Neutrinos get under your skin!

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Fermilab

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Special thanks to —

Susan Kayser

Gary Steigman

Milly Strelzoff

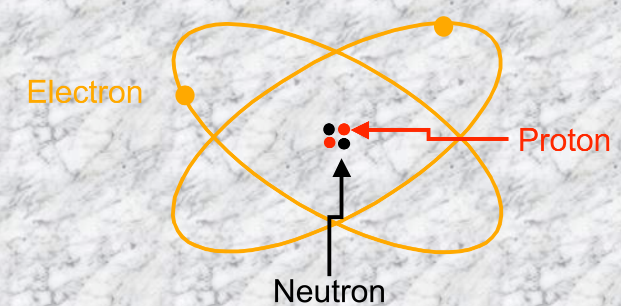
Alex Westmoreland

2

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

Electrons Protons Neutrons

These are bundled together to make Atoms:



These atoms make up—

3

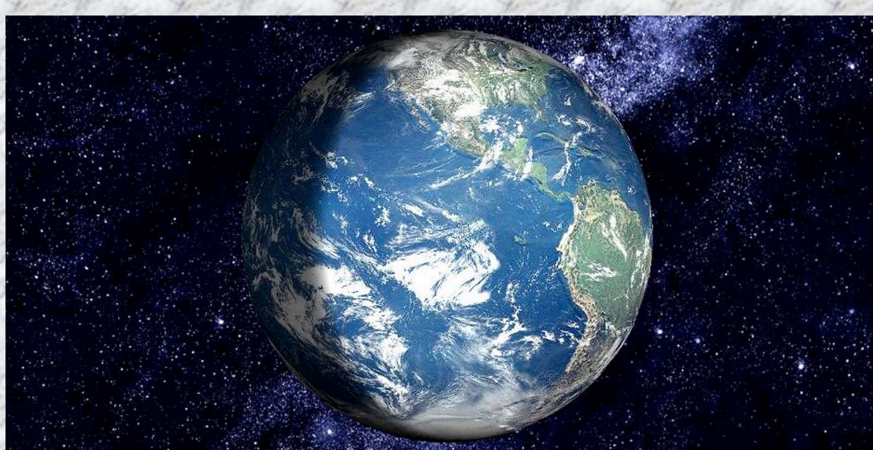
Living Creatures—

4

Buildings—

5

Our home planet—



6

Is The Whole Universe made of—
Electrons Protons Neutrons ?

NO!

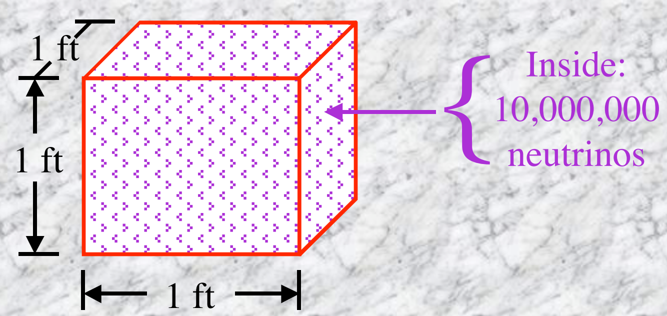
Electrons Protons Neutrons
are rareties!

For every one of them, the universe contains a billion neutrinos □!

To understand the universe, we must understand the neutrinos.

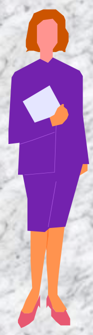
7

Within each cubic foot of space:
10 million neutrinos from the Big Bang.



8

Within each person:
Roughly 30 million Big Bang neutrinos



Inside:
30,000,000
neutrinos

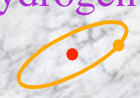
9

Passing through each person on earth every second:
One hundred trillion neutrinos from the sun.

The sun shines because of nuclear fusion in its core.

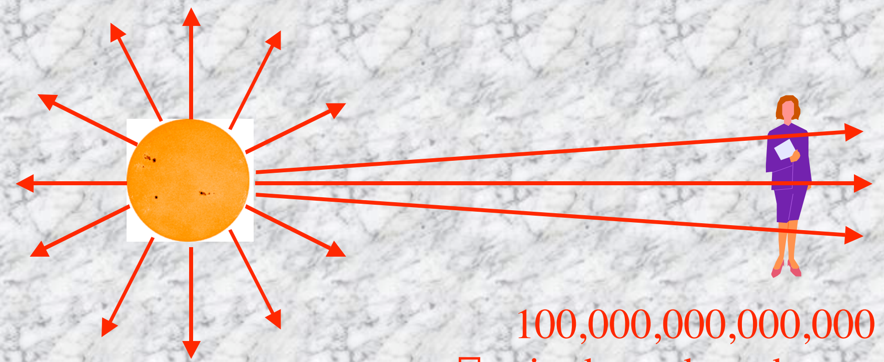
This fusion produces—

- Energy, including visible light
- Neutrinos
- The atoms more complicated than hydrogen



We are made of stardust!

10



100,000,000,000,000
νs zip through each second.

Neutrinos–lots of them–get under your skin!

11

Should we worry about all those neutrinos zipping through us?

No. Neutrinos interact with other matter VERY FEEBLY.

To a neutrino, we look like almost completely EMPTY SPACE.

12

Our view

□ View

Almost all neutrinos zipping through us do nothing at all.

Typically, a solar neutrino would have to zip through 10,000,000,000,000,000,000 people before doing anything.

The probability that a particular solar neutrino will interact as it zips through one of us is 1 / 10,000,000,000,000,000,000 .

13

This same feebleness of interaction makes neutrinos hard to detect and study.

They are ghostlike.

Abundant but Elusive.

14

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.

15

We depend on small amounts of heavy chemical elements like zinc and selenium.

These heavy elements are produced only in Supernova Explosions.

If there were no νs, there would be no supernova explosions. BAD news.

16

What Are Neutrinos?

neū·trĭ´nō: Little neutral object

Enrico Fermi

Q: How little are neutrinos?

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

Q: How much do neutrinos weigh?

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

17

Q: Could neutrinos be *completely* massless?
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 we have recently discovered that neutrinos are *not* like that.

Neutrinos weigh much less than electrons, protons, or neutrons, but they *do* have tiny nonzero masses.

18

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 Vanilla

The muon neutrino ν_μ Chocolate

The tau neutrino ν_τ Strawberry

The ν_e and ν_μ were discovered many years ago.

The ν_τ was discovered only recently.

19

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

A: All the particles of a given kind are identical.

All electrons are absolutely identical.

Electrons do not have birthmarks.

But 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

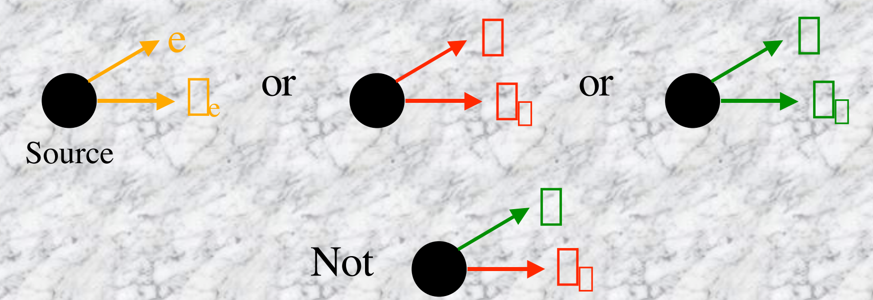
e, μ, and τ are electrically charged, and are known as the charged leptons.

20

Neutrinos are created in a variety of physical processes.

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

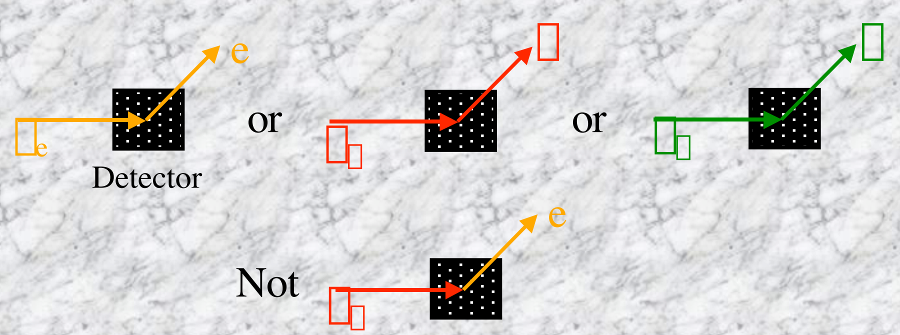
The neutrino and charged lepton always have the same flavor.



21

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.



22

Creation and Detection of a Neutrino

Flavors don't mix.

23

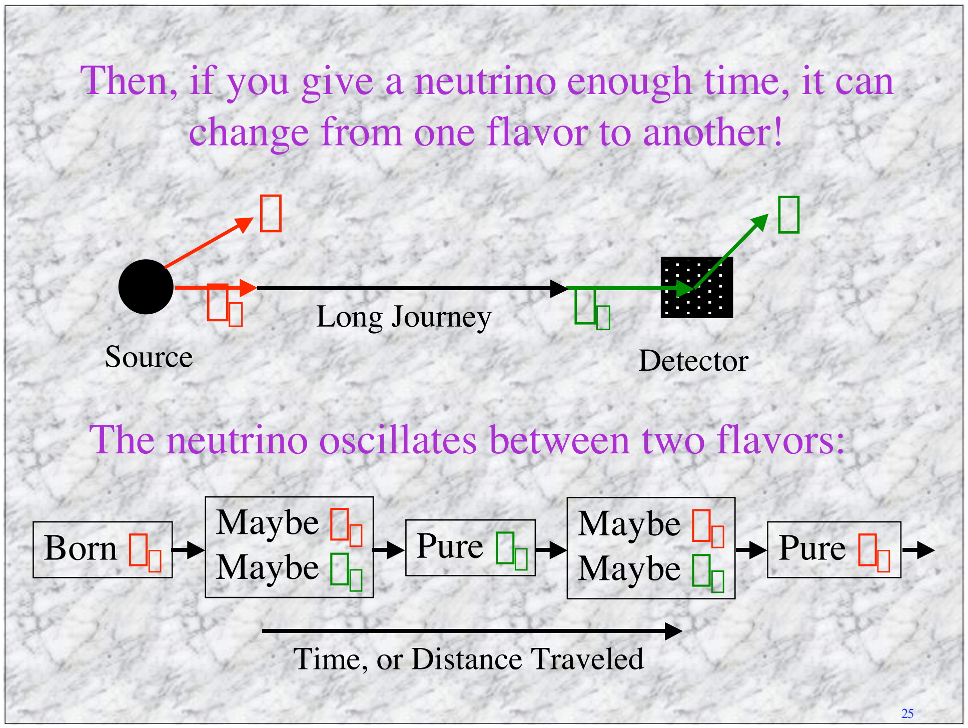
Neutrino Flavor Change and Neutrino Mass

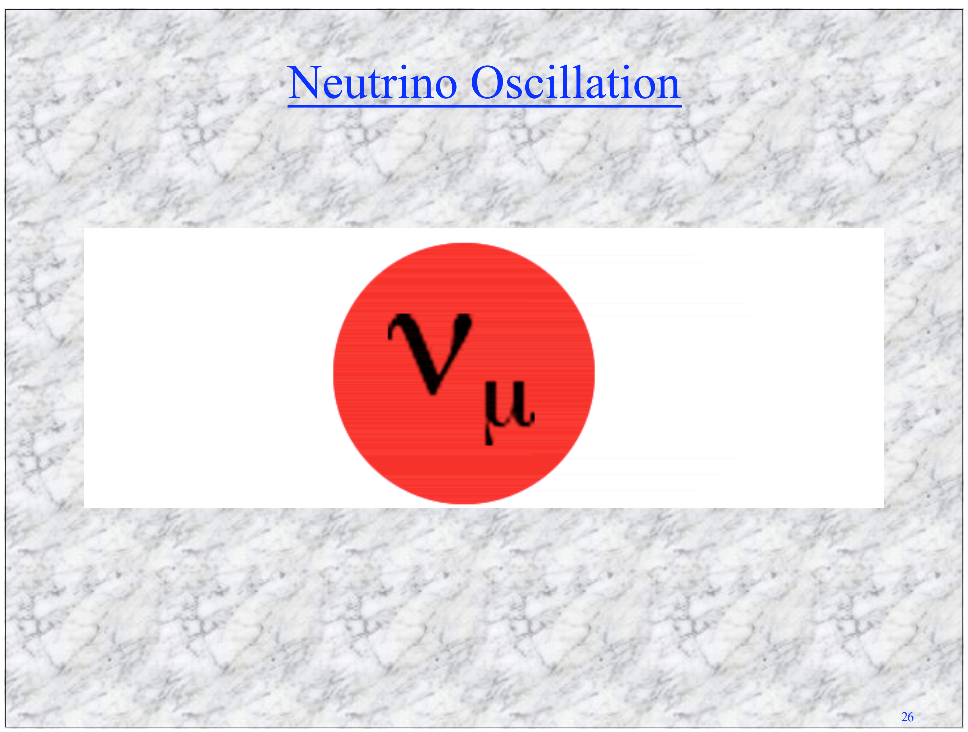
Neutrino masses, if nonzero, are still tiny compared to the masses of other particles.

How can we detect such tiny masses?

Suppose neutrinos do have nonzero masses…

24


Then, if you give a neutrino enough time, it can change from one flavor to another!
Long Journey
Source
Detector
The neutrino oscillates between two flavors:
Born
Maybe
Maybe
Pure
Maybe
Maybe
Pure
Time, or Distance Traveled
25


Neutrino Oscillation
ν_μ
26

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

Quantum mechanics involves *uncertainty* at its core.
(Copenhagen)

An object can be maybe here and maybe there.
It can be maybe this and maybe that.
It can be maybe a $\square_{\square}$ and maybe a $\square_{\square}$.

27

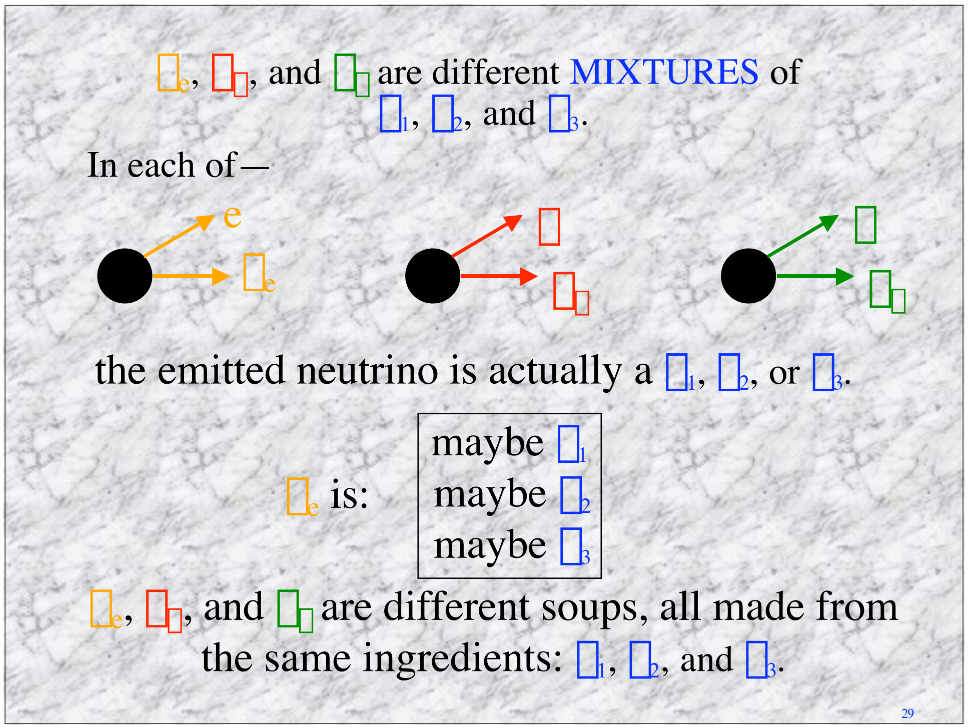
A proton is a proton is a proton.
It does not morph into something else.

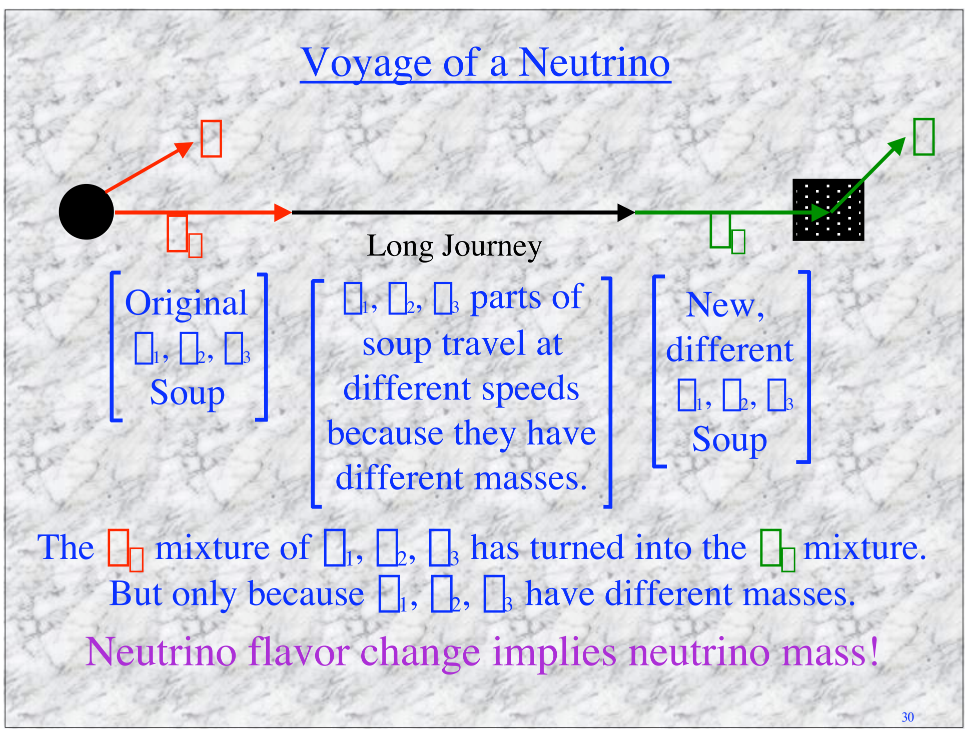
How does a $\square_{\square}$ morph into a $\square_{\square}$?
Answer: A $\square_{\square}$ is not a particle to begin with.

There *are* neutrino particles:

Neutrino Particle	Mass
$\square_1$	Lightest
$\square_2$	Heavier
$\square_3$	Heaviest

28


ν_e, ν_μ, and ν_τ are different MIXTURES of ν_1, ν_2, and ν_3.
In each of—
e
ν_e
μ
ν_μ
τ
ν_τ
the emitted neutrino is actually a ν_1, ν_2, or ν_3.
ν_e is:
maybe ν_1
maybe ν_2
maybe ν_3
ν_e, ν_μ, and ν_τ are different soups, all made from the same ingredients: ν_1, ν_2, and ν_3.
29

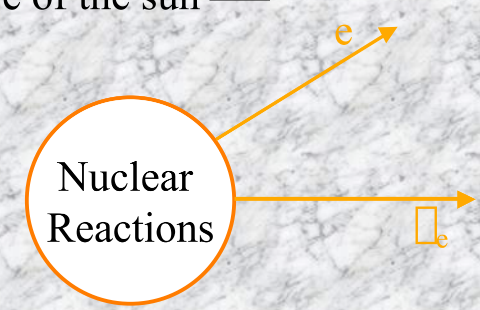

Voyage of a Neutrino
μ
ν_μ
Long Journey
ν_τ
τ
Original ν_1, ν_2, ν_3 Soup
ν_1, ν_2, ν_3 parts of soup travel at different speeds because they have different masses.
New, different ν_1, ν_2, ν_3 Soup
The ν_μ mixture of ν_1, ν_2, ν_3 has turned into the ν_τ mixture.
But only because ν_1, ν_2, ν_3 have different masses.
Neutrino flavor change implies neutrino mass!
30

Neutrino flavor change
("neutrino flavor oscillation")
can make even *tiny* neutrino masses visible
if we let the neutrinos travel far enough.

31

The Evidence for Neutrino Flavor Change

In the core of the sun —



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

32

To detect the solar neutrinos arriving at the earth, we go deep underground.

Protons and heavier particles are raining down on earth’s atmosphere from outer space.

These incoming particles are called cosmic rays.

In a neutrino detector, cosmic ray “events” can imitate neutrino events.

To eliminate the cosmic ray events, we put the detector deep underground, where the cosmic rays will not reach it.

33

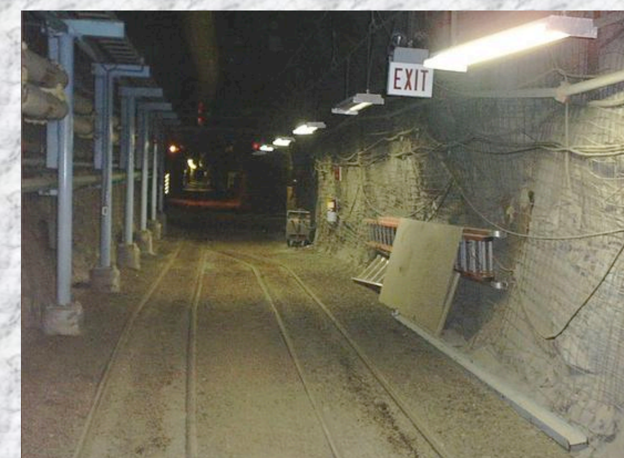


Photo courtesy of SNO

In the Creighton nickel mine, 6800 feet below Sudbury, Canada, is the Sudbury Neutrino Observatory (SNO).

34

The SNO detector.

The central sphere is 40 feet across, and is filled with heavy water.

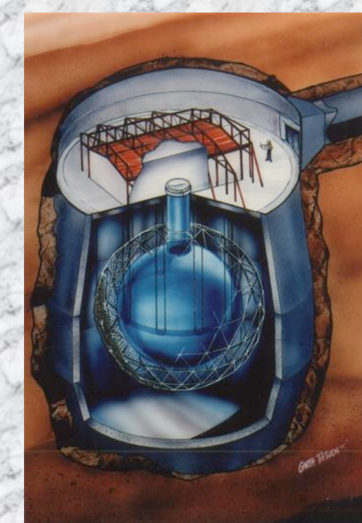


Photo courtesy of SNO

35

SNO detects solar neutrinos in several different ways.

One way counts —

Number (ν_e) .

Another counts —

Number (ν_e) + Number (ν_μ) + Number (ν_τ) .

SNO finds —

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

36

All the solar neutrinos are born as ν_e .

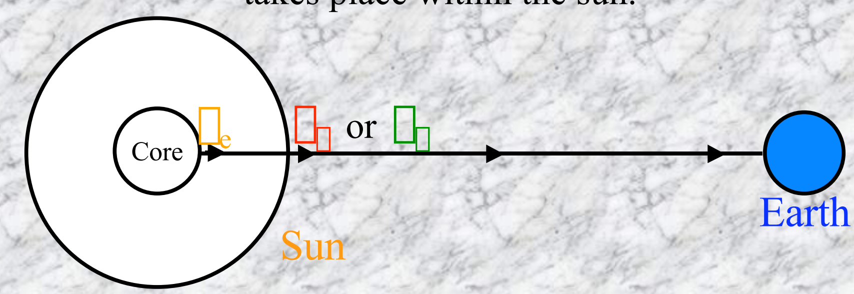
But 2/3 of them morph into ν_μ or ν_τ
before they reach earth.

Neutrinos do change flavor.

Therefore, neutrinos do have non-zero masses.

37

Detailed studies tell us the flavor change
takes place within the sun.



Neutrinos interact with solar material
like light with clear glass.

This doesn’t stop the light or the neutrinos.

But it increases the number of neutrinos
that change flavor.

38

The Neutrino Disappearing Act

When vanilla neutrinos change flavor, an experiment that can detect only vanilla neutrinos will think they have disappeared.

The original solar neutrino experiment, performed by **Ray Davis** and coworkers, could detect only ν_e .

This experiment saw only 1/3 the expected number of neutrinos.

39

Two-thirds had changed into invisible (to **Ray Davis**) ν_μ or ν_τ.

In 2002: Nobel Prize to **Ray Davis**

Nuclear power reactors produce $\bar{\nu}_e$.

Detectors of reactor $\bar{\nu}_e$ cannot see $\bar{\nu}_\mu$ or $\bar{\nu}_\tau$.

The observed solar neutrino flavor changing implies that many reactor $\bar{\nu}_e$ disappear into $\bar{\nu}_\mu$ or $\bar{\nu}_\tau$ by the time they have traveled 100 miles.

40

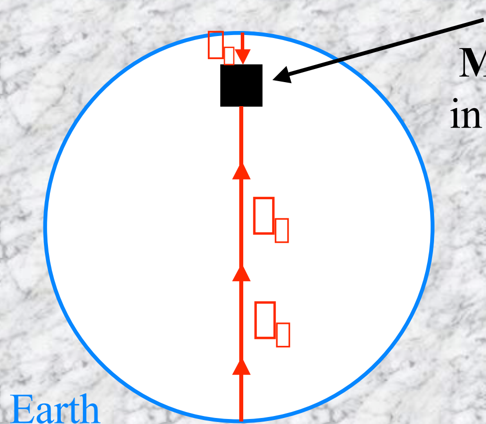
In the Kamioka zinc mine in Japan, 110 miles from some big reactors, is the Kamland $\bar{\nu}_e$ detector.

Kamland finds that 40% of the $\bar{\nu}_e$ emitted by the reactors have disappeared.

Cosmic rays colliding with atoms in the atmosphere make ν_μ .

Half these atmospheric ν_μ disappear while transiting the earth.

41



Detector placed by **Masatoshi Koshiba** et al. in the Kamioka zinc mine.

$$\frac{\text{Number } (\nu_\mu \text{ Up})}{\text{Number } (\nu_\mu \text{ Down})} = 1/2$$

42

2002: Nobel Prize to **Masatoshi Koshiba**

All the neutrino disappearing acts are beautifully described, in detail, as changes of flavor.

43

Open Questions

Q: Do neutrinos come in more than 3 flavors?

An experiment at Los Alamos, using man-made neutrinos, suggests the answer is yes.

But this is a big surprise, since we only know of 3 electron-like particles:
e, , and .

An experiment is currently in progress at Fermilab to confirm or refute the Los Alamos one.

44

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

Neutrino oscillation data tell us that —

Mass of ν_3 (the heaviest one) is **bigger than** —
{Mass of electron}/10,000,000.

The lumpiness of the universe (clusters of galaxies, voids) appears to tell us that —

Mass of ν_3 (the heaviest one) is **smaller than** —
5 x {Mass of electron}/10,000,000.

45

Neutrinos are abundant in the universe
and they do help to shape it.

Q: Why are the neutrinos so much lighter than
the other particles?

Knowing the answer might shed light on the
origin of all particle masses.

At this point there is only speculation………

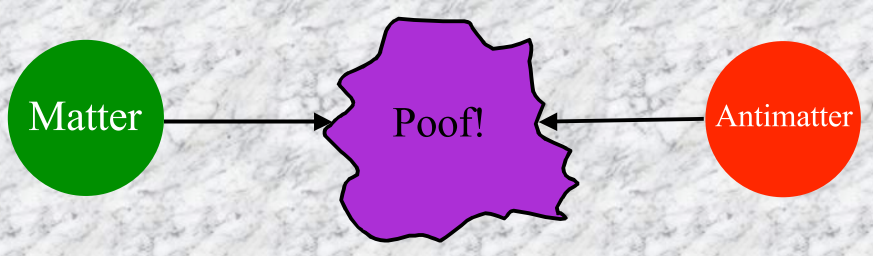
46

Q: Are neutrinos the reason the universe contains matter but almost no antimatter?

For every particle , there is a corresponding antiparticle.

Matter	Antimatter
Electron	Positron
Proton	Antiproton
Neutron	Antineutron
Neutrino ν	Antineutrino $\bar{\nu}$

47



Good thing for us there is no antimatter around!!

The development of a universe containing matter but no antimatter requires that matter and antimatter behave differently.

48

We have seen a difference, not involving neutrinos, that is way too small to explain the universe.

If neutrinos behave differently from antineutrinos, the physics of these particles might lead to an explanation of our
MATTER - antimatter lopsided universe.

Future experiments will look for that difference between □ and □ behavior.

49

□ Summary □

Neutrinos are abundant, but elusive.

They have tiny, but nonzero, masses.

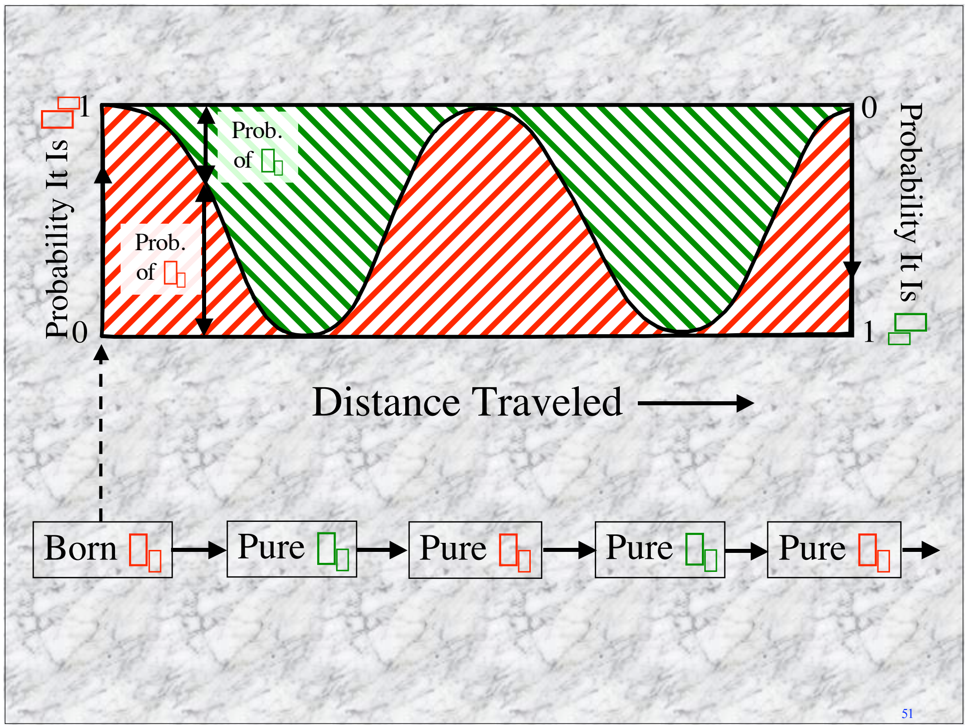
They can do amazing things, like change from chocolate- to strawberry-flavored.

Without them, we wouldn't be here.

They are under our skin—always.

□ □ □ □ □ □ □ □ □ □

50

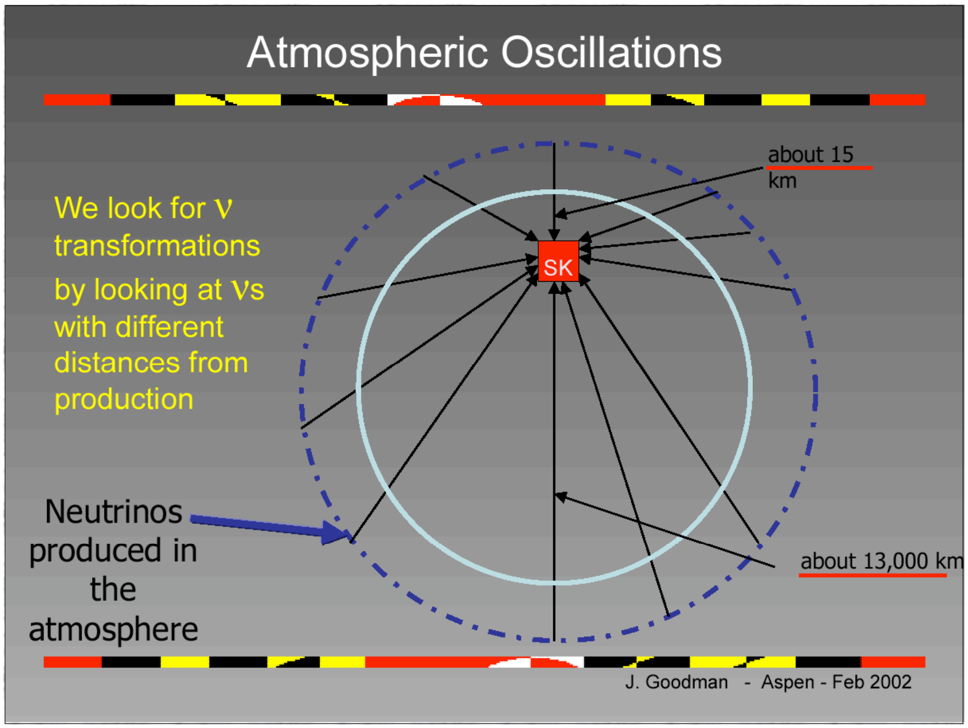


Atmospheric Neutrinos

In a zinc mine in Japan is the Super-Kamiokande (SK) detector, filled with 50,000 tons of water.

SK studies Atmospheric Neutrinos—
□e and □ created in the earth's atmosphere by cosmic rays colliding with atoms in the air. The cosmic rays do not make □.

52



In SK –

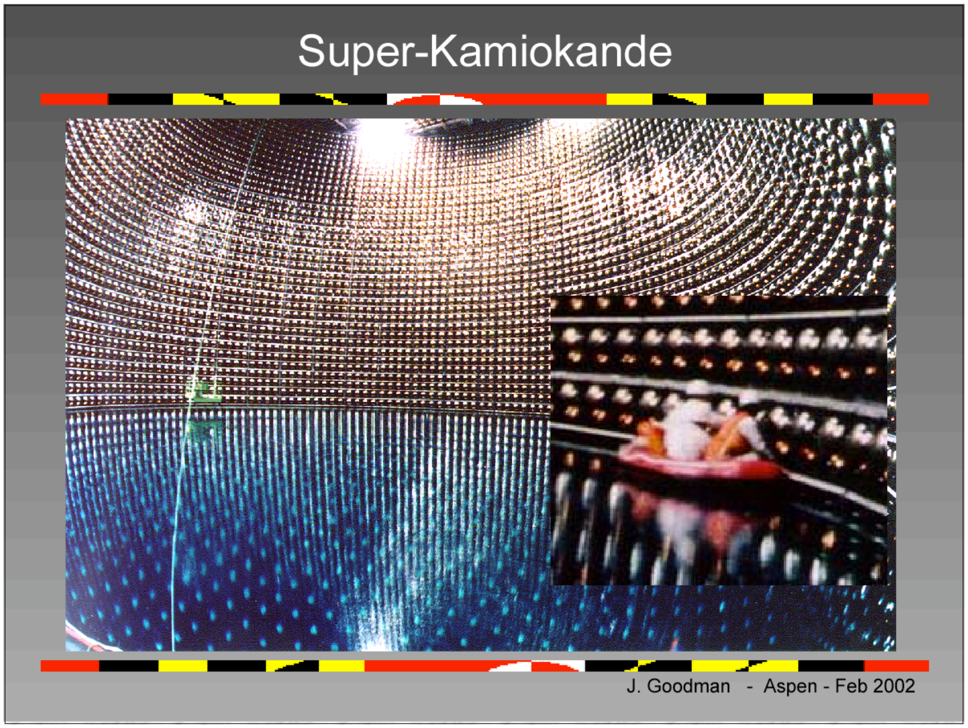
- Atmospheric neutrino makes a charged particle.

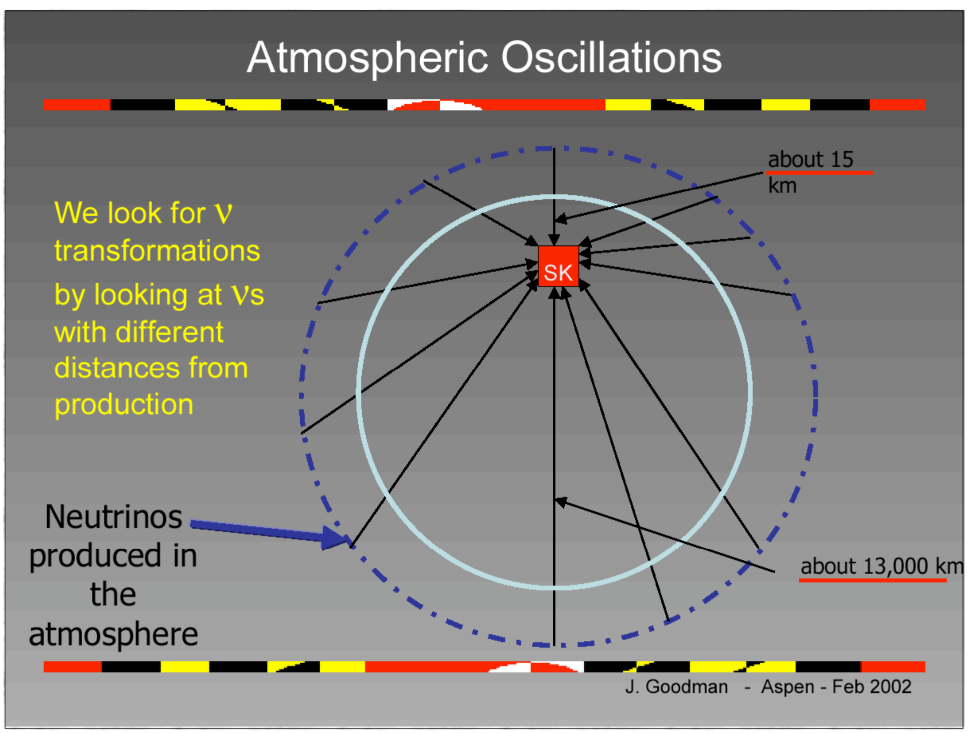
  ν_e makes e

  ν_μ " μ

- The charged particle, moving through the water, emits light.
- Electric eyes covering the inside walls of SK detect the light.
- From the light pattern, SK can tell an e from a μ.

54


Super-Kamiokande
J. Goodman - Aspen - Feb 2002


Atmospheric Oscillations
We look for ν transformations by looking at νs with different distances from production
Neutrinos produced in the atmosphere
about 15 km
SK
about 13,000 km
J. Goodman - Aspen - Feb 2002

SK finds—

Only *half* as many atmospheric ν_μ coming up from far side of earth as are coming down from nearby.

Half the ν_μ made far away disappear during their long journey.

Are they oscillating into neutrinos of another flavor???

The hypothesis that ν_μ oscillate into ν_τ fits a wealth of data from SK and other detectors beautifully.

This includes a weak signal in SK for ν_τ, even though cosmic rays don't make ν_τ.

57

Solar Neutrinos

The nuclear processes that power the sun produce gazillions of neutrinos. These processes make only ν_e, not ν_μ or ν_τ.

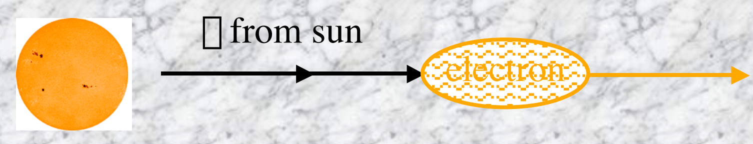
Underground solar neutrino detectors find that half or more of the ν_e expected to arrive every day from the sun are missing.

Are they oscillating into neutrinos of another flavor???

58

The SNO measurement counts only ν_e.
ν_μ and ν_τ are not seen.

Meanwhile, SK counts neutrinos from the sun using electrons in ordinary water:



This counts ν_e, ν_μ and ν_τ.

59

Just seeing the electron get struck by a neutrino doesn't tell us whether the neutrino was a ν_e, ν_μ or ν_τ.

But comparing the SNO count (ν_e only) to the SK count (ν_e, and ν_μ and ν_τ), we can count the number of ν_μ and ν_τ.

The result—

$$\frac{\text{Number } (\nu_\mu \text{ and/or } \nu_\tau \text{ from sun})}{\text{Number } (\nu_e \text{ from sun})} = 2$$

ν_e, made by the sun, oscillate into ν_μ and/or ν_τ.

60

Man-Made Neutrinos

- Beams of neutrinos can be made using particle accelerators like those at Fermilab.
- Oscillation of neutrinos made by an accelerator at Los Alamos has been reported.
- If this oscillation is genuine, nature contains a new kind of neutrino that interacts with matter even more feebly than the other neutrinos.
- To confirm or disprove the Los Alamos oscillation, the MiniBooNE experiment will soon be done at Fermilab.

61

To Confirm the Atmospheric Neutrino Oscillation

Send a man-made beam of neutrinos a long distance, to give the νs time to oscillate.

See if man-made ν_μ dis-appear in the same way that atmospheric ν_μ do.

Try to confirm that the probability that a ν_μ is still a ν_μ actually *oscillates* down and up, and down and up, and…

62