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Neutrinos: Ghosts of the Universe

Roger Huang
Physics Division, LBNL

QuarkNet 6/16/2025

Outline:

- About Me
- Neutrinos: Introduction and History
- Neutrino Research with DUNE

About Me

High School 2008-2012

Went to Foothill High School in Pleasanton

Lots of science and math competitions

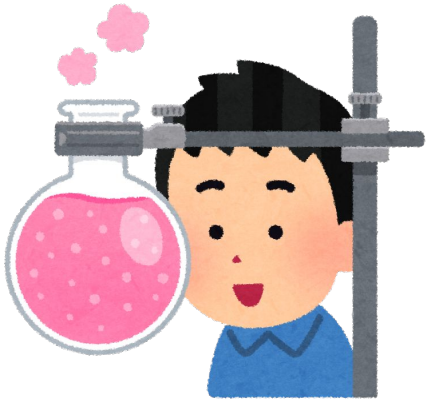
- Also piano competitions
- And Starcraft II tournaments

High School 2008-2012

Started out mostly interested in math, and then also computer science and physics

- COSMOS summer camp on Physics in Electro-Optics and Nuclear Technology
- Summer internship in LBNL Materials Sciences division

“Physics tells us how the world works, right?”



Applied to college as a physics major...

College 2012-2016

Went to Harvard University

Started with an equal share of math, CS, physics classes

- Decided didn't want to focus on math after the first year
- (Also filled almost all of my breadth requirements with history classes)

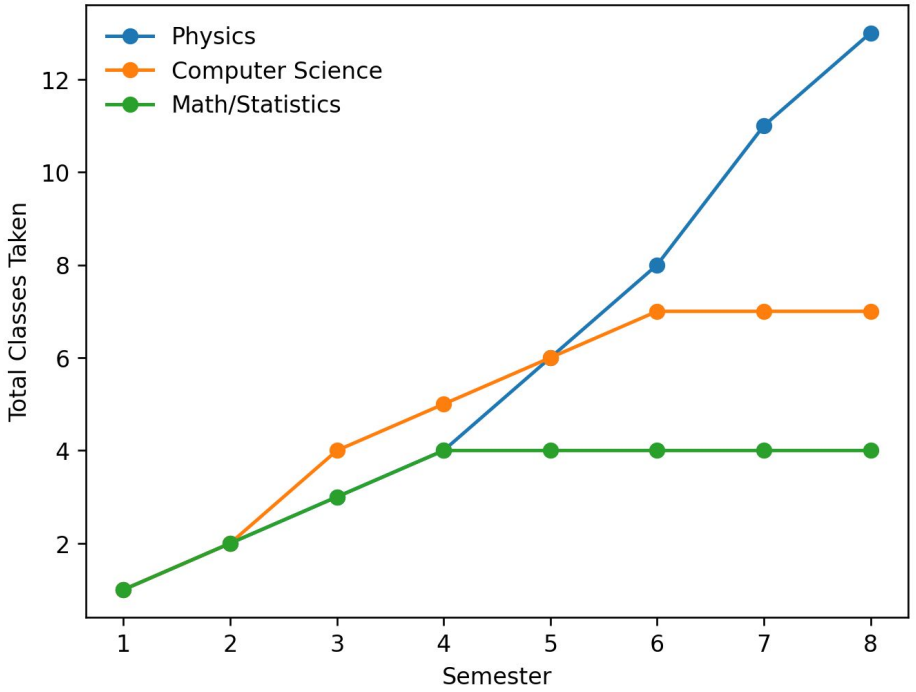
College 2012-2016

Software internships the first two summers (one at Google)

3rd year: machine learning project with a condensed matter physics group

- Still only light involvement in research at this point

3rd summer: got a return internship offer from Google, but...



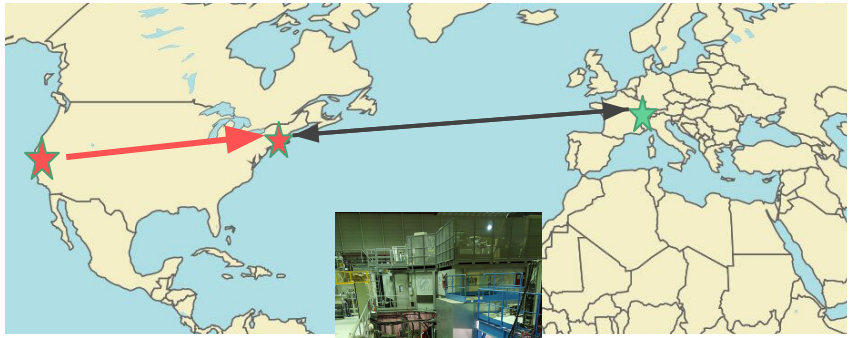
College 2012-2016

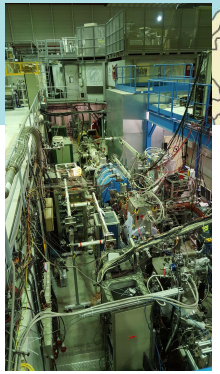
Spent 2015 summer at CERN in Switzerland with ATLAS group

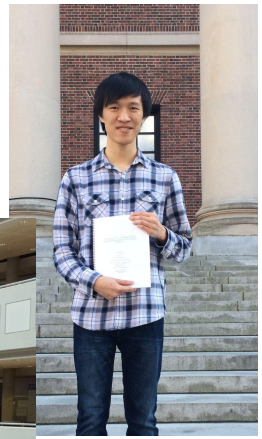
- Started with software work for one of their analysis frameworks

Graduated with A.B. in Physics and Computer Science

- Thesis on using boosted decision trees for jet analysis in ATLAS







Graduate School 2016-2021

Came to UC Berkeley for a PhD in **Experimental Particle Physics**, interested in studying neutrino behavior

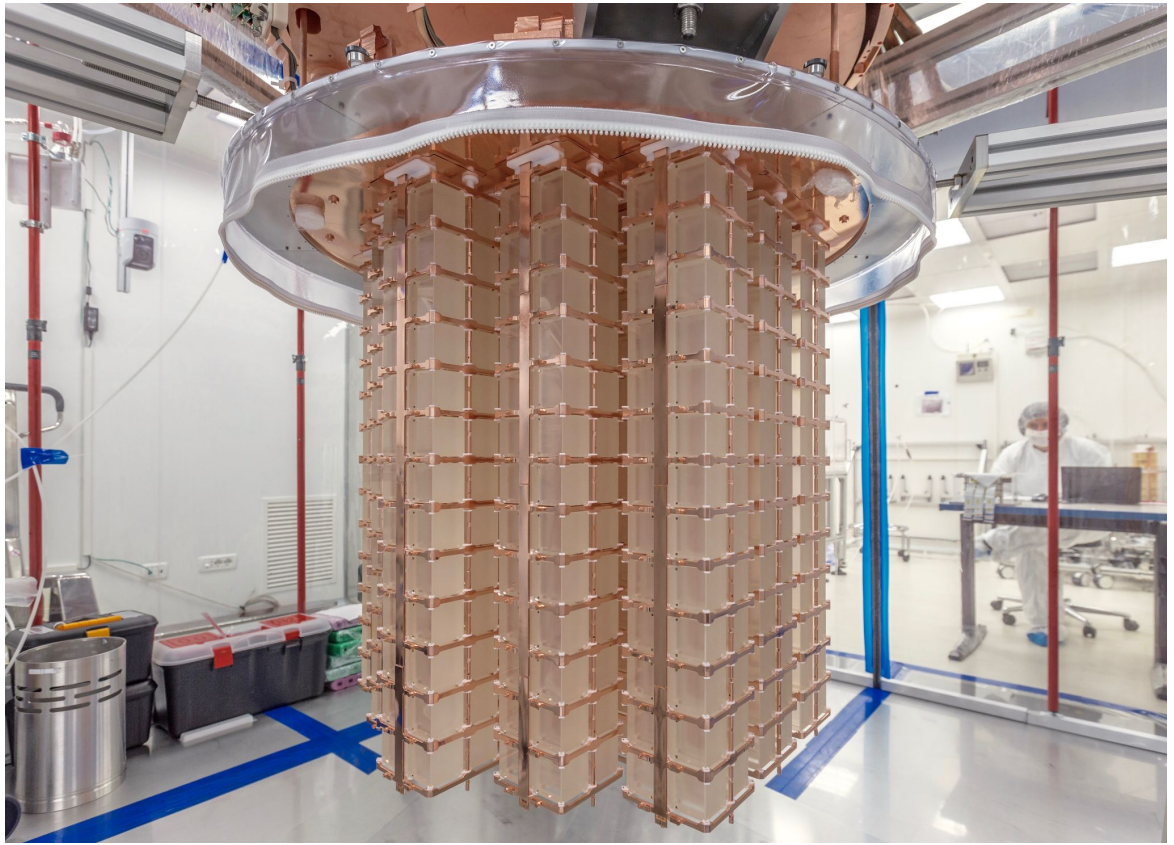
Worked on the CUORE/CUPID experiments in Italy

- Located under Gran Sasso mountains for shielding against cosmic rays

Graduate School 2016-2021

Thesis on CUORE, a search for ultra-rare nuclear decays

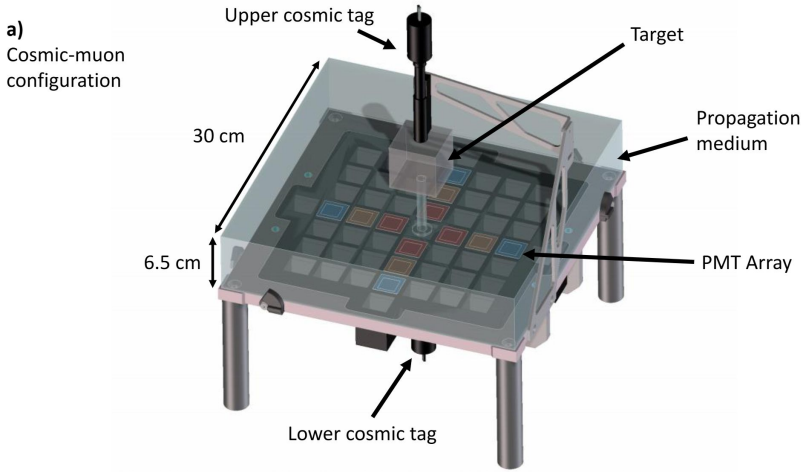
- Looking for processes with half lives > 10^{26} years (universe is 10^{10} years old!)
- Multiple tons of material cooled to 0.01 K (-459° F)
- Using ancient Roman lead for shielding

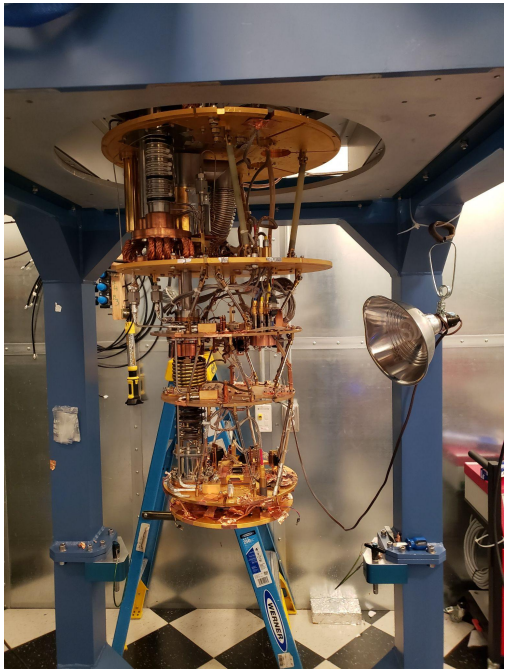


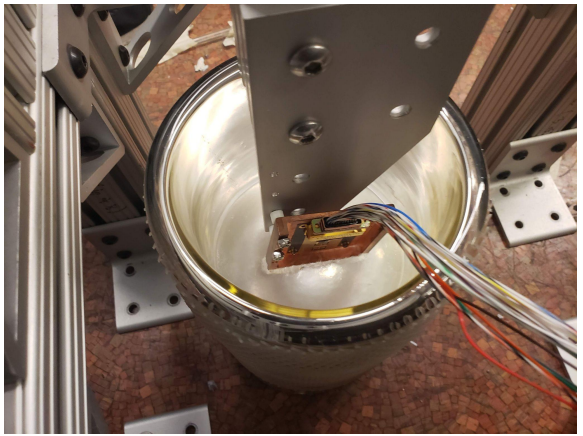
Graduate School 2016-2021

Local R&D!

- Light yield measurements
- Development of sub-Kelvin sensors and electronics

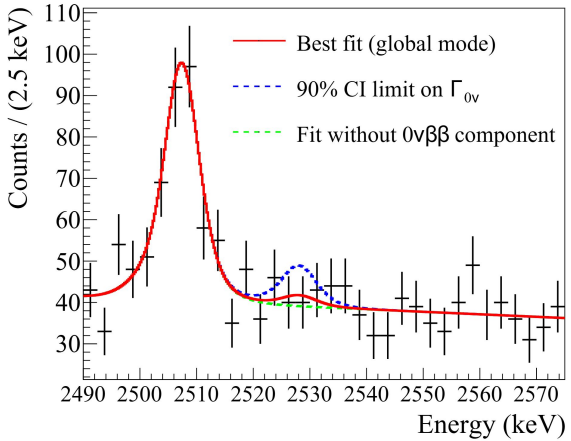


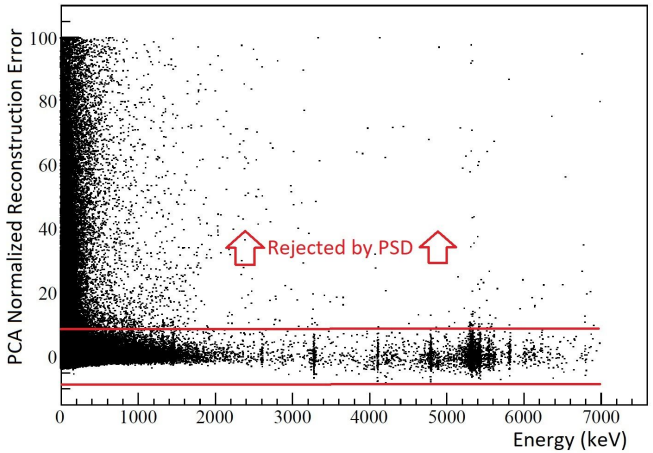


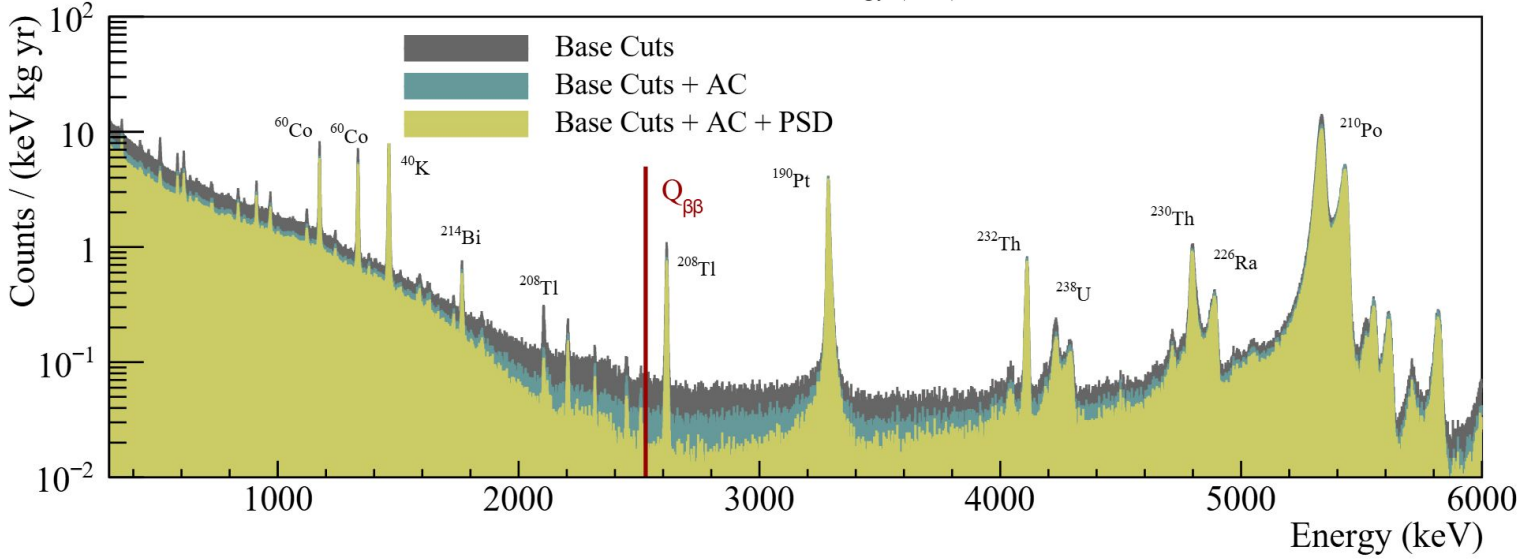


Graduate School 2016-2021

Data analysis!







Postdoc 2021 - Now

Joined neutrino physics group at LBNL at end of 2021

- Working on the DUNE experiment
- Different experiment and techniques...but using cryogenic electronics
- Spent 2022-2023 living in France/Switzerland and working at CERN

Q&A

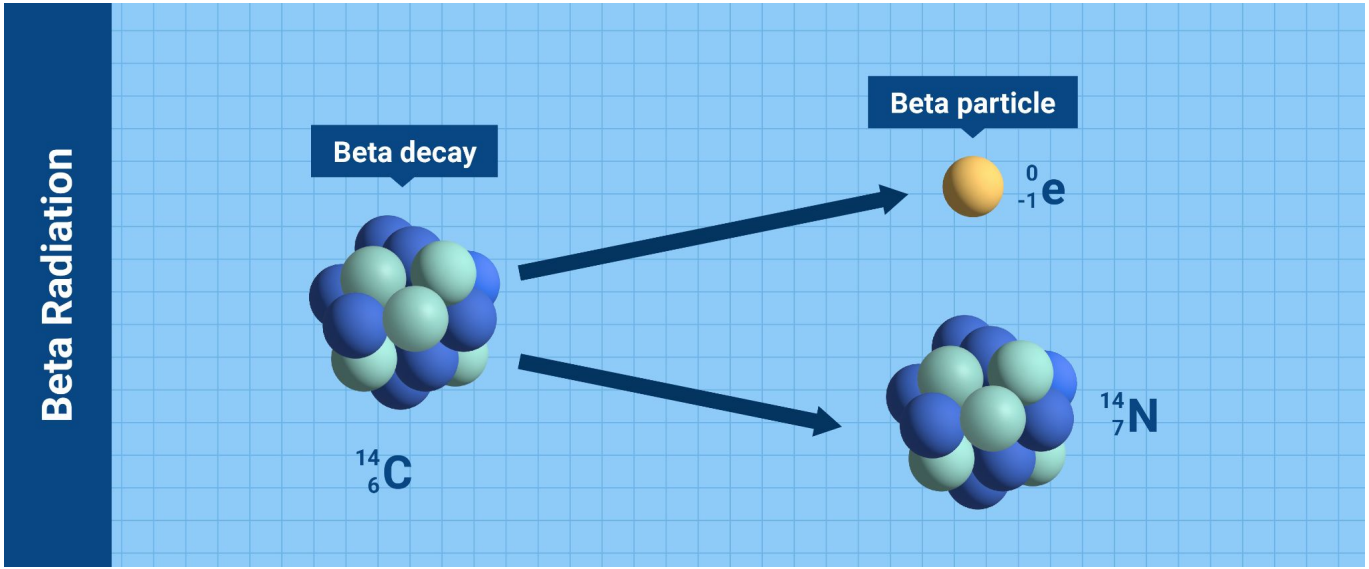
Neutrinos: A Brief History

Beginnings of the Neutrino Hypothesis

Radiation was an active field of study by the early 1900s

Beta decay was one type, which was believed to be a 2-body decay

By **conservation of energy and momentum**, the beta particle should always end up with the same energy in any particular decay

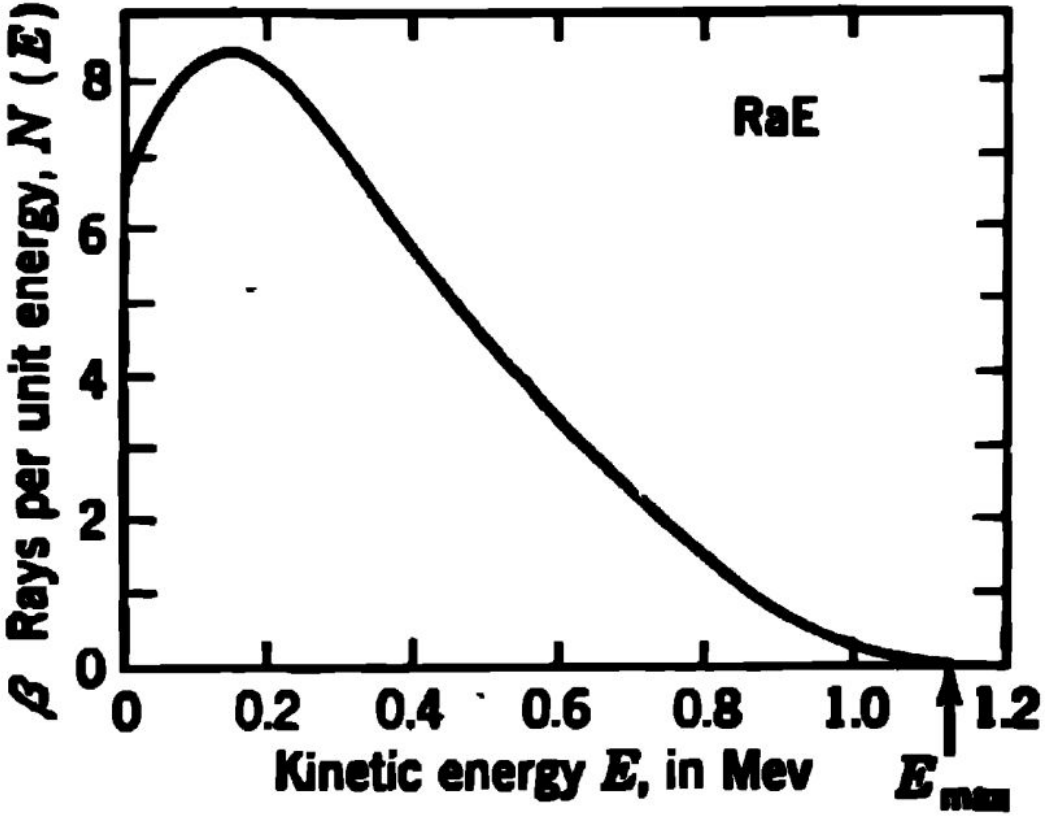


Beginnings of the Neutrino Hypothesis

Observed reality: each beta particle has a random energy that's something between 0 and the expected energy

Hypothesis: a ghost particle is carrying away the rest of the energy?

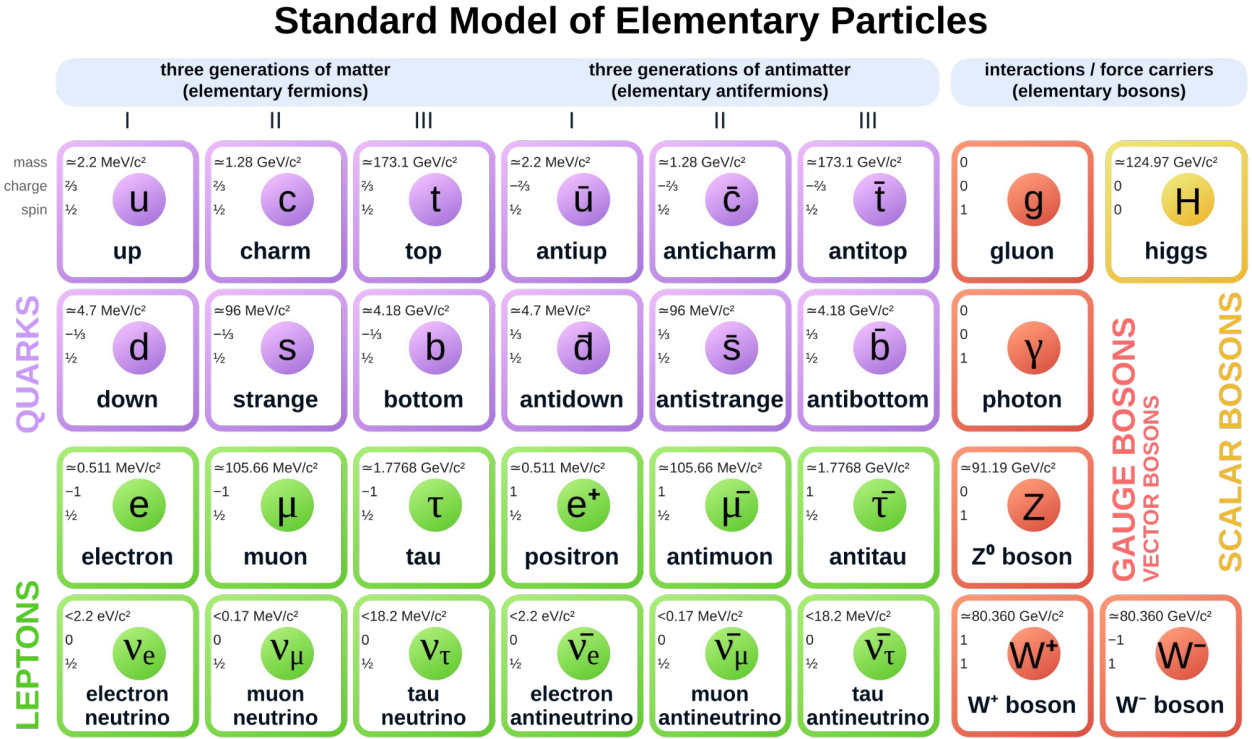
- Postulated by Pauli in 1930
- Dubbed **neutrinos** by Fermi in 1931
- If we can't detect the ghost, how do we test this theory?



Neutrinos in the Standard Model

1956: Neutrinos were detected for the first time (with the help of a nuclear reactor)

Neutrinos eventually integrated into the **Standard Model**, our current theory for how all particles interact via electromagnetic, weak, and strong forces



Neutrinos Around Us

100 trillion neutrinos pass through you every second!

On average, one neutrino will interact with you in your lifetime

- Neutrinos only interact via the **weak force**
- Nothing can block neutrinos!

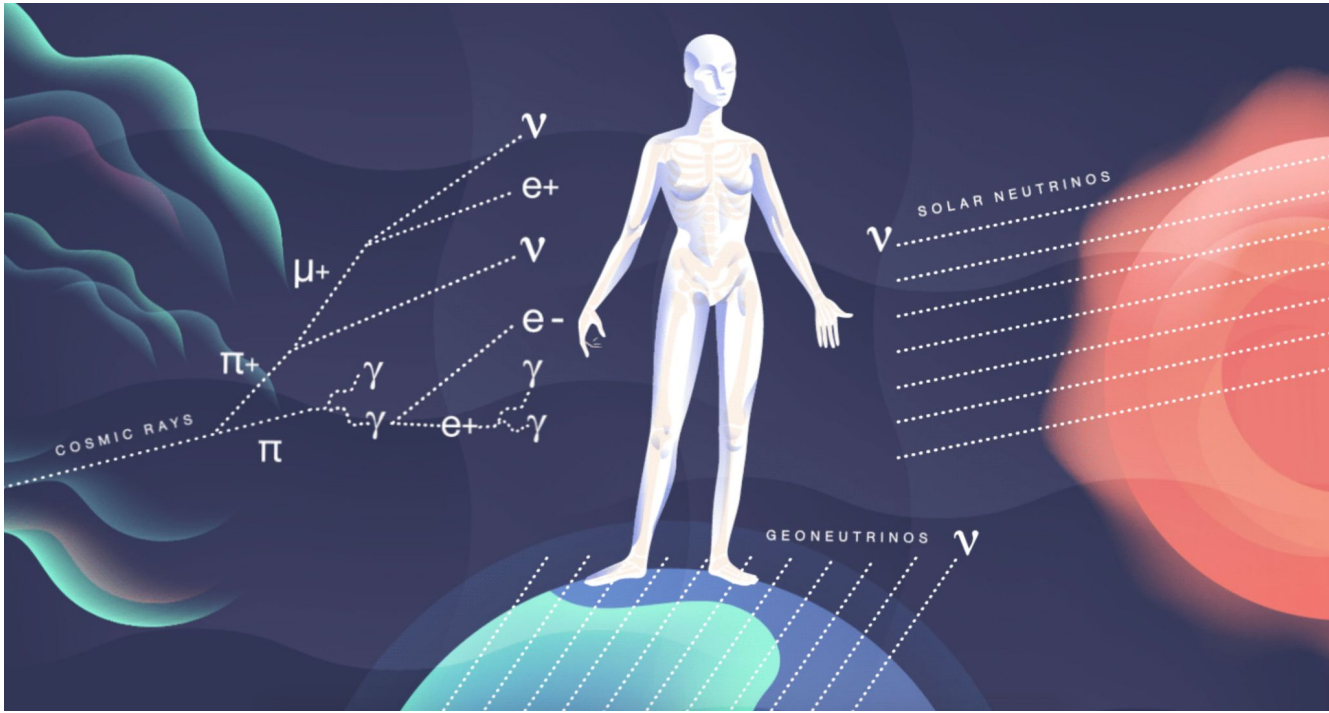


Image credit: Symmetry Magazine

Neutrinos outside the Standard Model?

By the late 1980s, there were signs that something was wrong with our picture of neutrinos

- Missing neutrinos from various sources

We now know that **neutrinos have mass and can change flavor**

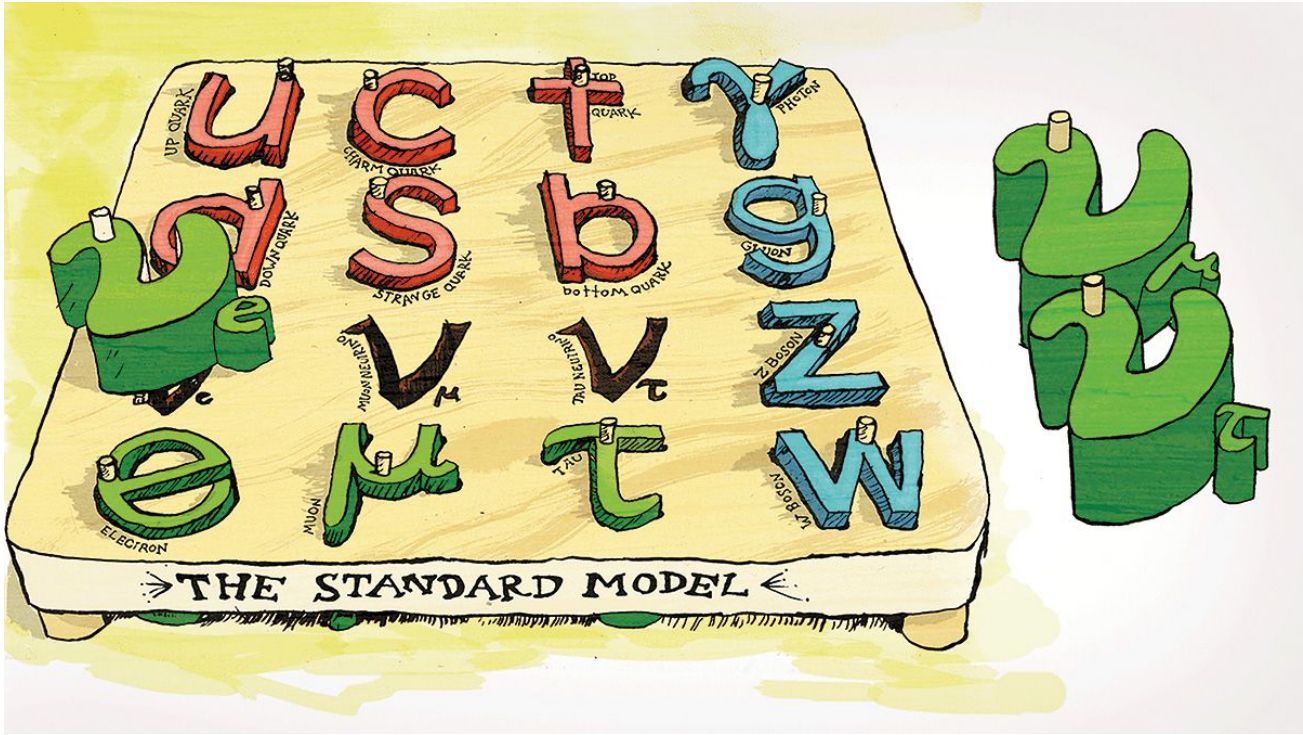


Image credit: Symmetry Magazine

Neutrino Oscillations

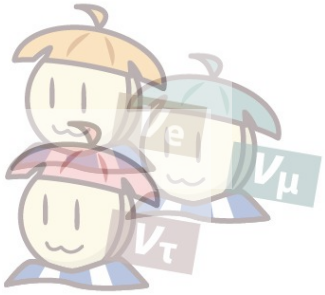
There are **3 types of neutrinos***: electron muon, and tau types (ν_e, ν_μ, ν_τ)

When we:

1. Create one type of neutrino at point A
2. Try to detect them at point B some distance away

We see that some of the neutrinos have transformed into a different type

B: detection point



A: creation point

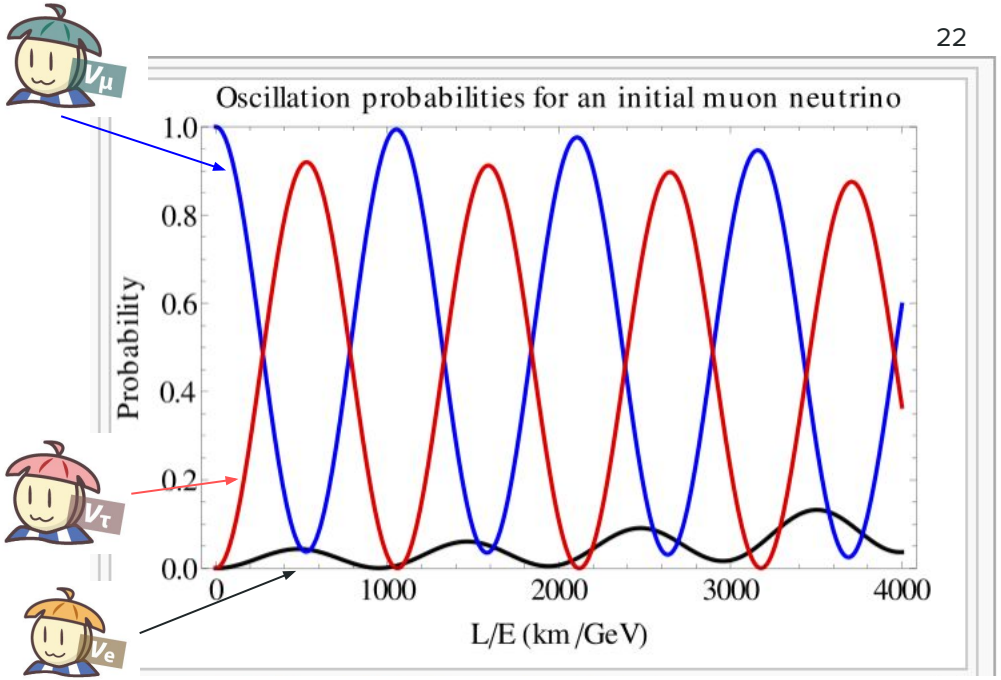
*That we know of

Image credits: Higgstan

Neutrino Oscillations

We call this phenomenon **neutrino oscillations**

Neutrinos are **quantum objects** that randomly change type as they travel through space



Oscillation probability

$$P_{\nu_\alpha \to \nu_\beta}(t) = \delta_{\alpha\beta} - 4 \sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$

$$+ 2 \sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin\left(\frac{\Delta m^2_{ij} L}{4E}\right),$$

A bunch of random numbers

Distance traveled by neutrino

Difference in neutrino masses

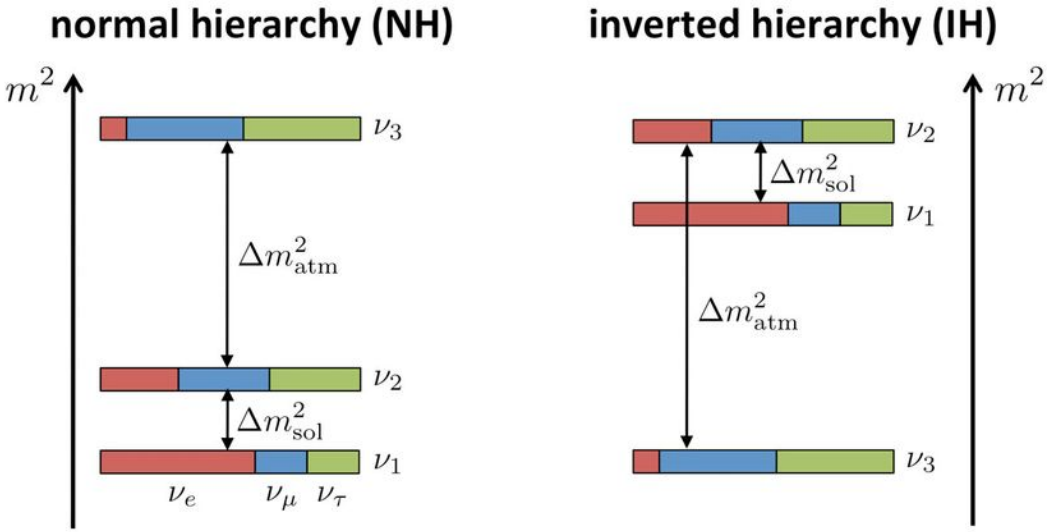
Energy of neutrino

Neutrino Oscillations - Outstanding Questions

Within the **3 flavor oscillation** theory of neutrino behavior, we now understand fairly well the rate at which the 3 types of neutrinos oscillate into each other

But some big questions remain:

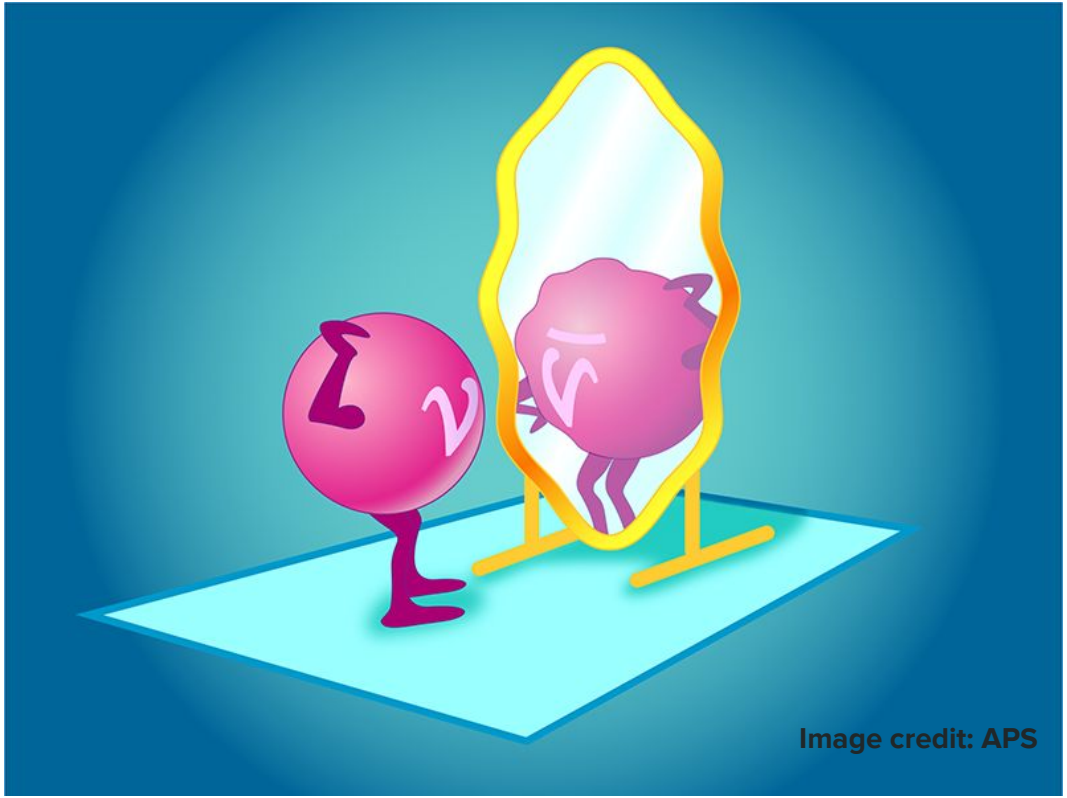
1) **Which neutrino state is the heaviest?**



Neutrino Oscillations - Outstanding Questions

2) Do neutrinos and antineutrinos oscillate differently?

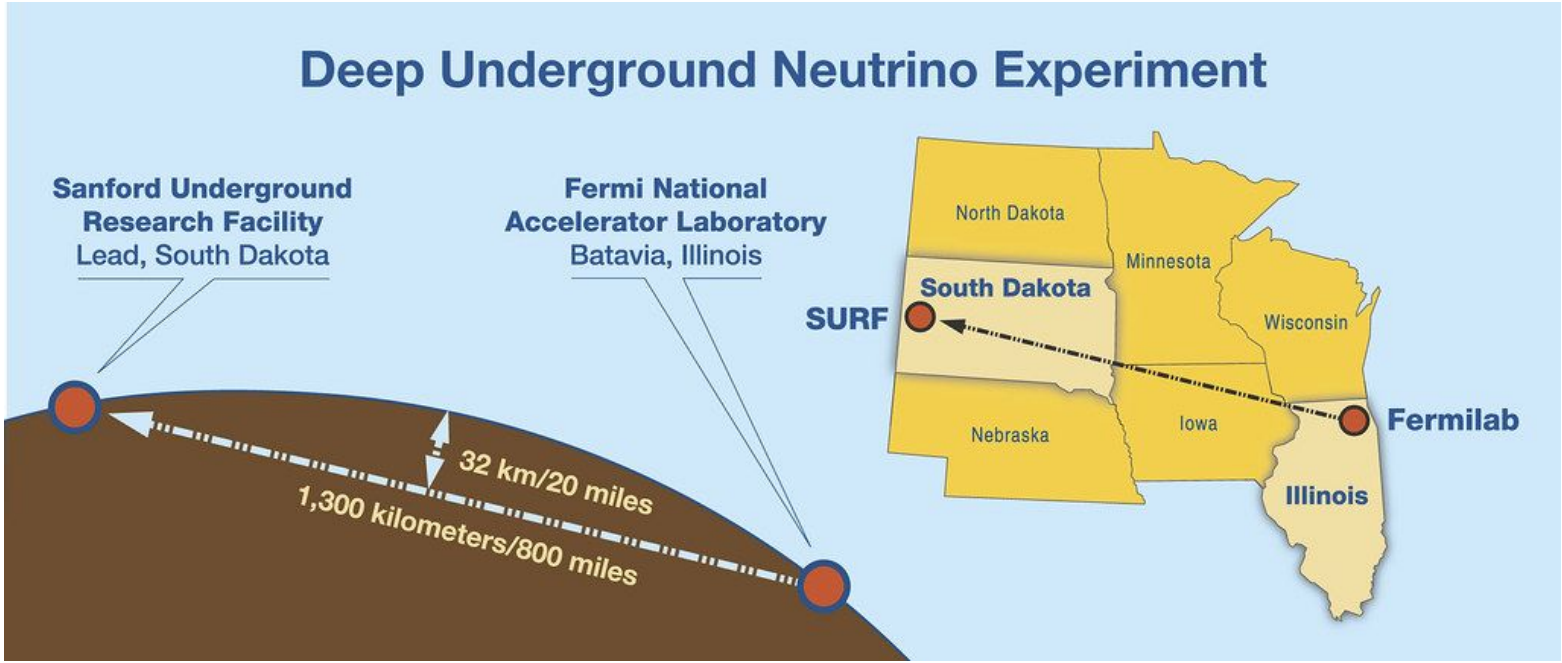
- Most particles behave pretty similarly to their antimatter counterparts, but neutrinos could be an exception
- Could this be related to why the universe has almost no antimatter?



Neutrinos: What's Next?

Deep Underground Neutrino Experiment (DUNE)

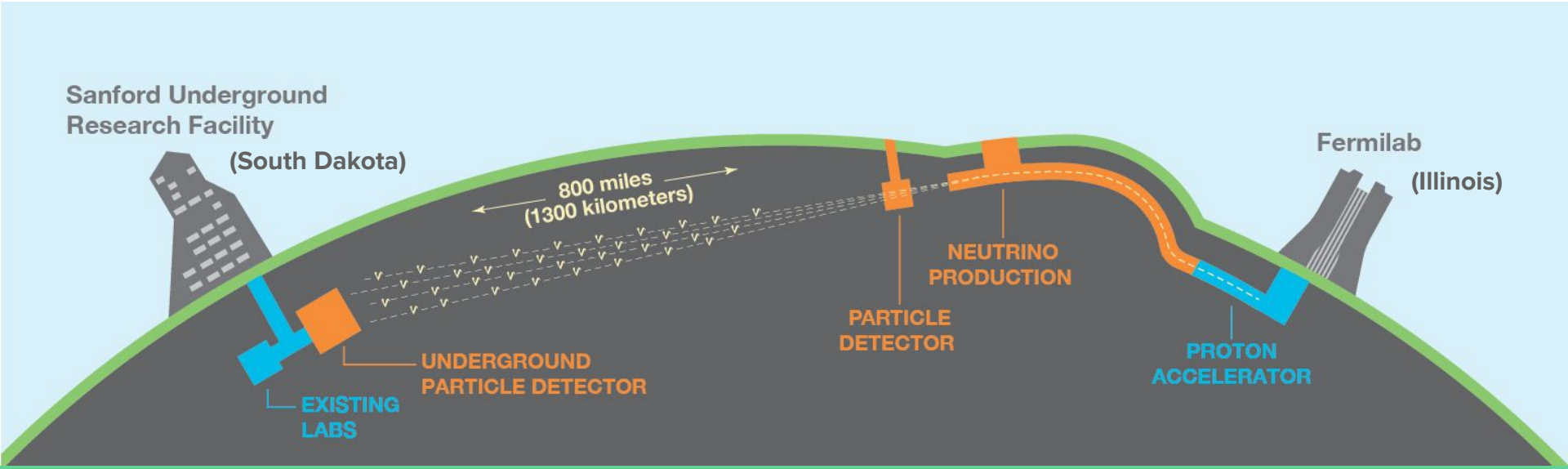
DUNE is a **long baseline neutrino experiment** that will shoot neutrinos from Fermilab, Illinois to SURF, South Dakota to study how they change over this distance



Deep Underground Neutrino Experiment (DUNE)

By looking at what neutrinos we see in South Dakota, DUNE can answer:

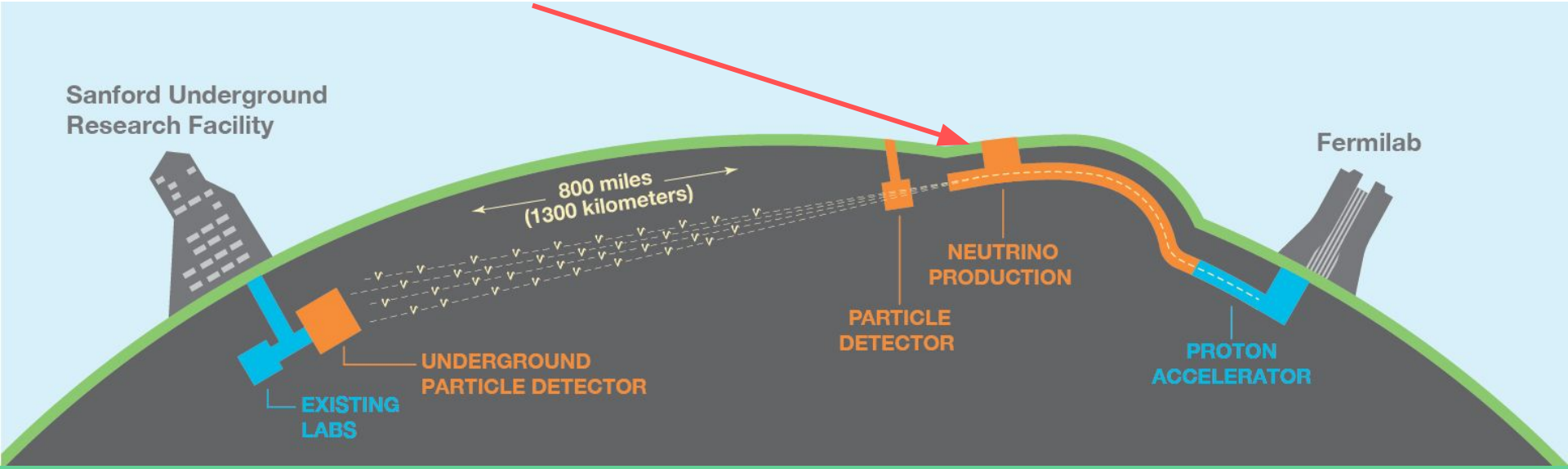
- Do neutrinos and antineutrinos change differently?
- Which is the heaviest neutrino type?



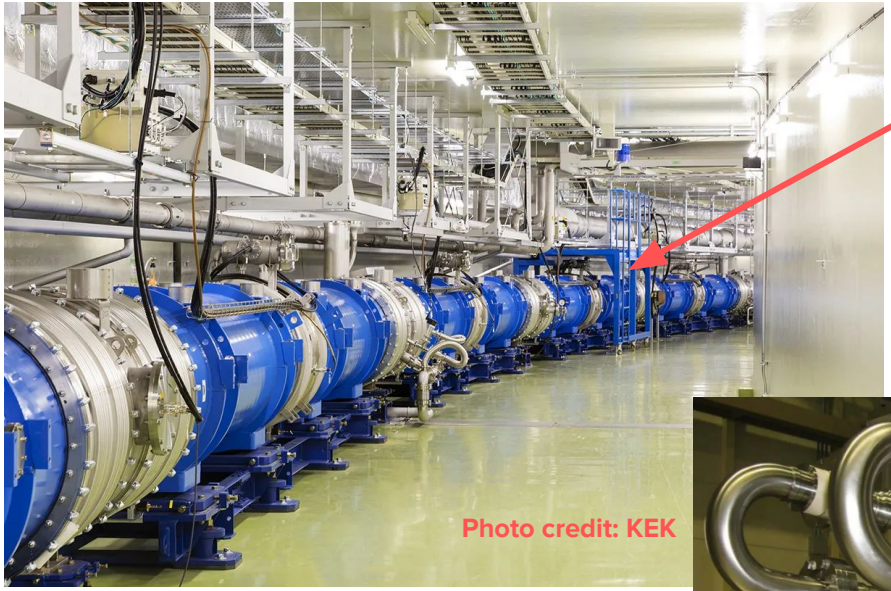
Making Neutrinos

Some neutrino experiments use pre-existing sources: nuclear reactors, the atmosphere, or the sun

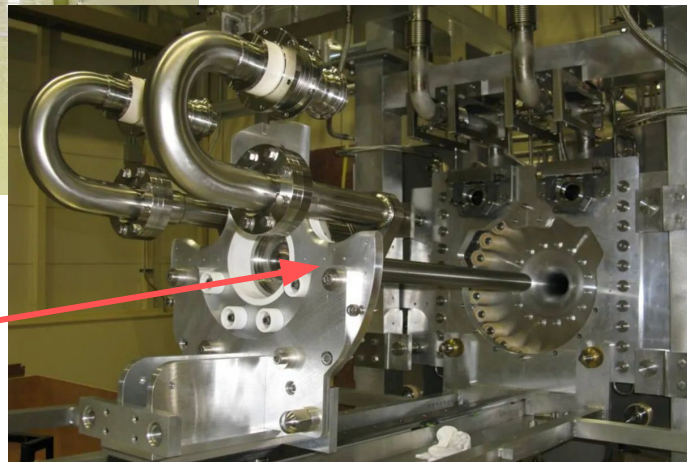
For DUNE, make our own neutrinos and control the direction, energy, and intensity



Making Neutrinos



Accelerate protons to >99.9% speed of light with the help of superconducting magnets

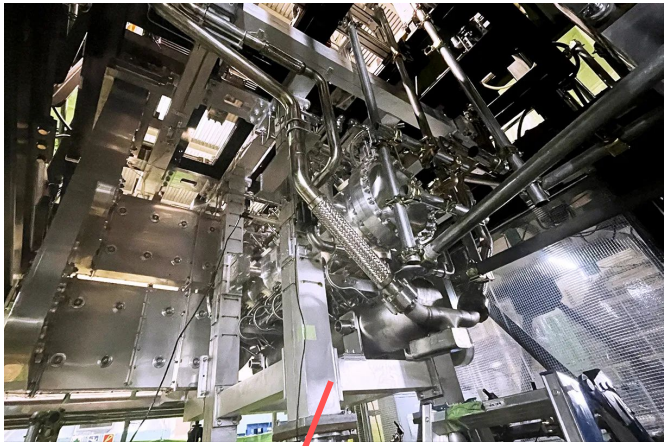


Then smash the protons into a solid target

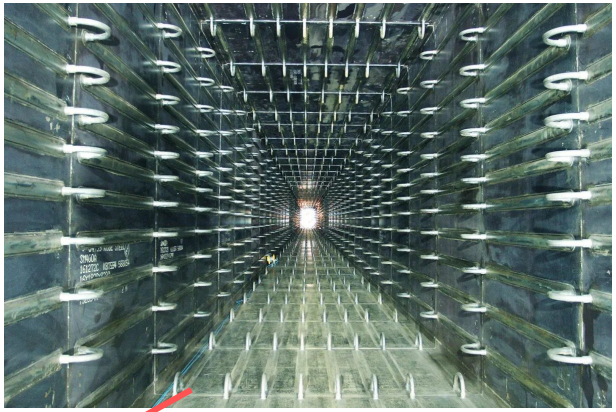
Credit: Higgstan

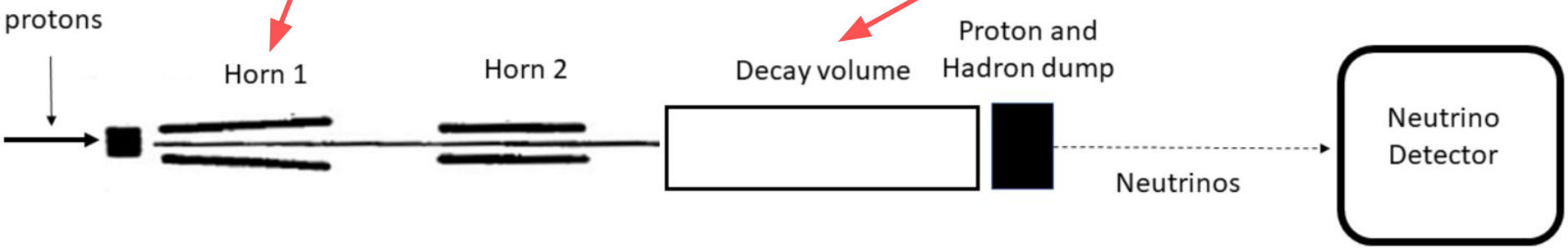
Making Neutrinos

More magnets focus the debris (pions, kaons) from the collision



Focused debris allowed to decay into neutrinos aimed at detectors



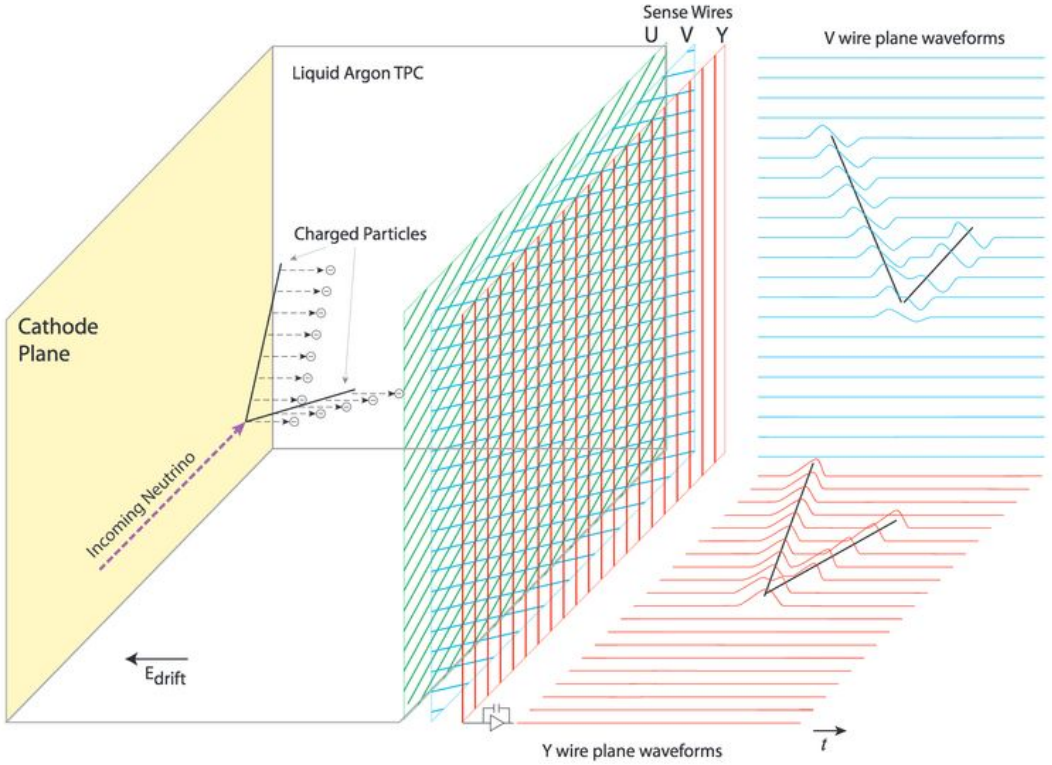


Detecting Neutrinos

In DUNE, we use **liquid argon time projection chambers** (LArTPCs) to detect neutrinos

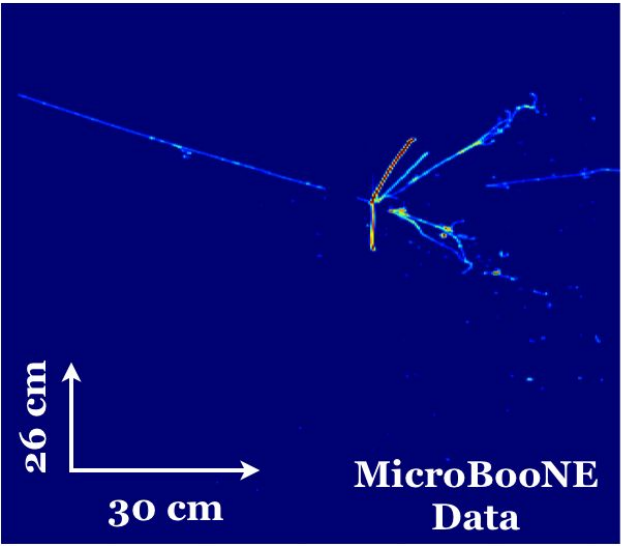
- 100s-1000s of tons of liquid argon (~87 K / –303° F)
- Ultra high purity argon
- Operation at 100,000s of volts

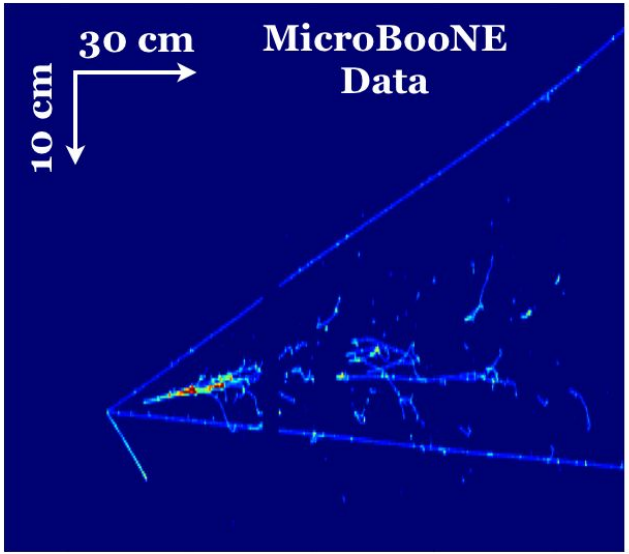
Neutrino signature is a bunch of stuff suddenly appearing in the detector

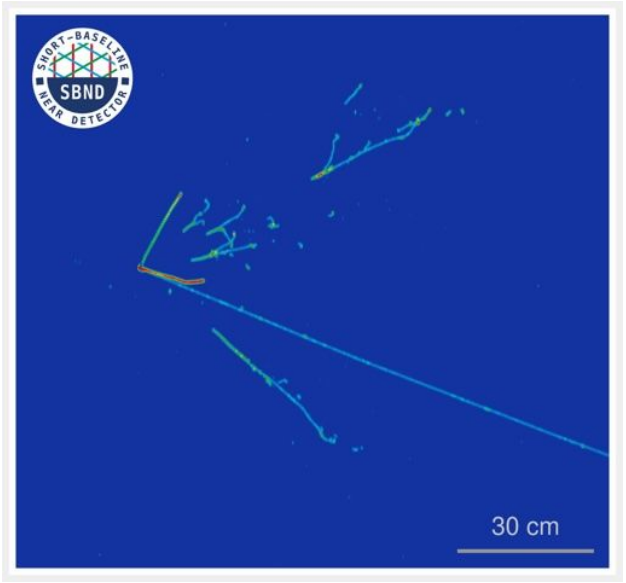


Liquid Argon Time Projection Chambers

Neutrino detections!





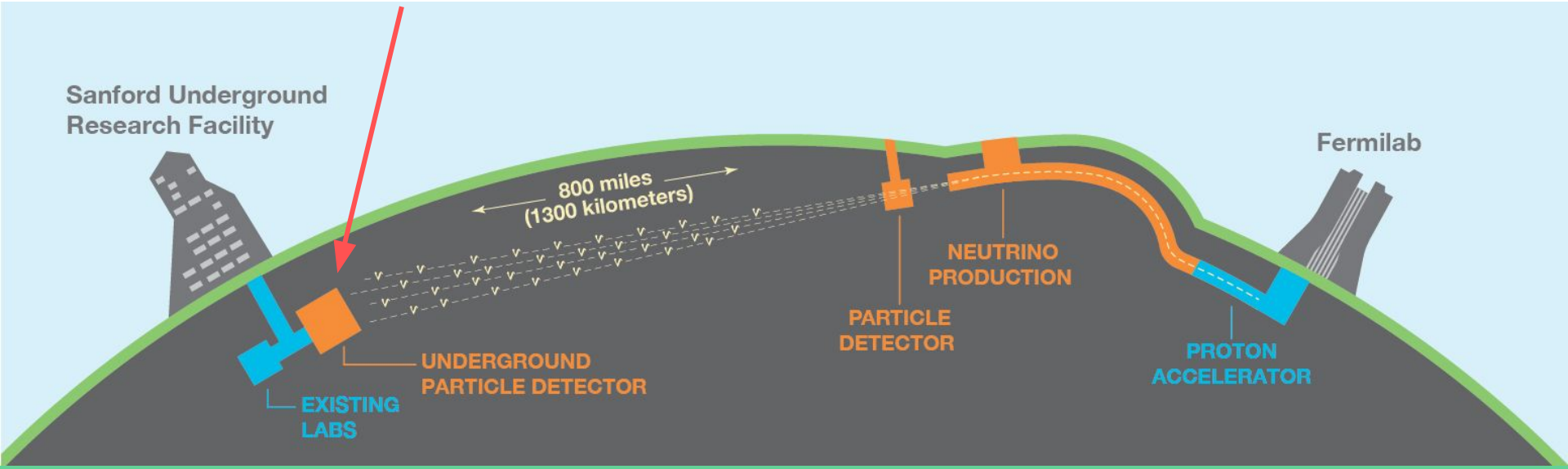


Neutrino beam direction

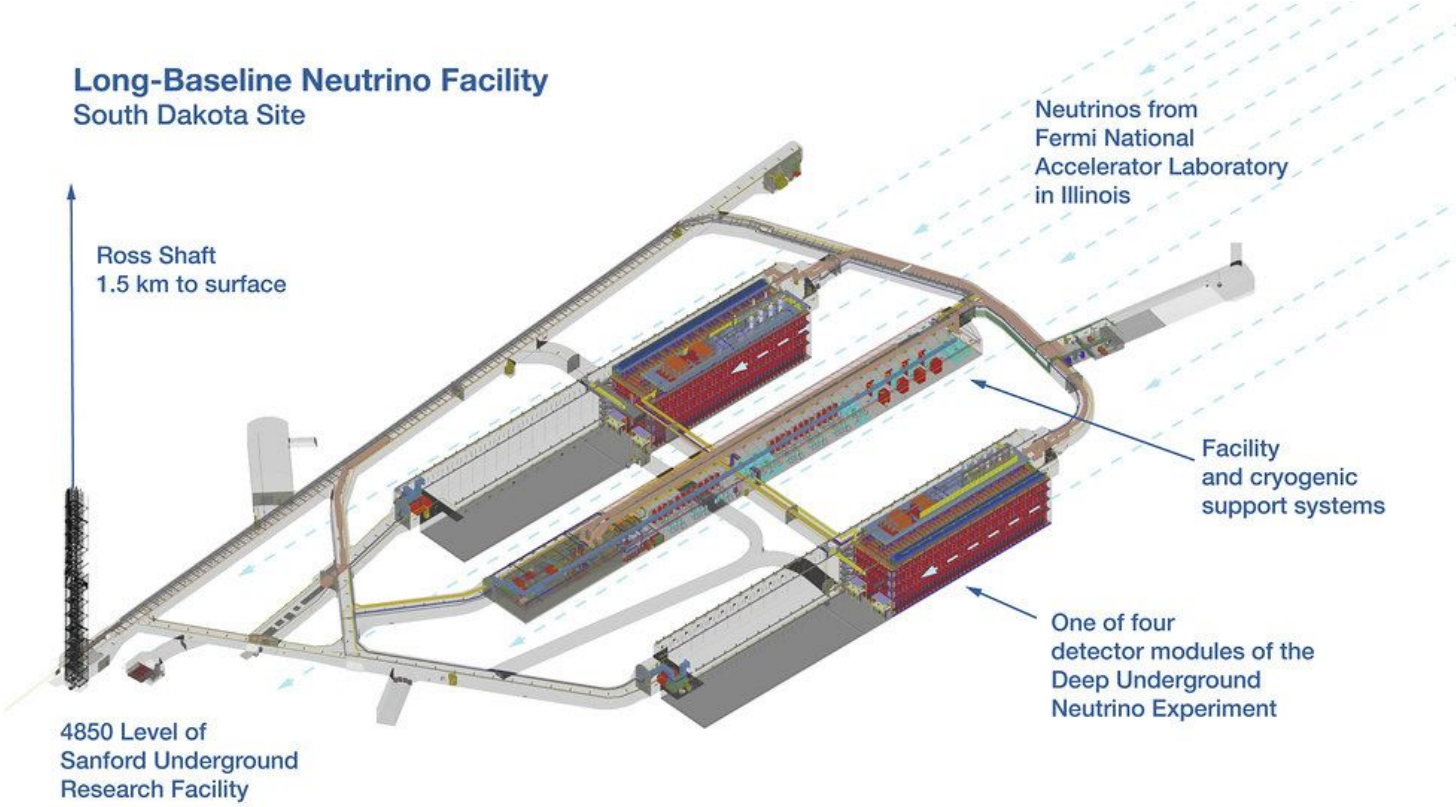
DUNE Far Detectors

Neutrino rates far away from the production point are going to be low

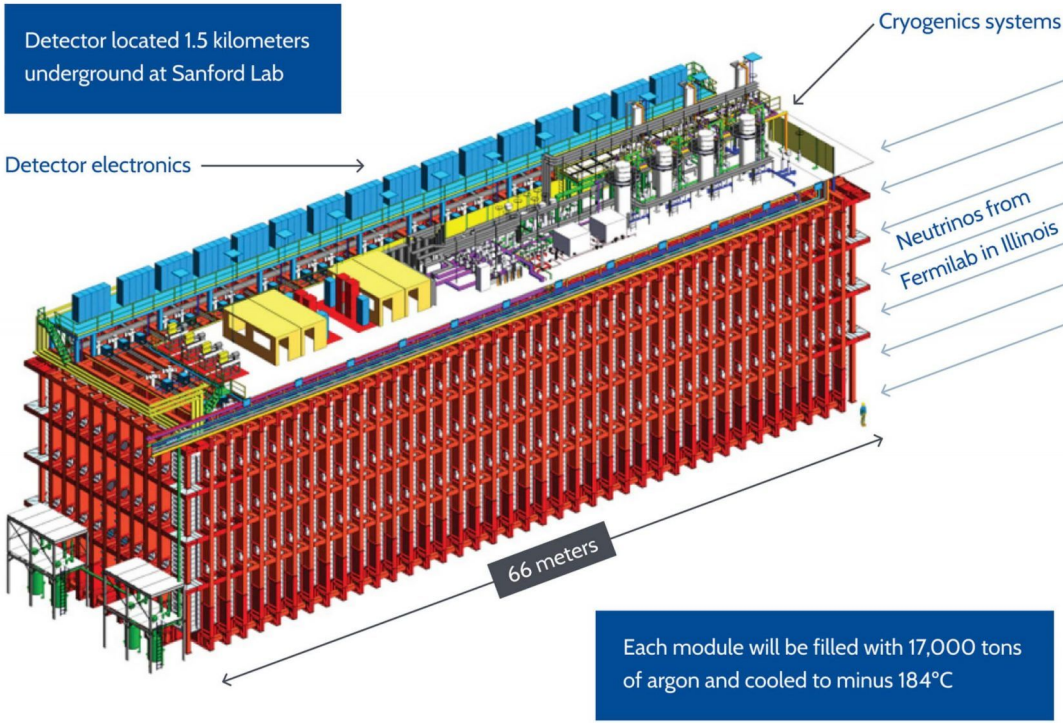
- Big detectors to maximize neutrino interaction probability
- 4850 feet underground to shield against cosmic rays



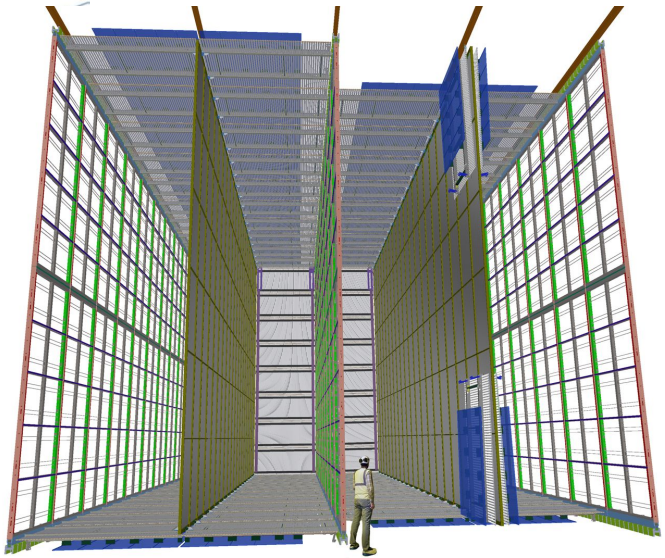
DUNE Far Detectors



DUNE Far Detectors

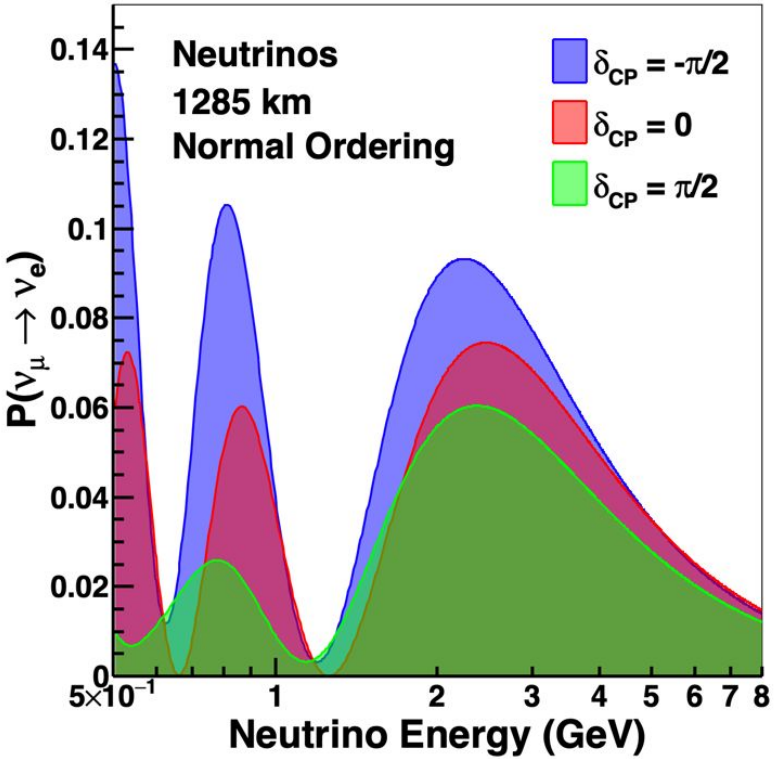


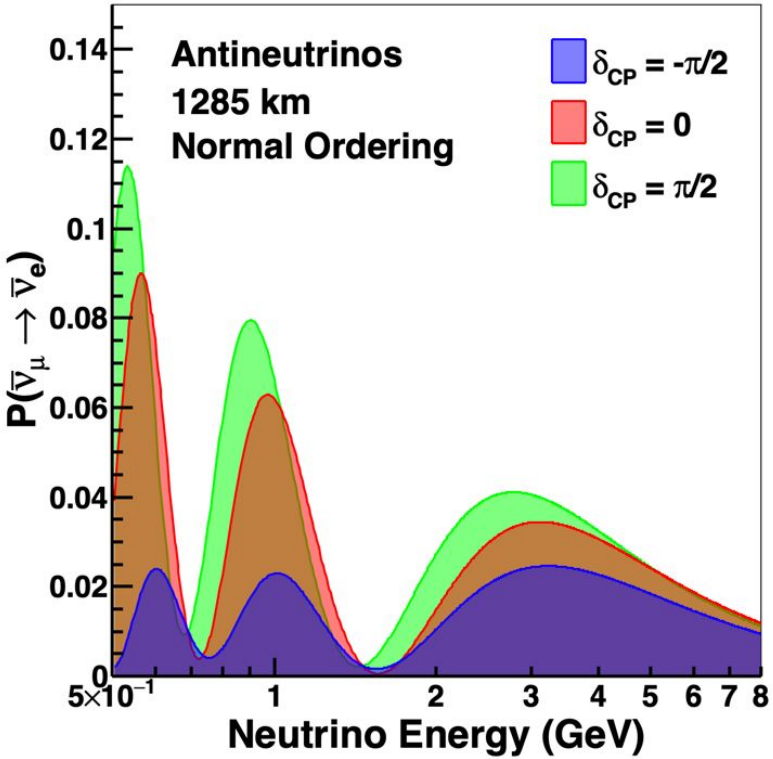
Even with this size, we expect to see ~1 neutrino per day



DUNE Measurement

After many years, use all of the neutrinos we've seen to distinguish between the colors here





DUNE Current Status

We finished digging the giant underground caves in South Dakota

But still a few more years before our detectors are installed down there...

DUNE Prototypes at CERN

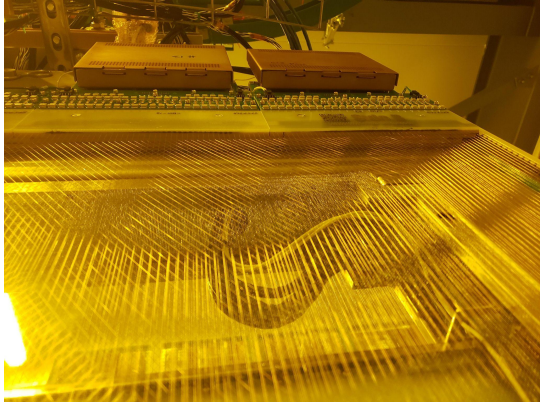
We've been testing the DUNE technologies at smaller scale first at CERN

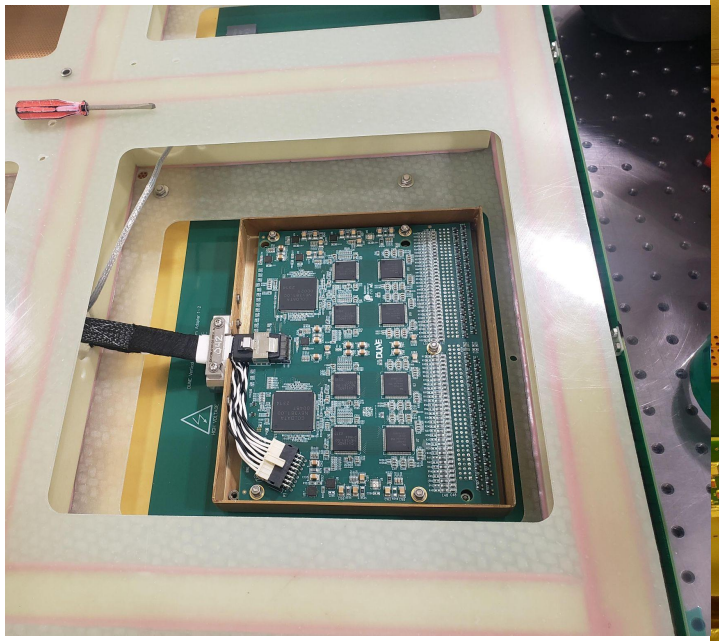
Cryostats holding 800 tons of liquid argon each
(~8 meters per side internally)

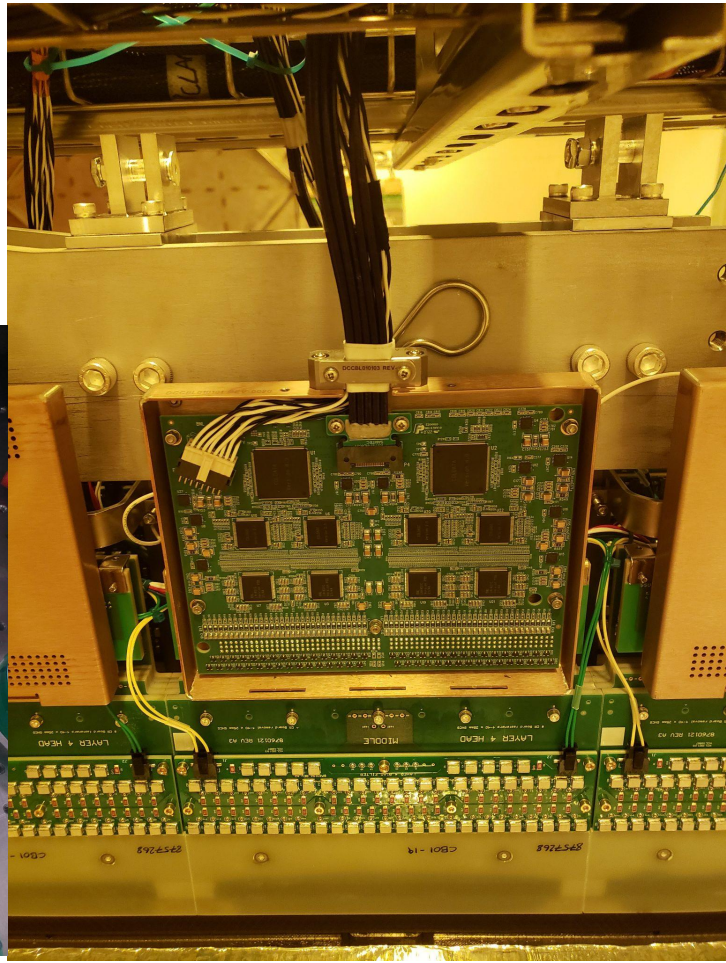
- The full DUNE detectors will contain 17000 tons of liquid argon each!

DUNE Prototypes at CERN

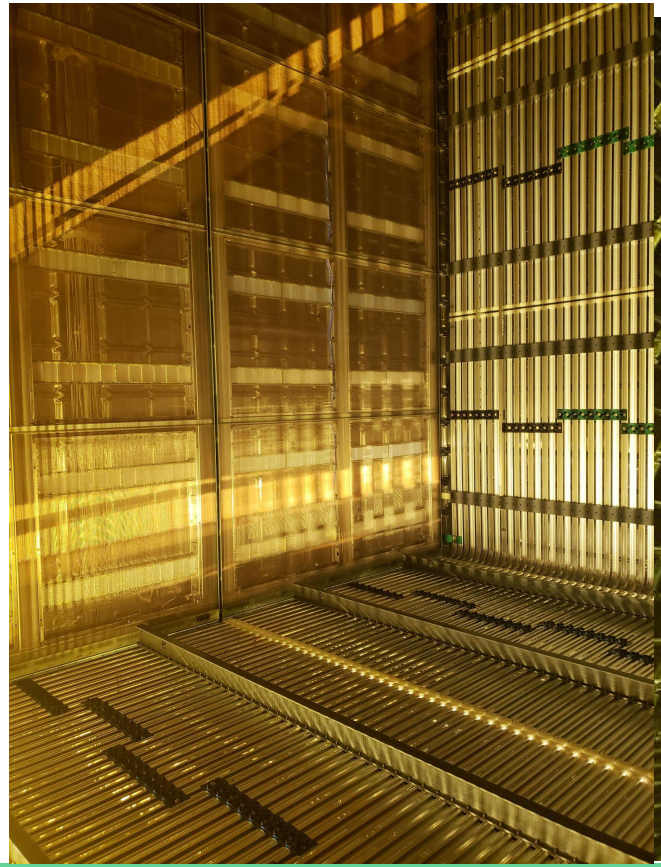
Electronics that work **inside** liquid argon (~87 K) to read out the detector signals

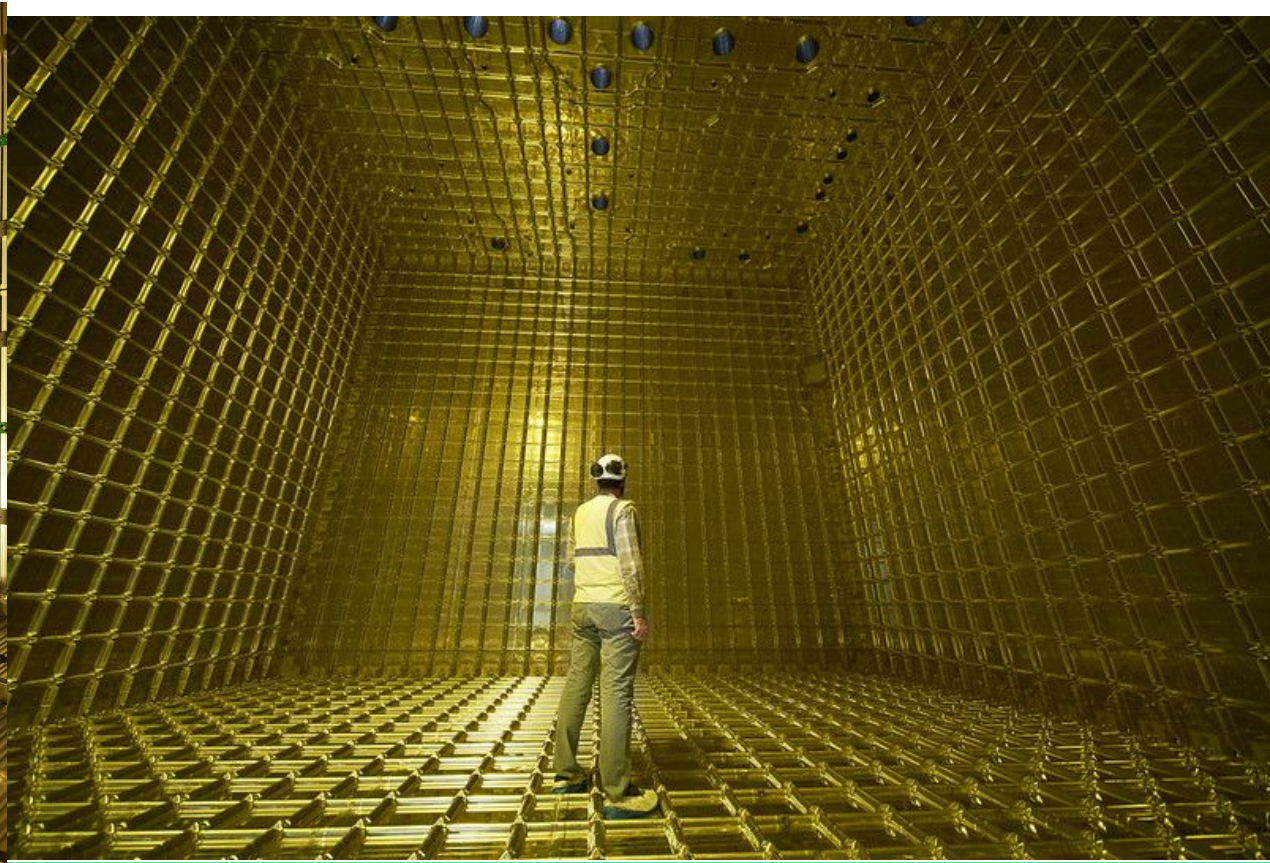




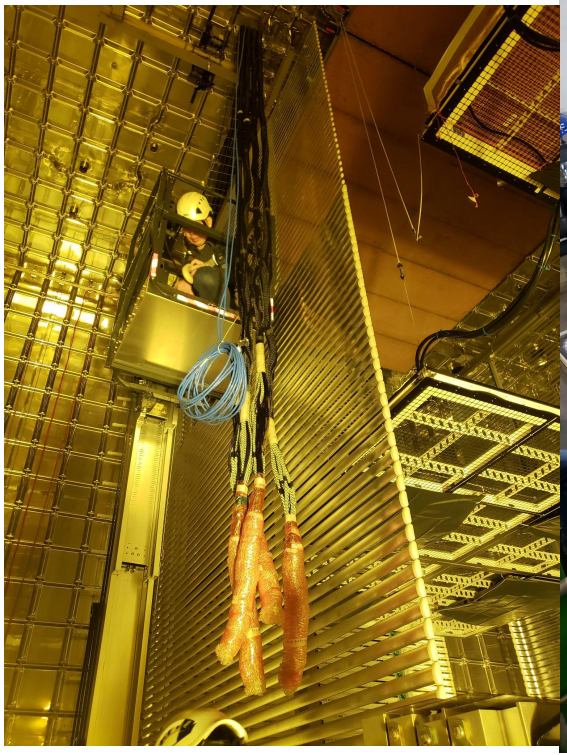


DUNE Prototypes at CERN





DUNE Prototypes at CERN



Summary

There are still a lot of open questions in fundamental physics

- Neutrinos have surprised us before, and they may surprise us again if we look closely enough
- I chose to focus on neutrino physics, but we're quite interconnected with other fields using other methods

Many different aspects to work on, depending on your interests!

- Designing detectors and electronics to operate them
- How to physically build the experiment
- Data processing for what comes out of the experiment
- Analyzing data to connect to the underlying theories

Thank You!