Neutrino Physics

P. Barham Alzás

International High School Teacher Programme

12/07/2023

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1. **History**
2. What we know today
3. What we *don’t* know
4. Where do they come from?
5. How do we study them?
6. The CERN Neutrino Platform

The sacred principle

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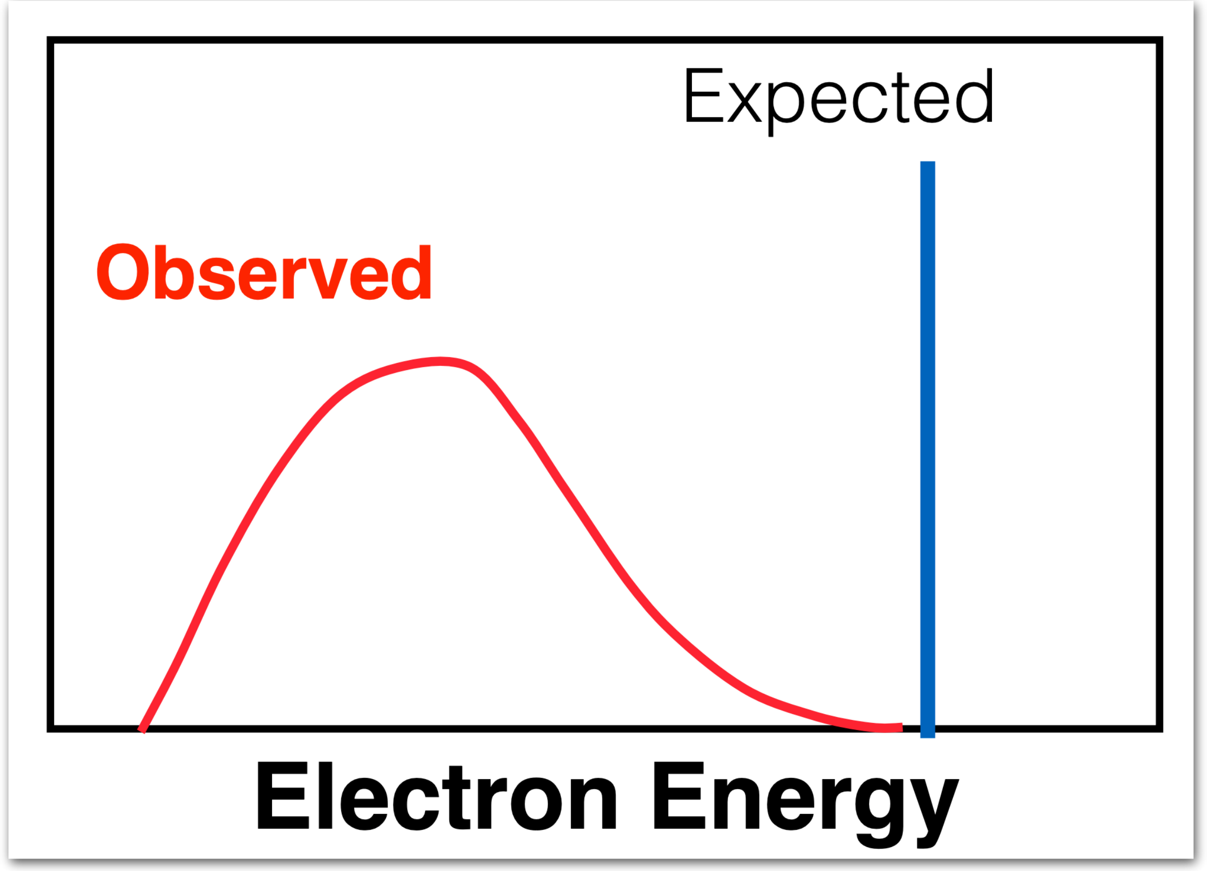

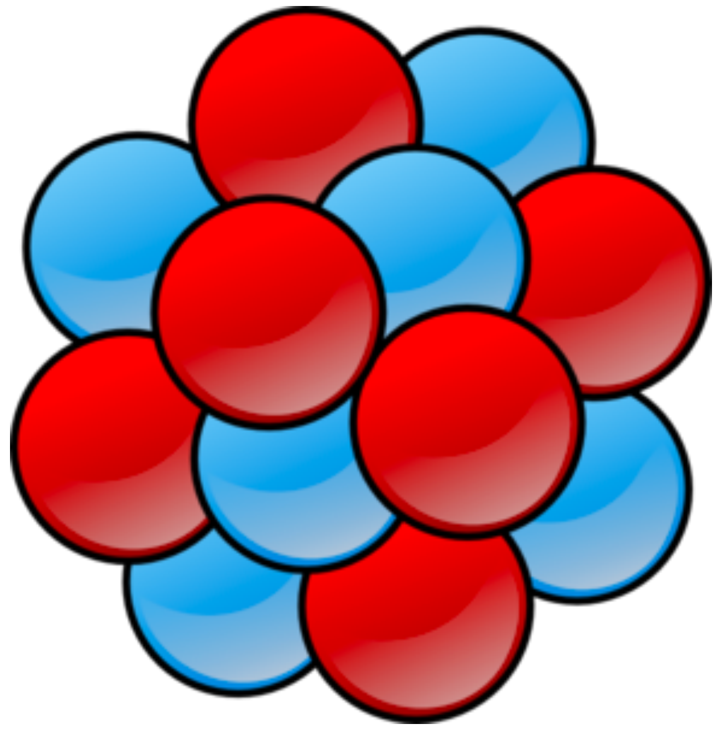

$$n \to p + e^-$$

Electron should always be emitted with the same energy.

Instead, a whole range of energies was observed.

Energy conservation was broken!

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- ***And hence the neutrino was born!***

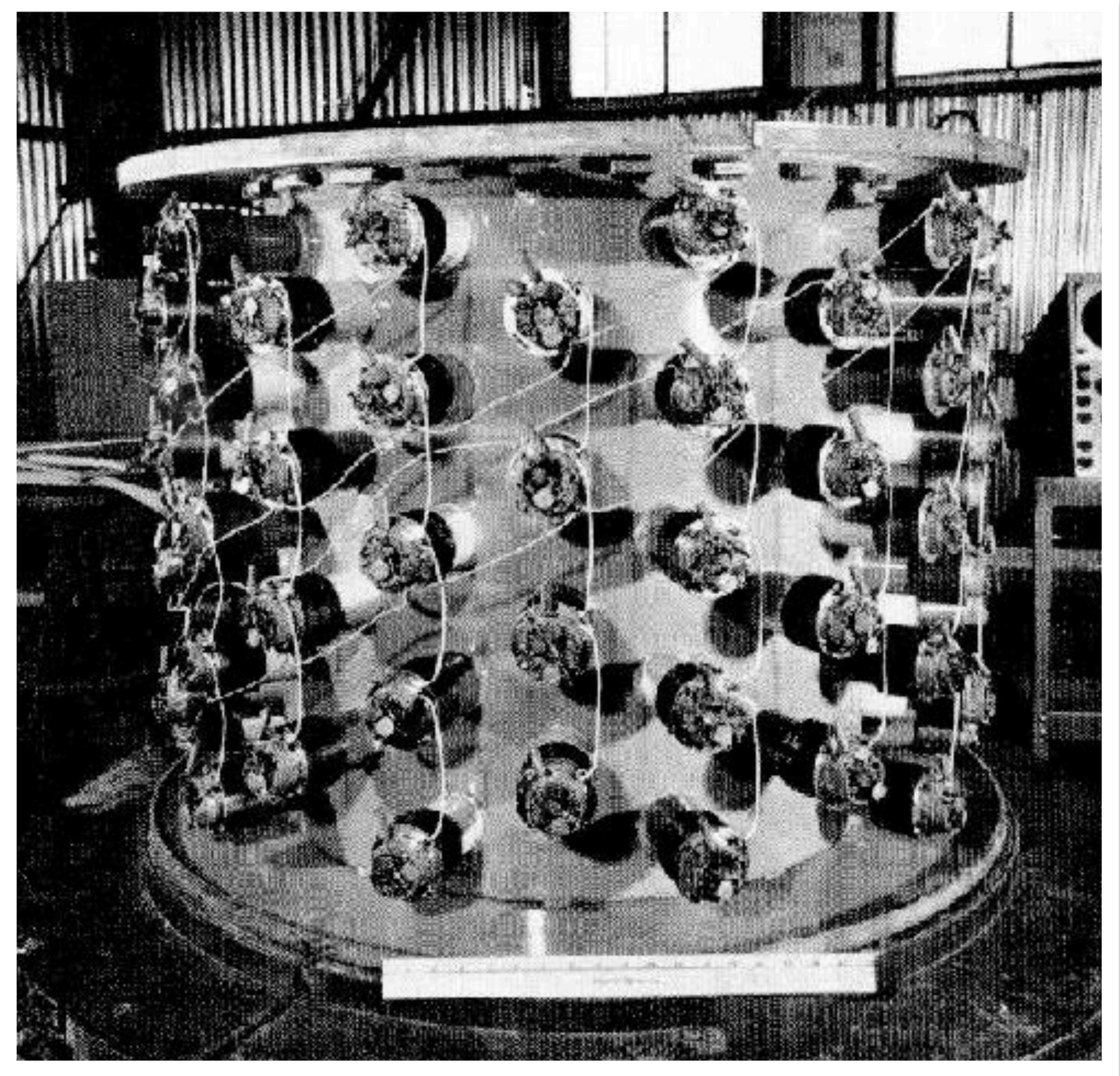
$$n \rightarrow p + e^- + \nu$$

Problem: This new particle is extremely hard to detect.
Pauli apologised for proposing a particle he thought could never be observed!

Neutrinos discovered!

Fortunately Pauli was wrong.
Neutrinos were first observed two decades later in 1956.

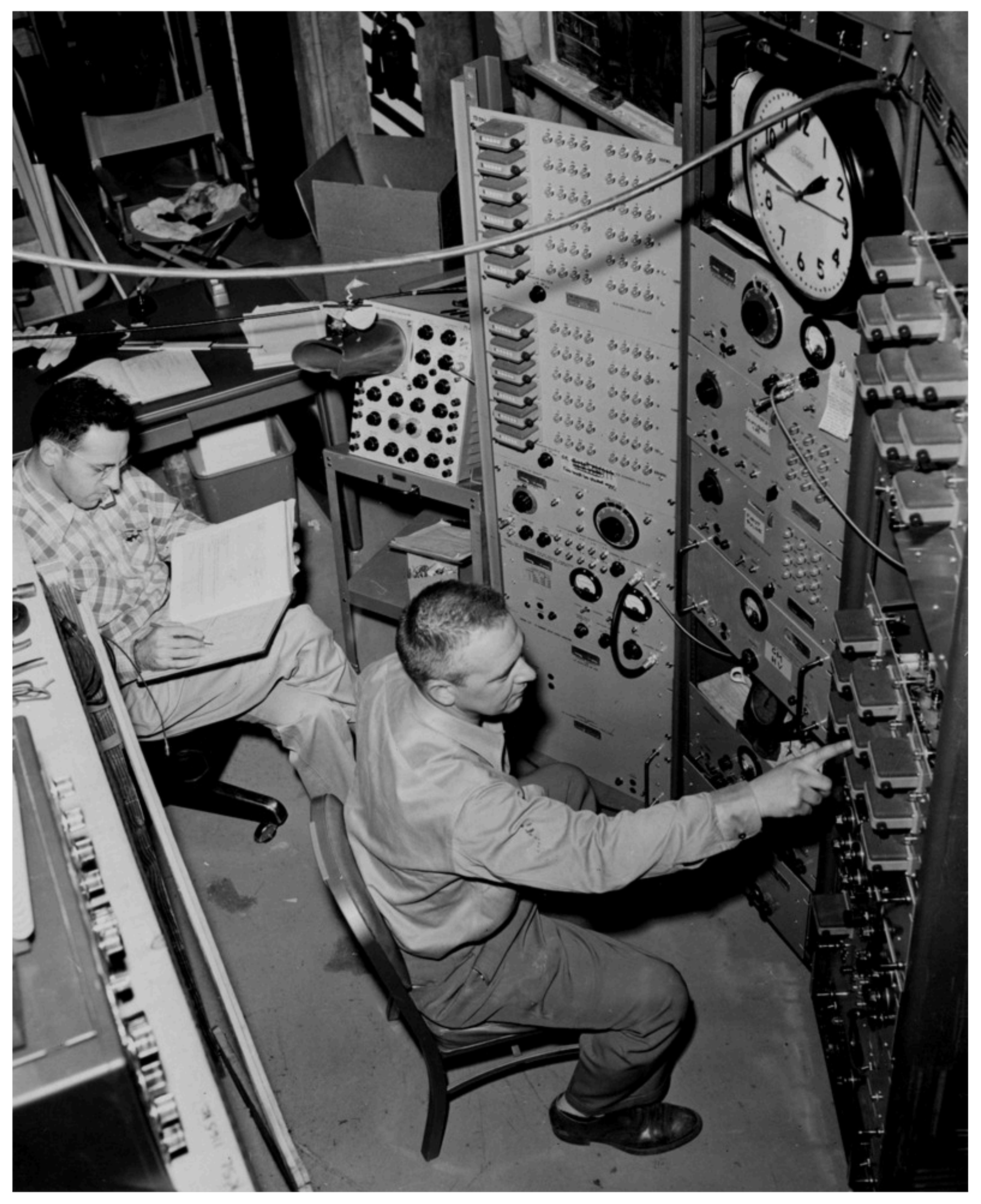
- Reines and Cowan observed antineutrinos from the Savannah River reactor (US) with a 1m^3 liquid scintillator. **1995 Nobel Prize.**



The actual thing

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

Inverse beta decay



Cowan operating the experiment

New surprises for the rest of the century…

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We now have a neutrino for each type of charged lepton: electron, muon and tau.
We call them “**flavours**”.

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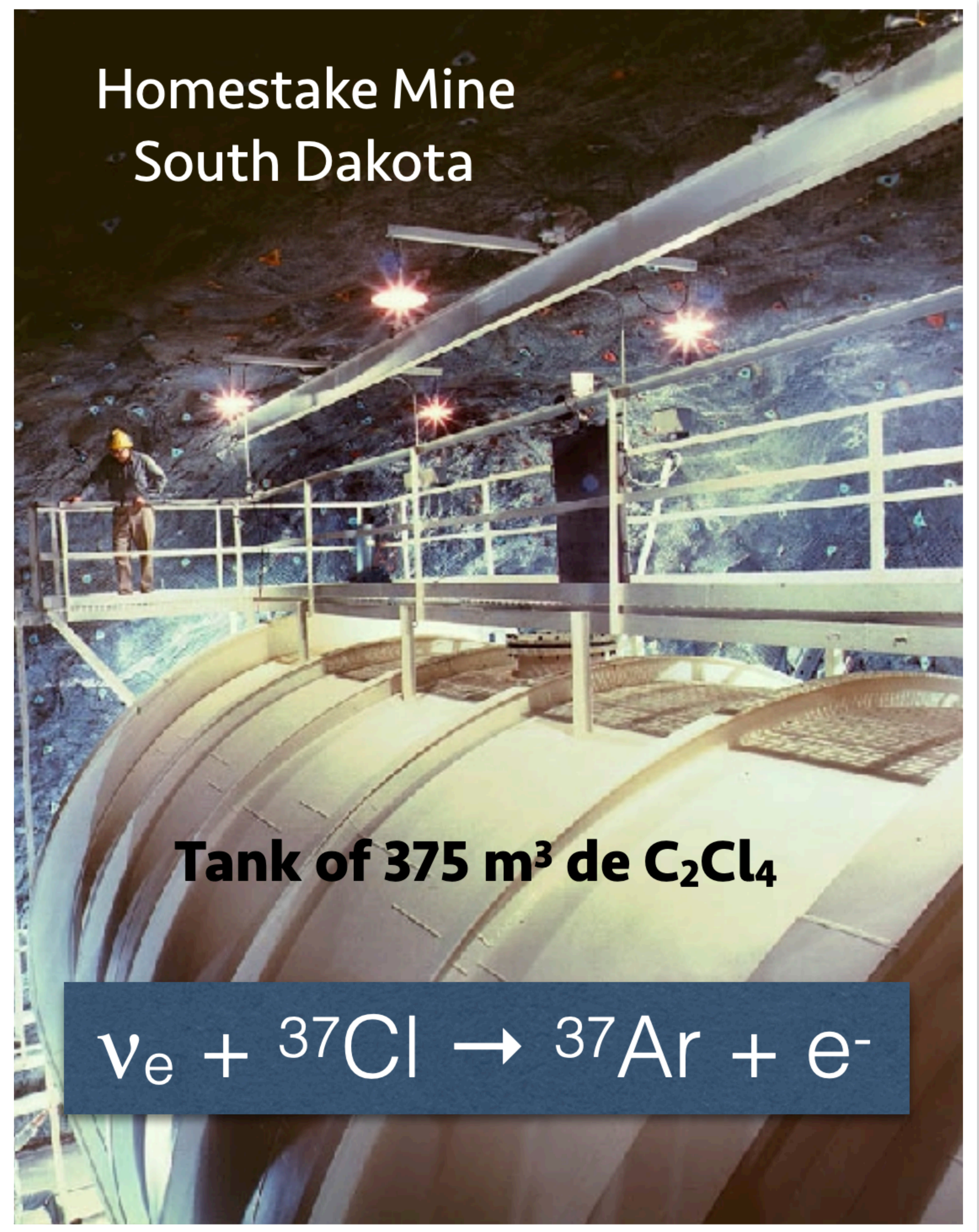
New surprises for the rest of the century…

Now the hard part: the solar neutrino problem.



One of the first dedicated solar neutrino experiments

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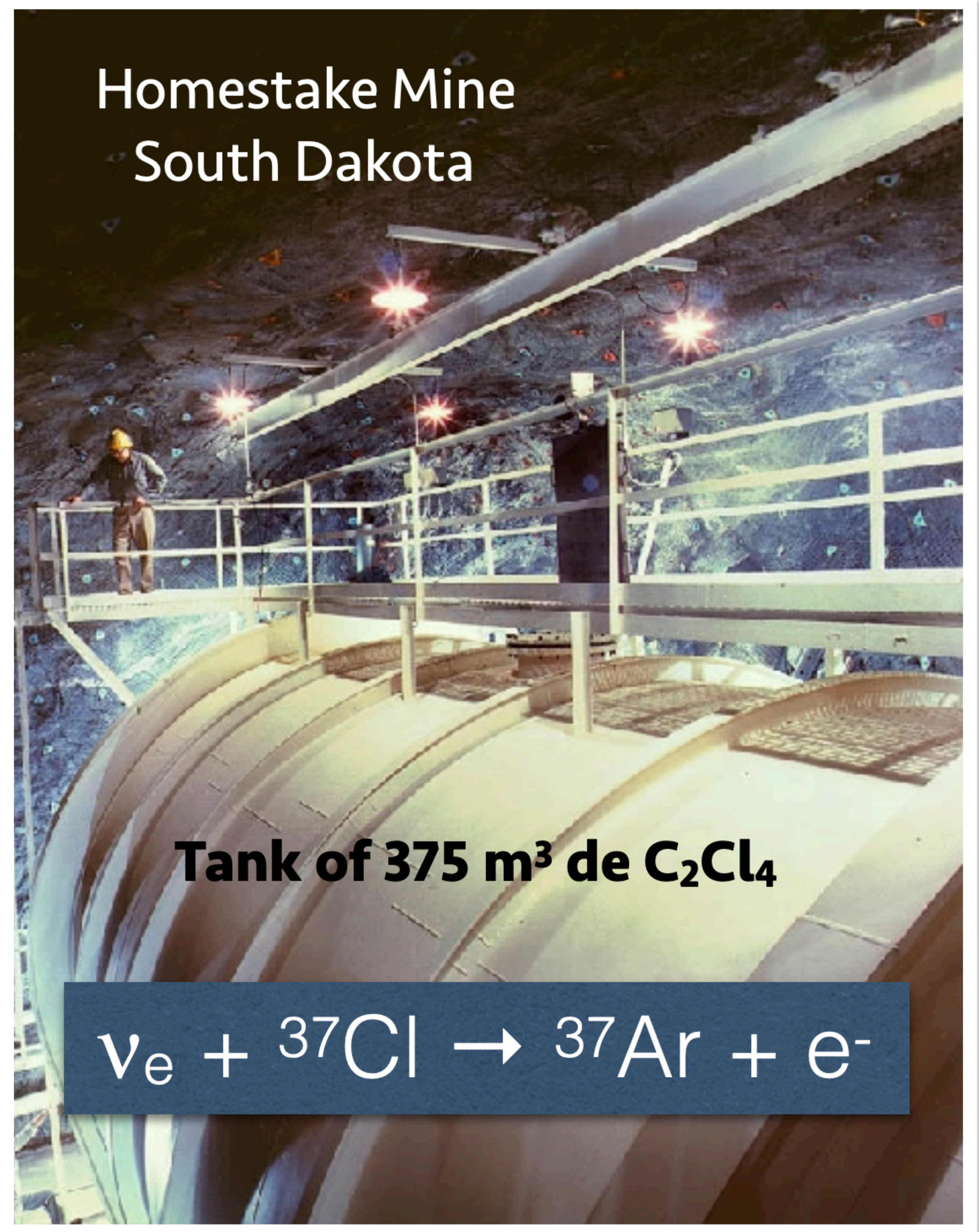
- The Sun is a bright emitter of light, but also neutrinos!

$$4p \rightarrow {}^4\text{He} + 2e^+ + 2\gamma + 2\nu_e$$

- By measuring the photon flux, we can estimate the neutrino flux
  → 1 photon ~ 1 neutrino.



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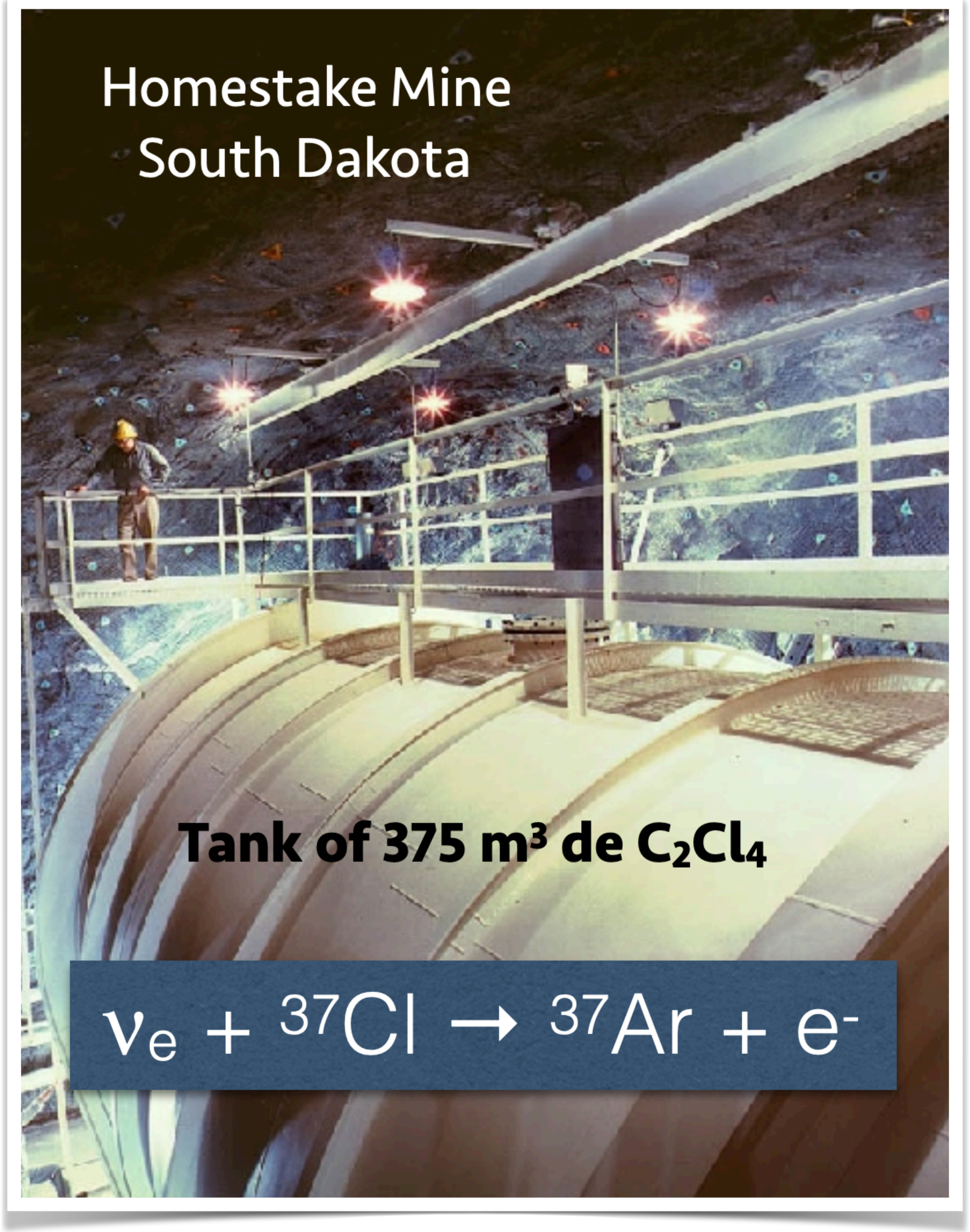
Problem: Experiments measuring this flux (60s to 90s) found only **~1/2 to ~1/3 of the expected neutrinos…**



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- Neutrinos are produced in the atmosphere from cosmic rays.
  The lowest energy muons have time to decay.

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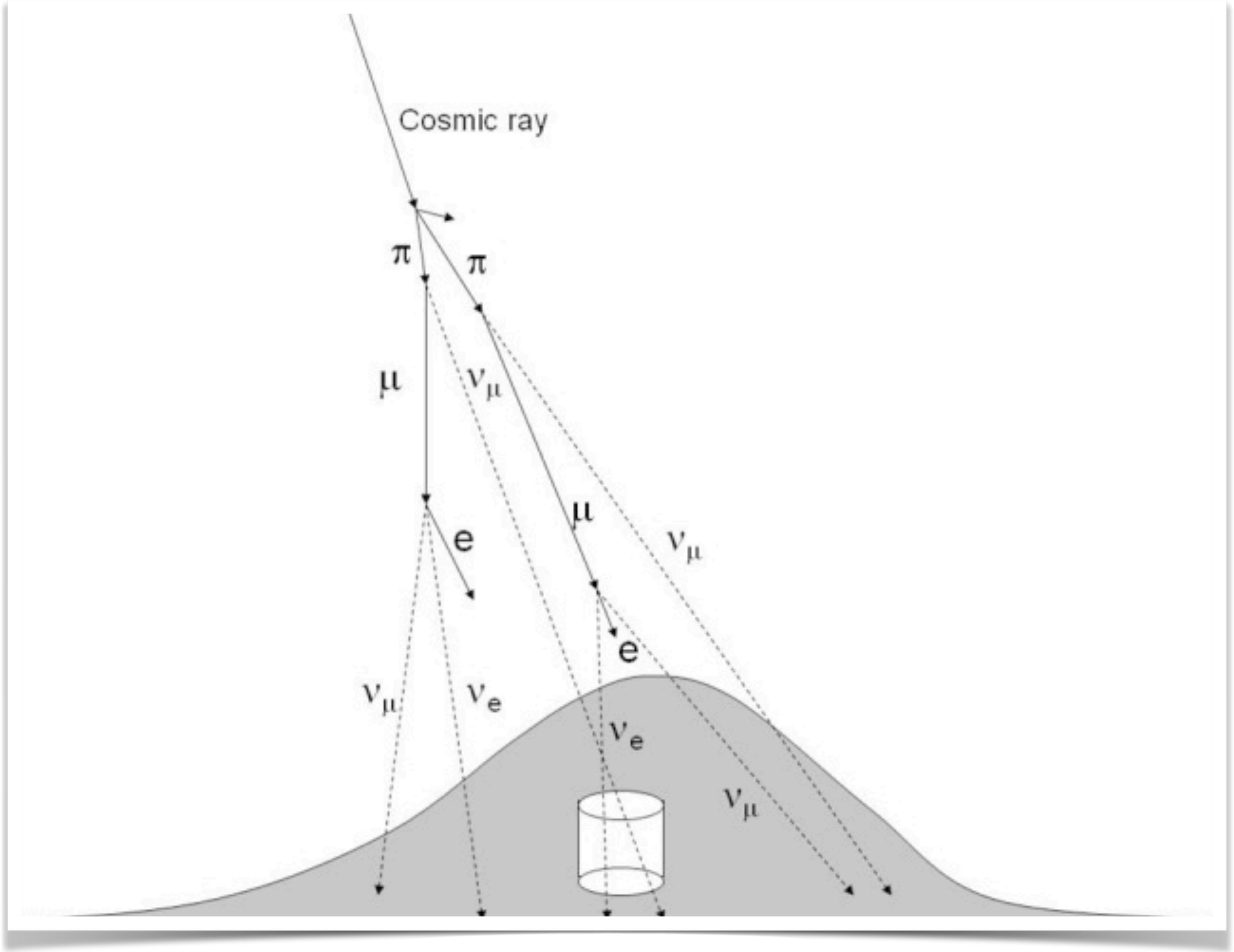

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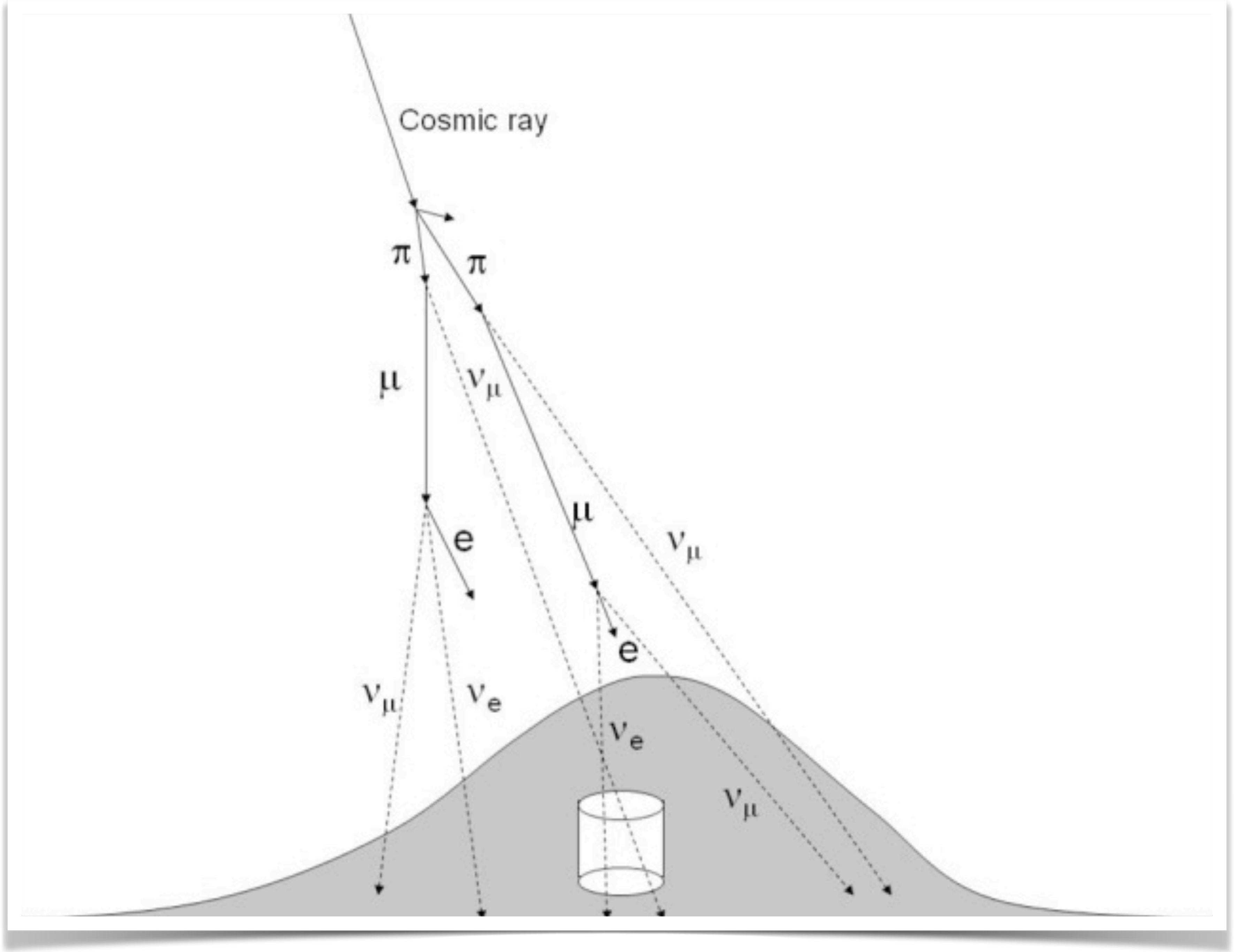
Problem: We expect 2 muon neutrinos per electron neutrino. **But the ratio found was ~1!**



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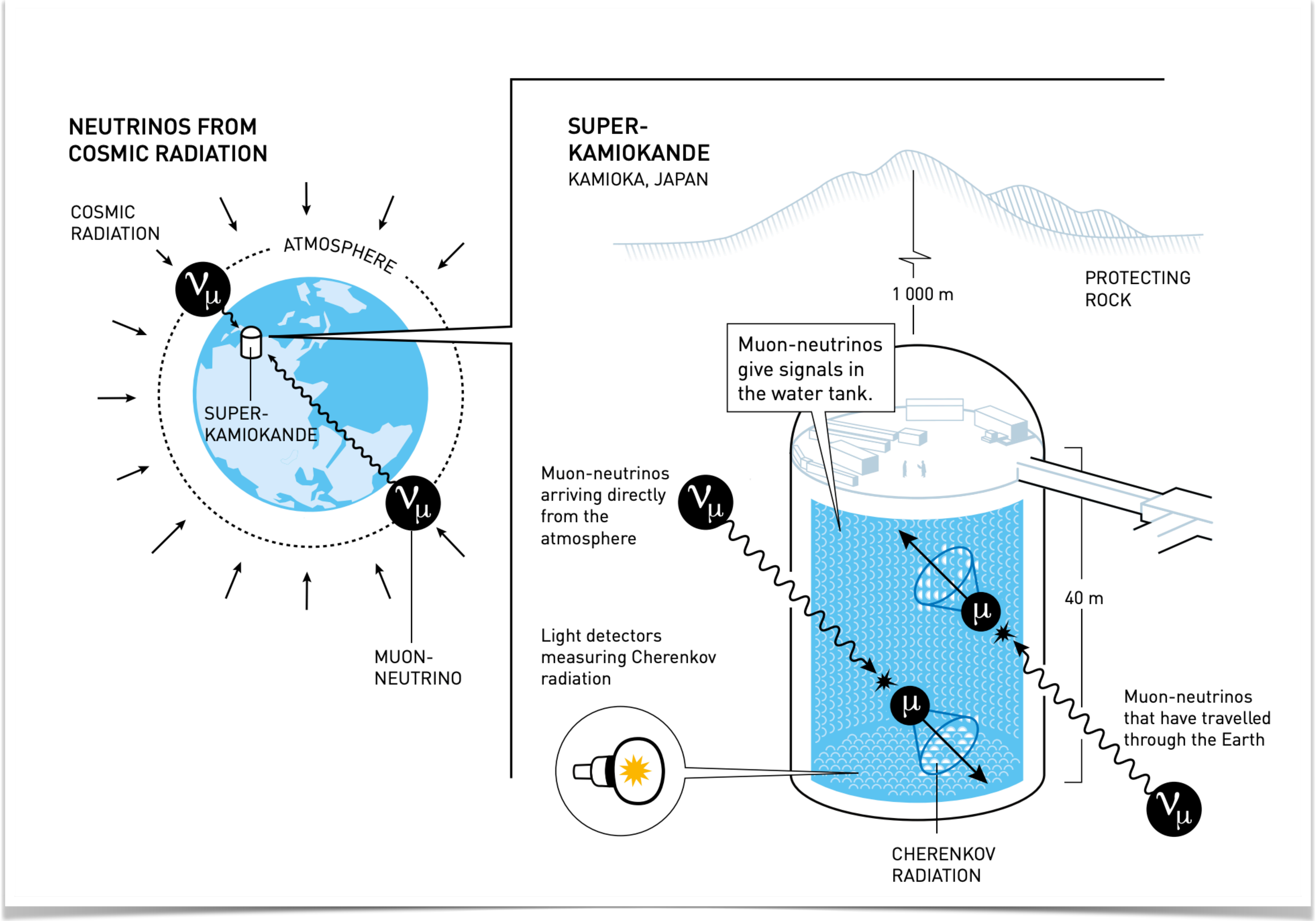
Oscillations and the Nobel Prize

What the hell is happening? 🤯



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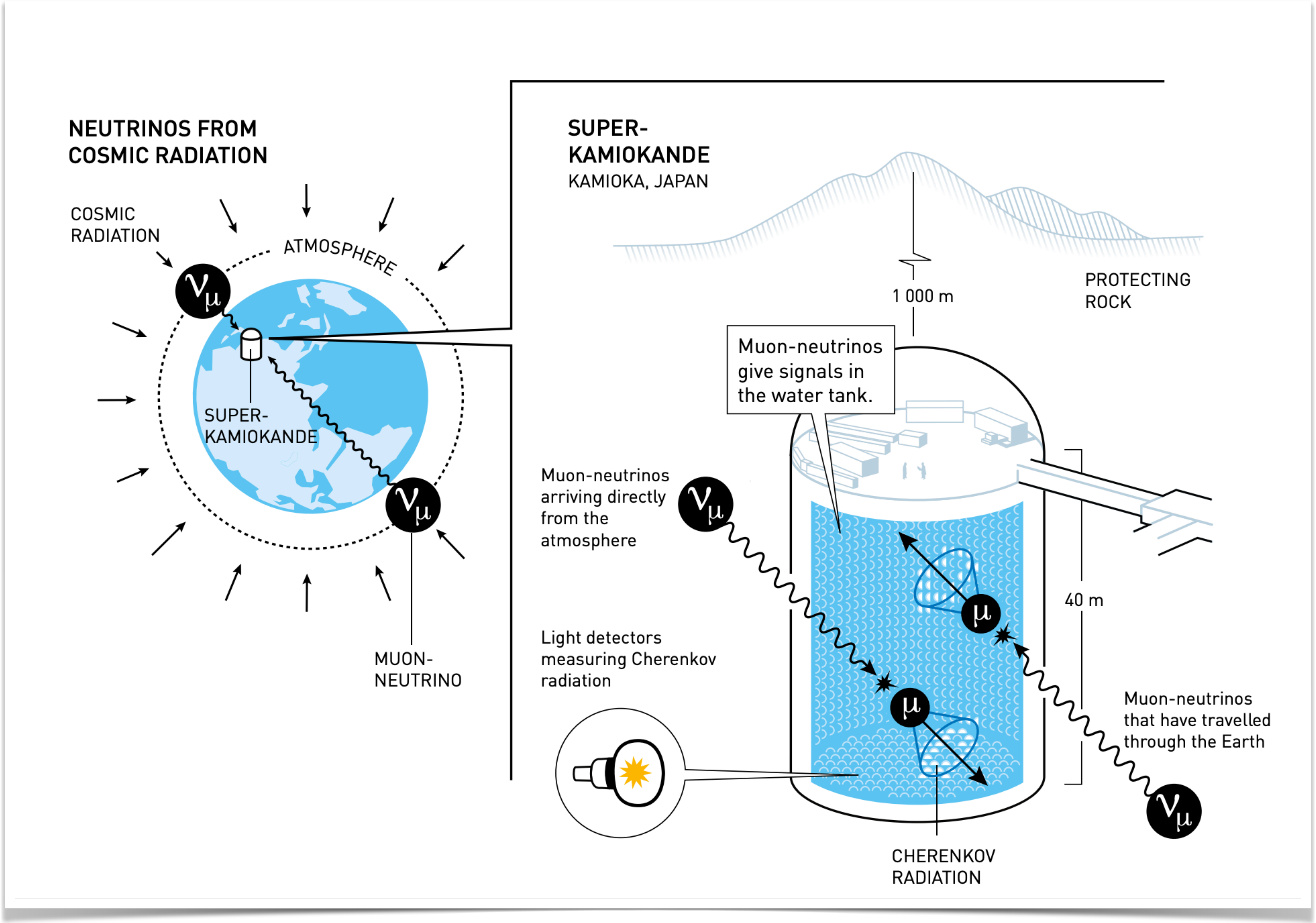
- The resolution to both of these problems is “simple”: **neutrinos “oscillate”** when they travel through space, changing from one type to another. **More about this later!**



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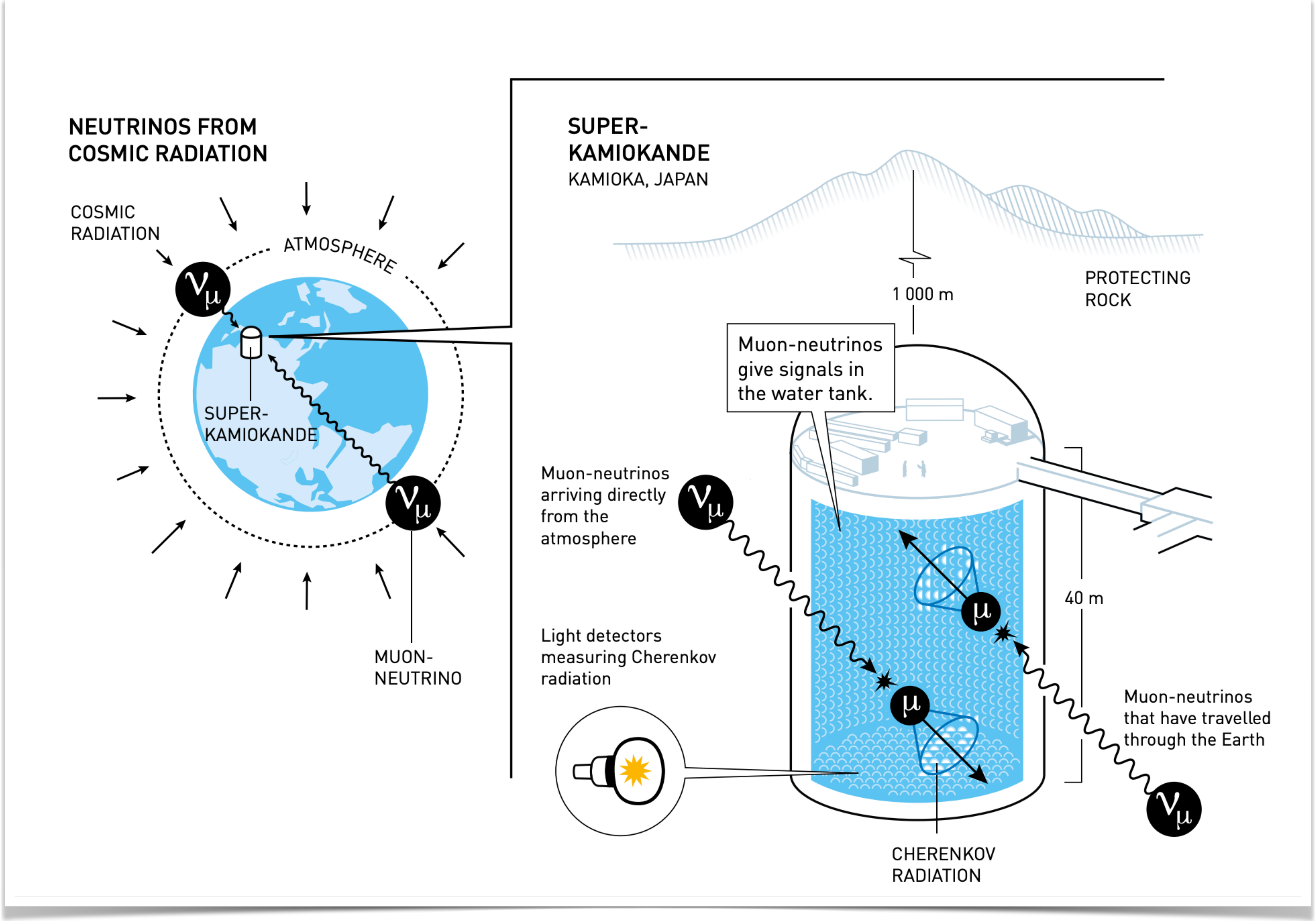
- **Super-Kamiokande** measured the angle at which atmospheric neutrinos hit the detector.
- Muon neutrinos coming from underground were observed at a lower rate than expected.
- Neutrino oscillations in matter explain this: most “missing” muon neutrinos were oscillating into tau neutrinos.



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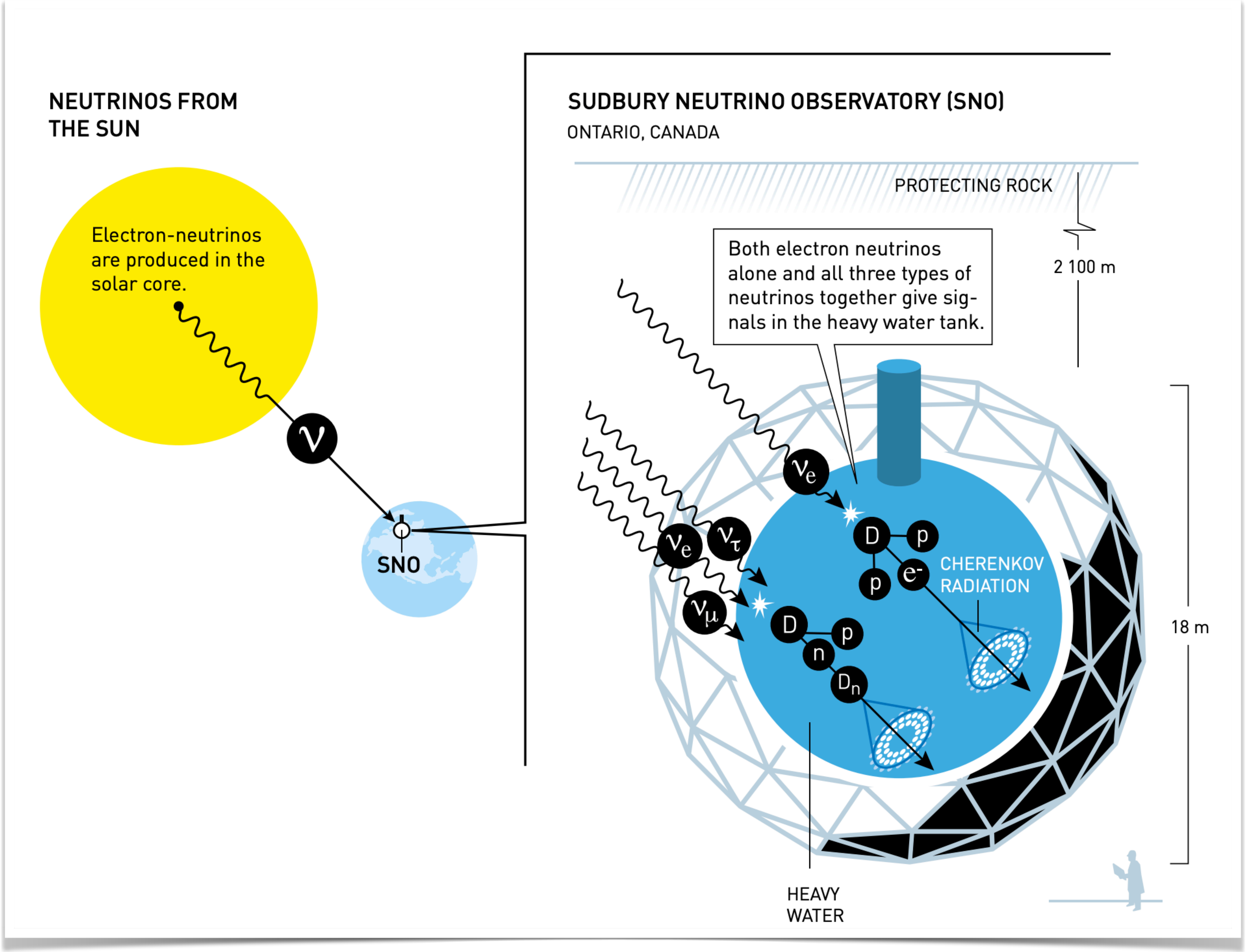

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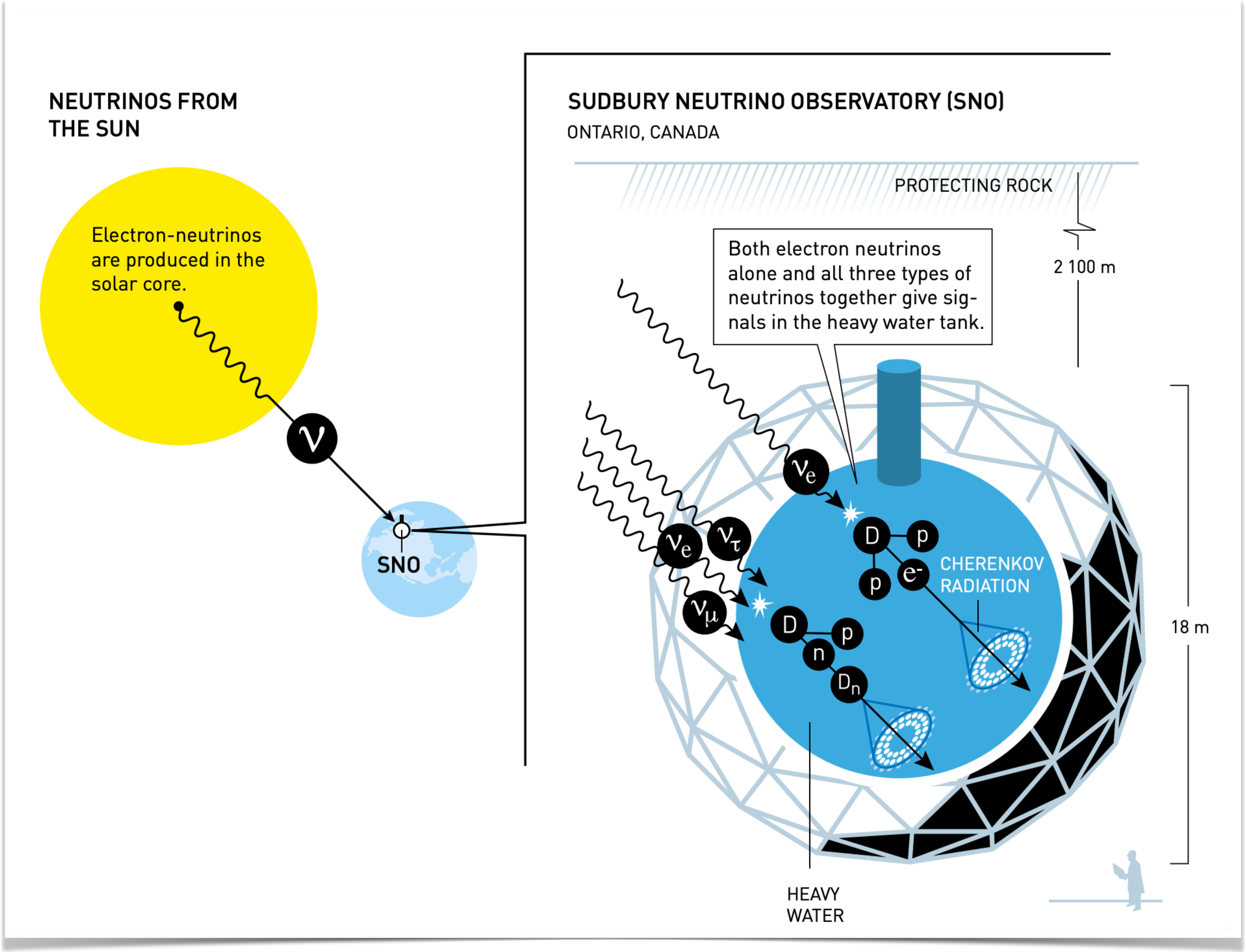
- These affect all neutrino flavours equally.
- Neutrinos were not "disappearing", but merely changing flavour!



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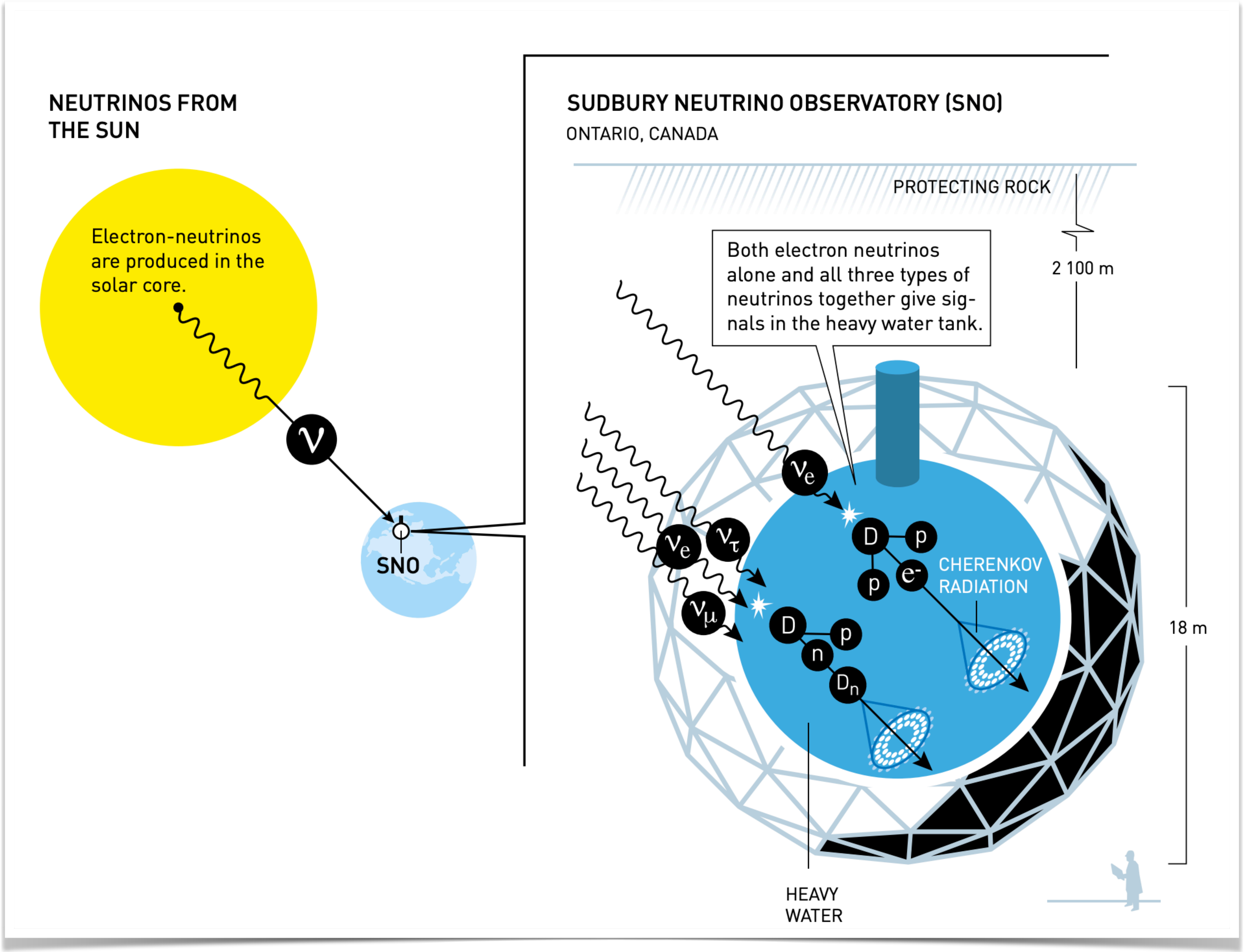
2015 Nobel Prize in physics awarded to A. McDonald and T. Kajita:
“for the discovery of neutrino oscillations, which shows that neutrinos have mass”



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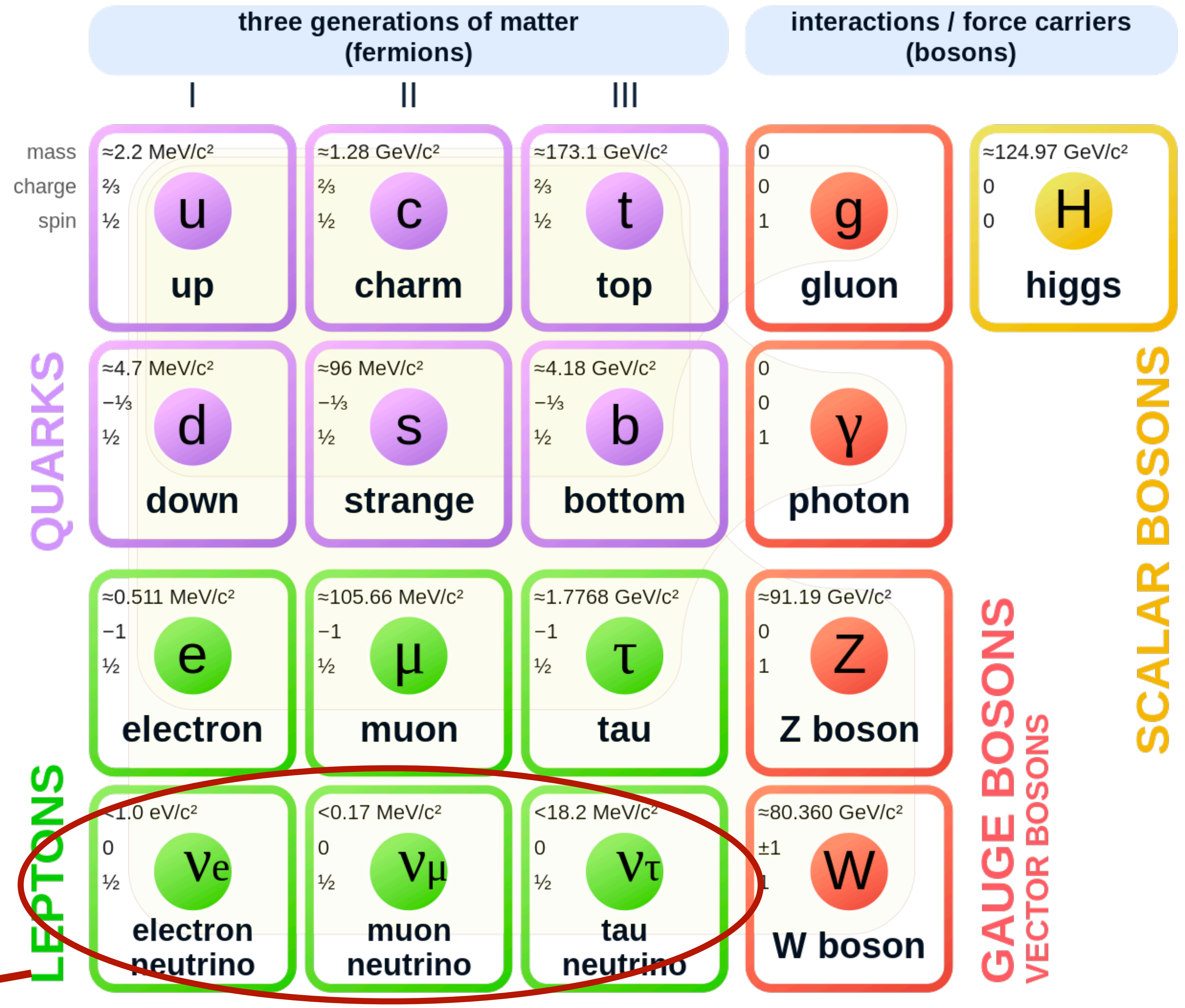
Neutrinos in the Standard Model

You've seen this before…

Standard Model of Elementary Particles



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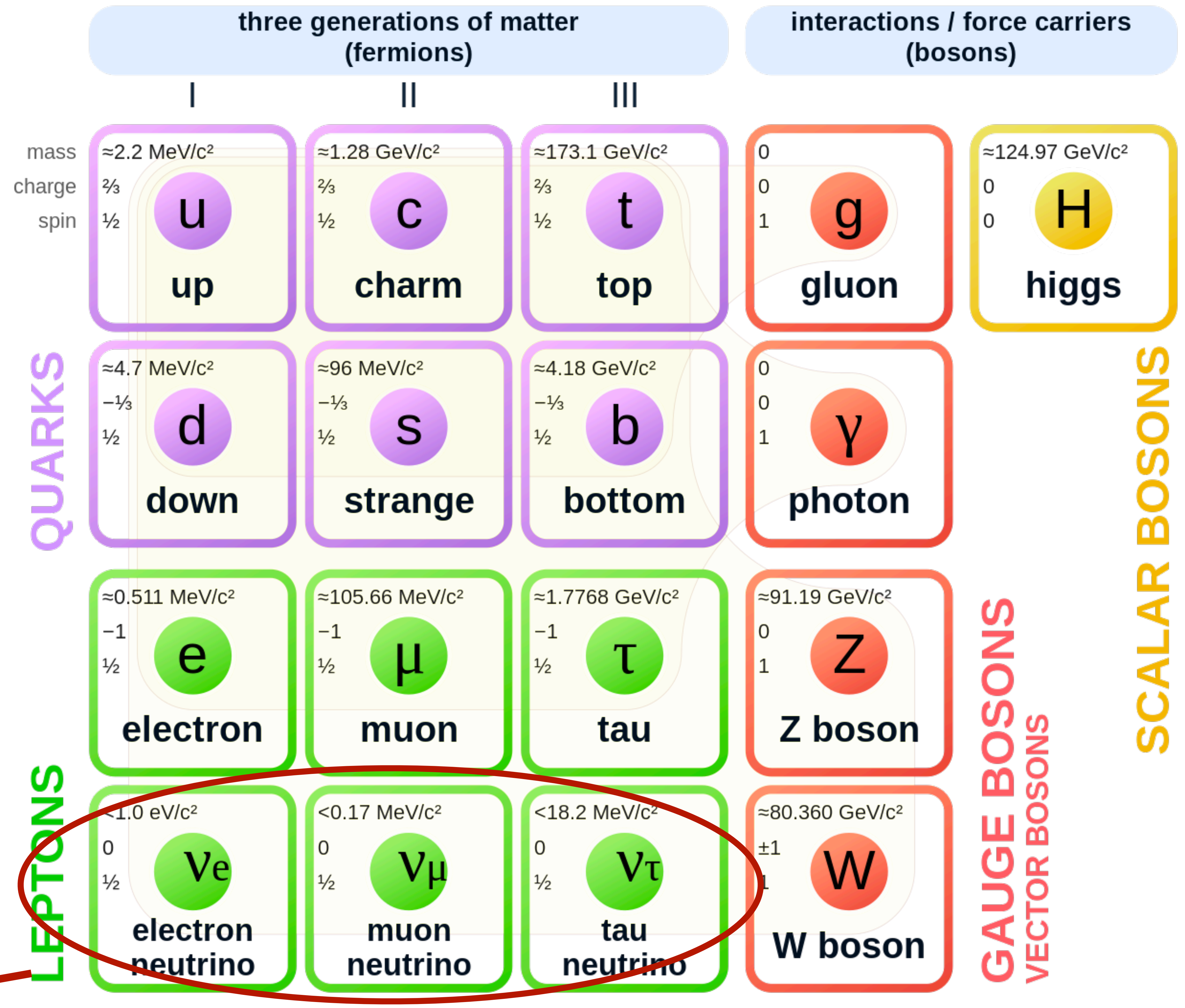

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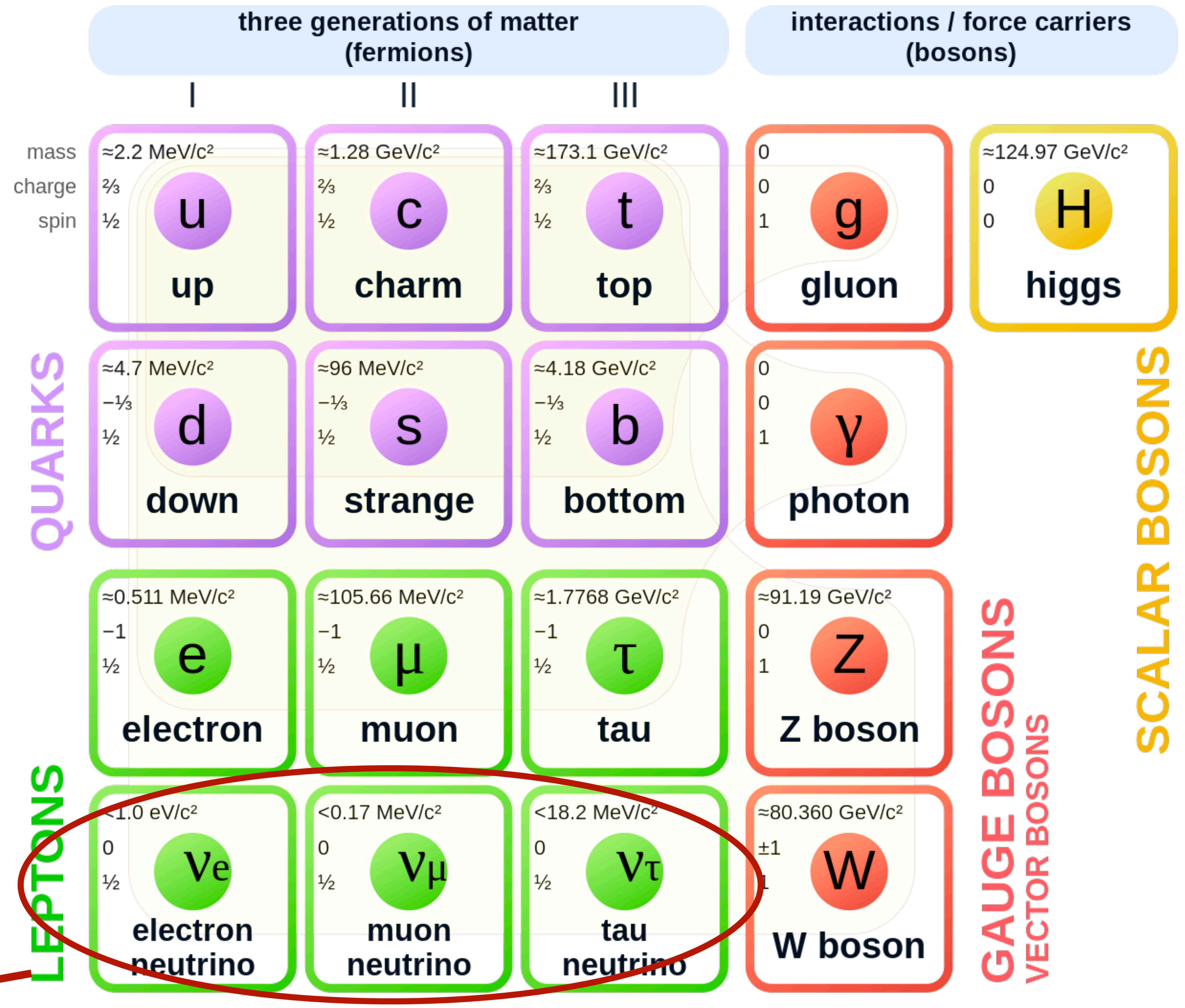

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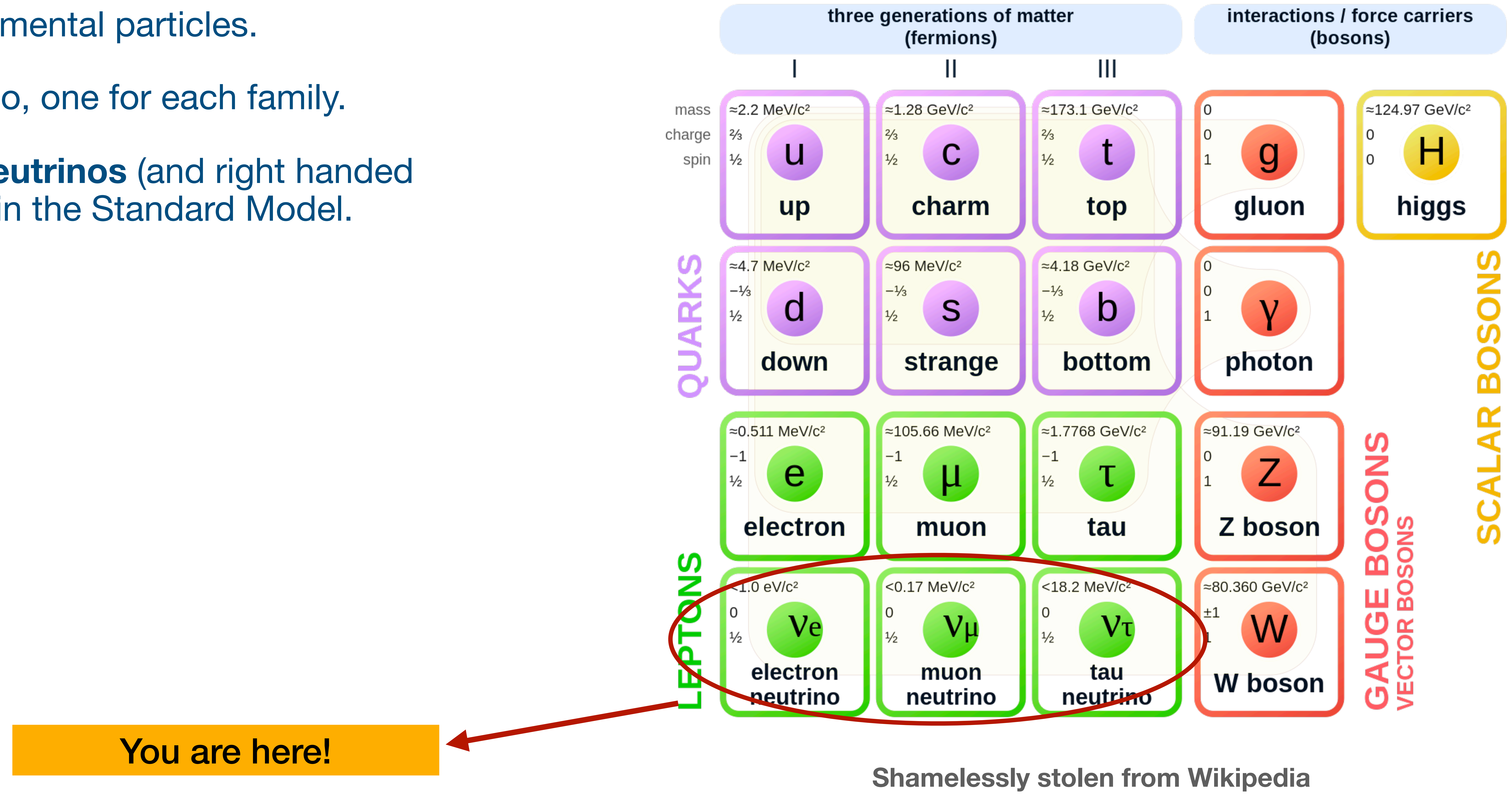

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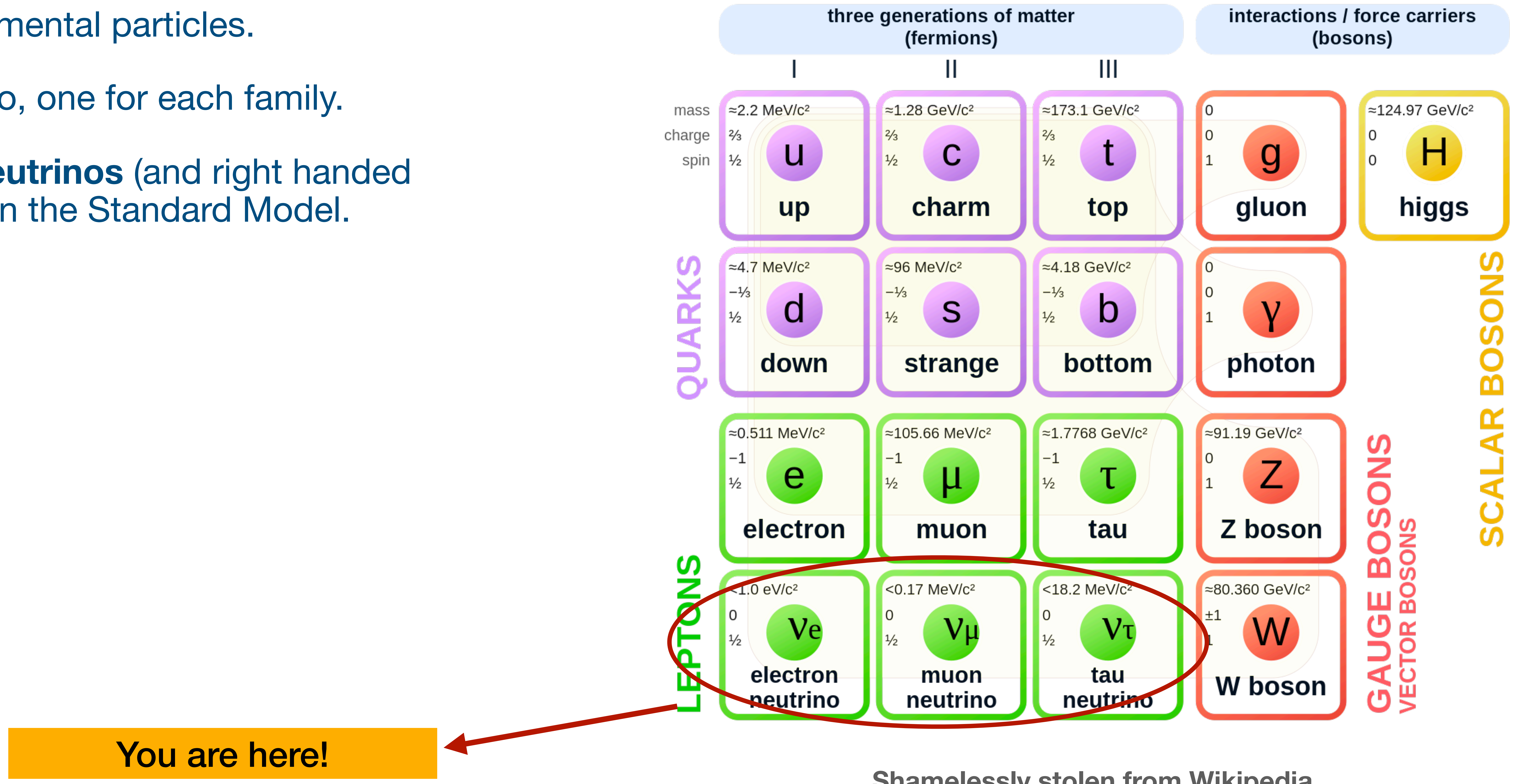

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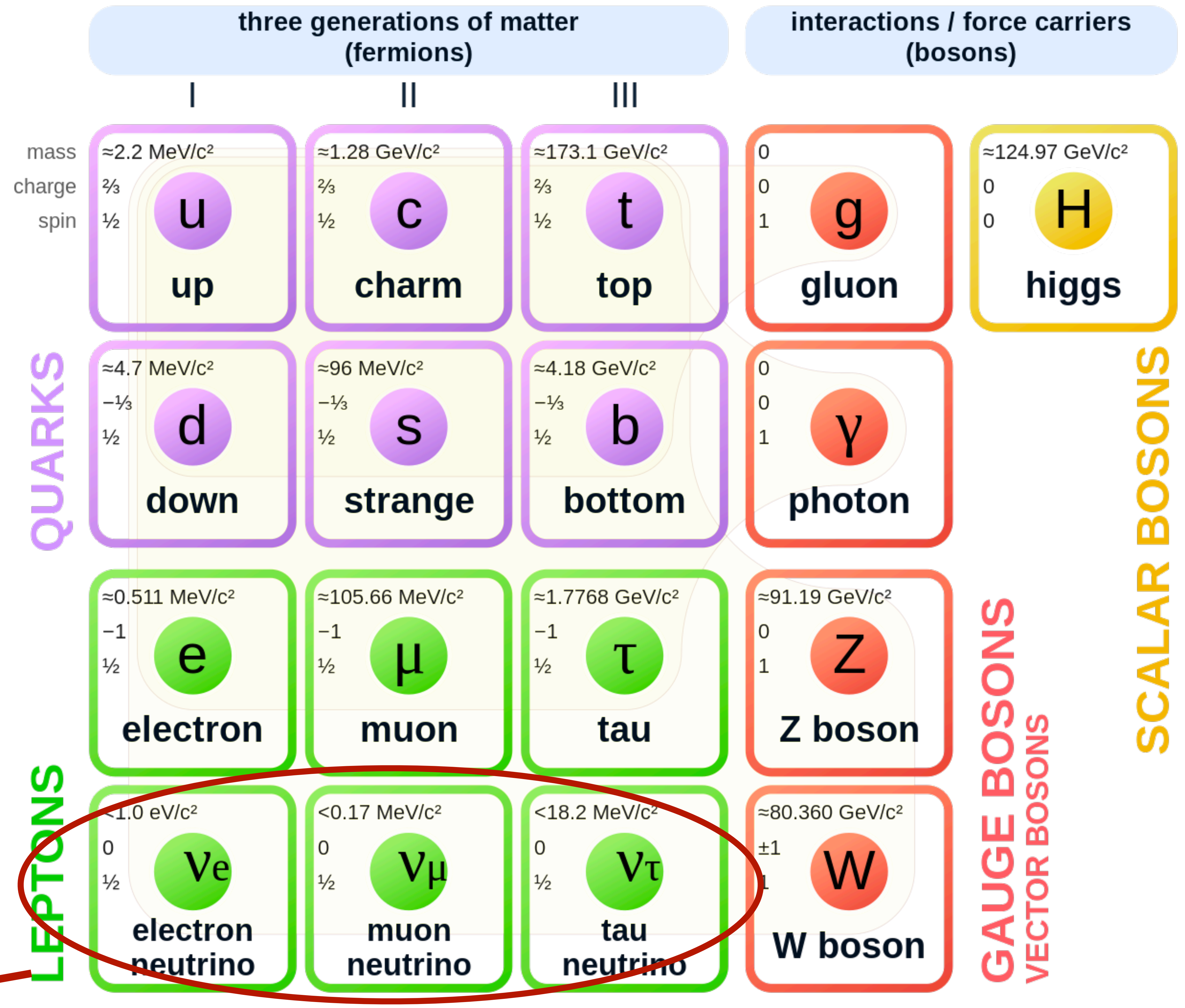

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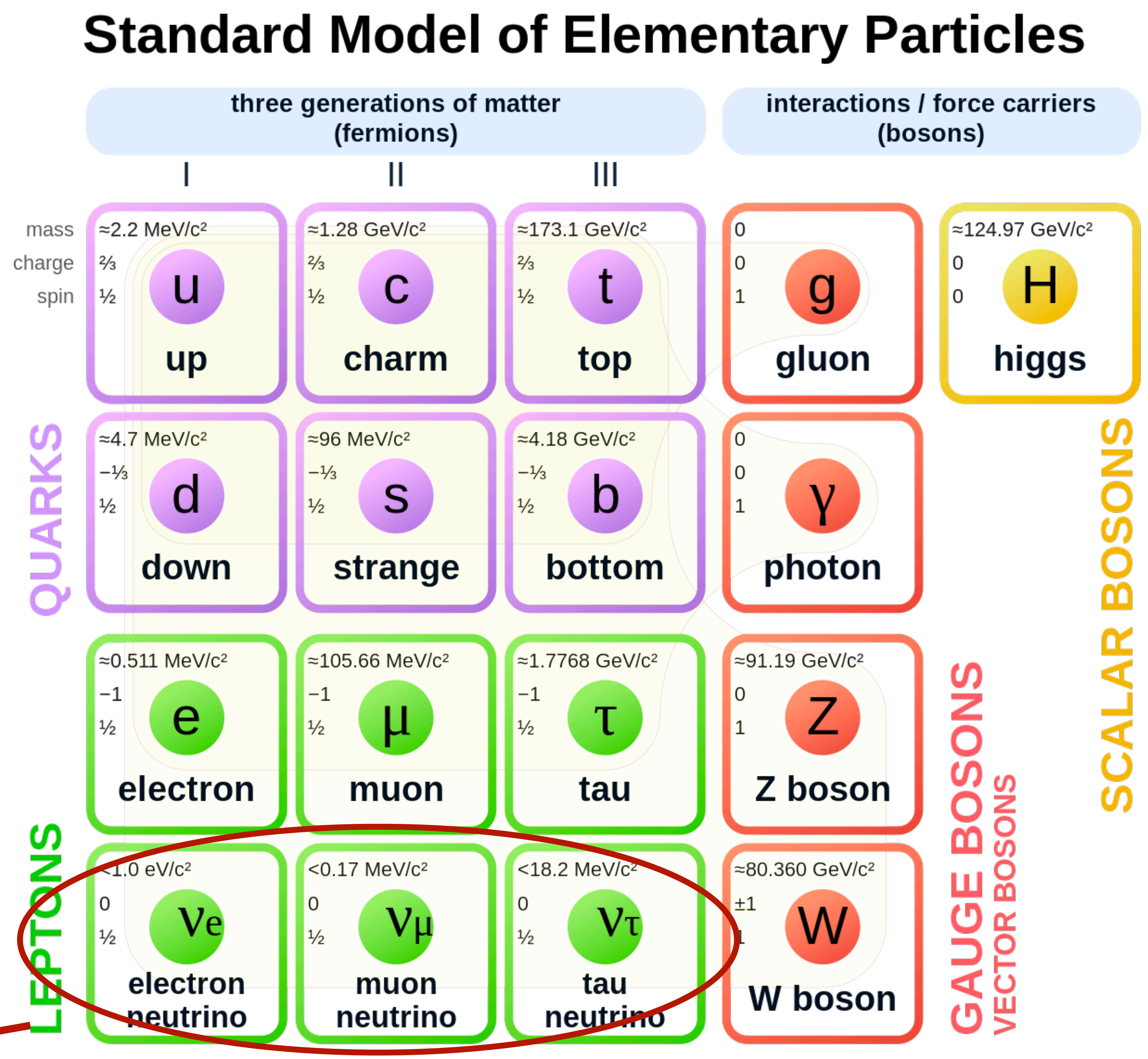

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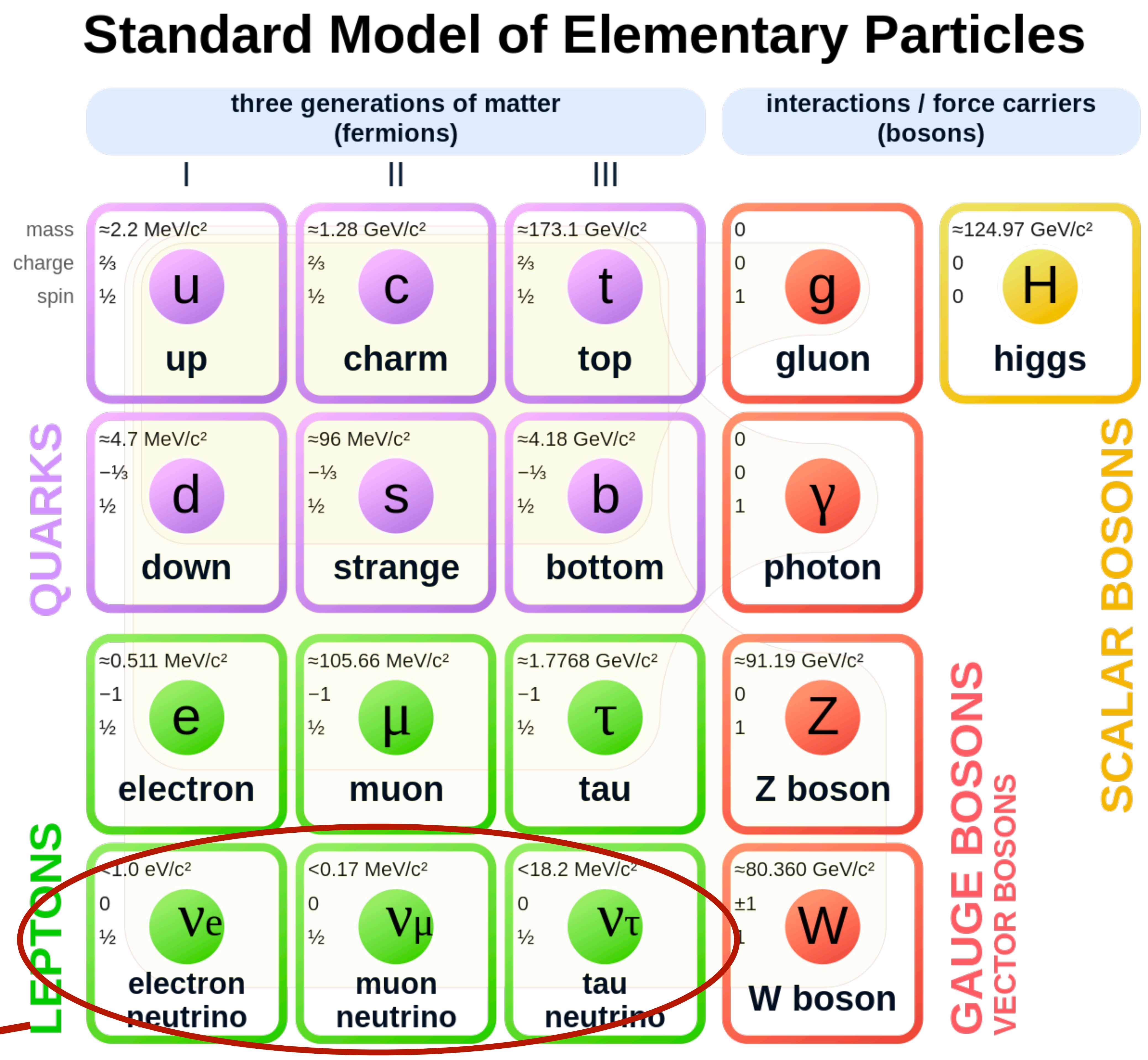

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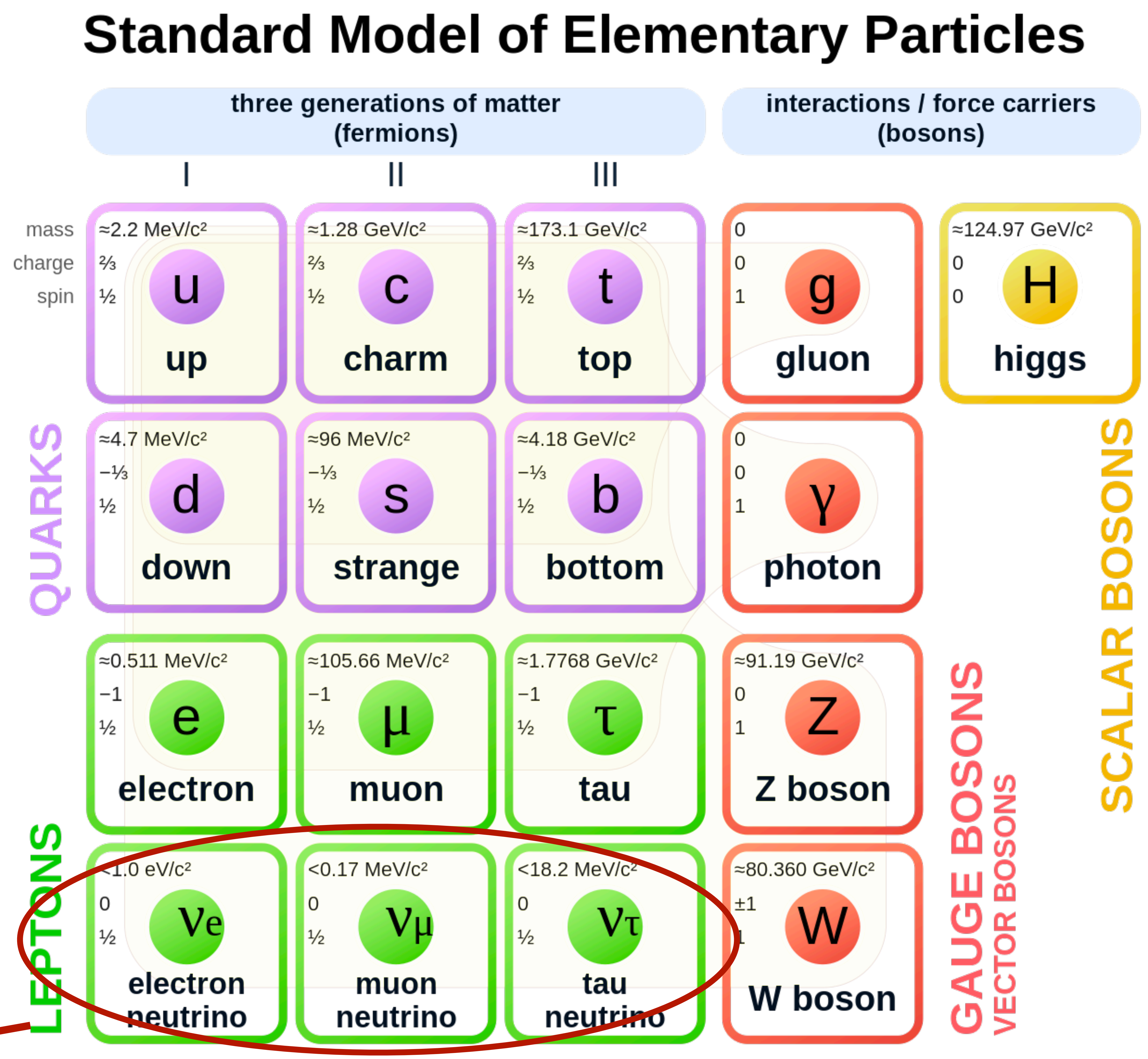
- Most abundant matter particle in the universe!

You are here!



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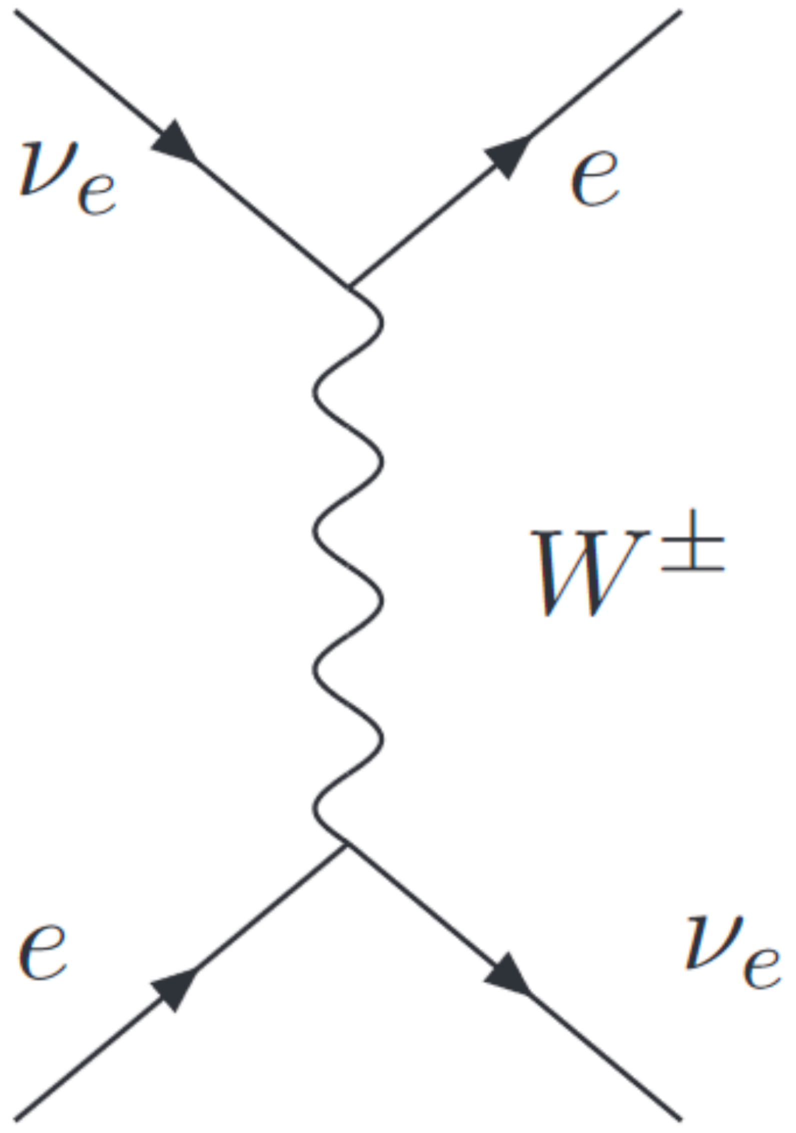
Neutrinos in the Standard Model

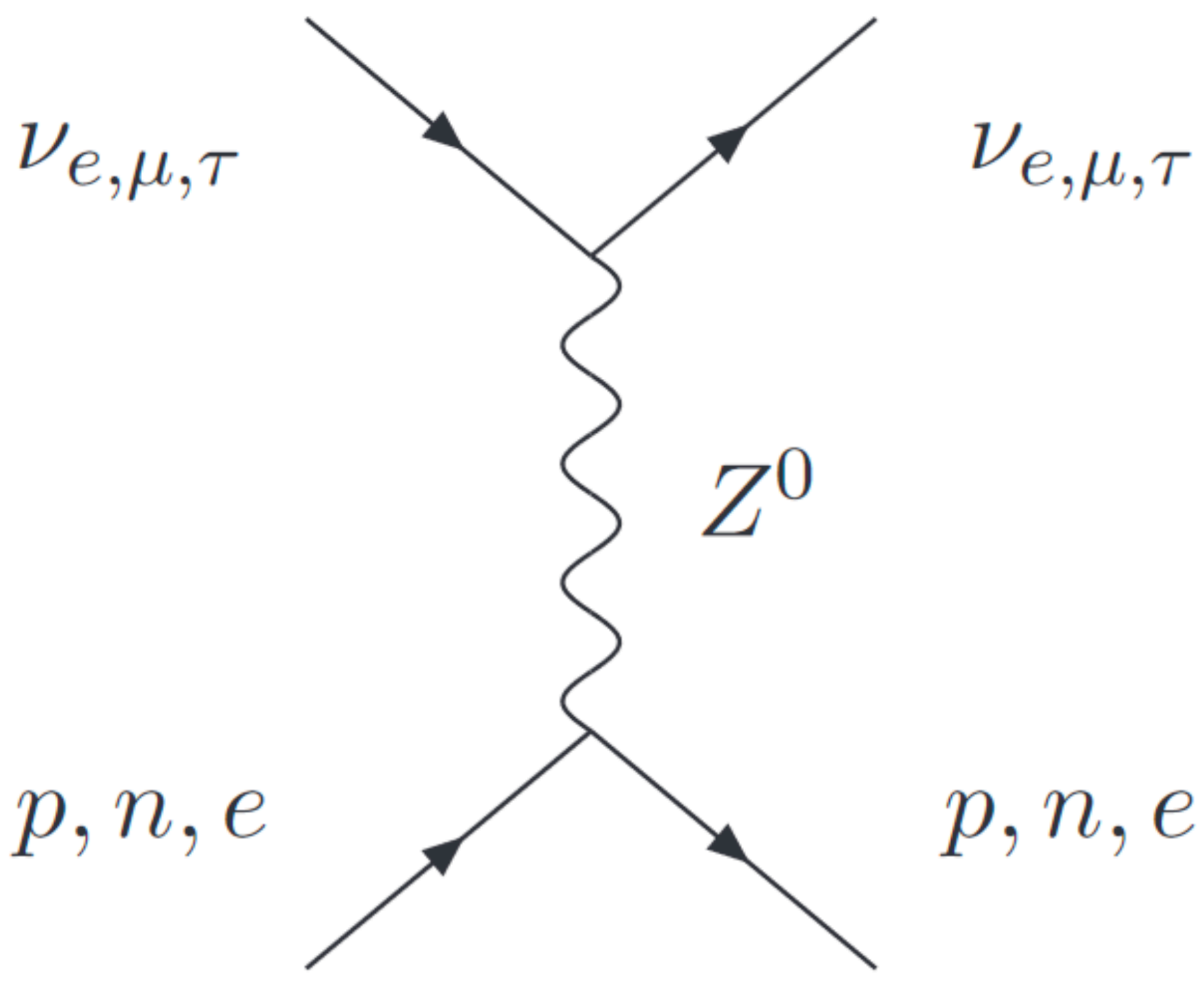
How do they interact?

- Neutrinos can only interact via the weak force (no electromagnetic or strong interactions) and gravity.
- This means their interaction with matter is very rare:
  - Trillions of neutrinos from the Sun pass through us every second, only ~1 interacts with us in our lifetime.
  - On average, a neutrino will go through ~350 billion km of lead before interacting.

We need a lot of neutrinos and huge detectors to study them properly!



Charged current (CC) interaction



Neutral current (NC) interaction

Neutrino oscillations

The only macroscopic quantum phenomenon?

- Neutrino **“flavour states”** don’t have a particular mass: they are superpositions of 3 different **“mass states”**. In QM lingo:
  $|\nu_e\rangle = \alpha|\nu_1\rangle + \beta|\nu_2\rangle + \gamma|\nu_3\rangle$

- When neutrinos *interact* (are produced or detected), they do so as a pure flavour state (ν_e, ν_μ, ν_τ).

- When neutrinos *propagate* (travel through space freely), they do so as mass states (ν_1, ν_2, ν_3).

$|\nu_\mu\rangle$ Neutrino is created as a flavour state (e.g, from pion decay)

Don’t mind me, just propagating…

$|\nu_e\rangle$ Neutrino is detected as a *different* flavour state (e.g., it bounces off a proton)

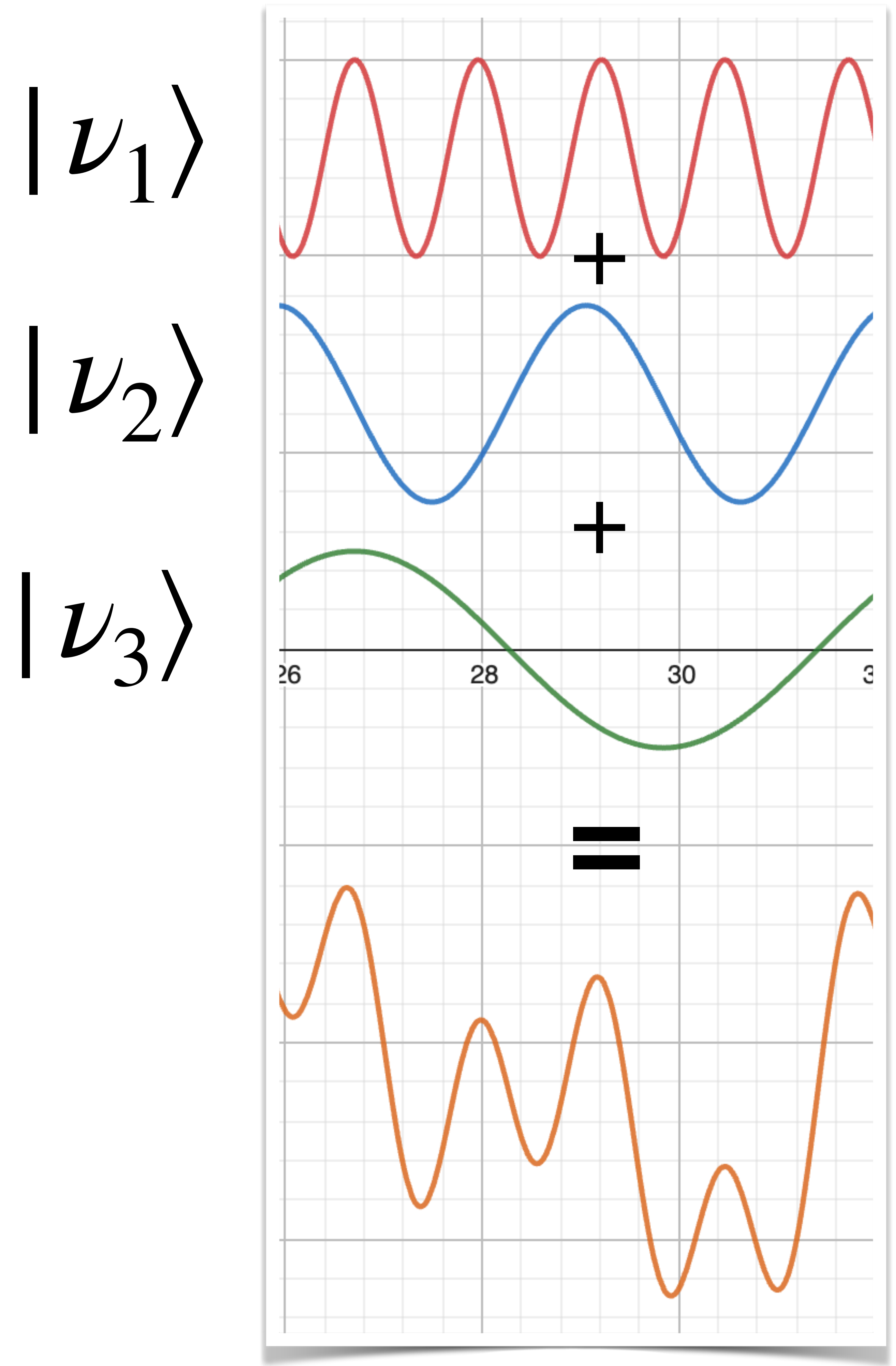
Neutrino oscillations

The only macroscopic quantum phenomenon?

- We can represent quantum states as a sort of wave. **Different mass states oscillate at different frequencies when they travel**: the larger the mass, the faster they oscillate.

- This makes the three mass states form different combinations as they travel.

- **There is a chance that, once measured, they neutrino will be of a different flavour! → Neutrino has oscillated.**



The combination of the three mass states changes!

Neutrino oscillations

The only macroscopic quantum phenomenon?

- Here's how the oscillation probability looks like if we focus on only two kinds of neutrino:

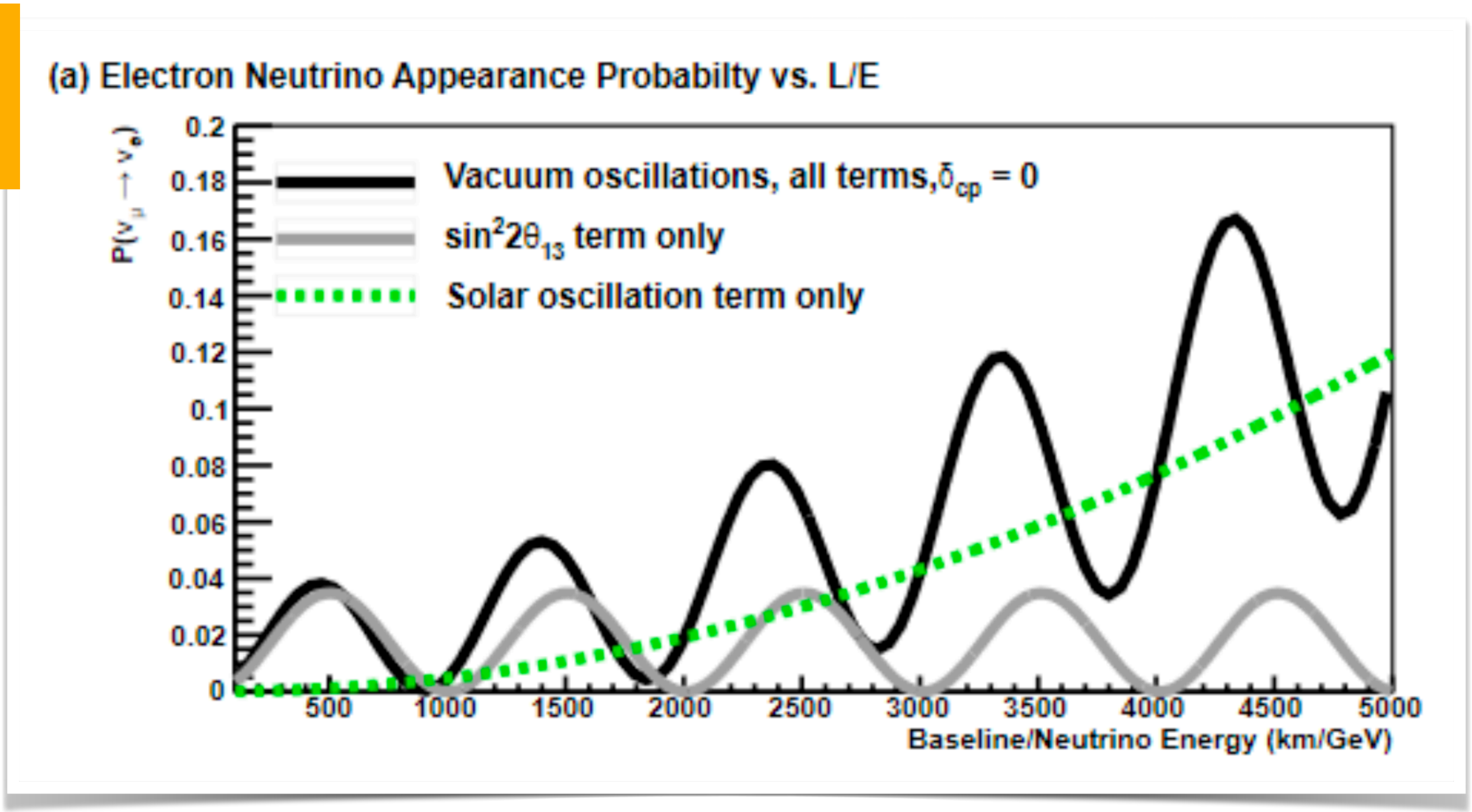
Neutrino mass difference: how large is the oscillation?

Mixing angle: how fast is the oscillation?

$$P(\nu_\mu \rightarrow \nu_e) = sin^2(2\theta)\frac{\Delta m^2 L}{4E}$$

Neutrino energy

Distance traveled



Oscillation probability from muon to electron neutrino

Neutrino oscillations

The only macroscopic quantum phenomenon?

- The full formula is a bit more daunting and looks like this:

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

$$\mp 2\sum_{j>i} \underbrace{\mathrm{Im}\left[U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right]}_{J\equiv\text{Jarlskog invariant}} \sin\left(\frac{\Delta \mathrm{m}^2_{\mathrm{ij}}\,\mathrm{L}}{2\mathrm{E}_\nu}\right),$$

Experiments aim to measure these parameters precisely!

PMNS Matrix

Takeaway: Neutrino oscillations depend on 6 physical parameters.

- 3 mass differences that tell us *how fast* they oscillate.
- 3 mixing angles that tell us *how much* they oscillate.
- 1 “delta CP” phase that tells us how different neutrinos and antineutrinos oscillate.

Neutrinos can only oscillate if the have mass!

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Open questions

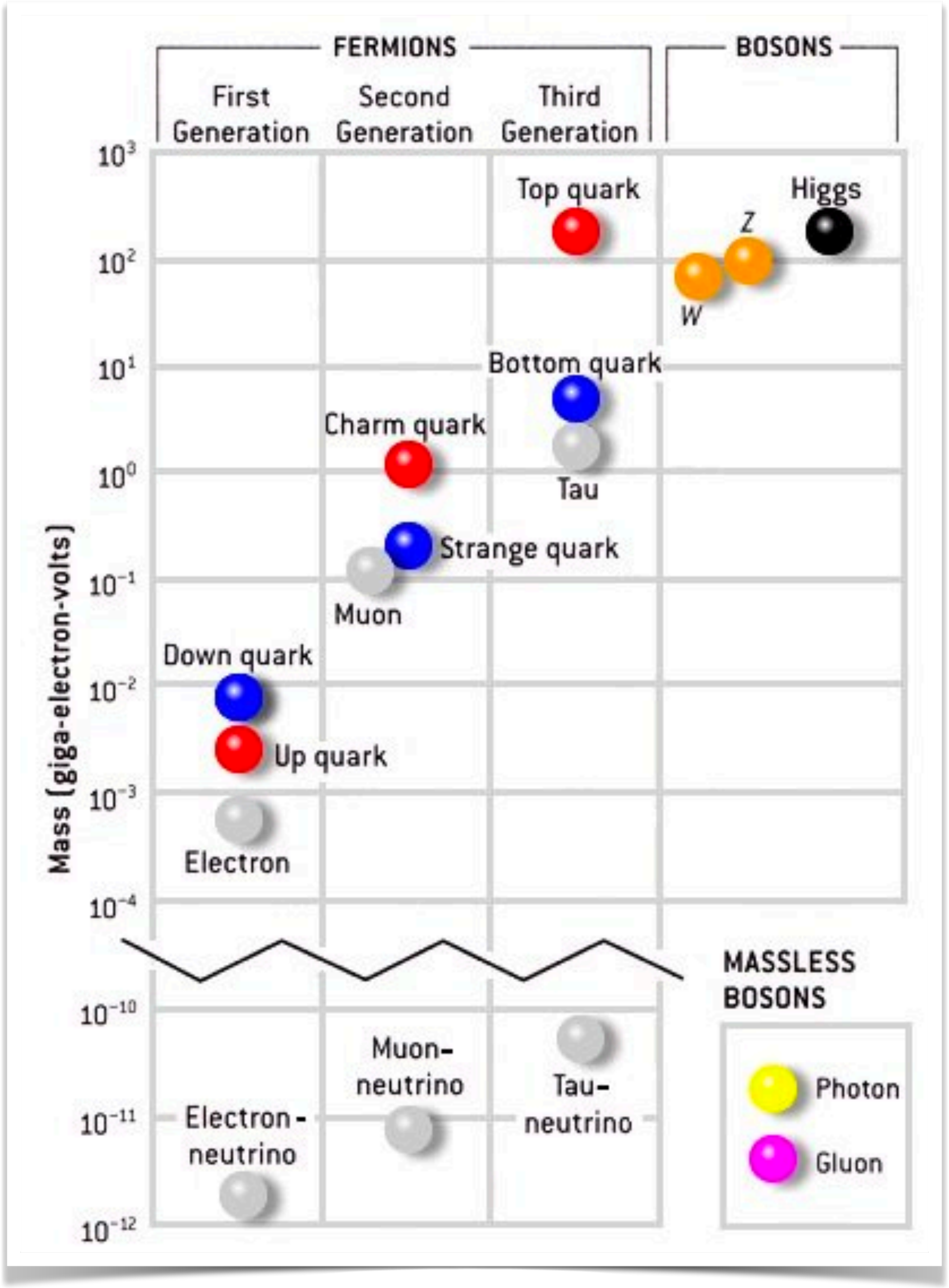
Neutrinos are still a challenging puzzle today

- **Neutrino masses:**
  - Why are they so small compared to the rest of the SM fermions?
  - What is their origin? (Dirac vs. Majorana). Are neutrinos their own antiparticles?
  - What is the neutrino mass hierarchy?
- **Is CP symmetry violated in the lepton sector?**
- **Are there more than 3 neutrinos?**

We still have a lot to figure out

Open questions

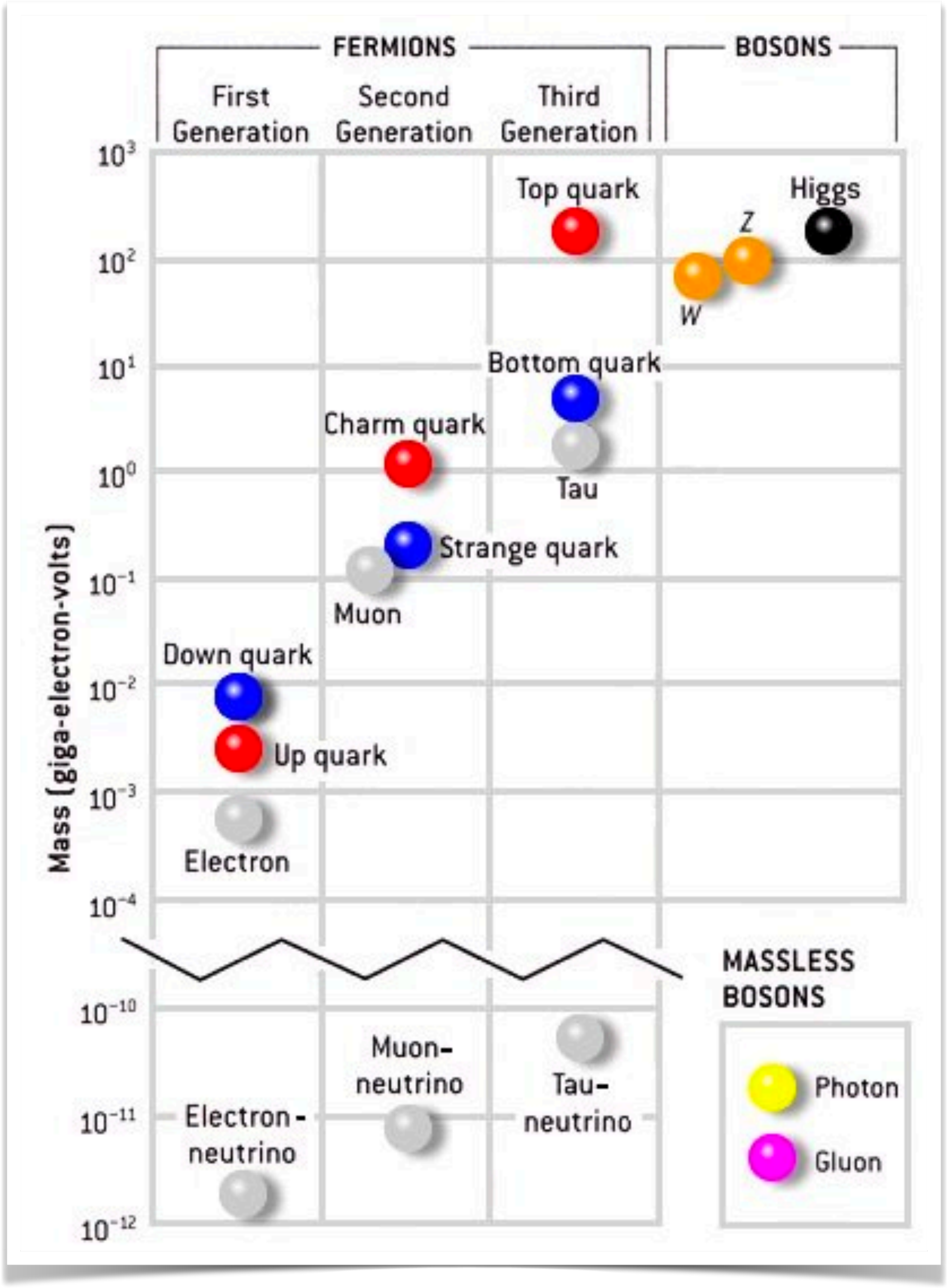
Neutrino masses



Open questions

Neutrino masses

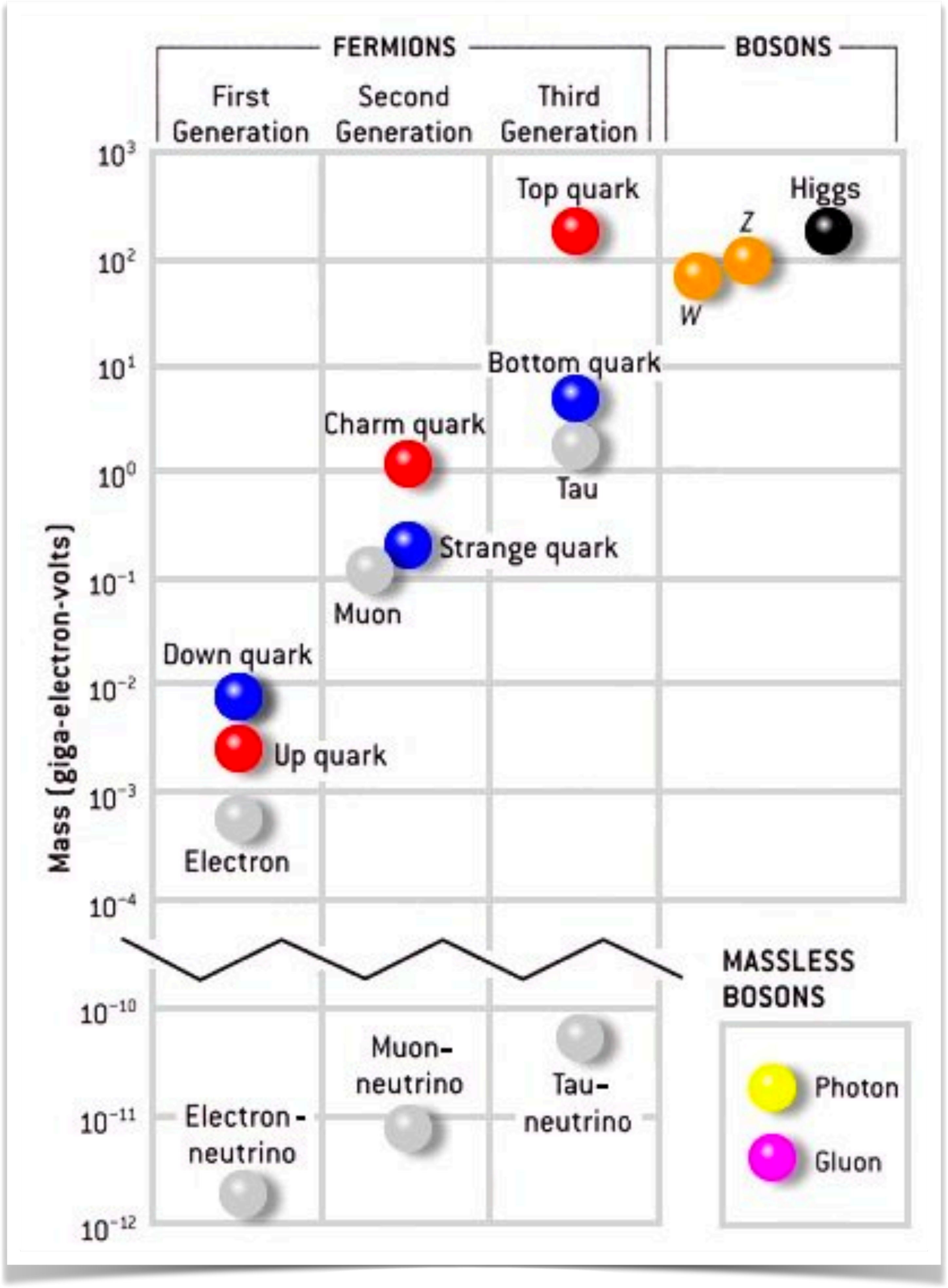
- **Neutrino masses** are the first and only evidence of physics beyond the Standard Model. *But they are not like the masses of every other fermion*:



Open questions

Neutrino masses

- **Neutrino masses** are the first and only evidence of physics beyond the Standard Model. *But they are not like the masses of every other fermion*:
  - They are (at least) 6 orders of magnitude smaller than the next lightest fermion (the electron).



Open questions

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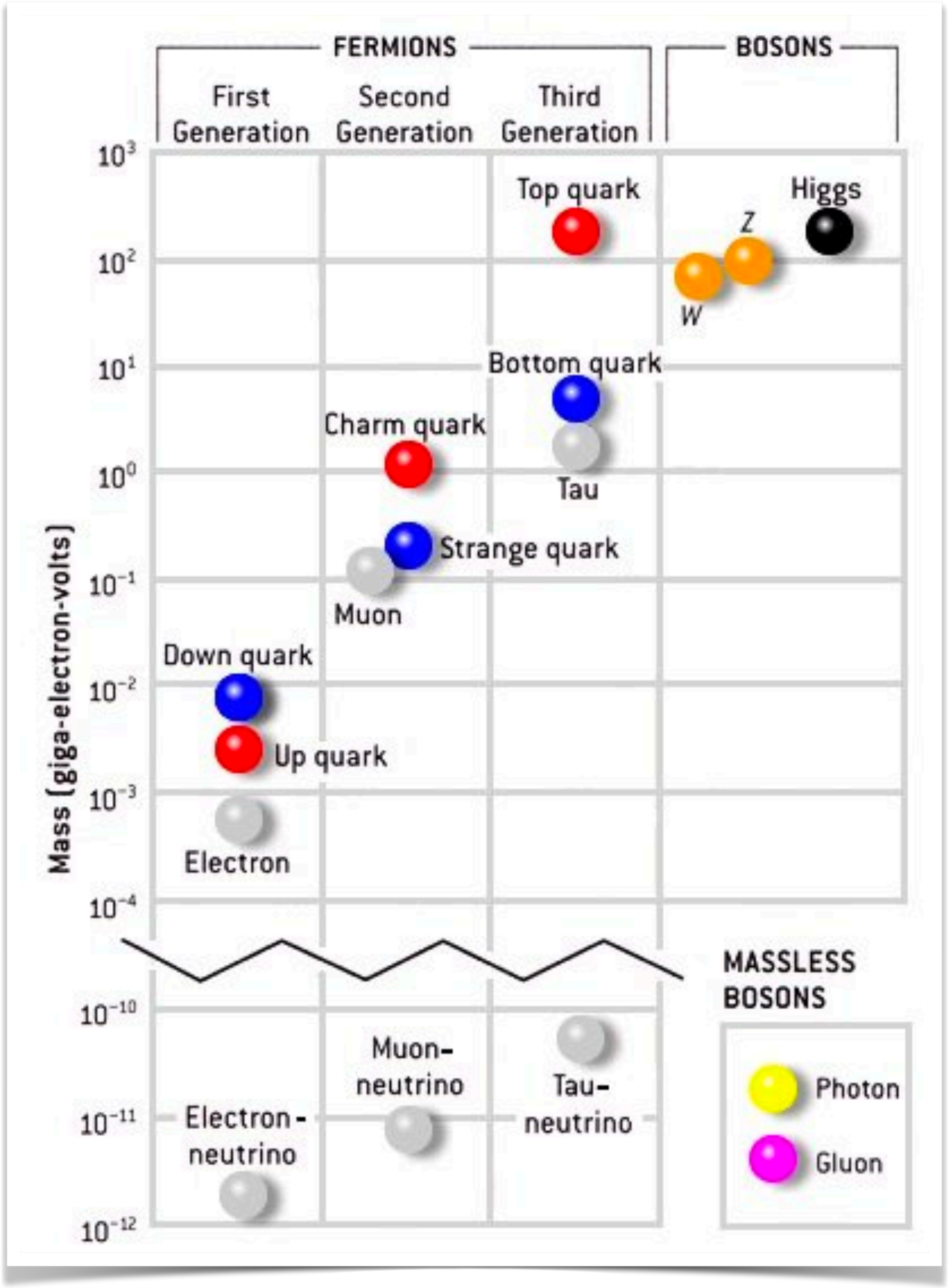

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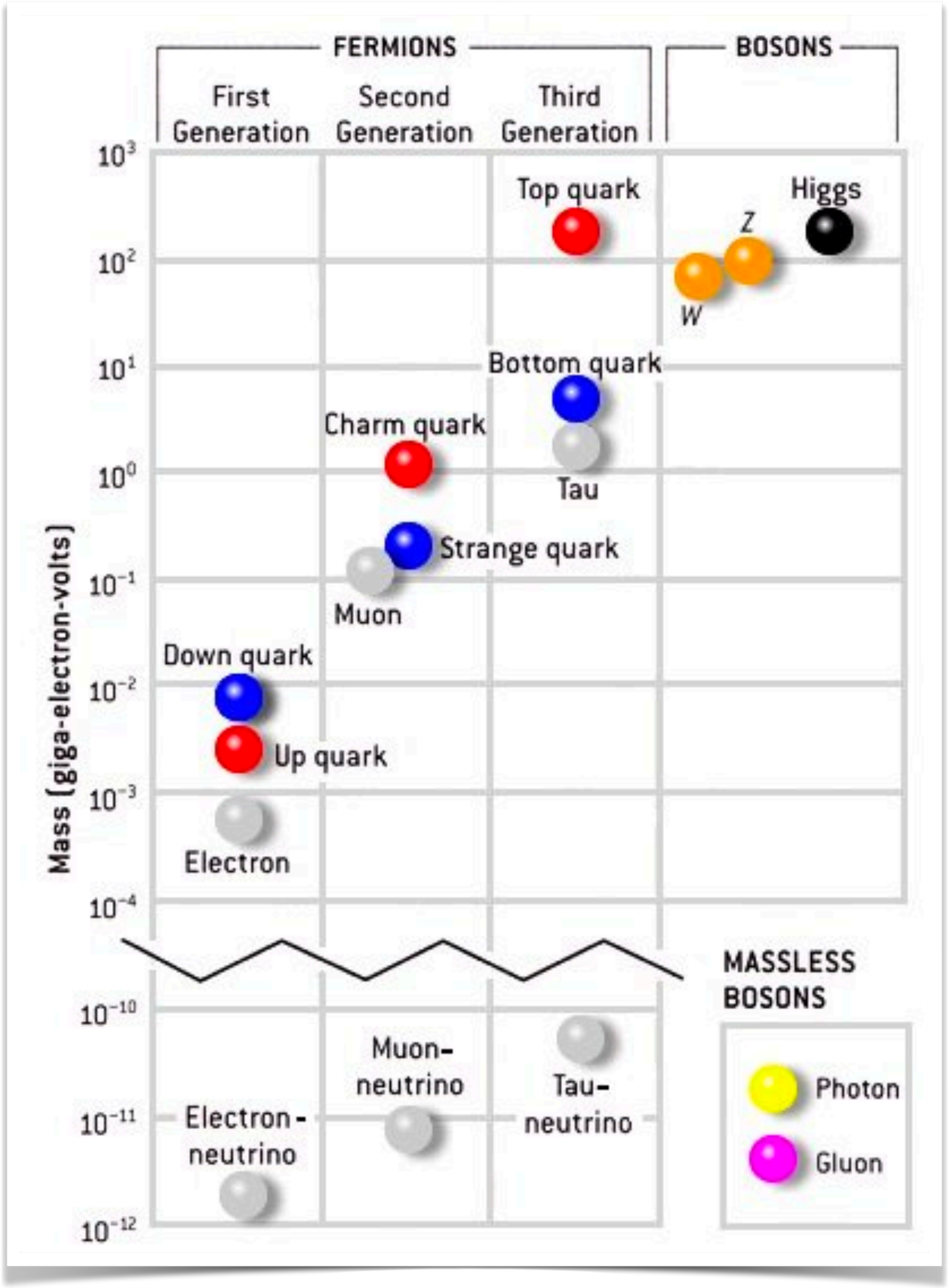

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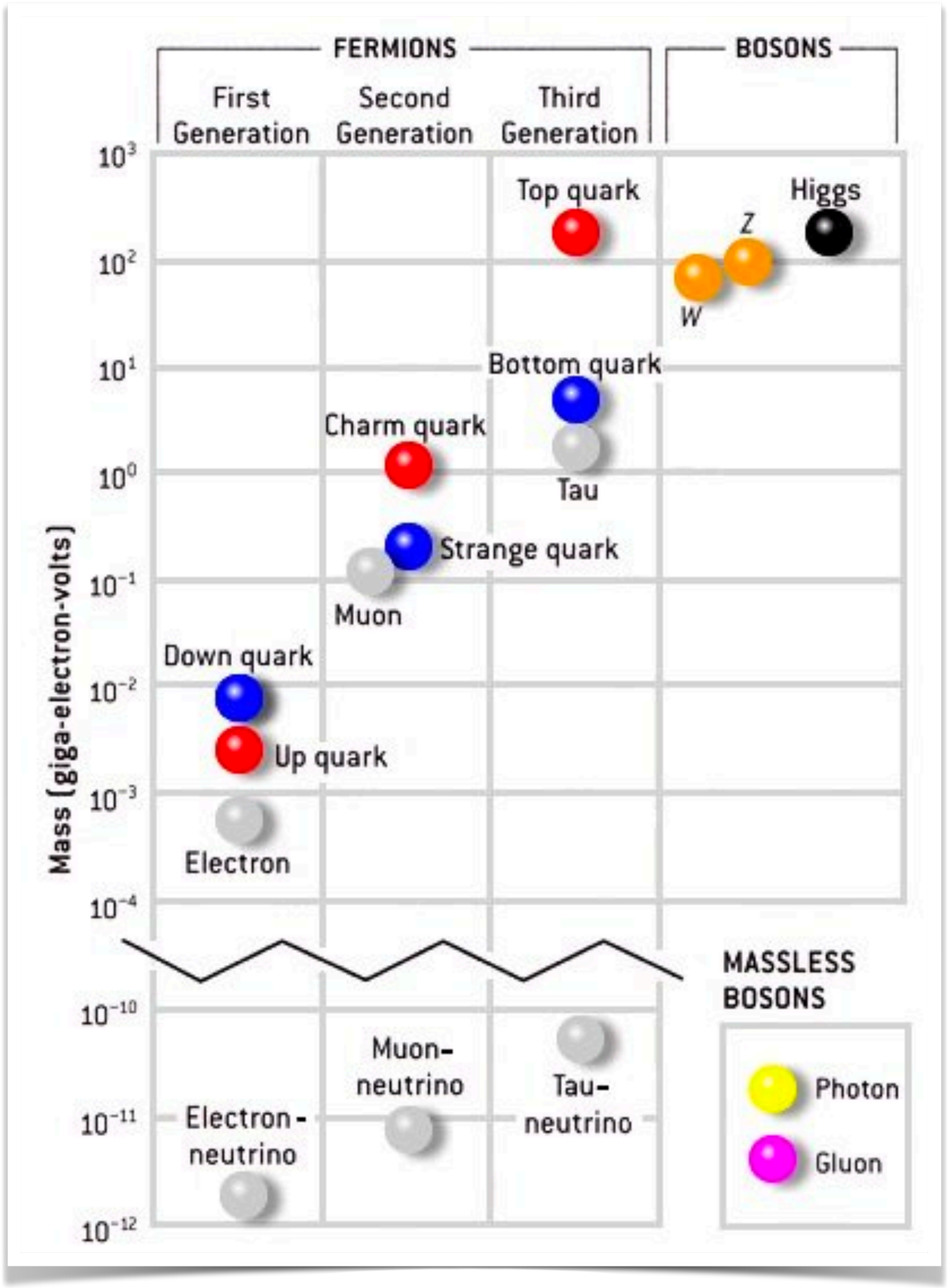

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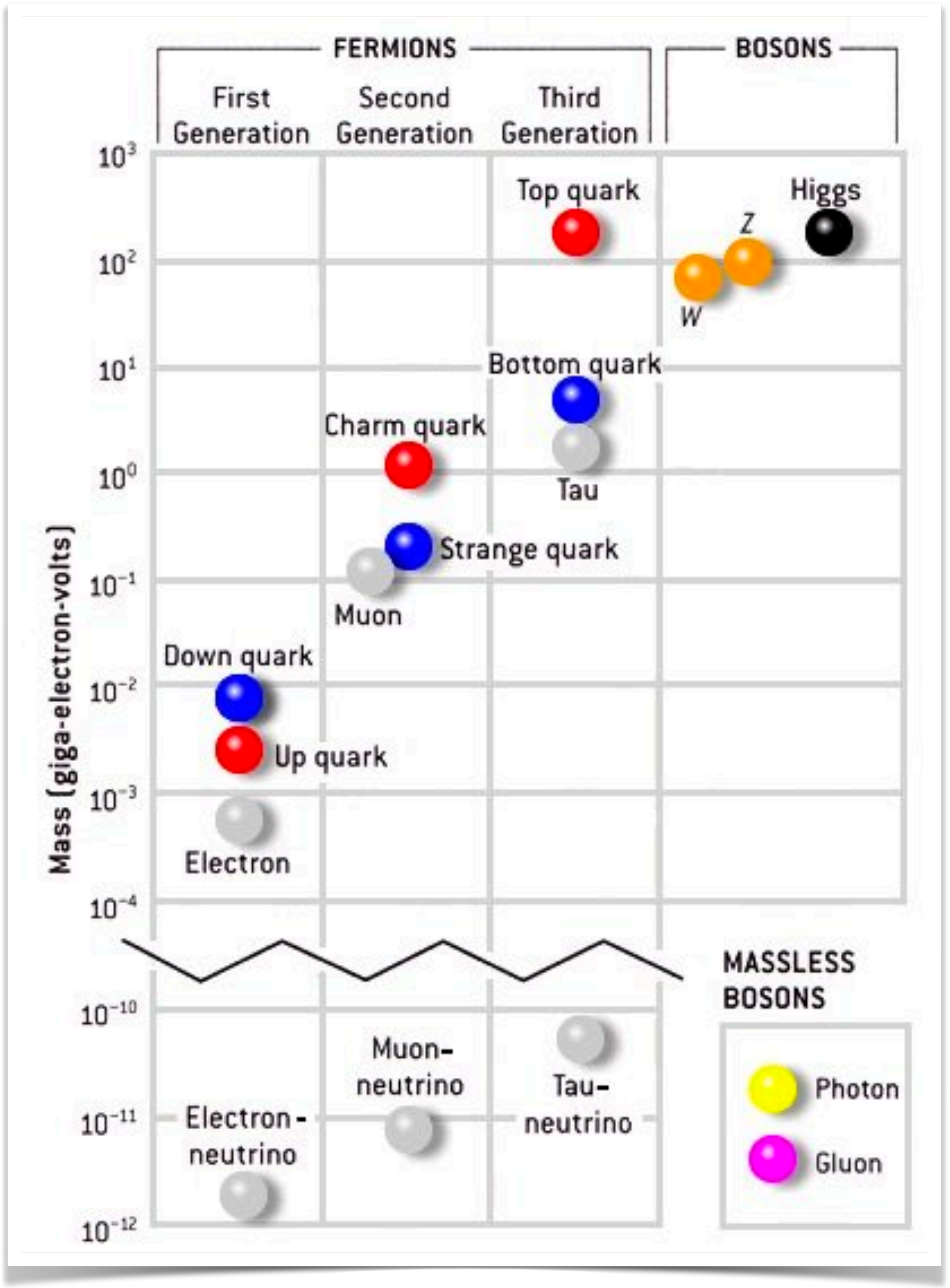
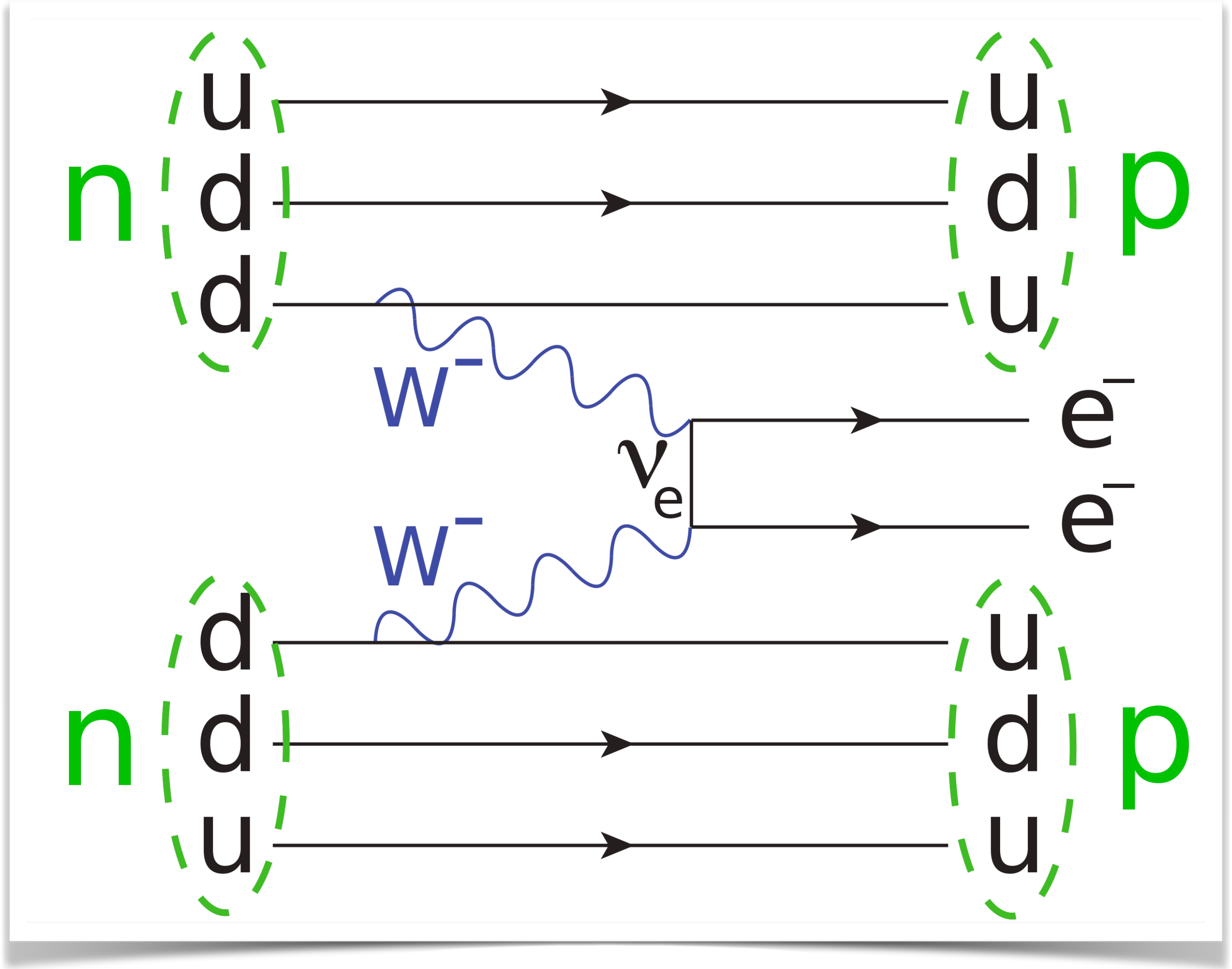
- Constraints from cosmology are also possible.



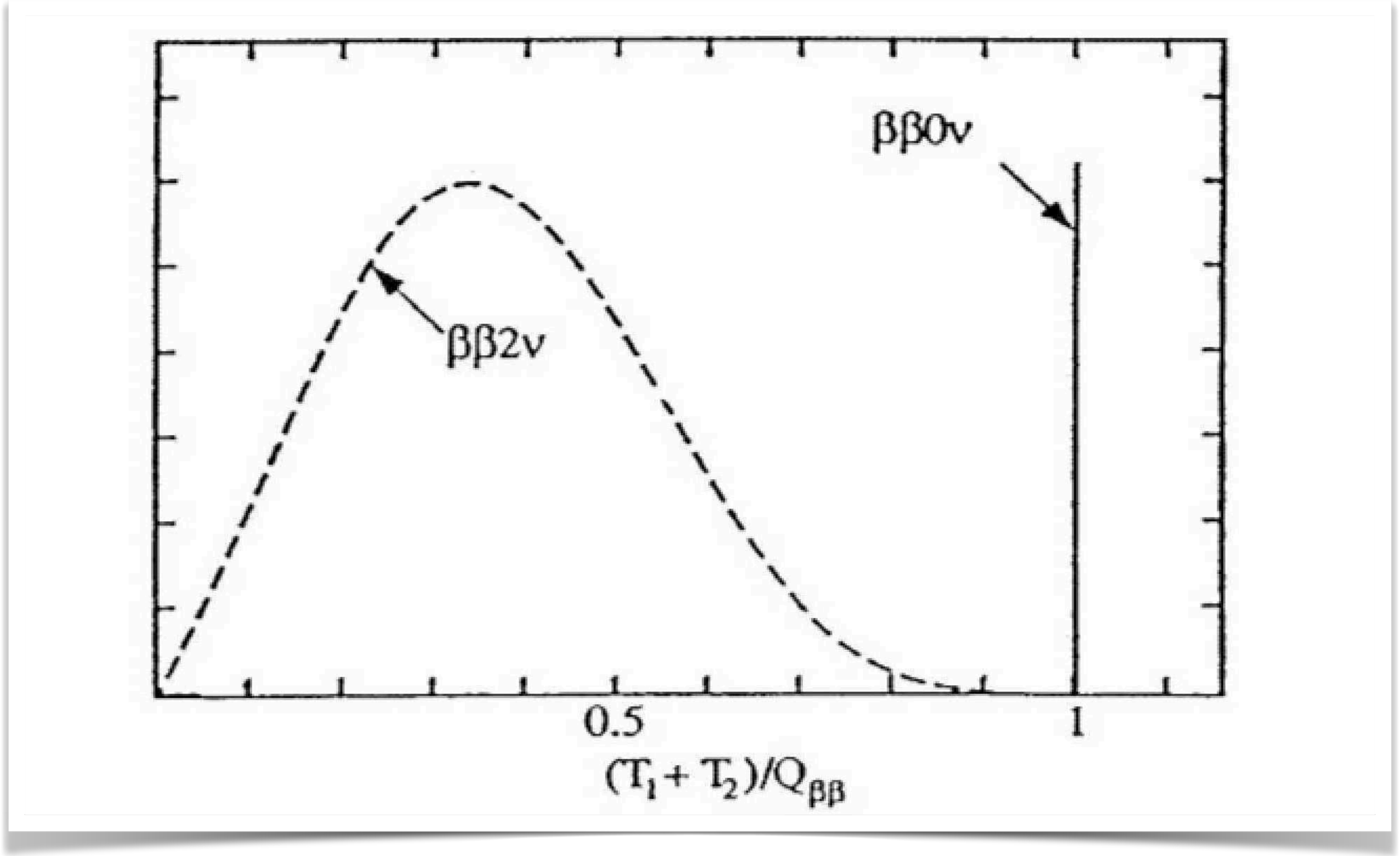
Open questions

Neutrino masses: Dirac vs. Majorana

- If neutrinos are **their own antiparticles**, they must be Majorana particles.
- Experiments like **GERDA**, **MAJORANA Demonstrator** or **NEXT** look for *neutrinoless double beta decay,* which is only possible if neutrinos are their own antiparticles.
- This process is **yet to be observed.**



Neutrinoless double beta decay



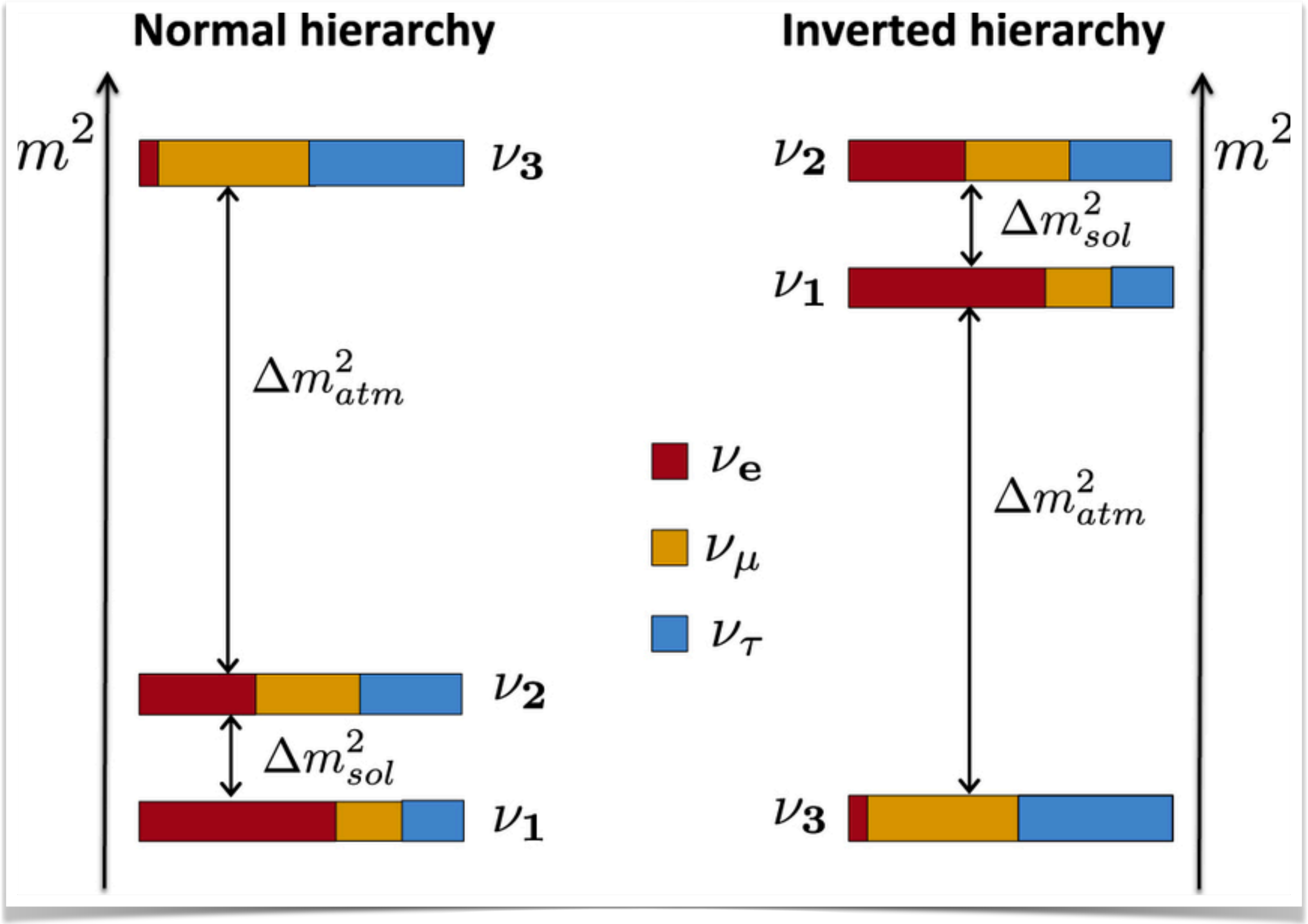
Looks familiar?

Open questions

Neutrino masses: mass hierarchy

- We know the *absolute* differences between the neutrino masses but… we don't know how they are ordered!

- Future oscillation experiments (**DUNE, HyperK**) will disambiguate this within few years of running!



Normal vs. Inverted hierarchies

Open questions

CP violation

- Is CP symmetry violated by neutrino interactions?
- CP violation = after applying charge conjugation and parity reversal, we do not return to the same state.
- CP violation is quantified by the δ_{CP} phase, one of the oscillation parameters. **DUNE** and **HyperK** will also measure it!
- It measures the difference in behaviour between neutrino and antineutrino → **could help explain the matter/antimatter asymmetry in the universe** (leptogenesis).

C conjugation: Switches all particles with their antiparticles.

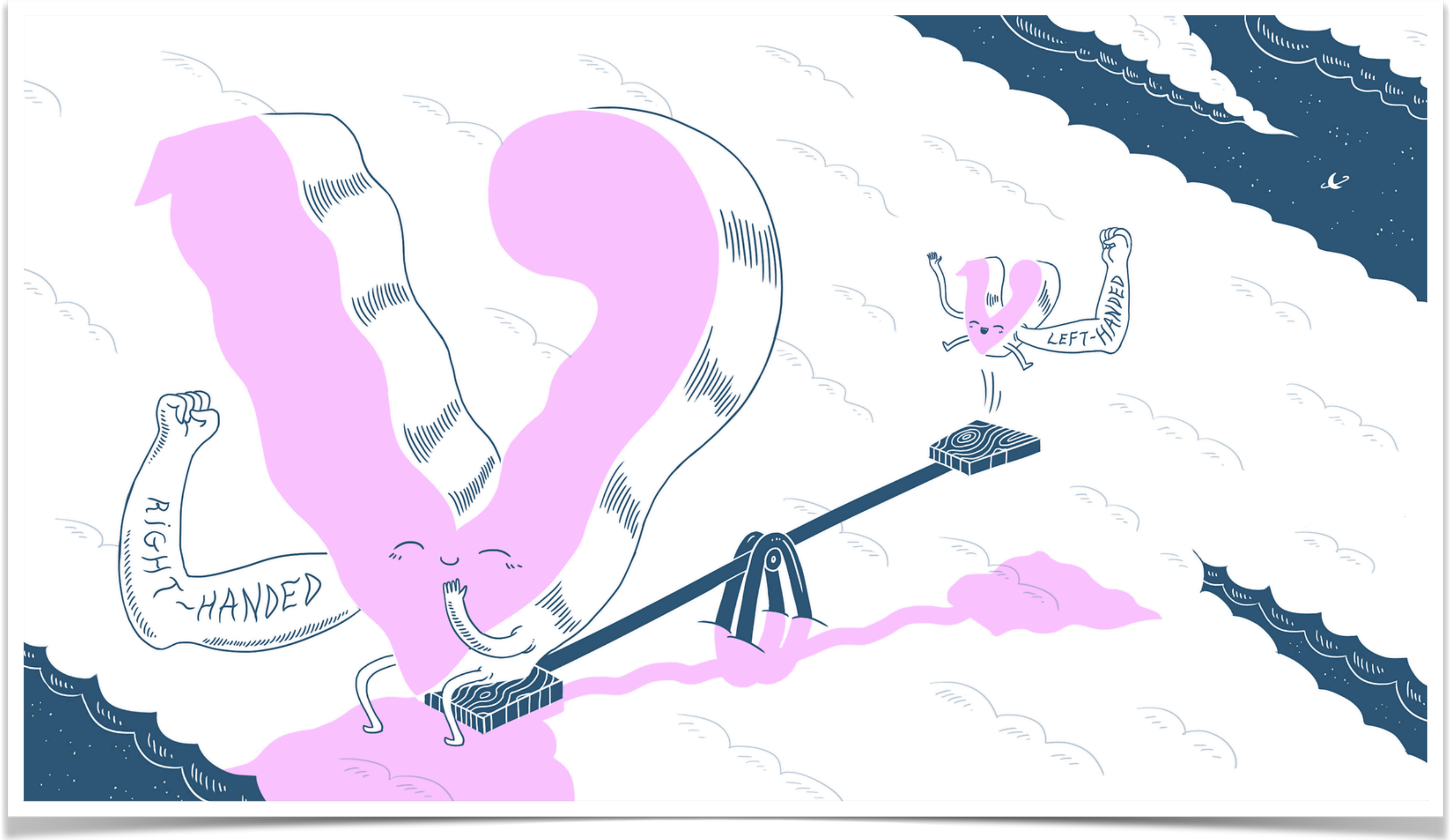
P reversal:
"Mirror reflection" of your state (switches particles from left to right handed, and viceversa).

Open questions

More neutrinos!?

- **Fourth neutrino:** some oscillation experiments (LSND, MiniBooNE) have seen a low-energy electron neutrino excess not compatible with 3 neutrinos. Not confirmed by ICARUS and MicroBooNE.

- **Heavy Neutral Leptons:** “Heavier” neutrino partners that could help explain the smallness of neutrino mass (seesaw mechanism) and be **dark matter** candidates. Also haven’t been observed.



The seesaw: the heavier the heavy neutrino, the lighter the regular one!

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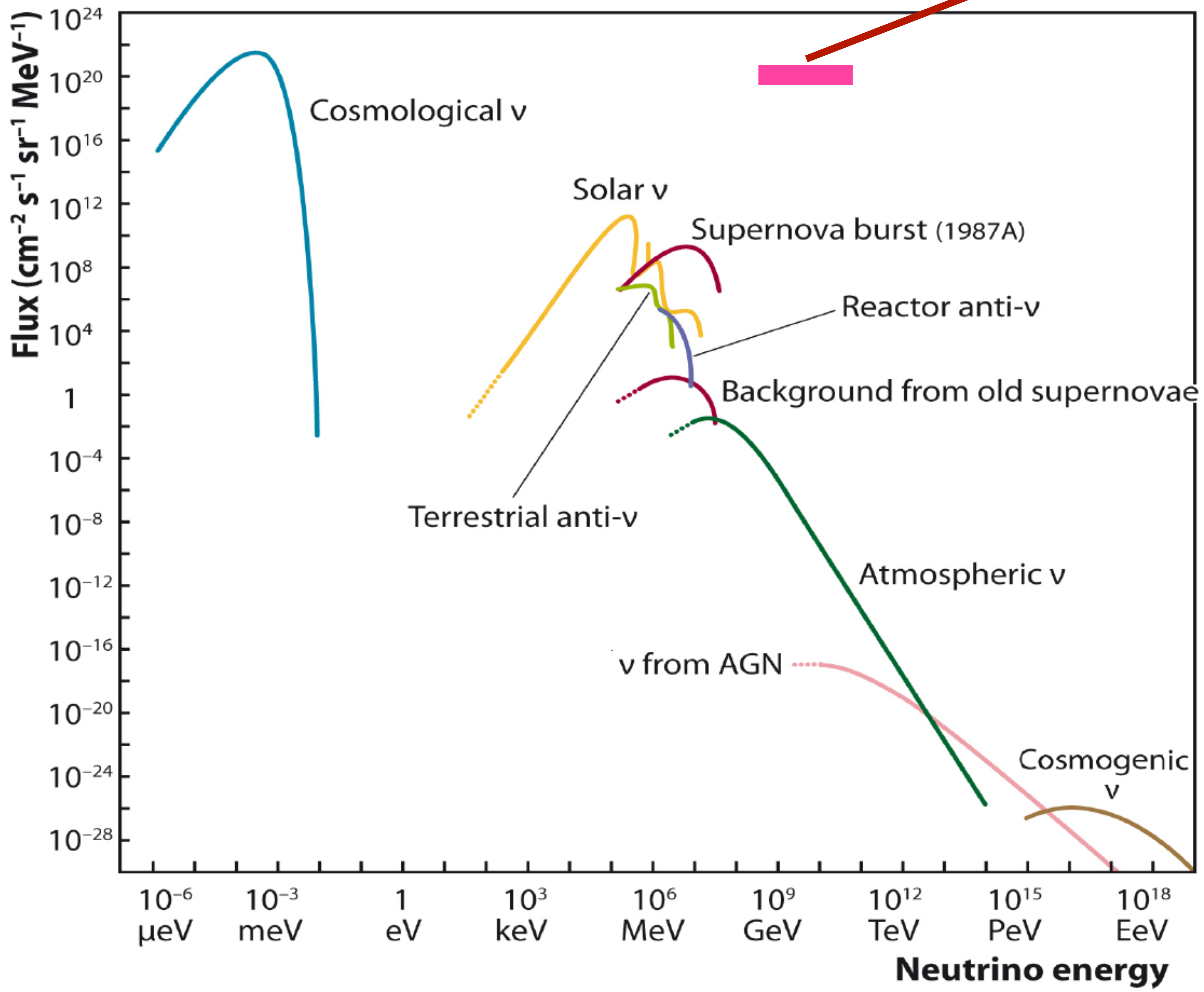
Where do they come from?

Neutrinos come from all over the place, literally.

Accelerator neutrinos
(we make 'em)



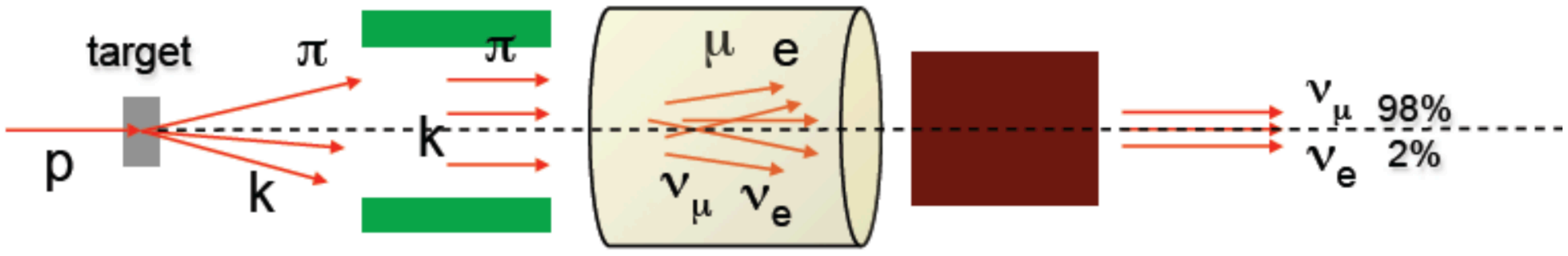
Most times an atomic nucleus changes, a neutrino is involved!

Accelerator neutrinos

Hand-made neutrinos used for oscillation experiments!

- We can create a **high intensity neutrino beam** from a proton beam:

1. We smash the proton beam into a target (berillium, carbon…).
2. Pions (and other mesons) are produced in the collision.
3. Pions decay into neutrinos (mostly ν_μ but also ν_e) mostly in a forward direction!
4. **We have our beam!**



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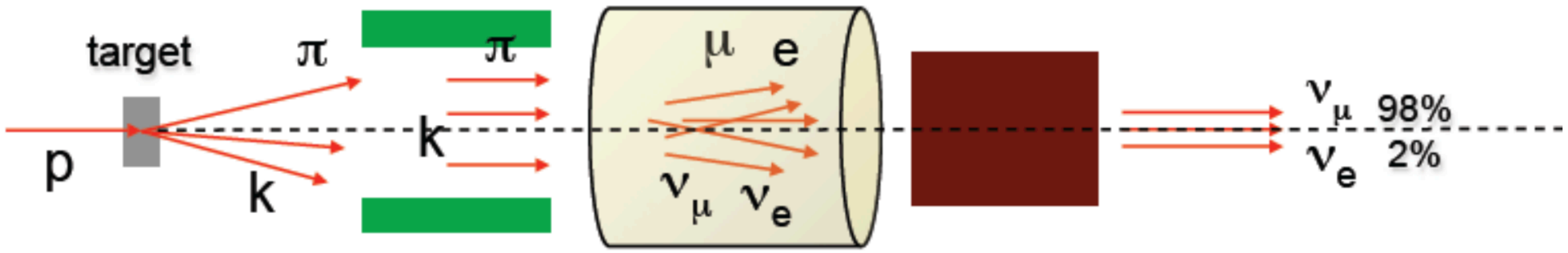

Advantages:

1. We can switch the beam on and off to know exactly when to expect the neutrinos (signal vs BG).
2. Neutrino energy can be selected.

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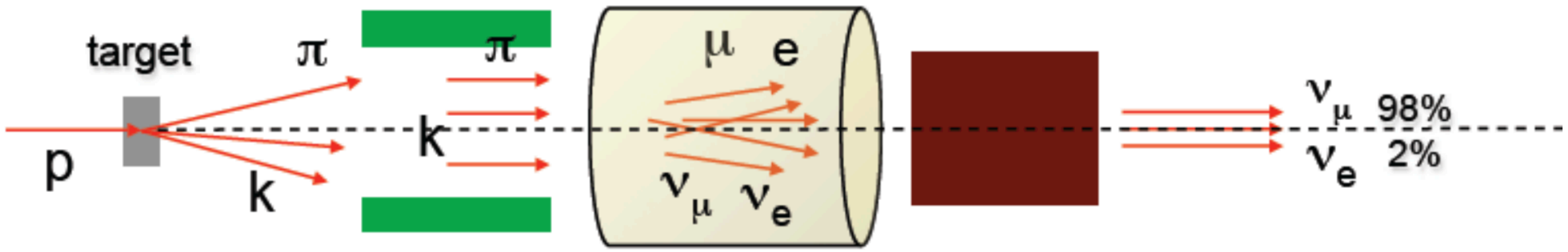

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2. Neutrino energy can be selected.

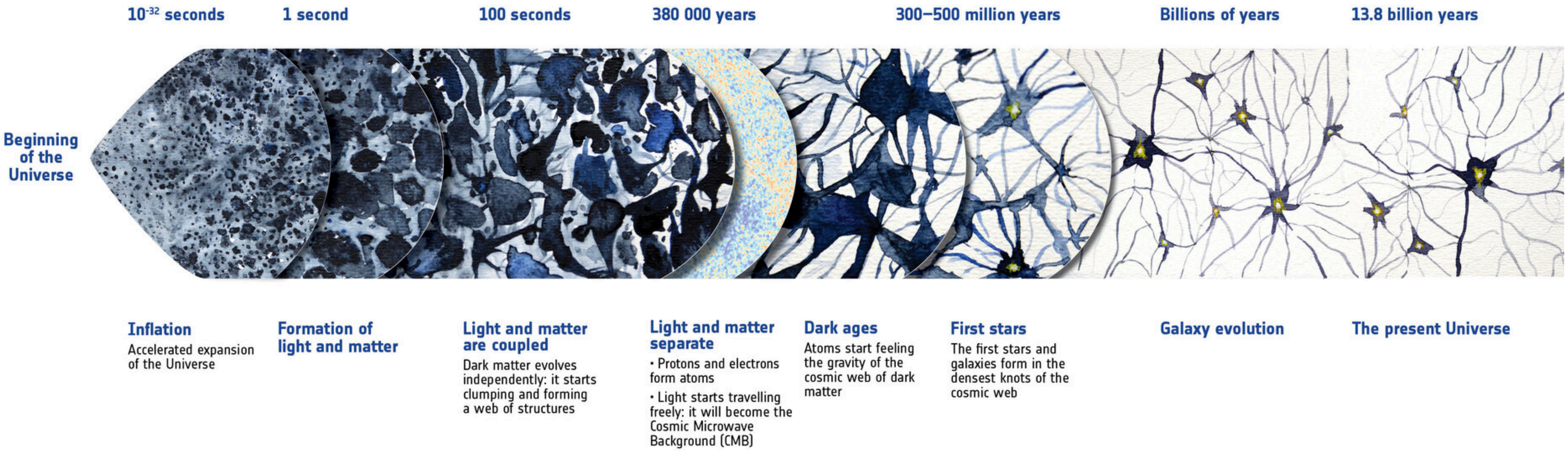
Problems:

1. Neutrino beam is not pure.
2. It's expensive to build and run the beamline!

Neutrinos from the Big Bang

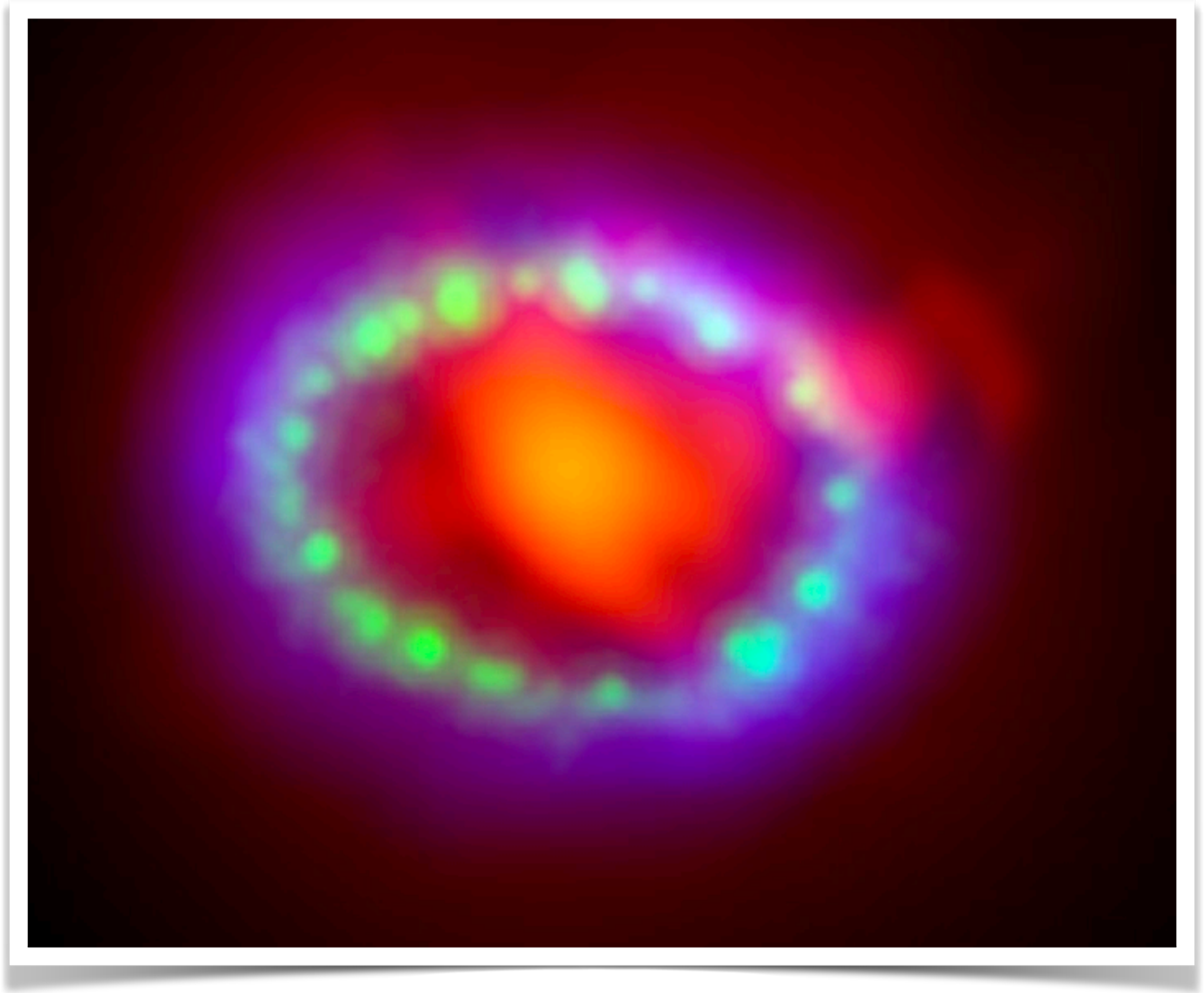
The cosmic neutrino background (CνB)!

- These **“relic neutrinos”** decoupled from matter when the universe was ~1 second old.
- They have **extremely low energy** (few milli-electron volts!) → very hard to detect.
- Are yet to be observed. Prospects: capture of relic neutrinos on tritium (**PTOLEMY**).



Supernova neutrinos

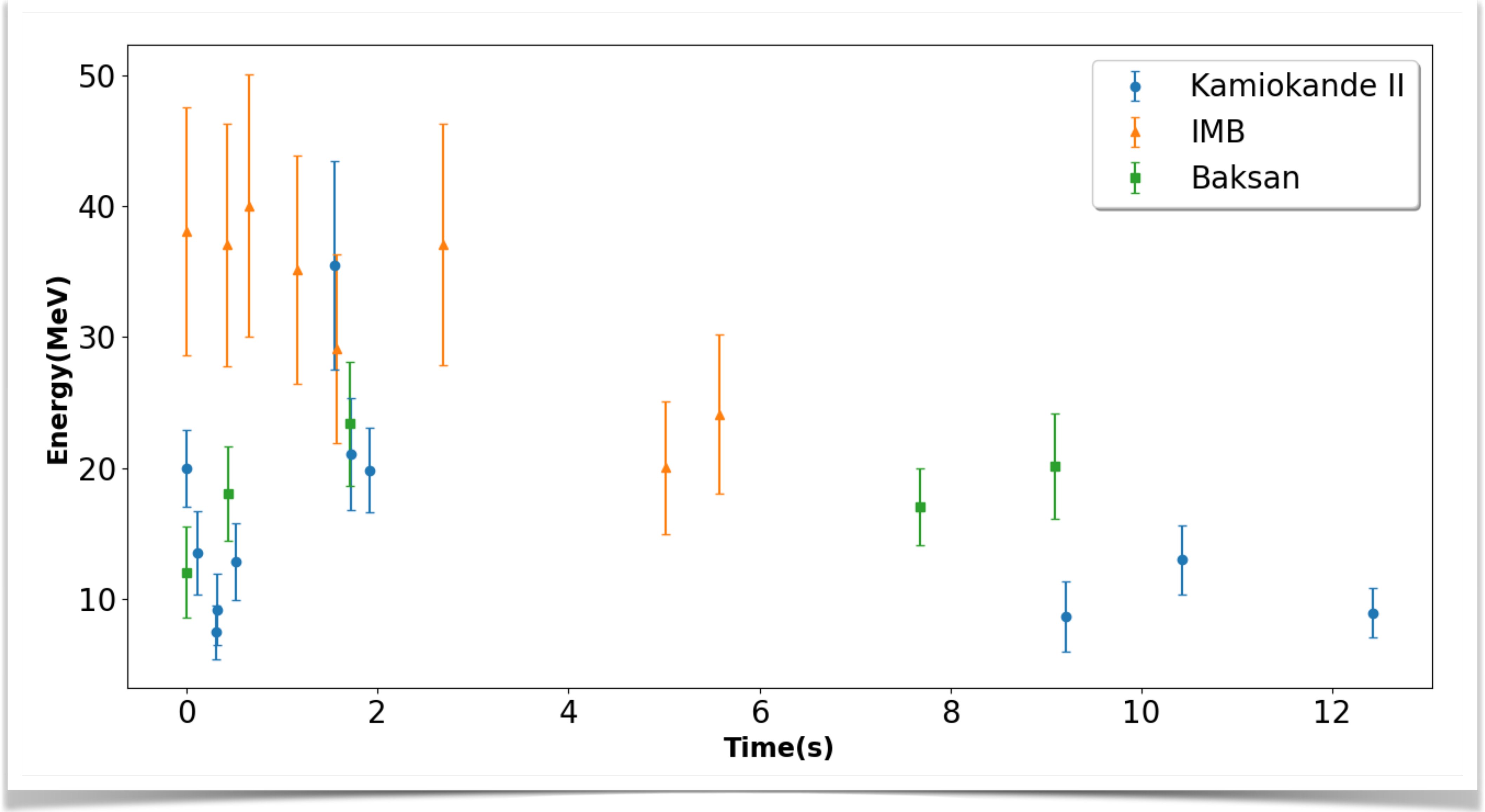
- Core-collapse supernovae are violent astrophysical events presenting a source of neutrinos of all flavours: >99% of the energy is carried by neutrinos!
- The neutrino burst lasts ~10 seconds.
- 1-3 events a century expected in our galaxy.



SN 1987A remnant

Measurement of spectra can give key physics info:

- Core-collapse mechanism.
- Neutrino physics: absolute masses, mass hierarchy or neutrino self-interactions.
- Exotic physics like sterile neutrinos or neutrino magnetic moments.



Neutrinos seen by IMB, Kamiokande and Baksan.

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Experiments and tech

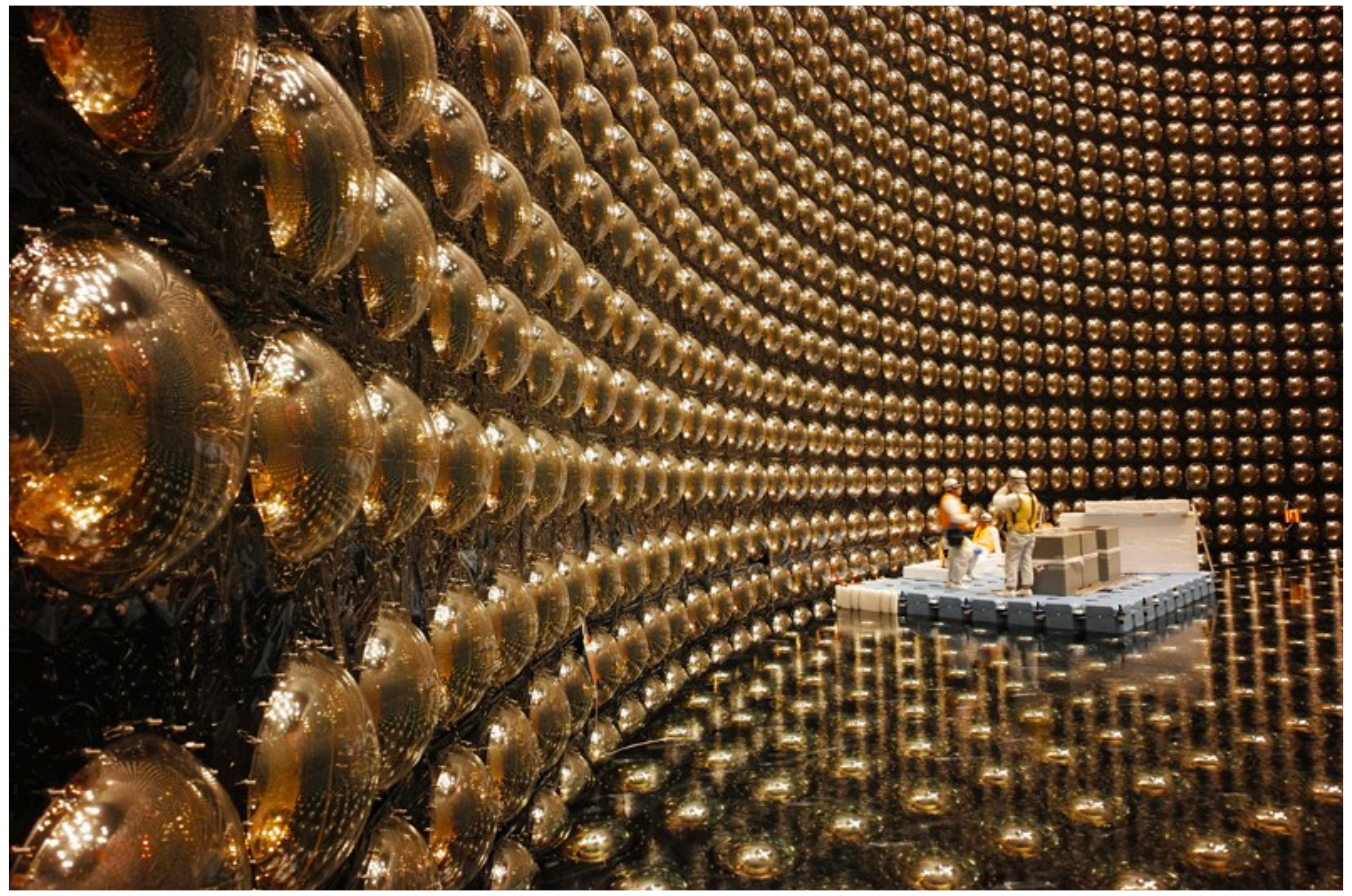
Neutrino oscillations

All neutrino oscillation experiments use a near and a far detector. They use neutrino beams from accelerators.

- **T2K (Japan):** Off-axis neutrino beam aimed at the Super-Kamiokande detector (water Cherenkov).
- **NOvA (USA):** Off-axis neutrino beam. Far detector uses a liquid scintillator.

Sterile neutrino searches

- **MicroBooNE (USA):** To further investigate the anomalies seen by MiniBooNE (liquid argon TPC). Part of the Fermilab Short-Baseline Neutrino (SBN) program.
- **ICARUS (USA):** Similar tech to MicroBoone, at a further distance from the neutrino beam.



T2K far detector (Super-Kamiokande)

MicroBooNE moving into place

Experiments and tech

Neutrinoless Double-Beta Decay searches

TPCs with isotopes prone to double-beta decay (Ge76, Xenon…)

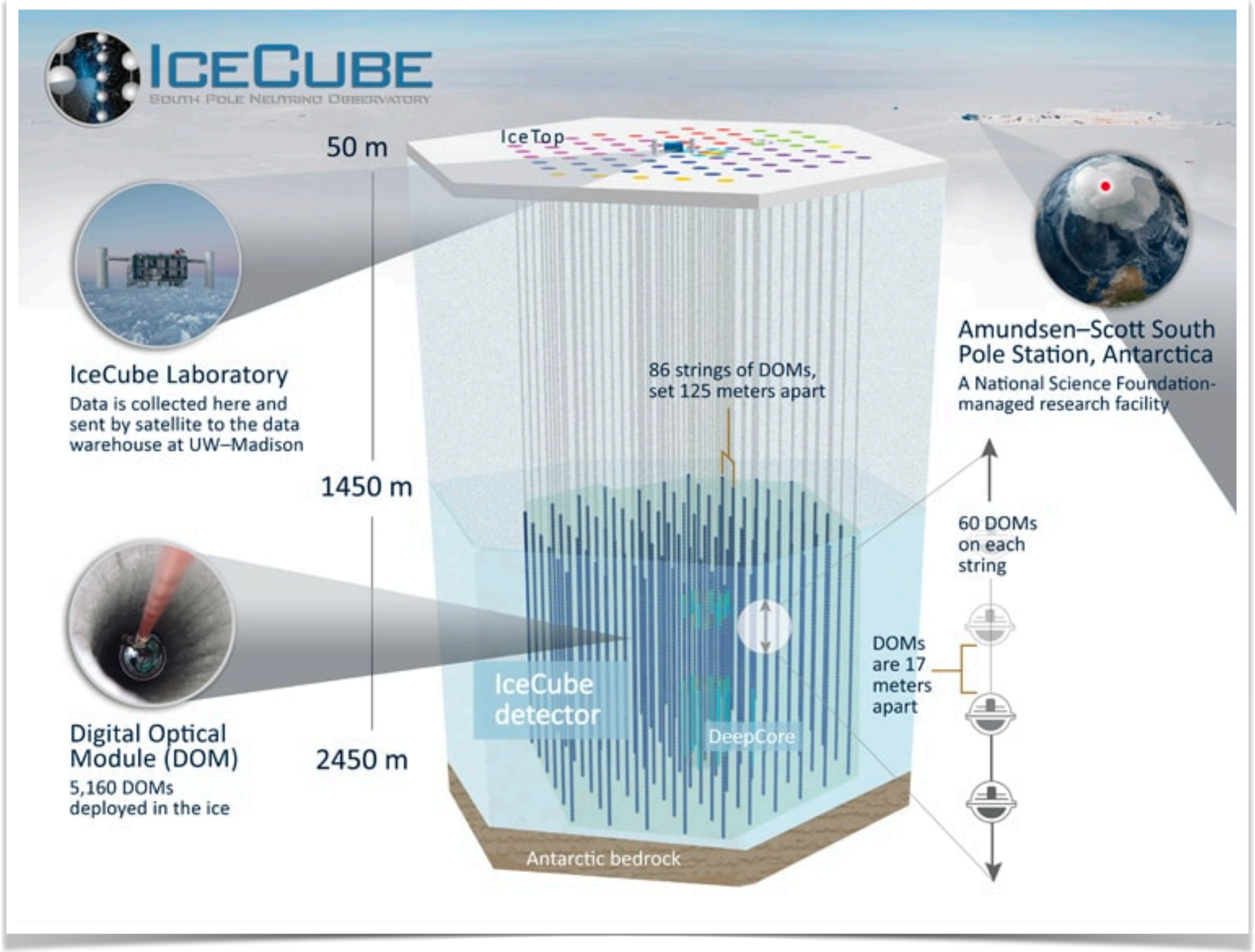
- **GERDA**, **MAJORANA Demonstrator** or **NEXT…** (and more)

Cosmic neutrino observations

- **IceCube (South Pole):** Digital optical modules (DOMs) deployed in the ice at the South Pole.

Direct neutrino mass measurements

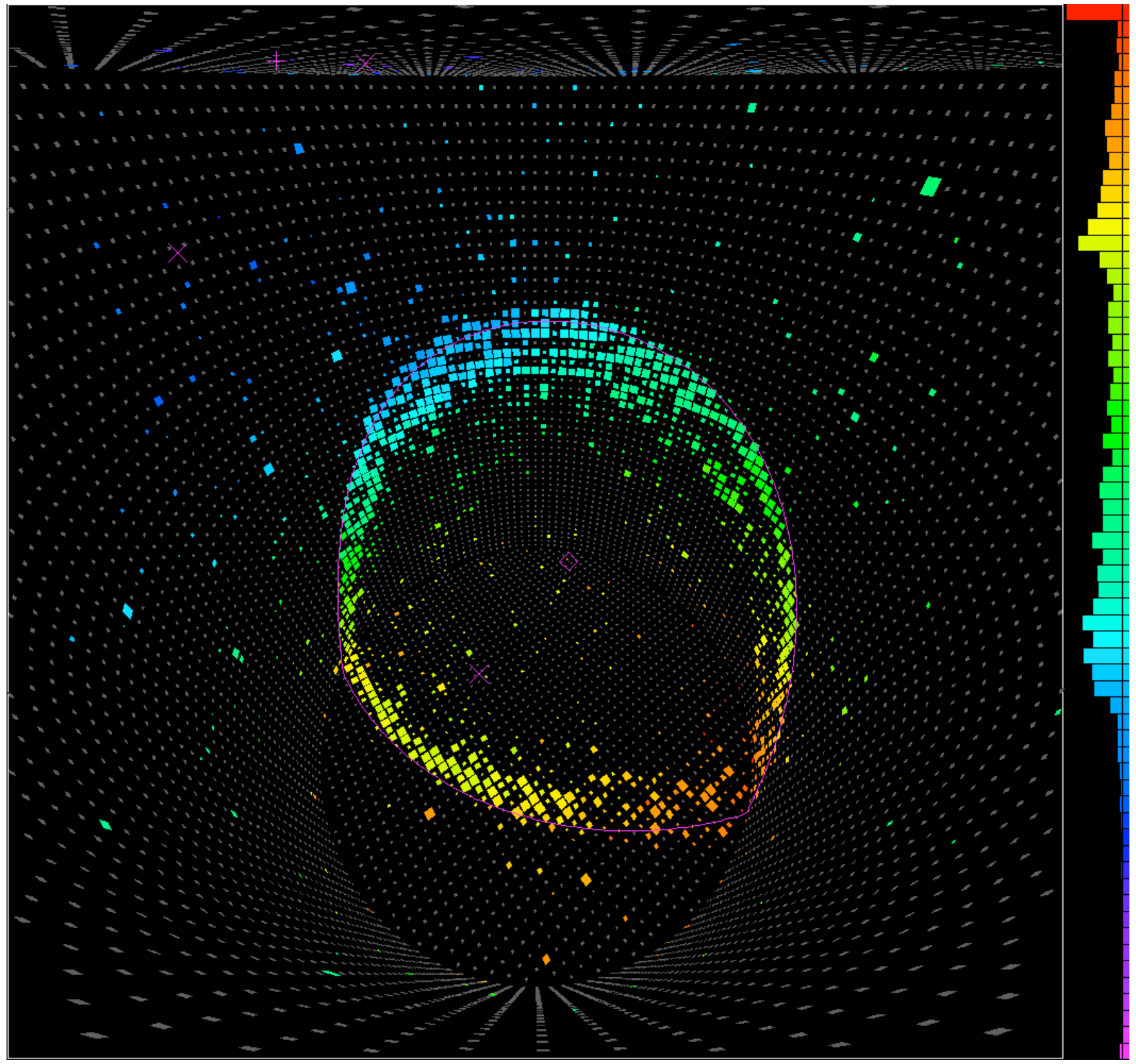
- **KATRIN (Germany):** Tritium beta decay with a high resolution spectrometer.



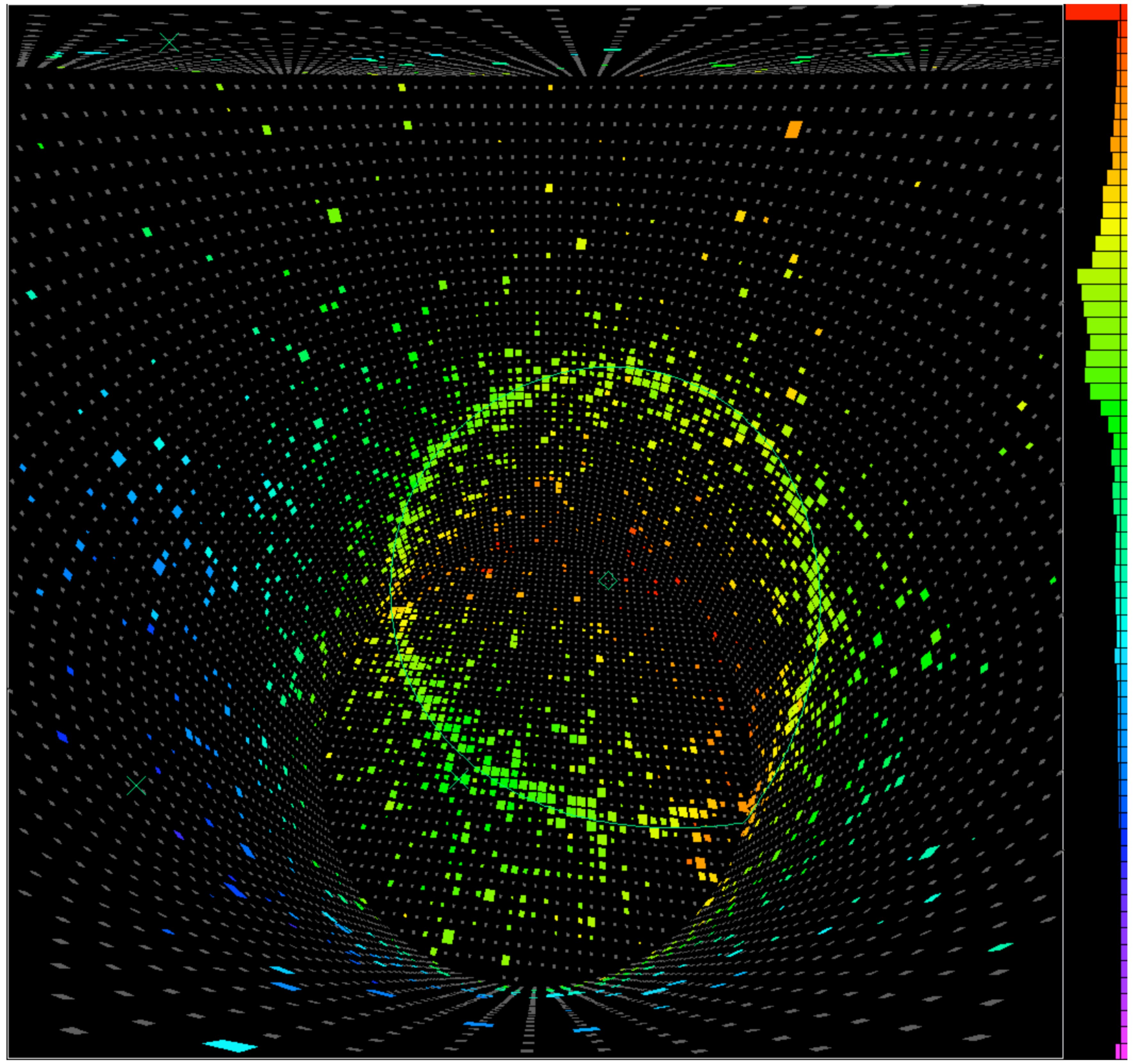
IceCube illustration

Some real neutrino pics!

Cherenkov rings at the T2K far detector



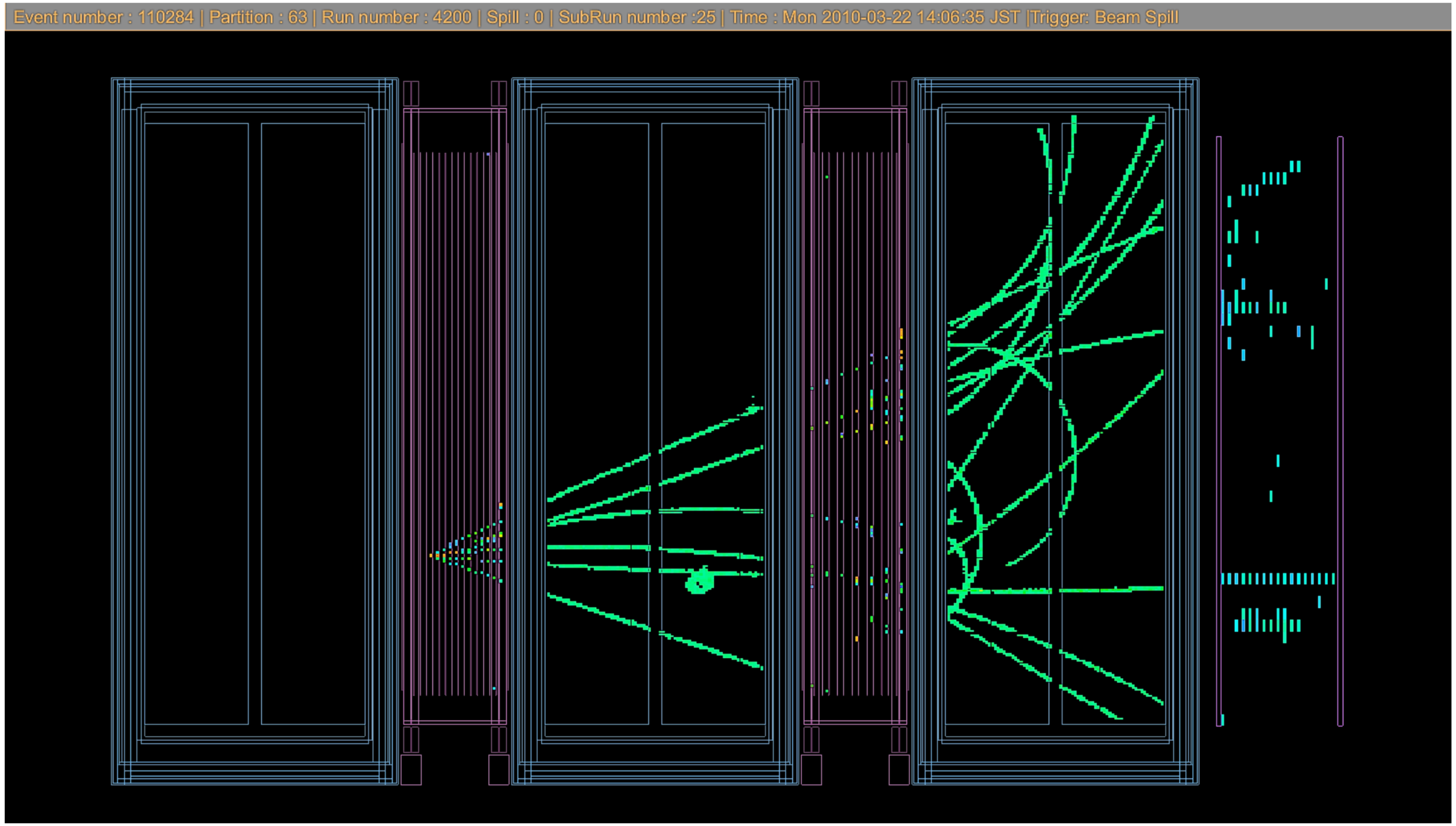
p_μ = 603 MeV



p_e = 492 MeV

Some real neutrino pics!

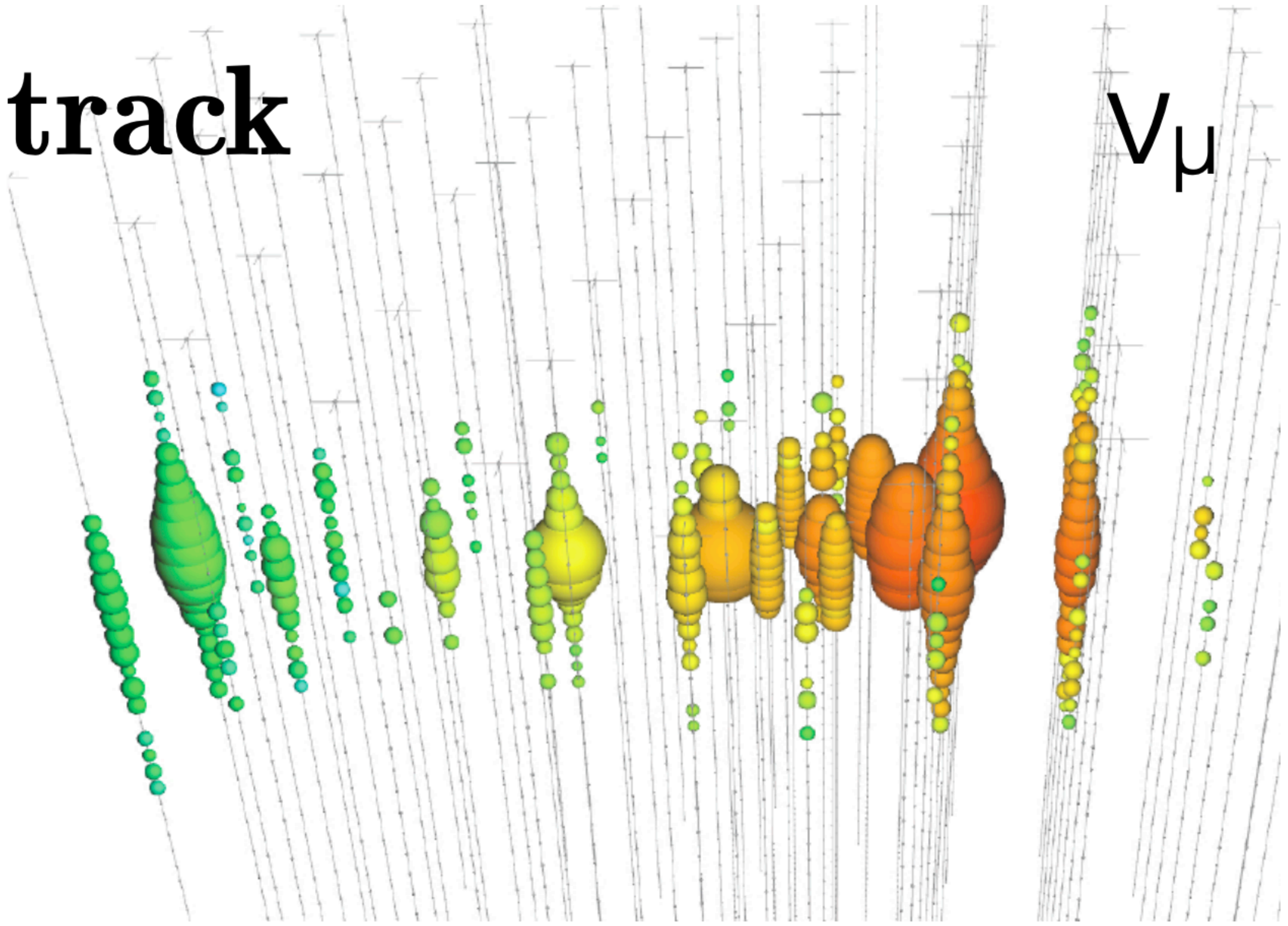
Neutrinos at the T2K near detector

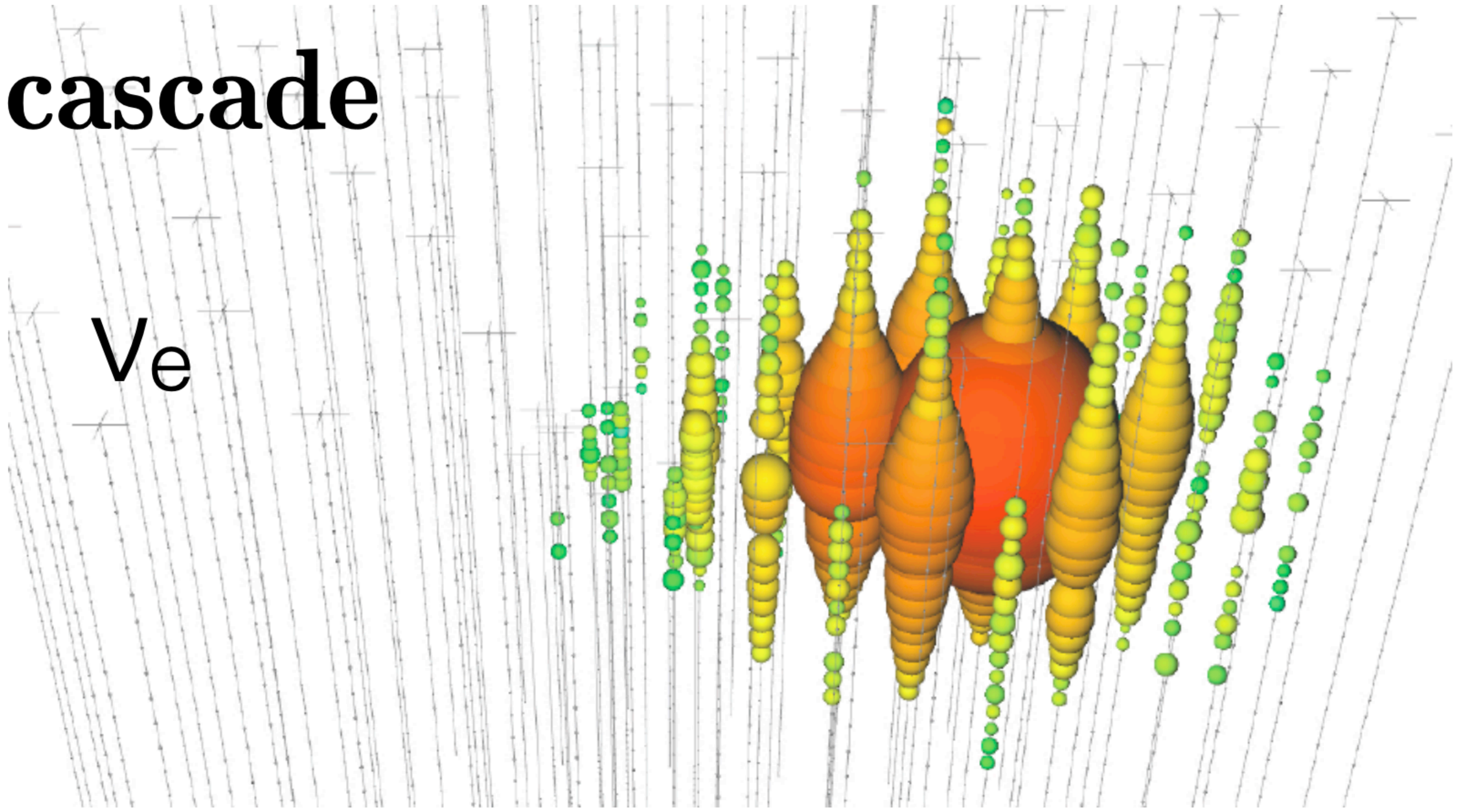


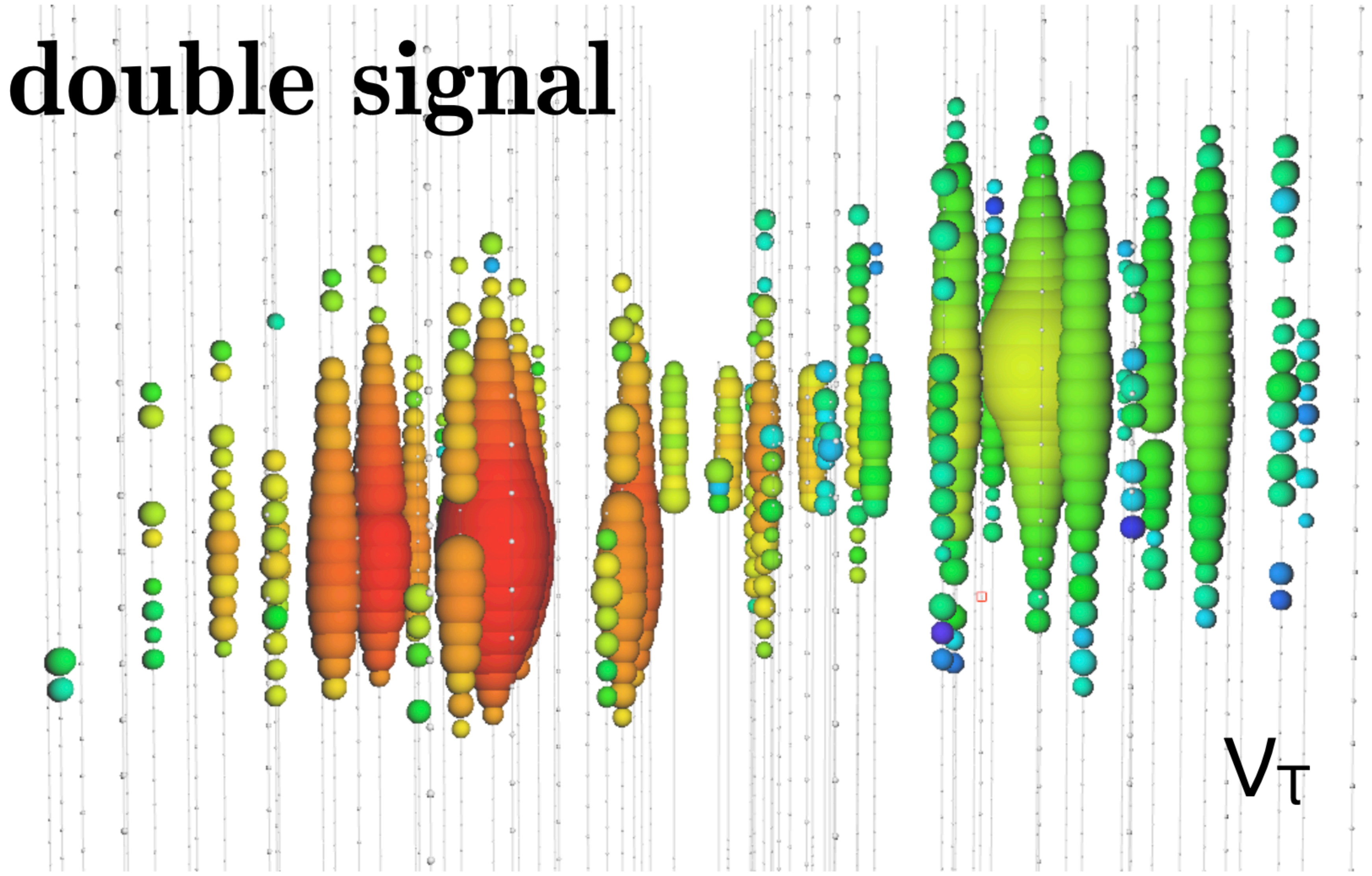
Tracks of charged particles produced by a neutrino interaction.

Some real neutrino pics!

High energy cosmic neutrinos in IceCube

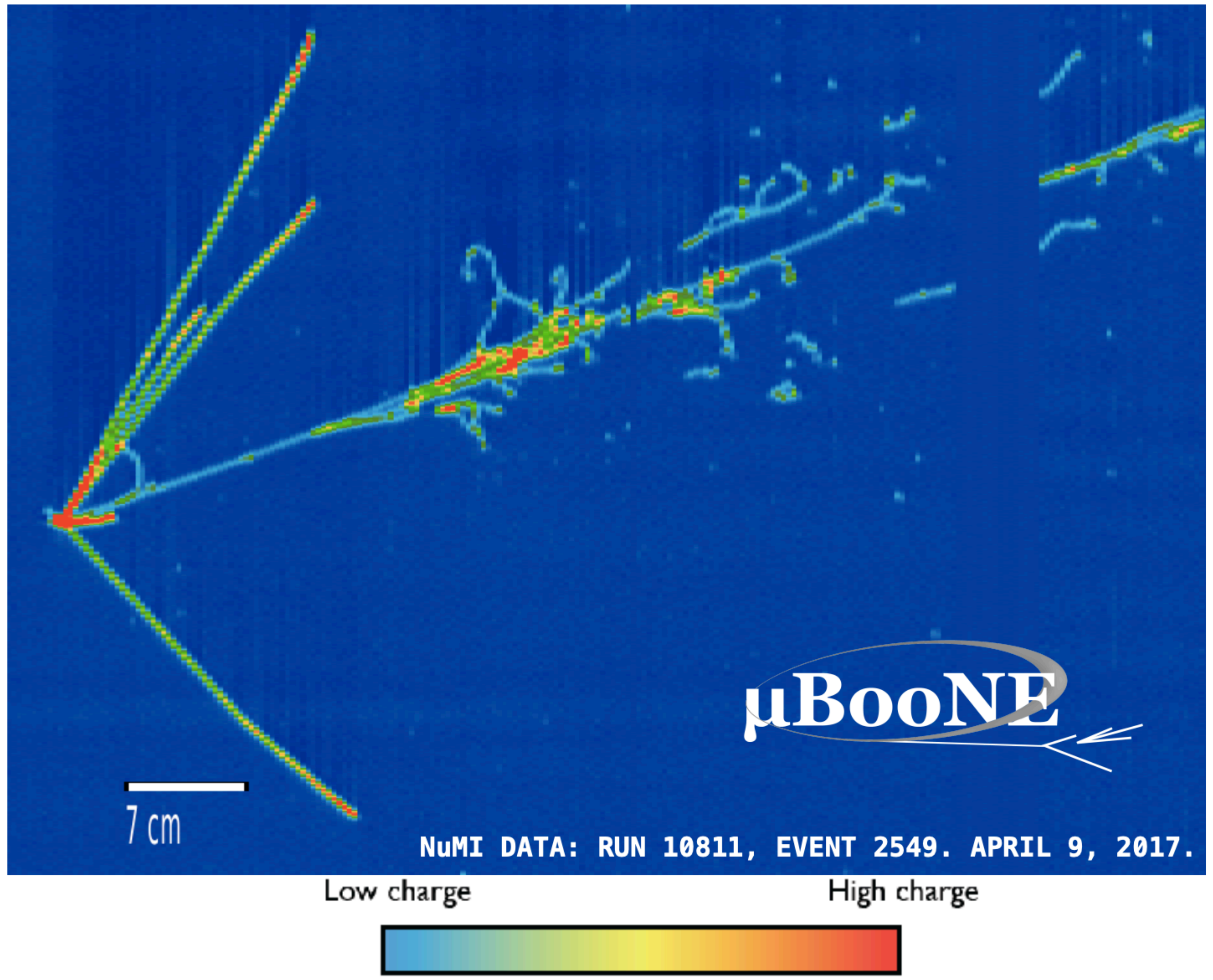




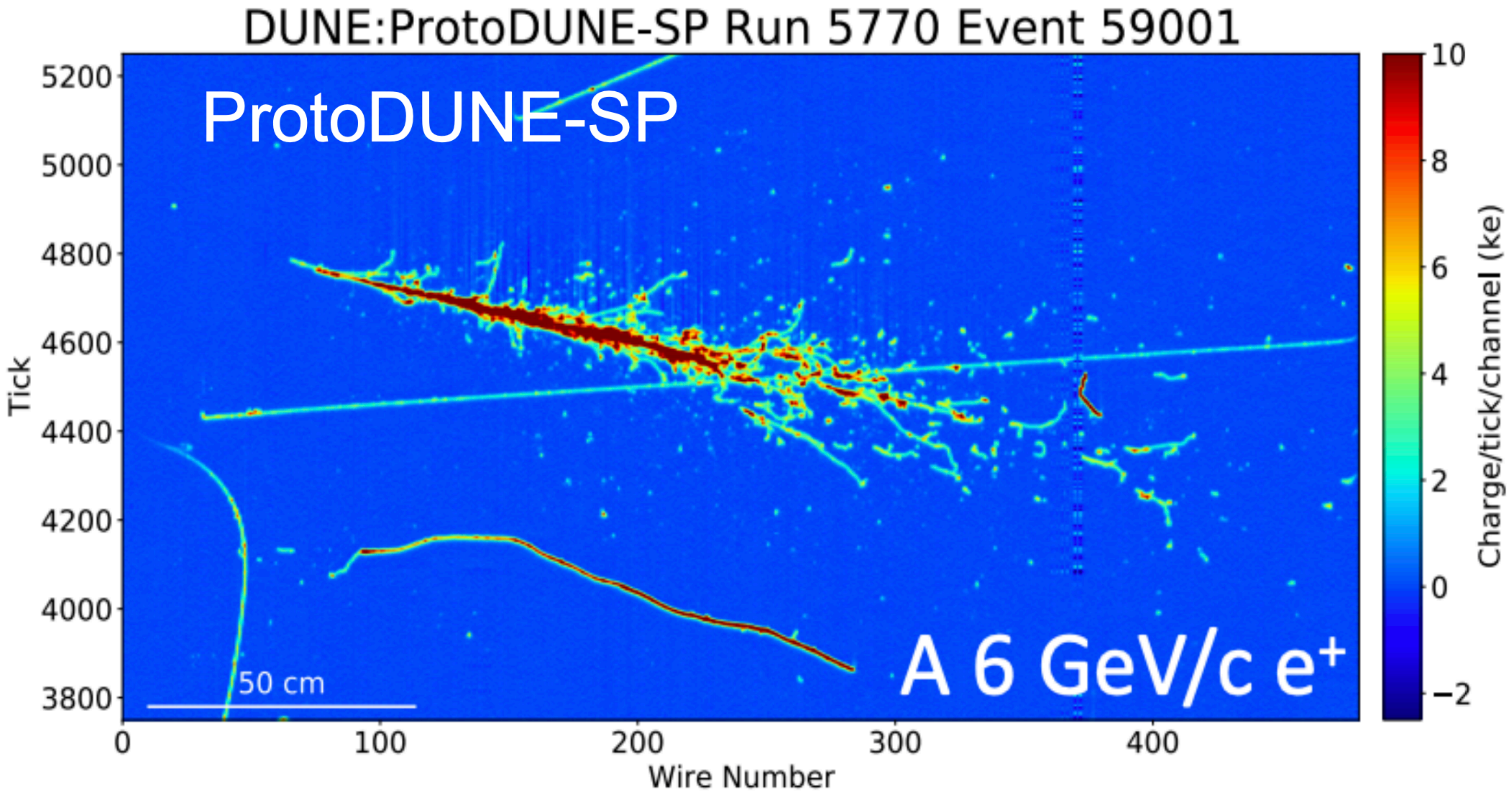


Some real neutrino pics!

Neutrinos in LArTPCs (you will learn all about them at the platform 😉)



Neutrino interaction in MicroBooNE



This is actually NOT a neutrino! (but I wanted to show a ProtoDUNE image 🤫)

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DUNE is a planned dual-site long baseline neutrino experiment starting operation in 2029.

DUNE Collaboration, DUNE Far Detector Technical Design Report, JINST 15 T08008 (2020).

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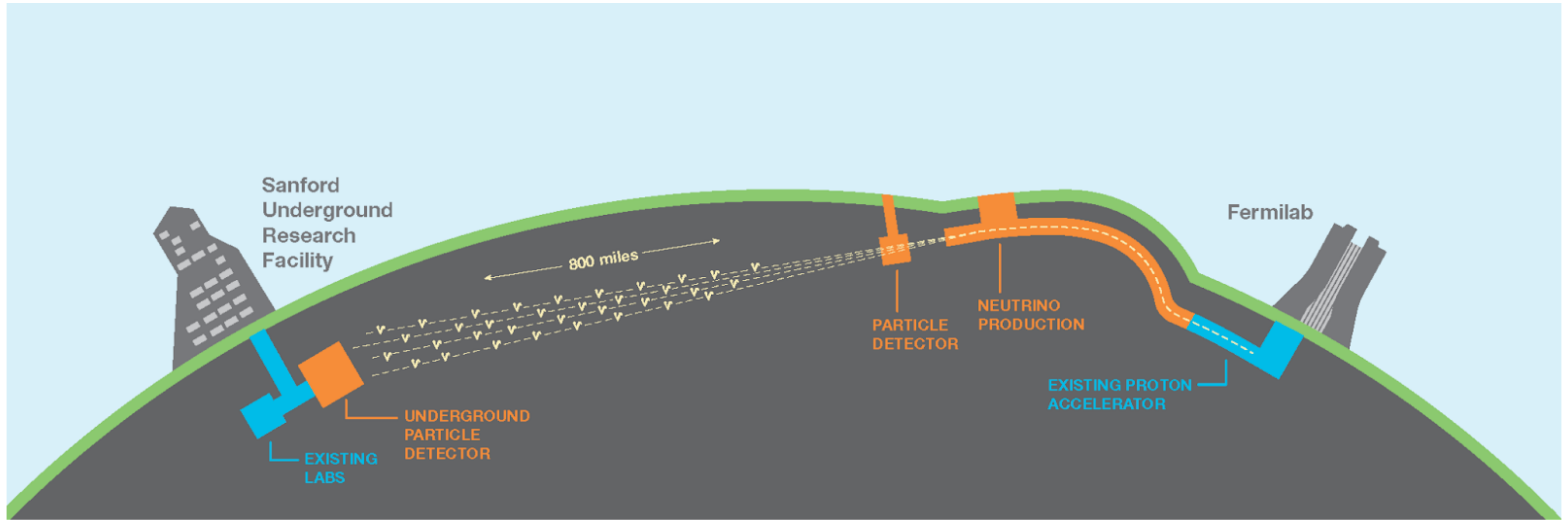

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- The **Far Detector** will be composed of four large liquid argon time projection chambers (LArTPCs) of 17 kilotons each.
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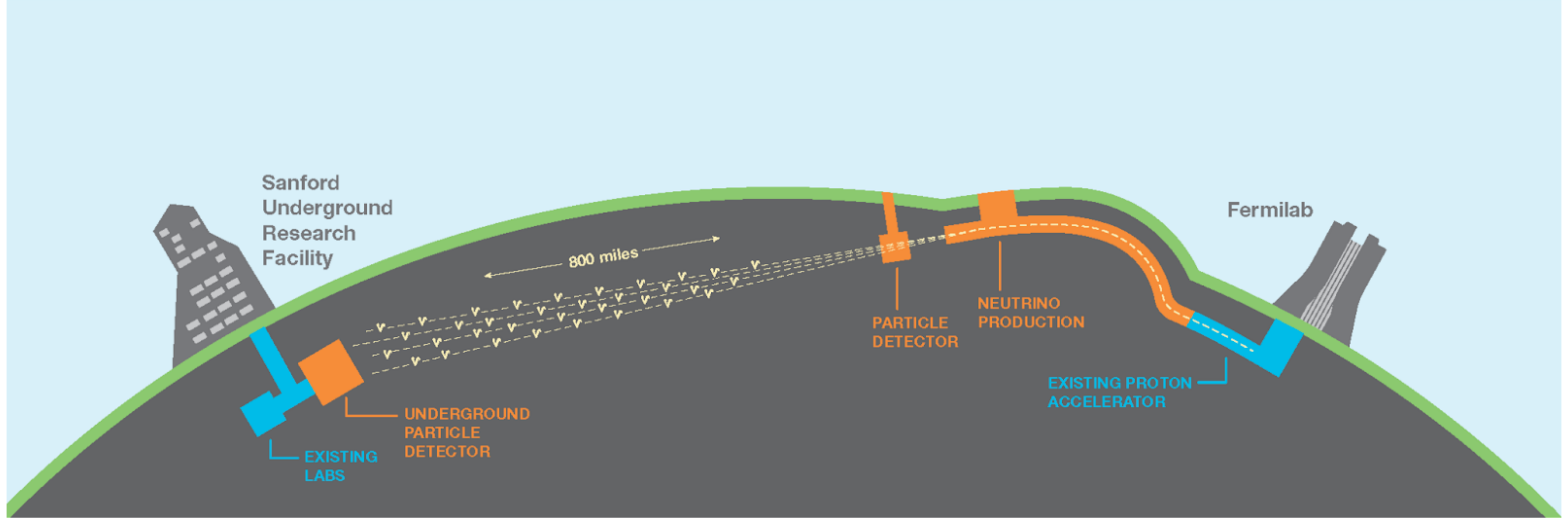

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Physics goals:

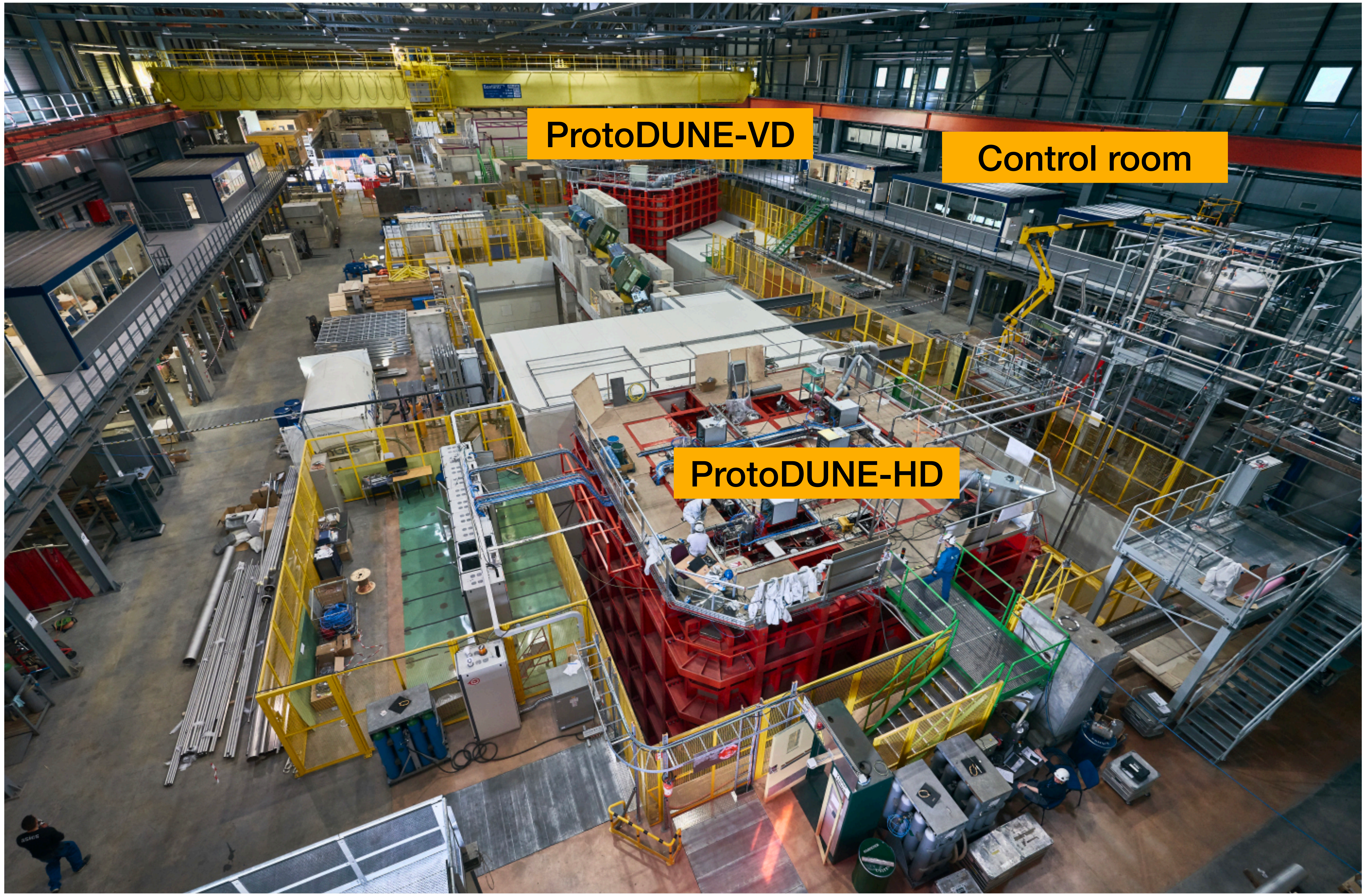
Neutrino oscillations. Precision measurements of oscillation parameters: focusing on δ_{CP}, mass ordering, and refinement of mixing angles → Completion of the three-flavour picture.

Beyond the Standard Model (BSM) searches.

Neutrino detection from core-collapse supernovae.

DUNE Collaboration, DUNE Far Detector Technical Design Report, JINST 15 T08008 (2020).

The CERN Neutrino Platform

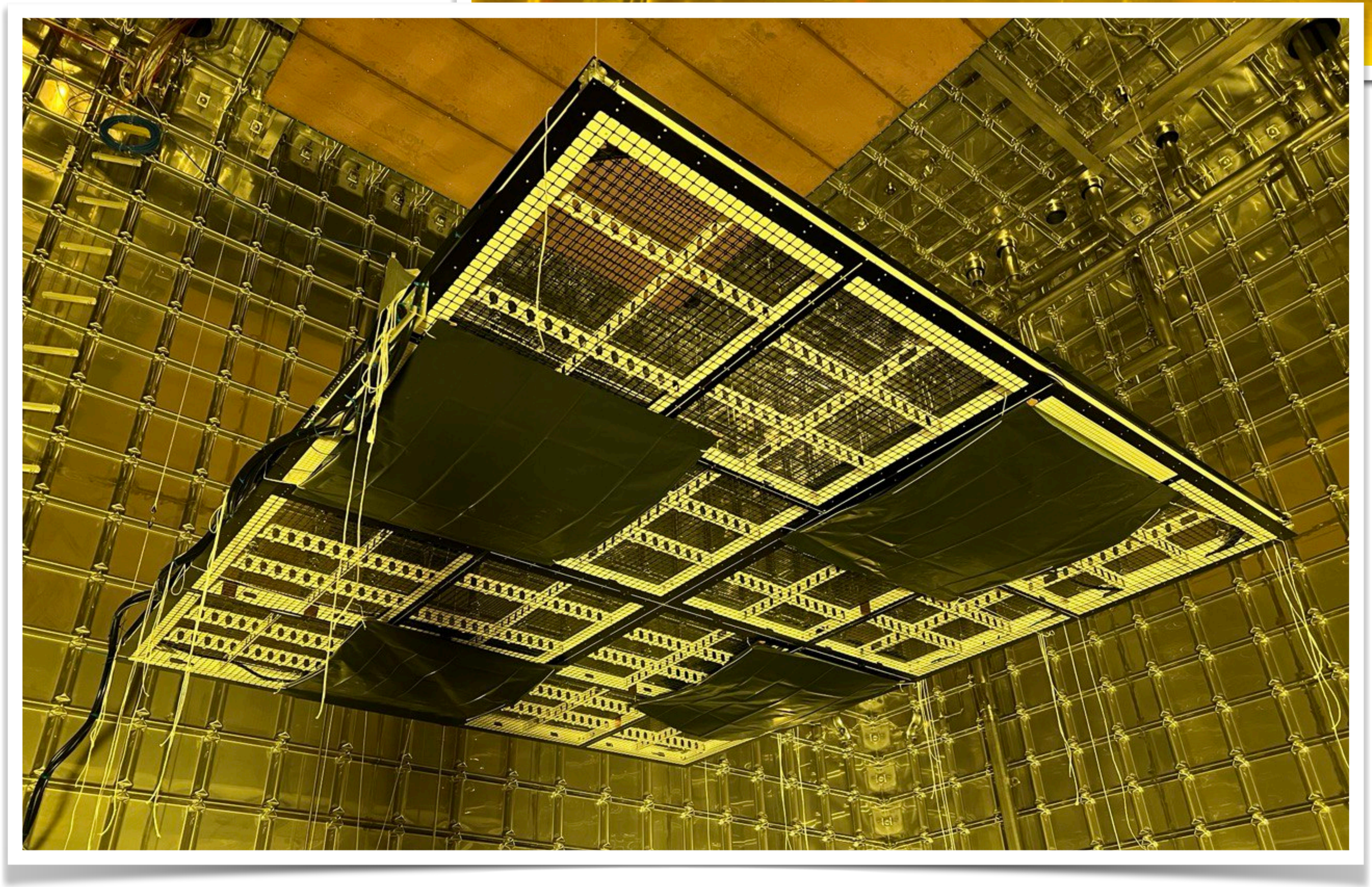


To build and test the technologies for the present and future of neutrino physics!

The CERN Neutrino Platform

ProtoDUNEs

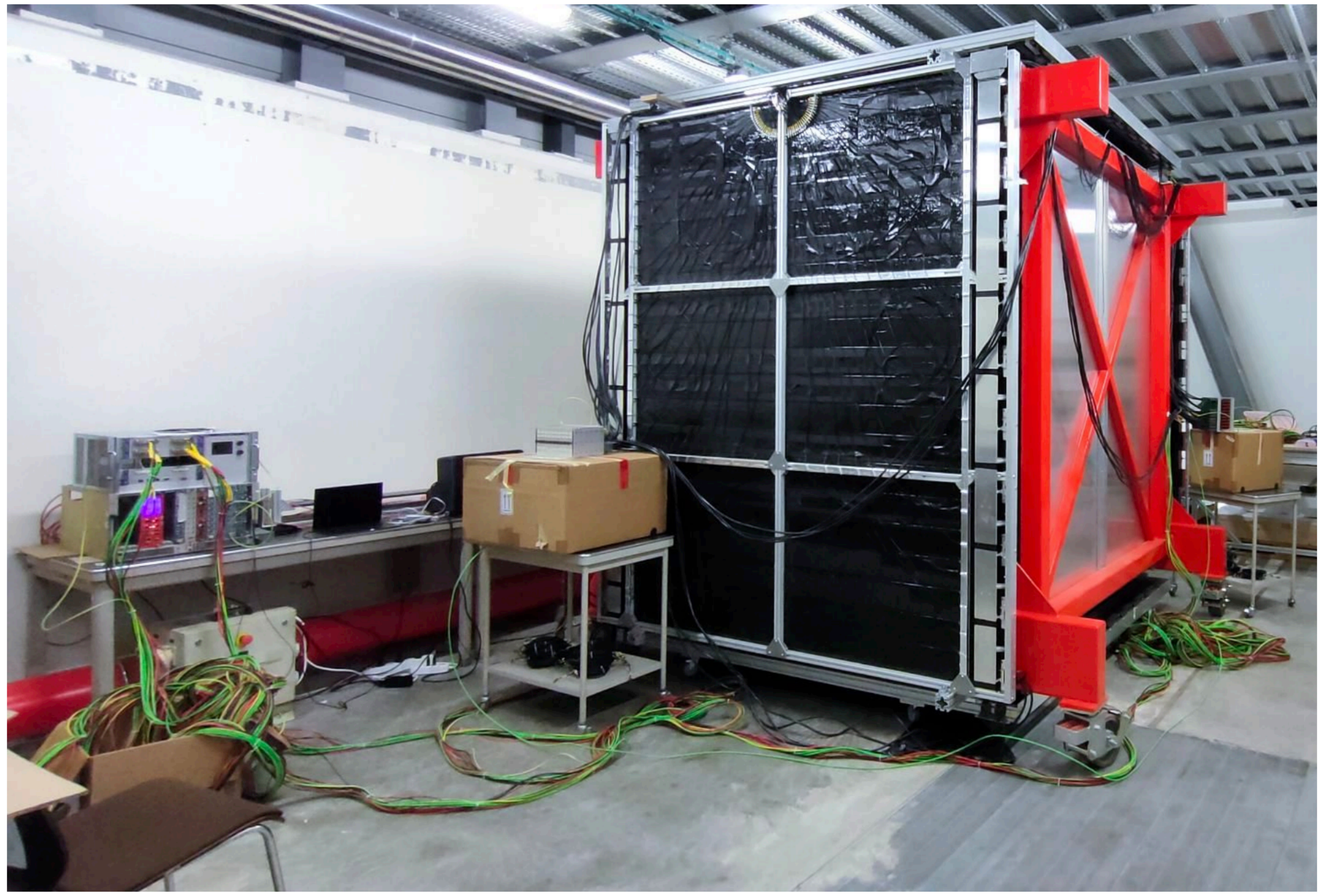
- DUNEs Far Detectors will be LArTPC of **unprecedented scale** (rough size: jumbo jet).
- We need to test this technology on prototypes: these are the ProtoDUNEs.
- Single-Phase and Dual-Phase technologies tested in previous years.
- Now getting ready for **Vertical** and **Horizontal** drift technologies!



Cathode plane setup inside Protodune-VD

The CERN Neutrino Platform

And more!



The ToF @CERN

The Time-of-Flight detector for the T2K Near Detector upgrade was just shipped to Japan!

ICARUS (now at Fermilab) was fully refurbished and upgraded at the Neutrino Platform in 2016

Conclusions

What's next, neutrinos?

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- They are the only neutral fermion.
- They don't fit in the three-family picture (tiny mass, order between families).
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Neutrinos are *messengers*

- They carry information from the Big Bang, from supernovas and from other astrophysical processes.
- They could help explain the excess of matter over antimatter in the universe.

What's next, neutrinos?

Thank you for listening!

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