

# PARTICLE PHYSICS

COLUMBIA SCIENCE HONORS PROGRAM

WEEK 9

NEUTRINOS

PART II

# COURSE POLICIES

- Attendance
  - Up to four excused absences
    - Two with notes from parent/guardian
    - shpattendance@columbia.edu
  - Valid excuses:
    - Illness, family emergency, tests or athletic/academic competitions, mass transit breakdowns
  - Invalid excuses:
    - Sleeping in, missing the train...
  - I will take attendance during class
- No cell phones
- Ask questions!

# LECTURE MATERIALS

- <https://twiki.nevis.columbia.edu/twiki/bin/view/Main/ScienceHonorsProgram>
- Questions: cristovao.vilela@stonybrook.edu

# SCHEDULE

1. ~~Introduction~~
  2. ~~History of Particle Physics~~
  3. ~~Special Relativity~~
  4. ~~Quantum Mechanics~~
  5. ~~Experimental Methods~~
  6. ~~The Standard Model - Overview~~
  7. ~~The Standard Model - Limitations~~
  8. ~~Neutrinos I~~ } Cris José
  9. **Neutrinos II** } José Cris
  10. LHC and Experiments
  11. The Higgs Boson and Beyond
  12. Particle Cosmology } Cris
- } Inês

# NEUTRINO MIXING

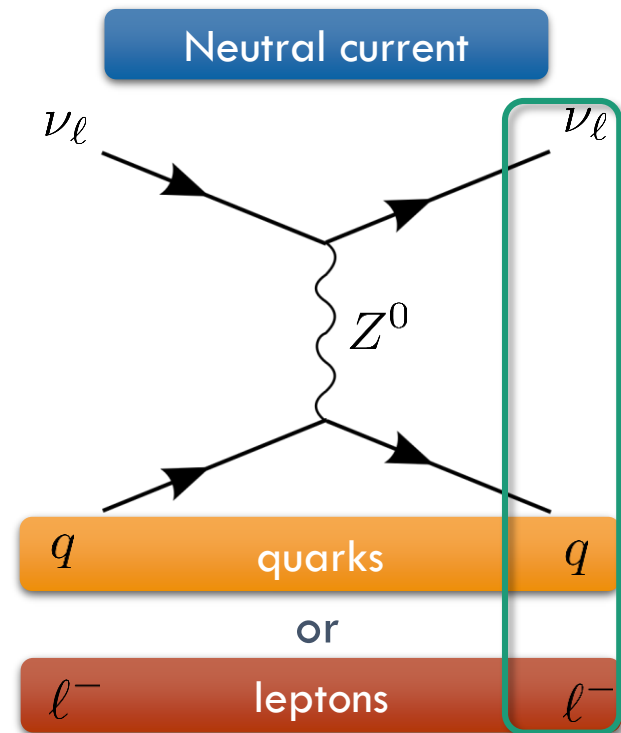
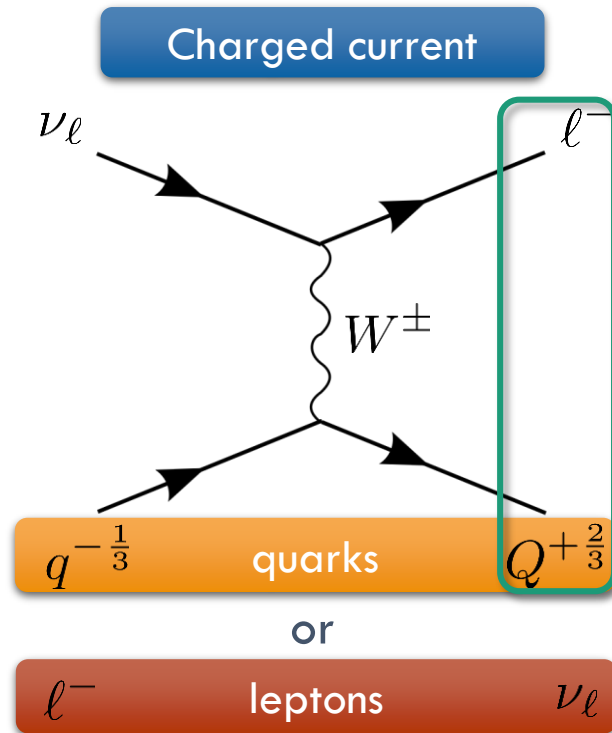
# THE WORLD, ACCORDING TO A PARTICLE PHYSICIST

<div>QUARKS</div>	mass → $\approx 2.3 \text{ MeV}/c^2$ charge → $2/3$ spin → $1/2$ <div>u</div> up	mass → $\approx 1.275 \text{ GeV}/c^2$ charge → $2/3$ spin → $1/2$ <div>c</div> charm	mass → $\approx 173.07 \text{ GeV}/c^2$ charge → $2/3$ spin → $1/2$ <div>t</div> top	mass → 0 charge → 0 spin → 1 <div>g</div> gluon	mass → $\approx 126 \text{ GeV}/c^2$ charge → 0 spin → 0 <div>H</div> Higgs boson
	mass → $\approx 4.8 \text{ MeV}/c^2$ charge → $-1/3$ spin → $1/2$ <div>d</div> down	mass → $\approx 95 \text{ MeV}/c^2$ charge → $-1/3$ spin → $1/2$ <div>s</div> strange	mass → $\approx 4.18 \text{ GeV}/c^2$ charge → $-1/3$ spin → $1/2$ <div>b</div> bottom	mass → 0 charge → 0 spin → 1 <div><math>\gamma</math></div> photon	
	mass → $0.511 \text{ MeV}/c^2$ charge → -1 spin → $1/2$ <div>e</div> electron	mass → $105.7 \text{ MeV}/c^2$ charge → -1 spin → $1/2$ <div><math>\mu</math></div> muon	mass → $1.777 \text{ GeV}/c^2$ charge → -1 spin → $1/2$ <div><math>\tau</math></div> tau	mass → $91.2 \text{ GeV}/c^2$ charge → 0 spin → 1 <div>Z</div> Z boson	
	<div>LEPTONS</div> mass → $< 2.2 \text{ eV}/c^2$ charge → 0 spin → $1/2$ <div><math>\nu_e</math></div> electron neutrino	mass → $< 0.17 \text{ MeV}/c^2$ charge → 0 spin → $1/2$ <div><math>\nu_\mu</math></div> muon neutrino	mass → $< 15.5 \text{ MeV}/c^2$ charge → 0 spin → $1/2$ <div><math>\nu_\tau</math></div> tau neutrino	mass → $80.4 \text{ GeV}/c^2$ charge → $\pm 1$ spin → 1 <div>W</div> W boson	<div>GAUGE BOSONS</div>

# NEUTRINO INTERACTIONS

## HOW WE DETECT NEUTRINOS

- Neutrinos interact with matter in two ways:



- Extremely rare processes!  $\sigma_{\nu e} \approx 10^{-44} \text{ cm}^2 @ 1 \text{ MeV}$
- Probability of 1 MeV neutrino interacting with electron while traversing the whole earth is  $10^{-11}$ !

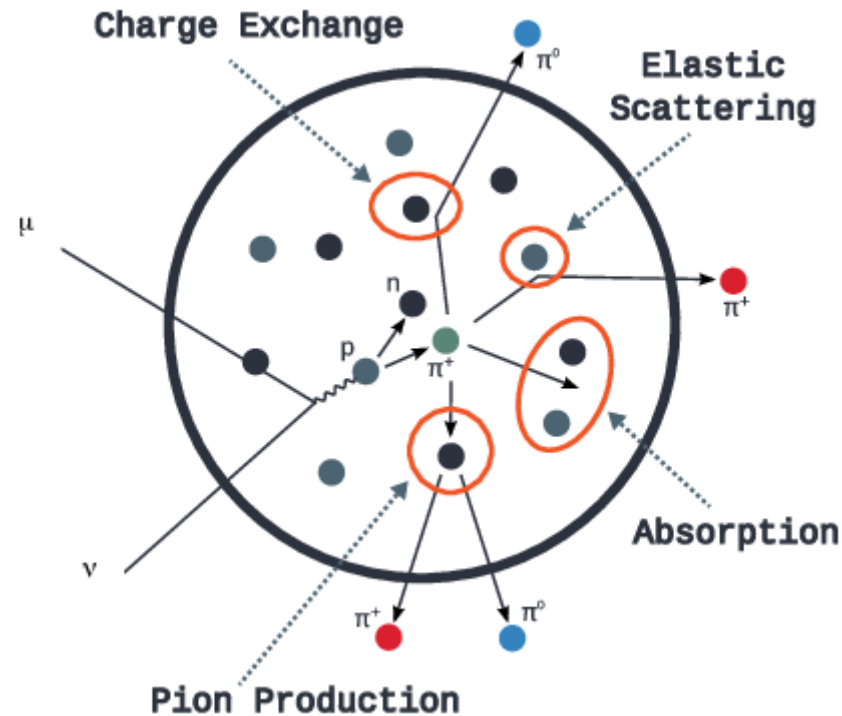
# NEUTRINO INTERACTIONS

## HOW WE DETECT NEUTRINOS

• Neutrinos

• Neutrino interactions with nucleons inside nucleus much more probable: at 1 GeV neutrino energy, about 3000 times more likely.

• Also way more complicated!



• Ext

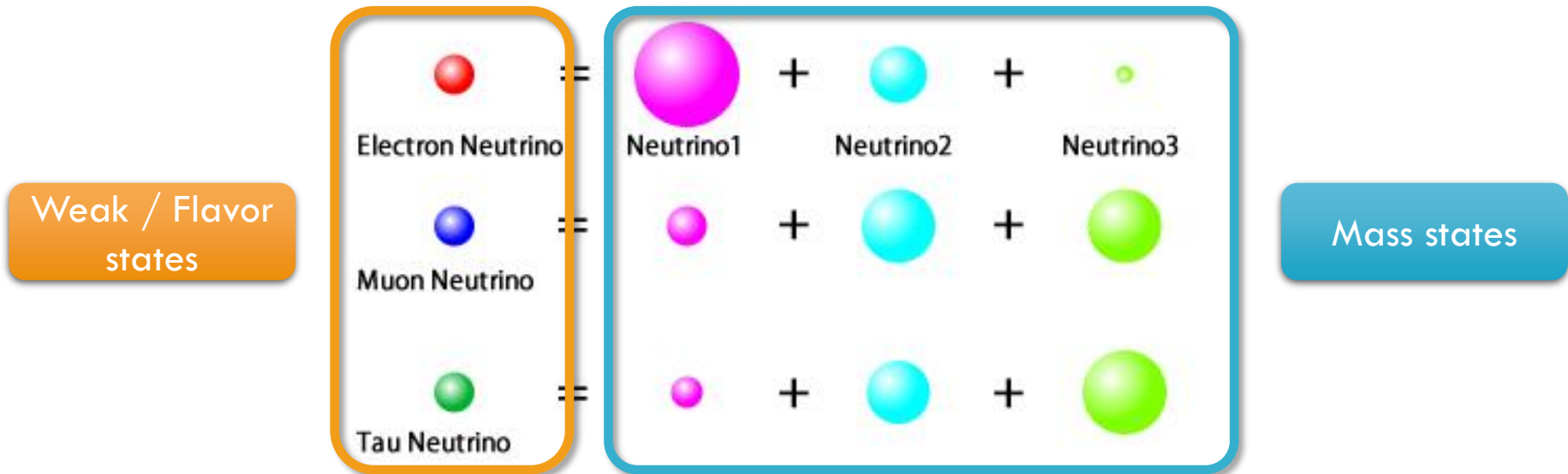
• Prob

traversing the whole earth is  $10^{-11}$ !



# NEUTRINO MIXING

- Neutrinos **interact** according to their **weak** states.
  - Defined by what charged lepton ( $e, \mu, \tau$ ) is produced in the interaction.
- ... but they **propagate** according to their **mass** states.
- These two **bases** with which to describe neutrinos are not “aligned”.
  - This leads to **superpositions** of “mixed” states and... wait for it...
    - Quantum **interference**!



# NEUTRINO MIXING FORMALISM

- Write the most general matrix that conserves number of particles.
  - Like rotations in three dimensions, but with complex numbers...

Weak / Flavor  
states

“Atmospheric”  
parameters

- The Pontecorvo-Maki-Nakagawa-Sakata (**PMNS**) matrix.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix}$$

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

$$\begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

“Reactor”  
parameters

CP violating  
phase

“Solar”  
parameters

Mass states

- We wouldn't be in this mess if neutrinos were **massless**!!
- So how do we know they're **not**?

# NEUTRINO MIXING FORMALISM

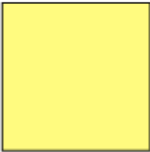



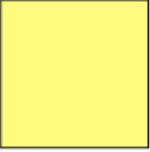



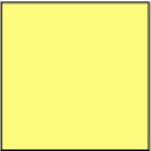
- Write

- L










By the way...

- Quarks also mix! But a lot less.
- A whole different story, for another occasion...

CKM

	d	s	b
u			
c			
t			

PMNS

	$\nu_1$	$\nu_2$	$\nu_3$
$\nu_e$			
$\nu_\mu$			
$\nu_\tau$			

awa-Sakata

$$\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass states

- We v

- So how do we know they're **not**?

# NEUTRINO OSCILLATIONS

- Assume, for simplicity only two neutrinos.
  - Two weak states that mix with two mass states.

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \qquad \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix}$$

- Wave functions “evolve” with time by rotating in the complex plane:

$$\begin{aligned} \begin{pmatrix} |\nu_1(x, t) \rangle \\ |\nu_2(x, t) \rangle \end{pmatrix} &= \begin{pmatrix} e^{-i\phi_1} & 0 \\ 0 & e^{-i\phi_2} \end{pmatrix} \begin{pmatrix} |\nu_1(0, 0) \rangle \\ |\nu_2(0, 0) \rangle \end{pmatrix} \\ &= \begin{pmatrix} e^{-i\phi_1} & 0 \\ 0 & e^{-i\phi_2} \end{pmatrix} \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} |\nu_\alpha(0, 0) \rangle \\ |\nu_\beta(0, 0) \rangle \end{pmatrix} \end{aligned}$$

- With a few lines of trigonometry:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta) \sin^2\left(\frac{\phi_2 - \phi_1}{2}\right)$$

# NEUTRINO OSCILLATIONS

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta) \sin^2\left(\frac{\phi_2 - \phi_1}{2}\right)$$

- Time evolution determined by energy of the state. If we assume\* the two superimposed mass states are produced with the same energy, we get:

$$\phi_2 - \phi_1 = \left(\frac{m_1^2}{2E_1} - \frac{m_2^2}{2E_2}\right)L = \frac{\Delta m^2 L}{2E}$$

- Substituting in oscillation probability expression gives:

$$P(\nu_e \rightarrow \nu_\mu) = \sin^2(2\theta) \sin^2\left(1.27 \Delta m^2 \frac{L}{E_\nu}\right)$$



Oscillation amplitude

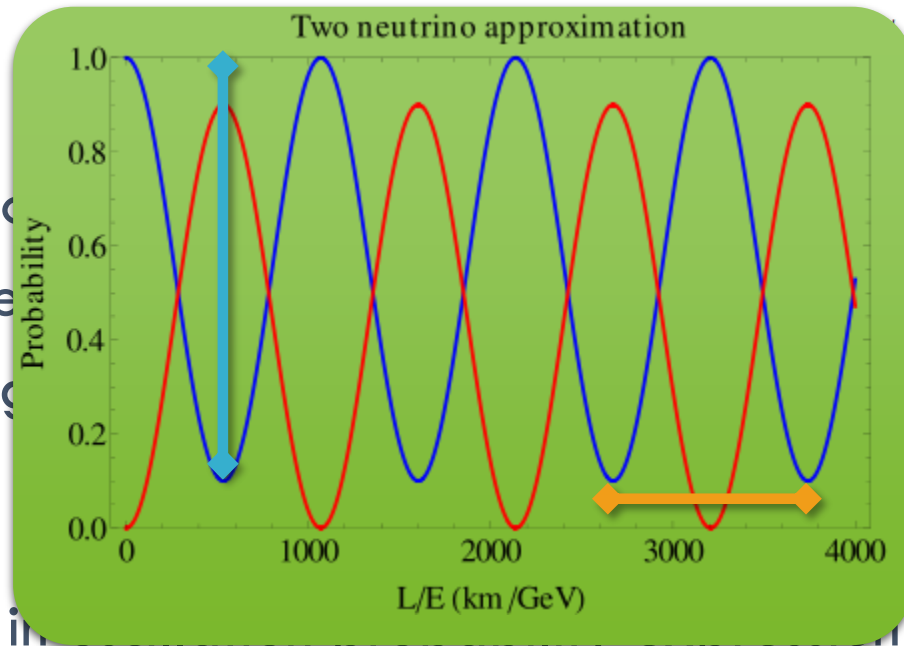


Oscillation frequency

\* Assumption not necessary if more detailed wavepacket formulation is used.

# NEUTRINO OSCILLATIONS

- Time evolution of neutrino states. If we assume\* the two superposition states have the same energy, we get



- Substituting in the values for  $\theta$  and  $\Delta m^2$  gives:

$$P(\nu_e \rightarrow \nu_\mu) = \underbrace{\sin^2(2\theta)}_{\text{Oscillation amplitude}} \underbrace{\sin^2\left(1.27 \Delta m^2 \frac{L}{E_\nu}\right)}_{\text{Oscillation frequency}}$$

Oscillation amplitude

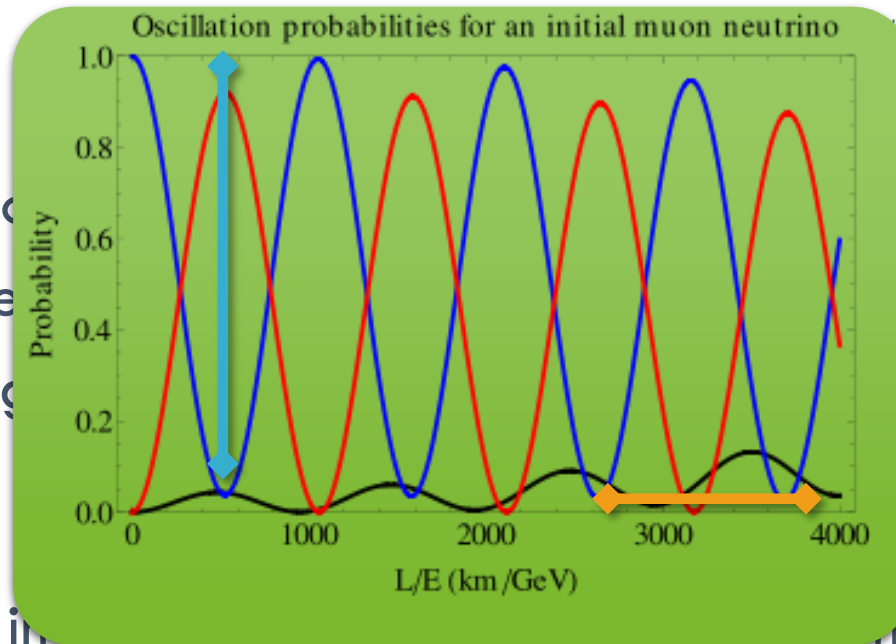
Oscillation frequency

Quantum interference on a (very) macroscopic scale!!!

\* Assumption not

# NEUTRINO OSCILLATIONS

- Time evolution of the neutrino state. If we assume\* the two superposition states have the same energy, we get



- Substituting in the values for  $\theta$  and  $\Delta m^2$  gives:

$$P(\nu_e \rightarrow \nu_\mu) = \underbrace{\sin^2(2\theta)}_{\text{Oscillation amplitude}} \underbrace{\sin^2(1.27 \Delta m^2 \frac{L}{E_\nu})}_{\text{Oscillation frequency}}$$

Oscillation amplitude

Oscillation frequency

Quantum interference on a (very) macroscopic scale!!!

\* Assumption not

# SOLAR NEUTRINOS

E:  $\sim 1$  MEV

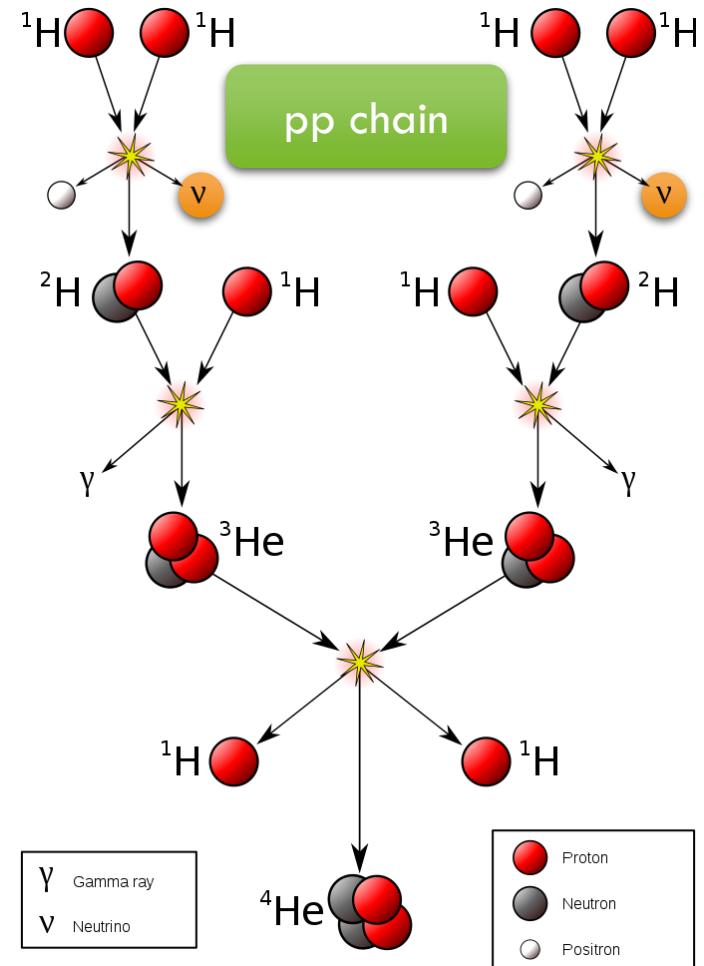
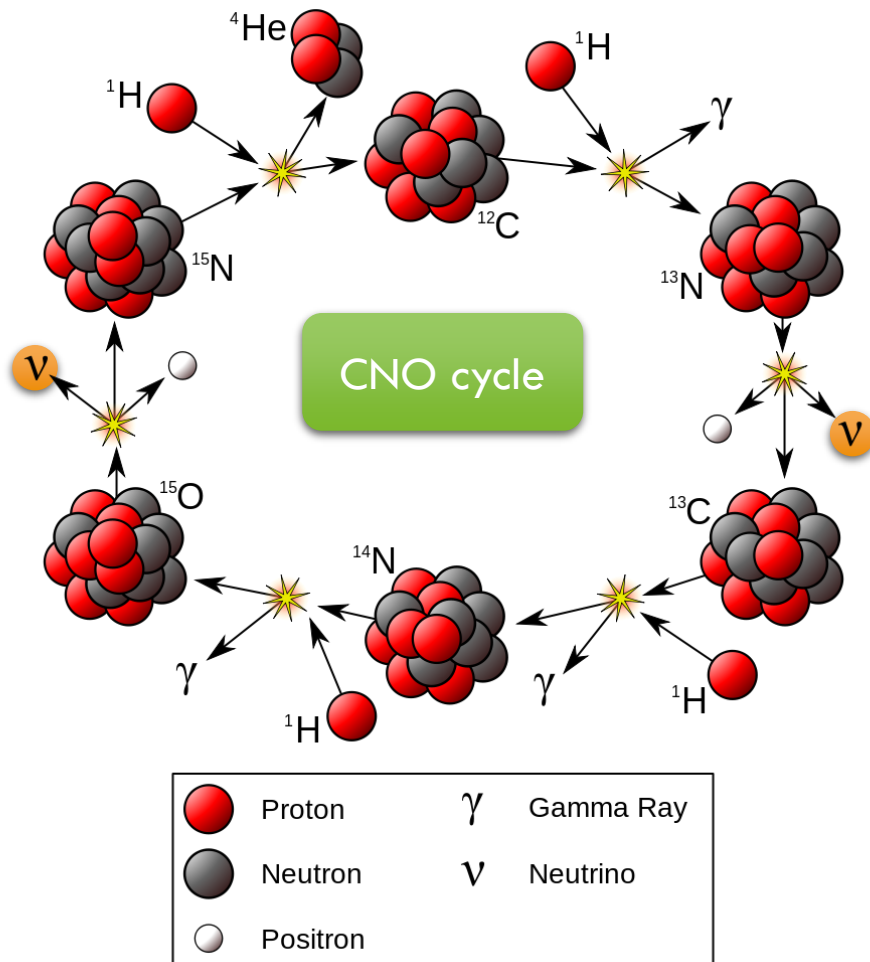
L:  $\sim 1.5 \times 10^8$  KM BUT MORE COMPLICATED THAN THAT...

MINIMUM  $\Delta M^2$ :  $10^{-11}$  EV<sup>2</sup>



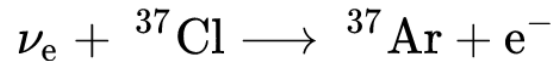
# THE STANDARD SOLAR MODEL

- Nuclear fission and decay processes power the Sun: **neutrinos everywhere!**



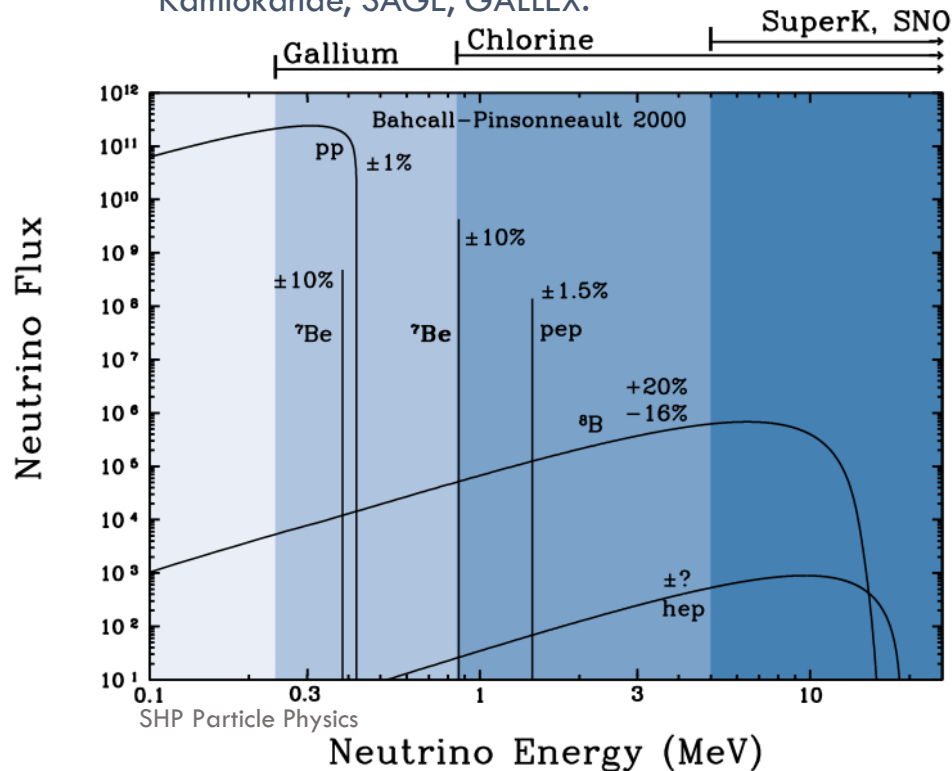
# THE SOLAR NEUTRINO PROBLEM

- In the late 1960s Ray Davis and John Bahcall set up an experiment to try to detect these solar neutrinos.



- They detected some, but not as many as they expected.
- This was soon confirmed by a number of other experiments.

- Kamiokande, SAGE, GALLEX.



2002

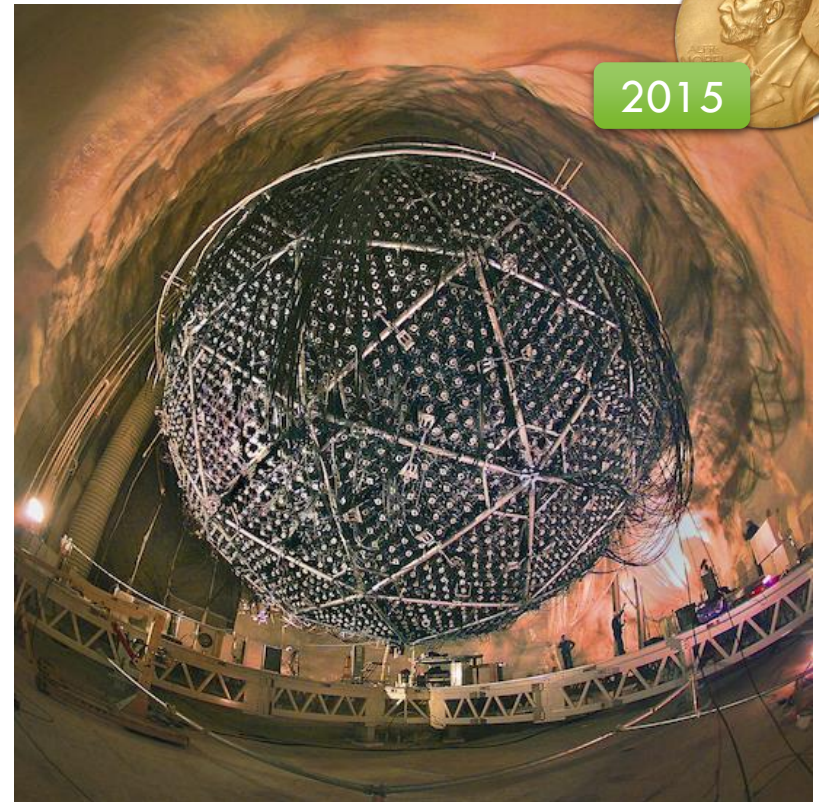
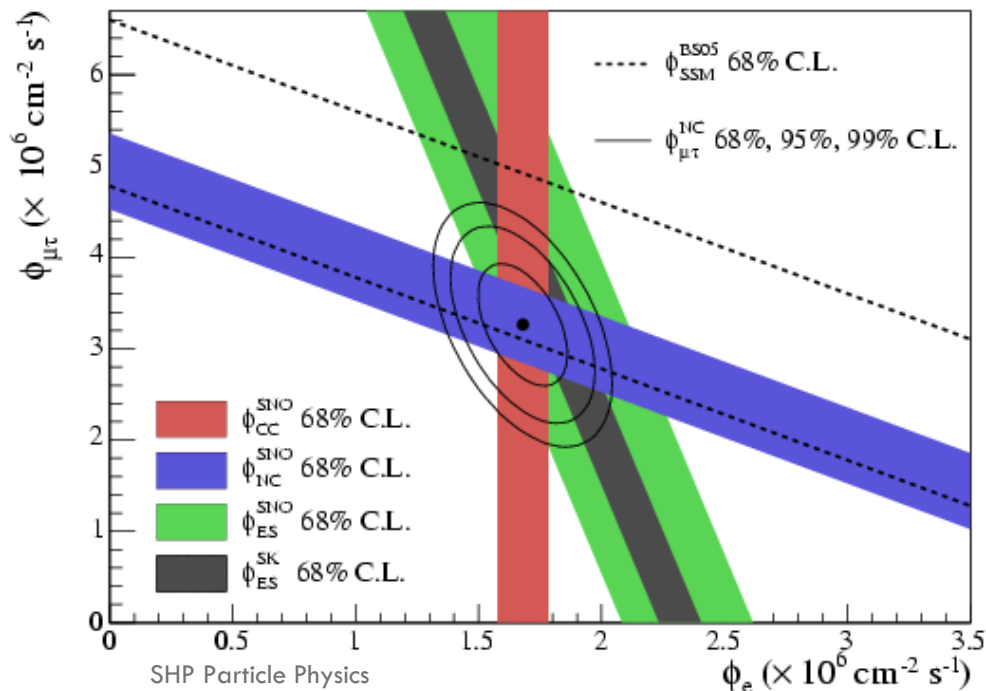


Homestake experiment  
1965 – 1994 (!)



# THE SOLAR NEUTRINO SOLUTION

- Two experiments provided confirmation of Ray Davis' observations: Super-Kamiokande and SNO.
- SNO measured total neutrino flux (NC) and electron neutrino flux (CC) independently.
- Confirmation that total neutrino flux from Standard Solar Model is correct.
- Electron neutrinos really are disappearing!



# ATMOSPHERIC NEUTRINOS

E:  $\sim 1000$  MEV

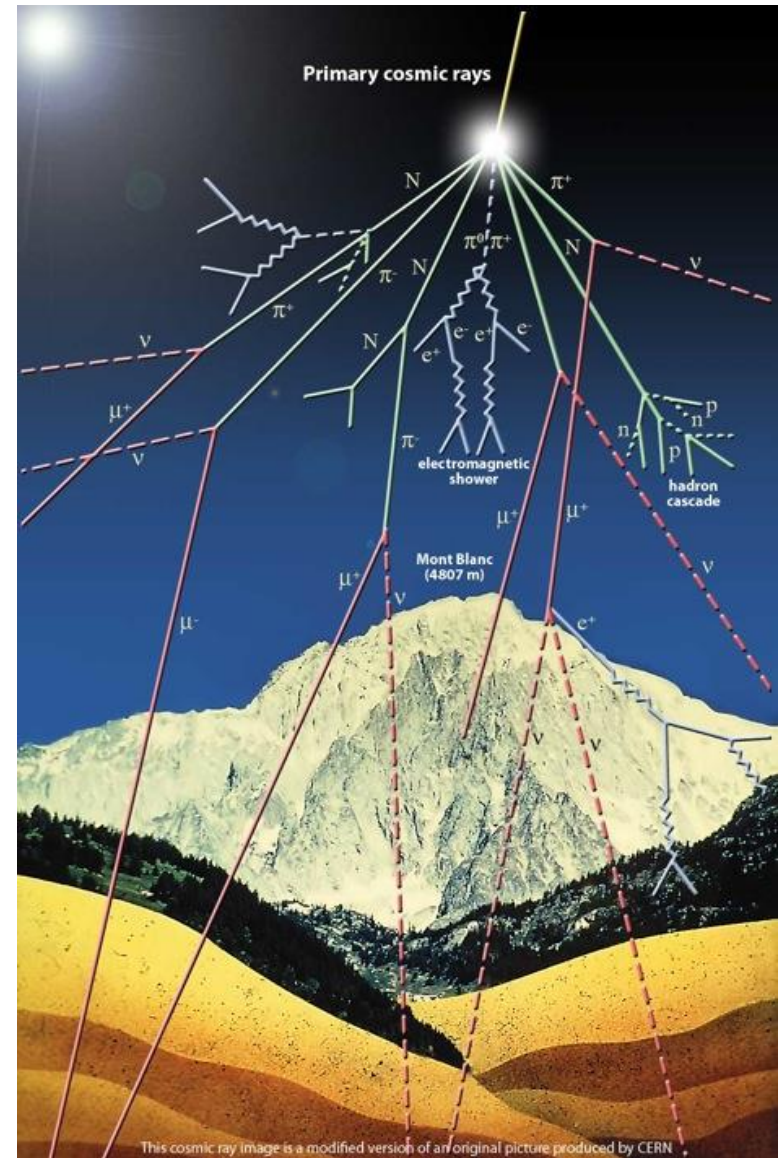
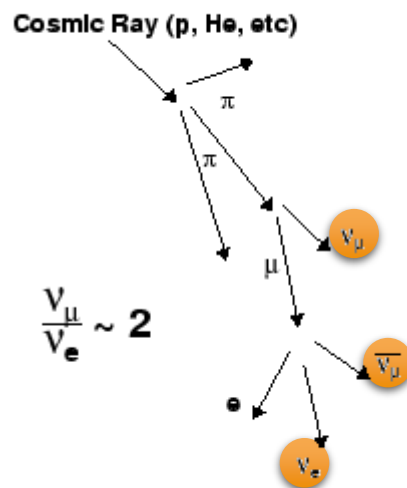
L:  $\sim 10^4$  KM

MINIMUM  $\Delta M^2$ :  $10^{-4}$  EV<sup>2</sup>



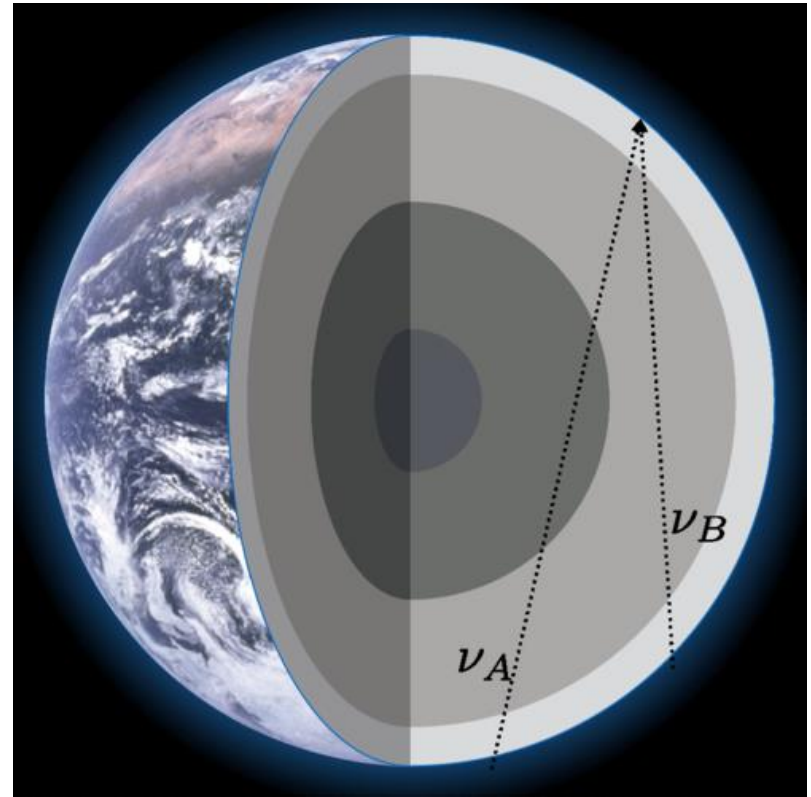
# NEUTRINOS FROM THE ATMOSPHERE

- The Earth is constantly being bombarded by cosmic rays (mostly protons) with astrophysical origin.
- These interact strongly with nuclei in the atmosphere, producing showers of hadrons.
- Unstable hadrons eventually decay to the lightest meson,  $\pi$ , which decays weakly, producing neutrinos!



# ATMOSPHERIC NEUTRINO OSCILLATIONS

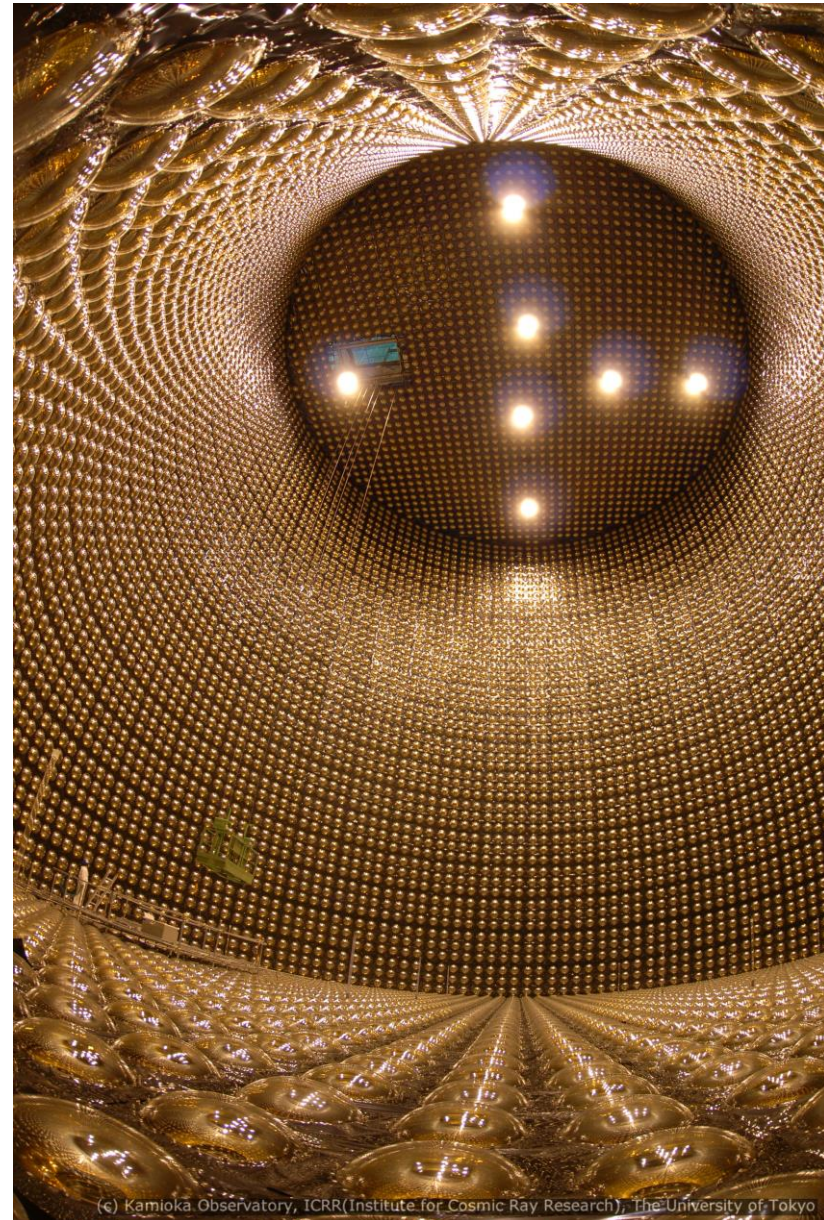
- Naïvely expect 2-to-1 ratio of muon to electron neutrinos.
- However, neutrinos produced on the “far” side of the earth travel thousands of kilometres before they reach a detector.
  - So, they oscillate!
- Comparing the number of neutrinos hitting the detector from the “top” (short L) to those coming from the “bottom” (long L) gives a direct measurement of atmospheric neutrino oscillations.





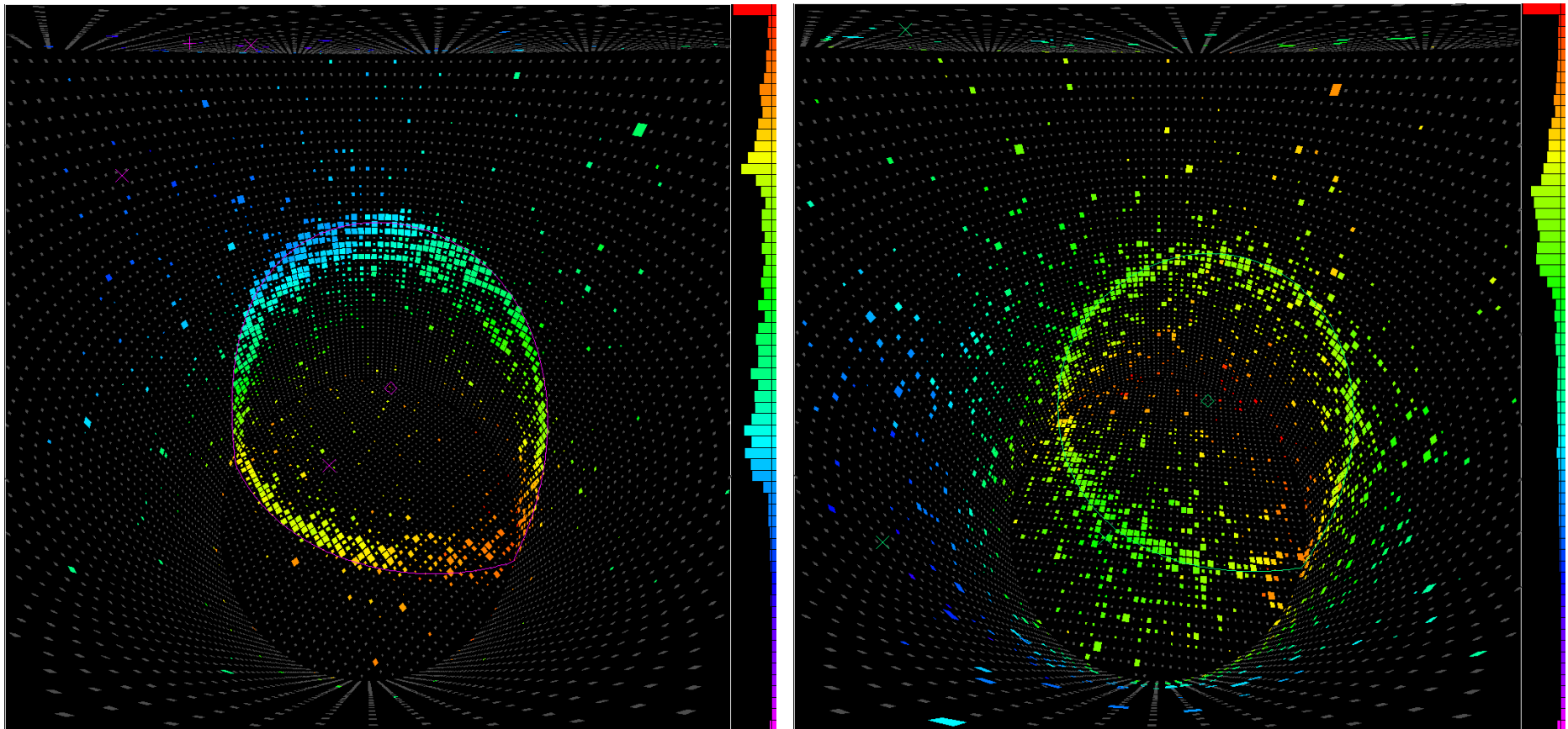
# SUPER-KAMIOKANDE

- The Super-Kamiokande experiment was designed to unambiguously observe oscillations in atmospheric neutrinos.
  - Following hints from its predecessor, Kamiokande.
- A tank containing 50 kilo-tons of ultra-pure water is instrumented with 11 000 photo sensors to detect Cherenkov radiation emitted by relativistic charged particles.
- Excellent particle identification and directionality.
  - Crucial for oscillation measurement.



(c) Kamioka Observatory, ICRR (Institute for Cosmic Ray Research), The University of Tokyo

# SUPER-KAMIOKANDE EVENTS



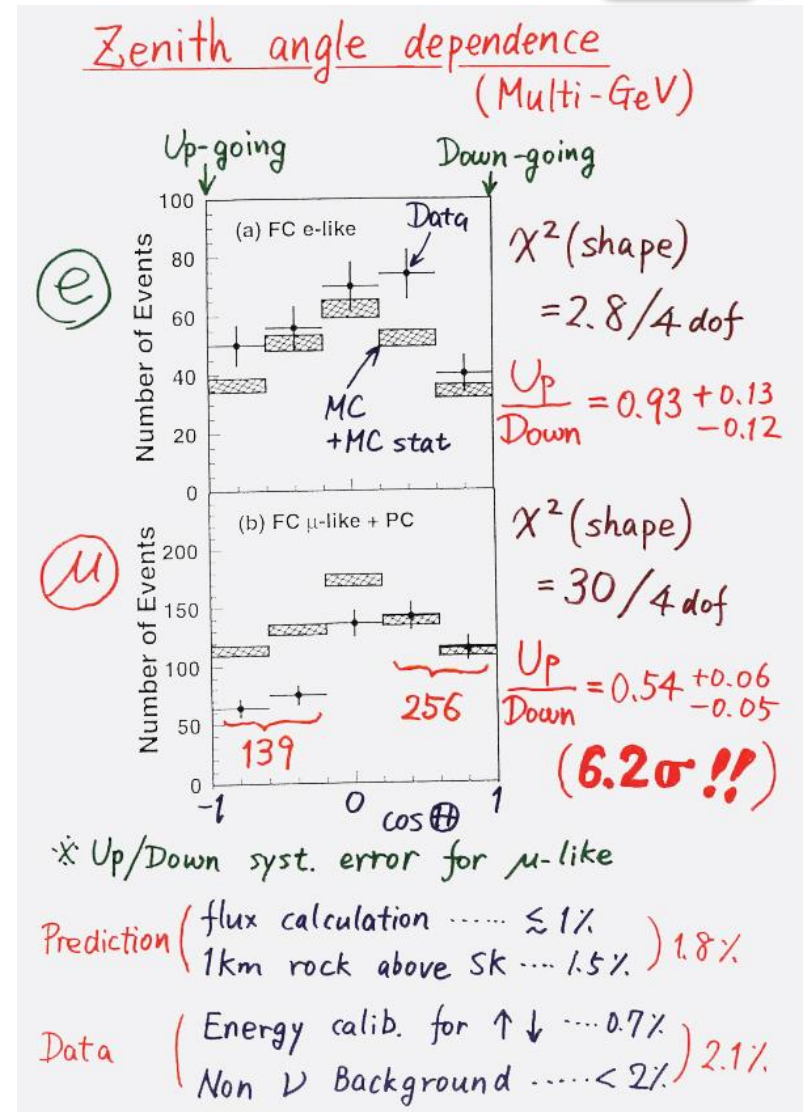


# SUPER-K FIRST RESULTS

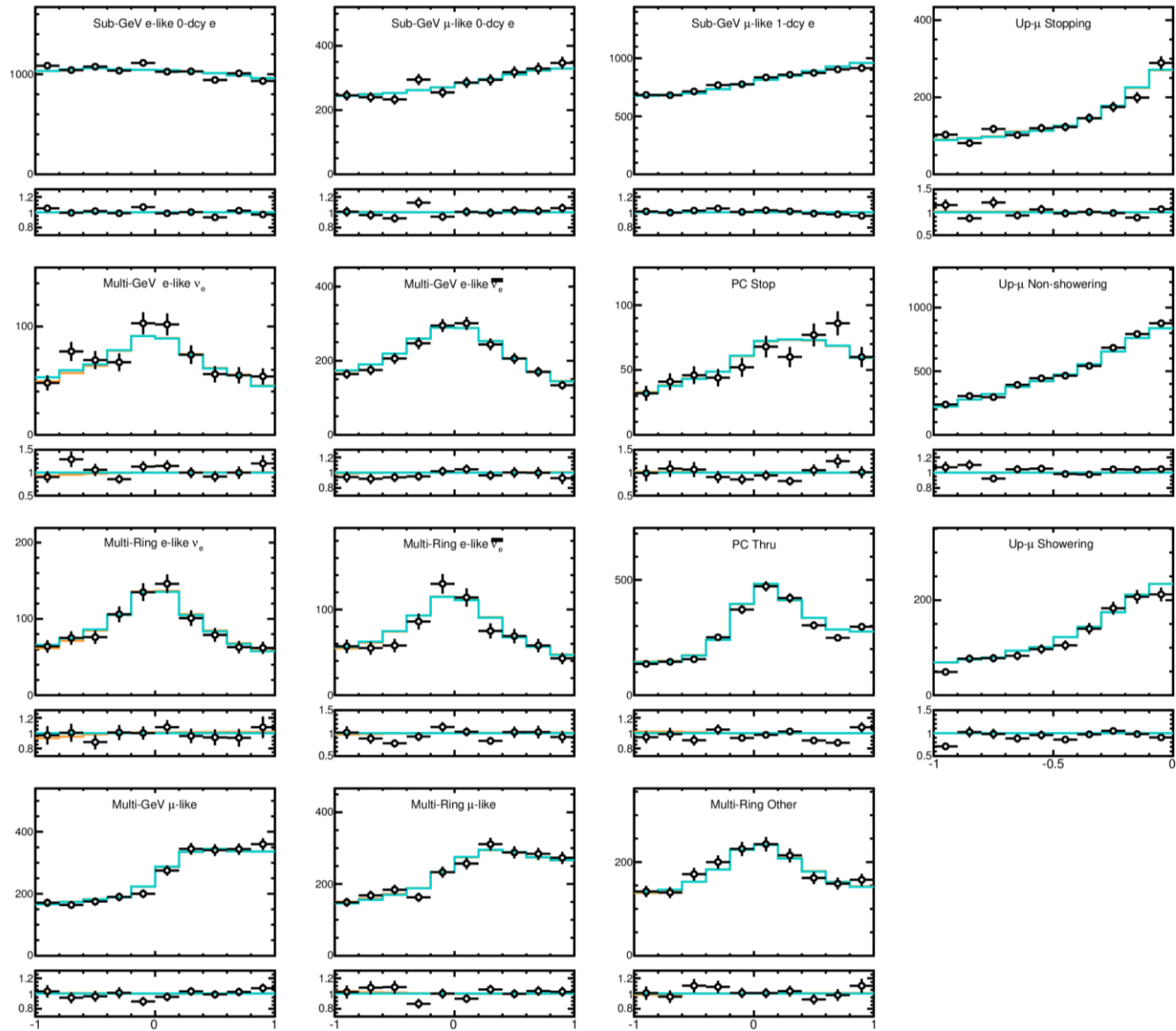
2015



- Super-Kamiokande announced its discovery of oscillations in atmospheric neutrinos in 1998.
- A clear deficit of “up-going” muon neutrinos was observed in the data.
  - Muon neutrinos are oscillating into tau neutrinos, which are not detected.
- Effect not seen in electron neutrinos.
  - Muon neutrino to electron neutrino oscillations are sub-dominant at this L/E.

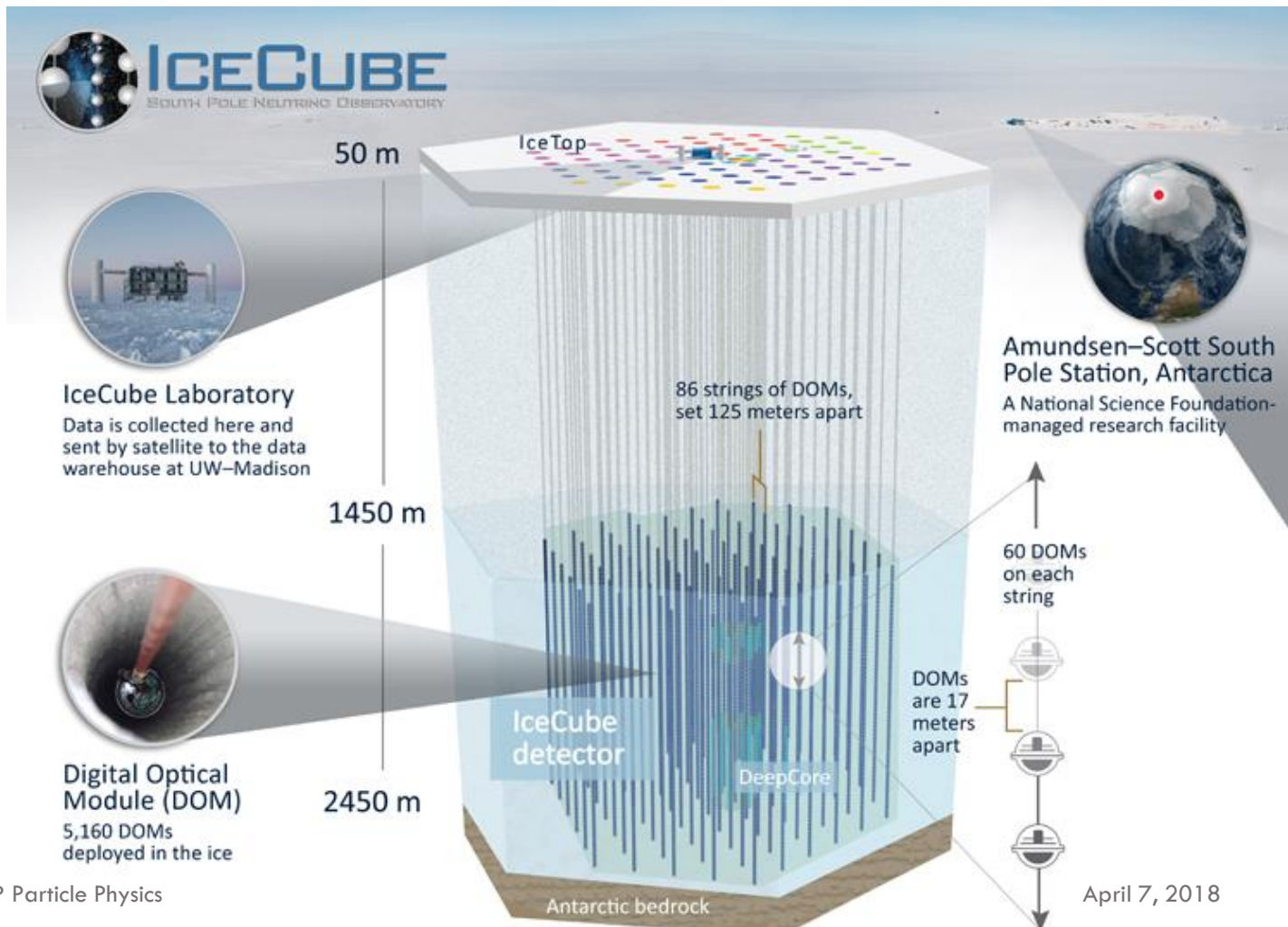


# SUPER-KAMIOKANDE APRIL 2018



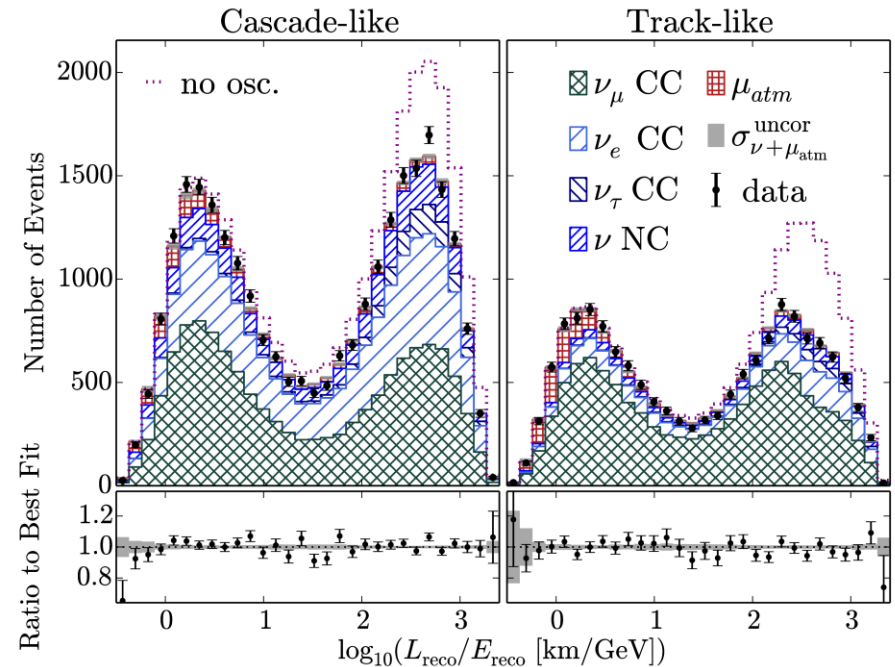
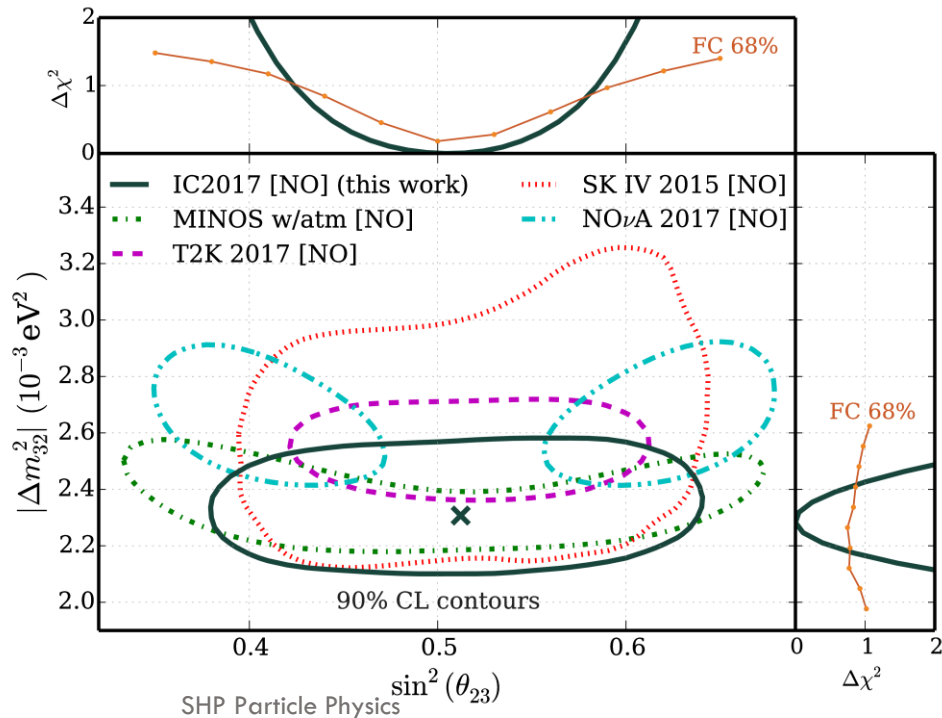
# ICECUBE ATMOSPHERIC NEUTRINOS

- Same principle as Super-K, but in the ice sheet at the South Pole! Not its primary science goal.



# ICECUBE ATMOSPHERIC NEUTRINOS

- Icecube sees atmospheric neutrino oscillations **consistent** with the Super-K results.



- Note  $\Delta m^2 \sim 10^{-3}$ , 100 times larger than solar mass splitting!
- Also, the mixing angle is **very** large – it looks like mixing is **maximal** or close...

# LONG BASELINE EXPERIMENTS

E:  $\sim 1000$  MEV (CAN TUNE PRECISELY)

L:  $\sim$  SEVERAL 100 KM (CAN TUNE PRECISELY)

MINIMUM  $\Delta M^2$ :  $10^{-3}$  EV<sup>2</sup>

# NEUTRINO BEAMS

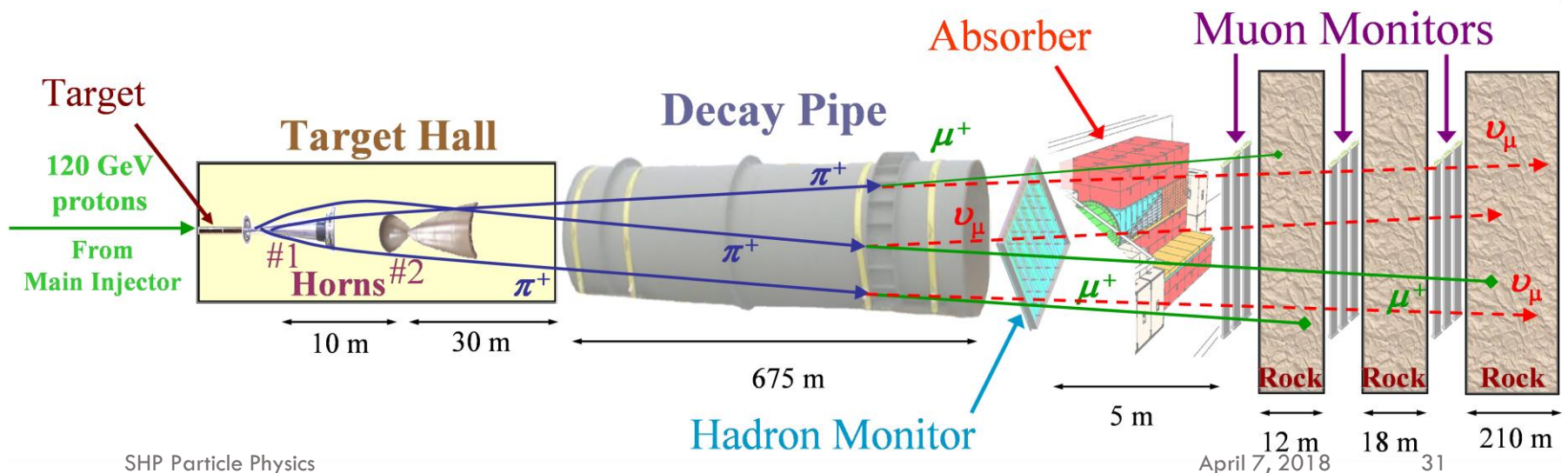
- So far, looked at experiments that use pre-existing neutrino sources.
  - Either natural: Sun, cosmic rays impinging on the atmosphere.
  - Or artificial: commercial nuclear reactors – electricity is paid for, but neutrinos are free!
- But we've been producing neutrino beams since the 60s.
- We can confirm neutrino oscillations using a well controlled neutrino source.
- Long baseline neutrino experiments:
  - Produce very intense muon neutrino beam
  - Point it at very large detector very far away.
  - Use well controlled beam energy, direction and timing to make very precise measurements.
    - Including searching for electron neutrino appearance from a muon neutrino beam.
      - Needs non-zero  $\theta_{13}$



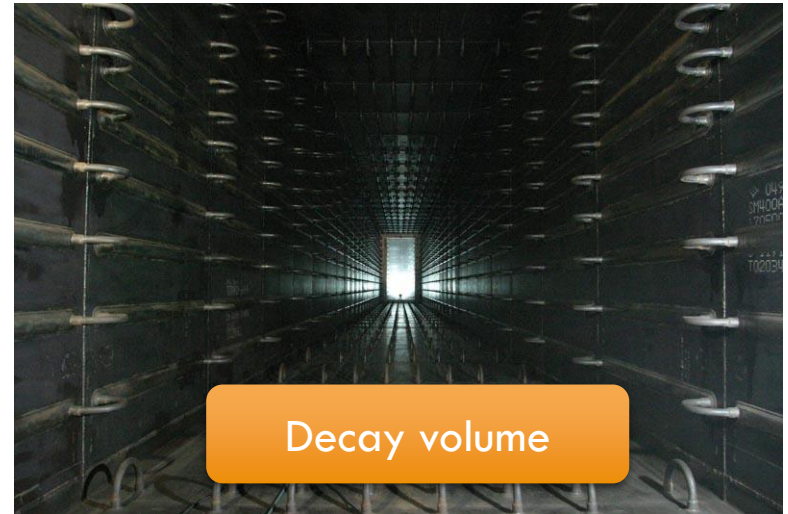
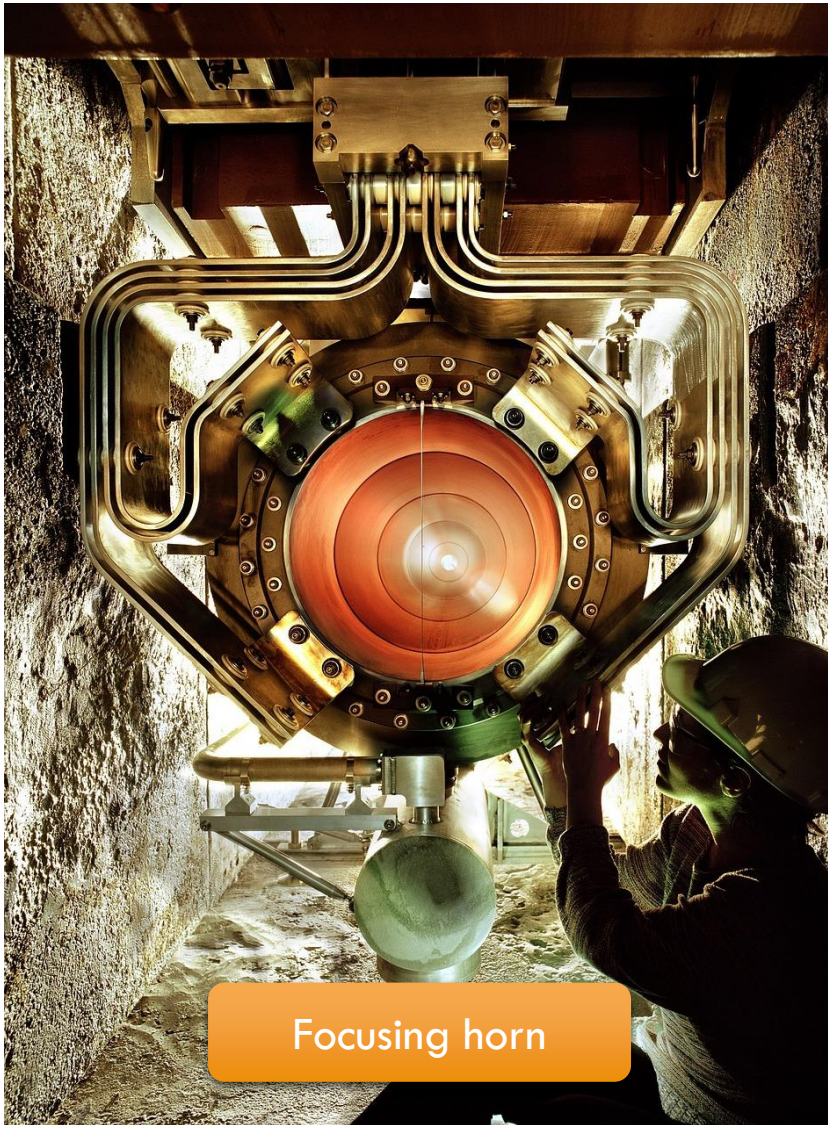
# PRODUCING A NEUTRINO BEAM

- [https://www.youtube.com/watch?v=U\\_xWDWKq1CM](https://www.youtube.com/watch?v=U_xWDWKq1CM)

1. Accelerate protons and aim them at a target.
2. Focus the resulting pions using magnetic horns.
  - Can focus positive or negative pions to give neutrinos or anti-neutrinos.
3. Allow pions to decay in empty volume, producing neutrinos and muons.
4. Absorb the muons, and neutrinos will go through.

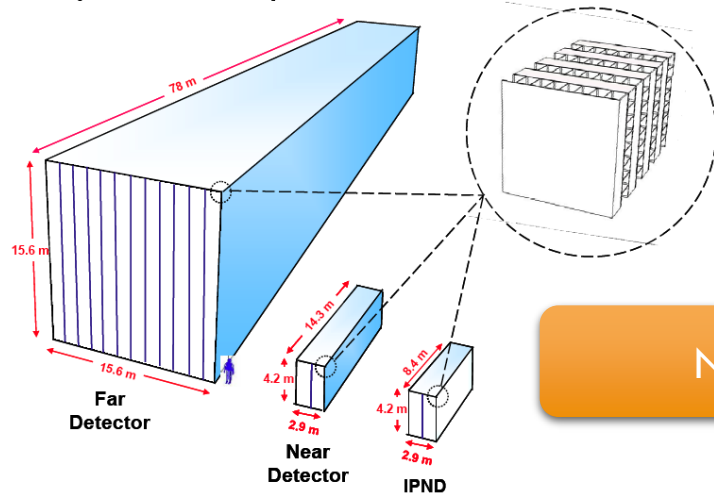


# NEUTRINO BEAMLINE

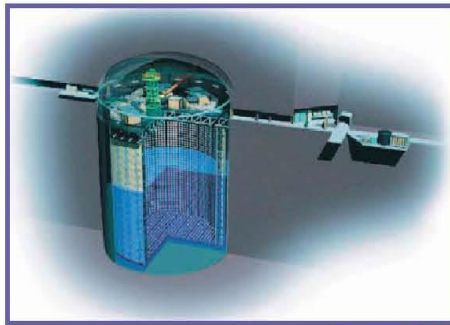
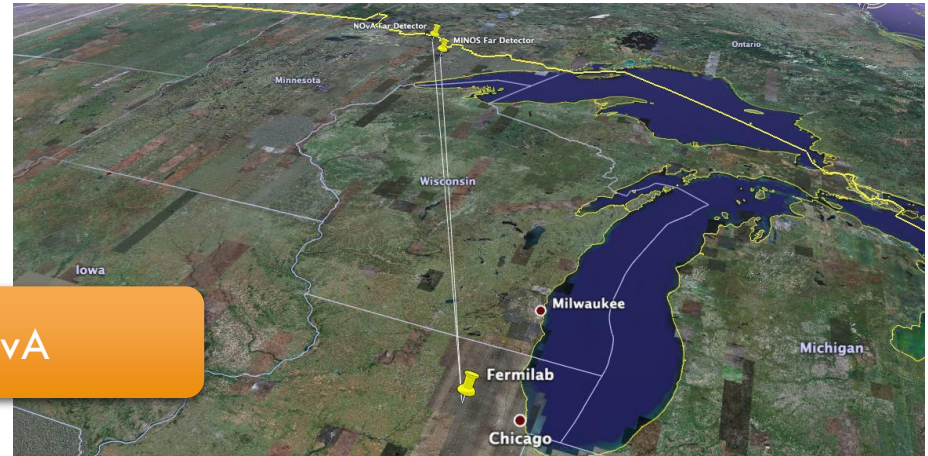




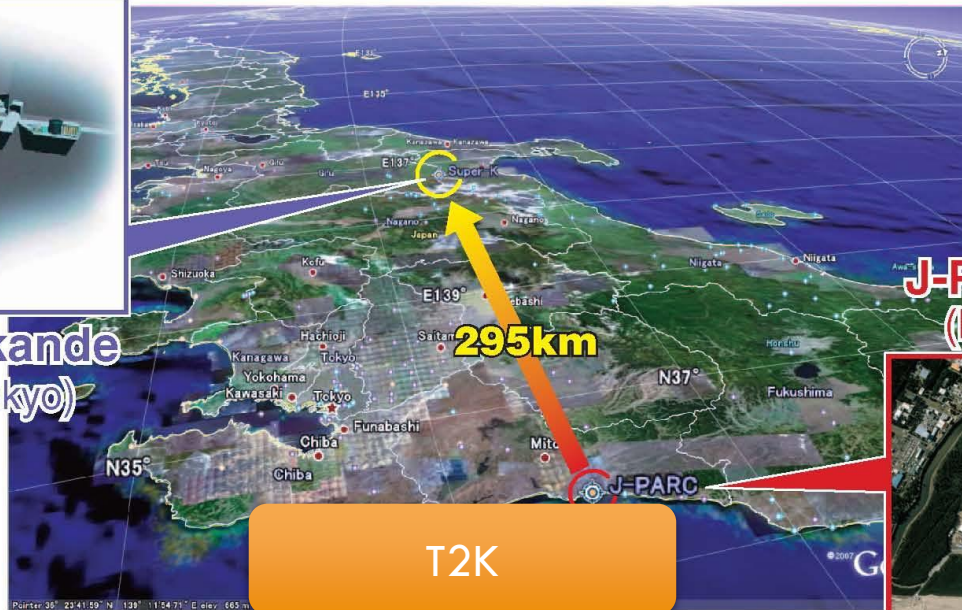
# CURRENT LONG BASELINE EXPERIMENTS



NOvA



**Super-Kamiokande**  
(ICRR, Univ. Tokyo)



T2K

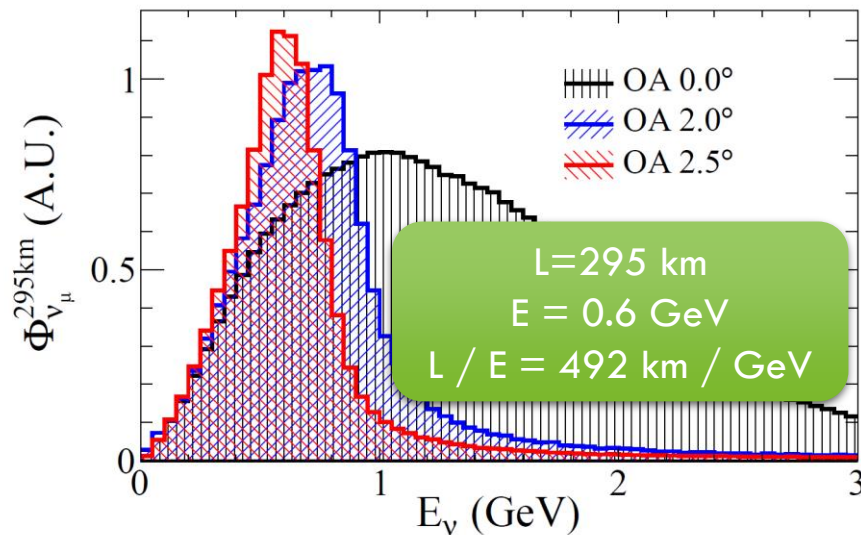
**J-PARC Main Ring**  
(KEK-JAEA, Tokai)



# THE OFF-AXIS TRICK

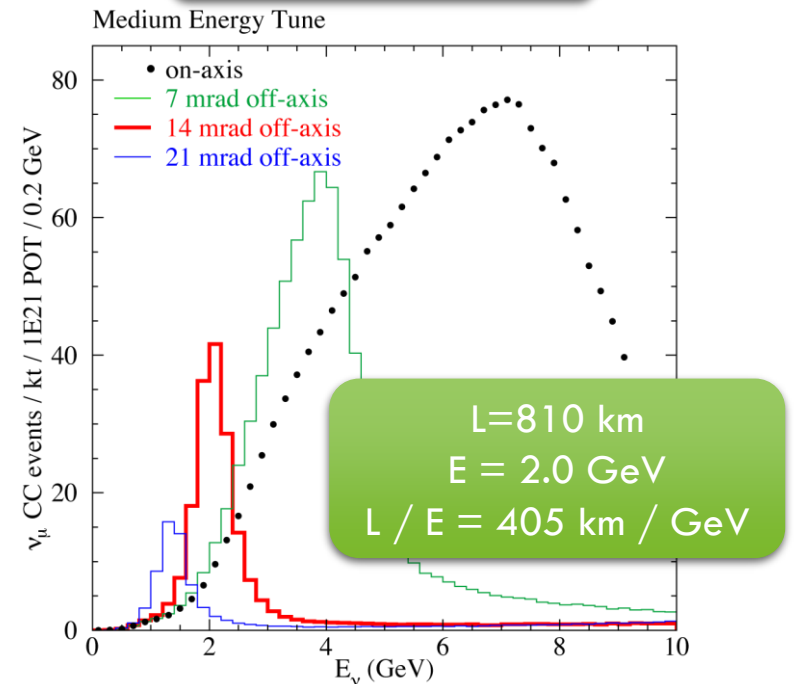
- Both NOvA and T2K use the “off-axis trick”.
- Don't place the detector right in front of the neutrino beam, but a little to the side.
- Neutrinos that leave the decay pipe at a high angle have a more well defined energy.
  - Can tune  $L / E$  very precisely!

T2K



SNR Particle Physics

NOvA

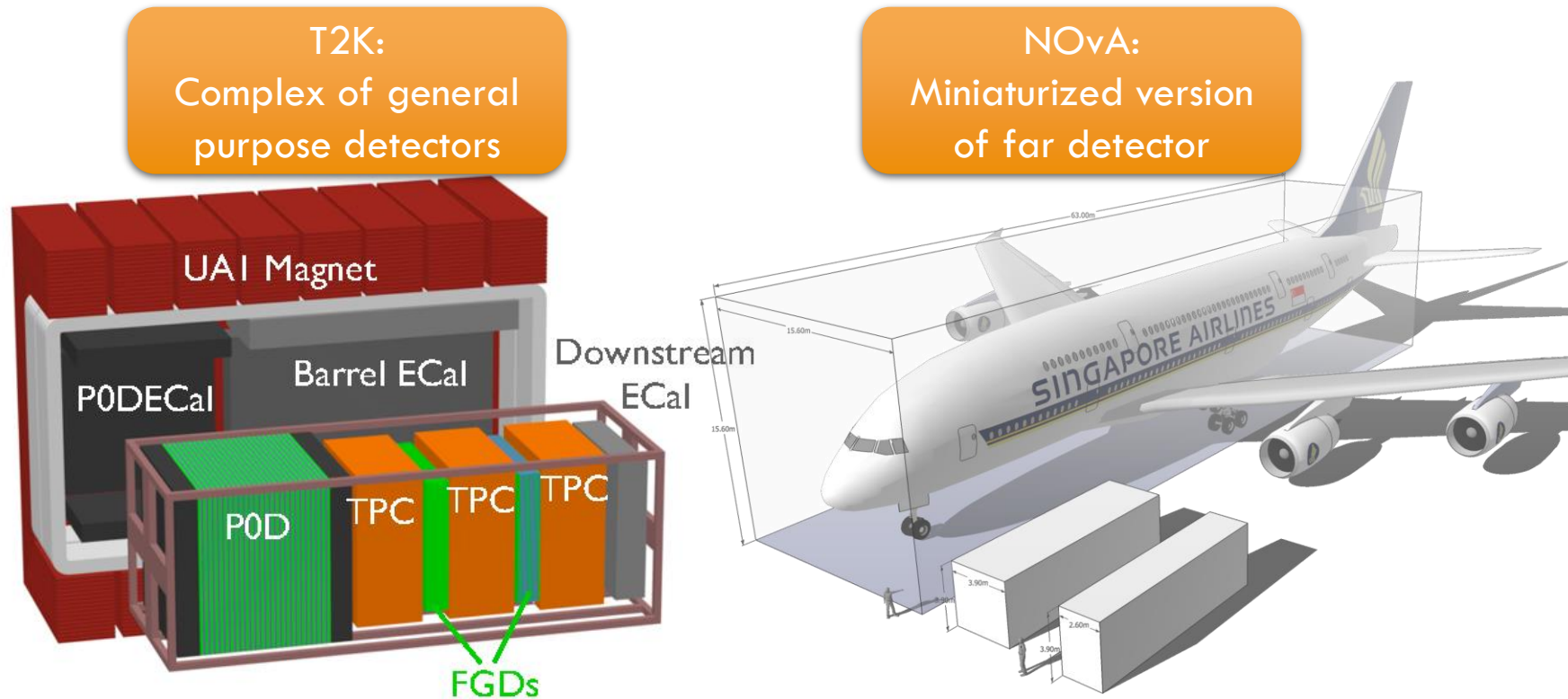


April 7, 2018

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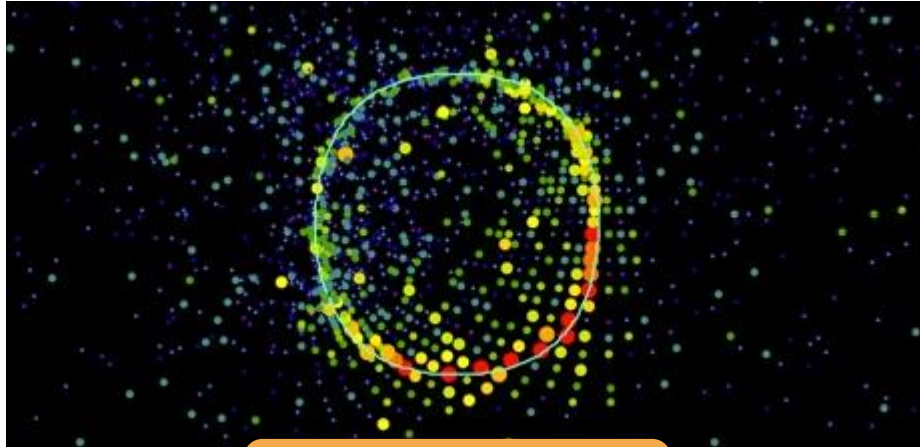
# NEAR DETECTORS

- Want to characterise the neutrino beam as well as possible before any oscillations.
- Place neutrino detectors near the neutrino production point.
- Use data from these detectors to measure neutrino cross sections.

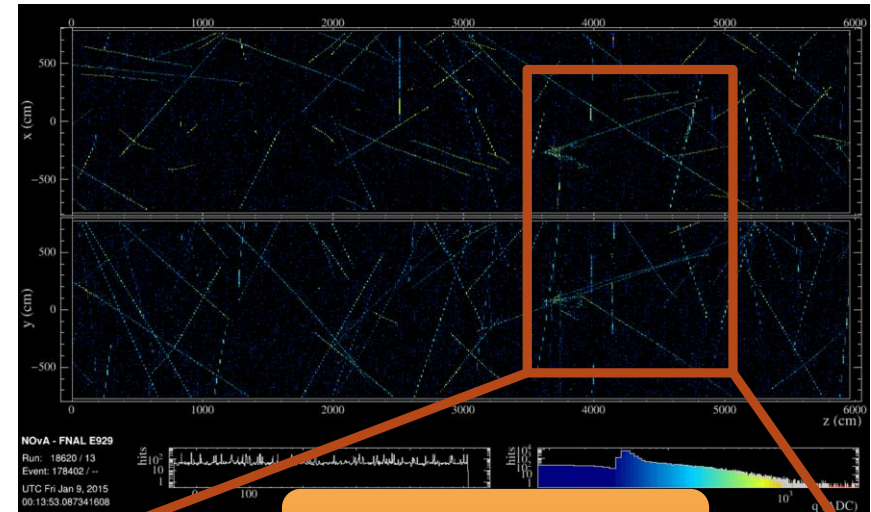
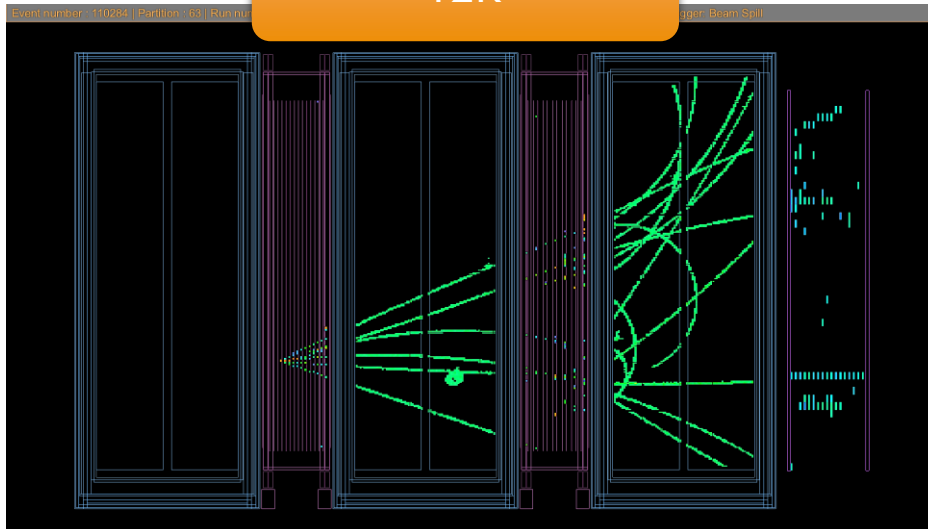




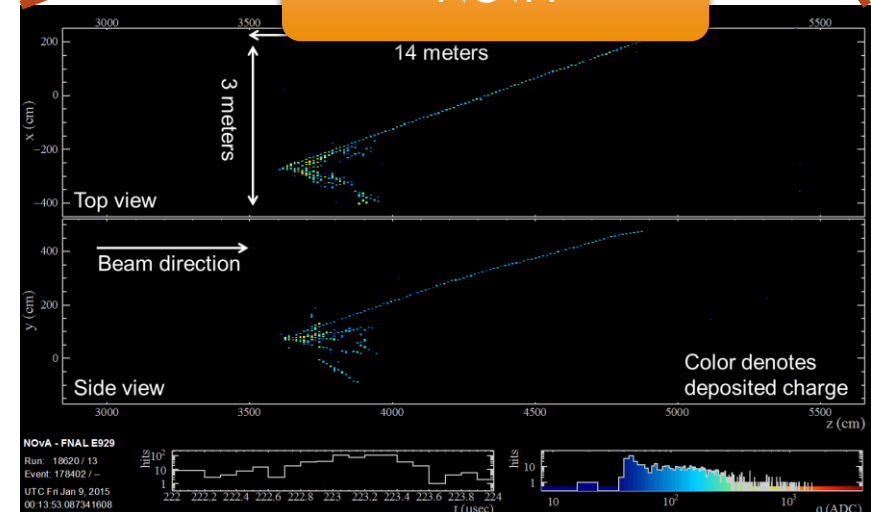
# T2K AND NOVA NEUTRINO EVENTS



T2K



NOvA

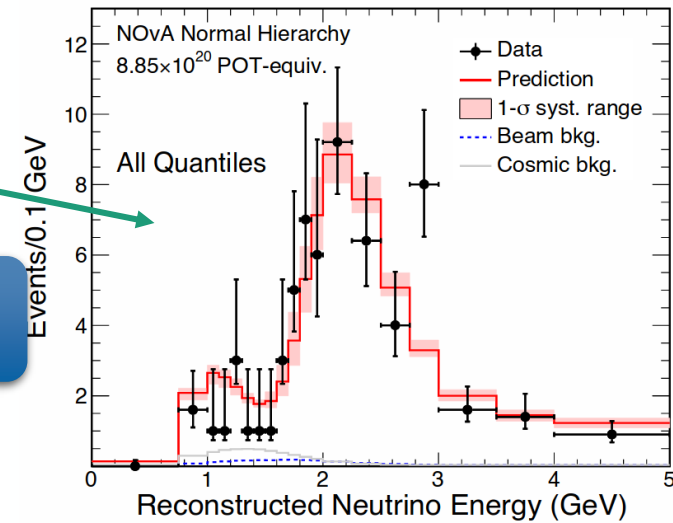


# T2K AND NOVA DATA

Muon neutrinos disappear

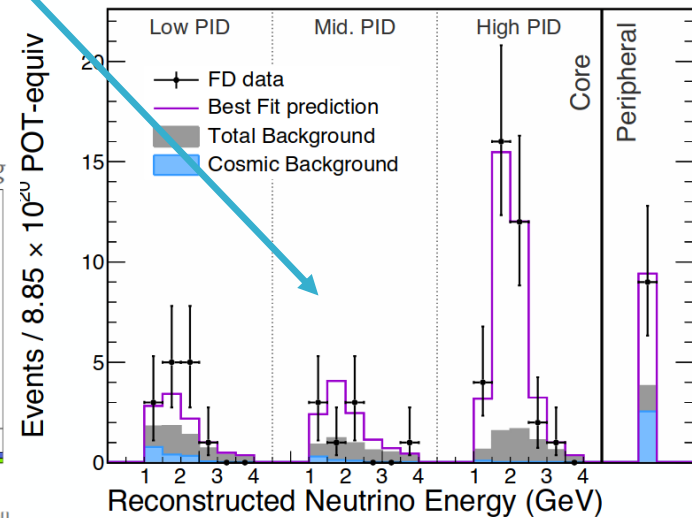
Electron neutrinos appear

NOvA Preliminary

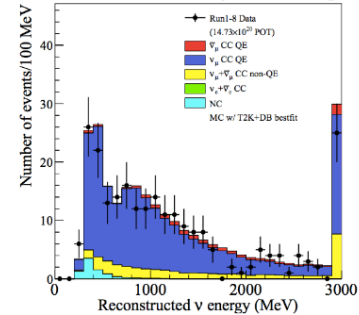


T2K Preliminary

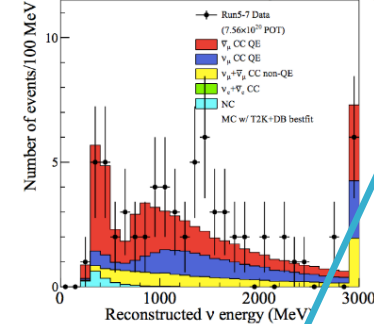
NOvA Preliminary



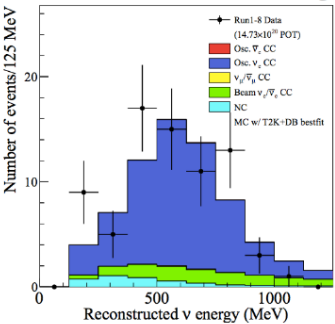
Neutrino CCQE 1 μ-like ring



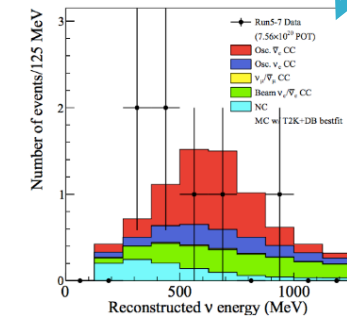
Antineutrino CCQE 1 μ-like ring



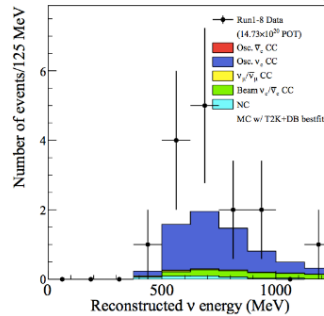
Neutrino CCQE 1 e-like ring



Antineutrino CCQE 1 e-like ring



Neutrino CC1π 1e-like ring

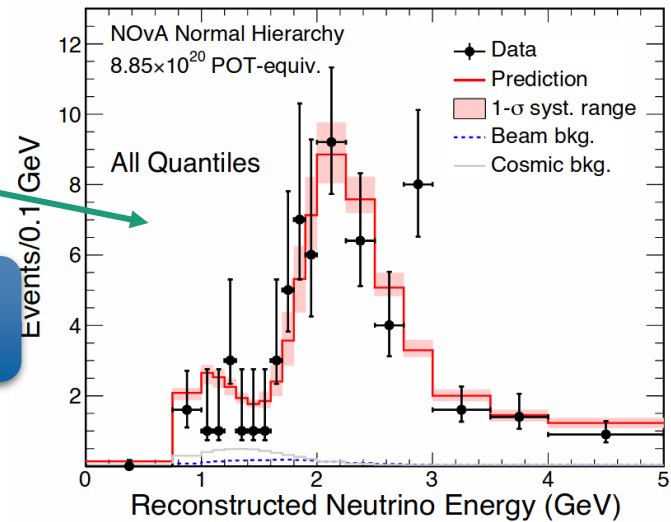


# T2K AND NOVA DATA

Muon neutrinos disappear

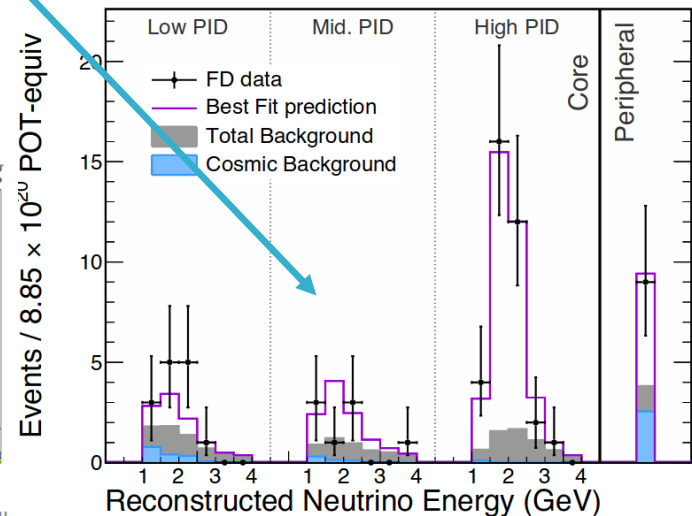
Electron neutrinos appear

NOvA Preliminary



T2K Preliminary

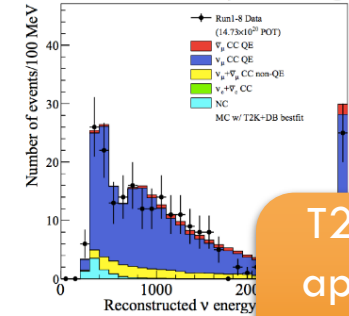
NOvA Preliminary



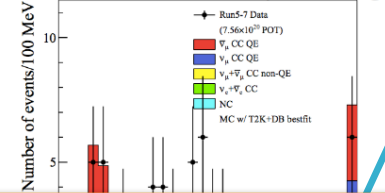
T2K observed electron neutrinos appearing from a muon neutrino beam for the first time in 2013

$$\theta_{13} \neq 0$$

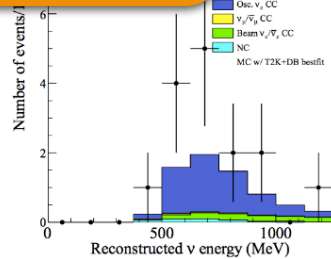
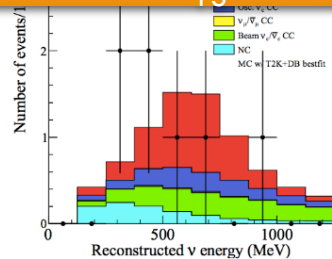
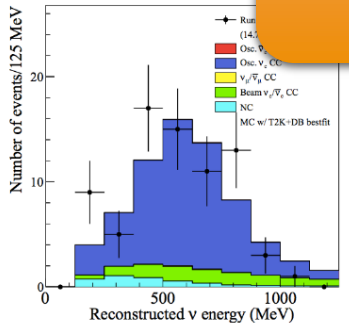
Neutrino CCQE 1  $\mu$ -like ring



Antineutrino CCQE 1  $\mu$ -like ring

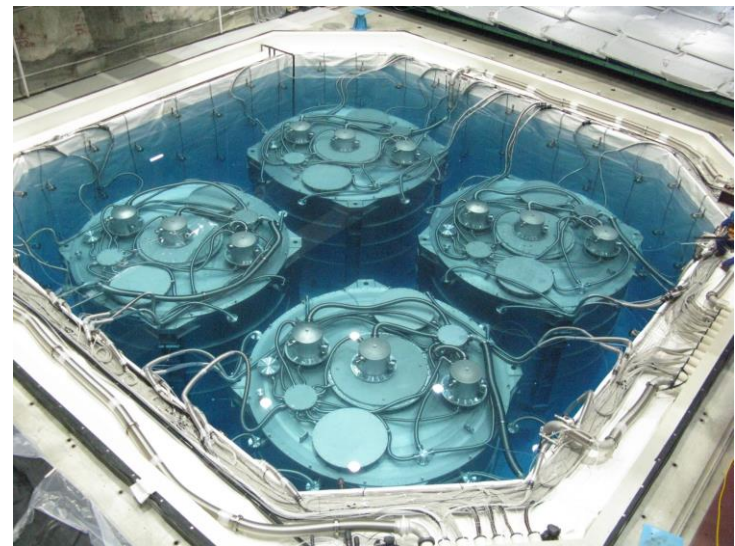
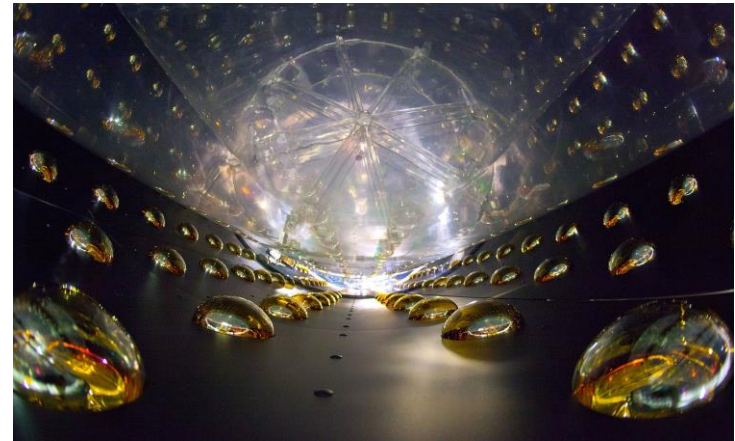
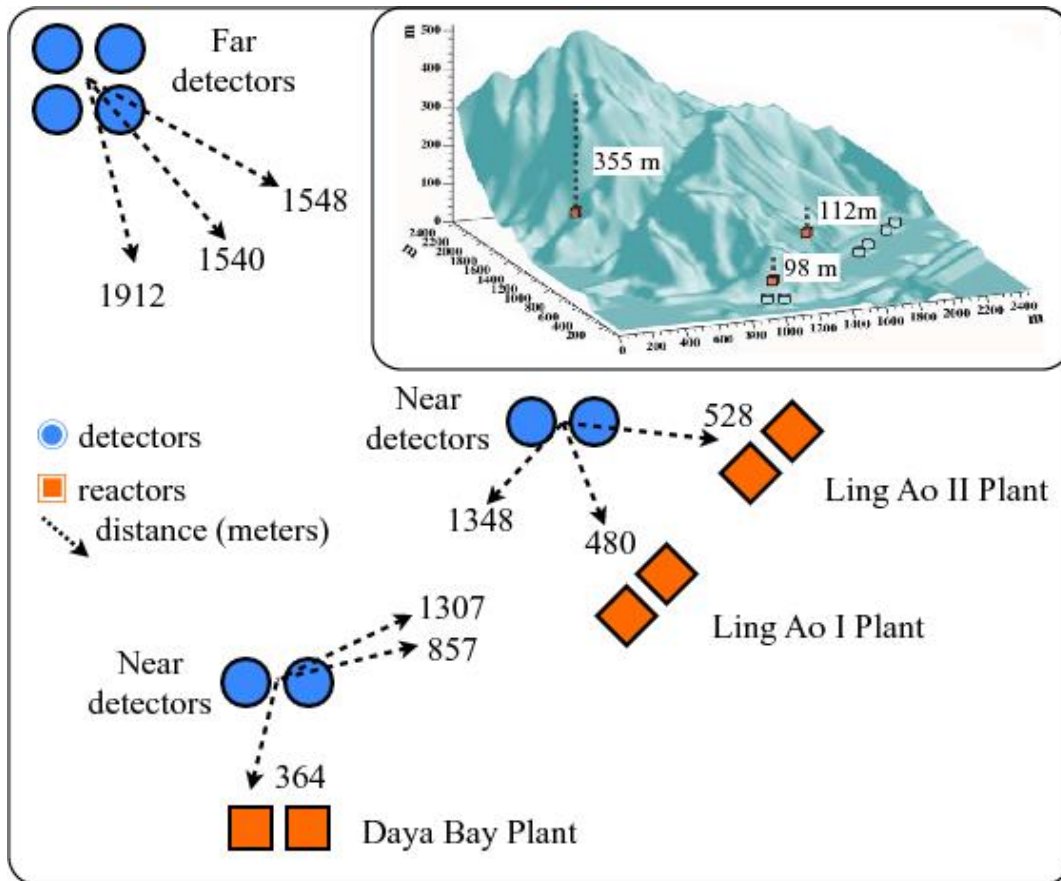


Neutrino CCQE 1  $e$ -like ring



# SHORT(ER) BASELINE REACTOR EXPERIMENTS

- Daya Bay experiment, south China.
- $L \sim 1.5 \text{ km}$ ;  $E \sim 1 \text{ MeV}$ ; Minimum  $\Delta m^2 \sim 10^{-3} \text{ eV}^2$



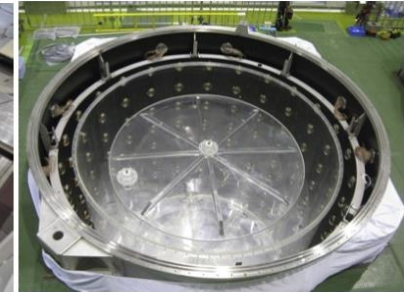
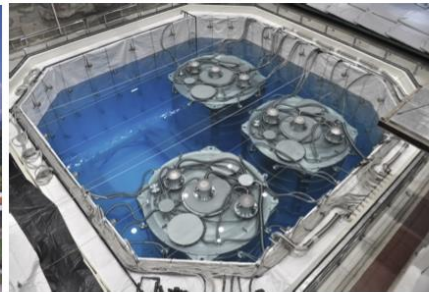


# SHORT(ER) BASELINE REACTOR EXPERIMENTS

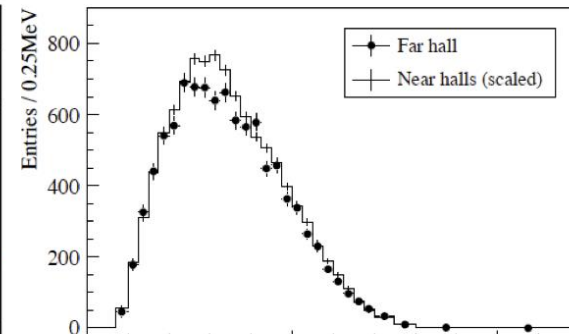
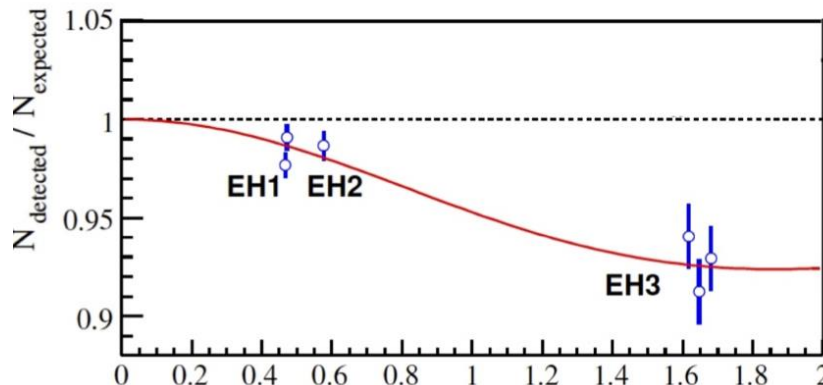
- In 2012,  $\theta_{13}$  went from being the least well known of the mixing angles to the most precisely measured!



## Observation of Electron Antineutrino Disappearance at Daya Bay



$$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$$





WHAT WE KNOW SO FAR

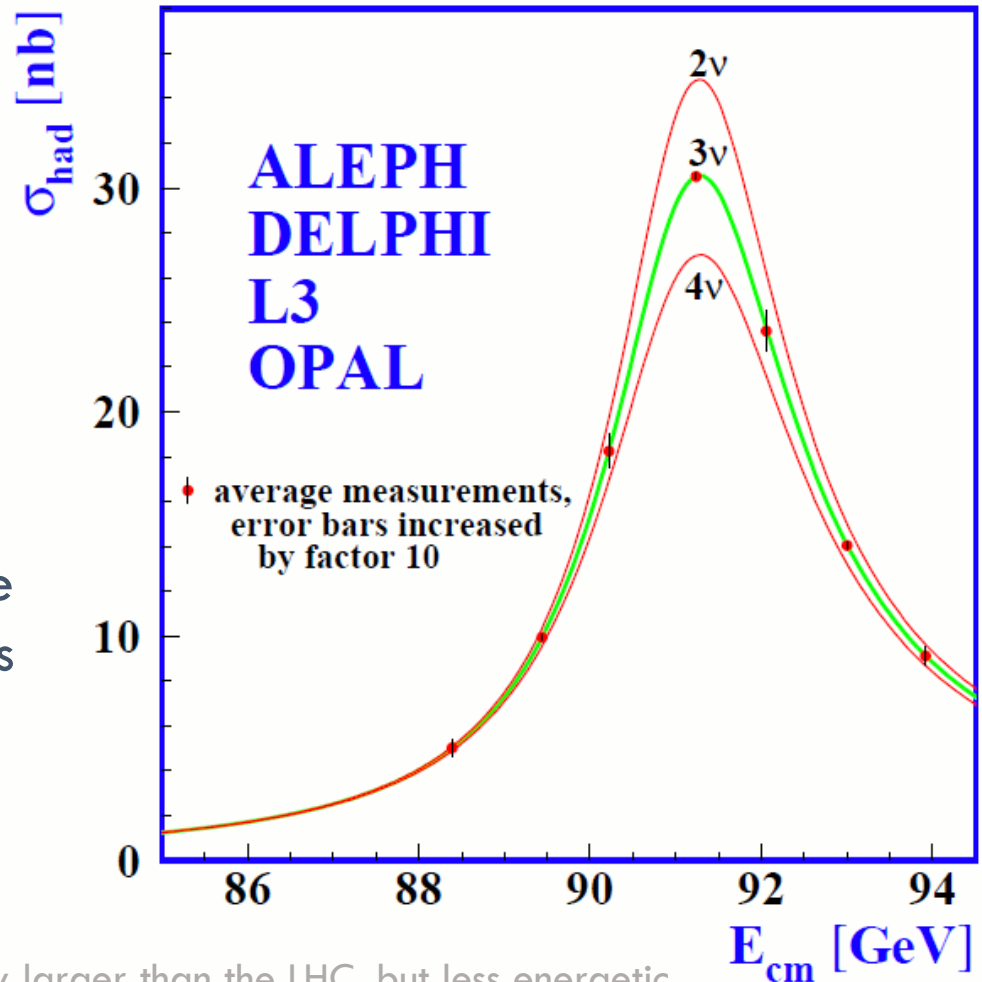
AND WHAT WE DON'T KNOW AND WOULD LIKE TO KNOW...

# FROM NEUTRINO OSCILLATIONS

- There are at least two (very) different neutrino mass splittings:
  - At least **3** neutrino mass states, but one of them might be zero.
  - But don't know which of the mass states is the lightest.
- The three mixing angles are non-zero and large.
  - Unlike in the quark sector, where they are small.
  - This makes it possible to measure the **CP violating** phase in the PMNS matrix.
    - Wouldn't be possible if any of the angles was zero, and it would be very difficult if any of the angles was very small.

# THREE NEUTRINOS!

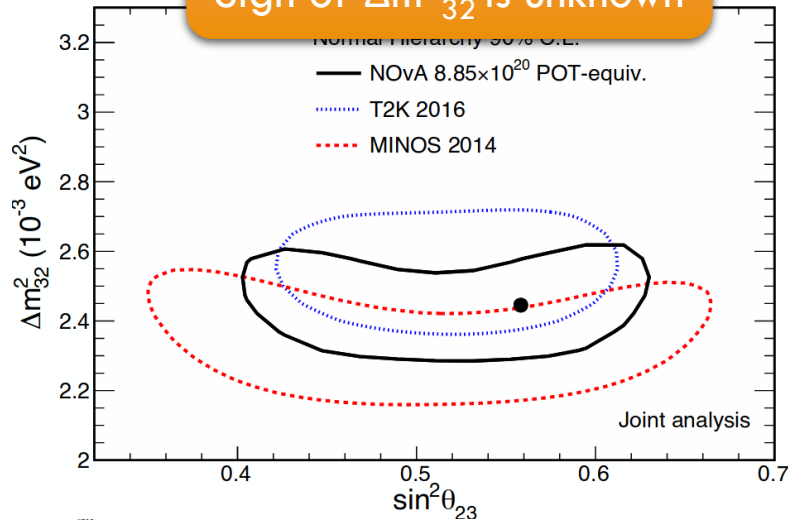
- Three mass states.
- Three flavour states.
- Three corresponding charged leptons.
- From LEP\* (large electron positron collider) at CERN we know, that at most there are three “active” neutrinos with mass below 45 GeV.



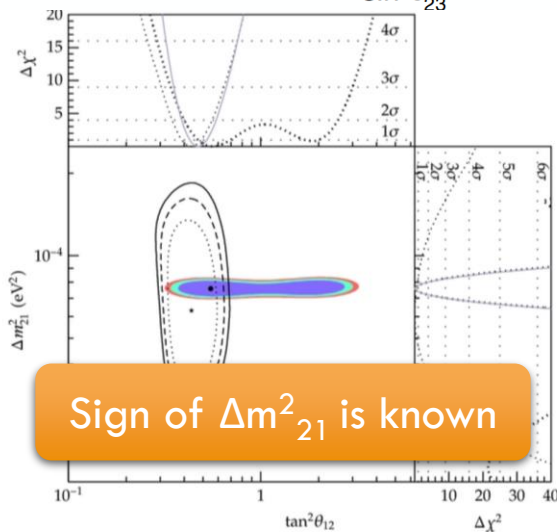
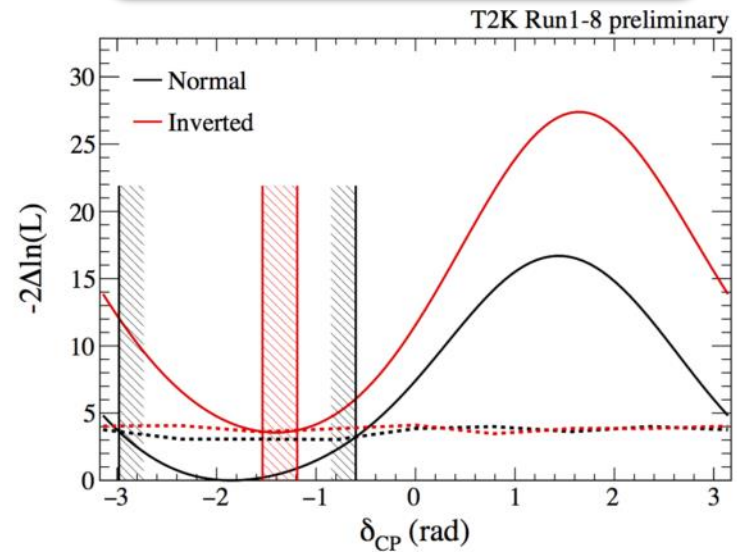
\* Actually the largest collider ever built. Slightly larger than the LHC, but less energetic.

# CURRENT STATUS OF THE PMNS MODEL

$\Theta_{23}$  might be maximal  
Sign of  $\Delta m^2_{32}$  is unknown



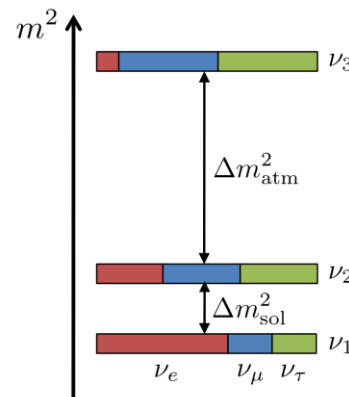
CP might not be conserved



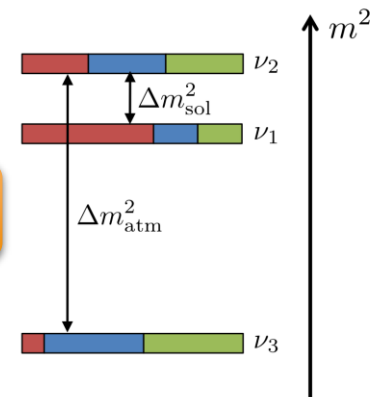
Sign of  $\Delta m^2_{21}$  is known



normal hierarchy (NH)



inverted hierarchy (IH)

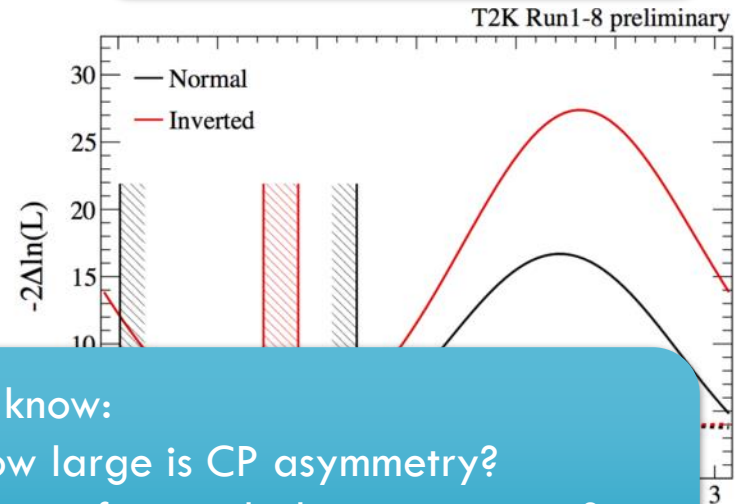
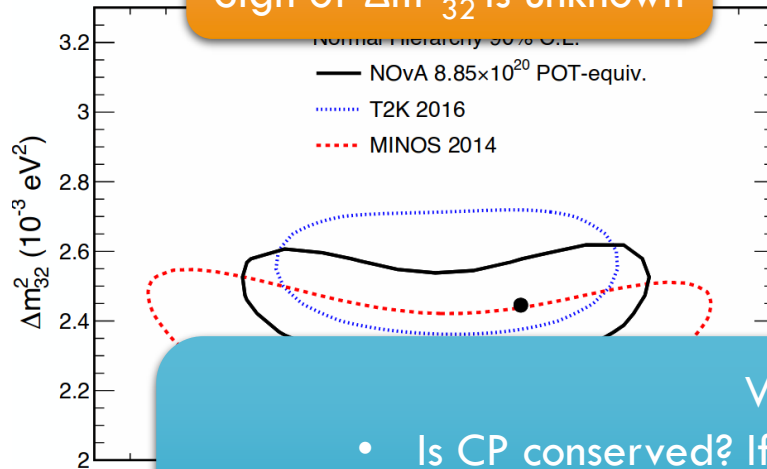


???

# CURRENT STATUS OF THE PMNS MODEL

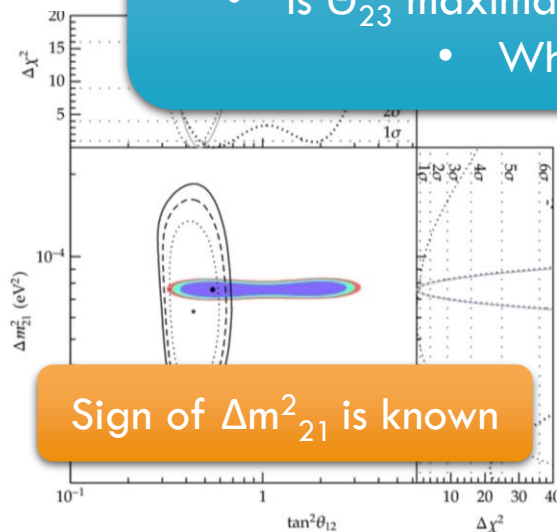
$\Theta_{23}$  might be maximal  
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CP might not be conserved



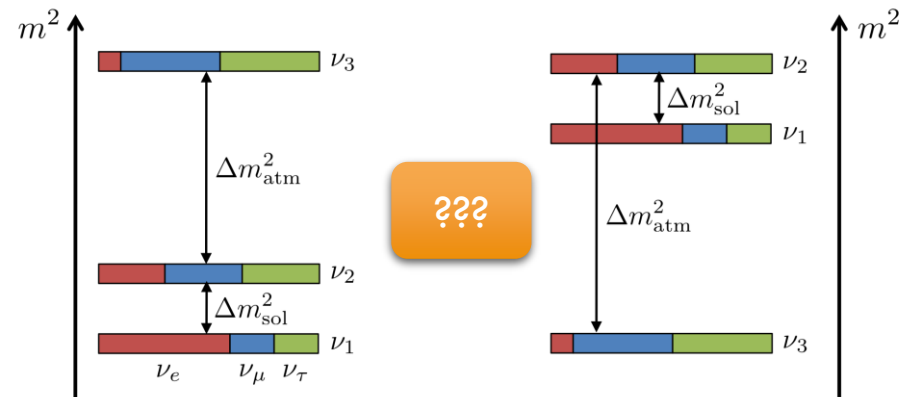
Want to know:

- Is CP conserved? If not, how large is CP asymmetry?
- Is  $\Theta_{23}$  maximal? If so, is that a hint of an underlying symmetry?
- Which is the heaviest mass state, 3 or 2?



Sign of  $\Delta m^2_{21}$  is known

normal hierarchy (NH)      inverted hierarchy (IH)

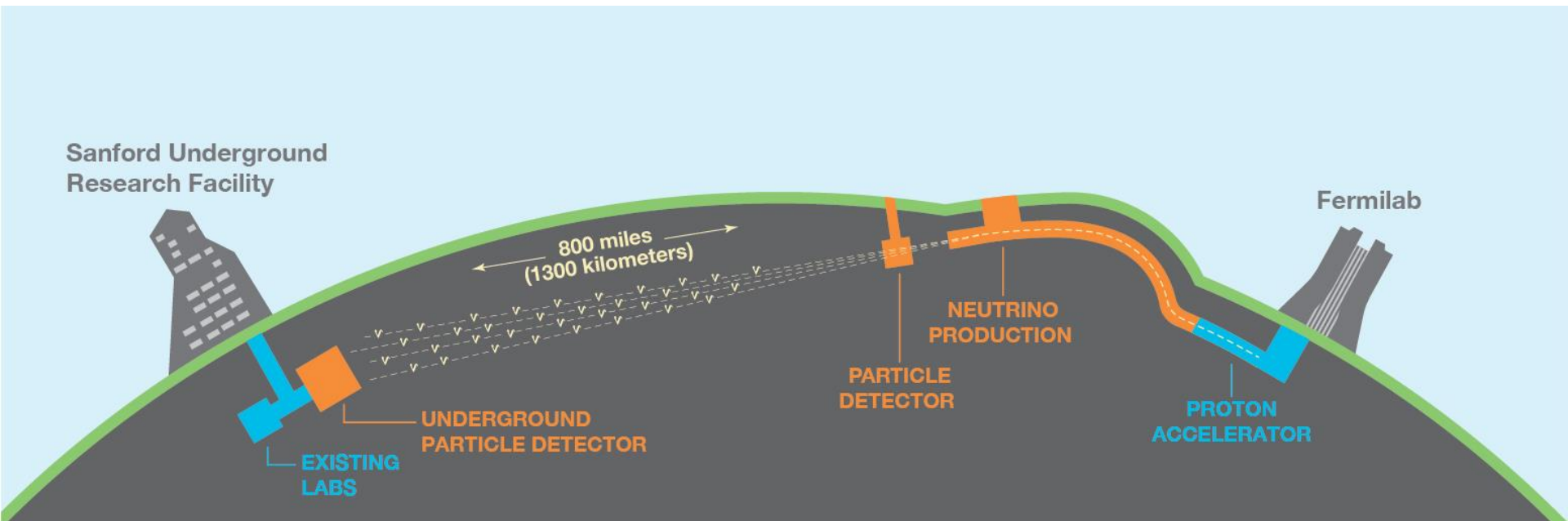


KamLAND  
 95% CL  
 99% CL  
 99.73% CL  
 • Best fit

Solar  
 95% CL  
 99% CL  
 99.73% CL  
 • Best fit

# DEEP UNDERGROUND NEUTRINO EXPERIMENT

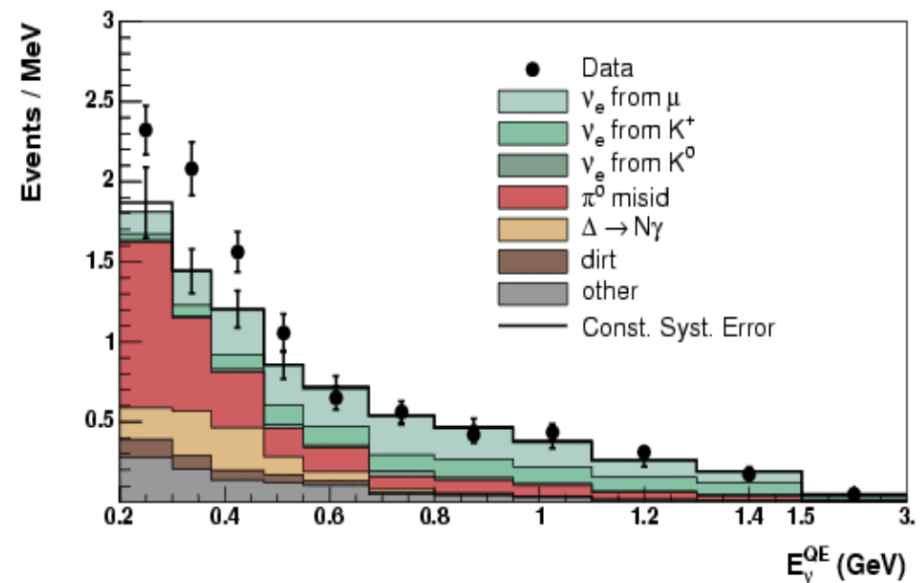
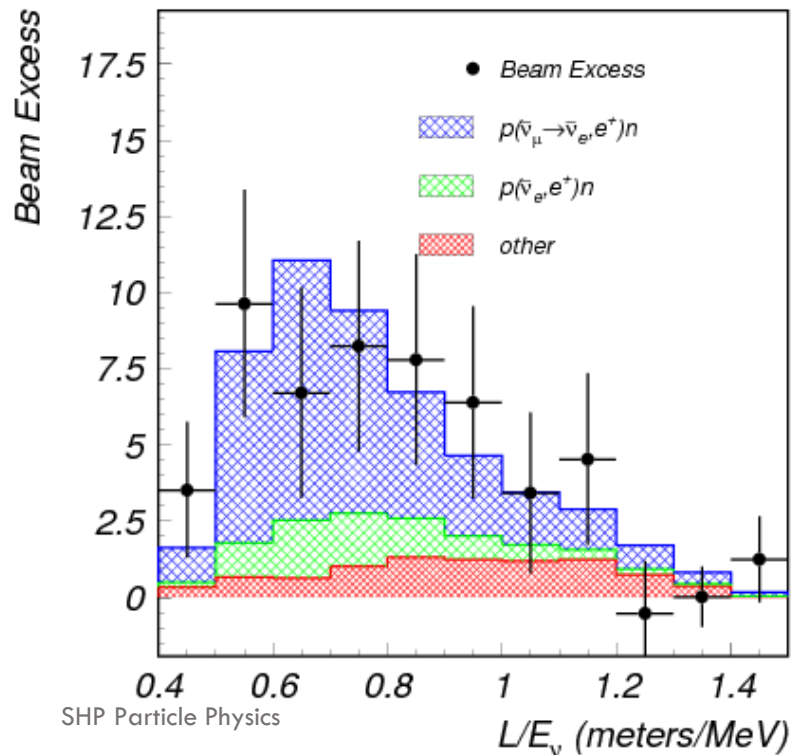
- <https://www.youtube.com/watch?v=nv13DswlKr8>





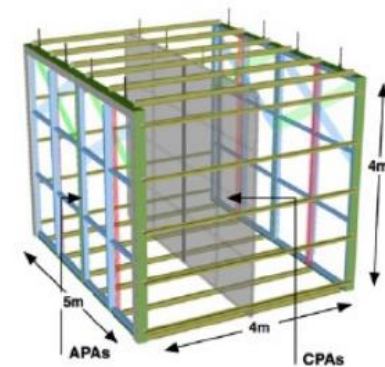
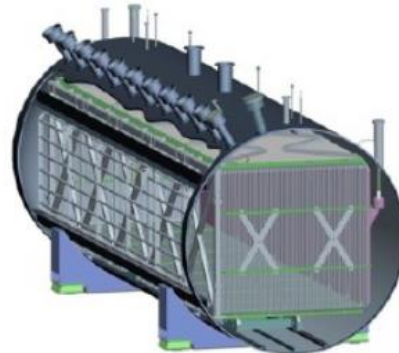
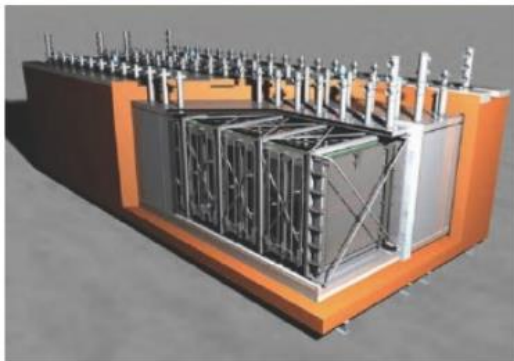
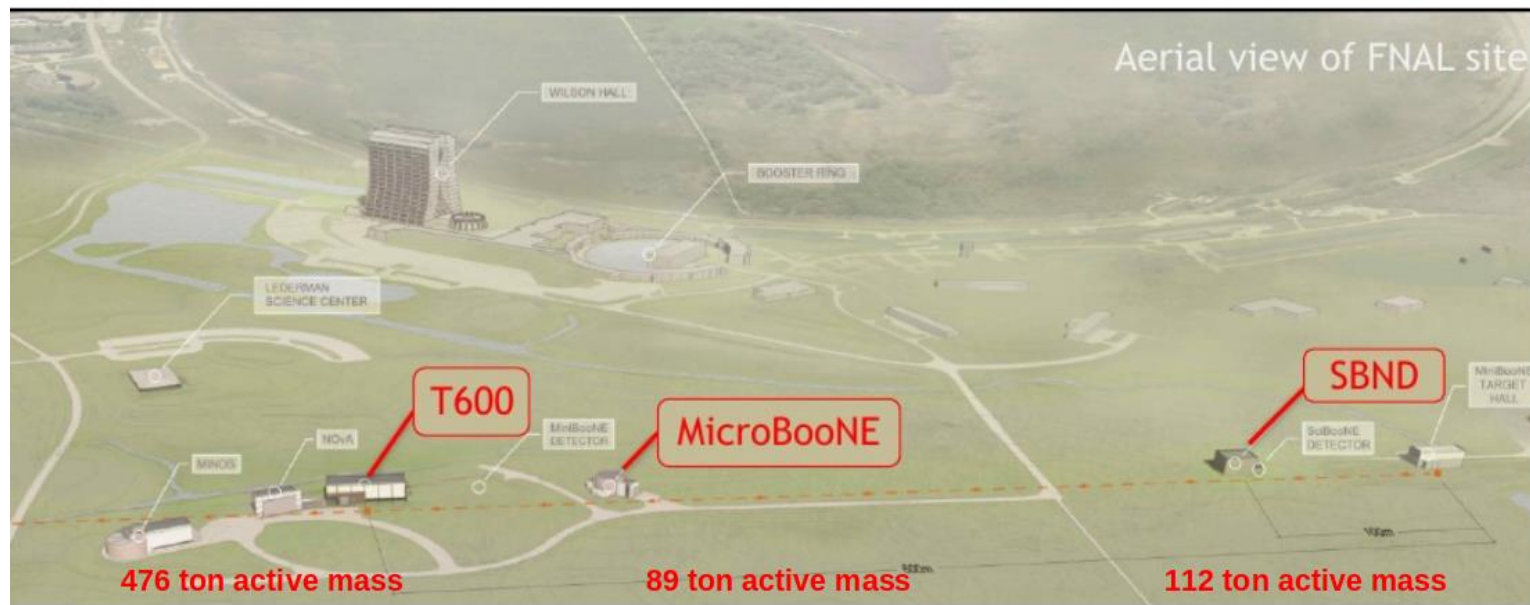
# BEYOND THE PMNS FRAMEWORK

- Is the PMNS framework the full story?
- In the late 90s, the Liquid Scintillator Neutrino Detector (LSND) claimed observation of electron neutrino appearance from a muon neutrino beam with a very short baseline.
  - Implication: there is a very large squared-mass splitting, around  $1 \text{ eV}^2$ , so there must be a 4<sup>th</sup> (heavier) neutrino mass state!
- MiniBooNE experiment built to confirm or disprove LSND result.
  - Also found excess of electron neutrinos, but **not** compatible with LSND...



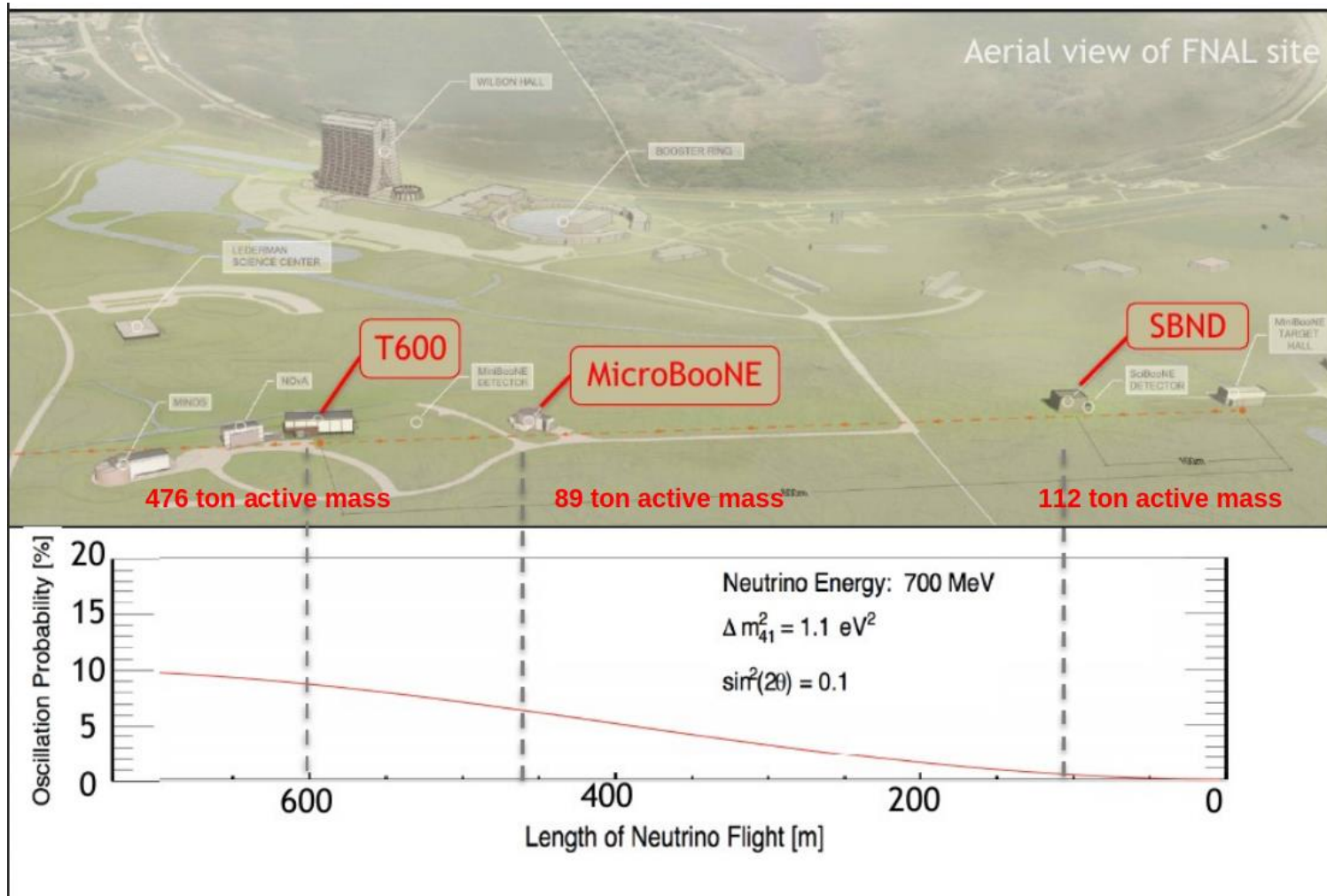
# SHORT BASELINE PROGRAM AT FERMILAB

- Use liquid argon TPC technology to try to settle the matter!



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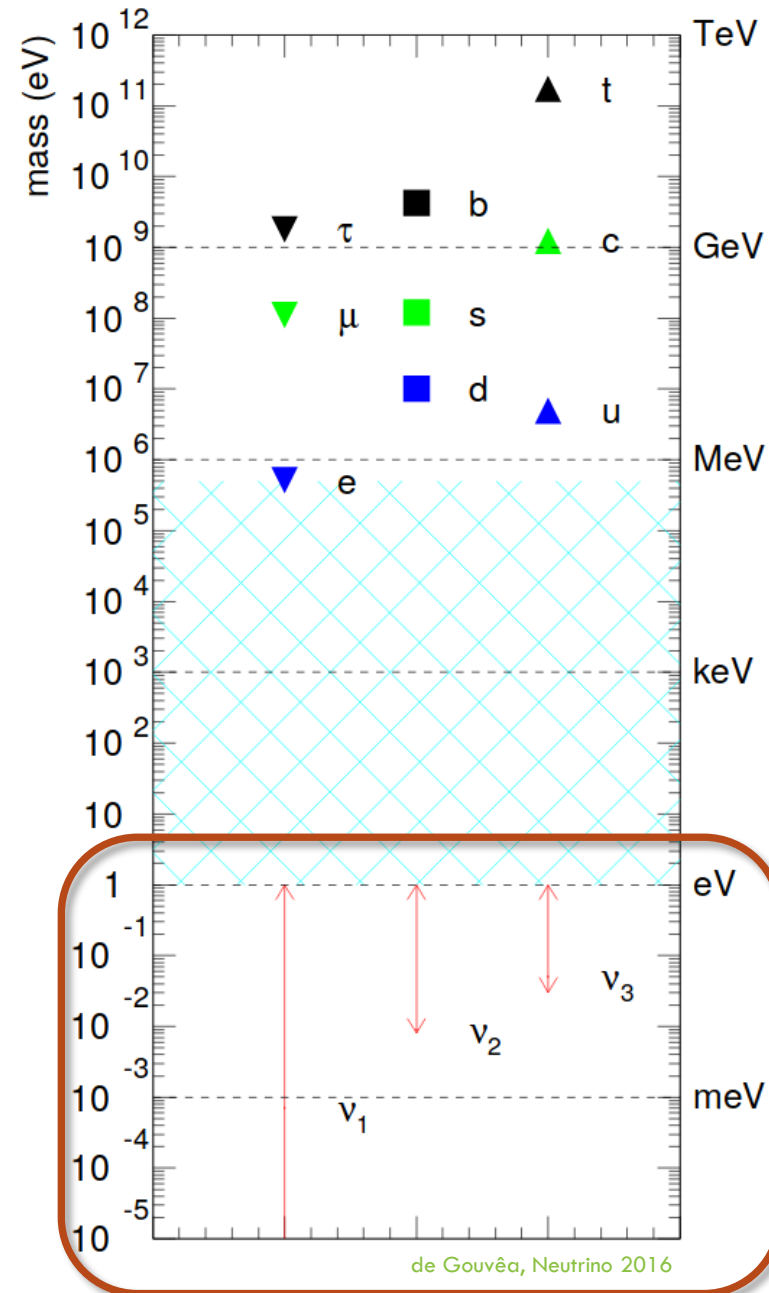
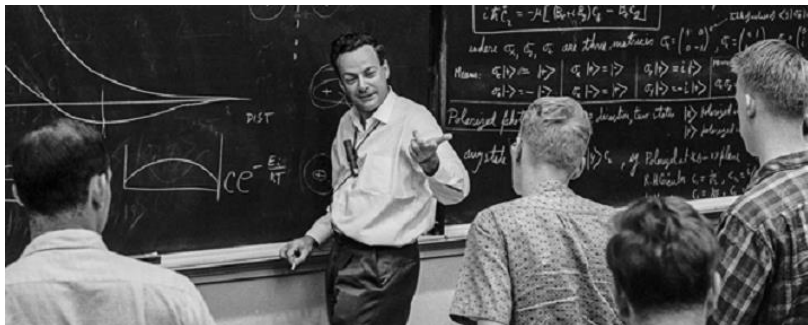


# NEUTRINO MASS

# PARTICLE MASSES

- “There remains **one especially unsatisfactory** feature [of the Standard Model of particle physics]: the **observed masses** of the particles,  $m$ . There is **no theory** that adequately **explains** these numbers. We **use** the numbers in all our theories, but we **do not understand** them — **what** they are, or where they **come from**. I believe that from a **fundamental** point of view, this is a very **interesting** and **serious problem**.”

- R. P. Feynman



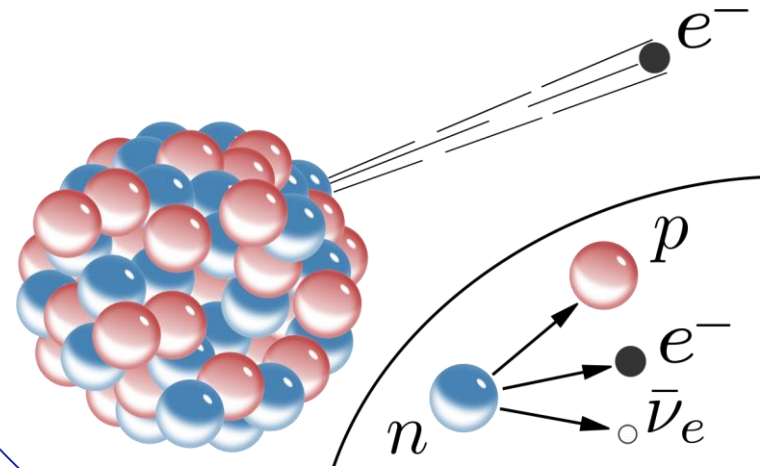
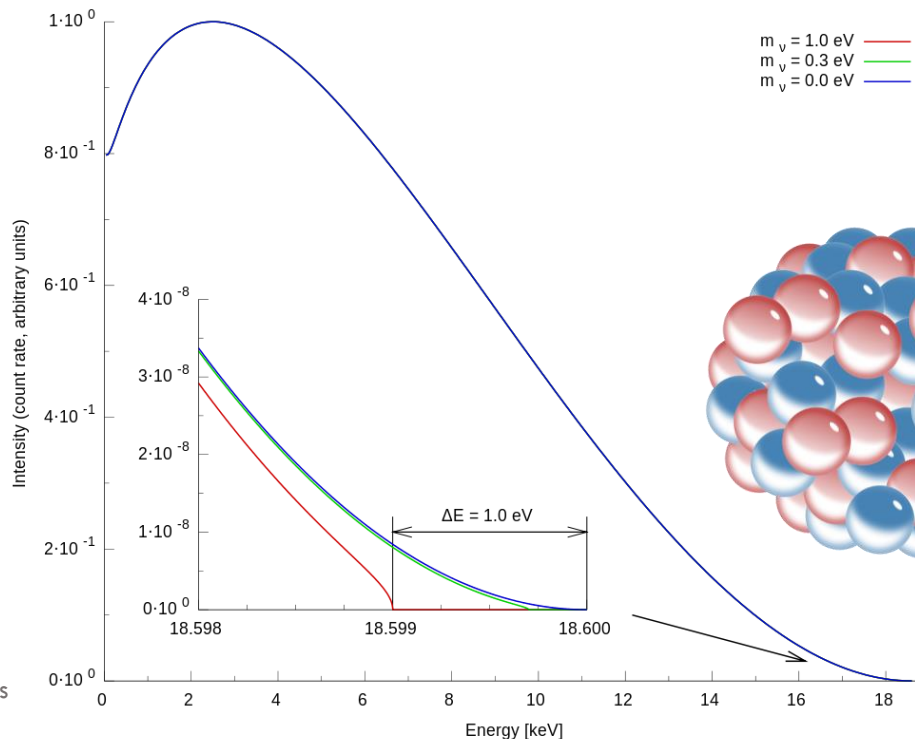
# WHAT'S SPECIAL ABOUT NEUTRINO MASS?

- It seems to be ridiculously small, compared to the rest of the mass spectrum...
  - We would like to imagine that particle masses are generated through some dynamic mechanism, and we wouldn't like to have to fine-tune it.
- Neutrinos are the only fundamental neutral fermions we know.
  - This means they could be their own anti-particle.
  - In a nutshell: if we want neutrino masses to be just like the other fermions (Yukawa couplings arising from coupling to Higgs field) then we need to postulate **right-handed** neutrino fields (**and left-handed** anti-neutrino fields) that **do not interact**.
  - It might be that there these fields do not exist and that the only difference between what we call a neutrino and what we call an anti-neutrino is its helicity.
    - These are called Majorana neutrinos, and lead to non-conservation of lepton number.
    - Also might help explain the smallness of neutrino masses, through see-saw mechanisms.



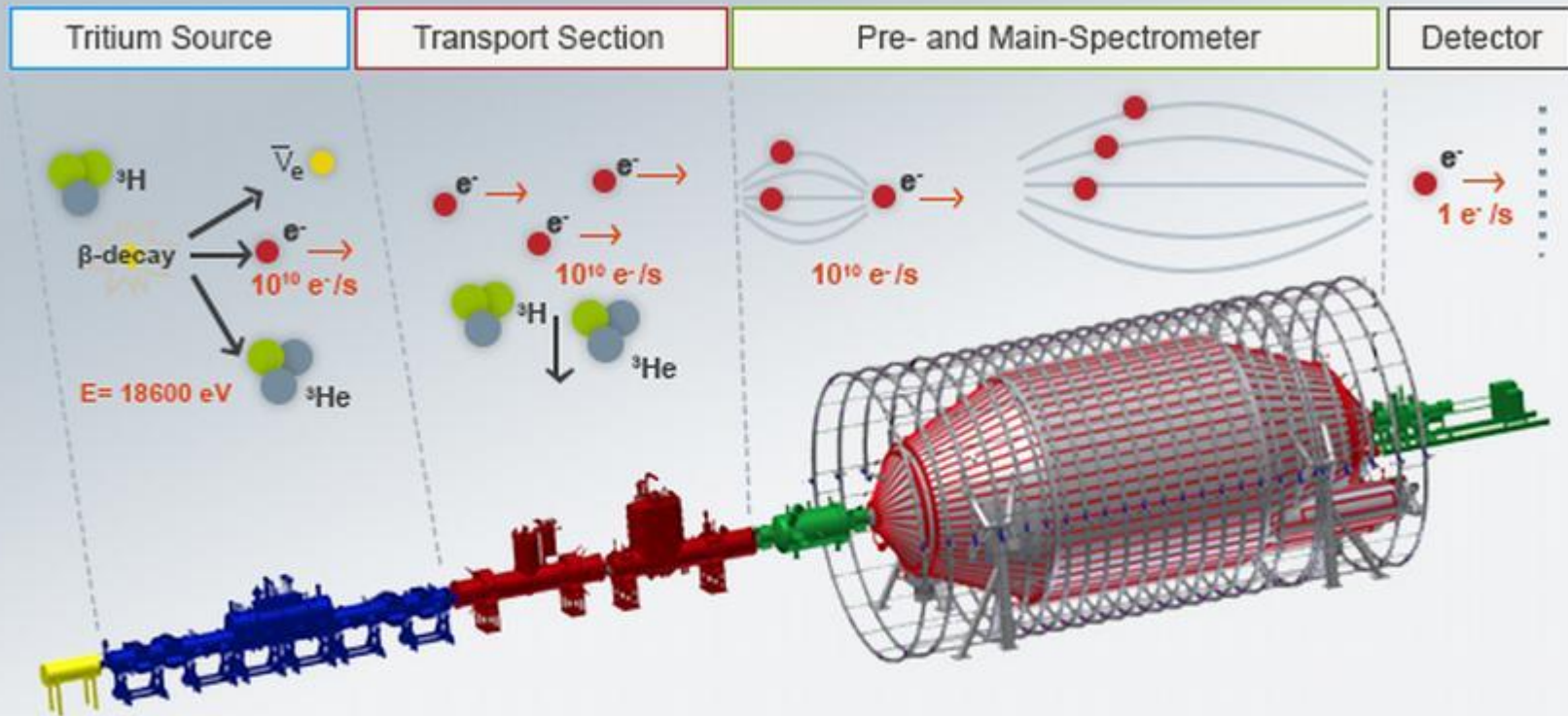
# DIRECT MASS MEASUREMENTS

- Neutrino oscillations give us only mass differences.
- If we are to understand the puzzle of neutrino mass, we need to measure the absolute mass scale of neutrinos.
- The most promising way to do this is to precisely measure the end-point of the beta-decay spectrum.
  - Conservation of energy requires that the maximum energy the electron can carry is the difference in mass between the initial and final state nucleus **minus** the neutrino mass.



# THE KATRIN EXPERIMENT

- An enormous spectrometer to look at the end point of the beta-decay of tritium.



Tritium decays, releasing an electron and an anti-electron-neutrino. While the neutrino escapes undetected, the electron starts its journey to the detector.

SHP Particle Physics

Electrons are guided towards the spectrometer by magnetic fields. Tritium has to be pumped out to provide tritium free spectrometers.

The electron energy is analyzed by applying an electrostatic retarding potential. Electrons are only transmitted if their kinetic energy is sufficiently high.

At the end of their journey, the electrons are counted at the detector. Their rate varies with the spectrometer potential and hence gives an integrated  $\beta$ -spectrum.

April 7, 2018

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# THE KATRIN EXPERIMENT

- An enormous spectrometer to look at the end point of the beta decay



Current upper bound: 2.2 eV  
 Katrin sensitivity: 0.2 eV  
 Cosmology bound:  $\sim 0.3$  eV

Tritium decays, releasing an electron and an anti-electron-neutrino. While the neutrino escapes undetected, the electron starts its journey to the detector.

SHP Particle Physics

Electrons pass through the spectrometer's magnetic fields. Tritium has to be pumped out to provide tritium free spectrometers.

electrostatic retarding potential. Electrons are only transmitted if their kinetic energy is sufficiently high.

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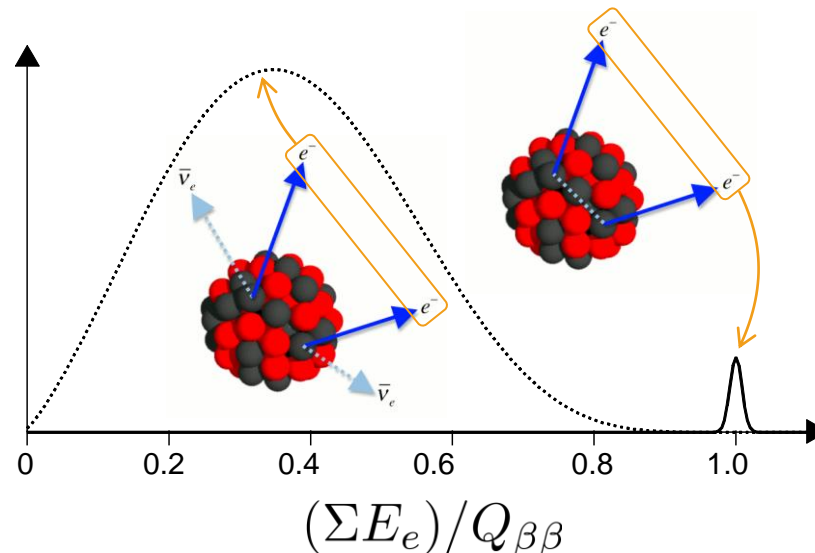
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# NEUTRINOLESS DOUBLE-BETA DECAY

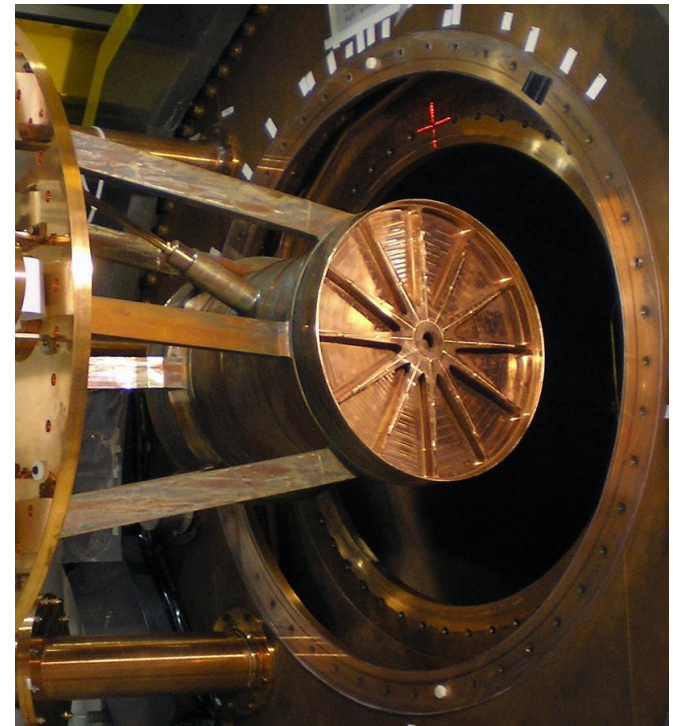
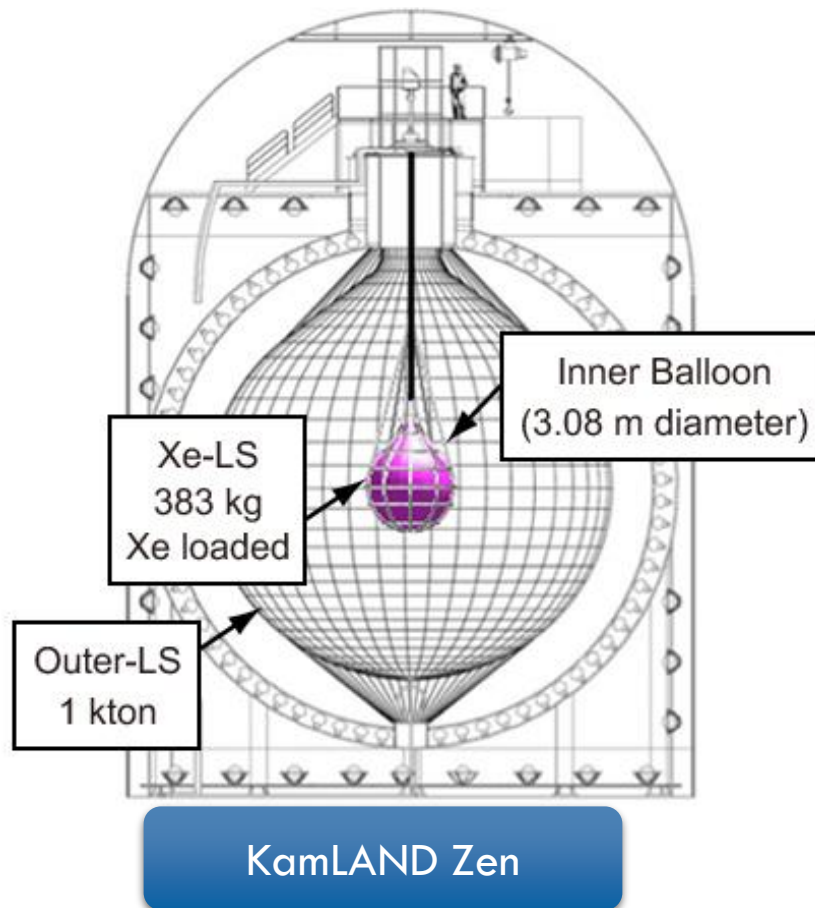
- Double-beta decay is a rare process where two beta decays occur simultaneously in a nucleus where a single beta decay is energetically forbidden.
  - Typical half-lives are on the order of  $10^{20}$  years!
- If neutrinos are Majorana particles (and hence their own antiparticles) the two neutrinos usually emitted in such a process might annihilate each other: neutrinoless double-beta decay!
- Observing such a process would imply that neutrinos are Majorana particles, and it would also give the absolute mass scale of neutrinos, as the rate for the process depends on it.





# NEUTRINOLESS DOUBLE-BETA DECAY

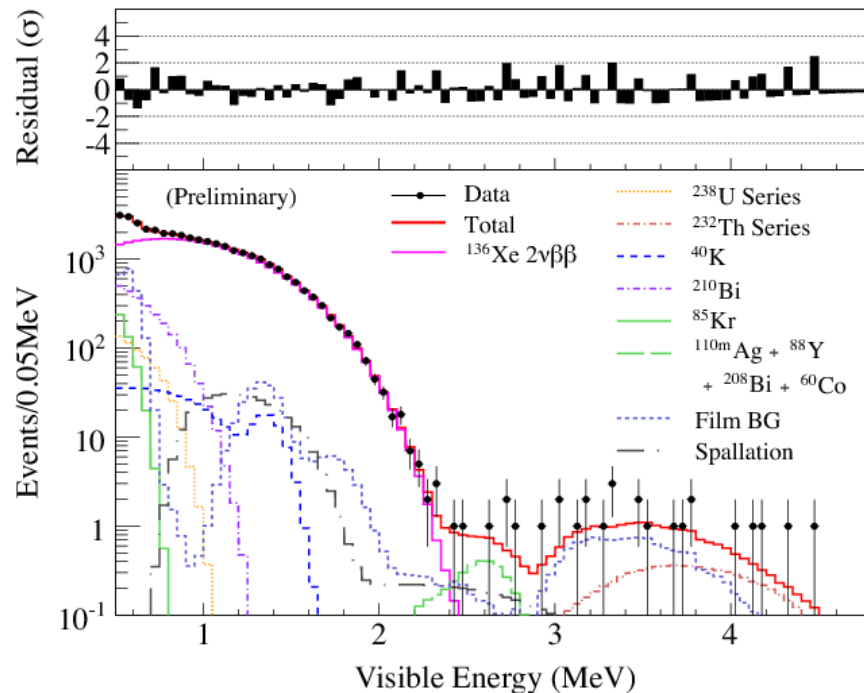
- Current best limits on the existence of this process come from two experiments that use xenon-136 as their source.



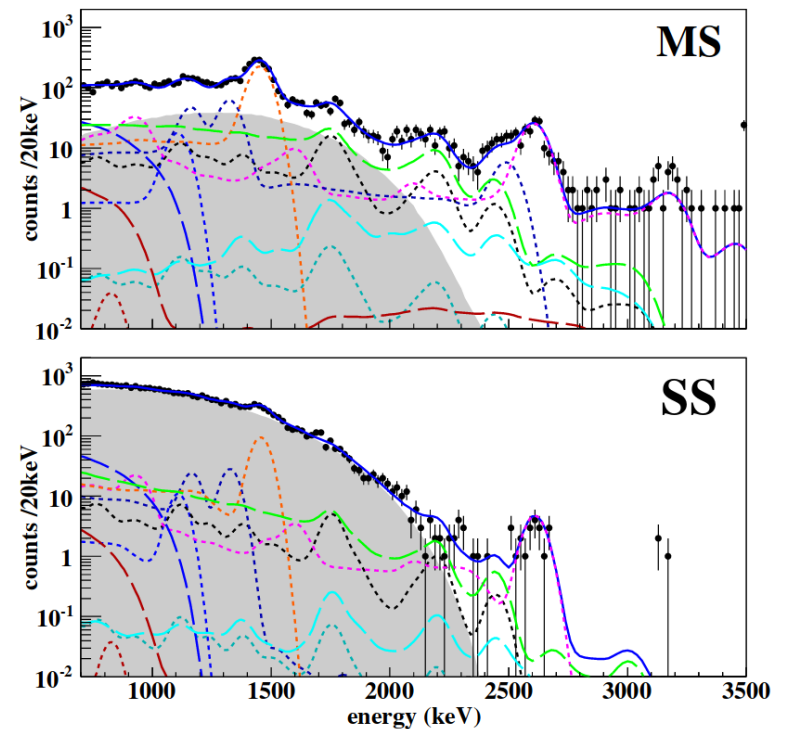


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KamLAND Zen



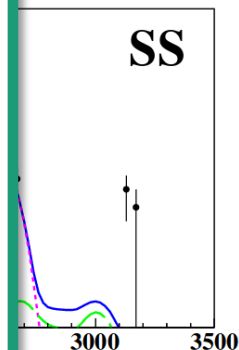
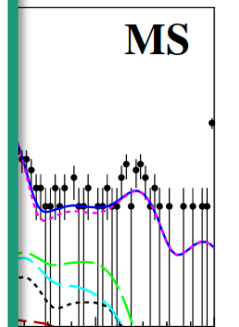
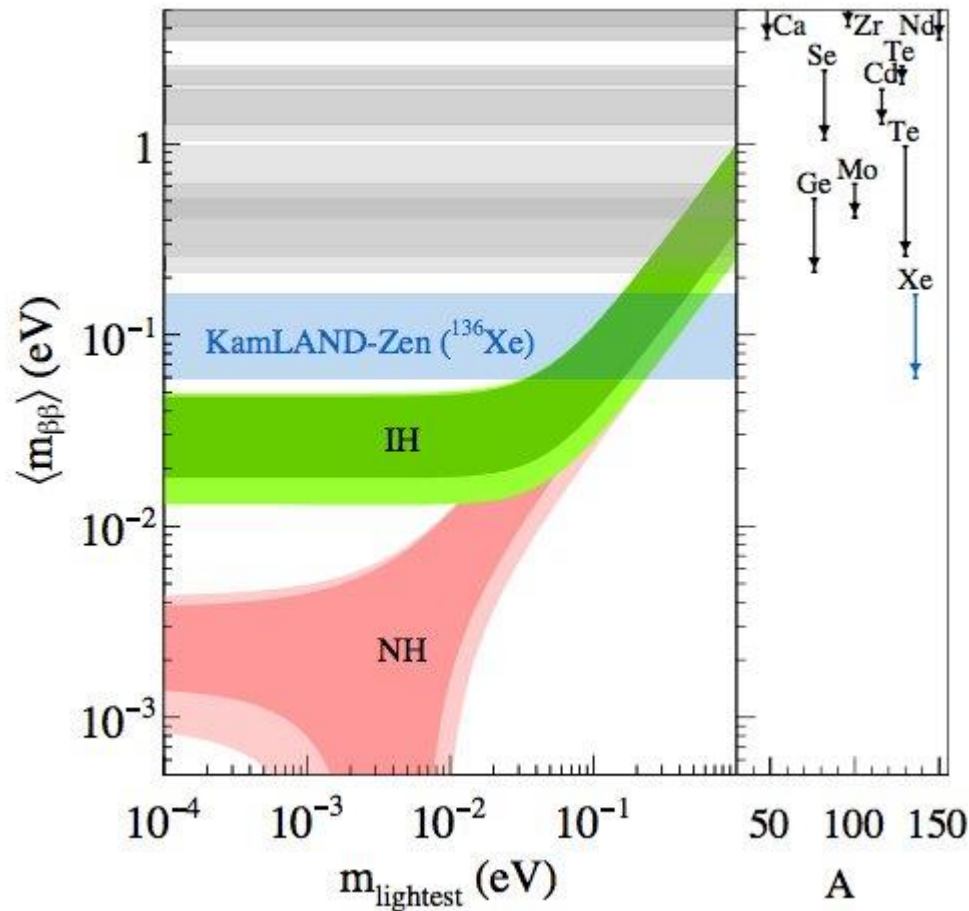
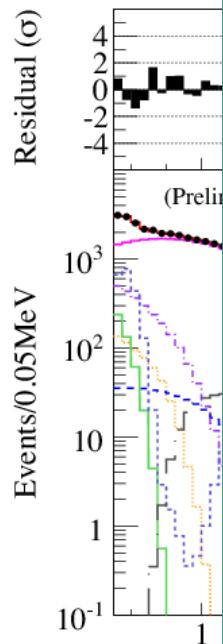
EXO

# NEUTRINOLESS DOUBLE-BETA DECAY

- Cu
- two

How does it fit in?

e from



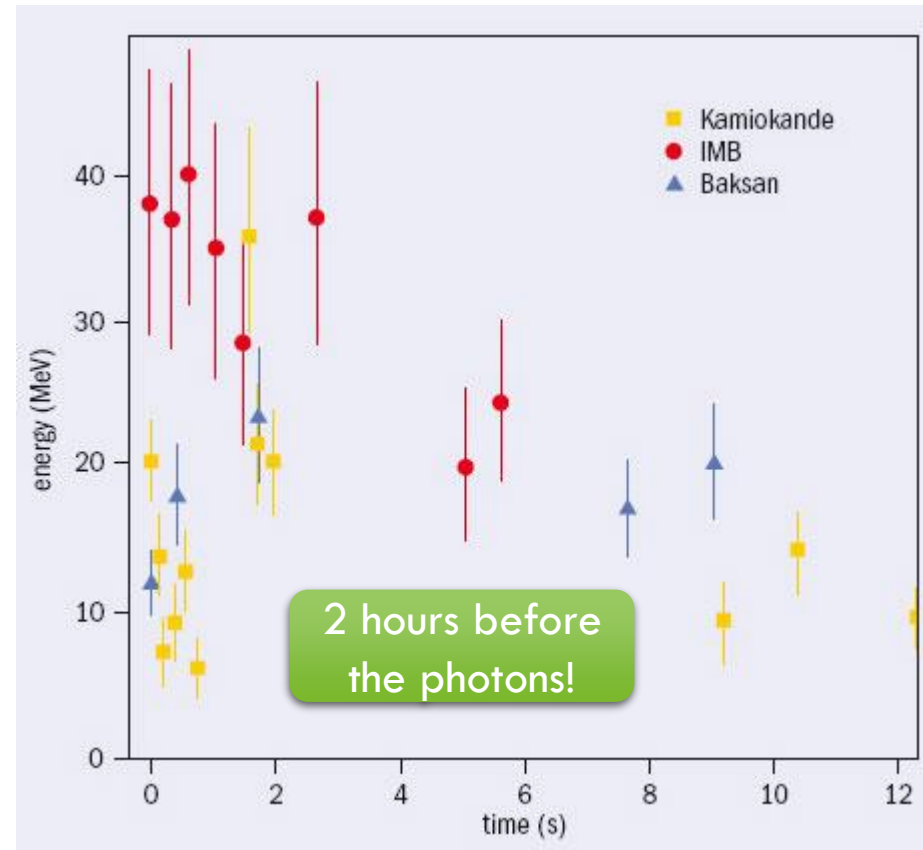
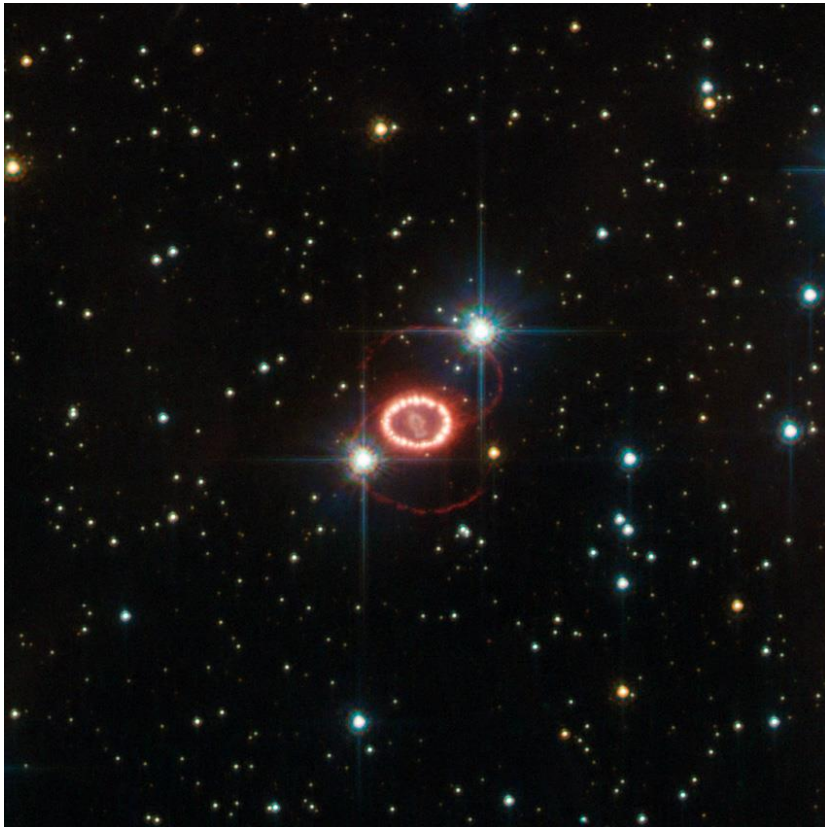
KamLAND Zen

EXO

# ASTROPHYSICAL NEUTRINOS

# SUPERNOVA 1987A

- Seen in photons (Hubble) on the left and neutrinos on the right.
- When another supernova occurs, many more (and larger) neutrino detectors will be listening!
- Supernova early warning system: SNEWS <https://snews.bnl.gov/>



# SCHEDULE

1. ~~Introduction~~
  2. ~~History of Particle Physics~~
  3. ~~Special Relativity~~
  4. ~~Quantum Mechanics~~
  5. ~~Experimental Methods~~
  6. ~~The Standard Model - Overview~~
  7. ~~The Standard Model - Limitations~~
  8. ~~Neutrinos I~~ } Cris José
  9. **Neutrinos II** } José Cris
  10. LHC and Experiments
  11. The Higgs Boson and Beyond
  12. Particle Cosmology } Cris
- } Inês



