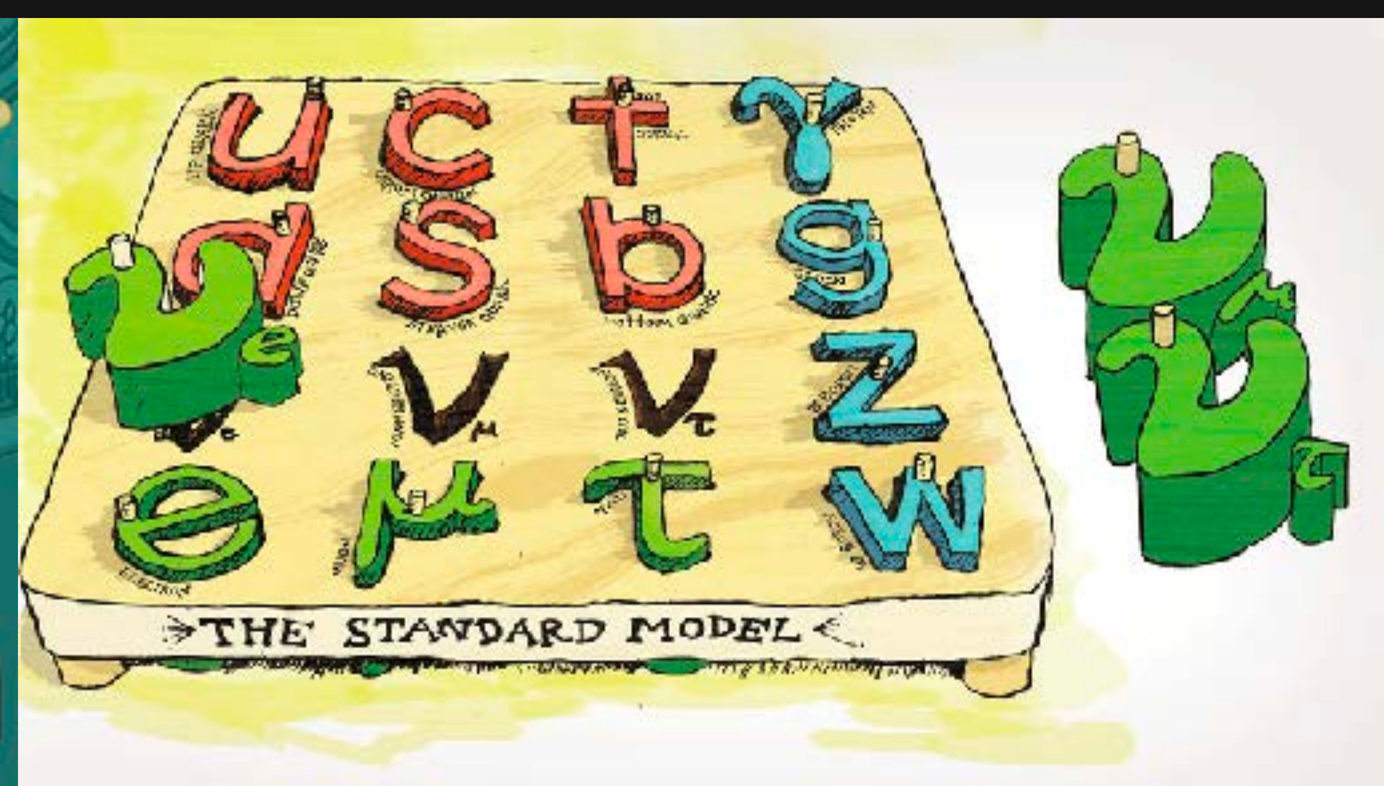
Neutrinos, from the lab to the cosmos

Kevin J. Kelly


NEUTRINO
NEUTRINO
NEUTRINO


GUESS
MY
WEIGHT


u c t γ
d s b g
ν_e ν_μ ν_τ Z
e μ τ W
THE STANDARD MODEL

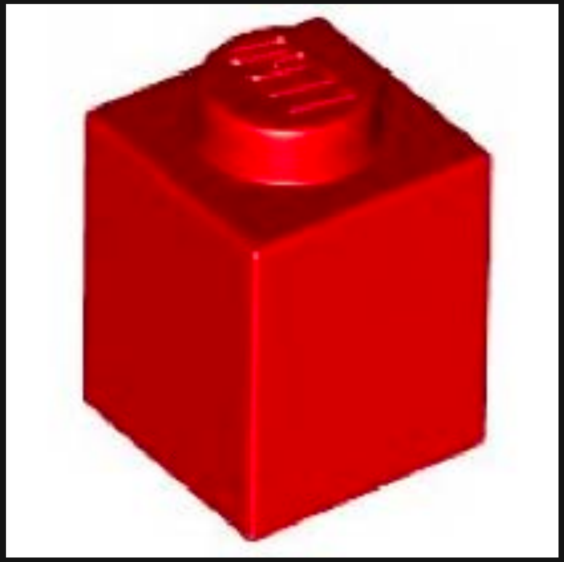
My motivating question:
What is everything made of?

As a kid, I was a BIG Fan of LEGOs

As far as LEGOs go, it's a fairly simple system: there are building blocks out of which we can make anything we want!

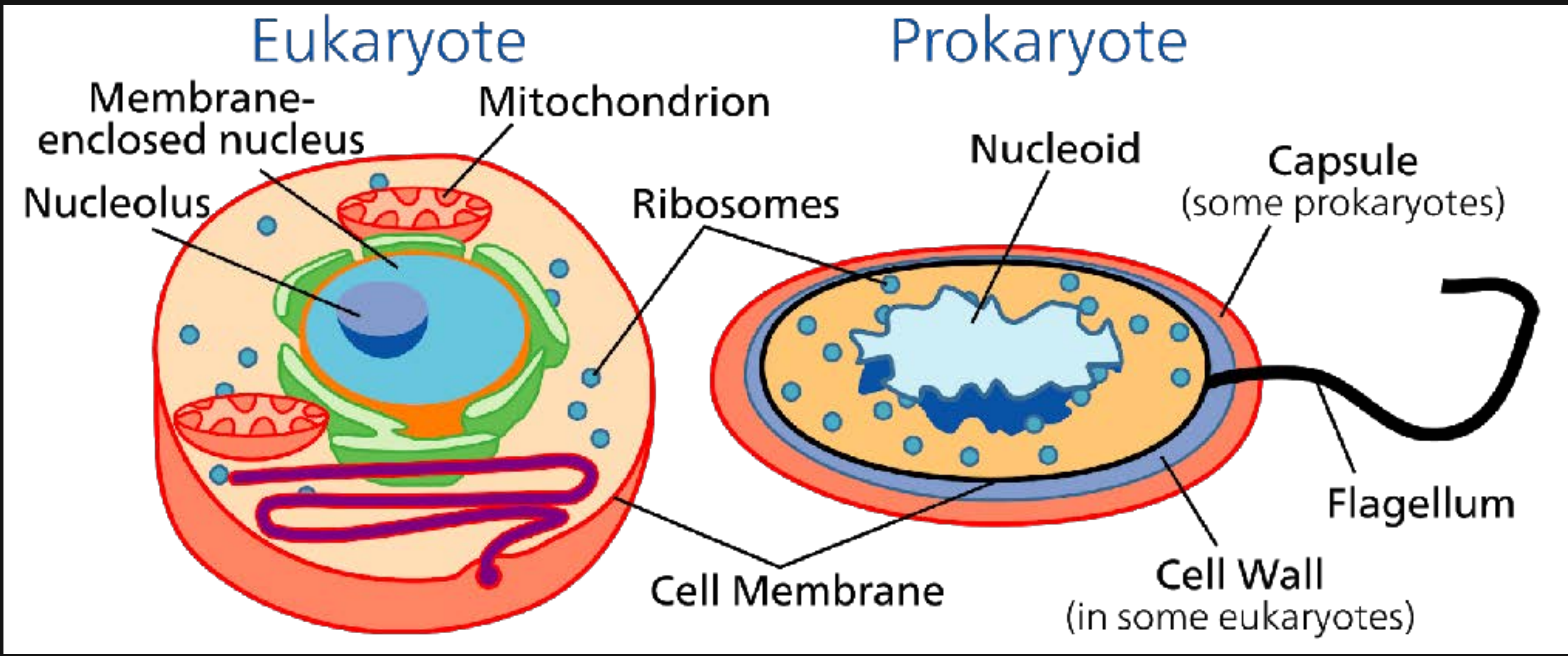
- The "fundamental building block" is a LEGO brick:

- But, we can find something even more fundamental:



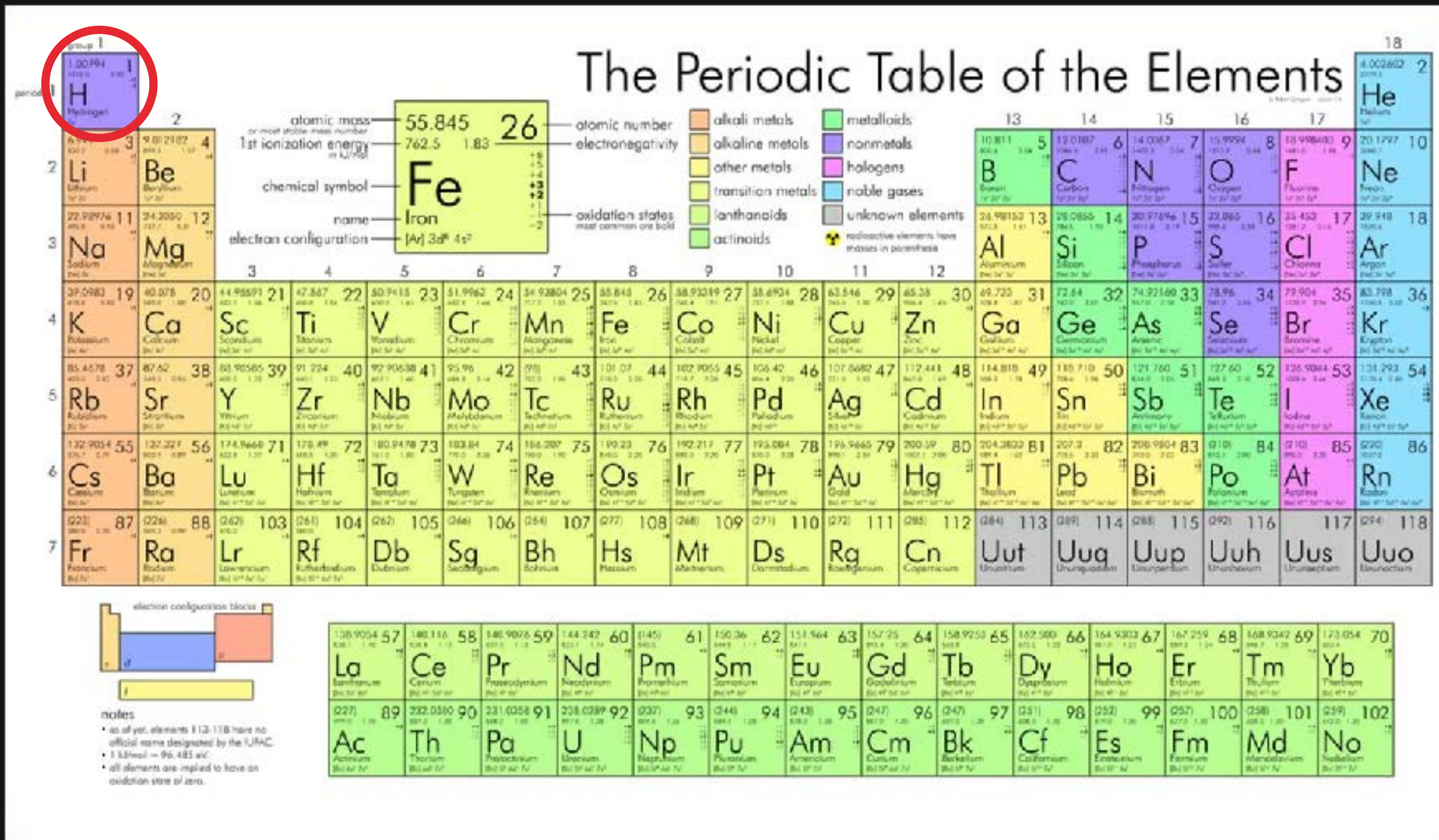
- Can we break them apart further and find something deeper?

Asking "what is something made of" gets many different answers, depending on whom you ask!



A biologist would say: everything is built up from cells

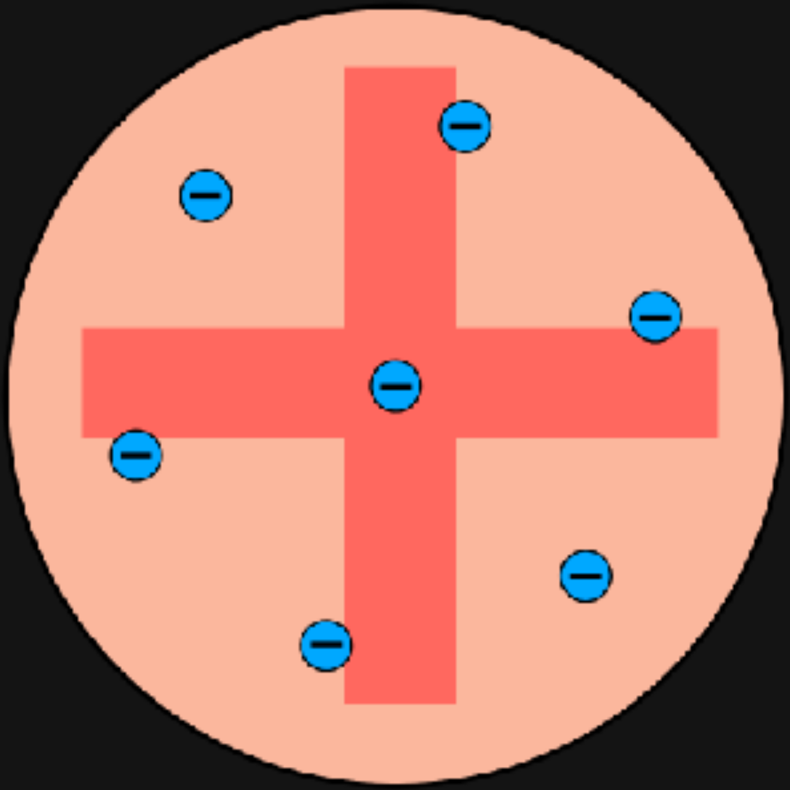
Asking "what is something made of" gets many different answers, depending on whom you ask!



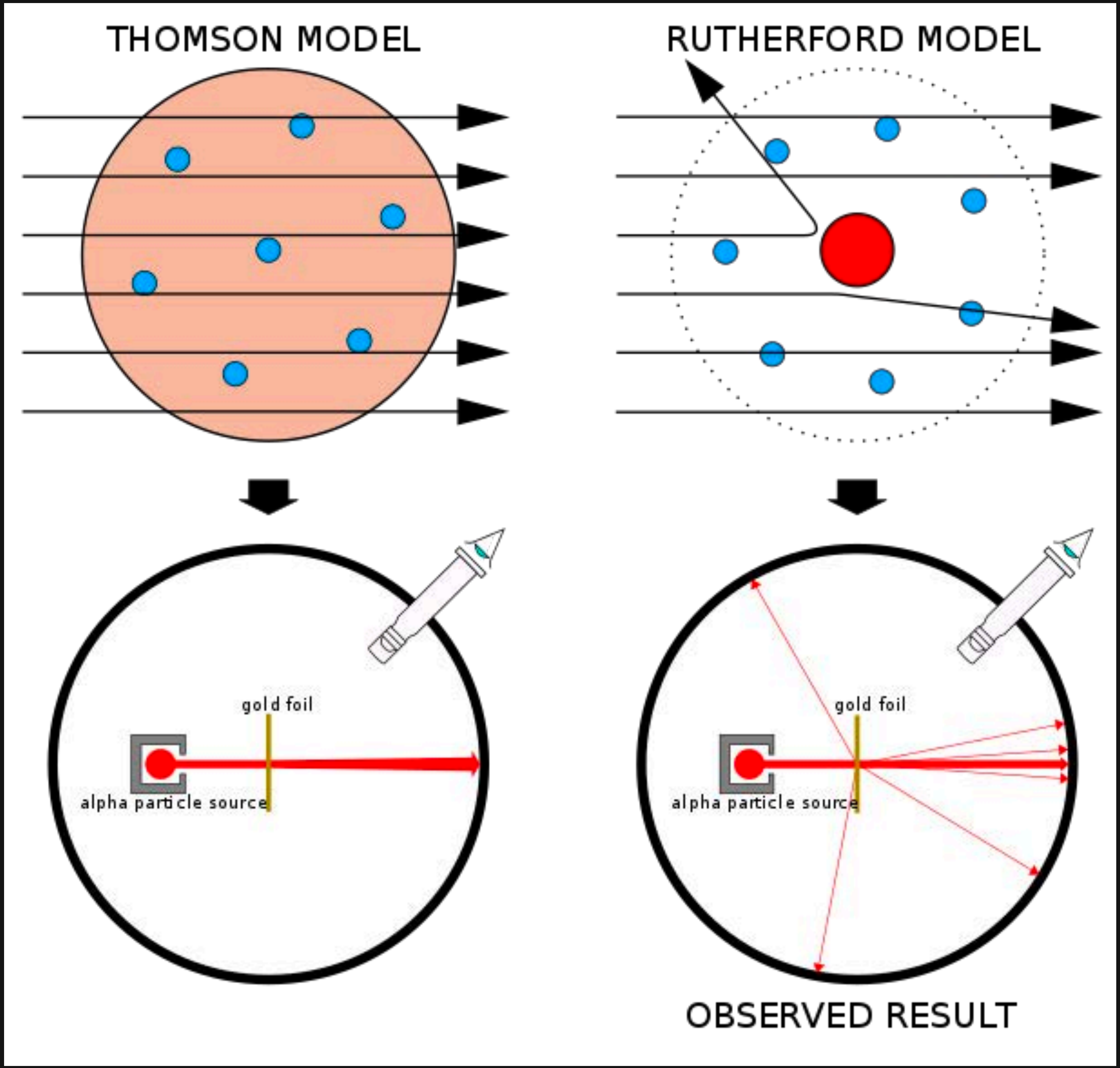
A chemist would say: everything is built up from atoms

Early 1900s…

- Before 1900, JJ Thomson had discovered electrons, which are very light, negatively charged particles.
- All stable elements we see are neutral, so there must be some positively charged particles balancing things out
- There were two competing theories for what atoms looked like, the plum pudding model and the nucleus model:



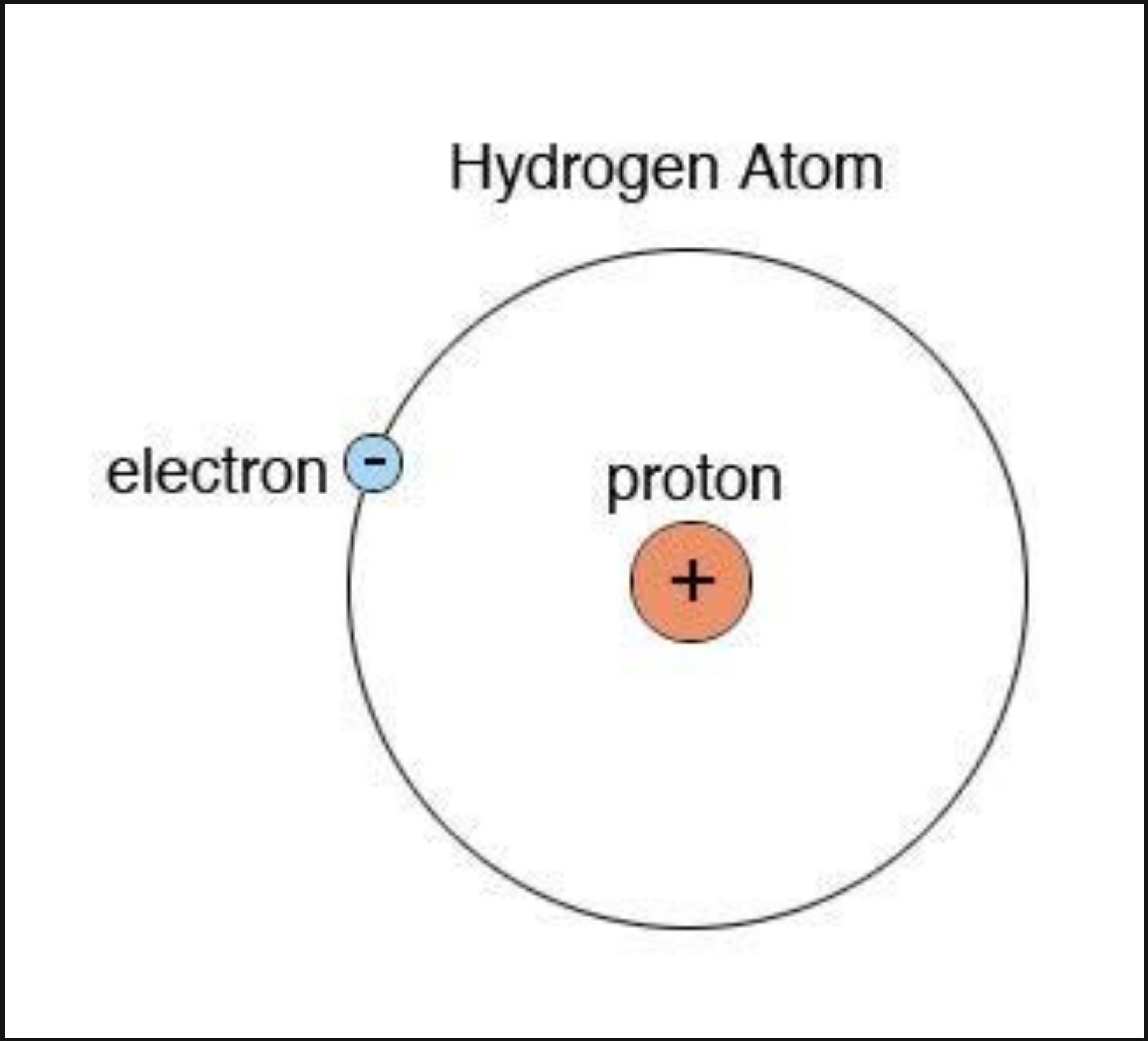
The Geiger-Marsden Experiment



This led to the discovery of the nucleus and of protons!

Let's take a closer look at Hydrogen

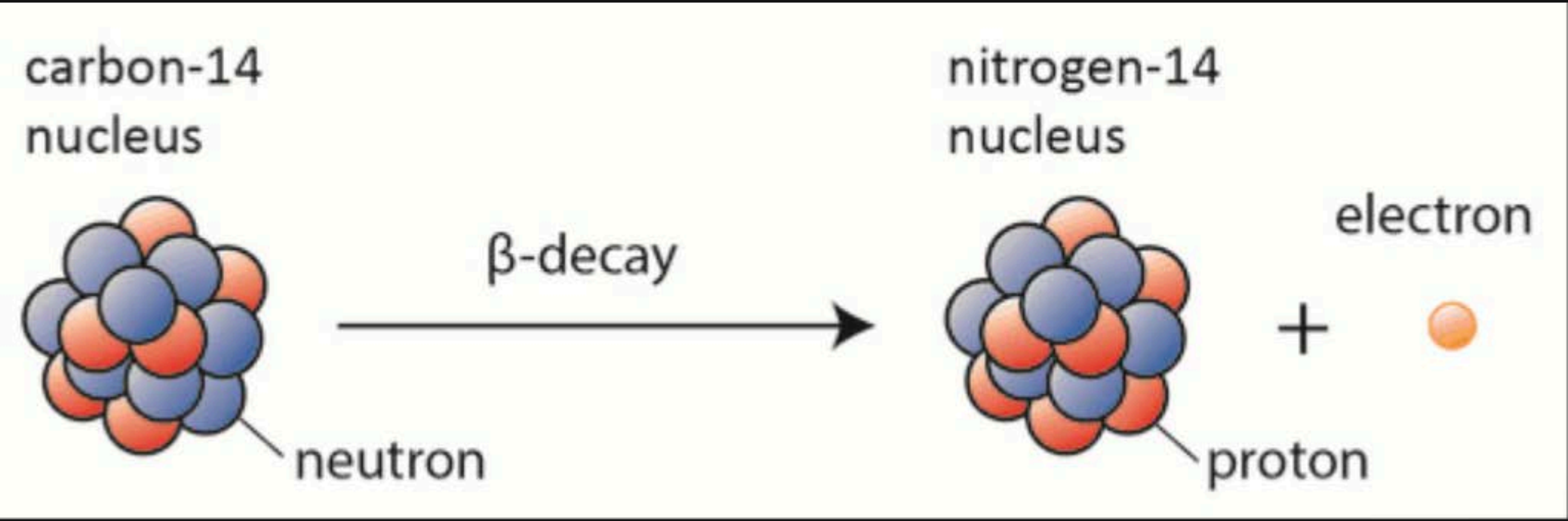
Hydrogen is the simplest atom possible: one heavy proton sitting at the center, and one very light electron around it.



More complicated atoms have more protons and electrons, as well as possibly having neutrons (neutral particles about the same mass as protons) as well as protons in the nucleus.

Radiation and Nuclear Decays

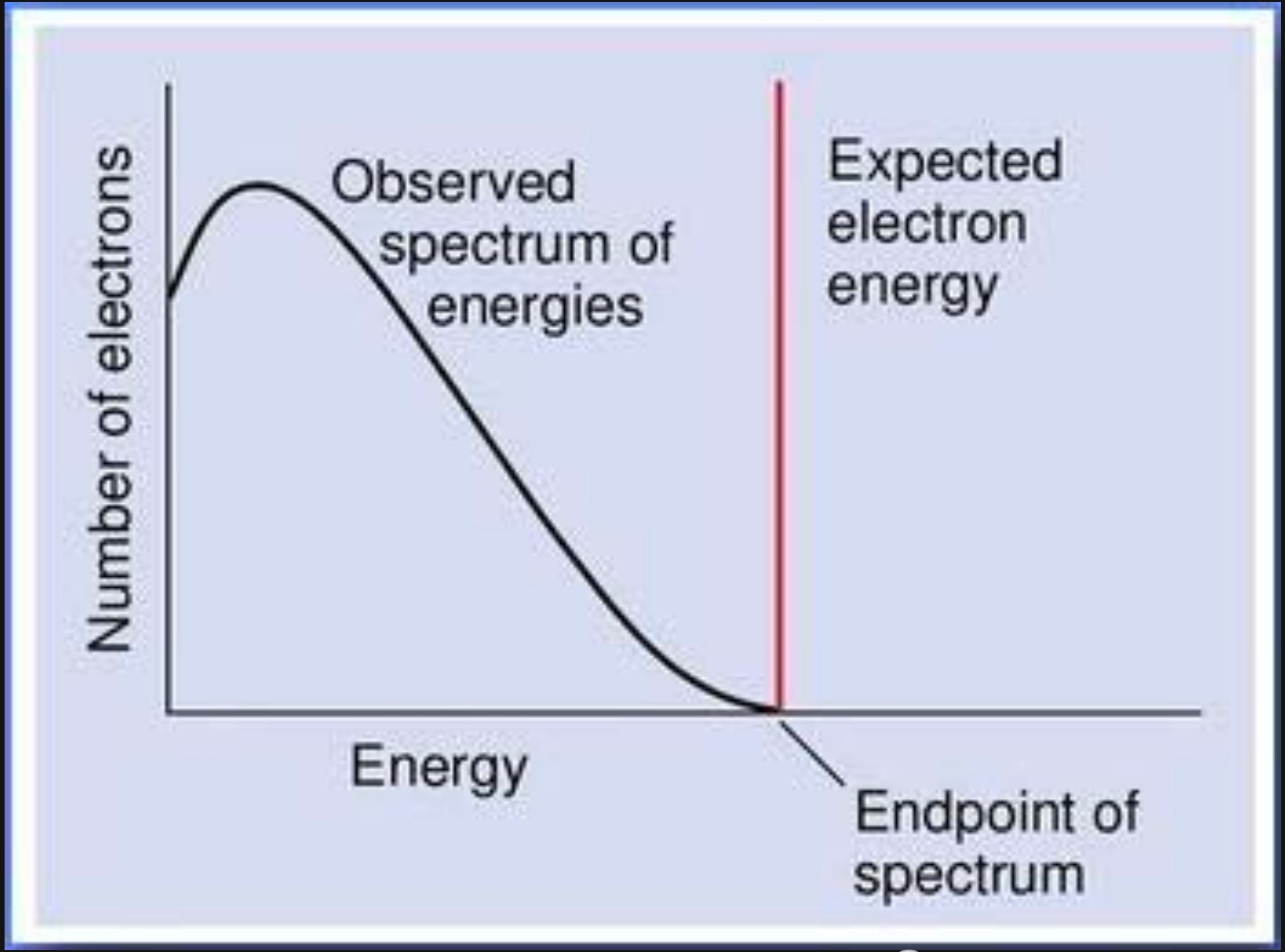
- Shortly after discovering protons, chemists started to see odd properties of certain elements. Occasionally, an atom will decay into a different type of element!



For instance, one of the neutrons at the center of a Carbon atom can spontaneously convert into a proton, and emit an electron so that charge is conserved.

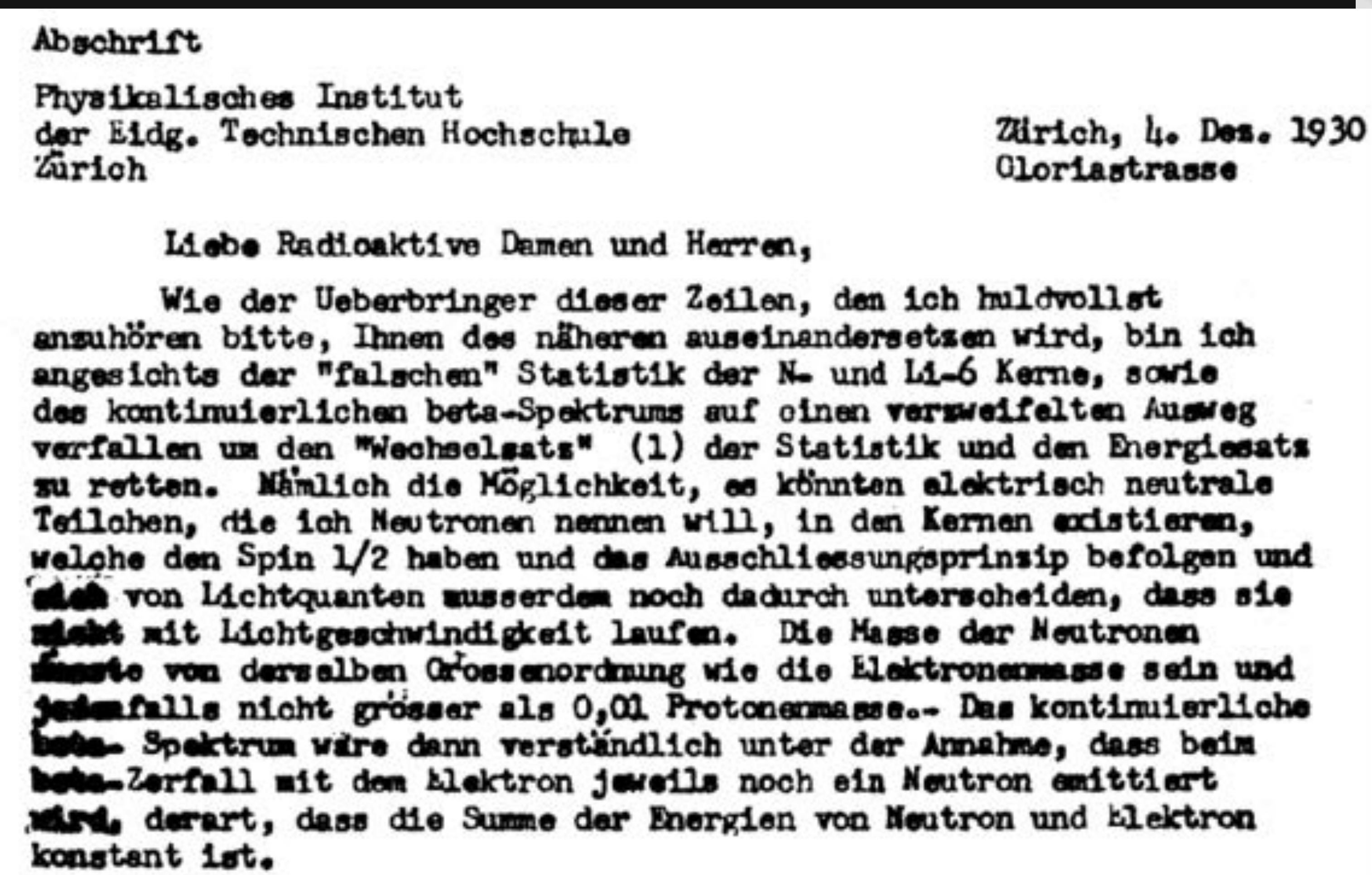
Conservation of Energy

- Processes like this decay must conserve energy. If we have a carbon nucleus become a nitrogen nucleus, then we can predict how much energy the electron has as it comes out.



Something seems fishy, as if a ghostly particle 👻 is stealing away some energy from the electron!

Wolfgang Pauli



Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

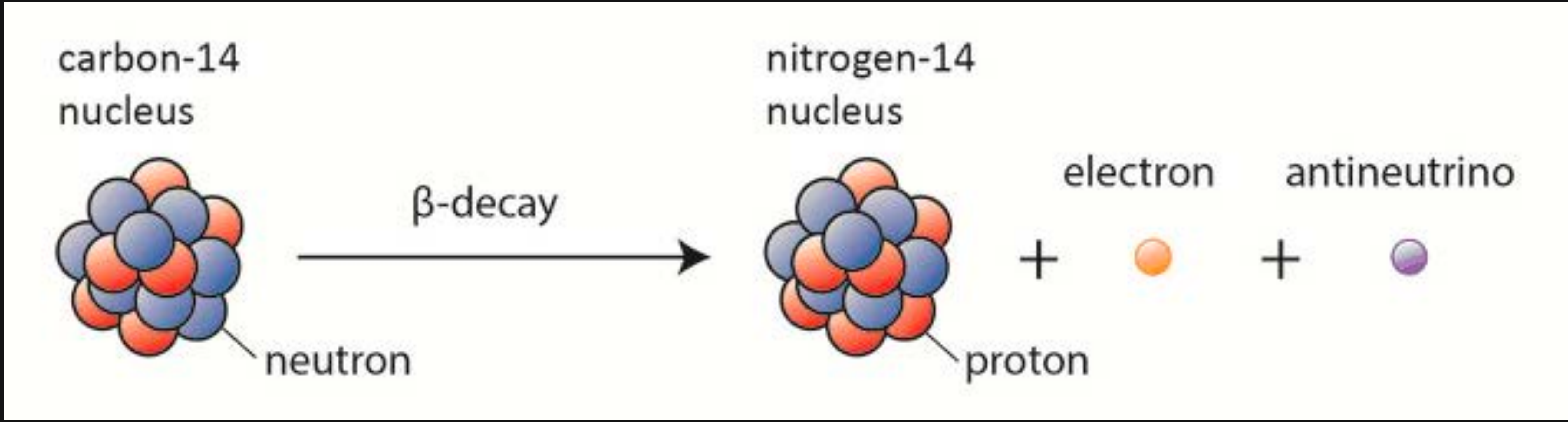
Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Dear radioactive ladies and gentlemen…

Pauli's Solution: A very very light particle being emitted with the electron

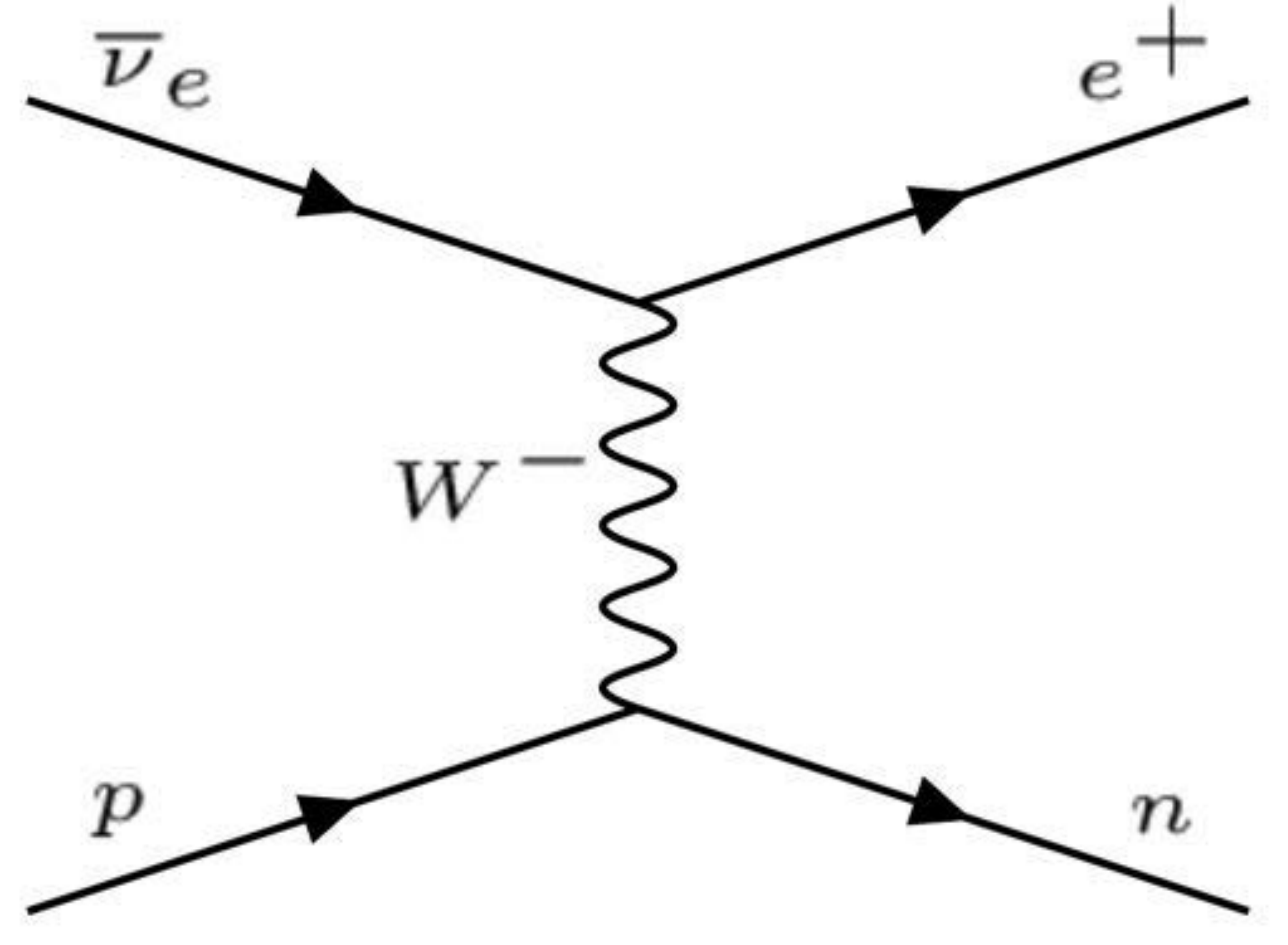
Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, because of the "wrong" statistics of the N- and Li-6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" (1) of statistics and the law of conservation of energy. Namely, the possibility that in the nuclei there could exist electrically neutral particles, which I will call neutrons, that have spin 1/2 and obey the exclusion principle and that further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton mass. - The continuous beta spectrum would then make sense with the assumption that in beta decay, in addition to the electron, a neutron is emitted such that the sum of the energies of neutron and electron is constant.



Pauli invents a new particle: What's so bad about that?

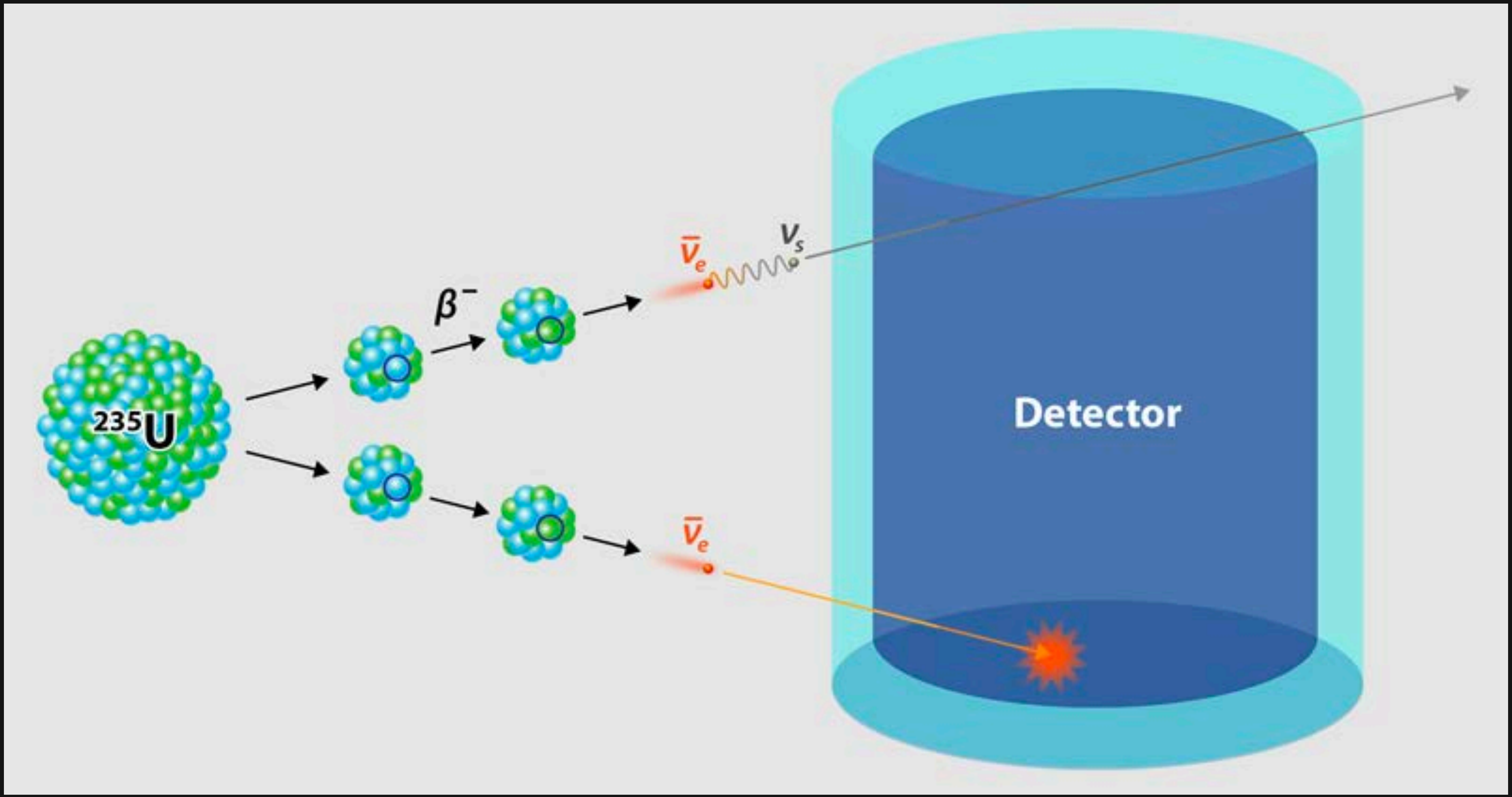
- Given how often we see nuclei decay, we can also infer how rare it is for a neutrino to interact with ordinary matter.
- In general, a neutrino can travel through a *lightyear* of lead before coming to a stop!



How the heck could we hope to detect these?!

We need an INTENSE source of neutrinos!

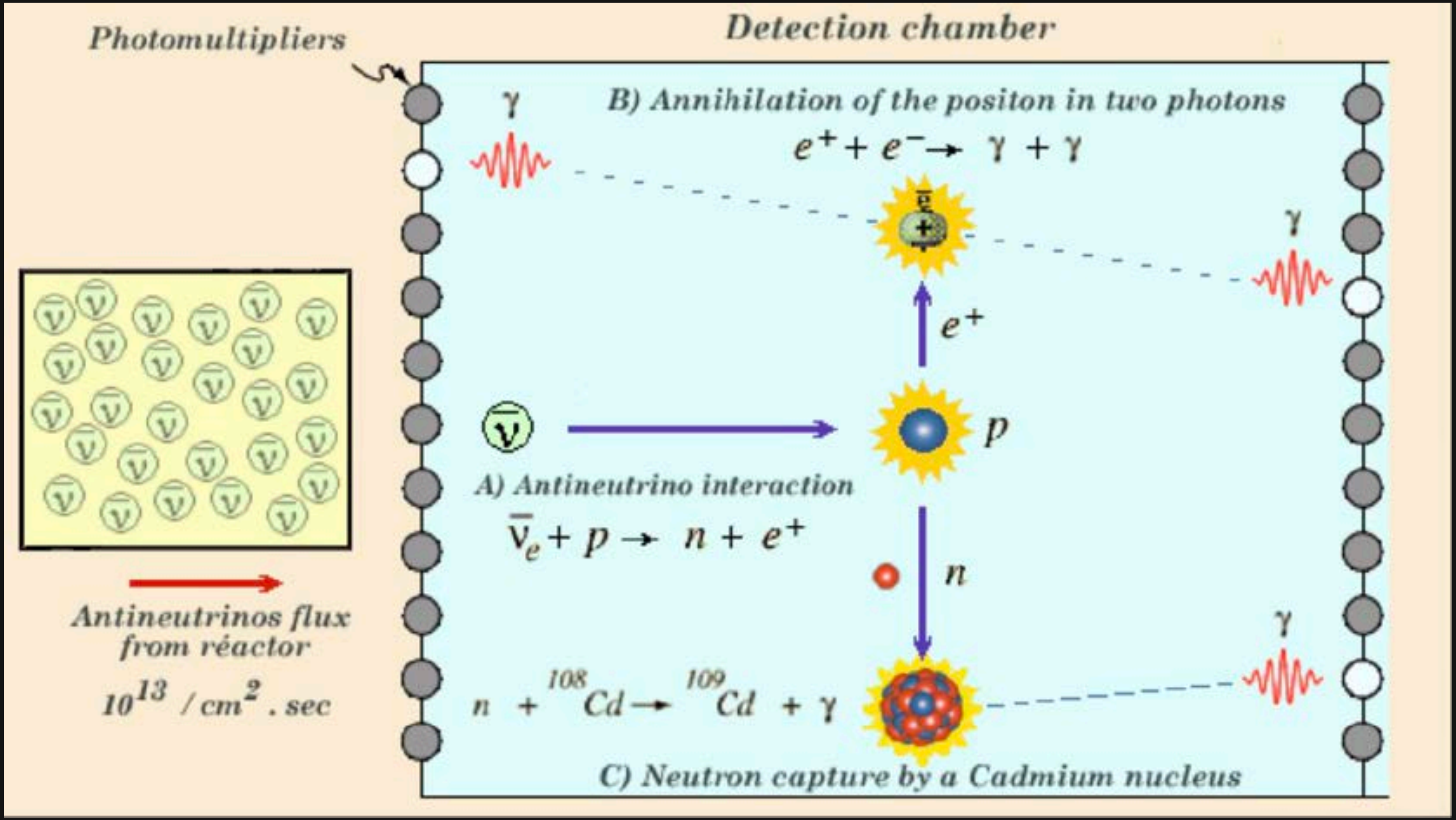
- Some of the most intense sources of neutrinos: nuclear reactors.



The simple rule is that any time a nuclear reaction happens, neutrinos are involved. This includes nuclear reactors, heavy elements down in the Earth's core, many fusion processes in the sun, and even the deaths of massive stars in supernovae! (More on these later)

Clyde Cowan and Frederick Reines, 1956

- Two Americans built a detector to place in front of a nuclear reactor at Savannah River in South Carolina, using what's called "liquid scintillator", where particles can create light in a detector.



Fast-forward to 1962

- Lederman, Steinberger, and Schwartz discovered a second type of neutrino at Brookhaven National Lab

What they designed was the forerunner for neutrino beams in operation today for enormous experiments!

$$p + Z \to \pi^+ X \to \mu^+ \nu_\mu \quad \Rightarrow \quad \begin{array}{l} \nu_\mu + Z \to \mu^- + Y \ \text{(“always”)} \\ \nu_\mu + Z \to e^- + Y \ \text{(“never”)} \end{array}$$

Finally, a third neutrino: 2001

- The DONUT 🍩 Experiment detected the third flavor, ν_τ

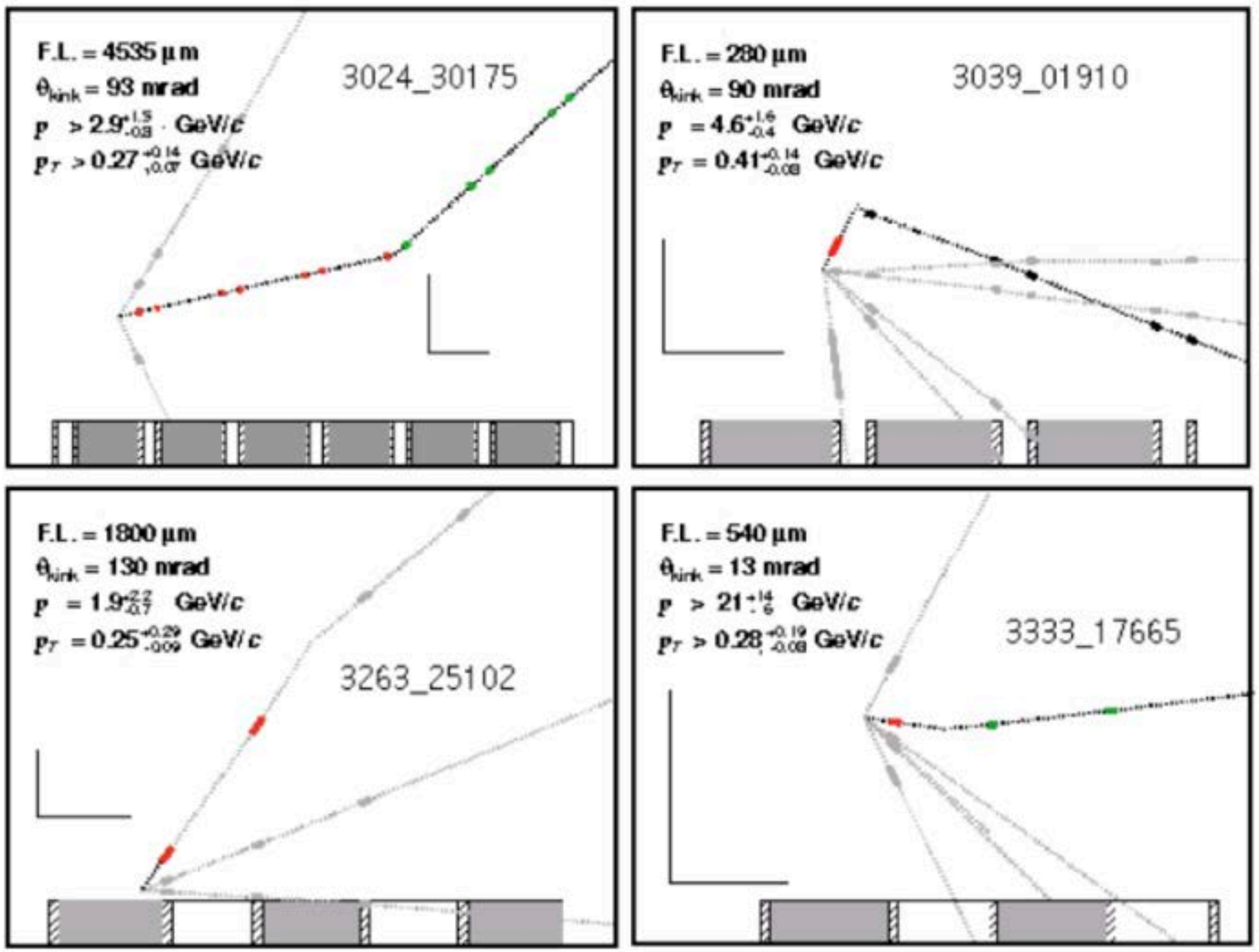


Figure 4-6: The four tau neutrino charged current events. The scale is given by the perpendicular lines (vertical: 0.1 mm, horizontal: 1 mm). The bar on the bottom shows the target material (solid: steel, hatched: emulsion, clear: plastic base).

Finally, a third neutrino: 2001

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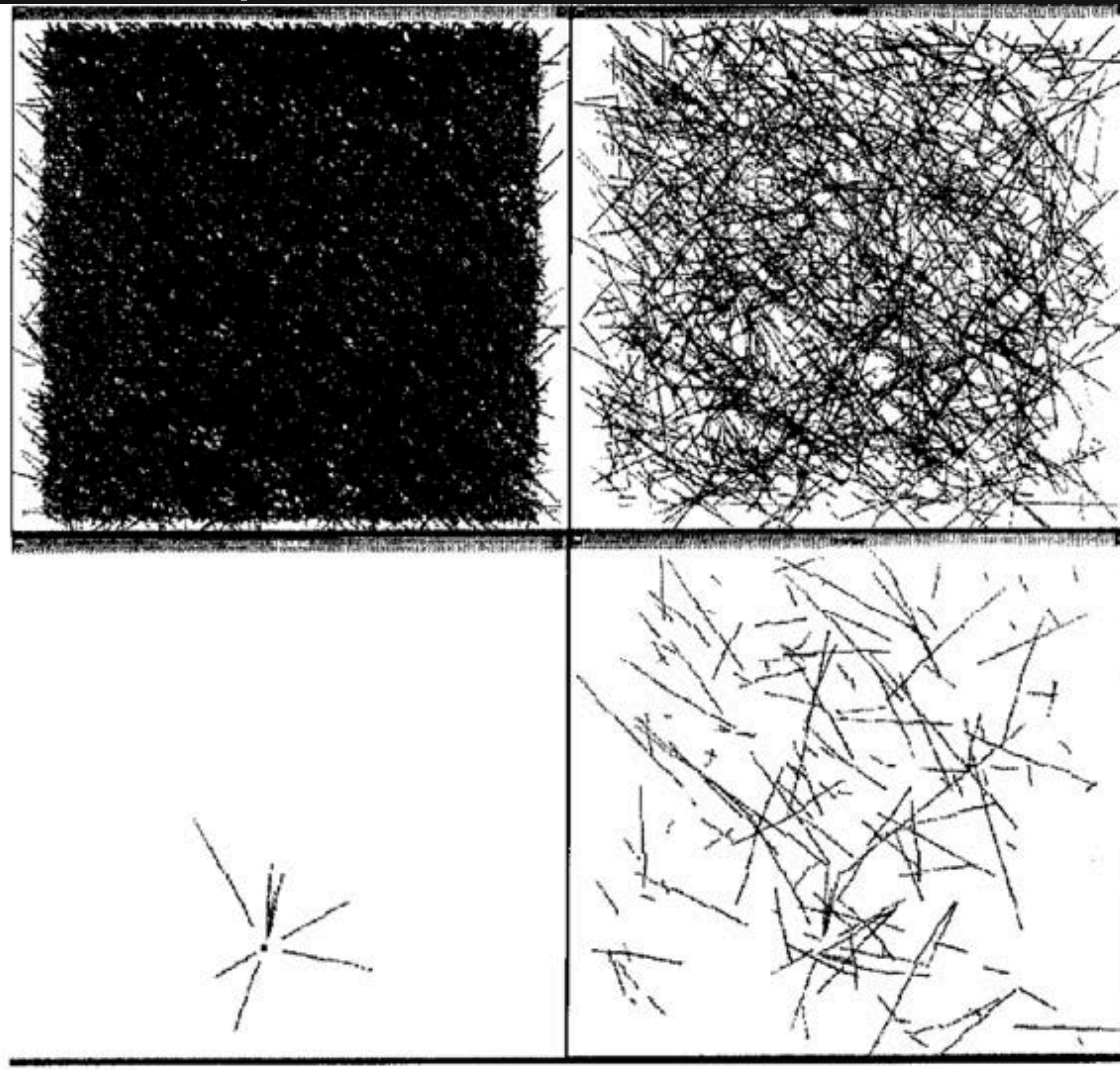
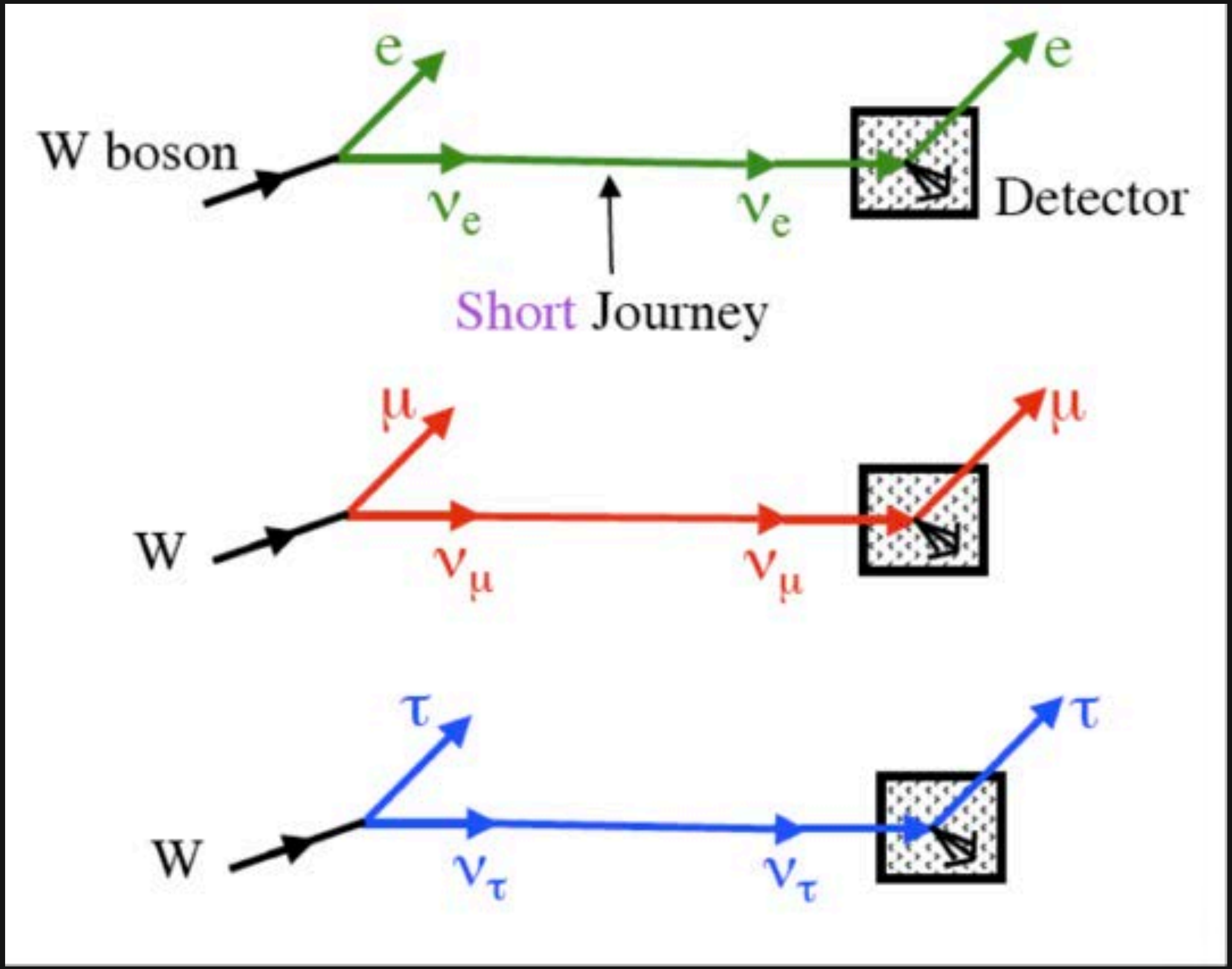


図 5.12: net scan 反応点探索の各段階 (左上から時計回り)。1) 読み込んだ全ての飛跡 ($5 \times 5\mathrm{mm}^2$)、2) 測定領域を突き抜けている飛跡の排除、3) 低運動量の飛跡の排除、4) 一点 ($4\mu\mathrm{m}$ 以内) 収束している飛跡

Here's what we knew about Neutrinos when I was a LEGO-playing child

(late 1990s)

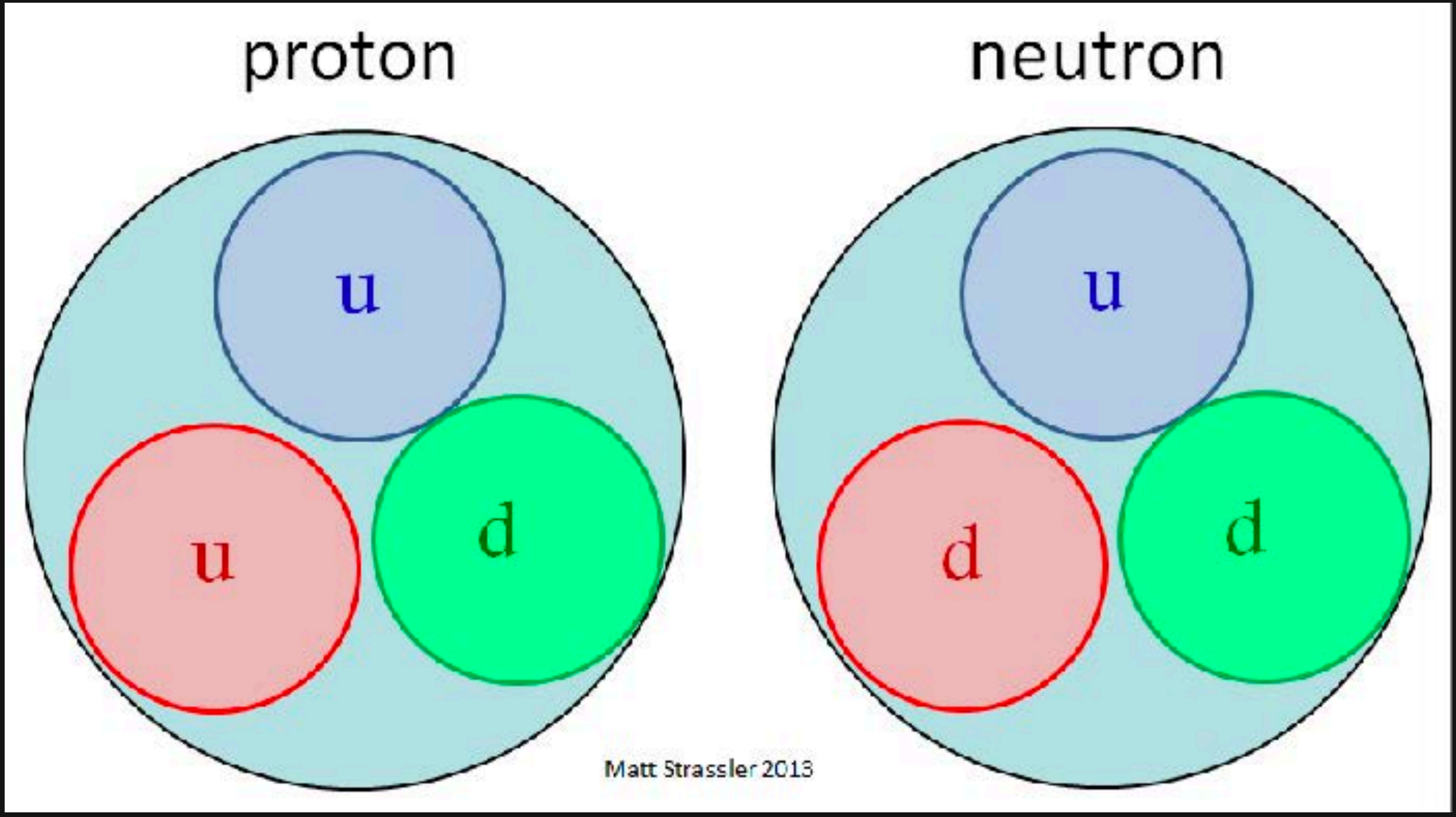


- Three types (flavors) of neutrinos, that are associated with each charged lepton.
- Massless (like light photons)
- Interact *very* rarely.

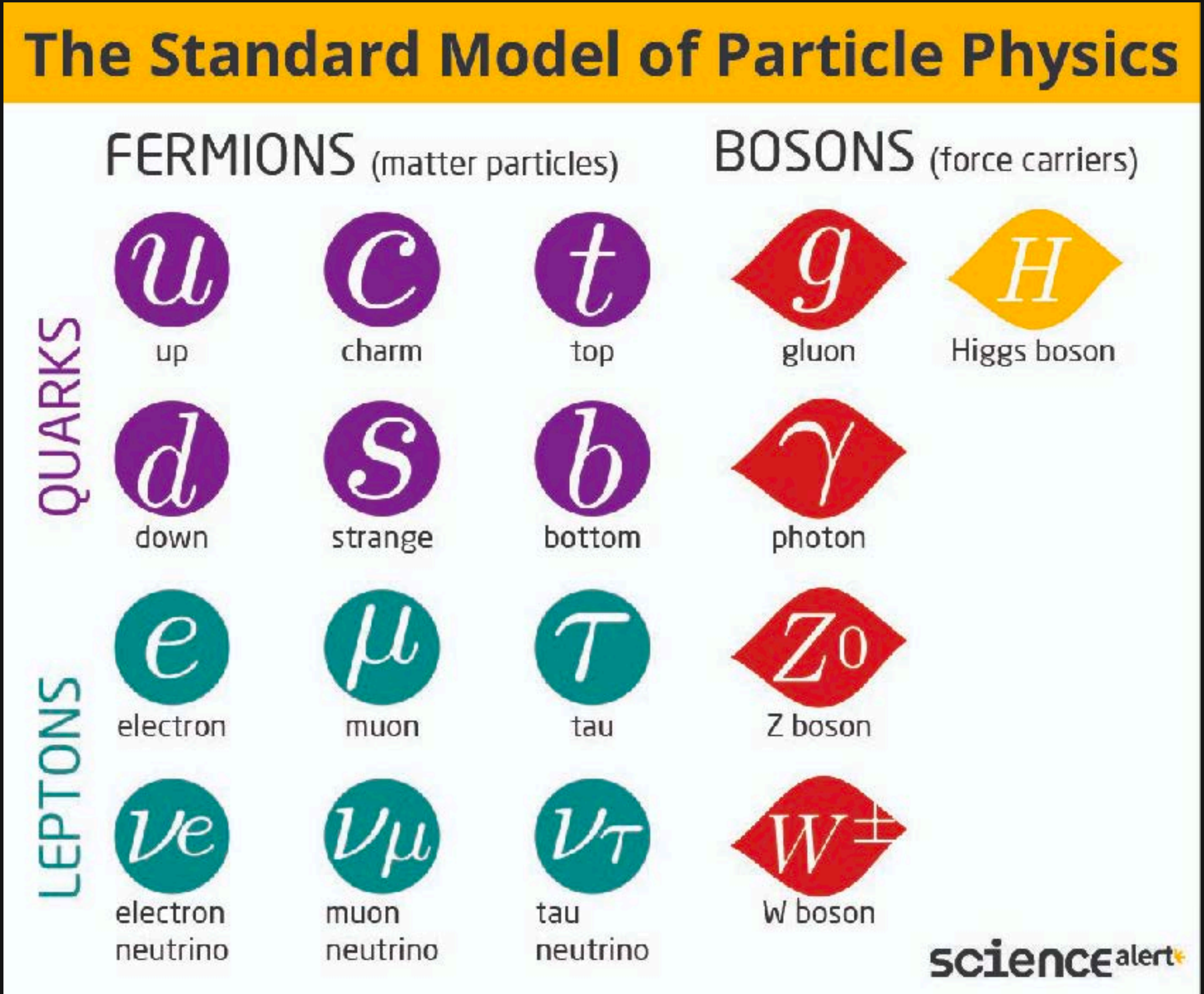
The Standard Model

In the meantime…

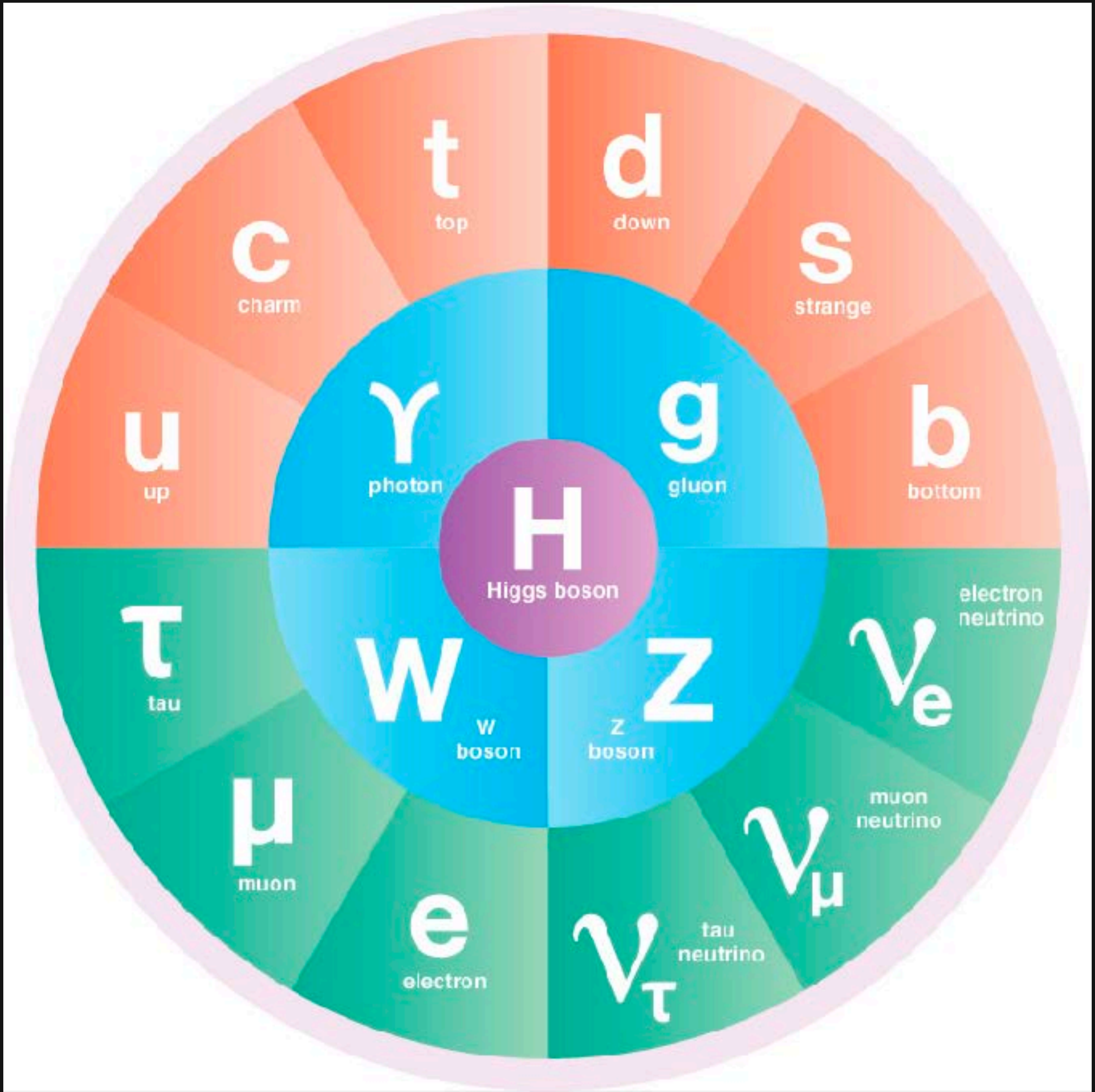
- During these decades, a large amount of progress was made in particle physics, building up what is now known as the Standard Model of Particle Physics.
- First big change: protons and neutrons are not fundamental, but are made up of "quarks"



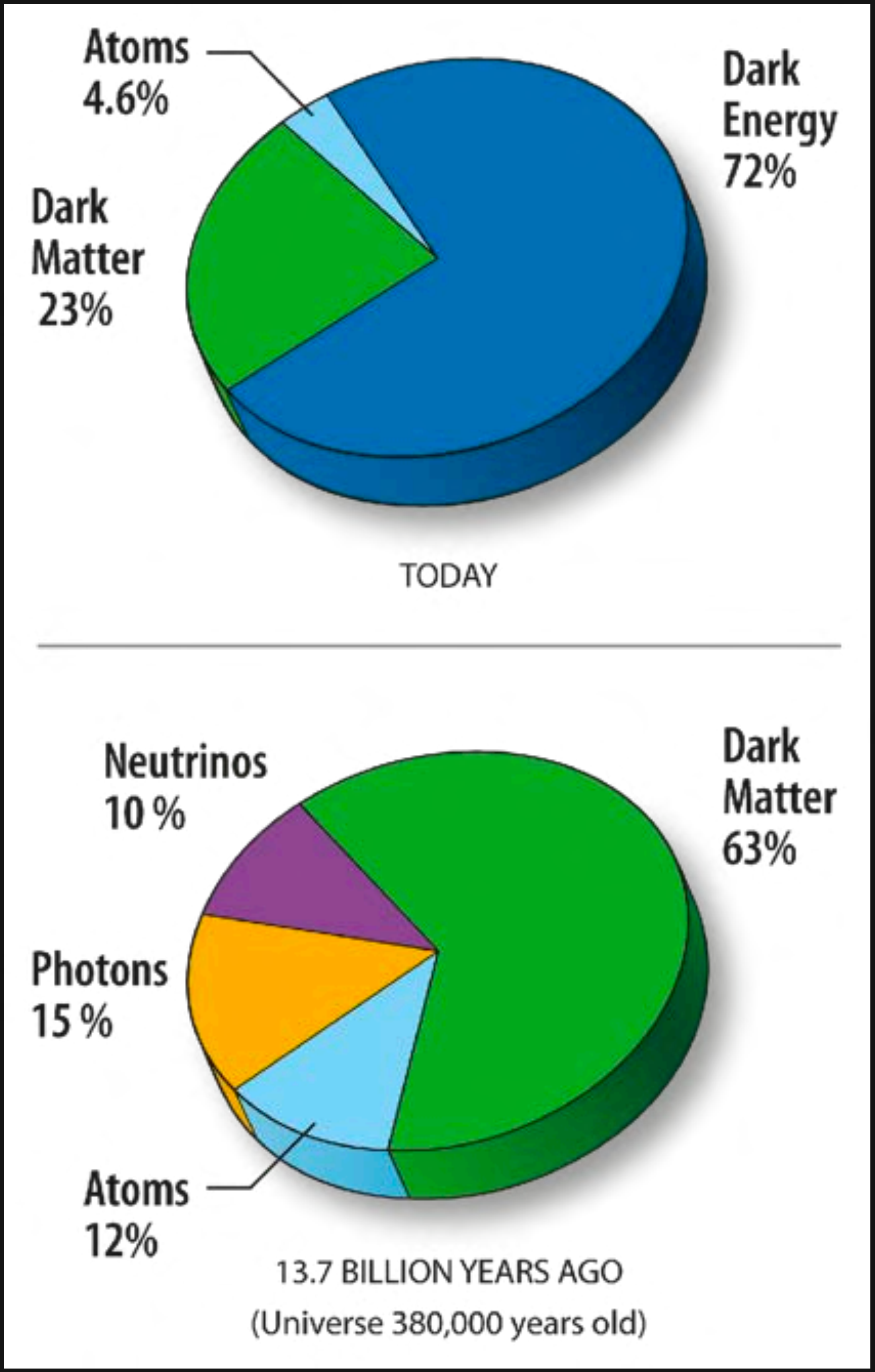
We also started finding heavier “copies” of the particles we knew of



Allowed us to Build a “New Periodic Table”



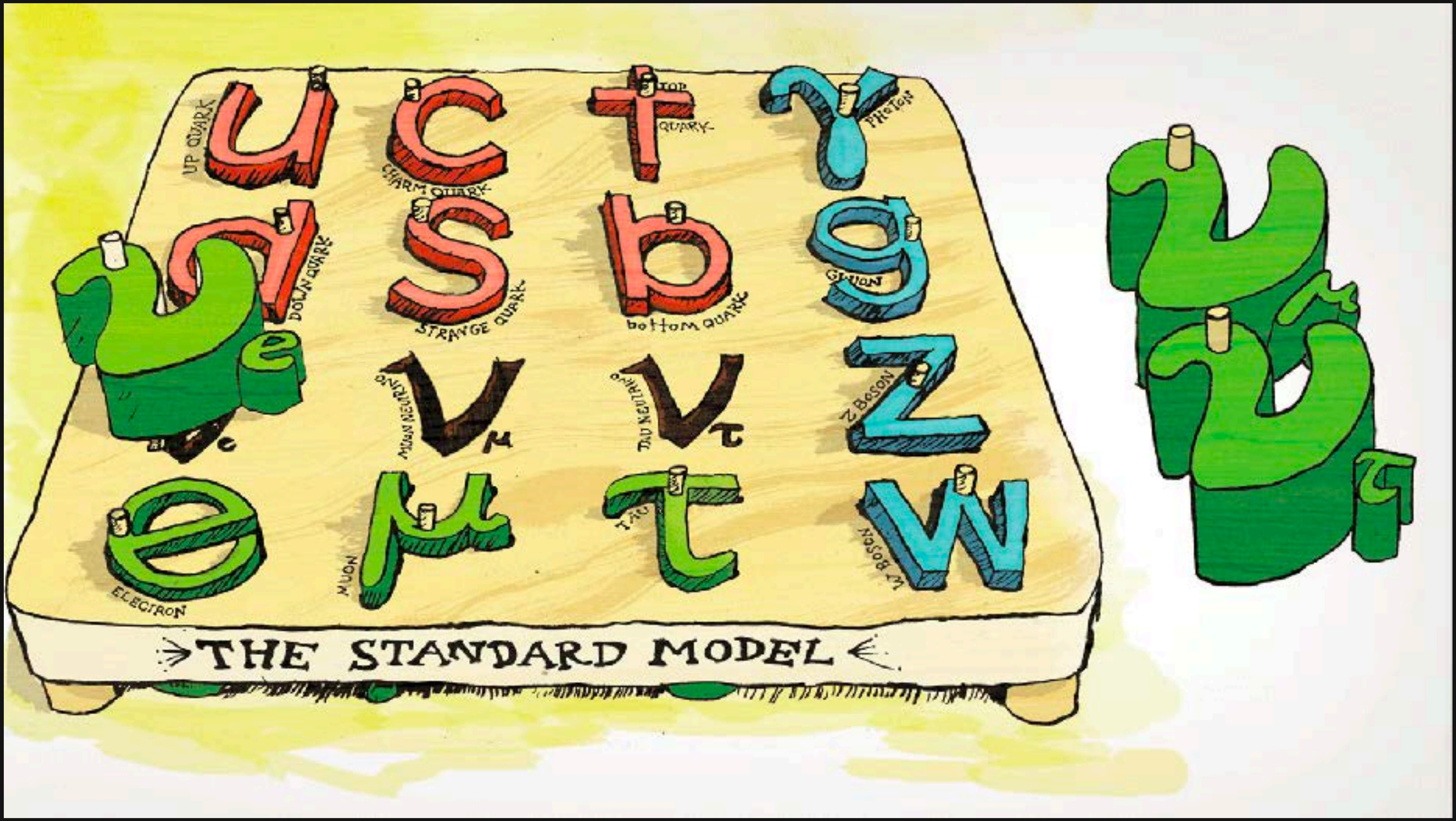
The Standard Model has its own Mysteries…



Today, we look out at the universe and find that only about 5% of the total energy in the universe can be described by the things we understand from the Standard Model!

The Standard Model doesn't have any idea what this Dark Matter or Dark Energy are, but scientists are actively working on this!

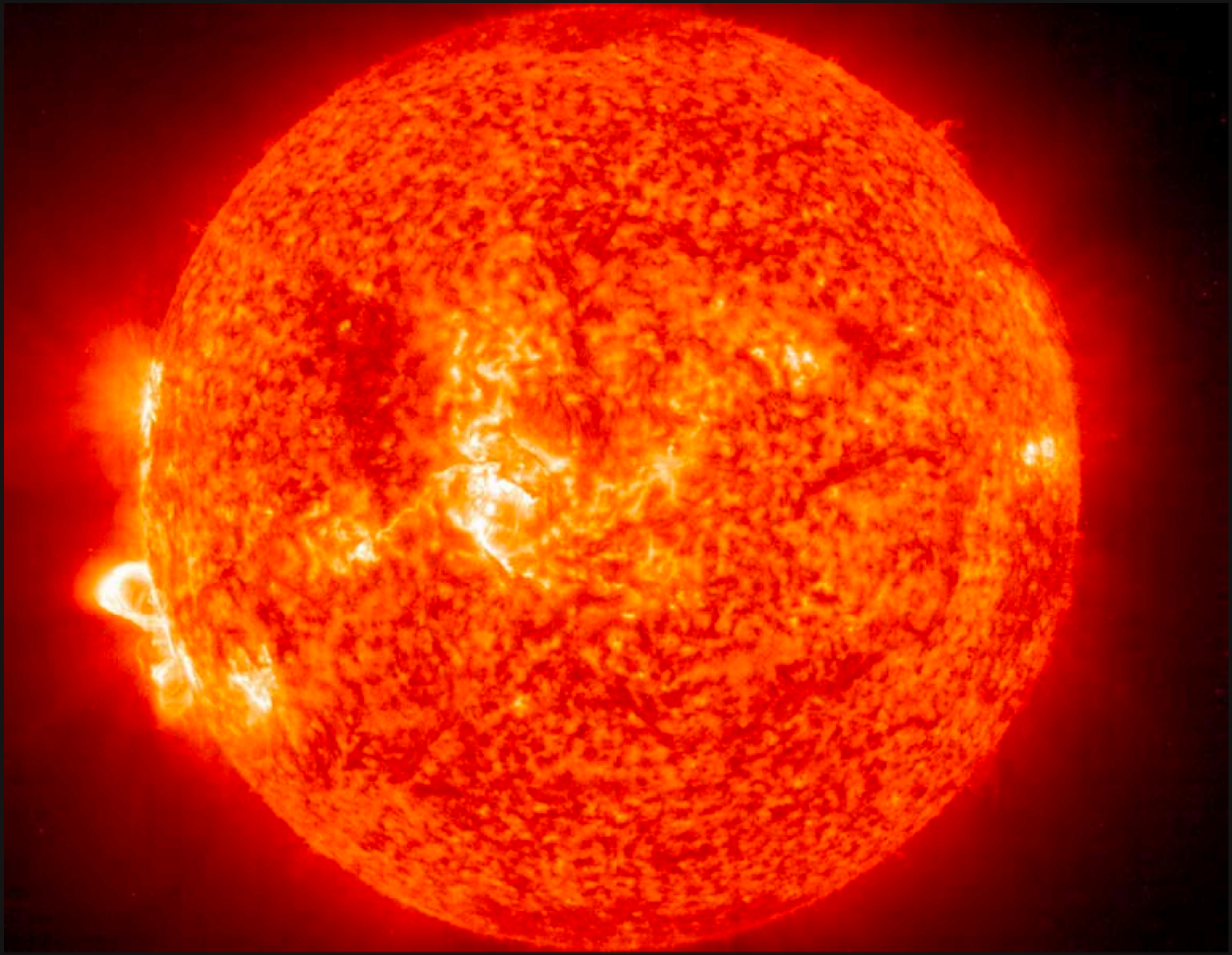
The Standard Model and Neutrinos



As I alluded to, the neutrinos don't quite "fit" in the Standard Model…

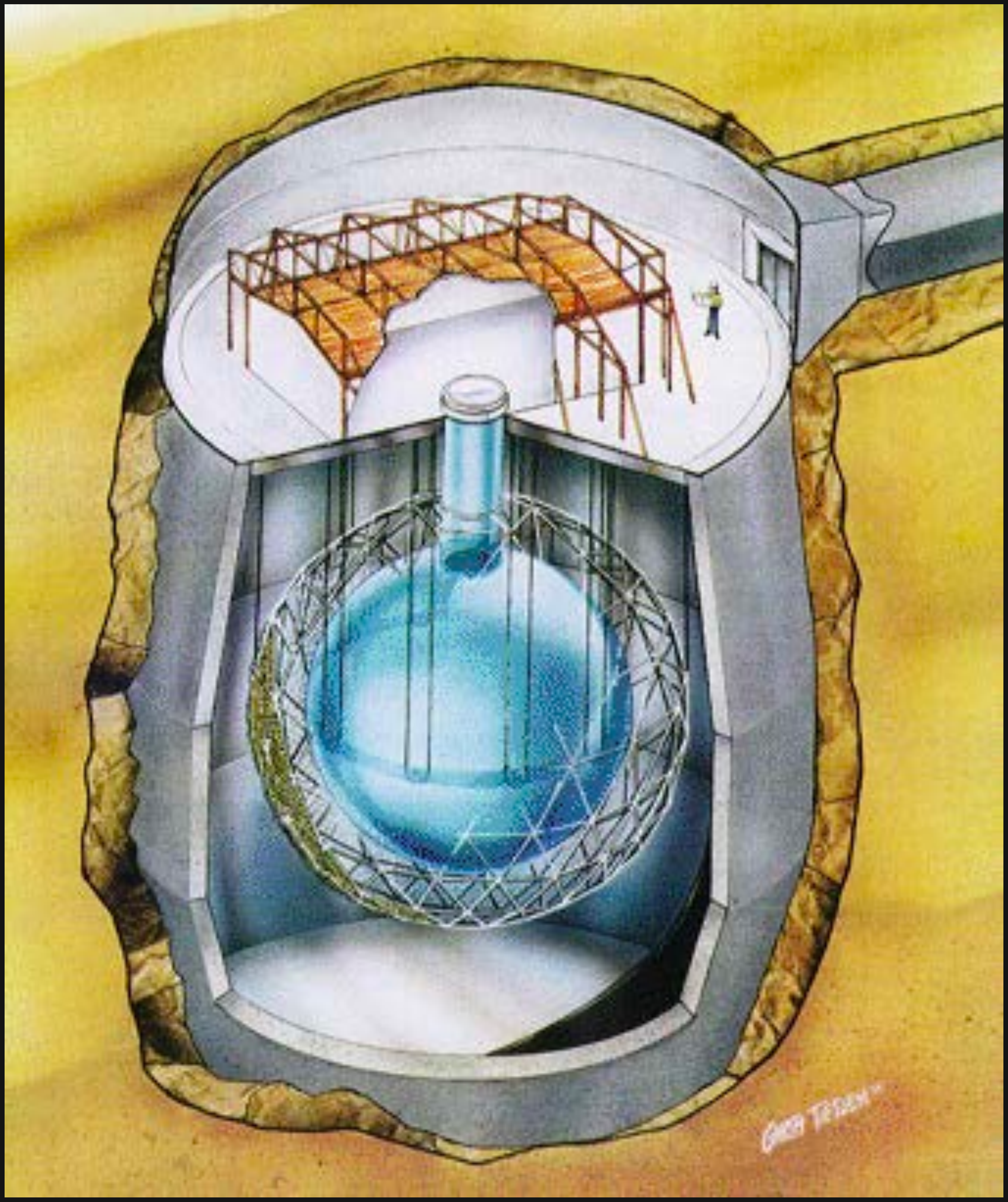
Neutrino Puzzles

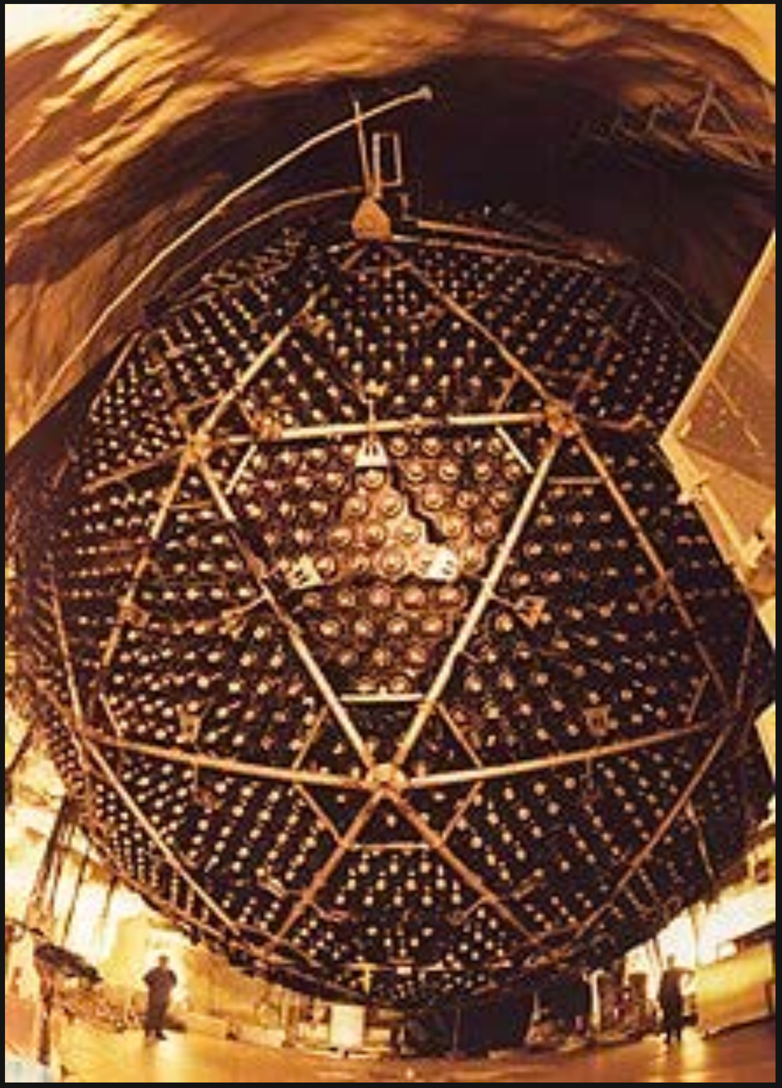
Another great source of neutrinos from nuclear reactions?



If you hold your hand up to the Sun, every second, 100 BILLION neutrinos pass through your fingertip!

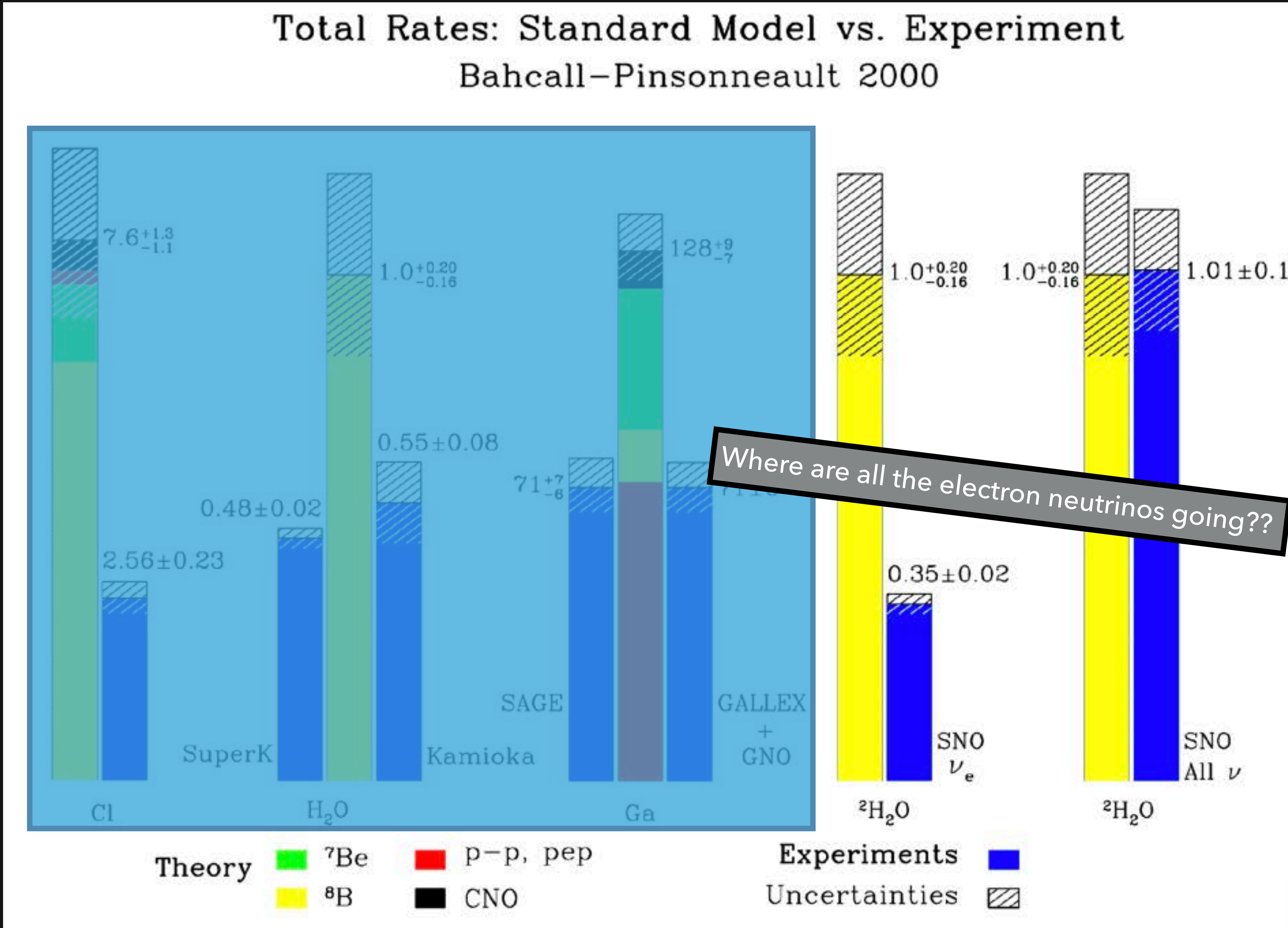
The SNO Experiment — Sudbury Neutrino Observatory





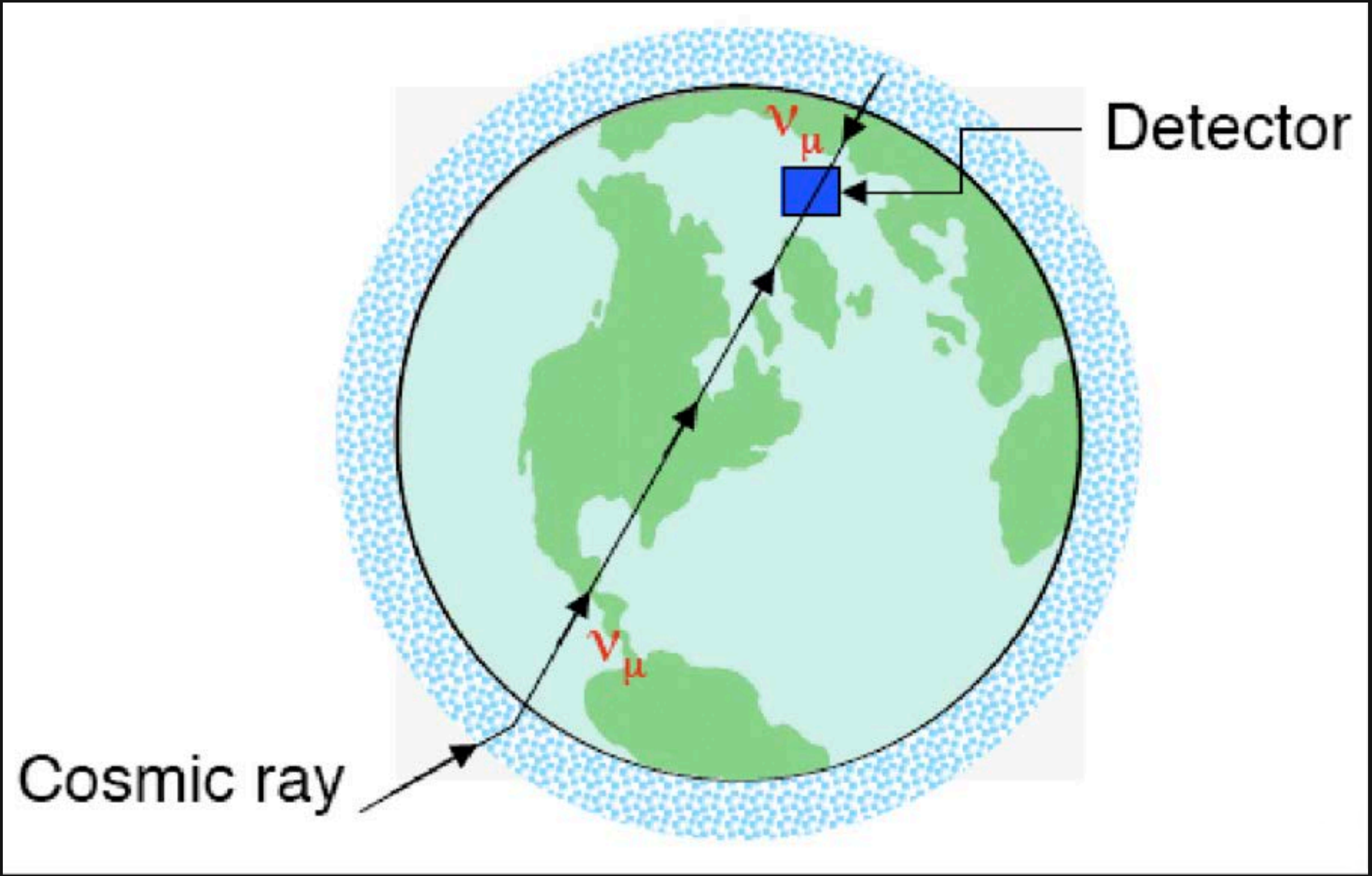
A giant tank of "heavy" water, deep underground, looking for neutrinos coming from the Sun.

The SNO Experiment's Results



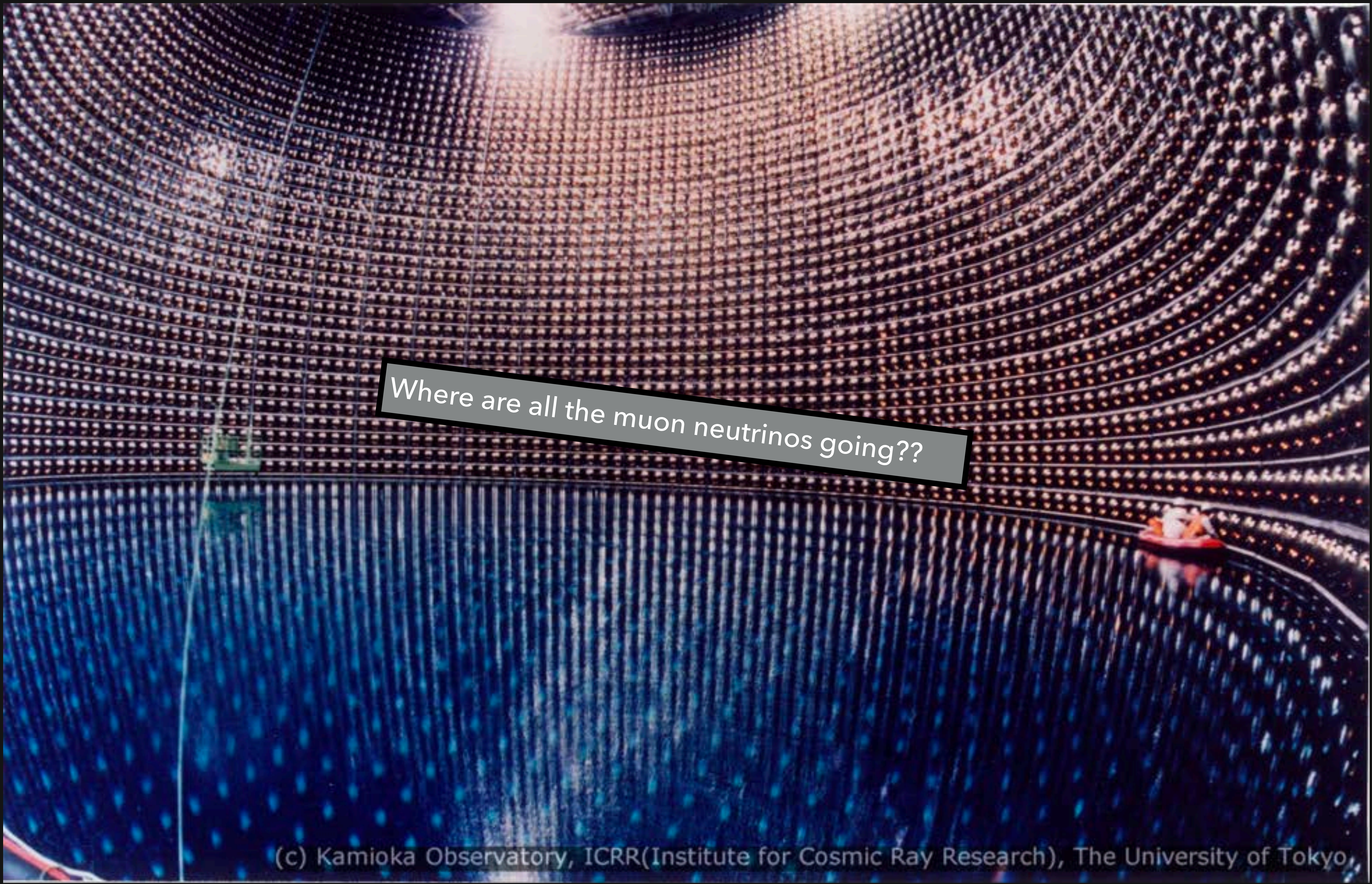
Where are all the electron neutrinos going??

One more Puzzle: Atmospheric Neutrinos



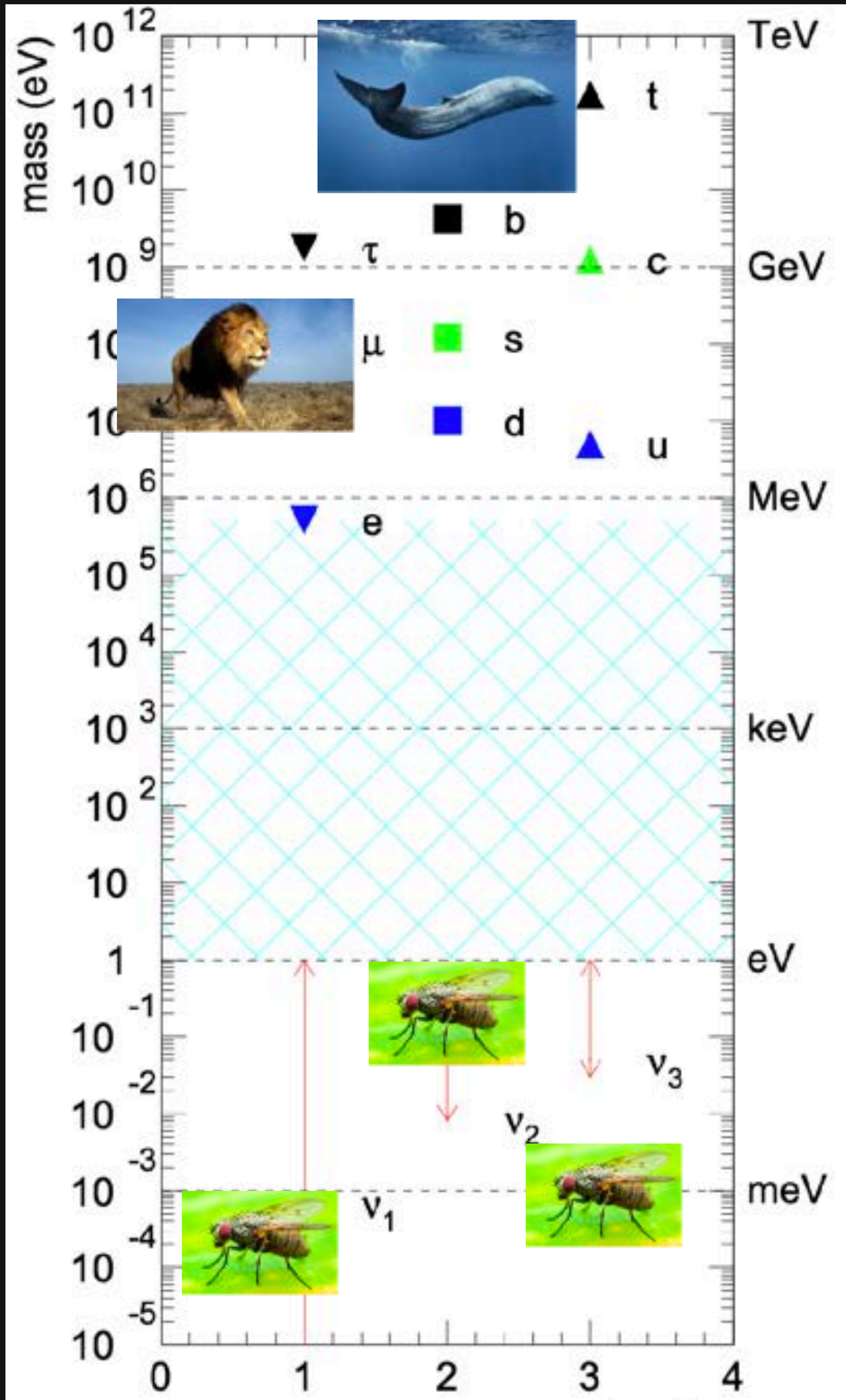
Geometry tells us that the number of neutrinos we see from below should equal the number seen from above.
Super-Kamiokande (in Japan) measures this ratio…

Super-Kamiokande (Deep underground in Japan)



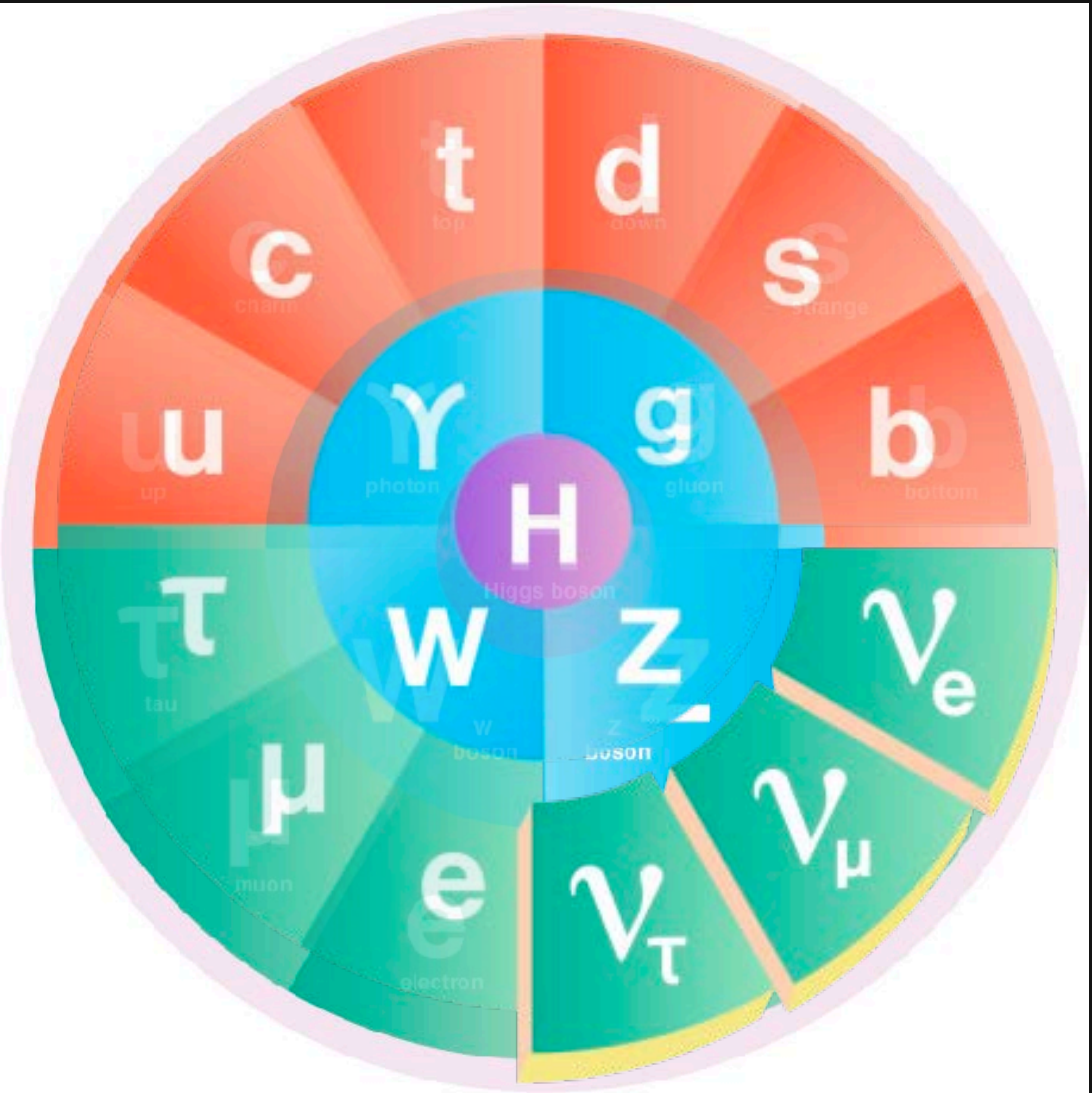
Twice as many neutrinos from above as from below!

Only consistent explanation —— Neutrinos have (tiny) masses!



- We don’t know the exact values of the neutrino masses, but they’re at most a million times lighter than electrons, which are way lighter than any other particles!

A crack in the Standard Model



The Standard Model predicts that neutrinos are massless. However, experimental evidence can only be explained by saying that they have masses, however they are *extremely* tiny ones! Less than one millionth the mass of electrons, which are way lighter than any other particle in the Standard Model.

Neutrinos have mass.
So what?
Where do we go next?

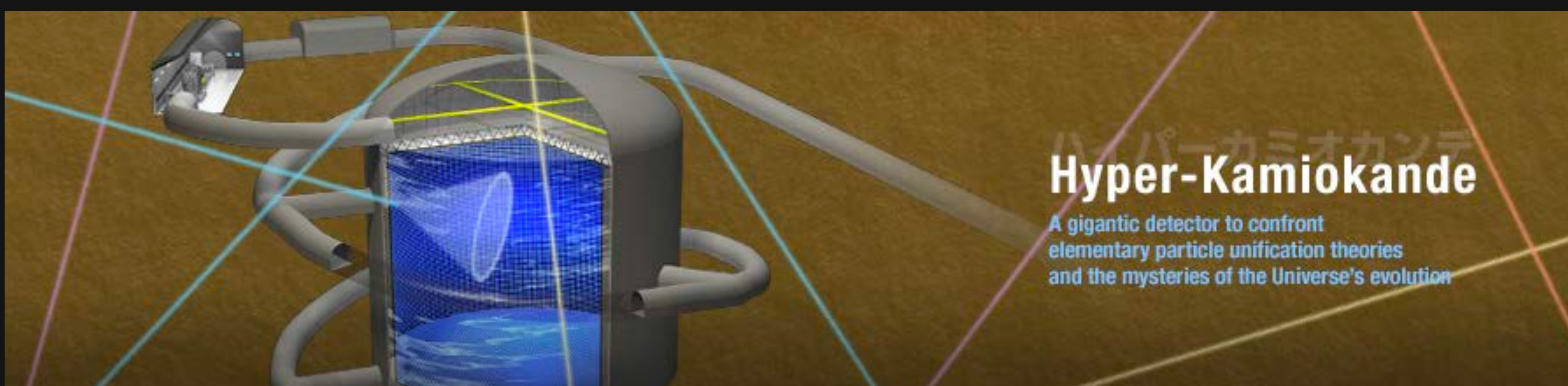
We should do everything possible to understand them!

Compared to the other standard model particles, we know the least about neutrinos.

Dedicated neutrino experiments allow us to understand their nature and determine whether the cracks we have found in the Standard Model are indicative of even further fault lines.

Upcoming Earth-based Experiments

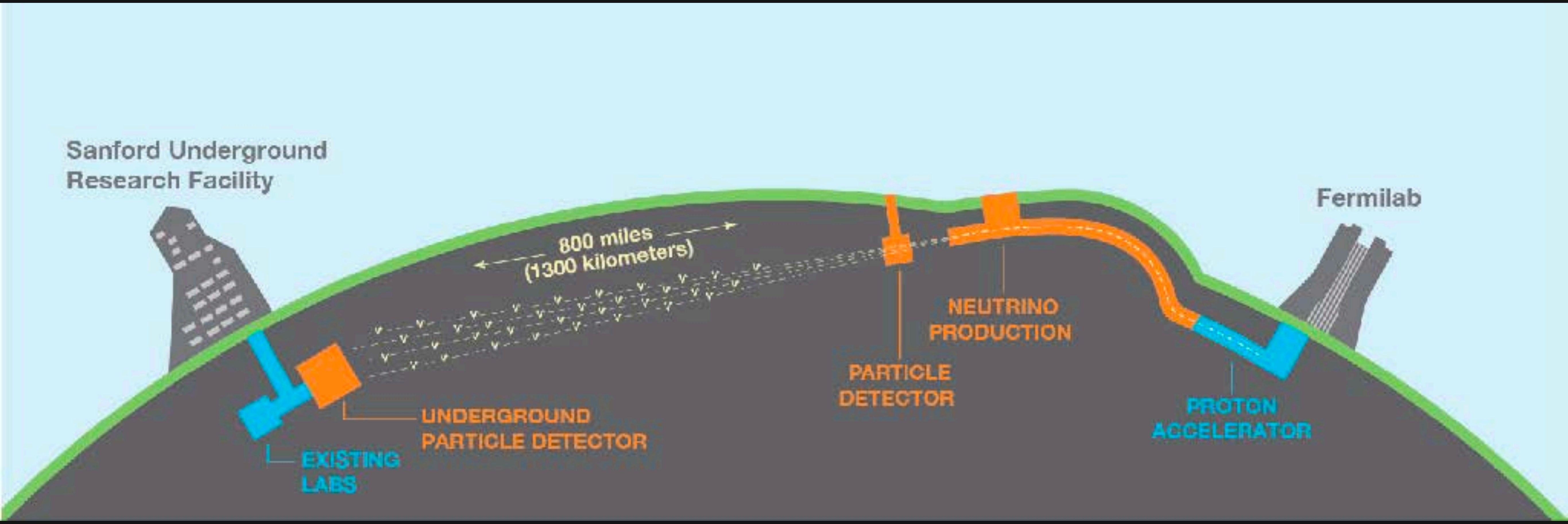
Hyper-Kamiokande



A successor to Super-Kamiokande, will be built in Japan

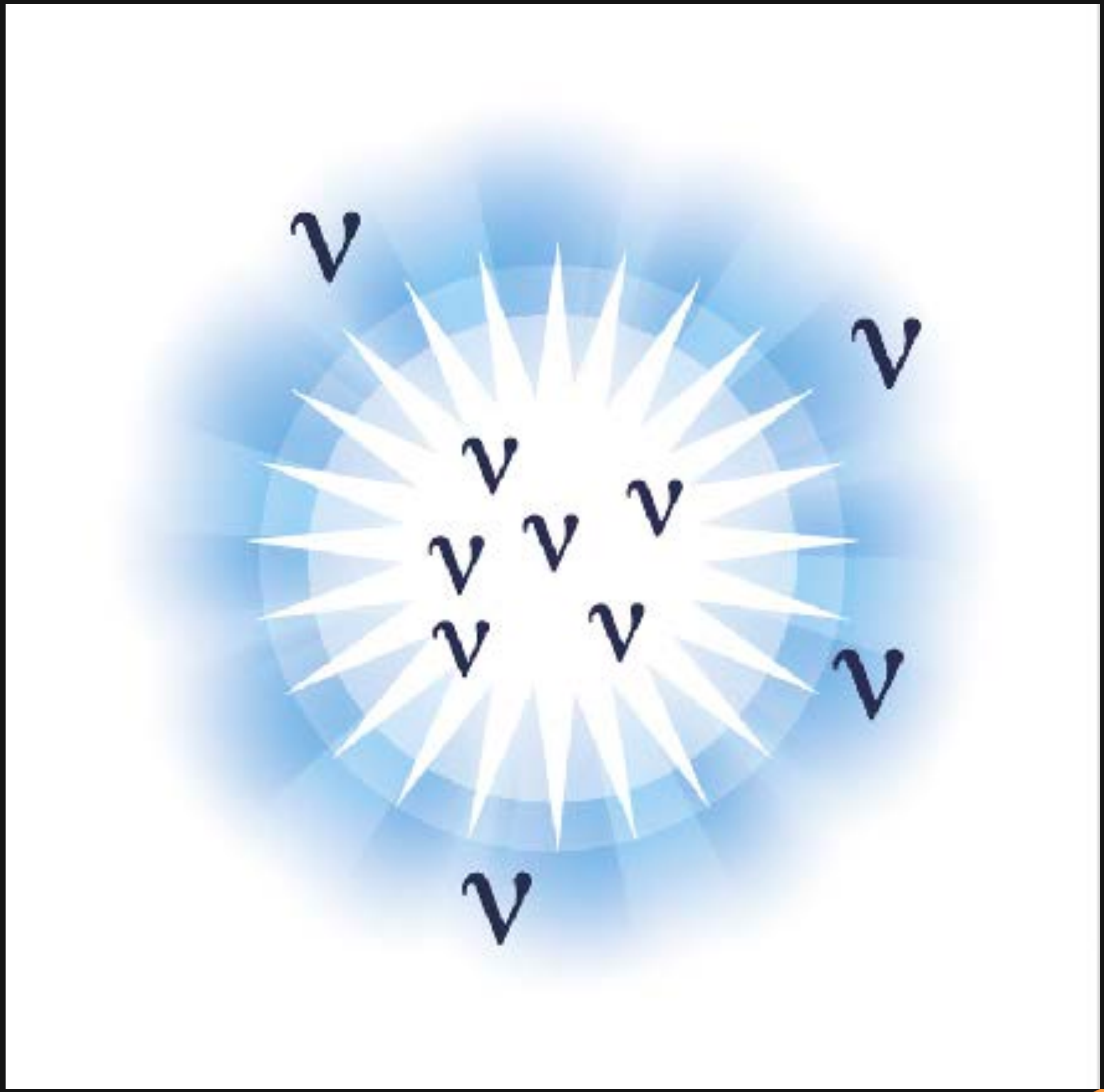
Upcoming Earth-based Experiments

DEEP UNDERGROUND NEUTRINO EXPERIMENT



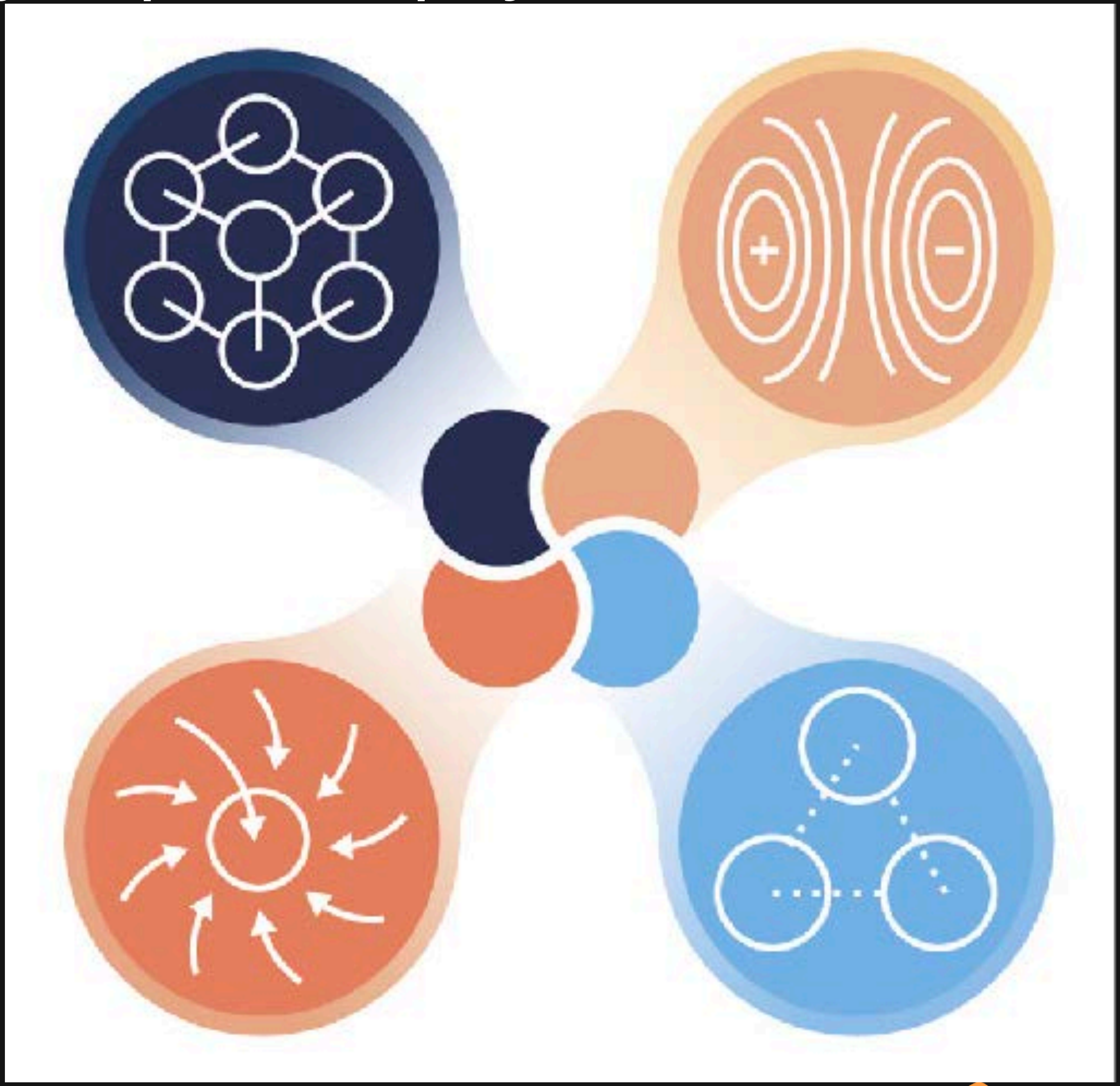
The goals of DUNE

- Understand whether neutrinos behave differently than antineutrinos – could this be connected to why our universe is made of matter instead of antimatter?



The goals of DUNE

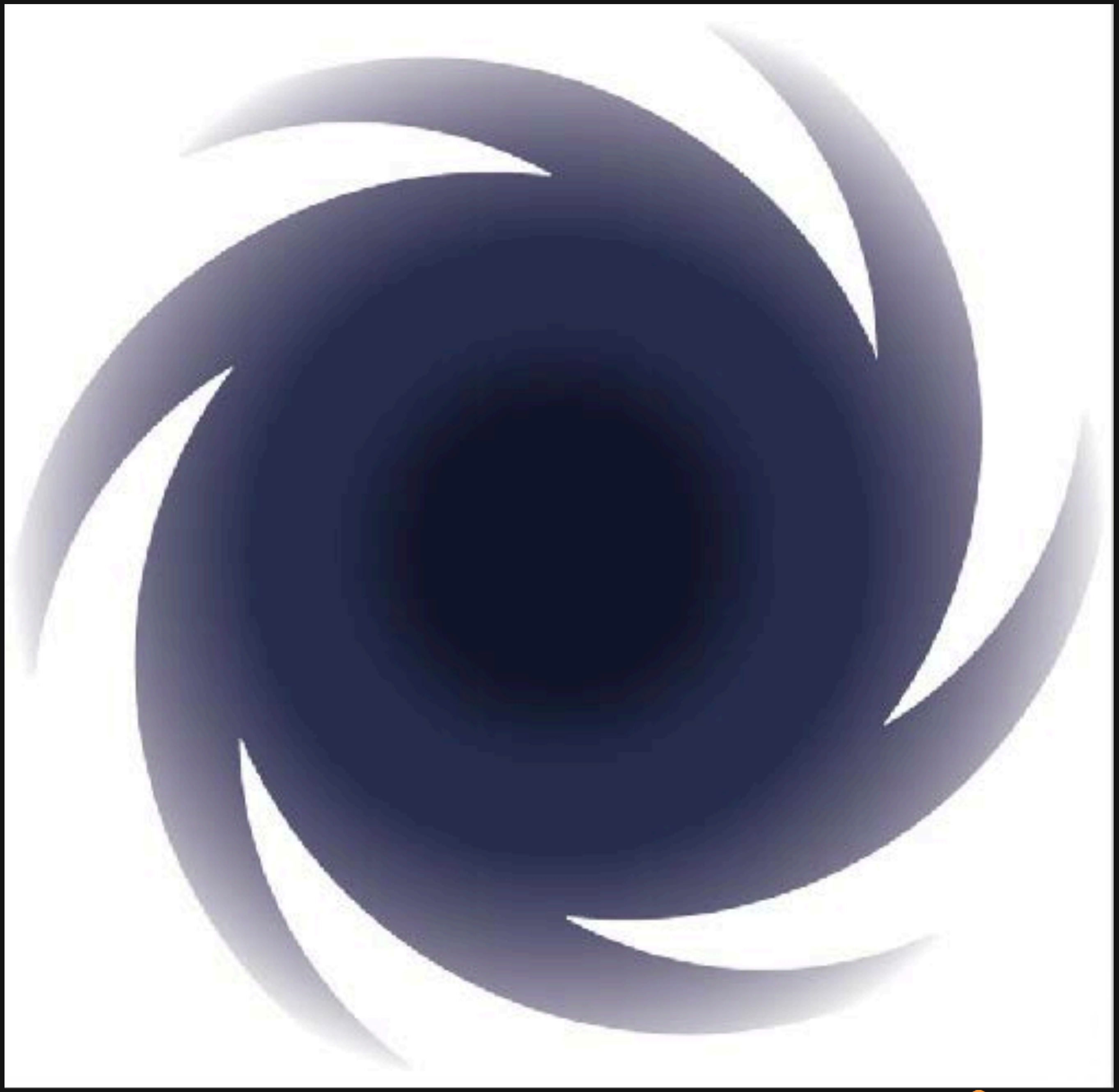
- Determine whether protons can decay – is there a grand, unified theory of particle physics, as Einstein dreamed?



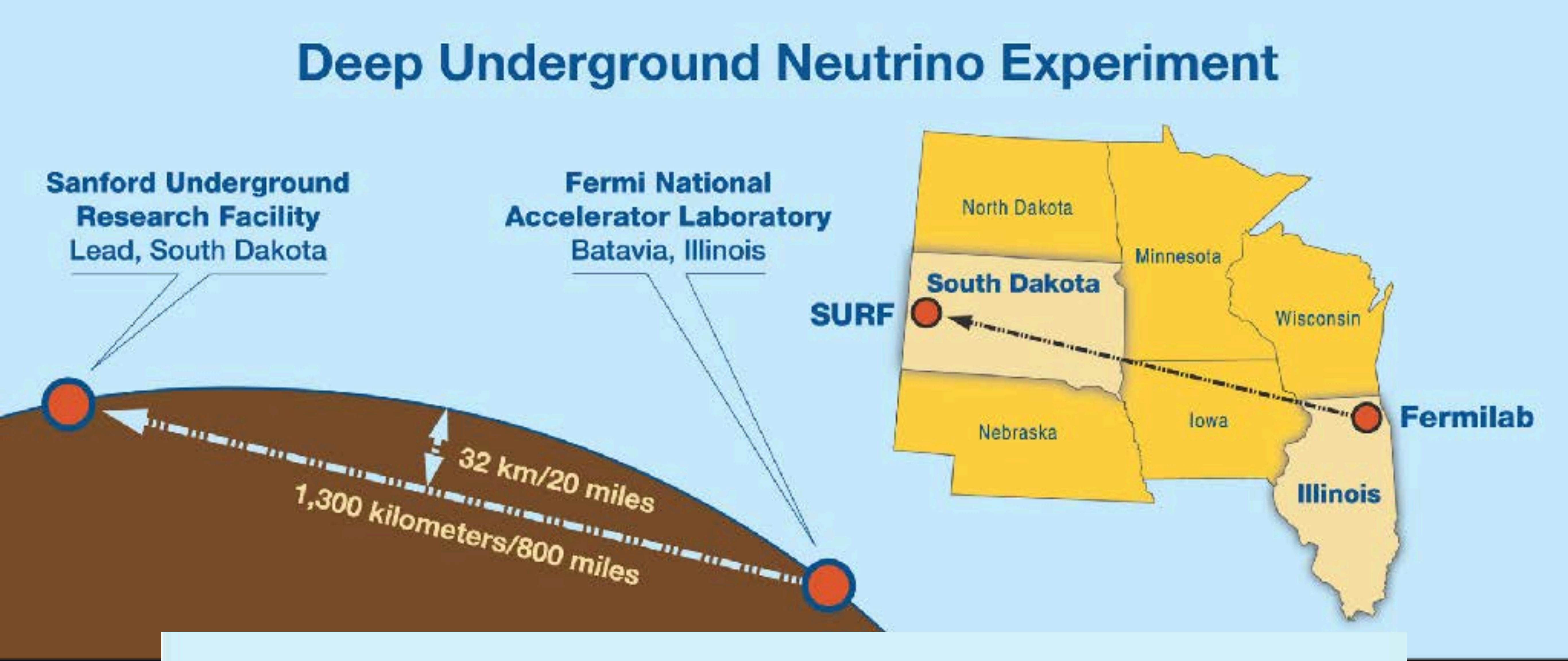
DEEP UNDERGROUND NEUTRINO EXPERIMENT

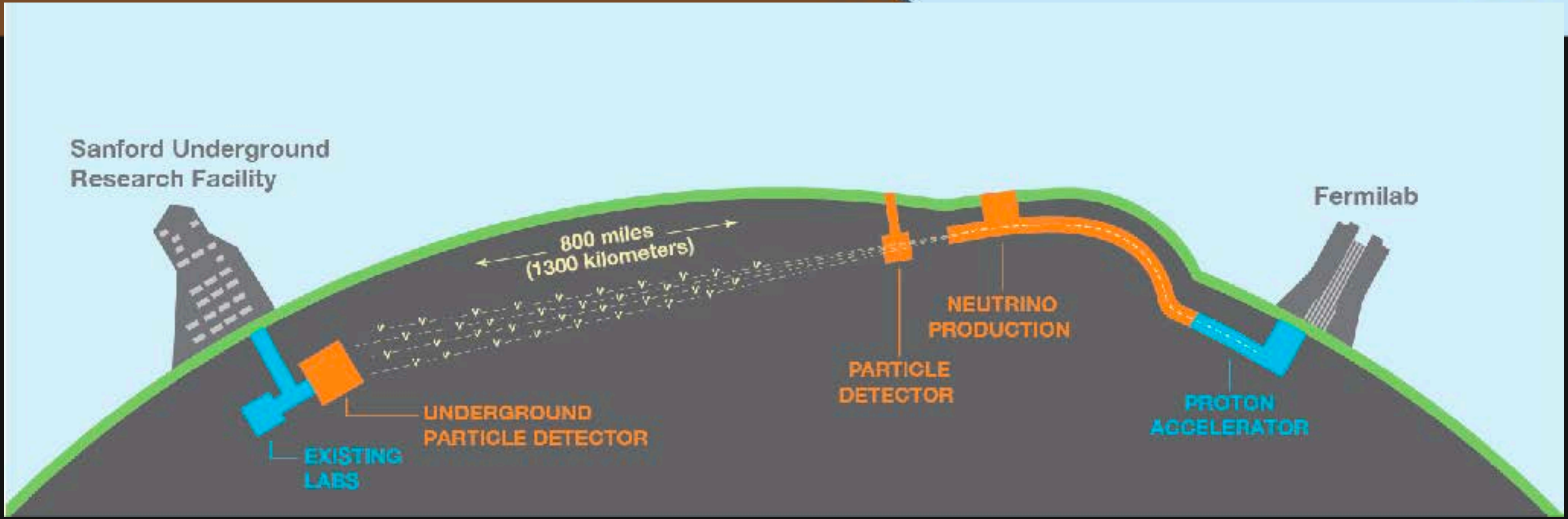
The goals of DUNE

- Understand what happens when massive stars die and witness the birth of a black hole

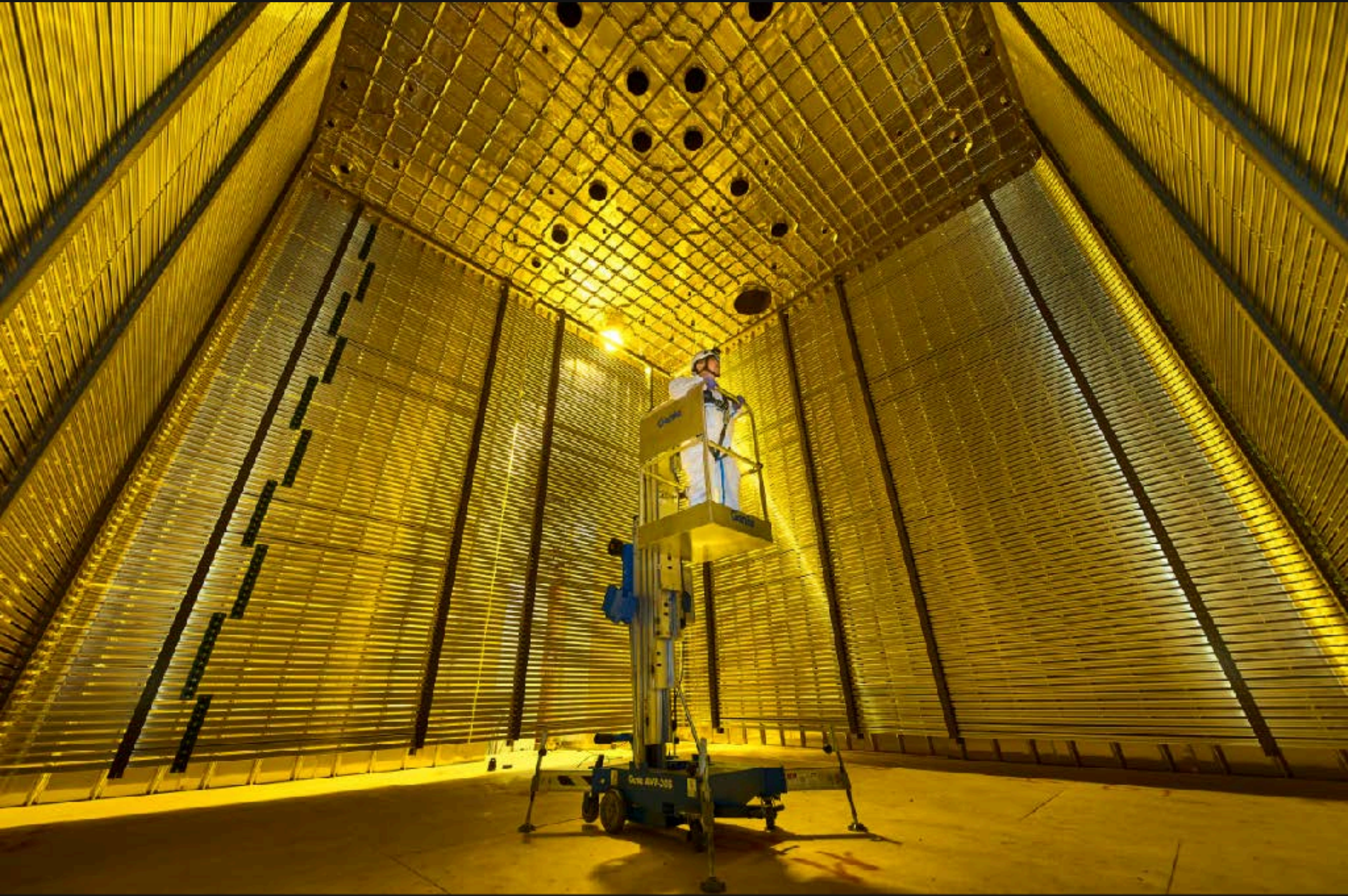


How does DUNE Do It?



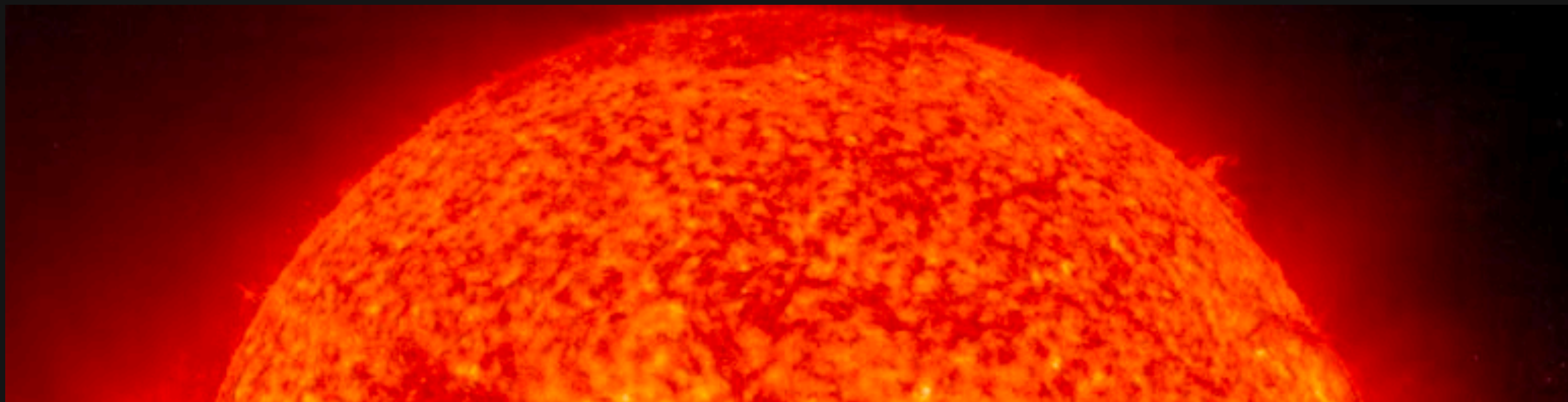


How does DUNE Do It?

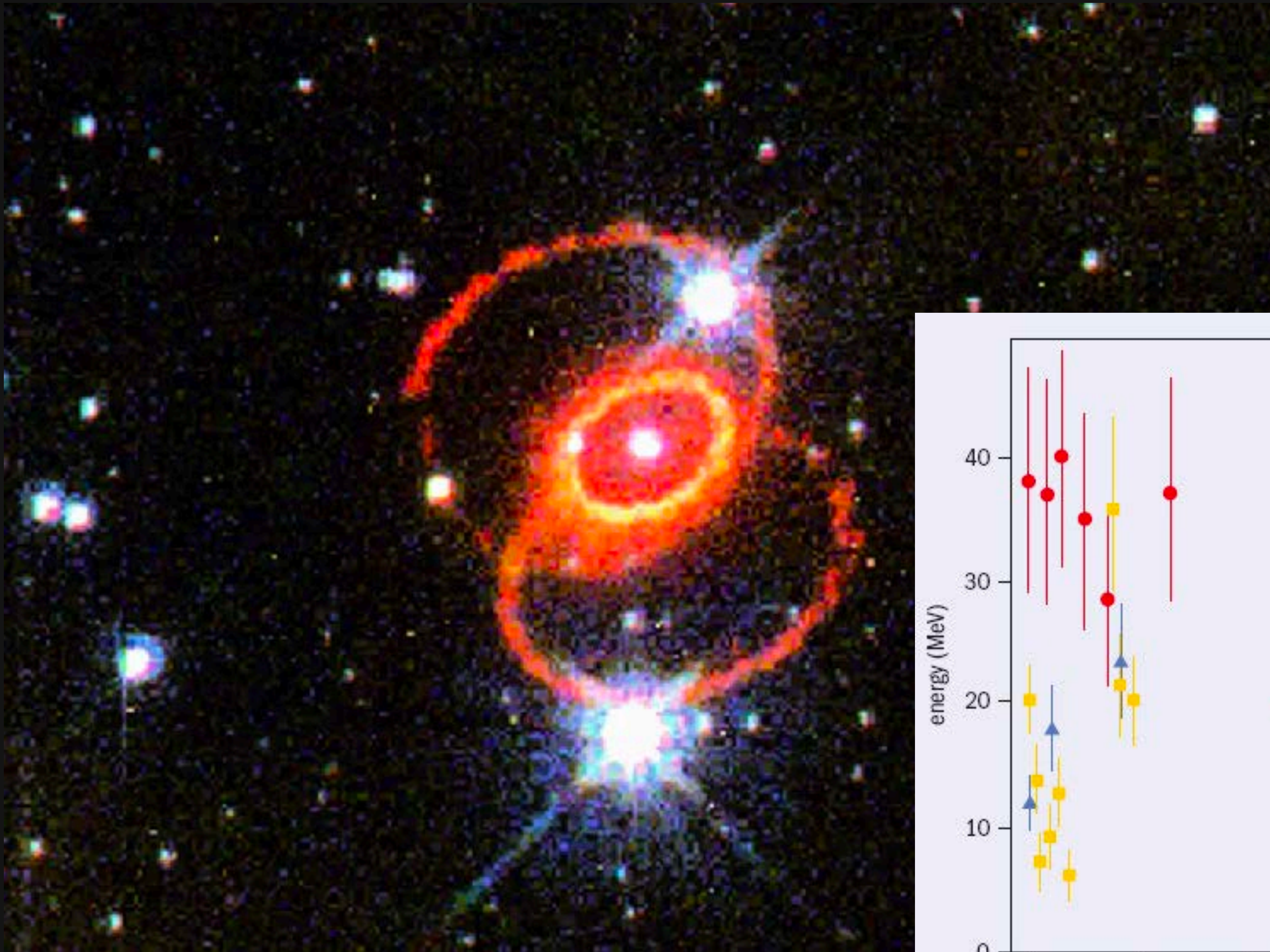


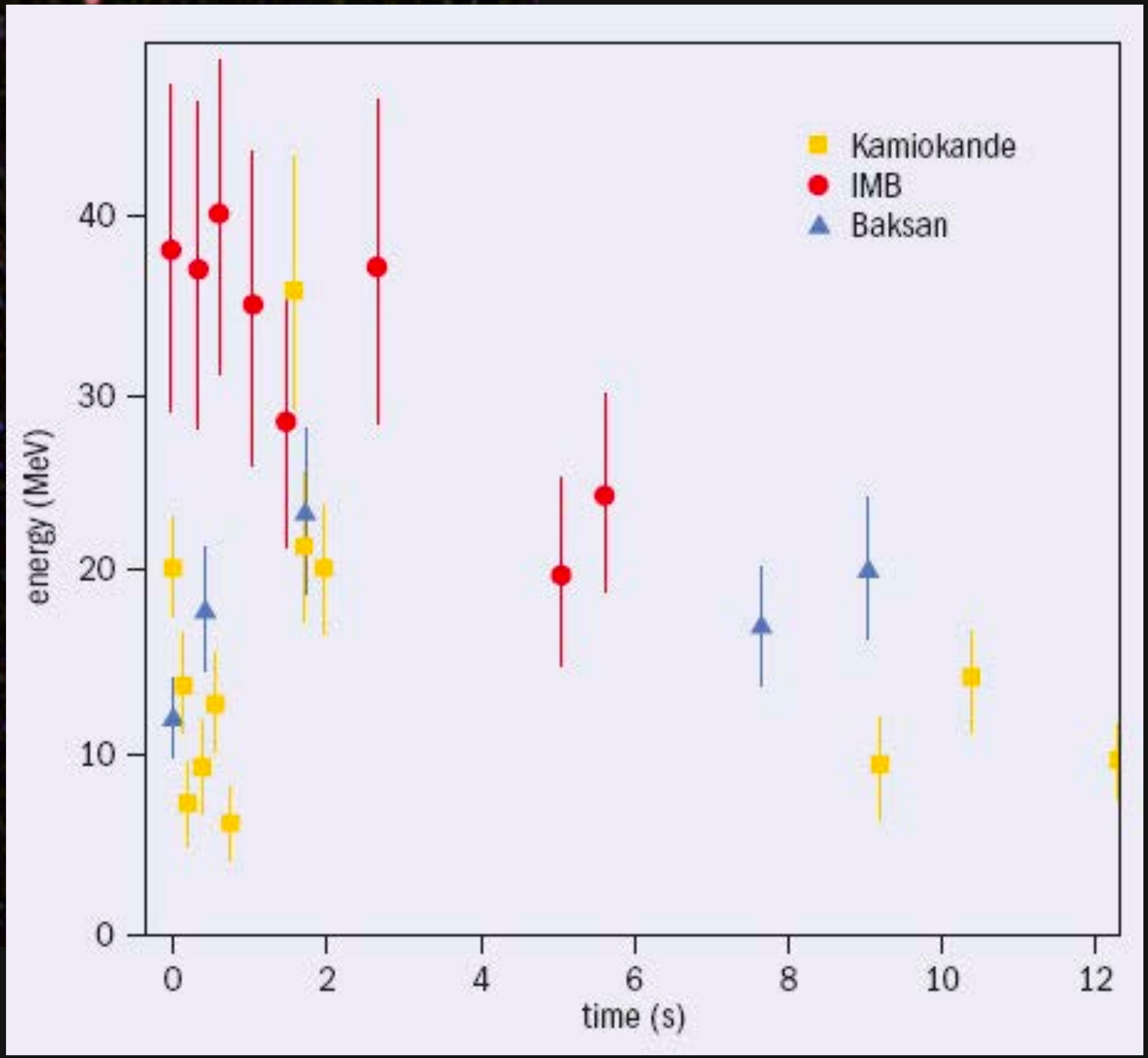
What about non manmade neutrinos?

Other sources of neutrinos



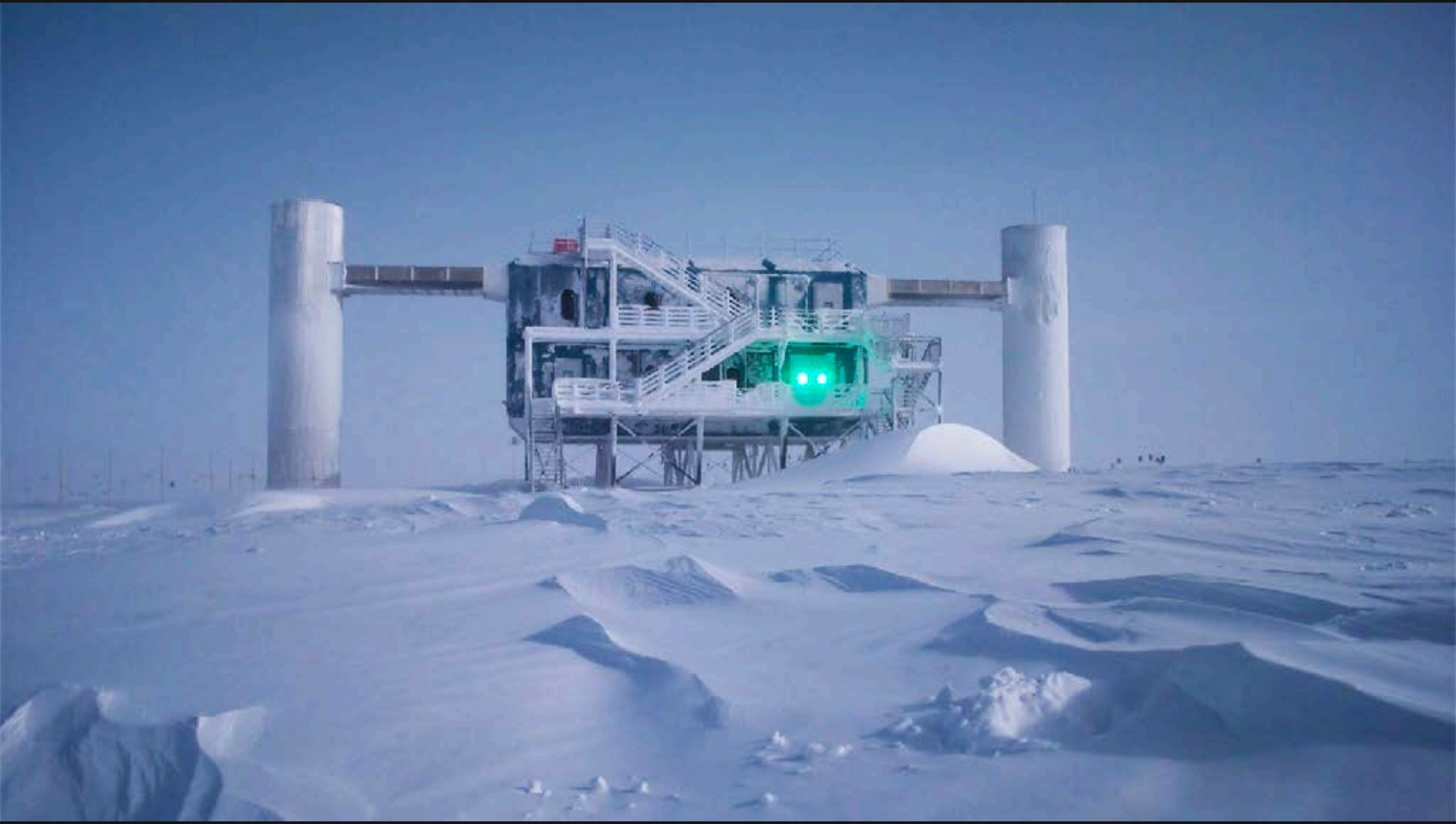
Rewind to 1987



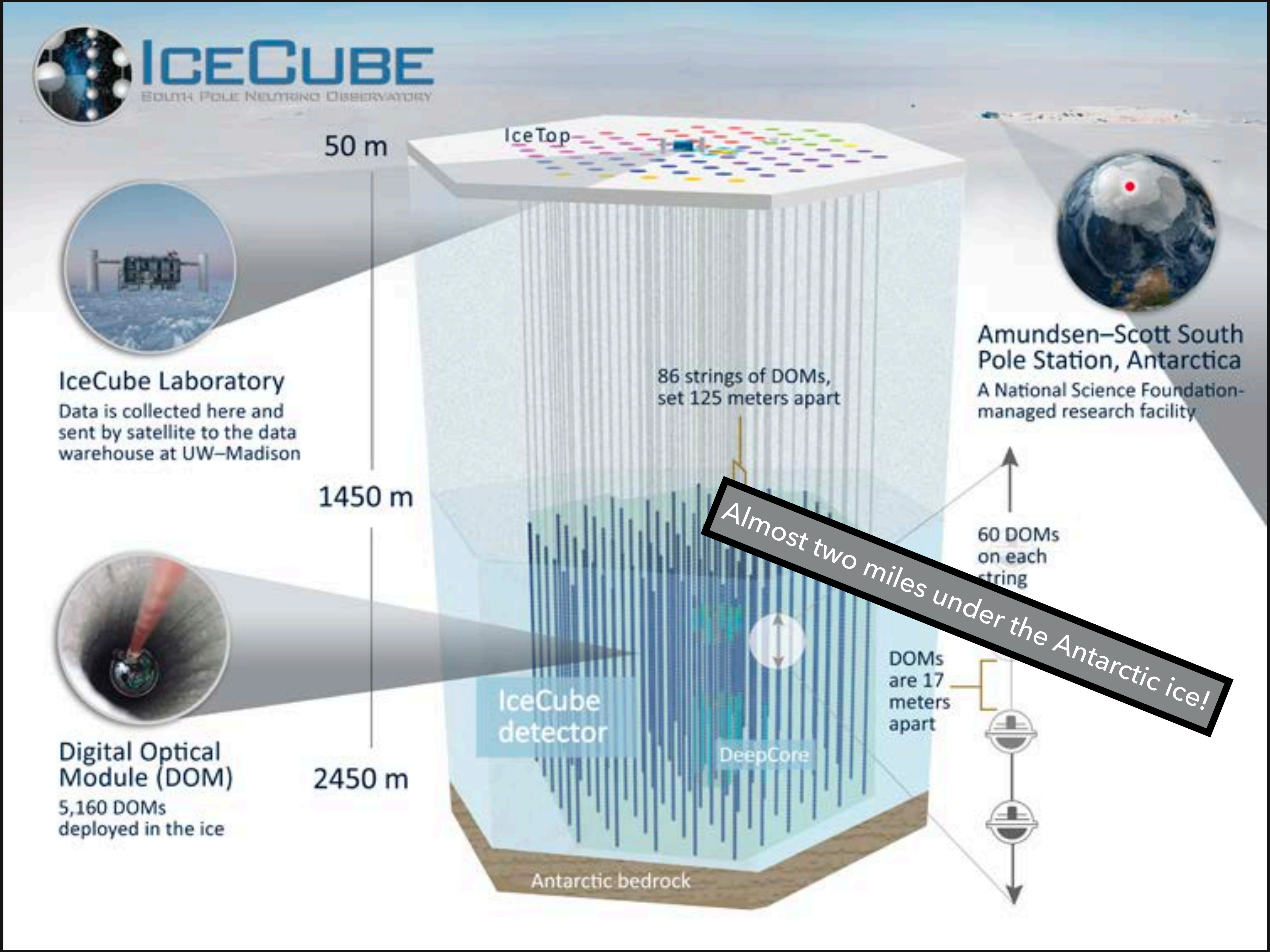


First case of multimessenger astronomy – detected a supernova with both light and with neutrinos!

The IceCube Experiment - a Neutrino Telescope

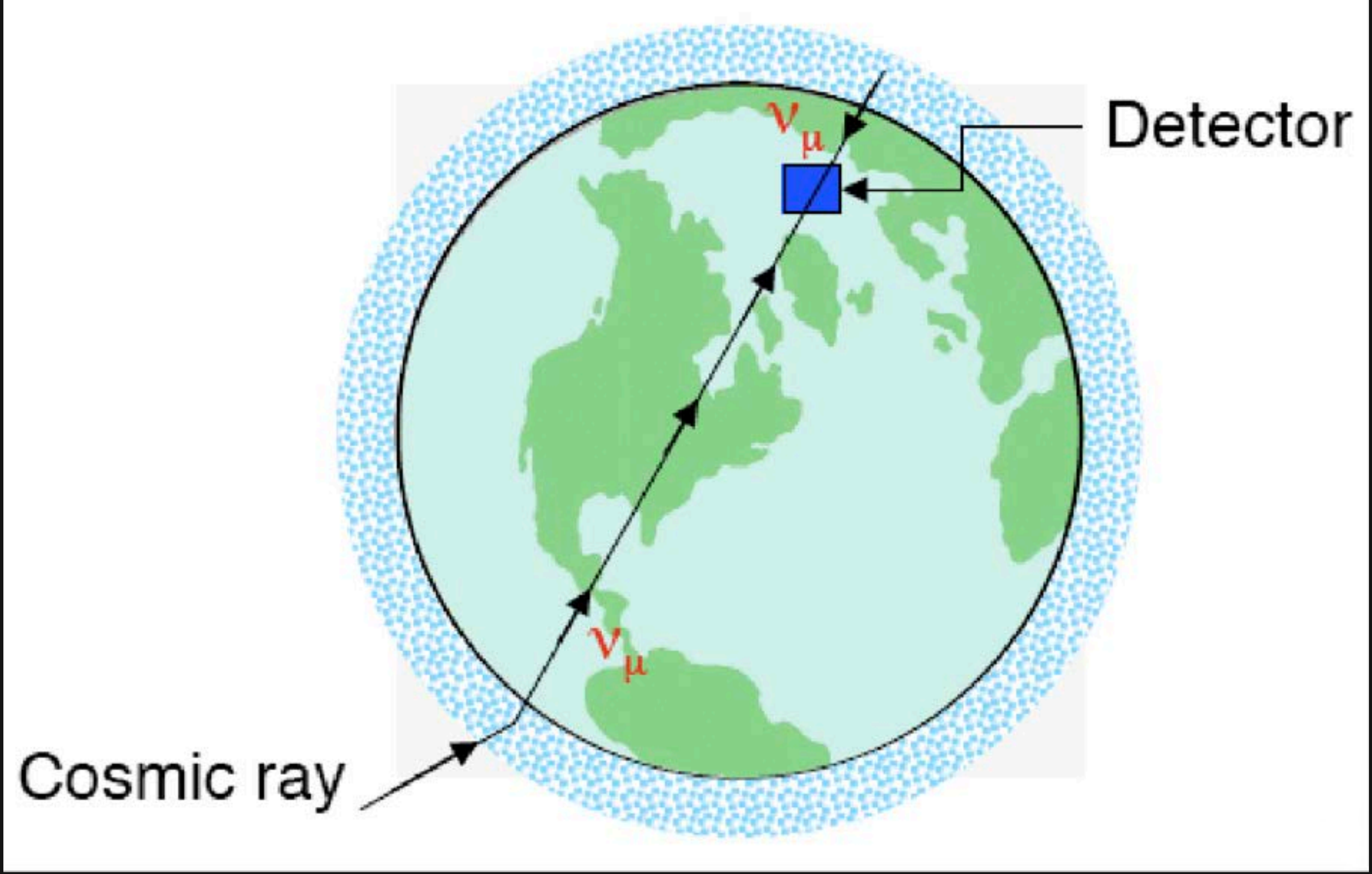


IceCube —— an instrumented cubic kilometer of ice!

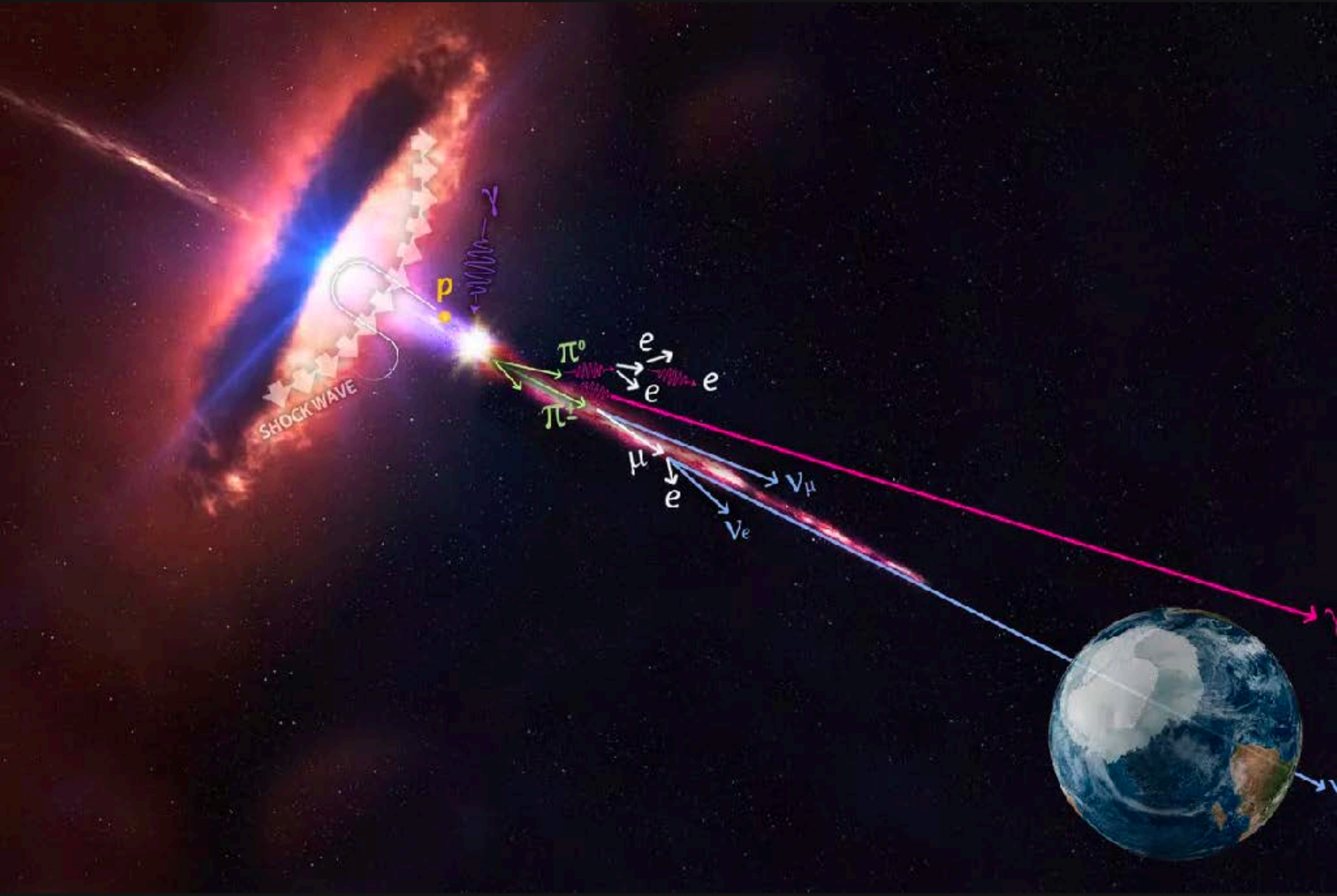


What can IceCube Do?

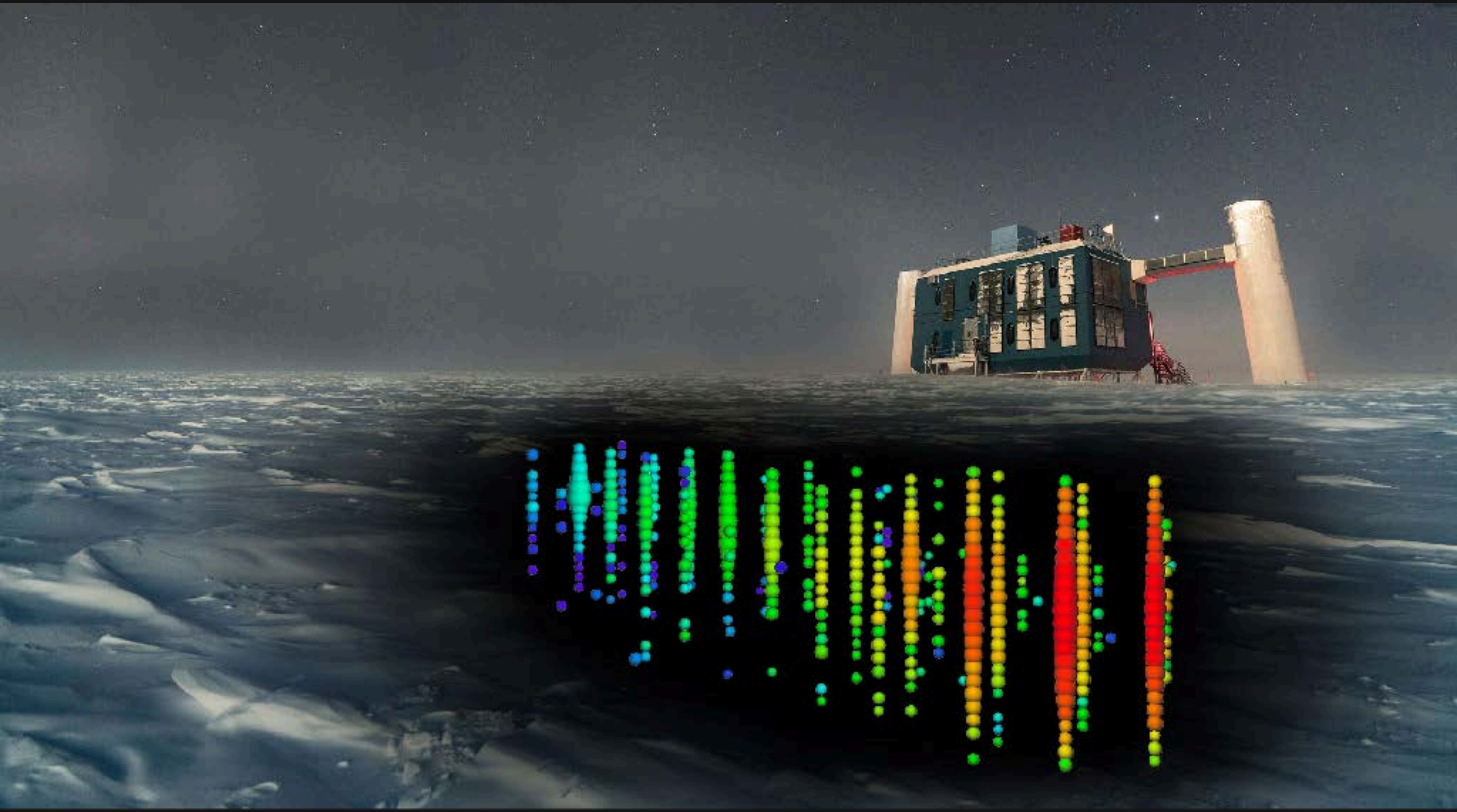
- Just like Super-Kamiokande and Hyper-Kamiokande, IceCube can look for Atmospheric Neutrinos, born above the Earth



But, IceCube can Seek Even more Distant Neutrinos!



On September 22, 2017…

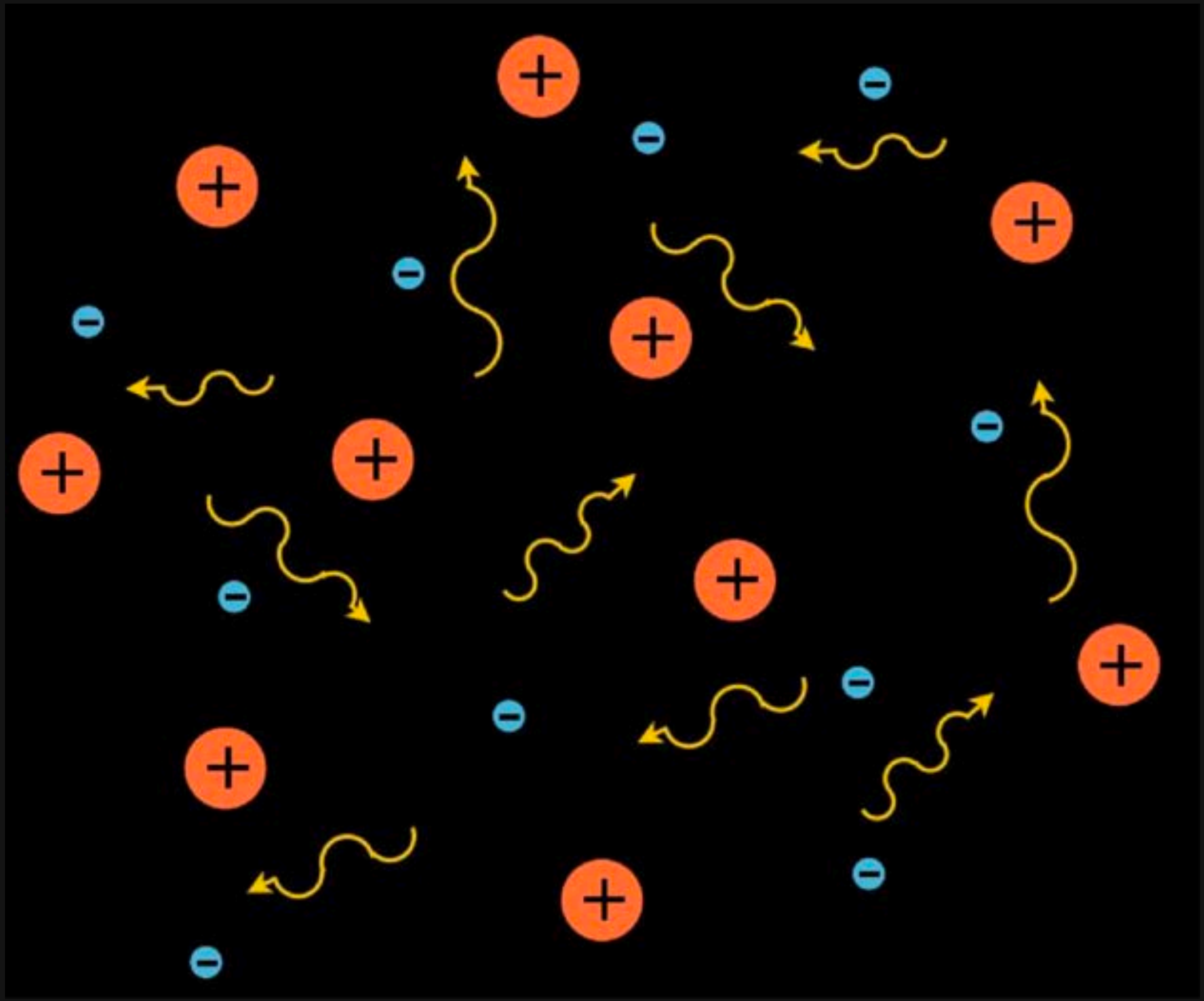


IceCube saw a neutrino coming from about 4,000,000,000 lightyears away!

Switching Gears, the Cosmic Microwave Background

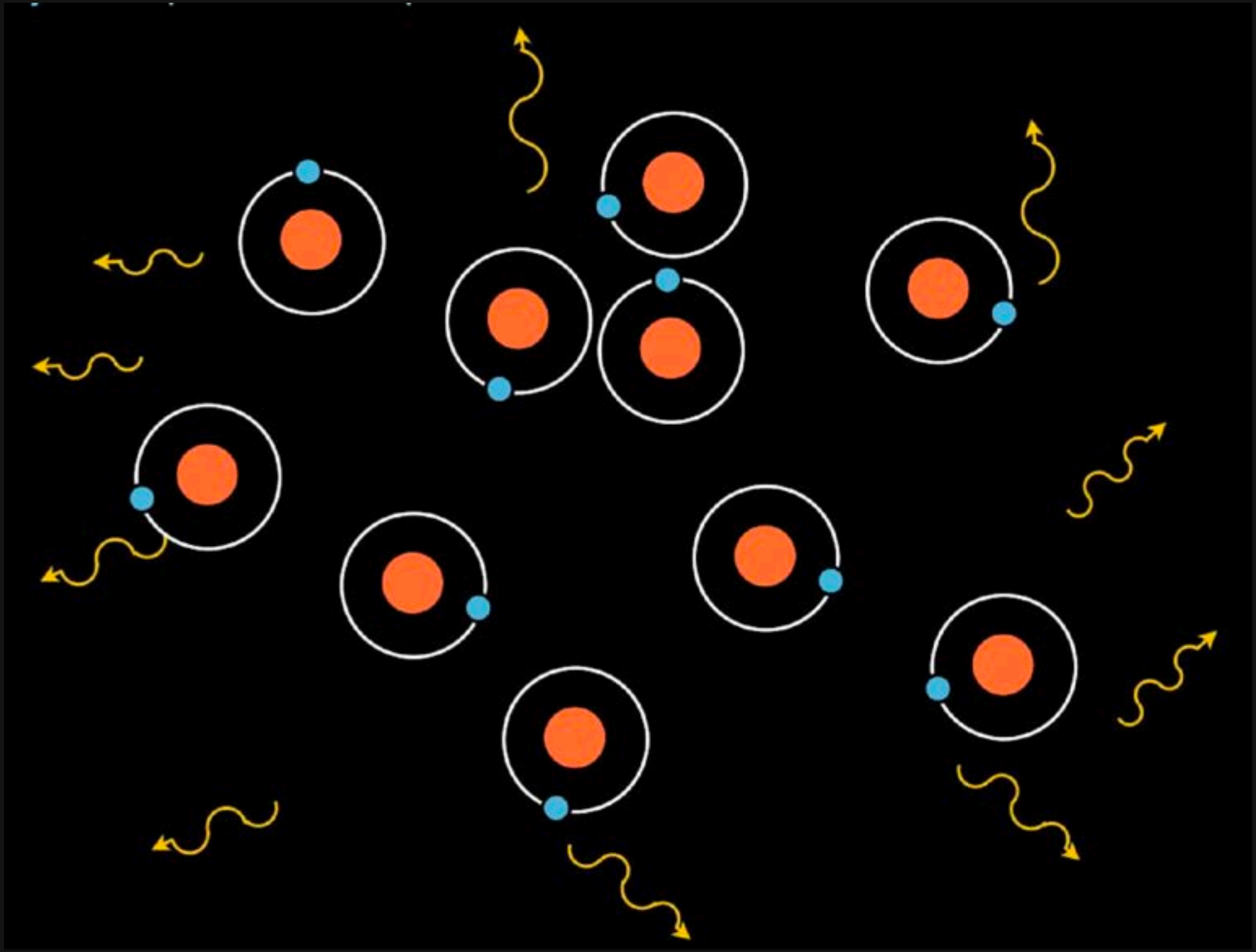
Rewind to the Early Universe…

- At a time not long after the Big Bang, the universe was so hot, and so dense, that protons and electrons preferred to zoom around on their own instead of pairing up into Hydrogen atoms.



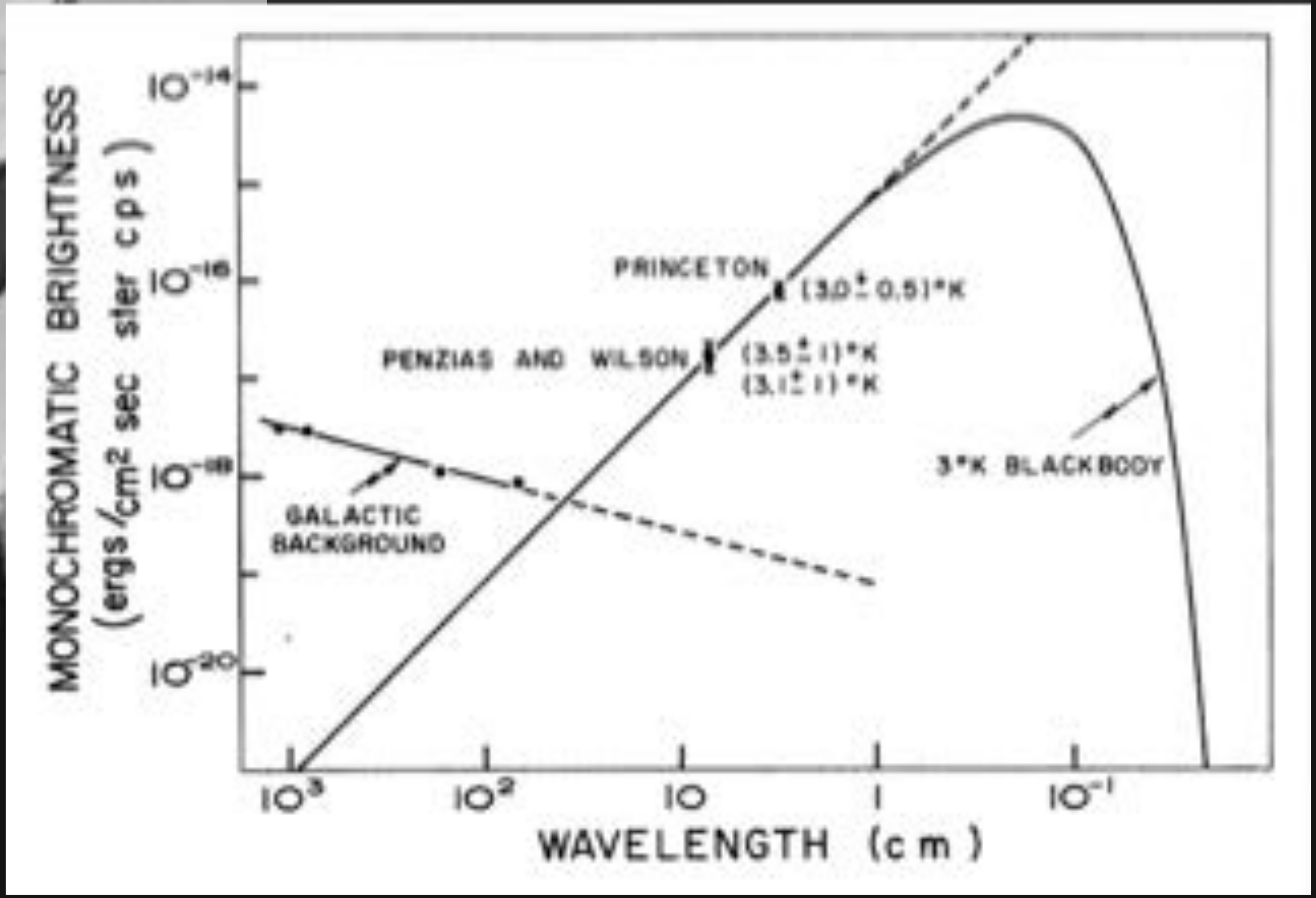
As the Universe Expands, it cools down

- At a very specific temperature, the protons and electrons will prefer to combine into neutral atoms

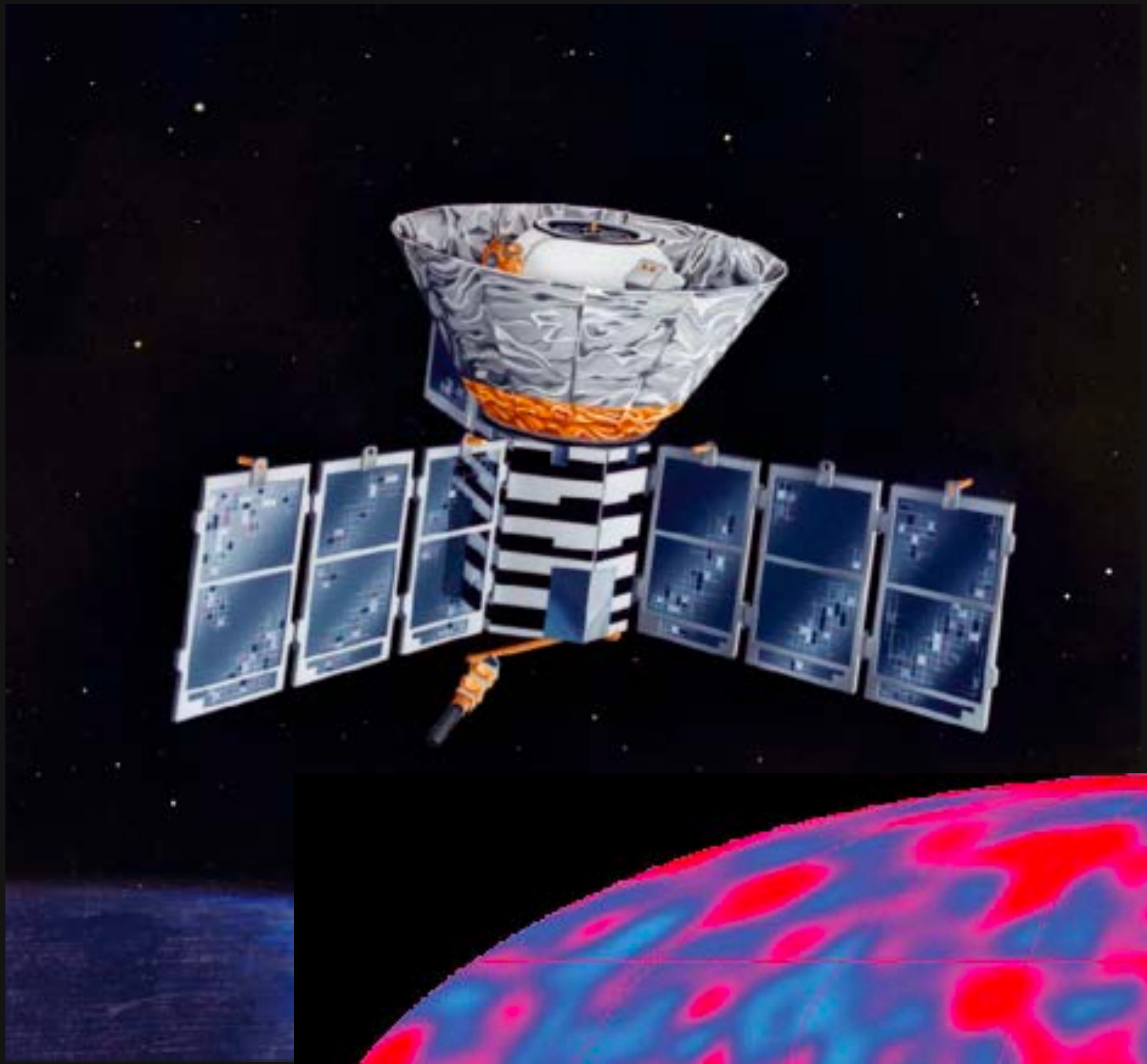


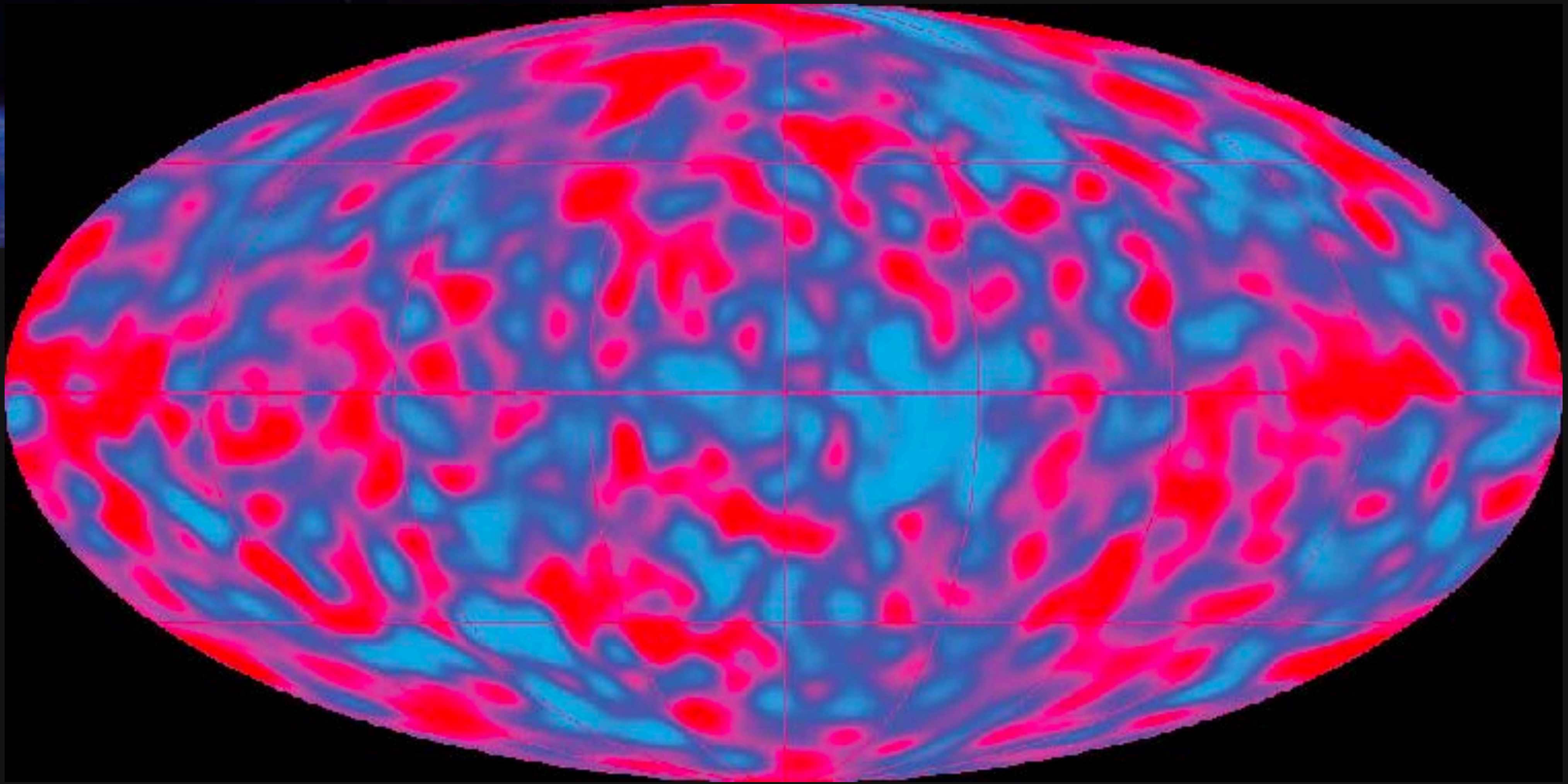
Every direction we look, we see these leftover photons of light

- 1964: Penzias and Wilson first detection
-



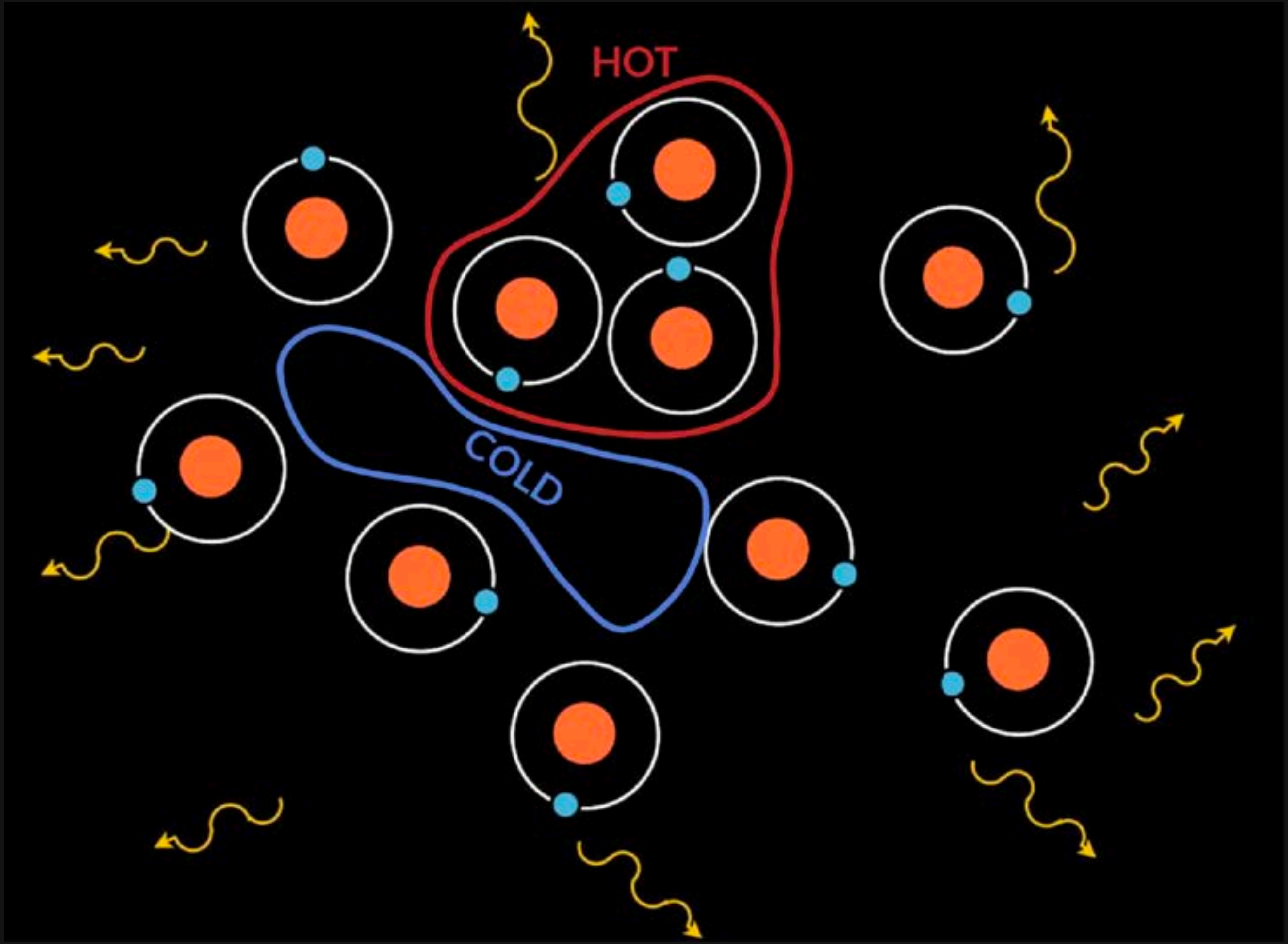
Early 1990s: COBE Satellite



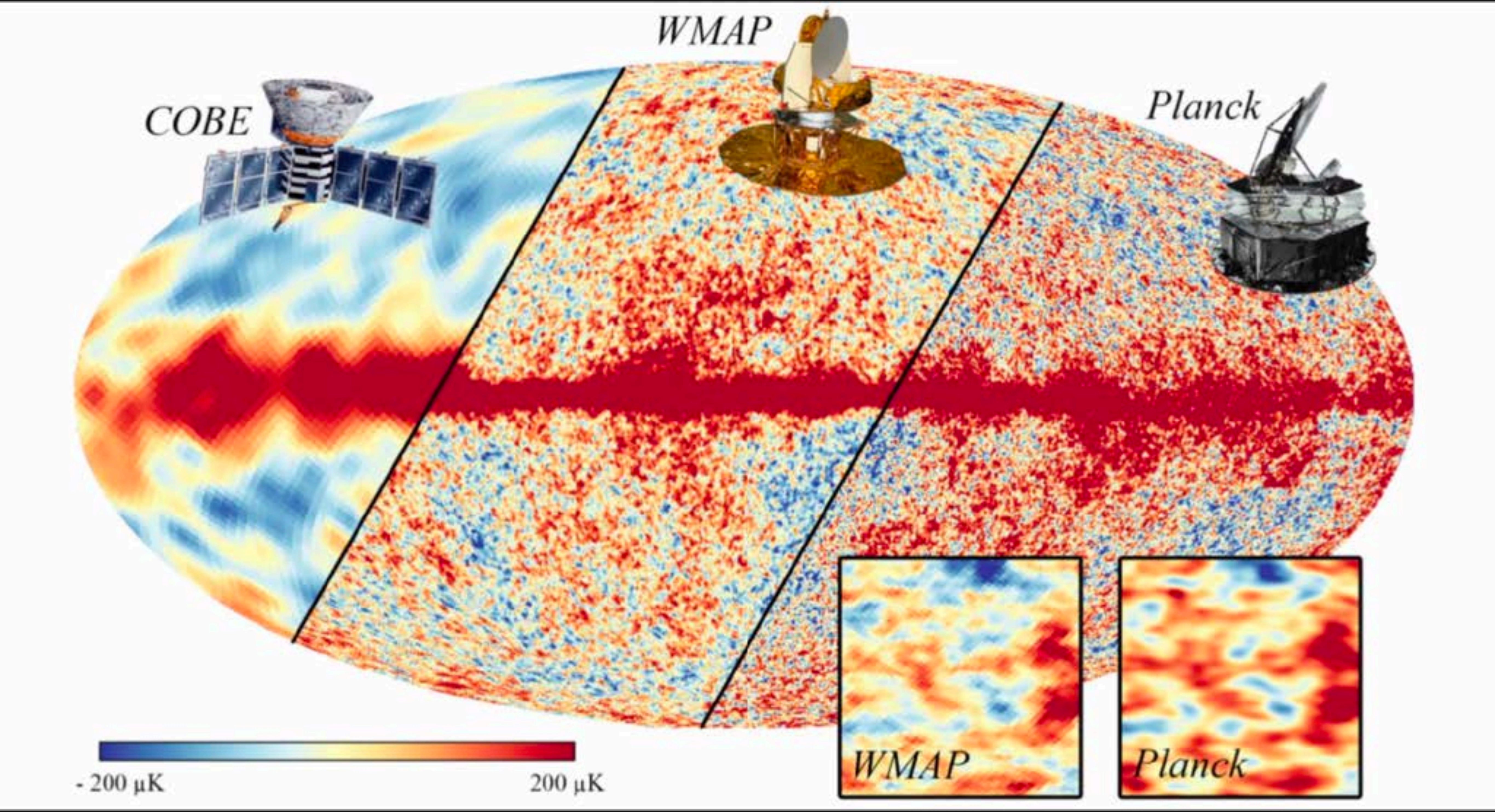


What is COBE Measuring?

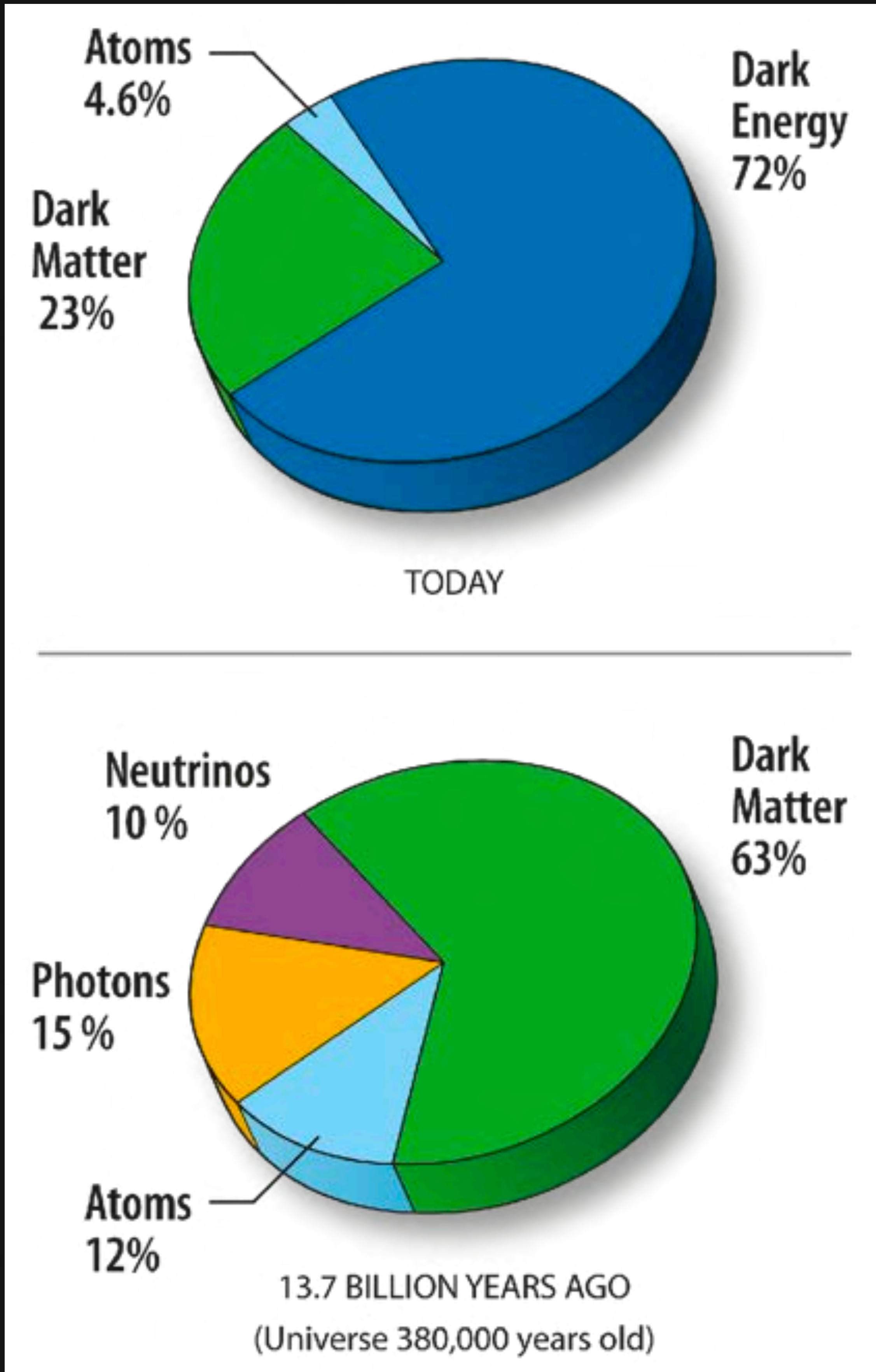
- Tiny, tiny differences in temperature of the photons it's measuring from every direction.

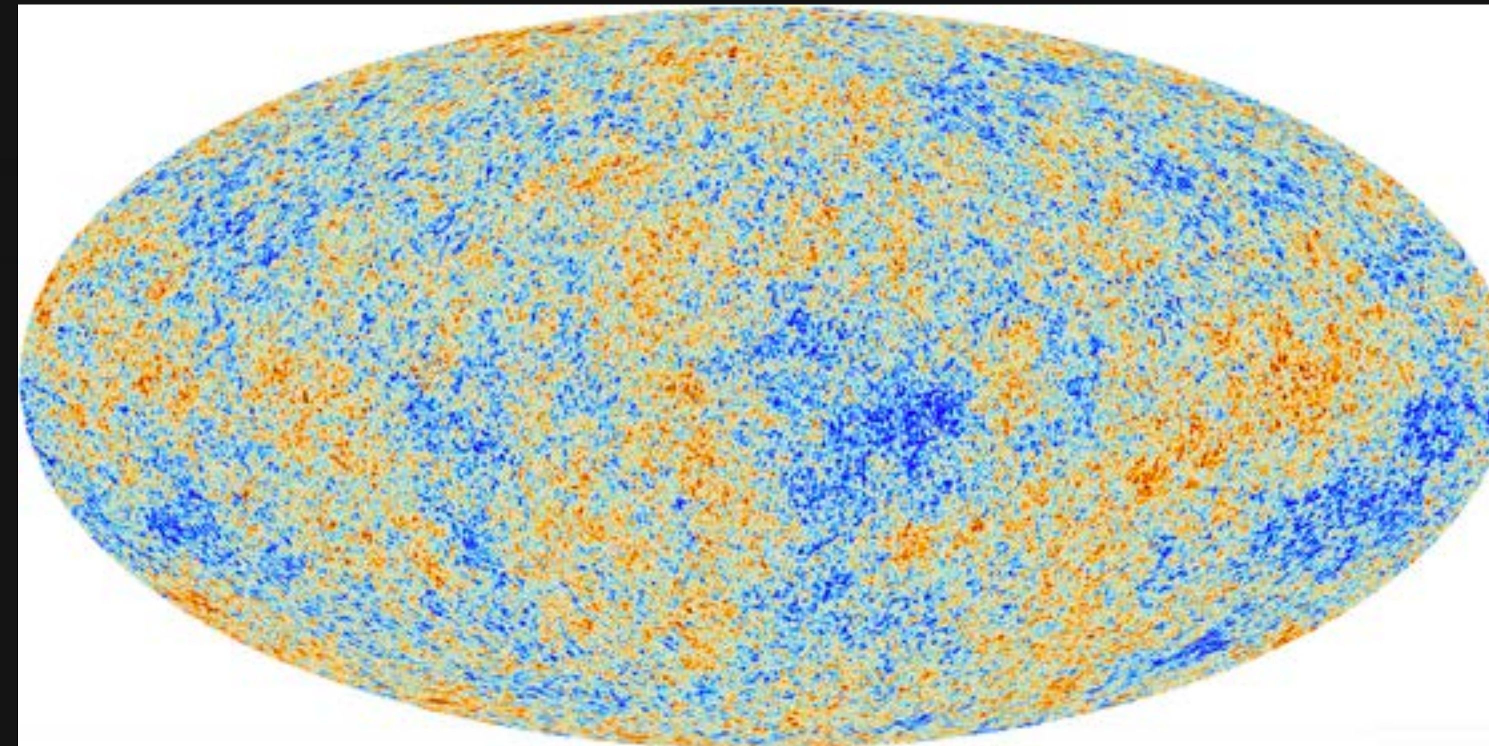


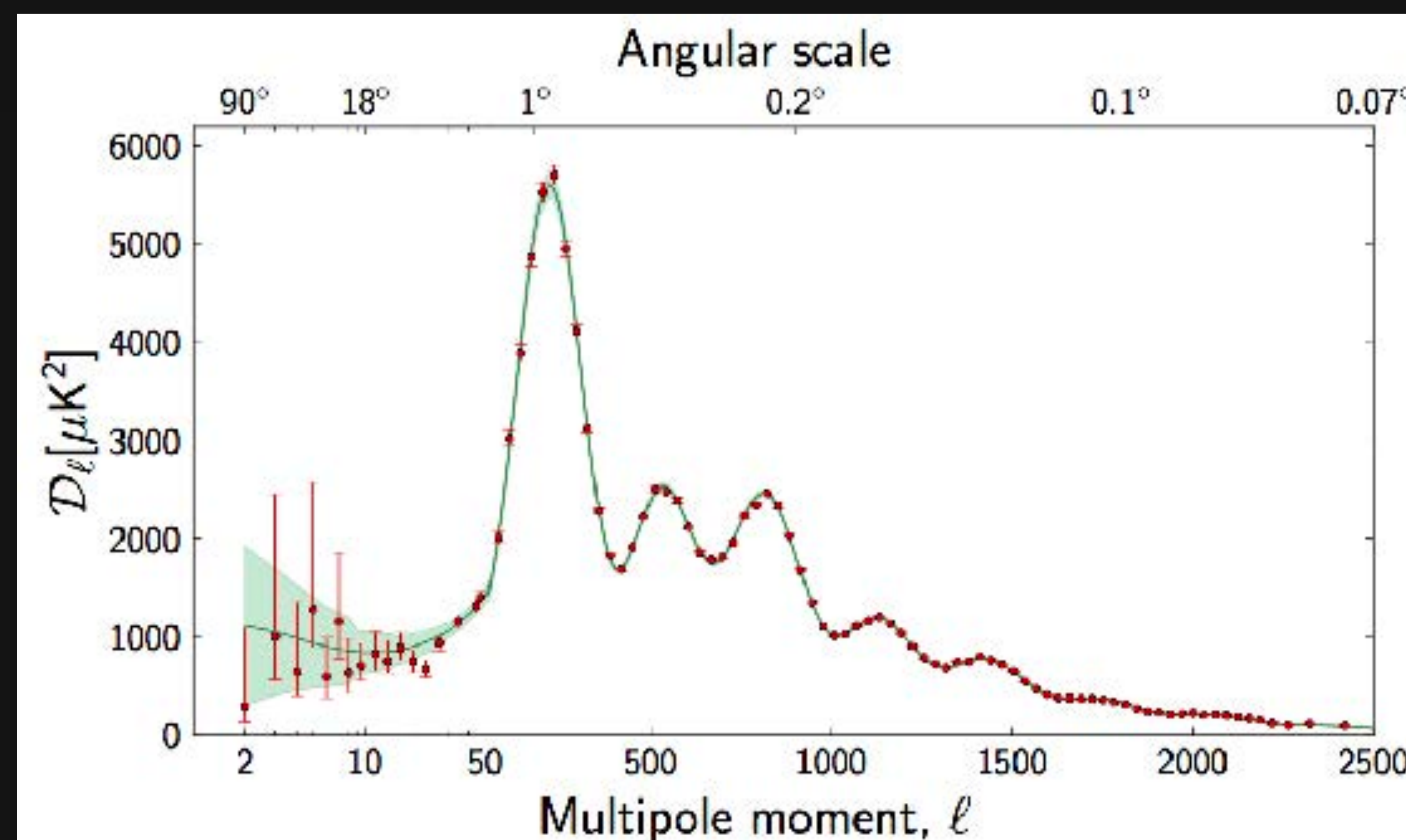
Advancement over 20+ Years



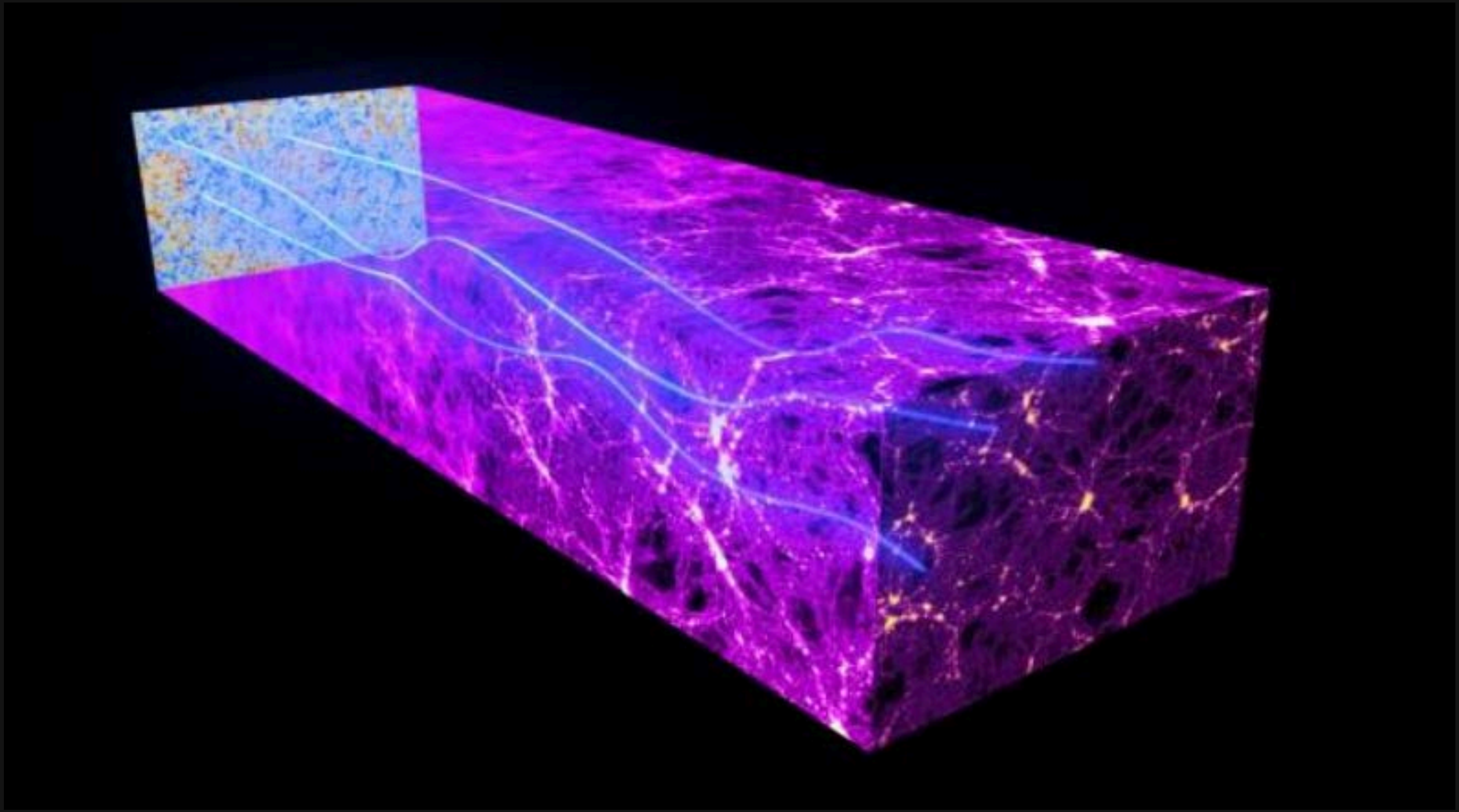
What can we learn from the Cosmic Microwave Background?





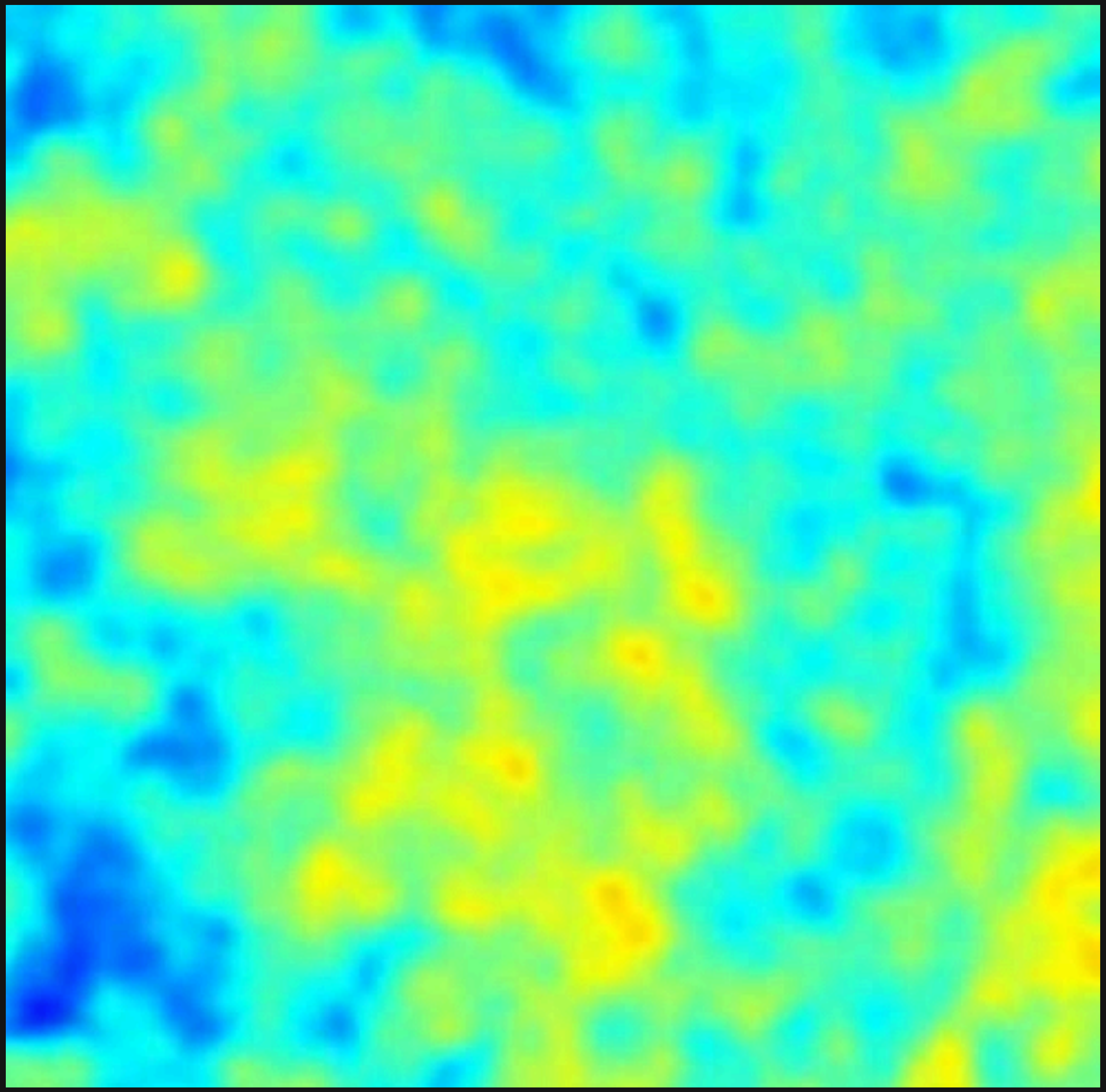


The CMB isn't viewed as it was, though…



But wait, there's more!

- The Cosmic Neutrino Background can also tell us about neutrinos, since they were around at the same time!



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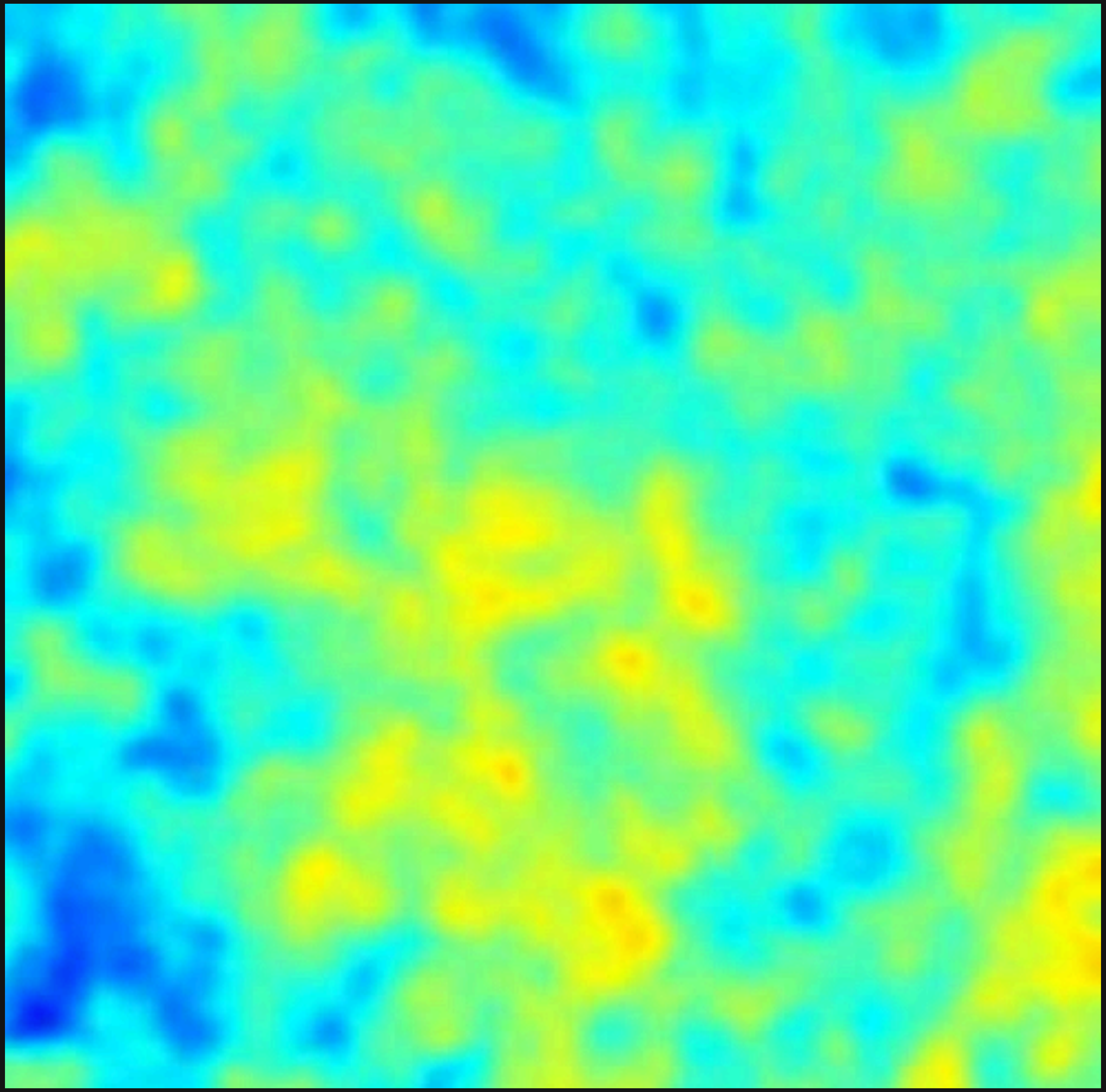
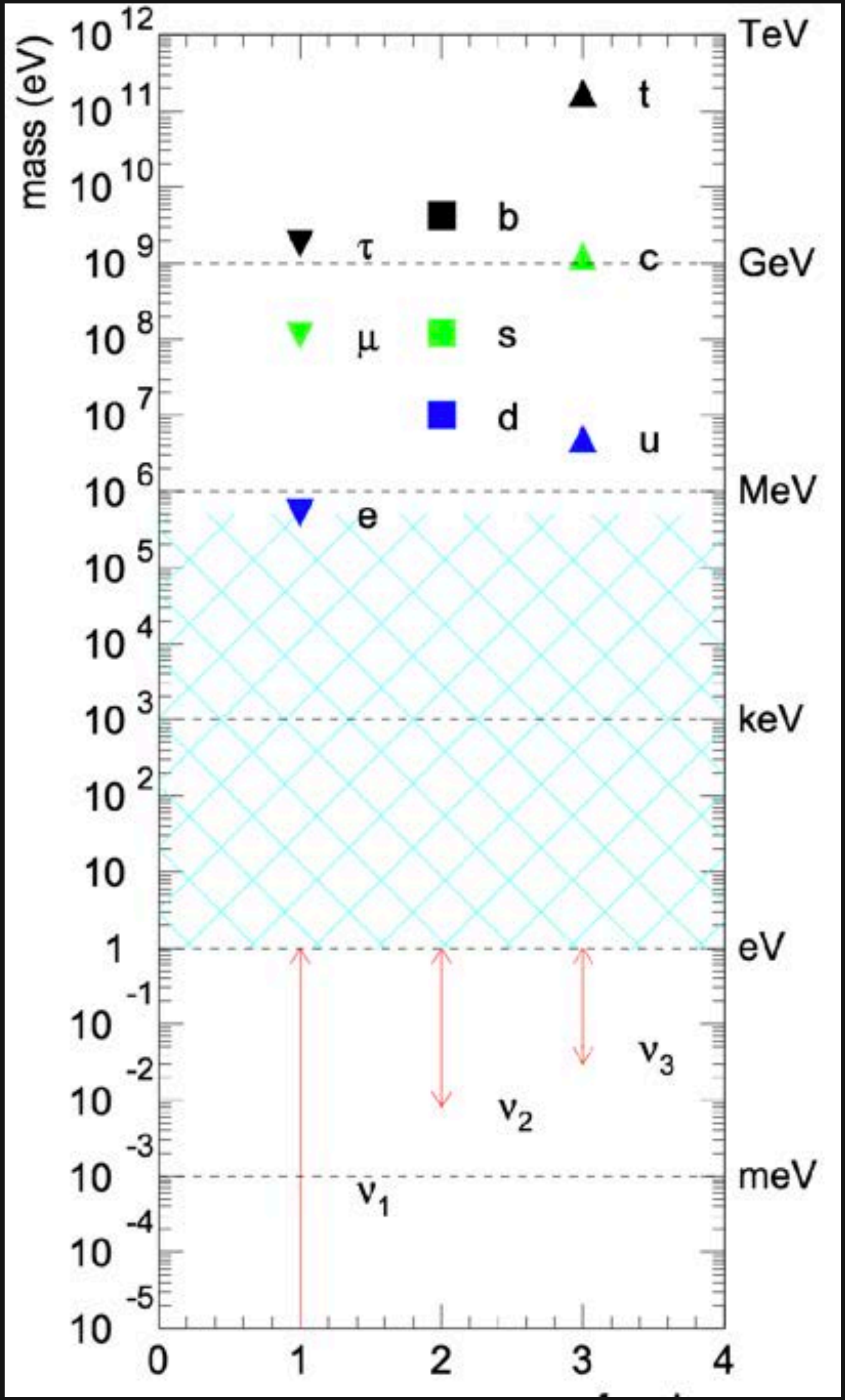


Currently, cosmological experiments haven't detected massive neutrinos

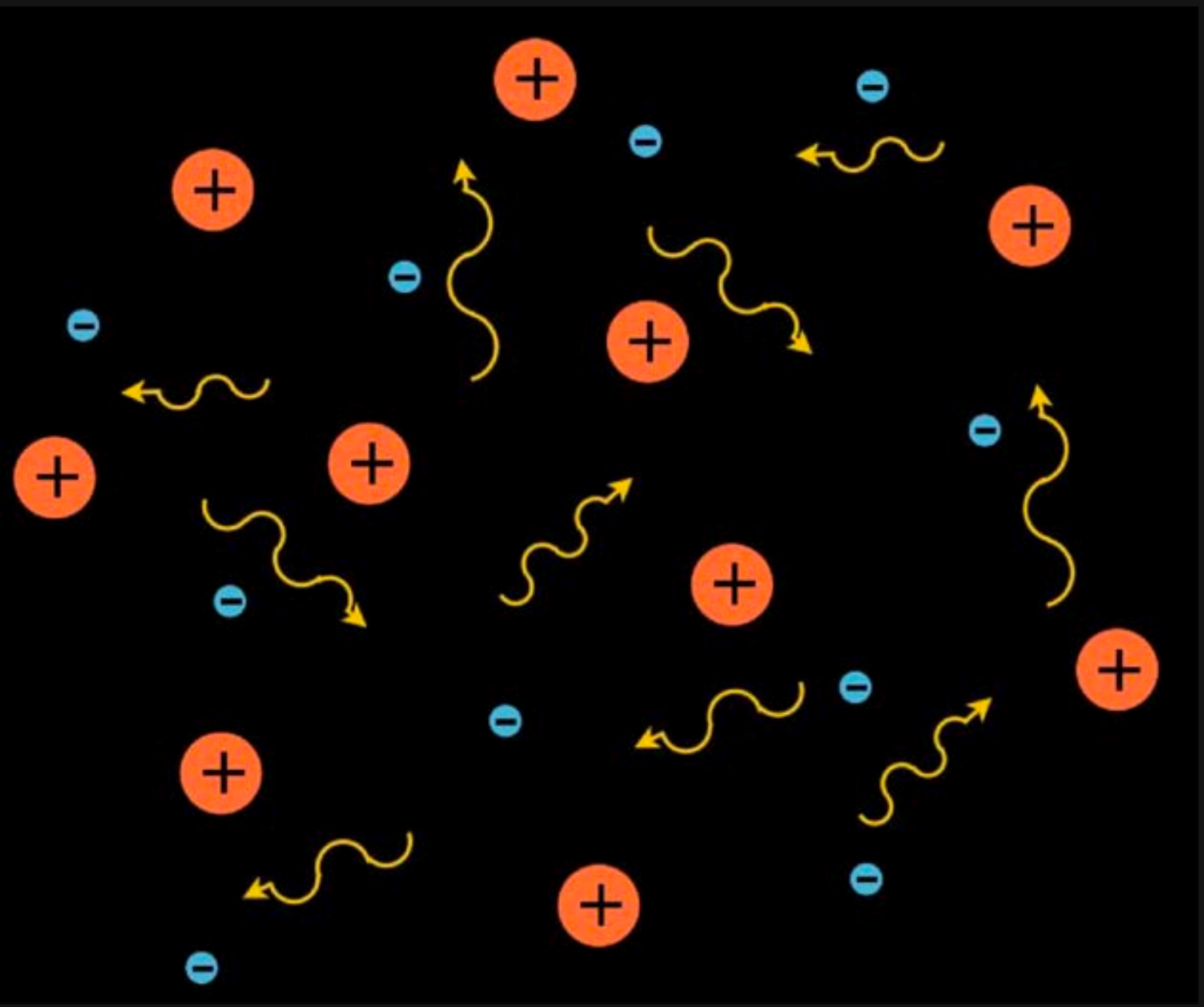


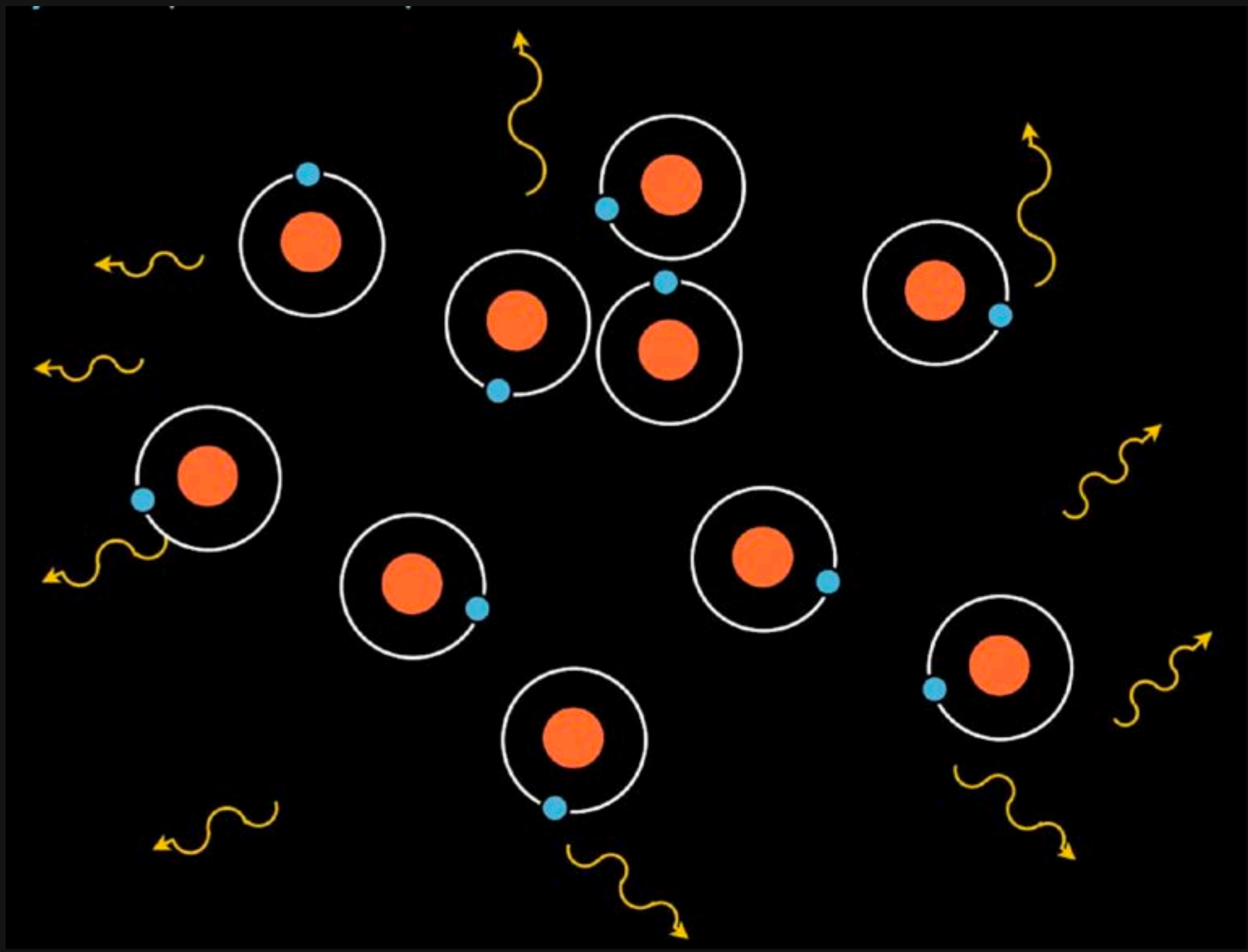
However, they are setting upper bounds on how heavy they can be! Even more competitive than Earth-based experiments.

Finally!

Cosmic Neutrinos

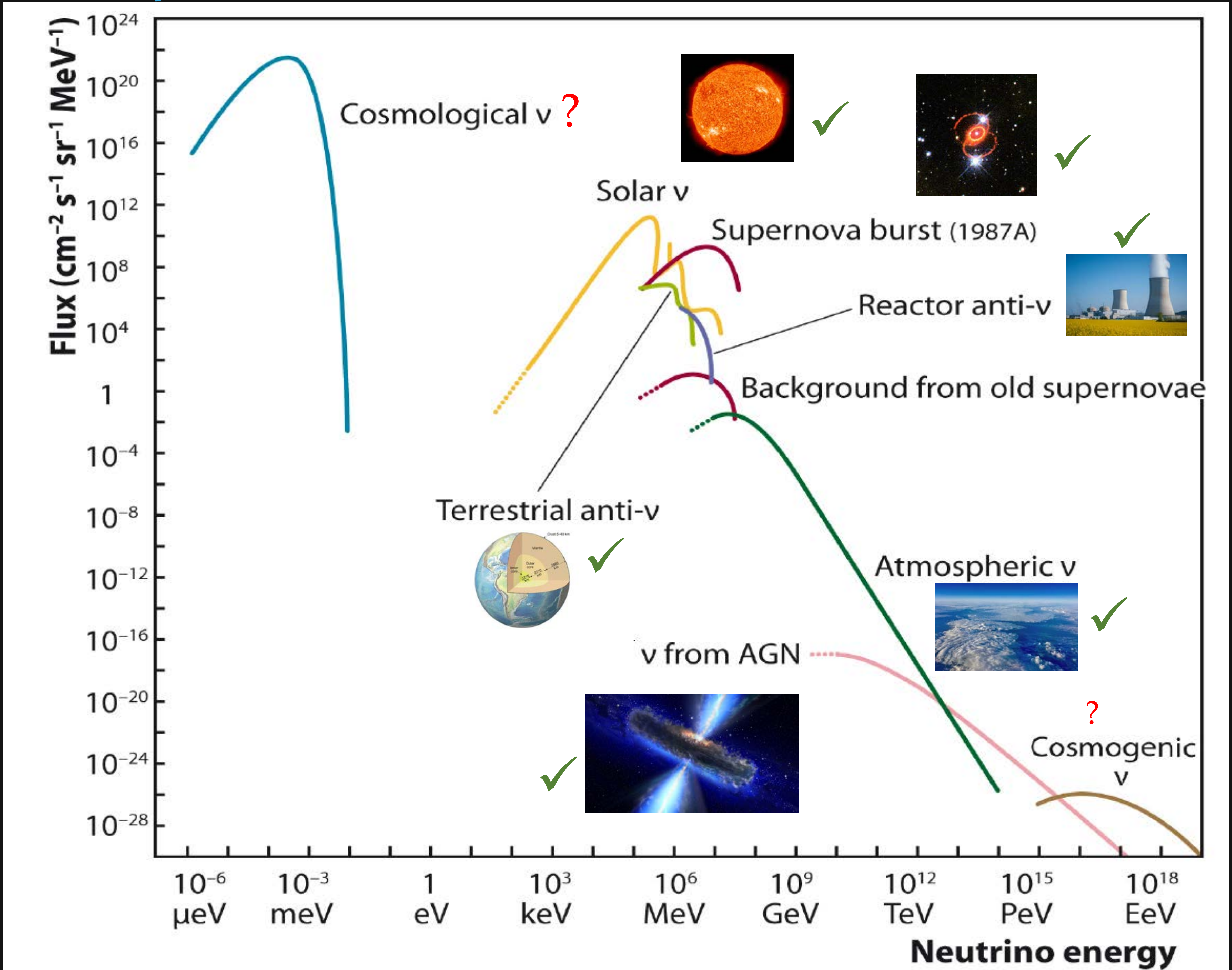
Just as the Cosmic Microwave Background Formed…





At an even hotter temperature, the same happened with neutrinos – they went from being happy scattering around, to being “free-streaming”

How many of these neutrinos are out there?



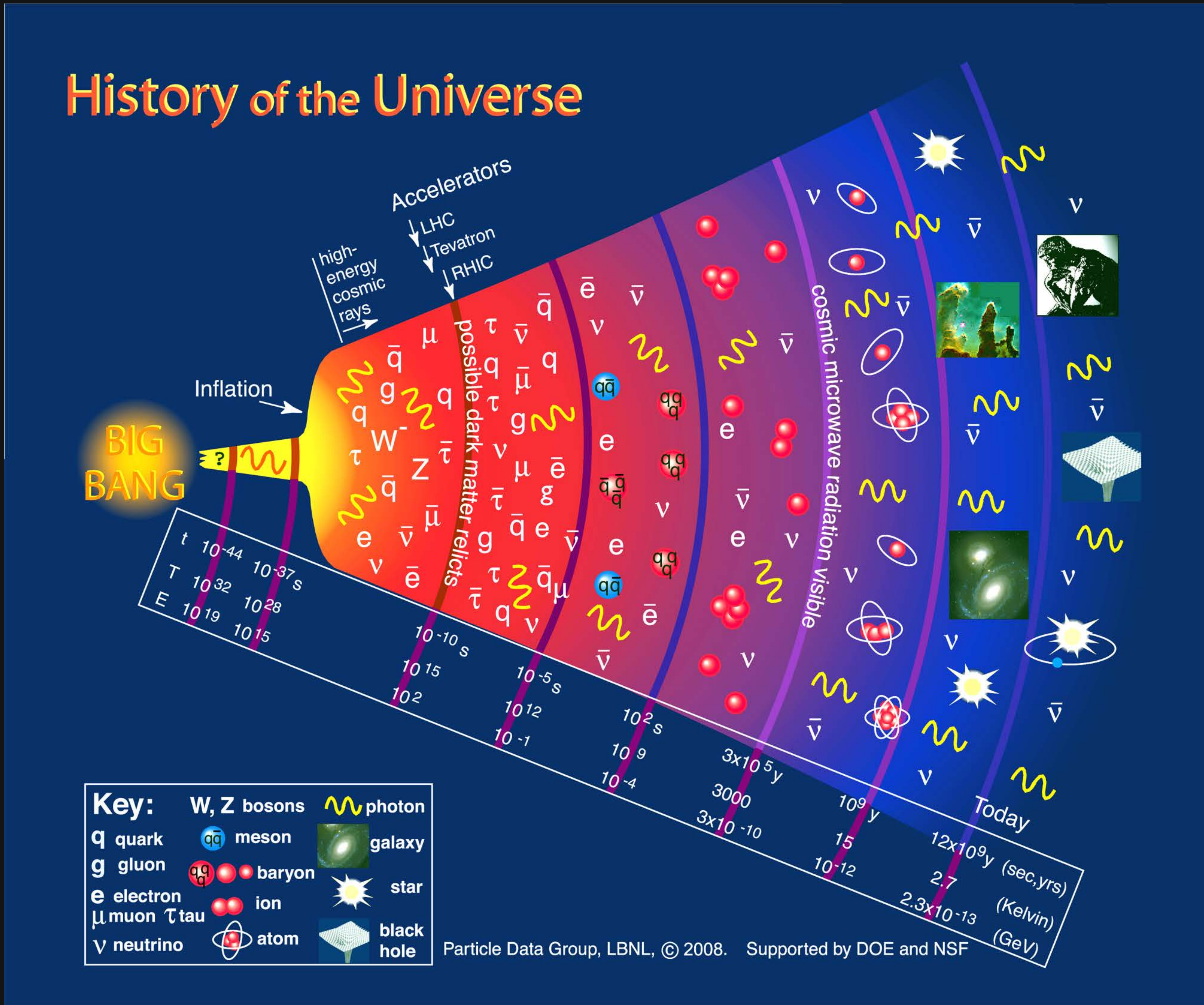
Pretty confident they're out there…

- The big problem is that since they started coming towards us, they have slowed down significantly.

Currently, the best idea about how to detect them is the Princeton Tritium Observatory for Light, Early-Universe, Massive-Neutrino Yield (PTOLEMY) Experiment, but that might even be a dream currently.

Even so, if we detected these neutrinos, we might be able to learn a ton about the universe!

Neutrinos could let us look even further back in time



Conclusions

- The last 50+ years have been an adventure in terms of what we have discovered about neutrinos, and new mysteries continue to pop up.

- We are exploring them as well as we can, hoping that they can shed insight onto other mysteries of nature!

Thank you!