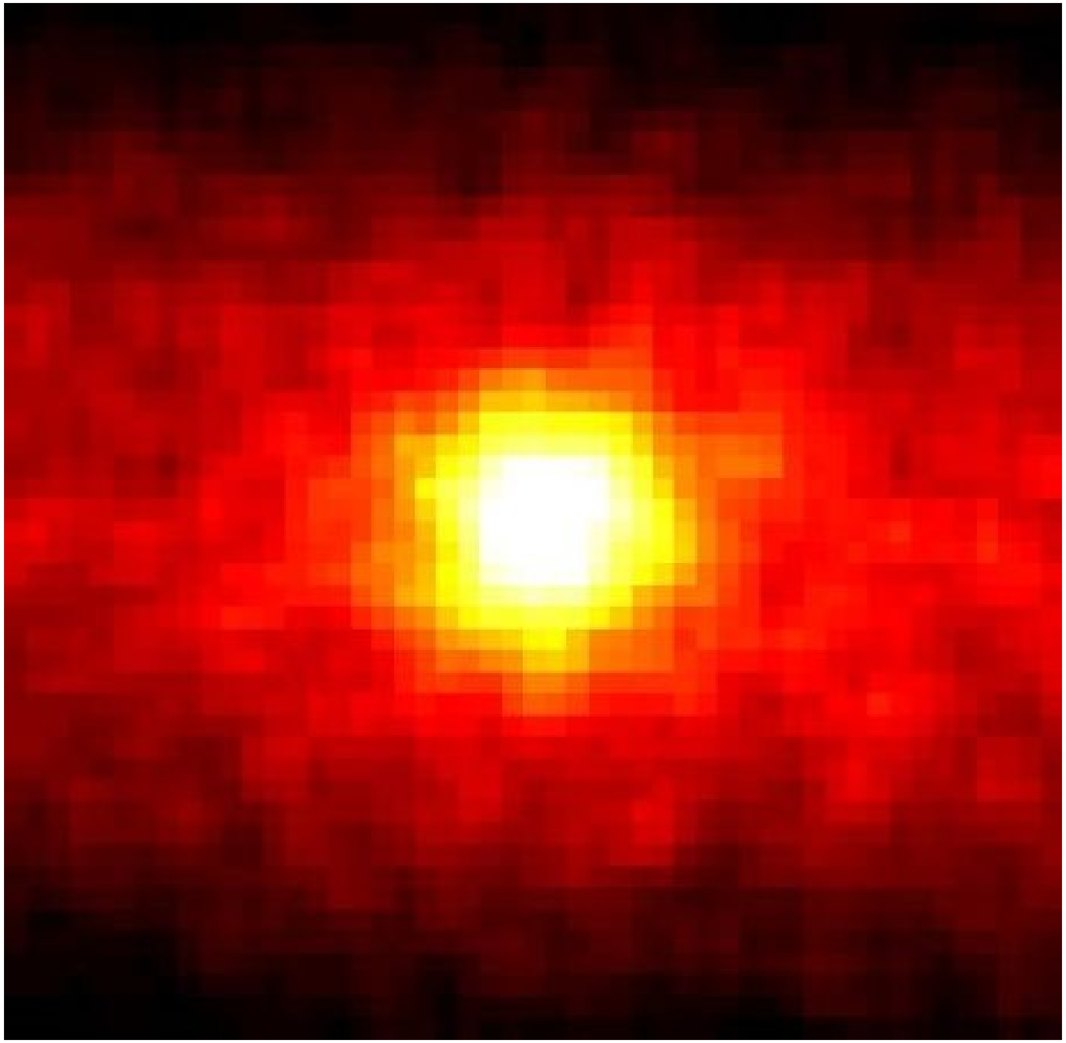
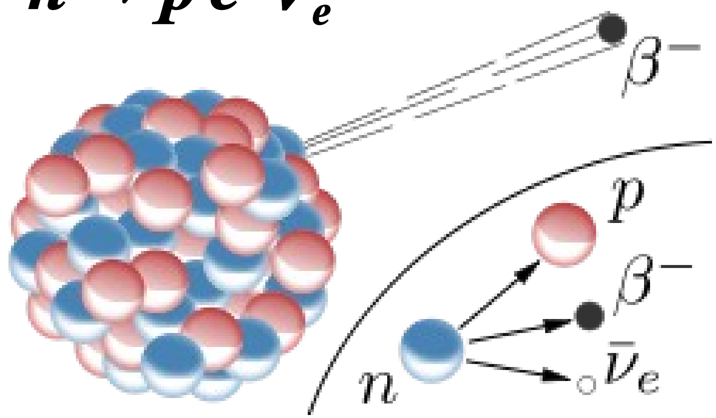
How does one know that neutrinos have mass?

Aleksandra Adametz



History

$$n \rightarrow p\, e^{-}\, \bar{\nu}_e$$



In 1930:

Continuous spectrum of electrons from nuclear decays could not be explained

➡ New neutral particle postulated

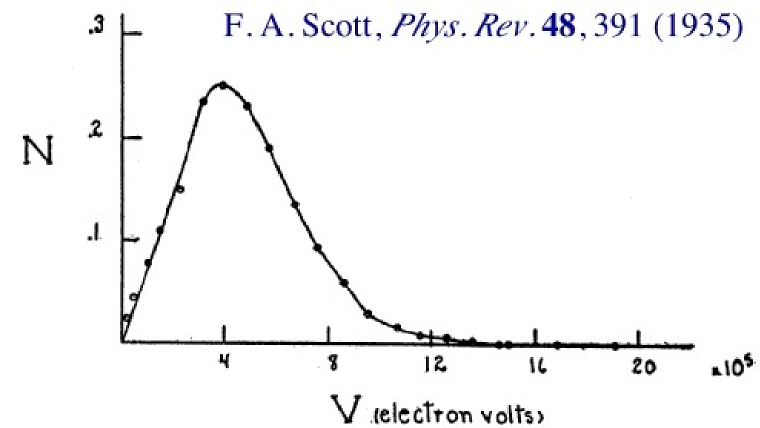


FIG. 5. Energy distribution curve of the beta-rays.

In 1956:

First observation of neutrinos

Anti-electron-neutrinos detected in reaction

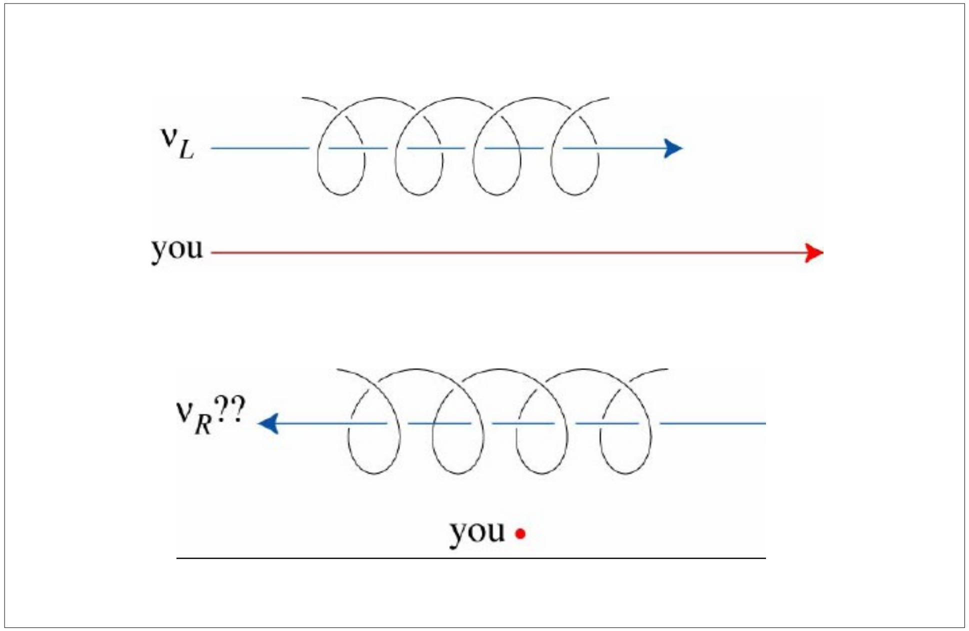
$$\bar{\nu}_e\, p \rightarrow e^{+}\, n$$

Standard Model

- neutrinos are always left-handed

  right-handed neutrinos
  never observed

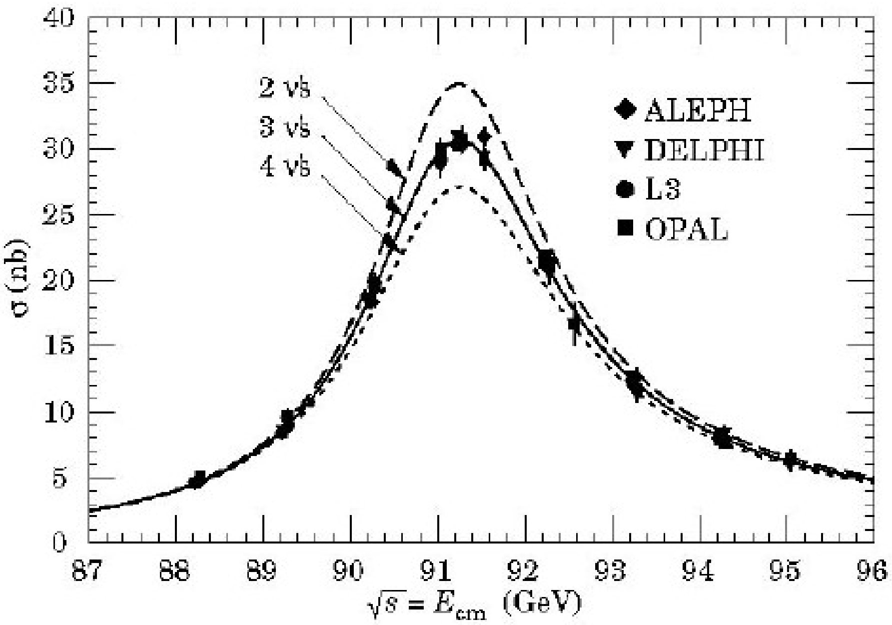
  ➡ neutrinos are massless



- 3 types of neutrinos

  measurment of Z^0-decays at LEP

$$\Gamma_Z = \Gamma_{hadr} + \Gamma_{l\bar{l}} + N_\nu \cdot \Gamma_{\nu\bar{\nu}}$$

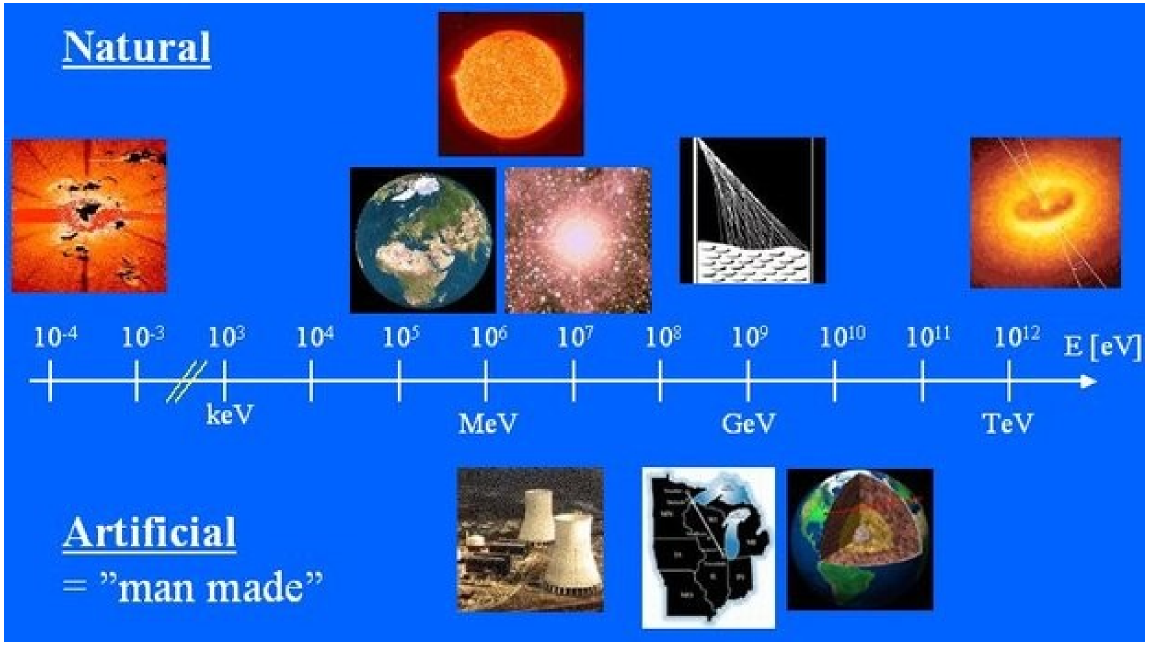


Neutrino Sources

- Sun
- Air showers (cosmic rays)

 "geoneutrinos" (e.g. decay of 238U within the Earth)

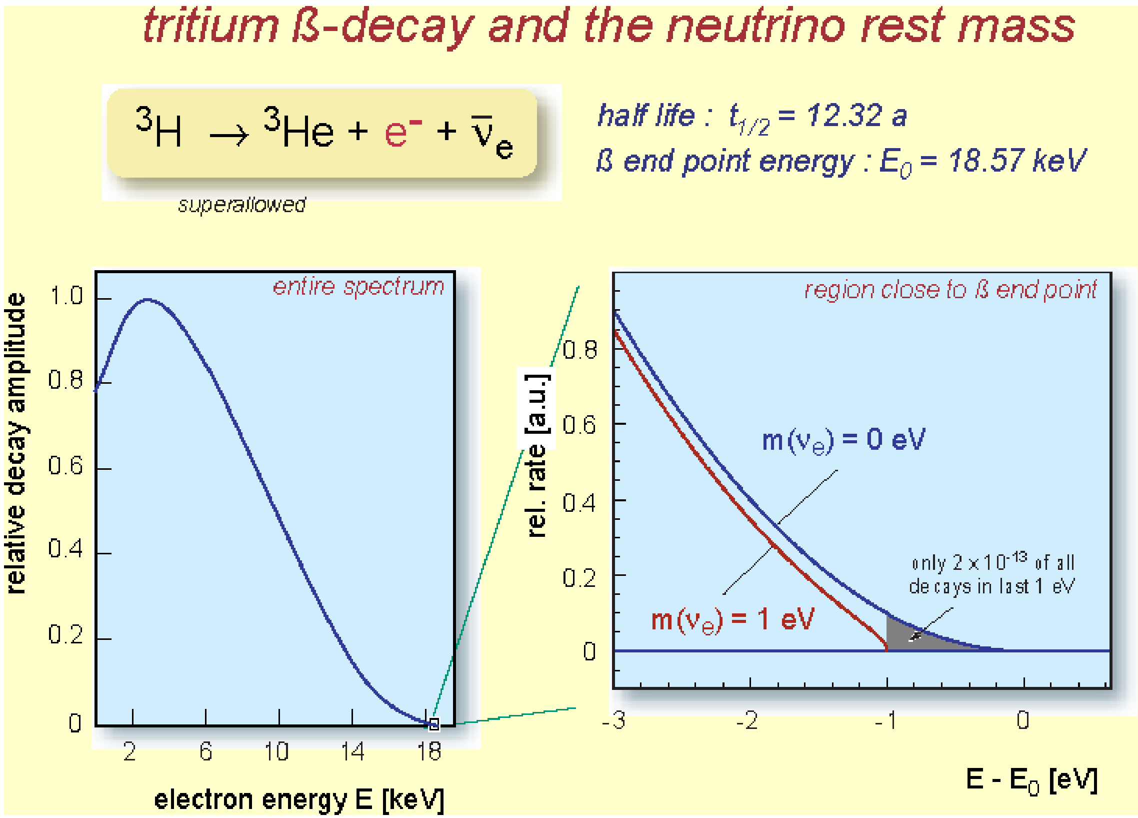
- cosmic neutrino background
- Supernovae
- Accelerators
- Reactors

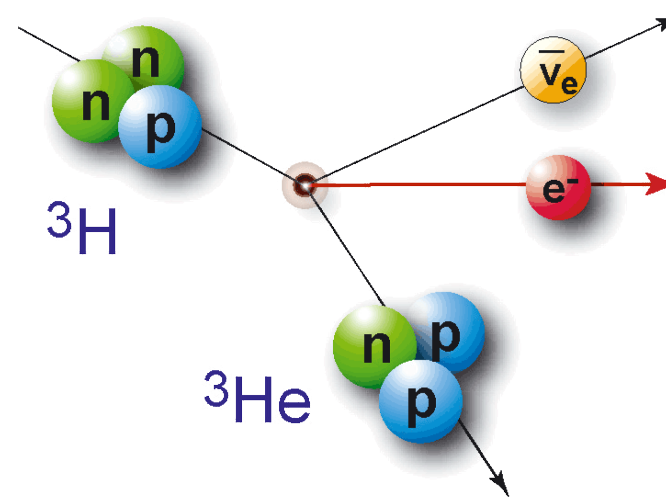


Direct Mass Measurements

Neutrino Mass Experiment:

- Mainz
- Troitsk
- KATRIN (future)





Upper limits on neutrino mass : ~ 2 eV

Atmospheric Neutrinos

<u>Production process:</u>

Proton collisions with nuclei

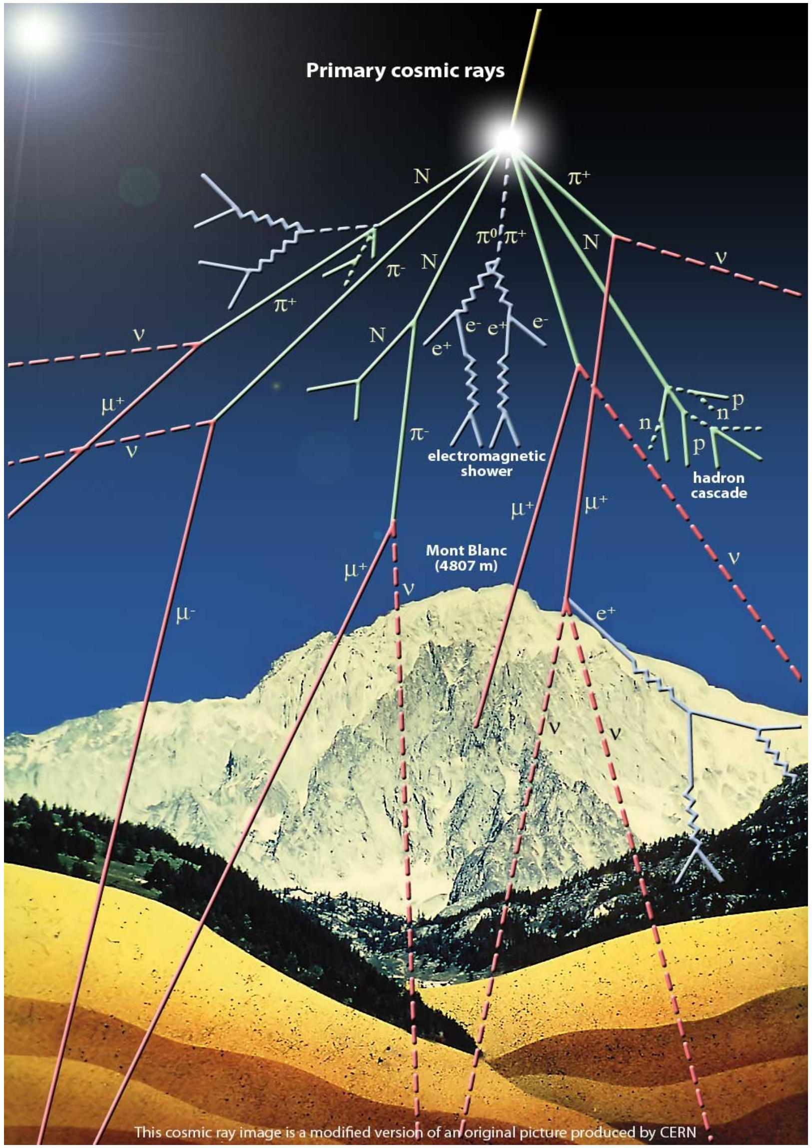
-> air showers

-> many charged Kaons ad Pions

$$K,\pi \rightarrow \mu + \nu_\mu$$

$$\hookrightarrow e + \nu_e + \nu_\mu$$

$$N(\nu_\mu) / N(\nu_e) = 2$$

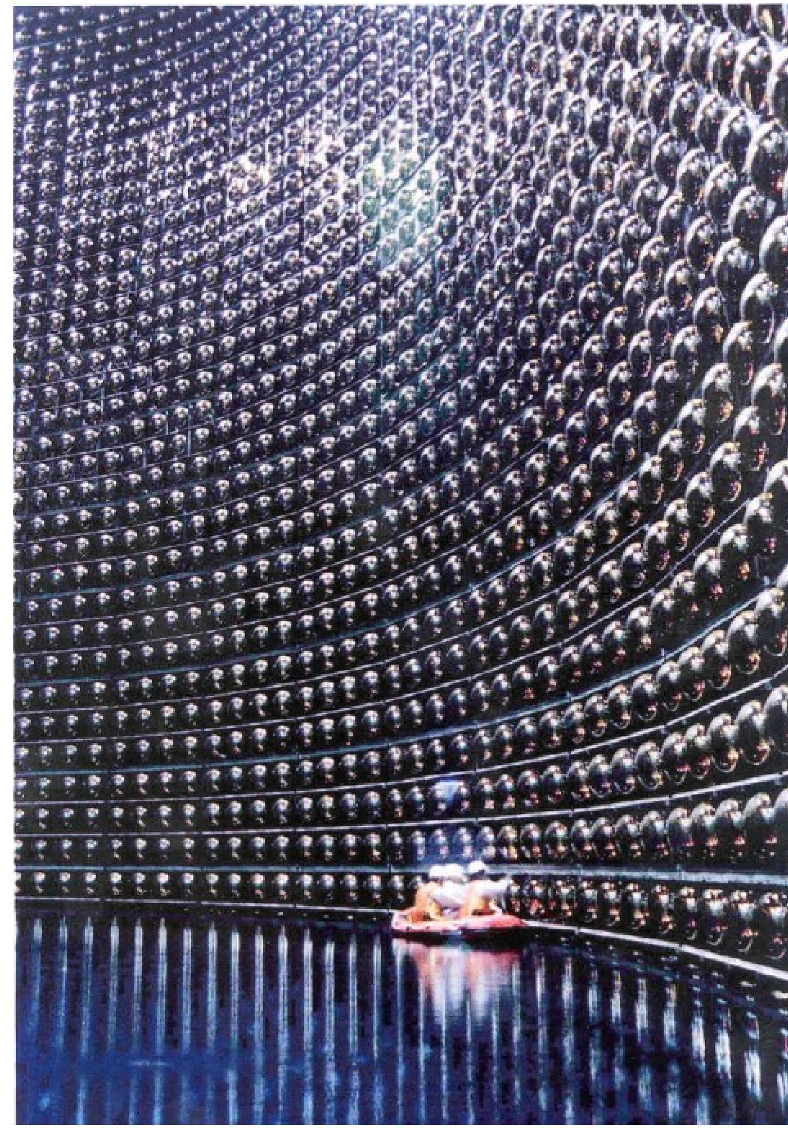


SuperKamiokande

1998 First evidence for neutrino mass

Detector:

- 50k m^3 H2O
- ~13k PMTs (50 cm Ø)
- 1000 m underground



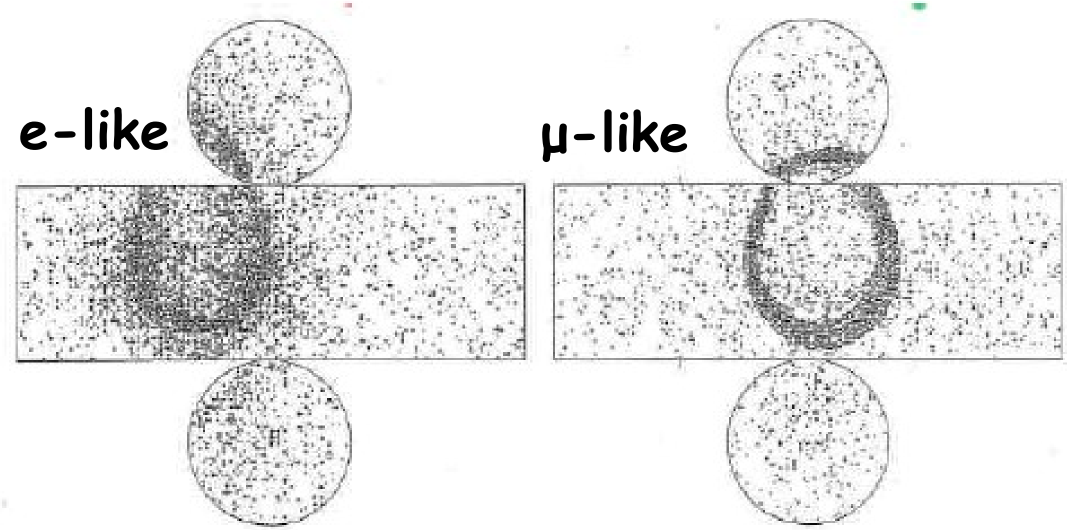
Principle:

- Reactions: $\nu\, n \rightarrow p\, l^-$
  $\bar{\nu}\, p \rightarrow n\, l^+$ (l=e,μ)

- Lepton emits Cherenkov-light in water
- Cherenkov-light detected in PMTs
- For multi-GeV events:
  neutrino direction ≈ lepton direction

SuperKamiokande: Event Reconstruction

Ring-shape allows discrimination between e-like and μ-like events



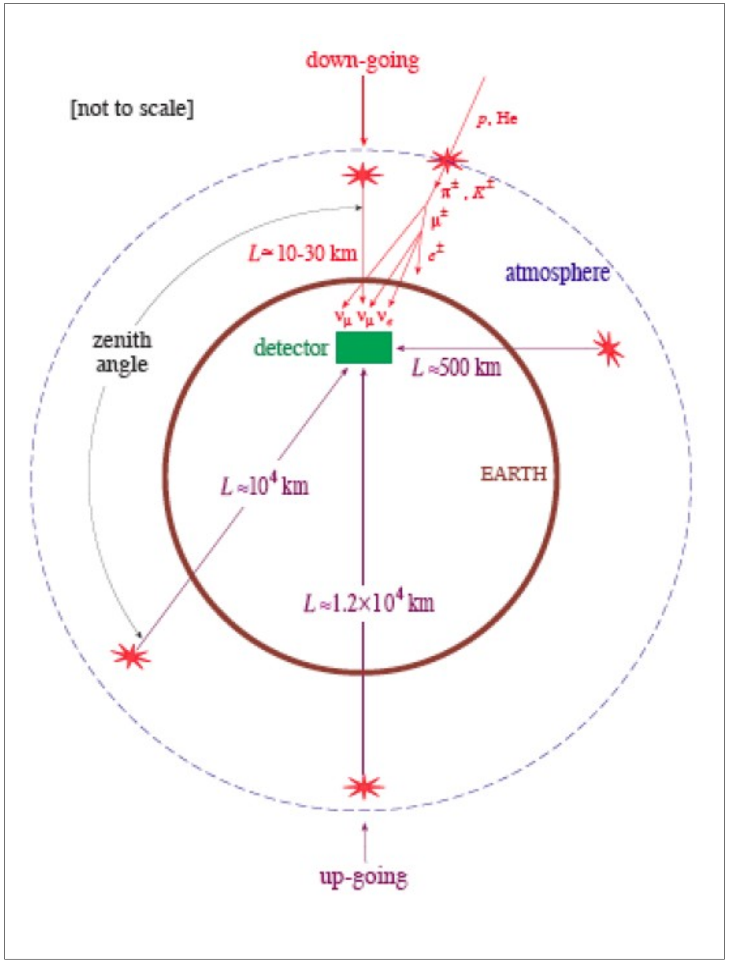
Determination of $R=\left(\frac{\mu-like}{e-like}\right)_{Data}/\left(\frac{\mu-like}{e-like}\right)_{MC}$

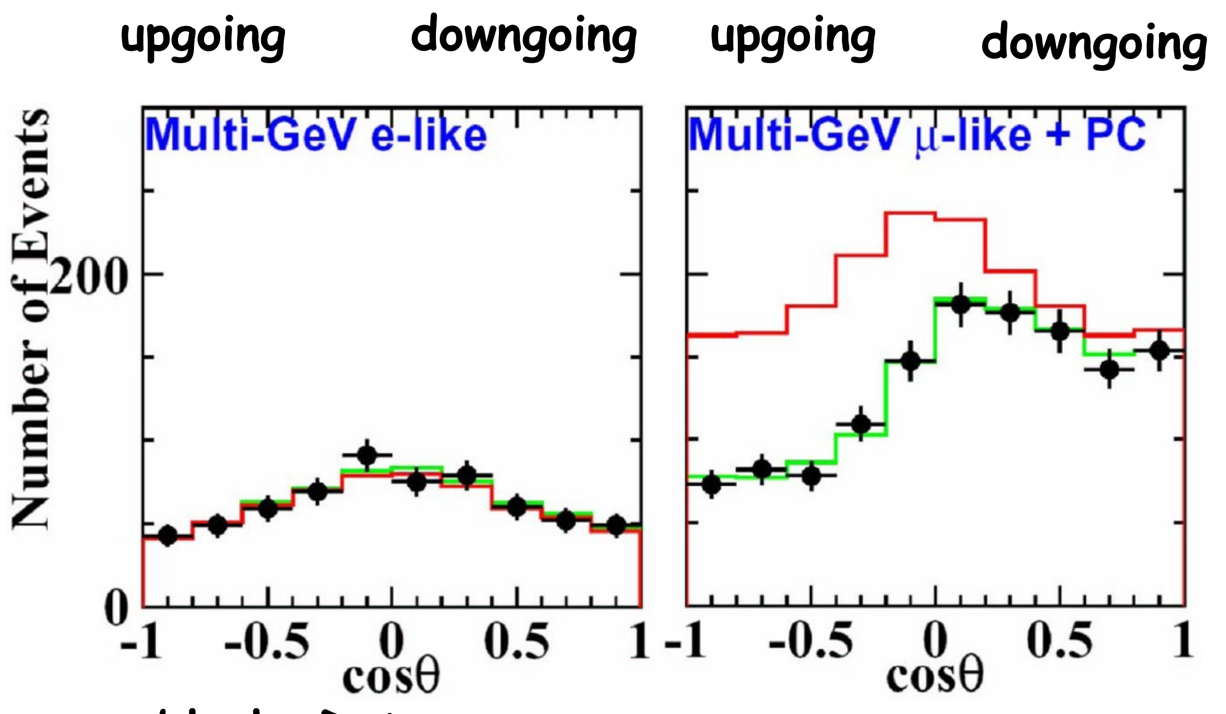
$$\frac{\mu-like}{e-like}=\frac{\nu_\mu+\bar{\nu}_\mu}{\nu_e+\bar{\nu}_e}$$

Prediction : R = 1

Measured : R = 0.6 → missing ν_μ or to many ν_e ?

SuperKamiokande: Zenith-angle dependence





black: Data

red : simulation

green: simulation with oscillation

Explanation for deficit: → Oscillation → Neutrino has mass!

From reactor neutrino experiments: Limits on $\nu_\mu \to \nu_e$

Conclusion: Oscillation is $\nu_\mu \to \nu_\tau$

Oscillation Formalism

- Flavor eigenstates expressed as superpositions of mass eigenstates:

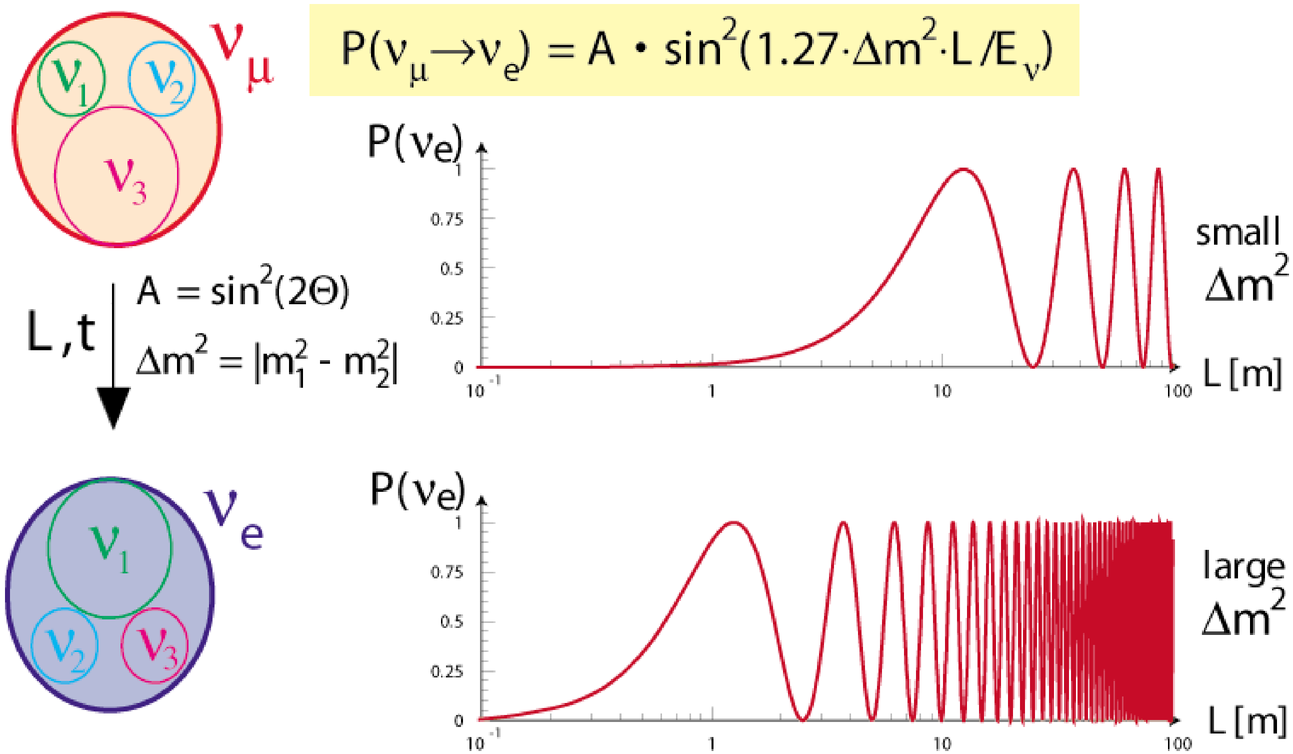
$$|\nu_l\rangle = \sum_i U_{li} |\nu_i\rangle \qquad l = e, \mu, \tau; \qquad i = 1,2,3$$

- States ν_i propagate in dependence of distance L (assumed $E \gg m_i$):

$$|\nu(L)\rangle \sim |\nu_i(L=0)\rangle \exp\left(-i \frac{m_i^2 L}{2E}\right)$$

- Oscillation Probability (assumed that only two flavors exist):

$$P(\nu_\mu \rightarrow \nu_e) = A \cdot \sin^2(1.27 \cdot \Delta m^2 \cdot L / E_\nu)$$



Three neutrino types mixing matrix

($c_{ij} = \cos\Theta_{ij}$, $s_{ij} = \sin\Theta_{ij}$)

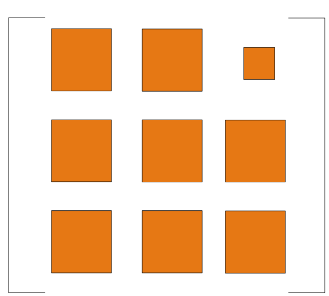
$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

By observing oscillations (measuring oscillation probabilities) one can determine:

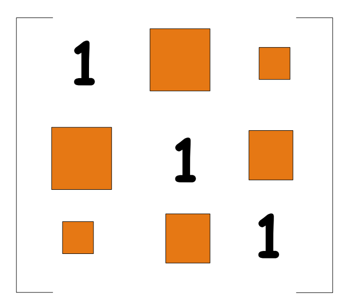
- 3 mixing angles: Θ_{12}, Θ_{23}, Θ_{13}
- 2 mass squared differences Δm_{21}, Δm_{31}
- CP violating phase

• U corresponds to CKM-matrix but :

U =



CKM =



Results from atmospheric neutrinos

SuperKamiokande:

$$1.9 \times 10^{-3}\ eV^2 < \Delta m^2_{atm} < 3.0 \times 10^{-3}\ eV^2$$

$$\sin^2 2\Theta_{atm} > 0.90$$

$$(36° < \Theta_{atm} < 53°)$$

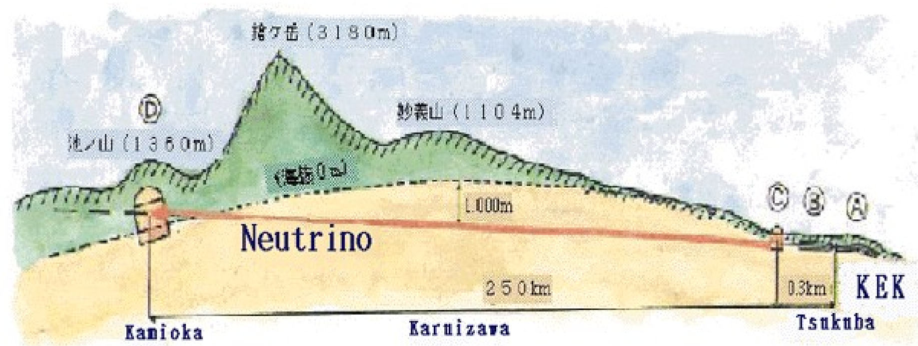
Other experiments: consistent results

- No information about sign of Δm^2_{atm}
- Lower bound on heaviest neutrino mass m_h from $m_h \geq \sqrt{\Delta m^2_{atm}}$:

$$m_h > 0.04\ eV$$

Accelerator Neutrinos: K2K experiment

long baseline experiment

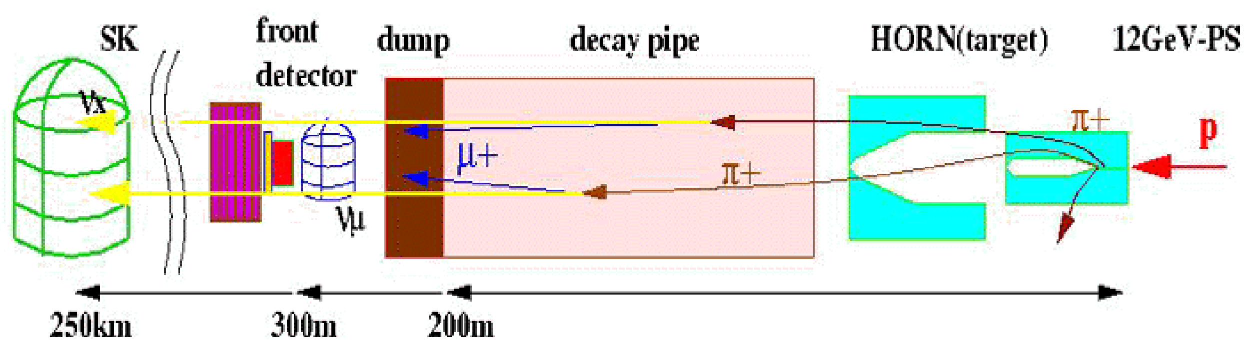


Muon-Neutrino beam (E_ν~1GeV):

- 12 GeV proton beam on target
  - -> Kaon and pions
  - -> K,π decay to $\mu + \nu_\mu$
  - -> muons stopped

Detection of neutrino events:

- in "Near Detector"
- in "SuperKamiokande"



L/E_ν such that Δm_{atm} observable

Result:

158 events expected without oscillation

122 events found

➡ vanishing ν_μ

determined Δm_{atm} consistent with other measurement

Solar Neutrinos

Production Mechanism:

Several reactions e.g.

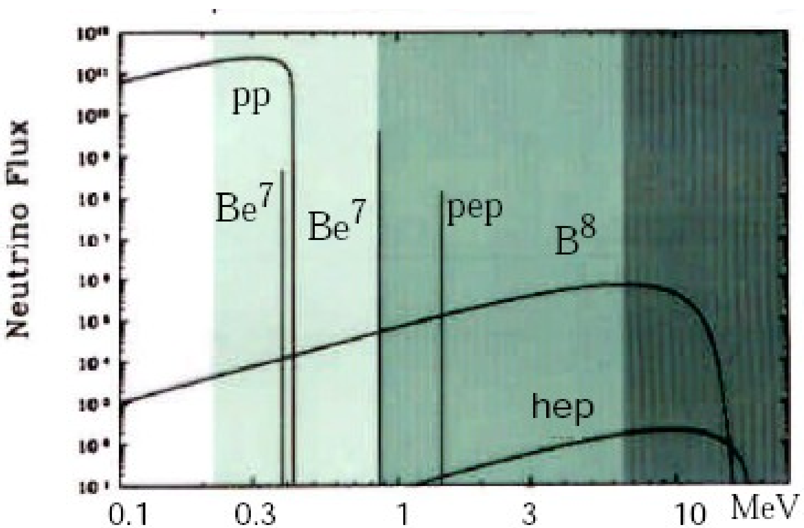
pp: $p+p \to D+e^{+}+\nu_e$ $E_\nu < 0.42$ MeV

Be^7: $Be^7 + e^- \to Li^7 + \nu_e$ $E_\nu = 0.86$ MeV

B^8: $B^8 \to Be^8 + e^+ + \nu_e$ $E_\nu < 14.6$ MeV

→ only electron-neutrinos

SSM (Standard Solar Model)
Neutrino Flux Prediction



Several experiments sensitive to a different energy range measure deficit in electron-neutrino flux:

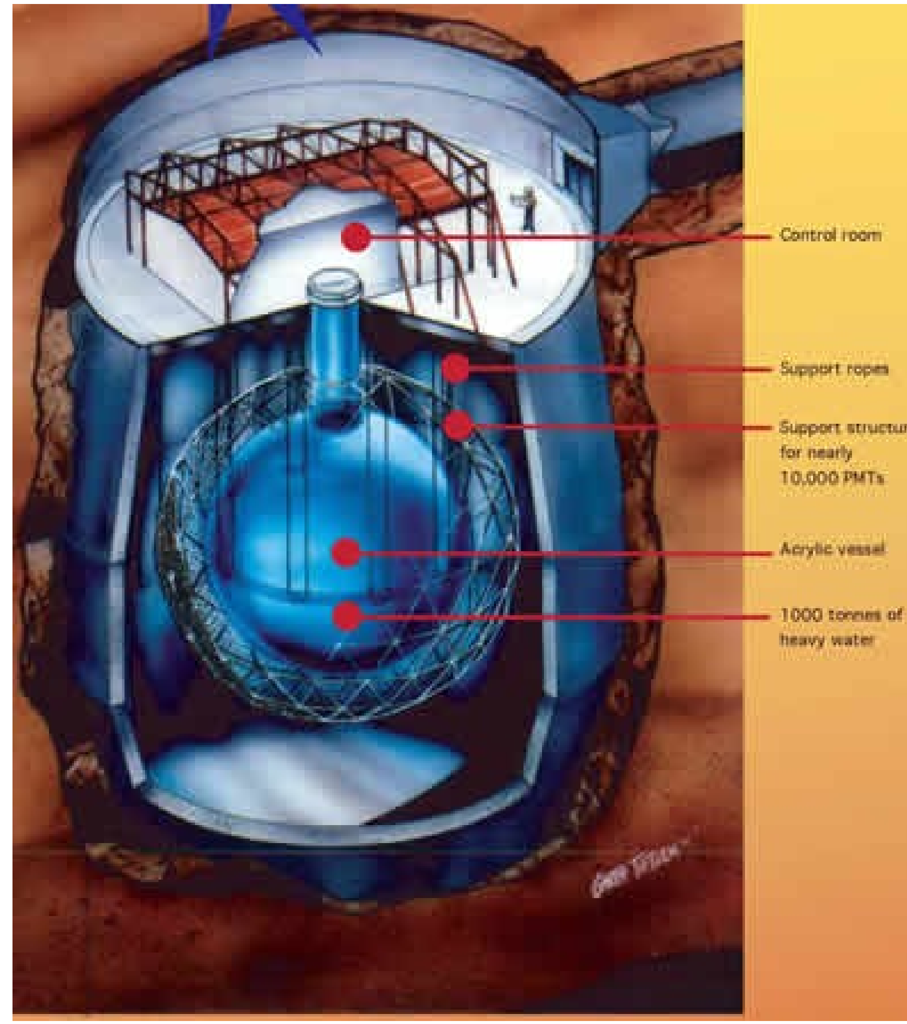
-> neutrino oscillations ?

-> SSM wrong ?

SNO Experiment

(Sudbury Neutrino Observatory, Kanada)

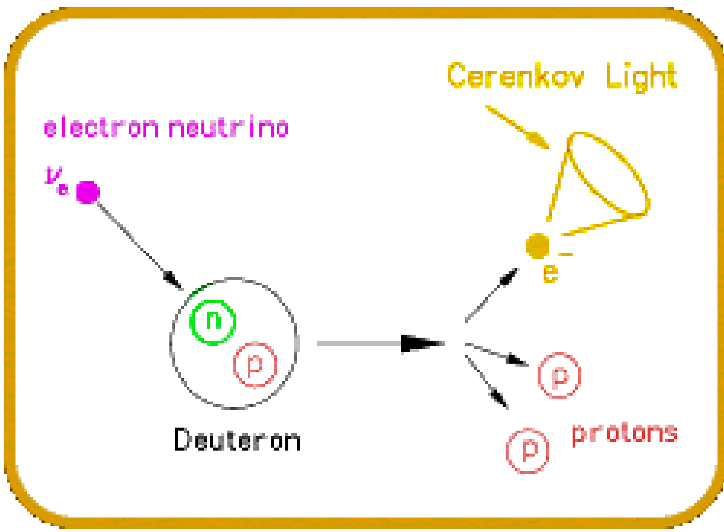
- ~2000m under ground (~6000 m.w.e)
- 12m diameter acrylic vessel
- 1000t of heavy water
- 2t of salt
  (Chlorine as neutron absorber)
- 7000 t water
- 9600 PMTs



SNO Measurement

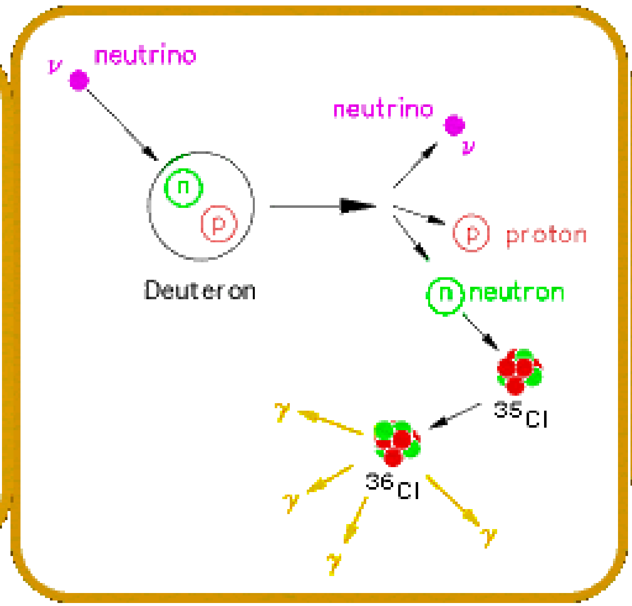
Charged Current:

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



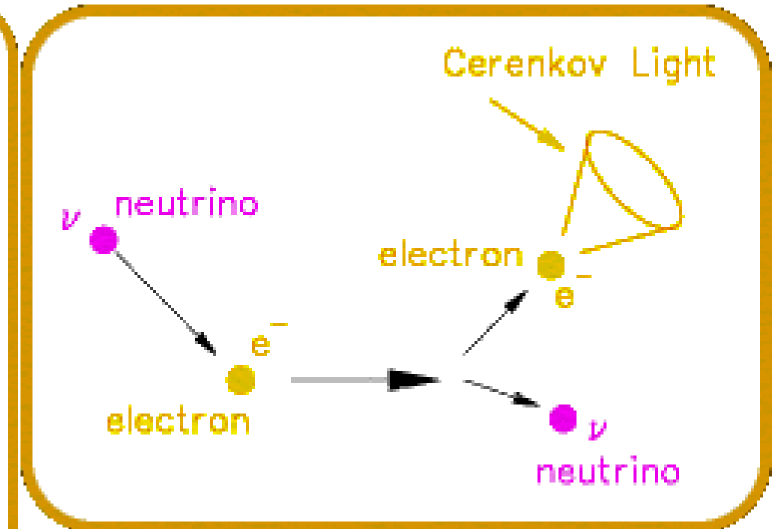
Neutral Current:

$\nu_x + D \rightarrow p + n + \nu_x$



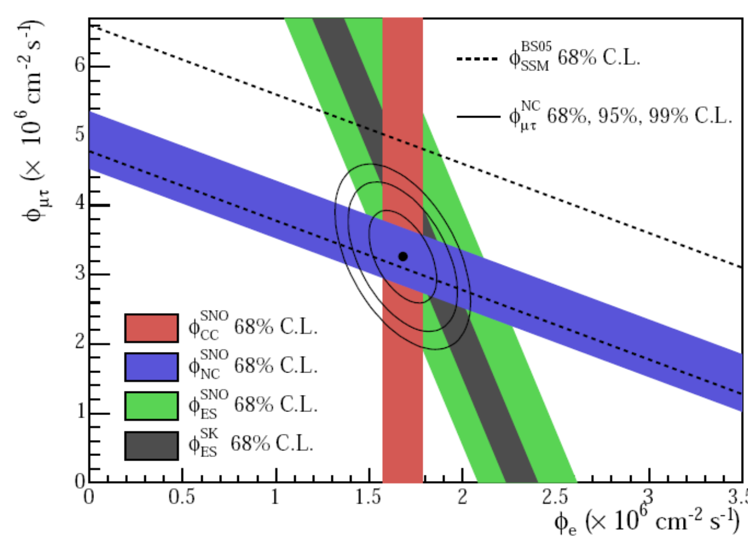
Electron Scattering:

$\nu_x + e^- \rightarrow \nu_x + e^-$



Comparison of the fluxes gives

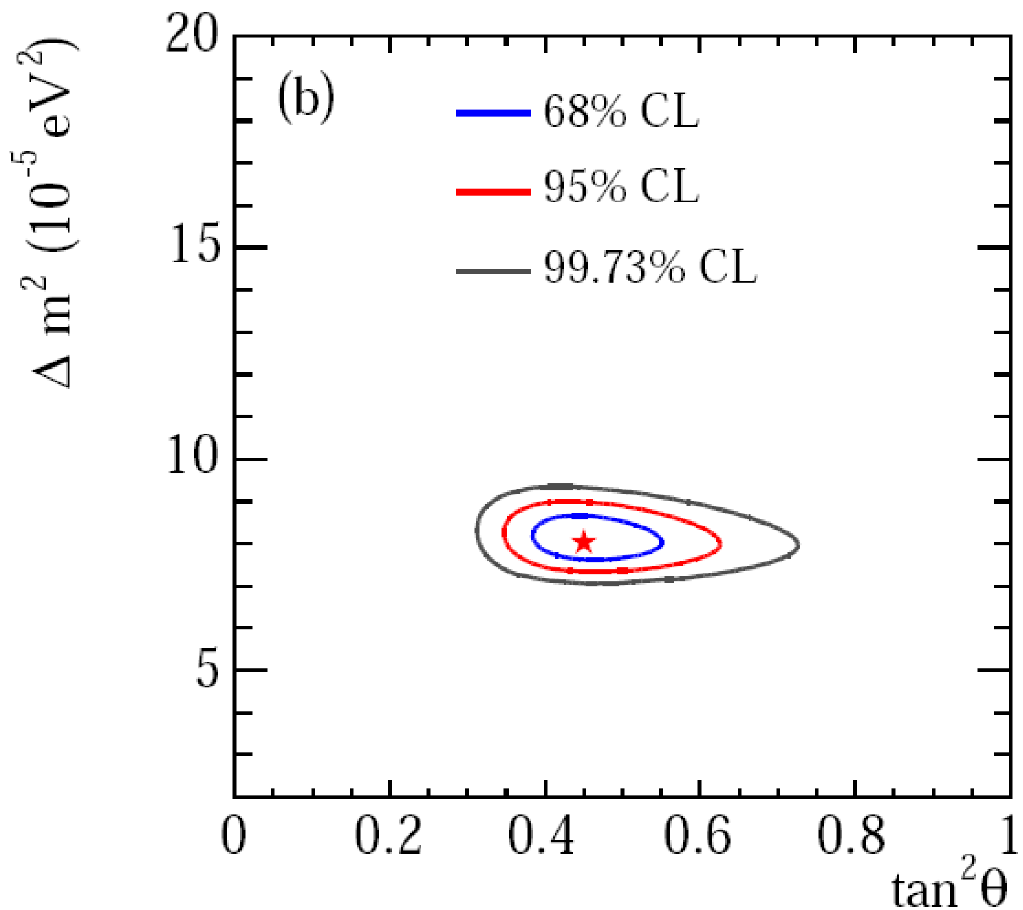
- evidence for $\nu_e \rightarrow \nu_\mu, \nu_\tau$ oscillation
- consistence with SSM
- consistence with other experiments



Results From Solar Neutrinos

$\Delta m^2_{sol} = 8.0^{+0.4}_{-0.3} \times 10^{-5}\ eV^2$

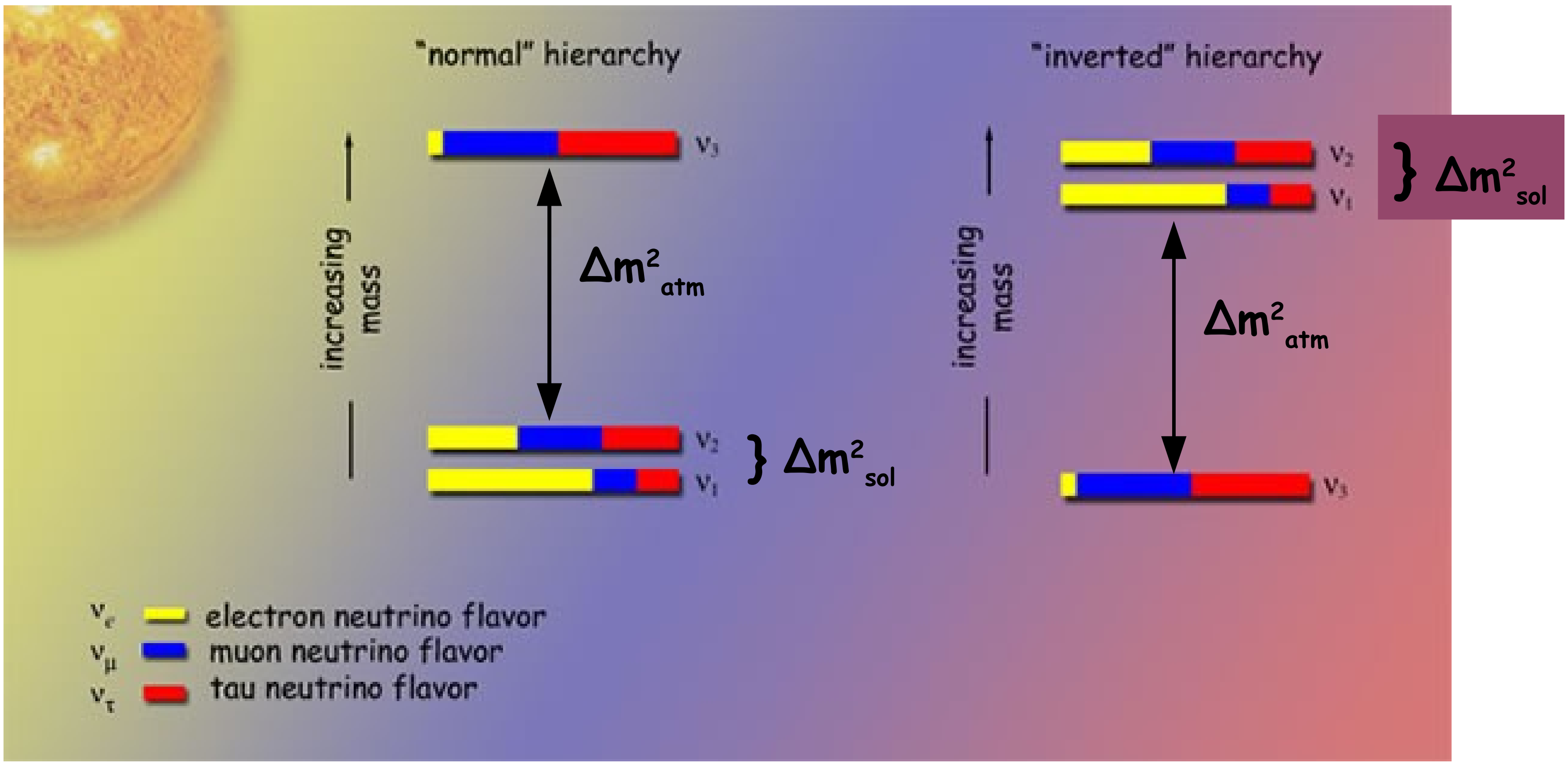
$\Theta_{sol} = 33.9 +/- 1.6\ °$



- Better determined than Δm^2_{atm}
- Due to predicted matter-effects in sun:

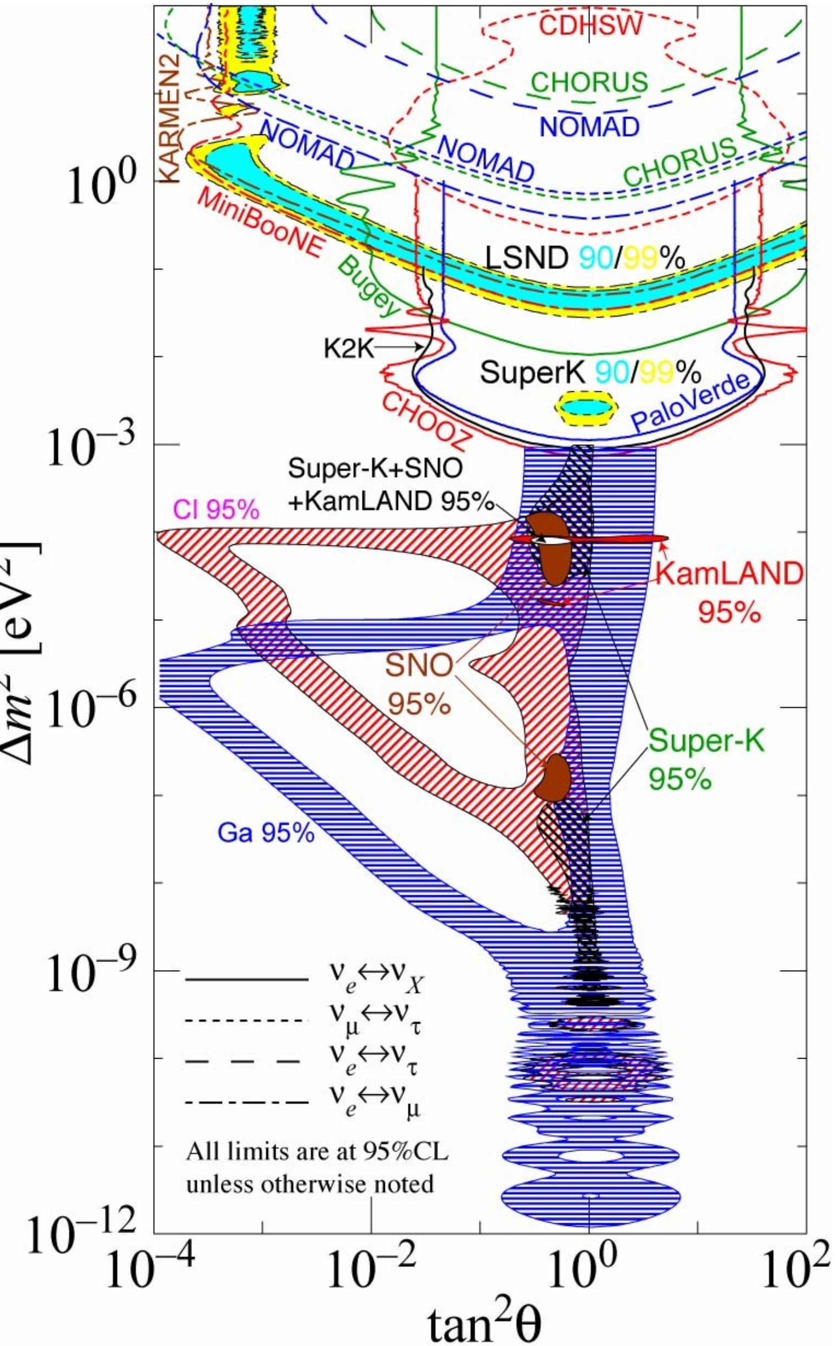
→ sign of Δm^2_{sol} is known

Three neutrino squared-mass spectrum



Many other neutrino-experiments to answer open questions

- What is the real Δm hierarchy ?
- What are the absolute masses ?
- Are there more neutrino types ?
  (sterile neutrinos)
- Are neutrinos and anti-neutrinos identical ?
  (Dirac or Majorana)
- Is there CP-violation ?
  (determination of small mixing angle Θ_{13})



http://hitoshi.berkeley.edu/neutrino