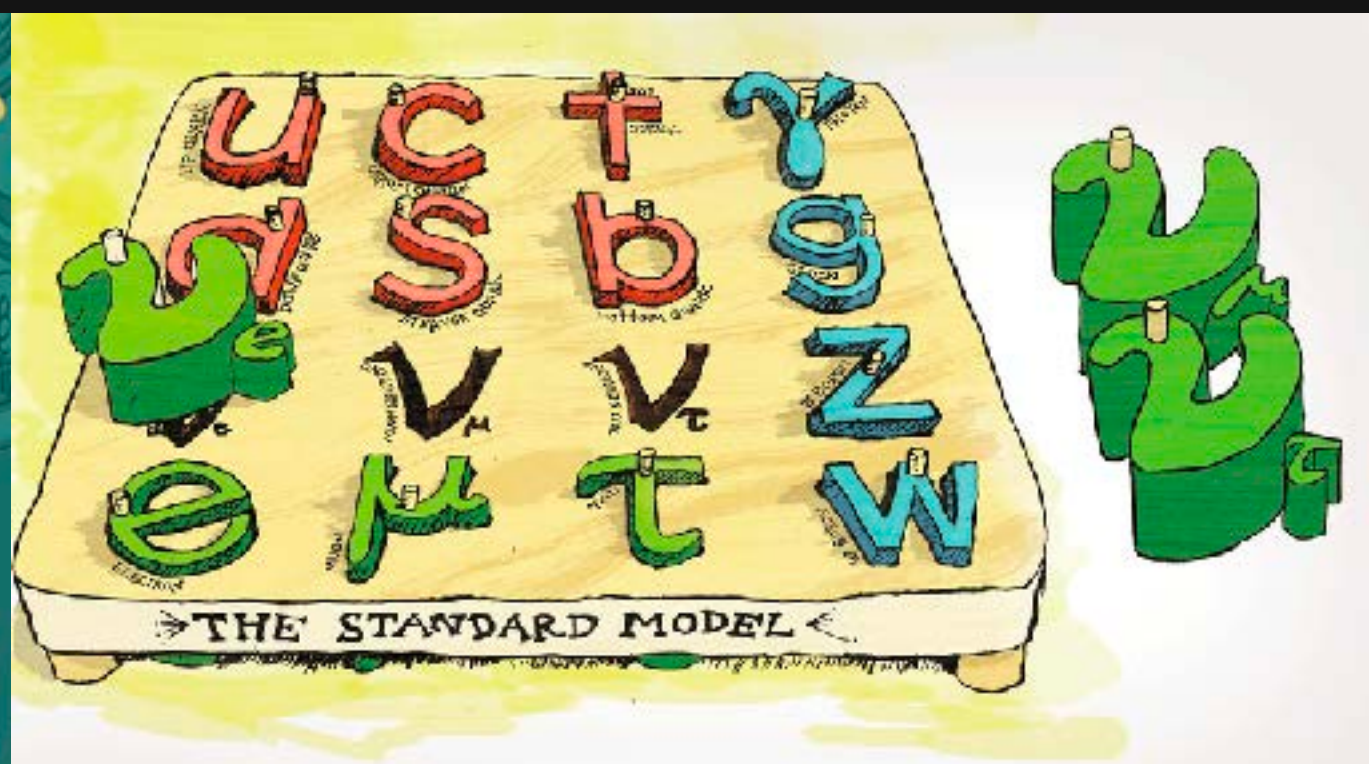


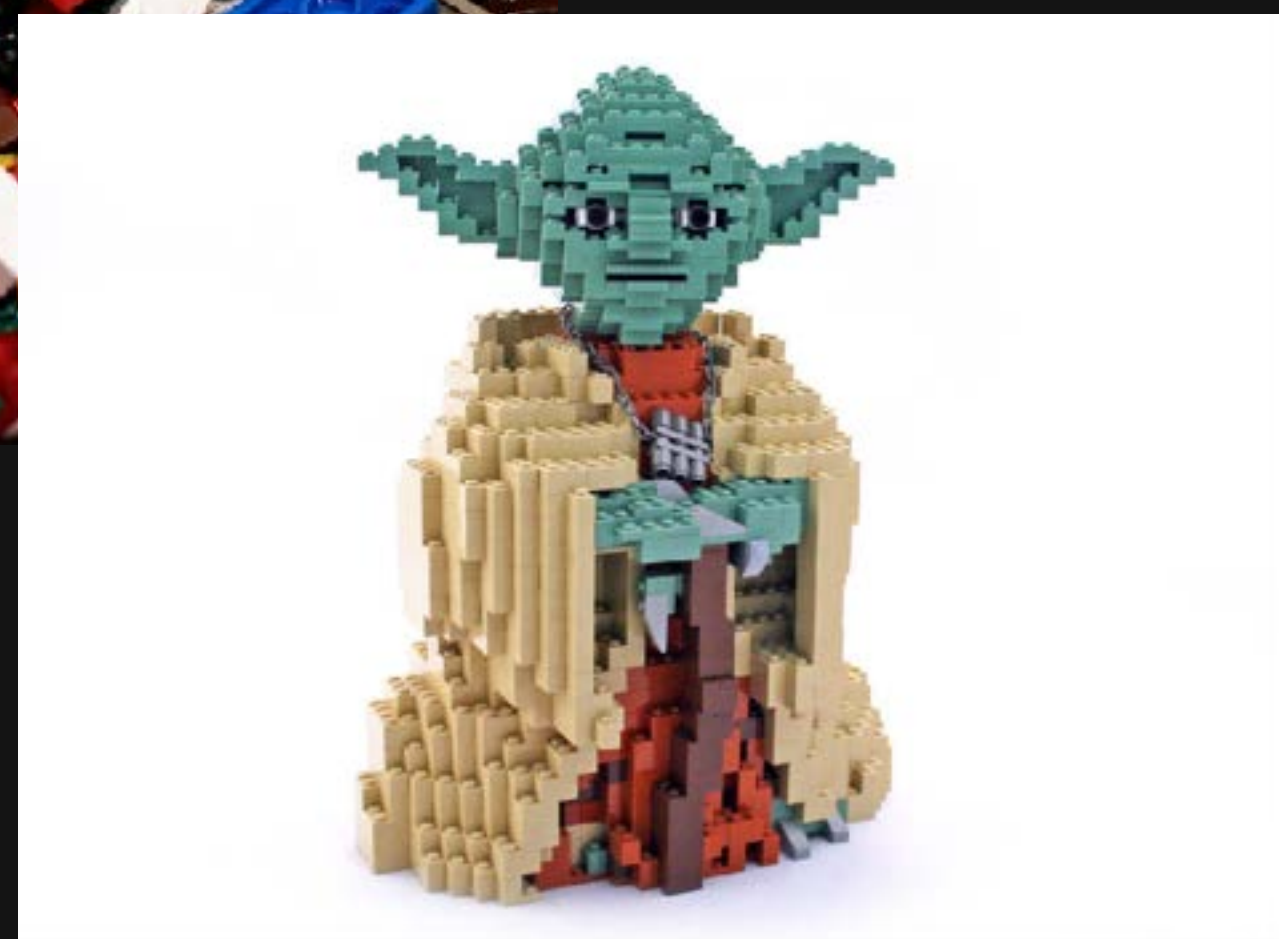
Neutrinos, from the lab to the cosmos

Kevin J. Kelly



**My motivating question:
What is everything made of?**

As a kid, I was a BIG Fan of LEGOs

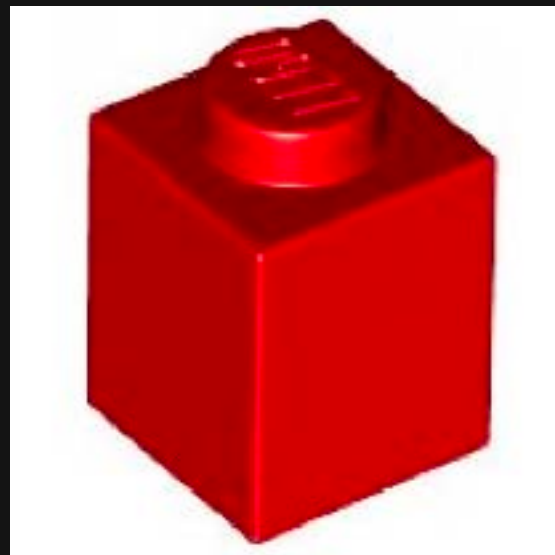


As far as LEGOs go, it's a fairly simple system: there are building blocks out of which we can make anything we want!

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

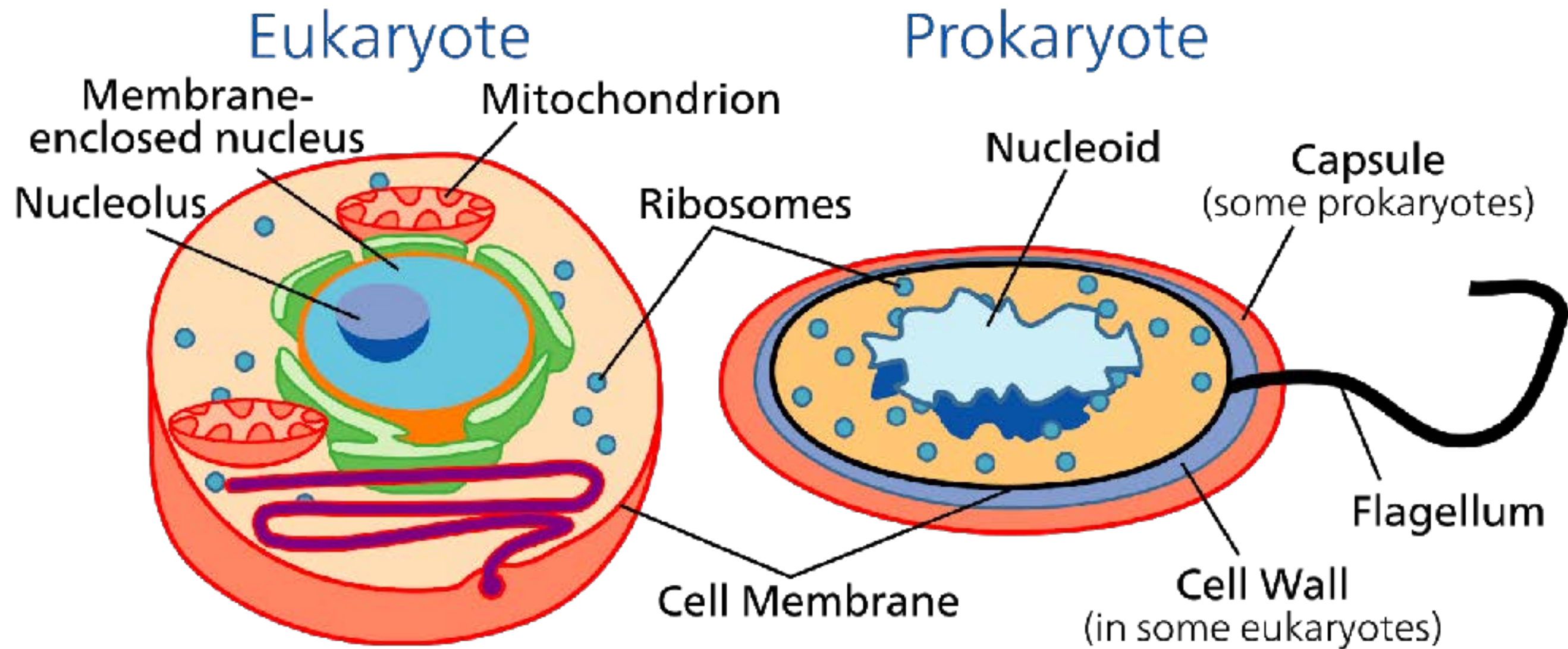


- ▶ But, we can find something even more fundamental:



- ▶ 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!

The Periodic Table of the Elements

atomic mass
or most stable mass number
1st ionization energy
in kJ/mol

atomic number
electronegativity

chemical symbol

name

electron configuration

oxidation states
most common one bold

alkali metals
alkaline metals
other metals
transition metals
lanthanoids
actinoids

metalloids
nonmetals
halogens
noble gases
unknown elements
radioactive elements have
masses in parentheses

electron configuration blocks

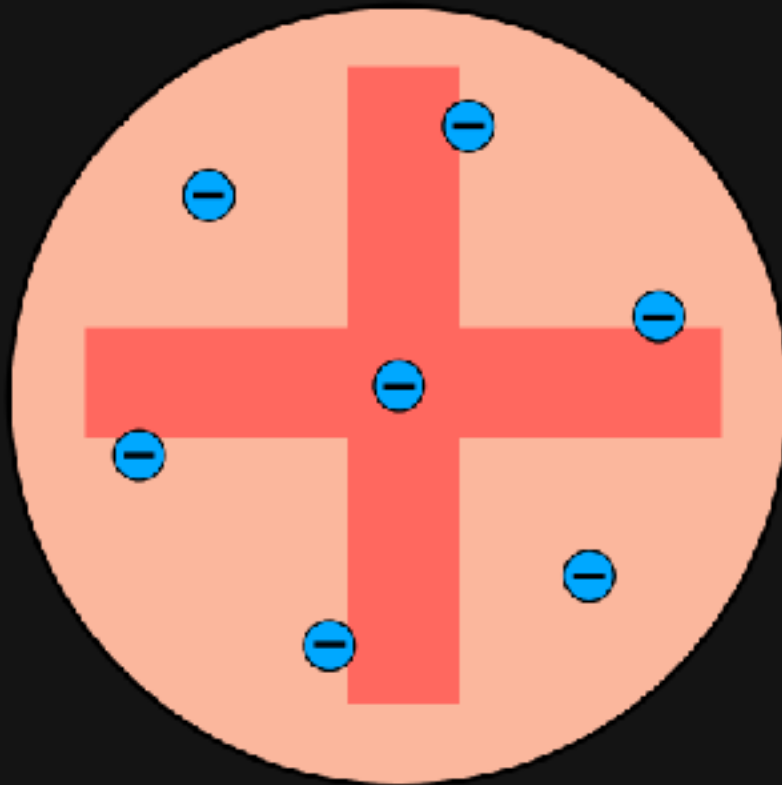
notes

- as of yet, elements 112-118 have no official name designated by the IUPAC
- 1.31 eV = 96.485 eV
- all elements are implied to have an oxidation state of zero

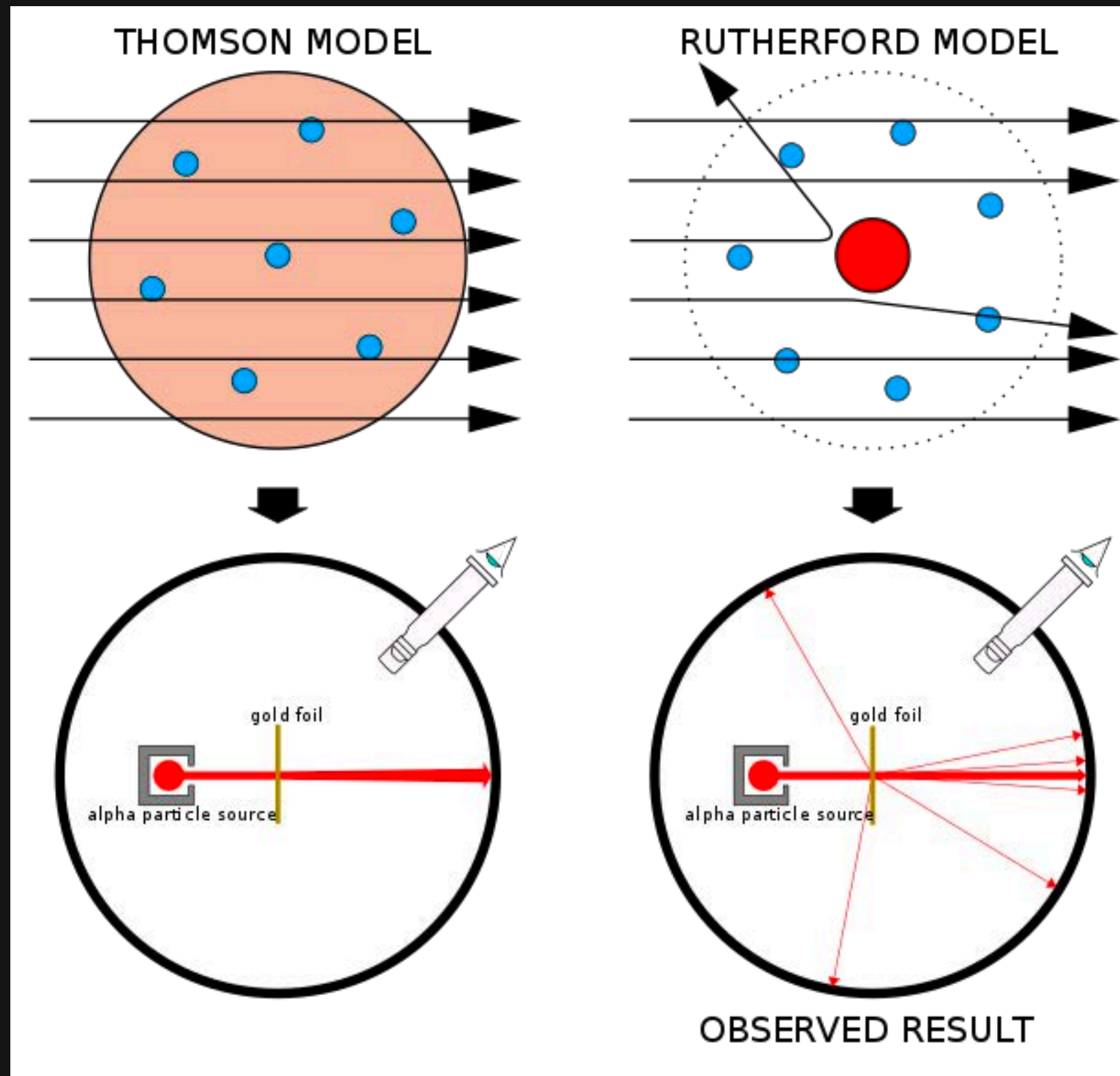
A chemist would say: everything is built up from atoms

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:



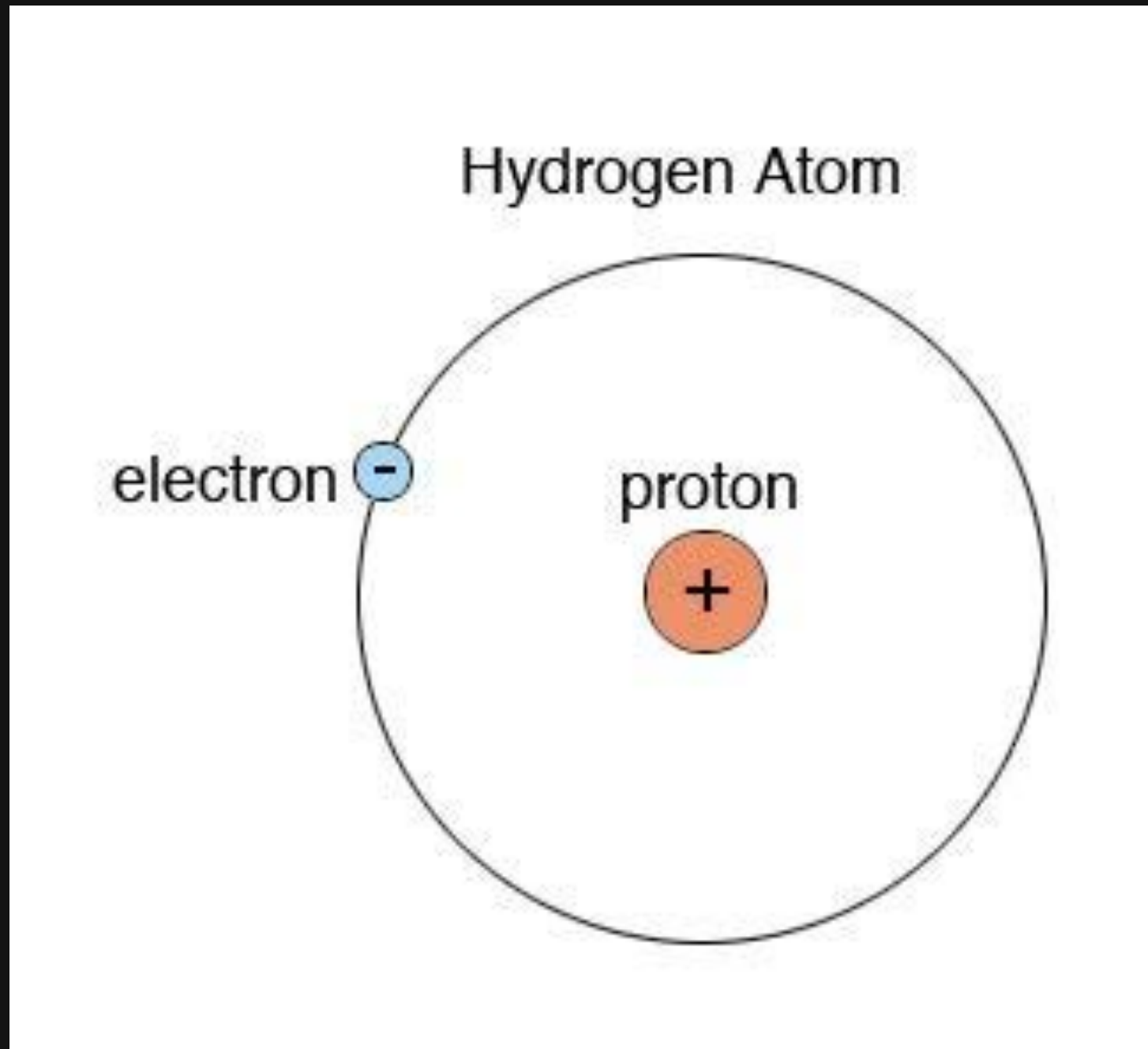
The Geiger-Marsden Experiment



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

Let's take a closer look at Hydrogen

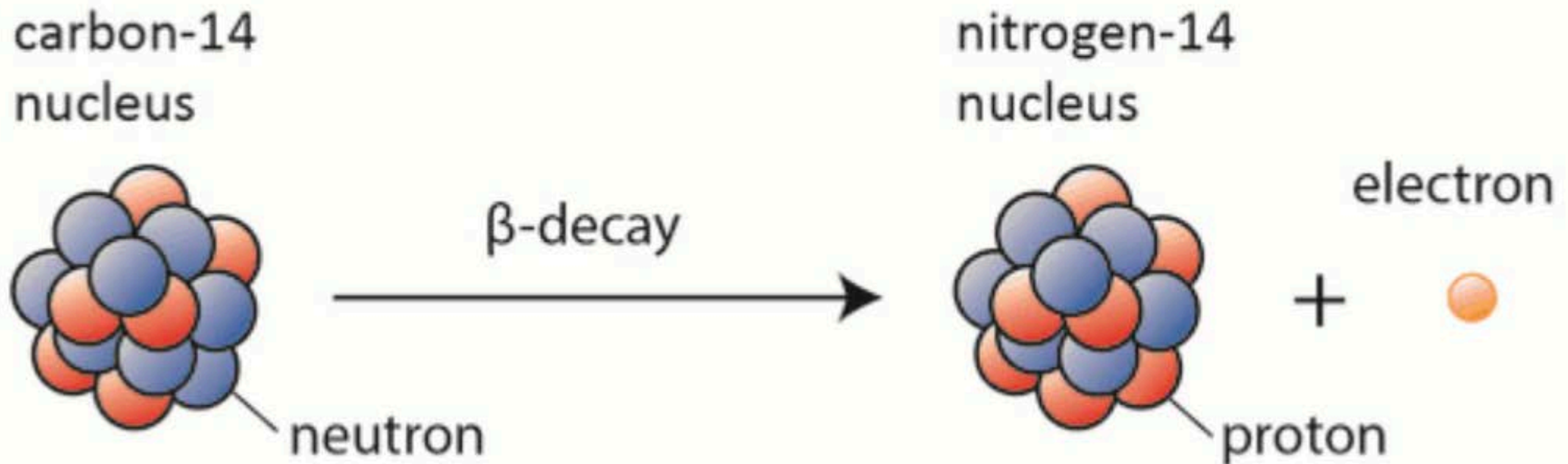
Hydrogen is the simplest atom possible: one heavy proton sitting at the center, and one very light electron around it.



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

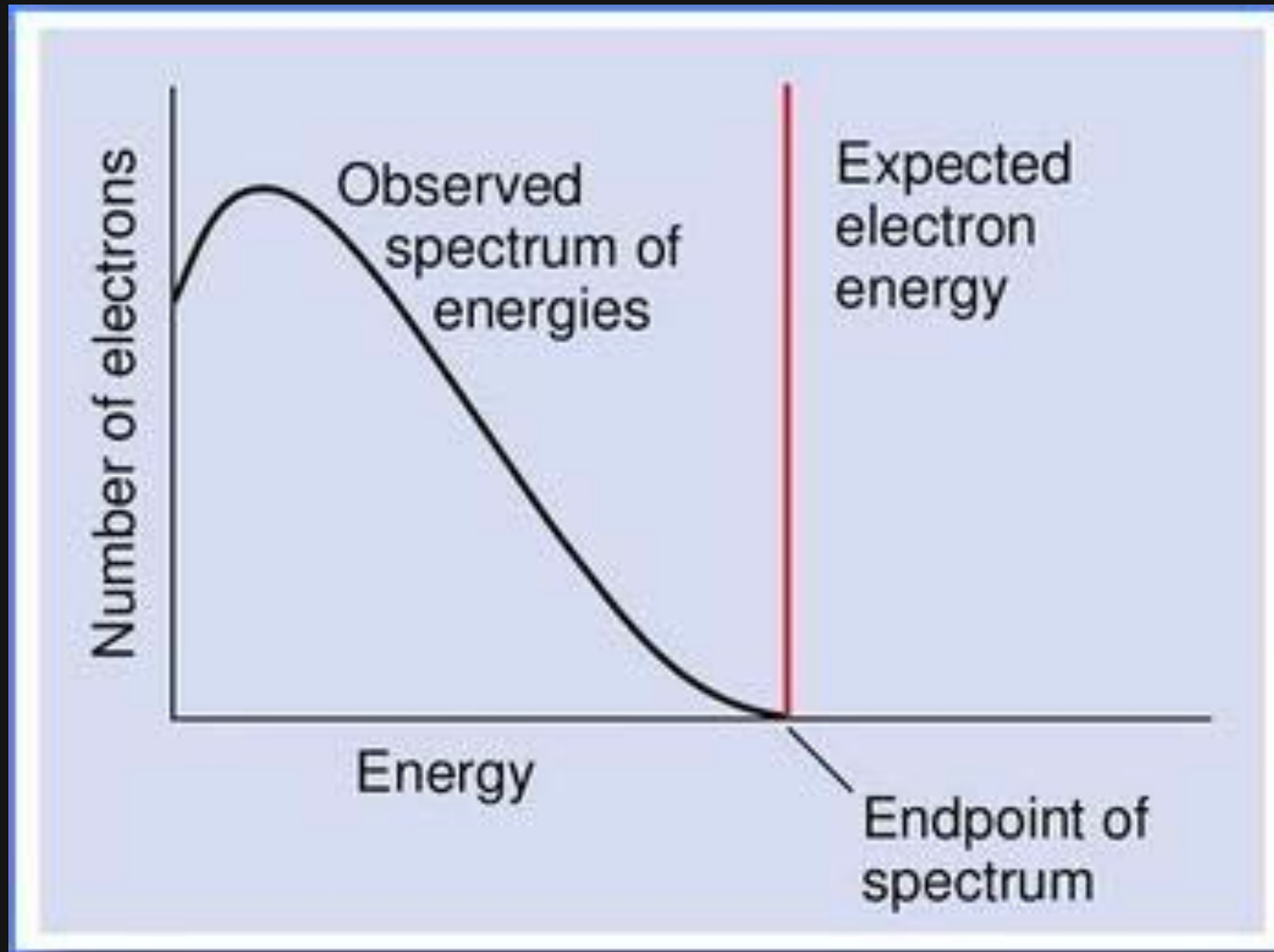
- ▶ Shortly after discovering protons, chemists started to see odd properties of certain elements. Occasionally, an atom will decay into a different type of element!



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 versweiferten 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 Grössenordnung 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.



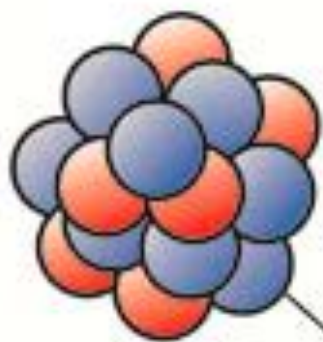
Dear radioactive ladies and gentlemen...

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

Dear Radioactive Ladies and Gentlemen,

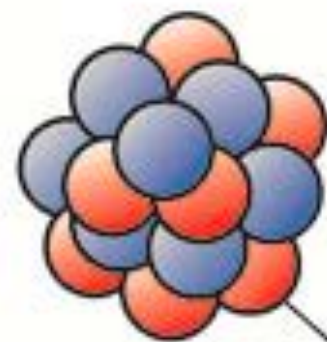
As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, because of the "wrong" statistics of the N- and Li-6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" (1) of statistics and the law of conservation 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.

carbon-14
nucleus



β -decay

nitrogen-14
nucleus



electron

antineutrino

+

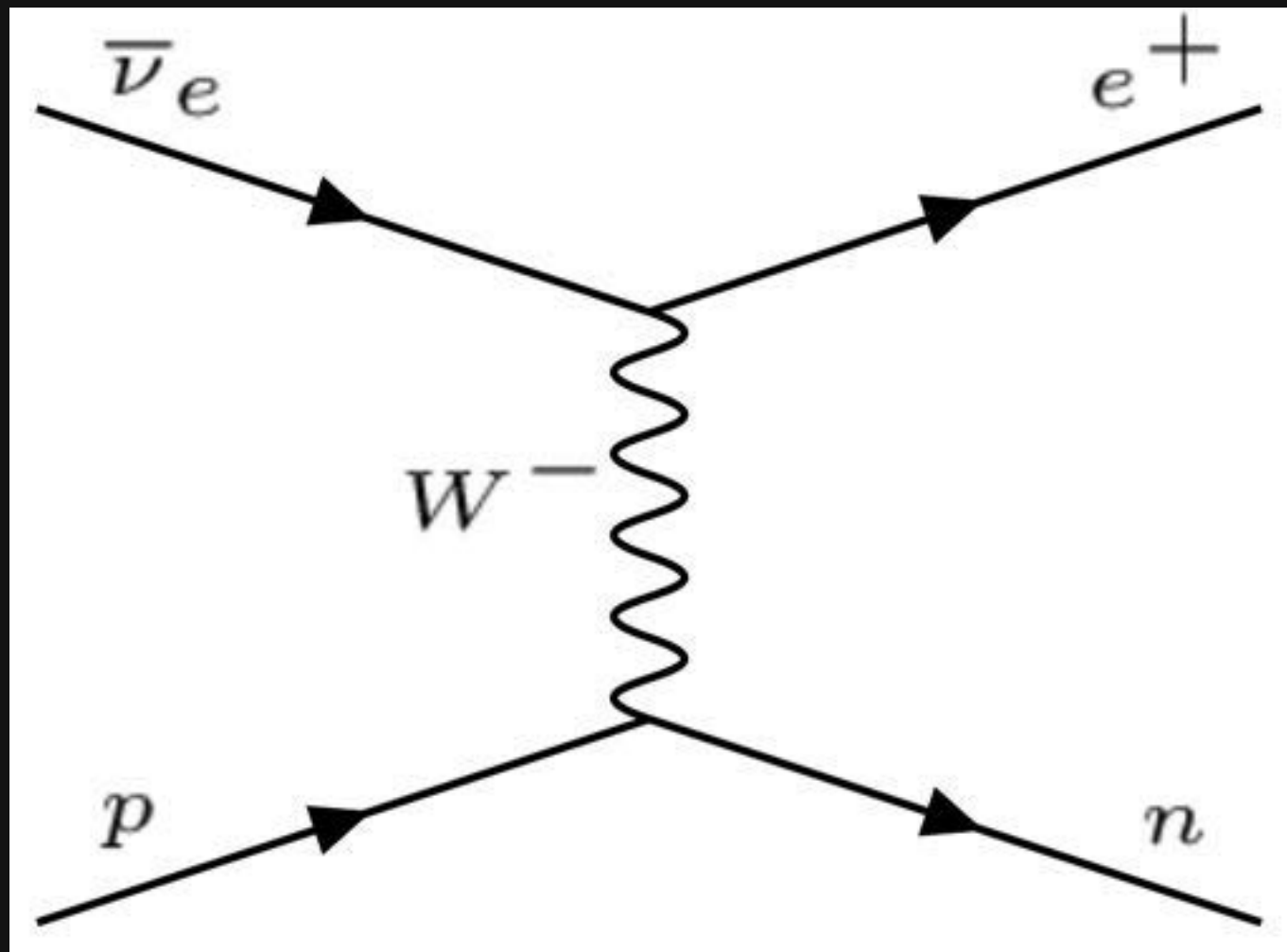


+



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

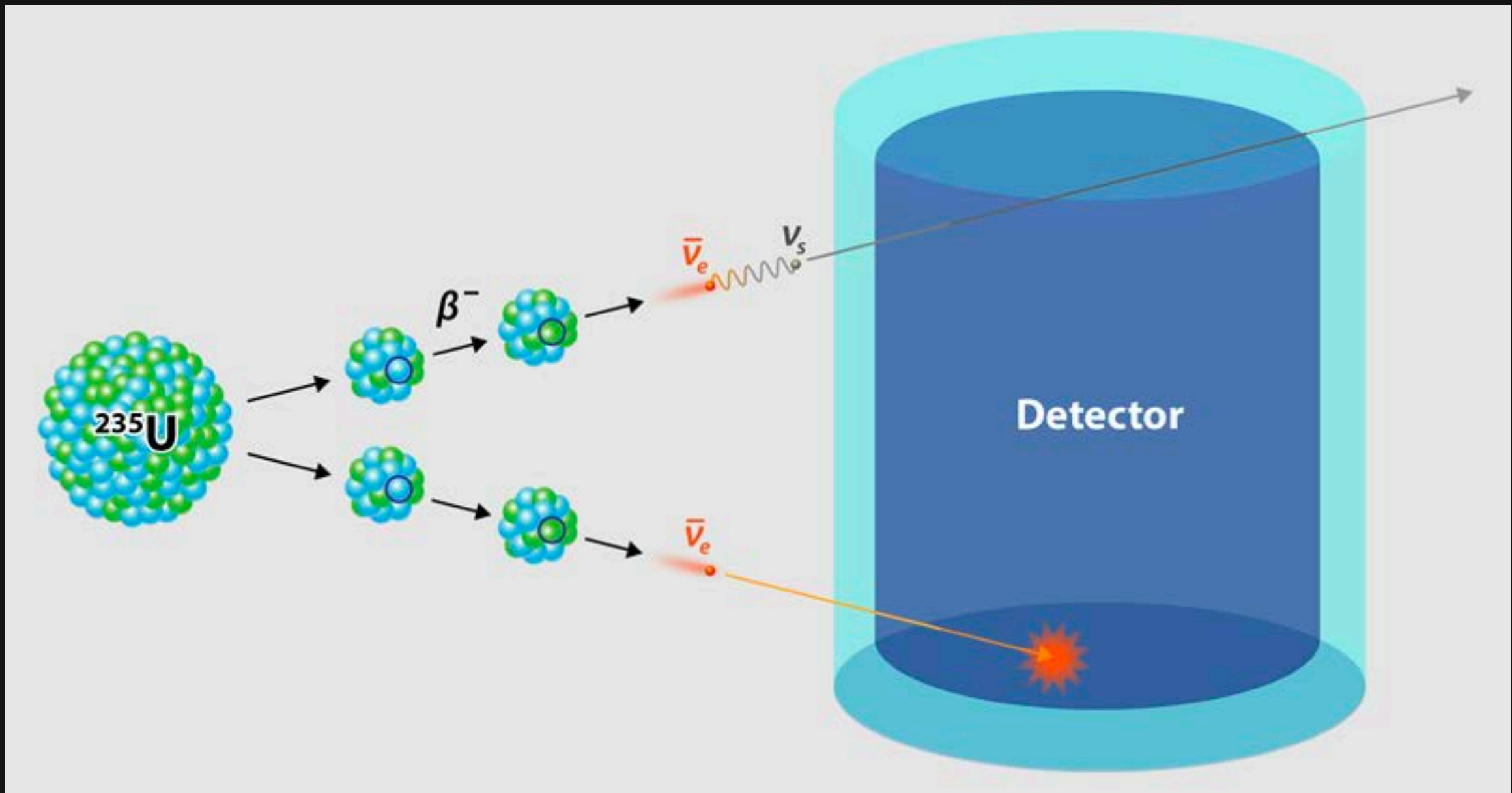
- ▶ Given how often we see nuclei decay, we can also infer how rare it is for a neutrino to interact with ordinary matter.
- ▶ In general, a neutrino can travel through a *lightyear* of lead before coming to a stop!



How the heck could we hope to detect these?!

We need an INTENSE source of neutrinos!

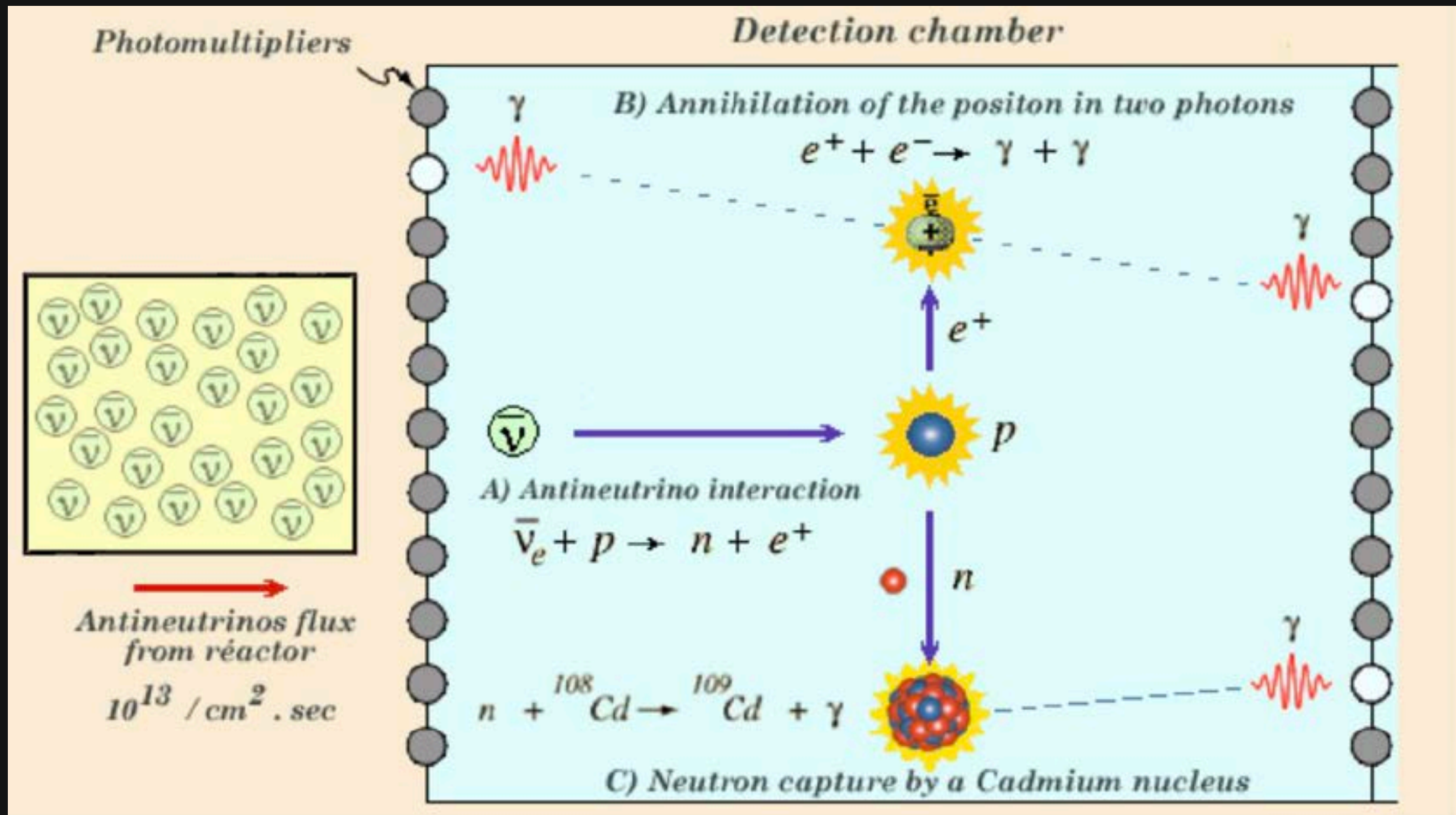
- Some of the most intense sources of neutrinos: nuclear reactors.



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!

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

Finally, a third neutrino: 2001

- ▶ The DONUT 🍩 Experiment detected the third flavor, ν_τ

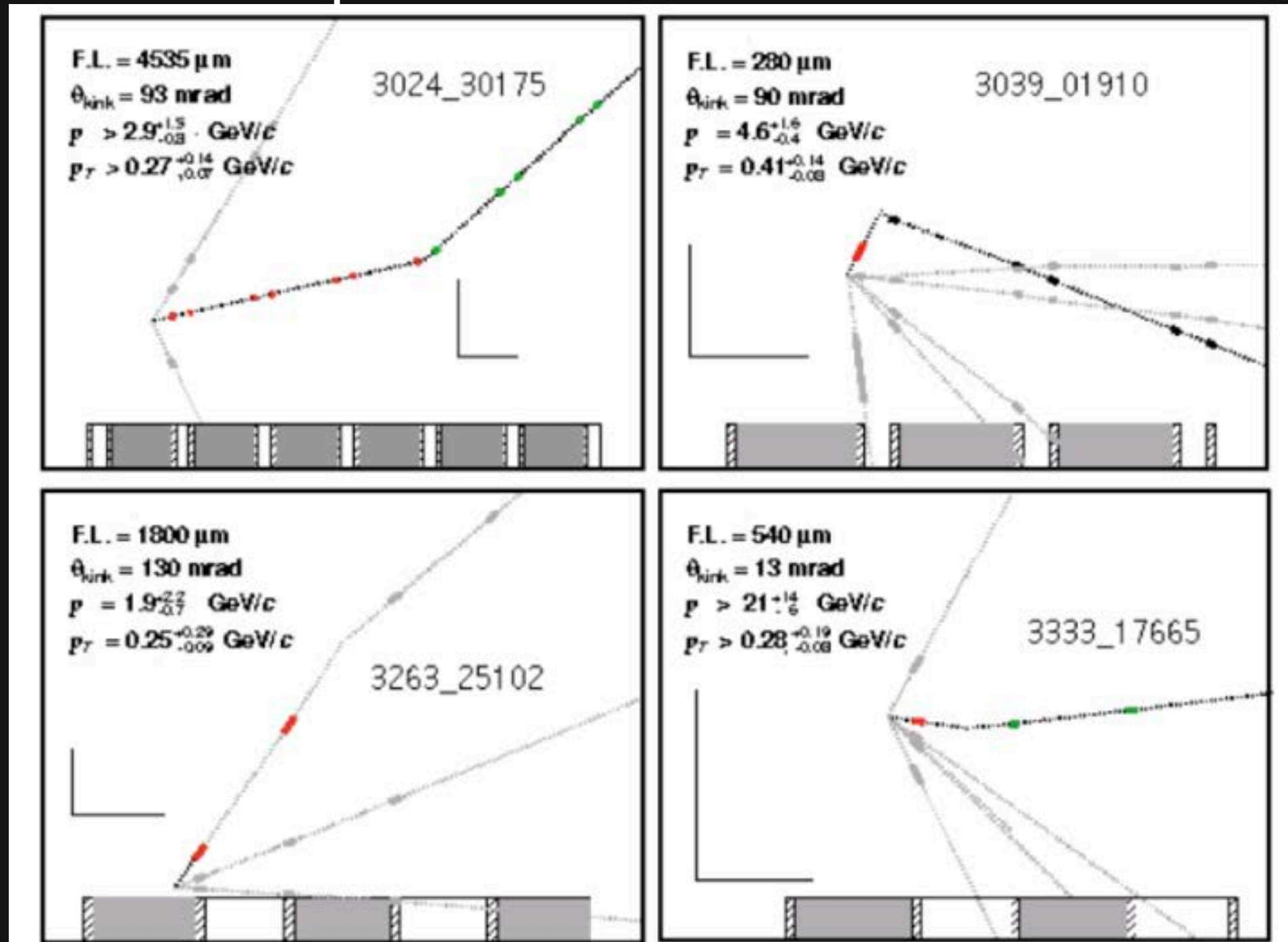


Figure 4-6: The four tau neutrino charged current events. The scale is given by the perpendicular lines (vertical: 0.1 mm, horizontal: 1 mm). The bar on the bottom shows the target material (solid: steel, hatched: emulsion, clear: plastic base).

Finally, a third neutrino: 2001

- The DONUT 🍩 Experiment detected the third flavor, ν_τ

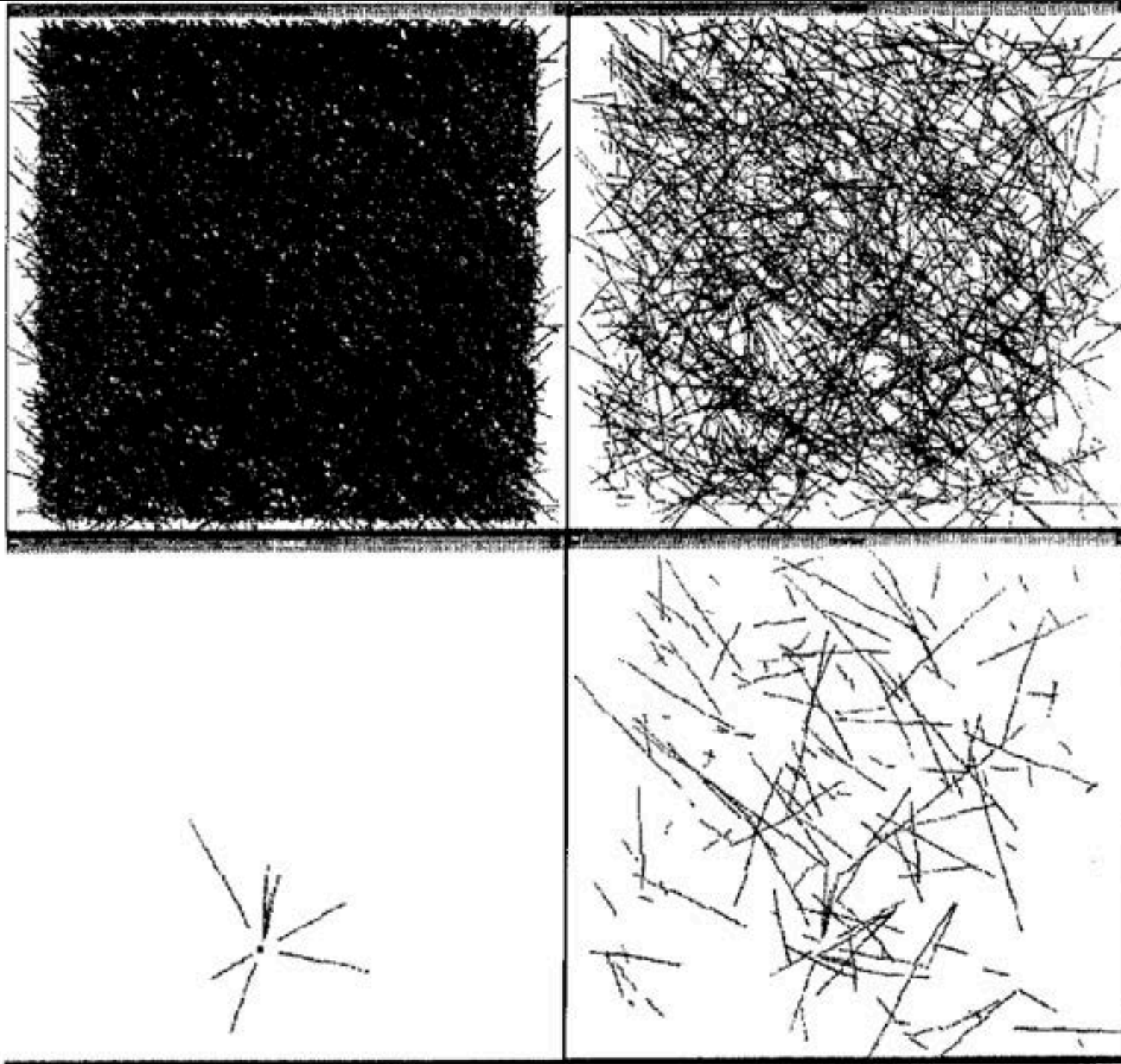
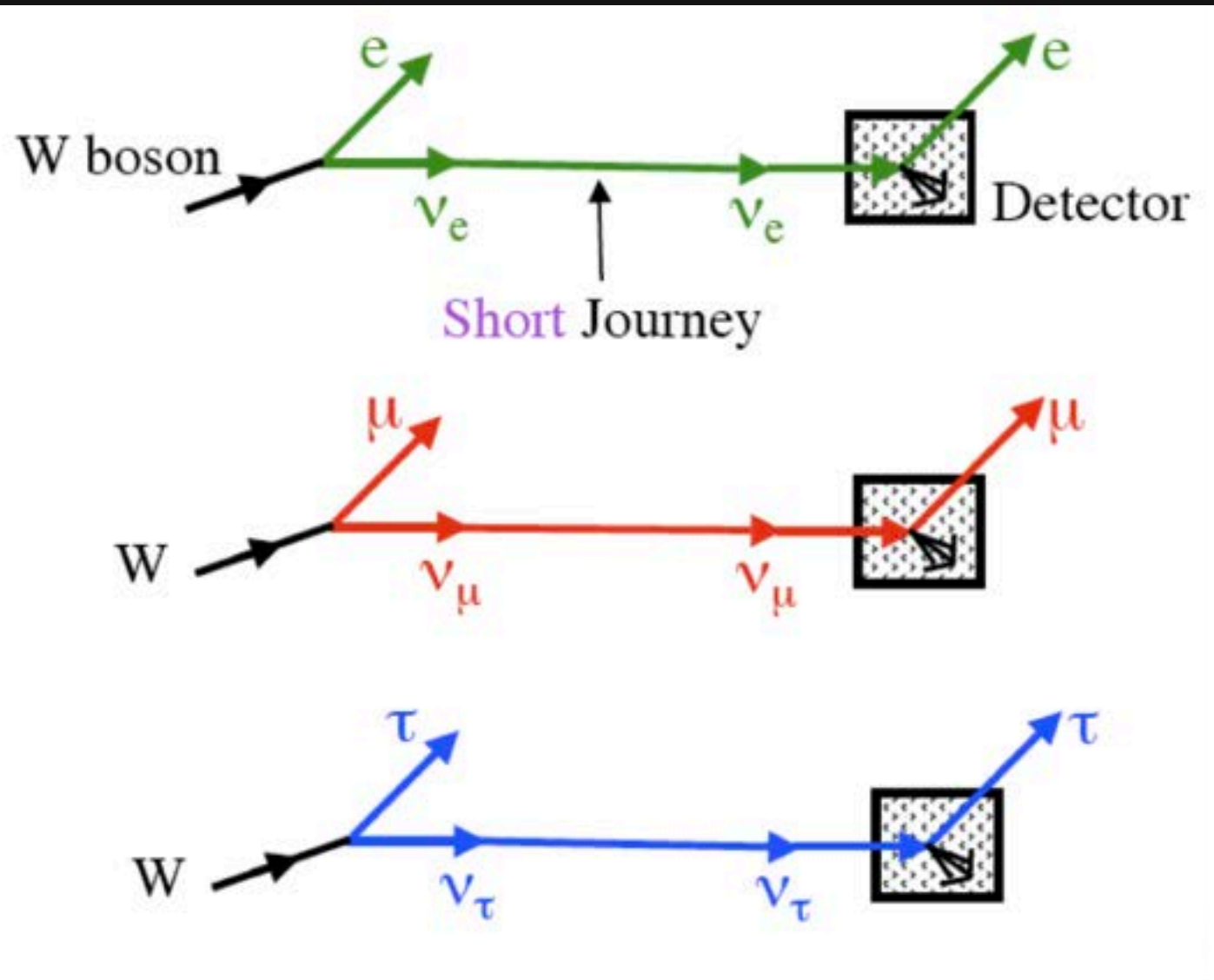


図 5.12: net scan 反応点探索の各段階 (左上から時計回り)。1) 読み込んだ全ての飛跡 ($5 \times 5\text{mm}^2$)、2) 測定領域を突き抜けている飛跡の排除、3) 低運動量の飛跡の排除、4) 一点 ($4\mu\text{m}$ 以内) 収束している飛跡

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

(late 1990s)

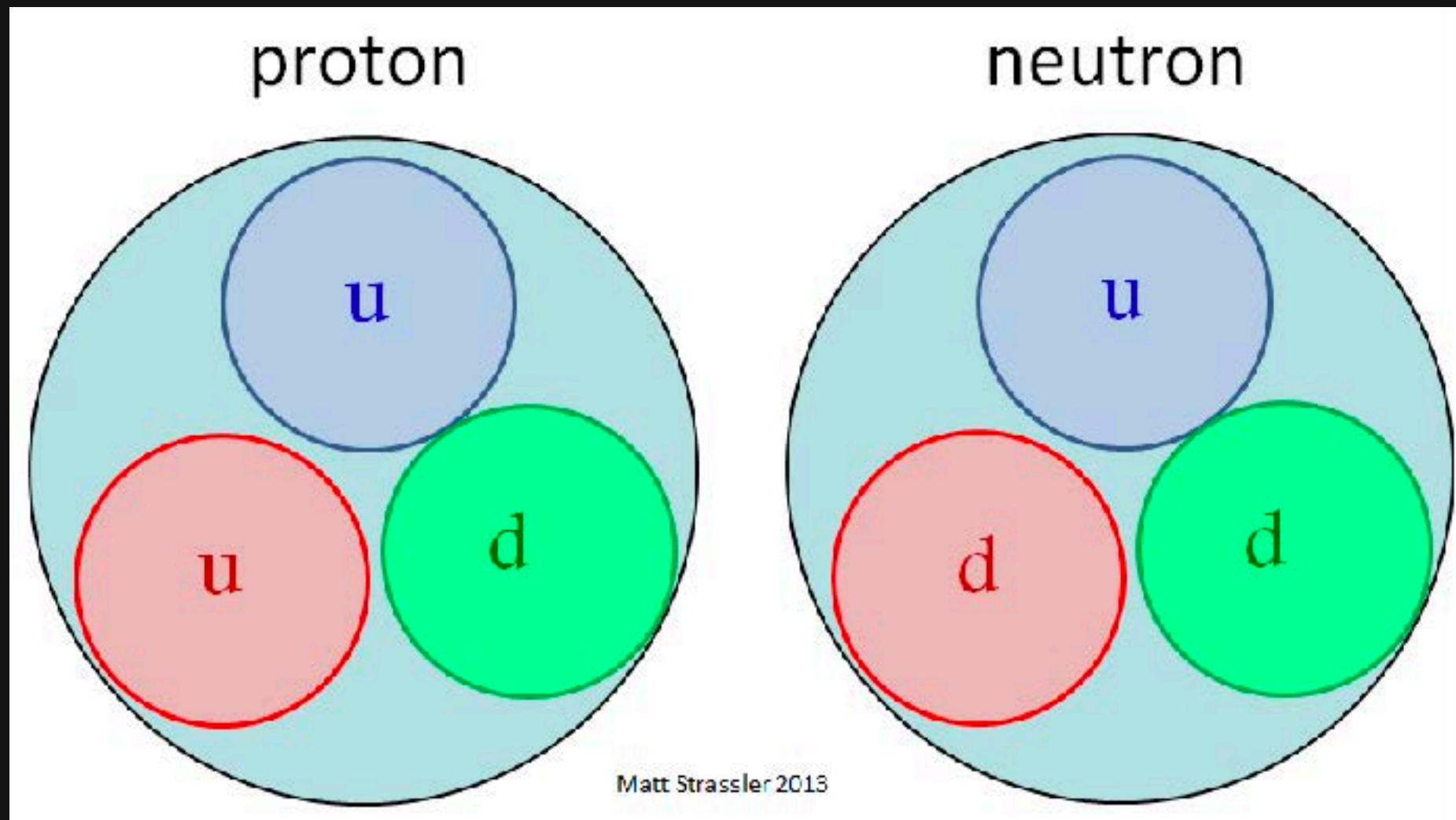


- ▶ Three types (flavors) of neutrinos, that are associated with each charged lepton.
- ▶ Massless (like light photons)
- ▶ Interact *very* rarely.

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"

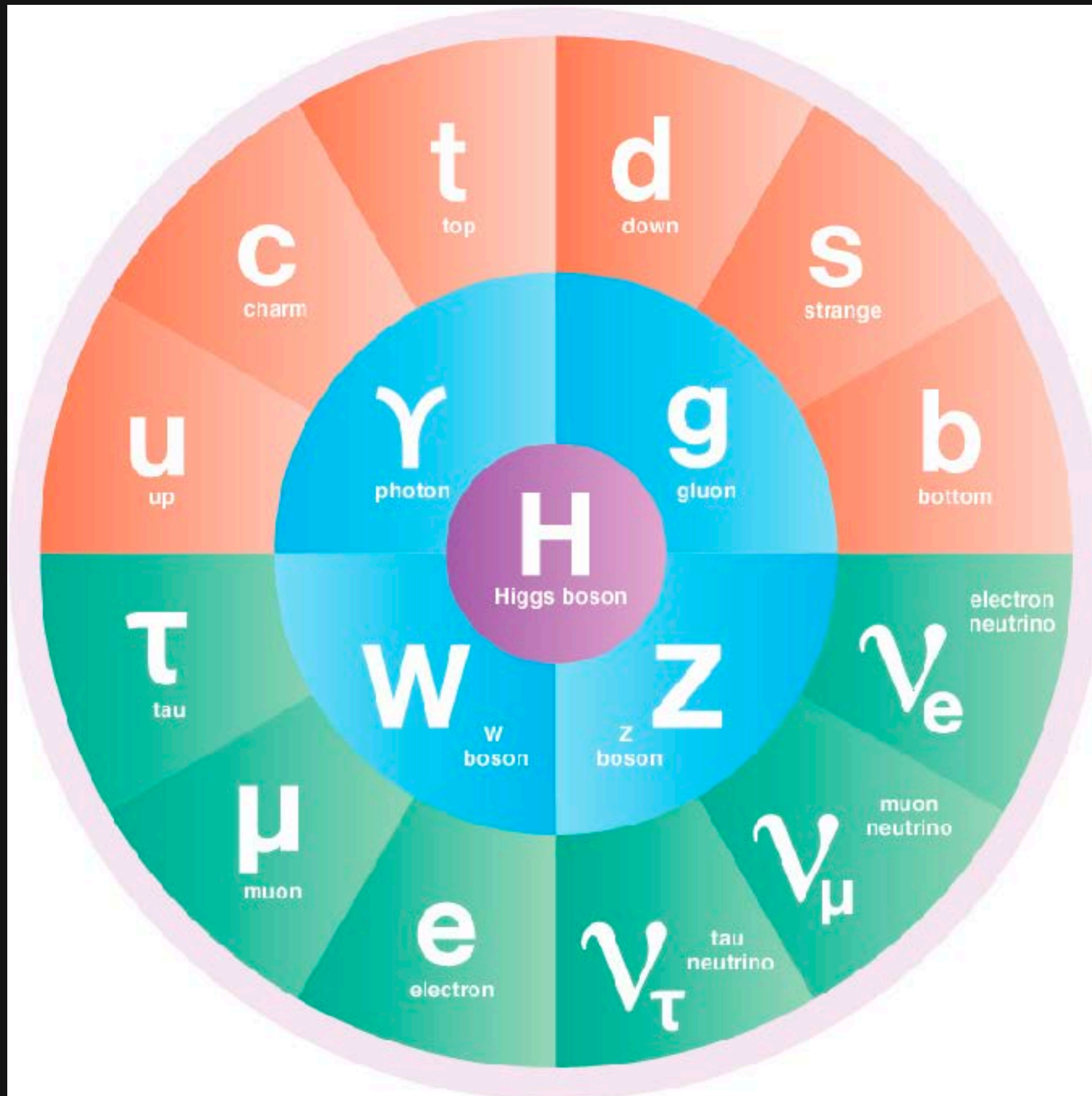


We also started finding heavier “copies” of the particles we knew of

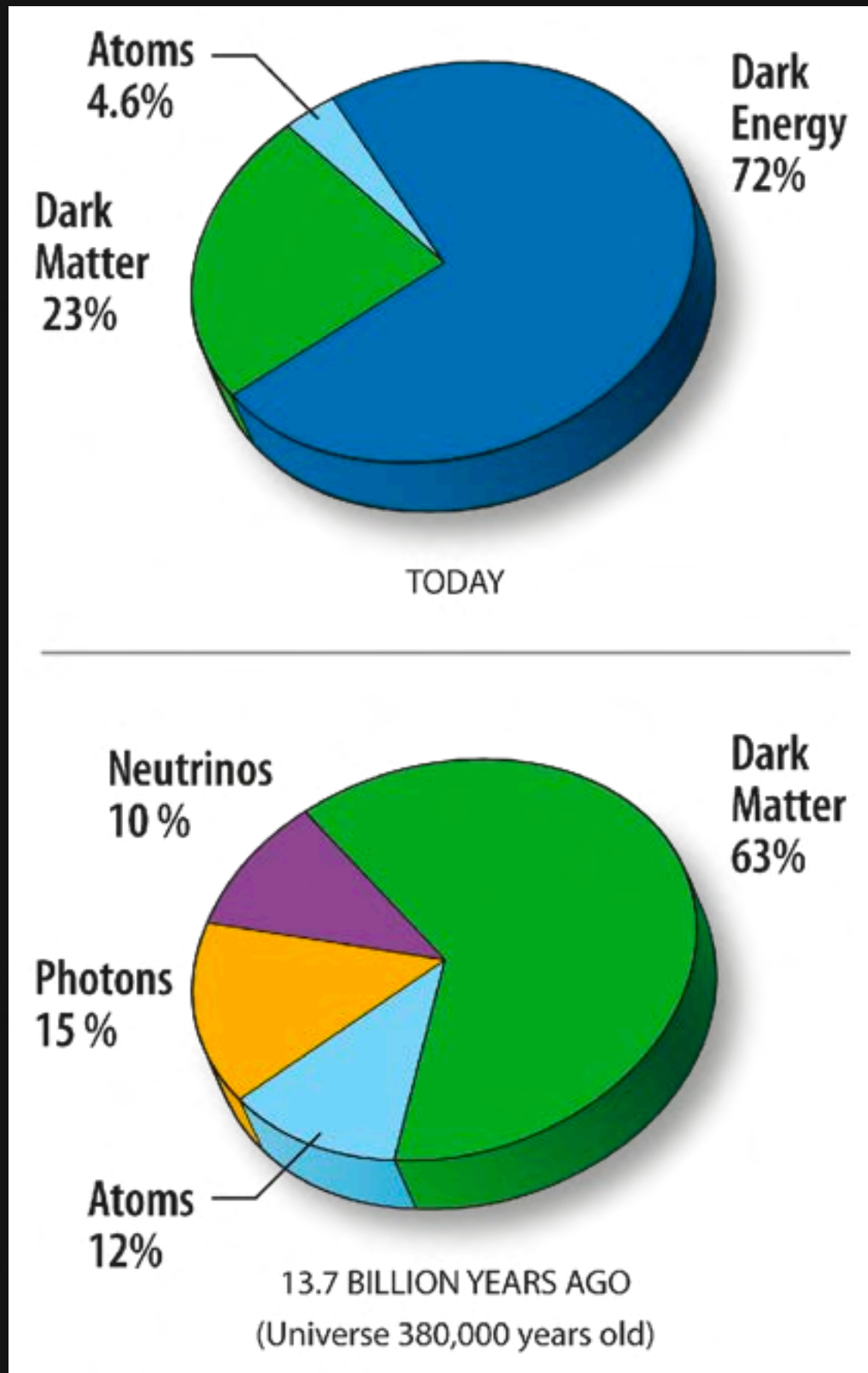
The Standard Model of Particle Physics

	FERMIONS (matter particles)			BOSONS (force carriers)	
QUARKS	 up	 charm	 top	 gluon	 Higgs boson
	 down	 strange	 bottom	 photon	
				 Z boson	
LEPTONS	 electron	 muon	 tau		
	 electron neutrino	 muon neutrino	 tau neutrino	 W boson	

Allowed us to Build a “New Periodic Table”



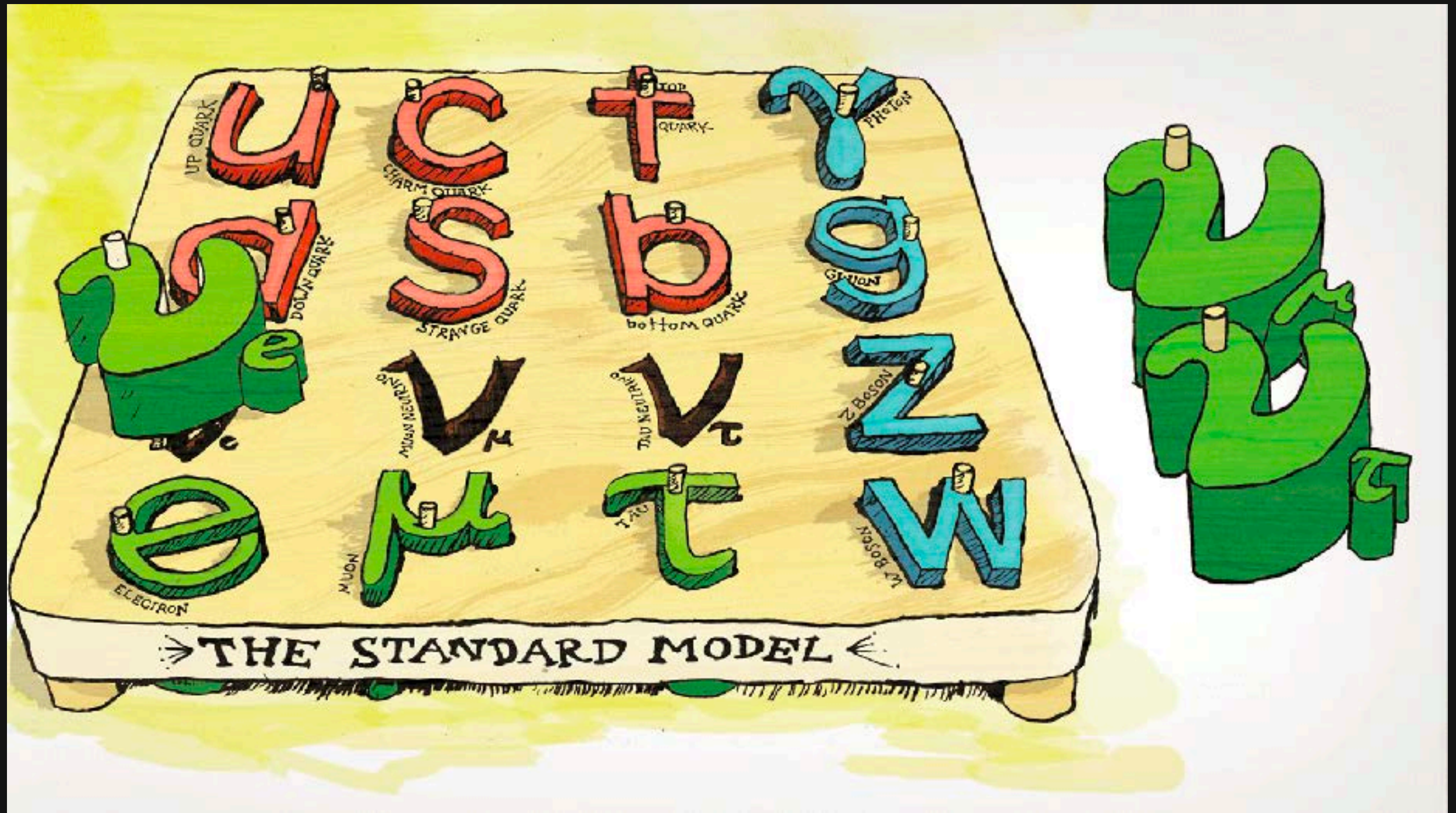
The Standard Model has its own Mysteries...



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!

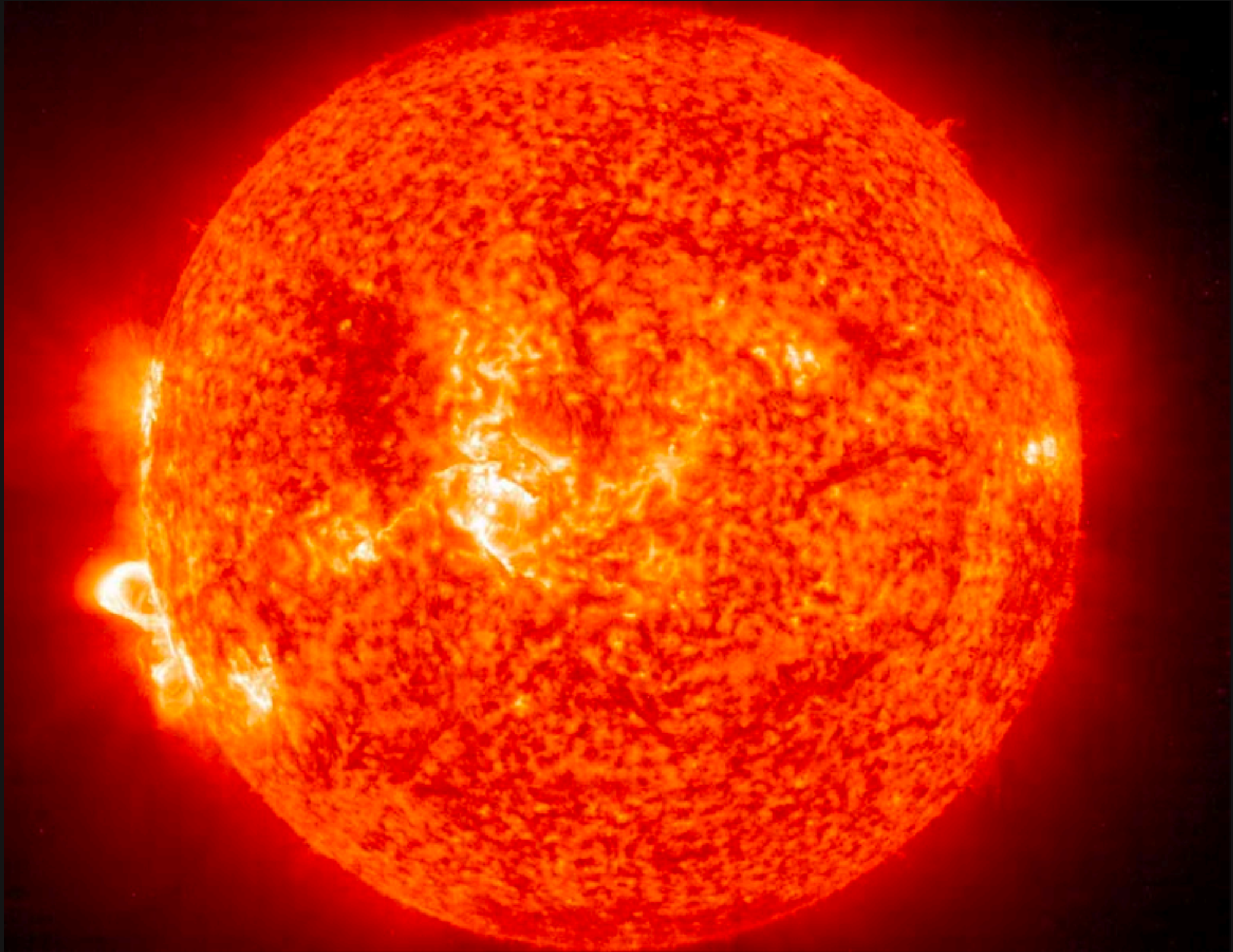
The Standard Model and Neutrinos



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

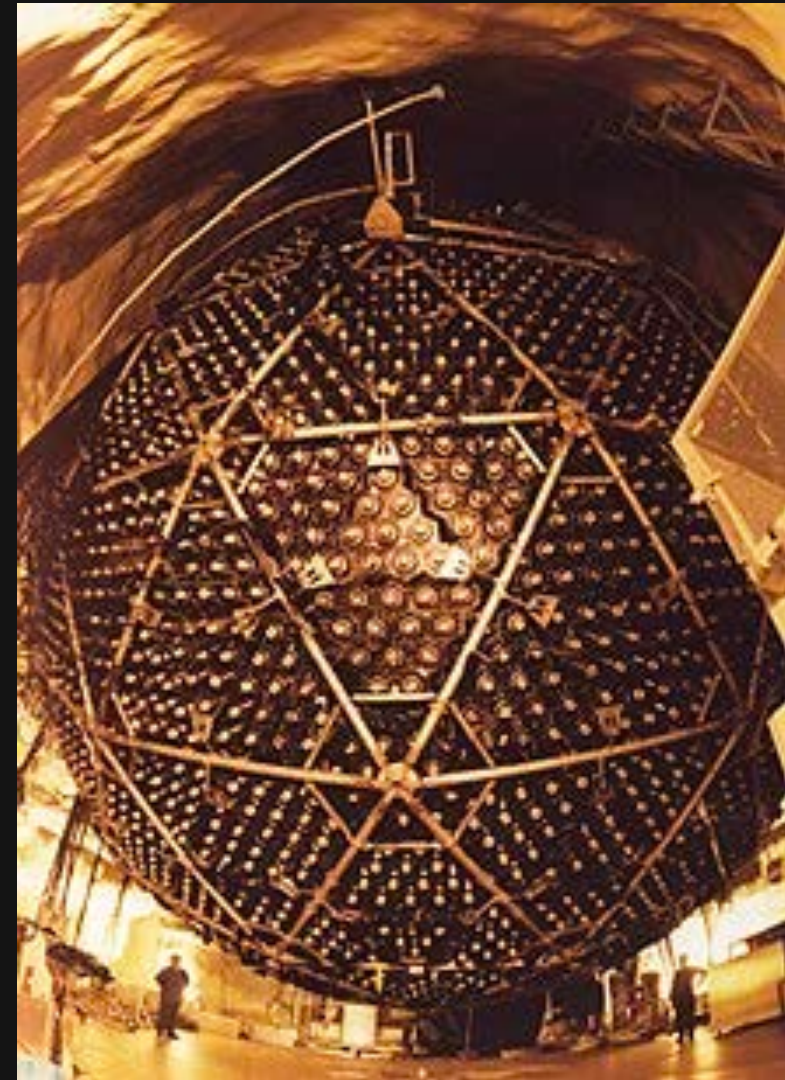
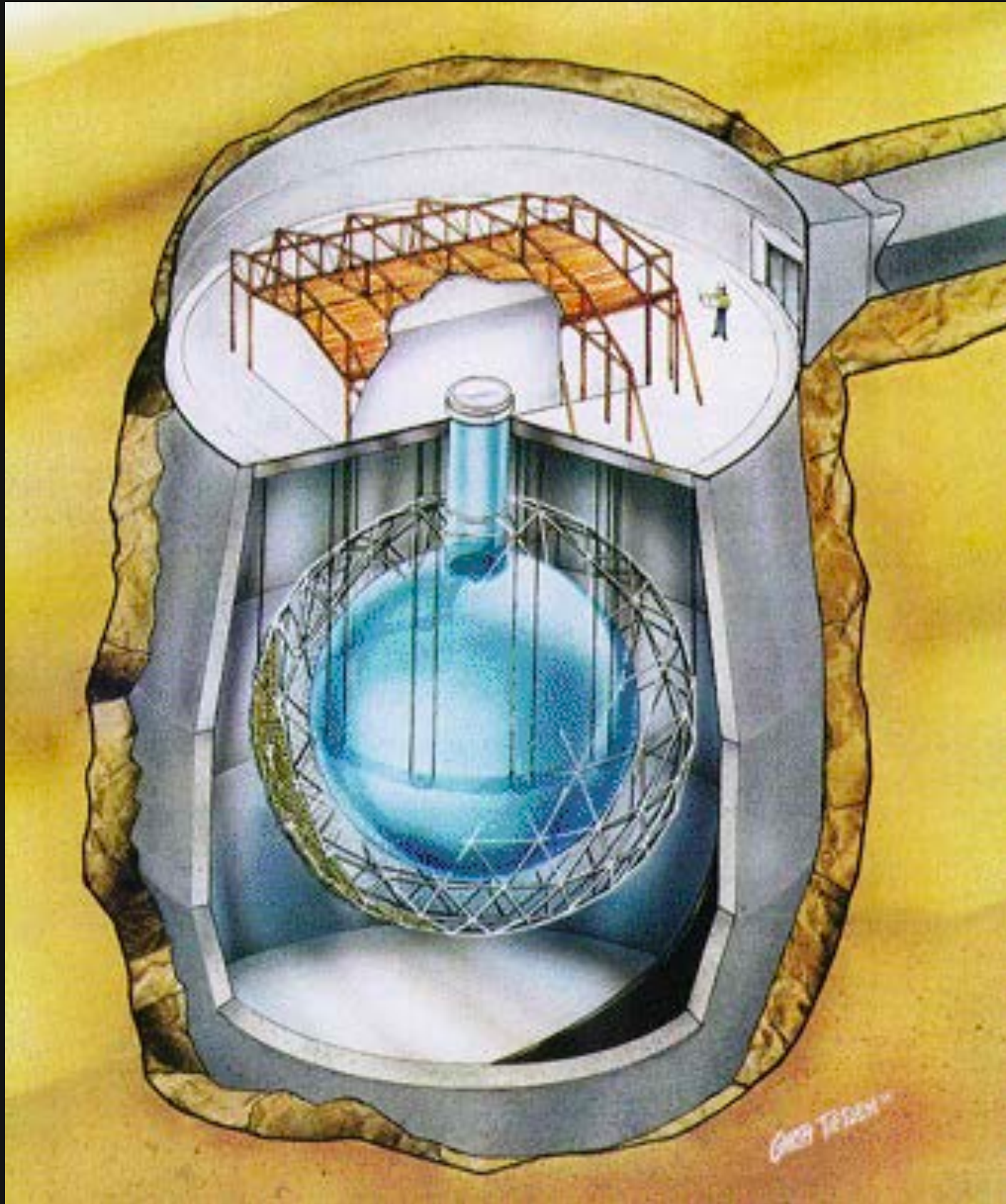
Neutrino Puzzles

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!

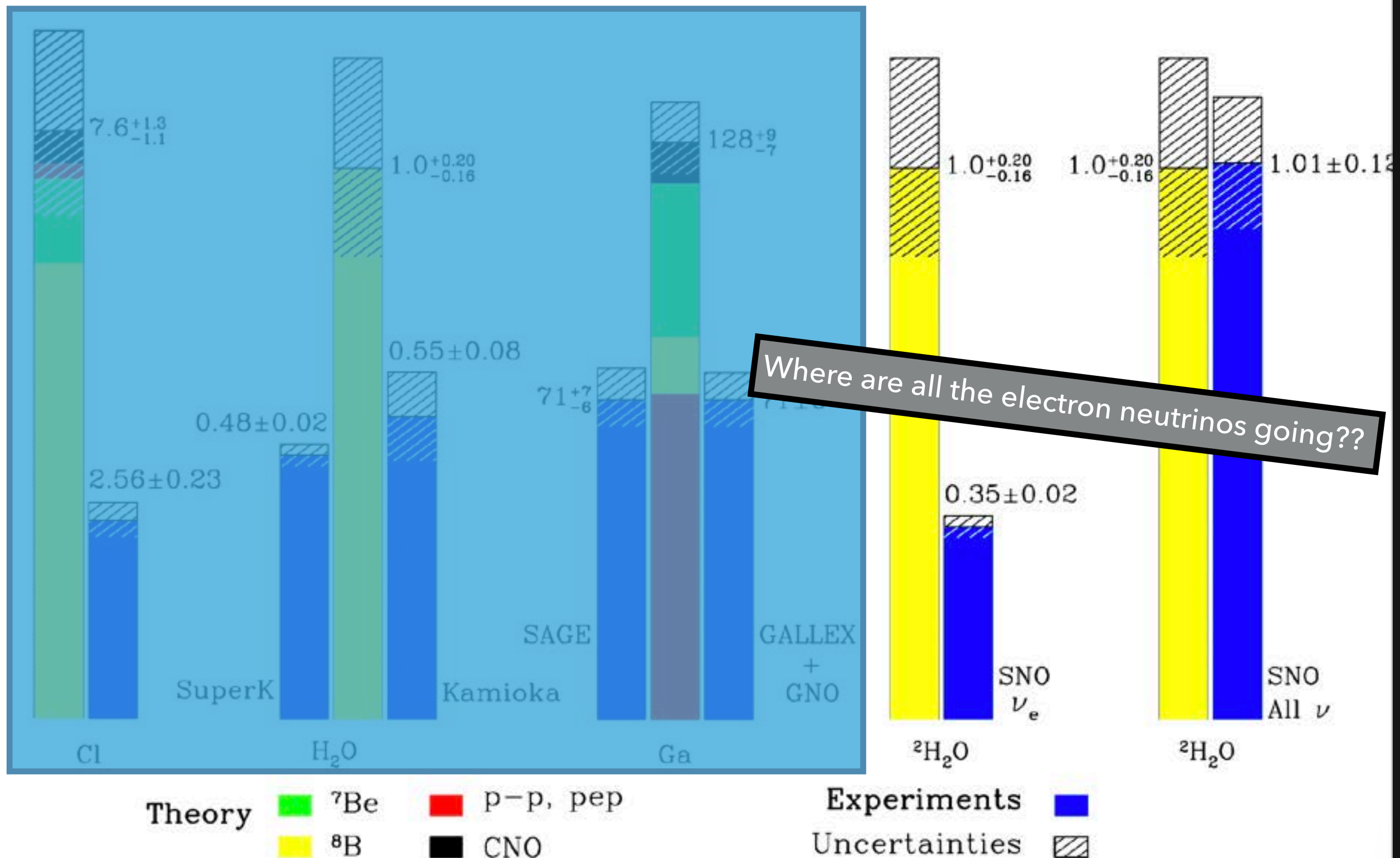
The SNO Experiment — Sudbury Neutrino Observatory



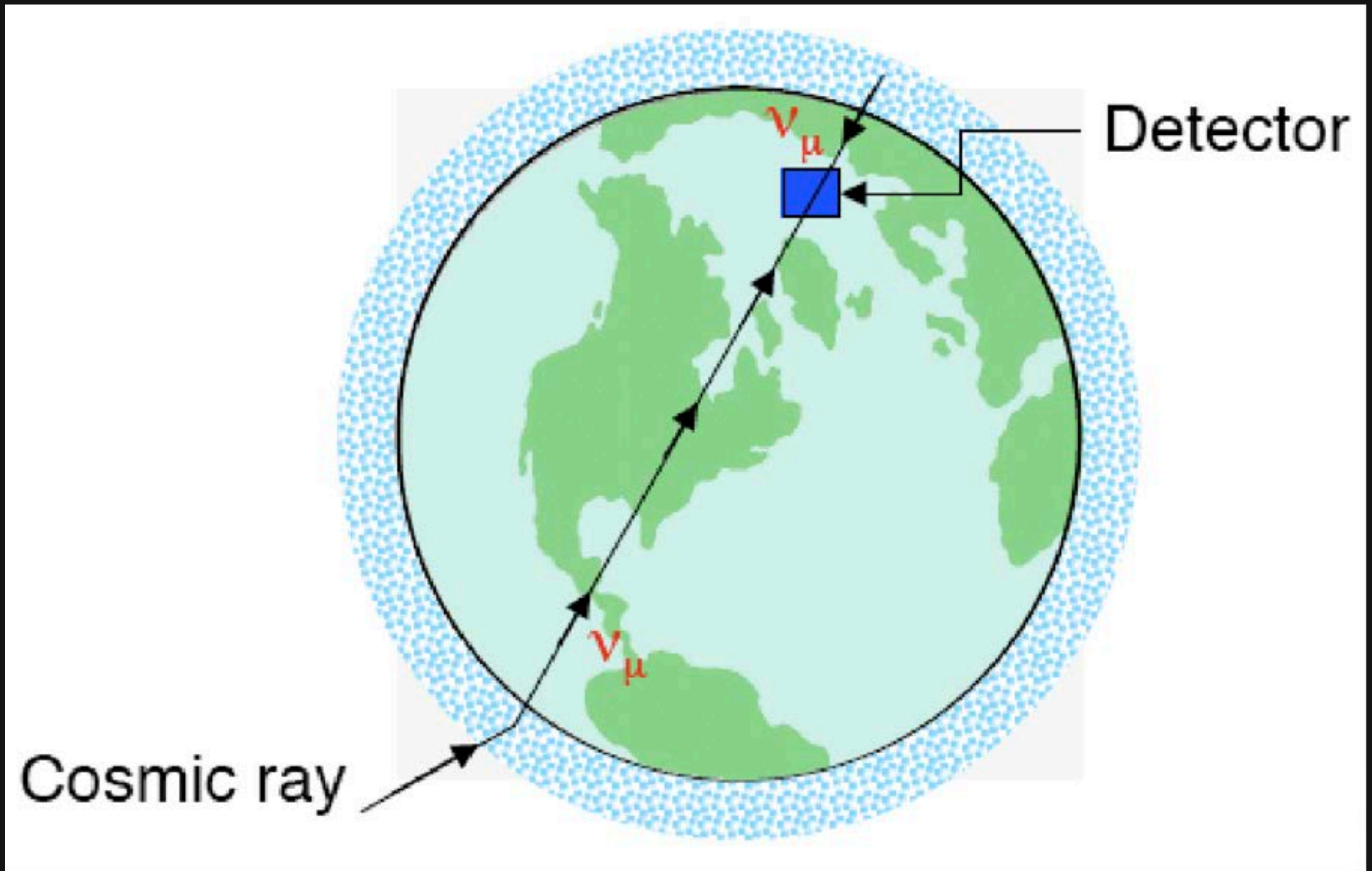
A giant tank of “heavy” water, deep underground, looking for neutrinos coming from the Sun.

The SNO Experiment's Results

Total Rates: Standard Model vs. Experiment
Bahcall-Pinsonneault 2000



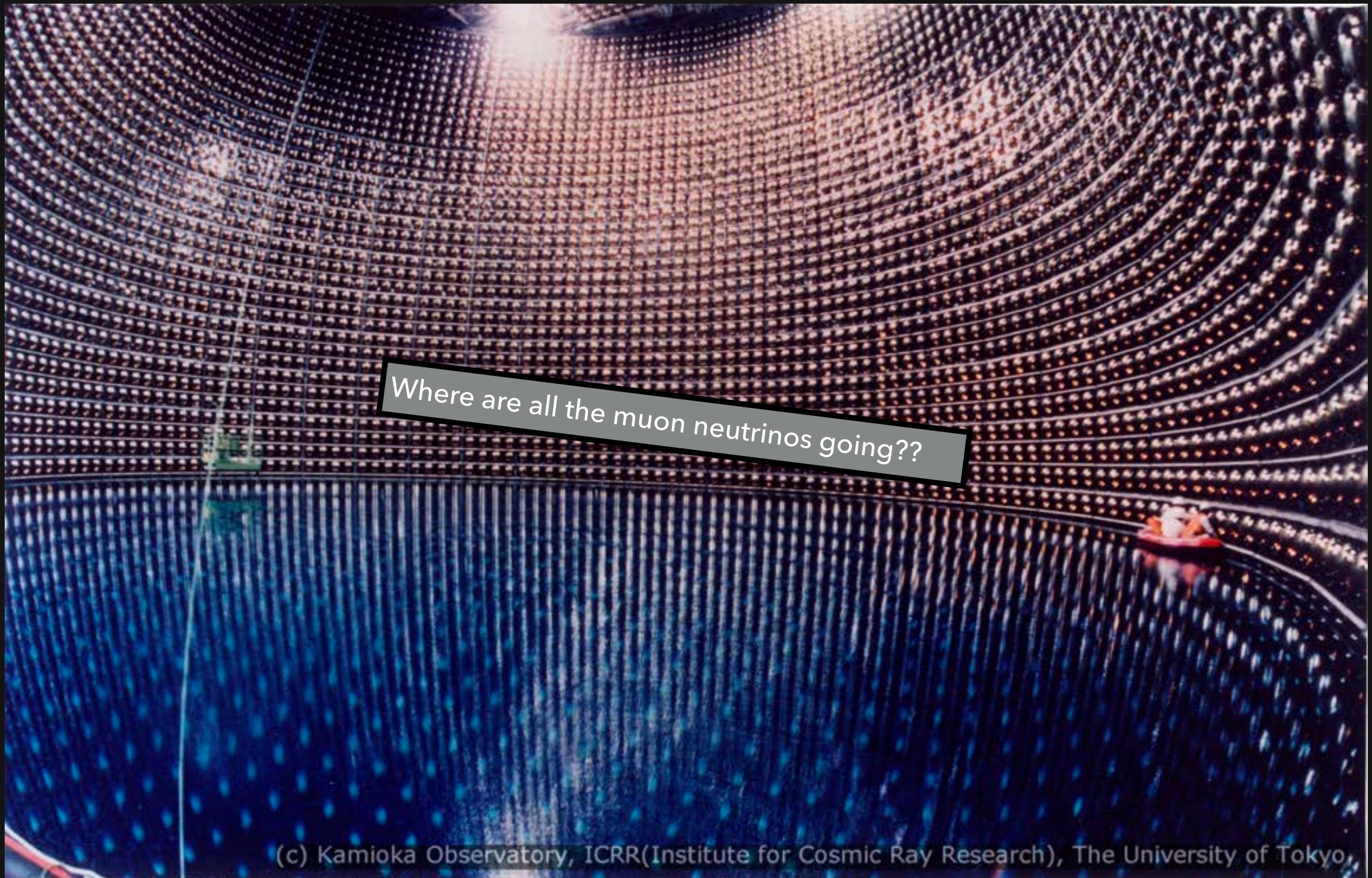
One more Puzzle: Atmospheric Neutrinos



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)

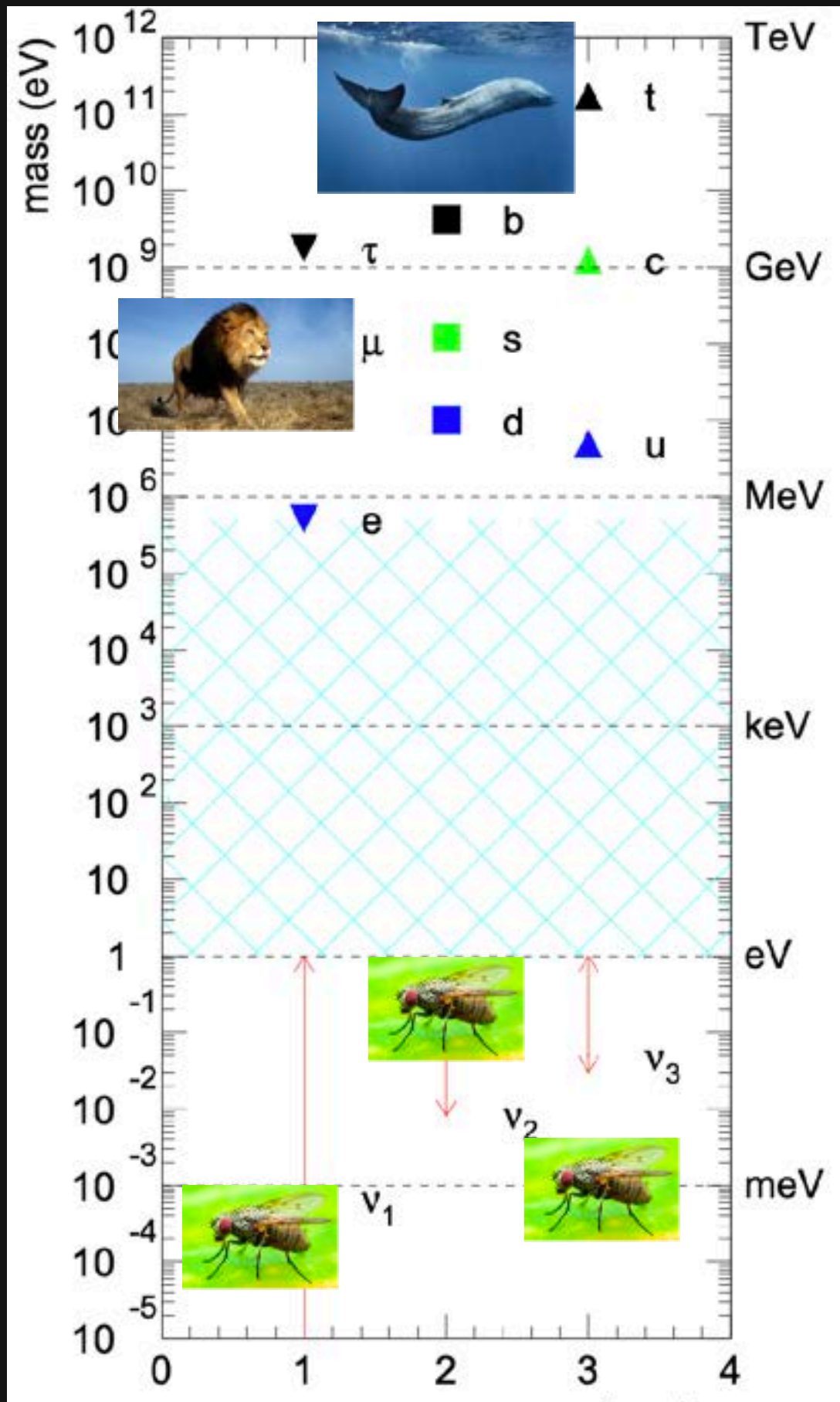


Where are all the muon neutrinos going??

(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo,

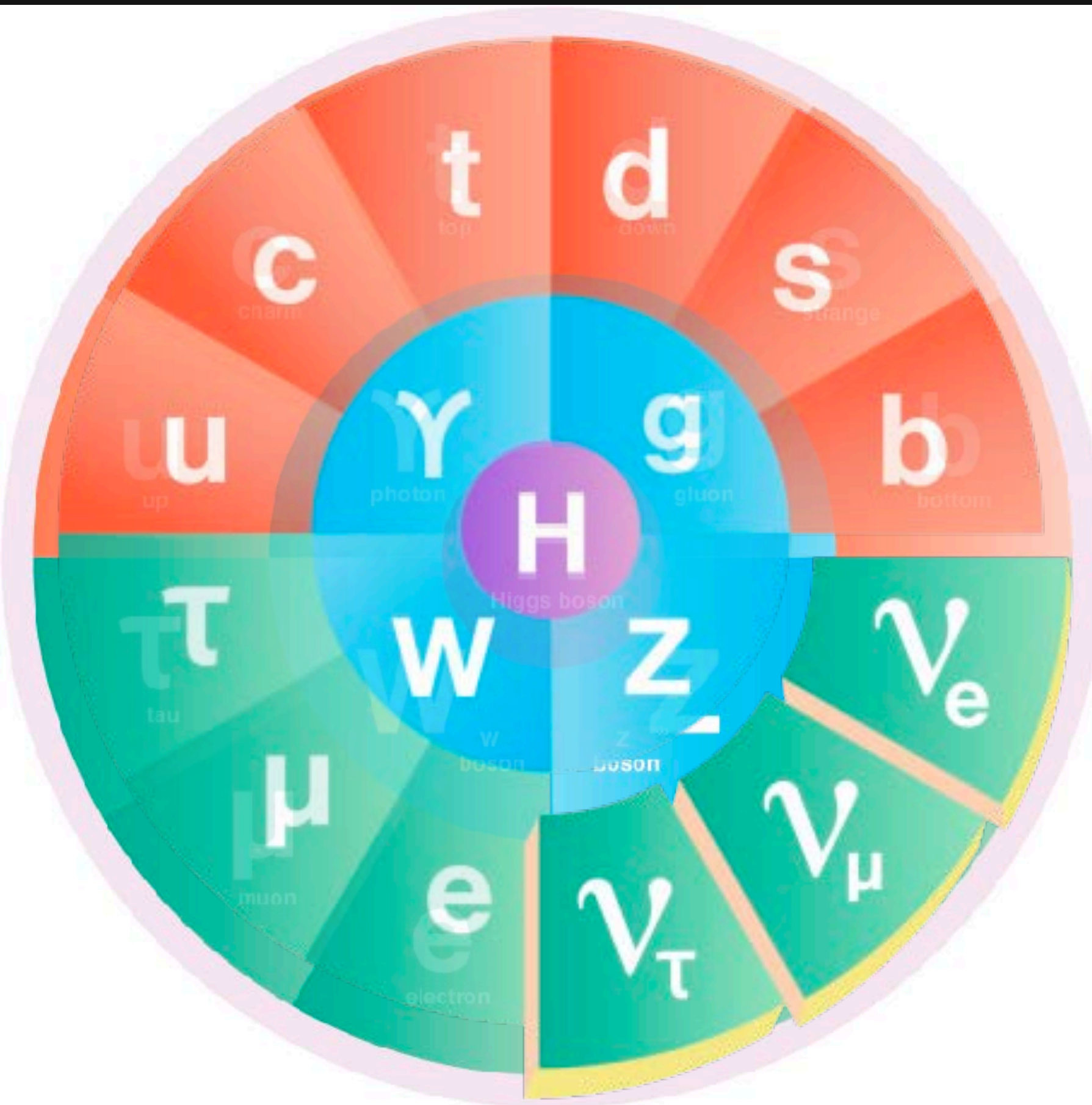
Twice as many neutrinos from above as from below!

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.

FUNDAMENTAL
Neutrinos are fundamental particles, which means that—like quarks and photons and electrons—they cannot be broken down into any smaller bits.

ABUNDANT
Of all particles with mass, neutrinos are the most abundant in nature. They're also some of the least interactive. Roughly a thousand trillion of them pass harmlessly through your body every second.

ELUSIVE
Neutrinos are difficult but not impossible to catch. Scientists have developed many different types of particle detectors to study them.

OSCILLATING
Neutrinos come in three types, called flavors. There are electron neutrinos, muon neutrinos and tau neutrinos. One of the strangest aspects of neutrinos is that they don't pick just one flavor and stick to it. They oscillate between all three.

NEUTRINOS ARE...

LIGHTWEIGHT
Neutrinos weigh almost nothing, and they travel close to the speed of light. Neutrino masses are so small that so far no experiment has succeeded in measuring them. The masses of other fundamental particles come from the Higgs field, but neutrinos might get their masses another way.

DIVERSE
Neutrinos are created in many processes in nature. They are produced in the nuclear reactions in the sun, particle decays in the Earth, and the explosions of stars. They are also produced by particle accelerators and in nuclear power plants.

MYSTERIOUS
Neutrinos are mysterious. Experiments seem to hint at the possible existence of a fourth type of neutrino: a sterile neutrino, which would interact even more rarely than the others.

VERY MYSTERIOUS
Scientists also wonder if neutrinos are their own antiparticles. If they are, they could have played a role in the early universe, right after the big bang, when matter came to outnumber antimatter just enough to allow us to exist.

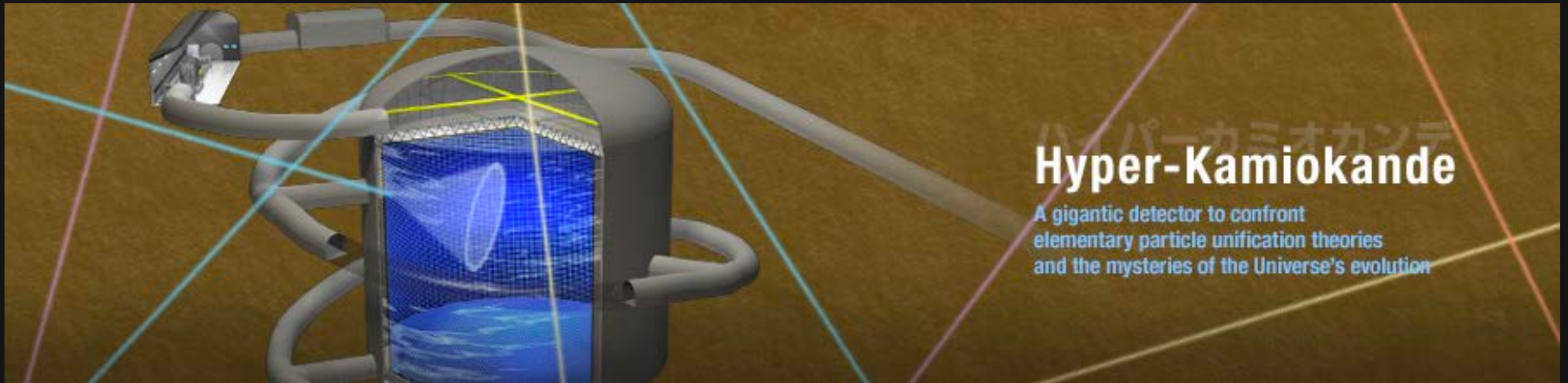
Interested in how the universe works? Read Symmetry, an online magazine about particle physics and its connections to life and other areas of science. Published by Fermi National Accelerator Laboratory and SLAC National Accelerator Laboratory. symmetrymagazine.org

symmetry | U.S. DEPARTMENT OF ENERGY | Office of Science

Upcoming Earth-based Experiments



Hyper-Kamiokande



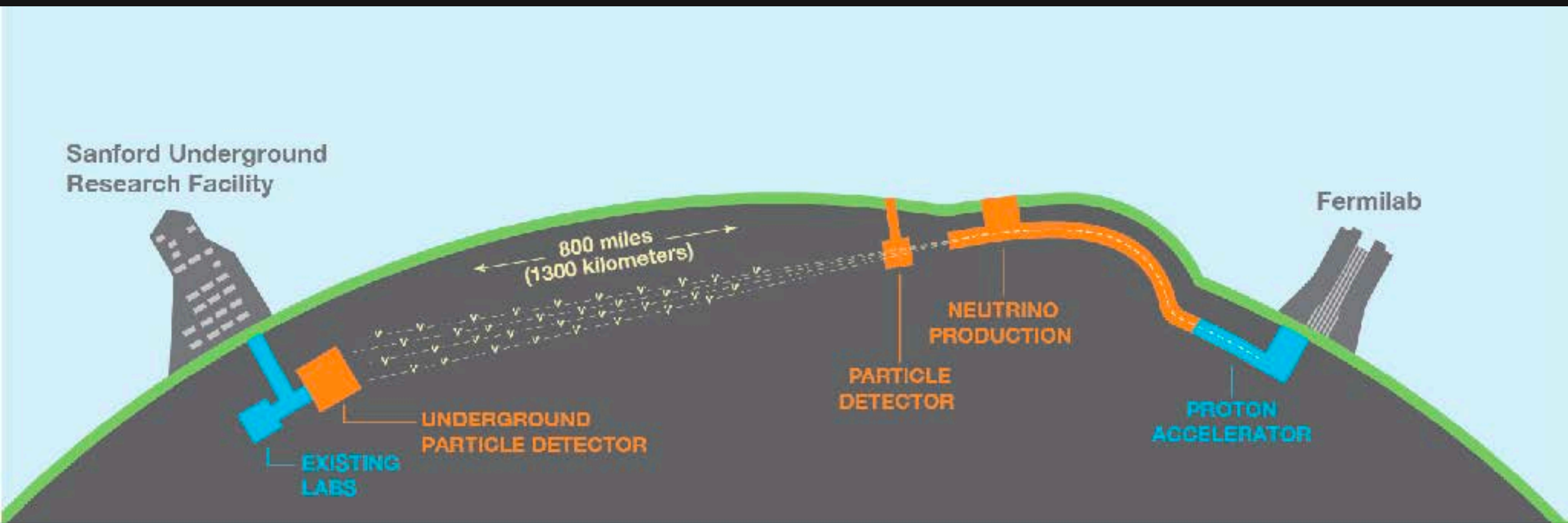
Hyper-Kamiokande

A gigantic detector to confront
elementary particle unification theories
and the mysteries of the Universe's evolution

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

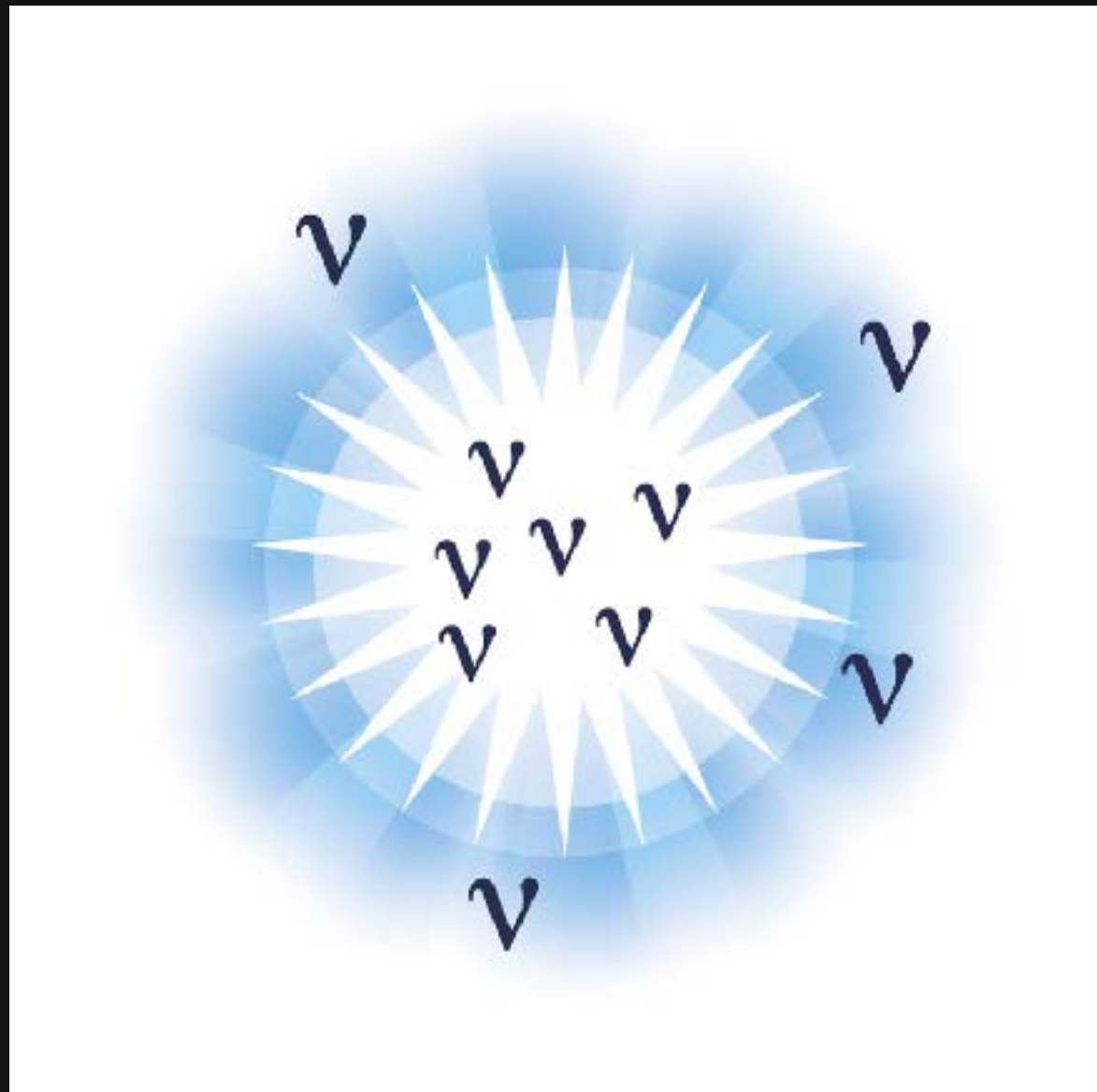
Upcoming Earth-based Experiments

DUNE 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?



DEEP UNDERGROUND
NEUTRINO EXPERIMENT

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

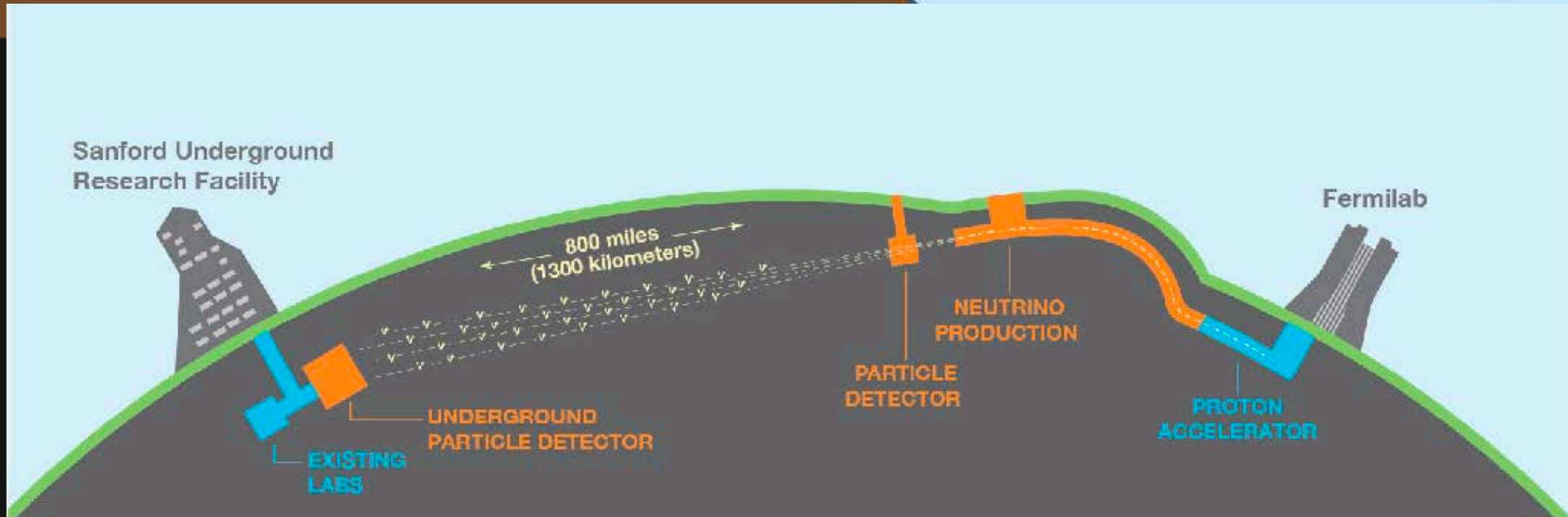
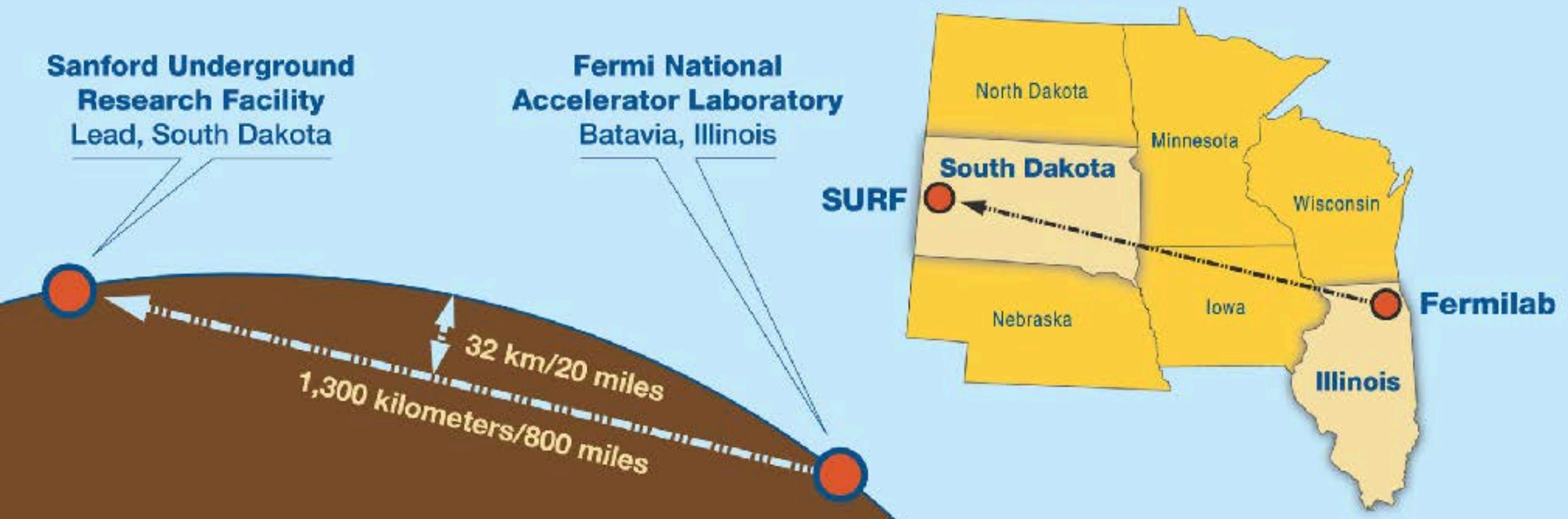
- Understand what happens when massive stars die and witness the birth of a black hole



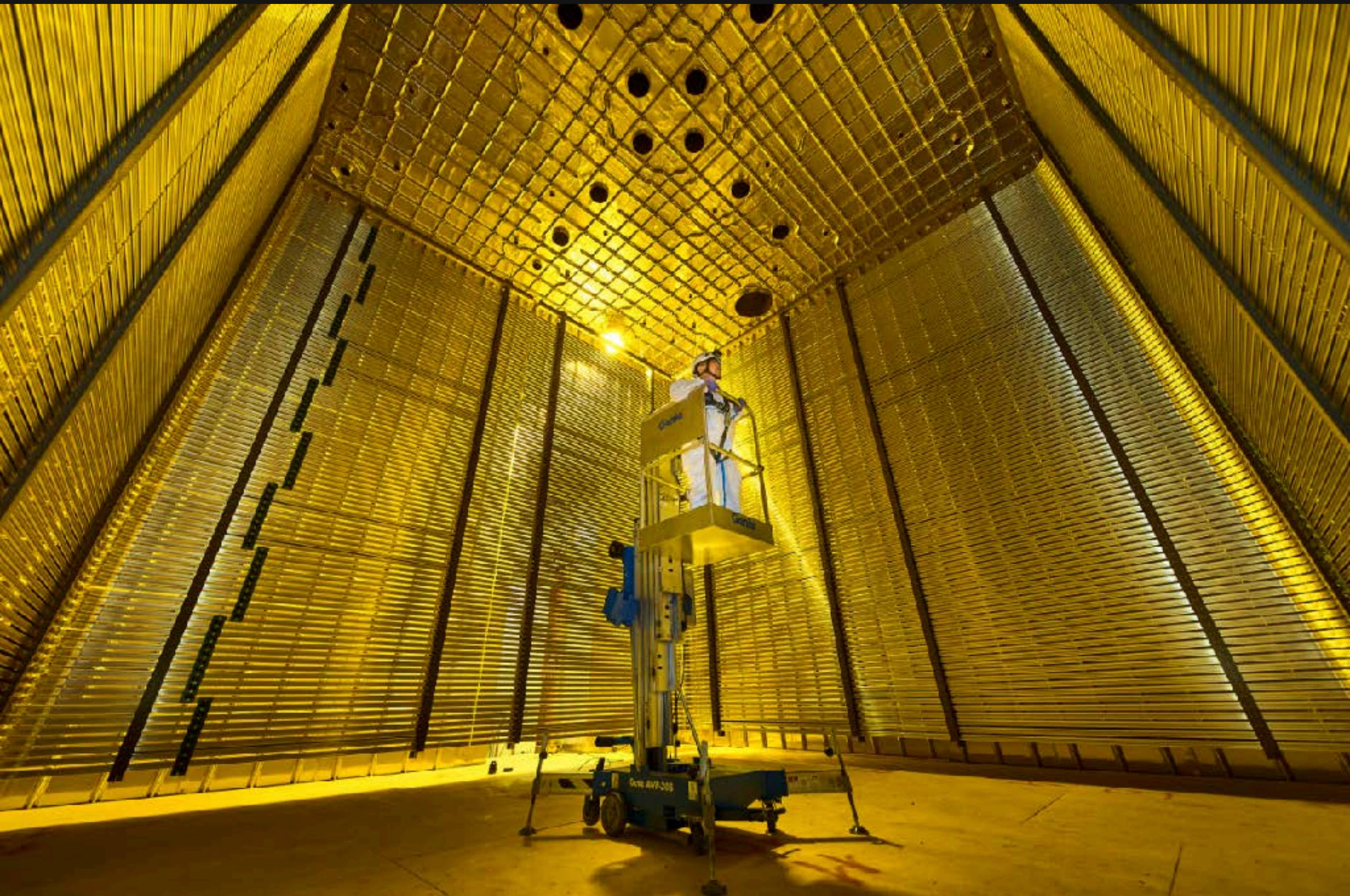
DEEP UNDERGROUND
NEUTRINO EXPERIMENT

How does DUNE Do It?

Deep Underground Neutrino Experiment

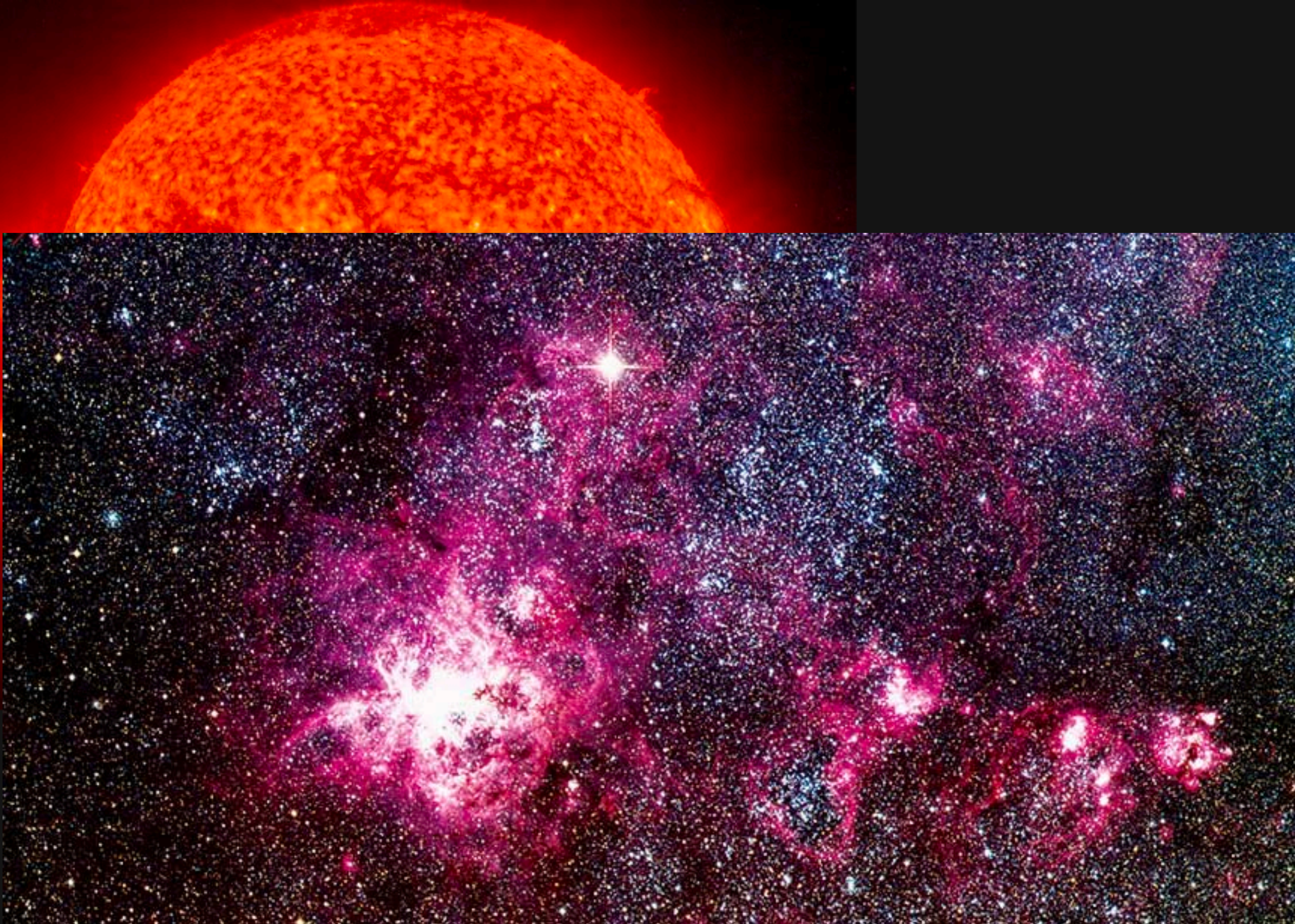


How does DUNE Do It?

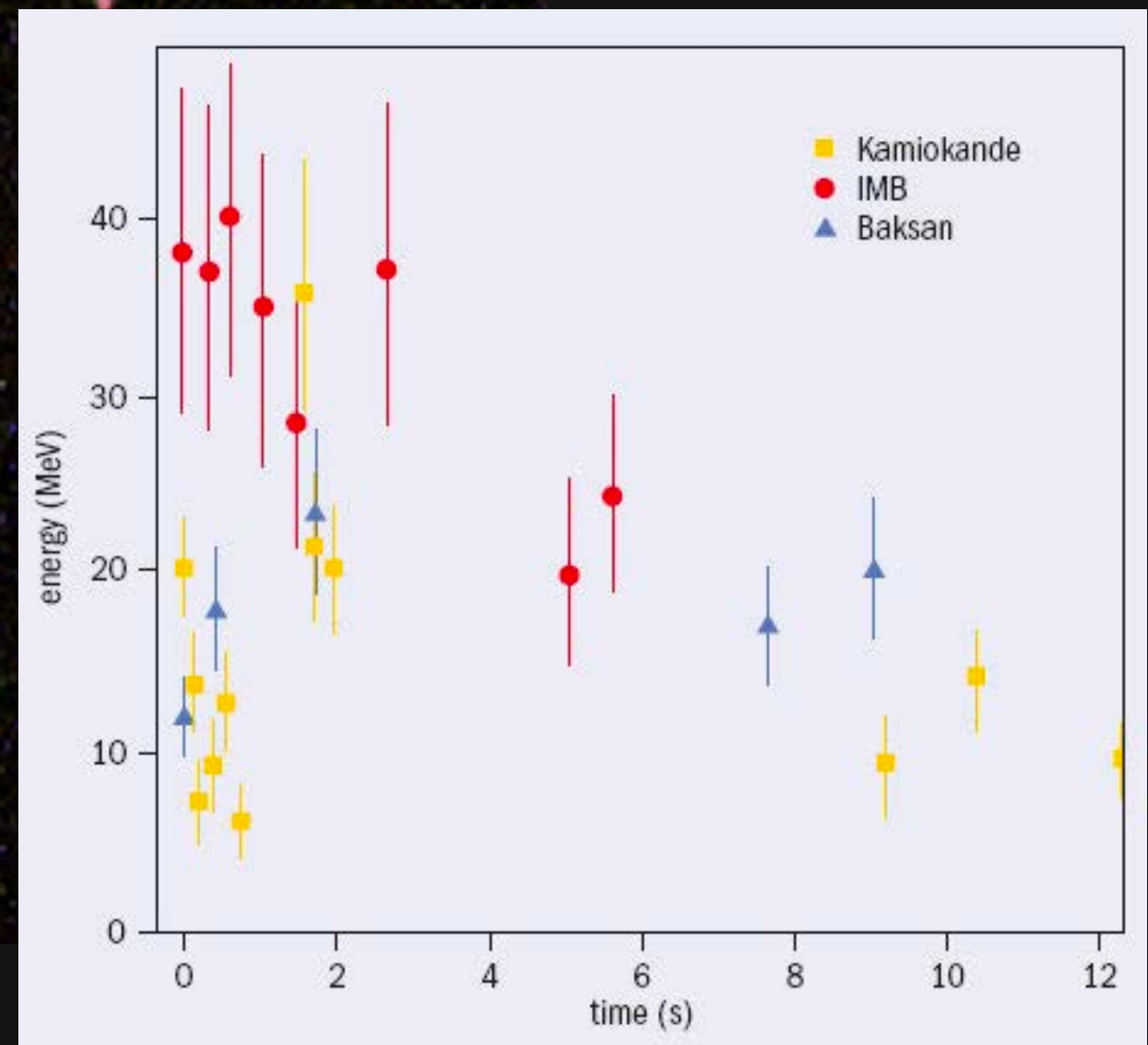
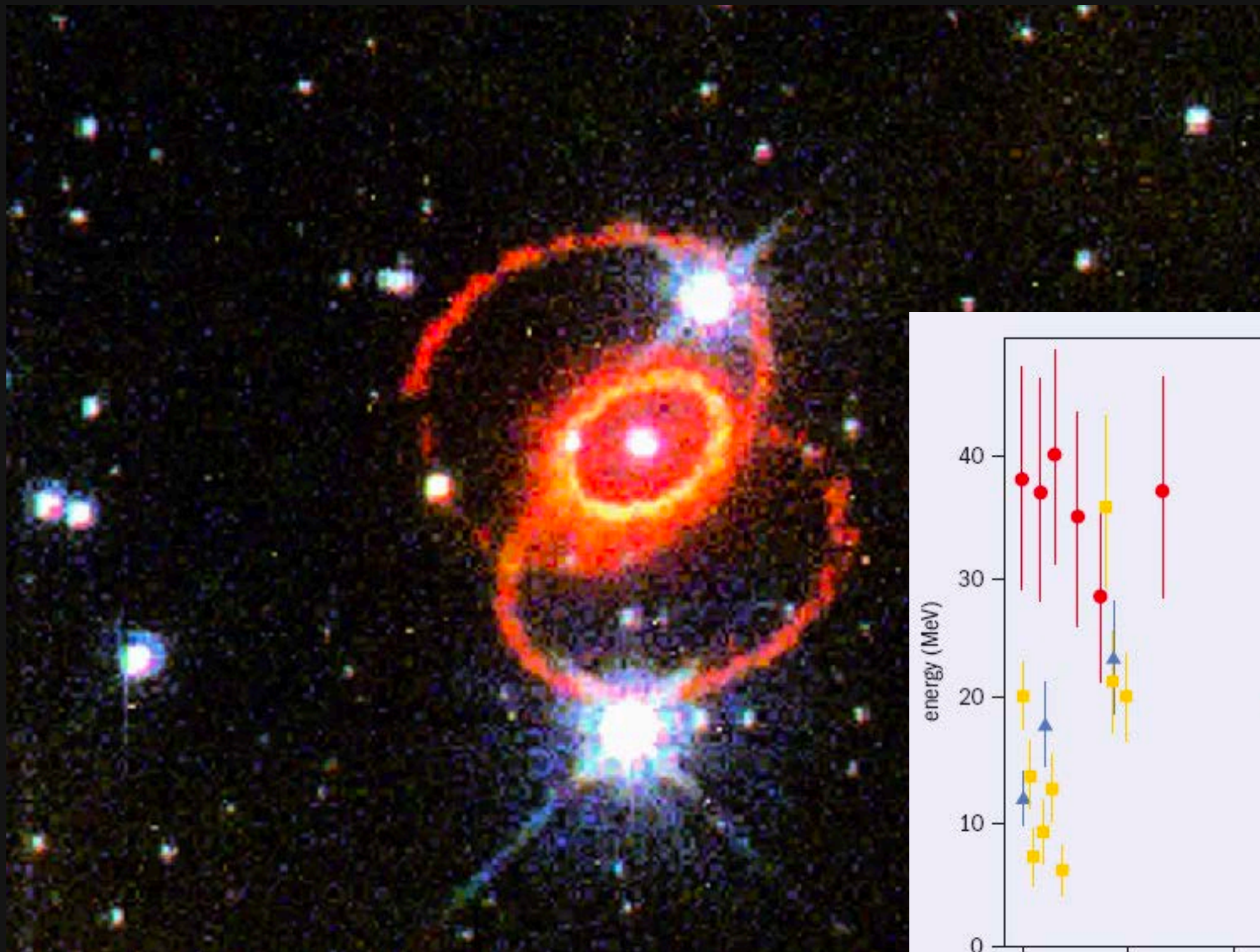


**What about non
manmade neutrinos?**

Other sources of neutrinos

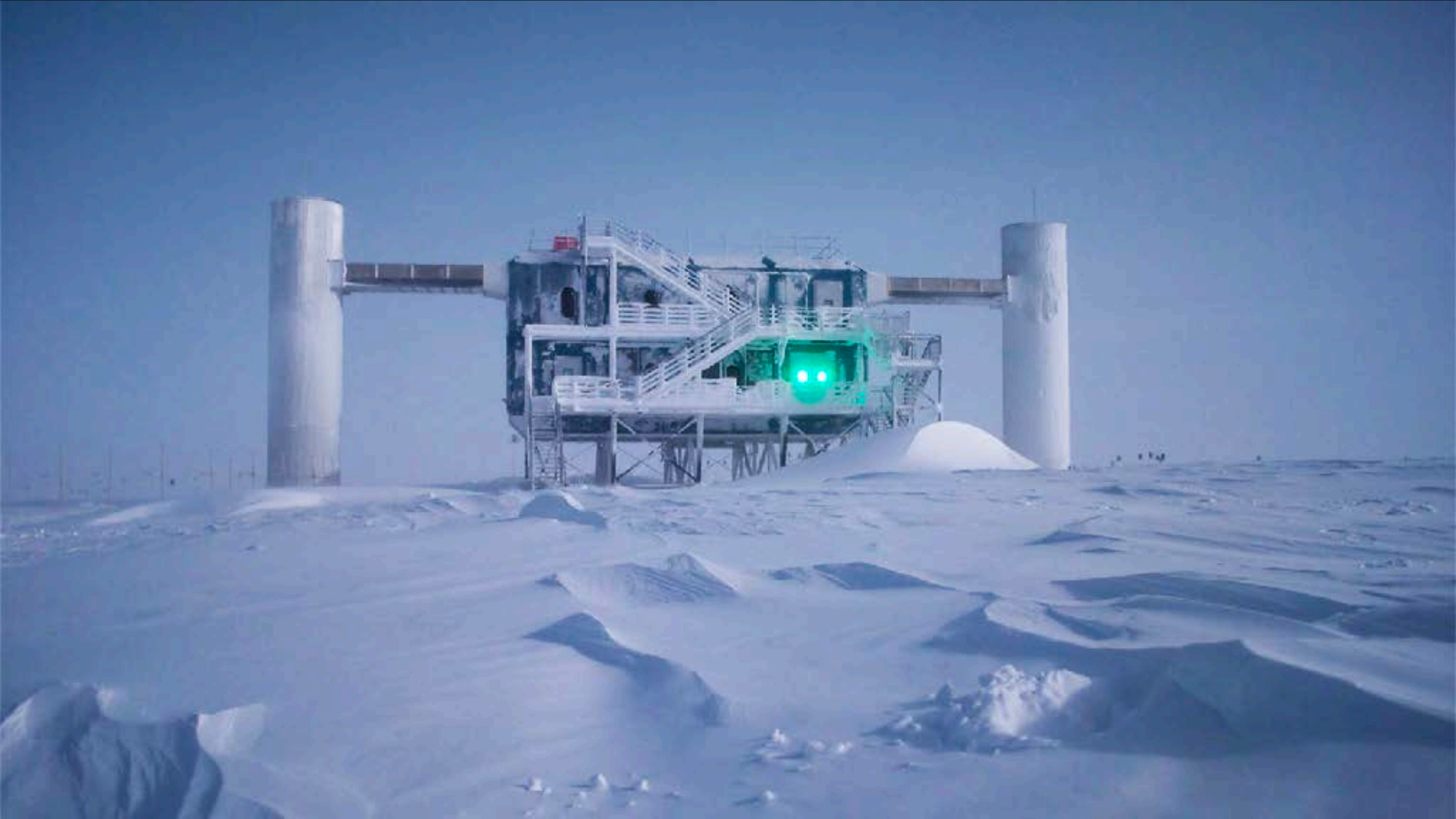


Rewind to 1987

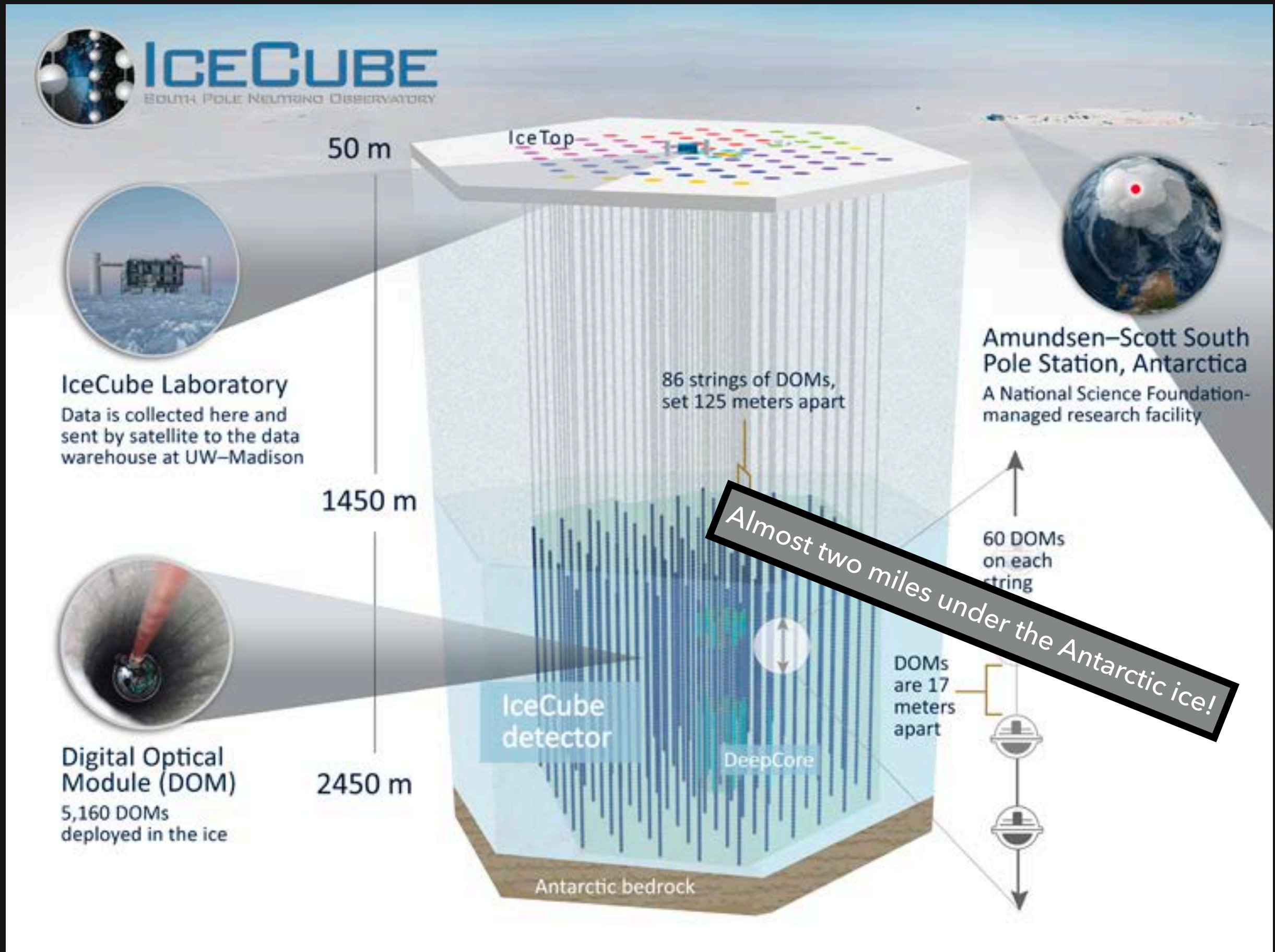


First case of multimessenger astronomy – detected a supernova with both light and with neutrinos!

The IceCube Experiment – a Neutrino Telescope

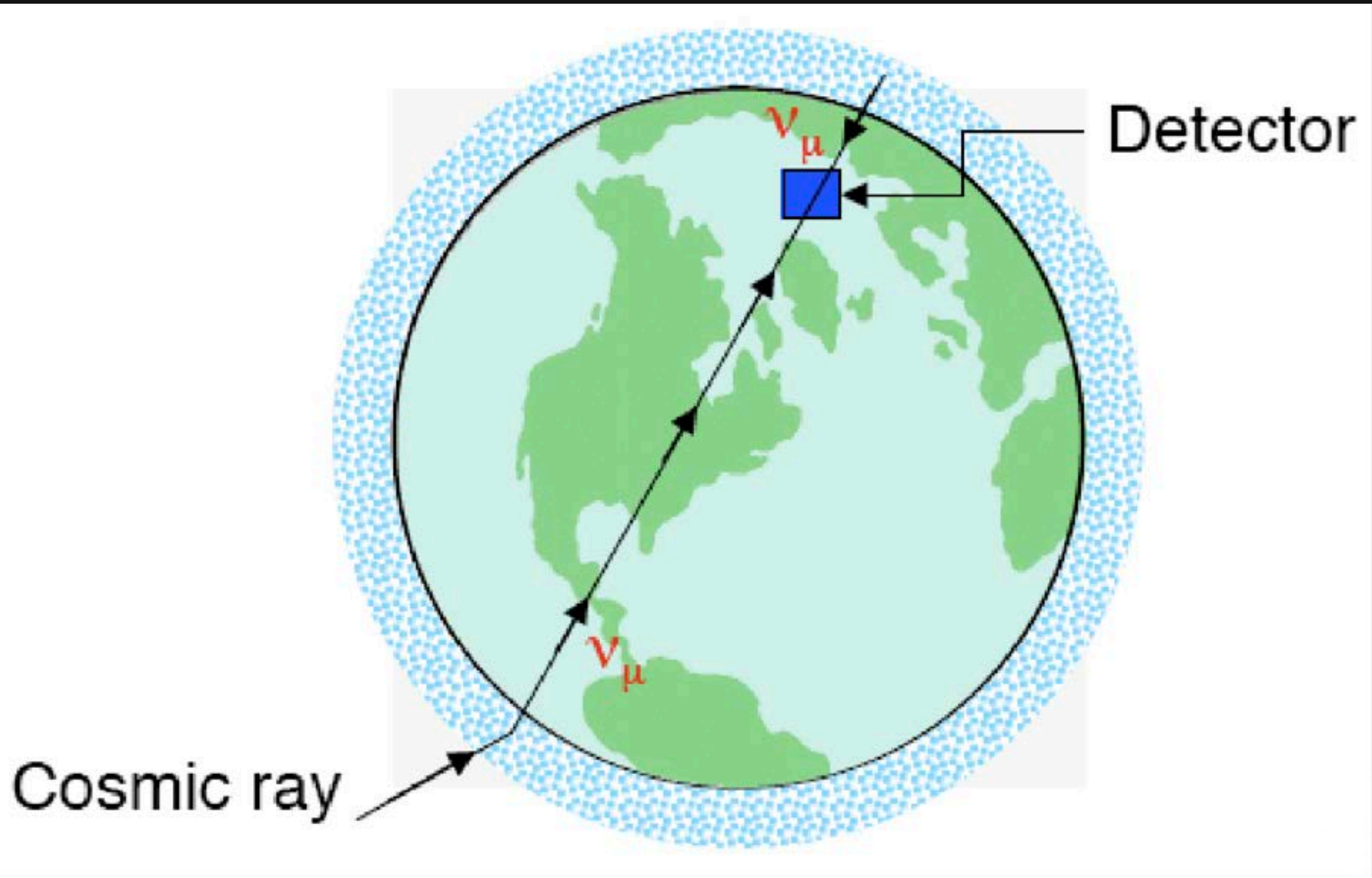


IceCube — an instrumented cubic kilometer of ice!

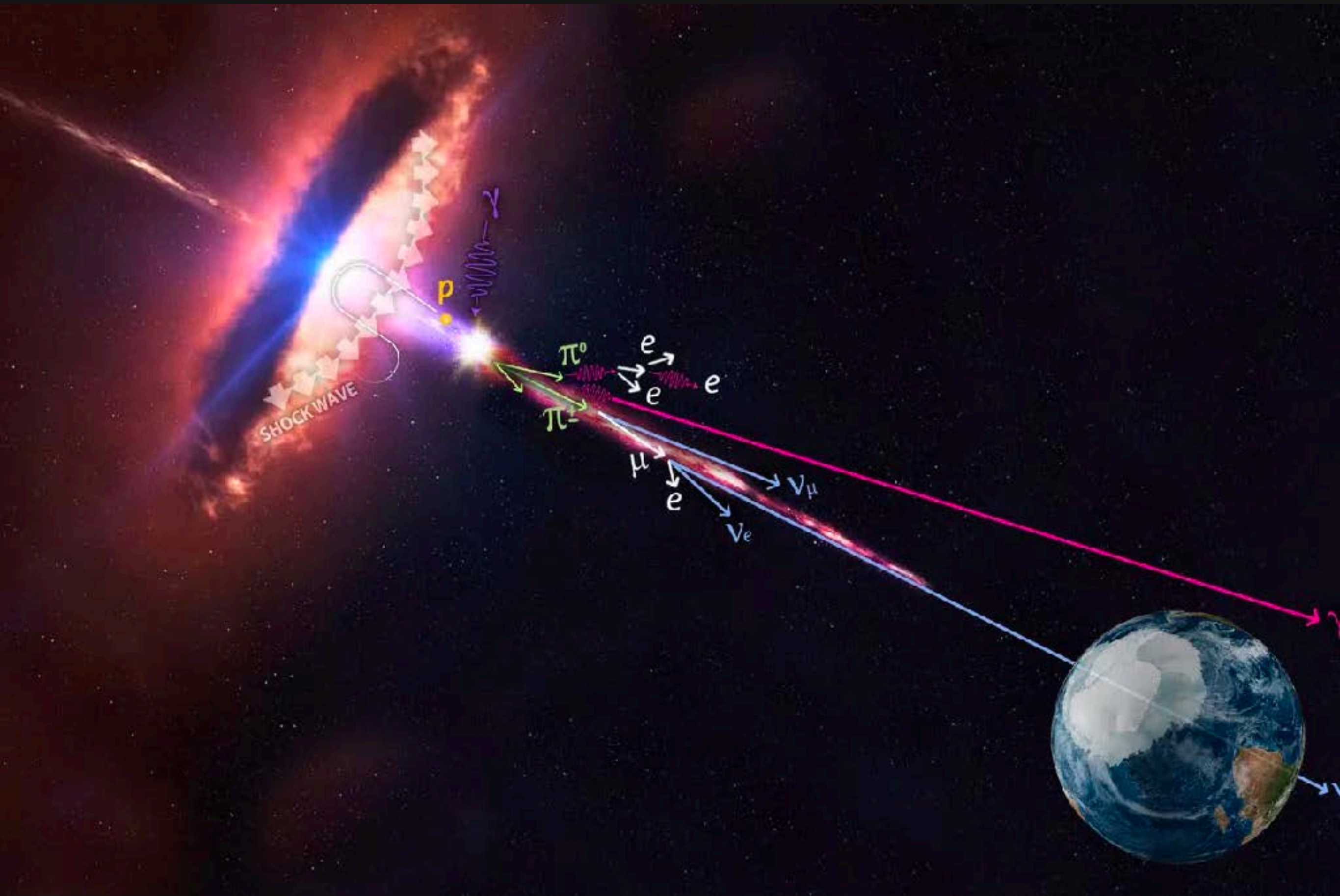


What can IceCube Do?

- ▶ 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...

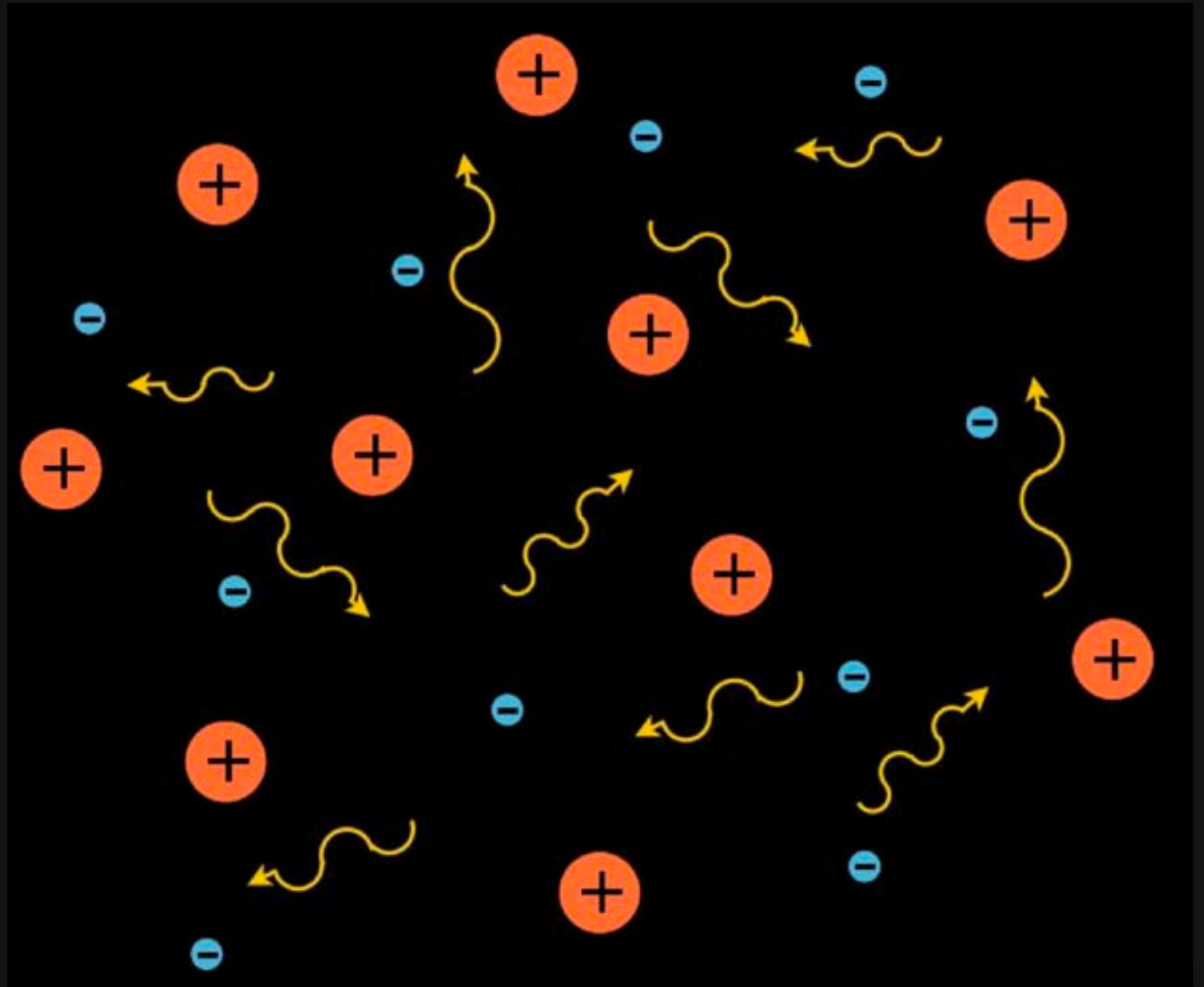


IceCube saw a neutrino coming from about 4,000,000,000 lightyears away!

Switching Gears, the Cosmic Microwave Background

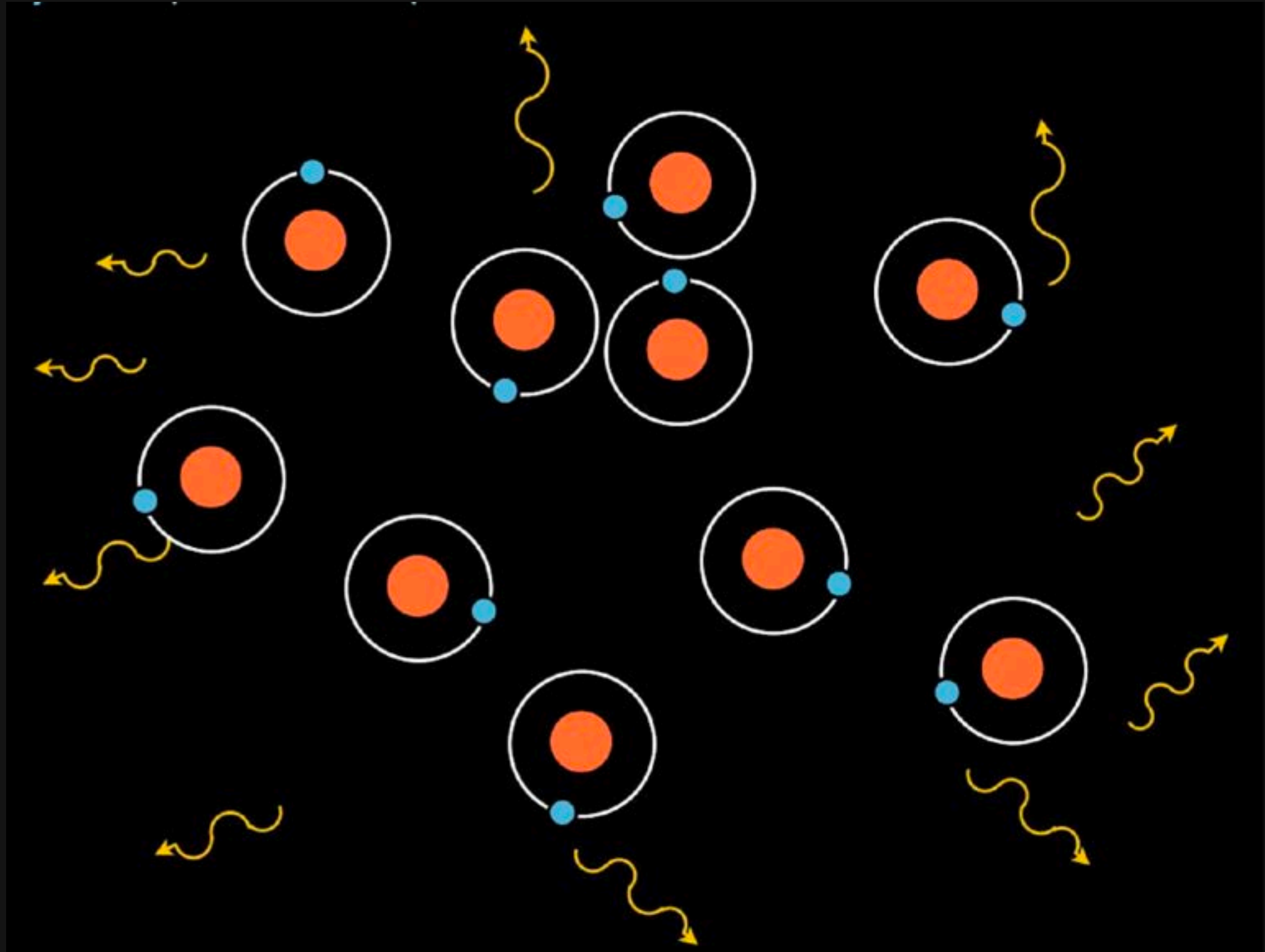
Rewind to the Early Universe...

- ▶ 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.



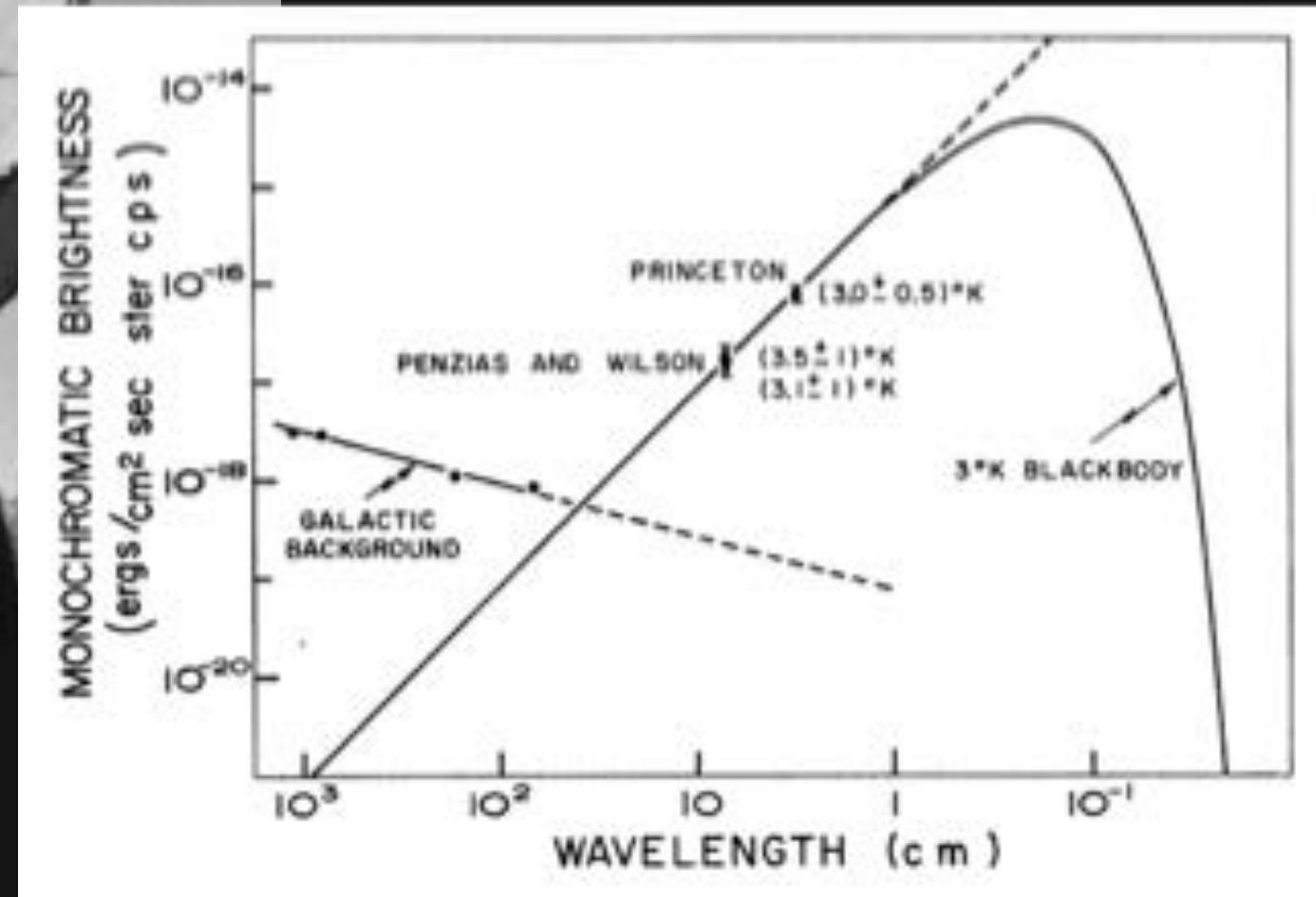
As the Universe Expands, it cools down

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

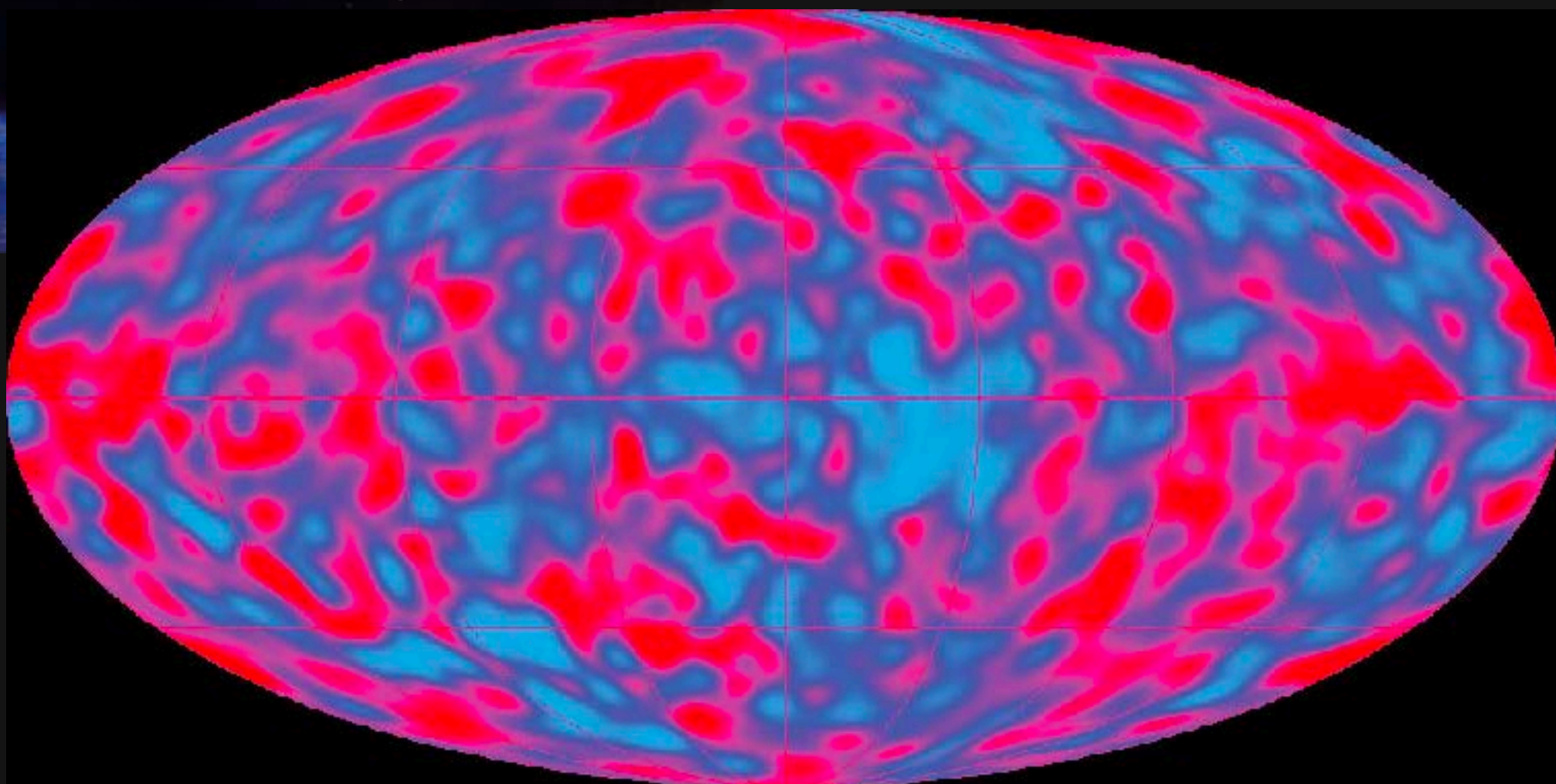
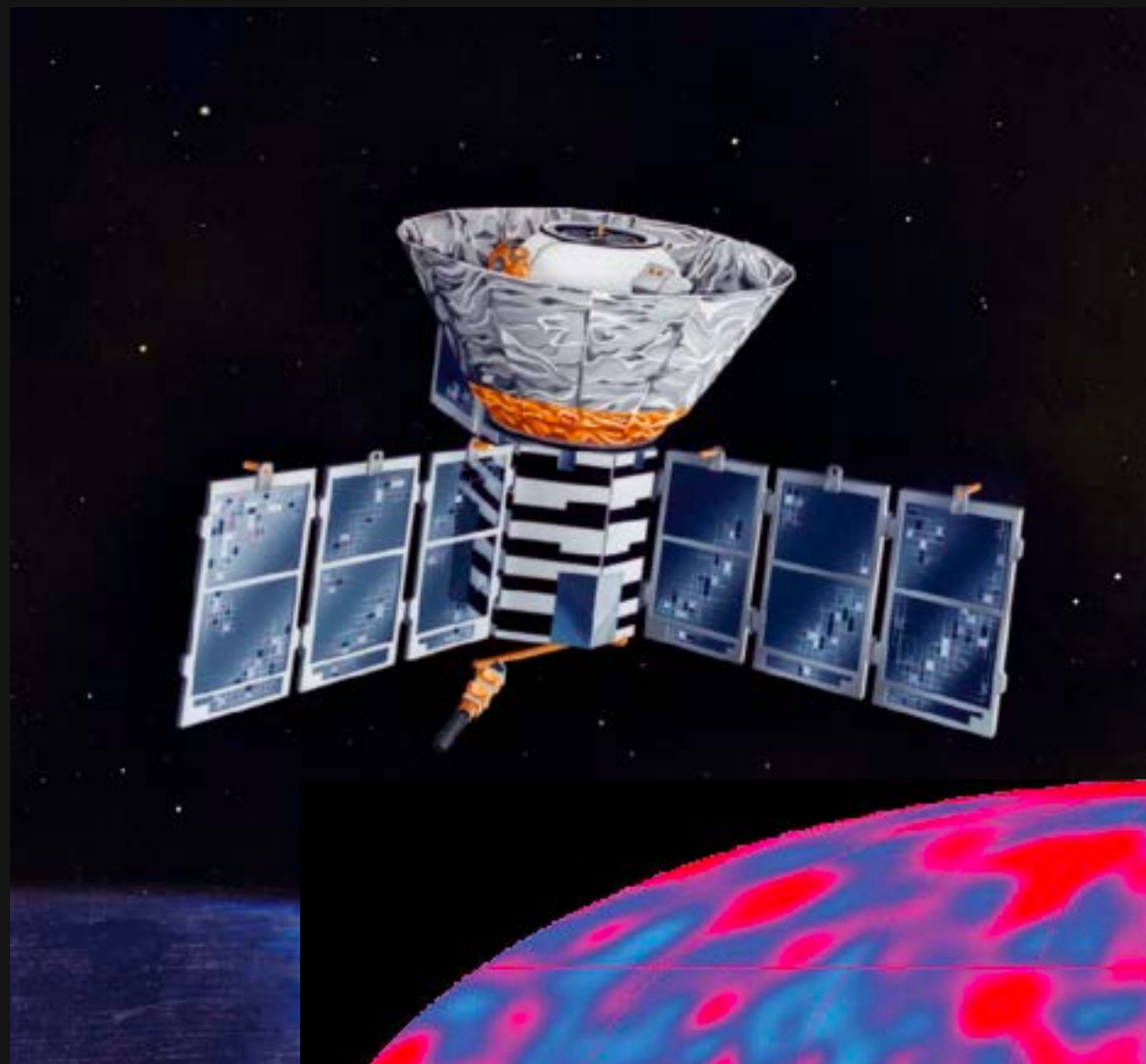


Every direction we look, we see these leftover photons of light

- ▶ 1964: Penzias and Wilson first detection

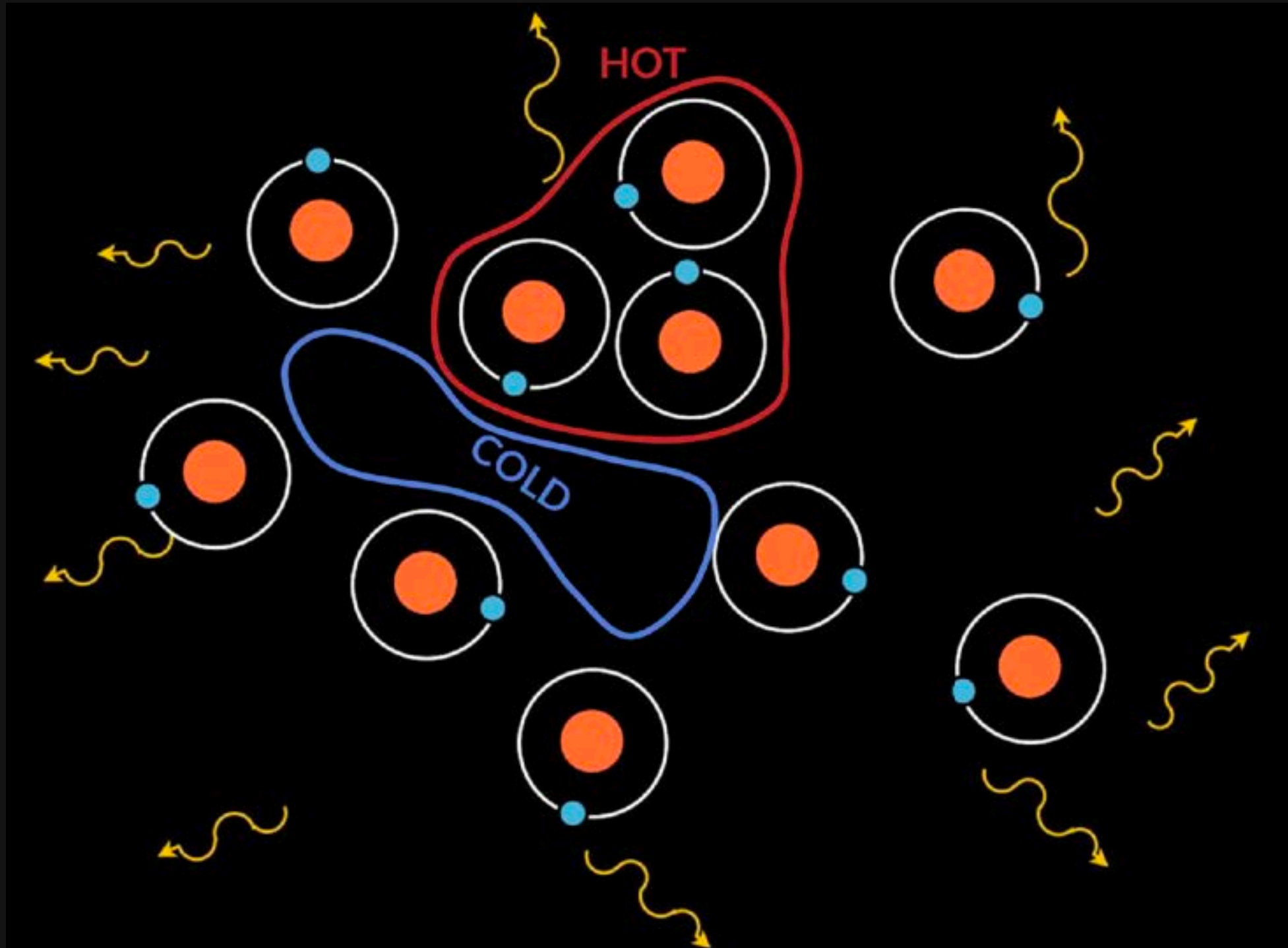


Early 1990s: COBE Satellite

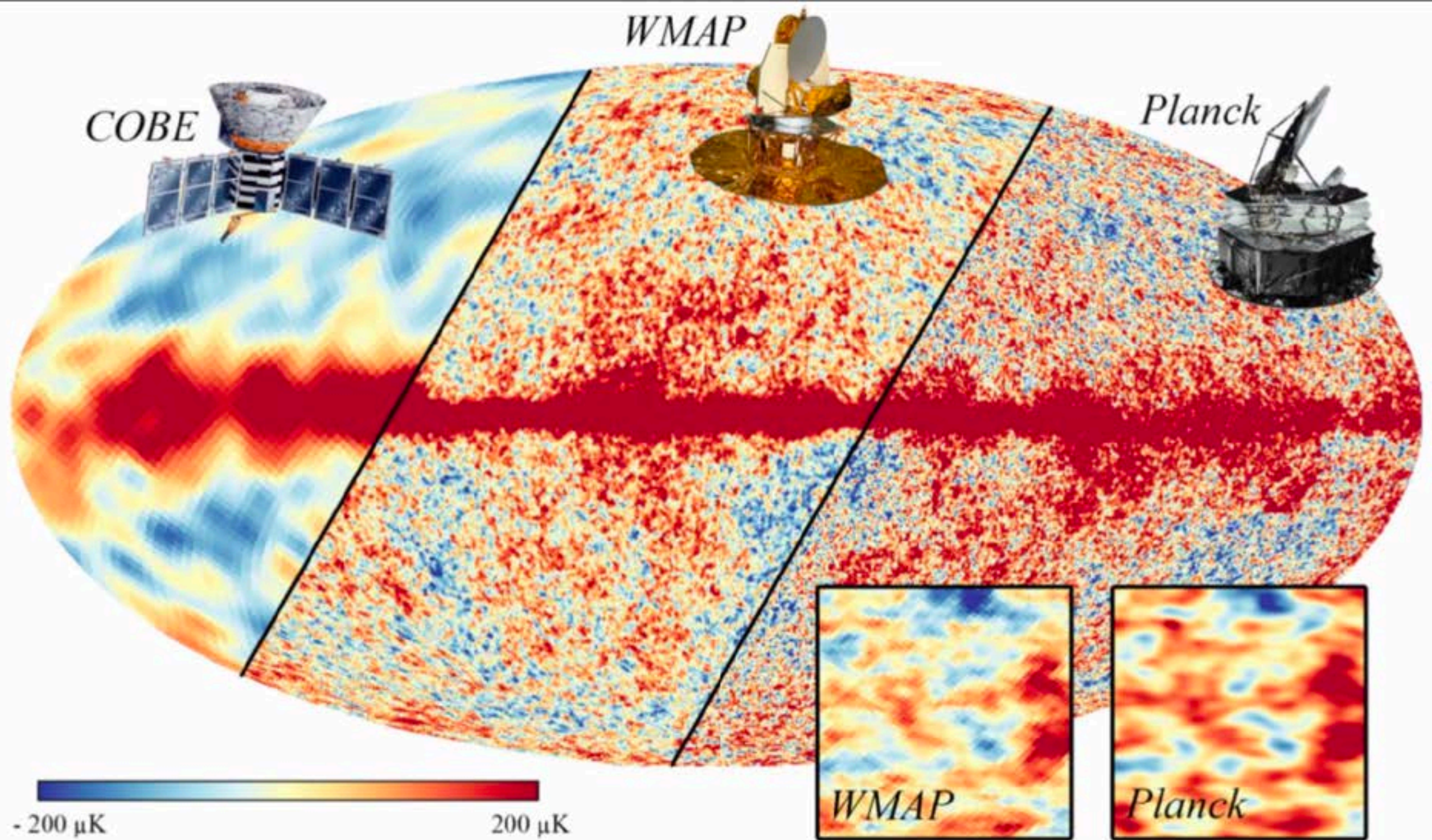


What is COBE Measuring?

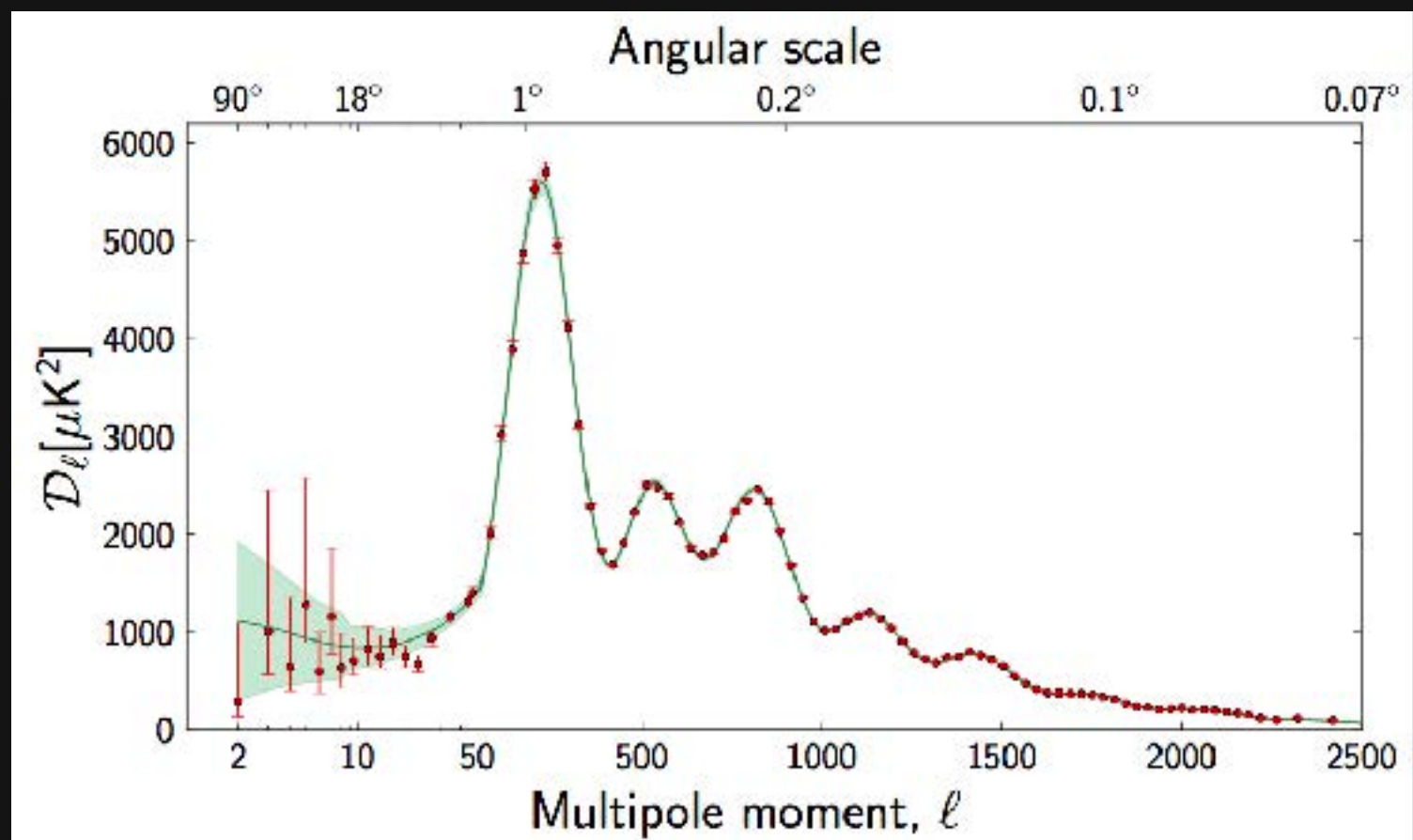
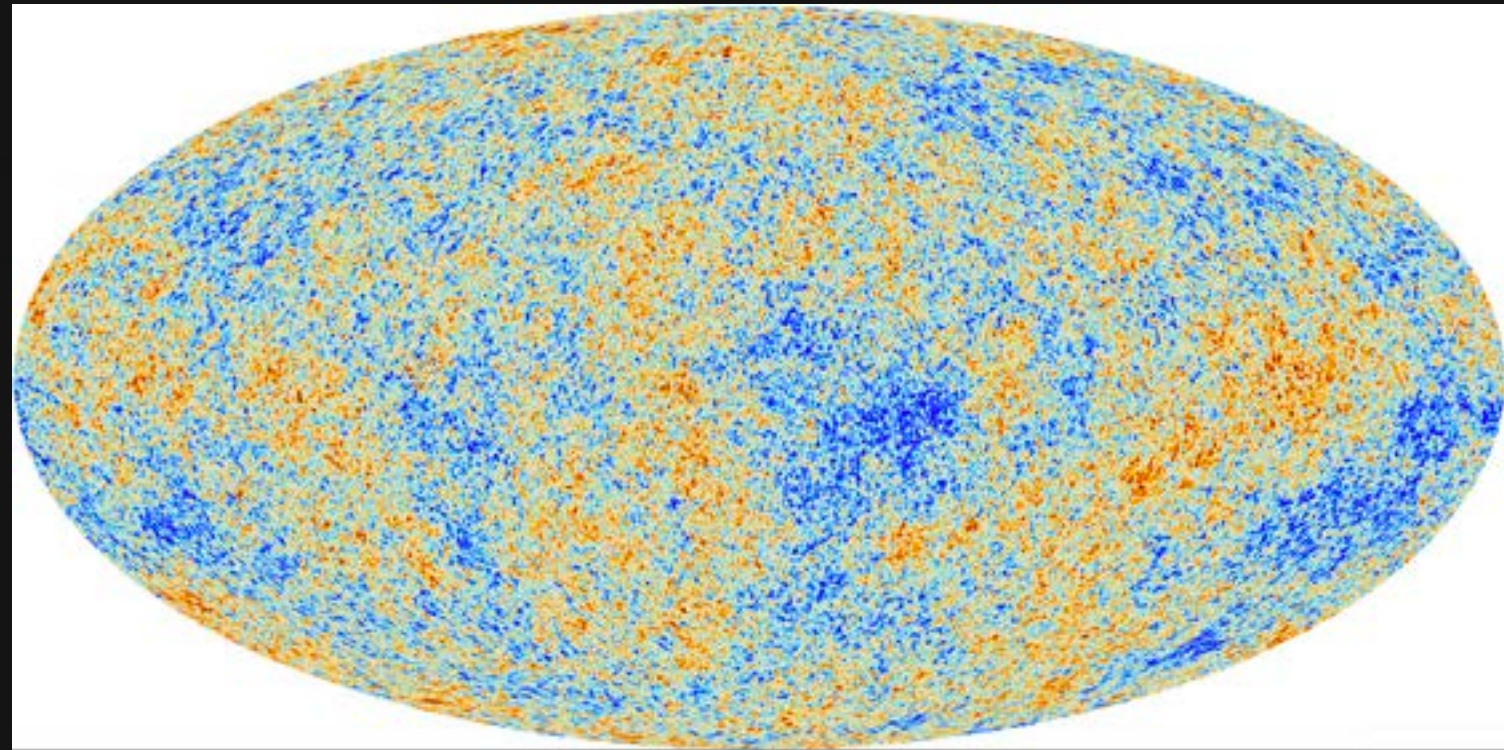
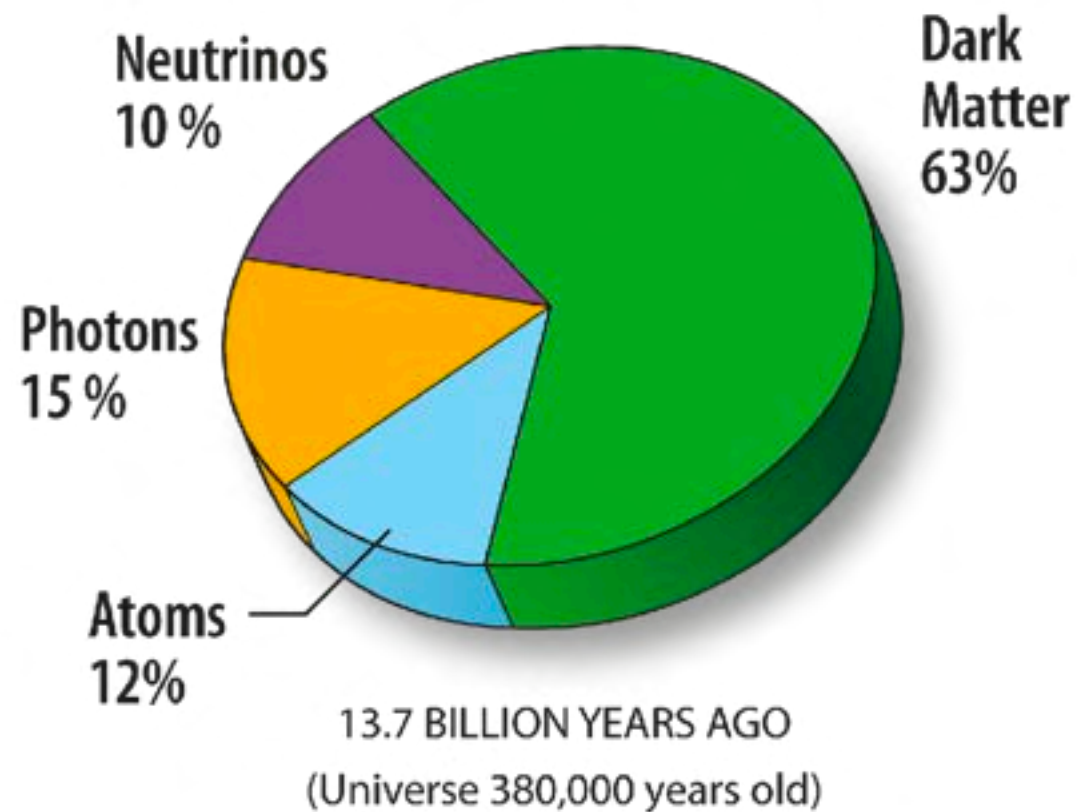
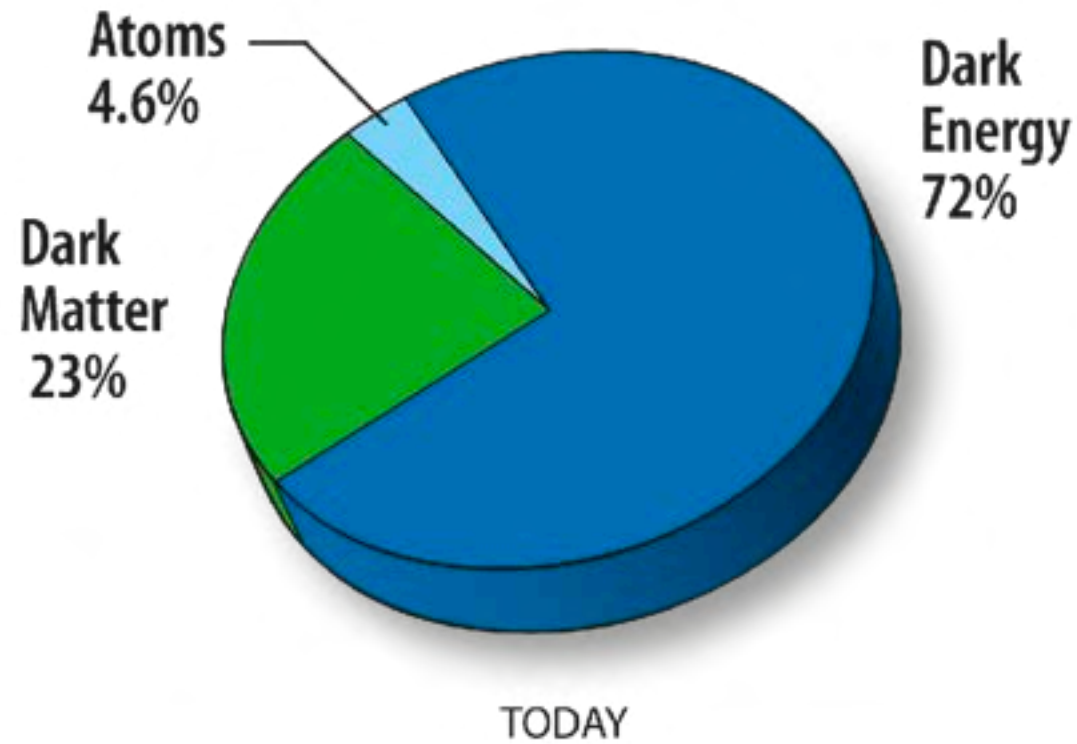
- ▶ Tiny, tiny differences in temperature of the photons it's measuring from every direction.



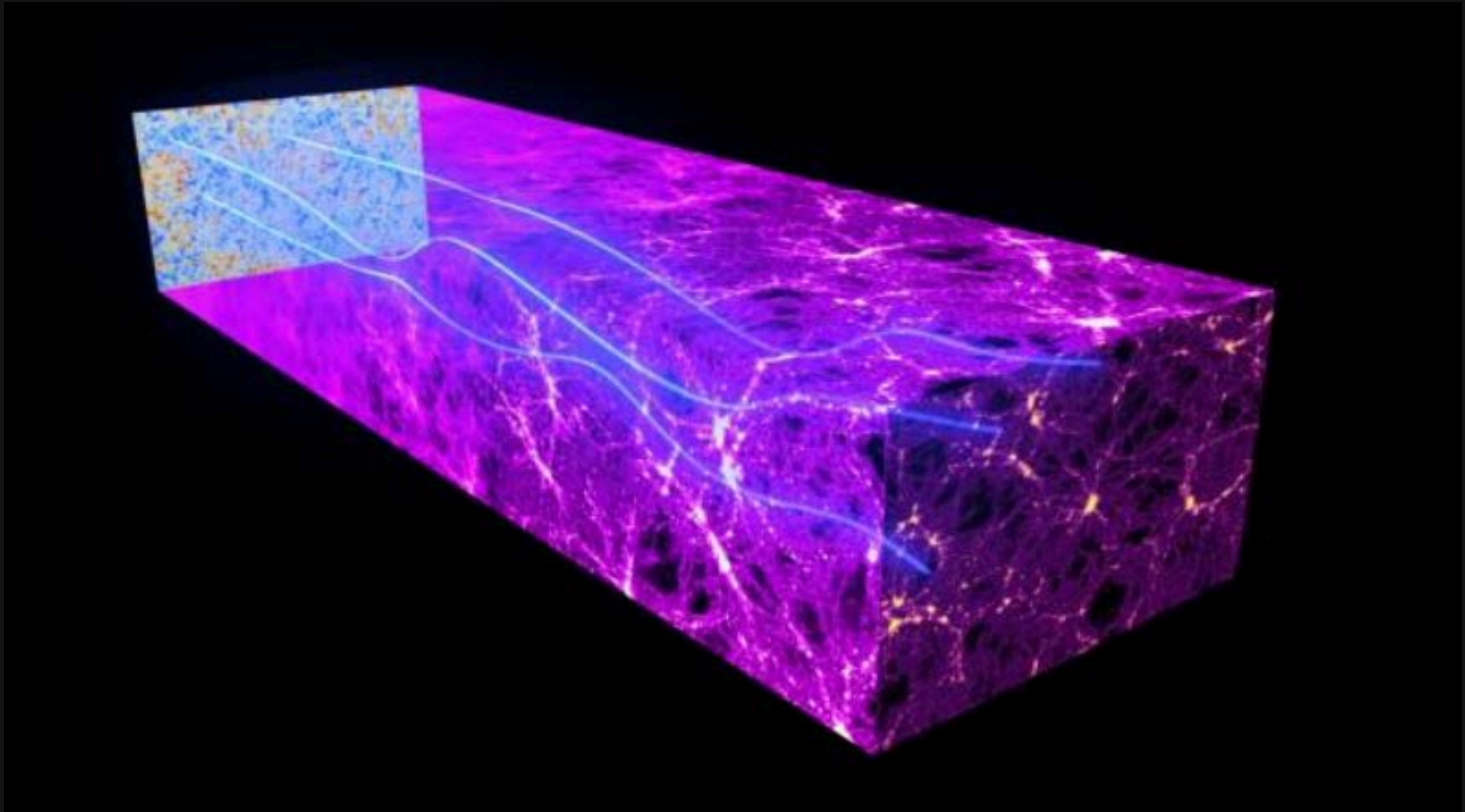
Advancement over 20+ Years



What can we learn from the Cosmic Microwave Background?

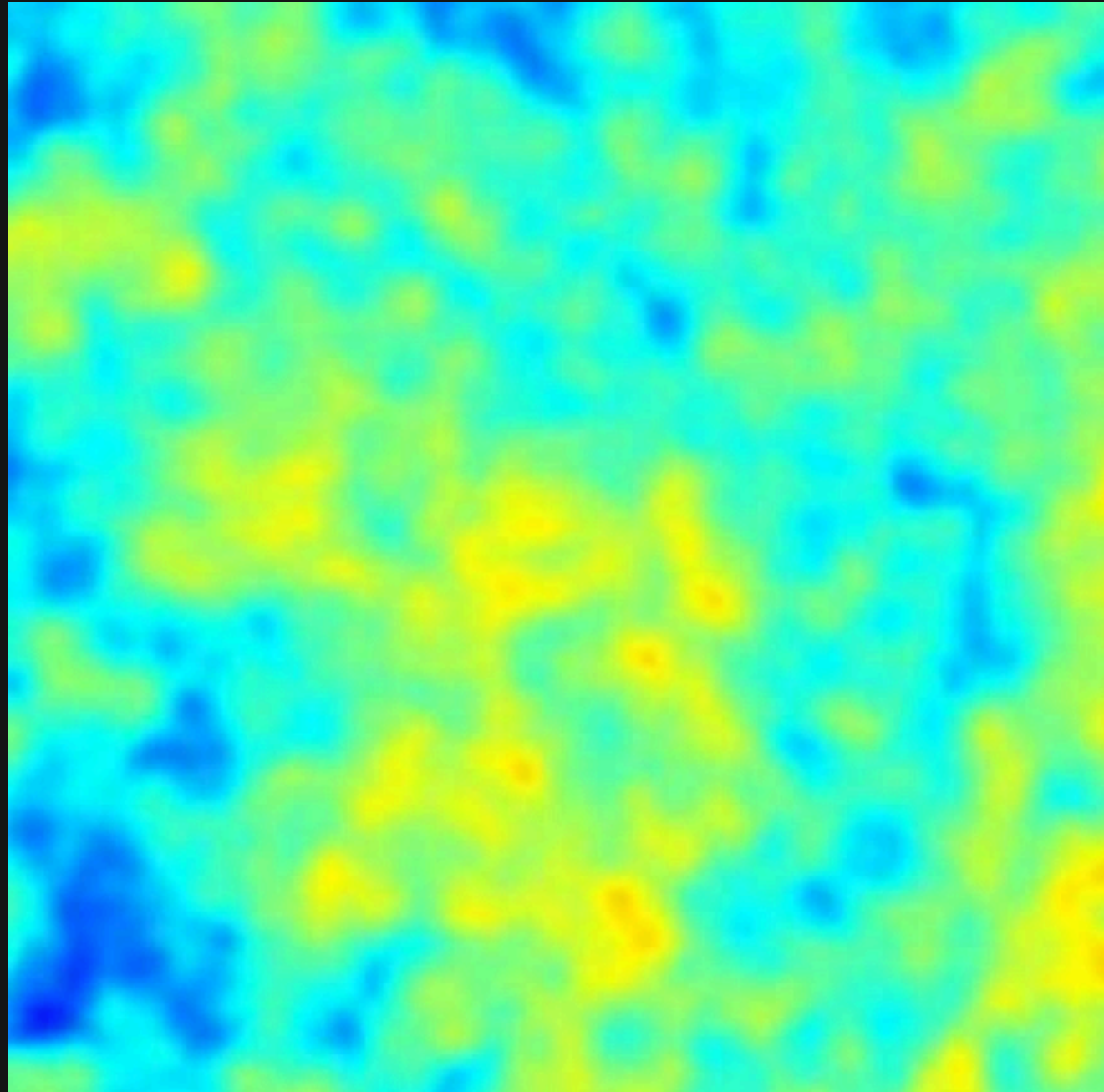


The CMB isn't viewed as it was, though...



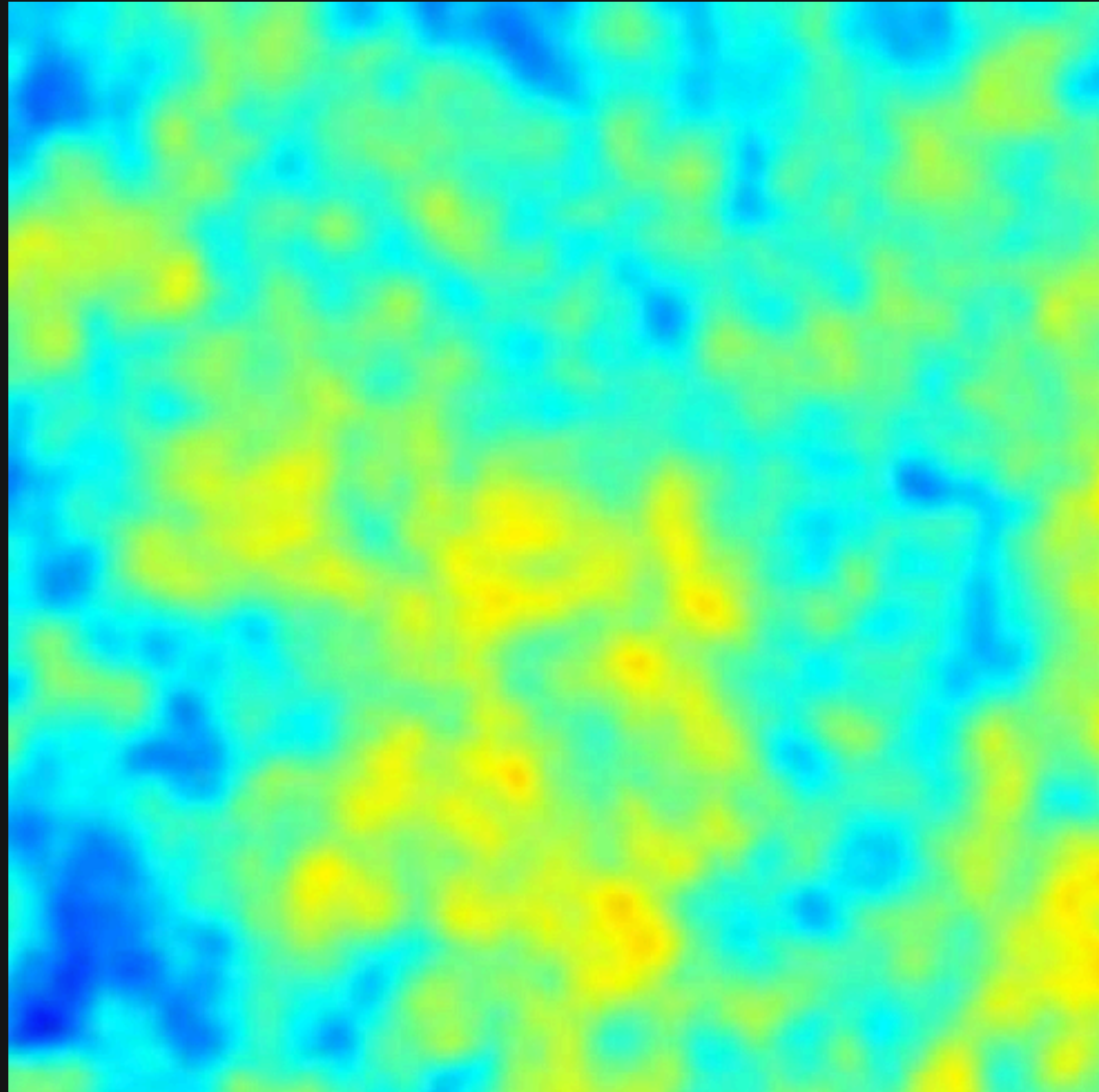
But wait, there's more!

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

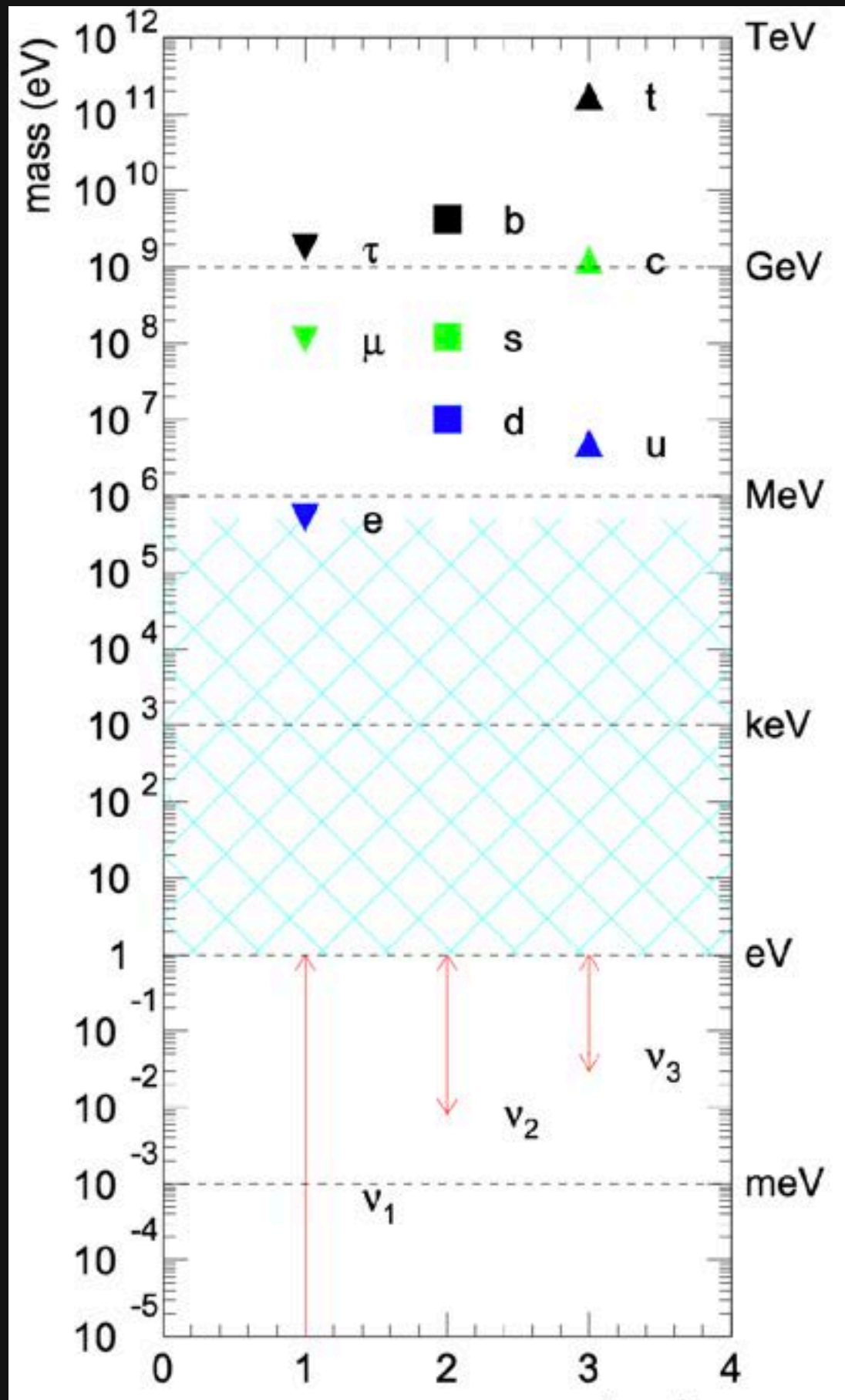


But wait, there's more!

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



Currently, cosmological experiments haven't detected massive neutrinos

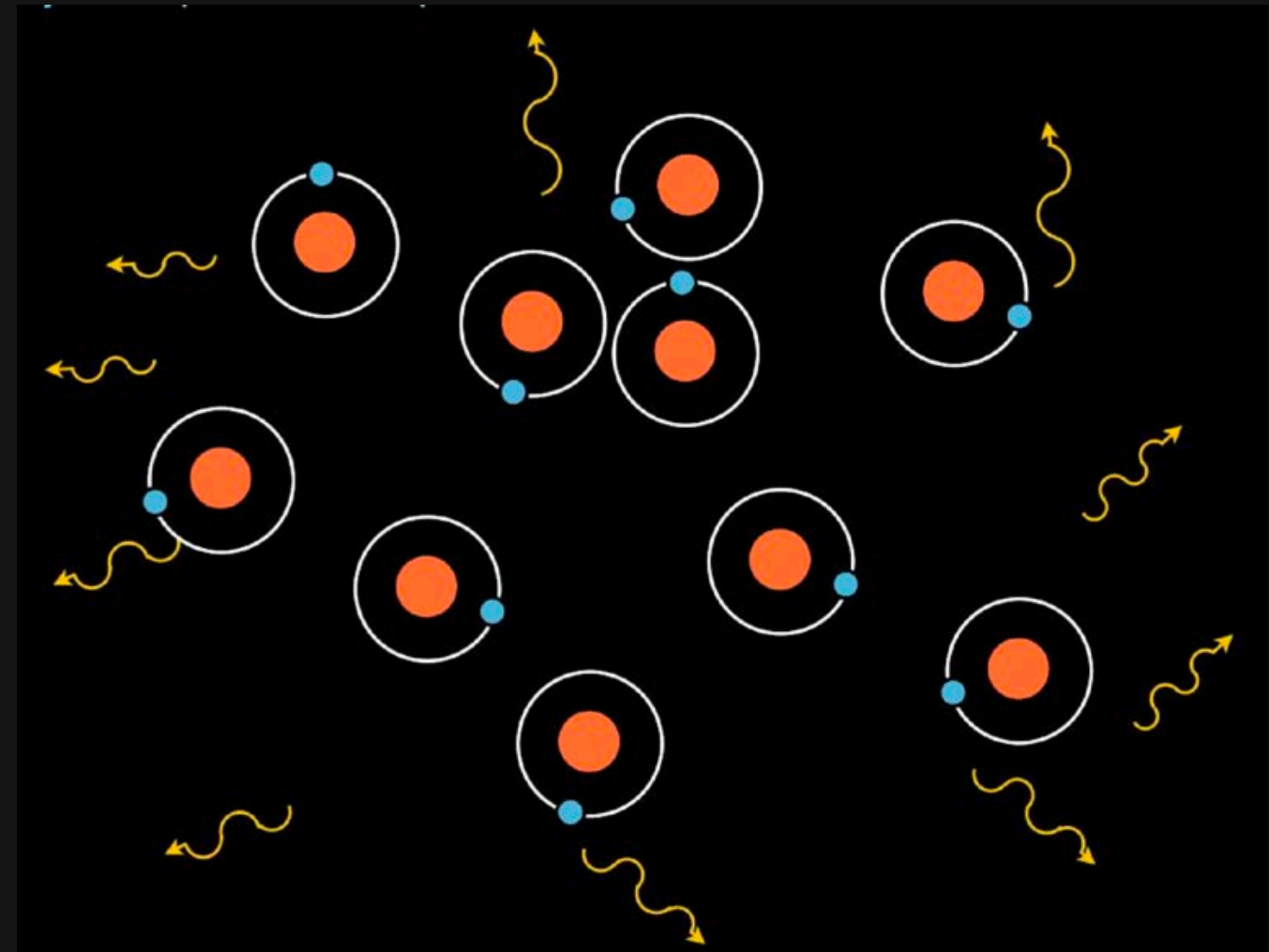
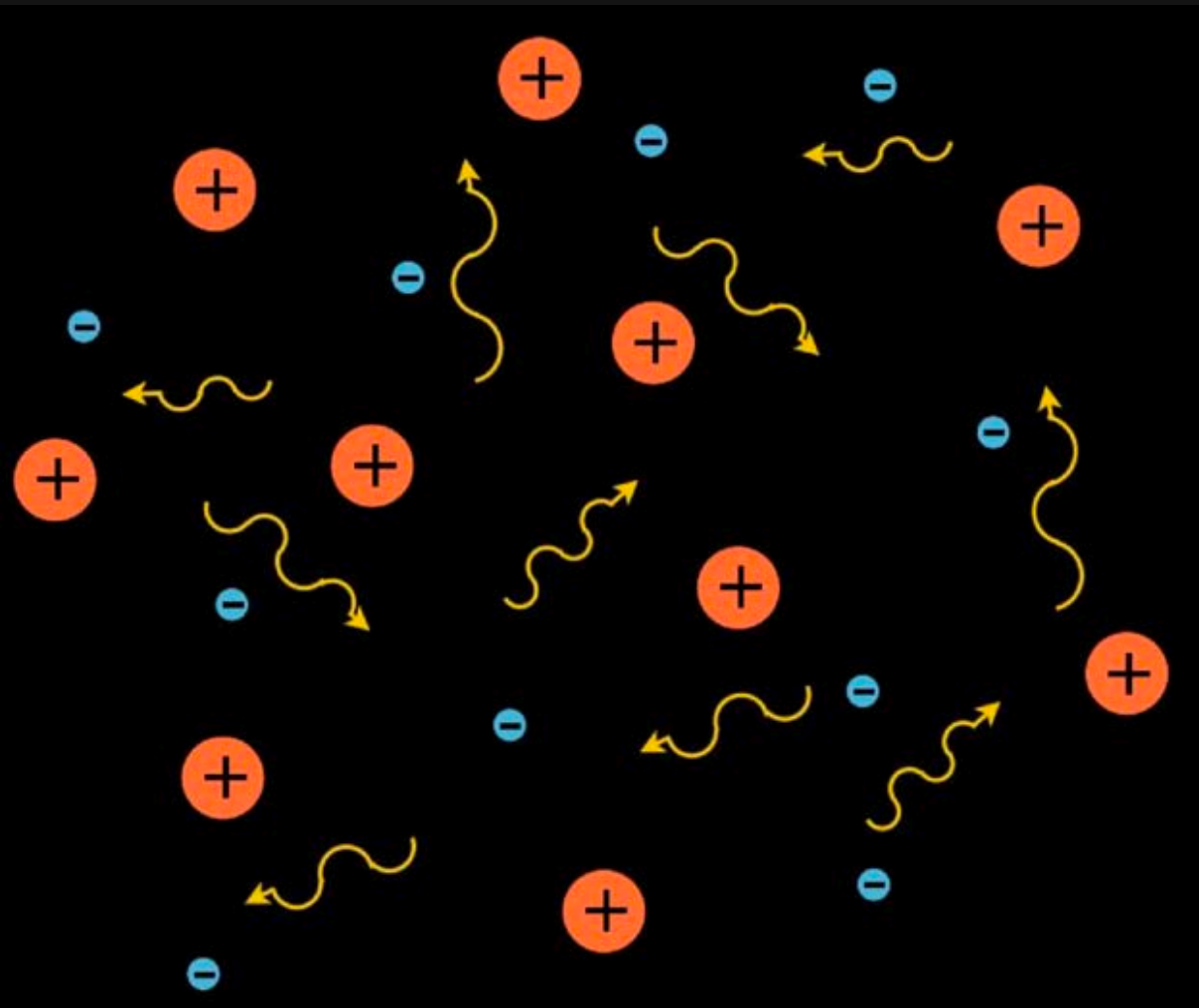


However, they are setting upper bounds on how heavy they can be! Even more competitive than Earth-based experiments.

Finally!

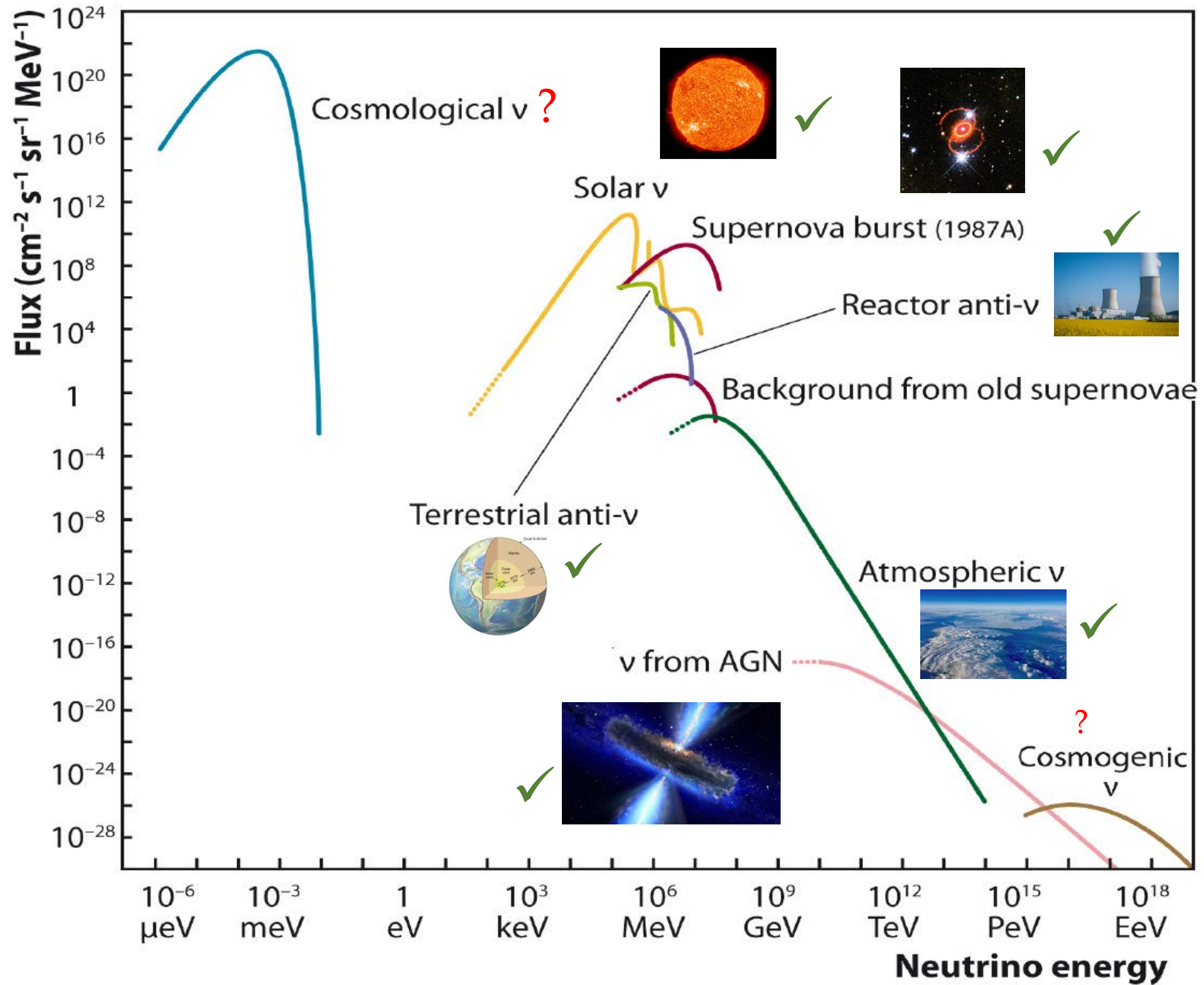
Cosmic Neutrinos

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.

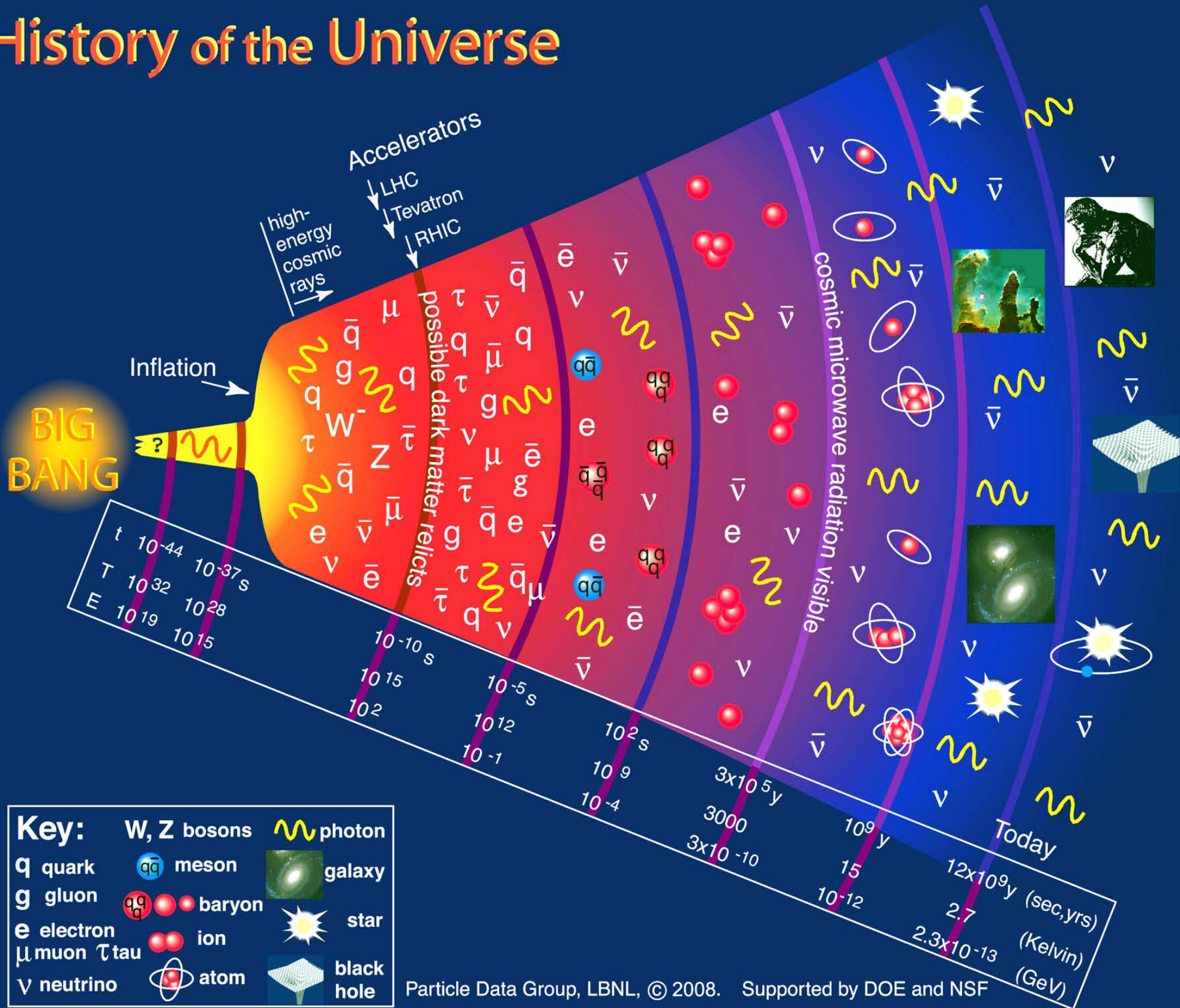


Currently, the best idea about how to detect them is the Princeton Tritium Observatory for Light, Early-Universe, Massive-Neutrino Yield (PTOLEMY) Experiment, but that might even be a dream currently.

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

History of the Universe



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!

