Neutrino Physics

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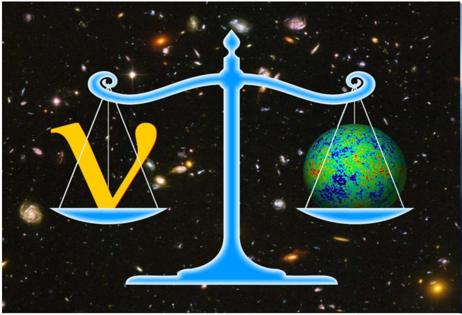
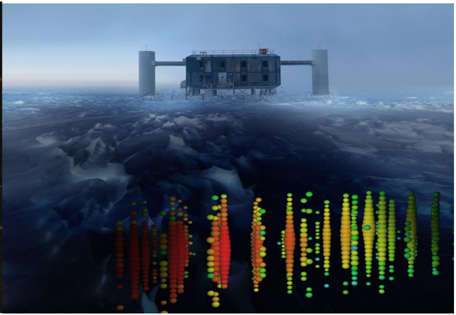
The Invisible Universe 2019

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 337 ν/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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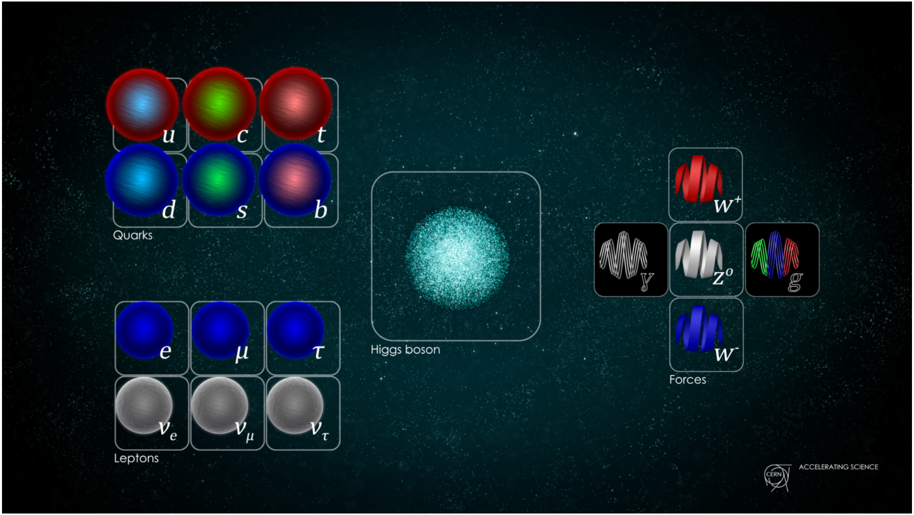
Introducing neutrinos...

Standard Model Particles



Introducing neutrinos...

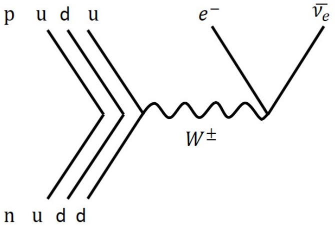
- Three neutrino flavours corresponding to the three charged leptons

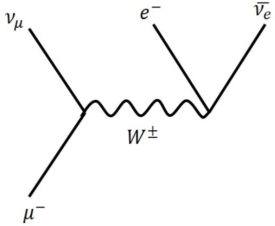
ν_e	ν_μ	ν_τ
electron neutrino	muon neutrino	tau neutrino

- And three flavours of anti-neutrinos

$\bar{\nu}_e$	$\bar{\nu}_\mu$	$\bar{\nu}_\tau$
electron anti-neutrino	muon anti-neutrino	tau anti-neutrino

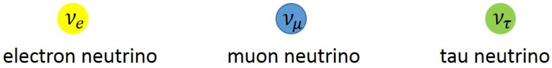
- Neutrino flavour and antiparticle/particle distinction determined by the interaction vertex and lepton flavour conservation





Introducing neutrinos... sterile neutrinos

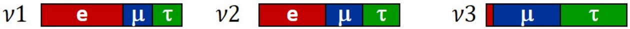
- Three active neutrino flavours corresponding to the three charged leptons



- 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

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 flavour and mass eigenstates

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This 3×3 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 δ_{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 oscillations - 2 flavour oscillations

$$\begin{pmatrix}\nu_\alpha \\ \nu_\beta\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta \\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1 \\ \nu_2\end{pmatrix} \qquad \begin{pmatrix}\nu_1 \\ \nu_2\end{pmatrix} = \begin{pmatrix}\cos\theta & -\sin\theta \\ \sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_\alpha \\ \nu_\beta\end{pmatrix}$$

Amplitude for oscillation from flavour state α to state β

$$A(\nu_\alpha \to \nu_\beta) = \sum_i \big[A(\text{neutrino born flavour } \alpha \text{ is a } \nu_i)$$
$$\times A(\nu_i \text{ propagates}) \times A(\text{when } \nu_i \text{ interacts it makes flavour}\beta)\big]$$

Neutrino oscillations - 2 flavour oscillations

Propagator:
In terms of time t and position L each mass eigenstate propagates as

$$\mathrm{e}^{-i(E_i t - p_i L)}$$

as neutrinos relativistic $t \cong L$ the propagator is $\mathrm{e}^{-i(E_i - p_i)L}$

$$p_i = \sqrt{E^2 - m_i^2} \cong E - m_i^2/2E$$

so

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

Neutrino oscillations - 2 flavour oscillations

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

$$\begin{aligned}
A(\nu_\alpha \to \nu_\beta) &= \cos\theta\, \mathrm{e}^{-i\left(m_1^2/2E\right)L}(-\sin\theta) + \sin\theta\, \mathrm{e}^{-i\left(m_2^2/2E\right)L}\cos\theta \\
&= \cos\theta\sin\theta\left(-\mathrm{e}^{-i\left(m_1^2/2E\right)L} + \mathrm{e}^{-i\left(m_2^2/2E\right)L}\right) \\
&= \frac{\sin 2\theta}{2}\left(-\mathrm{e}^{-i\left(m_1^2/2E\right)L} + \mathrm{e}^{-i\left(m_2^2/2E\right)L}\right)
\end{aligned}$$

$\sin 2\theta = 2\sin\theta\cos\theta$

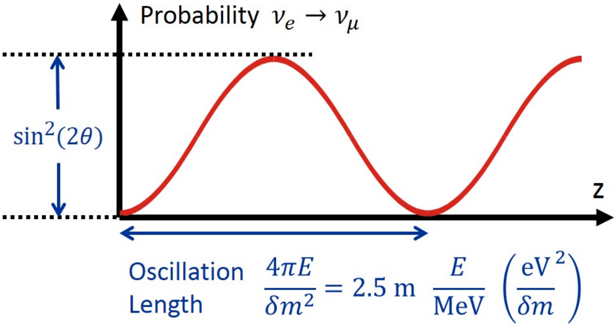
Neutrino oscillations - 2 flavour oscillations

$$
\begin{aligned}
P(\nu_\alpha \to \nu_\beta) &= |A(\nu_\alpha \to \nu_\beta)|^2 \\
&= \sin^2(2\theta)\frac{1}{4}\left|-\mathrm{e}^{-i\left(m_1^2/2E\right)L} + \mathrm{e}^{-i\left(m_2^2/2E\right)L}\right|^2 \\
&= \sin^2(2\theta)\frac{1}{4}\left[2 - \left(\mathrm{e}^{-i\left(\left(m_1^2-m_2^2\right)/2E\right)L} + \mathrm{e}^{+i\left(\left(m_1^2-m_2^2\right)/2E\right)L}\right)\right] \\
&= \sin^2(2\theta)\frac{1}{2}\left[1 - \cos\left(\left(m_1^2 - m_2^2\right)/2E\right)L\right] \\
&= \sin^2(2\theta)\sin^2\left(\frac{\delta m_{12}^2 L}{4E}\right)
\end{aligned}
$$

$\sin^2\theta/2 = \frac{1}{2}(1-\cos\theta)$

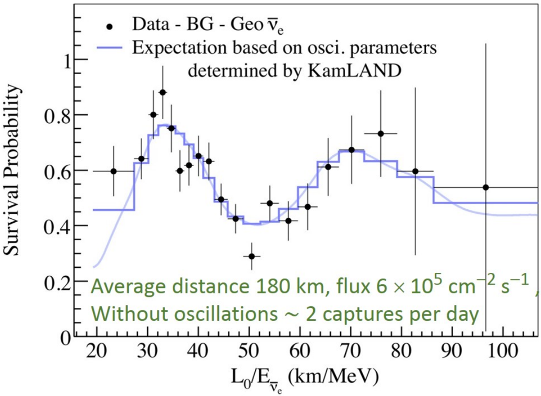
Neutrino oscillations - 2 flavour oscillations

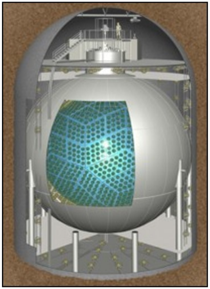
$$P(\nu_\alpha \to \nu_\beta) = |A(\nu_\alpha \to \nu_\beta)|^2 = \sin^2(2\theta)\sin^2\left(\frac{\delta m^2 L}{4E}\right)$$



Oscillation of reactor neutrinos at KamLAND

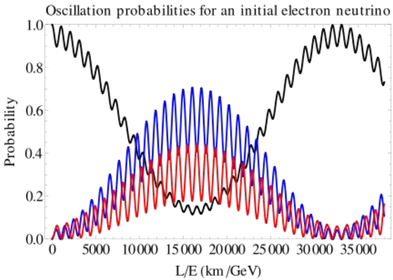
Oscillation pattern for anti-electron neutrinos from Japanese power reactors as a function of L/E

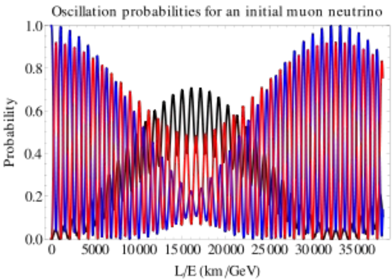


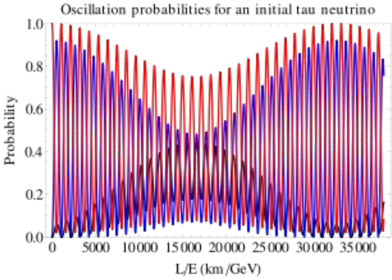


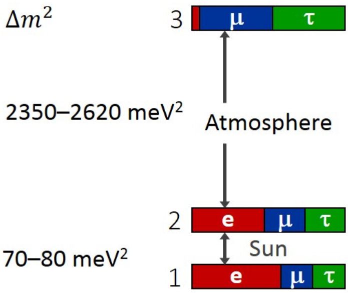
KamLAND Scintillator detector (1000 t)

Neutrino oscillations - 3 flavour oscillations









Neutrino oscillations- 3 flavour oscillations

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

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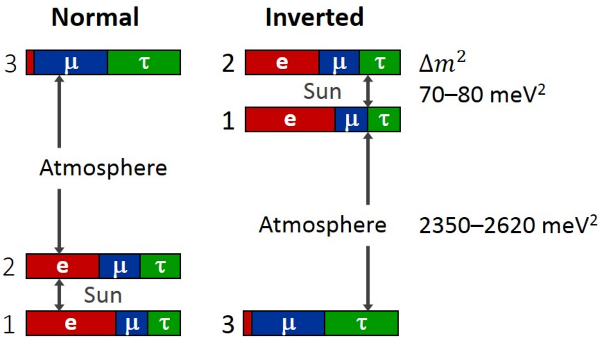


Ongoing

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

Neutrino oscillations - Summary

- Neutrinos exhibit flavour oscillations due to the misalignment of the neutrino flavour and mass eignenstates
- The flavour and mass eigenstates are related by a matrix which can be characterised by 3 mixing angles and a phase (CP violating)
- Observations of the flavour oscillations allow the mass differences and mixing angles to be determined
- Focus is on the undetermined mass hierachy, CP violating phase, and the mass values
- Neutrino parameters can probe extensions to the standard model

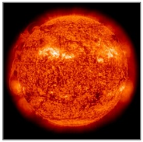
Sources of neutrinos

Reactors

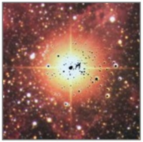
Particle accelerators

Geo-neutrinos

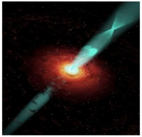
Atmospheric neutrinos – interactions of cosmic rays in the Earth's atmosphere



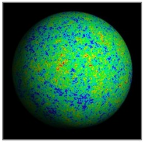
Sun



Supernova

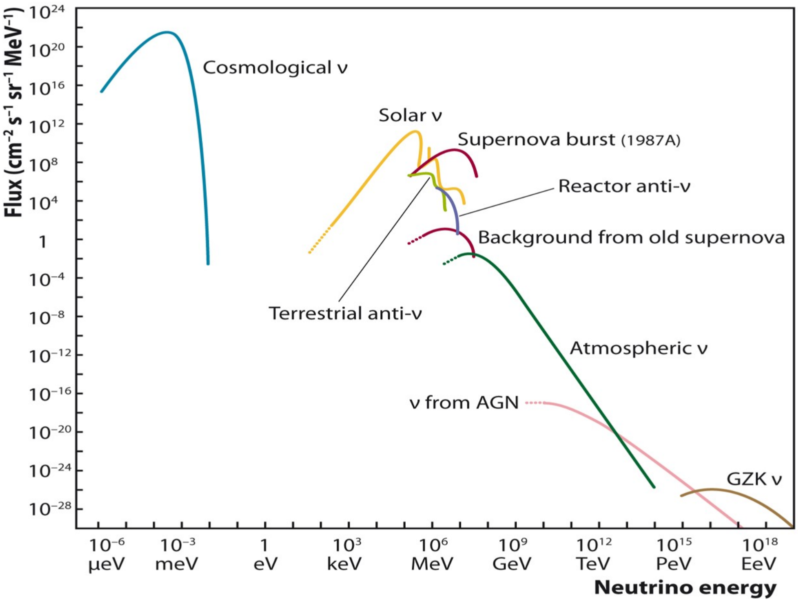


Astrophysical accelerators

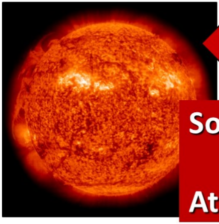


Cosmic neutrinos – prediction 337 ν/cm^3

Sources of neutrinos



Solar neutrinos

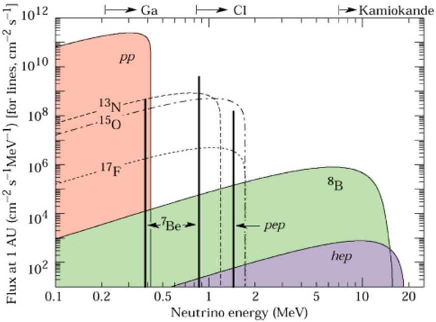


8.3 light minutes

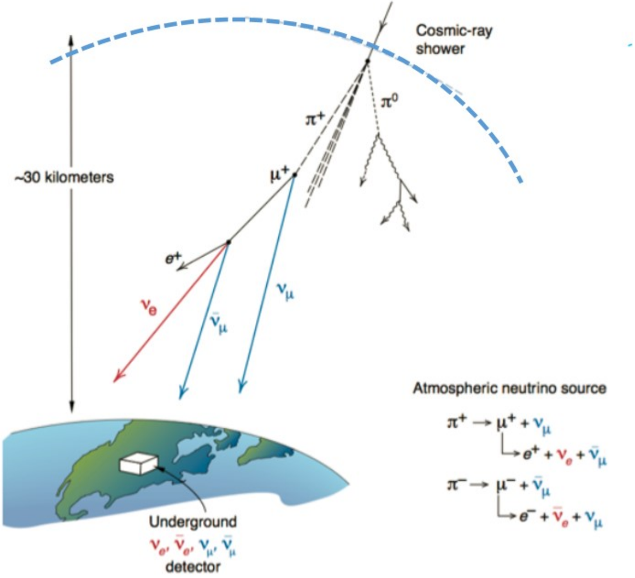
Solar radiation: 98 % light (photons)

2 % neutrinos

At Earth 66 billion neutrinos/cm² sec

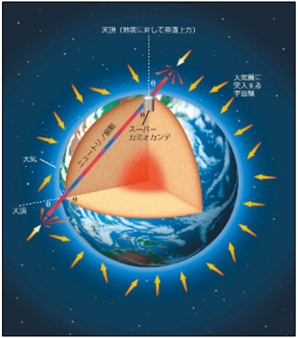


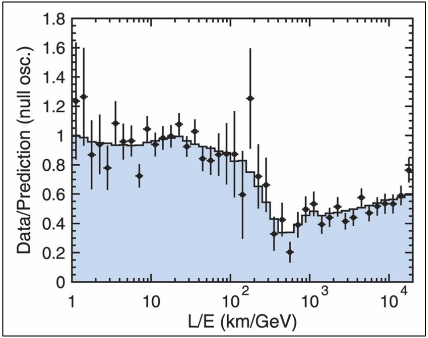
Atmospheric neutrinos



Atmospheric neutrino oscillations

Observation by SuperKamiokande - 2008

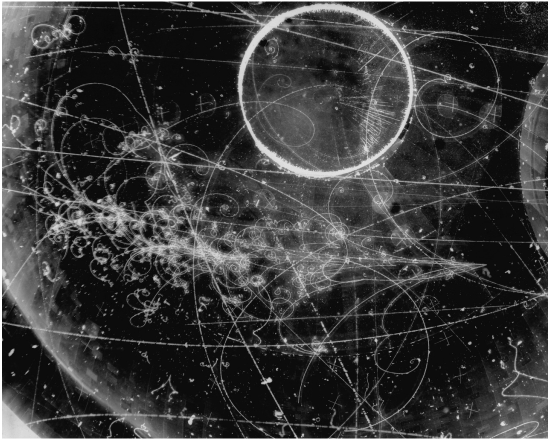




Atmospheric neutrino oscillations show characteristic L/E variation

Detecting neutrinos?

No neutrino tracks...



basic principle is to look for evidence that neutrinos have interacted, by detecting products of the interaction

Detecting neutrinos?

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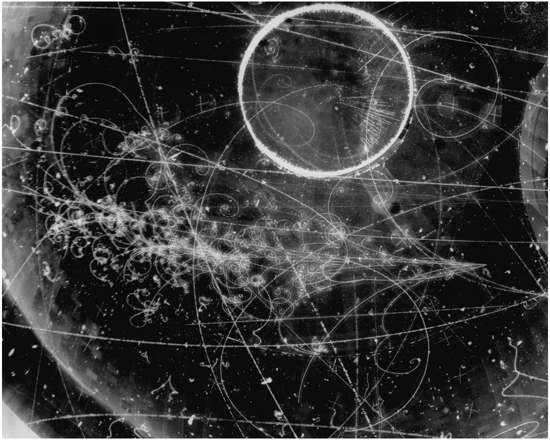

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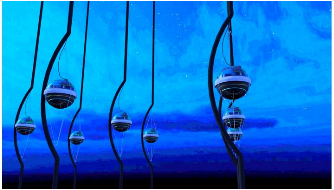
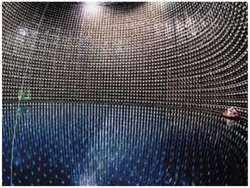
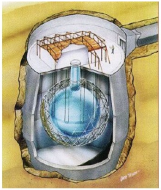
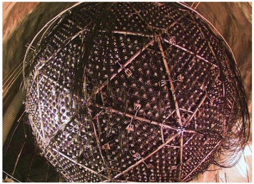
Neutrino Detectors



ANITA ANNIE ANTARES ARIANNA BDUNT (NT-200+) BOREXINO CLEAN COBRA Daya Bay Double Chooz EXO-200 GALLEX GERDA GNO HALO HERON HOMESTAKE ICARUS IceCube INO JUNO Kamiokande KamLAND KM3NeT LAGUNA LBNE/DUNE LENS MAJORANA DEMONSTRATOR MicroBooNE MINERvA MiniBooNE MINOS MINOS+ NEMO Experiment MOON NEMO Telescope NEVOD NOA OPERA RENO SAGE SciBooNE SNO SNO+ Super-K T2K UNO . . .

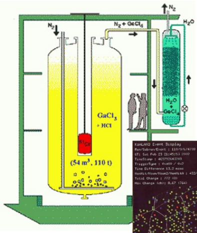


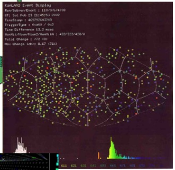
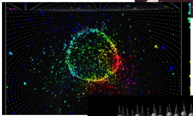
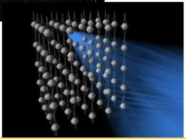




Detecting neutrinos

- Large volumes needed to combat weak interaction
- Shielding required to reduce backgrounds $\Longrightarrow$ underground
- Three main detection techniques



- Radio-chemical: Radioactive atoms formed by capture of neutrinos in target Eg Ray Davis's solar neutrino experiment, used the isotope ^{37}Cl, neutrino capture produces radioactive ^{37}Ar, a gas, which was removed from the target, purified, and counted.
- Scintillation Use liquid scintillator, organic liquid that gives off light, when charged particles pass through it. The scintillator is monitored by optical detectors.
- Cherenkov light detectors Cherenkov light is produced by particles moving faster than the speed of light in the medium. Optical detectors detect the Cherenkov light.

Neutrino Sources and Detectors