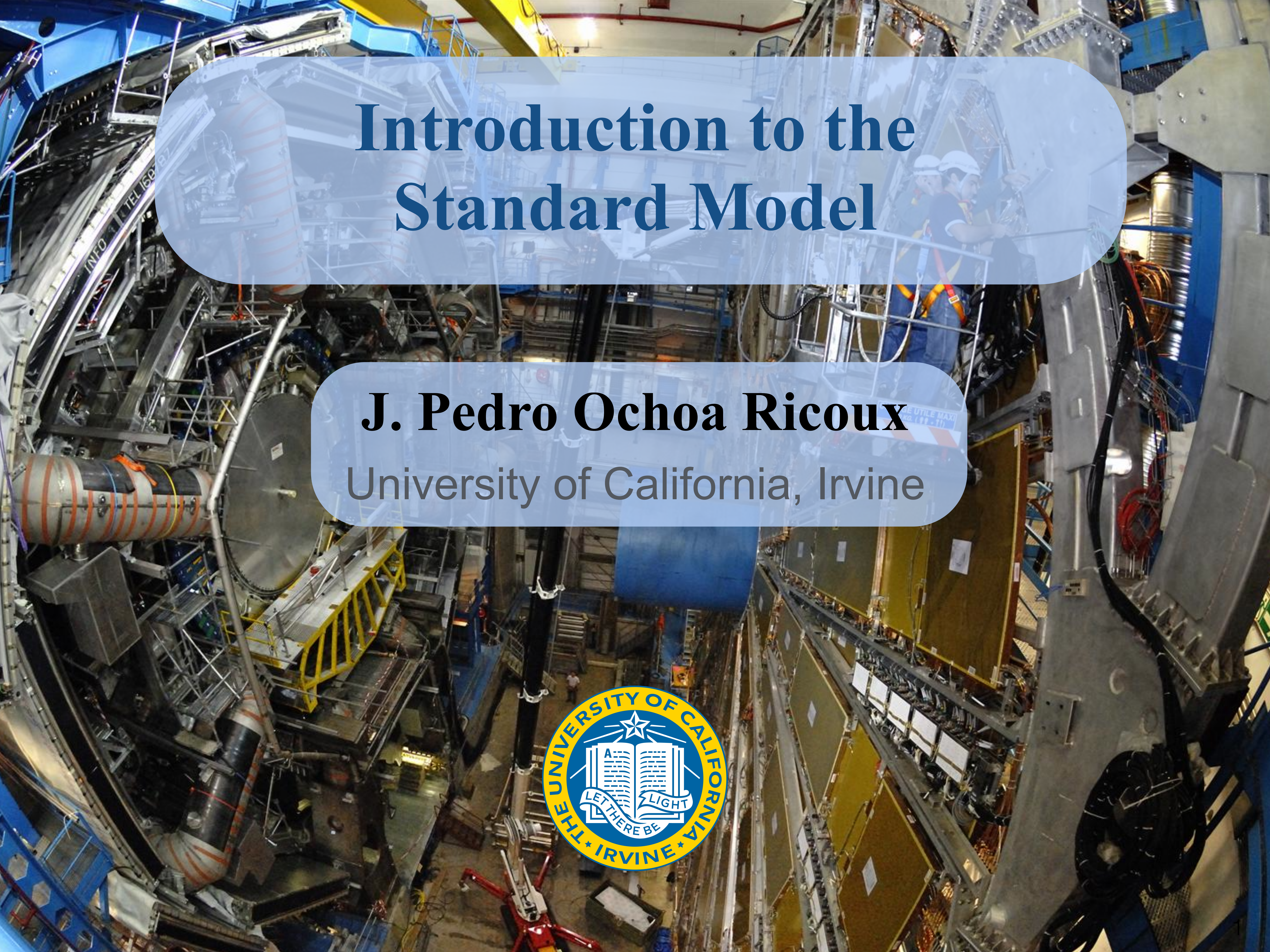
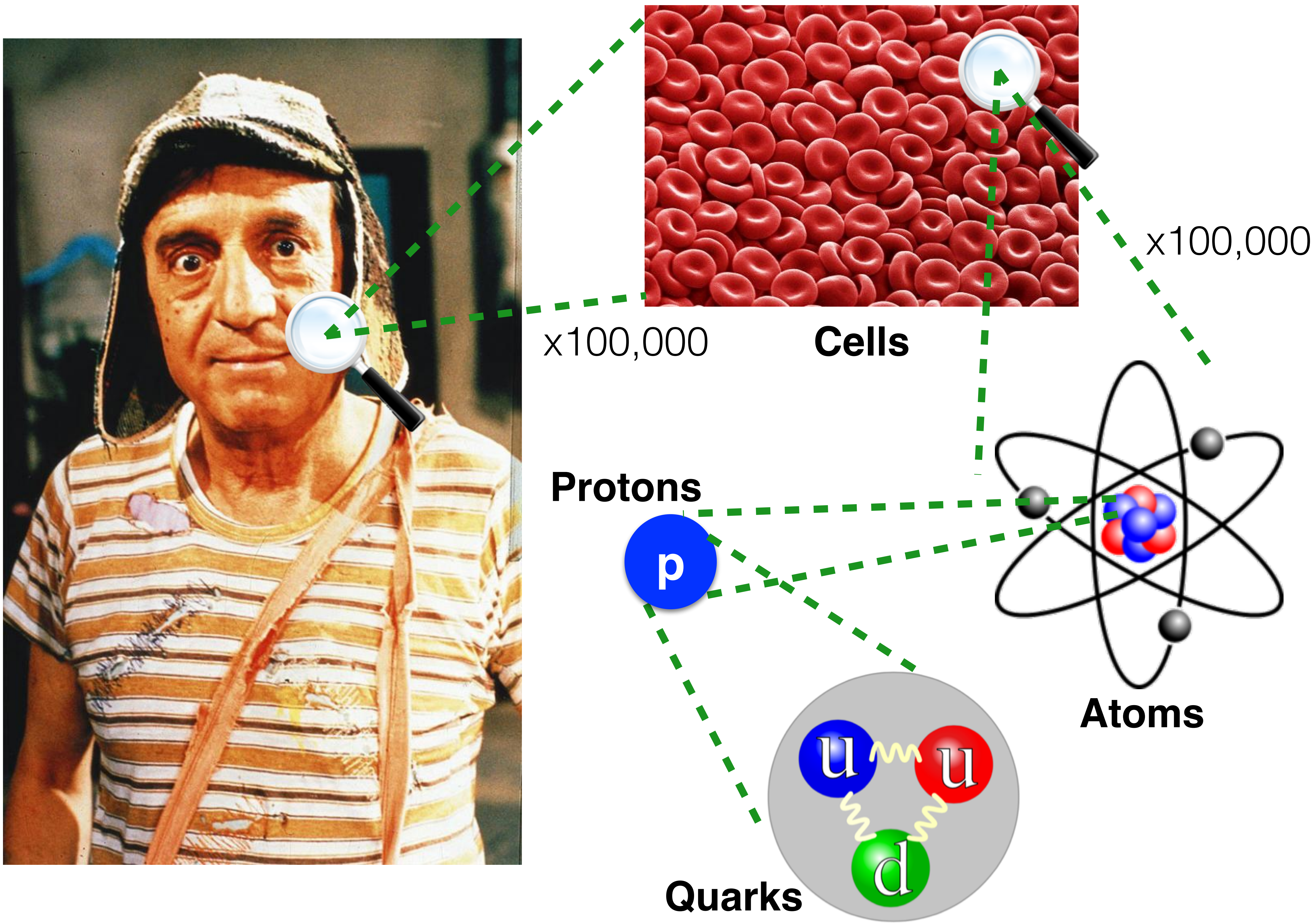


Introduction to the Standard Model

J. Pedro Ochoa Ricoux

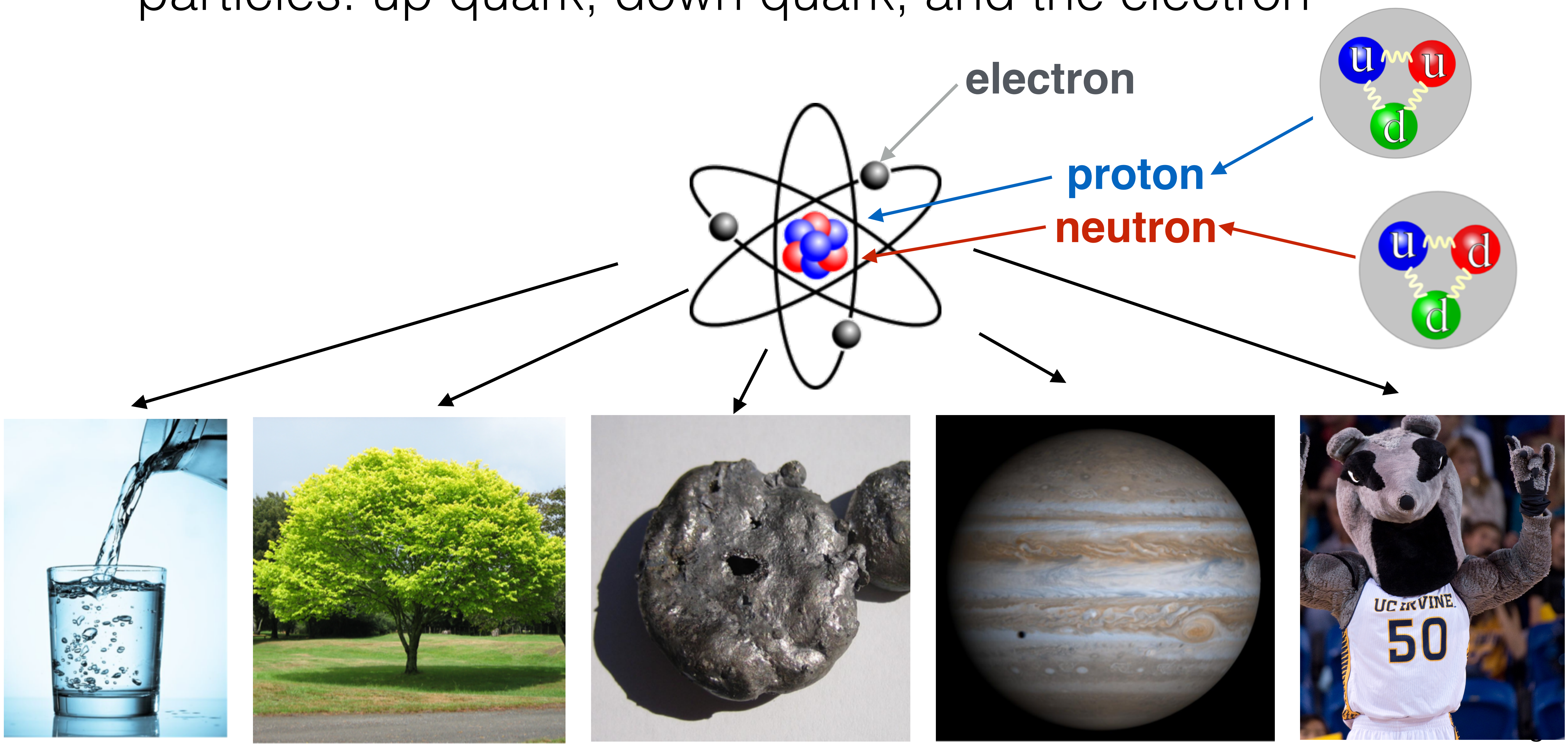
University of California, Irvine

What are we made of?



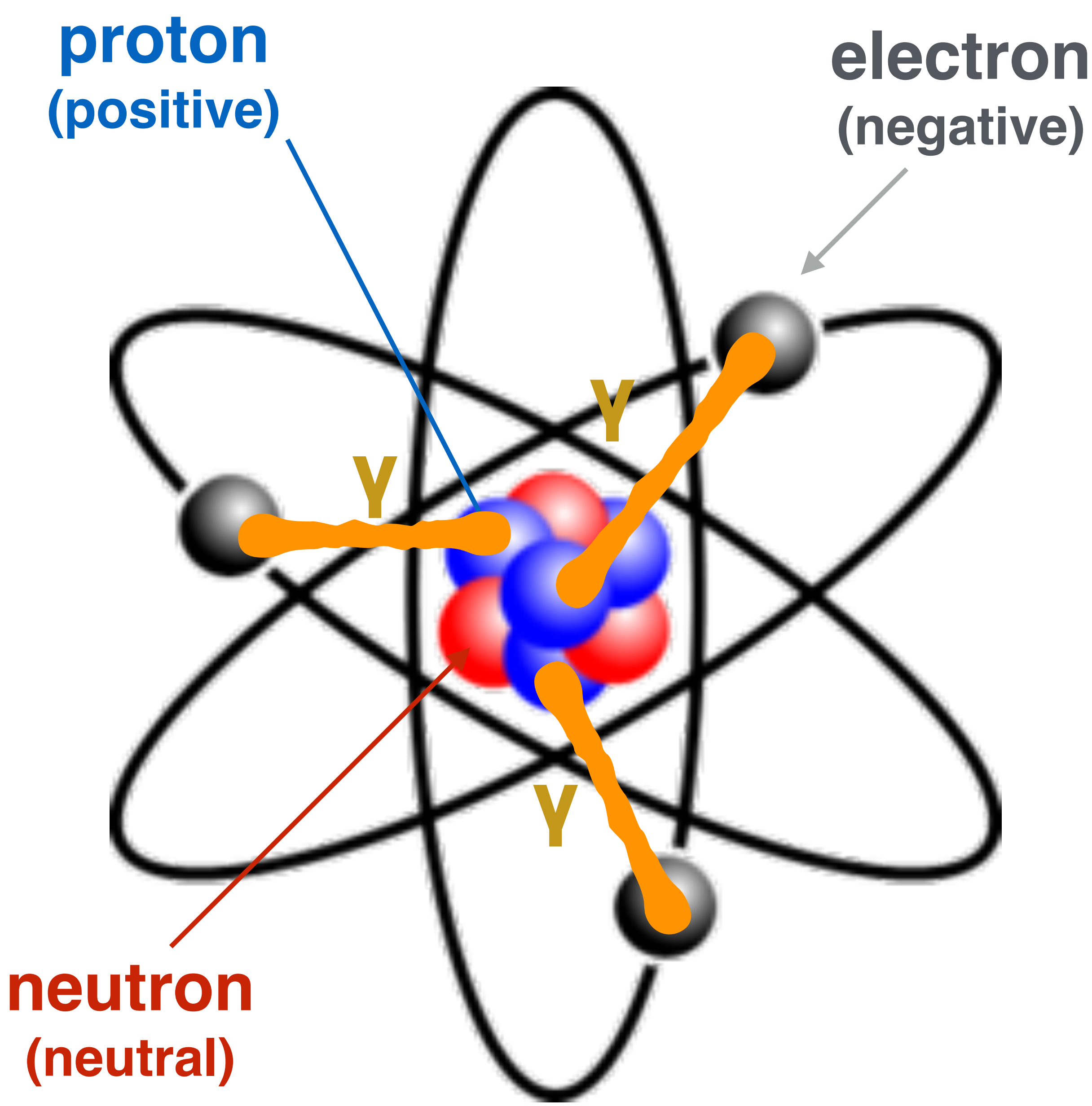
Elementary Particles

- They are the basic constituents of matter
- They cannot be subdivided (they have no internal structure)
- **Everything we see and touch** is made of only three particles: up quark, down quark, and the electron



The Forces of Nature

- Why are atoms this way?



– Electrons orbit the nucleus thanks to the electric force

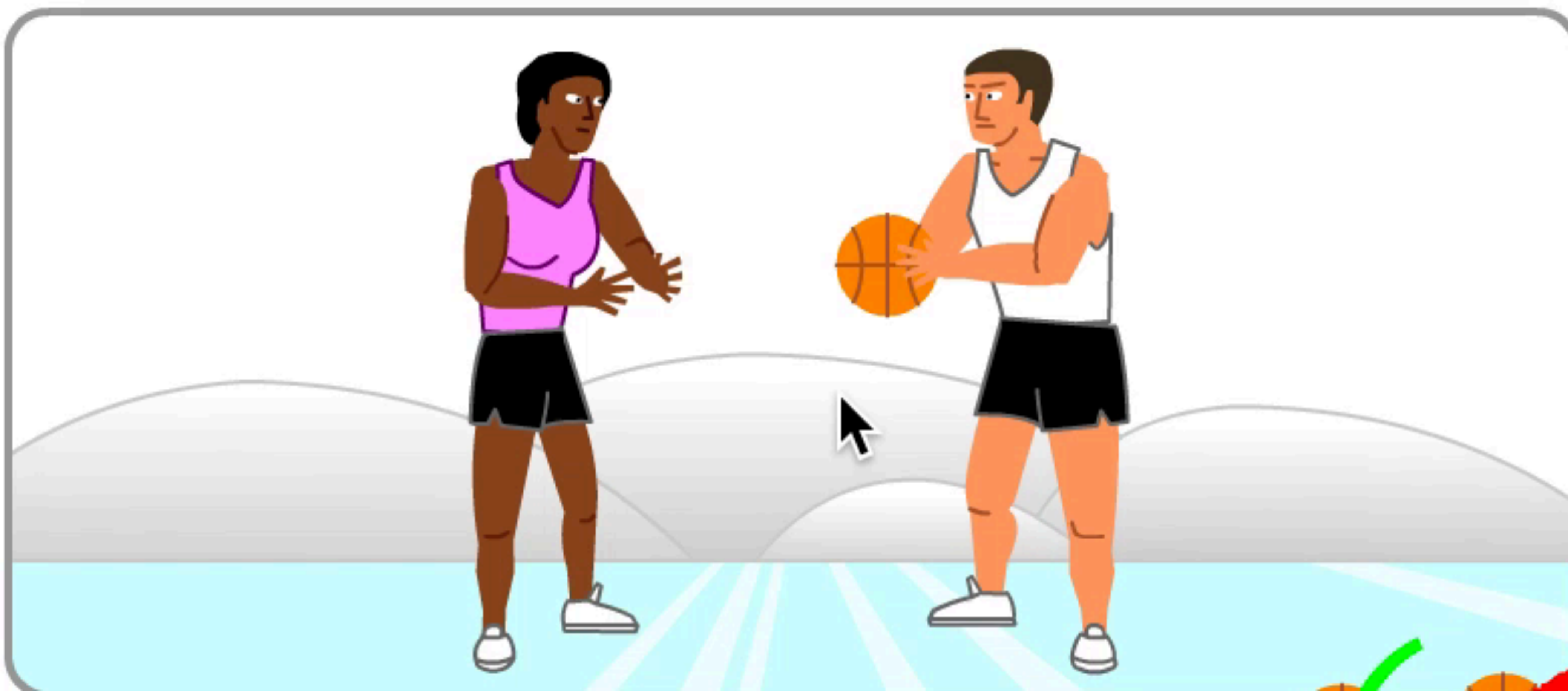
  - **Question #1 : What is a force?**

It's an exchange of particles (in this case photons)

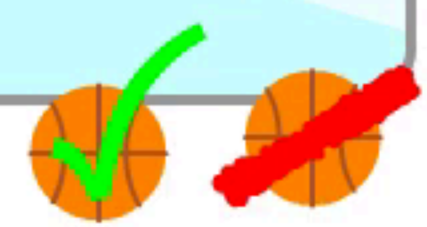
Analogy

- Two persons standing on an ice skating ring
- How can I move the other person without touching her?

Answer: by throwing something!



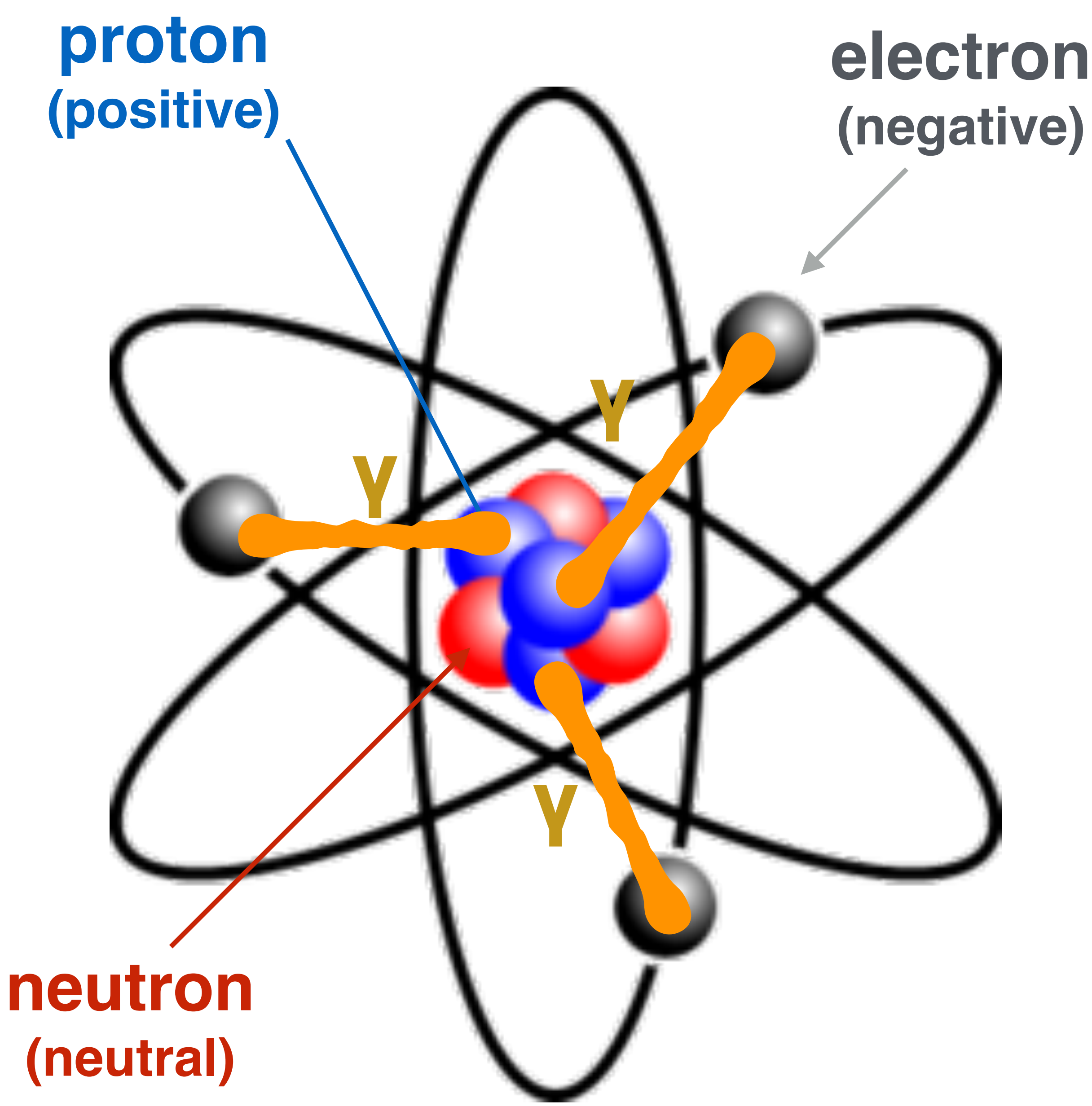
animation from "The Particle Adventure"



Note: to understand an attractive force you would have to imagine a ball with negative energy

The Forces of Nature

- Why are atoms like this?



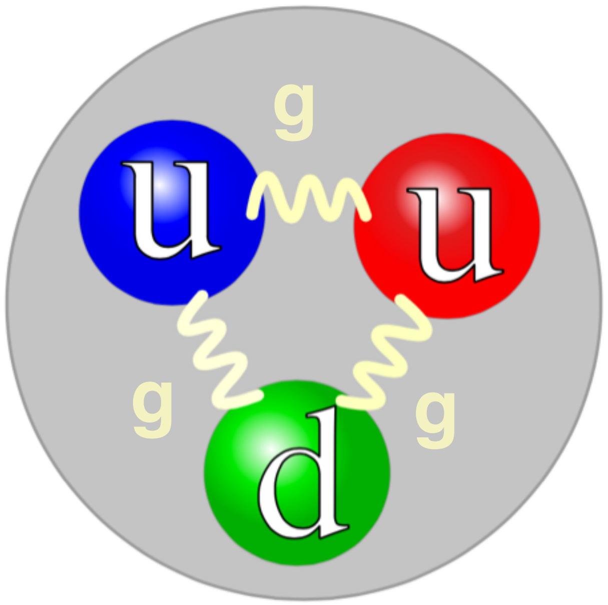
- Electrons orbit the nucleus thanks to the electric force

- **Question #2: how come the protons in the nucleus do not repel each other?**

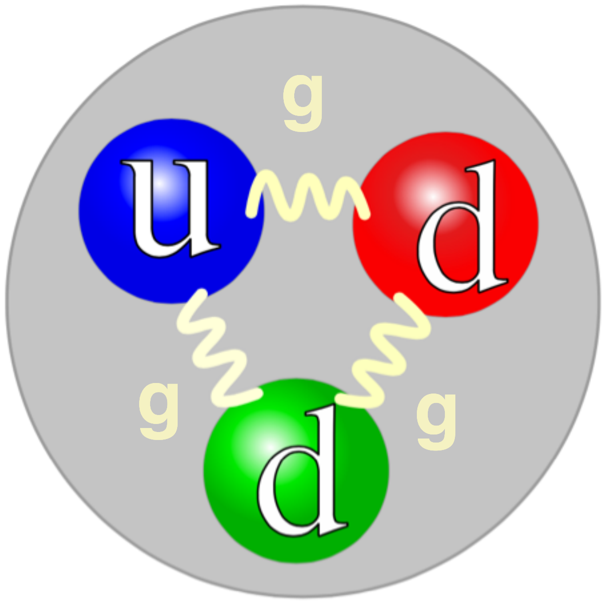
There is another force (only between quarks) that is stronger than the electric force: the strong force

The Strong Force

- As the name suggests, the strong force is very strong!



proton
(positive)



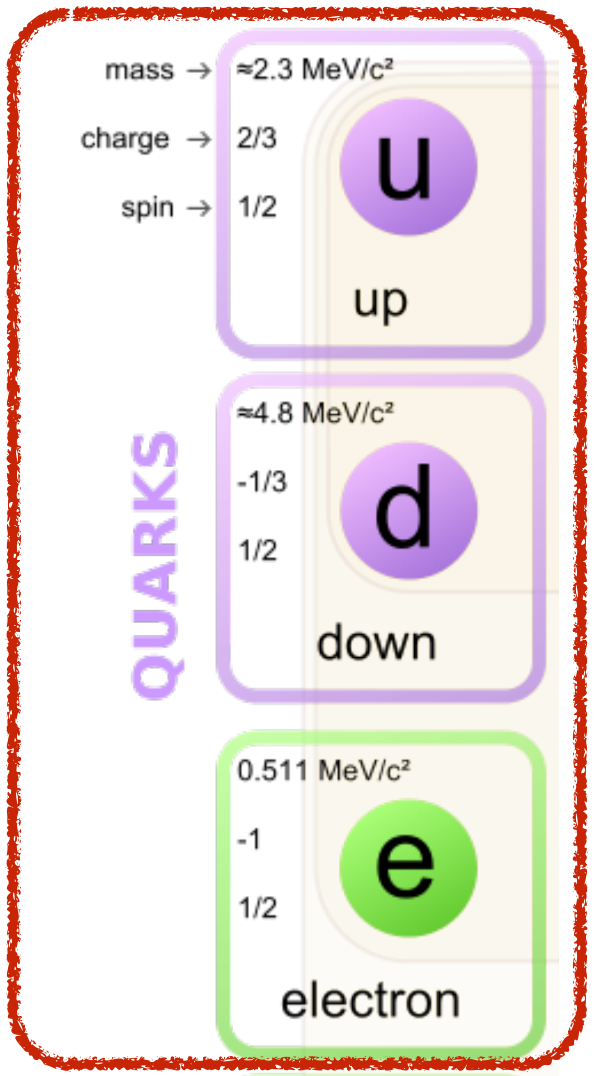
neutron
(neutral)

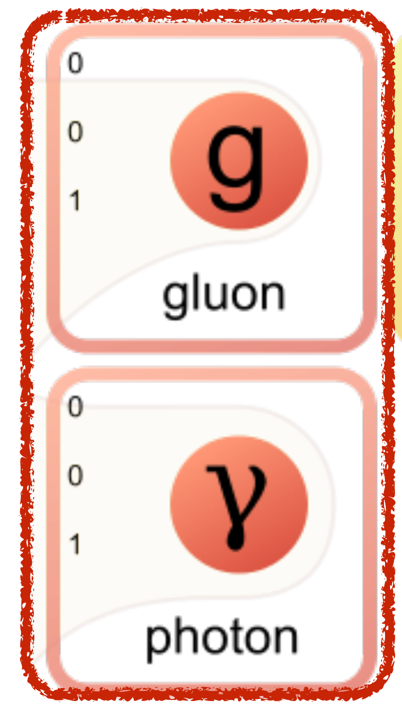
  - Occurs only between particles that have “color” (quarks)
  - Binds protons and neutrons individually and in a group inside the nucleus
  - Is transmitted through the exchange of **gluons**

The Particle Zoo

- So far we've only talked about 5 particles
- But that's just the tip of the iceberg

Mediator of the strong force





Mediator of the electromagnetic force

Constituents of "regular" matter

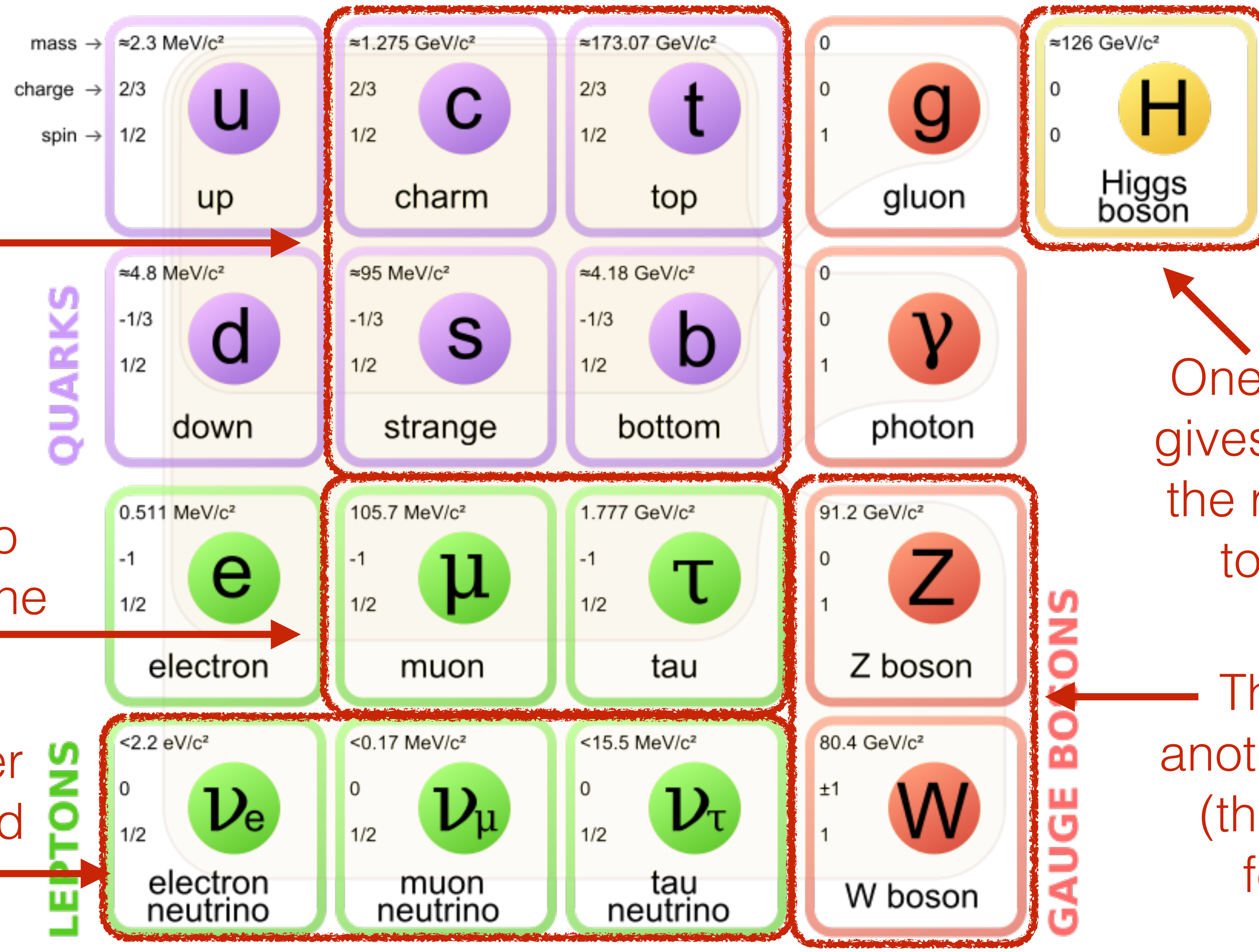
The Particle Zoom

- There are at least 17 fundamental particles!

There are 4 other quarks (a lot heavier!)

There are two "brothers" of the electron

There are other particles called "neutrinos"



One particle gives mass to the rest (and to itself)

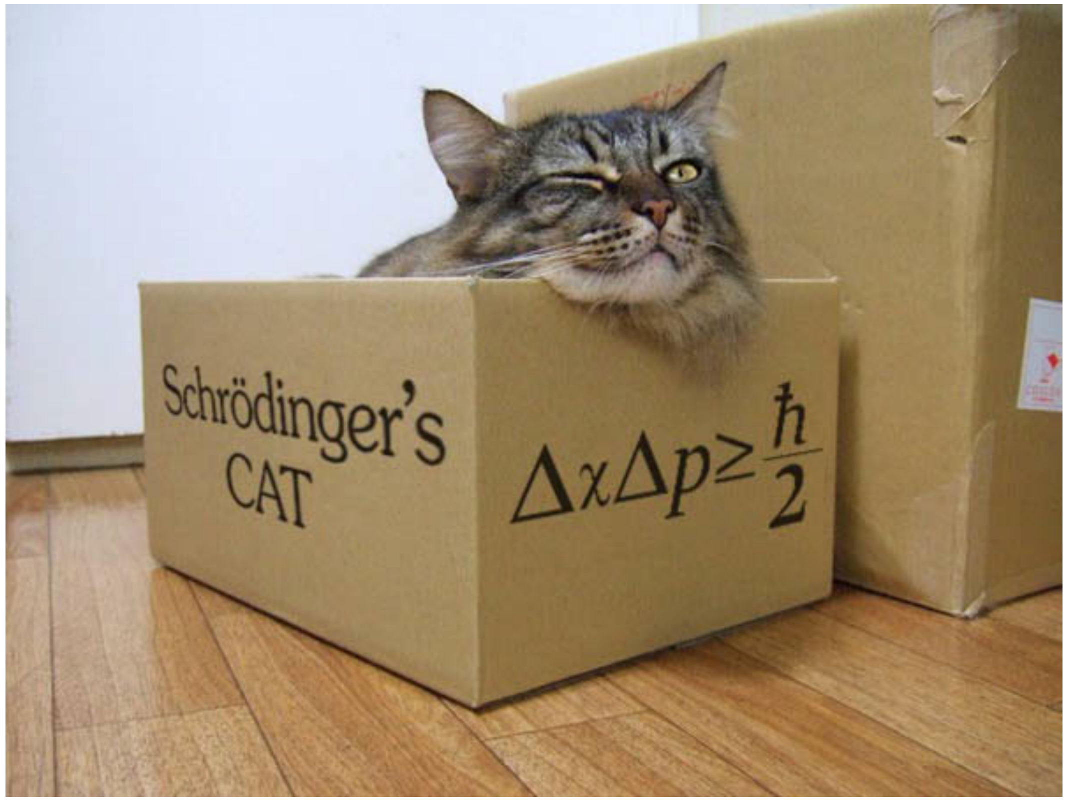
There is another force (the weak force)

Nota: the graviton is not listed

- Even though we tend to think of these particles as little marbles, they behave in a much stranger way

The Particle Zoo

- They obey Quantum Mechanics
  - They can be in multiple places at once



- Many of them are unstable

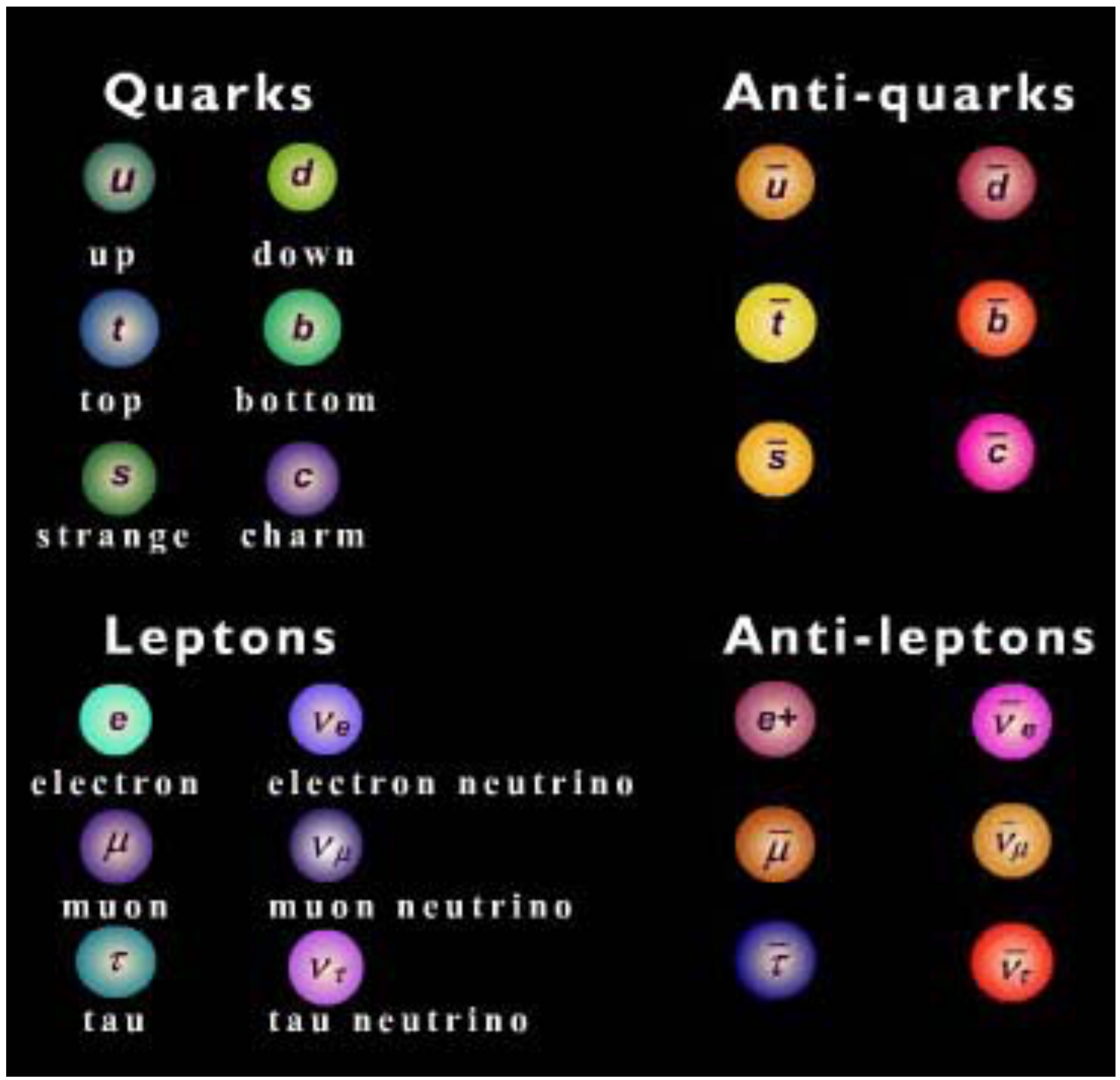
For example: $\mu^- \rightarrow e^- + \nu_\mu + \overline{\nu}_e$

muon → electron + muon neutrino + electron antineutrino

  - They decay in a few microseconds or less!
  - This is why we only find two types of quarks (up, down) and one type of lepton (electron) in conventional matter
  - But we can produce them in the lab and study them before they disintegrate

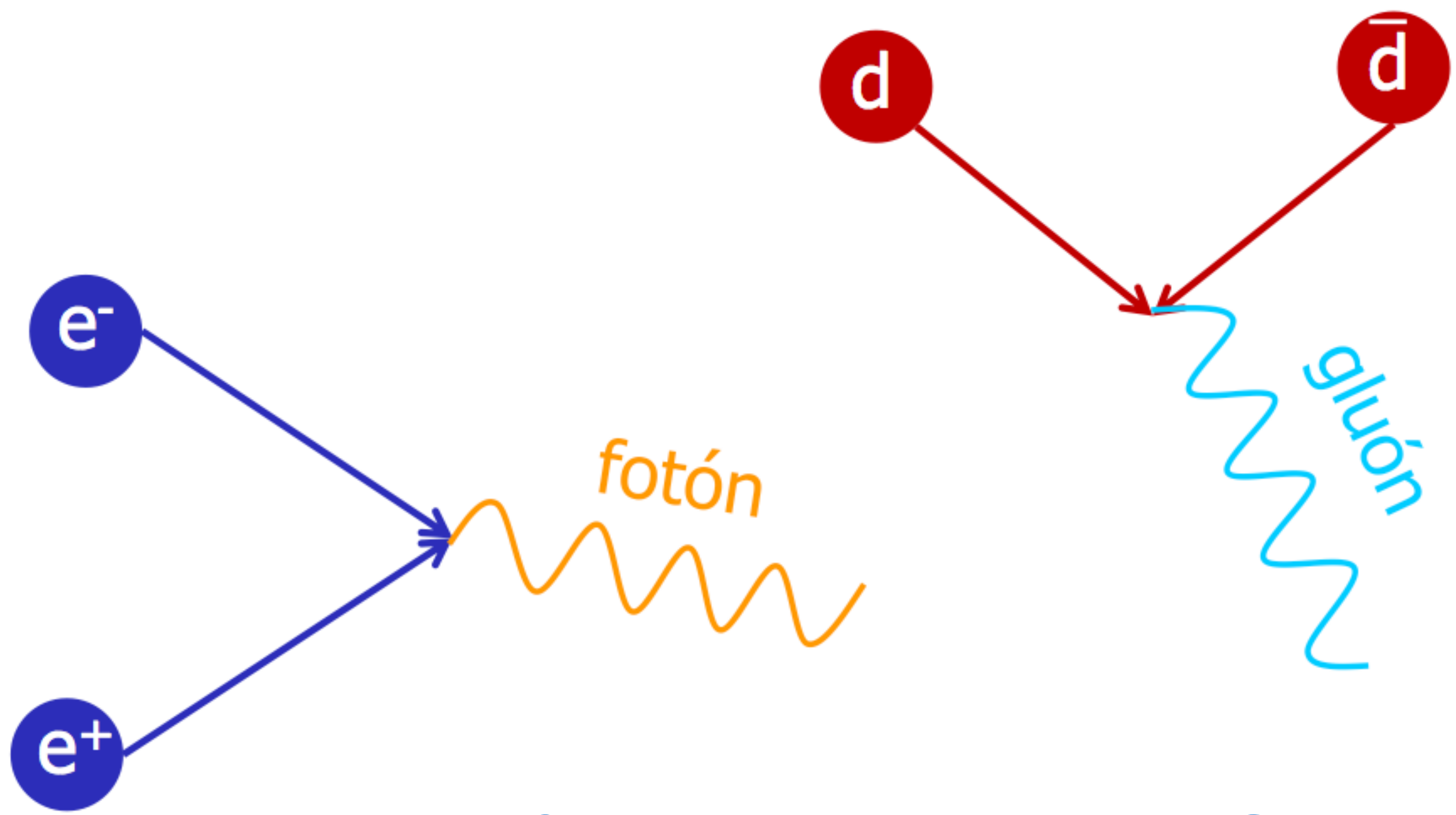
The Particle Zoo

- Each particle has its own antiparticle (identical in every way, but with opposite charge):



The Particle Zoo

- When a particle meets its antiparticle, they annihilate each other

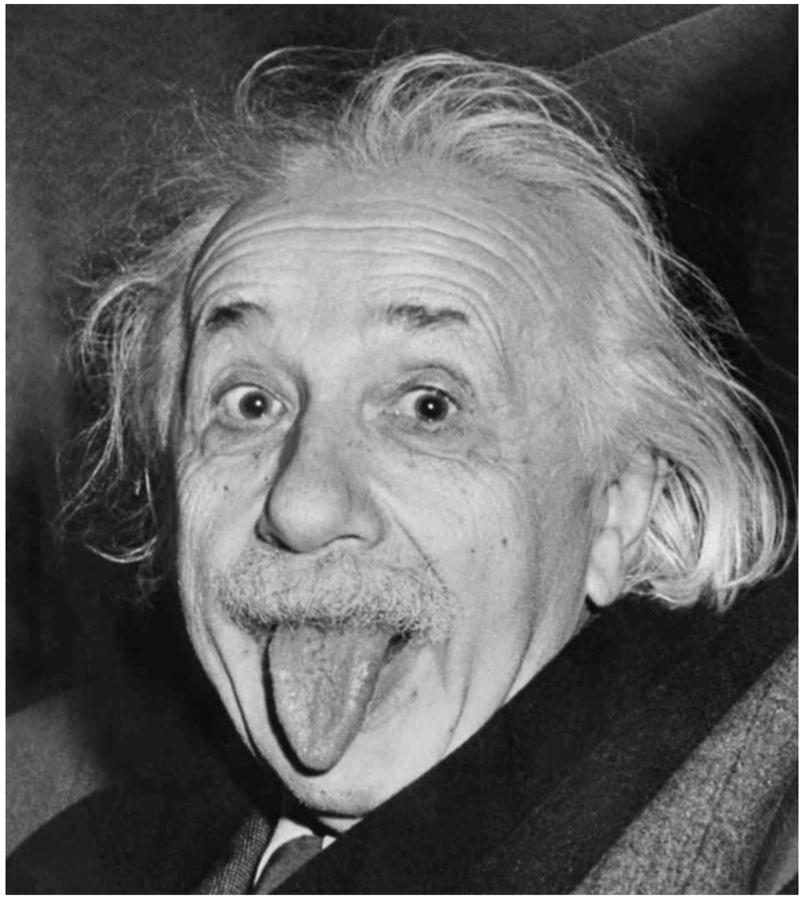


$$\boxed{E=mc^2}$$

- Our universe contains mostly matter, but we can produce antimatter in the lab

How are new particles created?

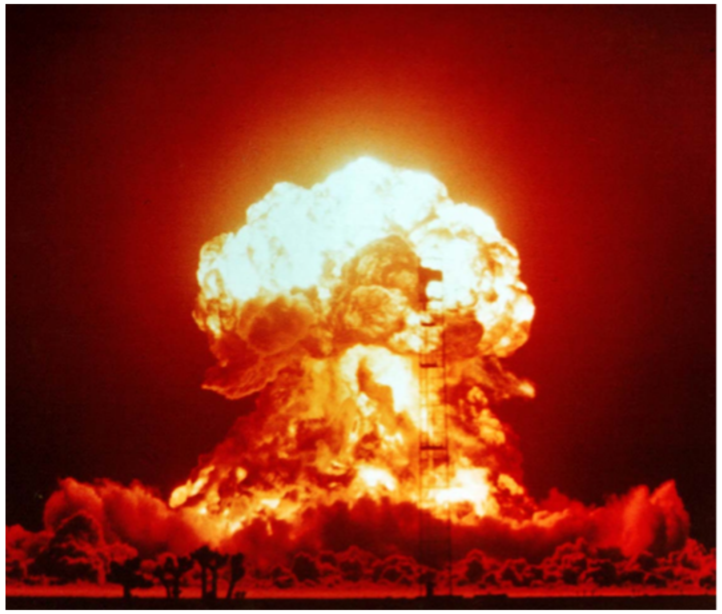
- The only way to study unstable particles is by creating them in the lab. How?



$$\boxed{E=mc^2}$$

(c is the speed of light in vacuum)

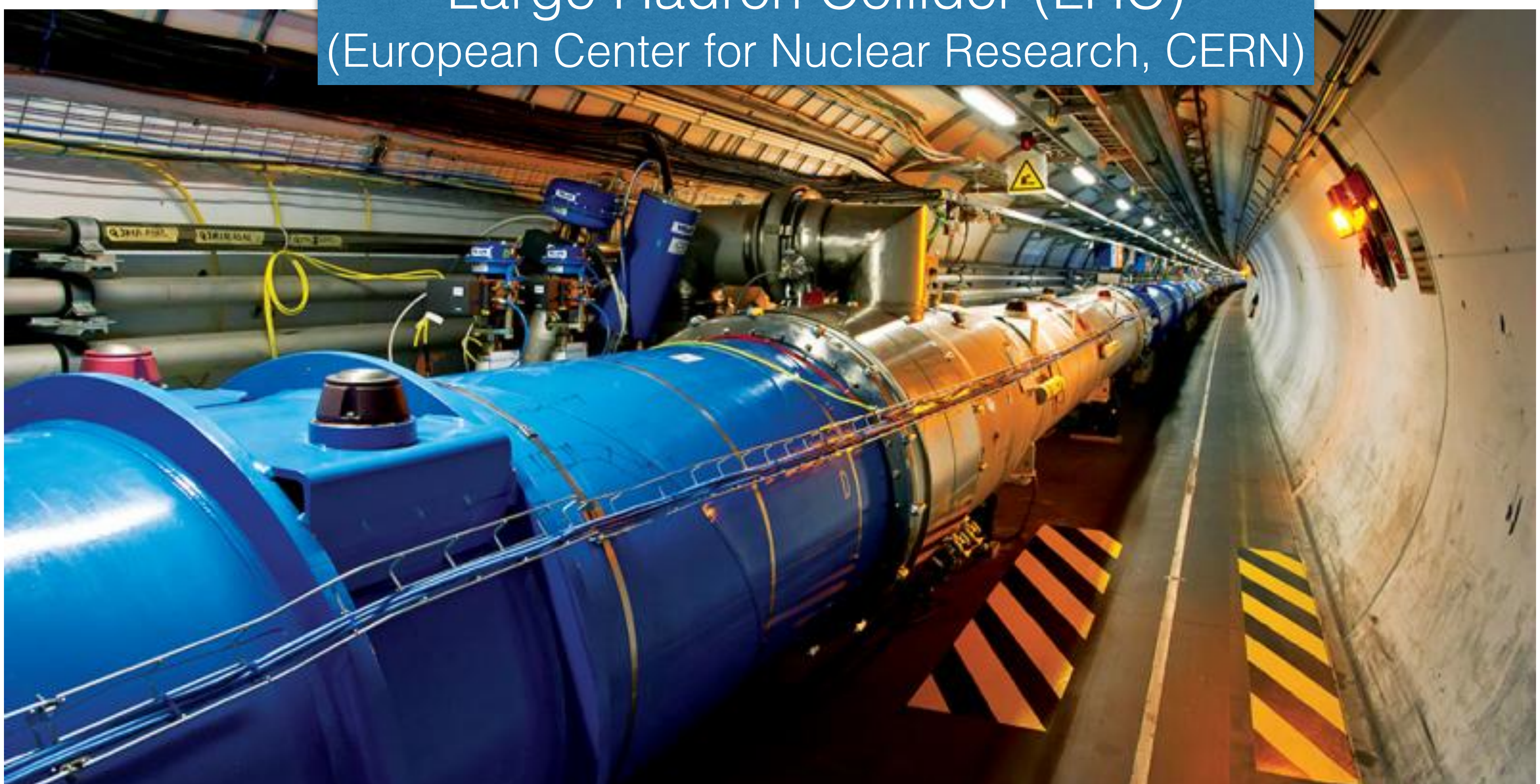
- A little bit of mass can be converted into A LOT of energy →
- It takes a lot of energy to create A LITTLE BIT of mass



How are new particles created?

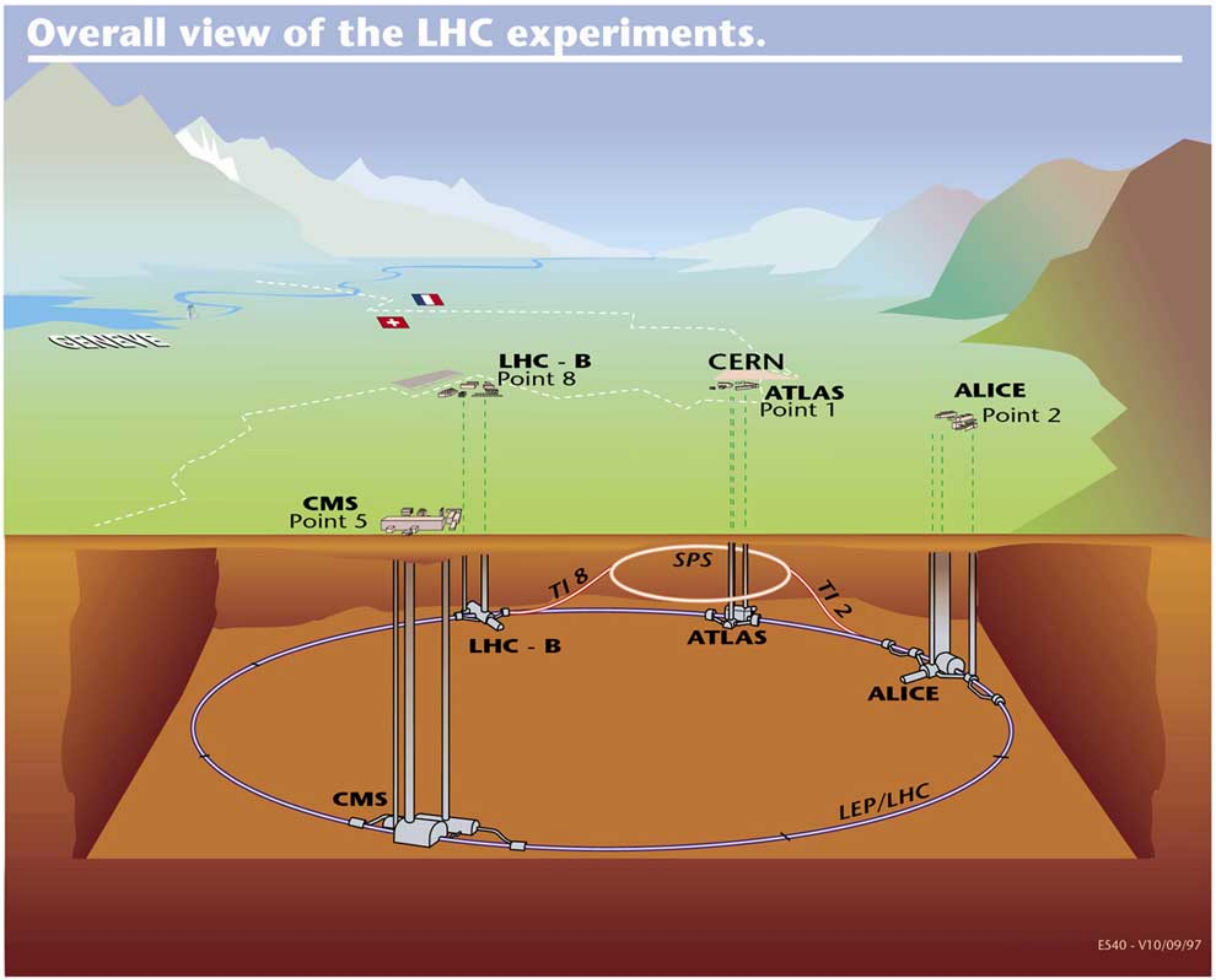
- Need to concentrate a big amount of energy
- The best way to do that currently is with the Large Hadron Collider

Large Hadron Collider (LHC)
(European Center for Nuclear Research, CERN)



How are new particles created?

- LHC: two proton beams, going around in opposite directions, in a 27 km circumference ring that is 100 m underground

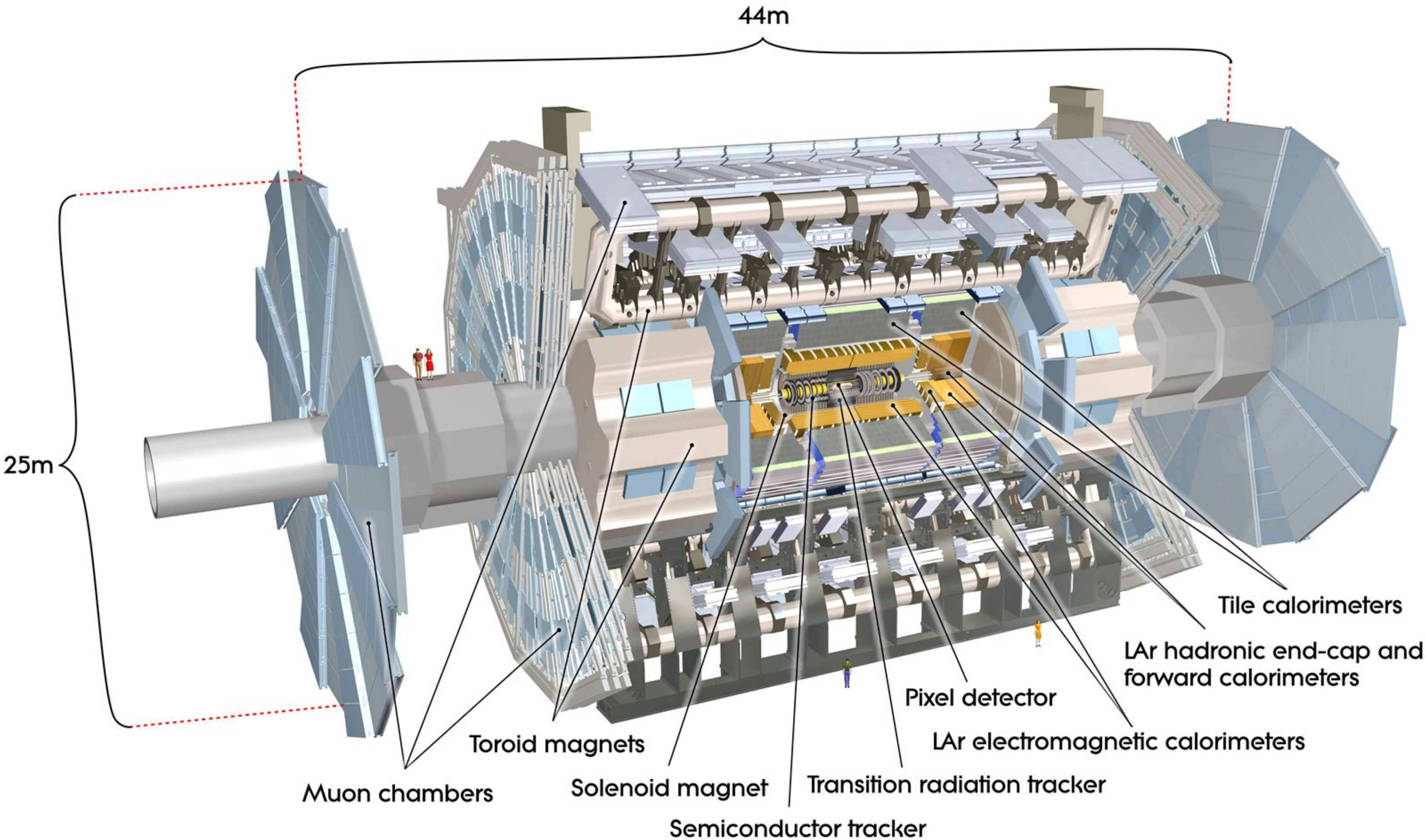


The most complex machine ever built!

Why so big? Magnets can only be made so strong…

Complex detectors surround each interaction point

Example: the ATLAS detector



Invisible particles?

- The detectors at the LHC can be used to study almost all the particles of the Standard Model
  - Even the Higgs, whose discovery was announced in 2012!

- The one notable exception? Neutrinos….

The Most Abundant Particles

- We mentioned that all conventional matter is made of two types of quarks (up, down) and electrons
- You would think that these are the most abundant particles in the universe

But no…

Number 1:

Photons (γ)

Number 2:

Neutrinos (ν)

Note: depending on what dark matter is, it could occupy the third place

Lots of Neutrinos!

For every electron and quark in the universe there are

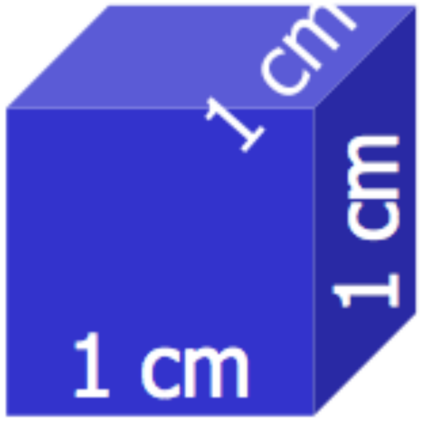
10 000 000 000

neutrinos

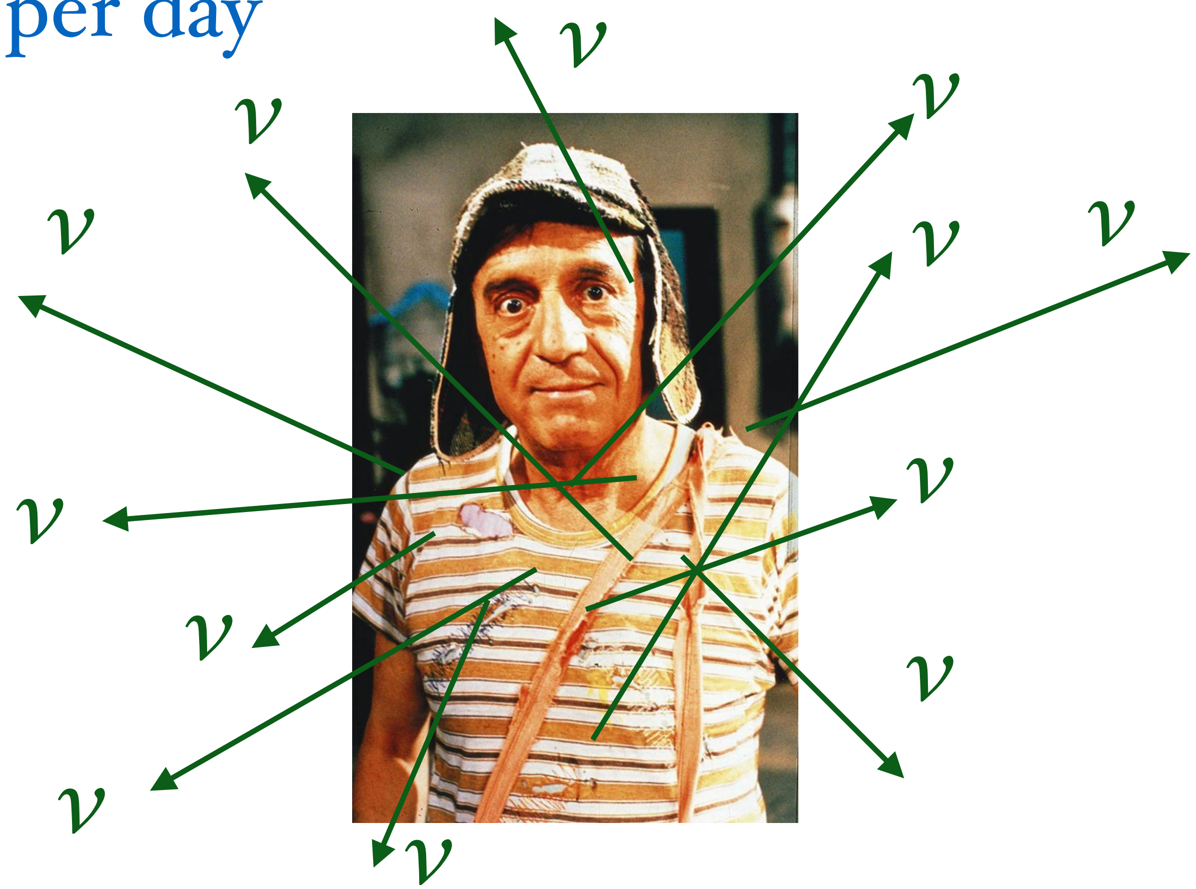
If we want to understand our universe, we need to understand neutrinos

Our Universe is Full of Neutrinos!

- **Our universe contains an extremely large amount of neutrinos**
  - Every cm³ contains about **300** neutrinos that are relics of the big bang (not yet detected)

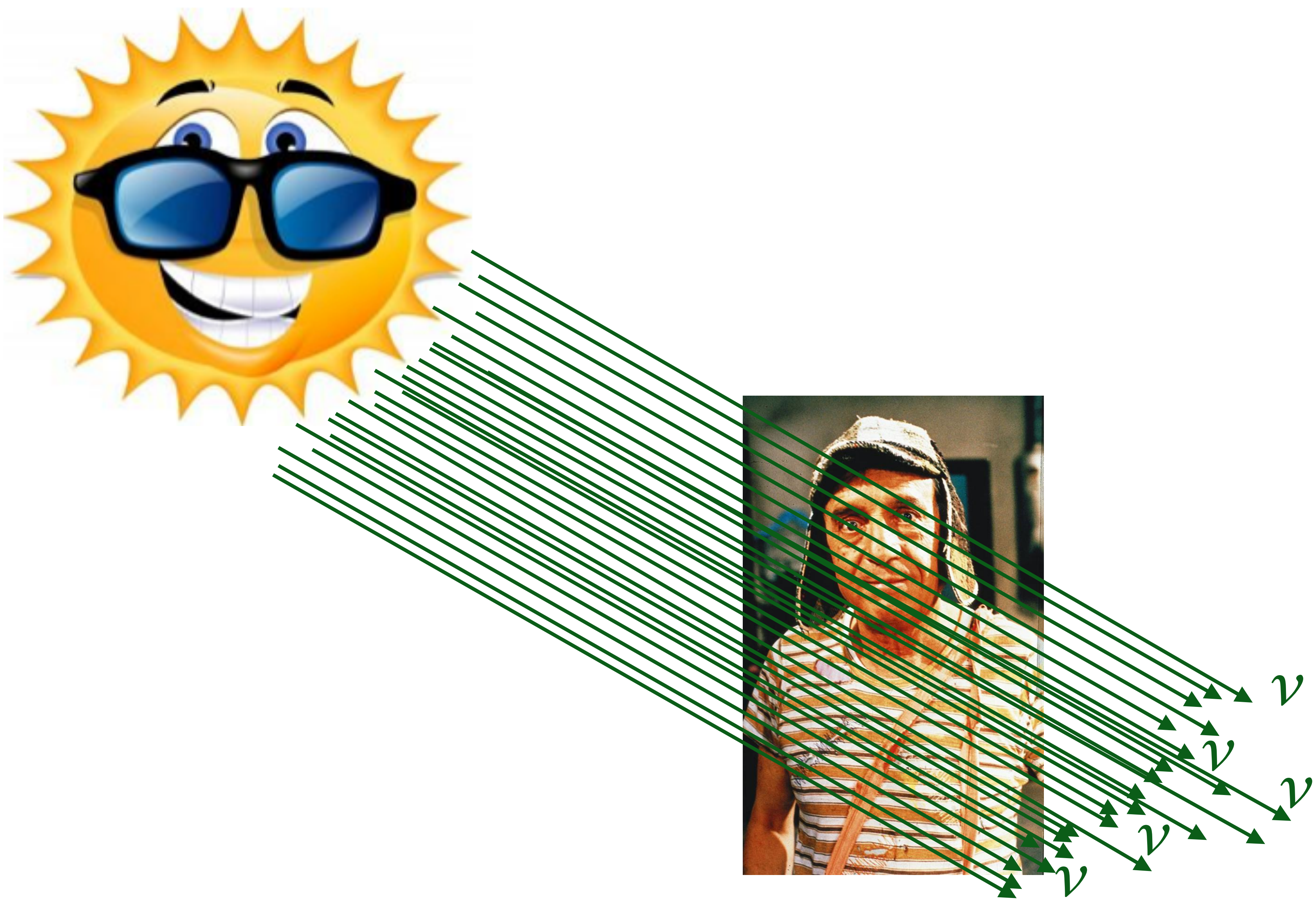


  - Our bodies produce **hundreds of millions** of neutrinos per day



Our Universe is Full of Neutrinos!

- The Sun produces so many neutrinos that every second we are traversed by approximately **100 000 000 000 000** neutrinos (one hundred million million)



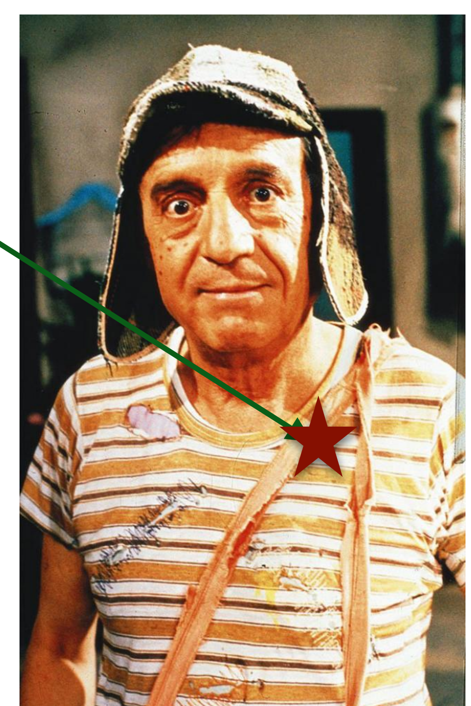
Our Universe is Full of Neutrinos!

- **Am I going to die?**
- **Yes, but not because of neutrinos…**

  of 100 000 000 000 000 000 000 solar neutrinos that go through our bodies, the number of them that interact (that exchange a particle with a proton, neutron or electron in our body) is:

1

ν

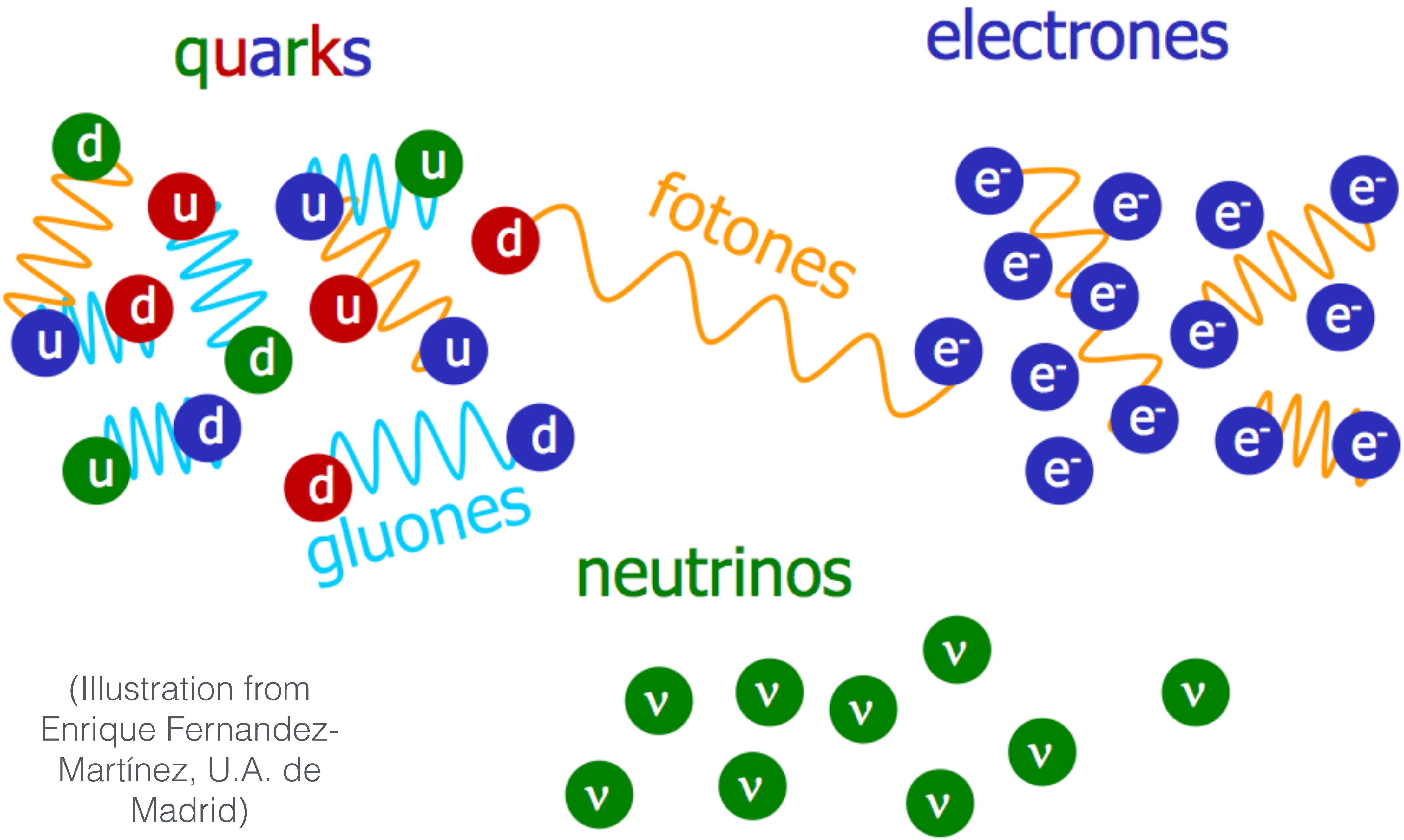


The rest just breeze through and do **absolutely nothing** (literally)

(of course, if these were protons, it would be a different story)

Why?

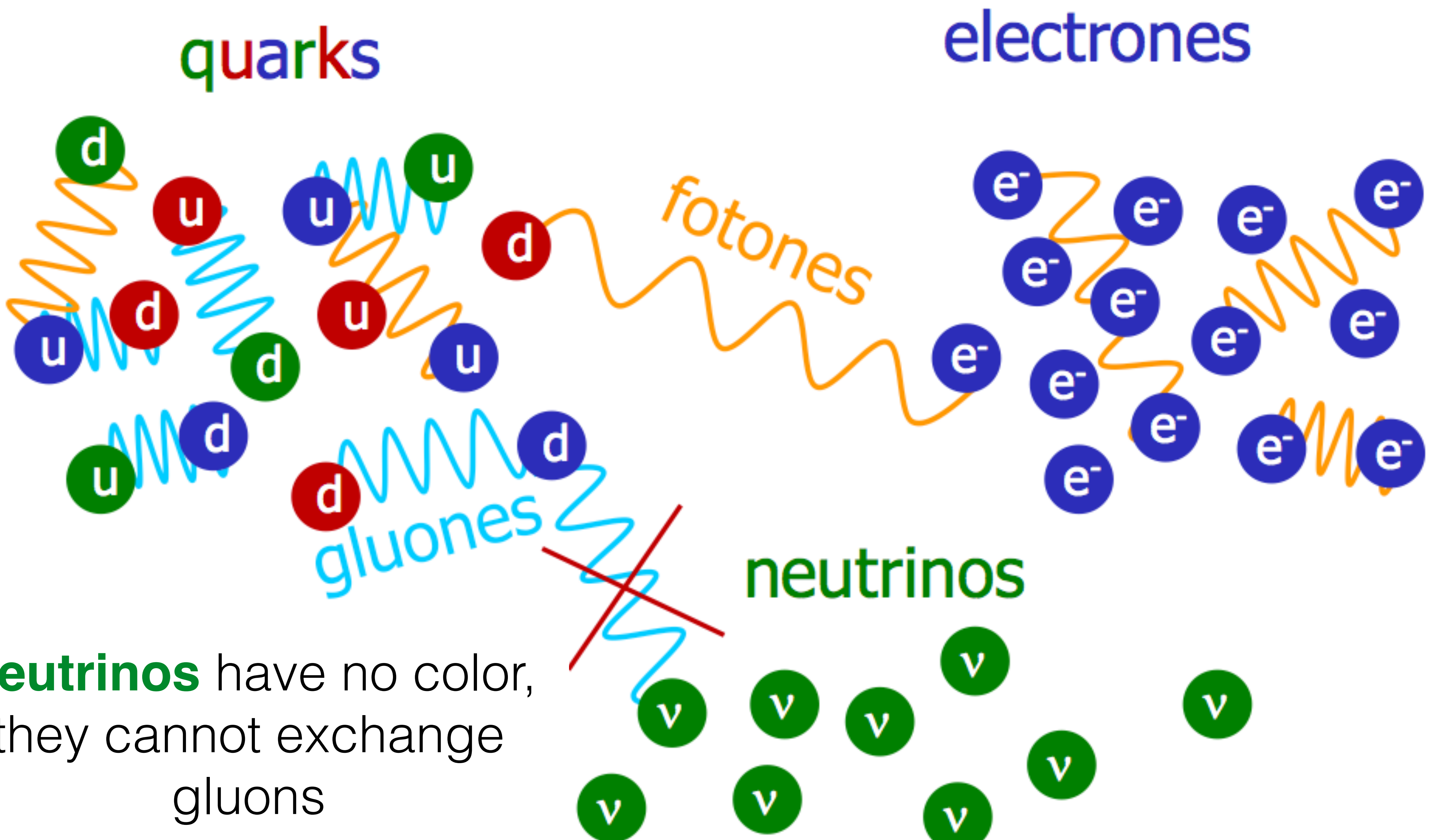
- **In fact, a neutrino can go through a light-year of lead!**
- Why do neutrinos interact so weakly with other particles?



(Illustration from Enrique Fernandez-Martínez, U.A. de Madrid)

Why?

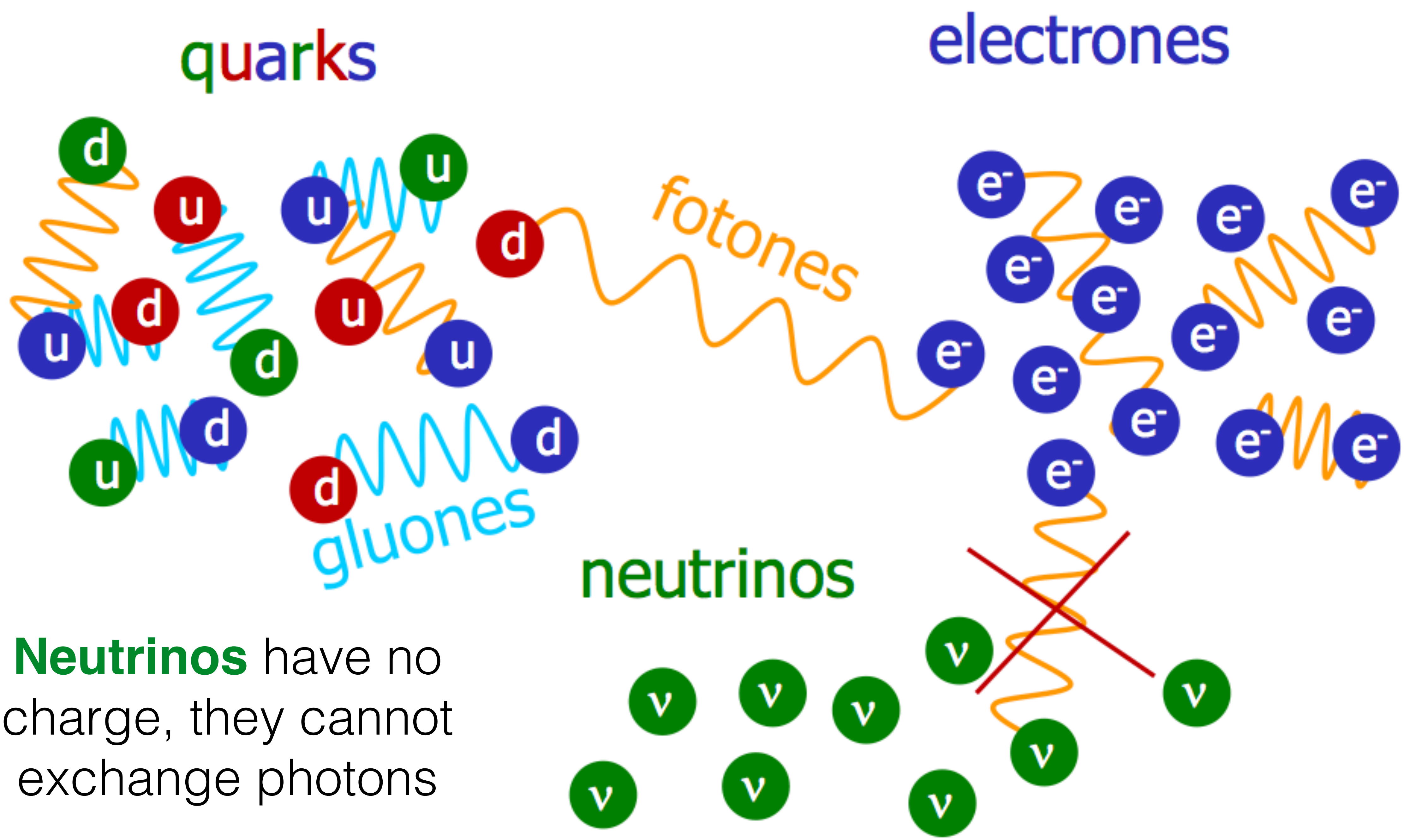
- Neutrinos do not interact via the strong force



Neutrinos have no color, they cannot exchange gluons

Why?

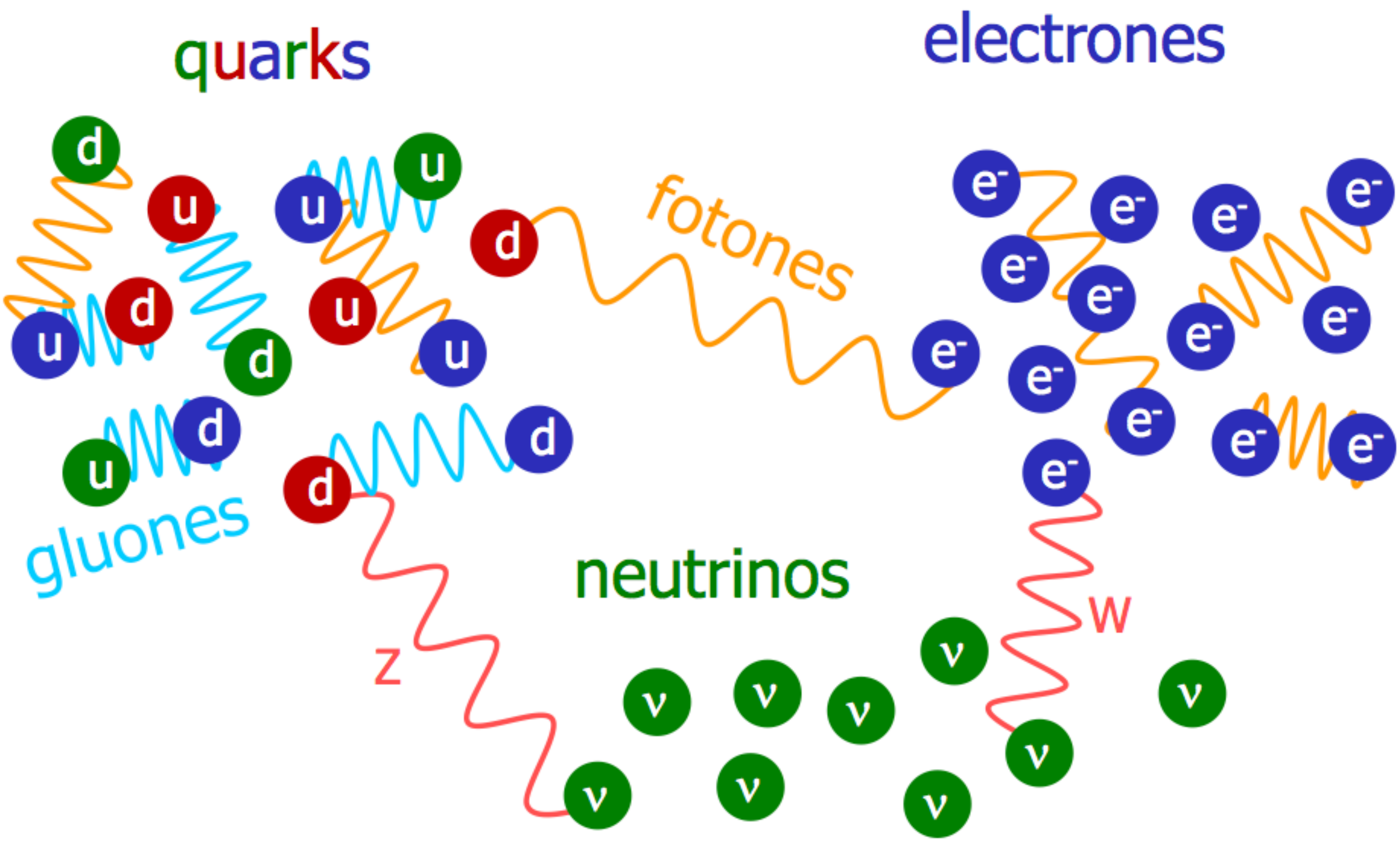
- Neither do they interact via the electromagnetic force (they have no charge)



Neutrinos have no charge, they cannot exchange photons

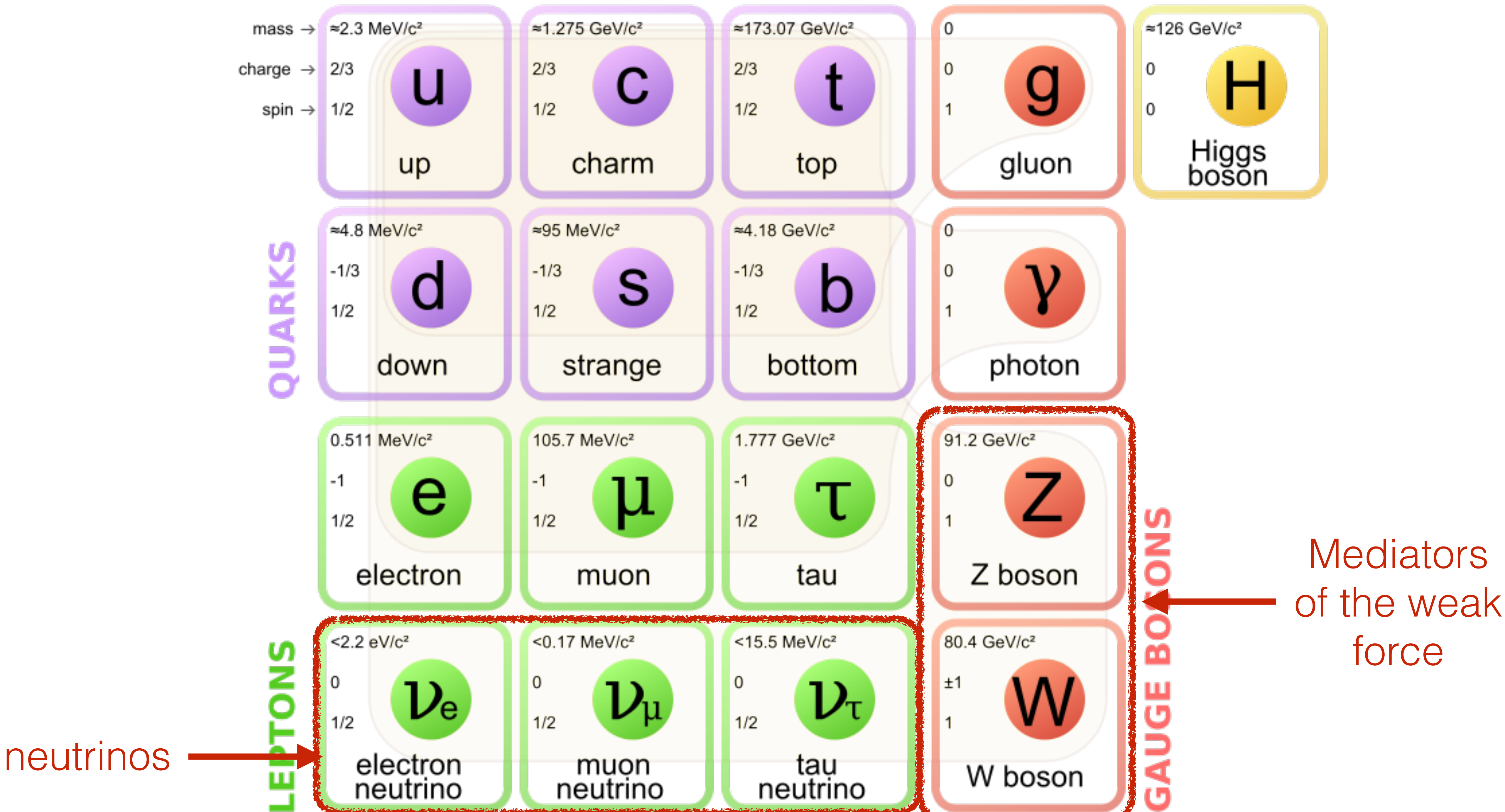
Why?

- They only interact via the weak force, which is mediated by the W and Z bosons



Flashback

- Going back to the previous diagram:



Why is the weak force so weak?

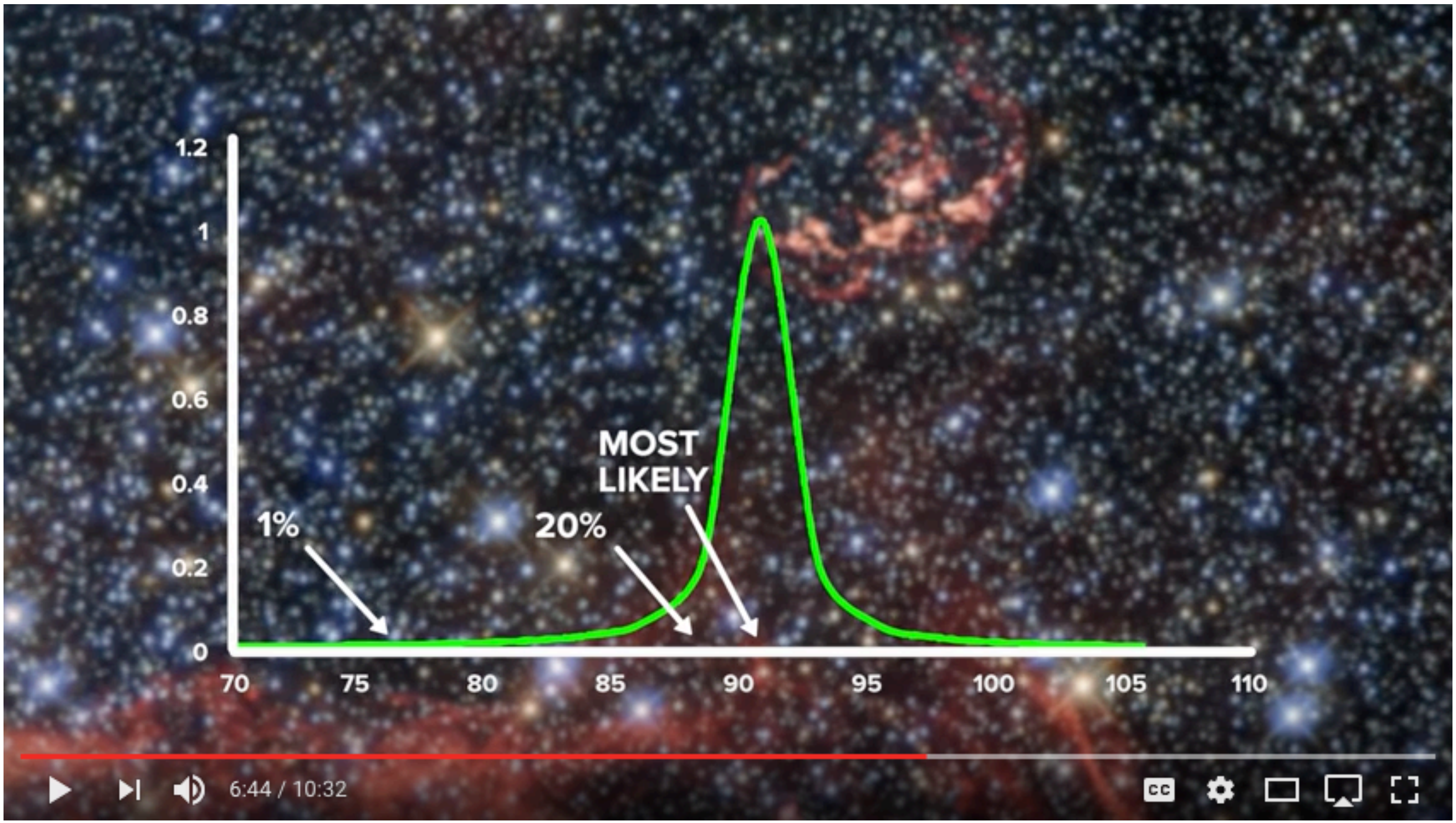
- What causes the weak force to be so weak?
  - We saw that a force is an exchange of particles
  - The greatest difference between the weak force and the others is that its mediators (W, Z) are extremely heavy

If interacting via the electromagnetic force can be compared to exchanging little marbles, then interacting via the weak force would be akin to exchanging this:

The W and Z bosons are approximately 100 times heavier than a proton

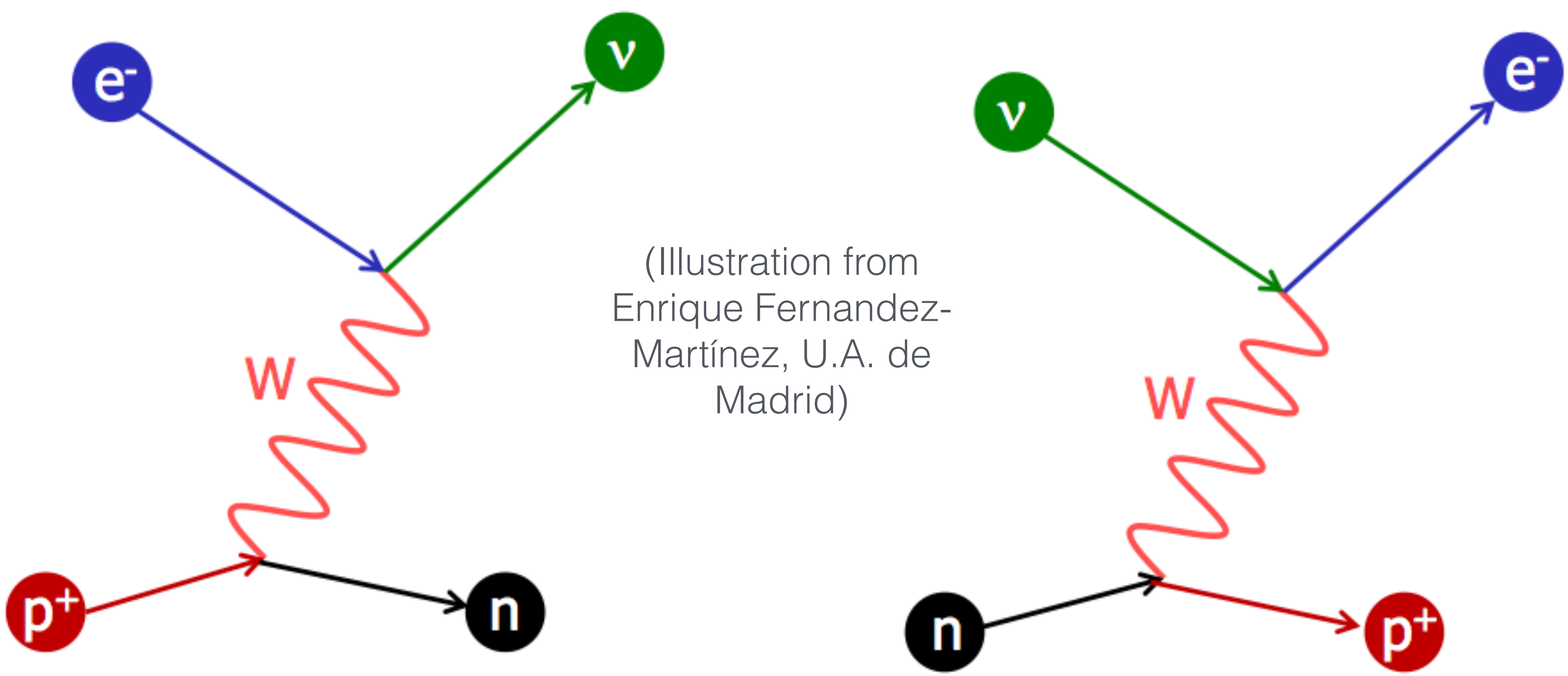
Why is the weak force so weak?

- A good resource to understand this: “Why is the weak force weak” in youtube, with Dr. Don Lincoln



The Weak Interaction

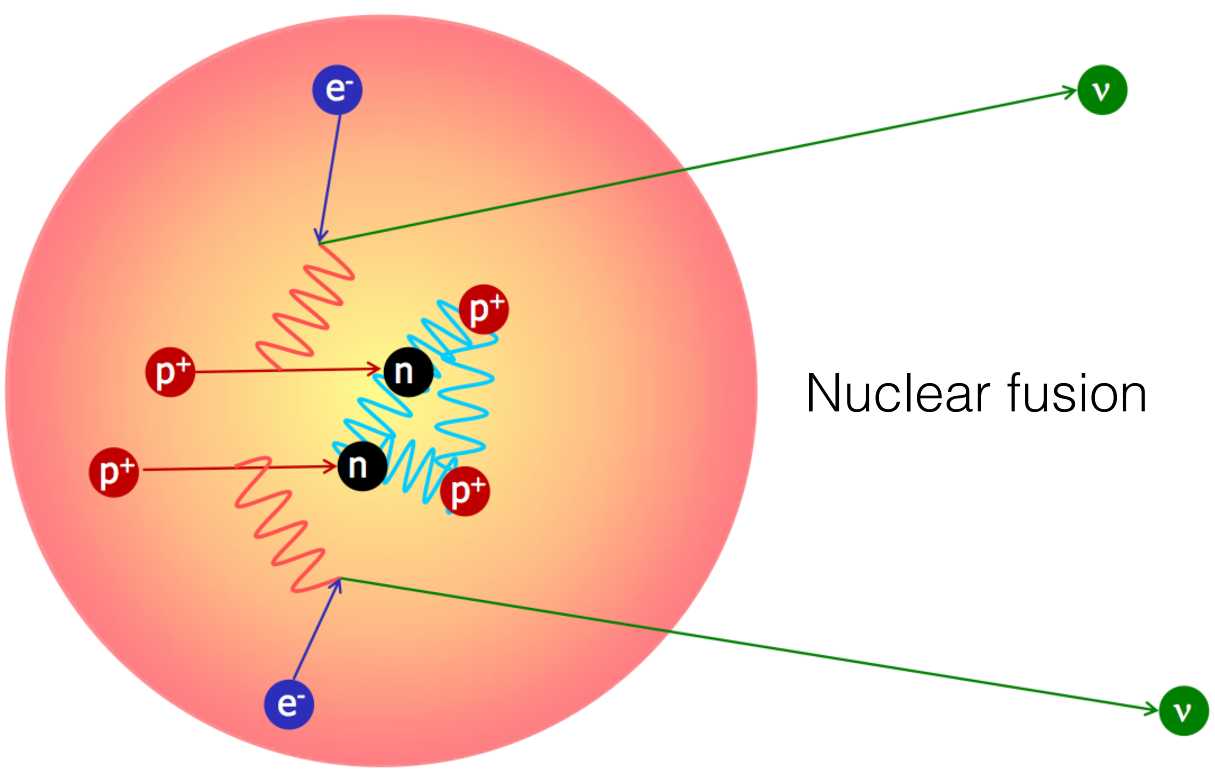
- If the weak force is so weak, then who cares?
- The weak interaction is *very* important because it is the only one that can transform particles into other ones

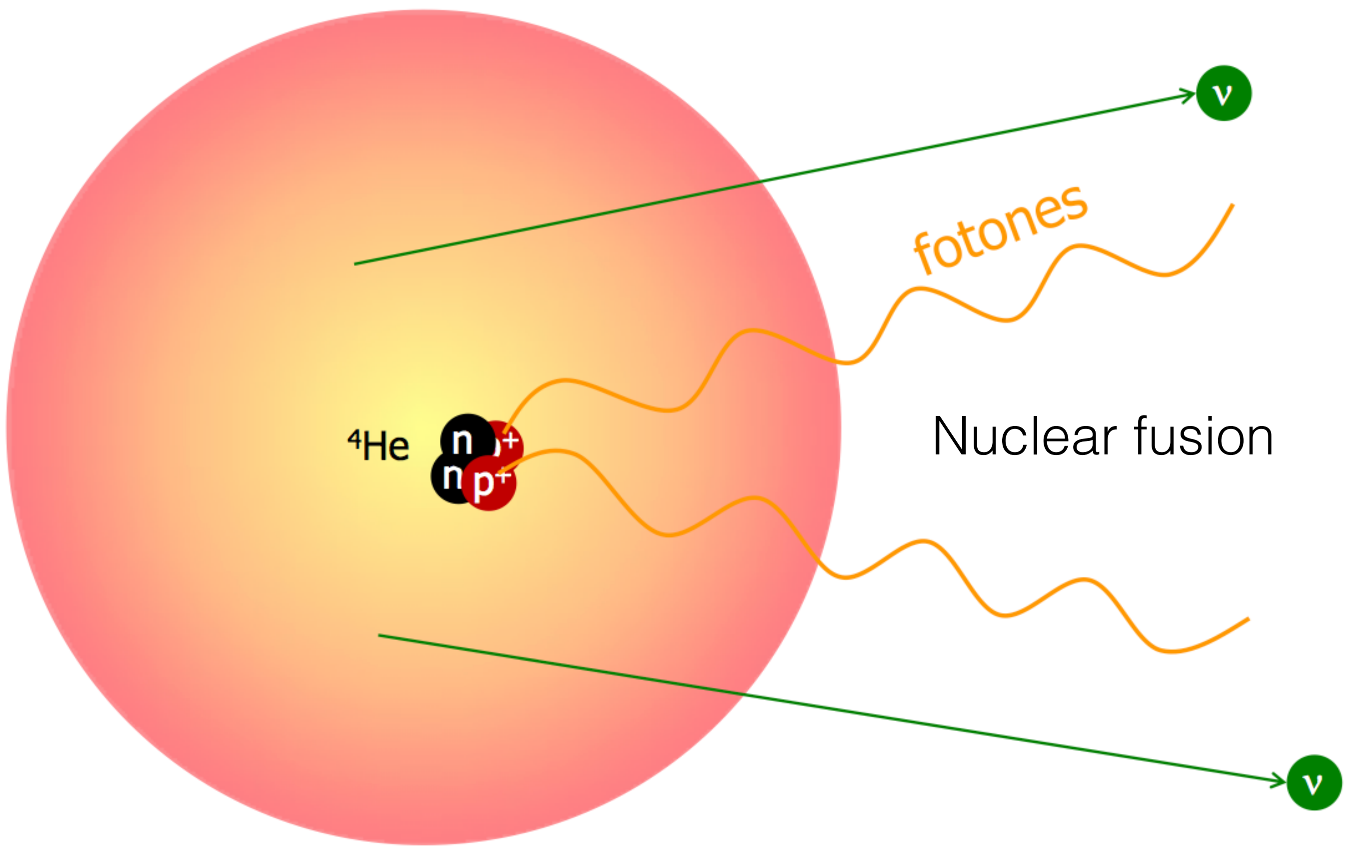


(Illustration from Enrique Fernandez-Martínez, U.A. de Madrid)

The Weak Interaction

- Without the weak interaction stars would not shine and there would be no light, heat, complex elements (oxygen, carbon, … etc), planets…. life!





- Also, it could be that neutrinos hold the key to some of the big answers, such as why is our universe made of matter.

How do you detect a neutrino?

- Reminder: of every100 000 000 000 000 000 000 solar neutrinos, only one in average interacts with a human being
- So **detecting them is not impossible…. just very hard!**
  - What should we do? Place a lot of mass in front of the neutrinos to increase the changes that at least a few will interact

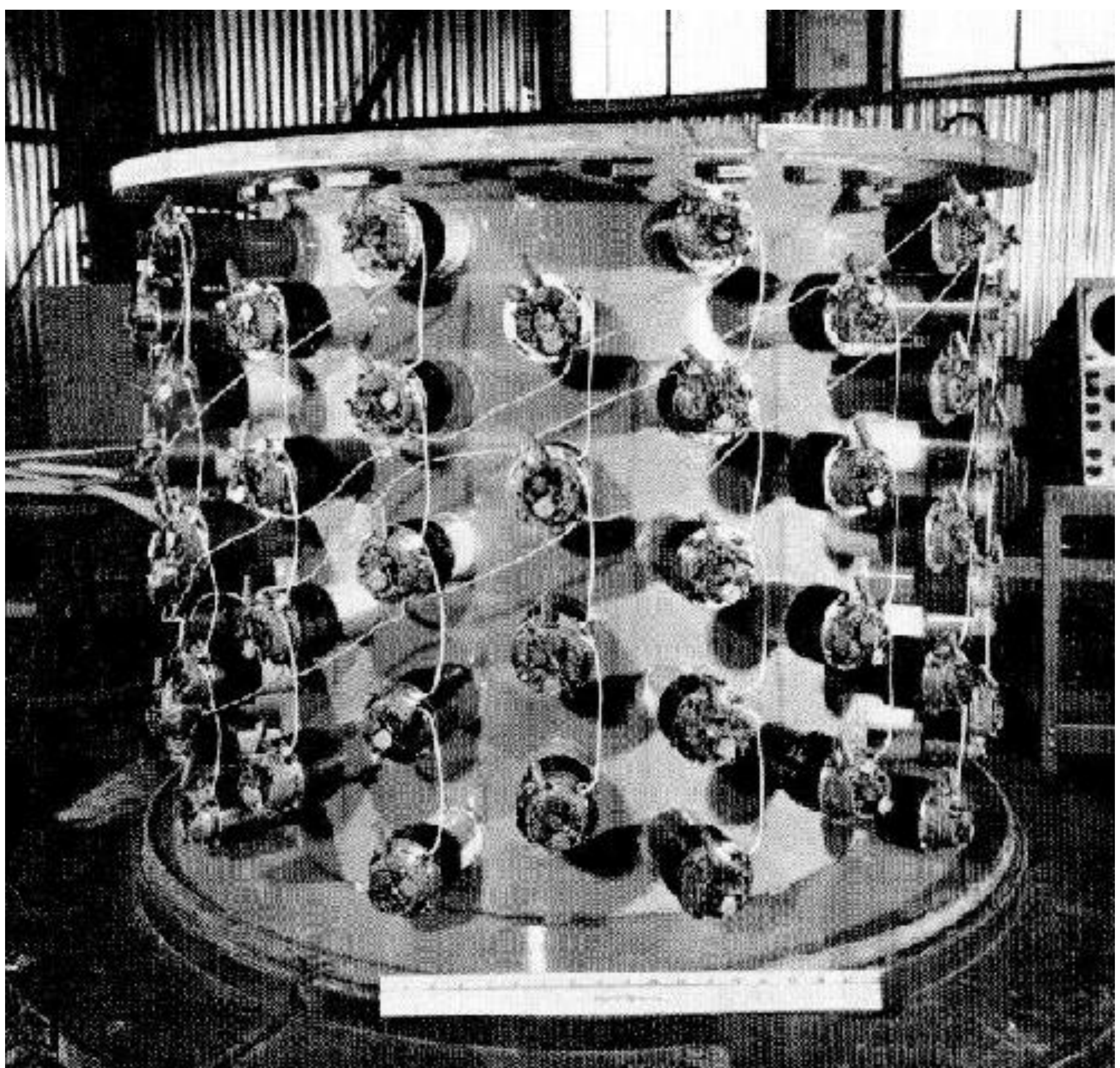
With a detector the size of one human being, 1 neutrino interacts

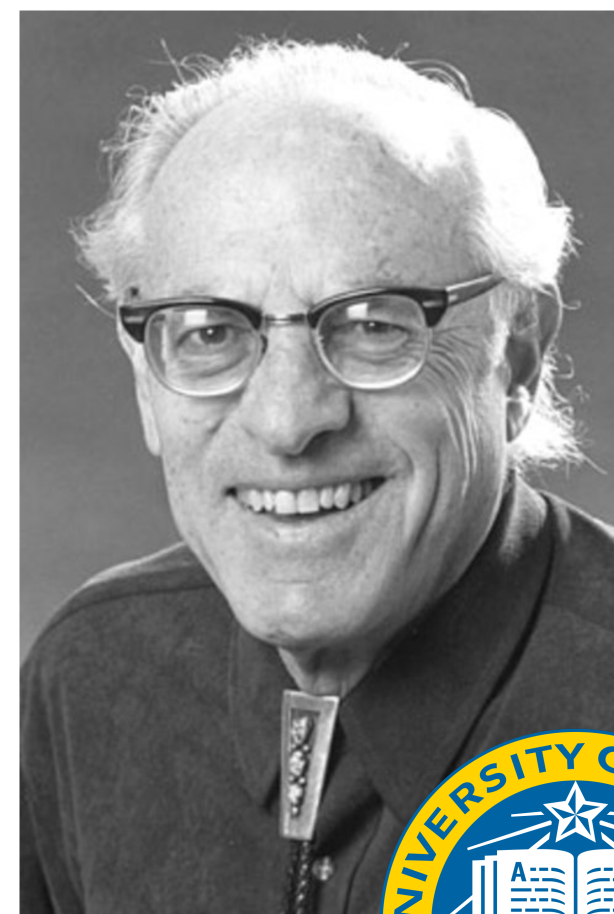
With a detector the size of 15 human beings, ~15 neutrinos will interact

Discovery of Neutrinos

– The other thing you do: expose your detector to the largest possible flux of neutrinos

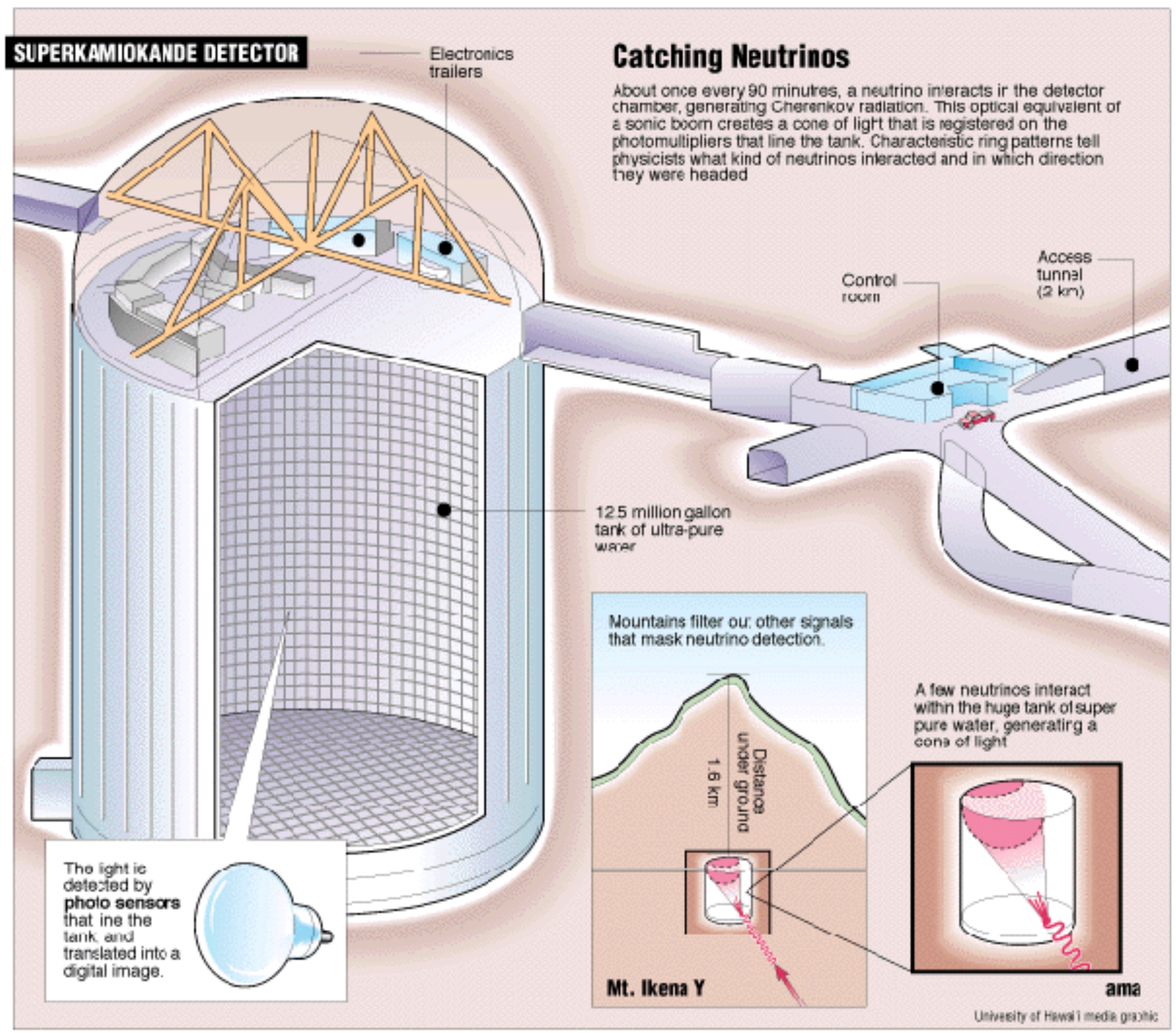
- This is why neutrinos were not discovered until 1956 by Frederick Reines and Clyde Cowan





Neutrino Detectors

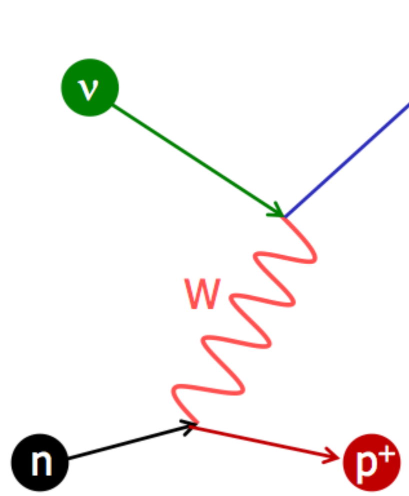
- That's why neutrino detectors typically have to be **HUGE**
- Example: **Super Kamiokande** in Japan
  - Cylindrical tank 41m high and 39m in diameter
  - 50,000 tons of ultra pure water



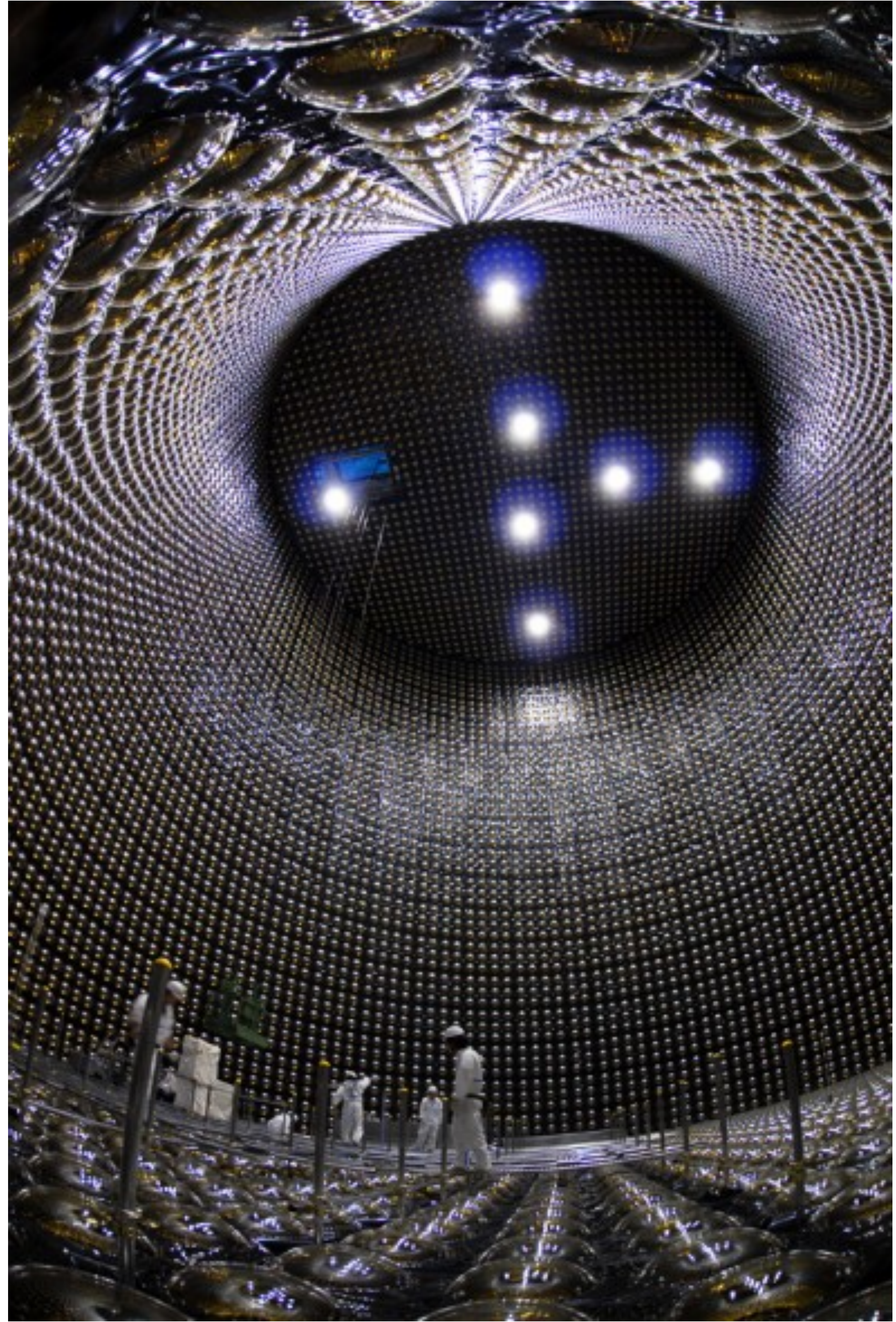
Super Kamiokande

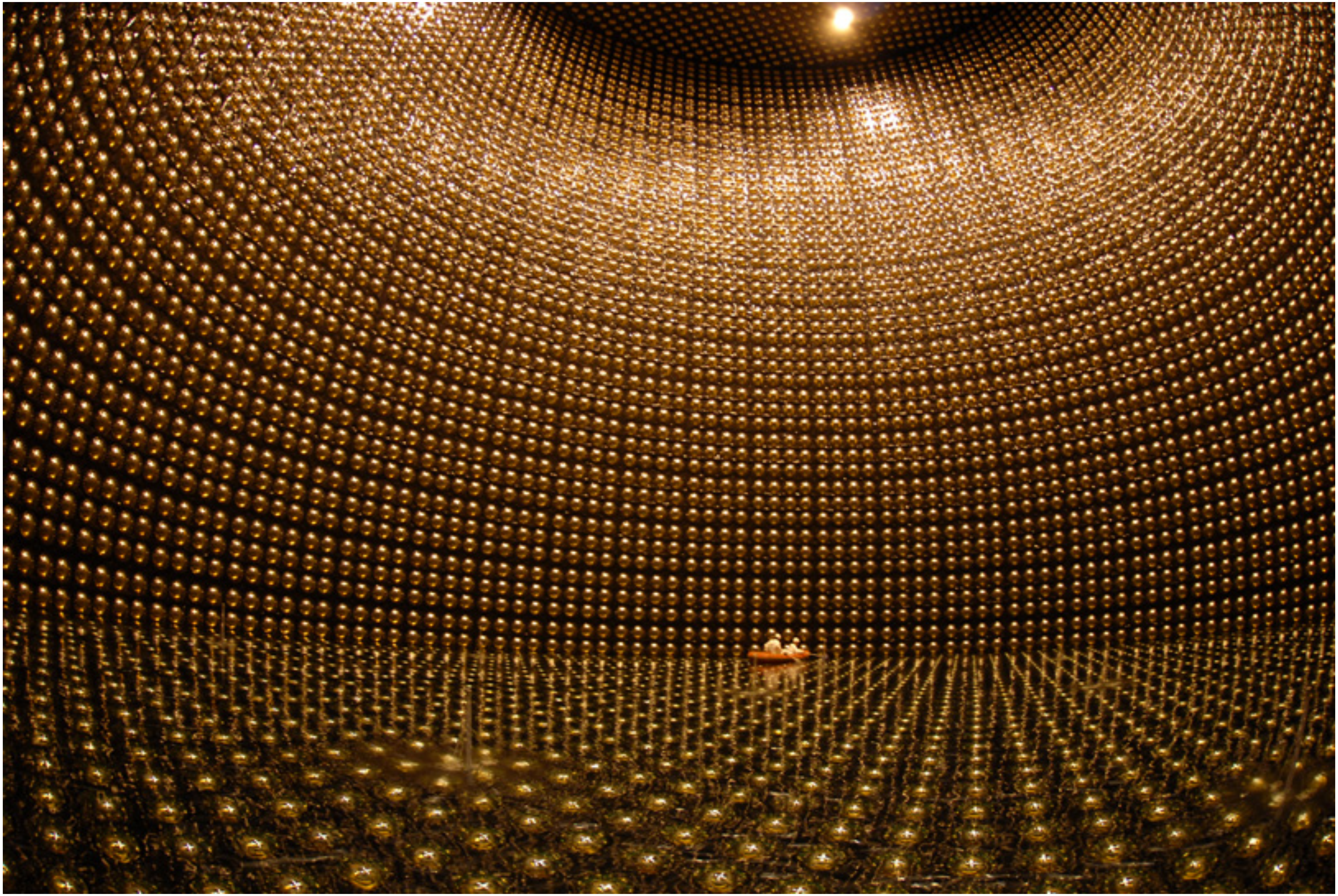
- The detector's interior is covered by approximately 11,146 photomultiplier tubes (extremely sensitive light sensors)

visible in the detector



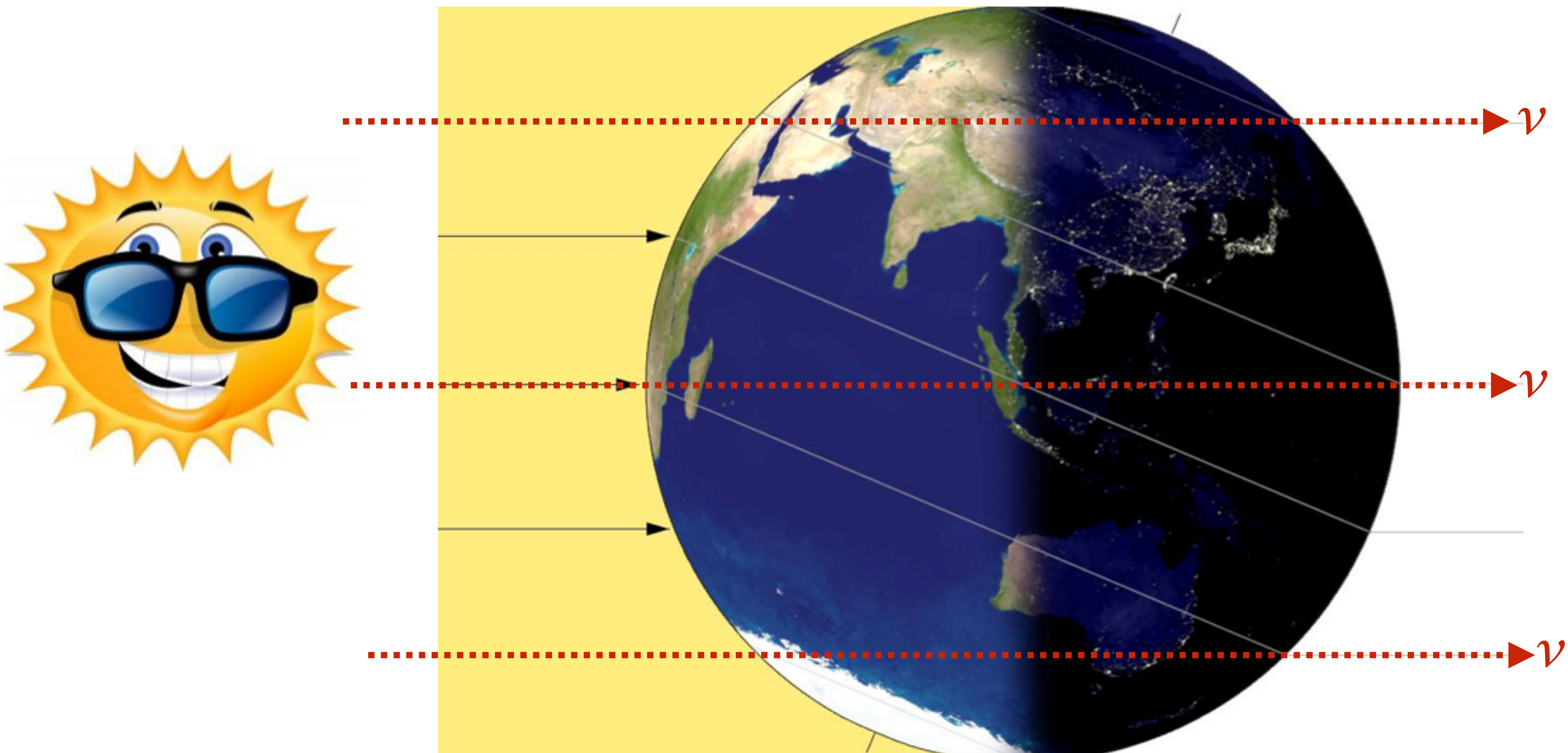
- Each tube costs a few thousand dollars





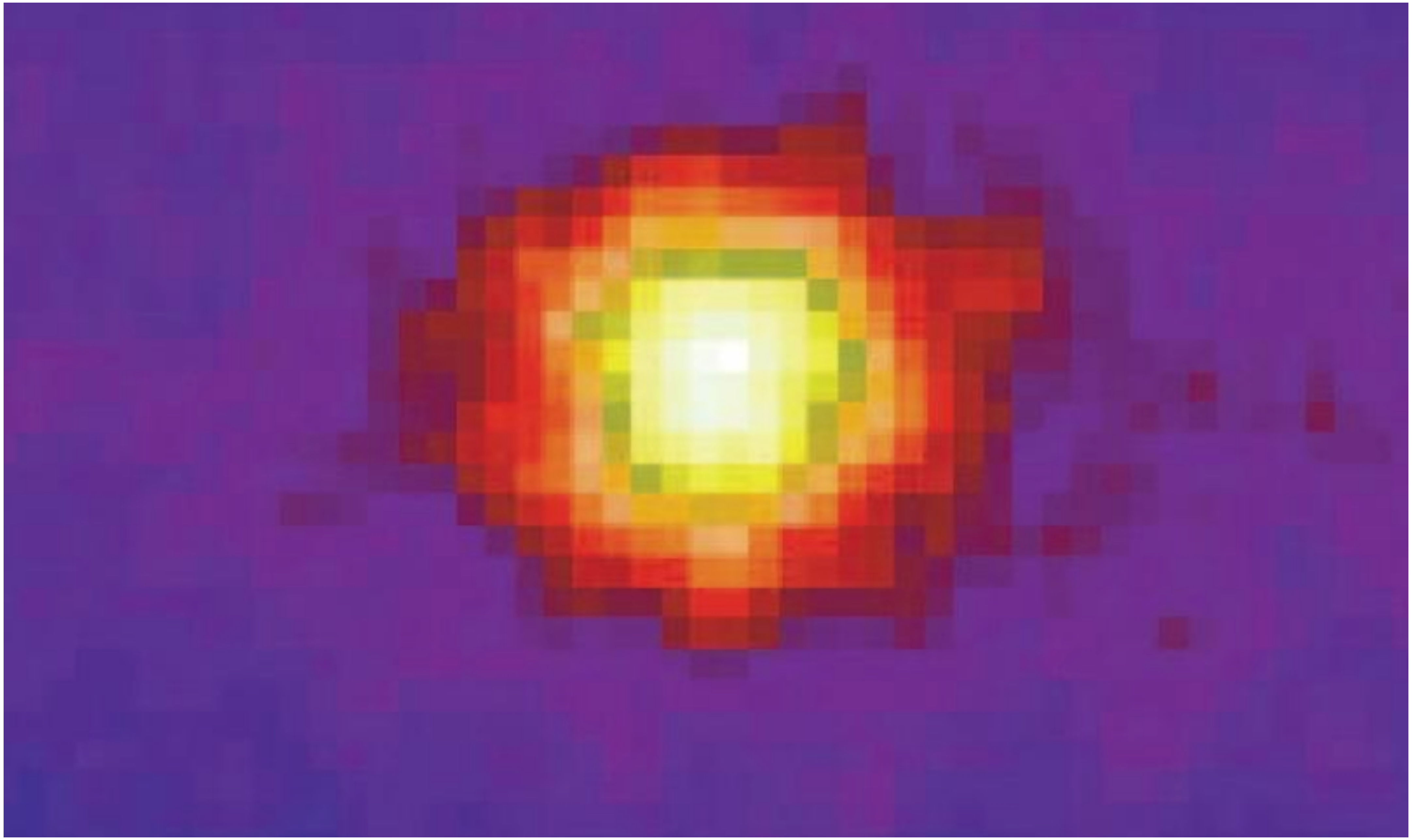
Super Kamiokande

- Among the many things you can do with this detector: **look at the sun at night**
  - How? Only with neutrinos



Super Kamiokande

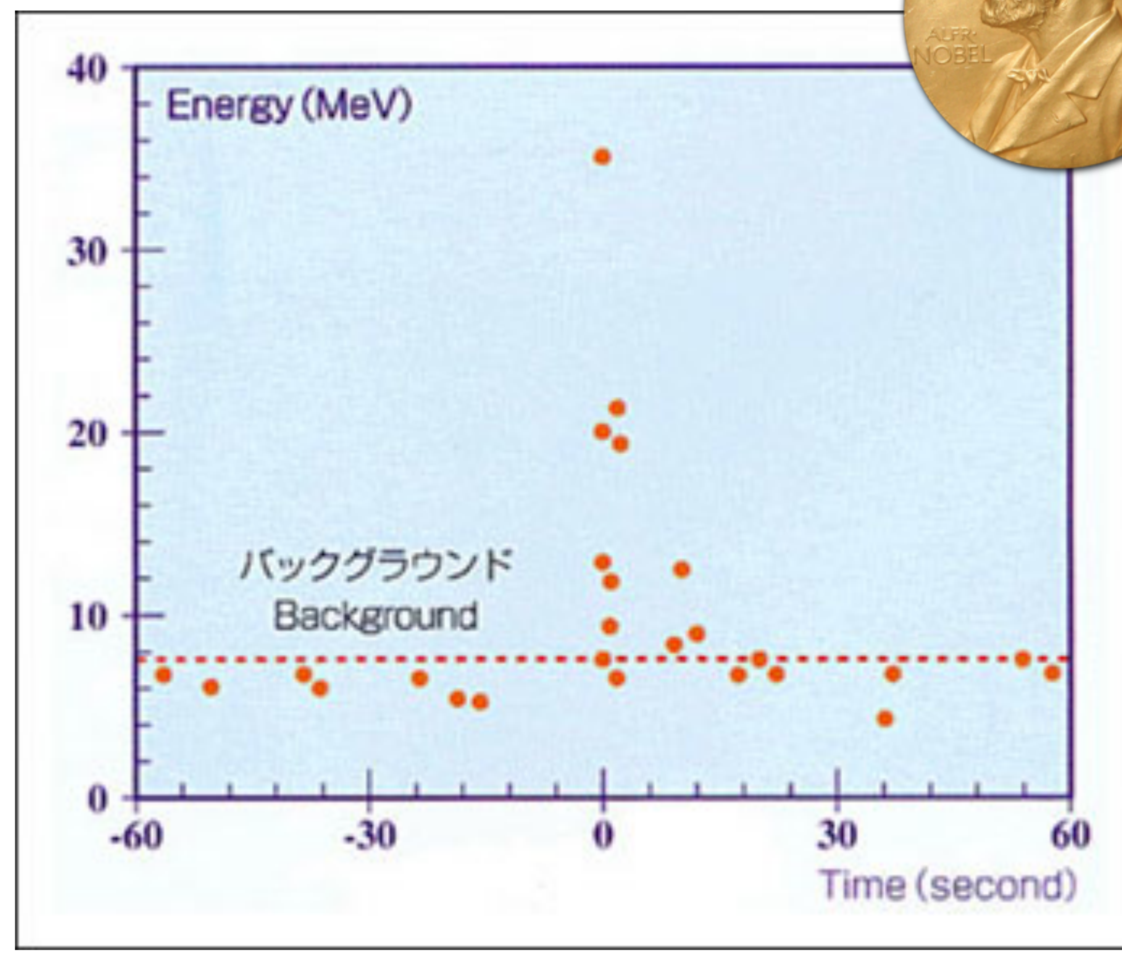
- The sun at night as seen with neutrinos:



  - Of course, we can do much more than just see the Sun: we can study it!

Kamiokande

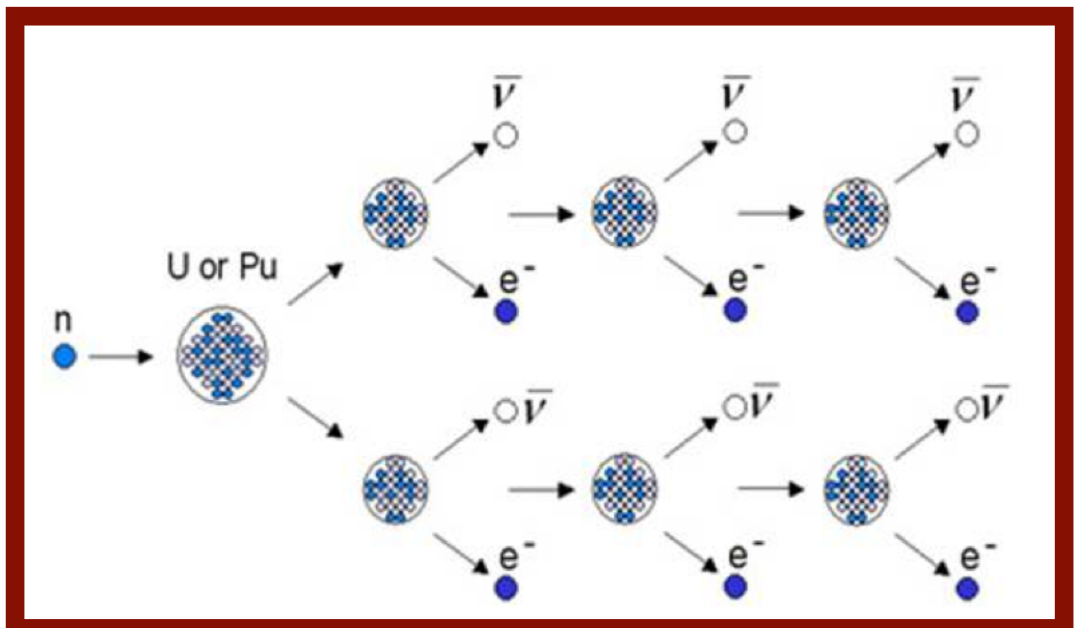
- Neutrinos from other cosmic sources have also been detected:
  - On February 23 1987 a supernova exploded in the Large Magellanic Cloud



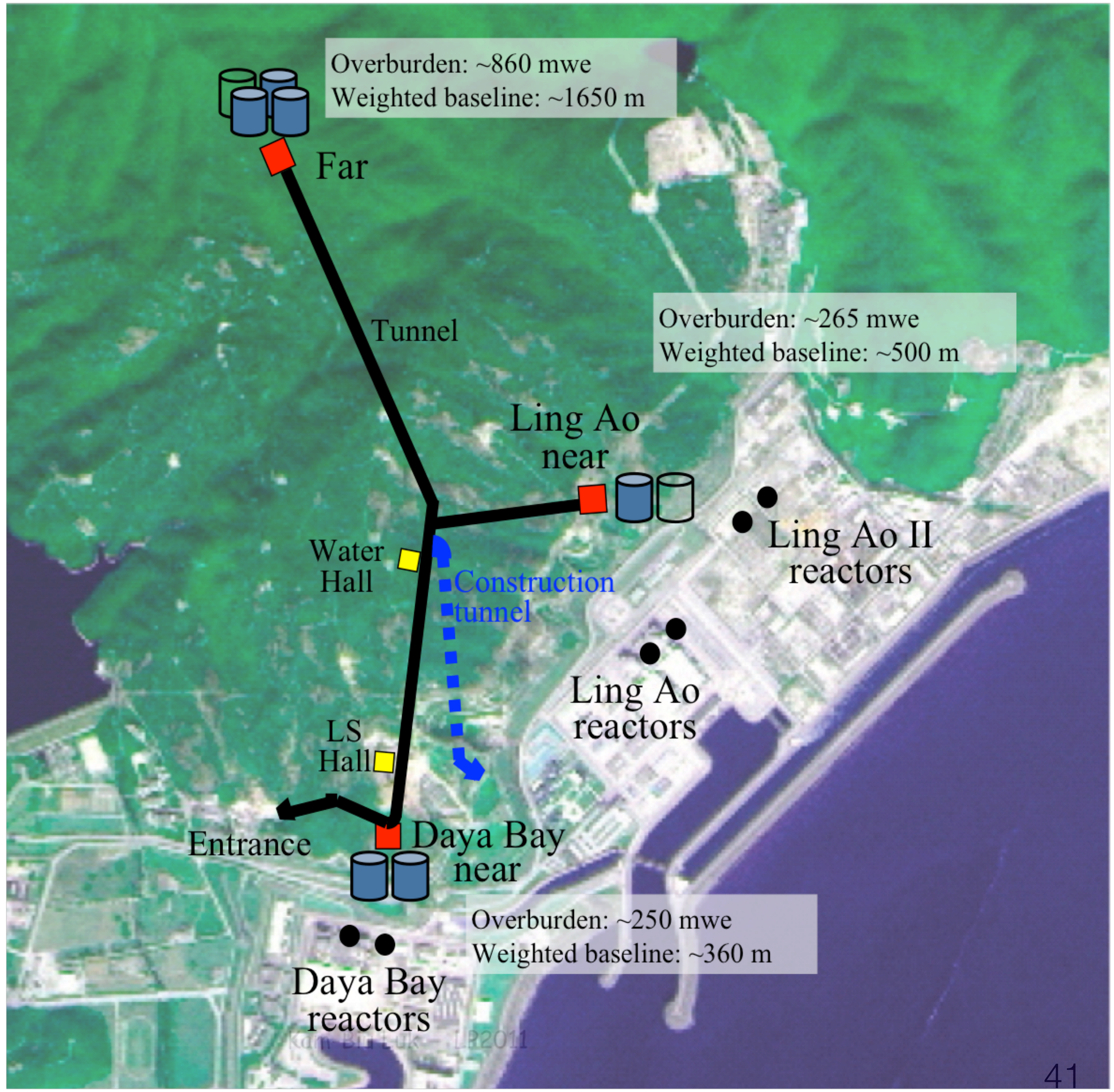
  - Kamiokande (Super Kamiokande's predecessor) and IMB detected 12 and 8 antineutrinos from this supernova, respectively
- If a supernova occurs now with our modern detectors, thousands of events will be detected

Reactor Neutrino Experiments

- There are other types of neutrino experiments
- You can for example go near nuclear reactors
  - Example: Daya Bay in China



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



Example: Daya Bay

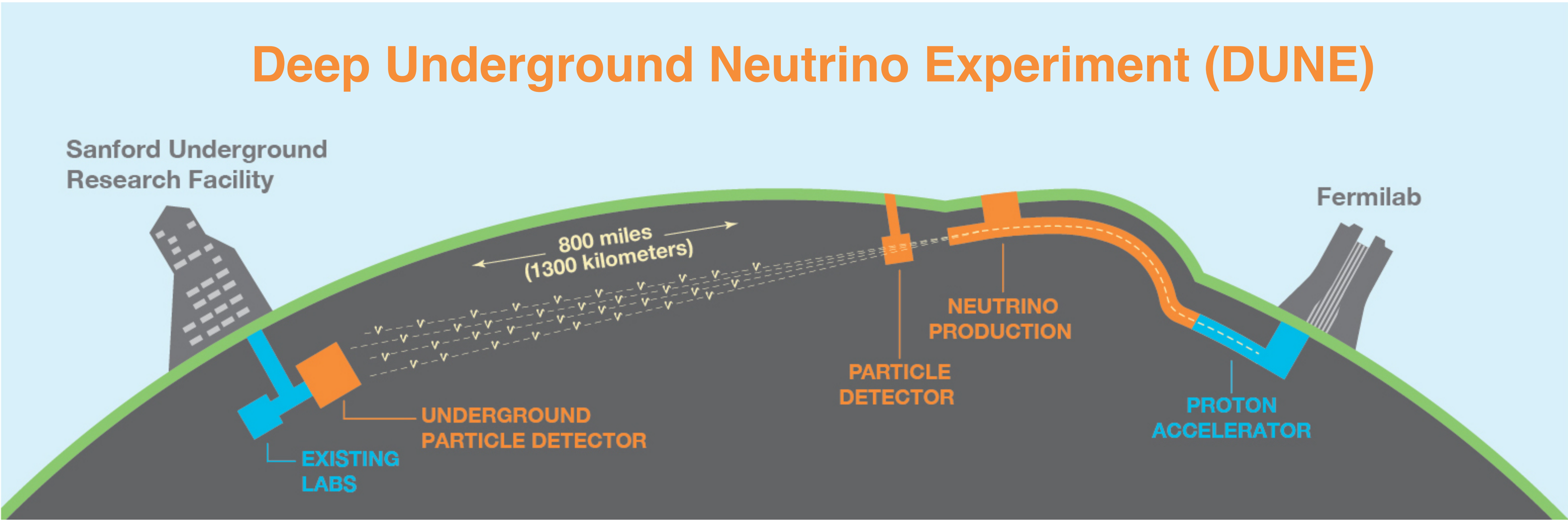
Daya Bay

- The detectors are so sensitive they had to be assembled in a clean environment

A few grams of sweat or dust could ruin everything!

Accelerator Neutrino Experiments

- You can also create a beam of neutrinos and send it through the Earth

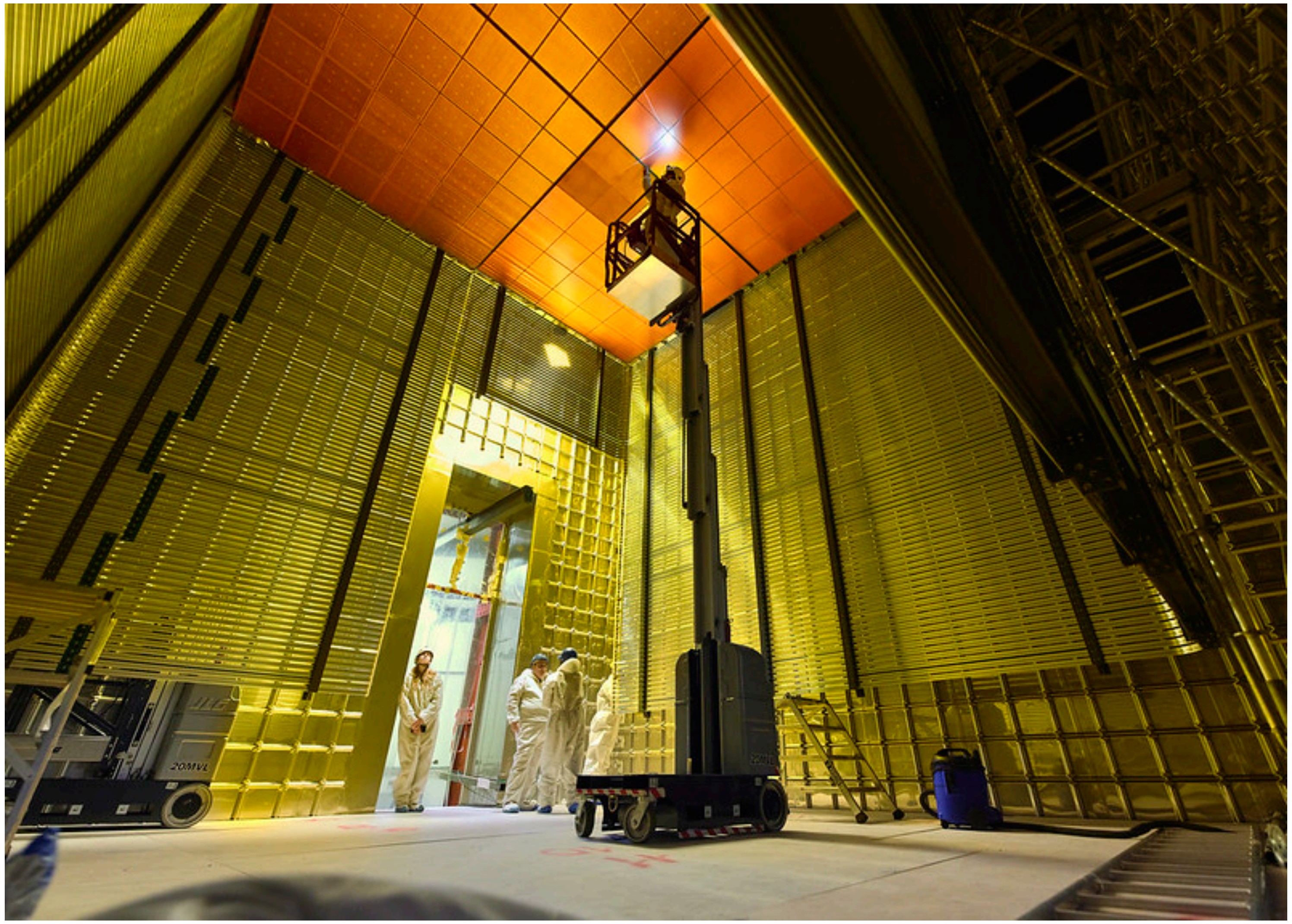


  - The beam is produced in Fermilab, near Chicago
  - Neutrinos travel for 1,300 km under the Earth until they reach detectors with mass of 40,000 tons in an underground mine

DUNE

One of DUNE's predecessors (MINOS)

- DUNE is currently under construction:



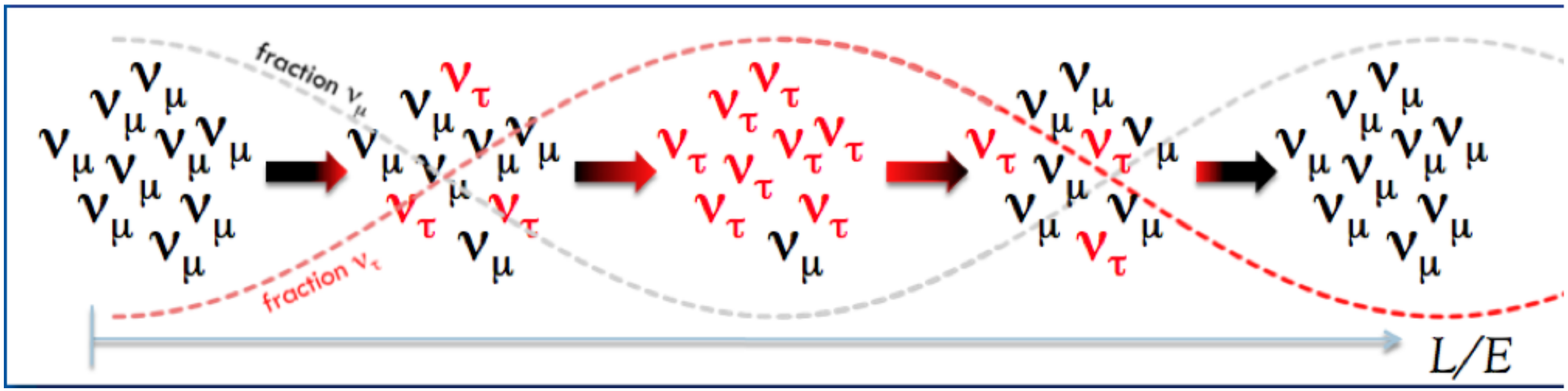
  – Here at UCI we are responsible for parts of the near detector and the purity monitors, among other areas (reconstruction and analysis)
  – Start of operations: end of this decade
- The million dollar question is… why?

Neutrino Oscillation

- It turns out neutrinos have another mysterious property:

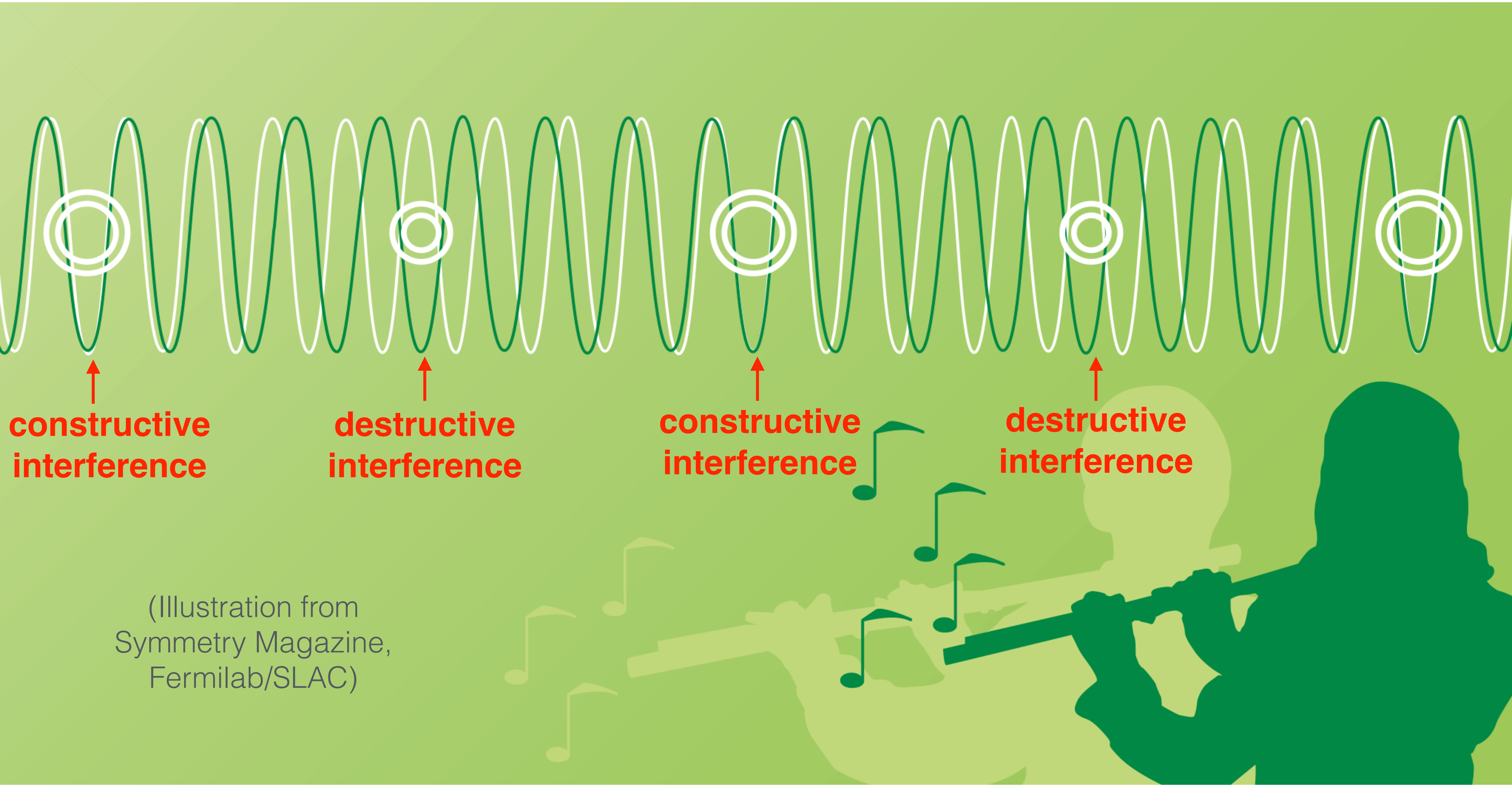
Neutrino Oscillation

- Neutrinos change flavor as they travel!



- How come?
  - It's a consequence of quantum mechanics, where particles behave like waves that interfere one with another
  - **When created, neutrinos are not in a definite state of mass, but are instead a superposition of different mass states**
  - Each mass state propagates slightly differently (in other words, each state is a wave with a slightly different frequency)

- Analogy: two musical notes that are slightly different (like when you tune a guitar)



– Same thing with the probability of observing a certain type of neutrino (probability increases, decreases, increases, decreases… etc.)

Who cares about neutrino oscillation?

- Our best theory of particles and their interactions (the Standard Model) can explain almost every single observation done so far
  - This is both good and bad, because we know this theory is incomplete (does not have gravity, dark matter… etc)
  - Neutrino oscillation is one of those phenomena not explained by the Standard Model

Neutrinos can show us how to expand the theory!

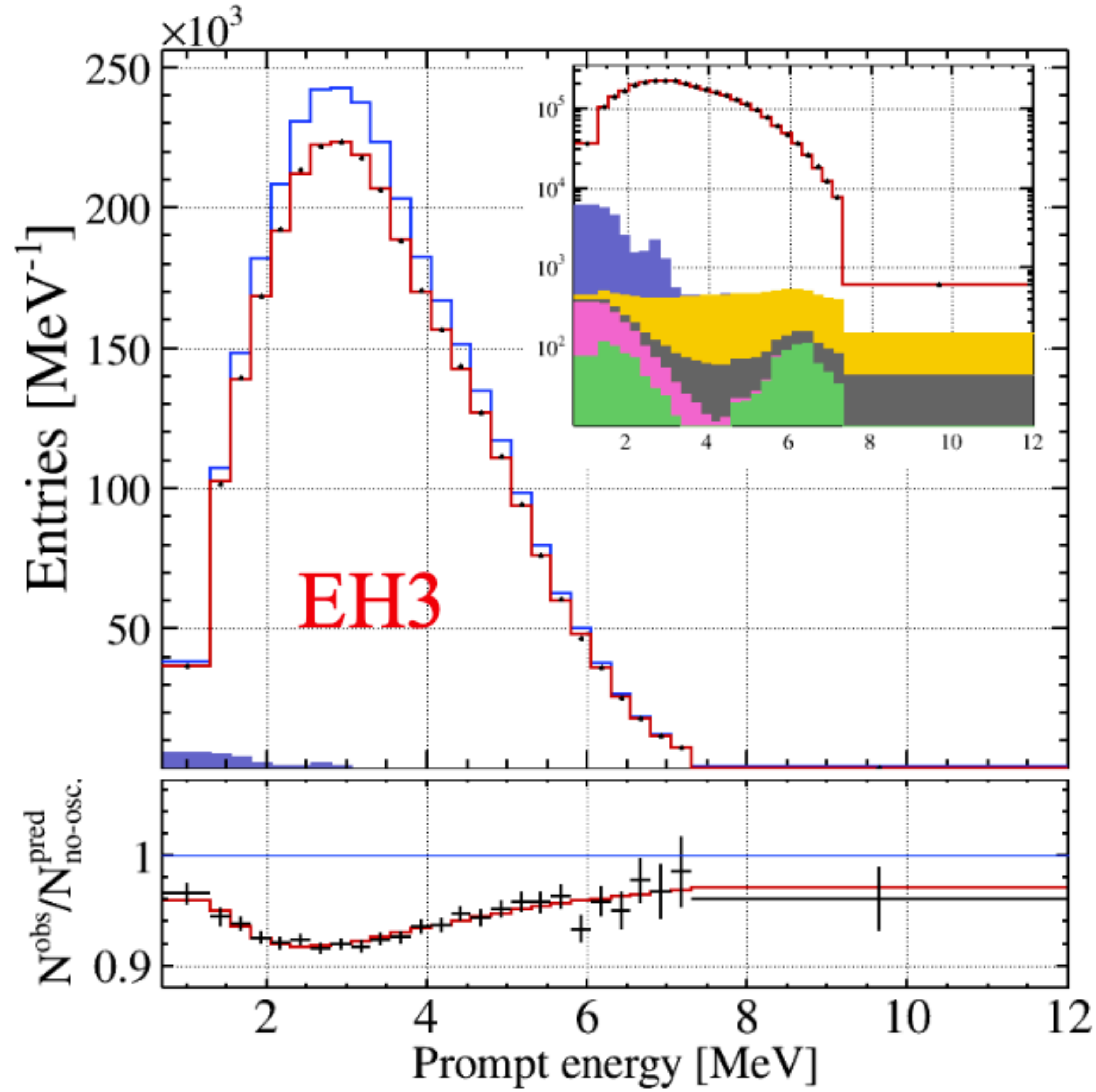
- To incorporate neutrino oscillations, it is necessary to incorporate at least three new parameters to the actual theory, called mixing angles **(θ_{12},θ_{23},θ_{13})**. It is also necessary to give neutrinos mass.
  - Let me finish by showing you one of our latest results

Latest Results from Daya Bay

- Latest results from Daya Bay
  - We use more than 6 million antineutrino interactions ⟶
  - Can measure one of the mixing angles and one of the mass differences to < 3%.

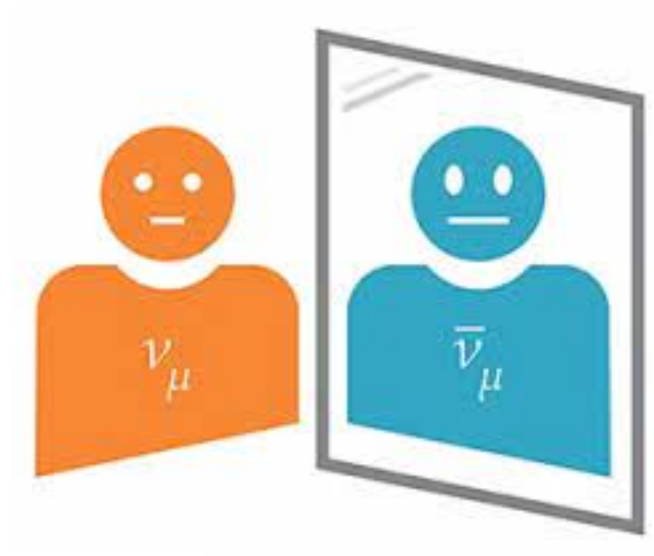
$$\sin^2 2\theta_{13} = 0.0853^{+0.0024}_{-0.0024}$$

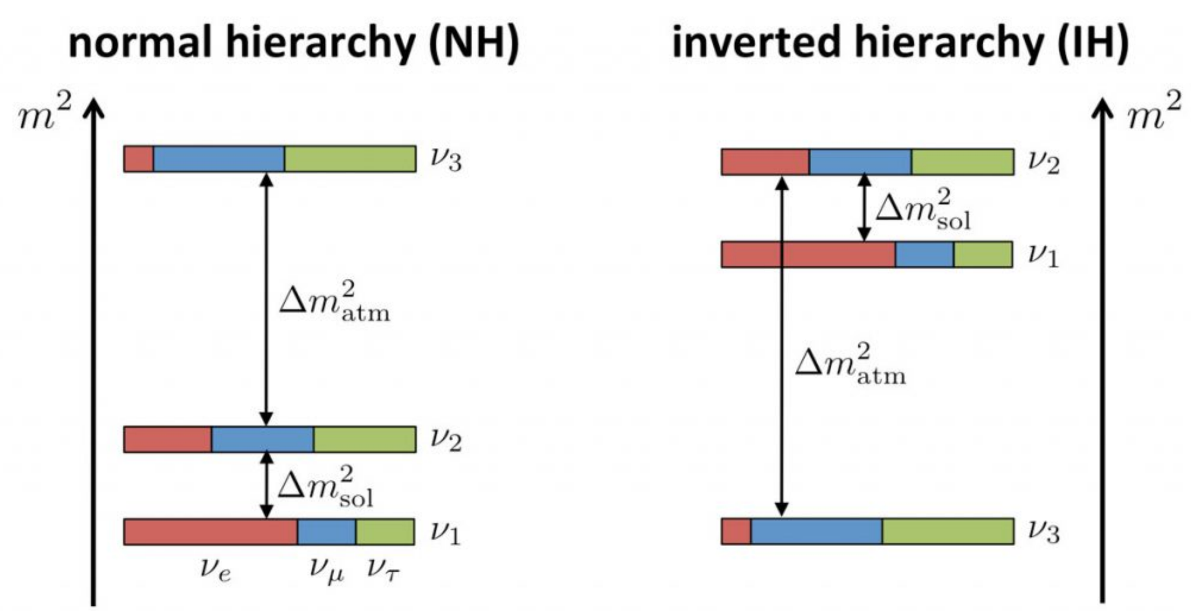
$$\Delta m^2_{32} = +\left(2.454^{+0.057}_{-0.057}\right) \times 10^{-3}\ \mathrm{eV}^2$$



Outlook

- There are still many open questions in neutrino physics:
  - Do neutrinos violate the charge-parity (CP) symmetry?
  - Are there more than three neutrinos?
  - How are neutrino masses ordered?



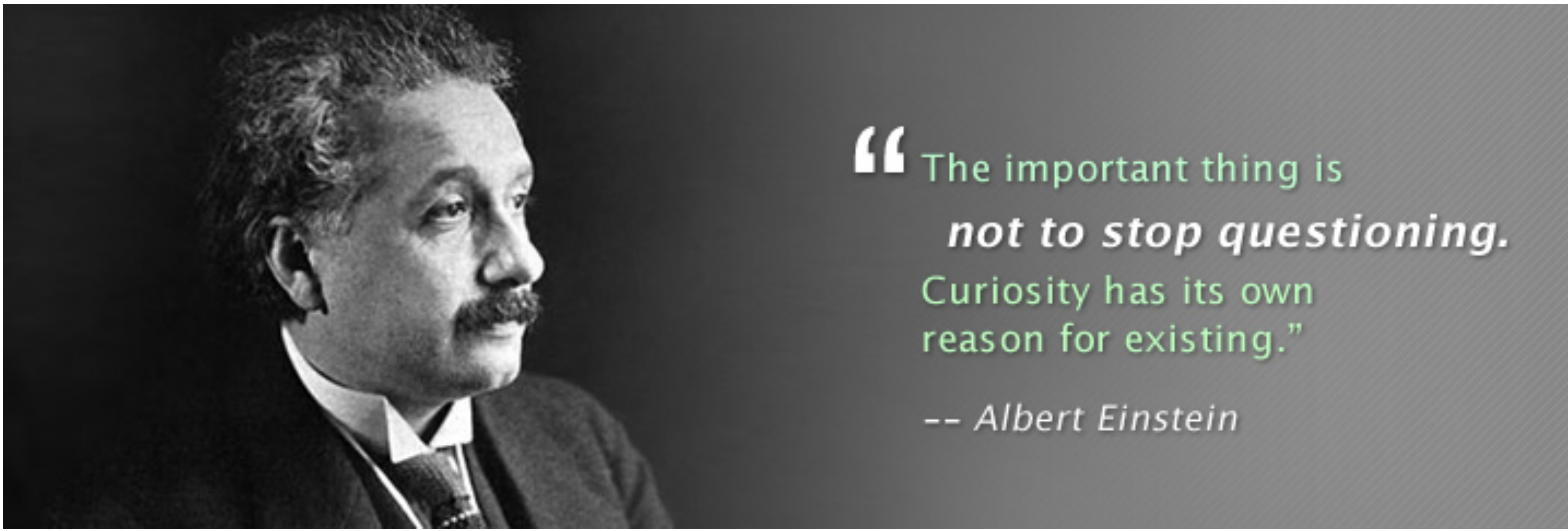


- These questions have important consequences in physics & cosmology
  - Our group here at UCI is working hard to answer these and other questions

Summary

- The Standard Model is our current best theory of particles and their interactions
  - It is extremely successful, perhaps too much so
- There are at least two ways of doing particle physics these days:
  - With collisions at colliders
  - With dedicated neutrino experiments (using accelerators, nuclear reactors, or natural sources)
- There are many open questions in our field
  - Neutrinos are one of the most promising ways of addressing some of these questions and of understanding the sources that produce them

Questions?



“The important thing is
not to stop questioning.
Curiosity has its own
reason for existing.”
-- Albert Einstein

Backup

The Higgs Mechanism

The Higgs Mechanism

The Higgs Mechanism

https://www.youtube.com/watch?v=joTKd5j3mzk