Ghosts of the Universe: Neutrinos

PIMA May 9th 2022

First Principals: Conservation!

Conservation laws: physics must always obey these!

- Energy can never be destroyed, only converted from one form to another

$$\boldsymbol{Energy\ in = Energy\ out}$$

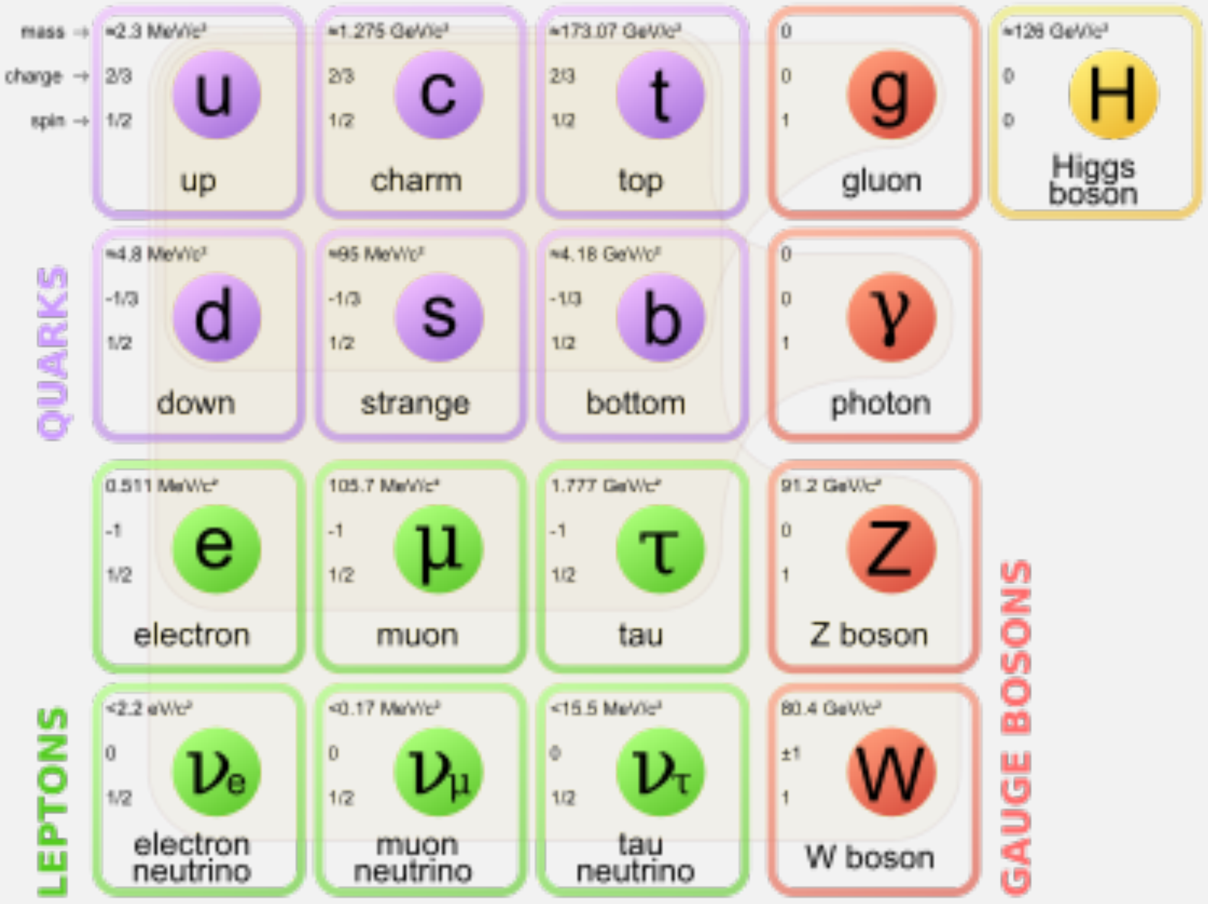
- Momentum

$$\mathbf{P} = \boldsymbol{mass\ * velocity}$$

- Angular Momentum
  - Same thing as momentum, just now when spinning

Brief History: Particle Zoo

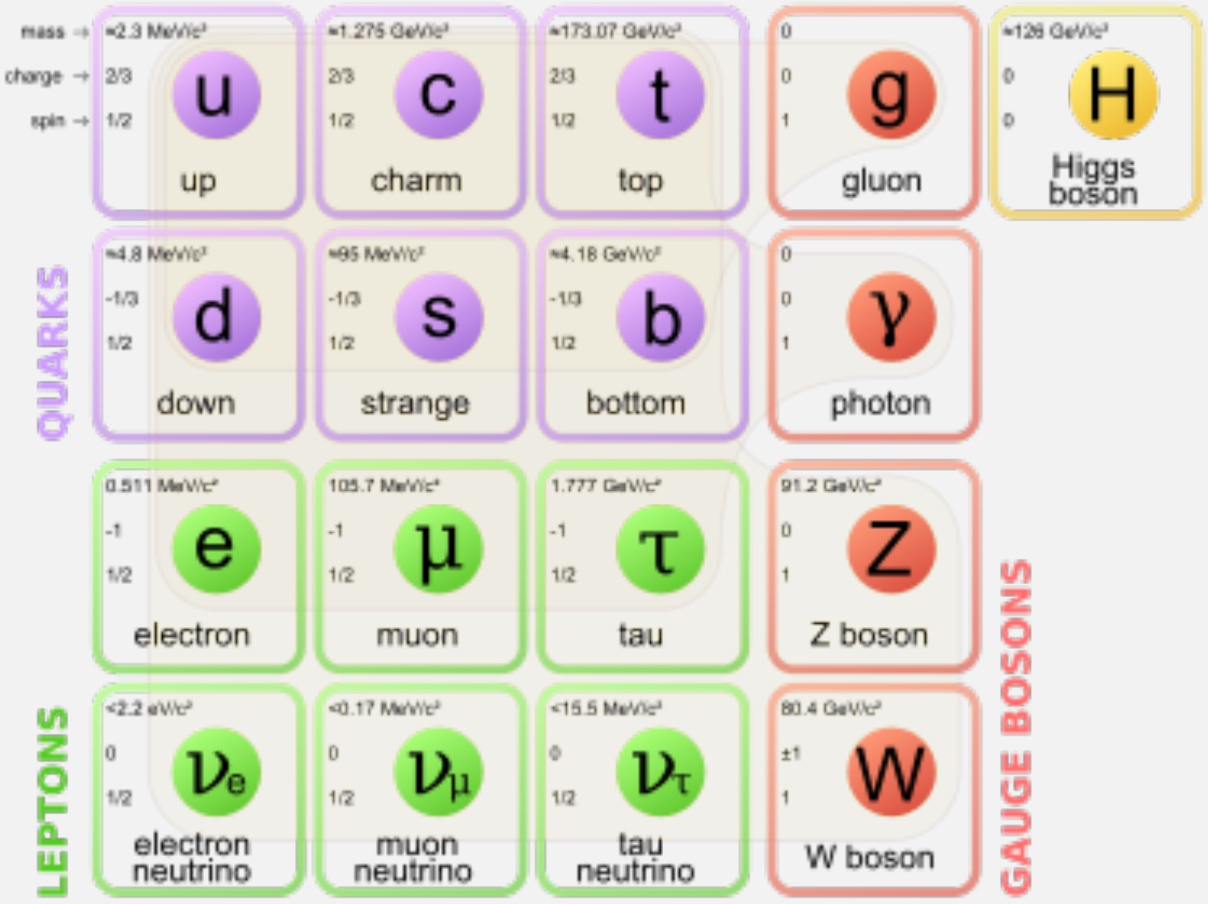
- The Universe as we know consists of quarks, leptons, and bosons
  - Quarks make up protons and neutrons, which in turn make up nuclei
- Leptons have no internal structure
- Gauge bosons are the carriers of forces



Brief History: Particle Zoo

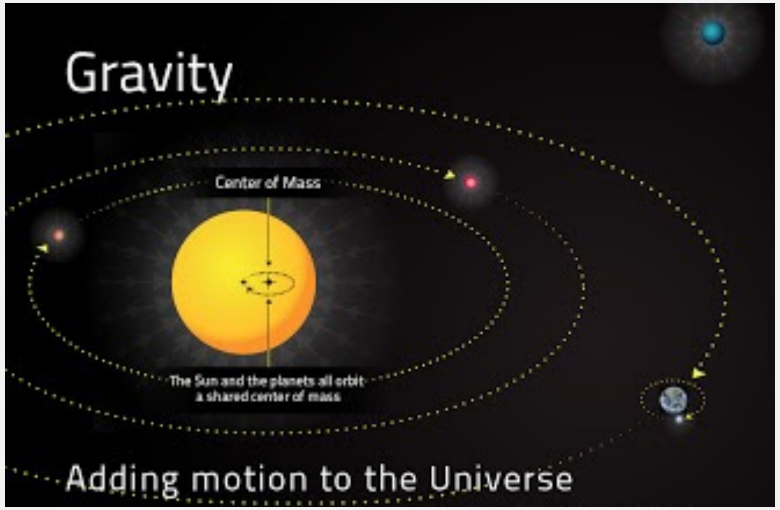
- The Universe as we know consists of quarks, leptons, and bosons
  - Quarks make up protons and neutrons, which in turn make up nuclei
- Leptons have no internal structure
- Gauge bosons are the carriers of forces

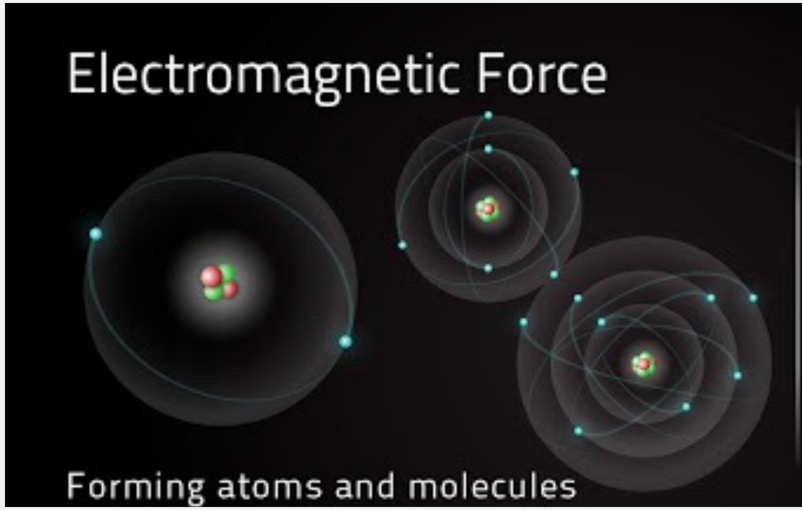
Q: How many forces are there?

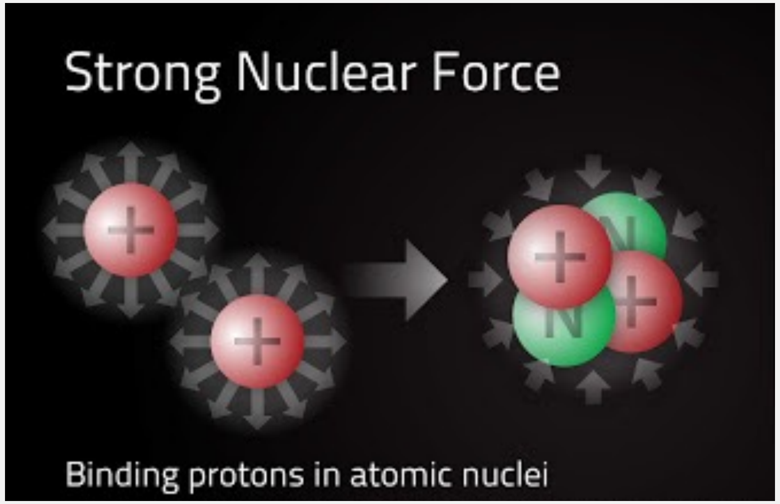


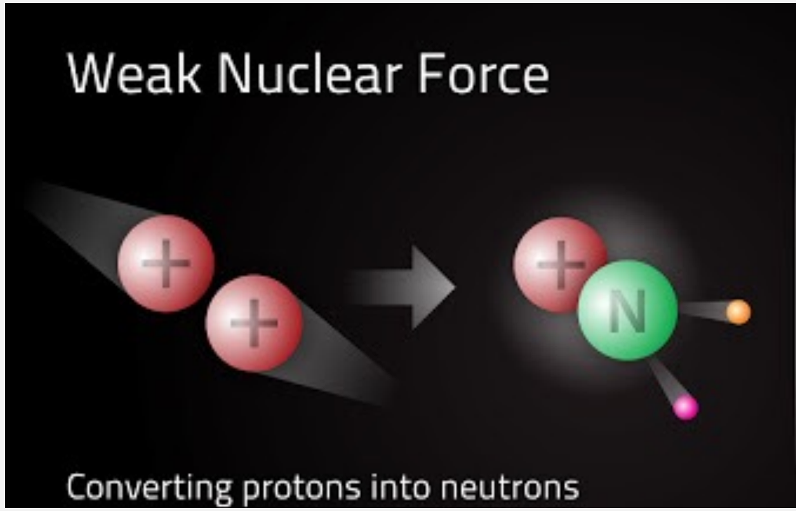
Brief History: Meet the Forces

- Gravity
  - Force arising from mass and energy bending spacetime
- Strong Nuclear
  - Holds nuclei together
- Weak Nuclear
  - Transmutation, decay
- Electromagnetic
  - Force that deals with charge







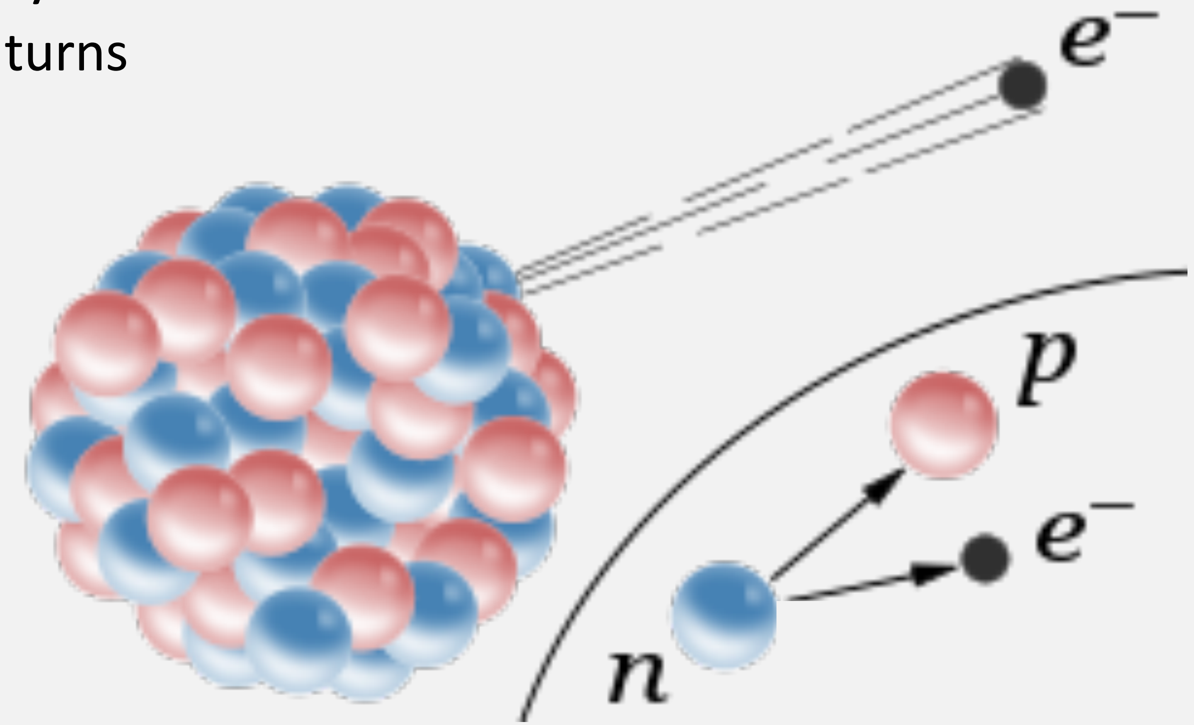


What is "radioactivity"?

Q: What does it mean to say when something is radioactive?

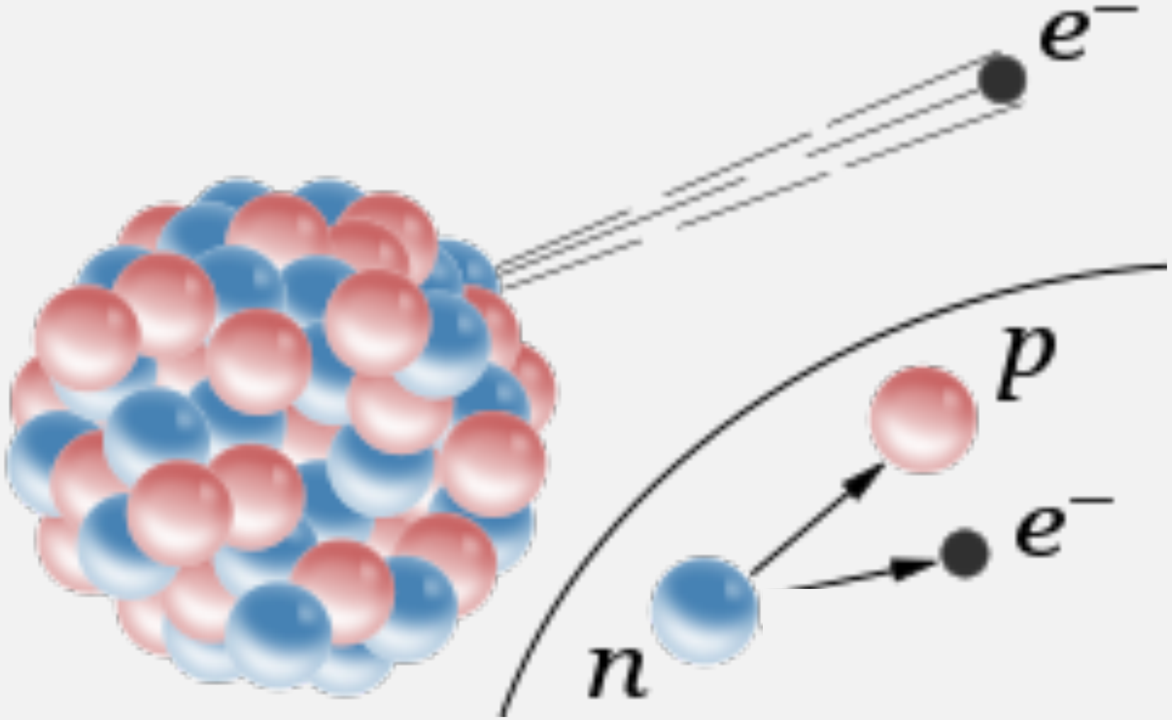
Brief History: Beta Decay

- One type of radioactivity is beta decay
  - A neutron releases an electron and turns into a proton



Brief History: Beta Decay

- At a first glance, this decay does not conserve
  - Energy
  - Momentum
  - Angular Momentum
- The electron gets ejected *too slow*
  - Should be going much faster!

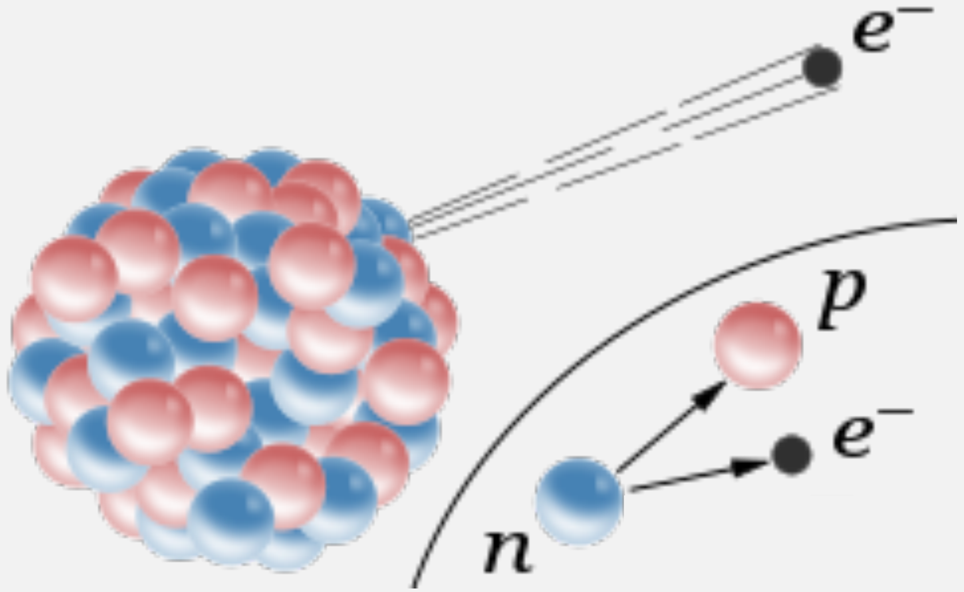


Brief History: Beta Decay

- Physicist Wolfgang Pauli, in 1930, postulated the existence of a particle that would conserve those three quantities
  - Q: What were those again?

- But if it existed, why wasn’t it observed?

- Pauli required the particle to be
  - Light, of low mass
  - have no electric charge

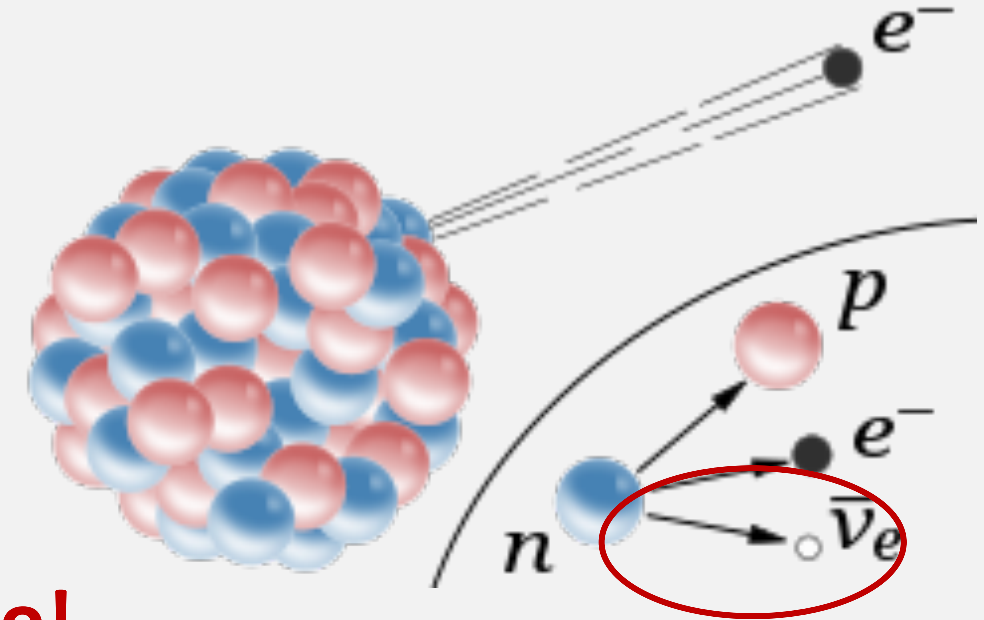


Brief History: Beta Decay

- Physicist Wolfgang Pauli, in 1930, postulated the existence of a particle that would conserve those three quantities
  - Q: What were those again?

- But if it existed, why wasn't it observed?

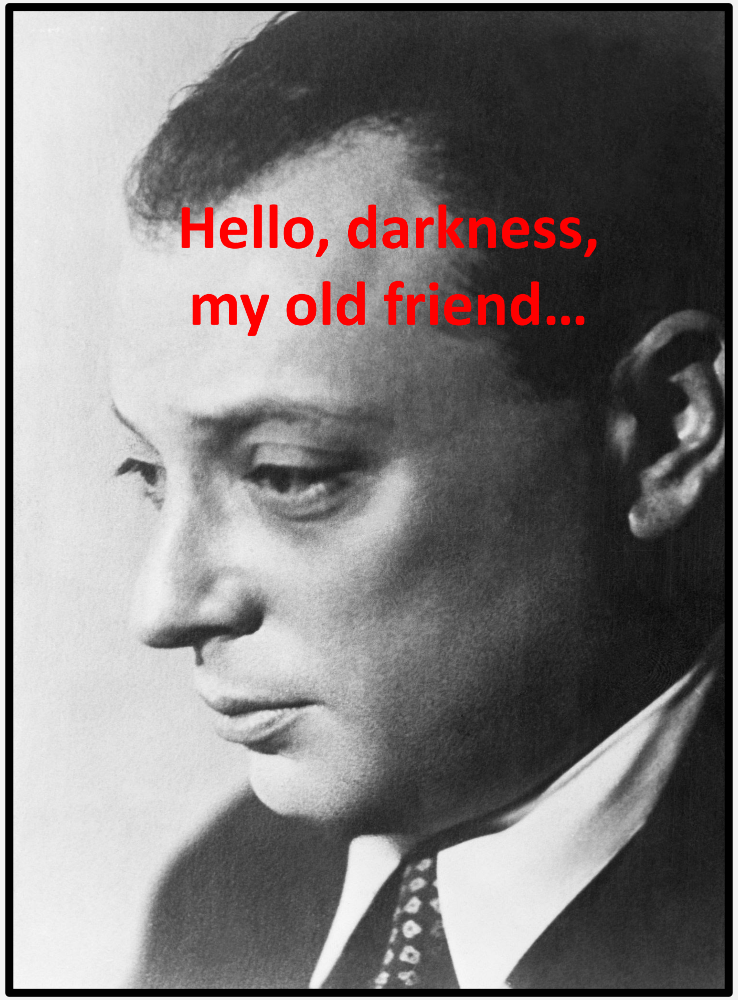
- Pauli required the particle to be
  - Light, of low mass
  - have no electric charge



Answer: a neutrino!

Brief History: Beta Decay

- Although Pauli was troubled with his theory
- "I have done a terrible thing. I have postulated a particle that cannot be detected"
- He predicted "a ghost" particle that was almost impossible to detect

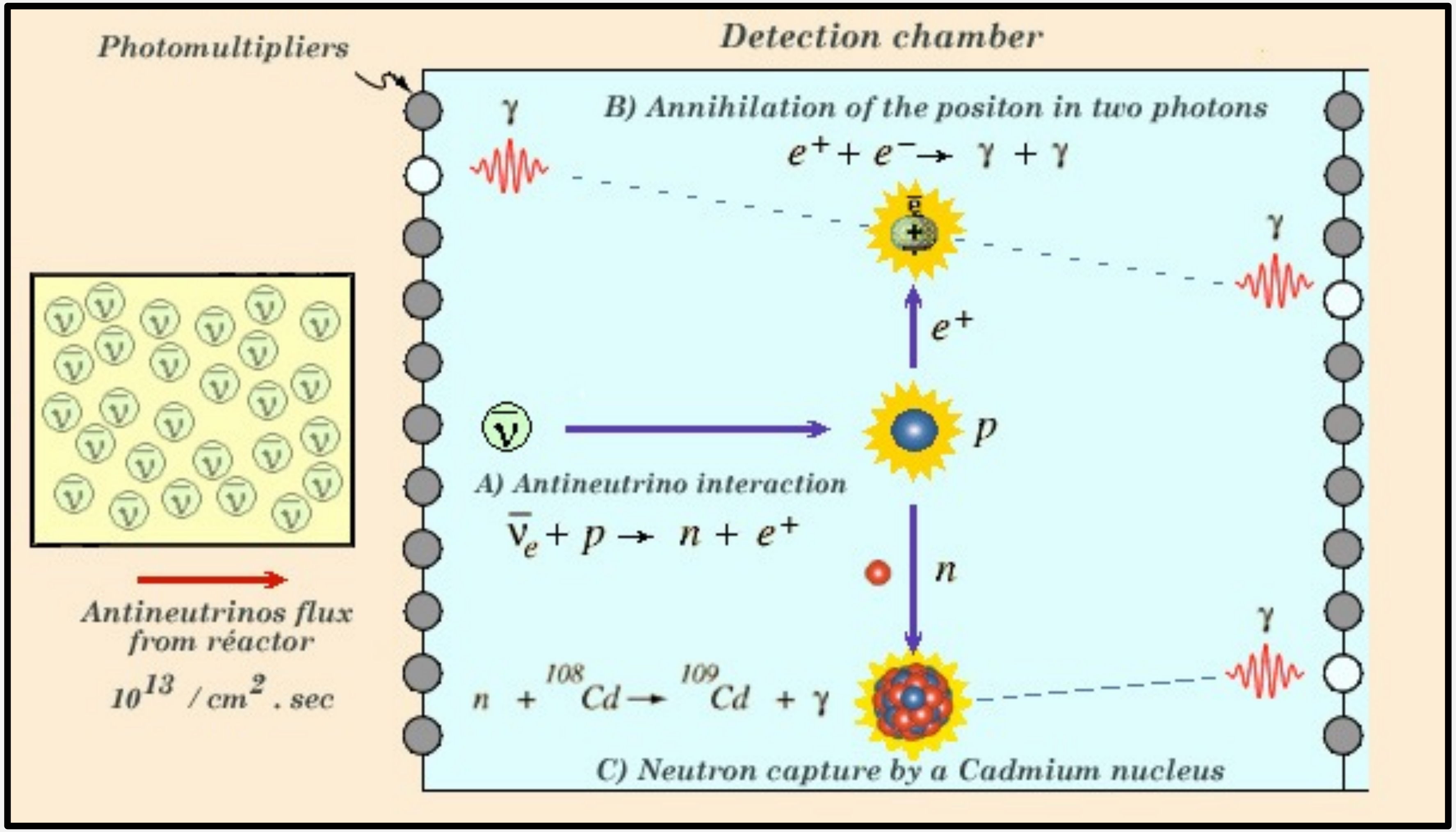


Brief History: Trying to Detect Neutrinos

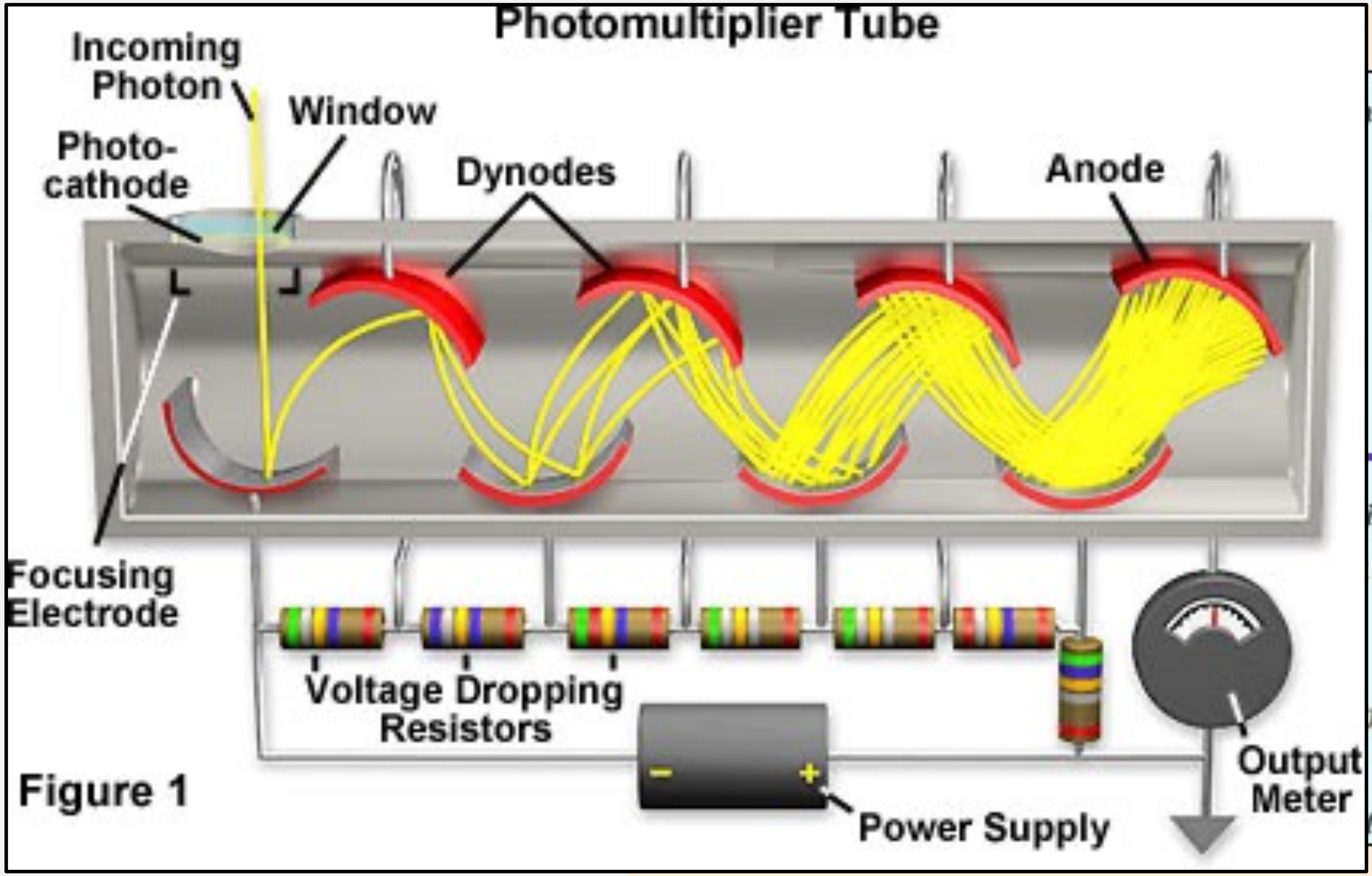
- In 1951, physicists Cowan and Reines setup an experiment using a nuclear reactor to produce neutrinos
  - They then looked for “inverse beta decay”, which is the flipped version of beta decay

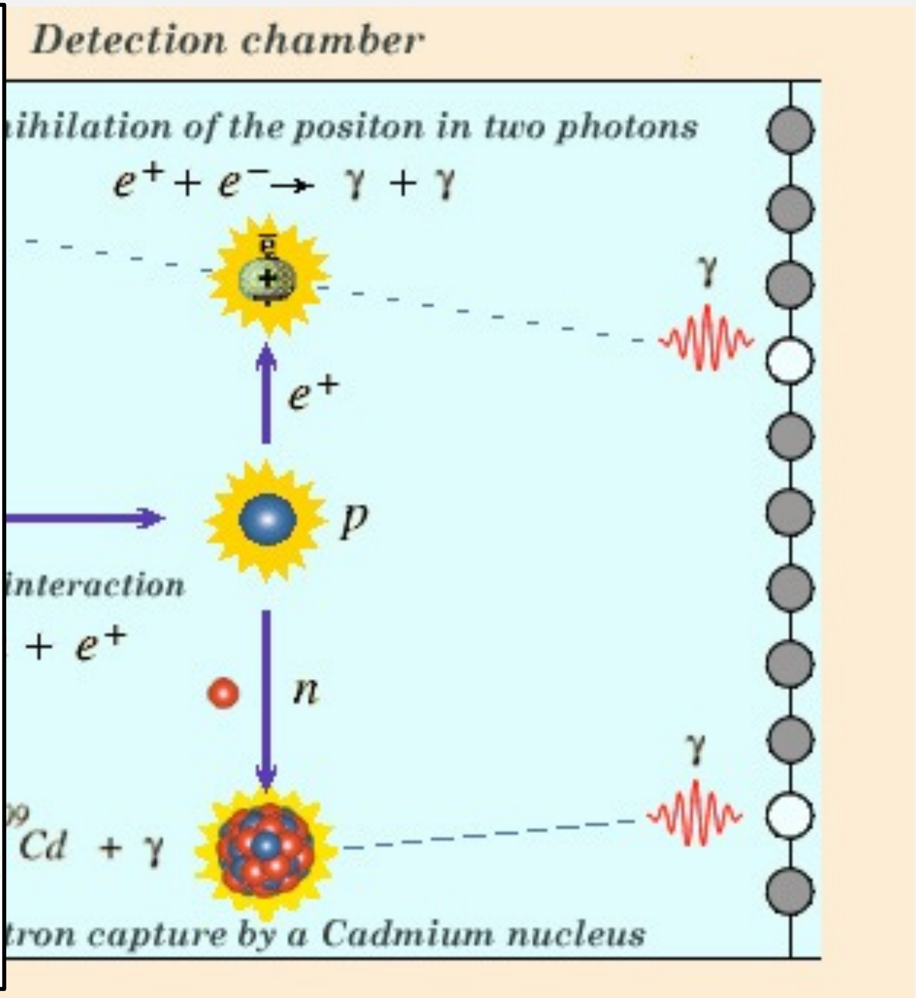
$$p^{+} + \overline{\nu}_{e} \rightarrow e^{+} + n^{0}$$

Cowan and Reines' Experiment



Cowan and Reines’ Experiment



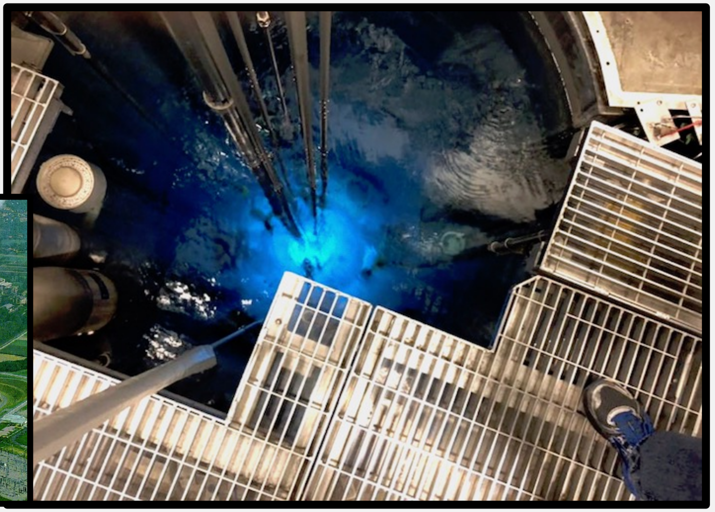


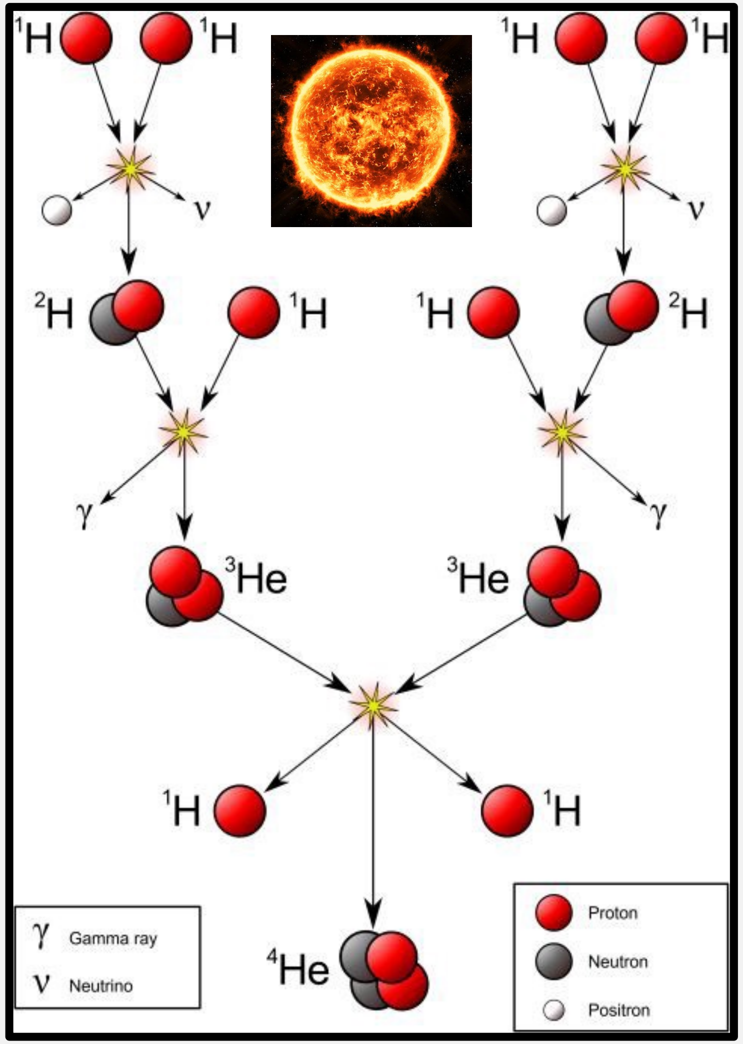
Q: What do we know so far?

What do we know so far?

- They have very tiny masses and are not electrically charged
  - Meaning they don't interact with other matter

- They are produced often in nuclear reactions
  - Such as the sun from fusion
  - Fission reactors here on Earth





Some Neutrino Fun Facts

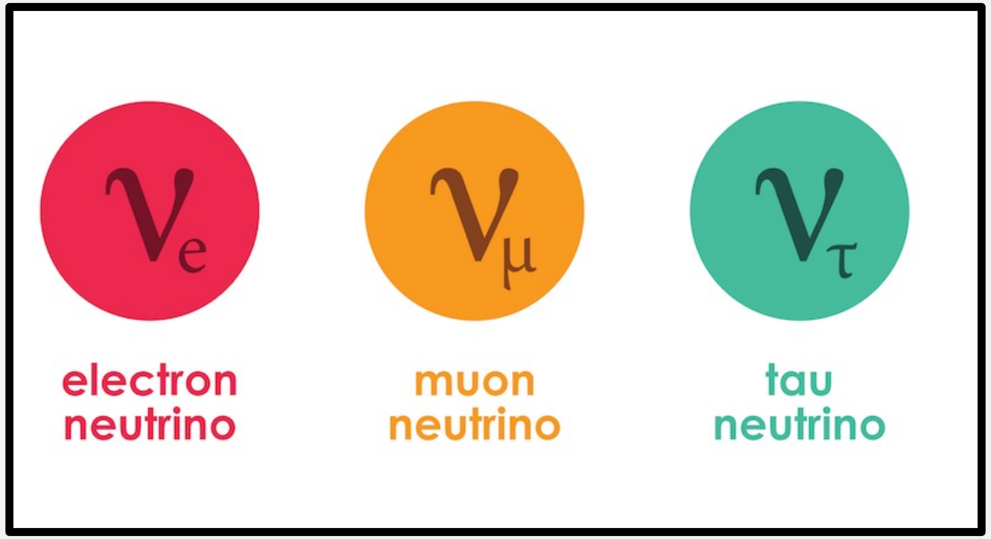
- Neutrinos are the 2^{nd} most numerous particle in the Universe, after photons
- Q: How many neutrinos do you think are passing through you every second?

Some Neutrino Fun Facts

- Neutrinos are the 2nd most numerous particle in the Universe, after photons

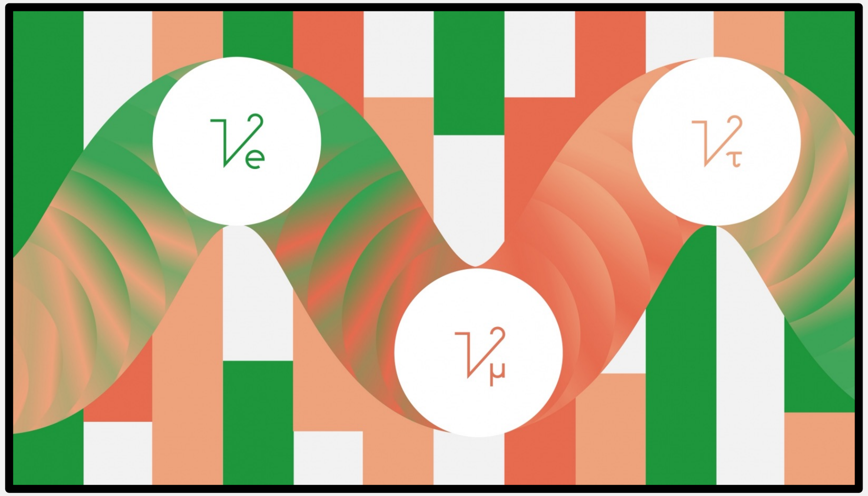
- From fusion, our sun produces $2x10^{38}$ neutrinos per second! 200000000000000000000000000000000000000
  - About $1x10^{11}$ neutrinos pass through you every second
  - Only *one* neutrino will interact with your body in your entire life

- There are three types of neutrinos
  - Electron, muon, tau neutrinos
  - Each type, or *flavor*, also has an “anti” version



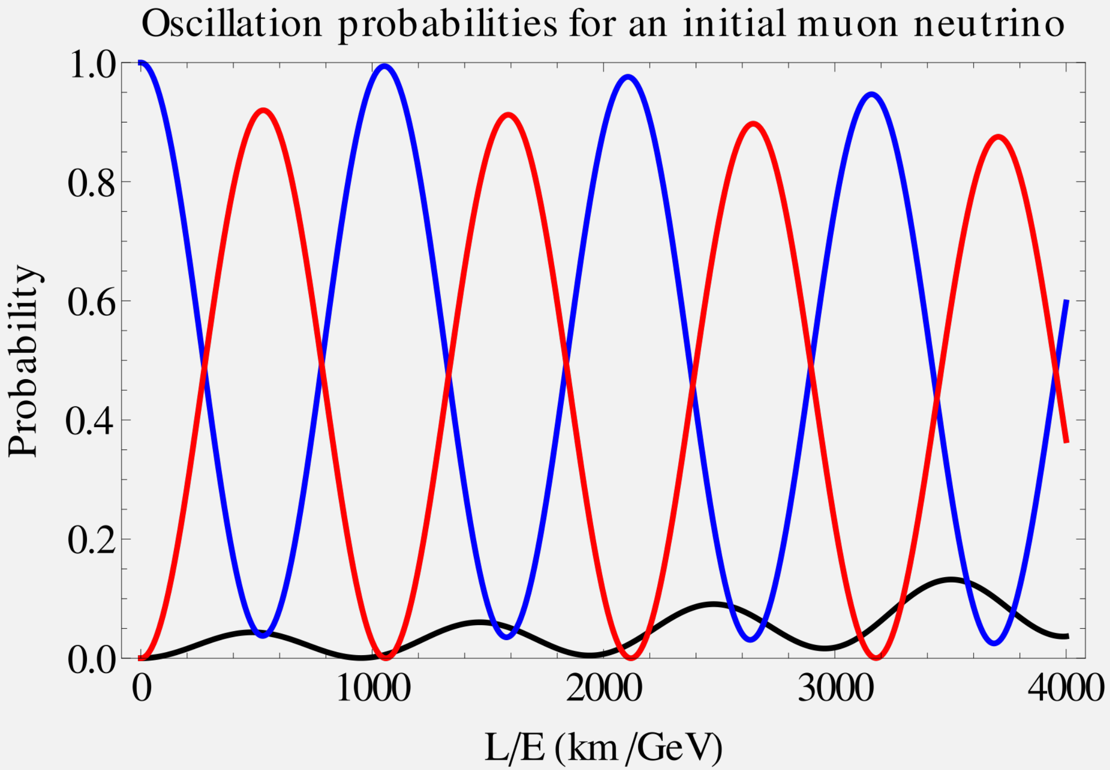
Neutrino Oscillations

- It was discovered by the Super-Kamiokande and Sudbury Neutrino Observatory that neutrinos *oscillate* between flavors as they travel through matter
  - Awarded the 2015 Nobel Prize in Physics

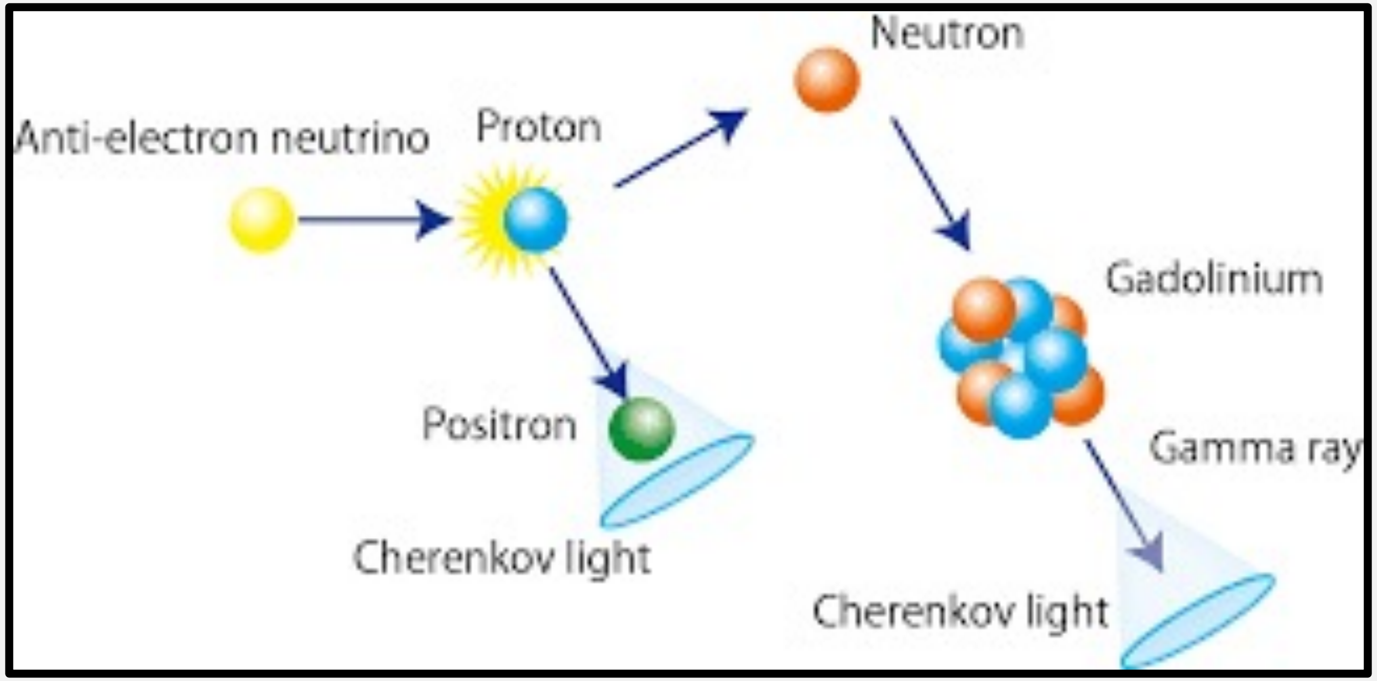


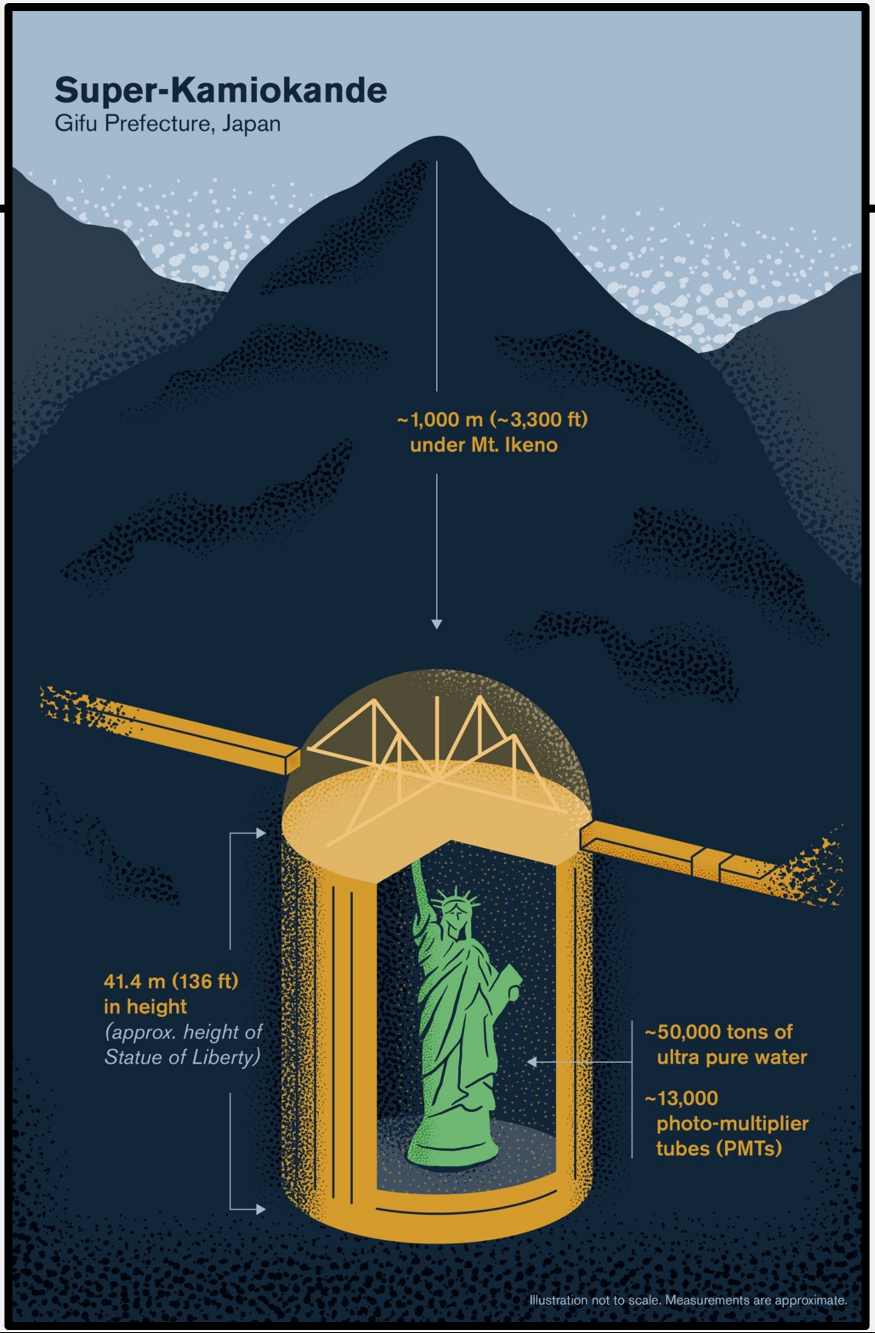
Neutrino Oscillations

- It was discovered by the Super-Kamiokande and Sudbury Neutrino Observatory that neutrinos *oscillate* between flavors as they travel through matter
    - Awarded the 2015 Nobel Prize in Physics

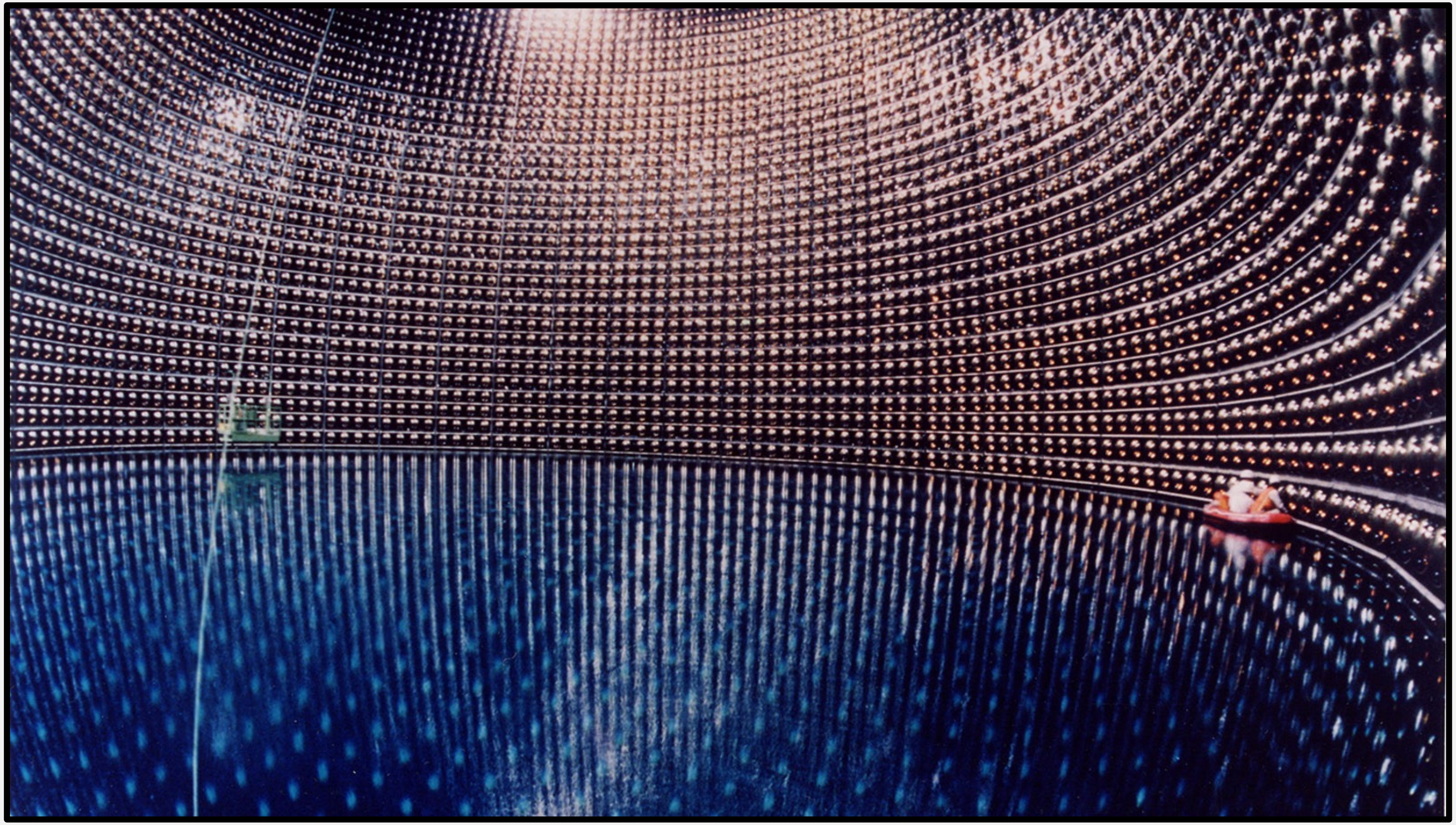


SuperKamiokande





SuperKamiokande



?

?

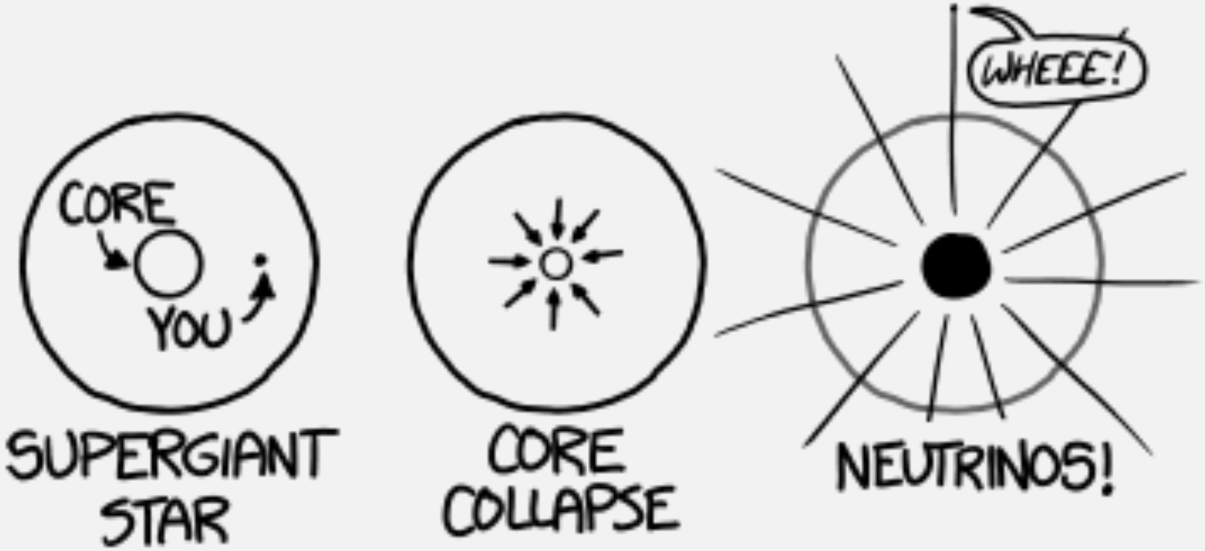
?

What can we do with neutrinos and what don’t we know?

?

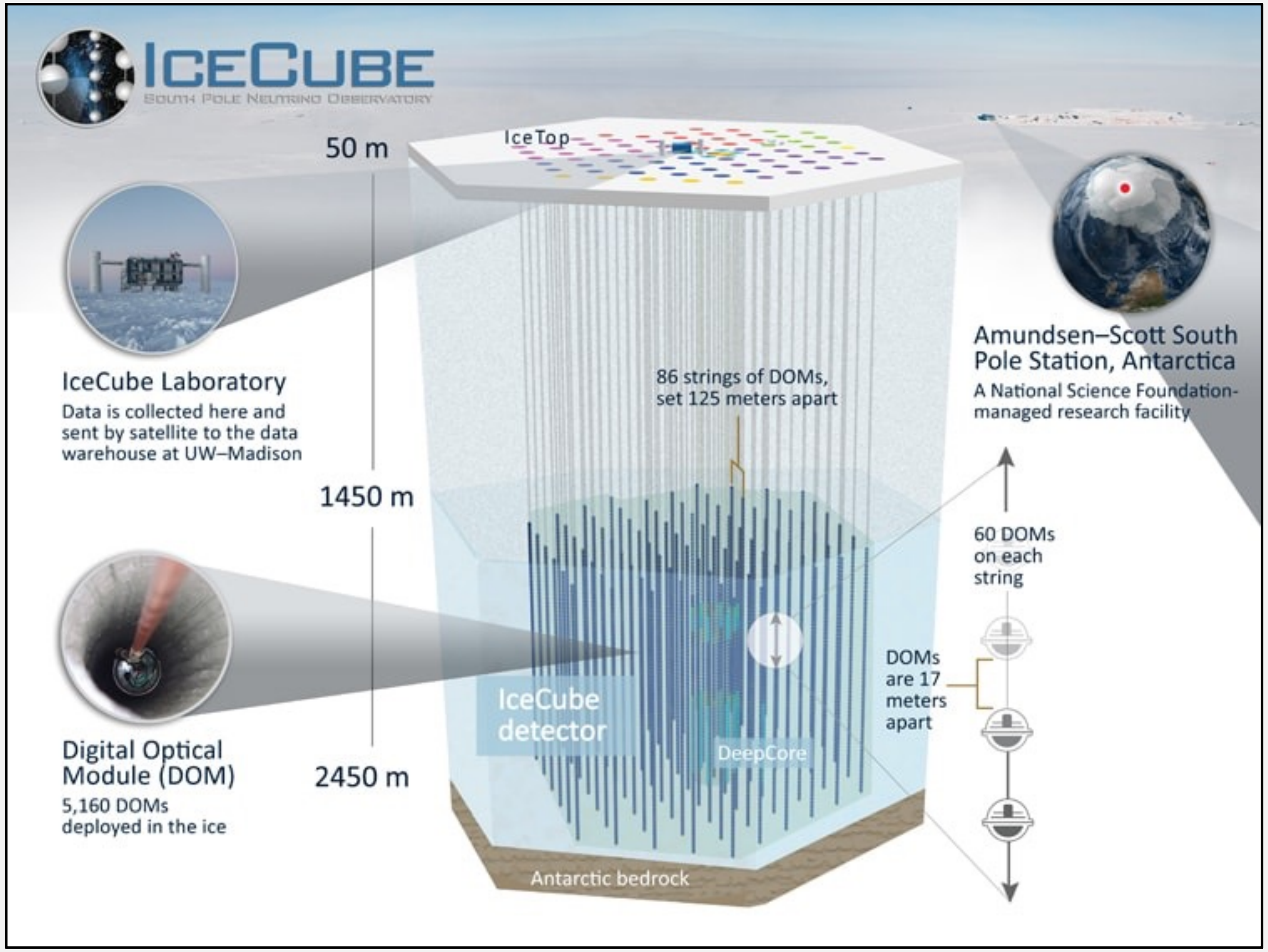
Astronomy with neutrinos?

- When stars go supernova, they create massive amounts of neutrinos
  - In a core-collapse SN, 99% of its energy is released as neutrinos!
- Because of how dense supernovae are, photons can often get "stuck" for hours inside of them
  - Neutrinos escape almost immediately and can be used as an early warning
  - Then we can point our telescopes at them!



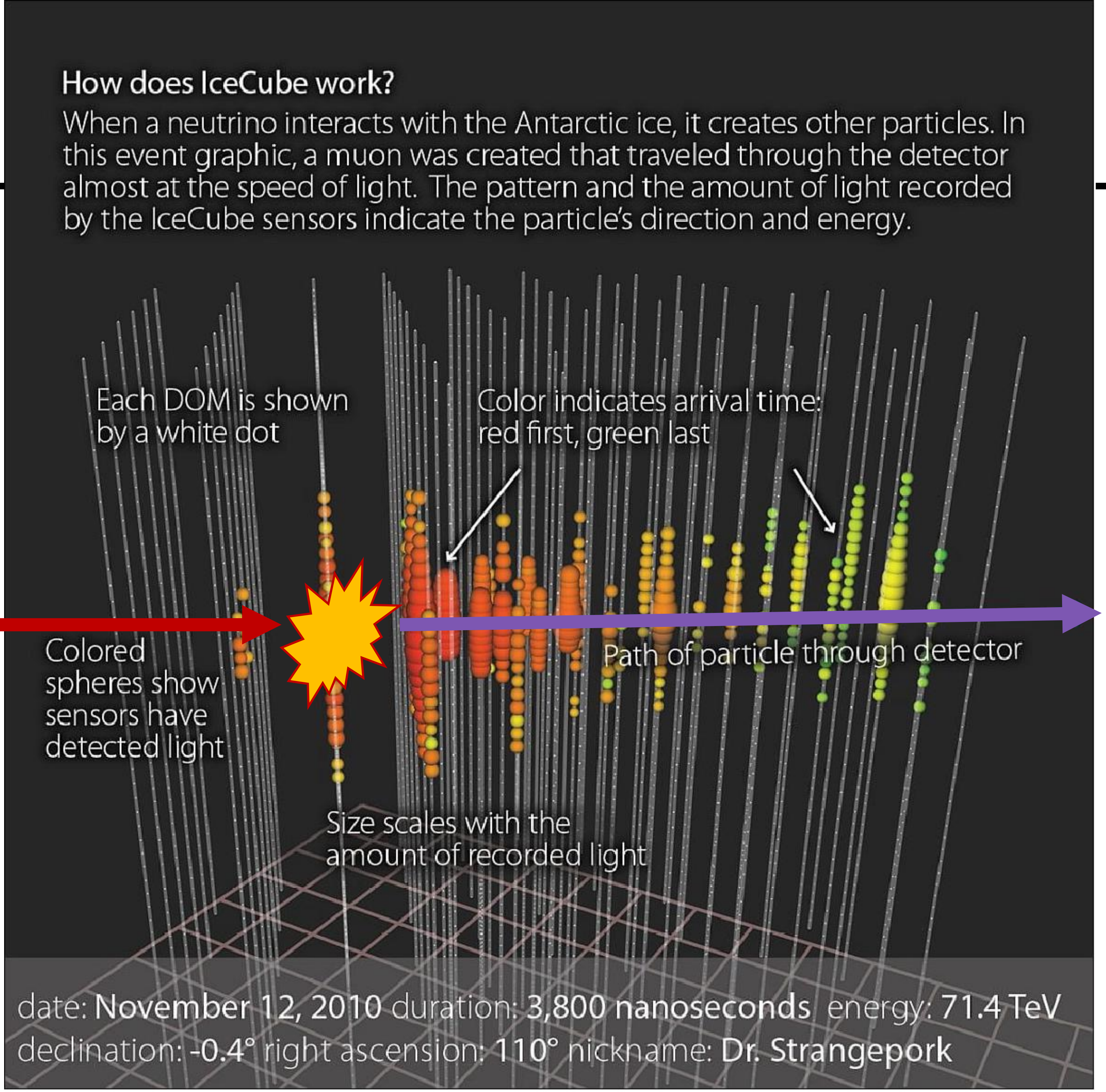
Supernovae Astronomy

- One neutrino observatory is IceCube, located in Antarctica
  - Contains PMTs on strings that are dropped down 1.5-2.5km holes in the ice
- Neutrinos interact with matter, creates a charged particle, and then creates light
  - Energy and direction can be reconstructed



Neutrino

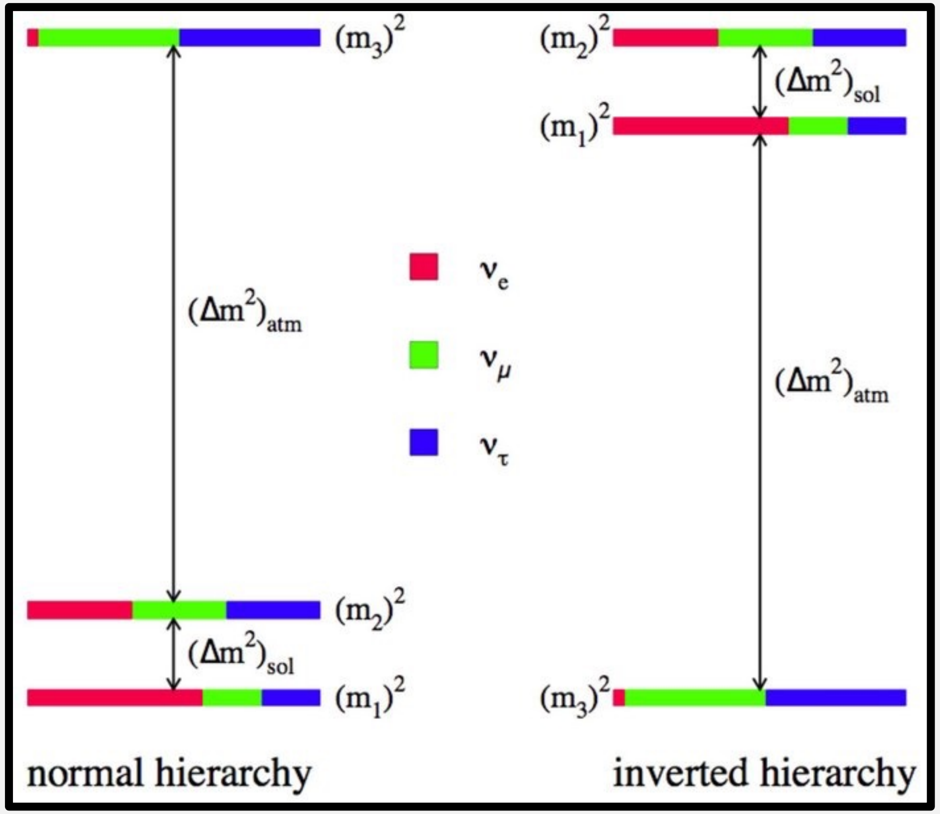
ν_e



How does IceCube work?
When a neutrino interacts with the Antarctic ice, it creates other particles. In this event graphic, a muon was created that traveled through the detector almost at the speed of light. The pattern and the amount of light recorded by the IceCube sensors indicate the particle's direction and energy.
Each DOM is shown by a white dot
Color indicates arrival time: red first, green last
Colored spheres show sensors have detected light
Path of particle through detector
Size scales with the amount of recorded light
date: November 12, 2010 duration: 3,800 nanoseconds energy: 71.4 TeV
declination: -0.4° right ascension: 110° nickname: Dr. Strangepork

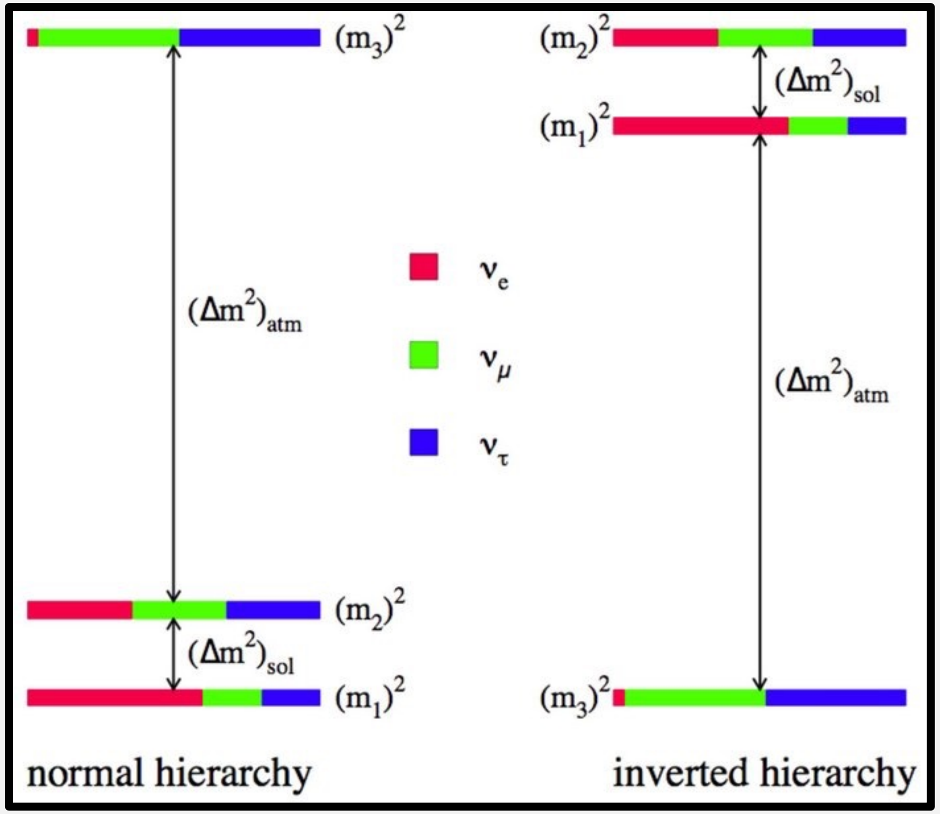
How Heavy Are Neutrinos?

- We don't exactly know how massive neutrinos are, but they are very small
  - Somewhere below 1 electron volt (eV)
  - A proton is 938,000,000eV
- But we don't know the mass ordering of the three flavors of neutrinos
  - Is one much more massive than the other two?
  - Or are two much more massive than the other?
- We don't know!



How Heavy Are Neutrinos?

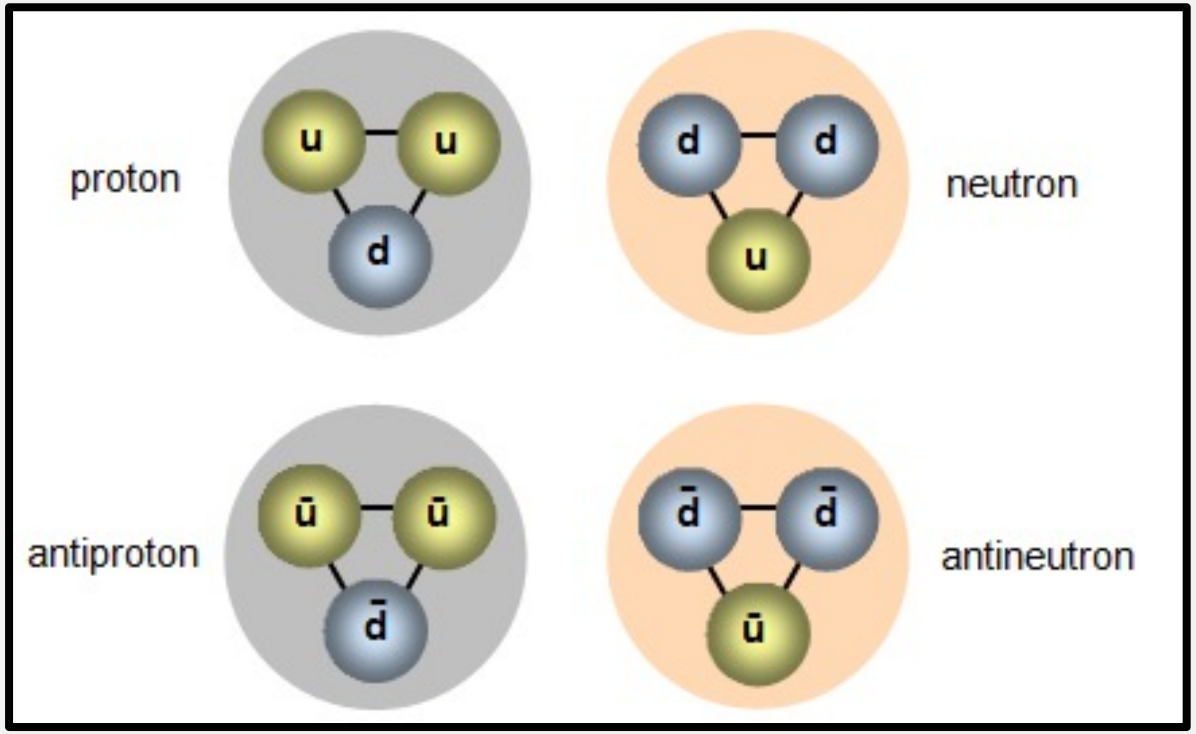
- We don’t exactly know how massive neutrinos are, but they are very small
  - Somewhere below 1 electron volt (eV)
  - A proton is 938,000,000eV
- But we don’t know the mass ordering of the three flavors of neutrinos
  - Is one much more massive than the other two?
  - Or are two much more massive than the other?
- We don’t know!



YET…

Neutrino Its Own Antiparticle?

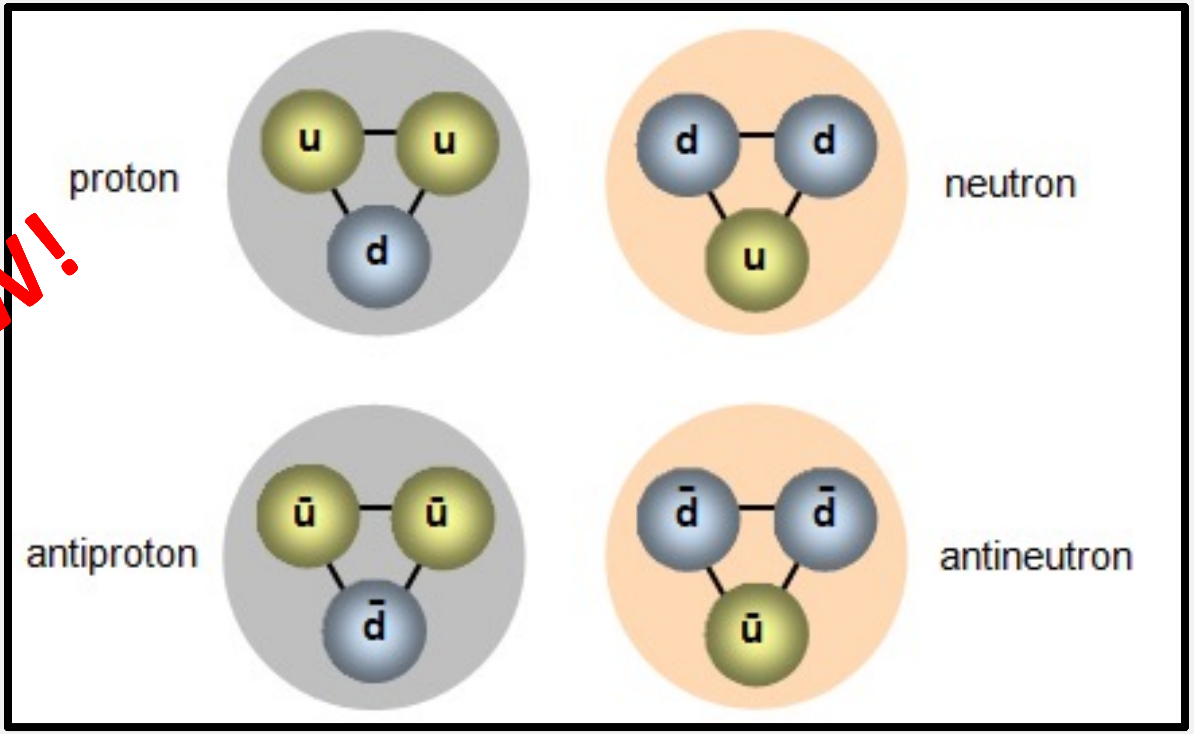
- An anti-particle is normally described by *conjugating* its electric charge or the charge of its constituents (flipping the sign)
- Neutrinos do not have any charge!
  - What about neutrons? Well neutrons have inner structure with charge that adds to 0
  - Neutrinos have no internal structure…
- So are neutrinos their own antiparticle?



Neutrino Its Own Antiparticle?

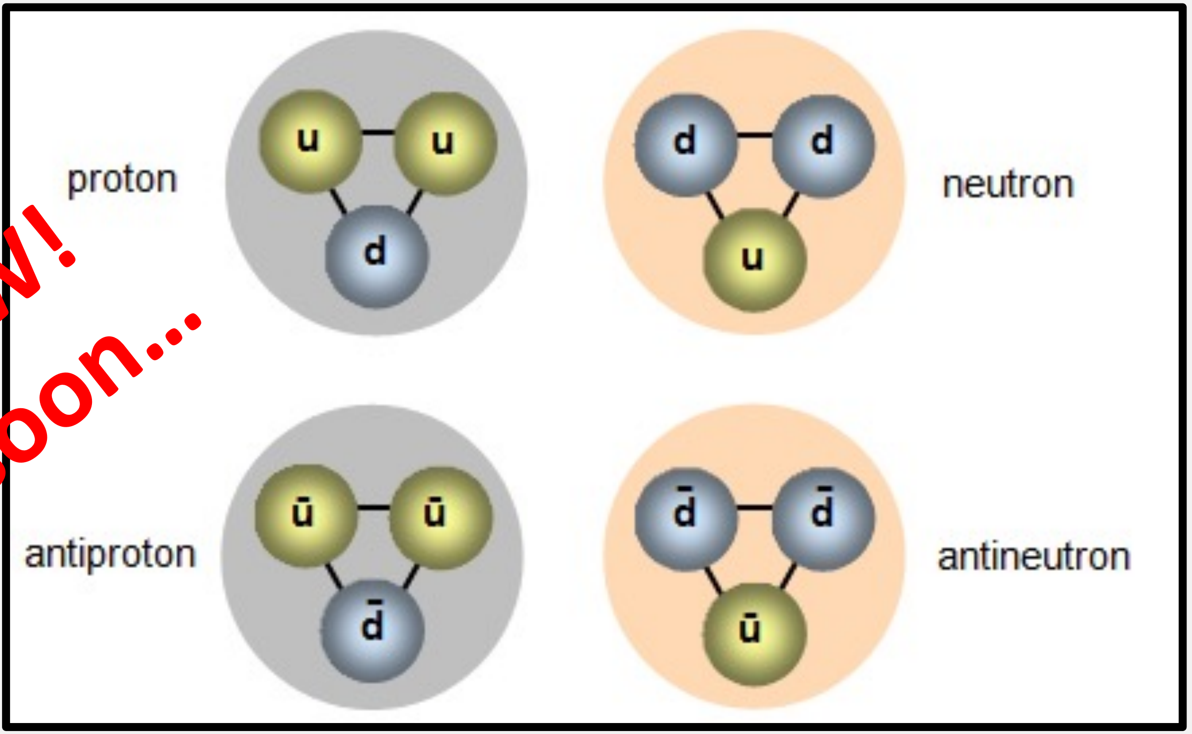
- An anti-particle is normally described by *conjugating* its electric charge or the charge of its constituents (flipping the sign)
- Neutrinos do not have any charge!
  - What about neutrons? Well neutrons have inner structure with charge that adds to 0
  - Neutrinos have no internal structure…
- So are neutrinos their own antiparticle?

WE DON'T KNOW!



Neutrino Its Own Antiparticle?

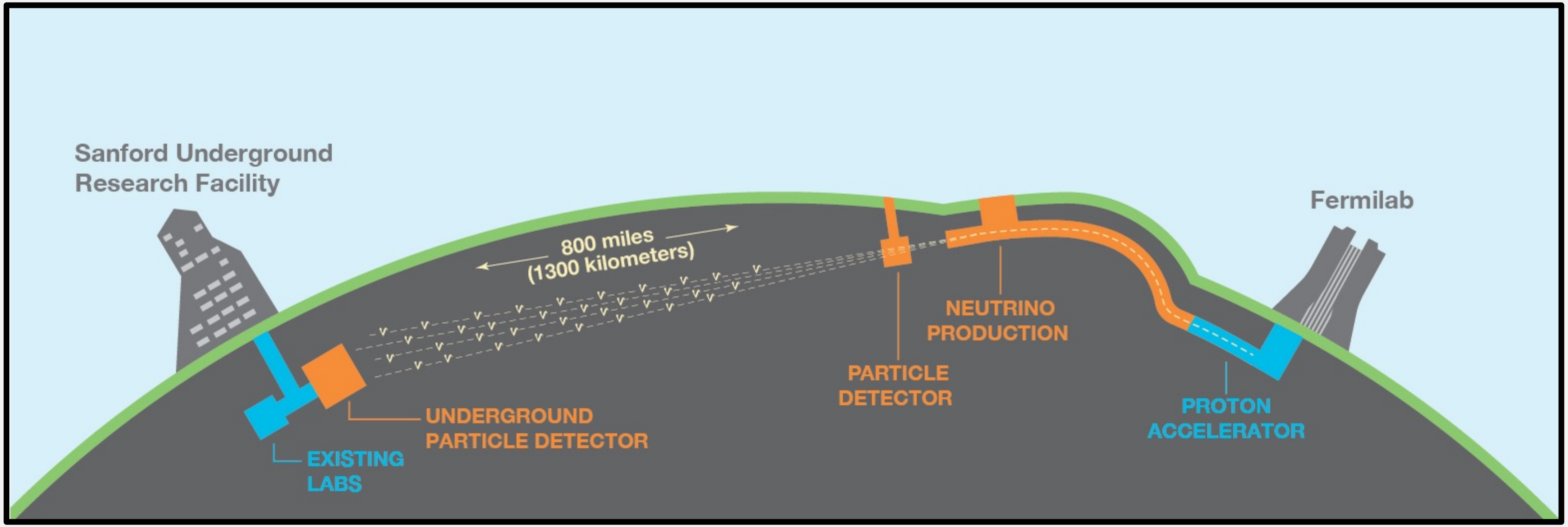
- An anti-particle is normally described by *conjugating* its electric charge or the charge of its constituents (flipping the sign)
- Neutrinos do not have any charge!
  - What about neutrons? Well neutrons have inner structure with charge that adds to 0
  - Neutrinos have no internal structure…
- So are neutrinos their own antiparticle?



WE DON'T KNOW!
But we might, soon…

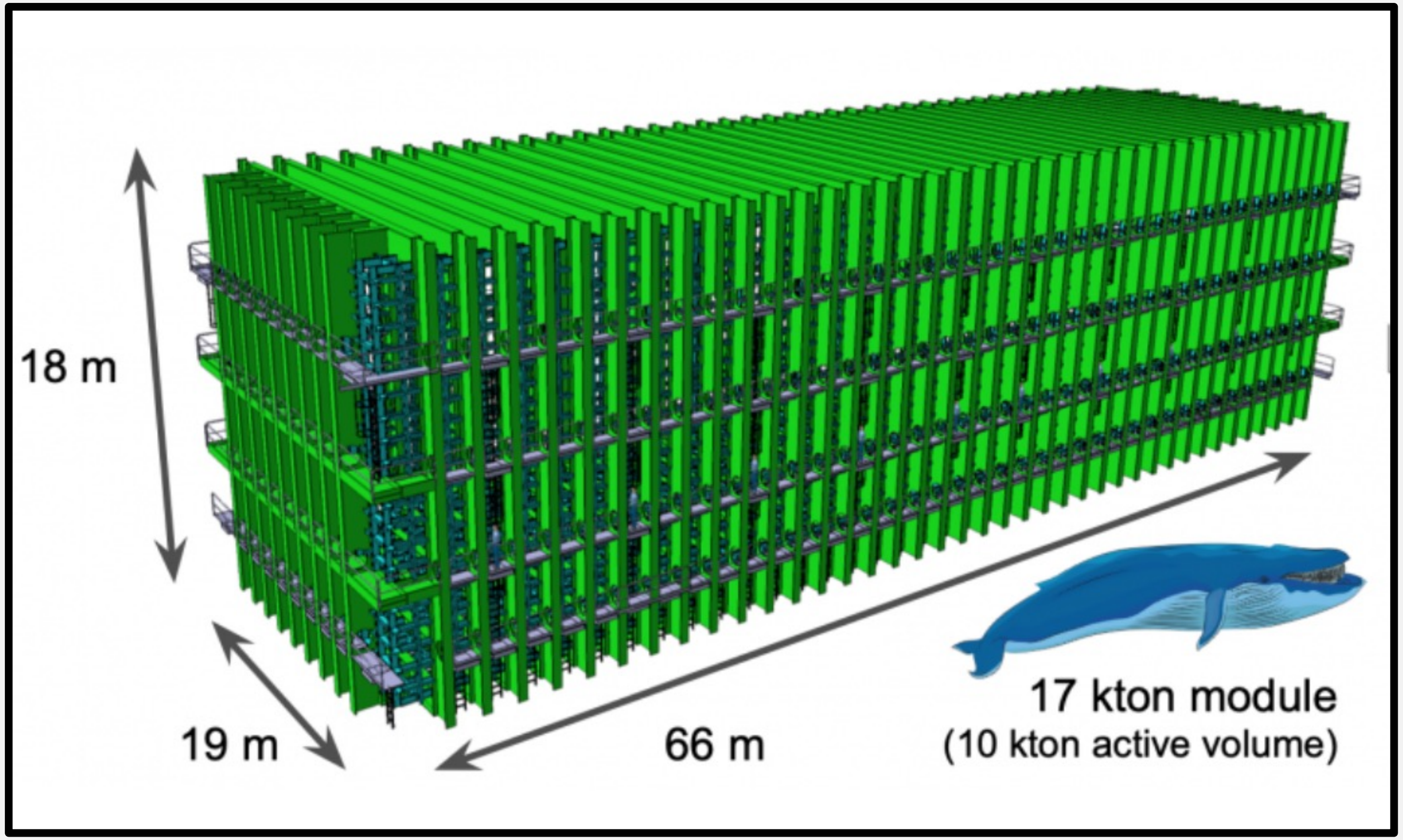
Deep Underground Neutrino Experiment

- Or DUNE, aims to better our understanding of neutrinos
- A neutrino beam is generated at Fermilab, and aimed 800km away in South Dakota
  - It will measure the oscillation neutrinos undergo on the journey

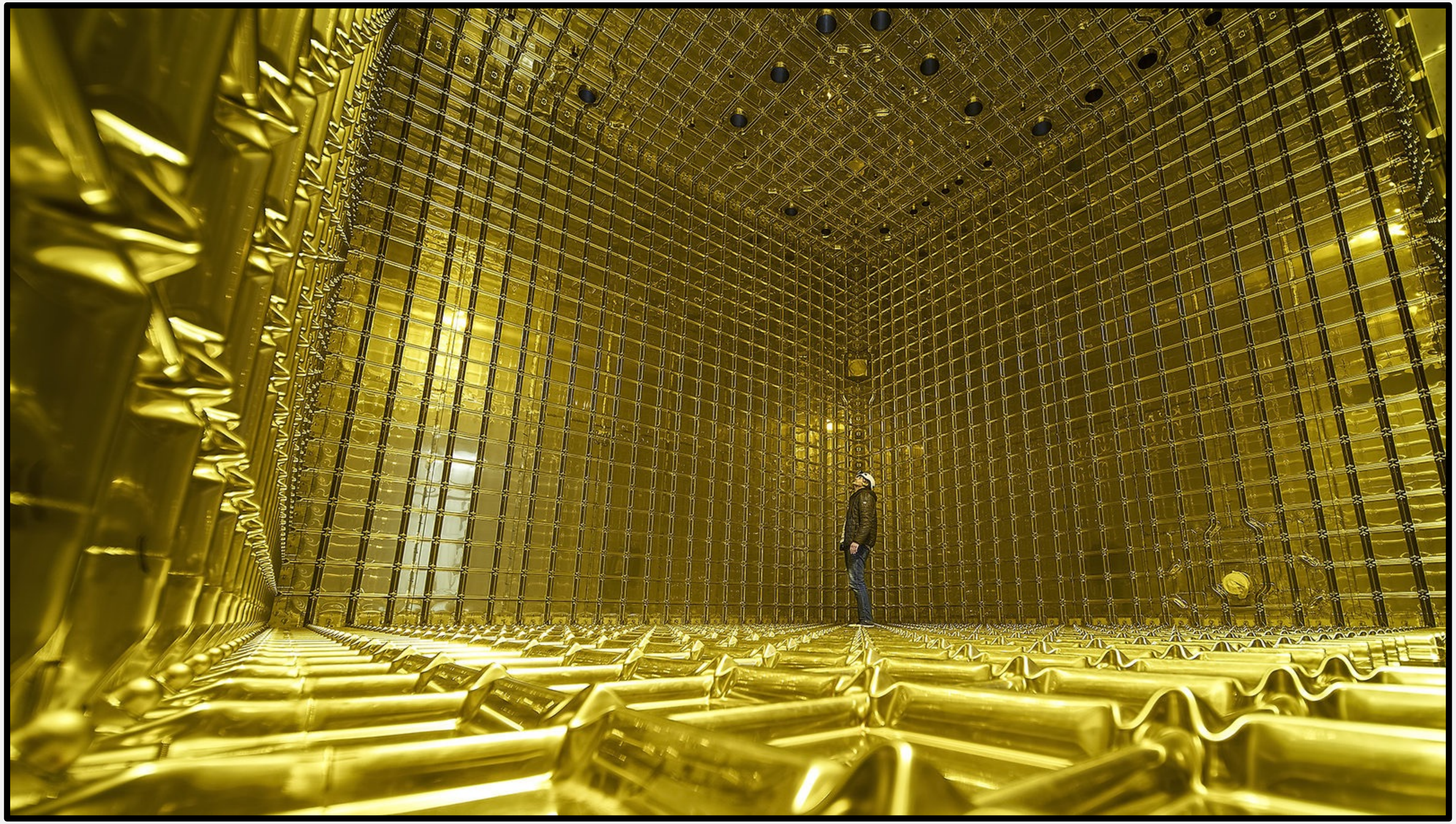


How Does DUNE Detect Neutrinos?

- First make a neutrino beam by shooting protons at graphite
  - This creates other particles called pions and kaons which then decay into neutrinos
- Wait for them to travel 800km
- Try to catch them with a REALLY BIG detector
  - Full of liquid argon
- When a neutrino interacts with Argon, it creates light!

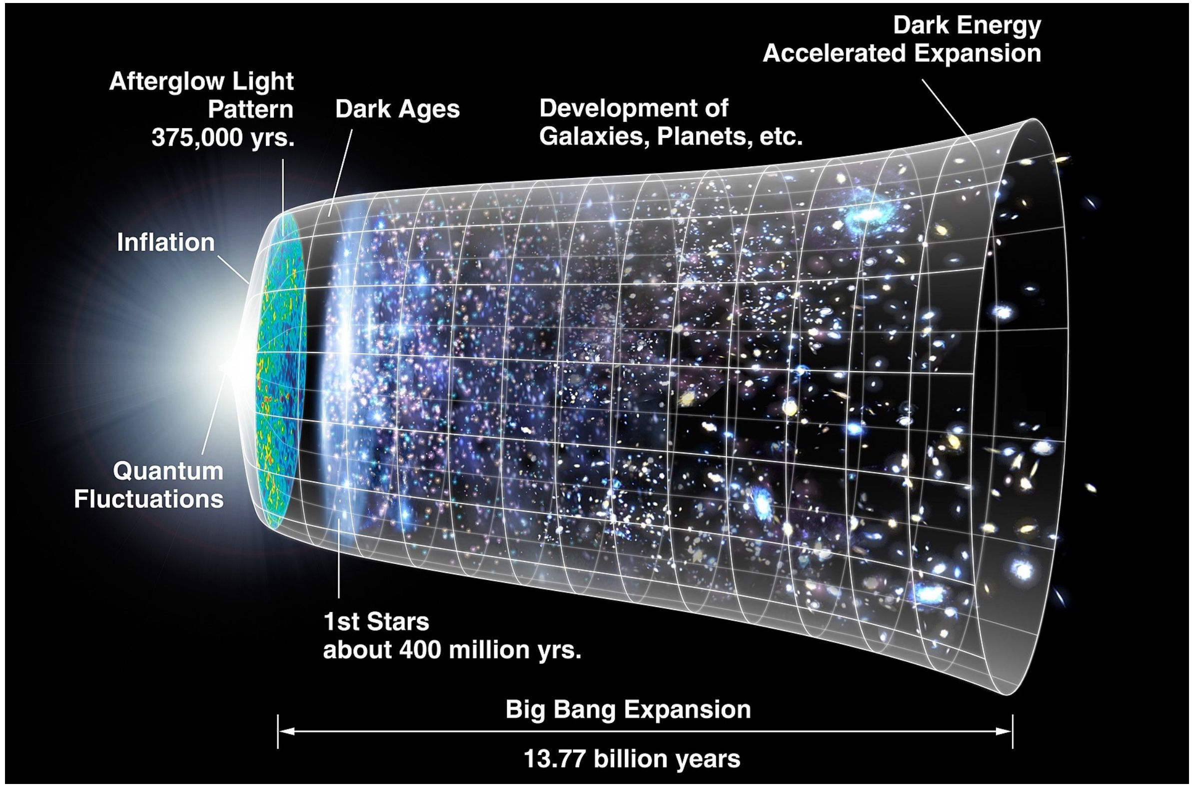


Deep Underground Neutrino Experiment



Using Neutrinos for Cosmic Archaeology?

- During the big bang, neutrinos were created when the universe was just 1 second old
  - After 1 second, they were too spread out to interact!
- Due to universe expansion, they are now very low energy, 10^{-4}-10^{-6}eV
  - Even harder to detect!
  - We need to know their mass *very* well!
- Detecting them will tell us about the conditions of the early universe!



Summary

- Neutrinos are very, very hard to detect
  - Even though they are *literally* everywhere!

- We still don’t understand them well. . .
  - What are their masses?
  - They oscillate, but our measurements suck
  - Are they their own antiparticle?

- Many uses!
  - Supernovae astronomy
  - Cosmic archaeology
  - Anti-nuclear proliferation
  - Imaging the core of the Earth