Neutrino Conversations

Boris Kayser
NeutrinoFest
April 18, 2005

The Universe and Us

It used to be thought that —

Our home planet—

— is the center of the universe.

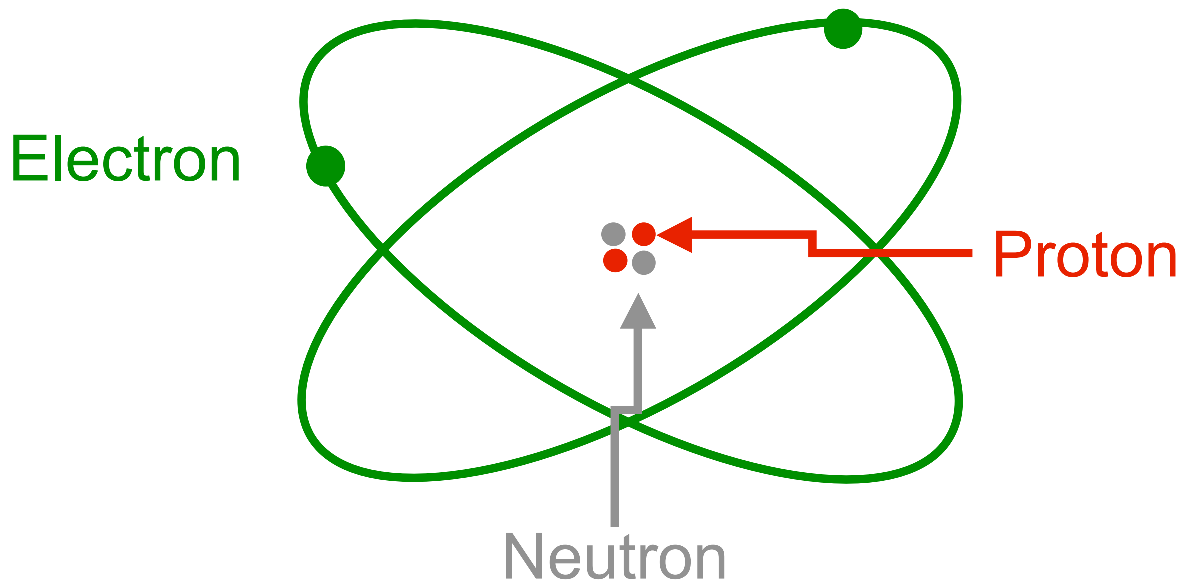
But we now know that the address of our home planet is —

#3 No-Place-Special Street.

We, and all everyday objects, are made of 3 kinds of tiny particles:

Electrons Protons Neutrons

These are bundled together to make Atoms:



It used to be thought that the Whole Universe is made of the same particles as we are:

Electrons Protons Neutrons

But we now know that in the universe as a whole, these particles are rareties.

For every electron, proton, or neutron, the universe contains over a billion neutrinos ν.

Together with photons (the particles of light), neutrinos are by far the most abundant particles in the universe.

To understand the universe, we must understand the neutrinos.

Are Neutrinos Important to Our Lives?

If there were no νs, the sun and stars would not shine.

- No energy from the sun to keep us warm.
- No atoms more complicated than hydrogen.
  No carbon. No oxygen. No water.
  No earth. No moon. No us.

No νs is very BAD news.

Getting Acquainted With Neutrinos

neu·trï´no: Little neutral object

Enrico Fermi

Q: How little are neutrinos?

A: About the same size as electrons. Roughly 1/10,000,000,000,000,000 inch across. This is 1/1,000 the size of an atomic nucleus.

Q: How strongly do neutrinos interact with other matter?

A: VERY FEEBLY.

Every day, 10,000,000,000,000,000,000,000 neutrinos from the sun pass through the Sudbury Neutrino Observatory (SNO), 1000 tons of heavy water in a sphere 40 feet across.

Only 10 of them interact. The rest zip right through.

BIG detectors are needed to stop and study neutrinos.

The Growing Excitement of Neutrino Physics

Pauli Predicts the Neutrino

Fermi's theory of weak interactions

Reines & Cowan discover (anti)neutrinos

Davis discovers the solar deficit

2 distinct flavors identified

Kamioka II confirms solar deficit

LEP shows 3 active flavors

SAGE and Gallex see the solar deficit

Kamioka II and IMB see atmospheric neutrino anomaly

Kamioka II and IMB see supernova neutrinos

Nobel prize for discovery of distinct flavors!

LSND sees possible indication of oscillation signal

Nobel Prize for $\overline{\nu}$ discovery!

Super K sees evidence of atmos-pheric neutrino oscillations

Super K confirms solar deficit and "images" sun

SNO shows solar oscillation to active flavor

Nobel Prize for neutrino astroparticle physics!

KamLAND confirms solar oscillations

K2K confirms atmospheric oscillations

1930 1955 1980 2005

Q: How much do neutrinos weigh?

A: *Almost* nothing. Years of experiments yielded no evidence that neutrinos have any mass at all.

Q: Can a particle have *no* mass at all?

A: A particle *can* be a bundle of pure energy, and have no mass at all.

The photon — the particle of light — is like that.

But in the last 7 years we have discovered that neutrinos are *not* like that. They have nonzero masses.

However, the mass of each neutrino is less than one-millionth the mass of an electron.

Q: How do we know neutrinos have masses?

A: We'll explain that shortly.

Q: Are all neutrinos the same, or are there different kinds of neutrinos?

A: Neutrinos come in three different flavors:

The electron neutrino ν_e

The muon neutrino ν_μ

The tau neutrino ν_τ

Q: How do ν_e, ν_μ, and ν_τ differ from one another?

A: There are 3 kinds, or flavors, of electron-like particles:

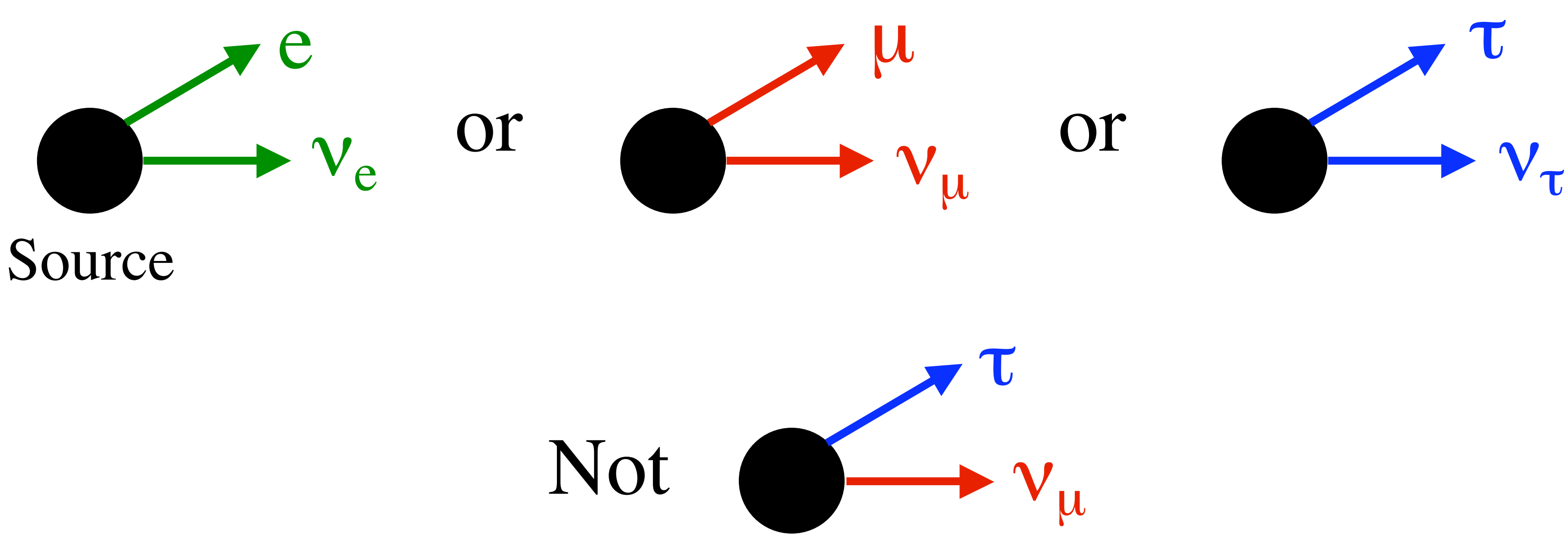
Particle	Symbol	Mass	Associated Neutrino
Electron	e	1	ν_e
Muon	μ	200	ν_μ
Tau	τ	3500	ν_τ

e, μ, and τ are electrically charged, and are known as the charged leptons.

Neutrinos are created in a variety of physical processes.

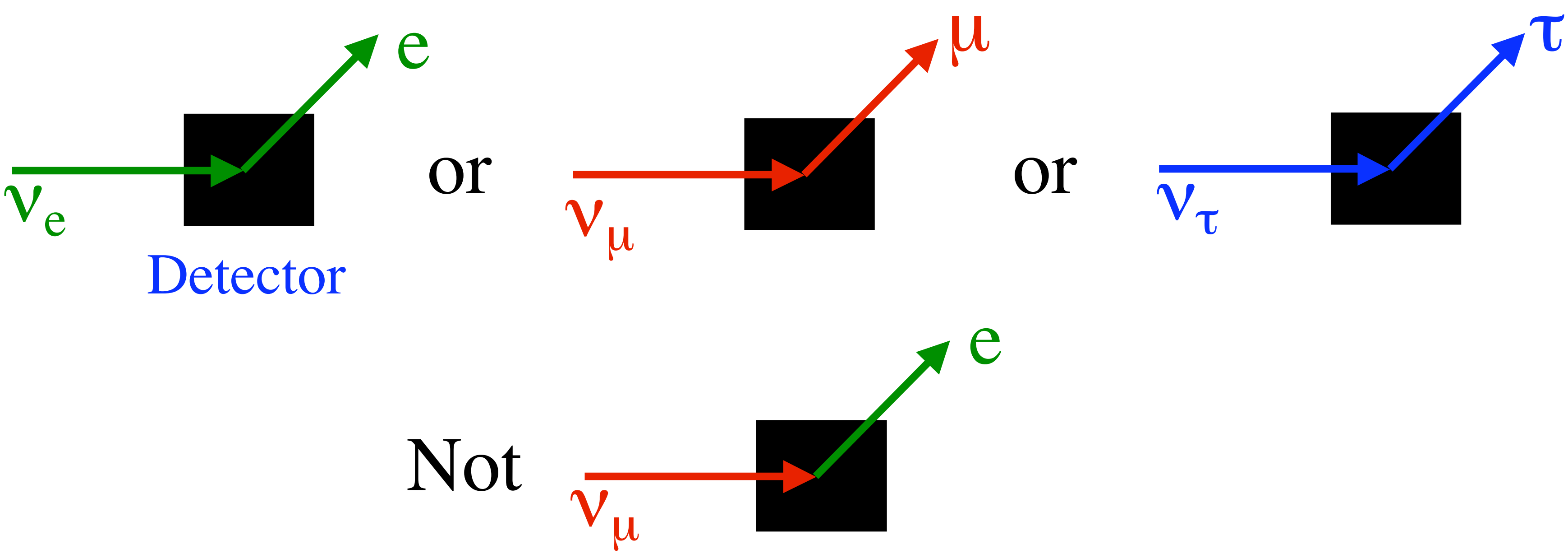
In nature or the laboratory, a neutrino is created together with a charged lepton.

The neutrino and charged lepton always have the same flavor.

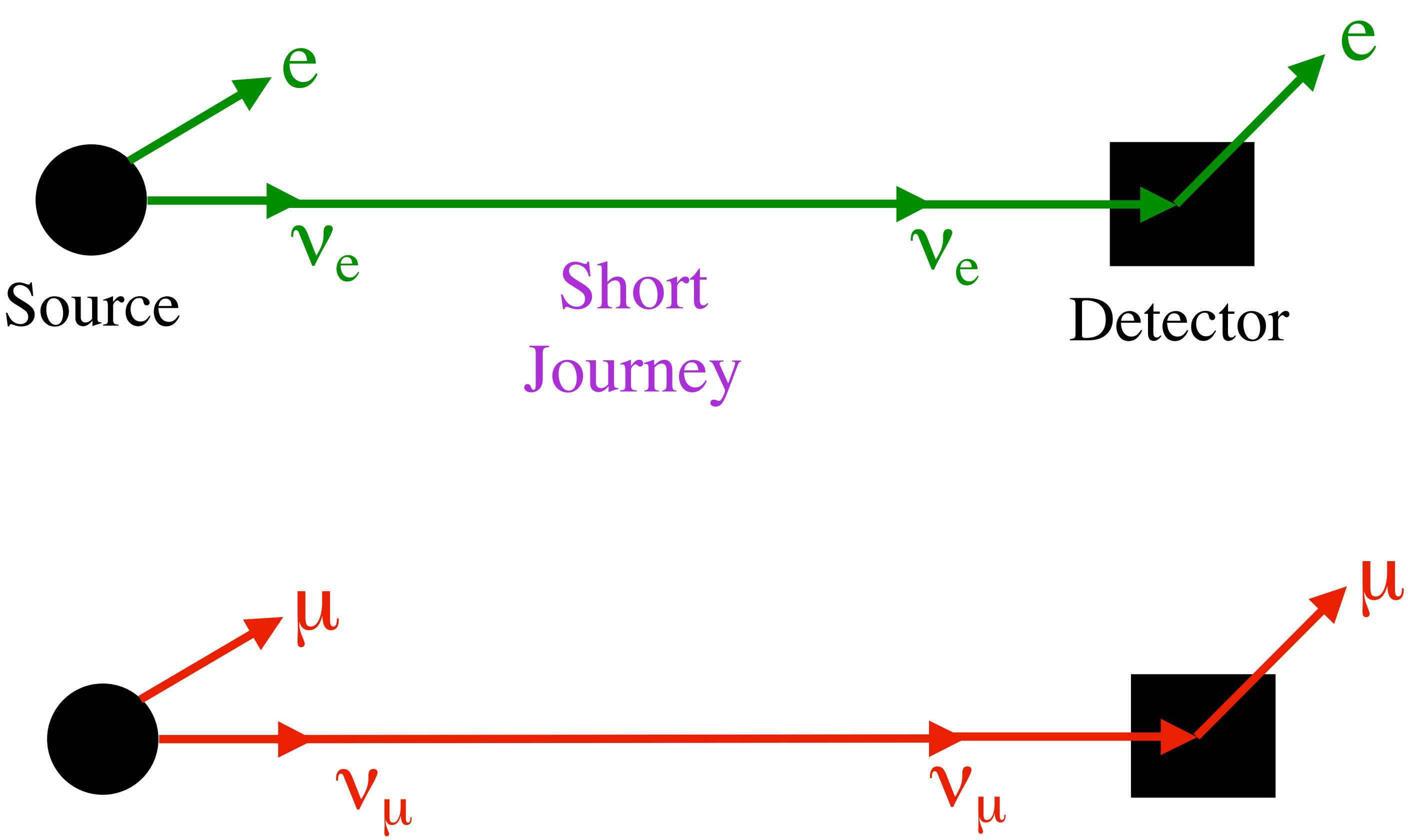


When a neutrino collides with an atom in a neutrino detector, it creates a charged lepton.

The charged lepton always has the same flavor as the neutrino.



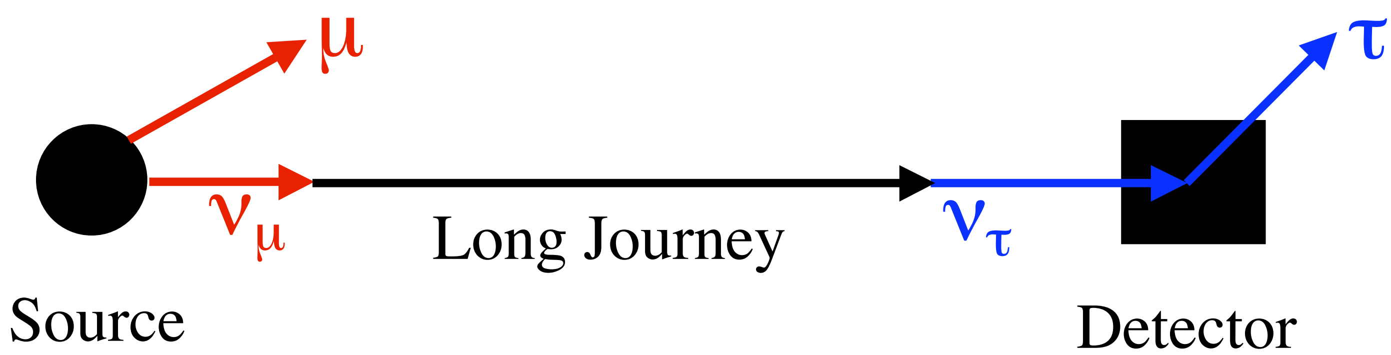
Creation and Detection of a Neutrino



The flavors match.

The Discovery of Flavor Change

The last 7 years have yielded compelling evidence that, given enough time, a neutrino can change from one flavor into another.



This is surprising behavior.

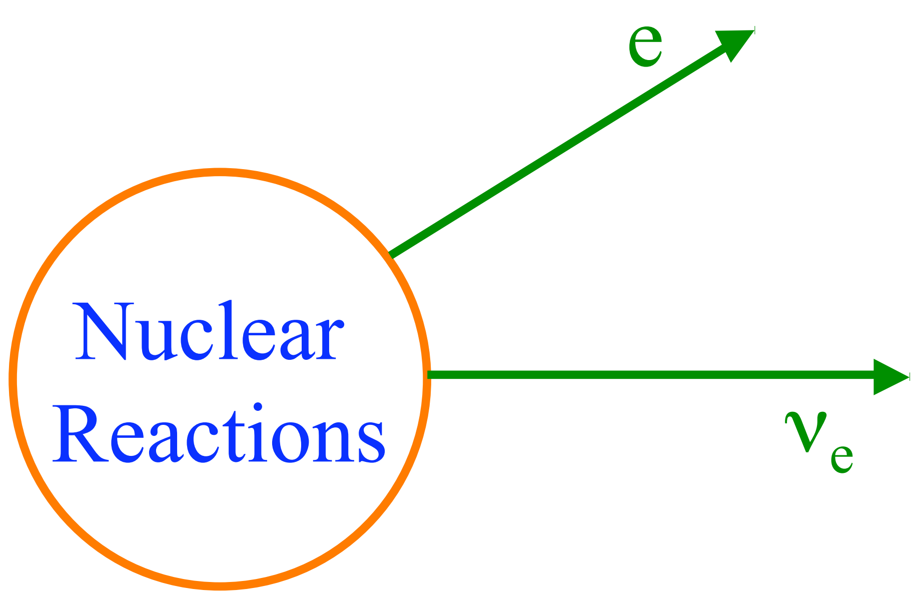
Once an electron, always an electron.

But once a ν_e, not always a ν_e.

How We Know
Neutrinos Change Flavor

— Solar Neutrinos —

In the core of the sun —



Solar neutrinos are all born as ν_e , not ν_μ or ν_τ .

SNO detects solar neutrinos in several different ways.

One way counts ——

$$\text{Number }(\nu_e)\ .$$

Another counts ——

$$\text{Number }(\nu_e) + \text{Number }(\nu_\mu) + \text{Number }(\nu_\tau)\ .$$

SNO finds ——

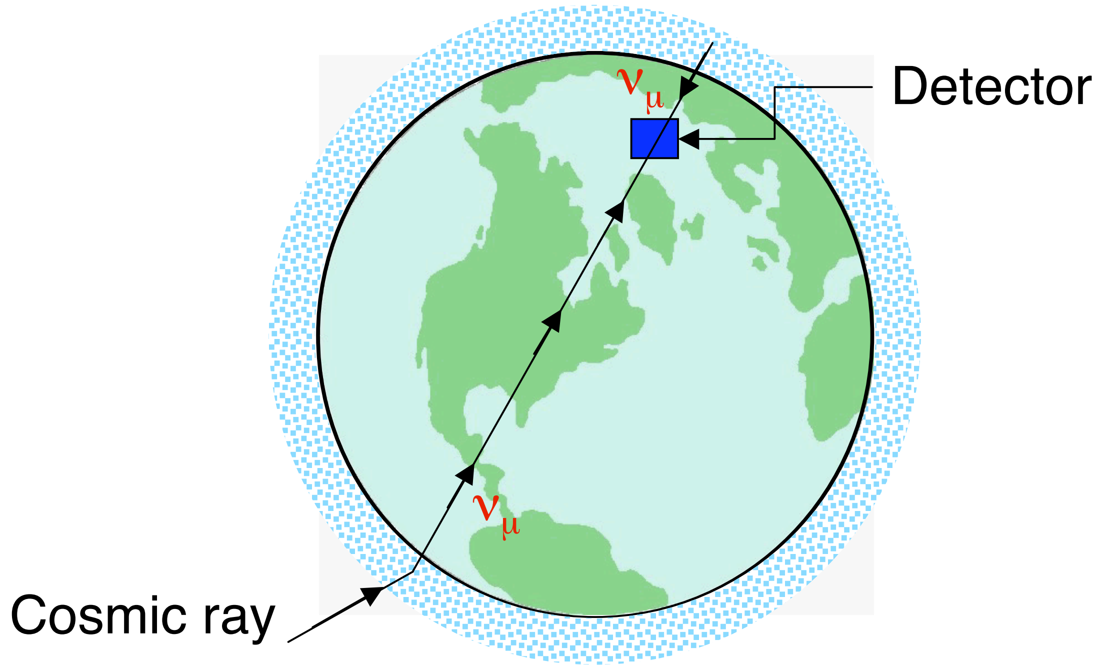
$$\frac{\text{Number }(\nu_e)}{\text{Number }(\nu_e) + \text{Number }(\nu_\mu) + \text{Number }(\nu_\tau)} = 1/3\ .$$

All the solar neutrinos are born as ν_e .

But 2/3 of them morph into ν_μ or ν_τ before they reach earth.

Neutrinos change flavor.

— Atmospheric Neutrinos —



Cosmic rays come from all directions at the same rate.

So atmospheric neutrinos are produced all around the earth at the same rate.

But Number (ν_μ Up) / Number (ν_μ Down) = 1/2.

Half the ν_μ that travel to the detector from the far side of the earth disappear en route.

The detailed data show that the disappearance is due to —

$$\nu_\mu \rightarrow \nu_\tau$$

Evidence For Flavor Change

Neutrinos	Evidence of Flavor Change
Solar	Compelling
Atmospheric	Compelling
Reactor	Compelling
Accelerator	Strong

Neutrino Flavor Change Implies Neutrino Mass

The neutrinos we study pass through matter between their source and our detector.

Can't their *interactions* with the matter change their flavor?

In practice, **no**.

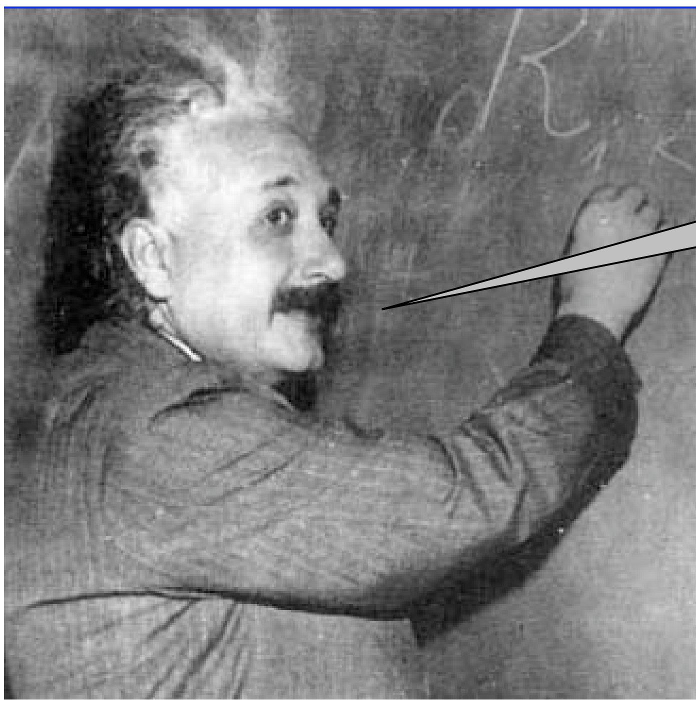
We have confirmed that the interactions between neutrinos and matter are very well described by the Standard Model of elementary particle physics.

Standard Model neutrino interactions do not change neutrino flavor.

Therefore, neutrinos must be changing their flavor *on their own*.

We observe that they do this *over time*.

A ν has a sense of time.



Only particles with mass have a sense of time.

Therefore, a neutrino must have a mass.

The Physics of Neutrino Flavor Change

If particles like the electron never morph into something else, how can a ν_μ morph into a ν_τ?

Answer: A ν_μ is not a particle to begin with.

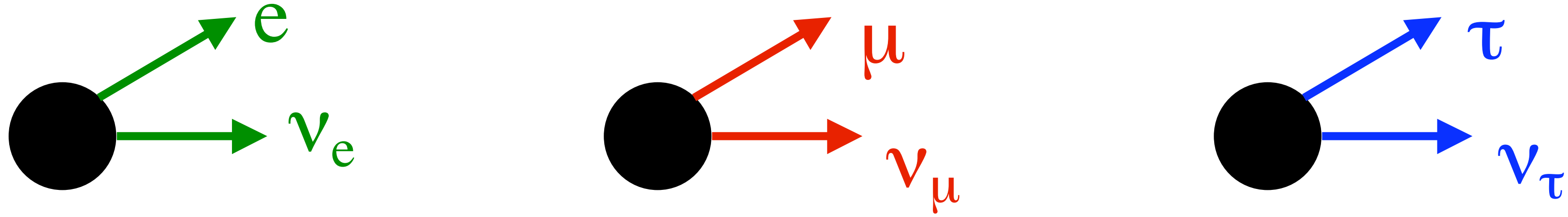
There *are* neutrino particles:

<u>Neutrino Particle</u>	<u>Mass</u>
ν_1	m_1
ν_2	m_2
ν_3	m_3

(And maybe more.)

ν_e, ν_μ, and ν_τ are different MIXTURES of ν_1, ν_2, and ν_3.

In each of—



the emitted neutrino is actually a ν_1, ν_2, or ν_3.

		Probability
	maybe ν_1	17 %
ν_μ is:	maybe ν_2	34 %
	maybe ν_3	49 %

The world of the subatomic particles is governed by QUANTUM MECHANICS.

Quantum mechanics involves *uncertainty* at its core.

An object can be maybe here and maybe there.
It can be maybe this and maybe that.
It can be maybe a ν_1, maybe a ν_2, and maybe a ν_3.

Voyage of a Neutrino

[Original ν_1, ν_2, ν_3 mixture]

[ν_1, ν_2, ν_3 travel differently because they have different masses.]

[New, different ν_1, ν_2, ν_3 mixture]

The ν_μ mixture of ν_1, ν_2, ν_3 has turned into the ν_τ mixture.

Neutrino flavor change is a quintessentially quantum mechanical phenomenon.

It occurs over VERY LARGE distances.

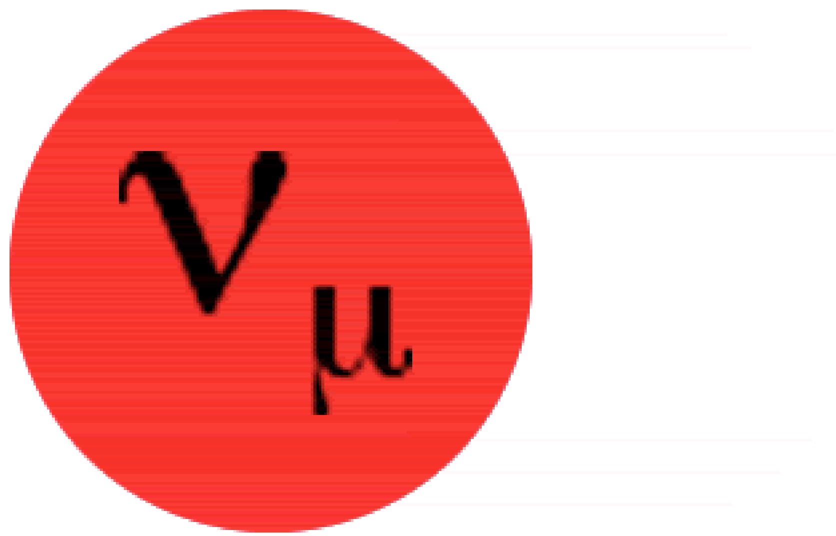
The quantum mechanics of flavor change results in an **oscillation** back and forth between the initial flavor and the new one.

Thus, flavor change is called —

NEUTRINO OSCILLATION

An example, starting with a ν_μ:

Neutrino Oscillation




What We
Have Learned

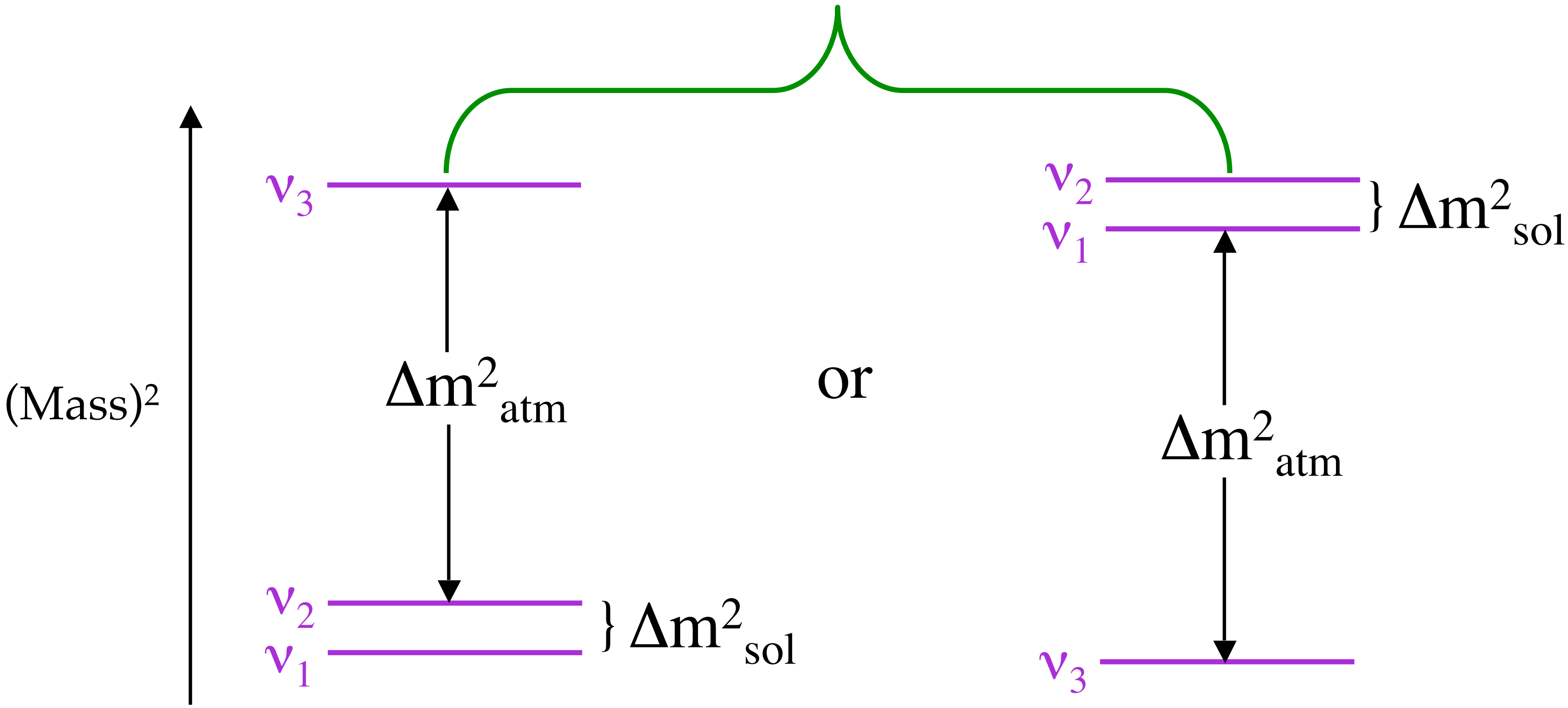
The Neutrino Mass Spectrum

There are at least 3 neutrino particles: ν_1, ν_2, ν_3.

Neutrino oscillation results have revealed the *differences* between the squares of their masses.

The spectrum of squared masses looks like —

Not above (Electron mass / 1,000,000)^2. {From Cosmology}



$$\Delta m^2_{atm} = (\text{Electron mass} \;/\; 10{,}000{,}000)^2$$

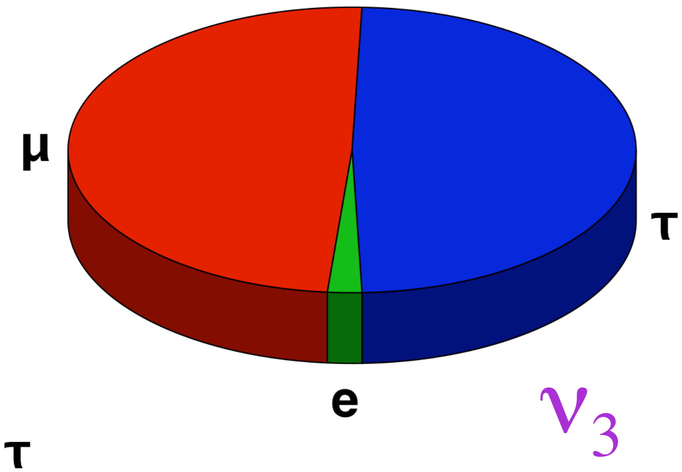
$$\Delta m^2_{sol} = \Delta m^2_{atm} / 30$$

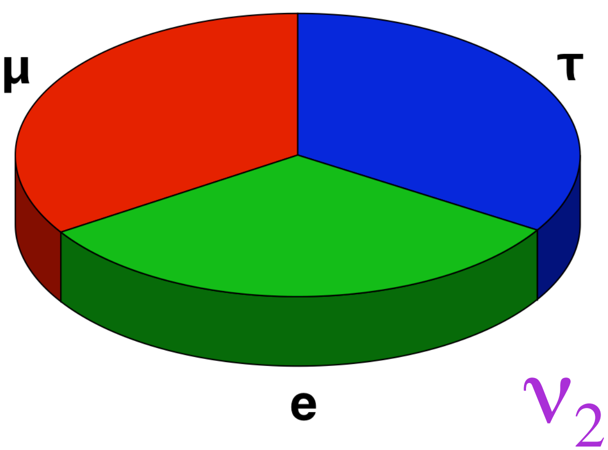
When one of the neutrino particles (ν_1, ν_2, or ν_3) interacts in a detector and makes a charged lepton, this charged lepton could be an e, a μ, or a τ.

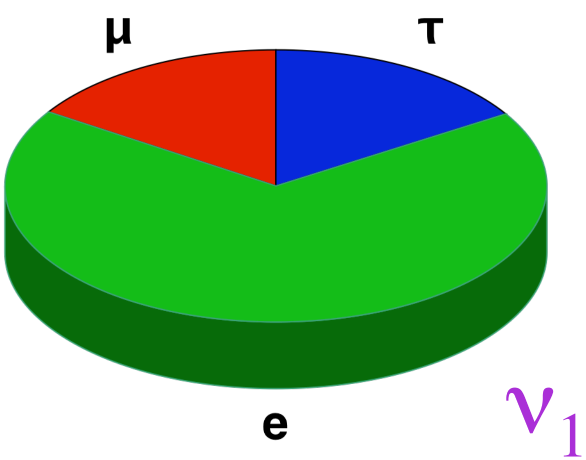
It's that quantum-mechanical uncertainty again!

But, for each neutrino particle, we know the probability that the charged lepton it produces will be of any particular flavor.

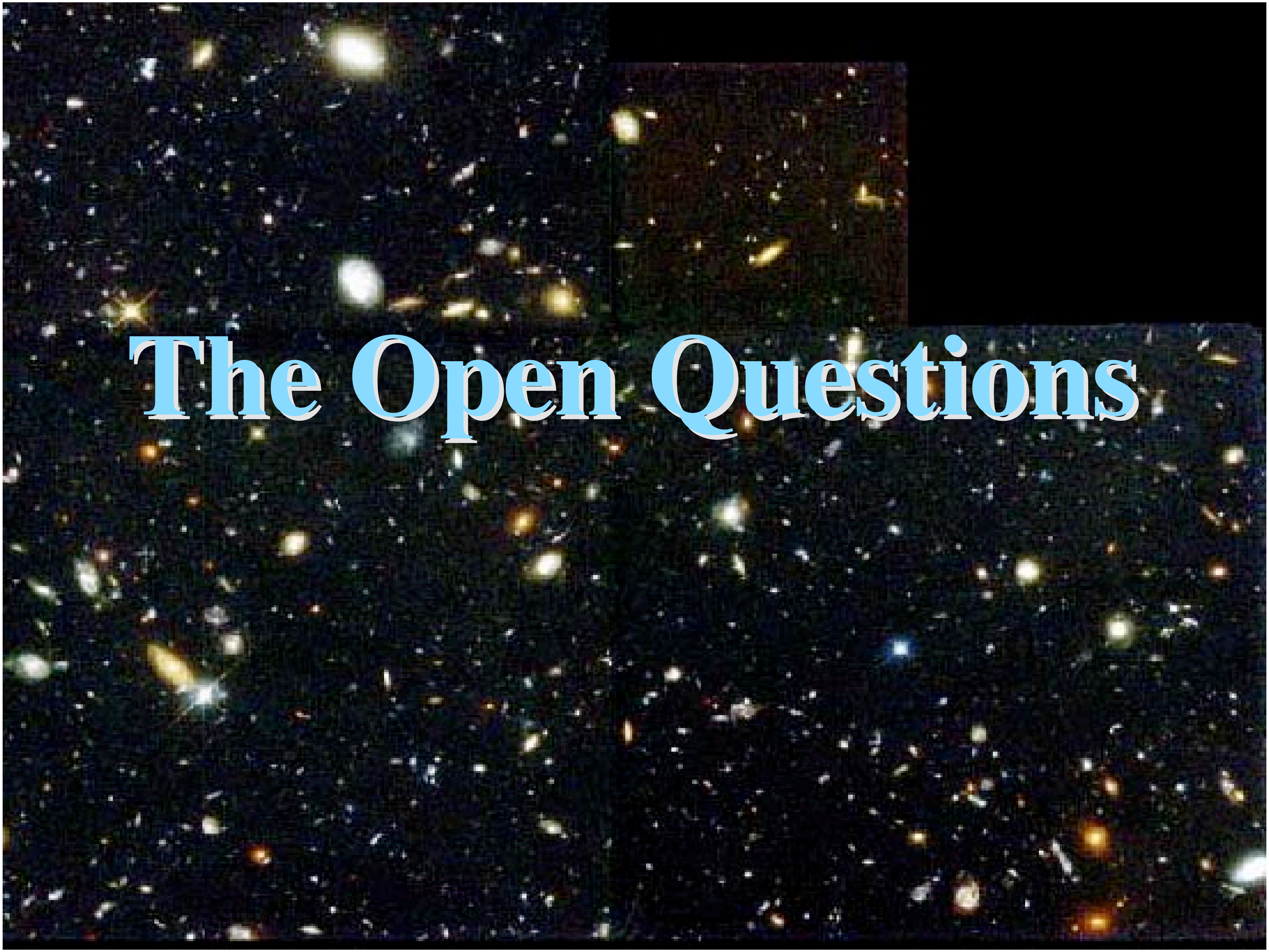
The Probabilities of Making e, μ, and τ







The Open Questions



✠How many different neutrino particles are there?

CERN: If there are more than 3, then at least one mixture of them does not participate in any of the known forces of nature except gravity.

All known particles participate in some force besides gravity. ν_e, ν_μ, and ν_τ participate in the weak nuclear force. An object that doesn't experience any of the known forces except gravity would be ***very*** different.

LSND (Liquid Scintillator Neutrino Detector): There are more than 3 neutrino particles.

MiniBooNE (in progress): Is the LSND experiment right or wrong?

✠How much do the neutrino particles ν_1, ν_2, and ν_3 weigh?

Can we use cosmology?

Can observations of the structure of the universe tell us, not just an upper limit on the mass of any neutrino particle, but the actual masses of these particles?

Can we use laboratory experiments?

Does the neutrino mass spectrum look like or like ?

Grand Unified Theories: The neutrinos and the charged leptons are cousins of the quarks.

The quark spectra look like .

So, if these theories are right, the neutrino spectrum should look like too.

To find out if it does, pass a beam of neutrinos through more than 500 miles of earth matter.

The behavior of the neutrinos in matter will depend on which kind of a spectrum we have.

✠Are neutrinos identical to their antiparticles?

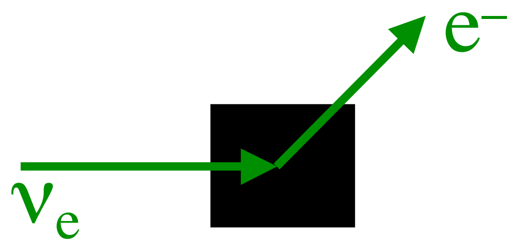
For every particle, there is a corresponding antiparticle.

Particle	Antiparticle	Difference
Electron	Positron	Electric Charge
Proton	Antiproton	Electric Charge
Neutron	Antineutron	Baryonic Charge
Neutrino ν	Antineutrino $\bar{\nu}$	??
Matter	*Antimatter*	

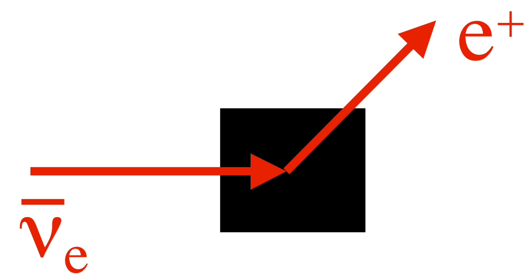
Is there a "leptonic charge" L such that —

$$L(\nu) = L(e^-) = -L(\bar{\nu}) = -L(e^+) = 1\ ?$$

That would explain why —



but



But if there is no such leptonic charge, then there is nothing to distinguish a ν from a $\bar{\nu}$.

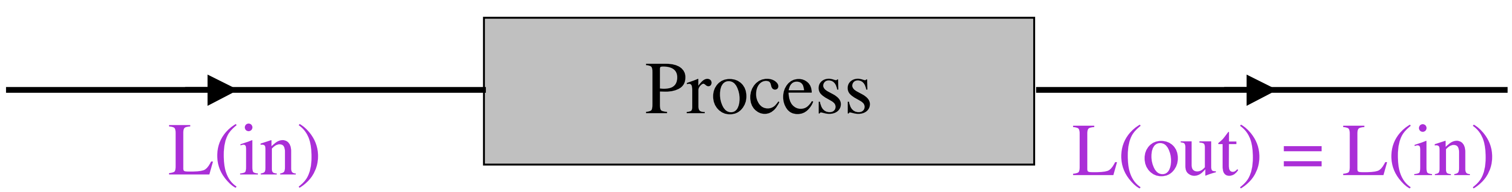
Then, unlike all the other constituents of matter — the charged leptons, and the quarks that make up protons and neutrons — the neutrinos are identical to their antiparticles:

$$\nu = \bar{\nu}.$$

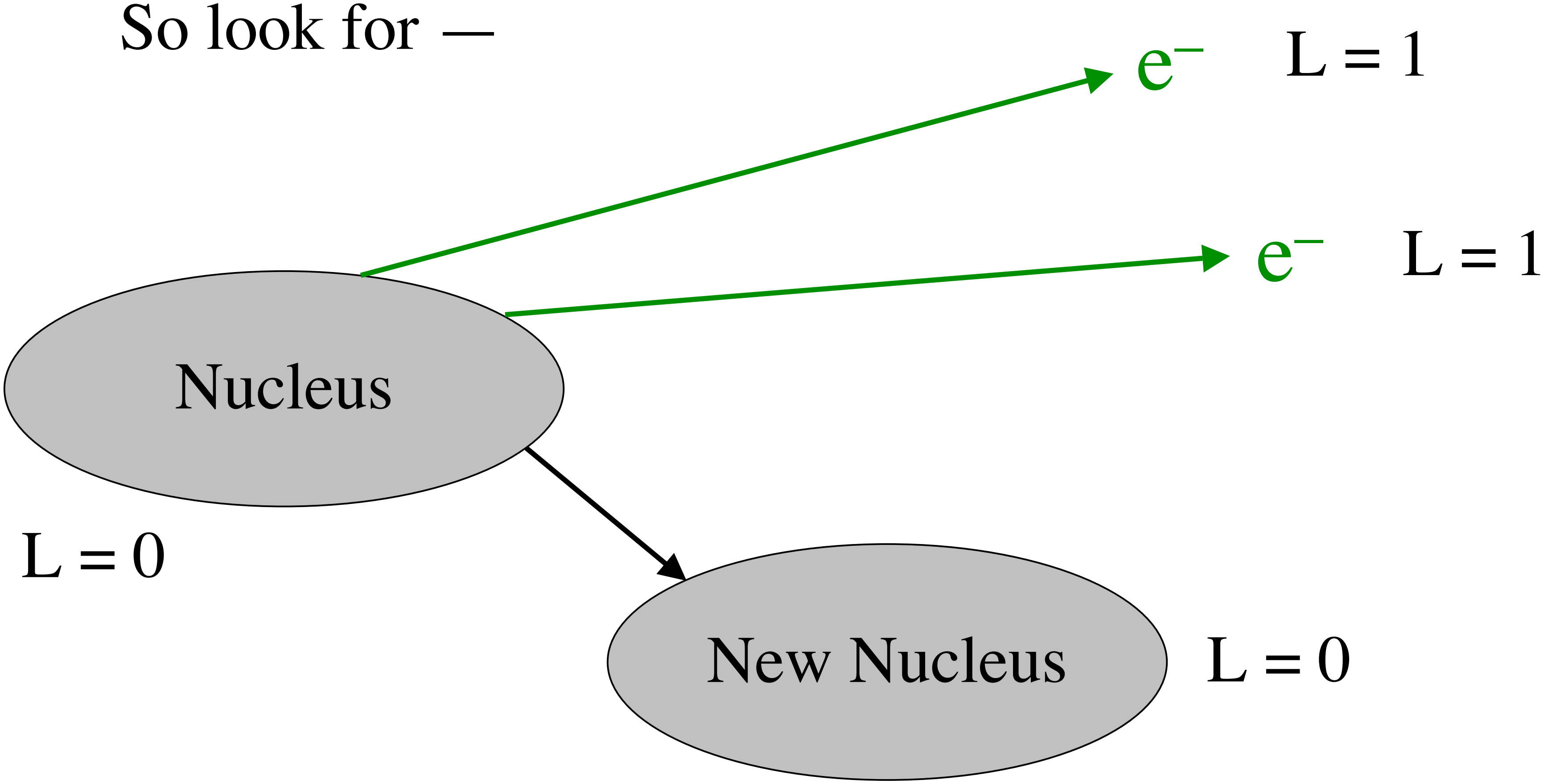
This would make neutrinos very distintive.

How can we confirm that $\nu = \bar{\nu}$?

"Charges," such as the hypothetical leptonic charge L, are conserved quantities:



So look for —



Neutrinoless Double Beta Decay ($0\nu\beta\beta$)

Does not conserve leptonic charge L, so $\Rightarrow$ $\nu = \bar{\nu}$.

- What is the origin of neutrino mass?

Observation of neutrinoless double beta decay would

The origin of neutrino mass is different from the origin of the masses of electrons, quarks, protons, neutrons, humans, the earth, and galaxies.

✠Are neutrinos the reason we exist?

The universe contains MATTER, but essentially no antimatter. Good thing for us:

This preponderance of MATTER over antimatter could not have developed unless the two behave differently ("CP violation").

A difference not involving neutrinos has been seen, but it is way too small to explain the universe.

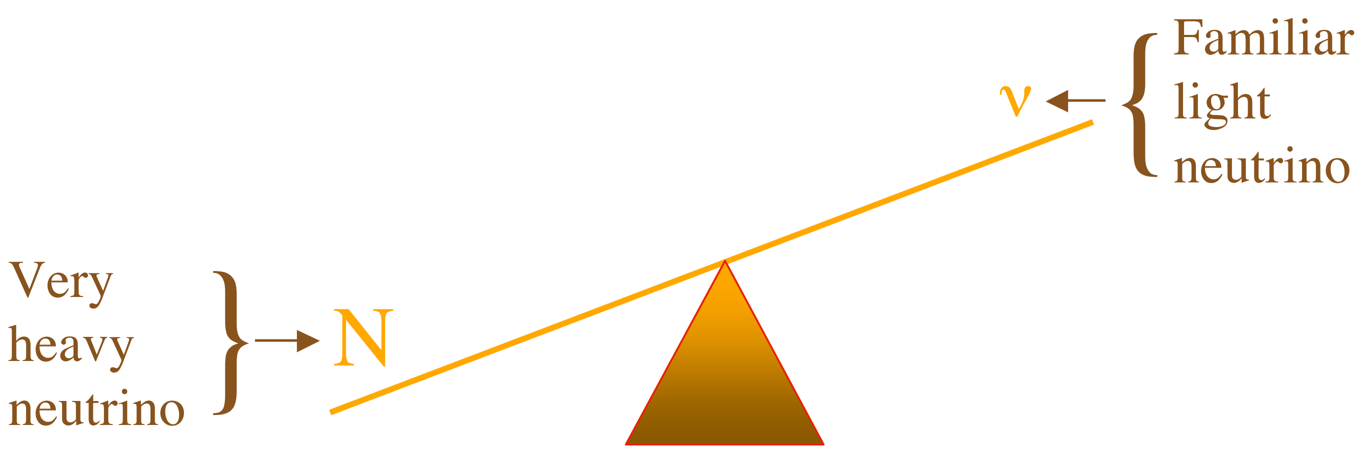
Does **MATTER** interact with **neutrinos**
differently than antimatter does?

Could this difference explain the universe?

There is a natural way in which it could.

The most popular theory of why neutrinos are so light is the —

See-Saw Mechanism



The heavy neutrinos N would have been made in the hot Big Bang.

Then they would have disintegrated into lighter particles:

$$N \rightarrow e^- + \ldots \quad \text{and} \quad N \rightarrow e^+ + \ldots$$

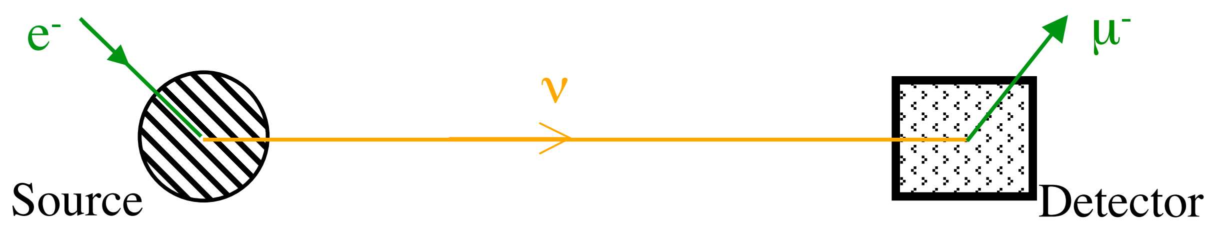
MATTER (for e^-) antimatter (for e^+)

If MATTER and antimatter interact differently with neutrinos, both heavy and light, then one of these disintegrations can be more likely than the other.

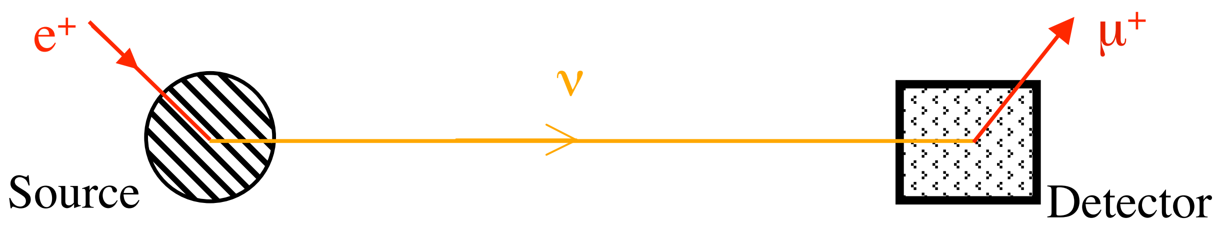
Then we would get a universe with unequal amounts of MATTER and antimatter.

Can we confirm that **MATTER** and antimatter actually do interact differently with neutrinos?

A neutrino flavor change involving **MATTER**:

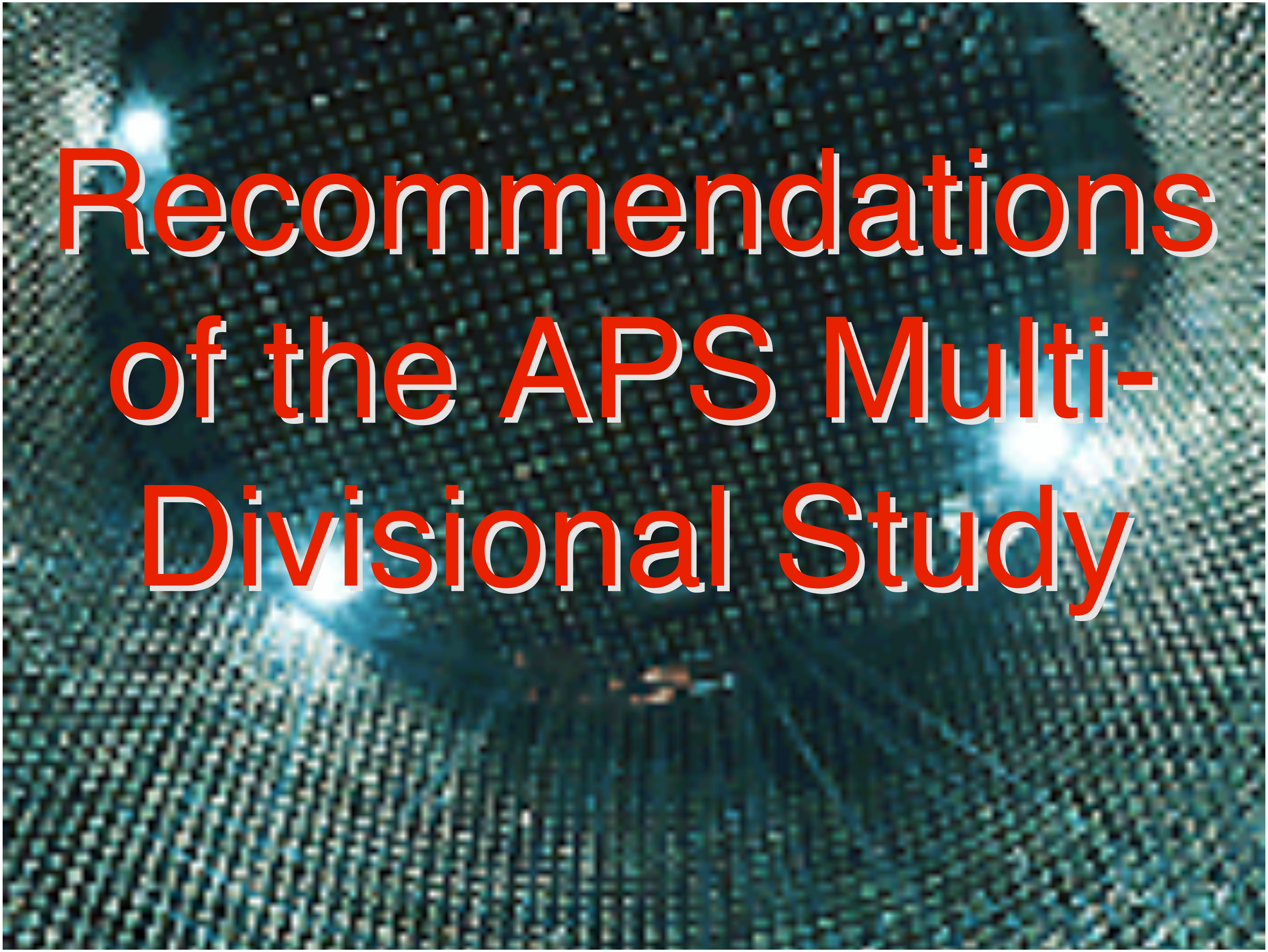


A neutrino flavor change involving antimatter:



Do these processes have different rates?

If N decays led to the present preponderance of MATTER over antimatter, then **we are all descendants of heavy neutrinos**.



Recommendations of the APS Multi-Divisional Study

High priority: Searches for neutrinoless double beta decay, to see if $\nu = \bar{\nu}$.

High priority: A program to —

- find out how big the small e-flavored wedge in ν_3 is
- determine whether the mass spectrum looks like  or like 
- search for CP violation in neutrino flavor change

CP violation: Neutrinos interact differently with matter than with antimatter.

There can be no CP violation unless the pie chart for every neutrino particle involves all three colors.

Important: Develop an experiment that can make detailed studies of the neutrinos from the primary fusion process that *we think* powers the sun.

These neutrinos have lower energy than those studied in detail so far.

Now that we understand *neutrinos* much better, we can use them to test whether we truly understand how the *sun* works.

Conclusion

There has been an explosion in our knowledge of the neutrinos in the last seven years.

The recent discoveries have raised very interesting questions that we must now try to answer.

Exciting, challenging, experiments to answer them will be launched in the coming years.