



# Neutrino Oscillations and the MINOS Experiment

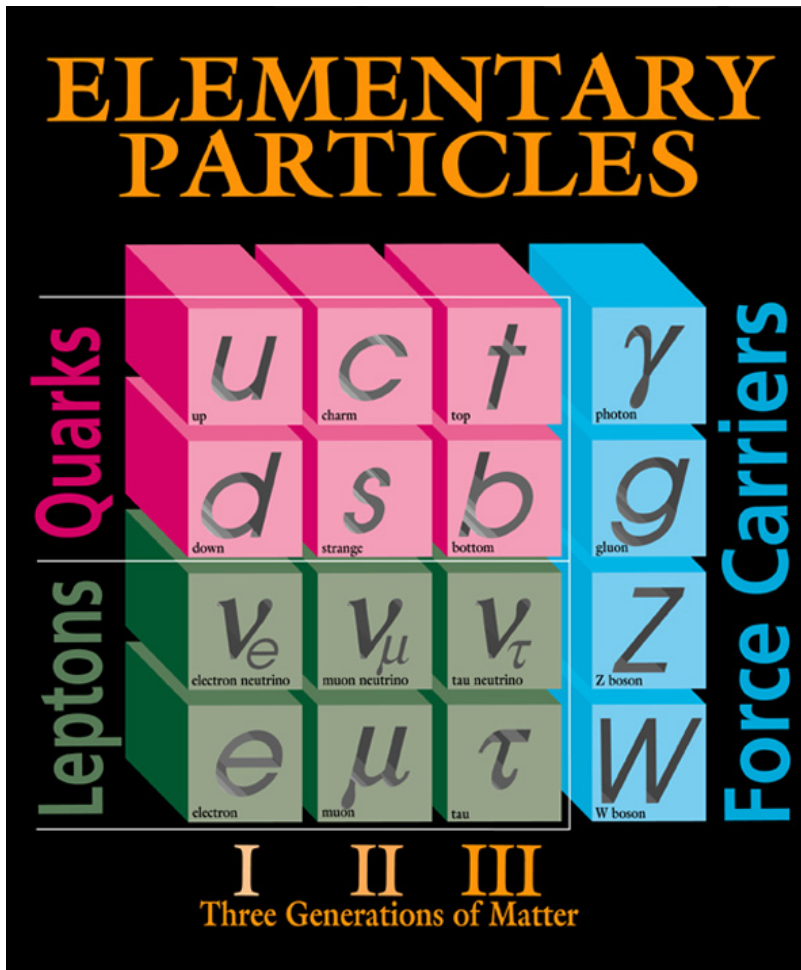


Matthew Strait  
University of Minnesota  
for the MINOS collaboration

St. Olaf  
24 March 2010



# What's a Neutrino?



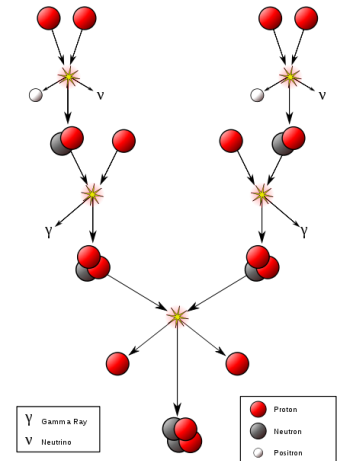
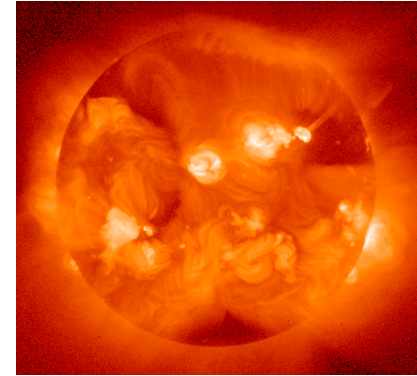
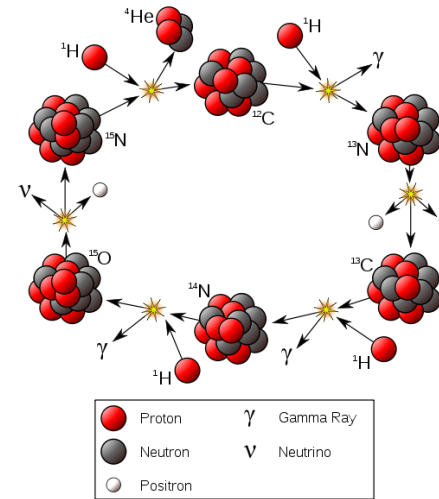
- Very small mass
  - $\lesssim 10^{-6}$  of electron
- No charge
- Interact only via weak force and gravity
- Takes about a light year of lead to stop the average neutrino



# Neutrinos Are Very Common



- Most prodigious source: Sun
  - $6.5 \times 10^{10}$  neutrinos/cm<sup>2</sup>/s at Earth
  - About 1 (!) of these interacts with you a day



- Also produced in detectable quantities by:
  - Cosmic rays
  - Supernovae
  - Radioactive decay in the Earth
  - Nuclear reactors
  - Particle accelerators

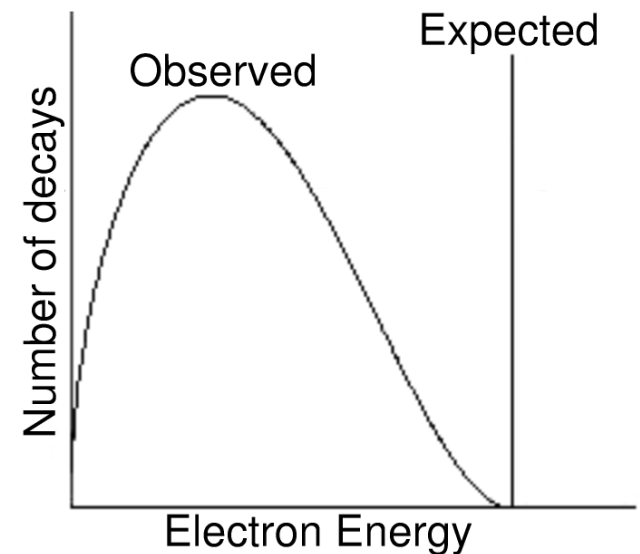


# Brief History of Neutrinos



- Beta decay in 1930:
  - $n \rightarrow p + e^-$
  - Electron should always have the same energy, but it doesn't!
- Crisis!
  - Bohr: Energy not conserved?
  - Pauli: Maybe there's an invisible particle emitted too?
    - $n \rightarrow p + e^- + \nu$
    - Required to have no charge & nearly no mass
    - Later: 'I have done a terrible thing, I have postulated a particle that cannot be detected'
  - How to test this?

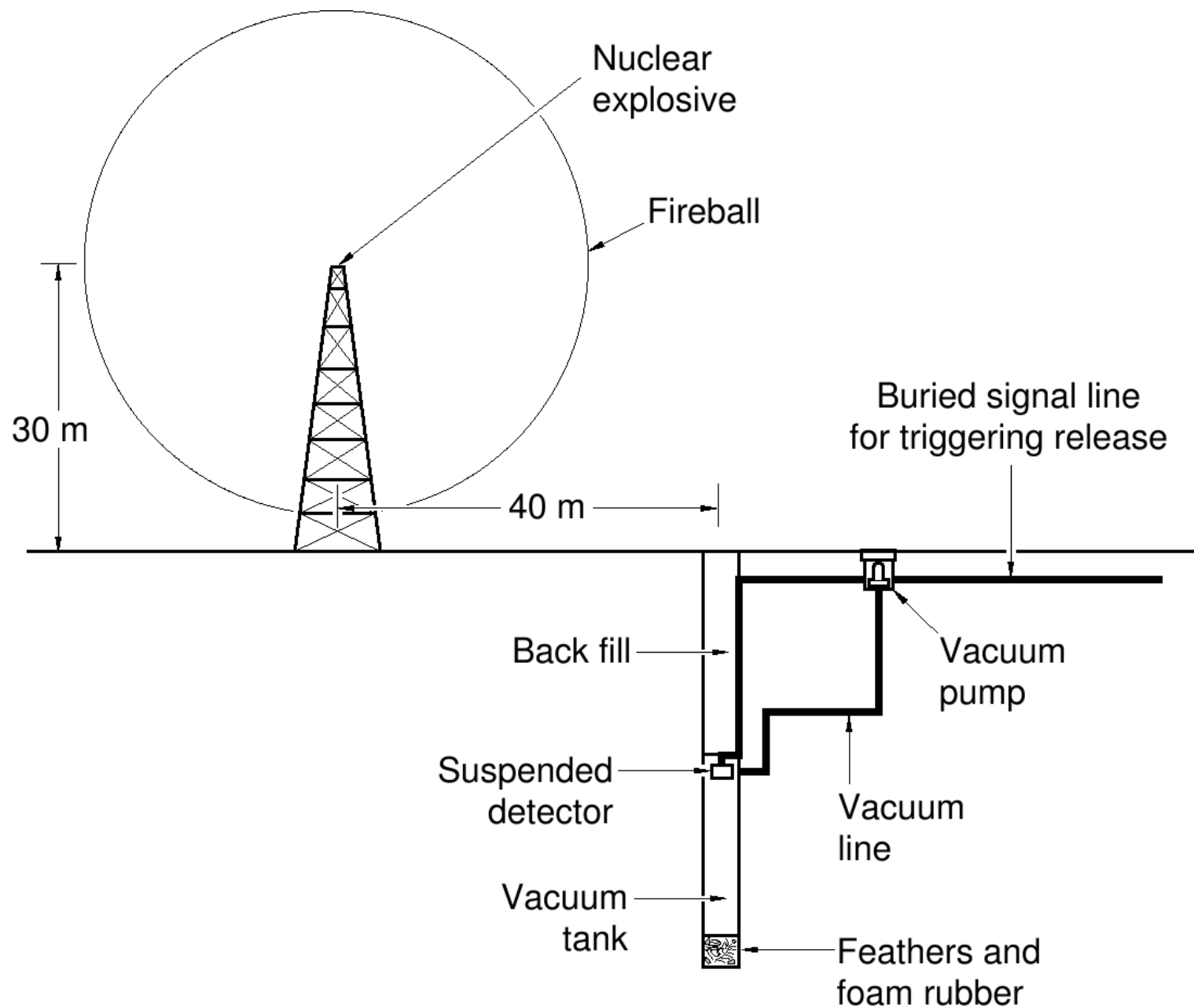
Beta Spectrum (Idealized)





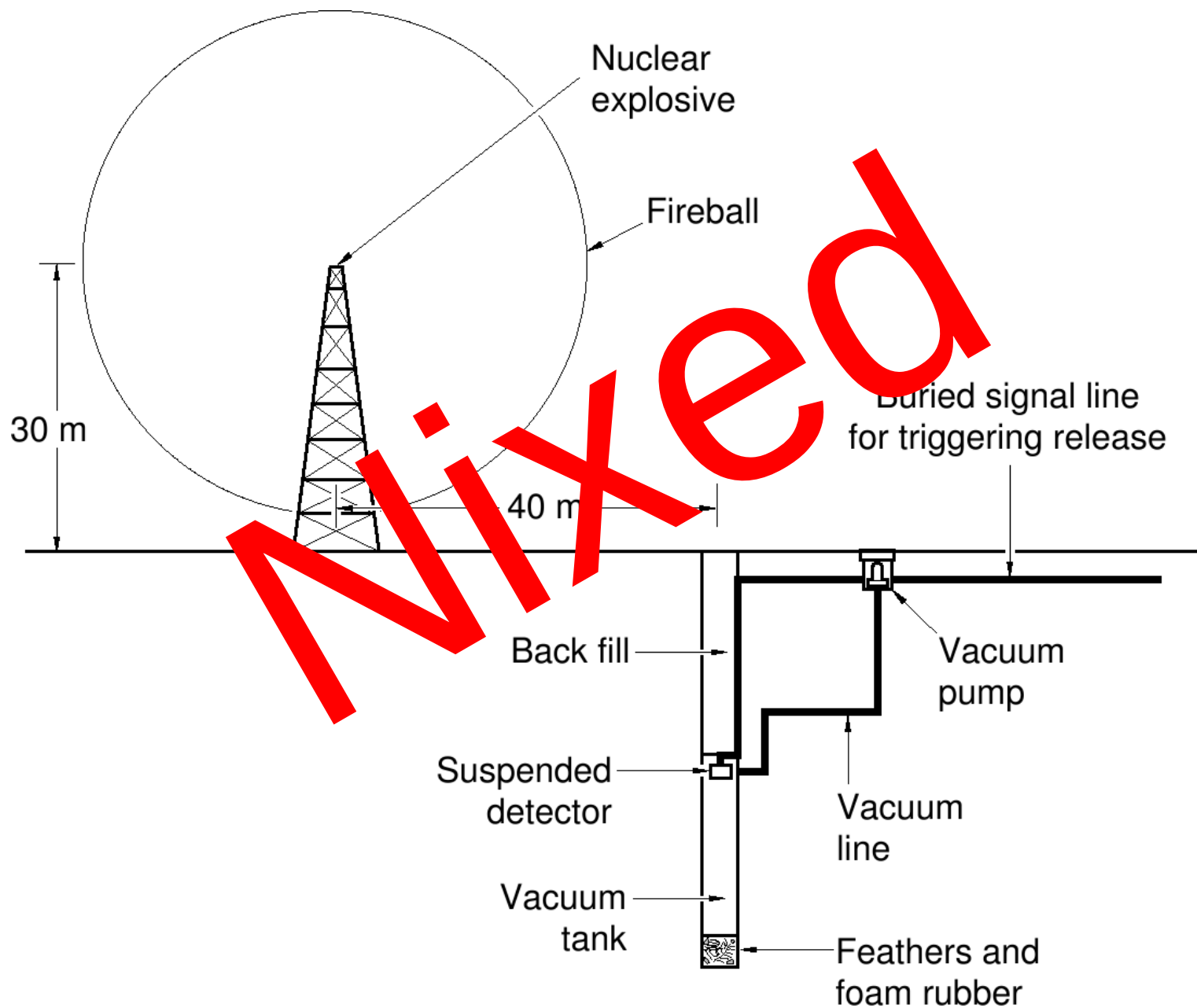


# Reines and Cowan





# Reines and Cowan

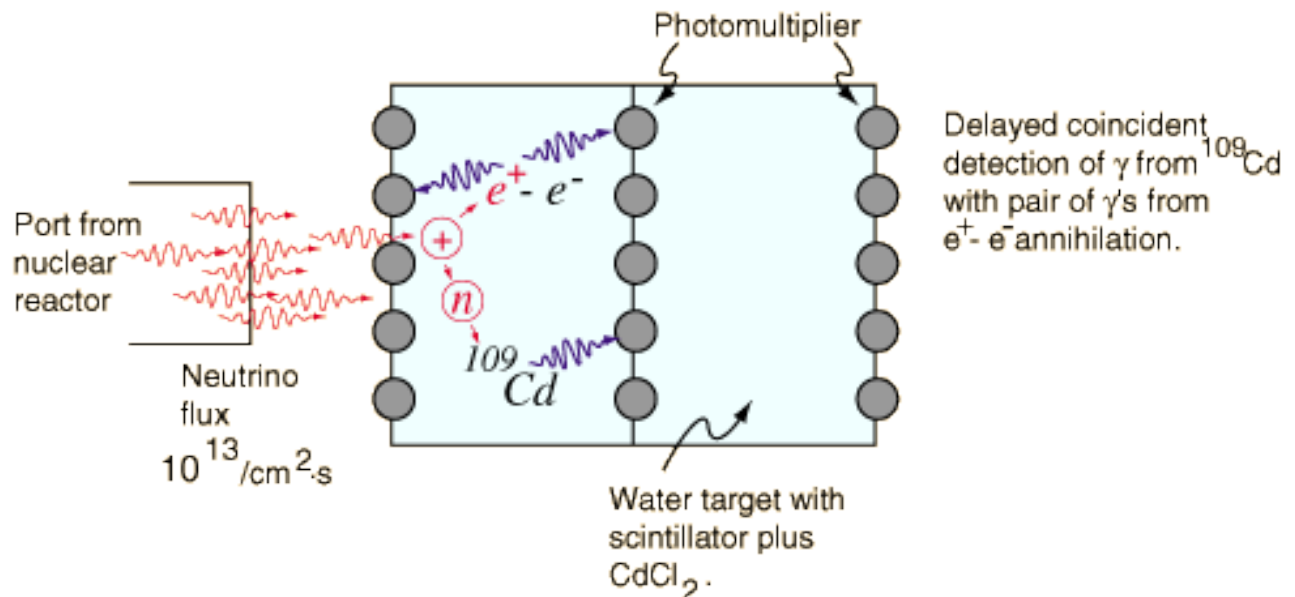
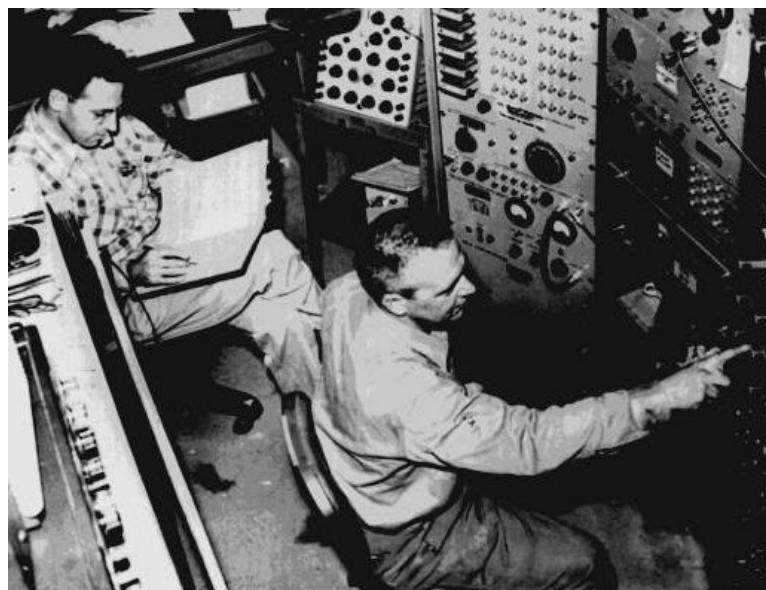
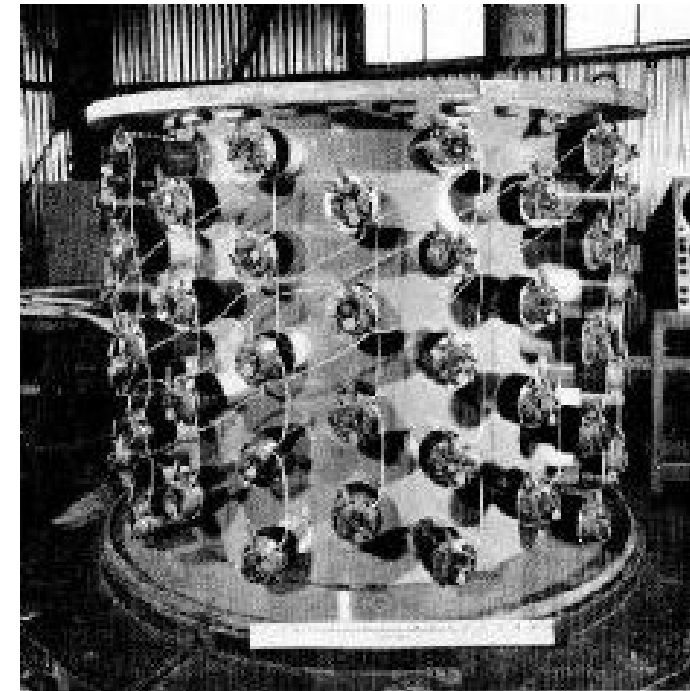




# Reines and Cowan



- Instead, "Project Poltergeist", which confirmed neutrino in 1956:
- Neutrinos from nuclear reactor make positrons in a water target
- $p + \nu \rightarrow n + e^+$ 
  - First detect  $2\gamma$  from positron annihilation
  - A bit later:  $^{108}\text{Cd} + n \rightarrow ^{109}\text{Cd} + \gamma$

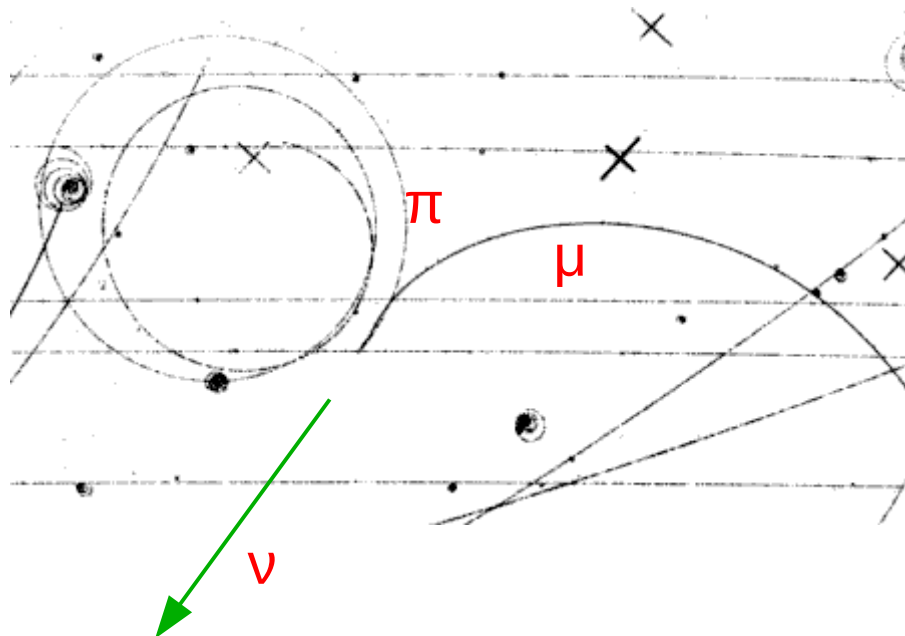




# Two Kinds of Neutrinos: AGS



- 1950's
  - Pions are a well-known particle, first discovered in cosmic rays
  - Visible decay:  $\pi \rightarrow \mu$
  - Clearly also involves a neutrino
  - So  $\pi \rightarrow \mu + \nu$
  - Is this the same neutrino, or a different one?





# Two Kinds of Neutrinos: AGS



– 1960, Brookhaven

- Created neutrino beam from decaying pions

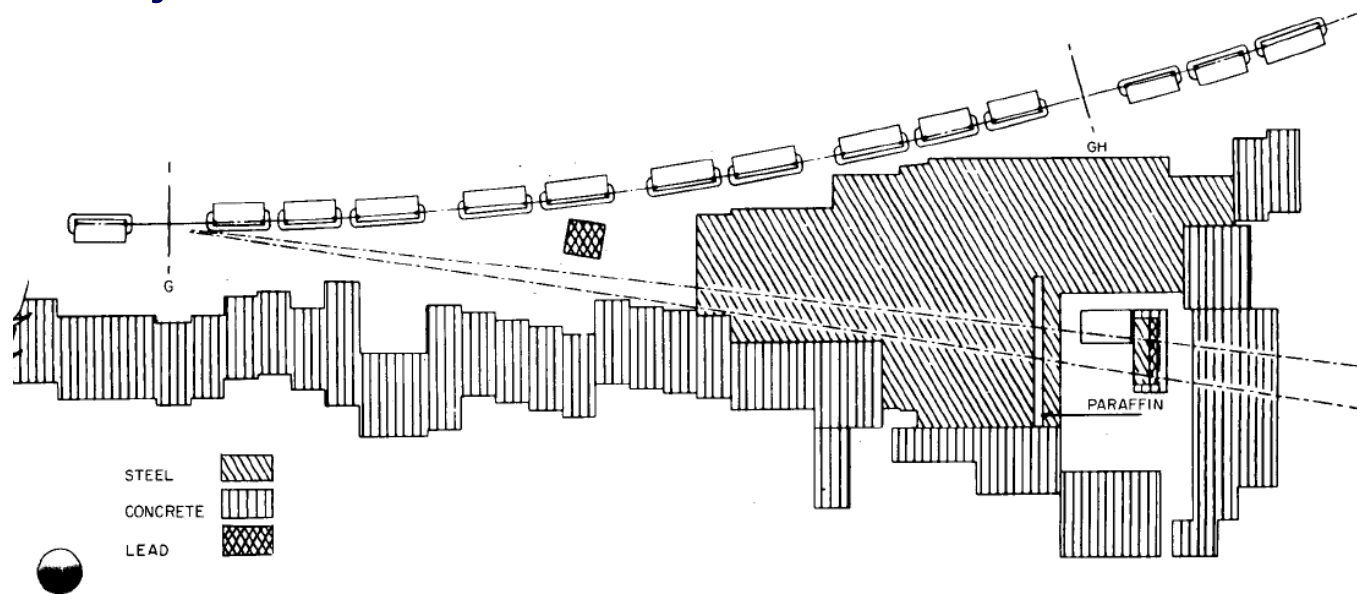
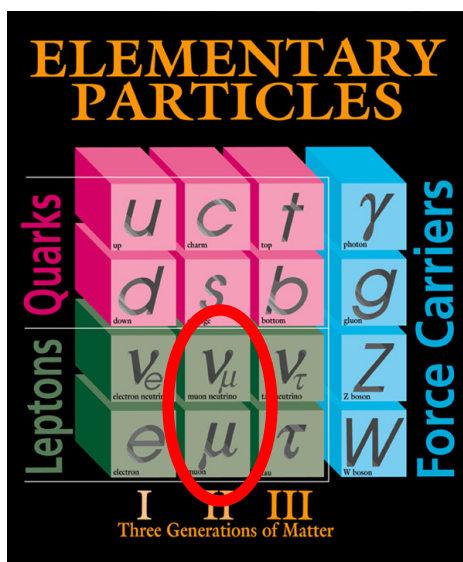
$$- \pi \rightarrow \mu + \nu$$

- Result:

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

$$- \nu + n \nrightarrow p + e^-$$

- This *muon neutrino* is not the same as the one from beta decay







# Three Kinds



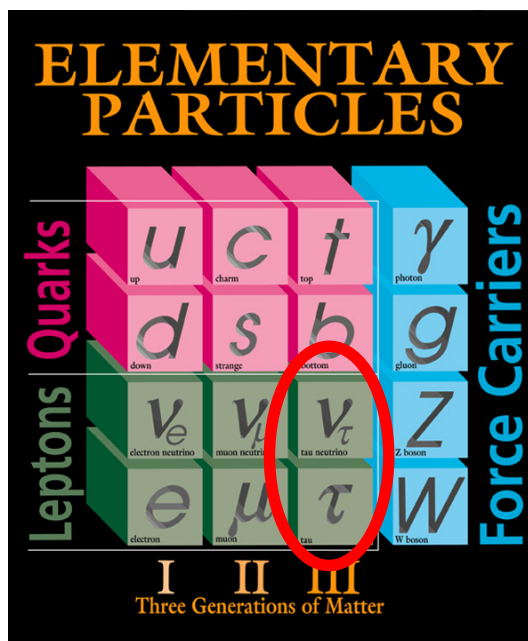
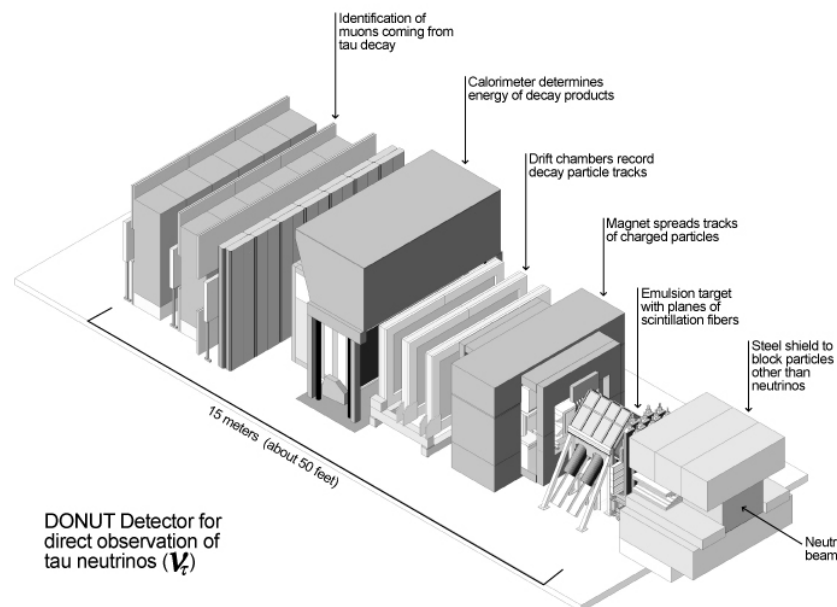
– 2000: Tau lepton had been known for some time

- Must also have an associated neutrino

– DONUT at Fermilab confirms this

- Same idea as at AGS
- Beam of neutrinos from  $D_s \rightarrow \tau + \nu$
- Observed:  $\nu + n \rightarrow p + \tau^-$
- More difficult, particularly since the tau lifetime is  $3 \times 10^{-13}$  s

**DONUT Detector**





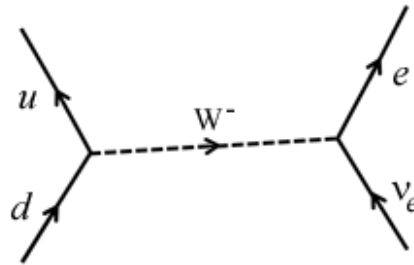
# Types of Interactions



Scale

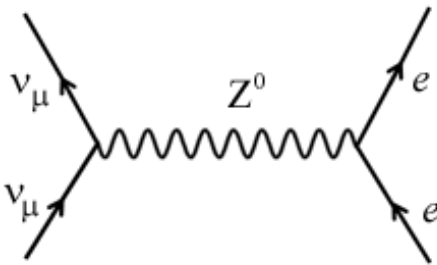
- So far I've talked about:

- $\nu_e + n \rightarrow e^- + p^+$
- $\nu_\mu + n \rightarrow \mu^- + p^+$
- $\nu_\tau + n \rightarrow \tau^- + p^+$

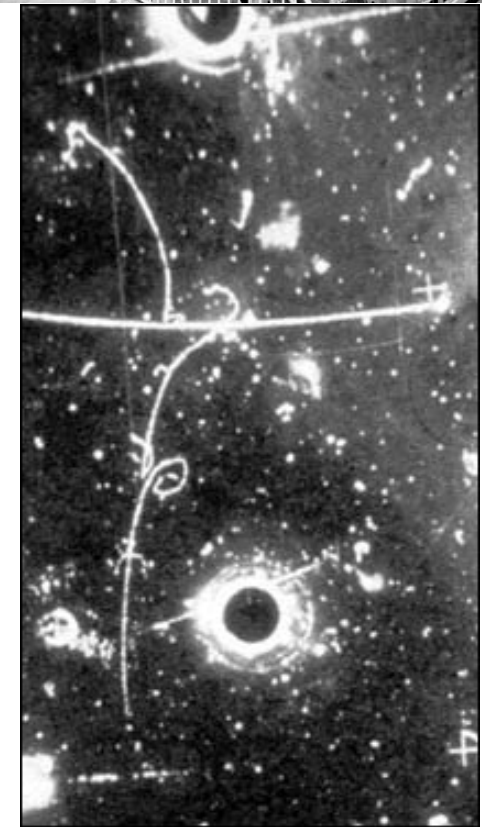


- 1973: Gargamelle bubble chamber

- $\nu_{e,\mu,\tau} + X \rightarrow \nu_{e,\mu,\tau} + X$
- Neutral current:  $Z^0$



ELEMENTARY PARTICLES			
Leptons	Quarks		
	I	II	III
	electron	muon	tau
	$\nu_e$	$\nu_\mu$	$\nu_\tau$
	$e$	$\mu$	$\tau$
	$u$	$c$	$t$
	$d$	$s$	$b$
	$\gamma$	$Z$	$W$
	photon	Z boson	W boson
	Force Carriers		



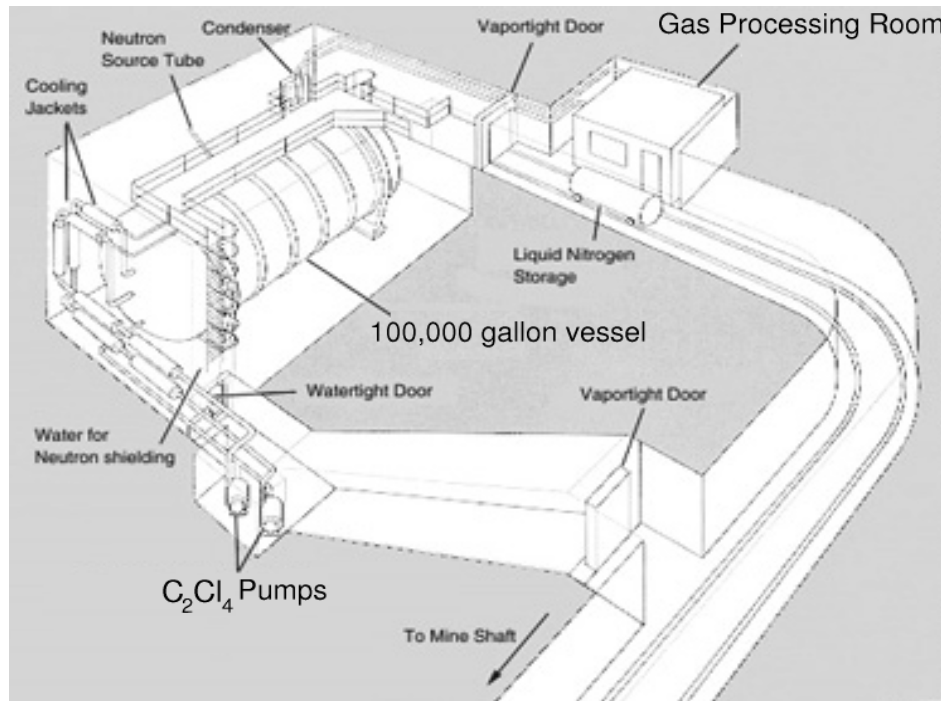
AEROMETRIC photo

- Picture seems complete, but...



# Solar Neutrino Problem

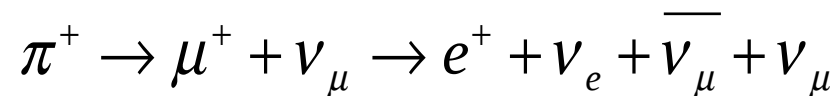
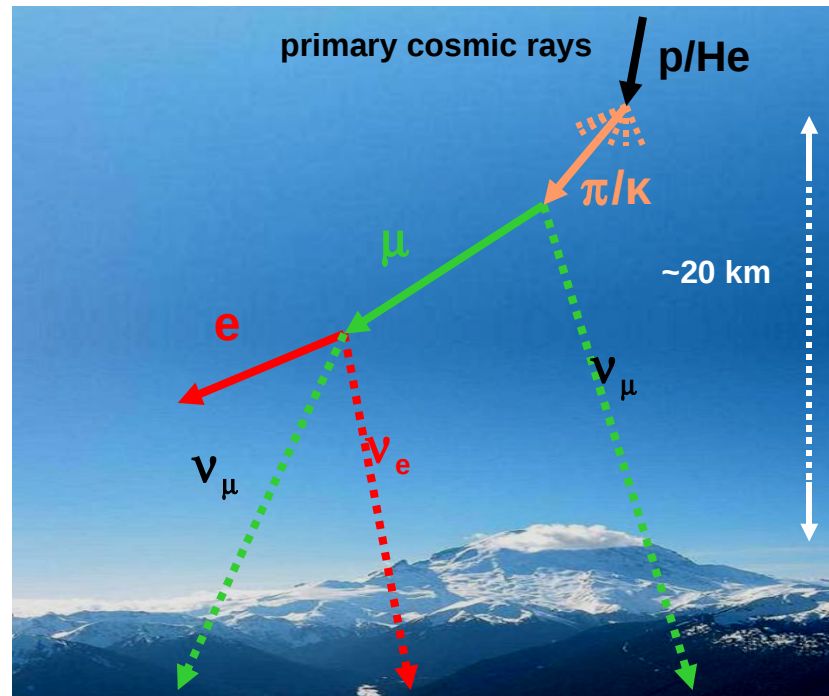
- Fusion in sun produces neutrinos; first detected in 1970 at Homestake mine, SD
  - $^{37}\text{Cl} + \nu_e \rightarrow ^{37}\text{Ar} + e^-$ 
    - Rate:  $\sim 20/\text{month}/100\,000$  gallons
  - The number was too low by a factor of 3!
- Experiments 1970-2000 observed deficits
  - Solar model wrong? All experiments in error?







# Missing Here Too

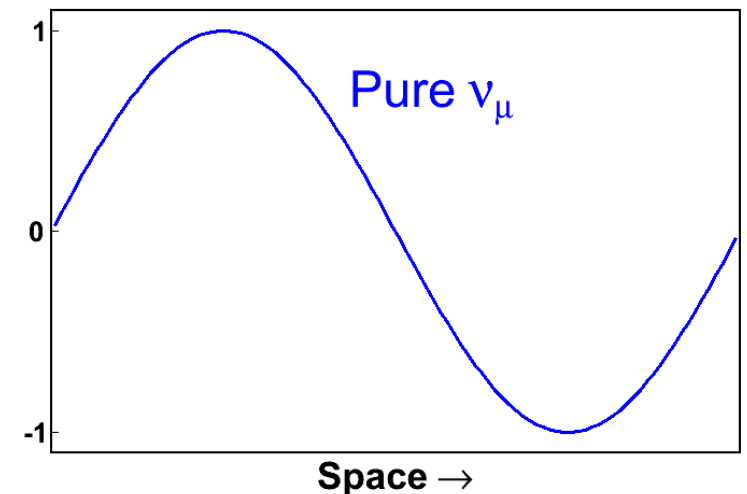


- Expect 2 muon neutrinos for each electron neutrino
- Experiments in the 1980's observed closer to 1:1
- Is there a common solution to both problems?



# Neutrino Oscillations

- First proposed by Pontecorvo in 1968. Premise:
  - We know neutrinos by their interaction states:  $\nu_e$   $\nu_\mu$   $\nu_\tau$
  - We could also label them by their masses:  $\nu_1$   $\nu_2$   $\nu_3$
  - Quantum mechanics does not require a one-to-one correspondence between these!
  - Maybe neutrino interaction states are mixtures of mass states
- For instance, it's a good approximation to say:
  - $\nu_\mu = \cos\theta \nu_2 + \sin\theta \nu_3$
  - $\nu_\tau = -\sin\theta \nu_2 + \cos\theta \nu_3$
  - $\theta$  is some number which is a constant of nature
- Take a muon neutrino. It's a wave:

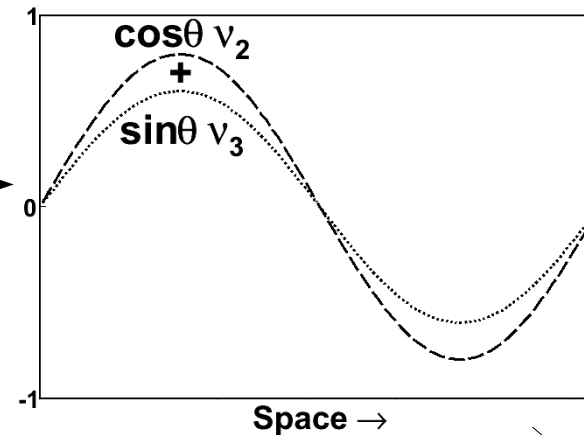
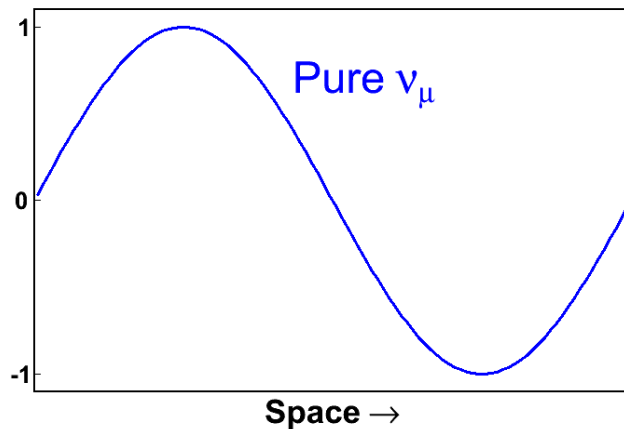




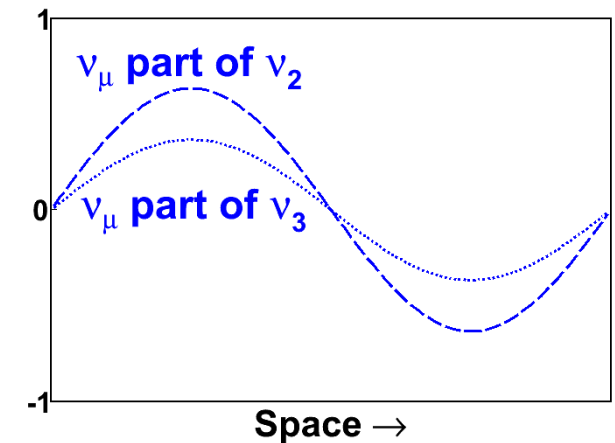
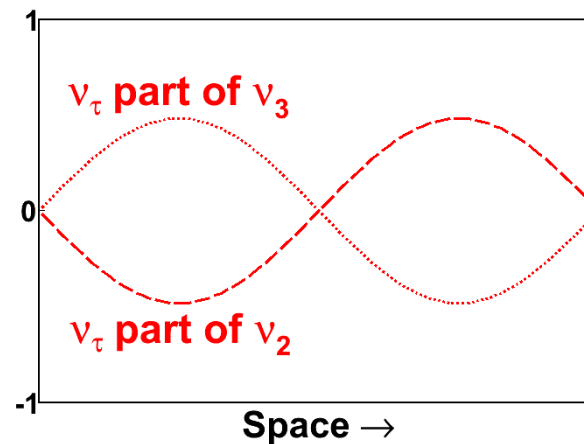


# Neutrino Oscillations

- $\nu_\mu = \cos\theta \nu_2 + \sin\theta \nu_3$



- Flip it around:

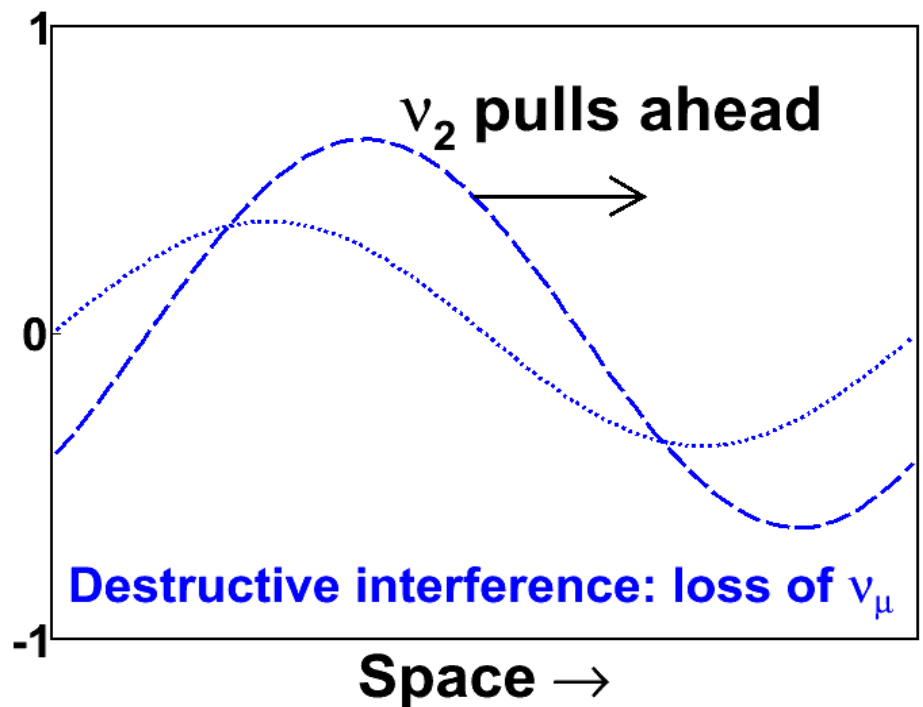
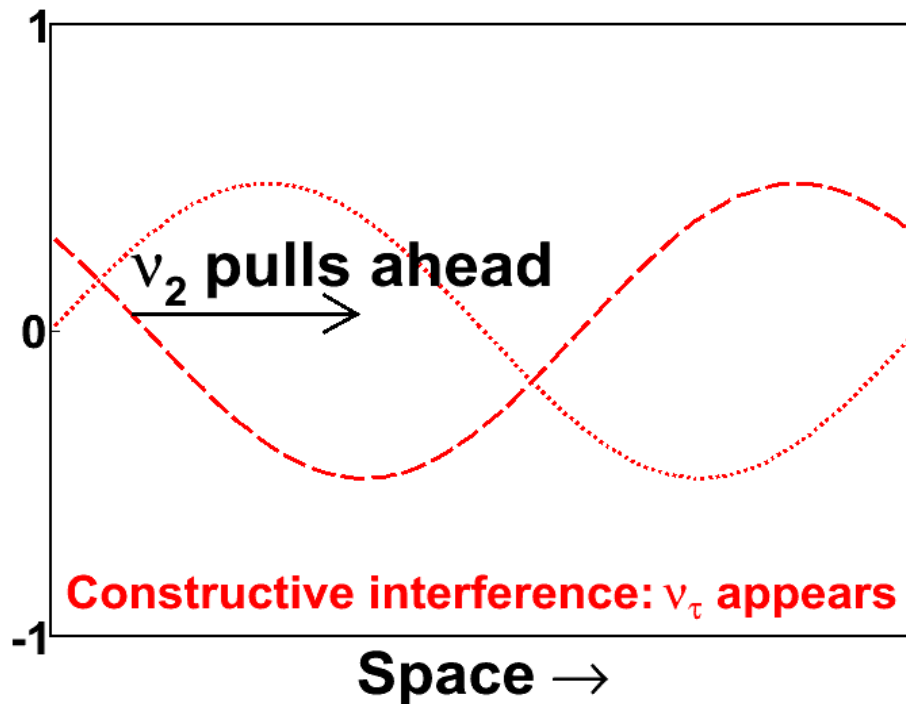


- Now we're back where we started!
  - Or are we?



# Neutrino Oscillations

- Suppose  $\nu_2$  is lighter:



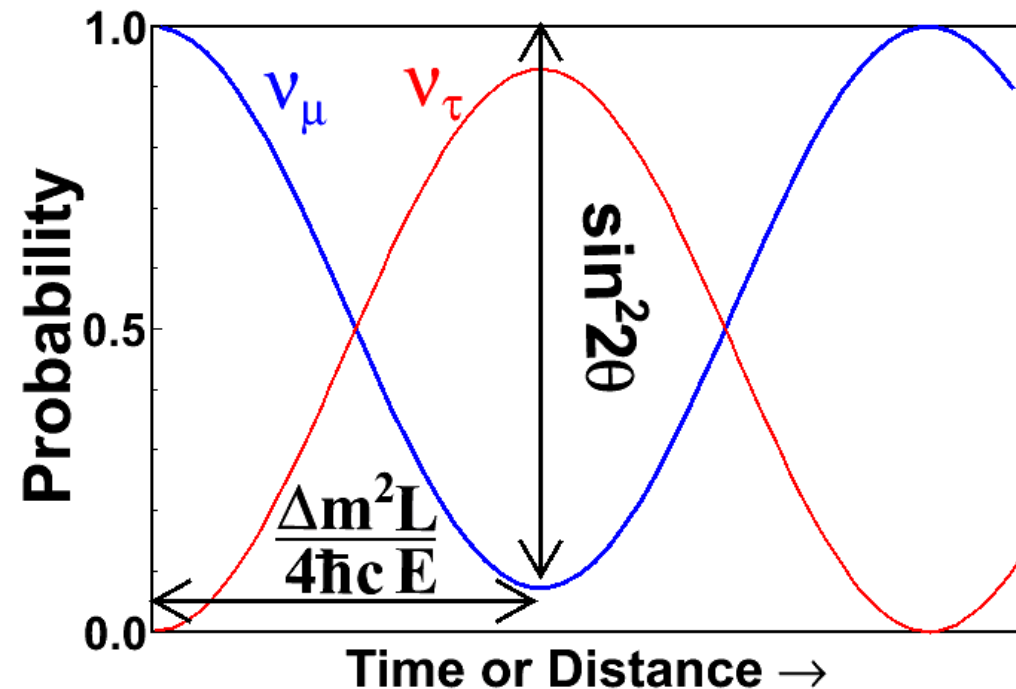
- As the waves interfere, probability of observing  $\nu_\tau$  and  $\nu_\mu$  change periodically (*oscillate*)



# Neutrino Oscillations



- Oscillation frequency is faster if mass difference is greater
  - Turns out to depend on  $\Delta m_{ij}^2 \equiv |m_i^2 - m_j^2|$
  - If masses are **the same** (maybe zero): no oscillation
- Amplitude controlled by  $\theta$ 
  - No clue of the value except from experiment

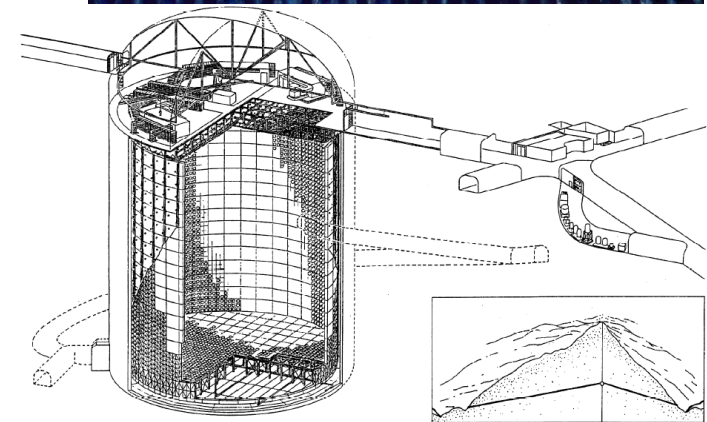
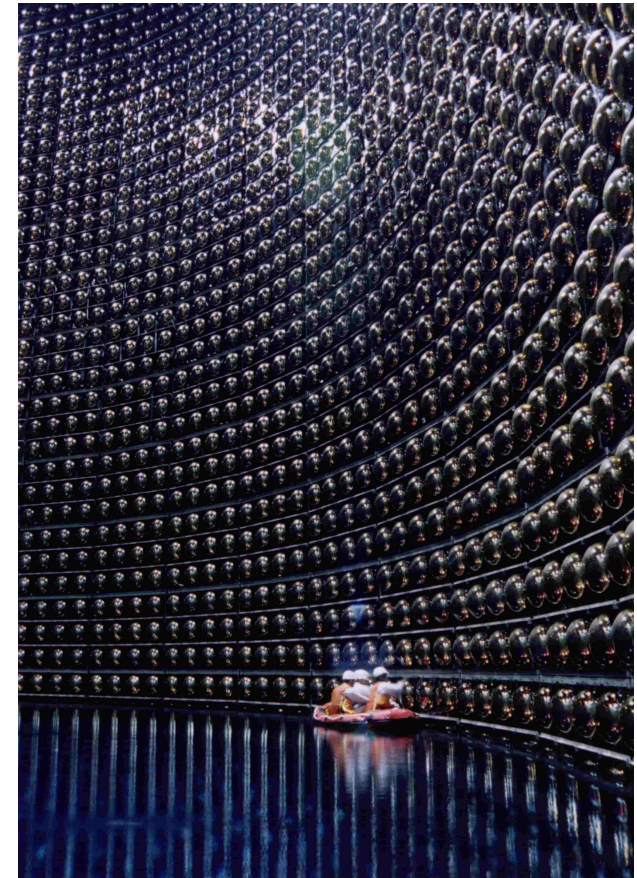
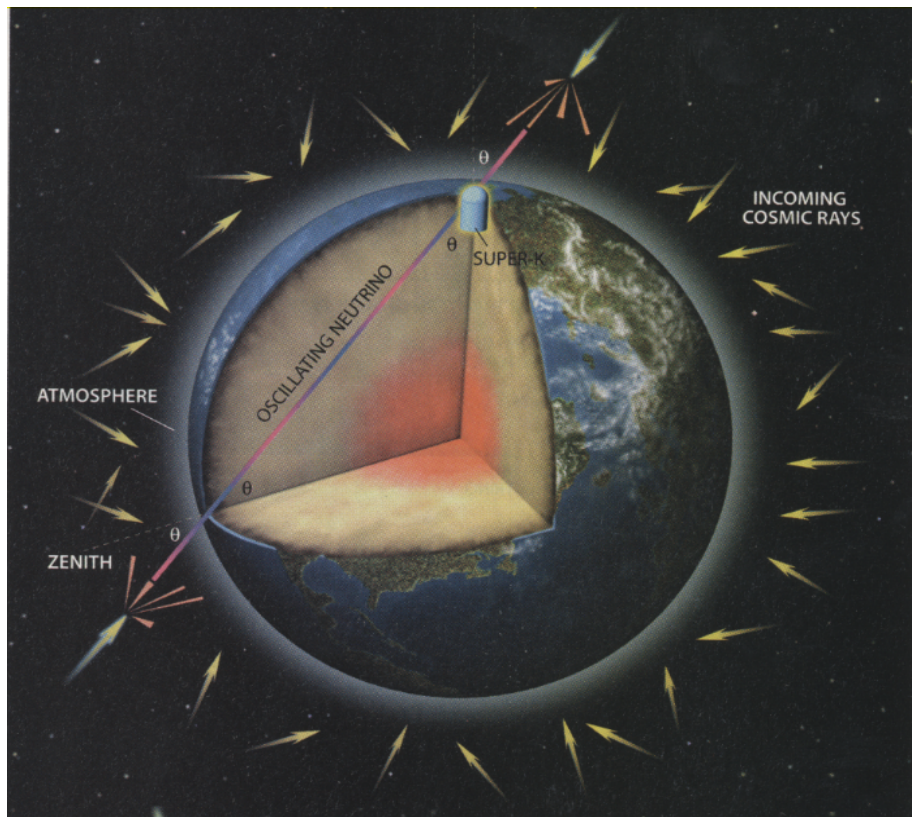




# Super-Kamiokande



- Found atmospheric neutrino deficit depends on angle!
  - From above:  $\nu_\mu : \nu_e = \sim 2:1$
  - From below:  $\nu_\mu : \nu_e = \sim 1:1$
  - Apparently many muon neutrinos change to an unobservable type if they go far enough



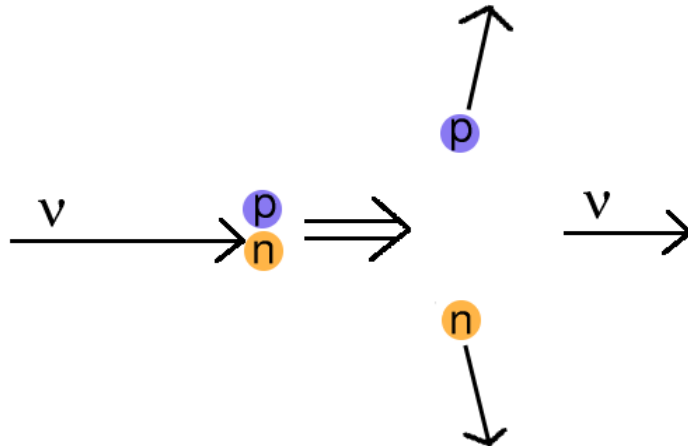




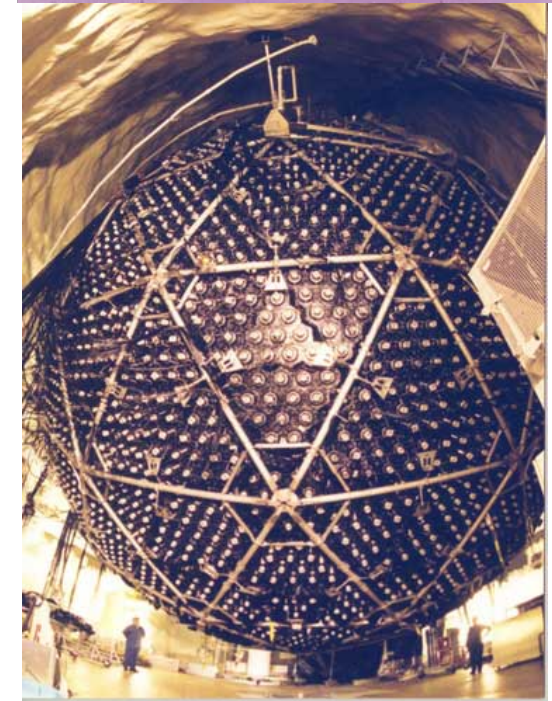
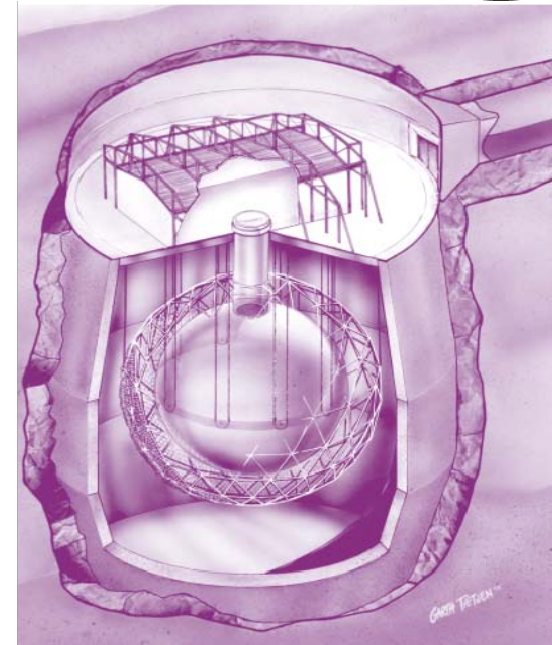
# SNO



- Designed to detect all solar neutrinos, regardless of type
  - 1000 ton sphere of heavy water
  - $\nu_x + {}^2\text{H} \rightarrow \text{p} + \text{n} + \nu_x$  (neutral current)



- 2001: Found neutral current interaction rate matched standard solar model
  - All the solar neutrinos were there, but some had changed flavor!





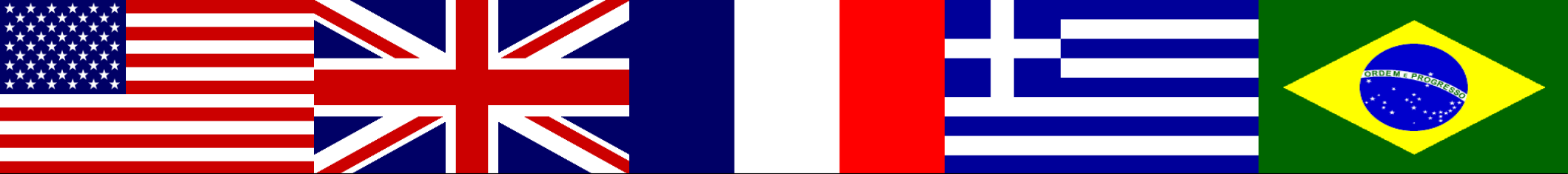


# Accelerator Neutrinos



- So far in our story, oscillations have only been observed from sources out of our control (the sun, cosmic rays)
- We'd like to make the neutrinos ourselves and then watch them oscillate, either:
  - $\nu_e$  from a reactor
  - A beam of  $\nu_\mu$
- Both are done; MINOS uses the second approach

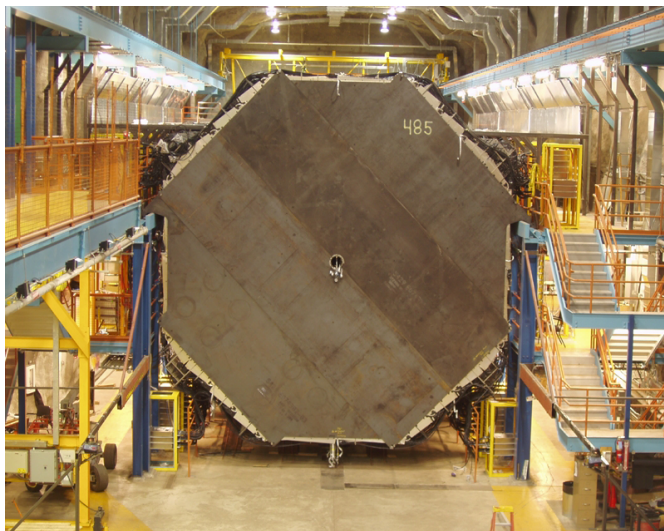




## **THE MINOS COLLABORATION**

Argonne • Athens • Benedictine • Brookhaven • Caltech • Cambridge • Campinas • College de France  
 Fermilab • Harvard • Holy Cross • IIT • Indiana • Iowa State • UC London • Minnesota Duluth • Minnesota Twin Cities  
 Otterbein • Oxford • Pittsburgh • Rutherford • Sao Paulo • South Carolina • Stanford • Sussex • Texas A&M • Texas Austin  
 Tufts • UCL • UFG-Brazil • UNICAMP-Brazil • USP-Brazil • Warsaw • William & Mary • Wisconsin





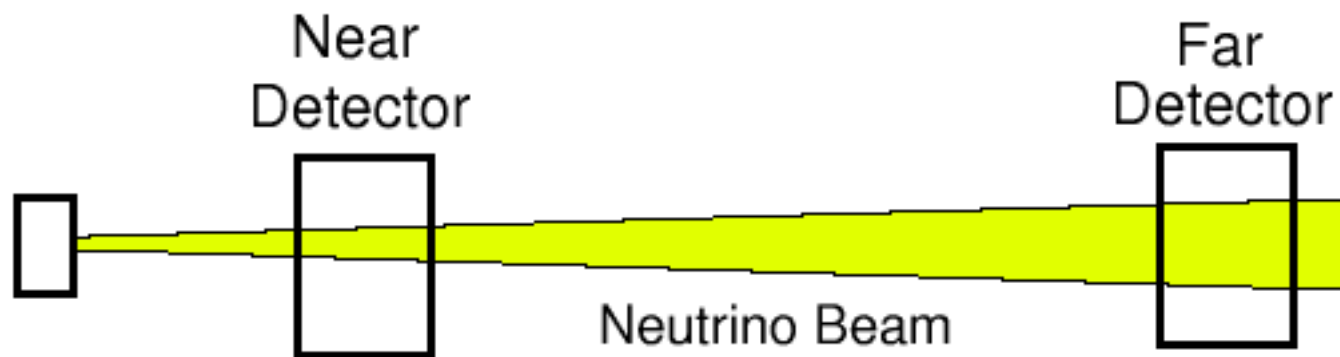
- MINOS is the second beam neutrino experiment to observe oscillations
  - Beam from Fermilab
  - 2 detectors, one 735 km away





# The Idea

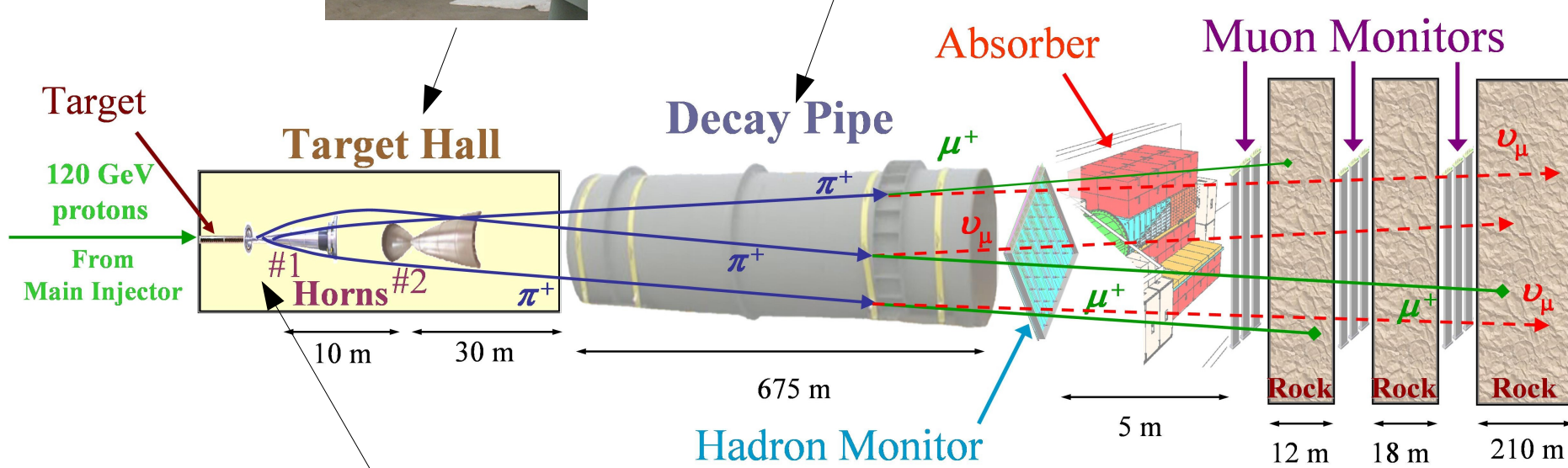
- Make a beam of neutrinos
- Observe it once near the source, again far away
- Look for a change







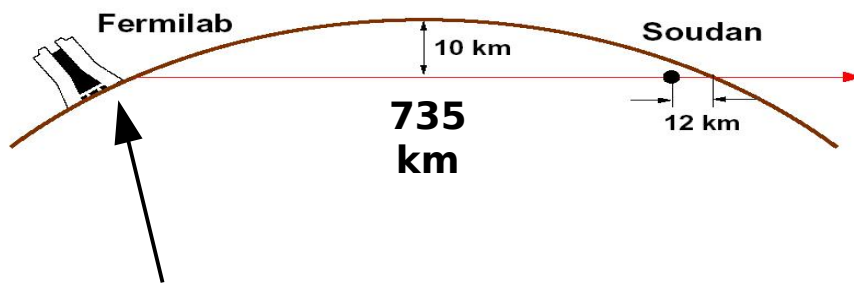
# Making a Neutrino Beam







# Near Detector



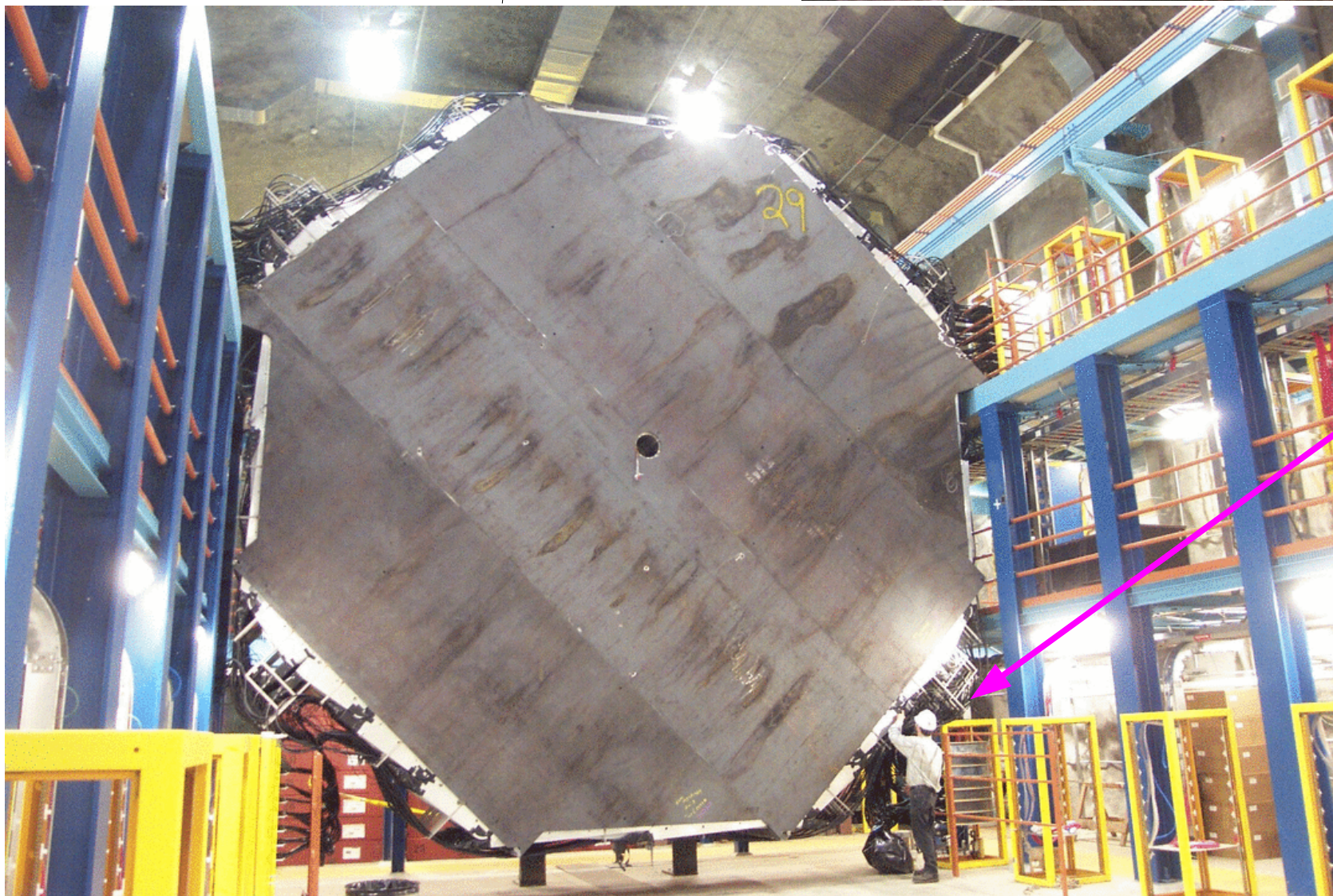
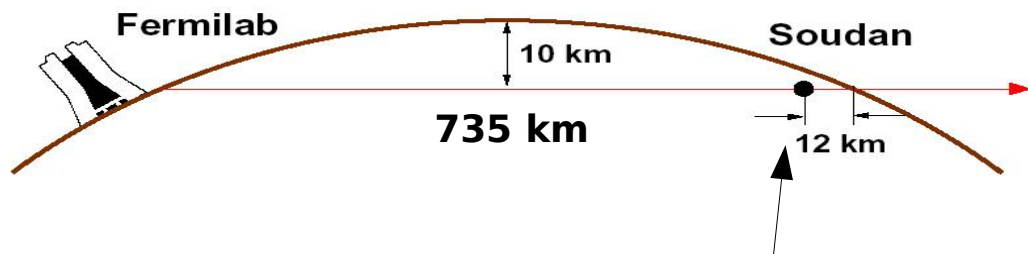
Tunnel bends out of the page here to filter out everything but neutrinos







# Far Detector



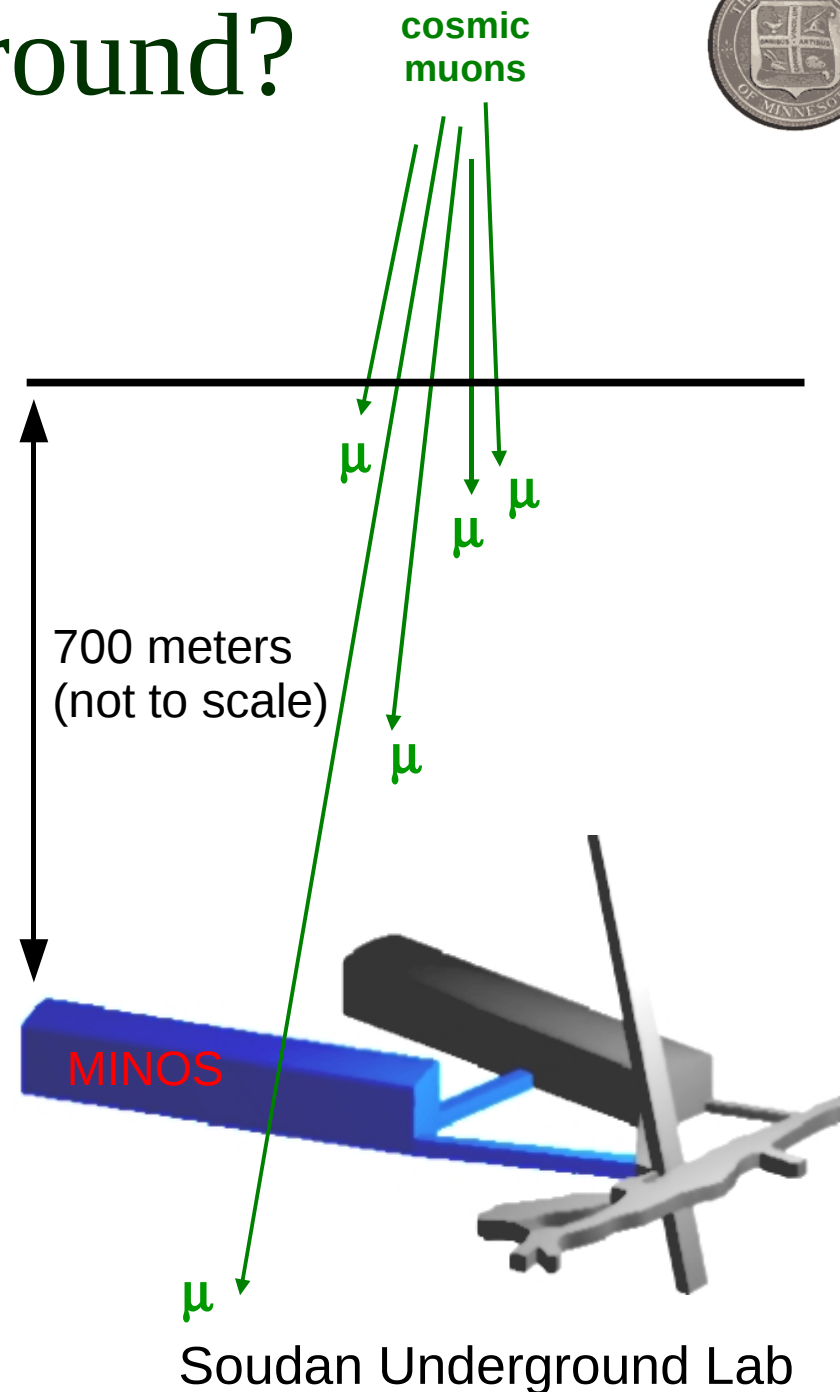
Scale



# Why Underground?



- Gets us away from cosmic rays
  - Might be confused with beam events
- On the surface,  $\sim 100/\text{m}^2/\text{s}$
- At MINOS,  $0.5/\text{s}$  for the entire detector!
- Beam is pulsed – on only  $10\mu\text{s}$  every 2 seconds
  - $\Rightarrow \sim 2$  minutes a year
  - So only  $\sim 100$  cosmics/year to worry about

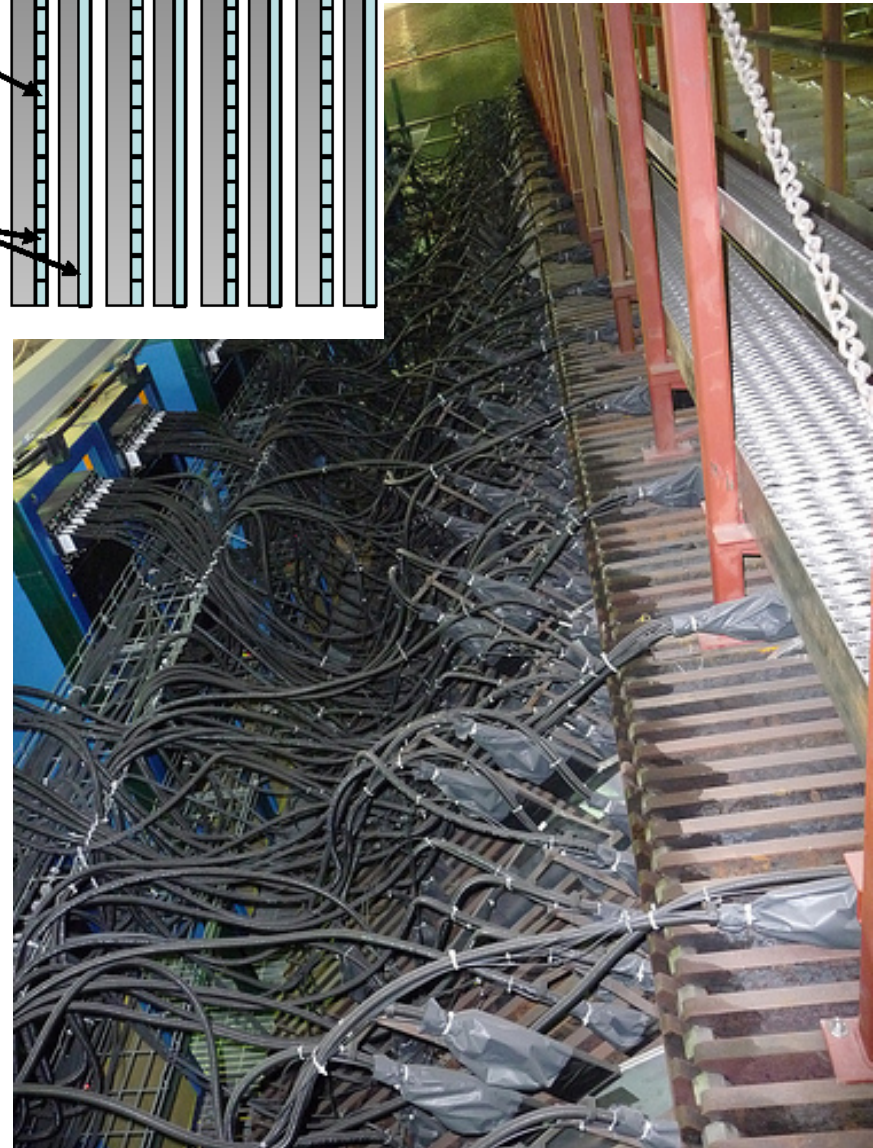
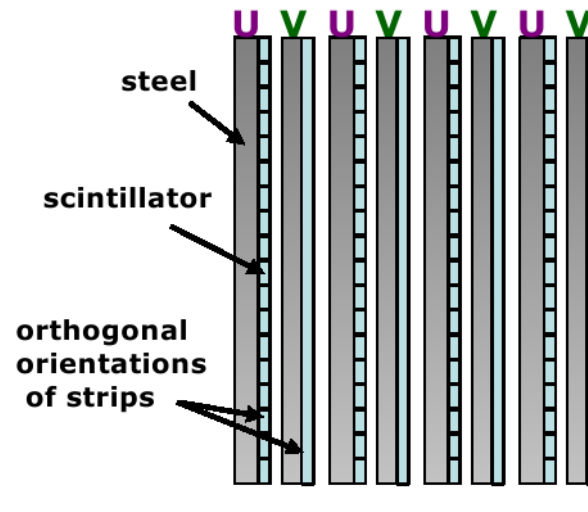






# Detector Technology

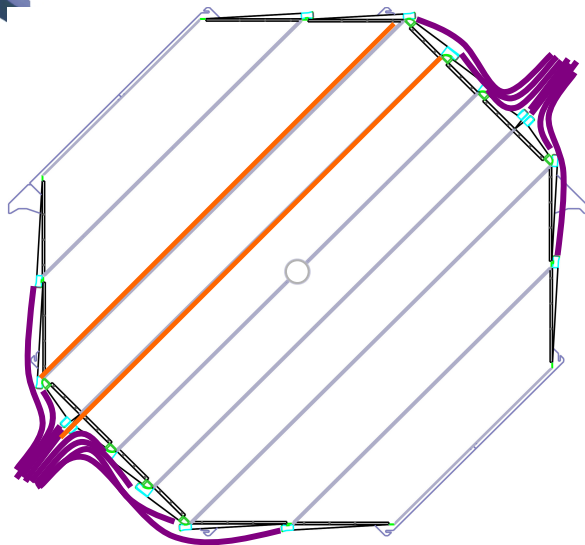
- Designed to be:
  - Massive (5400 tons)
  - Cheap (per piece)
  - Simple (helps with cheap)
- Alternating planes of steel & plastic scintillator
  - Steel provides mass and supports magnetic field
    - Field allows measurement of muon charge, momentum
  - Scintillator makes light when charged particles pass through
  - Phototubes detect light







# Scintillator and Fiber



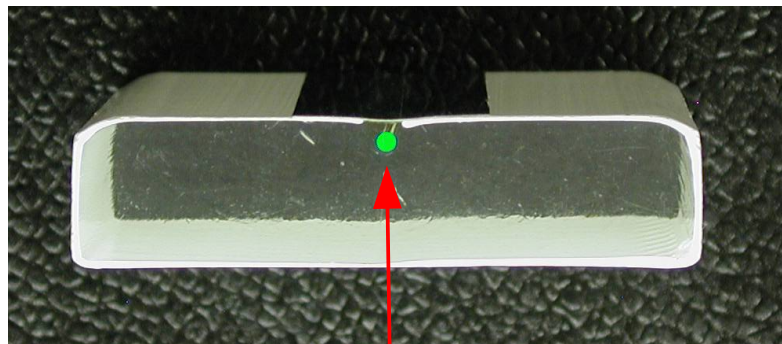
**A scintillator plane**



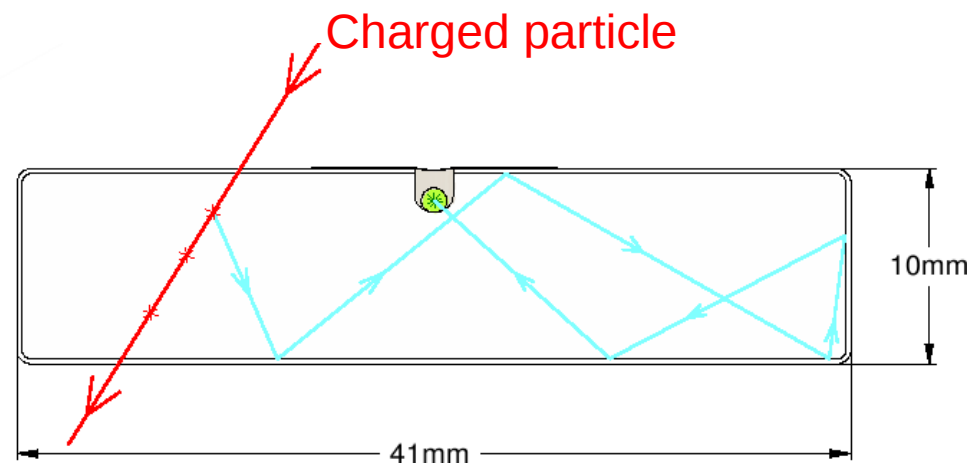
**A module**



**Blue LED lights up scintillator**



**Fiber**





# First Far Detector Beam Event

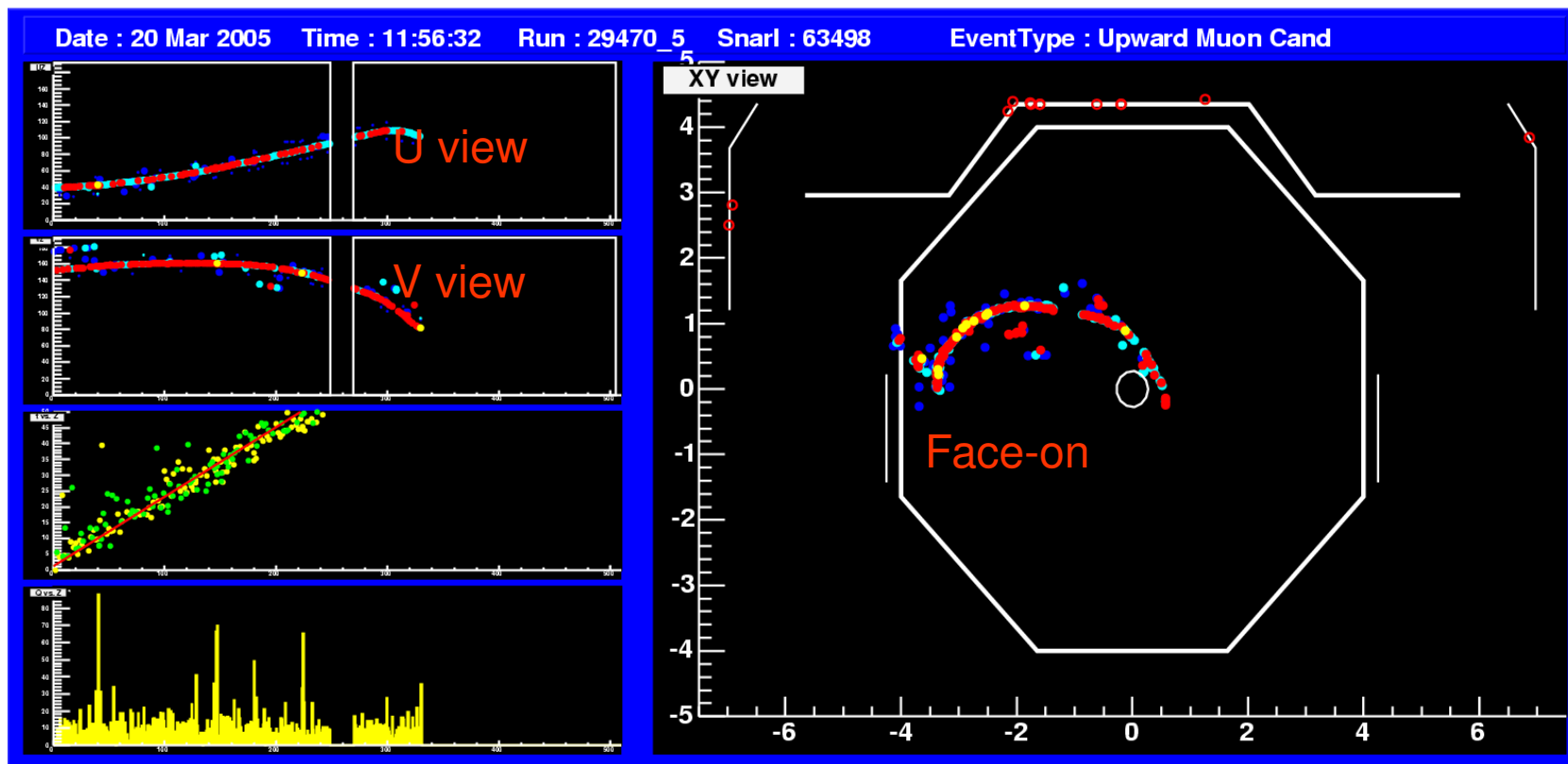
## 20 March 2005



We've now collected a few thousand

See [www.soudan.umn.edu](http://www.soudan.umn.edu) for live MINOS events!

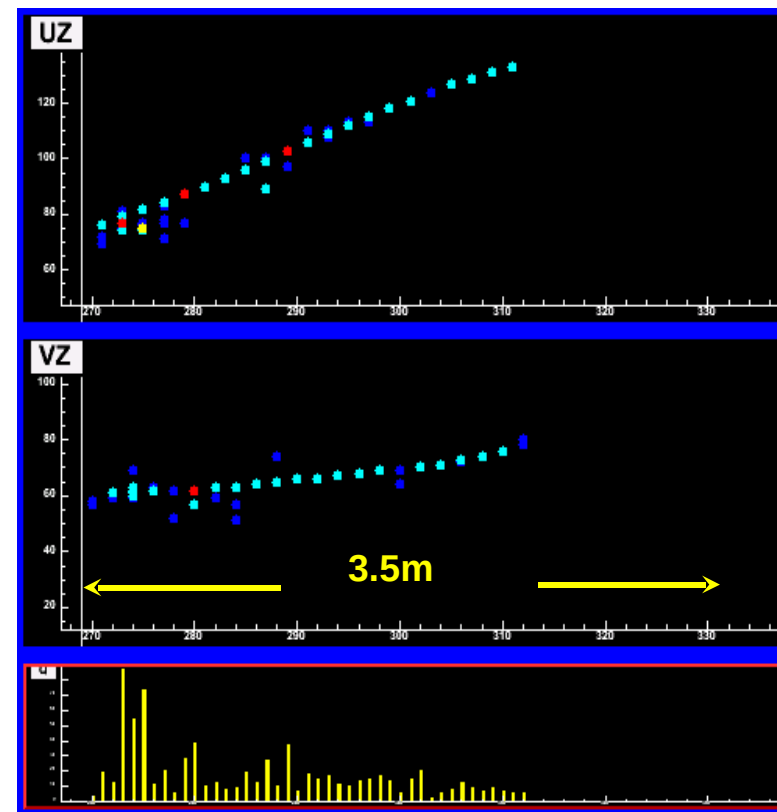
$\nu$  beam  
→  
direction



Note the curvature:  
this is a  $\mu^-$



- As in most neutrino experiments, MINOS can only see one type of neutrino well
  - Muon neutrino: easy to recognize from long clean muon track
  - $\nu + \text{Fe} \rightarrow \mu + X$
- Other two not so easy:
  - Electron neutrino: Possible, but no clear signature in a coarse detector
  - Tau neutrino: Beam is mostly too low energy to produce a tau
- So we look for disappearance



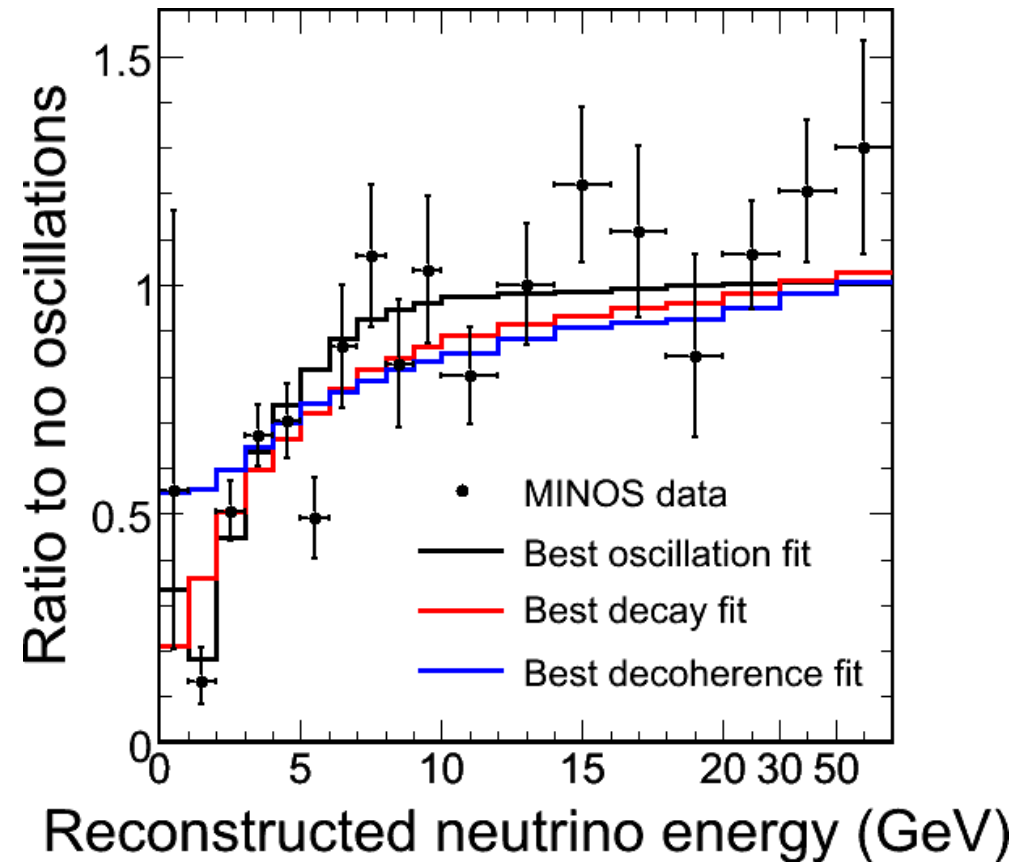
Long  $\mu$  track + hadronic shower at vertex



# MINOS Observation



- Clear deficit
- Energy dependent – looks like oscillation
- *Done*: MINOS has confirmed oscillations in a controlled environment
- *Current task*: precision measurement of parameters
  - Capable of  $\sim 5\text{-}10\%$

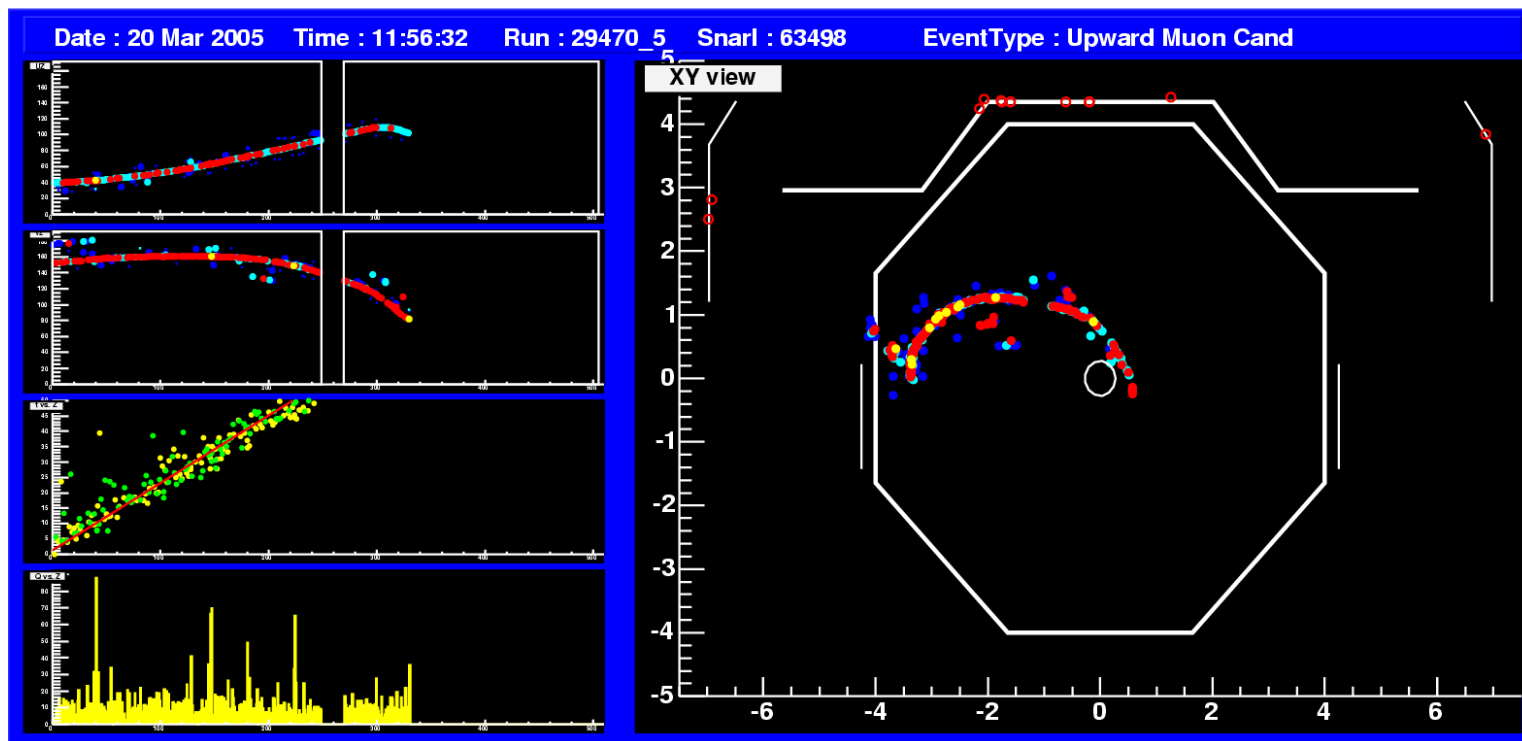






# But That's Not All

- Particle experiments milk their data for all it's worth
  - Grad students have lots of opportunities to figure out how to use the detector for things it wasn't designed for!
- I analyze beam events in the surrounding rock that send a muon into the detector, like our first event here:

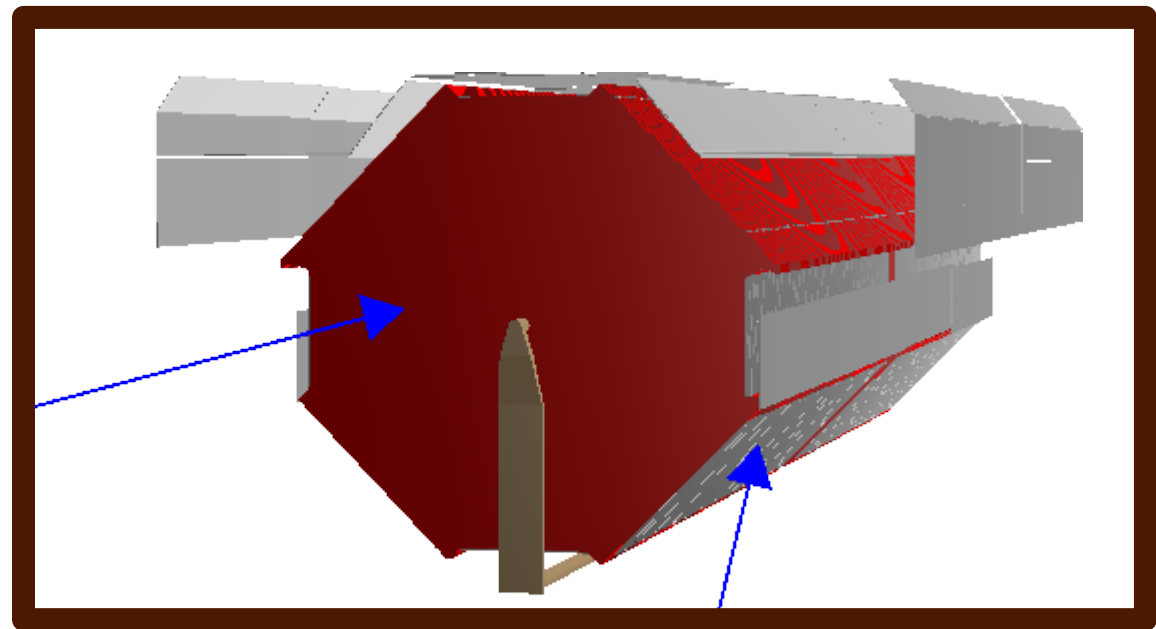




# Rock Muons



- Muon energy only gives a lower bound on  $\nu$  energy
- Major components of this study:
  - Making sure the rock simulation is accurate
    - Measured the cavern, drove to Hibbing to examine the core sample, chatted with geologists. Then lots of coding.
    - Finding best method of classifying events to squeeze the most information out of them

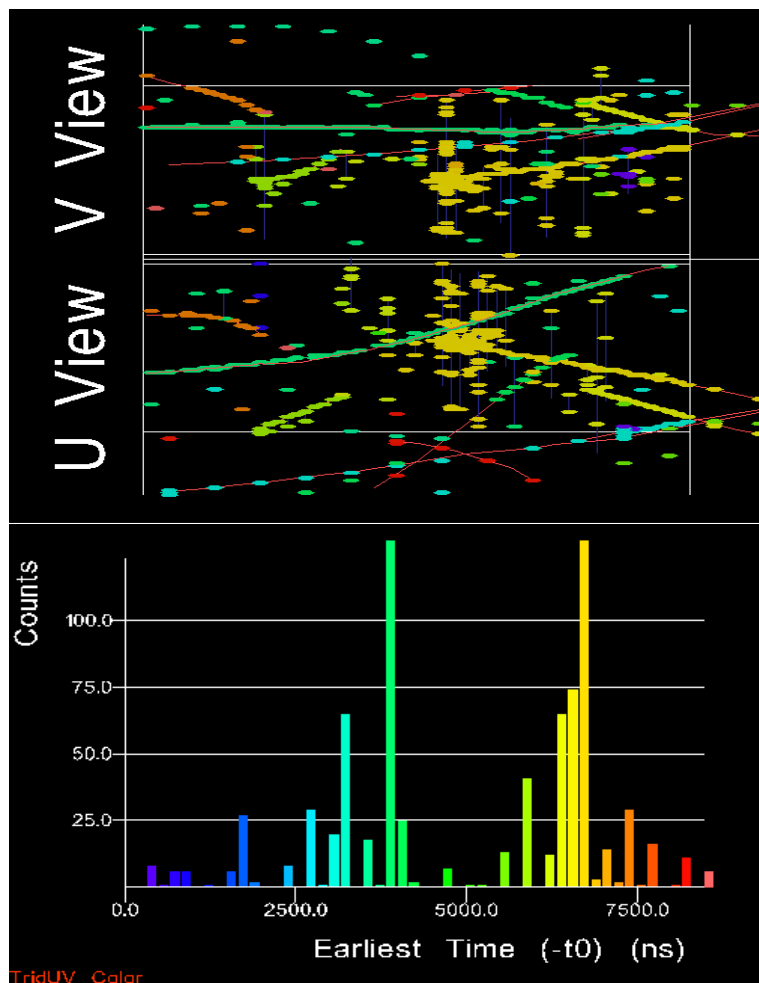




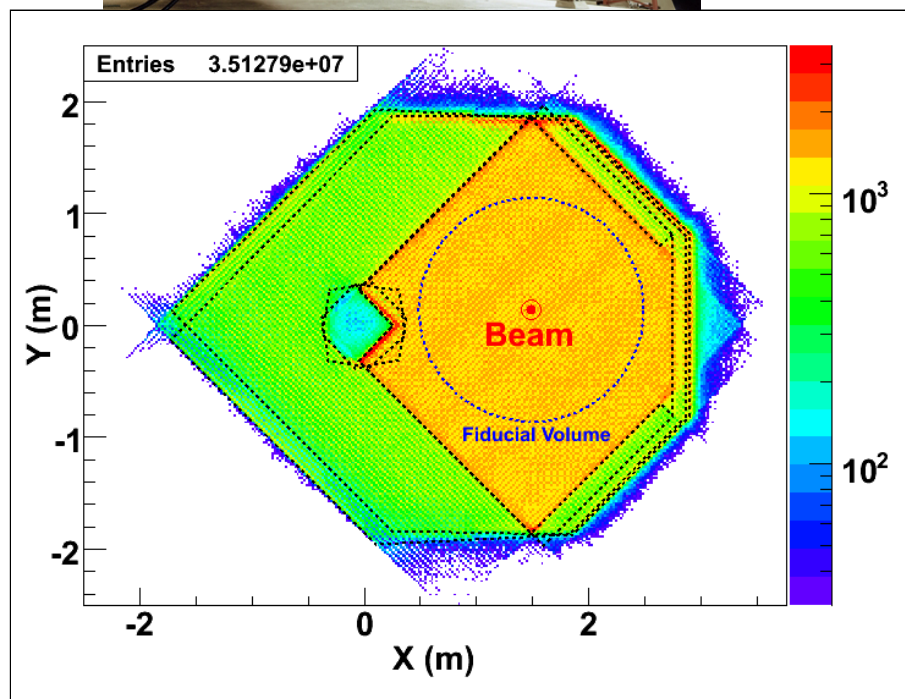
# Near Detector



- Variety of analyses using  $\sim$ infinite data

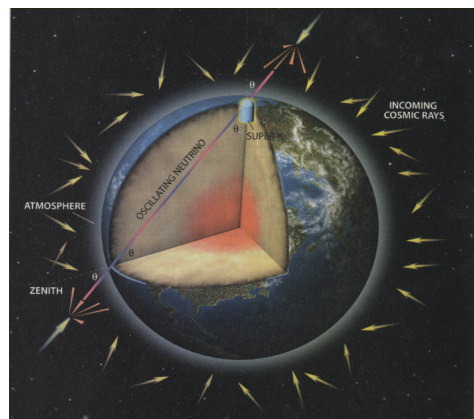
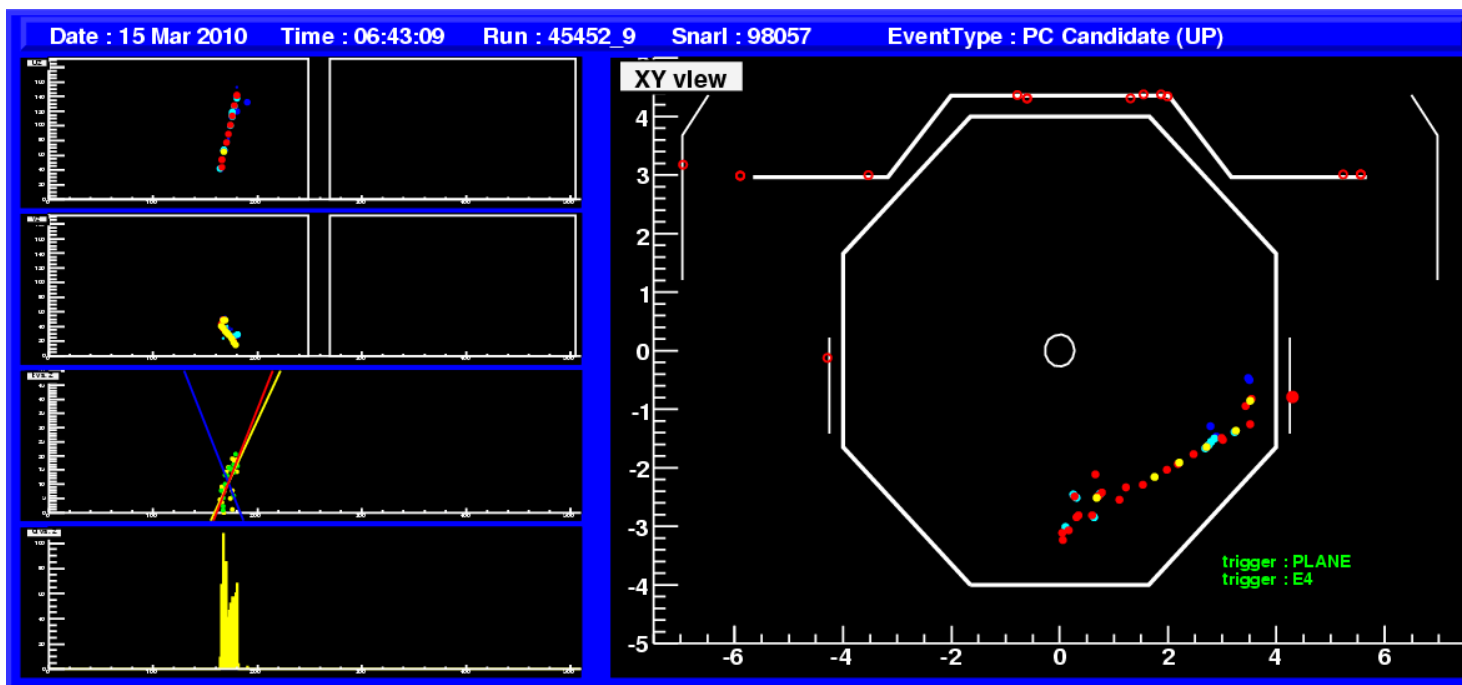


A typical 6-event spill,  
colored by time





- Atmospheric neutrinos from cosmic rays (like Super-K)

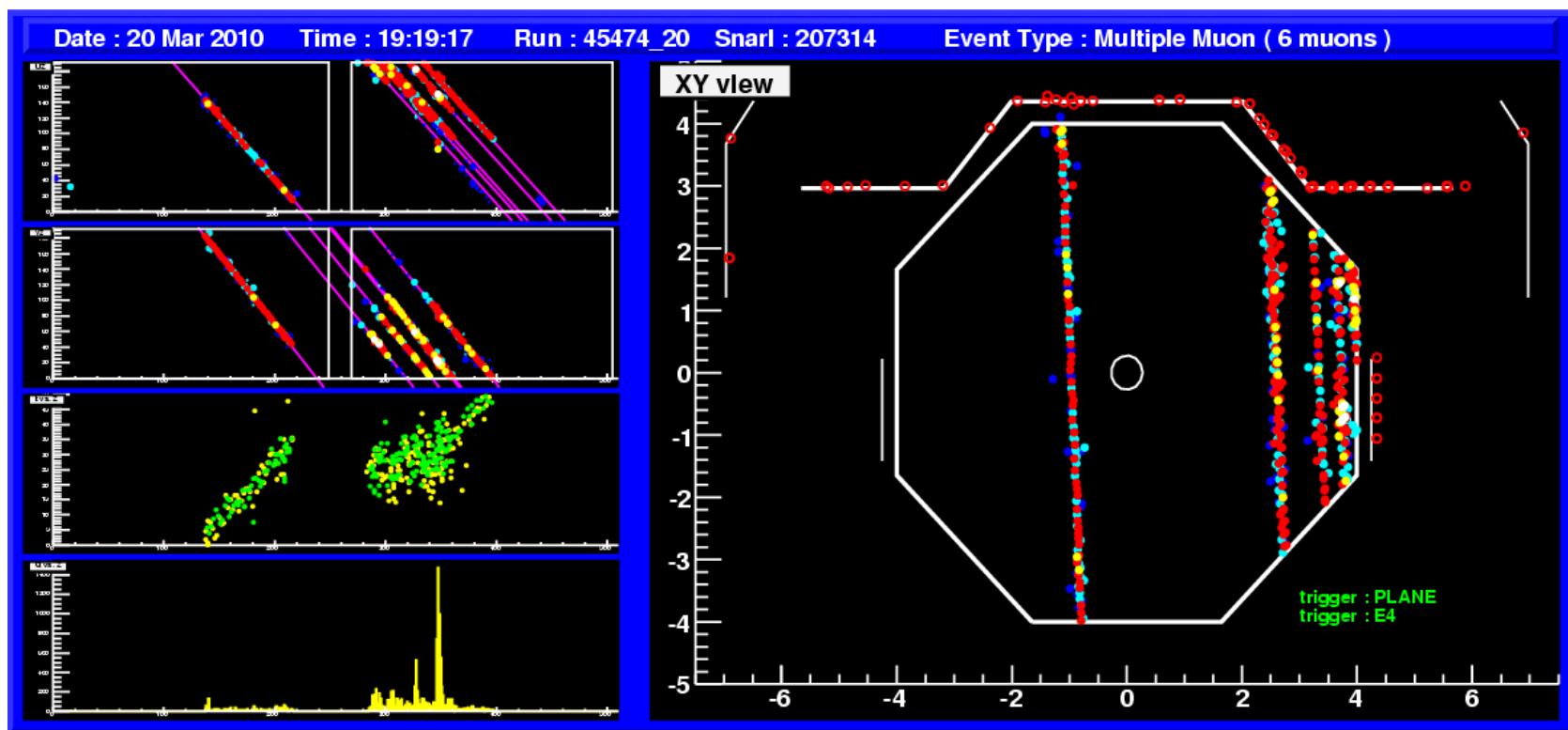


Neutrino from the other side of the Earth



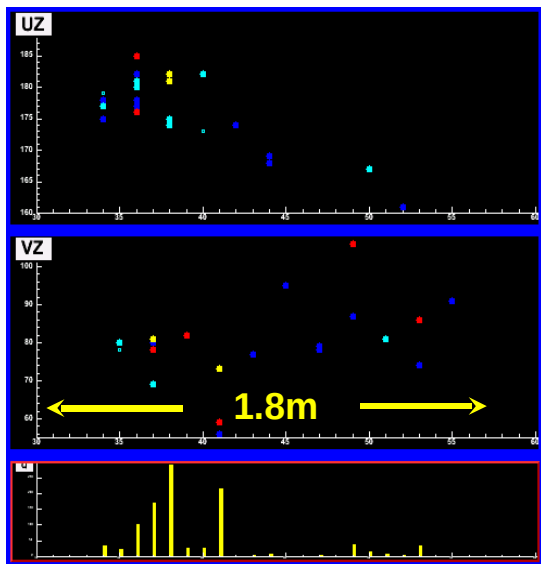
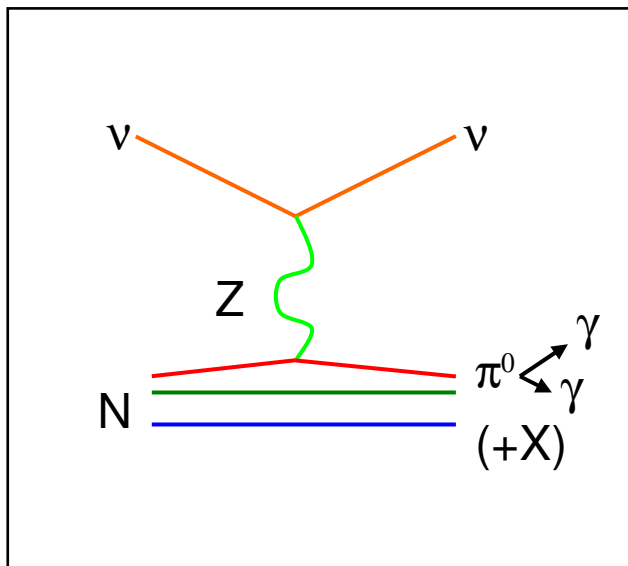


- Look at cosmic rays themselves for various things:
  - Astrophysical point sources or large scale anisotropy
  - Atmospheric effects — can measure the temperature of the stratosphere



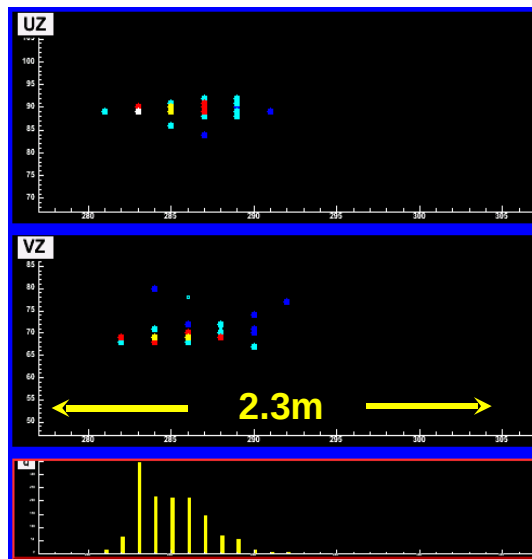
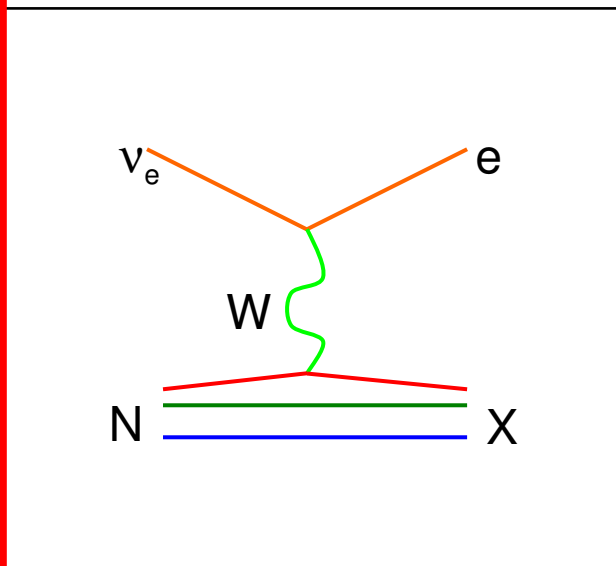


## Neutral Current



Short event, often diffuse

## $\nu_e$ Charged Current

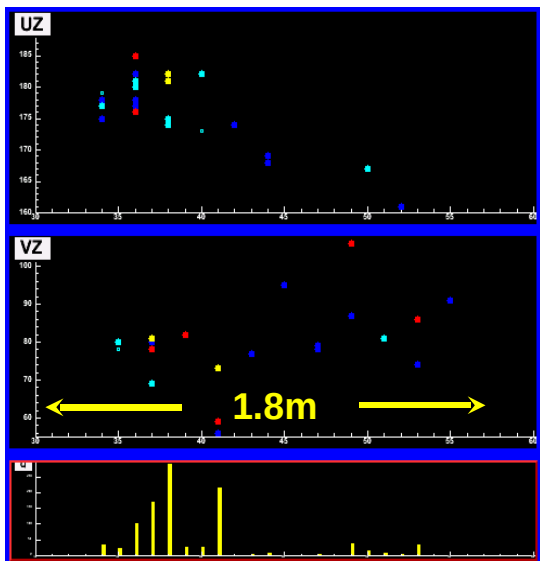
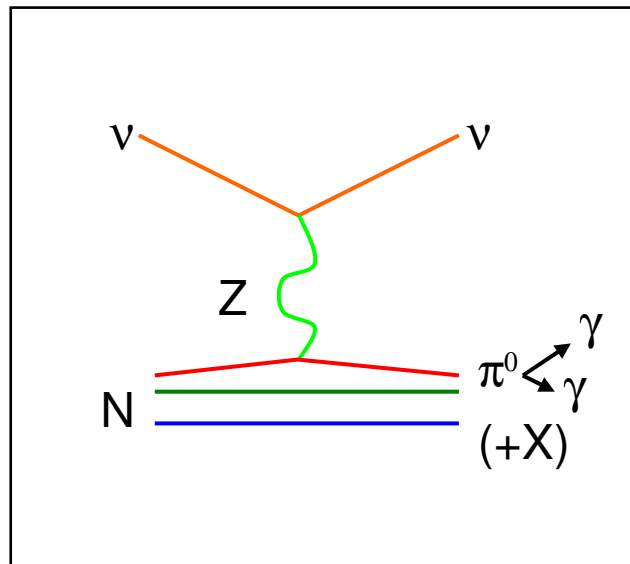


Short, with typical  
EM shower profile

- Neutral current disappearance?
- Ordinarily unaffected by oscillations
  - (remember SNO)
- This would imply extra neutrino types, **new physics**

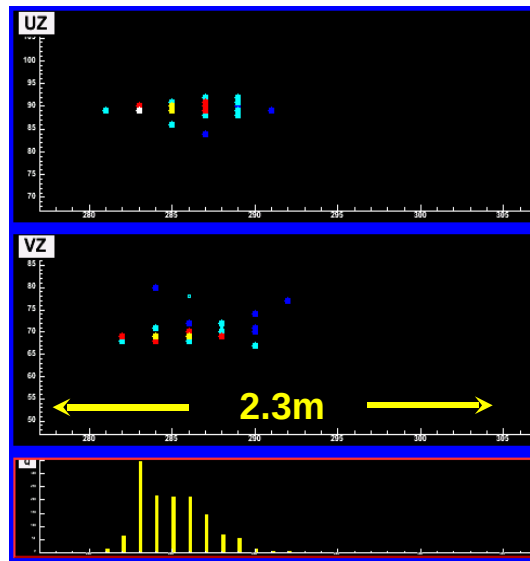
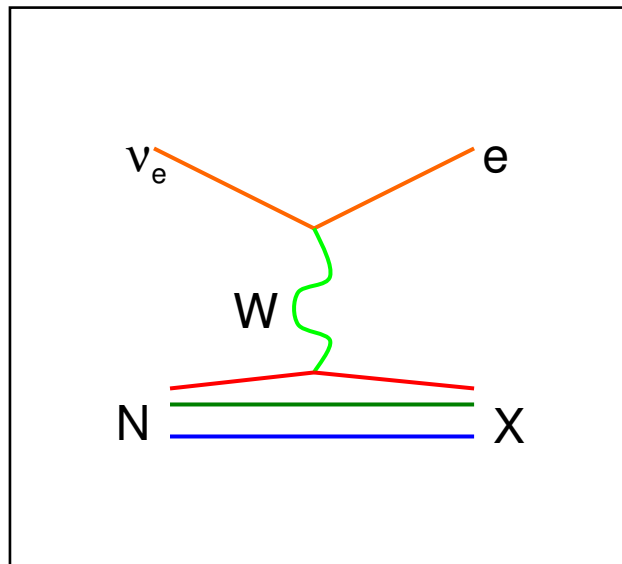


## Neutral Current



Short event, often diffuse

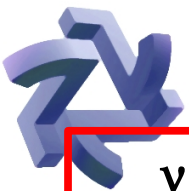
## $\nu_e$ Charged Current



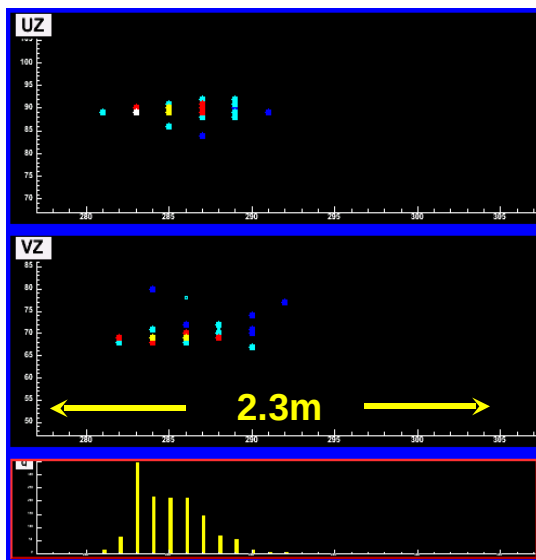
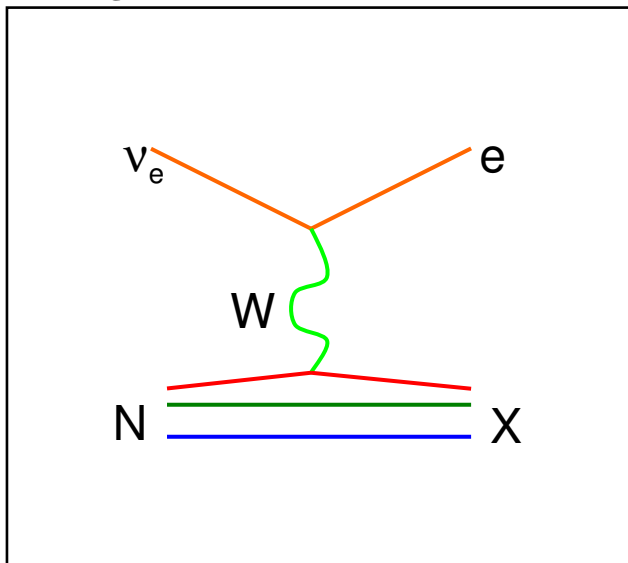
Short, with typical EM shower profile

- Electron neutrino appearance?
- We assume that in some fractions:
  - $\nu_\mu \rightarrow \nu_e$
  - $\nu_\mu \rightarrow \nu_\tau$
- We know that  $\nu_\mu \rightarrow \nu_e$  fraction is small or zero
- Both are hard to measure, but  $\nu_e$  is easier



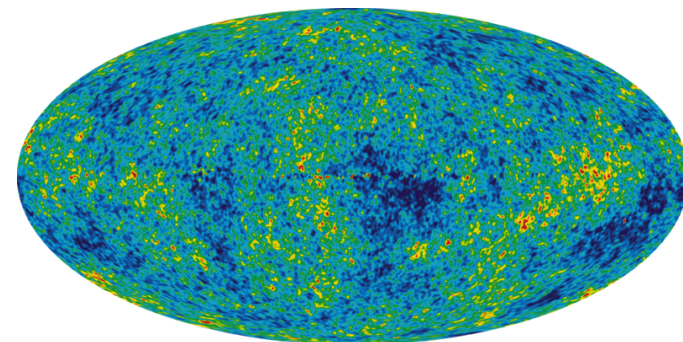
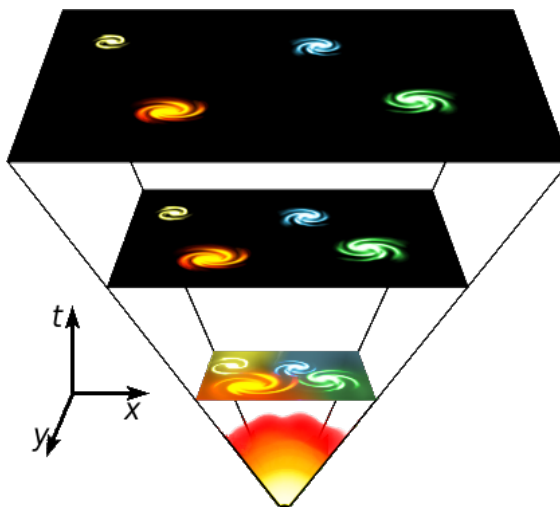


## $\nu_e$ Charged Current



Short, with typical  
EM shower profile

- If  $\nu_\mu \rightarrow \nu_e$ , there are enough degrees of freedom for a matter/antimatter asymmetry
- We need this to explain why the universe has large amounts of matter, but not antimatter
- Exciting topic! Many experiments racing to be the first to observe

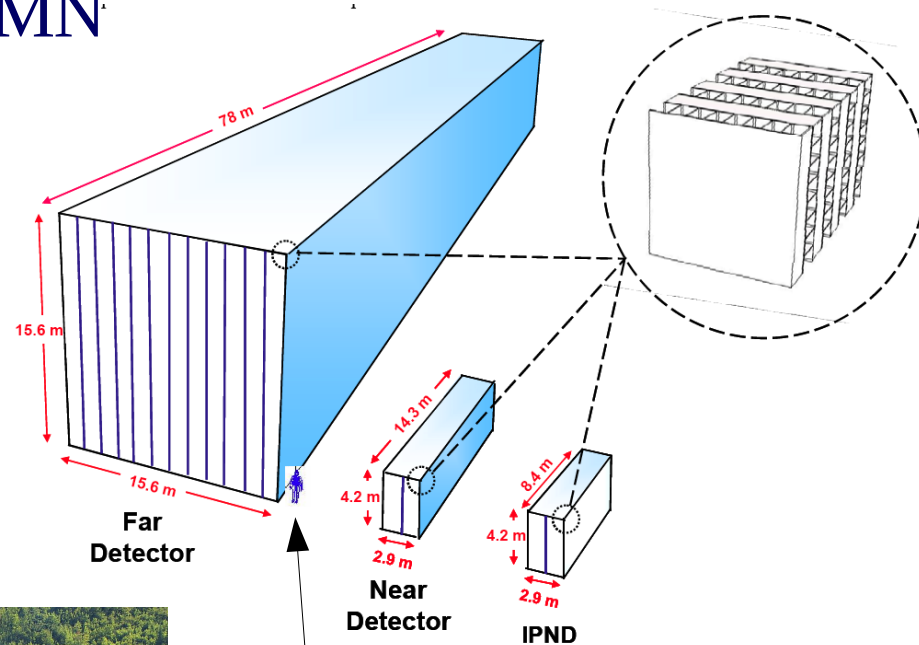




# NOvA



- Speaking of electron neutrino appearance...
- Minnesota is part of the NOvA collaboration
  - 15 000 ton detector in northern MN
  - Currently under construction
  - Will start taking data in ~2014



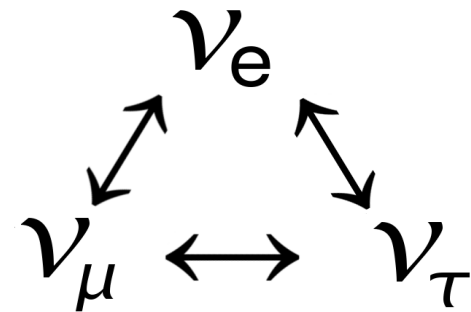
Aug 2009





# Summary

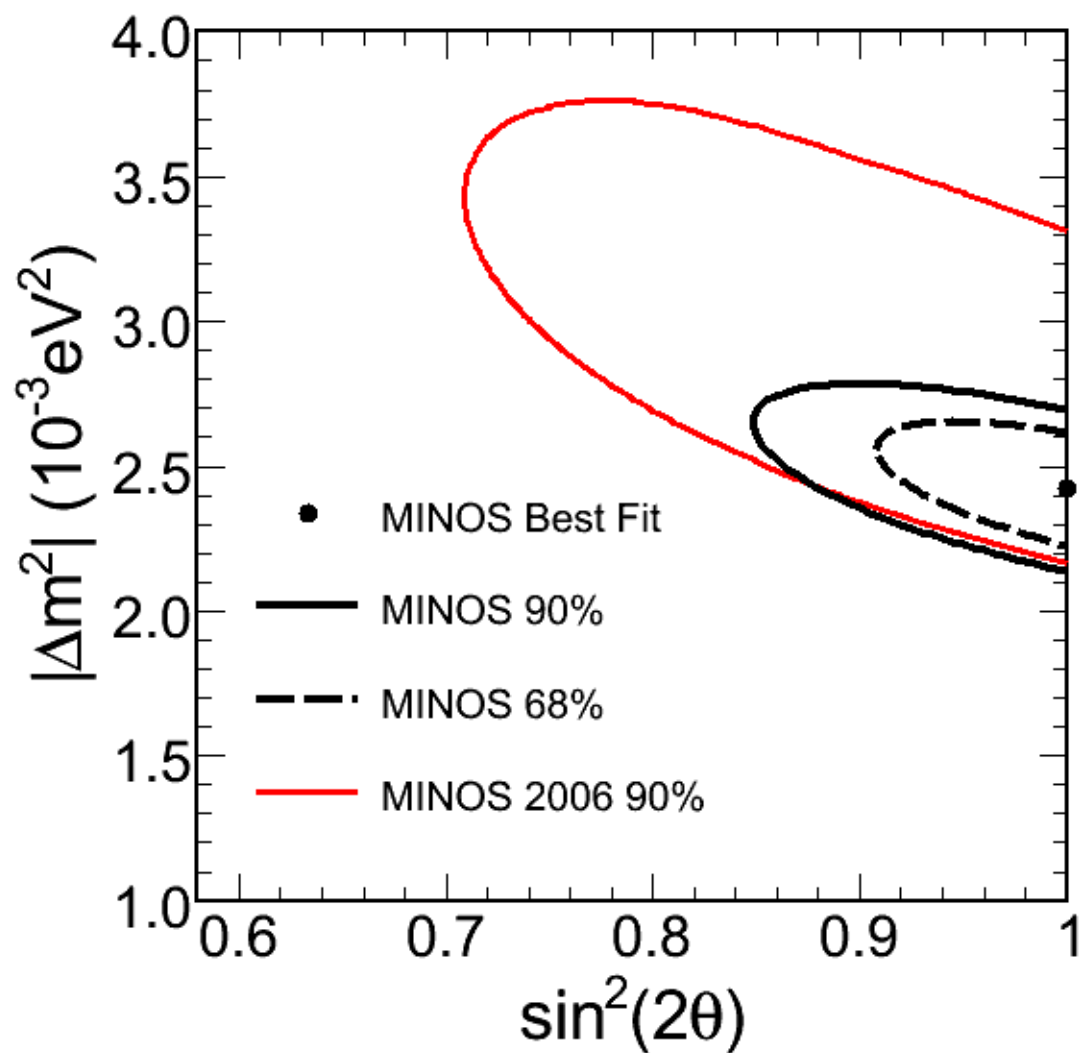
- Three kinds of neutrinos have been observed
- Puzzling deficits of neutrinos are well explained by neutrino oscillations, as shown by:
  - SNO (solar)
  - Super-K (atmospheric)
  - MINOS (beam)
  - And others
- The field is moving into the exploration phase
  - Many experiments coming on line
  - Plenty of potential for exciting discoveries
- Come visit! There are daily MINOS tours in the summer
  - Do the historical mine tour while you're there too
  - [www.soudan.umn.edu](http://www.soudan.umn.edu) for details





# Backup





This represents half of the data taken so far -- new result coming in 2010



# 3 Neutrino Oscillation

- Expand the two neutrino matrix to a three neutrino matrix (PMNS)
- Replace  $\cos(\theta_{ij}) = c_{ij}$  and  $\sin(\theta_{ij}) = s_{ij}$ , and include phase (CP violation)

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







# What Do We Really Do?



- During design and construction:
  - 50% hardware R+D
  - 50% writing/running simulations, documentation, etc. (sitting at a computer)
- Once experiment is running:
  - 95% analyzing data (sitting at a computer)
  - 5% on shift at Fermilab (sitting at a lot of computers)
  - $\lesssim 0.1\%$  working on detector — it's very stable!