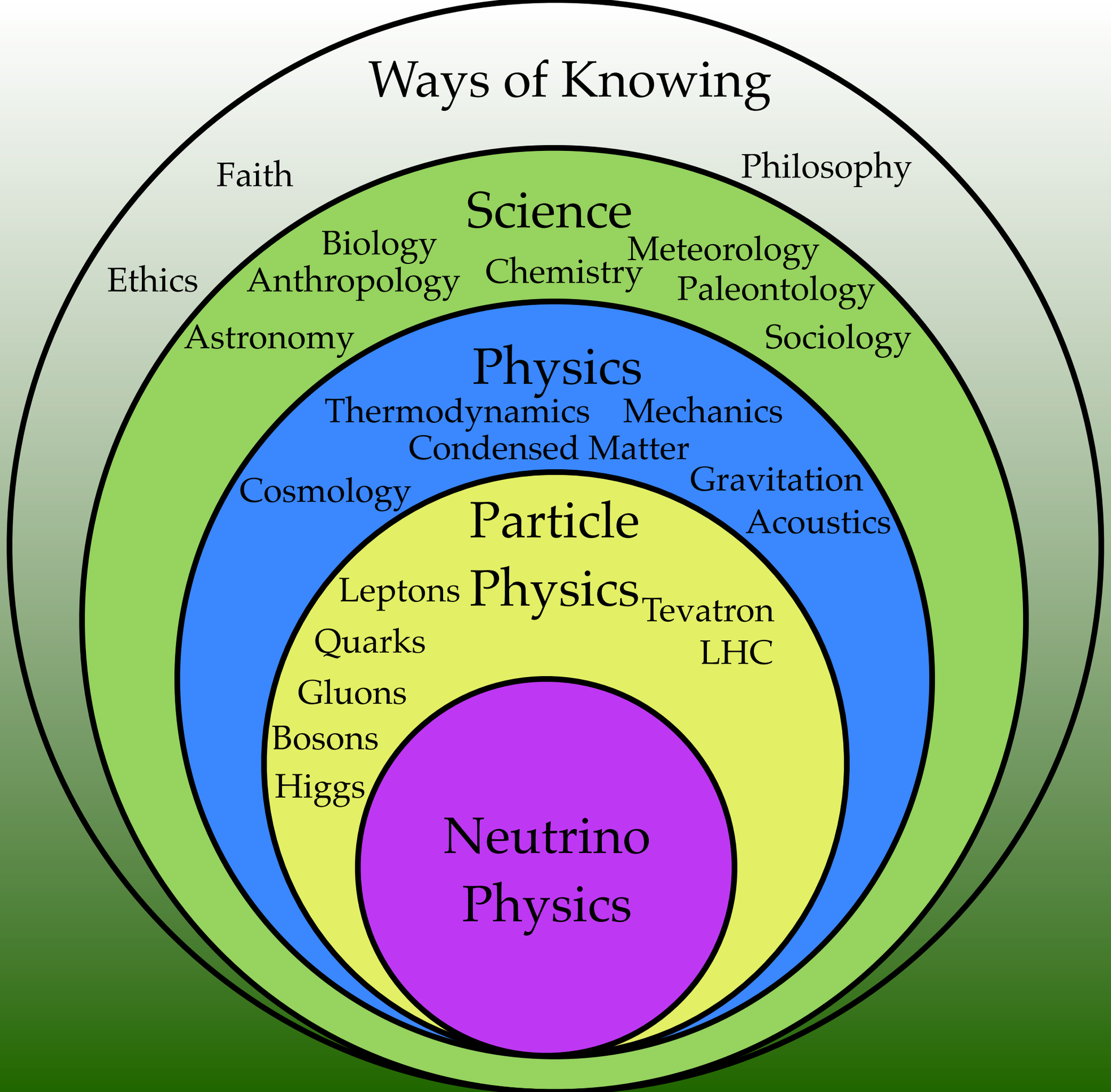
Neutrinos

The Little Particles that Could!

Dr. Luke A. Corwin
Indiana University

Ask-a-Scientist

Apr. 7, 2013


Ways of Knowing
Faith
Philosophy
Ethics
Science
Biology
Anthropology
Chemistry
Meteorology
Paleontology
Astronomy
Sociology
Physics
Thermodynamics
Mechanics
Condensed Matter
Cosmology
Gravitation
Acoustics
Particle Physics
Leptons
Tevatron
Quarks
LHC
Gluons
Bosons
Higgs
Neutrino Physics

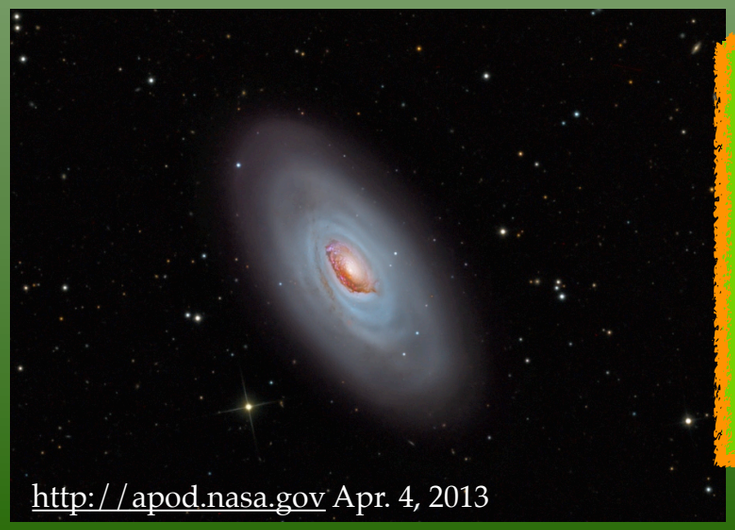
Science: The Basic Ideas

The laws of nature apply at all locations in the Universe, from your home to Paris to the most distant galaxies

These laws apply at all times from the Beginning to now and throughout the future

"... the **universality** and **immutability** of the fundamental **laws** is the basic postulate of all science."*

Nature follows foundational laws that humans can understand.



http://apod.nasa.gov Apr. 4, 2013

Image courtesy of Vichaya Kiatying-Angsulee / FreeDigitalPhotos.net

* Quinn, H. (2007, January). "Belief and knowledge — a plea about language." *Physics Today* Vol. 60, Iss. 1, pp. 8–9.

Science: The Method

"**scientific method** *n*. a method of procedure that has characterized natural science since the 17th century, consisting in systematic observation, measurement, and experiment, and the formulation, testing, and modification of hypotheses."*

- Ask a question
- Formulate a hypothesis (testable answer)
- Make a prediction
- Test the prediction
- Verify, Modify, or Reject Hypothesis
- Repeat

* *The Oxford English Dictionary* Online

Scientific Notation

- Electron mass = 0.000000000000000000000000000091 g
- To express very large or small numbers, we use the notation

$$10^x = 1 \text{ followed by } x \text{ zeroes.}$$

$$10^9 = 1,000,000,000$$

$$10^{-9} = \frac{1}{1,000,000,000} = 0.000000001$$

For Example

$$\text{World Population} = 7.08 \text{ billion} = 7{,}080{,}000{,}000 = 7.08 \times 10^9$$

$$\text{Electron Mass} = 9.1 \times 10^{-28} \text{ g}$$

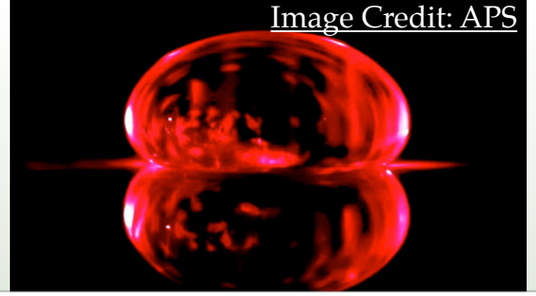


Image Credit: APS

Physics

Image courtesy of Zuzzuillo / FreeDigitalPhotos.net

"The branch of science … whose subject matter includes mechanics, heat, light and other radiation, sound, electricity, magnetism, gravity, the structure of atoms, the nature of subatomic particles, and the fundamental laws of the material universe."*

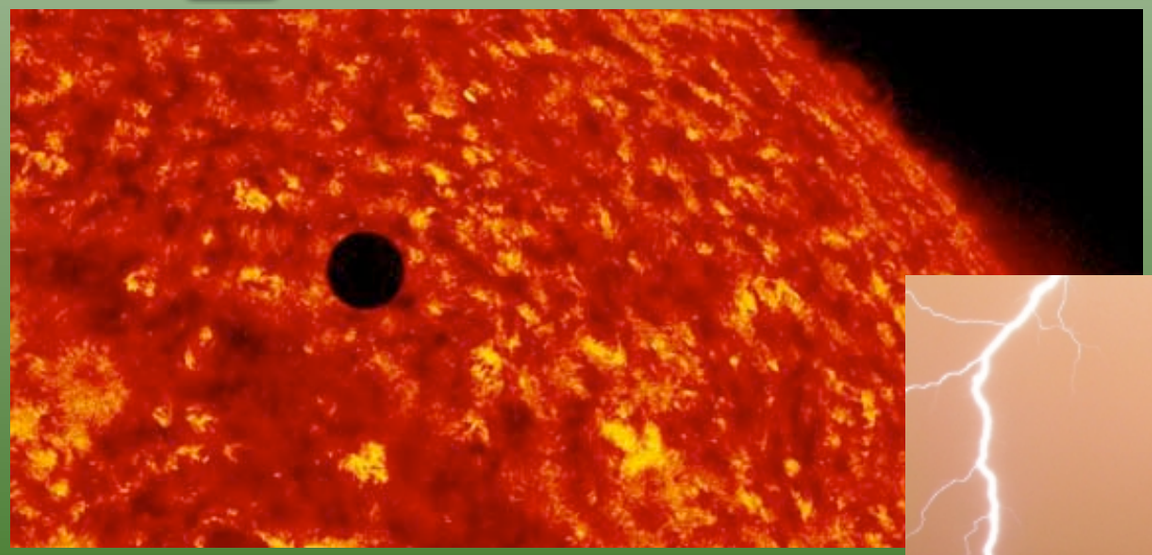
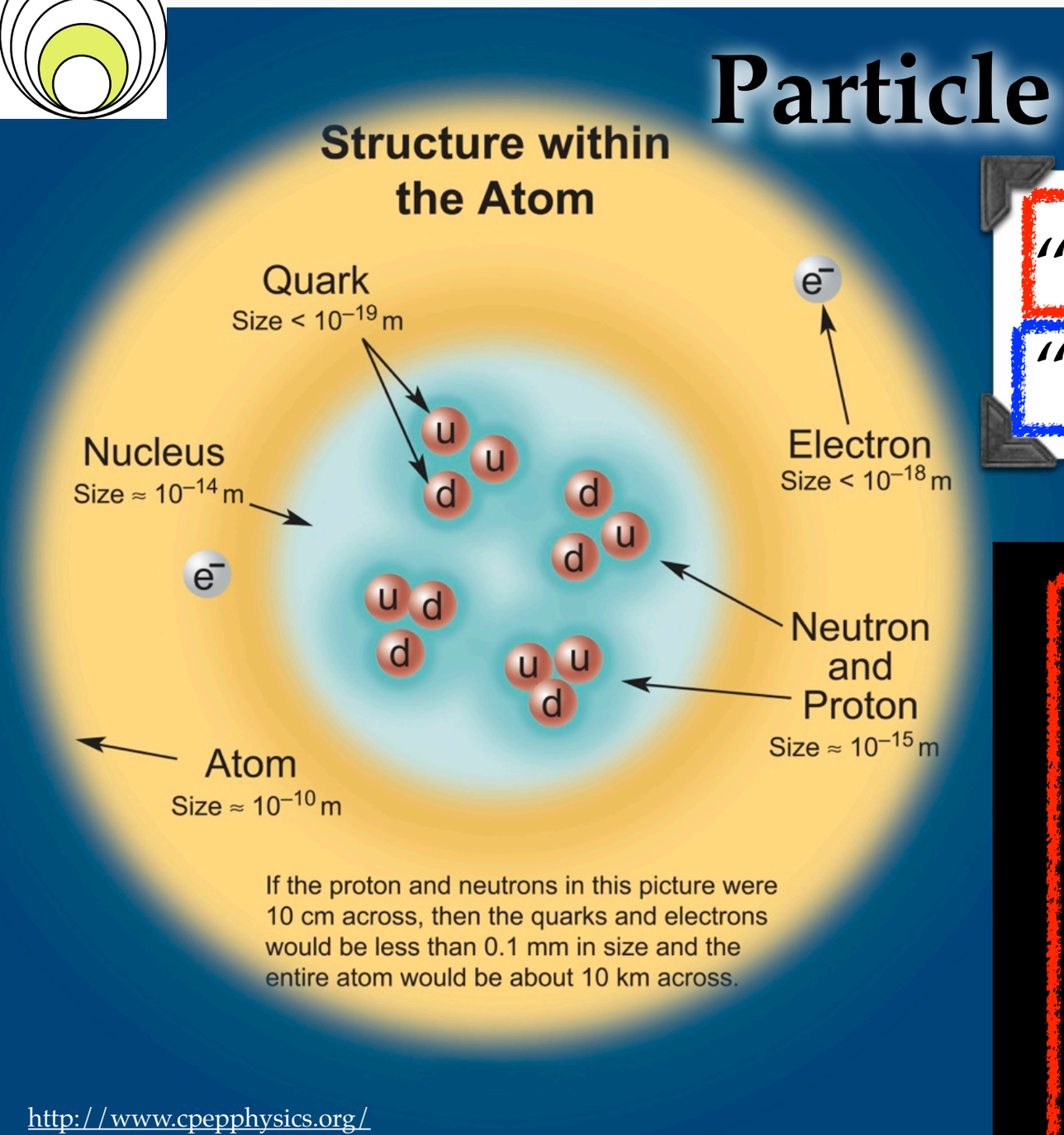

http://www.aps.org/about/physics-images/archive/venus.cfm

Image courtesy of Christian Meyn / FreeDigitalPhotos.net

CERN

* *The Oxford English Dictionary* Online

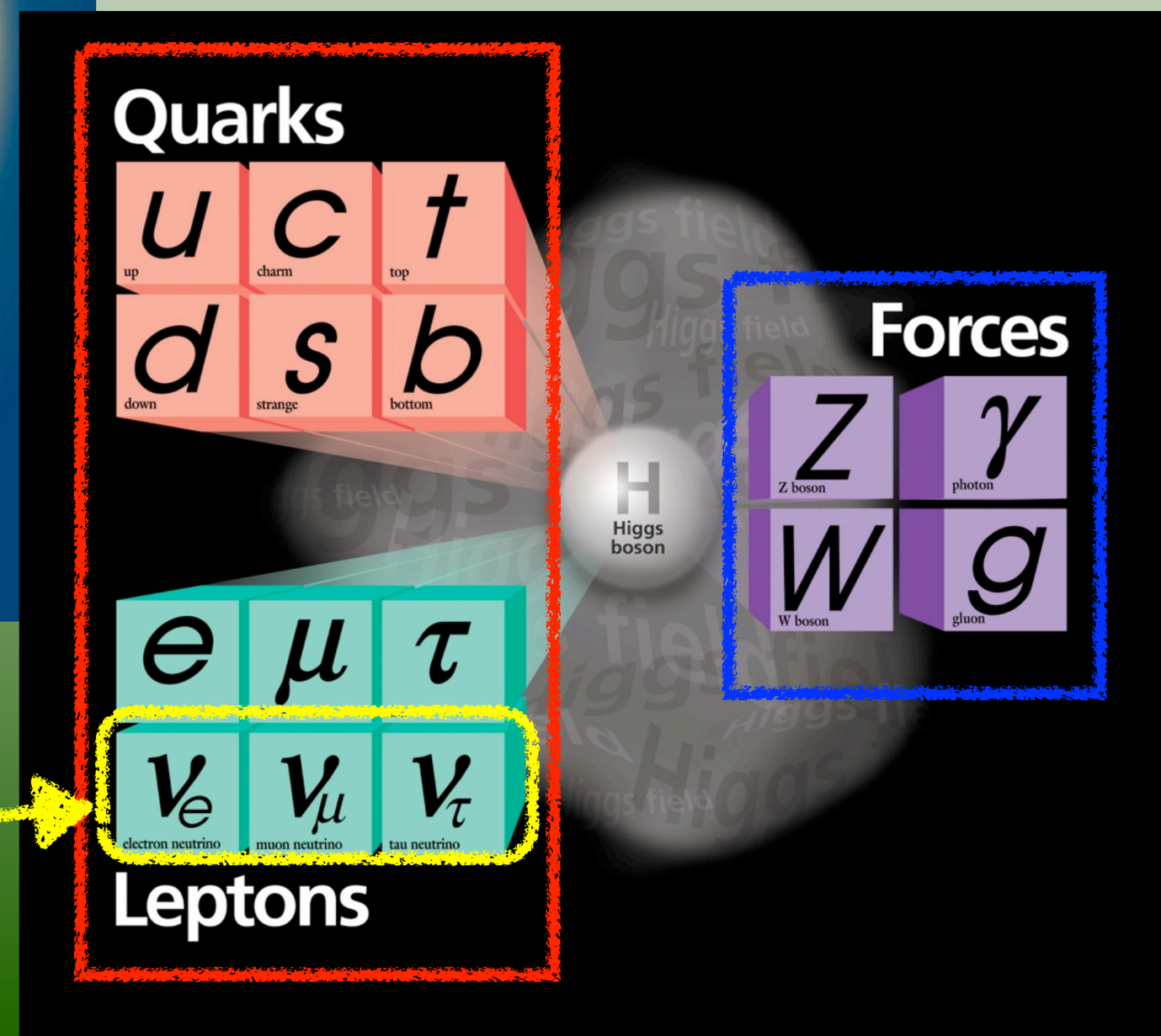
Particle Physics



http://www.cpepphysics.org/

"What is the world made of?"

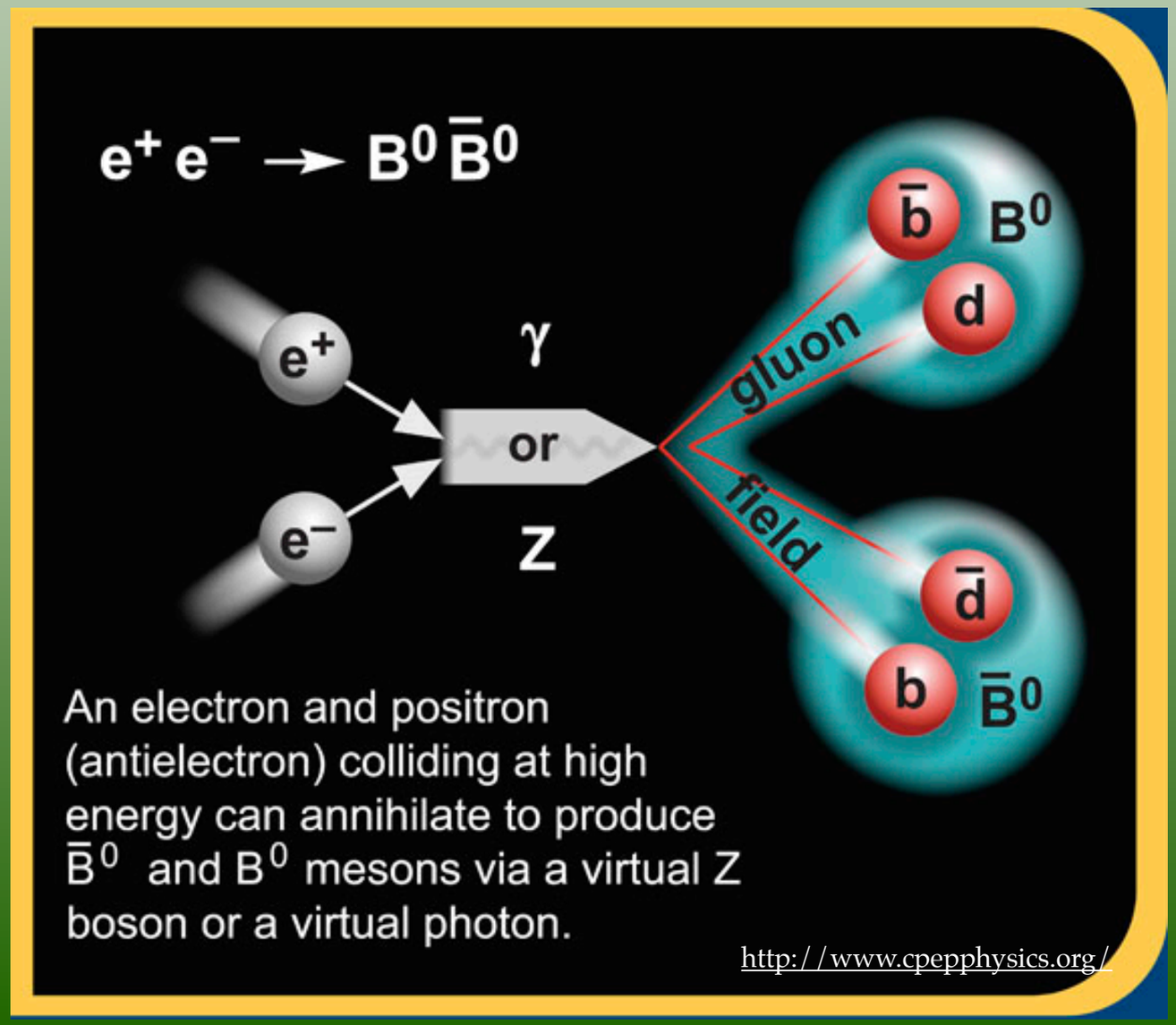
"What holds it together?"



Neutrinos!

Antimatter is Real!

- Every particle type has an antiparticle
- Antiparticles are denoted by
  - Bar over the particle symbol (e.g. d and $\bar{d}$ or ν_e and $\bar{\nu}_e$)
  - The opposite charge sign (e^+ or e^-)
- Matter and Antimatter particles annihilate and produce new particles and radiation



An electron and positron (antielectron) colliding at high energy can annihilate to produce $\bar{B}^0$ and B^0 mesons via a virtual Z boson or a virtual photon.

http://www.cpepphysics.org/

Mass Scales

The scales involved in particle physics are well outside of our everyday experiences.
Welcome to the world of the very small...

Image courtesy of Rawich / FreeDigitalPhotos.net

Imagine collecting 4 billion (4×10^9) electrons every second for the past 31,689 years. That would give you the mass of a grain of sand.

A neutrino is at least a *million* times lighter than an electron!

Neutrinos Could ... What?

- ...explain the “missing” energy of beta decay!
- ...be very hard (but not impossible) to detect!
- ...come in three flavors!
- ...seem to change flavors as they travel!
- ...have very very little, but not zero mass!
  - ...usually travel very very close to (but slower than) the speed of light
- ...explain why we exist!
- ...have many more surprises in store!

...explain the "missing" energy of beta decay!

The Mystery of the Missing Momentum...

- The scientific method in action.
- Question: *Does conservation of energy apply at the subatomic level?*
- Hypothesis: *Yes, it does*.
- Prediction: *We can calculate the energies (speeds) of the products of beta decay exactly*.
- Test: *Measure the energies.*

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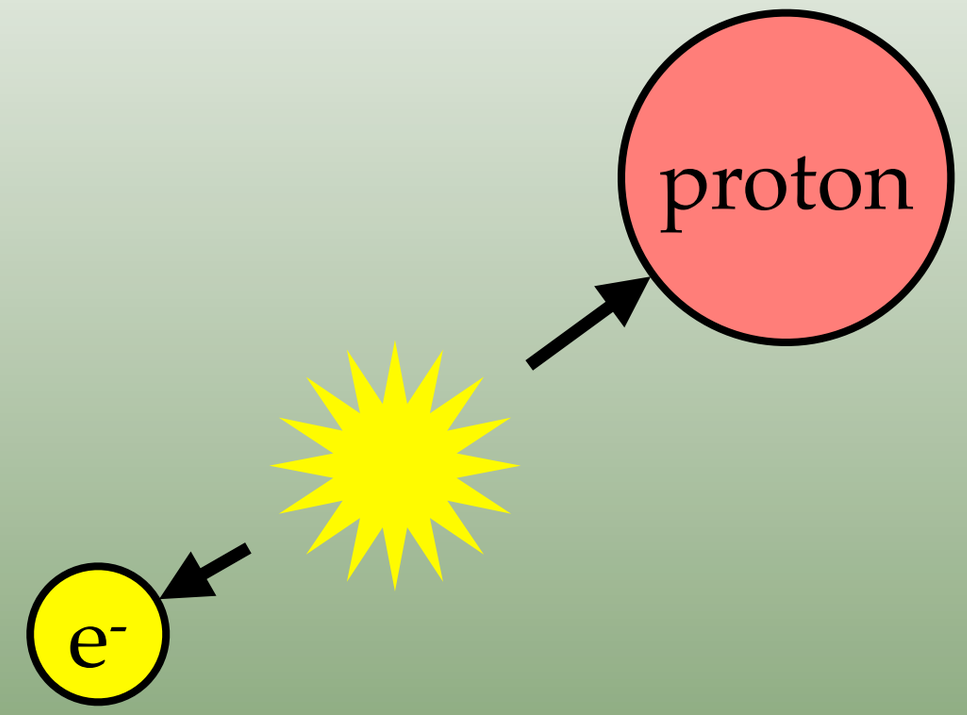

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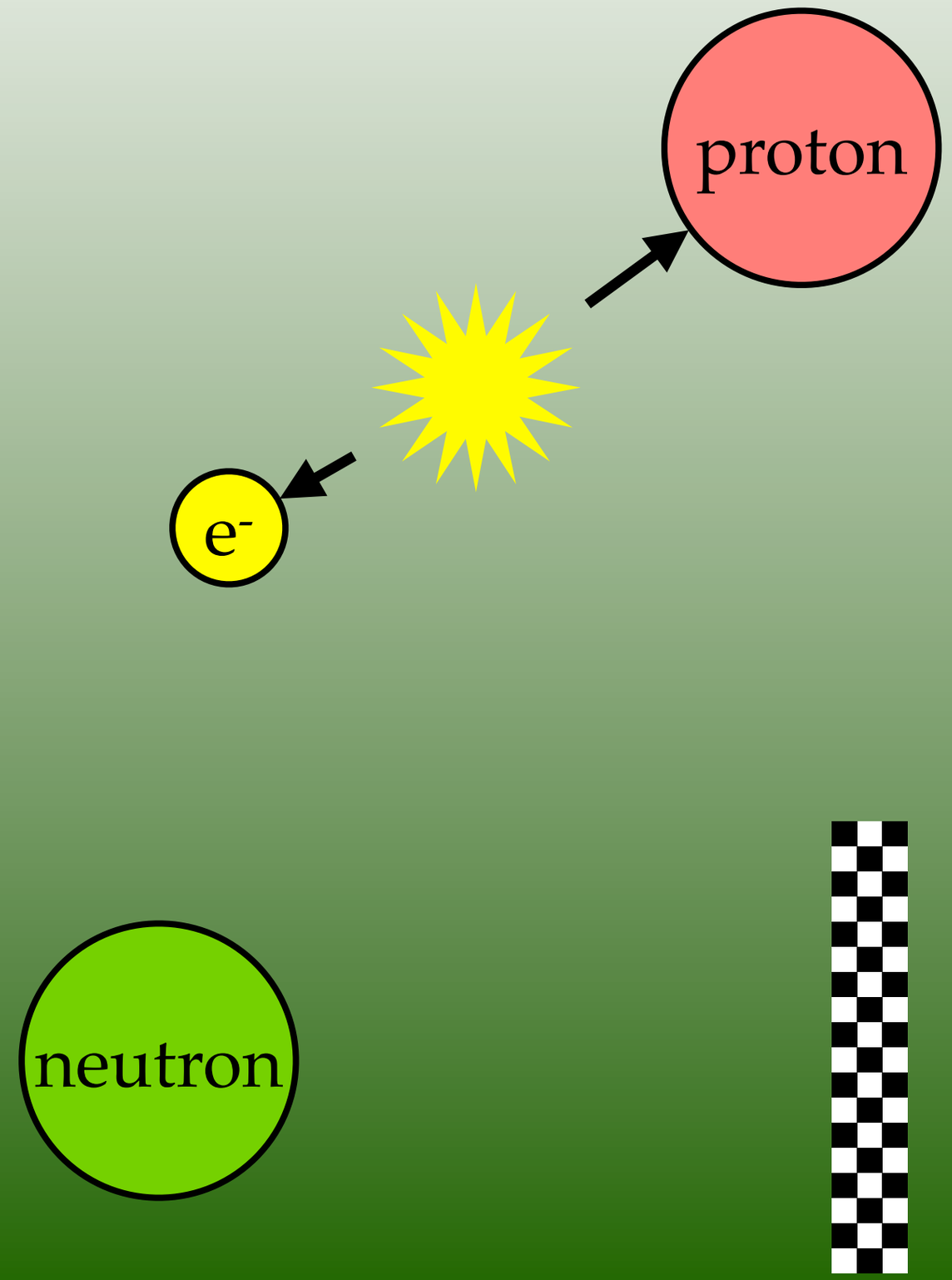

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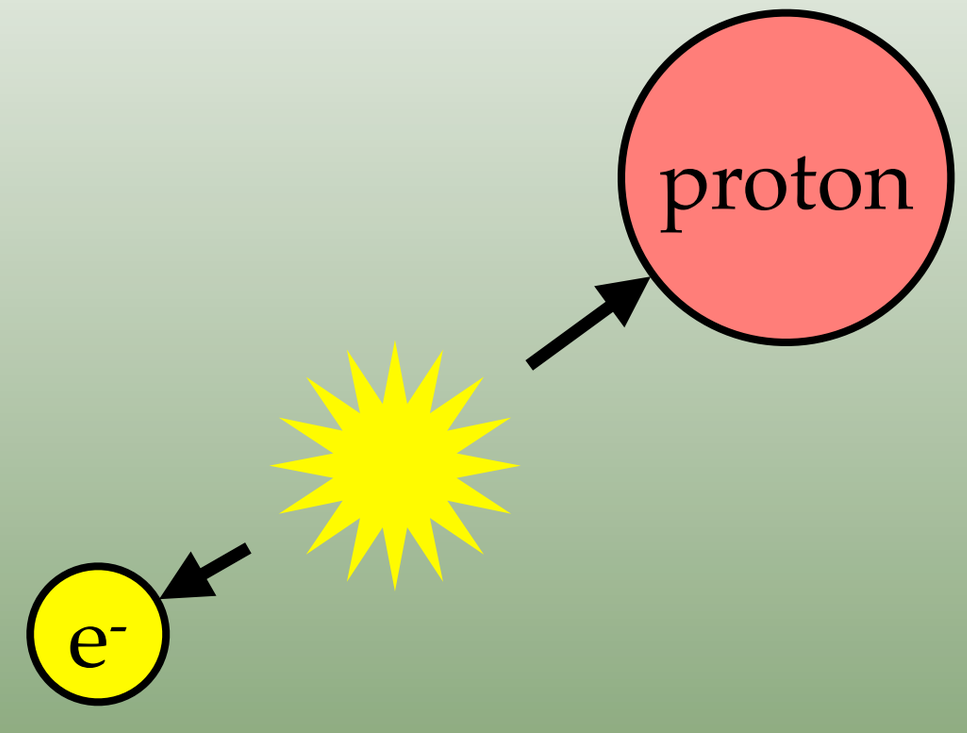

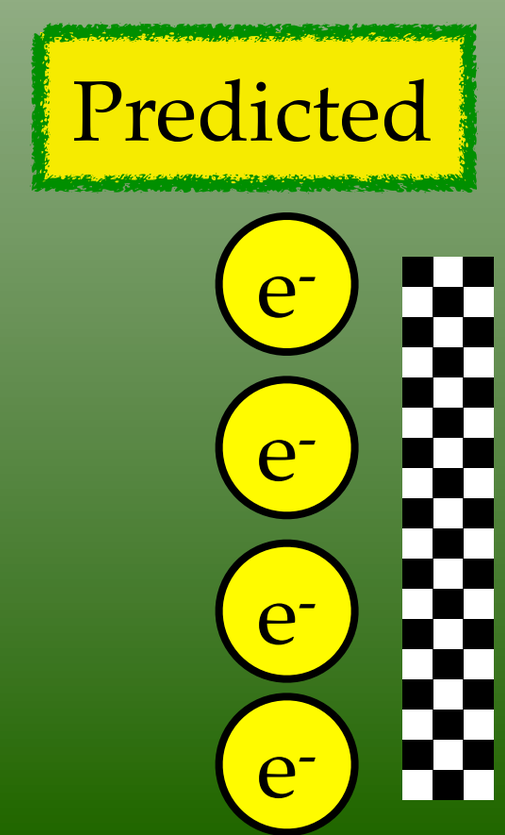

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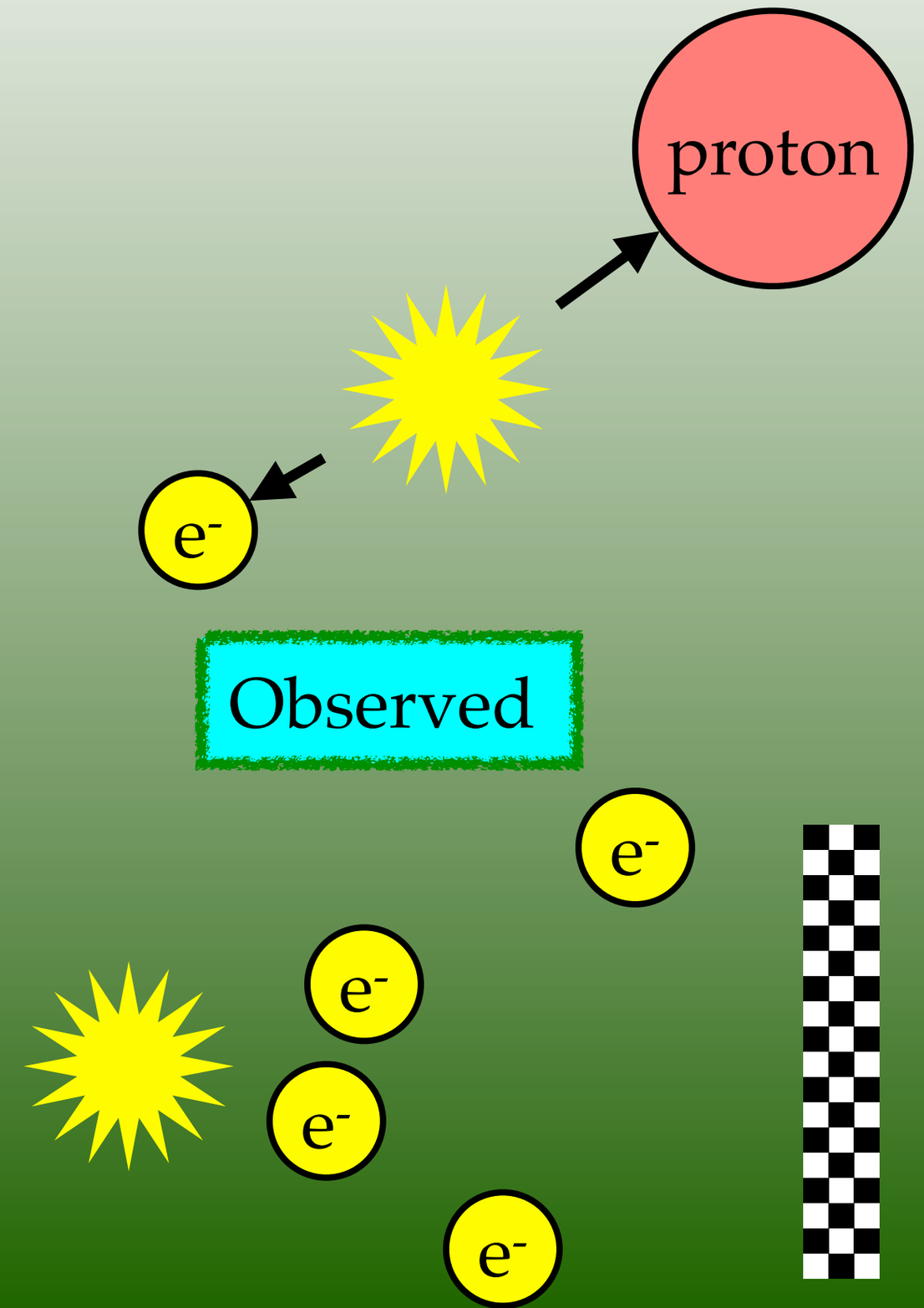
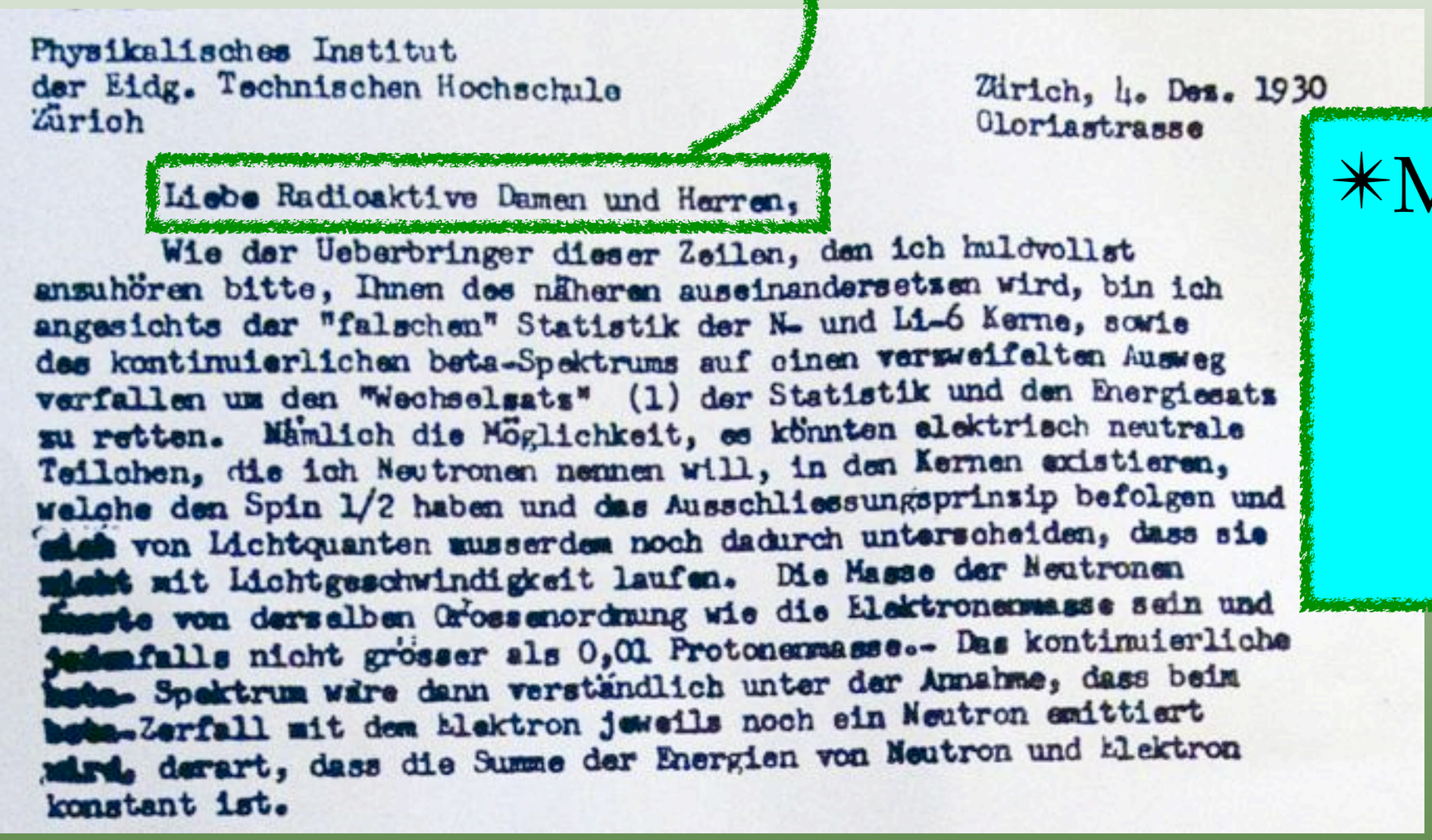


A New Hypothesis...

Dear Radioactive Ladies and Gentlemen,



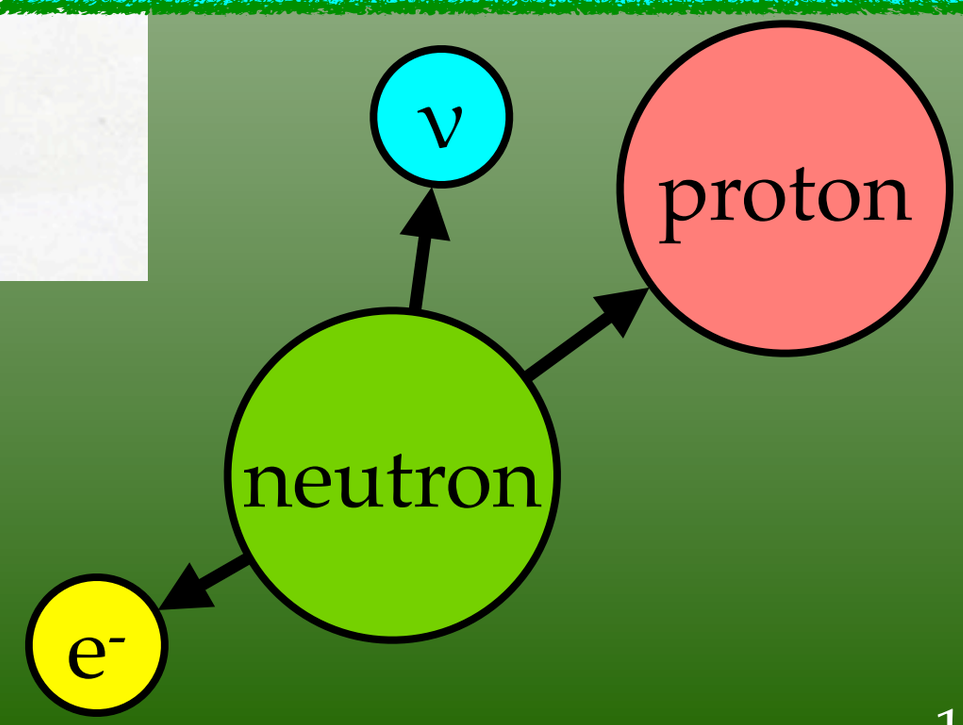
Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

- Must be
  - ★Electrically neutral
  - ★Weakly interacting
  - ★Very light



- Dec. 4, 1930: Wolfgang Pauli proposed a new particle (later called the neutrino)

...be very hard (but not impossible) to detect!

How Hard?

- They can pass through a *light year* of lead and not hit anything!
- About 50 trillion of them are passing though you every second of every day from the sun, and you don't notice!
- **To test this new hypothesis, we need to find these ghostly particles, but how?**

Image courtesy of digitalart / FreeDigitalPhotos.net

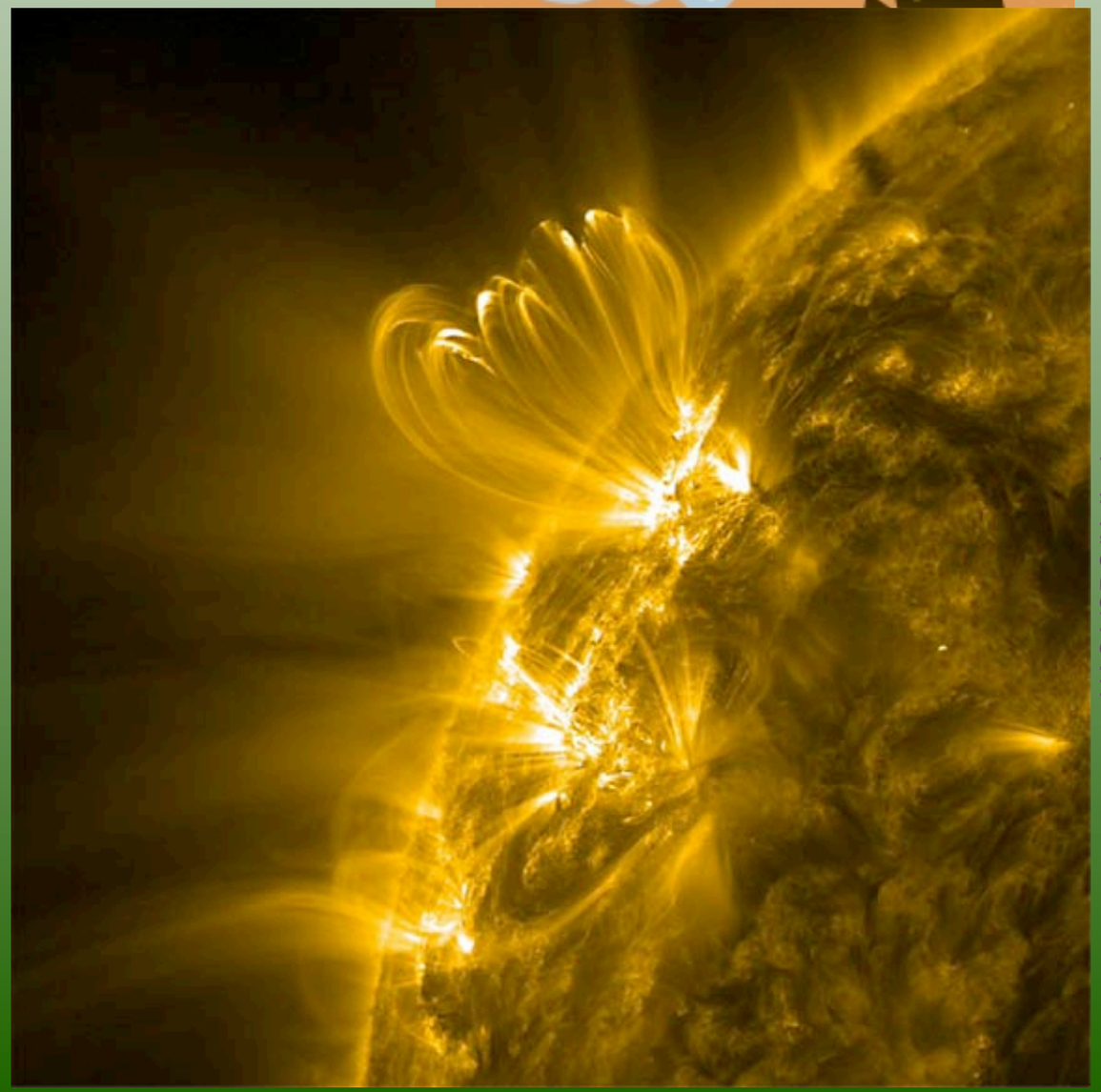
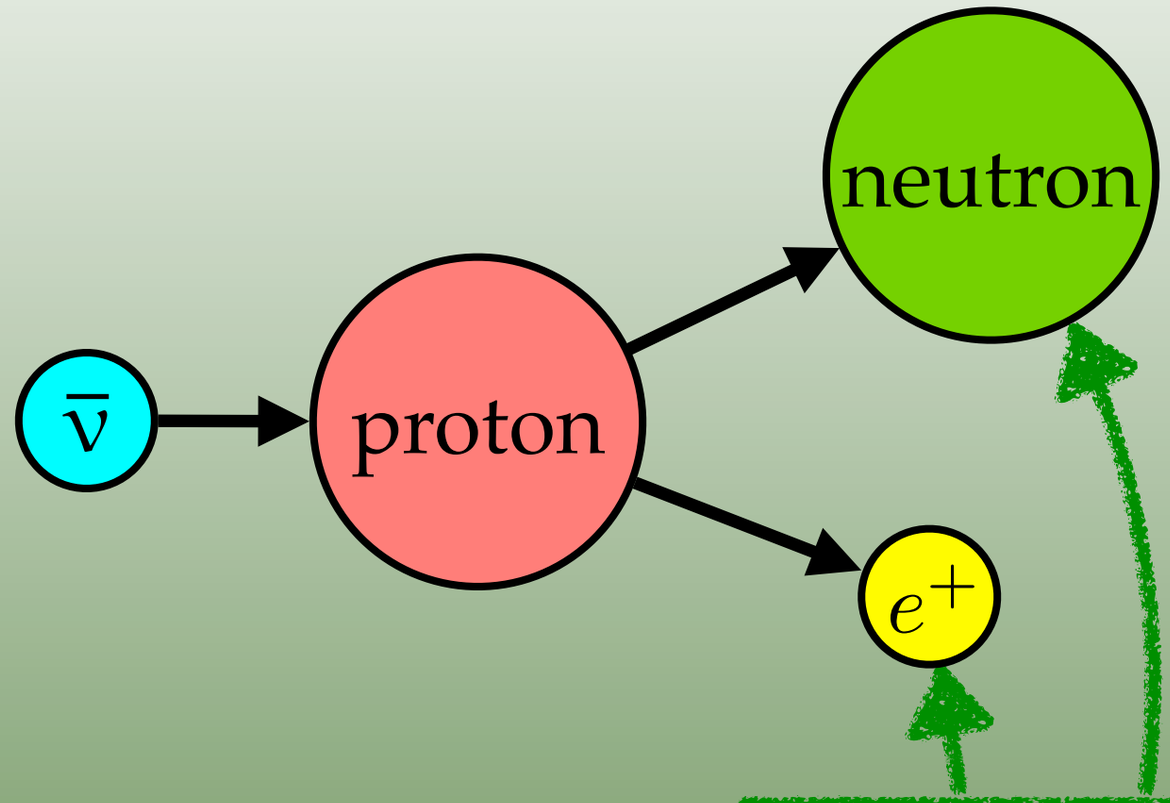


Image Credit: NASA/SDO/Helioviewer

How? Make a lot of neutrinos!



Fred Reines

Clyde Cowan, Jr.

Since neutrinos are detected via very improbable but not impossible collisions with nuclei, we need to stack the odds.

Lots of antineutrinos are produced by the Savannah River nuclear reactor.

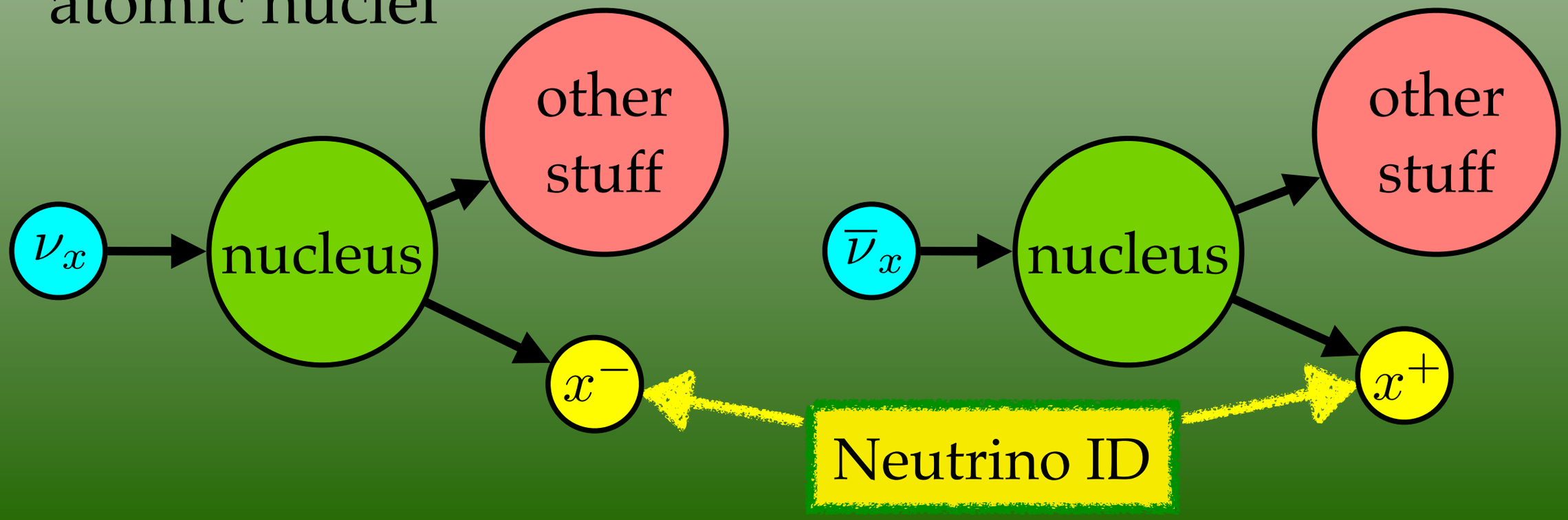
1956: Their experiment detected the products of the neutrino interactions.

...come in three flavors!

Flavors of a very different kind

- Pauli proposed one neutrino, but we have found 3

- Identified by the results of their collisions with atomic nuclei

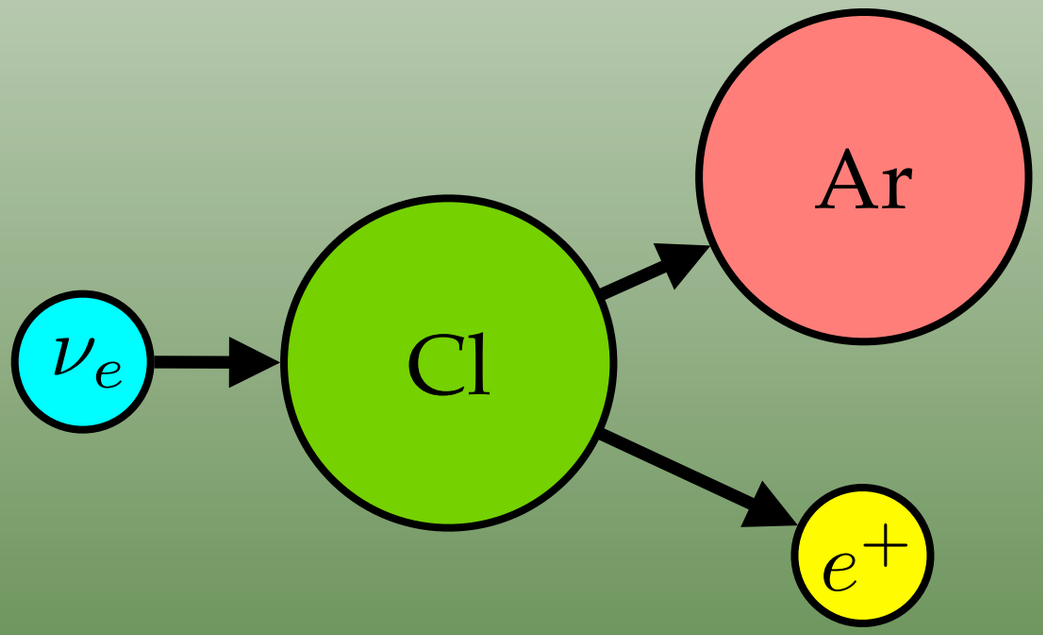


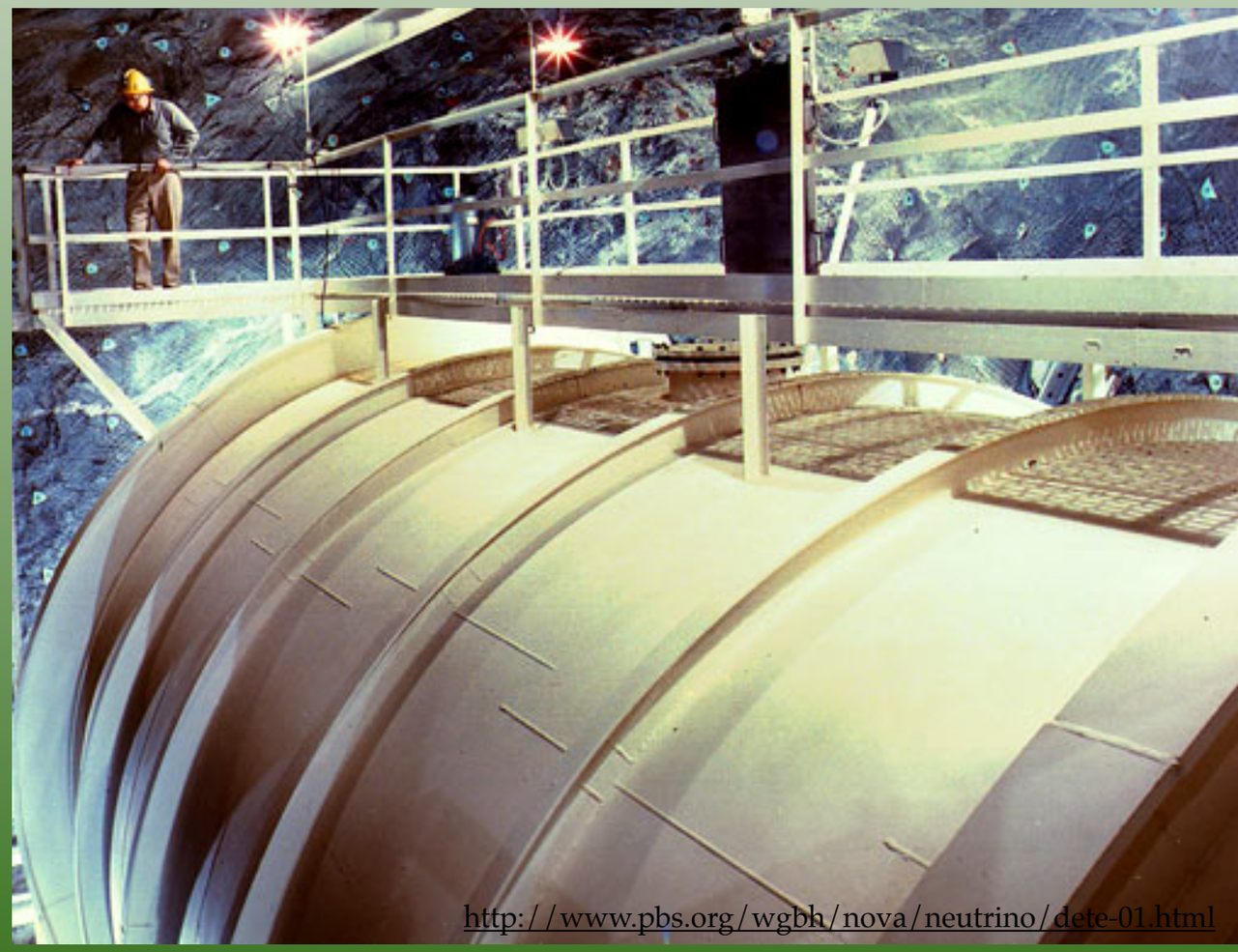
...seem to change flavors as they travel!

The First Hint of Flavor Change

Image Credit: Brookhaven National Lab.

- Beginning in 1968, Raymond Davis used dry cleaning fluid (containing Chlorine) to detect neutrinos from the sun





http://www.pbs.org/wgbh/nova/neutrino/dete-01.html

Found only 1/3 of the expected number of neutrinos!

A Neutrino Flavor Analogy

Ice cream analogy taken from *The MINOS Experiment: Mining the Imagination* (June, 2002)
Graphics taken from *Fermilab: Science at Work*

ν_e Source
(The Sun)

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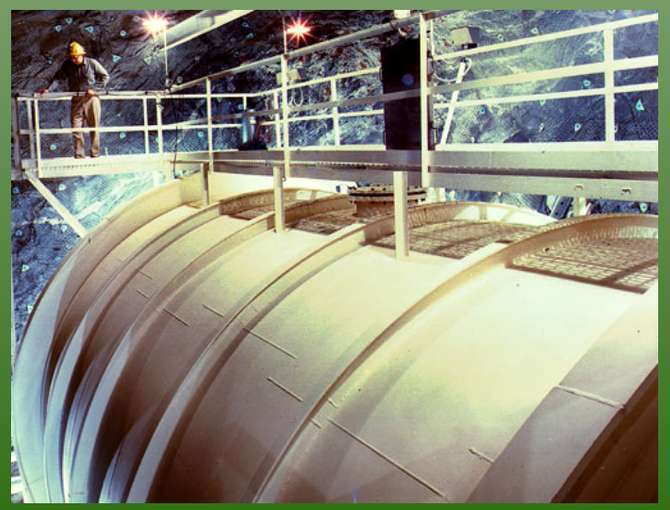
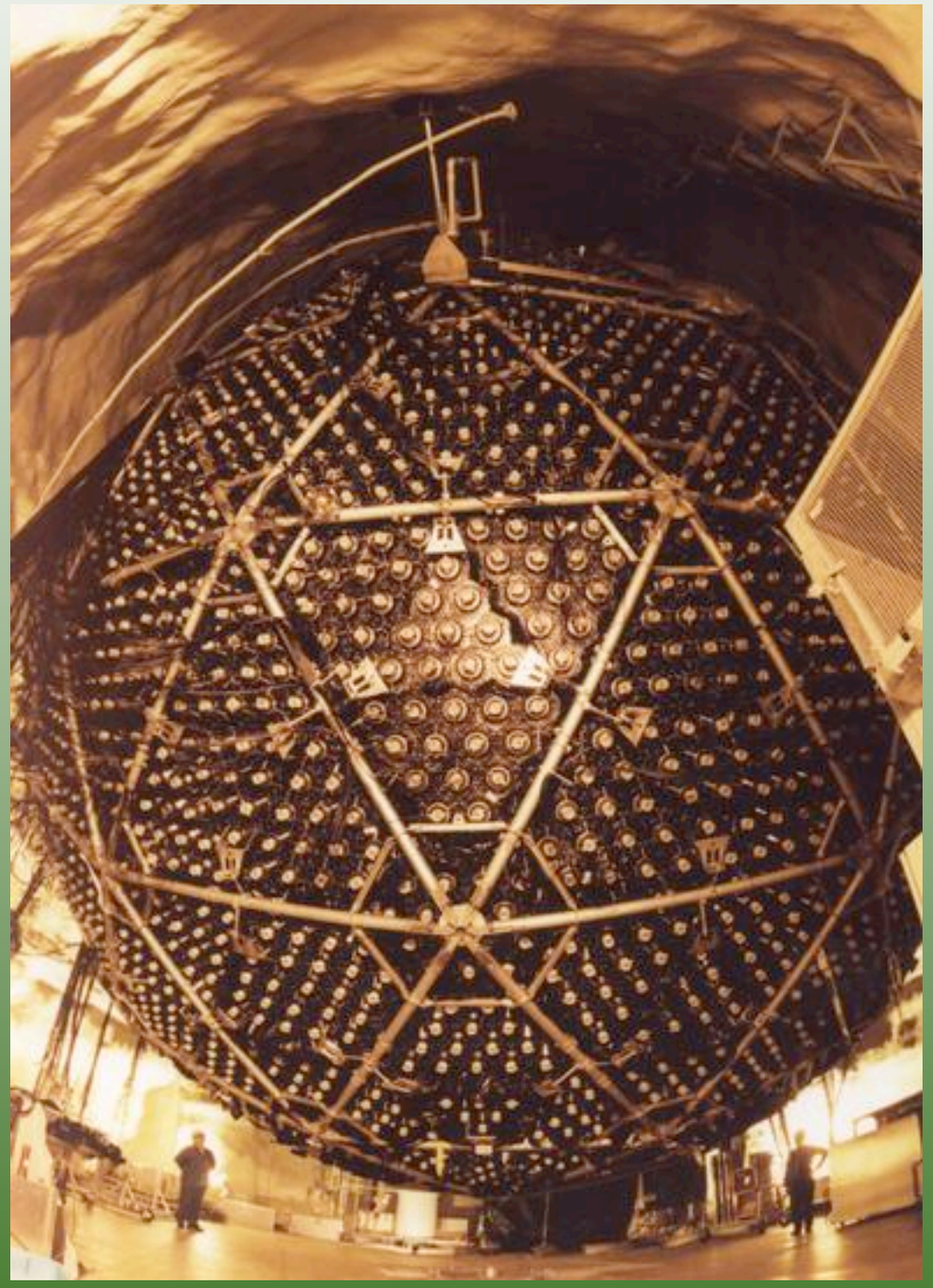


Confirmation…

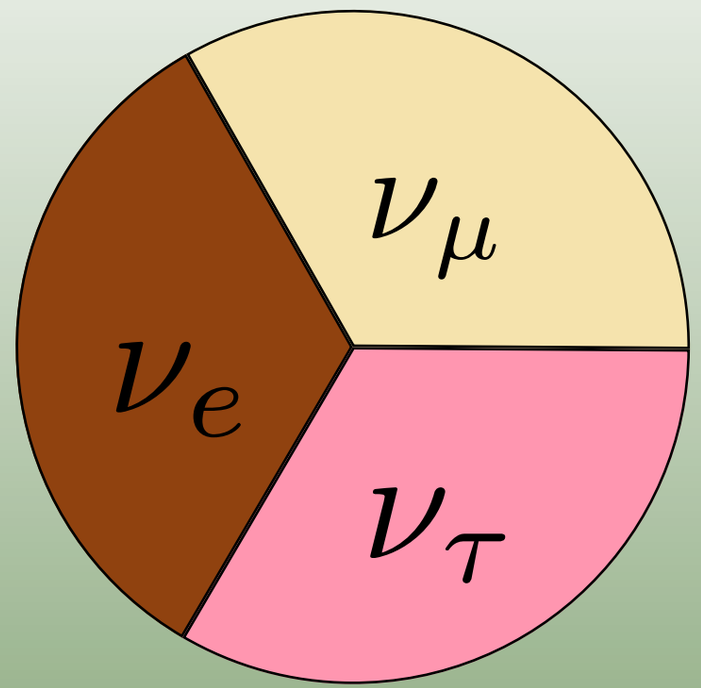
The Sudbury Neutrino Observatory in Canada used heavy water to detect all *three* kinds of neutrinos from the sun.



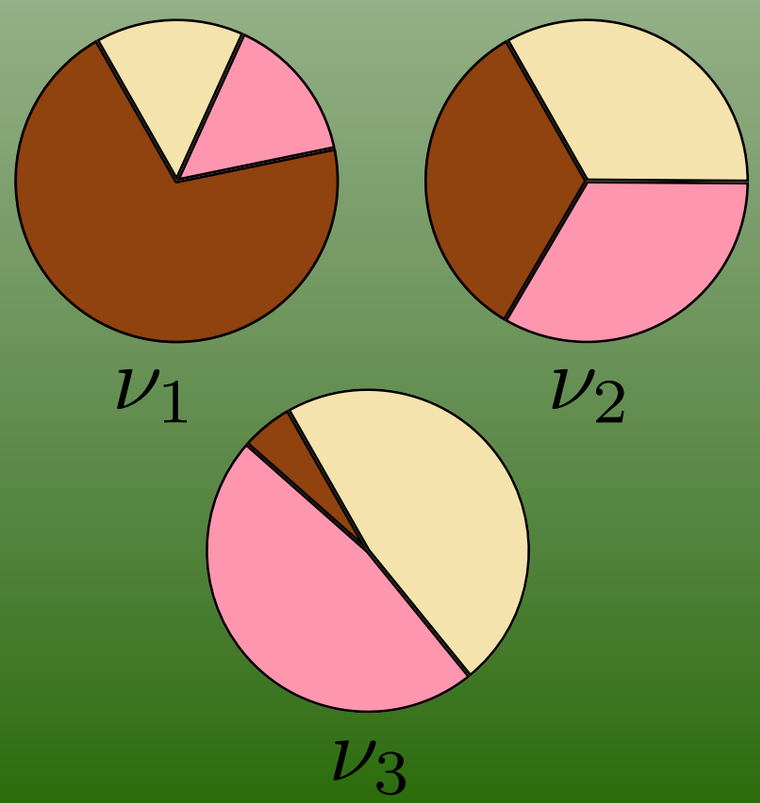
Images from SNO Image Catalog

- In 2001, SNO **confirmed that the solar neutrino problem was the result of neutrinos *oscillating* between flavors**

Let's Look From Another Angle



Each scoop (neutrino) is actually a combination of all three flavors. When seen from the side, only one is visible. As they travel, they rotate at a rate determined by the speed of the truck.



The neutrino that travels through space is a particle of definite mass that is a combination of the three flavors. There are three of these neutrinos, each with a different recipe using those flavors.

MINOS Measures Oscillations

- We make a beam of ν_μ and send it through the earth

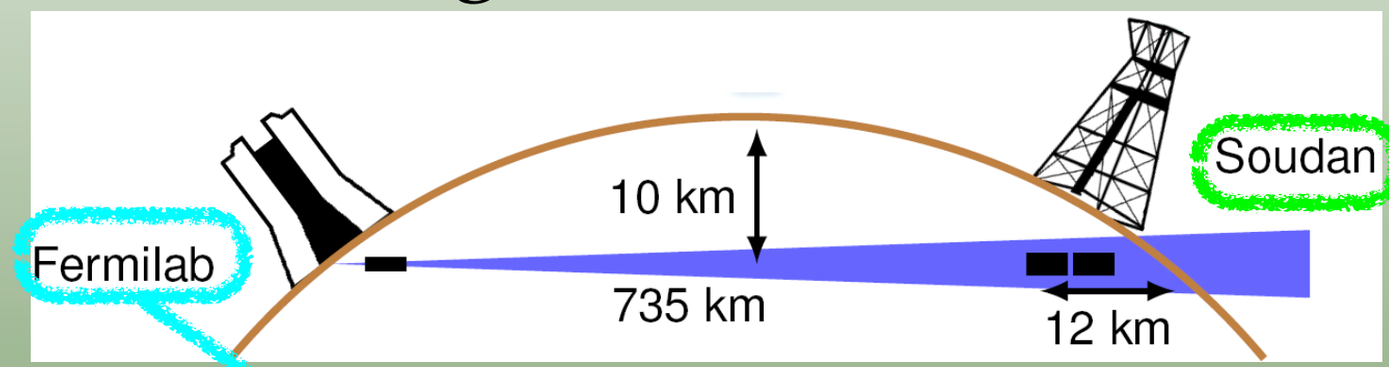
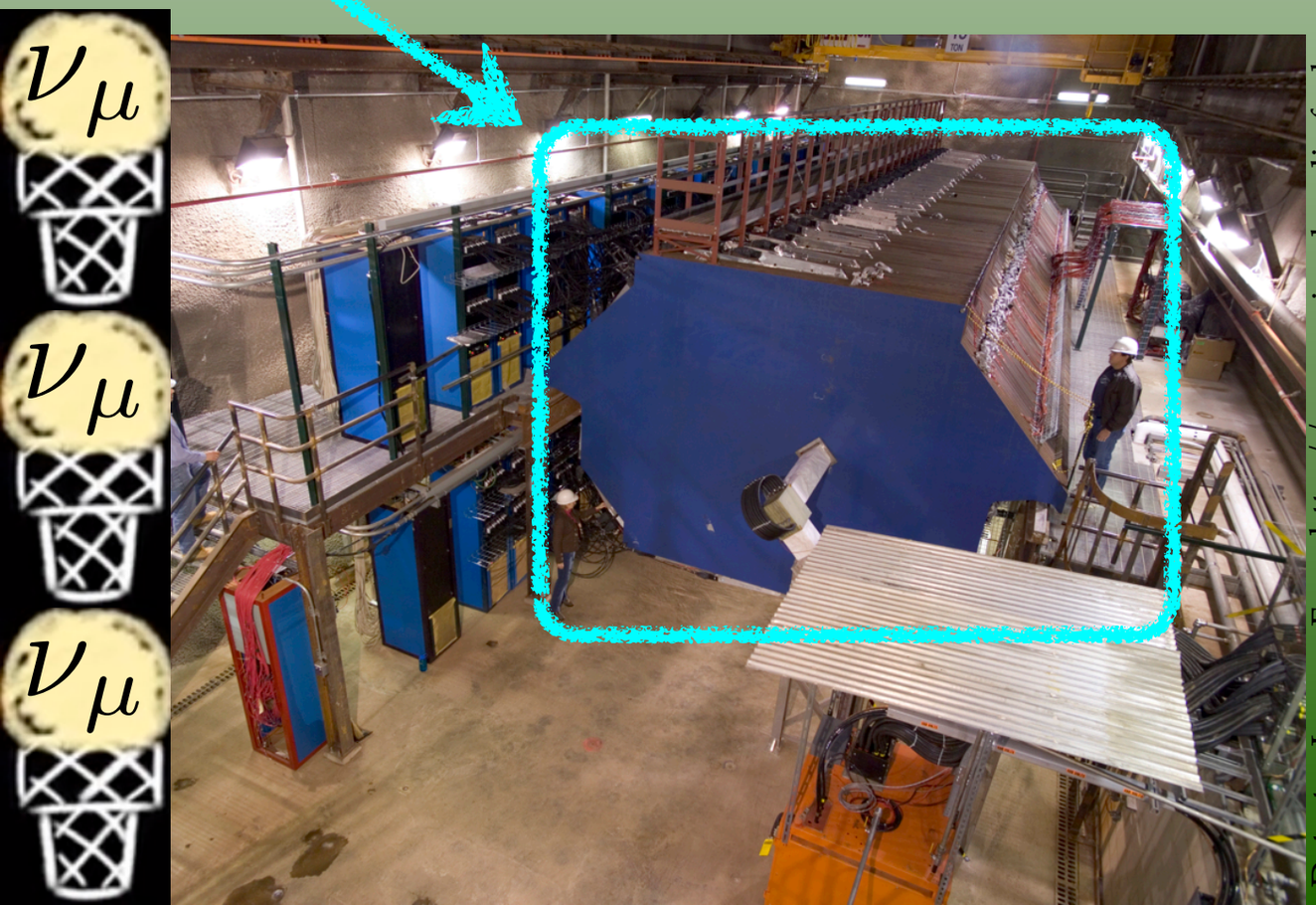
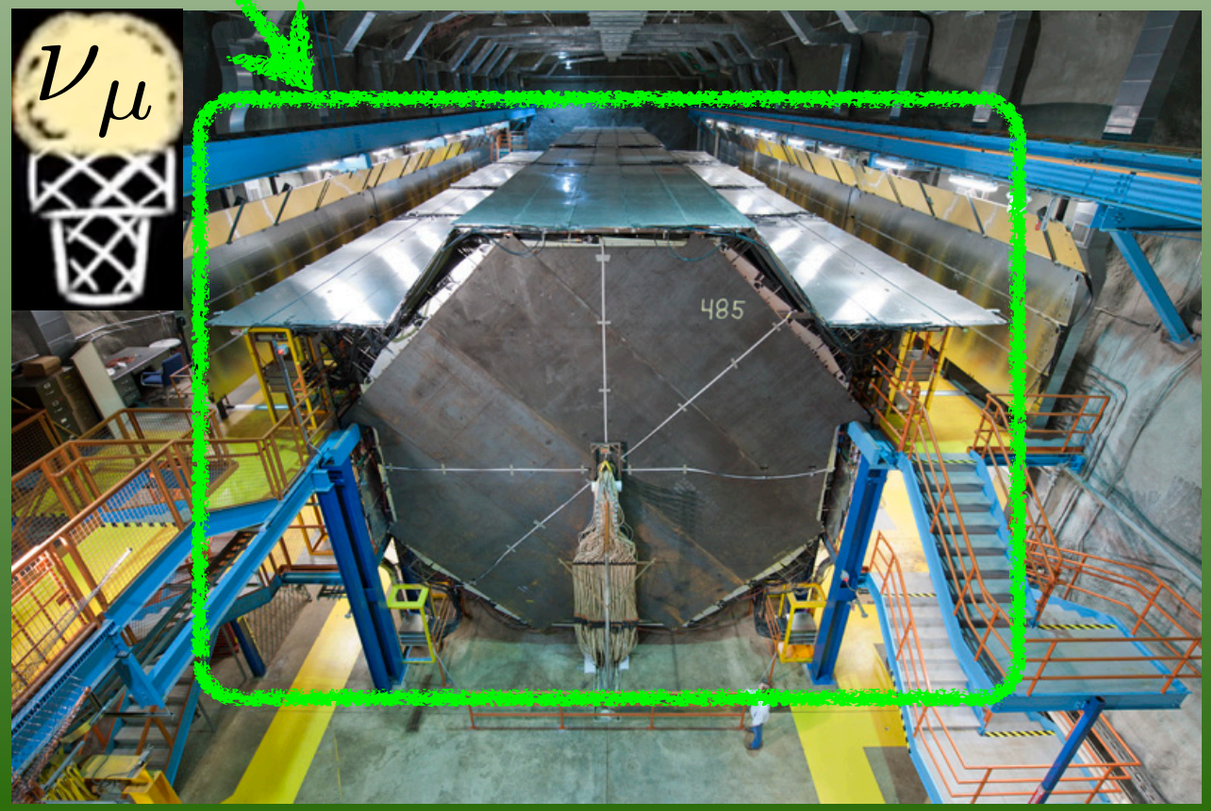


Image: Michelle M. de Medeiros, Universidade Federal de Goias Brasil

The MINOS detectors can only see ν_μ

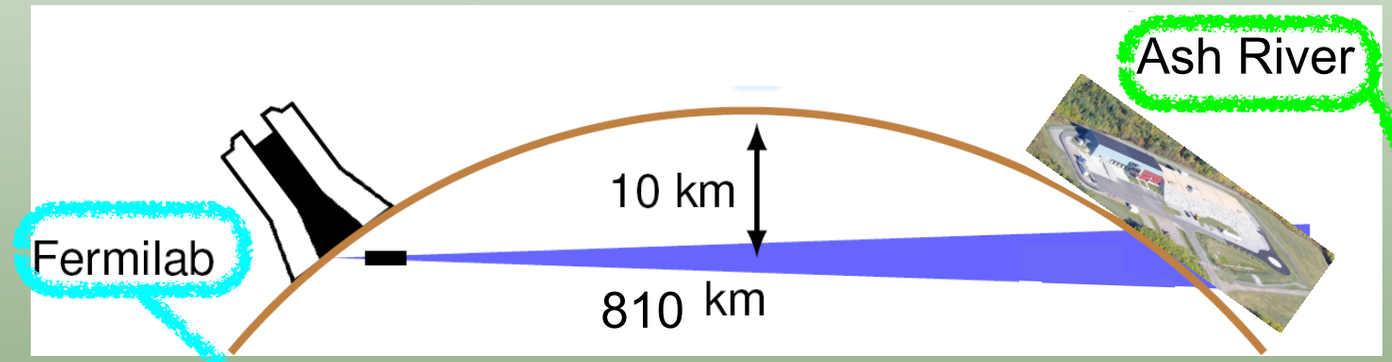


Detector Images From http://www-visualmedia.fnal.gov/



NOvA Will See Another Flavor

- We make a beam of ν_μ and send it through the earth



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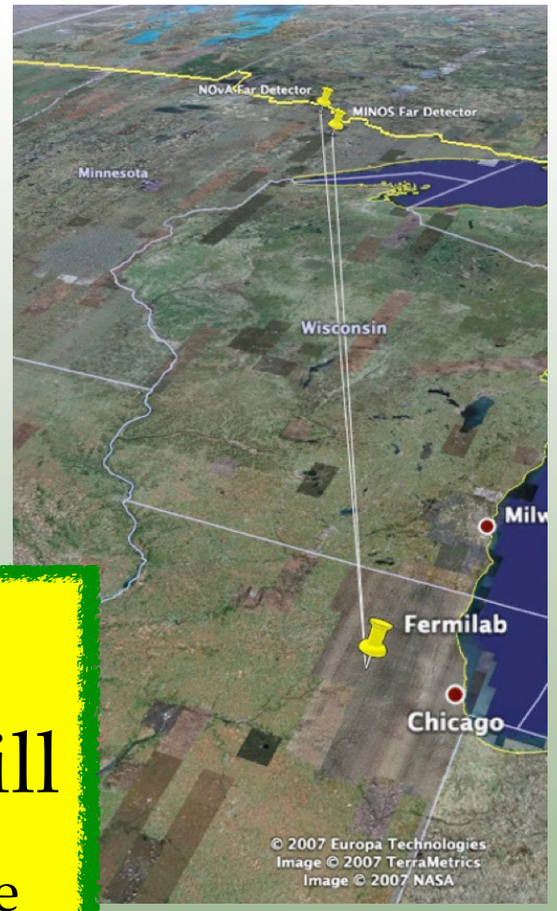
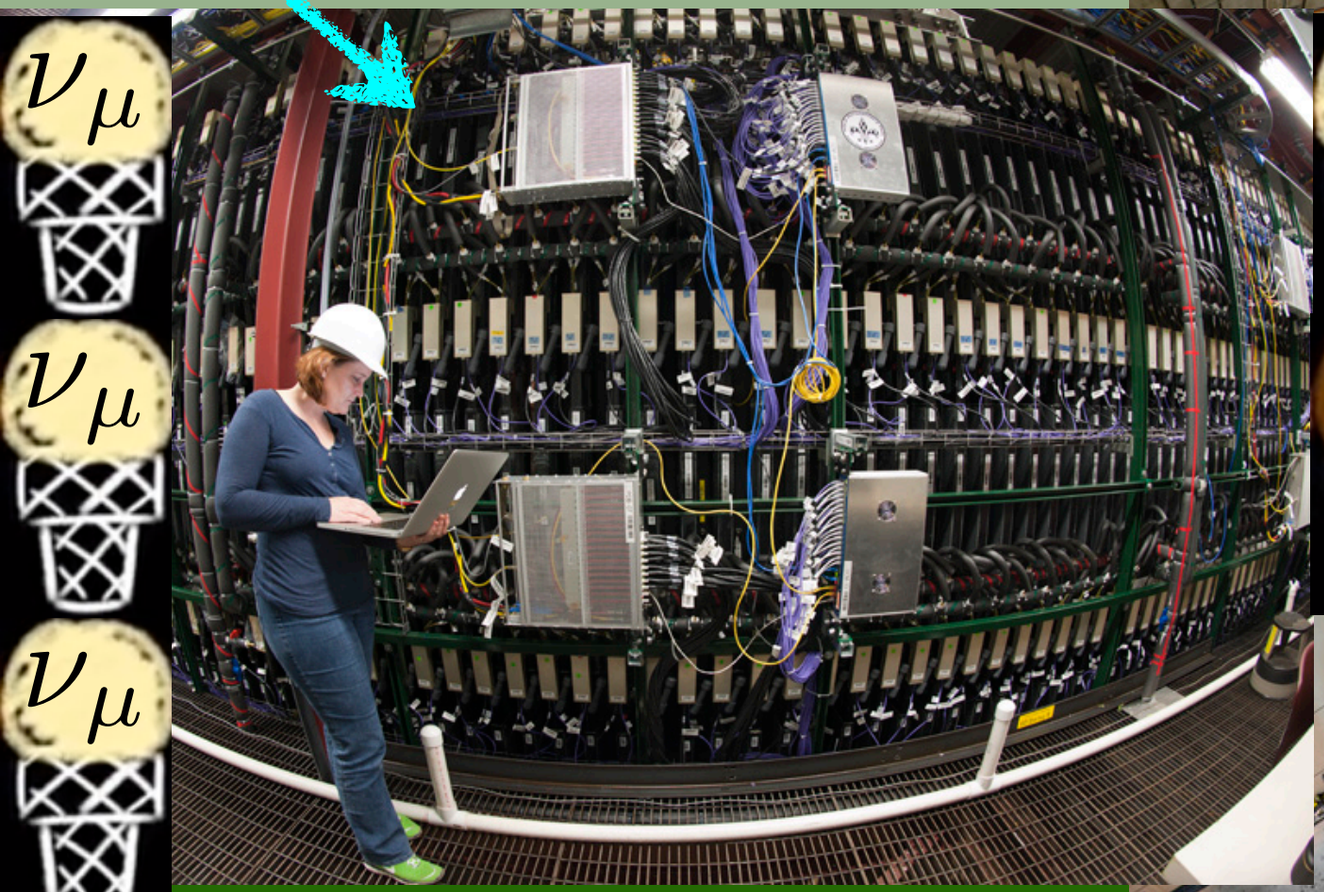
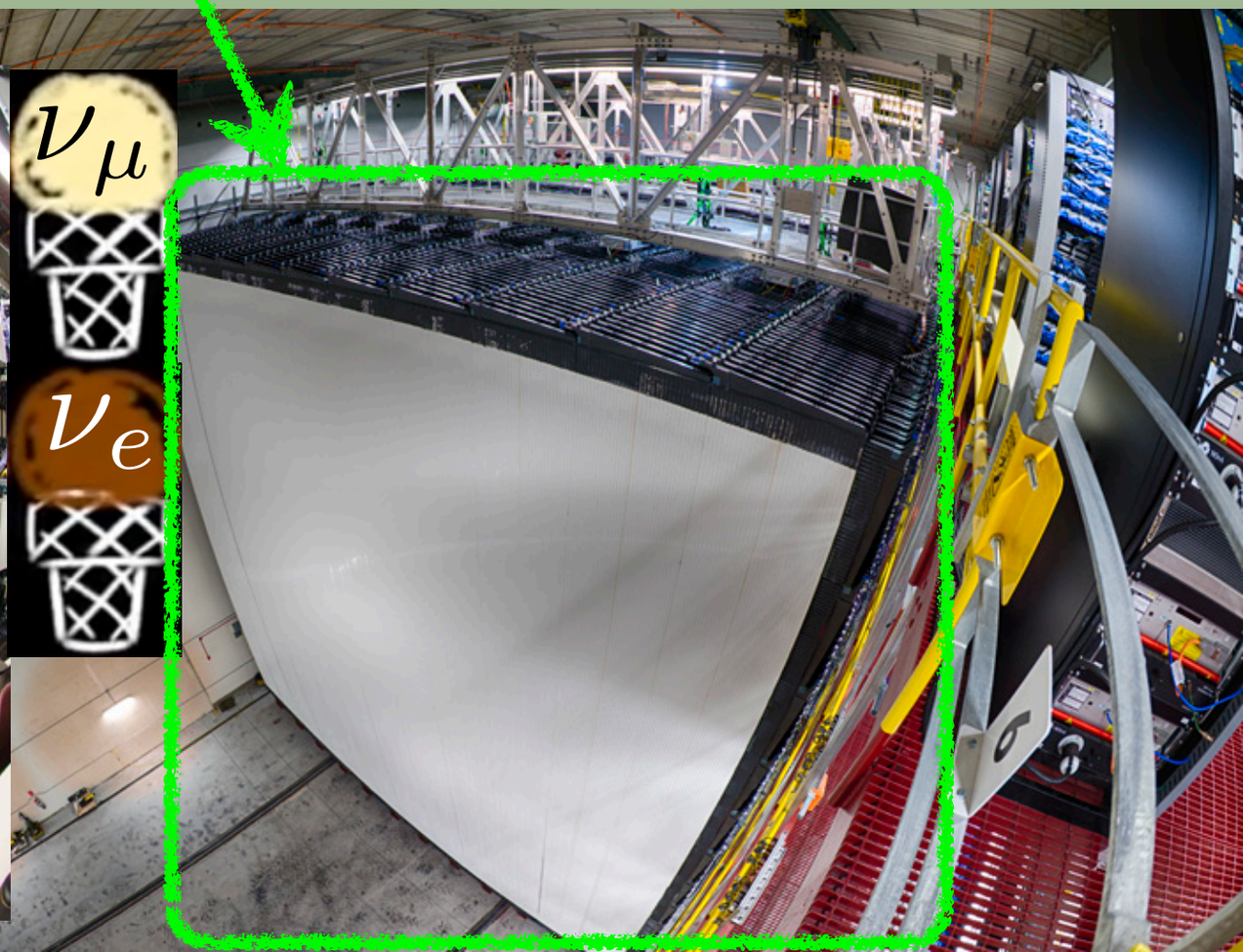


The NOvA detectors will see ν_μ *and* ν_e



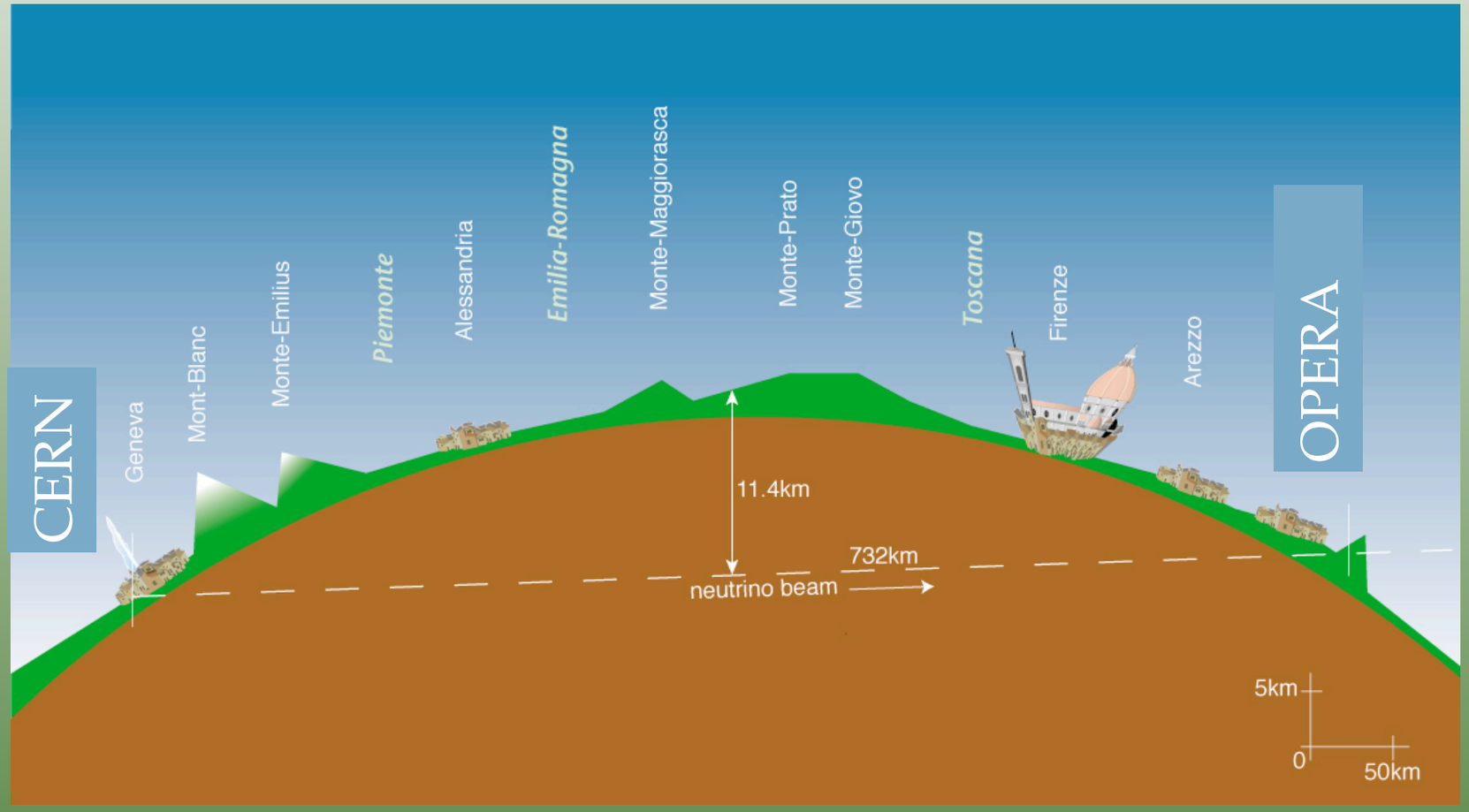


...usually travel very very close to (but slower than) the speed of light.

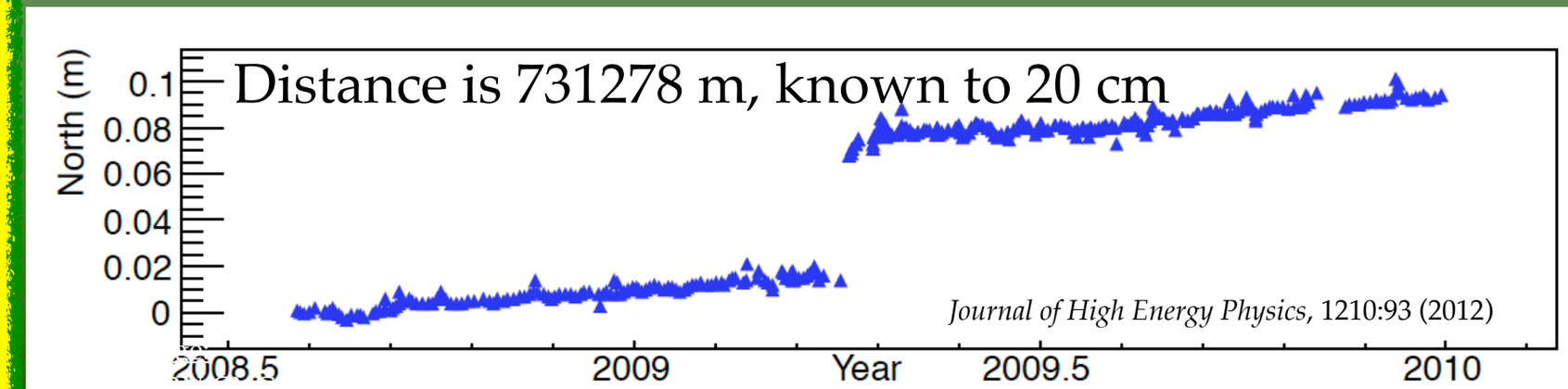
$$\text{Speed} = \frac{\text{Distance}}{\text{Time}}$$

Faster than light?

The Speed of Light $c = 299,792,458\,\frac{\text{m}}{\text{s}} = 670,616,629$ mph



GPS technology enables measurement of distance with sufficient precision.



$$\text{Speed} = \frac{\text{Distance}}{\text{Time}}$$

Measuring Time

In 2011, OPERA reported neutrinos arriving 60 ns (6×10^{-8} s) early!

If true, this would have disproven Einstein's Special Theory of Relativity.

In response, multiple other experiments made the same measurement and found no deviation from *c*.

In June 2012, OPERA announced they had found two mistakes.

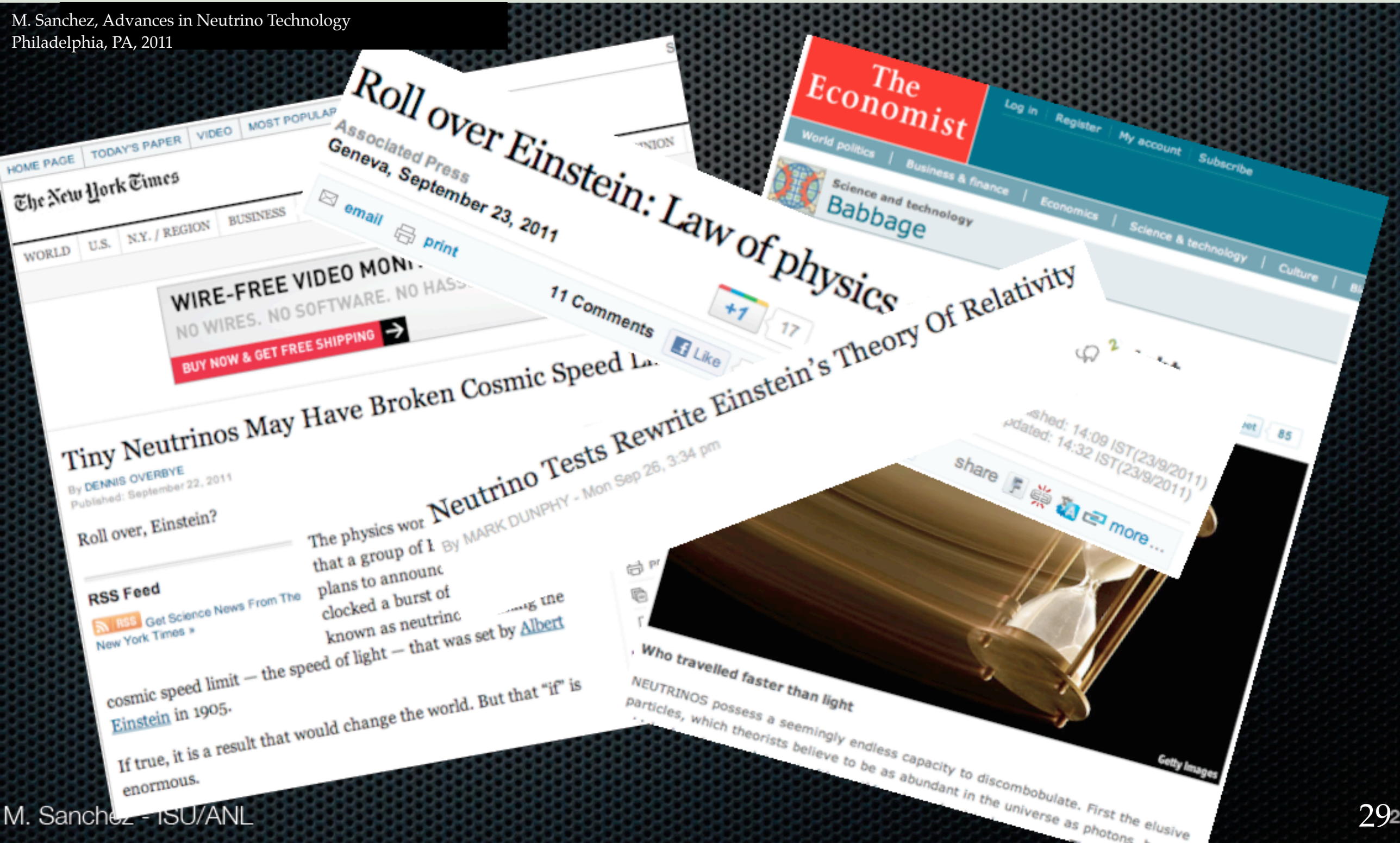
- Two identified issues:
  - Faulty connection of the optical fibre to the Master Clock artificially increasing the neutrino anticipation by ~74 ns.
  - Internal Master Clock frequency off by $\Delta f/f = 1.24\text{x}10^{-7}$ (124 ns/s) artificially decreasing the neutrino anticipation by ~15 ns
    (DAQ time bin 10 ns→9.99999877 ns).

Einstein is proven right again!

M. Dracos, The XXV International Conference on Neutrino Physics and Astrophysics, Kyoto, Japan, June 8, 2012

Is there any evidence they travel faster than light?

M. Sanchez, Advances in Neutrino Technology
Philadelphia, PA, 2011



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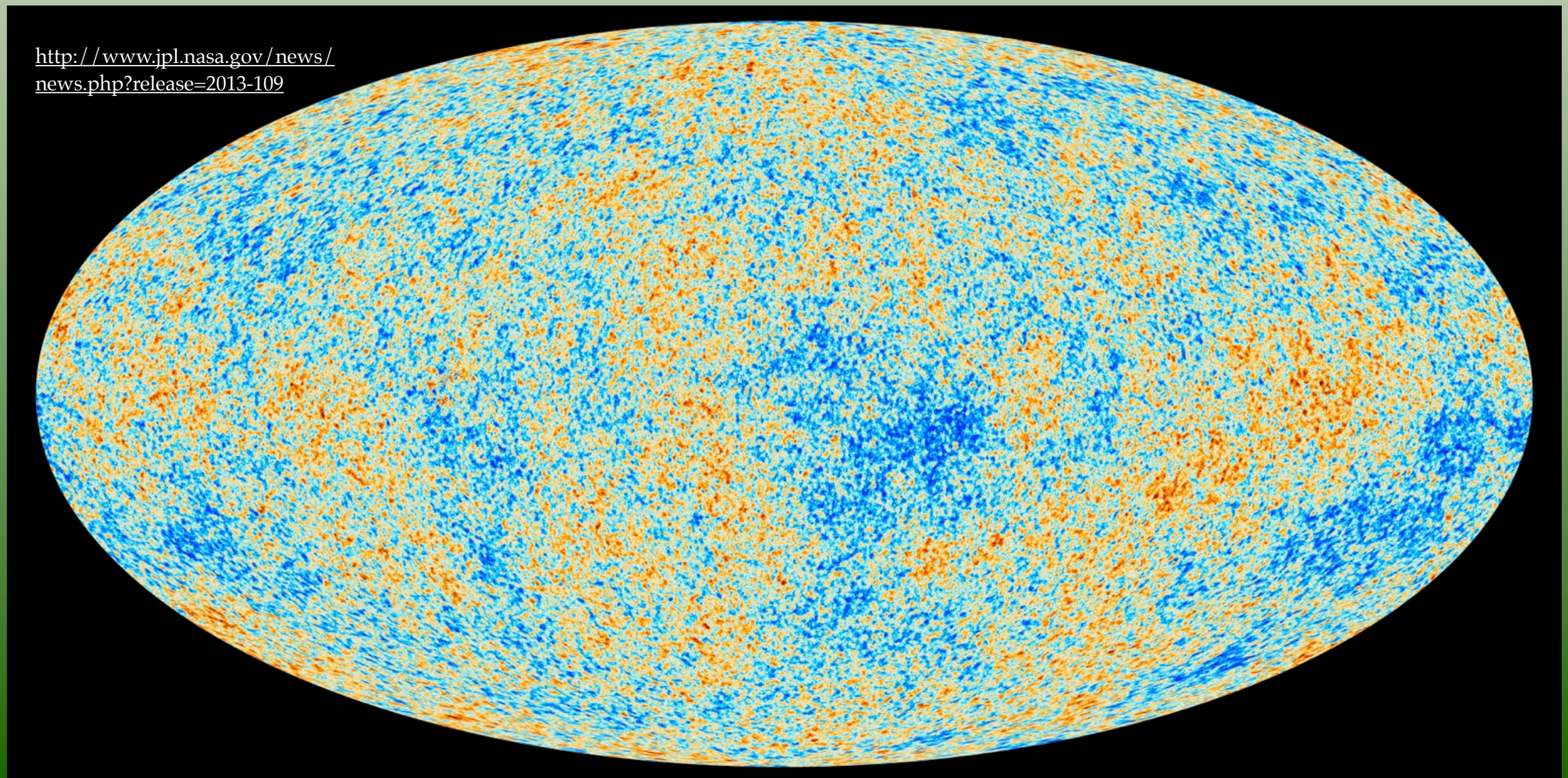
M. Sanchez, Advances in Neutrino Technology
Philadelphia, PA, 2011

...explain why we exist!

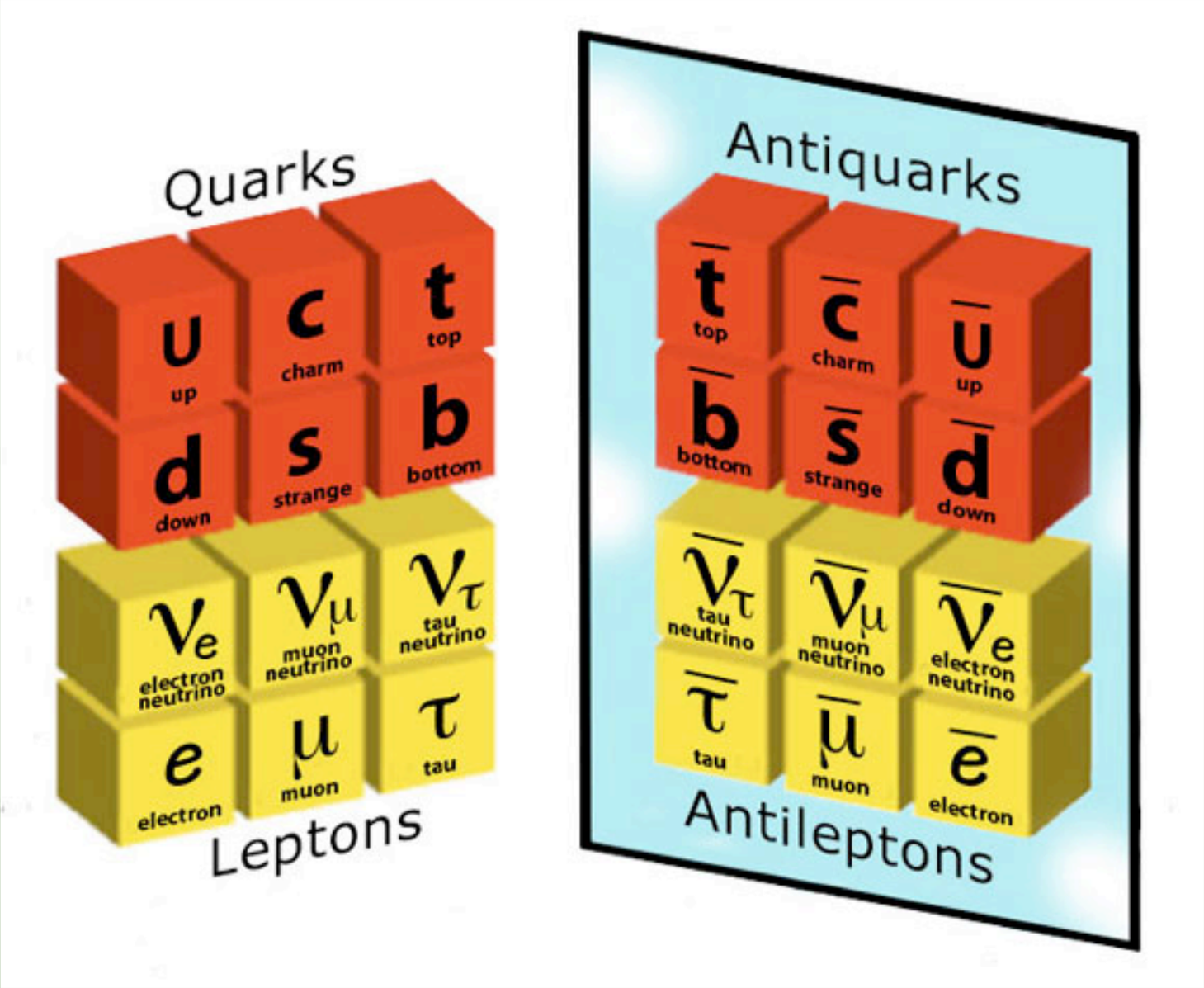
Why Are We (Still) Here?

- Matter had a slight (1 part in 10 billion) advantage over antimatter after the Big Bang. We do not know why. Neutrinos could hold the answer.



Is Antimatter Just Matter in a Mirror?

- Matter & antimatter must behave slightly differently in order to explain our existence.
- We have not found enough differences in the behavior of other particles.
- **It might be hiding in the neutrinos!**



...have many more surprises in store!

"...there are **known knowns;** there are **things we know we know**.
We also know there are **known unknowns;** that is to say **we know there are some things we do not know.**
But there are also **unknown unknowns -- the ones we don't know we don't know.**"

- US Secretary of Defense Donald Rumsfeld

Known Unknowns...

- ✳Do neutrinos explain the matter-dominated Universe?
- ✳What are the neutrino masses?
- ✳Why are they so light?
- ✳What exactly are the neutrino "recipes"?

- ✳Are neutrinos their own antiparticles?
- ✳Are there more than 3 flavors of neutrino?
- ✳Can we find the Cosmic *neutrino* background?
- ✳What can neutrinos tell us about Earth's interior?

Unknown Unknowns

Unknown Unknowns

Neutrinos could and probably do have many more surprises in store.

We do not know what great discoveries await. This is the most exciting part of science!

To those of you who are students, if you become a physicist, you could help answer some of the questions we know how to ask and even those we don't!

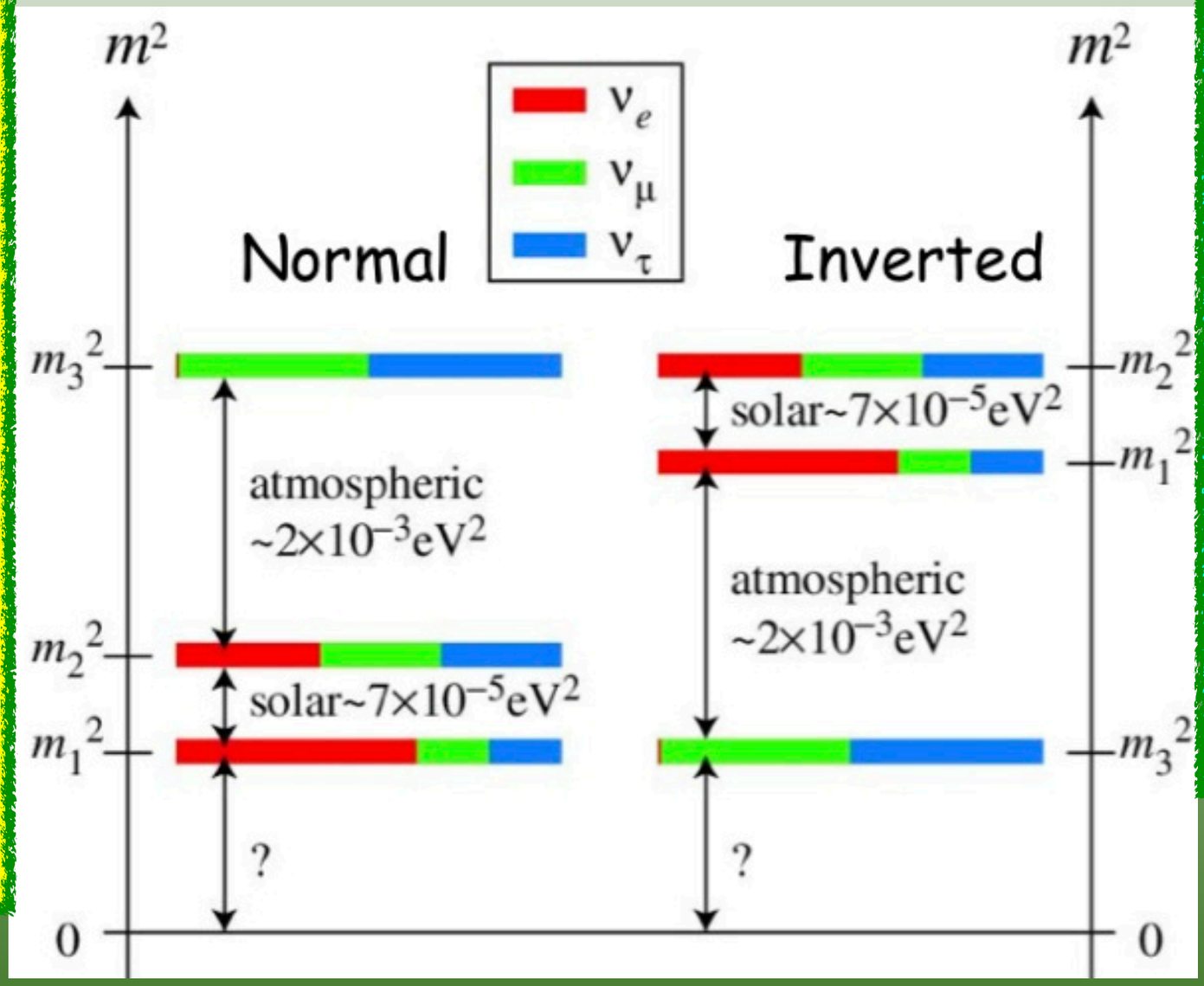
Thank You!

A Problem in the Sun?

- In *The Songs of Distant Earth* by Arthur C. Clarke, the neutrino deficit is a sign the sun will soon explode
- Fortunately, the real answer turns out to be a great relief (and even stranger)...
- Note that Davis' experiment could only detect *one* kind of neutrino

Great, now he's speaking German...

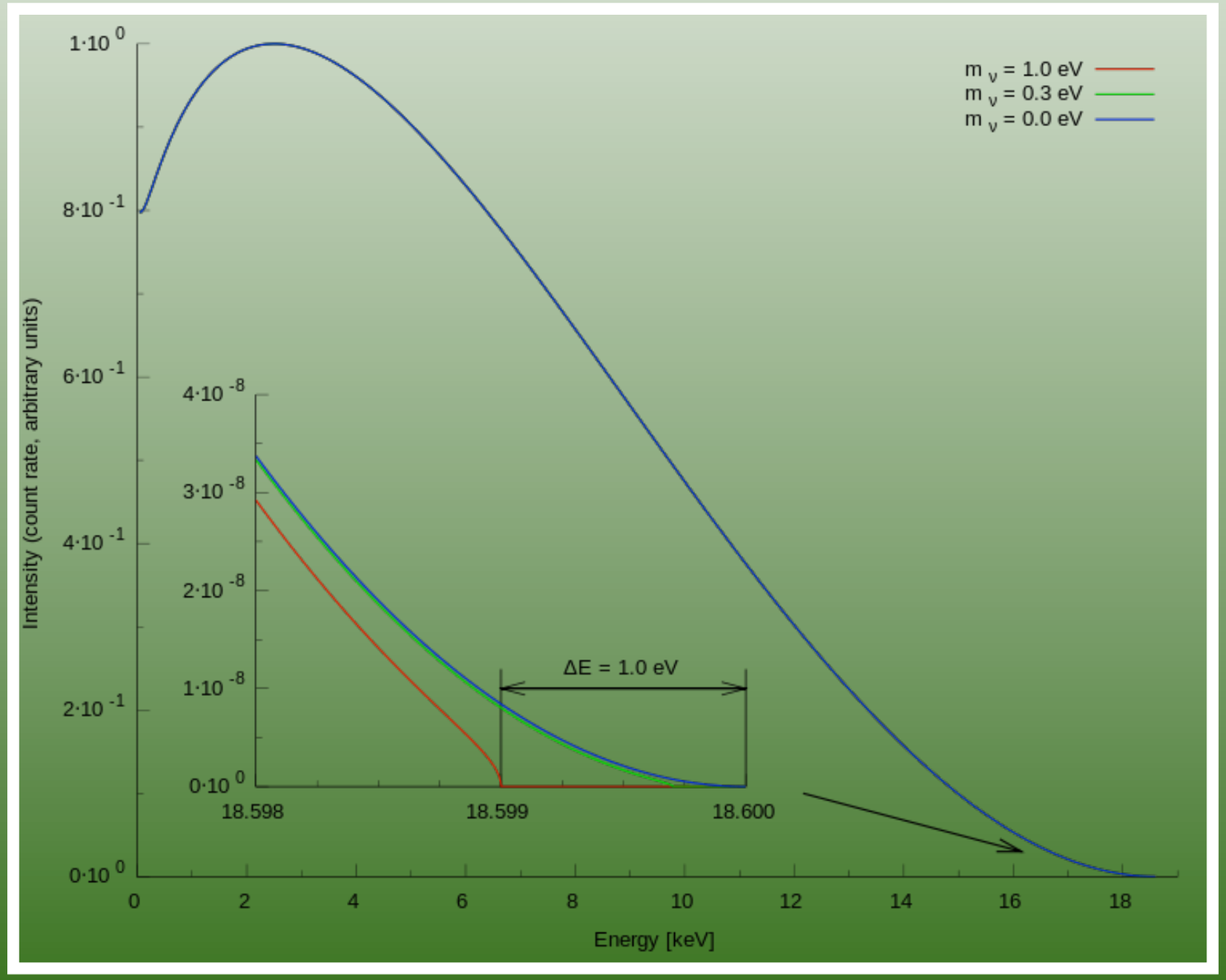
What actually propagates through space are ν_1, ν_2 ,ν_3, which have definite mass and are mixtures of ν_e, ν_μ ,ν_τ



We have measured and are measuring the difference between the masses and the composition of ν_1, ν_2, and ν_3

http://neutel11.wordpress.com/2011/03/16/neutrino-mass-models-by-steve-king/

How light are they



Connected to the Universe

✳The Universe is governed by four interactions

Strong Nuclear	Electromagnetic	**Weak Nuclear**	Gravity
Neutrinos do not feel these interactions	**Neutrinos are the only particles to feel *only* this force and gravity.**	Too weak to matter in particle physics

They are a unique window to understanding this foundational part of our Universe.

Scales and Units

The scales involved in particle physics are well outside of our everyday experiences.
Welcome to the world of the very small...

The Speed of Light $c = 299,792,458 \frac{\mathrm{m}}{\mathrm{s}} = 670,616,629 \text{ mph}$

<u>Energy</u>

An electron volt (eV) is the amount of energy required to move an electron across a 1 volt potential.

$1 \text{ eV} = 4.4 \times 10^{-20} \text{ kW}\cdot\text{hr}$

<u>Mass</u>

Mass and energy are related by Einstein's $E=mc^2$, which means $m = E/c^2$.

$$1 \text{ eV}/c^2 = 1.782 \times 10^{-33} \text{g}$$

The mass of a grain of sand is about $2 \times 10^{27} \text{ eV}/c^2$

Electron Mass $= 510,999 \text{ eV}/c^2$