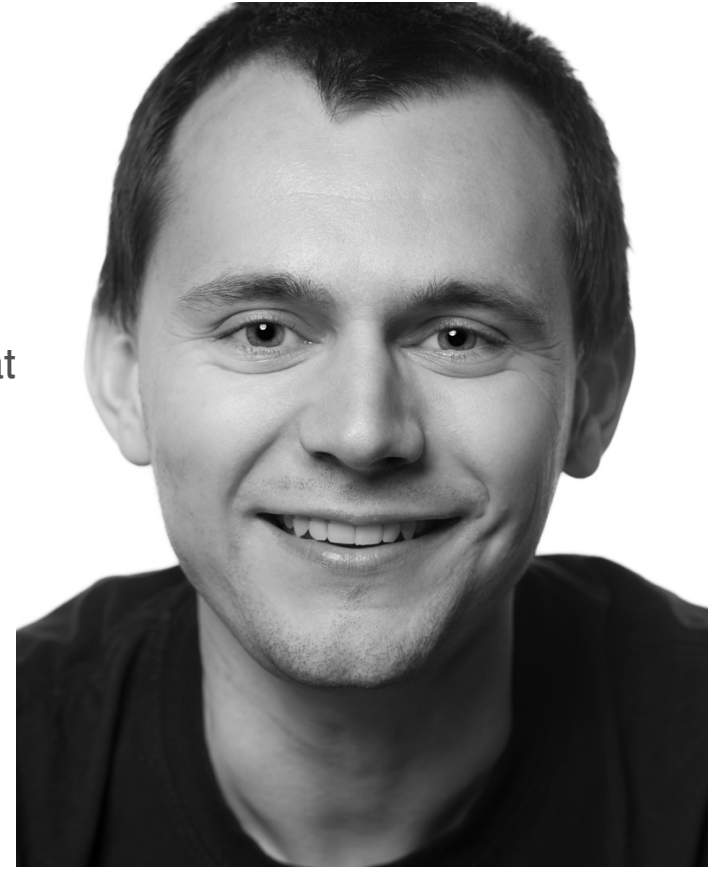
Saturday Morning Physics – The Ghostly Neutrinos

Karl Warburton (Iowa State University)

19th October 2019

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 2.5 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.



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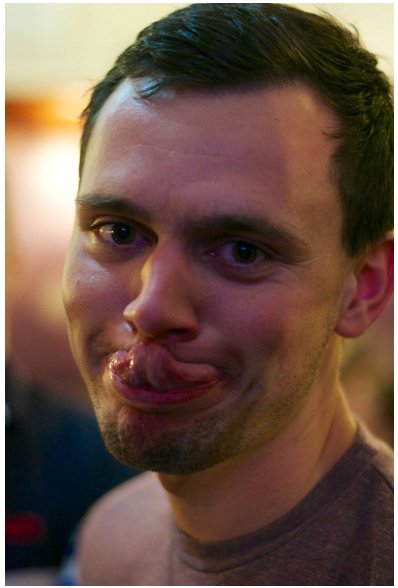
Who am I really?

- 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

- Reminder about the “The Standard Model” and then An Introduction to Neutrinos
  - Let’s talk about breaking the law.
- The first measurements of neutrinos
  - Let’s talk about nuclear bombs!
- The physics of neutrinos
  - Let’s get really confused
- How we study neutrinos now
  - Maybe we’ll find some gold.

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

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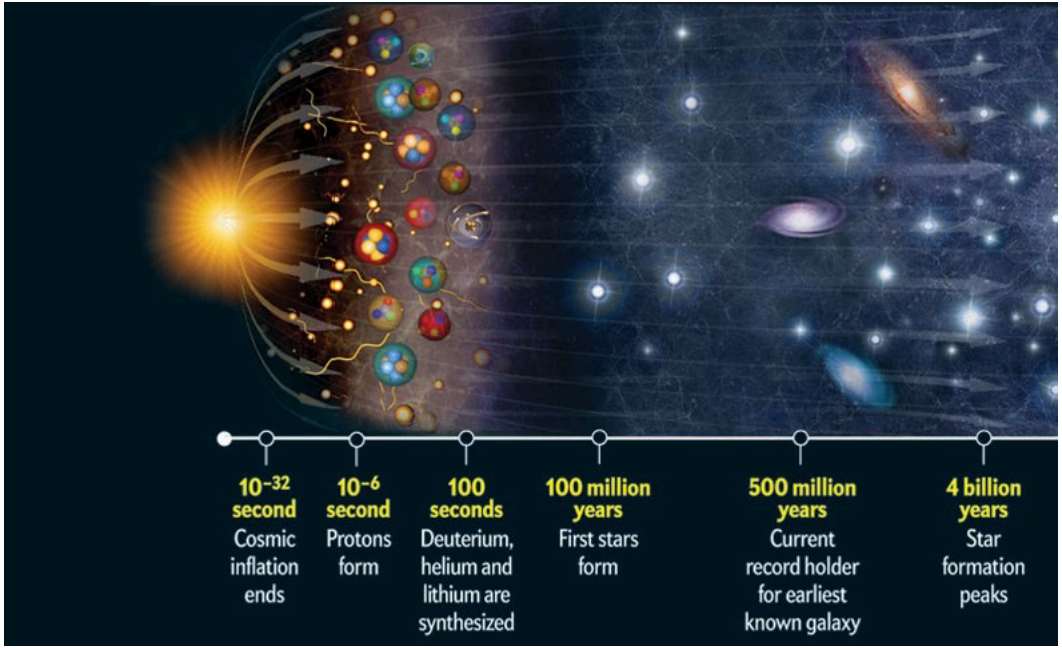
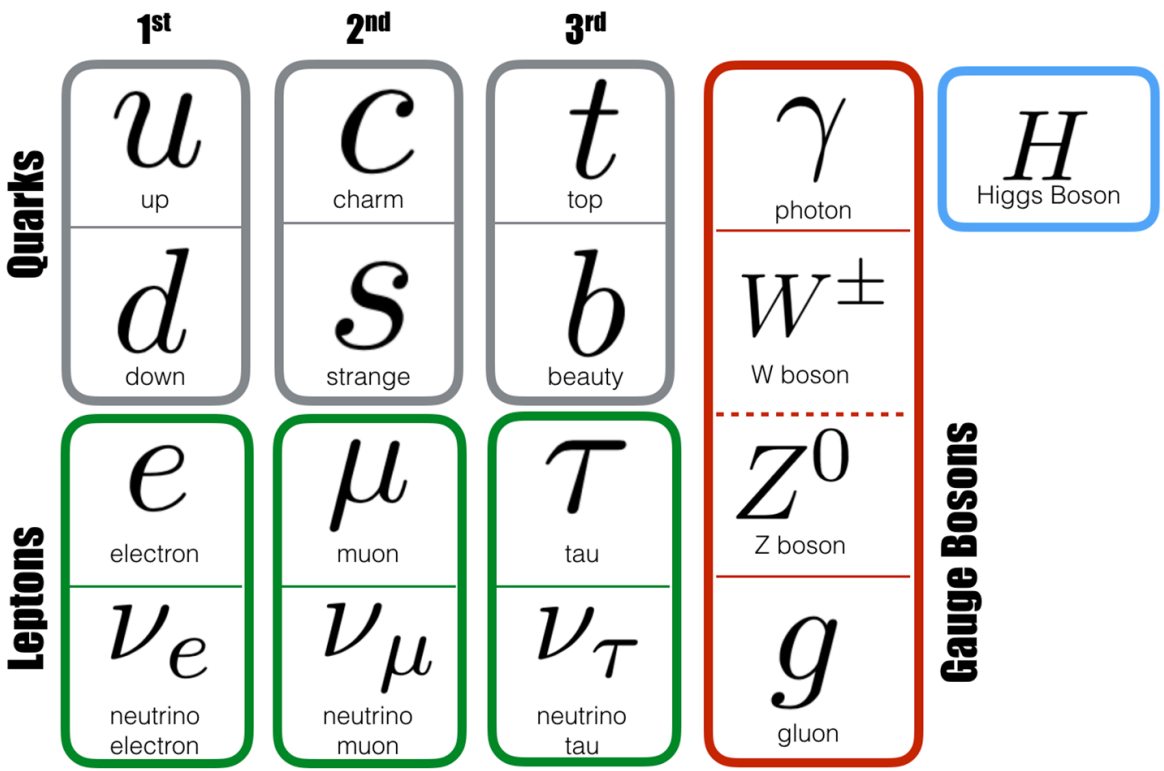
The Standard Model of Particle Physics and the big bang



- After the Big Bang, matter and anti-matter were created in roughly equal amounts.
  - For every 10,000,000,000 anti-matter particles, 1 more matter particle was created.
- After those particles we were left with the Universe that we see.
- But why was this the case?
  - The SM predicts that there should have been exactly equal amounts of each…

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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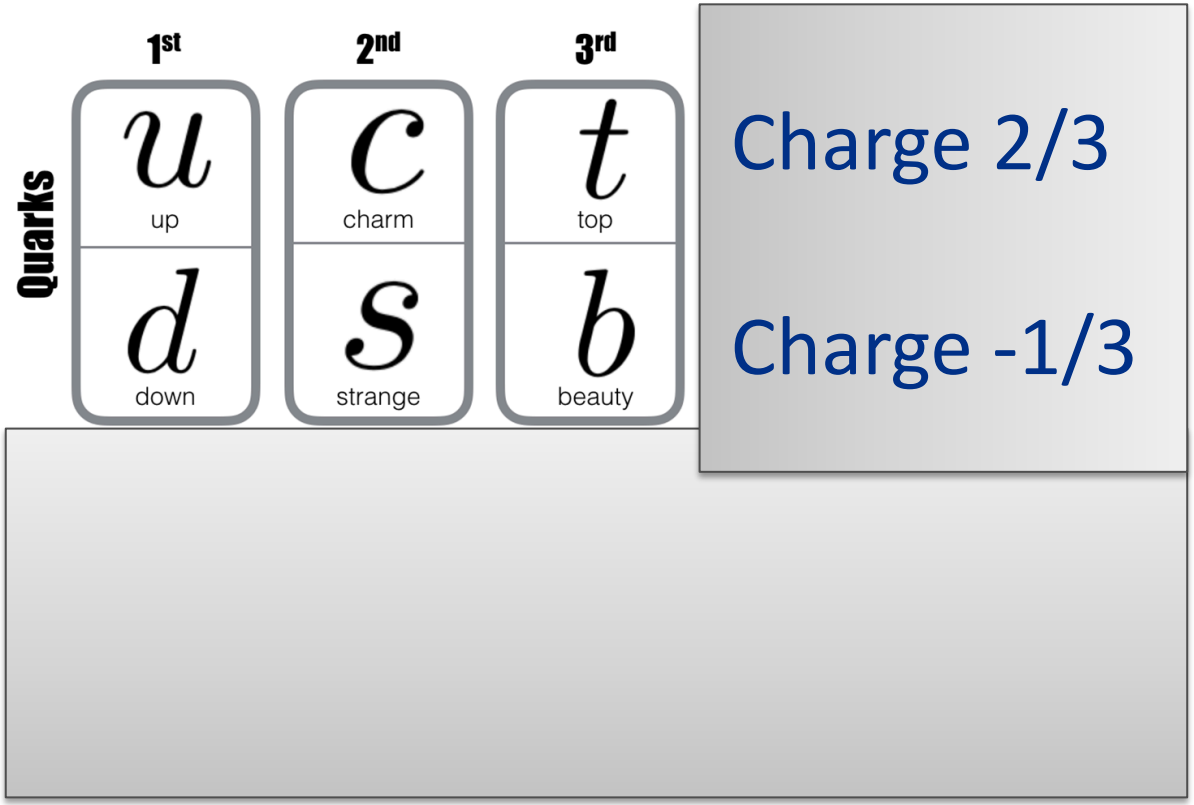
The Standard Model of Particle Physics - Quarks



- Quarks are fractionally charged.
- They are never seen by themselves.
- Combinations of quarks are called *Hadrons*.
  - The most common examples are protons and neutrons.
  - You may also have heard of pions or kaons.

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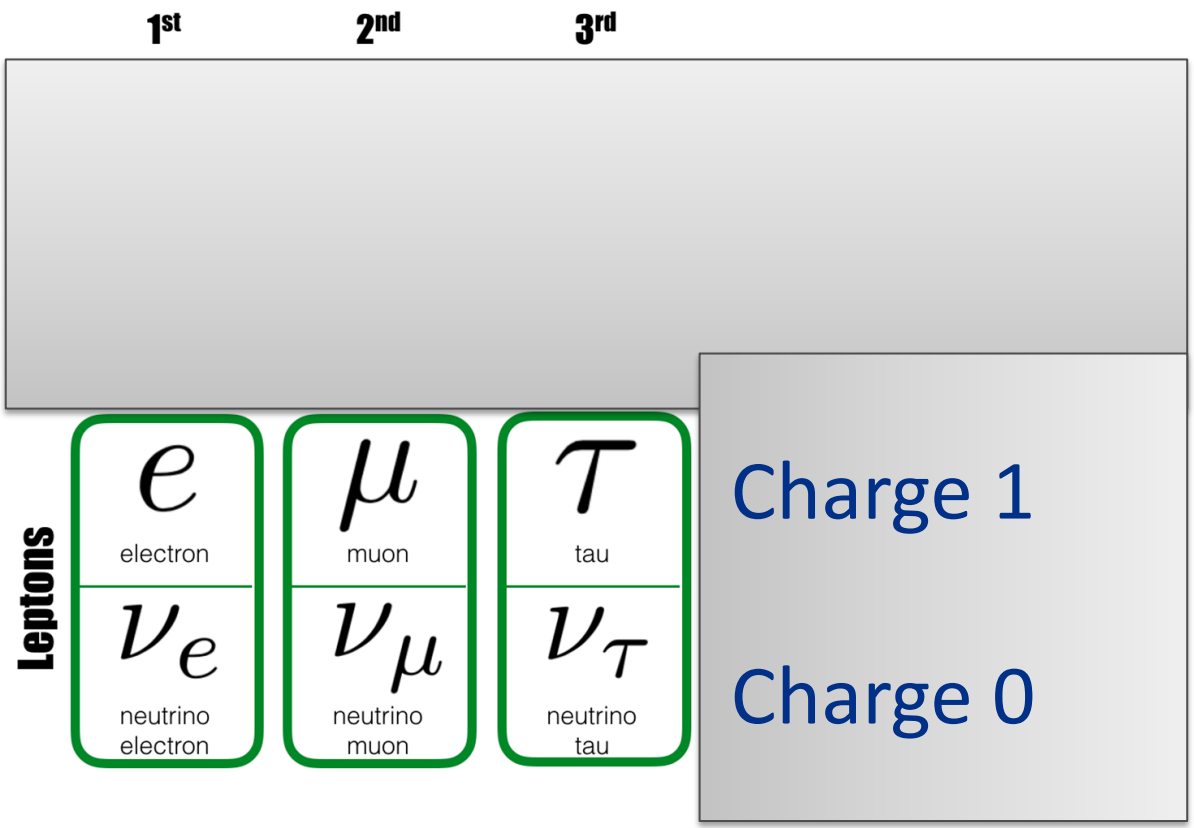
The Standard Model of Particle Physics - Leptons



- Quarks have integer charge.
- They are always seen by themselves.
- You have probably heard of an electron, and will learn about the neutrinos today.
  - The muon and tau families are more *massive* versions of electrons.

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The Standard Model of Particle Physics – Gauge Bosons

Electromagnetic

Weak

Weak

Strong

γ
photon

$W^{\pm}$
W boson

Z^0
Z boson

g
gluon

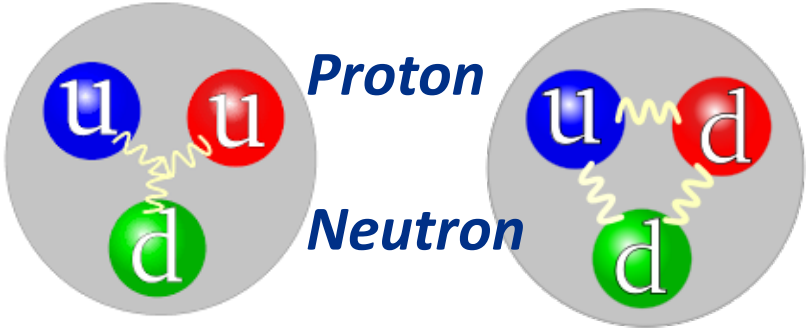
Gauge Bosons

H
Higgs Boson

- The Gauge Bosons are force carriers.
  - Only W bosons are charged, and have ± 1 charge.
  - The rest are neutral.
- The Higgs Boson produces a field by which particles gain mass.
- Gluons come in different colors!

The Standard Model of Particle Physics – The 1st Generation

	1st
Quarks	u up
	d down
Leptons	e electron
	ν_e neutrino electron



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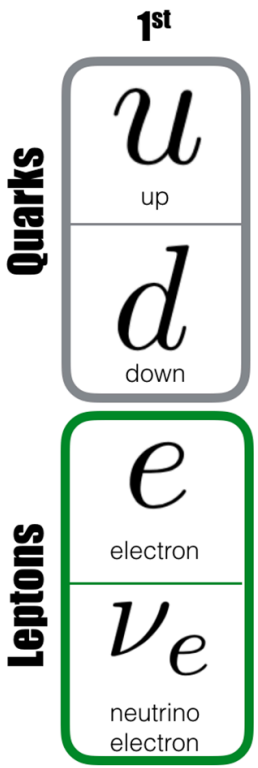
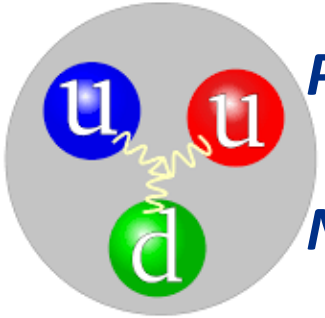
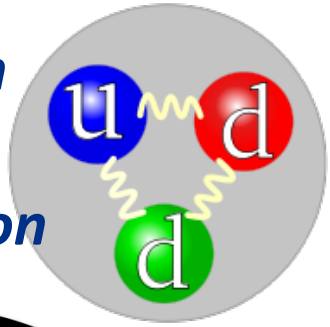
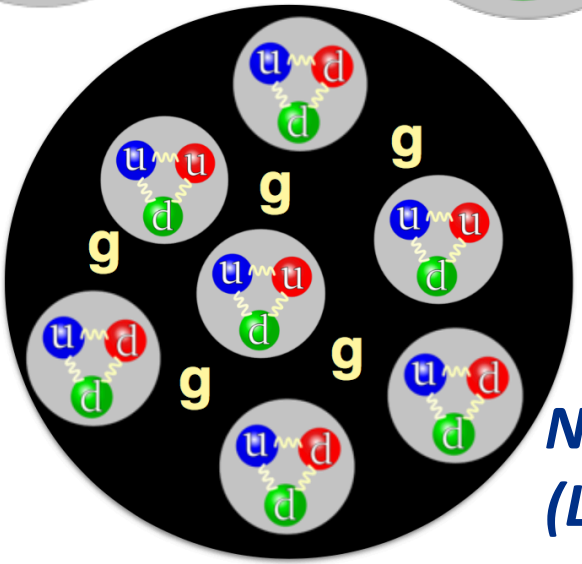




Proton



Neutron



Nucleus (Lithium)

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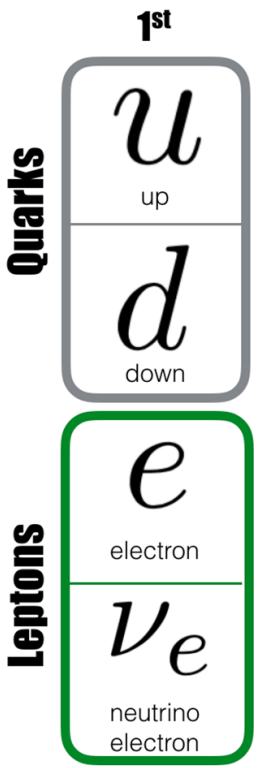

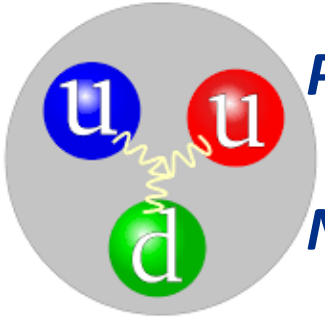

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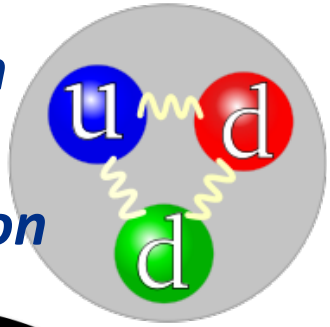

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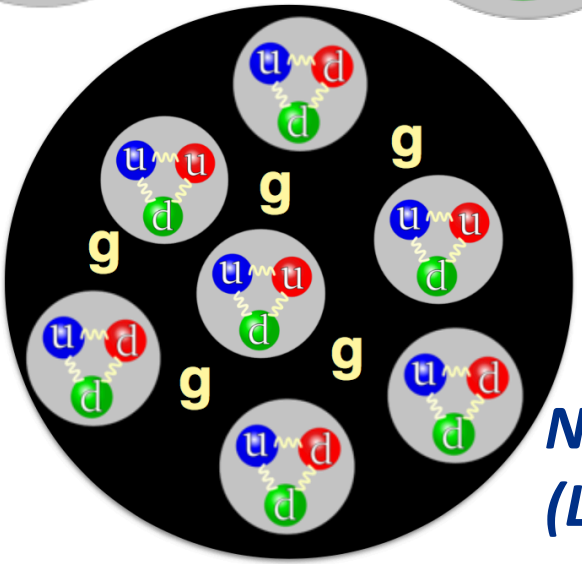

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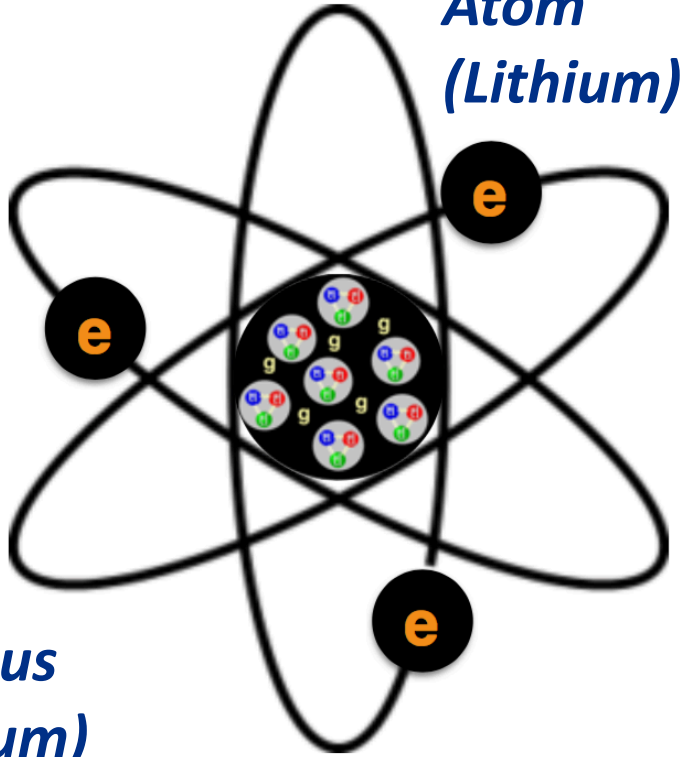

Atom (Lithium)

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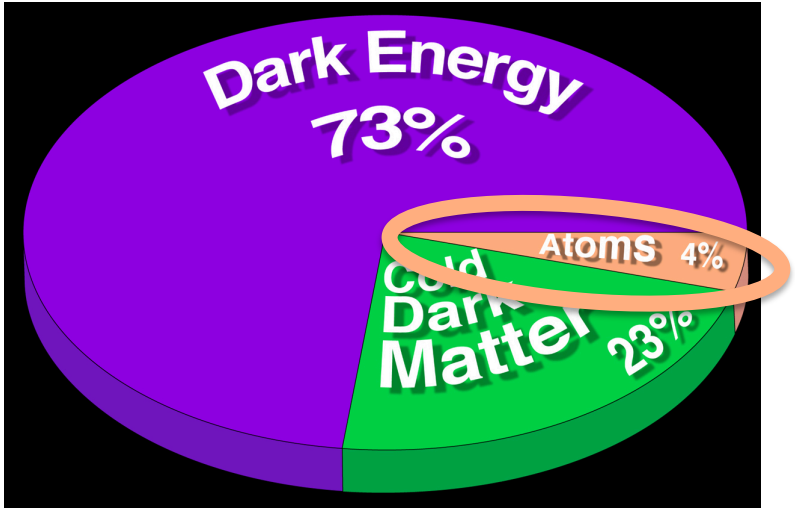
The Standard Model of Particle Physics – A series of Problems



- The Standard Model only predicts how 4% of the "*Energy Content*" of the Universe behaves.
  - It makes no prediction as to what *Dark Matter* or *Dark Energy* are.

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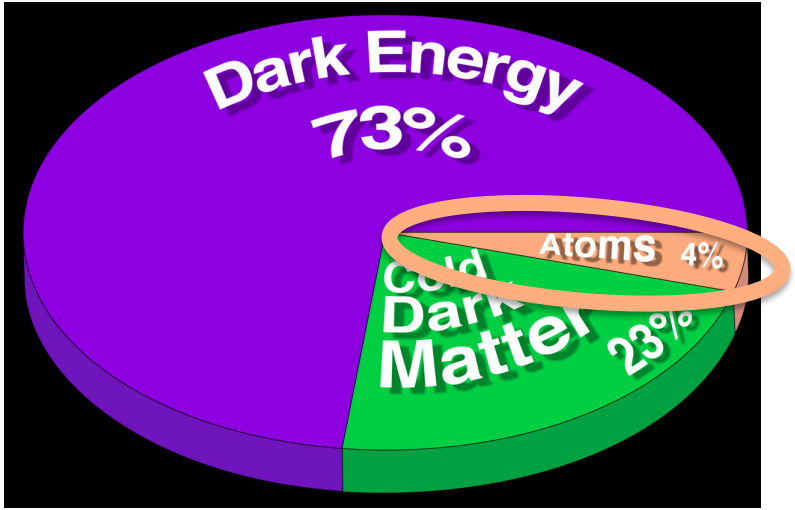

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- Dark Matter holds Galaxies together.
  - If it weren't for this they would fly apart at millions of miles per hour!

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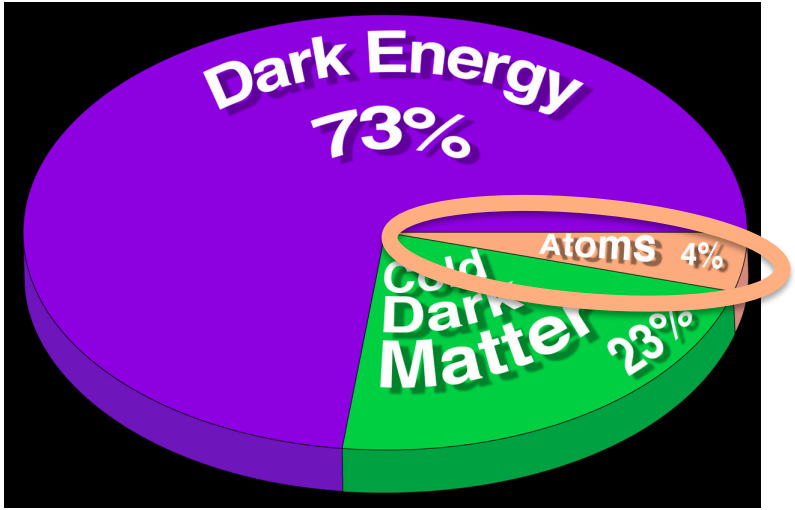
The Standard Model of Particle Physics – A series of Problems



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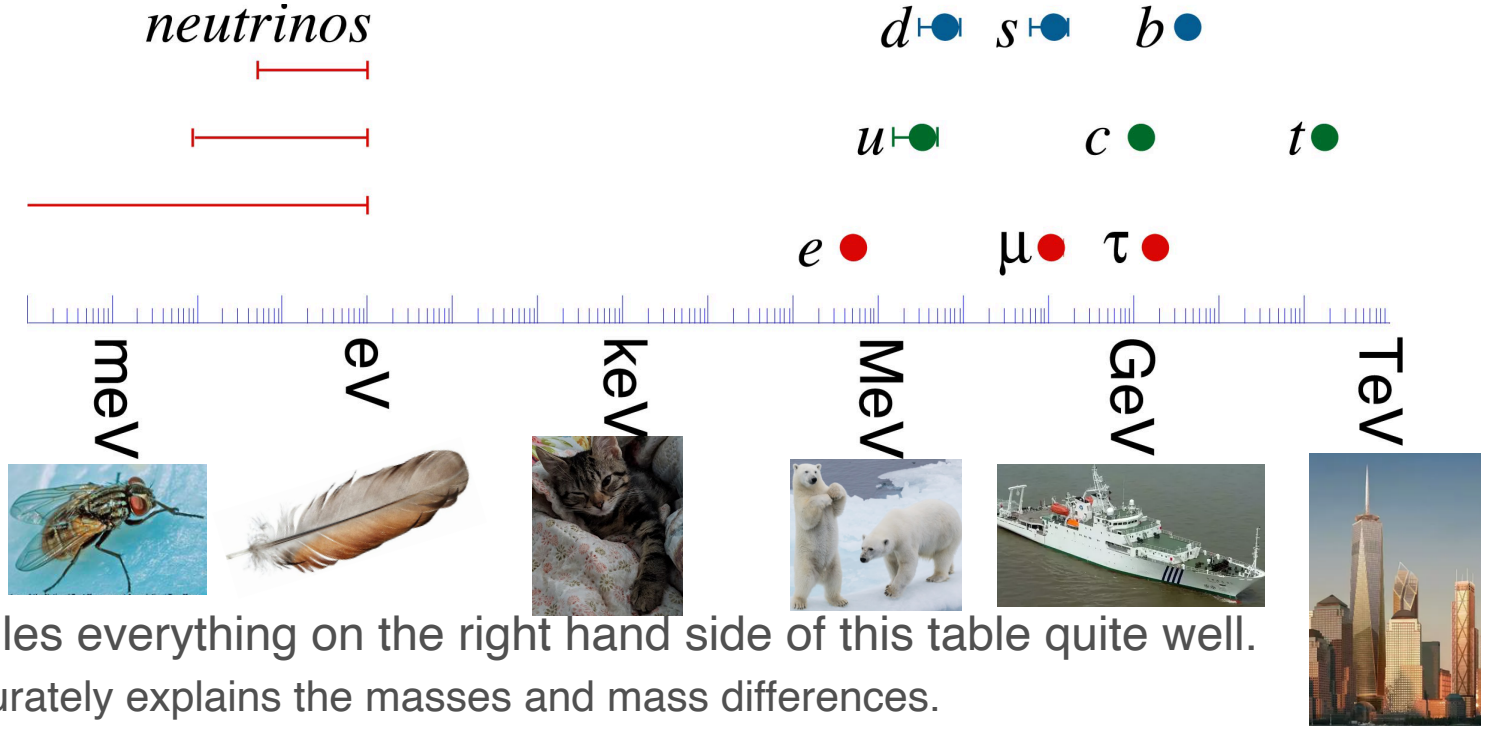
  - It makes no prediction as to what *Dark Matter* or *Dark Energy* are.
- Dark Matter holds Galaxies together.
  - If it weren't for this they would fly apart at millions of miles per hour!
- Dark Energy appears to be causing the Universe to expand faster and faster!
  - Counteracting the force of ***Gravity***

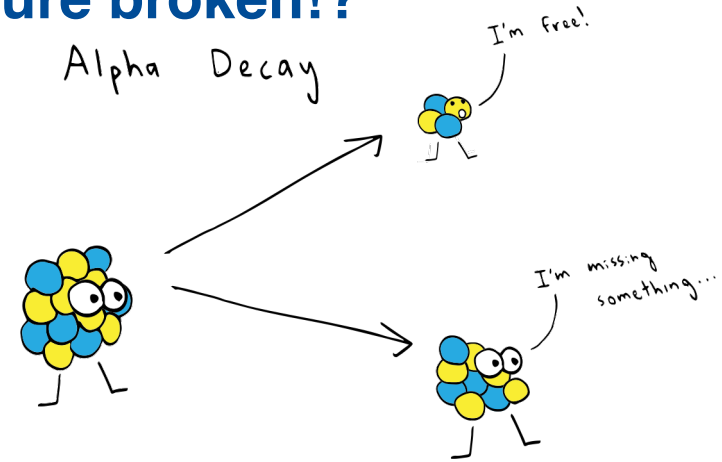
The Standard Model of Particle Physics – The Final Problem



- It handles everything on the right hand side of this table quite well.
  - Accurately explains the masses and mass differences.
- However, it really struggles to explain neutrino masses.
  - ***Something*** about them is fundamentally different to the all of the other particles.

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.



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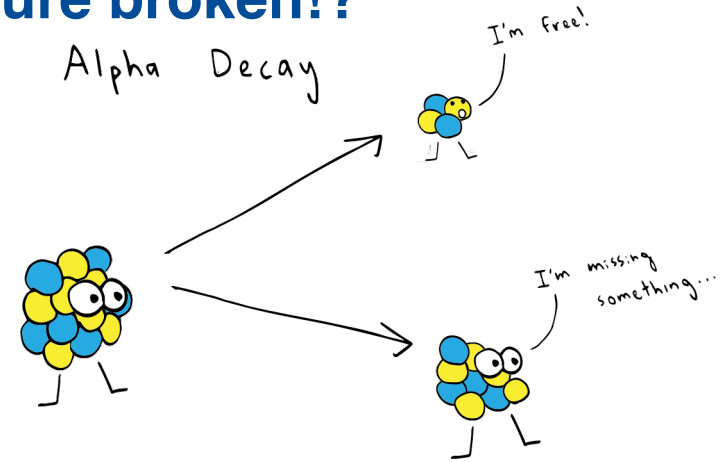

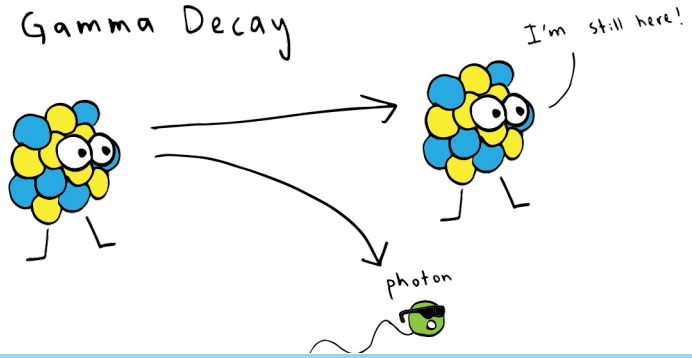

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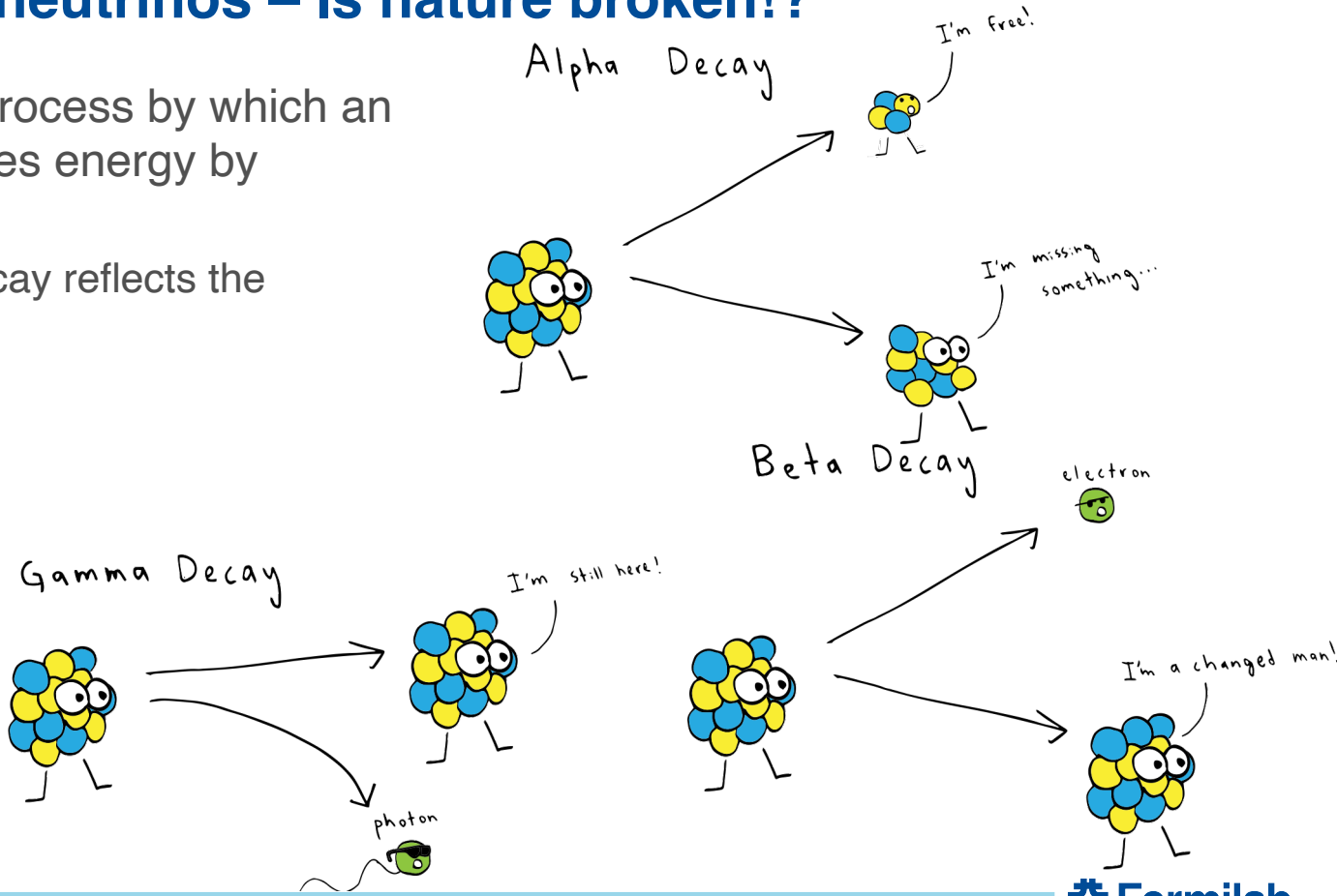

The discovery of neutrinos – Is nature broken!?

- Radioactivity is the process by which an unstable nucleus loses energy by emitting a particle.
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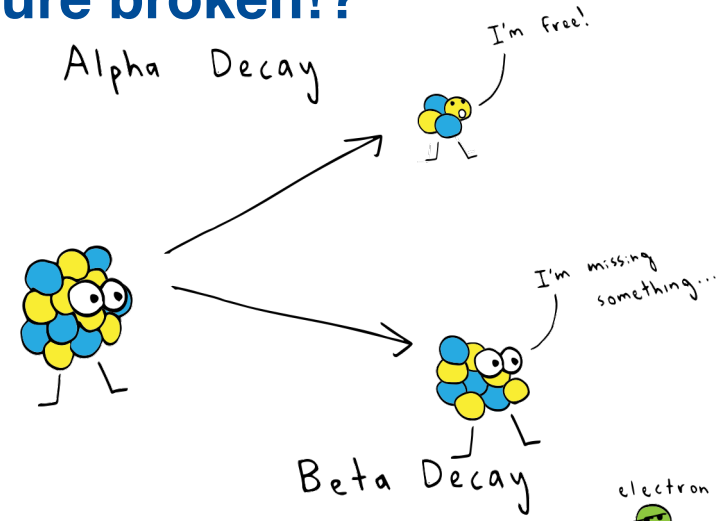
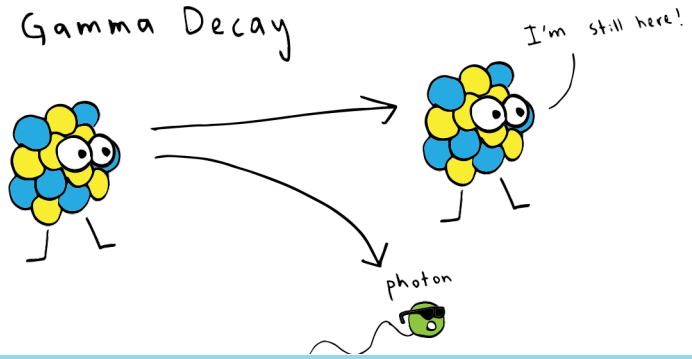
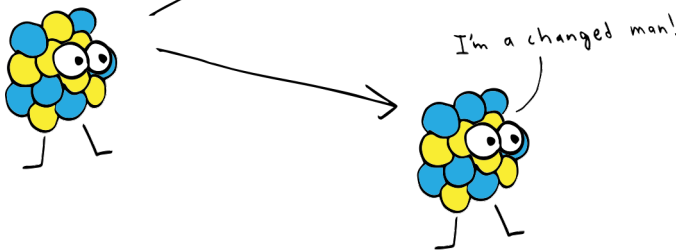
- Henri Becquerel, Marie Curie and Pierre Curie won the 1903 Nobel Prize for their work on radioactivity.







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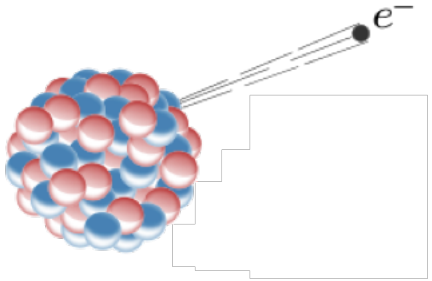
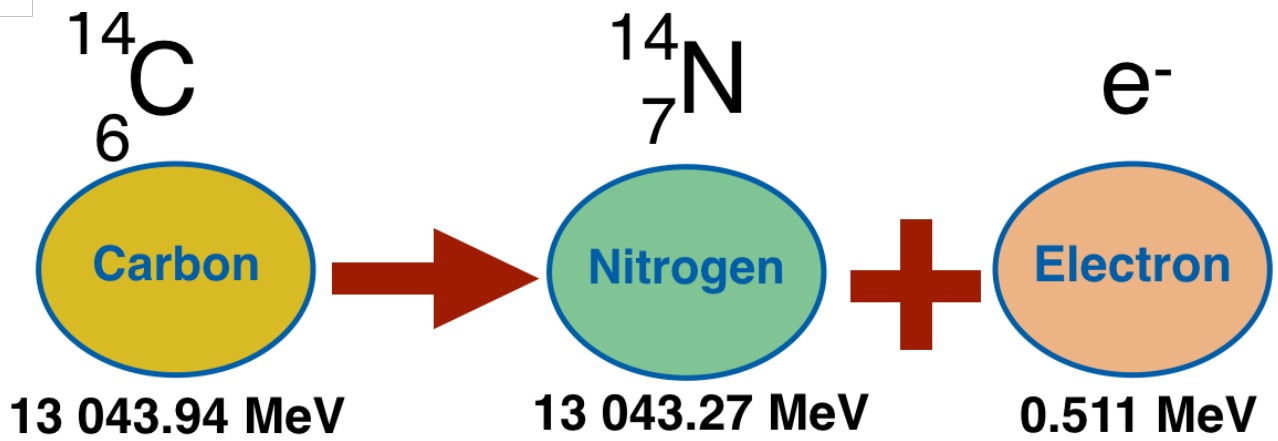
What is beta decay?



- 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:



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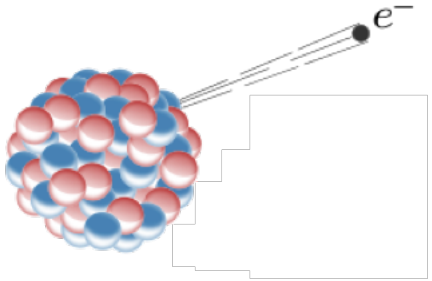

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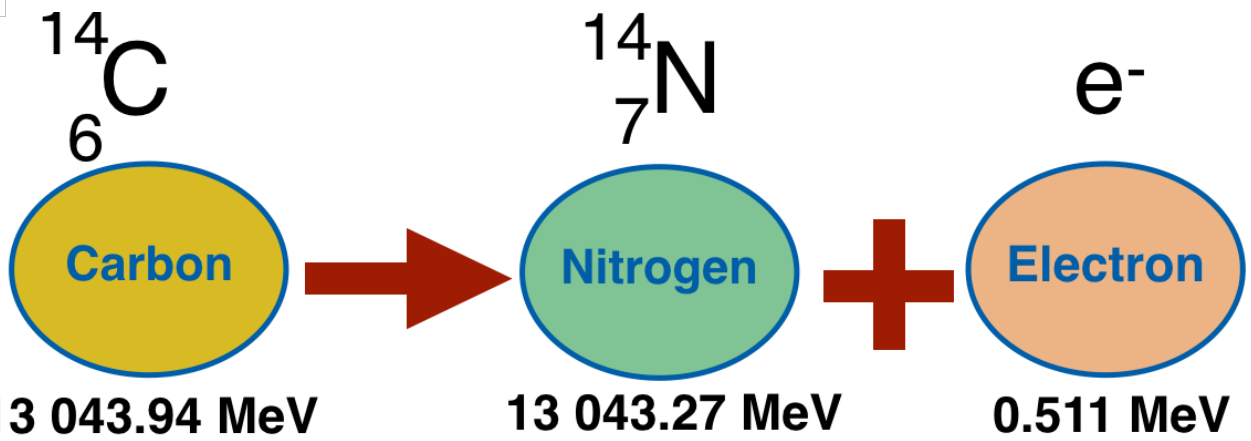
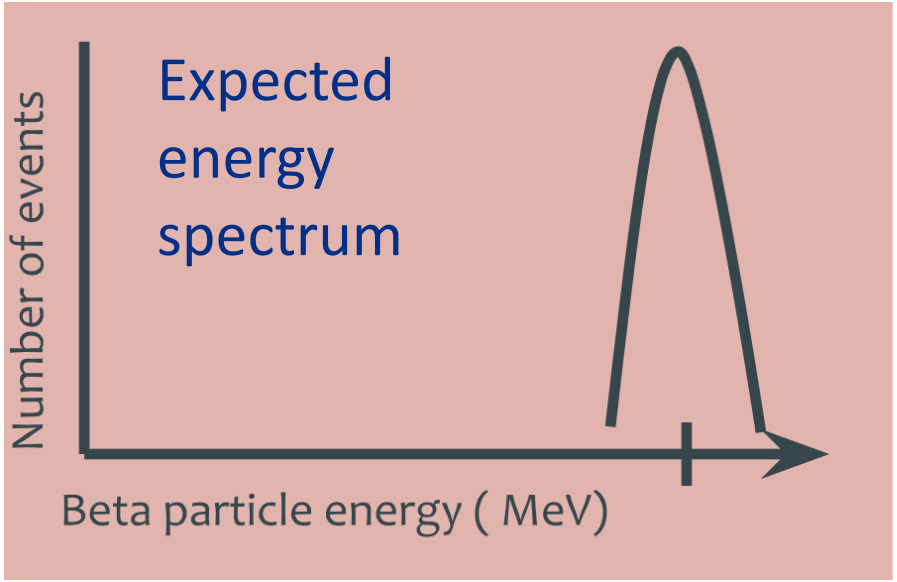
- Due to energy conservation the electron is kicked out of the nucleus with 0.159 MeV of energy.

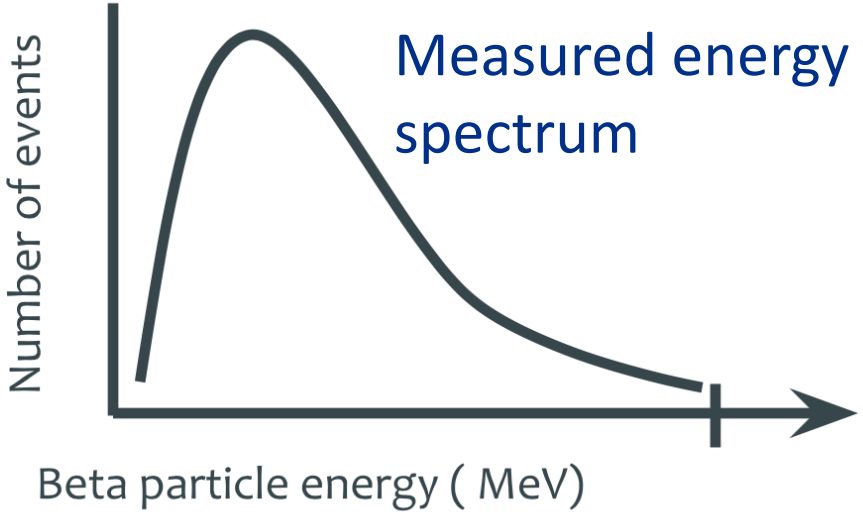
For instance:



The discovery of neutrinos – Is nature broken!?

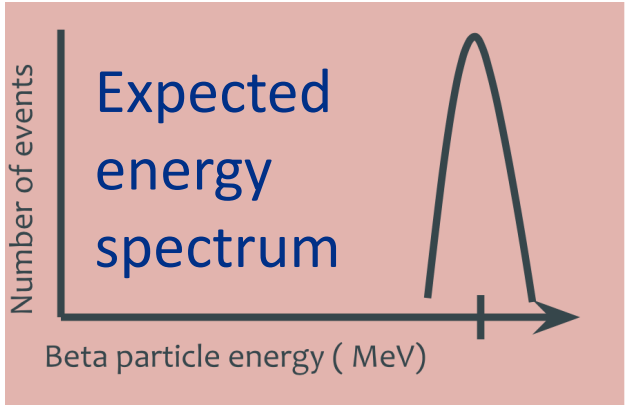
- The energy of the electron emitted by beta decay isn't 150 keV though…
- This means that something that something is wrong with our model.

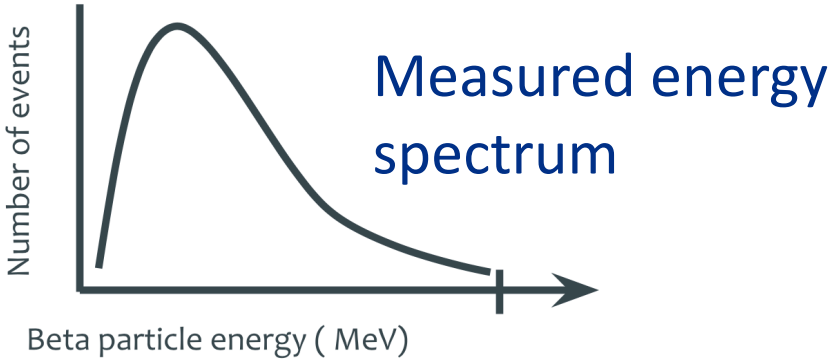




What do we do about it? The choices available in 1914

- A) Throw the experiment out of the window, it's broken, we'll make another one.
- B) Throw the theory in the bin, we'll get someone else to come up with one.
- C) Have a brew and wait for this whole thing to blow over.
- D) Ask for a billion dollars to dig a really big hole.





What do we do about it? The choices available in 1914

- ~~A) Throw the experiment out of the window, it's broken, we'll make another one.~~

  Unfortunately that's not going to work this time.

- B) Throw the theory in the bin, we'll get someone else to come up with one.

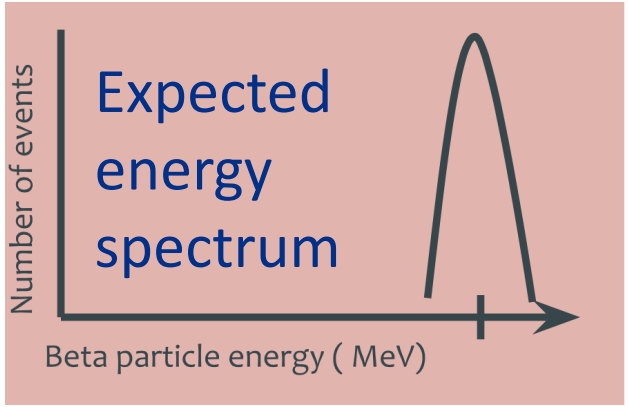
  Ok great, but who?

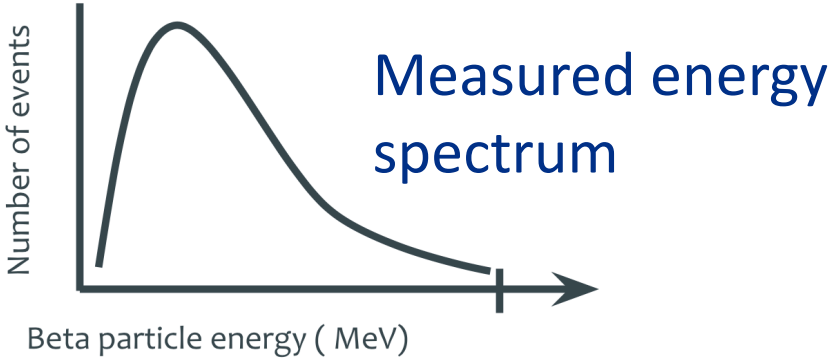
- ~~C) Have a brew and wait for this whole thing to blow over.~~

  Always a solid plan though.

- ~~D) Ask for a billion dollars to dig a really big hole.~~

  Strange choice, but I like your style





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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.

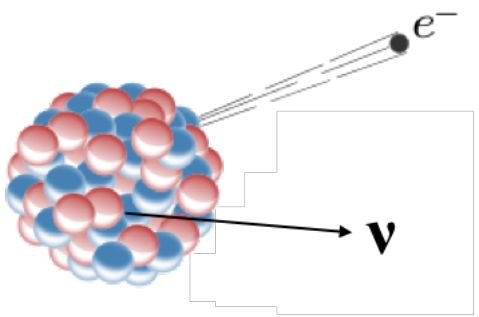
4th December 1930
Dear Radioactive Ladies and Gentlemen,
*As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the ”wrong” statistics of the N and ^{6}Li nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to 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...

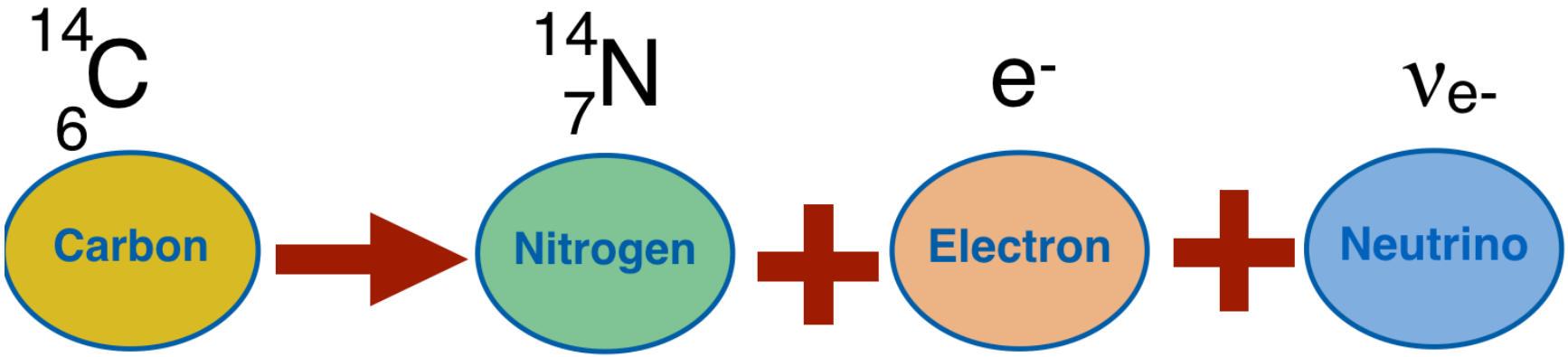
Your humble servant,
W. Pauli

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.





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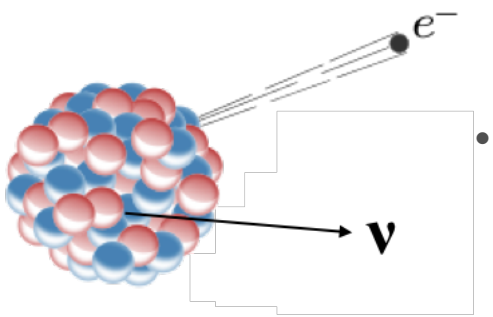
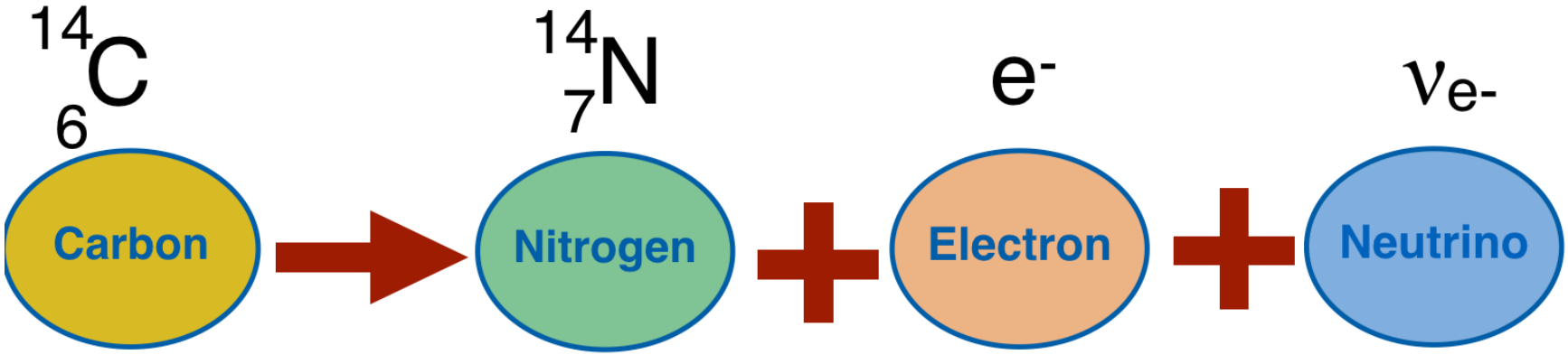


- A neutrino is emitted from the nucleus in addition to the electron.
- Energy is still conserved, but now the 0.159 MeV is split semi-randomly between the electron and neutrino.
  - Therefore we measure a continuum of electron energies.



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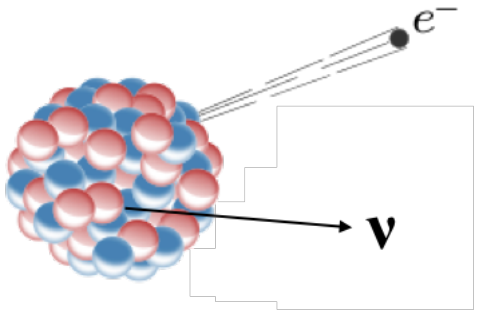
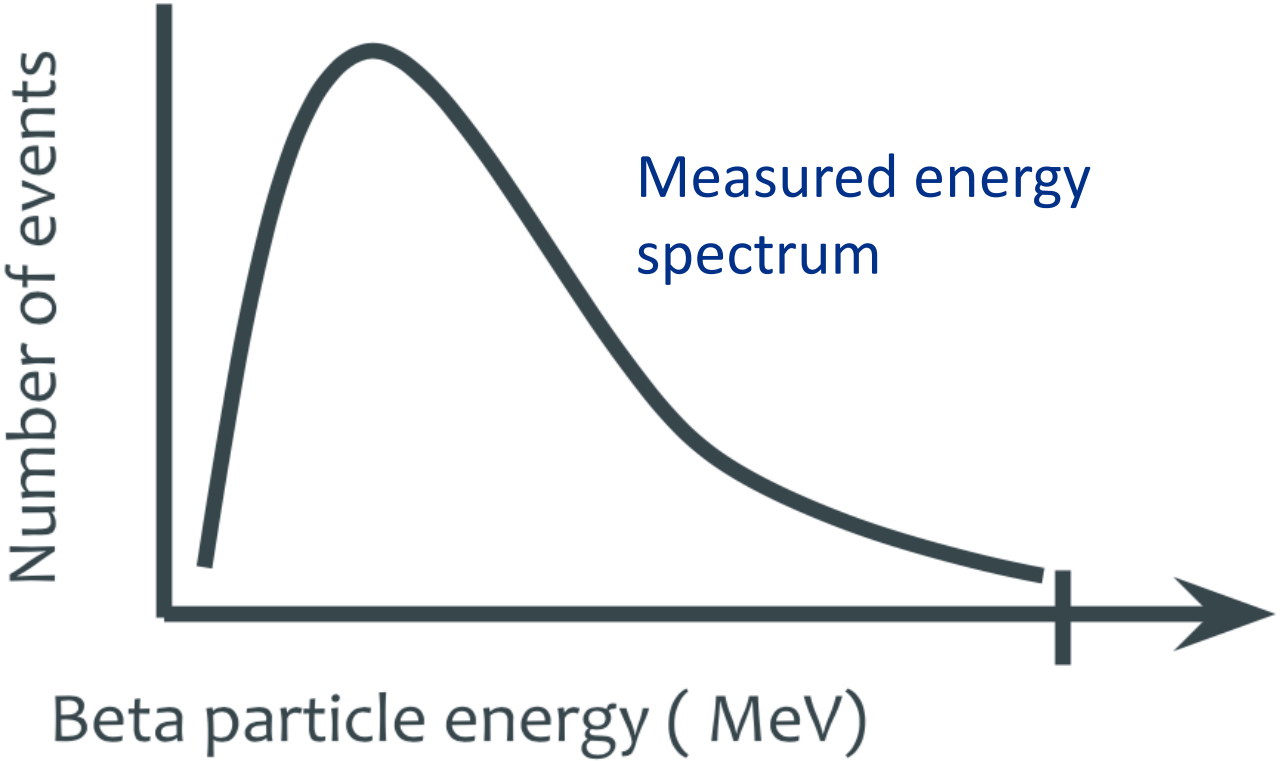


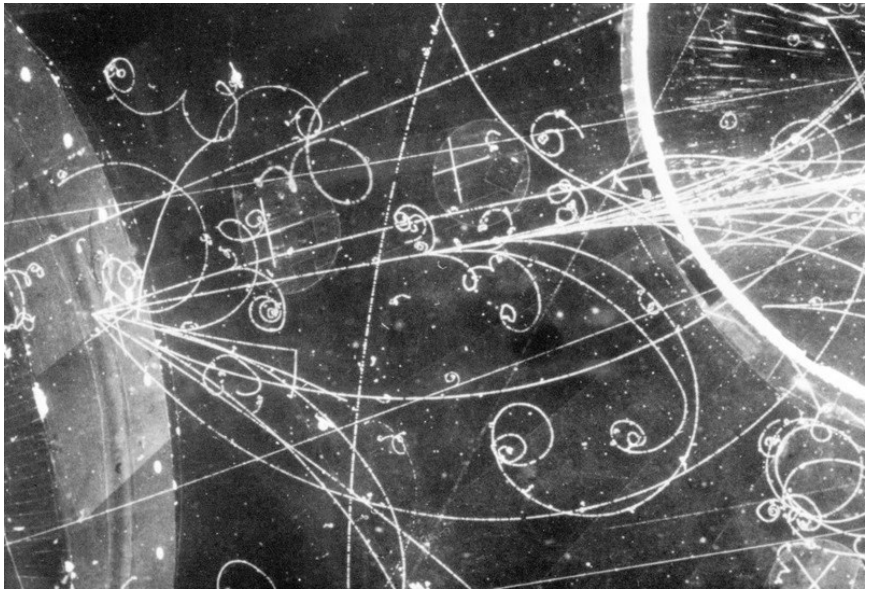


So how exactly do these “neutrino” things behave?

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

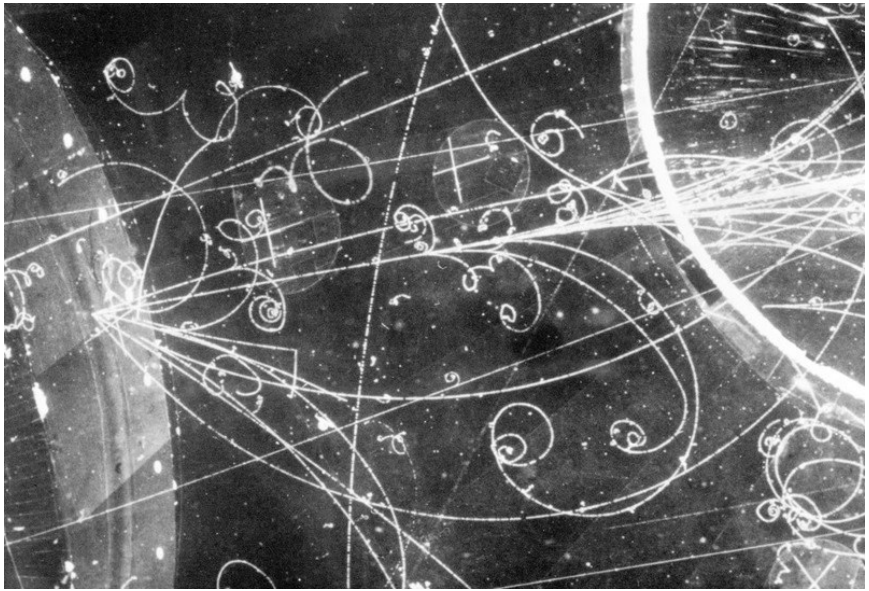
How do we measure neutrinos?

- Most particles interact quite readily.
  - A bubble chamber event from a high energy collision.
  - Can calculate energy and charge by applying Electric/Magnetic fields.



How do we measure neutrinos?

- Most particles interact quite readily.
  - A bubble chamber event from a high energy collision.
  - Can calculate energy and charge by applying Electric/Magnetic fields.



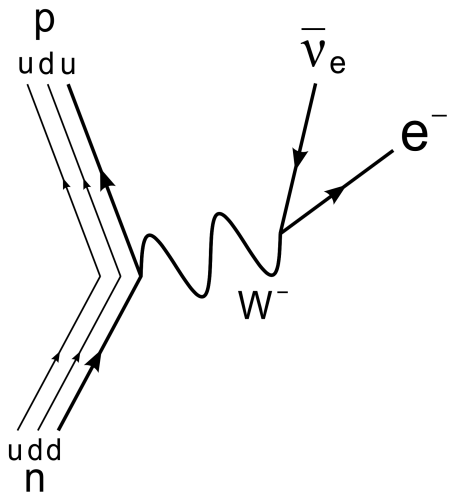
- None of this works for neutrinos.
  - They're neutral and so don't feel E/B fields.
  - They also barely interact, and could easily travel through 200 Earths before interacting!

The only solution therefore is to build HUGE detectors!

A planned experiment in Japan will be ONE MILLION TONS of water!

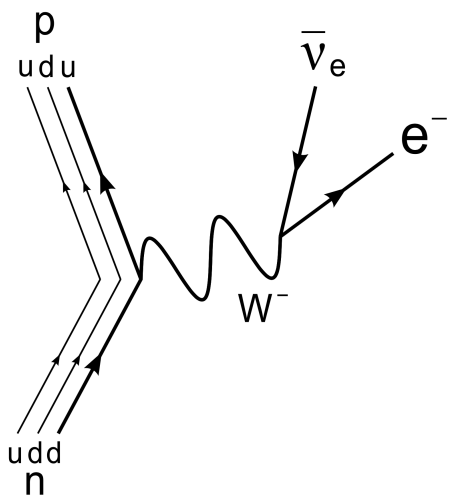
Fermilab

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.

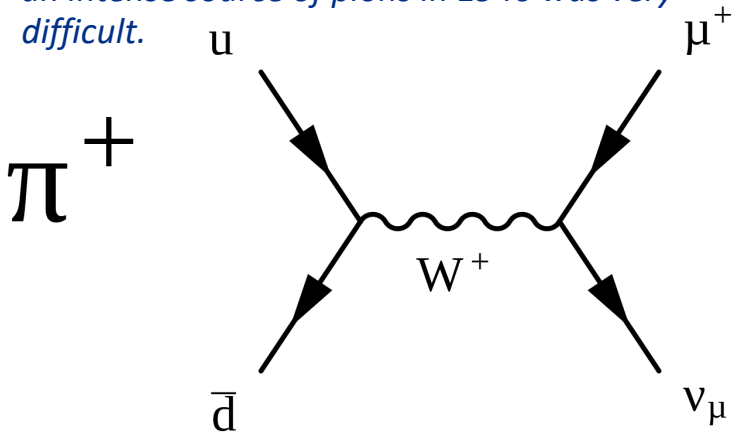
How do we produce neutrinos?



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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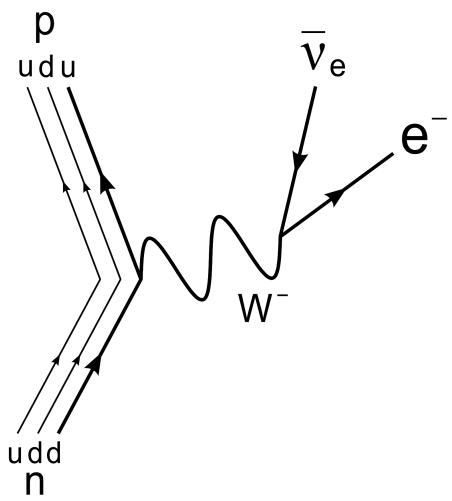

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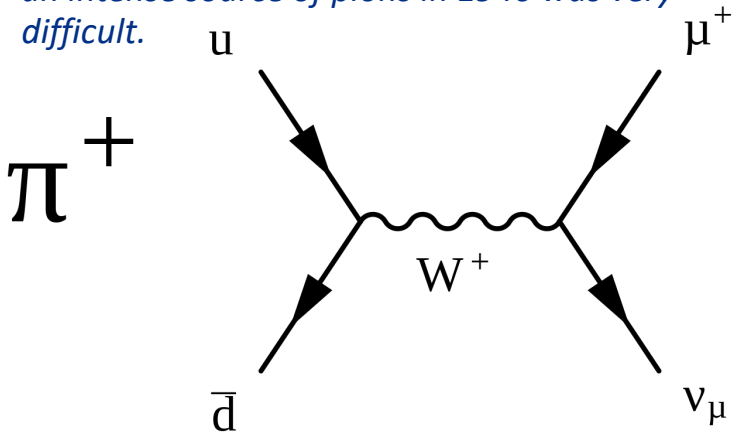
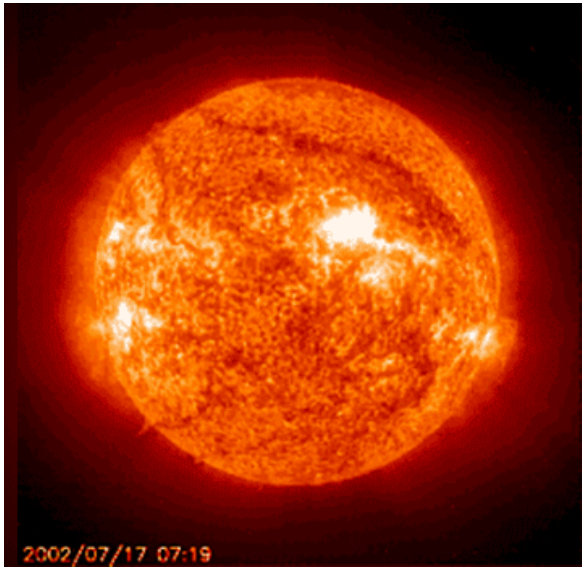




Neutrinos are produced by nuclear reactions – the sun is basically a huge nuclear reactor.
The sun is powered by fusing Hydrogen to make Helium (Fusion).
Man-made reactors break-up large elements (normally Uranium) into various smaller elements. (Fission).

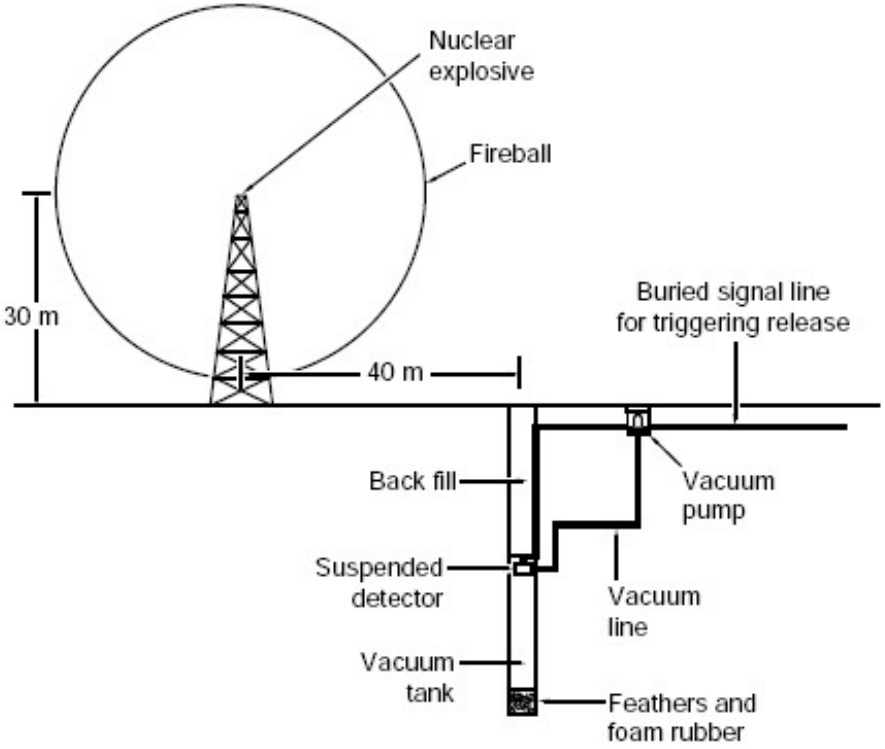
How do we produce neutrinos continued…

- 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?

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

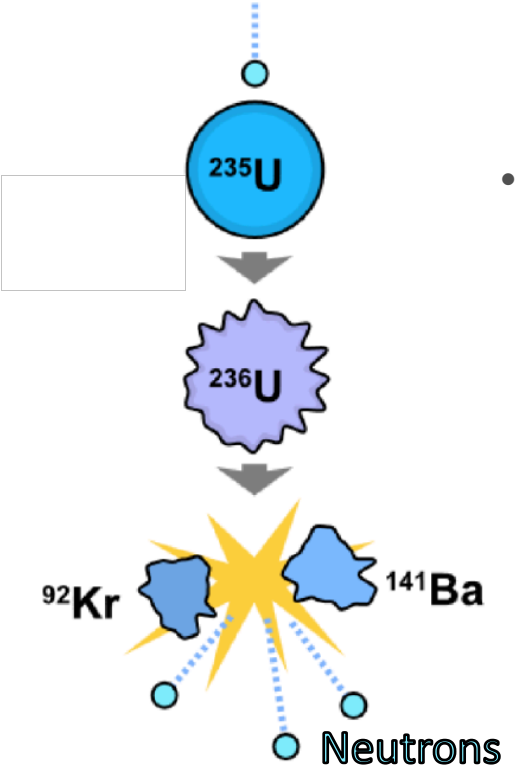
Project Poltergeist #1.



- 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…

Project Poltergeist #2.



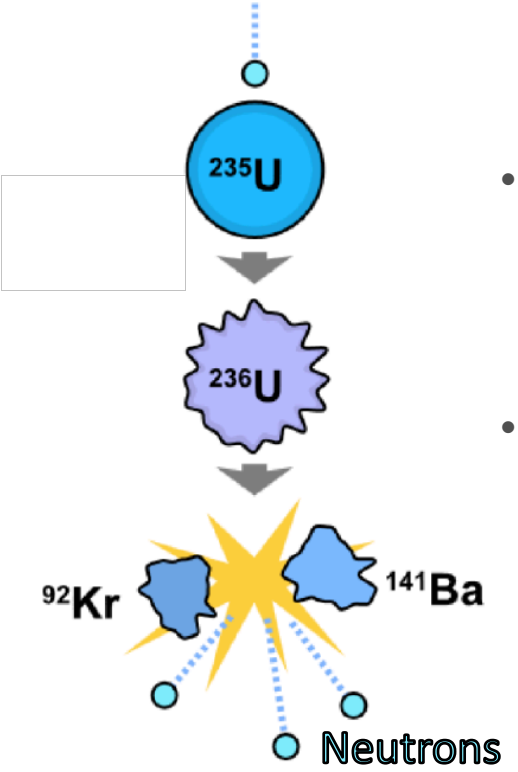
- It was noted that using the reactors at LANL might be more reproducible, sensible and simple (~~*read boring*~~).

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

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

Fermilab

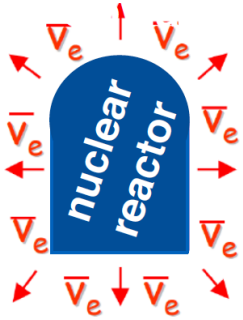
Project Poltergeist #2.



- 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.

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

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



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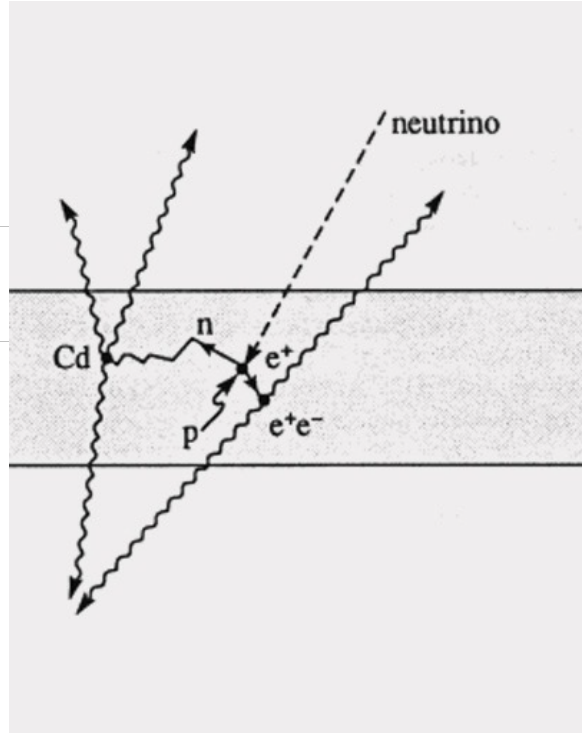
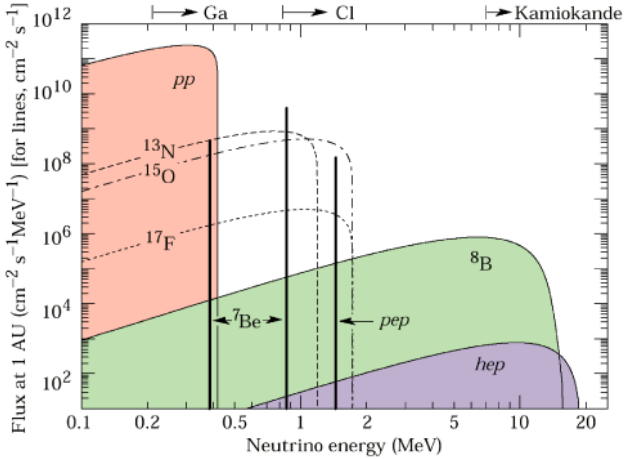


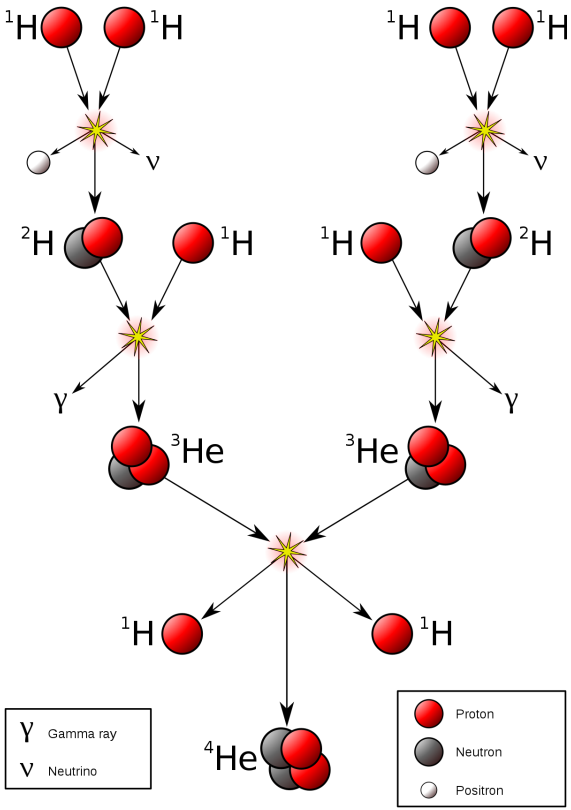
- In 1956 the neutrino was measured for the first time, by placing a Cadmium filled detector next to a reactor.
  - A rate of 0.56 neutrino interactions per hour was measured.

Studying Solar Neutrinos - The Homestake experiment

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

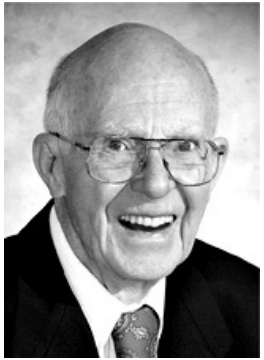
- Studying the neutrinos produced can tell us important things about the Suns structure.

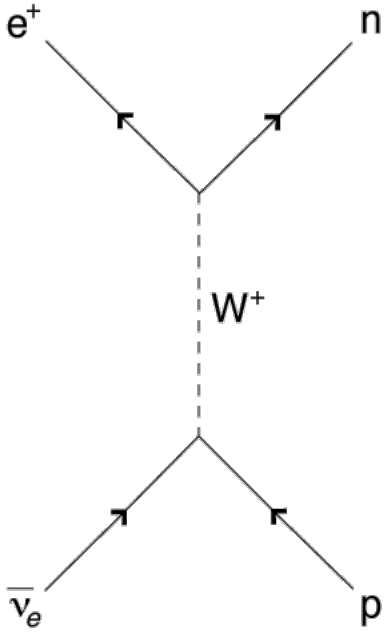




Studying Solar Neutrinos - The Homestake experiment

- 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*.





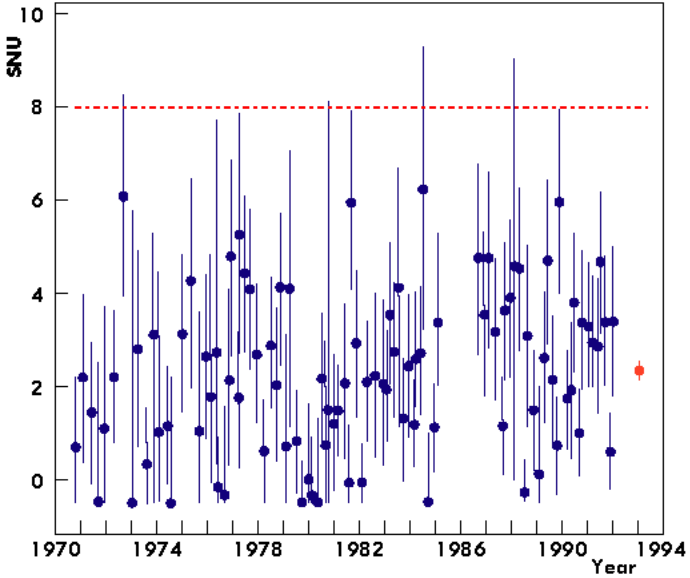
The Homestake experiment

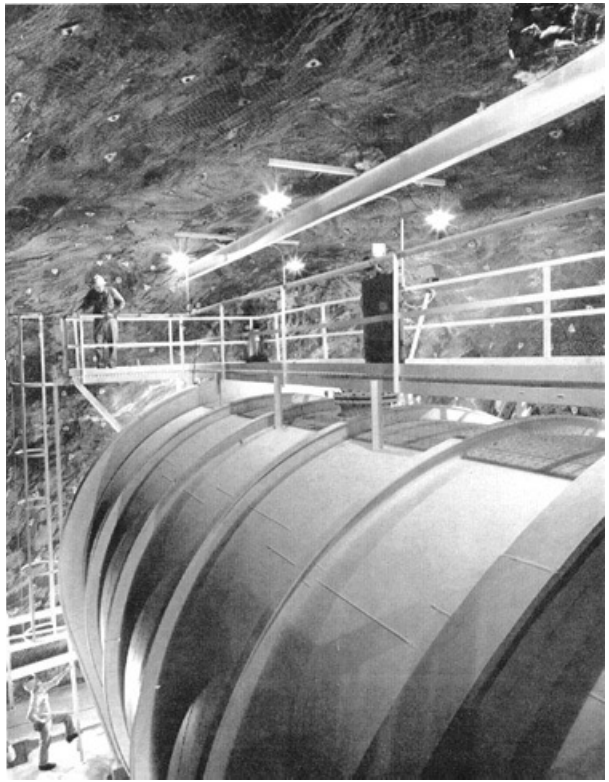
- Ran for 25 years, and consistently saw a rate roughly 1/3 of the expected solar flux.
  - They expected to see about 1 interaction per day, but they saw 1 interaction every 3 days.

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.





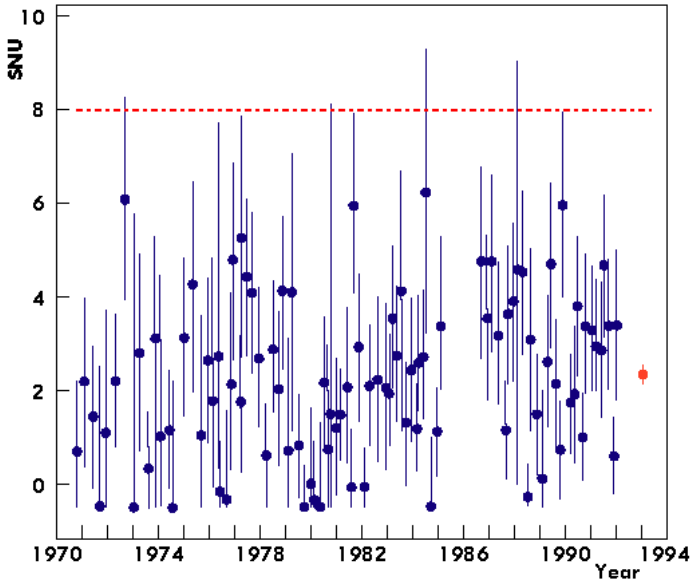
Fermilab

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

Fermilab

The solar neutrino problem…

- Only measuring 1/3 of the expected solar flux meant that ***something*** was wrong with the experiment…
- A) We don't understand what we're measuring, build another detector to look at it.
- B) We don't understand how the sun works, find someone to write a better theory about it.
- C) Go down t' pub, and have a chinwag.
- D) Ask for a billion dollars to dig a really big hole.



The solar neutrino problem…

- Only measuring 1/3 of the expected solar flux meant that ***something*** was wrong with the experiment…

- A) We don't understand what we're measuring, build another detector to look at it.

Good job, but what should we build…

- ~~B) We don't understand how the sun works, find someone to write a better theory about it.~~

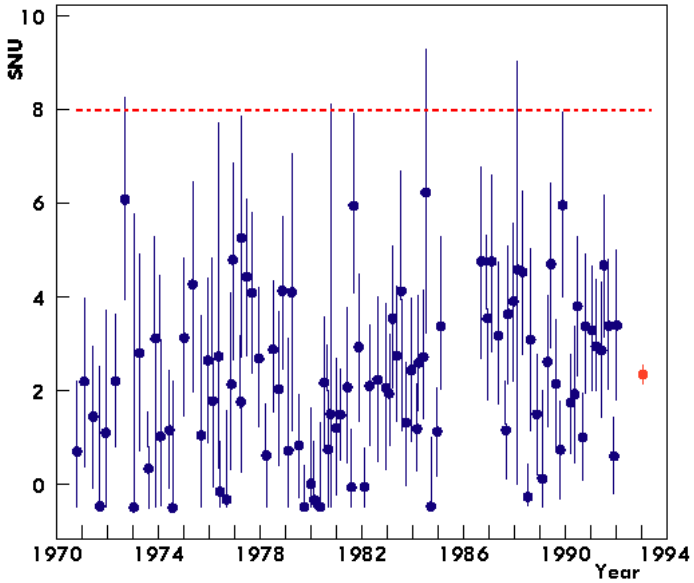
Sometimes the theory is right

- ~~C) Go down t'pub, and have a chinwag.~~

Alcohol and talking rubbish unfortunately isn't the best way to do science.

- ~~D) Ask for a billion dollars to dig a really big hole.~~

I like your persistence…



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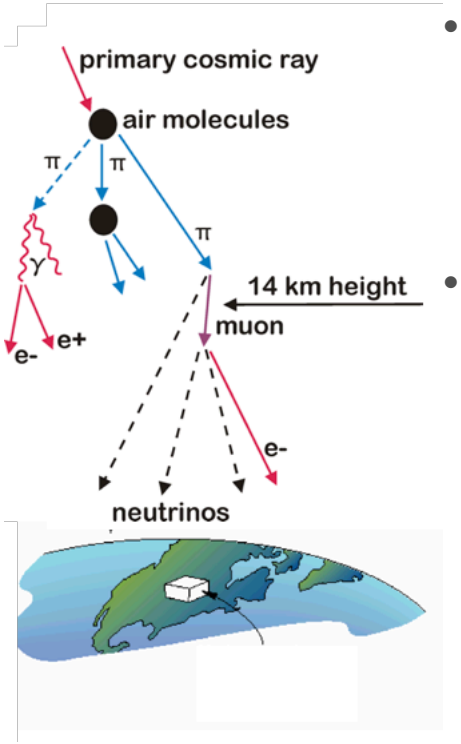
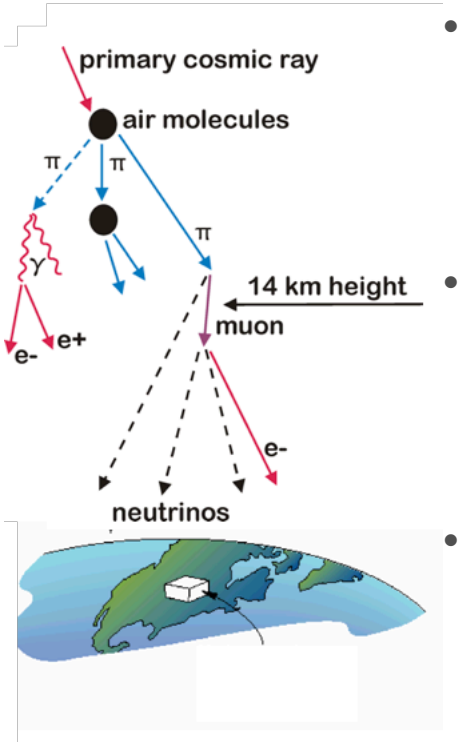
Atmospheric neutrinos

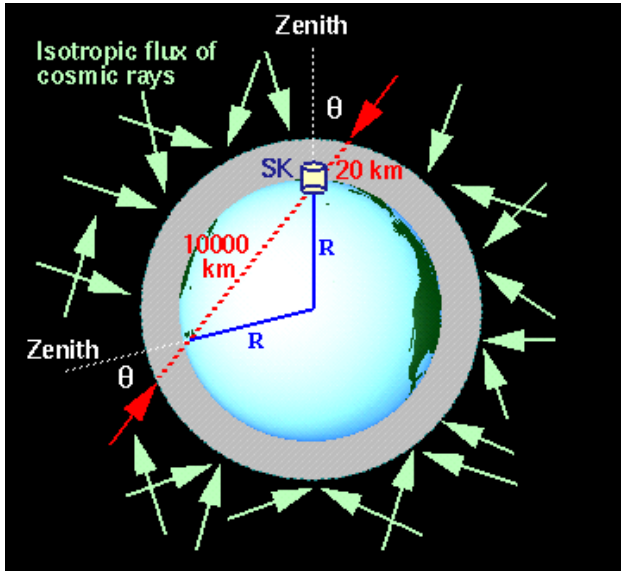


- Produced as high energy cosmic rays strike the upper atmosphere.
  - Produce particle showers (Right).
- As these showers develop and the particles decay, you end up with ~2 ν_μ for every ν_e.

Atmospheric neutrinos

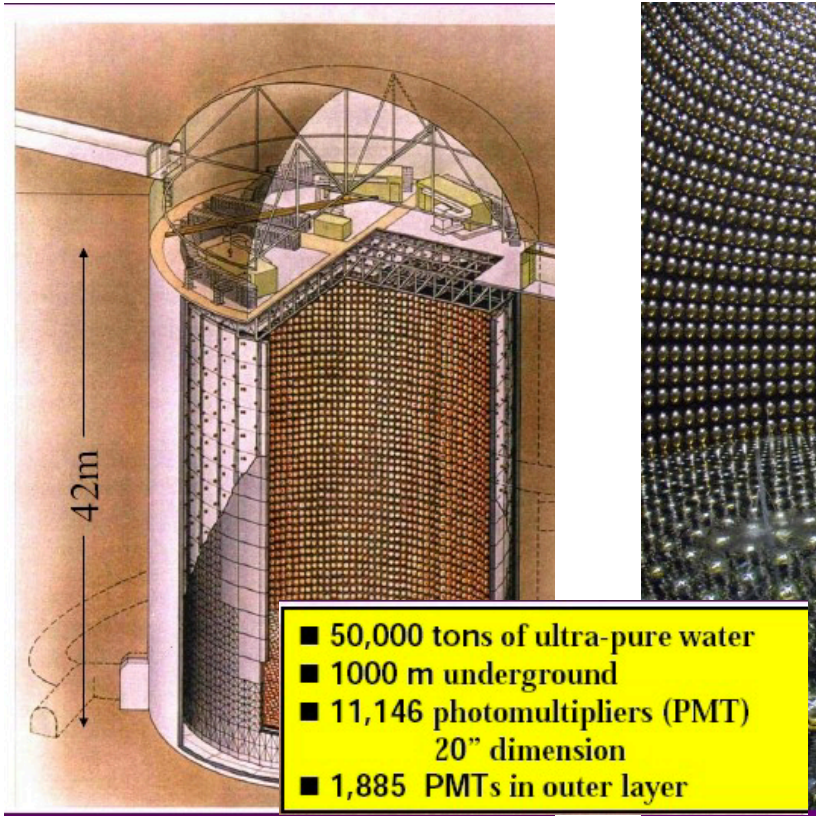


- Produced as high energy cosmic rays strike the upper atmosphere.
  - Produce particle showers (Right).
- As these showers develop and the particles decay, you end up with ~2 ν_μ for every ν_e.
- The Kamiokande detector set out to measure this ratio.
  - Super-Kamiokande, a larger analogue is currently still running in Japan.

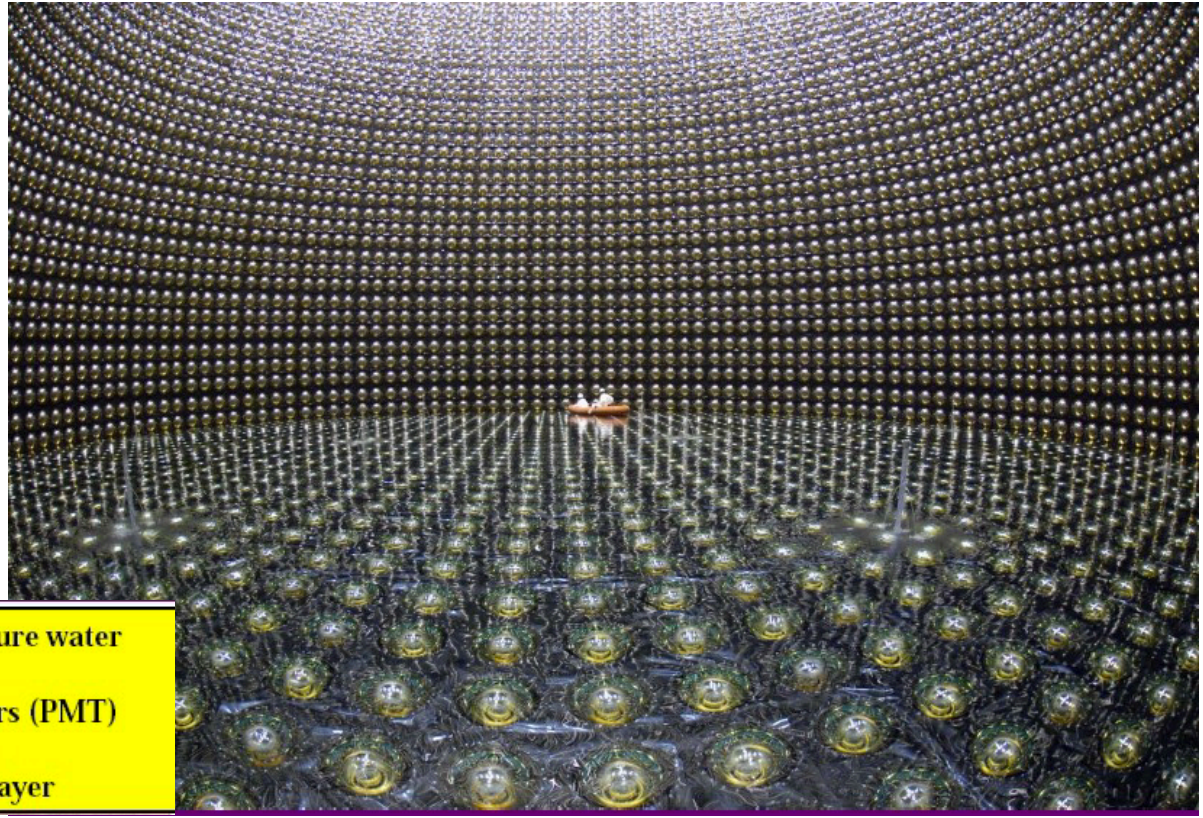


The Super-Kamiokande Experiment

Kamiokande was 3 ktons, not 50 ktons.



- 50,000 tons of ultra-pure water
- 1000 m underground
- 11,146 photomultipliers (PMT)
  20" dimension
- 1,885 PMTs in outer layer



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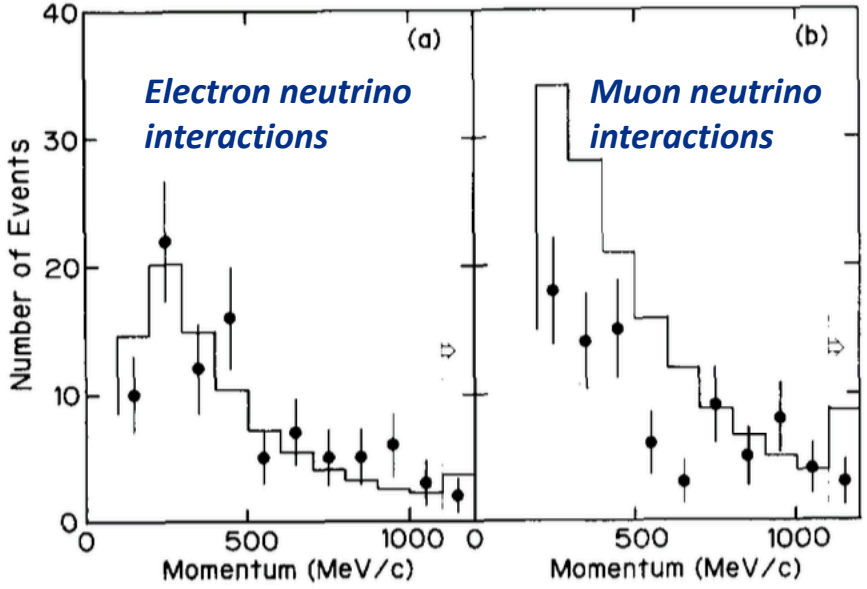
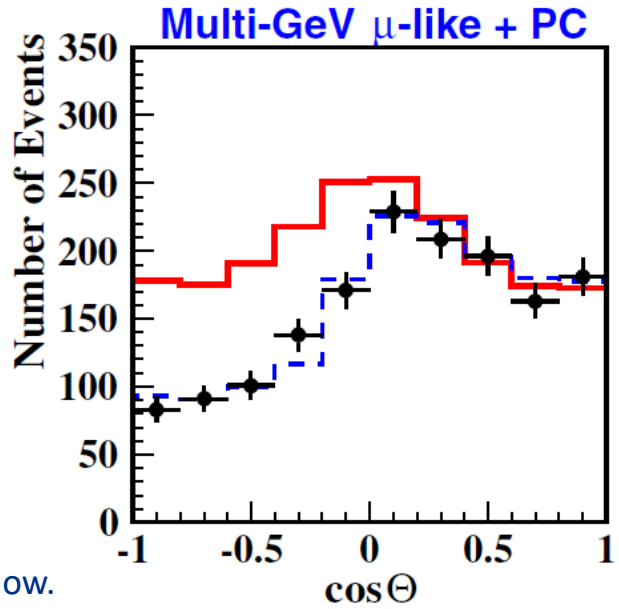
The atmospheric neutrino problem…



- 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 ν_e points are above and below lines, but ν_μ points are all below.

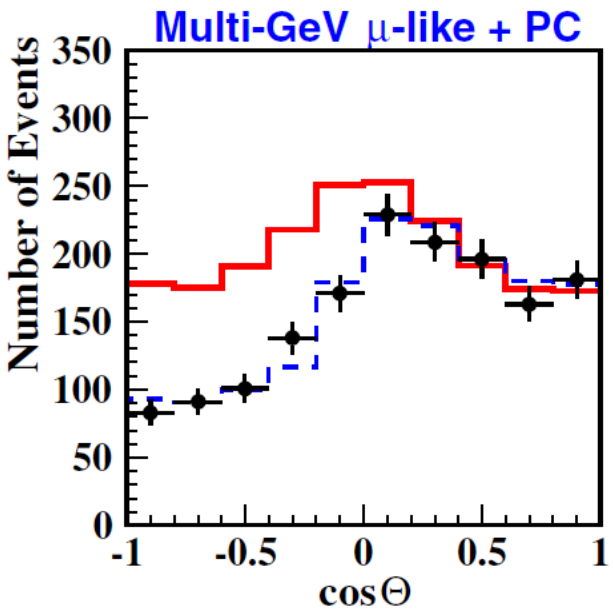
Fermilab

The atmospheric neutrino problem

- We have now made two measurements of neutrinos, and got confusing results.
  - Remember the solar neutrino problem from a few minutes ago.
- This all means that there is something seriously wrong…

So what are our next steps?

- A) Try a different kind of neutrino experiment, something about what we're doing isn't working.
- B) Find a new theory which can explain what is happening.
- C) Neutrino's are magic, watch some Barry Trotter.
- D) Ask for a billion dollars to dig a really big hole.



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So what are our next steps?

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  But how do we change our experiment?

- B) Find a new theory which can explain what is happening.

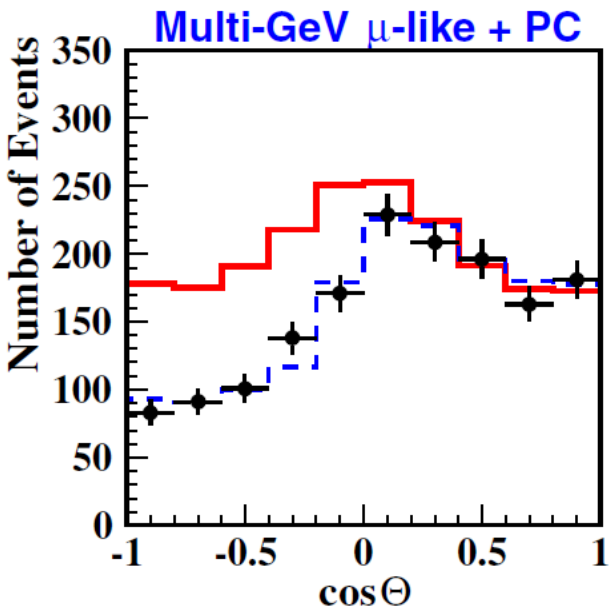
  But what kind of theory could explain things disappearing?

- ~~C) Neutrino's are magic, watch some Barry Trotter.~~

  Crackin' idea, but even Dumbledore can't help us here.

- ~~D) Ask for a billion dollars to dig a really big hole.~~

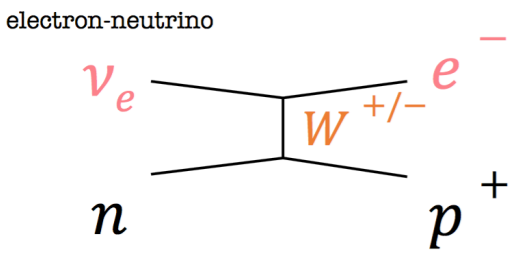
  It's surely got to be the right answer eventually right!?



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 "μ" or "τ".

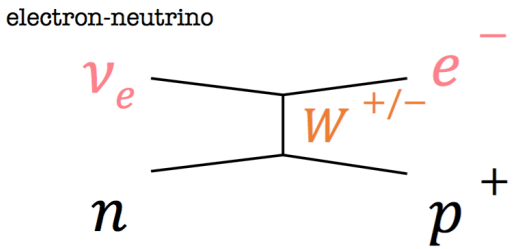
Fermilab

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.

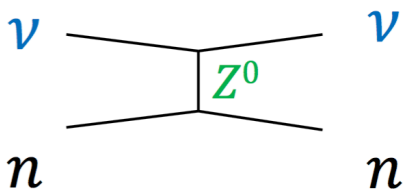
- However, the neutrino can also scatter off a nucleus without producing an electron or muon. These are called *Neutral Current* interactions.

charged-current



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

neutral-current



Z^0 = neutral boson

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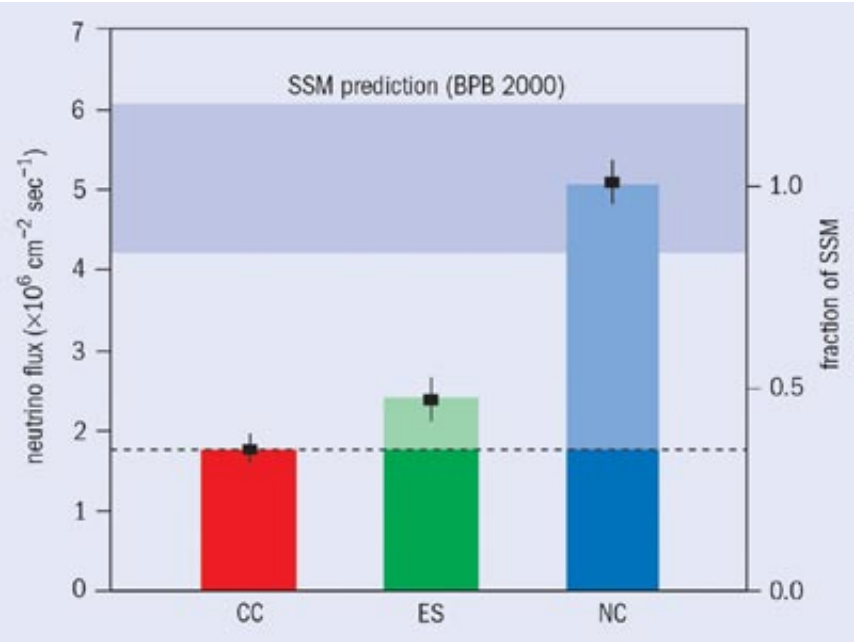
The Sudbury Neutrino Observatory (SNO)



- In a single experiment it was possible to measure both the 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.

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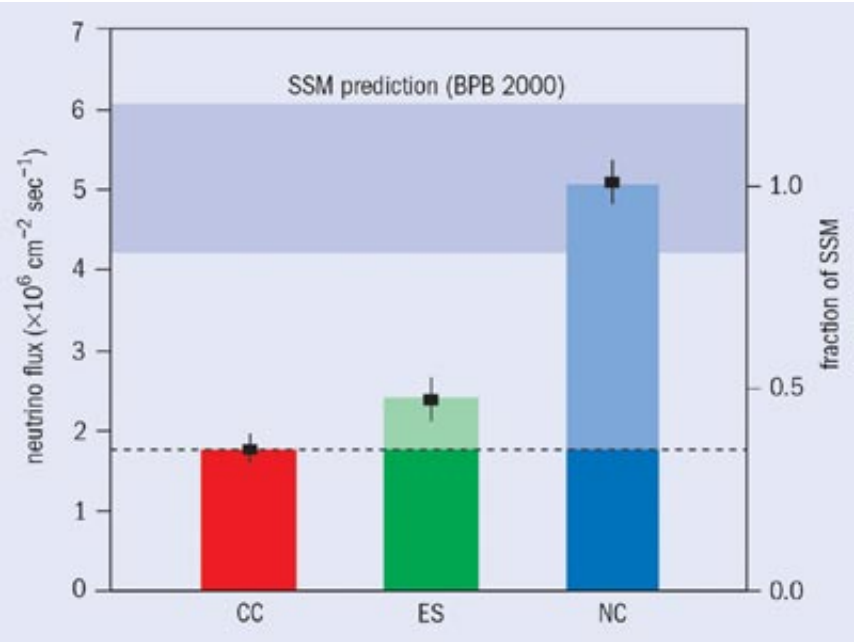

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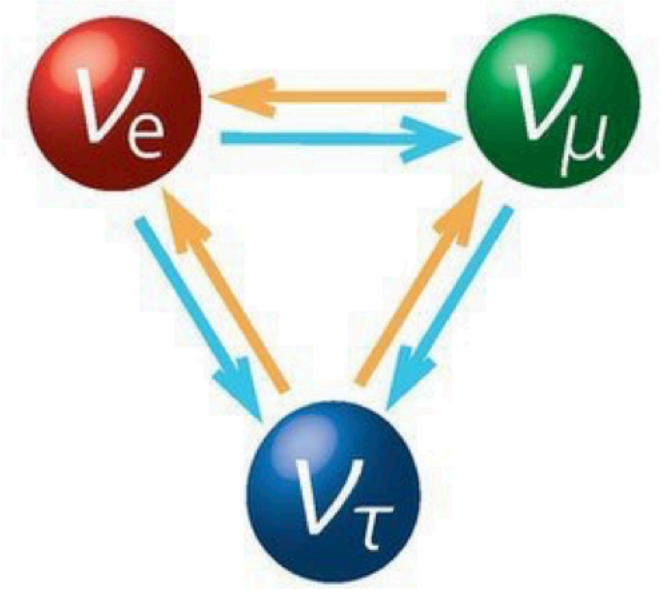
- Reproduced the Homestake measurements of ν_e *CC* interactions.
- Also measured the predicted number of *NC* interactions.

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!

Fermilab

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 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.

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.

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

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

The theory of neutrino oscillations

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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.

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

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

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

$$\begin{aligned} A(\nu_\alpha \to \nu_\beta) &= \left\langle \nu_\beta \middle| \nu_\alpha(t) \right\rangle \\ &= \sum_k \sum_j \left\langle \nu_j \middle| U_{\beta j} U^*_{\alpha k} e^{-i m_k^2 L/2E} \middle| \nu_k \right\rangle \end{aligned}$$

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.

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.

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

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

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

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

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

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The simplified theory of neutrino oscillations

Video about how oscillations occur.

If we assume only 2 neutrinos ($\boldsymbol{\alpha}, \boldsymbol{\beta}$), and have describe their oscillations using the relationship shown to the right things are much simpler.

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

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

$$\boldsymbol{\nu_\alpha = \cos\theta\, \nu_1 + \sin\theta\, \nu_2}$$
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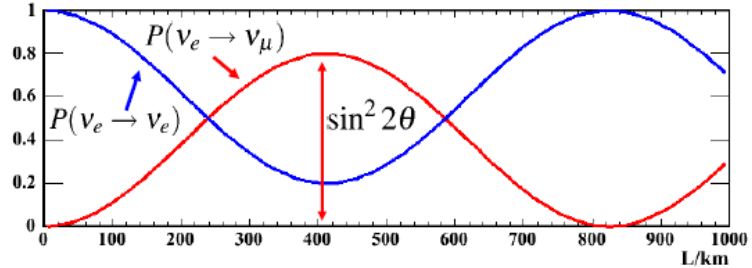
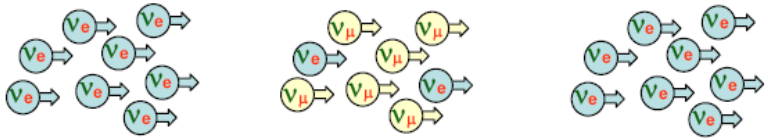
•e.g. $\Delta m^2 = 0.003\,\mathrm{eV}^2, \quad \sin^2 2\theta = 0.8, \quad E_\nu = 1\,\mathrm{GeV}$





After some complicated maths, you can eventually get to an oscillation probability which is shown graphically to the left and mathematically below.

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

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

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The Nobel Prize for the Discovery of Neutrino Oscillations

Measuring neutrinos in the 21st Century

- In order to make the best oscillation measurements we want;
  - Neutrinos with well known energies.
  - Neutrinos to interact at well known times (to remove from other events in our detectors).
  - To choose the distance the neutrinos travel, to maximise the chances of oscillations.

- The problems with Atmospheric and Solar neutrinos.
  - They come with a wide range of energies, and at all times.
  - They also have very fixed distances (The Earth is a fixed distance from the Sun!)

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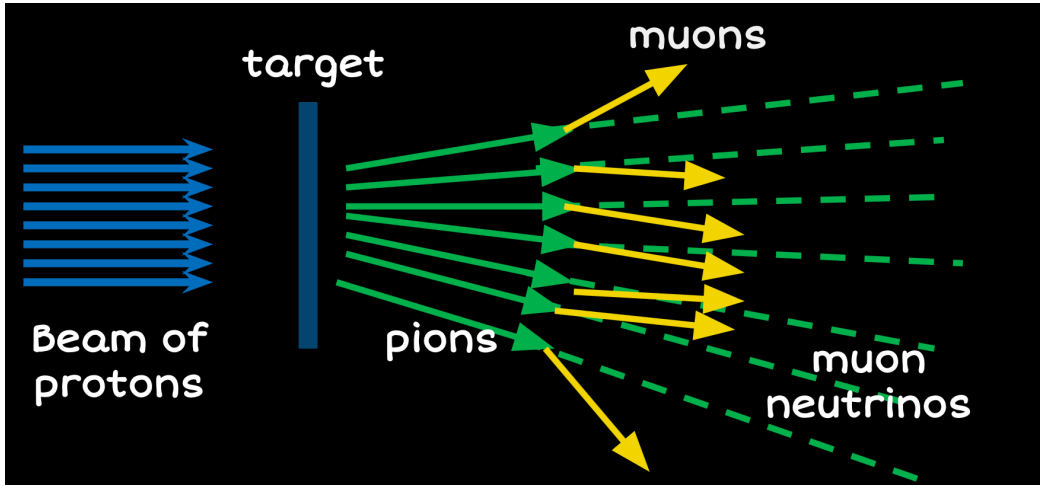
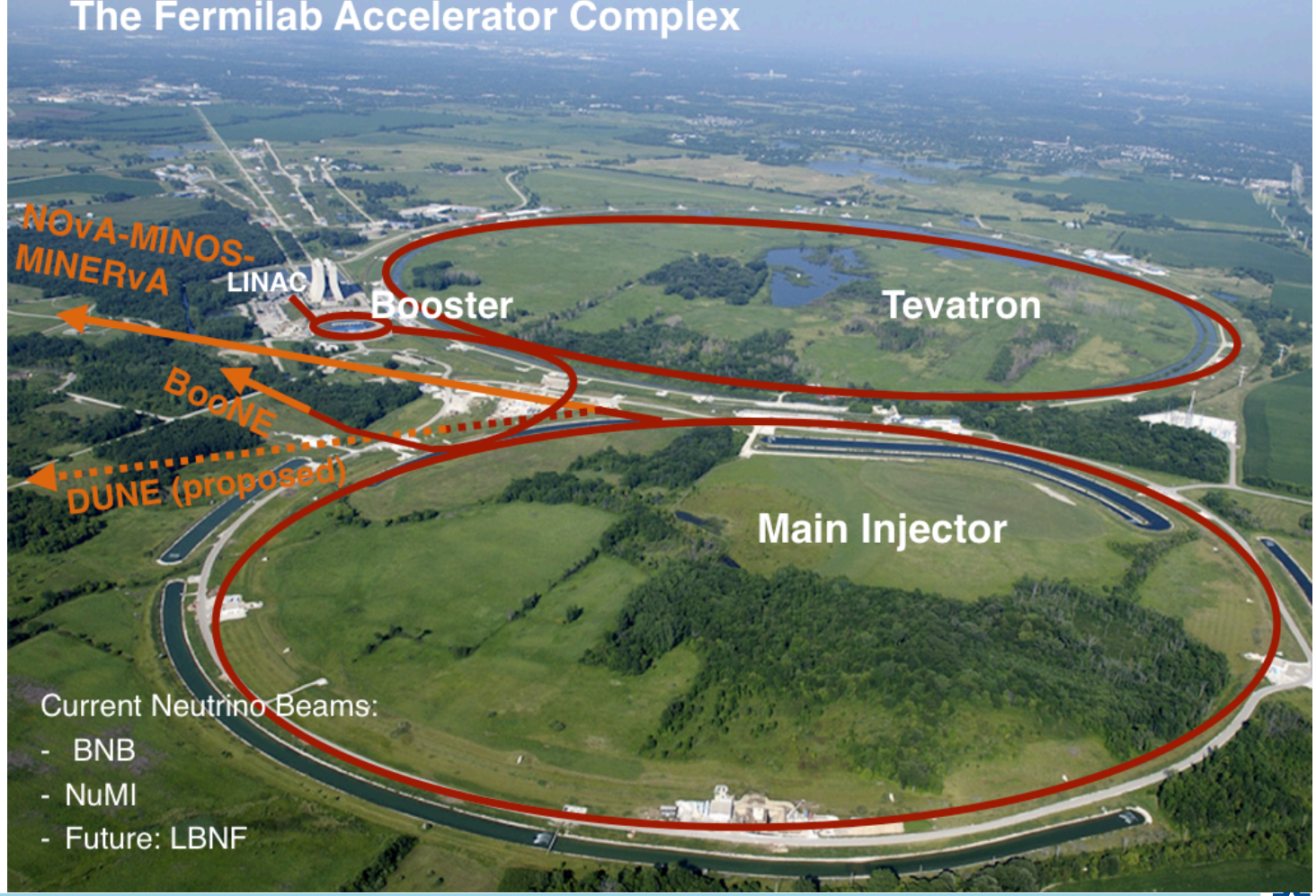


- Make our own neutrino beam!


The Fermilab Accelerator Complex
NOvA-MINOS-
MINERvA
LINAC
Booster
Tevatron
BooNE
DUNE (proposed)
Main Injector
Current Neutrino Beams:
- BNB
- NuMI
- Future: LBNF

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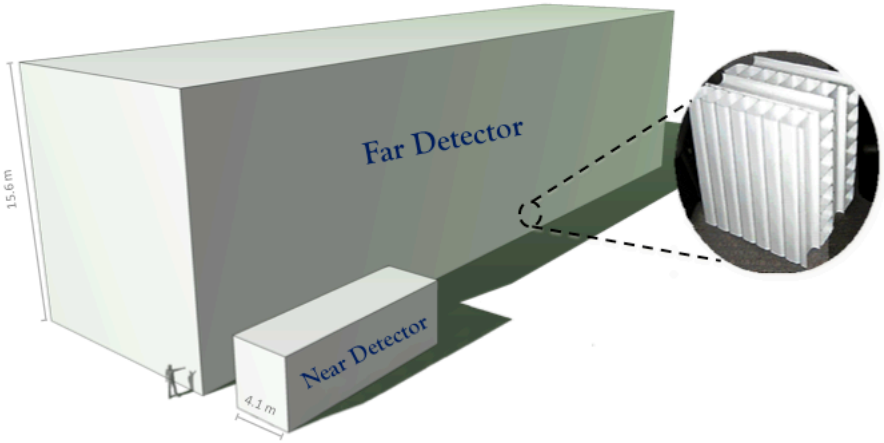
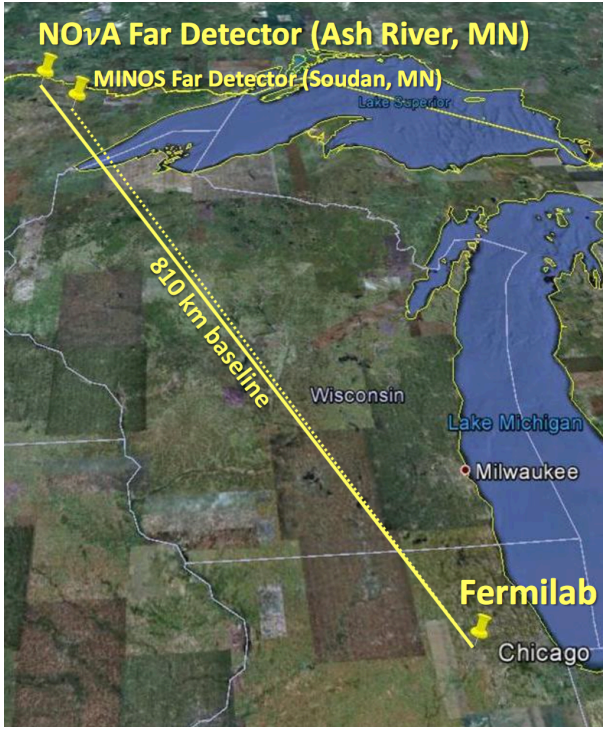
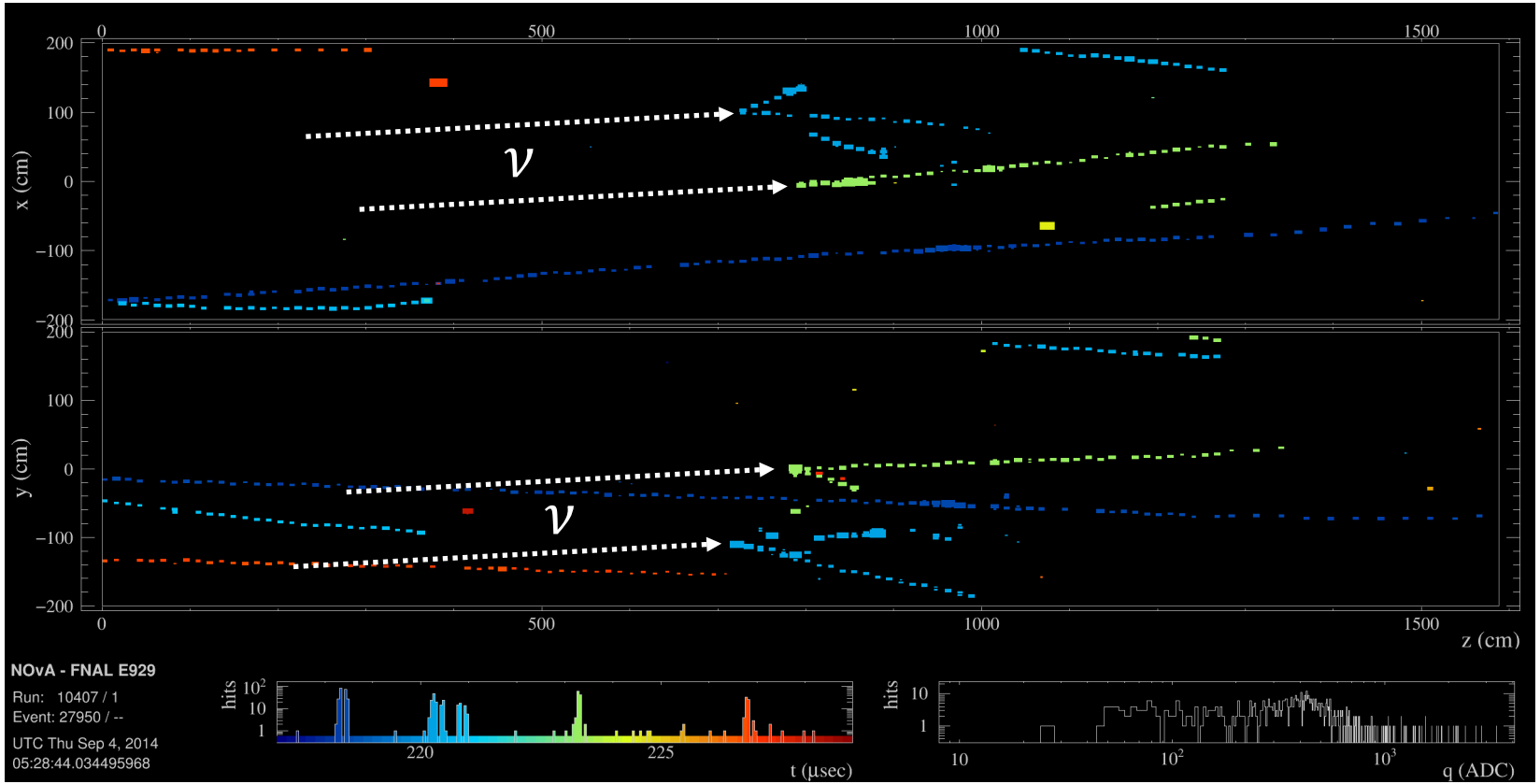
The NOvA Experiment

- 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.





Neutrino interactions in the NOvA Near Detector



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Physics measurements at the NOvA Far Detector

NOvA measures the number of muon neutrinos in the far detector to determine the probability that they oscillate.

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

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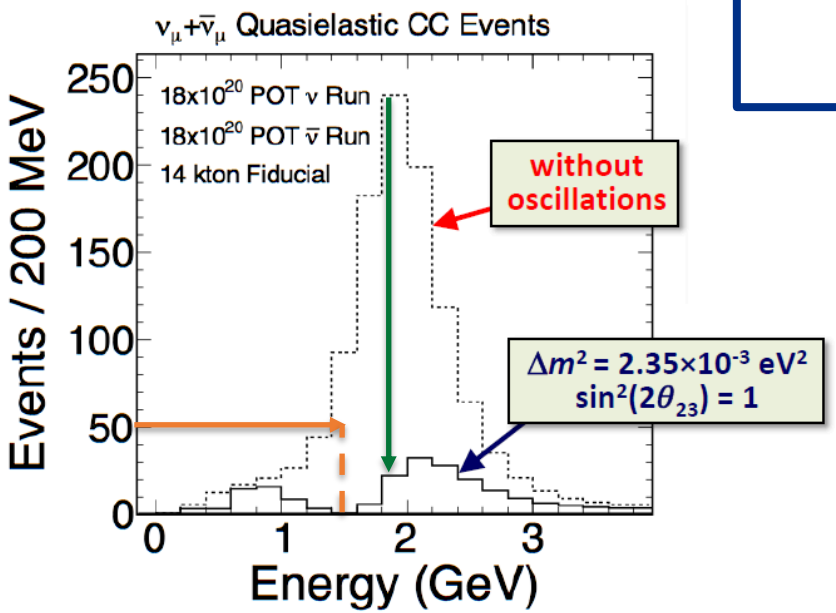

$$P(\upsilon_\mu \rightarrow \upsilon_\mu) \approx 1 - sin^2(2\theta_{23})sin^2\left(\frac{1.27\Delta m_{32}^2 L}{E}\right)$$

$$\Delta m_{ij}{}^2 \equiv m_i{}^2 - m_j{}^2$$

If muon neutrinos did not oscillate then the dashed line would be seen.

As muon neutrinos do oscillate, the solid line is seen.

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Building a detector to answer the remaining questions

- Experiments like NOvA and T2K among others have addressed many of the questions that we have in neutrino physics, however we need new experiments to make precise measurements.

- The question though, is what should those experiments be like?

- A) Scrap the technology, let's make something new!
- B) Keep the technology, it's great, let's just move the detector to a different Country.
- C) Go down t' local castle and speak t' our Liz.
- D) Ask for a billion dollars to dig a really big hole.

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I like your style, you can work on DUNE!

- B) Keep the technology, it's great, let's just move the detector to a different Country.

Good choice, you can work on Hyper-K and build a detector in South Korea which is 500 million tonnes of water!

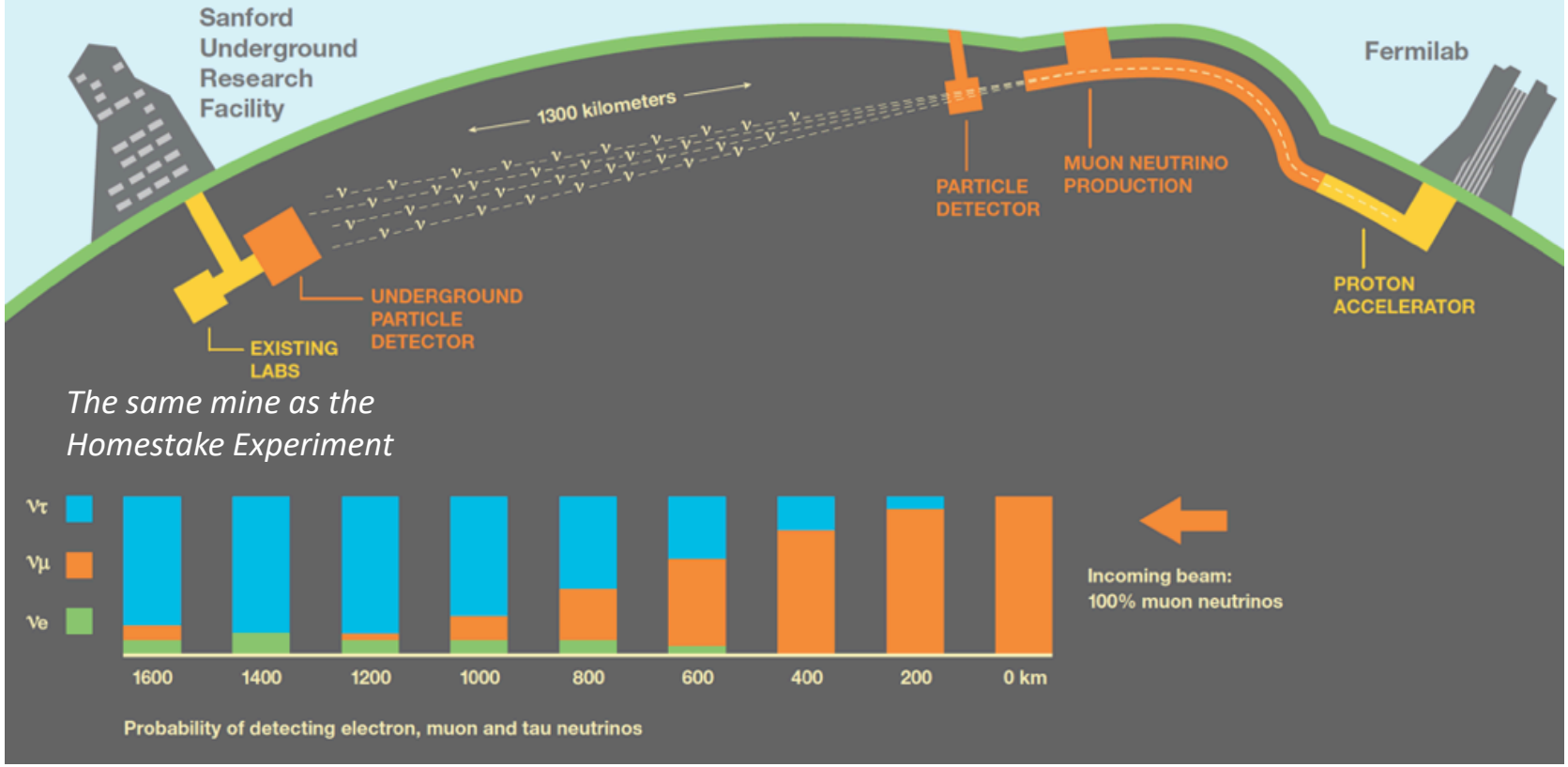
- ~~C) Go down t' local castle and speak t' our Liz.~~

The Queen, whilst everyone's friend, isn't a particularly good builder.

- D) Ask for a billion dollars to dig a really big hole.

Occasionally persistence pays off, let's talk about DUNE!

Deep Underground Neutrino Experiment



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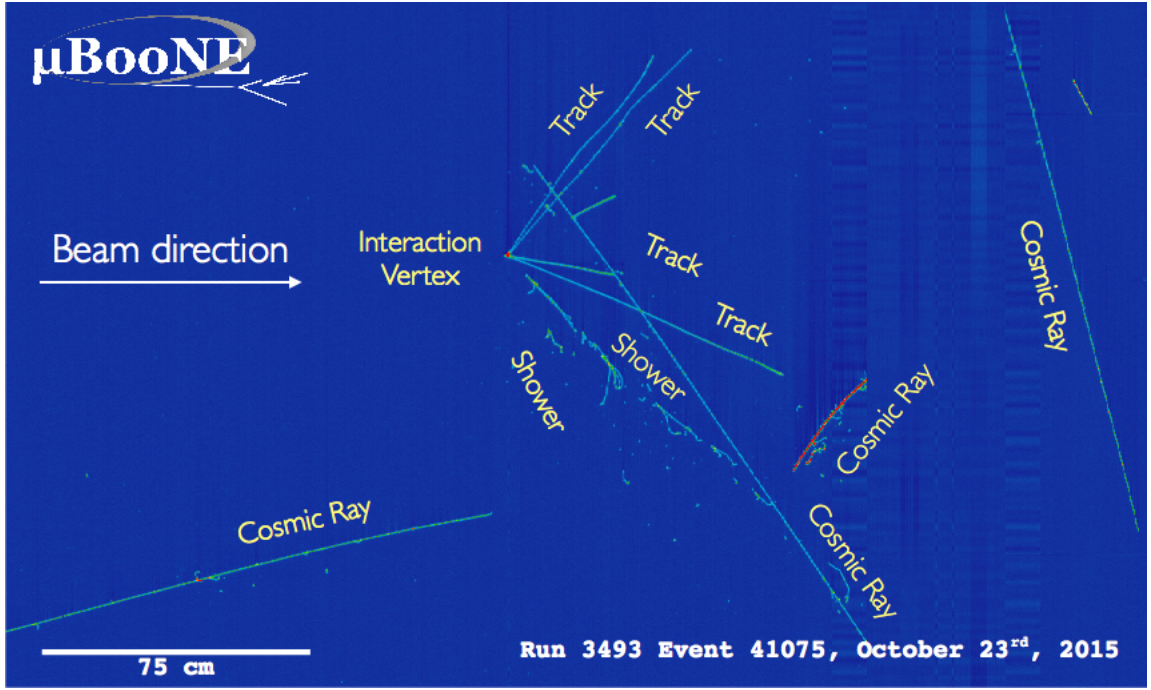
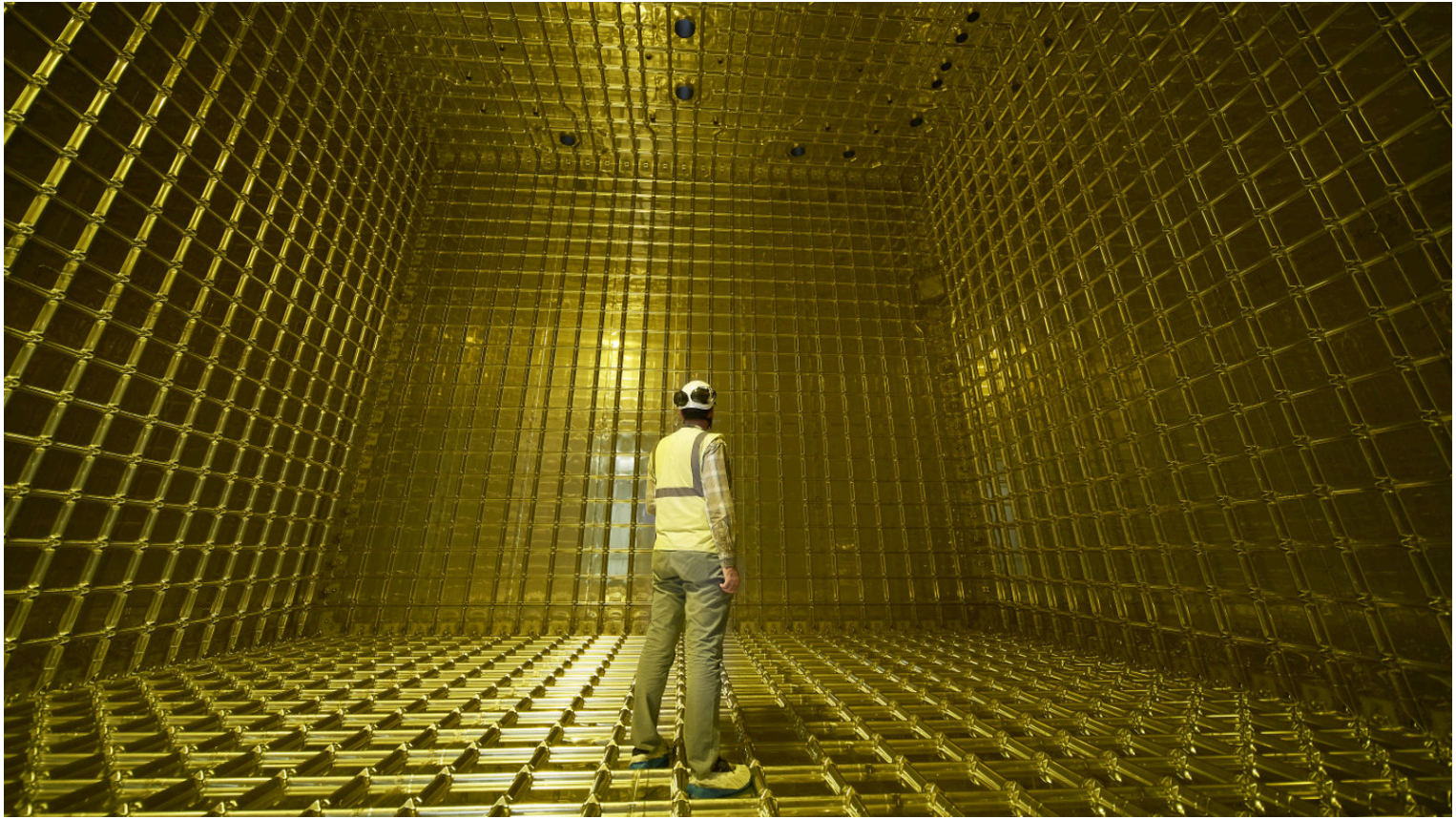
Detecting events in Liquid Argon (LAr)

- Liquid Argon lets us see interactions with great detail.
- DUNE will consist of 4 modules, each containing about 17 kton of LAr.
  - Each module will be as large as the NOvA Far Detector.
- DUNE will perform precision measurements of neutrino oscillations.



MicroBooNE is another Liquid Argon Experiment currently running at Fermilab.

Inside a Liquid Argon Time Projection Chamber *A fiddler inside ProtoDUNE*



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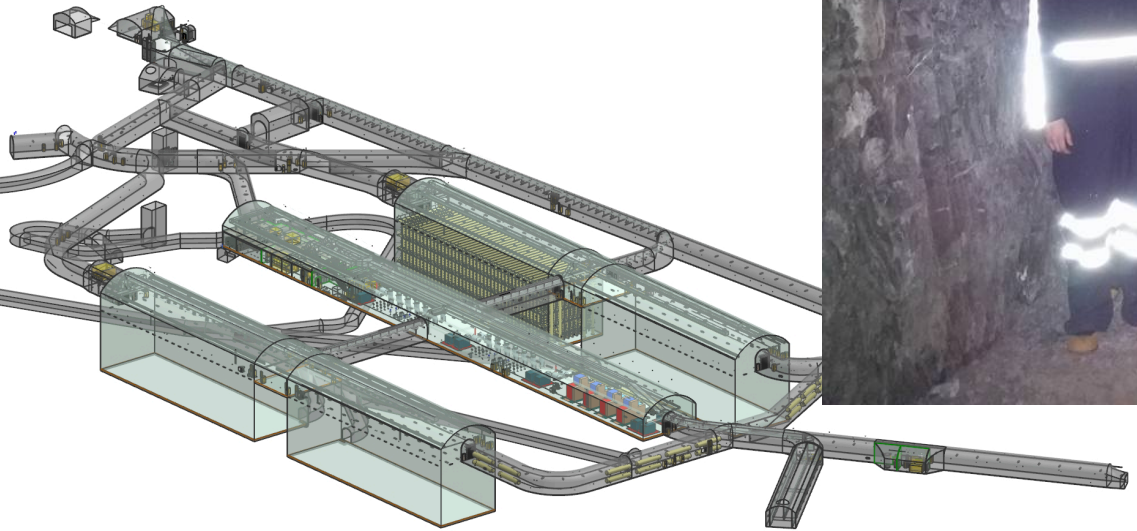
The DUNE Far Detector

Right: The Far Detector in May 2016.

Below: The Far Detector complex in 2025 when the detector starts taking data.



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The remaining questions in Neutrino Physics

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

1. Why are neutrino masses so small?
   - Huge difference between them and the other Standard Model particles.
2. What is the neutrino mass scale and what order are the masses in?
   - We know very little about their masses.
3. How do neutrinos acquire mass?
   - It is possible that neutrinos do not acquire their masses through interactions with the Higgs Boson.
4. Are there only 3 types of neutrino?
   - Various experiments have seen hints that there could be a fourth (or more) neutrinos which interact even more rarely than the other 3.
5. What exactly are the parameters which control neutrino oscillations?
   - This is actually three questions in one as the values of the PMNS matrix are so poorly understood.