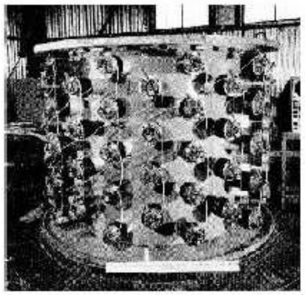
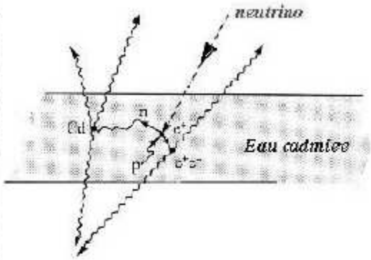
Neutrinos

Thanks to Ian Blockland and Randy Sobie for these slides

- spin $\frac{1}{2}$ particle with no electric charge; weak isospin partners of charged leptons
- ν_e observed in 1953, ν_μ in 1962 and ν_τ in the 1990s
- neutrino physics is very topical
  solar neutrino problem, neutrino mixing, neutrino masses

ν_e discovery



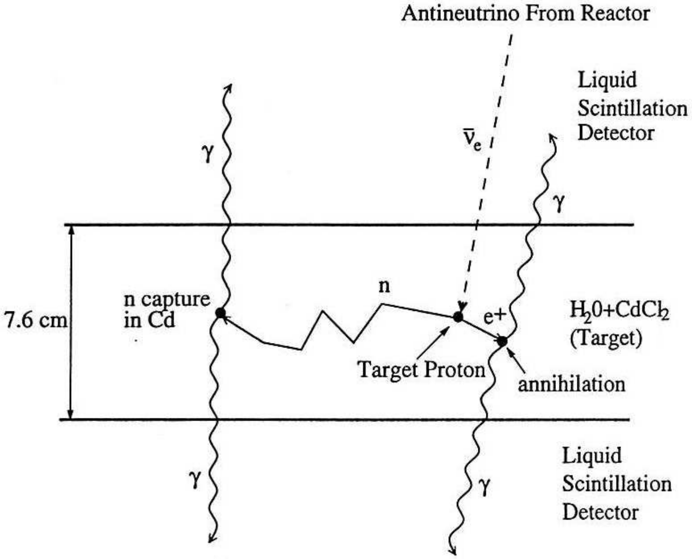


- See $\nu\ \bar{p}$ to e^{+} n
- Reines and Cowan, 1954-1957, 1 ton detector
- Nobel Prize, 1995

Neutrinos from Nearby Fission Reactor

- Observed 1 event every few minutes

Discovery of electron neutrino

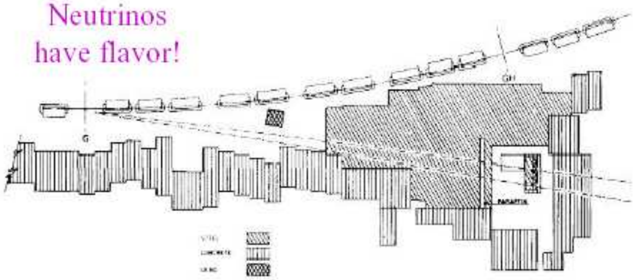


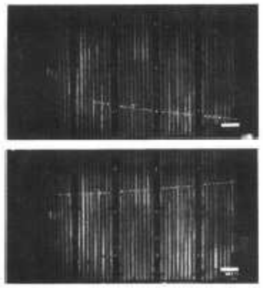
1953 Reines and Cowan (et al) at Hanford

ν_μ discovery

- Pions decay to muons, but again, energy was missing –must be a neutrino…
- But if $\mu^- \to e^- \nu\nu$ then $\mu^- \to e^- \gamma$ too unless…
- First Decay-in-flight ν beam BNL AGS
- 15BeV protons on Be Target
- 21m decay region,13.5m Fe Shield, 1 Ton Detector

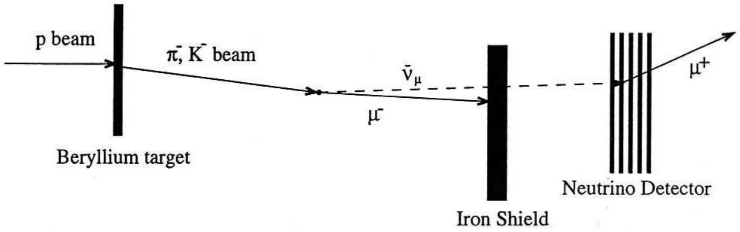
Neutrinos have flavor!





- $3.5\mathrm{x}10^{17}$ POT
- 34 single-μ events
- 5 background
- NO e-like events!
- PRL: 1960, NP: 1988
- Lederman, Swartz, Steinberger

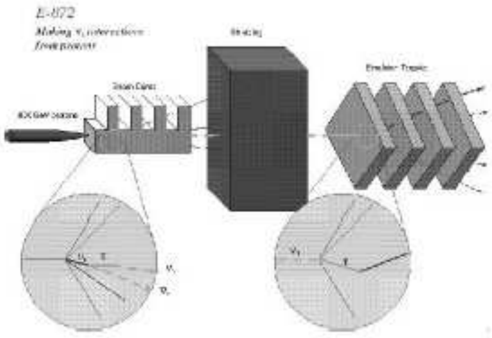
Discovery of muon neutrino



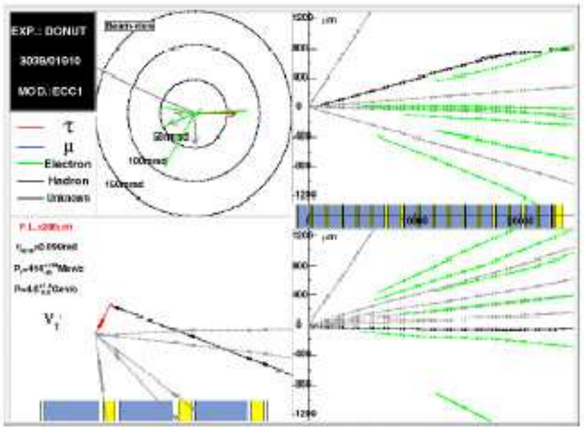
1962 Lederman et al at Brookhaven
(10^{14} $\overline{\nu}_\mu$ produced 29 events)

ν_τ discovery

- DONUT Experiment at FNAL: 1997-98
- Making a beam of ν_τ is hard! Want only D_s's to decay



- Seeing τ decay is also hard: need very sensitive detector
- 4 events seen, expect 0.34 background



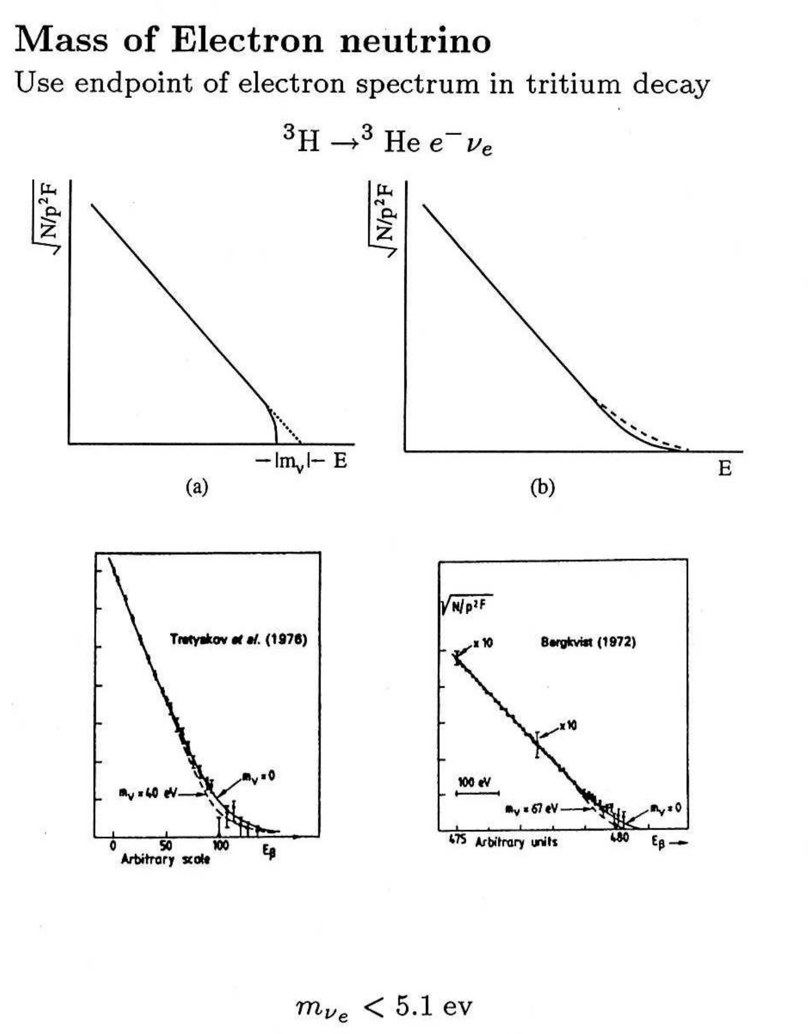
Do Neutrinos Have Mass?

- Although we have always known that neutrinos are light, it is an experimental matter to determine just how light.
- As far as *direct* measurements go:

ν Flavor	Mass Limit	Process
ν_e	$m_\nu < 3$ eV	${}^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e^- + \bar{\nu}_e$
ν_μ	$m_\nu < 190$ keV	$\pi \rightarrow \mu + \nu_\mu$
ν_τ	$m_\nu < 18.2$ MeV	$\tau \rightarrow 3\pi + \nu_\tau$

- There is no fundamental reason (e.g., a symmetry) why $m_\nu = 0$.
- The Standard Model assumes that neutrinos are precisely massless; accomodating non-zero masses is in many respects straightforward.

ν_e mass measurement



Mass of Electron neutrino

Use endpoint of electron spectrum in tritium decay

$$^3\text{H} \rightarrow ^3\text{He}\, e^- \nu_e$$

$$m_{\nu_e} < 5.1 \text{ ev}$$

Mass of Muon neutrino

Use the $\pi^+ \rightarrow \mu^+ \nu_\mu$ decay

For a pion at rest

$$m_{\nu_\mu}^2 = m_\pi^2 + m_\mu^2 - 2m_\pi \sqrt{p_\mu^2 + m_\mu^2}$$

Use the known values for the pion and muon masses

$$m_\pi = 139.56995 \pm 0.00035 \text{ MeV}$$

$$m_\mu = 105.658389 \pm 0.000034 \text{ MeV}$$

and measure the pion momentum

$$p_\mu = 29.79207 \pm 0.00012 \text{ MeV}$$

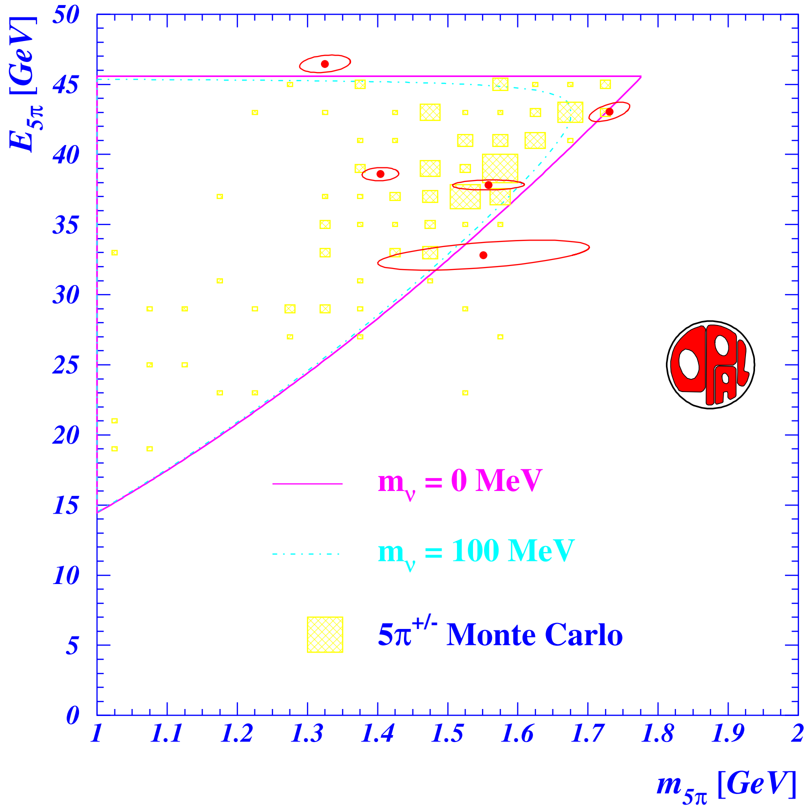
Giving an upper limit on the muon neutrino mass

$$m_{\nu_\mu} < 0.16 \text{ MeV}$$

ν_τ mass measurement

LEP experiments measured the limit on the ν_τ mass using $\tau \to 3\pi^- 2\pi^+ \nu_\tau$ decays.

$$M(\nu_\tau) < 18 \text{ MeV}$$



Neutrino Mixing

- Supposing that neutrinos have mass, we must now allow a mixing between the weak eigenstates and the mass eigenstates, just as we have done for the quarks.
- The neutrino analogue of the CKM matrix is the Maki-Nakagawa-Sakata (MNS) matrix.
- Like the CKM matrix, the MNS matrix can be parametrized in terms of 3 mixing angles and 1 CP-violating complex phase.
- We label the neutrino mass eigenstates (in order of ascending mass) as ν_1, ν_2, and ν_3.

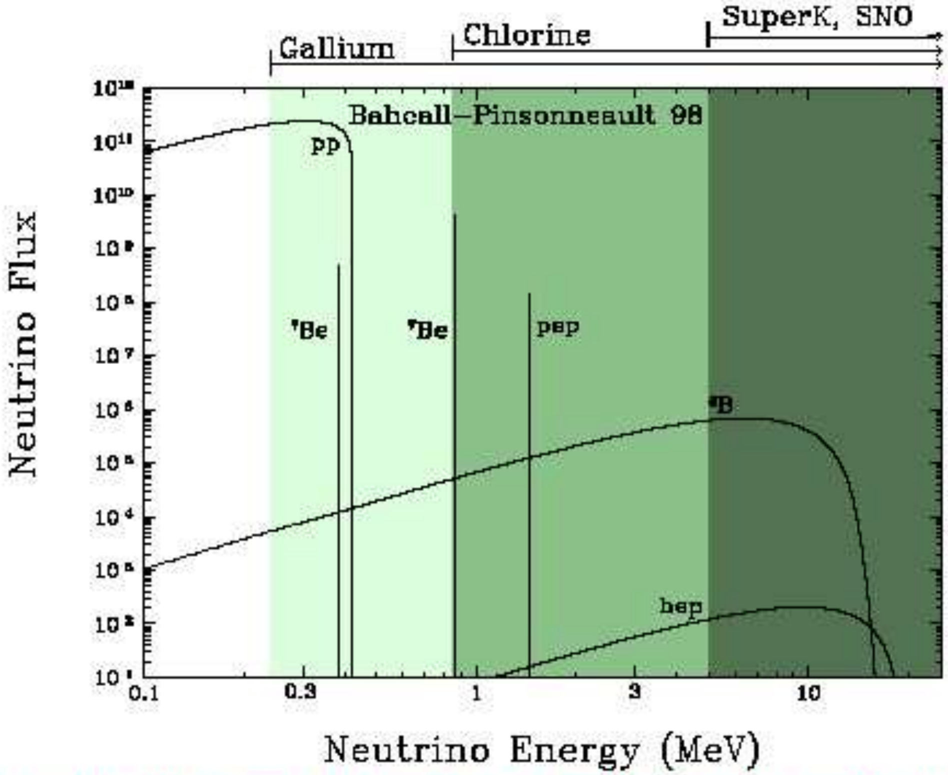
Neutrino Deficits

- In 1967, Ray Davis put 100,000 gallons of dry-cleaning fluid in a tank a mile underground to try to measure the solar neutrino flux.
- The measured flux (inferred from 1 Cl to Ar conversion every 2 days) was about a factor of 3 below the theoretical expectations from the Standard Solar Model.
- Similar neutrino deficits were later observed for the atmospheric neutrinos generated by cosmic rays.
- Surprisingly, both experiment and theory turned out to be right and these effects are now understood as *neutrino oscillation* effects.

Solar Neutrinos

The Sun is an intense source of MeV neutrinos!

$$4p + 2e^- \rightarrow {}^4\text{He} + 2\nu_e + 26.731\ \text{MeV}$$

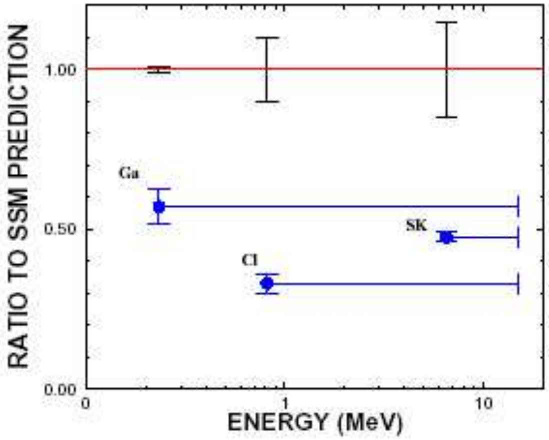


Solar models let us predict the rates of each neutrino-producing reaction.

Solar Neutrino Flux Measurements

Two Classes of Experiment (so far)

- Radiochemical
  - ν_e interactions convert target nuclei
  - Radioactive products extracted and counted after exposure time
- Water Cerenkov
  - Real-time detection of scattered atomic e^-'s
  - Mixed CC and NC sensitivity



Experiment	Detection Reaction	Threshold	Primary Sources
Homestake	$\nu_e + {}^{37}\mathrm{Cl} \to e^- + {}^{37}\mathrm{Ar}$	0.8 MeV	${}^{7}\mathrm{Be}, {}^{8}\mathrm{B}$
Kamiokande	$\nu_{e,(\mu,\tau)} + e \to \nu_{e,(\mu,\tau)} + e$	7.3 MeV	${}^{8}\mathrm{B}$
SAGE, GALLEX/GNO	$\nu_e + {}^{71}\mathrm{Ga} \to e^+ + {}^{71}\mathrm{Ge}$	0.23 MeV	$pp, {}^{7}\mathrm{Be}, {}^{8}\mathrm{B}$
Super-K	$\nu_{e,(\mu,\tau)} + e \to \nu_{e,(\mu,\tau)} + e$	5 MeV	${}^{8}\mathrm{B}$

Neutrino Oscillations: 2 Flavor Model

- We will now illustrate how neutrino oscillations work in the context of a 2-neutrino model.
- Neutrinos are always produced as weak eigenstates. Suppose that at $t = 0$ we produce an electron neutrino:

$$|\nu(0)\rangle = |\nu_e\rangle$$

- Neutrinos propagate as mass eigenstates. In a 2-neutrino model, the weak eigenstates and the mass eigenstates are related by

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

Neutrino Oscillations: Propagation

- In terms of the mass eigenstates, our original ν_e is

$$|\nu(0)\rangle = \cos\theta\ |\nu_1\rangle + \sin\theta\ |\nu_2\rangle$$

- When a particle propagates in free space, it accumulates a phase of e^{-iEt}.
- Assuming that the *spatial momentum* of the original ν_e is passed on to ν_1 and ν_2, the energy of each neutrino is given by

$$\begin{aligned} E_i &= \sqrt{\mathbf{p}^2 + m_i^2} \\ &\simeq |\mathbf{p}| \left(1 + \frac{m_i^2}{2\mathbf{p}^2}\right) \end{aligned}$$

Neutrino Oscillations: $|\nu(t)\rangle$

- The two mass eigenstates pick up different phases as they propagate, so that

$$|\nu(t)\rangle = e^{-iE_1 t}\cos\theta\ |\nu_1\rangle + e^{-iE_2 t}\sin\theta\ |\nu_2\rangle$$

- Going back to flavor eigenstates, this is

$$\begin{aligned} |\nu(t)\rangle &= e^{-iE_1 t}\cos\theta\ (\cos\theta\ |\nu_e\rangle - \sin\theta\ |\nu_\mu\rangle) \\ &\quad + e^{-iE_2 t}\sin\theta\ (\sin\theta\ |\nu_e\rangle + \cos\theta\ |\nu_\mu\rangle) \end{aligned}$$

- The probability of an oscillation from ν_e to ν_μ is then

$$\begin{aligned} P_{osc}(t) &= |\langle\nu_\mu|\nu(t)\rangle|^2 \\ &= \left|\sin\theta\ \cos\theta\ \left(-e^{-iE_1 t} + e^{-iE_2 t}\right)\right|^2 \end{aligned}$$

Neutrino Oscillations: P_{osc}

$$\begin{aligned} P_{osc}(t) &= \left|\sin\theta\ \cos\theta\ \left(-e^{-iE_1 t} + e^{-iE_2 t}\right)\right|^2 \\ &= \tfrac{1}{4}\sin^2 2\theta\ \left[2 - \left(e^{i(E_2-E_1)t} + e^{-i(E_2-E_1)t}\right)\right] \\ &= \tfrac{1}{2}\sin^2 2\theta\,[1 - \cos(E_2 - E_1)t] \end{aligned}$$

- With $\Delta E = \Delta m^2/2p$ and

$$E \simeq pc \quad \& \quad L \simeq tc \quad \Rightarrow \frac{t}{p} \simeq \frac{L}{E}$$

$$\begin{aligned} P_{osc}(t) &= \tfrac{1}{2}\sin^2 2\theta\left[1 - \cos\left(\Delta m^2 L/2E\right)\right] \\ &= \sin^2 2\theta\ \sin^2\left(\frac{1.27\,\Delta m^2\ (\mathrm{eV}^2)\ L\ (\mathrm{km})}{E\ (\mathrm{GeV})}\right) \end{aligned}$$

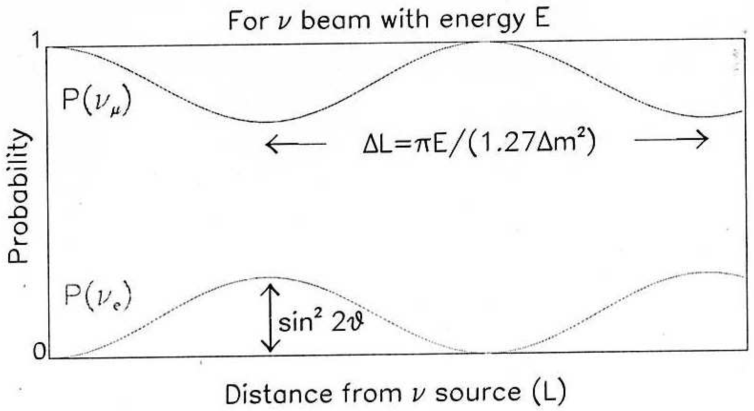
$$P_{osc} = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$$

...Depends Upon Two Experimental Parameters:

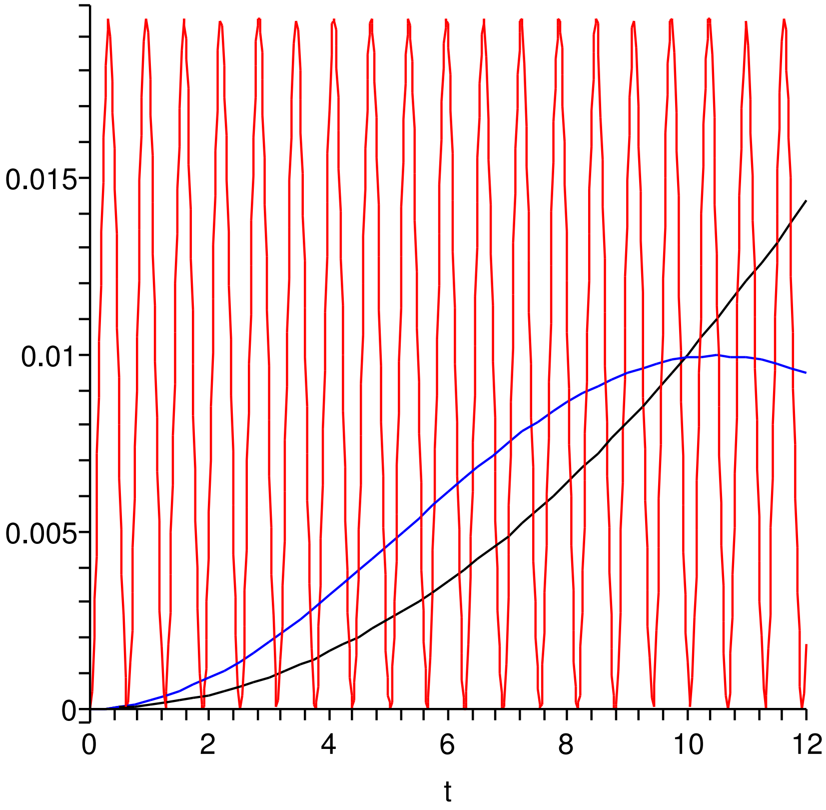
- L – The distance from the ν source to detector (km)
- E – The energy of the neutrinos (GeV)

...And Two Fundamental Parameters:

- $\Delta m^2 = m_1^2 - m_2^2 \quad (eV^2)$
- $\sin^2 2\theta$



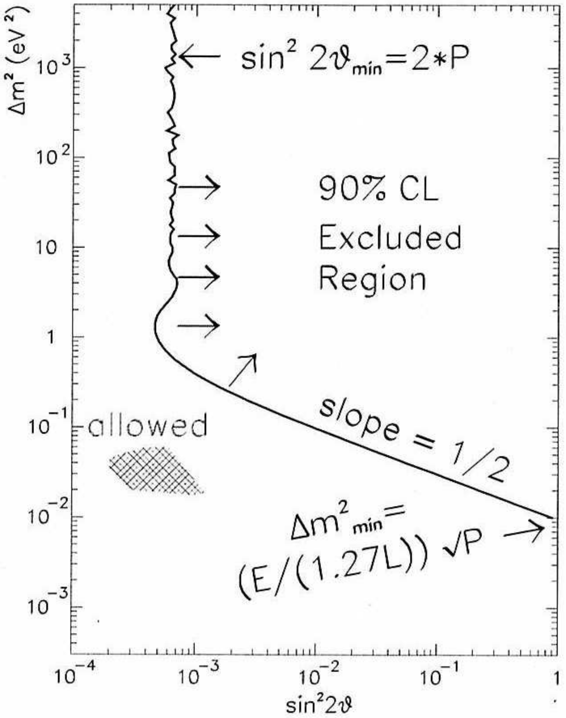
Curves (red, blue, black) for $2\theta = 0.14, 0.1, 1.57$ and frequency $5, 0.15, 0.01$, respectively. A detector might sample the region 8-12.



Oscillation Plots...

$$P_{osc} = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$$

No oscillation signal → limit at some Confidence Level
Example: $P_{osc} > P$ at 90% CL



Signal → "allowed region"

Ways of Observing Neutrino Oscillations

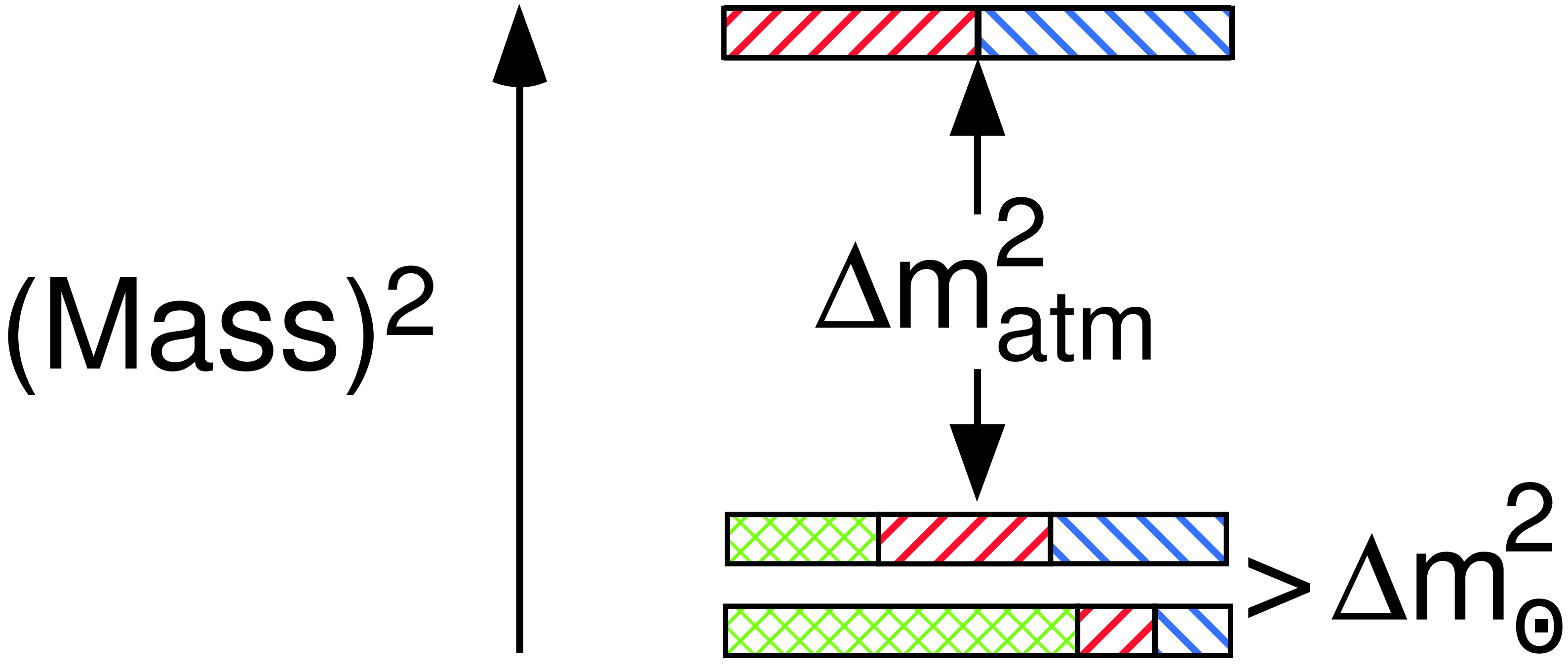
- The oscillation probabilities depend on θ, Δm^2, L, and E.
- We can either look for the *appearance* of a different neutrino flavor (usually limited by background) or we can measure the *disappearance* of the expected flavor (limited by calibration of source and target).

Source	ν Types	Mode	Advantage
Solar	ν_e	Disappearance	Great distance
Atmospheric	$\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu$	Disappearance	Variable distance
Reactor	$\bar{\nu}_e$	Disappearance	Low energy
Accelerator	$\nu_\mu, \bar{\nu}_\mu$	Either	Control E and L

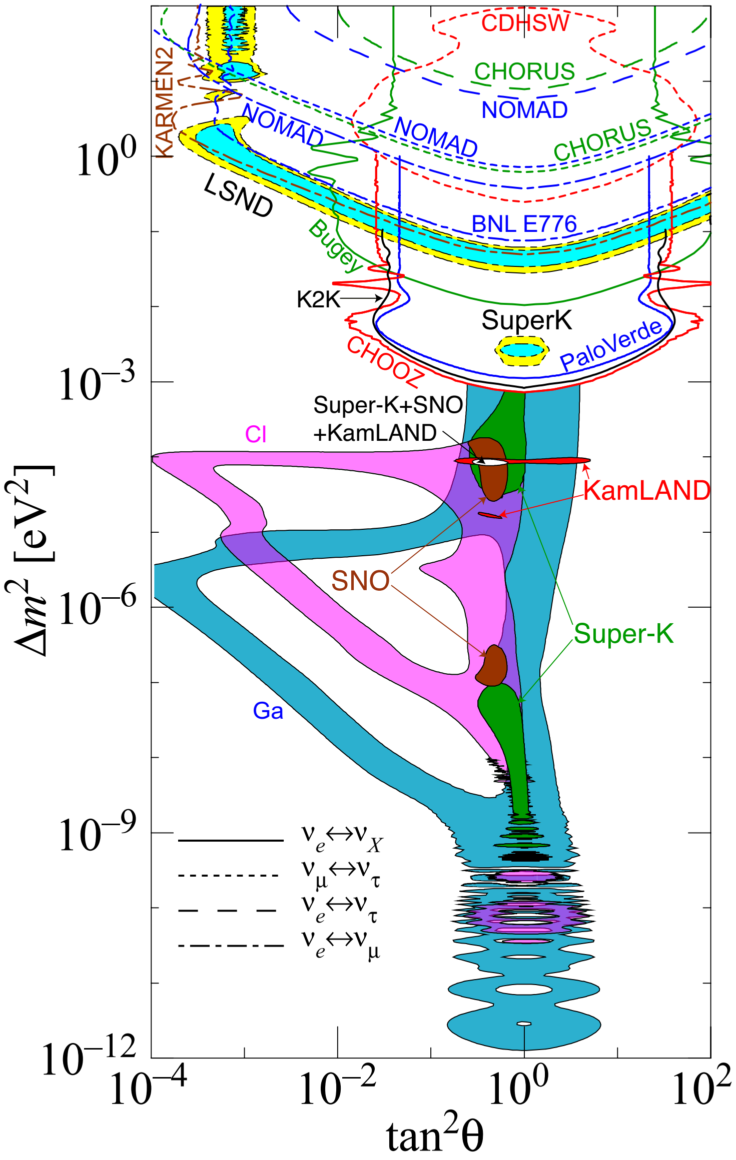
Current Status

- The mixing matrix appears to feature very large mixing angles (LMA); the following gives a crude view of the sizes of the matrix elements:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 0.35 & 0.95 & < 0.2e^{i\delta} \\ -0.35 & 0.25 & 0.70 \\ 0.65 & -0.25 & 0.70 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

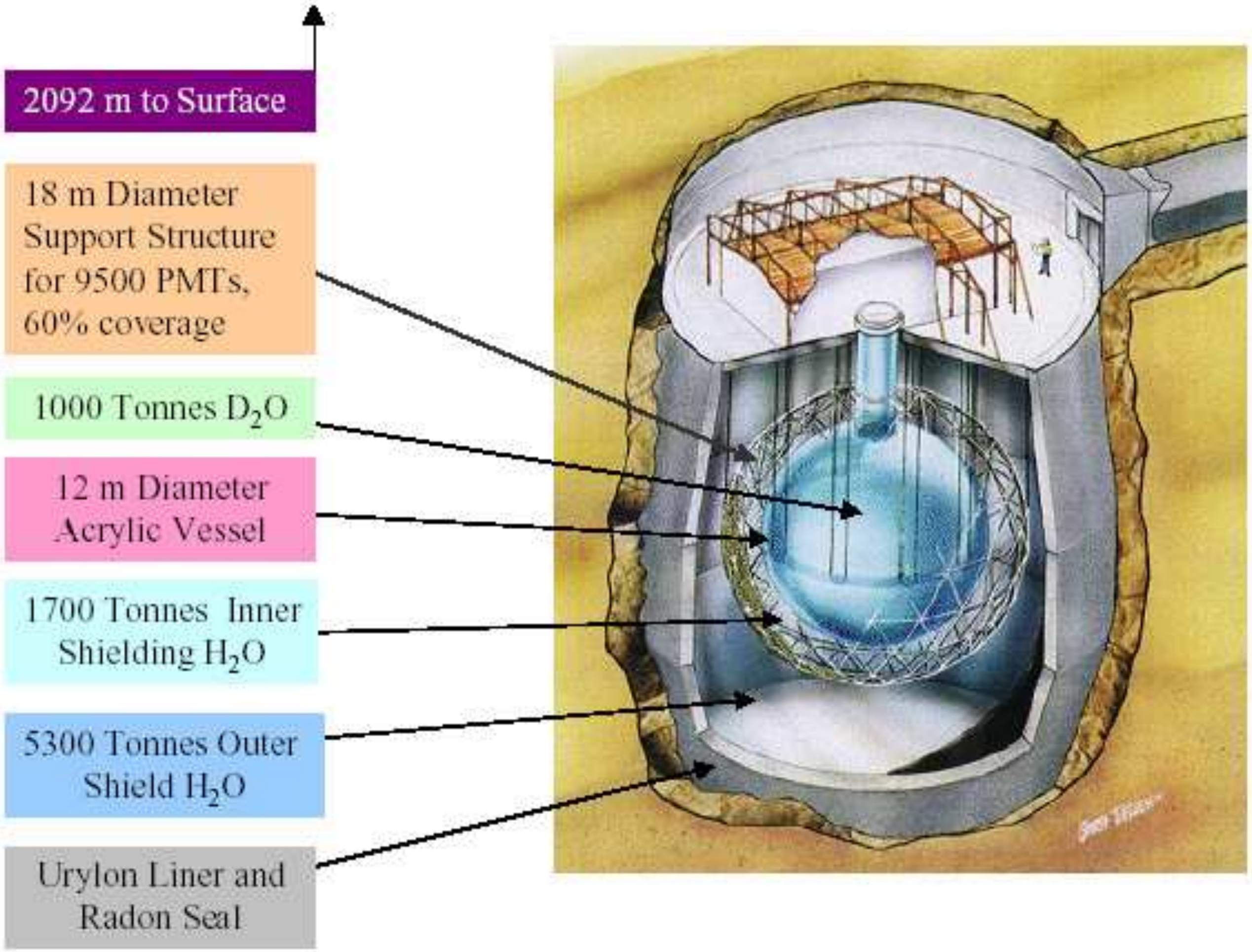


- Green hatch: ν_e
- Red right: ν_μ
- Blue left: ν_τ



http://hitoshi.berkeley.edu/neutrino

Sudbury Neutrino Observatory



2092 m to Surface

18 m Diameter Support Structure for 9500 PMTs, 60% coverage

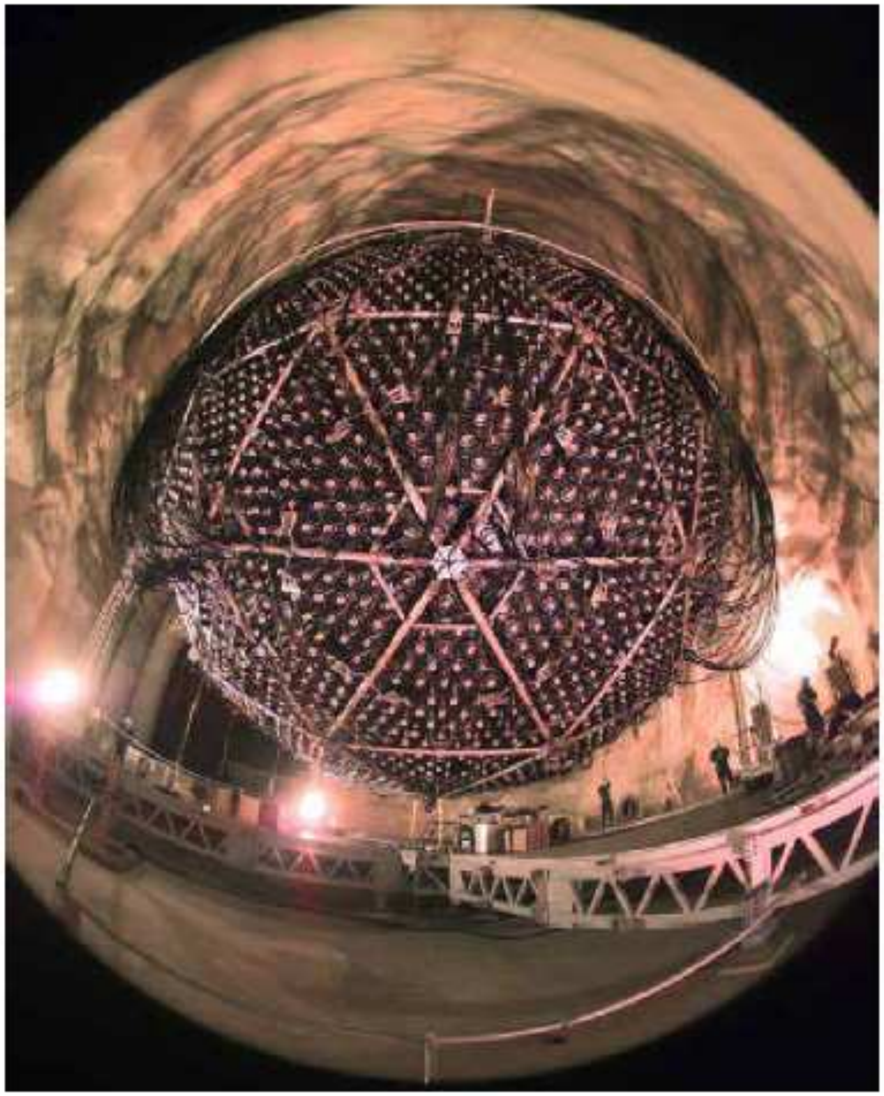
1000 Tonnes D_2O

12 m Diameter Acrylic Vessel

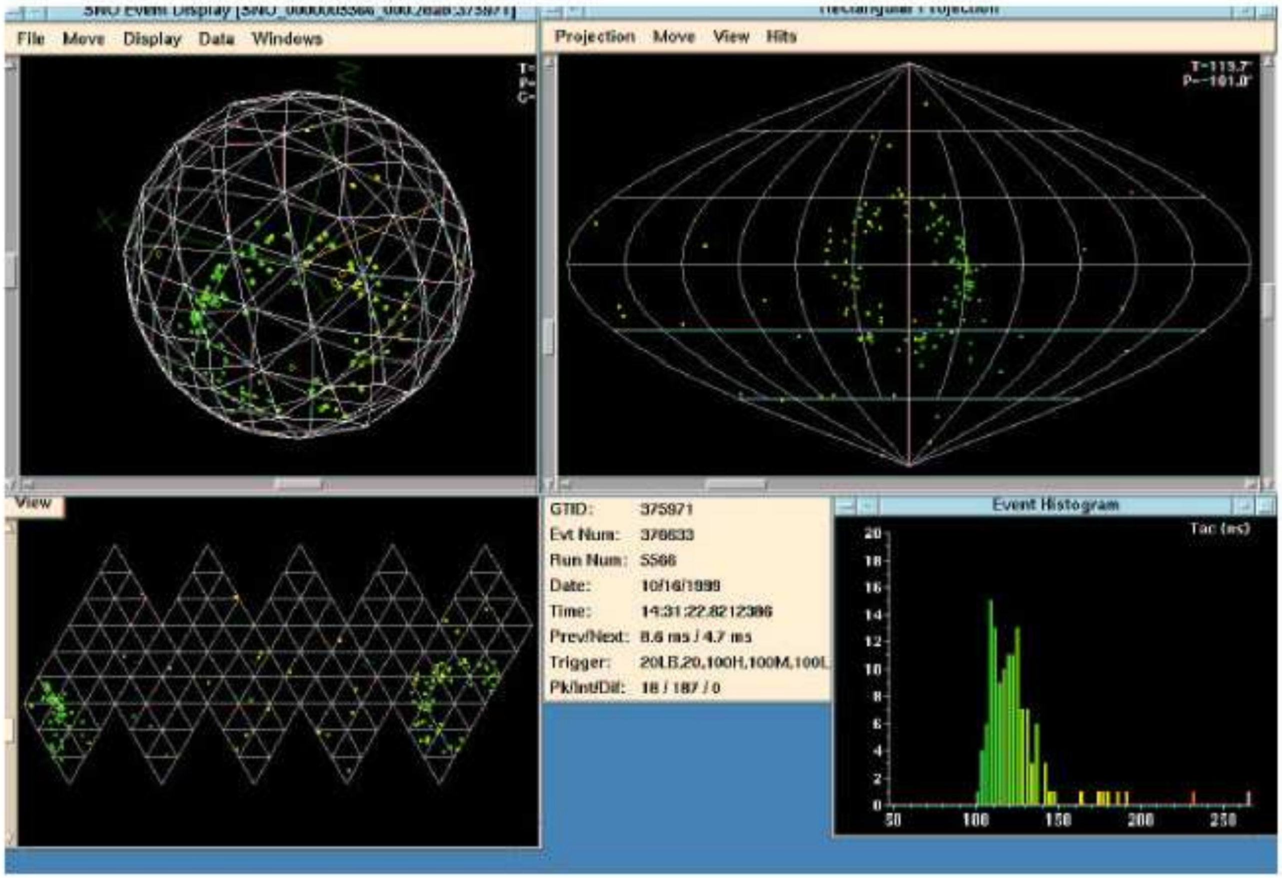
1700 Tonnes Inner Shielding H_2O

5300 Tonnes Outer Shield H_2O

Urylon Liner and Radon Seal



Event Display–Neutrino Event



GTID: 375971
Evt Num: 378633
Run Num: 5566
Date: 10/16/1999
Time: 14:31:22.8212386
Prev/Next: 8.6 ms / 4.7 ms
Trigger: 20LB,20,100H,100M,100L
Pk/Int/Dif: 18 / 187 / 0

Solar ν Interactions in SNO

Elastic Scattering (ES) $\nu_x + e^- \rightarrow \nu_x + e^-$

- Same way Super-K saw neutrinos
- Mostly measures ν_e, plus a little of ν_μ or ν_τ

Charged Current (CC) $\nu_e + d \rightarrow p + p + e^-$

- See only the electron neutrinos here

Neutral Current (NC) $\nu_x + d \rightarrow n + p + \nu_x$

- Measures total flux of all neutrino types!
- Total flux of active neutrinos above 2.2 MeV
- Detect neutrons if they are captured on other nuclei (e.g. $n+{}^{35}$Cl $\rightarrow{}^{36}$Cl$+\gamma$'s)

Physics of Long Baseline ν Experiments

Basic idea: shoot a man-made neutrino beam through the Earth, and study neutrino oscillations in controlled way

K2K: KEK to Kamioka

T2K: J-PARC to Kamioka

($\times 50$ stats.)

Far detector: Super-K

Measure	Determine
$P(\nu_\mu \to \nu_\mu)$	$\Delta m^2_{23}, \theta_{23}$
$P(\nu_\mu \to \nu_e)$	θ_{13}
$P(\overline{\nu}_\mu \to \overline{\nu}_\mu)$	CPT
$P(\overline{\nu}_\mu \to \overline{\nu}_e)$	δ_{CP}, sign(Δm^2_{23})

Neutrino Mass Terms

- If neutrinos do have a small mass, we could create *Dirac mass* terms (just like for m_ℓ and m_q).
- Since neutrinos do not carry non-zero quantum numbers, it is possible that a neutrino is its own antiparticle. Such a neutrino is known as a *Majorana neutrino*.
- Incorporating *both* Dirac and Majorana mass terms leads to the *seesaw mechanism*, whereby the presence of a right-handed neutrino at the GUT scale leads to

  $$m_\nu \sim \frac{m_D^2}{M_{GUT}}$$

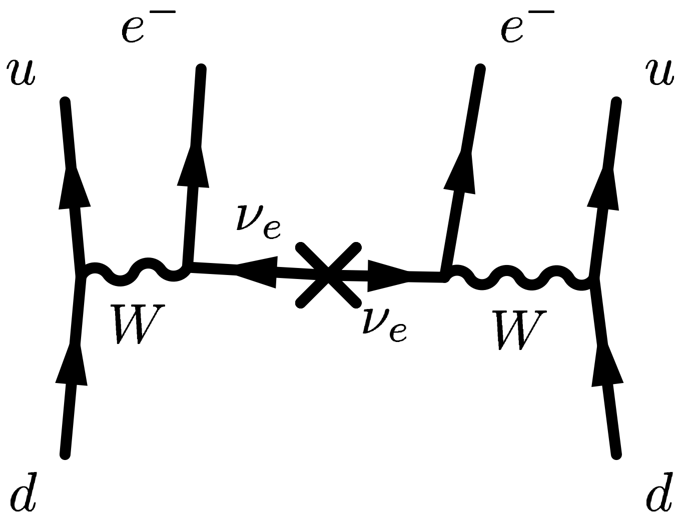
  where m_D is the Dirac mass of a typical Standard Model fermion and M_{GUT}, as we'll soon see, is approximately 10^{15} GeV.

Double β Decay

- Certain unstable atoms, such as ^{136}Xe and ^{76}Ge, can decay to elements with *two* additional protons via *double β decay*.
- These decays *cannot* be regarded as two separate β decays because the intermediate state is energetically off limits.
- As a result, double β decay is one big process in which two separate neutrons simultaneously decay via $n \rightarrow p + e^- + \bar{\nu}_e$.
- Because β decay is a 3-body decay, the energy of the emitted electron is not fixed.

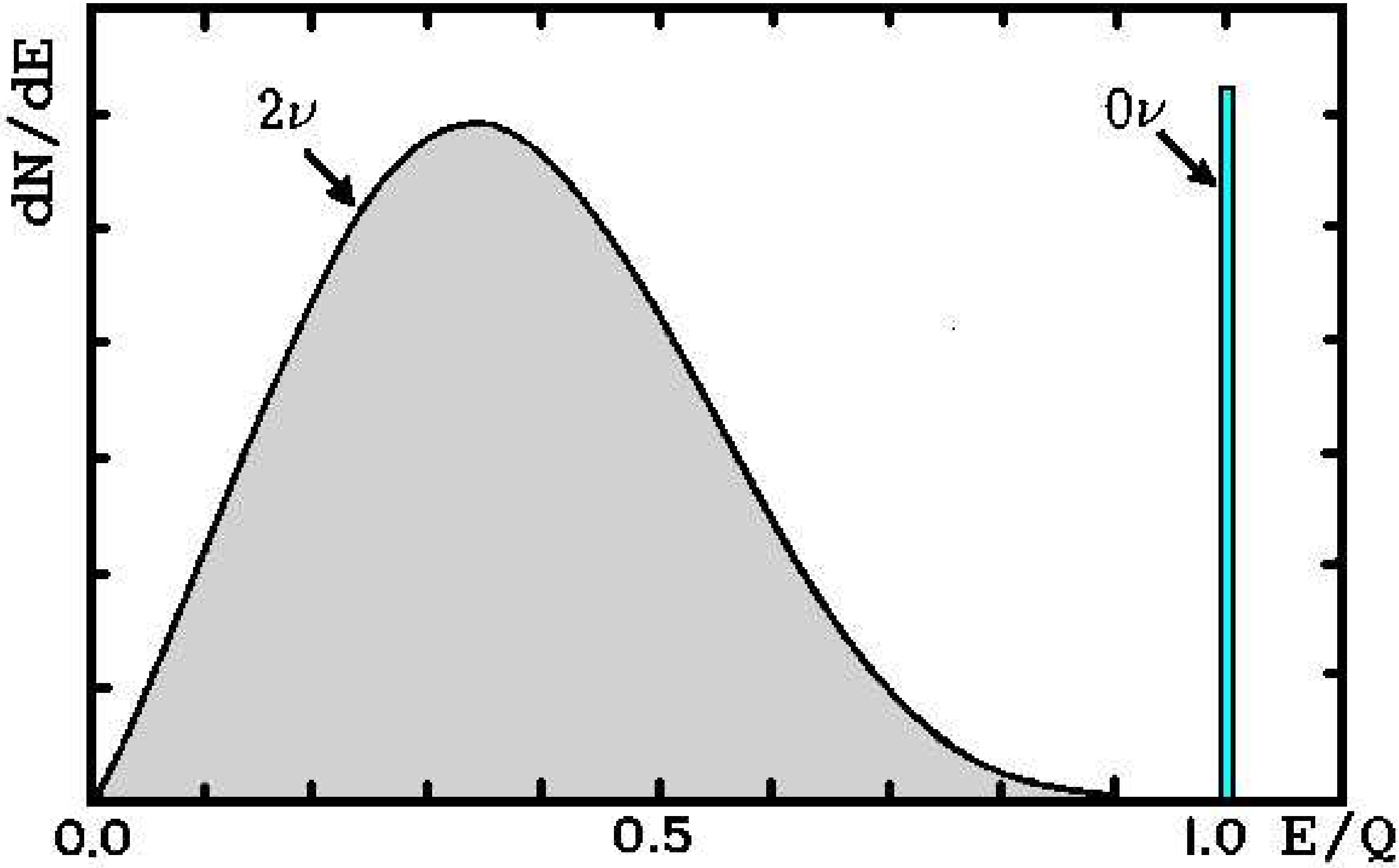
$0\nu\beta\beta$

- Supposing that neutrinos are Majorana particles, the two neutrinos involved in double β decay can actually be merged into an internal line so as to produce *neutrinoless double β decay*.



- The ✕ denotes the “transition” from ν to $\bar{\nu}$. This leads to a suppression of m_ν/E_ν.
- Now that each β decay is essentially a 2-body decay, the energy of the electrons is fixed.

$2\nu\beta\beta$ vs. $0\nu\beta\beta$



Summary

- Neutrino masses, although not present in the SM, can easily be incorporated, along with the MNS mixing matrix.
- $m_\nu \neq 0$ leads to neutrino oscillations (observed) and may lead to $0\nu\beta\beta$ (searched for).
- Structure of the MNS matrix is becoming better known; next generation experiments will possibly measure CP violation in neutrinos