# Neutrinos

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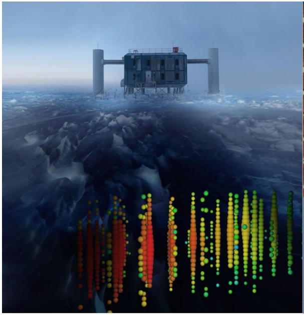


# What's so interesting about neutrinos?

Neutrinos are a key to understanding a range of physics.

- Neutrino sector expected to give clues to beyond the standard model physics and grand unification theories
- Neutrino nature is related to lepton number violation, which may be important for generating the matter/antimatter asymmetry in the early Universe
- There is a cosmic neutrino background (like the CMB) of 336 $\nu/\text{cm}^3$ which affects the Universe's evolution and large scale structure formation
- Neutrinos are a unique cosmic messenger, able to escape from dense regions and unaffected by magnetic fields
- ...

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# Introducing neutrinos...

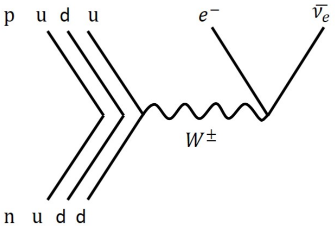
- Three neutrino flavours corresponding to the three charged leptons

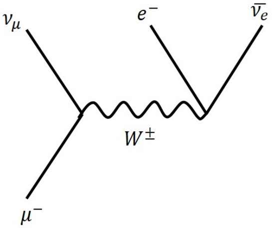
| $\nu_e$ | $\nu_\mu$ | $\nu_\tau$ |
|---|---|---|
| electron neutrino | muon neutrino | tau neutrino |

- And three flavours of anti-neutrinos

| $\nu_e$ | $\nu_\mu$ | $\nu_\tau$ |
|---|---|---|
| electron anti-neutrino | muon anti-neutrino | tau anti-neutrino |

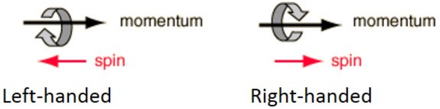
- Neutrino flavour and antiparticle/particle distinction determined by the interaction vertex and lepton flavour conservation



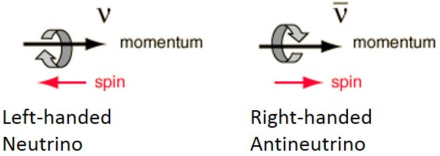



# Introducing neutrinos... parity violation

- Parity refers to the relative orientation of the spin and momentum vectors of a particle




- All neutrinos are left-handed and all anti-neutrinos are right-handed



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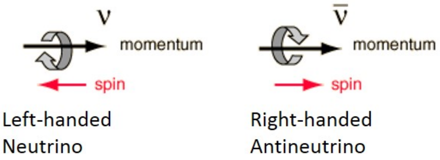
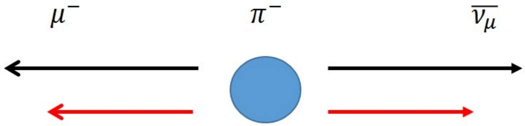


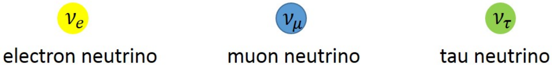

- Pion decay - pion has spin 0,
  in rest frame of pion, $\mu$ and $\nu_\mu$ emitted back to back eg




- Mirror process not allowed.

# Introducing neutrinos... sterile neutrinos

- Three active neutrino flavours corresponding to the three charged leptons




- It is possible that there are sterile neutrinos - neutrinos which do not interact by any force other than gravity
- Sterile neutrinos could oscillate with the active neutrinos - in that case the PMNS matrix would not be unitary (more later...)

# Neutrino - Majorana or Dirac particle?

What is a Majorana particle?

- A Majorana particle is its own antiparticle, ie it is self charge-conjugate $\psi = \psi^c \equiv C\bar{\psi}^T$ where $C$ is the charge conjugate matrix which has the property $C\gamma_\lambda C^{-1} = -\gamma^{\lambda^T}$
- A Majorana neutrino is described by the Lagrangian

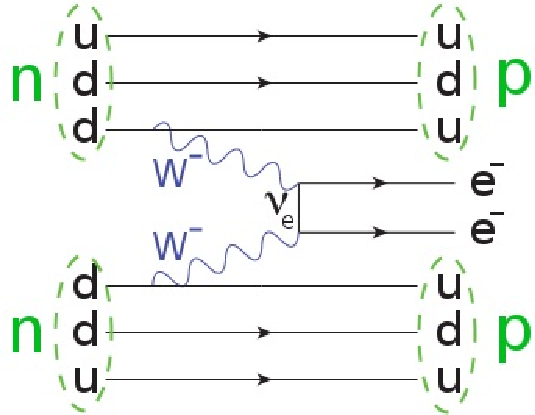
$$\mathcal{L}^{\mathrm{M}} = \bar{\nu_L} i\partial\!\!\!/ \nu_L - \frac{m}{2}\left(\bar{\nu_L^c}\nu_L + \bar{\nu_L}\nu_L^c\right)$$

compare to the Dirac Lagrangian

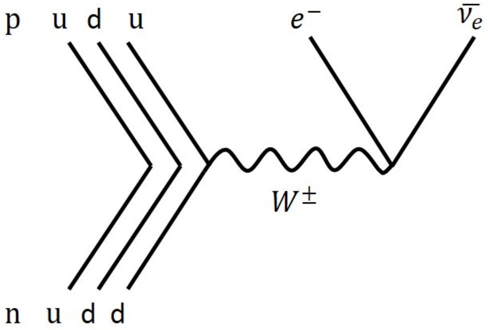
$$\mathcal{L}^{\mathrm{D}} = \bar{\nu_L} i\partial\!\!\!/ \nu_L + \bar{\nu_R} i\partial\!\!\!/ \nu_R - m\left(\bar{\nu_R}\nu_L + \bar{\nu_L}\nu_R\right)$$

- Majorana particles imply lepton number violation

# Majorana neutrinos $\Longrightarrow$ lepton violating neutrinoless double beta decay $\beta\beta0\nu$

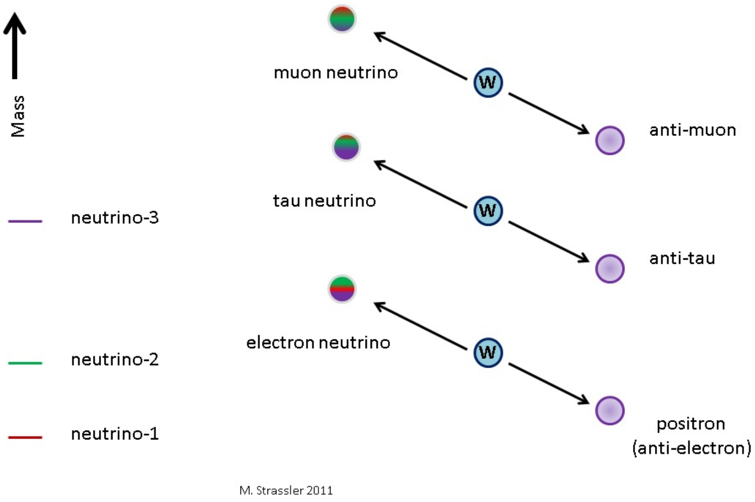


# Compare beta decay



# Neutrino masses

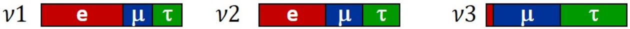
- Neutrino mass eigenstates are not neutrino flavour eigenstates



# Neutrino masses

Pontecorvo-Maki-Nakagawa-Sakata Matrix relating flavour and mass eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



# Neutrino masses

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This $3 \times 3$ unitary mixing matrix can be expressed in terms of four physical parameters conventionally chosen as three mixing angles $\theta_{12}, \theta_{23}, \theta_{13}$ (like 3 Euler angles describing rotation in 3D space) and one phase $\delta_{13}$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$c_{ab} \equiv \cos\theta_{ab} \qquad s_{ab} \equiv \sin\theta_{ab} \qquad 0 \leq \theta_{ab} \leq \frac{\pi}{2} \qquad 0 \leq \delta_{13} \leq 2\pi$$

# Neutrino masses - 2 flavour oscillations

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Amplitude for oscillation from flavour state $\alpha$ to state $\beta$

$$A(\nu_\alpha \to \nu_\beta) = \sum_i \big[A(\text{neutrino born flavour } \alpha \text{ is a } \nu_i)$$

$$\times A(\nu_i \text{ propagates}) \times A(\text{when } \nu_i \text{ interacts it makes flavour} \beta)\big]$$

In terms of time $t$ and position $L$ each mass eigenstate propagates as $\mathrm{e}^{-i(E_i t - p_i L)}$ and where $t \cong L$ it becomes $\mathrm{e}^{-i(E_i - p_i)L}$ where $p_i = \sqrt{E^2 - m_i^2} \cong E - m_i^2/2E$ so

$$A(\nu_i \text{ propagates}) = \mathrm{e}^{-i\left(m_i^2/2p\right)L}$$

and

$$P(\nu_\alpha \to \nu_\beta) = |A(\nu_\alpha \to \nu_\beta)|^2 = \sin^2(2\theta)\sin^2\left(\frac{\Delta m_{12}^2 L}{4E}\right)$$

# Neutrino masses - 2 flavour oscillations

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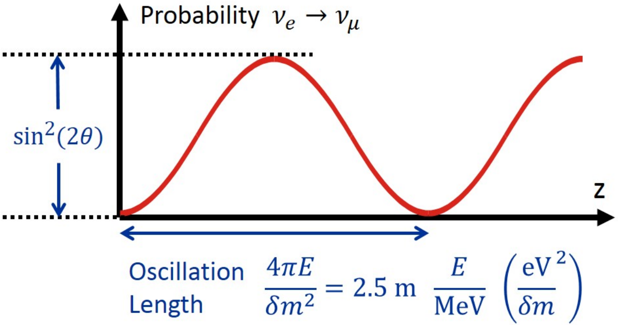
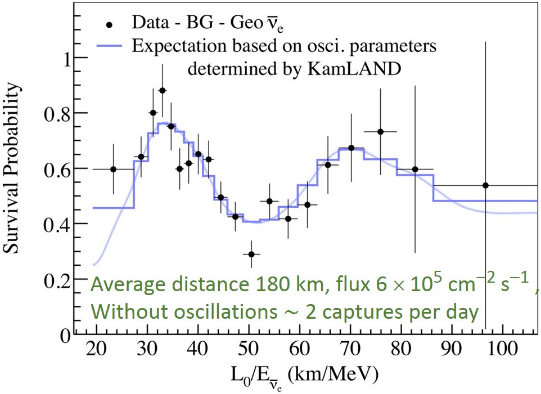
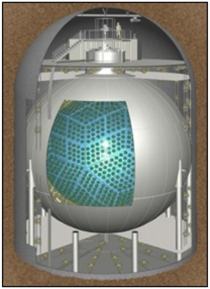


# Oscillation of reactor neutrinos at KamLAND

Oscillation pattern for anti-electron neutrinos from Japanese power reactors as a function of L/E

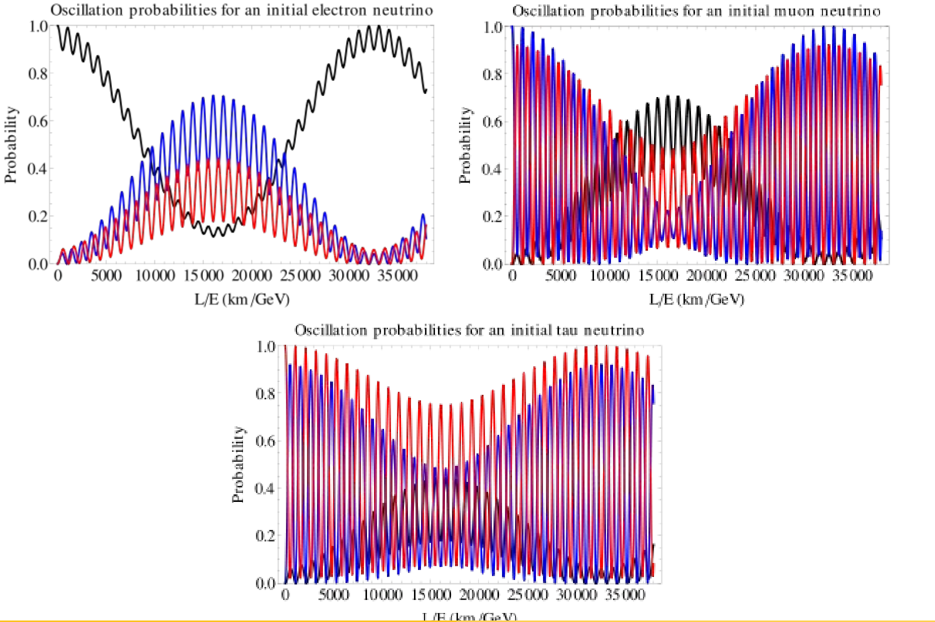






KamLAND Scintillator detector (1000 t)

# Neutrino masses - 3 flavour oscillations



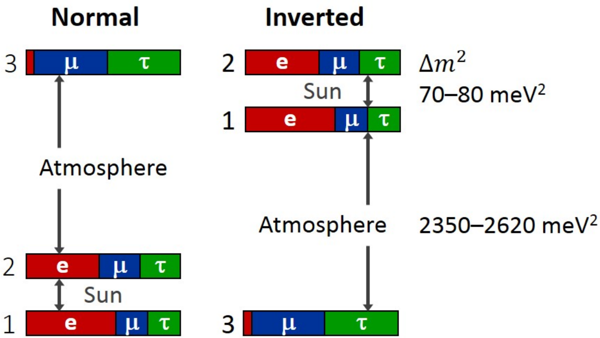
# Neutrino masses - 3 flavour oscillations

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{39^\circ < \theta_{23} < 53^\circ} \underbrace{\begin{pmatrix}c_{13} & 0 & e^{-i\delta}s_{13}\\ 0 & 1 & 0\\ -e^{i\delta}s_{13} & 0 & c_{13}\end{pmatrix}}_{7^\circ < \theta_{13} < 9^\circ} \underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{31^\circ < \theta_{12} < 37^\circ} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Atmospheric/LBL-Beams | Reactor | Solar/KamLAND

# Neutrino masses - 3 flavour oscillations

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{\substack{39^\circ < \theta_{23} < 53^\circ \\ \text{Atmospheric/LBL-Beams}}} \underbrace{\begin{pmatrix}c_{13} & 0 & e^{-i\delta}s_{13}\\ 0 & 1 & 0\\ -e^{i\delta}s_{13} & 0 & c_{13}\end{pmatrix}}_{\substack{7^\circ < \theta_{13} < 9^\circ \\ \text{Reactor}}} \underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\substack{31^\circ < \theta_{12} < 37^\circ \\ \text{Solar/KamLAND}}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

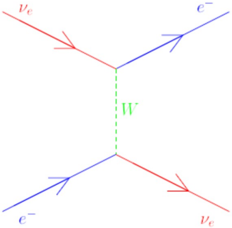



Ongoing

- Precision for all angles
- CP-violating phase $\delta$?
- Mass ordering? (normal vs inverted)

# Oscillations in matter - MSW effect

- The Mikheyev Smirnov Wolfenstein effect or matter effect describes a change in oscillation parameters for neutrinos propagating in matter
- Charged current coherent forward scattering of the electron neutrinos off electrons in matter changes the neutrino energy levels and oscillation amplitudes




$$V_{CC} = \sqrt{2} G_F N_e$$

- Propagation amplitude determined by Hamiltonian which is modified $H = H_0 + H_I$

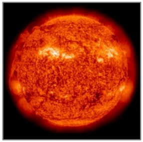
# Sources of neutrinos

Reactors

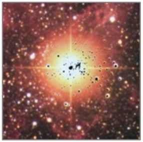
Particle accelerators

Geo-neutrinos

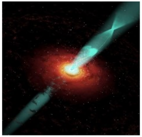
Atmospheric neutrinos – interactions of cosmic rays in the Earth's atmosphere



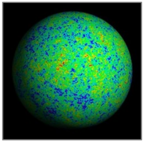
Sun



Supernova

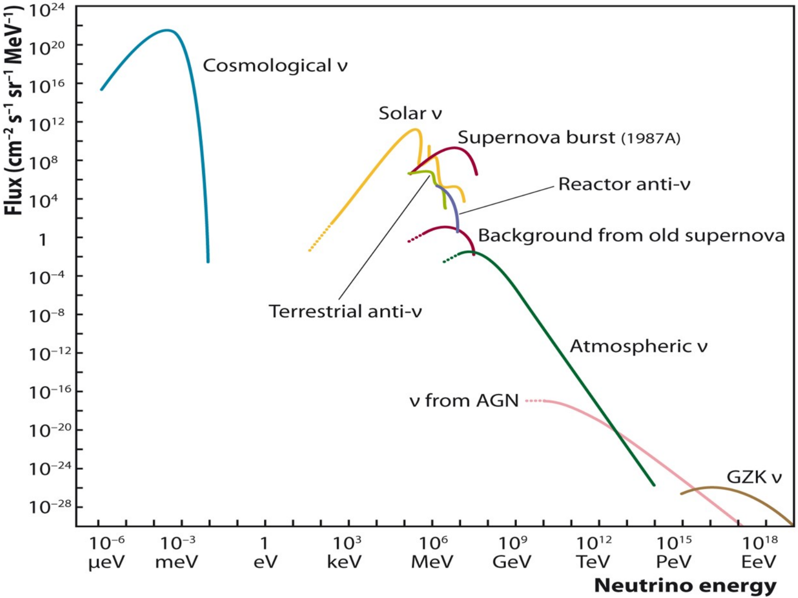


Astrophysical accelerators

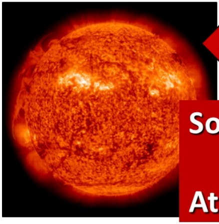


Cosmic neutrinos – prediction 337 $\nu/cm^3$

# Sources of neutrinos

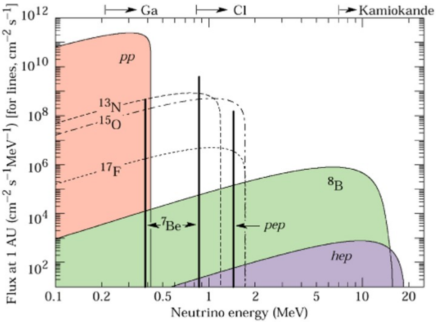


# Solar neutrinos

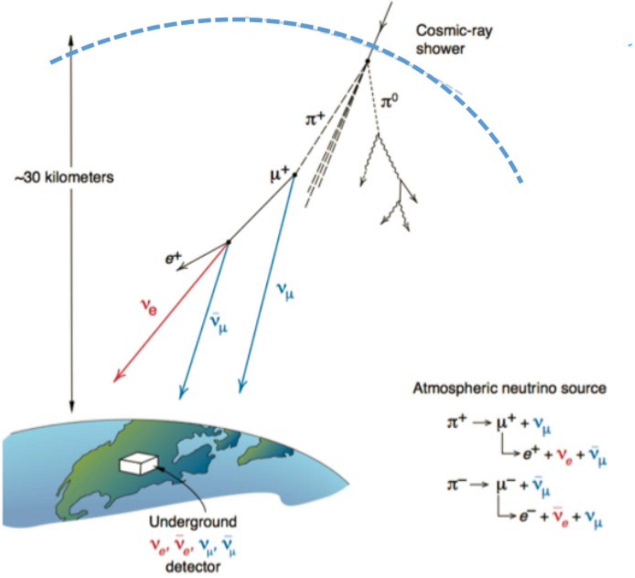


**8.3 light minutes**

**Solar radiation: 98 % light (photons)**
**2 % neutrinos**
**At Earth 66 billion neutrinos/cm² sec**

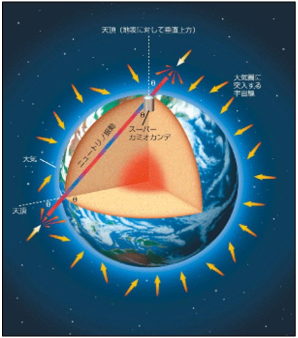


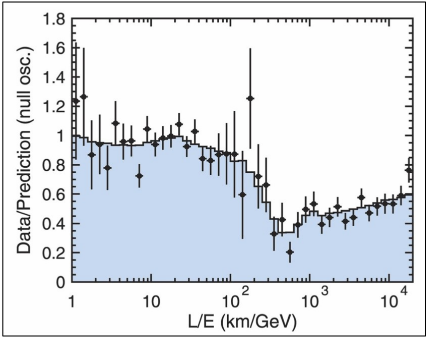

# Atmospheric neutrinos



# Atmospheric neutrino oscillations

## Observation by SuperKamiokande - 2008




Atmospheric neutrino oscillations show characteristic L/E variation