The Quest for Neutrino Mass

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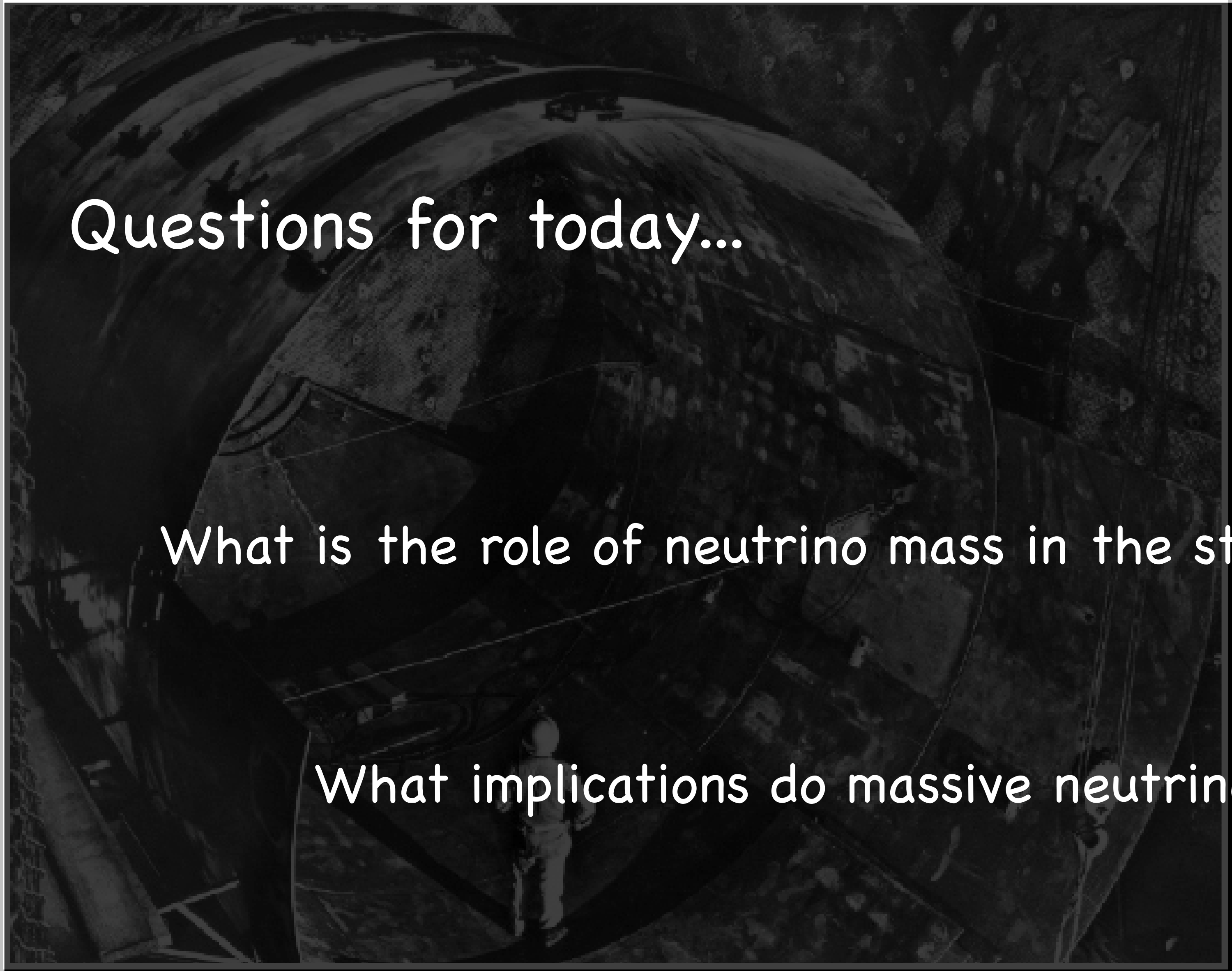


Questions for today...

What is the role of neutrino mass in the standard model?

What implications do massive neutrinos have?

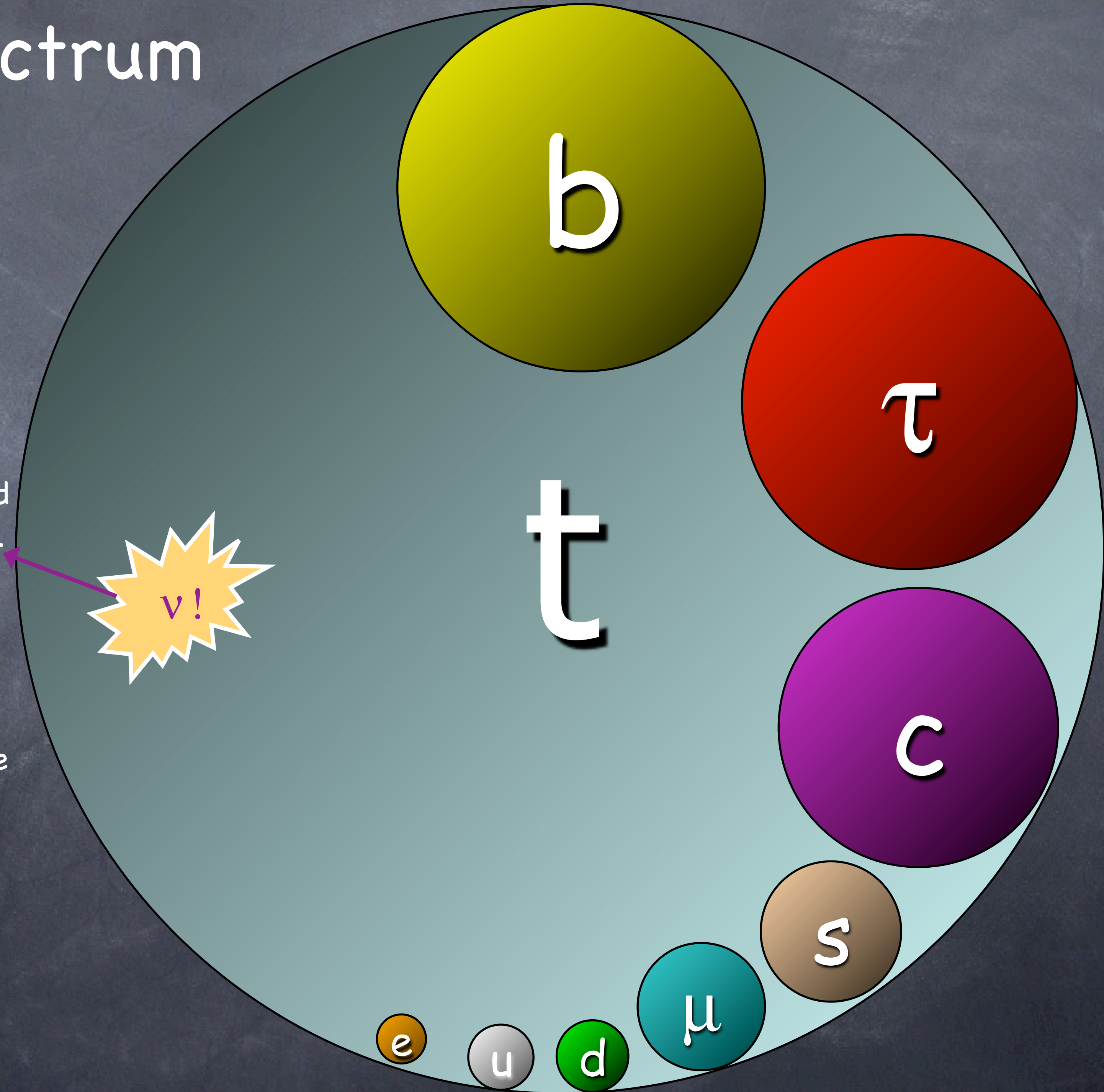
How can we measure neutrino mass?

The Lectures...

- Day One: Neutrinos in our World
- **Day Two: The Quest for Neutrino Mass (Oscillations)**
- Day Three: The Quest for Neutrino Mass (Other Methods)
- Day Four: Above and below ground...

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.

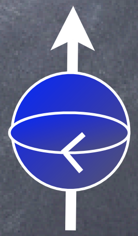


Handedness vs. Helicity

- 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

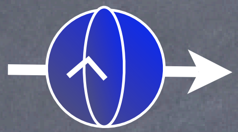


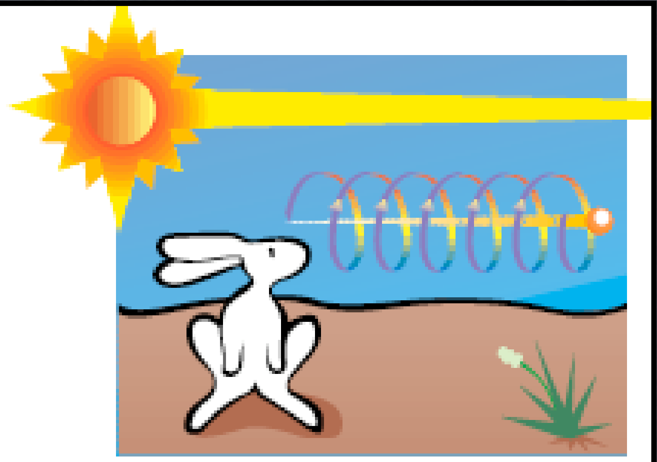
Left-helicity

Spin anti-along direction of motion

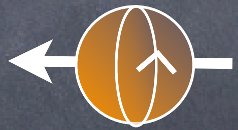
Handedness vs. Helicity

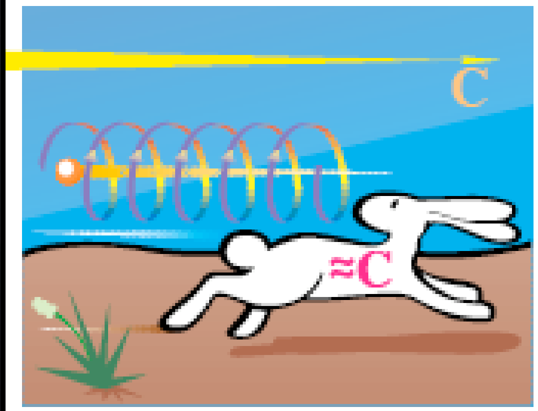
- Helicity is not invariant under Lorentz transformations.
    - Changes depending on the frame of reference.
- Since related to angular momentum (and angular momentum is conserved), the helicity can be directly measured.





Looks like a left-handed corkscrew.





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

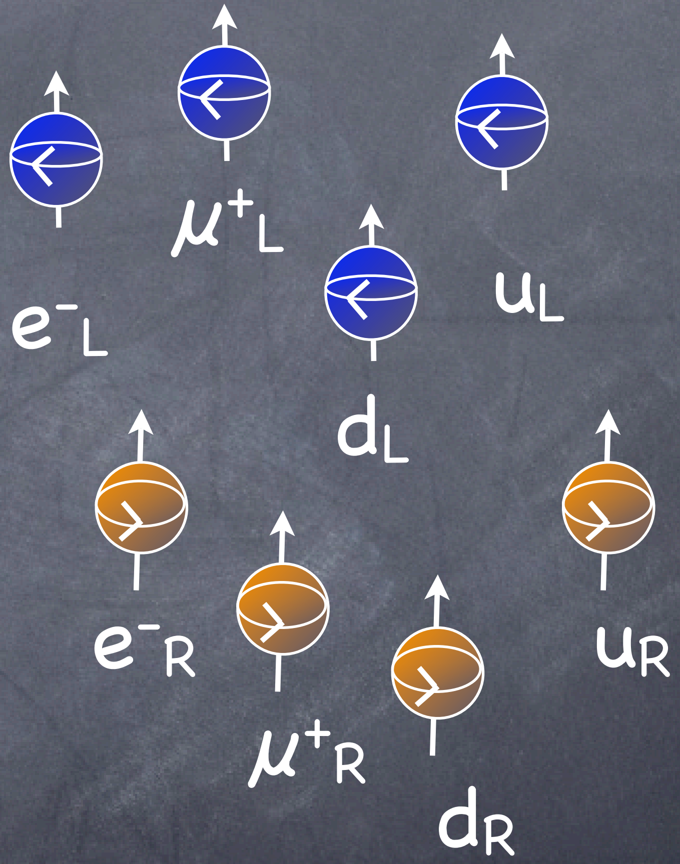
$$\psi_L = \frac{1}{2}(1 - \gamma^5)$$

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

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"

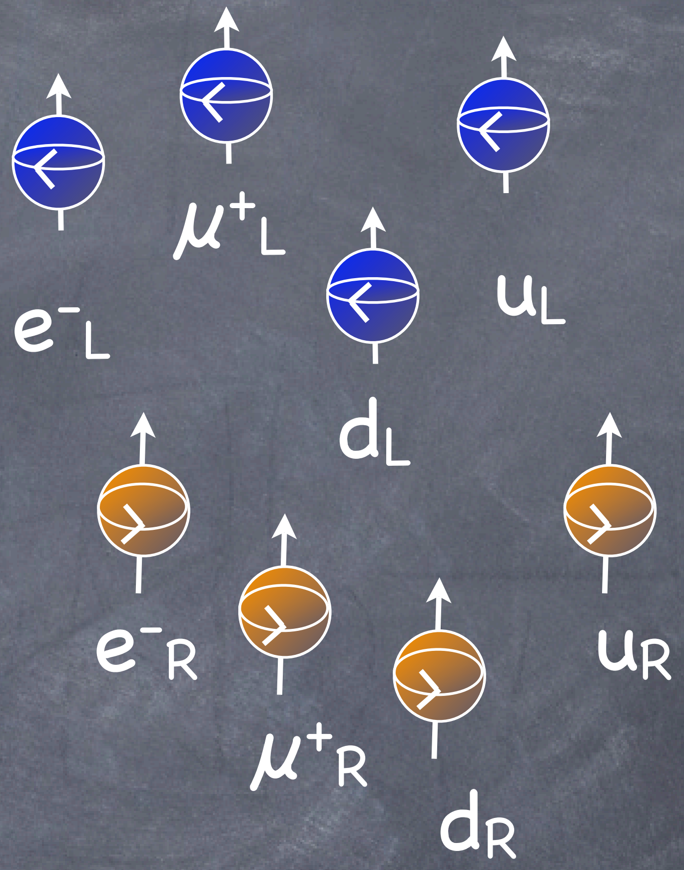
- All other forces studied at the time (electromagnetism and the strong force) rigidly obeyed parity conservation.
- Weak force violates parity conservation completely.

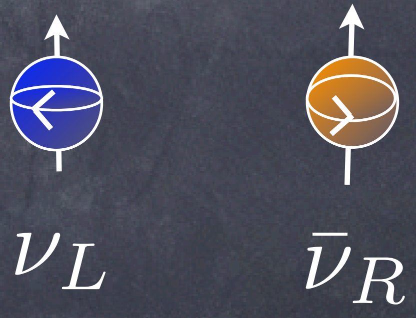
What makes neutrinos different...

- 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

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

- 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.

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

$$\begin{aligned}\mathcal{L}_{\text{mass}} &= m(\bar{\psi}\psi) \\ &= m(\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L)\end{aligned}$$

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

Mass & Handedness

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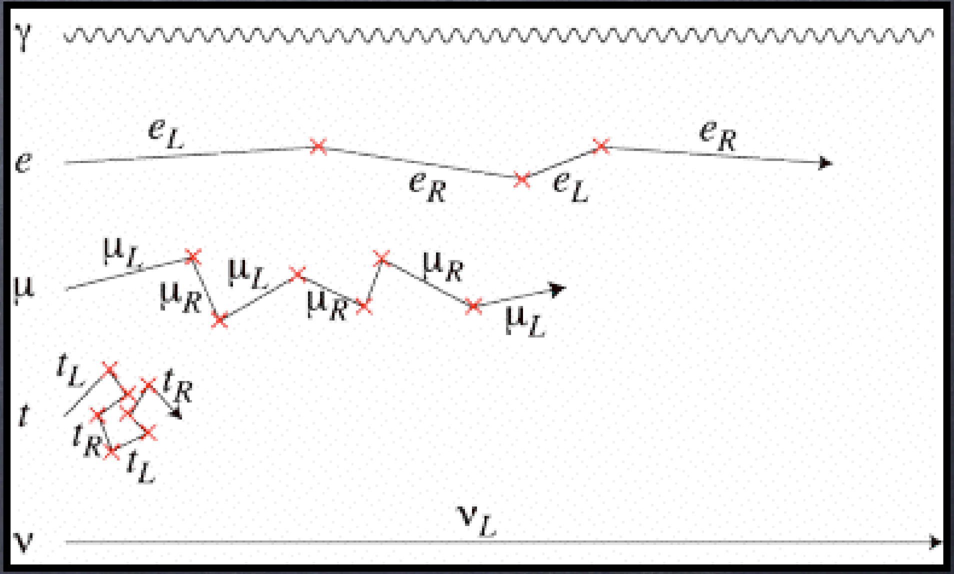


How to Introduce Neutrino Mass...

- **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 $W^{\pm}$)
- **Introduce neutrinos as Majorana particles:**
  - Neutrino & anti-neutrino as the same particle.
  - Mass introduced through charge conjugate term.

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

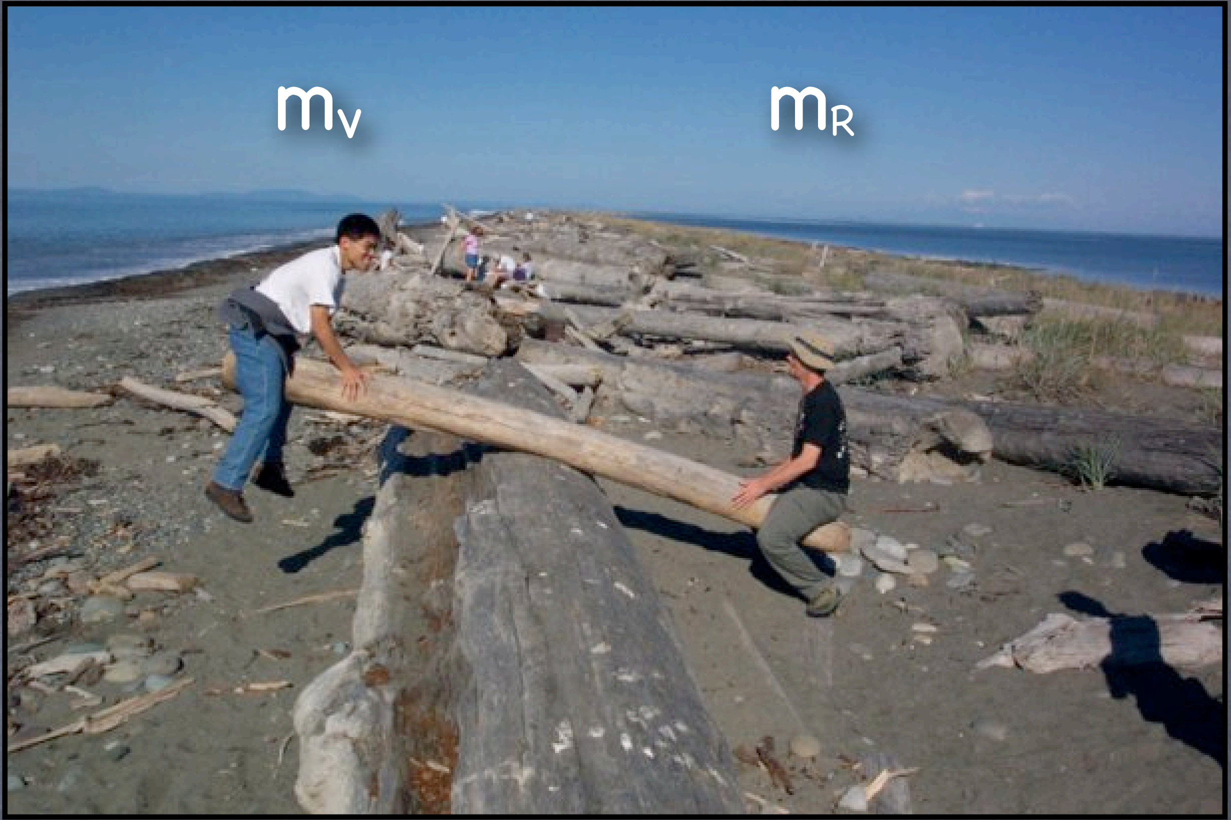
Sterile term

Complex 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

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

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

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

The Quest for Neutrino Mass...

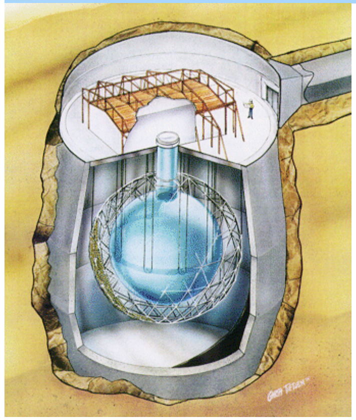
- It is recognized that, although neutrino mass can be “forced” into the Standard Model, it offers possibilities to probe physics at a much higher scale than is currently accessible.
- Majorana masses in particular offer a natural means to understand some of the very basic questions that remain in our 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

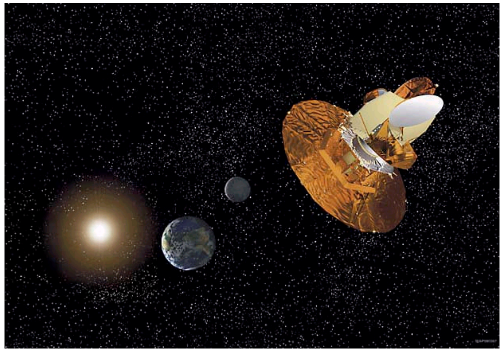
Sources: Reactor, solar, atmospheric, beams

Cosmology

Probe total neutrino mass

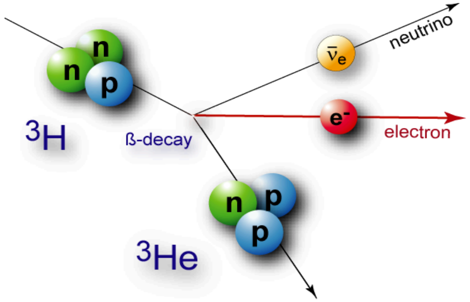
Use Gen. relativity

Satellites & ground observatories



ν

Single Beta Decay



Probe absolute mass scale

Use conservation of energy

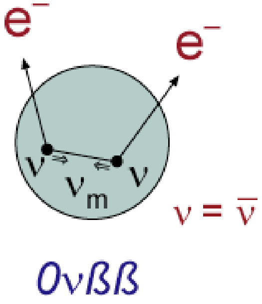
Model-independent

0ν Double Beta Decay

Probe Majorana masses

Use rarest decays on Earth

Probe identity of neutrinos



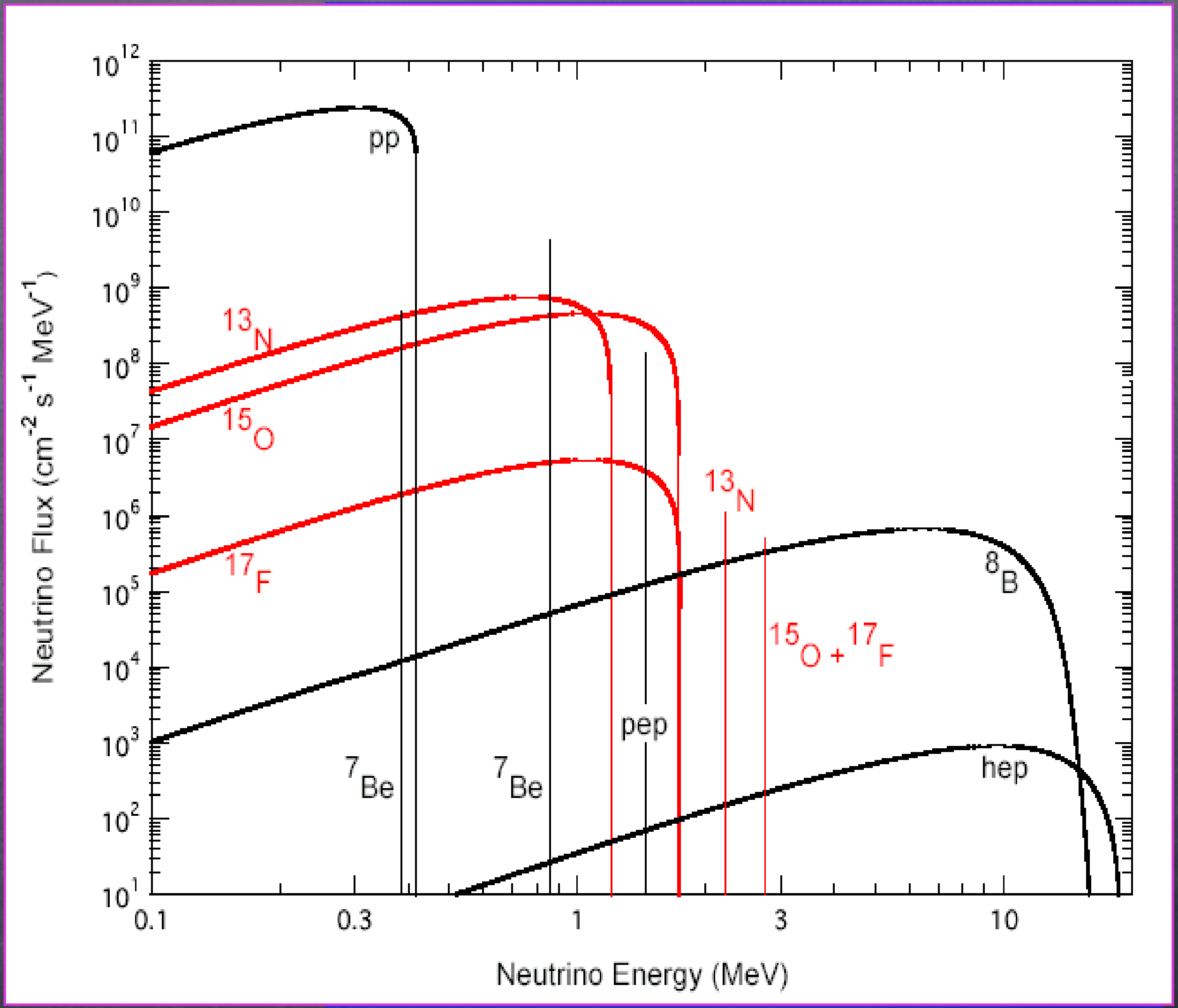
0νßß

$m_\nu \neq 0$

(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

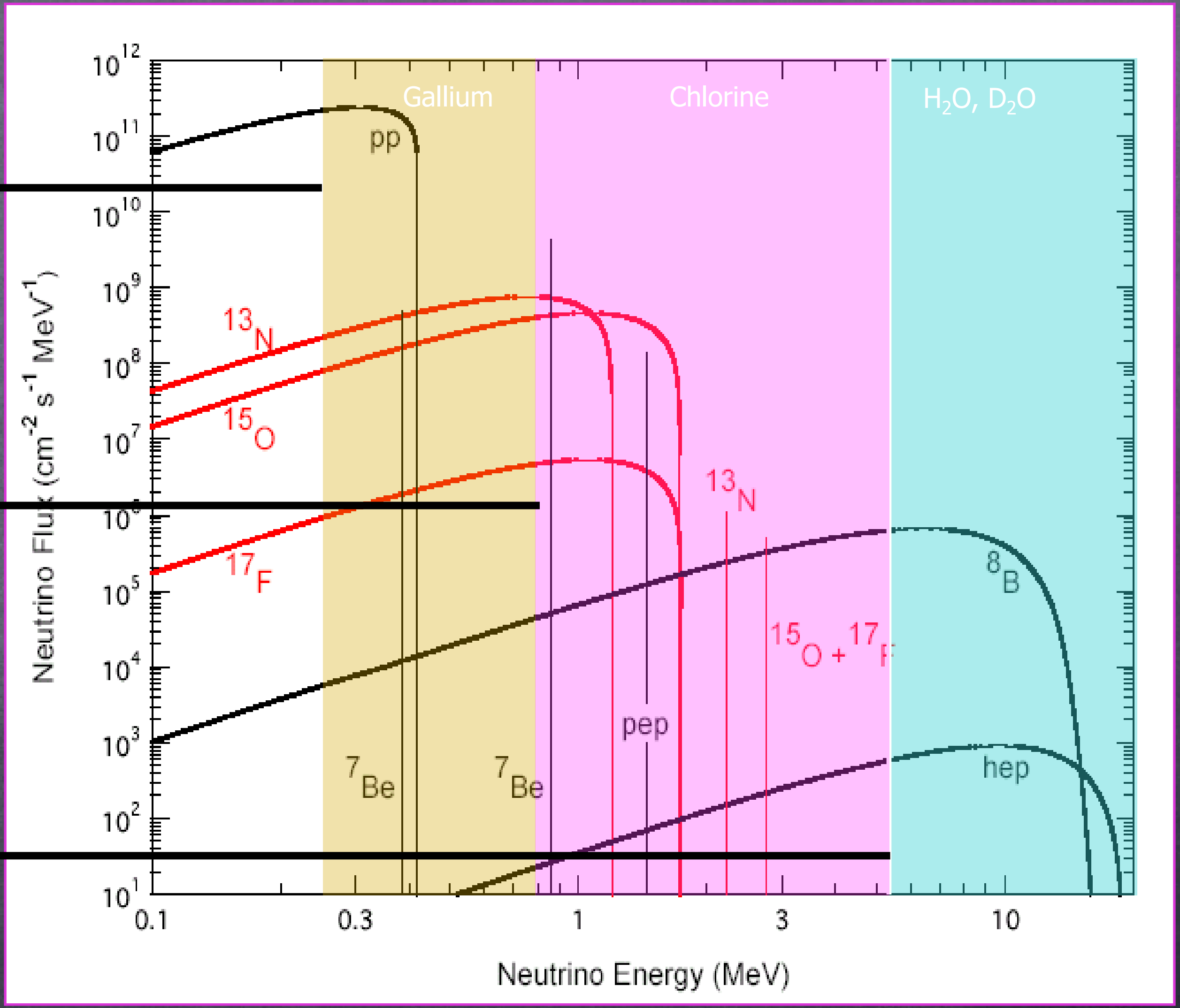
Technique: Radiochemical

Chlorine

Technique: Radiochemical

H_2O & D_2O

Technique: Cherenkov; Real Time



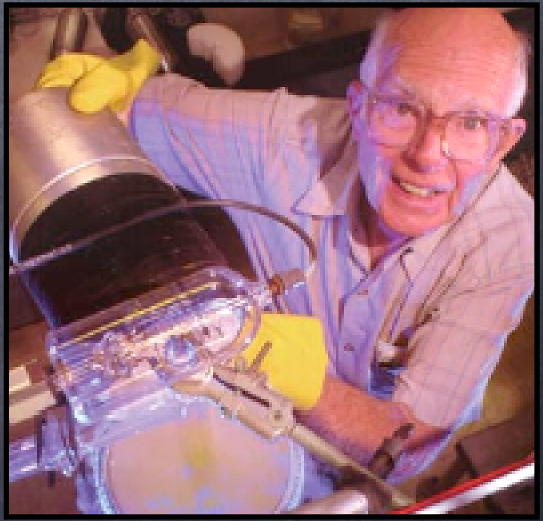
The Solar Puzzle Begins..

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

HOMESTAKE

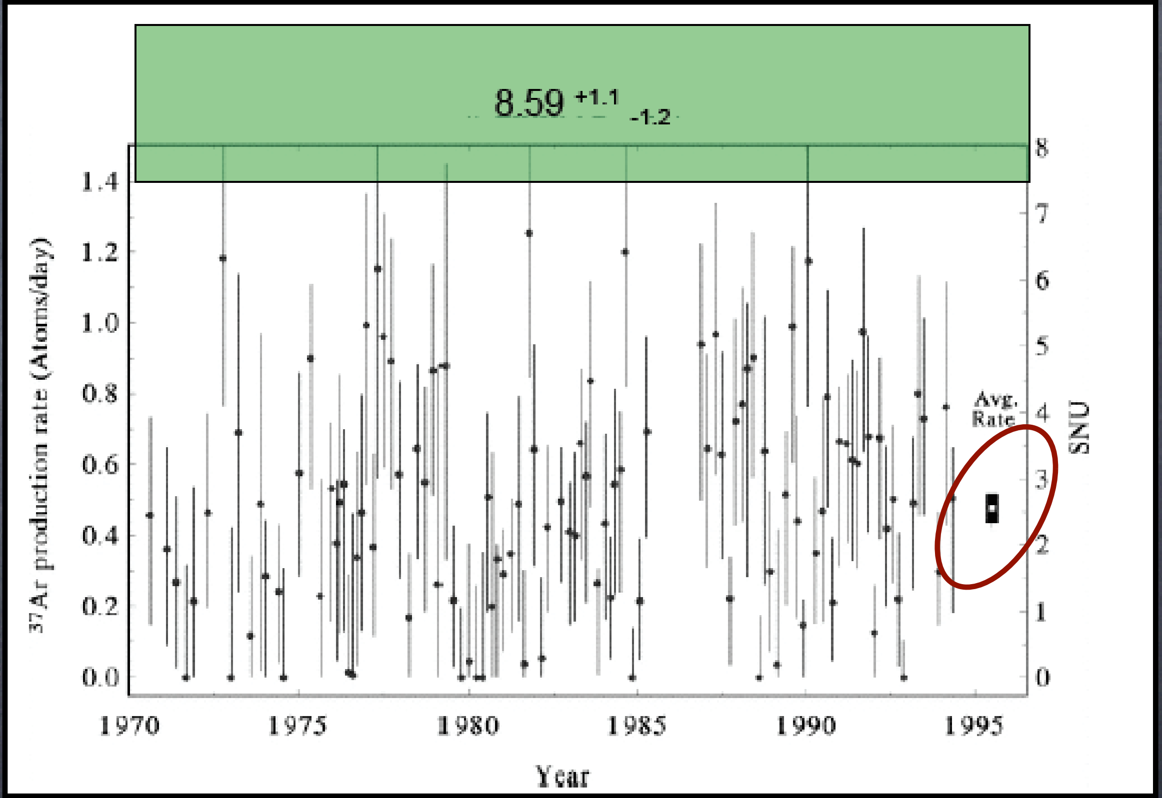
$^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-$

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

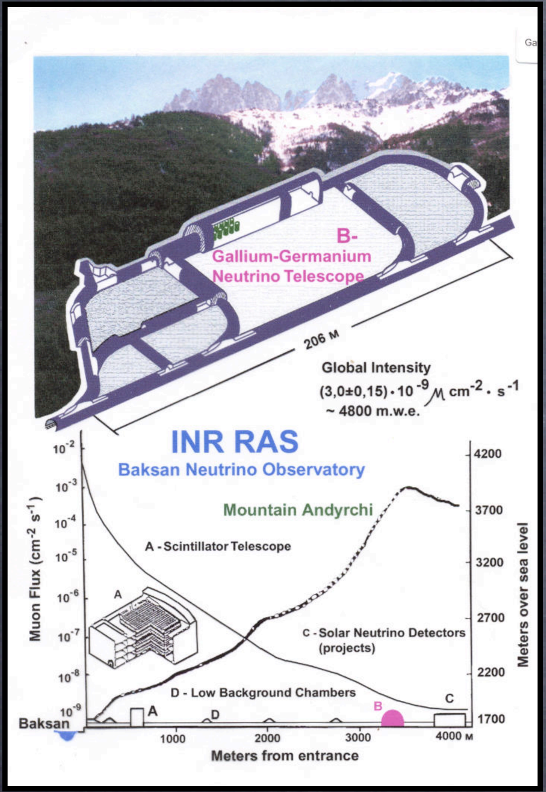


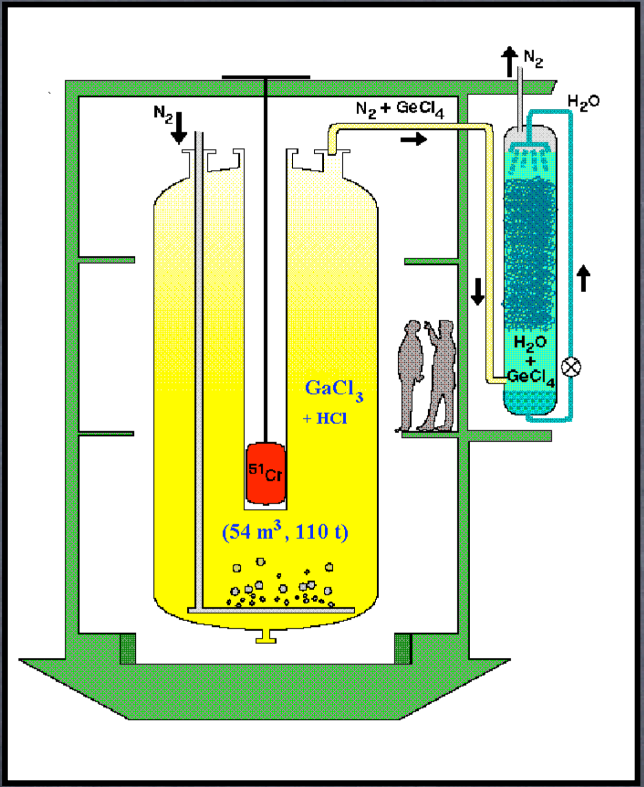
Homestake Results (1970-1994)

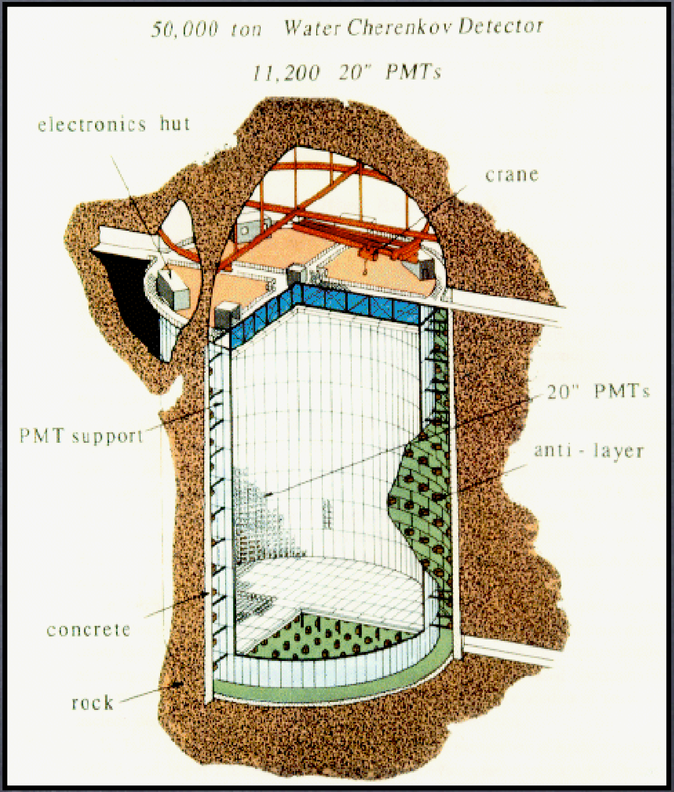
- Only 1/3 of the neutrinos expected from the sun are seen in the Homestake experiment.
- Doubts on hydrodynamic calculations and/or experimental data are raised.
- When in doubt, do it again.



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

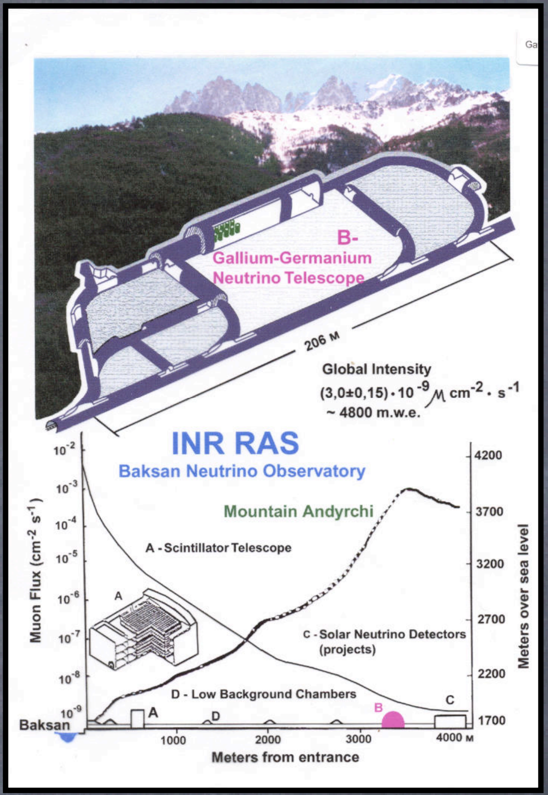
Super-Kamiokande

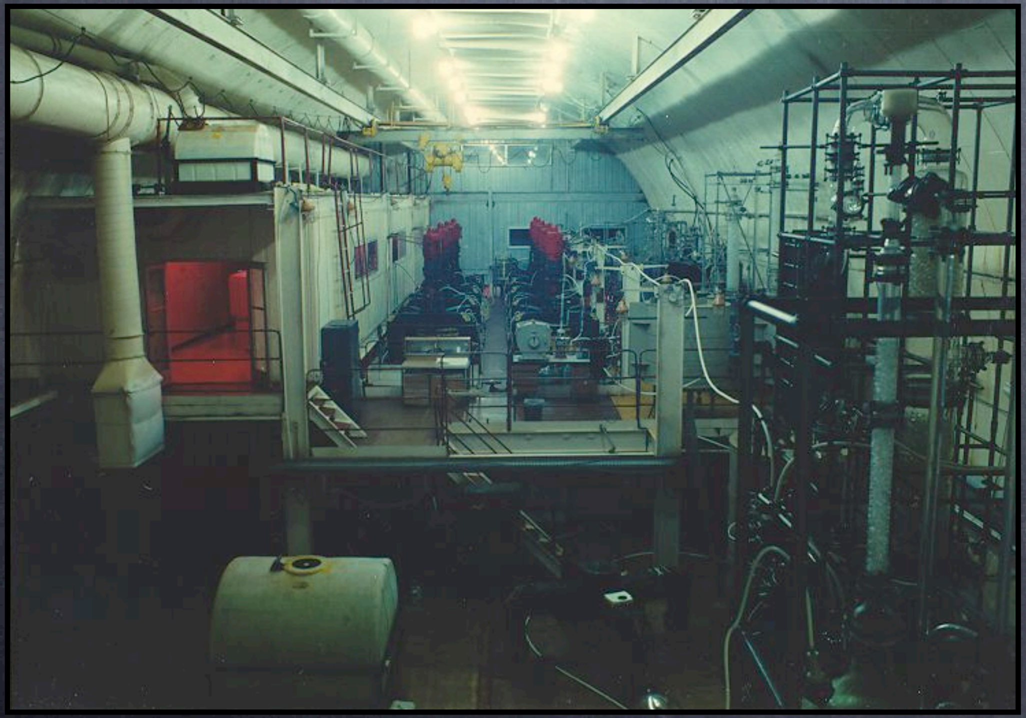
$e^- + \nu_e \rightarrow \nu_e + e^-$

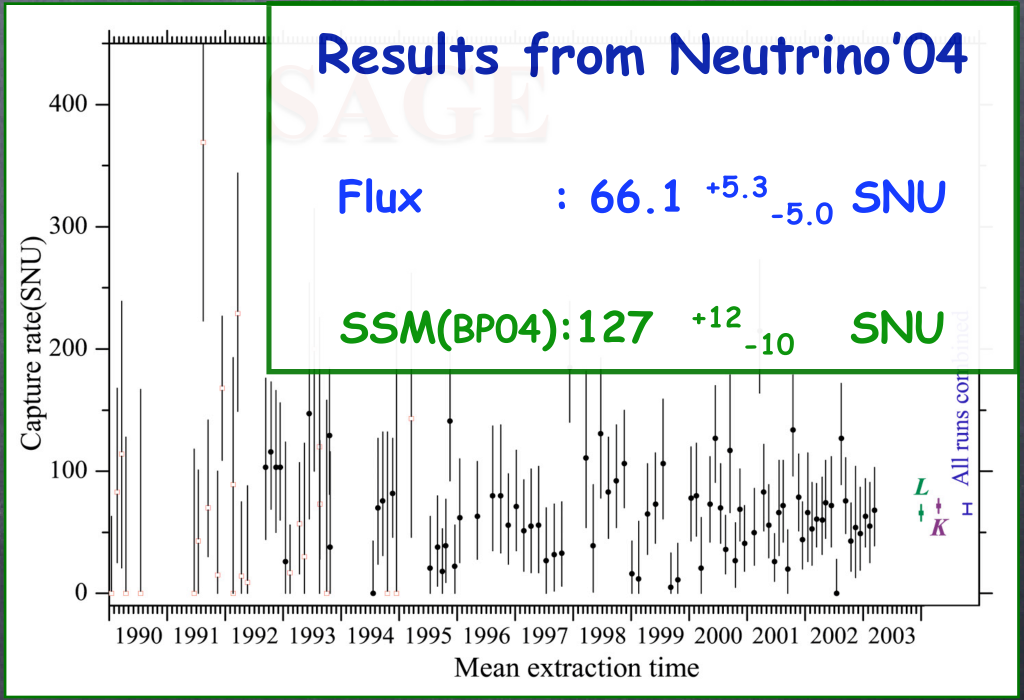
Measures 40% of expected flux

SAGE

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







Results from Neutrino'04

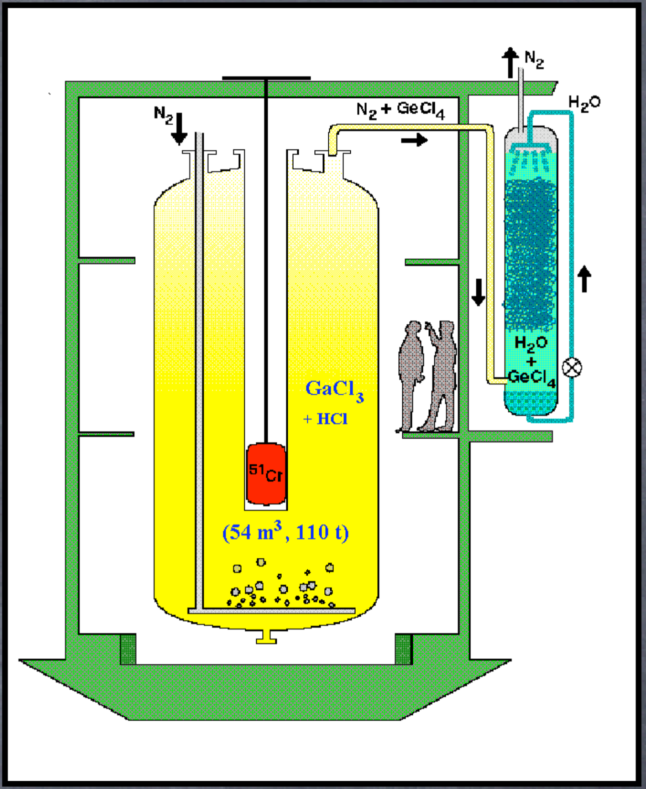
Flux : $66.1^{+5.3}_{-5.0}$ SNU

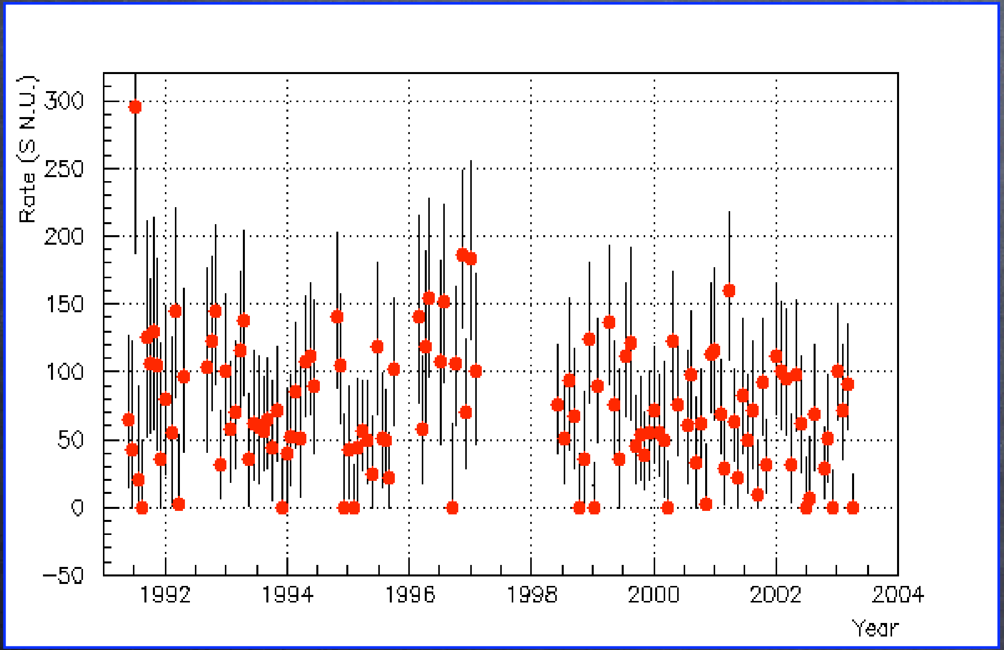
SSM(BP04): 127^{+12}_{-10} SNU

* 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



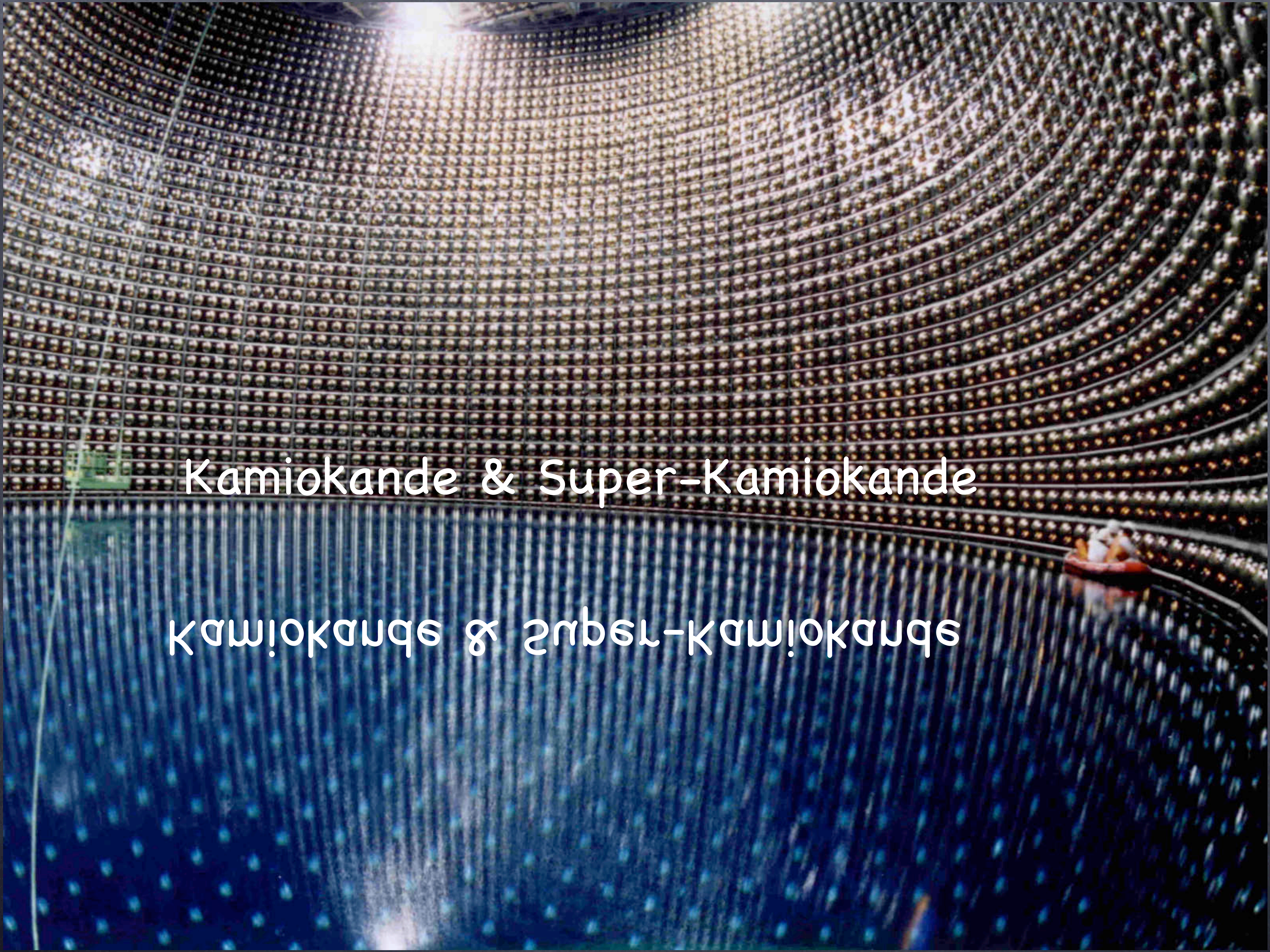


Results

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

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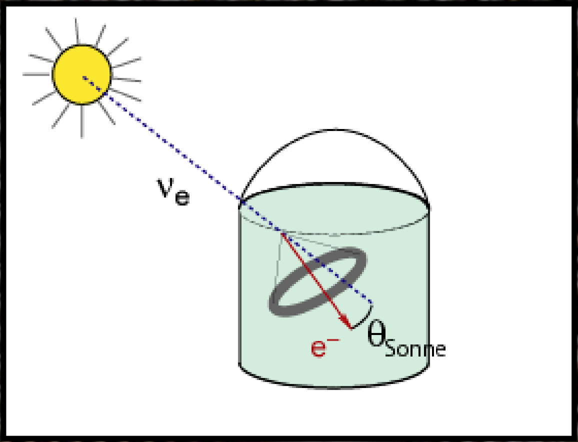
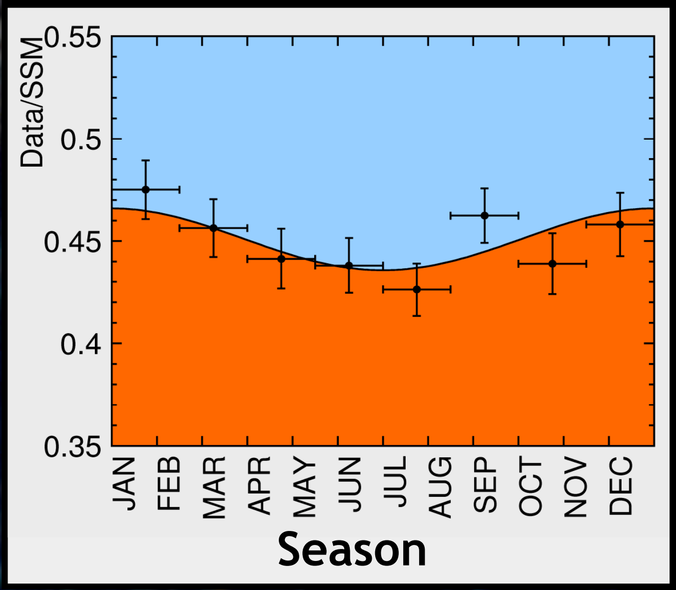


- First time Cerenkov, real-time detection is used for solar neutrinos.

- Use of elastic scattering as detection channel

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

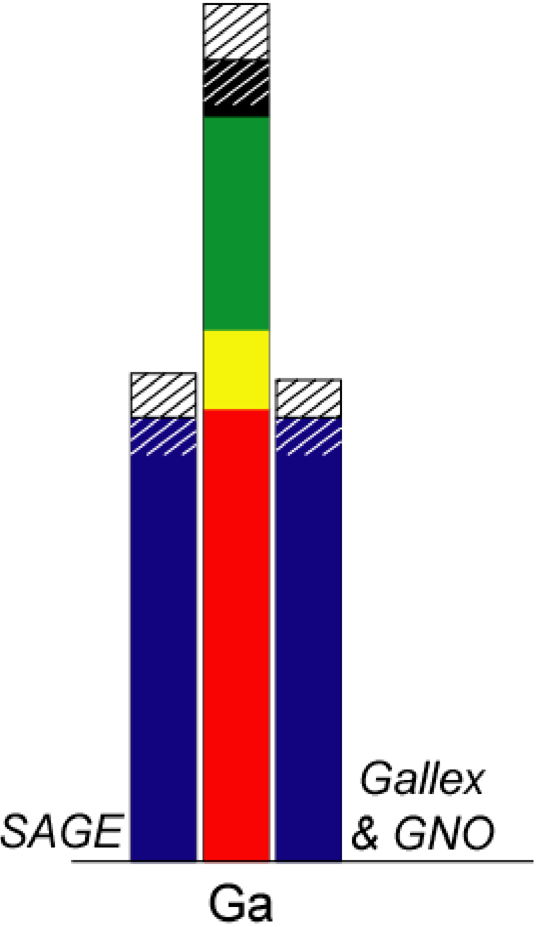


- Sensitive to highest energy (^{8}B) neutrino.

- Use neutrino direction to discern from background.

Comparison of total rates

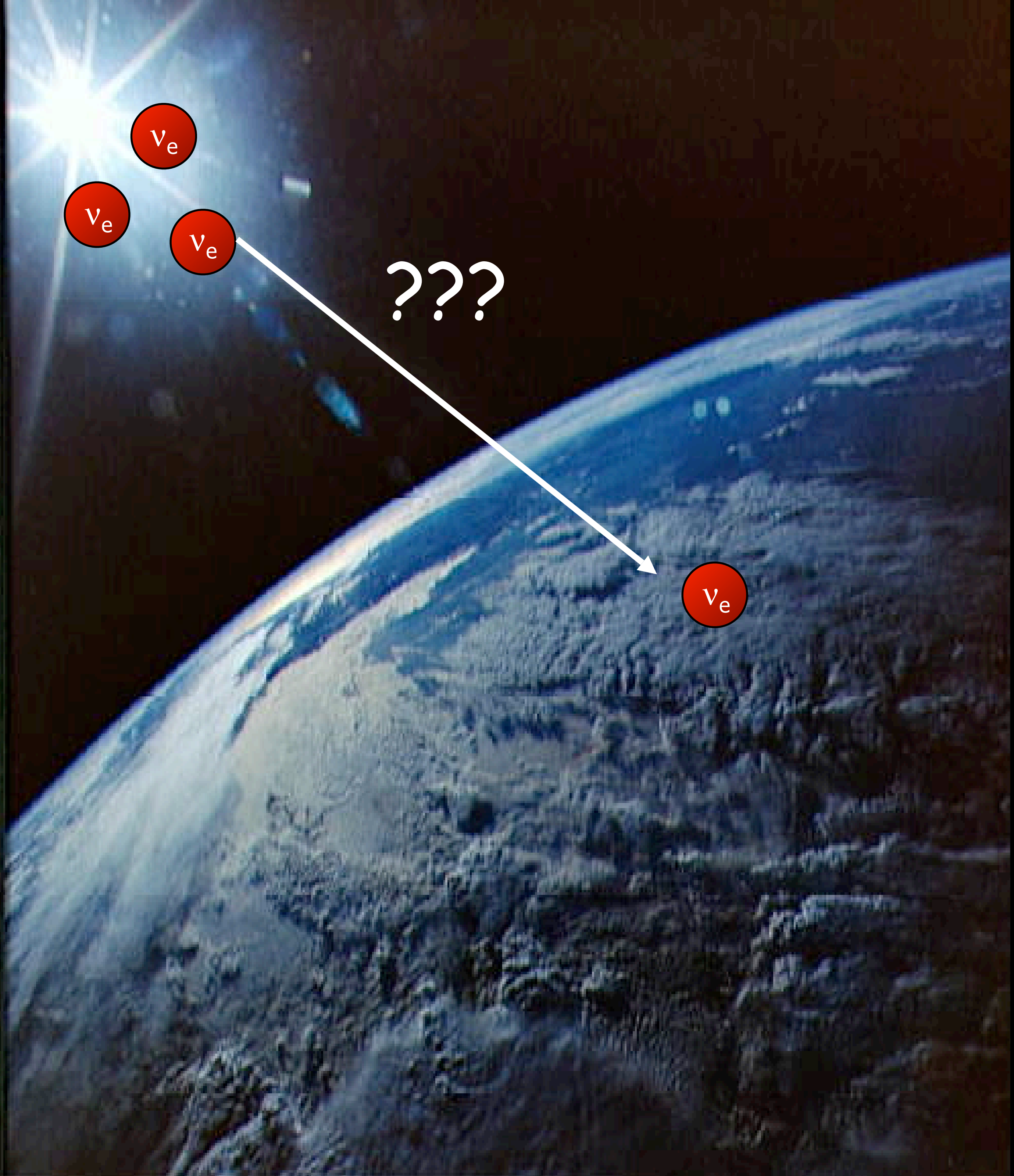
experiments and SSM (Bahcall-Pinsonneault



Theory: 🟩 ^{7}Be 🟥 pp / pep
🟨 ^{8}B ■ CNO

experiments ■
uncertainties ▨

H. Murayama

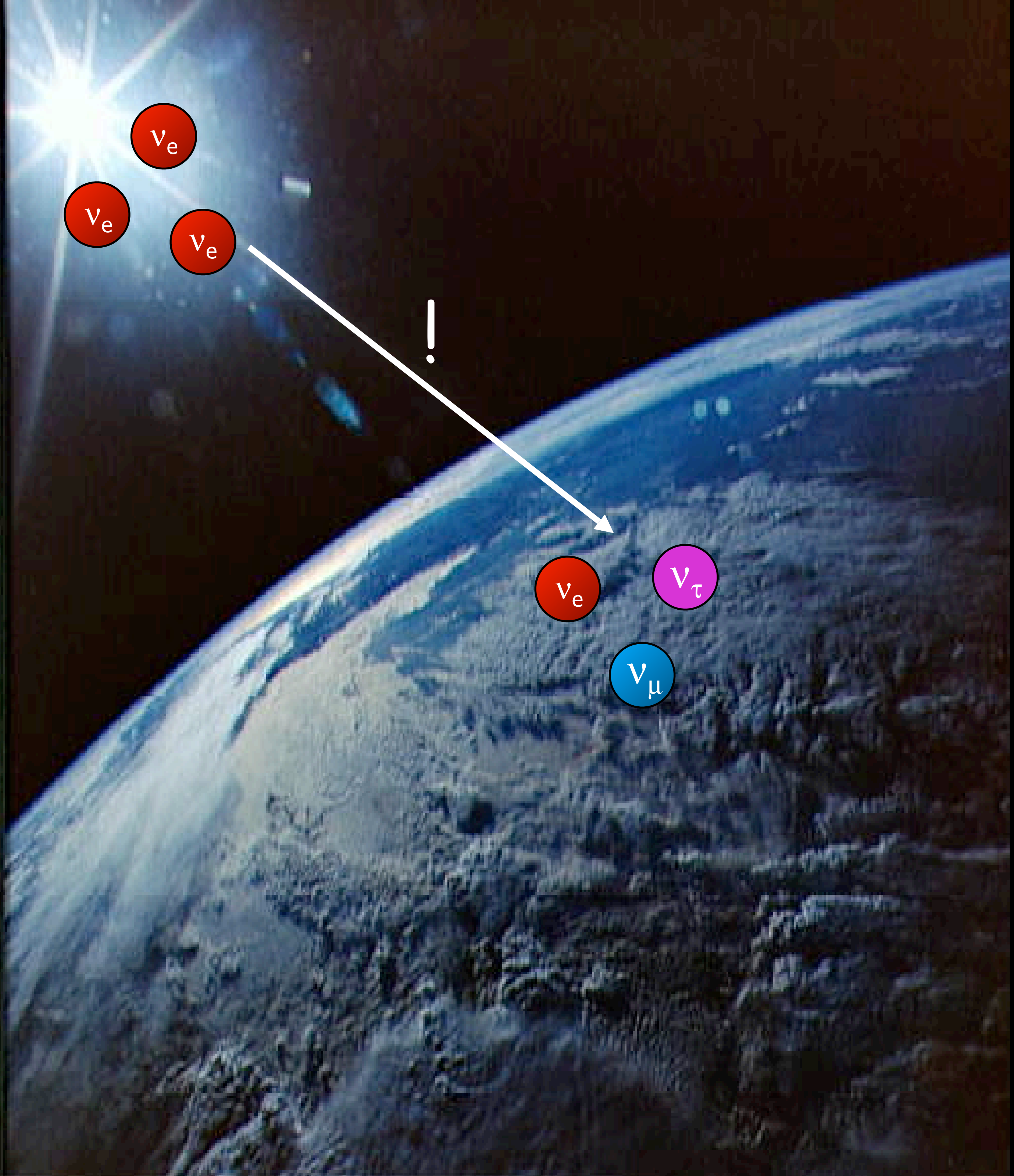


The sun only makes "electron-type" neutrinos

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…



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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.

$$\left|\nu\right\rangle = U_{e1}e^{-iE_1t}\left|\nu_1\right\rangle + U_{e2}e^{-iE_2t}\left|\nu_2\right\rangle + U_{e3}e^{-iE_3t}\left|\nu_3\right\rangle = \left|\nu_e\right\rangle$$

$$\left|\nu\right\rangle = e^{-iE_1t}(U_{e1}\left|\nu_1\right\rangle + U_{e2}e^{-iE_2t+iE_1t}\left|\nu_2\right\rangle + U_{e2}e^{-iE_3t+iE_1t}\left|\nu_3\right\rangle)$$

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

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

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

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

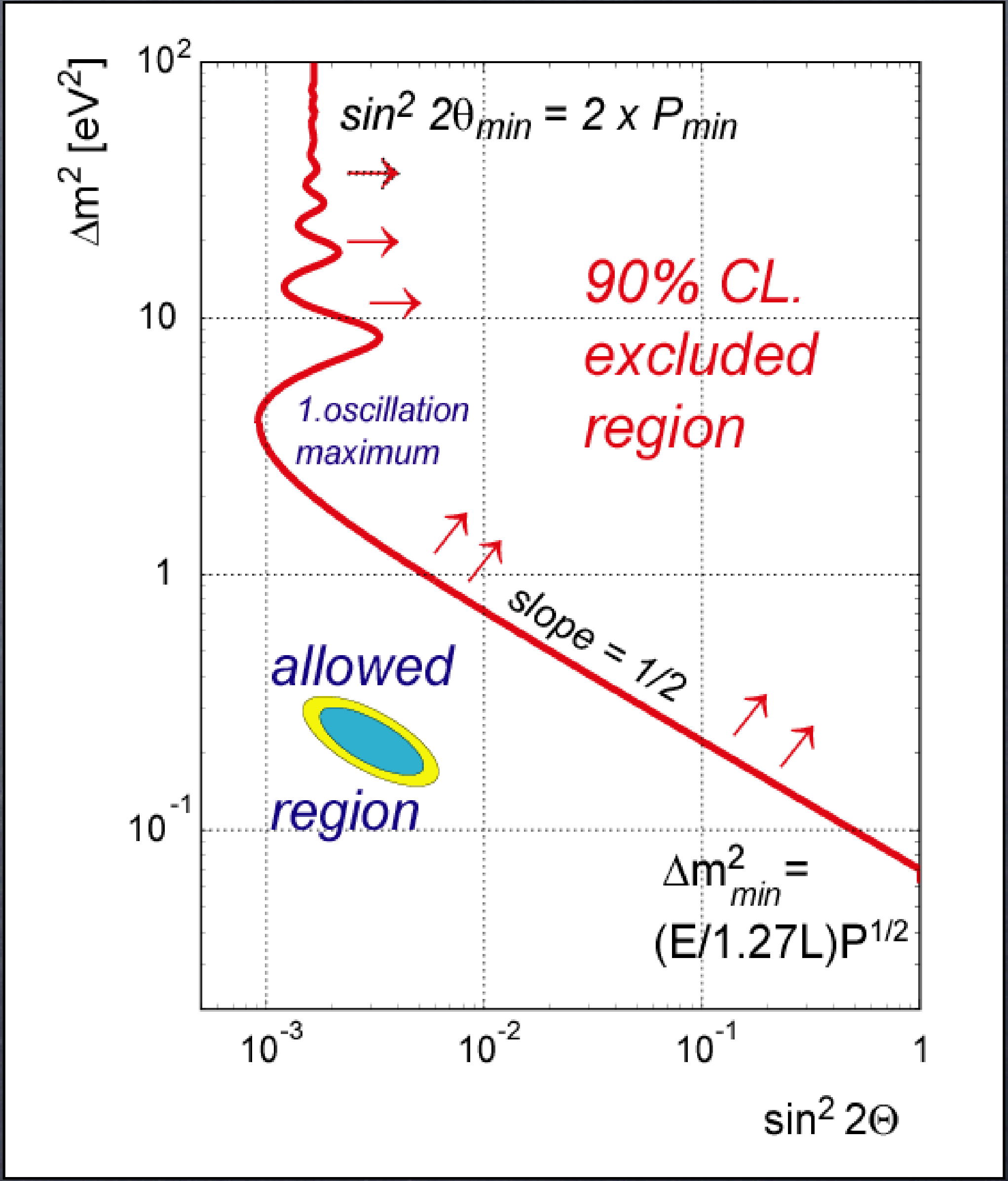
- Depends only on two fundamental parameter and two experimental parameters (for a given neutrino species).

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

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).

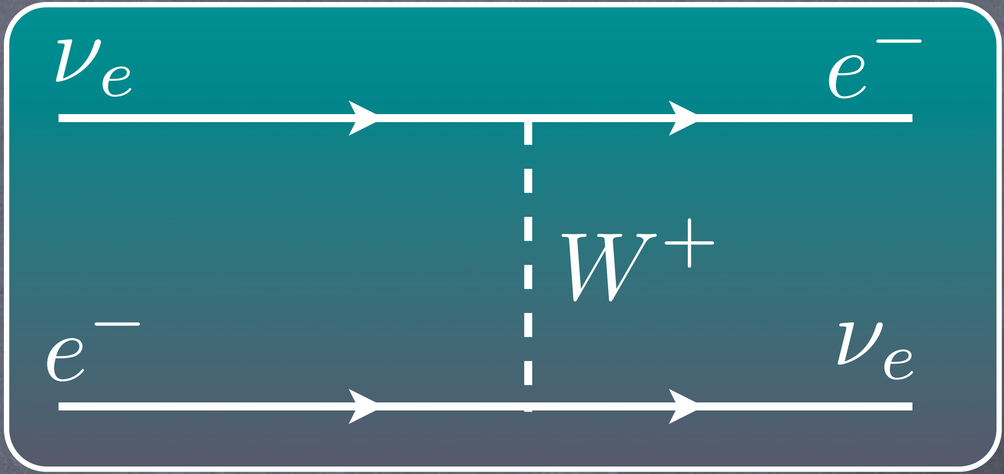
$$\mathcal{P}_{\rm surv} = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4E_\nu}L\right)$$

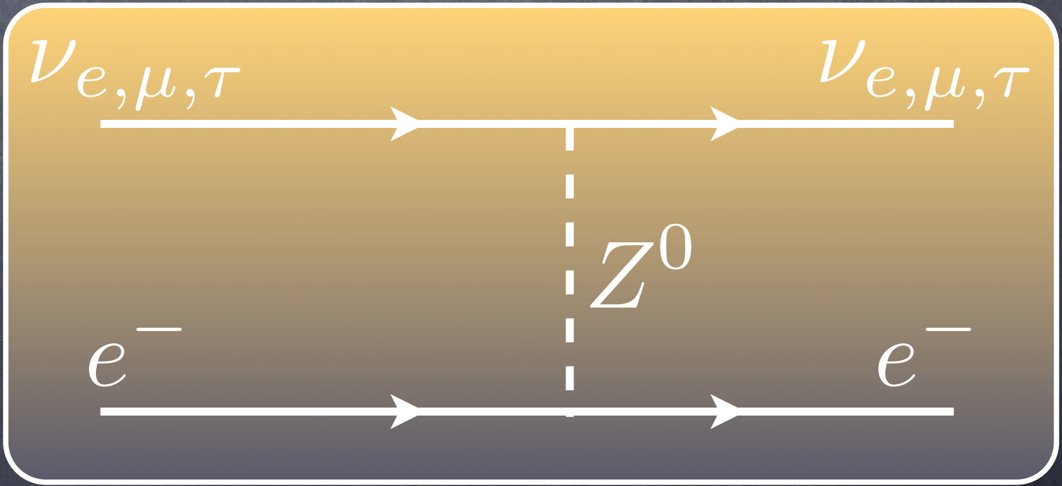


An Aside...
Neutrinos in Matter

- Neutrino oscillations can take place in vacuum or matter.

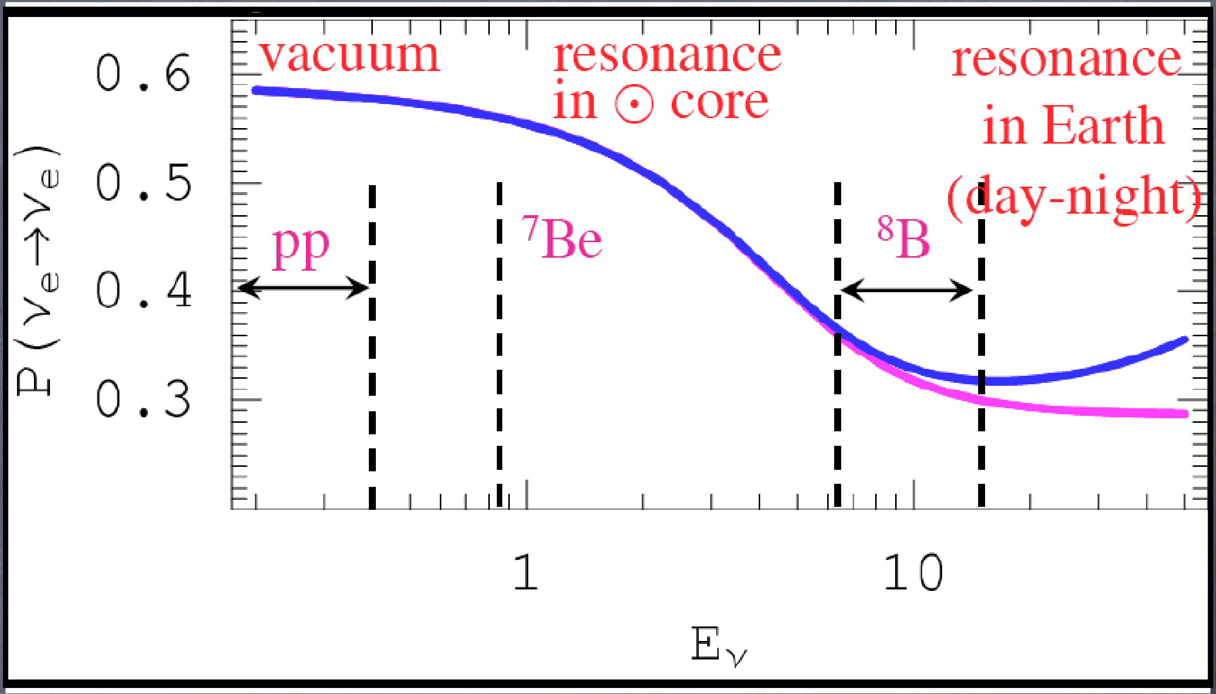
- Matter introduces a potential difference between electron and mu/tau reactions.





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

Let's Eat!