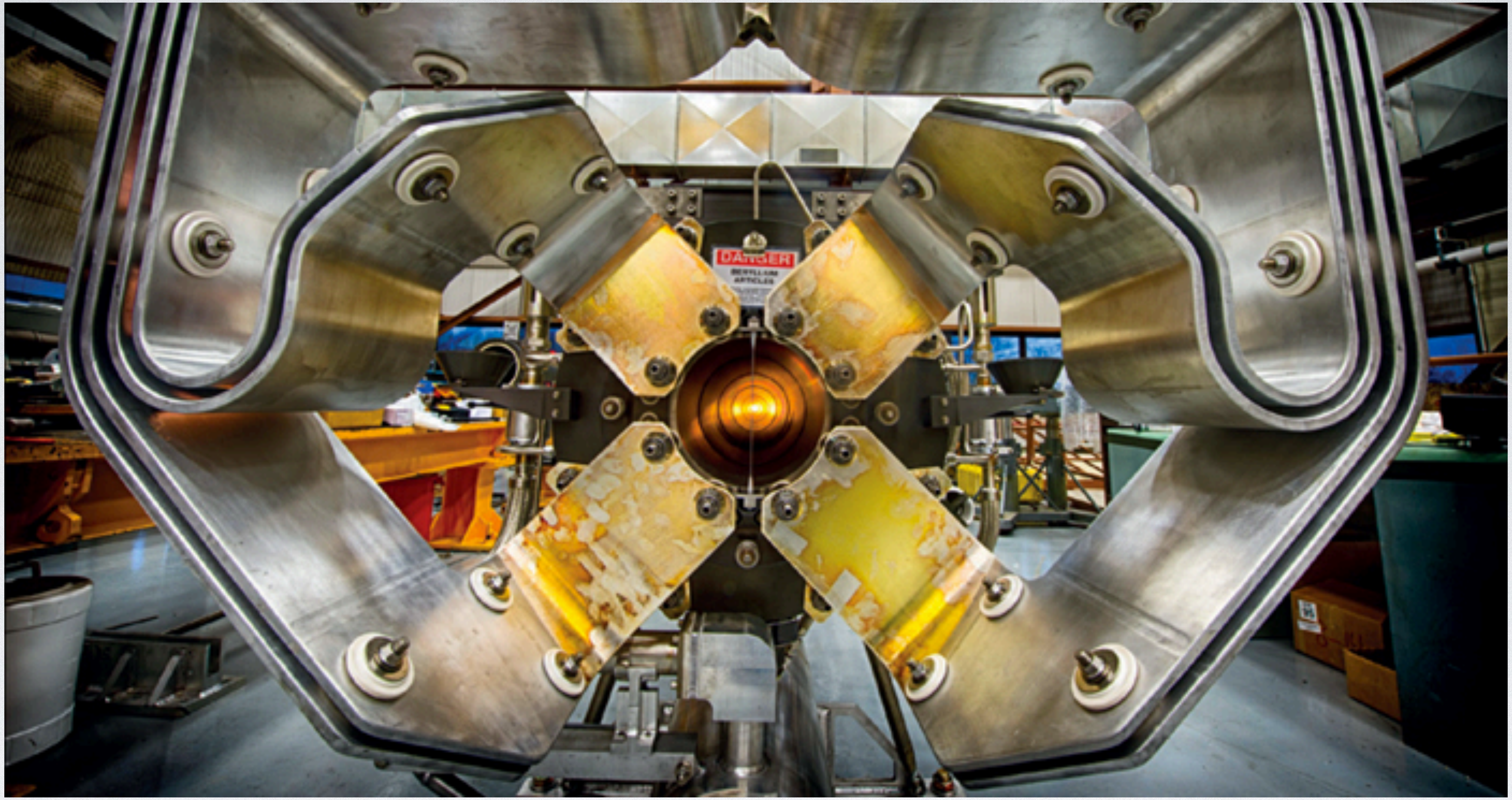
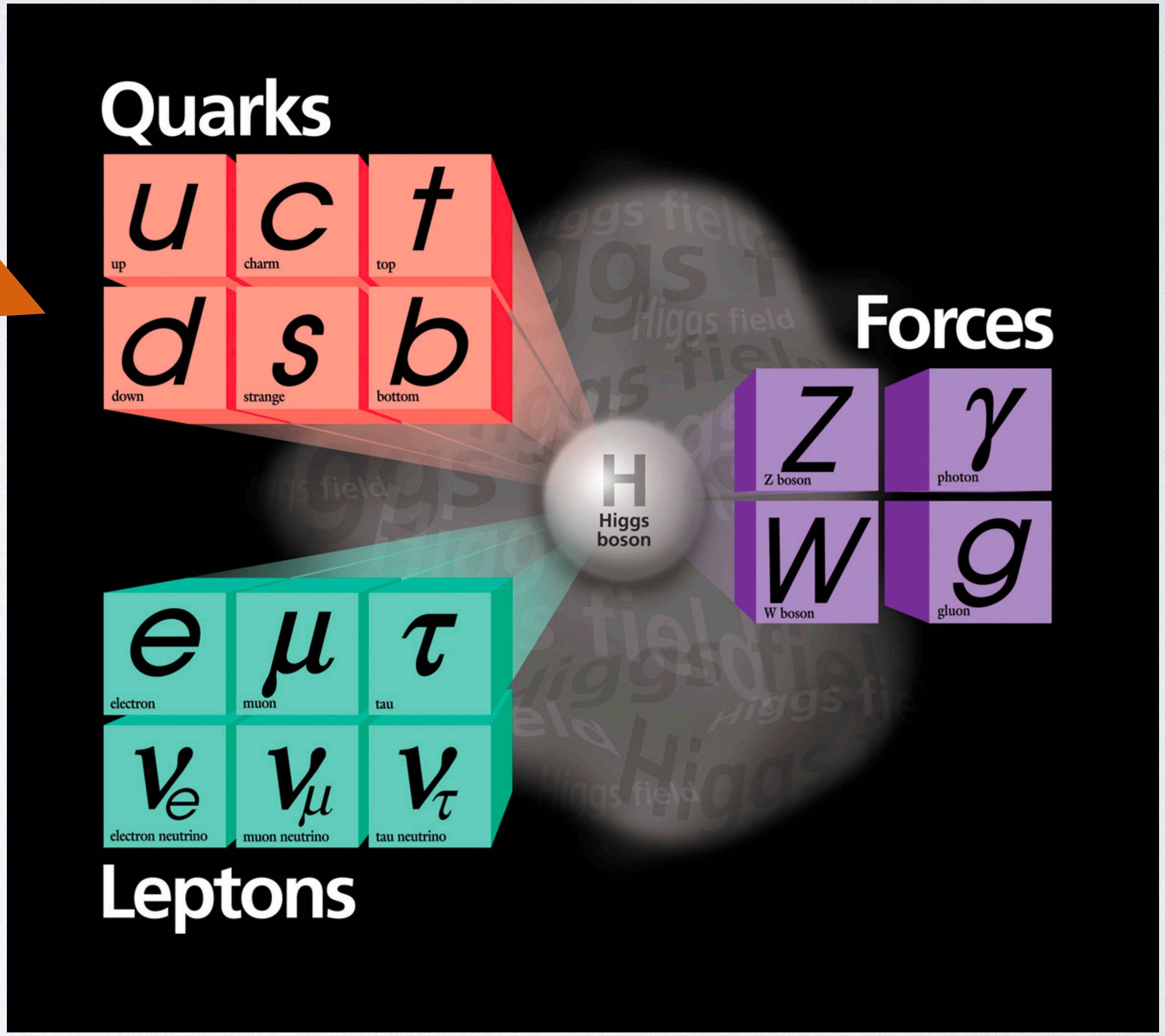

Reidar Hahn, Fermilab

INTRO TO NEUTRINOS

Laura Fields, University of Notre Dame
Quarknet 2022

PARTICLE PHYSICS: WHAT WE KNOW

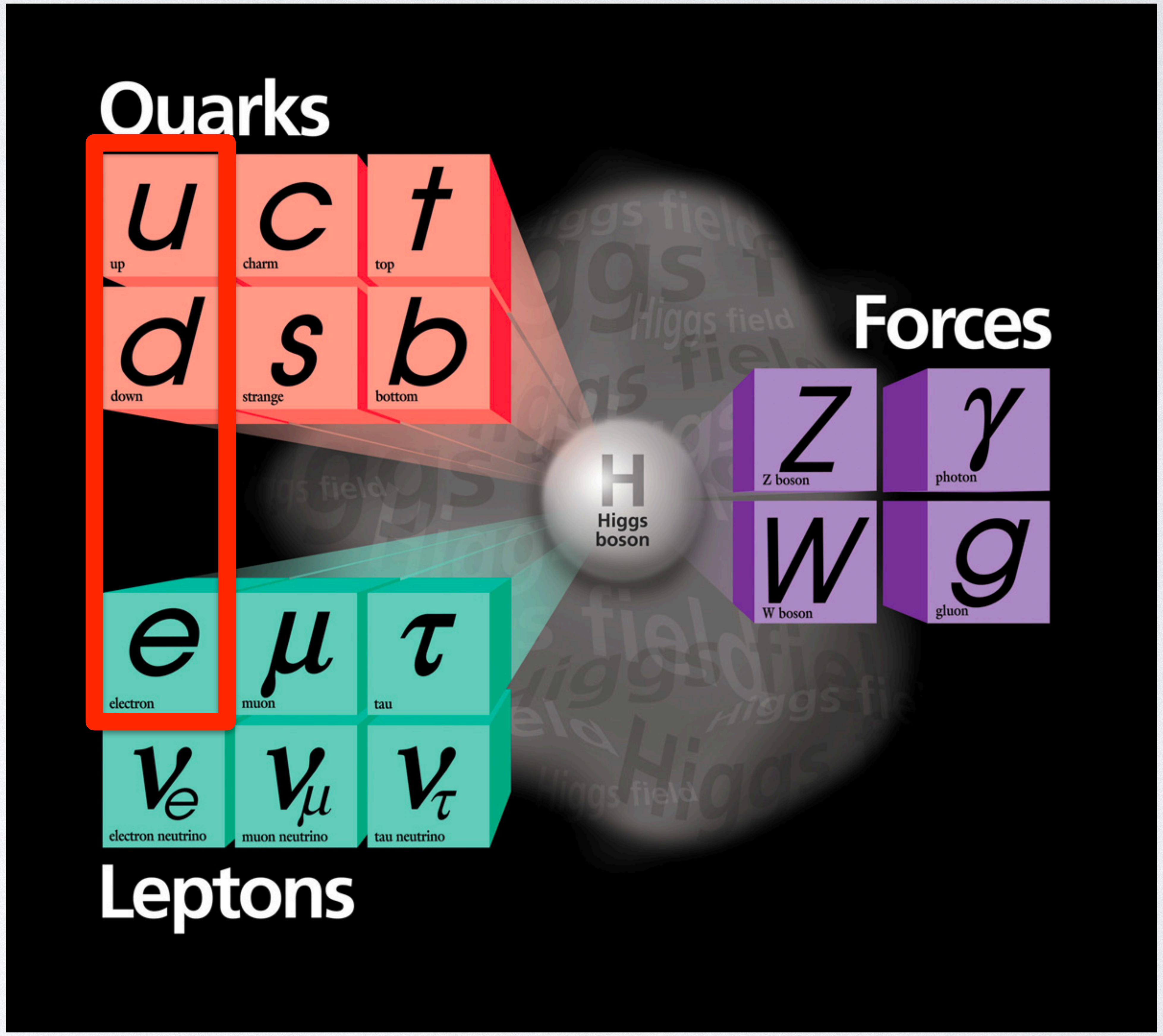
- This figure summarizes **particle physicist's view of the universe,** aka the Standard Model
- We think there are **17 fundamental particles** (although we are working hard to find more)



Question: how many of these actually make up the matter around us?

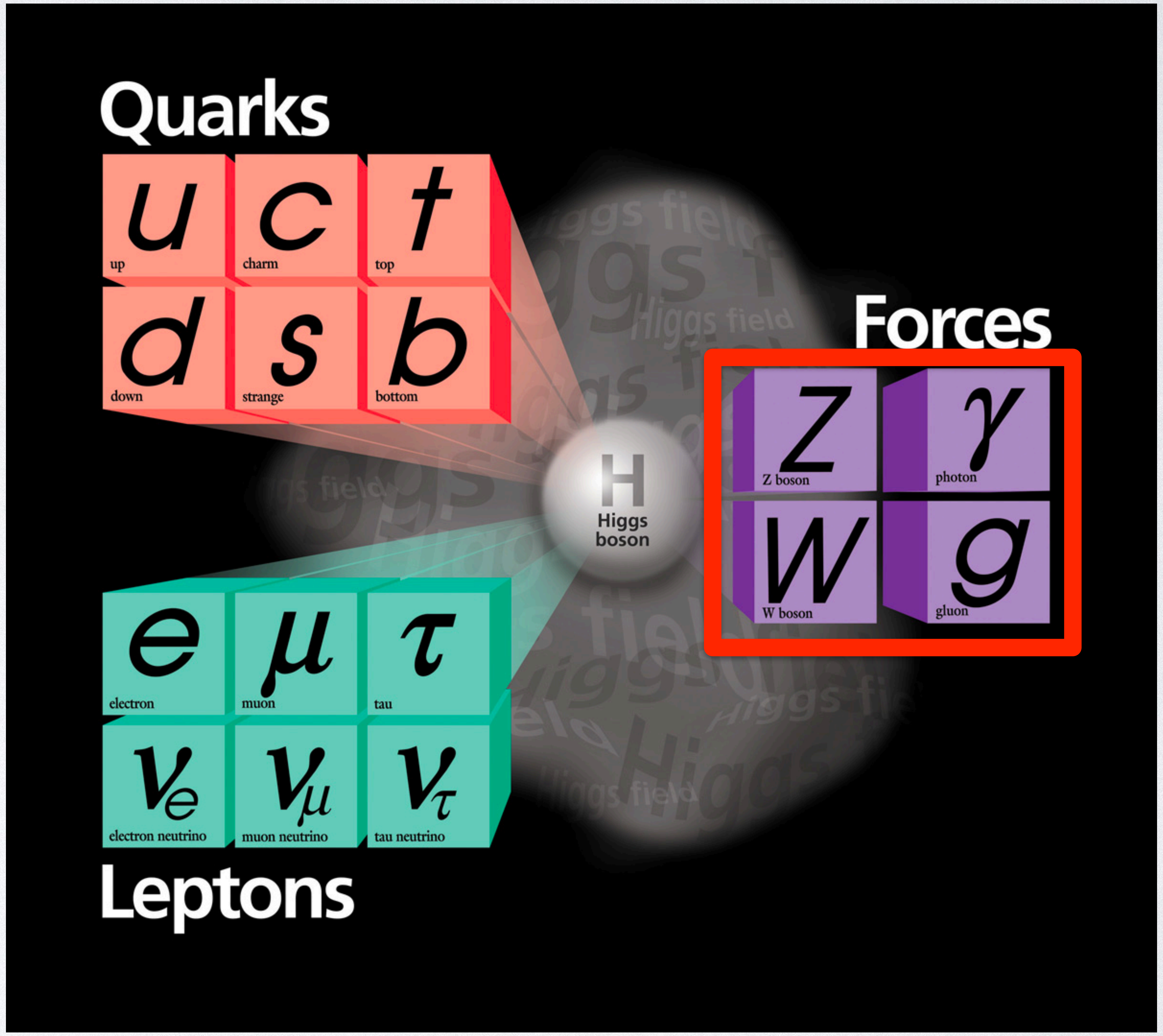
PARTICLE PHYSICS: WHAT WE KNOW

- Weirdly, you, me and the entire world around us are **made mainly of just three** of those particles
  - Up and down quarks, which form the nuclei of atoms
  - Electrons, which orbit the nuclei of atoms



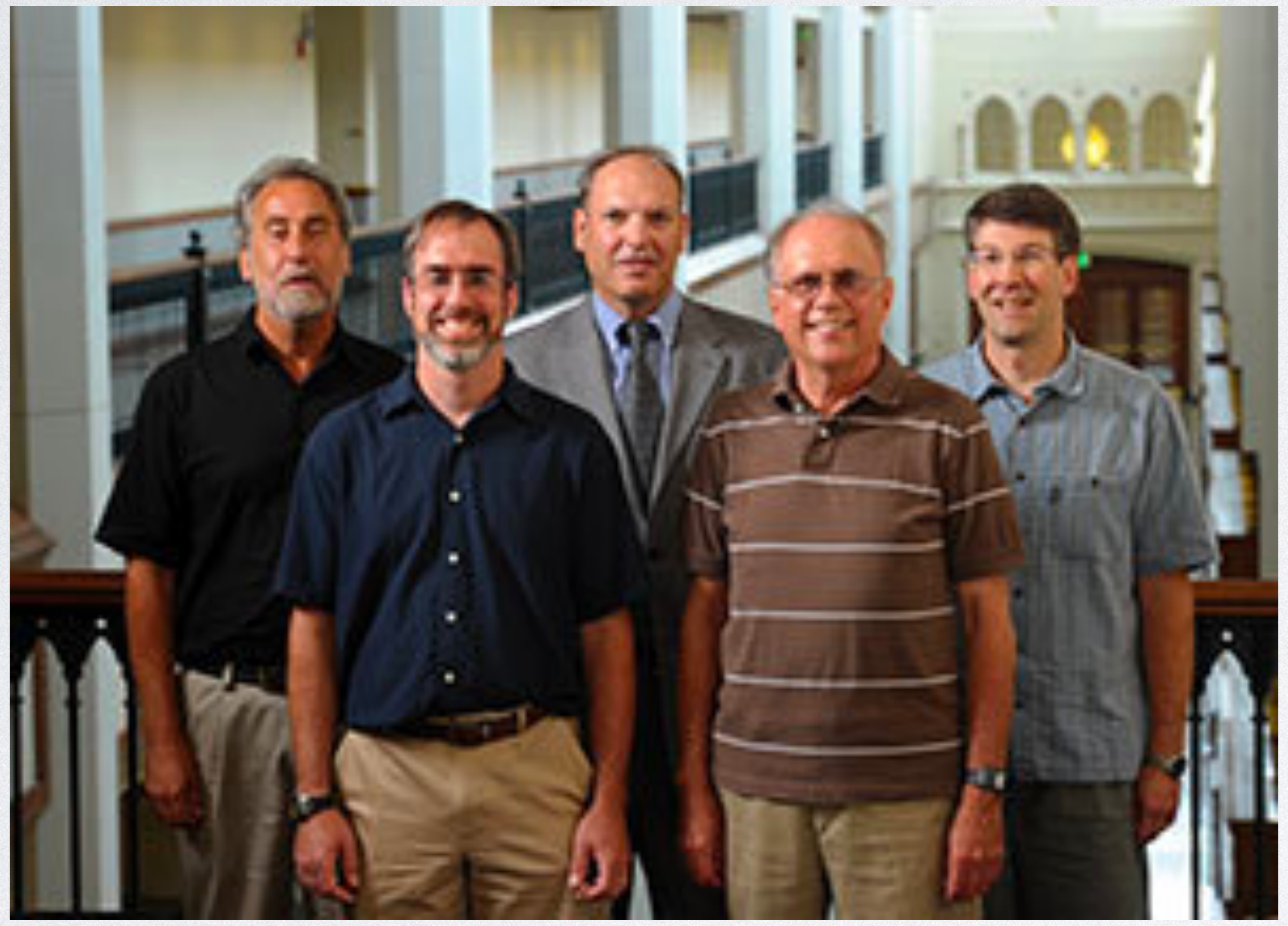
PARTICLE PHYSICS: WHAT WE KNOW

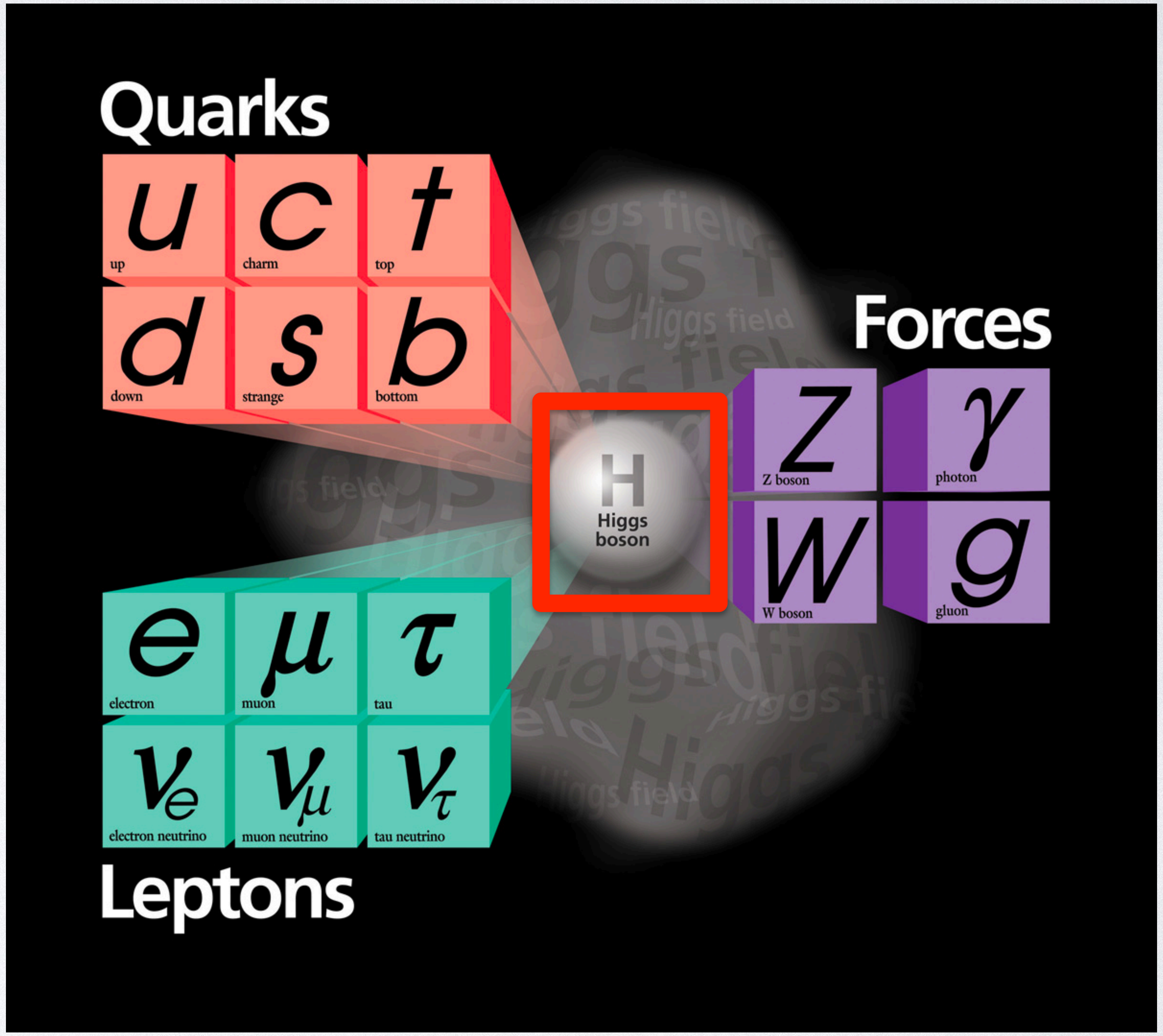
- There are four particles that help the particles we are made of **interact with each other**
  - The **photon** for the electromagnetic force
  - The **W and Z bosons** for the weak nuclear force
  - **Gluons** for the strong nuclear force
  - (Particle physicists generally pretend **gravity does not exist**!)



PARTICLE PHYSICS: WHAT WE KNOW

- Interactions with another particle, **the Higgs Boson**, is how particles become massive

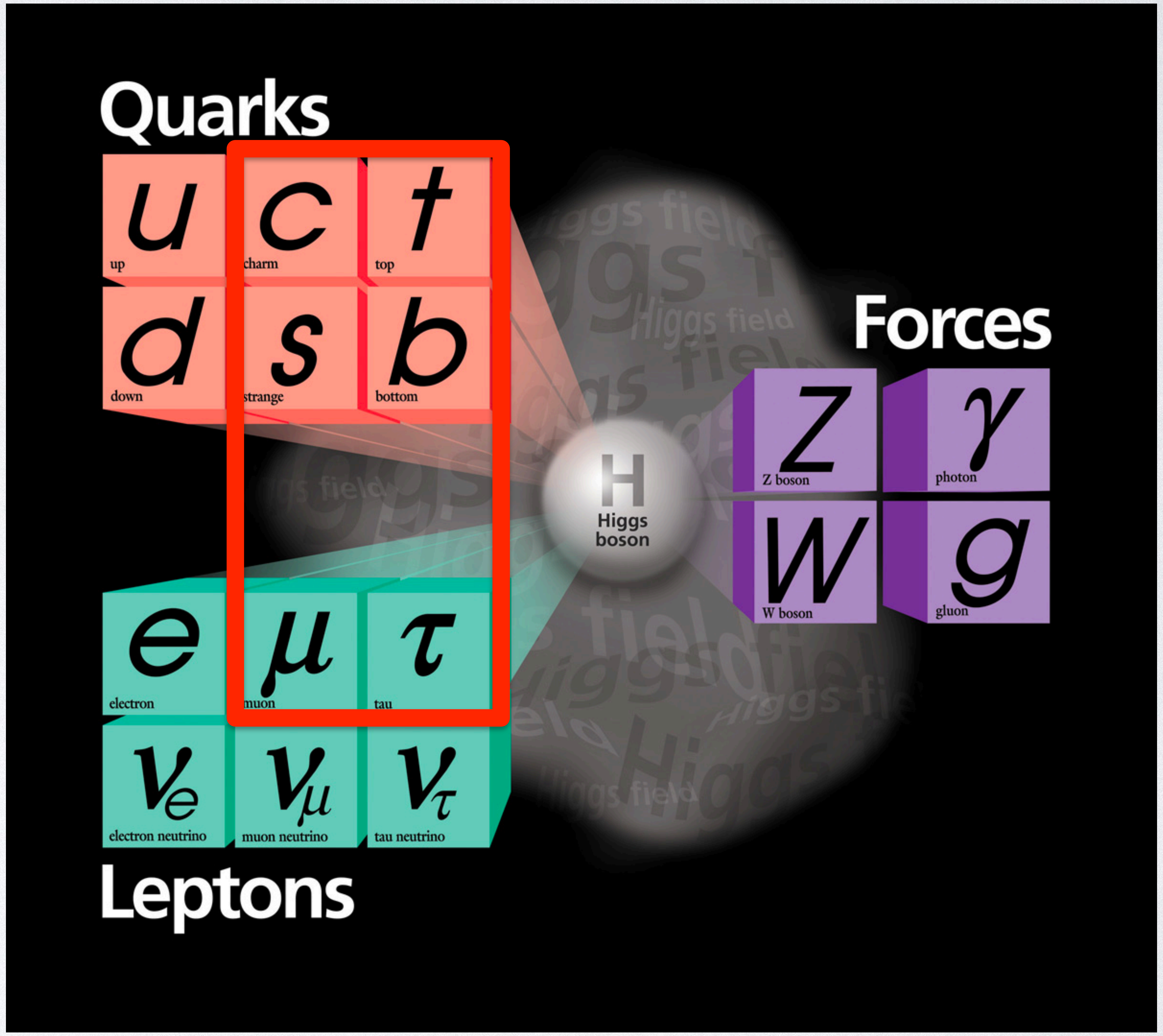




- My colleagues in the **HEP group at Notre Dame helped discover the Higgs** and continue to study its properties

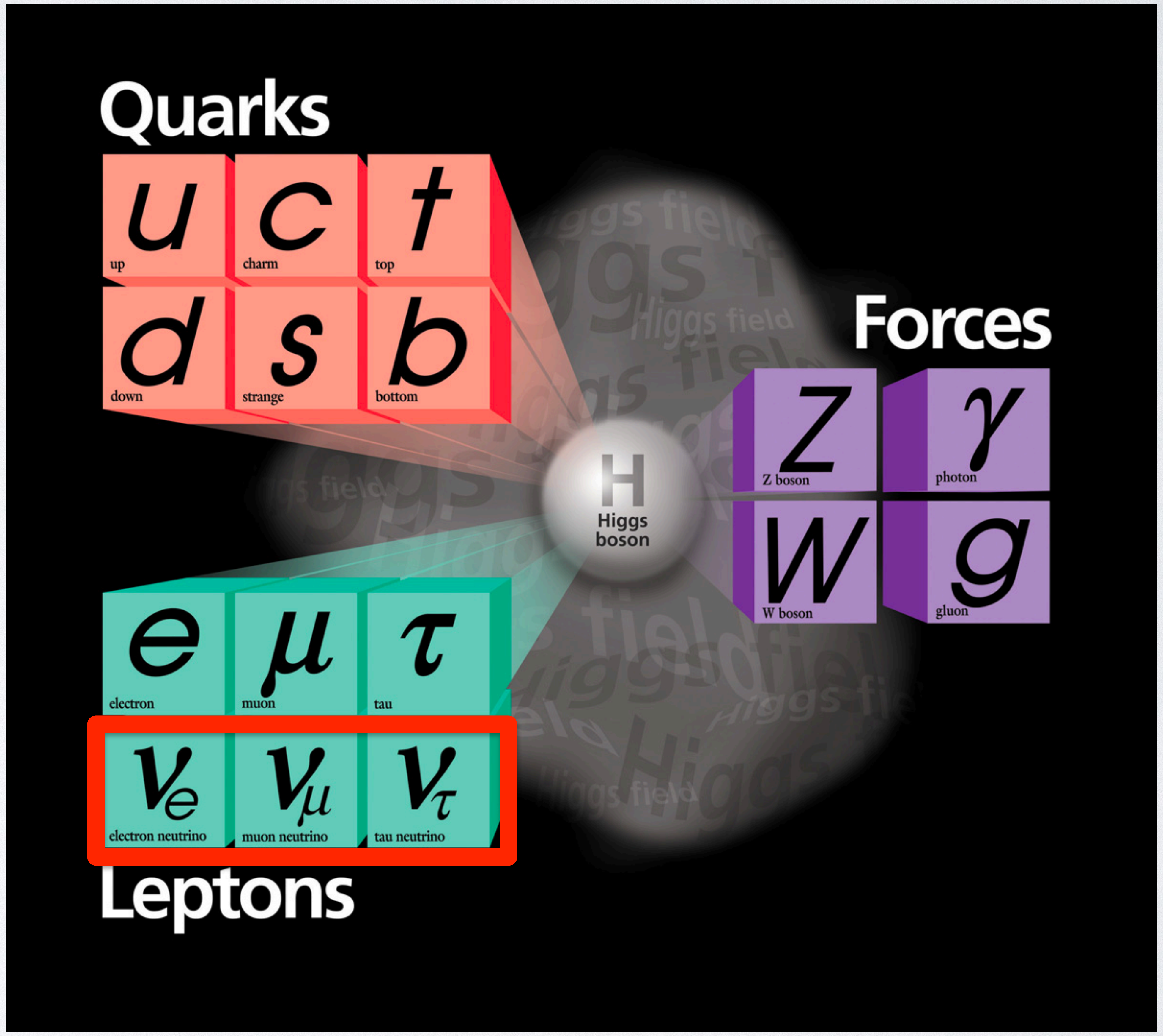
PARTICLE PHYSICS: WHAT WE KNOW

- Moving on in our tour of the Standard model, the up and down quarks and electrons all have **heavier sister particles**
- We have **no idea why** these extra particles exist!
  - Why these particles exist and have the characteristics they do is a big question in high energy physics!



NEUTRINOS: WHAT WE KNOW

- And finally, the electron and its sister particles (the muon and tau) **each has a partner neutrino**
- A neutrino gets made every time an electron, muon, or tau is made
- But they don't decay and **hardly ever interact, so they just float through the universe unimpeded**



NEUTRINOS: WHAT WE KNOW

- Neutrinos created in the sun, the Earth, the Big Bang, cosmic supernovae, nuclear reactors, bananas, etc are **flowing through you all the time**

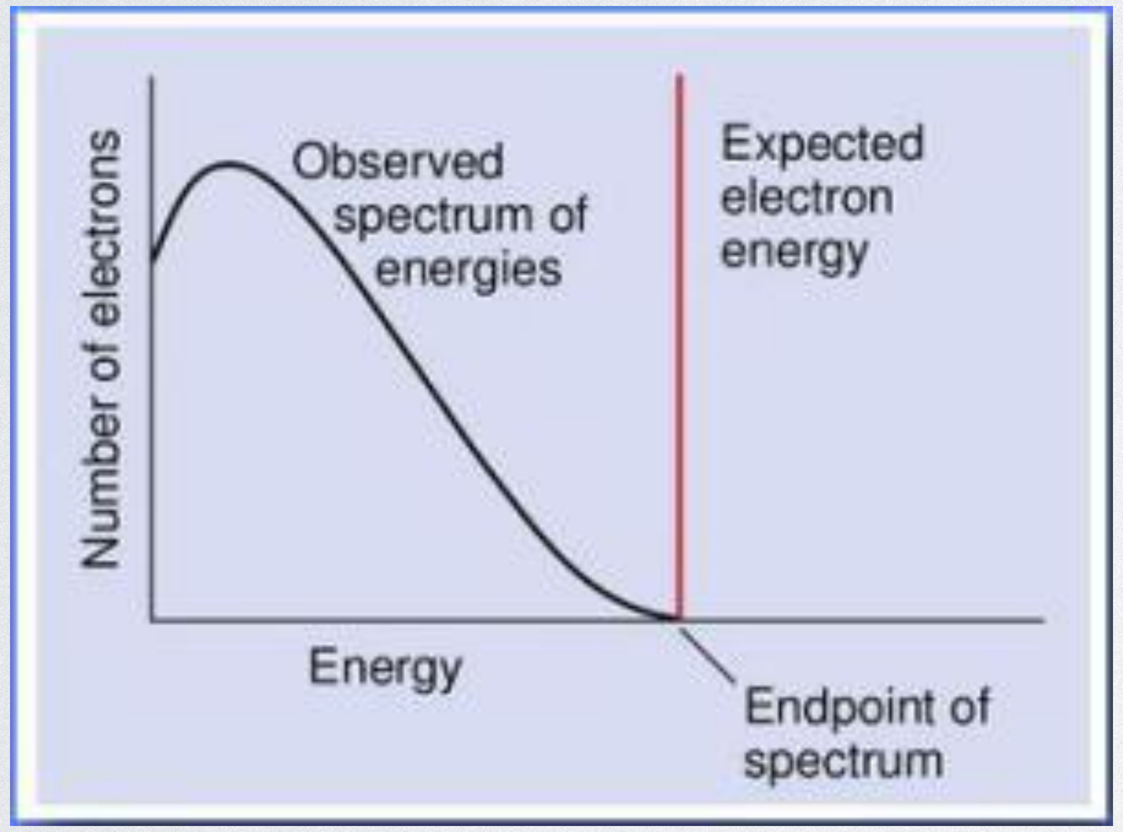
- **Billions and billions** of them, but they almost never interact — we are walking through **a ghost universe**

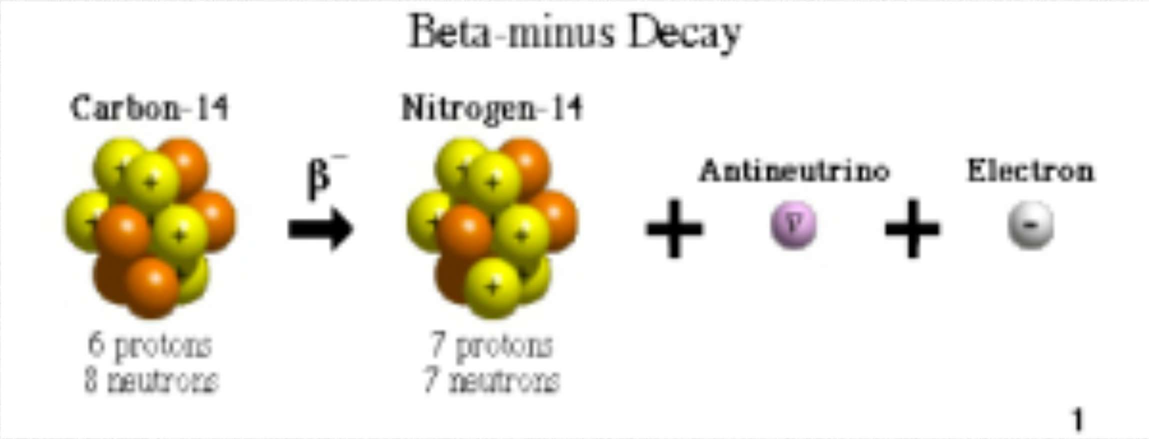
- You could choose to be afraid, like this cat, but I view it as an exciting **opportunity to learn about our universe**

NEUTRINOS: HOW DID WE GET THIS FAR?

NEUTRINOS:FIRST BIG QUESTION

- Neutrinos were first hypothesized by Wolfgang Pauli in 1930 to **explain the apparent non-conservation of energy in radioactive decays** (first observed by James Chadwick):

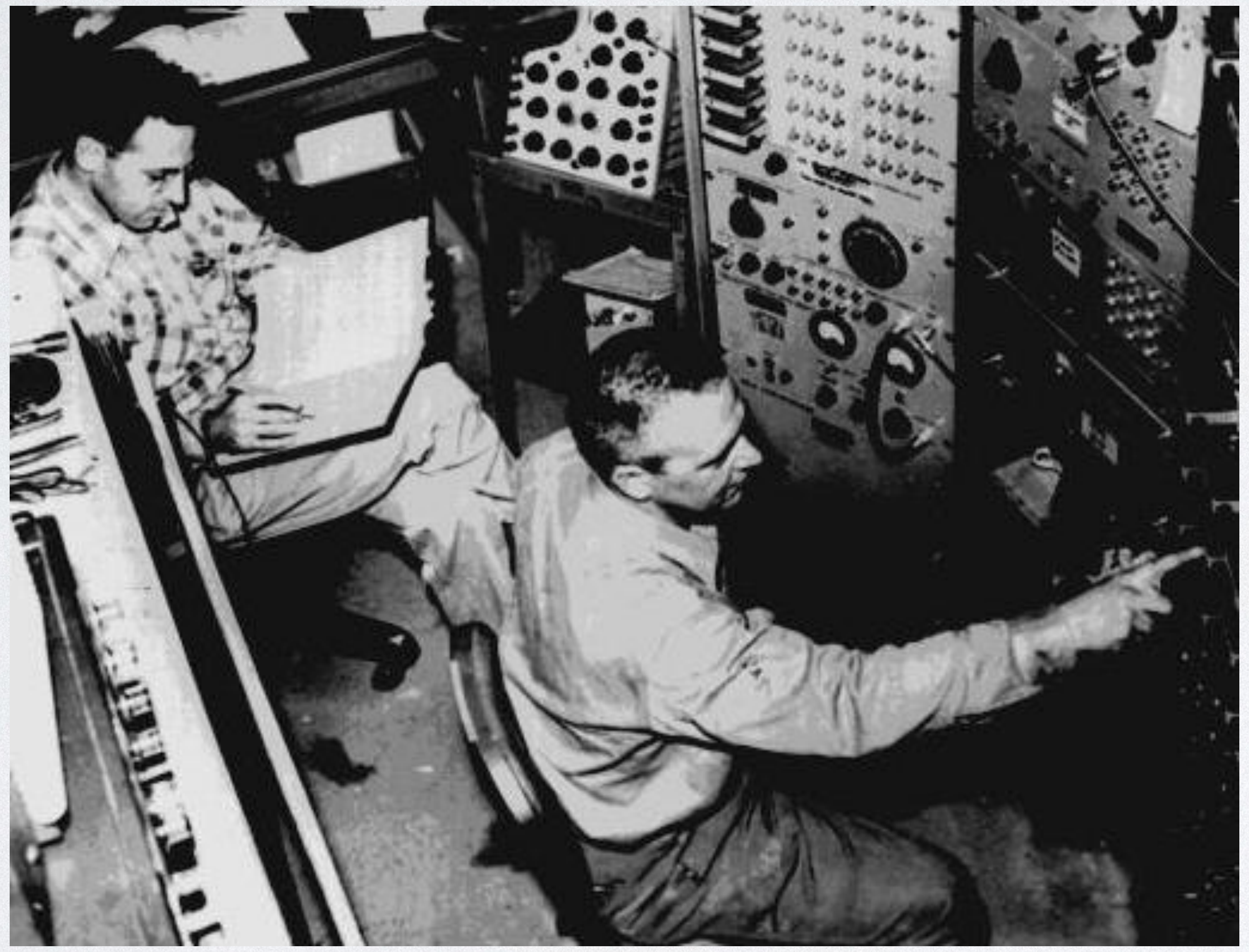




Neutrino = "Little Neutral One" in Italian

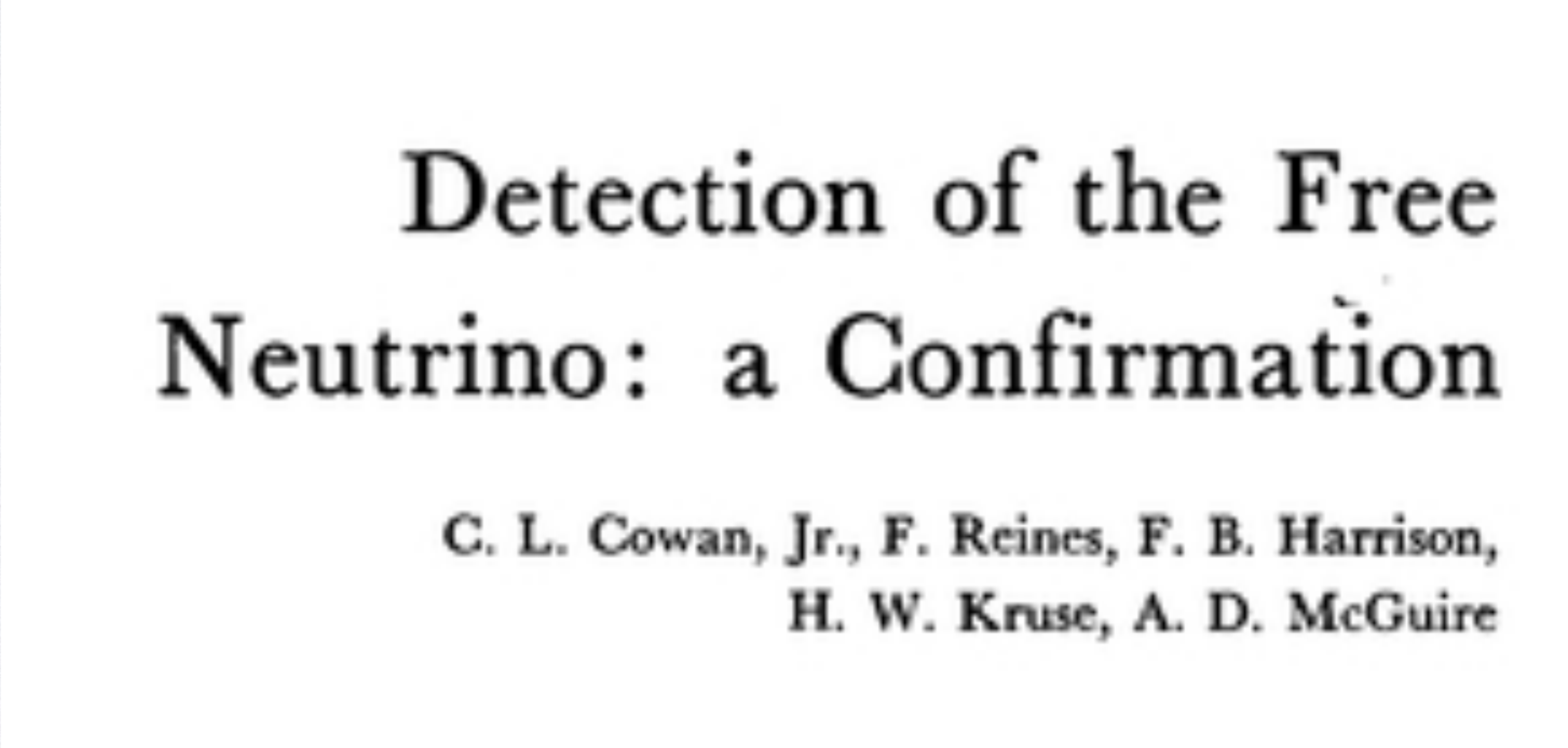
FIRST DETECTION

- Luckily, Pauli was wrong about neutrinos being undetectable: they were **first observed in 1956 at the Savannah River nuclear reactor** in South Carolina:



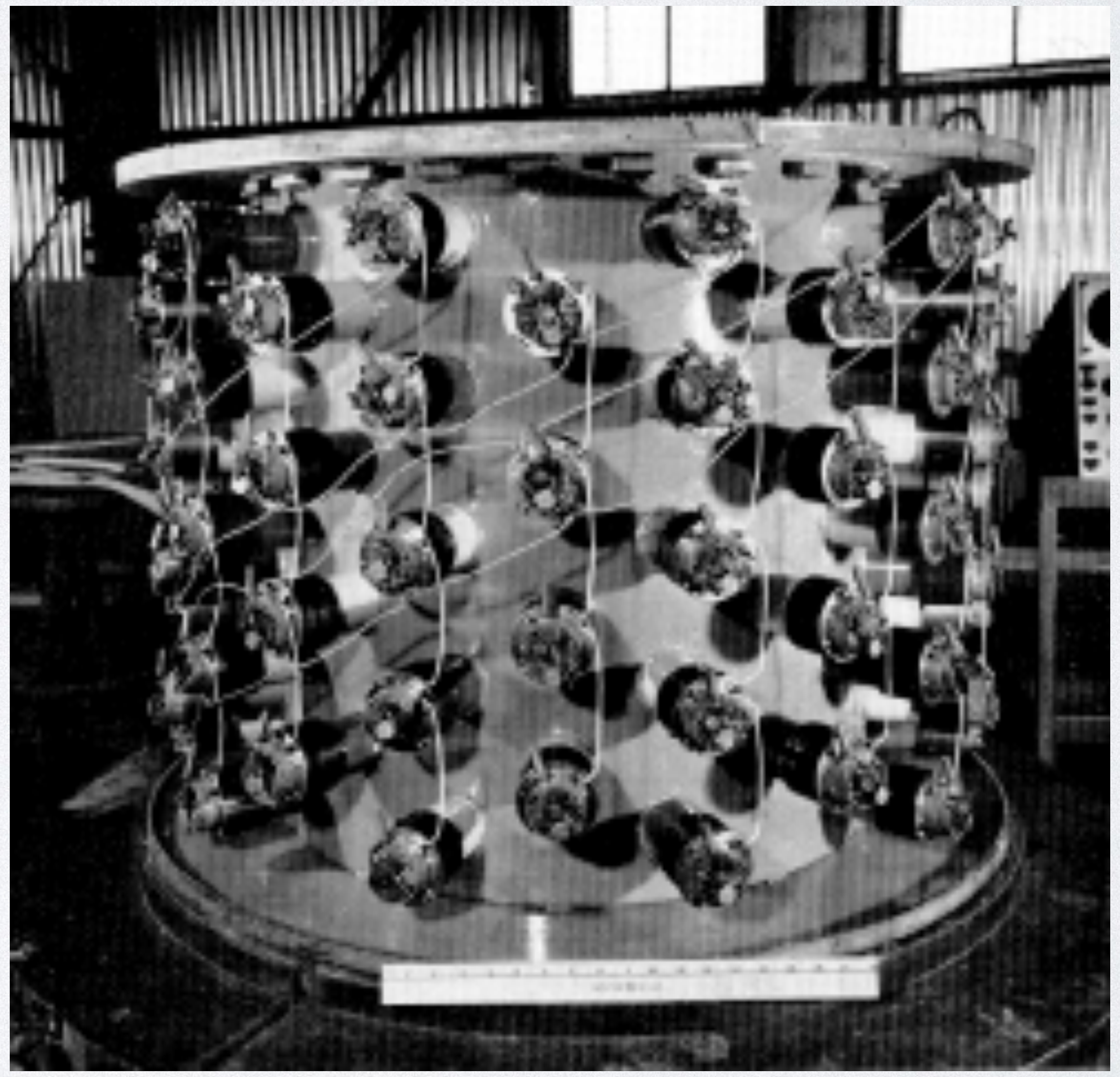
- $\bar{\nu}_e + p \rightarrow n + e^+$

Both particles produce light
→ signal was coincident blips of light



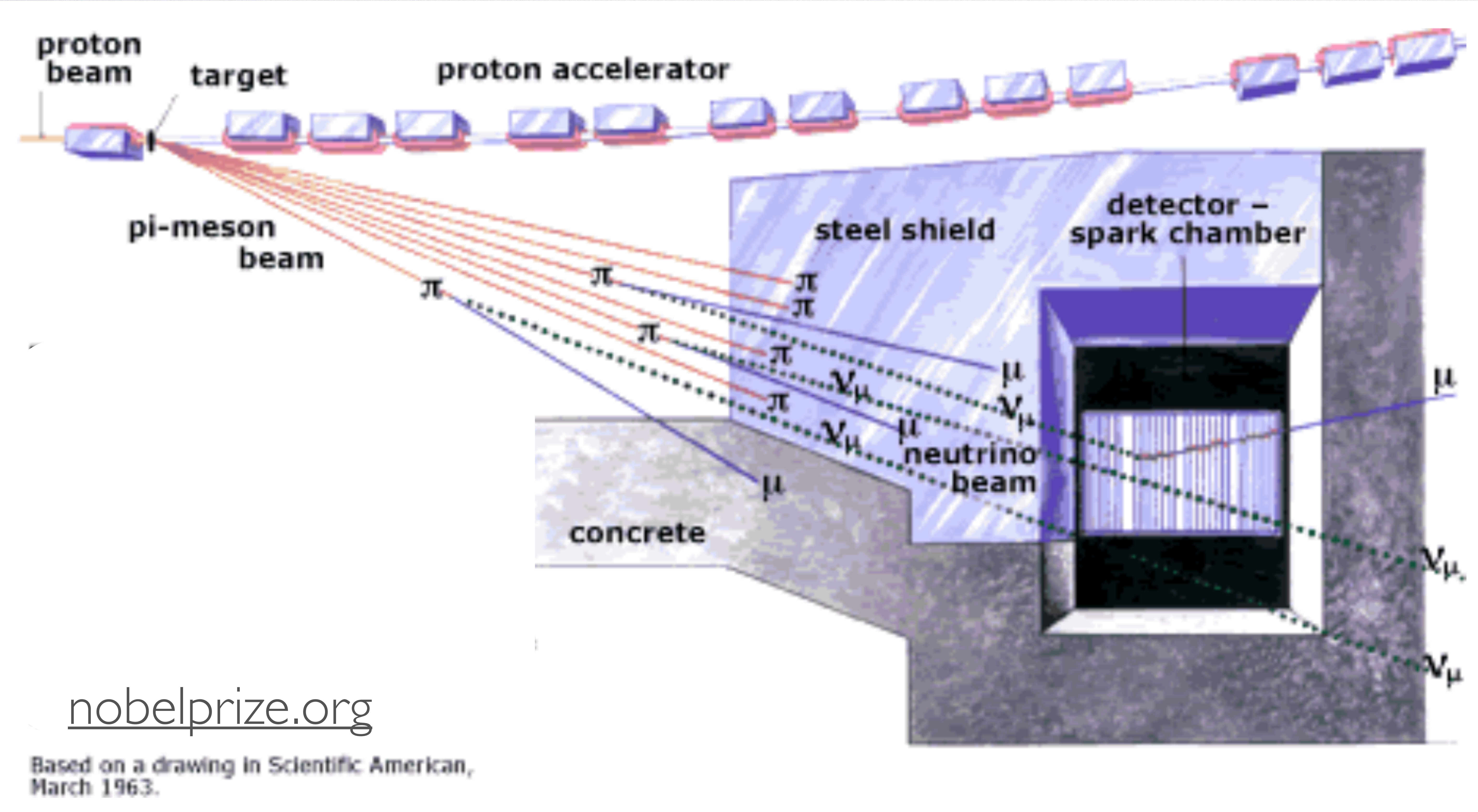
Detection of the Free Neutrino: a Confirmation

C. L. Cowan, Jr., F. Reines, F. B. Harrison, H. W. Kruse, A. D. McGuire



← **A big tank of water! You'll see this is a theme in Neutrino Physics**

MORE THAN ONE FLAVOR



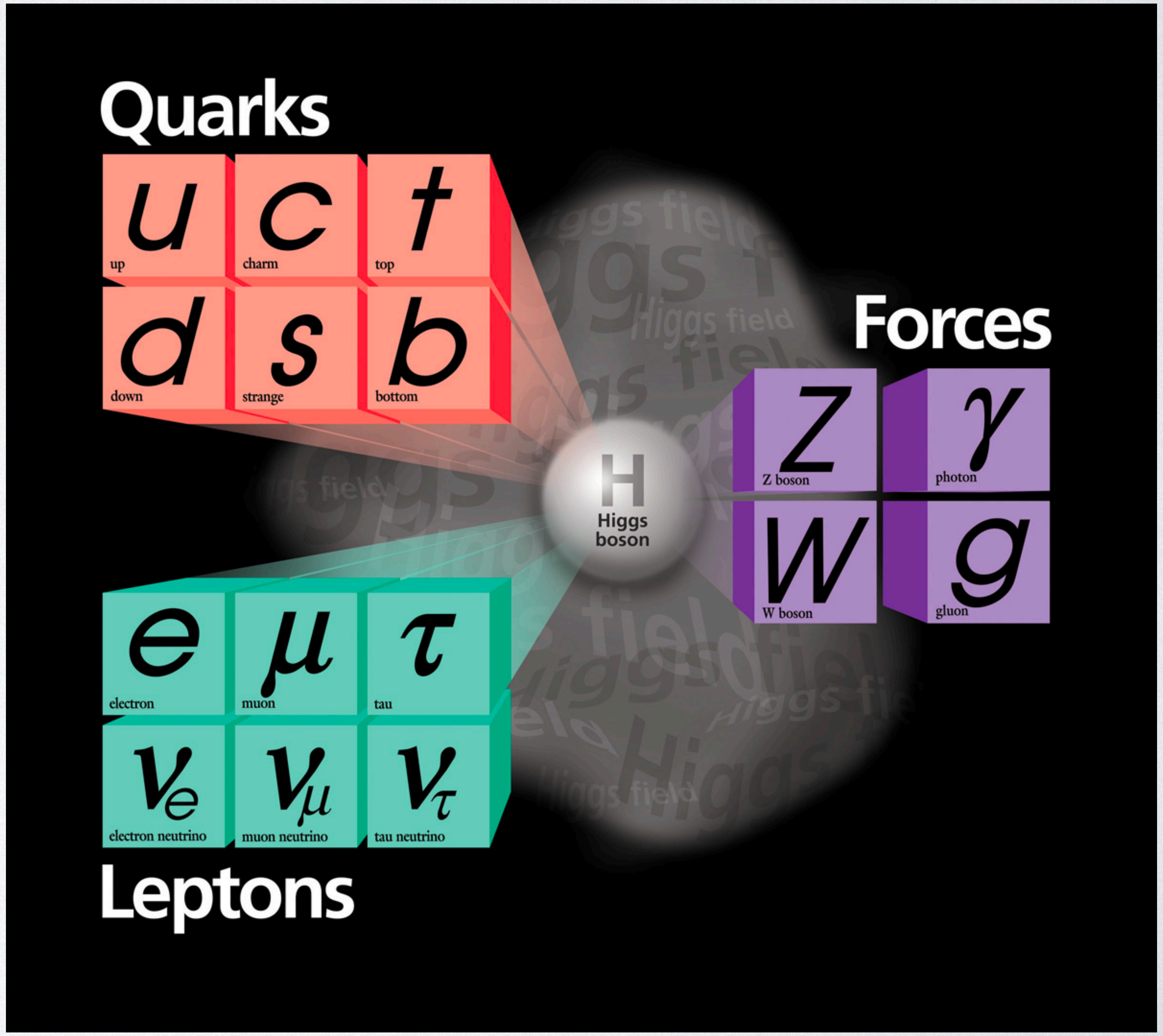
nobelprize.org

Based on a drawing in Scientific American, March 1963.

- In 1966, an experiment at Brookhaven National Lab (in upstate NY) discovered a second kind of neutrino — the muon neutrino.
  - Known to be a muon neutrino because it made a muon when it interacted
- The neutrino discovered at Savannah river made an *electron* when it interacted

NEUTRINOS IN THE STANDARD MODEL

- All of this led to the inclusion of **neutrinos in the standard model** of particle physics:
  - **Three neutrinos** and three antineutrinos
  - Electrically neutral — Interact only via the **weak force**, which means they interact very rarely
  - Originally, they were **massless**

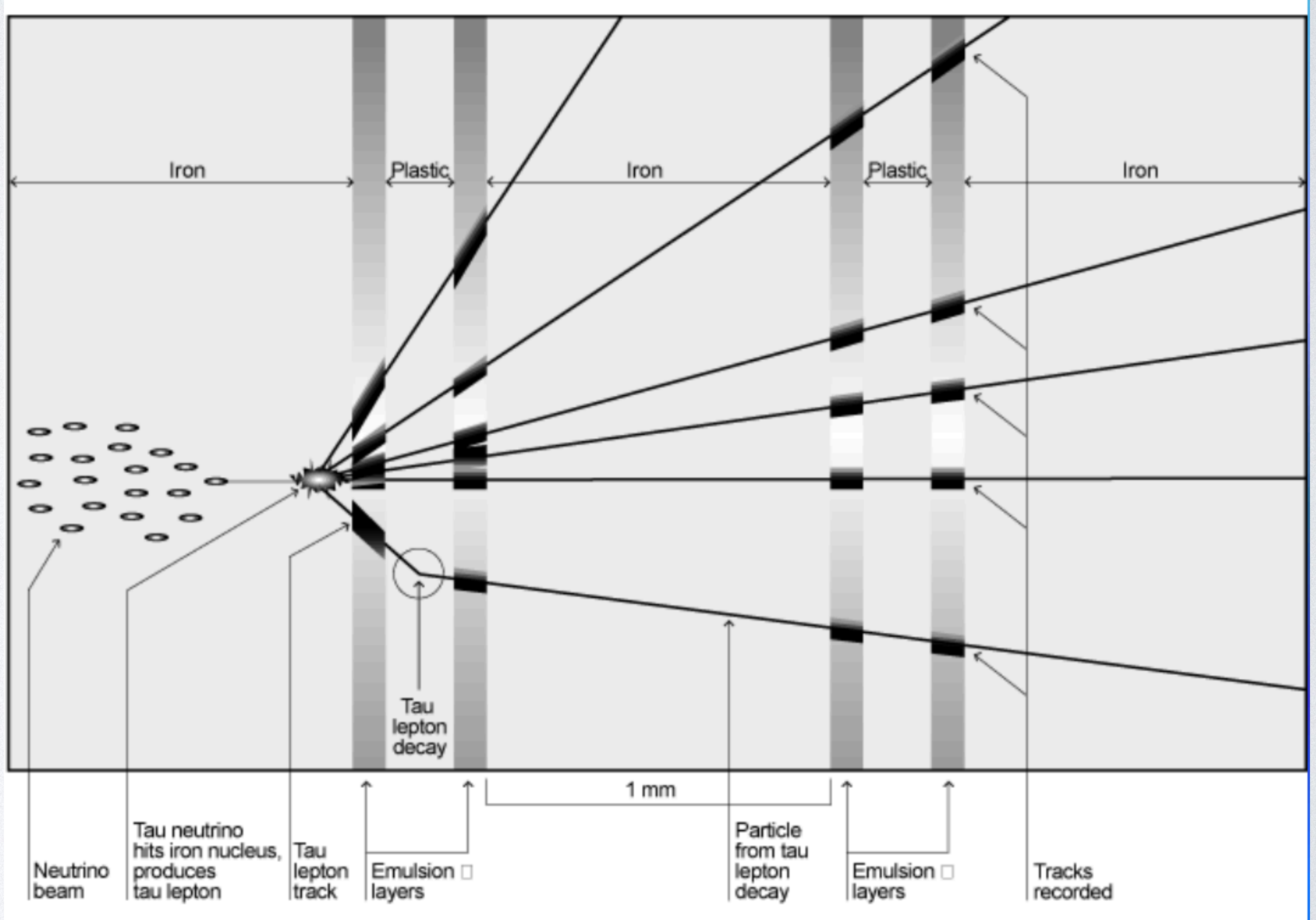


NEUTRINOS IN THE STANDARD MODEL

- The existence of the tau neutrino was one of the key predictions of the standard model

- That prediction was proven correct in 2000 by the DONUT experiment at Fermilab

Detecting a Tau Neutrino

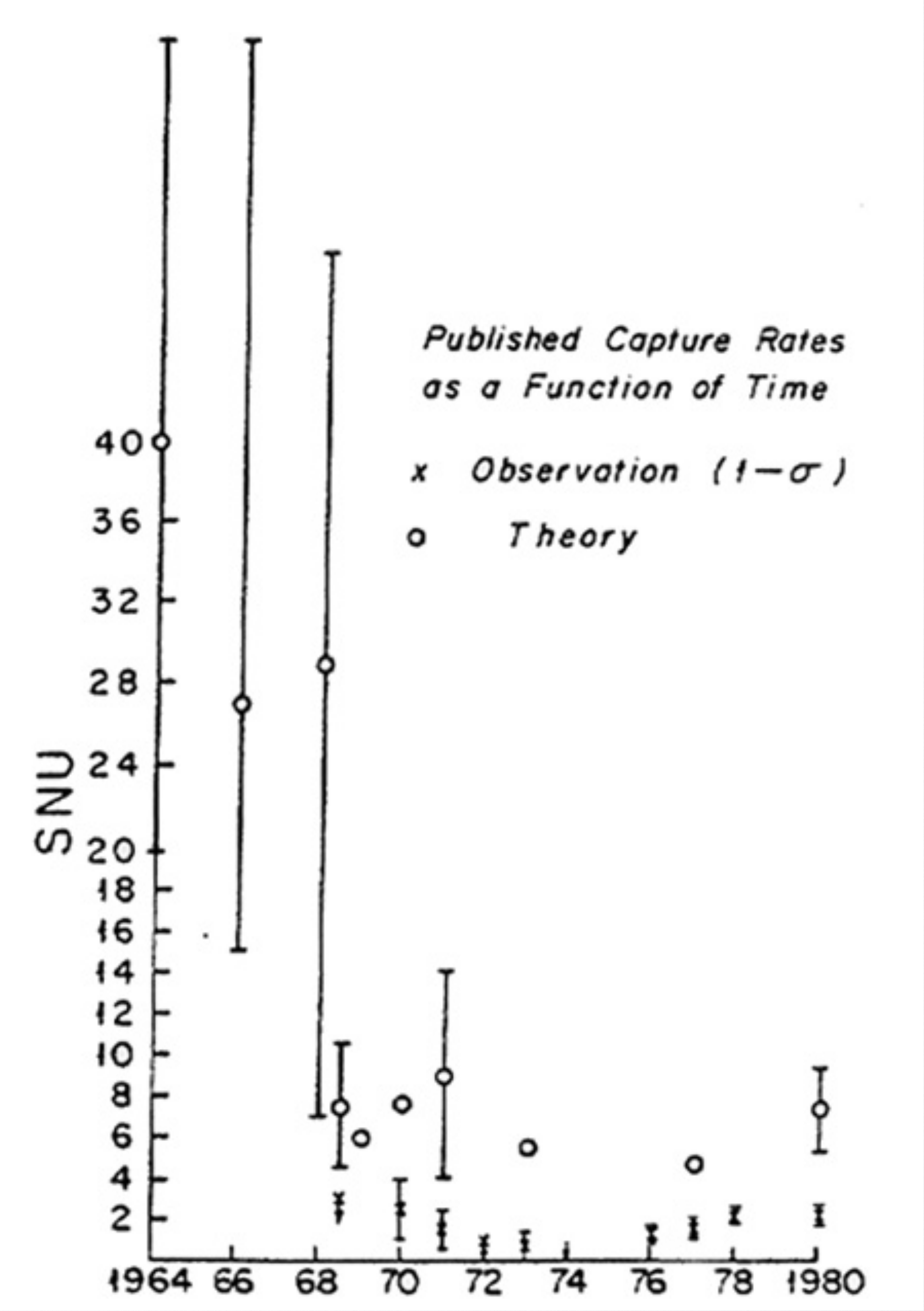


Of one million million tau neutrinos crossing the DONUT detector, scientists expect about one to interact with an iron nucleus.

SOLAR NEUTRINO PROBLEM

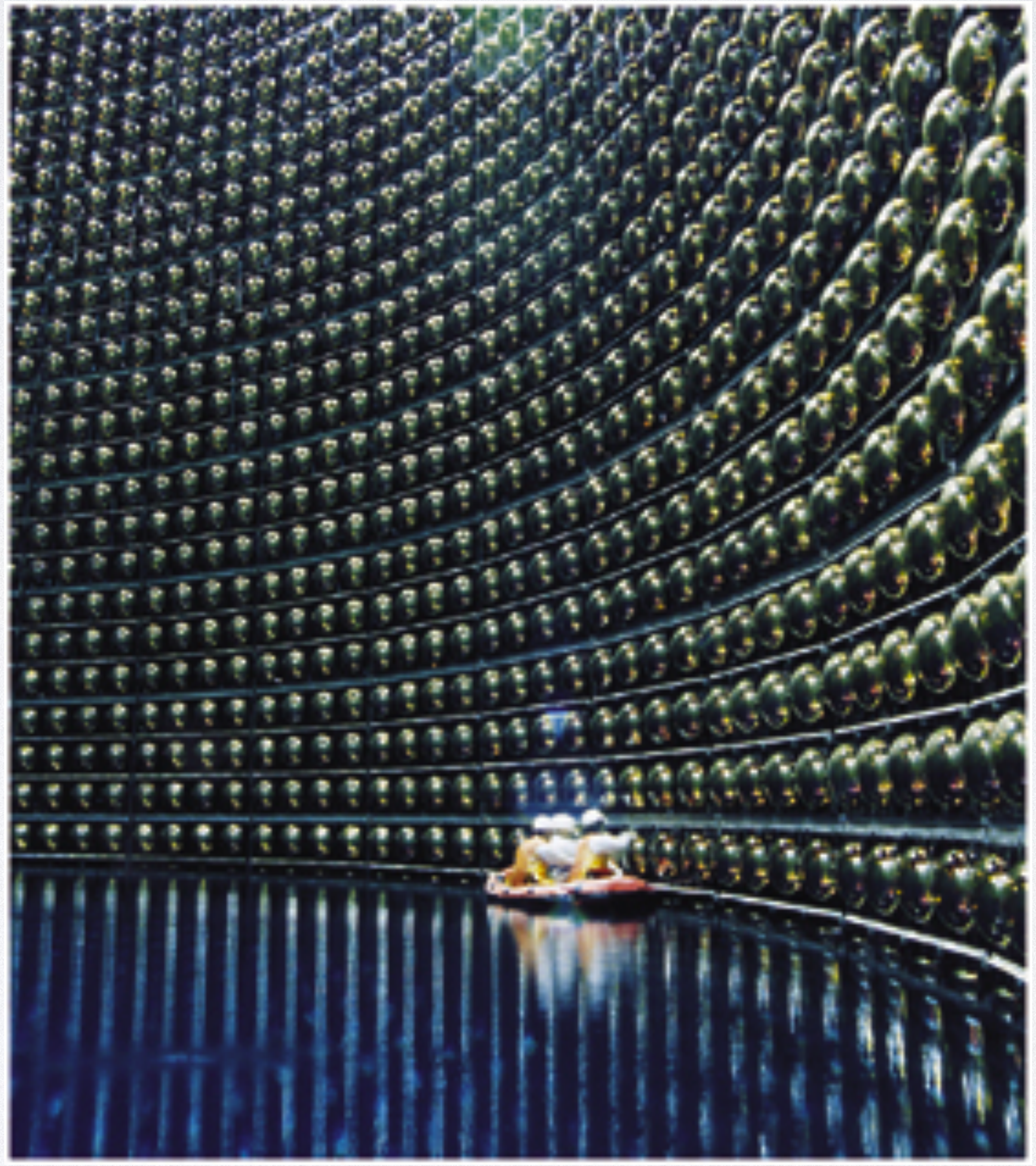
- But another key prediction proved problematic
- The **Ray Davis Experiment** studied solar neutrinos in the homestake mine in South Dakota in the 1960's.
- Was the first of many to observe **fewer solar neutrinos than expected** — "the solar neutrino problem"

A big tank of dry cleaning fluid

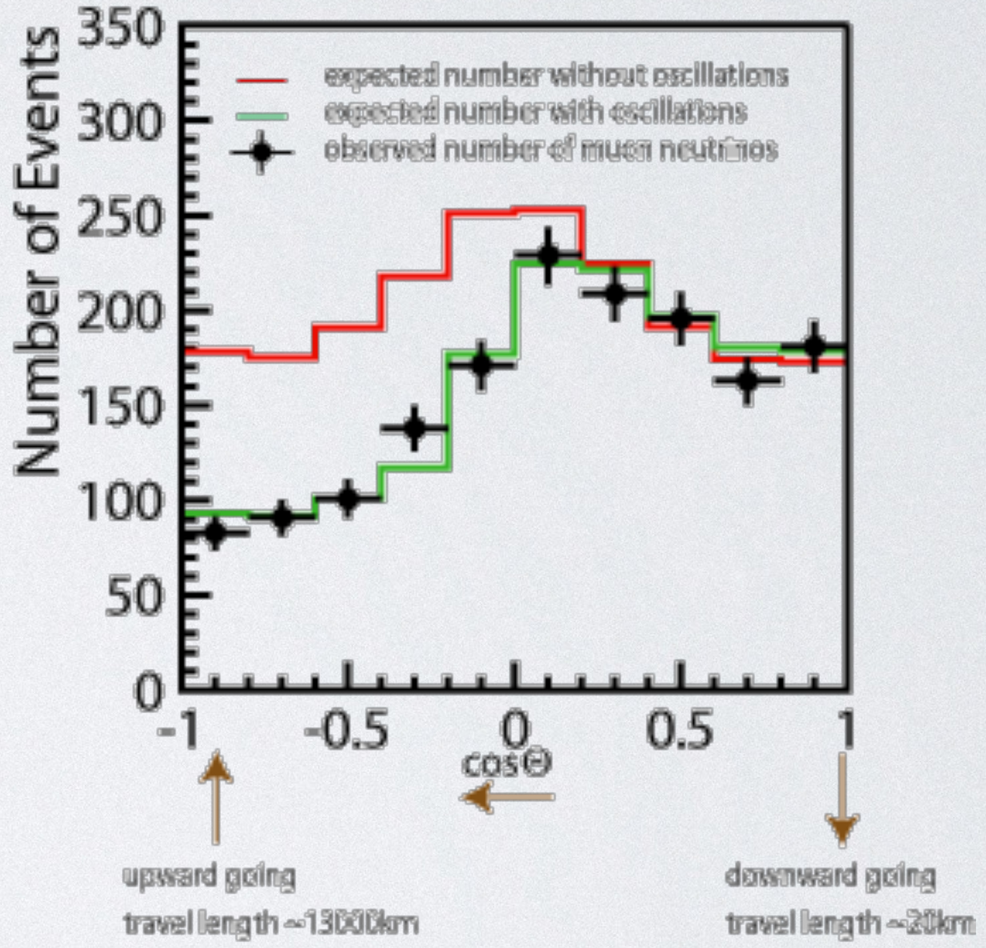


SOLAR NEUTRINO PROBLEM

- The solar neutrino problem was eventually **solved by the Super-Kamiokande experiment** (among others)
- Super-K's data indicated that **neutrinos oscillate between flavors** (ν_e, ν_μ and ν_τ) as they travel through space
- Ray Davis' experiment was only observing one kind of neutrino



A (beautiful) big tank of water that has done some amazing things



. Fukuda et al., Phys. Rev. Lett. 81, 1562 (1998);

THE NU STANDARD MODEL

- We think that these oscillations are happening because **neutrinos have mass** and the **interaction states and mass states are different** — the mass states are mixtures of weak interaction states

- Neutrinos have mass, but their **masses are very very tiny** — so tiny we have not yet measured them

NEUTRINO BIG QUESTIONS

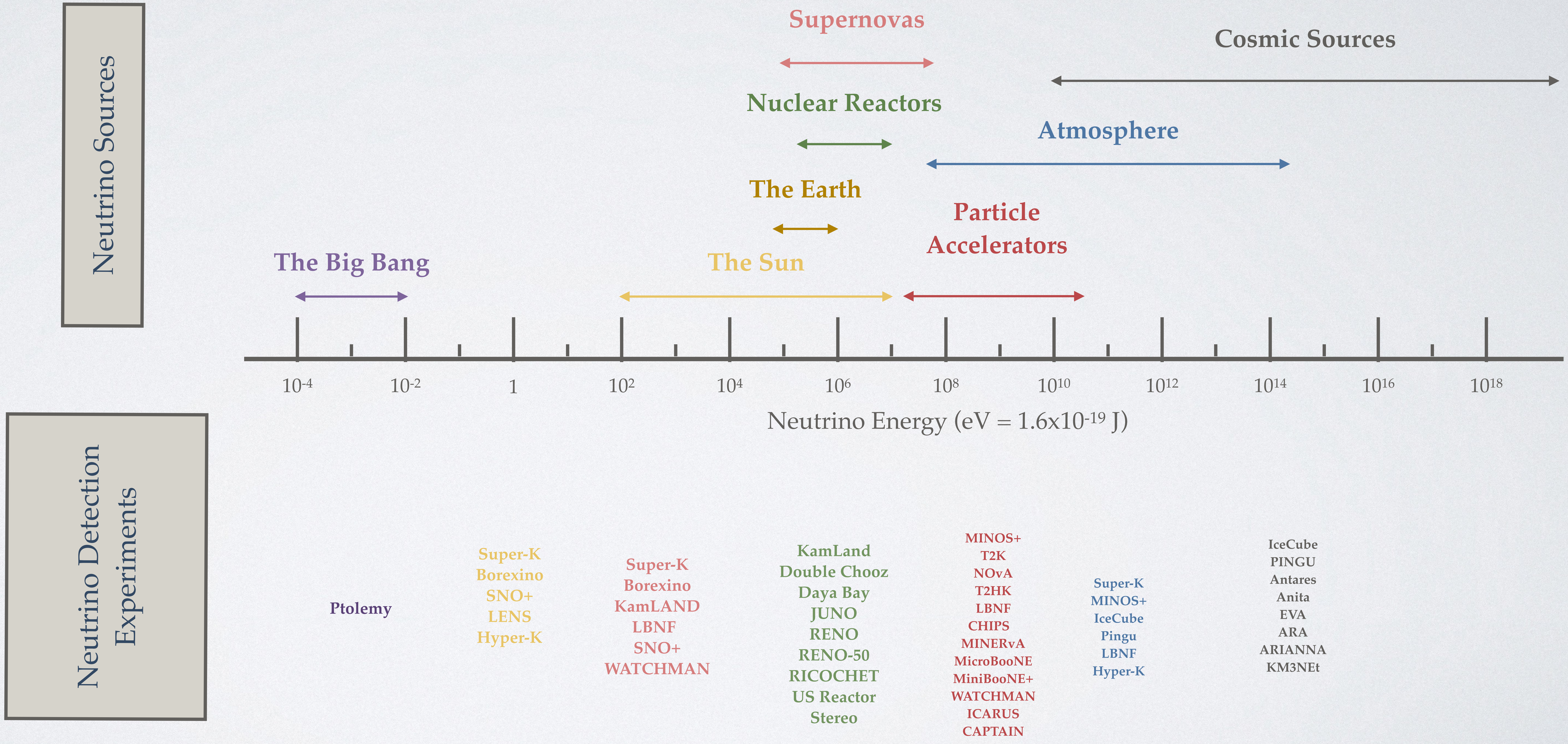
- We have **learned a lot about neutrinos** since Pauli first hypothesized them, but they are still the least well measured particles in the Standard Model
- A lot of current neutrino physics is aimed at **filling in our Standard Model** of neutrinos:
  - Want to measure all of the details of neutrino oscillations?
  - What are the neutrino masses?

NEUTRINO BIG QUESTIONS

- We are also looking for ways that **neutrinos could be a portal to New Physics** Beyond the Standard model
    - How do neutrinos **get their mass**?
        - Why are they **so much less massive** than all the other particles?
    - Are there more **neutrinos we haven't seen** (sterile neutrinos)?
        - How do they **impact our model of the universe**?
    - Do neutrinos **interact in ways not predicted by the standard model?**

THE MODERN NEUTRINO PROGRAM

Neutrino experiments all of the world are attempting to answer these questions by studying neutrinos from nearly **all available sources**:



Neutrino Sources

Supernovas

Cosmic Sources

Nuclear Reactors

Atmosphere

The Earth

Particle Accelerators

The Big Bang

The Sun

Neutrino Energy (eV = 1.6×10^{-19} J)

Neutrino Detection Experiments

Ptolemy

Super-K
Borexino
SNO+
LENS
Hyper-K

Super-K
Borexino
KamLAND
LBNF
SNO+
WATCHMAN

KamLand
Double Chooz
Daya Bay
JUNO
RENO
RENO-50
RICOCHET
US Reactor
Stereo

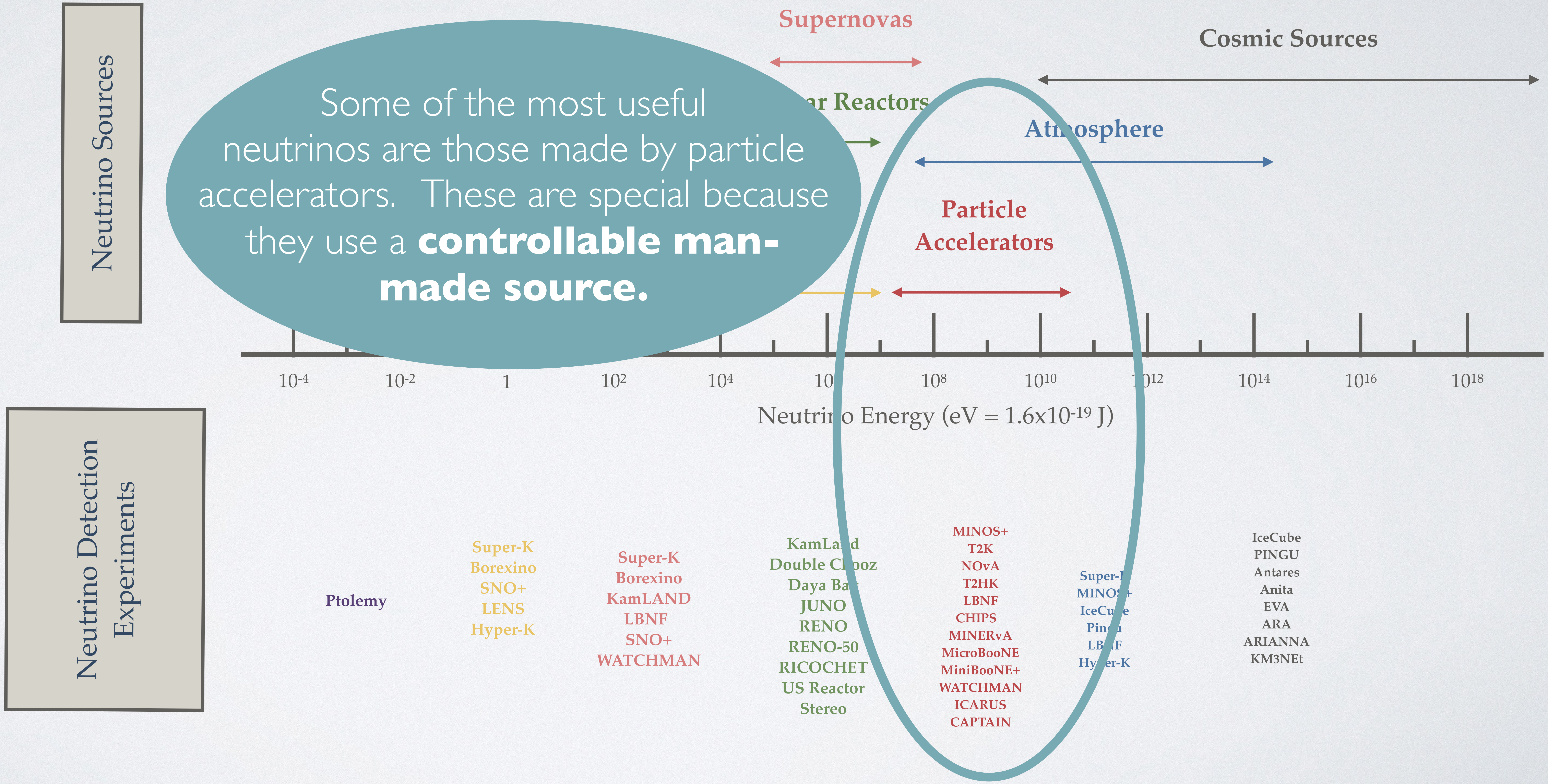
MINOS+
T2K
NOvA
T2HK
LBNF
CHIPS
MINERvA
MicroBooNE
MiniBooNE+
WATCHMAN
ICARUS
CAPTAIN

Super-K
MINOS+
IceCube
Pingu
LBNF
Hyper-K

IceCube
PINGU
Antares
Anita
EVA
ARA
ARIANNA
KM3NEt

THE MODERN NEUTRINO PROGRAM

Neutrino experiments all of the world are attempting to answer these questions by studying neutrinos from nearly **all available sources**:



Some of the most useful neutrinos are those made by particle accelerators. These are special because they use a **controllable man-made source.**

ACCELERATOR-BASED NEUTRINOS

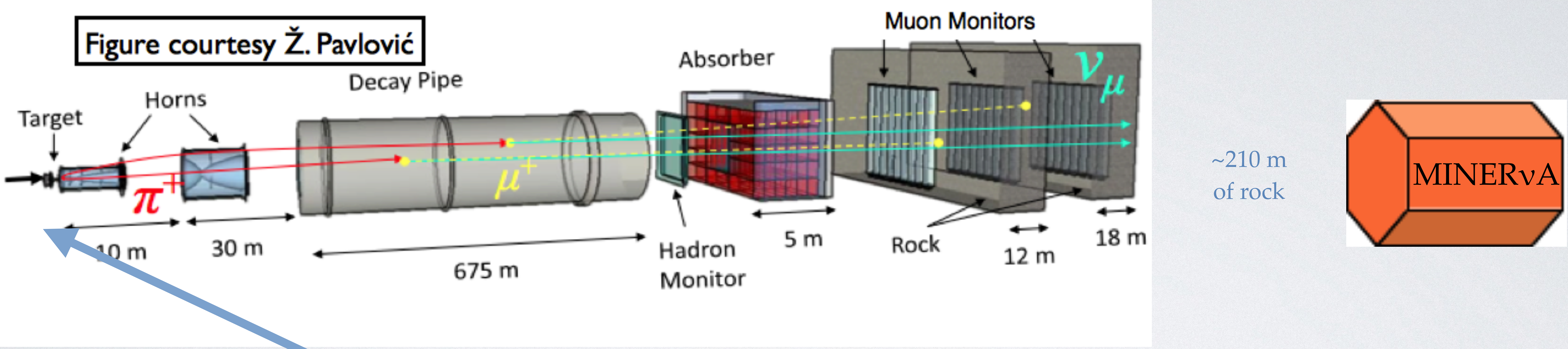


Figure courtesy Ž. Pavlović

~210 m of rock

The NuMI neutrino beam starts with a 120 GeV proton beam from Fermilab’s main injector

- Protons impinge on a graphite target, creating charged pions and kaons (among other things)

ACCELERATOR-BASED NEUTRINOS

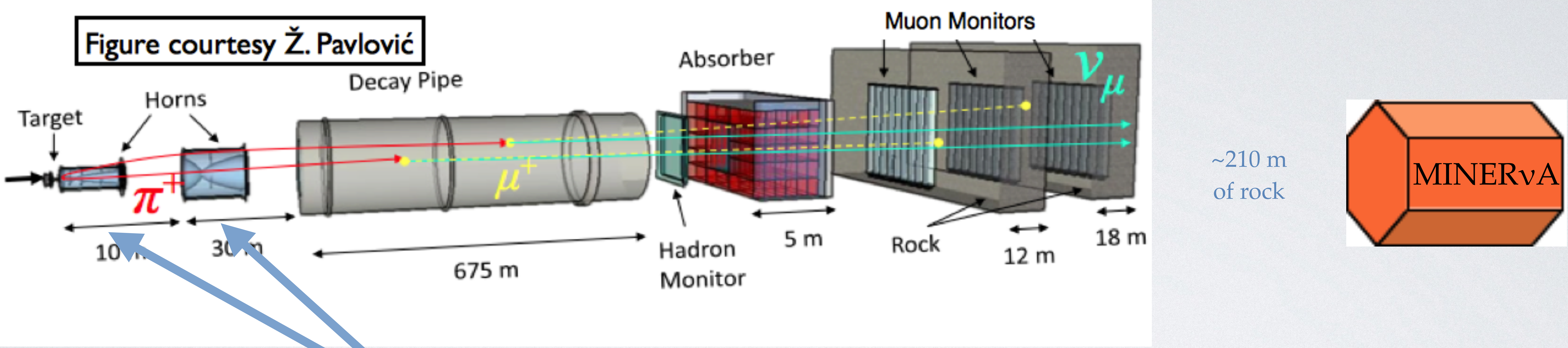
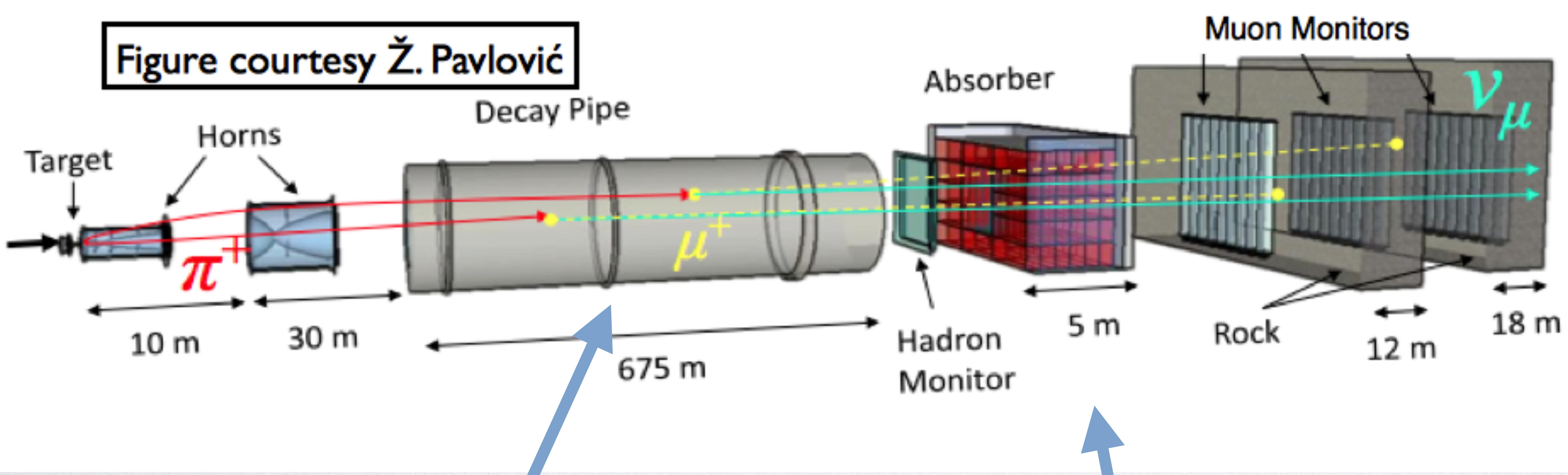


Figure courtesy Ž. Pavlović

The pions and kaons are focused by a pair of focusing horns.

- Horns are basically large electromagnets
- We can configure them to create neutrino beams or antineutrino beams

ACCELERATOR-BASED NEUTRINOS

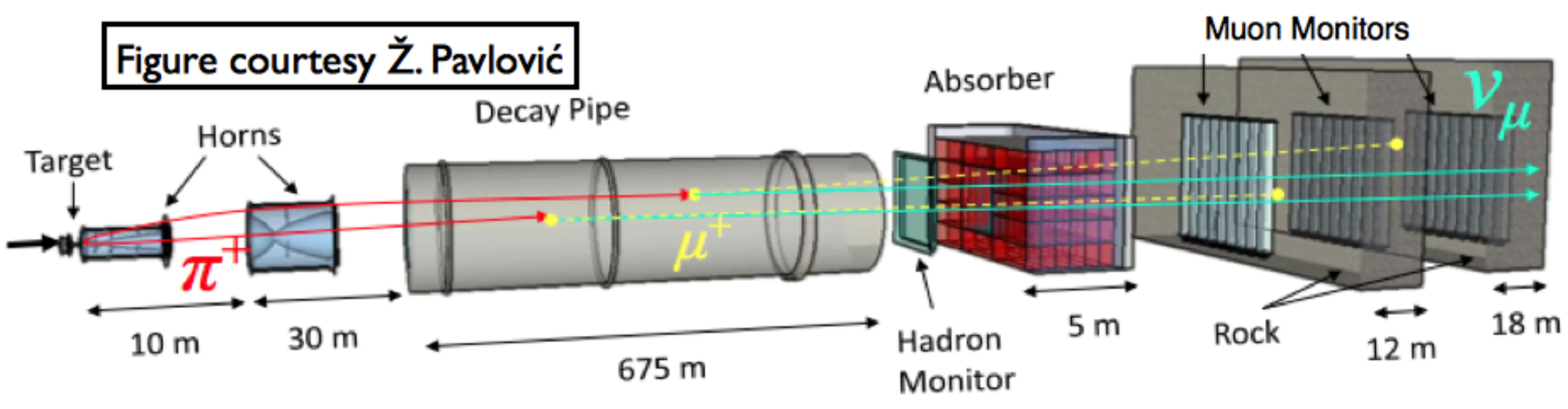


~210 m
of rock

The pions and kaons decay in a 675 m long pipe, producing muons and neutrinos

Everything but neutrinos is stopped in using an absorber+rock

ACCELERATOR-BASED NEUTRINOS



~210 m
of rock

Only neutrinos arrive at the detector

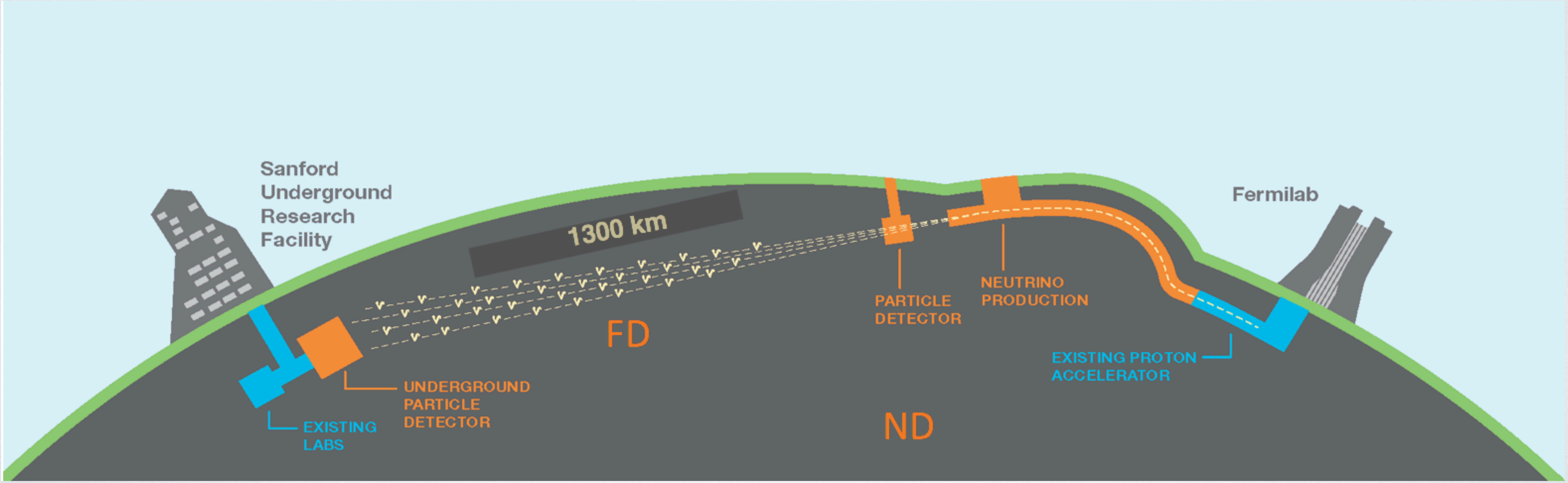
ACCELERATOR-BASED NEUTRINOS

- Accelerator based neutrino experiments involve **producing a neutrino beam** and observing it in detectors **a short or long distance** away

- There are **two currently operating** (NuMI and BNB) and **one planned** accelerator-based neutrino beams in the US (LBNF).

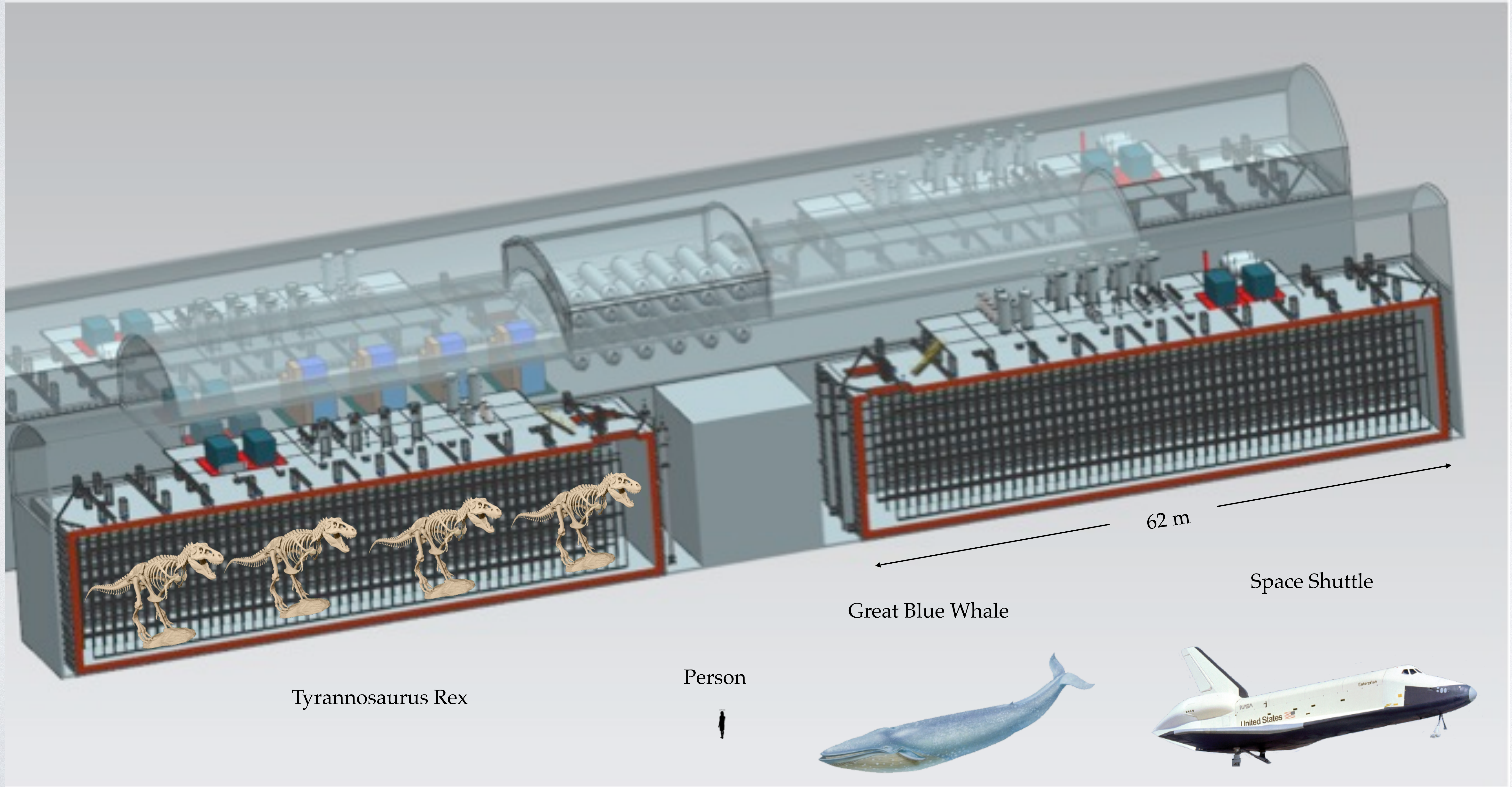
THE DUNE EXPERIMENT

- The planned beam (LBNF) will provide neutrinos to **Deep Underground Neutrino Detector (DUNE):**



THE DUNE EXPERIMENT

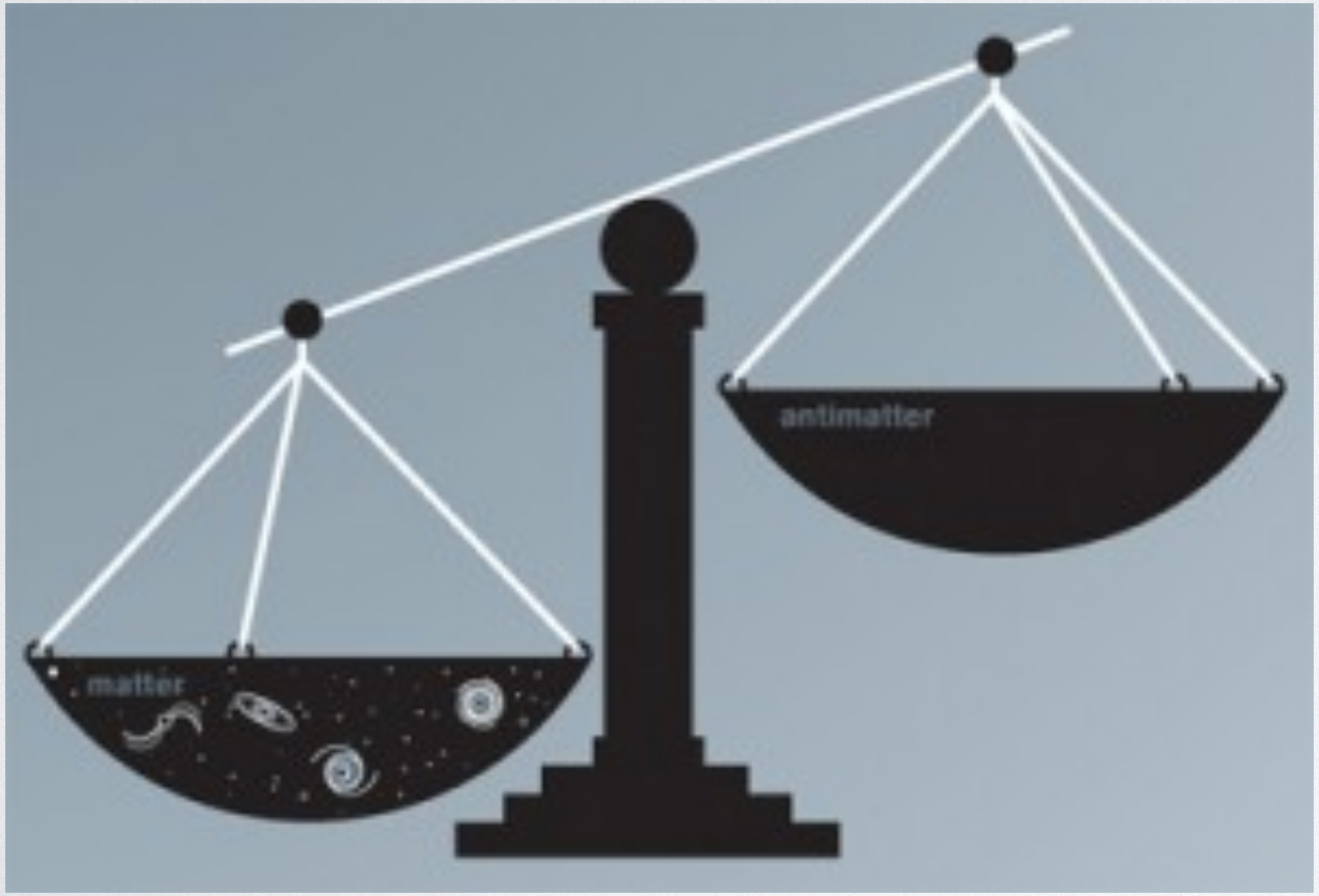
- DUNE will be a huge and very high resolution detector



- Will be **more massive and have more intense beam** than any currently running experiment
- Will be able to **measure neutrino oscillations, including CP violation**
- Also: **supernova, solar and atmospheric neutrinos, sterile** neutrinos

CP VIOLATION

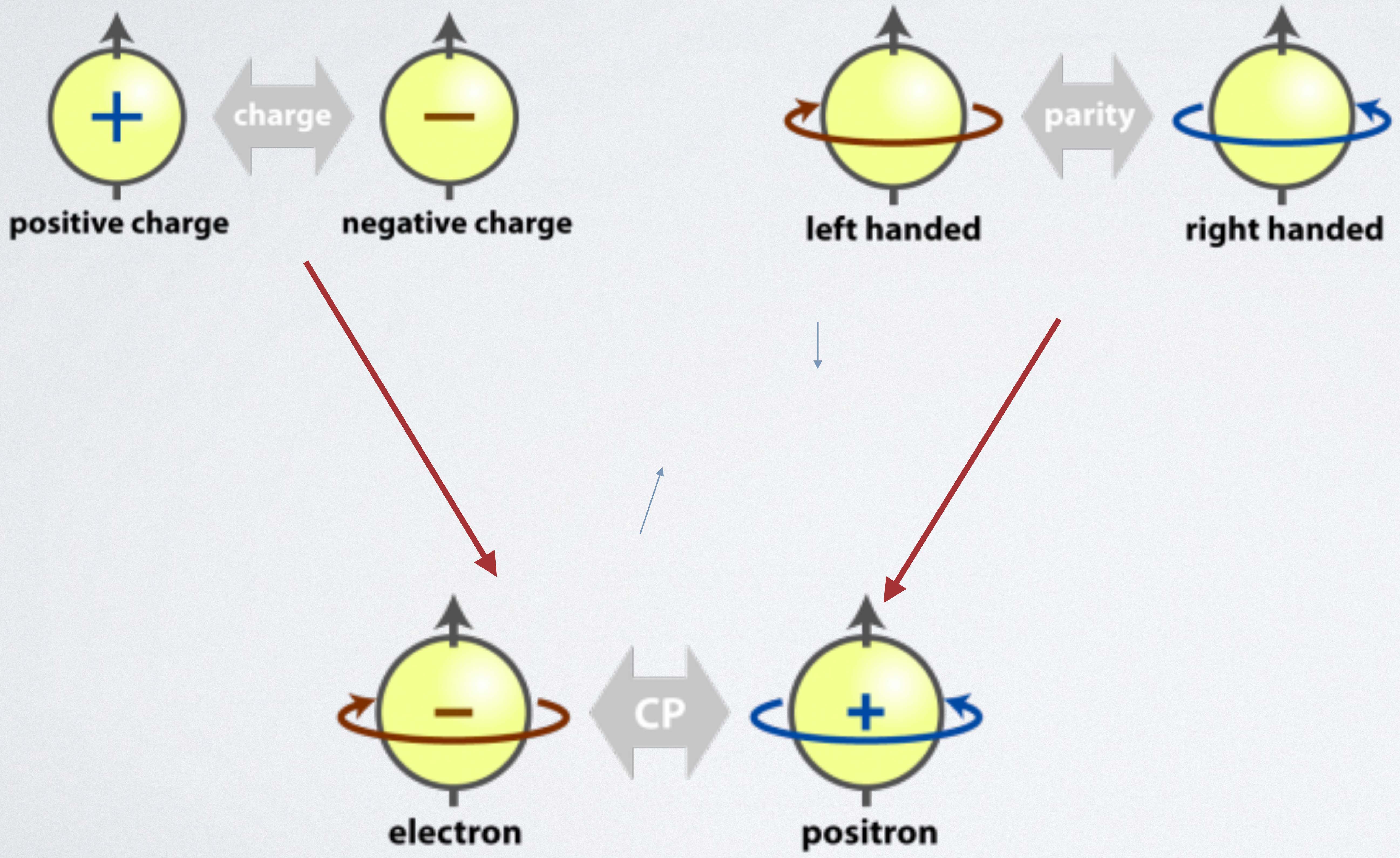
- Why we care so much about CP violation:



- The Universe apparently contains much **more matter than antimatter**
- This is not predicted by the Standard Model → clear cut evidence that the **Standard Model is flawed**!
- **CP violation** is something that would cause there to be more matter than antimatter…

CP VIOLATION

- Why we care so much about the CP violation:



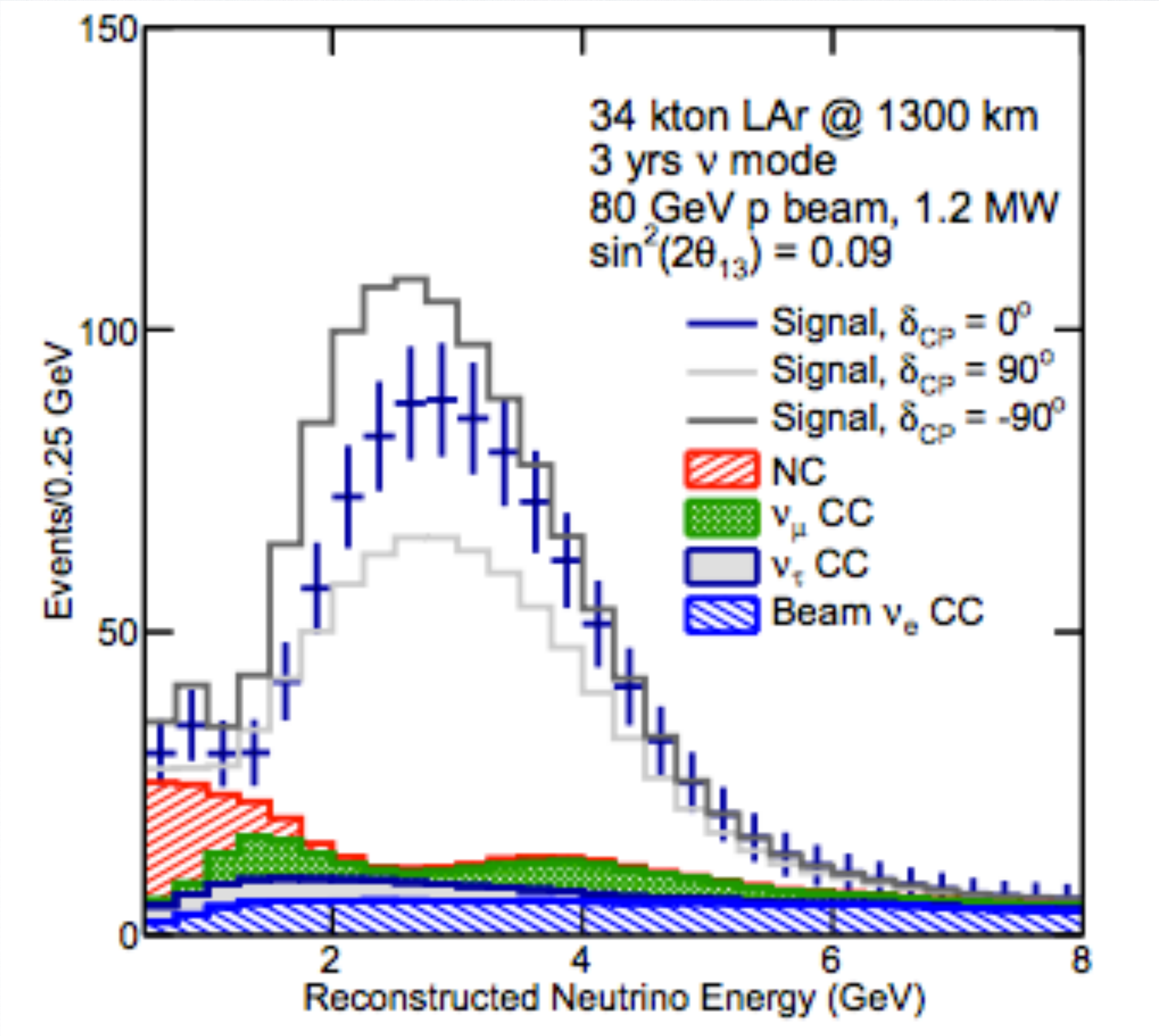
- CP violation allows **particles and their antiparticles to behave differently**

- We'd really like to know whether **neutrino oscillations are violating CP**

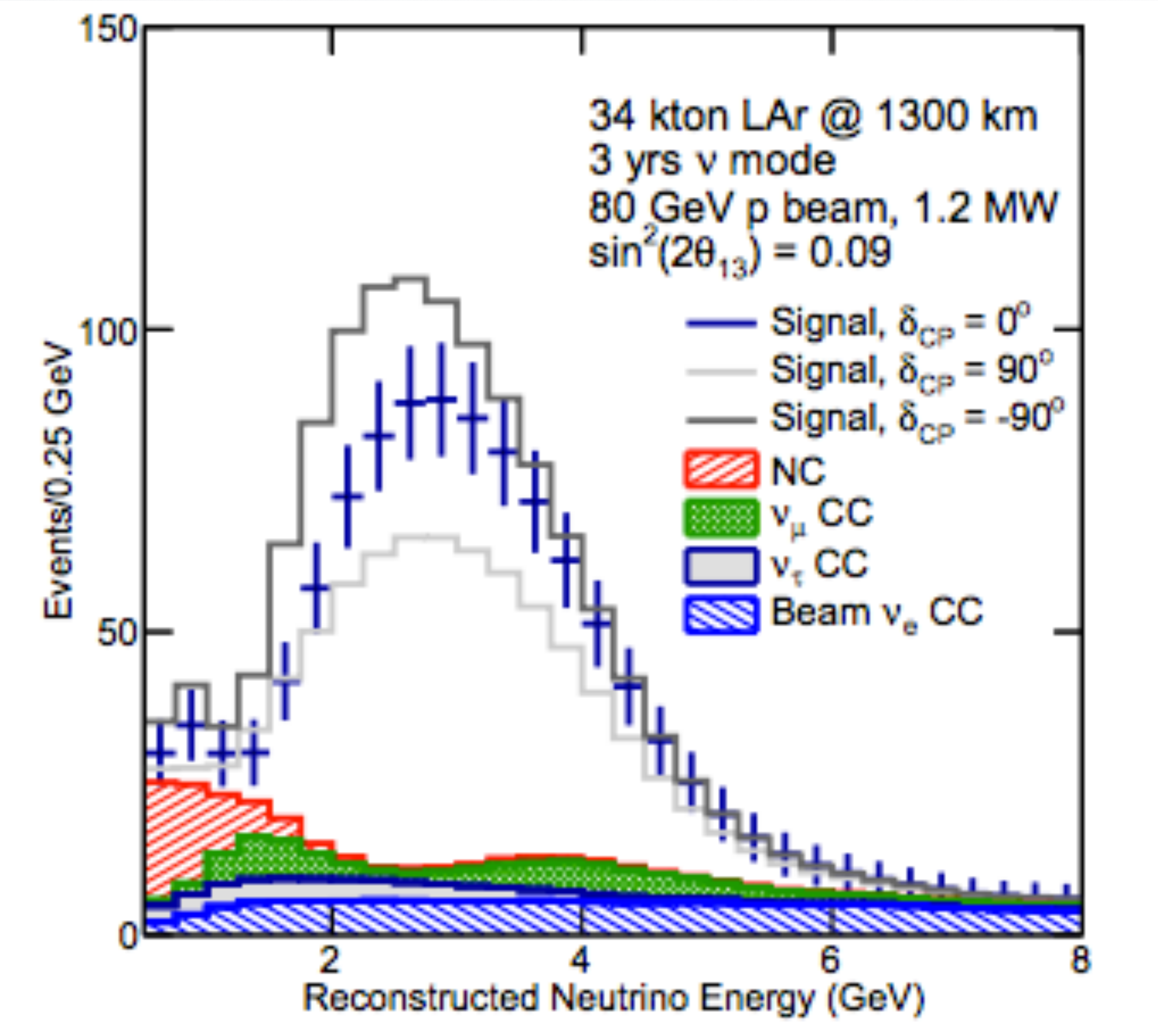
CP VIOLATION AT DUNE

- DUNE will measure CP violation by looking for **muon neutrinos that oscillate to electron neutrinos**

The energy spectrum of the neutrinos we observe in South Dakota will **look different, depending on whether neutrinos engage in CP violation**, and by how much



CP VIOLATION AT DUNE



- When DUNE data arrives, we will essentially place t**he energy spectrum that we observe on top of these predictions** and pick off the values of the mass hierarchy and CP phase that best match the data

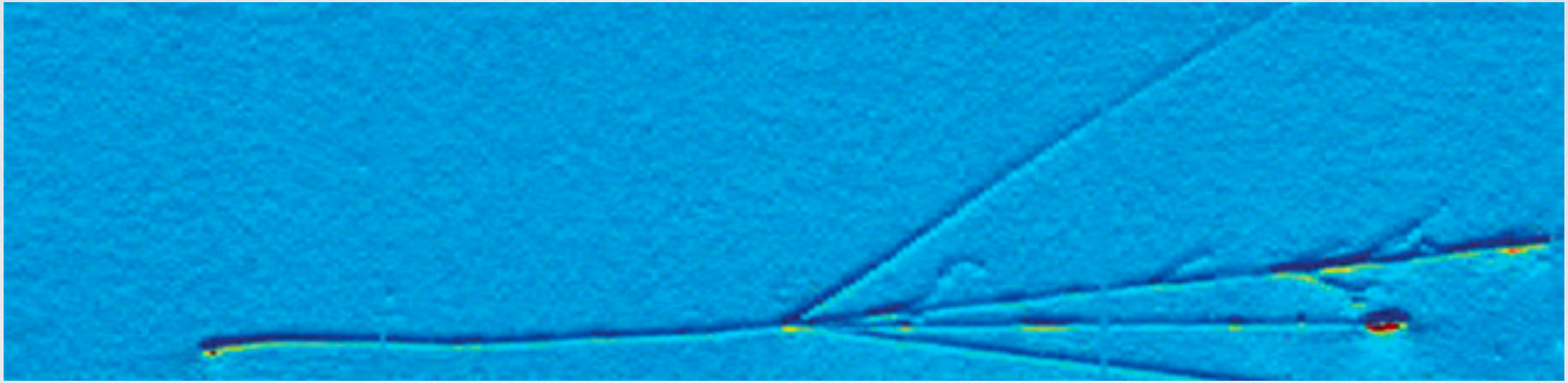
- Of course, we are physicists, so we will make things **a lot more complicated** than that

- But that is basically how it works

- So these **predictions are really critical** to our measurements of oscillations

NEUTRINO INTERACTIONS IN DUNE

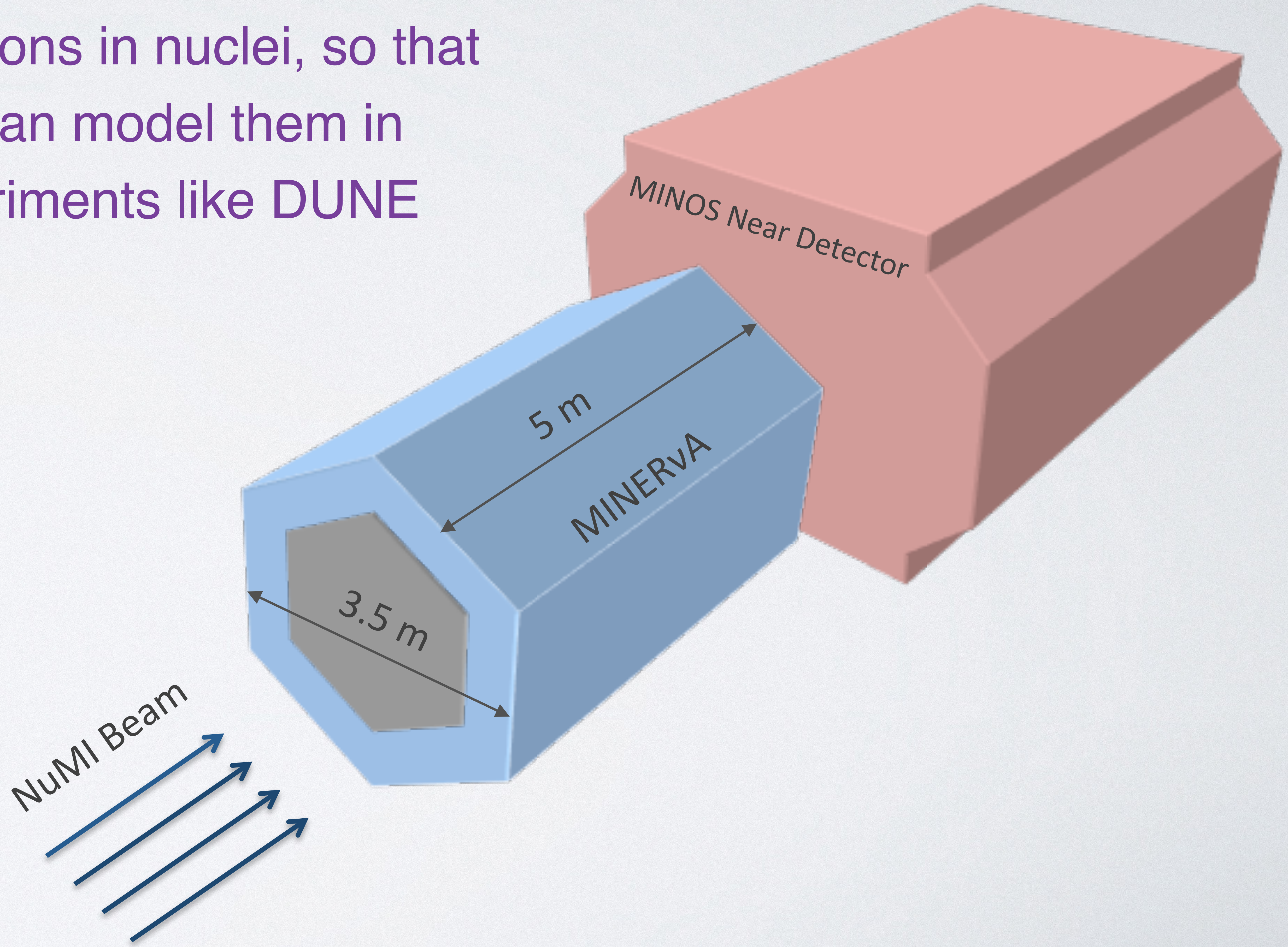
- To make those predictions, we need a precise model of the neutrino interactions that will happen in DUNE:, that will look something like this:



This turns out to be complicated, because neutrinos interact with nuclei, and nuclear reactions are very difficult to predict theoretically

THE MINERVA EXPERIMENT

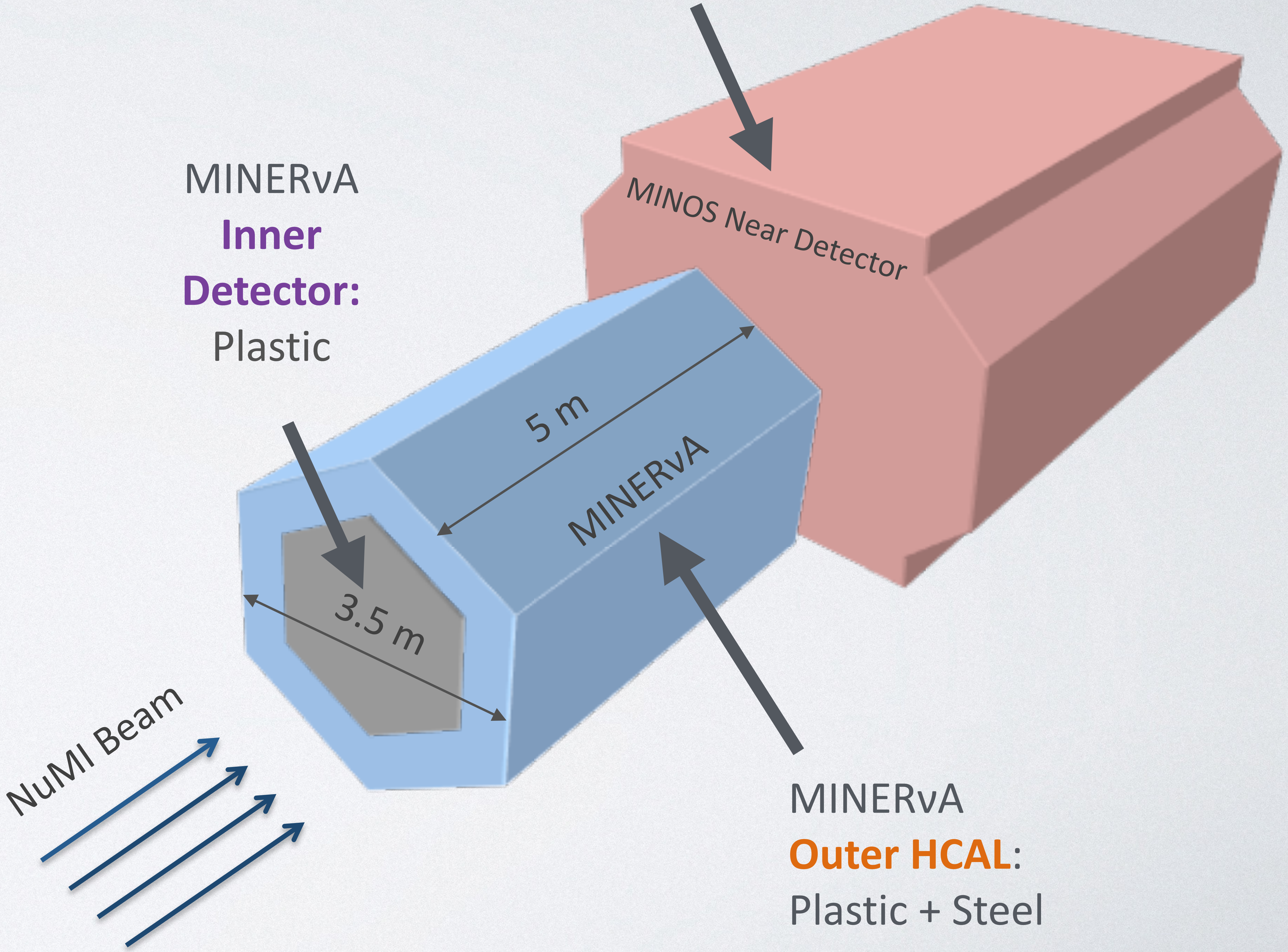
The MINERvA detector was to measure neutrino interactions in nuclei, so that we can model them in experiments like DUNE



THE MINERVA EXPERIMENT

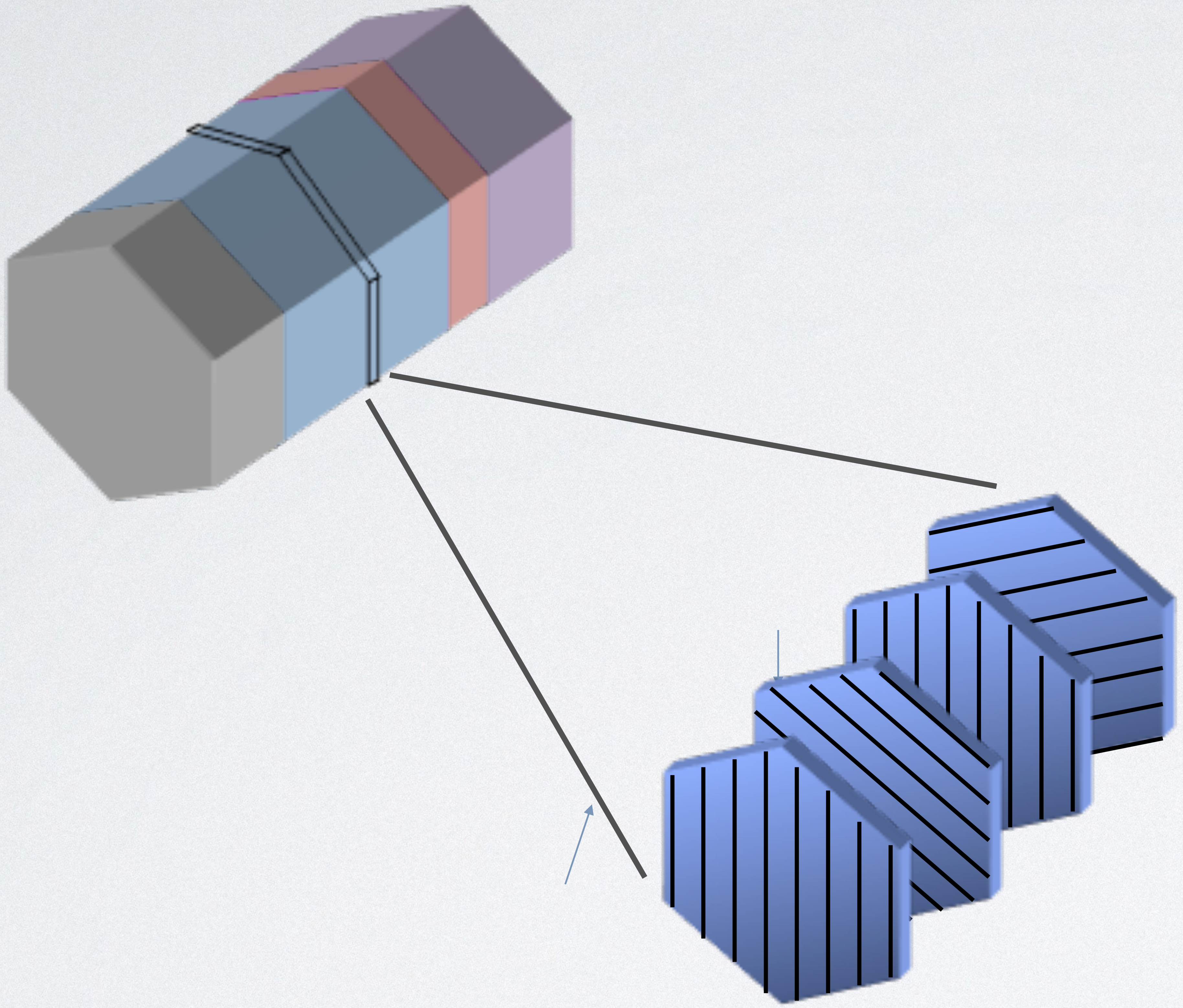
MINOS Near Detector: measures particles that exit the back of MINERvA

MINERvA **Inner Detector:** Plastic

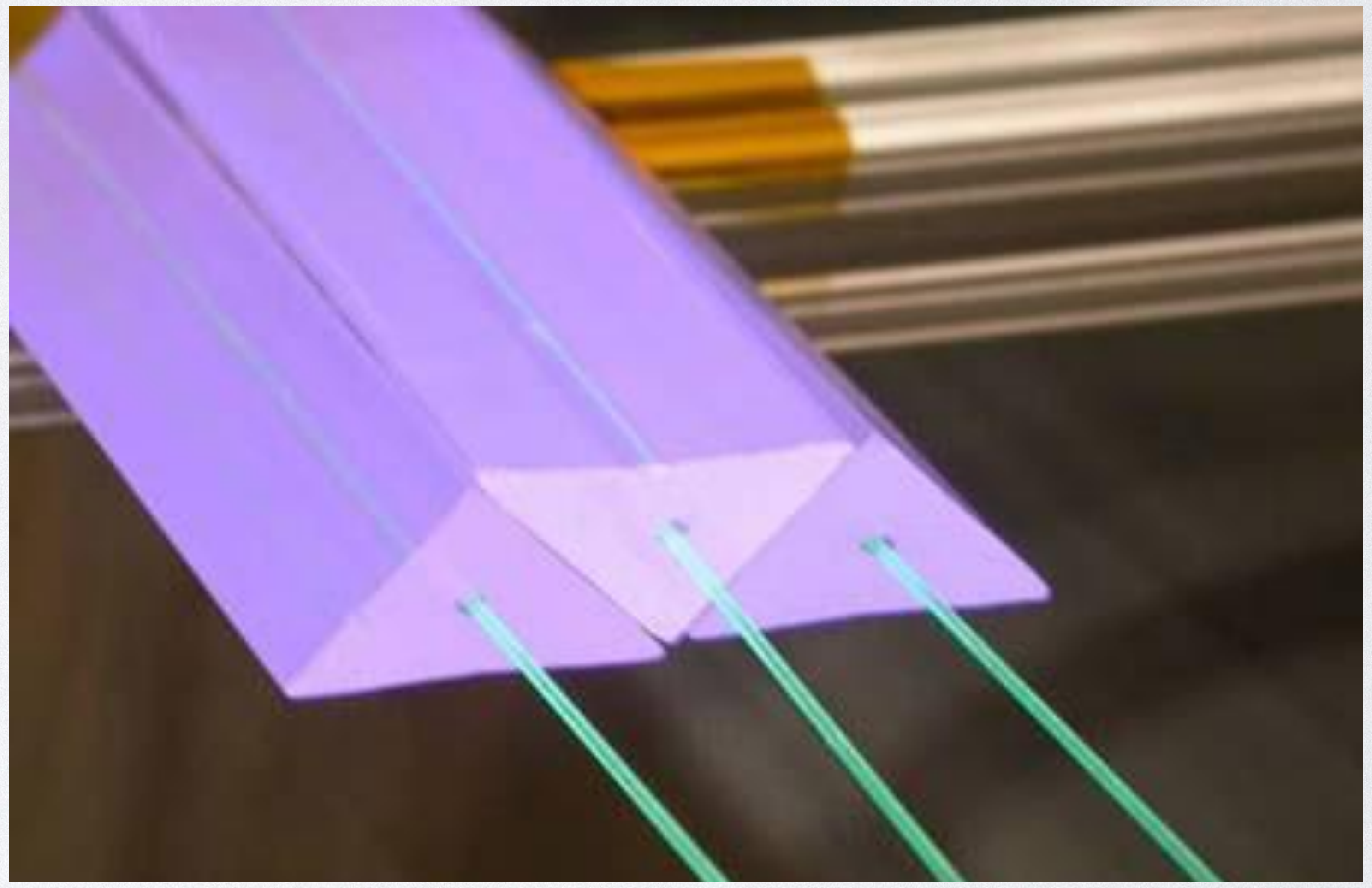


MINERvA **Outer HCAL**: Plastic + Steel

THE MINERVA EXPERIMENT

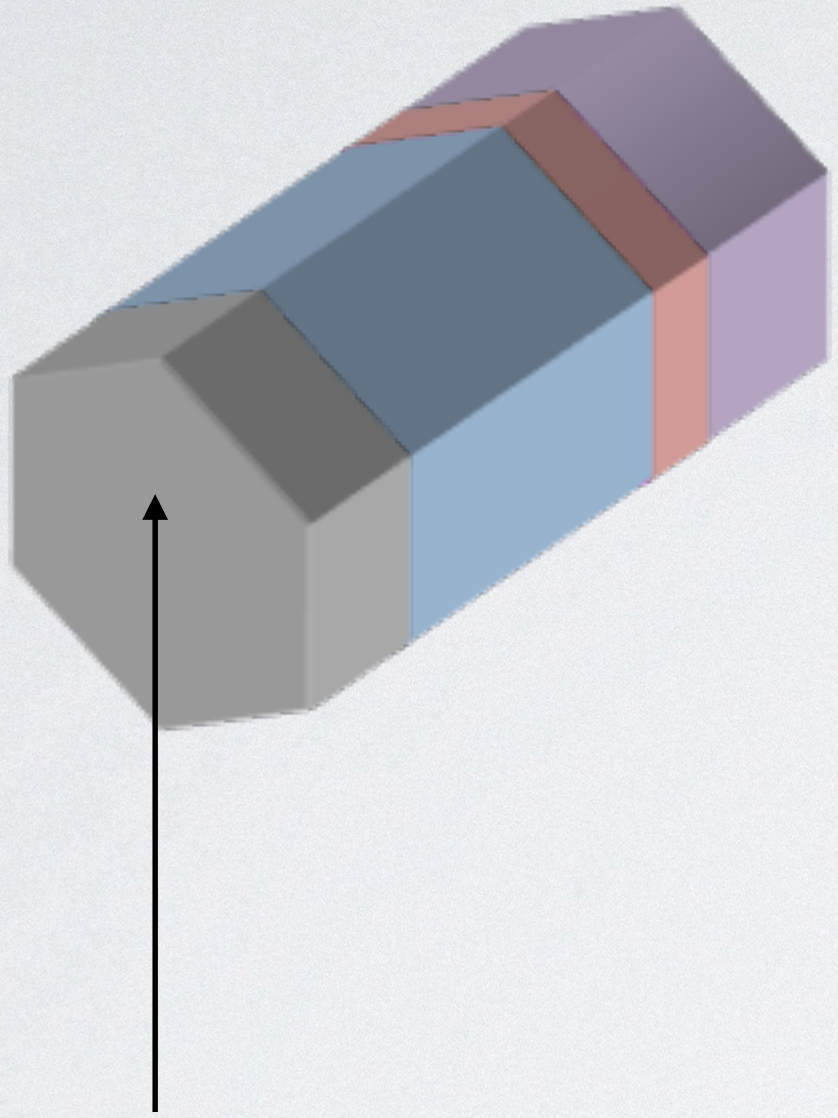


Each plane is formed from 127 **triangular plastic strips** (3.3 x 1.7 cm) arrayed in one of **three orientations for 3-dimensional reconstruction**

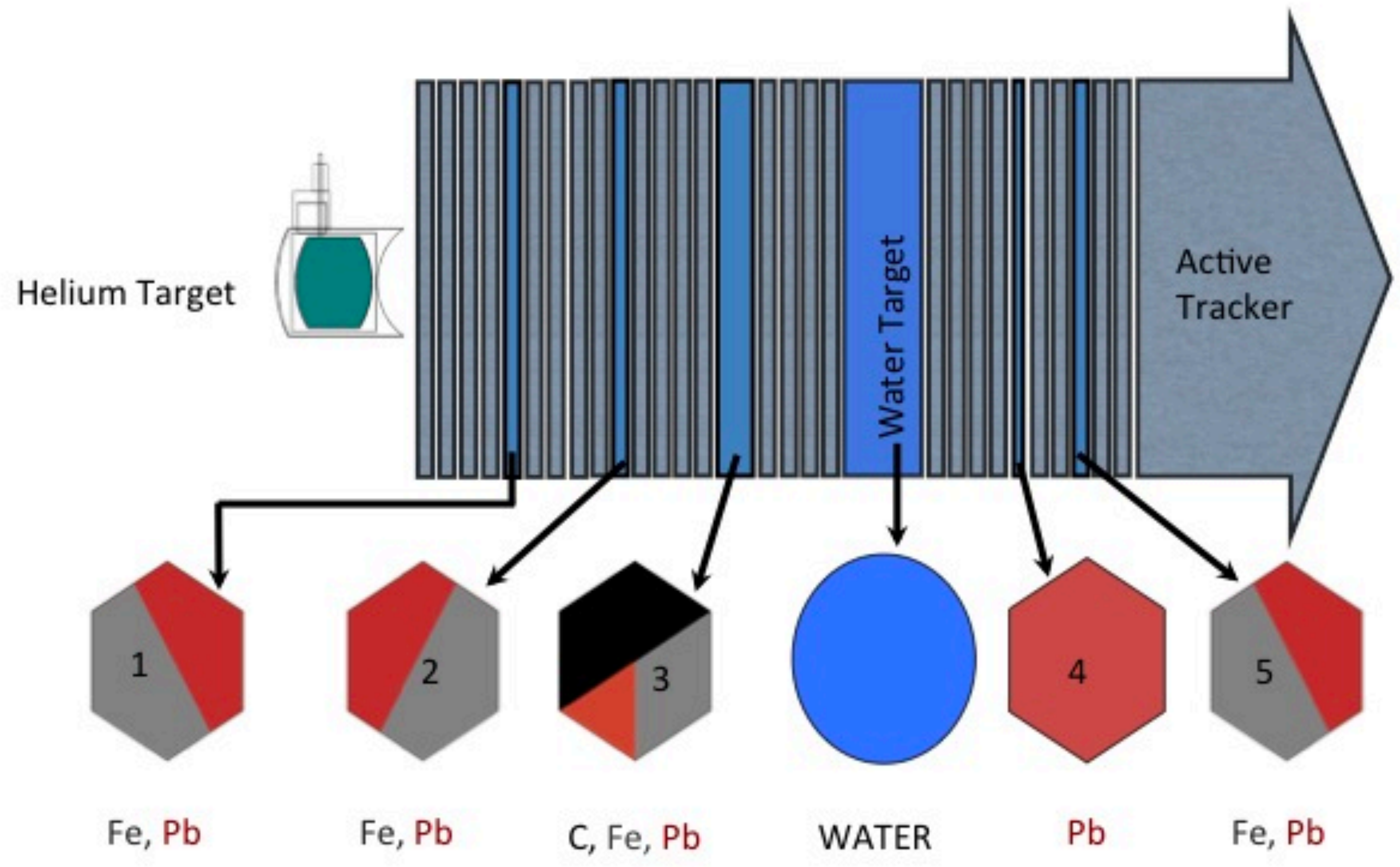


Inner tracking volume is made **entirely of plastic scintillator planes**

THE MINERVA EXPERIMENT



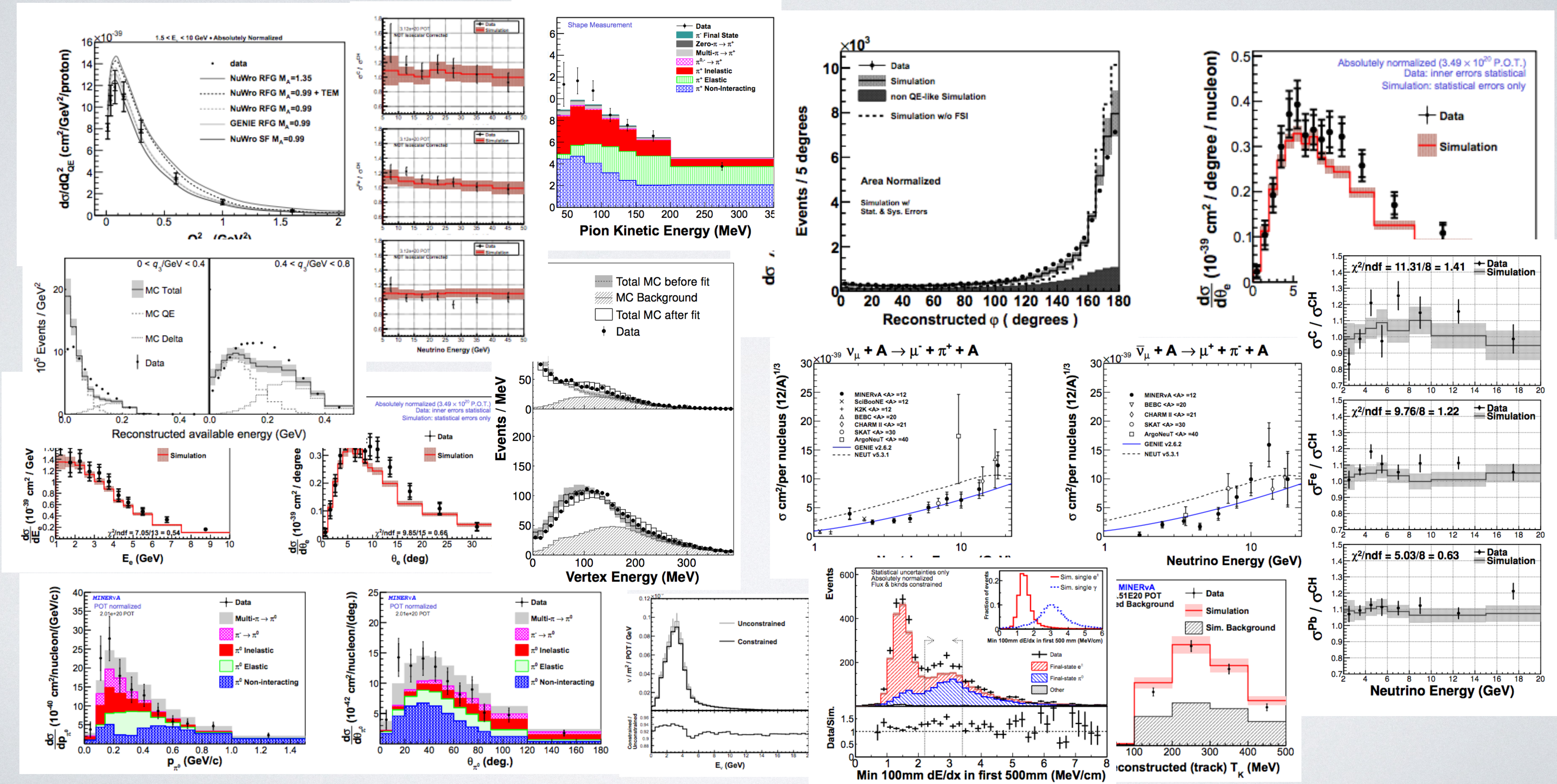
Most upstream region is designed to enable measurement of **cross sections across different nuclei**



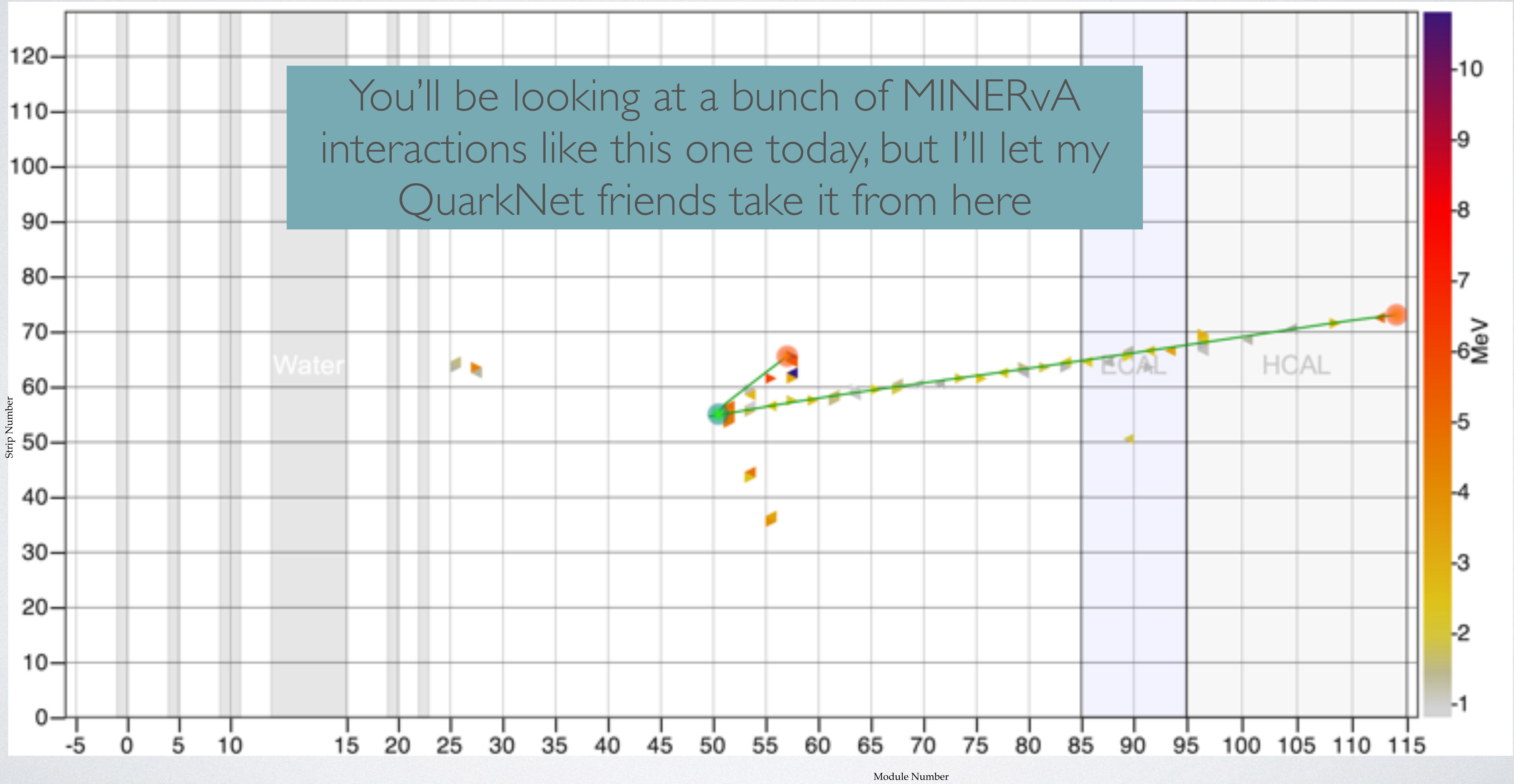
MINERVA TIMELINE

MINERvA Experiment Proposed	2002
Construction Begins	2006
Data-taking Begins	2009
Data-taking Complete	2019

MINERVA RESULTS

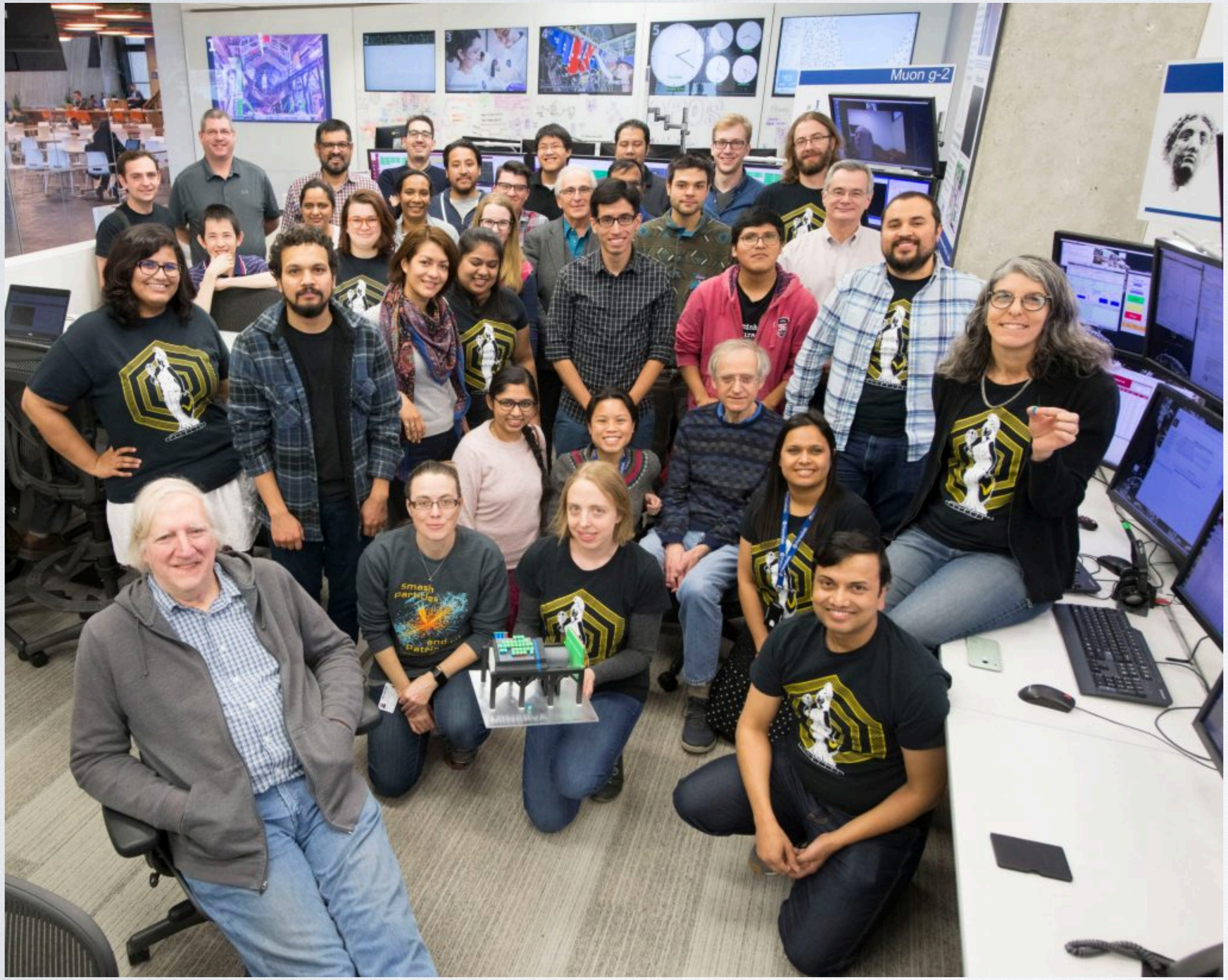


INTERACTIONS IN MINERVA



You'll be looking at a bunch of MINERvA interactions like this one today, but I'll let my QuarkNet friends take it from here

ON BEHALF OF MINERVA



THANKS FOR DOING THE MINERVA MASTERCLASS!