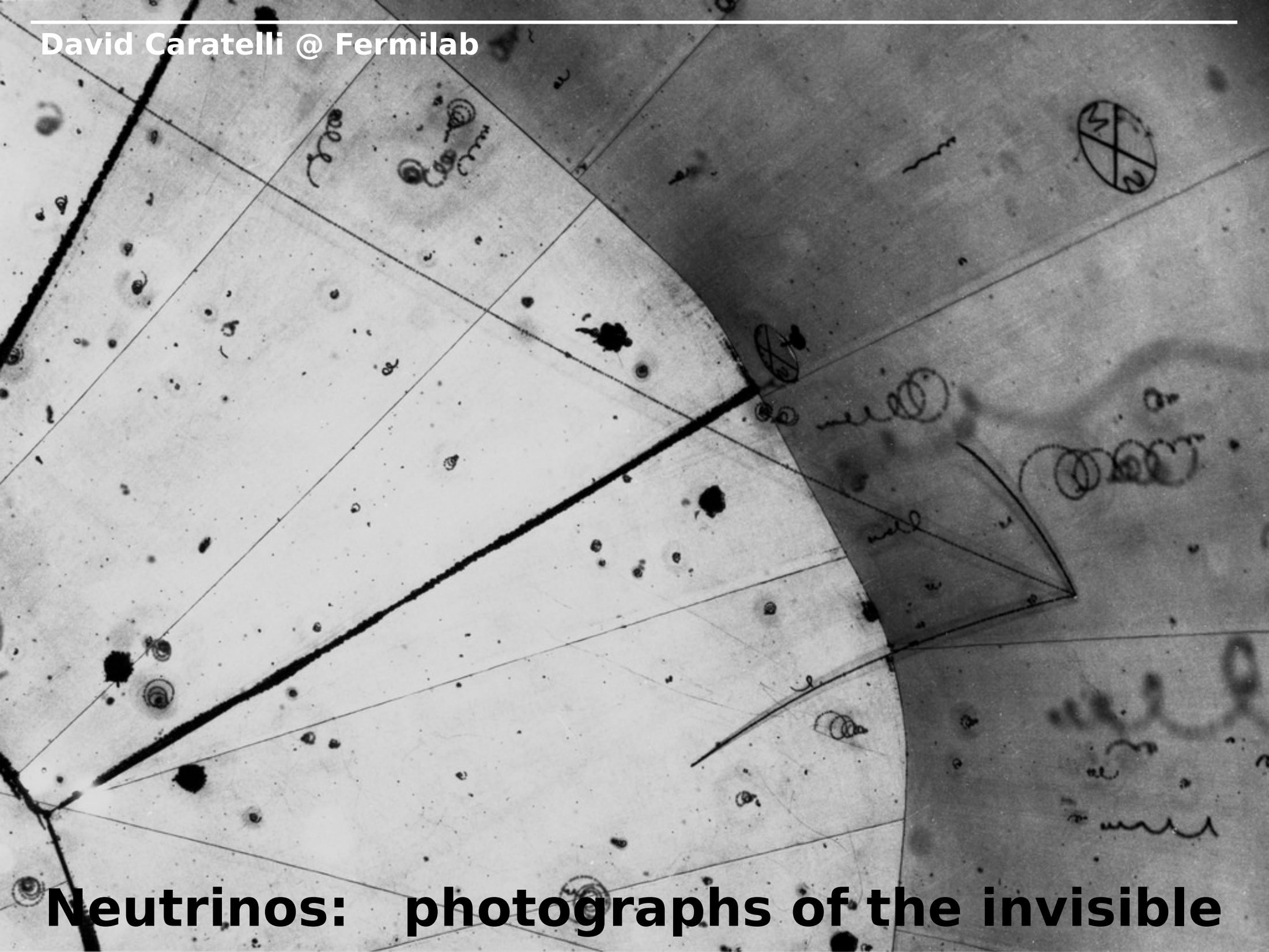
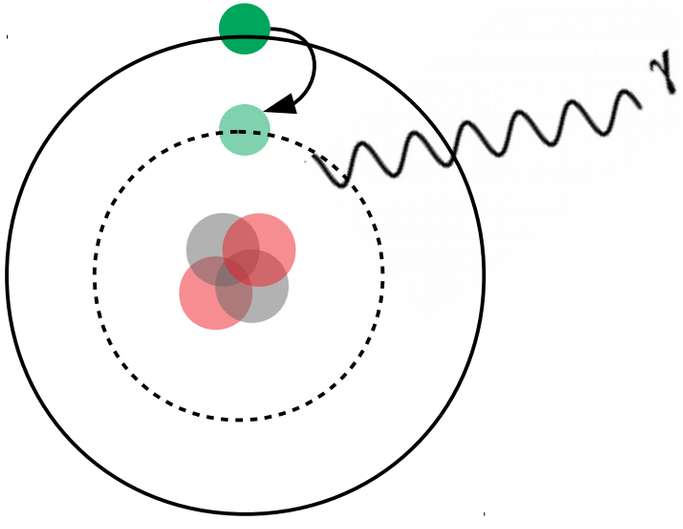
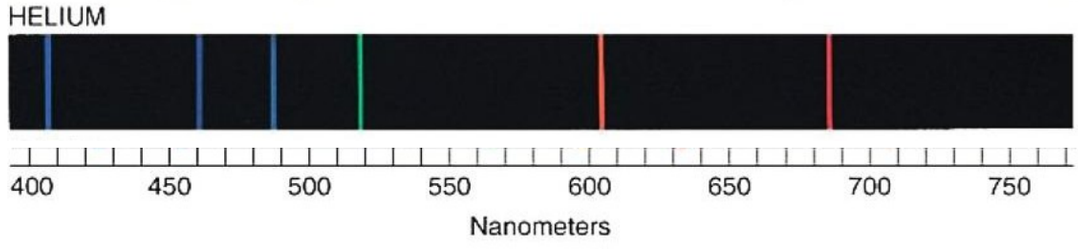
David Caratelli @ Fermilab

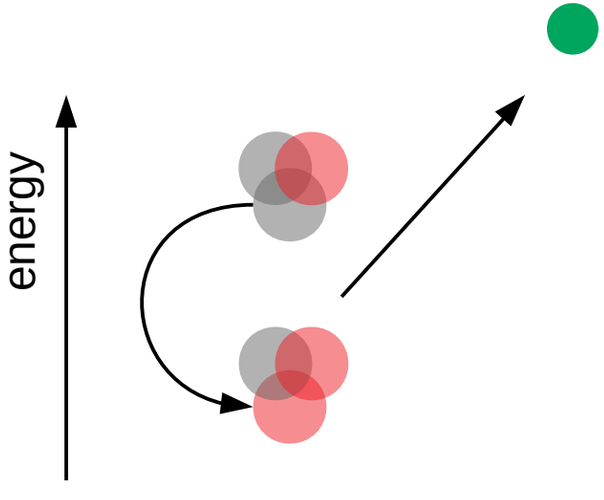


Neutrinos: photographs of the invisible

How the Neutrino came to be







what was expected to appear

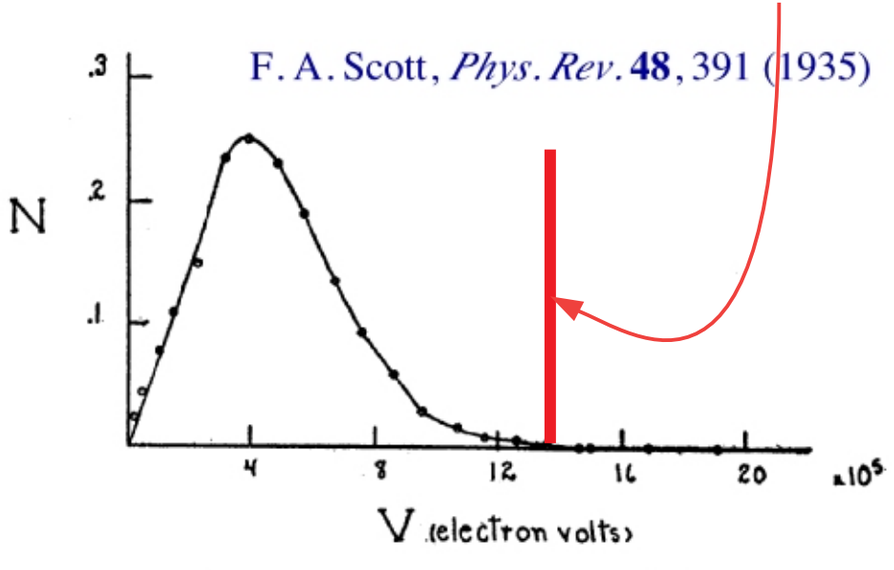
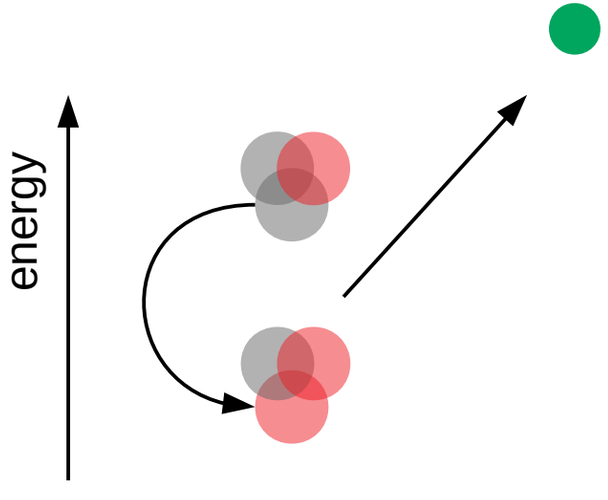


FIG. 5. Energy distribution curve of the beta-rays.

How the Neutrino came to be

Where is the missing energy going?



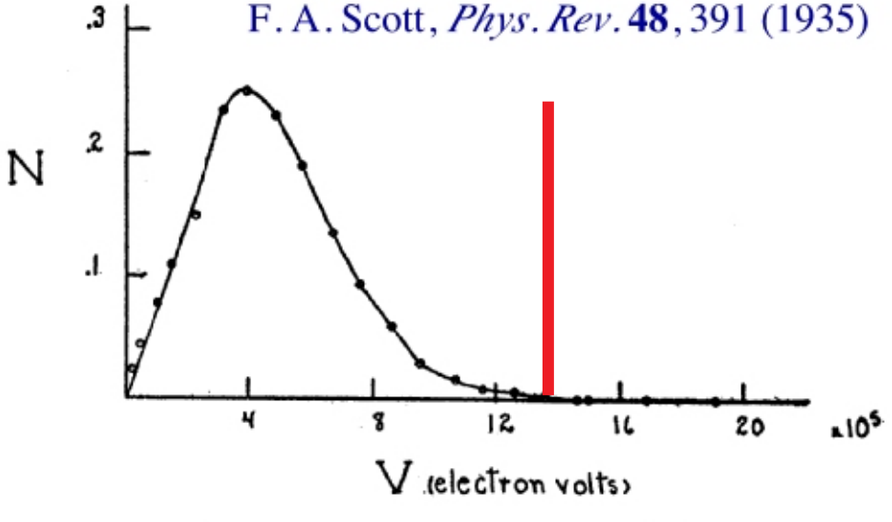


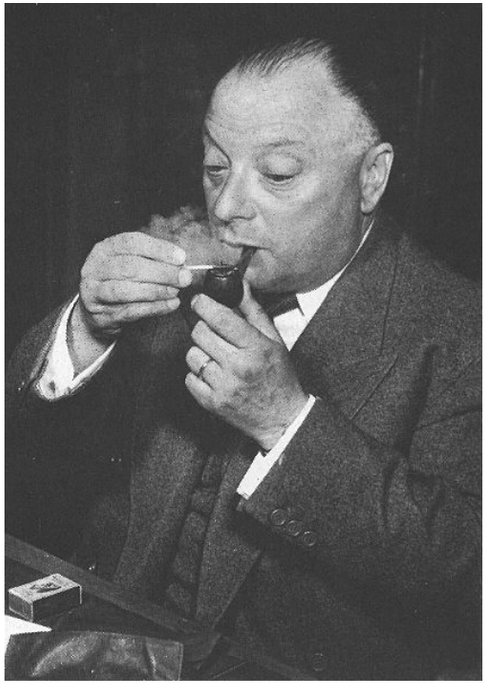
FIG. 5. Energy distribution curve of the beta-rays.

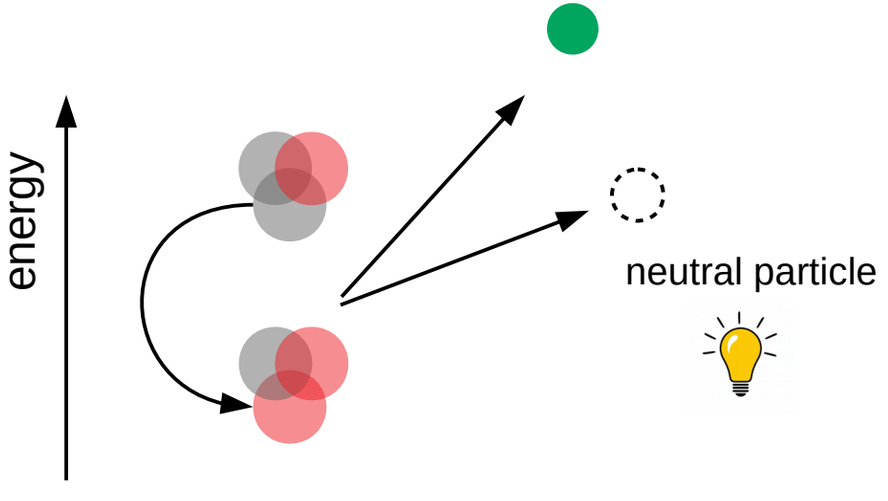
How the Neutrino came to be

Dear Radioactive Ladies and Gentlemen,
I have come upon a desperate way out […] regarding the continuous ß–decay spectrum.

A neutron is emitted in along with the electron, in such a way that the sum of the energies […] is constant.

For the time being I dare not publish anything about this idea…
December 4th, 1930 W. Pauli





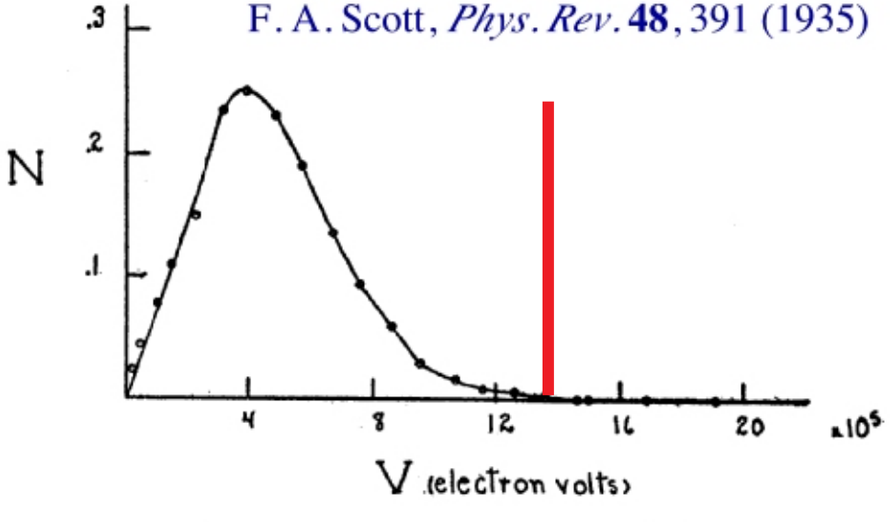
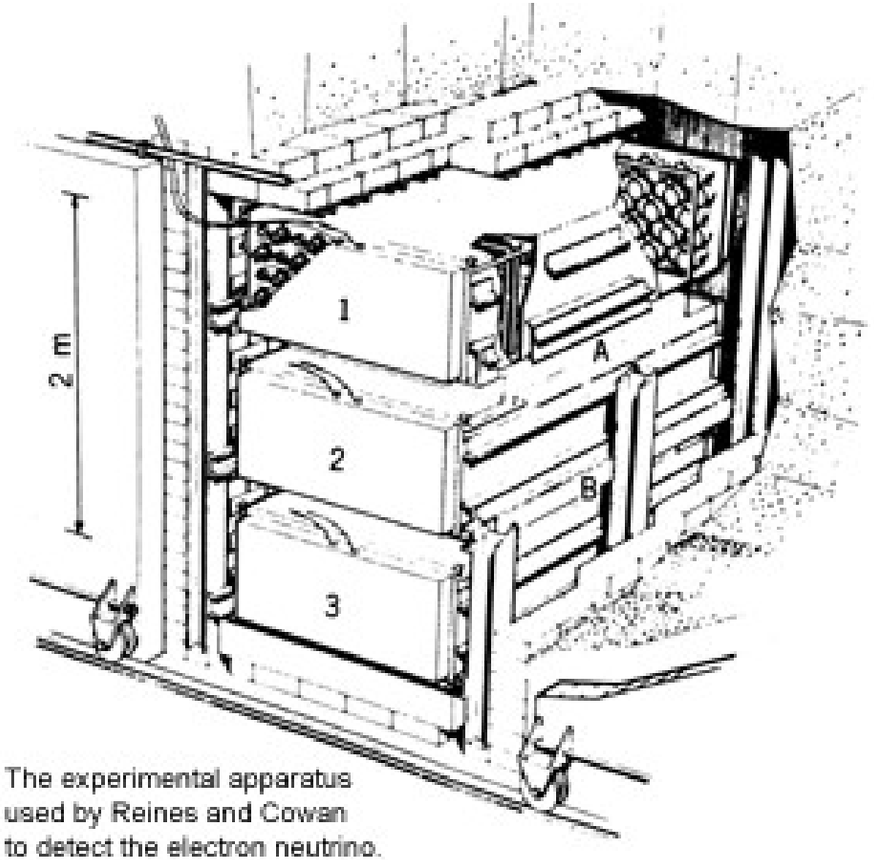


FIG. 5. Energy distribution curve of the beta-rays.

How the Neutrino came to be

Frederick Reines (left) and Clyde L. Cowan, Jr. with the control equipment used in their first tentative observations of the neutrino at Hanford, Washington, in 1953. Their definitive detection of the (anti) neutrino was performed at Savannah River, Georgia, three years later. (Courtesy General Electric Co.)



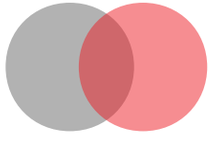
The experimental apparatus used by Reines and Cowan to detect the electron neutrino.

We are happy to inform you that we have definitely detected neutrinos from fission fragments by observing beta-decay protons…

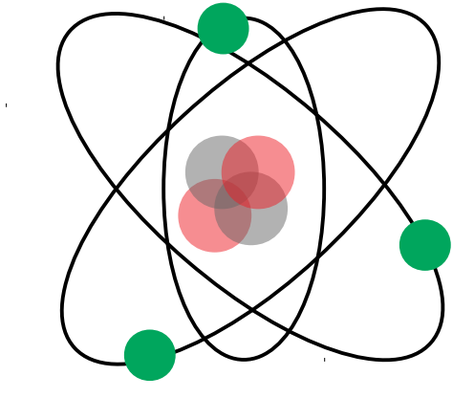
June 14th, 1956 Reines & Cowan

What took so long?

electrons are charged particles, interact electromagnetically



neutrons and protons interact via the strong force, which hold them together.



e-, p, and n make up atoms which are the building blocks of our world.

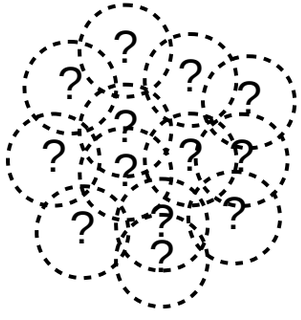
Photons are the carriers of the electromagnetic force

neutrinos have no charge, and interact only via the “weak” force

“detecting” neutrinos is difficult.

requires creative new detector technologies.

What took so long?



Where are neutrinos?

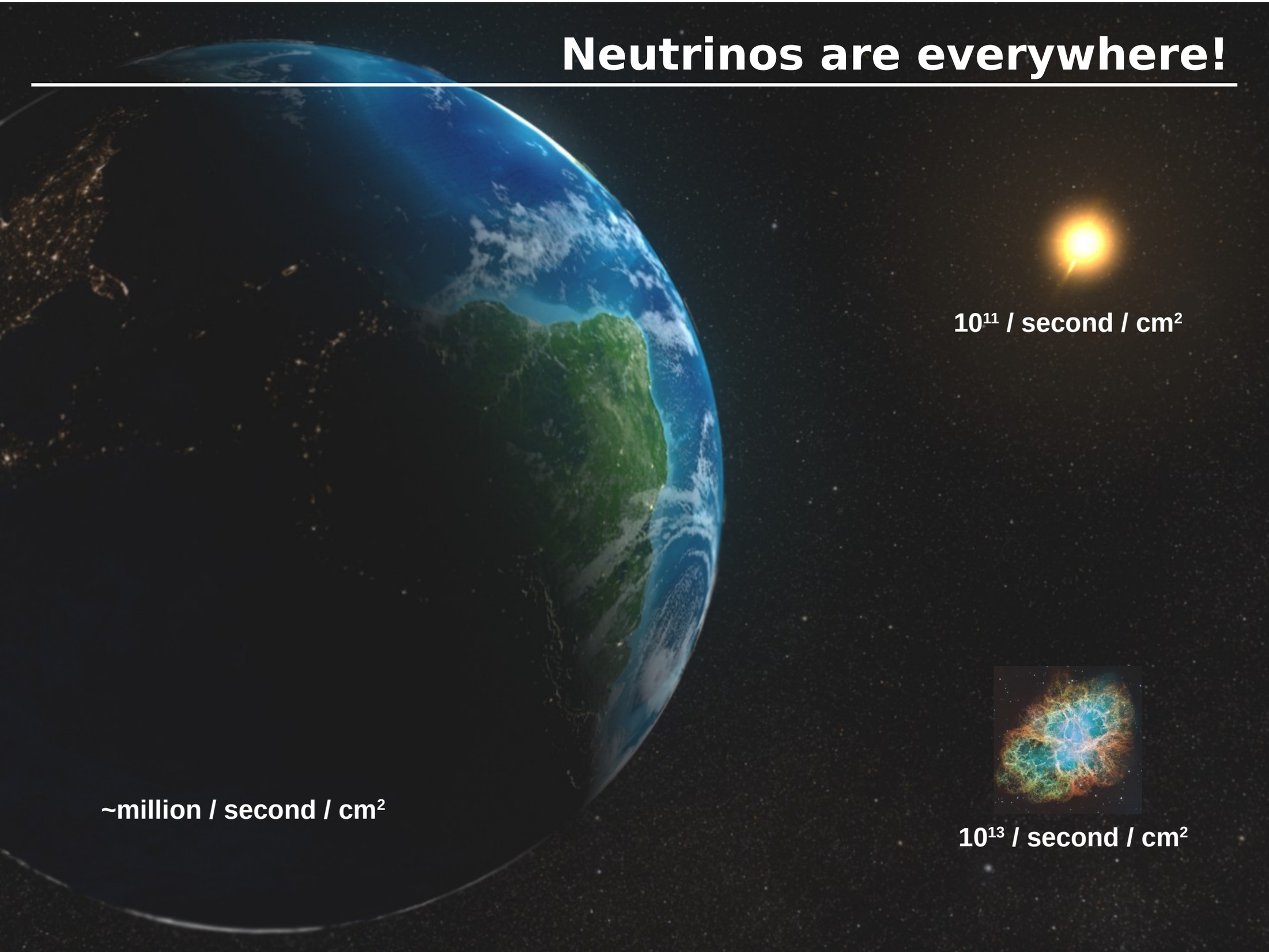
What role do they play in our universe?

neutrinos have no charge, and interact only via the “weak” force

“detecting” neutrinos is difficult.

requires creative new detector technologies.

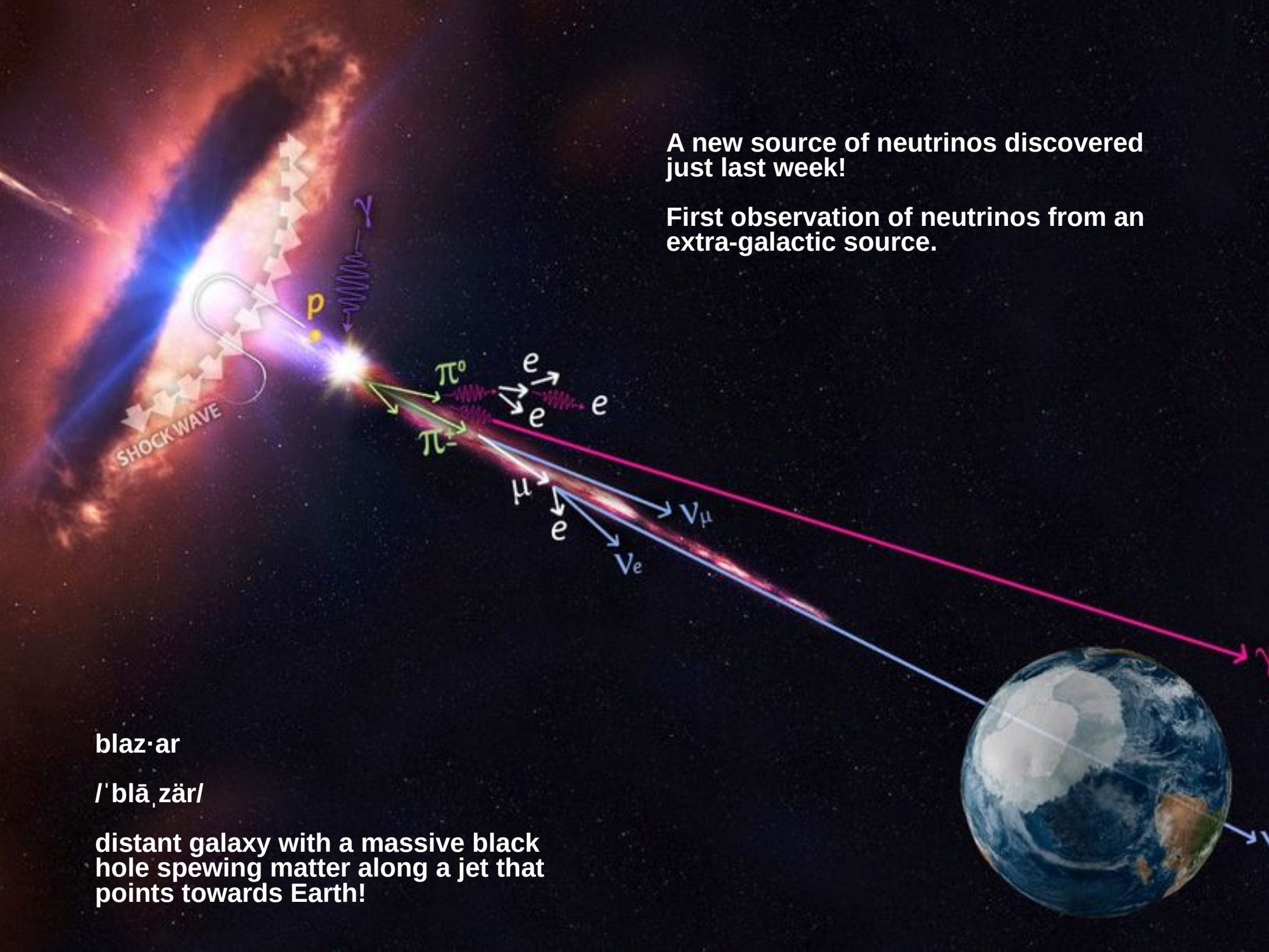
Neutrinos are everywhere!



~million / second / cm^2

10^{11} / second / cm^2

10^{13} / second / cm^2



A new source of neutrinos discovered just last week!

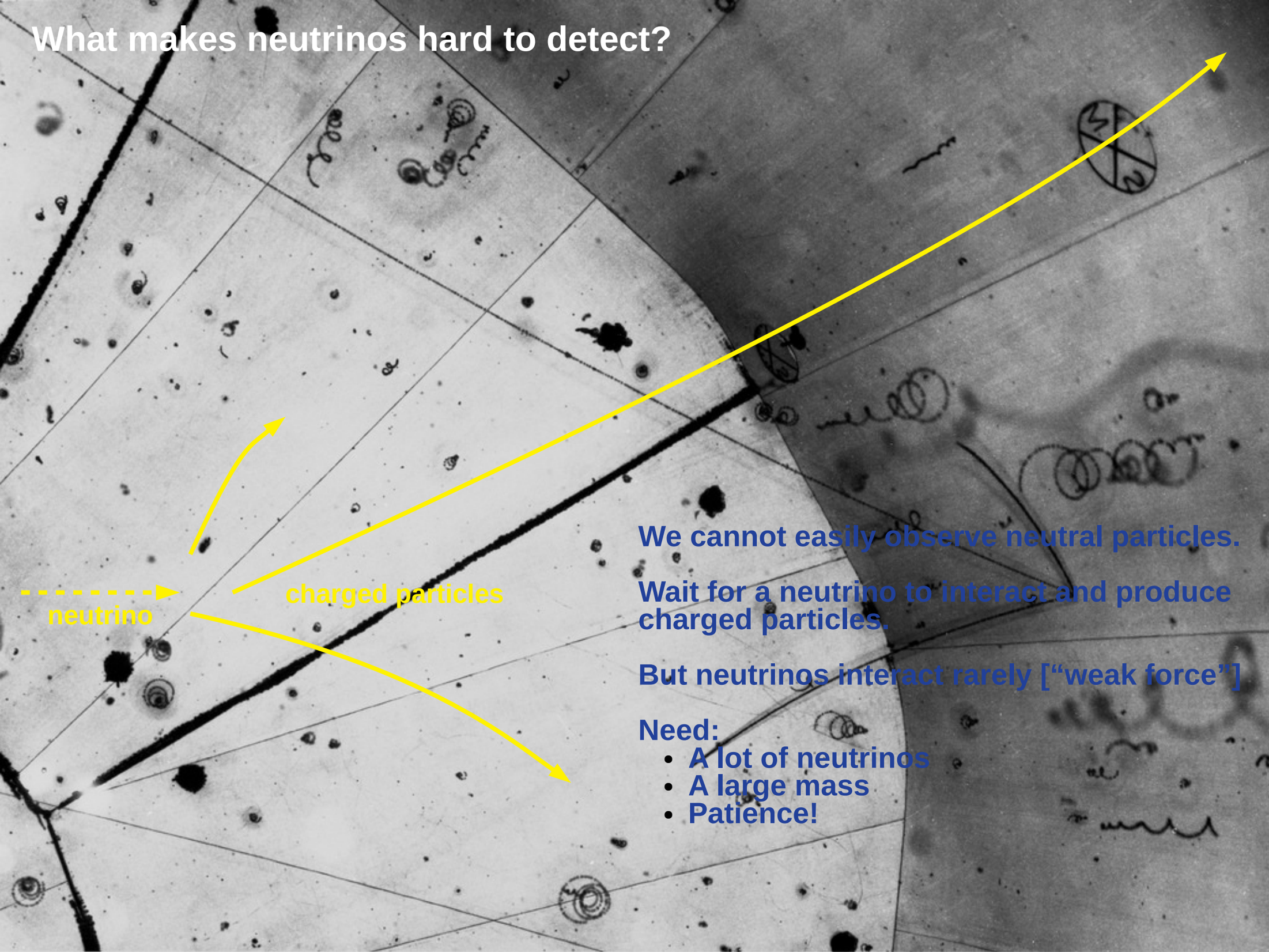
First observation of neutrinos from an extra-galactic source.

blaz·ar

/ˈblāˌzär/

distant galaxy with a massive black hole spewing matter along a jet that points towards Earth!

What makes neutrinos hard to detect?



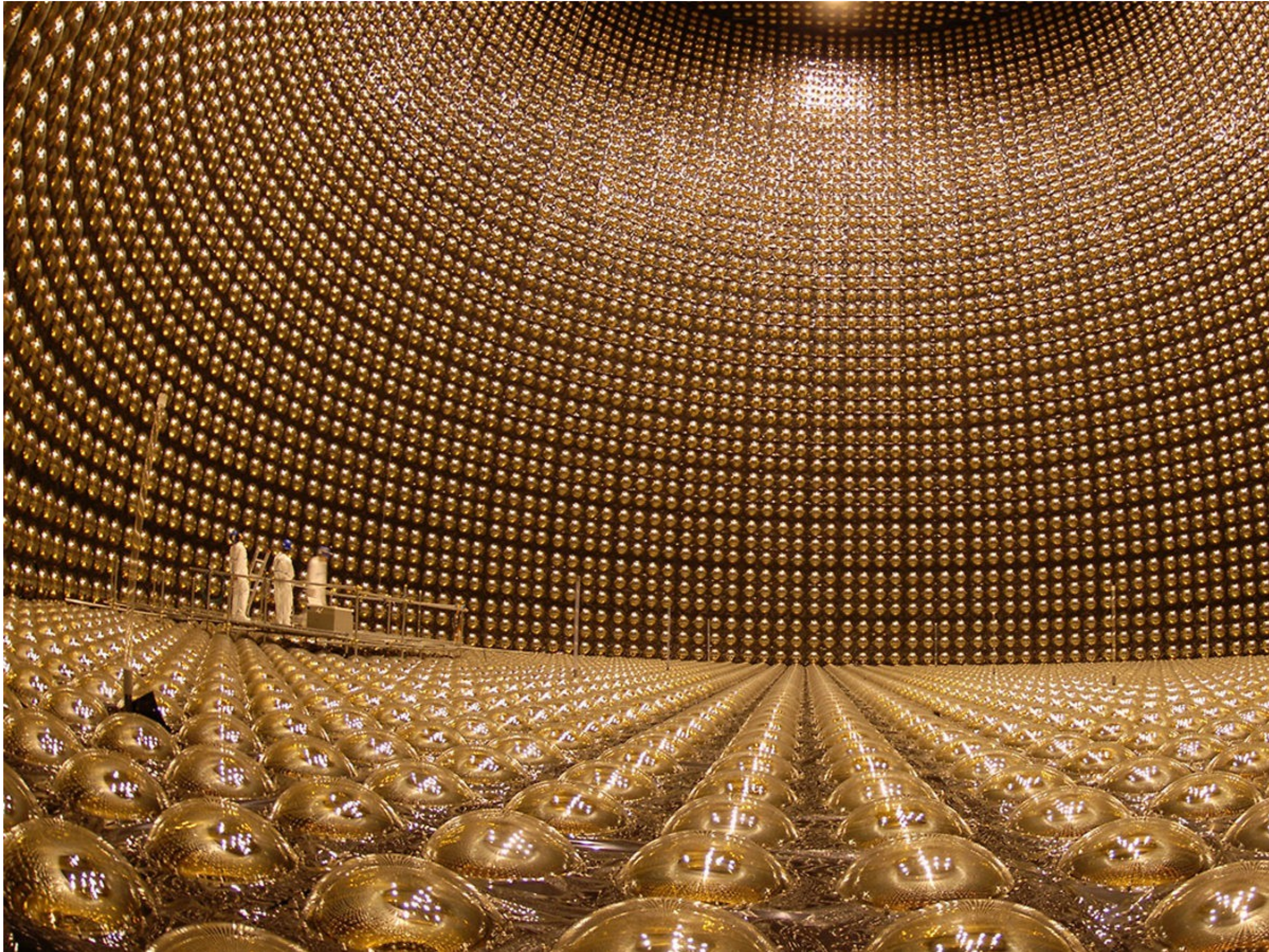
We cannot easily observe neutral particles.

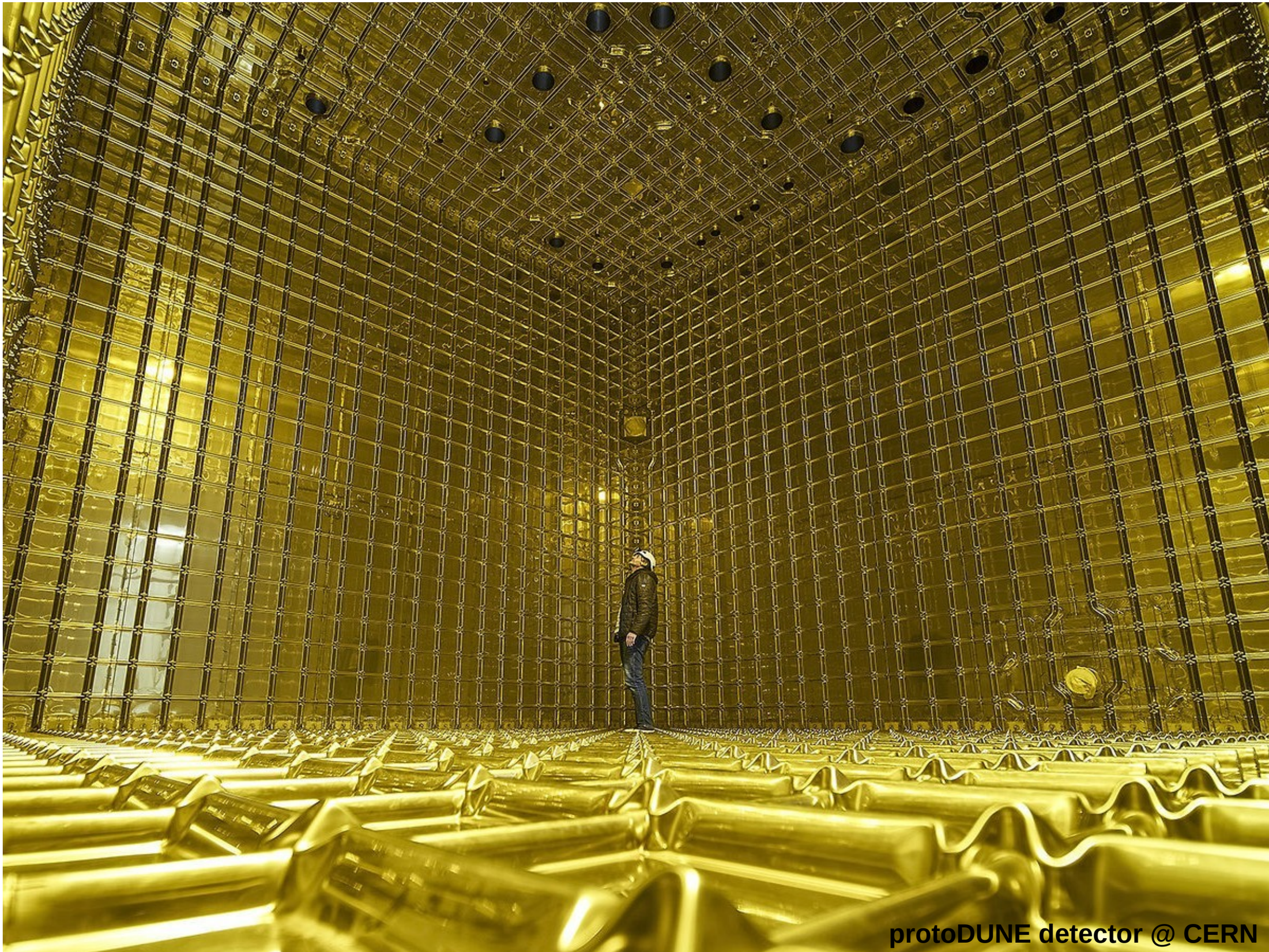
Wait for a neutrino to interact and produce charged particles.

But neutrinos interact rarely [“weak force”]

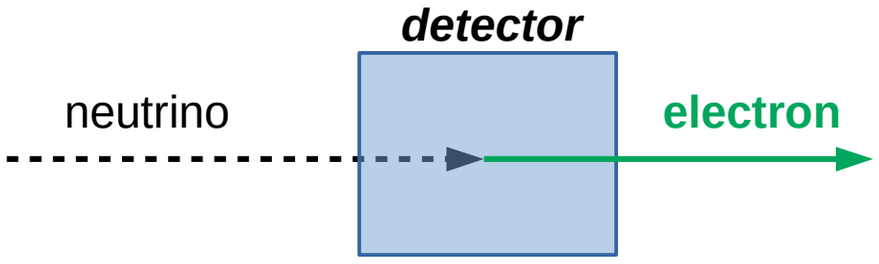
Need:

- A lot of neutrinos
- A large mass
- Patience!




protoDUNE detector @ CERN

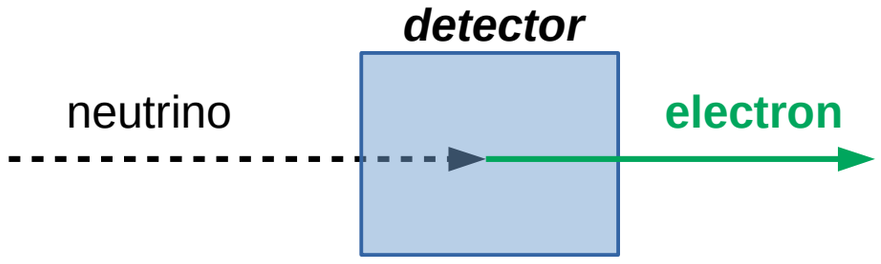
Why go through the trouble?



Cowan

Reines

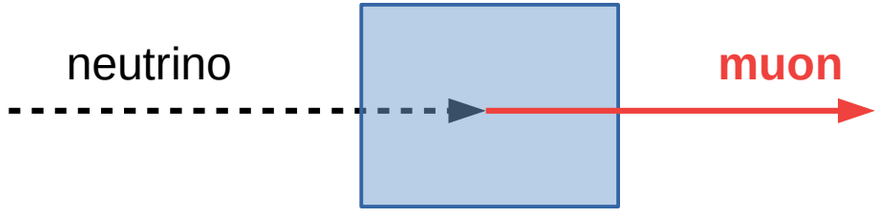
Savannah River - 1956



Cowan

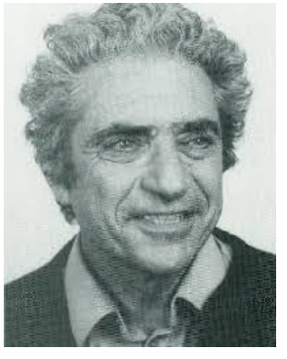
Reines

Savannah River - 1956



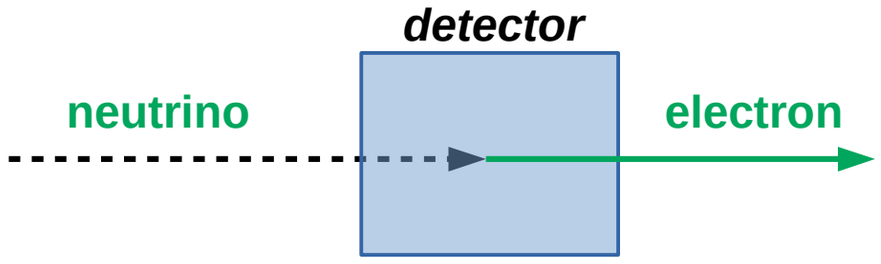
Schwartz

Lederman



Steinberger

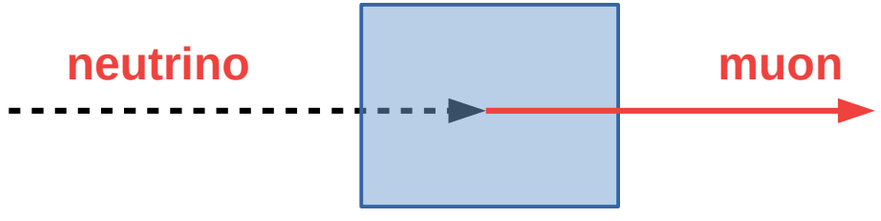
Brookhaven National Lab - 1962



Cowan

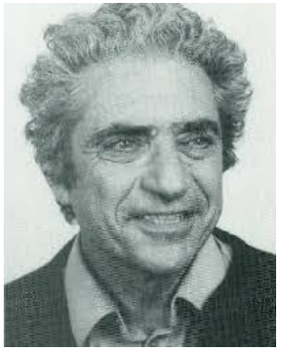
Reines

Savannah River - 1956



Schwartz

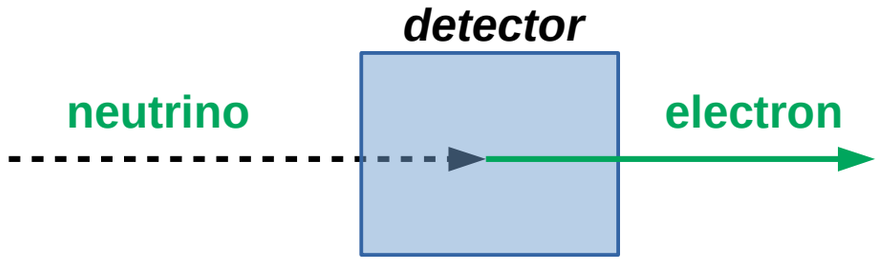
Lederman



Steinberger

Brookhaven National Lab - 1962

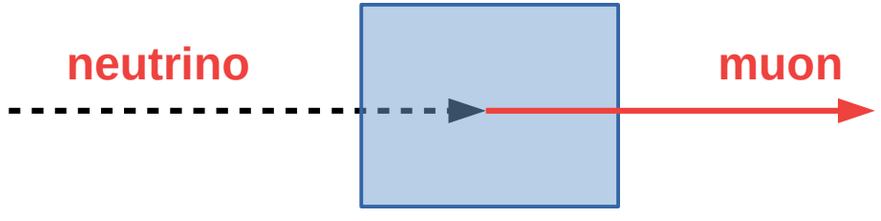
A new neutrino!



Cowan

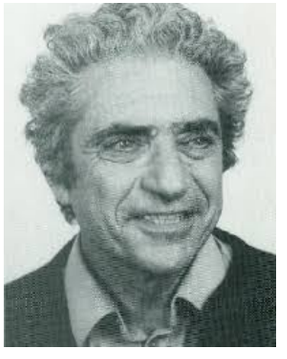
Reines

Savannah River - 1956



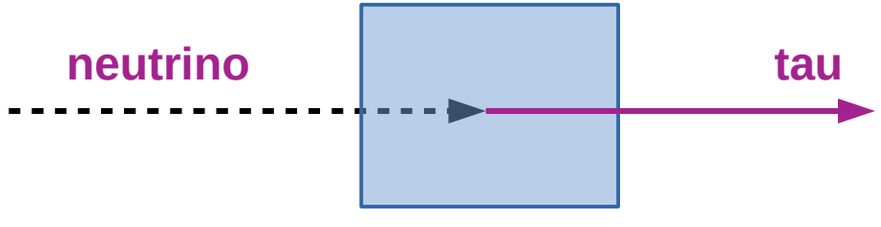
Schwartz

Lederman



Steinberger

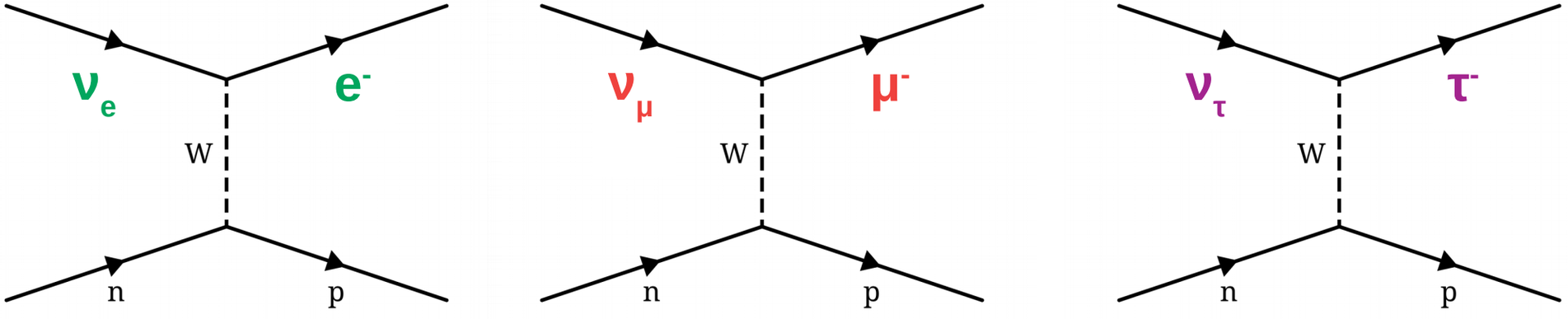
Brookhaven National Lab - 1962



Fermilab

Fermilab - 1997

Three Neutrinos. What sets them apart?



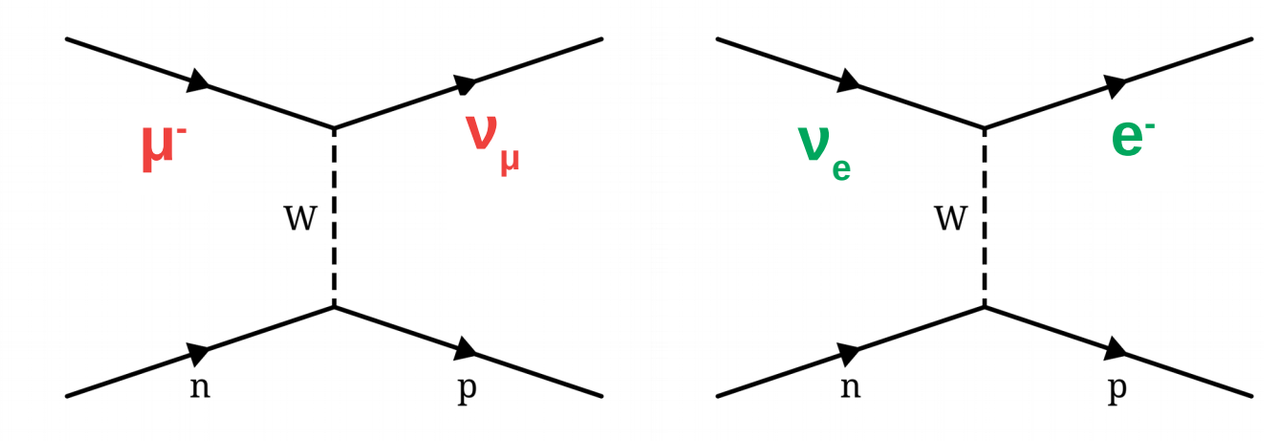
Just as charge is conserved in these interactions, so is the lepton “flavor”.

Electrons only interact with one type of neutrino, muons with another…

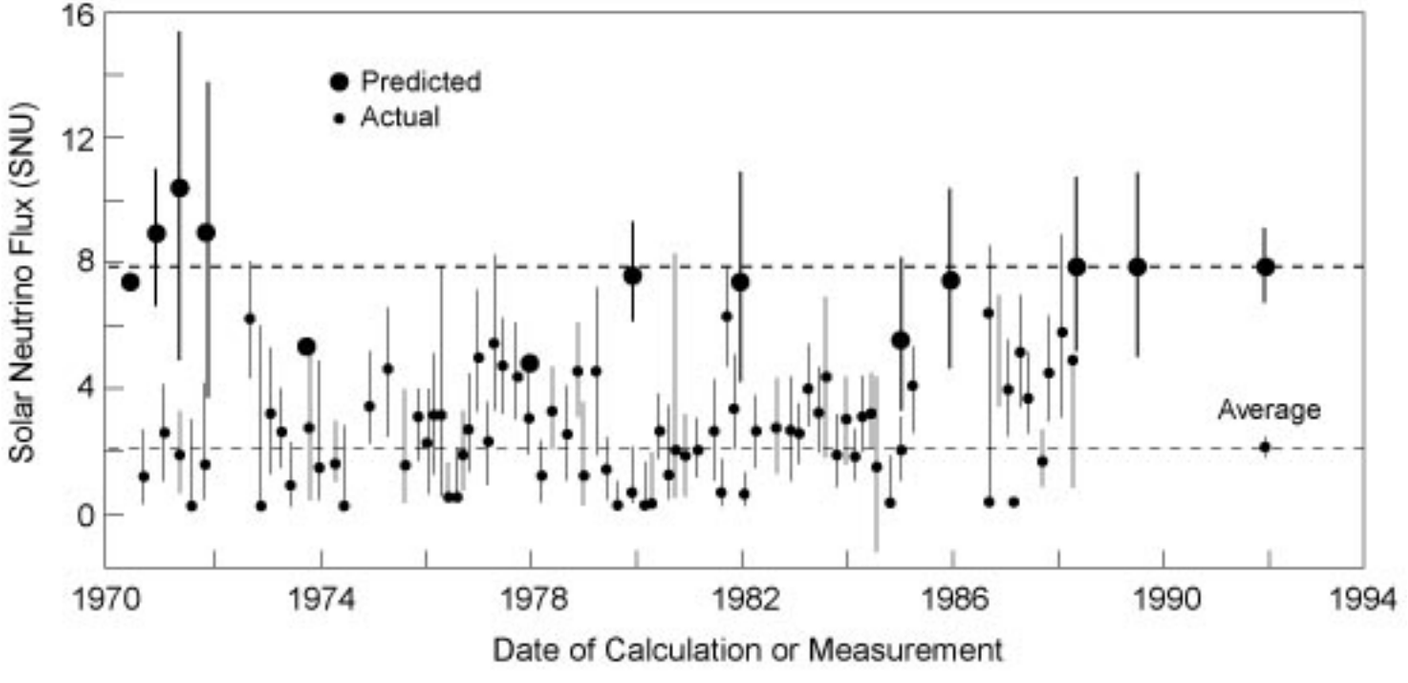
We call them the electron neutrino and muon neutrino respectively.

Conservation of lepton “flavor” is the manifestation of a fundamental symmetry.

Not so fast...

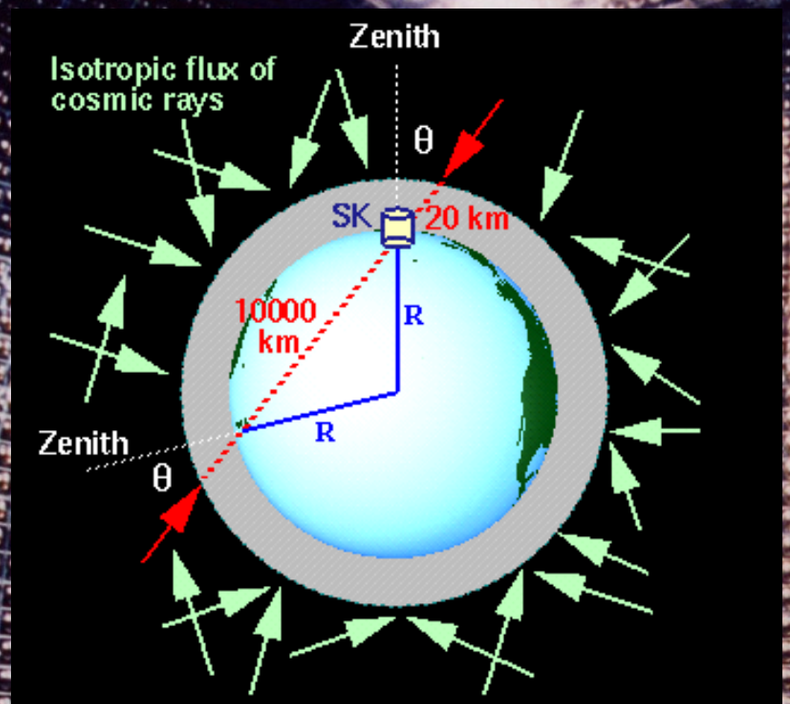


The “Solar Neutrino Problem”

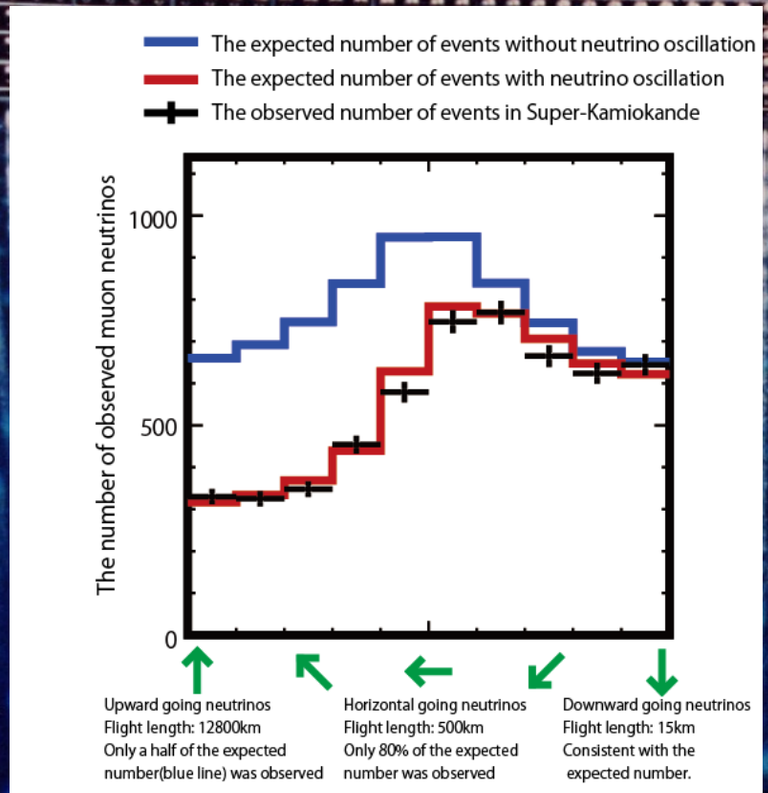


Observed 1/3 of the expected neutrino flux!

From missing energy to missing neutrinos!



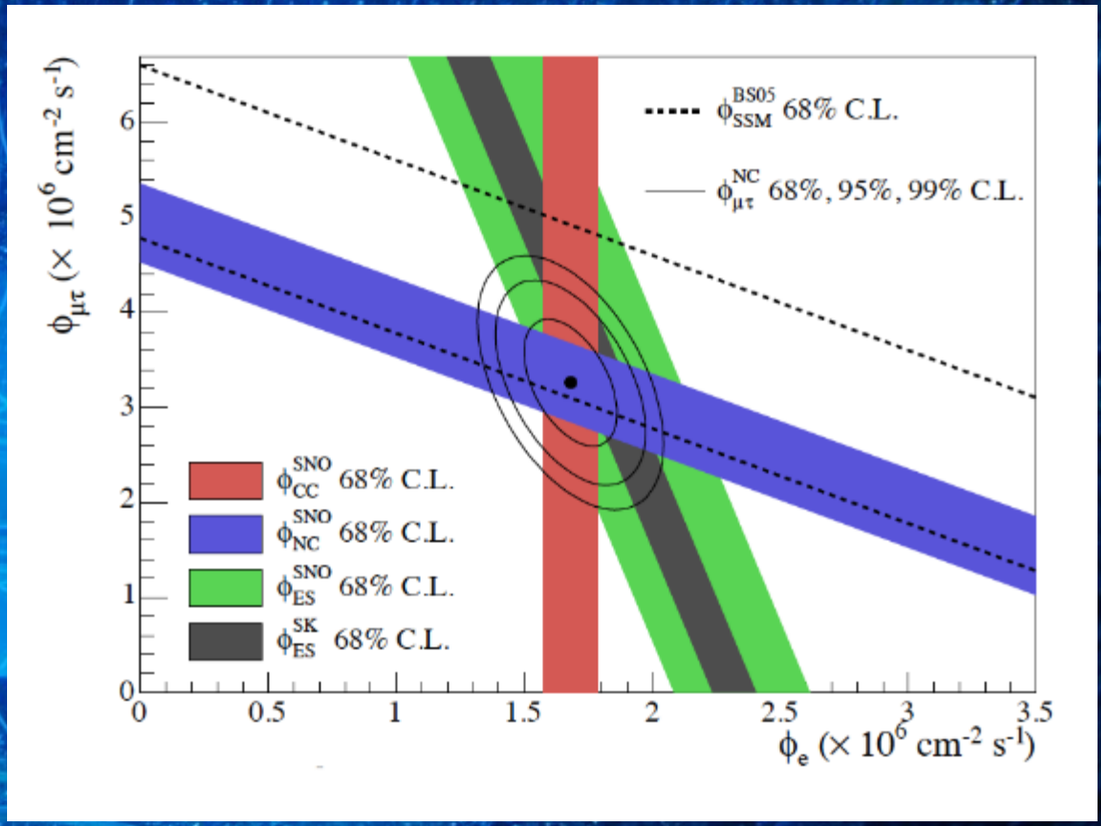
http://hep.bu.edu/~superk/atmnu/



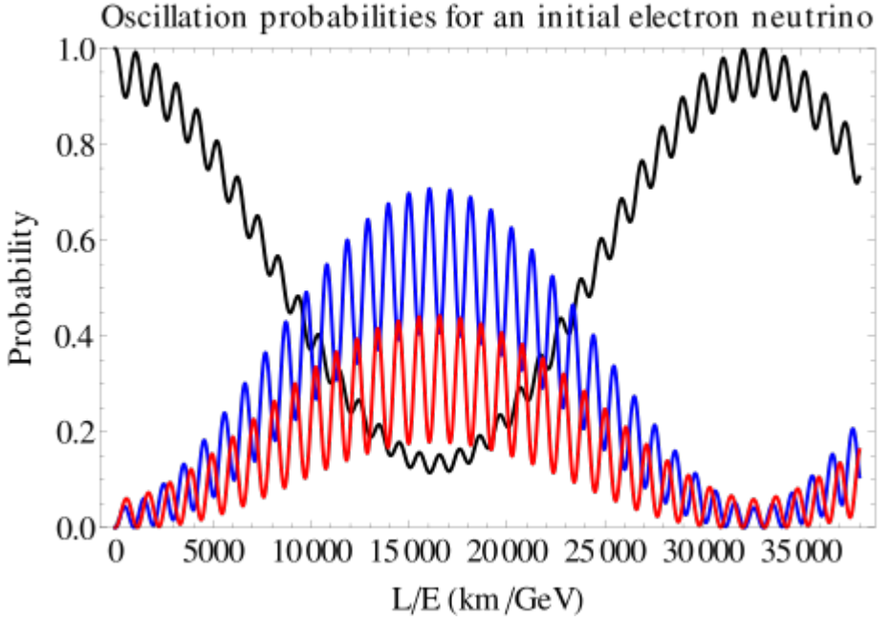
http://www-sk.icrr.u-tokyo.ac.jp/sk/sk/neutrino-e.html

$$\nu_e + {}^2H \rightarrow e^- + p + p$$

$$\nu_x + {}^2H \rightarrow \nu_x + p + n$$



Neutrino Oscillations



Neutrinos interact with a specific “flavor” but travel with different masses.

When one is known, the other is not. Think of light being both a particle and a wave.

Neutrino oscillations → quantum mechanics on a macroscopic scale!

Where are we Today?

We know neutrinos oscillate & have mass.

Experiment-based evidence for “new physics” beyond our current theories!

What we don’t know is:

What is the neutrino mass?

Do neutrinos behave the same as anti-neutrinos?

Are there more neutrino?

Is a neutrino its own anti-particle?

How light is light?

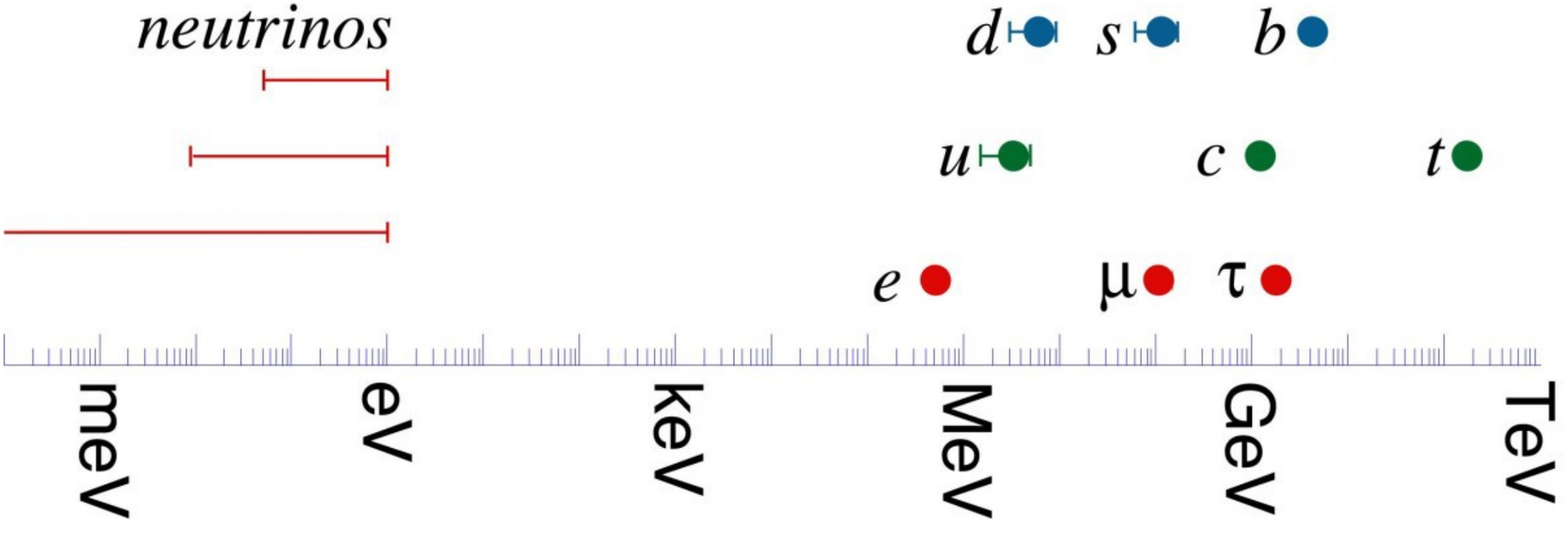
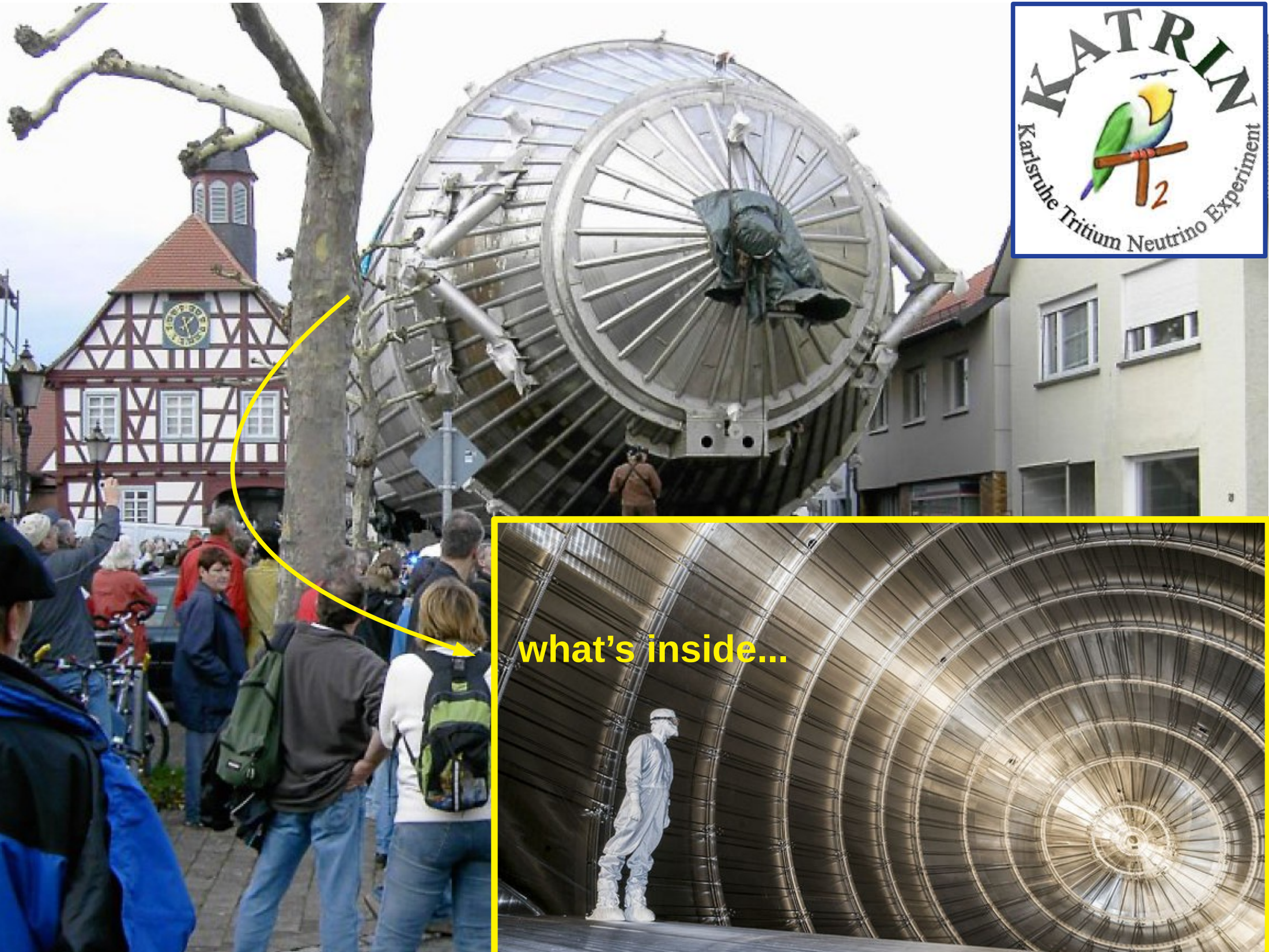
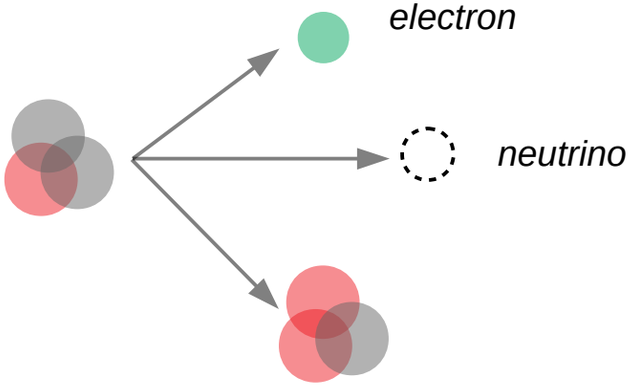
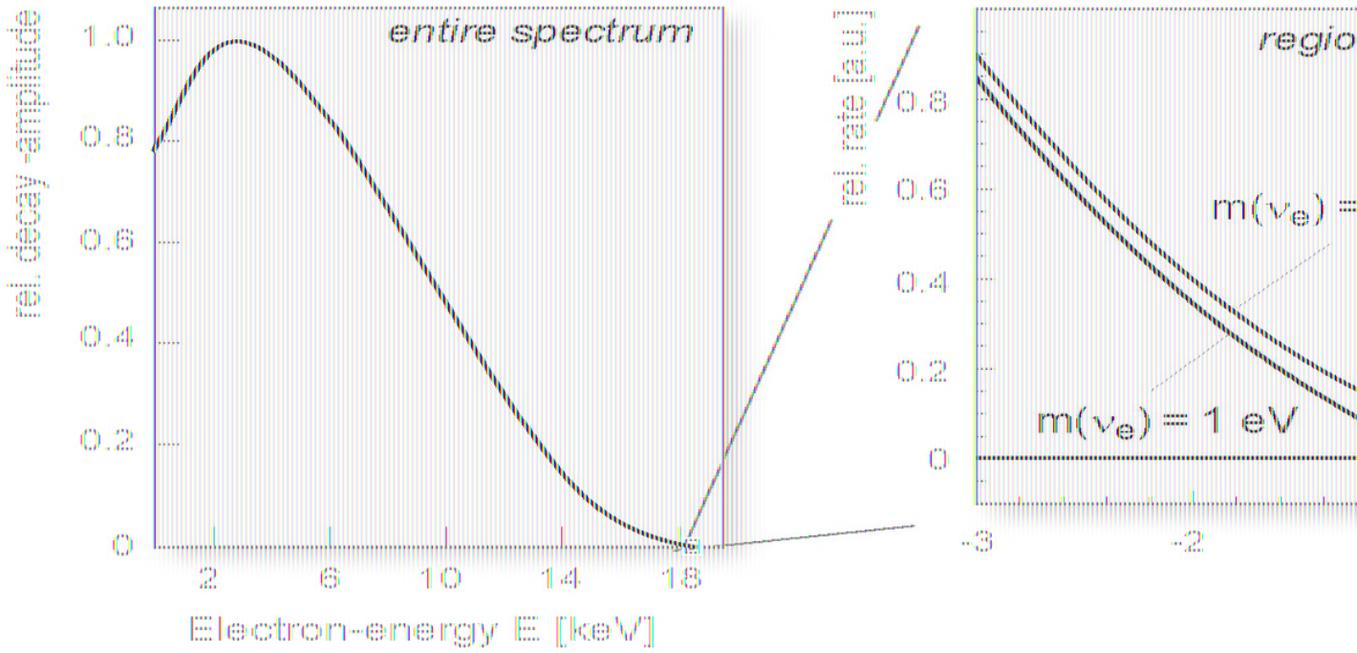


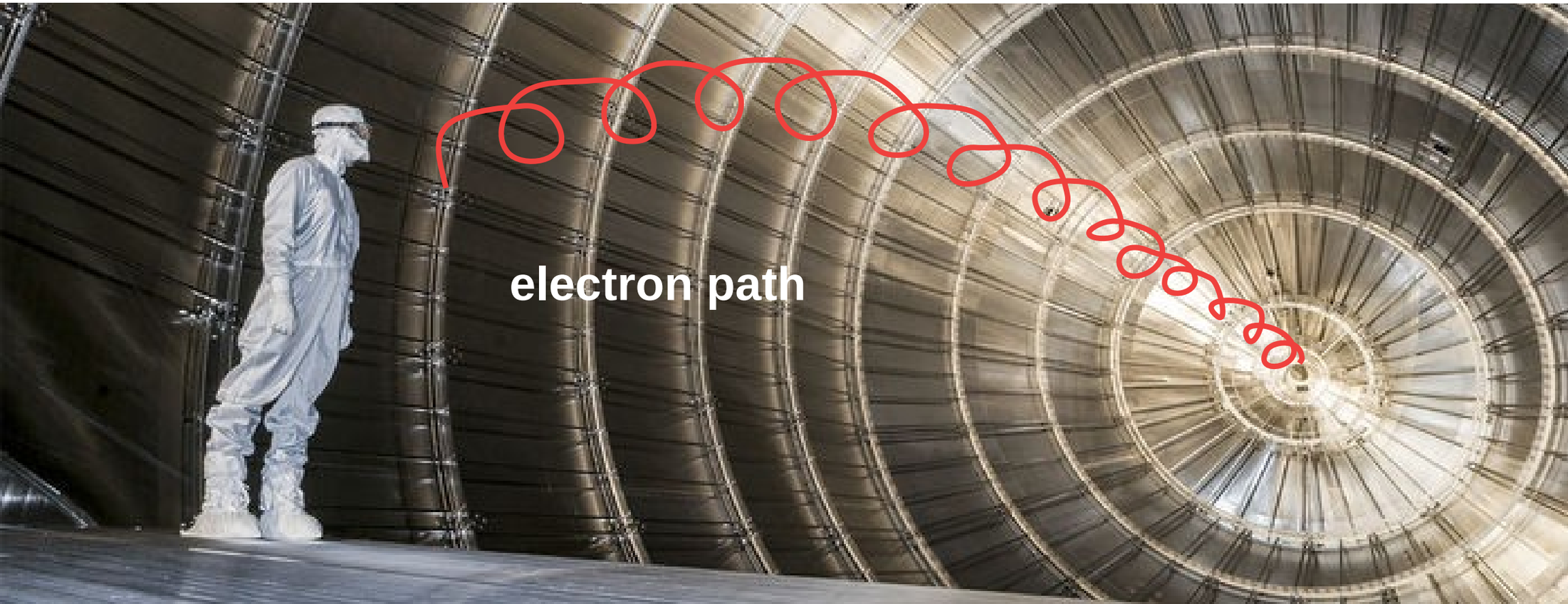
Image credit: Hitoshi Murayama, Berkeley


KATRIN
Karlsruhe Tritium Neutrino Experiment
what's inside...

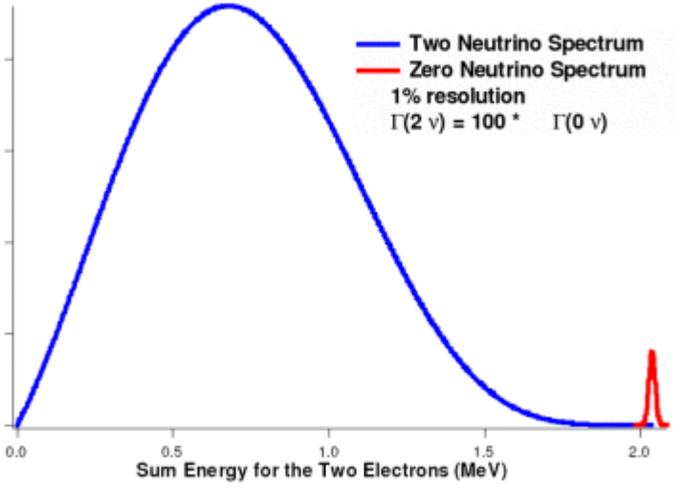
beta-decay

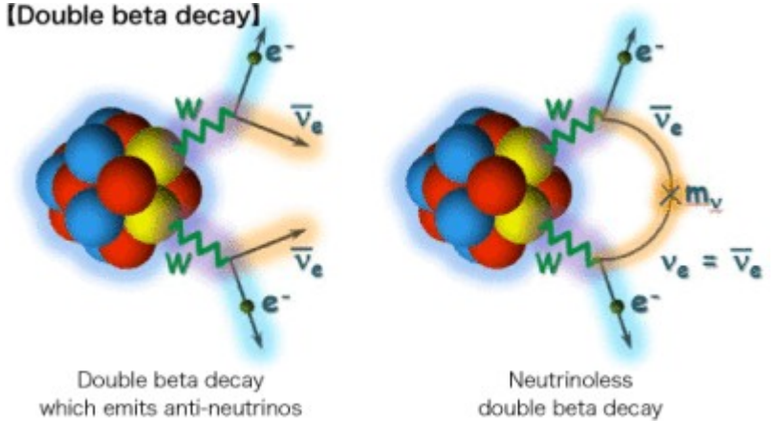

electron
neutrino


entire spectrum
rel. decay-amplitude
1.0
0.8
0.6
0.4
0.2
0
2
6
10
14
18
Electron-energy E [keV]
0.8
0.6
0.4
0.2
0
-3
-2
m(νe) = 1 eV


electron path

neutrino = anti-neutrino?





Search for a process with a half-life of 10^{25} years! [universe age: 10^{9}]

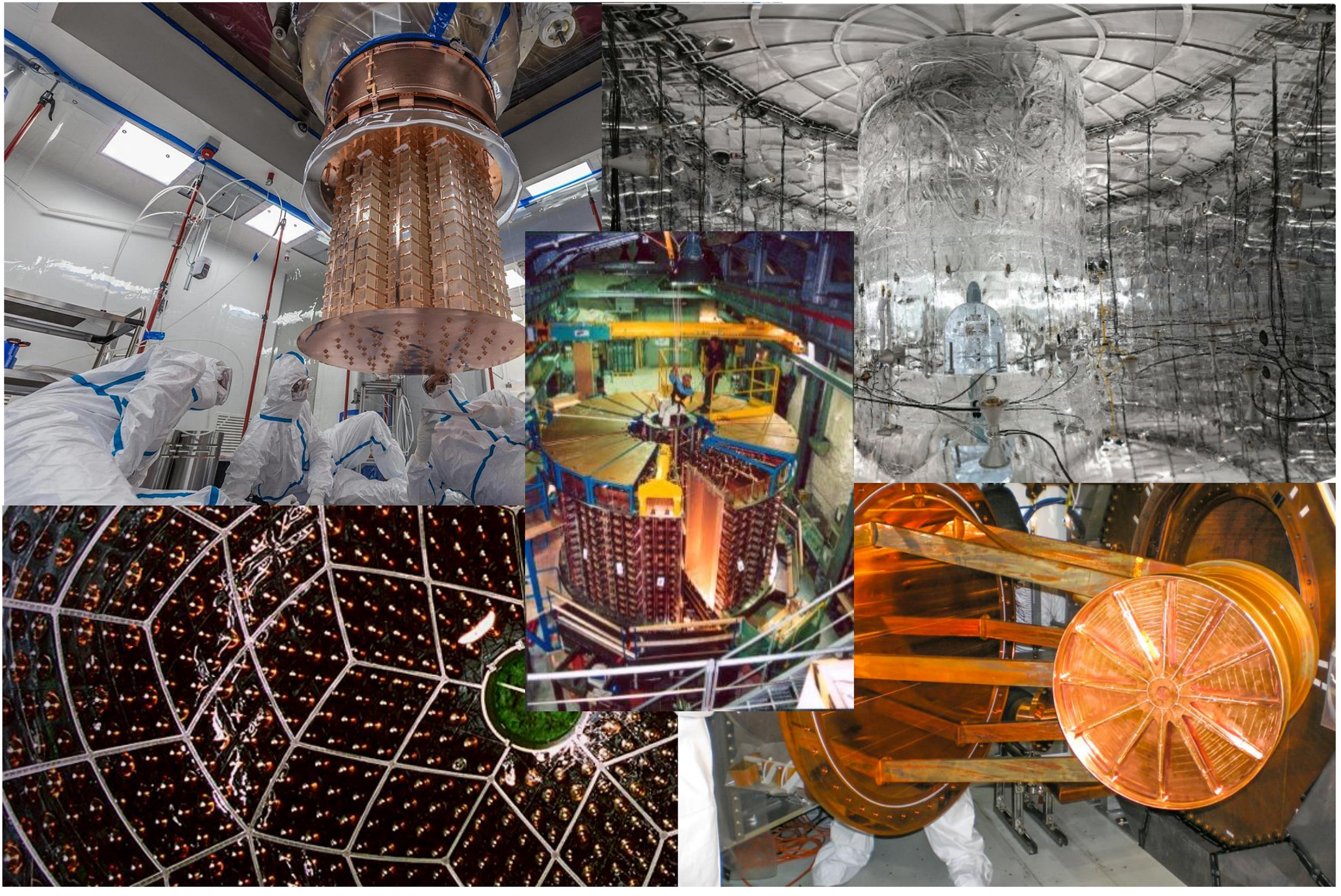
Design experiments which expect 1-2 events over many years!

Suppress background events : false positives.

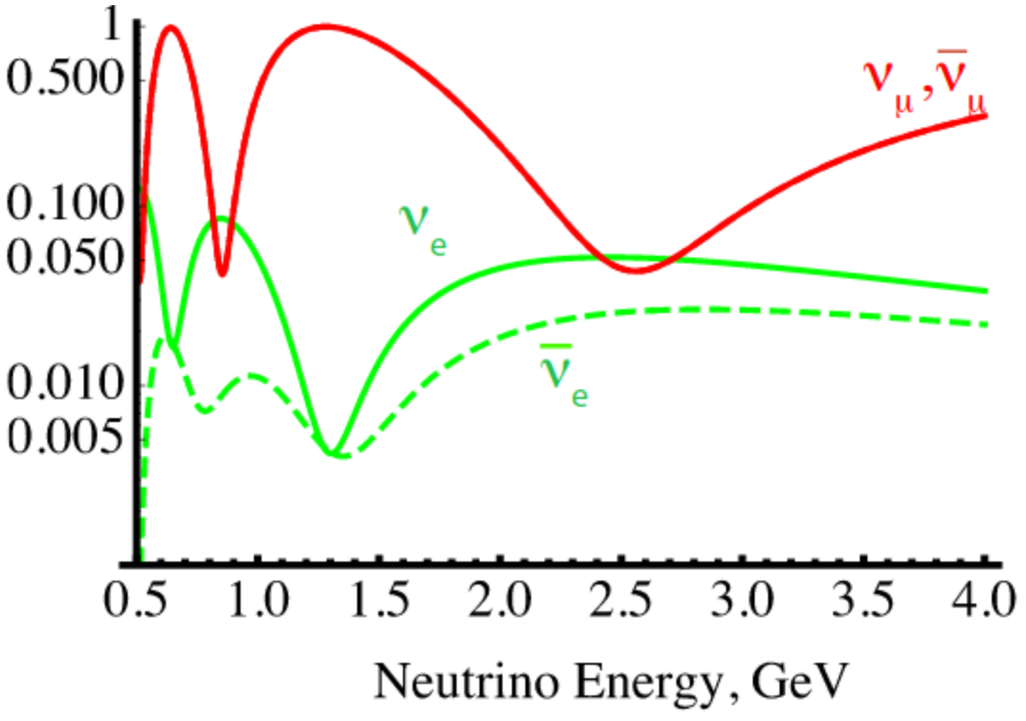
Again, you have to get clever with how you design the experiment!

Image credit: https://www.quantumdiaries.org/2015/09/22/majorananeutrinos-0vbb/

neutrino = anti-neutrino?



Neutrino oscillations : the new frontier



Neutrino oscillations are complex when studied in enough detail.

Two big questions we can address by studying oscillations:

1) Do neutrinos and anti-neutrinos oscillate the same way?

2) Are there more types of neutrinos that we don't yet know about?

Figure credit: Heidi Schellman, Oregon State University

Do neutrinos and anti-neutrinos oscillate the same way?

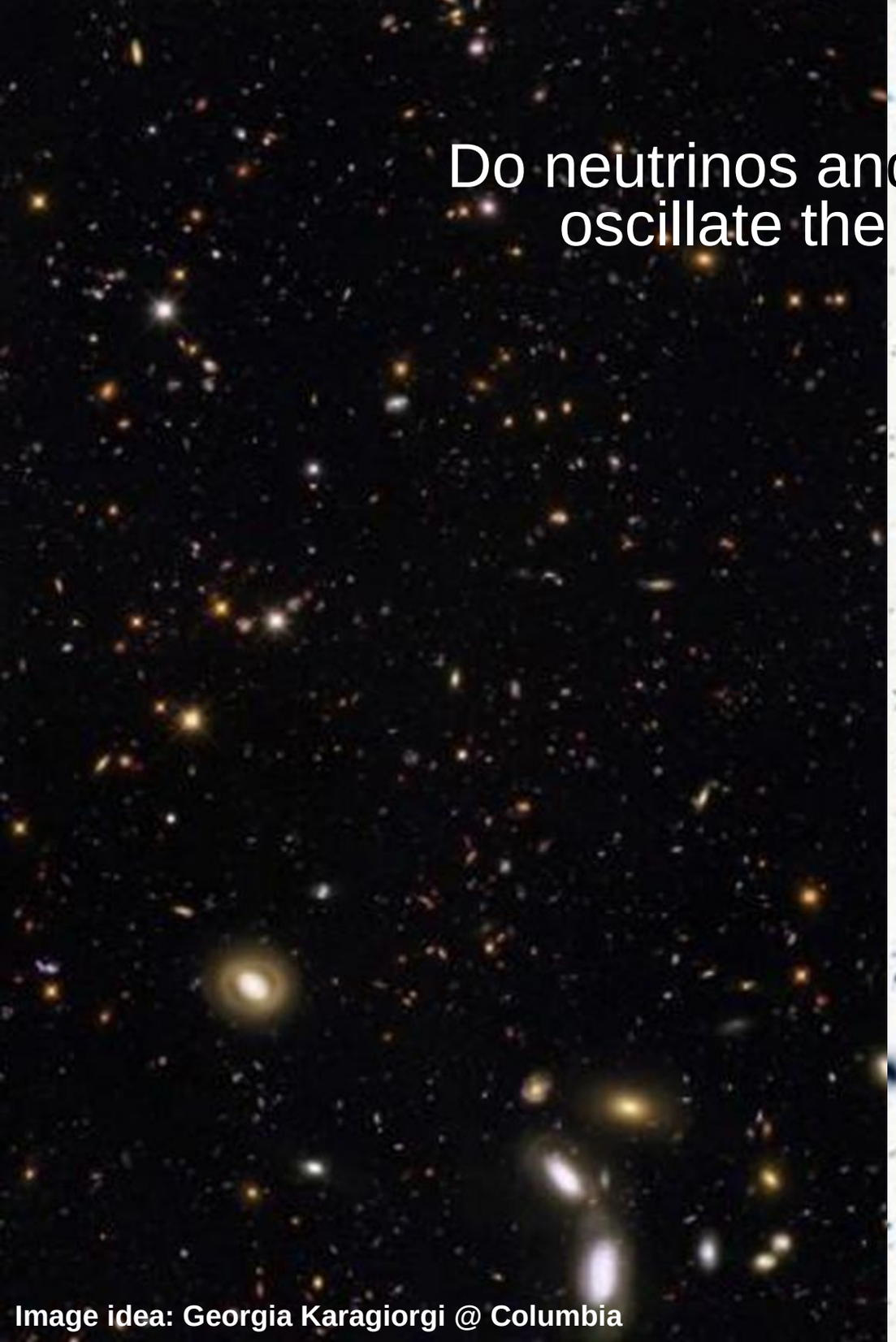


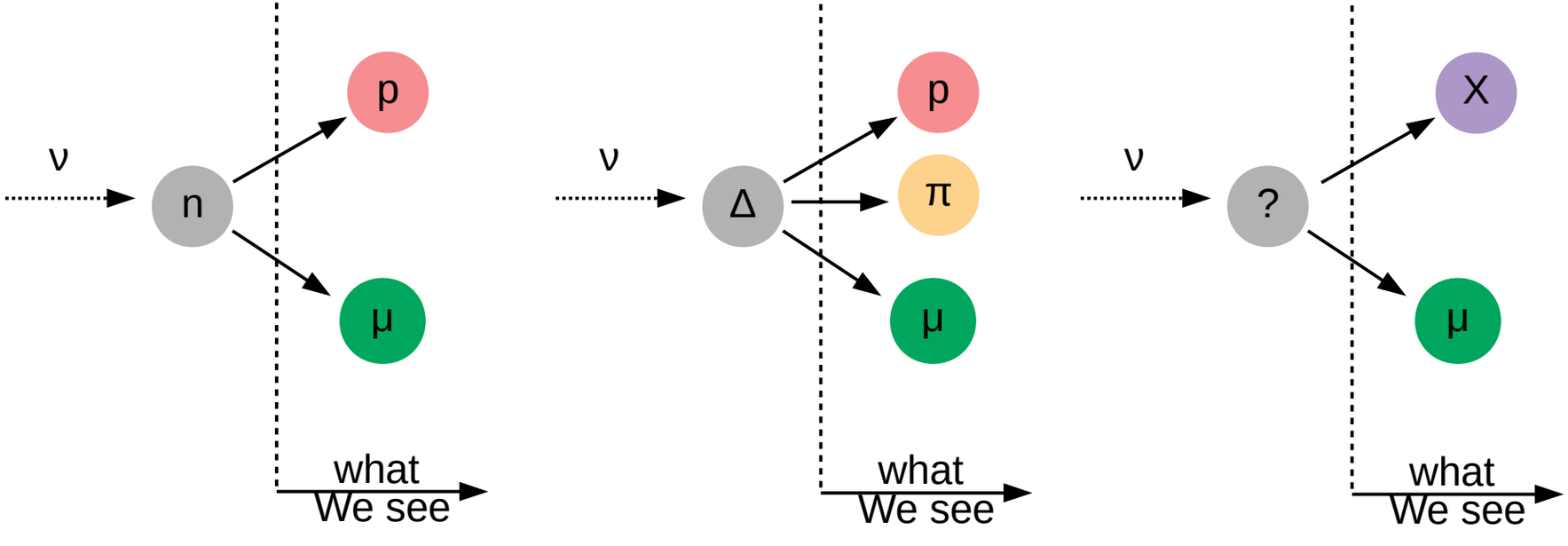
Image idea: Georgia Karagiorgi @ Columbia

Reconstructing Neutrino Energy

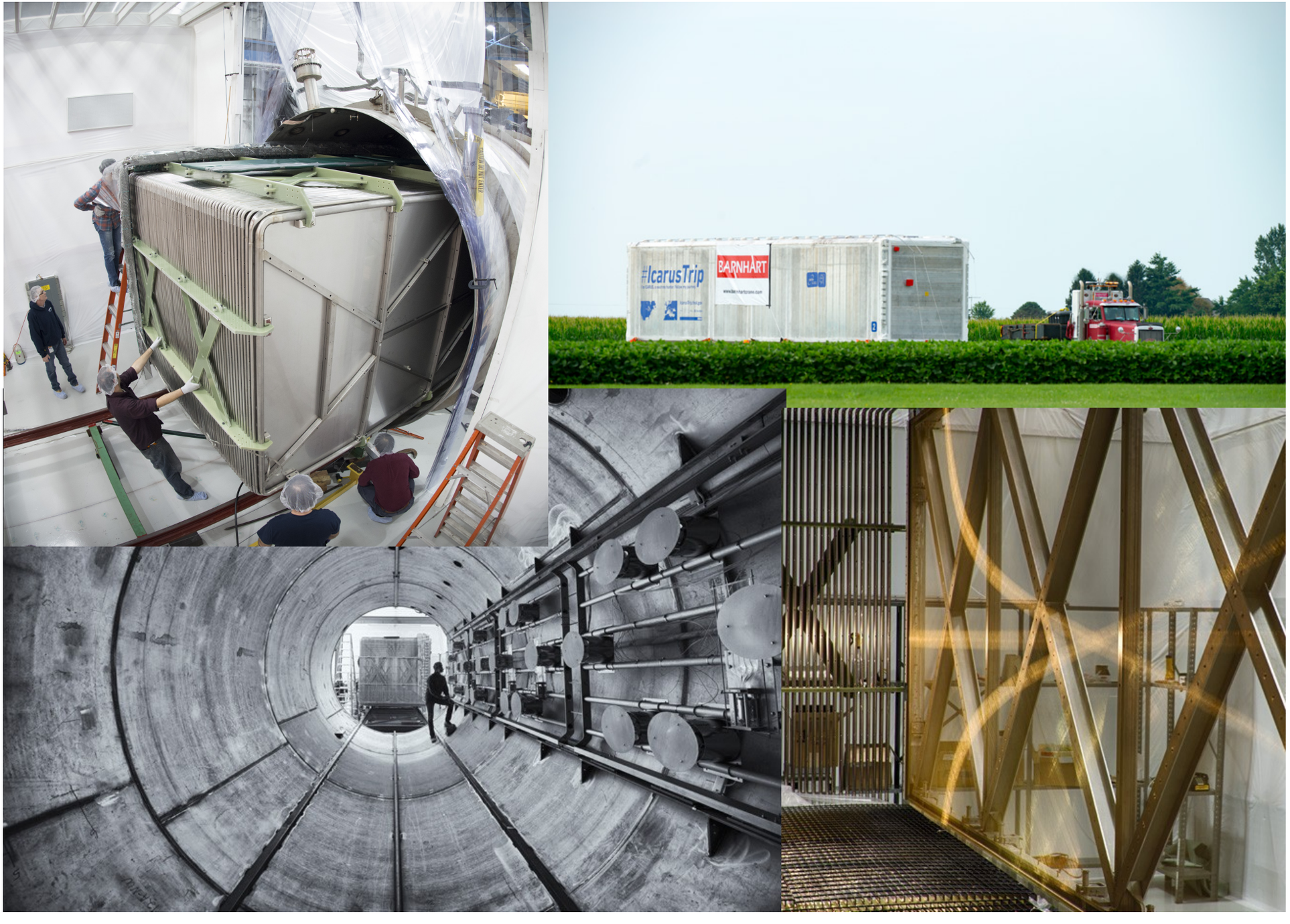
We don’t see the neutrino, only what is produced in neutrino interactions.

Neutrinos produced at Fermilab are in an energy range where their interactions with matter lead to complex events.

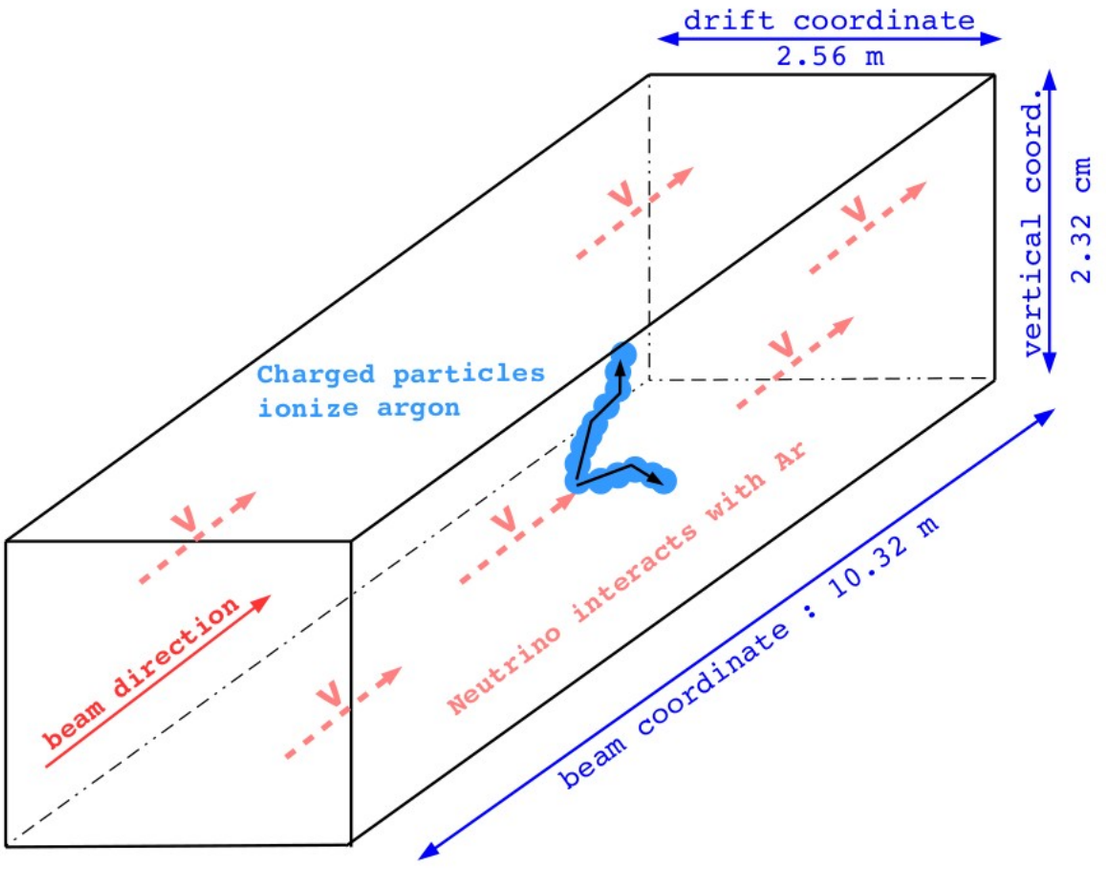
Having a detector capable of measuring the fine details of an interaction helps reconstruct energy, and thus measure oscillations.

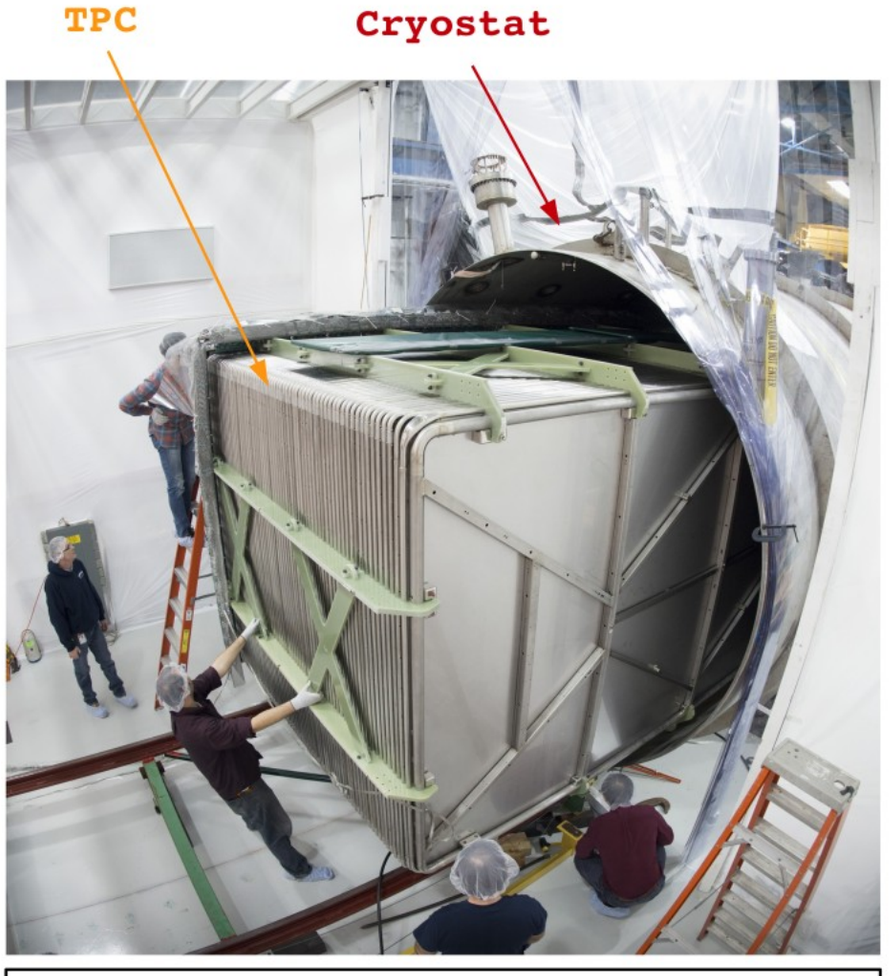


Neutrinos in HD



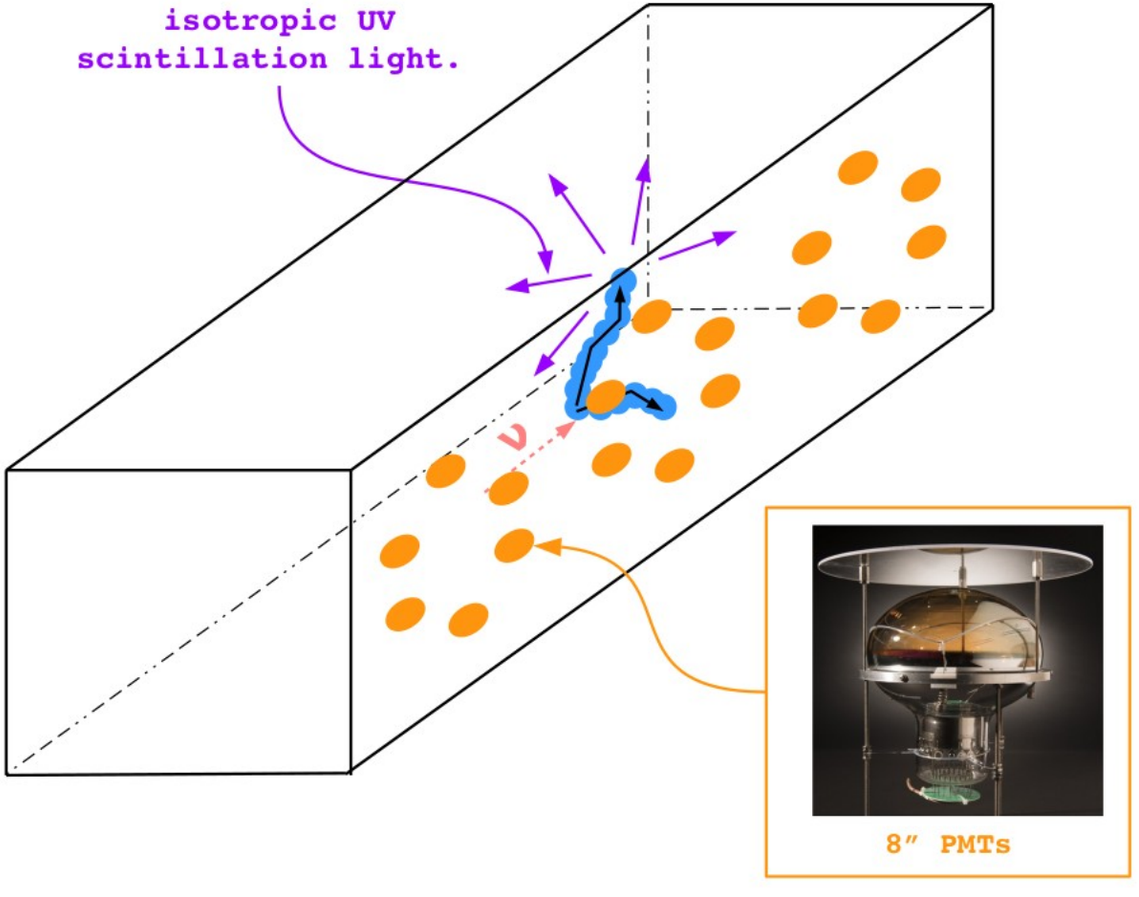
LArTPC Detectors





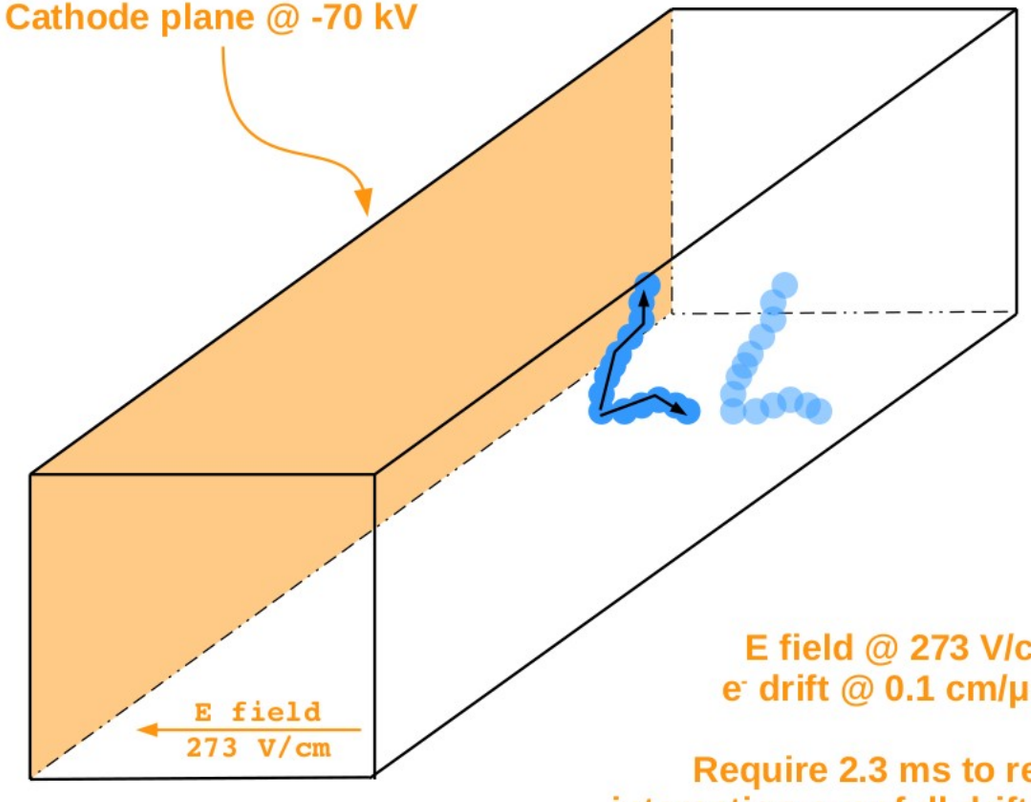
TPC being positioned in cryostat

LArTPC Detectors



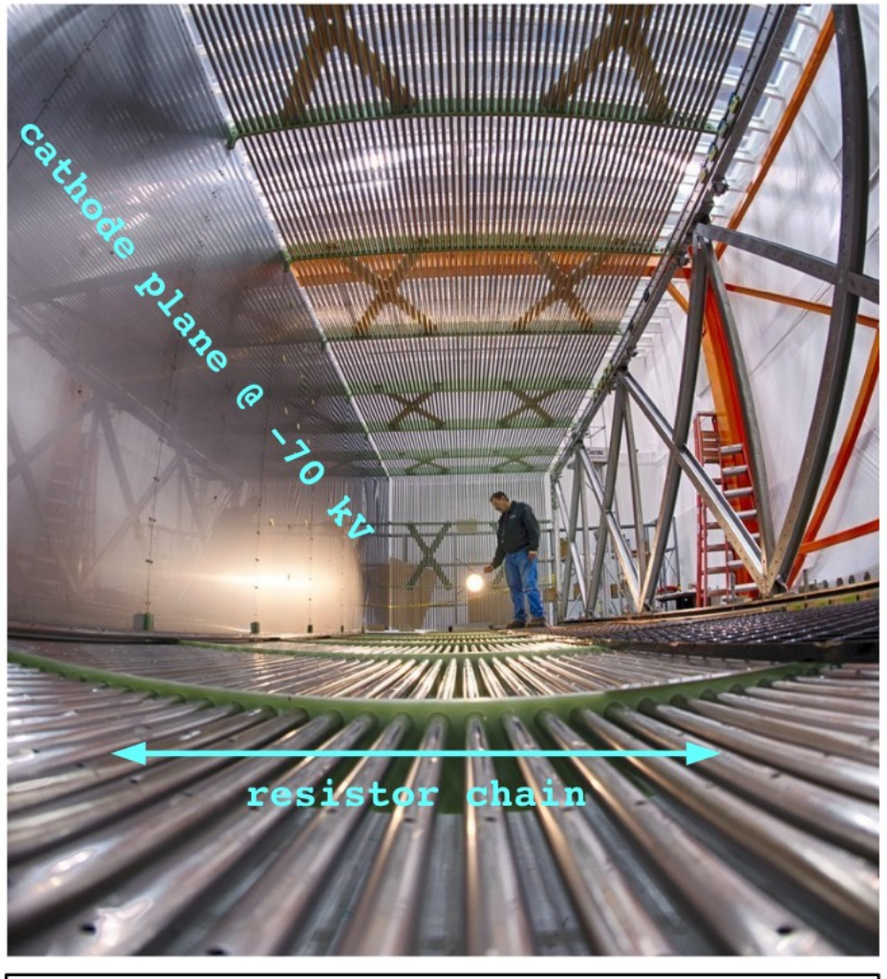
Looking inside cryostat, before TPC inserted

LArTPC Detectors



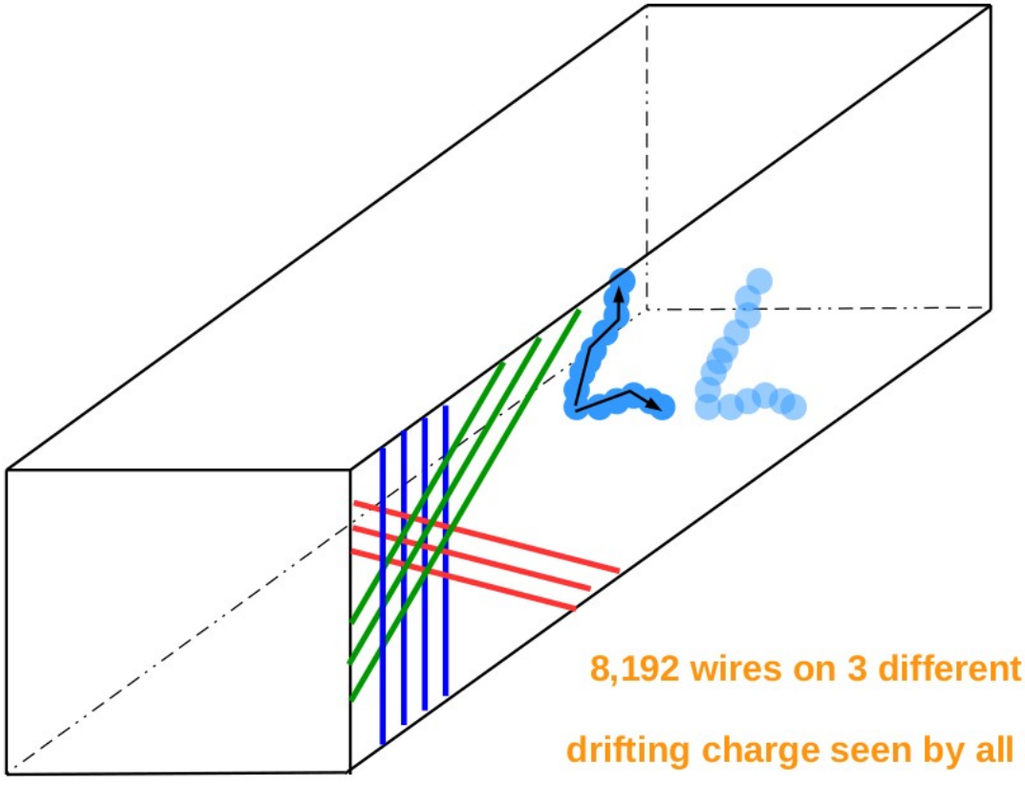
E field @ 273 V/cm
e^- drift @ 0.1 cm/μsec

Require 2.3 ms to record
interaction over full drift-distance!



Cryostat "skeleton"

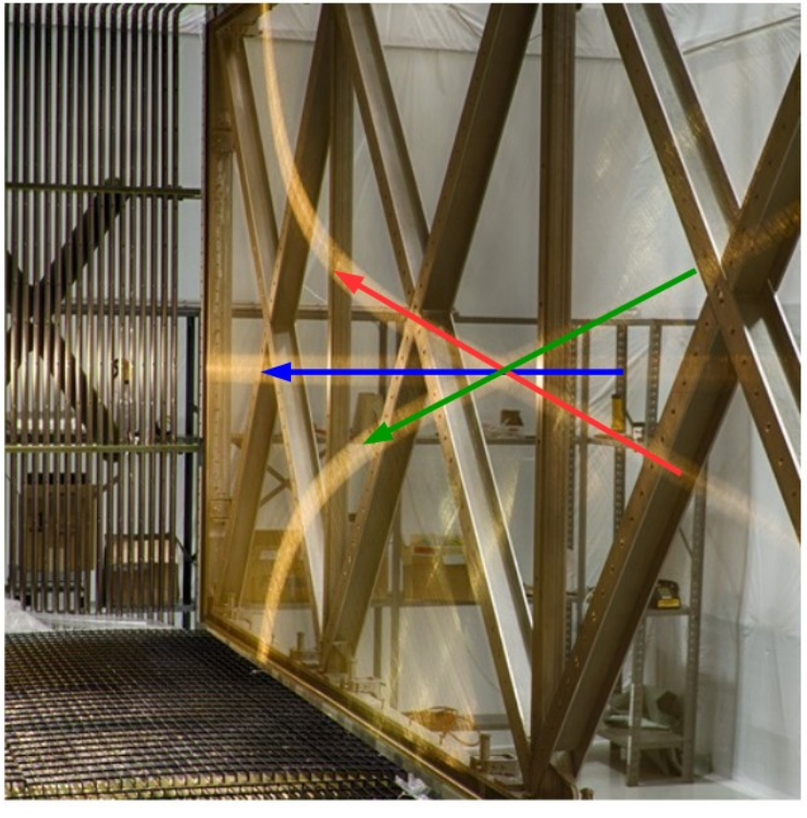
LArTPC Detectors



8,192 wires on 3 different planes.

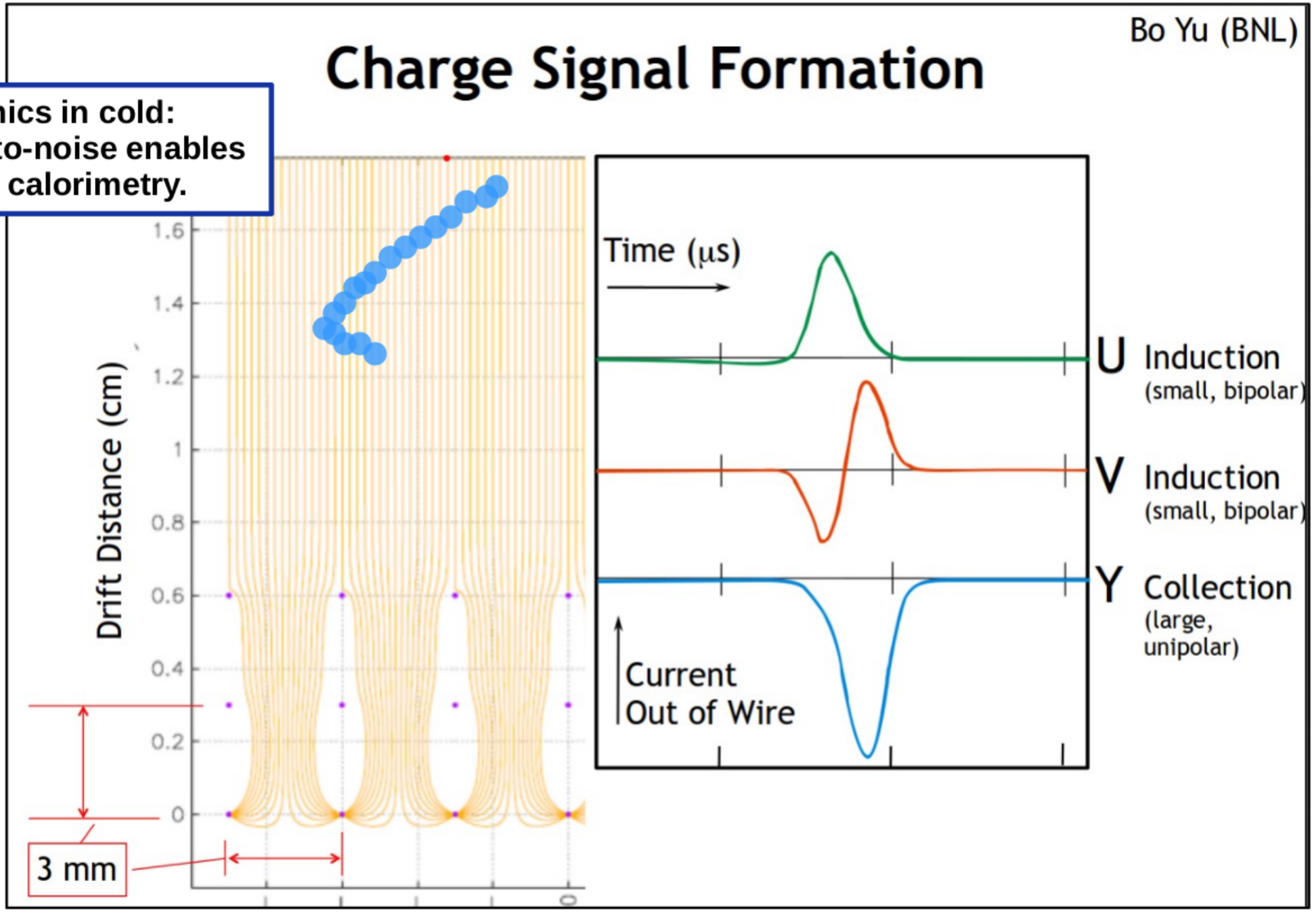
drifting charge seen by all 3 planes.

→ triangulate to recover 3D interaction.

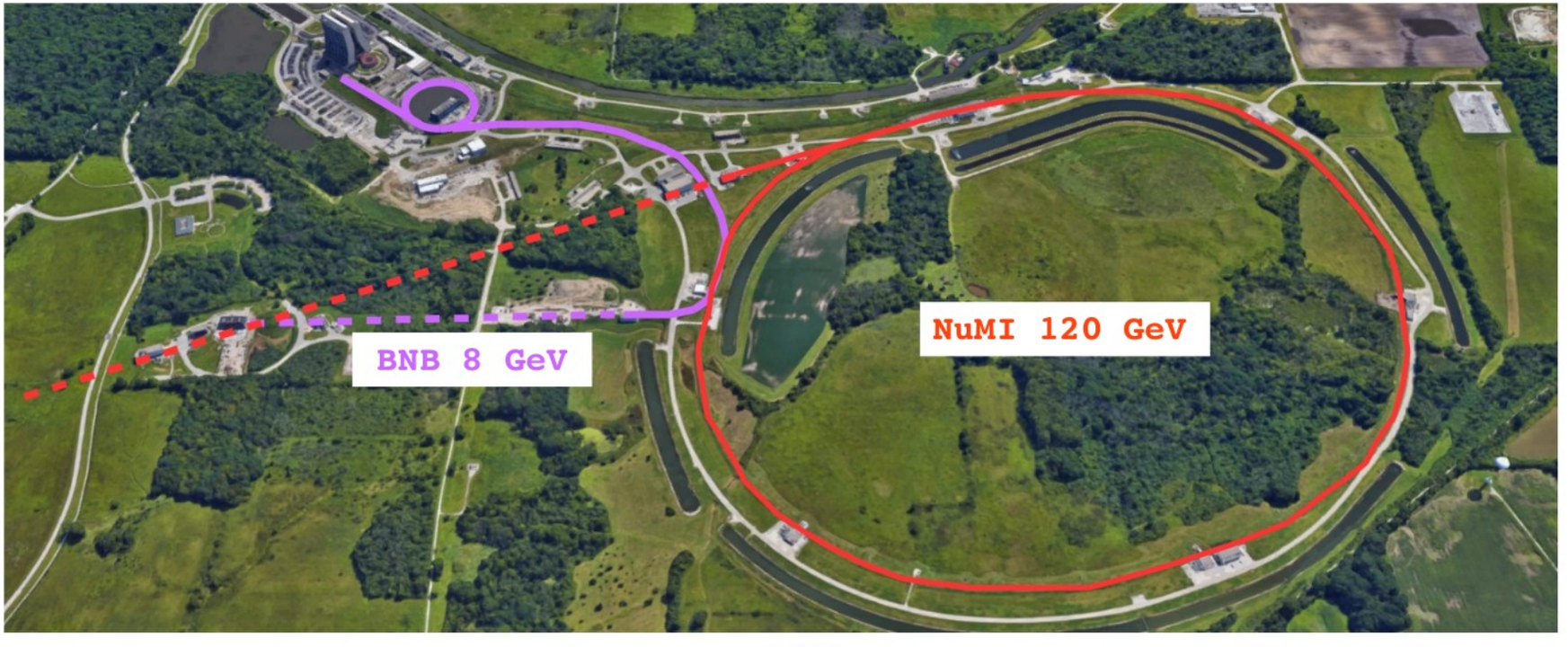


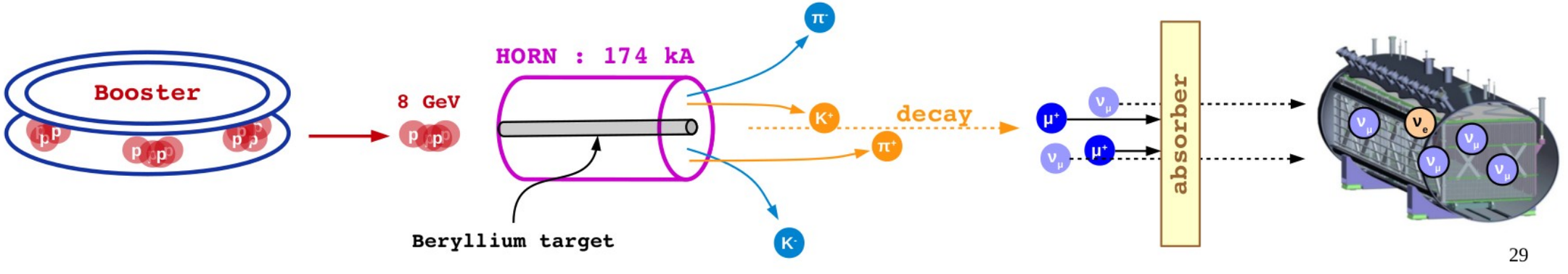
Anode wire-planes

Electronics in cold:
High signal-to-noise enables accurate calorimetry.



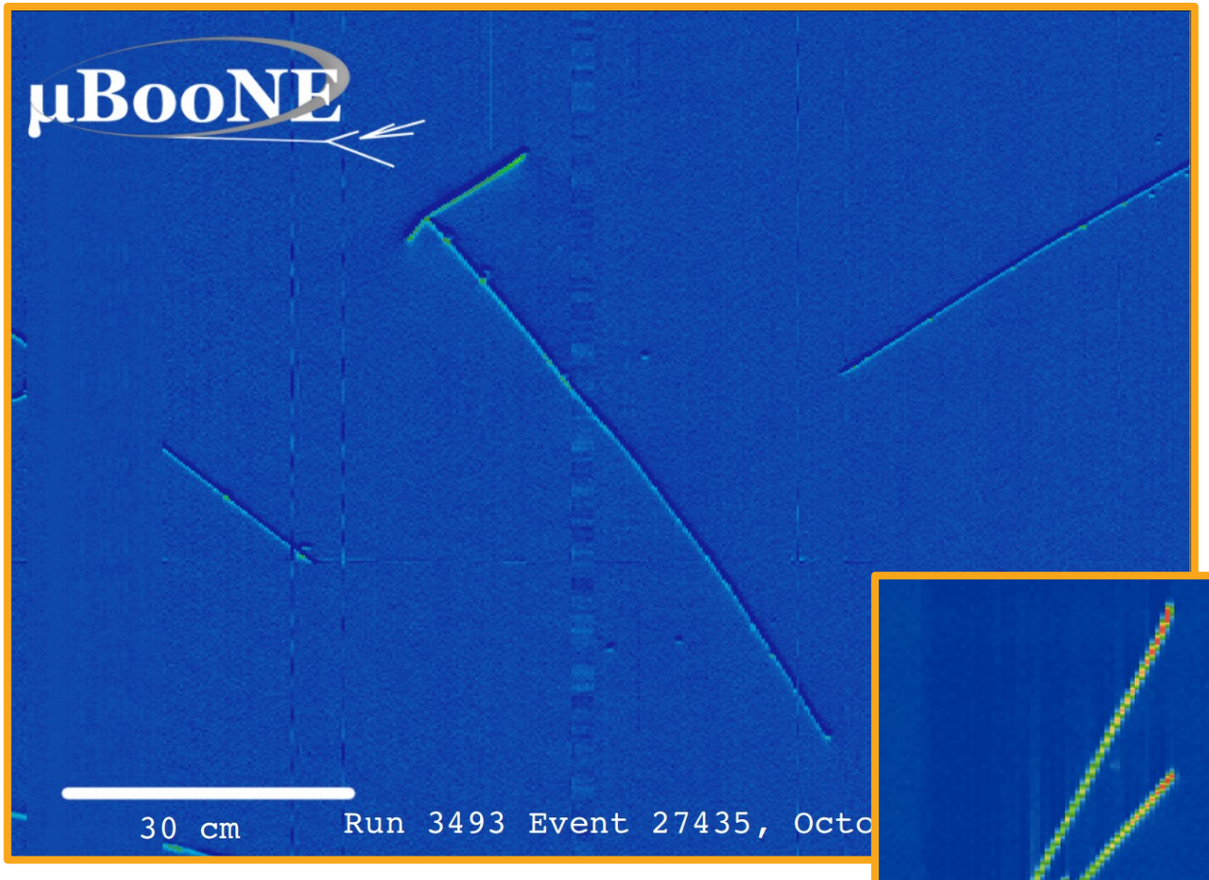
And...the neutrinos!

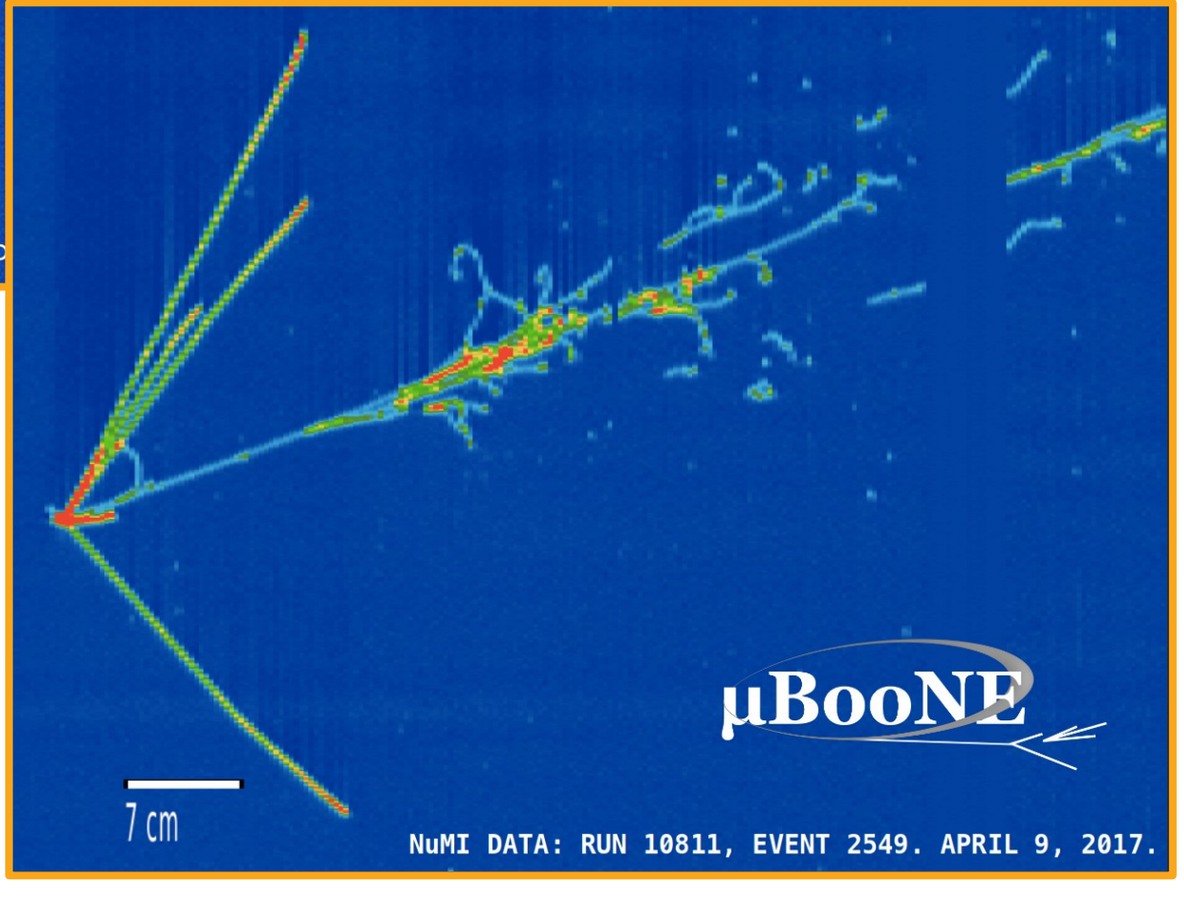


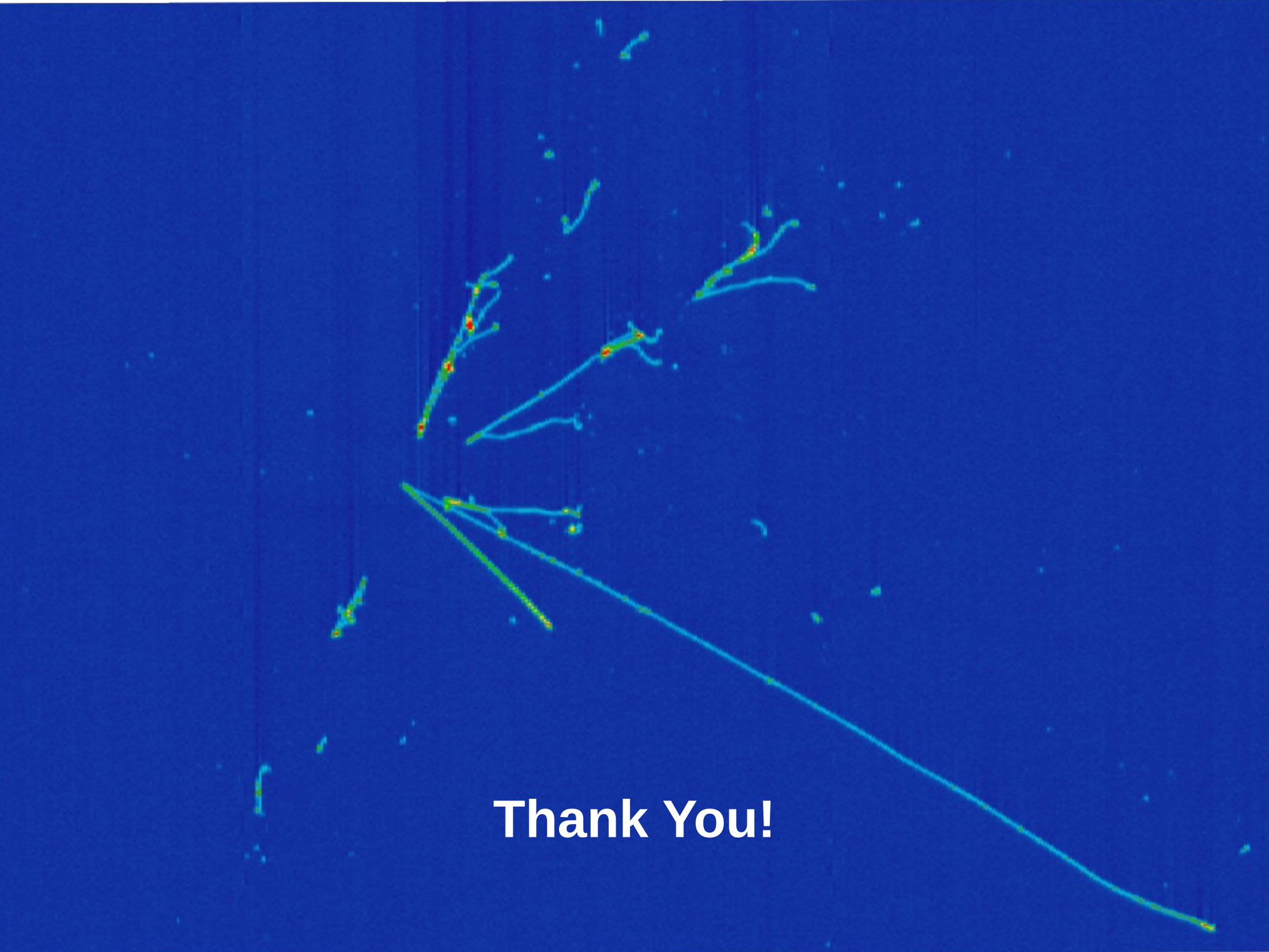


LArTPC Detectors

Neutrinos in HD






Thank You!