# Neutrino physics: past, present and future

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I. Introduction to neutrinos

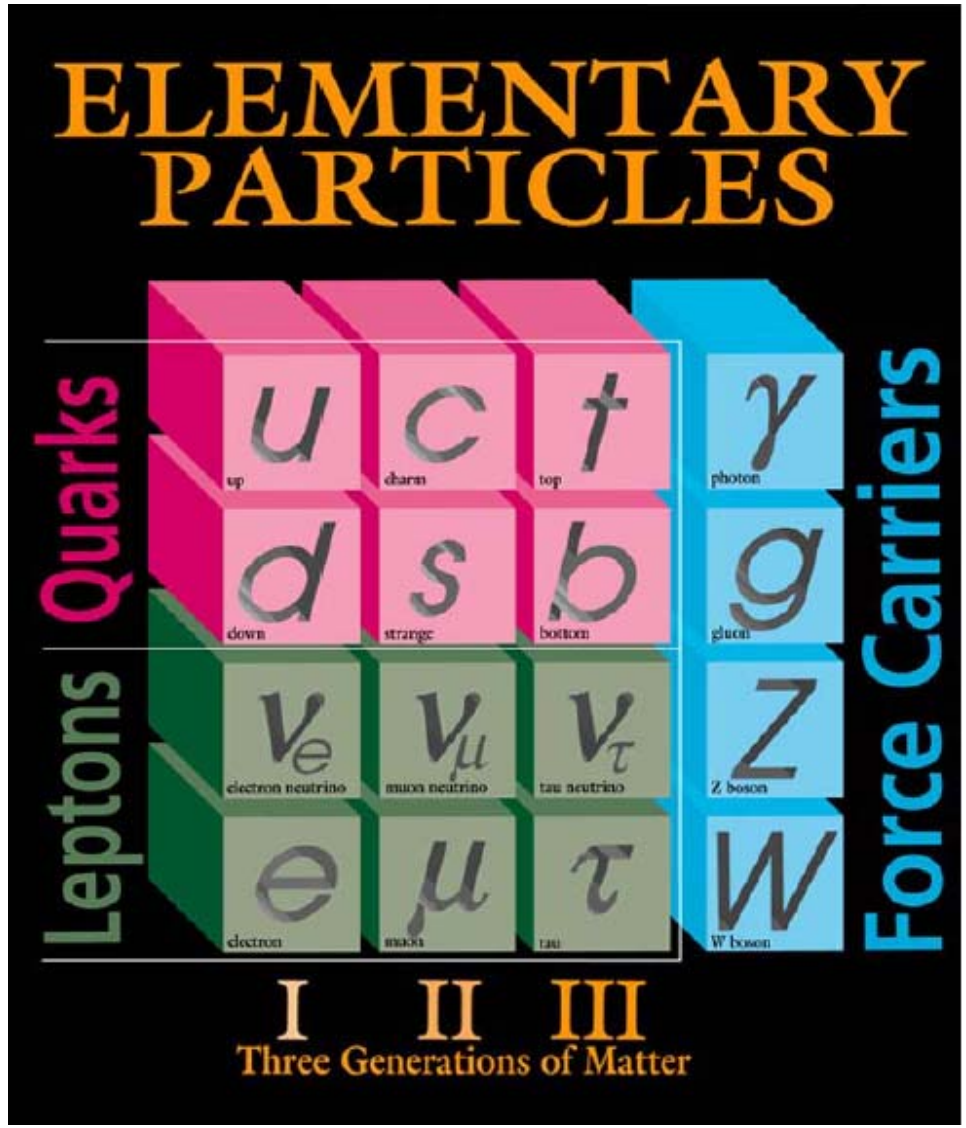
II. Neutrino oscillation

III. A future experiment

IV. Conclusion

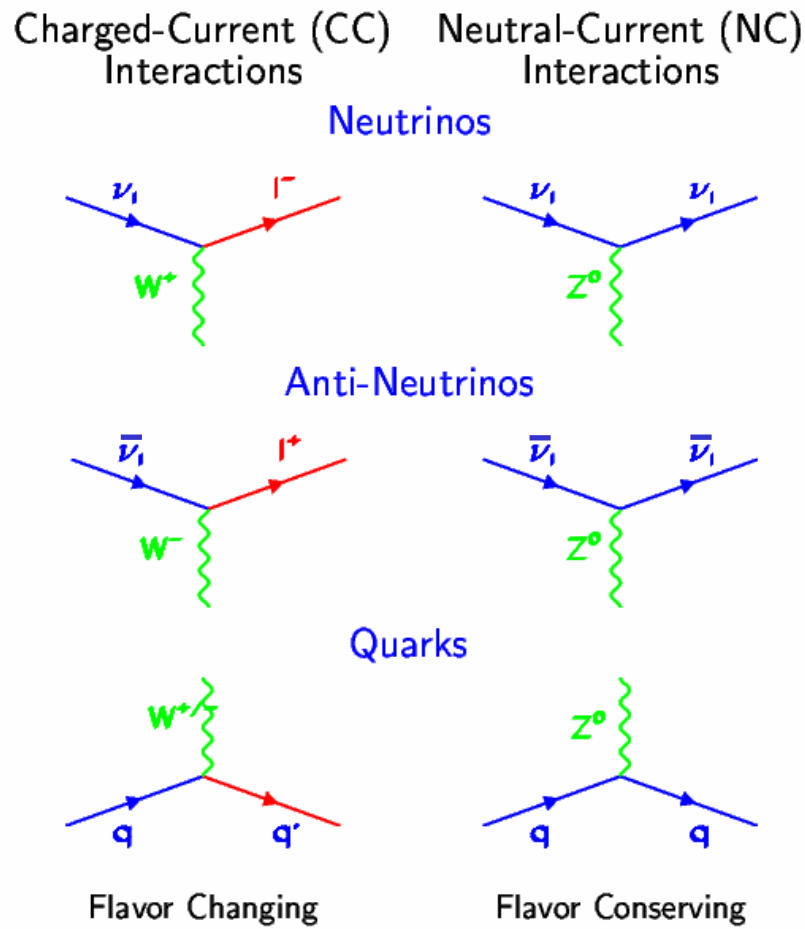
# Part I: All about neutrinos

- In the Standard Model, there are two different kinds of particles, quarks and leptons
  - 6 quarks (u,d,s,c,t,b) make p,n
  - 3 charged leptons ($e$, $\mu$, $\tau$)
  - 3 neutral leptons ($\nu_e$, $\nu_\mu$ ,$\nu_\tau$ )
- Flavor is like charge– an electron has 1 "electron-ness", or electron flavor and a anti-electron has -1



# Neutrino Interactions

- Neutrinos interact only via the weak force ($W^{+/-}$, $Z^0$ bosons)
  - Forces are "mediated" by a particle, called a boson
  - In the case of electricity, that particle is a photon (E&M wave)
- W exchange gives Charged-Current (CC) events and Z exchange gives Neutral-Current (NC) events
  - In CC events the outgoing lepton determines if neutrino or antineutrino (e.g. neutrino → electron, antineutrino → positron)
  - NC is just scattering (neutrino in, neutrino out)
- Weak force is a "V-A" force, which means only left handed particles participate in the weak force



# How weak is the weak force?

- Weak interactions are weak because of the massive W and Z boson exchange. We characterize the interaction with the constant $G_F$, which is related to the masses of the W and Z.

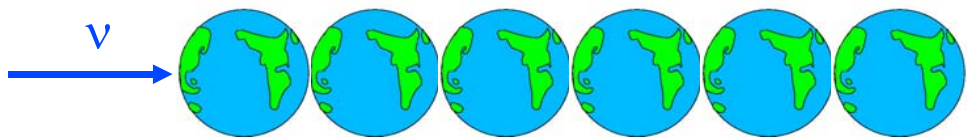
$$\Rightarrow \sigma^{\text{weak}} \propto G_F^2 \propto (1/M_{W\,or\,Z})^4 = \text{small!}$$

$M_W \sim 80$ GeV

$M_Z \sim 91$ GeV

- For 100 GeV Neutrinos:
  - $\sigma(\nu+e) \sim 10^{-40}$ cm$^2$ and $\sigma(\nu+p) \sim 10^{-36}$ cm$^2$
    compared to $\sigma(pp) \sim 10^{-26}$ cm$^2$

- A neutrino has a good chance of traveling through 200 earths before interacting at all!

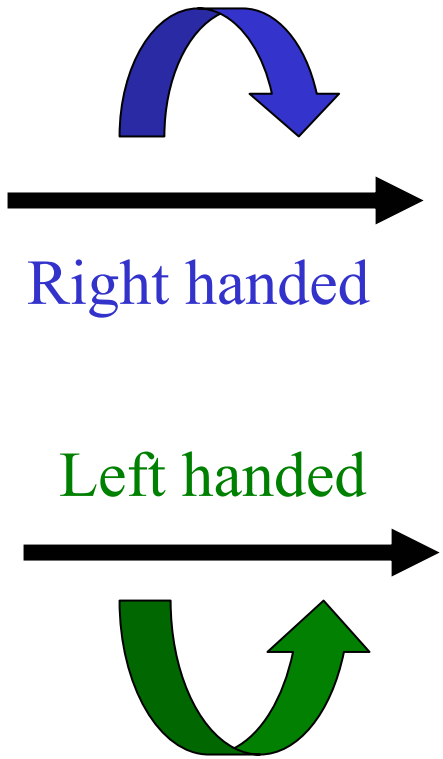



  - Mean free path length in Steel $\sim 3\times10^9$ meters!

- For detection, this means we need lots of ν's and a large detector.

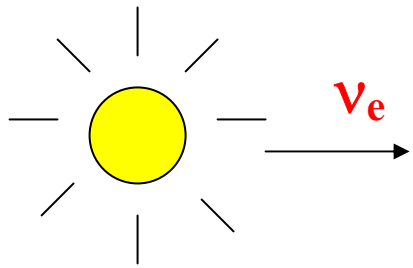
# More about neutrinos

- Neutrinos are expected to be massless
- Neutrinos are left handed and antineutrinos are right handed
  - Handedness is projection of spin along the particle's direction
  - If the particle is massive, this property is frame dependant and called helicity

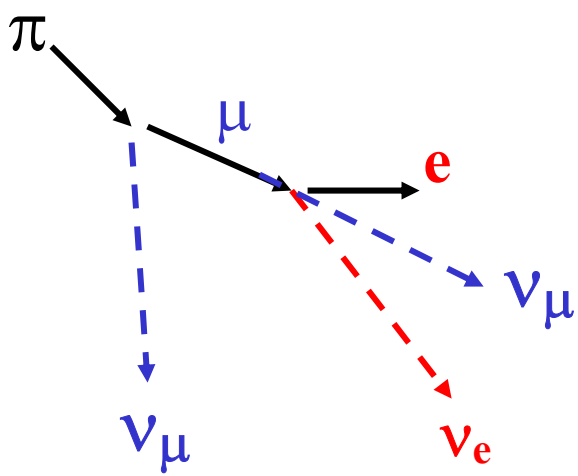


# Sources of neutrinos (I)

- Solar electron neutrinos
  - neutrinos produced in fusion reactions that cause the sun to shine
    - mainly via $p + p \rightarrow D + e^{+} + \nu_e$
  - Typical energy of ~1 MeV

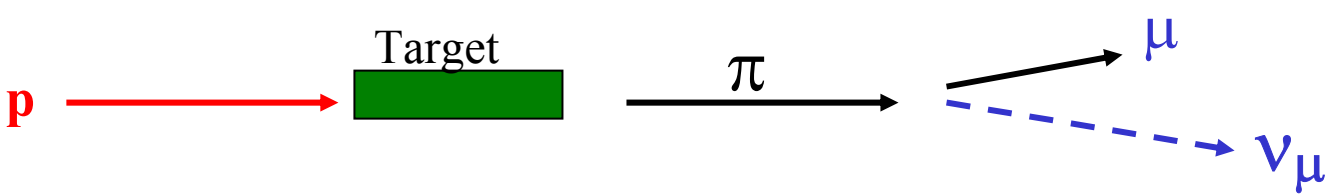



- Atmospheric neutrinos
  - Cosmic rays (high energy protons) hit nucli in atmosphere, producing pions, which decay to neutrinos
  - Typical energy of 100 MeV to 10 GeV and higher



# Sources of neutrinos (II)

- Reactor neutrinos
  - Fission reaction produces electron antineutrinos
  - Typical energy of few MeV
- Accelerator neutrinos
  - artificially produced with protons in an accelerator hitting a target producing pions (and subsequently neutrinos)
  - Typical energy of ~1 GeV

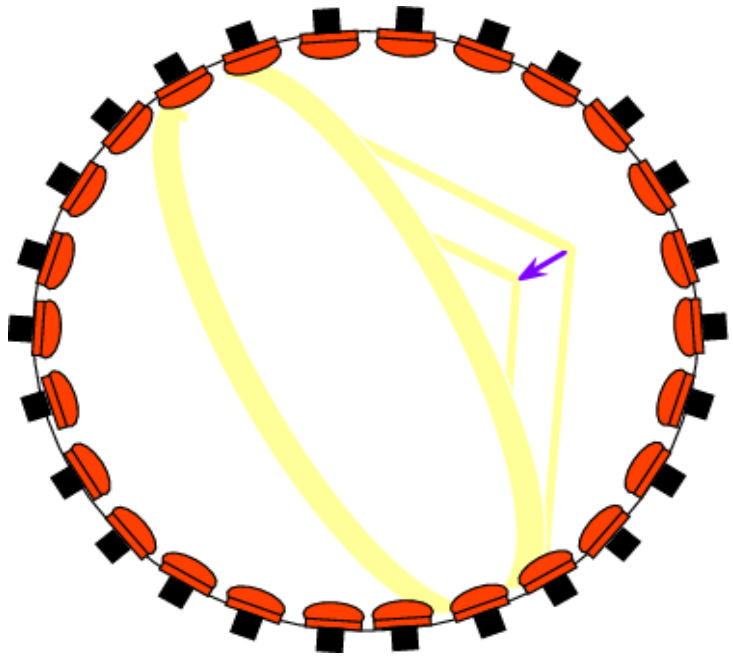


# Neutrino Detection

- Detection in particle physics is usually detection of a charged particle
- Neutrinos are neutral and hardly interact
  - Need lots of stuff for them to hit (1-50 kton detectors!)
  - Need indirect detection
- "See neutrino" by observing charged lepton partner interacting in material of detector
  - Example: Cherenkov light

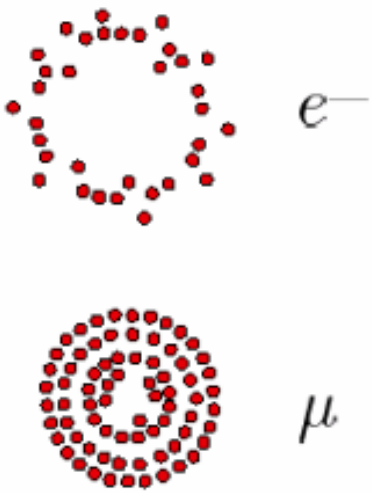
# Cherenkov light

- In semi-transparent mediums (water, oil) if a charged lepton is going faster than the speed of light in the medium, it will leave a "light boom" ring called Cherenkov light
- This ring is observable by light detectors called photomultiplier tubes (PMTs) placed around the edge of the detector
- A PMT is like an inverse flashlight– light comes in, electricity comes out

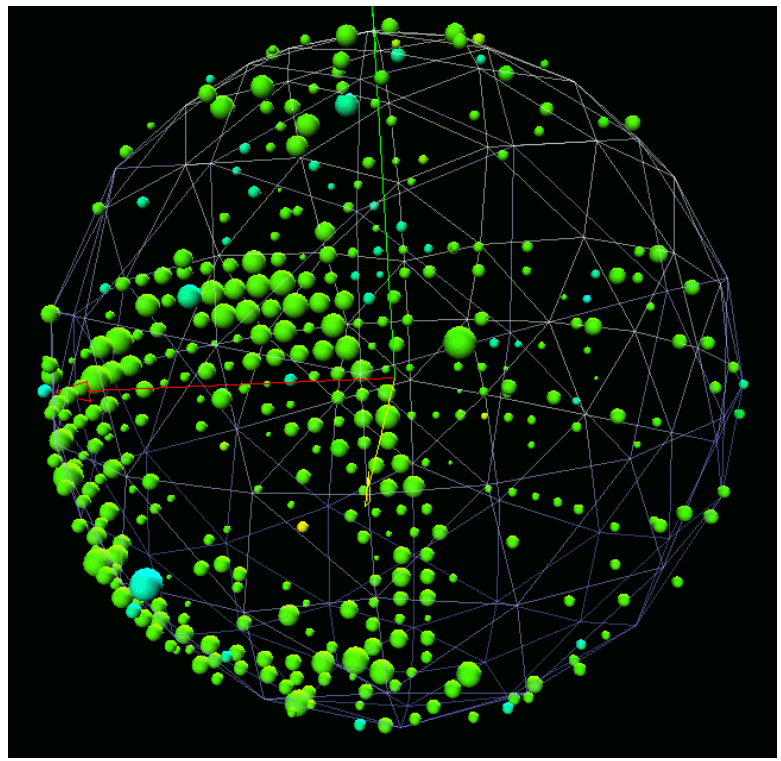


# Particle Identification

- The pattern of the Cherenkov ring determines which charged lepton interacted in the detector.
  - Fuzzy ring = electron (due to pair production, light everywhere)
  - Clear ring = muon (minimum ionizing particle radiates constant energy over distance)

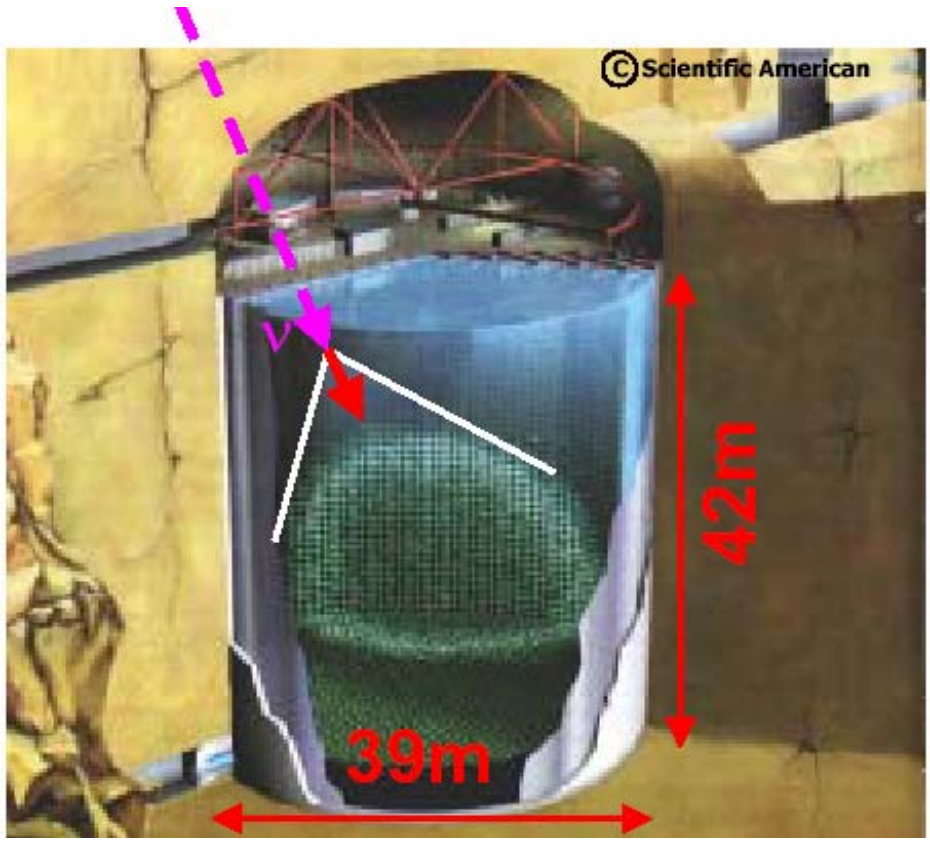


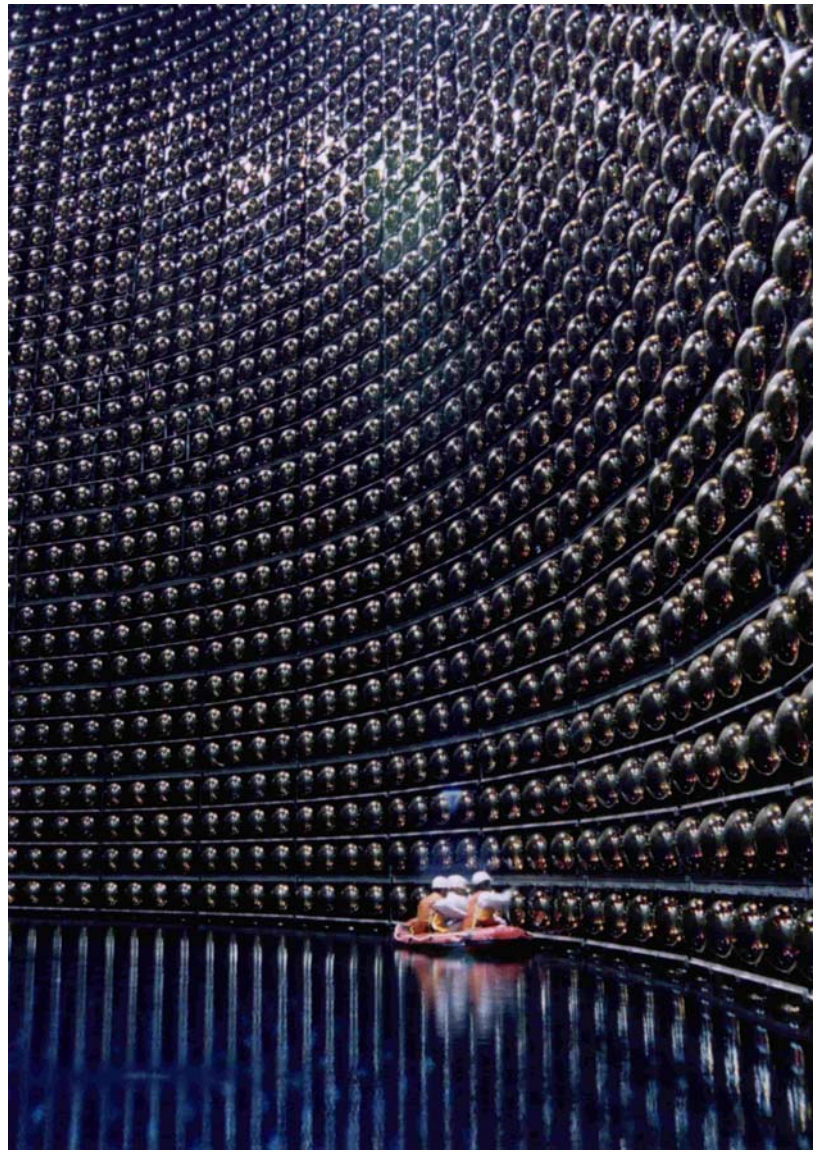

Example: a muon in MiniBooNE detector



# Super-Kamiokande (Super-K) Detector

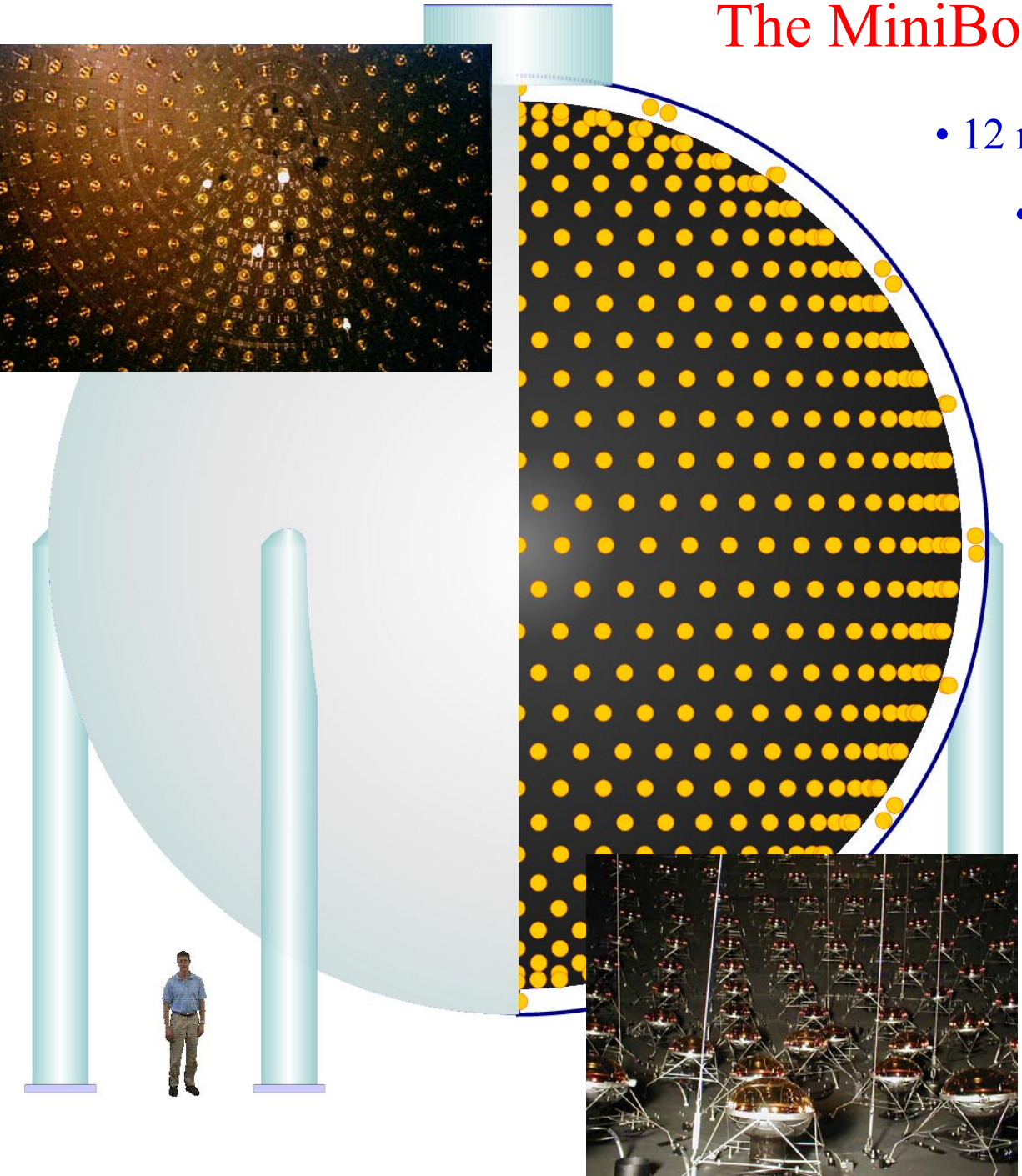
- Tank filled with 50 ktons of ultra-pure water
- 11,150 20 inch PMTs in inner detector
- Located in Kamioka mine at a depth of 1000m below the surface



# The MiniBooNE Detector



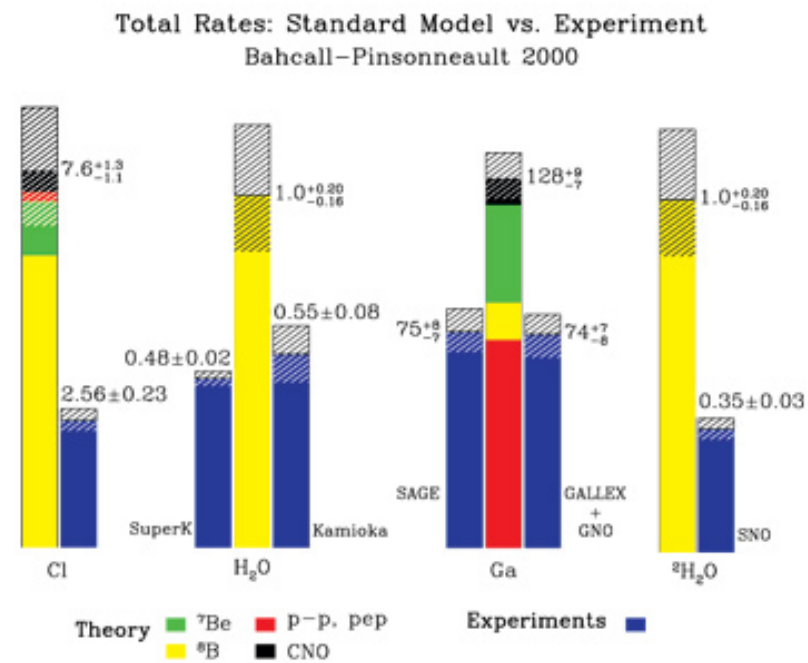


- 12 meter diameter sphere
  - Filled with 950,000 liters (900 tons) of very pure mineral oil
    - Light tight inner region with 1280 photomultiplier tubes
    - Outer veto region with 241 PMTs reject non-neutrino events (e.g. cosmic ray muons)

# The solar neutrino problem

- We see less electron neutrinos than we expect coming from the sun!
  - First observed by radiochemical experiments (Cl + $\nu_e$ → Ar, count Ar atoms)
  - The SNO experiment sees that the total neutrino flux is correct from sun but is just changing flavor
  - Kamland, using reactor $\nu_e$ also sees less events than expected
- Note: different energy ranges show different deficits

  ⇒ *there is an energy dependence*



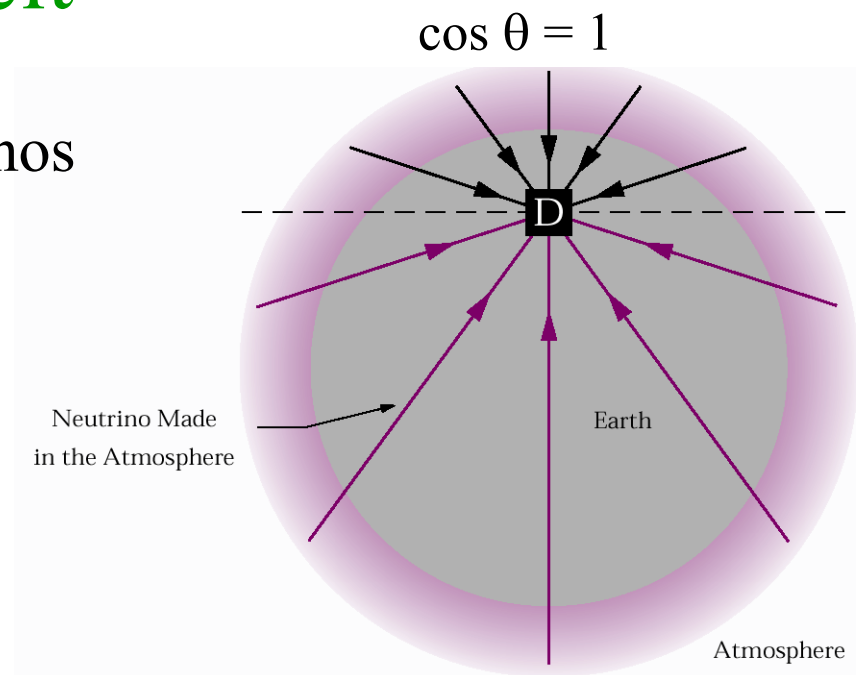

Blue: Experiment

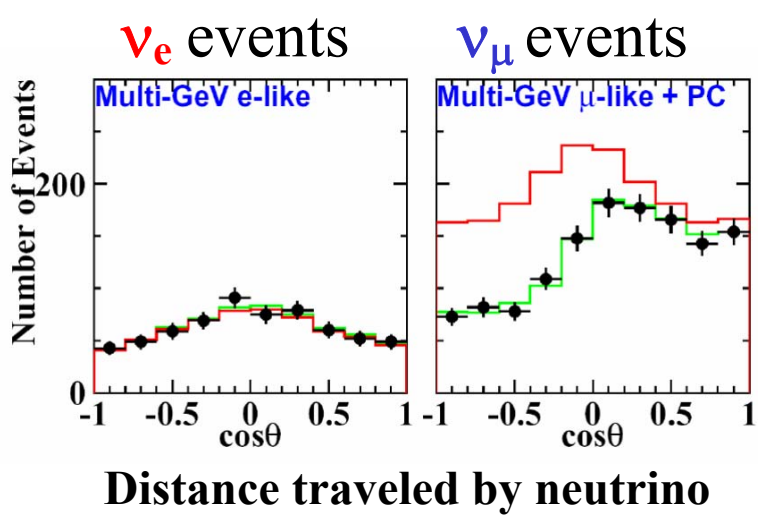
Yellow, green, black: Theory

Grey: error

# The plot thickens: atmospheric neutrino deficit

- We ALSO see less muon neutrinos from the atmosphere!
  - First observed by Kamiokande
  - Confirmed by Super-Kamiokande, K2K (with artificial beam of $\nu_\mu$ )




Super-K data shows we see less neutrinos than we expect at long distances but the right amount at short distances

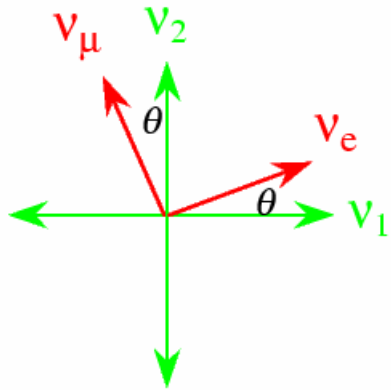
⇒ *disappearance depends on distance the neutrino travels*

# Solution: Neutrino Oscillation

- If we postulate:
  - Neutrinos have (different) mass
    $\Rightarrow \Delta m^2 = m_1^2 - m_2^2$
  - The ***Weak Eigenstates*** are a mixture of ***Mass Eigenstates***

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

  - Then, a pure $\nu_\mu$ beam at L=0, will develop a $\nu_e$ component as it travels a distance L, with a probability given by:




*2D "neutrino space"*

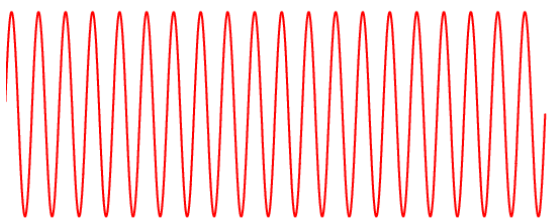
*The Probability for Oscillations...*

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

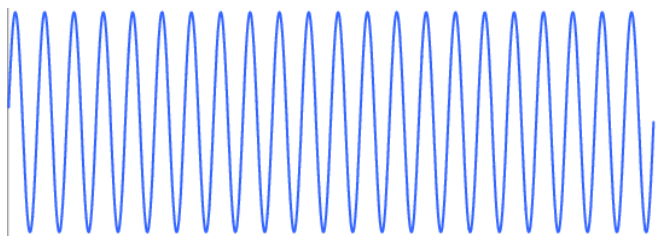
# Neutrino Oscillation

- We can think of neutrino oscillation like the interference of two waves.
  - $\nu_1$, $\nu_2$ are two waves with very close (but not equal) frequency

$\nu_1$

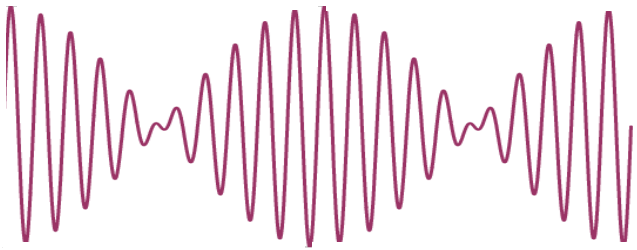


$\nu_2$



  - When we combine the two, we get

$\nu_{\mu,e}$



  - We can think of $\nu_\mu$ (or $\nu_e$) as this resulting wave

# Oscillation Formula Parameters

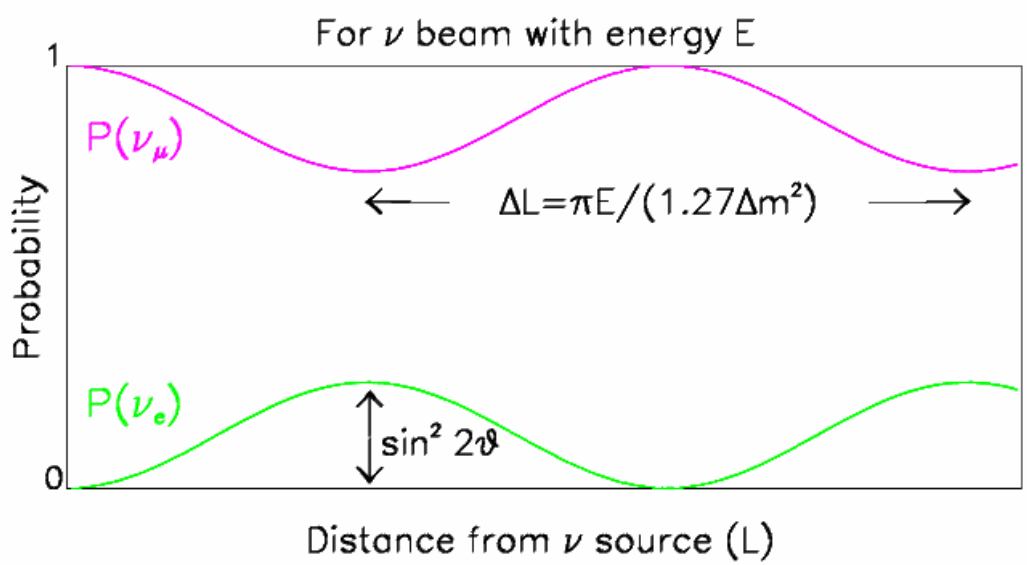
$$P_{Osc} = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 L / E\right)$$

*...Depends Upon Two Experimental Parameters:*

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

*...And Two Fundamental Parameters:*

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




***$\nu_\mu$ Disappearance***

***$\nu_e$ Appearance***

# 3-Generation Oscillation Formalism

- We have 3-generations: $\nu_e$ , $\nu_\mu$, and $\nu_\tau$
  $\Rightarrow$ extend our model to include mixing between all flavors

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

$$\begin{pmatrix} Flavor \\ Eigenstate \end{pmatrix} = \begin{pmatrix} Mixing & Matrix \end{pmatrix} \begin{pmatrix} Mass \\ Eigenstate \end{pmatrix}$$

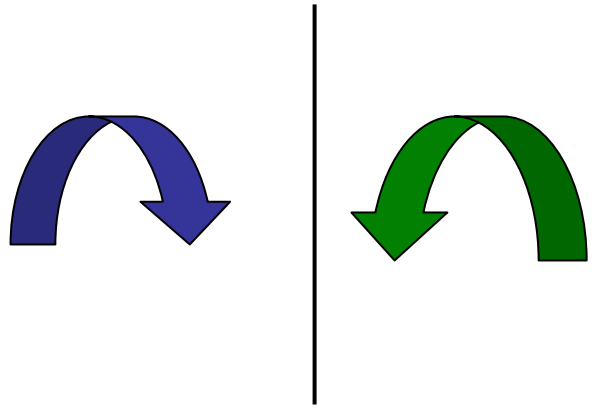
And there are three : $\Delta m_{12}^2 = m_1^2 - m_2^2$ , $\Delta m_{23}^2 = m_2^2 - m_3^2$ , $\Delta m_{31}^2 = m_3^2 - m_1^2$

But only two are independent since only three masses

- CP violating process can also occur if $\delta \neq 0$ $\Rightarrow$ $P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$

# CP violation

- Charge: $e^+ \rightarrow e^-$
- Parity: mirror inverse
  - Only "left handed" particles interact via the weak force, so parity is violated in weak interactions
- CP initially expected to be conserved
  - But CP is violated with K and B mesons
- CP violating phase in neutrino mixing matrix
  - if $\delta \neq 0 \Rightarrow P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
- "Leptogenesis"
  - CP violation in leptons could explain matter/antimatter asymmetry in the universe

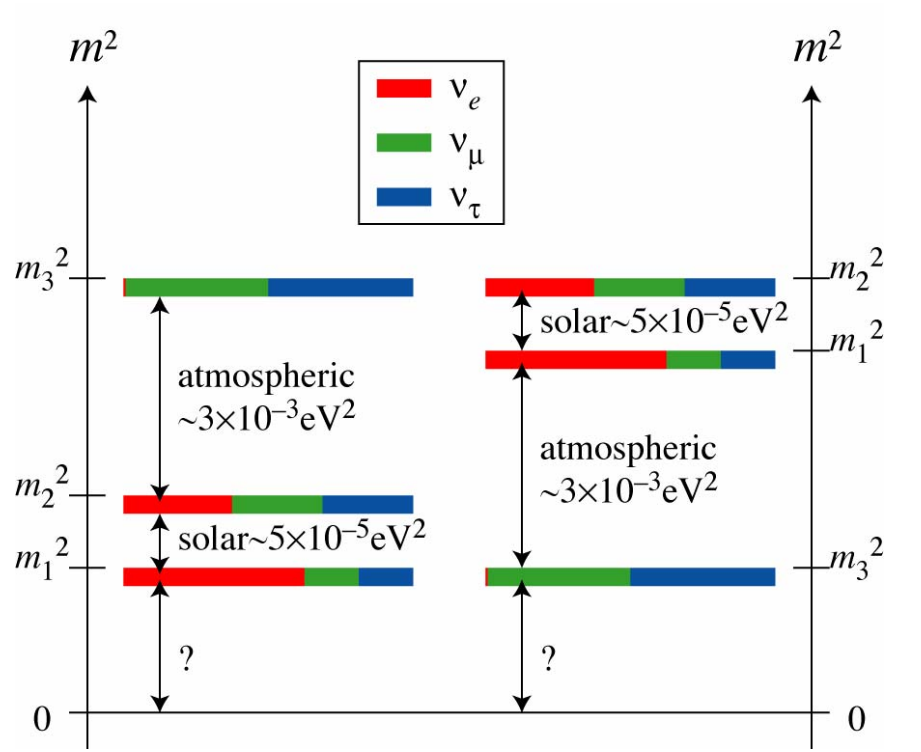


# Mass hierarchy

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

$$\Delta m^2_{13} = \Delta m^2_{12} + \Delta m^2_{23}$$

- The mass hierarchy is the ordering of the $\Delta m^2$ from lightest to heaviest
- $\Delta m^2_{(13)}$ can either be positive (normal hierarchy) or negative (inverted hierarchy)




Normal hierarchy ($\Delta m^2 > 0$ )

Inverted hierarchy ($\Delta m^2 < 0$ )

# Implications of neutrino oscillation

- If we see oscillation, that means neutrinos have mass
- This has big consequences!
  - Indication of beyond the Standard Model physics!
    - Why is the neutrino mass so small, but non-zero?
  - Cosmological implications
    - Massive neutrinos that oscillate are important for heavy element production in supernova
    - Light neutrinos affect galactic structure formation
- It's very hard to probe neutrino mass directly, oscillations are a way to measure the neutrino mass

***Current direct Mass Limits***

***Electron $\nu$: $m < 2$ eV***

***Muon $\nu$: $m < 170$ keV***

***Tau $\nu$: $m < 18$ MeV***

# What do we know about the mixing matrix?

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

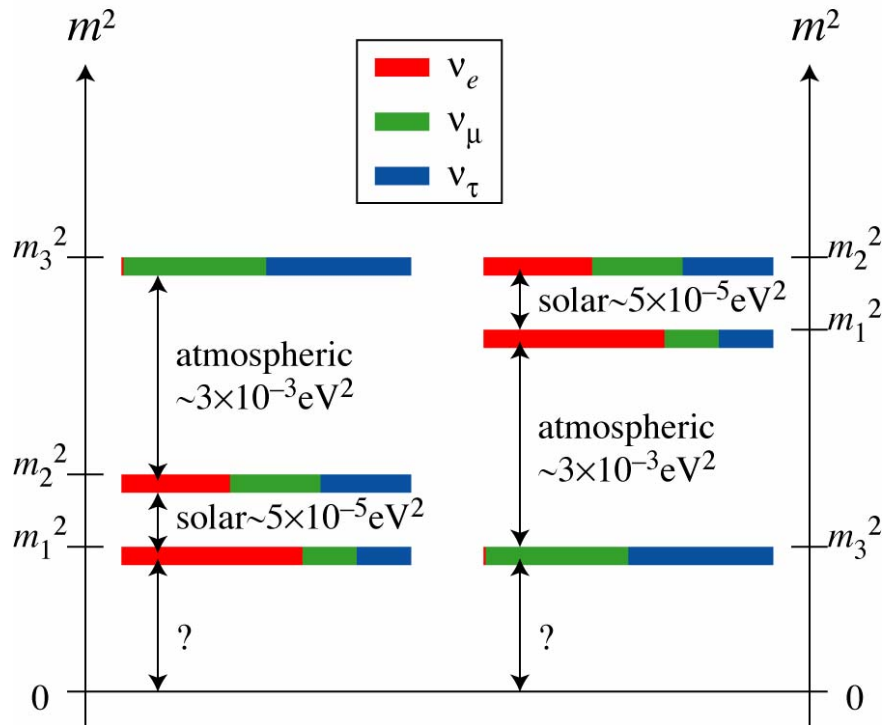
$$= \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

Solar: $\theta_{12} \sim 30°$ $\sin^2 2\theta_{13} < 0.2$ at 90% CL Atmospheric: $\theta_{23} \sim 45°$

- We can break the 3x3 mixing matrix into 3 matrixes, each representing approximately 2 flavor neutrino mixing
- We know:

  The solar and atmospheric mixing angles ($\theta_{12}$,$\theta_{23}$ )and $\Delta m^2$'s
- We don't know:

  The sign of $\Delta m^2_{(13)}$ (mass hierarchy), how small $\theta_{13}$ is, and CP violation?



# Neutrino vs. Quark mixing

- Mixing occurs in quarks, too
  - But the mixing matrix is much different, why?

MNS Lepton Mixing Matrix

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

$$\begin{pmatrix} 0.7 & 0.7 & < 0.2 e^{i\delta}\ ? \\ -0.5 & 0.5 & 0.7 \\ 0.5 & -0.5 & 0.7 \end{pmatrix}$$

$$\begin{pmatrix} big & big & small\ ? \\ big & big & big \\ big & big & big \end{pmatrix}$$

CKM Quark Mixing Matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} U_{ud} & U_{us} & U_{ub} \\ U_{cd} & U_{cs} & U_{cb} \\ U_{td} & U_{ts} & U_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\begin{pmatrix} 0.97 & 0.22 & 0.003\, e^{i\delta} \\ -0.22 & 0.97 & 0.04 \\ 0.01 & -0.04 & 0.999 \end{pmatrix}$$

$$\begin{pmatrix} big & small & very\ tiny \\ small & big & tiny \\ tiny & tiny & big \end{pmatrix}$$

# Key Questions

- What is value of $\theta_{13}$?
  - Small, very small, zero?
- What is mass hierarchy?
  - Normal or inverted?
- Do neutrino oscillations violate CP symmetry?

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \sin\left(\frac{\Delta m_{12}^2}{4E} L\right) \sin\left(\frac{\Delta m_{13}^2}{4E} L\right) \sin\left(\frac{\Delta m_{23}^2}{4E} L\right)$$

$\sin\theta_{13}$

- Why are quark and neutrino mixing matrices so different?

$$U_{Neutrinos} \sim \begin{pmatrix} Big & Big & Small? \\ Big & Big & Big \\ Big & Big & Big \end{pmatrix} \text{ compared to } V_{Quarks} \sim \begin{pmatrix} 1 & Small & Small \\ Small & 1 & Small \\ Small & Small & 1 \end{pmatrix}$$

Value of $\theta_{13}$ central to these questions; it sets the scale for experiments needed to resolve mass hierarchy and search for CP violation.

# Methods to measure $\sin^2 2\theta_{13}$

- Accelerators: Appearance ($\nu_\mu \rightarrow \nu_e$) at $\Delta m^2 \approx 2.5\times10^{-3}$ eV$^2$

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m_{13}^2 L}{4E} + \text{not small terms } (\delta_{CP},\ sign(\Delta m_{13}^2))$$

Use fairly pure, accelerator produced $\nu_\mu$ beam with a detector a long distance from the source and look for the appearance of $\nu_e$ events

T2K: $\langle E_\nu \rangle$ = 0.7 GeV, L = 295 km ⇐ Shoot across Japan (JPARC to Super-K)
NOνA: $\langle E_\nu \rangle$ = 2.3 GeV, L = 810 km ⇐ Fermilab to Minnesota

(These are very expensive programs with 100-200$M detectors and 200-500$M accelerator upgrades.)

- Reactors: Disappearance ($\bar{\nu}_e \rightarrow \bar{\nu}_e$) at $\Delta m^2 \approx 2.5\times10^{-3}$ eV$^2$

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}\sin^2\frac{\Delta m_{13}^2 L}{4E} + small$$

Use reactors as a source of $\bar{\nu}_e$ ($\langle E_\nu \rangle \sim 3.5$ MeV) with a detector 1-2 km away and look for non-$1/r^2$ behavior (isotropic rate loss) of the $\nu_e$ rate

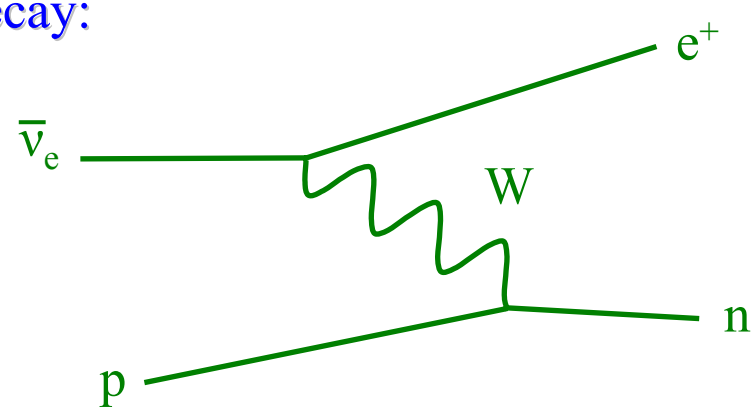
➡ Reactor experiments allow direct measurement of $\sin^2 2\theta_{13}$:
no matter effects, no CP violation, almost no correlation with other parameters.

# Long History of Reactor Neutrino Measurements

Reines and Cowan at the Savannah River Reactor

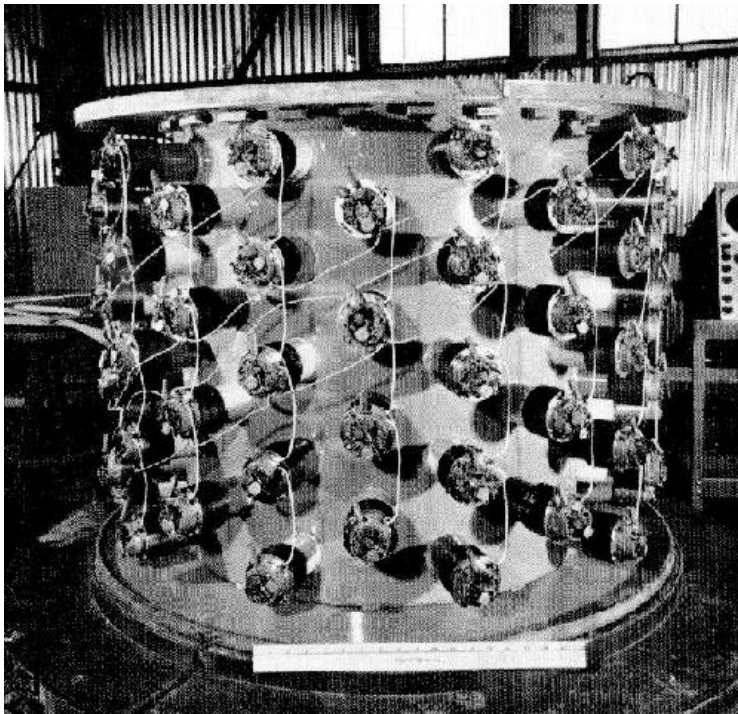
The original neutrino discovery experiment, by Reines and Cowan, used reactor anti-neutrinos…

The $\bar{\nu}_e$ interacts with a free proton via inverse β-decay:




Later the neutron captures giving a coincidence signal. Reines and Cowan used cadmium to capture the neutrons (modern exp. use Gadolinium)

The first successful neutrino detector



# Experimental Setup

- The reaction process is inverse β-decay followed by neutron capture
  - Two part coincidence signal is crucial for background reduction.

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

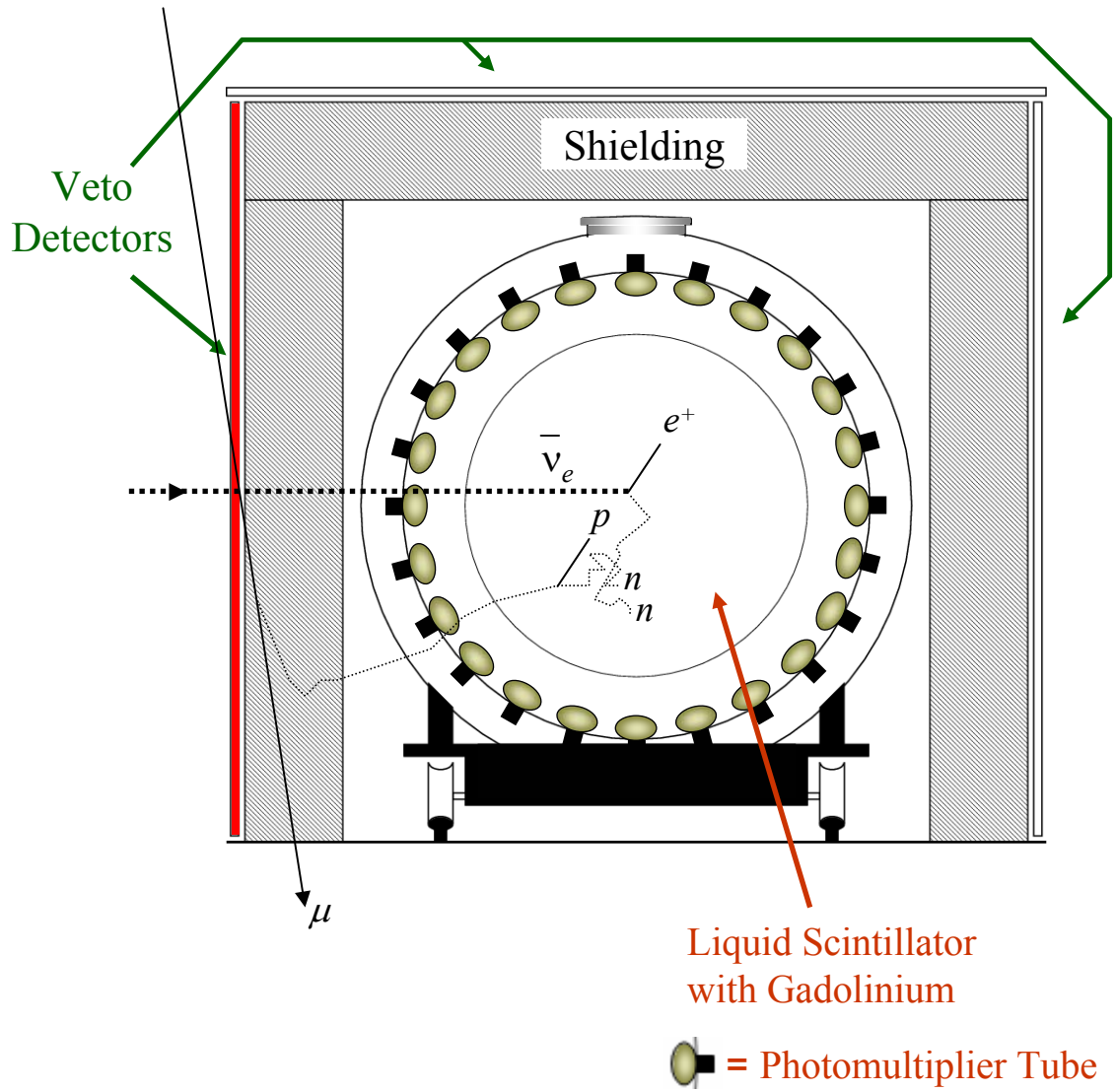
$$\hookrightarrow n \text{ capture}$$

- Positron energy spectrum implies the neutrino spectrum

$$E_\nu = E_{vis} + 1.8 \text{ MeV} - 2m_e$$

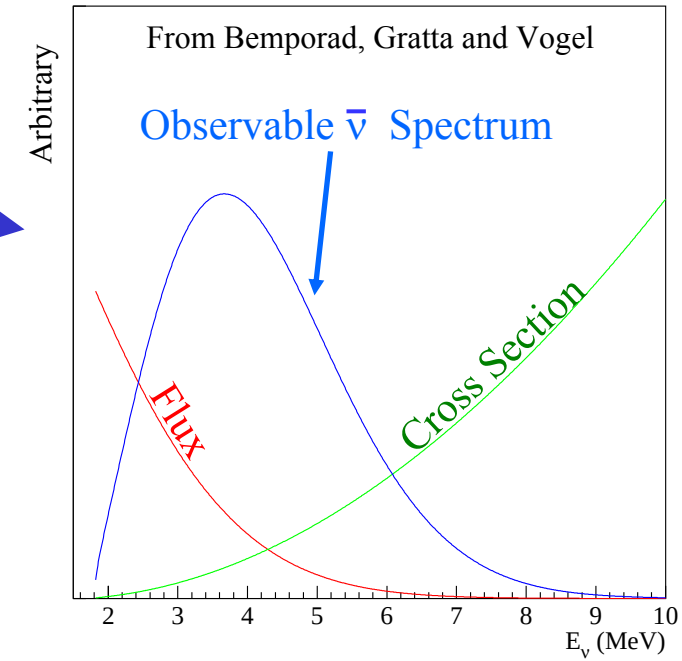
- The scintillator will be doped with gadolinium to enhance capture

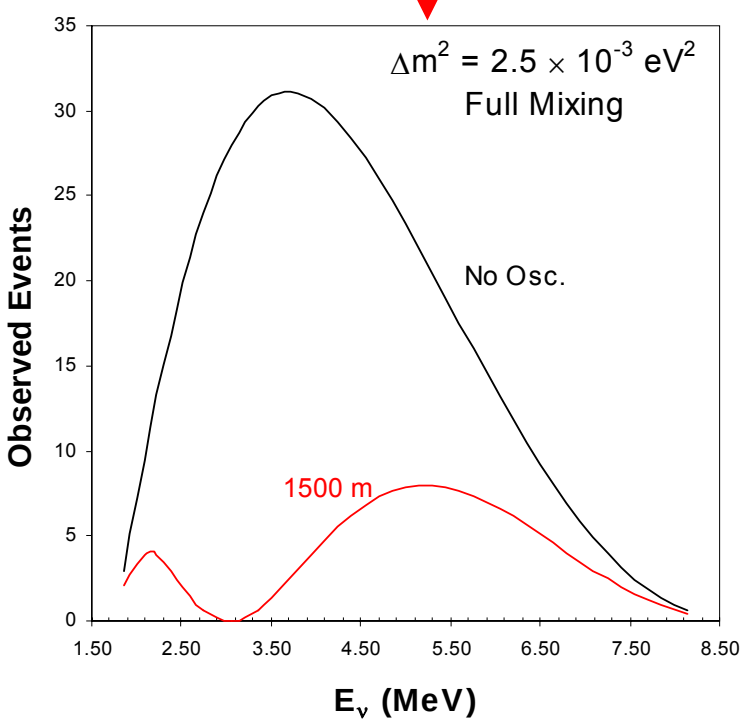
$$n\ {}^{m}\text{Gd} \rightarrow {}^{m+1}\text{Gd}\ \gamma\text{'s (8 MeV)}$$



# Reactor Measurements of $\theta_{13}$

- Nuclear reactors are a very intense sources of $\bar{\nu}_e$ with a well understood spectrum
  - 3 GW → $6\times10^{20}$ $\bar{\nu}_e$/s
    700 events / yr / ton at 1500 m away
  - Reactor spectrum peaks at ~3.7 MeV
  - Oscillation Max. for $\Delta m^2=2.5\times10^{-3}$ eV$^2$ at L near 1500 m

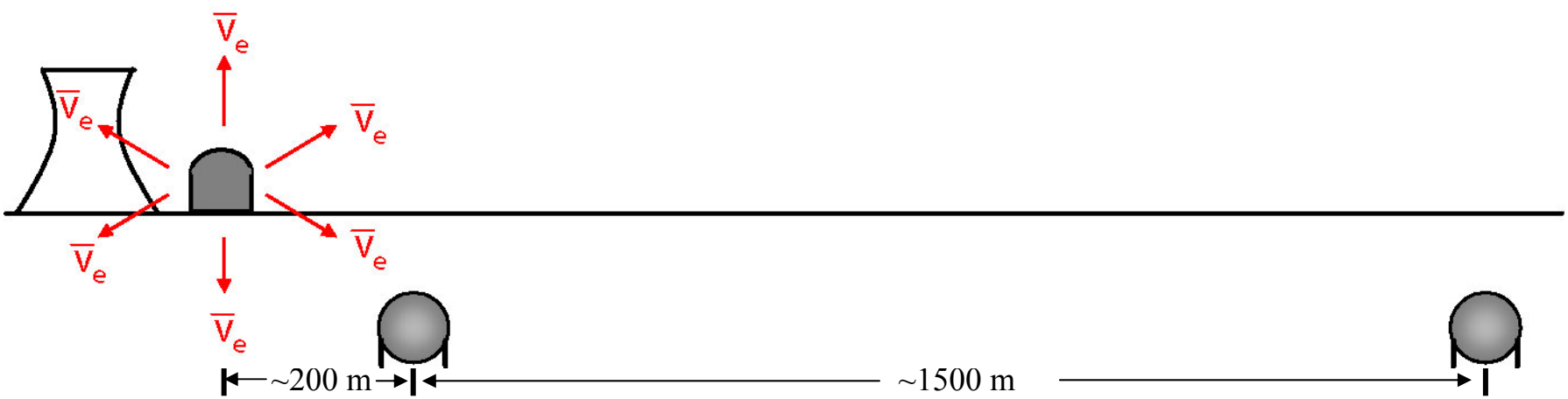



- Disappearance Measurement:
  *Look for small rate deviation from $1/r^2$ measured at a near and far baselines*
  - Counting Experiment
    - Compare events in near and far detector
  - Energy Shape Experiment
    - Compare energy spectrum in near and far detector

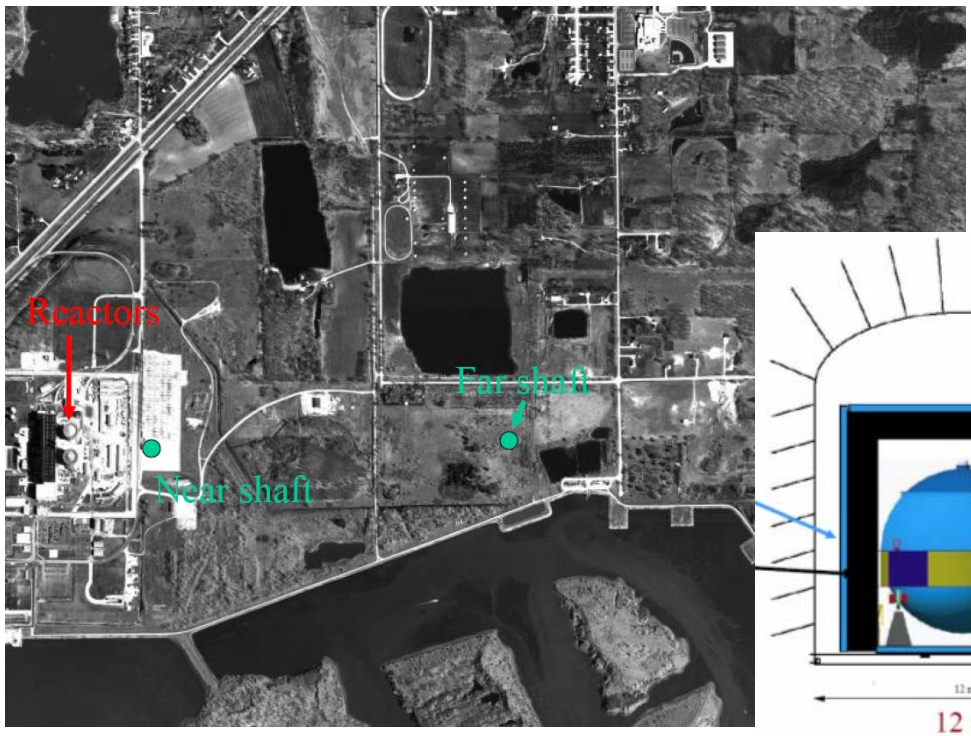
# How can we do better than previous reactor experiments?

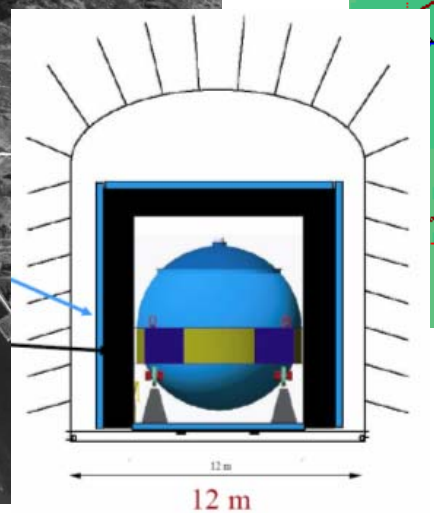
- Add an identical near detector
  Eliminate dependence on reactor flux and many detector effects
- Optimize baseline for oscillation signal (1500 m)
- Larger detectors
  Get more events, better shielding from events in surrounding rock (5 tons → 100 tons)
- Reduce backgrounds
  Go deeper 100m → 150 to 300m

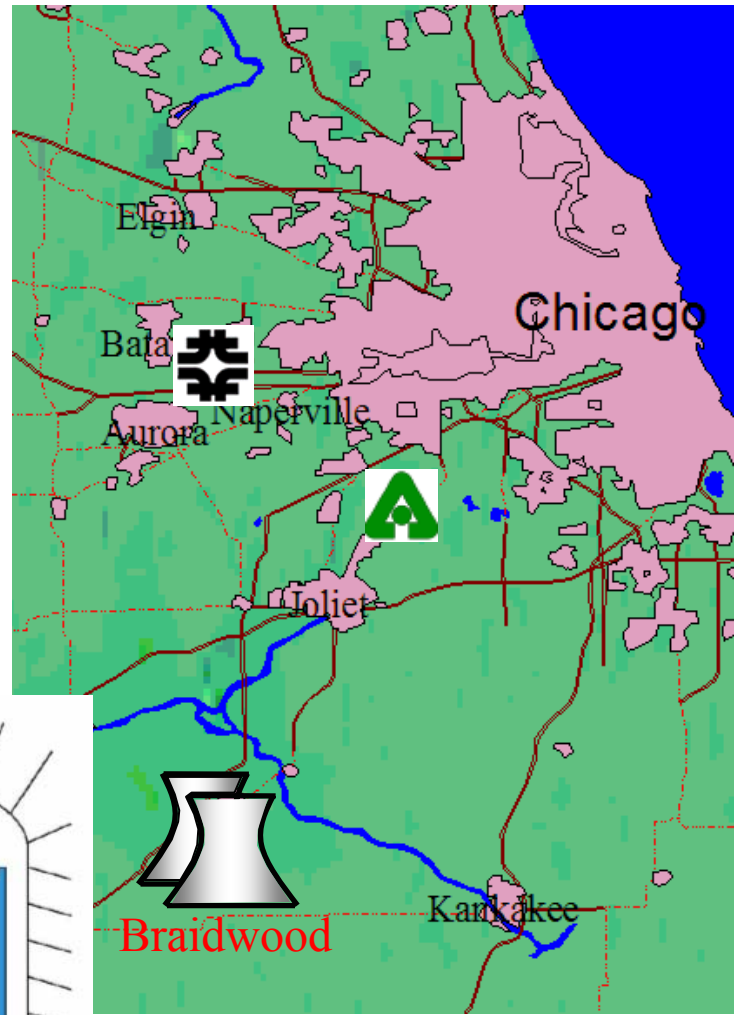


# Braidwood, Illinois

- Four 65 ton detectors (Fid. Radius = 2.6 m)
- Two near detectors at 200 meters & 450 mwe (meters water equivalent depth)
- Two far detectors located at 1500 meters, 450 mwe
- Sensitivity of $\sin^2 2\theta_{13} \leq 0.01$ in 3 years
- High level of cooperation with utility



# Braidwood Reactor Collaboration

- **Argonne Nat. Lab.:** M. Goodman, V. Guarino, D. Reyna
- **Brookhaven Nat. Lab.:** R. Hahn, M. Yeh
- **U. of Chicago:** E. Abouzaid, K. Anderson, E. Blucher, M. Hurwitz, A. Kaboth, J. Pilcher, E. Pod, M. Worcester
- **Columbia:** J. Conrad, Z. Djurcic, J. Link, K. McConnel, M. Shaevitz
- **Fermilab:** L. Bartoszek, D. Finley, H. Jostlein, C. Laughton, R. Stefanski
- **Kansas State:** T. Bolton, J. Foster, G. Horton-Smith, D. Onoprienko, N. Stanton
- **U. of Michigan:** B. Roe
- **MIT:** P. Fisher, L. Osborne, G. Sciolla, F. Taylor, R. Yamamoto
- **Oxford:** G. Barr, S. Biller, N. Jelley, S. Peeters, N. Tagg
- **U. of Pittsburgh:** D. Naples, V. Paolone
- **Sussex:** L. Harris
- **U. of Texas:** J. Klein
- **U. of Washington:** J. Formaggio

# Braidwood Experiment

- Experimental Goals: $\delta(\sin^2 2\theta_{13}) \approx 0.01$
  - Statistical error = 0.2%
  - Background error = 0.5%
  - Relative detector error = 0.6%

- Advantages:
  - Deep near site allows other reactor physics measurements
  - Favorable geology (for digging) and low bkgnd (radioactivity of stone)
  - Redundancy and cross checks
    - Can do both rate and spectral distortion analysis
    - Surface transport of detectors for cross calibration
    - Multiple near and far detectors
- Disadvantages:
  - Infrastructure costs high due to new undeveloped site

- Cost estimate:

  Civil: ~ $35M

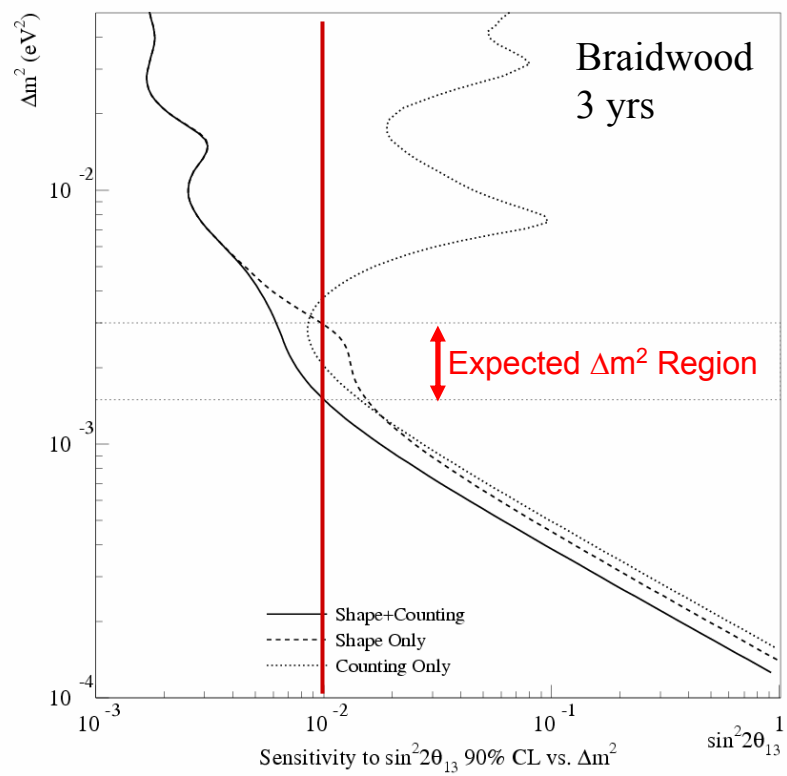
  Detectors: $15M
- Schedule:

  2005: R&D proposal submission.

  2006: Full proposal submission

  2007: Project approval; start const.

  2009: Start data collection



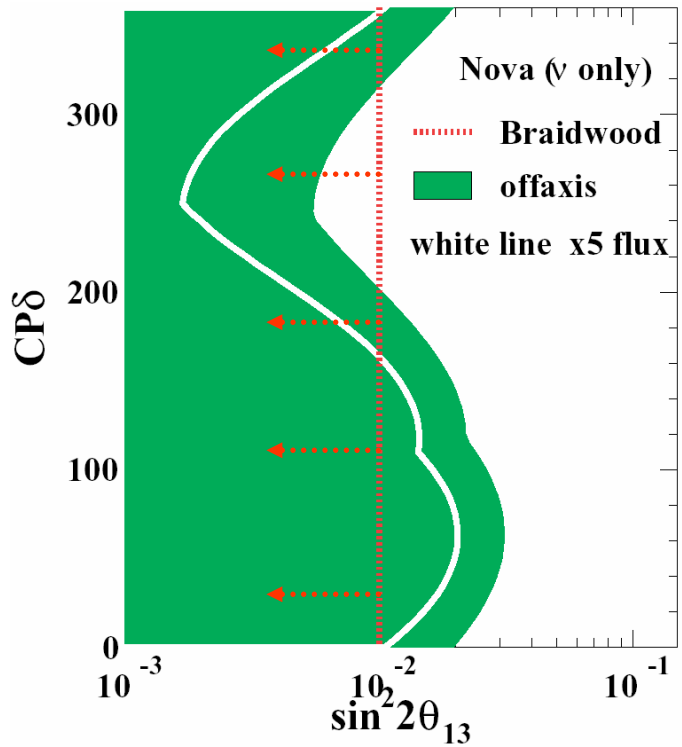
# Reactor Sensitivity Studies (Comparing and Combining with Accelerator Measurements)

(K. McConnel and M. Shaevitz – hep-ex/0409028)

Try to do estimate, including all exp. and theory effects,

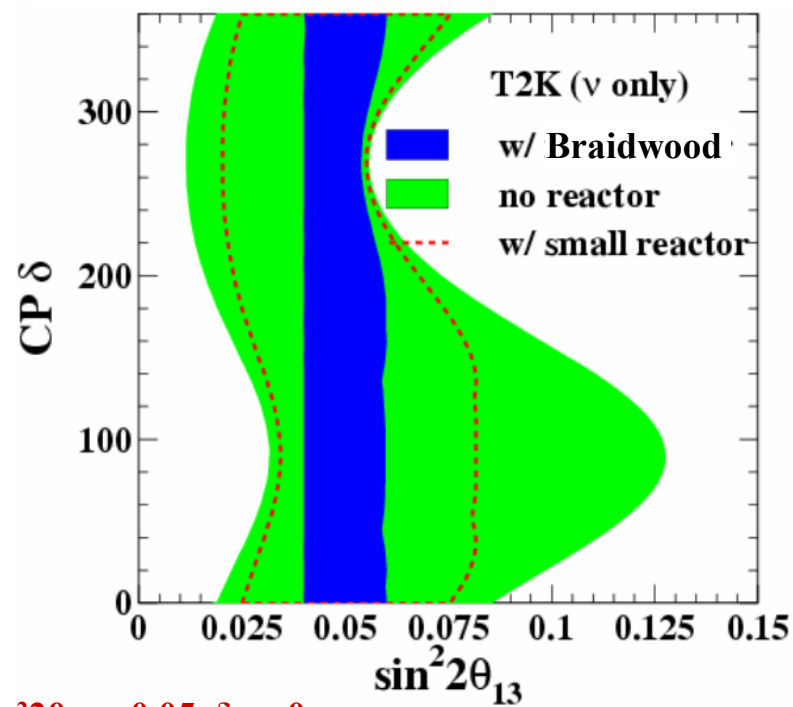
⇒ How well can you measure mixing angle $\theta_{13}$ , CP violation ($\delta_{CP}$), and mass hierarchy ?

**90% CL excluded regions with no osc. signal**




**$\Delta m^2 = 2.5\times10^{-3}$ eV$^2$, $\delta_{CP}$=0**
**(3 yr reactor, 5yr Nova)**

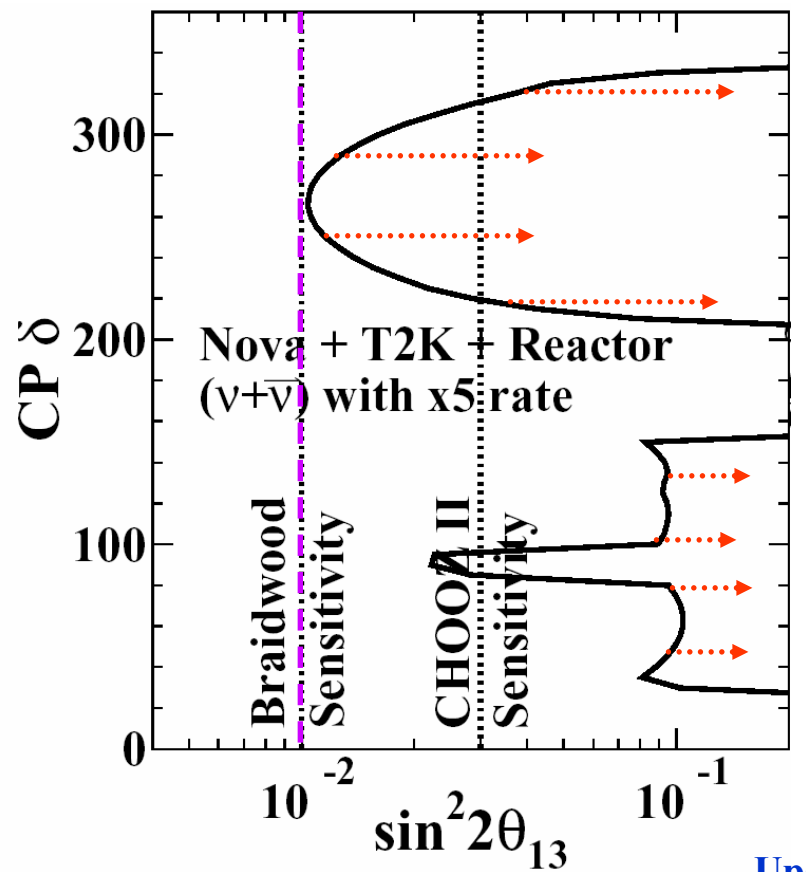
**90% CL allowed regions with osc. signal**



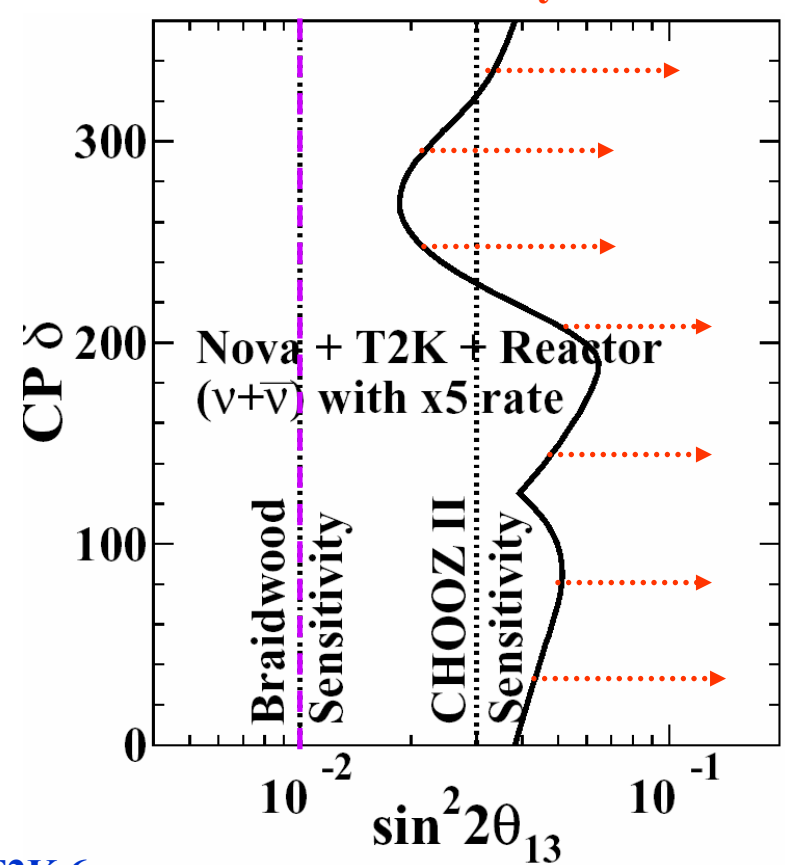

**$\sin^2 2\theta_{13} = 0.05$, $\delta_{CP}$=0,**
**$\Delta m^2 = 2.5\times10^{-3}$ eV$^2$**
**(3 yr reactor, 5yr T2K)**

# How Big Does $\sin^2\theta_{13}$ Need to Be?
# (In order to measure CP Violation or Mass Hierarchy)

**Sensitivity regions for observing CP Violation at 3σ**




**Sensitivity regions for resolving the Mass Hierarchy at 2σ**




**Upgraded T2K 6yrs**
**Nova with Proton Driver 6yrs**
**Reactor 3yr**

# Conclusions

- Neutrinos are particles which have surprised us in the past
  - Initially thought to be undetectable
  - Neutrino oscillations unexpected, but have been seen in solar, atmospheric sectors by multiple experiments
- Neutrino physics needs now
  - A clear measurement of $\theta_{13}$
    - Needed to constrain the models of lepton mixing matrix
    - If very small, probably indicates a new symmetry
    - Important for planning future long baseline experiments
      - If too small, not possible to probe CP violation/mass hierarchy with long baseline
- The future of neutrino physics will involve
  - Investigation of possible CP violation in the lepton sector
    - Possible explanation for matter/antimatter asymmetry (leptogenesis)
  - Determination of the mass hierarchy

# The Neutrino Matrix

The DNP/DPF/DAP/DPB
Joint Study on the Future of Neutrino Physics

One of the primary consensus recommendations:

" We recommend, as a high priority, a comprehensive US program to complete our understanding of neutrino mixing, to determine the character of the neutrino mass spectrum and to search for CP violation among neutrinos."

## The Growing Excitement of Neutrino Physics

- 1930: Pauli Predicts the Neutrino
- Fermi's theory of weak interactions
- 1955: Reines & Cowan discover (anti)neutrinos
- Davis discovers the solar deficit
- 2 distinct flavors identified
- Kamioka II confirms solar deficit
- LEP shows 3 active flavors
- SAGE and Gallex see the solar deficit
- Kamioka II and IMB see atmospheric neutrino anomaly
- Kamioka II and IMB see supernova neutrinos
- Nobel prize for discovery of distinct flavors!
- LSND sees possible indication of oscillation signal
- Nobel Prize for $\bar{\nu}$ discovery!
- Super K sees evidence of atmospheric neutrino oscillations
- Super K confirms solar deficit and "images" sun
- SNO shows solar oscillation to active flavor
- Nobel Prize for neutrino astroparticle physics!
- KamLAND confirms solar oscillations
- K2K confirms atmospheric oscillations
- 2005