# Introduction to Neutrino Physics

Karl Warburton ( Iowa State University )

9th June 2022

# Who am I?

- From Stoke-on-Trent in the UK.
- Went to the University of Sheffield for my undergraduate and PhD degrees.
  - Worked on simulations of cosmic rays.
  - Worked on reconstruction in neutrino experiments that use Liquid Argon Time Projection Chambers.
  - Was based at Fermilab for 2 years during my PhD.
- Currently at Iowa State University, I've been there for 5 years, but I'm based here at Fermilab.
  - Currently working on Supernova triggering in DUNE.
  - Currently leading the neutrino oscillation analysis in NOvA. I also work on a joint analysis with T2K (an experiment in Japan) and deep learning tasks.



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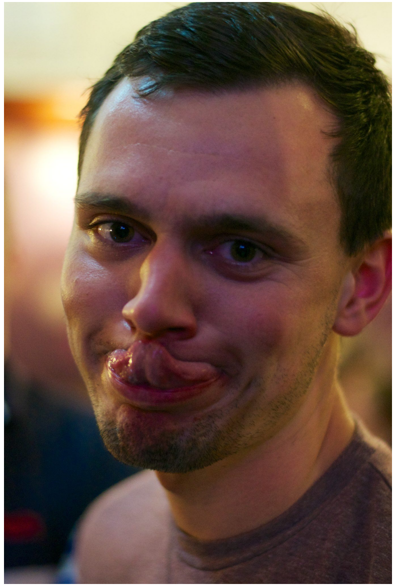
# Who am I really?

- Love sports.
  - *Real* football, cricket, rugby.
- Spent a year during undergrad in Australia.
  - Probably the best year of my life.
- I learned to scuba dive in New Zealand.
  - It’s incredible!
- Had my mind blown when I discovered deep dish pizza
  - Also known as pizza pies.





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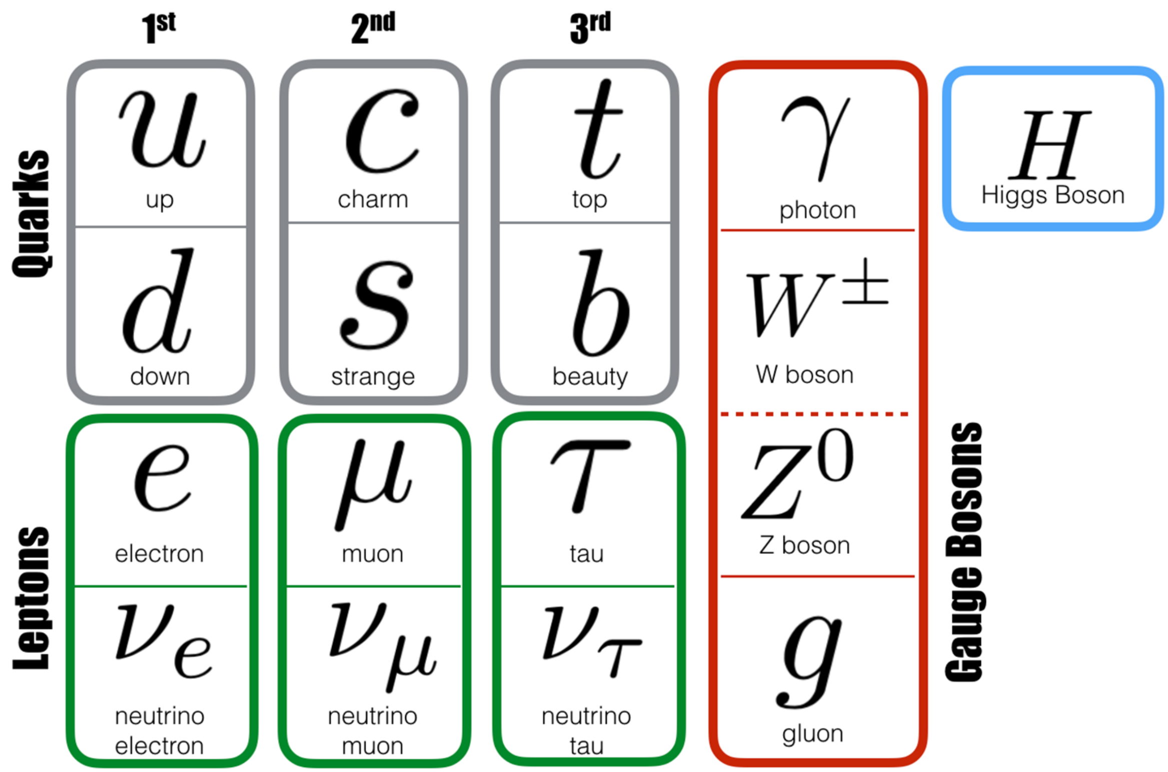
# Outline

- A quick review of The Standard Model, followed by an introduction to neutrinos
- A review of the history about how we first discovered neutrinos
- The physics of neutrinos
- How we study neutrinos now


Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

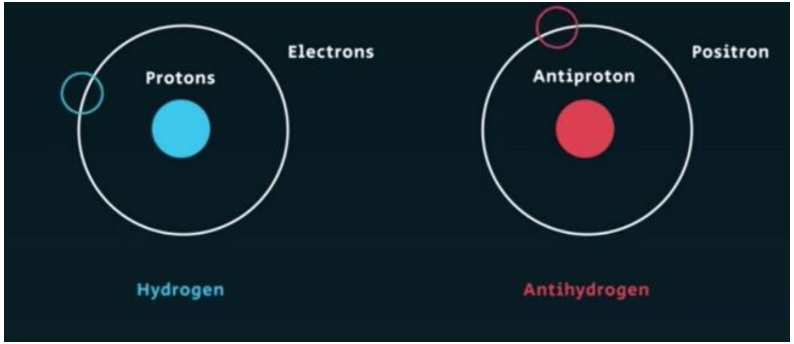
# The Standard Model of Particle Physics

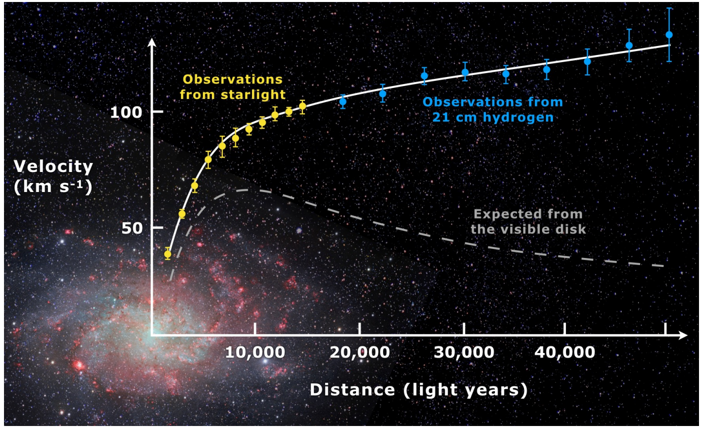



- The result of countless people's hard work.
- Aims to explain the Universe at its most fundamental level.
- The most successful theory that mankind has ever postulated.
  - But we know that it's wrong!

# What Does The Standard Model Not Explain?

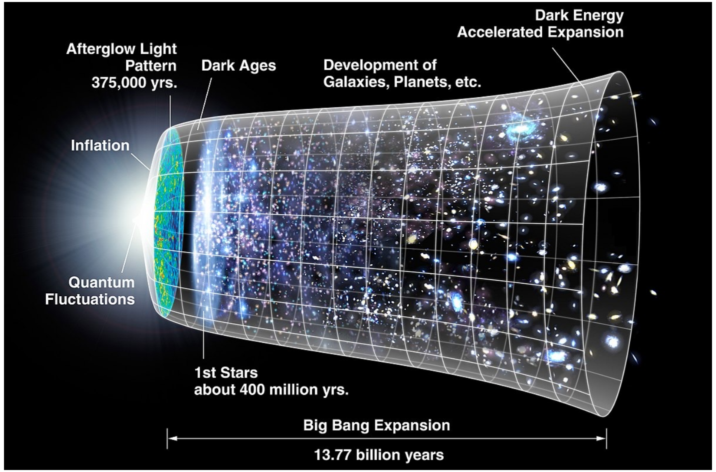
*Where is all of the anti-matter?*

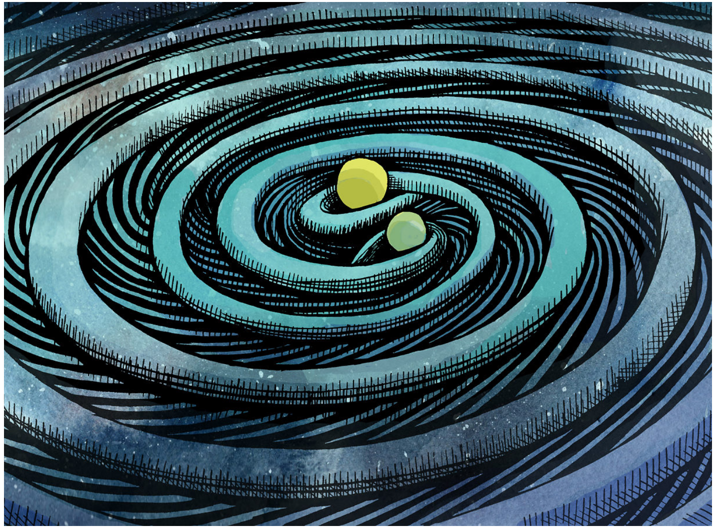



*What is dark matter?*

*What is dark energy?*



*How do we explain gravity?*



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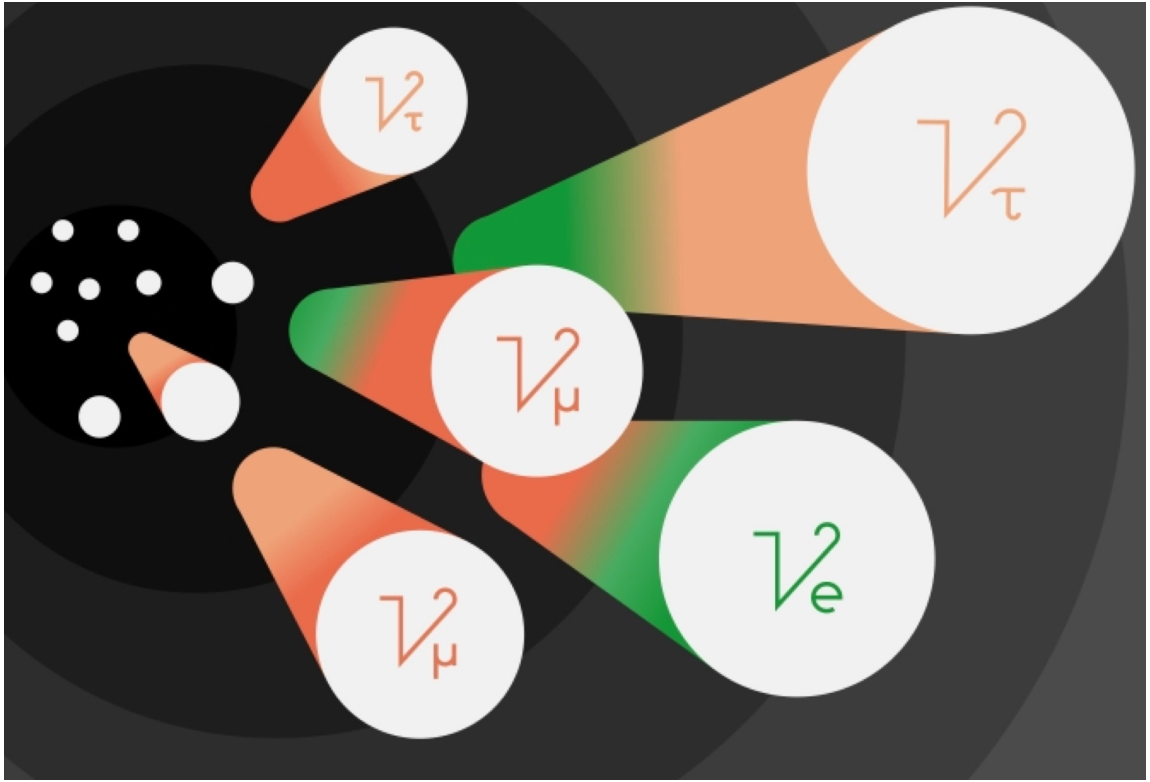
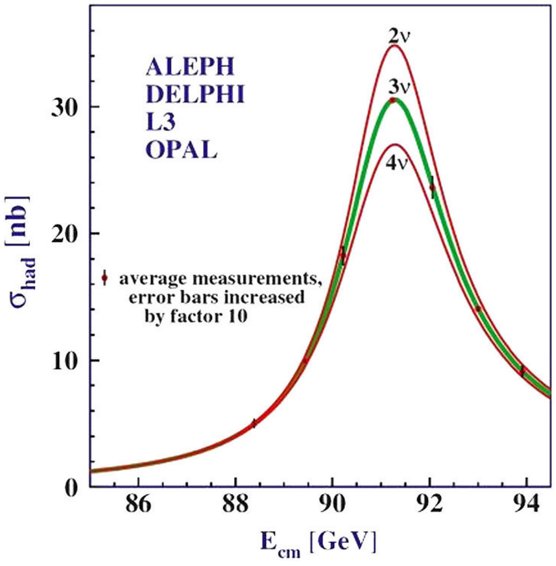
# Neutrinos: The Other Very Large, Yet Very Small Problem




- The most numerous particle in the Universe, yet the least understood.
- Many experiments around the World attempting to explain their properties.
- I am going to give some historical context, and then focus on neutrino oscillations, but first…

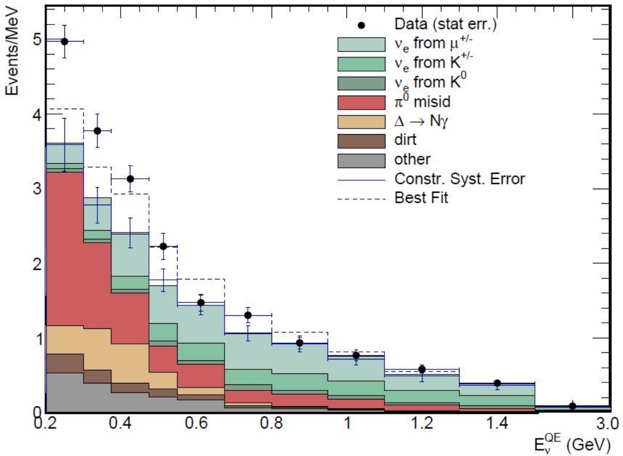
# How Many Neutrinos Are There & How Do They Acquire Mass?




Very accurate measurements have been made showing that there are exactly 3 "*active*" flavor states.

However, some experiments have made measurements which suggest additional "*sterile*" neutrino states to those described by the standard model.

How to accommodate these measurements is an open topic.



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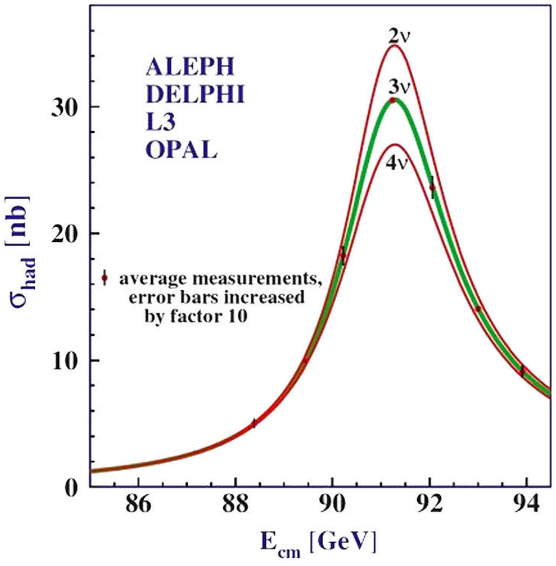


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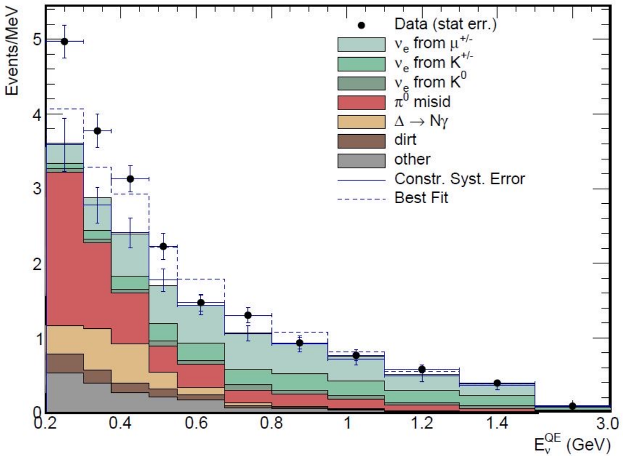


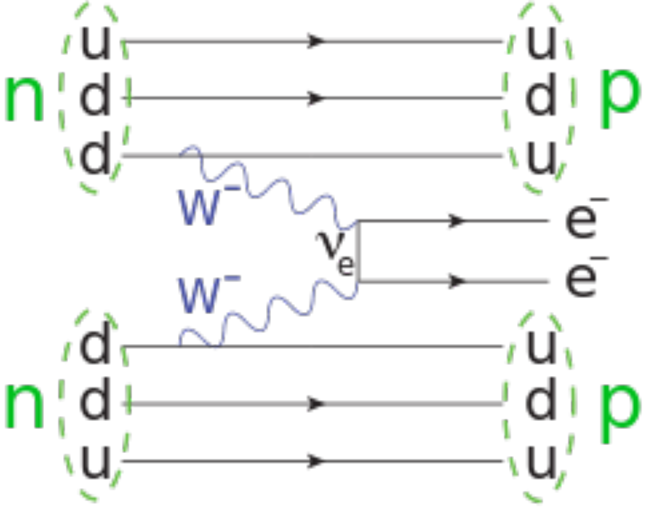


There also exists the possibility that neutrinos are their own particles, this would mean that they could acquire mass differently to all other particles (*Majorana mass*).



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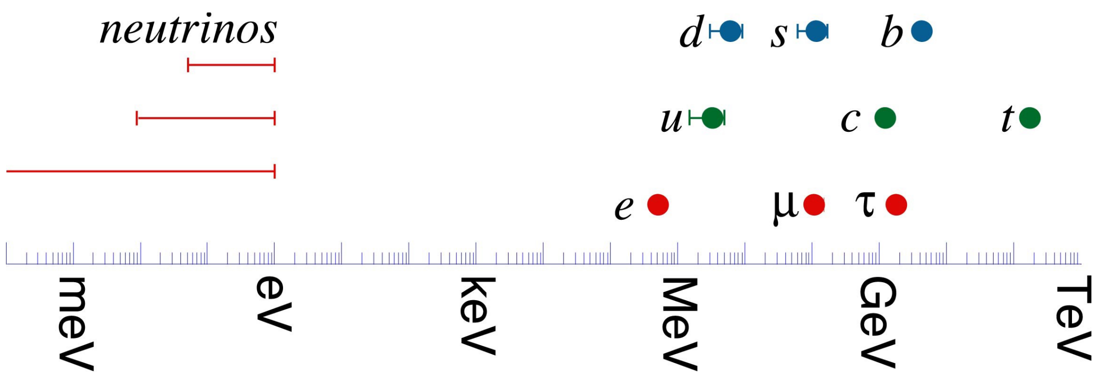
# What Is The Neutrino Mass Scale?




Neutrinos are much lighter than all of the other Standard Model particles, and we can't really explain why.

Measurements from cosmology and particle physics give us some upper estimates for their mass but their exact masses are unknown.



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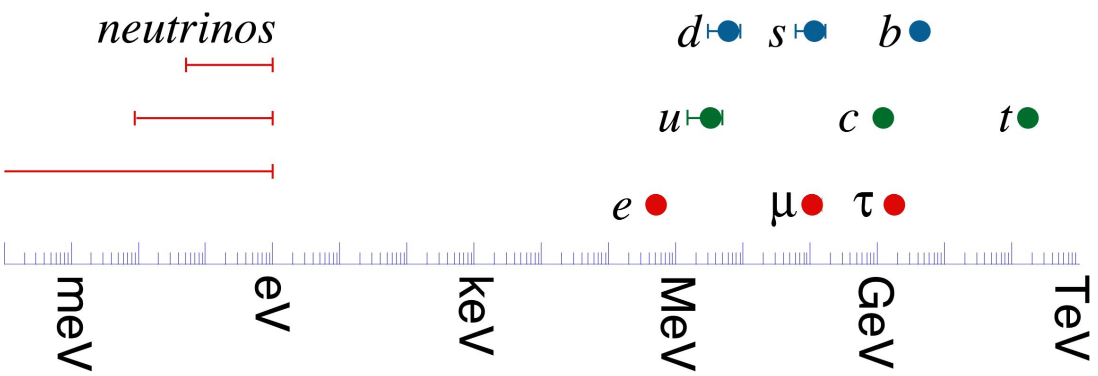


We know two neutrinos must have mass, but the third could be massless…

Need exceptionally accurate measurements to determine the mass scale of the neutrino (KATRIN)

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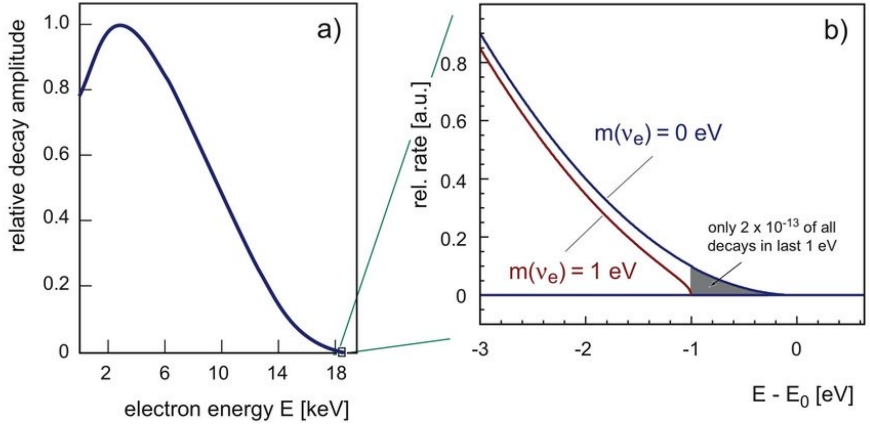




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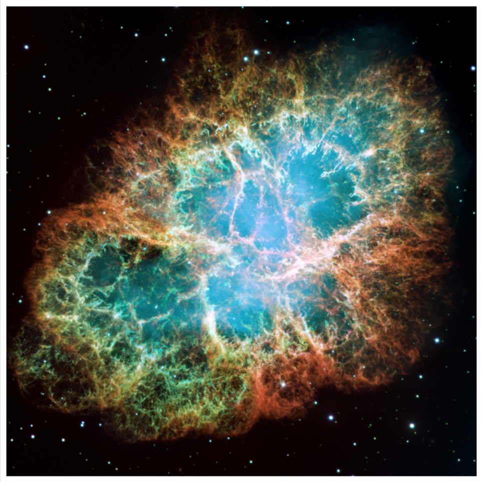
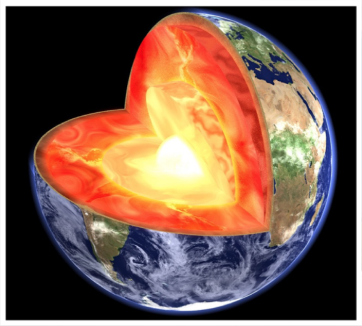
# What produces neutrinos? … Pretty much everything!

So many were produced in the Big Bang that the current density is still about 300 $cm^{-3}$.

99% of the energy from a Supernovae is neutrinos!





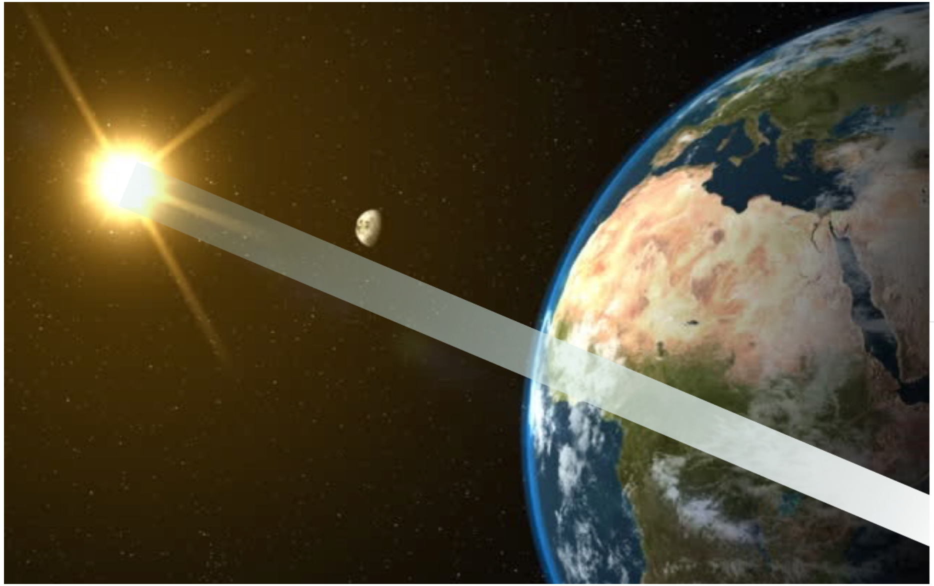
Any time there is a nuclear reaction;

- Inside the Earth's core.
- At nuclear power plants
- Even bananas! The decay of potassium produces about 1M neutrinos a day.

**Plus accelerators like we have at Fermilab!!!**

# How Often Do Neutrinos Interact? … Pretty much never!


- Most particles interact quite readily, but not neutrinos!
- A neutrino has only a 50% chance of interacting whilst travelling through 200+ Earths!
  - For reference, an electron is often stopped by a few inches of material.

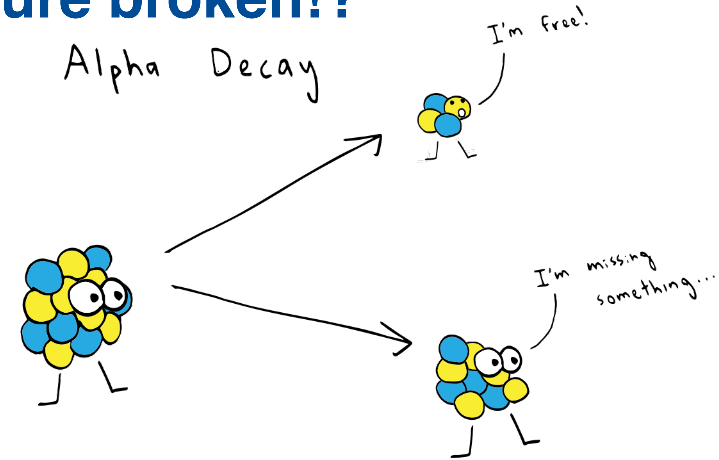


# A Bit Of History

# The discovery of neutrinos – Is nature broken!?

- Radioactivity is the process by which an unstable nucleus loses energy by emitting a particle.
  - The name of the decay reflects the emitted particle.

- Henri Becquerel, Marie Curie and Pierre Curie won the 1903 Nobel Prize for their work on radioactivity.



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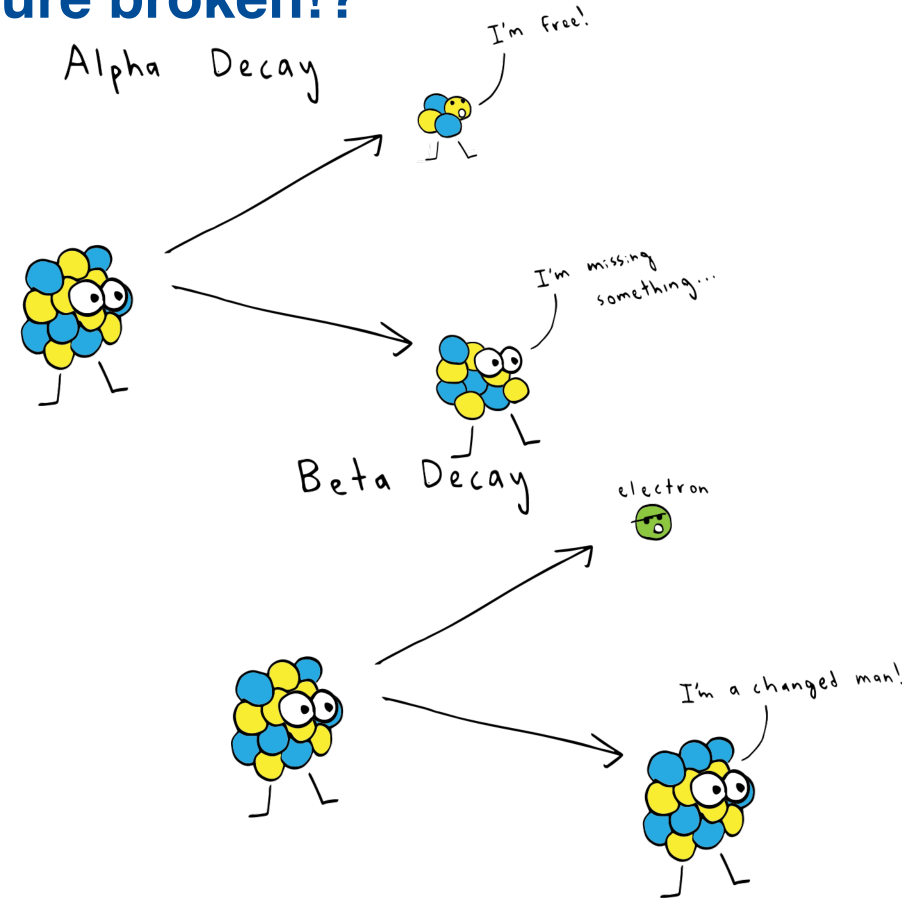



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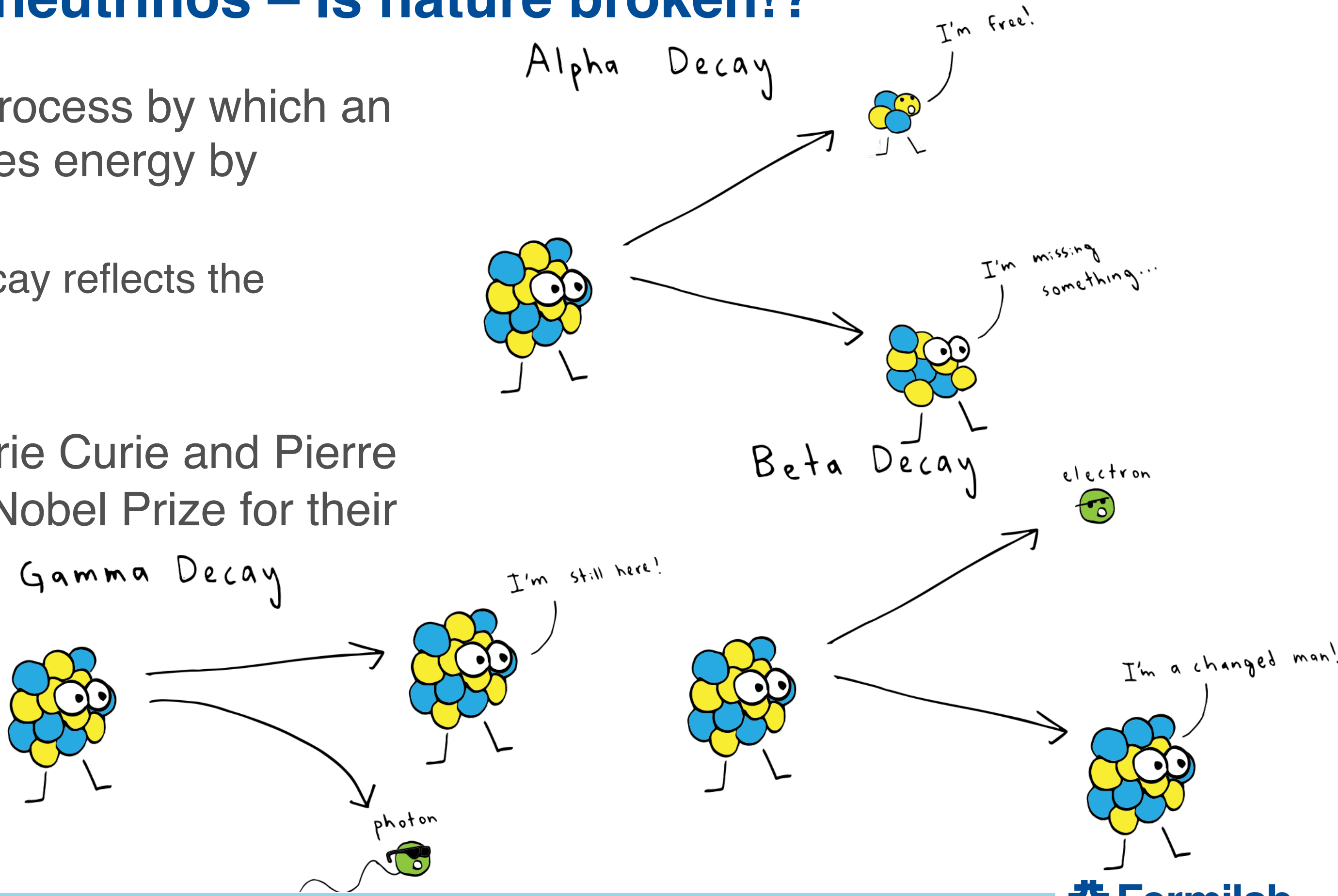




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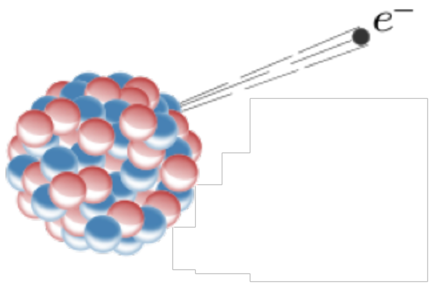
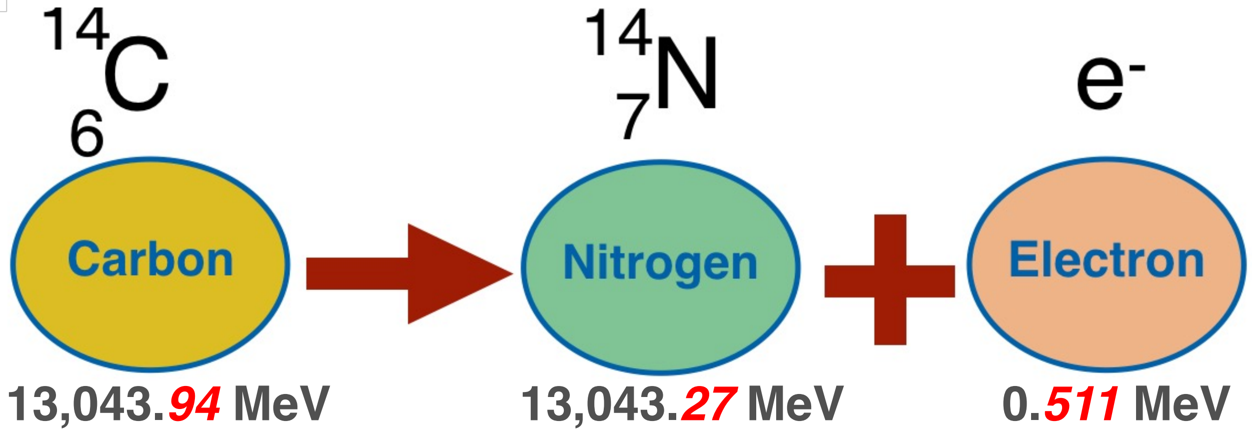
# What is beta decay?

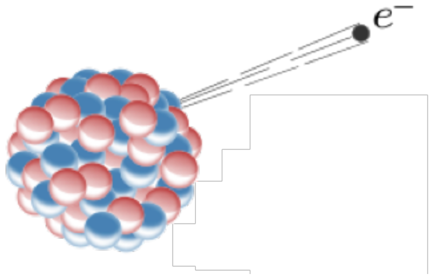



- Nitrogen-14 is more stable than Carbon-14 because it has the same number of protons and neutrons.
  - C-14, decays to N-14, and emits an electron in the process.

**For instance:**



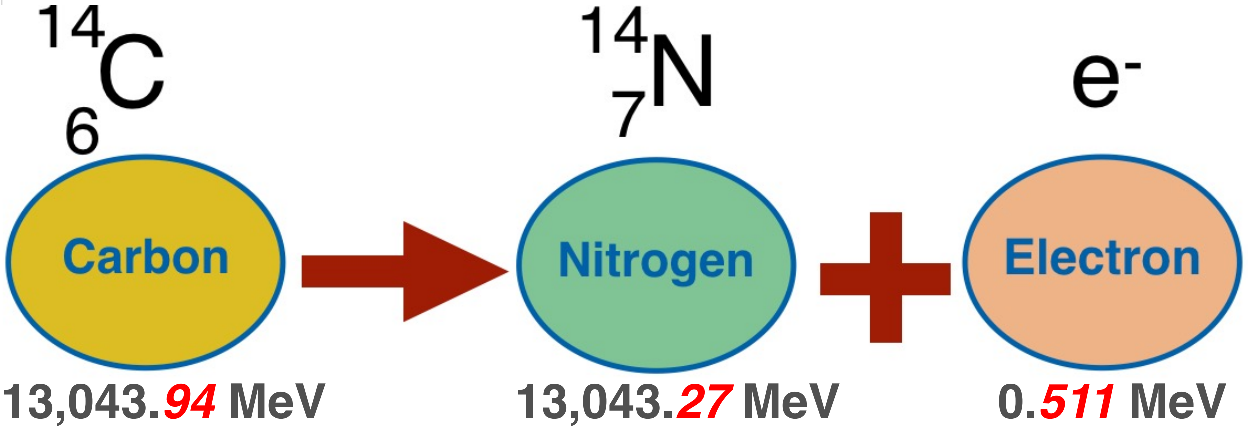
# What is beta decay?




- Nitrogen-14 is more stable than Carbon-14 because it has the same number of protons and neutrons.
  - C-14, decays to N-14, and emits an electron in the process.

- Due to energy conservation the electron is kicked out of the nucleus with roughly (94 - {27+51} =16) *0.159 MeV* of energy.

**For instance:**



## *Beta decay is a simple Two Body Problem:*

$$A \rightarrow B + C$$

## *Conservation of Momentum:*

$$p_A = p_B + p_C$$

## *Conservation of Energy:*

$$E_A = E_B + E_C$$

## *Yielding:*

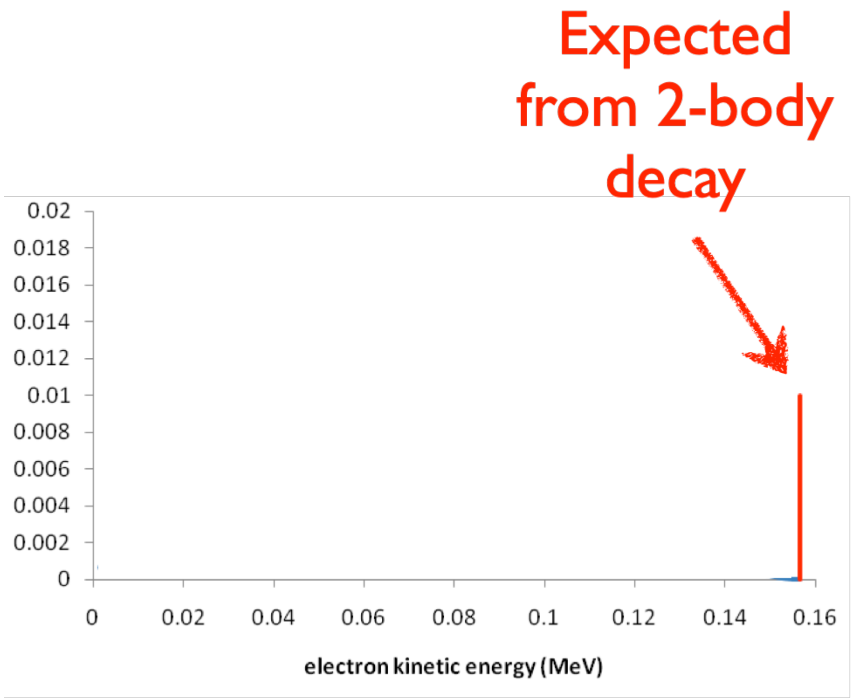
$${E_A}^2 = m_B c^2 + {p_B}^2 + m_C c^2 + {p_C}^2$$

*Have only two unknowns* $p_B, p_C$, *so can be easily solved, especially if we assume:*

$$p_A = 0, p_B = -p_C$$

## *Therefore:*

$$p_B = 0.5 \times \sqrt{{E_A}^2 - m_B c^2 - m_C c^2}$$



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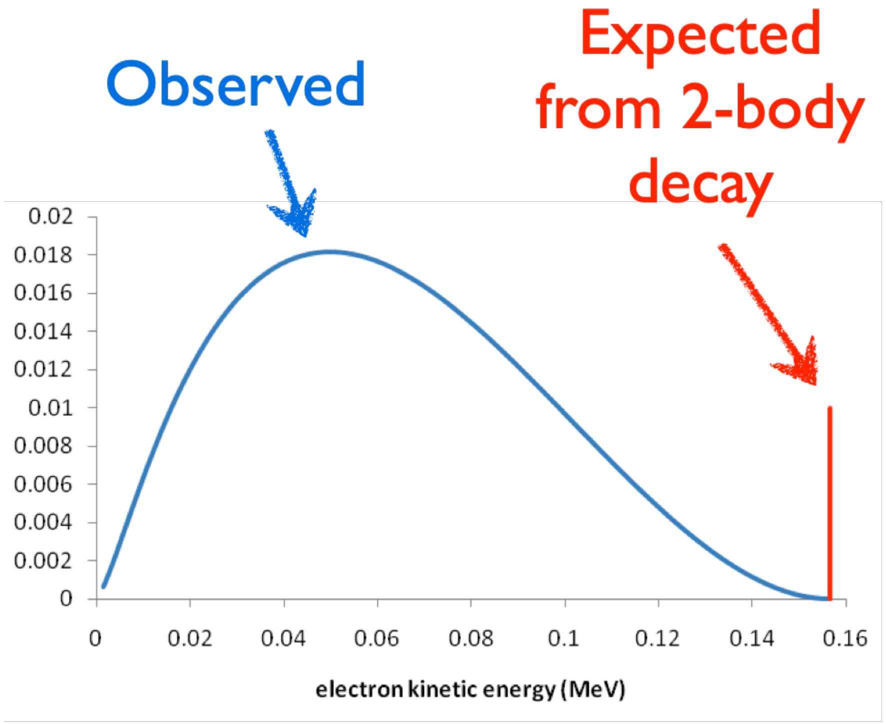
# What Was Actually Observed

- The energy of the electron emitted by beta decay isn't *159 keV* though…
- This means that something that something is wrong with our model.
- ***Is energy not conserved in beta decay!?***



# The "Little Neutral One"

(1930) Pauli postulated an additional particle (neutral and very small) in beta decays.

(1933) Fermi formulated the theory the weak force to explain the process.

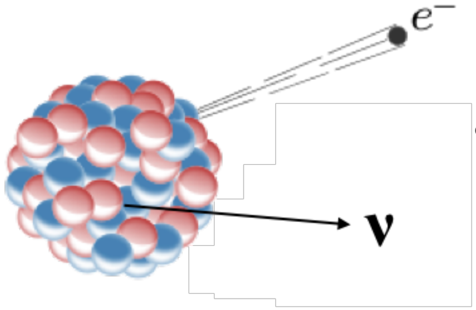
(1936) Yukawa proposed W boson as a carrier of the weak force.

*4th December 1930*
*Dear Radioactive Ladies and Gentlemen,*
*As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and $^6$Li nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call **neutrons**, which have spin and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass (and in any event not larger than 0.01 proton masses). The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...*
*From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge. Unfortunately I will not be able to appear in Tubingen personally, because I am indispensible here due to a ball which will take place in Zurich during the night from December 6 to 7...*

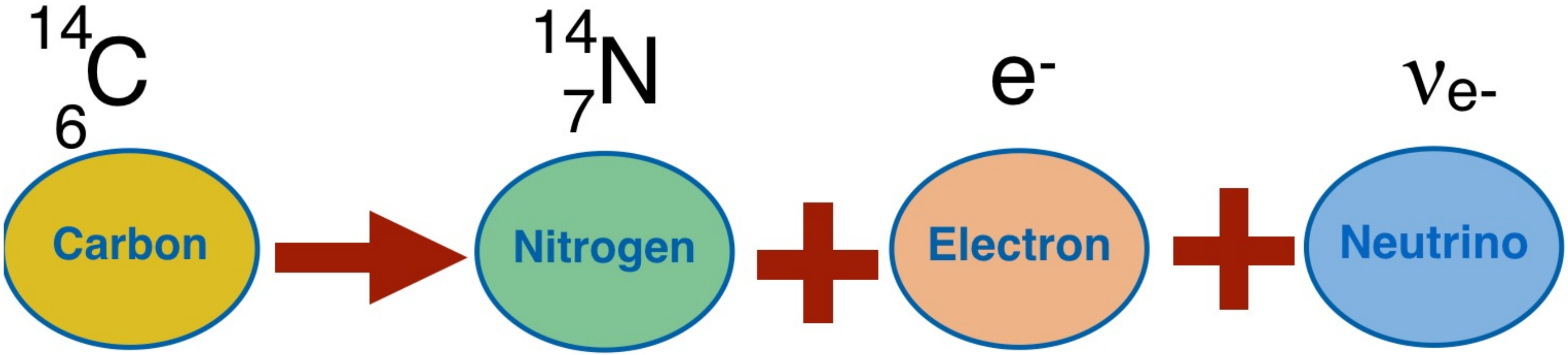
*Your humble servant,*
*W. Pauli*

*The neutron was discovered shortly after this letter, at which point Fermi proposed calling the above hypothesised particle the neutrino, or the "little neutral one."*

# What actually happens in beta decay then?



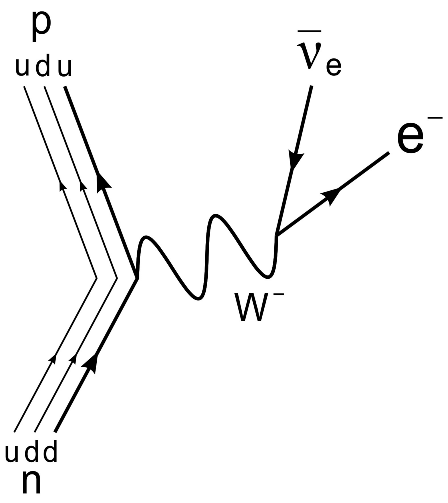

- A neutrino is emitted from the nucleus in addition to the electron.
- Energy is still conserved, but now the 0.159 MeV is split semi-randomly between the electron and neutrino.
  - Therefore we measure a continuum of electron energies.



# So how exactly do these “neutrino” things behave?

- Now that we have proposed a new particle, we need to figure out how it behaves!
- How do we produce them and in large enough numbers that we can find out something useful?

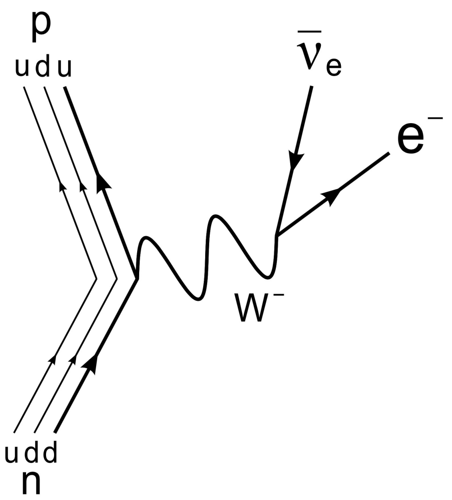
# How do we produce neutrinos?




*Neutrinos are produced by beta decay, but getting a large enough sample of radioactive material isn't easy.*

*These neutrinos are also quite low energy.*

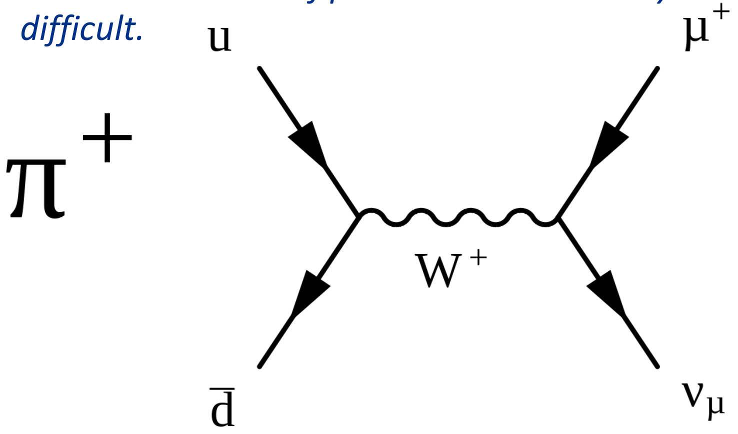
# How do we produce neutrinos?




*Pions are combinations of Up and Down quarks.*

*They decay very quickly (26 ns), and almost exclusively produce a muon (heavy electron) and a muon neutrino.*

*This is how we produce them now, but making an intense source of pions in 1940 was very difficult.*

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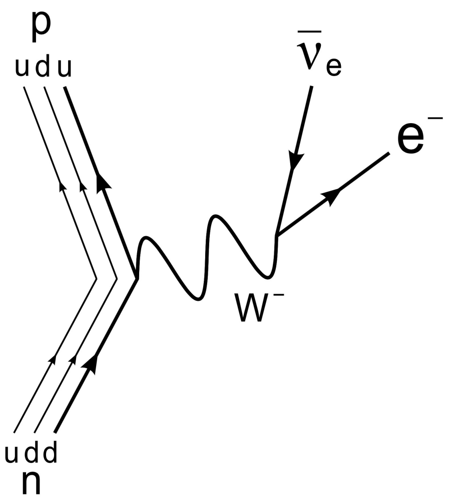


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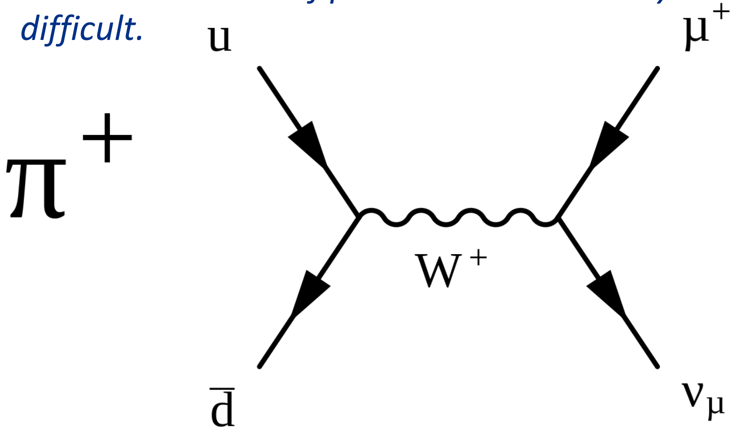


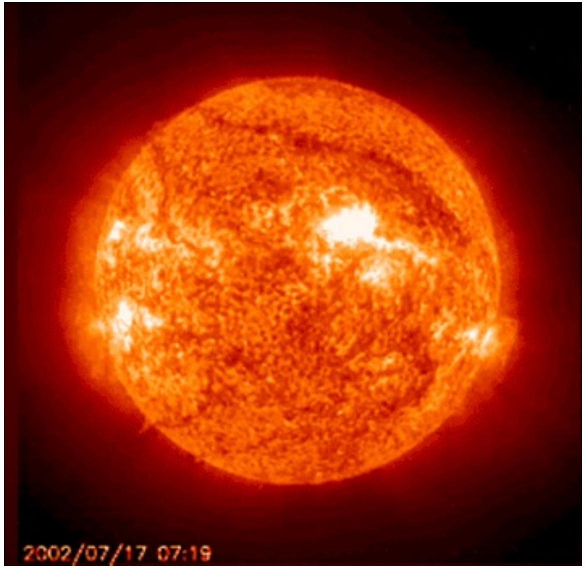


*Neutrinos are produced by the sun as it fuses Hydrogen to make Helium (fusion).*

*Man-made fusion reactors also make neutrinos as they split uranium into smaller elements.*

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# How do we produce neutrinos continued…

- In the 1950's Reines and Cowan set out to detect neutrinos at Los Alamos National Lab.
- If they could measure the neutrino, the Nobel Prize for Physics was assured.
- It had been theorised that the sun would emit neutrinos due to its fusion reactions.
  - What is the Sun but a huge nuclear reactor?

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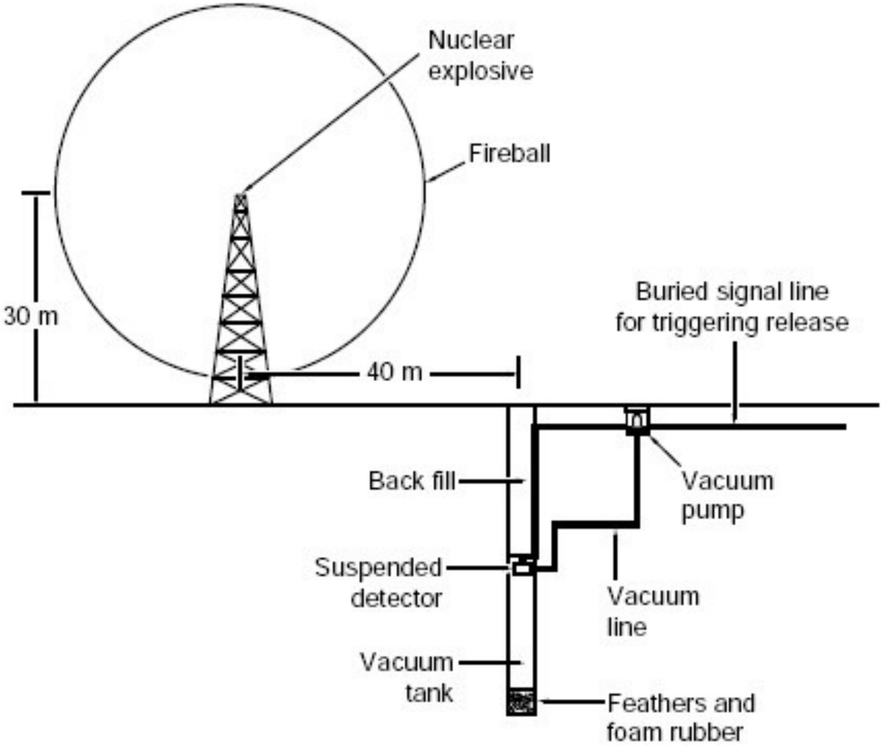
  - What is the Sun but a huge nuclear reactor?
  - ….
  - …
  - What is the Sun but a huge nuclear bomb…

# Project Poltergeist #1.




- Step 1. Explode nuclear bomb
- Step 2. Let the detector drop down the mine shaft at the same time.
- Step 3. Detect the neutrinos.
- Step 4:


*Quite frankly the best experiment ever, but not very reproducible…*



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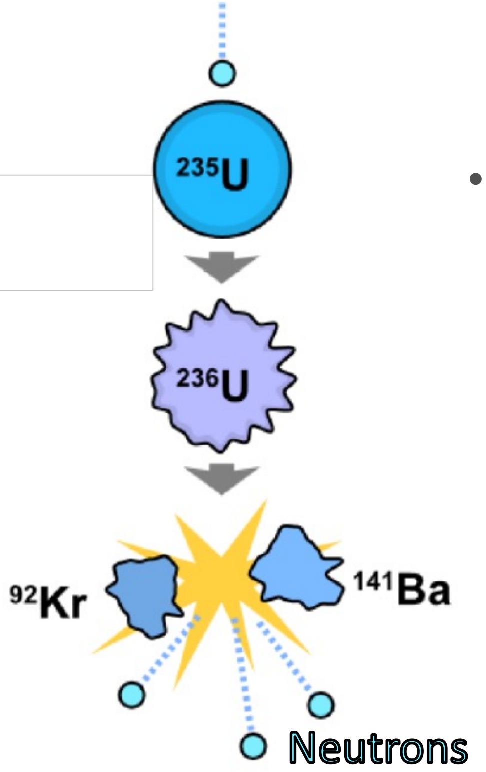
# Project Poltergeist #2.

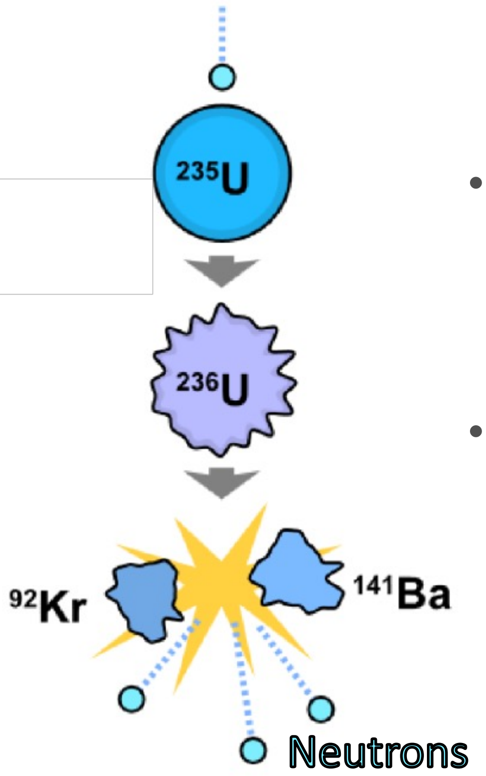



- It was noted that using the reactors at LANL might be more reproducible, sensible and simple (~~*read boring*~~).

- Neutrinos are produced when the neutrons produced by fission decay.

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

# Project Poltergeist #2.

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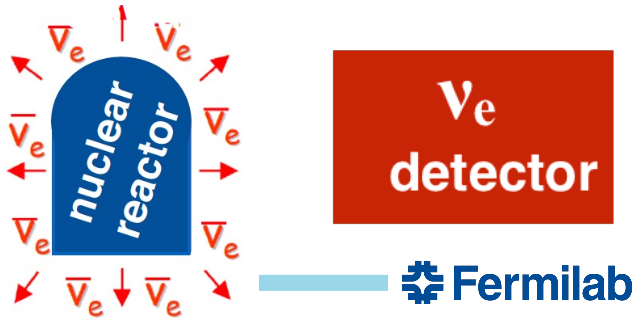
- A detector close to the reactor can measure emitted neutrinos.
  - An entire class of experiments currently work like this this.
  - Were crucial in measuring $\theta_{13}$.



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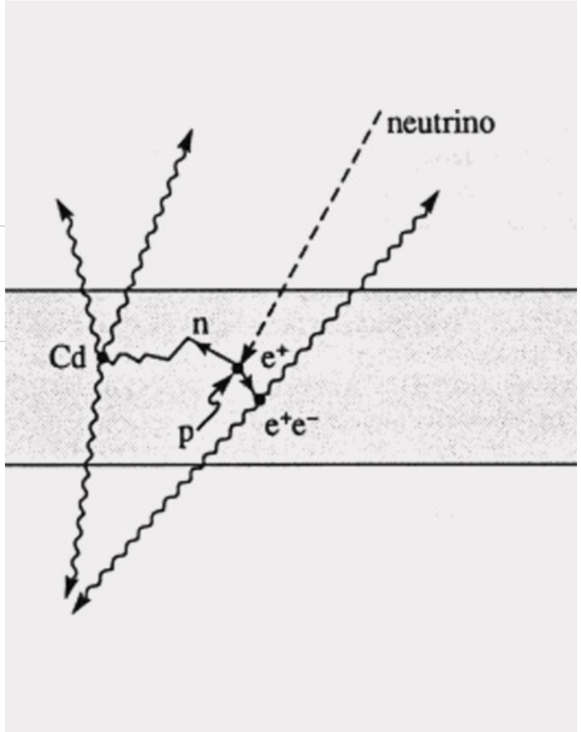



- In 1956 the neutrino was measured for the first time, by placing a Cadmium filled detector next to a reactor.
  - A rate of 0.56 neutrino interactions per hour was measured.

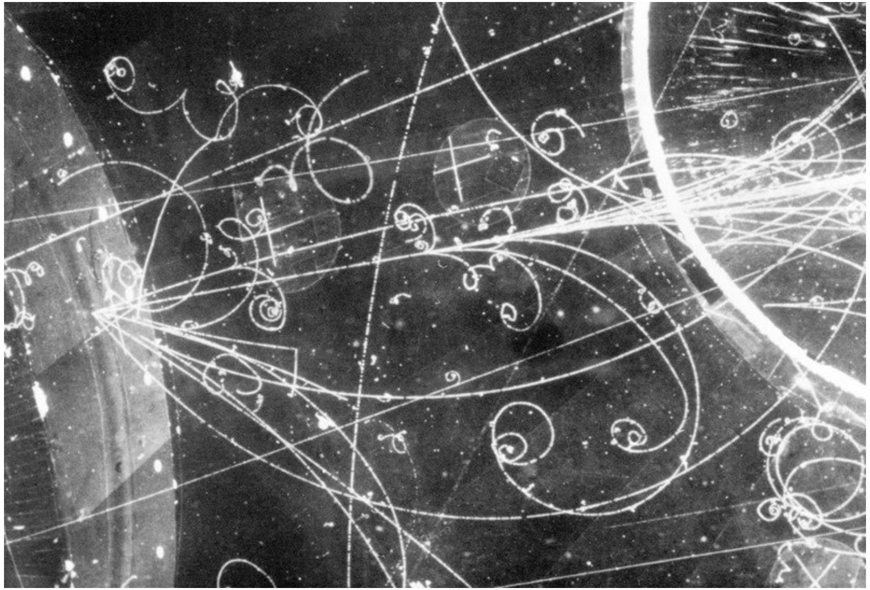
# A Short Note On Measuring Neutrinos

# How do we measure neutrinos?

- So now, we know they exist, but we want to study them better…

- Most particles interact quite readily.
  - On the left is a bubble chamber event from a high energy collision.
  - Can see tracks from many individual particles.
  - Can determine the charge and energy of particles by applying Electric/Magnetic fields.

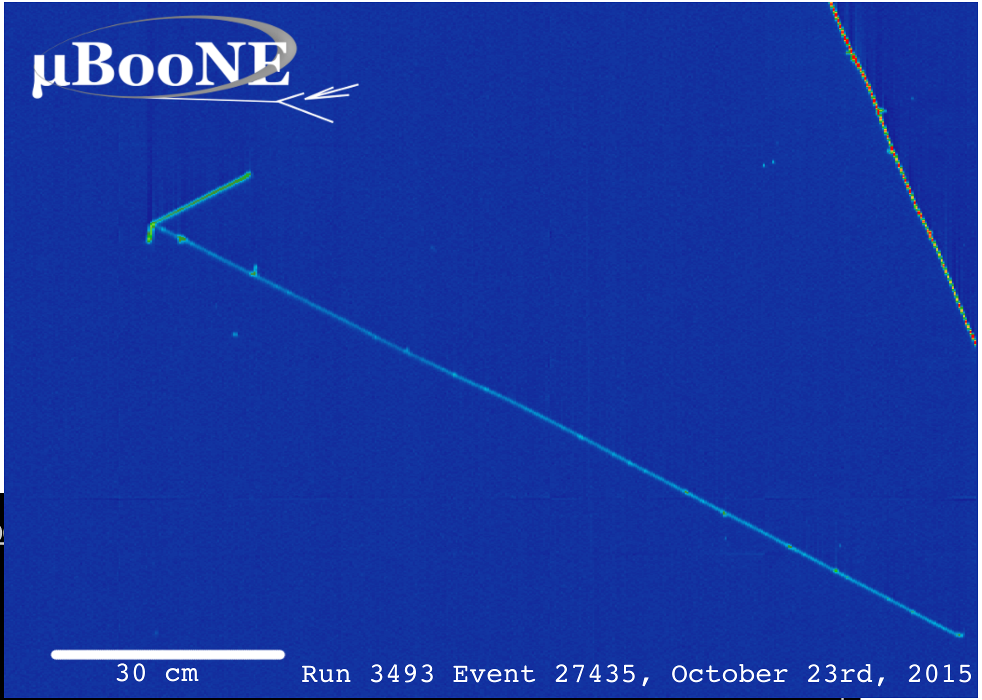
- This isn't possible for neutrinos though.
  - They're neutral, so don't produce tracks.
  - We can only detect interaction products.

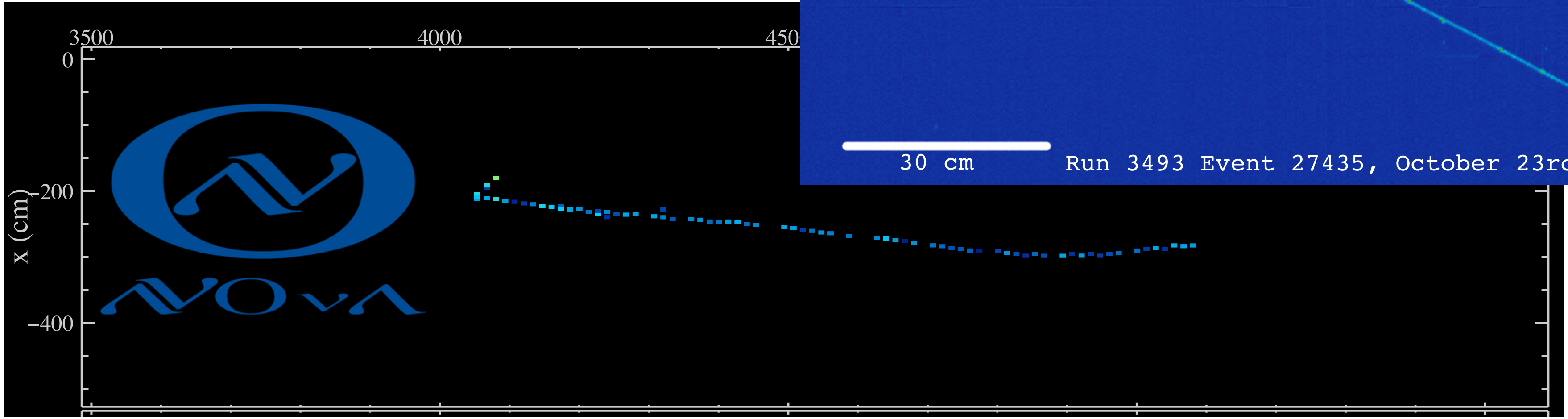


# Muon Neutrino Interactions

*If we see a long straight track the interaction is likely due to a muon neutrino.*

*The smaller tracks that we see near the interaction vertex are likely protons.*





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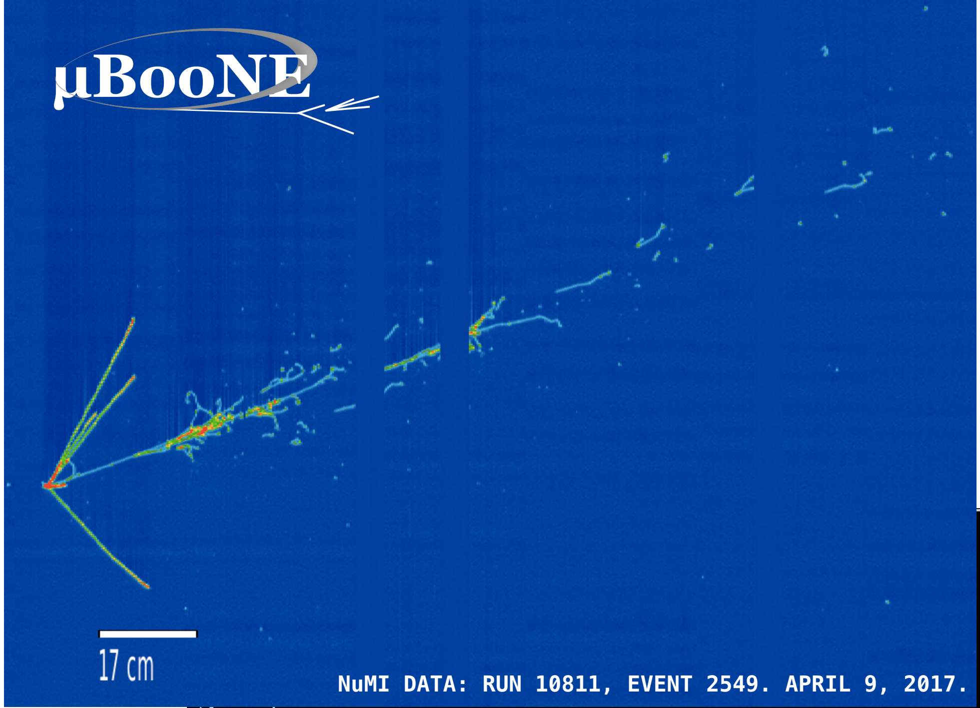
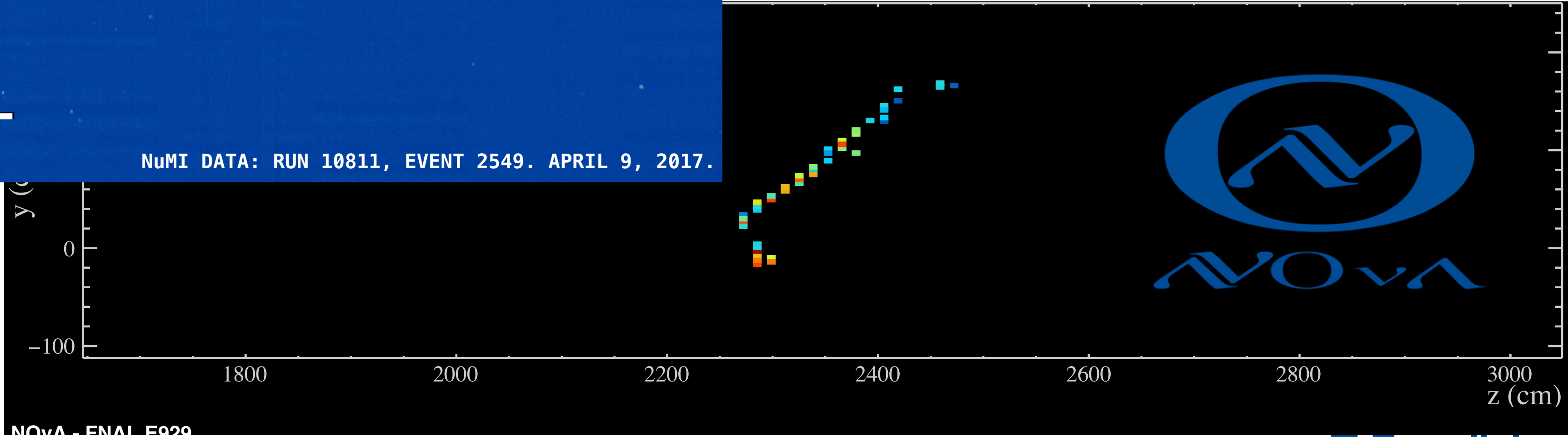
# Electron Neutrino Interactions

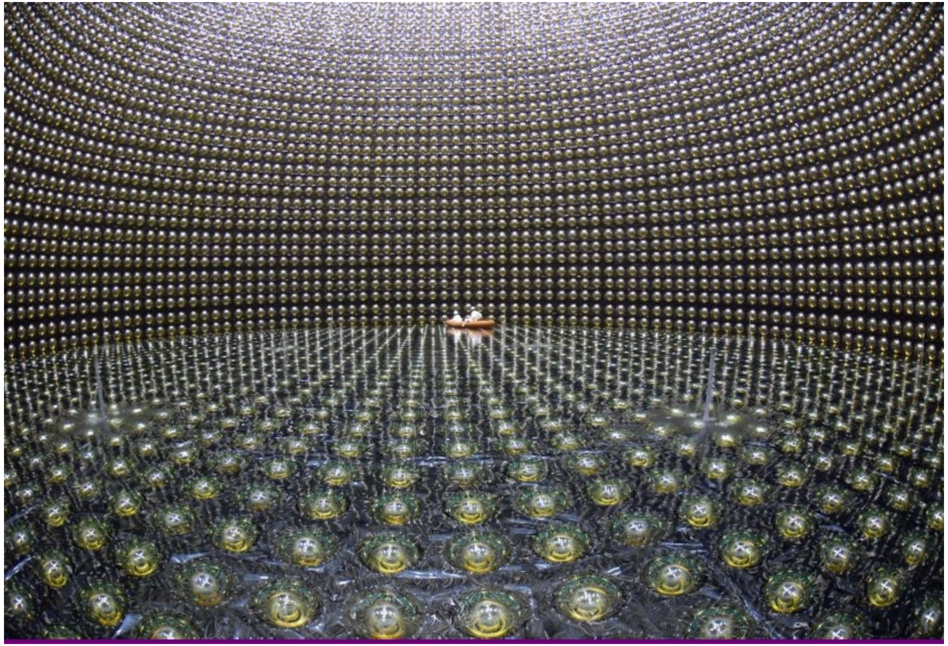
*If we see a shower that starts at the interaction vertex, then we likely have an electron neutrino interaction.*

*The smaller tracks that we see near the interaction vertex are again likely protons.*

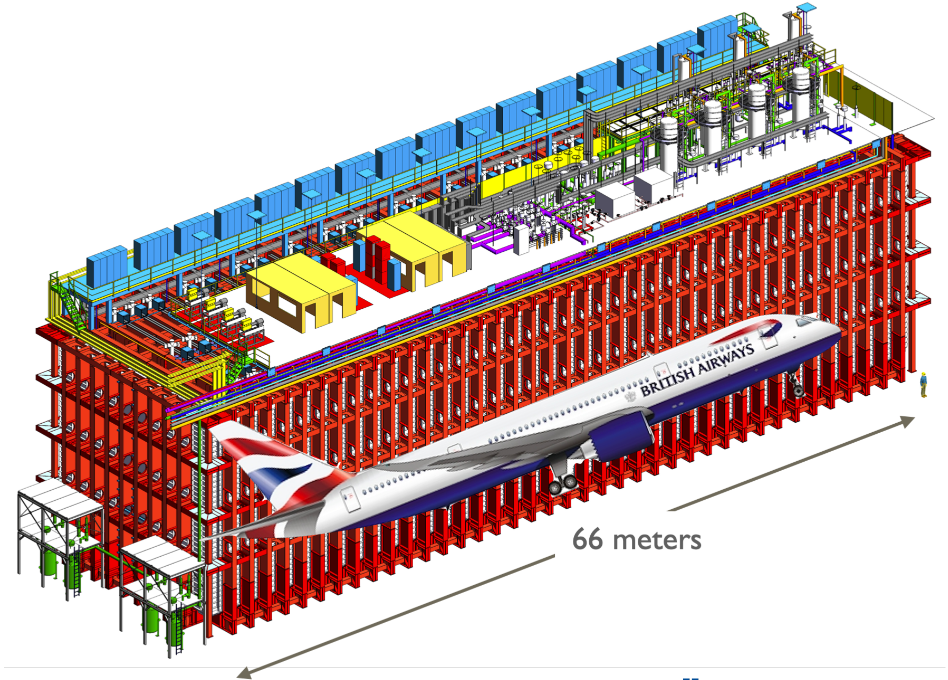


# Neutrino Detectors Also Have To Be Huge!



*DUNE, a future experiment in South Dakota will have four detectors, each as large as a Jumbo Jet Plane!*
*( More on this later )*



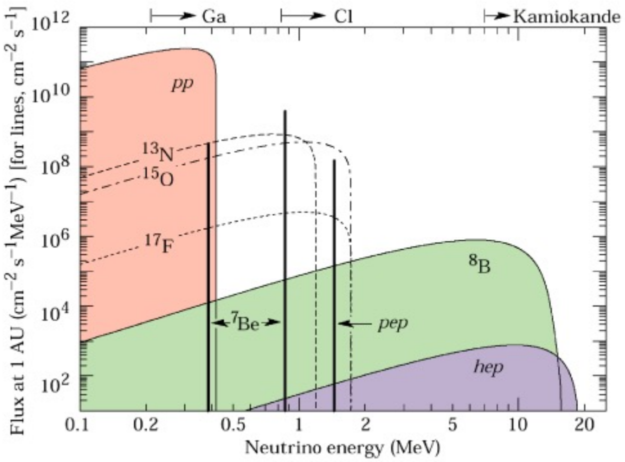

*Super-Kamiokande, an experiment in Japan is 50 ktons of ultrapure water, with 11k photo-multiplier tubes.*
*Hyper-Kamiokande, its successor will be 50 times larger!*

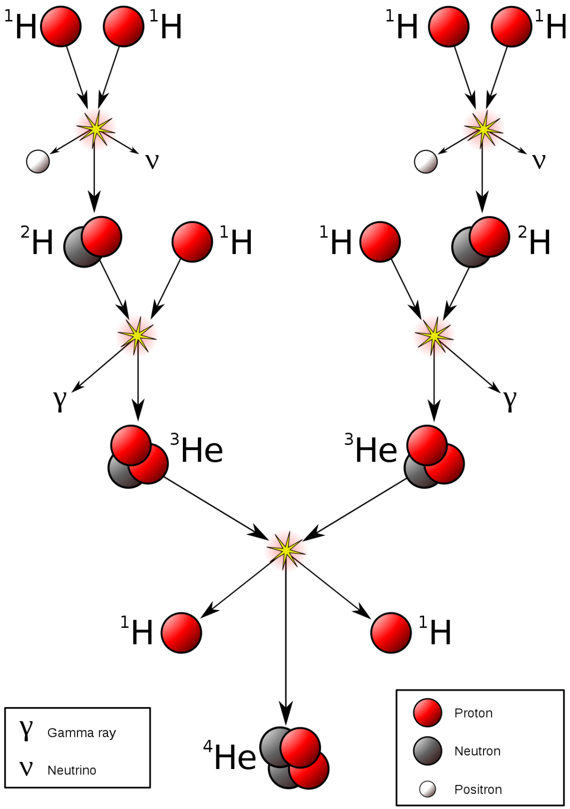
# Back To History

# Studying Solar Neutrinos - The Homestake experiment

- There are many complex reactions in the sun.
  - Neutrinos are produced at a range of energies.

- Studying the neutrinos produced can tell us important things about the Suns structure.





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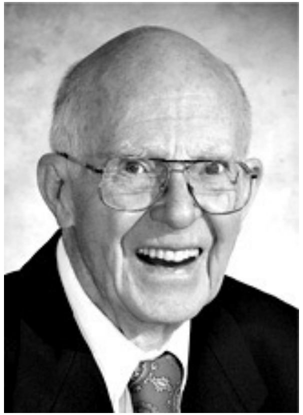
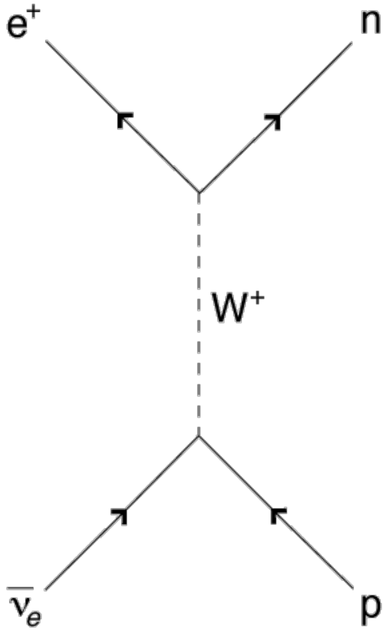
# Studying Solar Neutrinos - The Homestake experiment

- In 1961 Ray Davis proposed an experiment to measure the solar neutrino flux.
  - 615 tonnes of $C_2Cl_4$, 1 mile underground in an active gold mine.
    - More on this location later!
  - Measured inverse beta decay on the Chlorine atoms.
  - *It was therefore only sensitive to electron neutrinos*.







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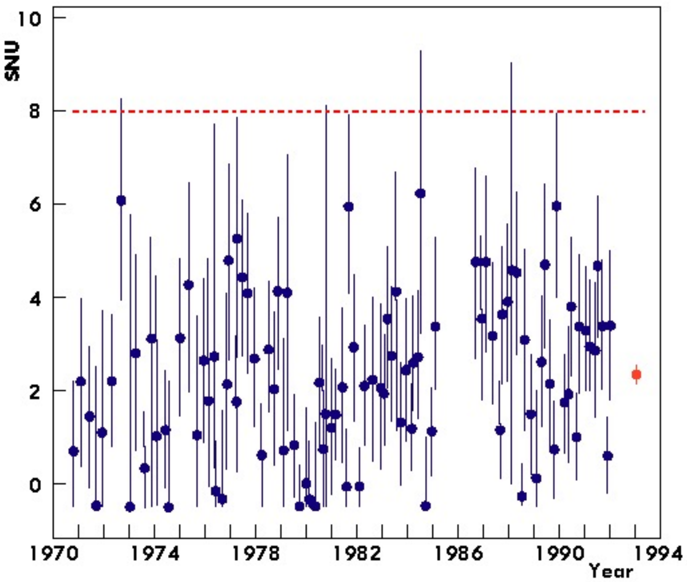
# The Homestake experiment

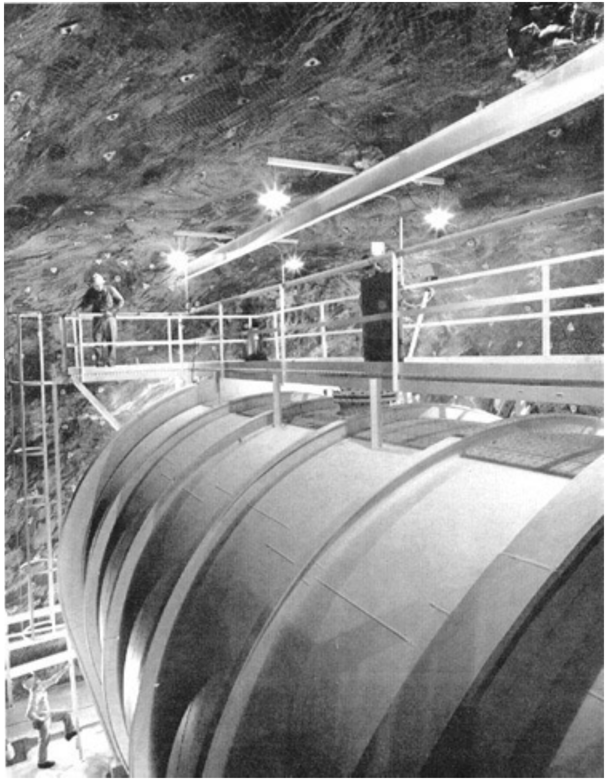
- Ran for 25 years, and consistently saw a rate roughly 1/3 of the expected solar flux.
  – They expected to see about 1 interaction per day, but they saw 1 interaction every 3 days.




*Blue points are the number of events measured per year.*

*The dashed red line is the expected solar flux.*

*The red point is the average taken over all 25 years.*

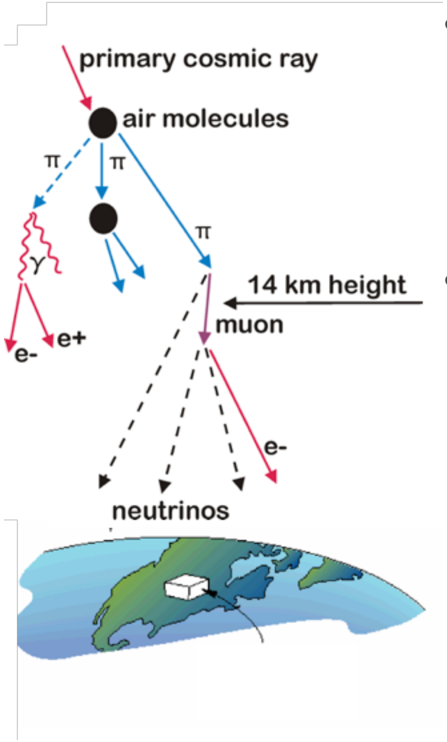


*A picture of a friend of mine standing in one of the segments of the Homestake Experiment which is now on the surface.*

*The Davis Cavern was recently dedicated as a "Historic Site" in recognition of its impact on research.*

*The plaque is mounted on a preserved piece of the experiment.*

# Atmospheric neutrinos




- Produced as high energy cosmic rays strike the upper atmosphere.
  - Produce particle showers (Right).

- As these showers develop and the particles decay, you end up with ~2 $\nu_\mu$ for every $\nu_e$.



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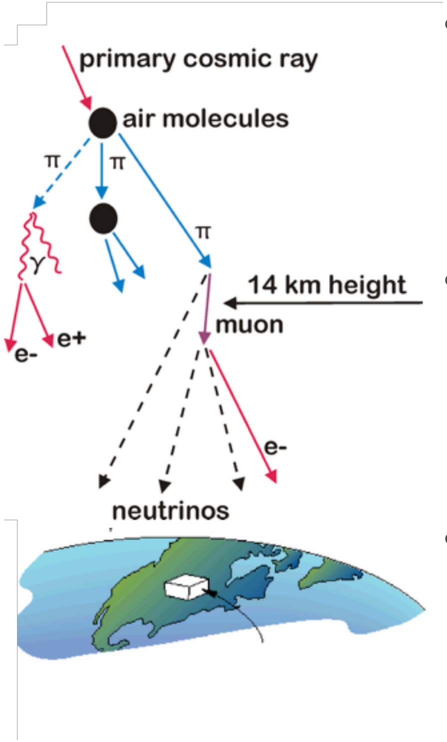
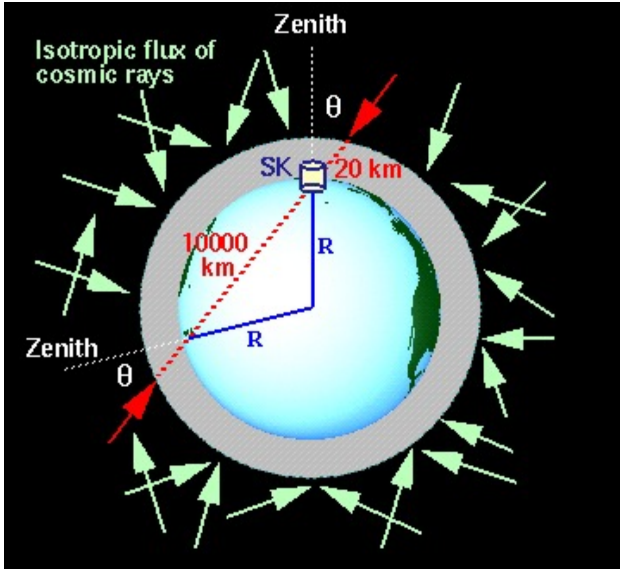
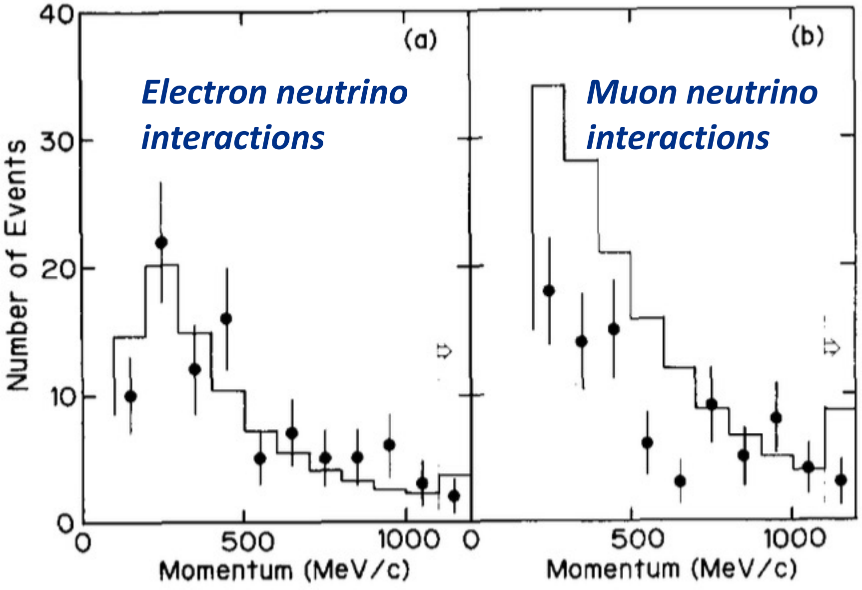
# Atmospheric neutrinos



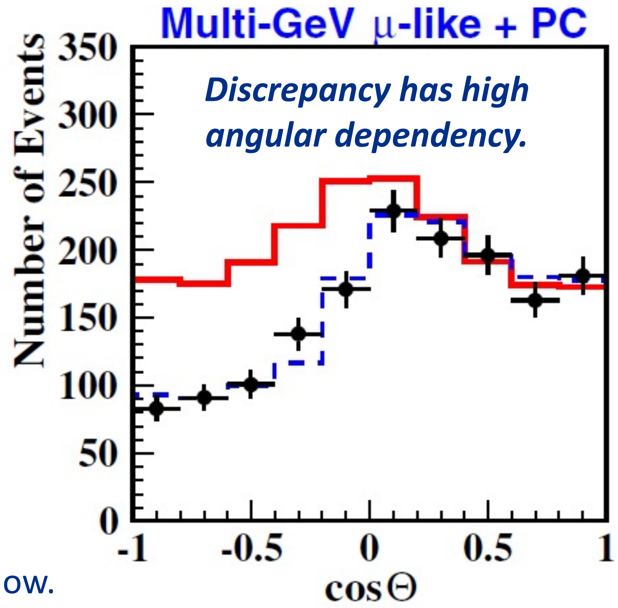

- Produced as high energy cosmic rays strike the upper atmosphere.
  - Produce particle showers (Right).
- As these showers develop and the particles decay, you end up with ~2 $\nu_\mu$ for every $\nu_e$.
- The Kamiokande detector set out to measure this ratio.
  - Was originally built to look for proton decay, but it became famous for measuring neutrinos.



# The atmospheric neutrino problem…




- In 1988 Kamiokande released its first atmospheric neutrino measurement.
  - *Only the electron neutrino results were consistent with theory.*




*Solid lines show the predicted fluxes in momentum and angle.*

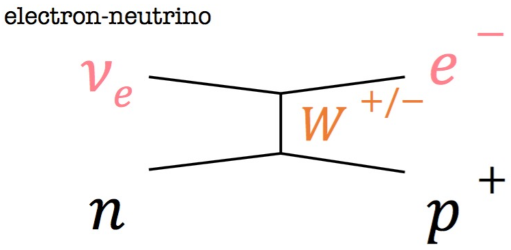
*Data points show the measured number of interactions.*

*Notice that the $\nu_e$ points are above and below lines, but $\nu_\mu$* points are all below.

# Beginning to find some answers to these problems…

- The previous experiments could only measure *Charged Current* interactions.
  - Neutrino interacts with the nucleus and produces an electron or muon.

charged-current




$W^{+/-}$ = charged boson

*The Muon and Tau neutrinos can interact via exactly the same mechanism.*

*Simply replace both examples of "e" in the diagram with "$\mu$" or "$\tau$".*



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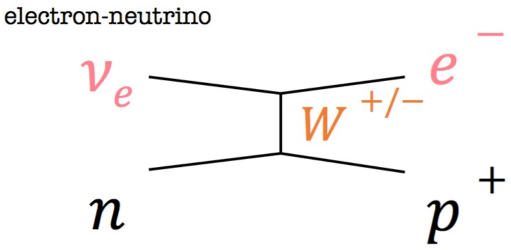
# Beginning to find some answers to these problems…

- The previous experiments could only measure *Charged Current* interactions.
  - Neutrino interacts with the nucleus and produces an electron or muon.

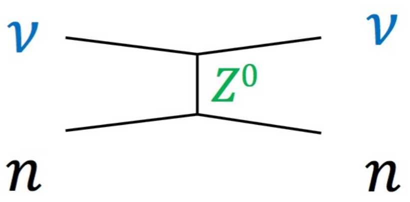
- However, the neutrino can also scatter off a nucleus without producing an electron or muon. These are called *Neutral Current* interactions.

charged-current




$W^{+/-}$ = charged boson

neutral-current




$Z^0$ = neutral boson



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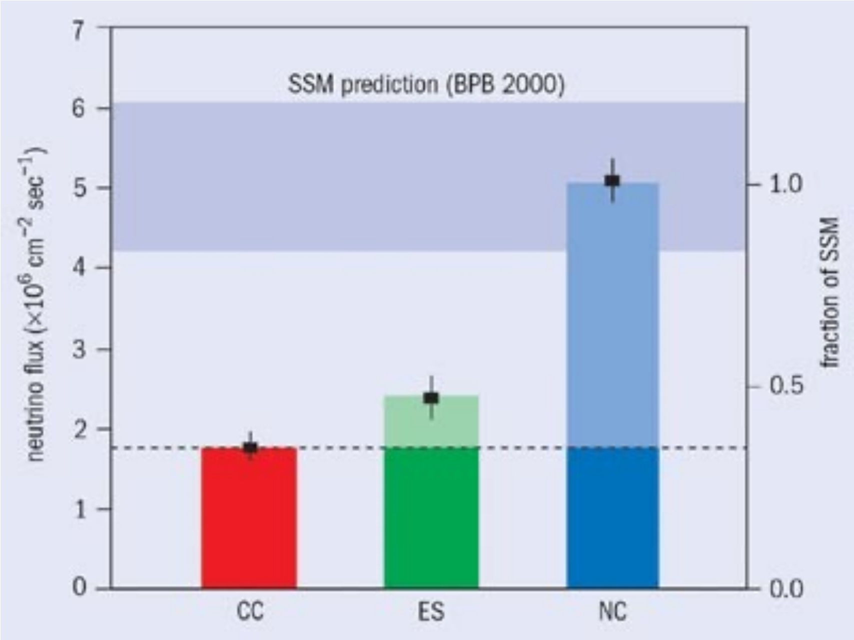
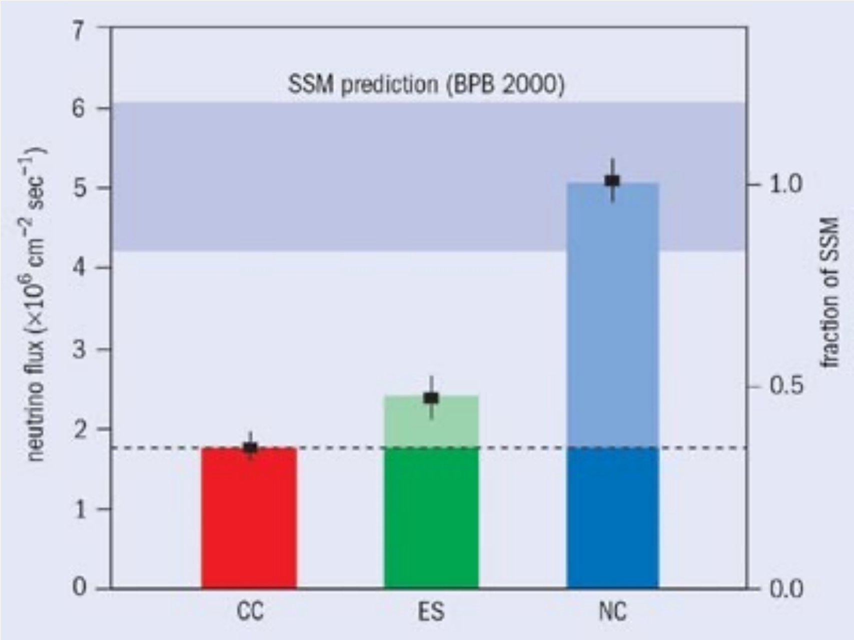
# The Sudbury Neutrino Observatory (SNO)




- In a single experiment it was possible to measure both the $\nu_e$ *Charged Current* interactions, and the *Neutral Current* interactions.
- Reproduced the Homestake measurements of $\nu_e$ *CC* interactions.
- Also measured the predicted number of *NC* interactions.

# The Sudbury Neutrino Observatory (SNO)




- In a single experiment it was possible to measure both the $\nu_e$ *Charged Current* interactions, and the *Neutral Current* interactions.
- Reproduced the Homestake measurements of $\nu_e$ *CC* interactions.
- Also measured the predicted number of *NC* interactions.

***If we can find a way for electron neutrinos to change into different flavors then we can explain both the solar and atmospheric neutrino problems!***



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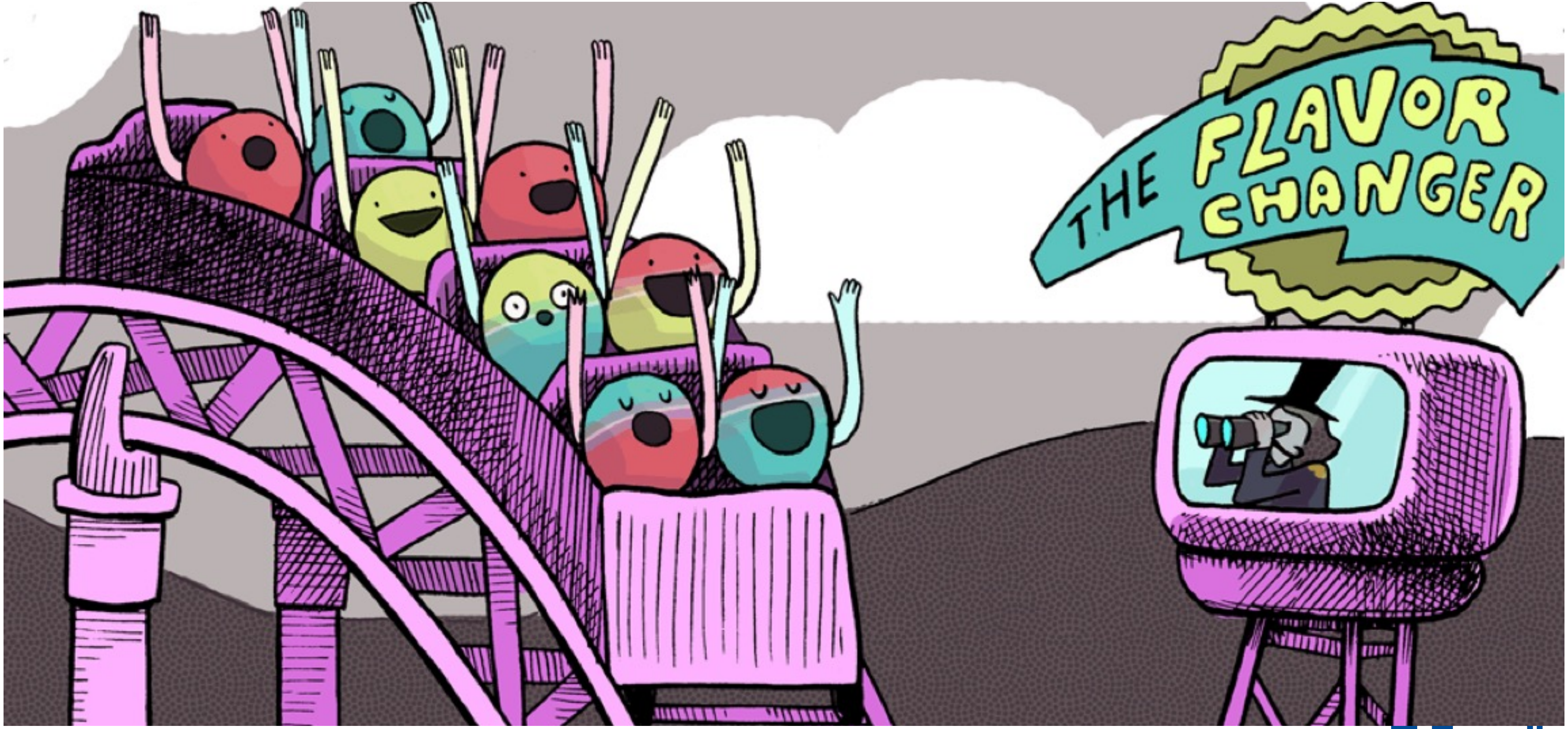
# OK, So What Is Happening?





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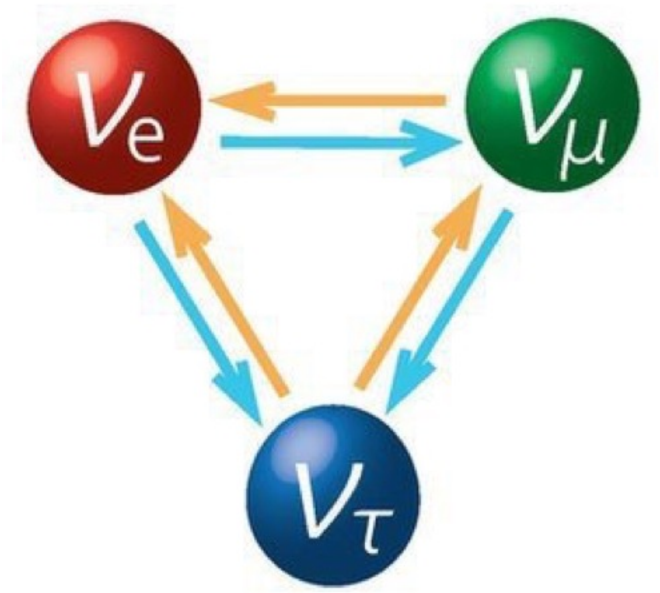
# The theory of neutrino oscillations

*A nice video explaining how oscillations occur.*




- To explain these experiments neutrinos must be able to change (or oscillate) from one flavor to another as they travel through space.
  - Some version of this was predicted as far as back as 1957, but it really gained traction after 1988.
- Ultimately this means that the neutrinos which we observe $\nu_e, \nu_\mu, \nu_\tau$ are not those that exist in nature.
  - They are so-called mass states $\nu_1, \nu_2, \nu_3$.
- How neutrinos oscillate between these states is described by the PMNS matrix, named after four of the theorists who proposed neutrino oscillations.



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# The simplified theory of neutrino oscillations

*Video about how oscillations occur.*

*Assume that there are only 2 neutrino flavors ($\boldsymbol{\alpha}, \boldsymbol{\beta}$), this makes describing their oscillations easier, and can be done using the relationship shown to the right.*

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

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*This means that the flavor states are combinations of the two mass states as such*

$$\boldsymbol{\nu_\alpha = \cos\theta\, \nu_1 + \sin\theta\, \nu_2}$$
$$\boldsymbol{\nu_\beta = -\sin\theta\, \nu_1 + \cos\theta\, \nu_2}$$

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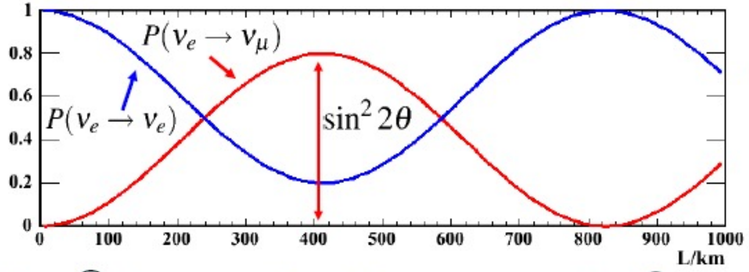
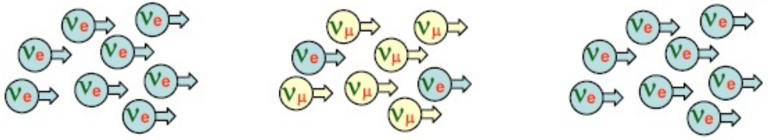
$$\boldsymbol{\nu_\alpha = \cos\theta\, \nu_1 + \sin\theta\, \nu_2}$$
$$\boldsymbol{\nu_\beta = -\sin\theta\, \nu_1 + \cos\theta\, \nu_2}$$

•e.g. $\Delta m^2 = 0.003\,\mathrm{eV}^2, \quad \sin^2 2\theta = 0.8, \quad E_\nu = 1\,\mathrm{GeV}$



*Plugging this into the Schrodinger equation, and following a bit of maths, you get the oscillation probabilities for two neutrino flavors.*

$$\begin{aligned} P(\nu_\alpha \to \nu_\beta) &= (|U_{\beta1}|^2|U_{\alpha1}|^2 + |U_{\beta2}|^2|U_{\alpha2}|^2) + U_{\alpha1}U^*_{\beta1}U_{\alpha2}U^*_{\beta2}(e^{i(\phi_2-\phi_1)} + e^{-i(\phi_2-\phi_1)}) \\ &= (|U_{\beta1}|^2|U_{\alpha1}|^2 + |U_{\beta2}|^2|U_{\alpha2}|^2) + 2U_{\alpha1}U^*_{\beta1}U_{\alpha2}U^*_{\beta2}cos(\phi_2-\phi_1) \\ &= (sin^2\theta cos^2\theta + cos^2\theta sin^2\theta) + 2(cos\theta)(-sin\theta)(sin\theta)(cos\theta)cos(\phi_2-\phi_1) \\ &= 2cos^2\theta sin^2\theta(1 - cos(\phi_2-\phi_1)) \\ &= 2sin^2(2\theta)sin^2(\frac{\phi_2-\phi_1}{2}) \end{aligned}$$

$$P(\nu_\alpha \to \nu_\beta) = sin^2(2\theta)sin^2(\frac{\Delta m^2 L}{4E_\nu})$$

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# The theory of neutrino oscillations

*A nice video explaining how oscillations occur.*

*The PMNS matrix (right) mathematically explains how the three neutrino flavor states relate to the three mass states.*

$$\begin{pmatrix} \upsilon_e \\ \upsilon_\mu \\ \upsilon_\tau \end{pmatrix} = \begin{bmatrix} C_{12}C_{13} & S_{12}C_{13} & S_{13}e^{-i\delta} \\ -S_{12}C_{23} - C_{12}S_{23}S_{13}e^{i\delta} & C_{12}C_{23} - S_{12}S_{23}S_{13}e^{i\delta} & S_{23}C_{13} \\ S_{12}S_{23} - C_{12}C_{23}S_{13}e^{i\delta} & -C_{12}S_{23} - S_{12}C_{23}S_{13}e^{i\delta} & C_{23}C_{13} \end{bmatrix} \begin{pmatrix} \upsilon_1 \\ \upsilon_2 \\ \upsilon_3 \end{pmatrix}$$

$$S_{ij} \equiv Sin(\theta_{ij}) \quad C_{ij} \equiv Cos(\theta_{ij})$$

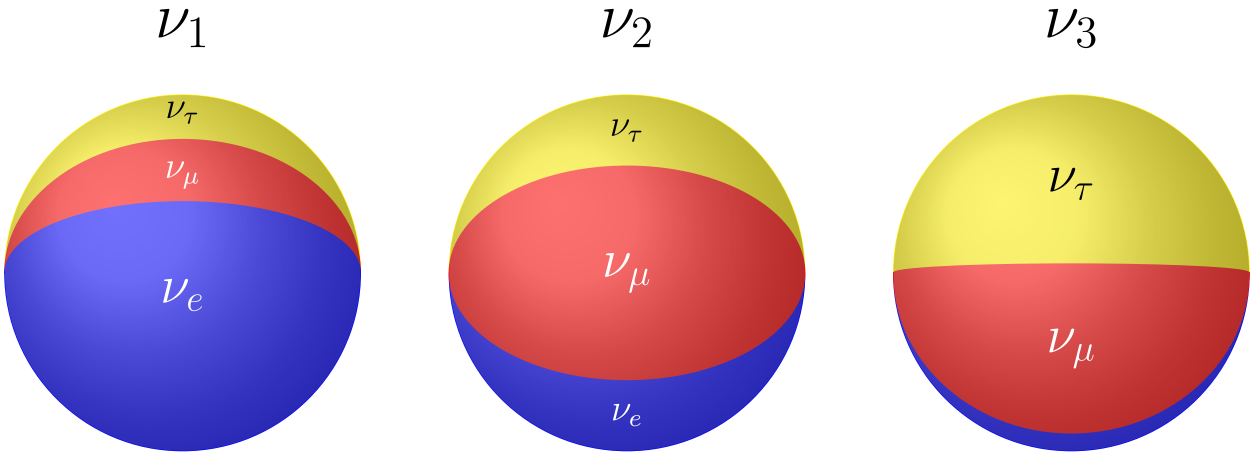
*By expanding the PMNS matrix, and using the Schrödinger equation to explain how the flavor states propagate. It is possible to determine the probability that one neutrino flavor will oscillate into another.*

$$|\nu_j(t)\rangle = e^{-i(E_j \cdot t - \vec{p}_j \cdot \vec{x}_j)} |\nu_j(0)\rangle$$

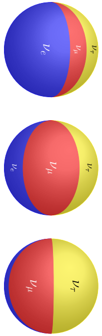
$$A(\nu_\alpha \to \nu_\beta) = \langle \nu_\beta | \nu_\alpha(t) \rangle = \sum_k \sum_j \langle \nu_j | U_{\beta j} U^*_{\alpha k} e^{-im_k^2 L/2E} |\nu_k\rangle$$

$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23} \sin^2 2\theta_{13} \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} \Delta_{31}^2 + \sin 2\theta_{23} \sin 2\theta_{13} \sin 2\theta_{12} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31} \frac{\sin(aL)}{(aL)} \Delta_{12} \cos(\Delta_{31} + \delta_{CP}) + \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(aL)}{(aL)^2} \Delta_{12}^2$$

# Visualising Neutrino Mixing & Oscillations




$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$





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# Three Flavour Neutrino Oscillations

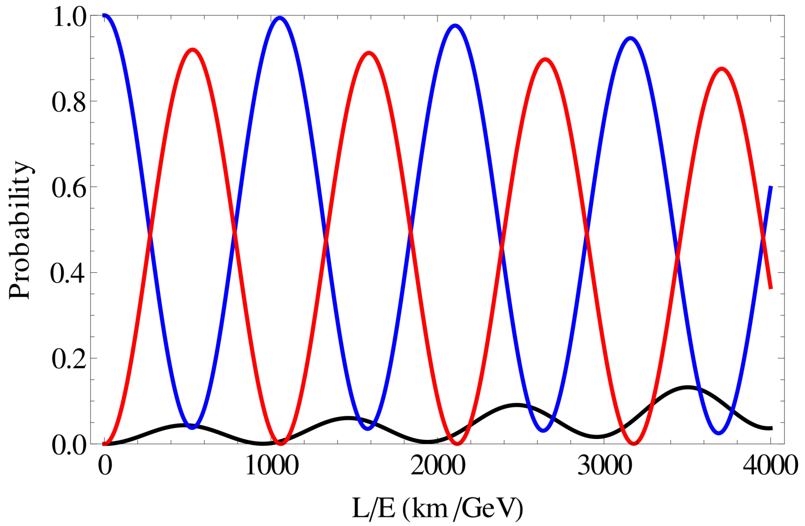
*Can see the effect of two mass squared differences.*

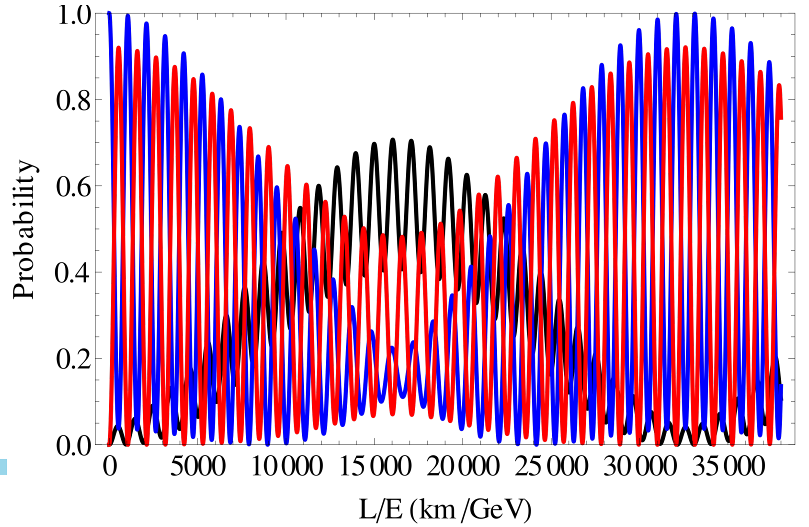
*Start with a primarily* $\nu_\mu$ *beam.*

*Can see that at "low" L/E most neutrinos oscillate to* $\nu_\tau$ *and back.*

*However, can see that as L/E increases, you get more* $\nu_e$*'s, and by the time you get to a L/E of around 16,000 60% of the neutrinos are* $\nu_e$*'s.*

*The NOvA and DUNE experiments are both built such that they as close as possible to the first oscillation maximum around L/E=500 km/GeV.*

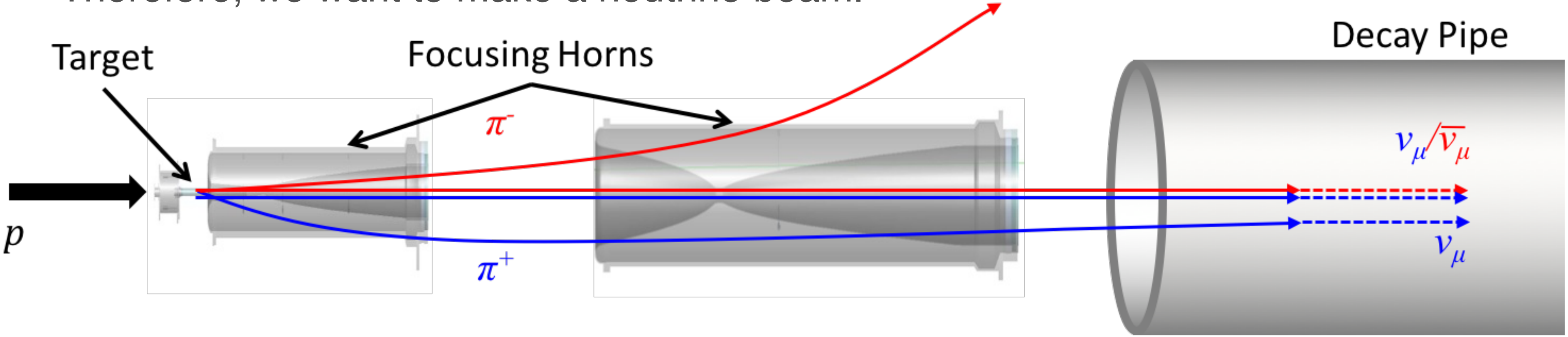


# The Nobel Prize for the Discovery of Neutrino Oscillations

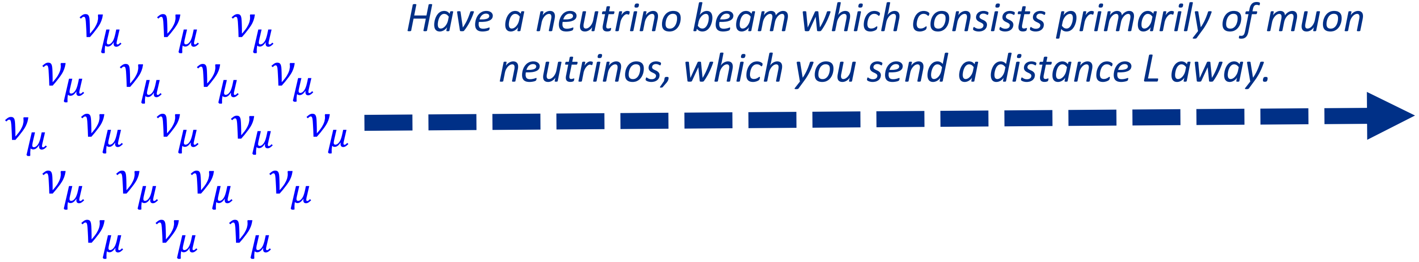
# Making The Most Accurate Measurements Possible

- Atmospheric and Solar neutrinos are unlimited, and continuous, however we can't choose their energies, or the distance that they travel.
  - Heavily limits the neutrino physics that we can do with them.
- To make the best measurements, we want to study;
  - Neutrinos with well defined energies
  - Neutrinos that have travelled well defined distances.
- Therefore, we want to make a neutrino beam.



# How Does This Work In Practice?

*Have a neutrino beam which consists primarily of muon neutrinos, which you send a distance L away.*



# How Does This Work In Practice?

$\nu_\mu \quad \nu_\mu \quad \nu_\mu$
$\nu_\mu \quad \nu_\mu \quad \nu_\mu \quad \nu_\mu$
$\nu_\mu \quad \nu_\mu \quad \nu_\mu \quad \nu_\mu \quad \nu_\mu$
$\nu_\mu \quad \nu_\mu \quad \nu_\mu \quad \nu_\mu$
$\nu_\mu \quad \nu_\mu \quad \nu_\mu$

*After travelling a distance L, most neutrinos will have oscillated from one flavor to another.*

*For NOvA L = 800 km & For DUNE L = 1300 km*

*In accelerator experiments the $\nu_\mu$s largely change to $\nu_\tau$s*

$\nu_\tau \quad \nu_\mu \quad \nu_\tau$
$\nu_\mu \quad \nu_\tau \quad \nu_\tau \quad \nu_e$
$\nu_\tau \quad \nu_\tau \quad \nu_\mu \quad \nu_\tau \quad \nu_\mu$
$\nu_\mu \quad \nu_\tau \quad \nu_\tau \quad \nu_\tau$
$\nu_\tau \quad \nu_\tau \quad \nu_\mu$

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$\nu_\mu \; \nu_\mu \; \nu_\mu$
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$\nu_\mu \; \nu_\mu \; \nu_\mu \; \nu_\mu \; \nu_\mu$
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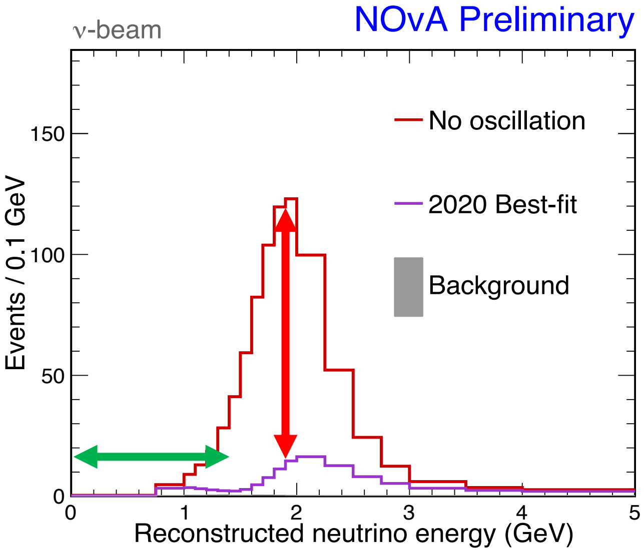
$\nu_\tau \; \nu_\tau \; \nu_\mu \; \nu_\tau \; \nu_\mu$
$\nu_\mu \; \nu_\tau \; \nu_\tau \; \nu_\tau$
$\nu_\tau \; \nu_\tau \; \nu_\mu$




*Oscillation rates are effectively a function of L/E in nature, so are energy dependent at a given distance. Mathematically they are described by 6 measurable parameters;*

*Charge-Parity-violating phase $\delta_{CP}$.*

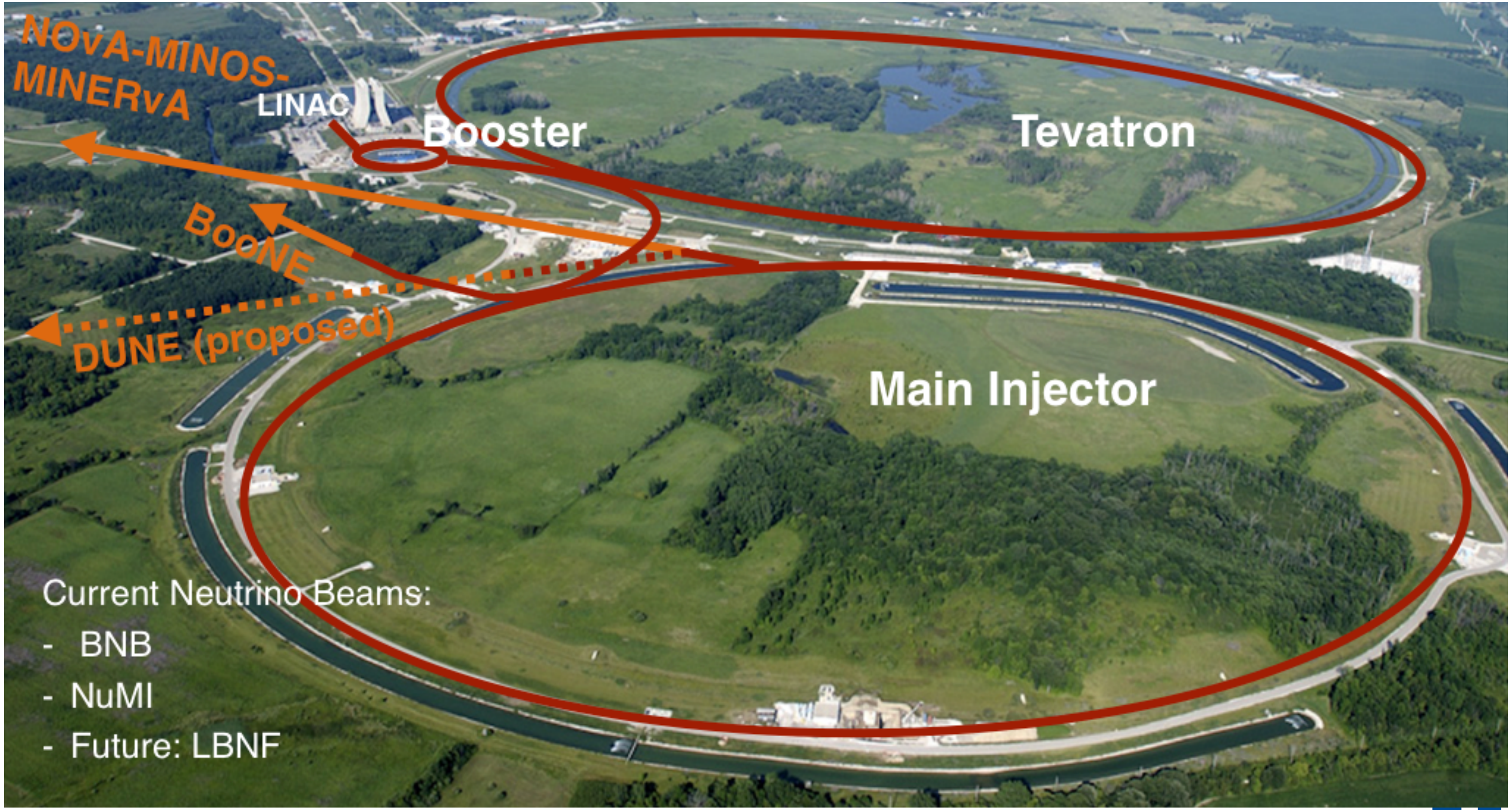
*Mass-squared differences $\Delta m^2_{21}, \Delta m^2_{32}$.*

*Determine where **maximal oscillation occurs**.*

*Mixing angles: $\theta_{12}, \theta_{13}, \theta_{23}$.*

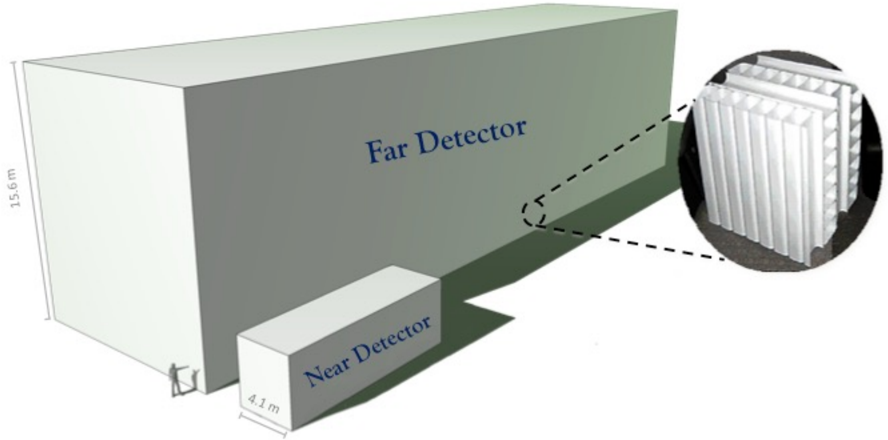
*Determine the **magnitude of oscillations** at a given energy.*

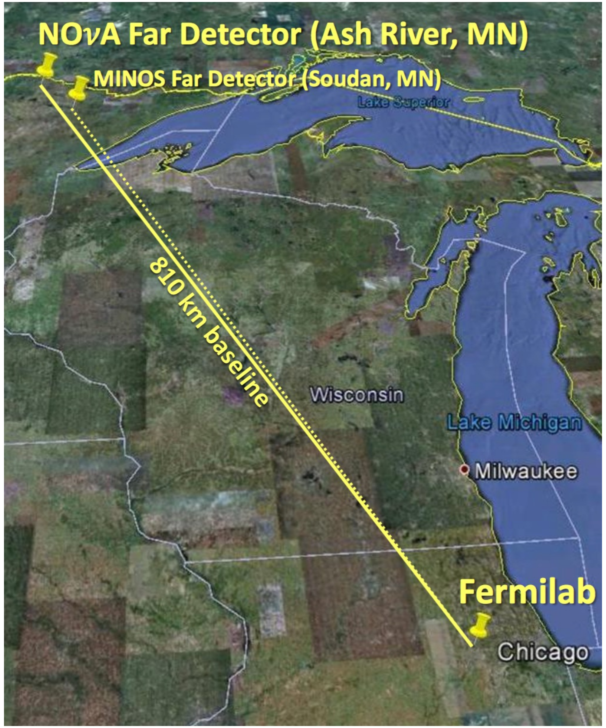
# The Fermilab Neutrino Program



# The NOvA Experiment

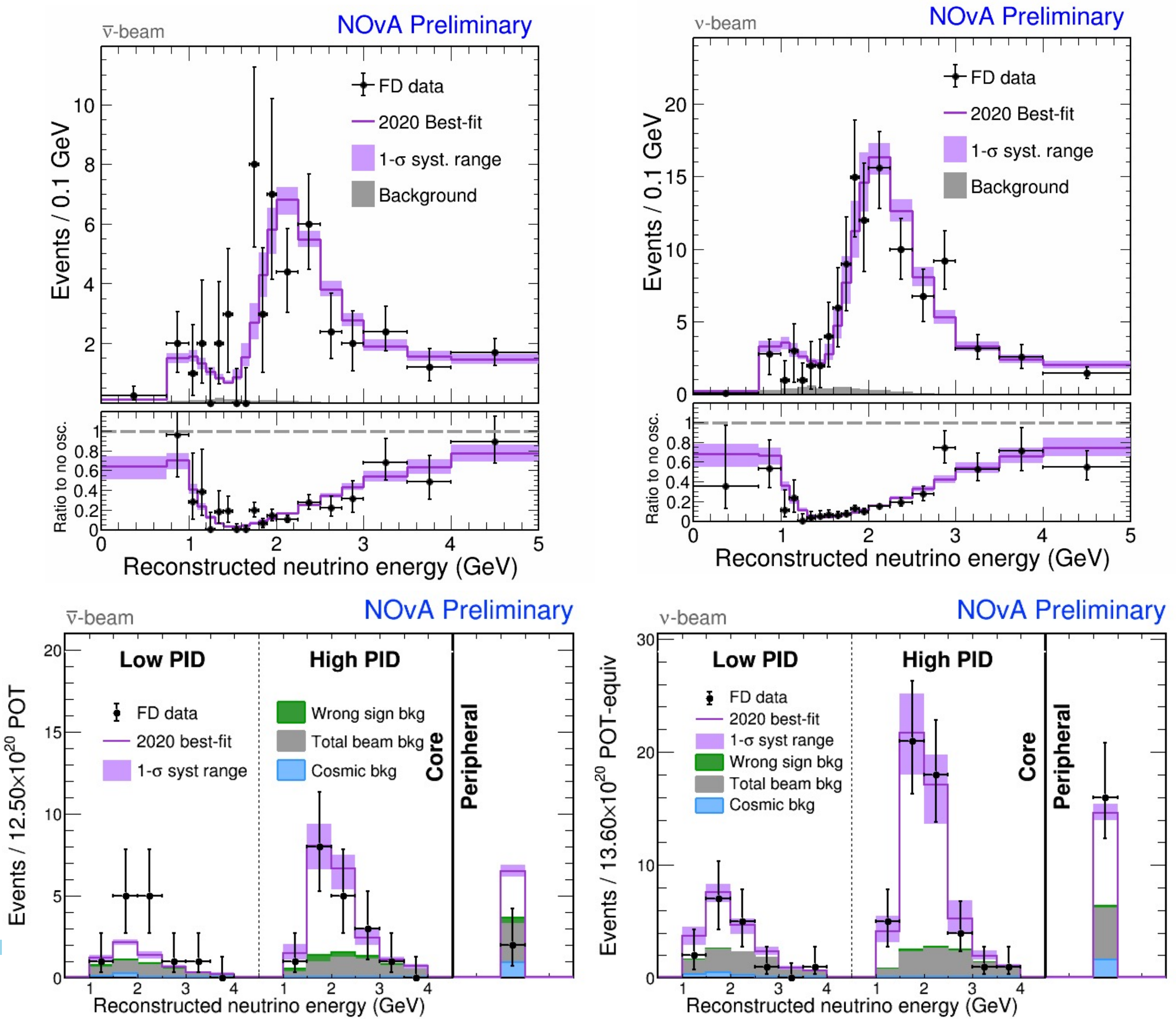
- Sends a beam of muon neutrinos 810 km (500 miles) from Fermilab to Northern Minnesota.
- Consists of 2 detectors, one here at Fermilab, one in Minnesota near the Canadian border.
- Detects the number of muon and electron neutrinos in each detector.



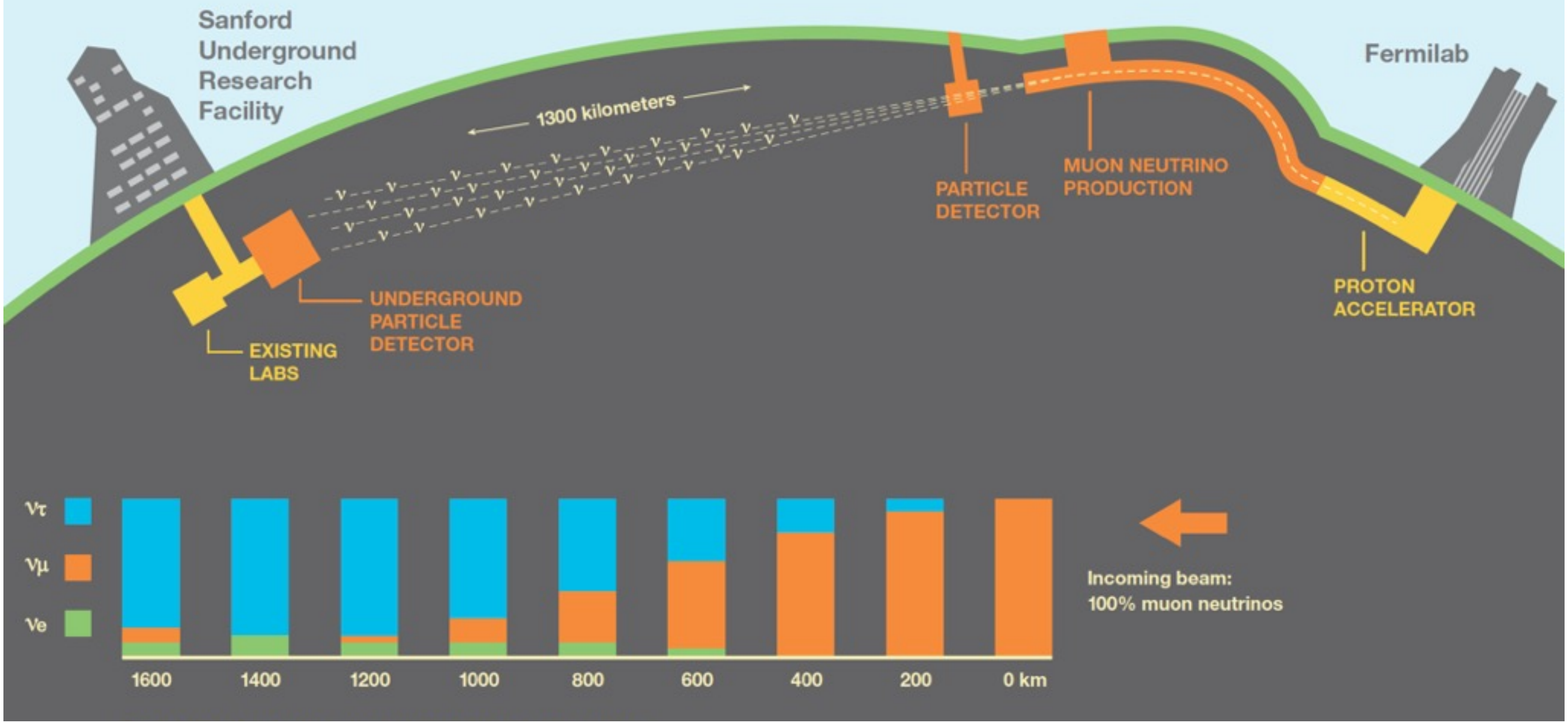



# Latest Results From NOvA

- The PMNS matrix allows NOvA to predict the number of observed events for different neutrino mixing params.
- By calculating the energy of $\nu_\mu$'s and $\nu_e$'s detected at Far Detector it is possible to extract the value of the mixing parameters.



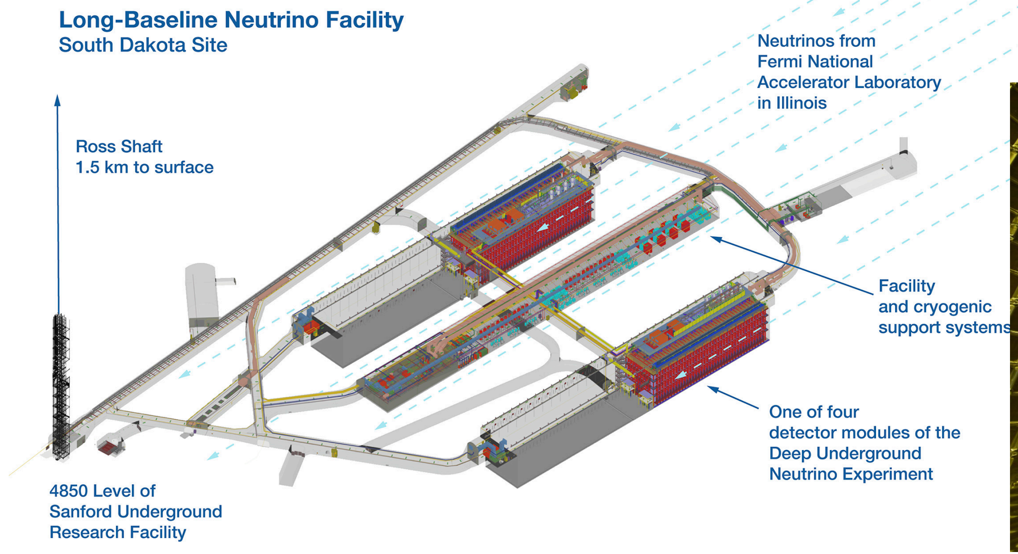
# The Deep Underground Neutrino Experiment (DUNE)

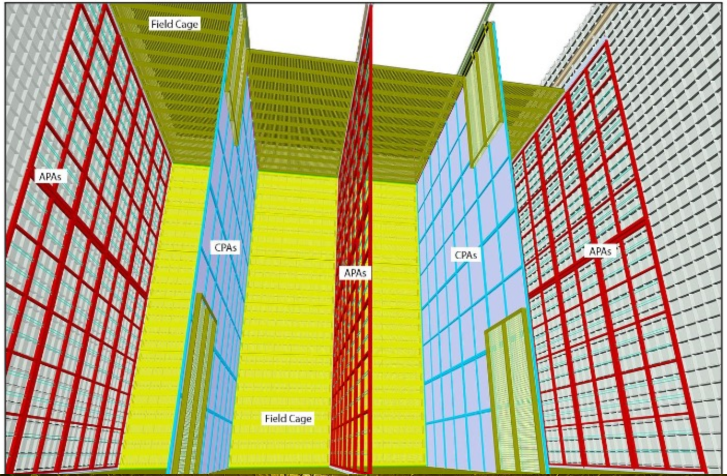


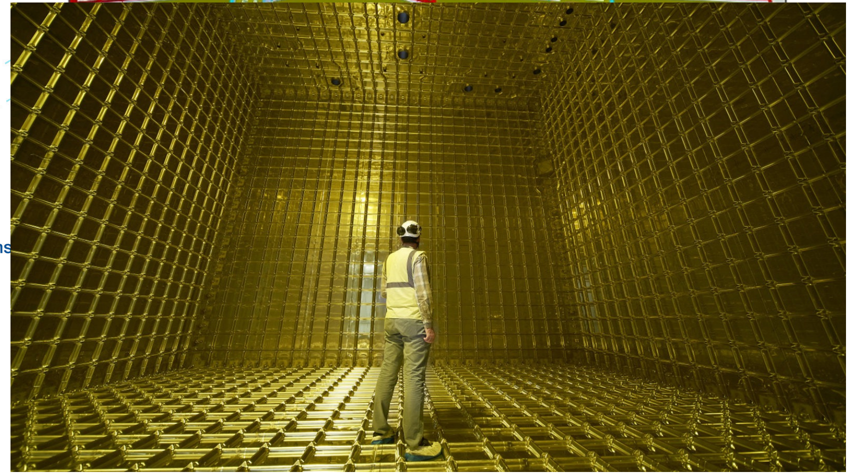
# The DUNE Far Detectors

*A huge engineering endeavor. The detector is 1 mile underground, consists of four separate modules, and each module is in effect 200 separate detectors.*

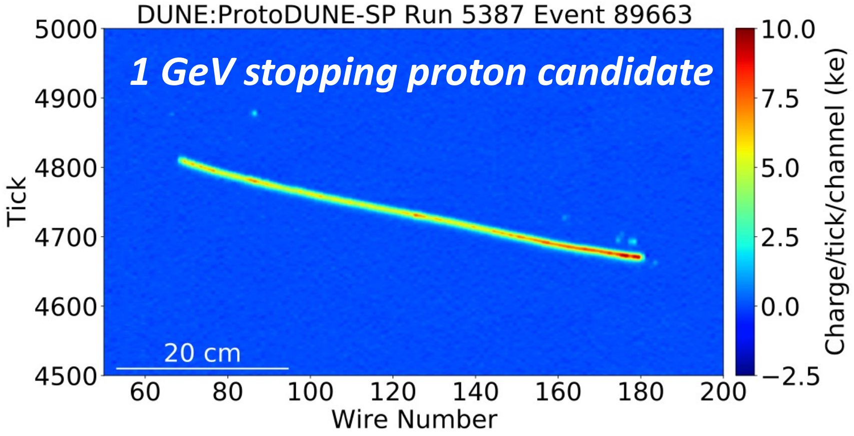
*Will use 70 kton of Liquid Argon (-303 F/-186 C/87 K).*

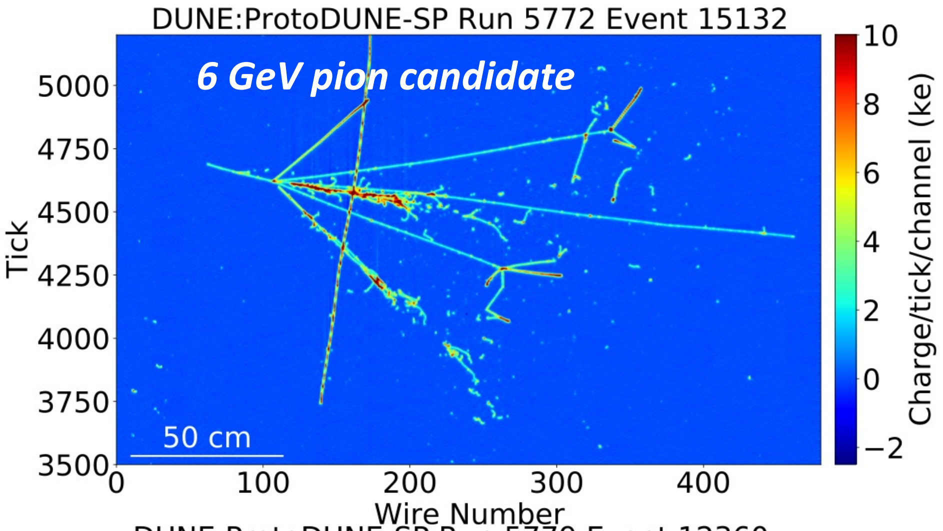


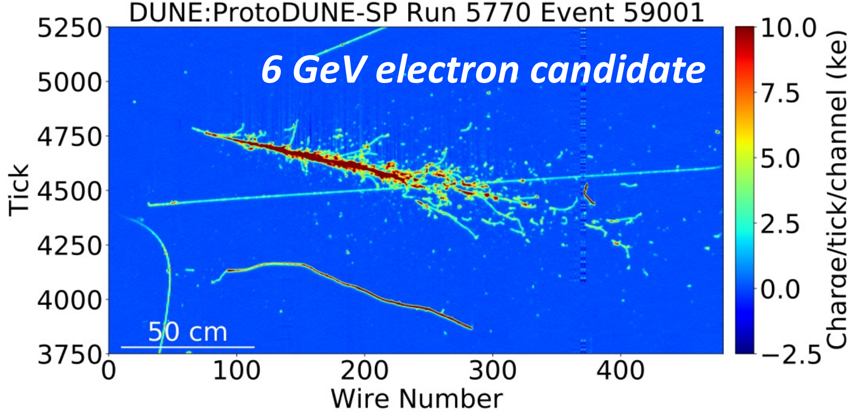



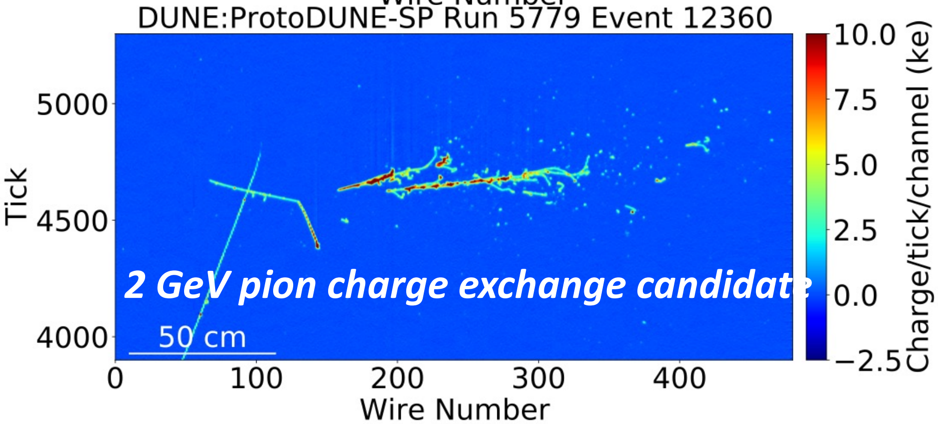



# Particles Interactions in DUNE

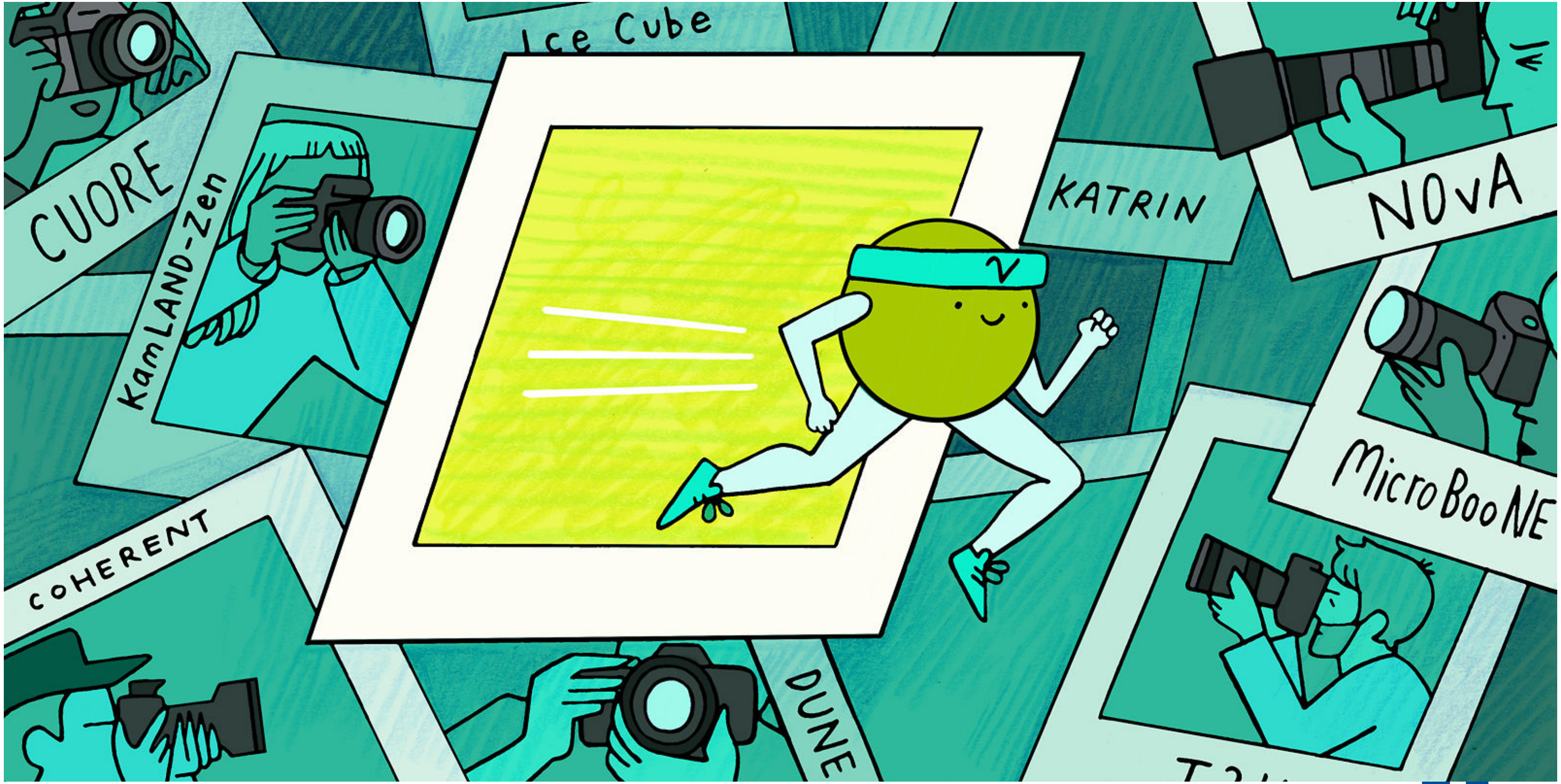


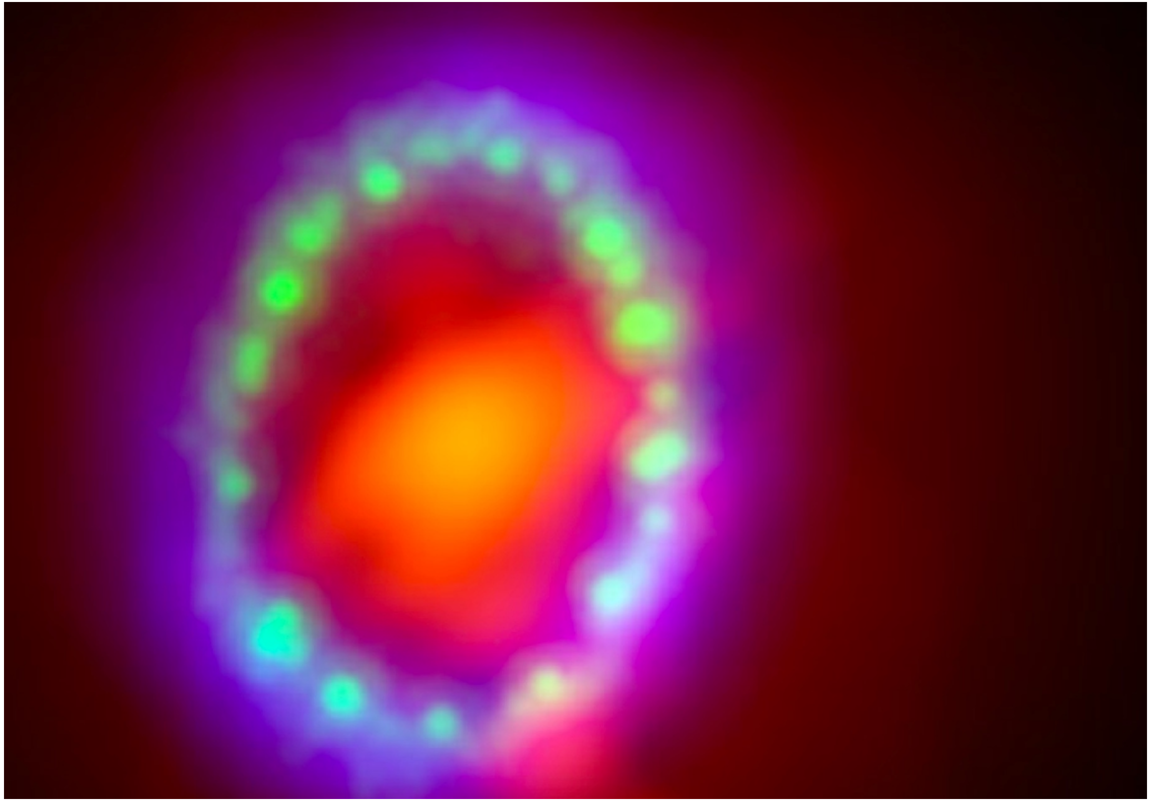



# A Couple Of Cool Other Things

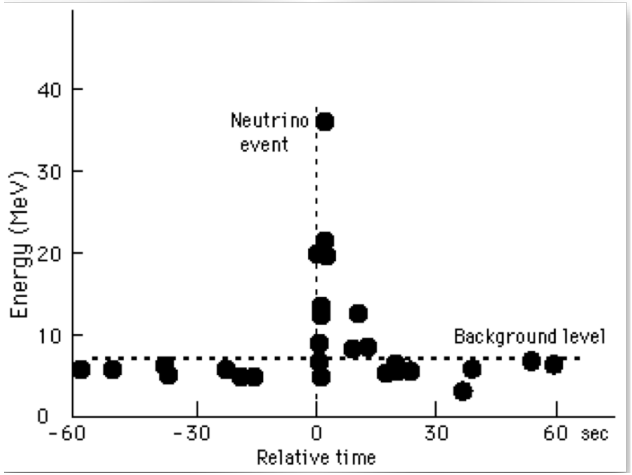


# The Detection of Supernova Neutrinos – 1987a



*Saw less than 30 neutrinos in total. With the next generation of experiments, we could see 10k+!*

*We detected the neutrinos from 1987a 2 hours before the light!*

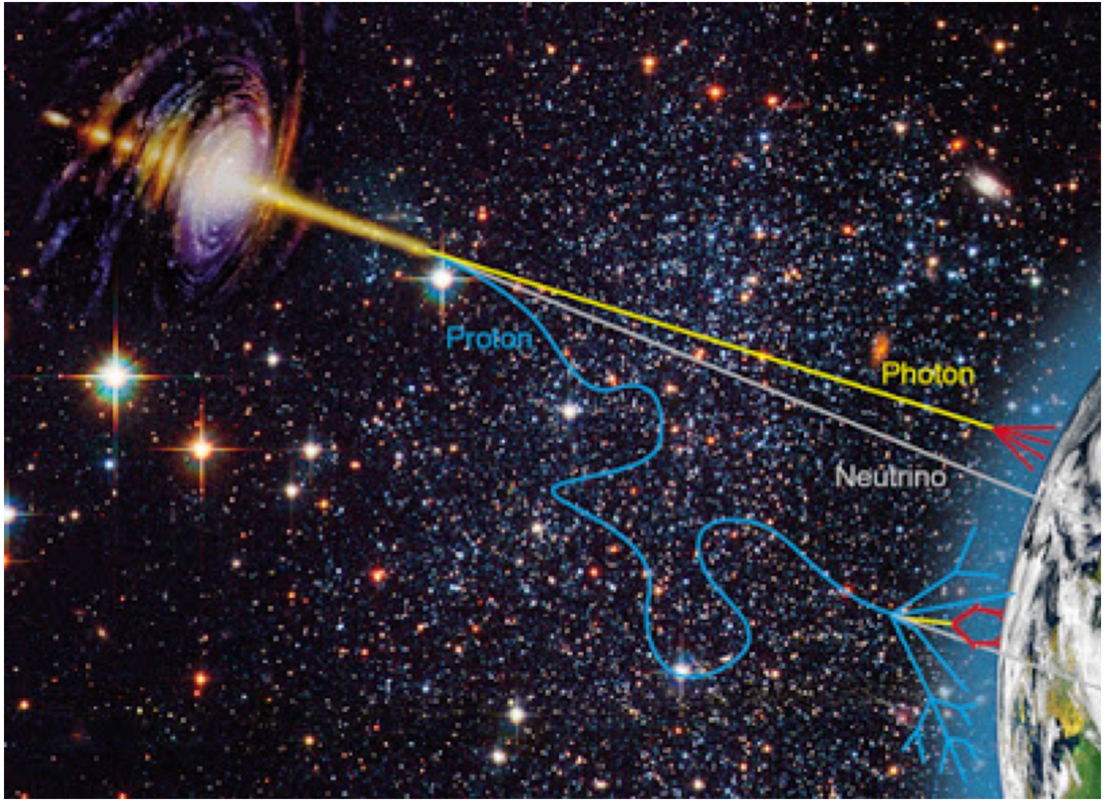


# Multi-Messenger Astronomy

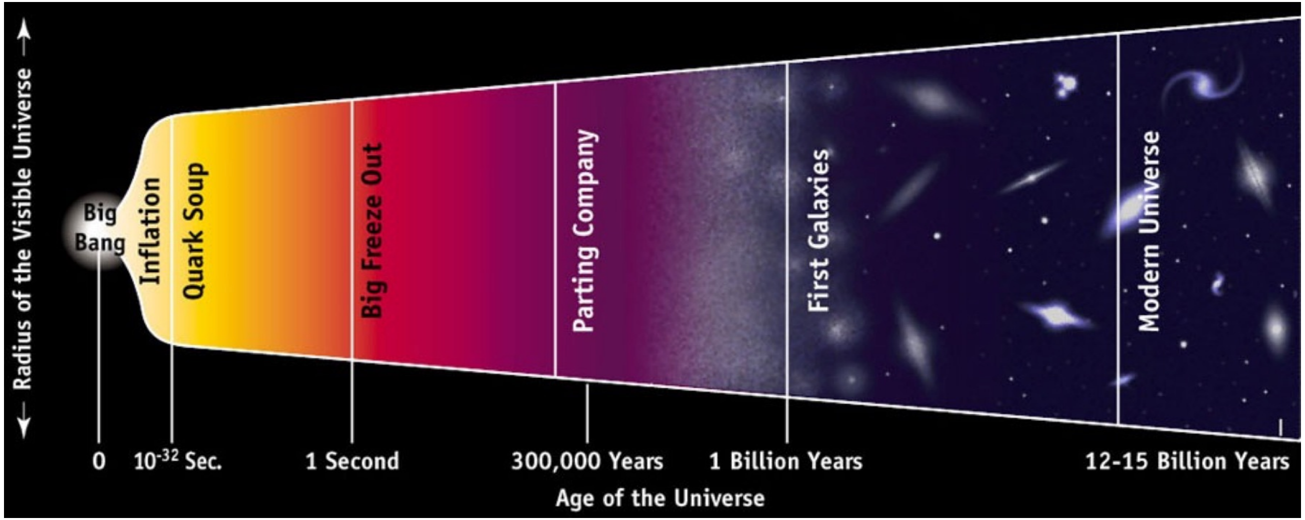
*We know that we can detect multiple signals from astronomical events;*

- *SN 1987a: saw light and neutrinos.*
- *Neutron star collision (Aug 2017): saw gravitational wave, gamma ray burst and an optical signal.*
- *Blazar: IceCube noticed an extremely high energy neutrino event. Gamma rays from a blazar were later identified to come from the same point in the sky.*

*Now looking for neutrino signals from all high-energy astronomical events. The signals will be weak, but the knowledge gained will be huge!*



# Relic Neutrinos From The Big Bang




*Produced when the Universe was 1 s old.*

*In comparison, the CMB became stable when the Universe was 300k years old, so much older info!*

*We are surrounded by these neutrinos, but they are extremely low energy.*

*We struggle to identify accelerator neutrinos which are $10^{10}$ times more energetic, so detecting these particles will be very hard…*



Fermilab

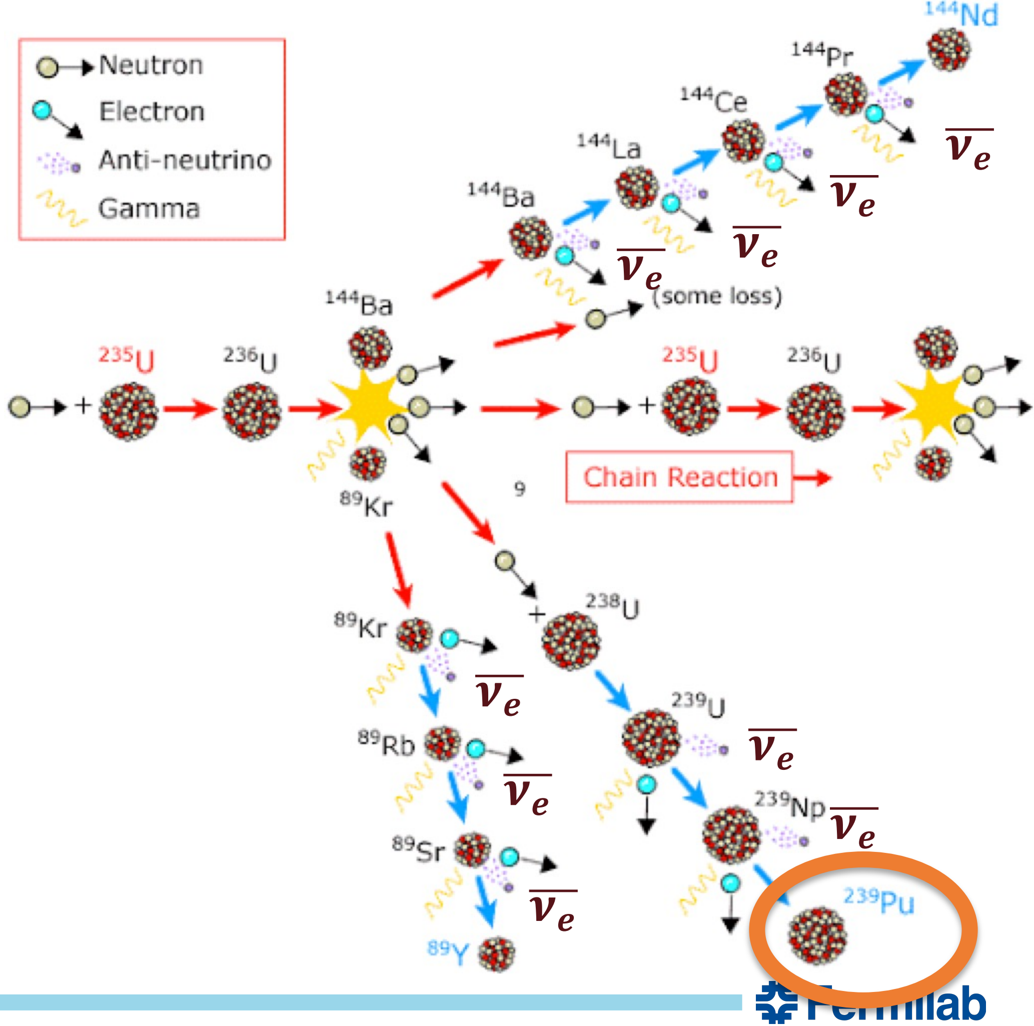
# Nuclear Non-Proliferation

*The first neutrinos were observed from a nuclear reactor, and they are still a reliable source of neutrinos.*

*As nuclear reactions progress, many* ***electron anti-neutrinos*** *are produced which cannot be stopped.*

*Nuclear weapons use a product of this reactions (**Plutonium 239**) which will decay, producing neutrinos of different energies.*

*By detecting neutrinos from these decays one can monitor if nuclear/weapons research is being performed from great distances.*



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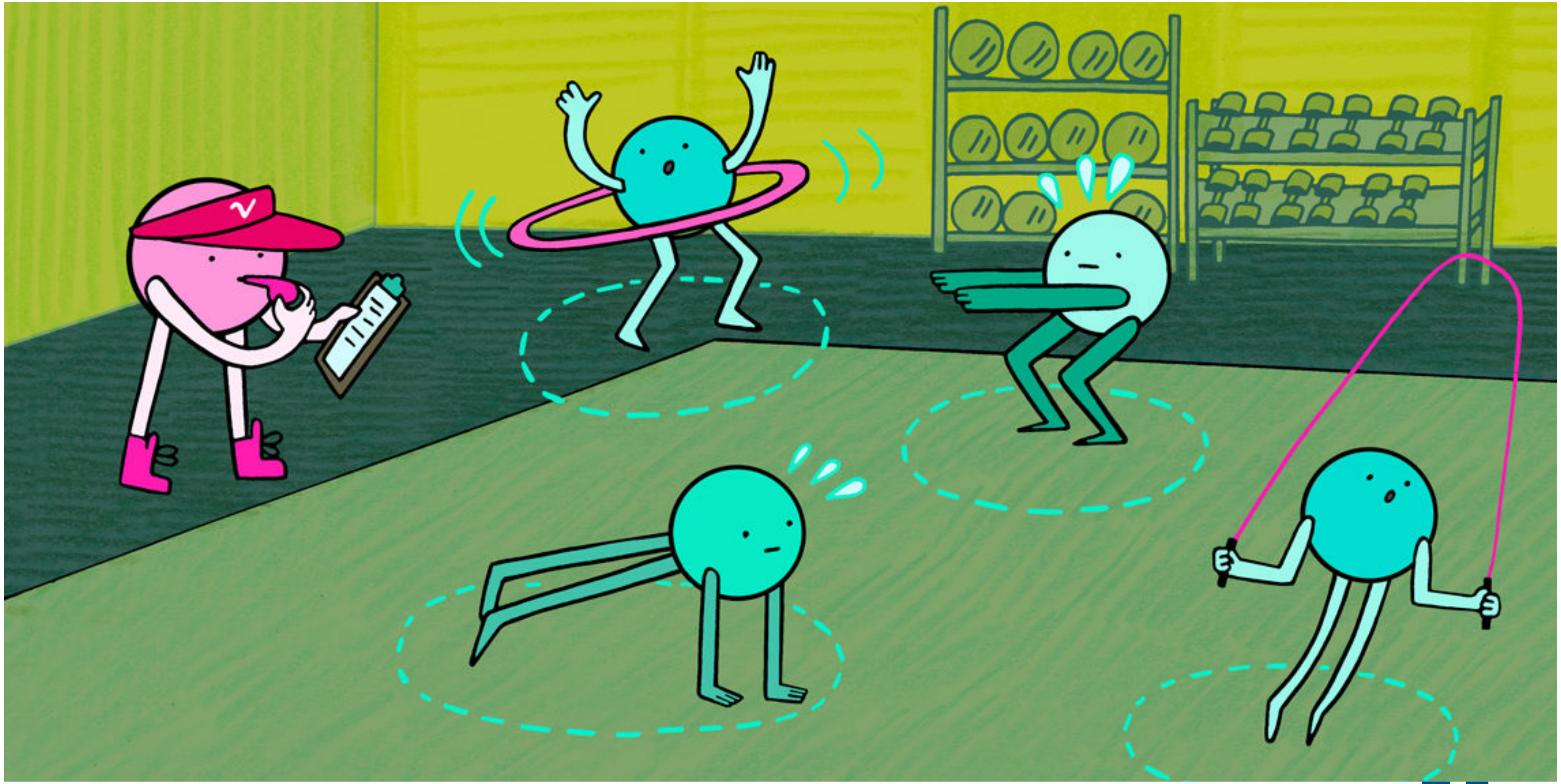
# A Recap Of Neutrino Physics & The Remaining Questions

- Neutrinos are one of the least understood Standard Model Particles.
  - This despite being the most common particle in the Universe
- They are the first known evidence of physics beyond the Standard Model
- They undergo a process known as oscillation.
  - They change flavor as they travel long distances.
- There many experiments running and planned to better understand neutrinos.
  - Fermilab is one of the best places in the World to do this!

***We have come a long way in the last 50 years but many questions remain.***

1. Why are neutrino masses so small?
2. What is the neutrino mass scale and what order are the masses in?
3. How do neutrinos acquire mass?
4. Are there only 3 types of neutrino?
5. What exactly are the parameters which control neutrino oscillations?
6. What cool stuff can we do with them?

# Some Additional Slides



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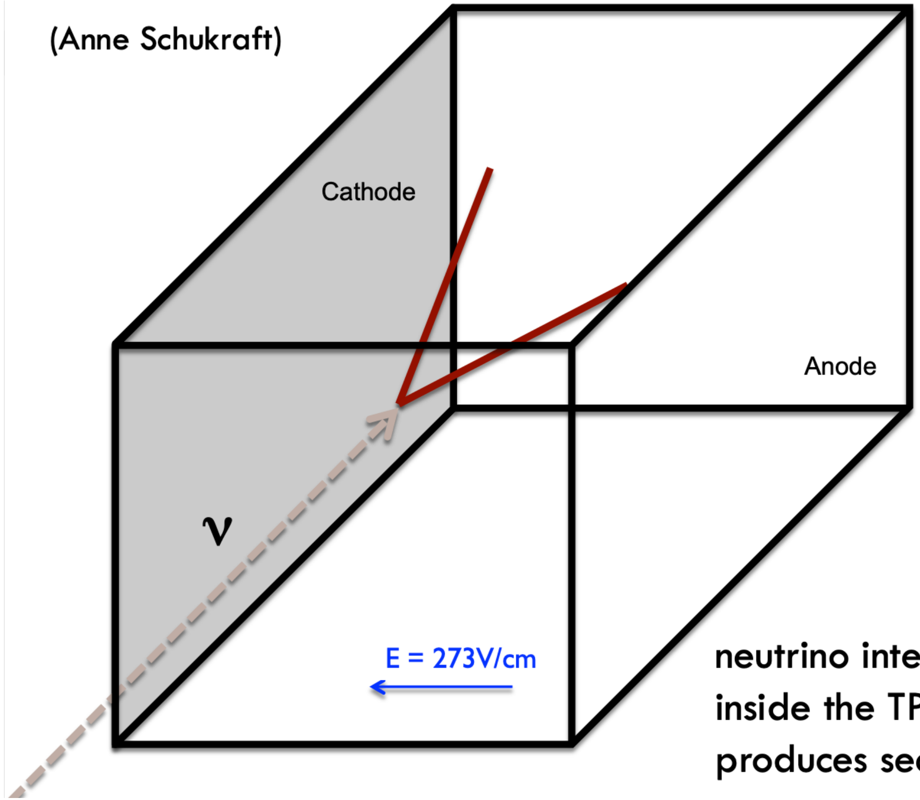
# How A Liquid Argon Time Projection Chamber Works




neutrino interacts with the argon inside the TPC volume and produces secondary particles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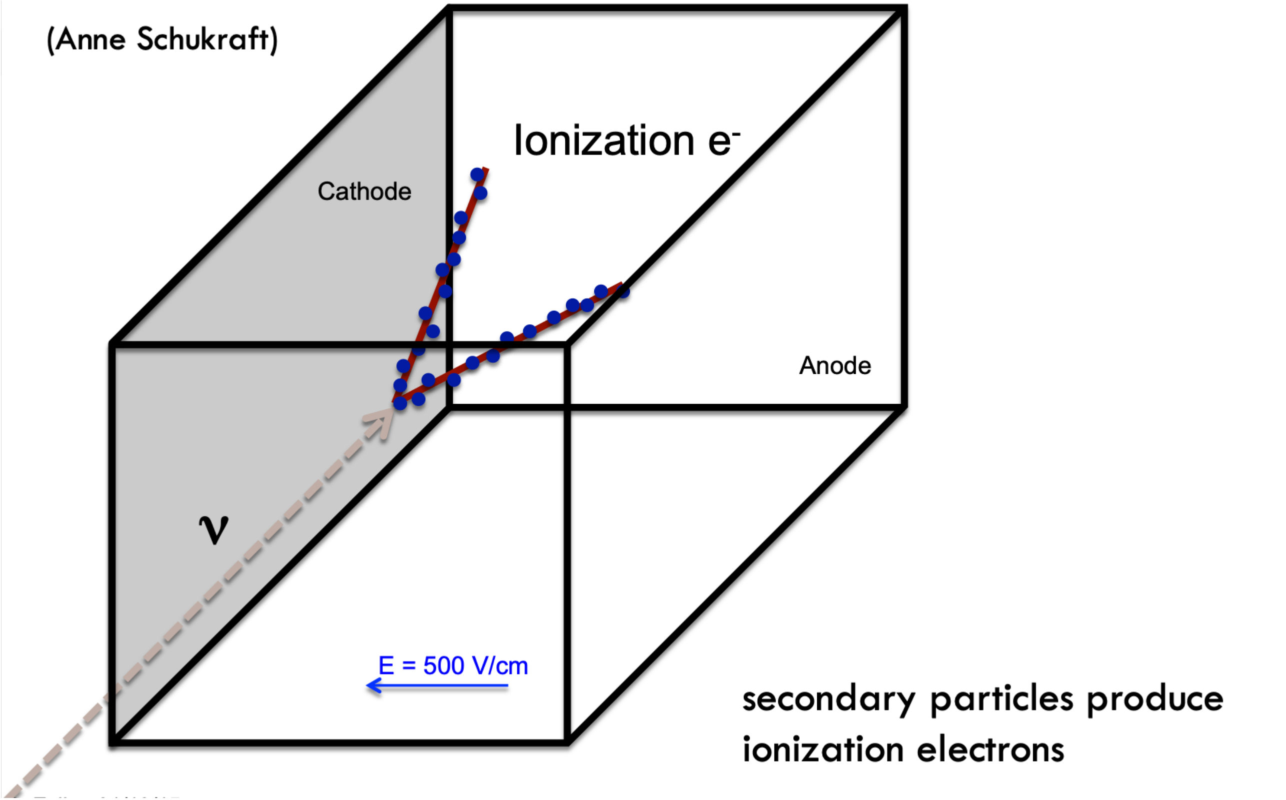
# How A Liquid Argon Time Projection Chamber Works





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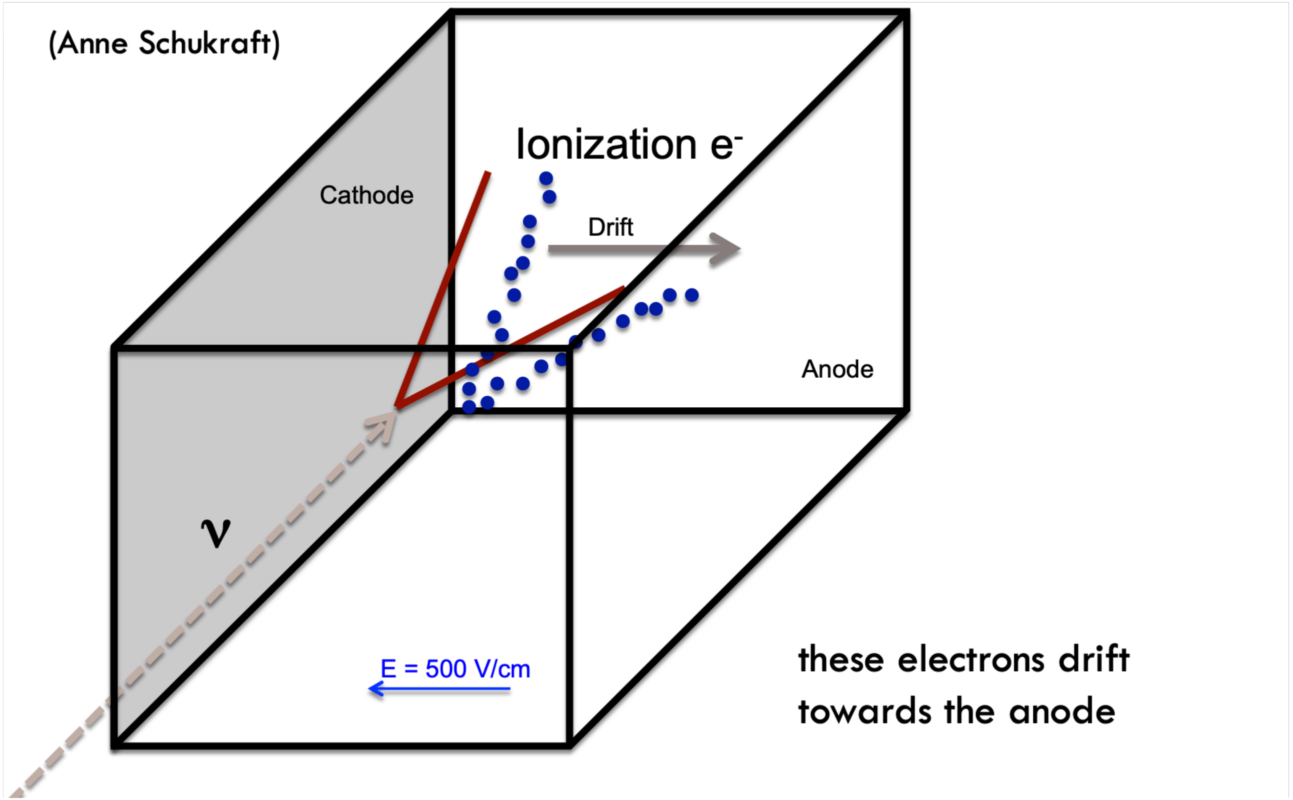

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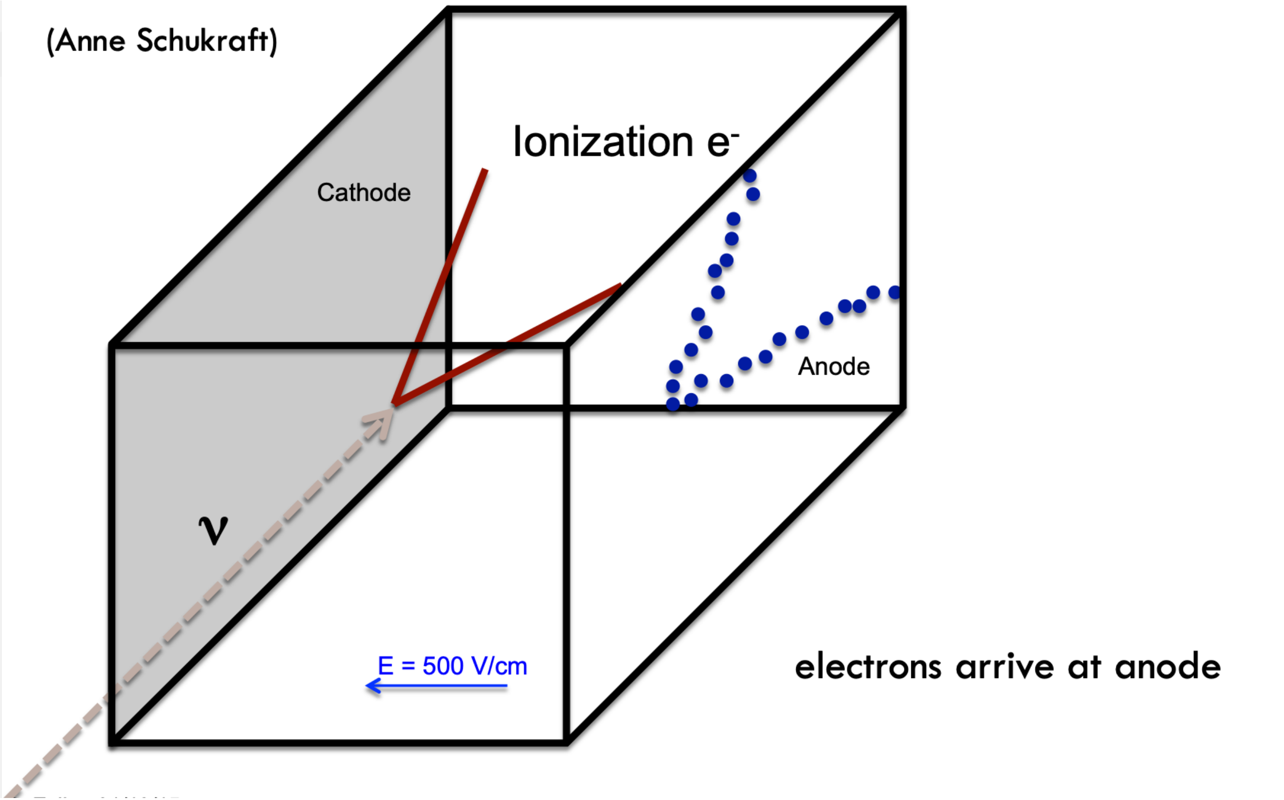

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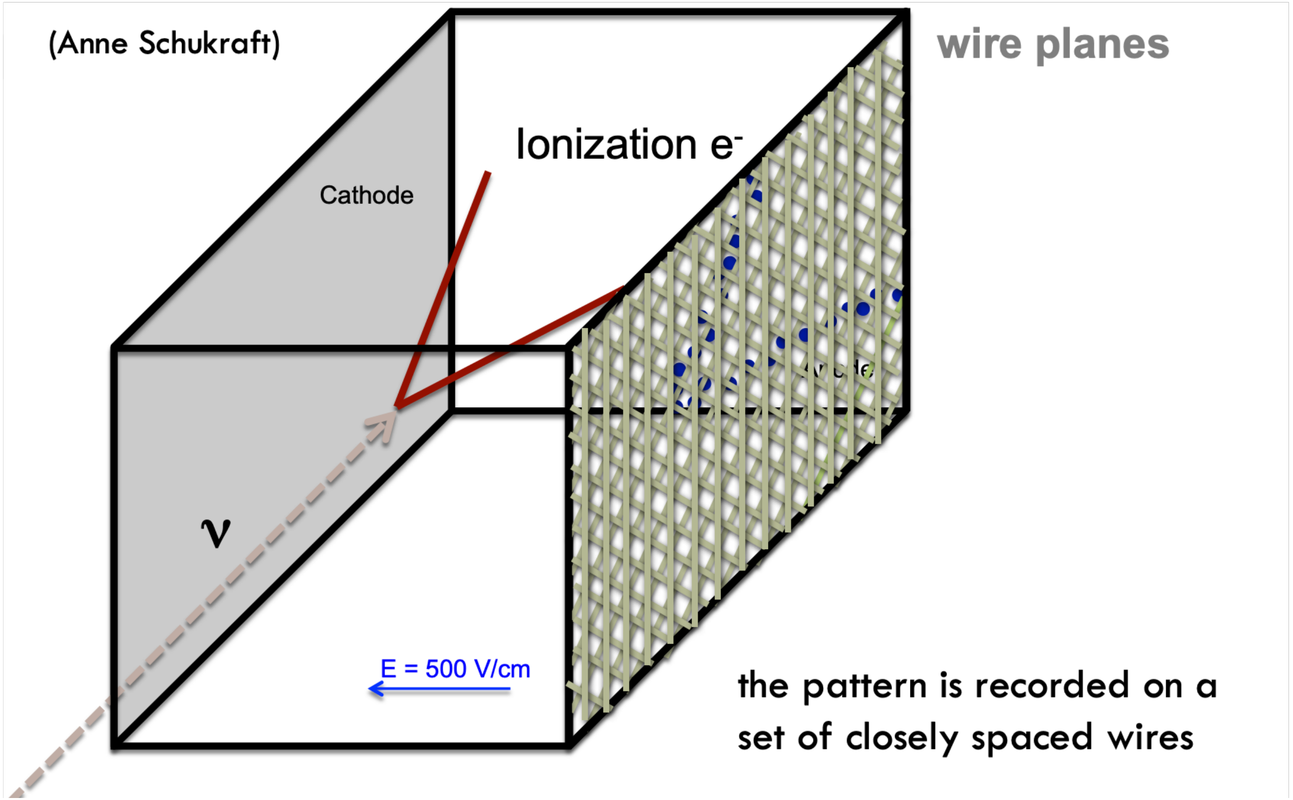

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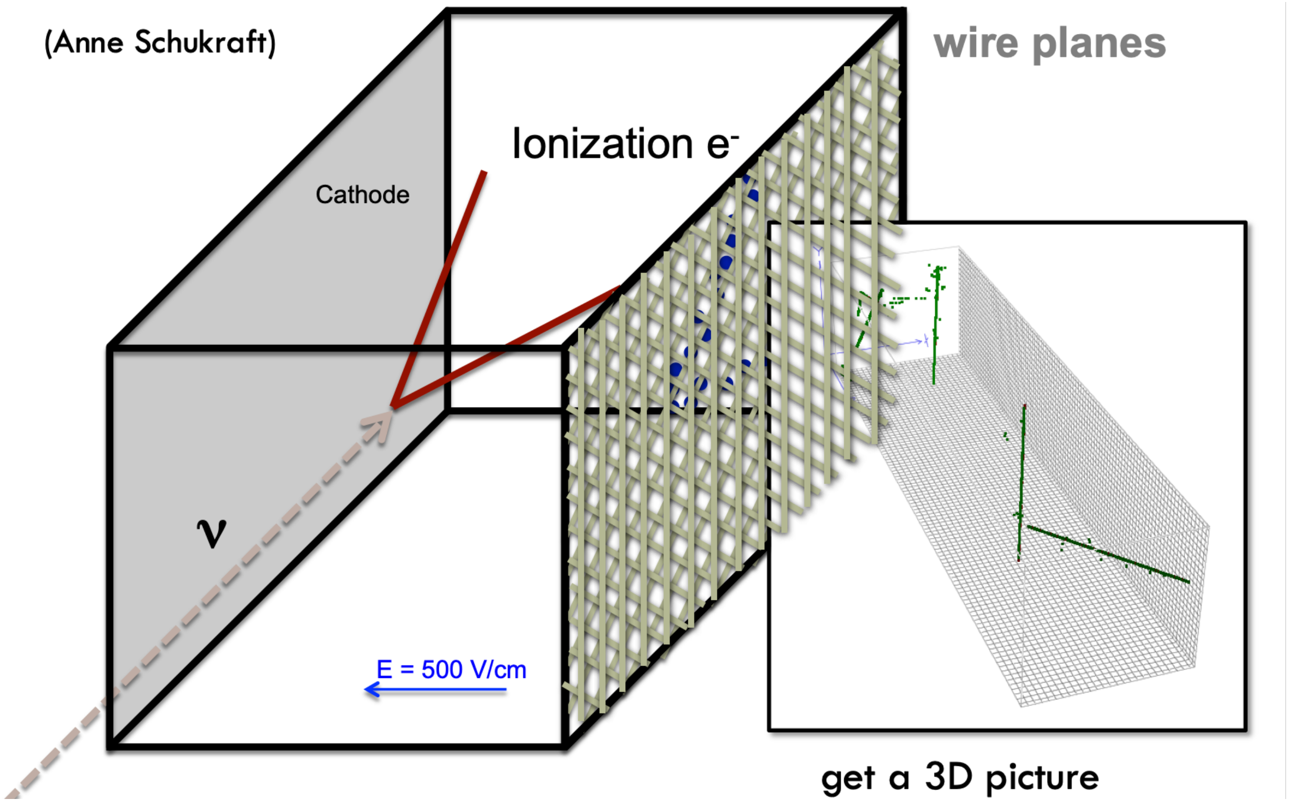

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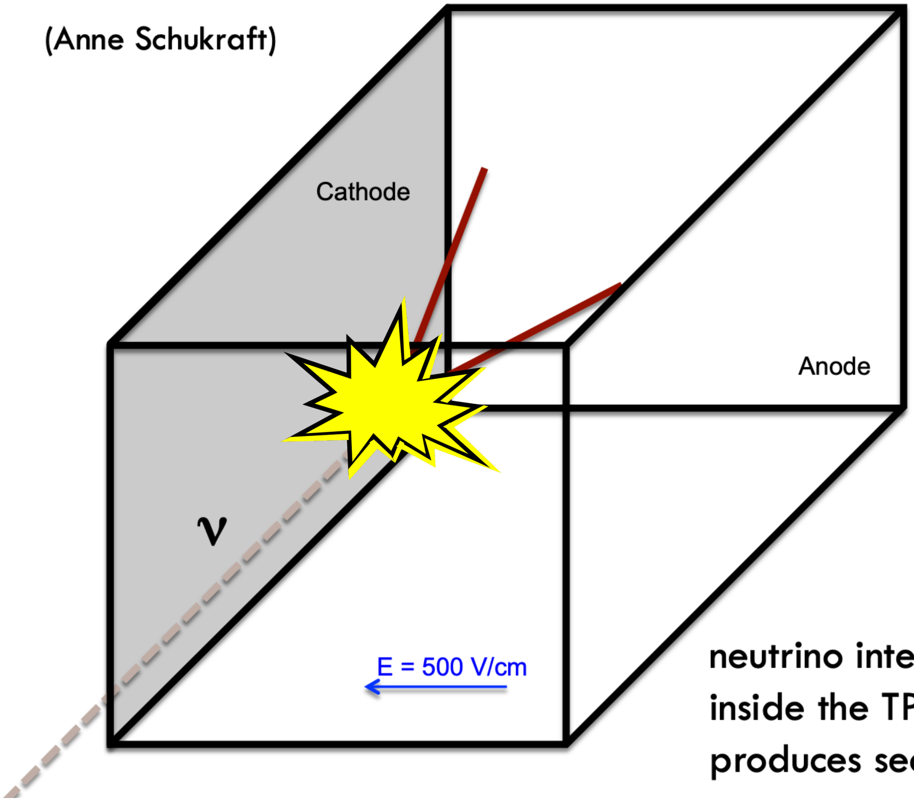



liquid argon detectors work differently than scintillator detectors so their “pictures” look different

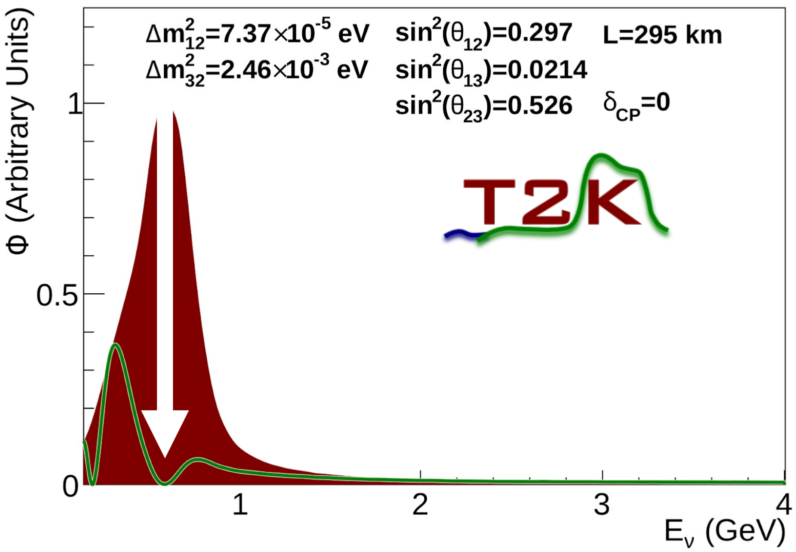
neutrino interacts with the argon inside the TPC volume and produces secondary particles

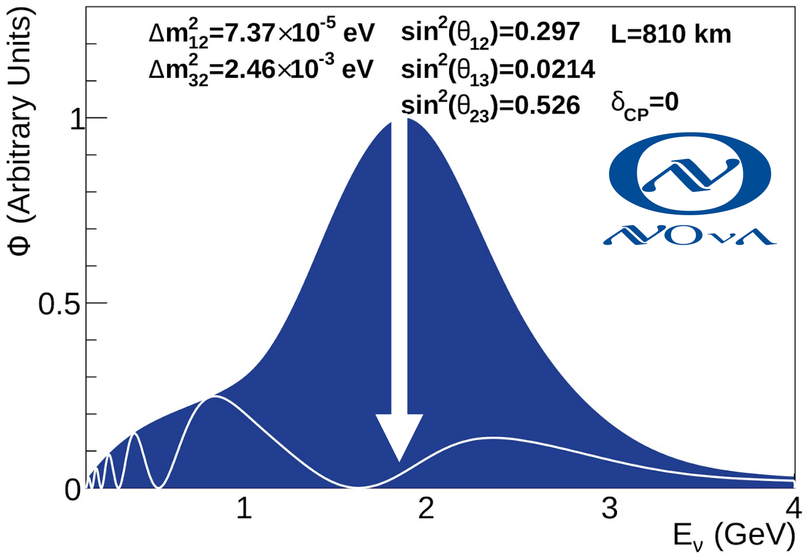
# How The Flux of Muon Neutrinos Changes in NOvA and T2K



- Both experiments are designed such that the neutrino flux is centred around the first oscillation maximum.
  - Most $\nu_\mu$'s oscillate away.
  - Maximal appeared $\nu_e$ flux.
  - Neither experiment directly measures the $\nu_\tau$'s which dominate the FD flux – only observe though neutral current interactions.

**T2K $L_1$ = 295 km, $E_{peak}$ = 0.6 GeV → L/E = 490 km/GeV**
**NOvA $L_1$ = 810 km, $E_{peak}$ = 1.9 GeV → L/E = 425 km/GeV**

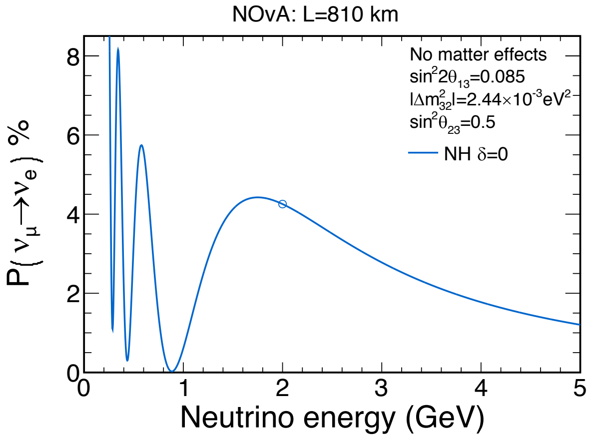


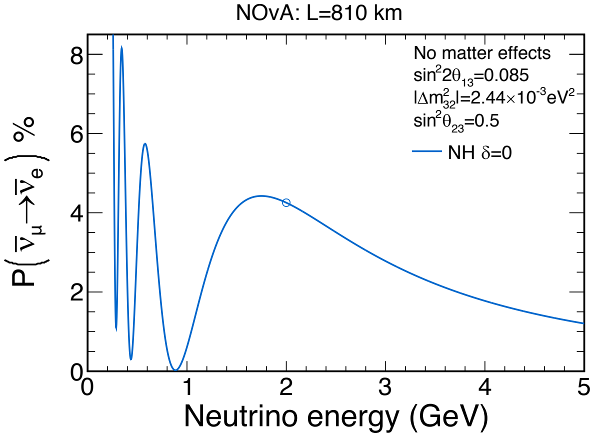
# How Oscillation Parameters Affect $\nu_e$ Appearance in NOvA

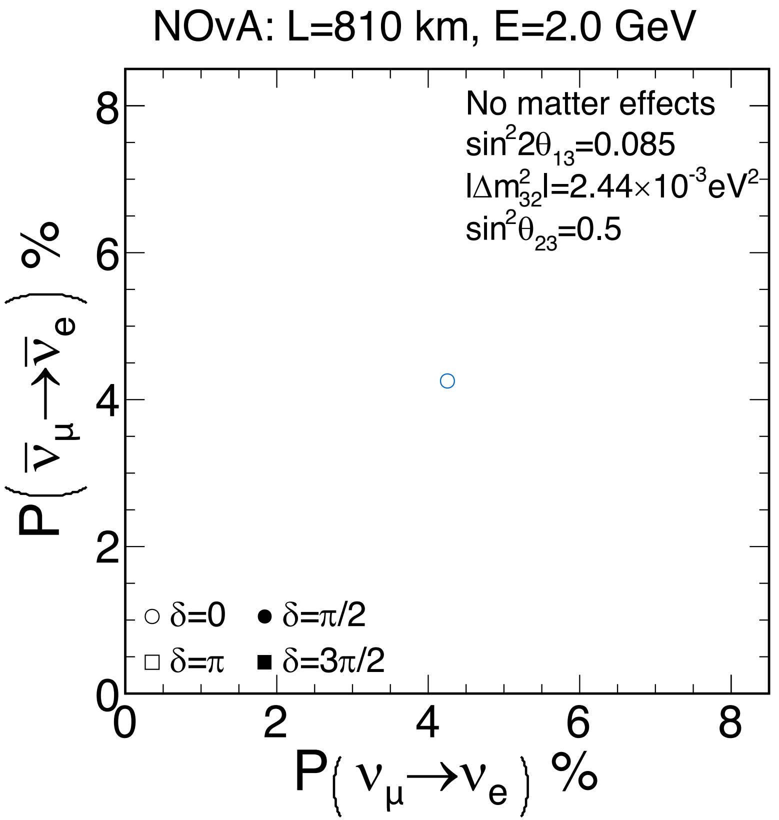


Neutrinos




Anti-Neutrinos



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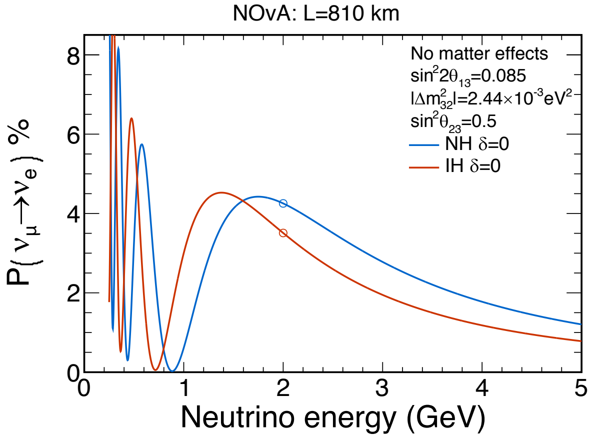
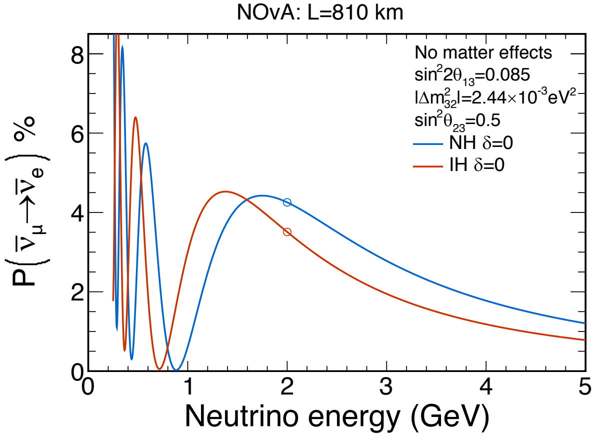
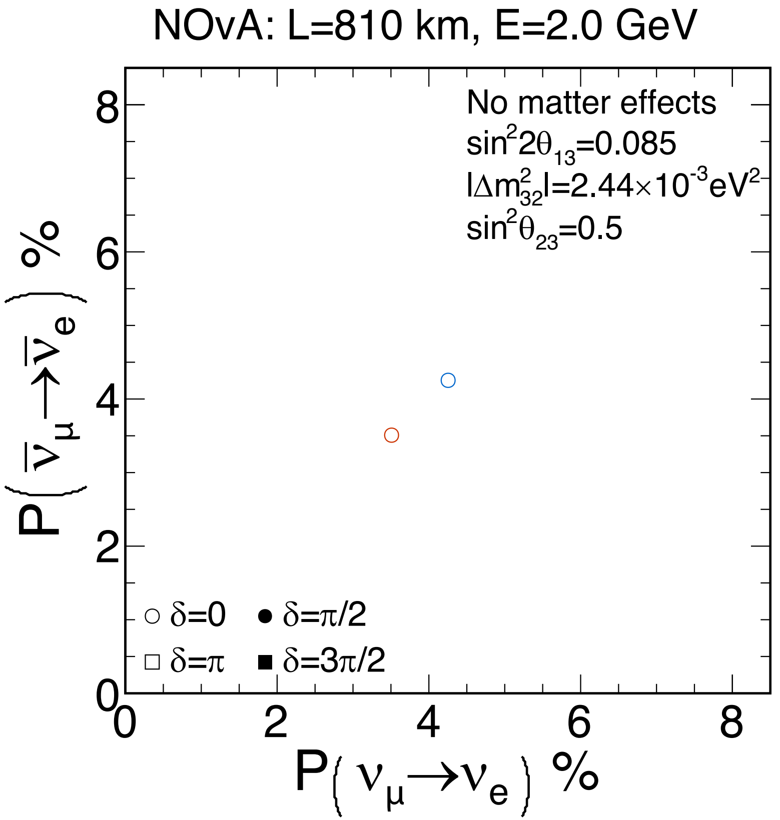



Anti-Neutrinos



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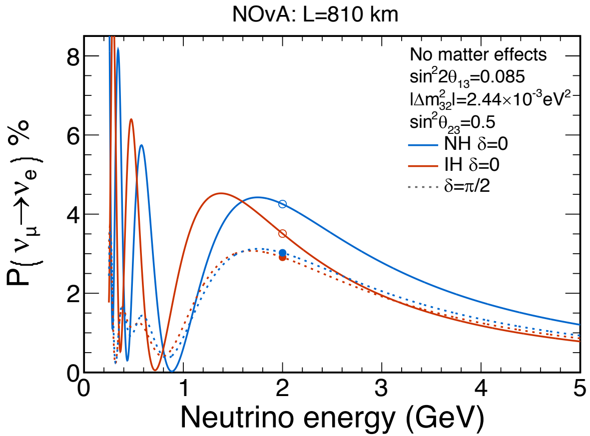
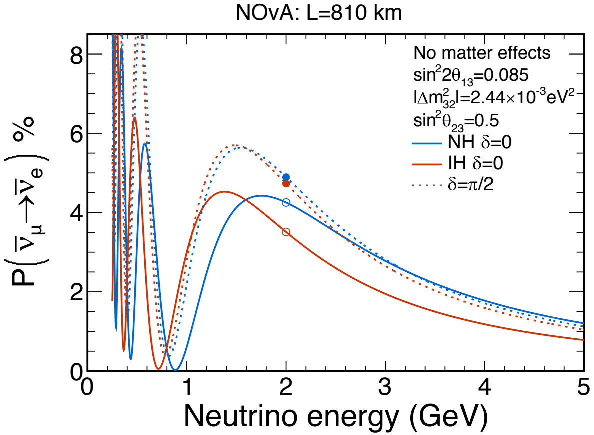
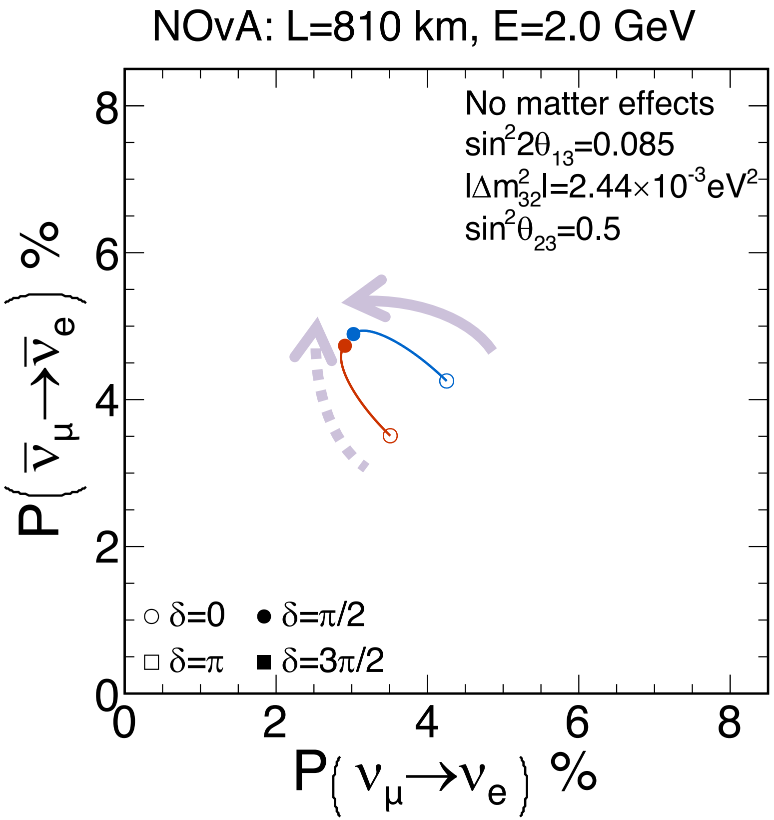



Anti-Neutrinos



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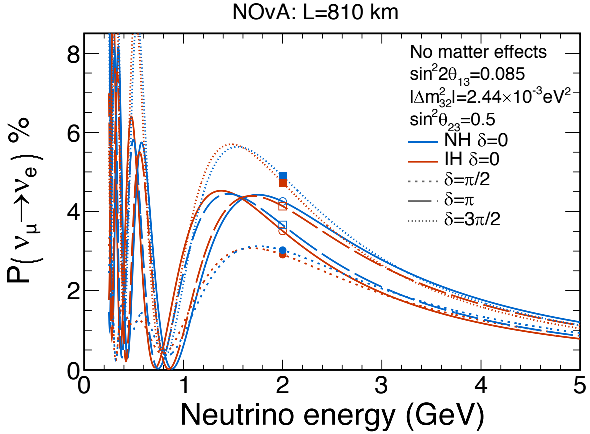
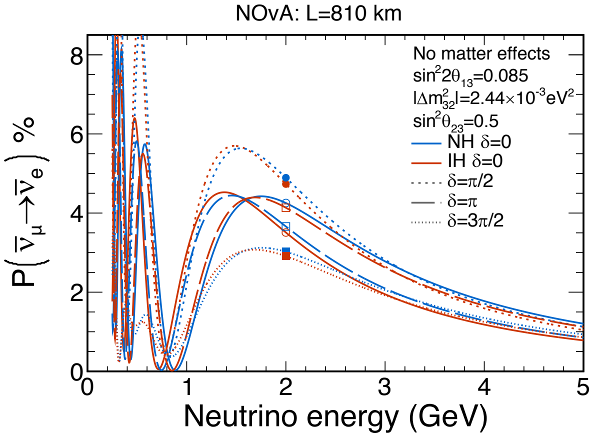
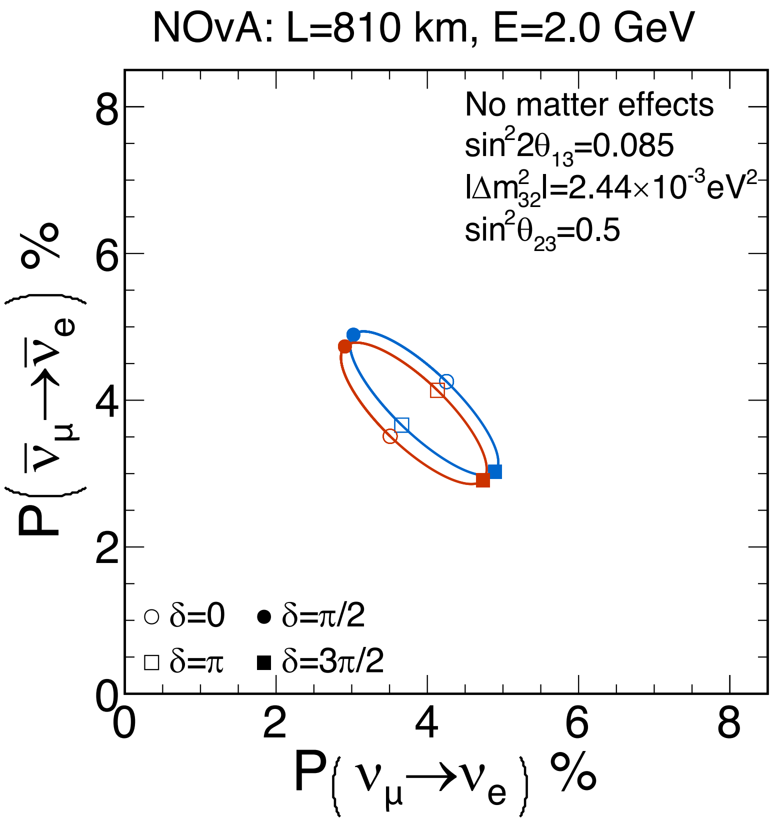
Neutrinos




Anti-Neutrinos

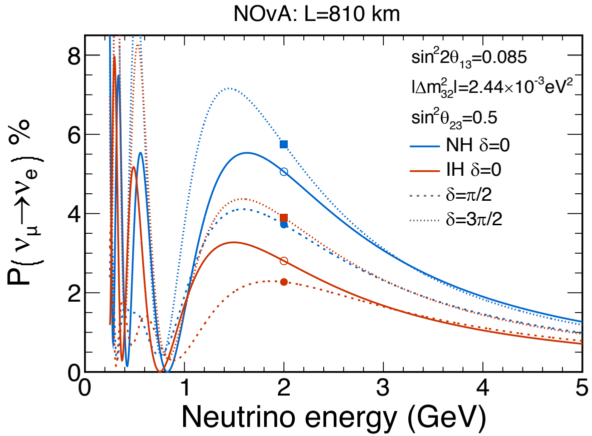


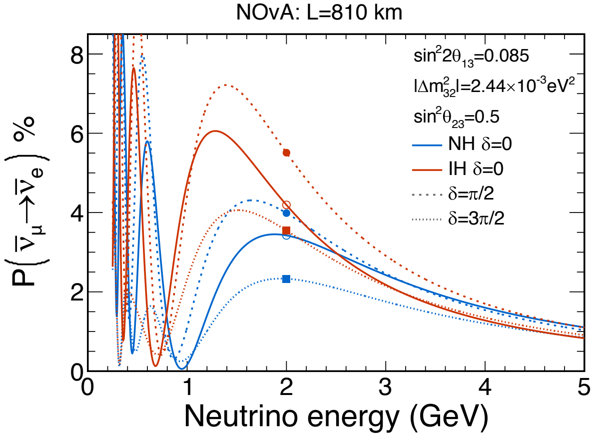
# How Oscillation Parameters Affect $\nu_e$ Appearance in NOvA

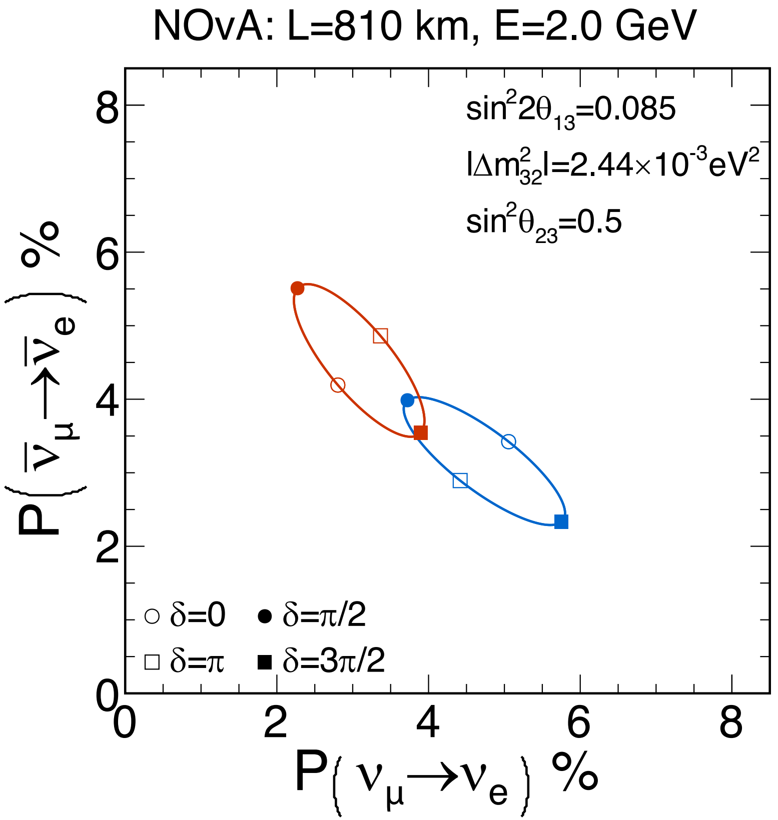


Neutrinos




Anti-Neutrinos

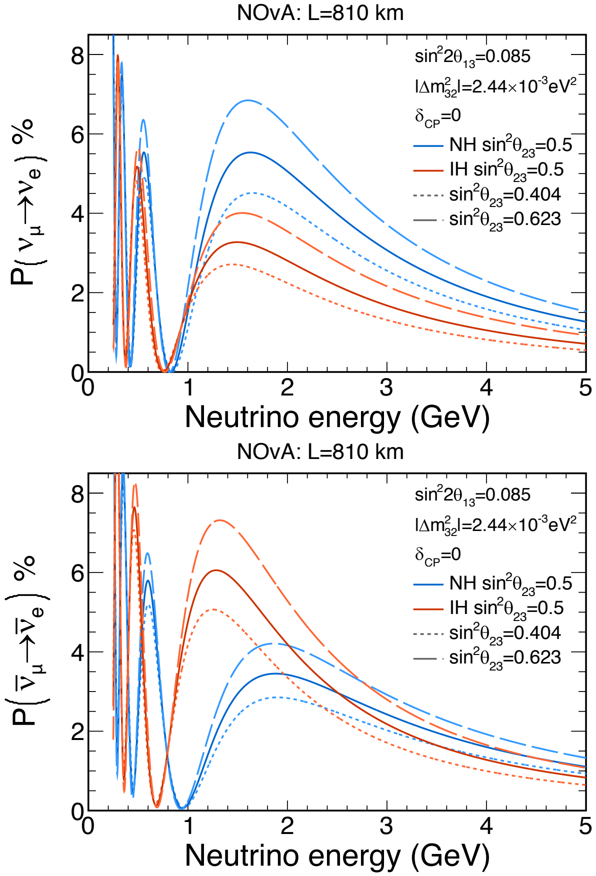


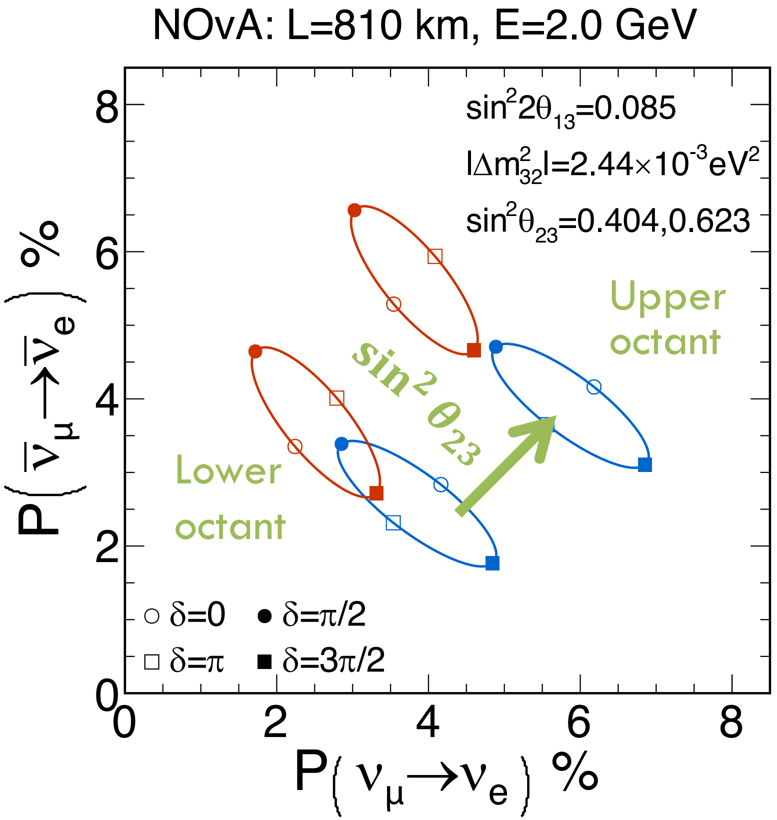



# How Oscillation Parameters Affect $\nu_e$ Appearance in NOvA

Neutrinos

Anti-Neutrinos



# Performing A Neutrino Oscillation Analysis

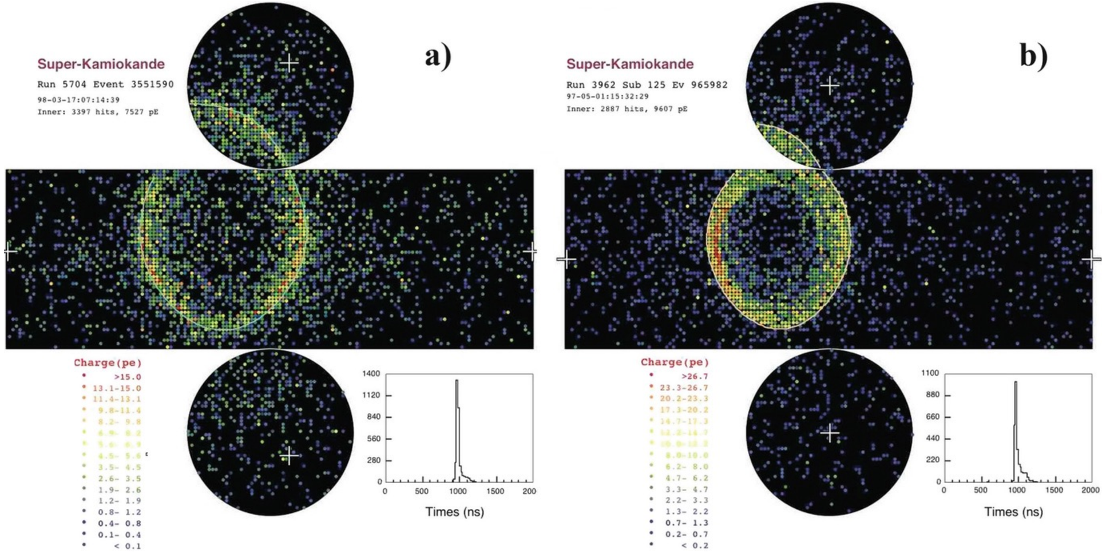


- Long-baseline neutrino oscillation experiments perform two sets of measurements;
  - Measure interactions before oscillations can occur at a Near Detector, using this data to study neutrino interactions.
  - Measure interactions after oscillations have occurred at a very large Far Detector, using this data to extract oscillation parameters.

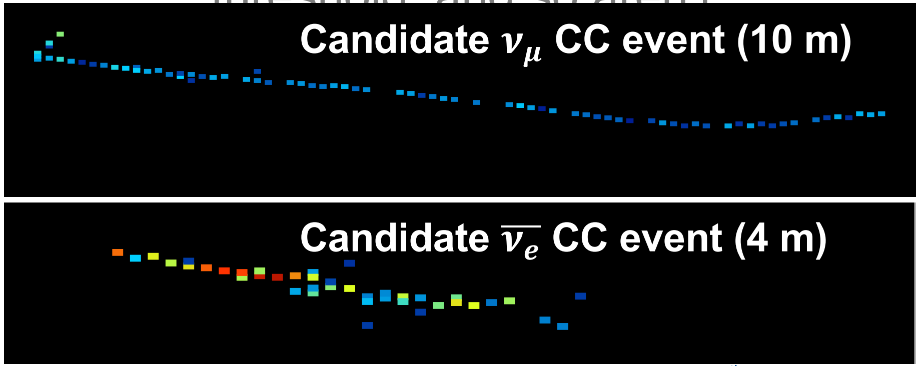
- NOvA and T2K have a number of differences both in design and approach.
  - These differences make their results very complementary and allow for a thorough test of neutrino physics measurements.

| ***Factor*** | ***Invert for $\bar{\nu}$*** | ***Effect of NOvA*** | ***Effect on T2K*** | ***Explanation*** |
| --- | --- | --- | --- | --- |
| *Mass Ordering* | *Yes* | $\pm\mathbf{19}\%$ | $\pm 10\%$ | *Binary, NOvA has longer Baseline.* |
| *CP Violation* | *Yes* | $[-20\ldots+20]\%$ | $[\mathbf{-30}\ldots\mathbf{+30}]\%$ | *Continuous, T2K beam energy closer to 1st Osc. Max.* |
| $\theta_{23}$ *Octant* | *No* | $[-20\ldots+20]\%$ | $[-20\ldots+20]\%$ | *Continuous and unbounded effect on Osc. rate.* |

# Example Far Detector Neutrino Interactions

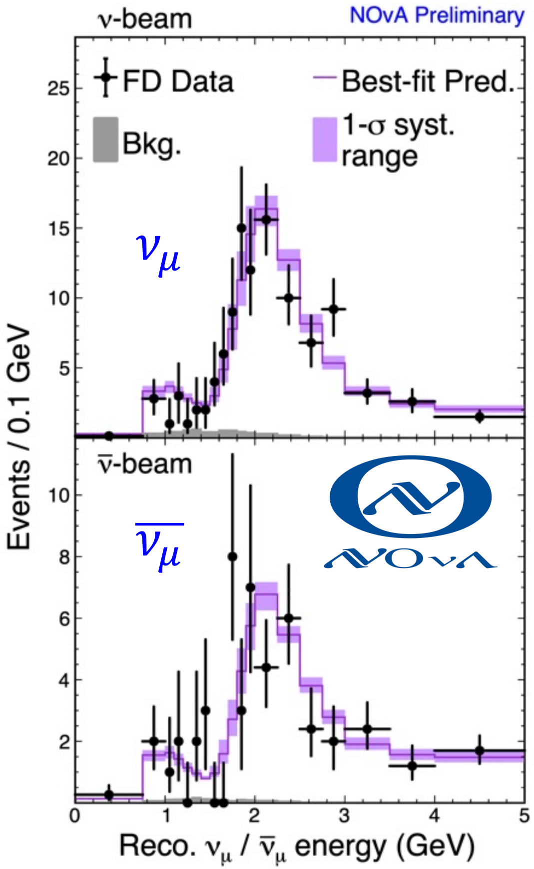


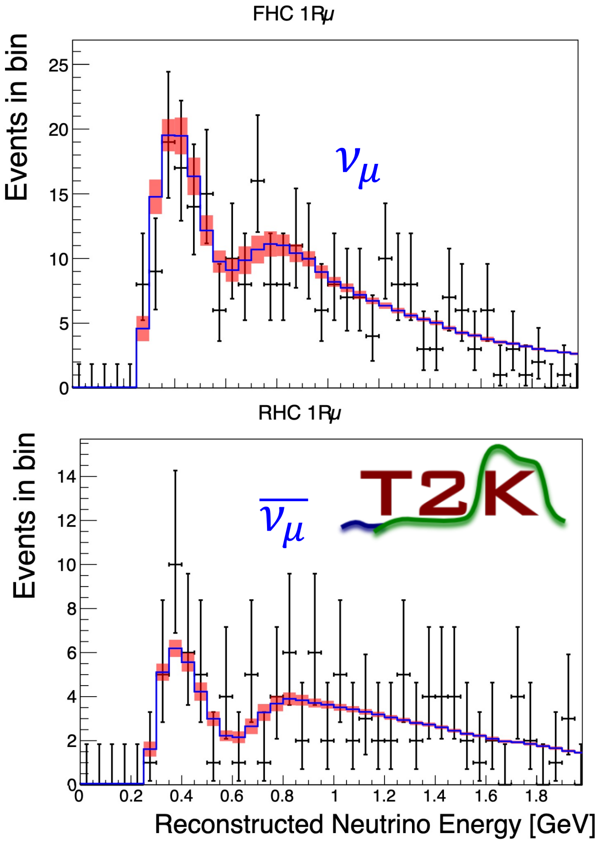

- Ring characteristics to identify neutrino flavour.
  - Electrons produce "fuzzy" rings.
  - Muons product "sharp" rings.
- Hadronic activity (protons) are below the Cherenkov threshold, and so aren't




- Outgoing charged lepton cluster to identify neutrino flavour.
  - Muons produce long, straight tracks.
  - Electrons create shorted, shower-like clusters of hits.
- It is possible to identify hits from hadronic activity.
  - Improves $E_{res}$ and minimises cross-section and FSI uncertainties.

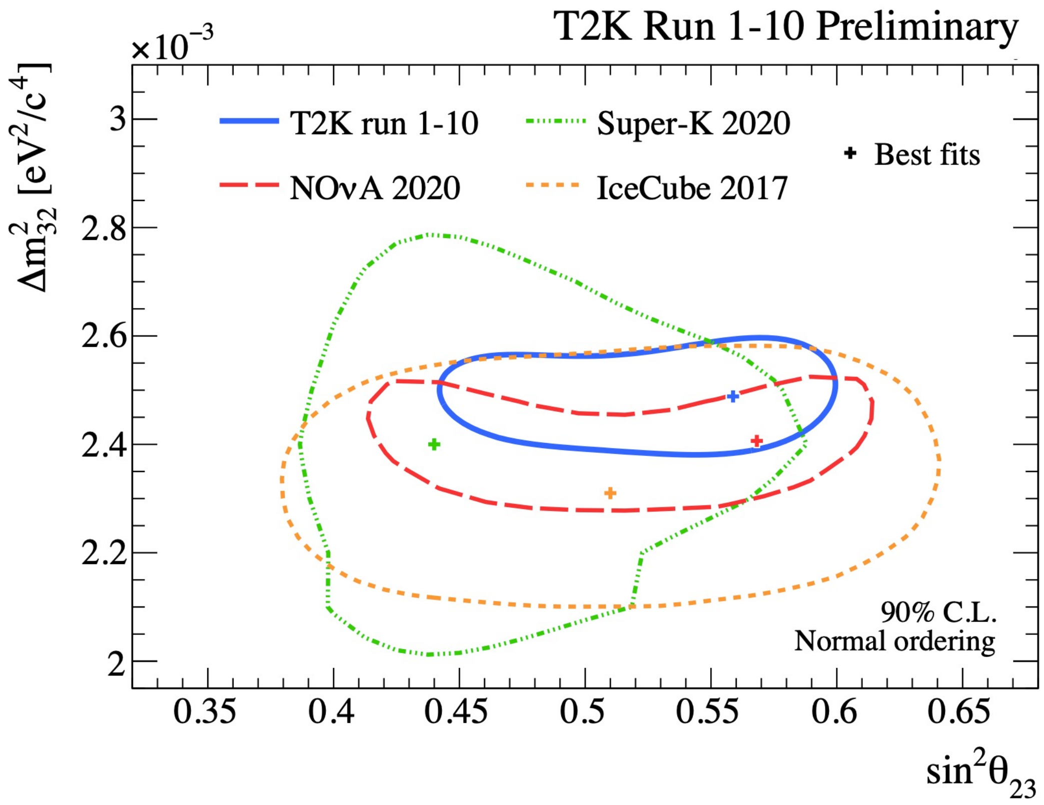
# Performing The $\nu_\mu$ Disappearance Analysis



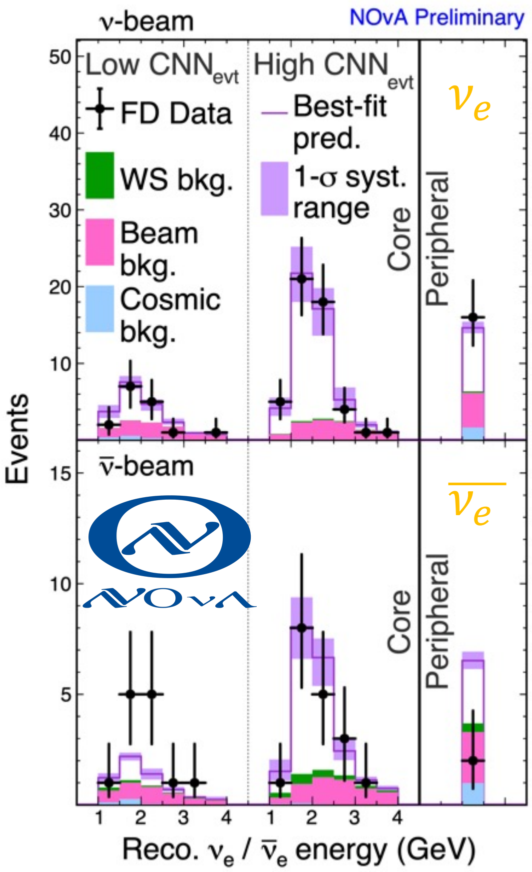

- Measure $\nu_\mu$ interactions in $\nu$ & $\bar{\nu}$ modes.
- Both experiments see clear disappearance signal in both samples.
  - The no oscillation prediction would be approaching >1k events for each experiment.
- Despite their different design choices achieve complementary sensitivity.

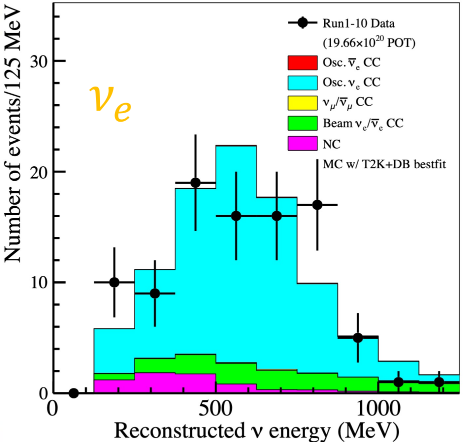
# The $\nu_\mu$ Disappearance Constraints

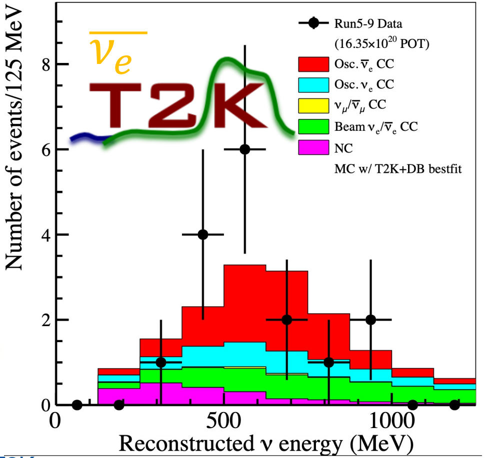



- Largely consistent phase spaces.
  - Neither exclude maximal mixing, though both have a best fit point in the upper octant.
  - Global average precision on $|\Delta m^2_{32}|$ is 1.1% for a given mass ordering.
- NOvA provides a slightly tighter constraint on the mass-squared splitting.
- T2K provides a slightly tighter constraint on the mixing angle.

# Performing The $\nu_e$ Appearance Analysis



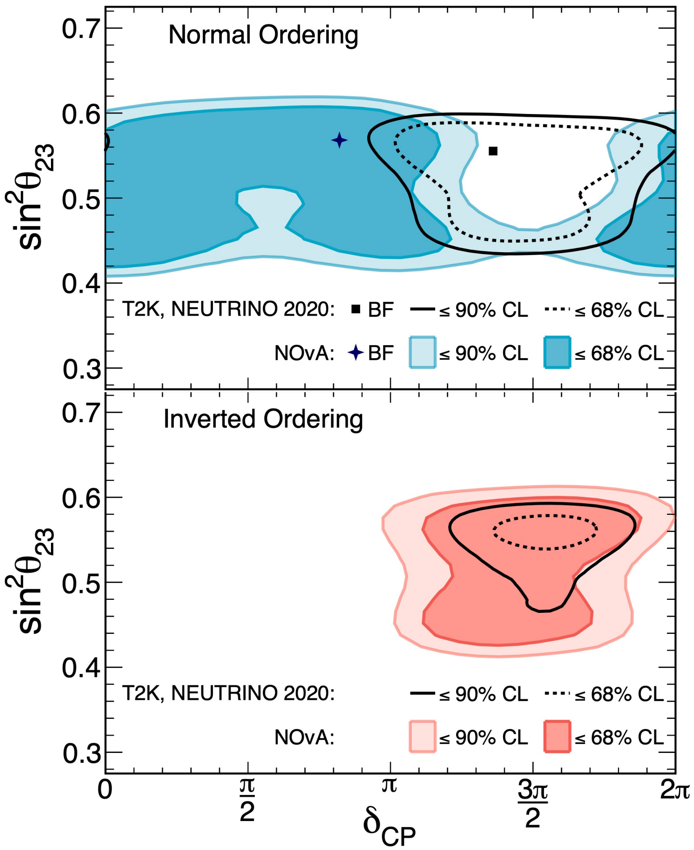




- Measure $\nu_e$ interactions in $\nu$ & $\bar{\nu}$ modes.
- Both experiments see clear appearance signal.
  - NOvA sees $> 4\sigma$ evidence of $\overline{\nu_e}$ appearance.
  - T2K also has a $1e1\pi$ sample in neutrino mode, where they tag the Michel electron from pion decay.
- Use appearance measurements to extract the value of $\delta_{CP}$ and the neutrino mass ordering.
  - NOvA generally has good sensitivity to $\nu MO$, but it can be difficult to ascertain for certain $\delta_{CP}$ values.

# The $\nu_e$ Appearance Constraints






- Both analyses include a constraint on $\theta_{13}$ from reactor expts.
- Both experiments favour the normal hierarchy.
  - Consistent ranges of $\theta_{23}$.
  - Very different $\delta_{CP}$ regions.
- In the disfavoured inverted hierarchy, they have better agreement for $\delta_{CP}$.

***NOvA Best Fit Point***

*Normal Hierarchy*

$\Delta m^2_{32} = (2.41 \pm 0.07)\times 10^{-3}\ eV^2$

$\sin^2\theta_{23} = 0.57^{+0.04}_{-0.03}$

$\delta_{CP} = 0.82\pi$

***T2K Best Fit Point***

*Normal Hierarchy*

$\Delta m^2_{32} = (2.49^{+0.06}_{-0.08})\times 10^{-3}\ eV^2$

$\sin^2\theta_{23} = 0.546^{+0.024}_{-0.046}$

$\delta_{CP} = 1.37\pi$