2011: The Year in Neutrinos

Deborah Harris
Fermilab

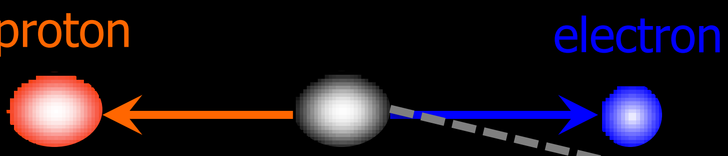
In Celebration of G. Rajasekaran's 75th Birthday
Institute for Mathematical Sciences
Chennai
December 21, 2011

Outline

- Neutrinos: the first 30 years…
  - The era of the first energy crisis
  - Lessons learned: patience is a virtue
  - Neutrinos in the Standard Model of Particle Physics
- Neutrinos: the next 30 years…
  - The era of “anomalies”
  - Lessons learned: patience is still a virtue
  - What it means for neutrinos to “oscillate”
- Neutrinos: what happened in 2011?
  - Oscillations
  - Interactions
  - Velocity
- Next steps for Neutrinos
  - Are we applying the lessons we have learned?

The first Energy Crisis…

- in 1930 there was a crisis in particle physics!

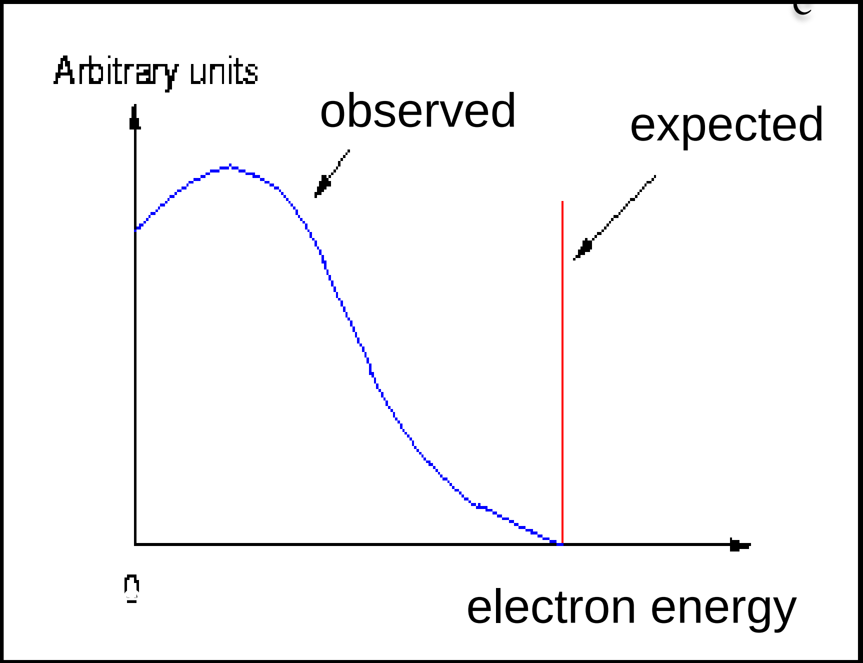


$$(A, Z) \rightarrow (A, Z+1) + e^- + \bar{\nu}_e$$

It was well known that nuclei could change from one variety to another by emitting a “**beta**” (electron).

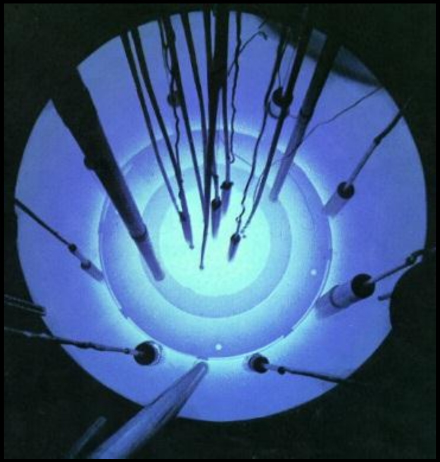
Some were ready to abandon **Conservation of Energy** to explain this missing energy

. . . until W. Pauli proposed his “**desperate remedy**”,the neutrino, which invisibly carried away the missing energy – and the neutrino was born



Slide courtesy D. Schmitz

26 years later, 1st Observation of neutrino

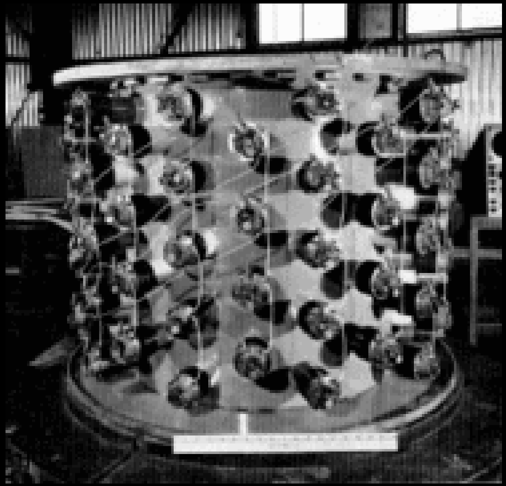


- **Reactors make huge fluxes of neutrinos**

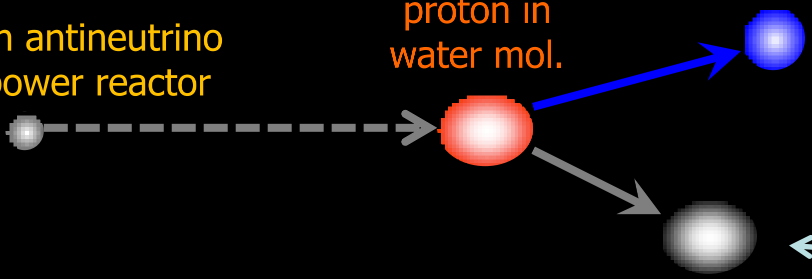
•can’t see a neutrino directly since they are neutral

method for observation was called “inverse beta decay”

Reines and Cowan



Water Target plus $CdCl_2$



electron antineutrino from power reactor

proton in water mol.

antielectron

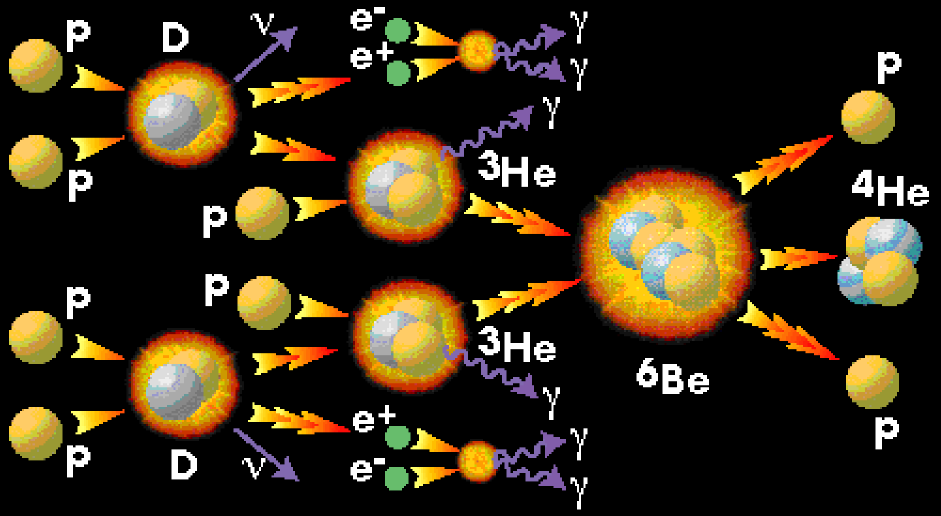
annihilates on normal electron
in water and releases 2 photons

neutron

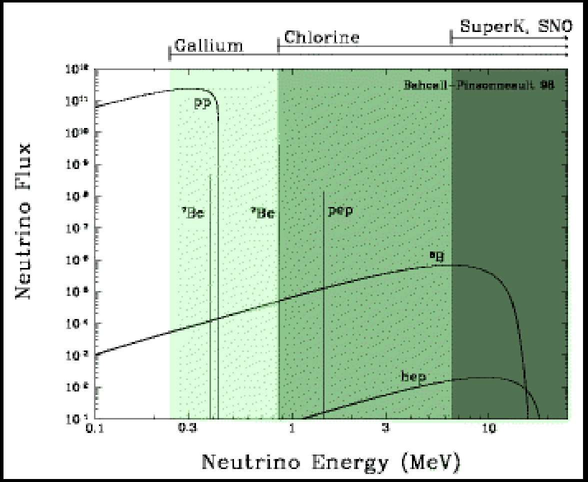
gets captured by Cadmium nucleus and releases one photon

inverse beta decay

Confirmation of first observation of neutrinos: look at the sun



Copyright © 1997 Contemporary Physics Education Project.



- Sun is prolific producer of neutrinos
- Goal was to test solar models of fusion: what makes the sun shine?
- Ray Davis looked for

$\nu + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$

- Found neutrinos, but 1/3 the number expected…

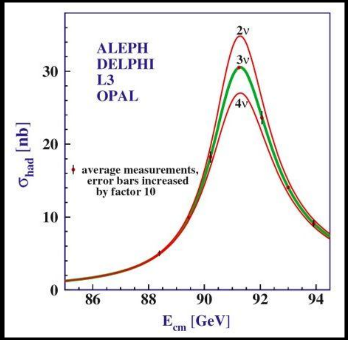
Ray Davis Experiment
Homestake Mine, USA

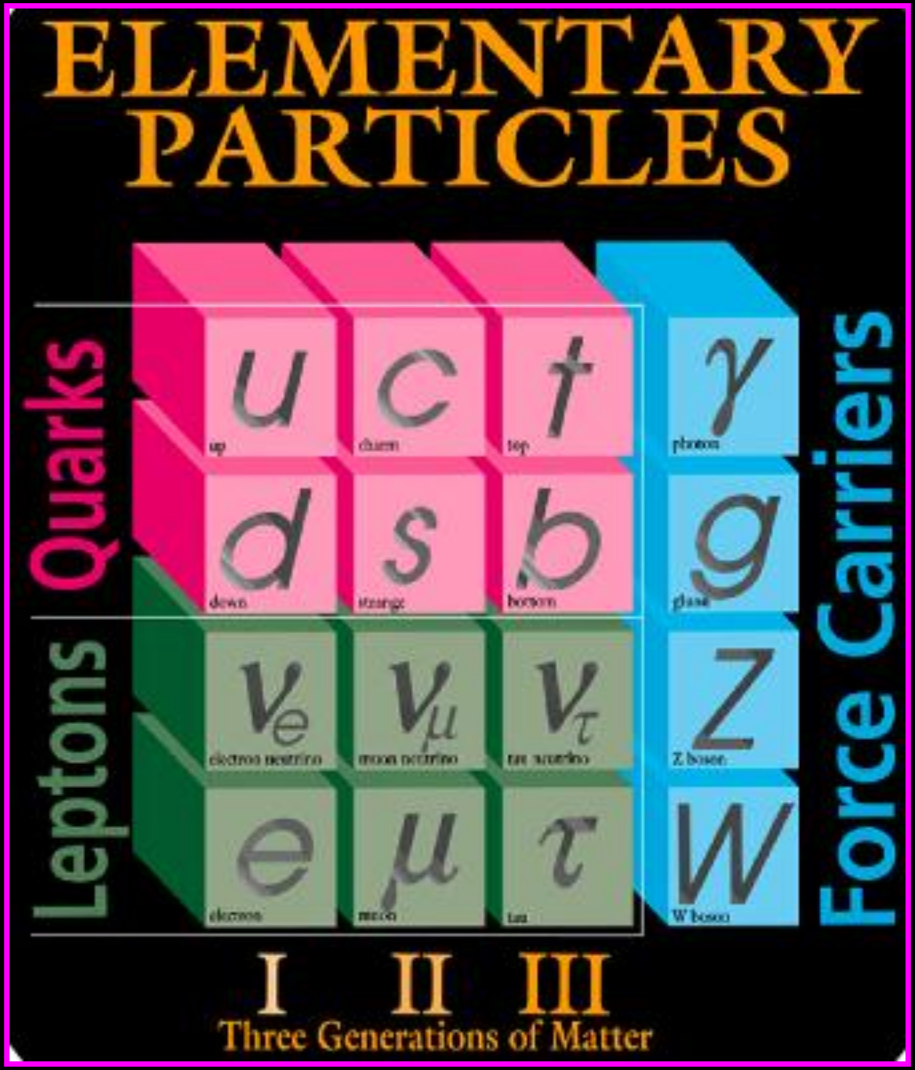
The morals of this story

- Patience is a virtue
  - 26 years between postulation that they exist and experimental confirmation
- Studying neutrinos takes more than one experiment, more than one technique
  - Seeing neutrinos from both reactors and the sun confirmed our understanding
- Answering one question inevitably leads to another
  - Why are only 1/3 of the neutrinos we expect from the sun arriving at the earth?

Neutrinos in the Standard Model

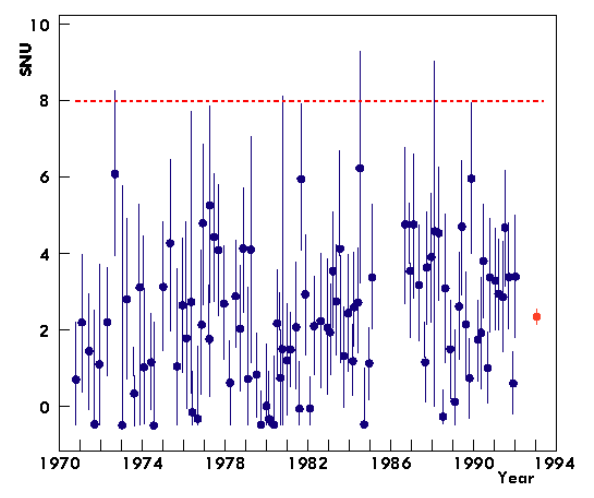
- 3 generations of quarks
- 3 generations of leptons
- 4 fundamental forces
  - Strong
  - Weak
  - Electromagnetic
  - Gravity
- Neutrinos
  - Only feel weak force
  - assumed to have 0 mass
  - Only 3 generations of light neutrinos



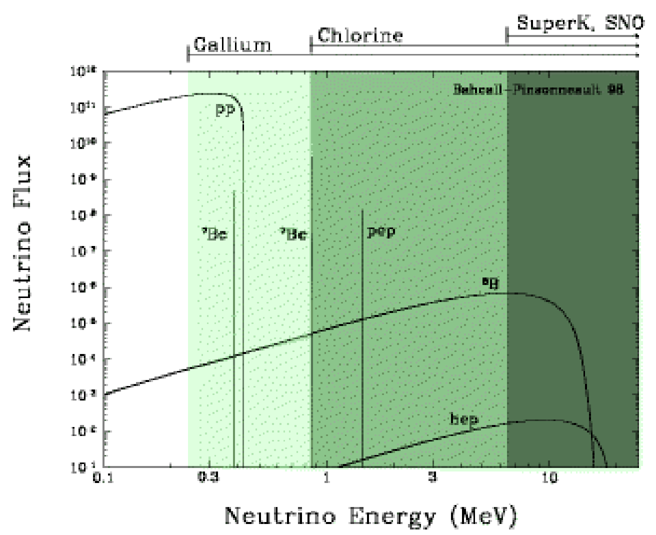


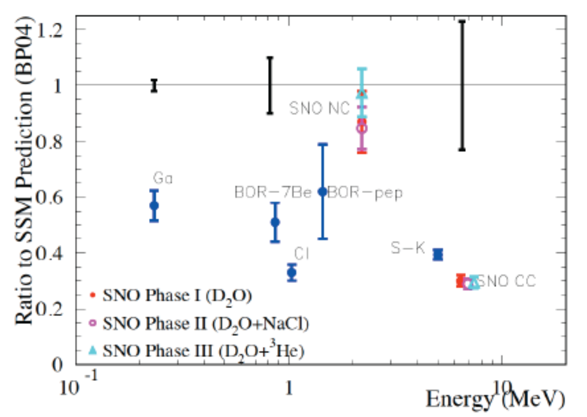
Returning to the sun…

- Over the next 29 years, different experiments tried repeatedly to address this puzzle of seeing the wrong numbers of neutrinos from the sun
- Many different techniques, many different answers
- Much finger pointing…



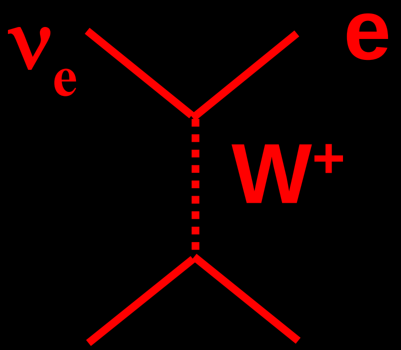
R. Davis, >20 year data plot





Neutrino Interactions

- Neutrinos interact only by the weak force, but there are two avenues: $W^{\pm}$ and Z



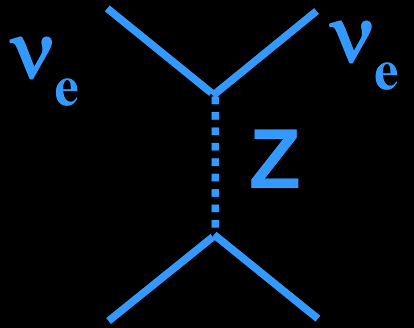
Charged Current

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

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

One generation shown, but all generations proceed this way

Way to see the flavor of the neutrino is by seeing what lepton is produced



Neutral Current

$$\nu_e + n \rightarrow \nu_e + n$$

$$\nu_e + p \rightarrow \nu_e + p$$

$$\nu_e + e \rightarrow \nu_e + e$$

How weak is weak?

– Average distance between interactions: mean free path
  - Probability of interaction/particle
  - Number of particles/kg
  - Number of kg/m^3

atomic mass unit

$$d_{lead} = \frac{1.66\times10^{-27}\text{ kg}}{(\sigma_{x\text{-}N}\text{ m}^2)(11400\text{ kg/m}^3)}$$

ν-N cross-section

density of lead

neutrinos produced in a reactor typically have a few MeV of energy

$$d \approx 1.5 \times 10^{16}\text{ m}$$

neutrinos produced at an accelerator typically have a few GeV of energy

$$d \approx 1.5 \times 10^{12}\text{ m (1.5 billion km!)}$$

What about a proton with a few GeV of energy?

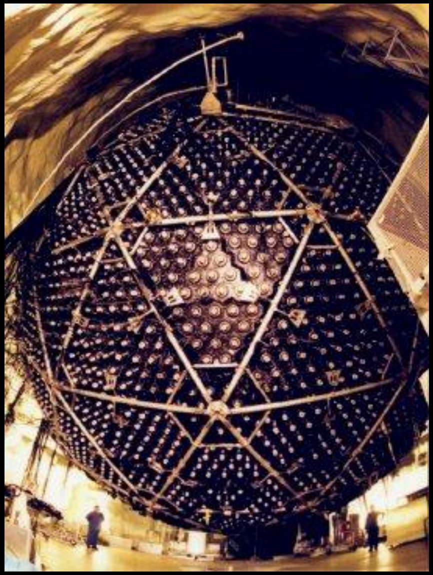
$$d \approx 10\text{cm in lead}$$

Slide courtesy D. Schmitz

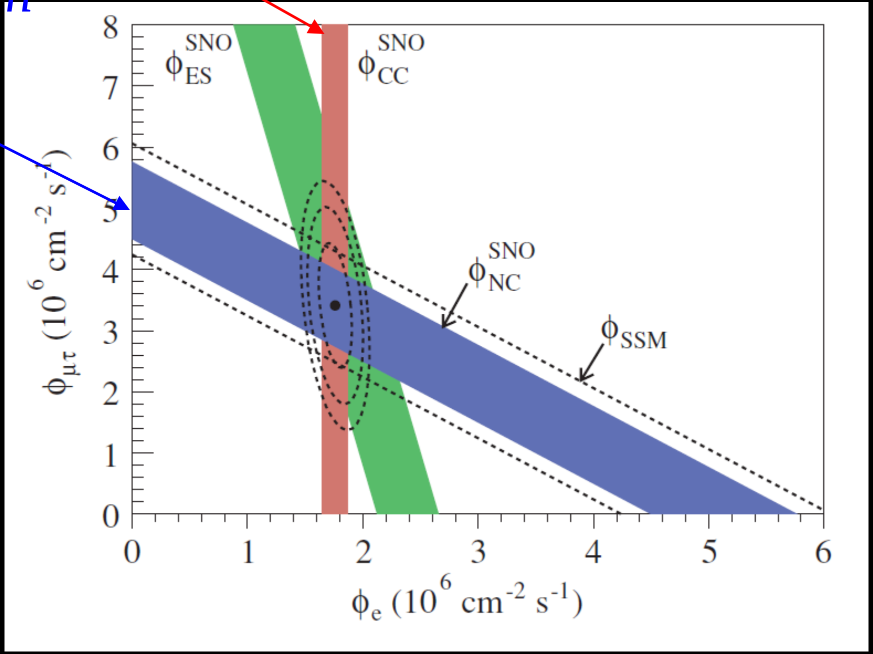
Tamil Nadu’s Support for Neutrino Physics

Dr. B. Lown, Nobel Peace Prize Recipient

Confirmation of Solar Neutrinos changing Flavors



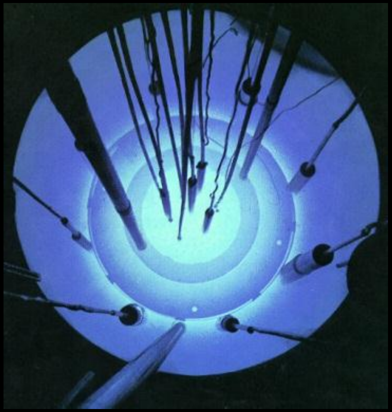
- D_2O target at SNO can uniquely tell ν_e from other neutrinos
  - charged-current $\nu_e d \rightarrow ppe^-$
  - neutral-current $\nu_X d \rightarrow \nu_X pn$
- The former is only observed for ν_e (lepton mass)
- The latter for all types
- Solar flux is consistent with models
  - but not all ν_e at earth



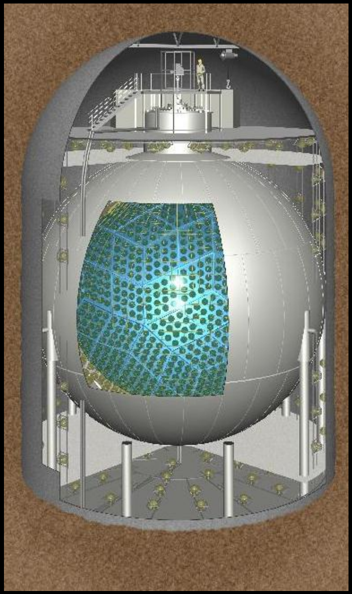
1000 tons of heavy water, 10,000 phototubes

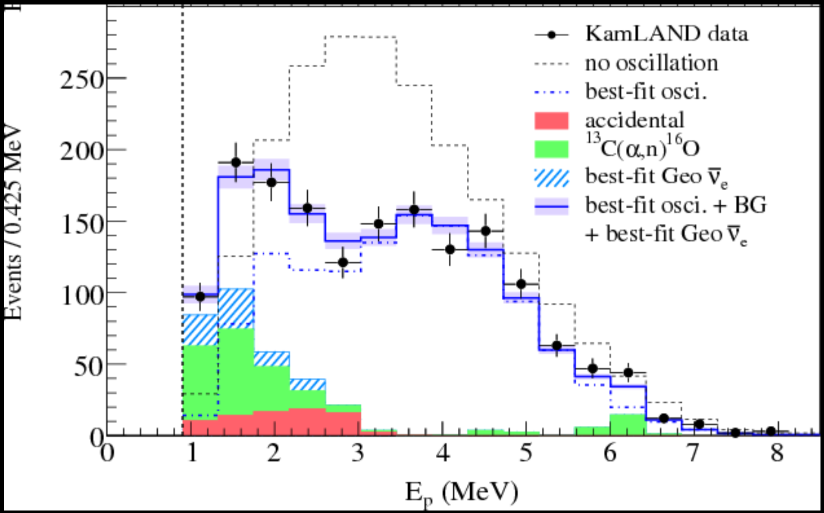
Confirmation of solar neutrino Oscillations

- Coming back to reactors to test the results from the sun
- Kamland Source: Suite of Japanese reactors
  - *150-200 km* for most of flux.
  - *Rate uncertainty ~4%*
  - *Total uncertainty ~6%*
- Kamland Detector:
  - 1 kTon scintillator Detector
  - inverse beta decay
- Kamland confirms oscillatory nature of disappearance



$\bar{\nu}_e$

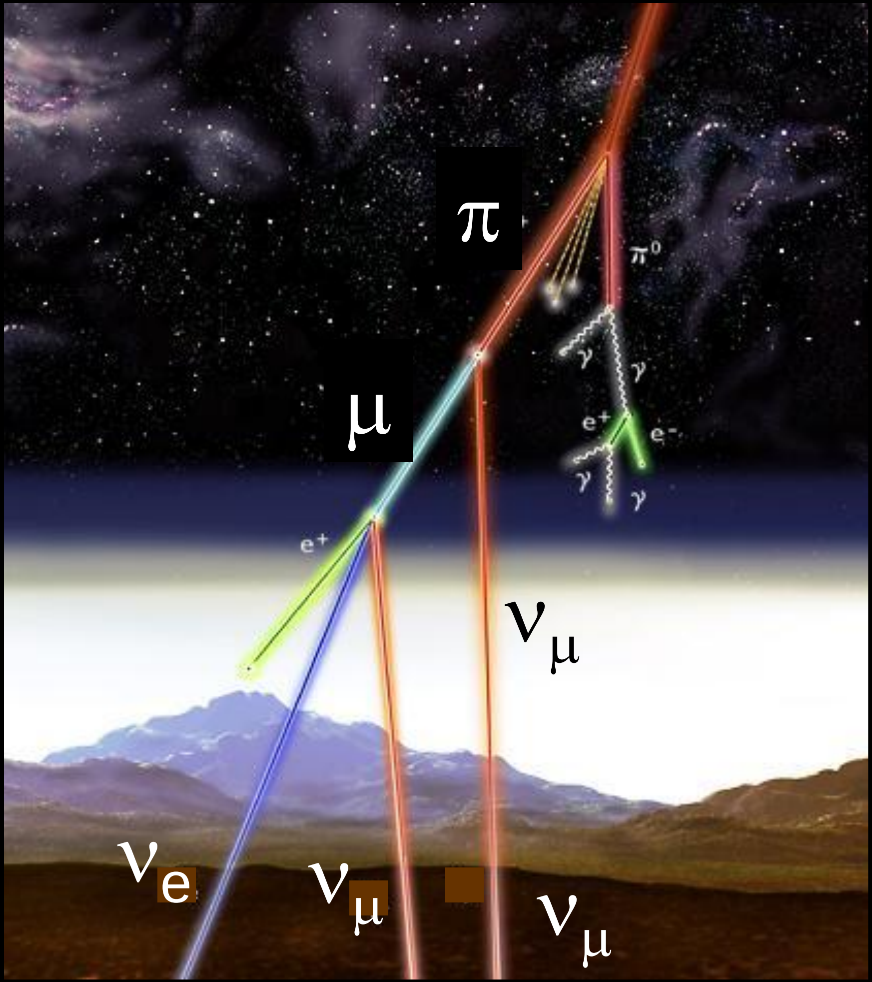




1000 tons of scintillator oil, 2,000 phototubes

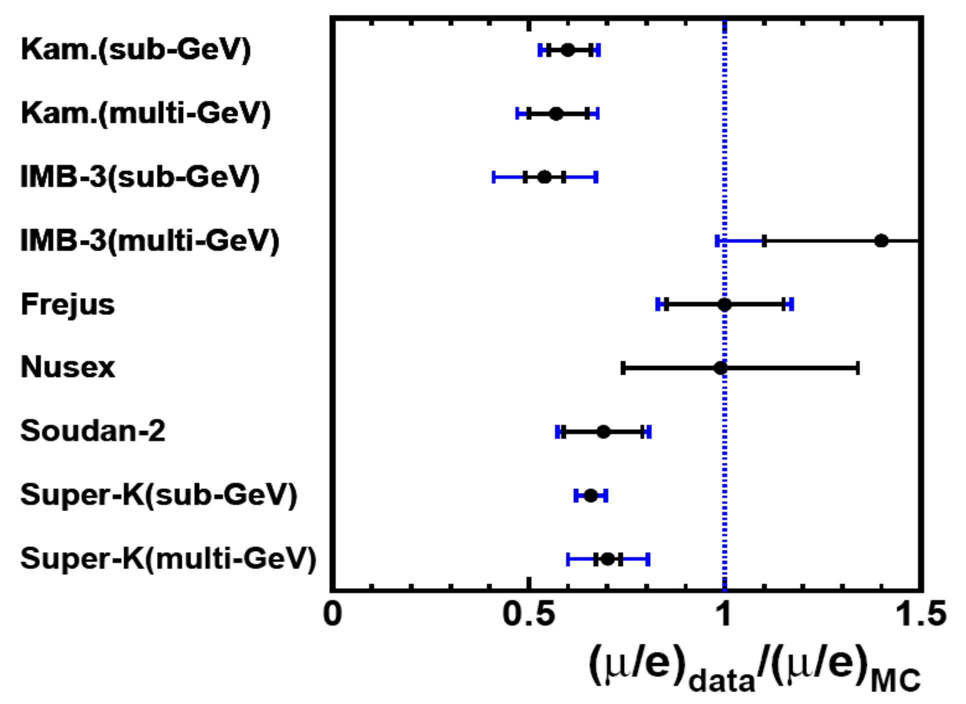
Neutrinos from the Atmosphere

- High energy protons fly through the galaxy, when they hit the Earth’s atmosphere, they make neutrinos
- $\pi \rightarrow \mu + \nu_\mu \quad \mu \rightarrow e + \nu_\mu + \nu_e$
- should reach Earth with ν_μ and ν_e in a 2:1 ratio
- If you can tell the direction the neutrino came from, you can determine how far it travelled, or how long it lived
- Challenge: telling ν_μ from ν_e

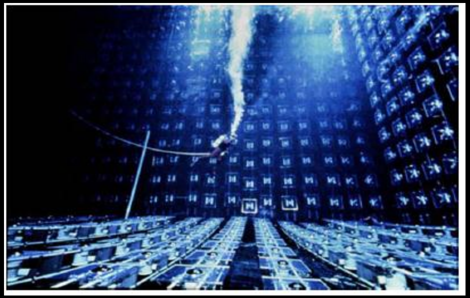


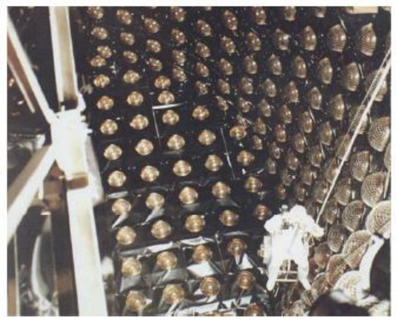
Many techniques, one Measurement

- Atmospheric neutrinos have been seen since 1978
- Deficit of muon-like events compared to electron-like events seen across many decades, many experiments

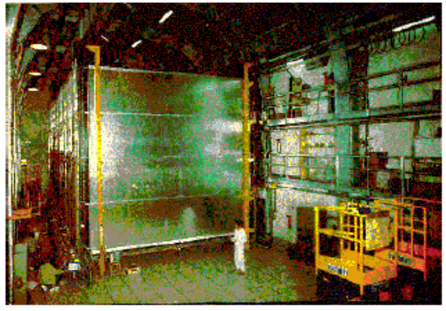


Slide courtesy T.Kajita



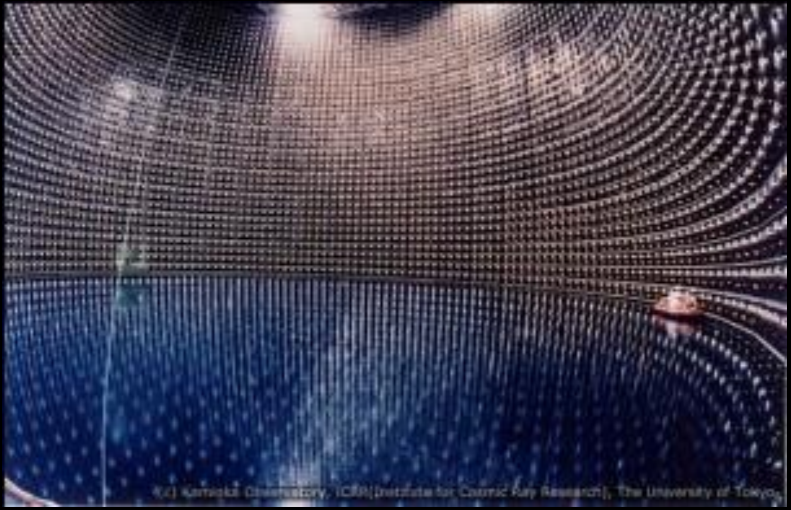


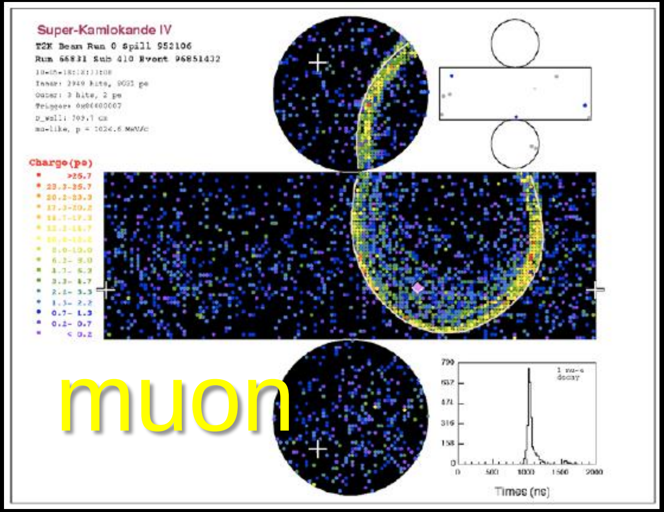
M



Telling ν_μ's from ν_e's…with water

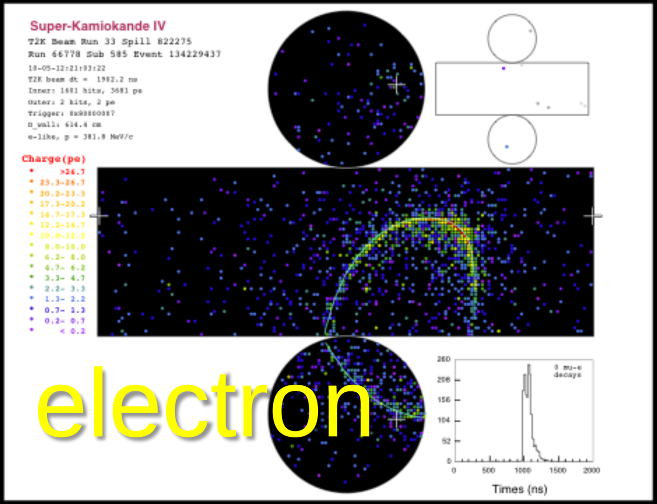
Detector: Super-Kamiokande
Ingredients: 50,000 tons of water, 11,000 phototubes





$$\nu_\mu + n \rightarrow \mu^- + p$$

Kobayashi, Neutrino 2010

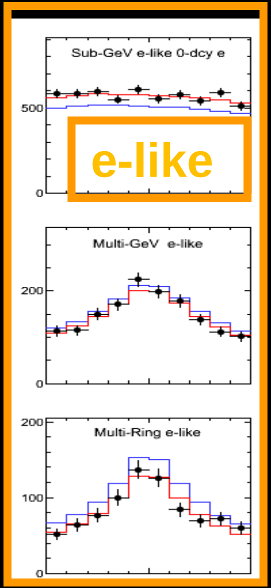


$$\nu_e + n \rightarrow e^- + p$$

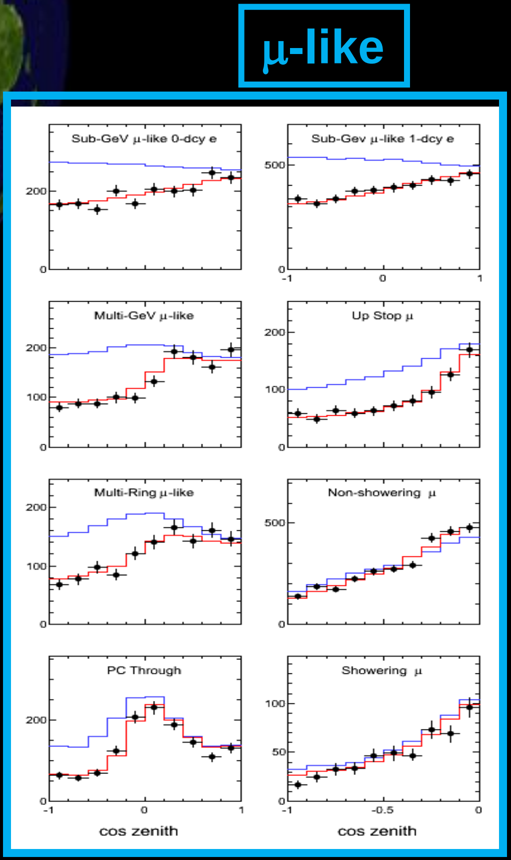
T2K electron candidate
(courtesy C. Walter)

Neutrinos at many distances…

- Measurements of neutrinos from atmosphere:
  - 80 to 10,000km
  - Muon Neutrinos from above don't disappear
  - Muon Neutrinos from below disappear
  - Electron neutrinos don't seem to be disappearing!

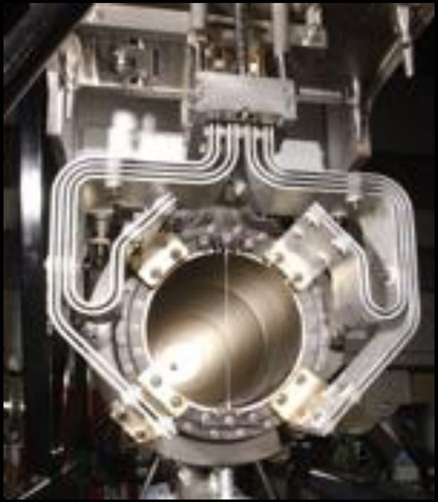


Super-Kamiokande Results Neutrino 2010

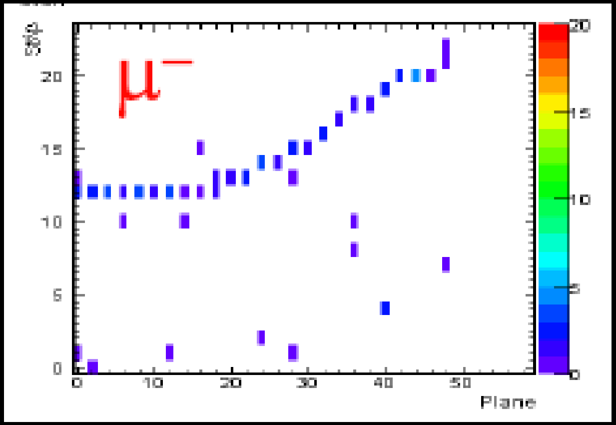


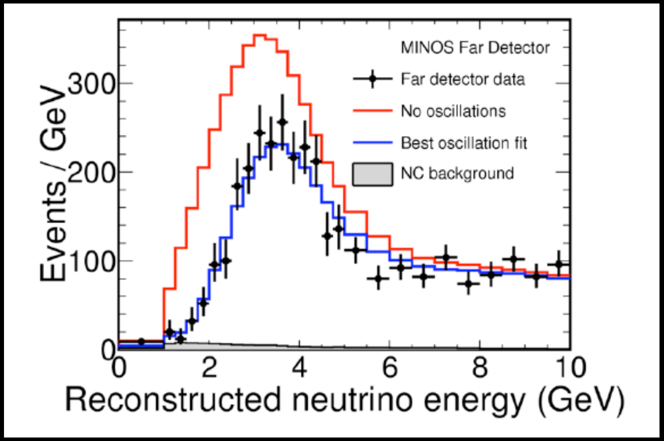
Confirmation of Atmospheric Neutrino Anomaly: ν_μ Disappearance

- Use an accelerator to make a beam
- $p+C \rightarrow \pi^+ \rightarrow \mu^+ \nu_\mu$
- Detector only has to see muons and measure their energy



- K2K in Japan; 250km, first confirmation by accelerator beam
- MINOS in USA: 735km, most precise measure of muon neutrino disappearance
- Near Detectors…





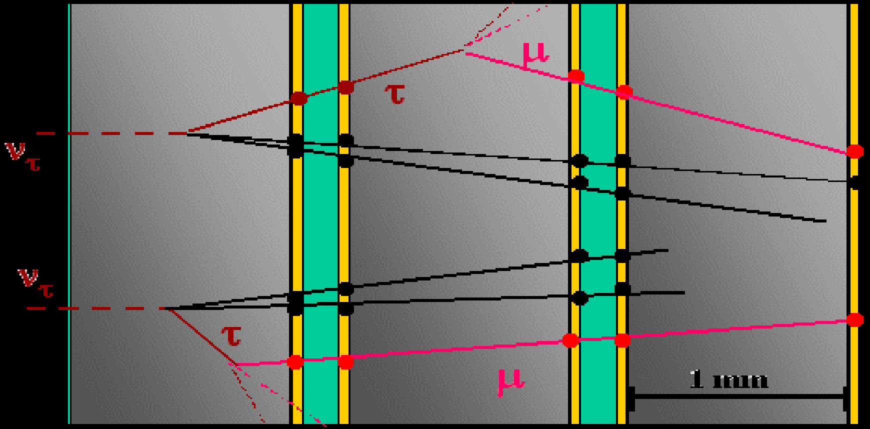
Ingredients: 5,400 tons of steel, 1500 PMT's

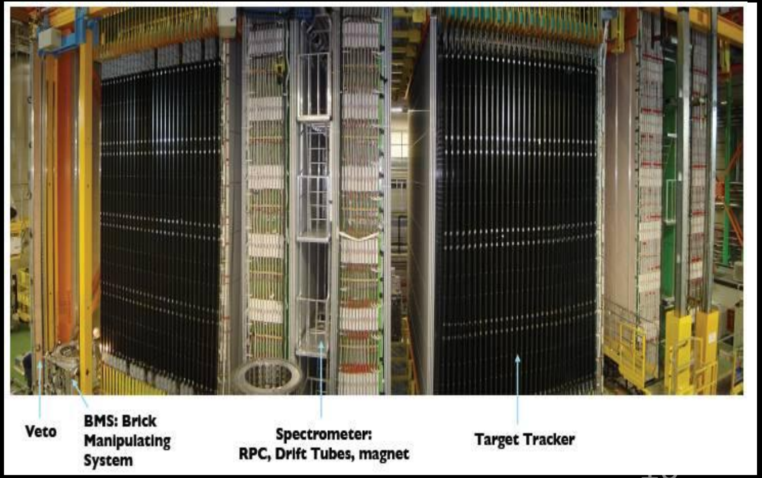
J. Thomas, Lepton Photon 2011

Confirmation using ν_τ appearance

- OPERA experiment: designed to see ν_τ appearance in a ν_μ beam
- Beam produced at CERN
  - Mean energy is 25GeV
- Detector placed 732km away under Gran Sasso mountain in Italy
  - Very fine-grained photo of the way neutrinos interact
- Very challenging measurement
  - τ lepton is very heavy, so need high energy ν to produce τ
  - The higher the neutrino energy, the less time it has to change flavor
  - Seeing a τ decay is also very challenging,
  - $c\tau$ for a tau lepton is 90 microns!

Ingredients: 1,800 tons of emulsion in 150,000 bricks of lead/emulsion sandwhiches





Sometimes one event is enough…

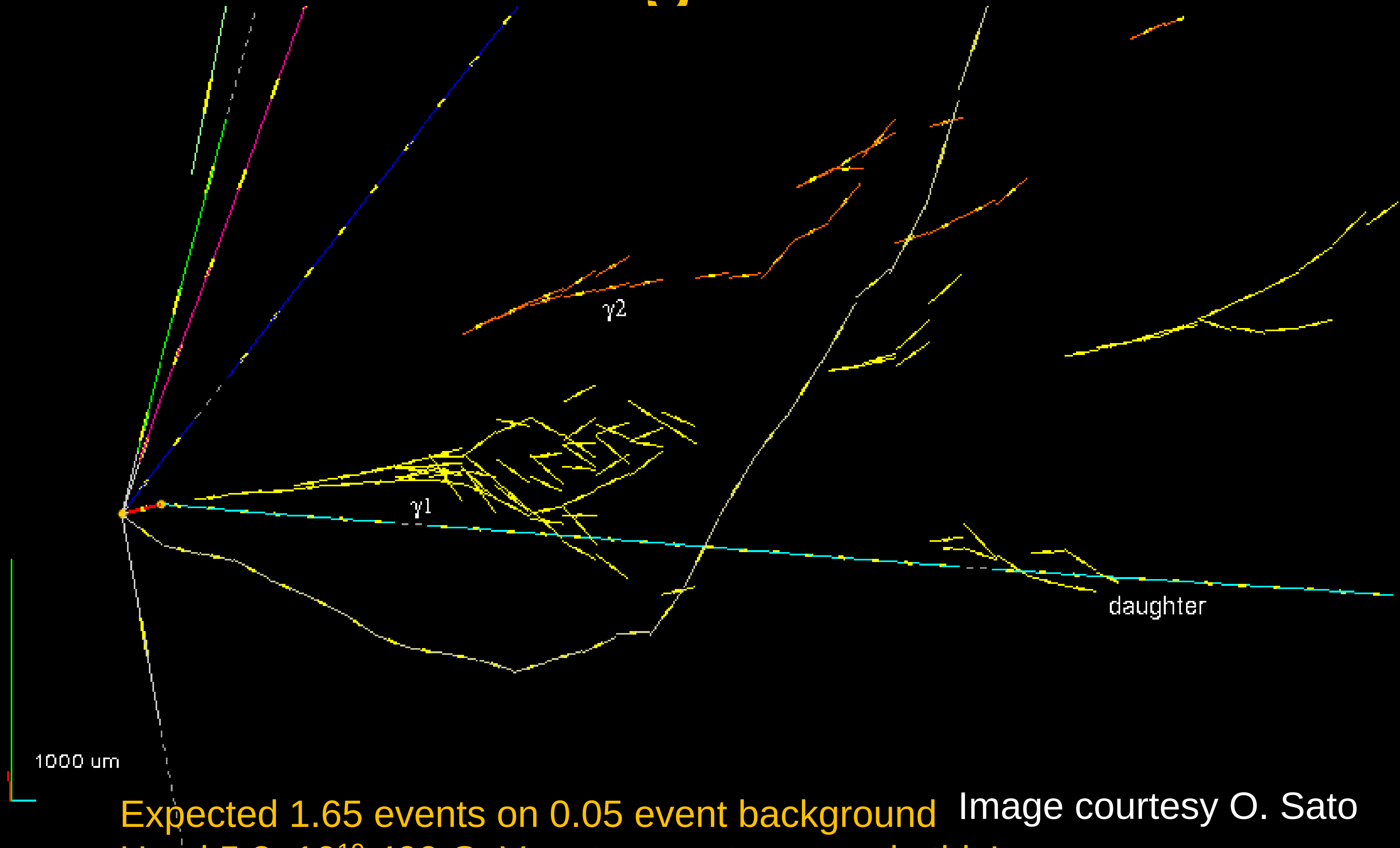


Image courtesy O. Sato

Expected 1.65 events on 0.05 event background
Used 5.3×10^{19} 400 GeV protons on target to do this!

The morals of this story

- Patience is a virtue
  - 26 years between Ray Davis’s first paper and “smoking gun” evidence from SNO
  - 20 years between first atmospheric neutrino deficit and up/down asymmetry from Super-K, 30 to see OPERA ν_τ
- Studying neutrinos takes more than one experiment, more than one technique
  - Studied with atmospheric and accelerator-made neutrinos
  - Studied with appearance and disappearance
  - Most precise measurement of the phenomena may not be the first technique that sees the effect
- Answering one question inevitably leads to another
  - Okay, neutrinos oscillate, but how different is this from quarks?
  - OPERA’s Neutrino velocity measurement—how can this be?

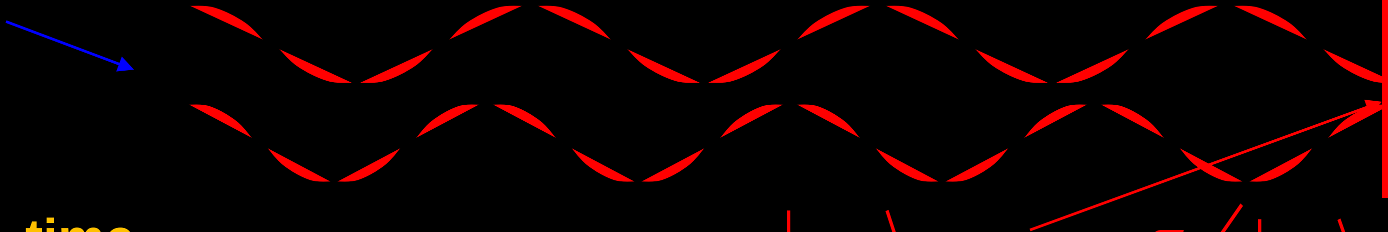
Minimal Oscillation Formalism

- If neutrino mass eigenstates: ν_1, ν_2, ν_3, etc.
- … are not flavor eigenstates: ν_e, ν_μ, ν_τ
- … then one has, e.g.,

$$\begin{pmatrix}\nu_\alpha\\ \nu_\beta\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_i\\ \nu_j\end{pmatrix}$$

take only two generations for now!

$$|\nu_\alpha\rangle = \cos {}^{\pi}\!/_{4}\,|\nu_i\rangle + \sin {}^{\pi}\!/_{4}\,|\nu_j\rangle$$



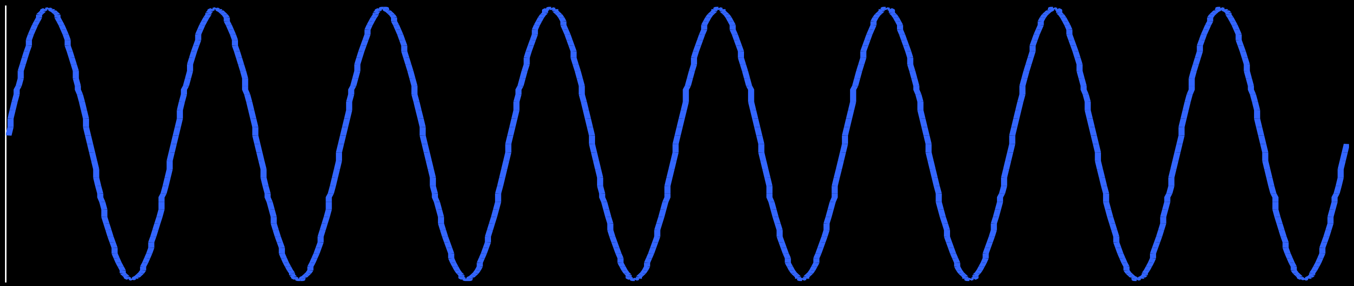
different masses alter time evolution

time →

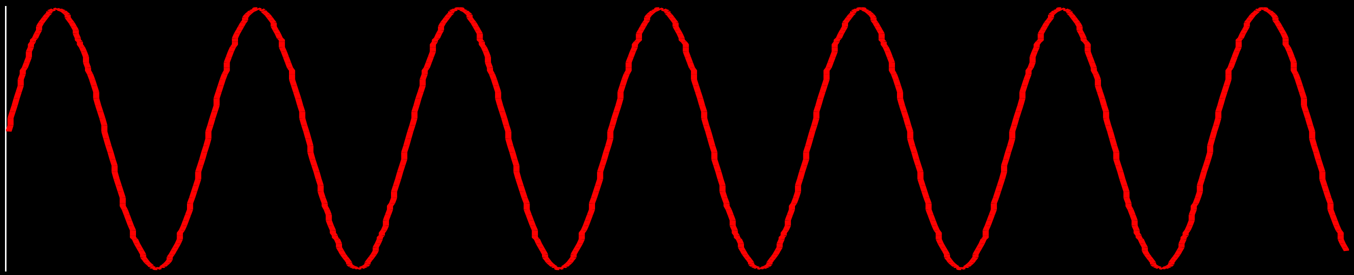
$$|\nu_\beta\rangle = -\sin {}^{\pi}\!/_{4}\,|\nu_i\rangle + \cos {}^{\pi}\!/_{4}\,|\nu_j\rangle$$

Slide courtesy K. McFarland

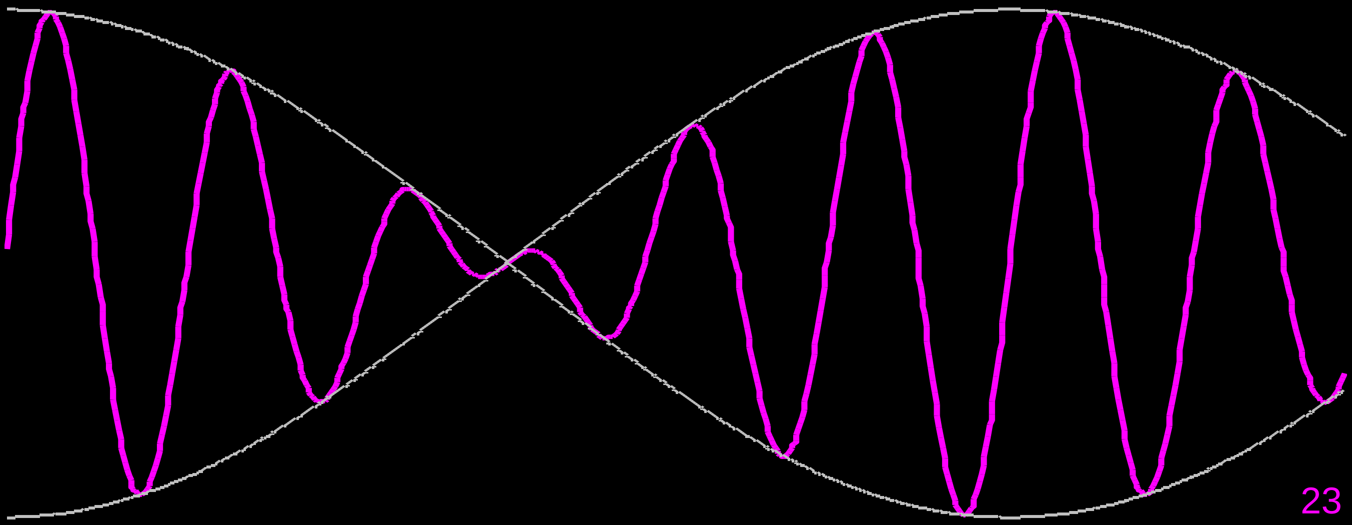
Acoustic Analogy (for musicians…)



wave 1

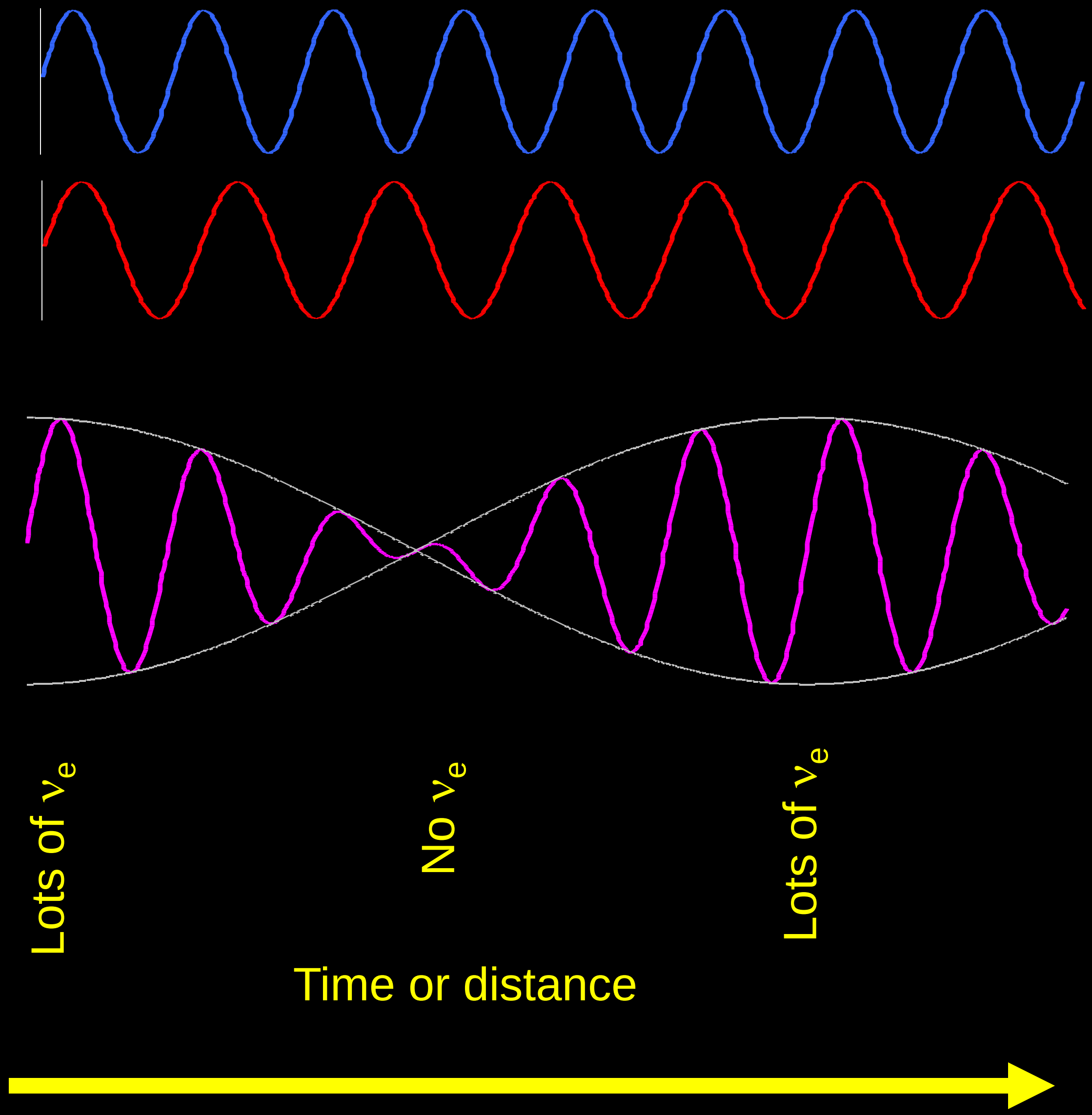


wave 2



wave 1
+ wave 2

Neutrino Oscillations



If neutrinos are waves of slightly different frequencies:

Over time, they disappear and reappear

The bigger the frequency difference, the faster the disappearance

Particles are like waves particle mass determines its frequency

Measuring neutrinos oscillating:
Measuring mass differences

If one kind of neutrino disappears, another kind must appear

Oscillation Formalism (cont’d)

- So, still for two flavors…

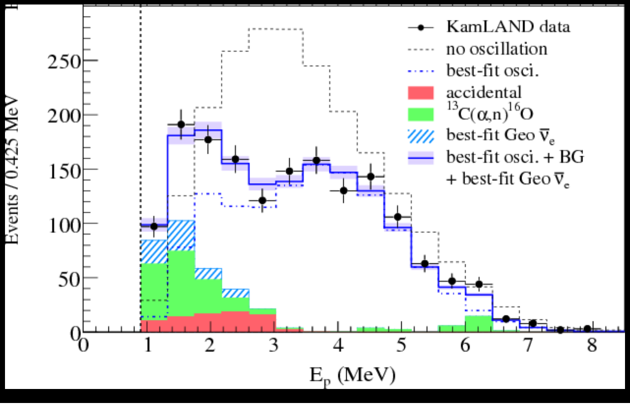
$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta \sin^2\left(\frac{(m_2^2 - m_1^2)L}{4E}\right)$$

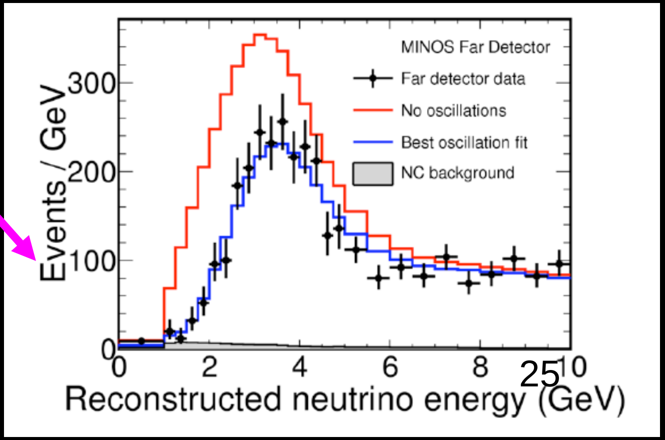
Experimental Details:

L: Baseline

E: Neutrino Energy

- Oscillations require mass differences
- Oscillation parameters are mass-squared differences, Δm^2, and mixing angles, θ.
- But remember the signals:
  - Kamland: 3MeV neutrinos, 180km
  - MINOS: 3000MeV neutrinos, 735km
- There must be more than two mass eigenstates…





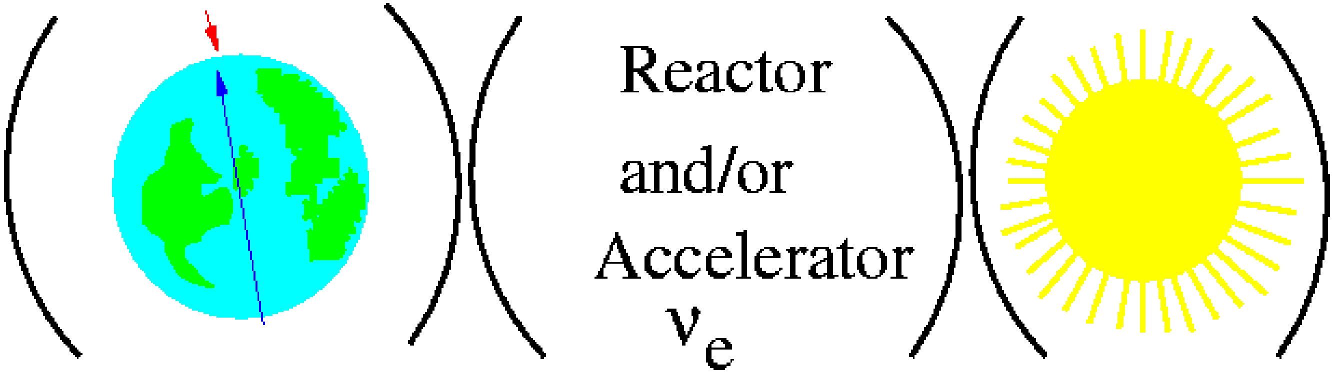
Three Generation Mixing

Lesson learned from studying quarks:
3x3 Unitary matrix is defined by 3 mixing angles and one phase

Call them $\theta_{12}, \theta_{23}, \theta_{13}, \delta$ if $s_{ij} = \sin\theta_{ij}, c_{ij} = \cos\theta_{ij}$, then

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

U=



- Note the new mixing in middle, and the phase, δ

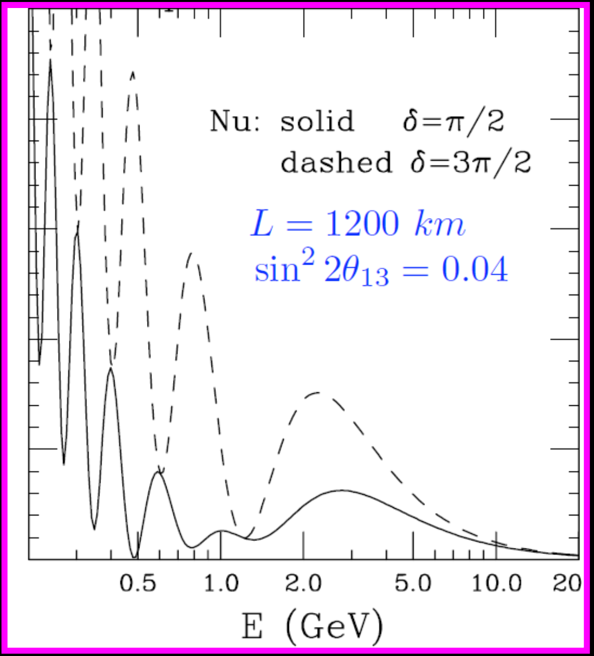
3-generation $\nu_\mu \rightarrow \nu_e$ Probabilities

$$P_{\mu\to e} \approx \left| \sqrt{P_{atm}}\, e^{-i(\Delta_{32} \underset{\updownarrow}{\pm\delta})} + \sqrt{P_{sol}} \right|^2$$

where $\sqrt{P_{atm}} = \sin\theta_{23}\sin 2\theta_{13}\ \sin\Delta_{31}$

and $\sqrt{P_{sol}} = \cos\theta_{23}\sin 2\theta_{12}\ \sin\Delta_{21}$

$$\Delta_{ij} = \delta m^2_{ij} L/4E$$



S. Parke, INSS 2009

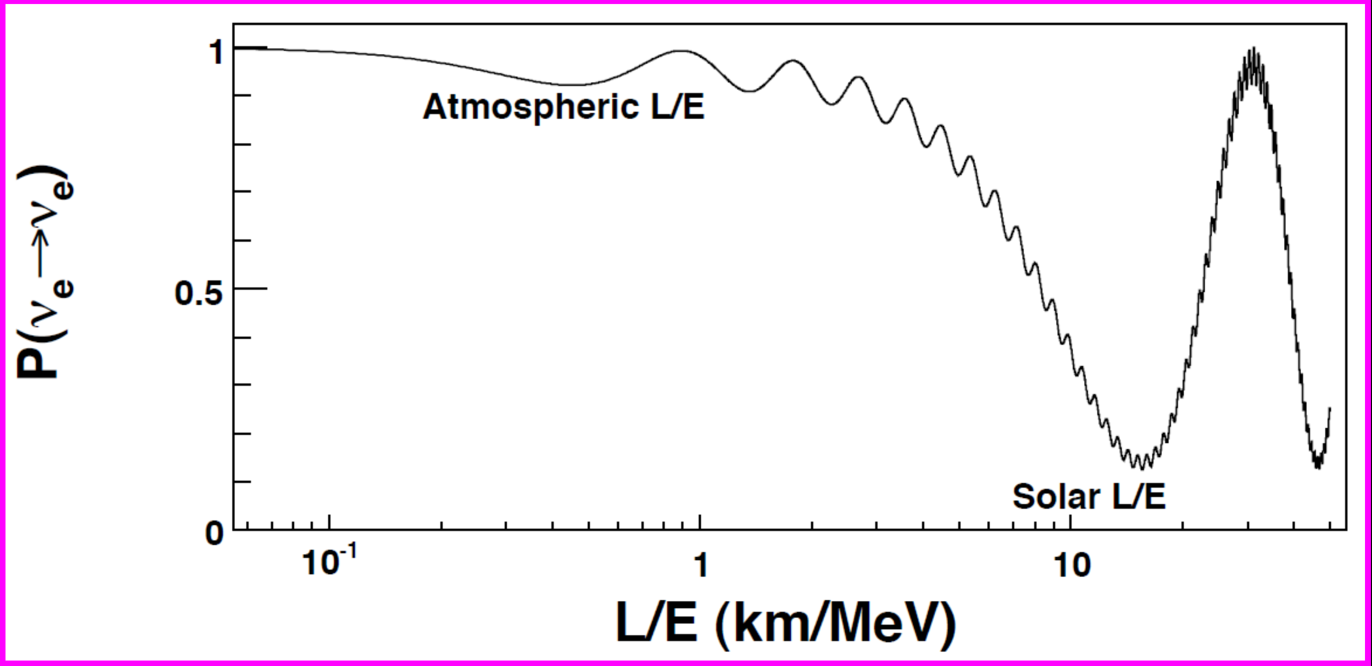
- Much more complicated than 2-generation mixing
- Interference between atmospheric and solar terms is where CP violation arises
- Size of that interference is function of all angles, including θ_{13}

3 Generation ν_e Disappearance Probabilities

- Electron neutrino example:

$$\Delta_{ij} \equiv \frac{\delta m^2_{ij} L}{4E}$$

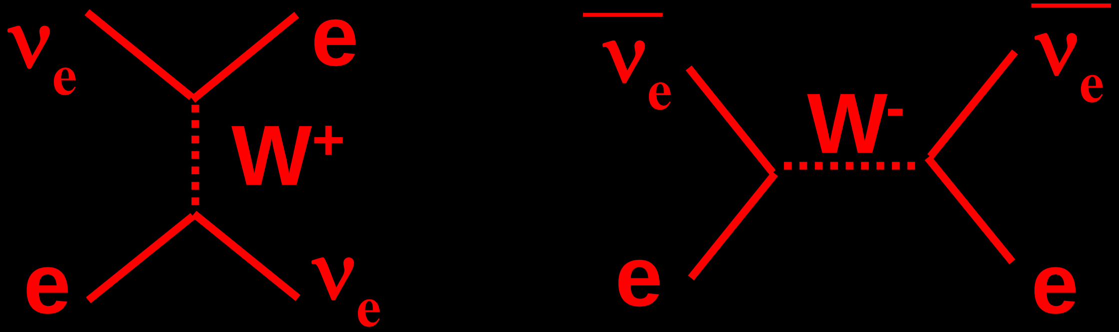
$$\begin{aligned} P(\bar\nu_e \to \bar\nu_e) \quad &= \quad 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} \\ &\quad - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) \end{aligned}$$



S. Parke, INSS 2009

What about neutrinos passing through the earth?

- Electrons in the earth act on ν_e and $\overline{\nu_e}$'s differently from eachother, and from ν_μ or ν_τ



Wolfenstein, PRD (1978)

- For 2 generations…

$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta \sin^2\left(\frac{(m_2^2 - m_1^2)L}{4E}\right)$$

$$\sin^2 2\Theta_M = \frac{\sin^2 2\Theta}{\sin^2 2\Theta + (\pm x - \cos 2\Theta)^2}$$

$$x = \frac{2\sqrt{2}G_F n_e E_\upsilon}{\Delta m^2}$$

$n =$ e$^-$ density

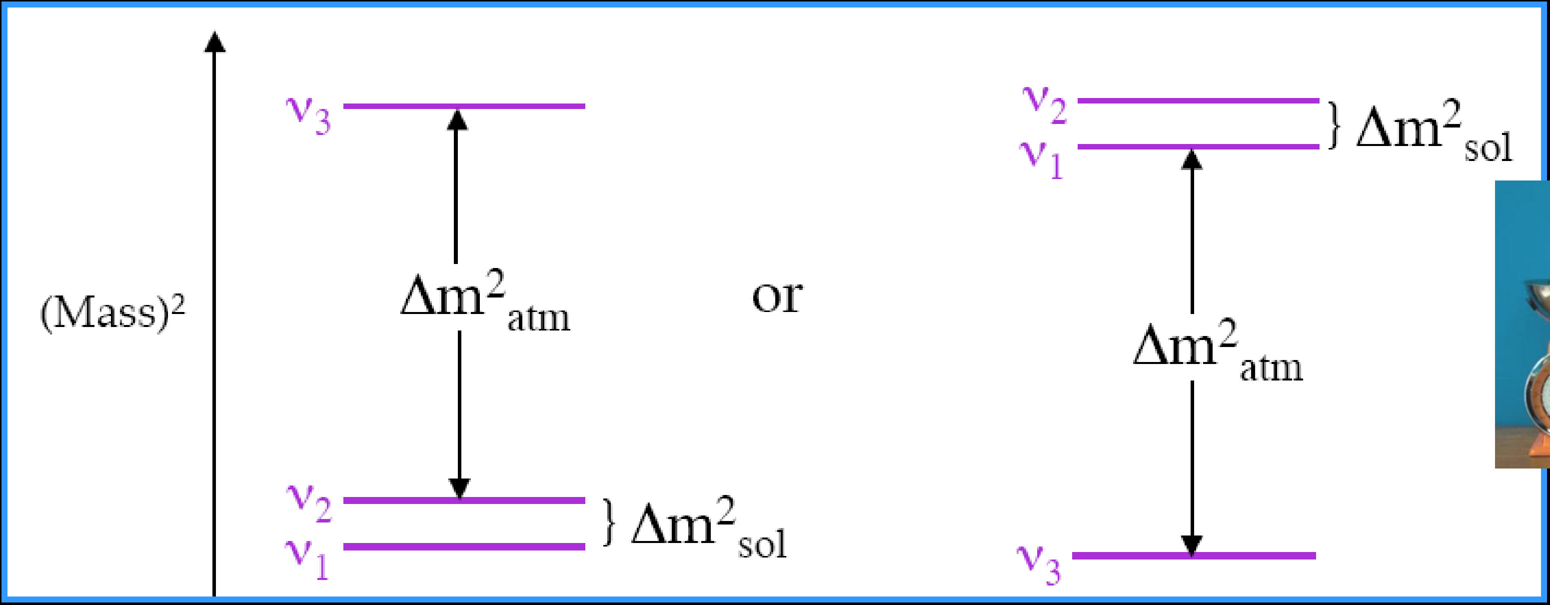
$$L_M = L \times \sqrt{\sin^2 2\Theta + (\pm x - \cos 2\Theta)^2}$$

Bad news: this complicates trying to see CP violation,
good news: it means you can measure the mass hierarchy

What don’t we know yet?

- Do Neutrinos and Anti-neutrinos change the same way?
  - We know there’s lots of matter in the universe, no antimatter
  - We know quark sector CP violation is very small
- Do neutrino mass states have the same mass structure as the quark mass states?

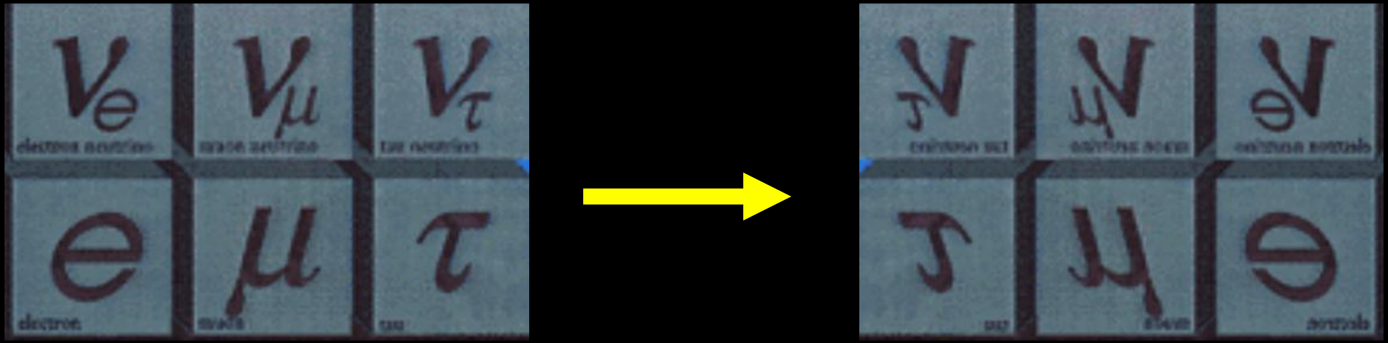
figures courtesy B. Kayser



$\Delta m_{sol}^2 \rightarrow \delta m_{12}^2 \approx 8\text{x}10^{-5}\text{eV}^2$ $\Delta m_{atm}^2 \rightarrow \delta m_{23}^2 \approx 2.5\text{x}10^{-3}\text{eV}^2$

Why is CP violation so important?

- Every fundamental particle has an anti-matter partner



- When they meet, they annihilate into pure energy
- Alternatively, energy can become matter plus anti-matter

Slide courtesy K. McFarland

So you might ask…

- The early Universe had a lot of energy. Where is the anti-matter in the Universe?
- Good question… how do we know it isn't around today?
  - look for annihilations.
  - As far away as we can tell, today there aren't big matter and anti-matter collisions

  - Maybe it's the neutrinos which are different from anti-neutrinos!

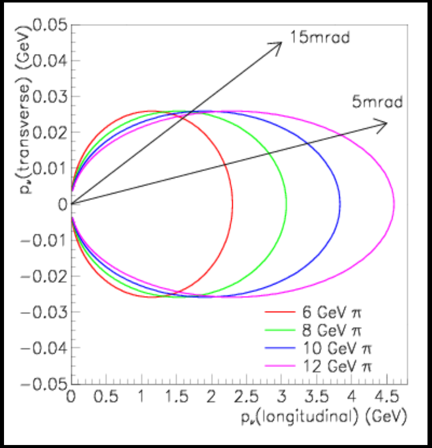
Slide courtesy K. McFarland

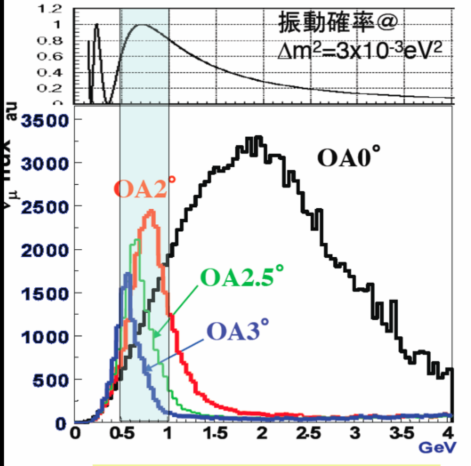
2011: Answering the new questions

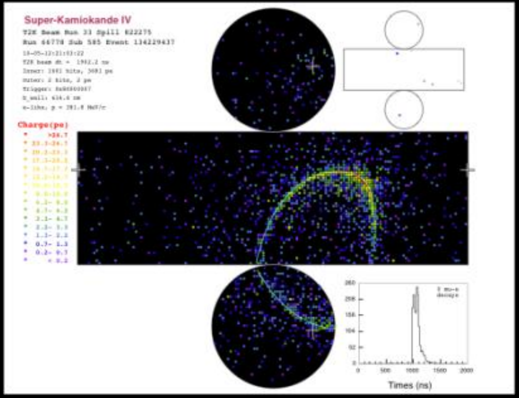
- 2011: Need to see if the last mixing angle θ_{13} is above 0
  - Precision Reactor experiments at 2km, not 180km
    - Larger mass splitting meanst a shorter distance
    - Small disappearance rate means need a near detector
    - Double CHOOZ, Daya Bay, RENO all taking data
  - Electron neutrino appearance in muon neutrino beam at 150km/1GeV
    - MINOS and T2K operating in 2011, NOvA under consstruction
- 2016 and beyond:
  - Want to start seeing neutrino and antineutrino transitions
- Ultimate Precision: compare neutrino and antineutrino oscillation probabilities precisely, over long distances
  - LBNE, T2KK, INO

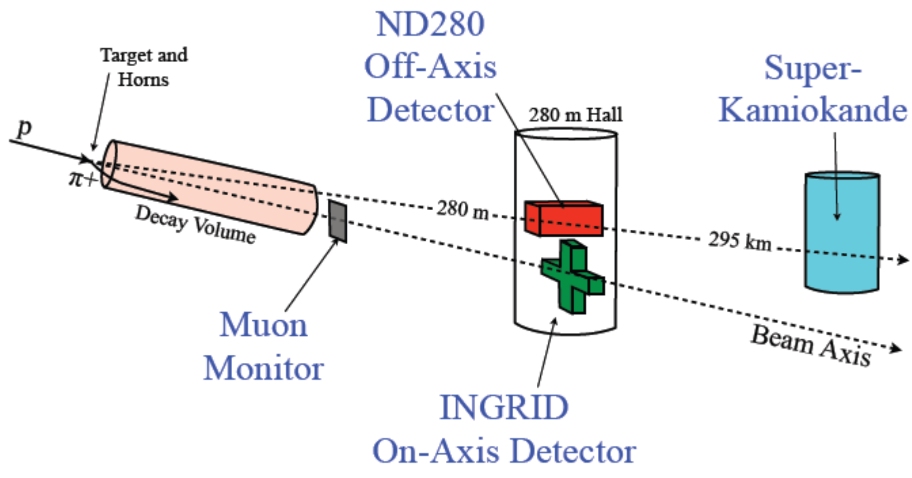
2011: First Signal for Last Mixing Angle

- T2K experiment:
  - Use accelerator, target, and horn, but aim 2 degrees off from Super-Kamiokande detector
  - Resulting neutrino beam means a test at one energy, one distance, very low backgrounds
  - Precise Near Detector suite to predict backgrounds





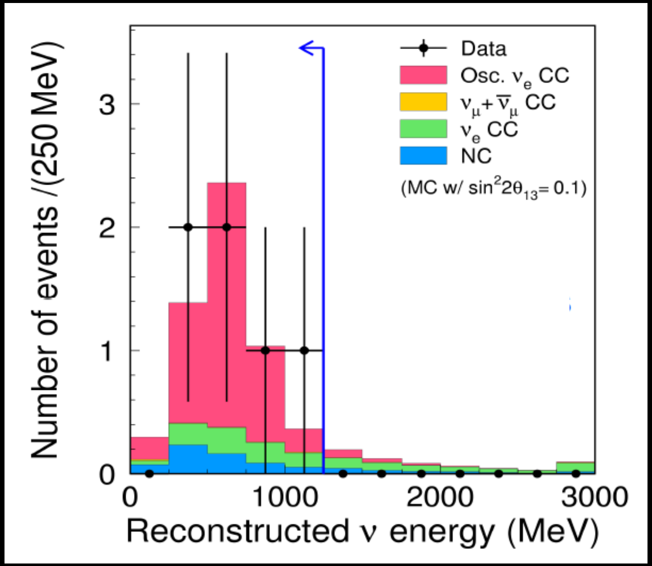


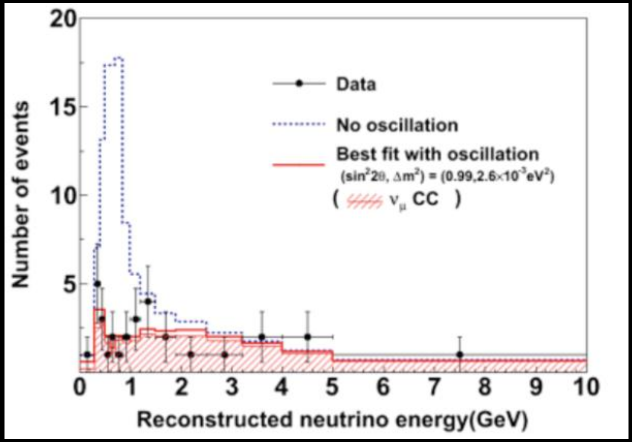


Figures: H.A. Tanaka, Lepton Photon 2011

2011: T2K Results

- June 2011: T2K announces results from pre-earthquake data set
- 6 ν_e events seen, background prediction of 1.5 events
- 2.5 sigma "indication" of $\nu_\mu \rightarrow \nu_e$ oscillations at smaller mass splitting
- Also see muon neutrino disappearance at expected rates, shows power of the off-axis technique
- Prospects: expect to resume run by end of this month!

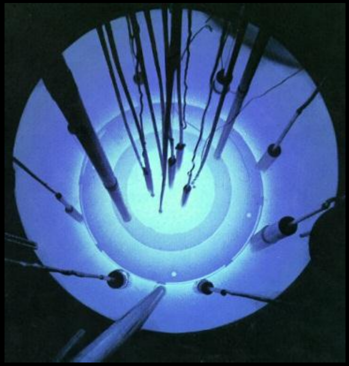




Figures: H.A. Tanaka, Lepton Photon 2011

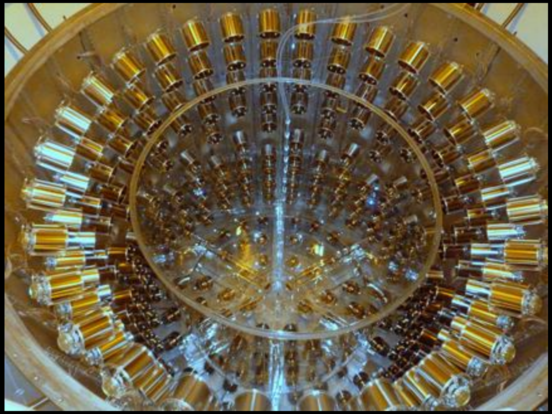
Search for ν_e disappearance…

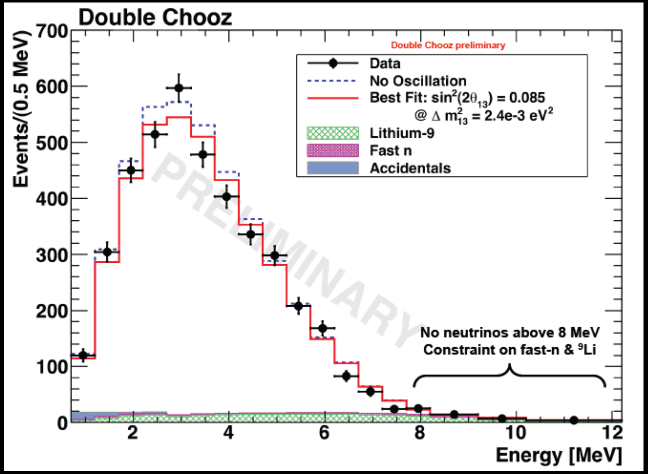
- Double Chooz Reactor Experiment:
  - started taking data with reactor and one far (2km) detector
  - Signal: inverse beta decay, liquid scintillator
  - 4121 events seen, statistical precision already <2%
  - Future most precise measurements will come with two detectors, one near one far



$\xrightarrow{\quad}$

$\bar{\nu}_e$





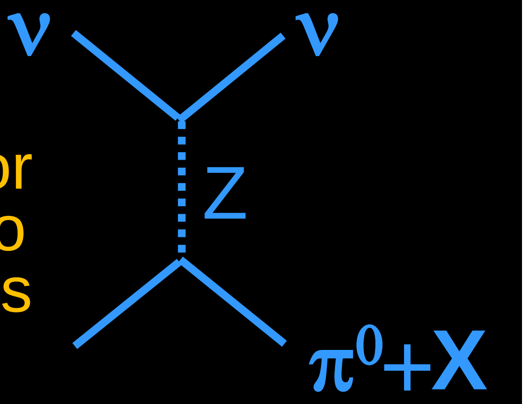
Ref: Th. Lasserre, et al, Saclay Seminar 9 Nov. 2011

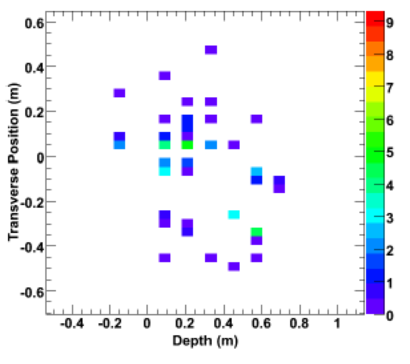
Rate and shape: no oscillation excluded at 92.9%

10 tons of Gd-doped scintillator, 100 ton mineral oil buffer, 390 PMT's per detector

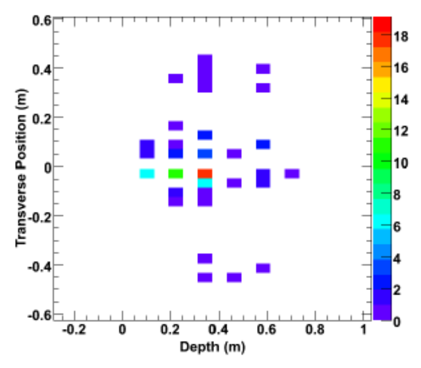
Independent ν_e appearance search

- MINOS: detector optimized for ν_μ, not ν_e, so backgrounds are much higher



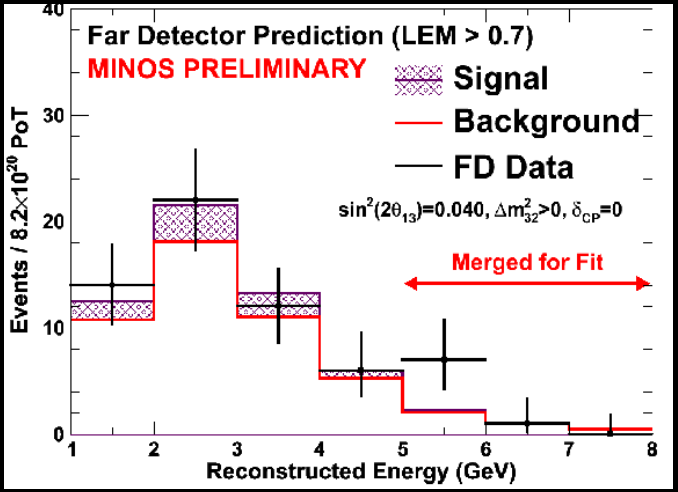


(NC background)



(signal)

- MINOS has most of the data set already in hand, statistical precision at limit
  - 62 events seen, expect 49.5 events
  - 11% likely to be fluctuation if $\theta_{13}=0$

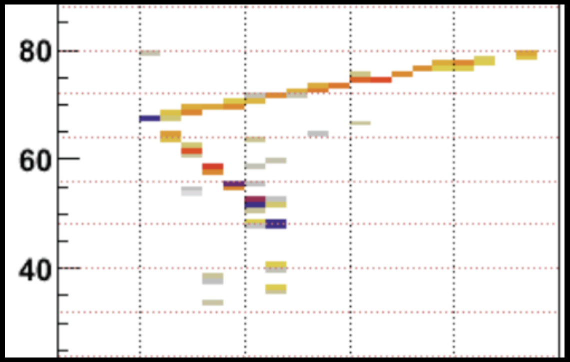


Ref: L. Whitehead, Fermilab Seminar June 24 2011

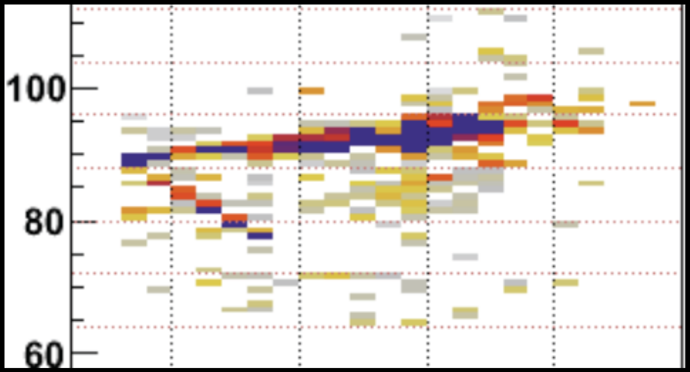
What else should we learn from Neutrinos

- MINERvA:
  - See how different nuclei affect how neutrinos interact
  - Will help next generation of oscillation experiments
  - How many photons can neutrinos make?
  - Need many more pixels per neutrino event…

8 tons solid scintillator, 32,000 PMT channels



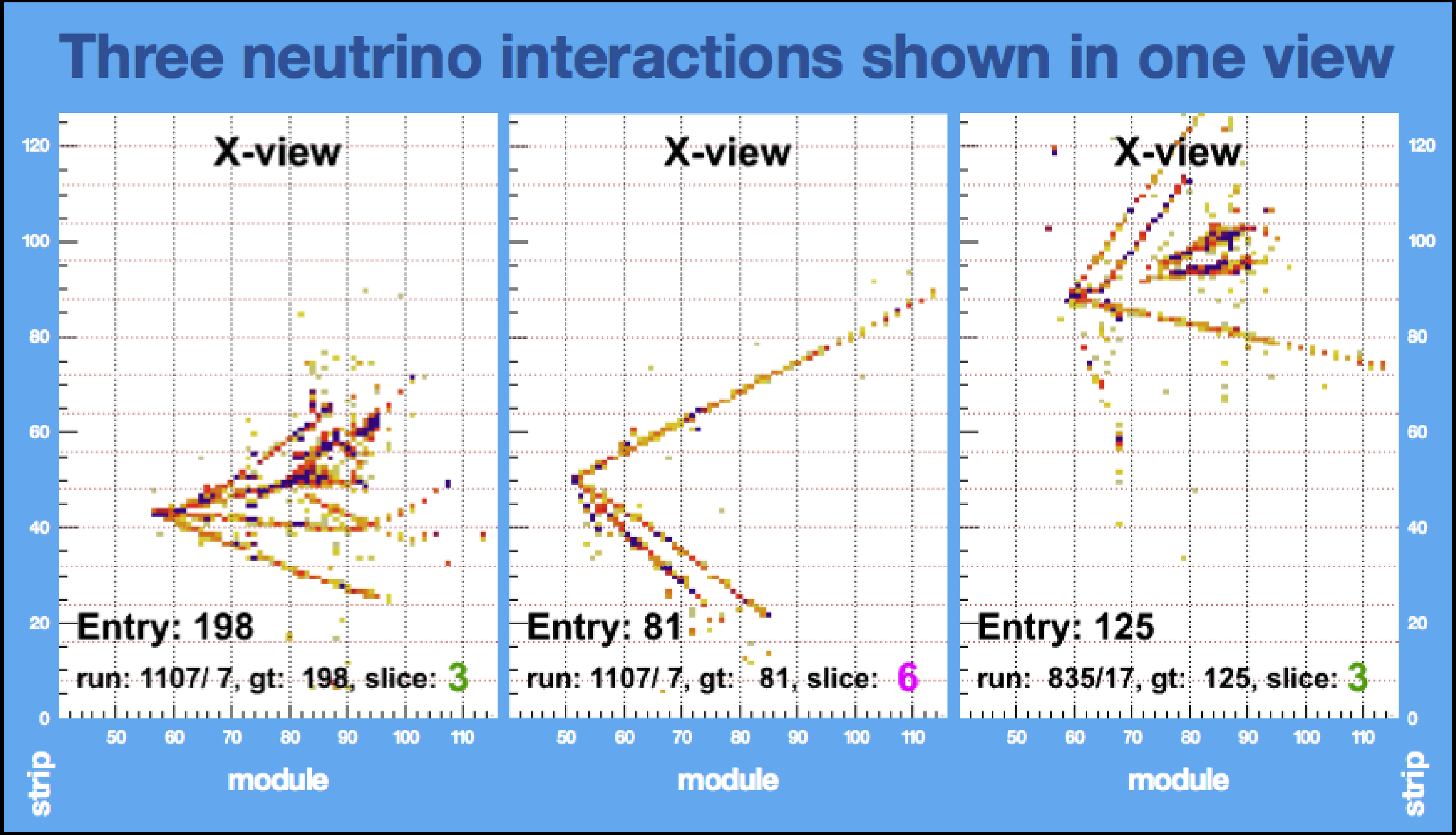
$\nu_{\mu +}$ n$\rightarrow$p+μ Candidate



ν_{e+} n$\rightarrow$p+e Candidate

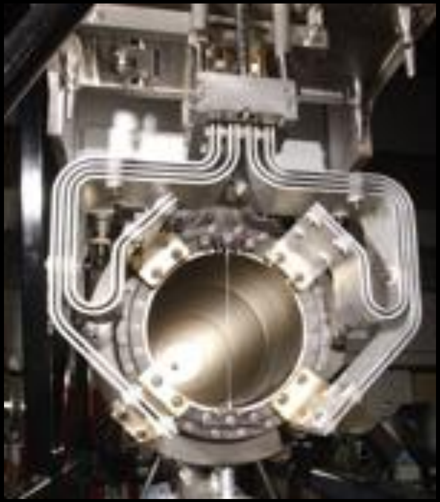
What else happens when neutrinos hit nuclei?

- Wide variety of particles can emerge, just ask MINERvA

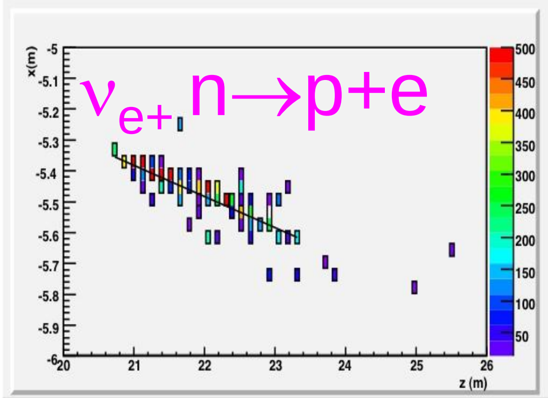


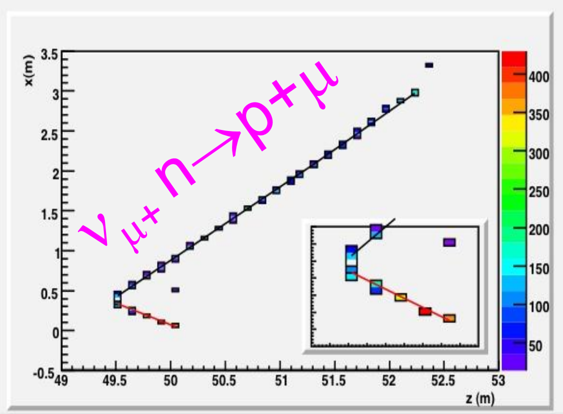
Next ν_e Appearance Experiment: NOvA

- NOvA: use narrow energy beam of muon neutrinos (already in use by MINERvA and MINOS)
- Place detector off axis, 810km away
- 15kton segmented liquid scintillator detector, segmented into 385,000 volumes
- Run to start in 2013, expect to take both neutrino and anti-neutrino data



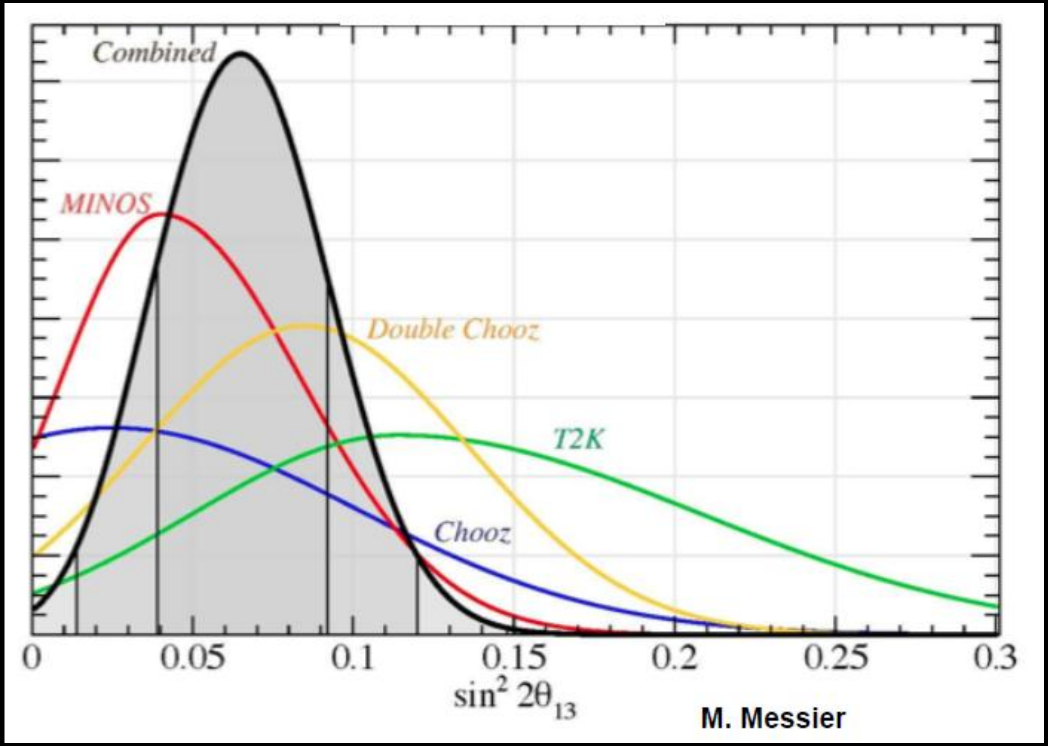
Differences from T2K:
3x higher energy
2.5x higher distance
Very different detector
Different “near detector” strategy





Summarizing 2011 Highlights

- T2K has seen evidence that θ_{13} is not too small
- MINOS and Double Chooz have seen evidence that θ_{13} is not too large
- More opportunities:
  - Double Chooz to add near detector
  - Daya Bay and RENO reactor experiments taking data now
  - T2K to resume running by 2012
  - NOvA to start in 2013

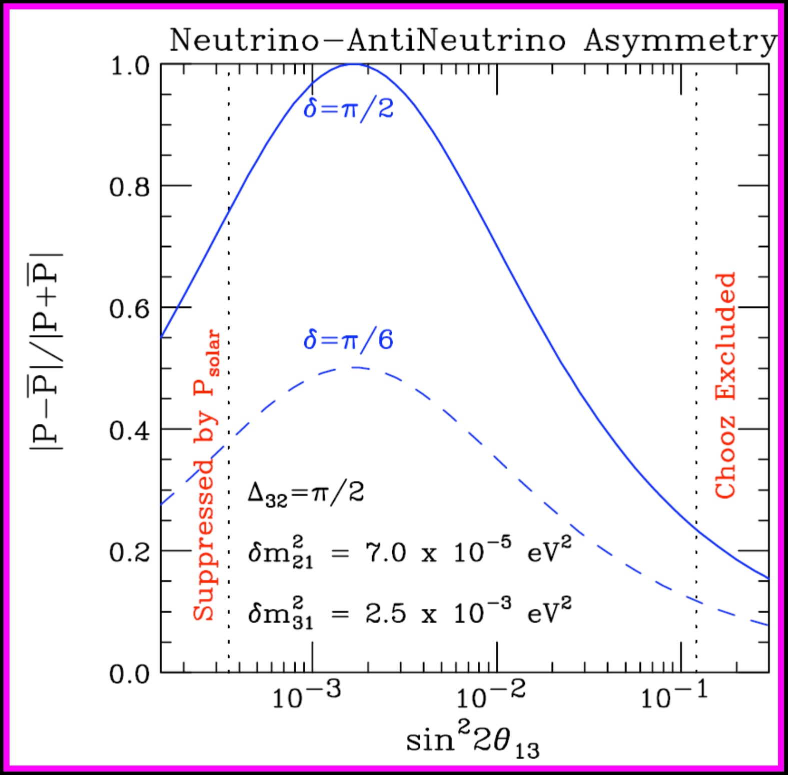


What does $\sin^2 2\theta_{13} > 0.01$ mean?

- It means that no mixing angles are zero
- It means that each flavor eigenstate has some of each mass
- It means that CP violation could be large enough to see in next generation neutrino experiments
- Need to keep the lessons learned in mind!
  - Be patient
  - Plan to do this measurement in many ways!
  - Beware, what you see at the end may surprise you

What else does $\sin^2 2\theta_{13} > 0.01$ mean?

- Consider asymmetry between neutrino (P) and anti-neutrino (P) probabilities…



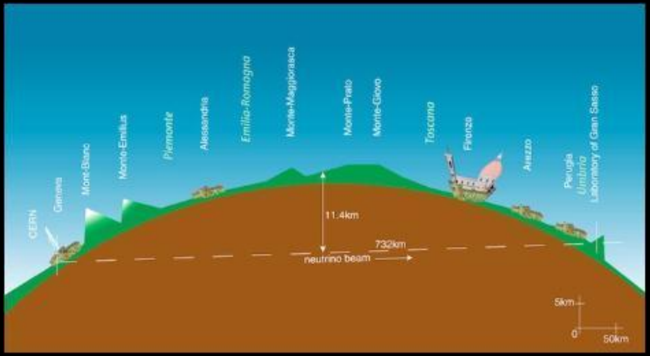
Two regimes:

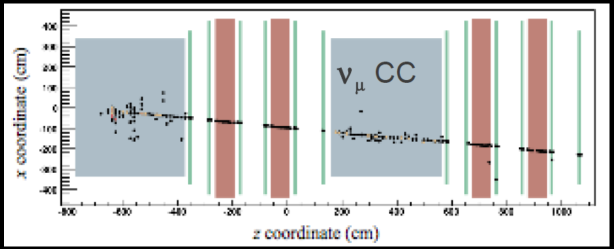
Small θ_{13}: looking for large asymmetries in very small numbers

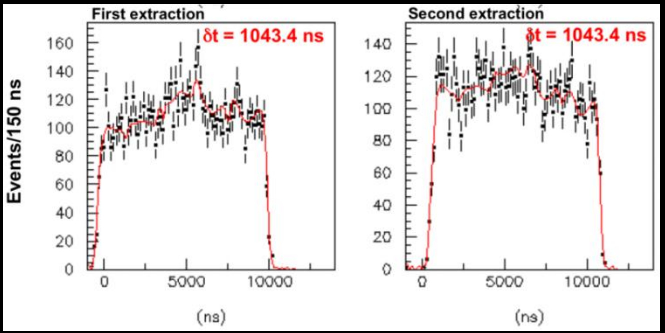
Large θ_{13}: looking for small asymmetries in “large” numbers

Systematics will count much more if θ_{13} is large!

Are Neutrinos traveling faster than the speed of light?





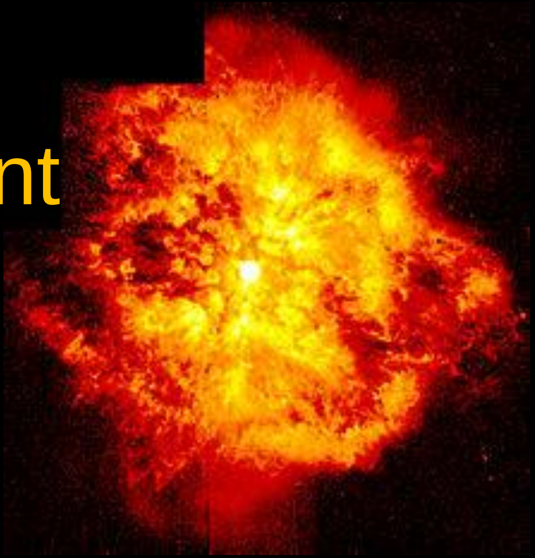


- OPERA in Italy: 732km from CERN
- Original Goal: ν_τ appearance
- Need high energy to see $\nu_\tau + N \rightarrow \tau + X$
- Side effect: OPERA has 15.2k events that have interacted in or just in front of the detector
- If light could travel through the earth, this would take 2.4 msec to travel from Geneva to Gran Sasso
- Hard measurement: precision of 8nsec quoted
- OPERA results:

$$\delta t = TOF_c - TOF_\nu = (1043.4 - 985.6)\ \text{ns} = (57.8 \pm 7.8\ (\text{stat.})^{+8.3}_{-5.9}(\text{sys.}))\ \text{ns}$$

$$(v-c)/c = \delta t/(TOF_c - \delta t) = (2.37 \pm 0.32\ (\text{stat.})^{+0.34}_{-0.24}\ (\text{sys.})) \times 10^{-5}$$

Many techniques, one measurement



- Supernova 1987A: neutrinos arrived at the earth within seconds of the light that arrived, distance=168,000 light years
  - $|v-c|/c \leq 2 \times 10^{-9}$ PL**B201**, (1988)
- MINOS tried to measure this in 2007, but measurement not precise enough to see this shift
  - $(v-c)/c = (5.1 \pm 2.9) \times 10^{-5}$ PR**D76**, (2007)
- MINOS will improve their timing to try to confirm/refute OPERA result
  - Using the detectors already in the beamline, plus better GPS system and calibration
- Note: OPERA doesn't have a near neutrino detector…

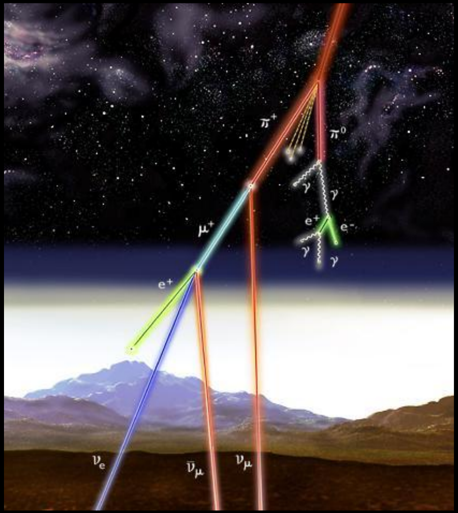
Next steps

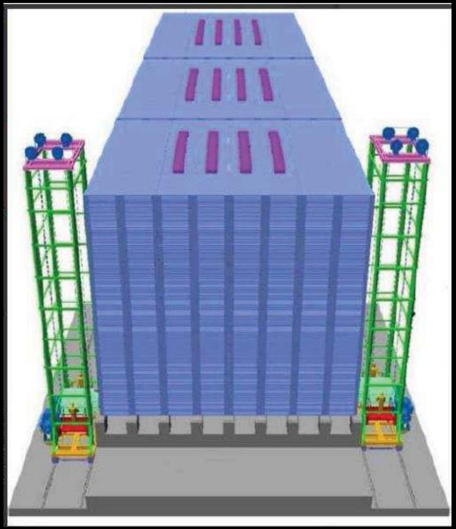
In thinking about these efforts in a global way…

- Want to see confirmation of any result this important
- Want to see confirmation in as different a way as possible
  - Different detector technologies
  - Different neutrino energies
  - Different channels:
    - appearance, disappearance
    - Electron and muon neutrinos in initial and final states

India: Indian Neutrino Observatory

- Flux: Atmospheric Neutrinos for first stage
- Farther away: beam from muon decays ($\mu \rightarrow e\ \nu_e \nu_\mu$) would allow study of $\nu_e \rightarrow \nu_\mu$
- Detector: RPC and magnetized iron to compare ν_μ and anti-ν_μ disappearance
- Matter effects predicted to be very large at "resonant energy" of the earth

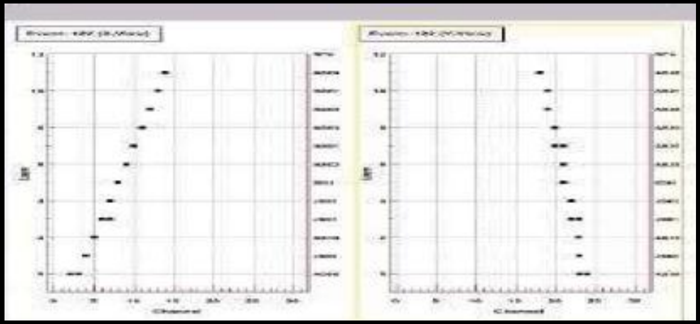




$$x = \frac{2\sqrt{2}G_F n_e E_\upsilon}{\Delta m^2}$$

$n =$ e$^-$ density

$$\sin^2 2\Theta_M = \frac{\sin^2 2\Theta}{\sin^2 2\Theta + (\pm x - \cos 2\Theta)^2}$$



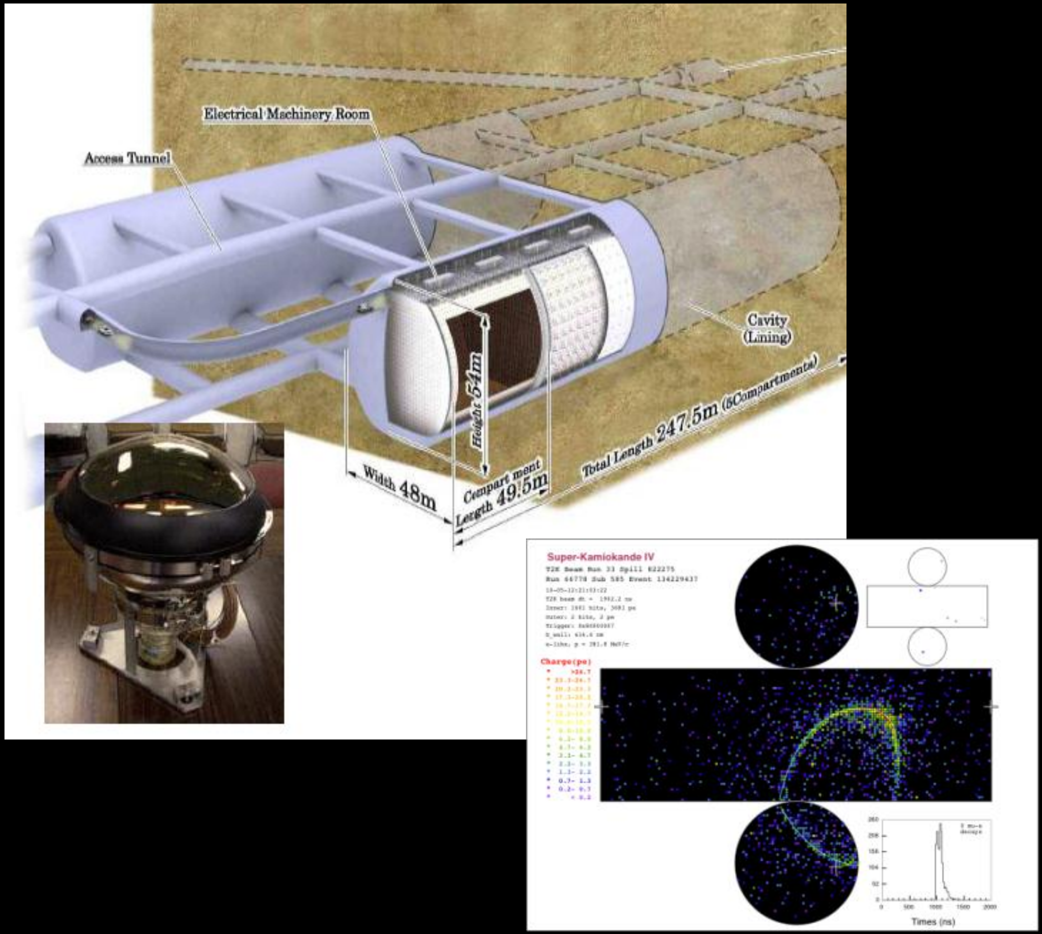
Cosmic Ray Tracking in Prototype

Hint: What happens at $x=\cos 2\Theta$?

Ref: M.V.N. Murthy, NuINT11

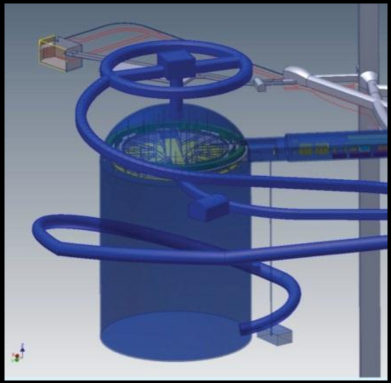
Japan: Tokai to Hyper-Kamiokande

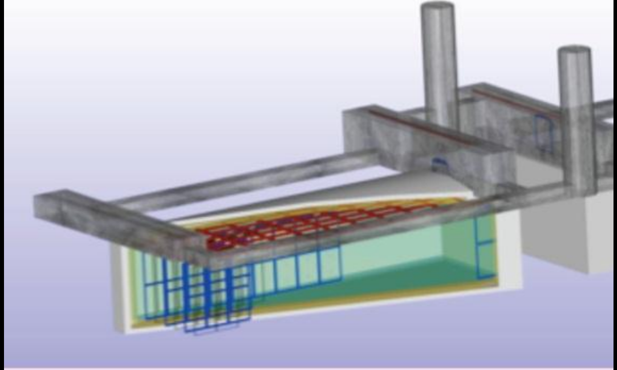
- Increase neutrino intensity by increasing proton power
- More protons means more $\pi \rightarrow \nu\mu$ decays
- Use same neutrino beam currently used by T2K
- Increase detector mass, from 50 kton to 1,000 kton!
- Keep Off-Axis technique, new detector cavern near Super-Kamiokande
- New near detector at 2km from source
- Precision test of oscillations at first maximum

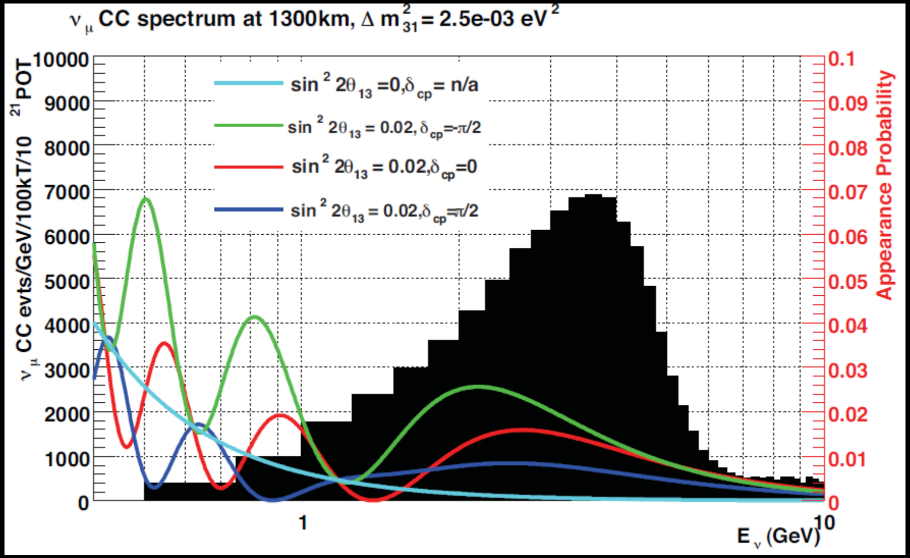


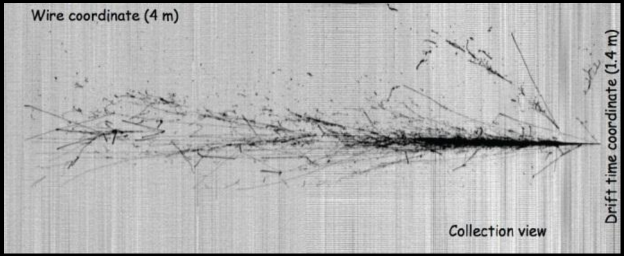
USA: Long Baseline Neutrino Experiment

- US plan for broad energy spectrum neutrino beam
- Baseline of 1300 km
- Detector technologies under consideration
- Water Cerenkov detector: 200kton, or Liquid Argon: 35kton
- Beam power: 700kW to start, upgrade to 2.3MW





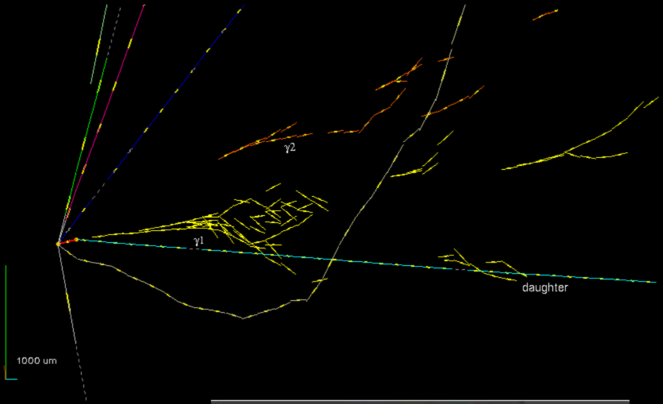


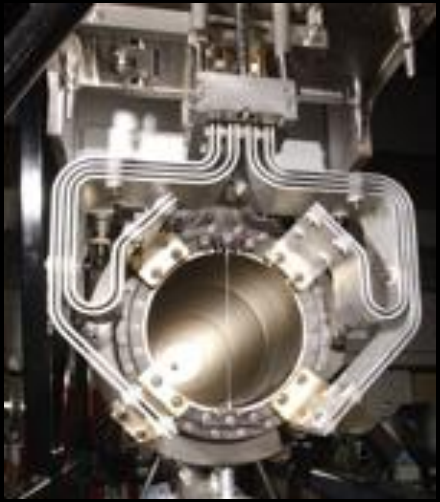


G. Rameika, Intensity Frontier Workshop 2011

Conclusions

- 2011 has been an exciting year for neutrinos
- But the lessons remain the same
  - Need patience!
    - Experiments are just getting started to see last mixing angle, far from ultimate precision expected
  - Understanding CP violation and neutrino masses demands a coherent but varied world-wide program
    - Want to see disappearance and appearance, want to see phenomena across many neutrino energies
    - The payoff will be huge, glimpse into why we are here
  - We may be asking very different questions once we see full statistics of next generation of experiments





நன்றி ধন্যবাদ

धन्यवाद Thank You