# Introduction to Neutrino Physics

Karl Warburton (Iowa State University)

15th June 2021

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 3.5 years, but I'm based here at Fermilab.
  - Currently working on Supernova triggering in DUNE.
  - Currently working on neutrino oscillation measurements in NOvA, and also in charge of the Deep Learning and Reconstruction group.

🔷 **Fermilab**
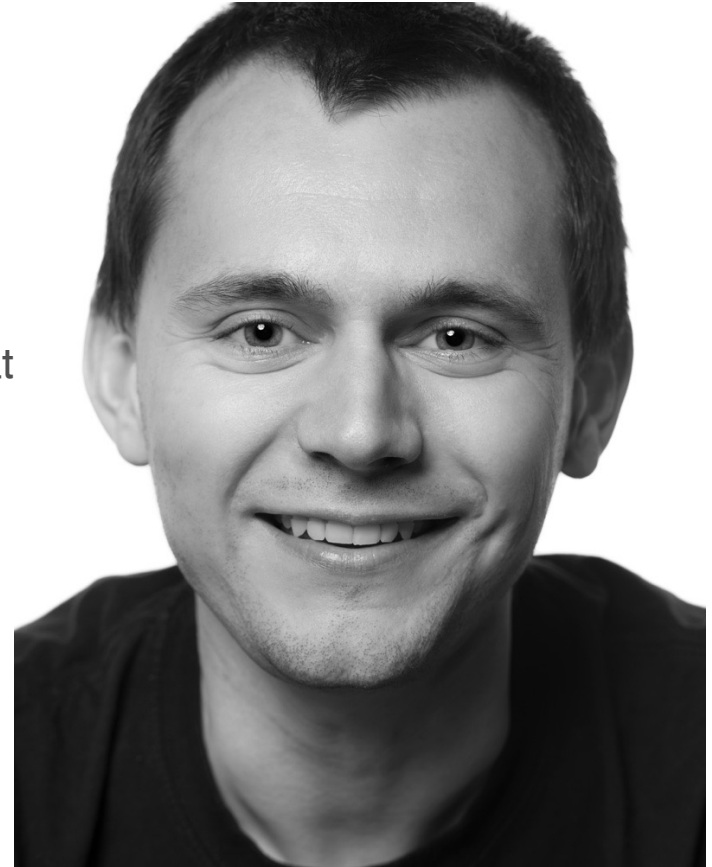
Who am I really?

- 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.
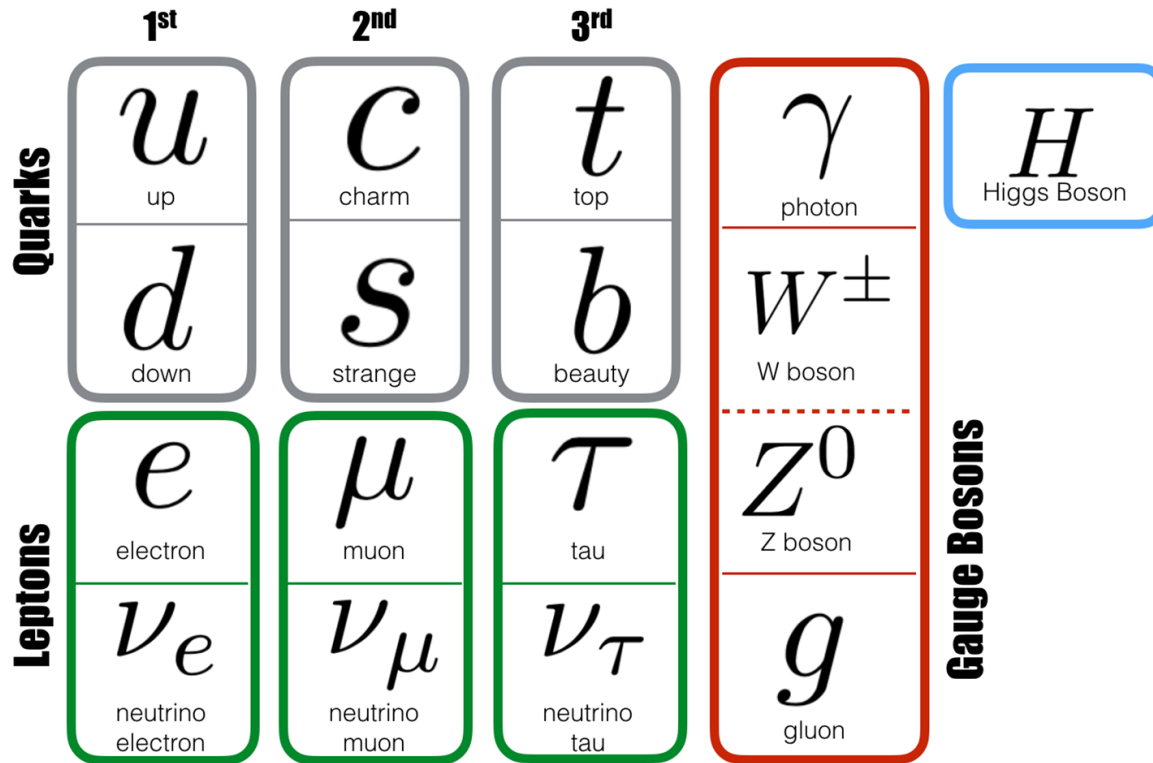
🟦 **Fermilab**
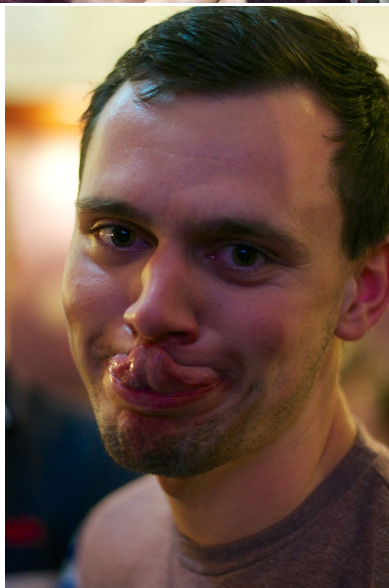
Outline

- 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

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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.
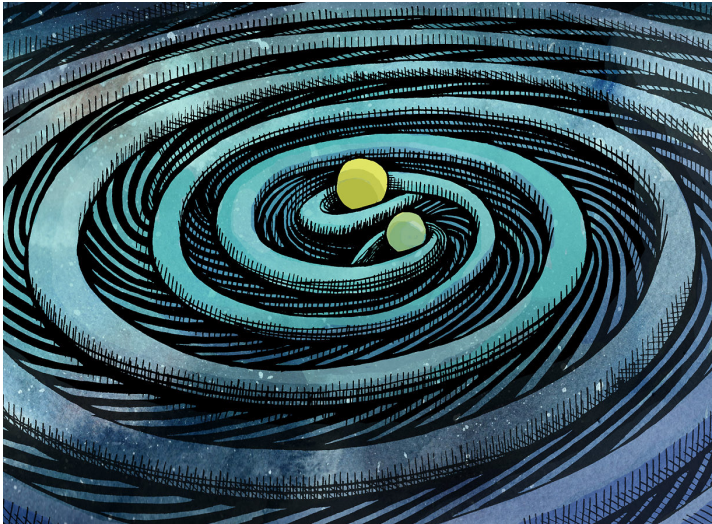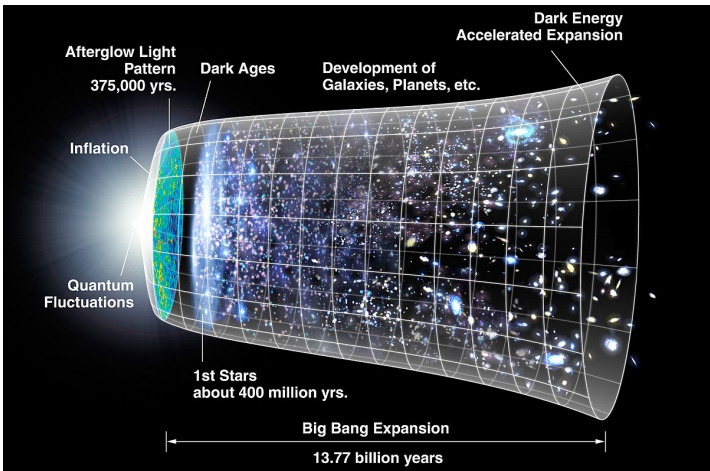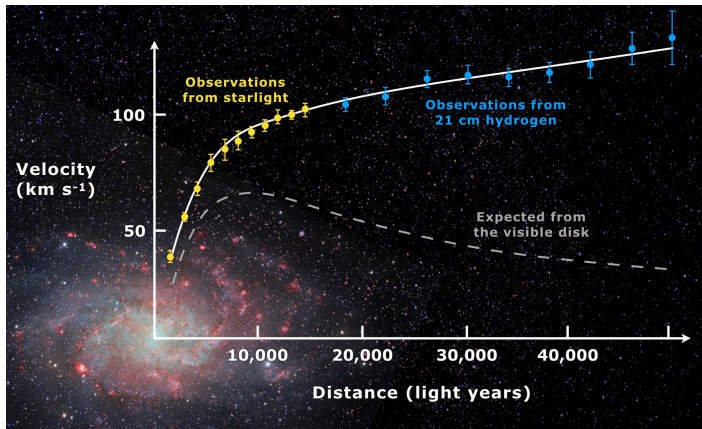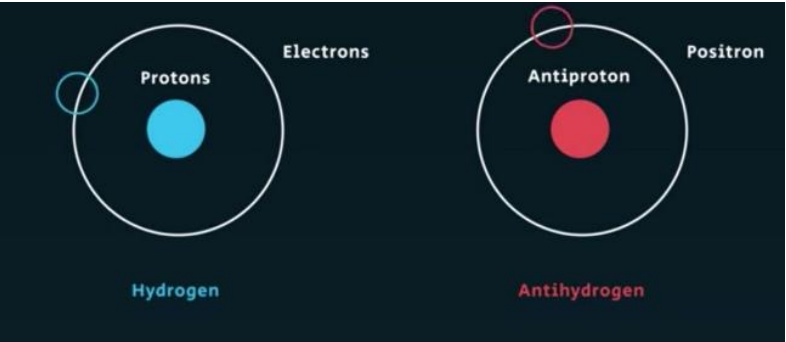 - But we know that it's wrong!

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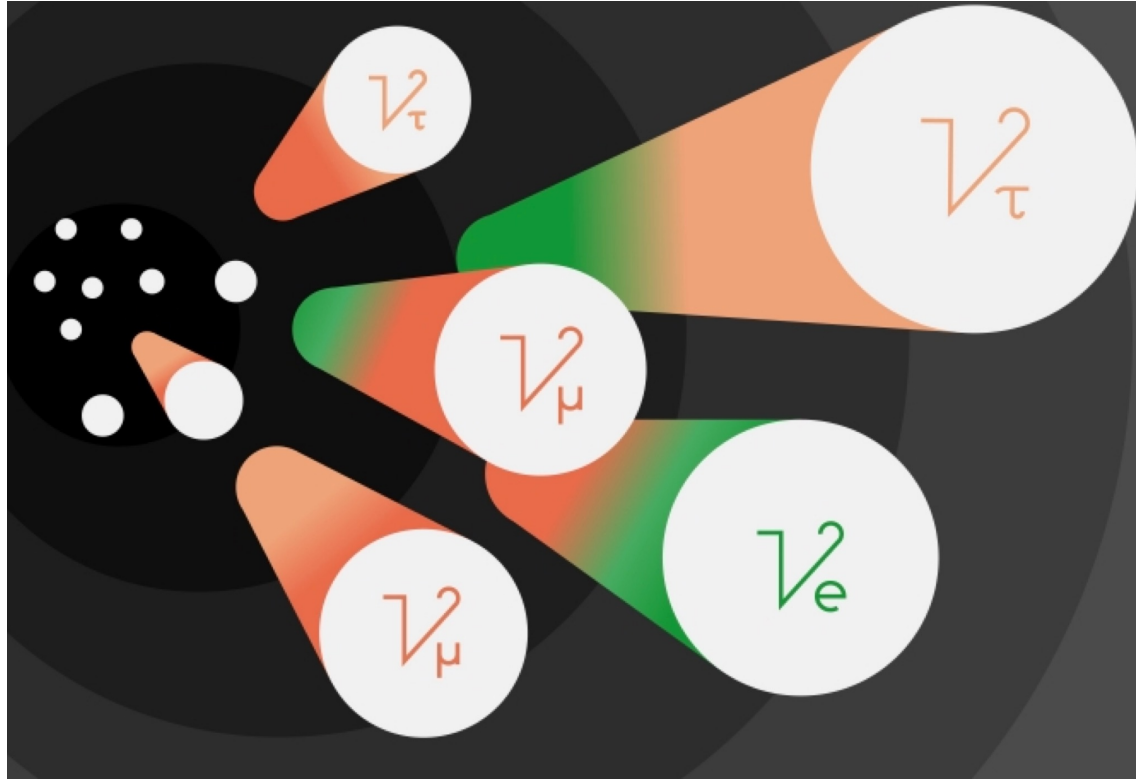# What Does The Standard Model Not Explain?

Where is all of the anti-matter?

What is dark matter?

What is dark energy?
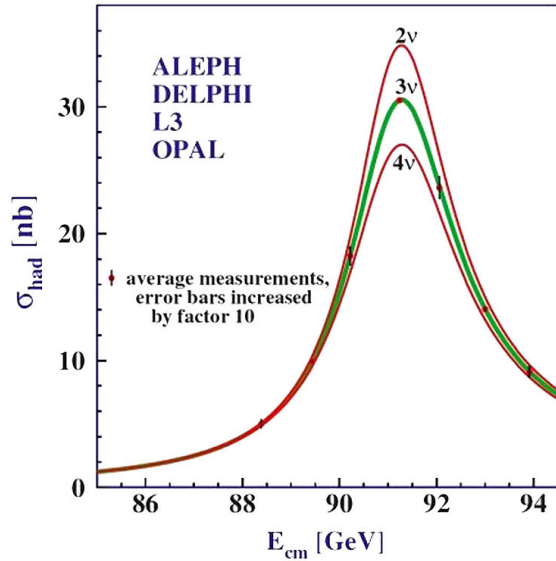
How do we explain gravity?

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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…

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

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.

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

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

ALEPH DELPHI L3 OPAL

average measurements, error bars increased by factor 10

However, some experiments have made measurements which suggest additional "*sterile*" neutrino states to those described by the standard model.
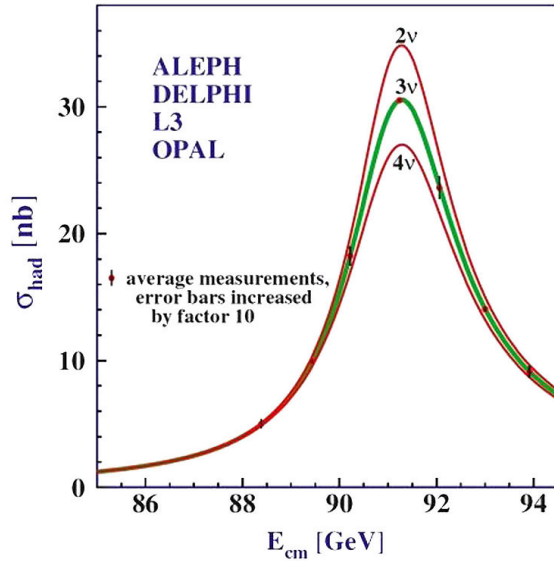
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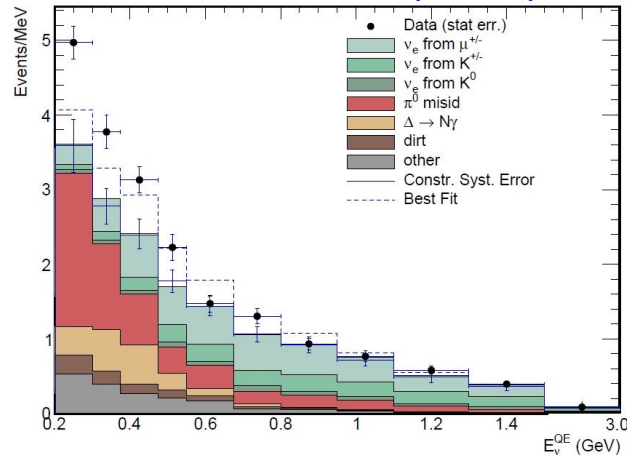
Very accurate measurements have been made showing that there are exactly 3 "*active*" flavor states.

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*).
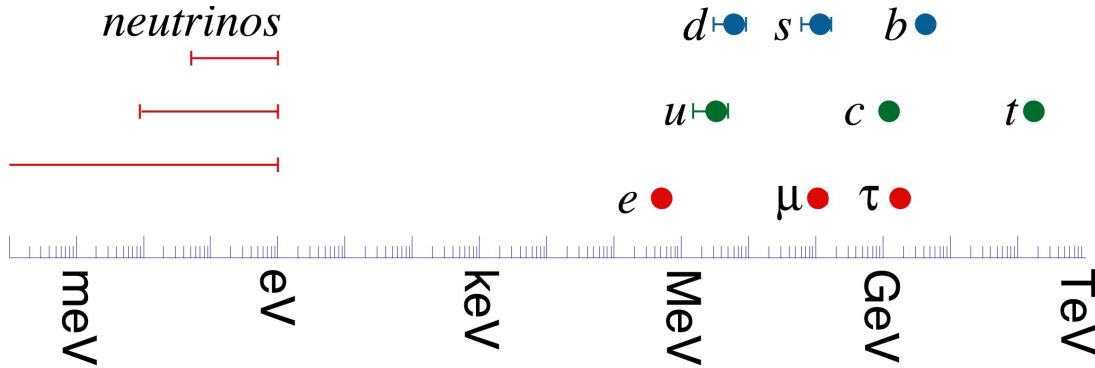
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What Is The Neutrino Mass Scale?

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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What Is The Neutrino Mass Scale?

neutrinos

d s b

u c t

e μ τ
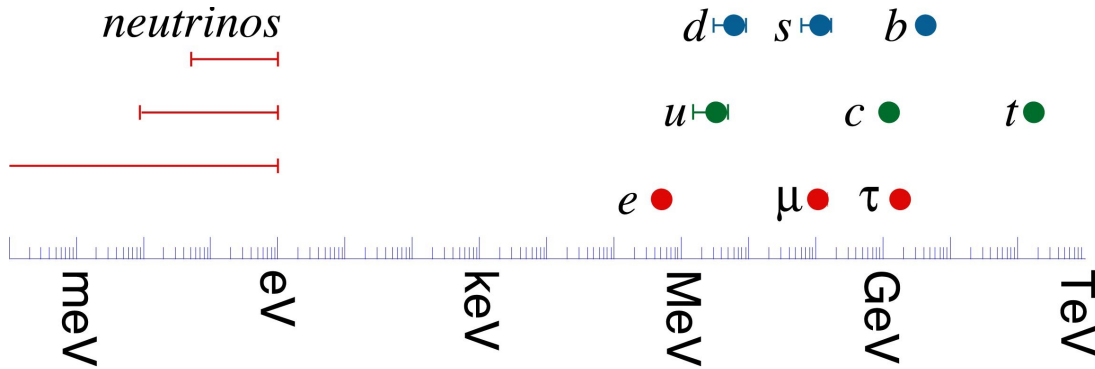
meV   eV   keV   MeV   GeV   TeV

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)

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

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a)

relative decay amplitude

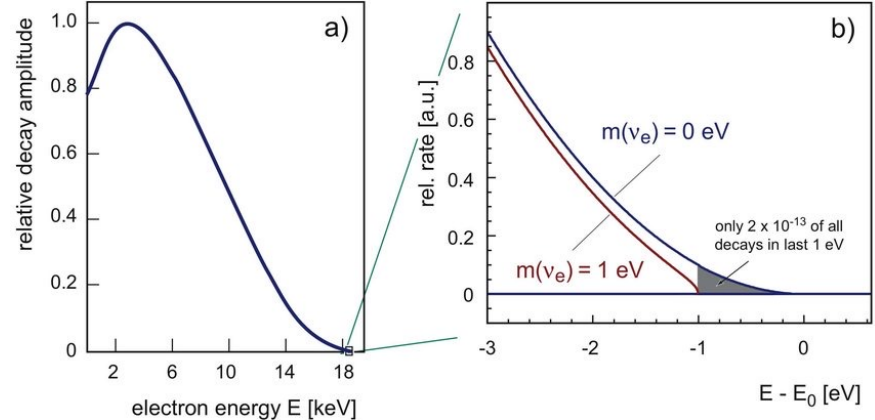electron energy E [keV]

b)

rel. rate [a.u.]

$m(\nu_e) = 0$ eV

only 2 x 10^{-13} of all decays in last 1 eV

$m(\nu_e) = 1$ eV

E - E$_0$ [eV]

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What produces neutrinos? … Pretty much everything!

The Big Bang, so many were produced that there currently there are still about 300 cm^{-3}.

99% of the energy from a Supernovae is neutrinos!
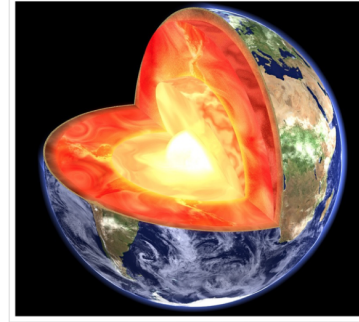
Any time there is a nuclear reaction;

- 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!!!

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How Often Do Neutrinos Interact? … Pretty much never!

- Most particles interact quite readily, but not neutrinos!
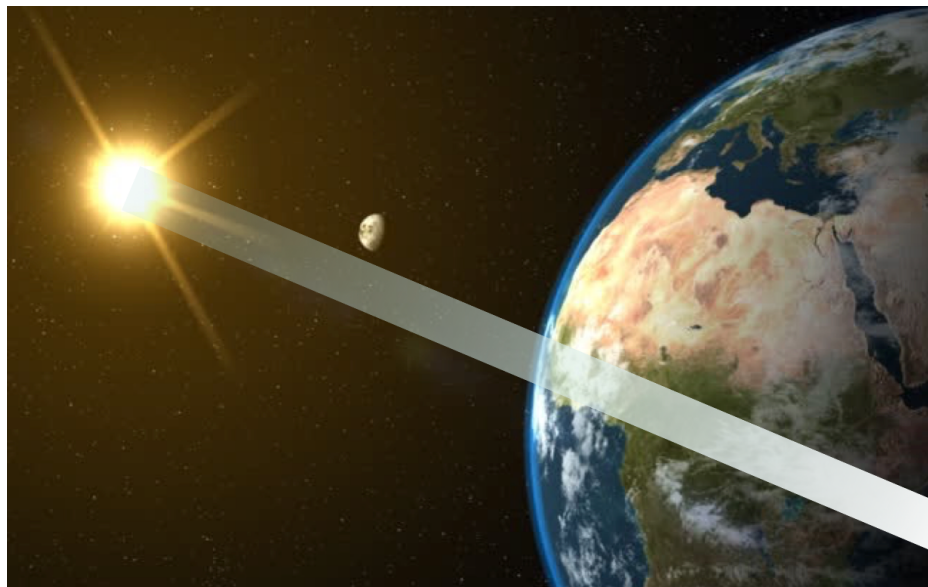
- We'll explain why on the next slide, but neutrinos could easily travel through 200+ Earths before interacting!
  - For reference, an electron is often stopped by a few inches of material.

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A Bit Of History

 Karl Warburton, Introduction to Neutrino Physics

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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The discovery of neutrinos – Is nature broken!?

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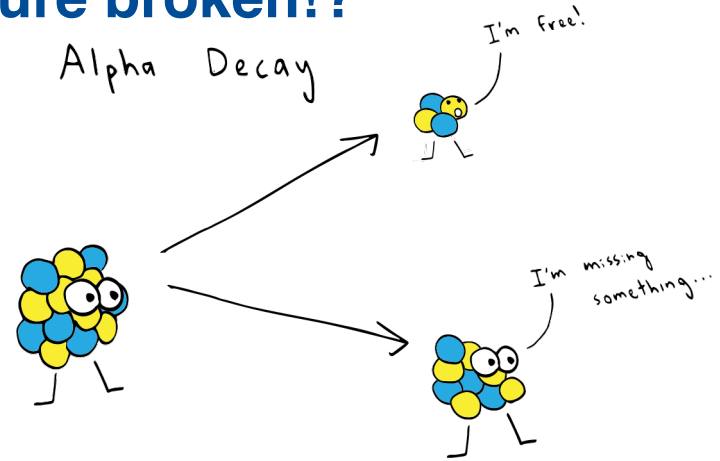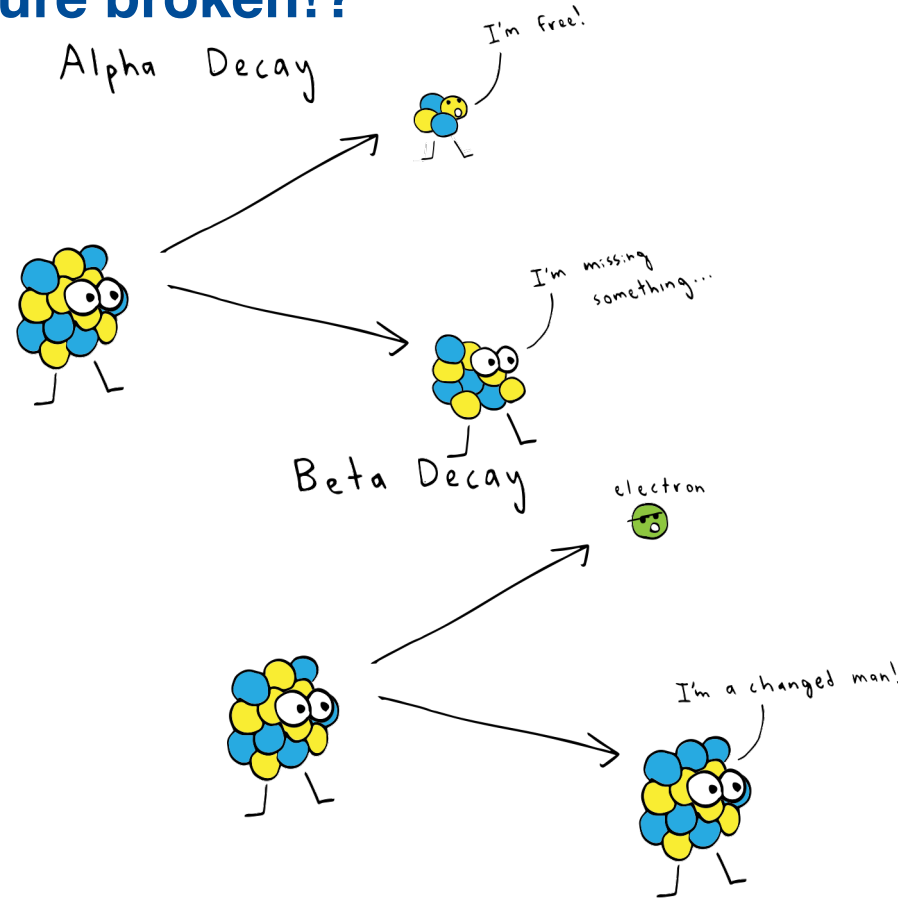
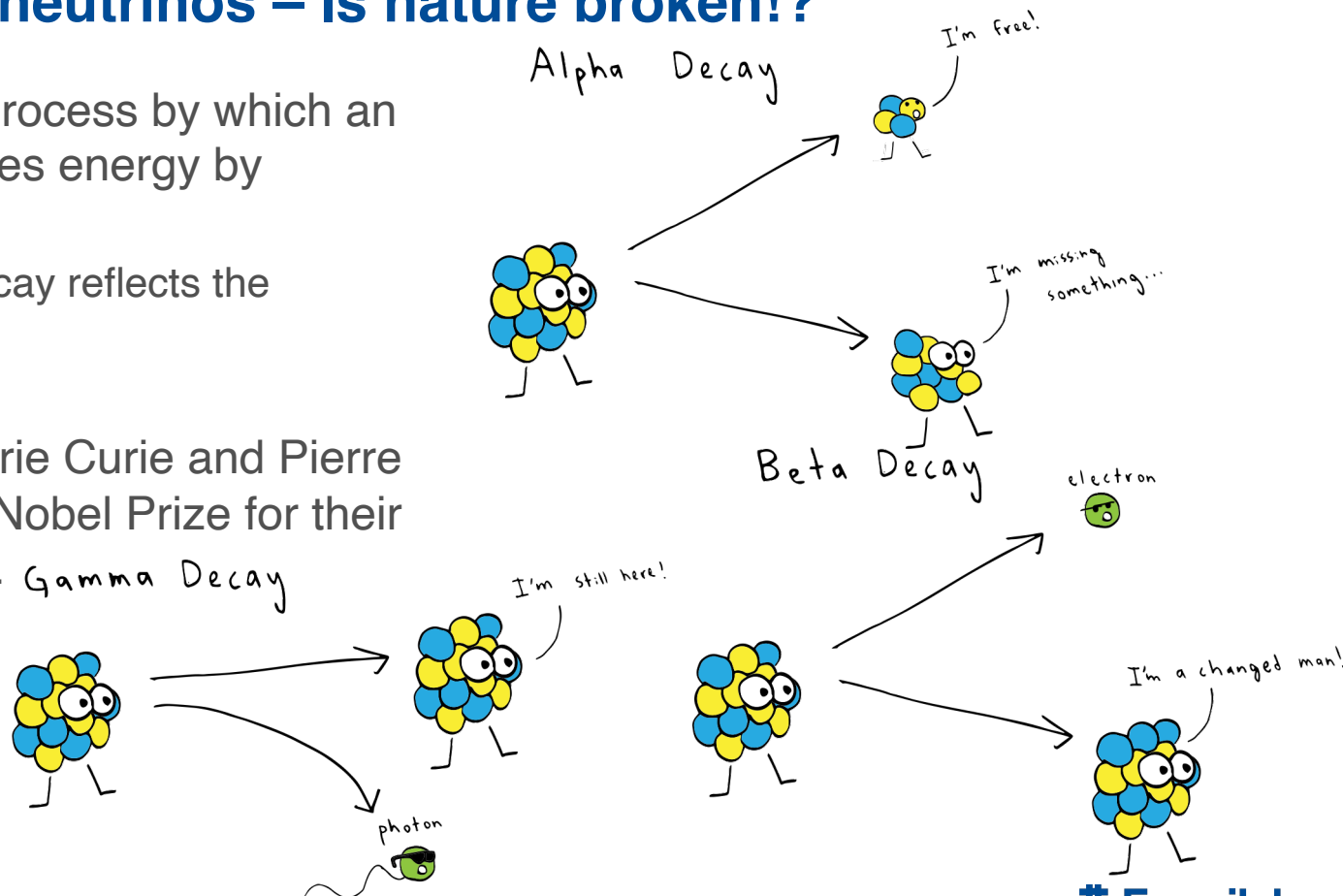# The discovery of neutrinos – Is nature broken!?

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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.

e^-

$^{14}_{6}\text{C}$ $^{14}_{7}\text{N}$ e^-

For instance: **Carbon** ➡ **Nitrogen** ➕ **Electron**

13,043.*94* MeV   13,043.*27* MeV   0.*511* MeV

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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.

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

$$^{14}_{6}C \longrightarrow \ ^{14}_{7}N \ + \ e^{-}$$

For instance:

Carbon	Nitrogen	Electron
13,043.*94* MeV	13,043.*27* MeV	0.*511* MeV
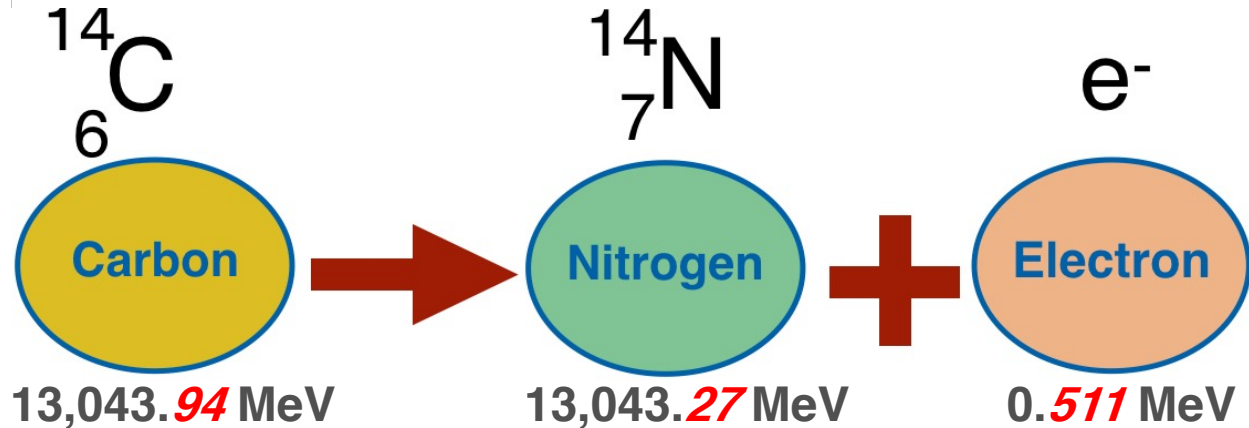
Beta decay is a simple Two Body Problem:

$$A \rightarrow B + C$$

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:

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

Expected from 2-body decay

electron kinetic energy (MeV)

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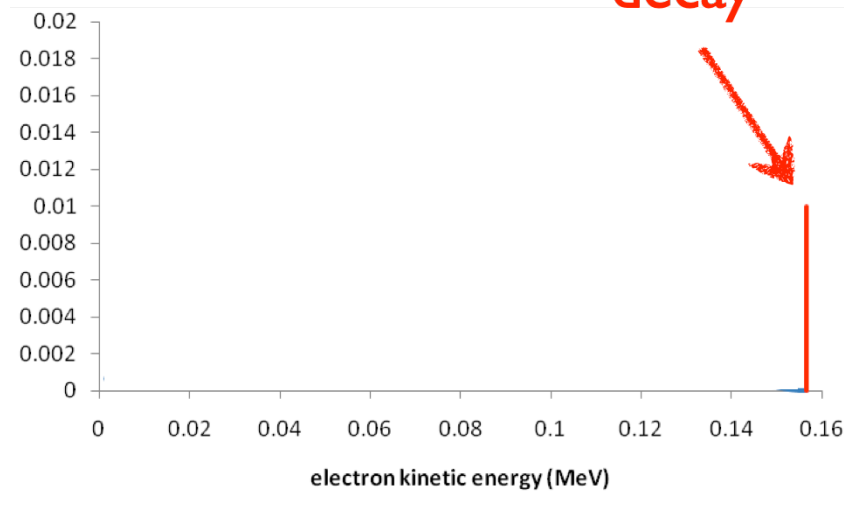
What Was Actually Observed

- 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!?***

Observed

Expected from 2-body decay

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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.

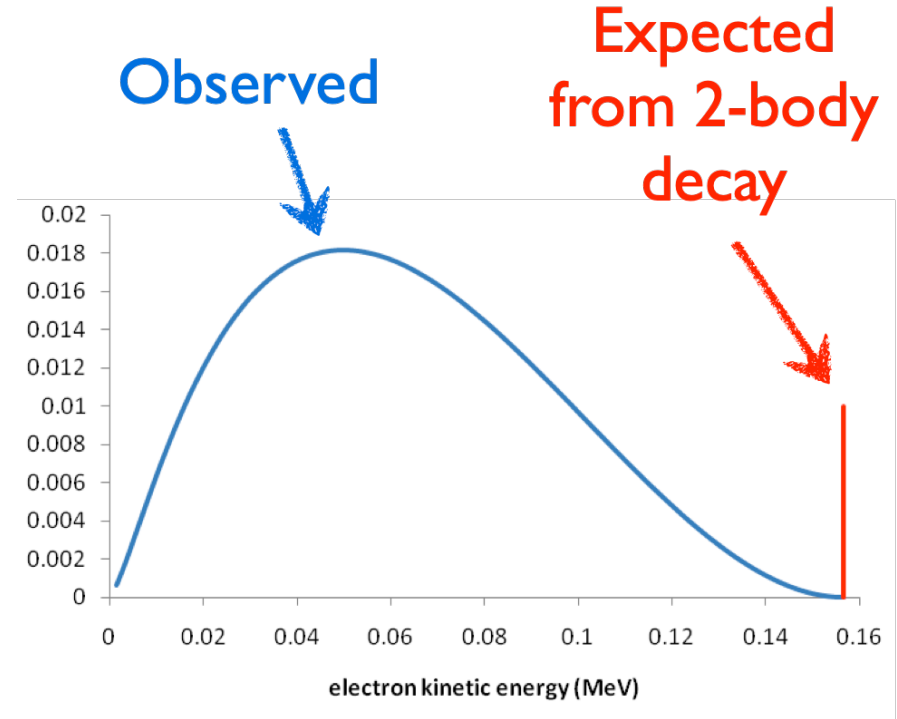(1936) Yukawa proposed W boson as a carrier of the weak force.

*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 ^6Li 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."

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What actually happens in beta decay then?
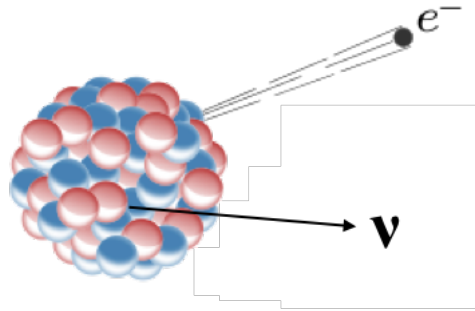
- A neutrino is emitted from the nucleus in addition to the electron.

- 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.

$^{14}_{6}$C $\quad$ $^{14}_{7}$N $\quad$ e- $\quad$ ν_{e-}

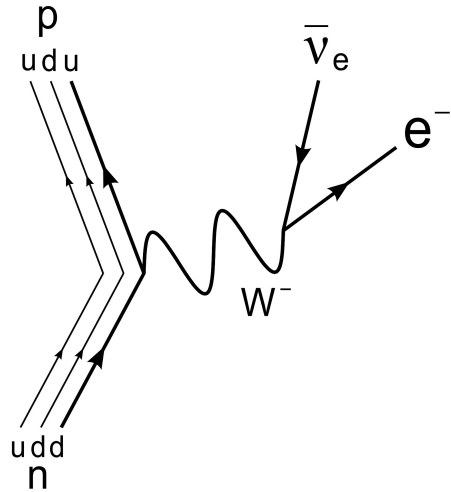Carbon ➡ Nitrogen ➕ Electron ➕ Neutrino

🔶 Fermilab
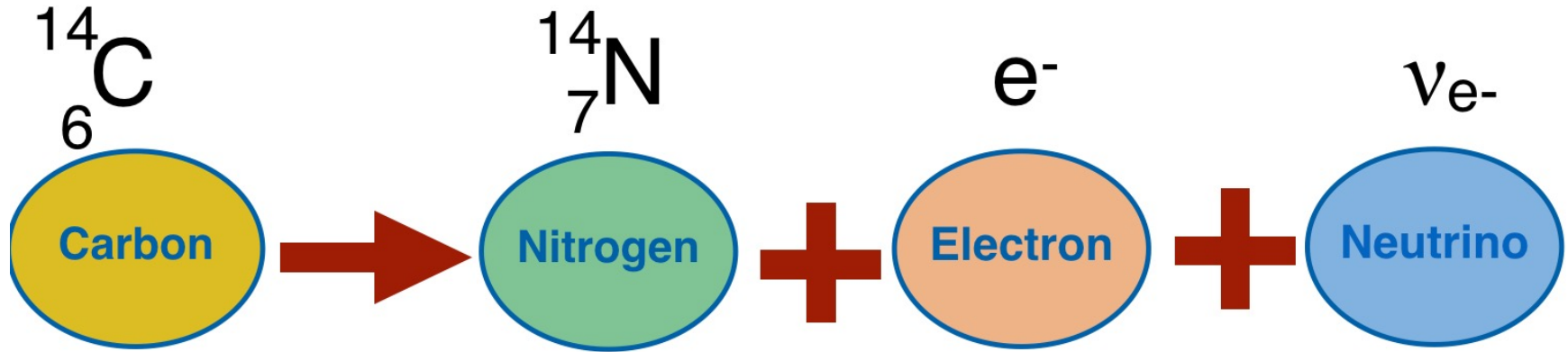
So how exactly do these "neutrino" things behave?

- 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?

🐝 **Fermilab**

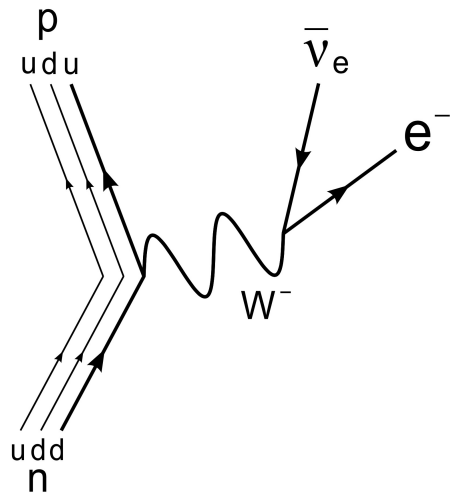# How do we produce neutrinos?

p
u d u

$\overline{\nu}_e$

e^-

W^-

u d d
n

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.

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How do we produce neutrinos?

p
u d u

$\overline{\nu}_e$

e⁻

W⁻

u d d
n

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.

Neutrinos are produced by beta decay, but getting a large enough sample of radioactive material isn't easy.
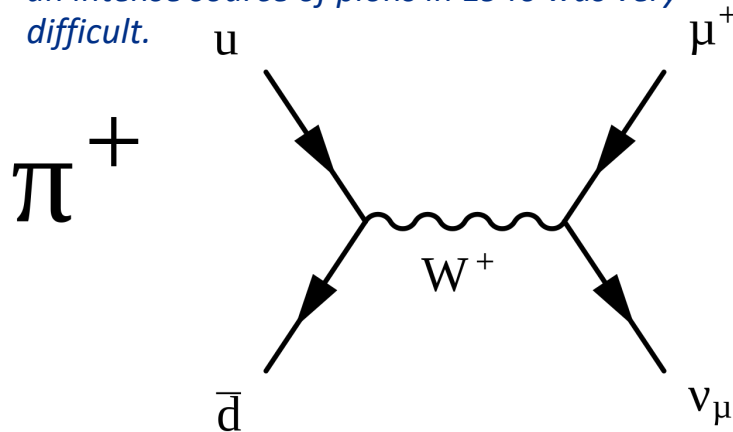*These neutrinos are also quite low energy.*

u

μ⁺

π^+

W⁺

$\overline{d}$

ν_μ

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How do we produce neutrinos?

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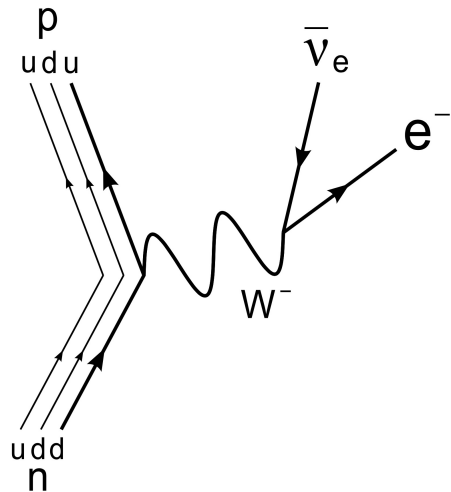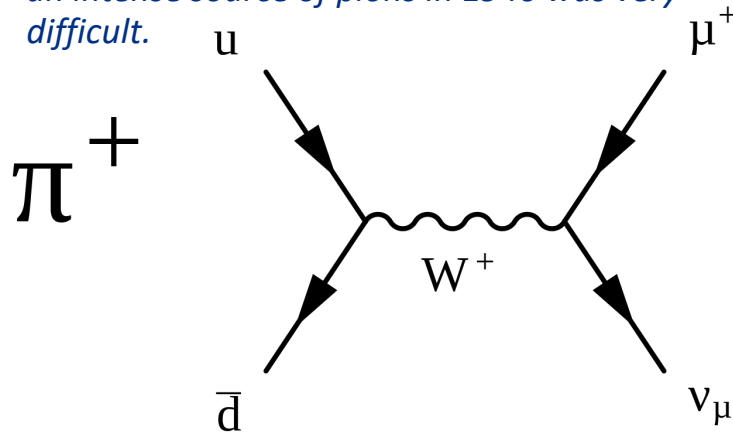They decay very quickly (26 ns), and almost exclusively produce a muon (heavy electron) and a muon neutrino.

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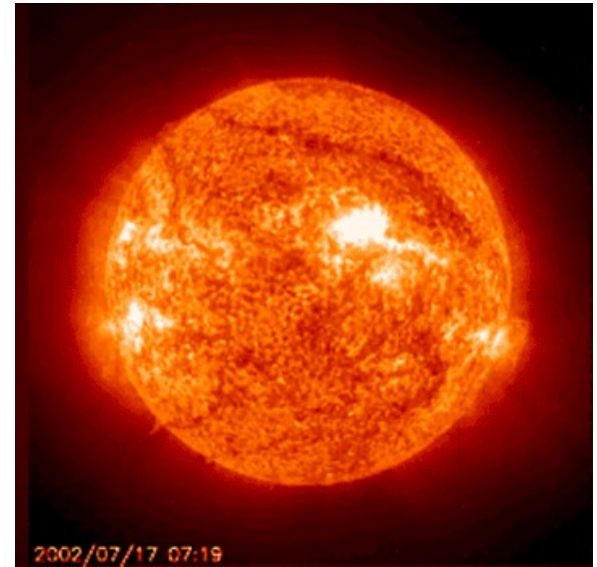
Neutrinos are produced by the sun as it fuses Hydrogen to make Helium (fusion).

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?

Step 1: _____.
Step 2: _____.
Step 3:

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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.

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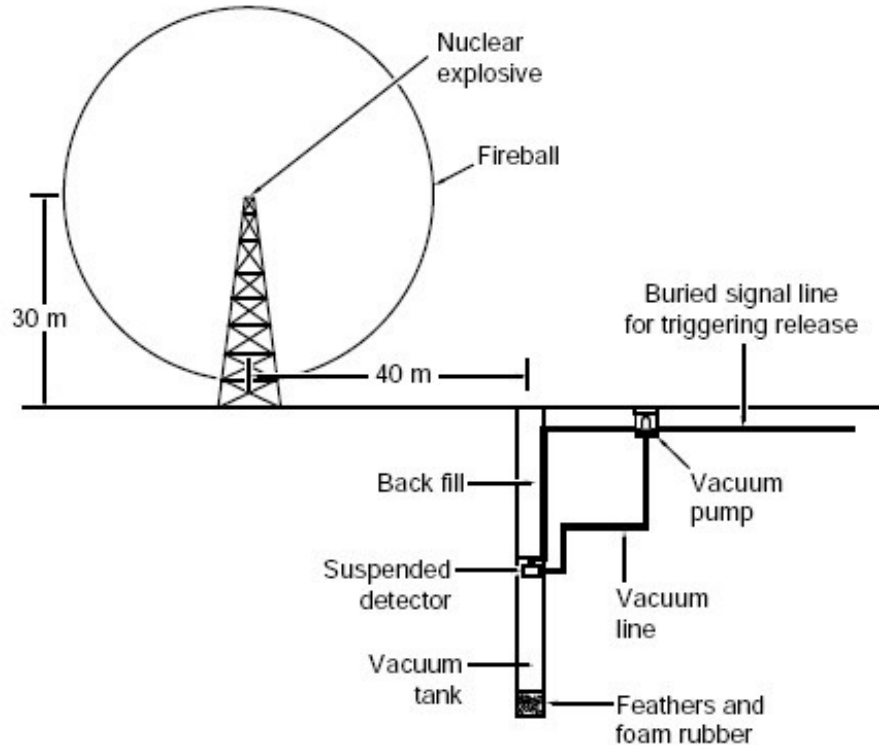 - ….
  - …
  - What is the Sun but a huge nuclear bomb…

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Project Poltergeist #1.

Nuclear explosive

Fireball

30 m

40 m

Buried signal line for triggering release

Back fill

Vacuum pump

Suspended detector

Vacuum line

Vacuum tank

Feathers and foam rubber

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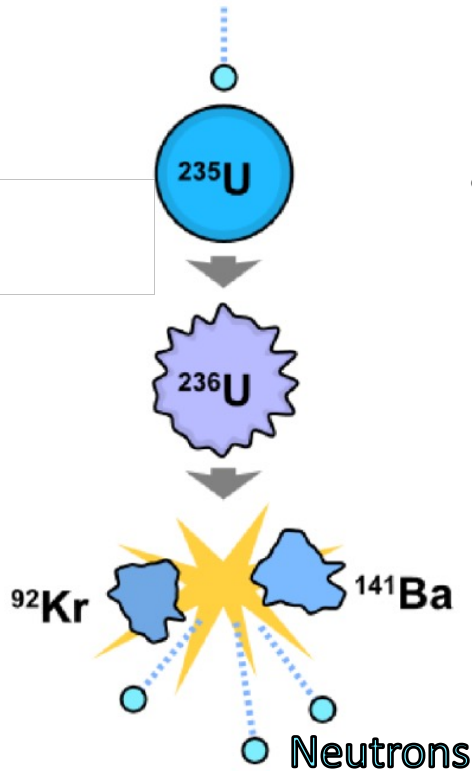- Step 3. Detect the neutrinos.

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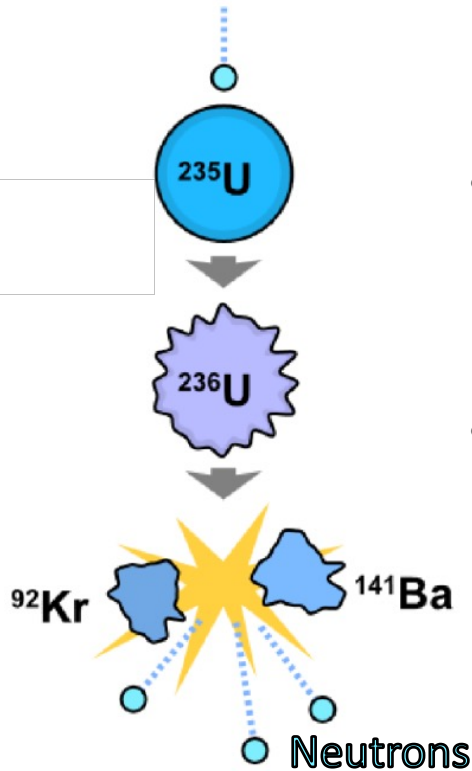
$$n \rightarrow p + e + \nu_e$$

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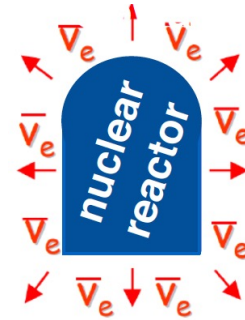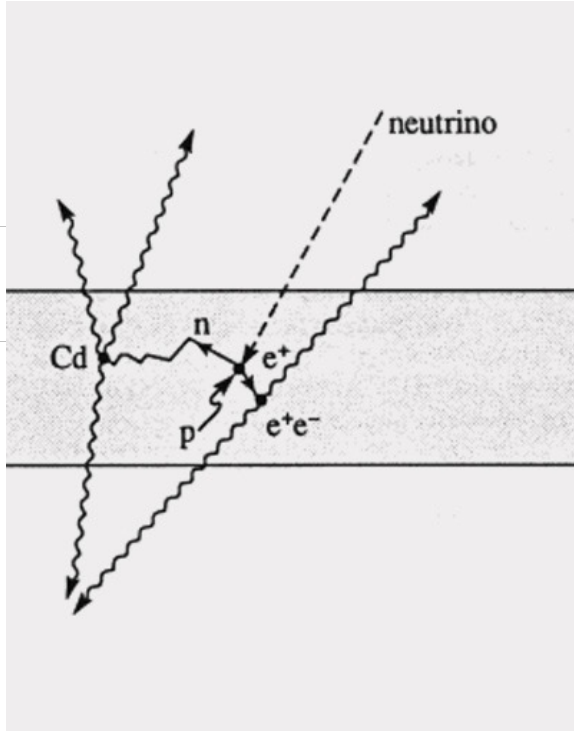
$$n \rightarrow p + e + \nu_e$$

- By placing a detector close to the reactor, neutrinos can be measured.

Project Poltergeist #2.

- 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.

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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.
  - A bubble chamber event from a high energy collision.
  - Can see all of the individual particles, and can calculate their energy and charge by applying Electric/Magnetic fields.

- Neutrinos don't this however.
  - They're neutral, so we don't actually see them.
  - We instead can only detect what they produce.

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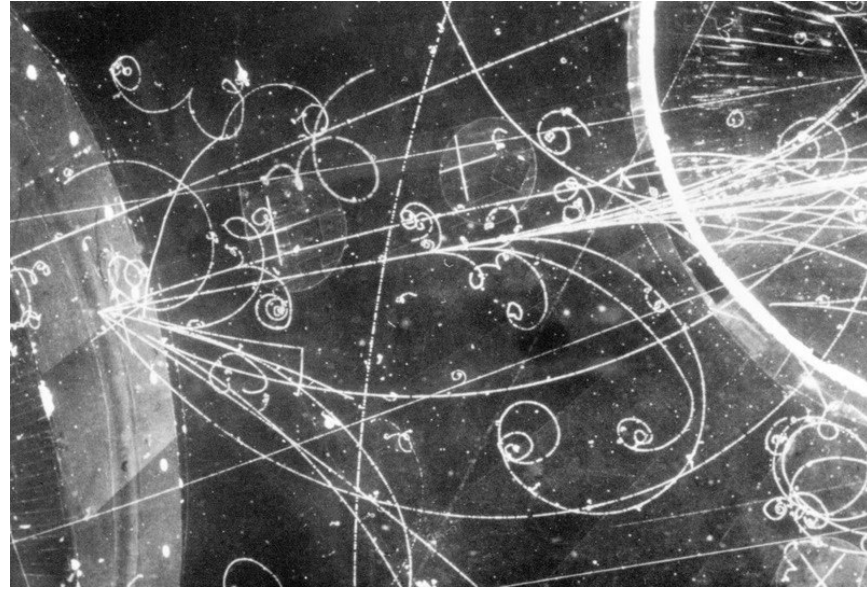
Muon Neutrino Interactions

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.

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.

μBooNE
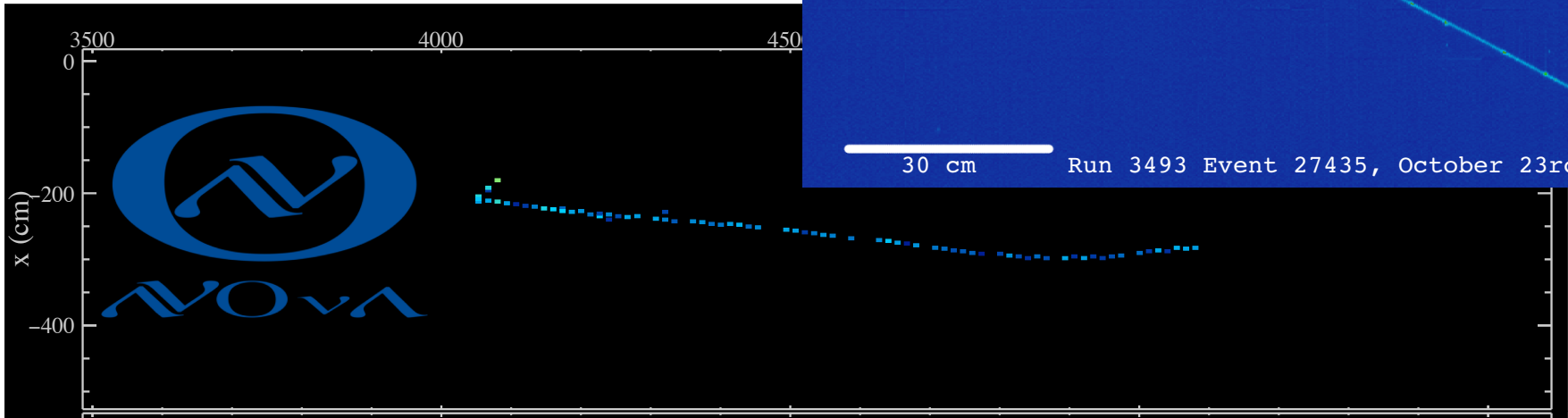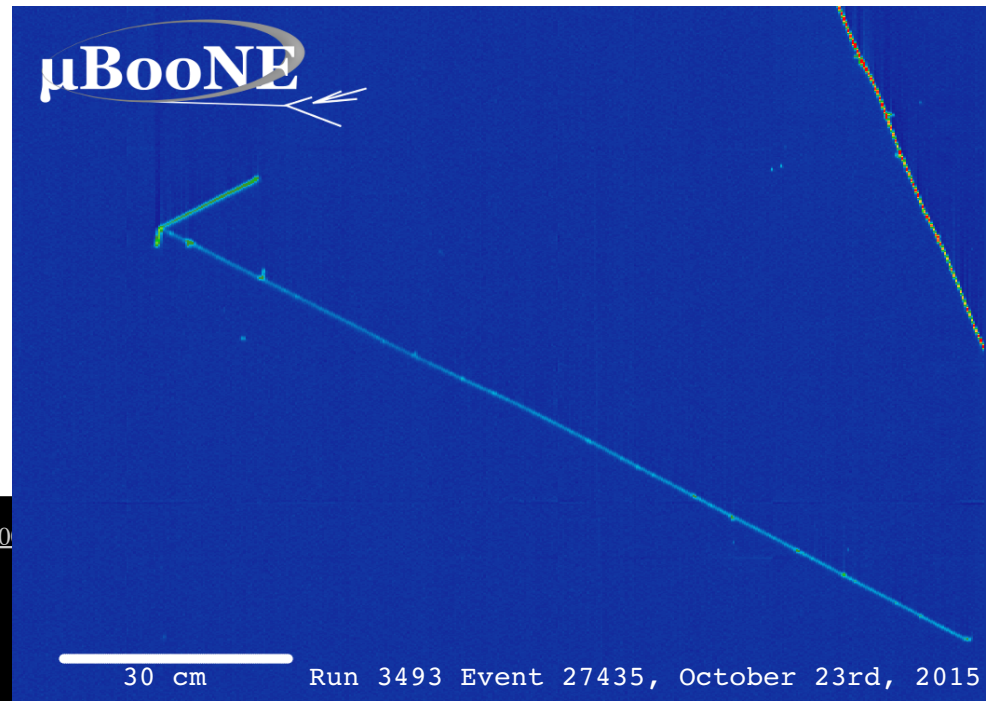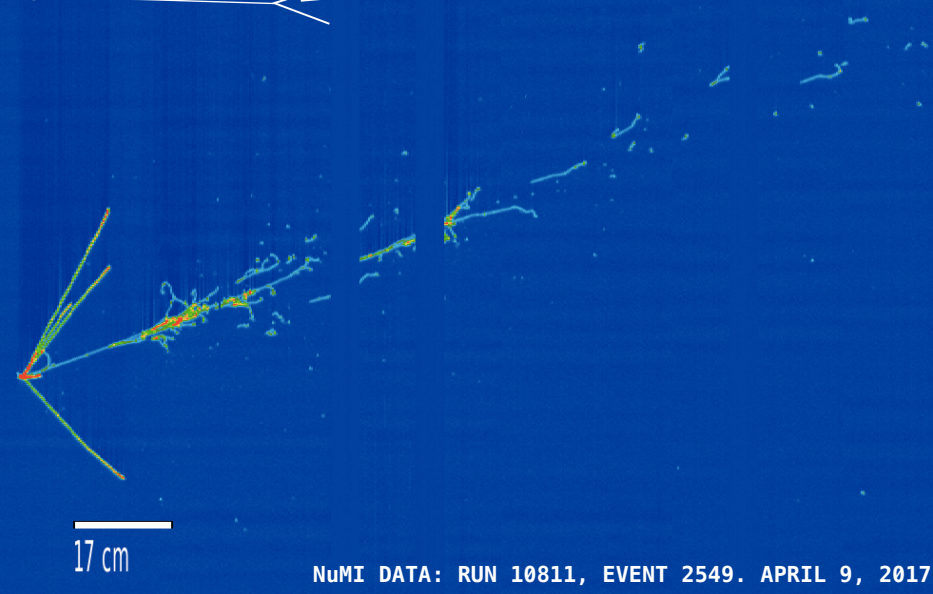
NuMI DATA: RUN 10811, EVENT 2549. APRIL 9, 2017.

17 cm

NOvA - FNAL E929
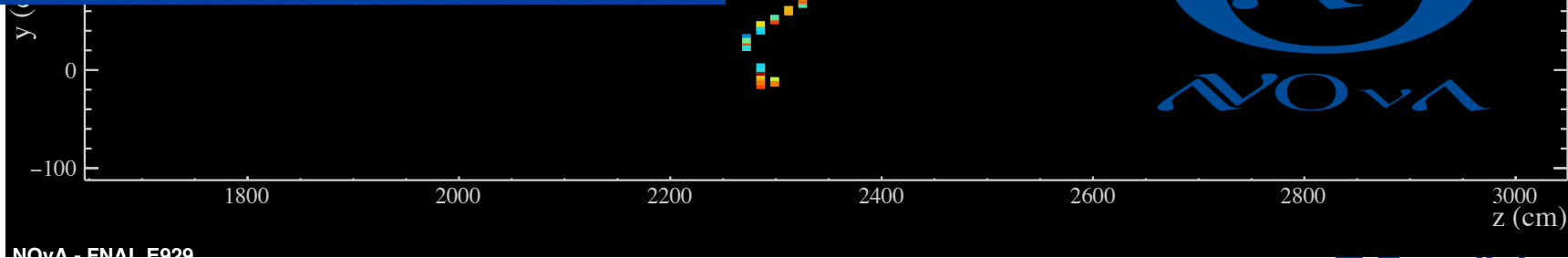
Neutrino Detectors Also Have To Be Huge!
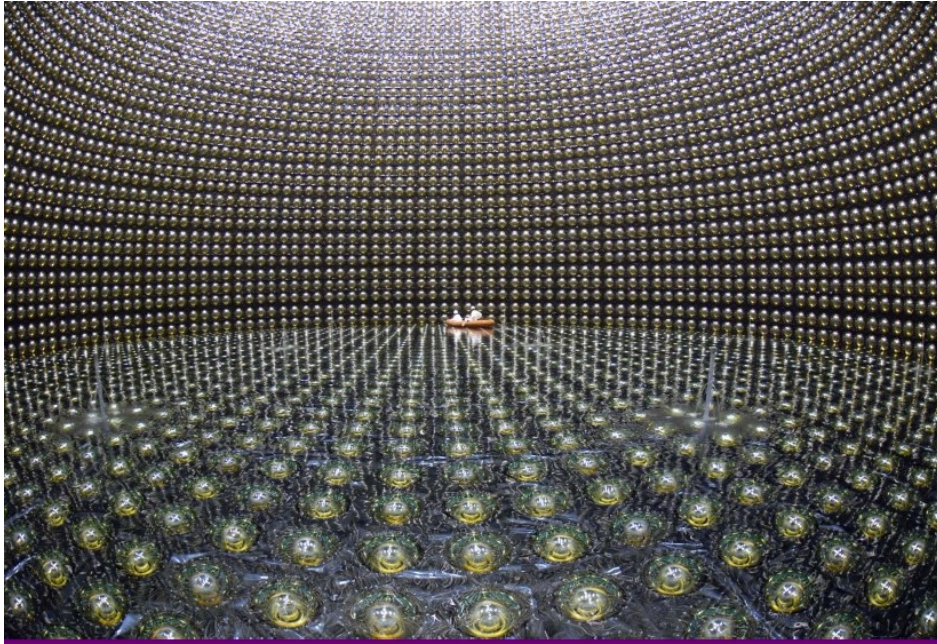
Super-Kamiokande, an experiment in Japan is 50 ktons of ultrapure water.
Hyper-Kamiokande, its successor will be 50 times larger!

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

66 meters

BRITISH AIRWAYS

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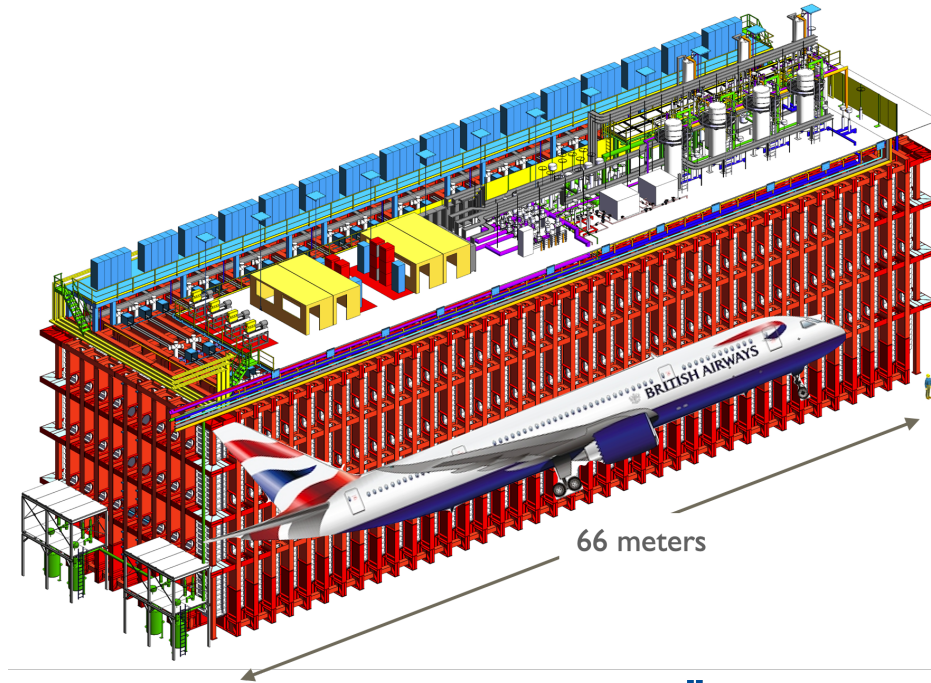
Back To History

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.

🔷 Fermilab
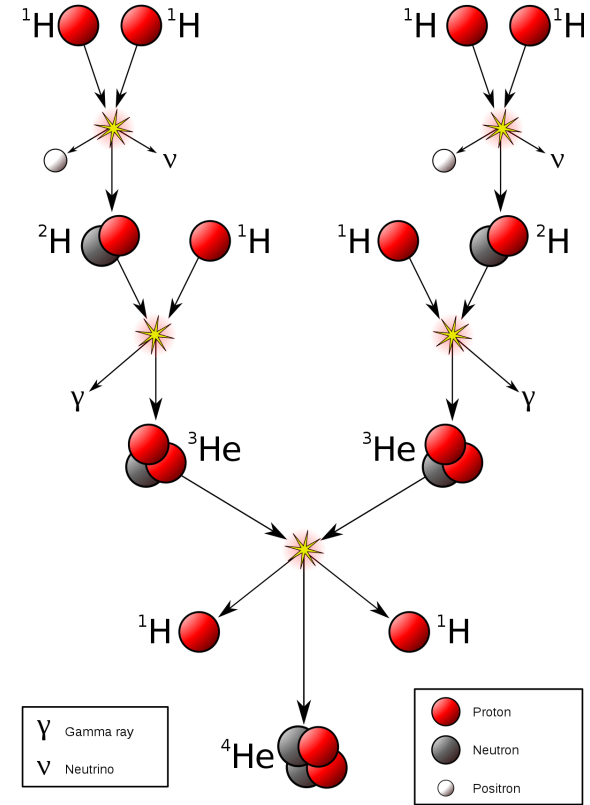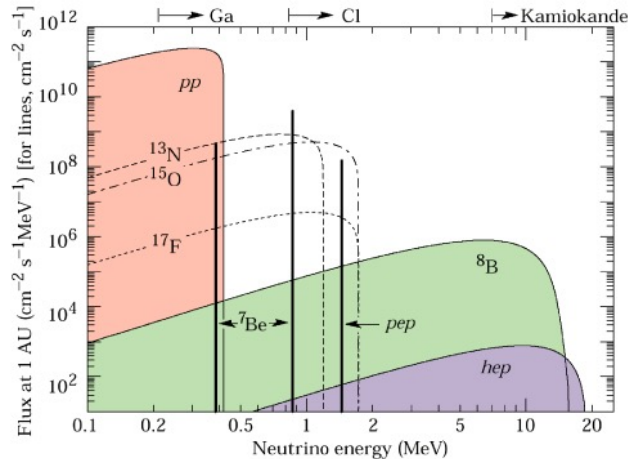
Studying Solar Neutrinos - The Homestake experiment

- 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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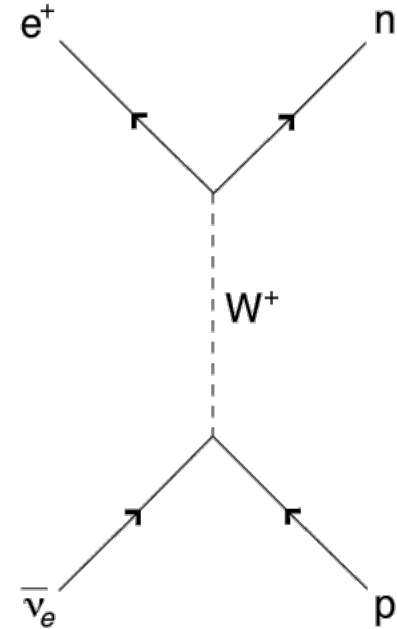
The Homestake experiment

- 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.

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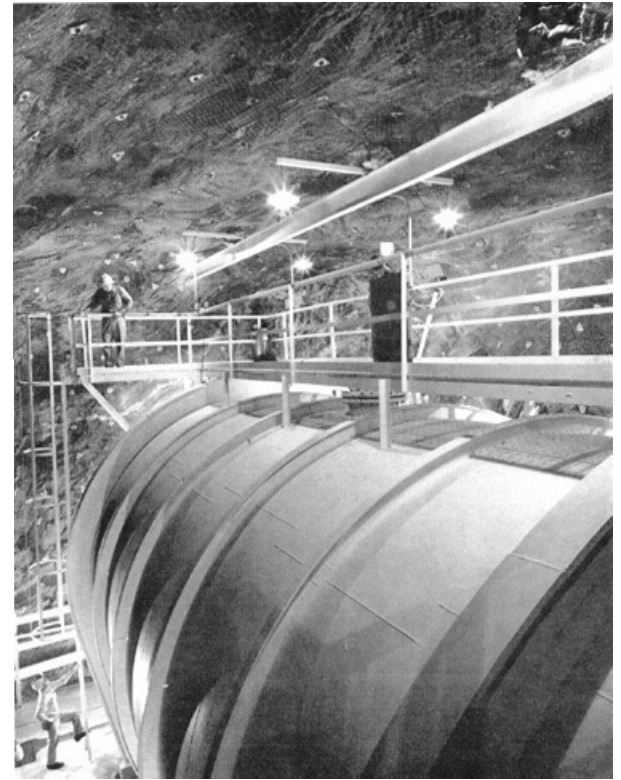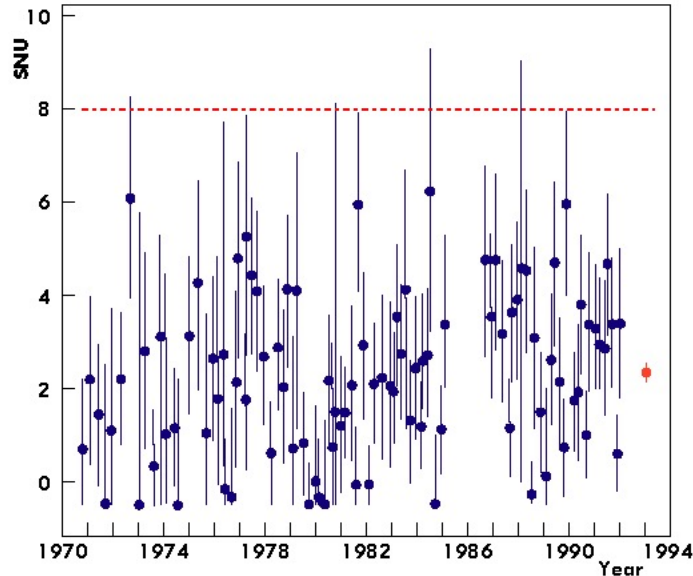
A picture of a friend of mine standing in one of the segments of the Homestake Experiment which is now on the surface.
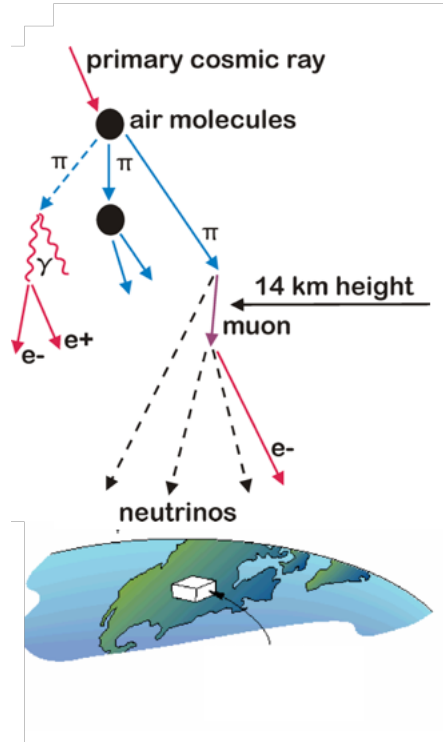
🔷 **Fermilab**

Atmospheric neutrinos

primary cosmic ray

air molecules

π

π

γ

π

e- e+

14 km height

muon

e-

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 ν_μ for every ν_e.

🎇 Fermilab

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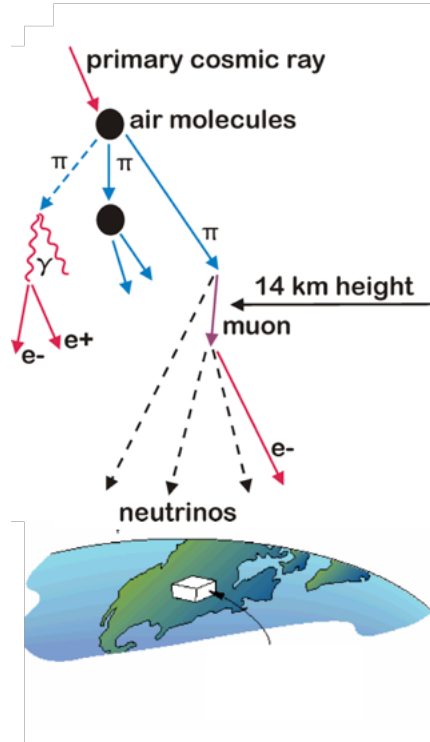
- Produced as high energy cosmic rays strike the upper atmosphere.
  - Produce particle showers (Right).

- As these showers develop and the particles decay, you end up with ~2 ν_μ for every ν_e.

- The Kamiokande detector set out to measure this ratio.
  - Super-Kamiokande, a larger analogue is currently still running in Japan.

🔹 **Fermilab**

The atmospheric neutrino problem…

Electron neutrino interactions

Muon neutrino interactions

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

Multi-GeV μ-like + PC
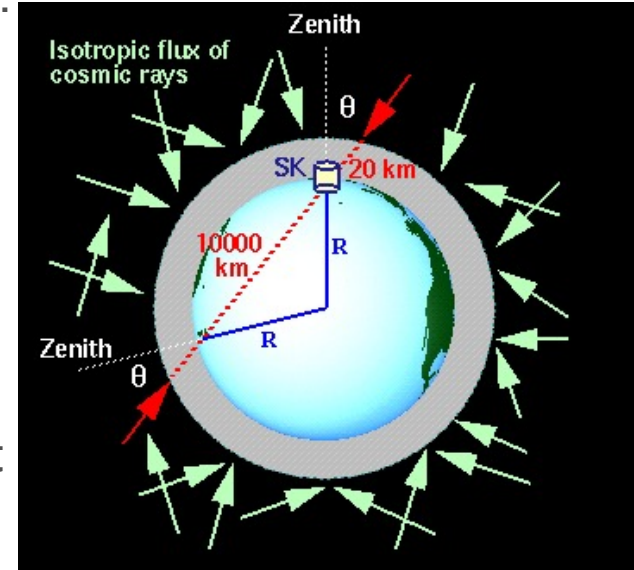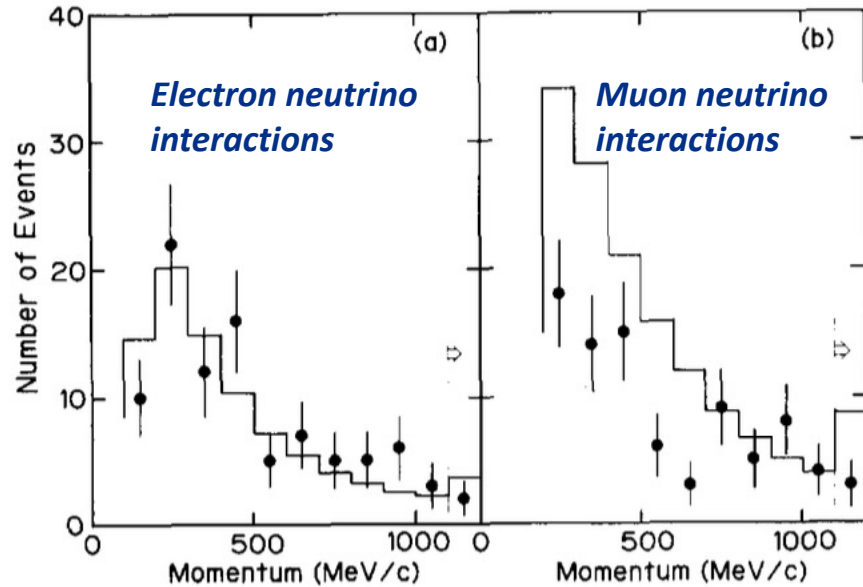
Solid lines show the predicted fluxes in momentum and angle.

Data points show the measured number of interactions.

Notice that the ν_e points are above and below lines, but ν_μ points are all below.

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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.

charged-current

electron-neutrino

$$\nu_e \quad \diagdown \diagup \quad e^-$$
$$W^{+/-}$$
$$n \qquad\qquad p^+$$
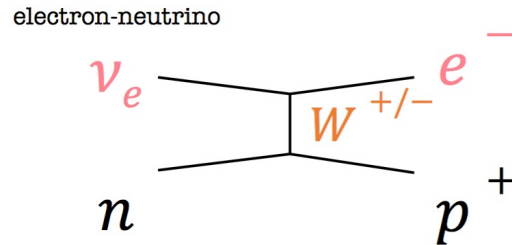
$W^{+/-}$ = charged boson

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

Simply replace both examples of "e" in the diagram with "μ" or "τ".

🐝 **Fermilab**

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

electron-neutrino

$\nu_e \quad e^-$

$W^{+/-}$

$n \qquad p^+$
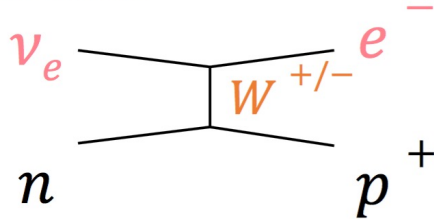
$W^{+/-}$ = charged boson

neutral-current
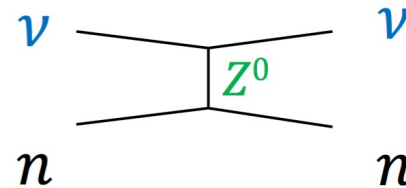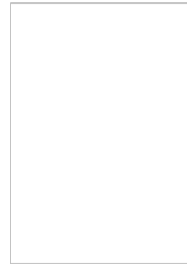
$\nu \qquad \nu$

Z^0

$n \qquad n$
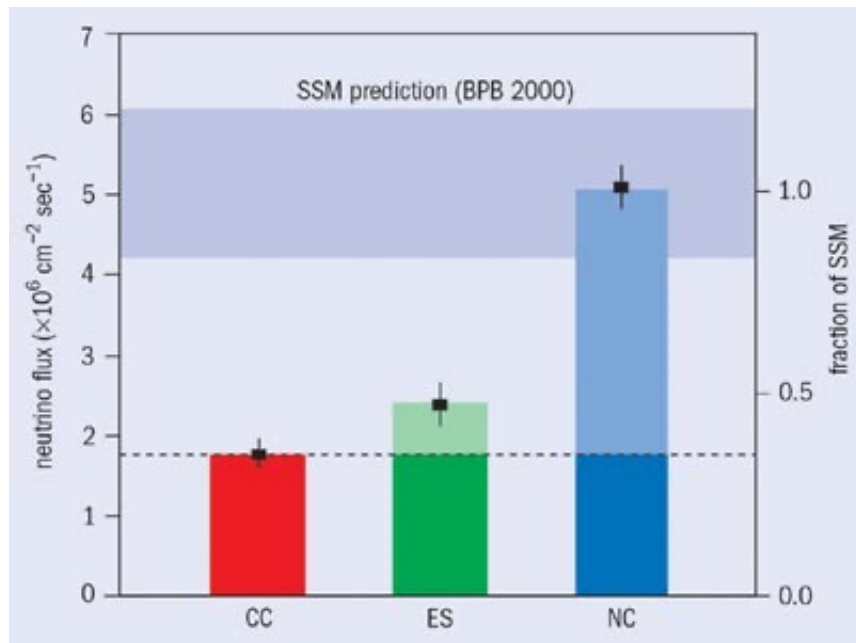
Z^0 = neutral boson

🔷 Fermilab

The Sudbury Neutrino Observatory (SNO)

- In a single experiment it was possible to measure both the ν_e *Charged Current* interactions, and the *Neutral Current* interactions.

- Reproduced the Homestake measurements of ν_e *CC* interactions.

- Also measured the predicted number of *NC* interactions.

The Sudbury Neutrino Observatory (SNO)
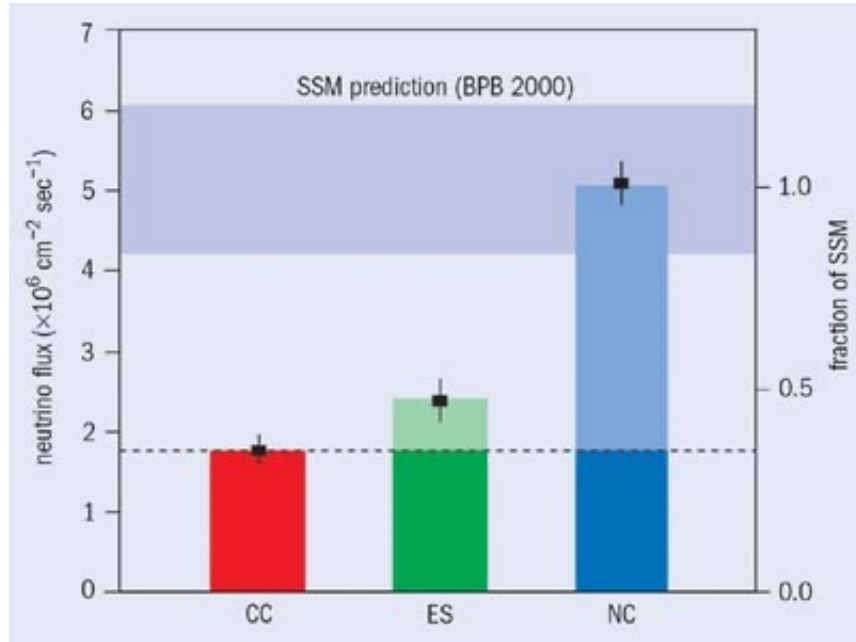
- In a single experiment it was possible to measure both the ν_e *Charged Current* interactions, and the *Neutral Current* interactions.

- Reproduced the Homestake measurements of ν_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!

OK, So What Is Happening?
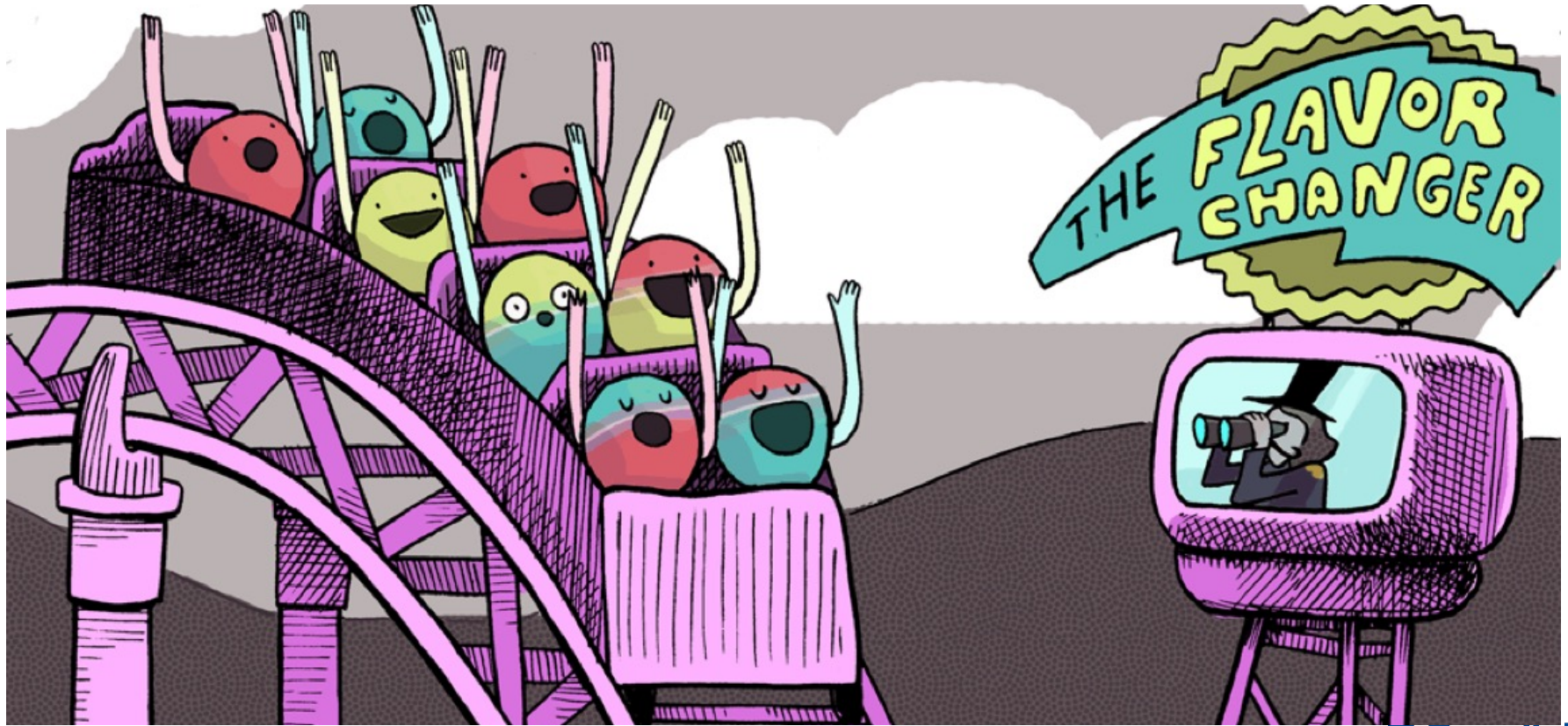
The theory of neutrino oscillations

A nice <u>video</u> explaining how oscillations occur.
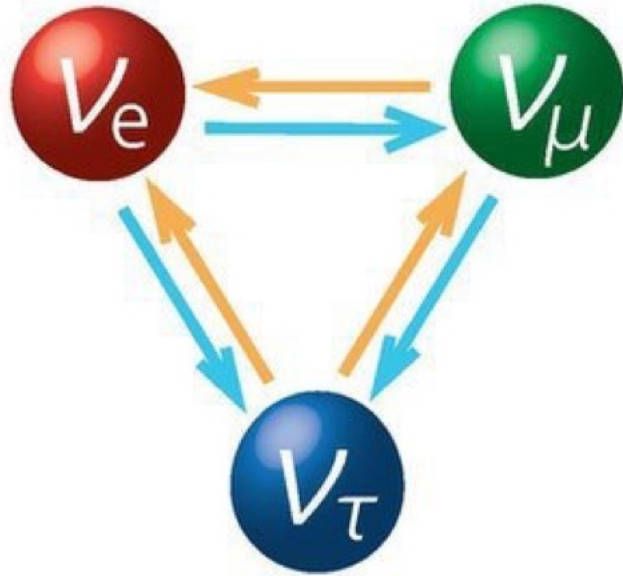
- To explain these experiments neutrinos must be able to change (or oscillate) from one flavor to another as they travel through space.
  - Some version of this was predicted as far as back as 1957, but it really gained traction after 1988.

- Ultimately this means that the neutrinos which we observe ν_e, ν_μ, ν_τ are not those that exist in nature.
  - They are so-called mass states ν_1, ν_2, ν_3.

- How neutrinos oscillate between these states is described by the PMNS matrix, named after four of the theorists who proposed neutrino oscillations.

Fermilab

The simplified theory of neutrino oscillations

*If we assume only 2 neutrinos (**α**, **β**), and have describe their oscillations using the relationship shown to the right things are much simpler.*

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

🍀 **Fermilab**

The simplified theory of neutrino oscillations

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

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

Fermilab

The simplified theory of neutrino oscillations

Video about how oscillations occur.

If we assume only 2 neutrinos (α, β), and have describe their oscillations using the relationship shown to the right things are much simpler.

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

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

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

•e.g. $\Delta m^2 = 0.003\,\text{eV}^2$, $\sin^2 2\theta = 0.8$, $E_\nu = 1\,\text{GeV}$
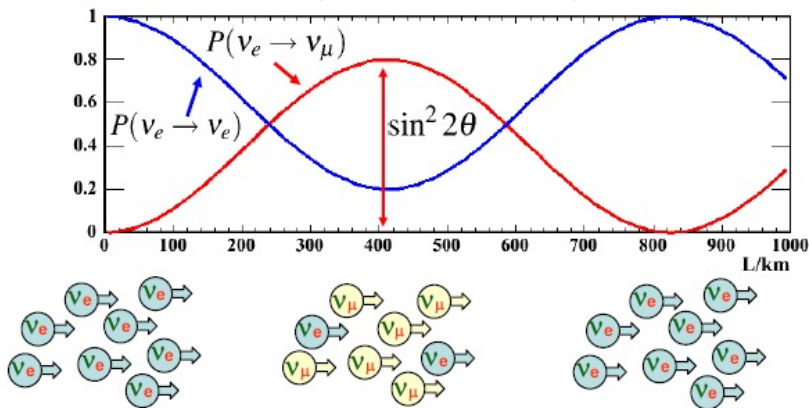
Plugging this into the Schrodinger equation, and following a bit of maths you get the oscillation probabilities for two neutrino flavours.

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

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

🔷 Fermilab

The theory of neutrino oscillations

A nice <u>video</u> explaining how oscillations occur.

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

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.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} C_{12}C_{13} & S_{12}C_{13} & S_{13}e^{-i\delta} \\ -S_{12}C_{23} - C_{12}S_{23}S_{13}e^{i\delta} & C_{12}C_{23} - S_{12}S_{23}S_{13}e^{i\delta} & S_{23}C_{13} \\ S_{12}S_{23} - C_{12}C_{23}S_{13}e^{i\delta} & -C_{12}S_{23} - S_{12}C_{23}S_{13}e^{i\delta} & C_{23}C_{13} \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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

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

$$A(\nu_\alpha \rightarrow \nu_\beta) = \left\langle \nu_\beta \left| \nu_\alpha(t) \right\rangle \right.$$

$$= \sum_k \sum_j \left\langle \nu_j \left| U_{\beta j} U_{\alpha k}^* e^{-im_k^2 L/2E} \right| \nu_k \right\rangle$$

$$P(\nu_\mu \rightarrow \nu_e) \simeq \sin^2 \theta_{23} \sin^2 2\theta_{13} \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} \Delta_{31}^2$$

$$+ \sin 2\theta_{23} \sin 2\theta_{13} \sin 2\theta_{12} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31} \frac{\sin(aL)}{(aL)} \Delta_{12} \cos(\Delta_{31} + \delta_{CP})$$

$$+ \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(aL)}{(aL)^2} \Delta_{12}^2$$

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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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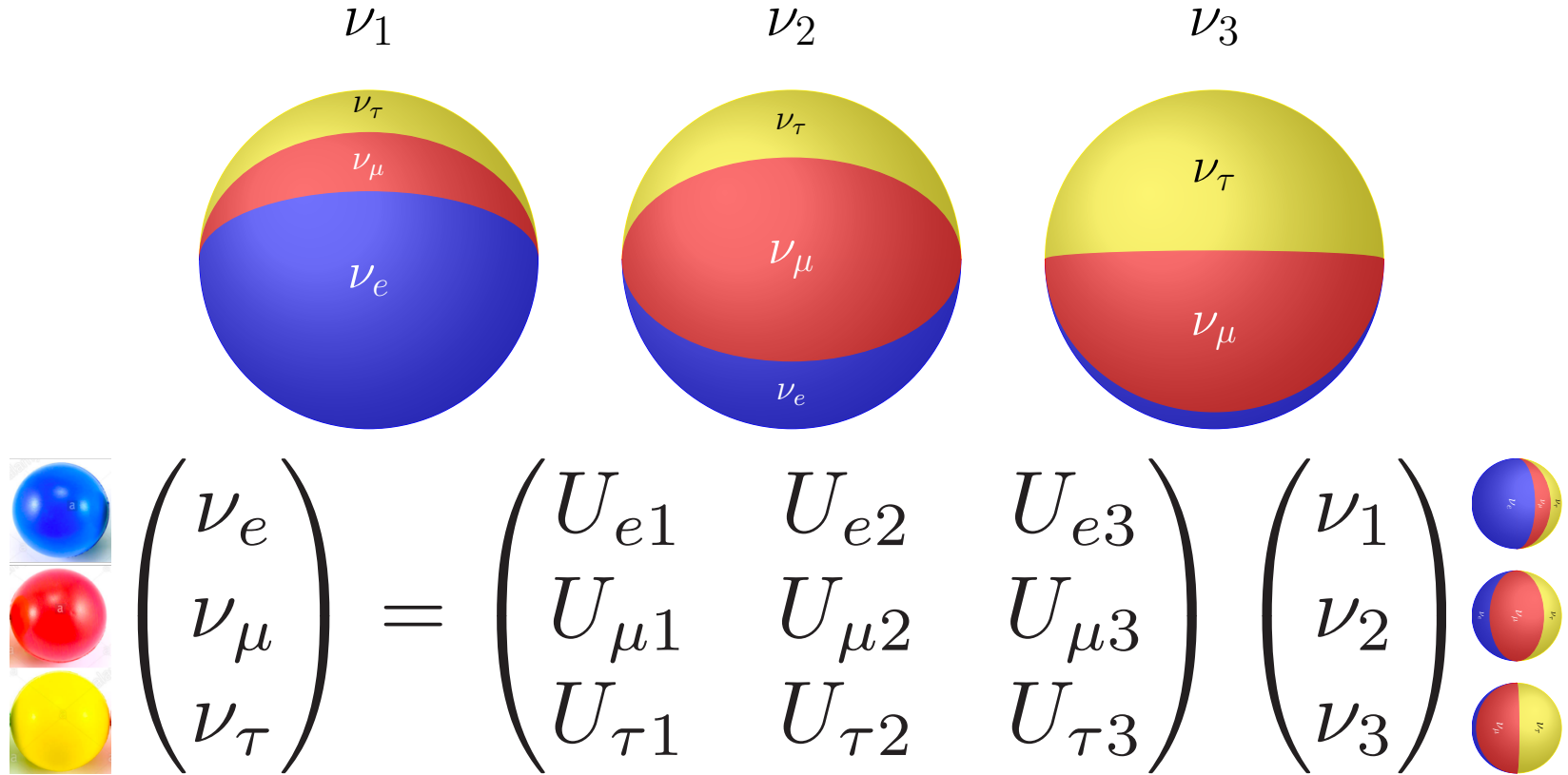
Three Flavour Neutrino Oscillations

Can see the effect of two mass squared differences.

Start with a primarily ν_μ beam.

Can see that at "low" L/E most neutrinos oscillate to ν_τ 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.
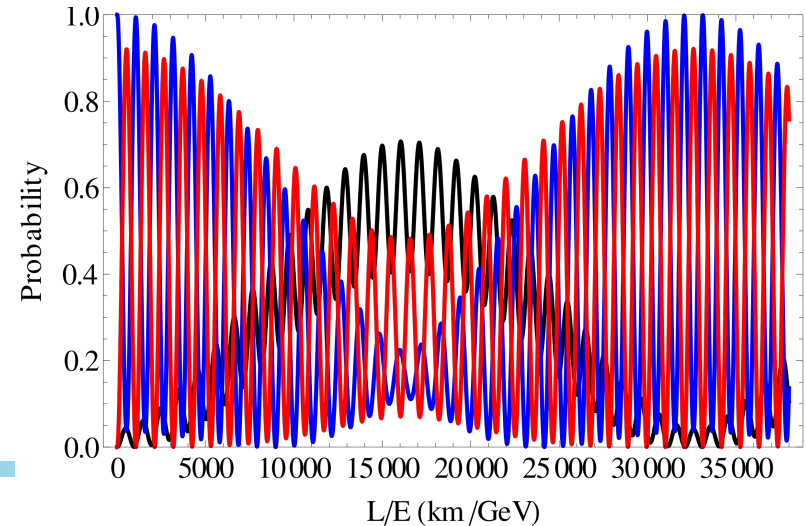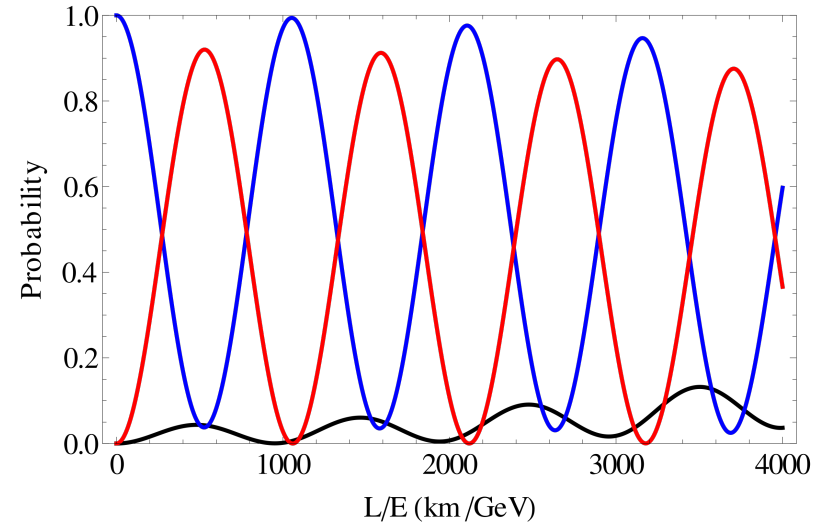
The Nobel Prize for the Discovery of Neutrino Oscillations

Nobelpriset i fysik 2015

KUNGL. VETENSKAPS-AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

Takaaki Kajita
Super-Kamiokande Collaboration
University of Tokyo, Kashiwa, Japan

Arthur B. McDonald
Sudbury Neutrino Observatory Collaboration
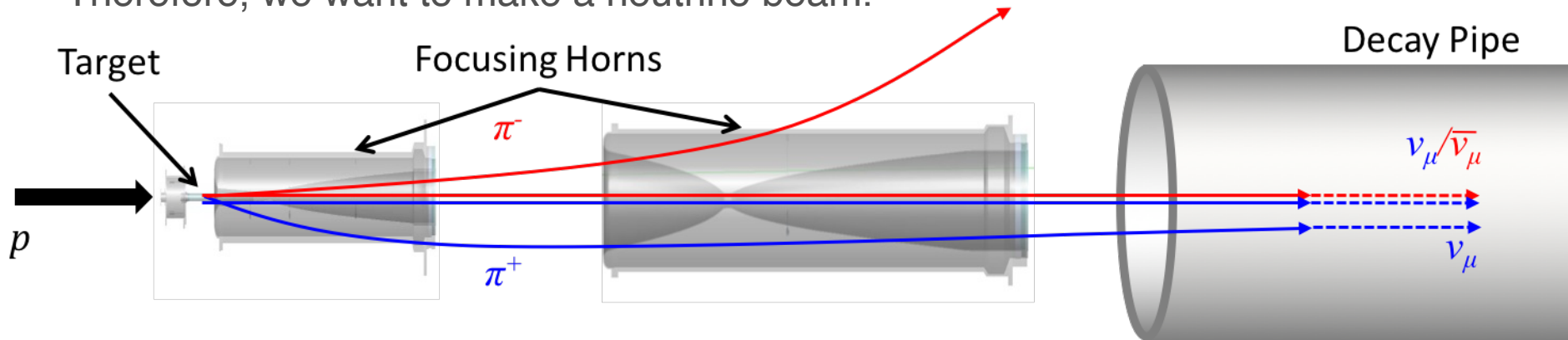Queen's University, Kingston, Canada

"för upptäckten av neutrinooscillationer, som visar att neutriner har massa"
"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

2015-10-06

© Kungl. Vetenskapsakademien

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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?

ν_μ ν_μ ν_μ
ν_μ ν_μ ν_μ ν_μ
ν_μ ν_μ ν_μ ν_μ ν_μ
ν_μ ν_μ ν_μ ν_μ
ν_μ ν_μ ν_μ

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

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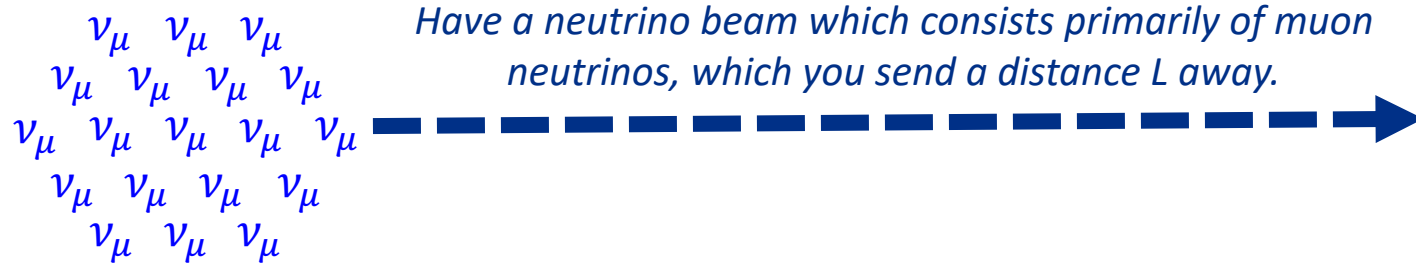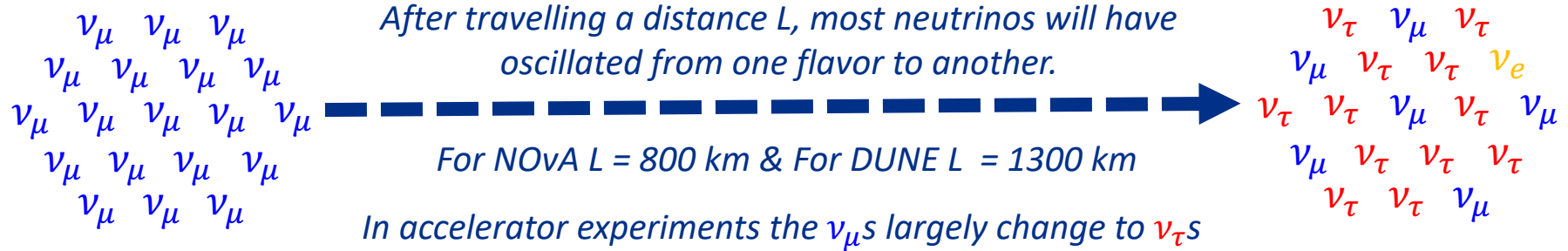
How Does This Work In Practice?

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

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 ν_μs largely change to ν_τs

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

🎇 **Fermilab**
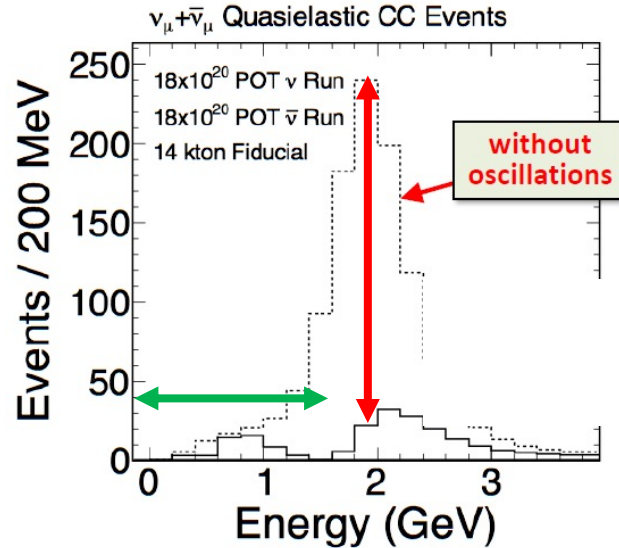
How Does This Work In Practice?

ν_μ ν_μ ν_μ
ν_μ ν_μ ν_μ ν_μ
ν_μ ν_μ ν_μ ν_μ ν_μ
ν_μ ν_μ ν_μ ν_μ
ν_μ ν_μ ν_μ

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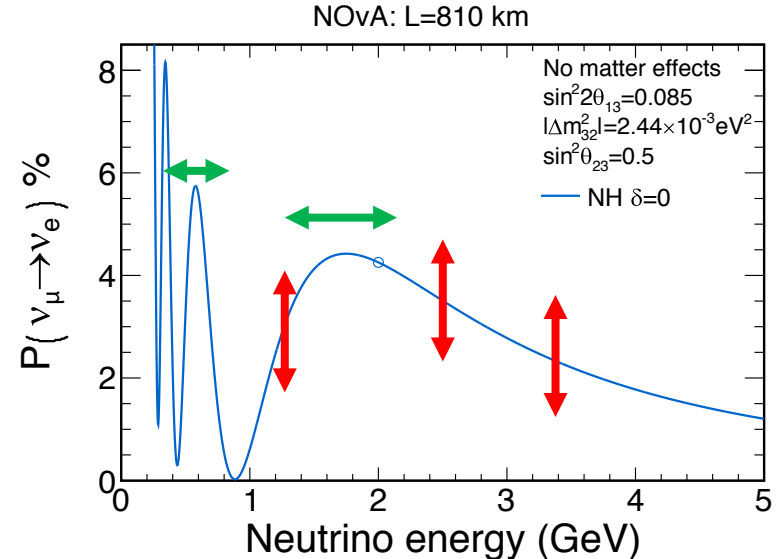
For NOvA L = 800 km & For DUNE L = 1300 km

In accelerator experiments the ν_μs largely change to ν_τs

ν_τ ν_μ ν_τ
ν_μ ν_τ ν_τ ν_e
ν_τ ν_τ ν_μ ν_τ ν_μ
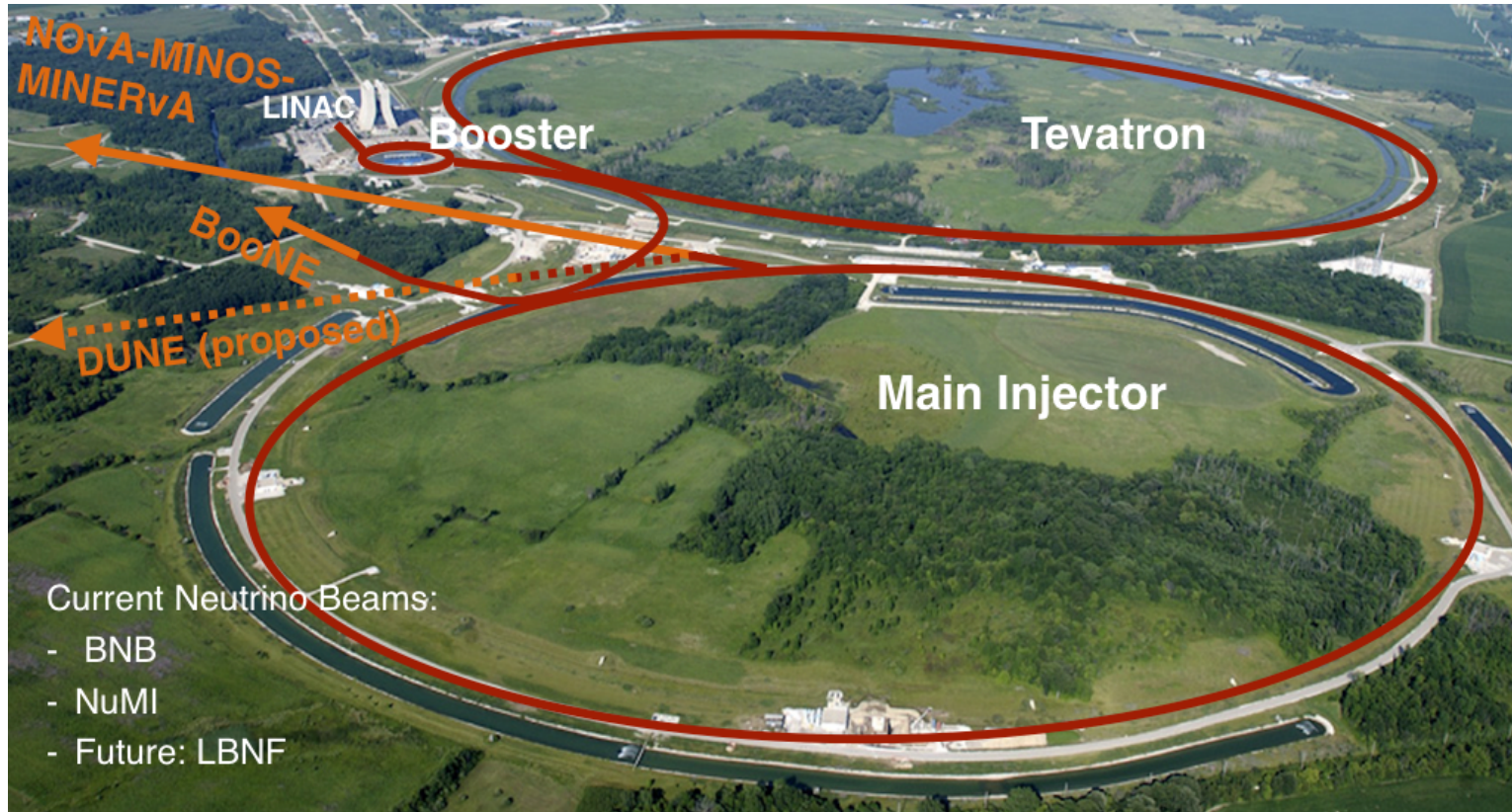ν_μ ν_τ ν_τ ν_τ
ν_τ ν_τ ν_μ

Mixing Angle values determine the magnitude of Oscs.

*Mass Squared Diffs determine the energies at which Max Osc occurs.*

$\nu_\mu + \bar{\nu}_\mu$ Quasielastic CC Events

18×10^{20} POT ν Run
18×10^{20} POT $\bar{\nu}$ Run
14 kton Fiducial

without oscillations

Events / 200 MeV — Energy (GeV)

NOvA: L=810 km

No matter effects
$\sin^2 2\theta_{13} = 0.085$
$|\Delta m^2_{32}| = 2.44 \times 10^{-3} eV^2$
$\sin^2 \theta_{23} = 0.5$
NH $\delta = 0$

$P(\nu_\mu \rightarrow \nu_e)$ % — Neutrino energy (GeV)

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The Fermilab Neutrino Program

NOvA-MINOS-MINERvA

LINAC

Booster

Tevatron

BooNE

DUNE (proposed)

Main Injector

Current Neutrino Beams:
- BNB
- NuMI
- Future: LBNF

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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.

- Detects the number of muon and electron neutrinos in each detector.
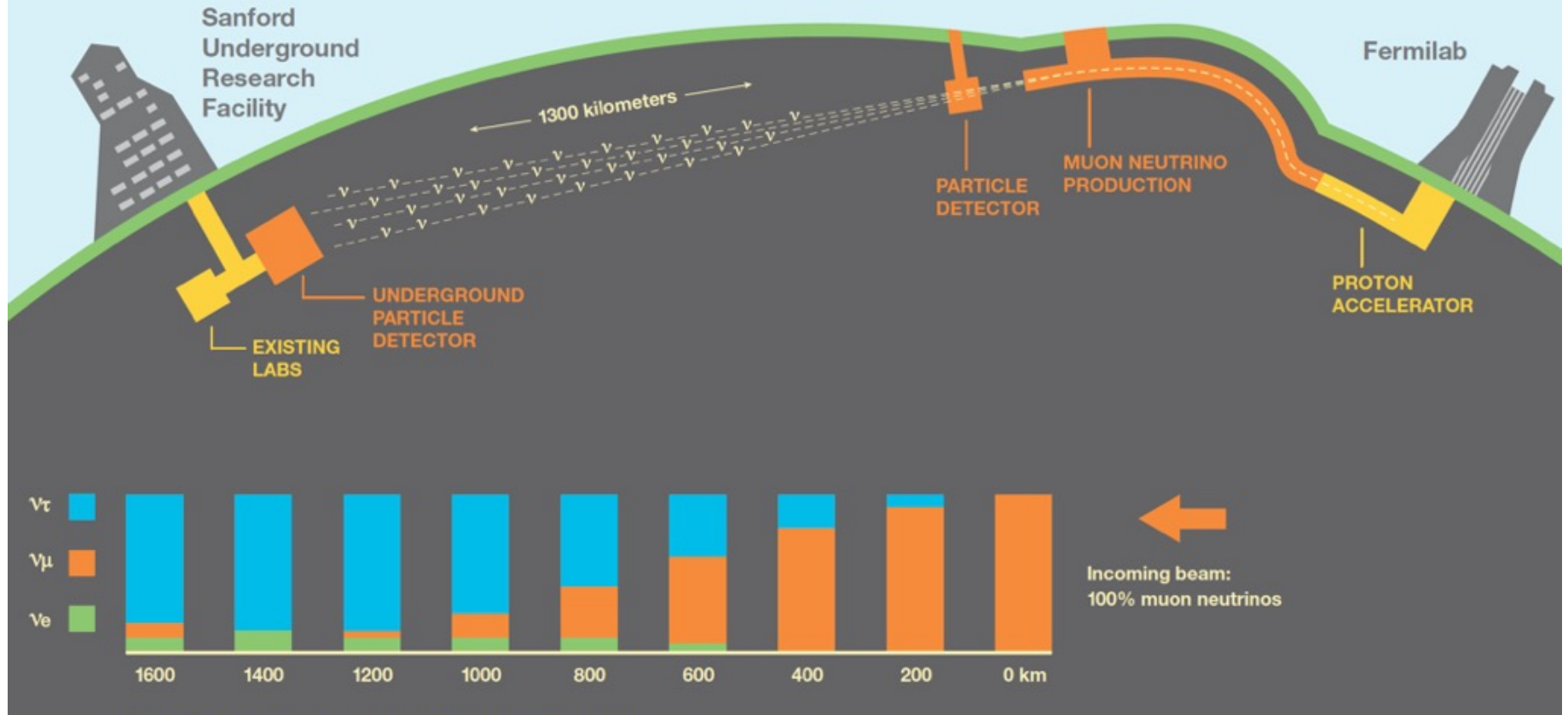
🔷 **Fermilab**
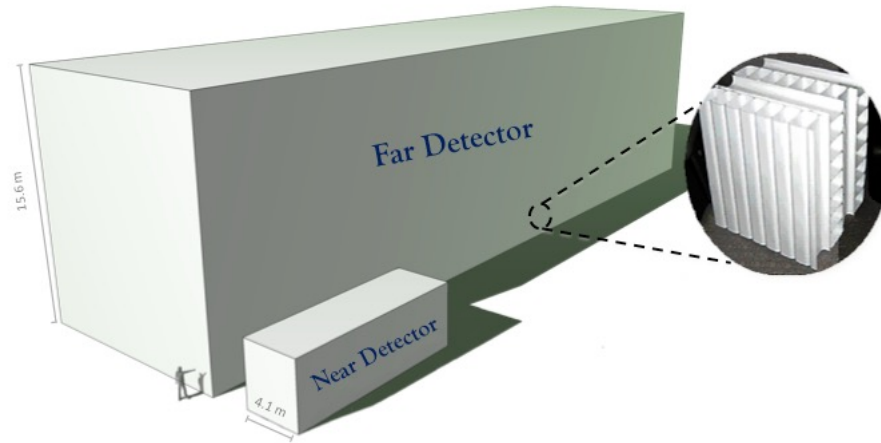
Latest Results From NOvA

- The PMNS matrix allows NOvA to predict the number of observed events for different neutrino mixing params.

- By calculating the energy of ν_μ's and ν_e's detected at Far Detector it is possible to extract the true value of these parameters.
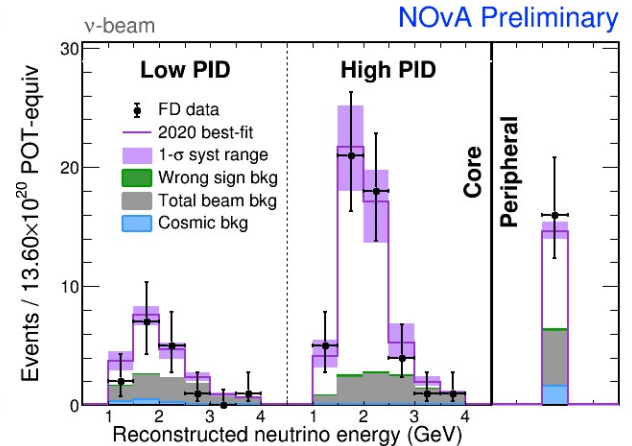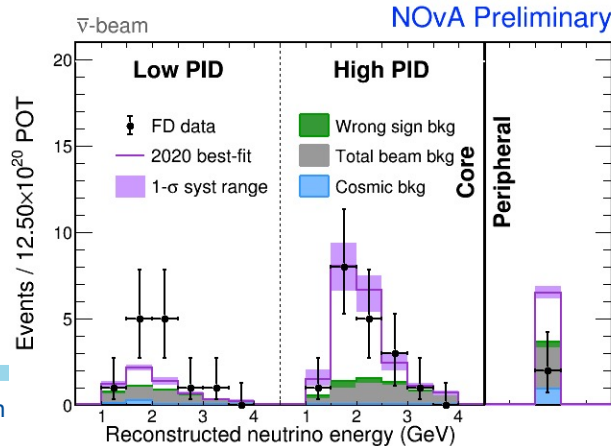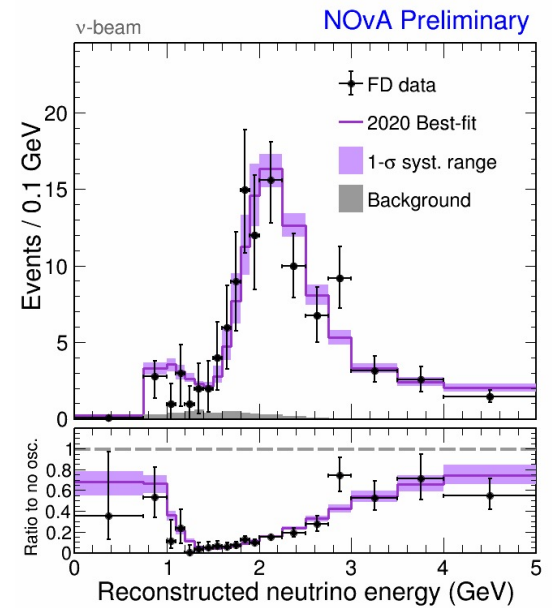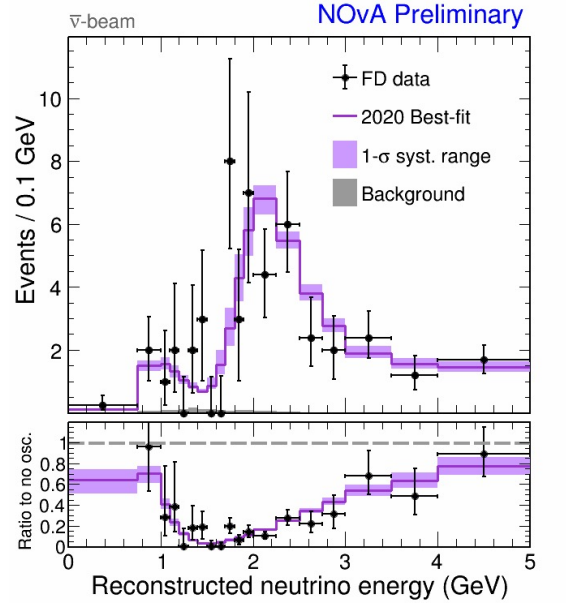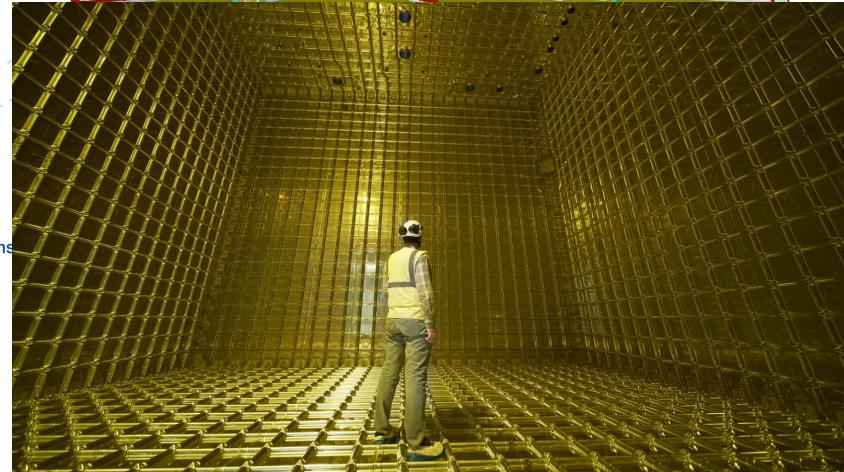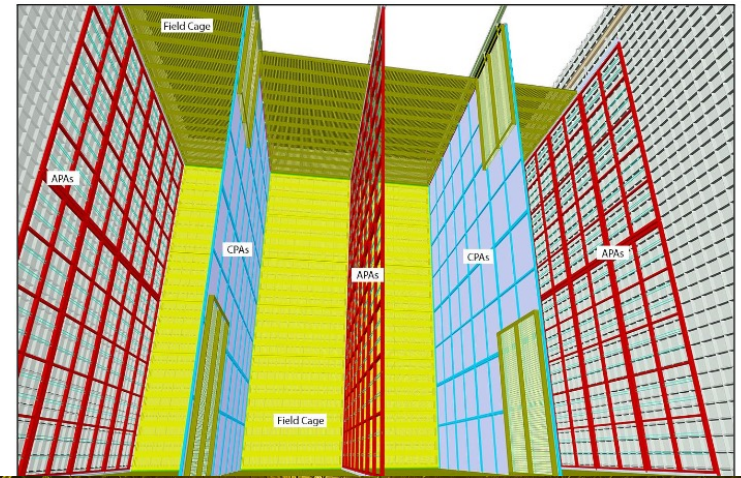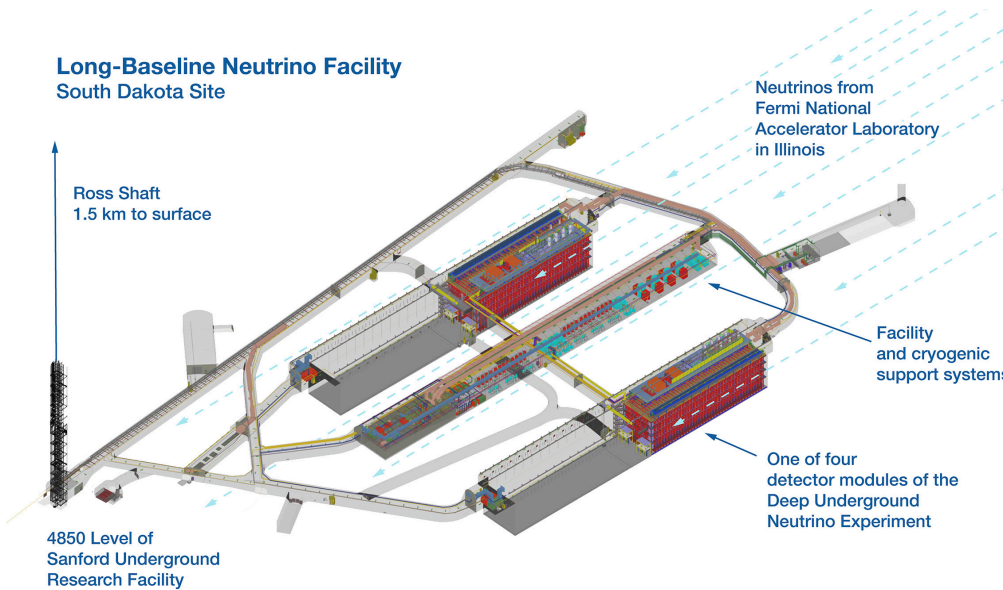
The Deep Underground Neutrino Experiment (DUNE)
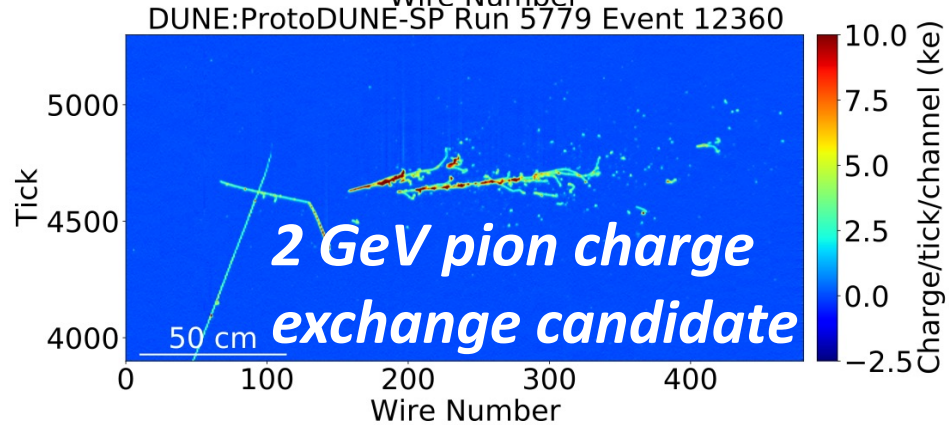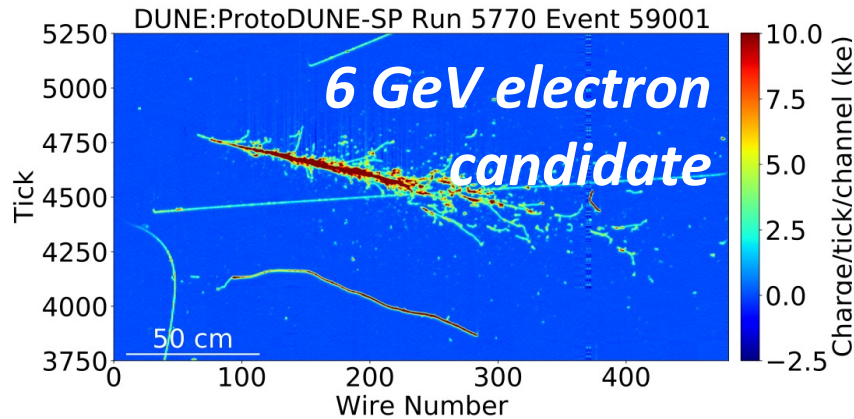
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The DUNE Far Detectors

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 be filled with Liquid Argon (-303 F/-186 C/87 K).

Long-Baseline Neutrino Facility
South Dakota Site

Ross Shaft
1.5 km to surface

Neutrinos from
Fermi National
Accelerator Laboratory
in Illinois

Facility
and cryogenic
support systems

One of four
detector modules of the
Deep Underground
Neutrino Experiment

4850 Level of
Sanford Underground
Research Facility

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Particles Interactions in DUNE

DUNE:ProtoDUNE-SP Run 5387 Event 89663

1 GeV stopping proton candidate

20 cm

DUNE:ProtoDUNE-SP Run 5772 Event 15132

6 GeV pion candidate

50 cm

DUNE:ProtoDUNE-SP Run 5770 Event 59001

6 GeV electron candidate

50 cm

DUNE:ProtoDUNE-SP Run 5779 Event 12360

2 GeV pion charge exchange candidate

50 cm

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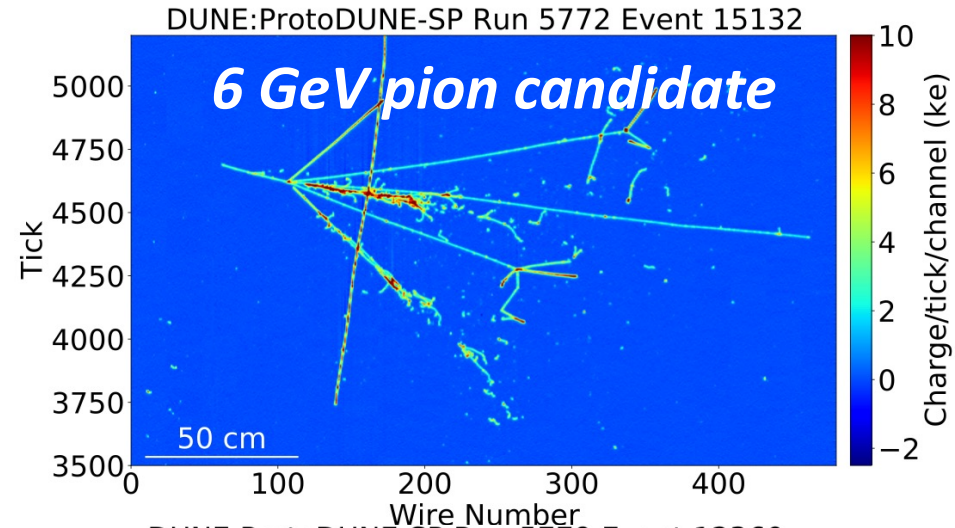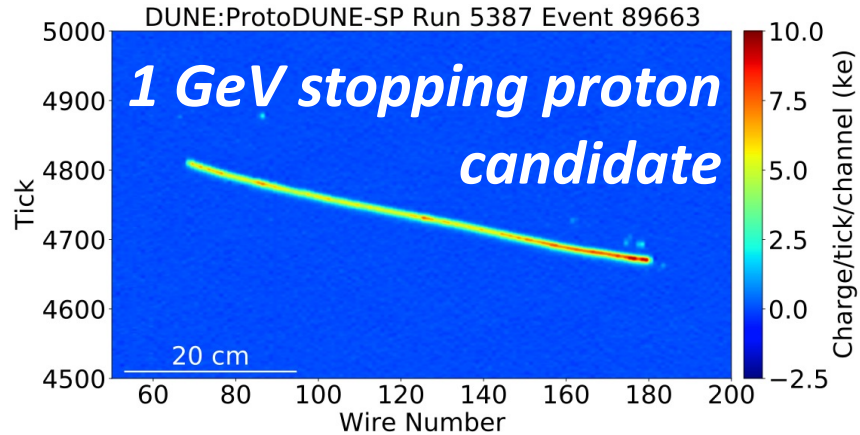
A Couple Of Cool Other Things

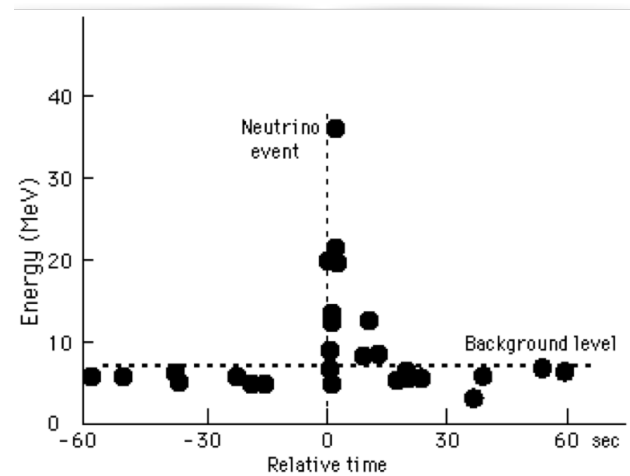15/6/2021 Karl Warburton, Introduction to Neutrino Physics
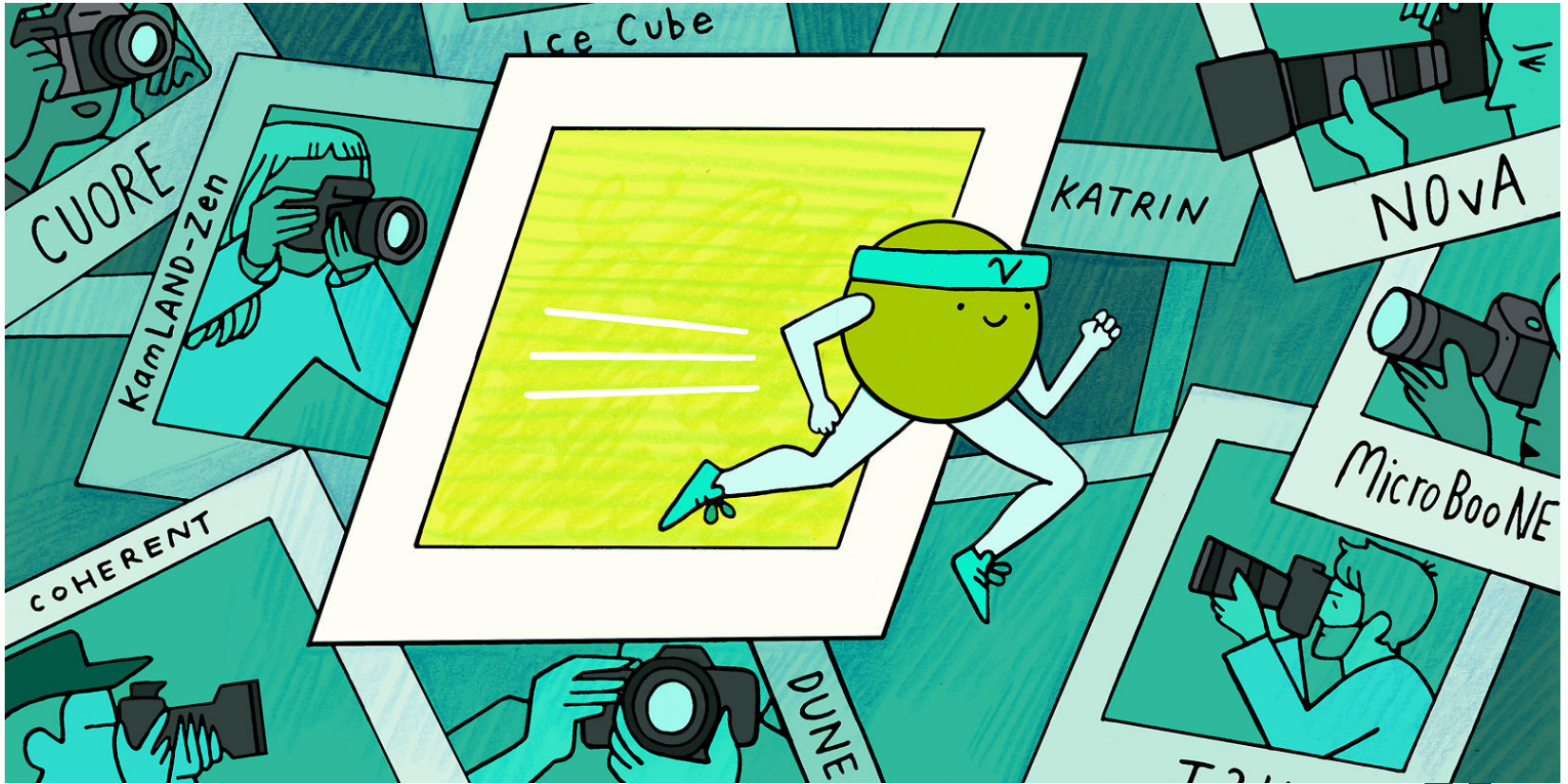
The Detection of Supernova Neutrinos – 1987a
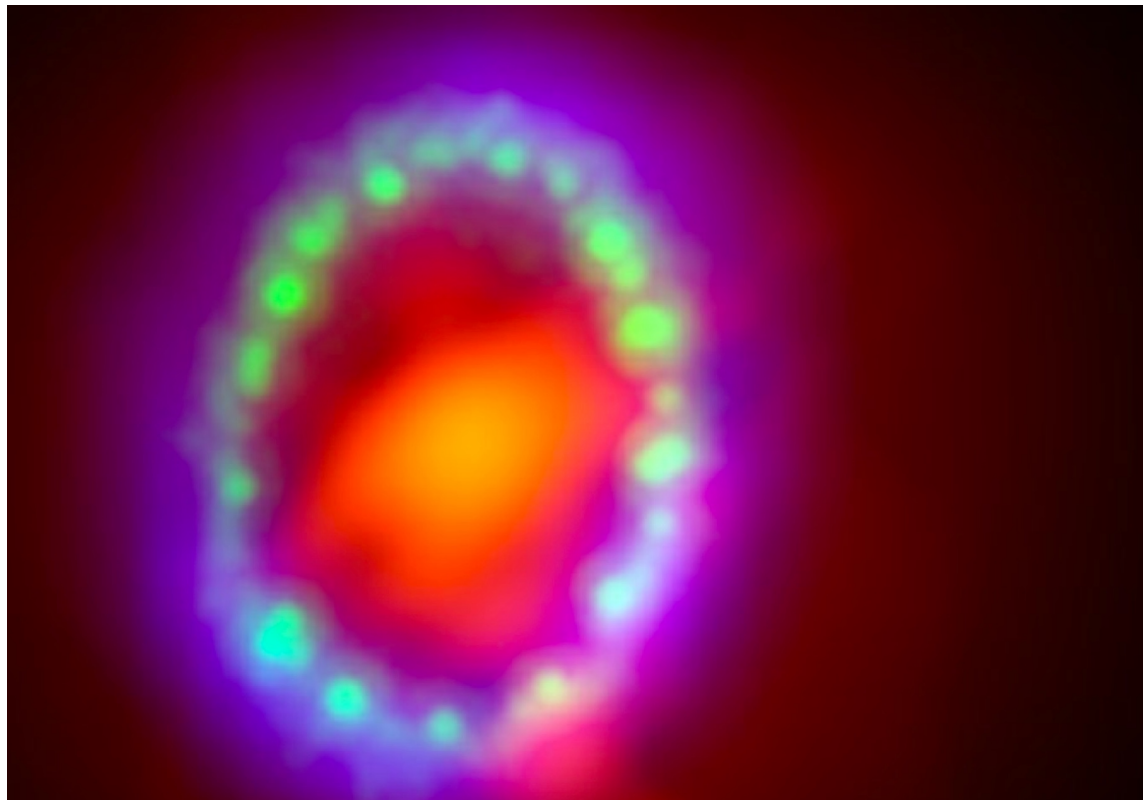
Saw less than 30 neutrinos in total. With the next generation of experiments, we could see 10k+!

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

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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!

Fermilab
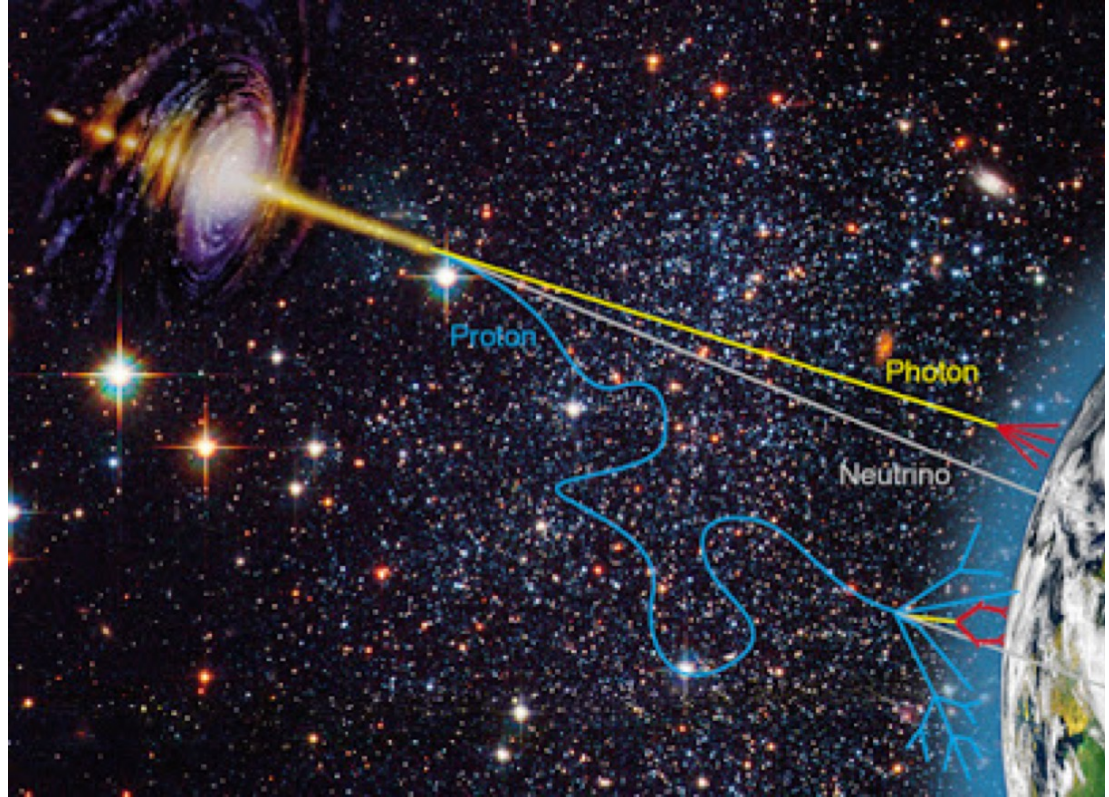
Relic Neutrinos From The Big Bang
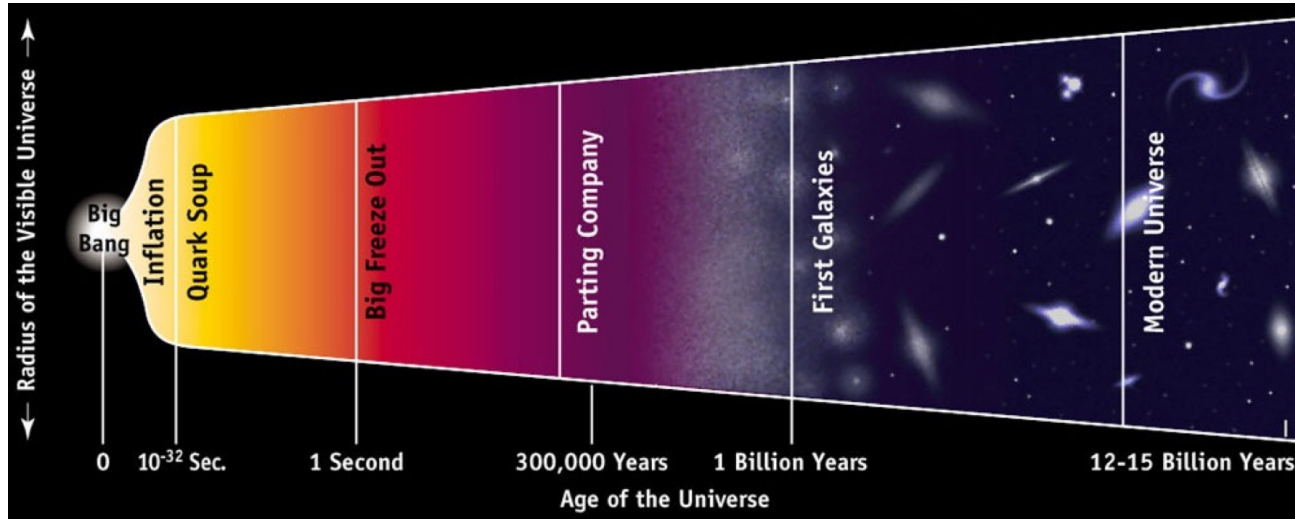
Produced when the Universe was 1 s old.

*   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…

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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.
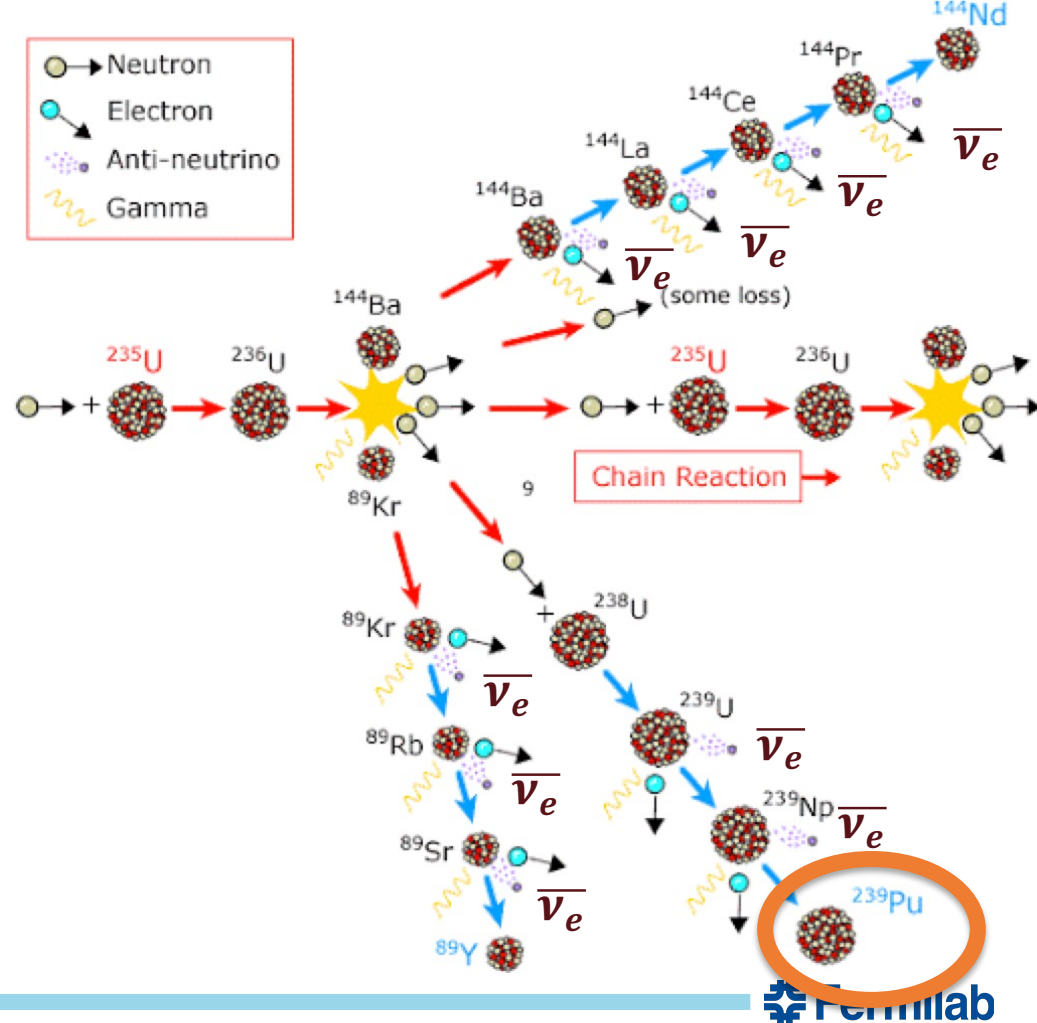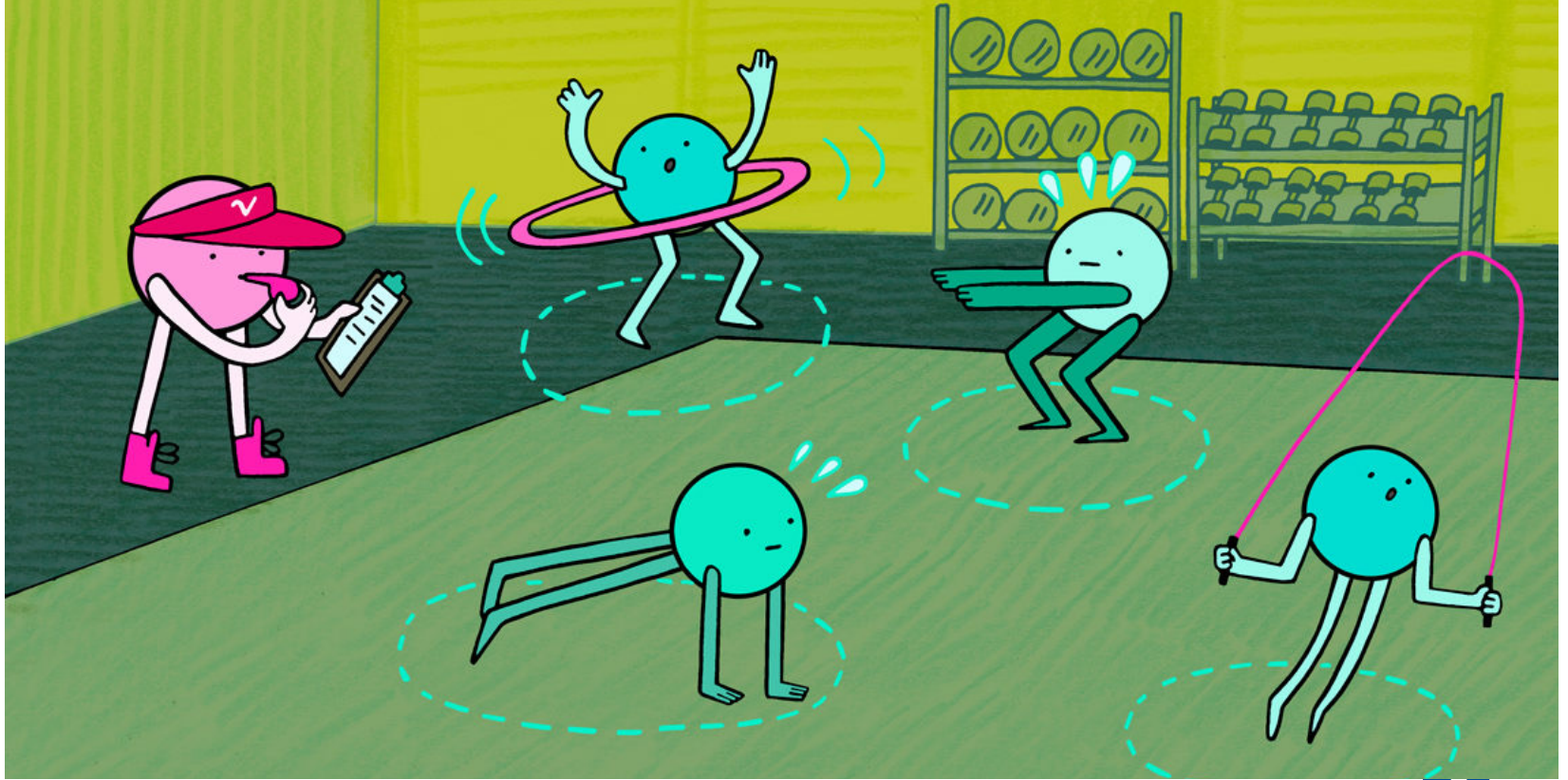
A Recap Of Neutrino Physics & The Remaining Questions

- 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.
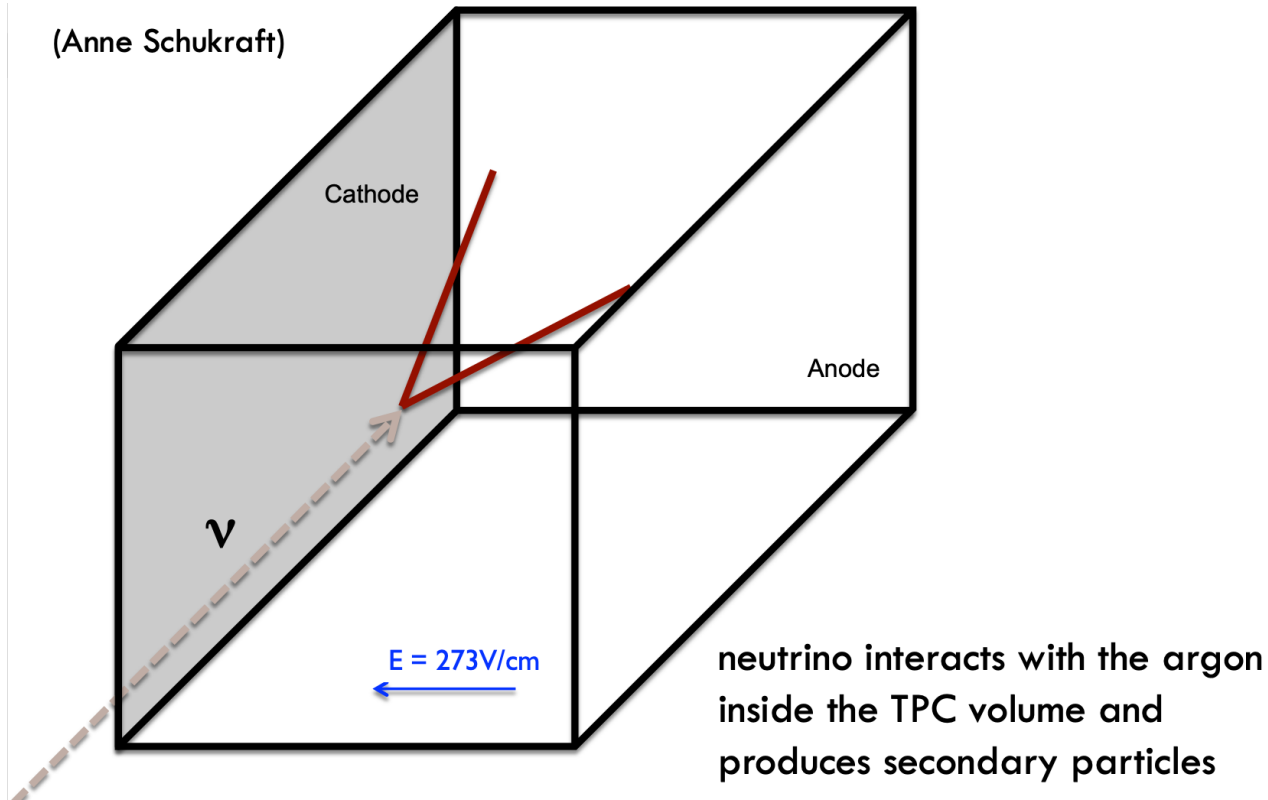 - Fermilab is one of the few places in the World to do this!

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?

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Some Additional Slides

How A Liquid Argon Time Projection Chamber Works

(Anne Schukraft)

Cathode

Anode

ν

E = 273V/cm

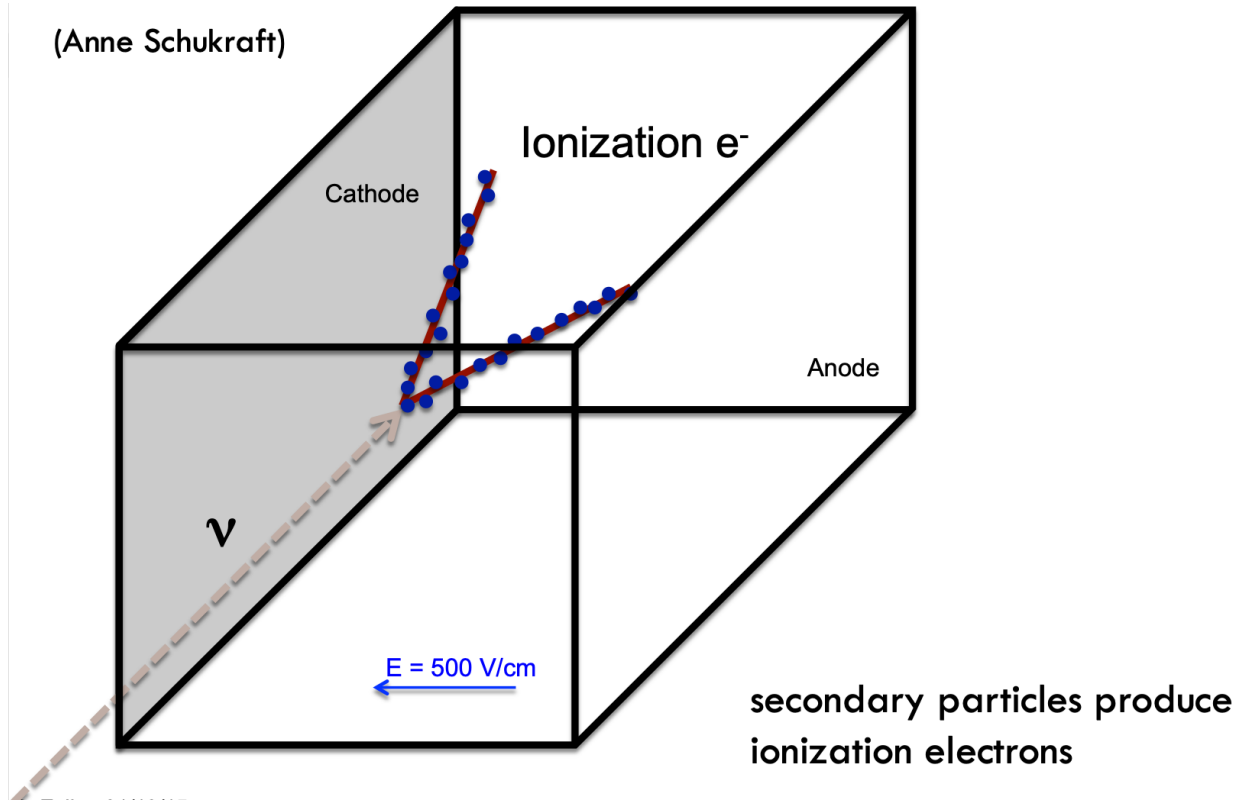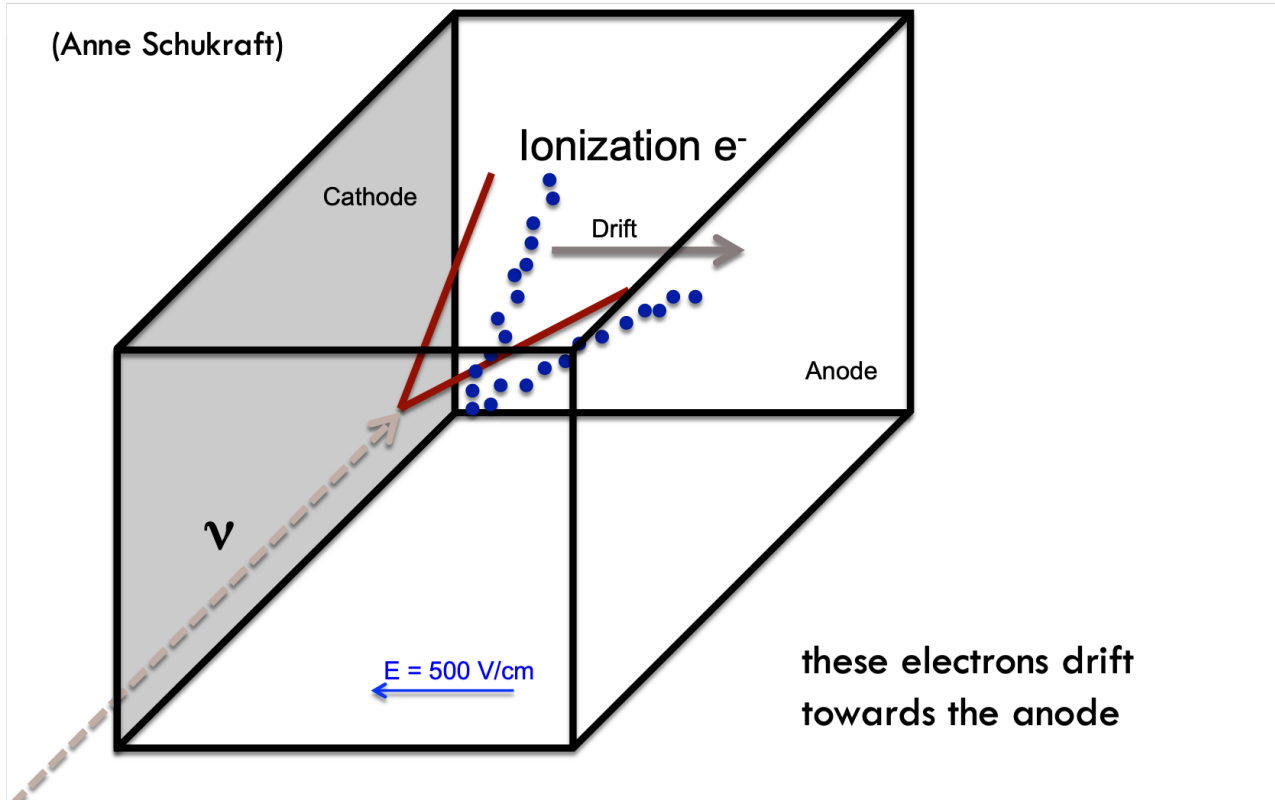neutrino interacts with the argon inside the TPC volume and produces secondary particles

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How A Liquid Argon Time Projection Chamber Works

How A Liquid Argon Time Projection Chamber Works

(Anne Schukraft)

Cathode

Ionization e⁻

Drift

Anode

ν

E = 500 V/cm

these electrons drift towards the anode

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How A Liquid Argon Time Projection Chamber Works

(Anne Schukraft)

Cathode

Ionization e⁻

Anode

ν

E = 500 V/cm

electrons arrive at anode

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How A Liquid Argon Time Projection Chamber Works

(Anne Schukraft)

wire planes

Ionization e⁻

Cathode

ν

E = 500 V/cm

the pattern is recorded on a
set of closely spaced wires

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How A Liquid Argon Time Projection Chamber Works

(Anne Schukraft)

wire planes

Ionization e⁻

Cathode

ν

E = 500 V/cm

get a 3D picture

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How A Liquid Argon Time Projection Chamber Works

(Anne Schukraft)

Cathode

Anode

ν

E = 500 V/cm

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

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