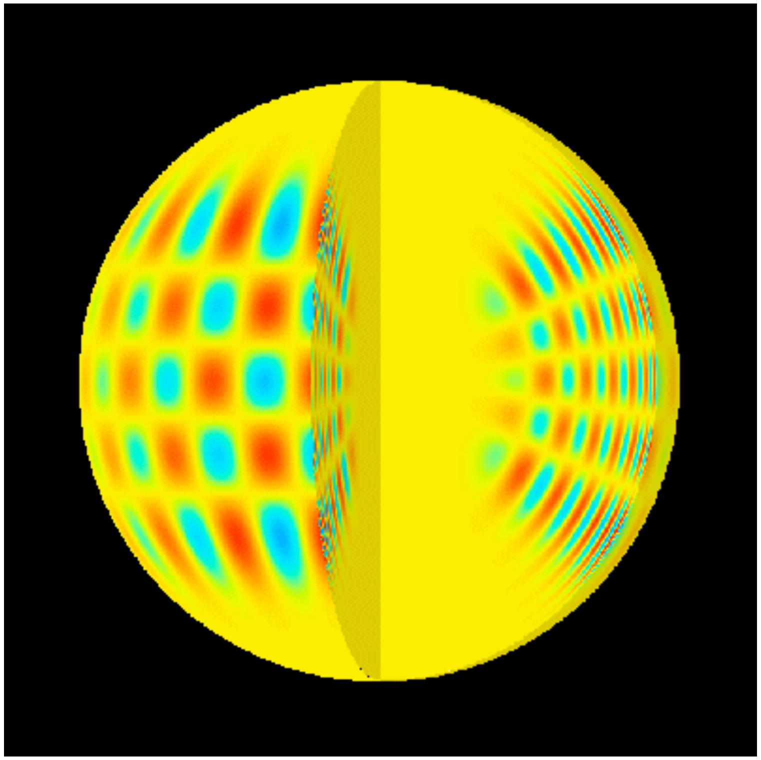
- **Study of MOTION and BRIGHTNESS variations in the SURFACE of the sun**

- **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

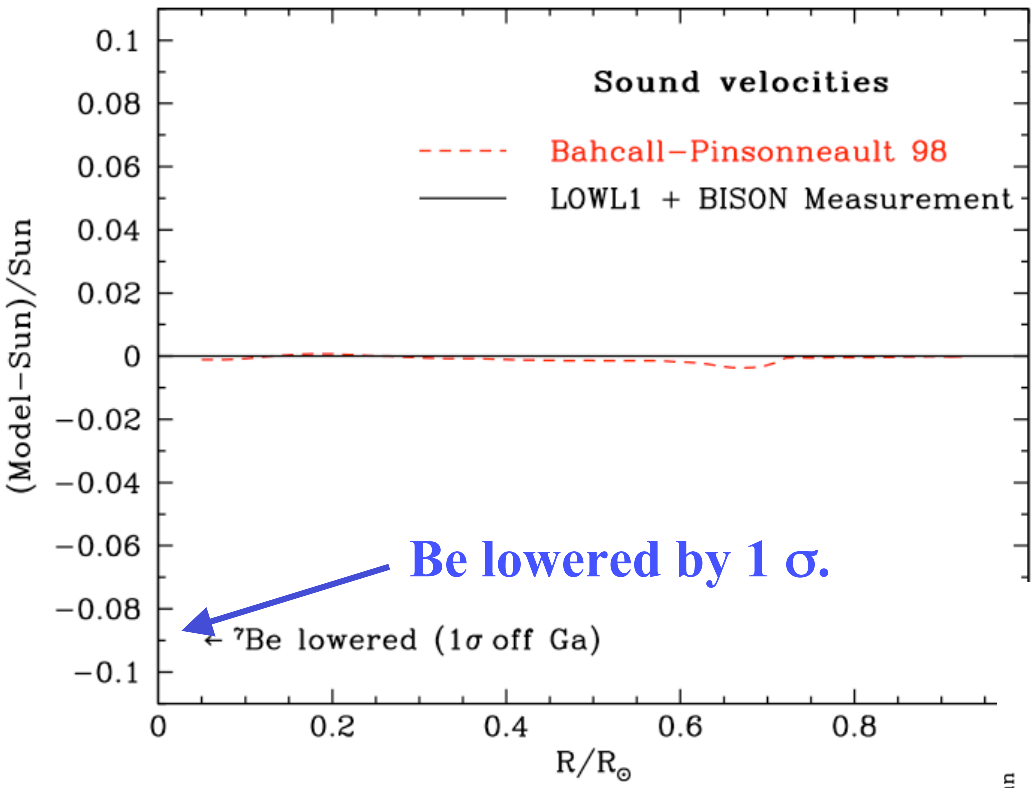
Solar Modes





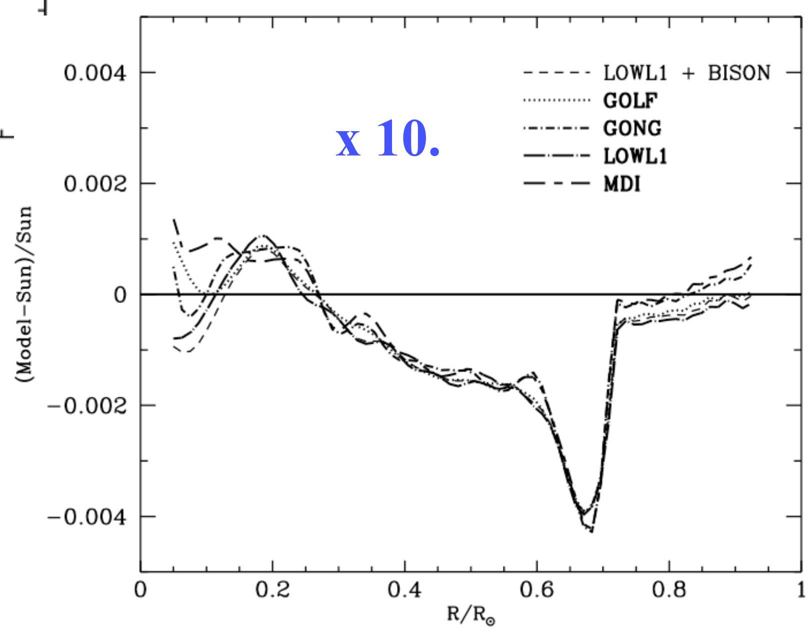


Helioseismology results



Be lowered by 1 σ.

Very good agreement between data and Standard Solar Model predictions.



x 10.

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.

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}Be: 90% at 0.86 MeV…..10% at 0.38 MeV
^{51}Cr 90% at 0.75 MeV….10% at 0.43 MeV

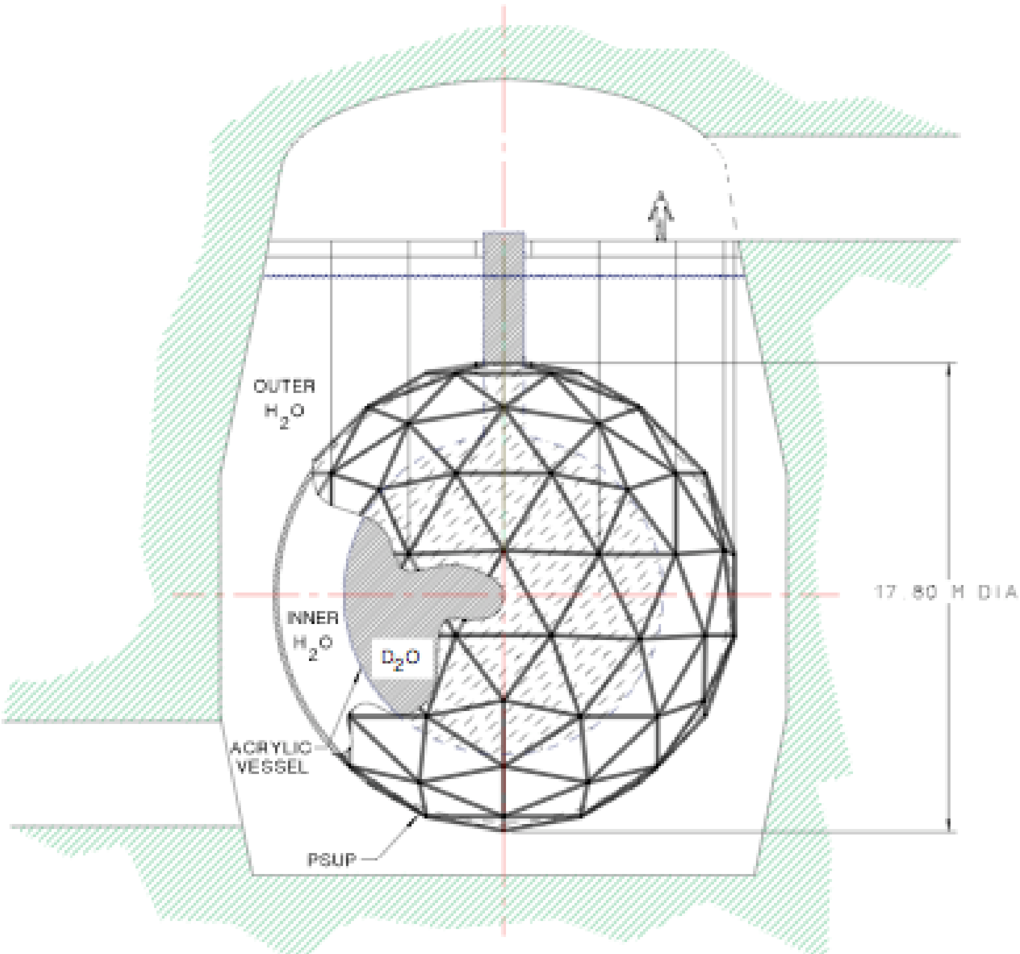
Extract in same way as for solar exposure
Calculate rate from cross section calculation and known activity of source

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)



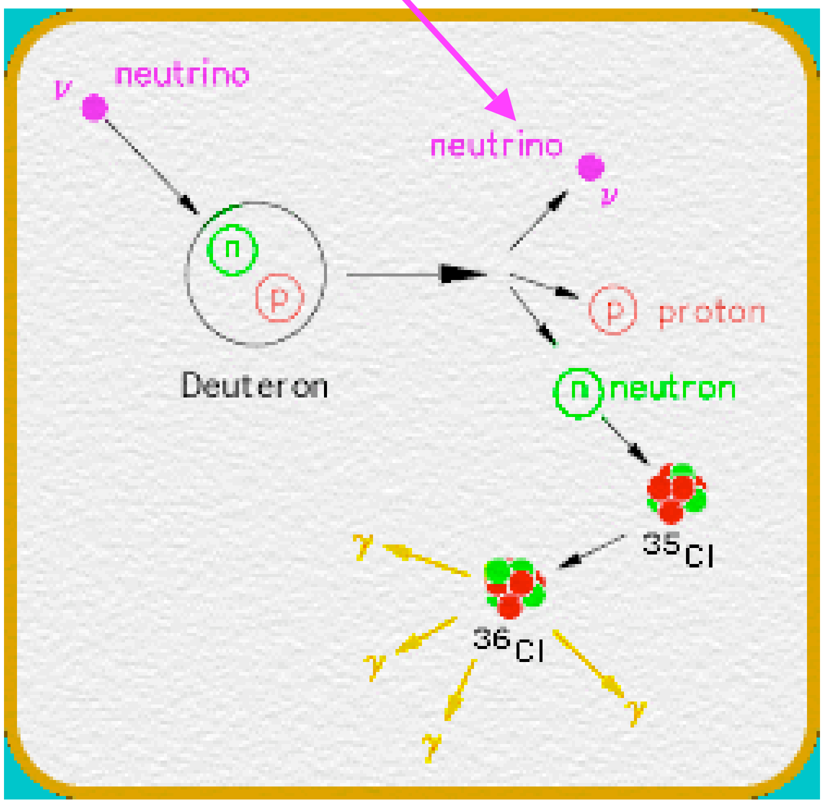
- 1000 tons of heavy water (**D_2O**)
- In sphere 12m in diameter
- 9438 photomultipliers
- 2039m below surface

to reduce cosmic ray flux

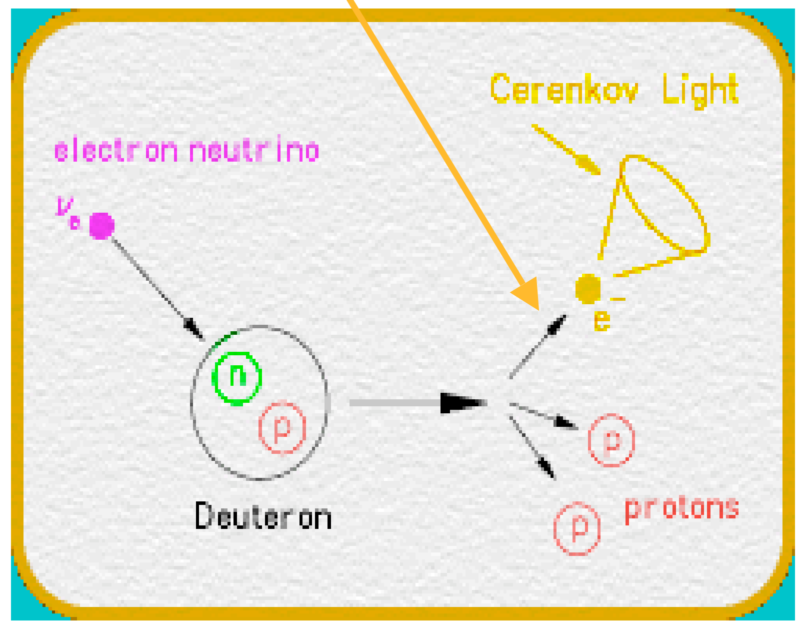
(70 muons/day)

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.

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

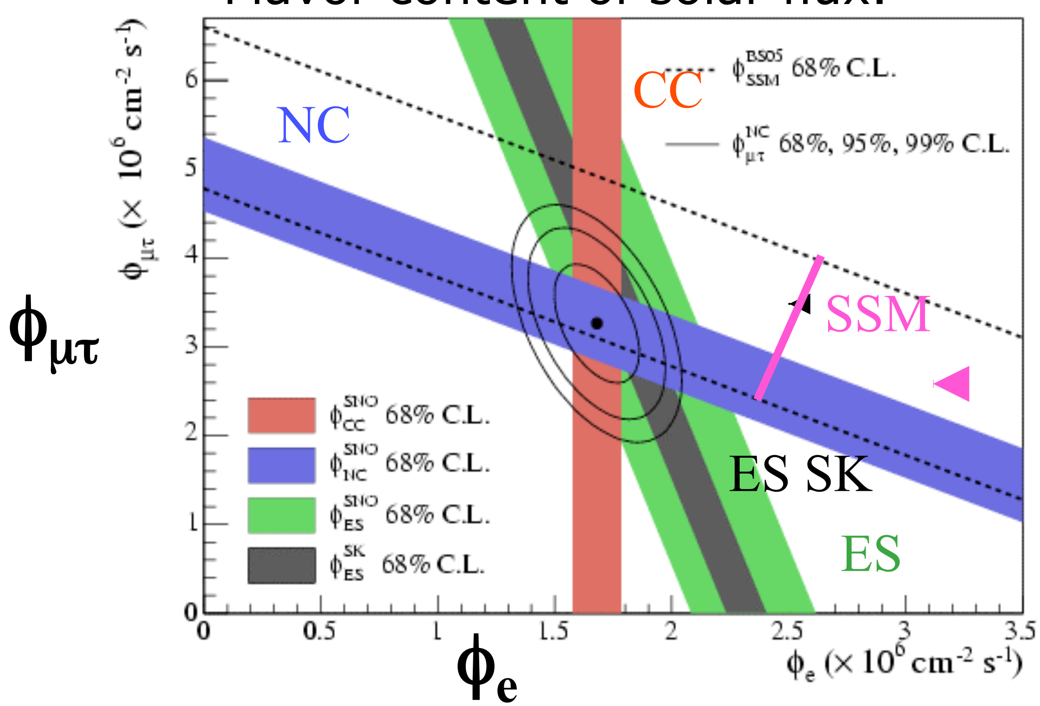
$$\Phi_{ES} = 2.35^{+0.22}_{-0.22}(stat.)^{+0.15}_{-0.15}(sys.)\times 10^6 cm^{-2}s^{-1}$$ ← **ν_e mostly**

$$\Phi_{NC} = 4.94^{+0.21}_{-0.21}(stat.)^{+0.38}_{-0.34}(sys.)\times 10^6 cm^{-2}s^{-1}$$ ← **ν_e, ν_μ, ν_τ**

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

Using ALL neutrinos Fully Consistent with Standard Solar Model

Flavor content of solar flux.



Neutrinos DO NOT disappear. They just Change Flavour !

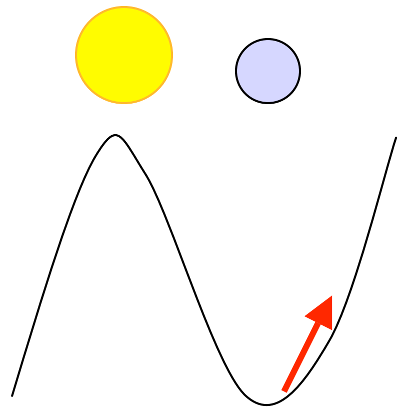
How do we explain their metamorphosis?

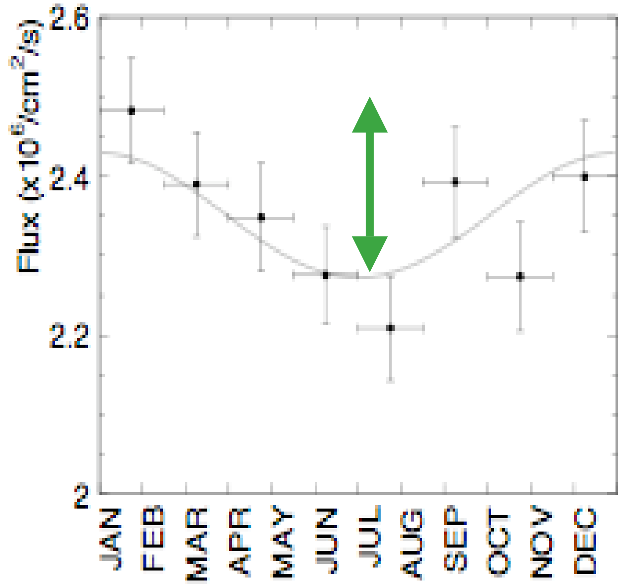
Are they oscillating between the Sun and the Earth in vacuum?
If so 2 possibilities:

- 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 ($1/R^2$).

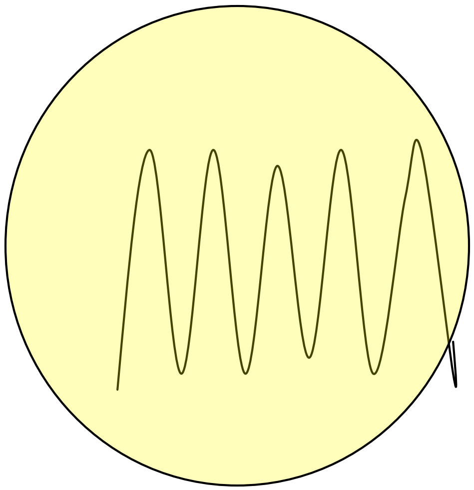
  No extra oscillation effect





How do we explain their metamorphosis?

Are they oscillating between the Sun and the Earth?
Other possibility:



oWe 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(1.4×10^6 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

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

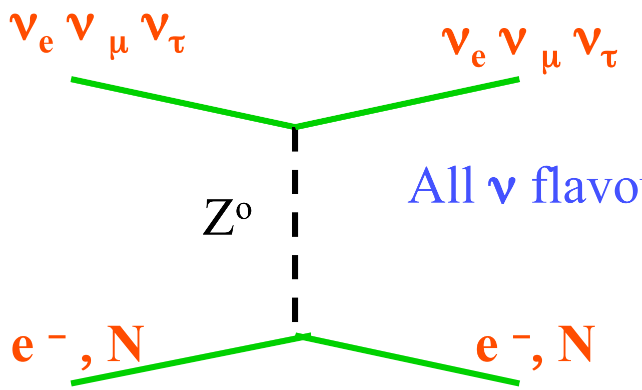
To $\mathbf{(1/2) \sin^2 2\theta}$

Independent of energy. Unlike what we see.

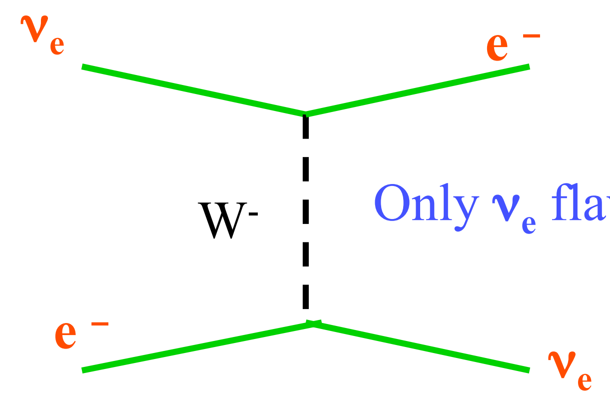
Matter effects: Mikheyev-Smirnov-Wolfenstein

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

In forward scattering:

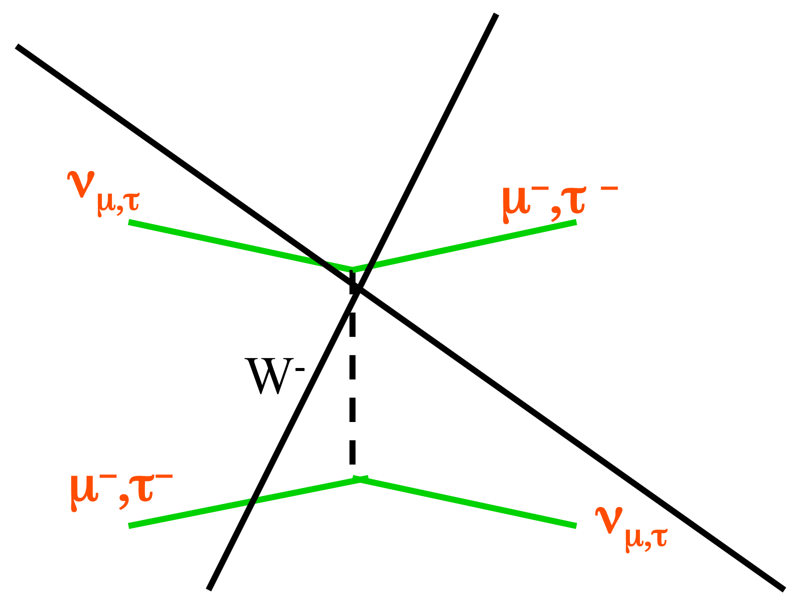


All $\boldsymbol{\nu}$ flavours



Only $\boldsymbol{\nu_e}$ flavour

Same for all flavours. Just introduces extra phase.Neglect it.



No μ^- or τ^- in matter.
So only happens for ν_e's.
Introduces extra potential, V_W, for $\boldsymbol{\nu_e}$ only

$V_W = \sqrt{2}\ G_F N_e$ $\quad N_e$ = density of electrons in matter

$V_W = -\sqrt{2}\ G_F N_e$ for antineutrinos. **Changes sign.**

Matter effects

Since the extra potential is JUST for ν_e's we have to work in FLAVOUR basis and not MASS

$$\mathbf{H_M} = \mathbf{H_{vac}} + \mathbf{V_W} \begin{array}{cc} \begin{array}{cc} \nu_e & \nu_\mu \end{array} & \\ \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} & \begin{array}{c} \nu_e \\ \nu_\mu \end{array} \end{array} + \mathbf{V_Z} \begin{array}{cc} \begin{array}{cc} \nu_e & \nu_\mu \end{array} & \\ \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} & \begin{array}{c} \nu_e \\ \nu_\mu \end{array} \end{array}$$

$$\mathbf{H_M} = \mathbf{H_{vac}} + \frac{\mathbf{V_W}}{\mathbf{2}} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} + \frac{\mathbf{V_W}}{\mathbf{2}} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

Neglecting identity matrices

$$\mathbf{H_M} = \mathbf{H_{vac}} + \frac{\mathbf{V_W}}{\mathbf{2}} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$\mathbf{H_M} = \frac{\mathbf{\Delta m^2}}{\mathbf{4E}} \begin{pmatrix} -cos2\theta & sin2\theta \\ sin2\theta & cos2\theta \end{pmatrix} + \frac{\mathbf{V_W}}{\mathbf{2}} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Vacuum oscillations in Flavour basis

Derivation of H_{vac}

$$\mathbf{i}\frac{\mathbf{d}}{\mathbf{dt}}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix} = \begin{pmatrix}E_1 & 0\\ 0 & E_2\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix} = \mathbf{p}\begin{pmatrix}1 & 0\\ 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix} + \begin{pmatrix}m_1^2/2p & 0\\ 0 & m_2^2/2p\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$$

$$\mathbf{i}\frac{\mathbf{d}}{\mathbf{dt}}\begin{pmatrix}\nu_e cos\theta - \nu_\mu sin\theta\\ \nu_e sin\theta + \nu_\mu cos\theta\end{pmatrix} = \begin{pmatrix}m_1^2/2p & 0\\ 0 & m_2^2/2p\end{pmatrix}\begin{pmatrix}\nu_e cos\theta - \nu_\mu sin\theta\\ \nu_e sin\theta + \nu_\mu cos\theta\end{pmatrix}$$

$$\mathbf{i}\frac{\mathbf{d}}{\mathbf{dt}}(\nu_\mathbf{e}\mathbf{cos}\theta - \nu_\mu\mathbf{sin}\theta) = \frac{\mathbf{m_1^2}}{\mathbf{2p}}(\nu_\mathbf{e}\mathbf{cos}\theta - \nu_\mu\mathbf{sin}\theta) \qquad \mathbf{A}$$

$$\mathbf{i}\frac{\mathbf{d}}{\mathbf{dt}}(\nu_\mathbf{e}\mathbf{sin}\theta + \nu_\mu\mathbf{cos}\theta) = \frac{\mathbf{m_2^2}}{\mathbf{2p}}(\nu_\mathbf{e}\mathbf{sin}\theta + \nu_\mu\mathbf{cos}\theta) \qquad \mathbf{B}$$

A x cos θ + B x sin θ and B x cos θ - A x sin θ

c

Flavour basis II

A x cos θ + B x sin θ

B x cos θ - A x sin θ

$$i\frac{d}{dt}(\nu_e) = [\frac{\Delta m^2}{4p}(-\cos 2\theta) + \frac{m_1^2+m_2^2}{4p}]\nu_e - \frac{\Delta m^2}{4p}\sin 2\theta \nu_\mu$$

$$i\frac{d}{dt}(\nu_\mu) = \frac{\Delta m^2}{4p}(\sin 2\theta)\nu_e + [\frac{\Delta m^2}{4p}\cos 2\theta + \frac{m_1^2+m_2^2}{4p}]\nu_\mu$$

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

Neglect Unity matrix term and p ~ E

Matter effects

$$\mathbf{H_M} = \mathbf{H_{vac}} + \mathbf{V_W} \begin{array}{cc} \begin{array}{cc} \nu_{\mathbf{e}} & \nu_\mu \end{array} & \\ \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} & \begin{array}{c} \nu_e \\ \nu_\mu \end{array} \end{array} + \mathbf{V_Z} \begin{array}{cc} \begin{array}{cc} \nu_{\mathbf{e}} & \nu_\mu \end{array} & \\ \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} & \begin{array}{c} \nu_e \\ \nu_\mu \end{array} \end{array}$$

$$\mathbf{H_M} = \mathbf{H_{vac}} + \frac{\mathbf{V_W}}{\mathbf{2}} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} + \frac{\mathbf{V_W}}{\mathbf{2}} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

$$\mathbf{H_M} = \mathbf{H_{vac}} + \frac{\mathbf{V_W}}{\mathbf{2}} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$\mathbf{H_M} = \frac{\mathbf{\Delta m^2}}{\mathbf{4E}} \begin{pmatrix} -cos2\theta & sin2\theta \\ sin2\theta & cos2\theta \end{pmatrix} + \frac{\mathbf{V_W}}{\mathbf{2}} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$V_W = \sqrt{2}\ G_F N_e$ N_e = density of electrons in matter

$V_W = -\sqrt{2}\ G_F N_e$ for antineutrinos. **Changes sign.**

Matter effects

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

$$\mathbf{H_M} = \frac{\mathbf{\Delta m^2}}{\mathbf{4E}} \begin{pmatrix} -(cos2\theta - x) & sin2\theta \\ sin2\theta & cos2\theta - x \end{pmatrix}$$

Defining:

$$\mathbf{cos2\theta_M} = \frac{\mathbf{-(cos2\theta - x)}}{\mathbf{\sqrt{(cos2\theta - x)^2 + sin^2 2\theta}}} \qquad \mathbf{sin2\theta_M} = \frac{\mathbf{sin2\theta}}{\mathbf{\sqrt{(cos2\theta - x)^2 + sin^2 2\theta}}}$$

$$\mathbf{H_M} = \frac{\mathbf{\Delta m_M^2}}{\mathbf{4E}} \begin{pmatrix} -cos2\theta_M & sin2\theta_M \\ sin2\theta_M & cos2\theta_M \end{pmatrix}$$

with:

$$\mathbf{\Delta m_M^2} = \mathbf{\Delta m^2 \sqrt{(cos2\theta - x)^2 + sin^2 2\theta}}$$

Same structure as in vacuum with θ ---> θ_M, Δm^2 ---> Δm^2_M

Oscillations in matter MSW

$|\nu_e\rangle = \cos\theta_m\,|\nu_1\rangle + \sin\theta_m\,|\nu_2\rangle$ and $|\nu_\mu\rangle = -\sin\theta_m\,|\nu_1\rangle + \cos\theta_m\,|\nu_2\rangle$

$|\nu_1\rangle = \cos\theta_m\,|\nu_e\rangle - \sin\theta_m\,|\nu_\mu\rangle$ and $|\nu_2\rangle = \sin\theta_m\,|\nu_e\rangle + \cos\theta_m\,|\nu_\mu\rangle$

Consequences (Earth)

- Travelling through the earth, away from the very dense core, the density is **constant**
- The oscillation probability is just modified to use θ_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 ---> $\theta_M \neq \overline{\theta}_M$

Matter effects introduce an **asymmetry** between neutrinos and antineutrinos.

But **NOT** related to CP violation.

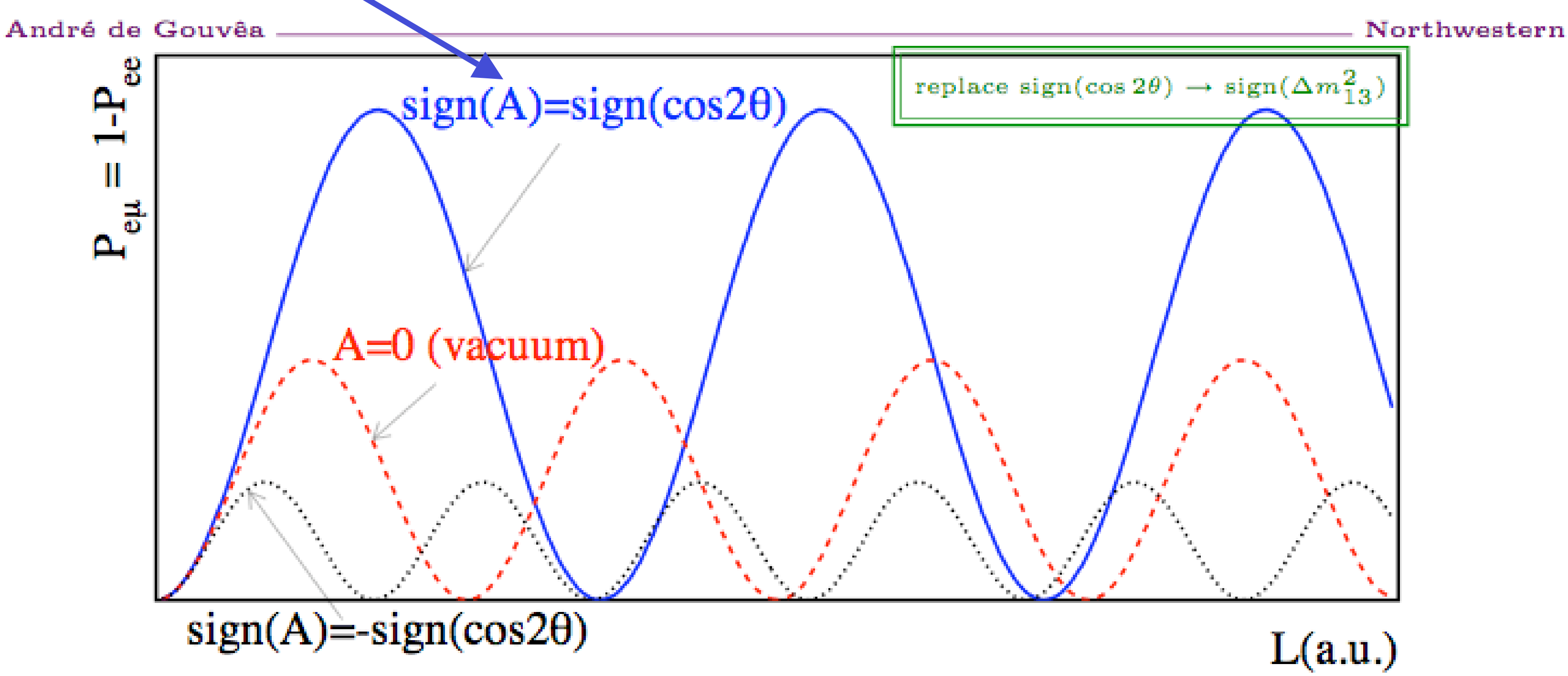
When searching for CP violation this has to be taken into account

Consequences (Earth)

- V_W changes sign for antineutrinos: x changes sign ---> $\theta_M \neq \bar{\theta}_M$
- x also changes sign when Δm^2 changes sign : with the mass hierarchy (m_1^2 smaller or larger than m_2^2?).

- (cos 2θ -x) term is affected

A is same as x



Consequences (Sun)

$$\sin 2\theta_{\mathrm{M}} = \frac{\sin 2\theta}{\sqrt{(\cos 2\theta - \mathrm{x})^2 + \sin^2 2\theta}}$$

IF $\cos 2\theta = x = (2\sqrt{2}\ G_F N_e E) / \Delta m^2 = 1.5 \times 10^{-13}\ (Z/A)$ **E** ρ

Matter density

then even if θ (vacuum) is very small

$\sin 2\theta_M = 1$ ----> $\theta_M = \pi/4$ ----> **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 ----> 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:

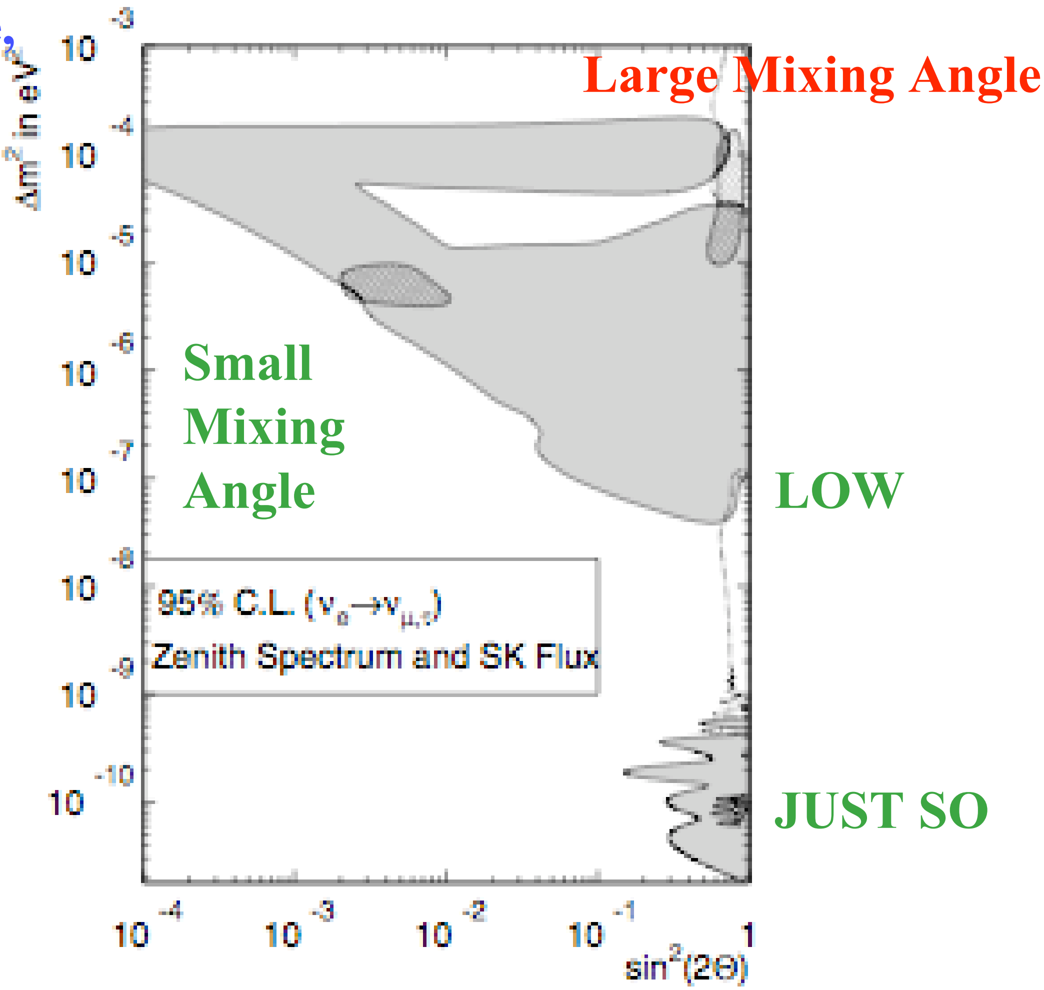
Affected by matter in Earth.

Grey area disfavoured

JUST SO and most of SMA

Excluded.

LMA and LOW left.

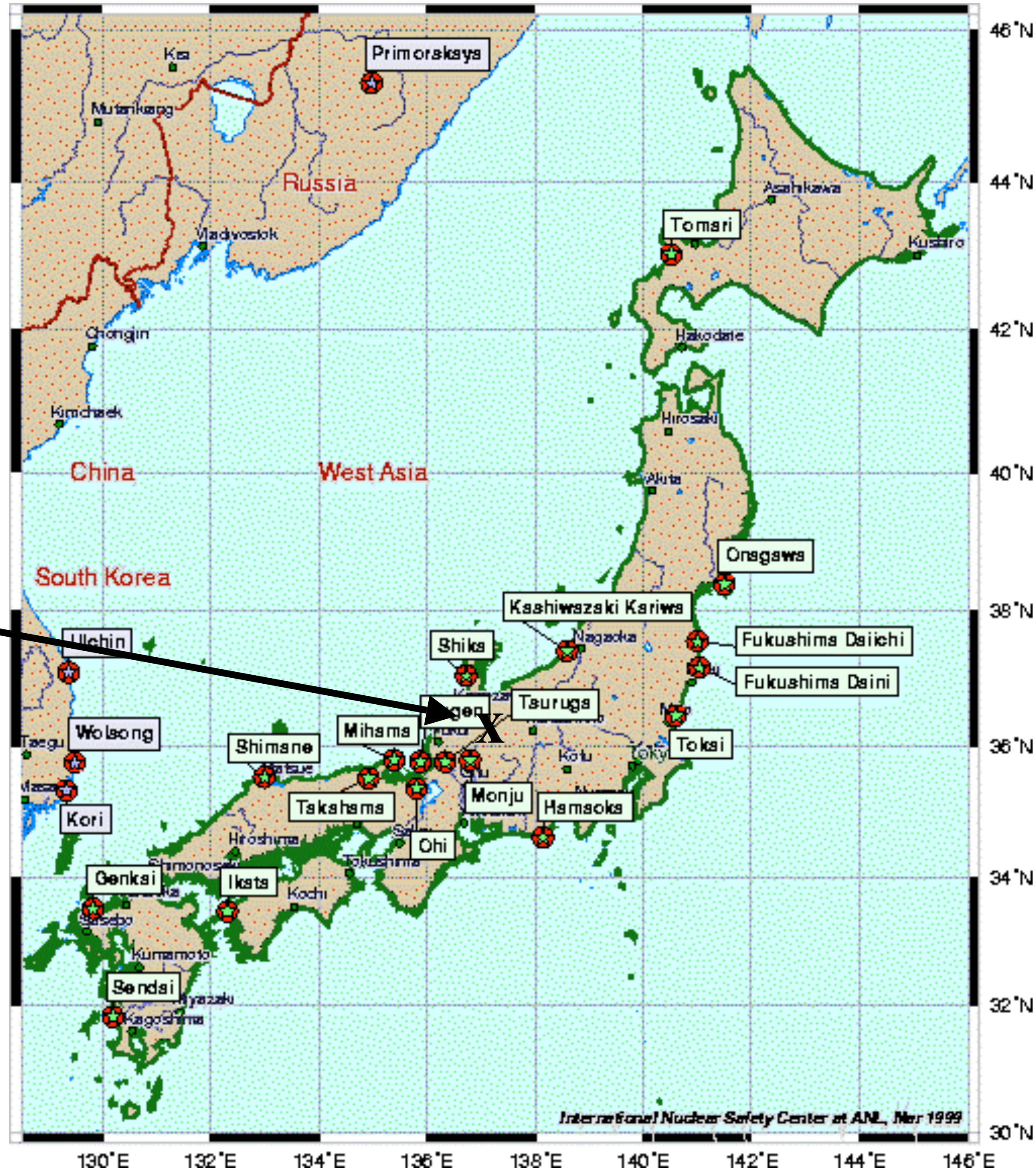


KamLAND

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



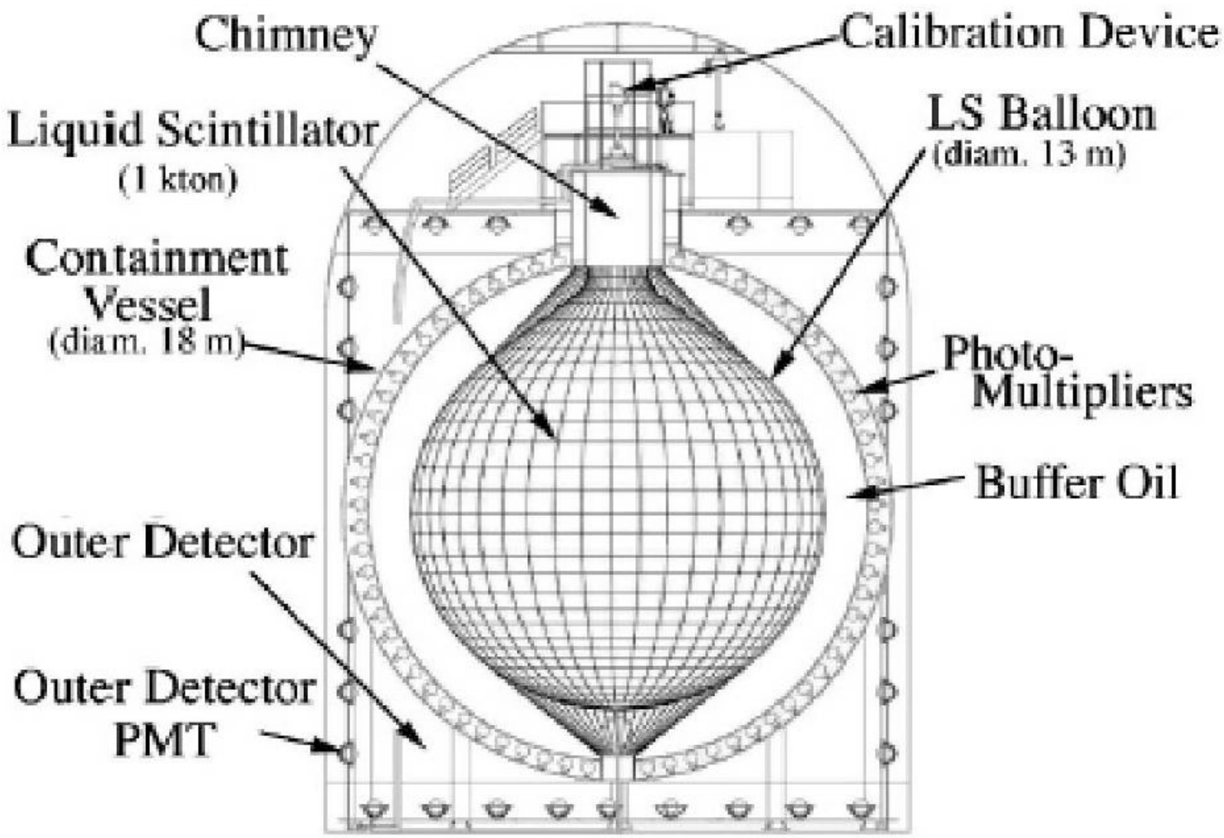
What should they see?

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

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

They should see an **energy-averaged** oscillation.

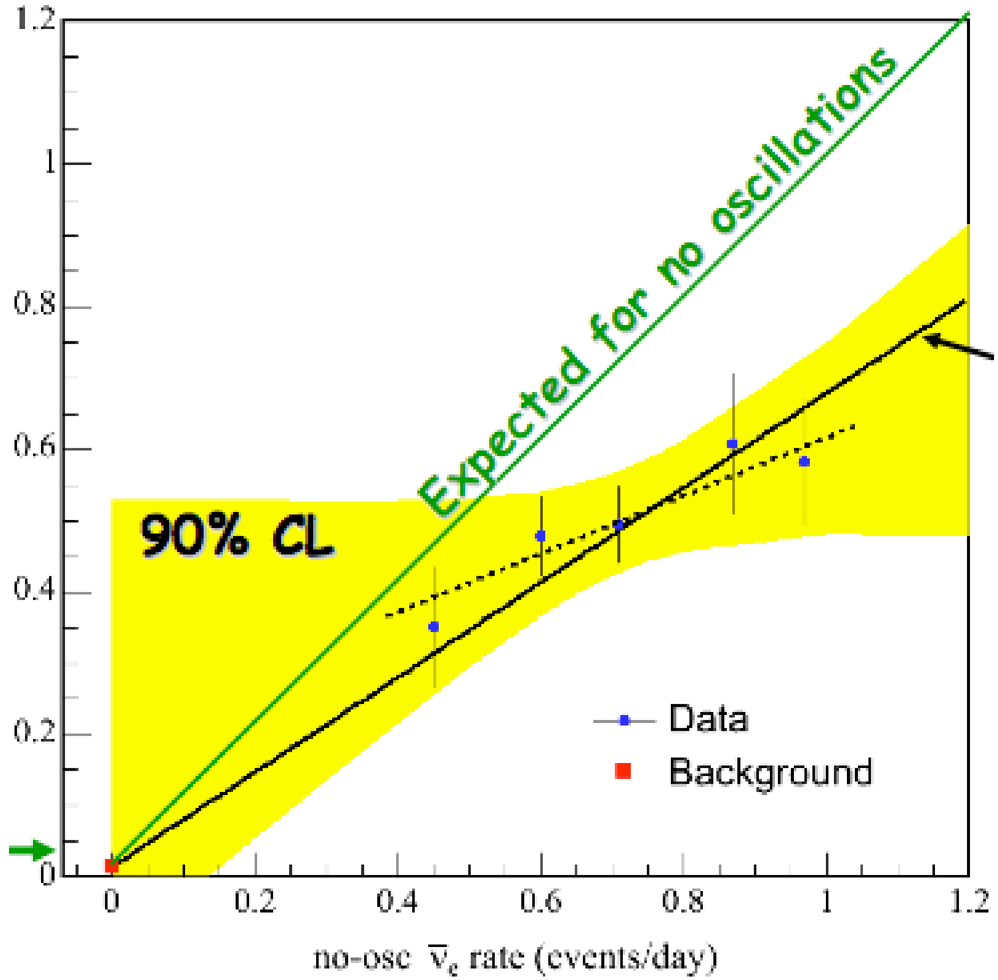
KamLAND detector



1 kton of liquid scintillator

Correlation with known reactor flux

Observed
Flux
(events/day)

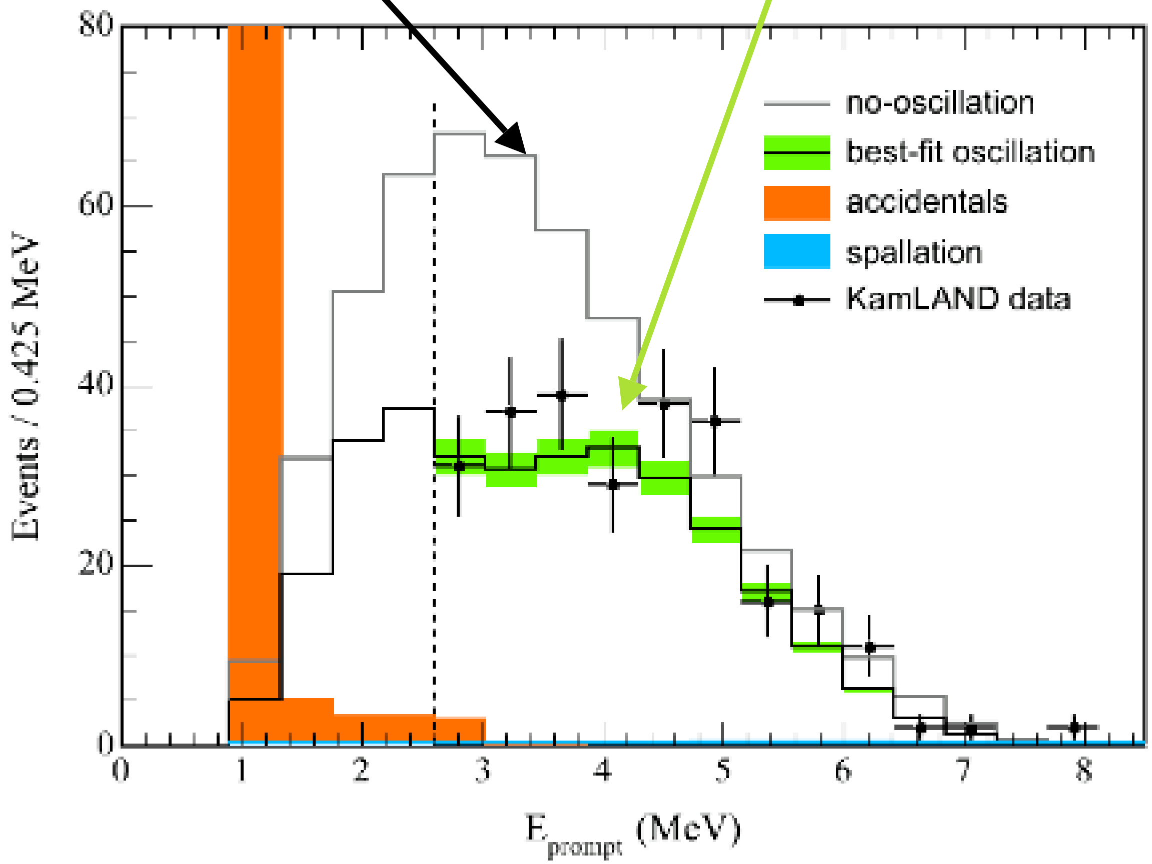


They REALLY see reactor neutrinos

KamLAND results

Expectation for
No oscillation

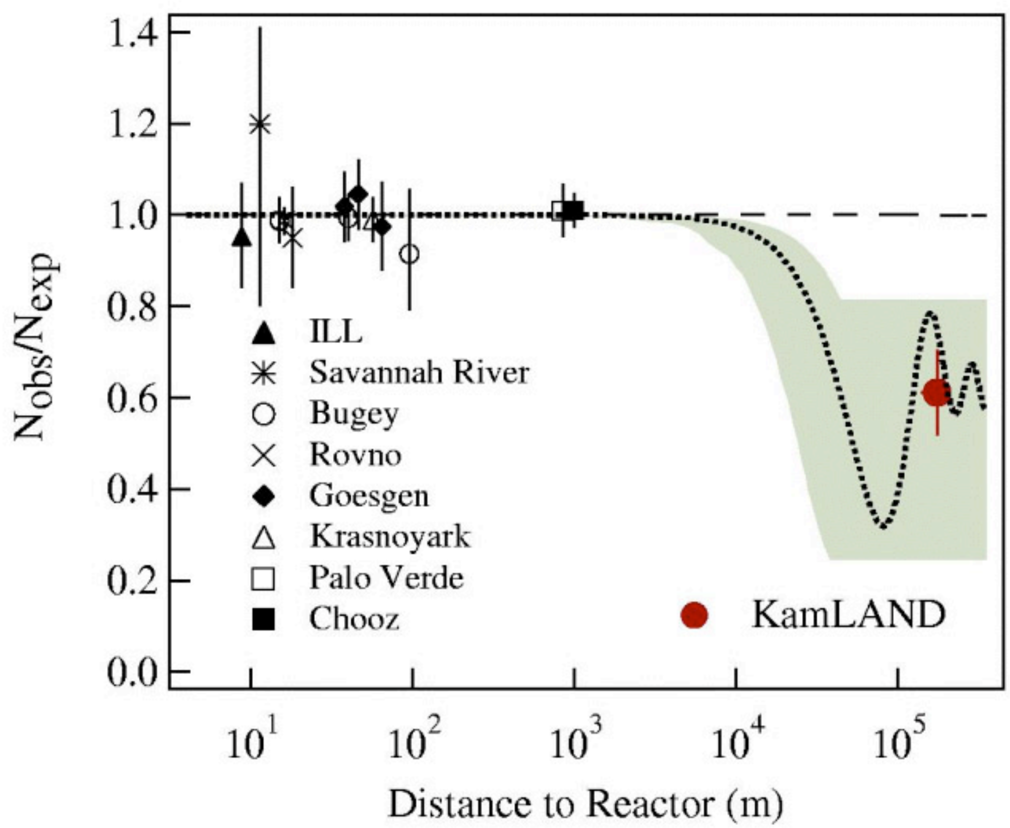
Best fit for
oscillation



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

Reactor results

KamLAND average suppression: first observation of reactor antineutrinos disappearance

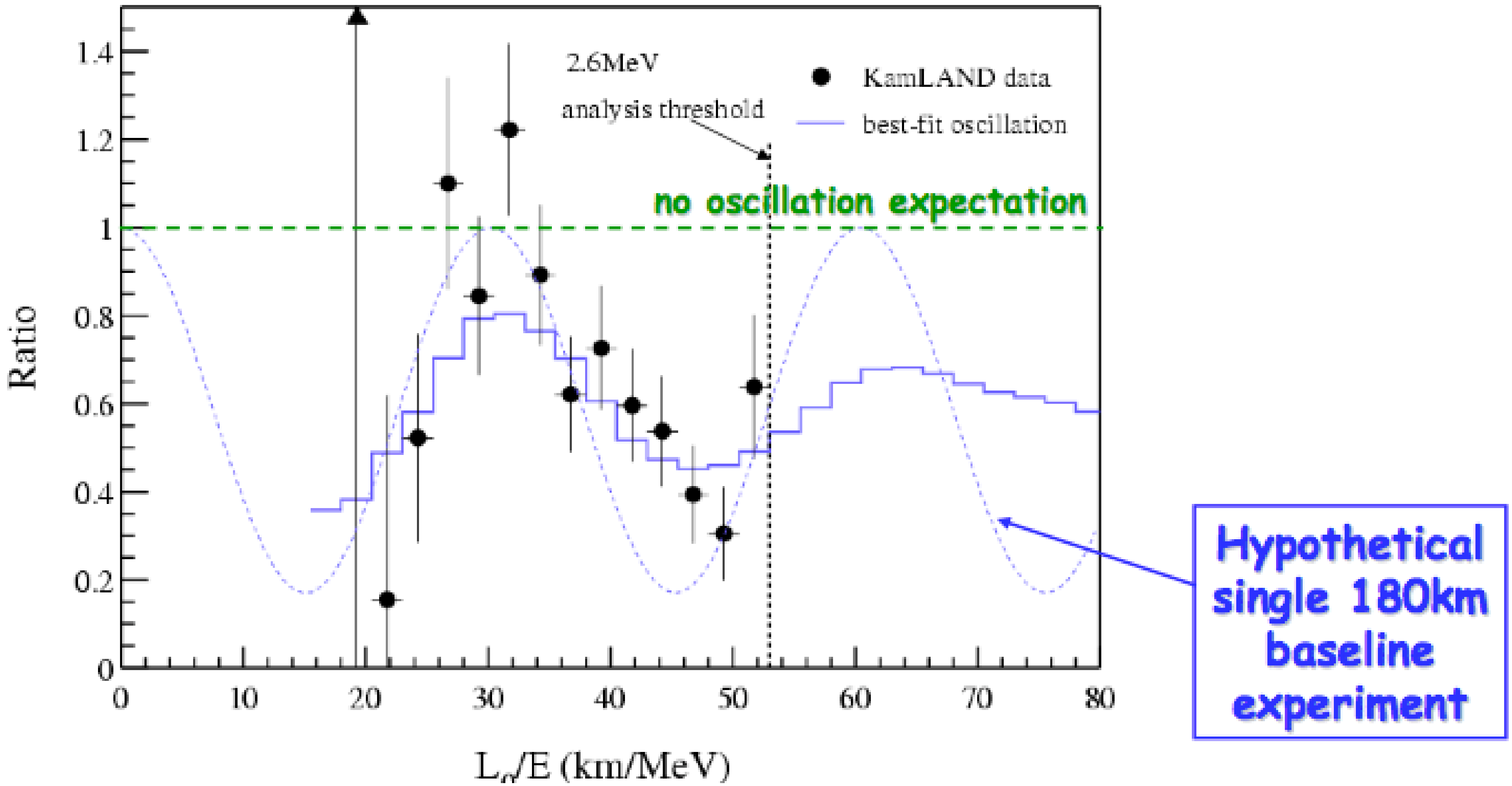


KAMLAND: Oscillation fit.

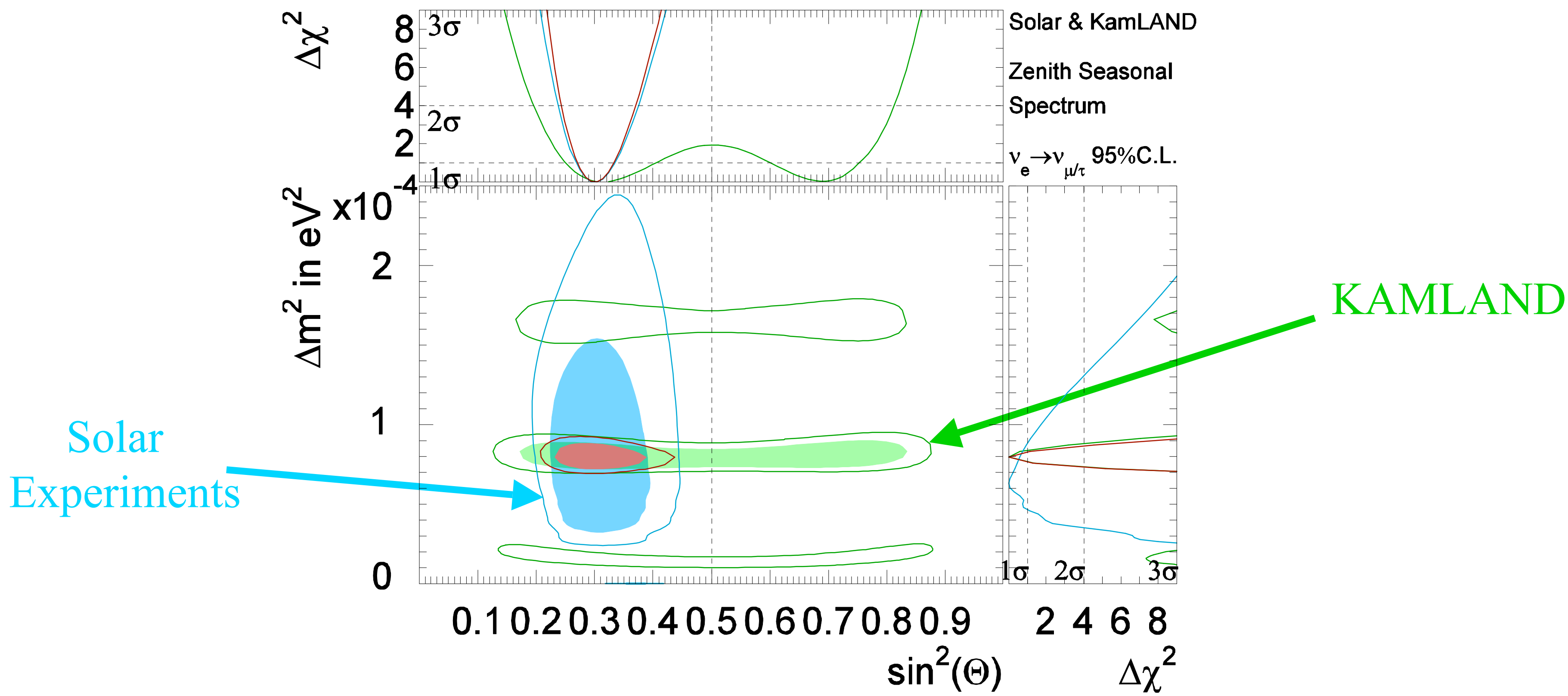
KamLAND can do better than an average suppression:

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

Clear oscillation pattern



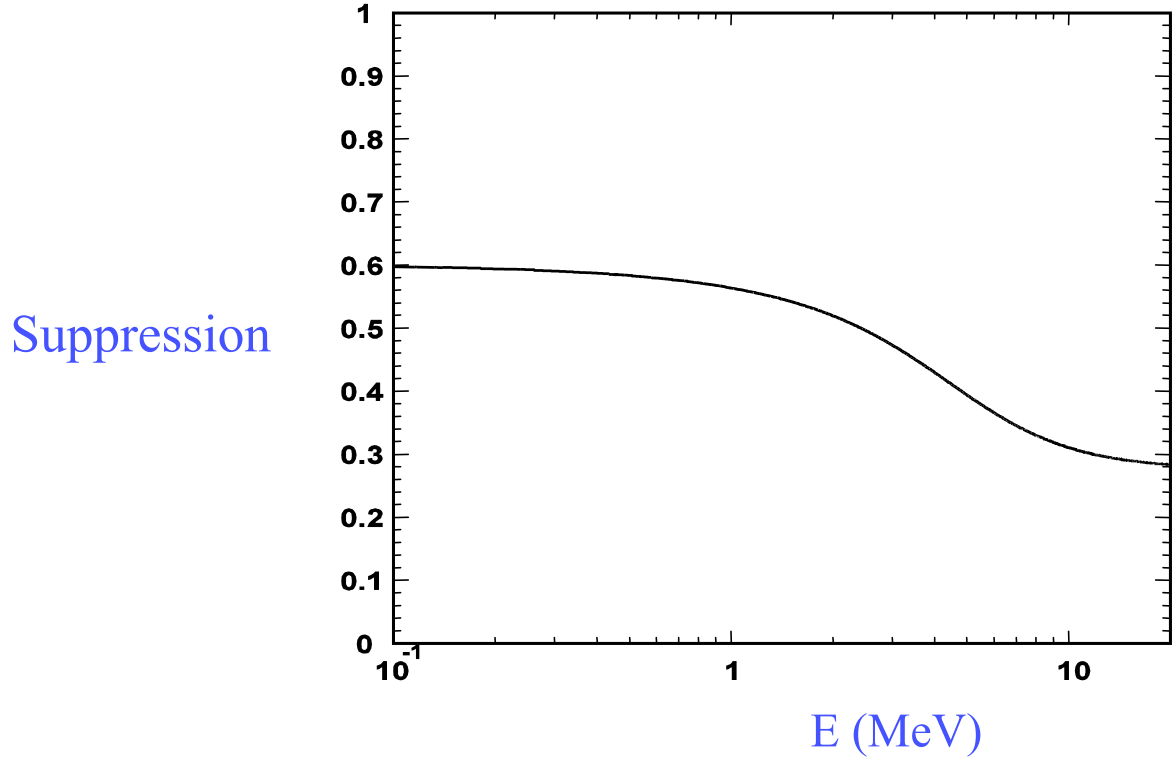
Solar suppression confirmed by KAMLAND:



KamLAND + Solar
Completely consistent
LMA solution only one.

Solar+KamLAND:
Δm^2=(7.9 +0.4/-0.3)X10^{-5} ev^2
$\sin^2\theta$=0.30 +0.04/-0.025

Suppression for Large Mixing Angle Solution



No HOLE at the beryllium neutrino energy: just a smooth suppression.
How do we explain this?
For the accepted solar solution:
Cos 2θ = **0.43** and ($2\sqrt{2}\ G_F N_e E$) is always smaller (**1.5×10^{-5} E**)
even for the highest solar density and the highest Boron neutrino energy ~ 15 MeV.

So no resonance.

MSW

$$H_M = H_{vac} + V_W \begin{array}{c} \begin{array}{cc} \nu_e & \nu_\mu \end{array} \\ \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \end{array} \begin{array}{c} \nu_e \\ \nu_\mu \end{array} + V_Z \begin{array}{c} \begin{array}{cc} \nu_e & \nu_\mu \end{array} \\ \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \end{array} \begin{array}{c} \nu_e \\ \nu_\mu \end{array}$$

$$H_M = \frac{\Delta m^2_{sol}}{4E} \begin{pmatrix} -cos2\theta_{sol} & sin2\theta_{sol} \\ sin2\theta_{sol} & cos2\theta_{sol} \end{pmatrix} + \sqrt{2} G_F N_e \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$$

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

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

So the interaction term dominates. ν_e is an eigen state of H. No off-diagonal terms.

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

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

$\sin 2\theta_M \sim 0 \quad 2\theta_M = \pi$

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

$|\nu_e\rangle = \cos\theta_m |\nu_1\rangle + \sin\theta_m |\nu_2\rangle$ = Pure $|\nu_2\rangle$ state

Oscillations in matter MSW: Boron ν

- The ν_e is then in a pure ν_2 state. $|\nu_e\rangle = \cos\theta_m |\nu_1\rangle + \sin\theta_m |\nu_2\rangle$
- As it propagates out of the sun, the density drops.
- The density decreases slowly, adiabatically. This gives time to the ν_e to oscillate to ν_μ
- The ν_μ content increases.
- But at a decreased density, θ_m decreases and the description of a pure ν_2 has an increased ν_μ content. $|\nu_2\rangle = \sin\theta_m |\nu_e\rangle + \cos\theta_m |\nu_\mu\rangle$

- So this increased ν_μ content means a pure ν_2 is retained all the way out of the sun.
- It remains a ν_2 all the way to Earth.
- No oscillations possible: there is just ONE mass state , ν_2 at the exit from the sun.
- Once it reaches the earth $\theta = \theta_v$ and the ν_2 will interact according to

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

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

pp ν Oscillations

For the pp neutrinos, the other end of the spectrum at ~ 0.2 MeV,

The vacuum term dominates.

The ν_e will oscillate away to ν_μ, ν_τ with a probability governed by $\theta_{vac} = \theta_{sol}$.

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

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 ν will be a ν_e or have oscillated to a ν_μ ν_τ.

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

And the survival probability will be: 1 - (1/2) $\sin^2\theta_{sol}$

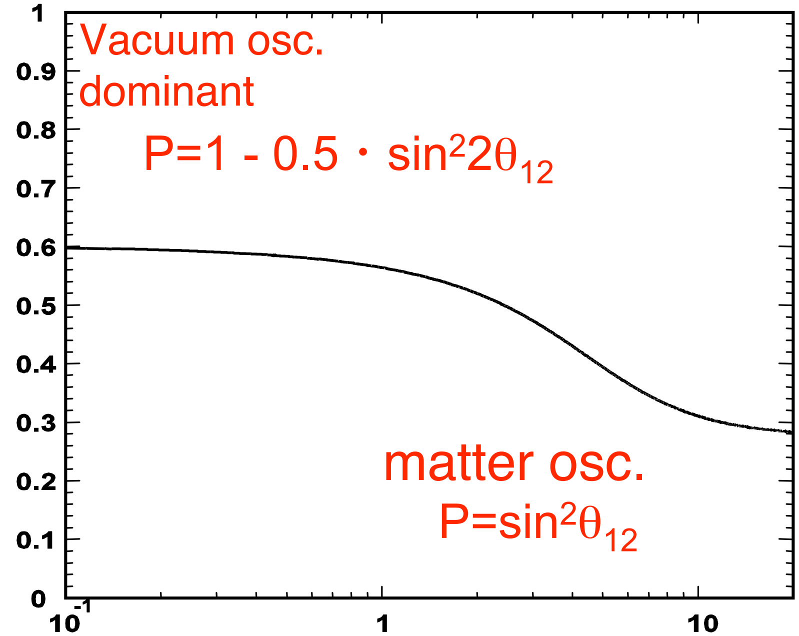
Survival probability

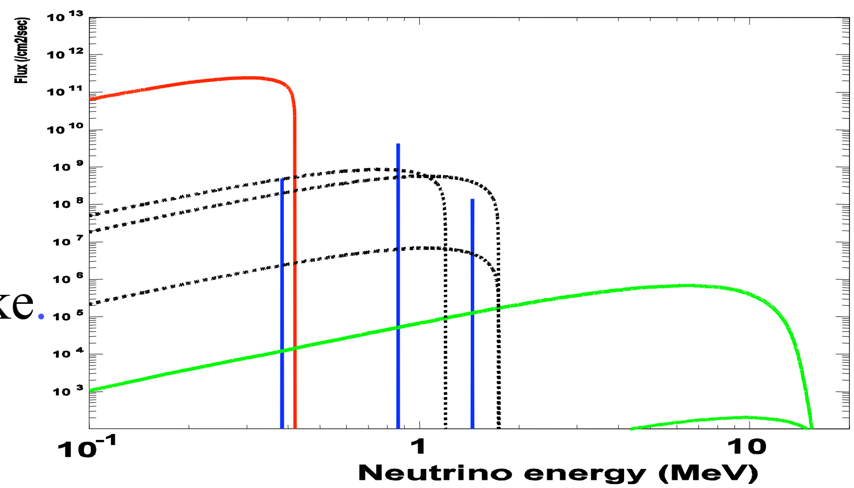
So what kind of oscillations are these?

- 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

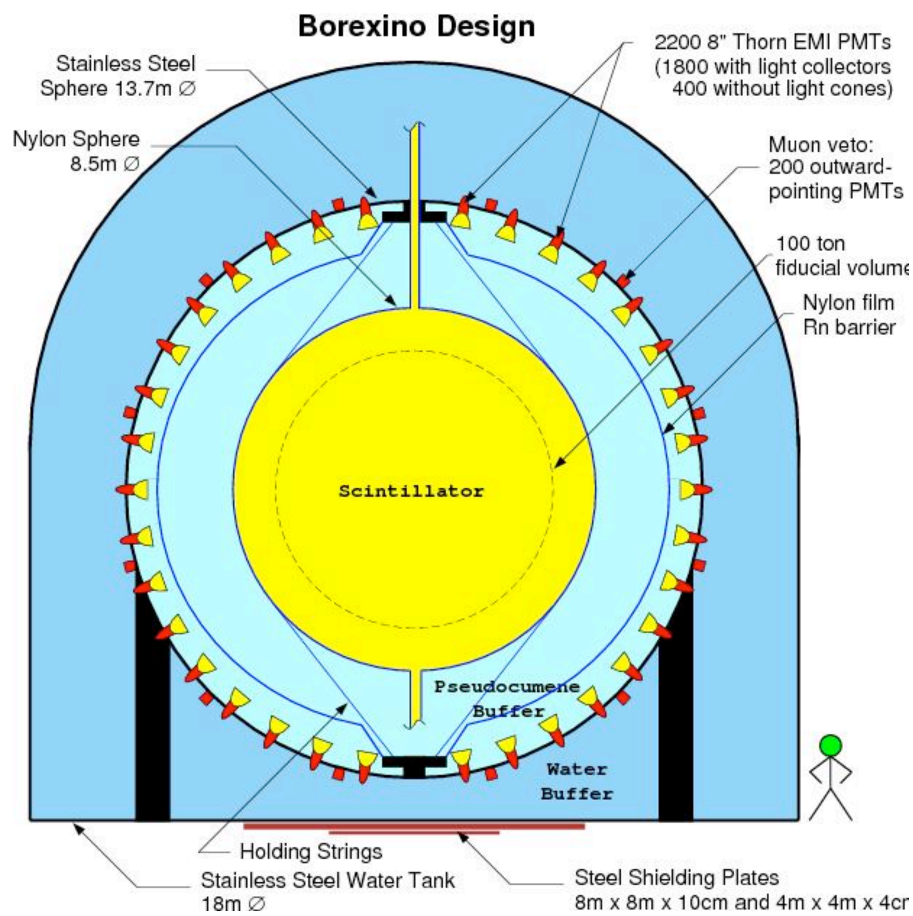
Borexino

- **PURPOSE:**

- Investigate the region of the
- ^{7}Be (862 keV) line.
- Was Homestake right?

- **METHOD:**

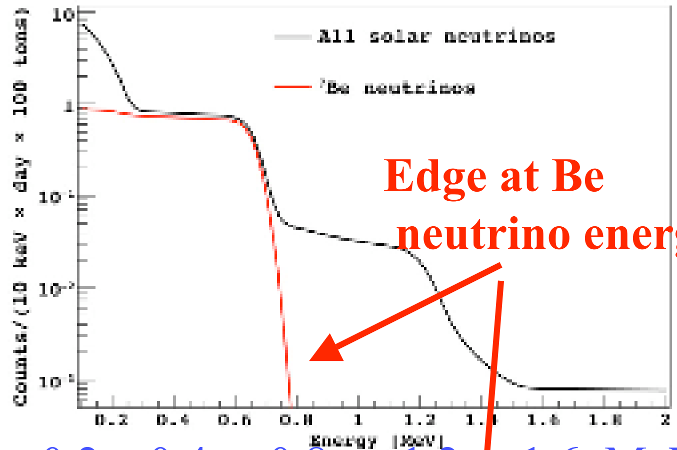
- 300 tons of organic scintillator
- Use scattering on electrons
- $\nu + e \rightarrow \nu + e$
- Measure electron energy spectrum



Borexino rates

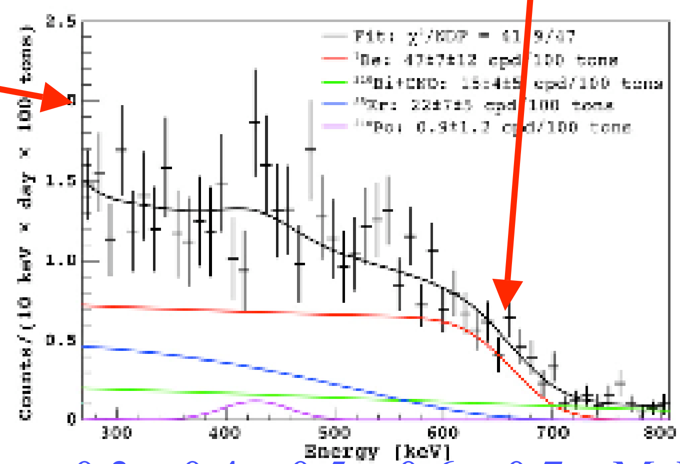
- Must set very low threshold in event acceptance
- This is difficult because of radioactive contaminants such as ^{14}C in the scintillator.
- In 270-800 keV e-recoil energy window Expect
  - **75 ± 4 events** / (day.100tons) if SSM right and no oscillations
  - **49 ± 4** if LMA.
- First results: **47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

Recoil electron energy spectrum
Recoil electron energy spectrum



Edge at Be neutrino energy

0.2 0.4 0.8 1.2 1.6 MeV



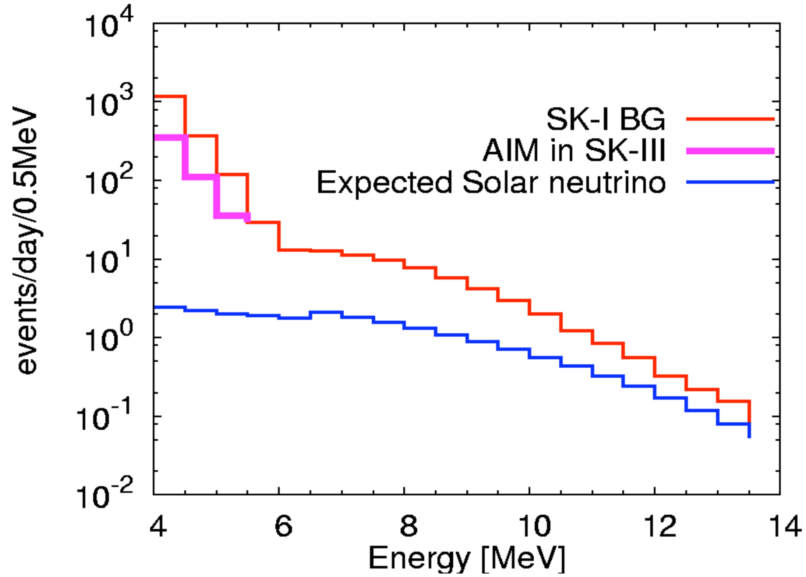
0.3 0.4 0.5 0.6 0.7 MeV

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

Boron spectrum distortion

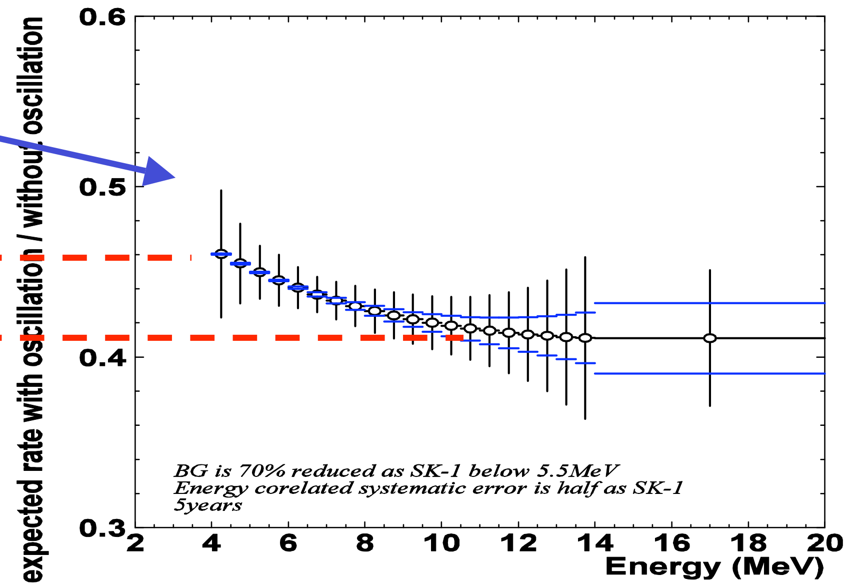
- SuperK is working to reduce its threshold to be able to track the Boron spectrum down to 4 MeV.

- This should lead to a 10% reduction of the suppression
- From 0.4 to 0.45.



0.45

0.40



Summary and status

3-family oscillation matrix
(Pontecorvo, Maki, Nakagawa, Sakata)

S = sine c = cosine

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

➢ δ CP violation phase.

➢ θ_{12} drives SOLAR oscillations: $\sin^2 \theta_{12} = 0.32^{+0.05}_{-0.04}$ (+- 16%)

➢

➢ θ_{23} drives ATMOSPHERIC oscillations: $\sin^2 \theta_{23} = 0.50^{+0.13}_{-0.12}$ (+-18%)

➢

➢ θ_{13} the MISSING link ! $\sin^2 \theta_{13} < 0.033$ Set by a reactor experiment: CHOOZ.

Present status of the mixing matrix

$$U_{CKM} \dashrightarrow \begin{bmatrix} 1.0 & 0.2 & 0.001 \\ 0.2 & 1.0 & 0.01 \\ 0.001 & 0.01 & 1.0 \end{bmatrix}$$

$$U_{MNS} \dashrightarrow \begin{bmatrix} 0.8 & 0.5 & <0.3 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{bmatrix}$$

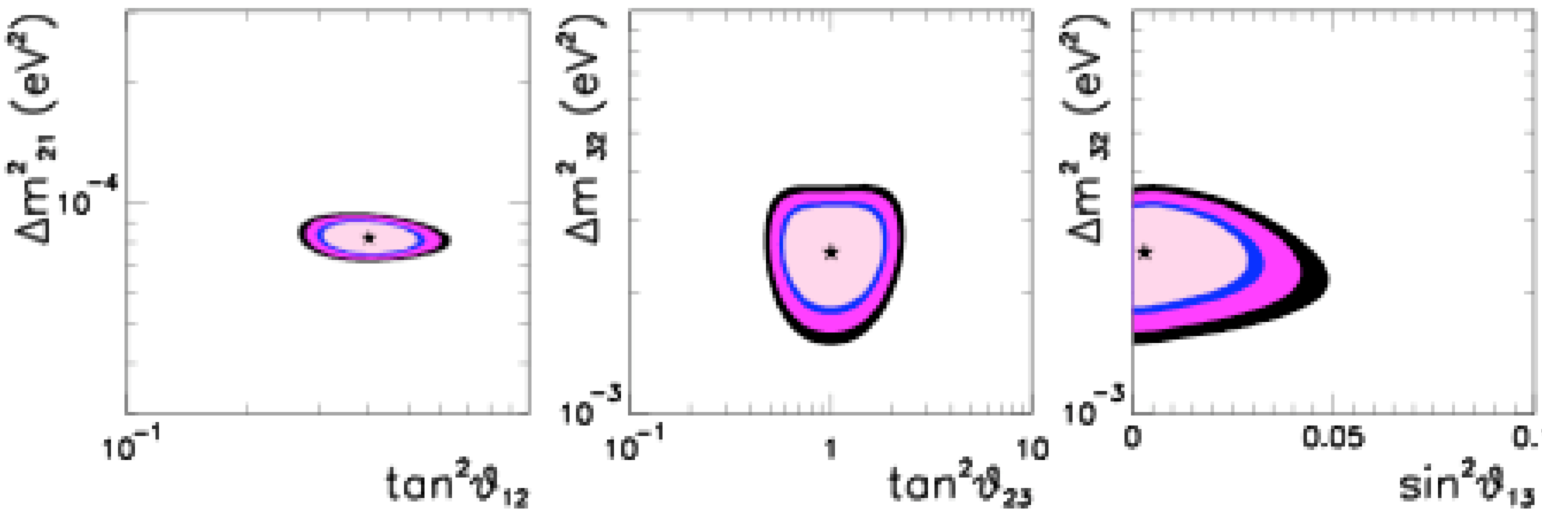
The quark mixing matrix

- 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



- $\sin^2\theta_{13}$: amount of $\boldsymbol{\nu_e}$ in ν_3 : $U_{e3}\nu_e + U_{\mu 3}\nu_\mu + U_{t3}\,\nu_\tau$

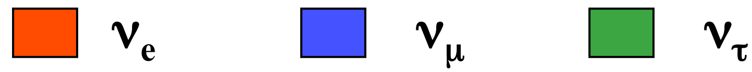
  $s_{13}\,e^{-i\delta}\,\boldsymbol{\nu_e} + s_{23}c_{13}\nu_\mu + c_{23}c_{13}\nu_\tau$ ---> $s_{13}^{\,2}$

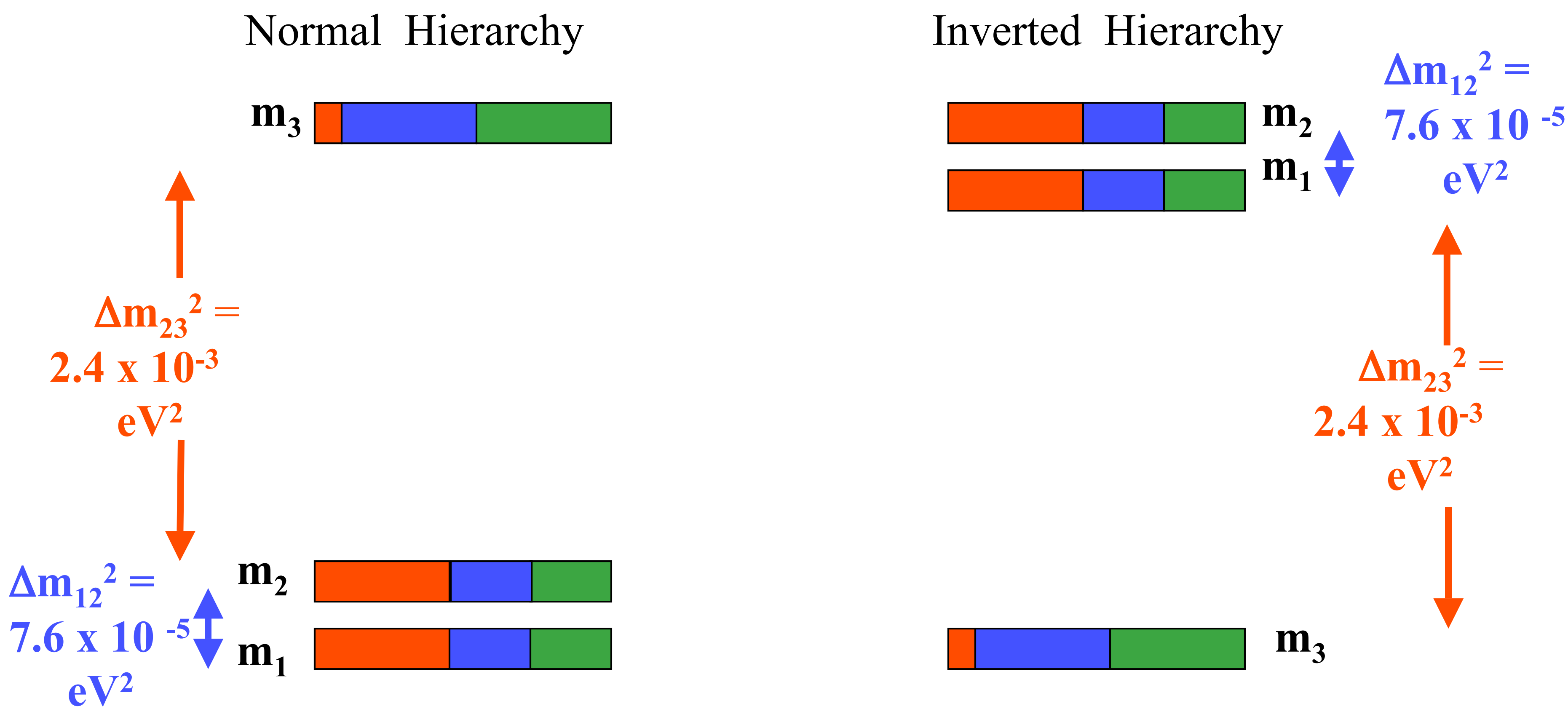
- $\tan^2\theta_{12}$: Ratio of ν_e in ν_2 to ν_e in ν_1 $|U_{e2}|^2/|U_{e1}|^2$

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

- $\tan^2\theta_{23}$: Ratio ν_μ to ν_τ in ν_3. If $\theta_{23}=\pi/4$ Maximal mixing equal amounts.

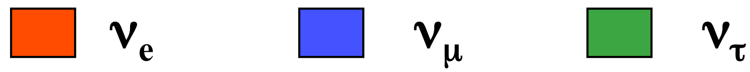
Mass hierarchy
Sign of Δm^2_{23}

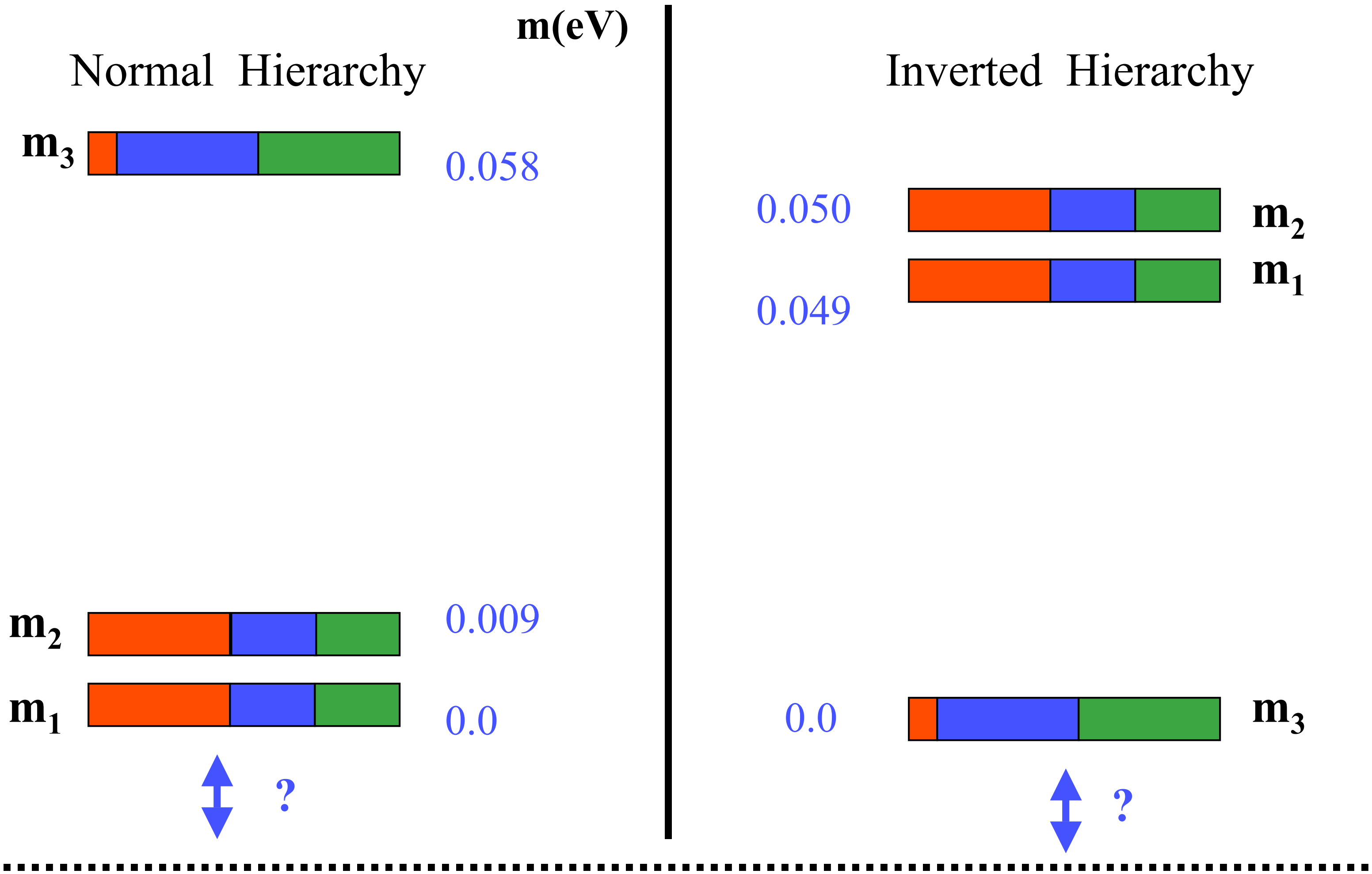




Oscillations only tell us about DIFFERENCES in masses
Not the ABSOLUTE mass scale: Direct measurements or Double β decay

Absolute ν Masses





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…….