The Quest for Neutrino Mass

Topics in Nuclear Physics
8.712

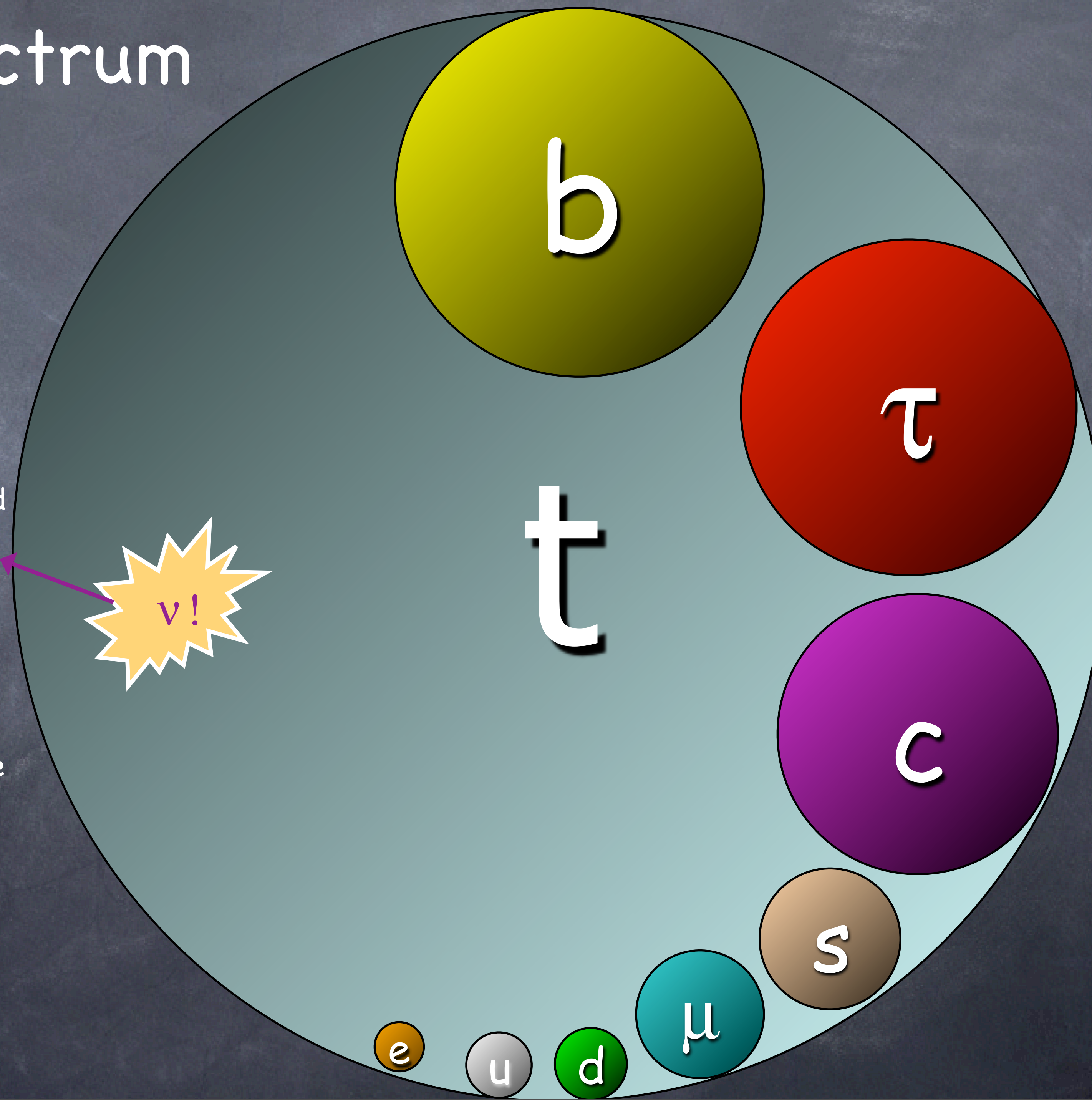
Lecture 1 : Neutrino mass

The Lectures...

- Lecture 1: The Implications of Neutrino Mass
- Lecture 2: Neutrino Detection Techniques

The Mass Spectrum

- Various symmetries distinguish neutrinos from other quarks and leptons.
- Neutrinos would be a period at the end of this sentence.
- Insight into the mass spectrum.
- Insight into the scale where new physics begins to take hold.

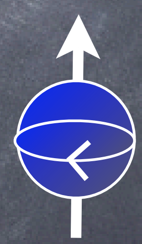


Handedness vs. Helicity

- All particles have "helicity" associated with them.
- Helicity is the projection of spin along the particle's trajectory.
- Can be aligned with or against the direction of motion.

Right-helicity

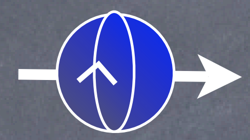
Spin along direction of motion

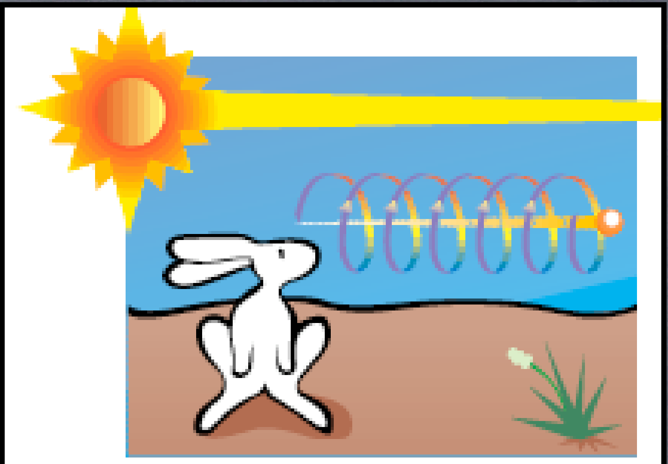


Left-helicity

Spin anti-along direction of motion

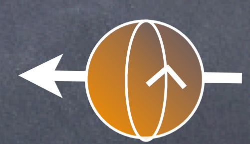
Handedness vs. Helicity

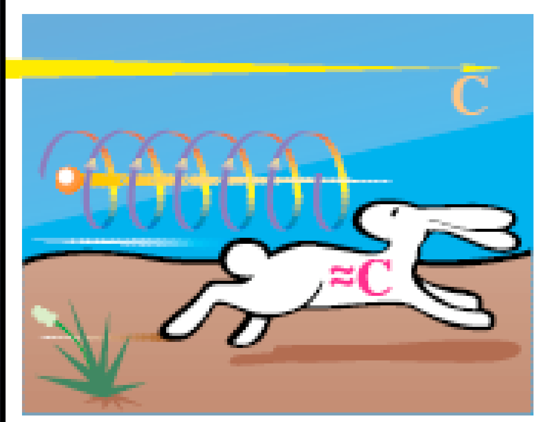




Looks like a left-handed corkscrew.

- Helicity is not invariant under Lorentz transformations.
    - Changes depending on the frame of reference.
- Since related to angular momentum (and angular momentum is conserved), the helicity can be directly measured.





No—like a right-handed corkscrew!

Handedness vs. Helicity

- One can also describe a particle's **handedness** or **chirality**.
- Chirality IS Lorentz invariant. It does not depend on the frame of reference. It is the LI counterpart to helicity.
- In the limit that the particle mass is zero, helicity and chirality are the same.

Left-handed

Right-handed

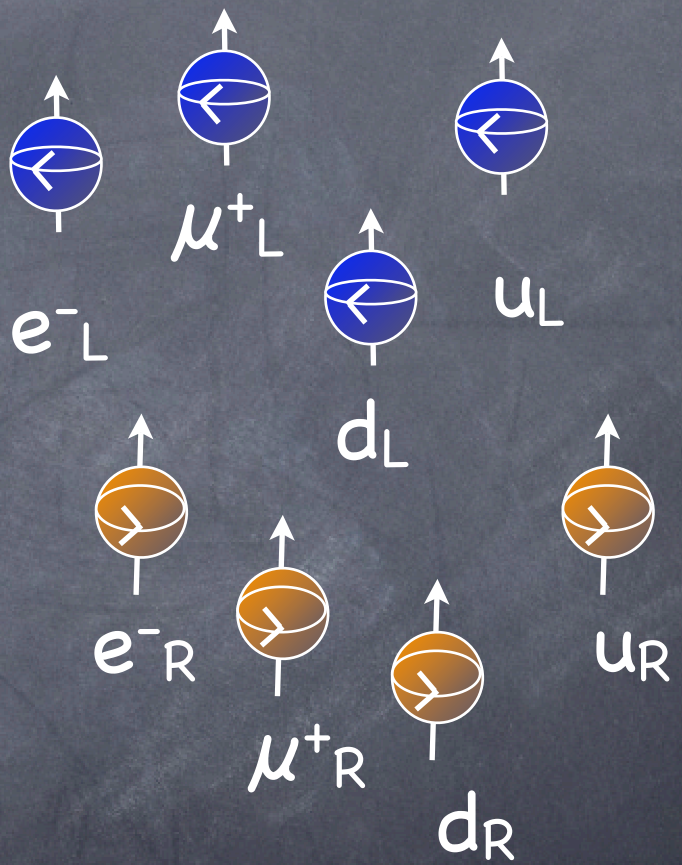
$$\psi_L = \frac{1}{2}(1 - \gamma^5)$$

$$\psi_R = \frac{1}{2}(1 + \gamma^5)$$

What makes neutrinos different...

- All charged leptons and quarks come in both left-handed and right-handed states...

This implies parity conservation



Recall...

Weak force does not conserve parity....

C. S. Wu demonstrates parity violation in the weak force using ^{60}Co decay

"Parity Violation"

- All other forces studied at the time (electromagnetism and the strong force) rigidly obeyed parity conservation.
- Weak force violates parity conservation completely.

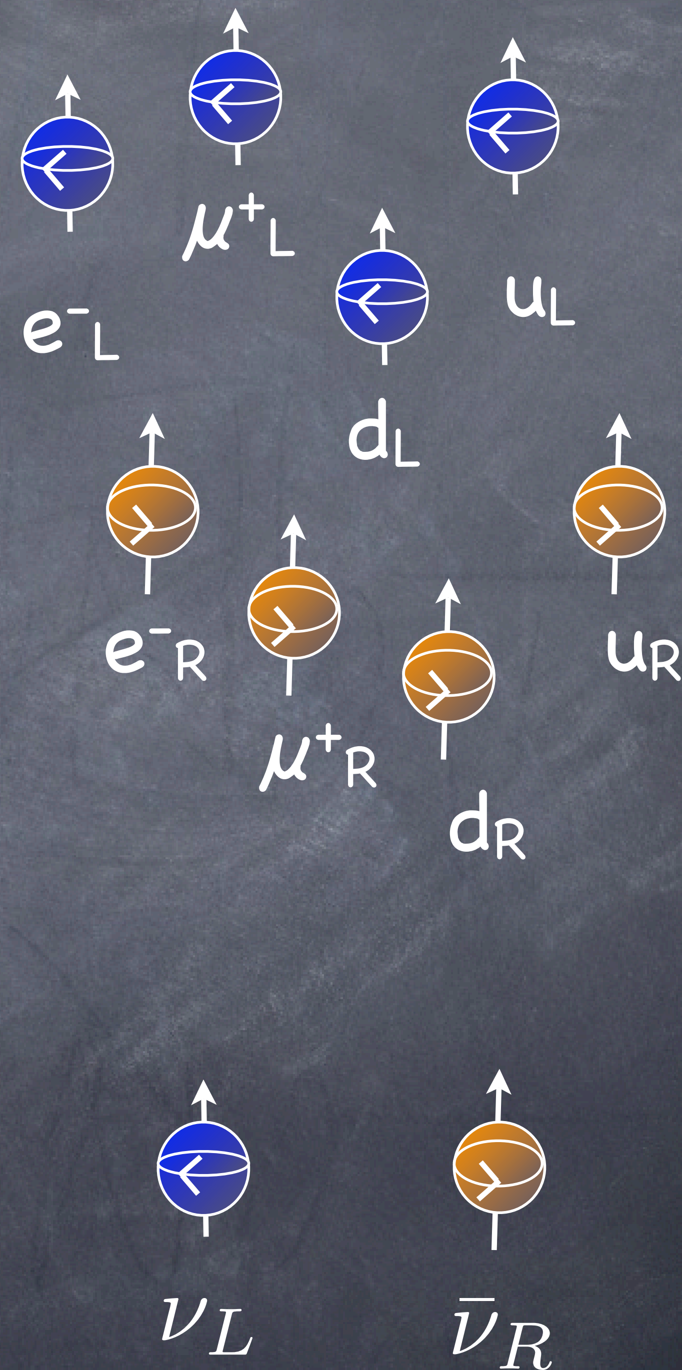
What makes neutrinos different...

- All charged leptons and quarks come in both left-handed and right-handed states...

  This implies parity conservation

- ...except for neutrinos!

- Neutrinos only come as left-handed particles (or right-handed anti-particles).



Mass & Handedness

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu \partial_\mu - m)\psi$$

- Left- and right-handed components come into play when dealing with mass terms in a given Lagrangian...

$$\mathcal{L}_{\text{mass}} = m(\bar{\psi}\psi)$$

$$= m(\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L)$$

- Because neutrinos only appear as left-handed particles (or right-handed anti-particles), the Standard Model wants massless neutrinos.

- All other spin 1/2 particles have both right-handed and left-handed components.

Set m = 0!
and the right-handed neutrinos never appear

Mass & Handedness

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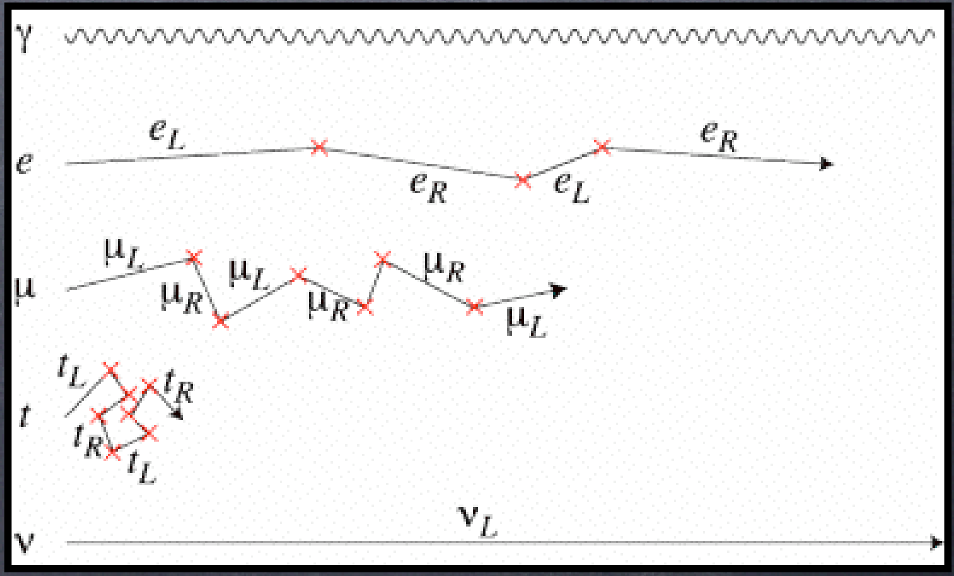


How to Introduce Neutrino Mass...

- **Introduce right-handed neutrino:**
  - Would allow a Dirac mass in the model.
  - Introduces two new states to the standard model.
  - New states would be sterile neutrinos (no coupling to the $W^{\pm}$)

$$\psi = \psi_L + \psi_R$$

Sterile term

Complex conjugate term

- **Introduce neutrinos as Majorana particles:**
  - Neutrino & anti-neutrino as the same particle.
  - Mass introduced through charge conjugate term.

$$\psi = \psi_L + \psi_R^c$$

Naturalness of Neutrino Mass

- Why is the neutrino mass so small compared to the other particles?
- Perhaps neutrinos hold a clue to theories beyond the Standard Model.
- For example, a number of Grand Unified Theories {Left-Right Symmetric; SO(10)} predict the smallness of neutrino mass is related to physics that take place at the unification level.

The See-Saw Mechanism

$$\mathcal{L} = (\bar{\phi}_L \ \bar{\phi}_R)\mathcal{M}\begin{pmatrix} \phi_L \\ \phi_R \end{pmatrix} \qquad \mathcal{M} = \begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix}$$

$$m_R \sim m_{\text{GUT}}$$

$$m_\nu \sim \frac{m_D^2}{m_R}$$

The Quest for Neutrino Mass...

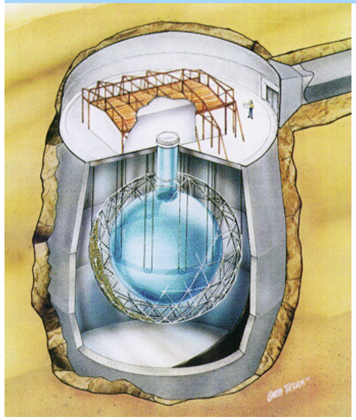
- It is recognized that, although neutrino mass can be "forced" into the Standard Model, it offers possibilities to probe physics at a much higher scale than is currently accessible.
- Majorana masses in particular offer a natural means to understand some of the very basic questions that remain in our cosmological picture.
- As experimentalists, we are driven toward one goal...

Sir Galahad

...measuring it!

Four Methods

Neutrino Oscillations



Probe mass differences

Use quantum mechanical effects

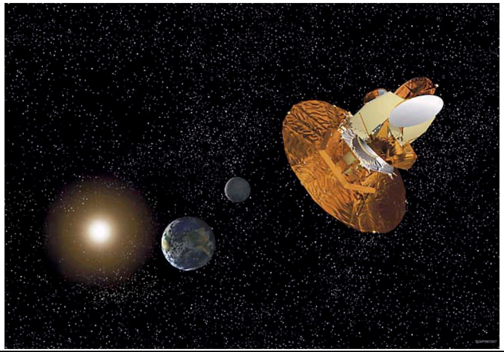
Sources: Reactor, solar, atmospheric, beams

Cosmology

Probe total neutrino mass

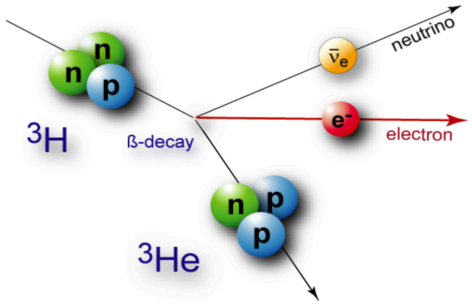
Use Gen. relativity

Satellites & ground observatories



ν

Single Beta Decay



Probe absolute mass scale

Use conservation of energy

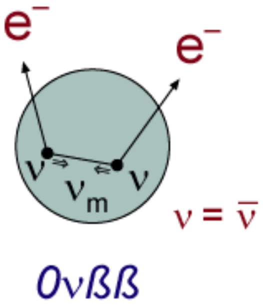
Model-independent

0ν Double Beta Decay

Probe Majorana masses

Use rarest decays on Earth

Probe identity of neutrinos

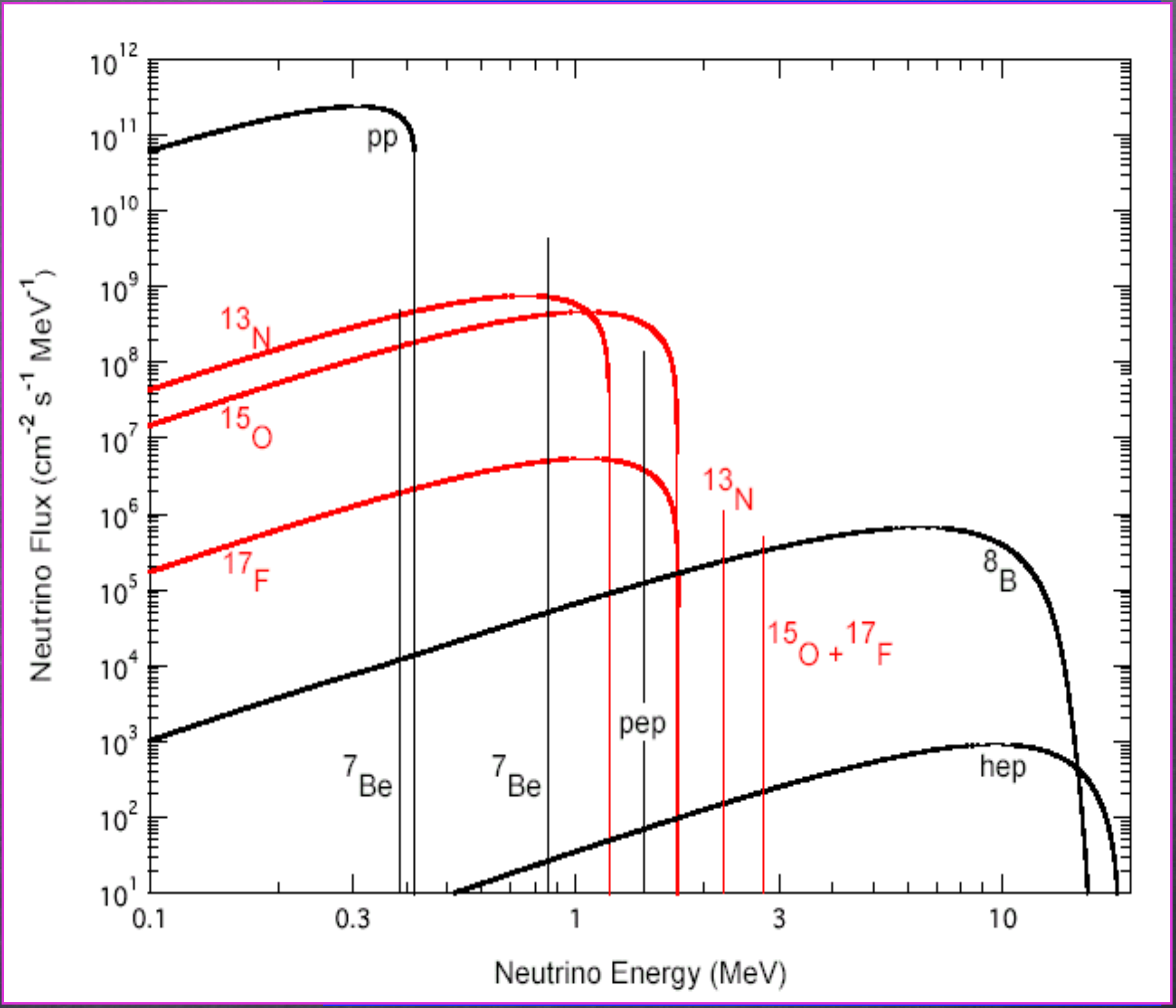


$m_\nu \neq 0$

(The Role of Oscillation Experiments)

Mapping the Sun with ν's

- Neutrinos from the sun allow a direct window into the nuclear solar processes.
- Each process has unique neutrino energy spectrum
- Only electron neutrinos are produced at these energies.
- Different experiments sensitive to different aspects of the spectrum.



Measuring Neutrinos from the Sun

Gallium

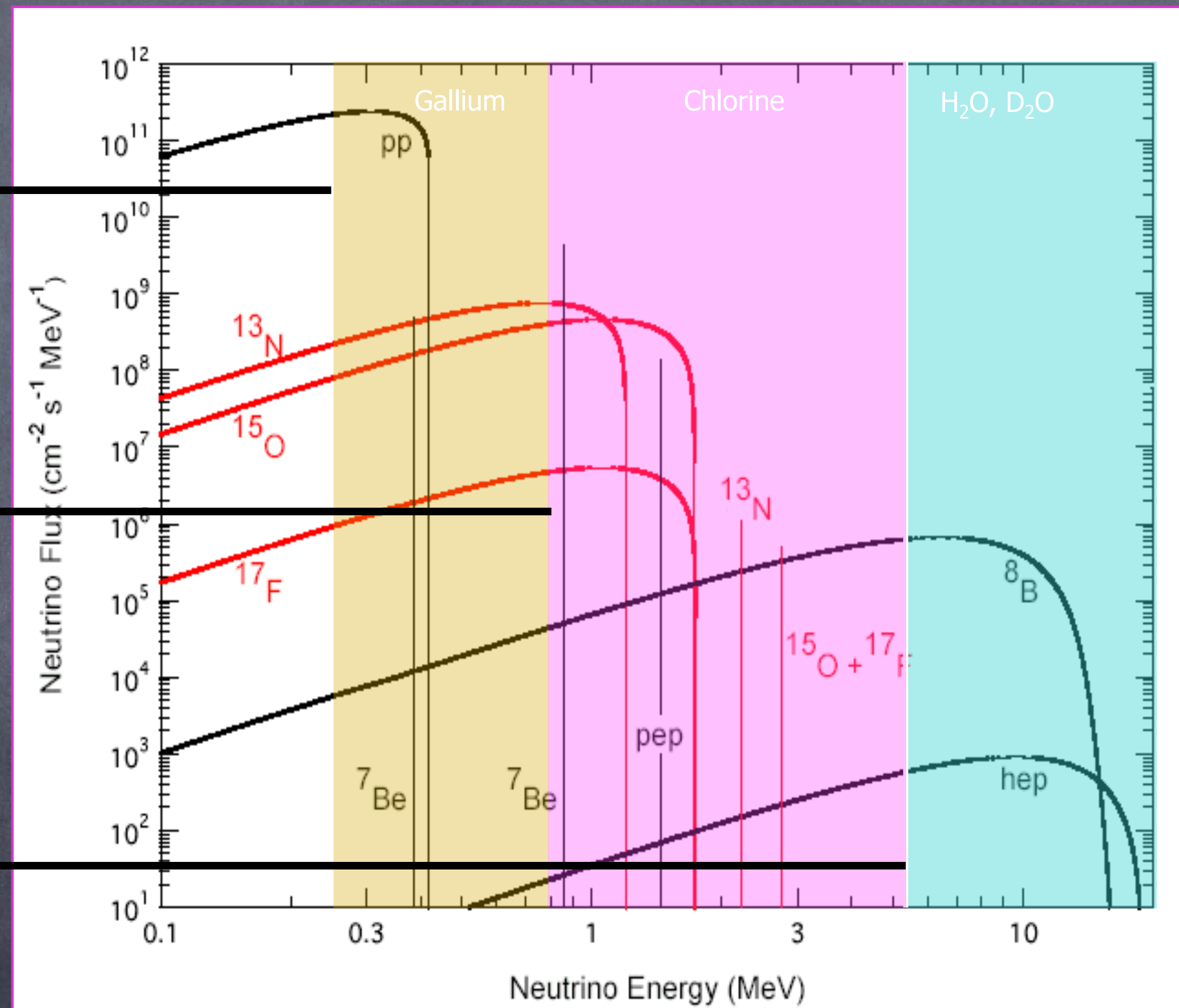
Technique: Radiochemical

Chlorine

Technique: Radiochemical

H_2O & D_2O

Technique: Cherenkov; Real Time

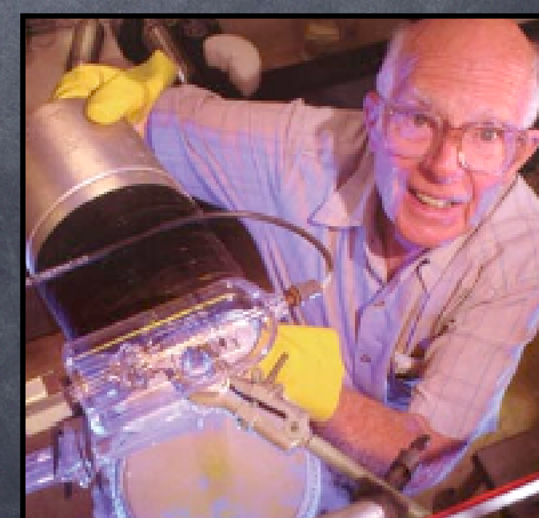


The Solar Puzzle Begins..

- Davis designs first experiment to measure electron neutrinos coming from the sun.
- Experiment counted individual argon atoms (~40 atoms/mo).

HOMESTAKE

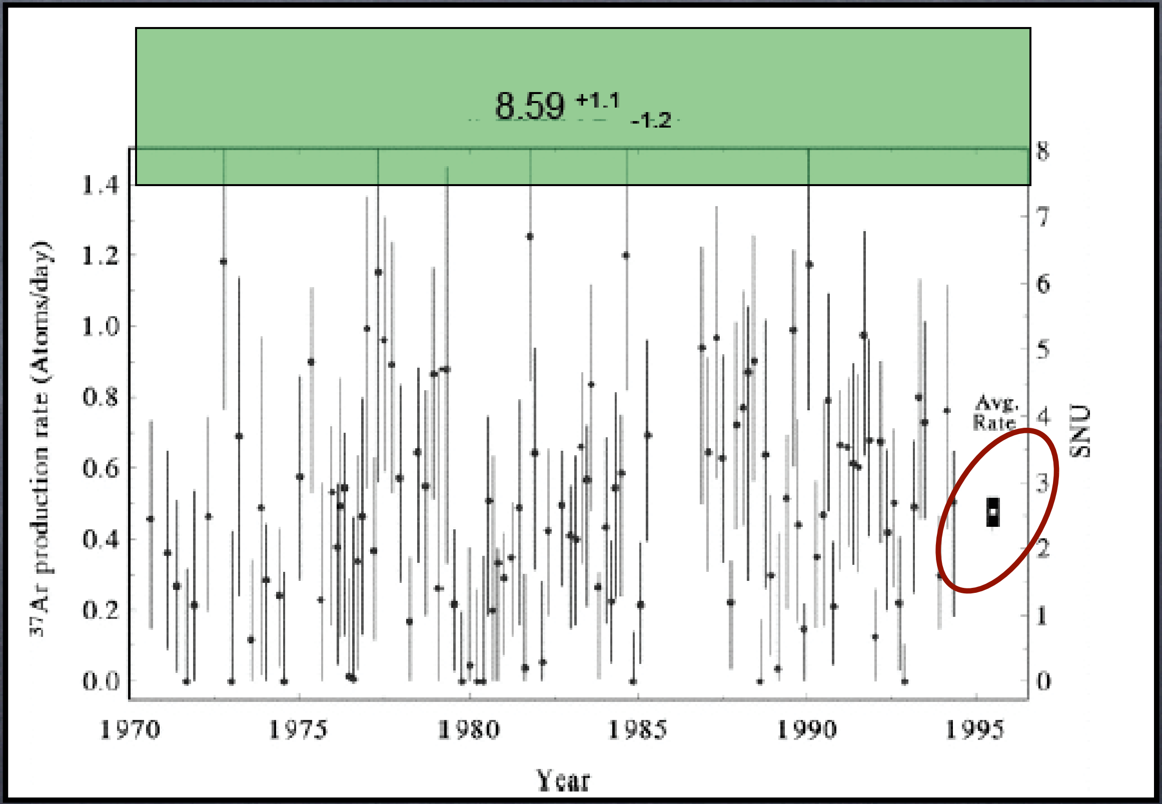
$^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-$



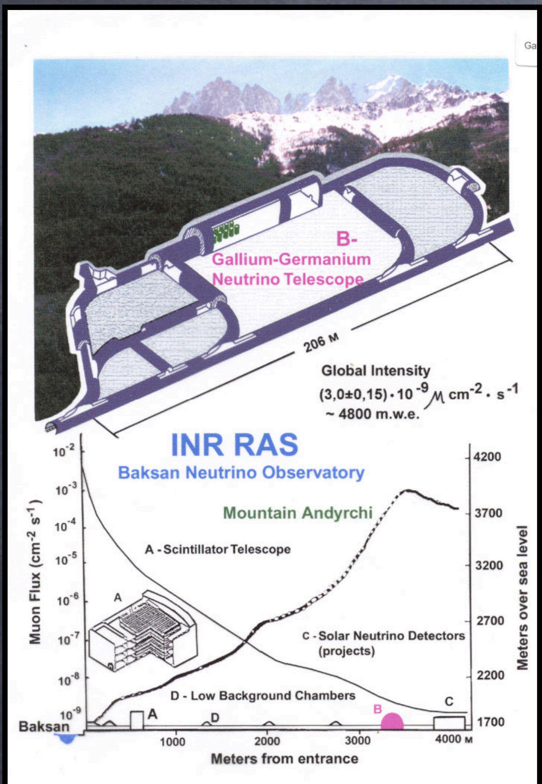
Raymond Davis, Jr.
Winner of 2002 Nobel Prize in Physics

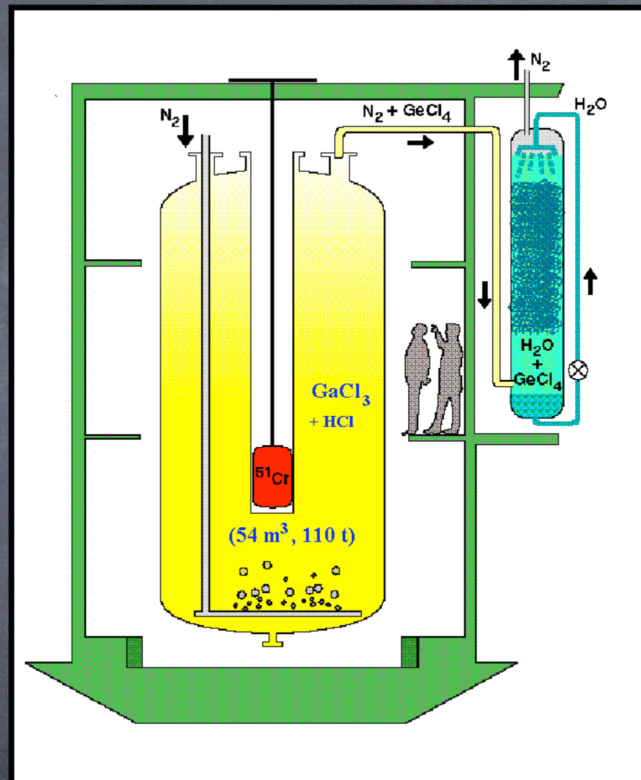
Homestake Results (1970-1994)

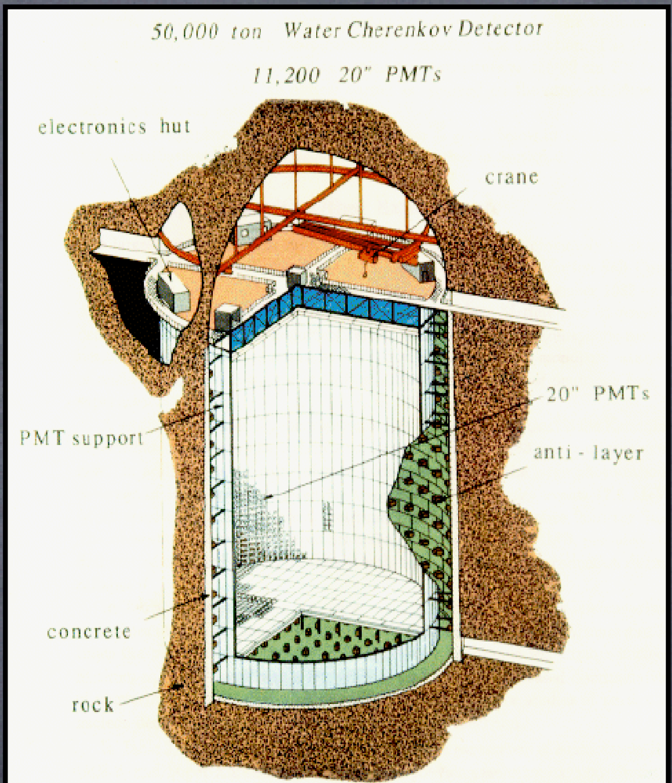
- Only 1/3 of the neutrinos expected from the sun are seen in the Homestake experiment.
- Doubts on hydrodynamic calculations and/or experimental data are raised.
- When in doubt, do it again.



Repeat as necessary...







SAGE

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

Measures 1/2 of expected flux

Gallex/GNO

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

Measures 1/2 of expected flux

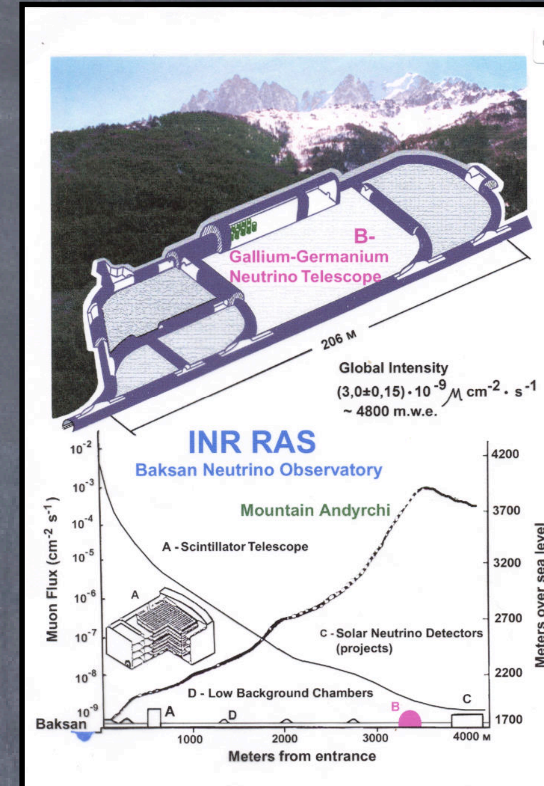
Super-Kamiokande

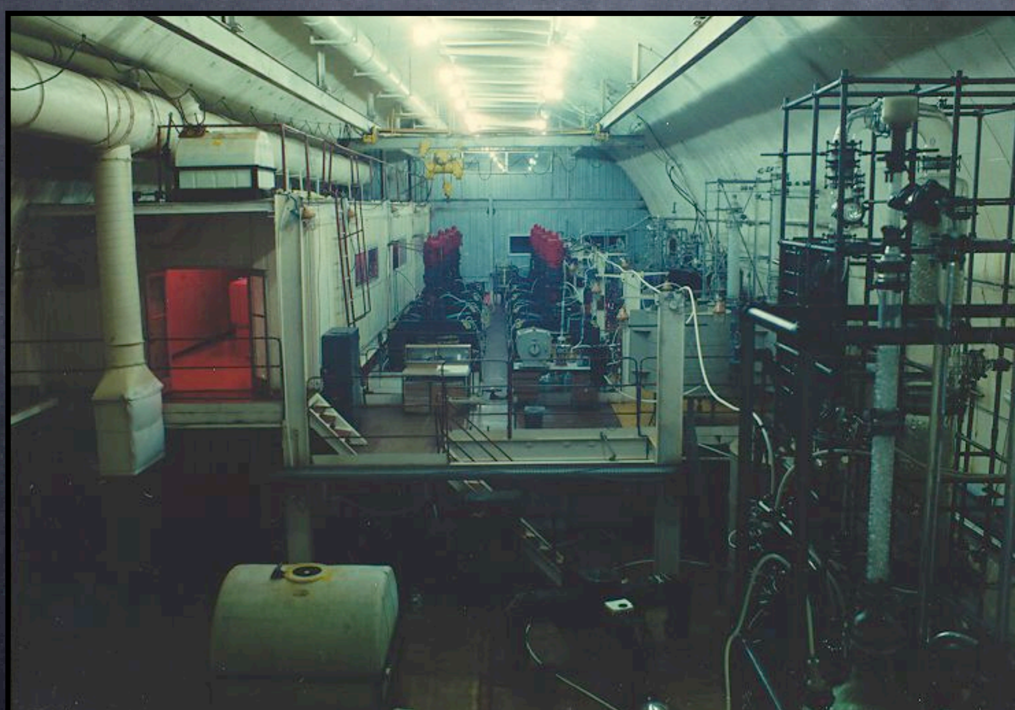
$e^- + \nu_e \rightarrow \nu_e + e^-$

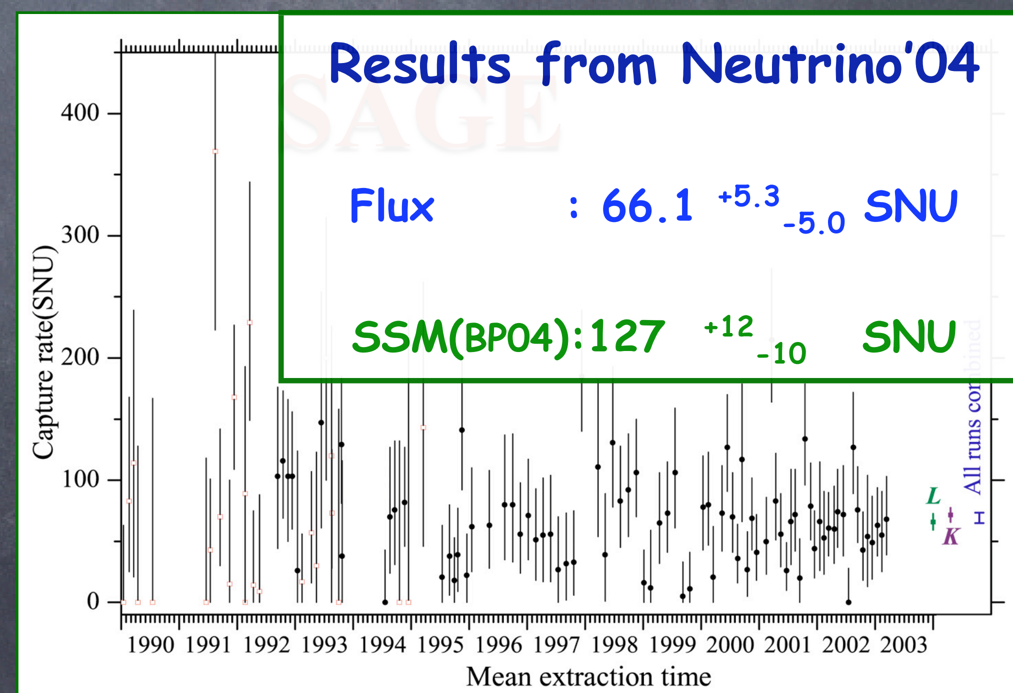
Measures 40% of expected flux

SAGE

- Uses ^{71}Ga metal to measure ν_e flux.
- Threshold = 233 keV
- Sensitive to lowest (pp chain) energy neutrinos.



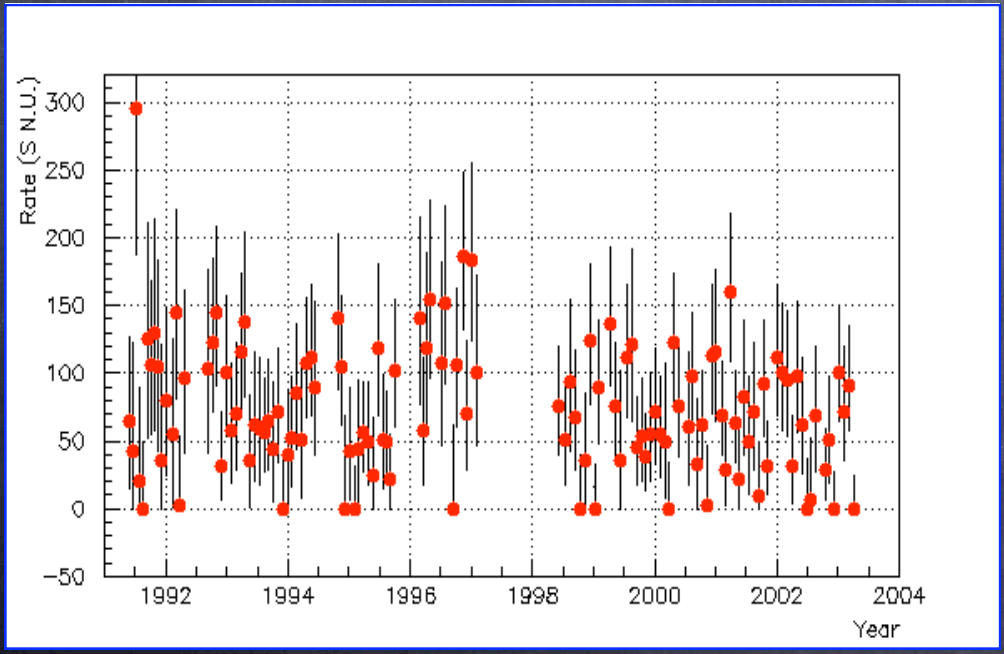


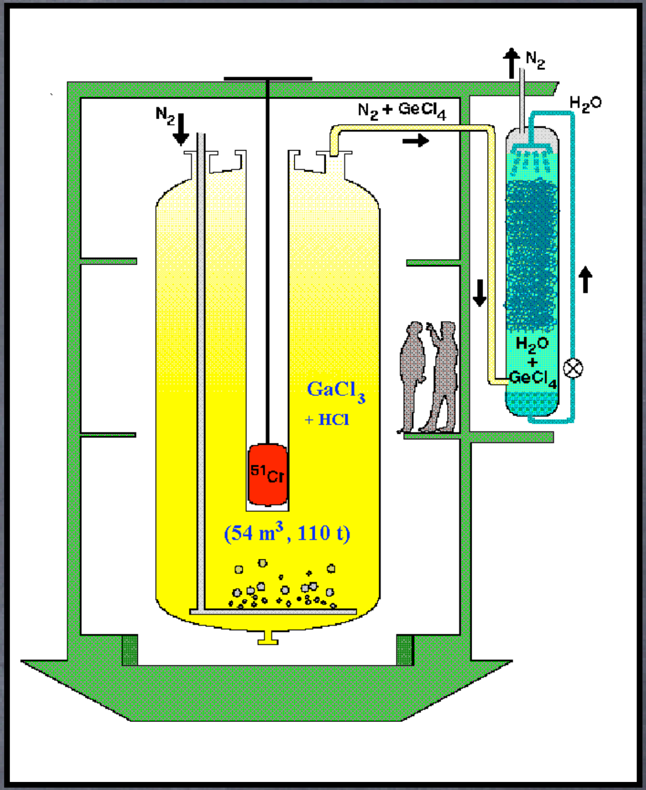


* 1 SNU = 1 ν interaction per sec in 10^{36} atoms.

GALLEX/GNO

- Uses $GaCl_3$ acid to measure ν_e flux.
- Improved counting technique from GALLEX
- Also used ^{51}Cr source for neutrino calibration





Results

GNO = 62.9 ± 5.4 ± 2.5 SNU

GALLEX = 77.5 ± 6.2 $^{+4.3}_{-4.7}$ SNU

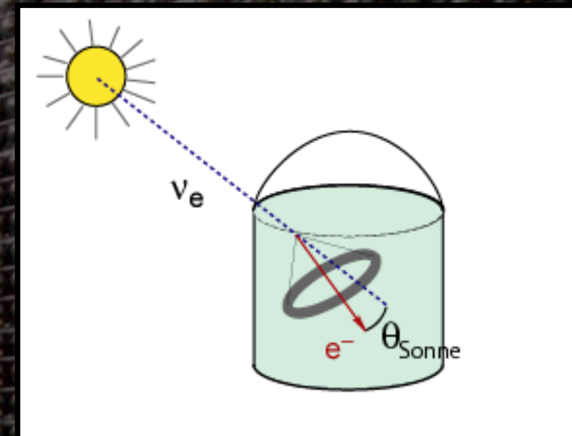
GALLEX+GNO 69.3 ± 4.1 ± 3.6 SNU

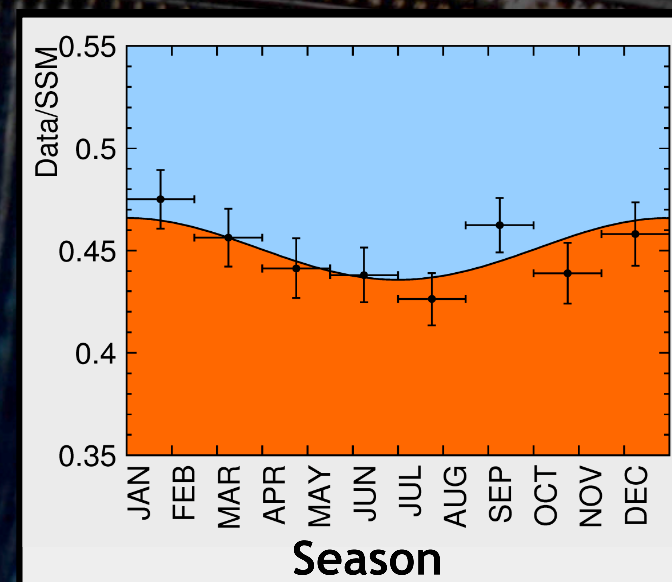
Kamiokande & Super-Kamiokande

- First time Cerenkov, real-time detection is used for solar neutrinos.
- Use of elastic scattering as detection channel

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

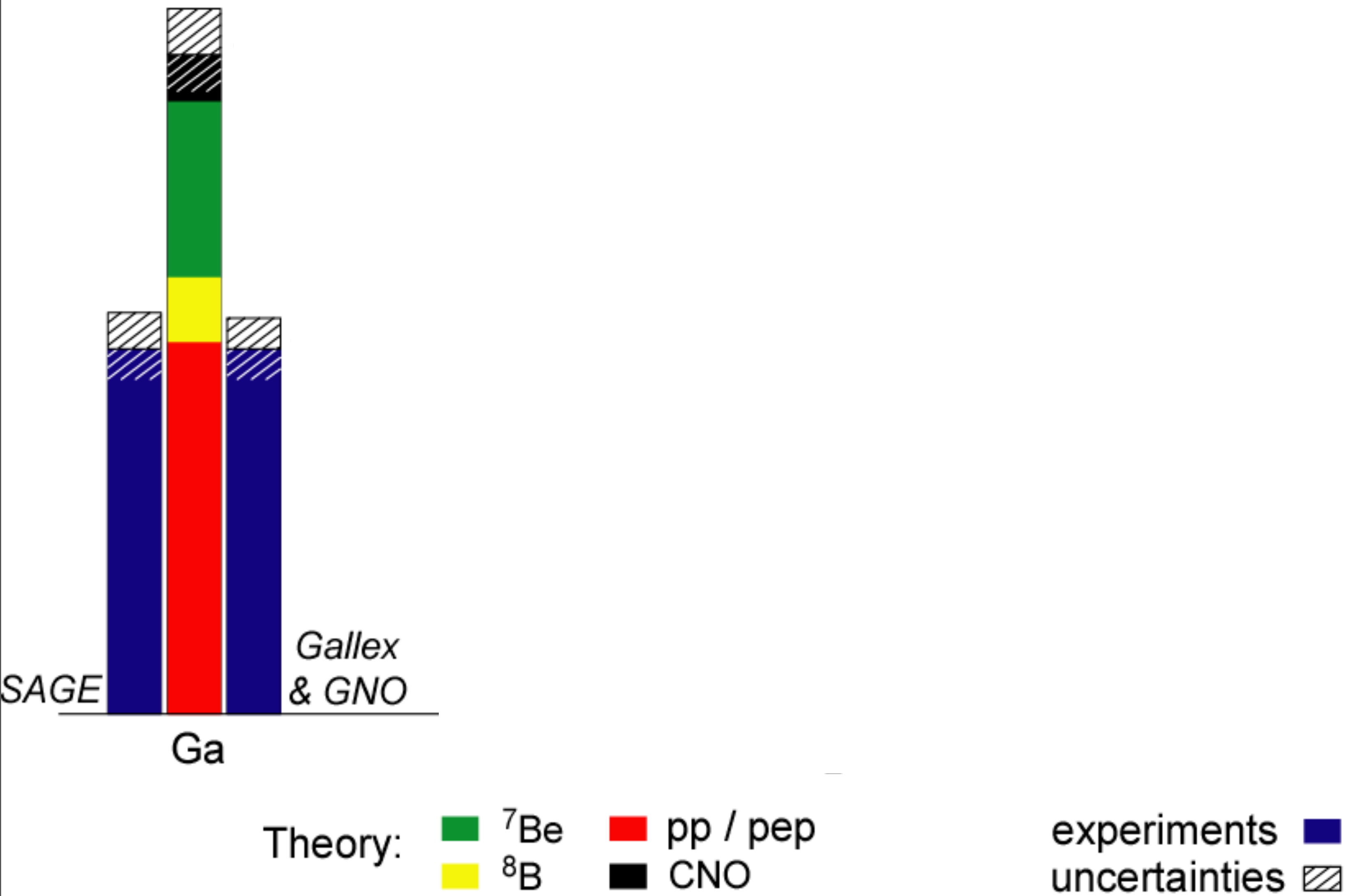
- Sensitive to highest energy (^{8}B) neutrino.
- Use neutrino direction to discern from background.



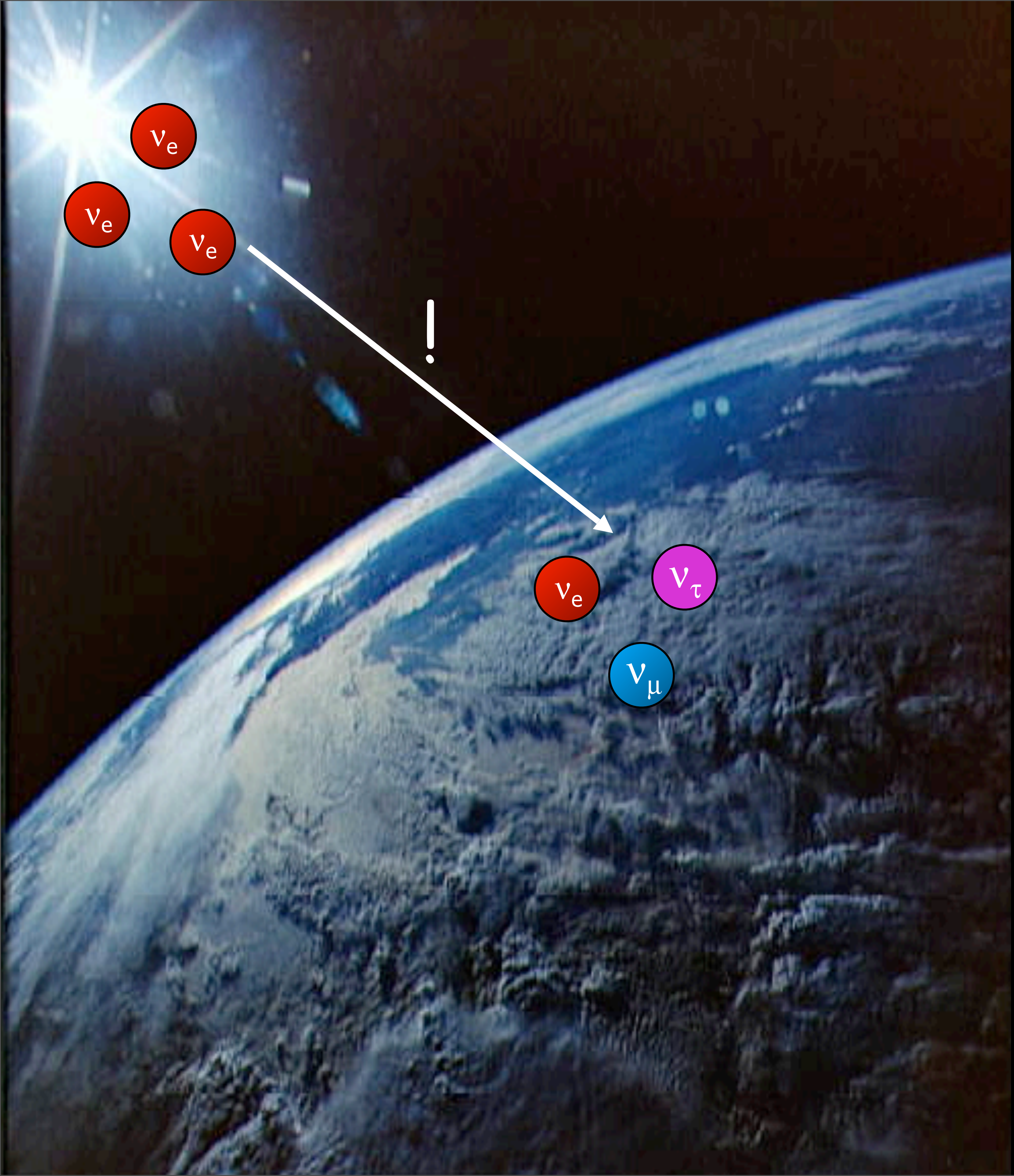


Comparison of total rates

experiments and SSM *(Bahcall-Pinsonneault*



H. Murayama



The sun only makes "electron-type" neutrinos

Detectors only detect electron-type neutrinos.

What if neutrinos are changing from one type to the other?

Need to measure ALL neutrino types, regardless of what kind (flavor) they are...

Neutrino Oscillations

- Neutrino oscillations is the mechanism by which neutrinos can change from one type to the other…

Flavor ≠ Mass

- Mixing occurs if…
  - Neutrino flavors mix
  - Neutrinos have mass
- Look for appearance of different neutrino type or deficit of the total neutrinos expected.

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

$$\left|\nu\right\rangle = e^{-iE_1 t}(U_{e1}\left|\nu_1\right\rangle + U_{e2}e^{-iE_2 t+iE_1 t}\left|\nu_2\right\rangle + U_{e2}e^{-iE_3 t+iE_1 t}\left|\nu_3\right\rangle)$$

$$E_j - E_i \approx (m_j^2 - m_i^2)\frac{L}{2E}$$

$$P(\nu_\alpha - \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{j>i} U_{\alpha,j}U_{\beta,j}U_{\alpha,i}U_{\beta,i}\sin^2(1.27\Delta m_{ij}^2 L/E)$$

Neutrino Oscillations

- In general, we have a 3 x 3 matrix that describes neutrino mixing (the Maki-Nakagawa-Sakata-Pontecorvo, or MNSP mixing matrix):

- However, the picture simplifies if one of the mixing angles is small...

Bruno Pontecorvo

$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{atmospheric}} \times \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}}_{\text{reactor, accelerator}} \times \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar, KamLAND}} \times \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}_{0\nu\beta\beta}$$

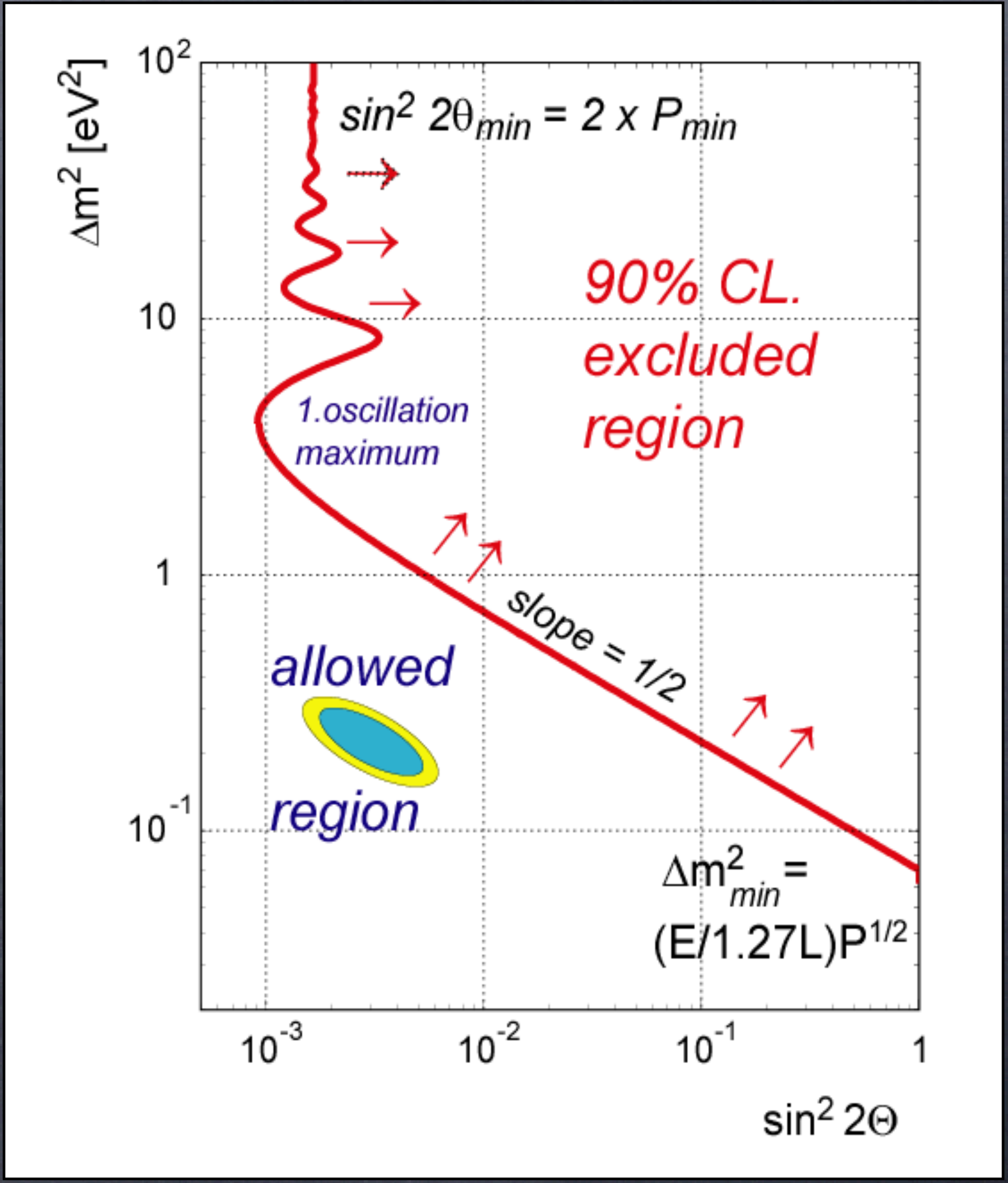
- Depends only on two fundamental parameter and two experimental parameters (for a given neutrino species).

$$\mathcal{P}_{\mathrm{surv}} = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4E_\nu} L\right)$$

Neutrino Oscillations

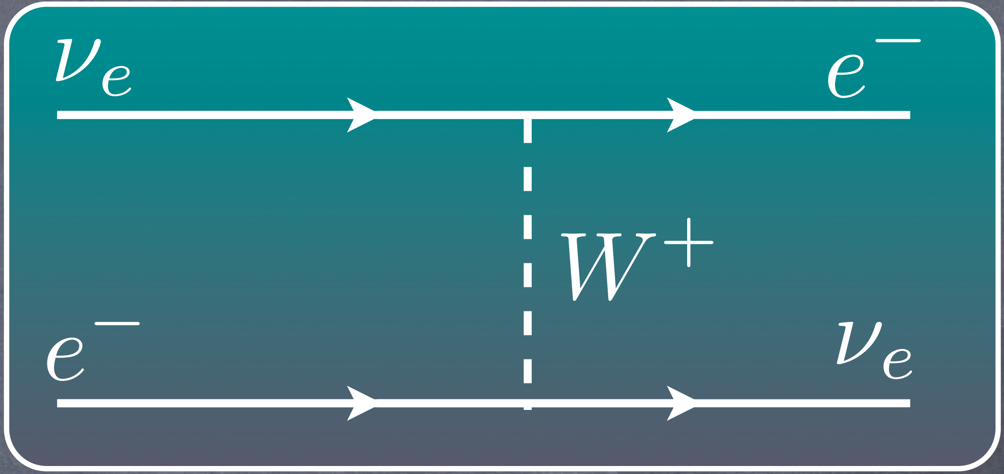
- One often uses mass-mixing plots to denote exclusion/allowed regions.
- Fair to use in 2 x 2 approximation (but can be confusing if more than one neutrino mixing is shown).

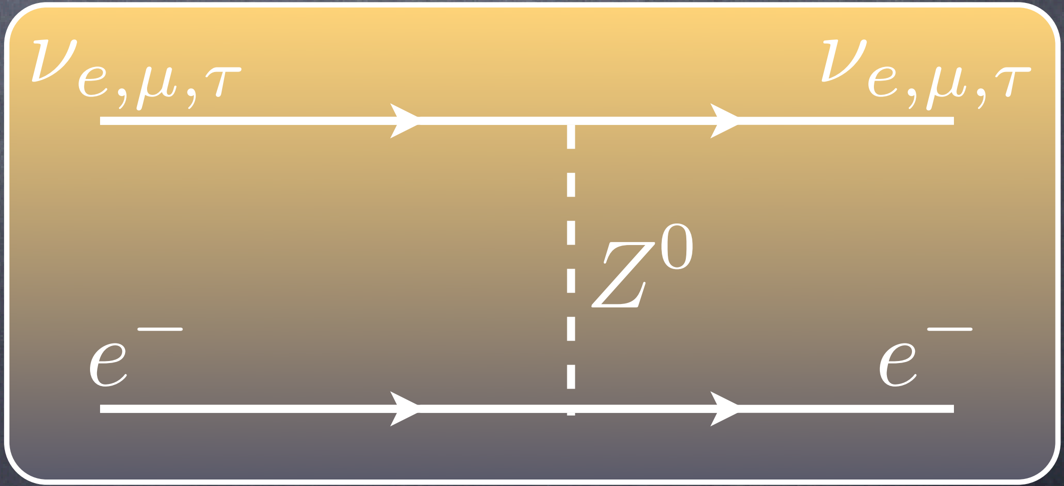
$$\mathcal{P}_{\rm surv} = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4E_\nu}L\right)$$



An Aside...
Neutrinos in Matter

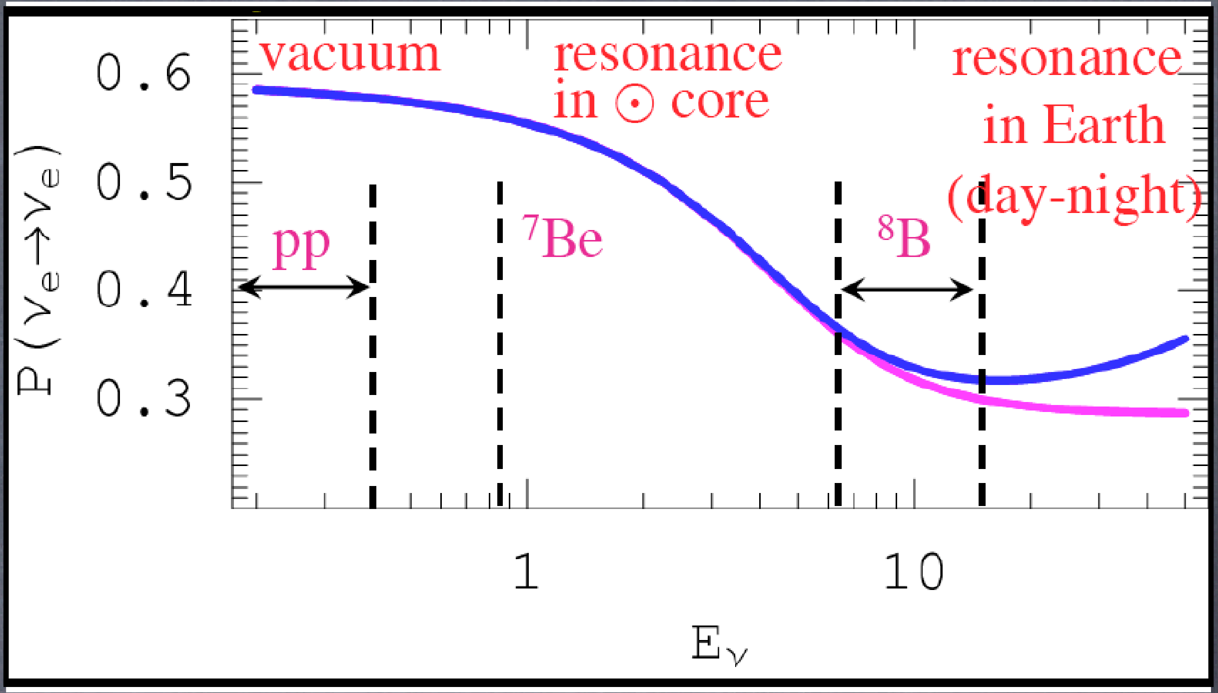
- Neutrino oscillations can take place in vacuum or matter.
- Matter introduces a potential difference between electron and mu/tau reactions.





An Aside...
Neutrinos in Matter

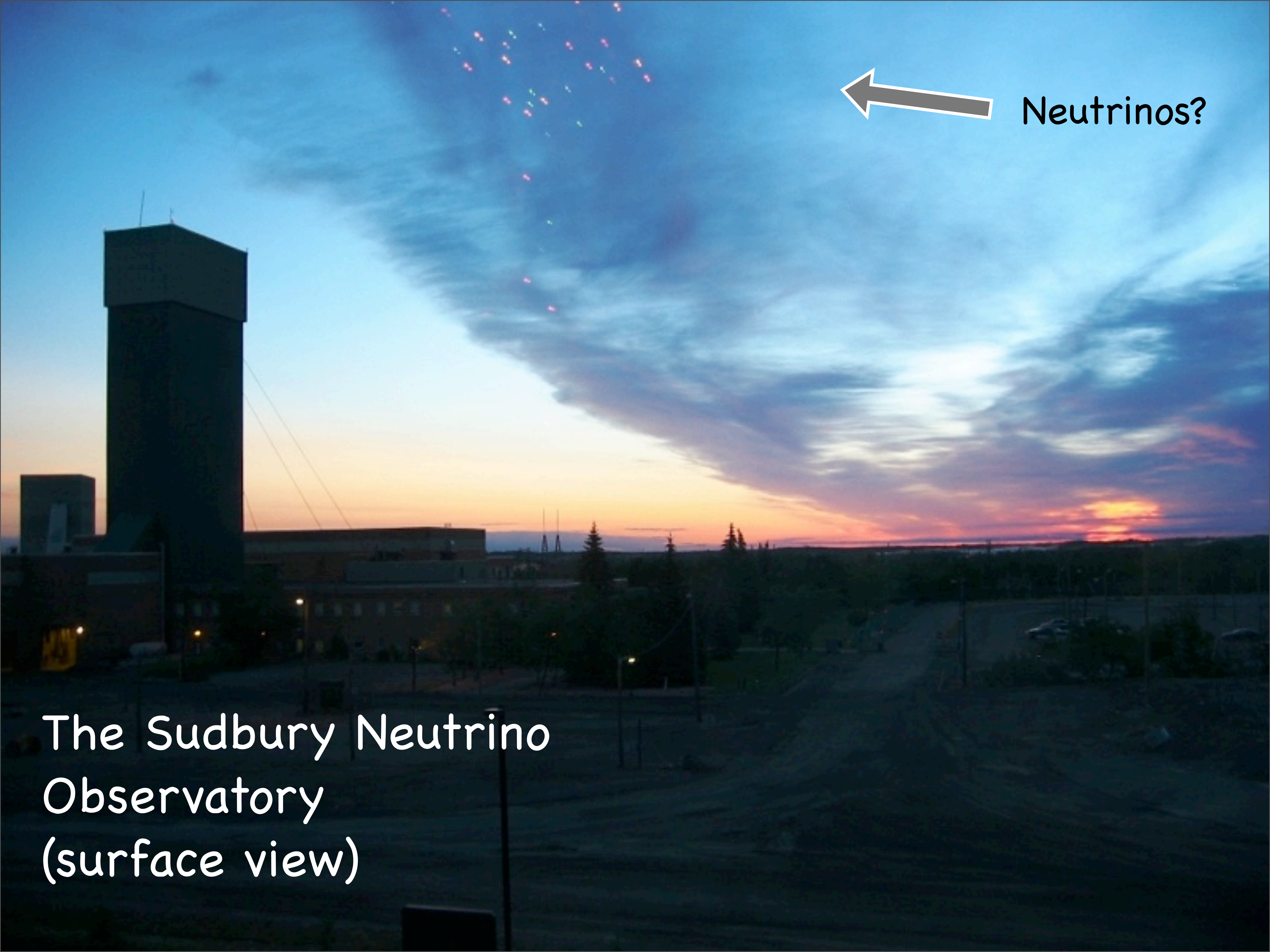
- This creates a potential in the Hamiltonian.
- Depends on the electron density of the medium.
- Effect : it can enhance oscillations as neutrinos propagate in matter



$$\frac{\hbar}{i}\frac{\partial}{\partial x}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix} = \begin{pmatrix} E - V_{11} - \frac{m_1^2}{2E} & -V_{12} \\ -V_{12} & E - V_{22} - \frac{m_2^2}{2E}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$$

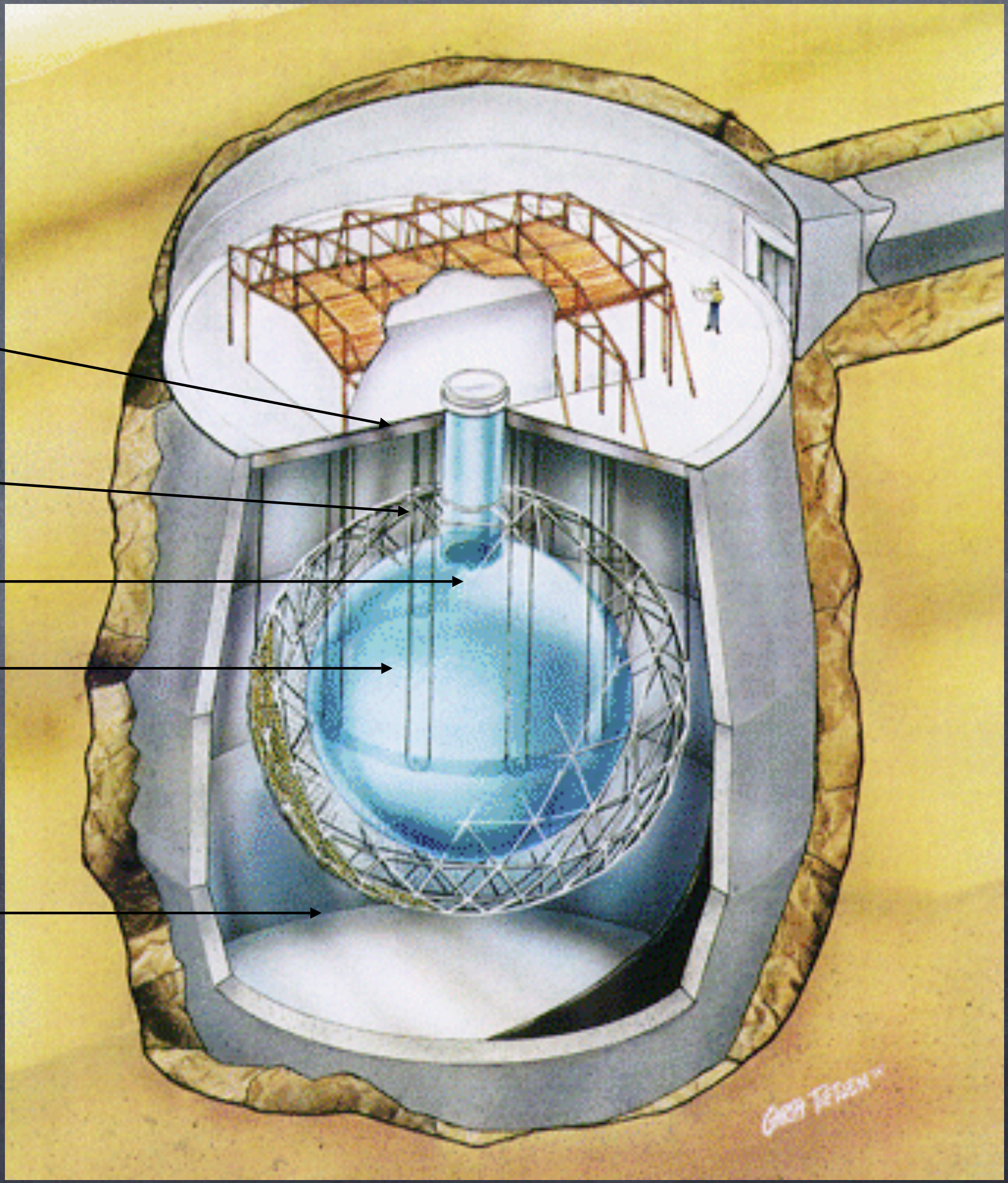
$$V_C = \langle \nu_e | \int d^3x\ H_C^{(e)} | \nu_e \rangle = \frac{G_F N_e}{\sqrt{2}}\frac{2}{V}\int d^3x\ u_\nu^\dagger u_\nu = \sqrt{2} G_F N_e\ .$$

Mikheyev-Smirnov-Wolfenstein (MSW) effect


Neutrinos?
The Sudbury Neutrino
Observatory
(surface view)

The Sudbury Neutrino Observatory

2092 m underneath the surface
(6800 ft level)



Almost 10,000 phototubes to detect light emitted when neutrinos interact.

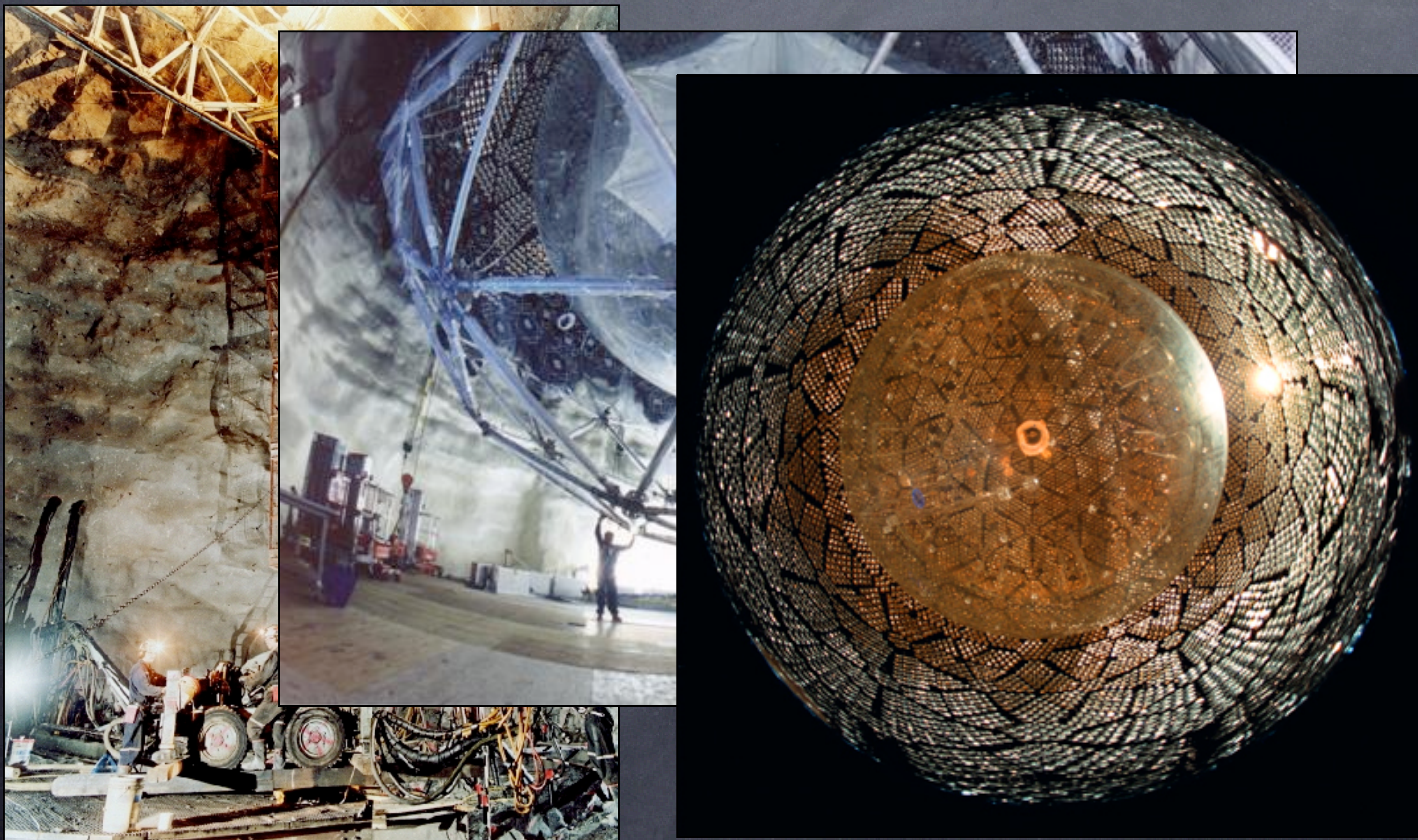
Acrylic vessel 12 meter diameter

1000 Tonnes heavy water

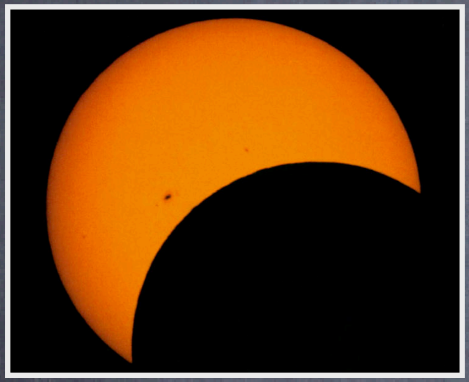
7000 Tonnes of ultra clean water, as a shield.

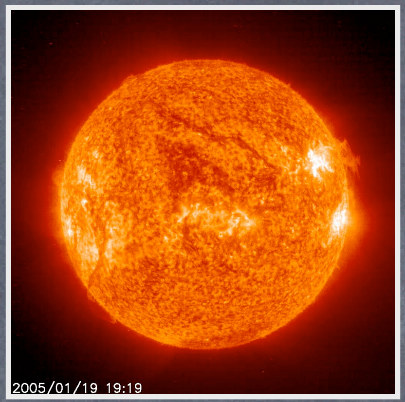
Urylon Liner and Radon Seal

SNO during Construction



Mixing Established





= Oscillations

If one looks only
at electron neutrinos, only 1/3
are seen

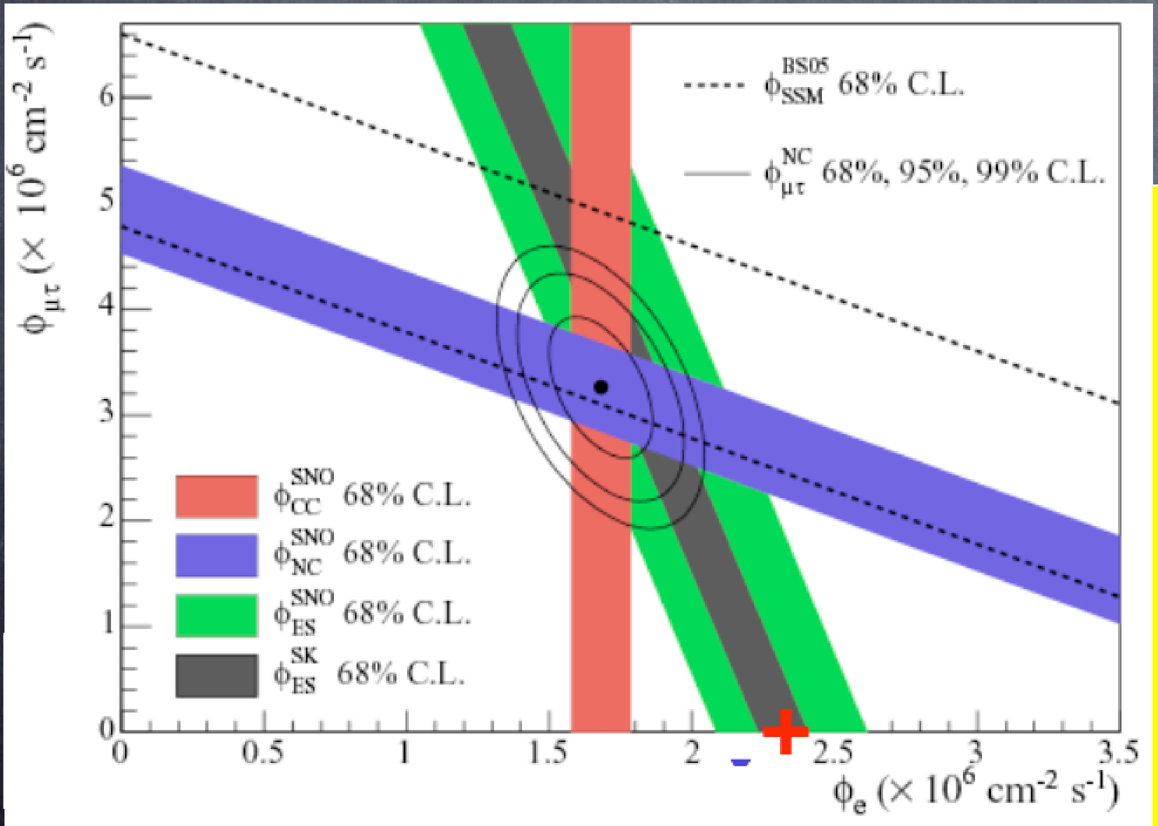
ν_e

However, if one looks at all
neutrino flavors, we see the
number expected

ν_e ν_τ ν_μ

Neutrino Mixing Confirmed

- Neutrino mixing established (non-electron flavors coming from the sun).
- Original ^{8}B fluxes confirmed.
- Solar core temperature known to 1%.



Fluxes

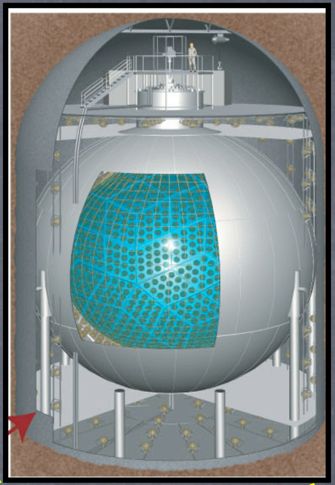
(10^6 cm^{-2} s^{-1})

ν_e:	1.68(11)
$\nu_{\mu\tau}$:	3.26(47)
ν_{total}:	4.94(43)
ν_{SSM}:	5.69

KamLAND

- Using reactor neutrinos to match the sun...

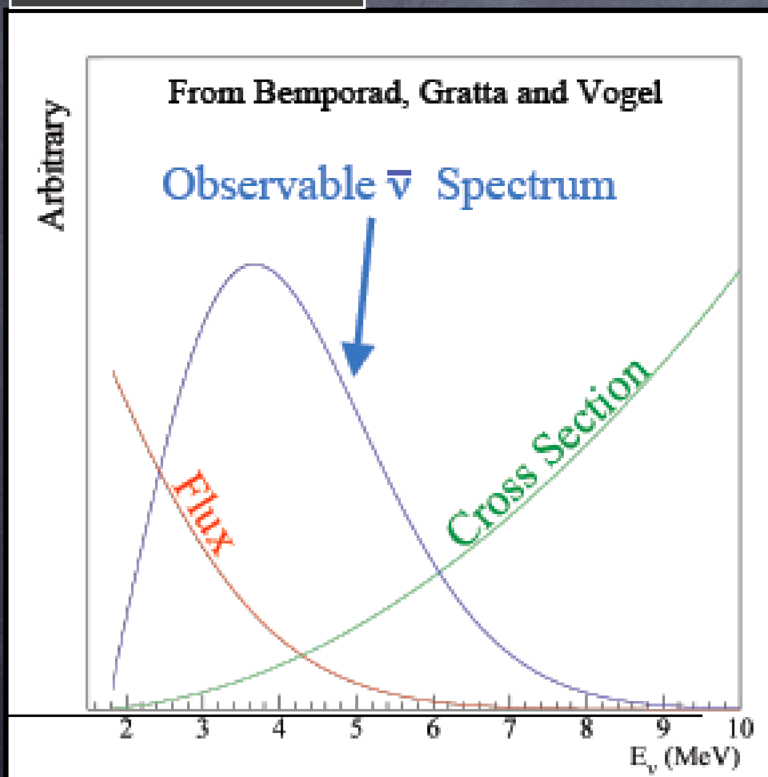
KamLAND

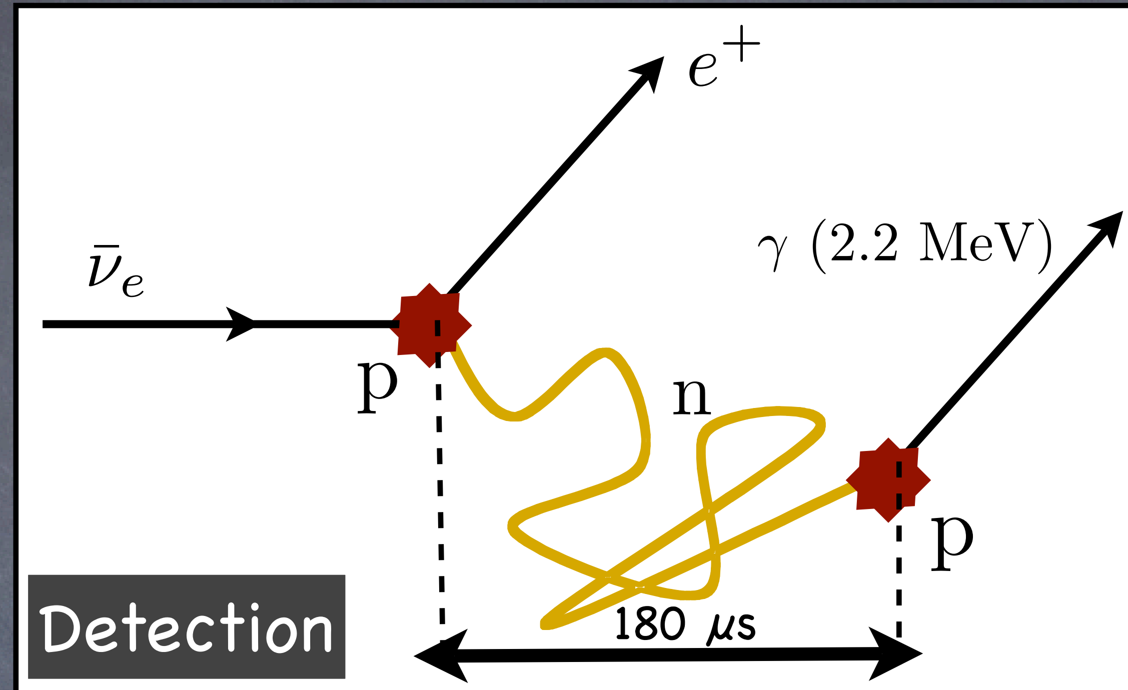


- Located approximately 180 km (average) from strongest reactors
- Distance is selected so as to probe same oscillation length as solar experiments.

Reactor Flux & Interactions

Production

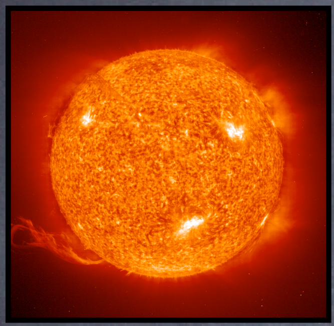




- Combination of falling flux and rising cross-section yields average energy ≈ 4 MeV.
- Sensitive to both q_{13} and q_{12}.

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

Solar vs. KamLAND



Produced in the sun (fusion).

MSW/matter effects.

Neutrinos.

Baseline ≈ 10^{11} km

Nuclear reactors (fission)

No matter effects

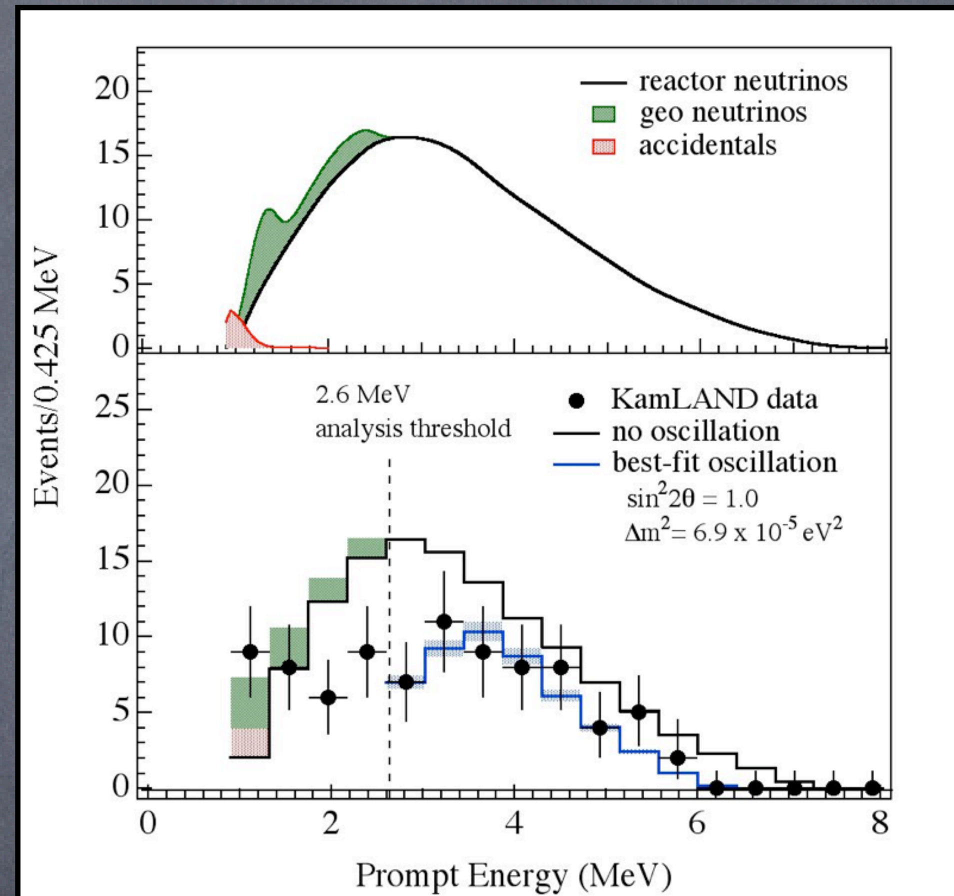
Anti-neutrinos.

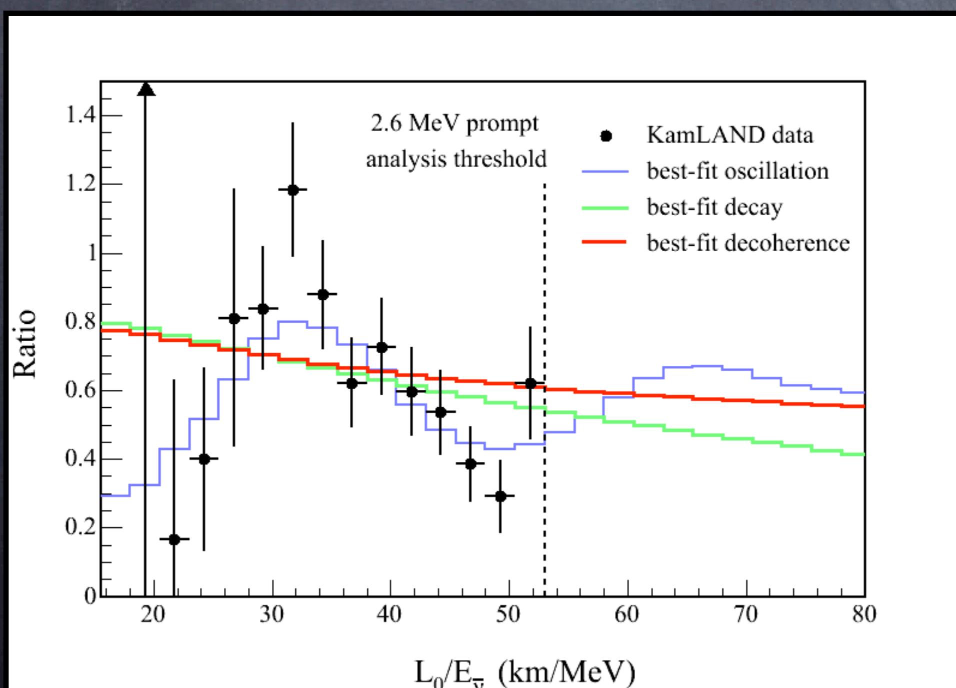
Baseline ≈ 10^{3} km

No common systematics!

Confirmation!

- Can look at deficit in neutrinos OR L/E behavior.
- Both consistent with solar neutrino oscillations (in vacuum)

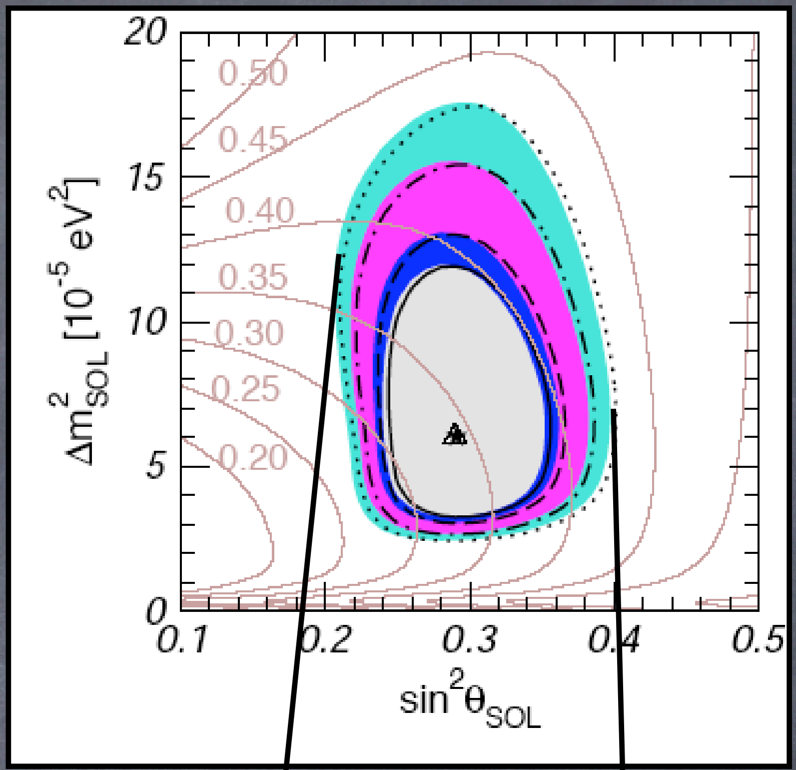


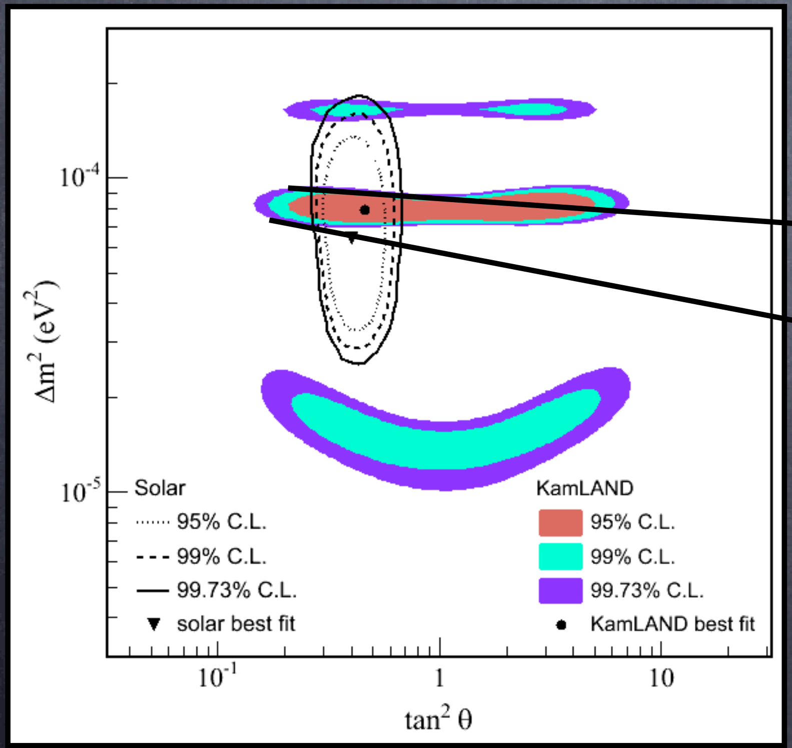


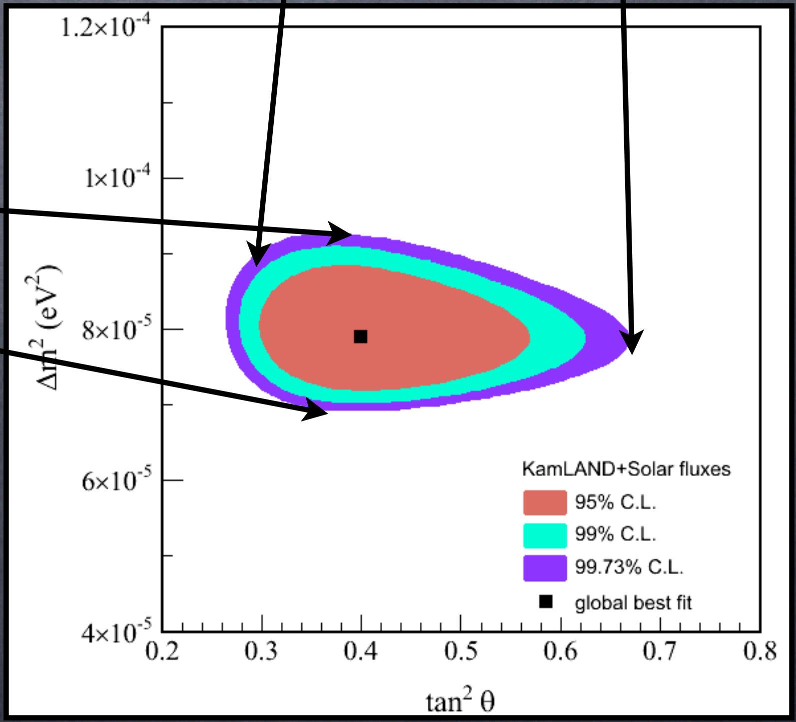
$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

Confirmation

- Combination of reactor and solar data confirms oscillation mechanism.
- Rule out various exotic explanations (CPT violation, etc.)







Neutrino Mass Established

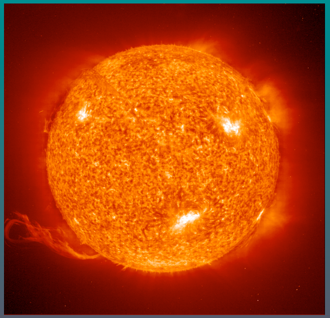
Solar/reactor neutrino experiments:

(SNO, KamLAND, Super-K, GNO, etc)

$$\theta_{12} = 37^0 \pm 3^0$$

$$\Delta m^2_{12} = (8.0 \pm 0.5) \times 10^{-5} \mathrm{eV}^2$$

Limit solar mixing parameters:



Atmospheric neutrino experiments:

Super-K, Soudan, Kamiodande, new MINOS results)

$$\theta_{23} = 45^o \pm 15^o$$

$$\Delta m^2_{23} = (2.72 \pm 0.25) \times 10^{-3} \mathrm{eV}^2$$

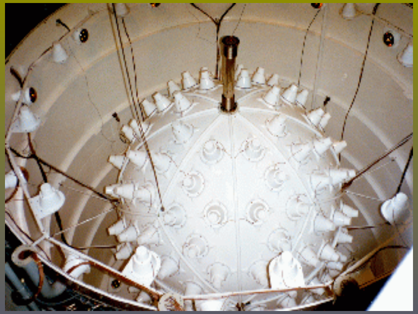
Limit atmospheric mixing parameters:

Short baseline & reactors experiments:

(LSND, CHOOZ, Palo Verde, etc...)

$$\theta_{13} < 9.5^0 \ (90\% \ \mathrm{C.L}).$$

Limits on last mixing angle; hints of sterile ν's?:



A Revolution

- Neutrino physics has provided a new framework in understanding electroweak interactions and particle masses.

- The culmination of forty years of data now indicates that neutrinos have mass and oscillate from one flavor to the other.

- Redundancy has been a key component in being able to make this claim:

Atmospheric

Reactor

Solar

Neutrino beams