Digging for Gold:
Long Baseline Neutrino Experiment in the

Brian Rebel
February 8, 2012

LBNE Nuggets

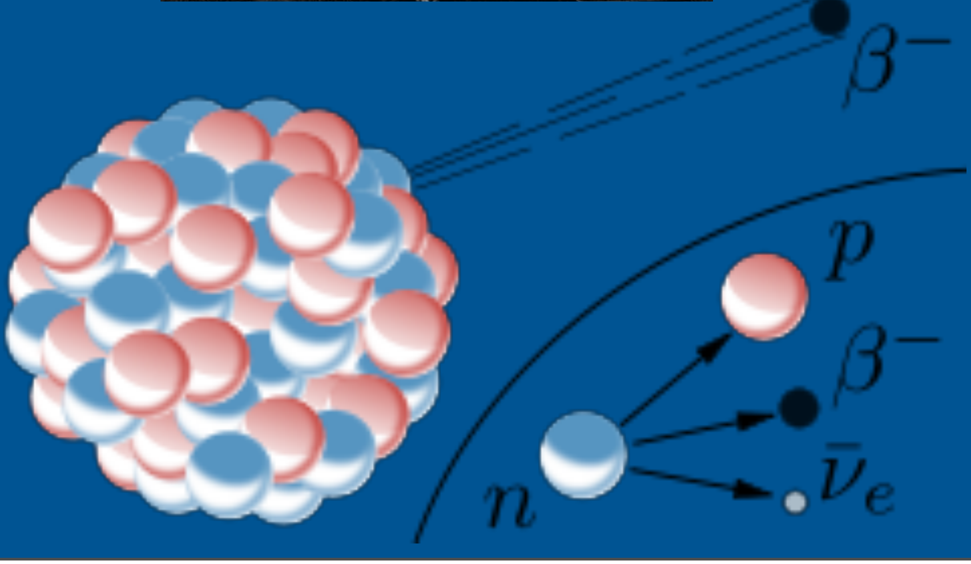
- LBNE is the next generation of neutrino experiment after NOνA
- The processes LBNE will look for are all really rare, like gold nuggets
- Need to have a grand scale to even begin: massive detectors, long distances for the neutrinos to travel, intense beams
- The knowledge gained will be revolutionary - maybe even answer the question as to why we are here

Outline

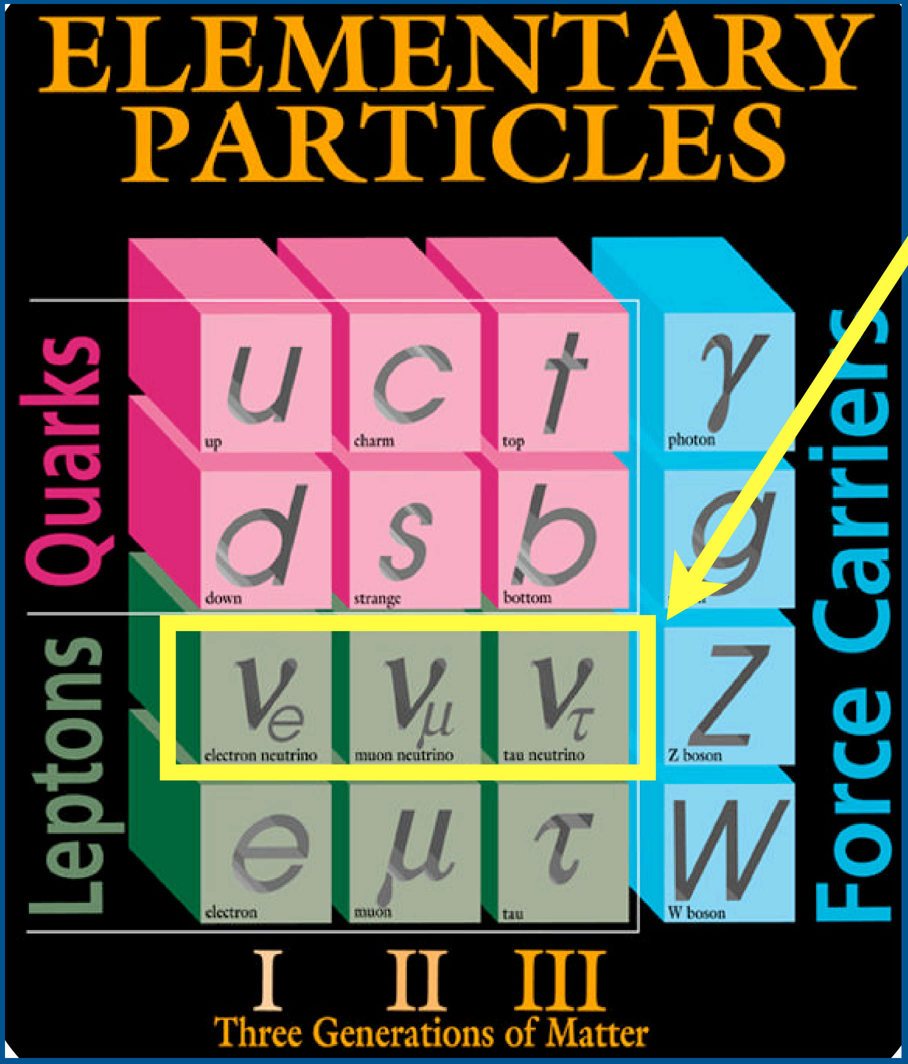
- What are neutrinos and why study them
- How to detect neutrinos
- Long Baseline Neutrino Experiment (LBNE)
- Summary

Origin Story

- The existence of the neutrino was first suggested by Wolfgang Pauli in 1930
- Used to explain missing energy when neutrons convert (decay) to protons and electrons
- Pauli proposed the neutrino in a letter to a conference as his presence at a ball in Zurich was "indispensable"
- Enrico Fermi was the first person to call them neutrinos

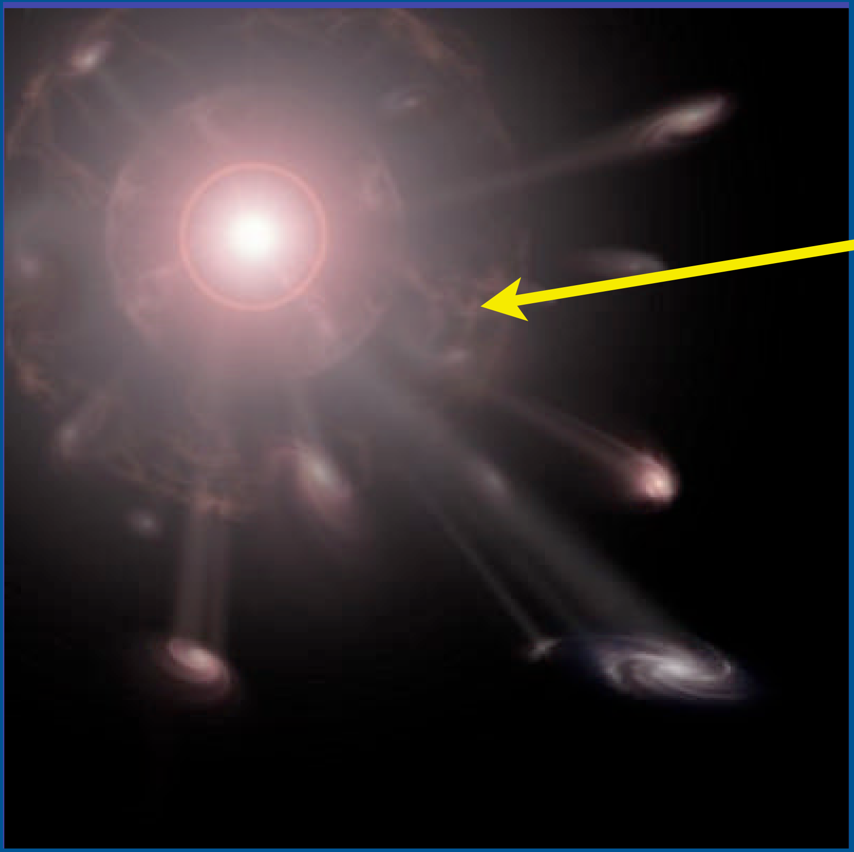


What is a Neutrino?



- Neutrinos make up 1/4 of the known elementary particles
- Neutrinos have no charge
- Neutrinos have very little mass
- Neutrinos tend to ignore other forms of matter
- Can travel 1 light year in lead on average before interacting - 5.9 trillion miles
- Neutrinos are everywhere! They play many roles in the universe so we want to understand how they behave

Where Do Neutrinos Come From?

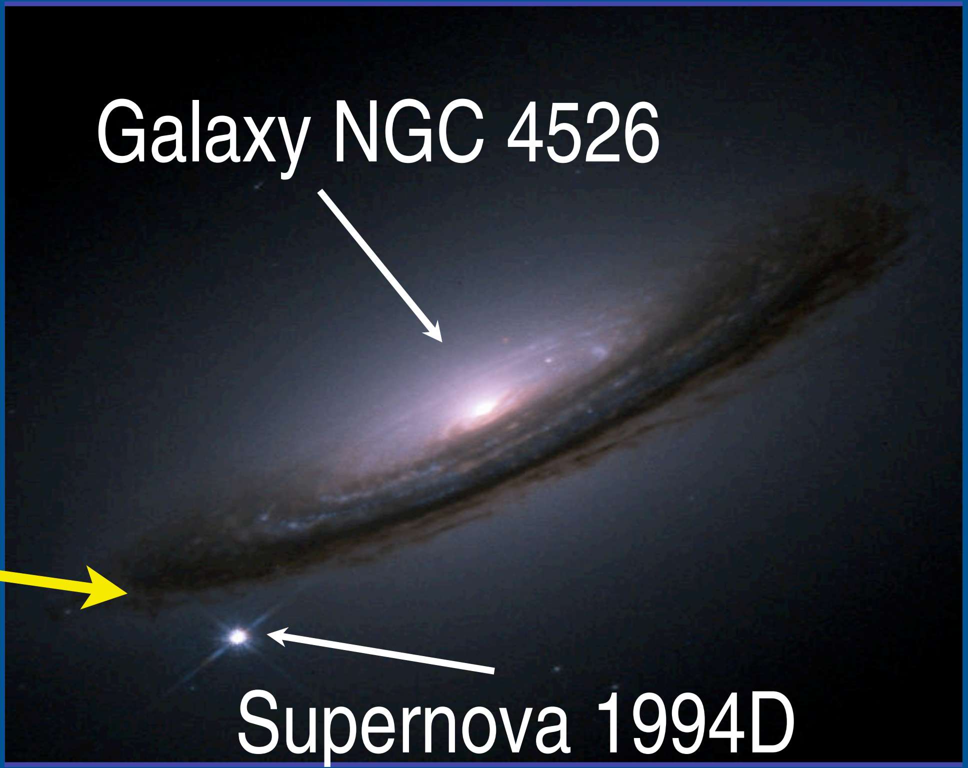


Big Bang - neutrinos from the start of time are everywhere in the universe - about 400 in the tip of your thumb right now

Important to formation of galaxies in early universe

Super Novae - 99% of the energy is in neutrinos

Observing neutrinos from super novae would tells us about how stars die



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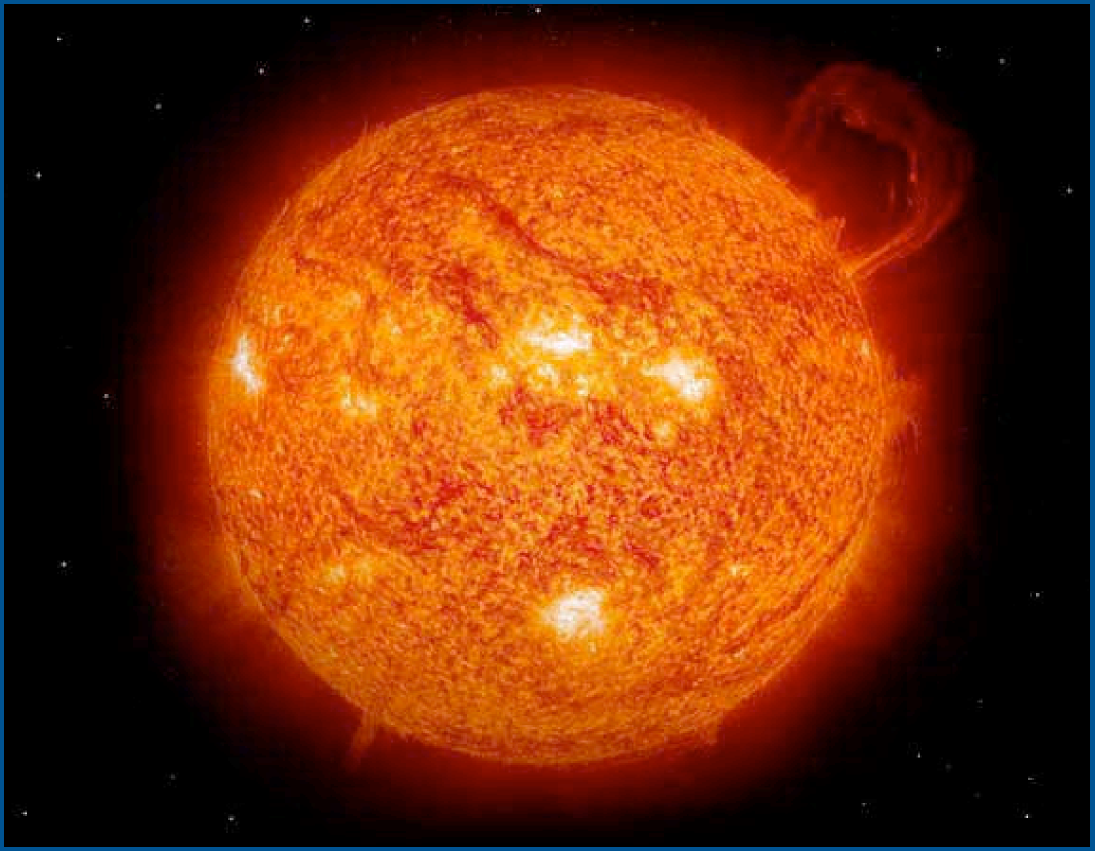
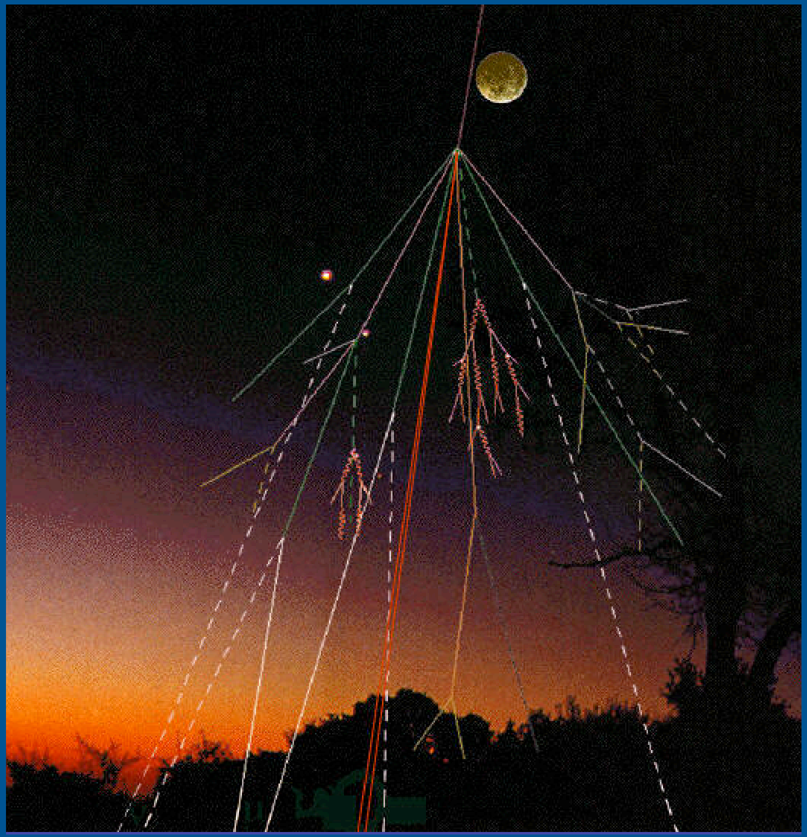




Stars - 100 billion neutrinos produced in fusion reactions in the sun go through your thumbnail every second, day or night

Neutrinos offer a way to see inside of the sun and understand how it shines

The atmosphere - high energy cosmic particles strike molecules in the atmosphere creating neutrinos. 10 atmospheric neutrinos pass through your thumbnail each second

Where Do Neutrinos Come From?

Nuclear Reactors - 400,000 Braidwood reactor neutrinos will pass through your thumbnail each second during this talk

Accelerators - Like those at Fermilab

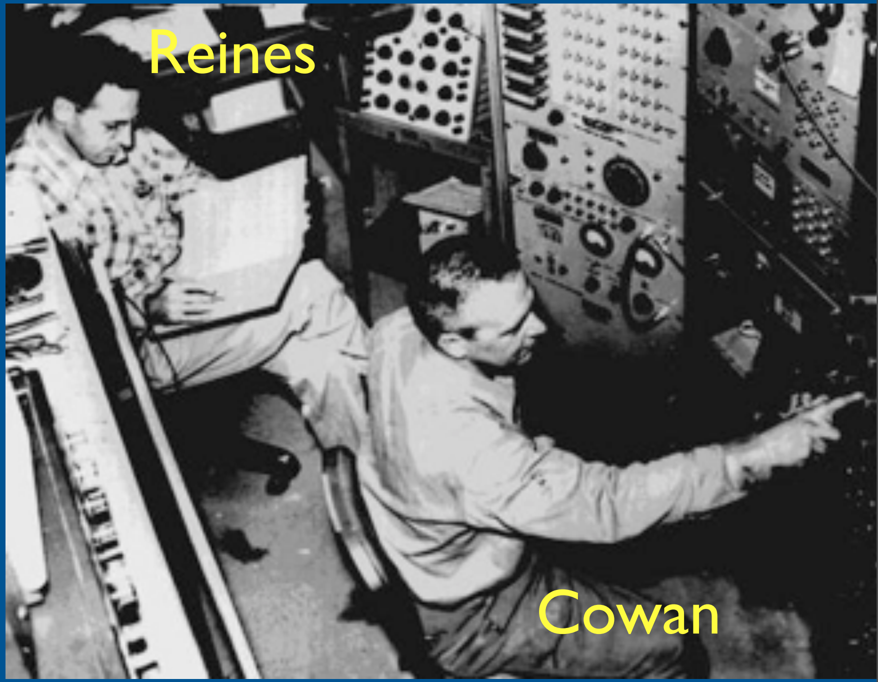
Produce about 5 neutrinos for each proton from the Main Injector that strikes the target

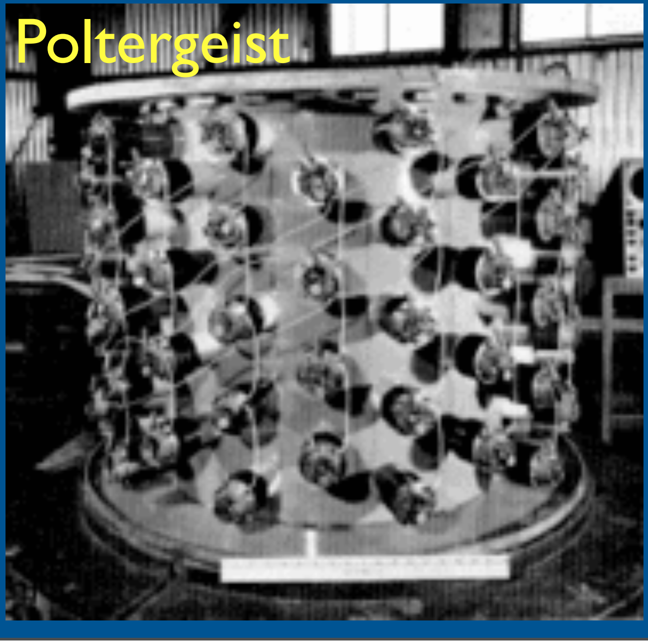
Where Do Neutrinos Come From?

Bananas - an average banana emits about 1 million neutrinos/day from the decays of the small number of naturally occurring radioactive potassium atoms in it

If you had a banana today, you are a neutrino source!

Finding Neutrinos





- Cowan and Reines (1956) were the first to detect neutrinos using a nuclear reactor as the source
- The experiment was called Poltergeist - a nod to the ghostly nature of the neutrino
- The interaction they detected was

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

- The e+ annihilated with an e- in the detector producing 2 photons
- The neutron was captured and produced another photon 5 μs later

Detecting Neutrinos

- Because neutrinos rarely interact with other forms of matter, neutrino detectors are typically very big
- Modern detectors tend to have thousands of tons of mass
- Play the statistics game - the chance of any one neutrino interacting is small, so use as many neutrinos as you can and give the neutrinos many chances to interact
- Never actually see the neutrino, just the particles produced by the interaction
- Just like mining - only get a few ounces of gold for every ton of rock

Neutrino Detectors

- Like any good sluice box, neutrino detectors have to separate gold (neutrinos) from common rock (backgrounds)
- The current neutrino detectors at Fermilab are MiniBooNE, MINERνA, MINOS and NOνA
- Other major neutrino detectors in the world include Super-K (Japan), Daya Bay (China), Opera (Italy)

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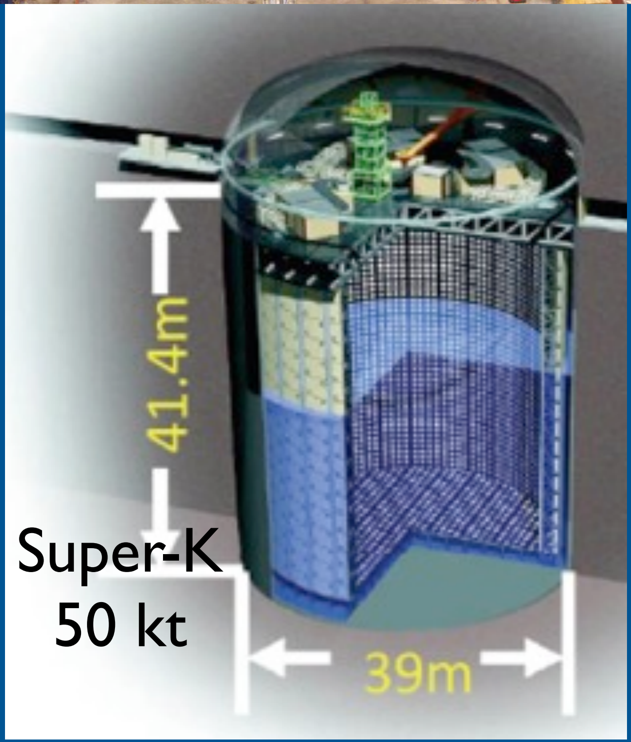
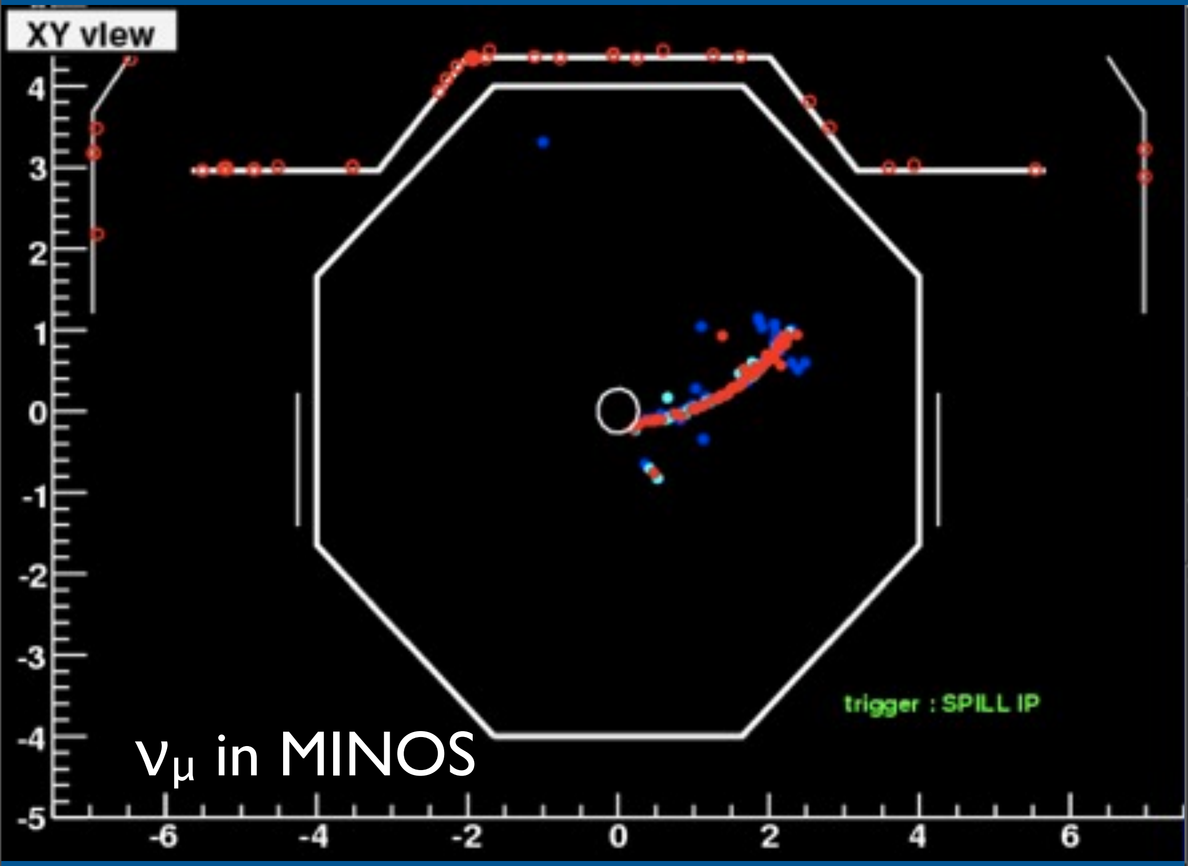
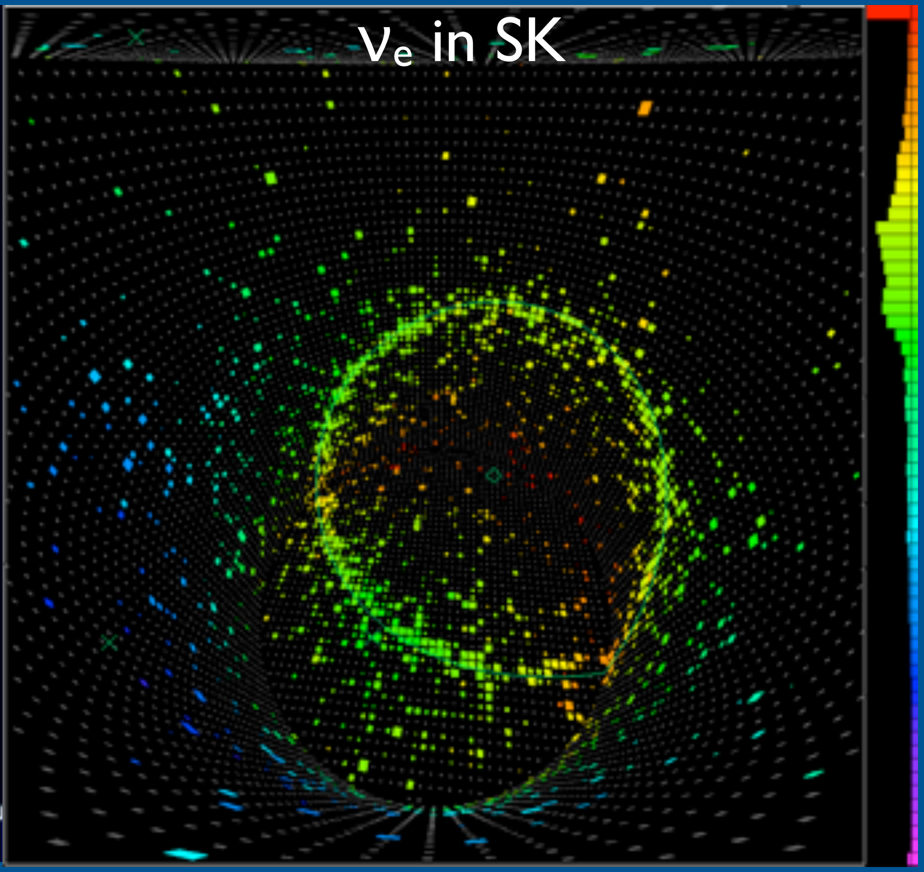


Neutrino Interactions in the MINOS and Super-K Detectors





Missing Neutrinos

- Neutrinos from the sun were first observed by the Homestake experiment in the 1960’s
- Only found ~1/3 the number of solar neutrinos expected
- A similar mystery was found with the atmospheric neutrinos - ~1/2 the number expected were observed

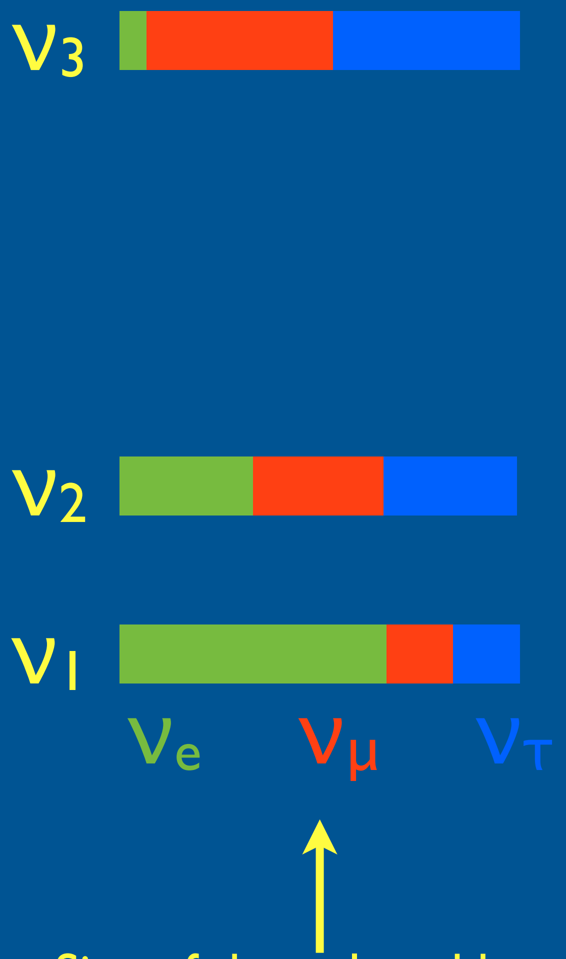
Neutrinos Change Type!

- Neutrinos change from one type (flavor) to another, called oscillations
- Oscillations occur because the neutrino flavors we observe are actually combinations of other neutrinos defined by their mass
- We have learned a lot about how these changes happen

Symmetry Magazine

What We Know

- MINOS has made the most precise measurement of the difference between 2 neutrino masses
- Experiments in Japan and Canada measured the other difference
- Neutrinos coming from the Sun have an equal chance of being detected as any of the 3 types
- Neutrinos produced in the atmosphere are muon neutrinos and change into tau neutrinos about 1/2 the time
- Muon neutrinos may change into electron neutrinos, MINOS and NOνA are looking for that process as are T2K and several other experiments



Size of the colored box indicates probability of interacting as a specific flavor

Why Build LBNE?

- We need a new experiment to answer new questions about neutrino conversion
  - Is our current understanding enough to explain all observations?
  - Are there more neutrinos than the 3 types we directly observe?
  - How often does a ν_μ change into a ν_e? Maybe it is so infrequent that MINOS, NOνA and others won't see it
  - What is the relative ordering of the masses?
  - Do neutrinos and anti-neutrinos oscillate with the same probability?

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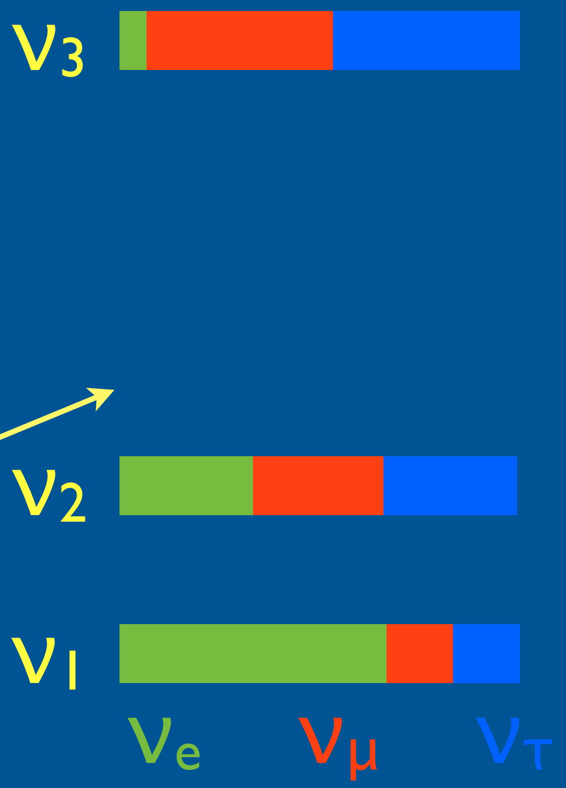

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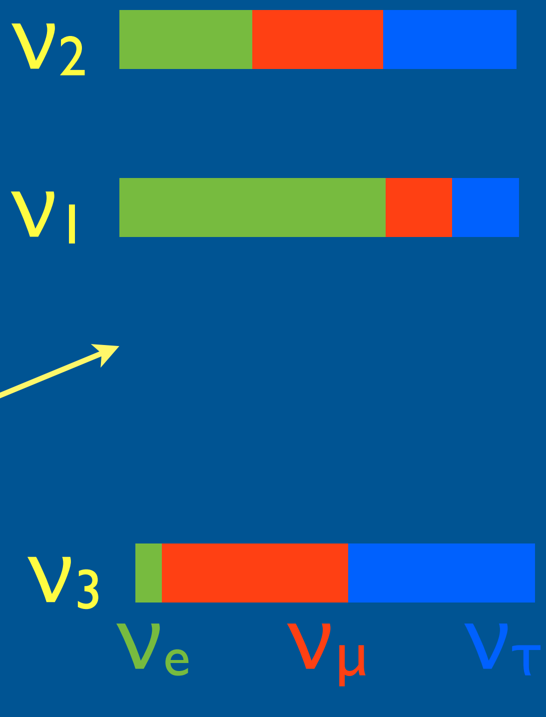

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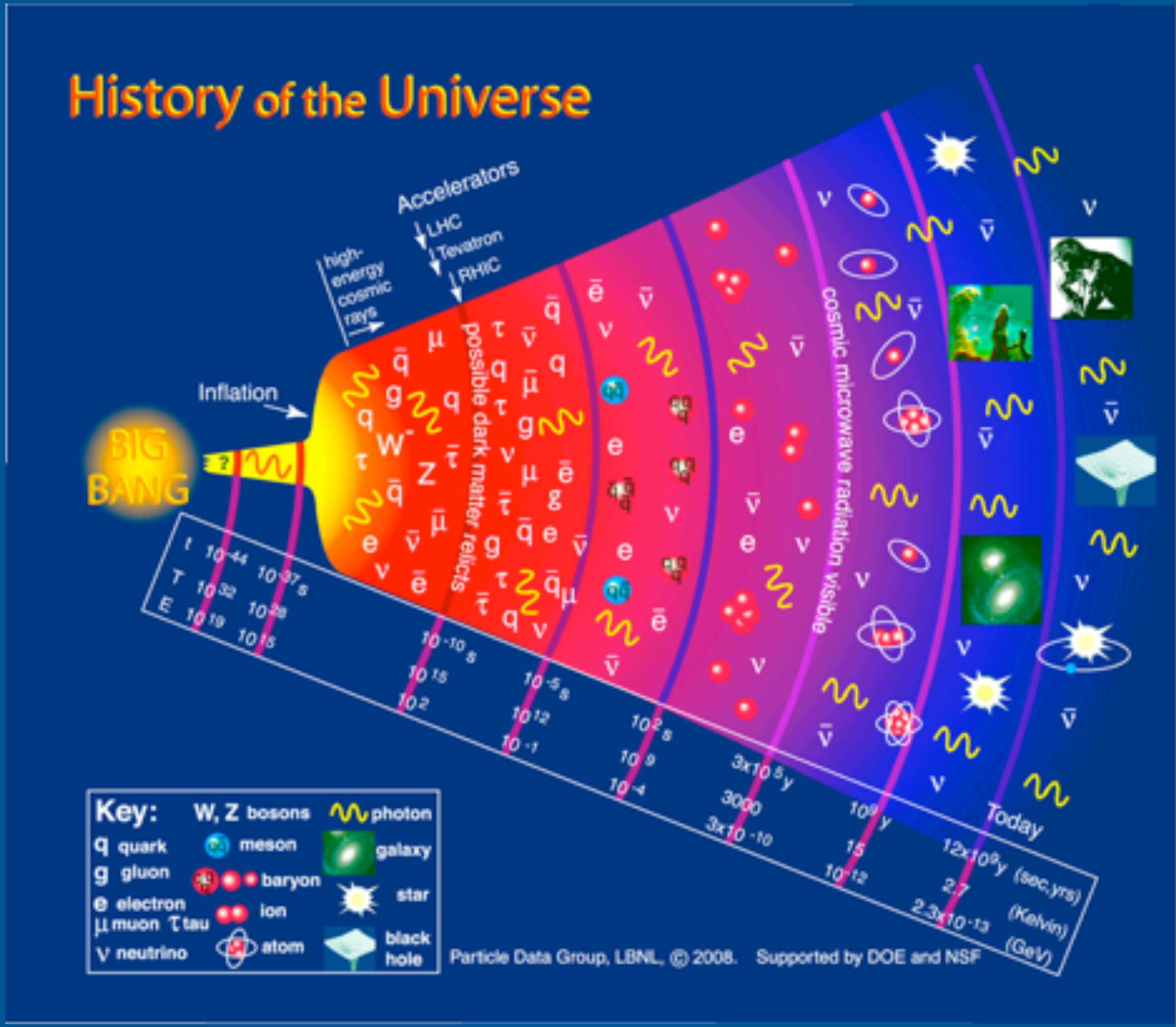
Why We Care about Neutrino vs Antineutrino Oscillations

- In the early Universe there were equal amounts of matter and antimatter
- At some point the amount of matter becomes slightly larger
- Almost all of the matter and antimatter annihilate
- What is left over becomes us
- How did it happen? Maybe neutrinos hold the key



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Matter: 100,000,001

Antimatter: 100,000,001

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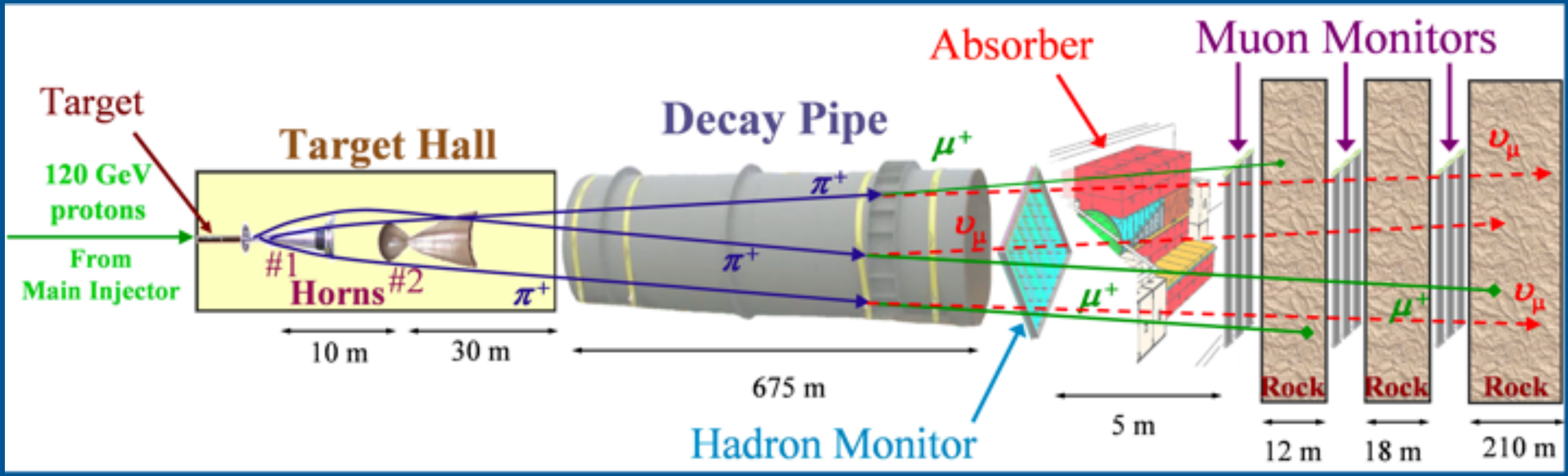
Matter: 2

Antimatter: 0

Long Baseline Neutrino Experiment

- LBNE is the next generation of neutrino oscillation experiments
- 3 main ingredients: a beam and 2 detectors
- Near detector is at at Fermilab and far one is 800 miles away in South Dakota
- Far detector is 40,000 tons of liquid argon
- Very large detector is needed to allow us to observe enough neutrinos to answer the outstanding questions

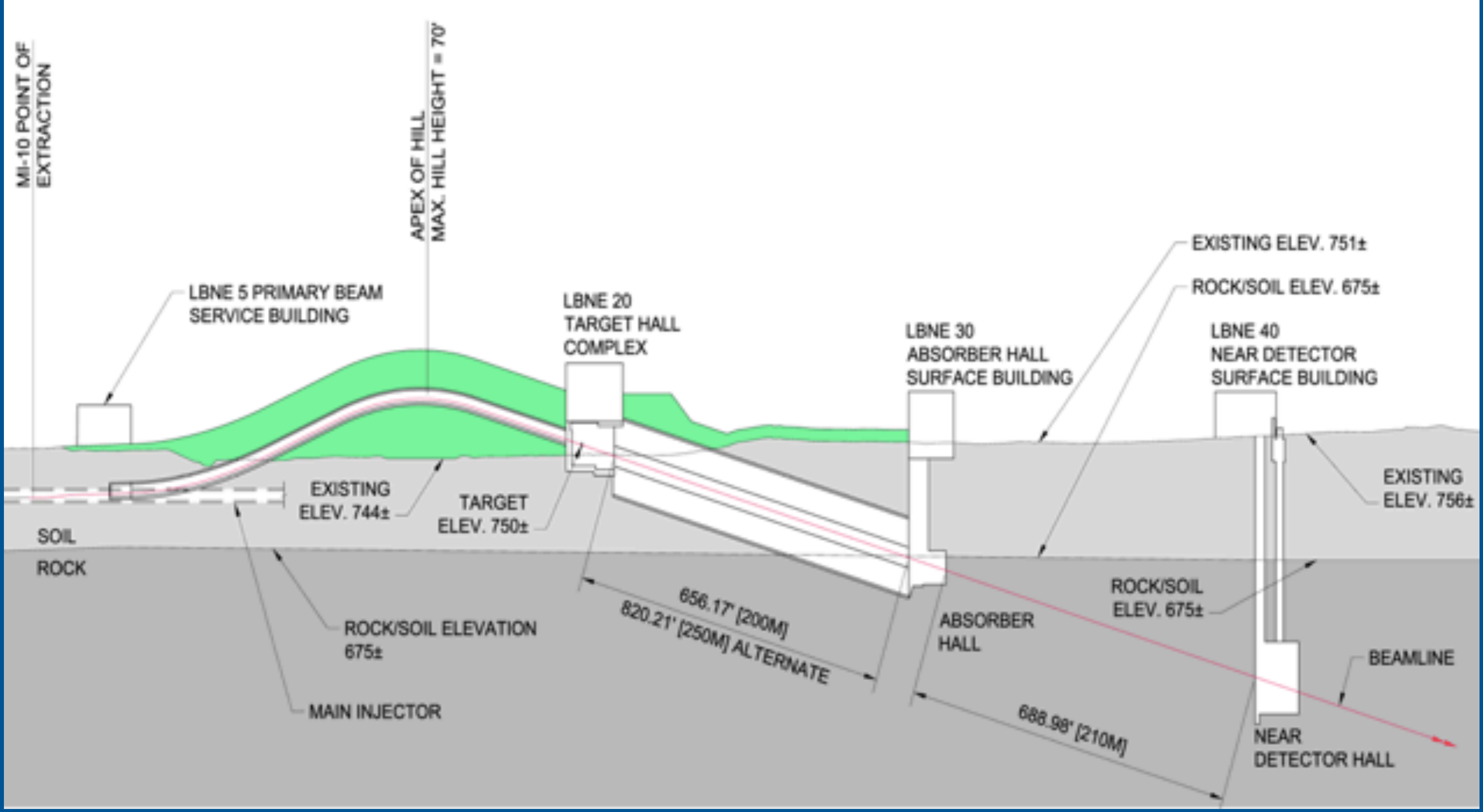
Making a Neutrino Beam



- Accelerate protons to have the desired energy and then smash them into a target
- Use magnetic horns to focus the produced particles which are unstable and decay into muons and neutrinos
- Make sure to deliver as many protons as possible as quickly as possible to make lots of neutrinos
- LBNE and NOνA want to double the number of protons hitting the target compared to what NuMI currently provides in the same amount of time

The LBNE Beam

The LBNE Beam



- Design is to build a hill to take the beam up before pointing it toward South Dakota
- Allows the near detector to be at a shallower depth than otherwise

Why Do the Neutrinos have to Travel So Far?

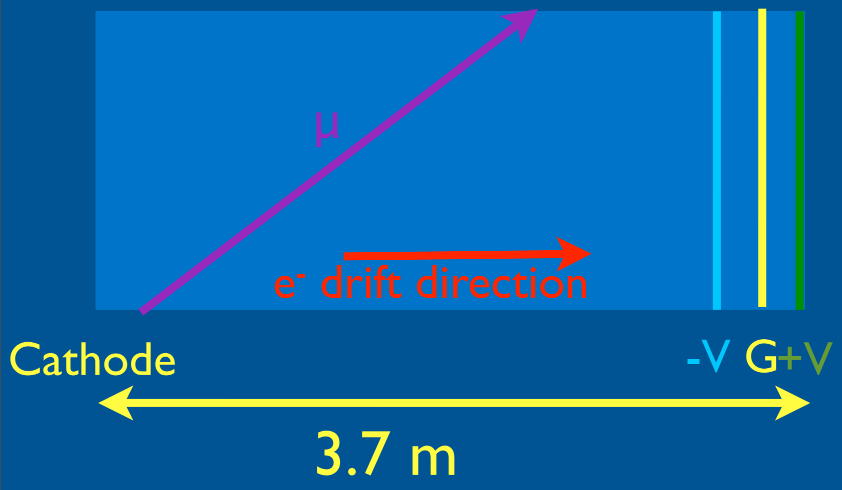
- Finding gold today is more challenging than in the gold rush, need bigger equipment to do it
- Supersize the experiment to measure the low probability conversion, ie $\nu_\mu \rightarrow \nu_e$
- New experiments need longer distances - ν_e are more likely to appear due interactions with e^- in the Earth's crust
- Which neutrino is the most massive also influences appearance probability
- Using beams of neutrinos and then anti-neutrinos helps establish if their appearance rates are different

Why Underground?

SANFORD
UNDERGROUND
LABORATORY
AT HOMESTAKE

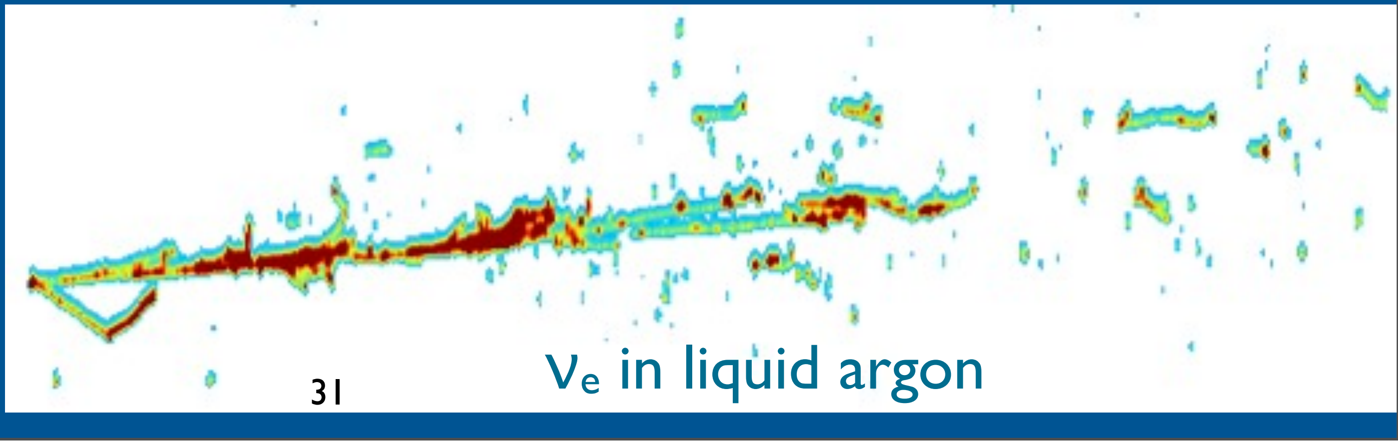
- The target location for LBNE is at the 4850’ level of the Homestake mine
- Same location as the cavern that housed the Davis experiment that discovered the solar neutrino problem
- The rock between the cavern and the surface reduces the back ground from cosmic rays to be 3 million times smaller than at the surface
- Depth allows us to look for neutrinos and other phenomena not associated with the beam (more later)

The Far Detector

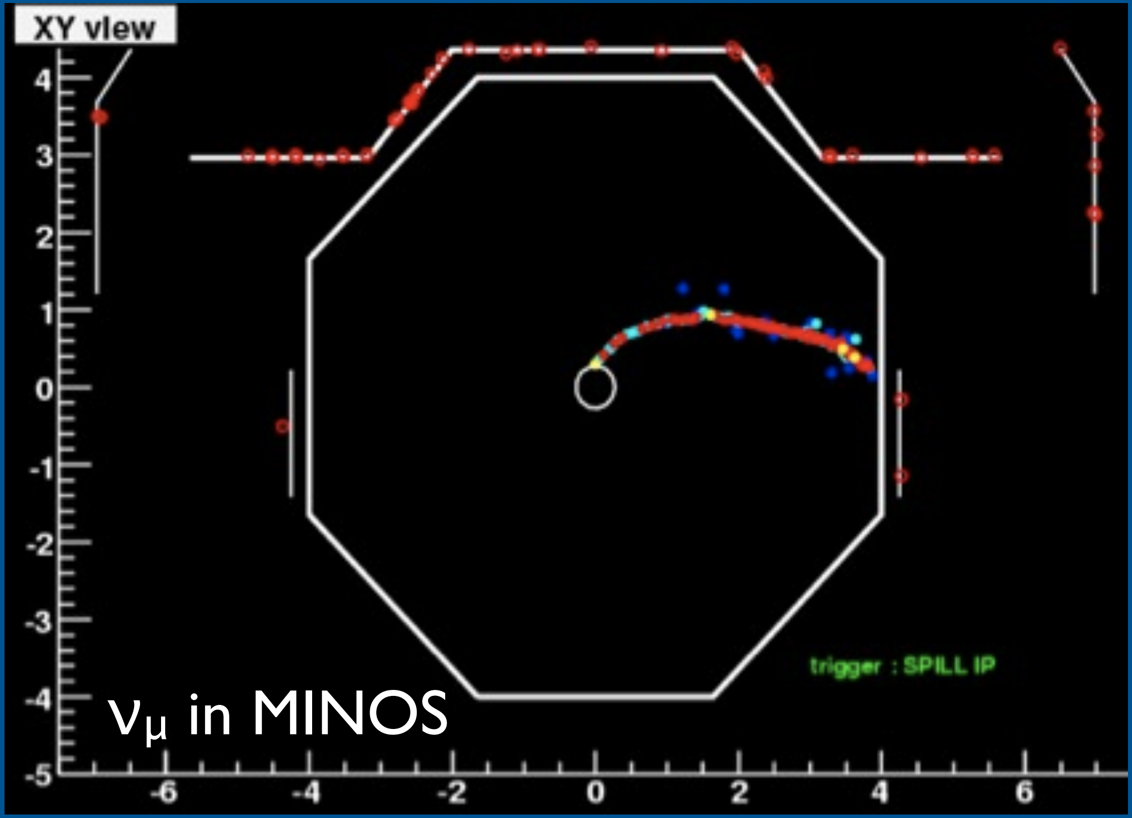


- Liquid argon time projection chamber chosen as technology
- Charged particles going through liquid argon release 23,000 electrons/inch
- Electrons drift toward readout planes over a period of 2.4 ms, starting positions of the electrons are recorded to produce an image of the interaction
- Like taking a digital photograph of a neutrino interaction

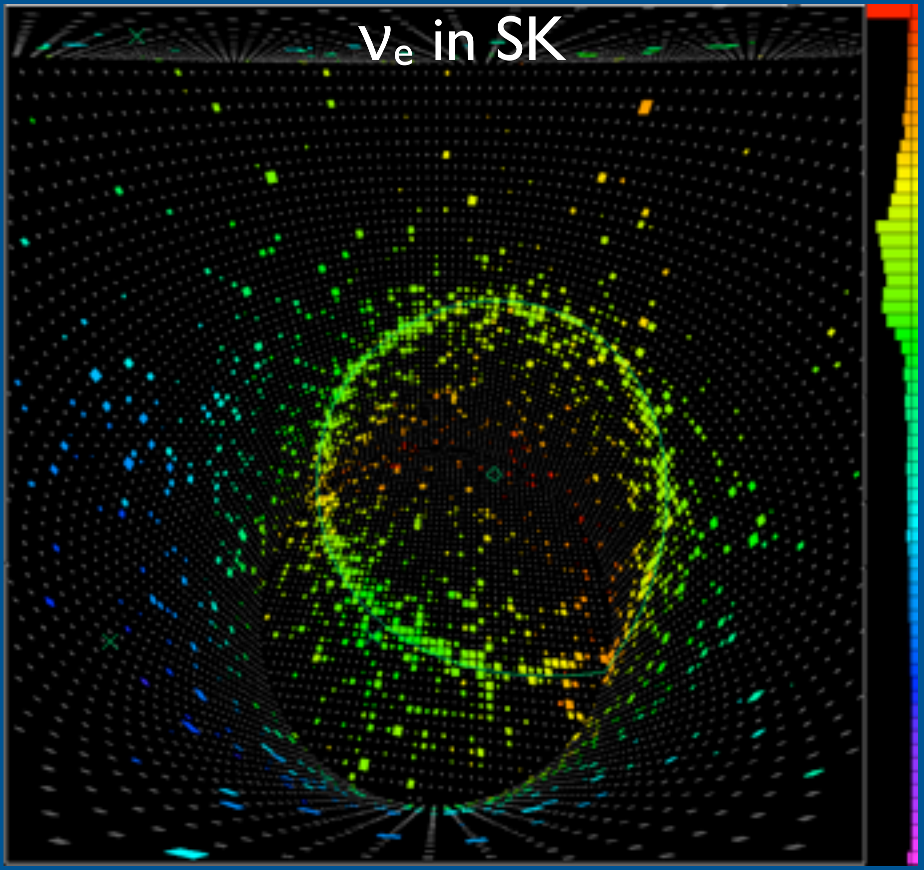

Liquid Argon in a FNAL test stand


ν_e in liquid argon

Comparing Detectors

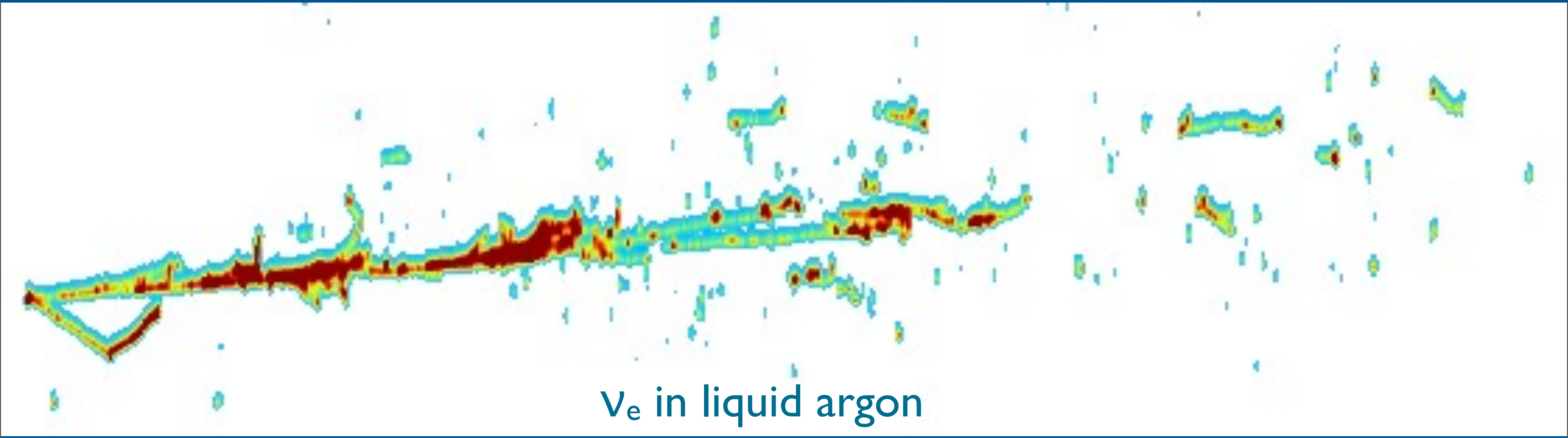


ν_μ in MINOS



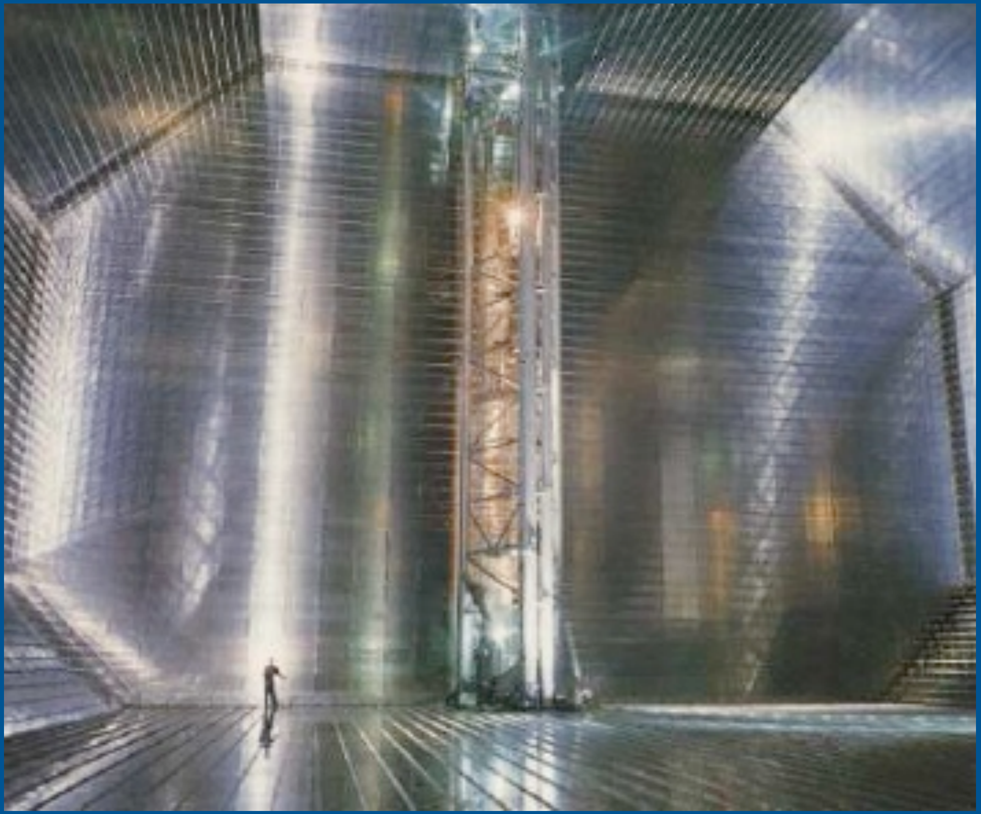
ν_e in SK

Comparing Detectors



ν_e in liquid argon

Building the Far Detector



- Far detector will contain 40,000 tons of liquid argon
- Membrane cryostat is the chosen technology to hold it
- Makes effective use of cavern space
- Liquid natural gas tankers have used the technology for decades with much larger volumes
- Working with industry to develop design

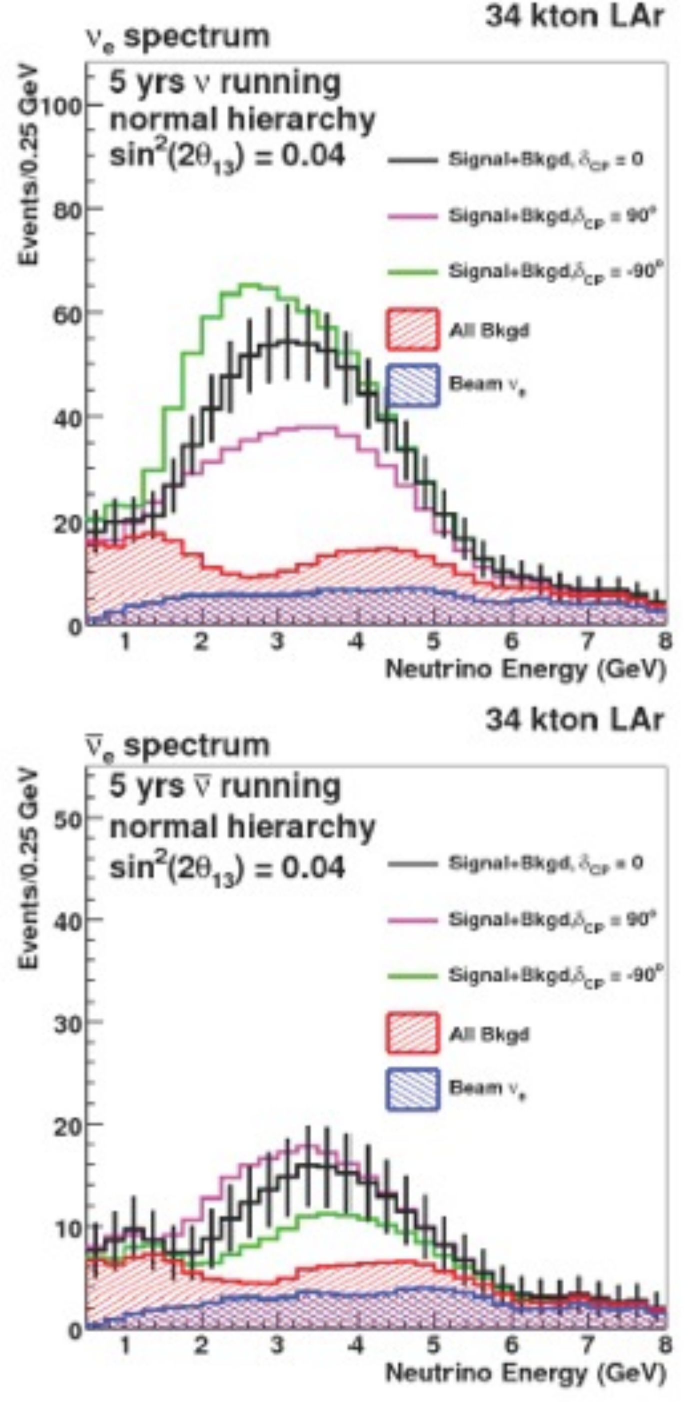
LBNE Expected Event Rate

- Plots at right show the expected number of electron (anti)neutrino events at the far detector for 5 years in each beam configuration

- Would see about 500 electron neutrinos and 100 electron antineutrinos, depending on the probability of the conversion from muon (anti) neutrinos

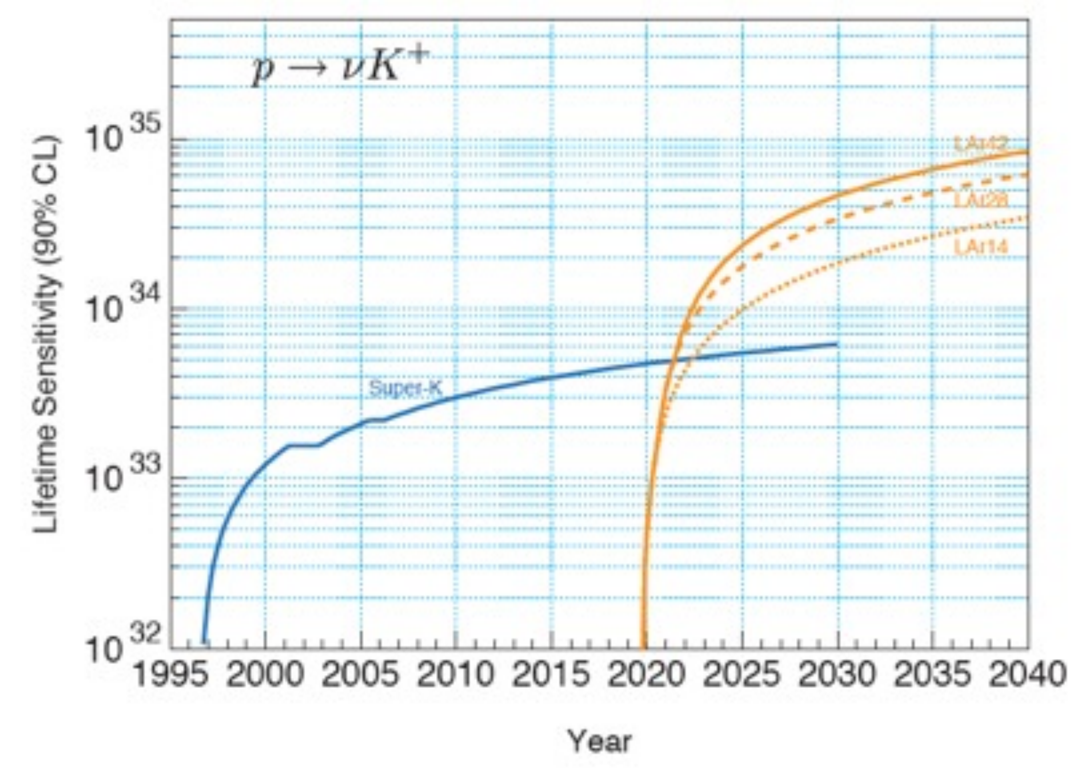
- The order of the masses and the differences between neutrino and antineutrino oscillations can change those numbers

- 600 total "golden" events for 10 years of running - mining may be easier



Other Physics with LBNE

- The LBNE far detector can also be used for physics beyond neutrino oscillations
- Can dramatically improve the limits on how stable protons are, also complimentary to on-going measurements
- Will detect thousands of neutrinos from any super novae that explode in our area of the galaxy - last one we only saw 24 from the last one
- Can even look for neutrinos from super novae that exploded in the past

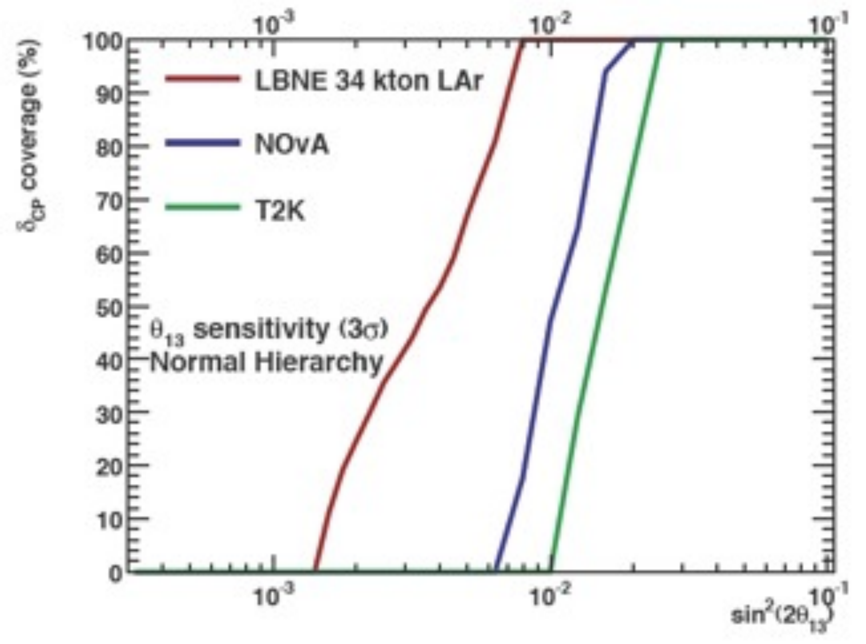


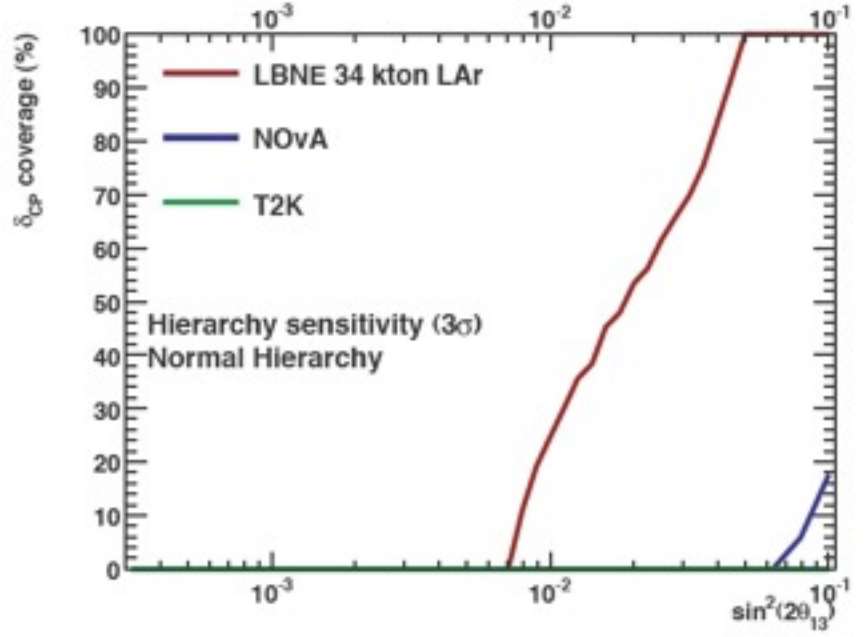
	Livermore	Kneller
$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$	2308	2848
$\bar{\nu}_e + {}^{40}Ar \rightarrow e^+ + {}^{40}Cl^*$	194	134
$\nu_x + e^- \rightarrow \nu_x + e^-$	296	178
Total	2798	3160

Pay Dirt

- The processes LBNE will look for are all really rare
- Need to have a grand scale to even begin: massive detectors, long distances for the neutrinos to travel, intense beams
- The knowledge gained will be revolutionary - maybe even answer the question as to why we are here

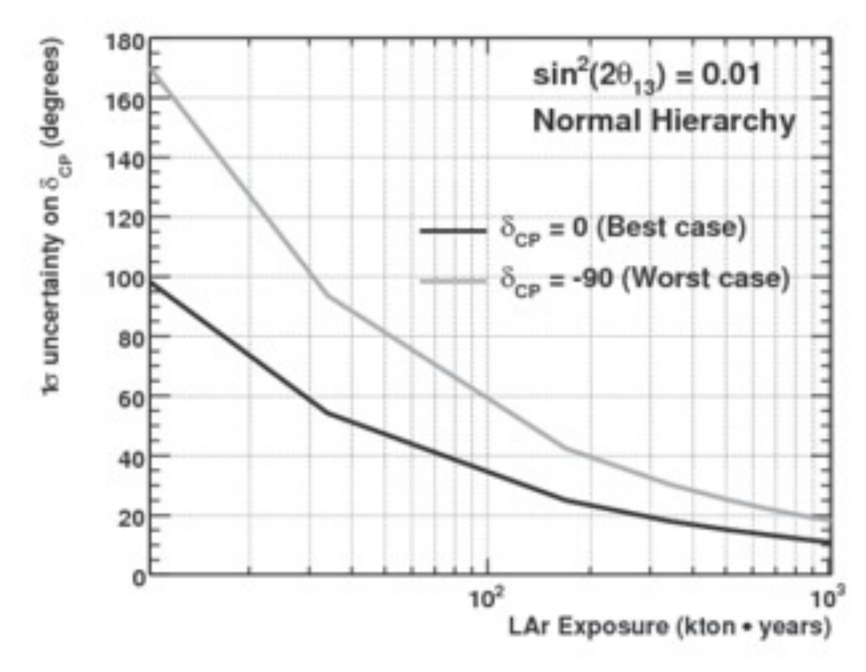
Oscillation Measurement Performance



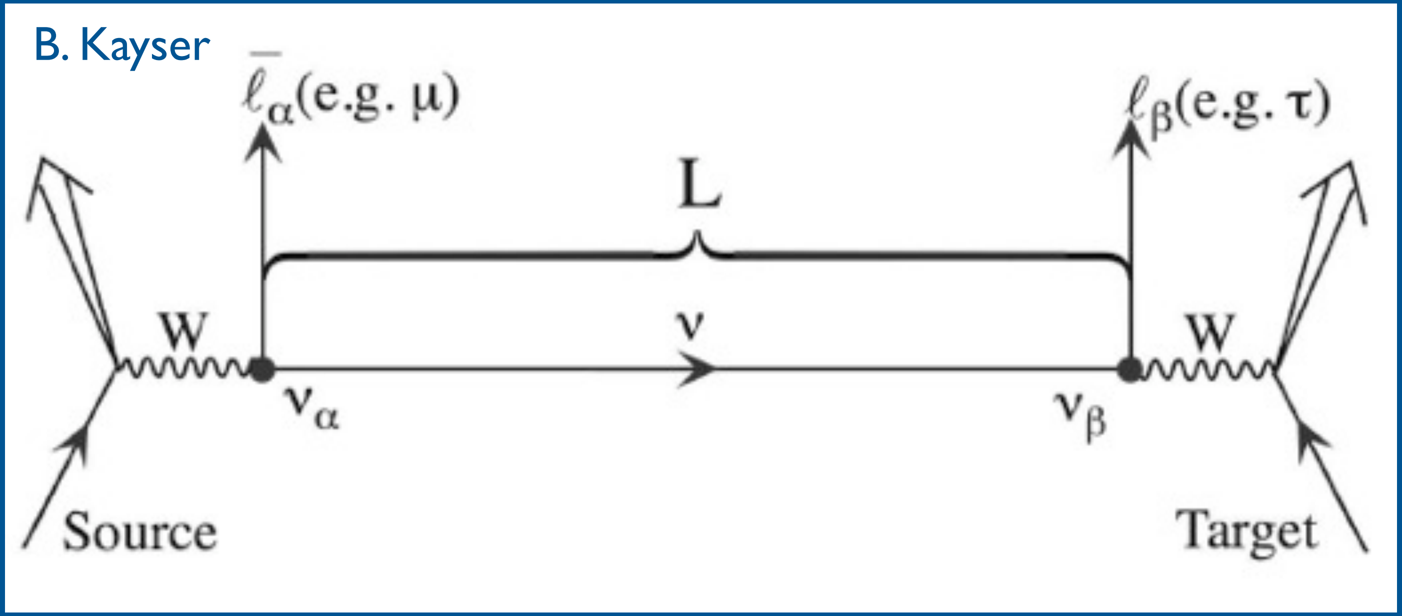


- LBNE will be able to determine both the mixing between muon and electron neutrinos as well as the mass hierarchy for larger portions of phase space than NOvA and T2K

- Will be able to quickly reduce the uncertainty on the difference between neutrino and antineutrino appearance probabilities



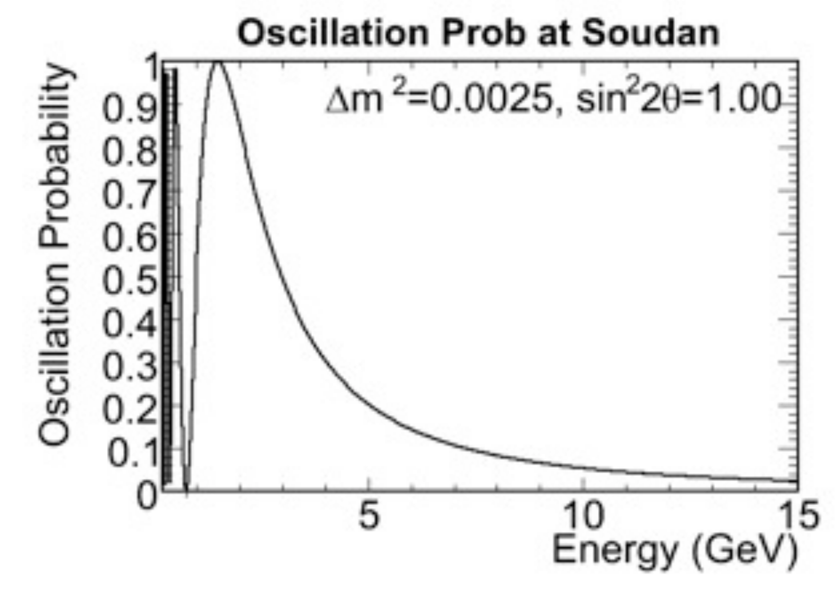
Neutrino Oscillations

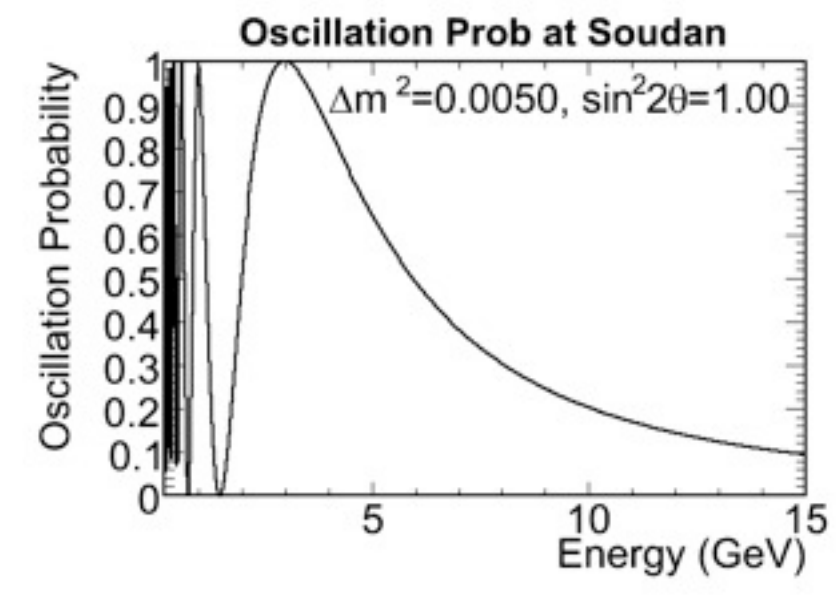


- Source produces a neutrino of flavor α, the neutrino propagates a distance *L*, and is then detected as flavor β
- Neutrinos interact in the flavor states, but propagate in the mass states
- The propagating neutrino is a combination of mass states - differences in the masses causes the oscillations

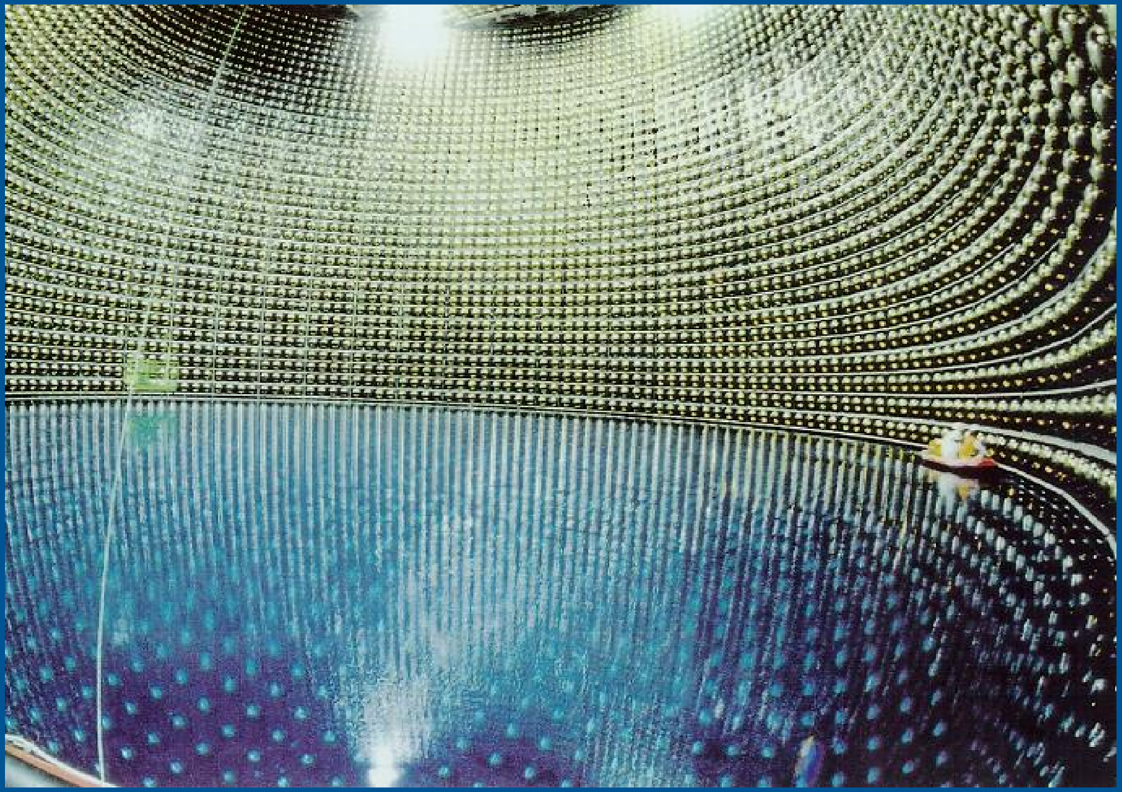
Neutrino Oscillations

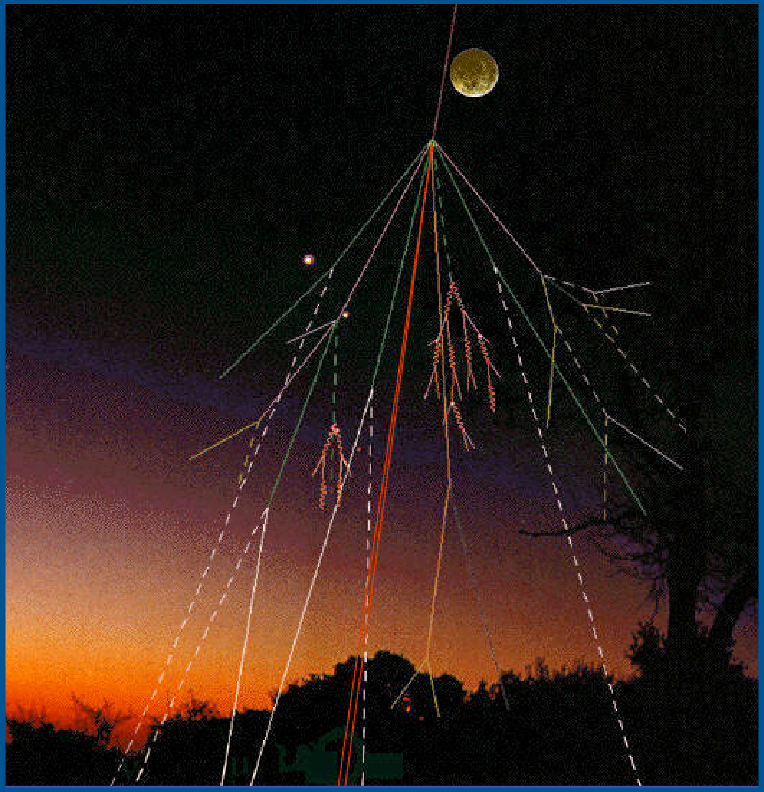
- Probability for flavor change between two flavors depends on 4 things:
  - Distance the neutrino travels
  - Energy of the neutrino
  - Mixing angle - how much each mass contributes to a flavor
  - Difference in square of masses between the two neutrino states
- Probability is larger than zero only if neutrinos have mass and the masses are different from each other
- Can see where the term oscillation comes from looking at the low energy portion of the graphs (left side)





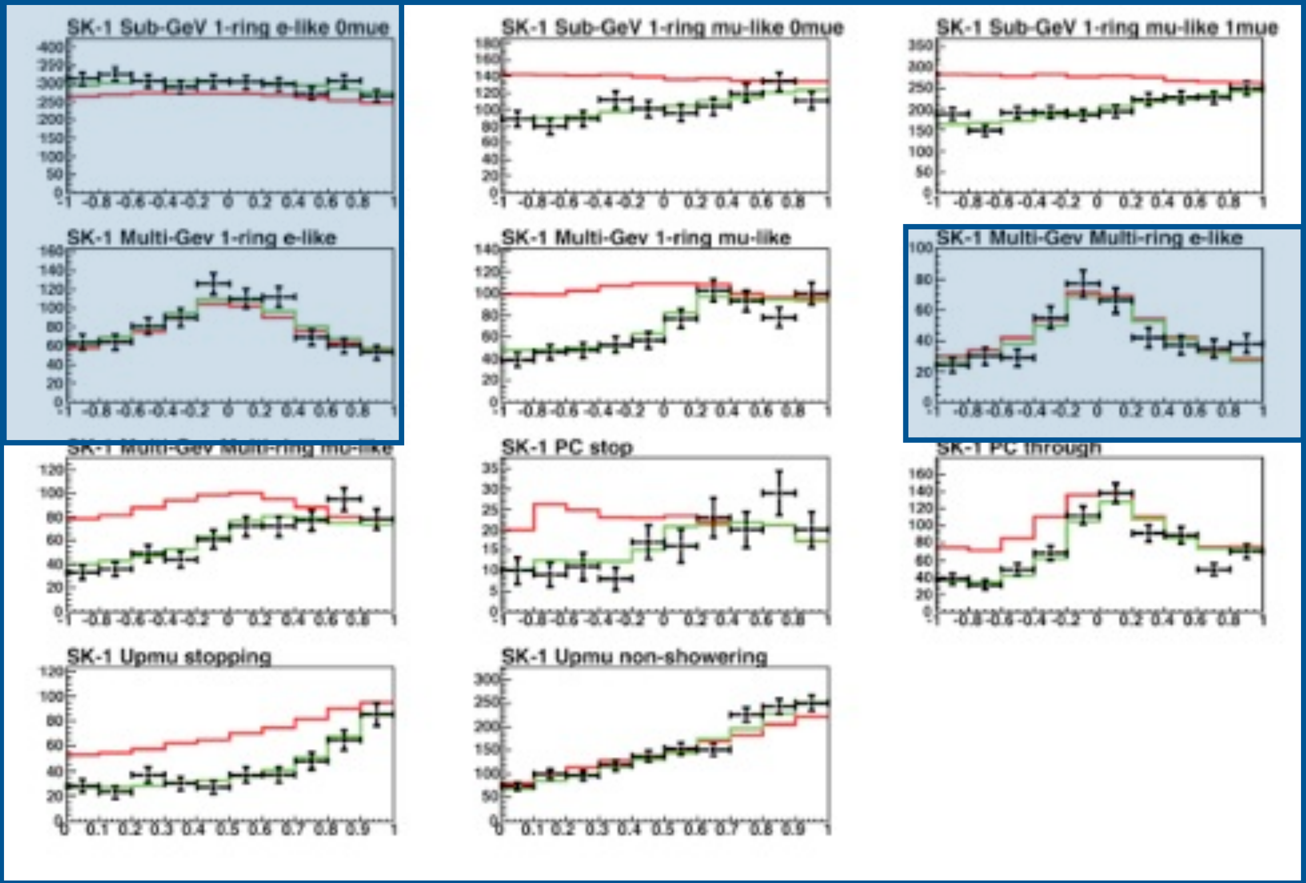
Atmospheric Neutrinos

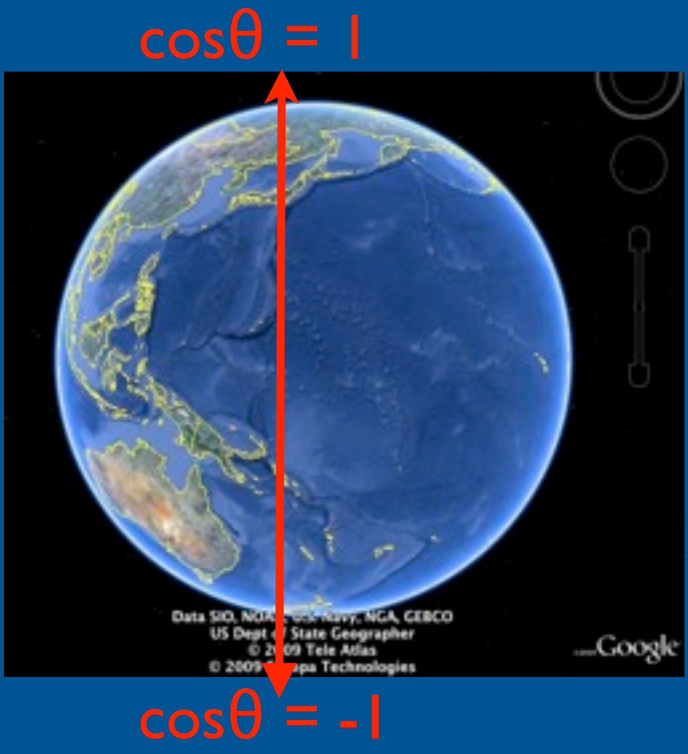




- First real evidence for oscillations from Super-K experiment - Water Cherenkov detector
- 50 kt of ultra pure water, 22.5 kt fiducial mass
- Built to look for proton decay, made lasting impact on neutrino physics

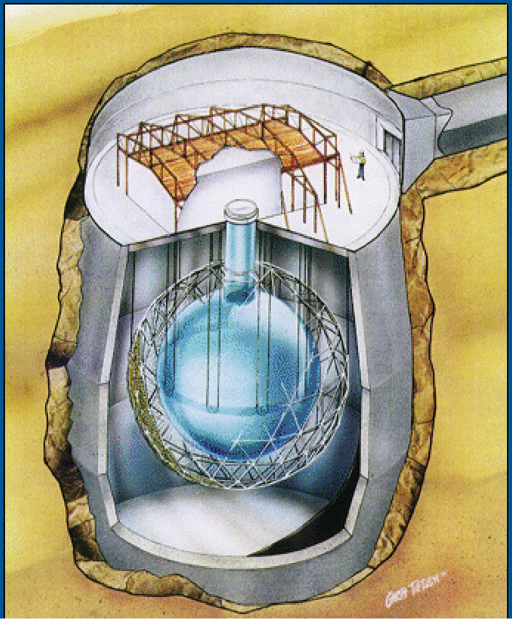
Atmospheric Results





- Super-K events classified as either e-like or μ-like
- No deficit on rate of ν_e as a function of direction or energy
- Clear deficit of ν_μ from below the detector, rate from above as expected
- Interpreted as $\nu_\mu \rightarrow \nu_\tau$ oscillations with maximal mixing

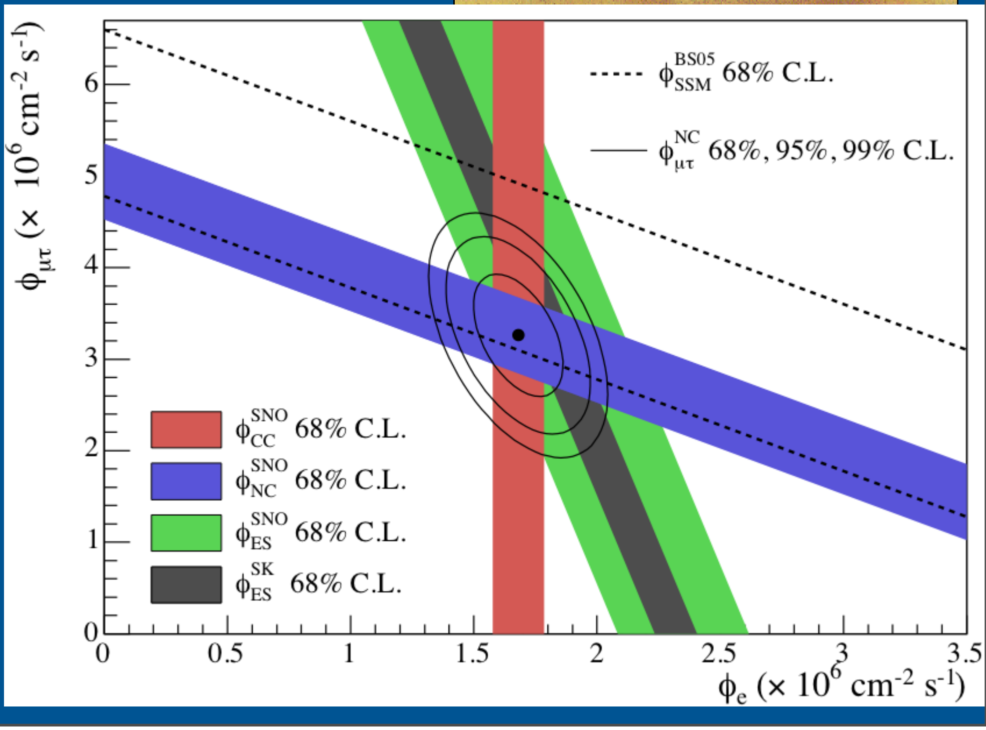
Neutrino Oscillations - Solar



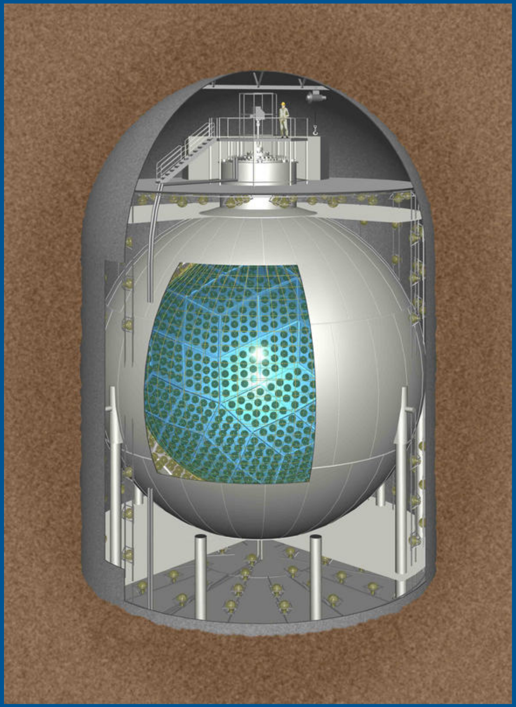
- Sudbury Neutrino Observatory built to study solar deficit
- 1 kt of $D_2 0$, 2100 m below the surface
- Uses both charged current and neutral current reactions to measure solar neutrino flux

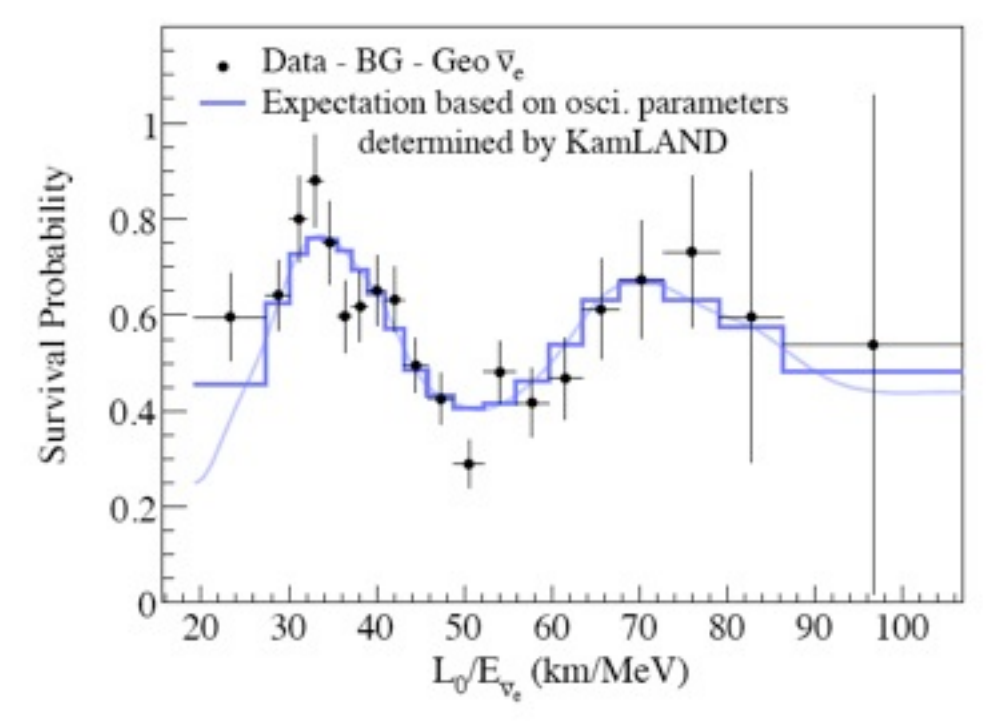
$$\nu_e + d \rightarrow p + p + e^-$$
$$\nu_x + d \rightarrow n + p + \nu_x$$

- CC only detects ν_e, NC detects all flavors
- Total rate shows no deficit, indicates flavor change



Long-Baseline Reactor Results





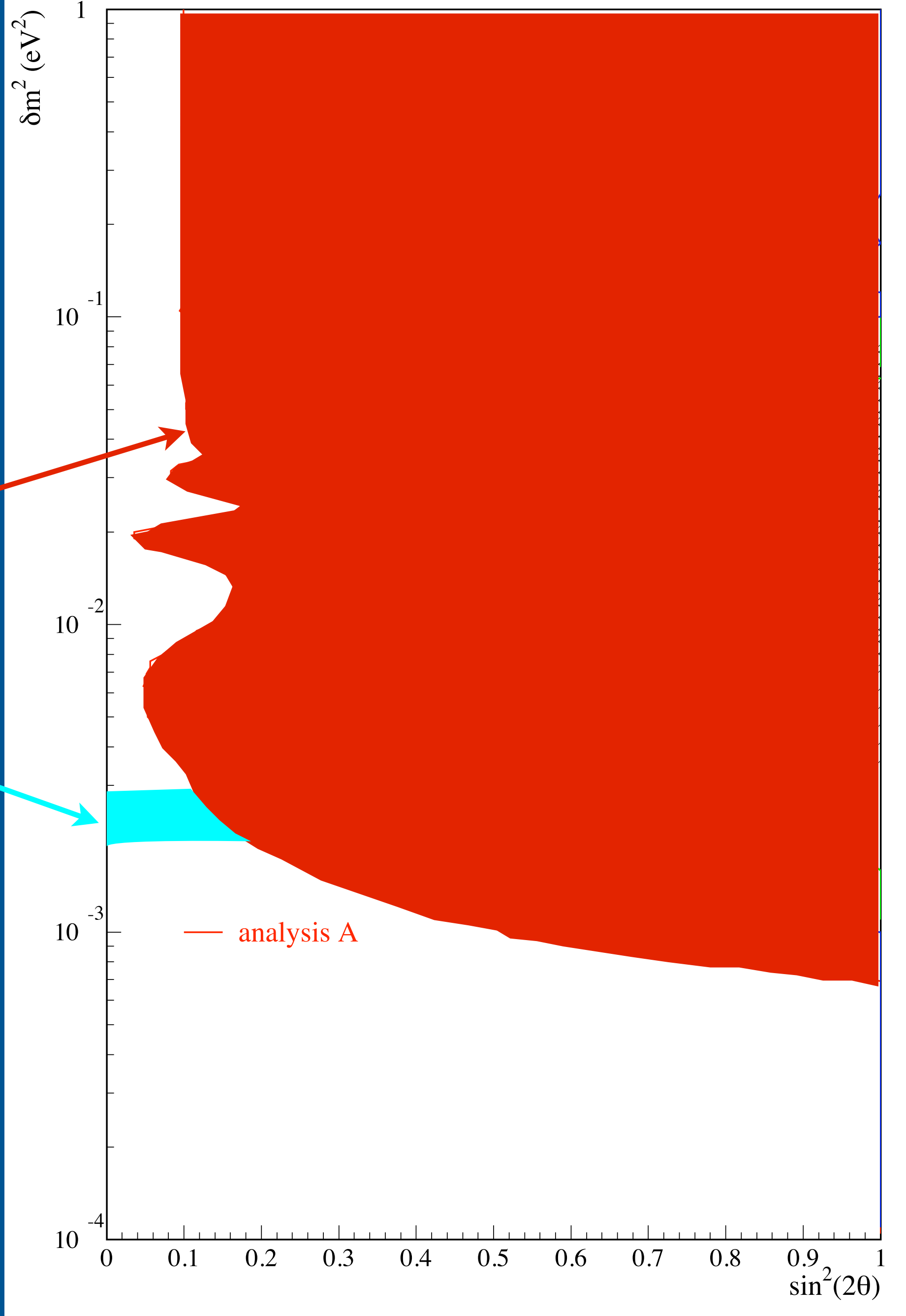
- KamLAND - 1kt liquid scintillator detector
- Measured anti-neutrinos from Japanese and Korean power reactors

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

- Weighted average reactor distance of 180 km
- L/E dependence shows two cycles of oscillation

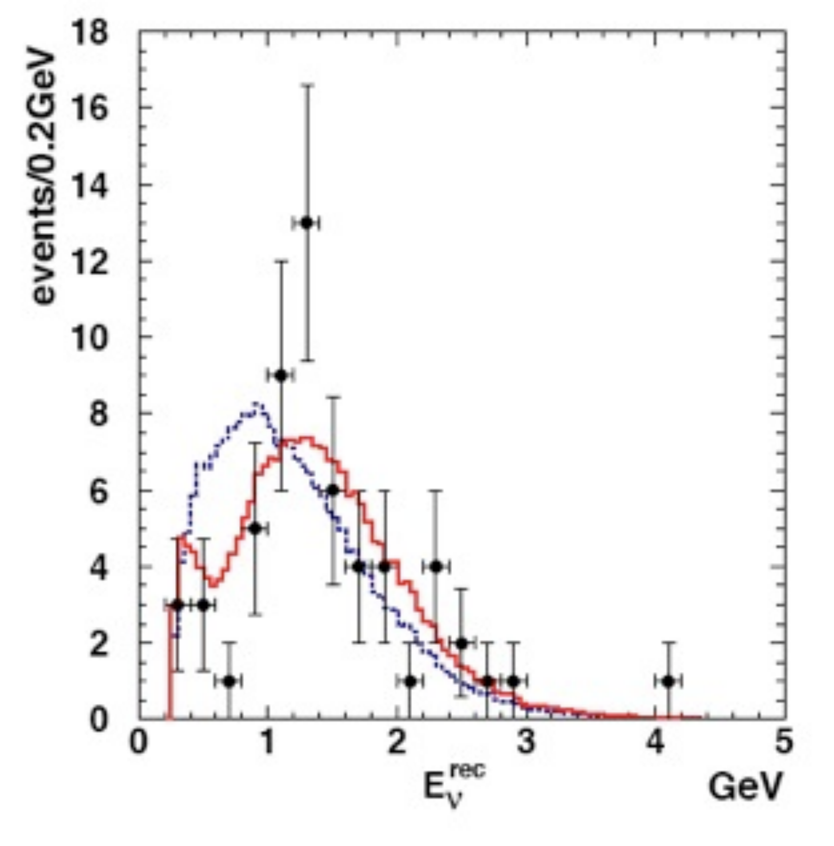
Short-baseline Reactor Results

- CHOOZ experiment searched for reactor ν_e disappearance over ~1 km baseline
- No evidence for disappearance, coupling of ν_e to ν_3 excluded in red region
- Allowed region for by blue box
- New reactor experiments coming online this year!
- Also possible to search for the coupling using accelerator beams



Accelerator Results - K2K

- K2K was first experiment to report results with accelerator neutrino beam
- Looked for disappearance of ν_μ over a 250 km baseline, attempting to measure same mass splitting as seen in atmospheric results
- Near detectors measure flux of neutrinos before oscillations
- Far detector (Super-K) used to look for energy dependent deficit of ν_μ



Accelerator Results - MINOS

- MINOS used charged-current interactions and observed deficit of ν_μ at far detector 735 km from source
- Deficit is well described by oscillations at the atmospheric mass-splitting
- Made most precise measurement of difference in square of masses for this mode

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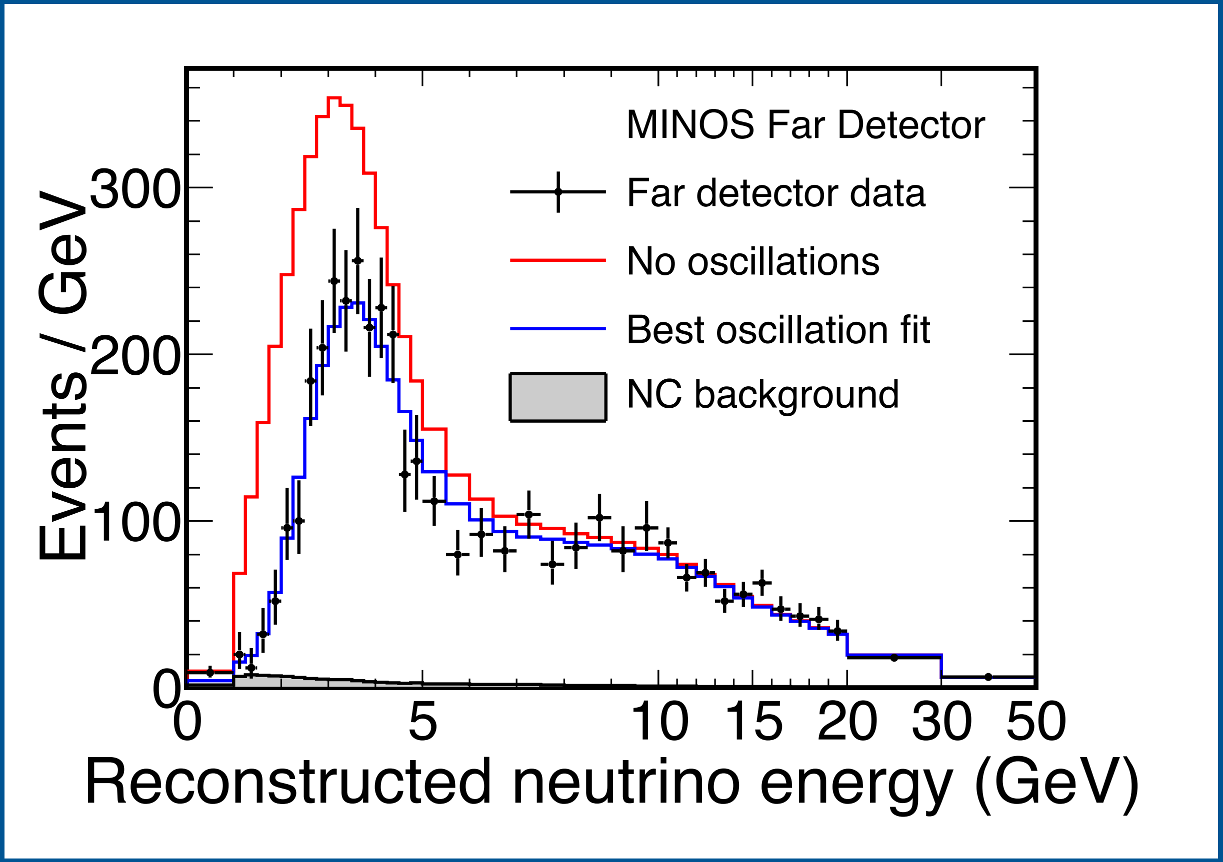

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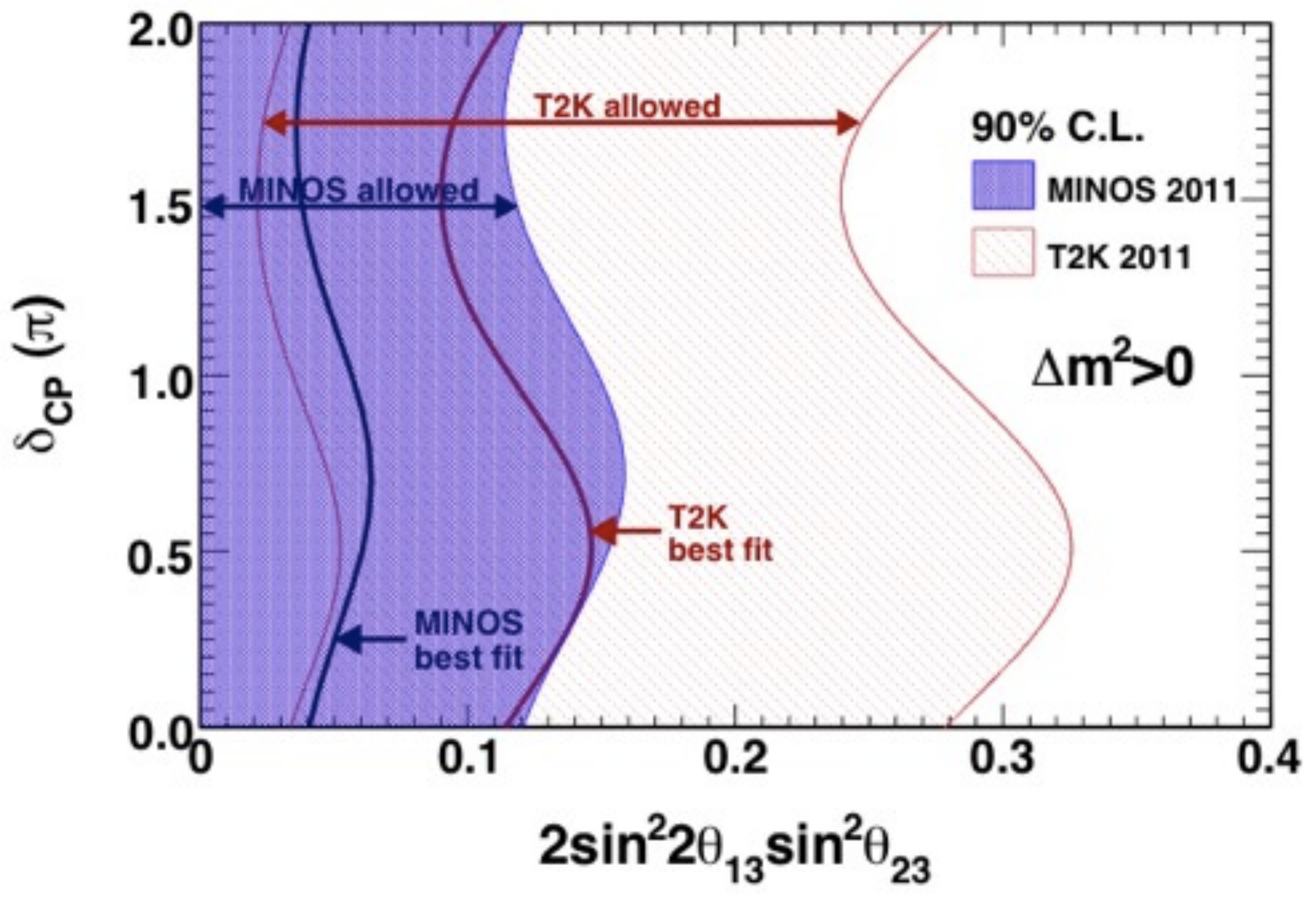
MINOS and T2K ν_e Appearance



- MINOS and T2K are attempting to look for ν_e appearance in a beam of ν_μ
- T2K observed 6 events with an expectation of 1.5 indicating a non-zero, and relatively large value of θ_{13}
- MINOS also sees an excess; cannot rule out $\theta_{13} = 0$, but does limit the size of the mixing angle at the other end

Tying it all Together

- A variety of experiments (solar, reactor, atmospheric) have shown us there are two different regimes for neutrino oscillations
- The different regimes are determined by the differences in the squares of the 3 mass states
- Figure shows the probability of a mass state interacting as a given flavor state
- Most probabilities are relatively large
- Zero point of mass scale currently unknown

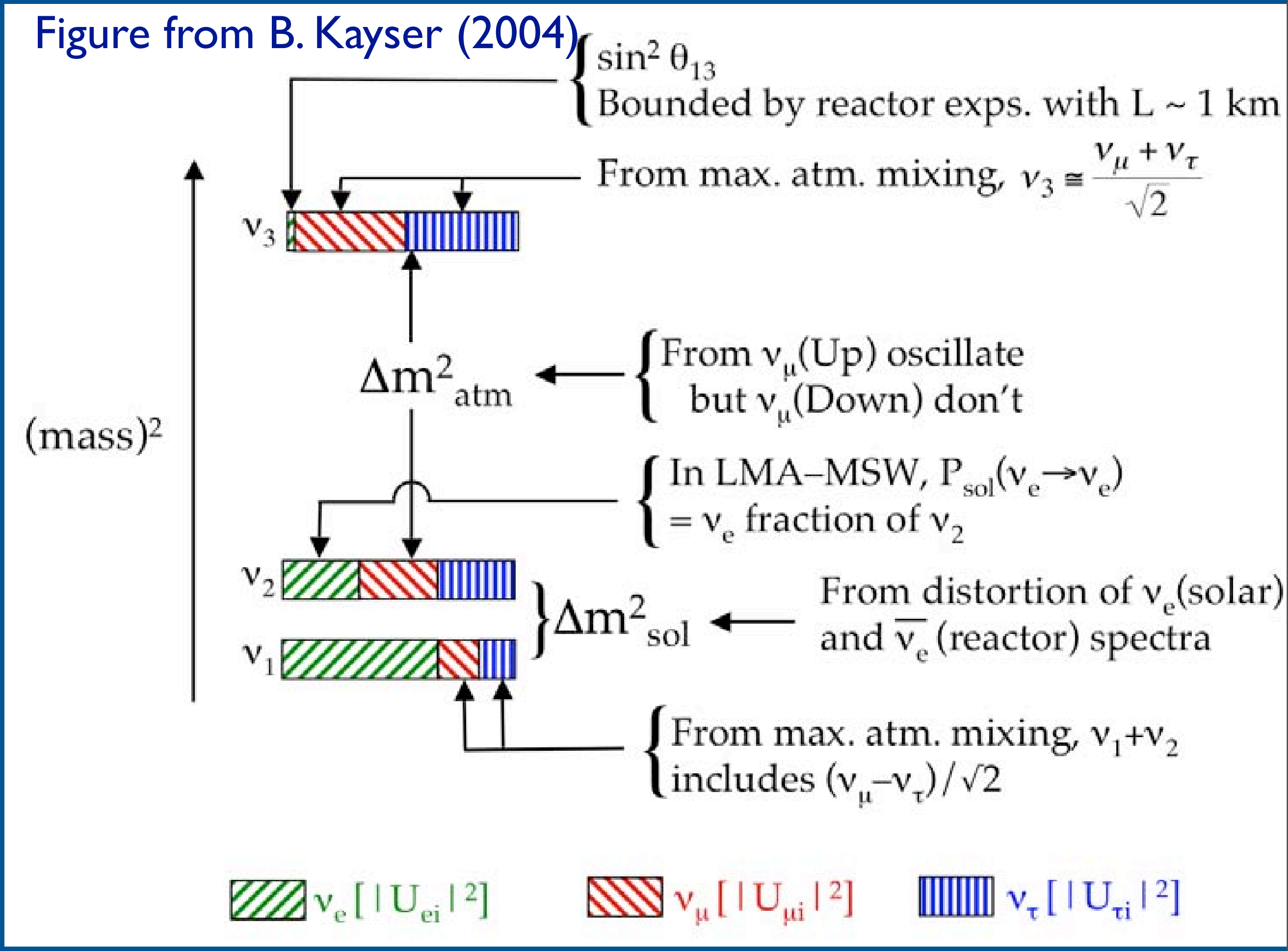


Figure from B. Kayser (2004)