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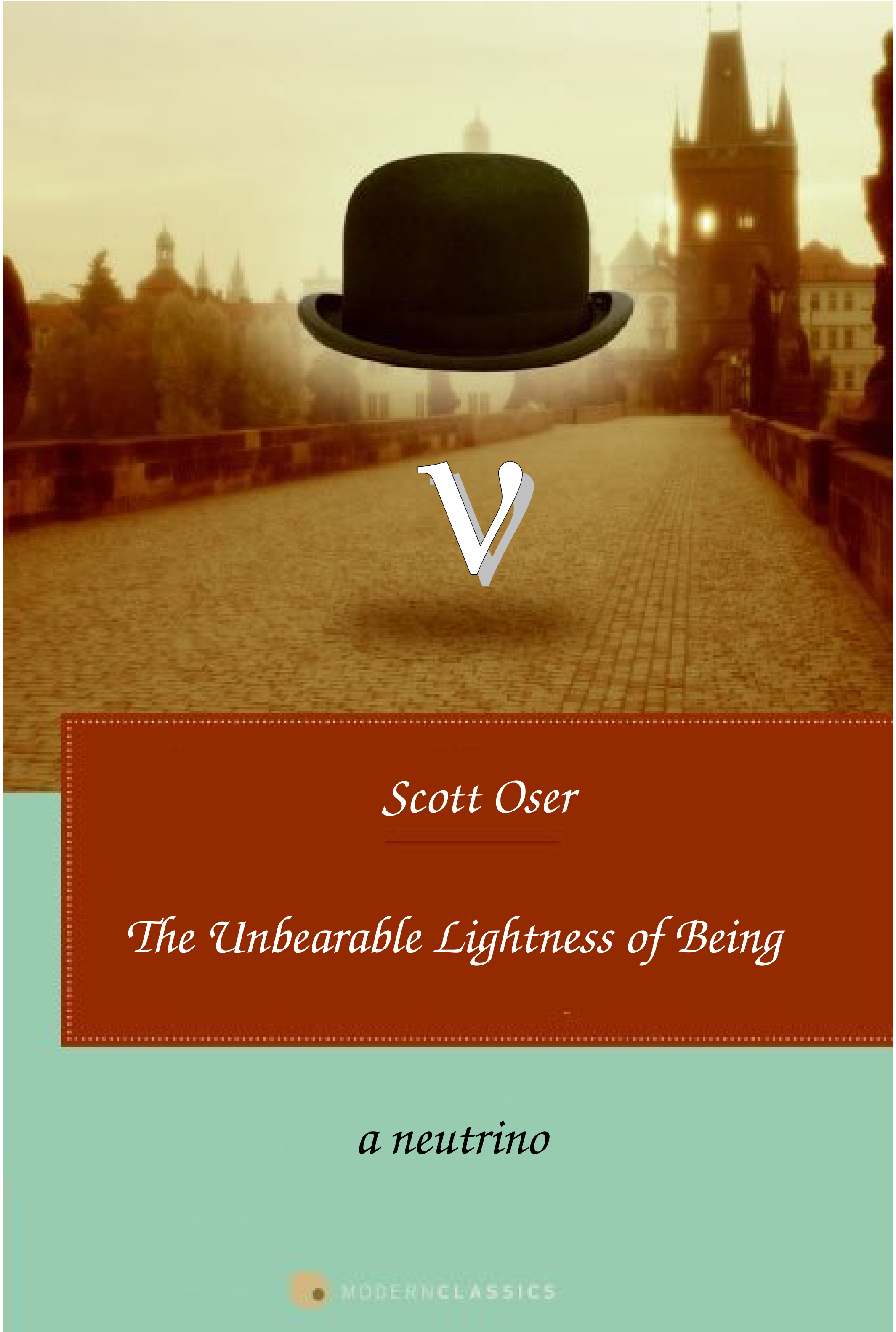
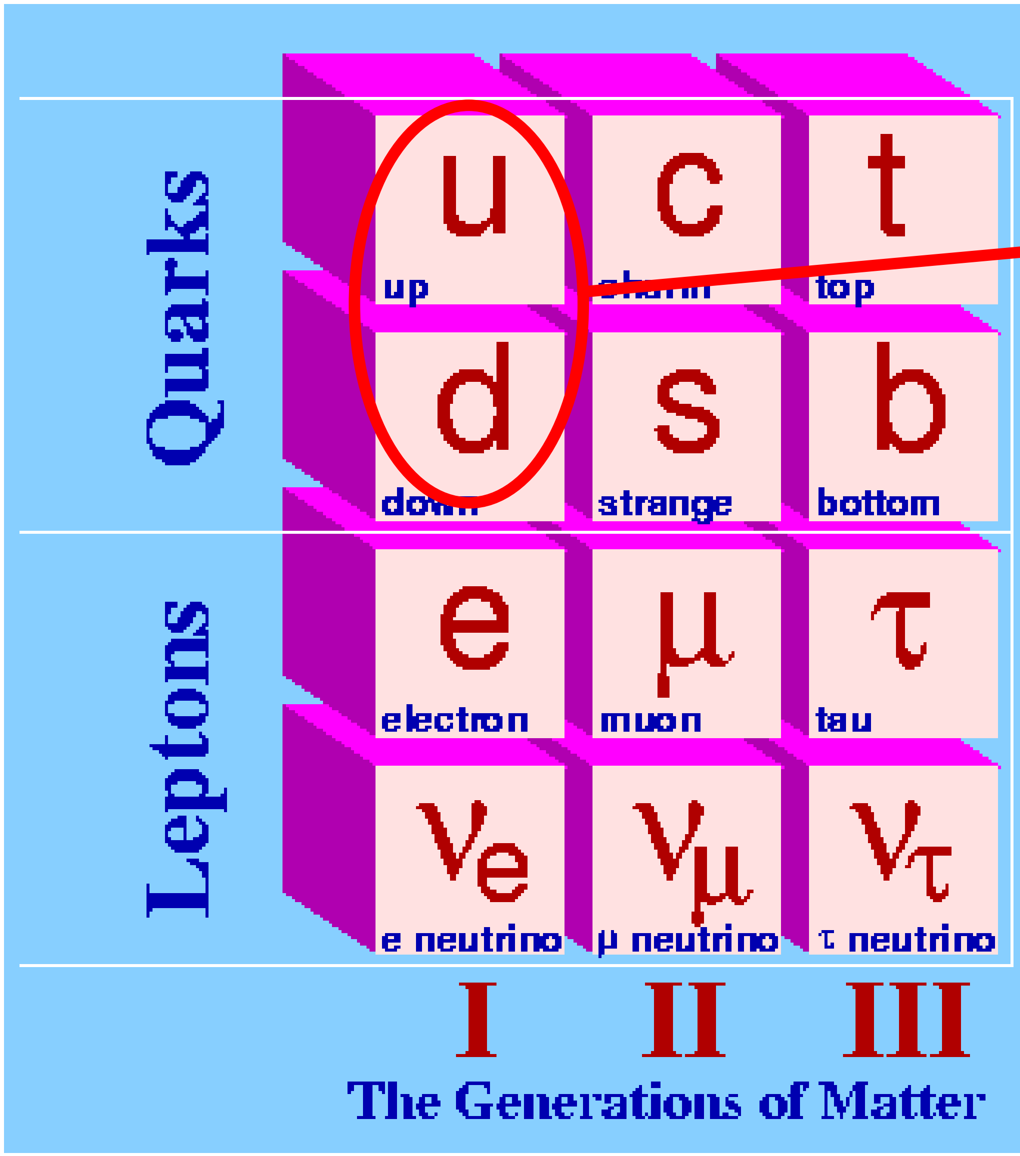


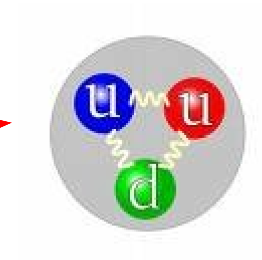
Outline

1. What's a neutrino?
2. How do you detect neutrinos?
3. The solar neutrino problem
4. Neutrino oscillations
5. A tour through the world of experiment
6. Conclusions

Chapter 1: What's a neutrino?

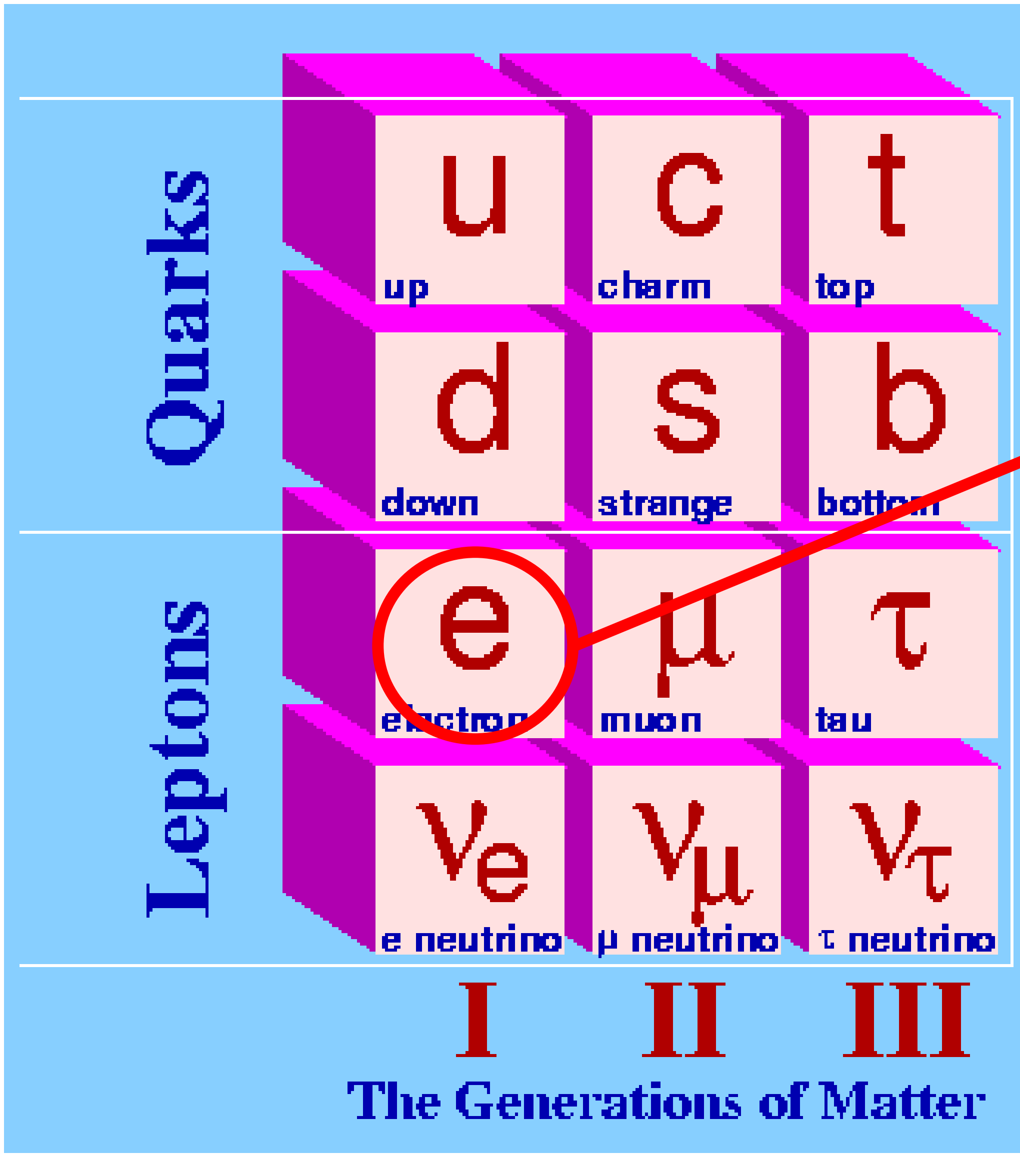
The Building Blocks of Matter

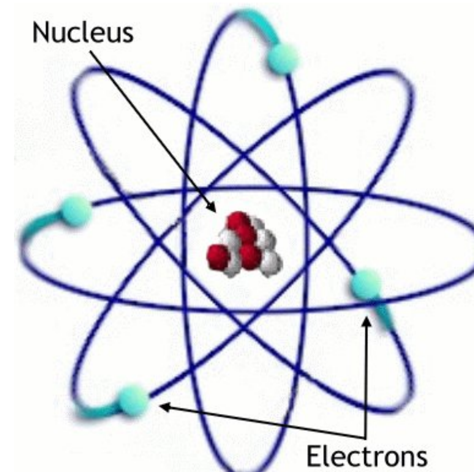




Up and down quarks are inside protons and neutrons

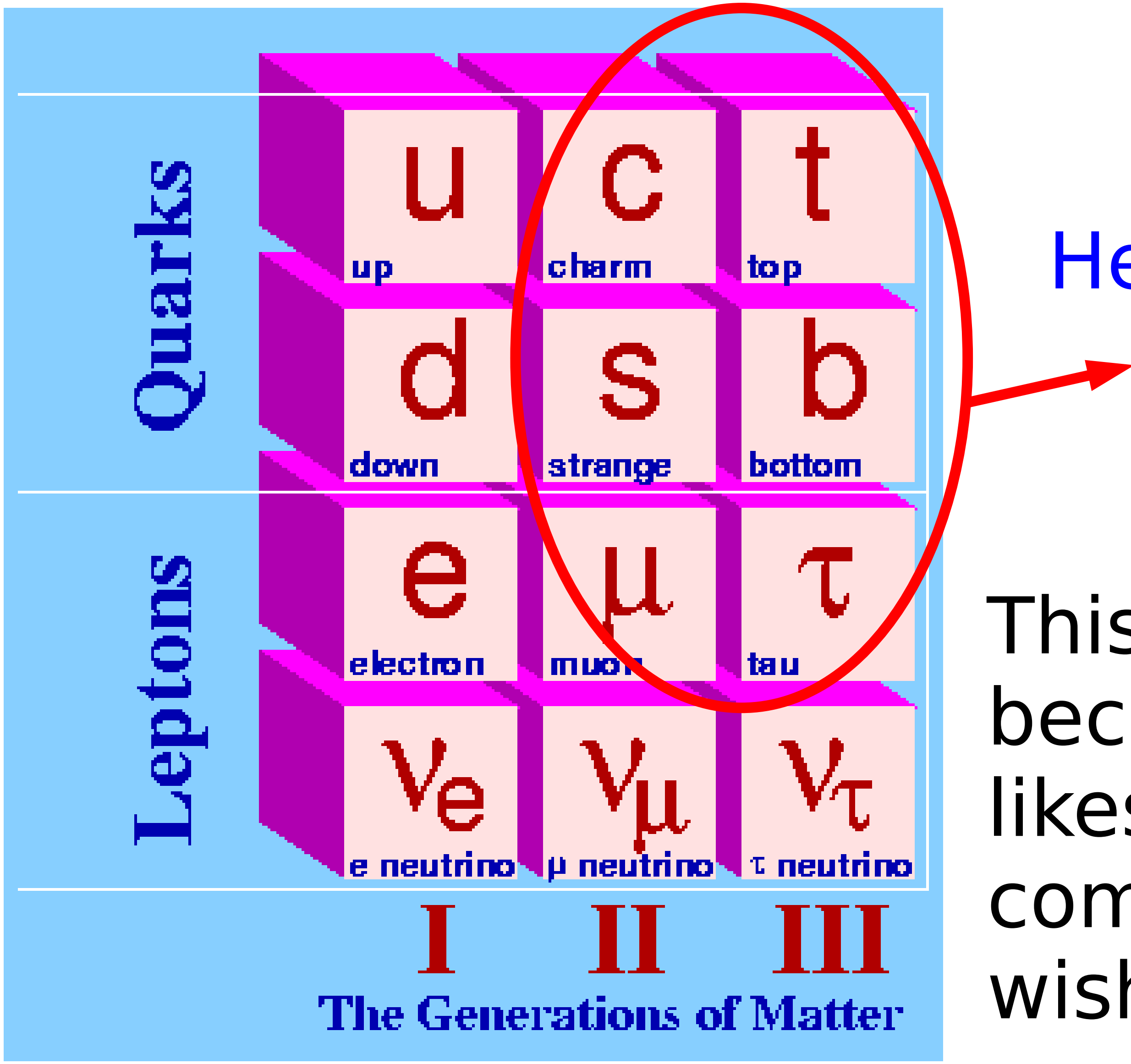
The Building Blocks of Matter





Electrons orbit atoms, flow through wires, and are responsible for chemistry

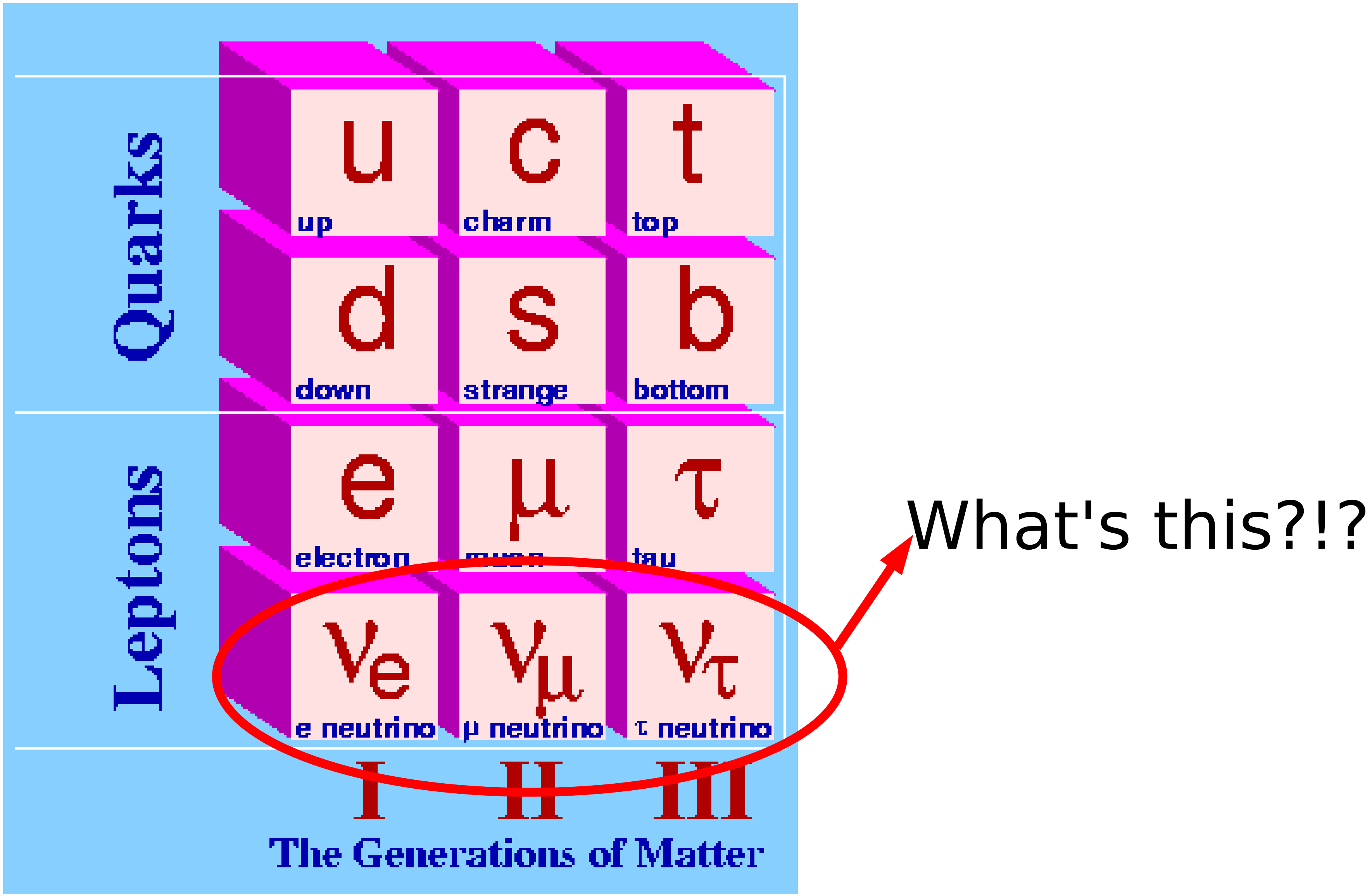
The Building Blocks of Matter



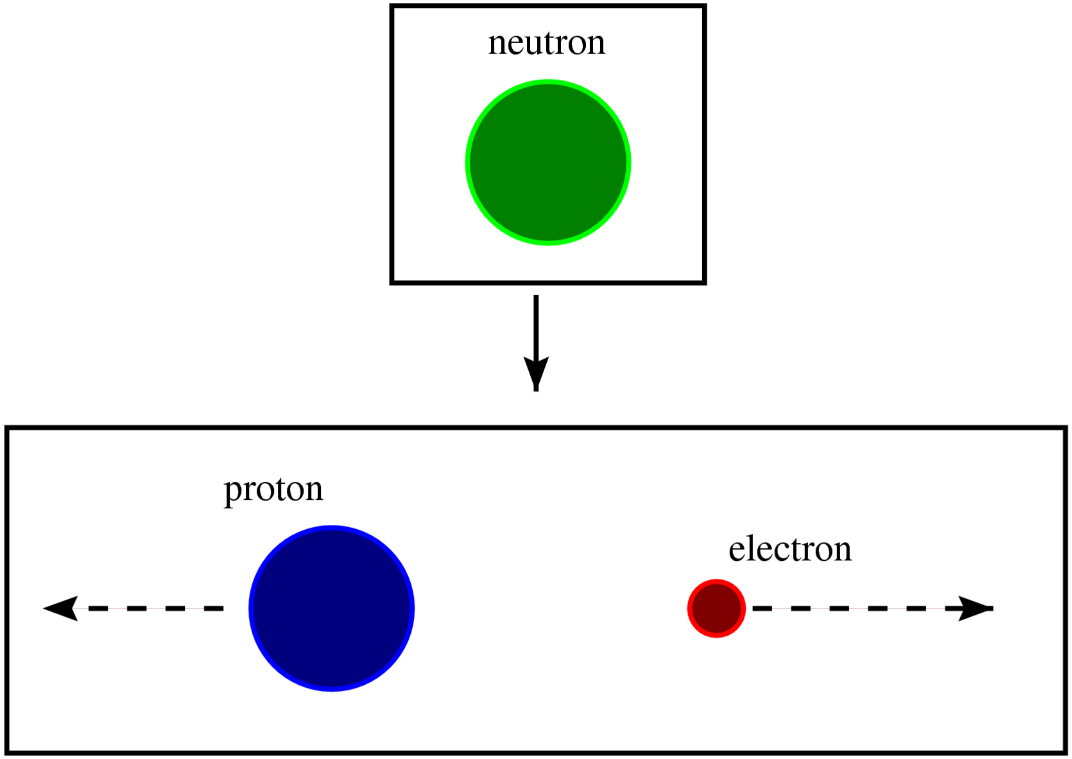
Heavier versions of quarks and electrons

This stuff is here because nature likes things to come in threes. I wish I knew why!

The Building Blocks of Matter



A Problem With Beta Decay

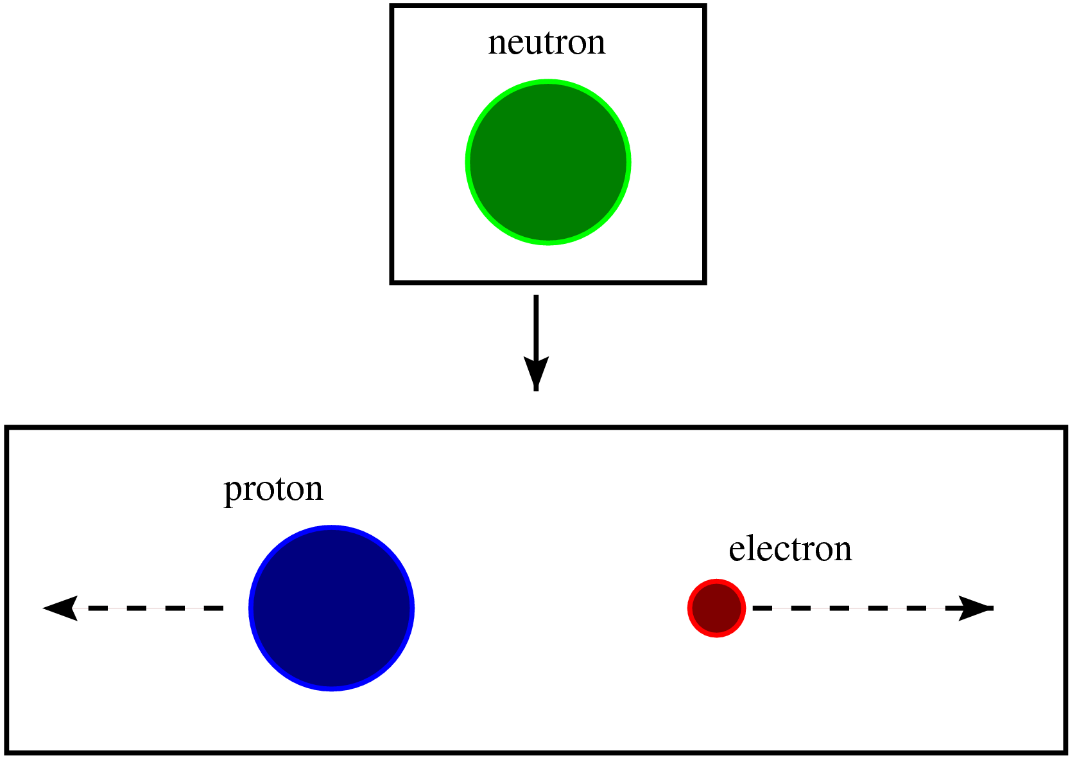


Neutrons were observed to radioactively decay into a proton and an electron.

If neutron is at rest, then proton and electron fly off with equal and opposite momenta.

Their total energy must equal the energy of the neutron ($E=mc^2$)

A Problem With Beta Decay



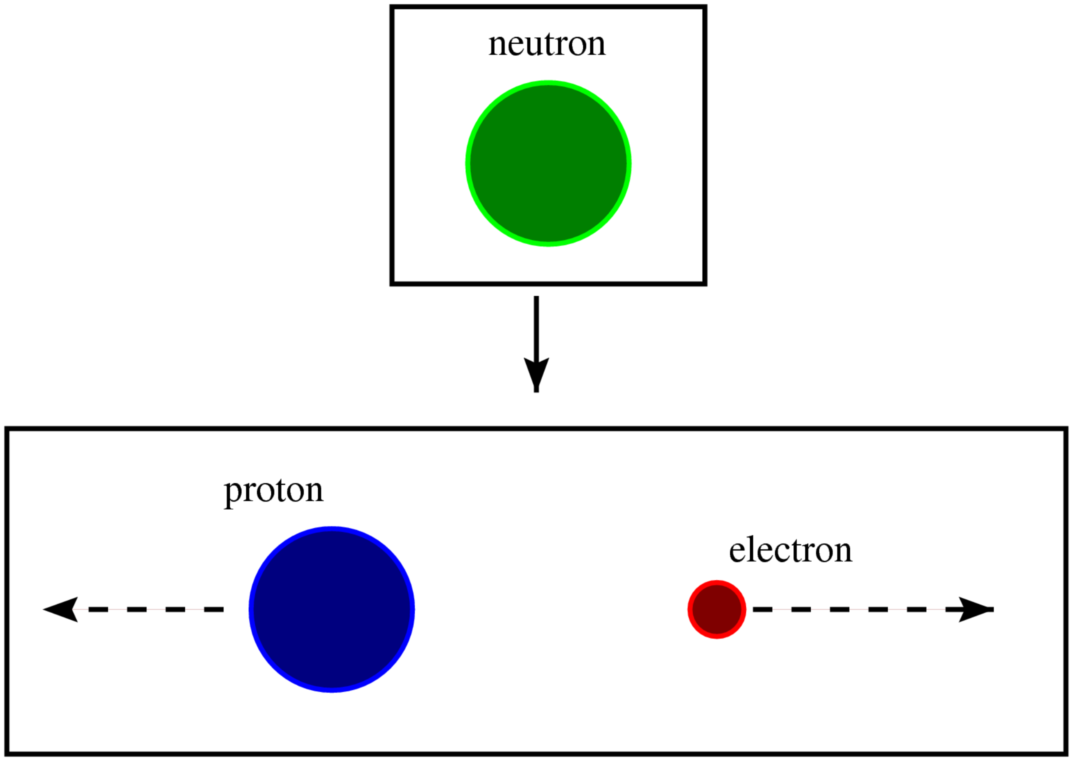
Neutrons were observed to radioactively decay into a proton and an electron.

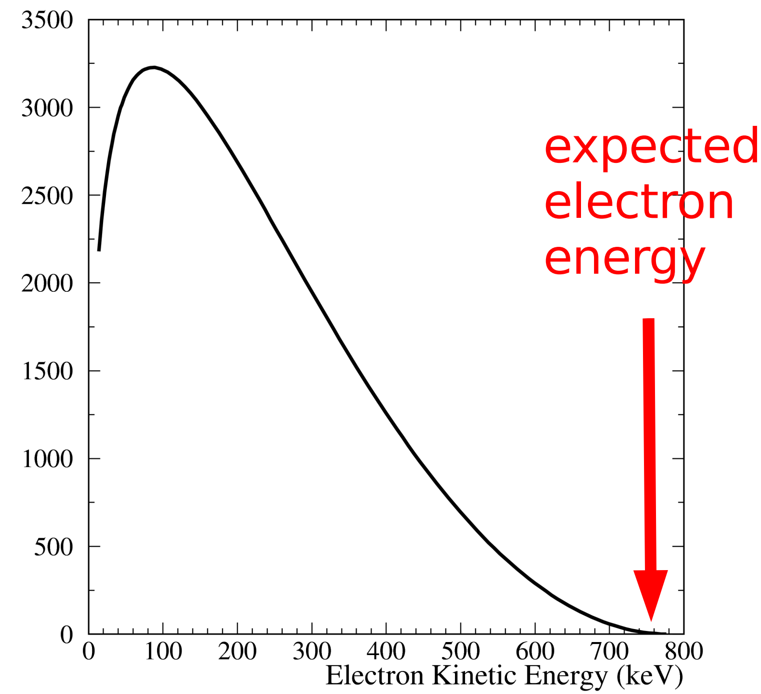
If neutron is at rest, then proton and electron fly off with equal and opposite momenta.

Their total energy must equal the energy of the neutron ($E=mc^2$)

The electron should always have the same energy!

A Problem With Beta Decay



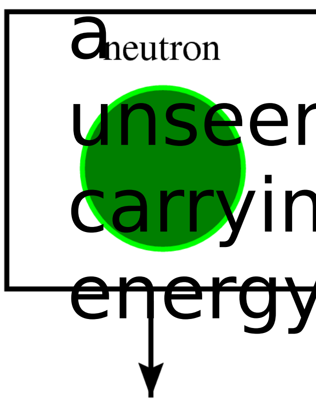


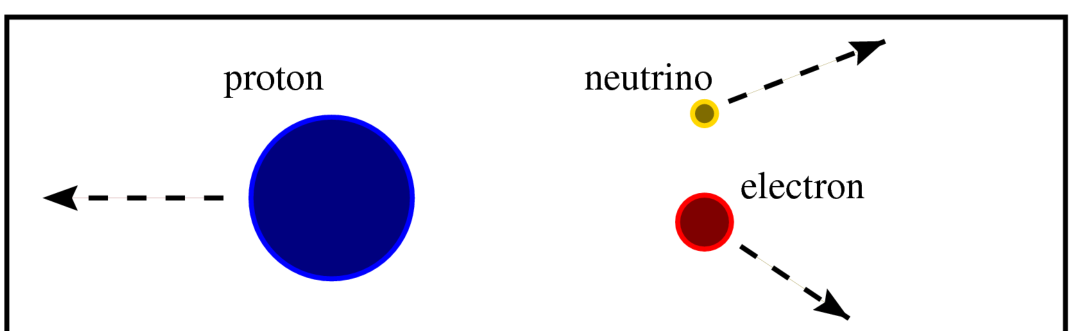
The data disagree! Electrons have a wide range of energies, always less than the expected amount.

Wolfgang Pauli's desperate gambit

Either energy isn't conserved in nuclear decays, or else the energy is going somewhere we can't see!

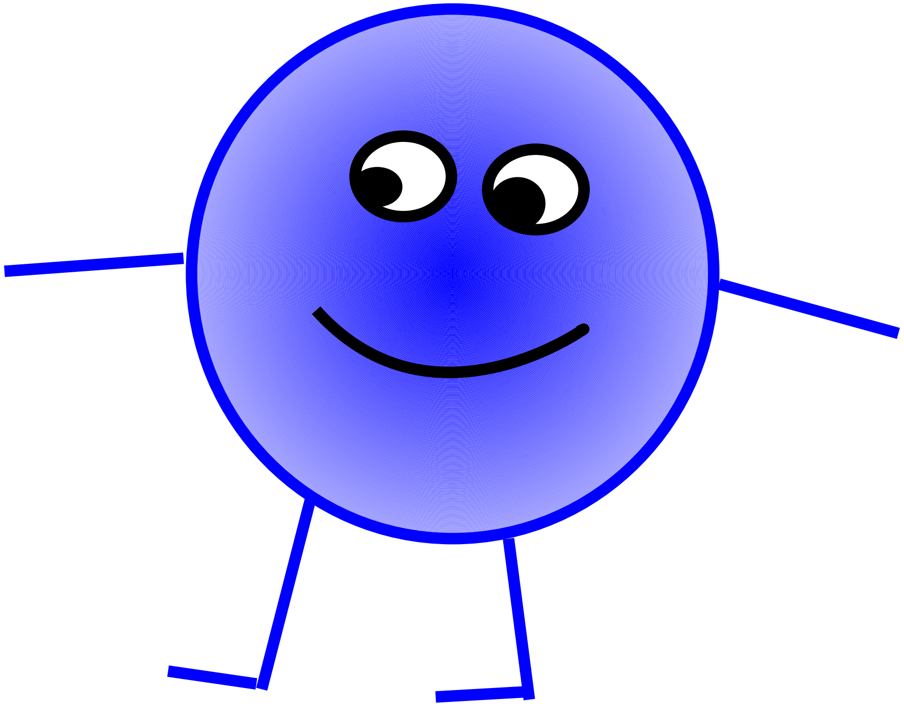
In 1930 Wolfgang Pauli proposes a desperate measure ... some unseen neutral particle must be carrying away some of the energy.





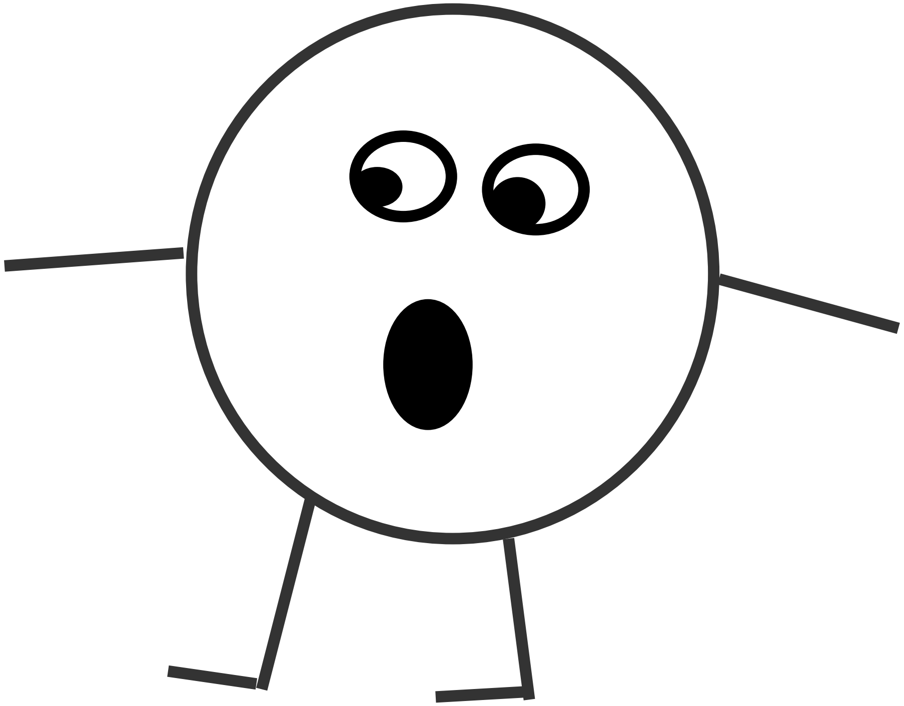
This particle has to be virtually massless and chargeless!

How to make a neutrino



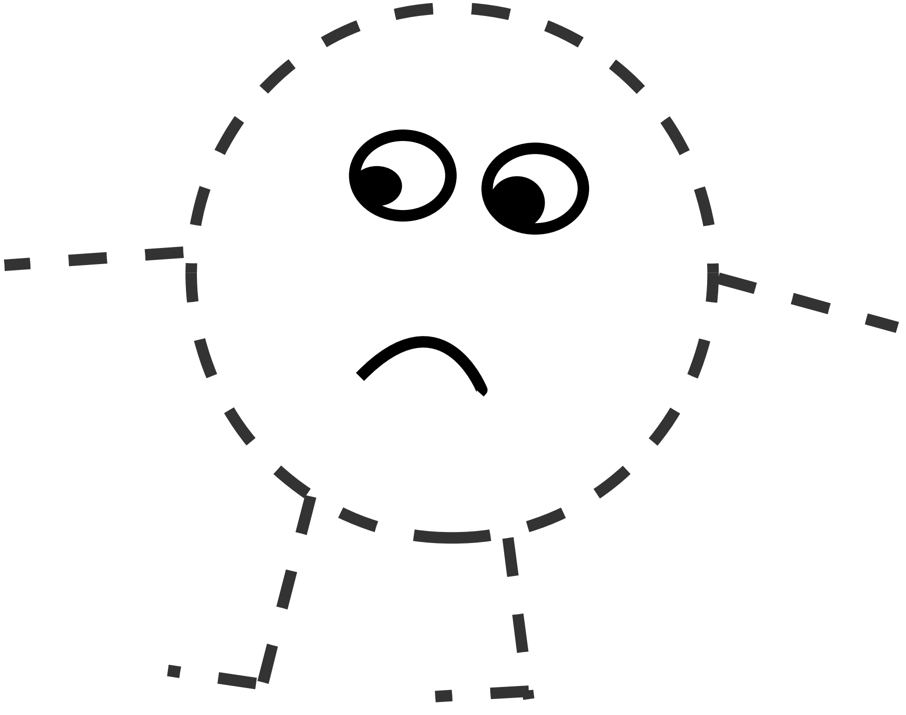
Start with an electron.

How to make a neutrino



Now take away his electric charge.

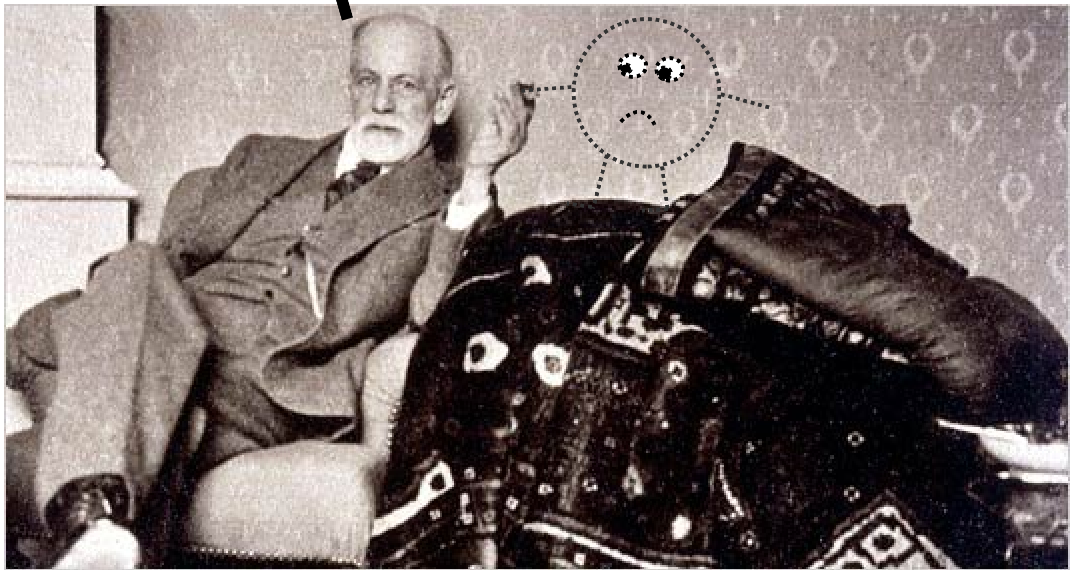
How to make a neutrino



Then take away his mass!

How to make a neutrino

"You are experiencing a profound sense of loss from the removal of your charge and mass. Now, tell me about your mother."



Finally, provide some counselling to help him deal with the resulting identity crisis.

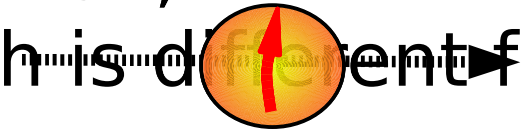
The particle that is barely there

If you have no mass and no charge, what's l
Very little it turns out ...

Neutrinos still have energy and carry momentum.

They carry angular momentum (spin) as well.

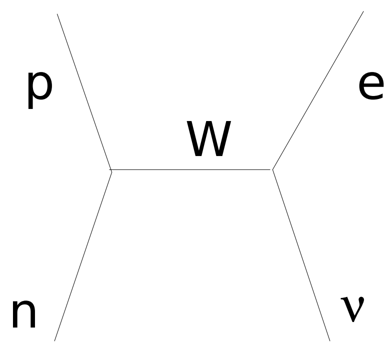
WEIRD fact: neutrinos always spin the same direction,
which is different from other particles!



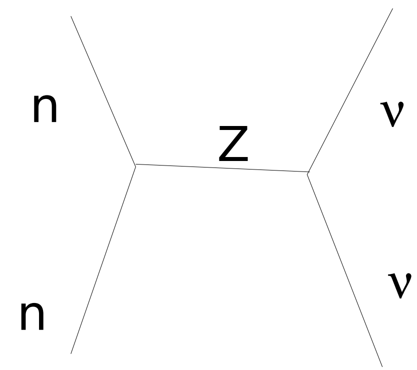
(spins clockwise when viewed head-on)

And they have interactions

Basic neutrino interactions



“Charged current”: convert a neutrino into an electron, with a W particle carrying charge & momentum

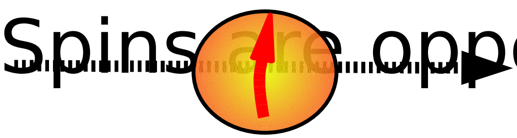


“Neutral current”: the neutrino survives, but some energy and momentum is transferred by a Z particle

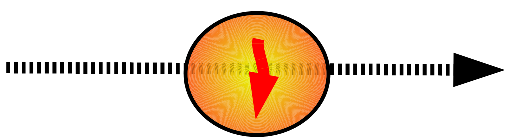
Antineutrinos

Like all other particles, neutrinos have antiparticles.
How do you tell a neutrino from an antineutrino?

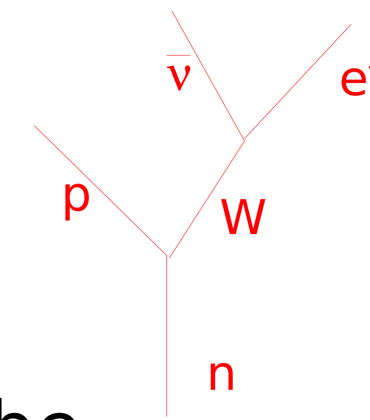
1) Spins are opposite



neutrino



antineutrino

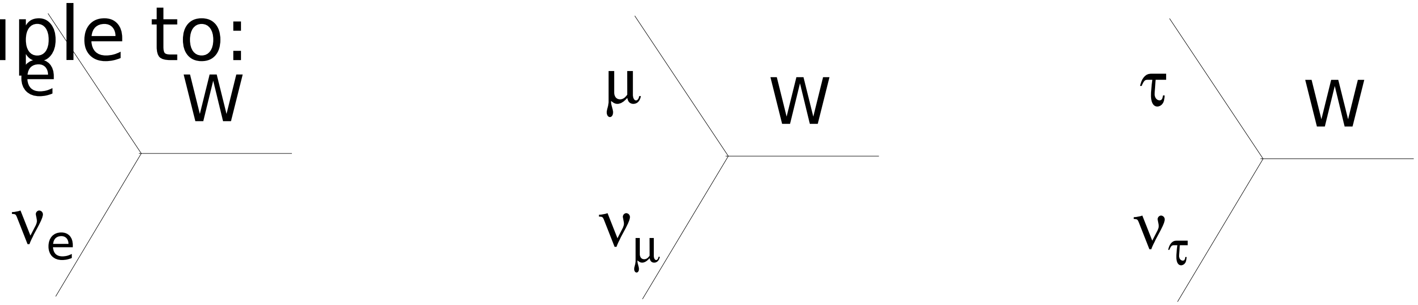


2) Neutrinos can only be turned into electrons, but antineutrinos can only be turned into positrons (antielectrons):

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

Three flavours of neutrinos

Like quarks and electrons, neutrinos come in 3's. The distinction is what kind of charged lepton they couple to:



The result is there's something like "electron-ness" or "mu-ness" or "tau-ness" that gets carried by the neutrino.

If for example a particle decays to make a μ and a ν_μ, then that neutrino later on should only ever be capable of making a μ. CONSERVATION OF

Chapter 2: How do you detect neutrinos?

The shy particle

Neutrinos are notoriously difficult to detect because they have a very small probability of interacting with regular matter!

A charged particle like an electron exerts a long-ranged electric force on other charged particles. An electron passing by a proton can exert a measurable force from meters away.

Neutrinos have only weak interactions, which are extremely short-ranged. The range is determined by the masses of the W and Z particles, which are heavy (heavy mass = short range). Typical range is on the order of a few x 10^{-18} m---a thousand times smaller than a proton.

A neutrino interacts only with a nearly perfect "head-on"

Shielding against neutrinos

Lead bricks are a usual way of blocking radioactivity (think of the lead apron you wear during a dental X-ray)

To block a neutrino, the lead has to be about one light year thick (10 trillion kilometers) !!!!

Almost always, a neutrino passes right through matter without hitting anything or stopping.

Three requirements for detecting neutrinos

Because it's extremely rare for a neutrino to interact in a detector, the detectors have to satisfy three requirements:

1) BIG: The more mass, the more targets for the neutrinos to hit. Shoot for tonnes or kilotonnes.
2) DEEP: On the surface, cosmic rays from space swamp most neutrino signals. Bury the detector underground.
3) CLEAN: Avoid even small amounts of radioactive materials, to prevent radioactive decays from swamping the signal.

Radiochemical detection

Neutrinos can cause nuclear transmutations by converting protons ↔ neutrons:

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

$$\nu_e + {}^{71}\mathrm{Ga} \rightarrow e + {}^{71}\mathrm{Ge}$$

So one approach is to get a big mass of some element, expose it to neutrinos, then chemically count how many atoms have turned into other elements.

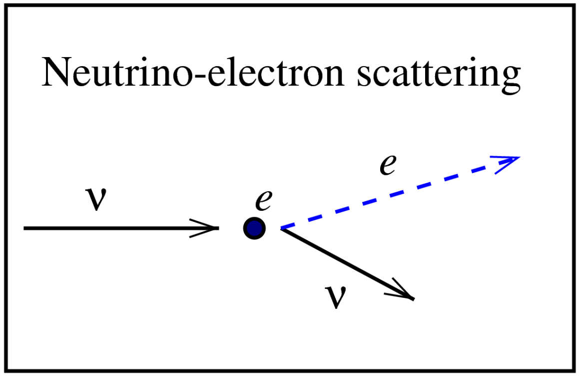
Homestake Experiment

600 tonnes of cleaning fluid (C_2Cl_4) in a big tank deep underground

Look for ν-induced Cl → Ar

Nobel Prize winner Ray Davis swimming in the water shield--- 1.5km underground!

Cherenkov detection

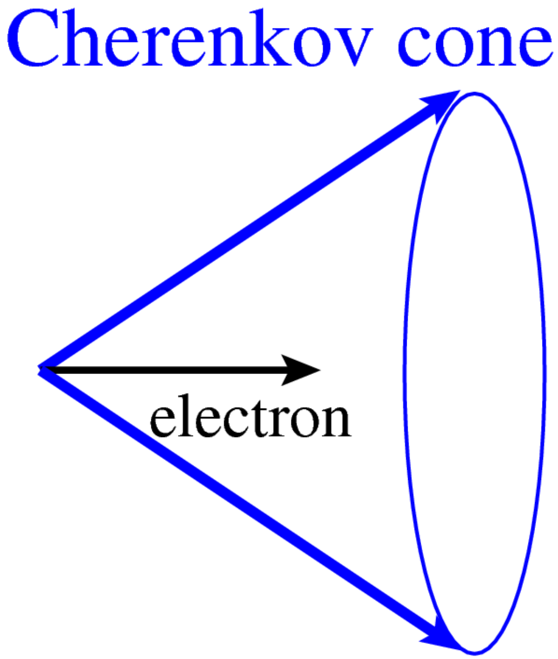


Neutrino interactions often produce energetic charged particles.

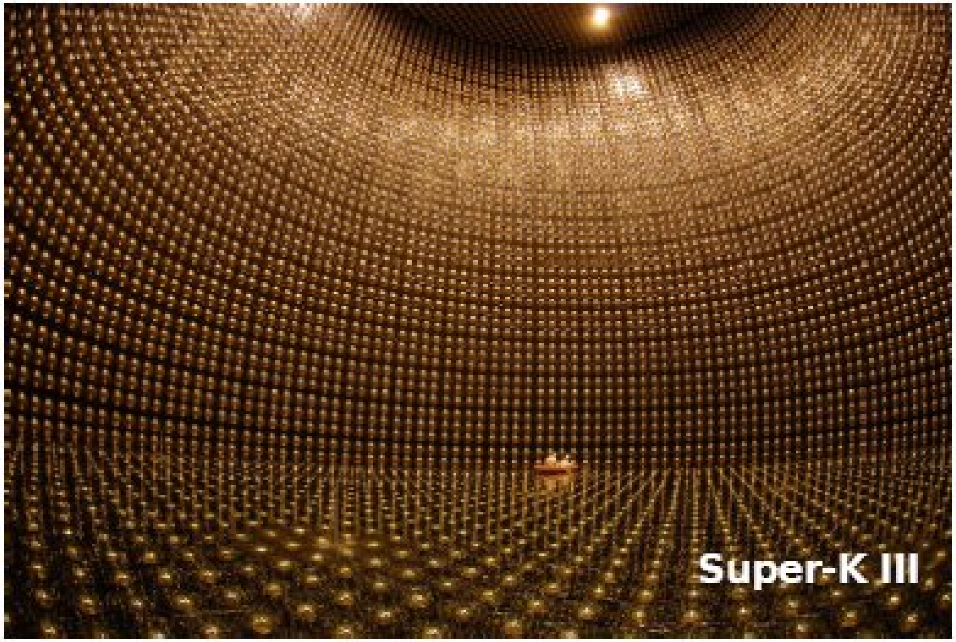
These particles can be moving faster than the speed of light in water (since water has slowed down the light).

This creates Cherenkov light---an electromagnetic sonic boom!

- Light is blue
- Comes out in cone
- More energy-more light



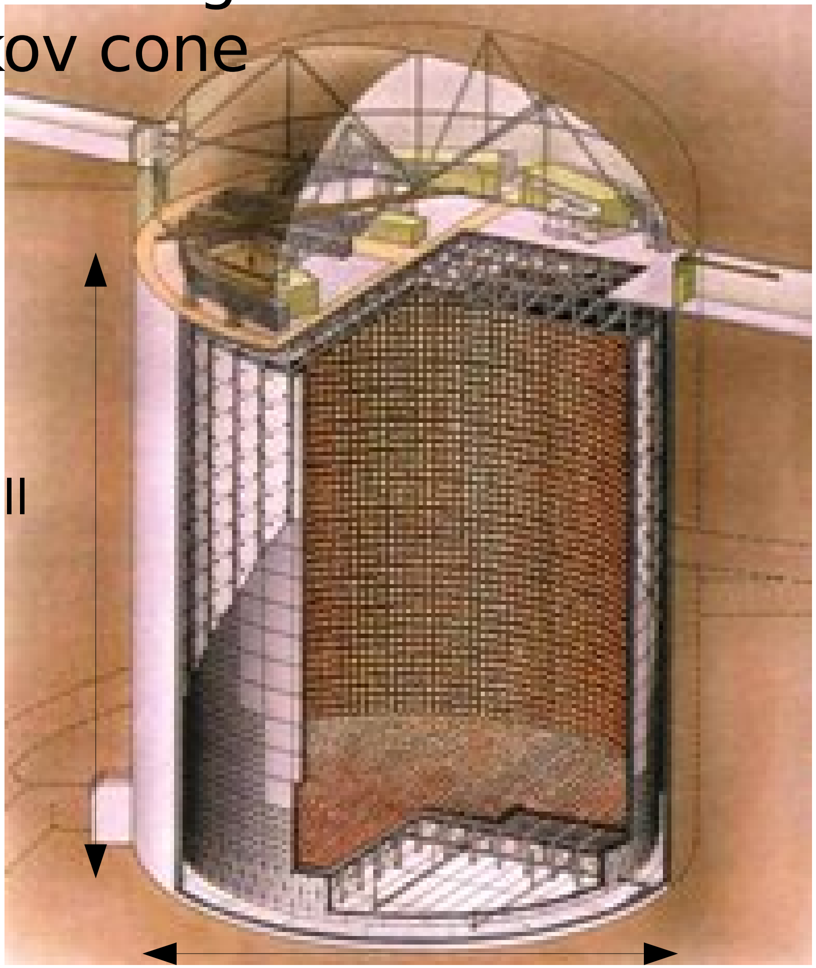
Super-Kamiokande (Japan)



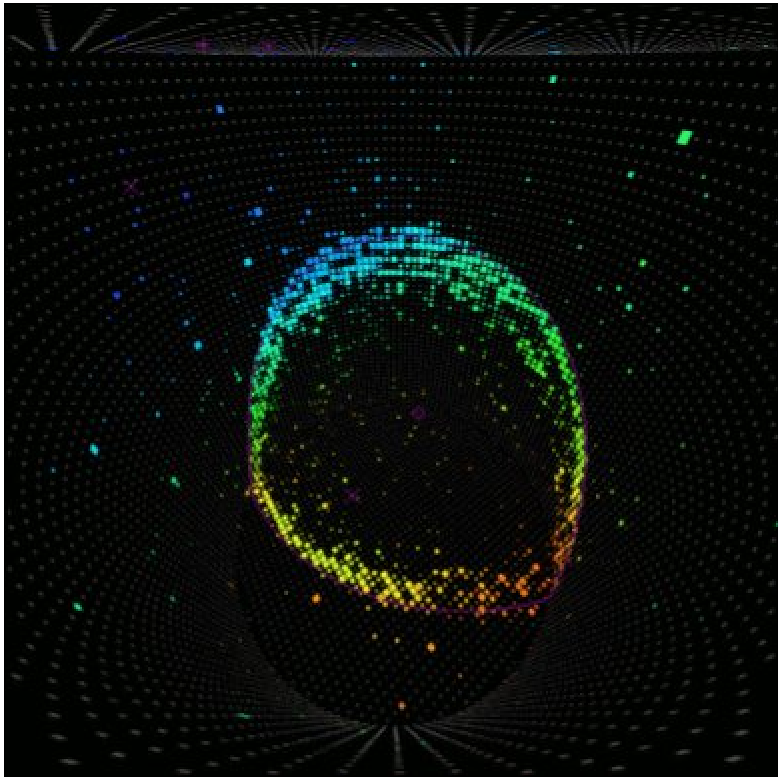
50 kilotonne tank of water with 11,000 photomultiplier tubes inside it!

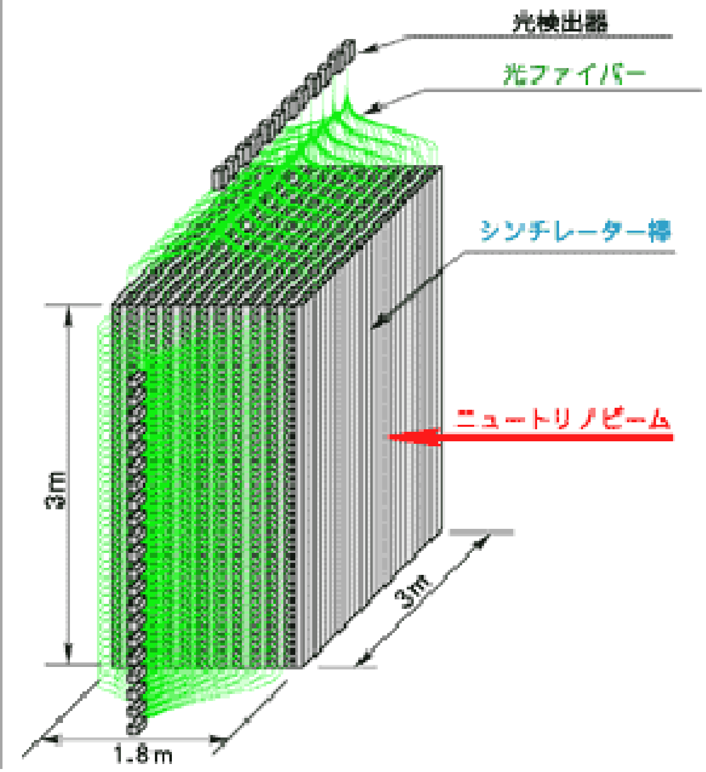
Tubes detect light from Cherenkov cone

41m tall



39m wide





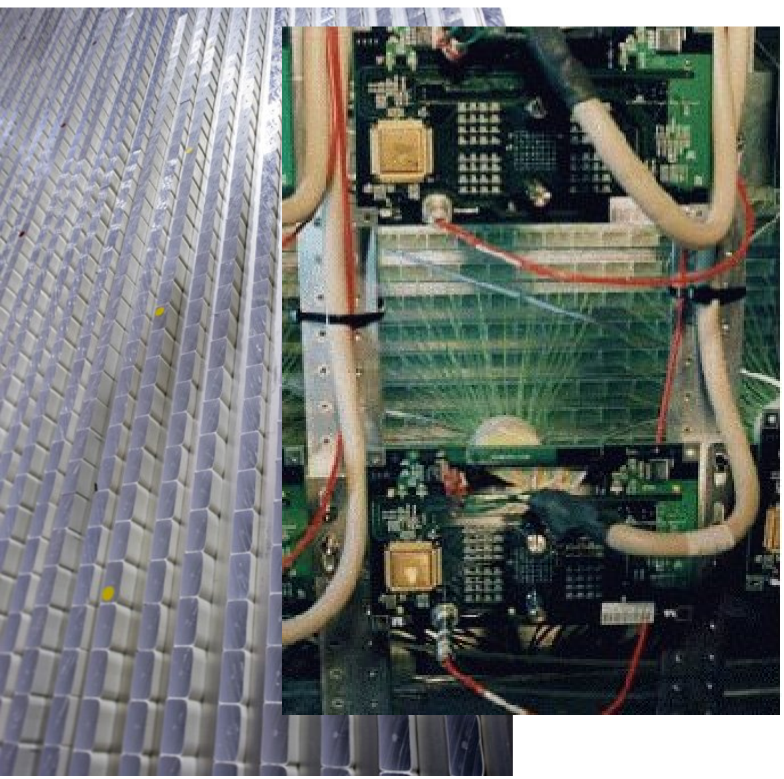
Tracking detectors

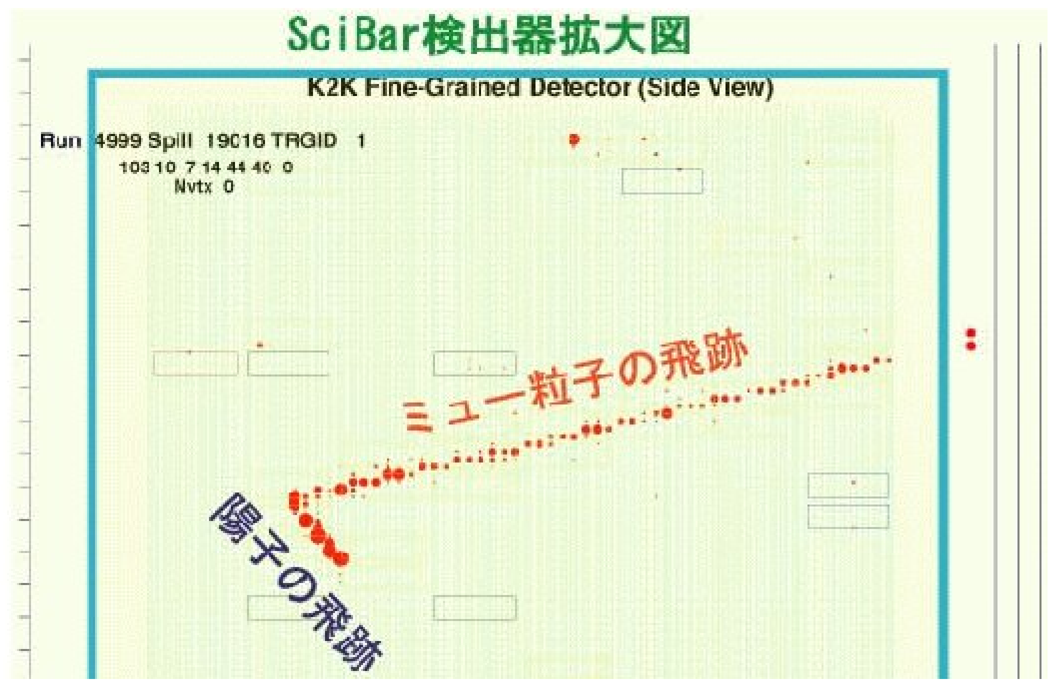
SCIBAR: Layers of plastic scintillator bars read out with optical fibers. Finely segmented tracking of charged particles

muon

incoming ν_μ hits neutron

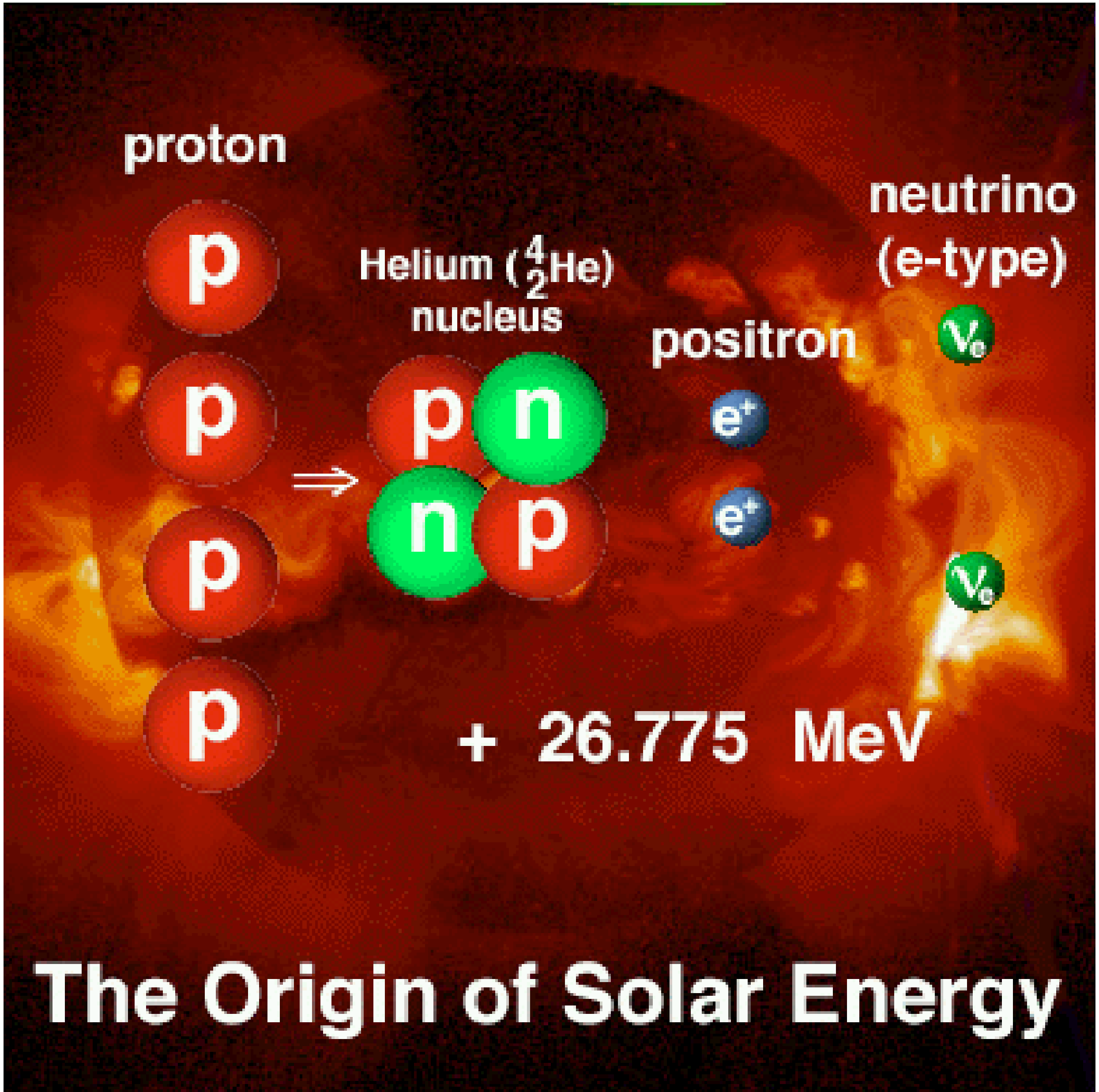
recoil proton





Chapter 3: The solar neutrino problem

Our friend the Sun

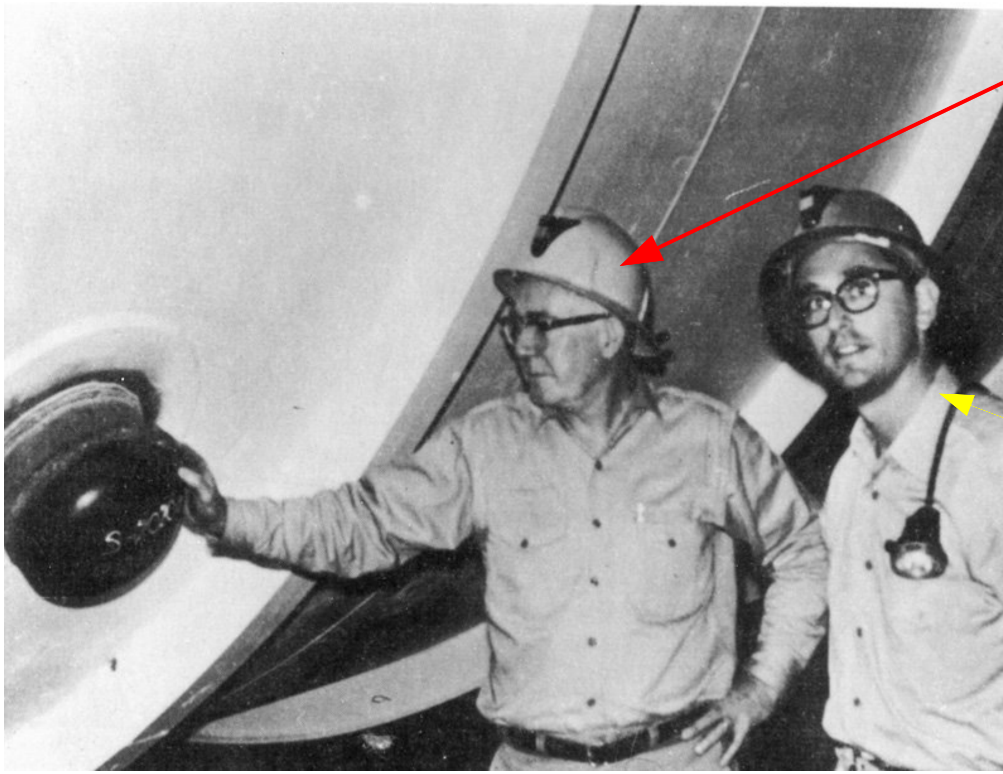


The Sun's fusion reactions produce copious quantities of electron neutrinos!

We know how bright the Sun is and how the fusion reactions work ...

so we calculate that 60 billion neutrinos from the Sun pass through your thumbnail every

Looking for solar neutrinos at Homestake



Remember Ray Davis and his big tank of cleaning fluid?

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

Theorist John Bahcall predicted that solar neutrinos would produce 5.7 atoms/day of Ar in the 600 tonne tank.

Ray went looking for them ...

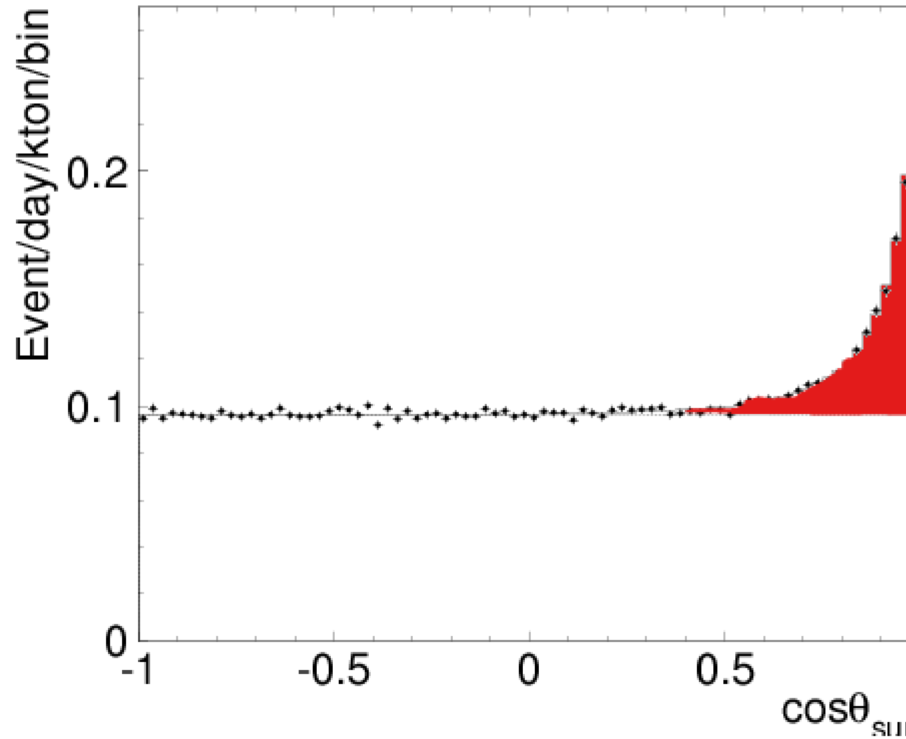
Expected rate: 5.7 ± 0.9 atoms/day
Measured rate: 1.9 ± 0.2 atoms/day

Two-thirds of the solar neutrinos were missing!

Other solar neutrino experiments also find too few neutrinos!

GALLEX experiment: big tank of liquid gallium

$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$



(direction of neutrino relative to Sun)

Super-Kamiokande sees electrons knocked away from the Sun by neutrinos ... but not enough!

What's going on?!?

Multiple experiments looked for neutrinos coming from the Sun, and found fewer than expected.

• Are the experiments wrong?
• Is something wrong with the Sun?
• Is something wrong with the neutrinos?

This quandry is known as the

solar neutrino problem.

Chapter 4: Neutrino oscillations

A possible answer to the solar neutrino problem

The Sun should only make electron neutrinos:

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

So the experiments to look for solar neutrinos only looked for electron neutrinos.

What if the electron neutrinos turned into ν_μ or ν_τ on their way to Earth?

It would look like the Sun was putting out too few neutrinos, but in reality the missing ones would still be there, but just not detectable by the usual experiments!

But how could a neutrino change its type?

Neutrino Mixing

Neutrino mixing is the idea that the neutrinos we always thought were basic particles, such electron or muon neutrinos, are actually mixtures of other particles ...

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

I don't mean that if you looked inside an ν_e that you would see two little particles ν_1 and ν_2 inside. Rather, in a weird quantum mechanics way, it's both at once!

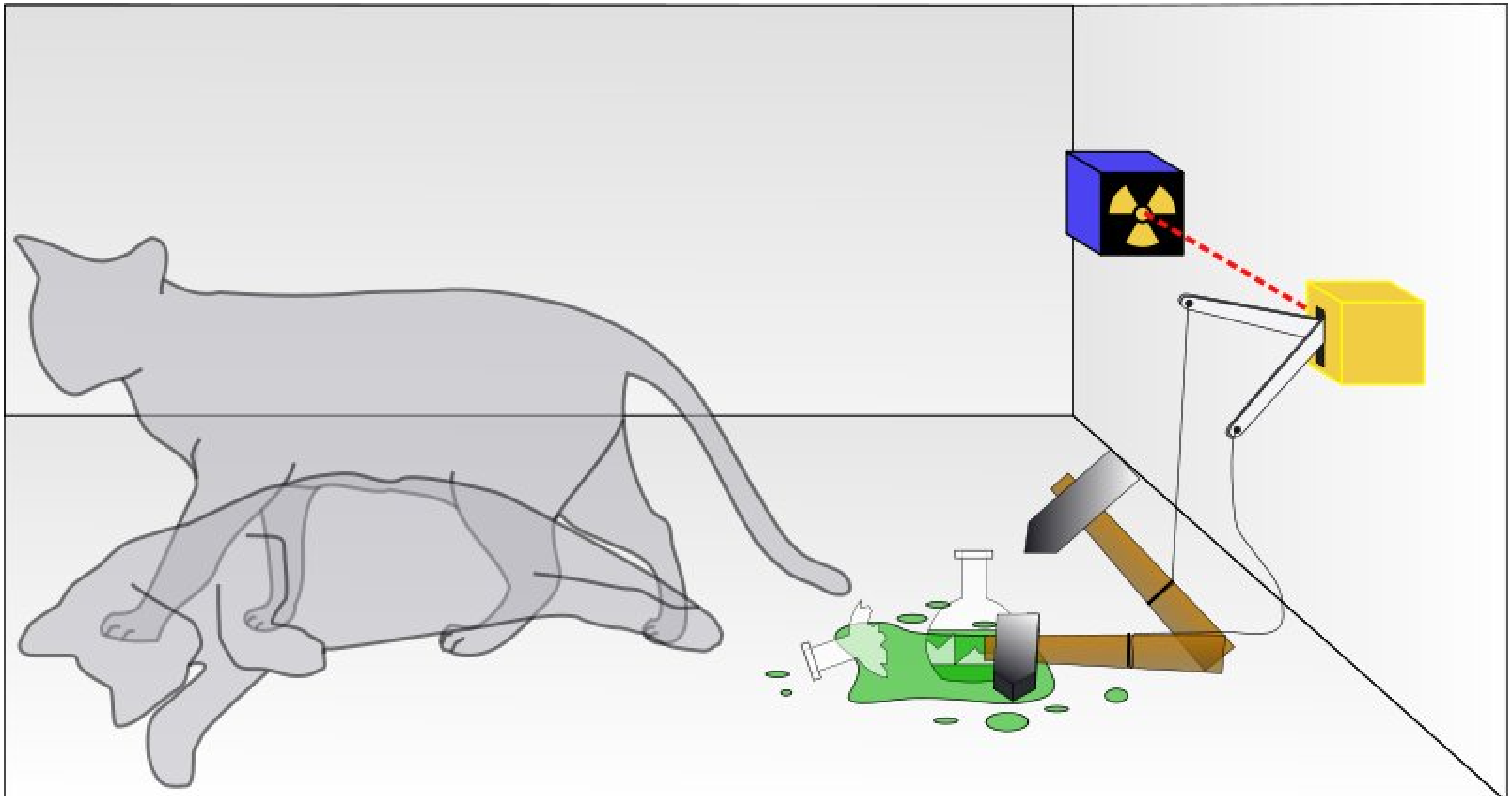
How can it be both at once?!

This is the weirdest thing I have to explain, because it's quantum mechanics, and quantum mechanics is just weird.

Quantum mechanics says that subatomics particles can exist in superpositions, in which they act as if they are simultaneously in two opposite states!

The canonical example is Schrödinger's cat ...

Poor kitty!

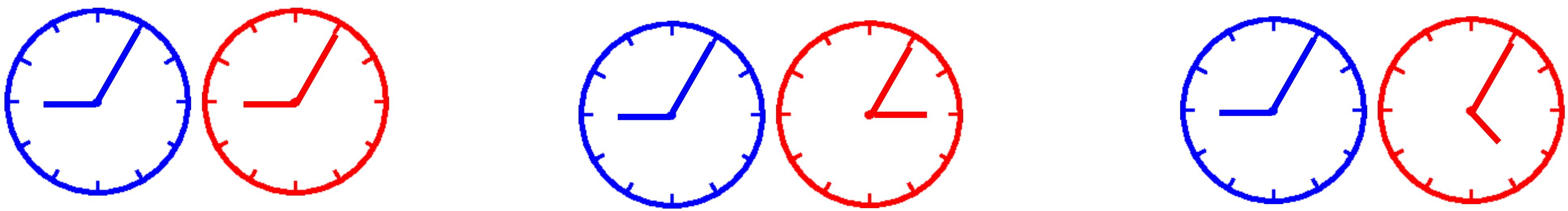


If a random radioactive decay happens, poison is released and the cat dies!

If you put the cat in a box, cover it up, and don't look, is the cat alive or dead? QM says that until you look, it's both!

A way to think about 2-component neutrinos

Imagine each neutrino as a pair of clocks

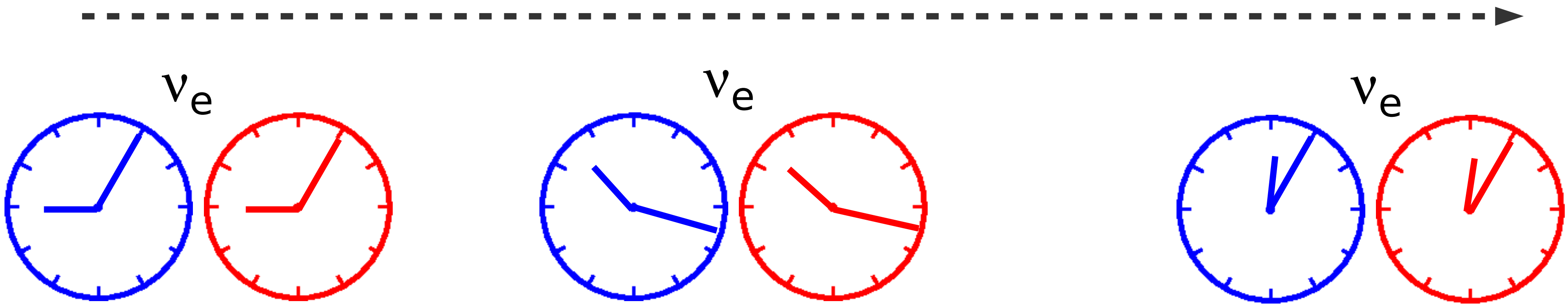


If both clocks read the same time, the neutrino acts like an electron neutrino.

If the red clock is 6 hours ahead, the neutrino acts like an muon neutrino.

If the red clock is 4 hours ahead or four hours behind, then ⅔ of the time it acts like a ν_μ, and ⅓ of the time like a ν_e

Neutrinos are created as either ν_e *or* ν_μ

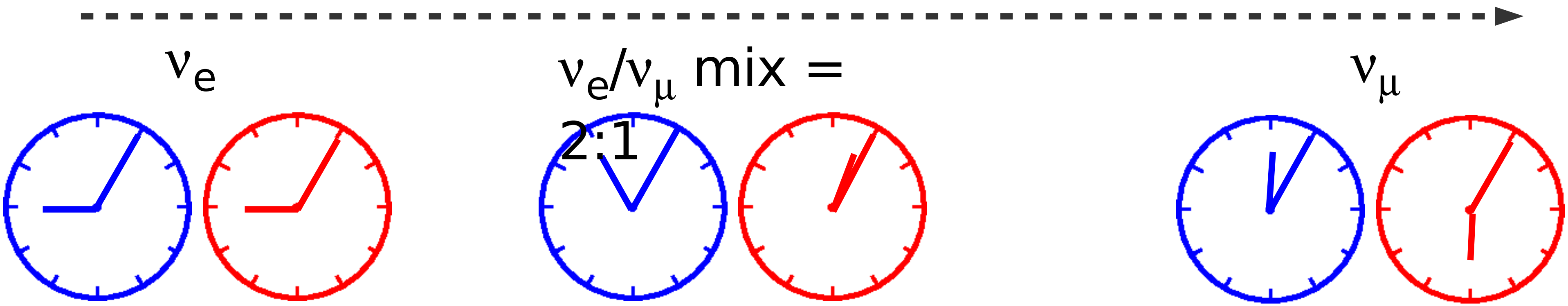


At the start, the clocks each read 9:05---in sync, so acts like electron neutrino

After a while, the clocks both read 10:17---still synchronized, still an electron neutrino

At a later time the situation is the same---clocks stay in sync!

What if the clocks get out of sync?



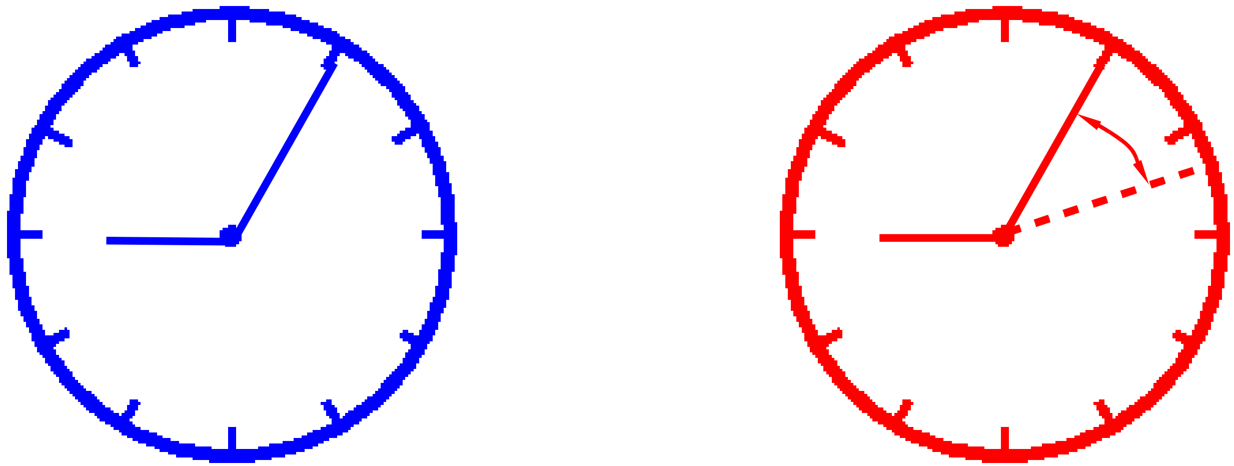
At the start, the clocks each read 9:05---in sync, so acts like electron neutrino

After a while, the red clock is 2 hours ahead: a mix of ν_e and ν_μ

Later still the clocks are the maximum of 6 hours apart---this neutrino acts like a ν_μ

What started out as an electron neutrino can then act like a muon neutrino!

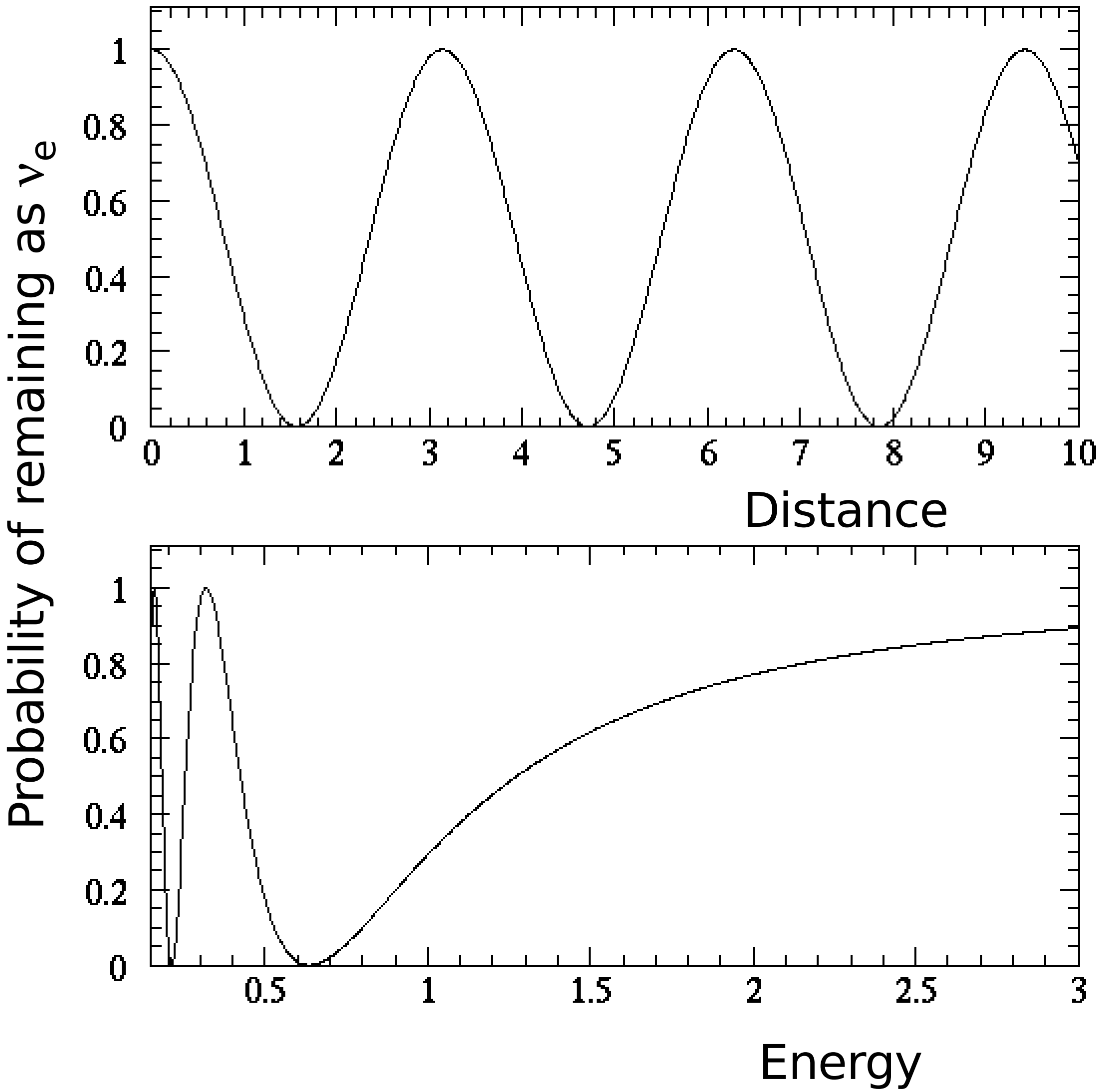
What makes clocks get out of sync?



It works out that quantum mechanically what controls the rates of the clocks are the masses and energies of the two kinds of neutrinos ν_1 and ν_2.

If ν_e's and ν_μ's are really mixtures of ν_1 and ν_2 that happen to have different masses, then one flavour of neutrino can oscillate into another flavour over time.

Neutrino Oscillations



The formula for a neutrino changing into a different kind is:

$$\sin^2 2\theta \sin^2\left(\frac{1.27\,\Delta m^2 L}{E}\right)$$

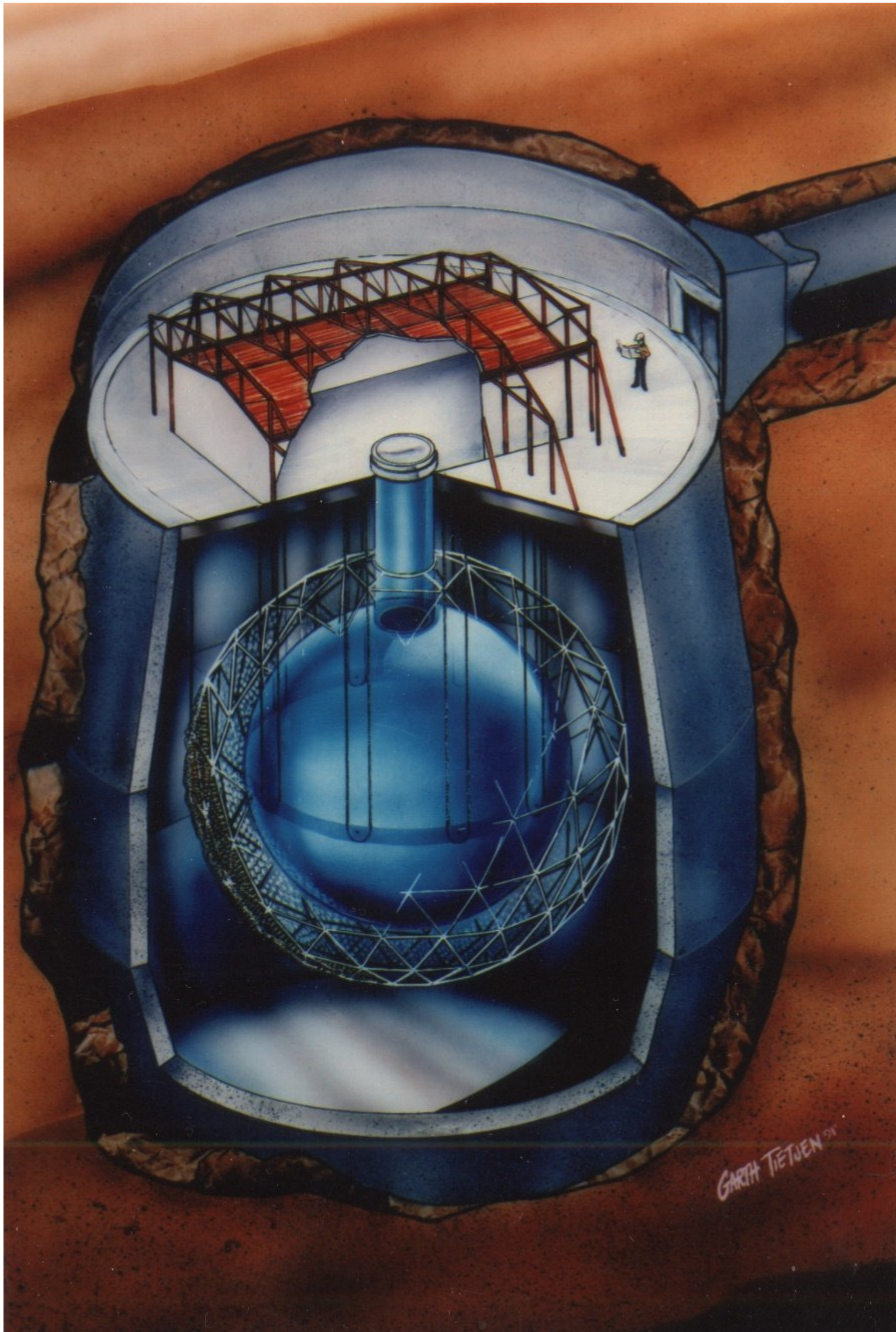
$\sin^2 2\theta$ = a parameter that controls the amplitude of the oscillation (the maximum fraction that can convert)

$\Delta m^2 = (\text{mass}_2)^2 - (\text{mass}_1)^2$

L = distance neutrino has gone

E = energy of neutrino

Chapter 5: A tour through the world of experiment

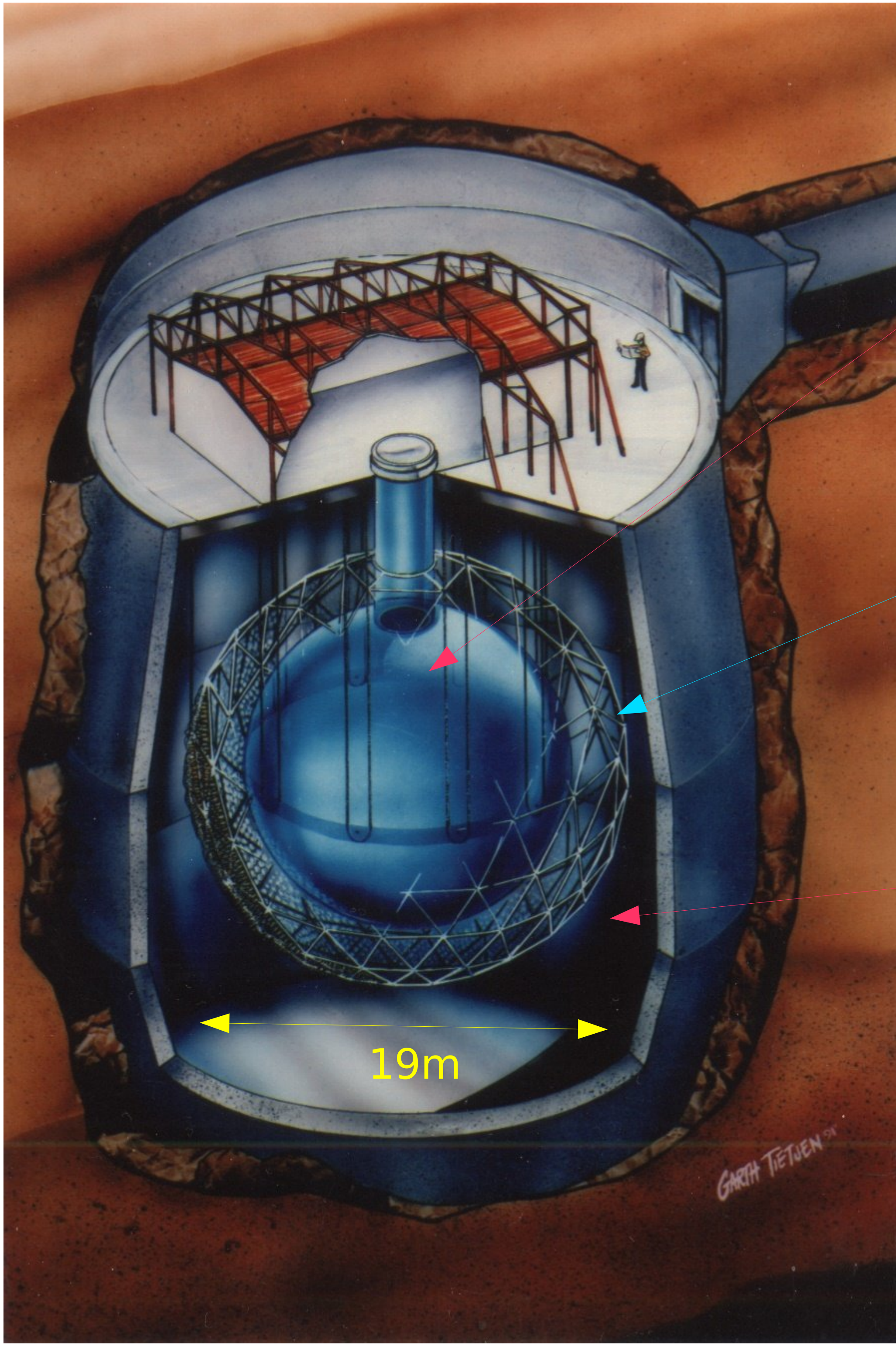


Solving the solar neutrino problem

If electrons neutrinos from the Sun really are changing into other flavours on their way to us, why not look for these ν_μ or ν_τ?

This was the goal of Canada's own Sudbury Neutrino Observatory, located 2km underground in Lively, ON.

SNO

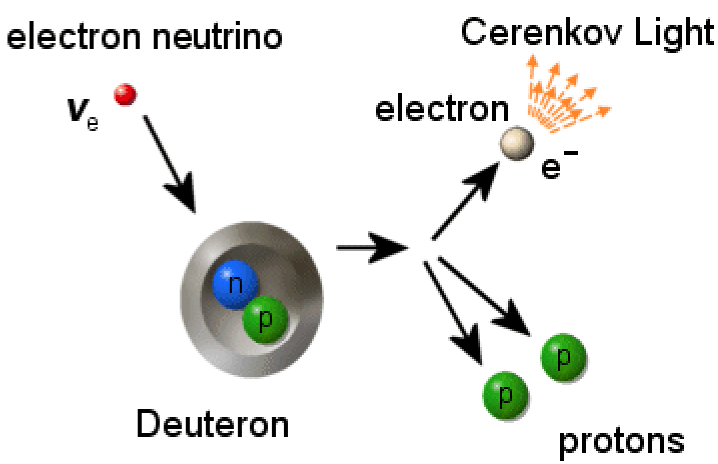


1000 tonnes of heavy water (D_2O) inside a 12m wide spherical acrylic vessel, with a little NaCl (salt) mixed in

9500 inward-looking photomultiplier tubes to detect Cherenkov light from the heavy water

ultra-pure ordinary water (H_2O) surrounding the sphere to act as shielding

Neutrino Reactions On Deuterium



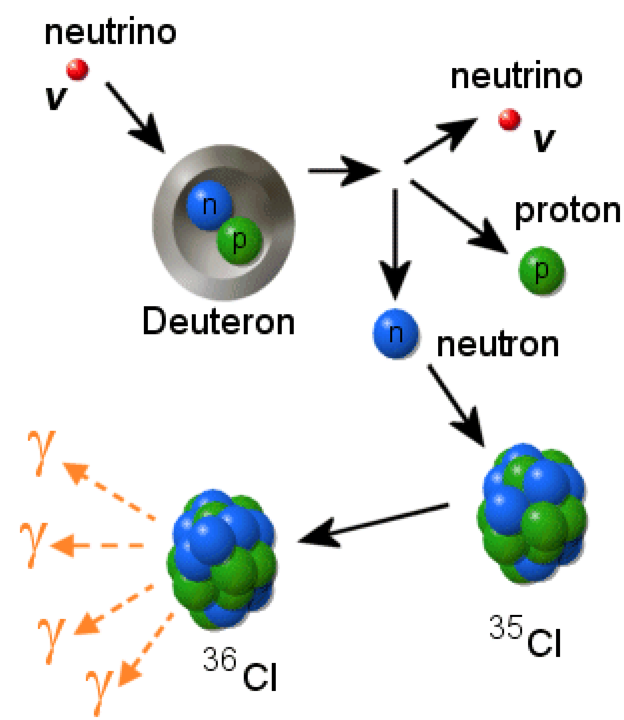
Electron neutrinos only:

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

There are two possible reactions for solar neutrinos on deuterium.

One measures the flux of electron neutrinos.

The second measures all types!

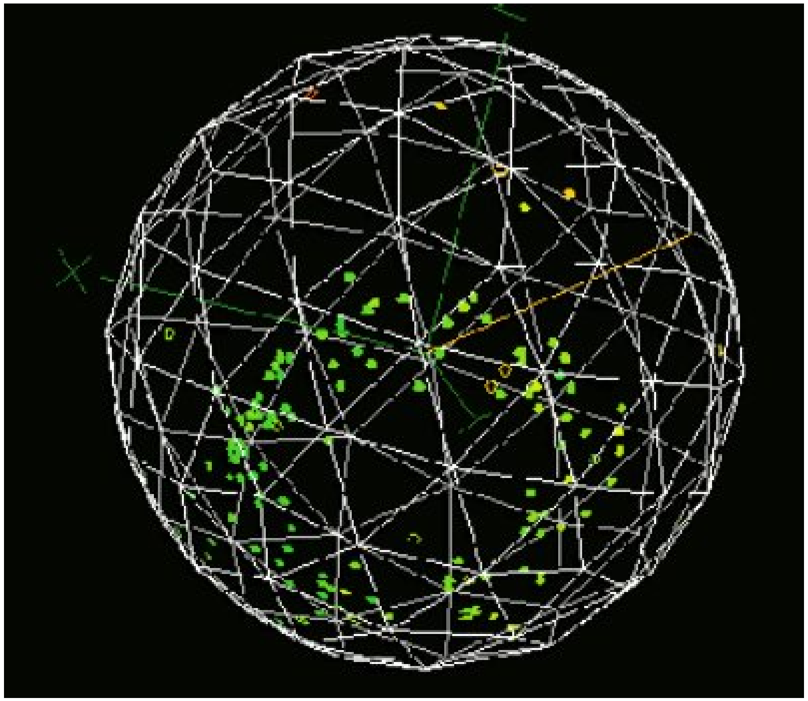


Any type of neutrino:

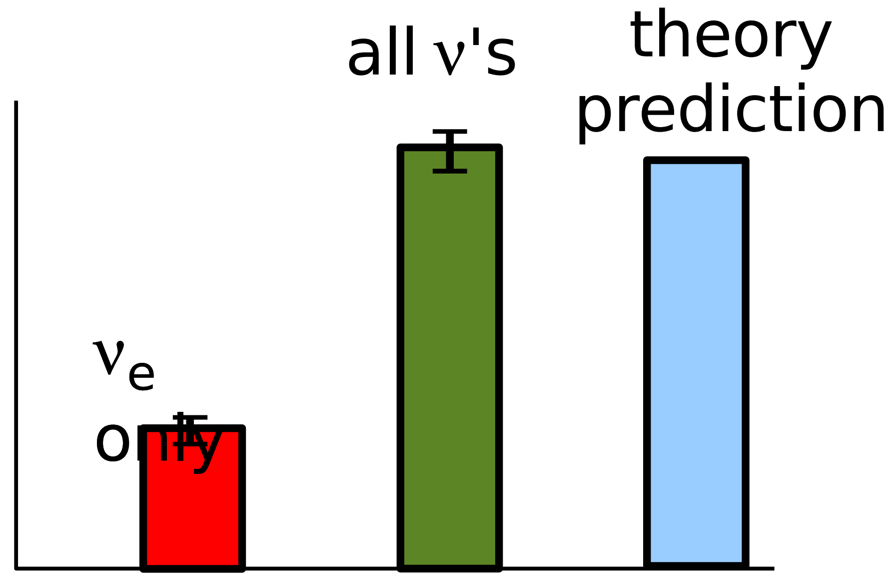
$\nu_x + d \rightarrow \nu_x + n + p$

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

SNO Results!



A ring of Cherenkov light from an electron produced by a solar neutrino

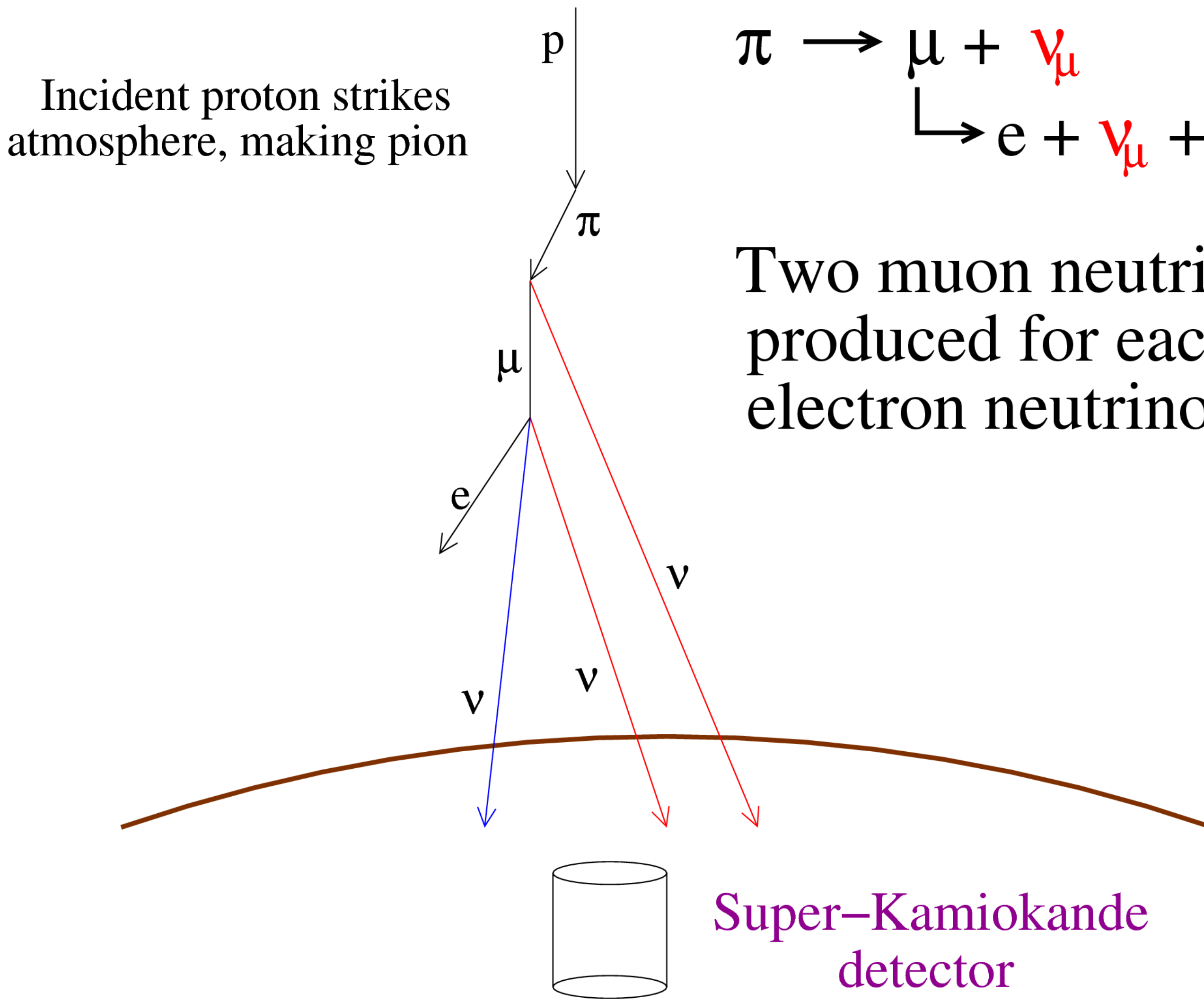


Electron neutrino flux only 1/3 of model prediction

But total flux of all flavours agrees with theory!

Neutrinos change flavour!

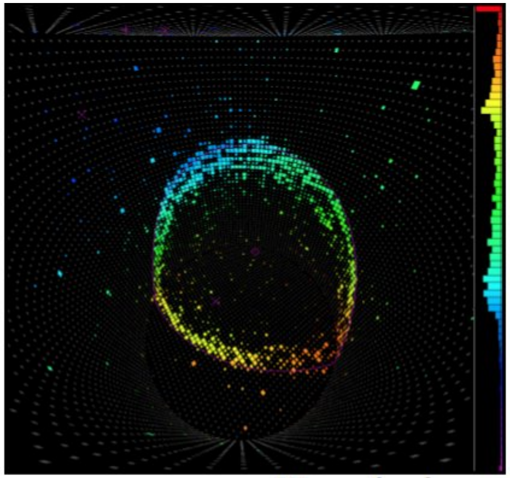
Atmospheric Neutrinos



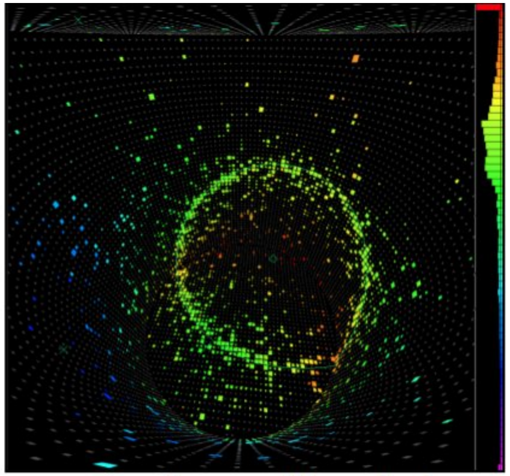
$$\pi \longrightarrow \mu + \nu_\mu$$
$$\hookrightarrow e + \nu_\mu + \nu_e$$

Two muon neutrinos produced for each electron neutrino!

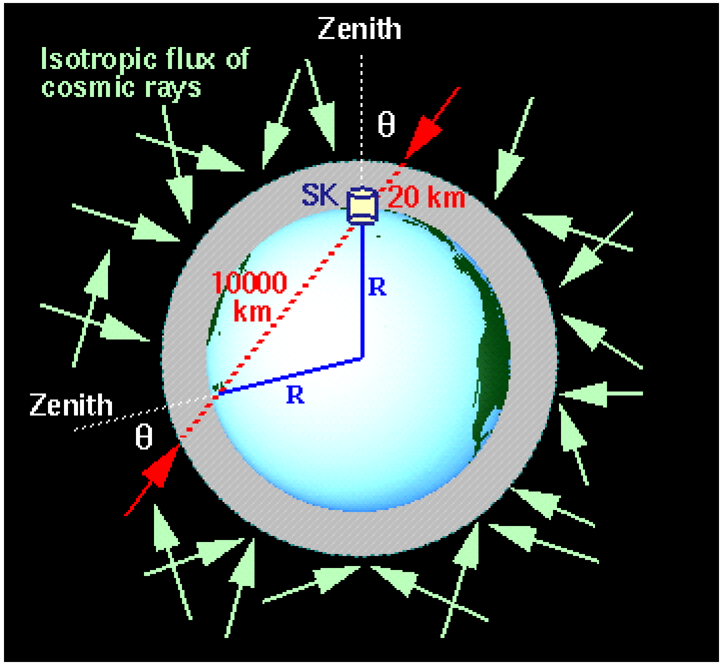
Measuring ν_μ vs ν_e at Super-K



muon-like (ν_μ)



electron-like (ν_e)



Electrons are light, so get buffeted around a lot as they move through the water in Super-K. Their rings get smeared out.

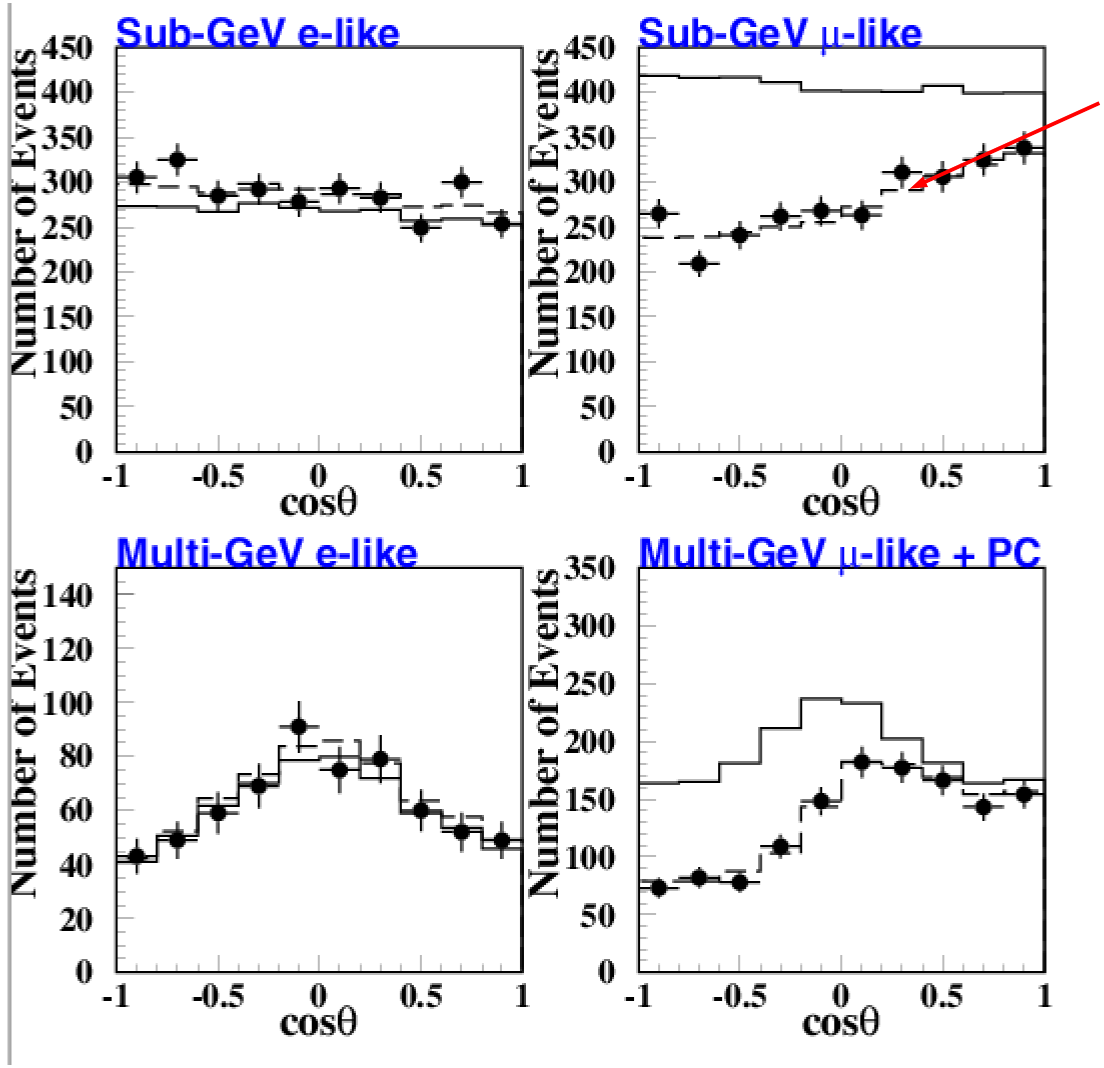
Muons give nice crisp rings.

Downward-going neutrinos come from close by, but upward-going from the far side of the Earth

Super-K's atmospheric neutrino results

lower energy

higher energy



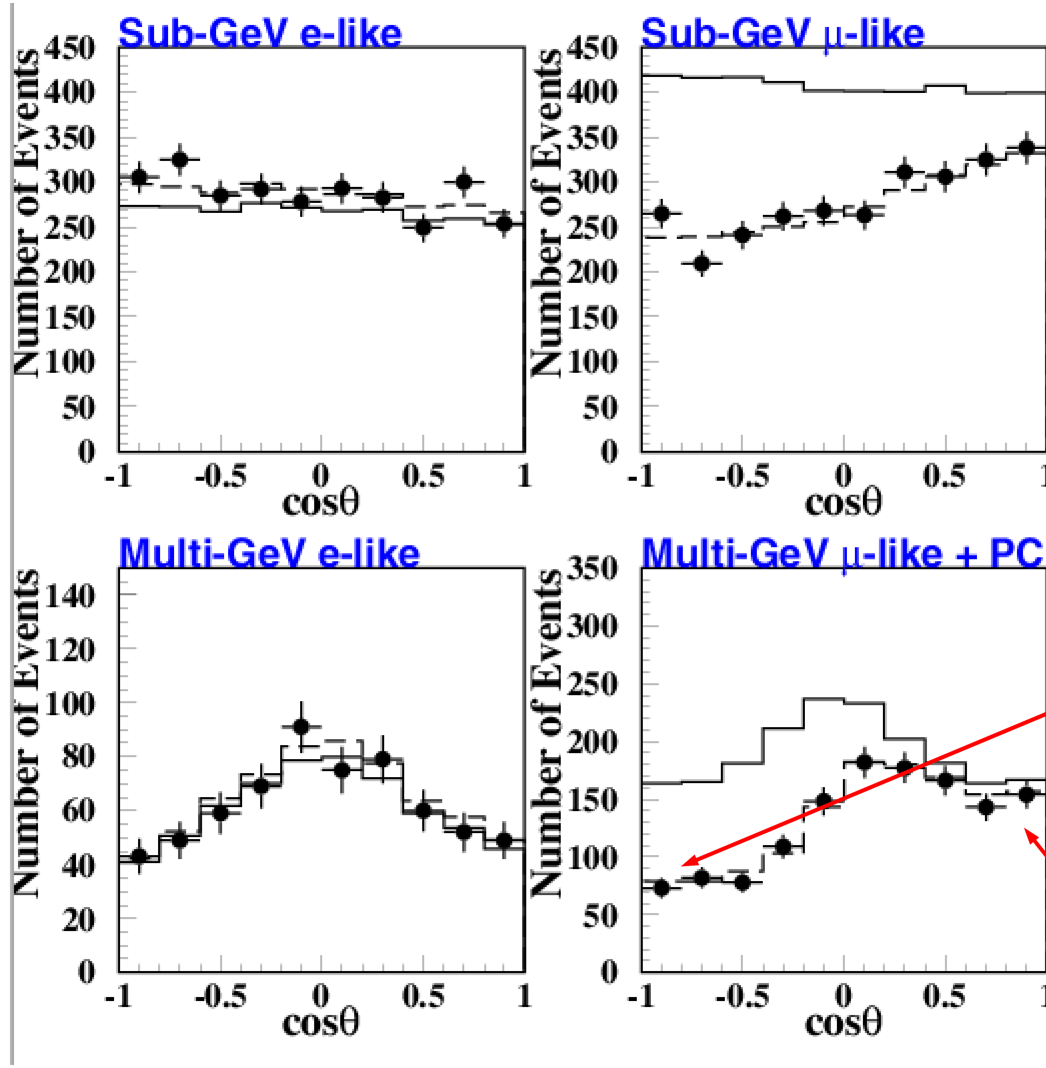
ratio of muons to electrons is 1:1, not expected 2:1!

more upward-going muons are missing than downward-going!

Super-K's atmospheric neutrino results

lower energy

higher energy



ratio of muons to electrons is 1:1, not expected 2:1!

more upward-going muons are missing than downward-going!

Interpretation of Super-K results

Muon neutrinos are missing, mostly at lower energy and at longer distances.

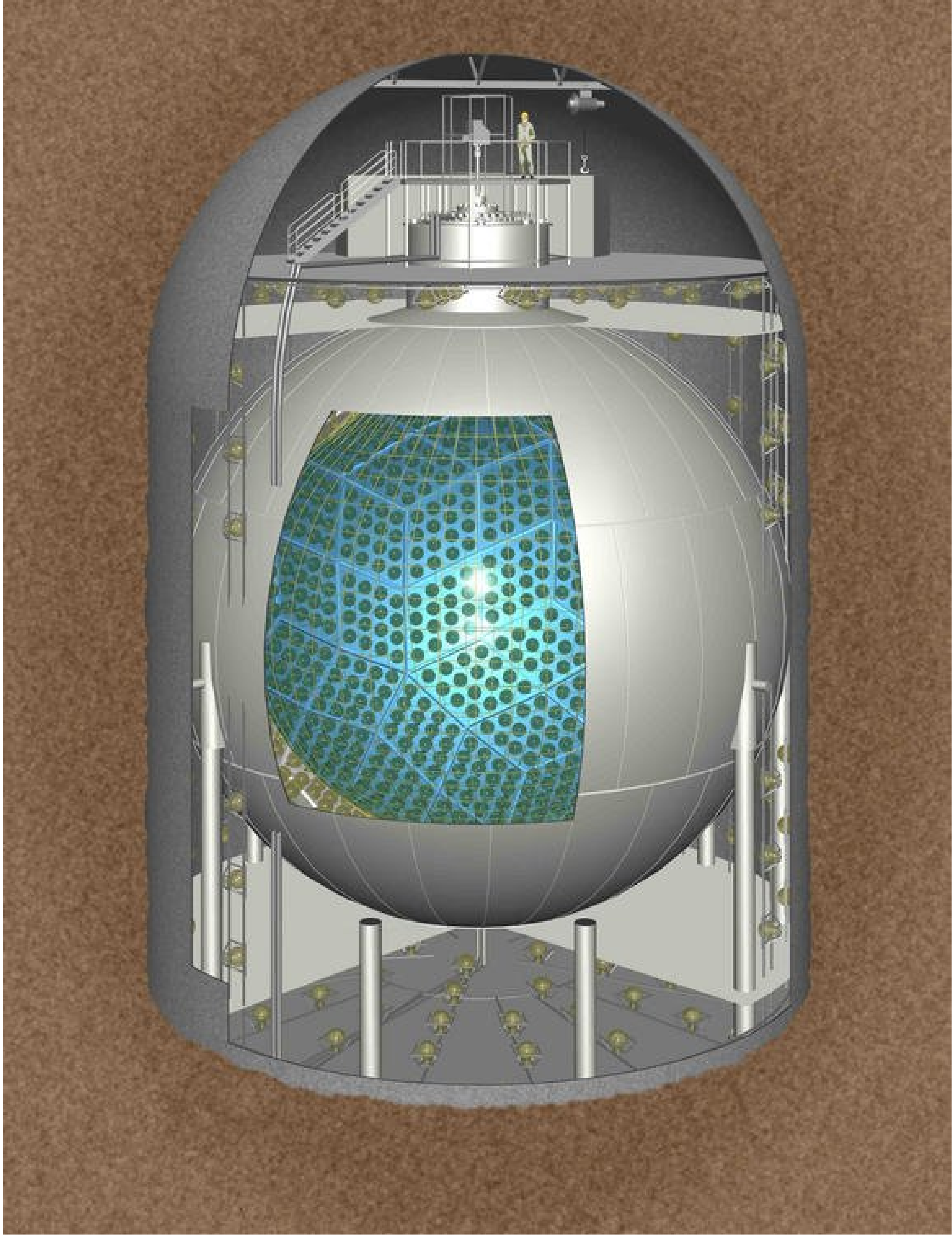
This is a signature of oscillation!

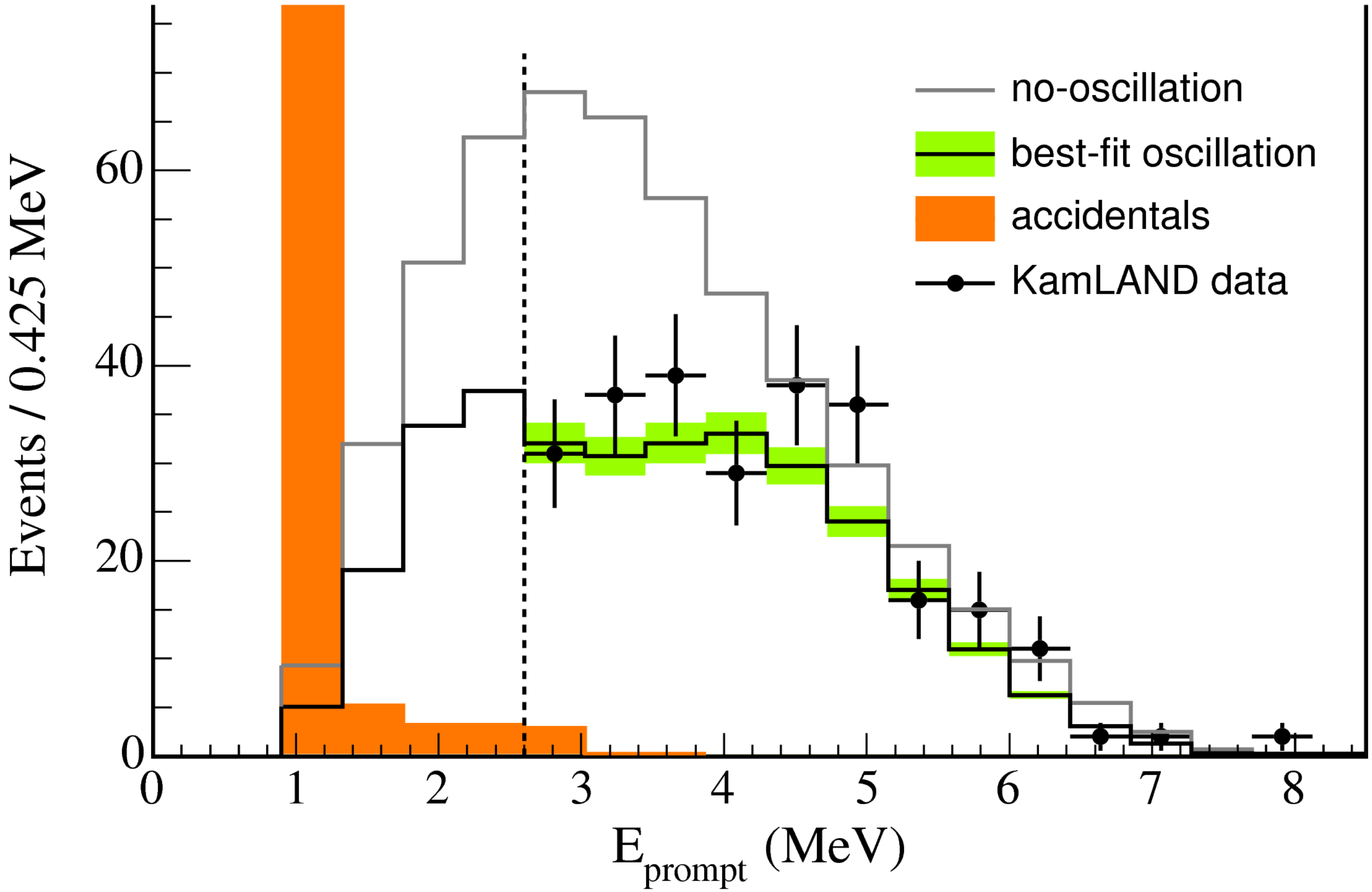
This is probably $\nu_\mu \rightarrow \nu_\tau$ oscillation. The tau neutrinos don't have enough energy to interact in Super-K, since it takes a lot more energy to make a tau, so the ν_τ just don't interact.

KamLAND

Look at antineutrinos from reactors all across Japan!

Target: big tank of mineral oil

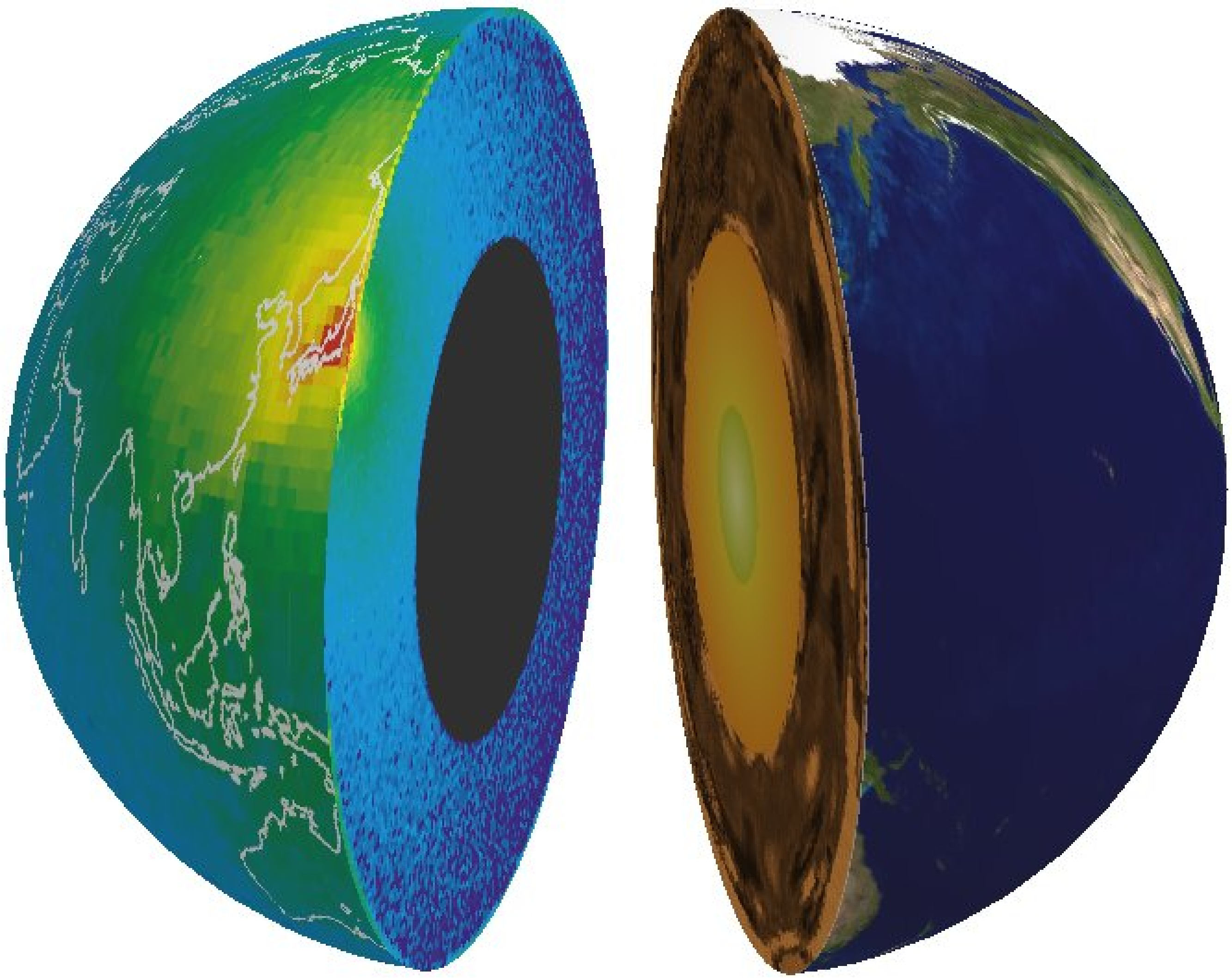




KamLAND sees fewer neutrinos than expected from the reactors, which on average are ~200km from their detector.

Energy-dependent suppression fits neutrino oscillation!

KamLAND geo-neutrinos



KamLAND has also detected some antineutrinos coming from radioactive decays of uranium and thorium inside the Earth.

These decays provide about 20 terawatts of power inside the Earth, and are

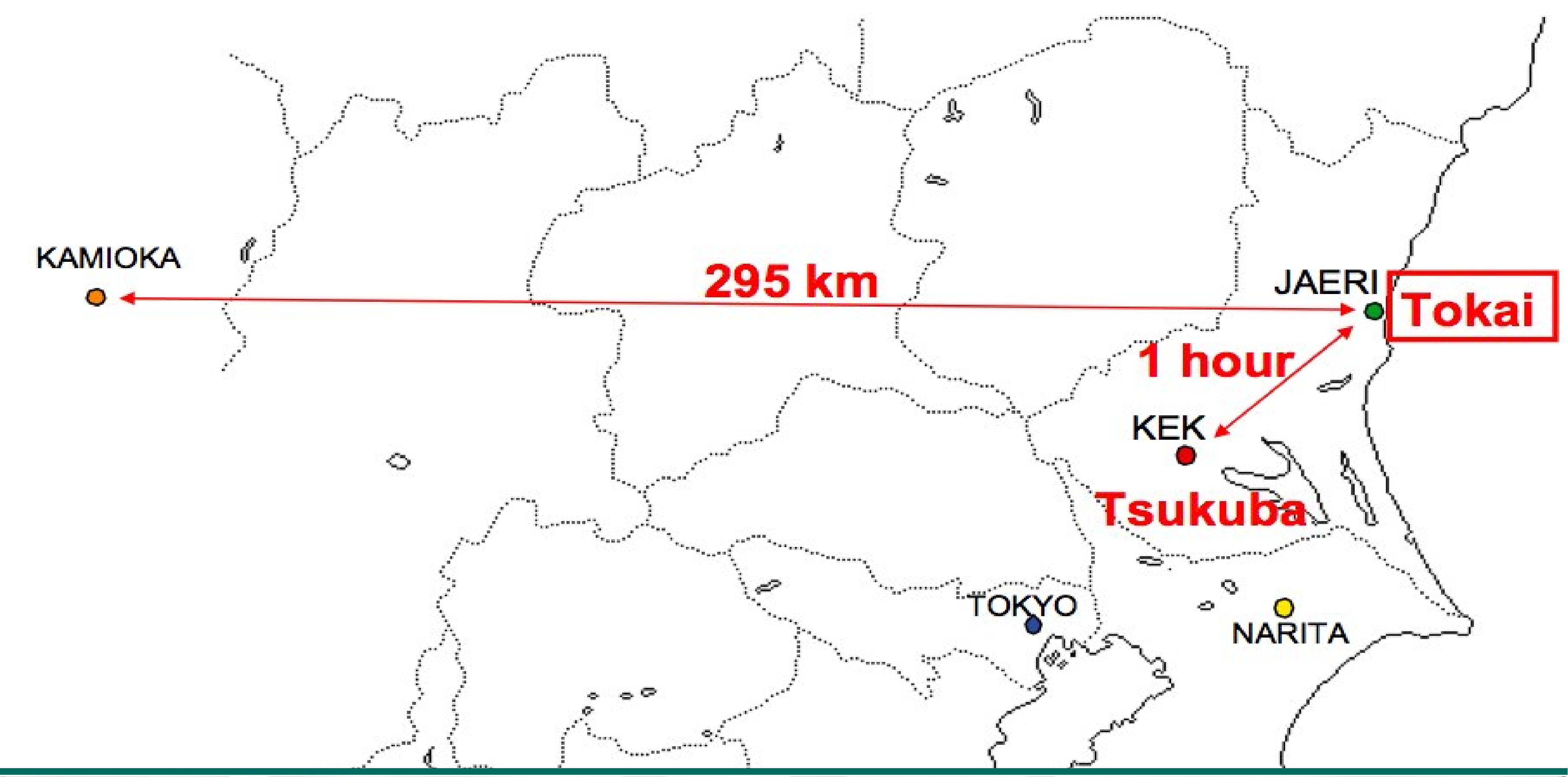
How to make a neutrino beam

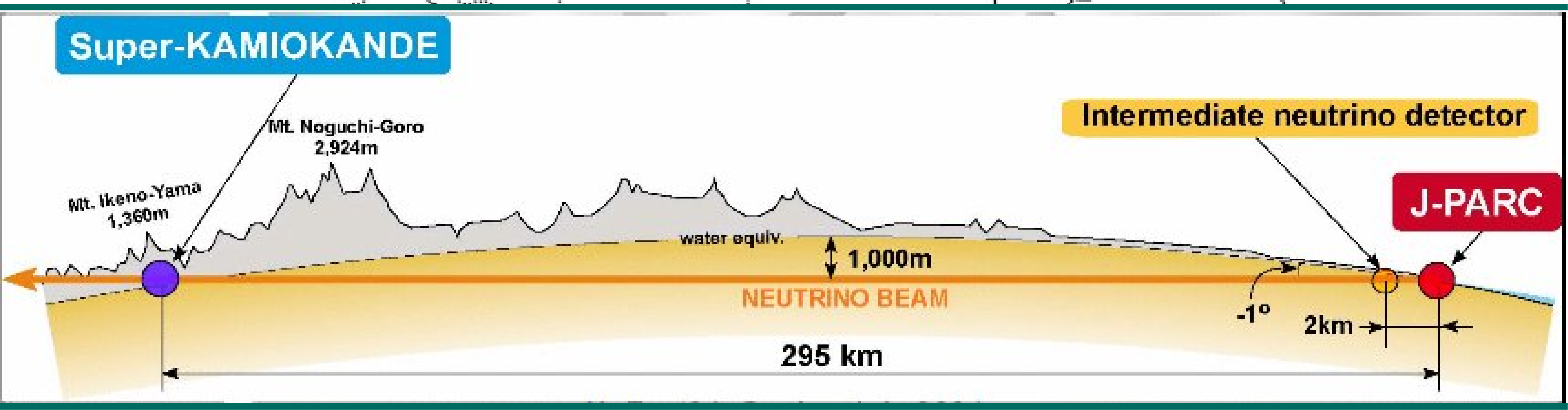
Wouldn't it be nice if we could make our own neutrino beams and change their energies or directions at will?

This isn't easy to do, since neutrinos are neutral particles and can't be steered by ordinary means.

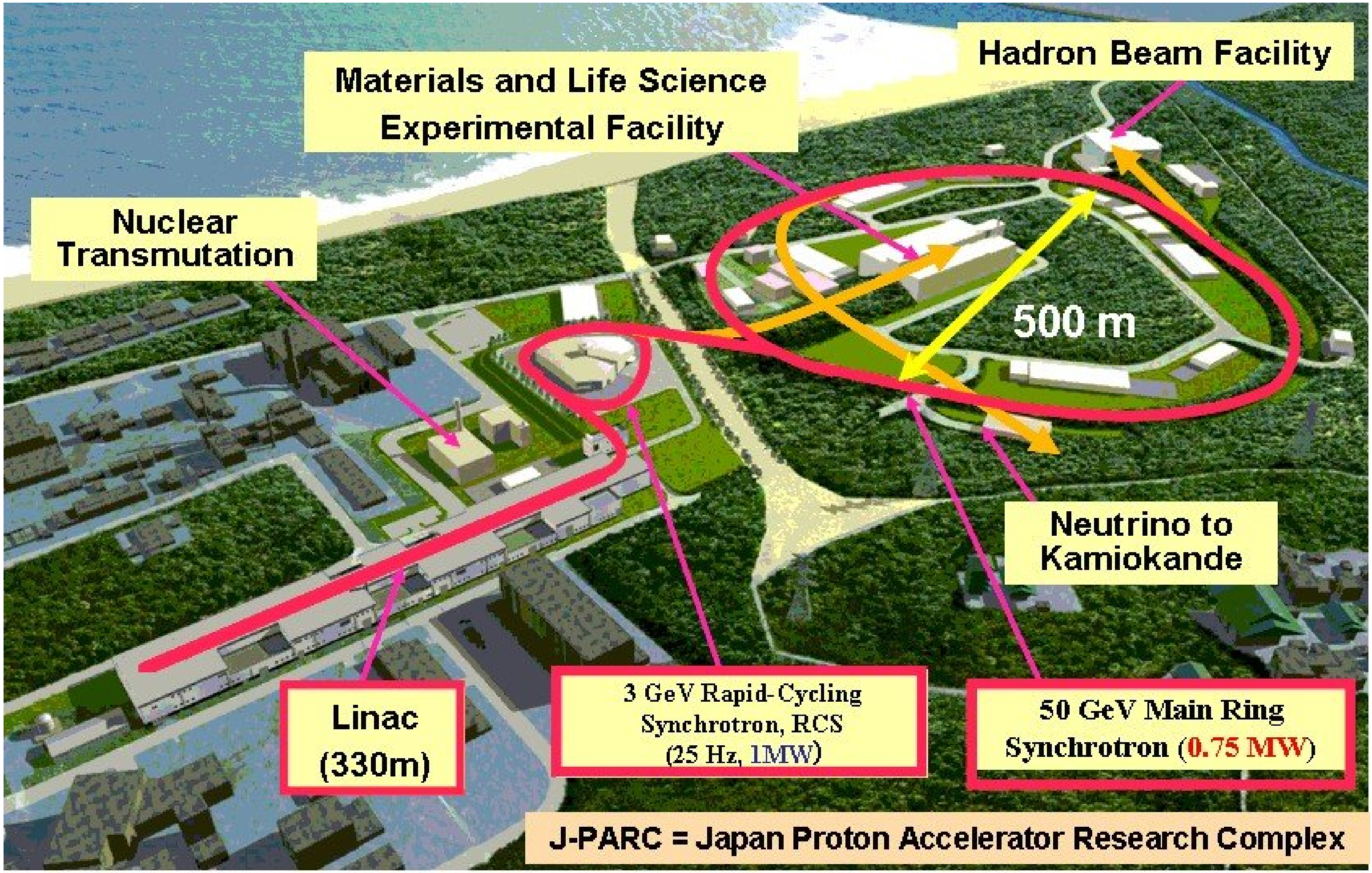
But, incredibly, it's not that hard to make a beam of them nonetheless!

The T2K Neutrino Beam


KAMIOKA
295 km
JAERI
Tokai
1 hour
KEK
Tsukuba
TOKYO
NARITA


Super-KAMIOKANDE
Mt. Noguchi-Goro
2,924m
Mt. Ikeno-Yama
1,360m
Intermediate neutrino detector
J-PARC
water equiv.
1,000m
NEUTRINO BEAM
-1°
2km
295 km

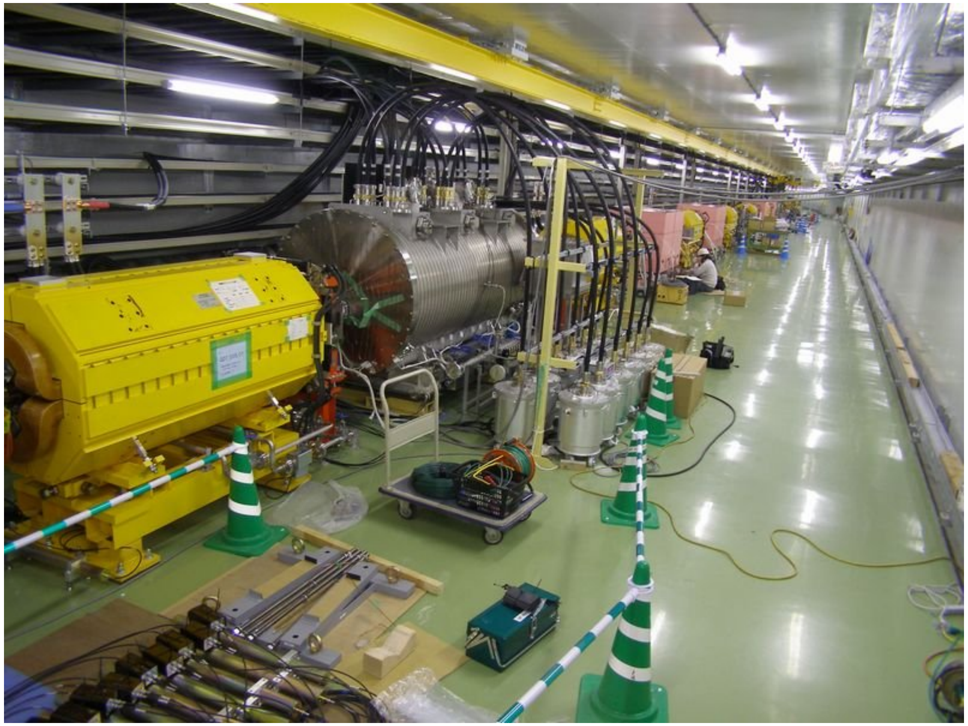
Start with a proton accelerator



Tracks

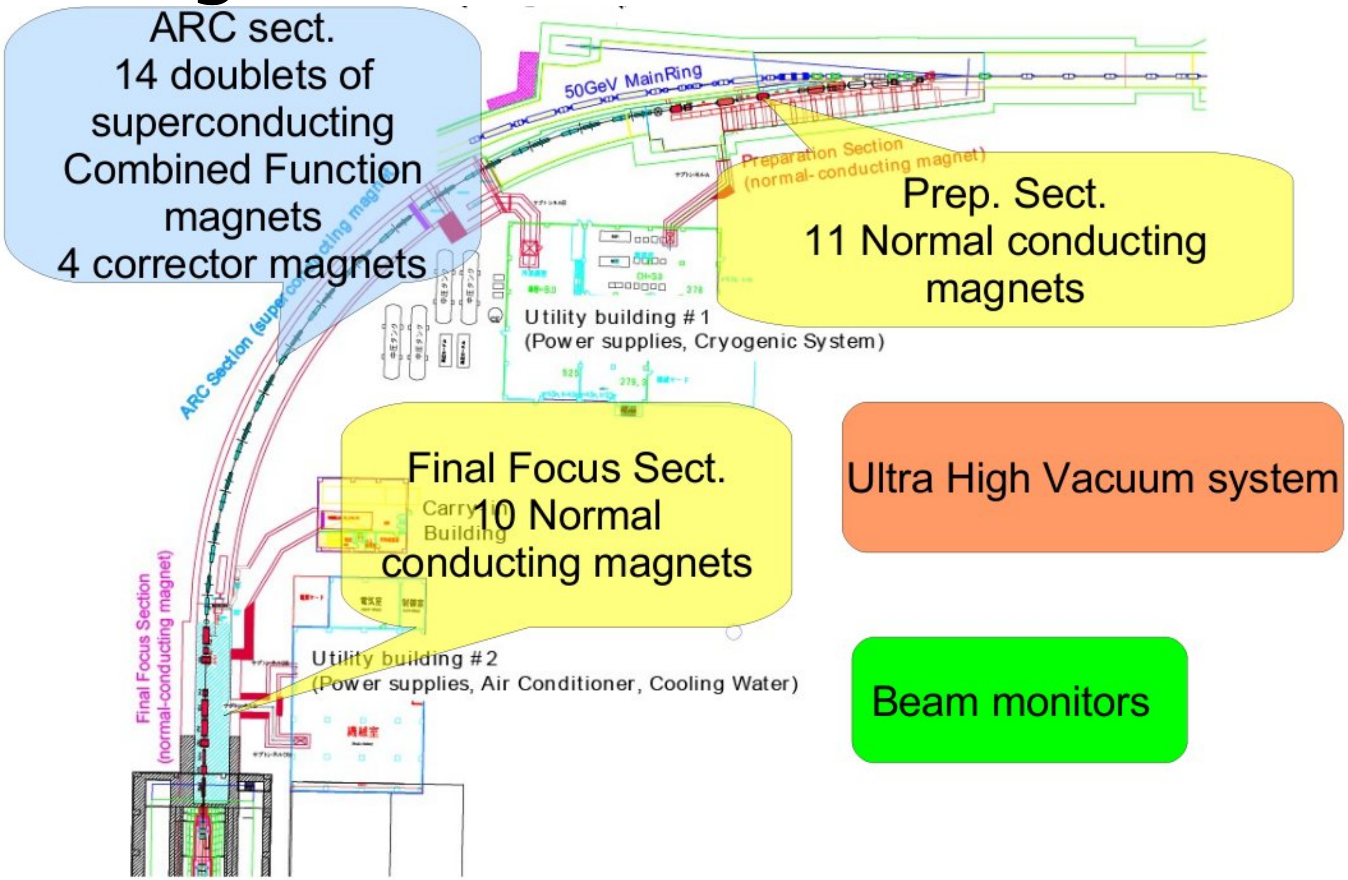
1. **Godzilla Attacks Tokai - Japan's Energy Crisis** (M2)
2. Fateful Confrontation (M3)
3. Main Title (M4)

Accelerate protons to high energies …

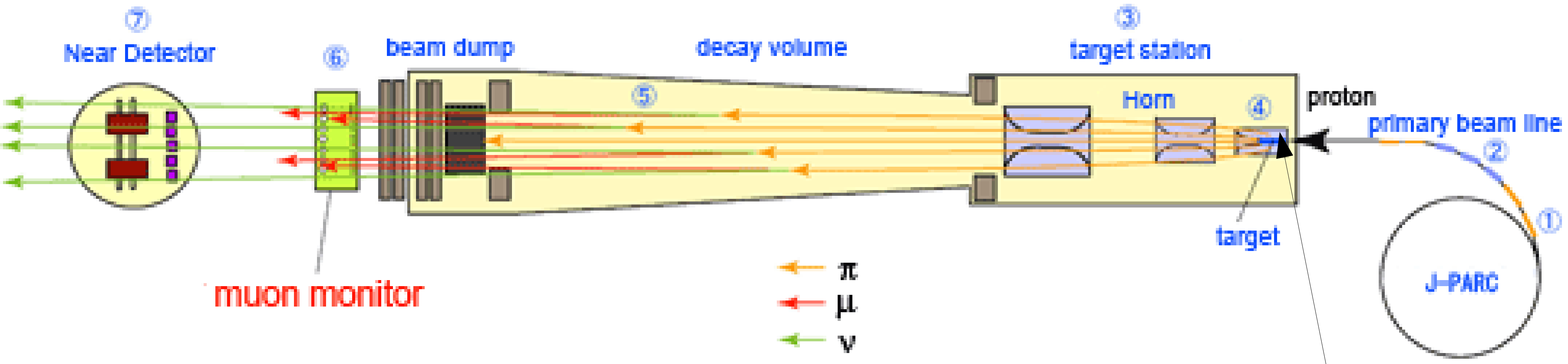


Extract the protons ...

- Steer the proton beam until it's pointing the right direction



Target Area



Slam proton beam into a graphite target. All kinds of particles are produced.

Use magnetic horns to collect, focus, and collimate π^+ particles.

T2K's 90cm graphite target

This horn uses magnetic fields to focus pions into a beam.

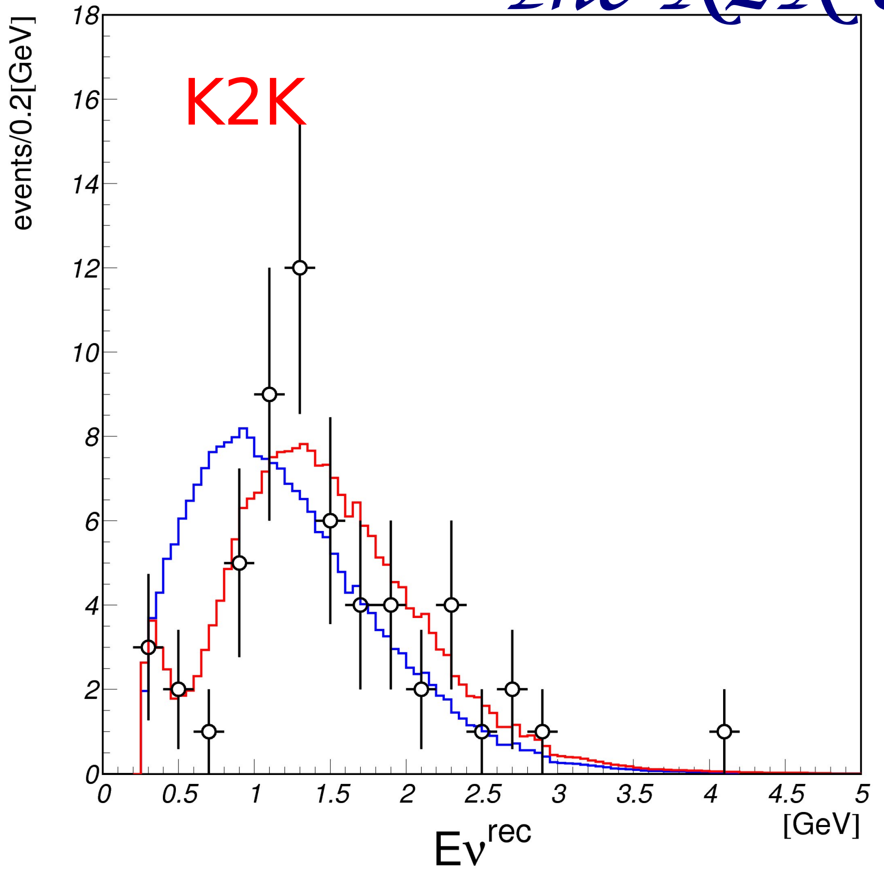
Inside the decay volume

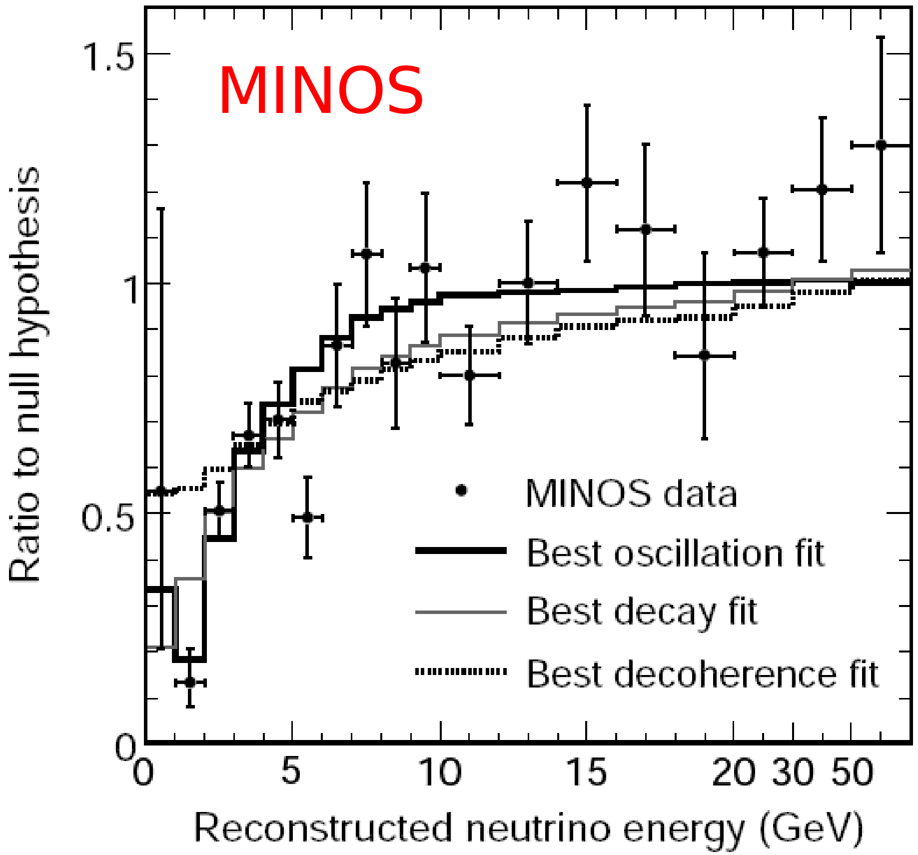
Pions fly down this big empty pipe, and decay in flight:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

Because the particles are moving at relativistic speeds, the neutrinos' momenta carries them in the forward direction. A beam of decaying pions gives a beam of muon neutrinos.

The K2K & MINOS Experiments





(K2K:Across Japan) (MINOS: Chicago to Minnesota)

Long baseline neutrino experiments confirm oscillations using manmade beams.

Chapter 6: Conclusions

Nu Discoveries!

A mere 12 years ago all the evidence said:

- neutrinos have no mass
- one kind of neutrino can't mutate into any other kind
- the solar neutrino problem is a big mystery

But thanks to tremendously clever (and difficult!) experiments, we know this is all wrong!

The first crack in the Standard Model in 30 years!

So how much does a neutrino weigh?

Neutrino oscillation means neutrinos have mass.

In spite of the great progress, we don't know the exact amount yet, but we have both lower and upper limits for each mass state:

$$0 < m_1 < 0.2 \text{ eV}$$

$$0.009 < m_2 < 0.2002 \text{ eV}$$

$$0.05 < m_3 < 0.2006 \text{ eV}$$

Most likely the true answer is at the low end of the range. In any case, even the

That's not a lot!

Neutrinos are by far the lightest particles that still have mass---so light that for 60 years people thought they didn't have any mass.

But even with their tiny masses, they are so numerous that the total mass of neutrinos in the universe is about equal to the total mass of stars!

Conclusions

Neutrinos push the limit of how small ethereal something can be and yet still exist!

Billions of these things zip through your body every second, never stopping for anything.

We now know that neutrinos have mass, and can change from one type into another. This is without question the most surprising and important discovery in particle physics