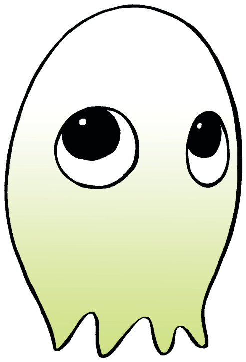
Neutrinos
Ghost particles of the Universe

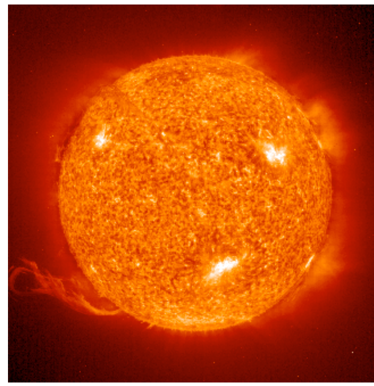
Kendall Mahn, TRIUMF
January 15th 2011

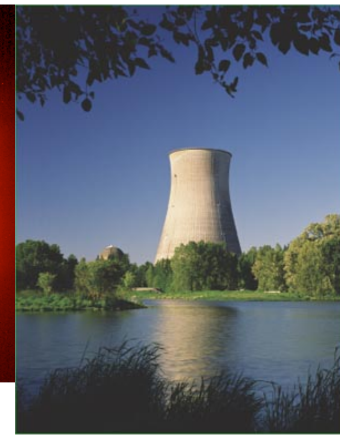
What you'll learn today

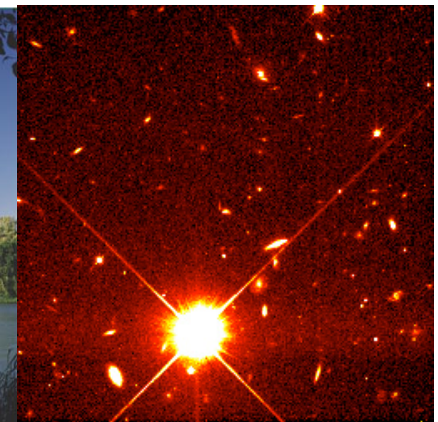
What a neutrino is



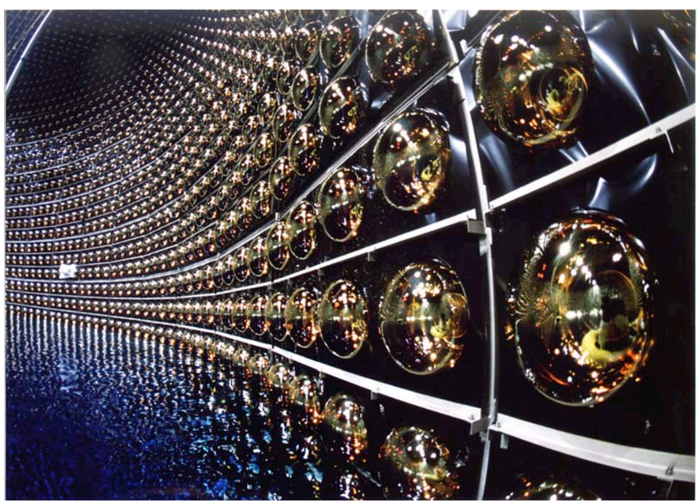
Where neutrinos come from







How we detect neutrinos



Why we study neutrinos

How neutrinos are useful

What’s a neutrino?

A. A penny sized pet jumping spider

B. Indie rock band in the UK

C. A media player for Mac OS

D. All of these are named after the particle you’ll learn about today, the neutrino

The world as you never saw it

A neutrino is a sub-atomic particle.

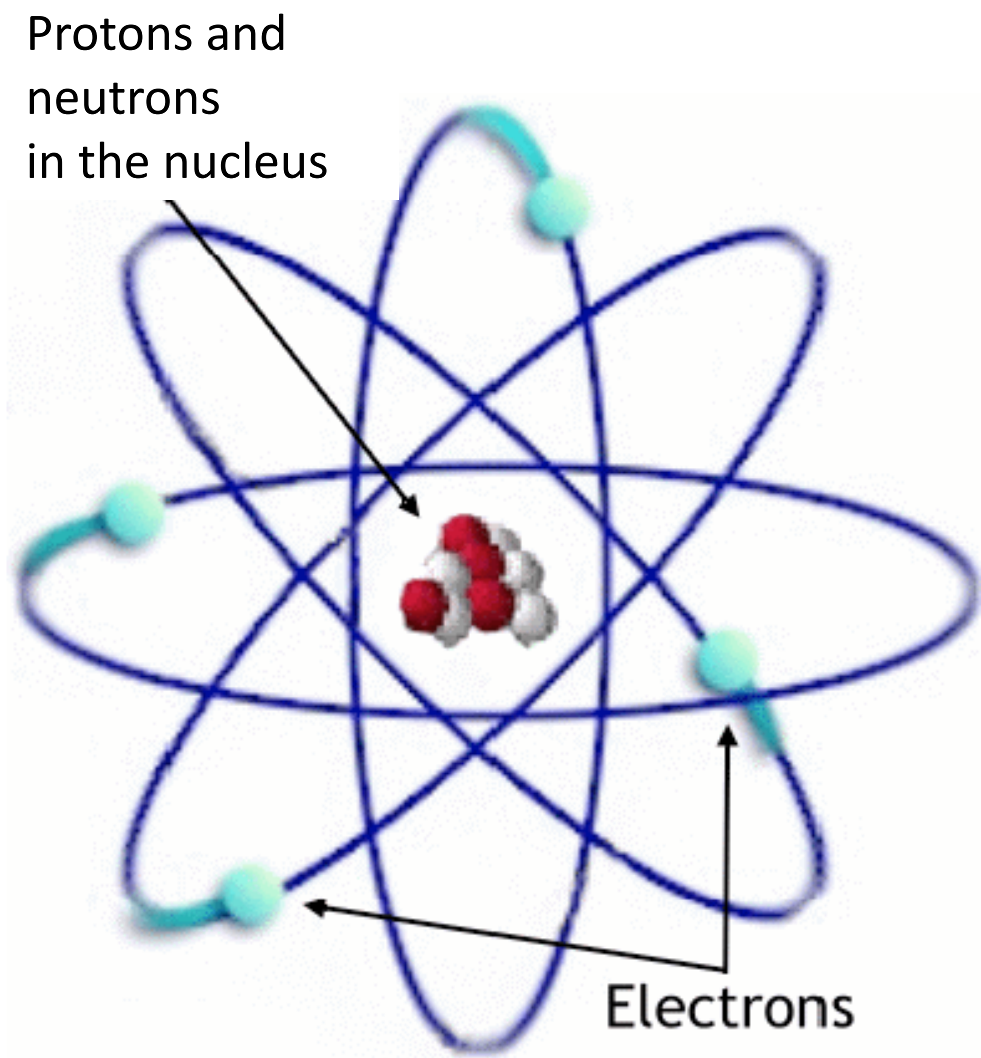
What's a sub-atomic particle?

The world is made up of the elements in the periodic table

Each element is an atom, made of protons, neutrons and electrons

An atom's isotopes all have the same number of protons, but different numbers of neutrons

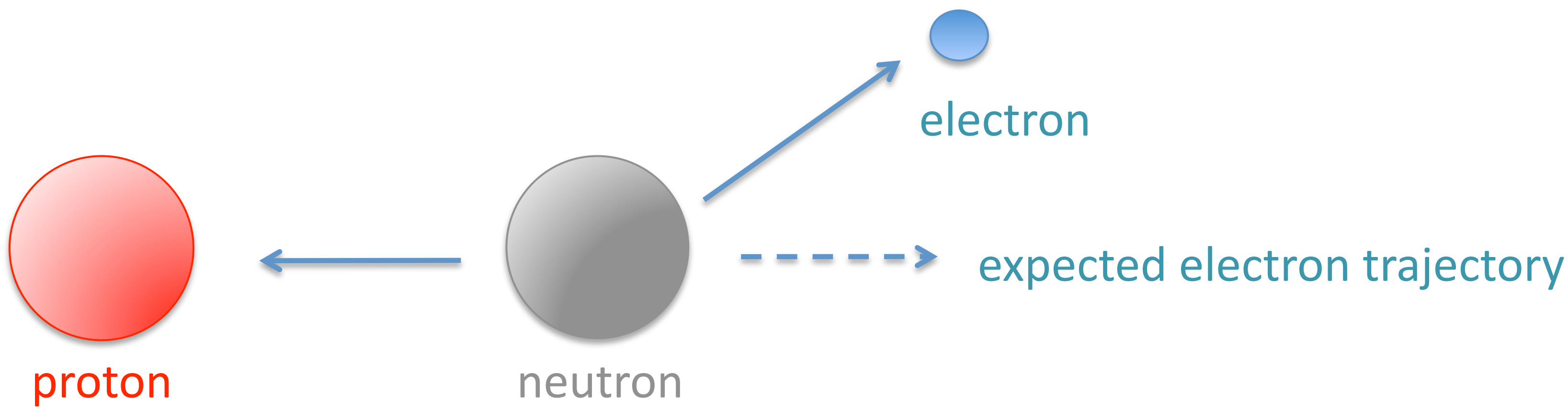
All three are sub-atomic particles, because they are smaller than an atom



A problem...

In the early 1900s, we discovered radioactive decays

This is when a neutron decays into an electron and a proton



Since there were only two particles observed from the decay, the momentum of the electron and proton should be equal and opposite

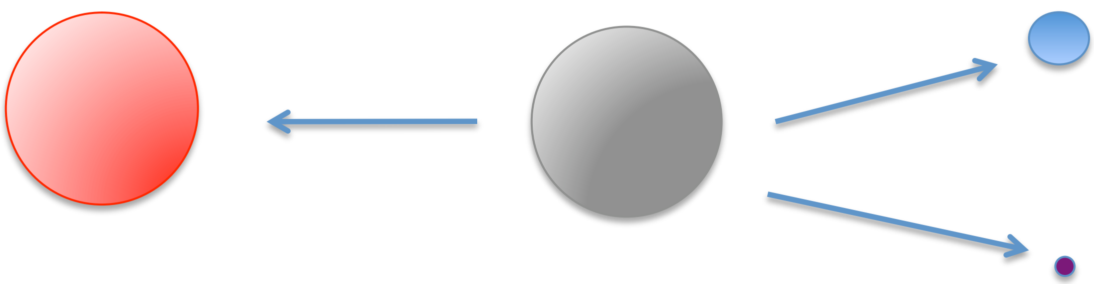
CONSERVATION OF MOMENTUM & ENERGY, fundamental law of physics

But this isn't what scientists found, some energy was missing...

``A desperate remedy''

Many prominent scientists, including Niels Bohr (right) were willing to abandon energy conservation

But Wolfgang Pauli (left) proposed the existence of a tiny particle, neutral in charge which carried the remaining energy with it



The neutrino!

"I do not dare publish this idea...."
"I have done a terrible thing, I have postulated a particle that cannot be detected''

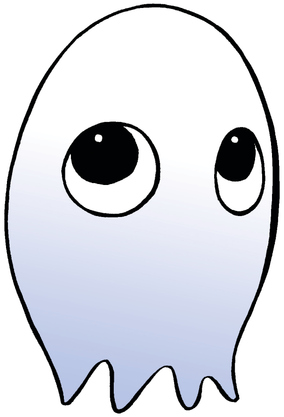
The ghost particle

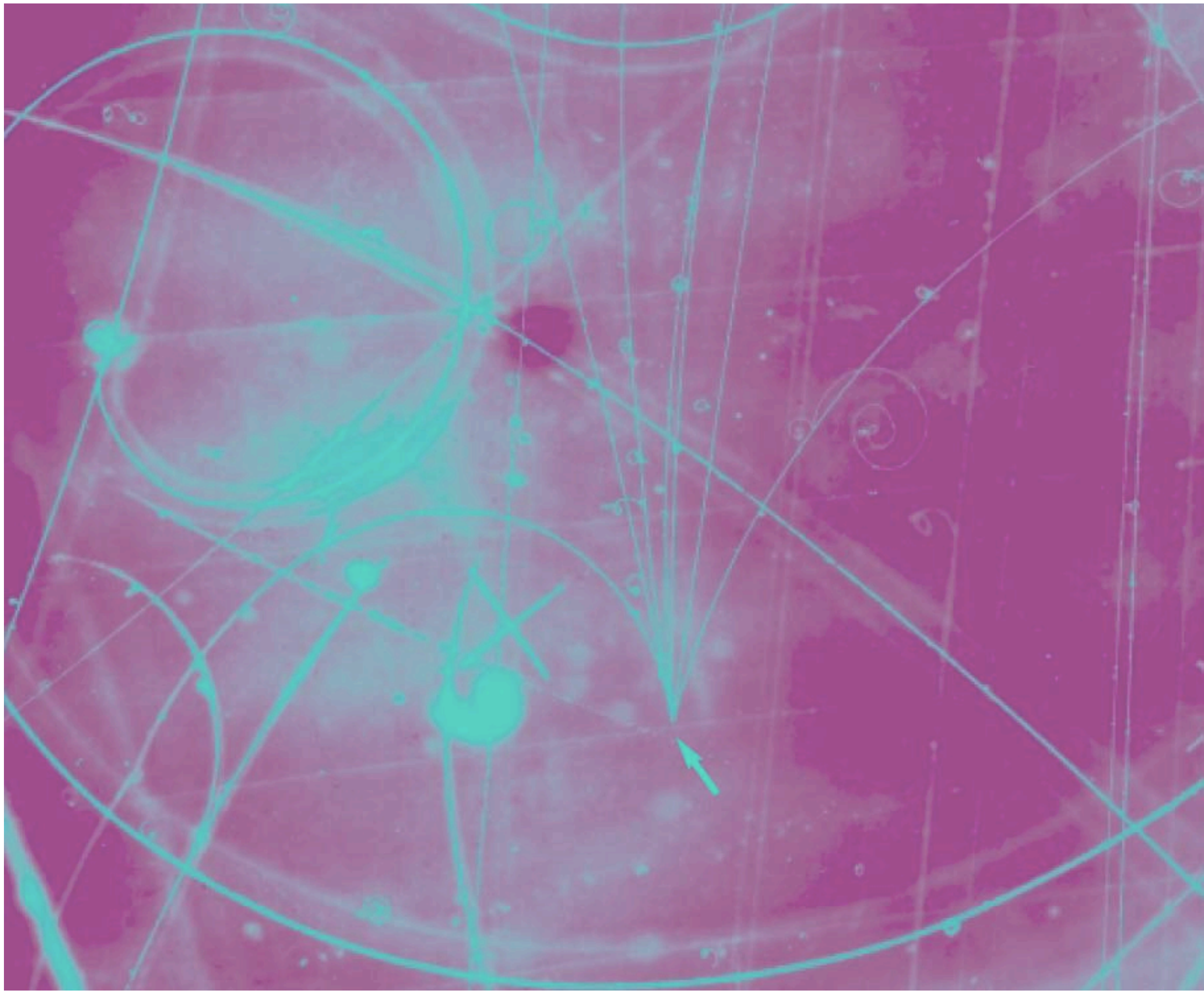
What we now know about neutrinos:

1) Neutrinos are tiny

2) Neutrinos are neutral

3) Neutrinos move fast because they are light





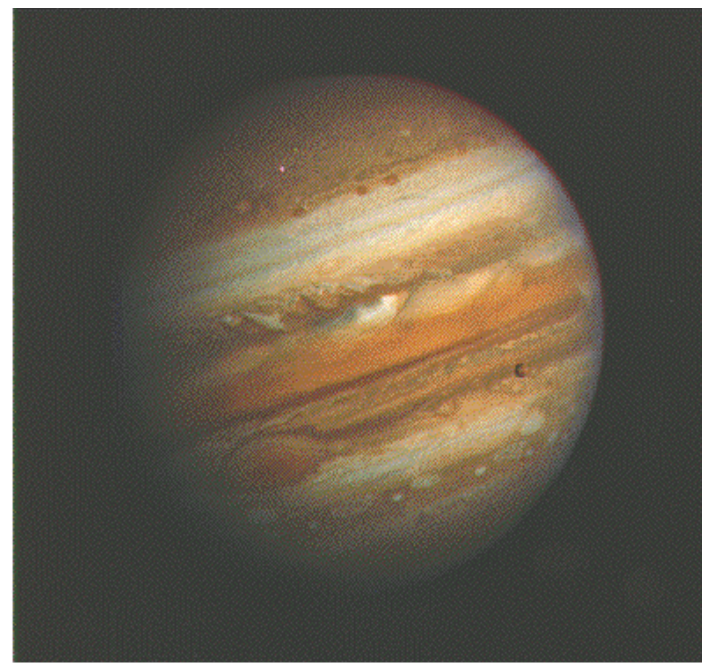
4) Neutrinos are like ghosts– they hardly interact with anything! This is what makes them so hard to detect

How tiny is tiny?

If a neutrino weighs as much as a penny, then

An electron would weigh as much as a car

A proton would weigh as much as the space shuttle

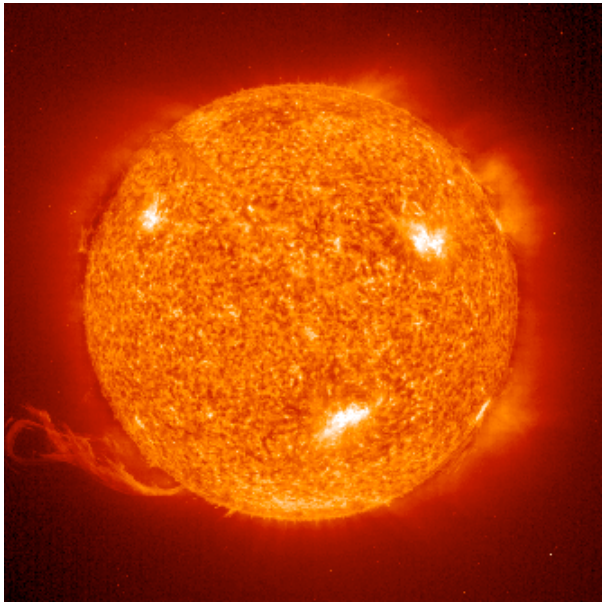


And a human would weigh about 20x Jupiter

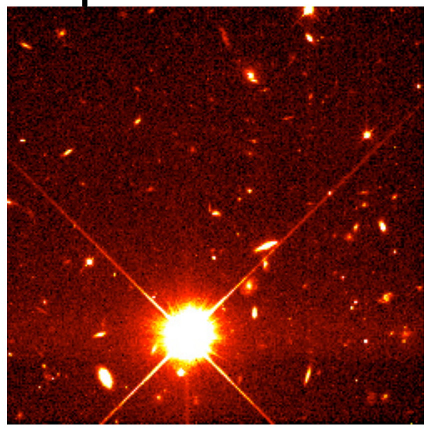
<u>Neutrinos are SMALL</u>

Where do neutrinos come from?

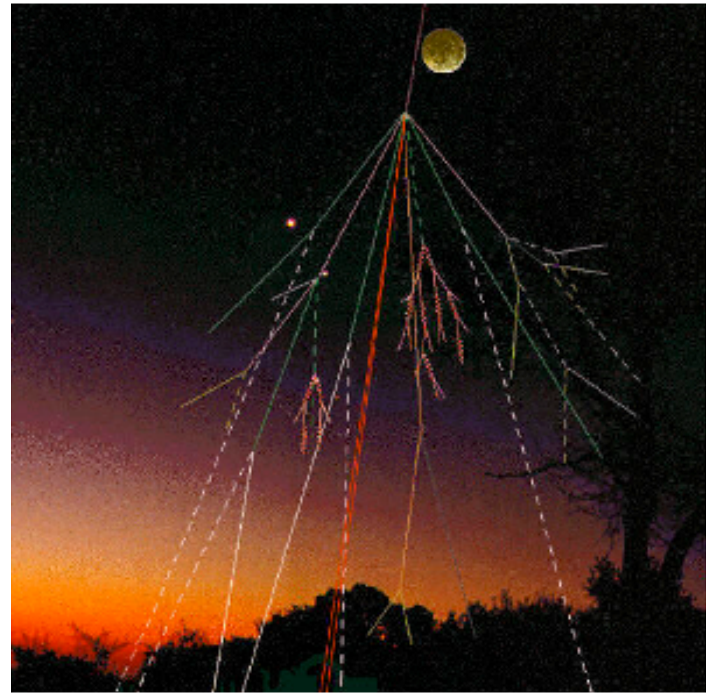
The Sun (fusion)



Supernova

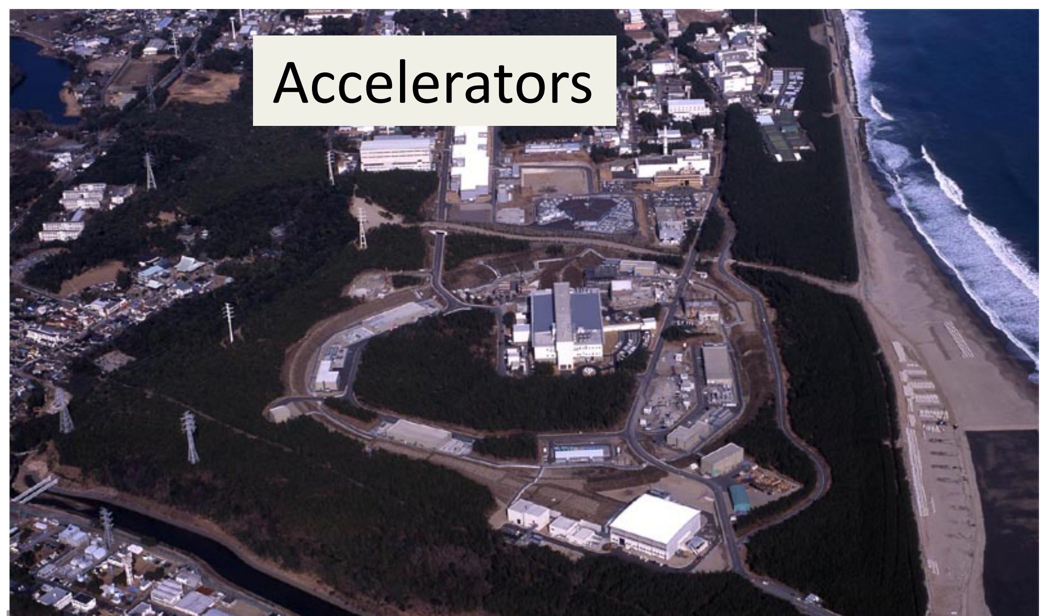


Our atmosphere

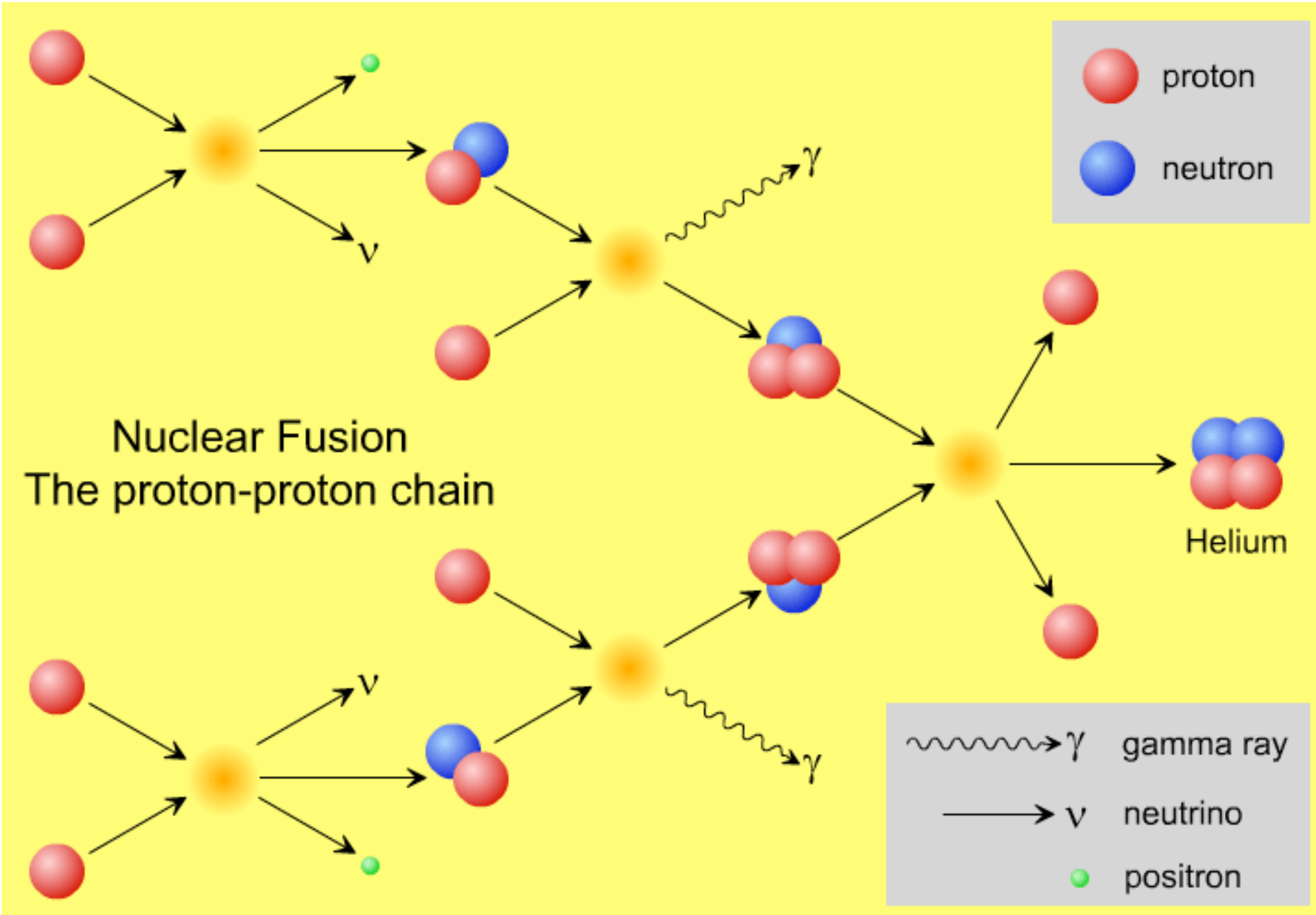


Everywhere!

Reactors (radioactive decays)



Neutrinos from the sun



Fusion combines two protons to releases light (γ) and neutrinos (ν)

Over 60 billion neutrinos from the sun pass through your thumbnail every second!

Why haven't I seen a neutrino?

Neutrinos interact only via the ``weak force'', but charged particles interact via electromagnetic interactions

An electron can exert a force on a proton from meters away

The typical range of the weak force is ~10^{-18} m!

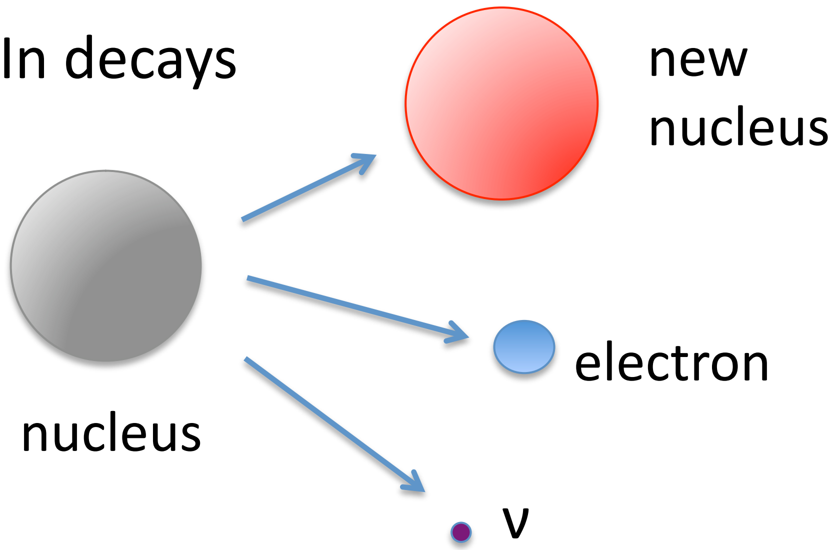
Lead is a common radiation shield; X rays interact in the lead vest at the at the dentists office instead of interacting in you

To block a neutrino from reaching you, you'd need a light year of lead (10 trillion km!)

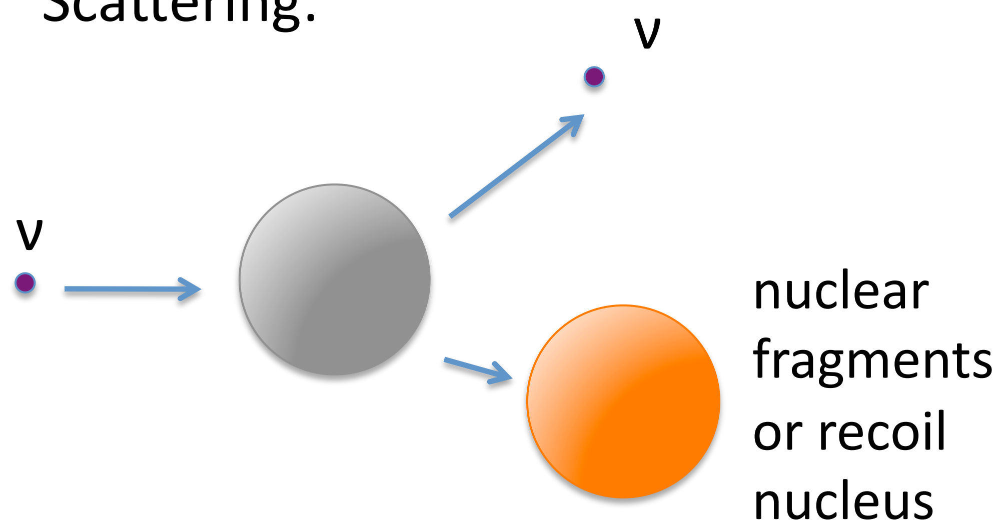
So how do neutrinos interact?

A neutrino (ν) can interact in three ways:

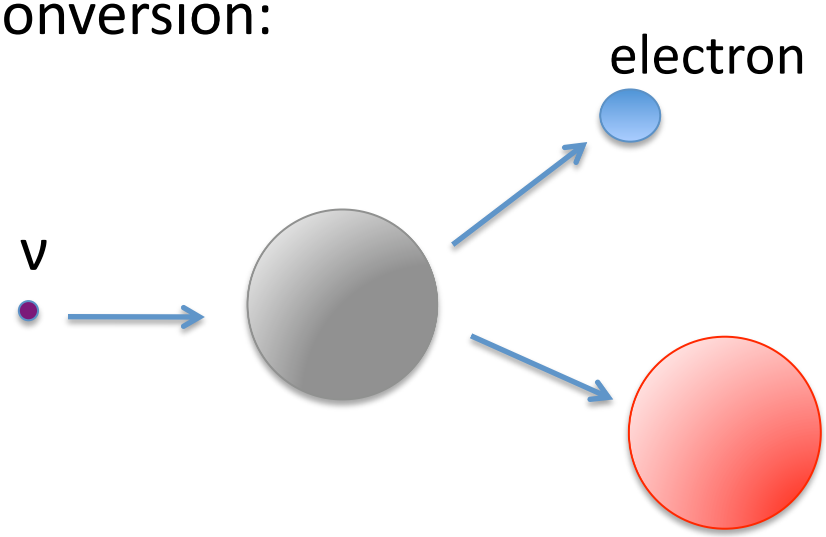
In decays



Scattering:



Conversion:



We detect neutrino interaction by detecting:

- Nothing coming in, then
- the outgoing electron or
- the nucleus (or fragments)

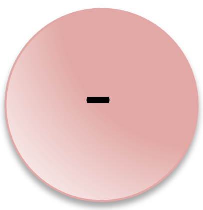
Even more neutrinos!

There are actually three neutrinos, each with a charged particle partner

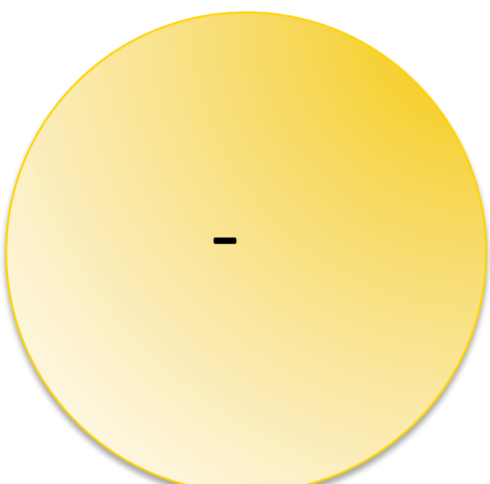
All of these particles are called ``leptons''

Electron (e)
mass (1)

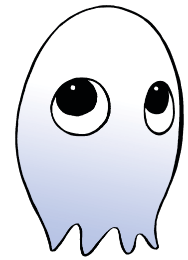
Muon (μ)
mass (200)



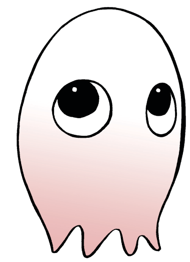
Tau (τ)
mass (3500)



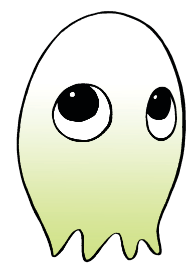
- Electron neutrino (ν_e)



- Muon neutrino (ν_μ)



- Tau neutrino (ν_τ)

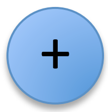


Even more neutrinos!

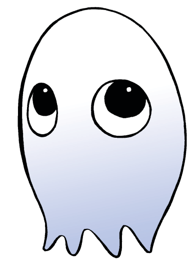
There are three antineutrinos, each with a positively charged partner

These are all antimatter (see next talk for what we can do with positrons)

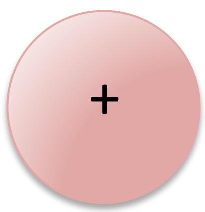
Positron (e)
mass (1)



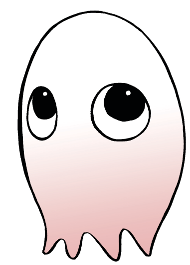
Electron Antineutrino ($\bar{\nu}_e$)



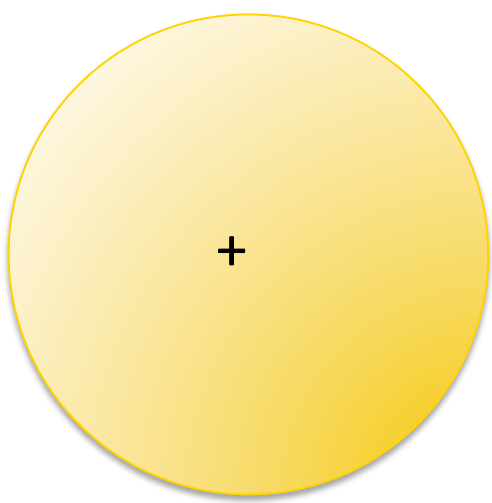
Muon (μ)
mass (200)



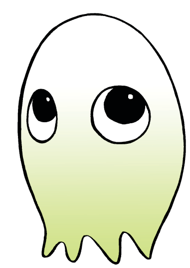
Muon Antineutrino ($\bar{\nu}_\mu$)



Tau (τ)
mass (3500)



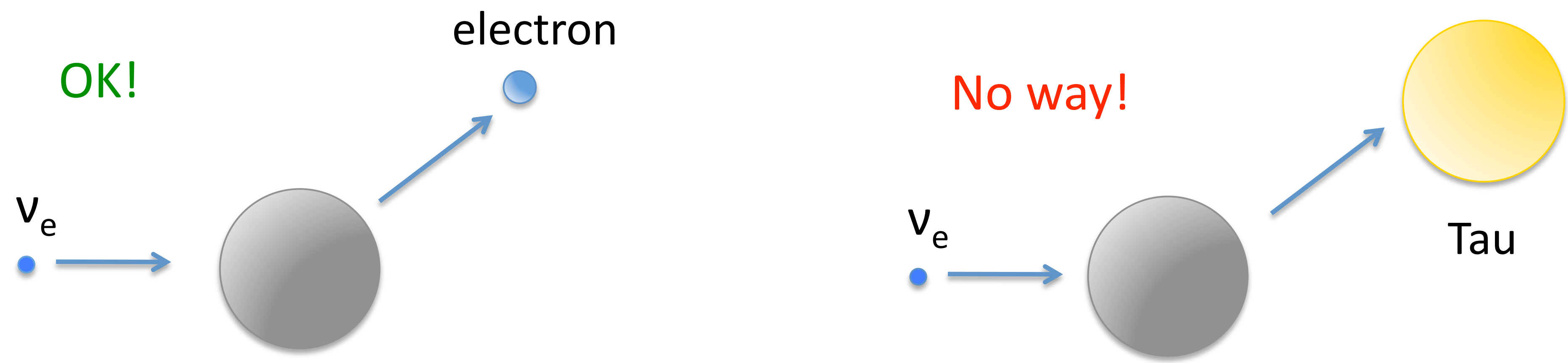
Tau Antineutrino ($\bar{\nu}_\tau$)



So how do neutrinos interact?

We only see each neutrino type with its partner:

Electron neutrinos with electrons, etc



That is, the three types of neutrinos each have their own ``flavor''

Three flavors: electron-type, muon-type, tau-type

Lets go neutrino hunting!

One way to look at electron neutrinos from the sun is:

1) Get a giant (600 tons) vat of cleaning fluid (C2Cl4) and wait

2) After some time, the neutrinos will interact with the chlorine, producing argon:

$$\nu_e + {}^{37}Cl \rightarrow e + {}^{37}Ar$$

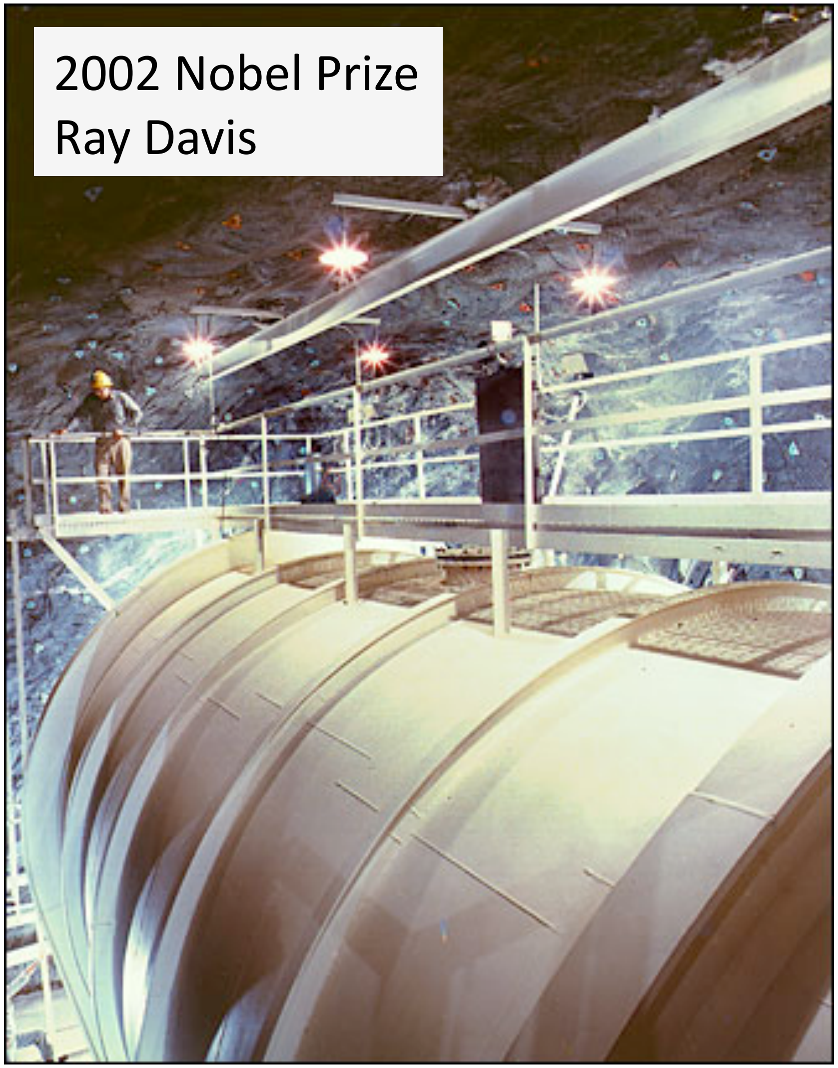
3) Count the argon atoms

4) Compare to expected number of neutrinos produced in the sun....

Expected rate: 5.7+/-0.9 atoms/day

Measured rate: 1.9+/- 0.2 atoms/day

Two thirds of the neutrinos are missing?



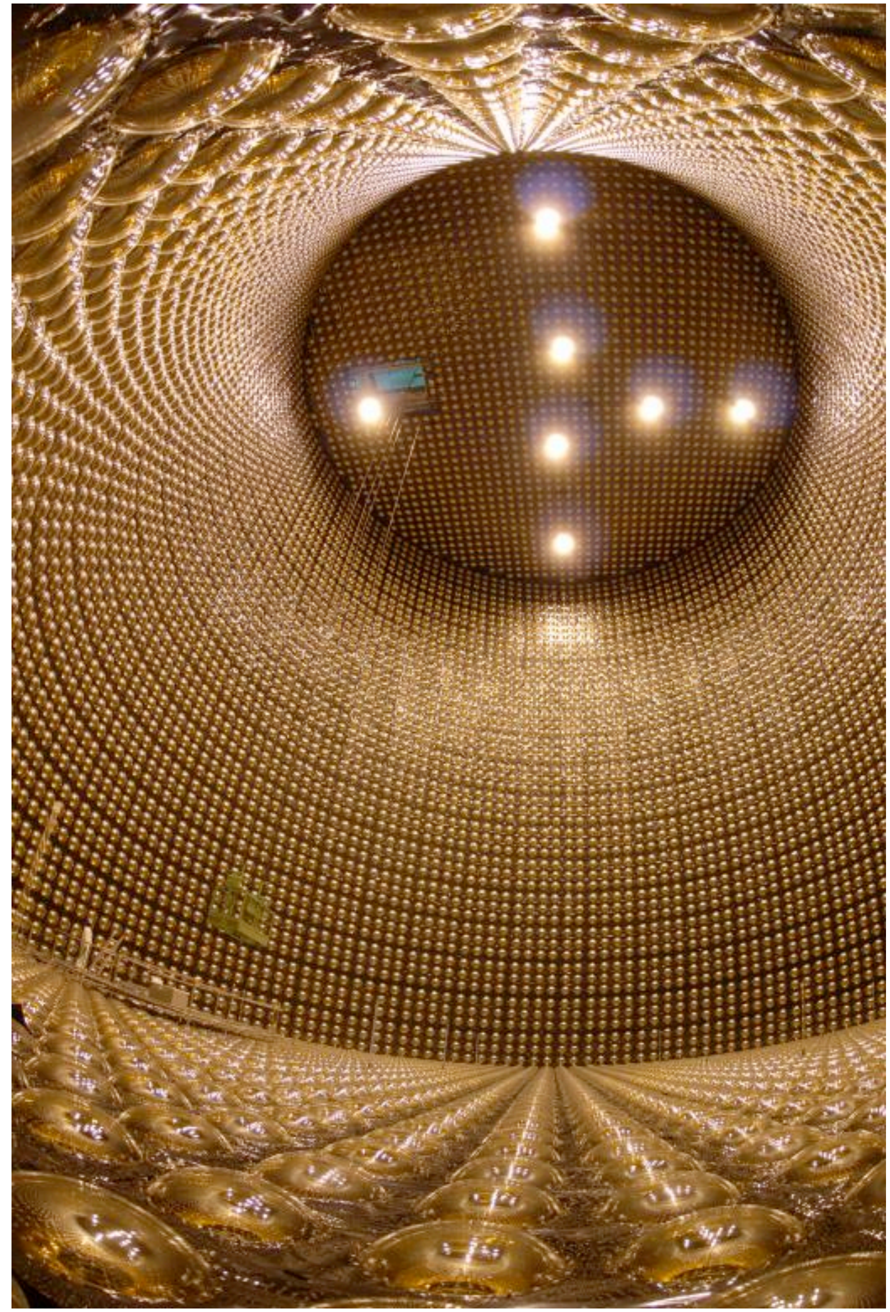
Another experiment

Lets try to detect neutrinos with a different method

The Super-Kamiokande detector is a 41m tall water tank lined with 11,000 gold orbs inside a mountain in Japan

Here's what the tank looks like without water, it usually holds 50,000 tons of ultra pure water

The orbs are 50cm of handblown glass ''electronic eyes'' designed to detect light produced by charged particles

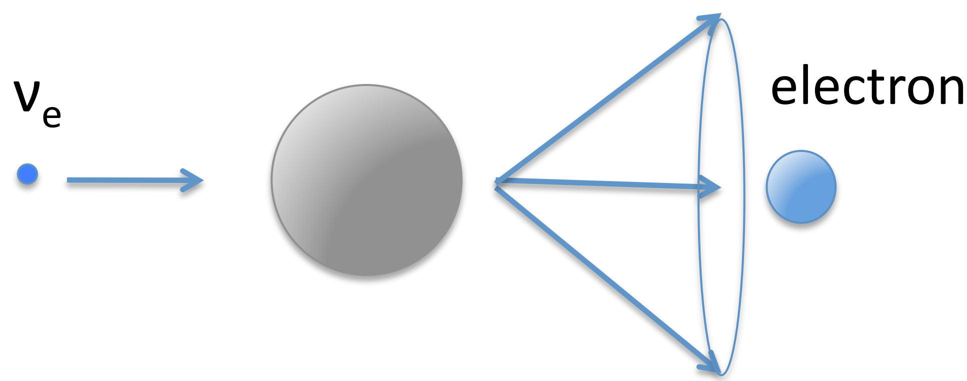


What's Cherenkov light?

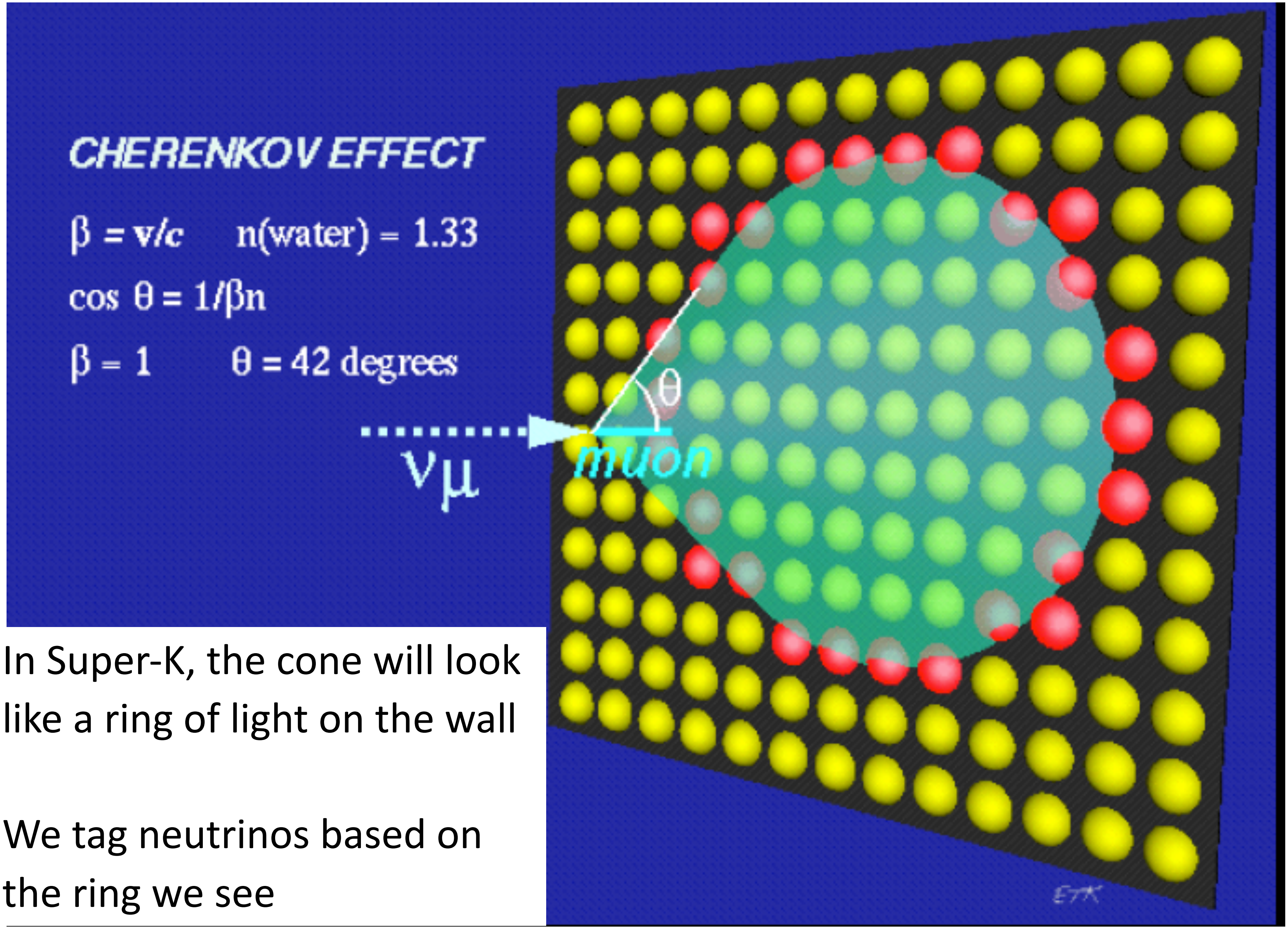
The light detectors see Cherenkov light, produced by the neutrino's ``buddy"
When the electron is emitted, it is going faster than the speed of light in water

Nothing goes faster than the speed of light... in a vacuum, which is 'c'
Light itself travels slower in a material

A sonic boom is when an airplane is going faster than the speed of sound
This is a light boom, a forward cone of blue light as the electron moves



What a neutrino looks like to Super-K

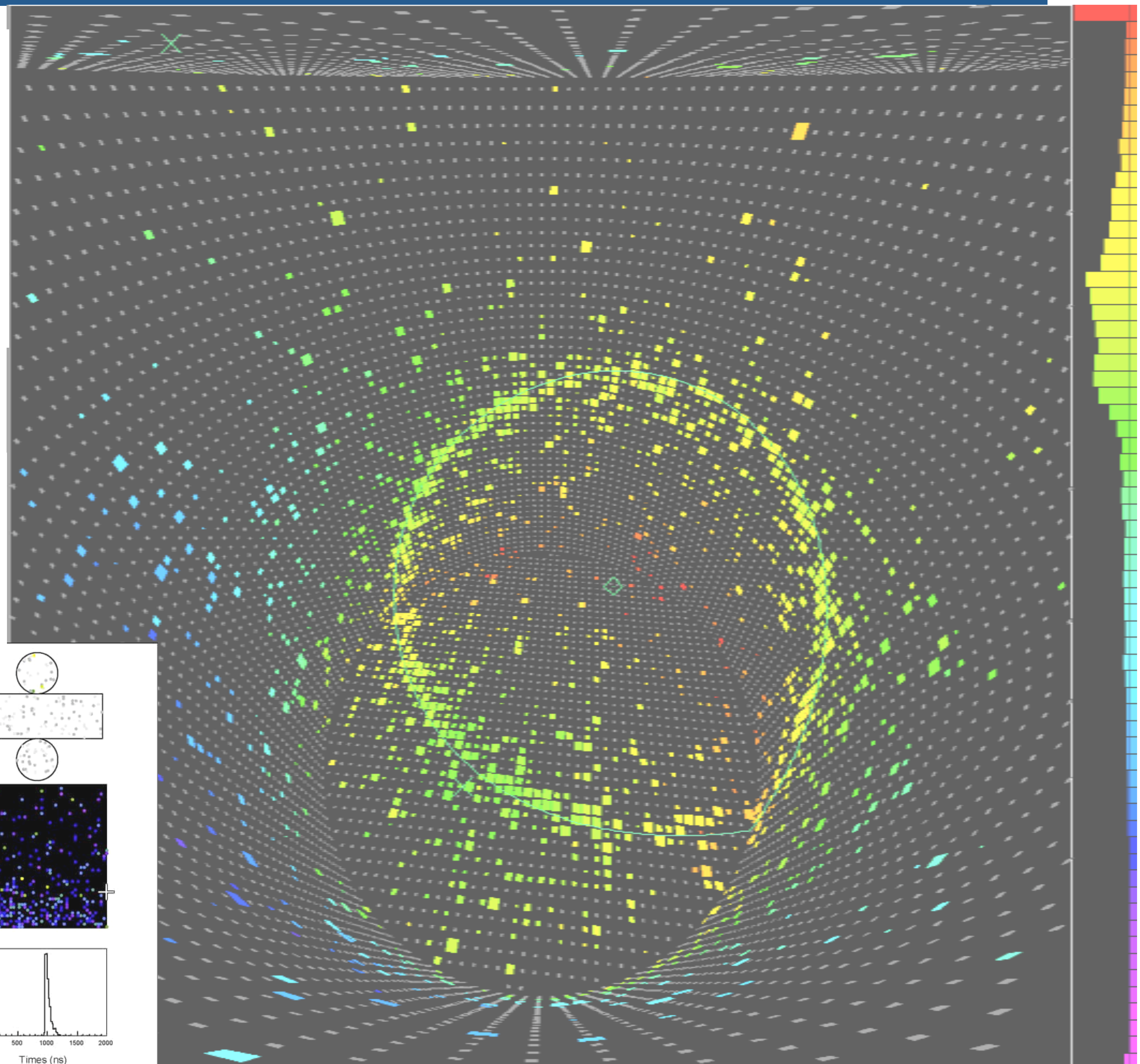


In Super-K, the cone will look like a ring of light on the wall

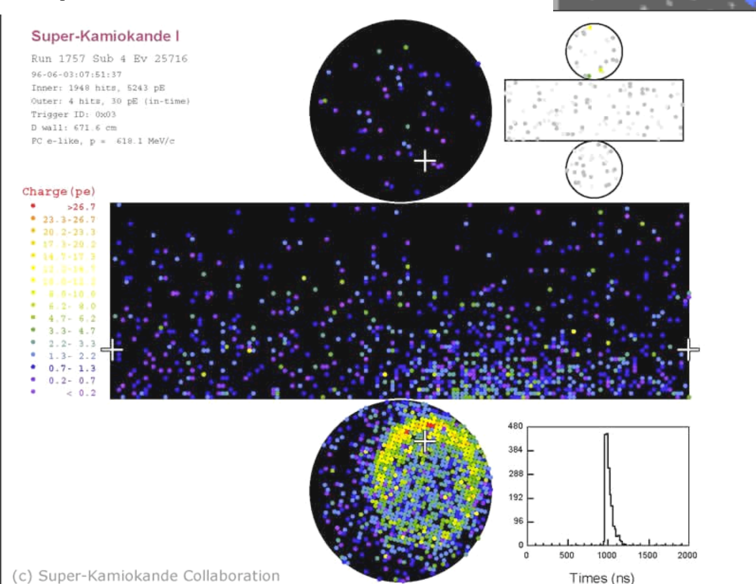
We tag neutrinos based on the ring we see

Example electron neutrino events

Color represents the time of the light and which electronic eye saw light



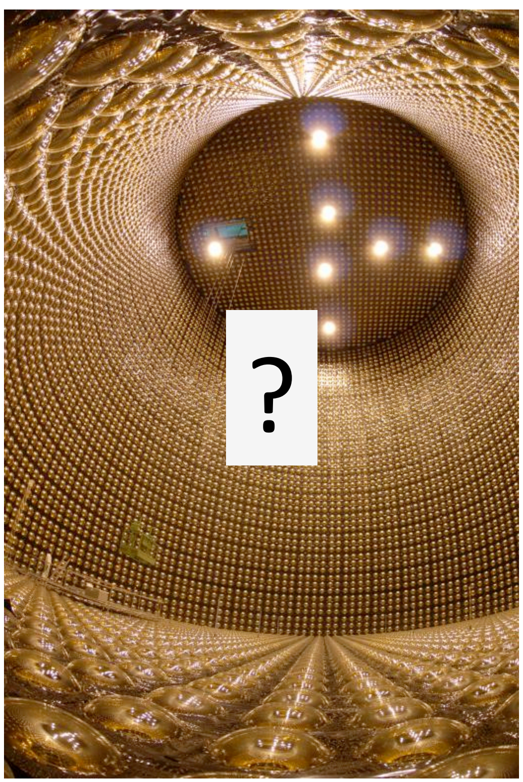
Another event, with Super-K opened like a can:

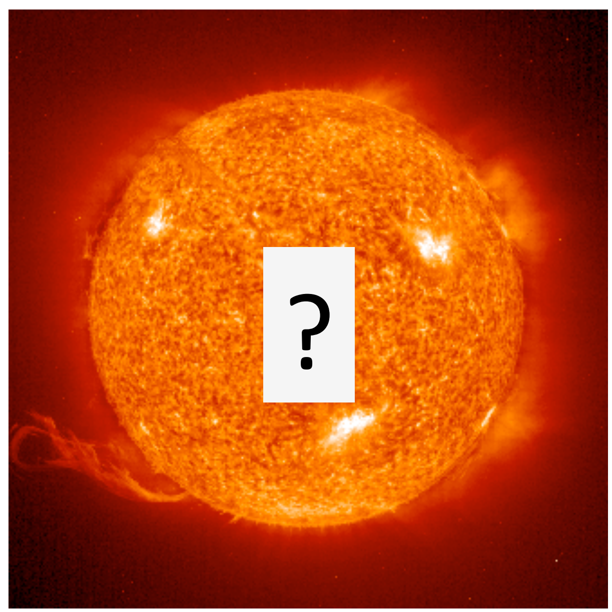


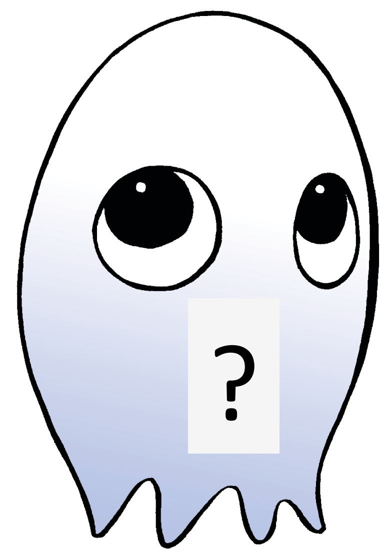
The problem with solar neutrinos

Super-K and other experiments all confirmed the same thing:
that there were fewer electron neutrinos from the sun than expected

1) Are the experiments wrong?
2) Is there something wrong with our physics model of the Sun?
3) Is something happening to the neutrinos?

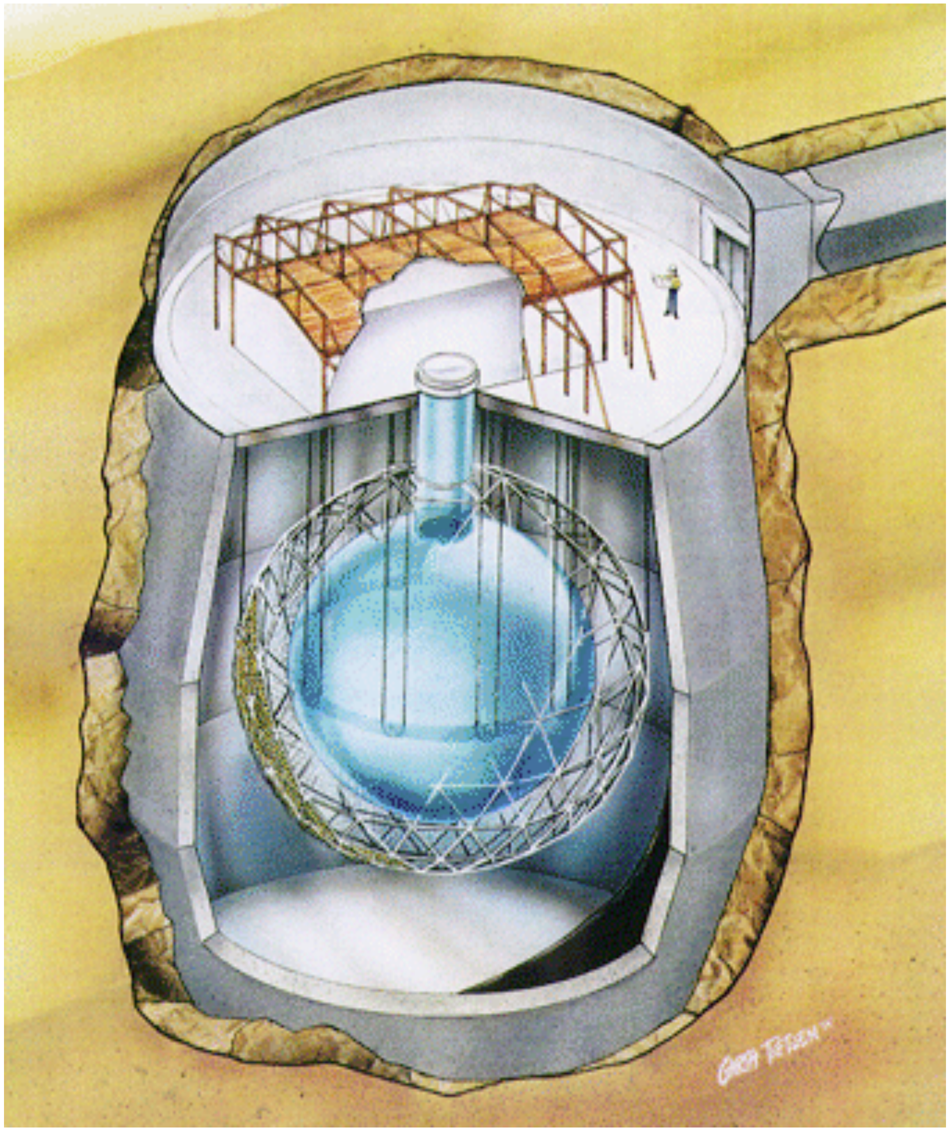






A solution with SNO

A neutrino experiment in Canada (Sudbury Neutrino Observatory, or SNO) solved the solar neutrino problem



1000 tons of heavy water (D_20) and some salt (NaCl) inside an acrylic vessel

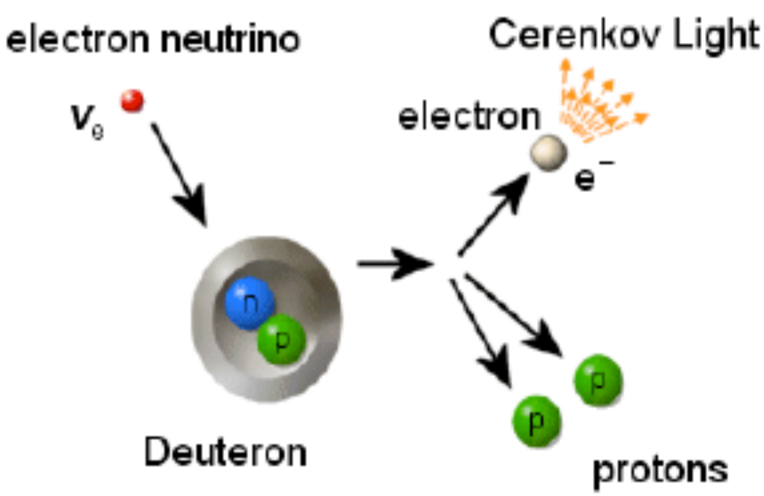
Heavy water on loan from Ontario Hydro, worth 200$million!

Surrounding the heavy water is a structure with 9500 inward looking electronic eyes and ultra pure water

Also in a mine, 2km underground!

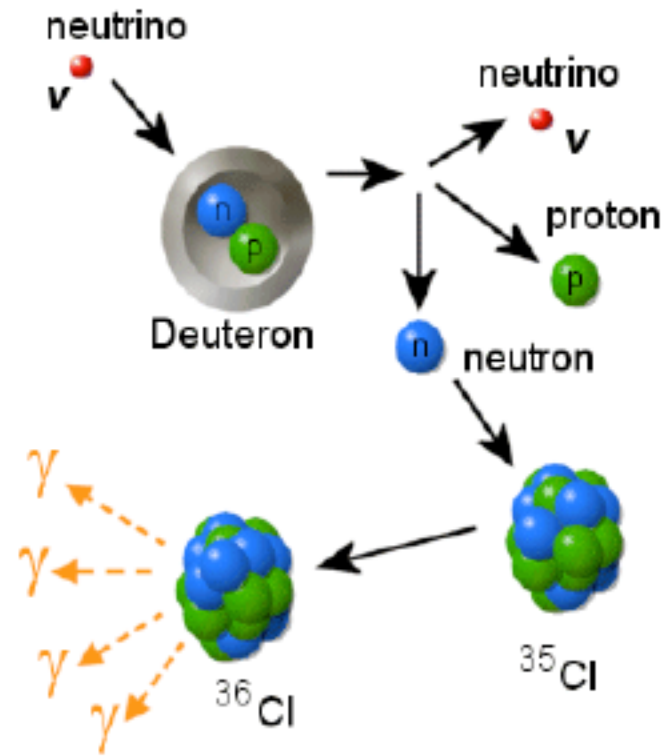
What SNO sees

SNO had the unique capability to look at all neutrino flavors (ν_e, ν_μ, ν_τ) at once and also look at just ν_e



Electron neutrinos only:

$\nu_e + d \rightarrow 2p + e^-$

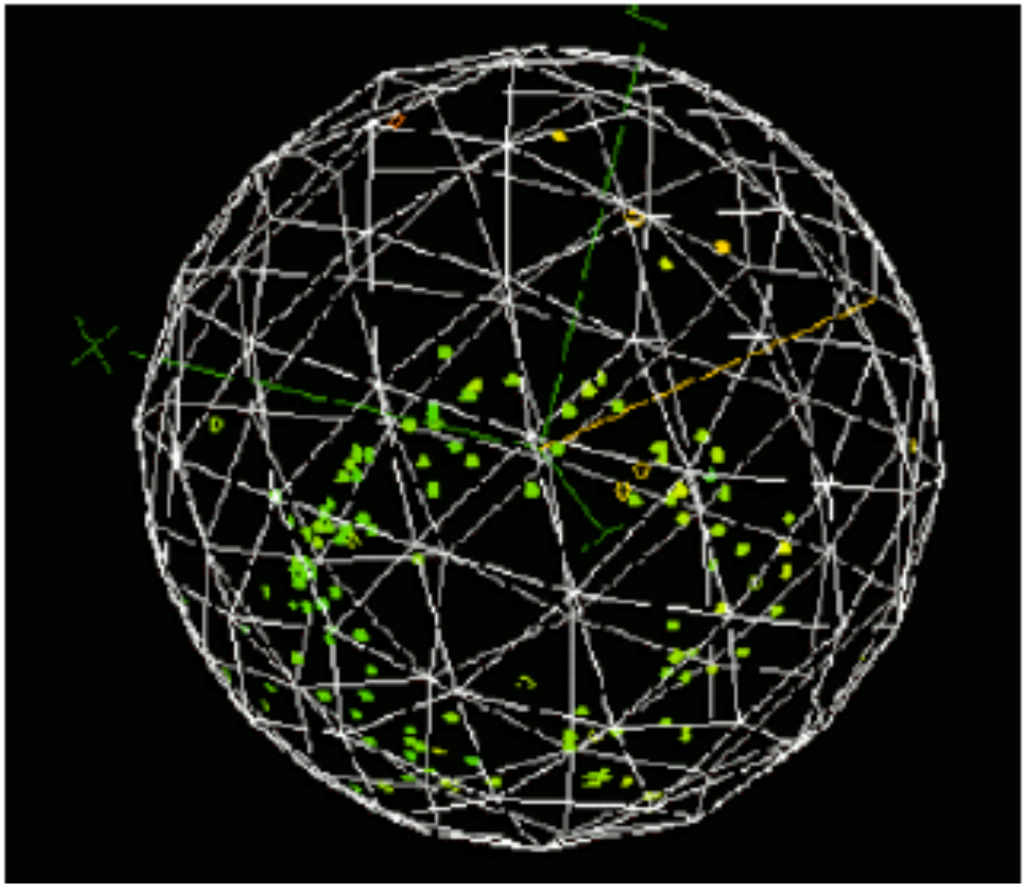


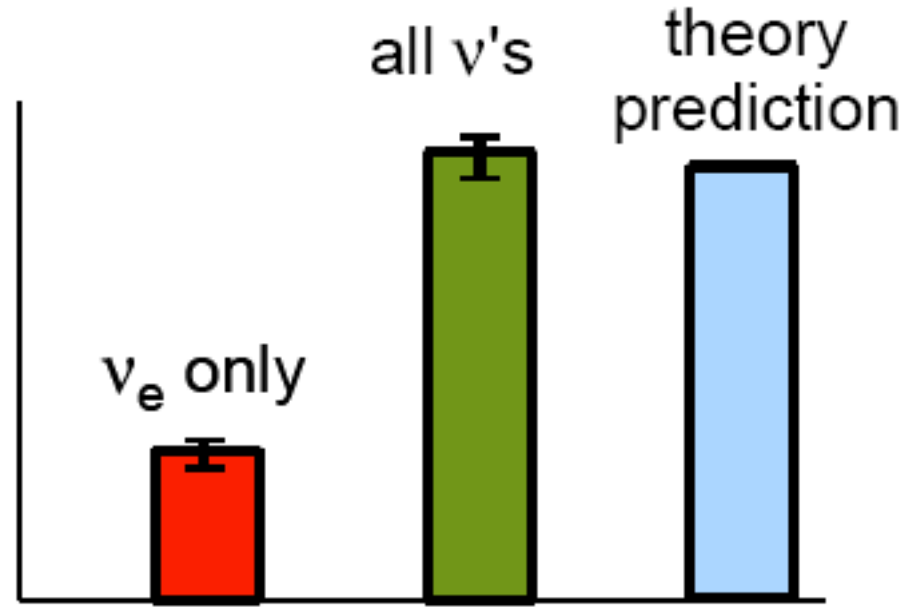
Any type of neutrino:

$\nu_x + d \rightarrow \nu_x + n + p$

$n + {}^{35}Cl \rightarrow {}^{36}Cl$ + multiple γ's

A surprising discovery





The total number of neutrinos from the sun matches theory and

The ν_e are transforming into ν_{μ}, ν_{τ} between the Sun and earth!

This is called "neutrino oscillation!"

How do neutrinos oscillate?

Warning: You are entering a dimension, filled with Quantum Mechanics
You may become a little uncomfortable, but don't panic!

Quantum mechanically speaking, a neutrino isn't just a singular thing, it's a combination of three ``mass states'':

$$\nu_e = \nu_1 + \nu_2 + \nu_3$$

I don't mean if I open up a neutrino there are little ν_1, ν_2 and ν_3 inside

If I dumped all the jelly beans into a bowl, and I pulled out a green jelly bean (ν_e) it could've come from the ν_1 jar, ν_2 jar or ν_3 jar

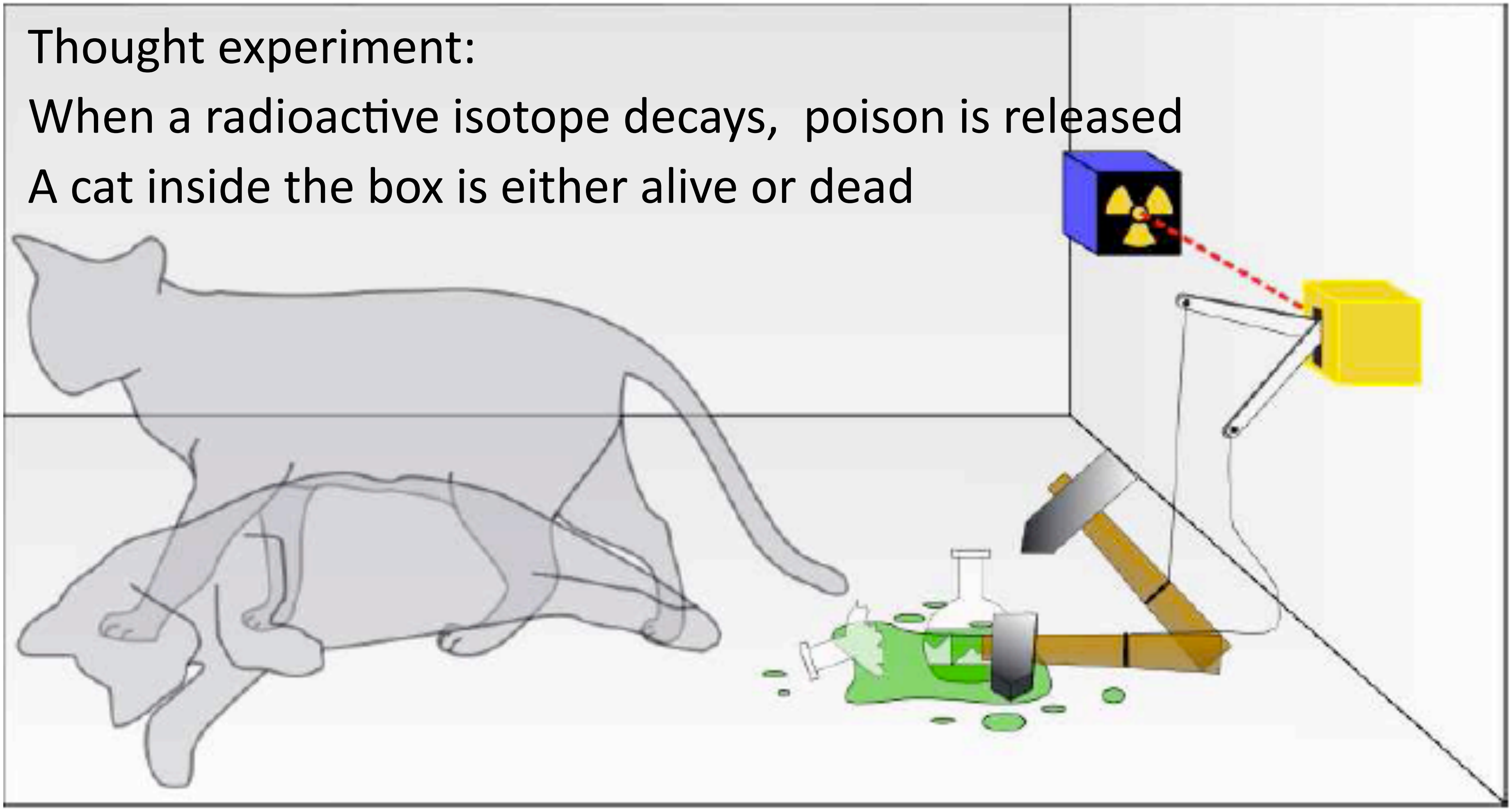
ν_1, ν_2, and ν_3 represent what I could see (ν_e, ν_μ or ν_τ) before I measure it

Schrödinger's Cat wanted: Dead or Alive

Thought experiment:

When a radioactive isotope decays, poison is released

A cat inside the box is either alive or dead



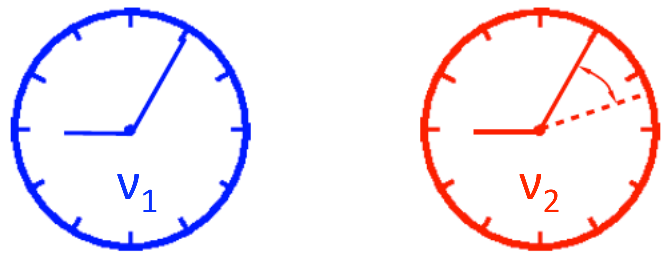
Quantum mechanically, the state inside the box is a combination of 'alive' state and 'dead' state, each with a probability

I can't see the ν_1 and ν_2 states, but I represent them with a similar combination

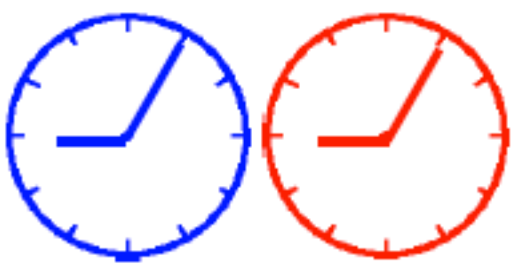
A cat friendly explanation with clocks

Imagine I have just two neutrino flavors (ν_e and ν_μ) and two mass states (ν_1 and ν_2)

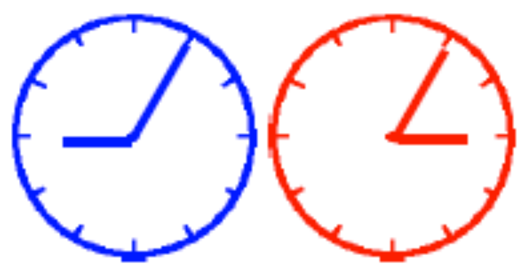
Each mass state I will represent as a clock. The speed of the clock is set by the energy of the mass state



The difference in the clock time is what defines a muon or electron neutrino



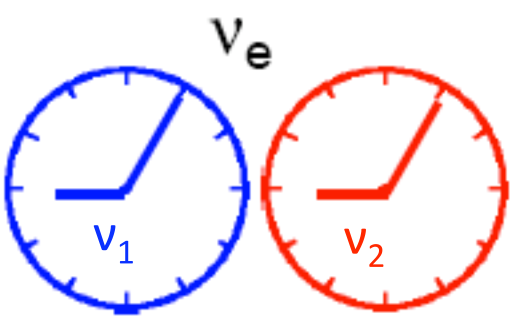
When the clocks read the same time, that's an electron neutrino



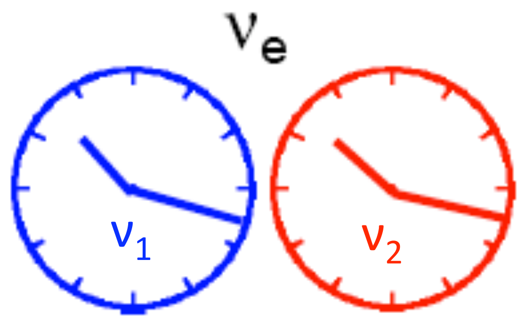
When the clocks are 6 hours apart, that's an muon neutrino

Synchronized clocks

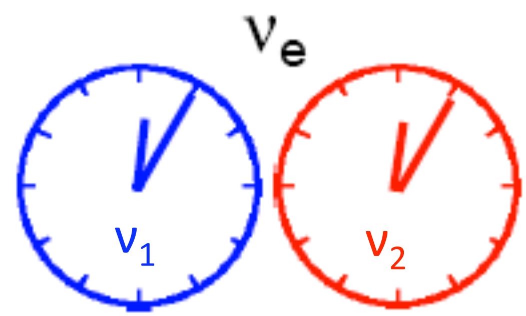
If $\nu_1 = \nu_2$, then the two clocks run at the same speed



At the start, the clock are in synch so it is a electron neutrino



Still an electron neutrino at 10:17



Even later, still an electron neutrino

If neutrinos had no mass or all the same mass, then there could be no oscillation

Need two different mass states for there to be oscillation

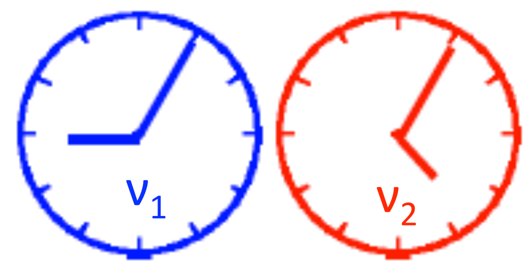
Example with clocks (cont'd)

When the clocks read the same time, that's an electron neutrino

When the clocks are 6 hours apart, that's an muon neutrino

If the red clock is 4 hours ahead or behind, then it behaves like a muon neutrino 2/3 of the time

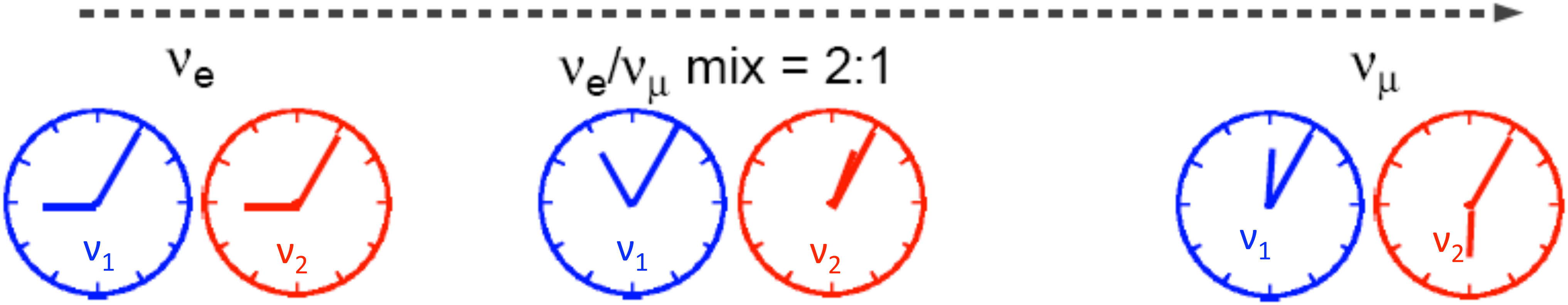
and an electron neutrino 1/3 of the time



I only measure a ν_e or a ν_μ, but if I did 300 measurements of neutrinos with this time difference, I would see ~200 muon neutrinos and ~100 electron neutrinos

What if the clocks get out of sync?

Now let the red clock run fast relative to the first clock ($\nu_1 \neq \nu_2$)



At the start, the clock are in synch so it starts as an electron neutrino

Red clock runs fast, now it's 2 hours ahead

Later, the red clock is 6 hours ahead, so we have a muon neutrino!

Two distinct mass states (two clocks with different speeds) imply we will observe a muon neutrino even if we started with an electron neutrino

Next generation neutrino oscillation

Wow, so neutrinos oscillate? That's amazing!

What more is there to learn?

We predict that the ν_3 mass state is mostly ν_μ and ν_τ

Can we see that remaining tiny ν_e fraction?
No one's seen it yet!

We need a new experiment...

Tokai to Kamioka experiment

We need to make a LOT of neutrinos (an accelerator based neutrino beam)

We also need a LONG distance (for the clock phases to be out of sync)

And we need a LARGE detector (Super-K)

How to make a beam of neutrinos

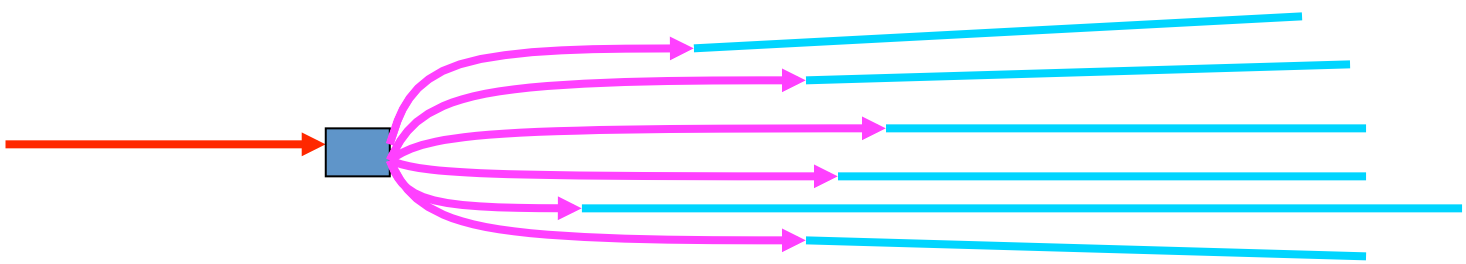
Tunneling neutrino beam on Star Trek

How do I get one of those? I don't have a spaceship....

Instead, start with a ``photon beam'', or a flashlight:

Electrical current hits a filament

Producing light, which is focused into a beam

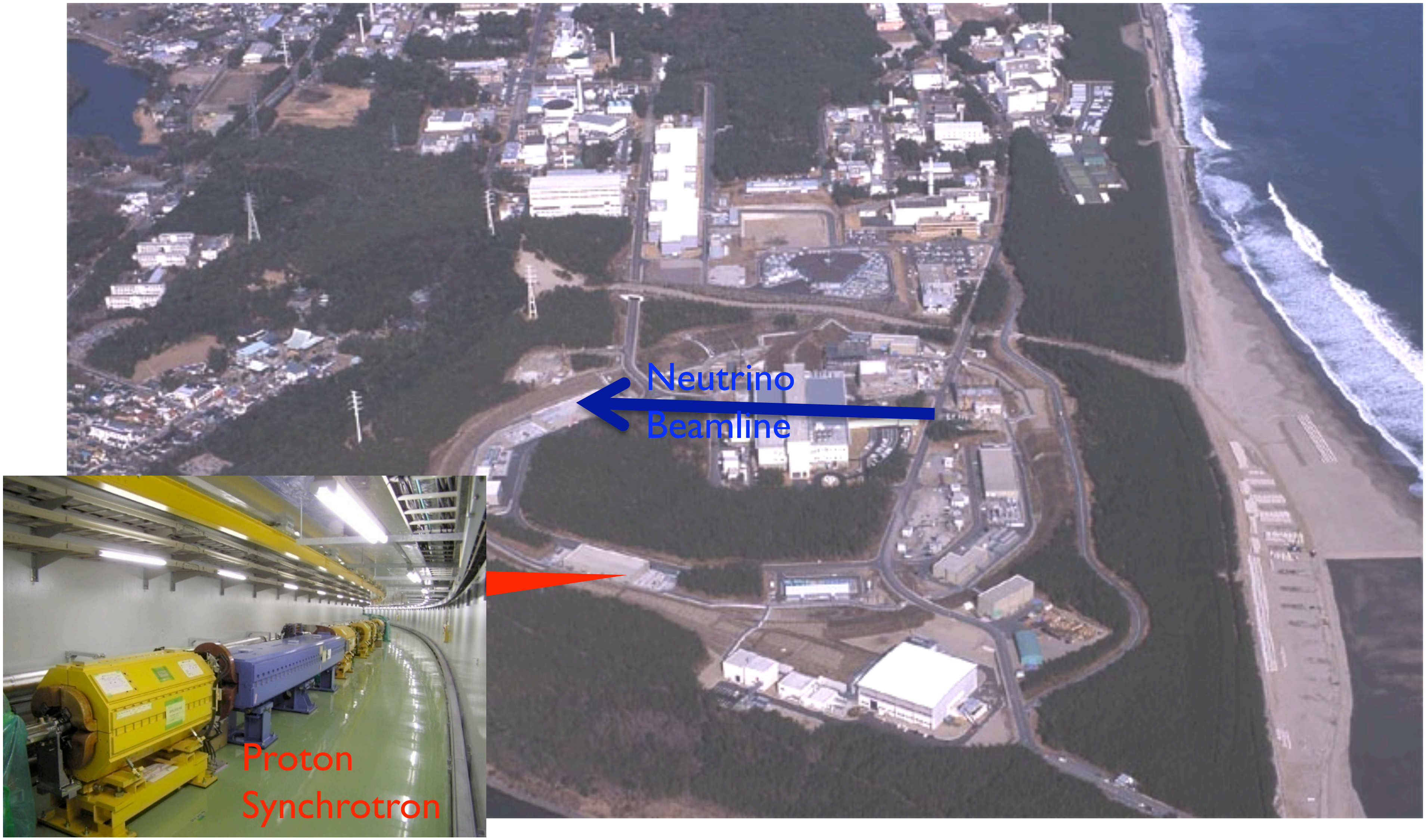


protons→carbon target→unstable particles→neutrinos

Proton accelerator

``Battery” in flashlight example is a proton accelerator located in Tokai

30 billion volt battery: not what you can find at Canadian Tire



Target

"Filament" is a 13mm radius cylindrical graphite rod ~1m in length

Trillions of protons blow apart the graphite to release unstable particles called mesons

- This is a 23.4 kW heat load in 5/1000 seconds, a challenge to keep cool!
- Special Ti alloy to contain beam and target

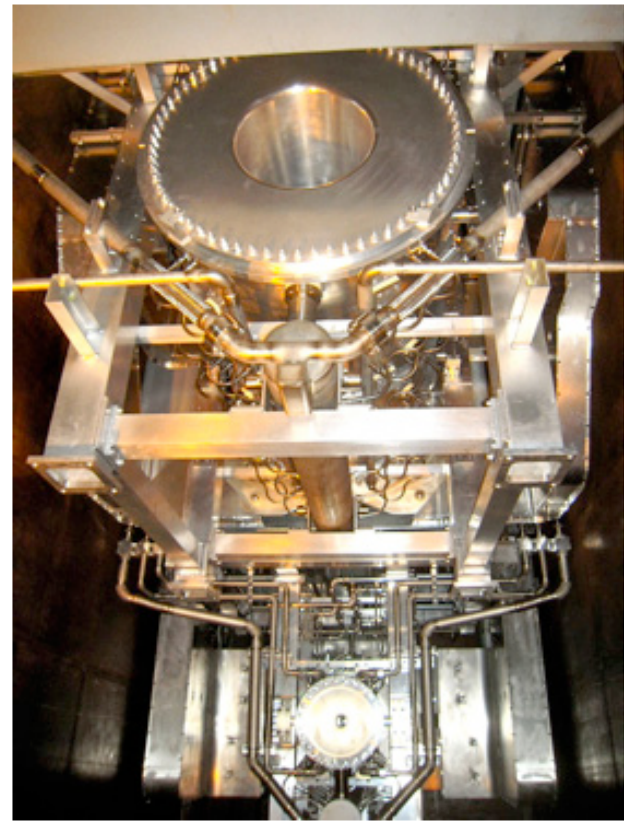
The T2K Target
Graphite Target in Ti-alloy capsule

Magnetic focusing lens

The unstable mesons are charged, so we can focus them like a lens focuses light

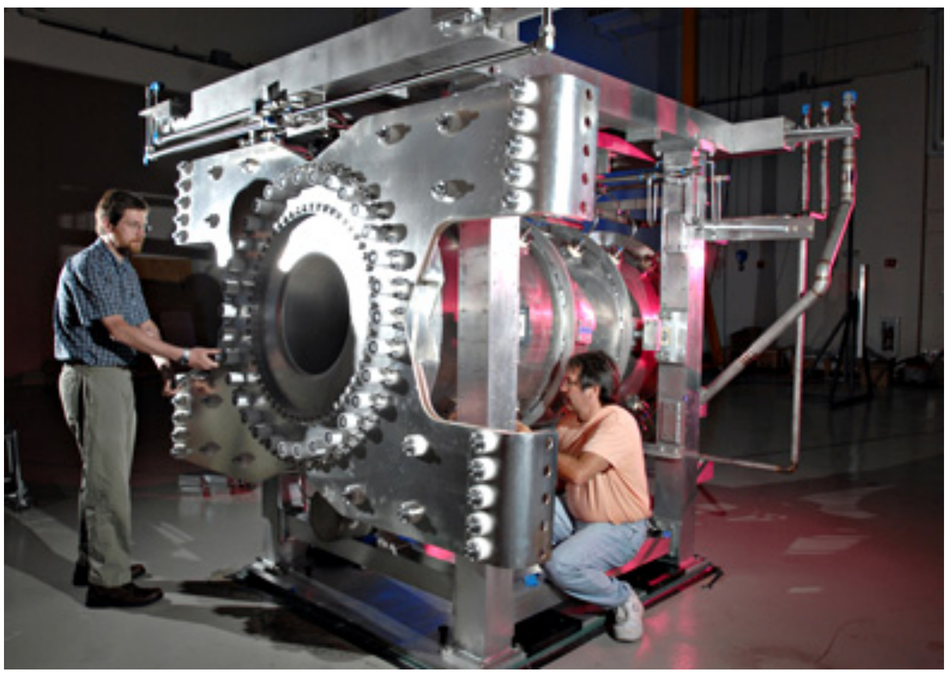
A magnetic focusing lens uses a strong current to create a magnetic field to bends the particles into a beam

Then the particles decay into a focused neutrino beam



T2K uses 3 lenses with 250kA of current each

Large striplines supply the current to the lens only when there is beam, every few seconds

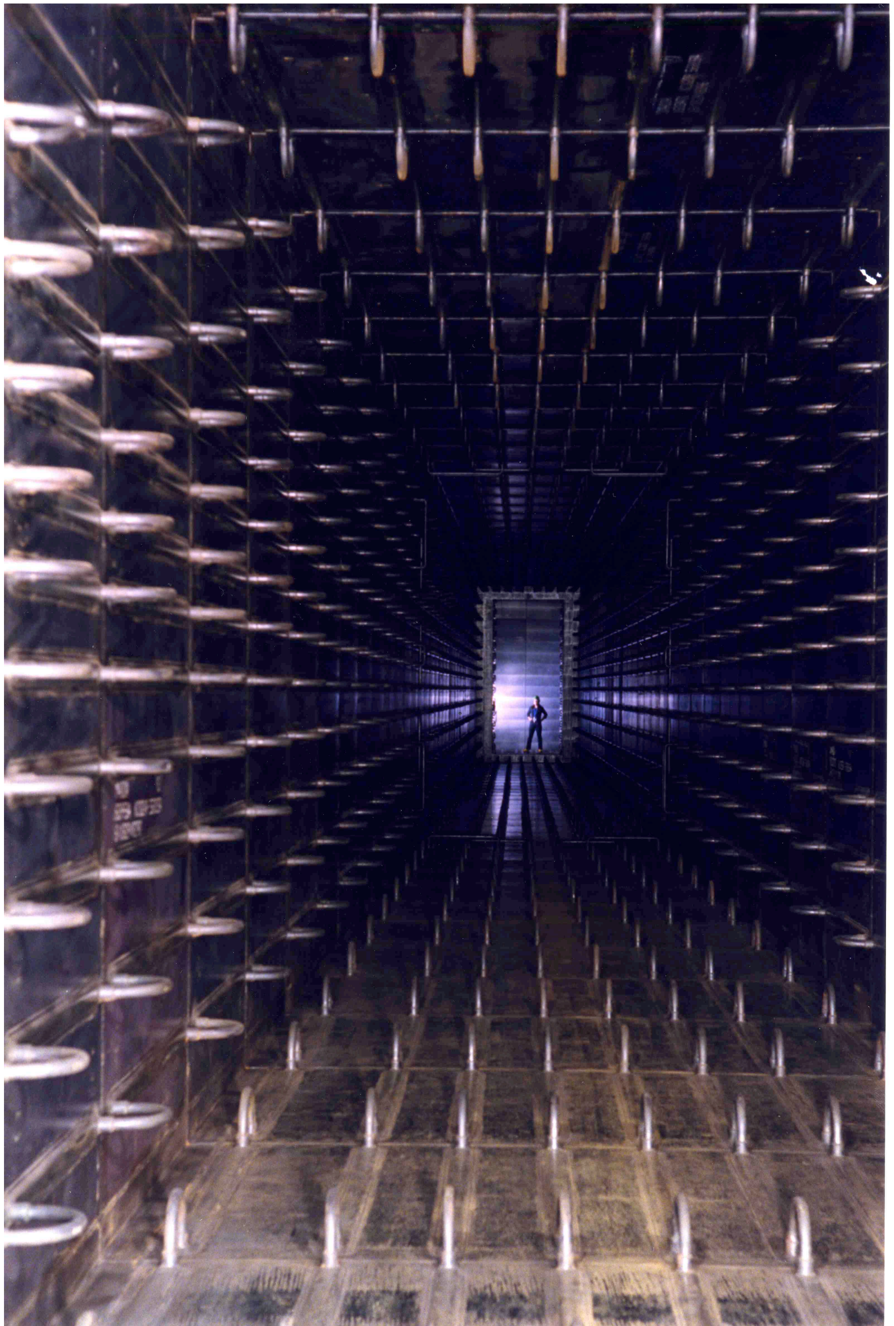


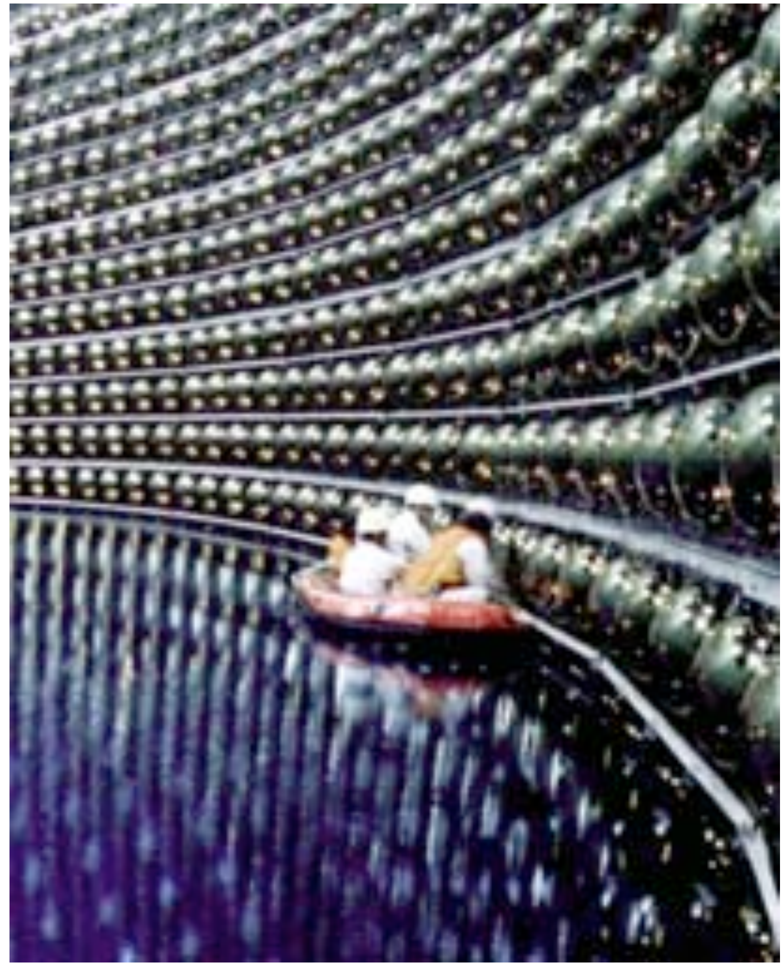
Your toaster, on the other hand, ~10A

That's 250,000 toasters at work, each!

The neutrino beam

The unstable particles decay in a long tunnel into a neutrino beam





A car takes ~6 hours

An airplane takes ~1hour

The neutrino beam reaches

Super-K in 1/1000th of a second

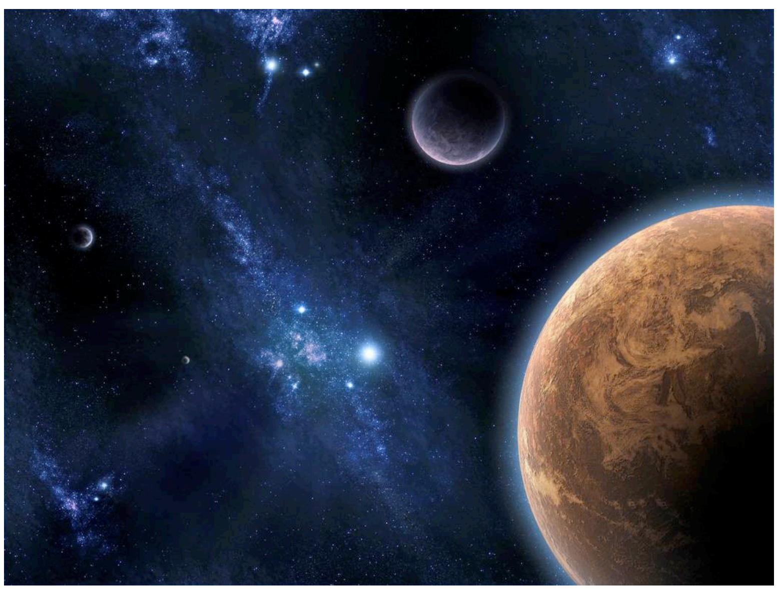
What will T2K learn about neutrinos?

T2K will see if our understanding of neutrino oscillation physics is correct

- There could be more to this extraordinary physics than our initial work suggests

Neutrino oscillations could hold a clue for how matter converted to antimatter in the big bang

- There's more matter in the universe than antimatter, why?
- T2K can also study oscillations with antineutrinos and look for differences



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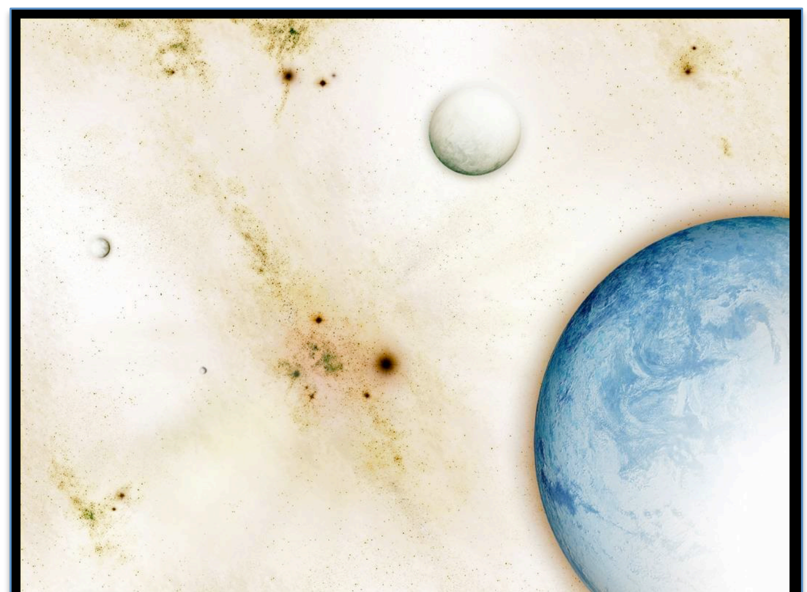
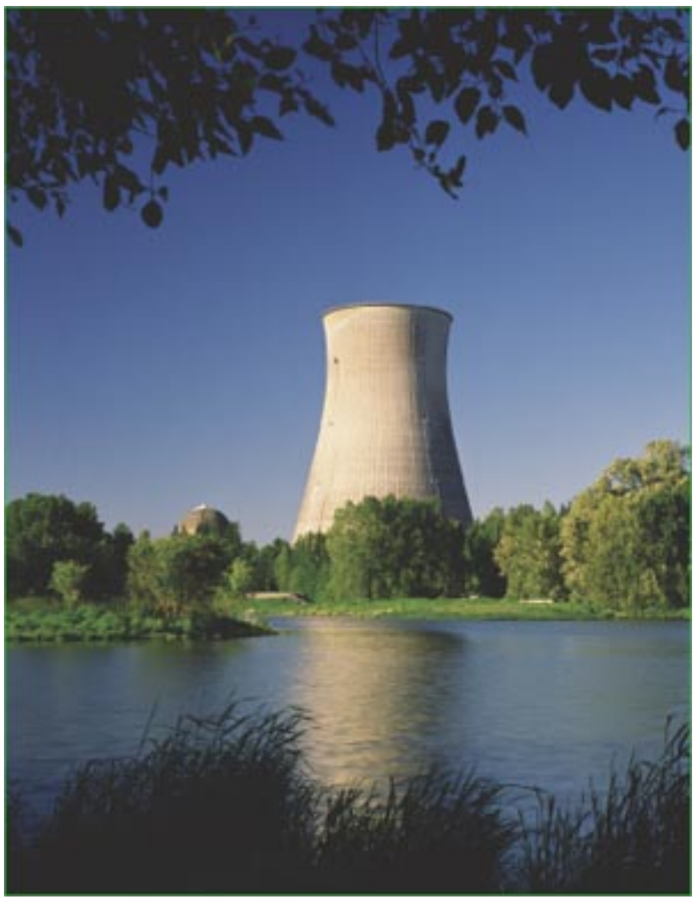


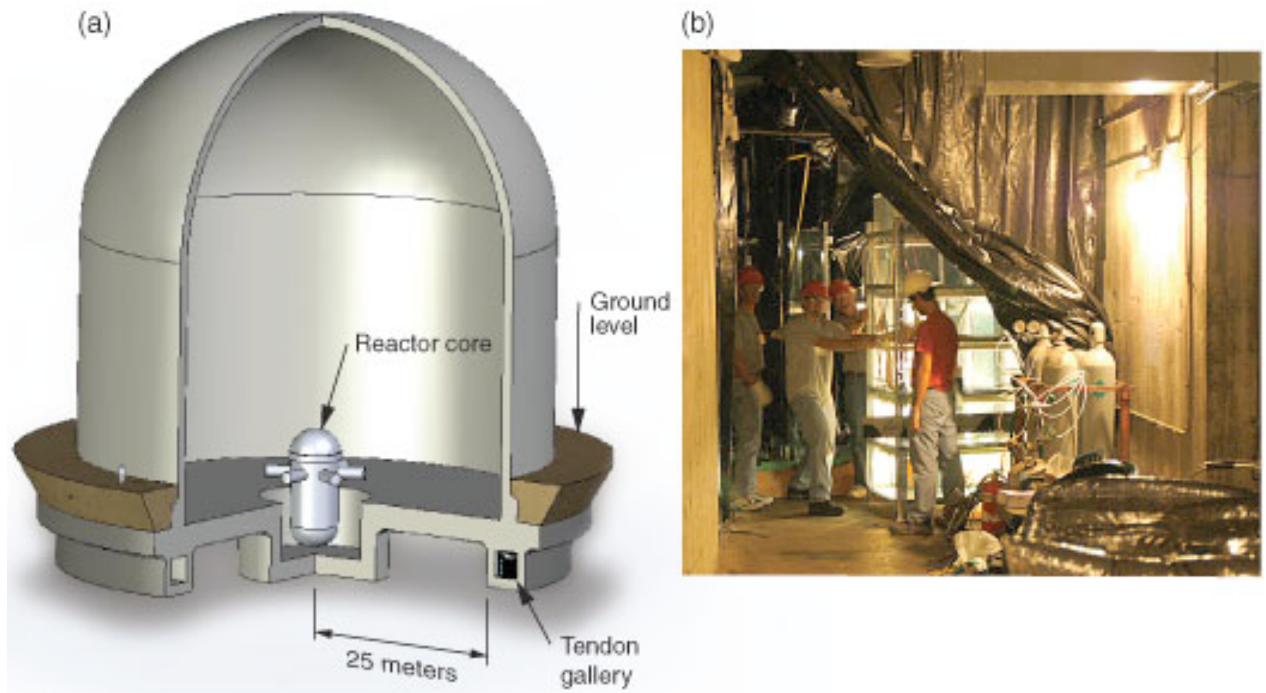
Neutrinos as reactor monitors

Reactors produce many many antineutrinos

20% of the power is carried away by neutrinos

Idea: use antineutrinos and a measure of the power of the reactor to give information about the core of the reactor

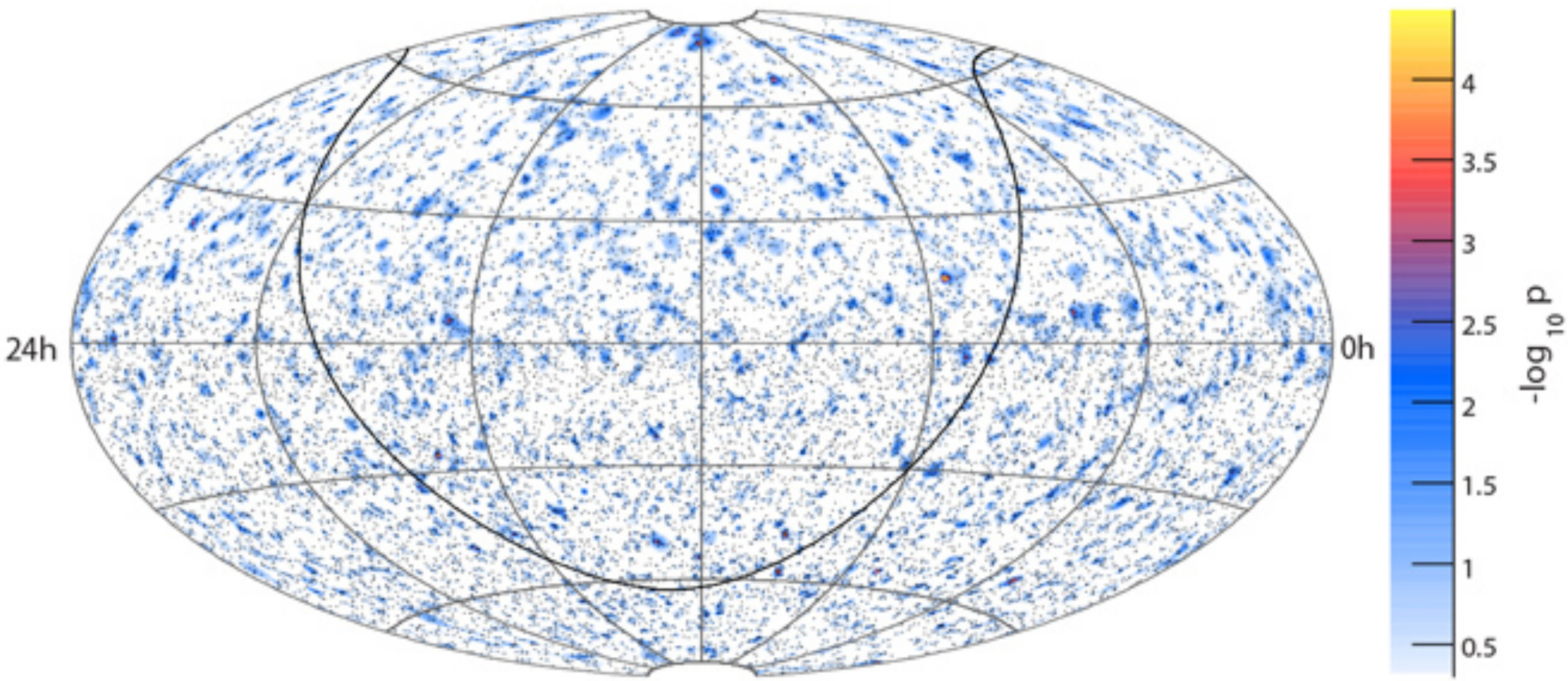




This will tell you if plutonium has been removed from the reactor core (non-proliferation)

Neutrinos as a window to the sky

If you could just see the world with neutrinos, what would you see when you looked at the nights sky?



Neutrinos are useful to astronomers because:

They don't get absorbed or scattered by dust, gas between us and the source

They aren't affected by magnetic fields and so point right back to the source

Neutrinos are produced in the most violent processes in the universe
(exploding stars, gamma-ray bursts, etc)

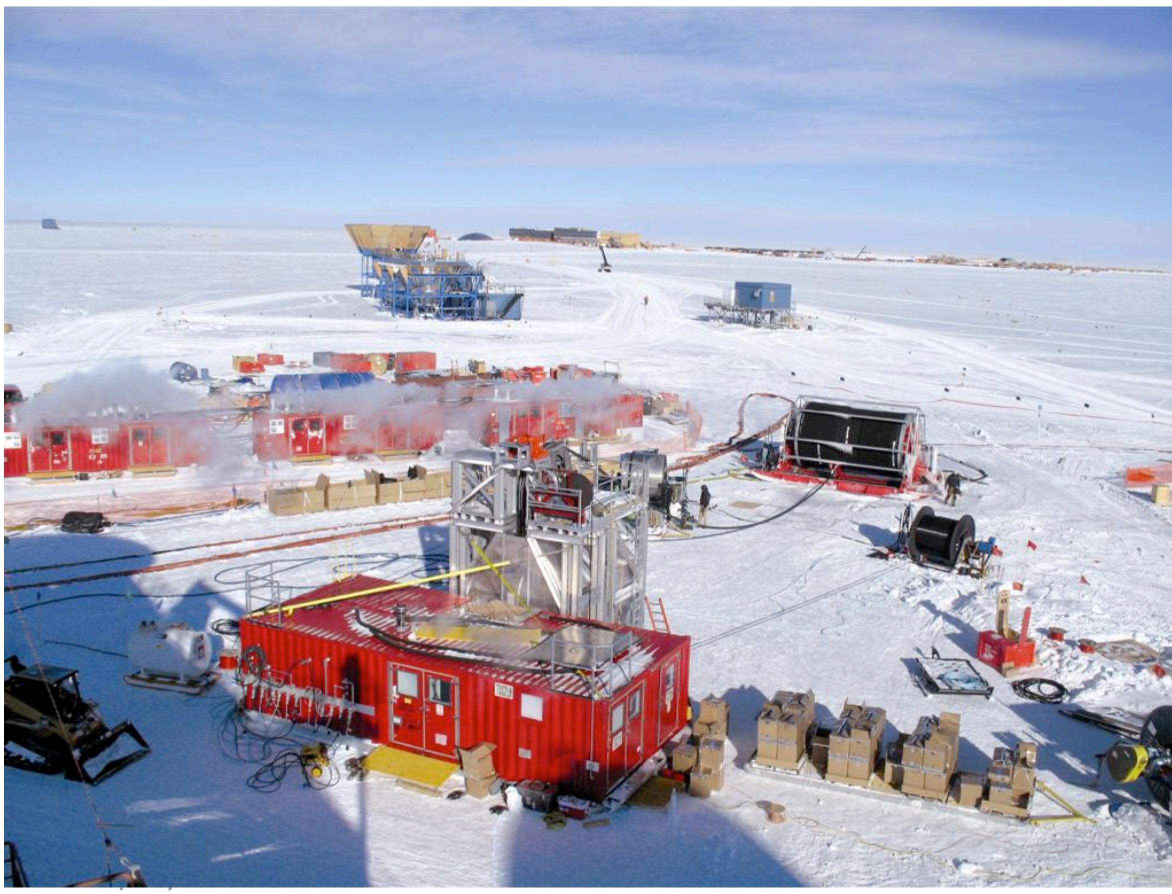
A neutrino telescope

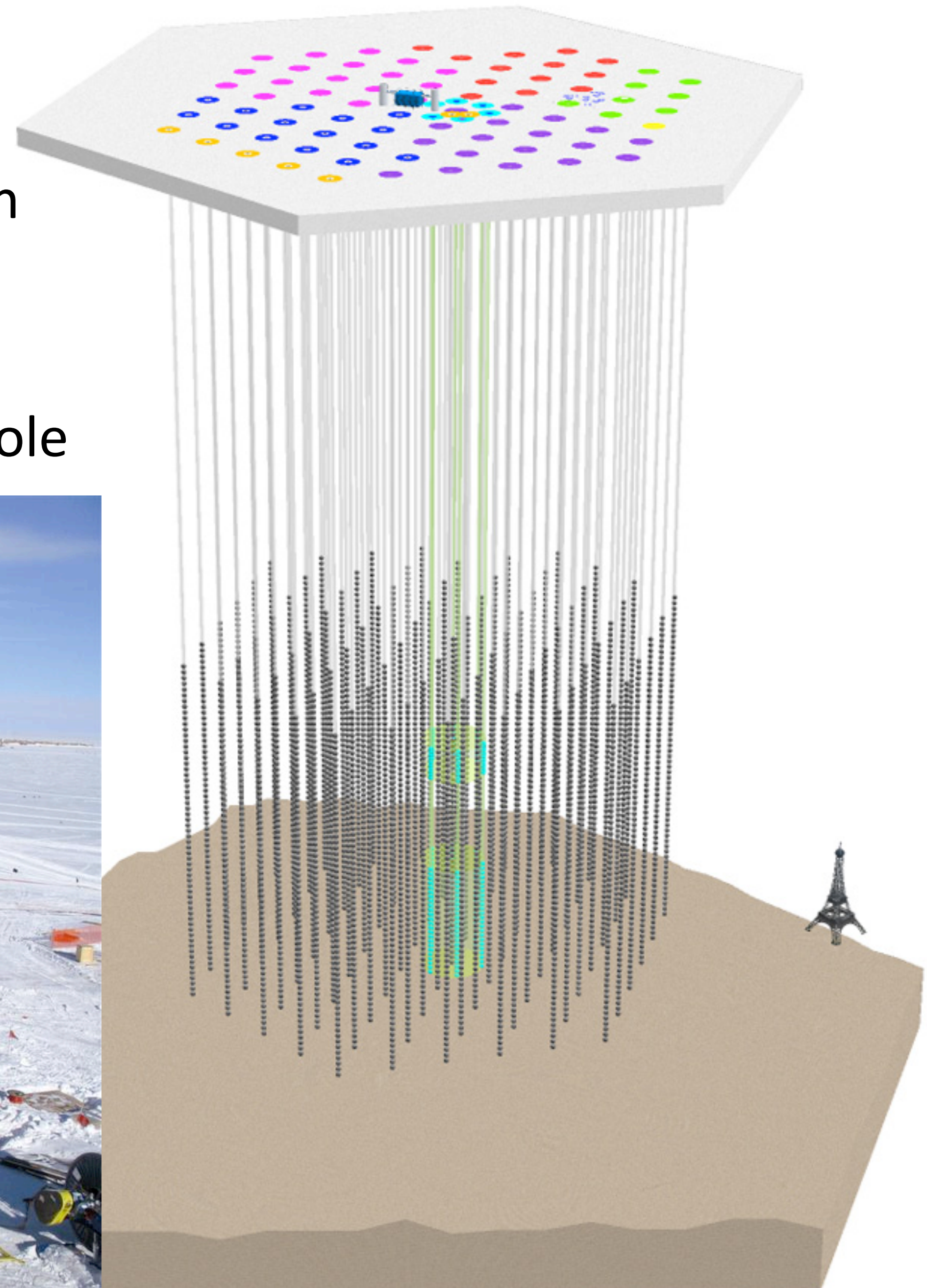
ICECUBE is a cubic kilometer of ice in Antarctica (Eiffel Tower for scale)

Electronic eyes on a string are buried in the ice with a water drill

86 strings in total

200,000 gallons of ice per each hole



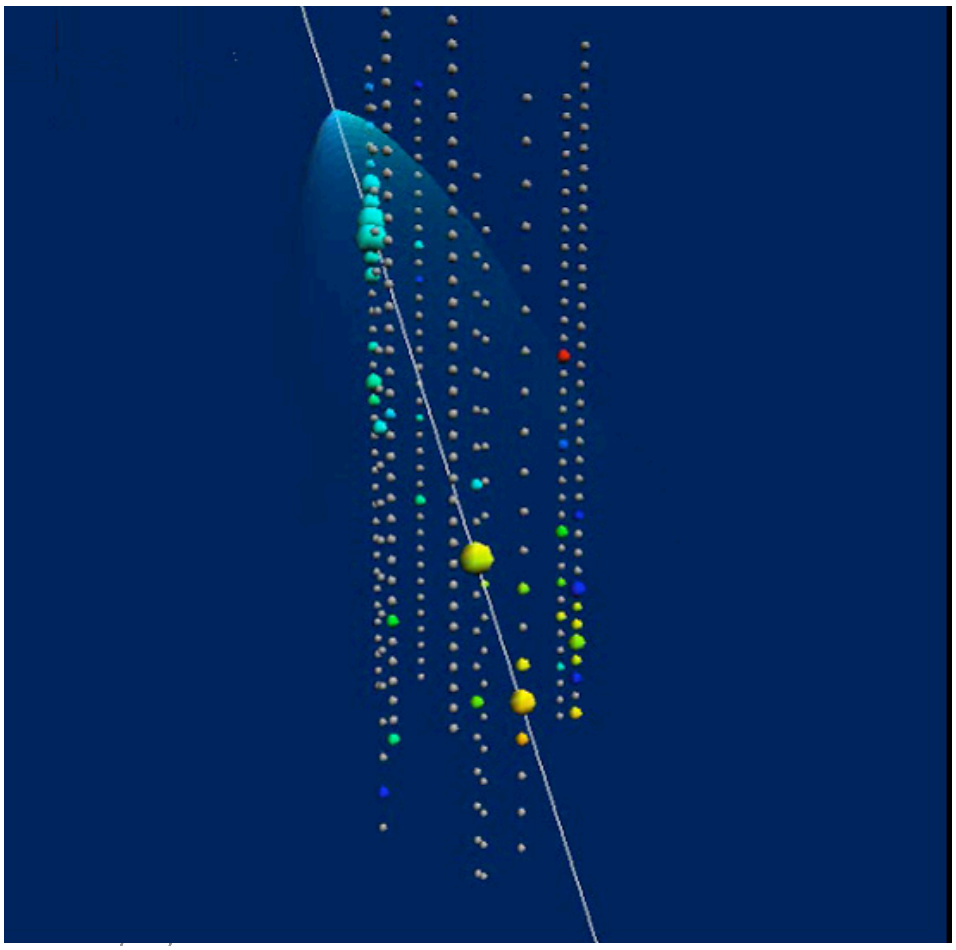


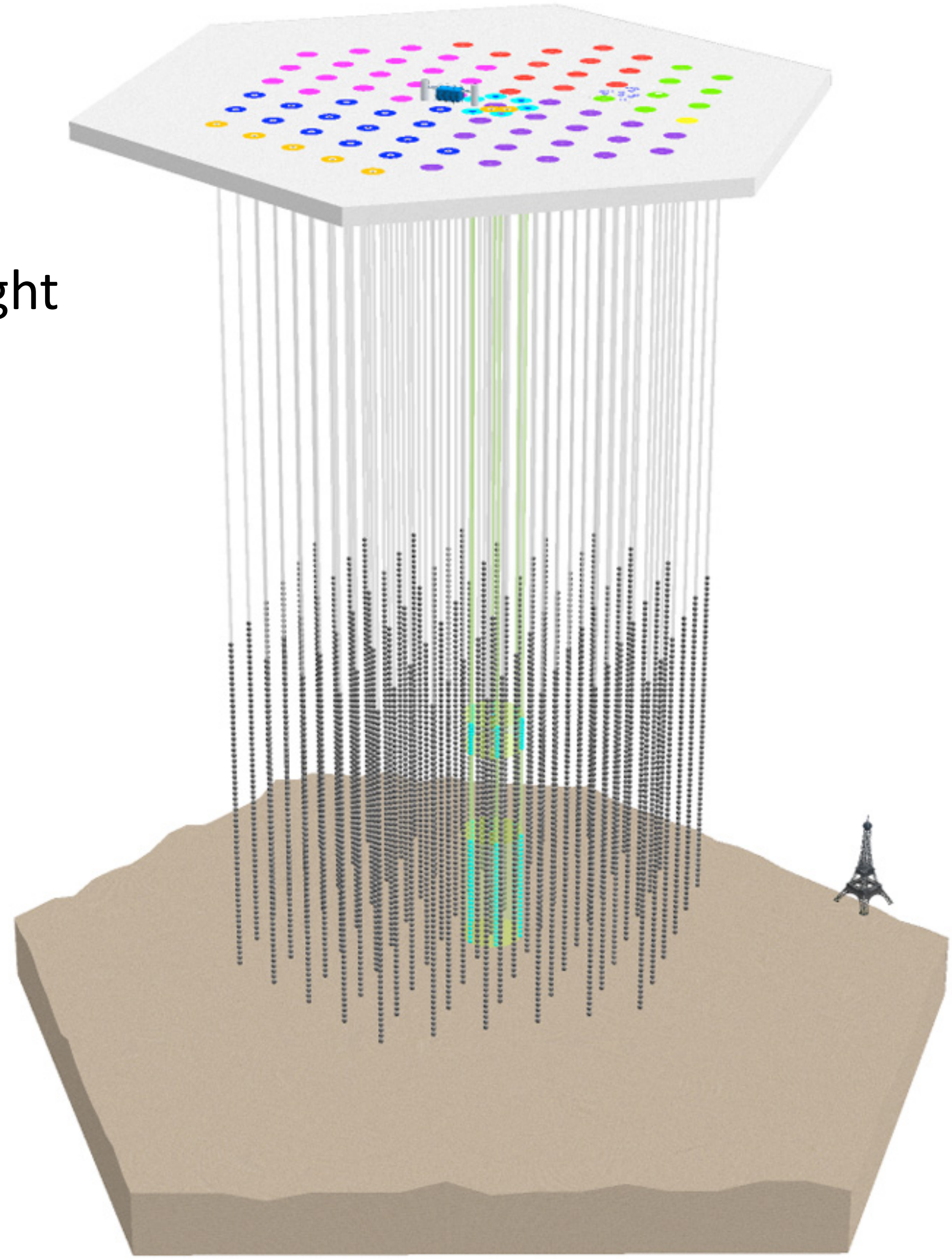
A neutrino telescope

ICECUBE is a cubic kilometer of ice in Antarctica (Eiffel Tower for scale)

Same idea as Super-K

Neutrinos produce Cherenkov light visible by the electronic eyes





Supernova neutrinos

10^{58} neutrinos are emitted for each supernova, over ~10 seconds

They arrive earlier than light does (light can take hours or days to escape)

They also encode information about what happens at the center of a core-collapse, as they carry 99% of the energy of the supernova

24 neutrinos from Supernova 1987A were observed in three neutrino detectors worldwide

The HALO experiment in SNOLab and other neutrino detectors around the world are a part of SNEWS (SuperNova Early Warning System)

- Notify astronomers about a supernova before light reaches Earth

HALO is sensitive to electron neutrinos, combined with other detectors it will help describe how a supernova occurs with neutrinos

The little neutrino packs a punch

We only imagined the existence of the neutrino ~80 years ago, but we now know:

Neutrinos are everywhere

Billions go through you every second!

Neutrinos have mass

The total mass of the neutrinos in the universe is about the same as the total mass of the stars!

Neutrinos change from one type to another

This was the most shocking and important discovery in particle physics of the decade

Neutrinos push the limit of how small something can be and still exist.

What more do they still have to tell us?

Thank you!

The work we do here is funded by the Canadian government

It's not just my research, it's yours too

Basic research, or ``blue sky'' research done to learn about the world around us, without a specific product or result intended. However, it brings us:

New tools to improve our life, such as the invention of the world wide web

Novel methods to do other science, such as the use of particle detectors to "x ray" pyramids for hidden chambers

Ways to improve medicine: see next talk!