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Neutrino Lecture 1

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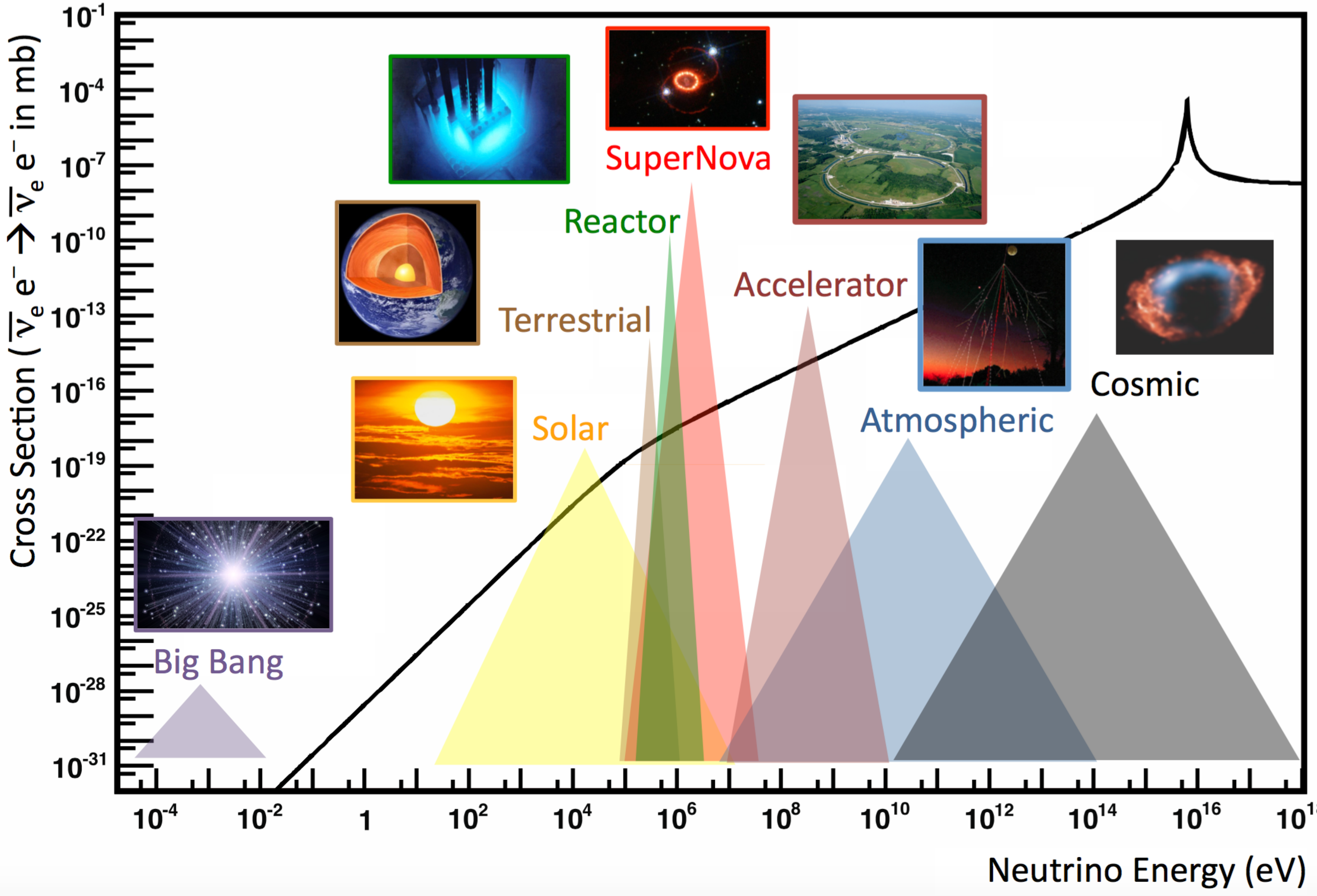
Outline

- Today:
  - A quick history of neutrinos
  - Basic of week interactions
  - Neutrino oscillations
- Tomorrow:
  - How we produce a neutrino beam
  - Neutrino interactions
  - Examples of nuclear effects in neutrino interactions
  - Cross section measurements

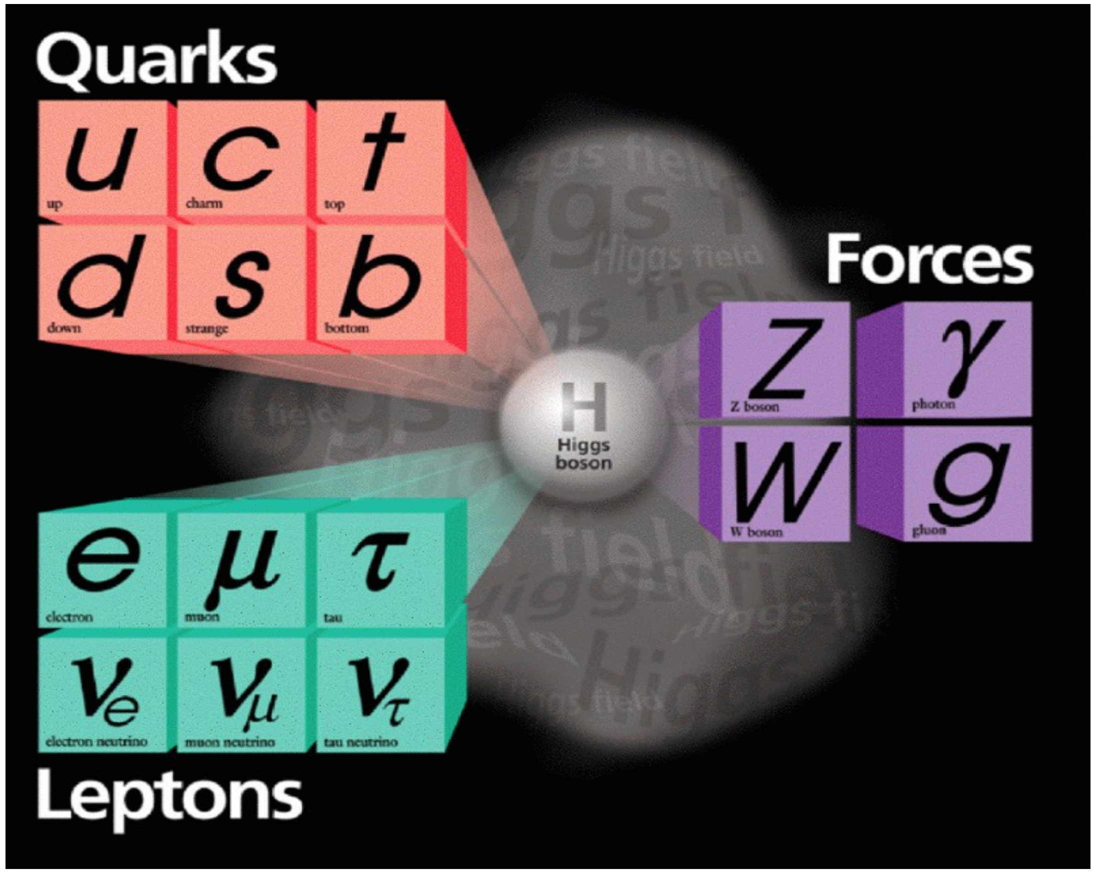
Where do neutrinos come from?

- Neutrinos are the most common matter particles in the universe

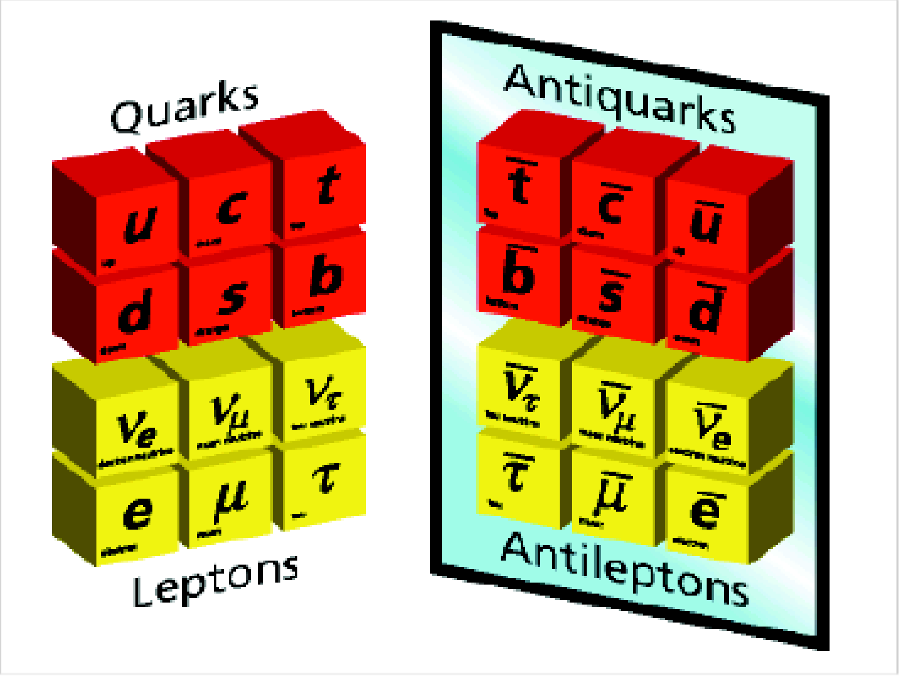


- Concentrating on few neutrino interactions relevant to neutrino oscillation at the few GeV region

The Standard Model of Elementary Particles

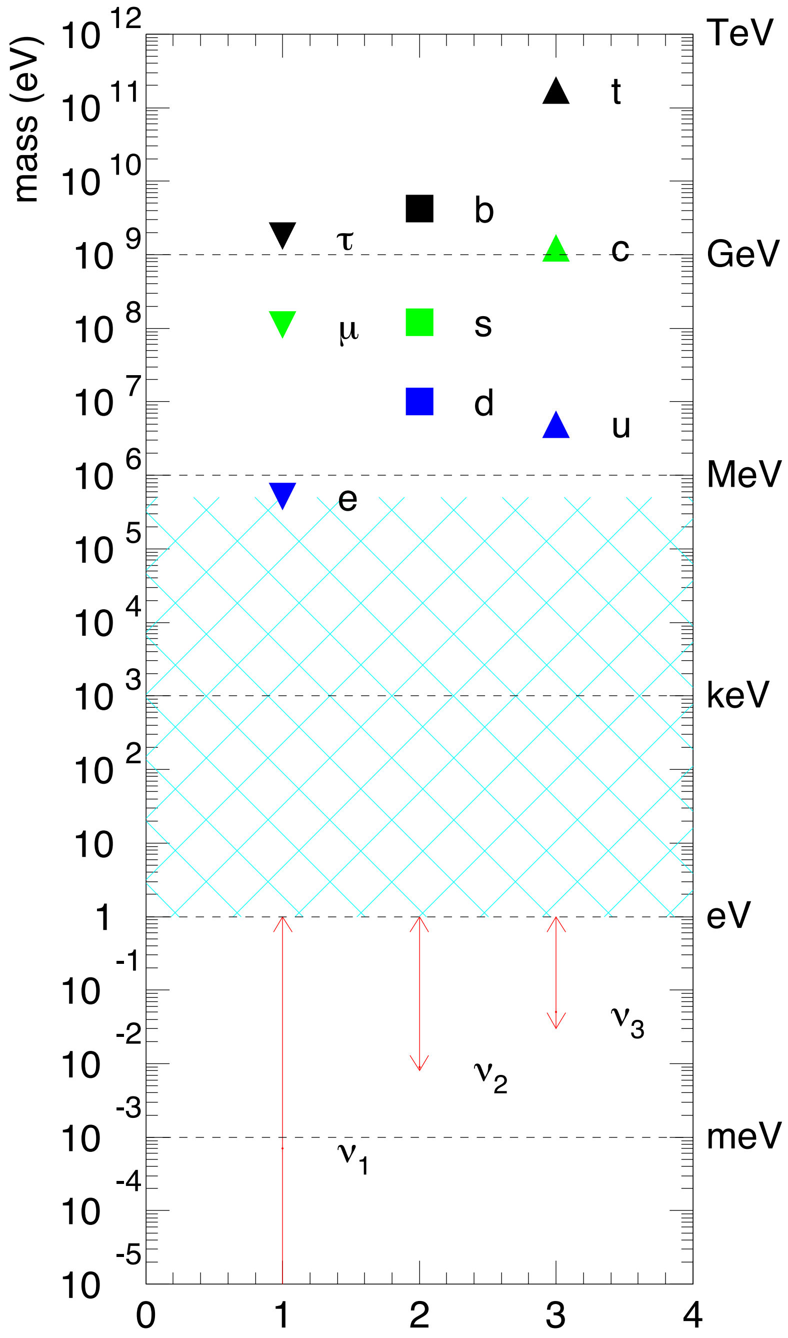


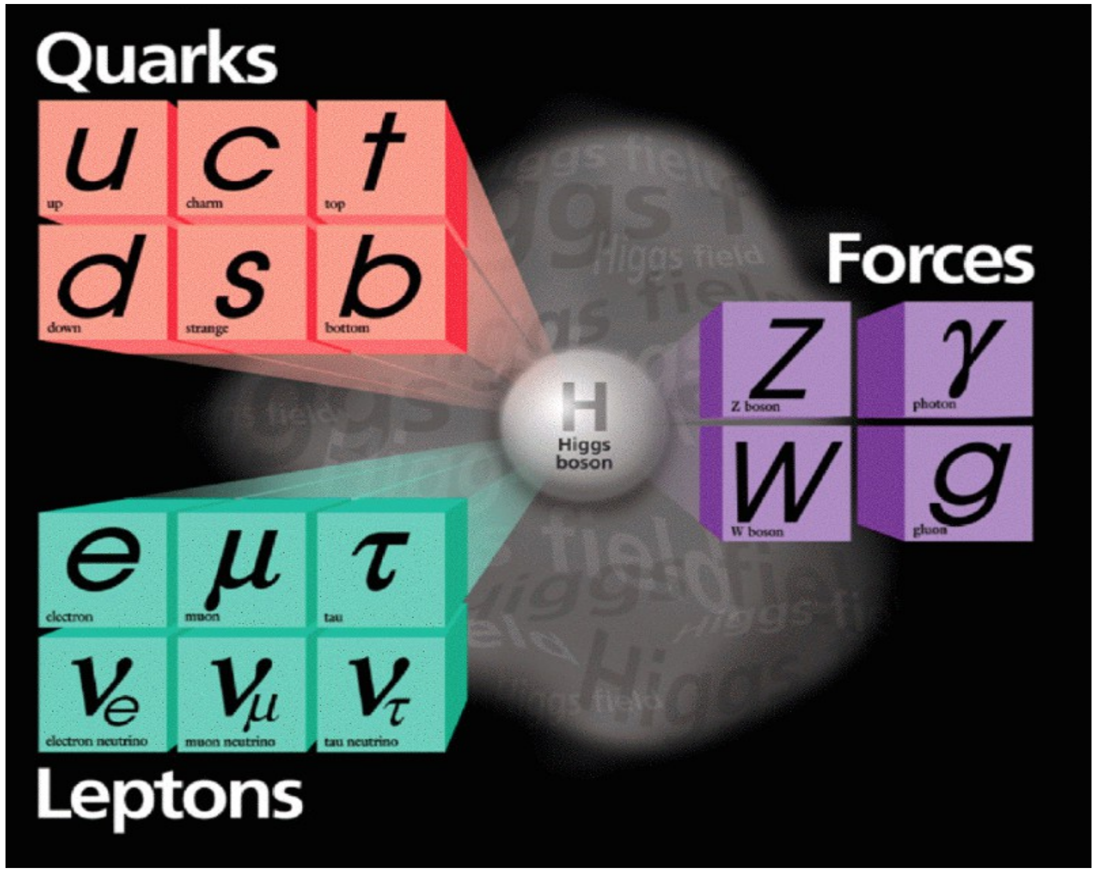
- Theory about fundamental ingredients of matter and how they interact with each other
- Everything known in this world is made of these (and the mirror images)



- Is the standard model complete?
  - Neutrino in the Standard Model has no mass
  - However neutrino mass has been observed, and it is much smaller than all other particles

Neutrinos have mass

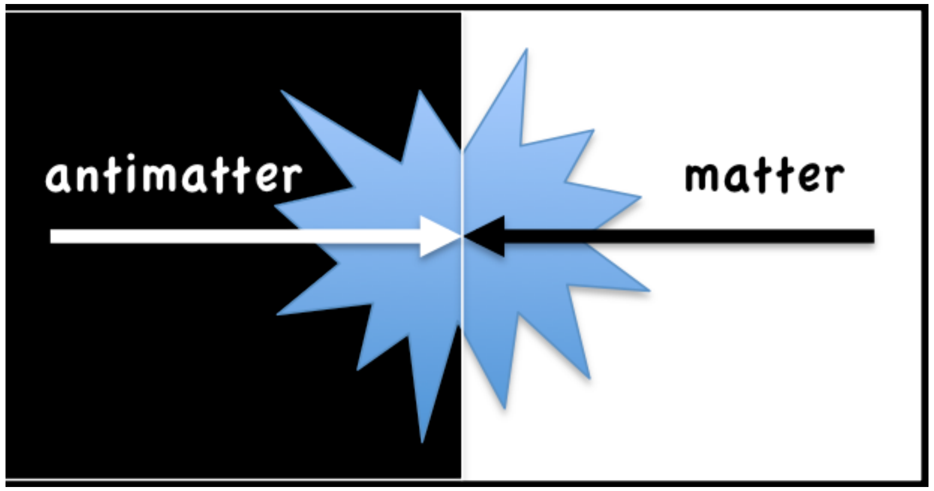


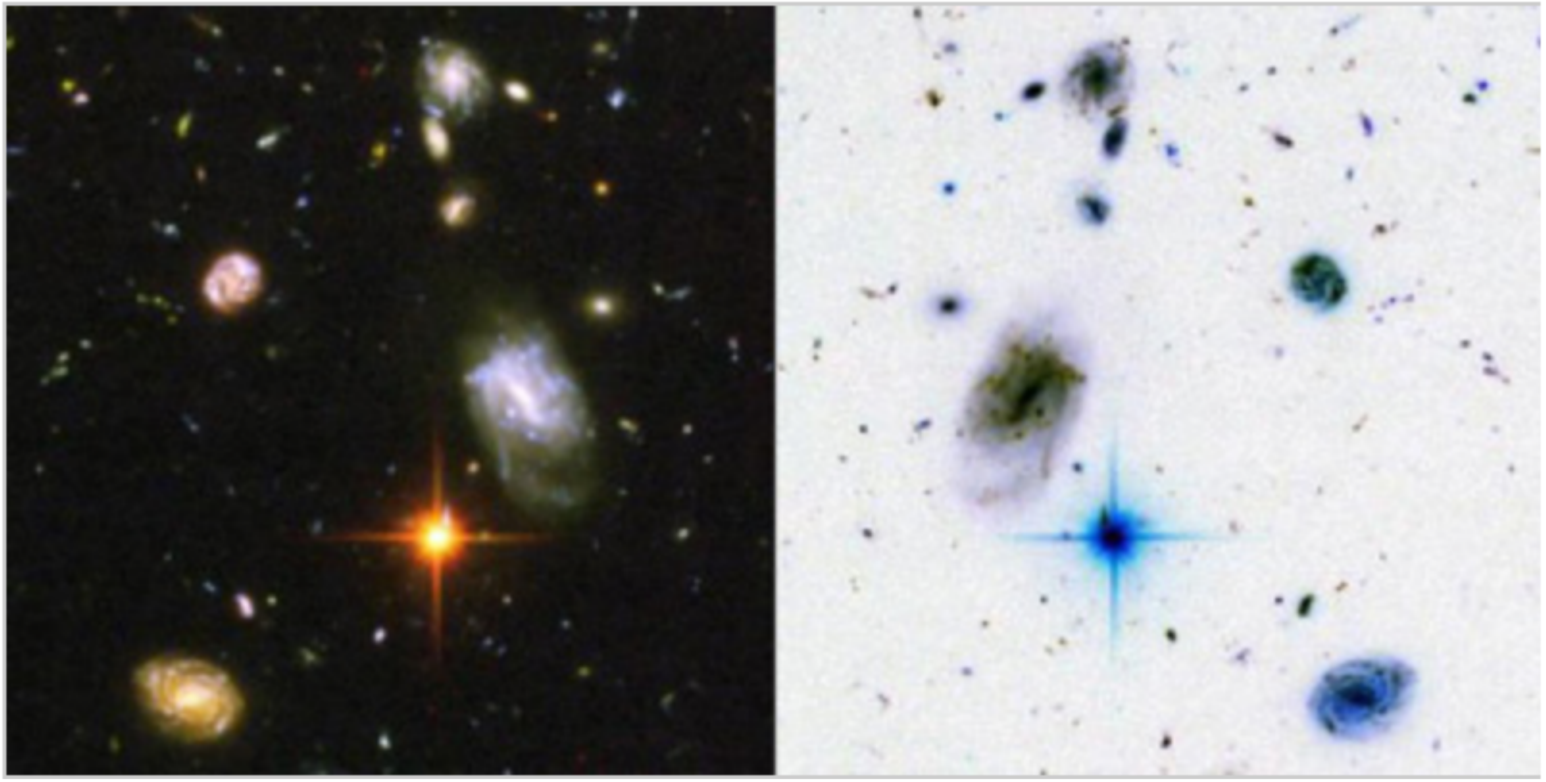


- Why is there such large gap between neutrino masses and quark masses?
- Why do quarks and leptons exhibit different behavior?
- What is the absolute mass of neutrino?

What is the symmetry between matter and antimatter?

- Physics theorize that the big bang created equal amounts of matter and antimatter
- When corresponding particles of matter and antimatter meet, they annihilate one another





- But somehow we are still here and antimatter, for most part, has vanished
- Neutrinos could help to explain why the universe has more matter than antimatter!

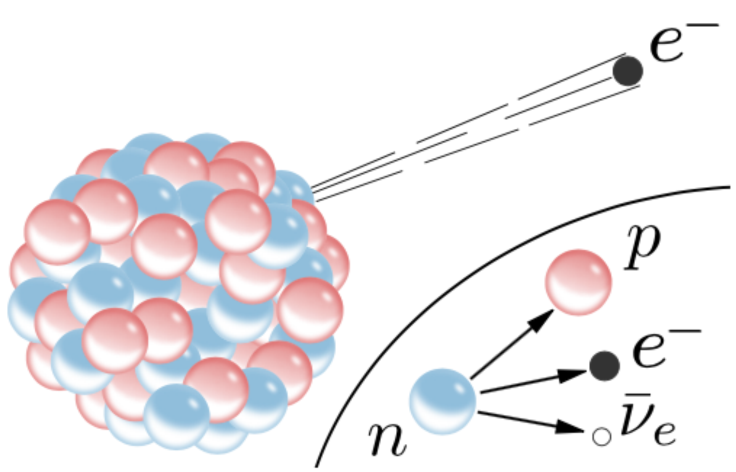
How did we discover neutrinos?

- Radioactivity: Nucleus emits particle due to nuclear instability
- While studying the beta decay, the energy did not seem to be conserved in beta decay?
  - We know energy is always conserved
  - Energy can neither be created nor destroyed only can be transformed into a different form
- In 1930, Pauli postulated the neutrino

Dear Radioactive Ladies and Gentlemen,

I have done a terrible thing.

I have postulated a particle that cannot be detected



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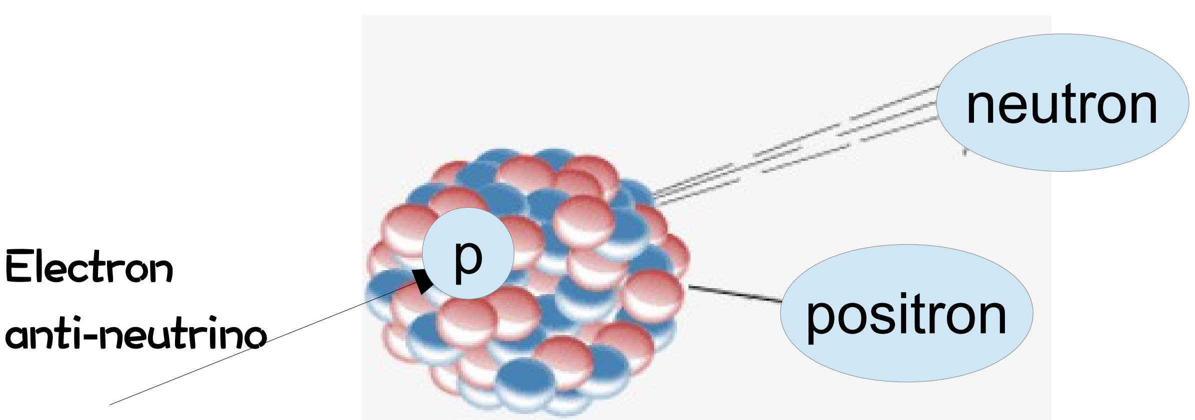
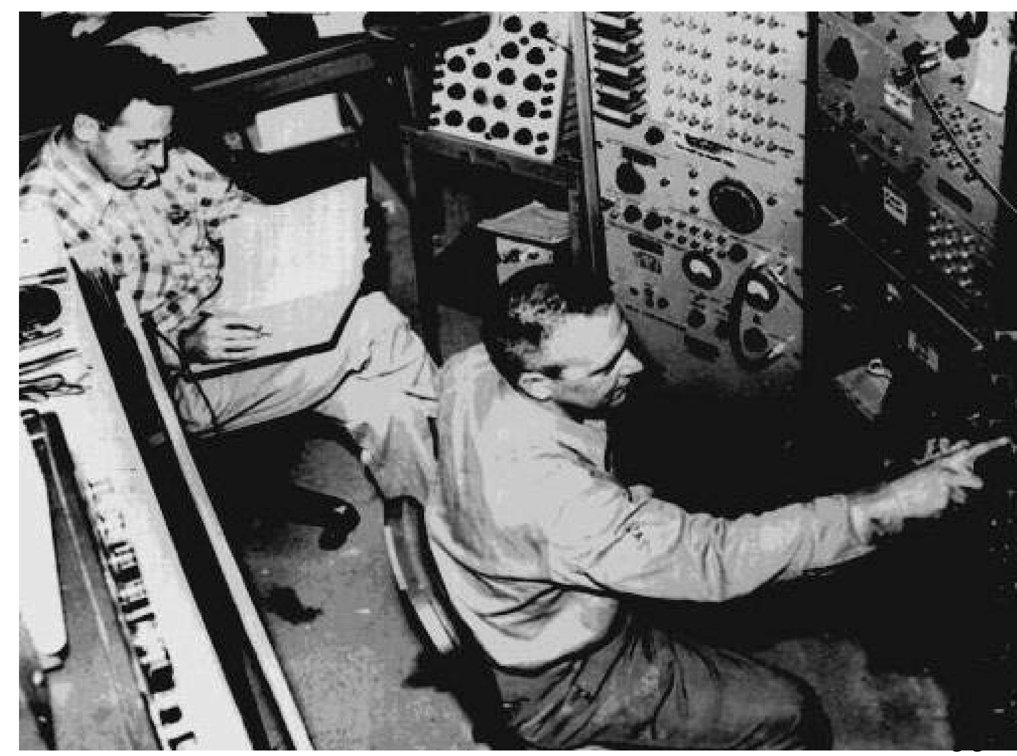
The Discovery of Anti-Neutrino (1956)

- Artificially produced neutrinos from nuclear reactors
  - Emits around 10 trillion anti-neutrinos per cm^2/s
- Inverse Beta decay

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



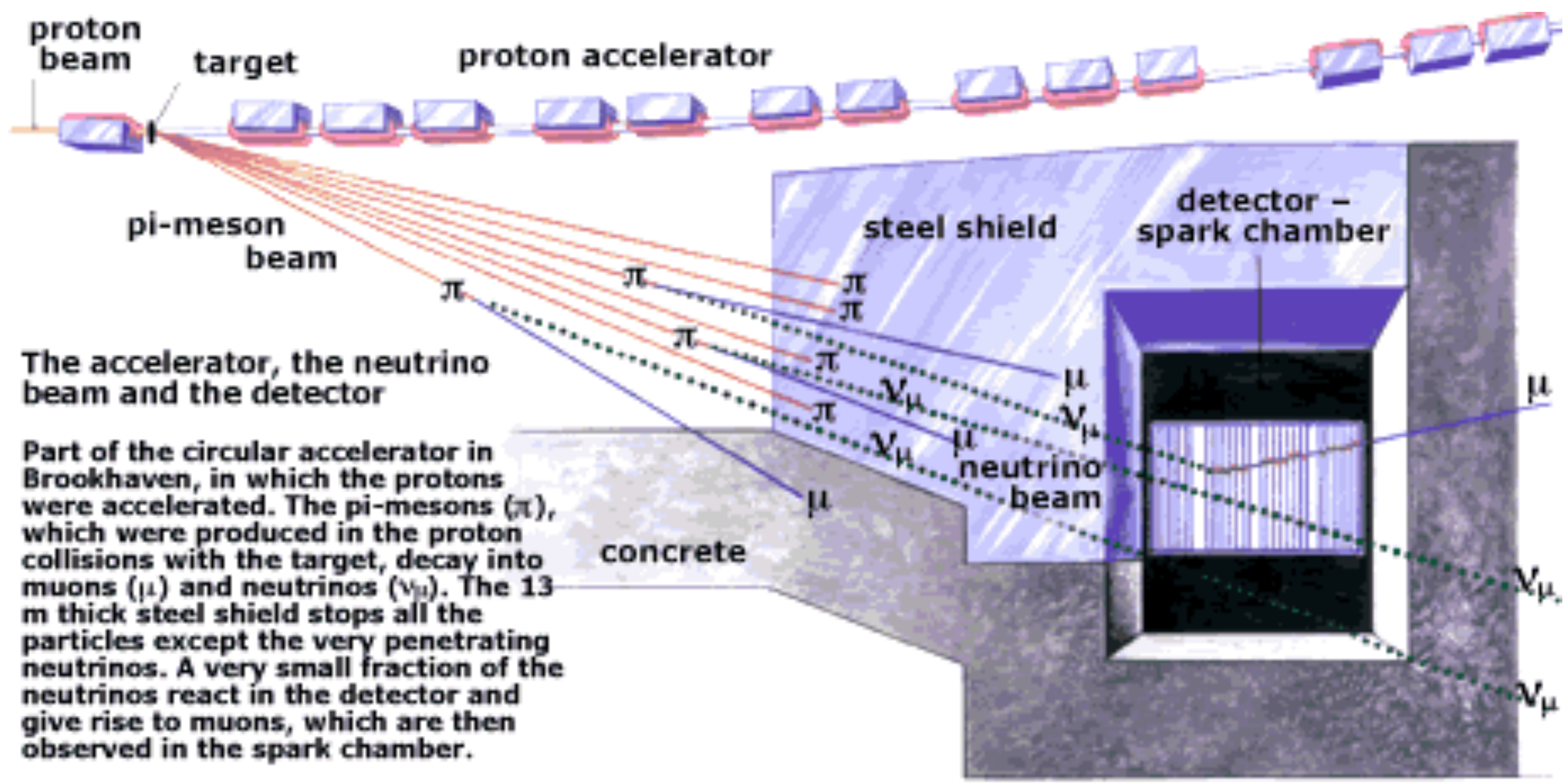
1995 Nobel Prize



The Discovery of the Muon Neutrino

1962

BROOKHAVEN NATIONAL LABORATORY



The accelerator, the neutrino beam and the detector

Part of the circular accelerator in Brookhaven, in which the protons were accelerated. The pi-mesons (π), which were produced in the proton collisions with the target, decay into muons (μ) and neutrinos (ν_μ). The 13 m thick steel shield stops all the particles except the very penetrating neutrinos. A very small fraction of the neutrinos react in the detector and give rise to muons, which are then observed in the spark chamber.

Based on a drawing in Scientific American, March 1963.

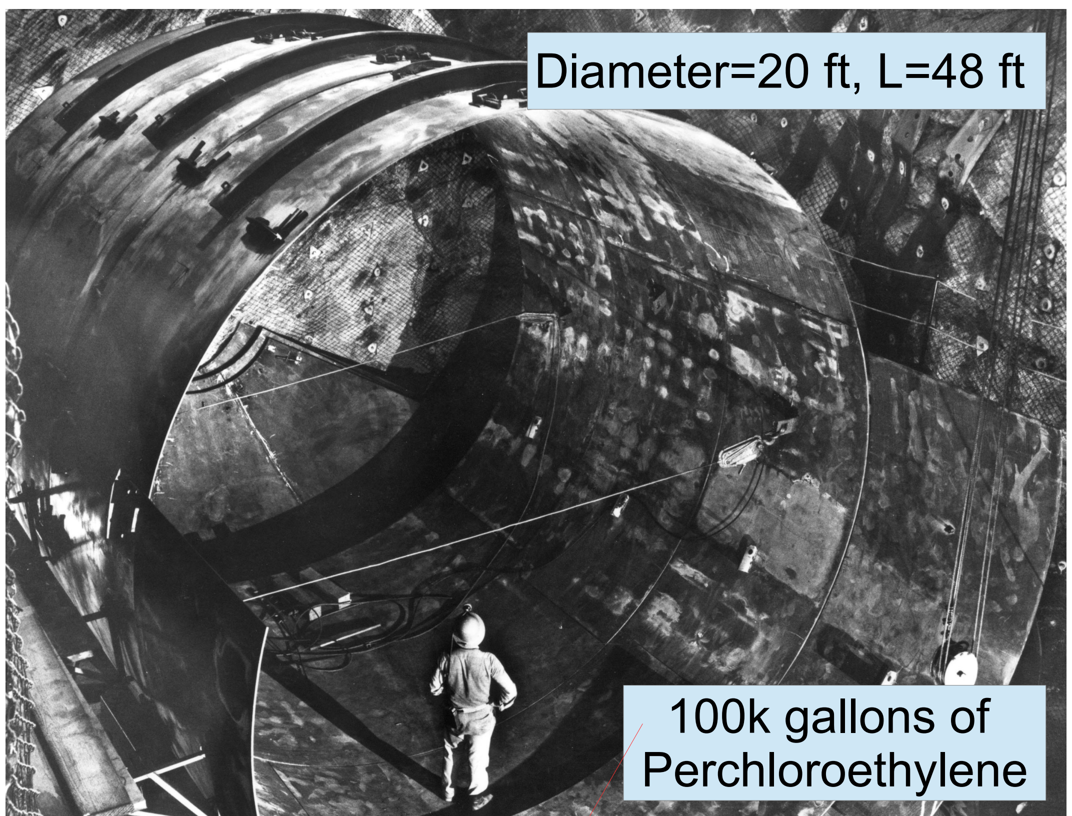
Nobel Prize

1988 Nobel prize for the neutrino beam method and the demonstration of the doublet structure of leptons through the discovery of the muon neutrino

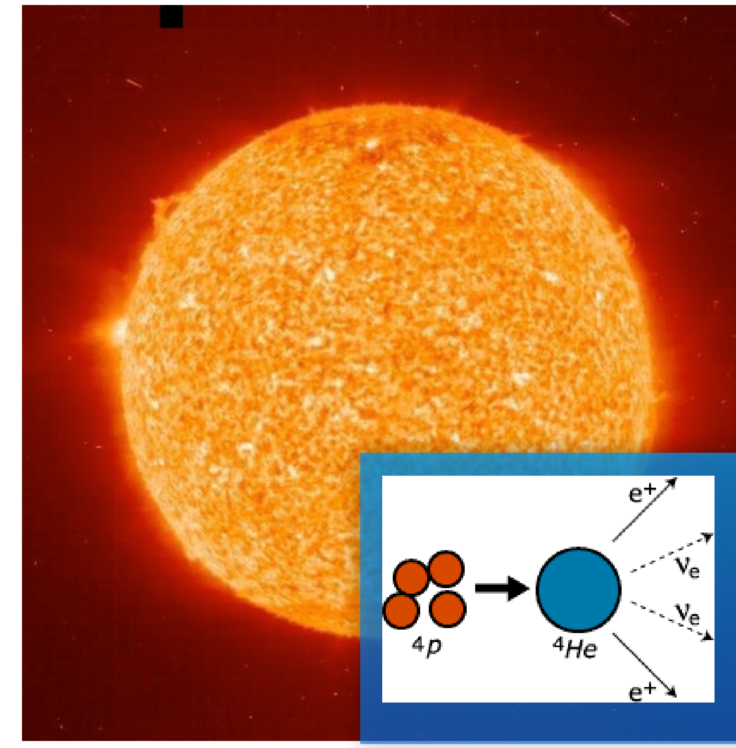
The Solar Neutrino Problem (1968)

- Nuclear reactions in the core of the sun produce νe
- In 1968, Ray Davis's HomeStake experiment measured the νe that arrives at earth using a huge tank of cleaning fluid

solar neutrino+chlorine atom−>electron+argon atom



Cleaning fluid



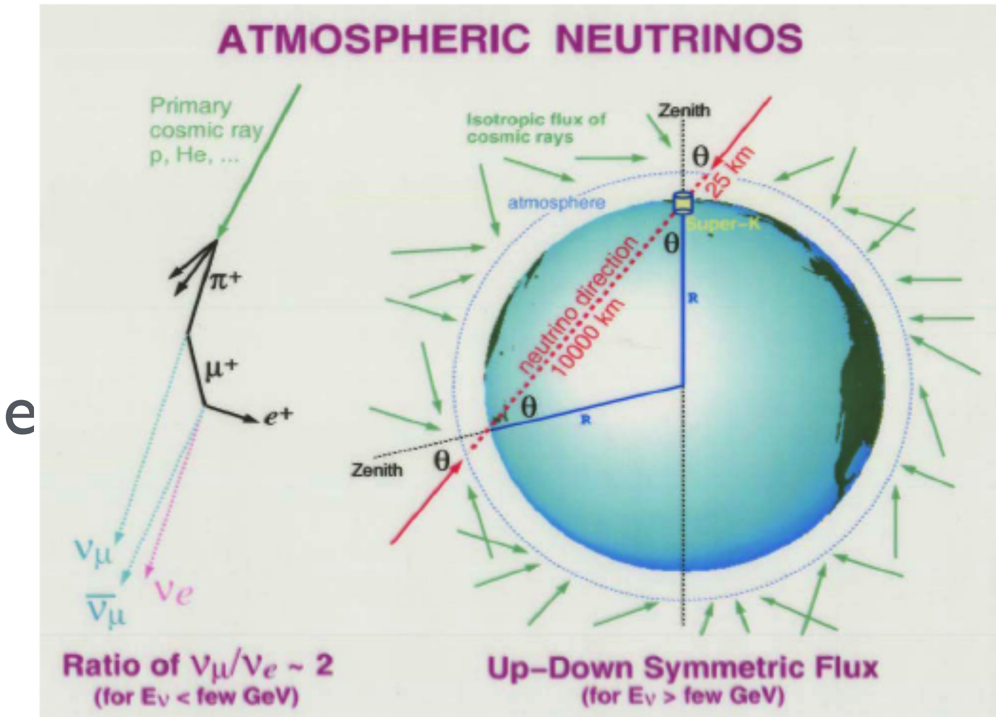
2002 Nobel Prize

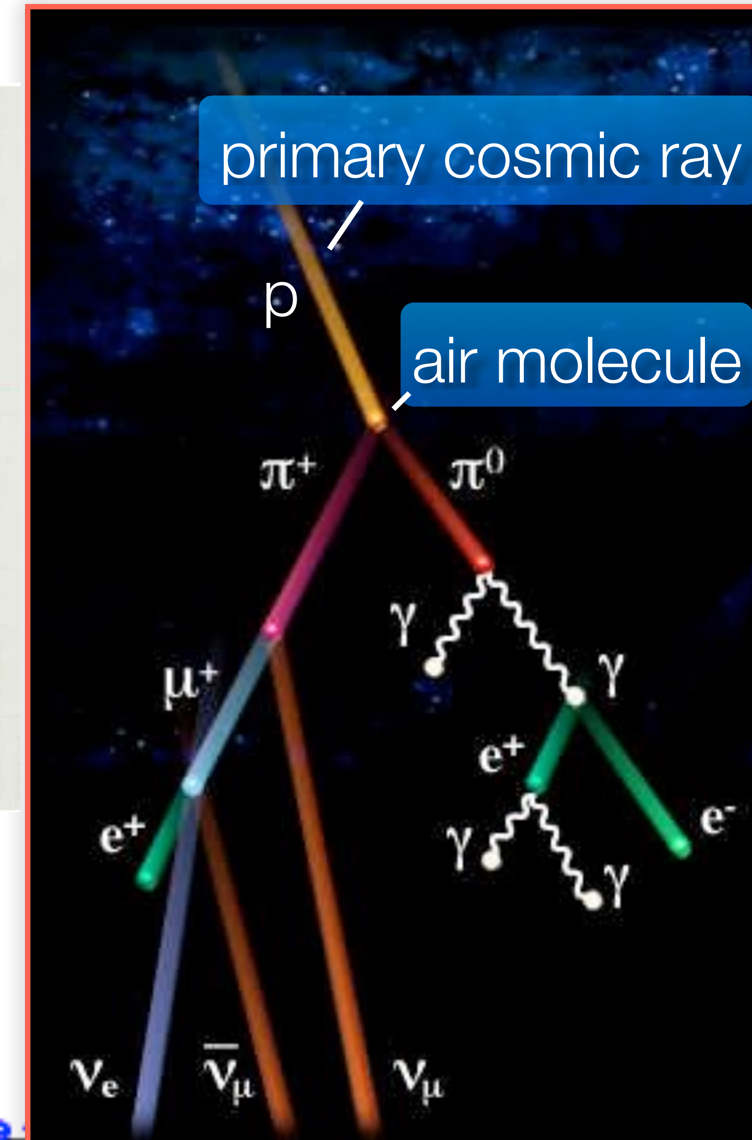
- Davis published the first results indicating that only 1/3 of the neutrinos were observed, i.e. the solar neutrino problem

The Atmospheric Neutrino Anomaly

- Cosmic rays hit the earth isotropically
- People expected:

$$\frac{\Phi_{\nu_\mu}(Up)}{\Phi_{\nu_\mu}(Down)} = 1$$

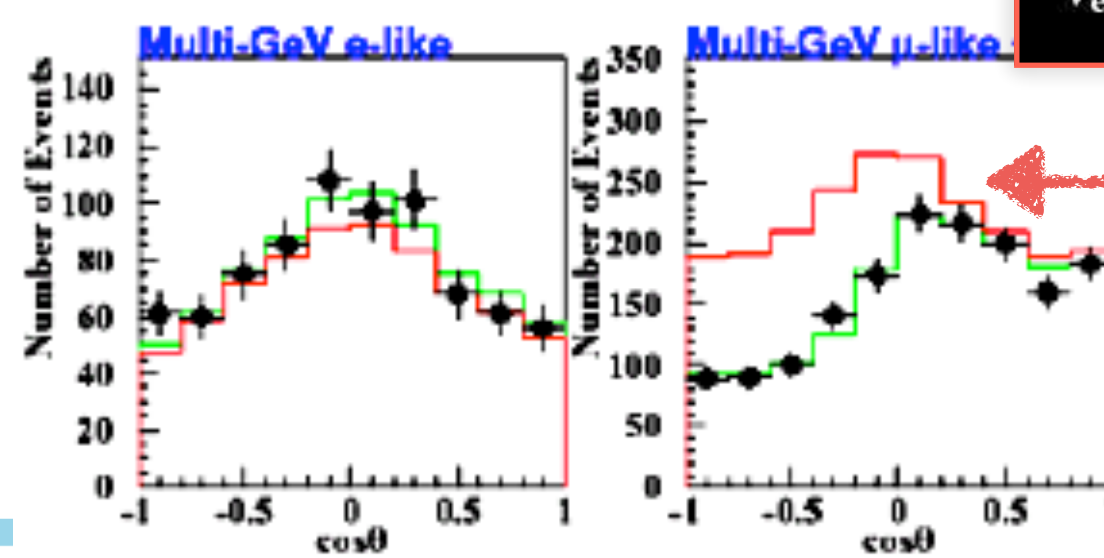




- However, Super-Kamiokande found

$$\frac{\Phi_{\nu_\mu}(Up)}{\Phi_{\nu_\mu}(Down)} = 0.54 \pm 0.04$$

- In 1998 Super-Kamionkande announces the discovery of neutrino oscillation



Upward-going muon neutrinos depleted

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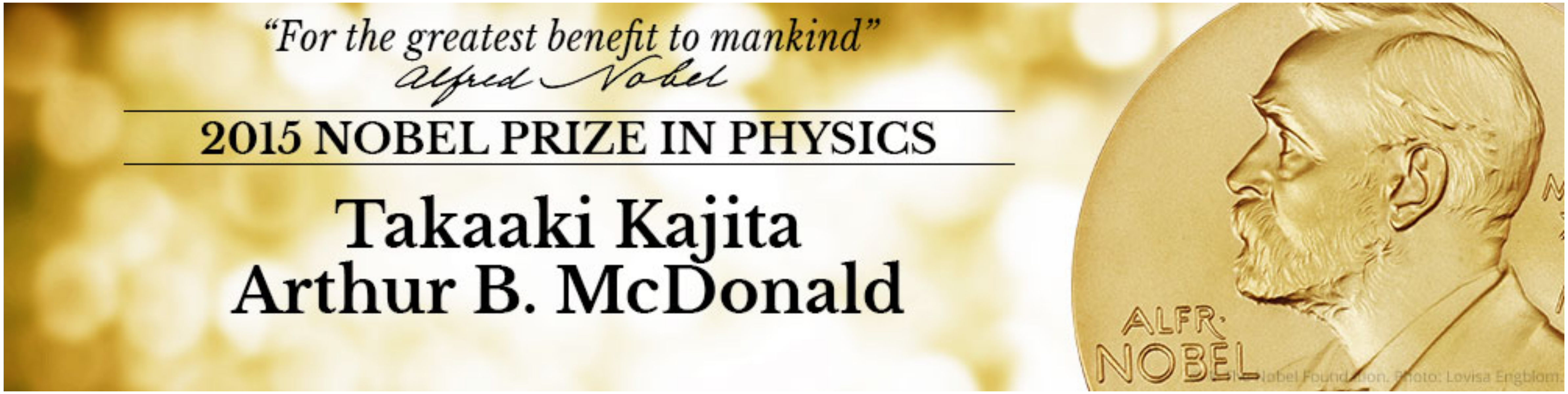
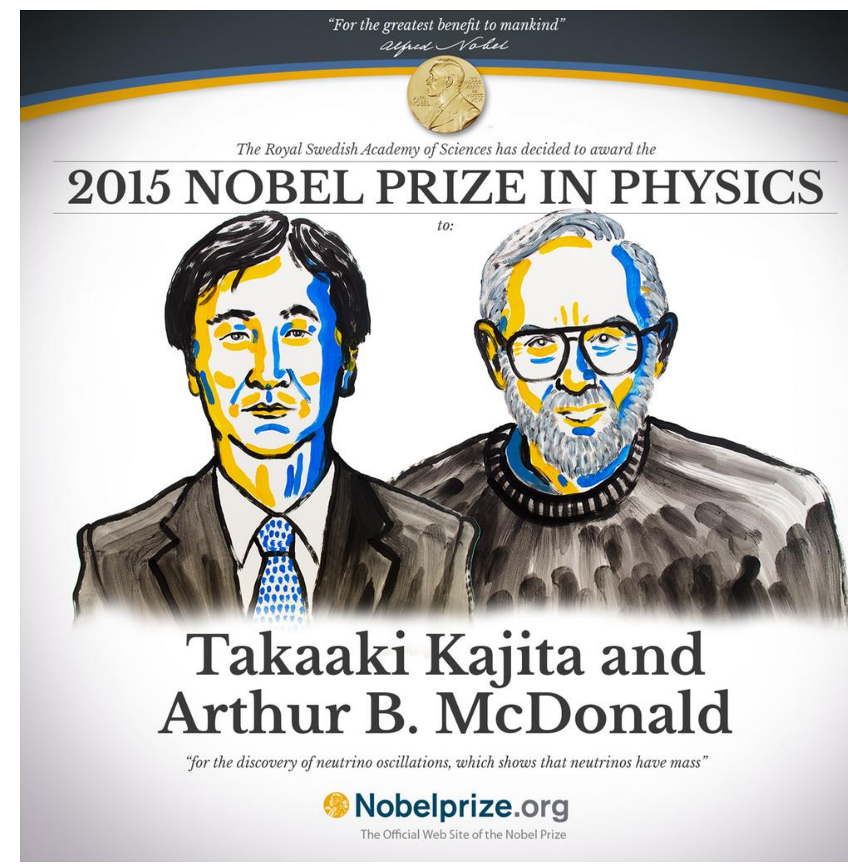
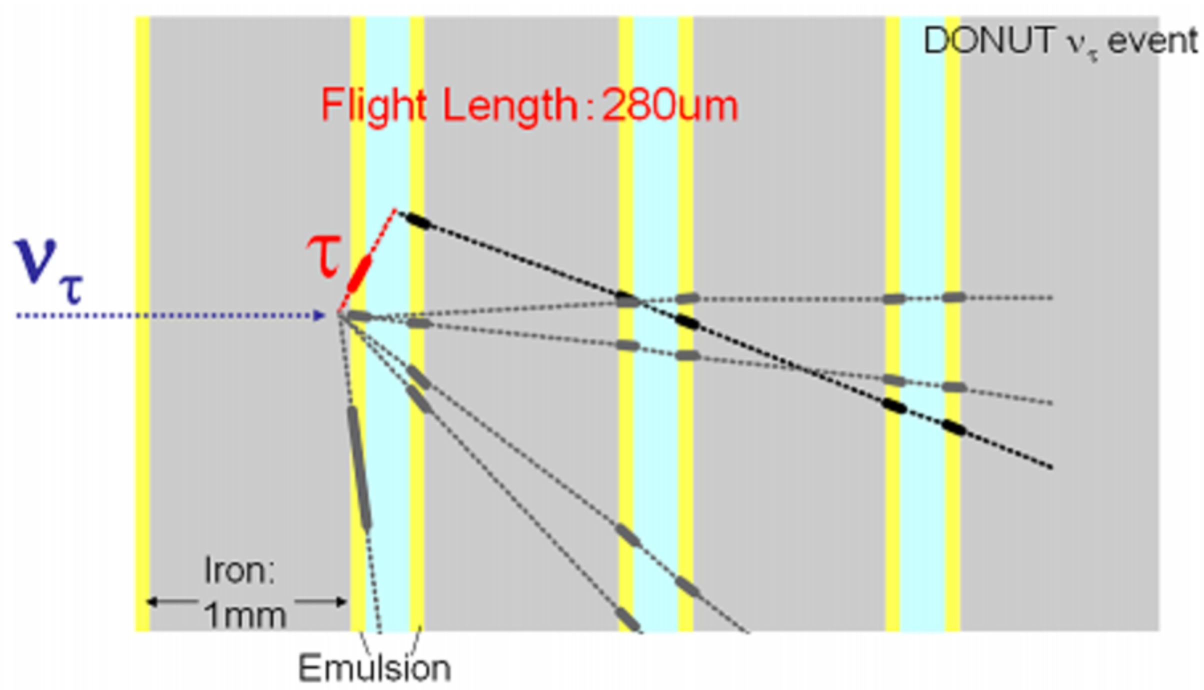
2015 NOBEL PRICE in PHYSICS

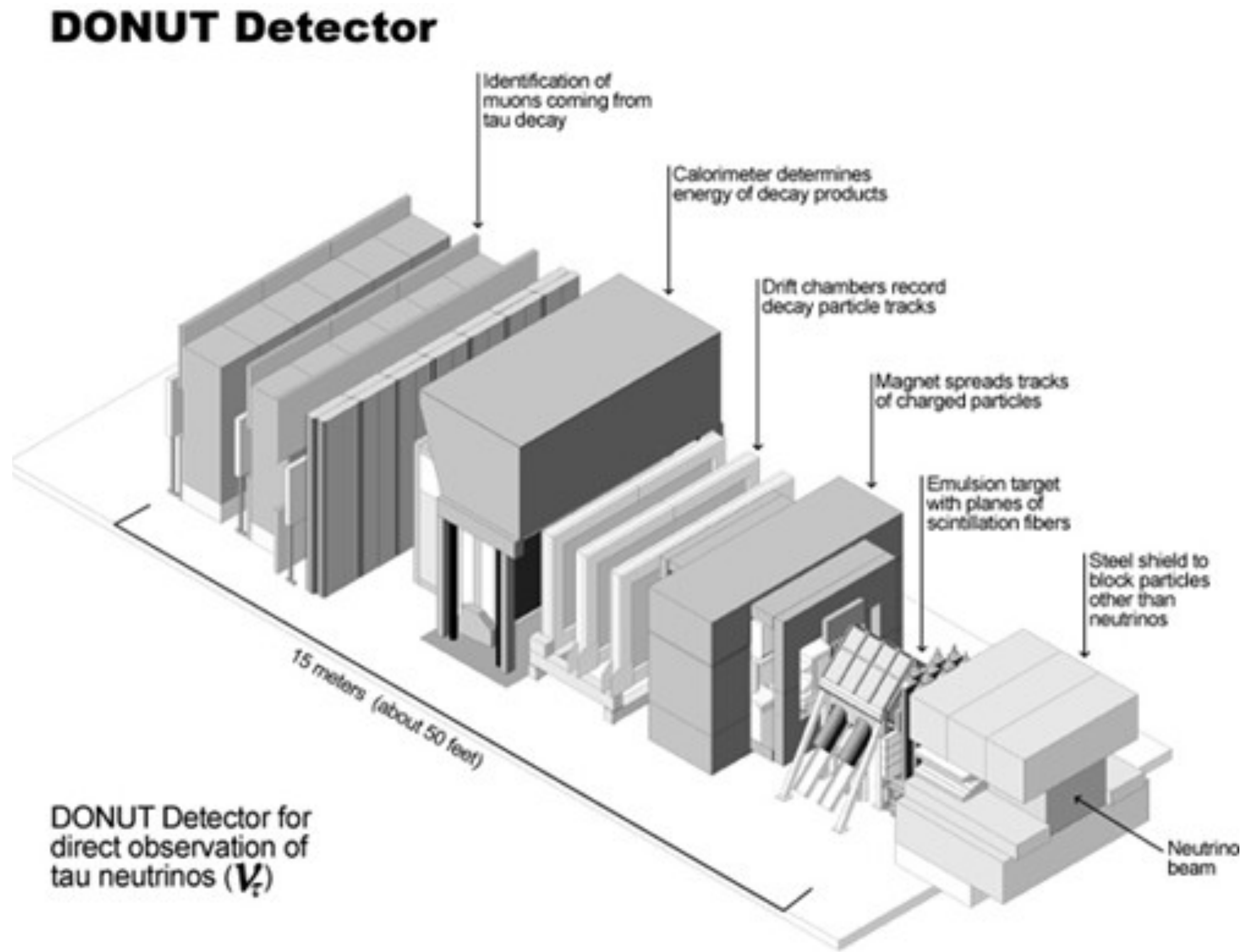


"for the discovery of neutrino oscillations, which shows that neutrinos have mass"



Discovery of Tau Neutrino (2000)





Weak-Isospin Eigenstates, mass eigenstates and mixing

- In the SM, there is a weak Isospin Iw that is conserved until the Higgs develops a nonzero vacuum expectation value
- Particles are given the following Iw assignments

Weak-Isospin eigenstate

$$\begin{array}{c} I_{W3} \\ +1 \\ 0 \\ -1 \end{array} \begin{pmatrix} W^+ \\ W^0 \\ W^- \end{pmatrix}, \quad \begin{array}{c} I_{W3} \\ +1/2 \\ -1/2 \end{array} \begin{pmatrix} \nu_{Le}^0 \\ e_L^0 \end{pmatrix} \begin{pmatrix} \nu_{L\mu}^0 \\ \mu_L^0 \end{pmatrix} \begin{pmatrix} \nu_{L\tau}^0 \\ \tau_L^0 \end{pmatrix}, \quad \begin{array}{c} I_{W3} \\ 0 \end{array} \; e_R^0 \quad \mu_R^0 \quad \tau_R^0$$

The W – lepton coupling conserves I_W.

- With

$$\ell_L^0 \equiv \begin{bmatrix} e_L^0 \\ \mu_L^0 \\ \tau_L^0 \end{bmatrix} \equiv \begin{bmatrix} \ell_{Le}^0 \\ \ell_{L\mu}^0 \\ \ell_{L\tau}^0 \end{bmatrix} \quad \text{and} \quad \nu_L^0 \equiv \begin{bmatrix} \nu_{Le}^0 \\ \nu_{L\mu}^0 \\ \nu_{L\tau}^0 \end{bmatrix},$$

From Boris Kayser's lecture INSS

The Lagrangian

- The W-lepton coupling is

Semi-weak coupling

$$\mathcal{L}_{SM} = -\frac{g}{\sqrt{2}}\left(\bar{\ell}^0_L \gamma^\lambda \nu^0_L\right) W_\lambda^- + h.c.$$

- When the lepton masses are turned on, the charged lepton weak-isosping eigenstates are linear combinations of the charged lepton mass eigenstates

3 x 3 matrices

$$\ell^0_{L,R} = A_{L,R}\,\ell_{L,R}$$

Column vectors including the 3 generations

$$\ell \equiv \ell_L + \ell_R = \begin{bmatrix} e \\ \mu \\ \tau \end{bmatrix}$$

These are the familiar mass eigenstates.

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From Boris Kayser's lecture INSS

The Lagrangian

$$\mathcal{L}_{SM} = -\frac{g}{\sqrt{2}}\left(\bar{\ell}^0_L \gamma^\lambda \nu^0_L\right) W_\lambda^- + h.c. = -\frac{g}{\sqrt{2}}\left(\overline{A_L \ell_L}\gamma^\lambda \nu^0_L\right) W_\lambda^- + h.c.$$

$$= -\frac{g}{\sqrt{2}}\left(\bar{\ell}_L \gamma^\lambda A_L^\dagger \nu^0_L\right) W_\lambda^- + h.c.$$

$$A_L^\dagger \nu^0_L = \begin{bmatrix} \nu_{Le} \\ \nu_{L\mu} \\ \nu_{L\tau} \end{bmatrix}$$

These are the neutrinos of definite "flavor".

$\bar{\ell}_L$: Mass eigenstates

- The interaction is written in terms of the charged lepton mass eigenstates, but not the neutrino mass eigenstates

From Boris Kayser's lecture INSS

The Lagrangian

All mass eigenstates

$$\mathcal{L}_{SM} = -\frac{g}{\sqrt{2}}\left(\bar{\ell}_L \gamma^\lambda A_L^\dagger \nu_L^0\right) W_\lambda^- + h.c. = -\frac{g}{\sqrt{2}}\left(\bar{\ell}_L \gamma^\lambda \underbrace{A_L^\dagger B_L}\nu_L\right) W_\lambda^- + h.c.$$

This is the leptonic mixing matrix ***U***

Explicitly —

$$\mathcal{L}_{SM} = -\frac{g}{\sqrt{2}} \sum_{\substack{\alpha=e,\mu,\tau \\ i=1,2,3}} \left(\bar{\ell}_{L\alpha} \gamma^\lambda U_{\alpha i} \nu_{Li} W_\lambda^- + \bar{\nu}_{Li} \gamma^\lambda U_{\alpha i}^* \ell_{L\alpha} W_\lambda^+\right)$$

- We can use this form of the SM $l\nu W$ interaction to derivate the probability for neutrino oscillation

From Boris Kayser's lecture INSS

Standard Model Neutrino Interactions

- Lagrangian for electroweak interactions:

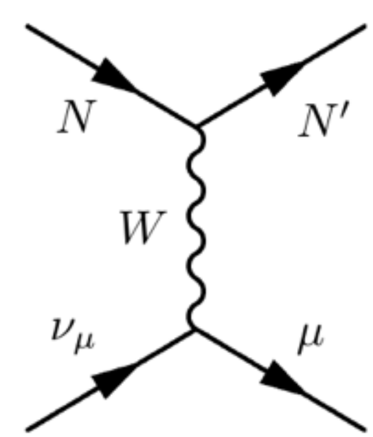
$$L_{\text{int}} = i\frac{g}{\sqrt{2}}\left[j_\mu^{(+)}W^\mu + j_\mu^{(-)}W^{\mu+}\right] + i\left[g\cos\theta_W\, j_\mu^{(3)} - g'\sin\theta_W\, j_\mu^{(Y/2)}\right]Z^\mu + \\ + i\left[g\sin\theta_W\, j_\mu^{(3)} + g'\cos\theta_W\, j_\mu^{(Y/2)}\right]A^\mu$$

- First term: charged current interactions (W^+,W^- exchange)
- Second term: neutral current interactions (Z^0 exchange)
- Third term: electromagnetic interactions (photon exchange)

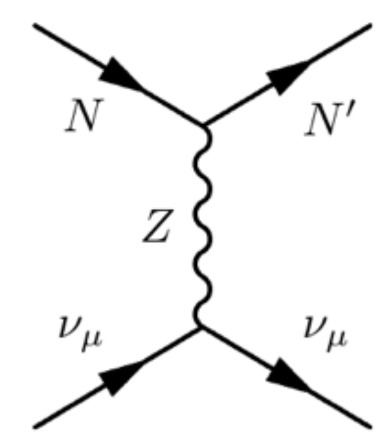
- Electron charge: $e = g\sin\theta_W = g'\cos\theta_W$

Neutrinos only couple to W and Z^0

Charged Current (CC) interactions via a W-boson



Neutral Current (NC) interactions via a Z-boson



Neutrino Mass and Leptonic Mixing

- There is some spectrum of 3 neutrino mass and eigenstates

$\ell_e \equiv e,\ \ell_\mu \equiv \mu,\ \ell_\tau \equiv \tau$

When $W^+ \rightarrow \ell_\alpha^{\ +} + \nu_\alpha$,

$e,\ \mu,\ \text{or}\ \tau$

the produced neutrino state $|\nu_\alpha\rangle$ is

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}\, |\nu_i\rangle \ .$$

Neutrino of flavor α

Neutrino of definite mass m_i

Leptonic Mixing Matrix

Neutrino Oscillations

- Interaction eigenstate (produced by weak interactions)
- Mass eigenstate (eigenstate of the Hamiltonian)

$$\mathcal{H}|\nu_i\rangle = E_i|\nu_i\rangle$$

$$|\nu_\alpha\rangle = \sum_{i=1}^{n} U^*_{\alpha i}|\nu_i\rangle$$

$$\nu_\alpha = \sum_i U_{\alpha i}\nu_i$$

Field ψ annihilates state |ψ>

$$|\nu_\alpha\rangle = \nu^\dagger_\alpha|0\rangle = \sum_i \nu^\dagger_i U^*_{\alpha i}|0\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle$$

- After producing a neutrino in a well defined flavor, it evolves like

$$|\nu_\alpha(t)\rangle = \sum_{i=1}^{n} U^*_{\alpha i}|\nu_i(t)\rangle$$

- We also detect it in a defined flavor, so the amplitude we measure is

$$A_{\alpha\beta}(t) = \langle\nu_\beta|\nu_\alpha(t)\rangle$$

Neutrino Oscillations

$$A_{\alpha\beta}(t) = \langle \nu_\beta | \nu_\alpha(t) \rangle$$

$$A_{\alpha\beta}(t) = \sum_{i=1}^{n} \sum_{j=1}^{n} U^*_{\alpha i} U_{\beta j} \langle \nu_j | \nu_i(t) \rangle$$

- The hamiltonian is related to the time evolution operator, so

$$|\nu_i(t)\rangle = e^{-i\,E_i t} |\nu_i(0)\rangle$$

- Neutrinos are relativistic

$$E_i = \sqrt{p_i^2 + m_i^2} \simeq p + \frac{m_i^2}{2E}$$

$$A_{\alpha\beta}(t) = \langle \nu_\beta | \nu_\alpha(t) \rangle = U^*_{\alpha i} U_{\beta j} \langle \nu_j | e^{-iE_i t} | \nu_i \rangle$$

$$= e^{-ipt} U^*_{\alpha i} U_{\beta i} \exp\left(-i \frac{m_i^2 t}{2E} \right)$$

Isolated an overall phase
Got lazy and stopped writing the sums
Used orthogonality condition:
$\langle \nu_j | \nu_i \rangle = \delta_{ij}$

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Neutrino Oscillations

- Let's isolate another overall phase

$$A_{\alpha\beta} = e^{-i(pt+m_1^2 t/2E)} U^*_{\alpha i} U_{\beta i} \exp\left(-i\frac{\Delta m_{i1}^2 t}{2E}\right)$$

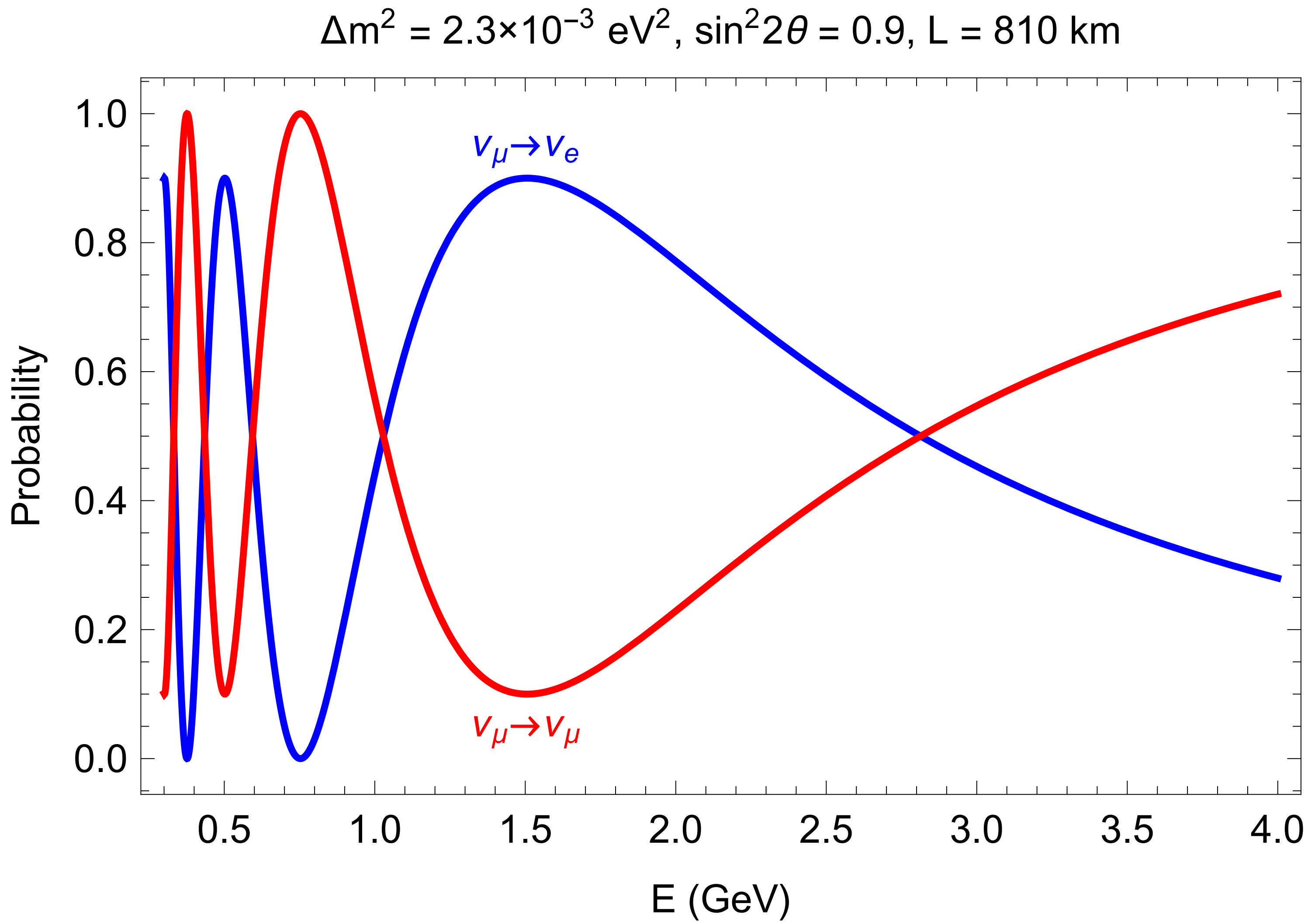
- To make it simpler, consider two neutrinos (say ν_e and ν_μ)

$$U = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$$

$$P(\nu_\mu \to \nu_e; L) = |A_{\mu e}(L)|^2 = 4c_\theta^2 s_\theta^2 \sin^2\left(\frac{\Delta m^2 L}{4E}\right) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Neutrino Oscillations

$$P(\nu_\mu \to \nu_e; L) = |A_{\mu e}(L)|^2 = 4c_\theta^2 s_\theta^2 \sin^2\left(\frac{\Delta m^2 L}{4E}\right) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$



The probability of producing ν_μ and detect ν_e really *oscillates*!

Neutrino Oscillations

- For the three families there are 3 mixing angles, 2 mass splitting and one complex phase

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

- The components of U involve θ_{13}, θ_{23}, θ_{12}, $\Delta^2 m_{13}$, $\Delta^2 m_{23}$, $\Delta^2 m_{12}$, δ

Probability of ν_μ—>ν_e Oscillation in Vacuum

$$
\begin{aligned}
P(\nu_\mu \rightarrow \nu_e) \quad &= \quad s_{23}^2 sin^2 2\theta_{13} sin^2 \frac{\Delta m_{31}^2 L}{4E} + c_{13}^2 c_{23}^2 sin^2 2\theta_{12} sin^2 \frac{\Delta m_{21}^2 L}{4E} \\
&+ \quad 8 c_{13}^2 s_{13} c_{12} s_{12} s23 c_{23} sin \frac{\Delta m_{21}^2 L}{4E} sin \frac{\Delta m_{31}^2 L}{4E} cos(\frac{\Delta m_{32}^2 L}{4E} + \delta) \\
&- \quad 2 s_{12}^2 s_{23}^2 sin^2 2\theta_{13} sin \frac{\Delta m_{21}^2 L}{4E} sin \frac{\Delta m_{31}^2}{4E} cos \frac{\Delta m_{32}^2 L}{4E} \\
&+ \quad 4 c_{13}^2 s_{12}^2 s_{13} s_{23} (s_{23} s_{13} s_{12} - 2 c_{12} c_{23} cos\delta) sin^2 \frac{\Delta m_{21}^2 L}{4E} \qquad (2.8)
\end{aligned}
$$

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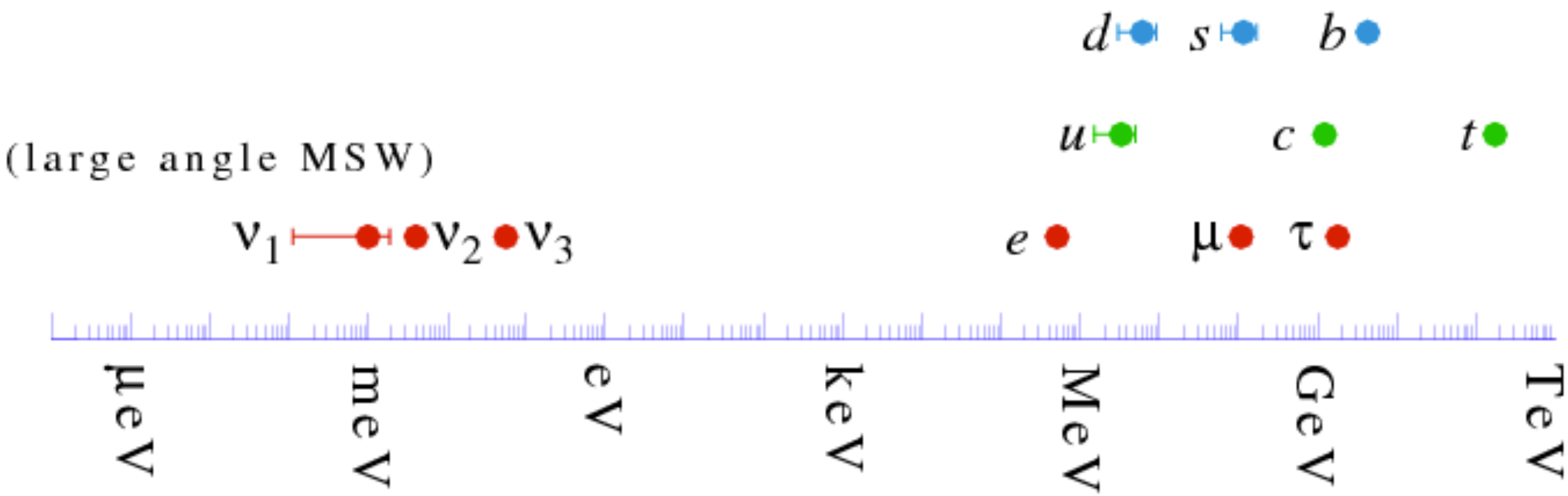
Is there a reason behind the masses and mixing?

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & \mathbf{0.2} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

- Lepton mixing is very different from quark mixing



What do we know?

- The probability of a neutrino ν_μ transforming into a ν_e

$$P(\nu_\alpha \to \nu_\beta) = |\sum_j U_{\beta j} e^{-i\frac{\Delta m_j^2 L}{2E}} U_{\alpha j}|^2$$

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = U^* \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

- where the mixing matrix has 3 mixing angles and one phase

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

Atmospheric+Accelerator

$$\Delta m_{32}^2 \sim 2.5 \times 10^{-3} eV^2$$

$$\theta_{23} \sim 45^\circ$$

Reactor+Accelerator

$$\theta_{13} \sim 9^\circ$$

$$\delta_{CP} = ?$$

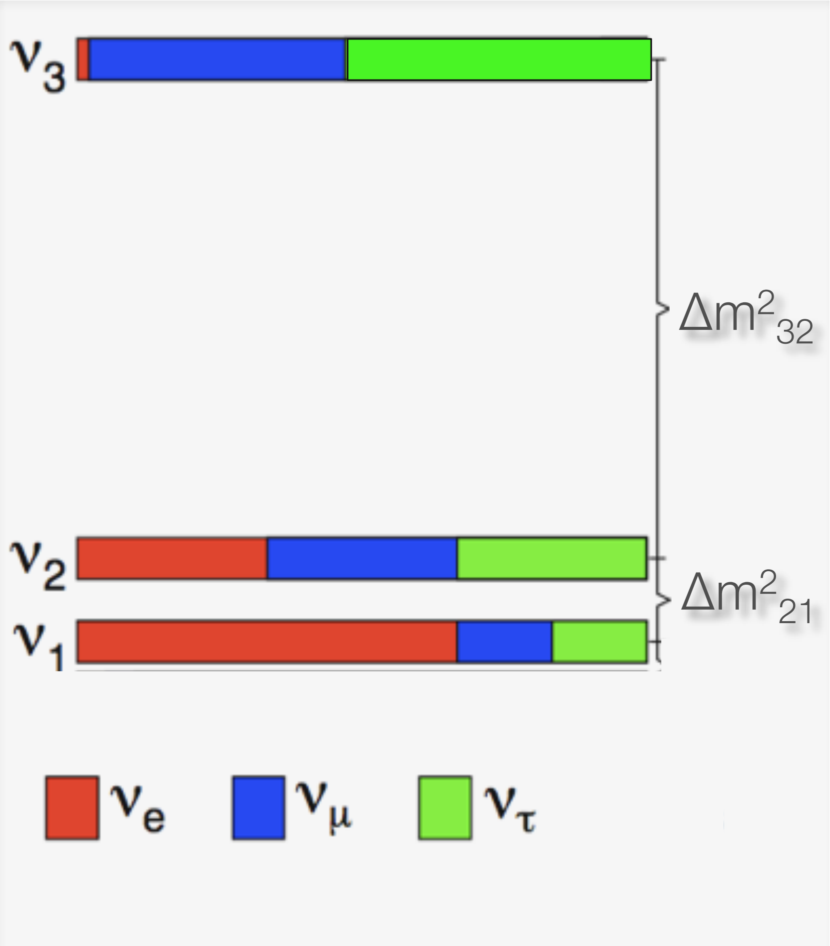
Solar+Reactor

$$\delta m_{21}^2 \sim 8 \times 10^{-5} eV^2$$

$$\theta_{12} \sim 34^\circ$$

Remaining Questions

- Is there CP violation in the lepton sector?
  - May explain matter-antimatter asymmetry
- What is the mass hierarchy? (sign of Δm^2_{32})
  - Important to be able to understand the reach of experiments that study whether neutrinos are their own antiparticle or not
- Is θ_{23} maximal?
- Is there a fourth "sterile neutrino"?



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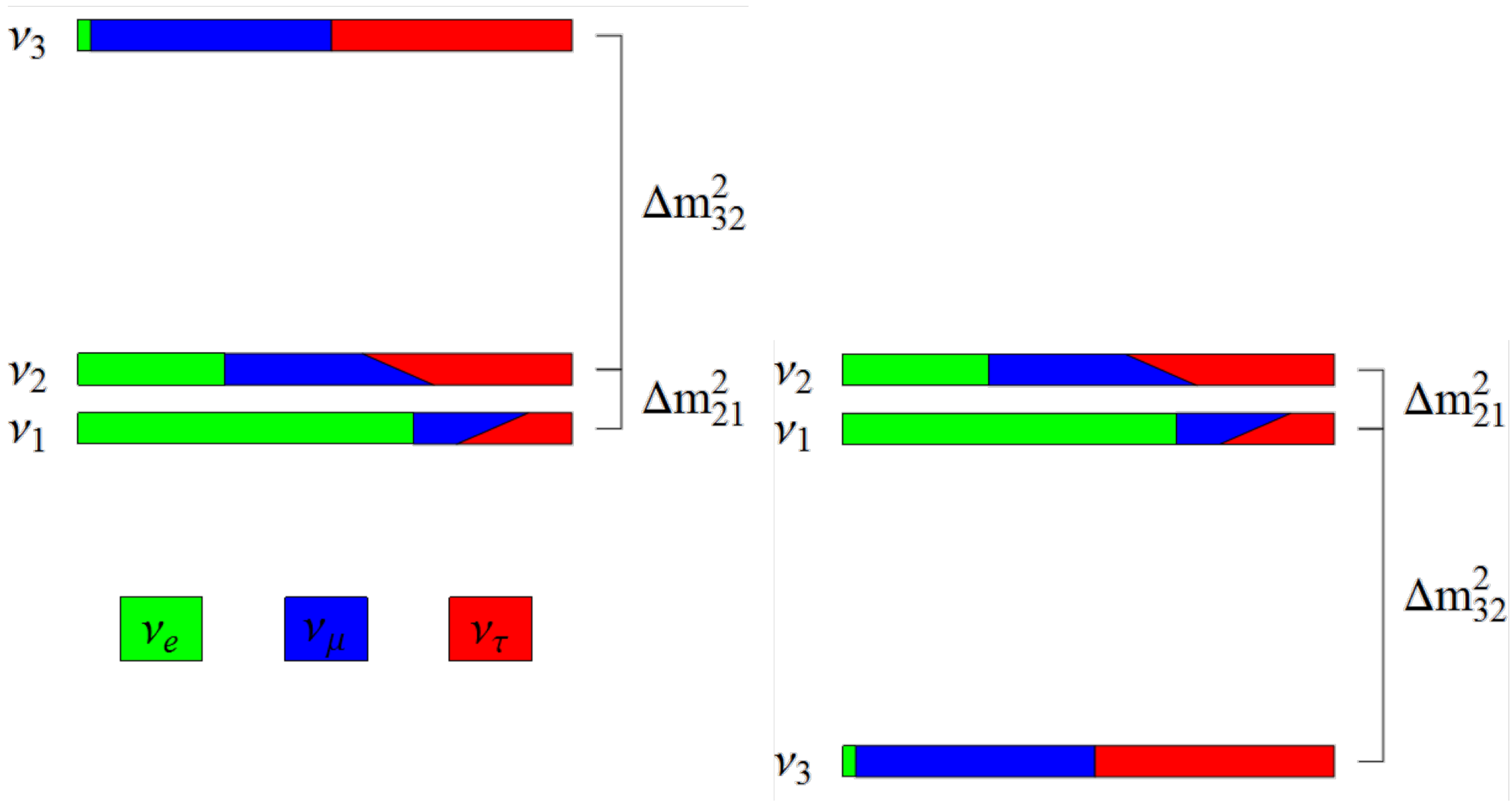
Remaining Questions

- Is the mass hierarchy "normal" or "inverted"?



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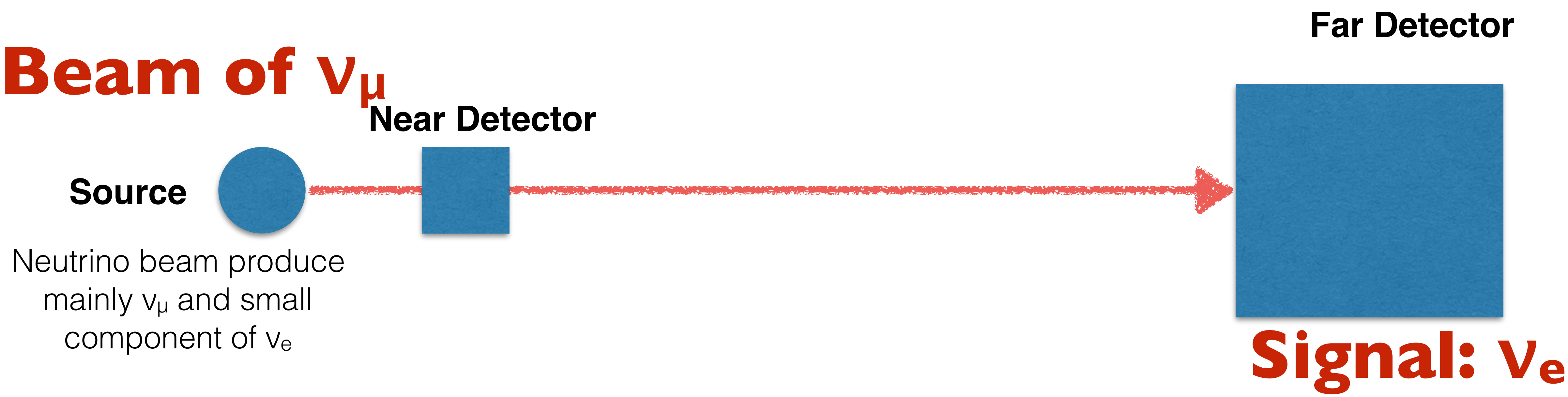
Addressing the Remaining Questions

- Is there CP violation in the lepton sector $P[\nu_\mu \rightarrow \nu_e] \neq P[\overline{\nu}_\mu \rightarrow \overline{\nu}_e]$?
- What is the mass hierarchy? (sign of Δm^2_{32})



$\phi \times \sigma \times$ **Nuclear Effects**

$\phi' \times \sigma \times$ **Nuclear Effects** $\times P_{\nu_\mu \rightarrow \nu_e}$

Nuclear model

- Use simulations to extrapolate from near detector to far detector $\sigma_{\nu\mu} \rightarrow \sigma_{\nu e}$
- We definitely need a nuclear model to convert from produced to detected energy spectra and topologies in the near and the far detectors

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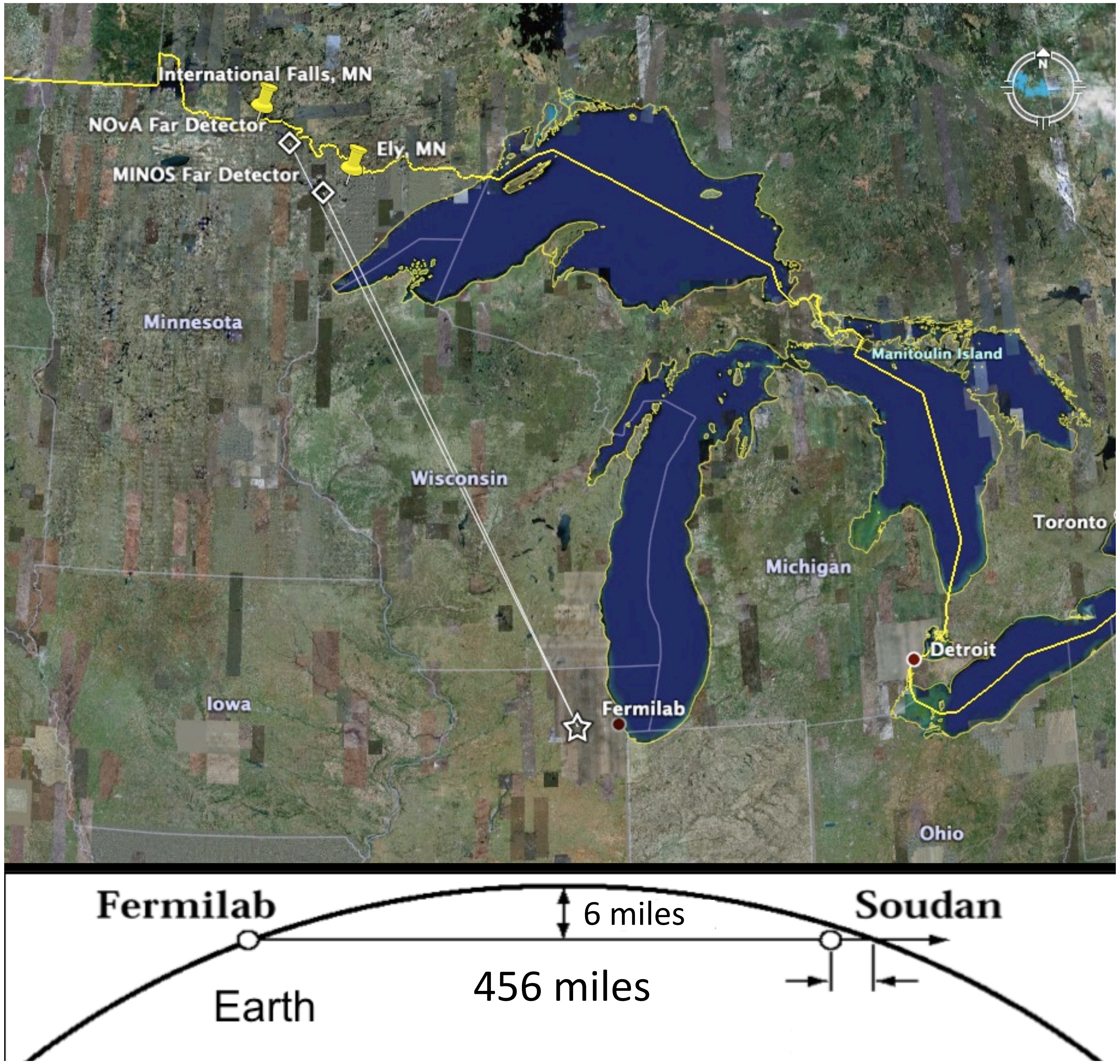
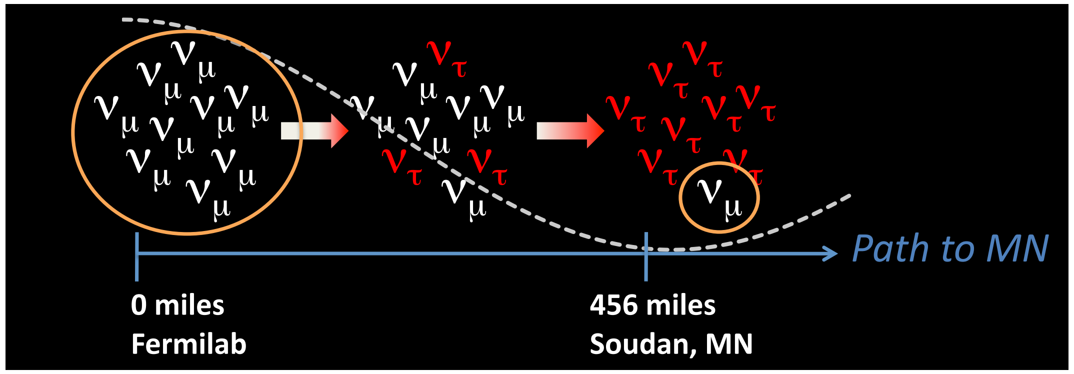
Where is the Far and Near Detector?



Neutrinos make the journey from Fermilab to northern Minnesota

Illinois
Wisconsin
Minnesota

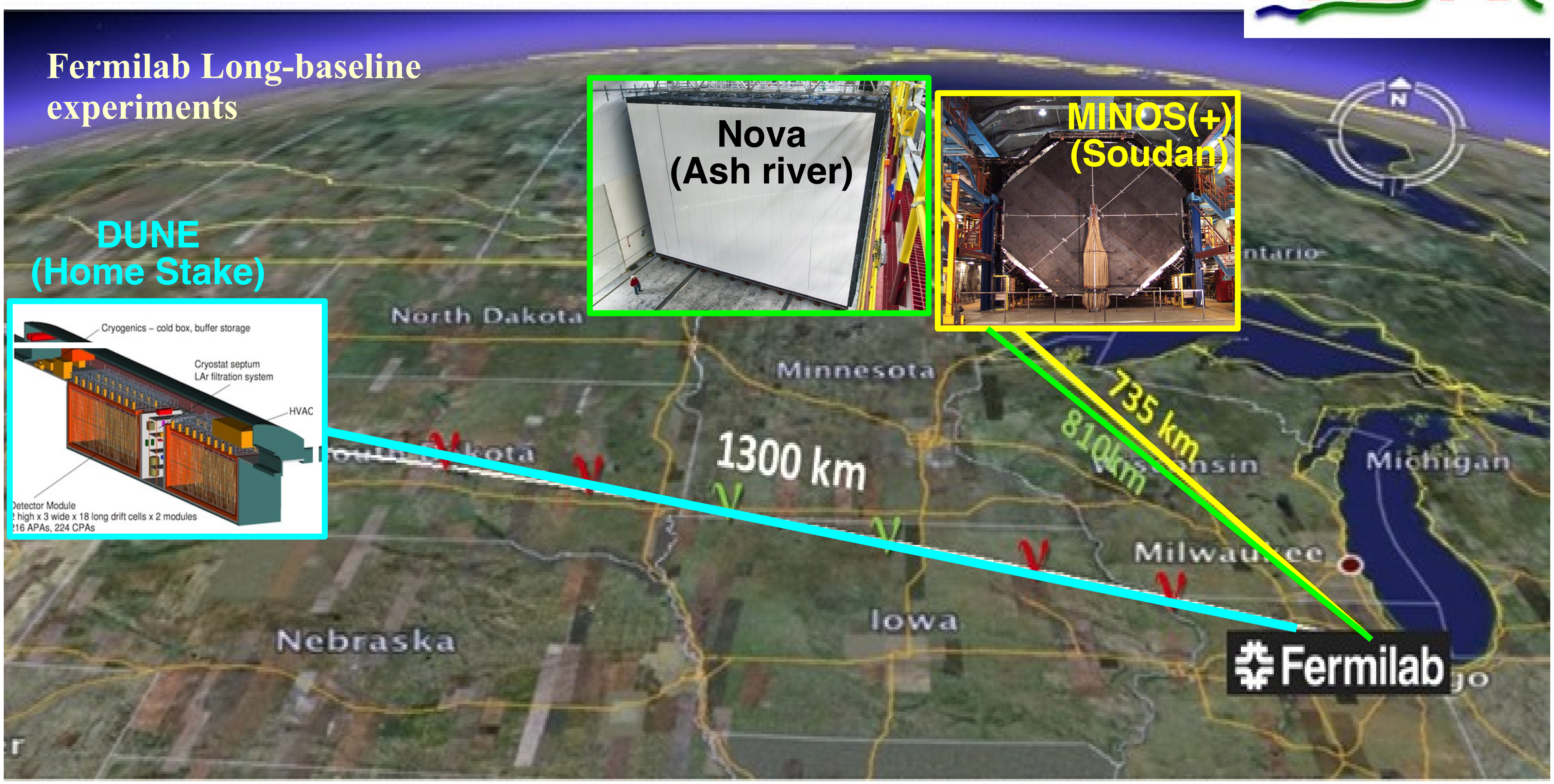


Long-baseline Experiments: What can we learn?

- Use a high intensity beam of neutrinos from Fermilab
- Construct detectors at far locations: MINOS+ at 735 Km (ended data-taking), NOvA at 810 km (taking data) and DUNE at 1300 km (in design)

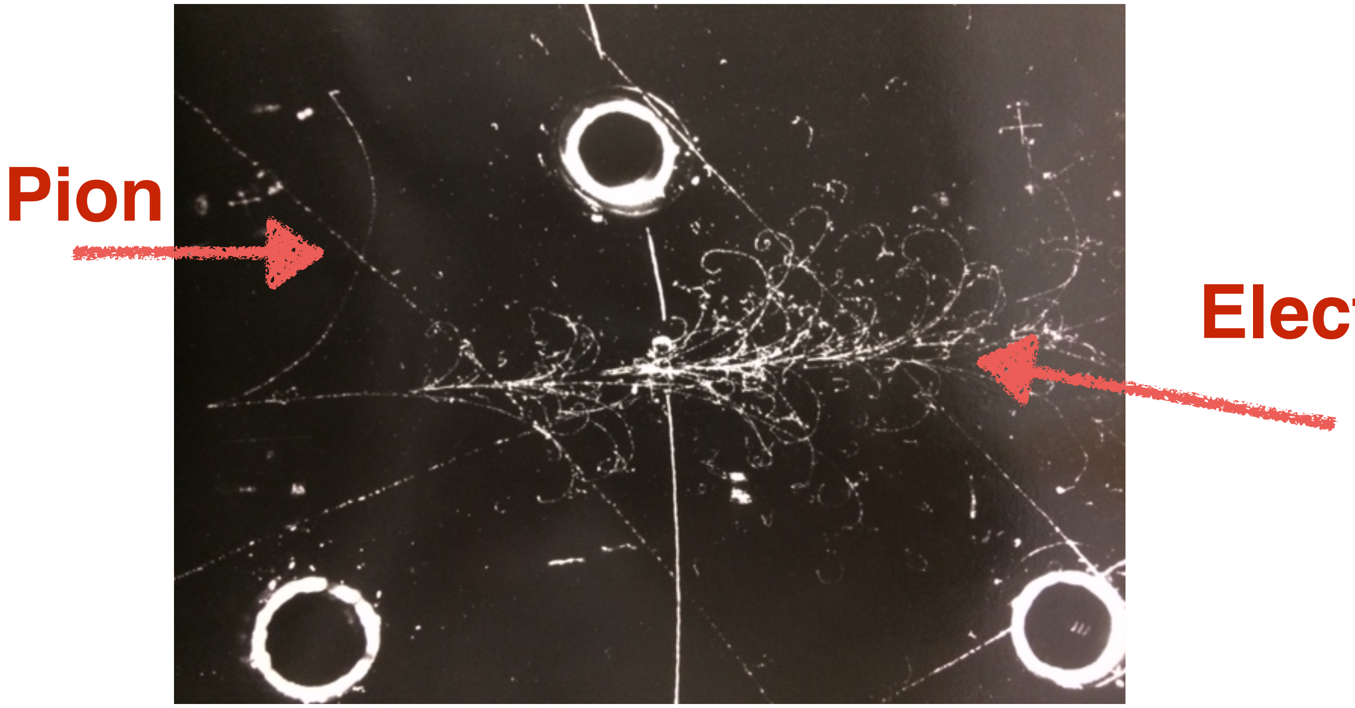
$$P[\nu_\mu \rightarrow \nu_e] \neq P[\overline{\nu}_\mu \rightarrow \overline{\nu}_e] \ ?$$

also, T2K in Asia

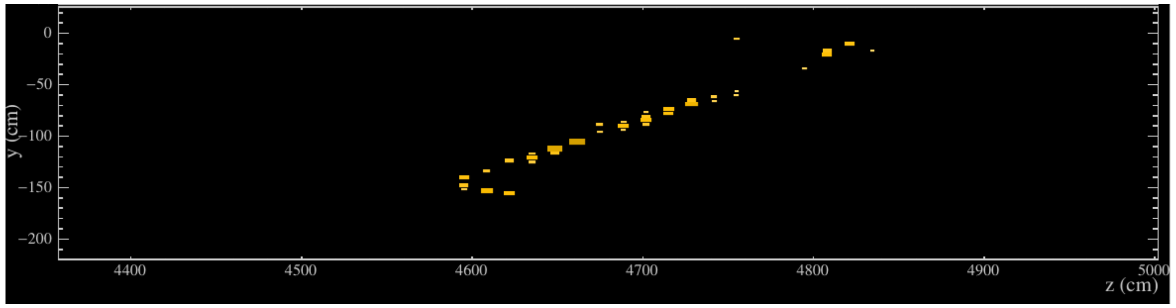


Electron Neutrinos Topologies at Different Detectors

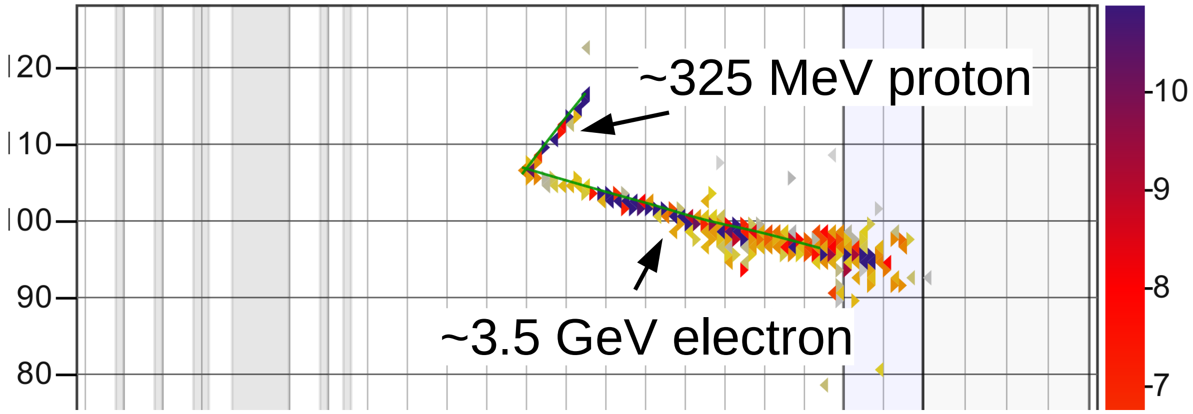
Electron Neutrino from Gargamelle (1978)



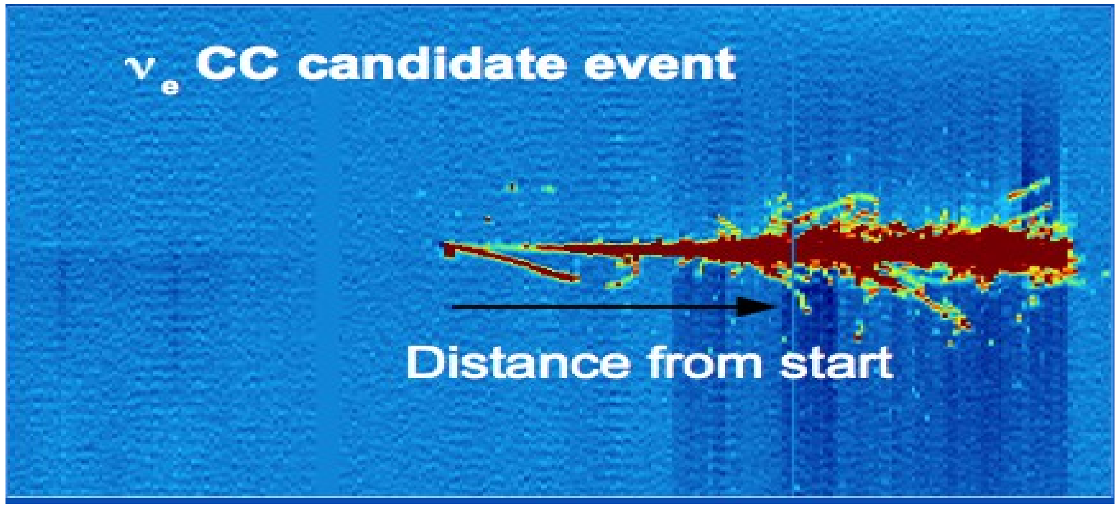
NOvA Experiment



MINERvA Experiment

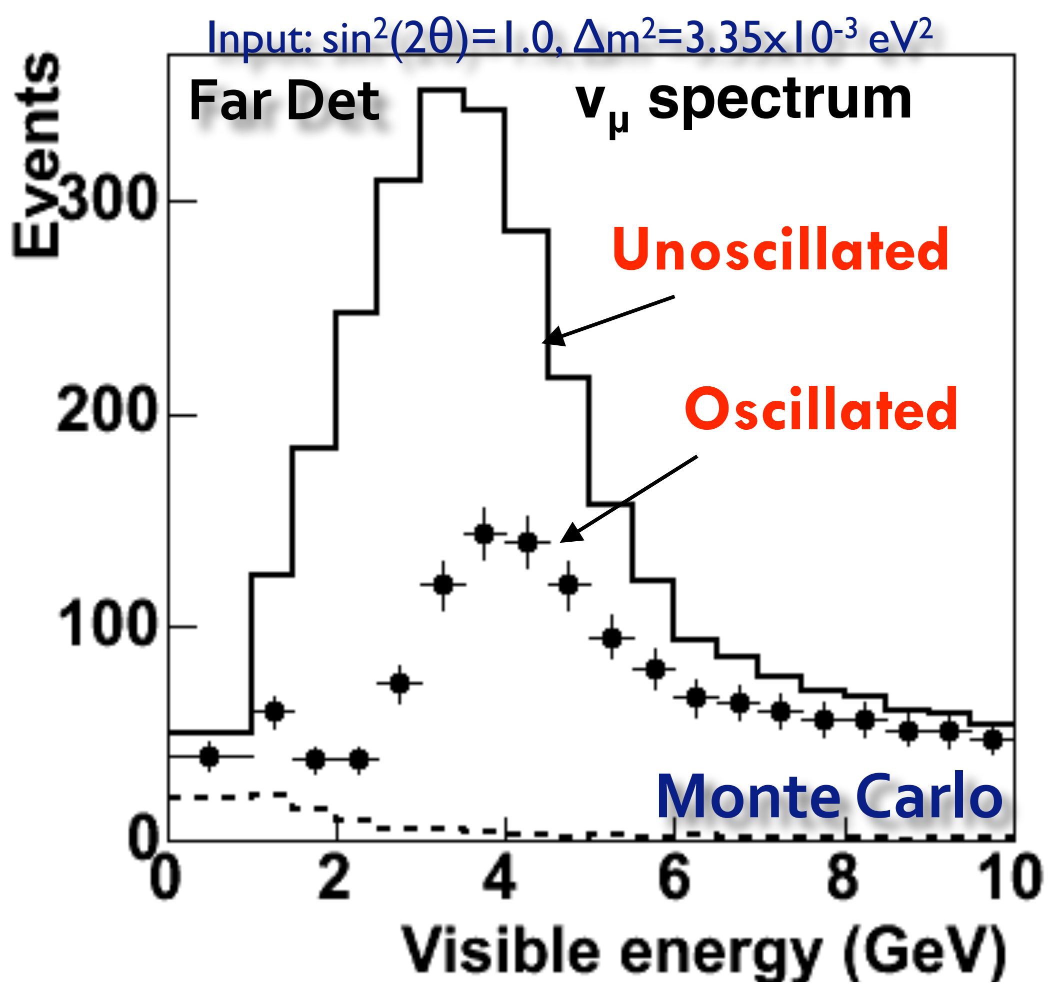


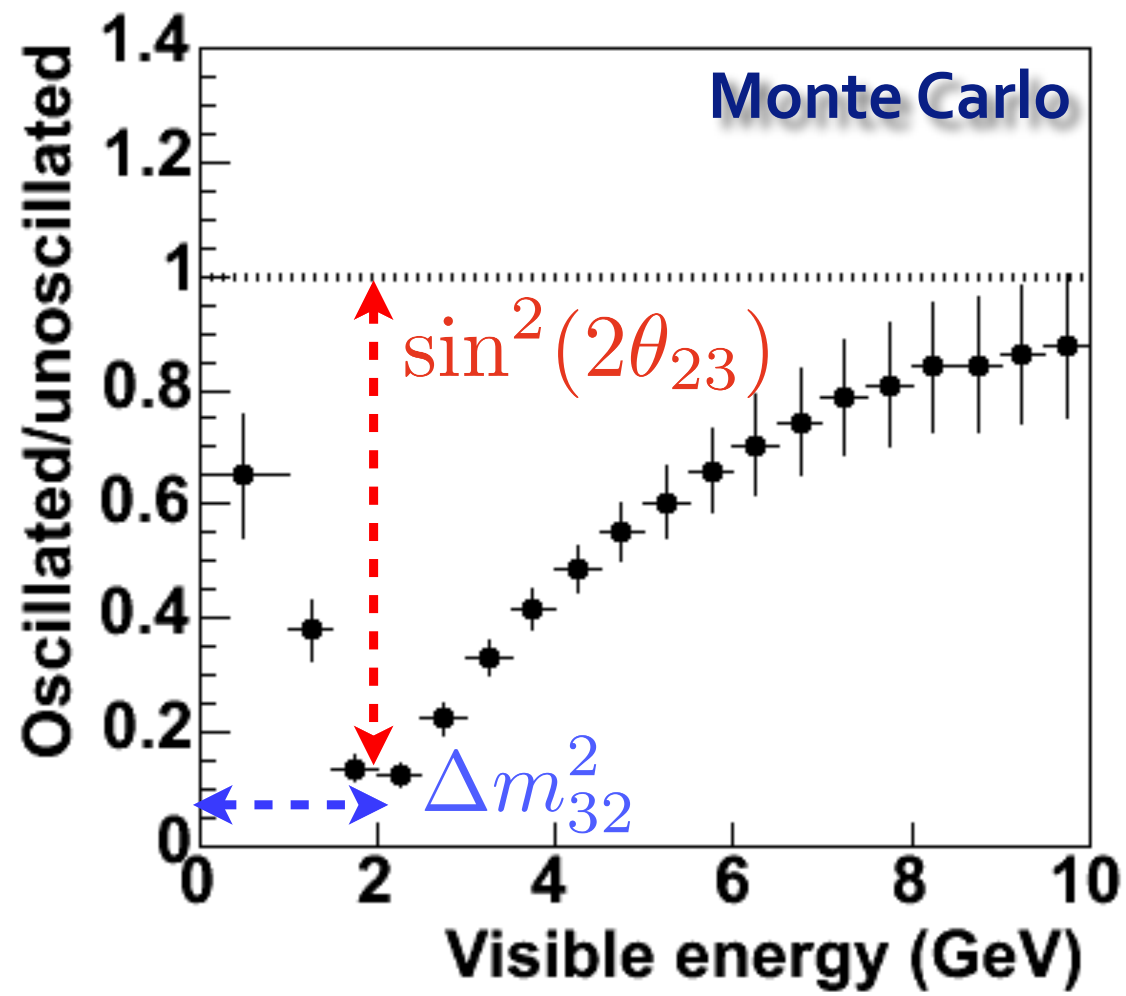
Electron Neutrino from Liquid Argon



Searching for ν_μ Disappearance

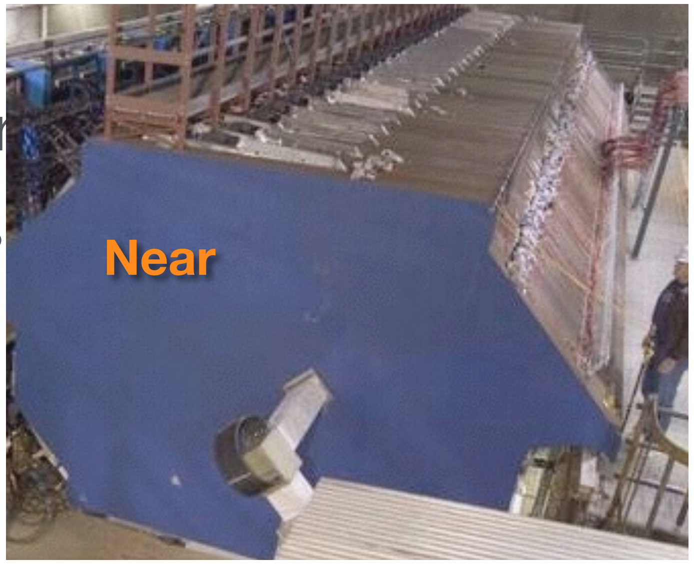
- In long baseline experiment, we compare a prediction obtained from Near Detector data with a Far Detector measurement

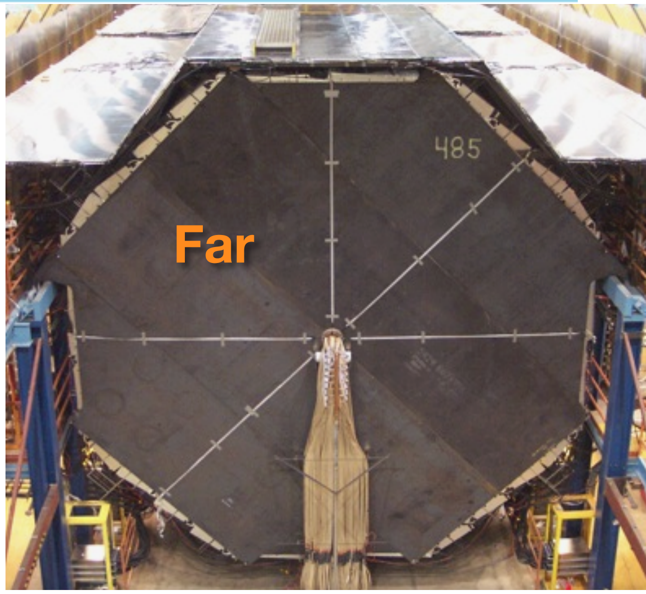


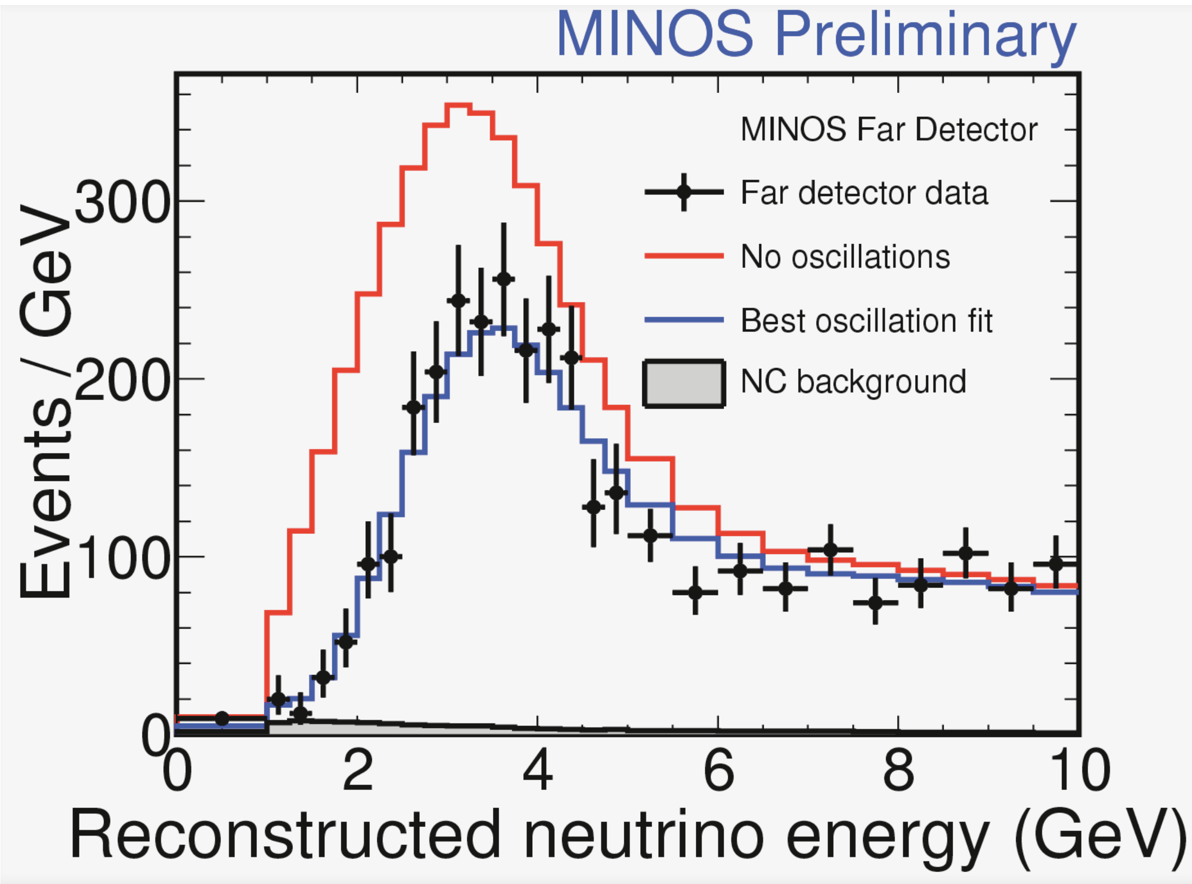


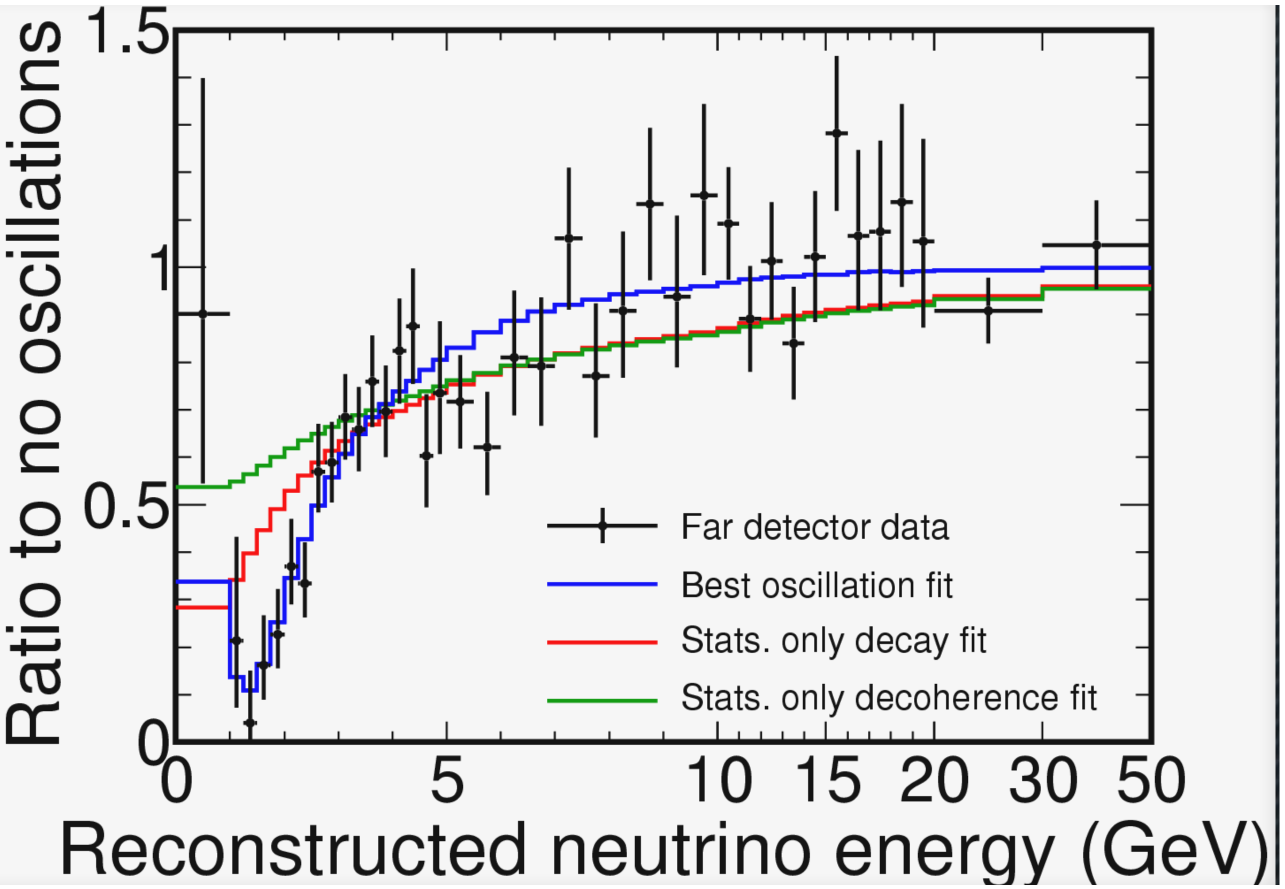
MINOS Experiment

- Near and Far detectors
- Steel planes (2.54 cm), magnetized detector
- Alternating with planes of scintillator strips
  - Near detector: 1 ton
  - Far detector: 5.4 kton



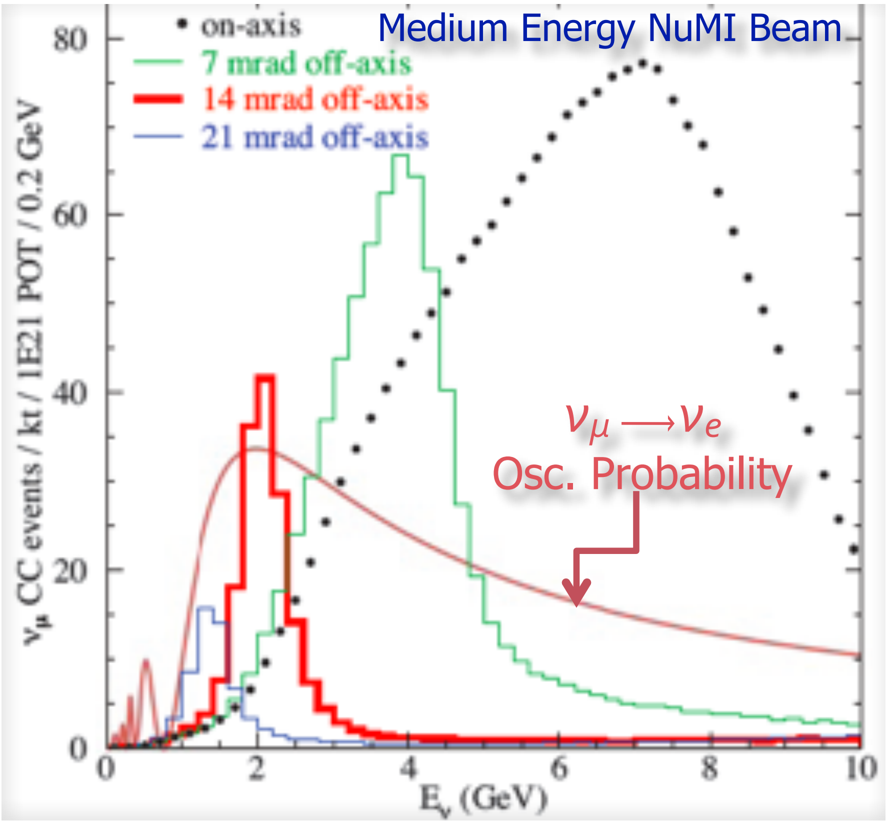


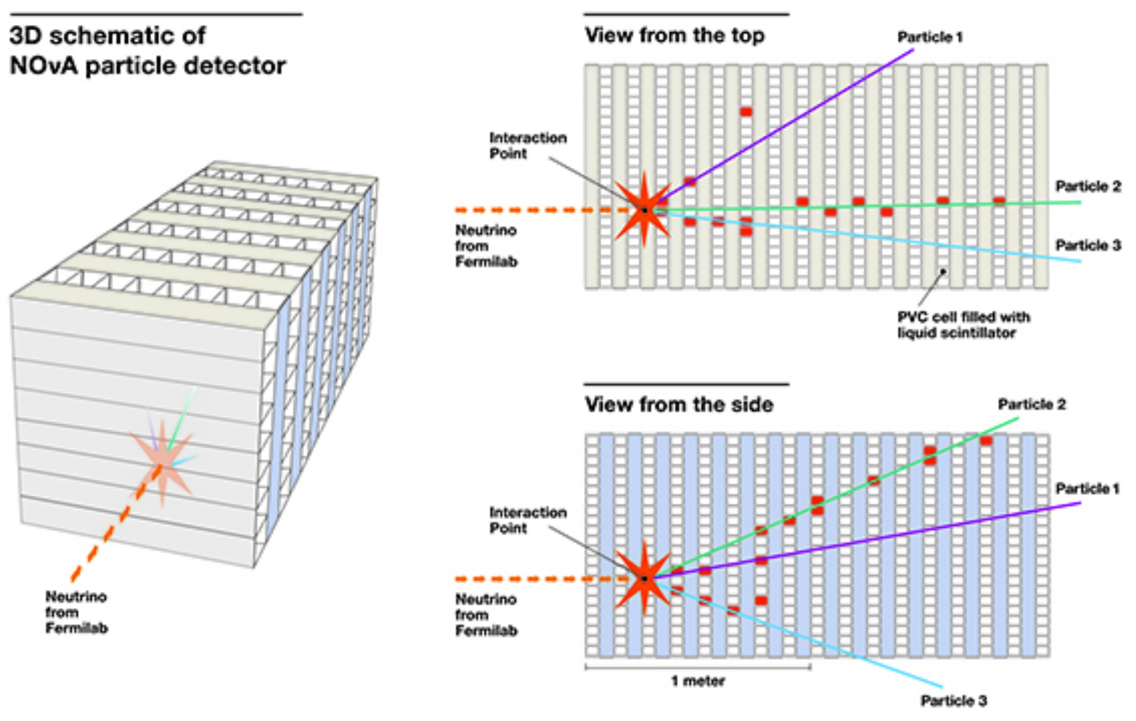




NOvA Experiment

- Far detector is 14 ktons, sits at Minnesota
- Near Detector is 290 tons placed 300 ft underground
- Identically functionality
  - Consist of plastic cells filled with liquid scintillator
- Off axis beam neutrinos



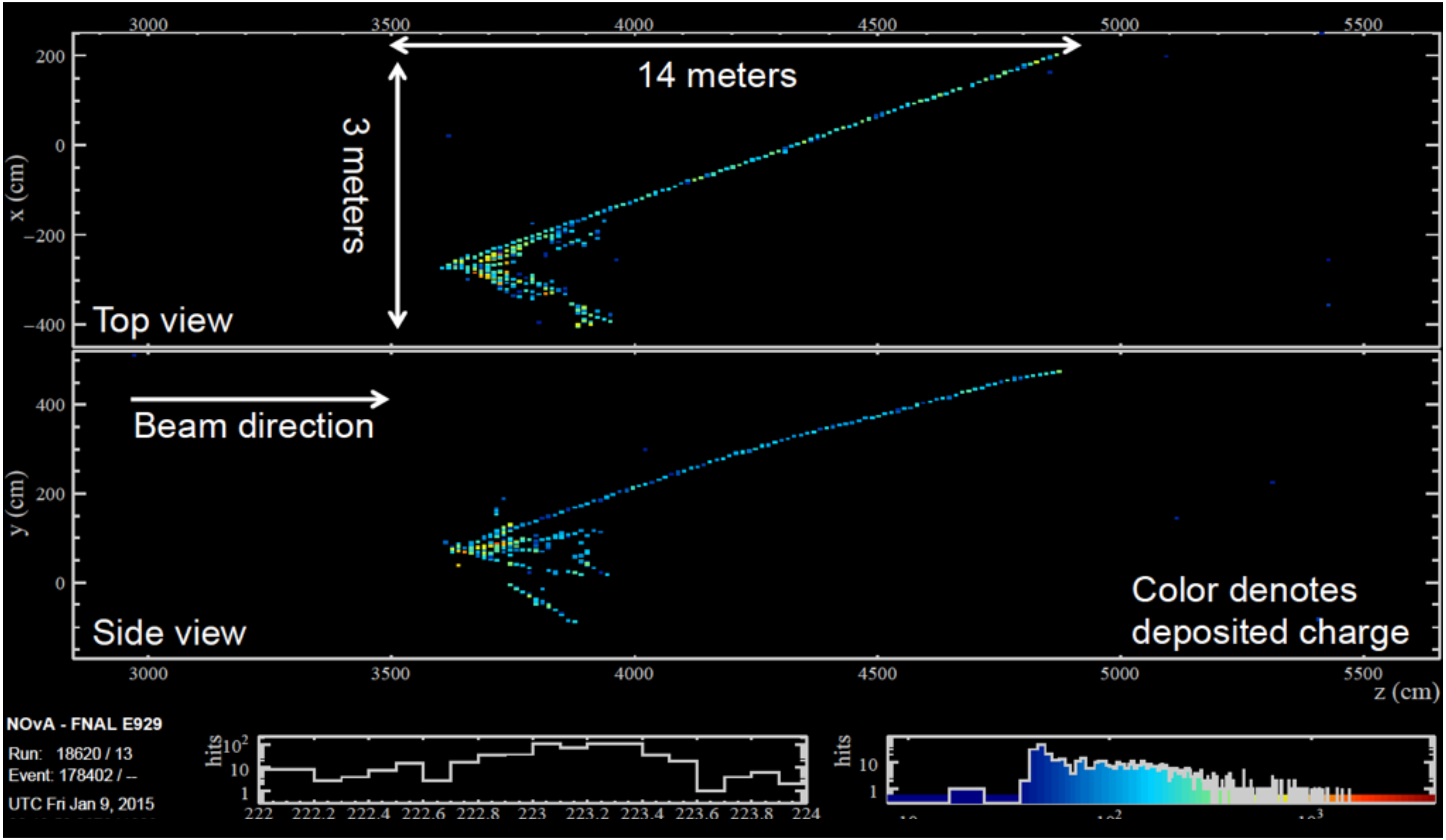


Fermilab

NOvA Experiment

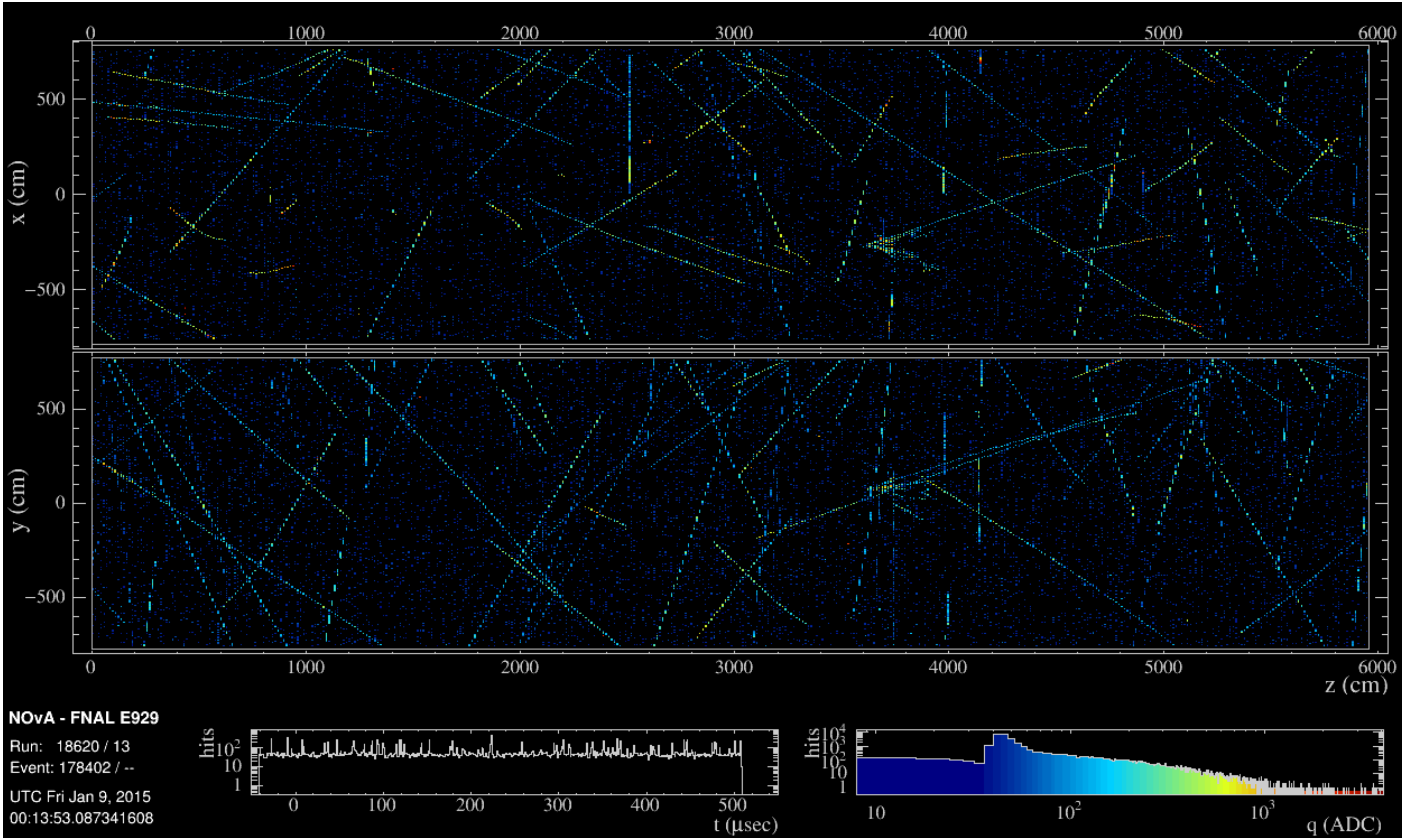
Fermilab

A Neutrino Interaction from the NOvA Experiment



Fermilab

What do we see at the NOvA Experiment?



NOvA Experiment

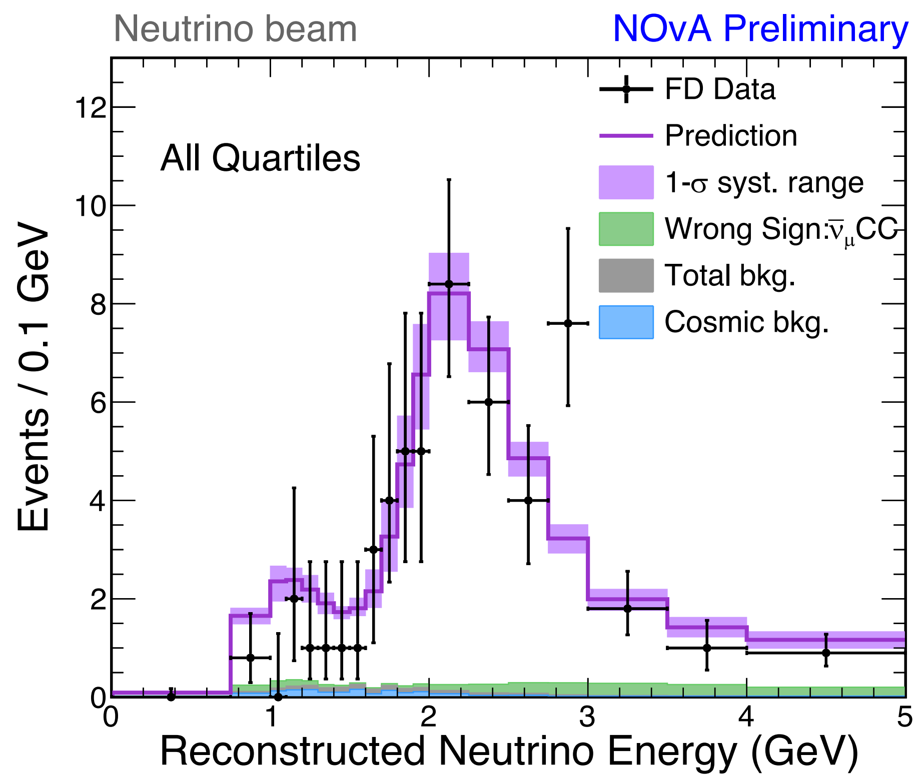
ν_μ

Total Observed	113
Best fit prediction	121
Cosmic Bkgd.	2.1
Beam Bkgd.	1.2
Unoscillated	730

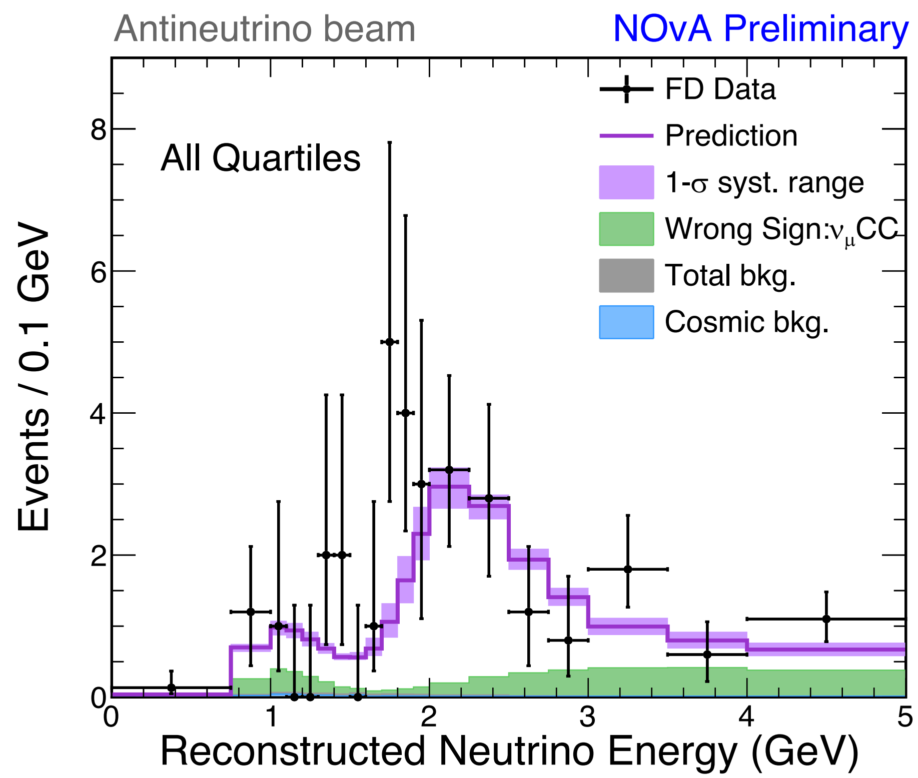
$\bar{\nu}_\mu$

Total Observed	65
Best fit prediction	50
Cosmic Bkgd.	0.5
Beam Bkgd.	0.6
Unoscillated	266

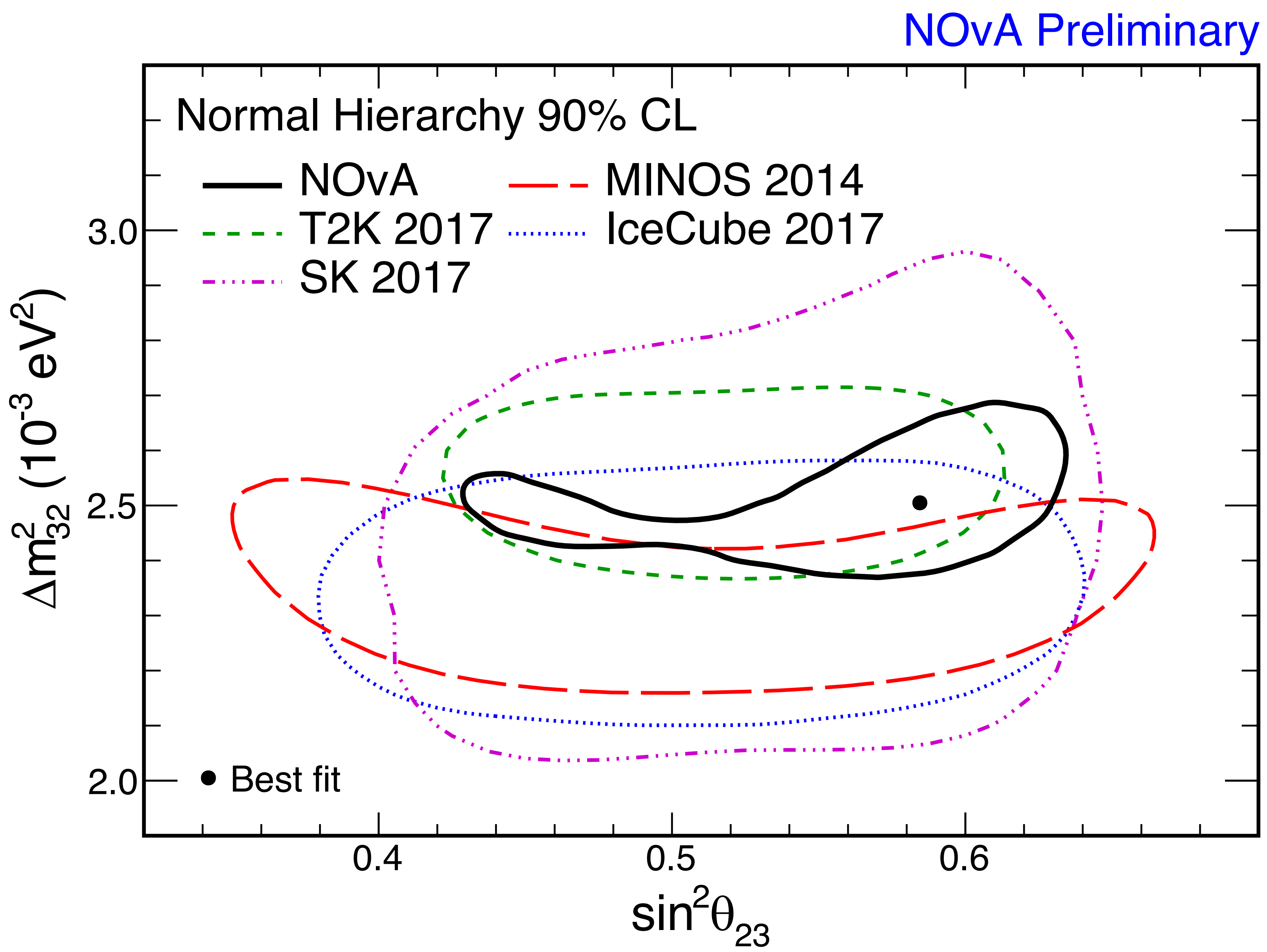
ν_μ



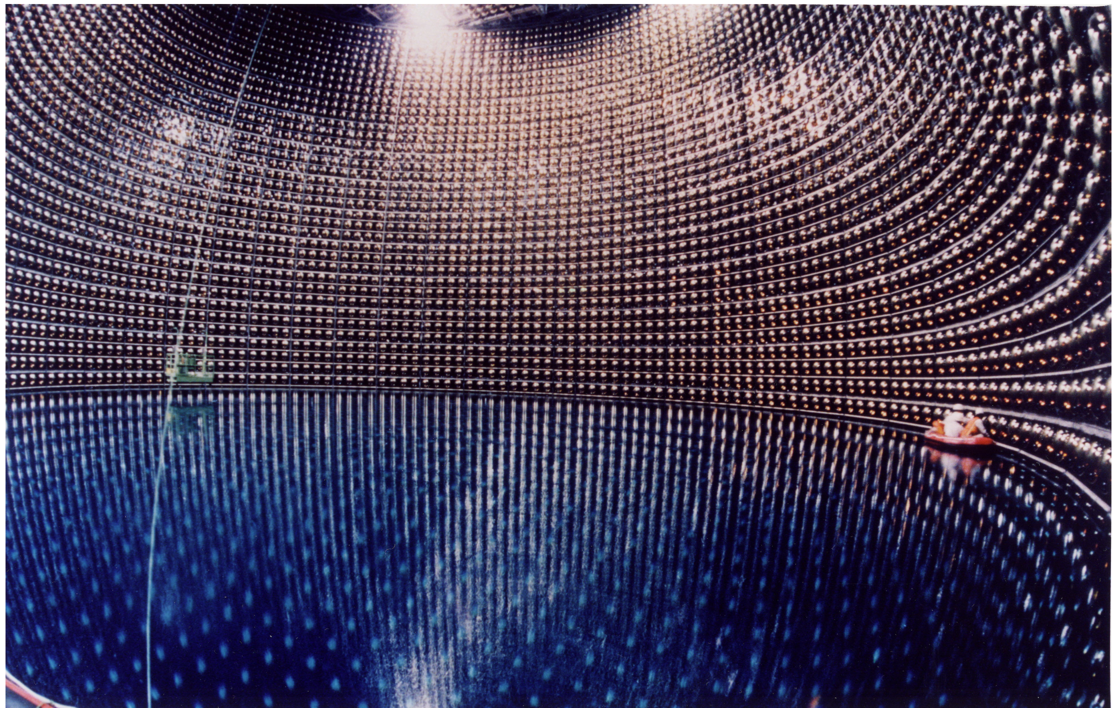
$\bar{\nu}_\mu$

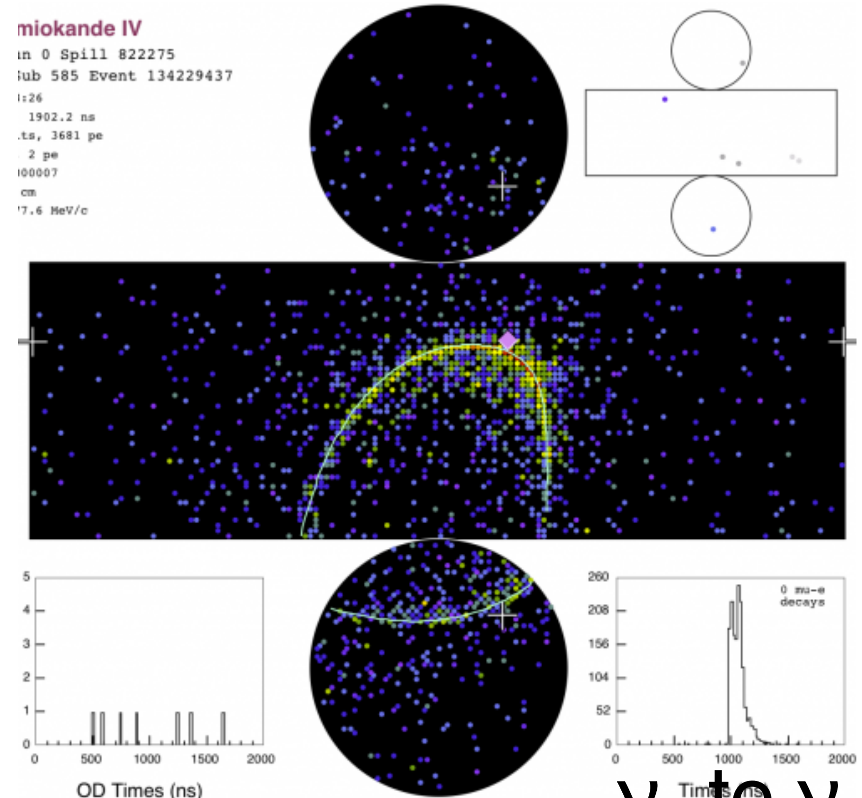


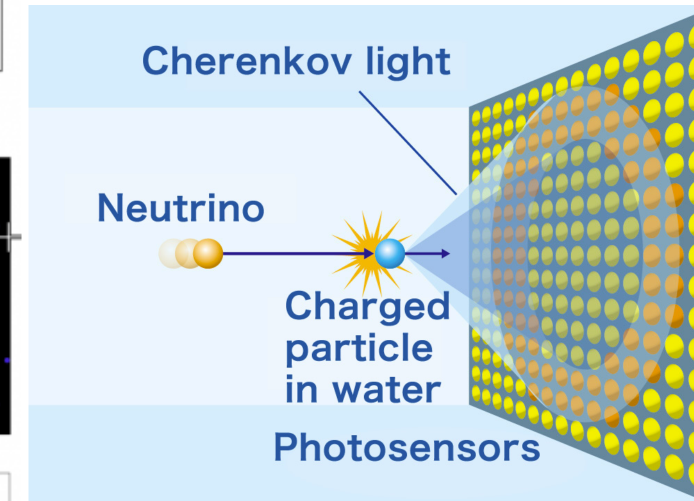
Results


NOvA Preliminary
Normal Hierarchy 90% CL
NOvA
MINOS 2014
T2K 2017
IceCube 2017
SK 2017
Best fit
3.0
2.5
2.0
0.4
0.5
0.6
Δm^2_{32} (10^{-3} eV^2)
$\sin^2\theta_{23}$

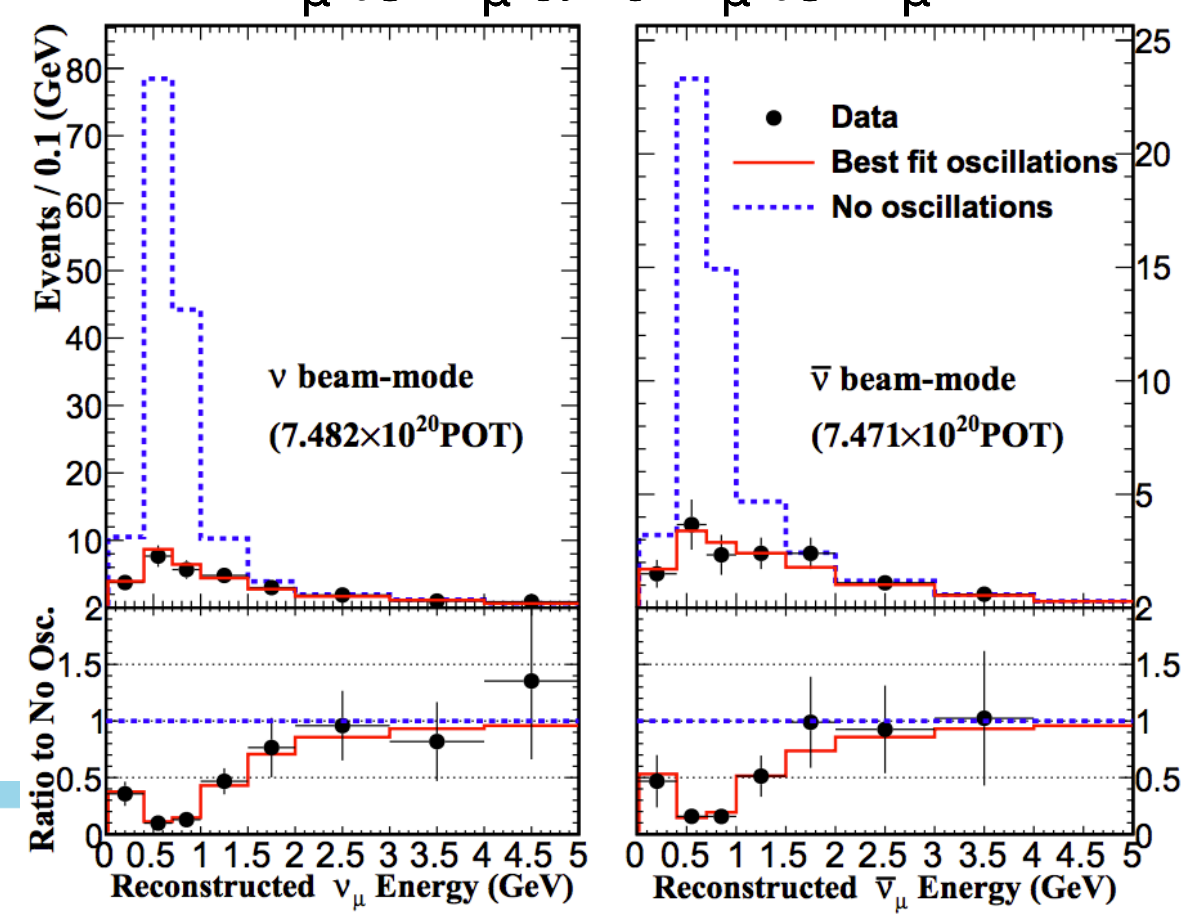
T2K Experiment



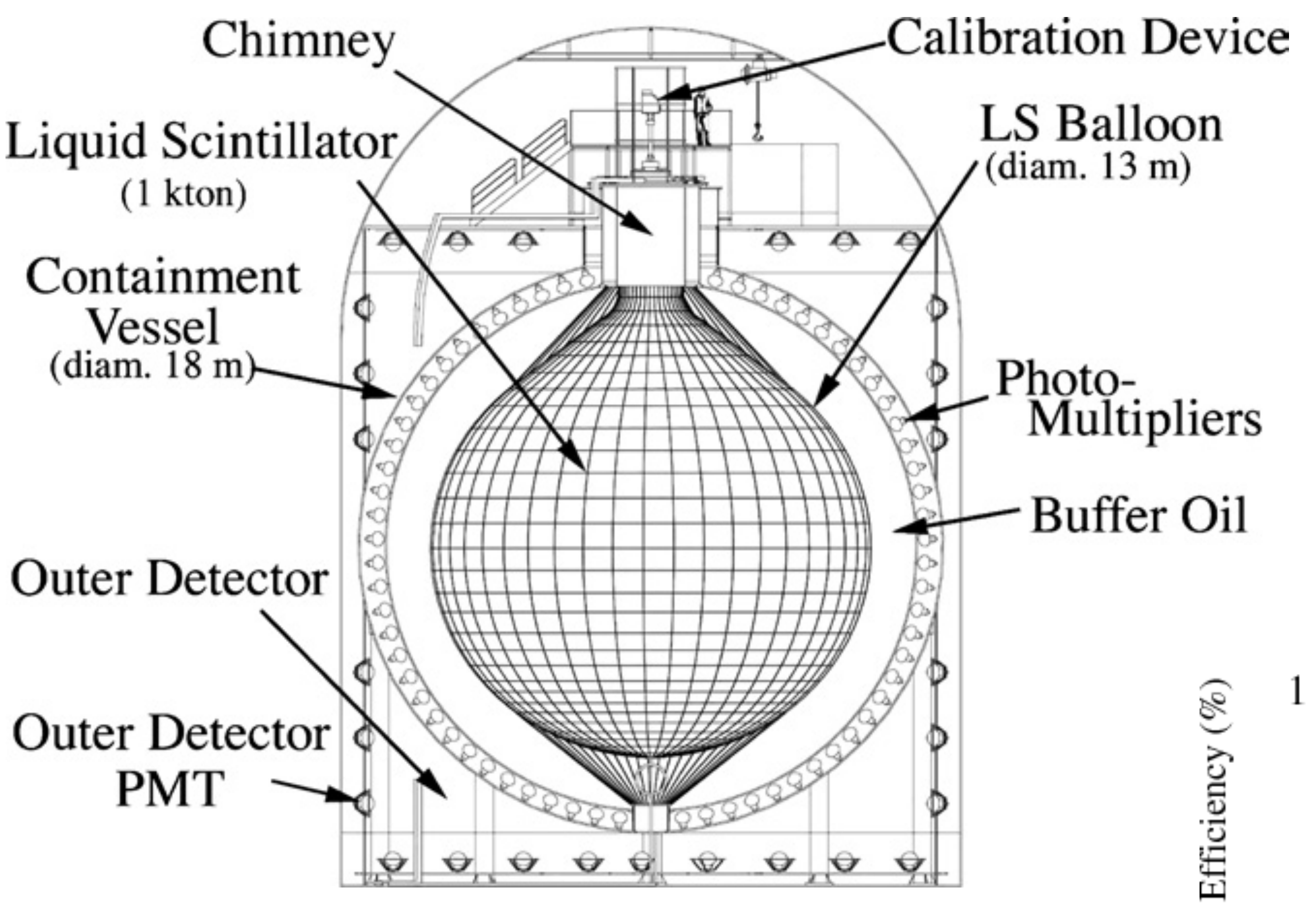


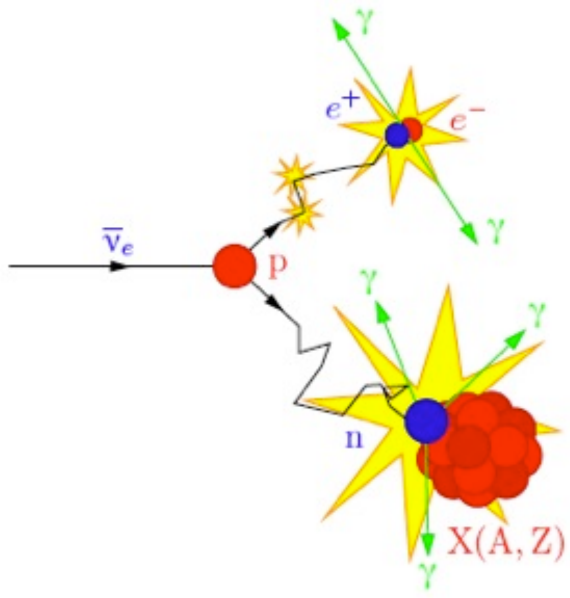


ν_μ to ν_μ and $\bar{\nu}_\mu$ to $\bar{\nu}_\mu$:

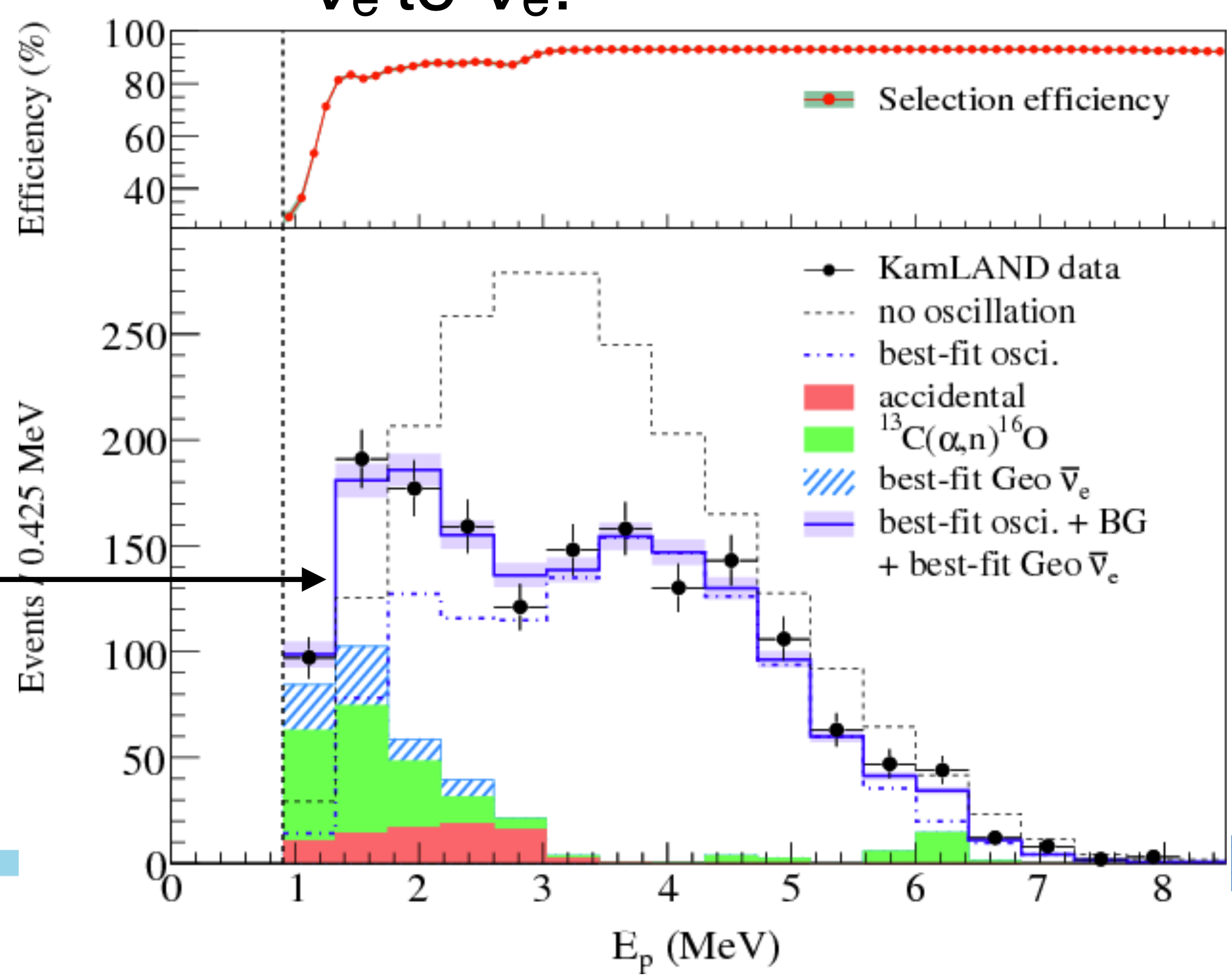


KamLAND Experiment





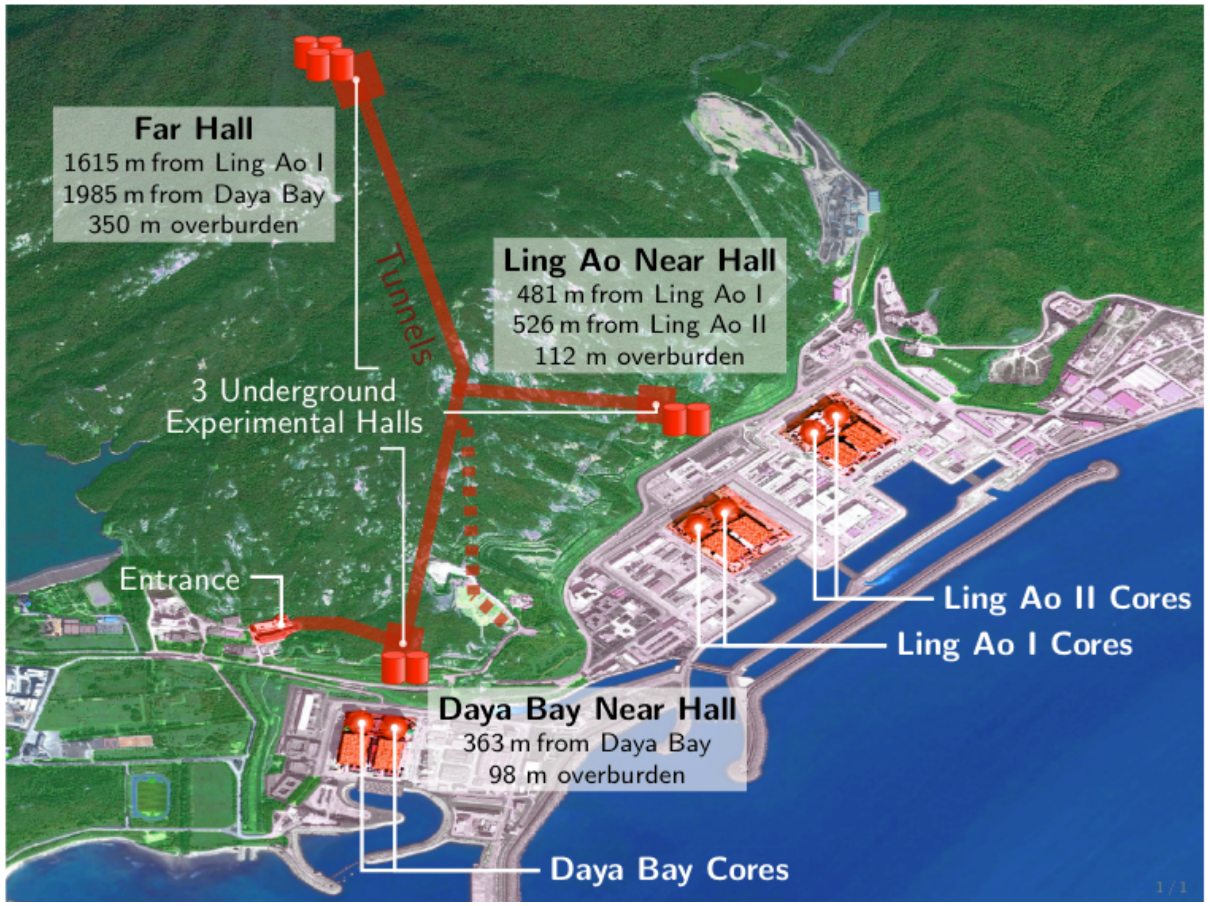
$\bar{\nu}_e$ to $\bar{\nu}_e$:

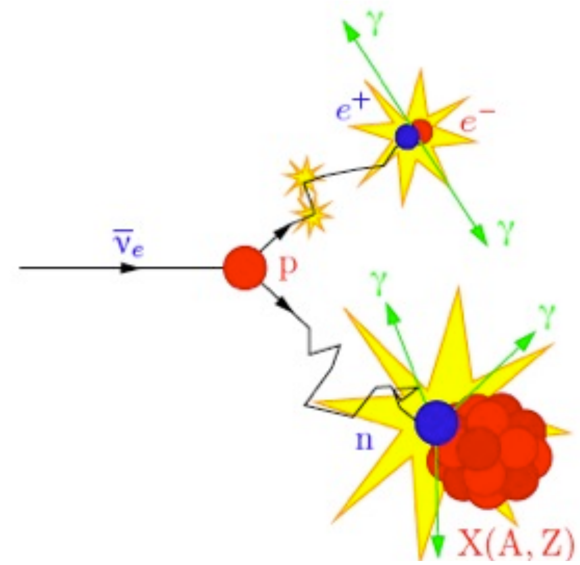


$|\Delta m^2_{sol}| \sim 7 \times 10^{-5}\ eV^2$

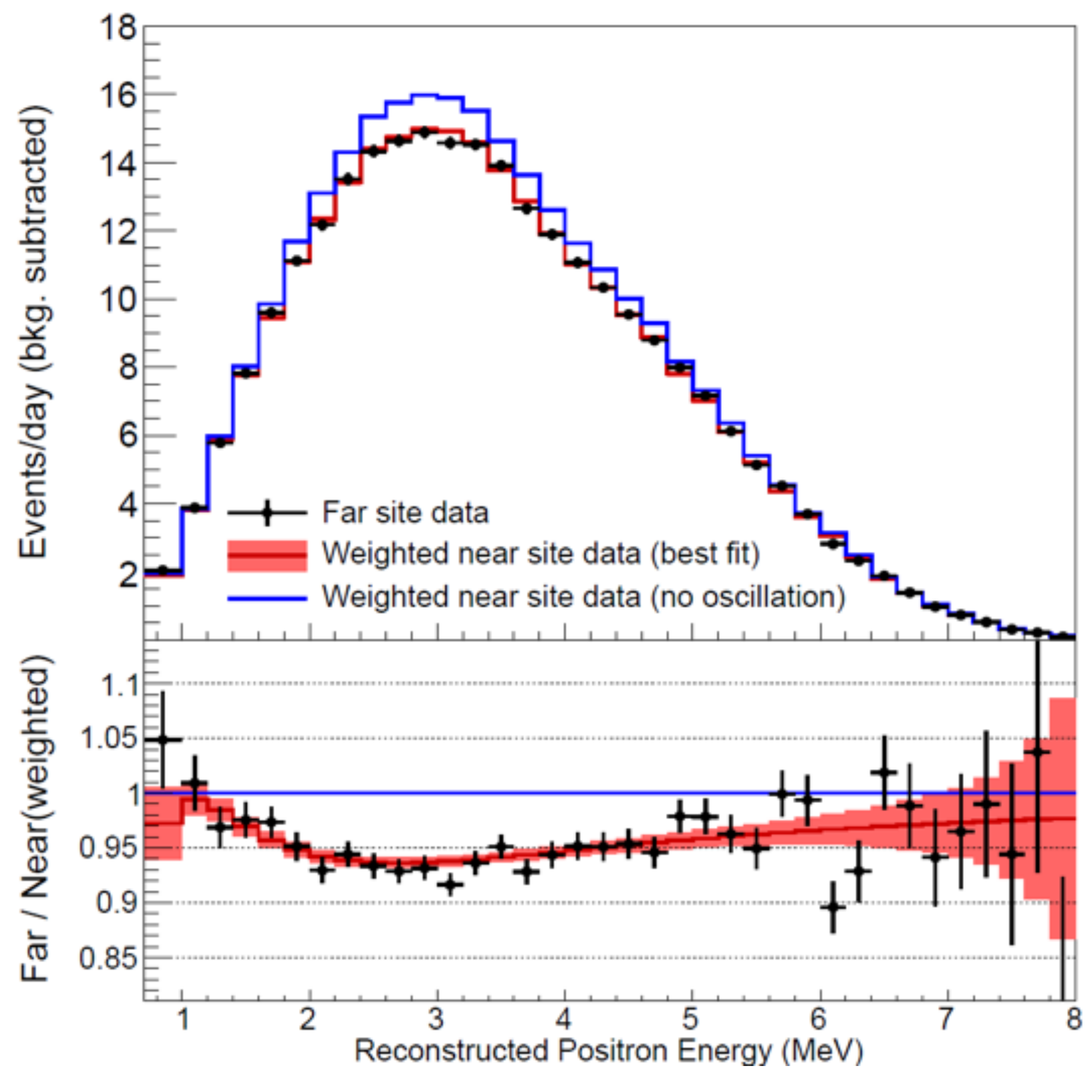
lab

Day Bay Experiment





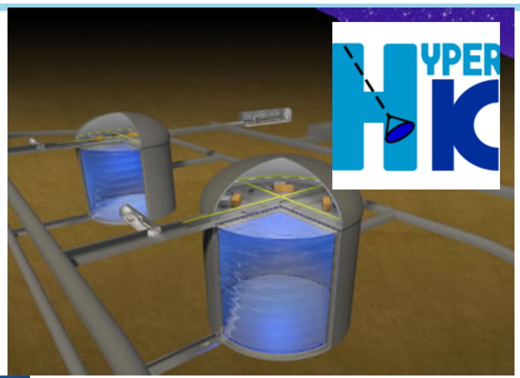
$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2(2\theta_{13}) \sin^2(\Delta m^2_{atm} \frac{L}{4E}) - \sin^2(2\theta_{12}) \cos^4(\theta_{13}) \sin^2(\Delta m^2_{sol} \frac{L}{4E})$$

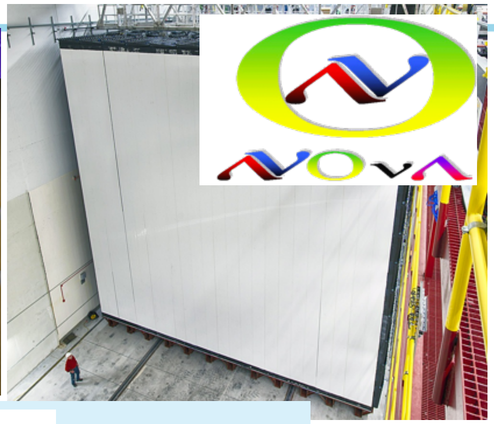


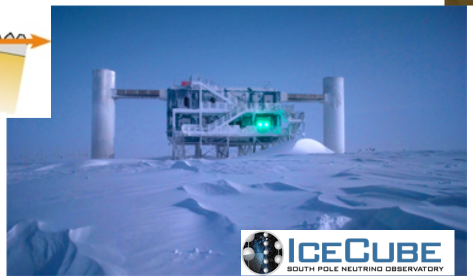
- Disappearance of electron antineutrinos provides clean measurement of θ_{13}

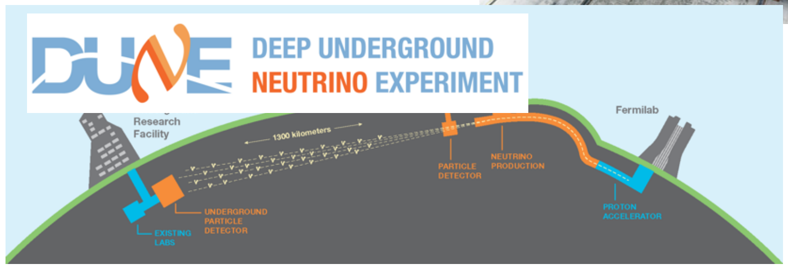
Many Experiments!

Accelerator and Atmospheric

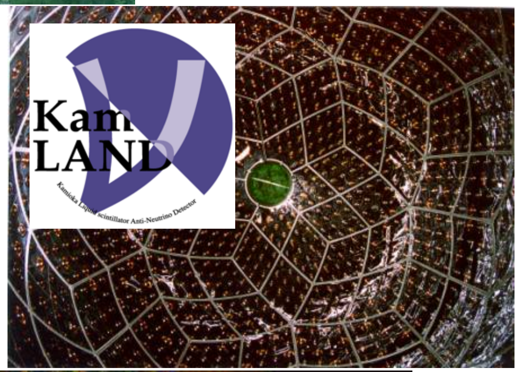


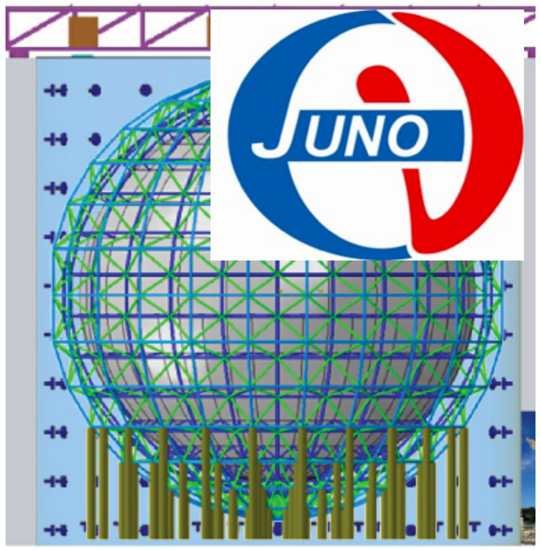




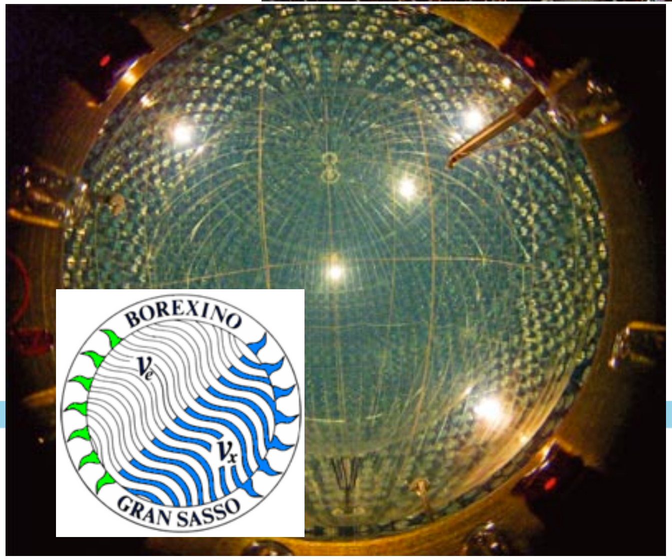


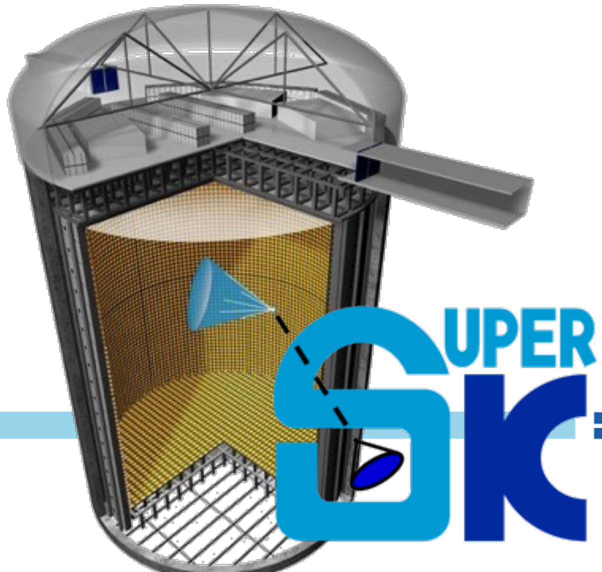
Reactor





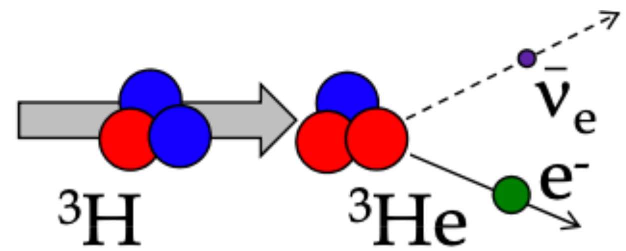
Solar





What about direct measurements of absolute mass of neutrinos ?

- When a neutrino is produced, some of the energy exchanged in the process should be spent by the non-zero neutrino mass
- The most sensitive observable is the electron energy spectrum from tritium decay



- This decay is sensitive to an effective "electron neutrino mass"
- Experiment measure the shape of the end-point of the spectrum, not the value of the end point

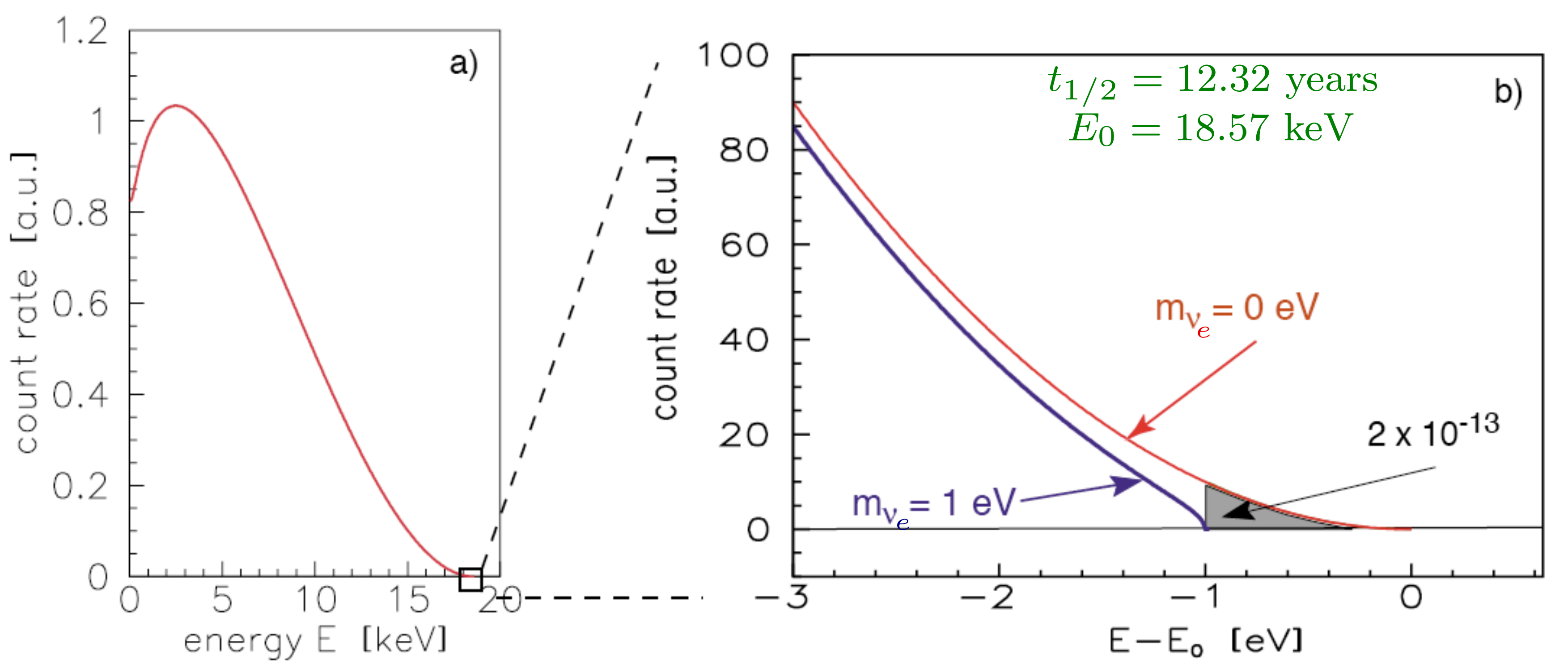


Figure 2: The electron energy spectrum of tritium β decay: (a) complete and (b) narrow region around endpoint E_0. The β spectrum is shown for neutrino masses of 0 and 1 eV.

Fermilab

KATRIN Experiment

- First tritium injection May 18 2018
- Commissioned the detector 2018

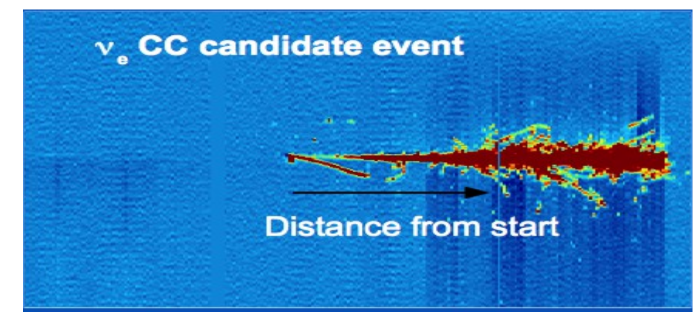
sensitivity $m^2_{\nu_e} > (0.2 \text{ eV})^2$

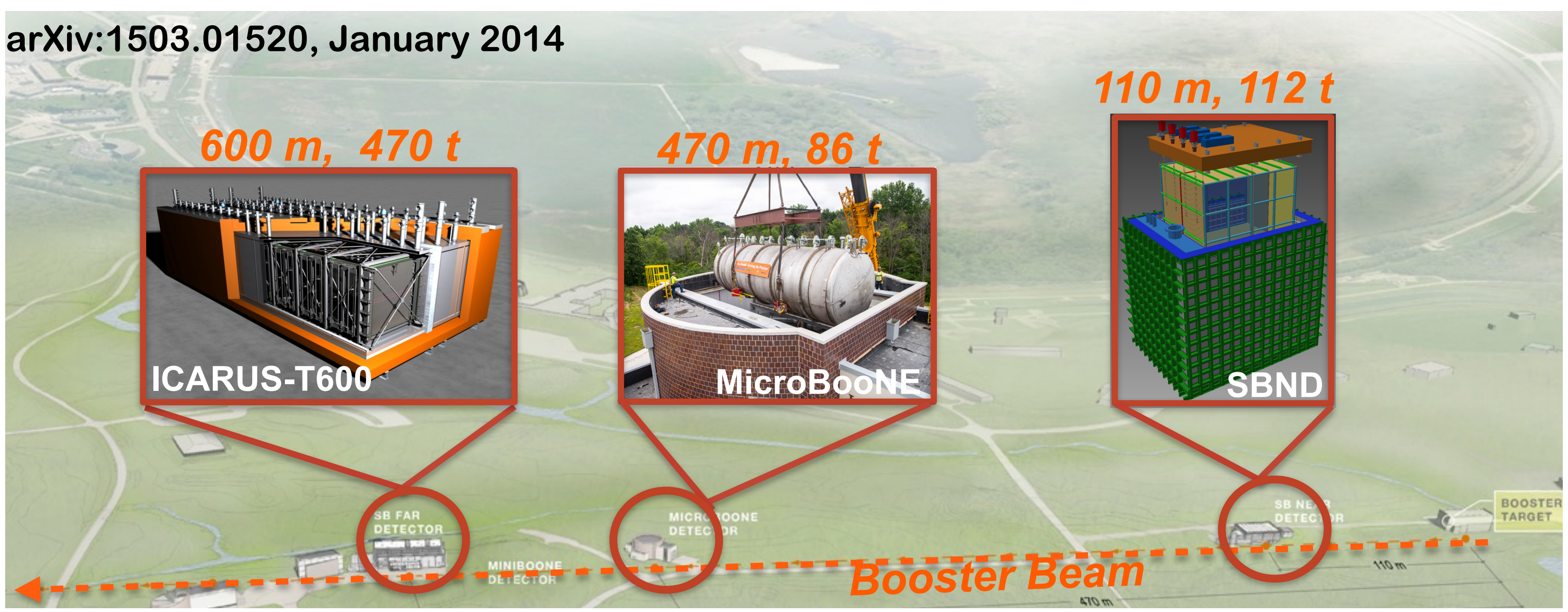
- Taking data!

Fermilab

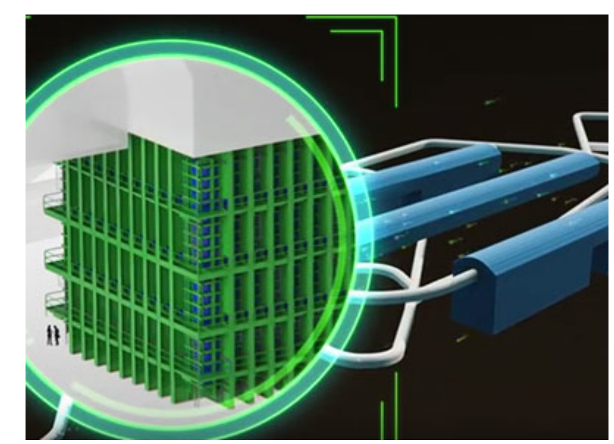
Short-Baseline Neutrino Program

- Short-baseline neutrino program at Fermilab:
  - Search for a fourth type of neutrino (sterile neutrino)
  - Measure cross sections on liquid argon
  - First time multiple liquid argon detectors are putting together: understand how systematics cancel in preparation for DUNE



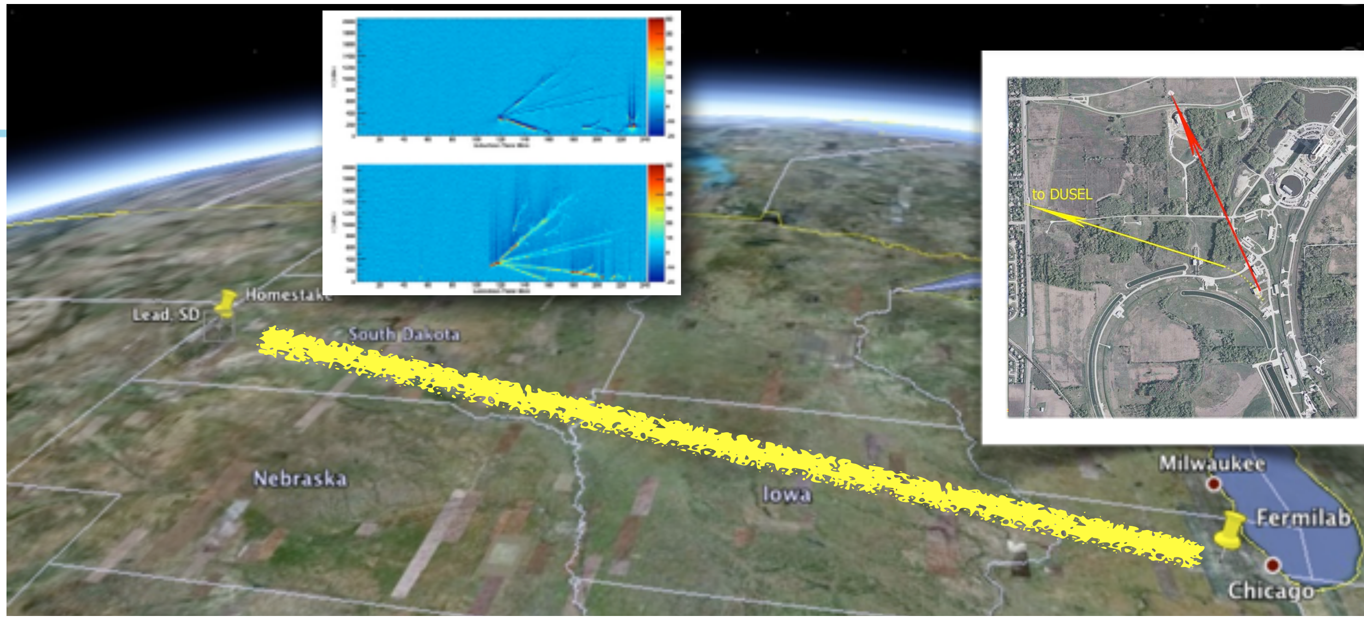


DUNE (40Kton)

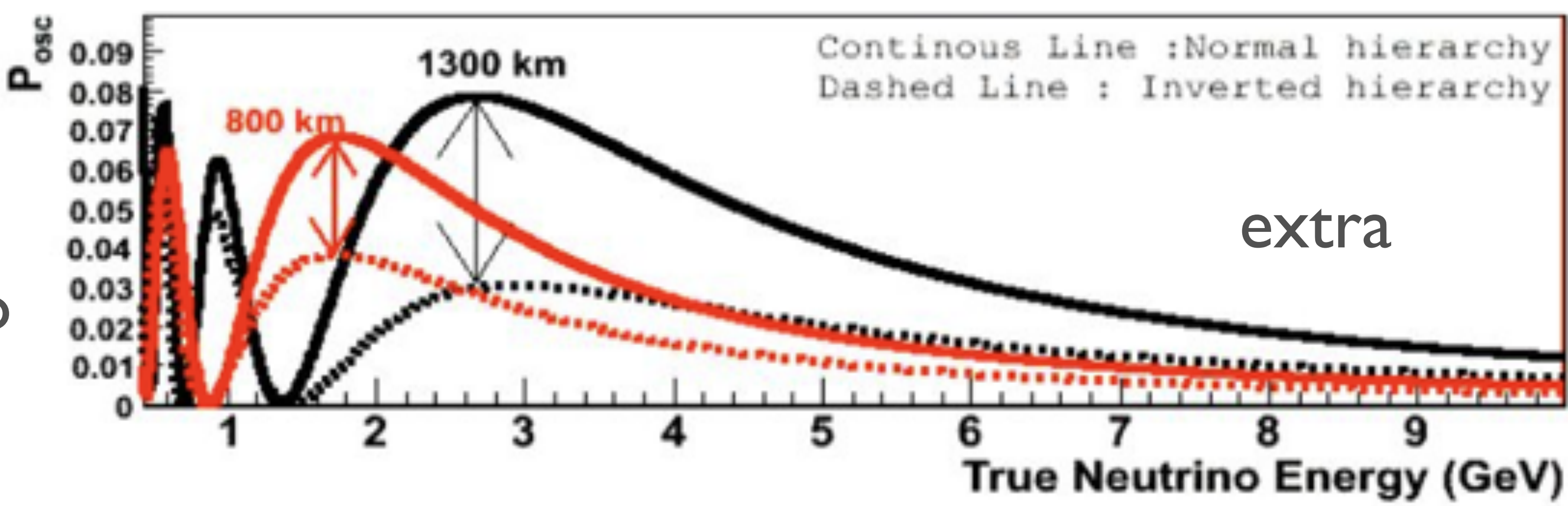


- MicroBooNE is running, SBND: commissioning is scheduled to start in 2020 and ICARUS: commissioning is scheduled to start in 2019

DUNE Experiment



- Build new detectors farther away (1300 km) on axis
- A longer baseline provides more matter effects enhancing the asymmetry between neutrino and antineutrino appearance probabilities
- DUNE will measure the mass hierarchy and search for the δ
- DUNE will constrain $\sin^2(\theta_{13})$, $\sin^2(\theta_{23})$, $\Delta^2 m_{13}$, $\Delta 2m_{23}$
- Has the potential to determine the θ_{23} octant
- Physics goals include
  - Constrain the PMNS metric
  - Search for exotic physics like NSI, CPT/Lorentz violation, extra dimensions and sterile neutrino



Back Slides

From Quarks

- The interaction basis

$$\sum_{i=1}^{3} \bar{Q}_{Li} \not{D} Q_{Li} = \sum_{i=1}^{3} \frac{g}{\sqrt{2}} \left(\bar{u}_{Li} \gamma^{\mu} d_{Li} W_{\mu}^{+} + \text{h.c.} \right) + \ldots$$

- The masses do not need to be diagonal

$$\sum_{i,j=1}^{3} y_{ij} \bar{Q}_{Li} \tilde{H} u_{Rj} \rightarrow \bar{\mathcal{U}}_L \cdot \mathbf{M}_u \cdot \mathcal{U}_R = \bar{\mathbf{u}}_L \cdot \underbrace{(V_L^u)^{\dagger} \cdot \mathbf{M}_u \cdot V_R^u}_{\mathbf{M}_u^{\text{diag}}} \cdot \mathbf{u}_R$$

quarks in mass basis
(masses are diagonal)

$$\sum_{i,j=1}^{3} y_{ij} \bar{Q}_{Li} H d_{Rj} \rightarrow \bar{\mathcal{D}}_L \cdot \mathbf{M}_d \cdot \mathcal{D}_R = \bar{\mathbf{d}}_L \cdot (V_L^d)^{\dagger} \cdot \mathbf{M}_d \cdot V_R^d \cdot \mathbf{d}_R$$

From Quarks

- The interaction basis

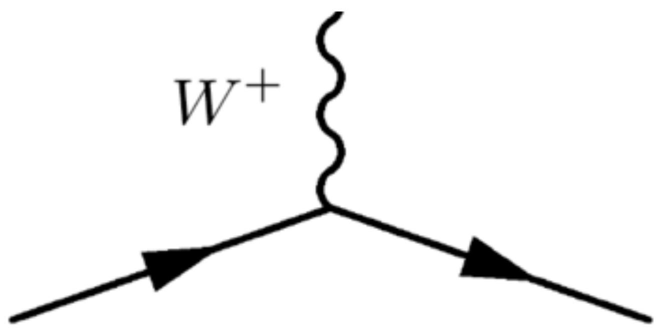
$$\sum_{i=1}^{3} \bar{Q}_{Li} \not{D} Q_{Li} = \sum_{i=1}^{3} \frac{g}{\sqrt{2}} \left(\bar{u}_{Li} \gamma^{\mu} d_{Li} W_{\mu}^{+} + \text{h.c.} \right) + \ldots$$

- The mass basis

$$\sum_{i=1}^{3} \bar{Q}_{Li} \not{D} Q_{Li} = \frac{g}{\sqrt{2}} \left[\bar{\mathbf{u}}_{L} \gamma^{\mu} \underbrace{(V_{L}^{u})^{\dagger} V_{L}^{d}}_{\text{CKM mixing matrix}} \mathbf{d}_{L} W_{\mu}^{+} + \text{h.c.} \right] + \ldots$$

From Quarks

- Fermion states that have a well defined mass can have mixing under weak interactions



- Same thing happens to neutrino, but we do not know the mechanism that generates neutrino masses!