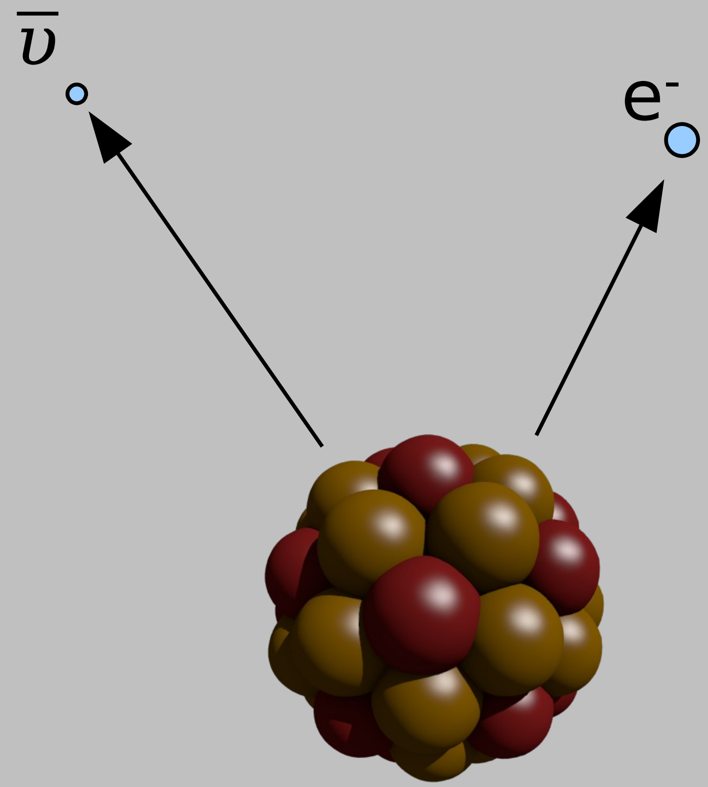
Neutrino Oscillations



Robert Knop

Associate Professor of Physics

Westminster College

Science Center, Second Life, 2016-01-02

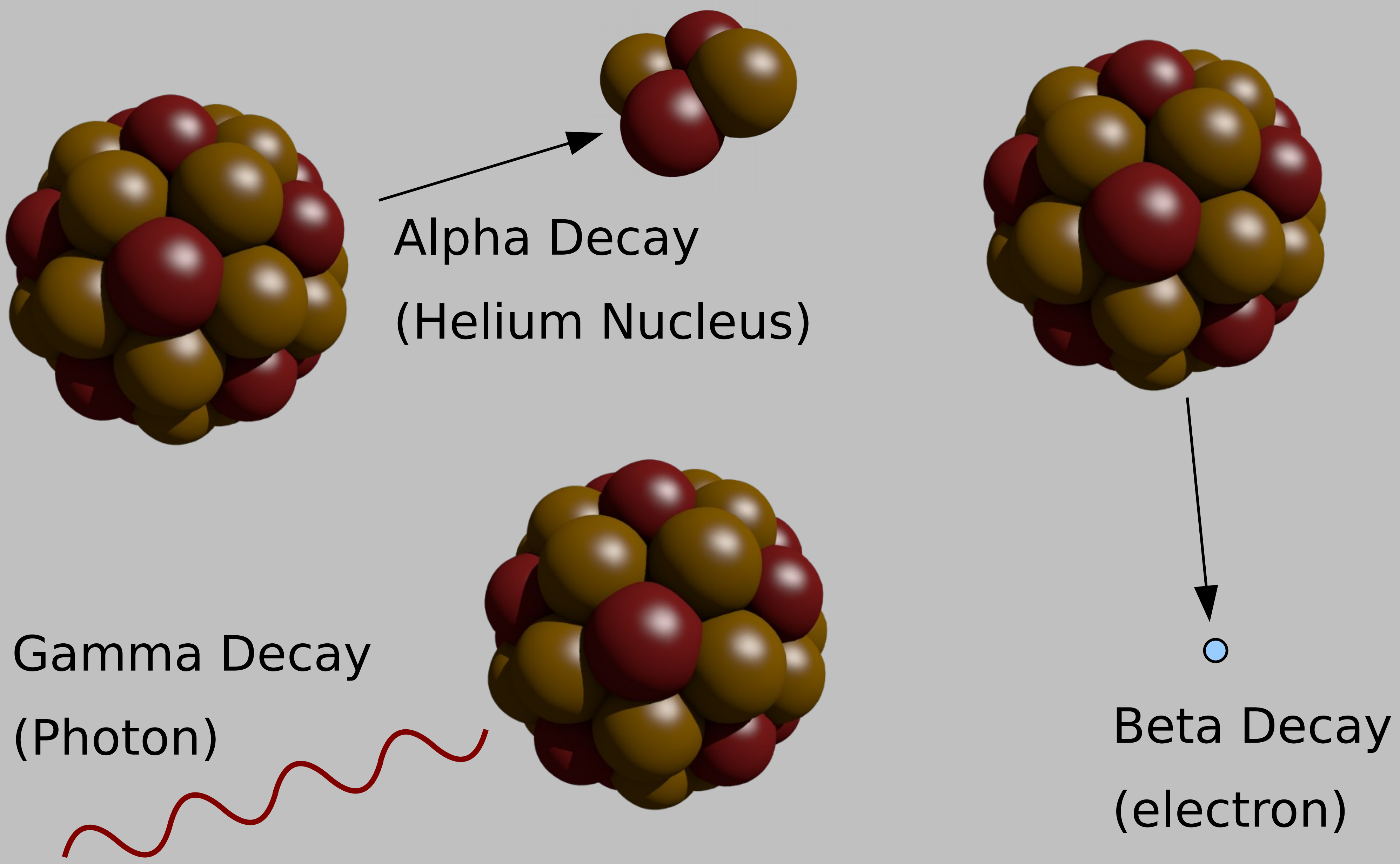
The 2015 Nobel Prize in Physics

Takaaki Kajita

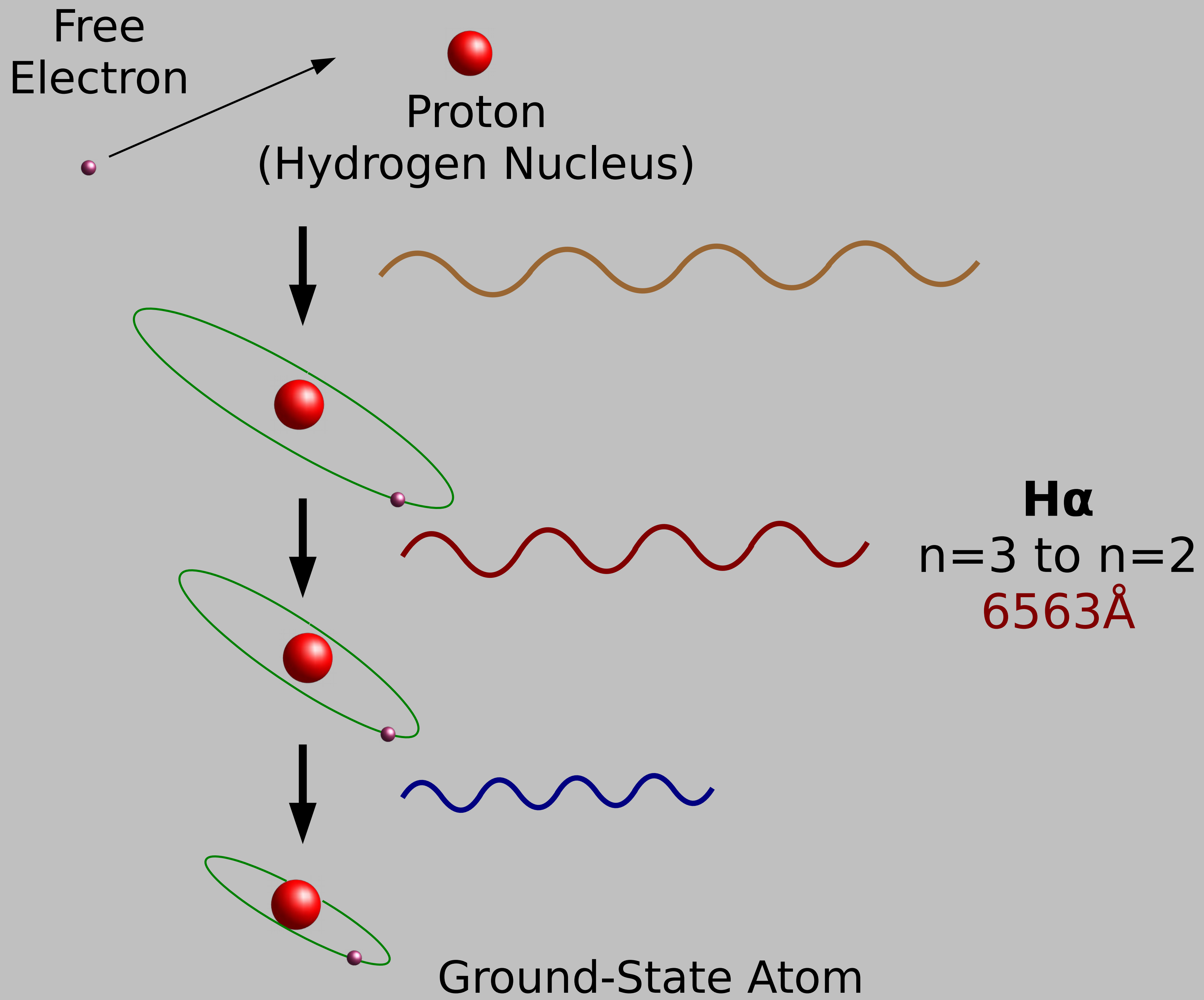
Arthur B. McDonald

"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

Nuclear Decay



Hydrogen Recombination Radiation

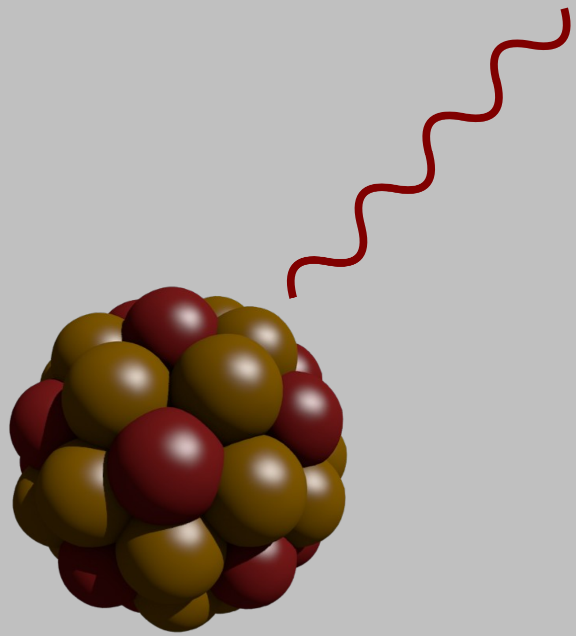


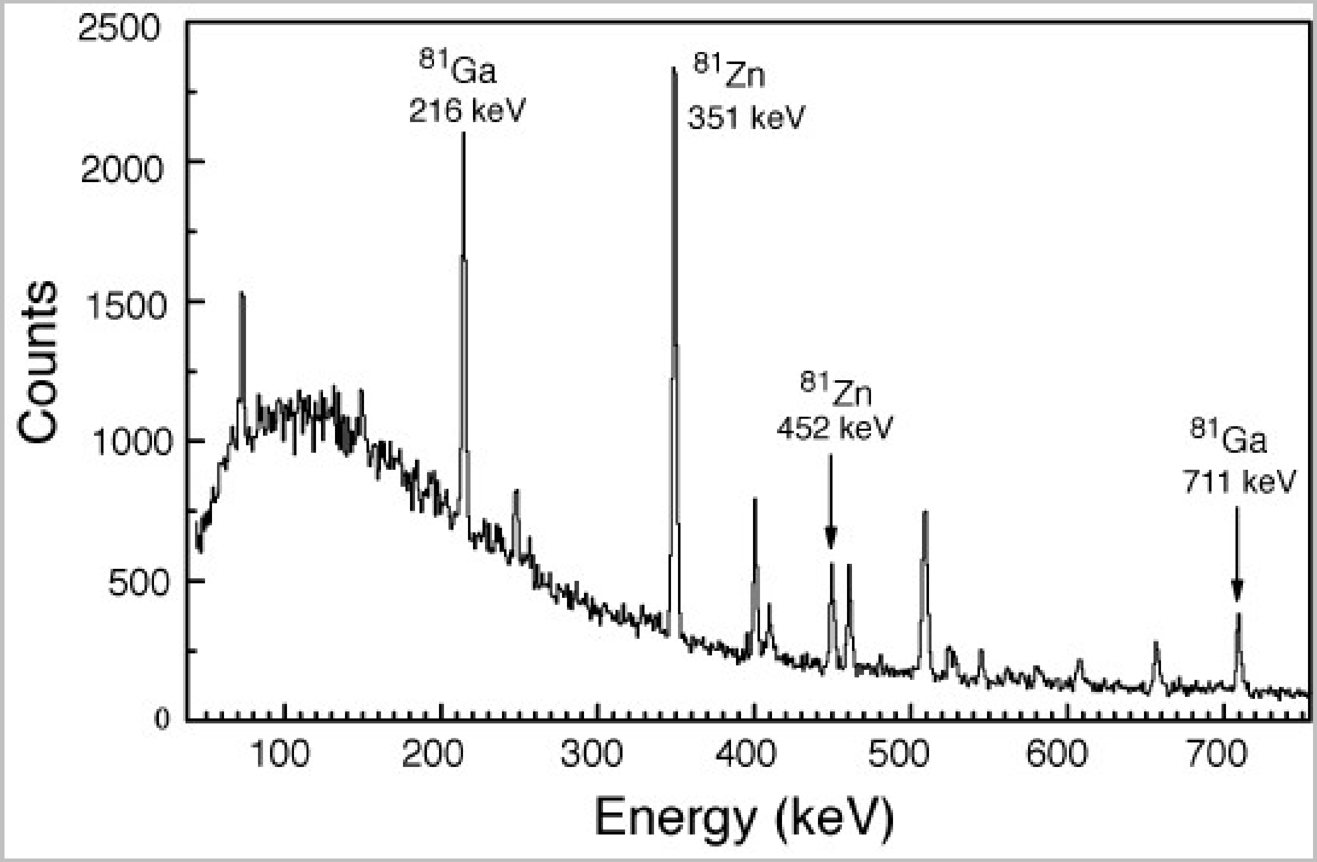
Visible Spectrum of Hydrogen

Hα
n=3 to n=2
6563Å

Image: Jan Homann

Nuclear Gamma Decay

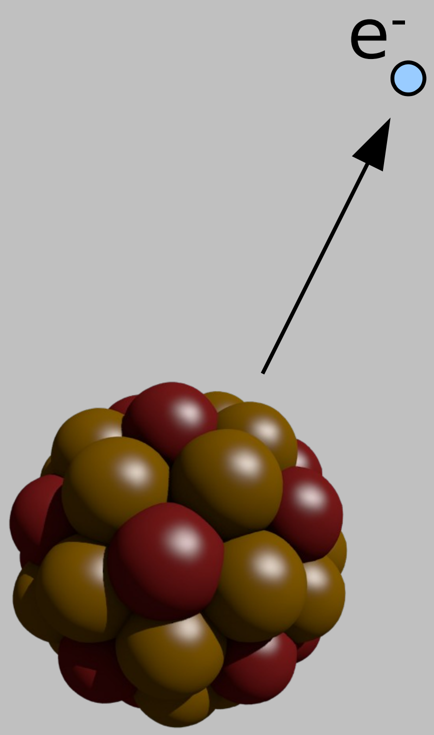




- Comes in specific emission lines like atomic transitions
- Indicates nucleon states are also quantized

Gamma spectrum from Rykaczewski et al., http://www.phy.ornl.gov/hribf/news/feb-09/printable.html

Nuclear Beta Decay



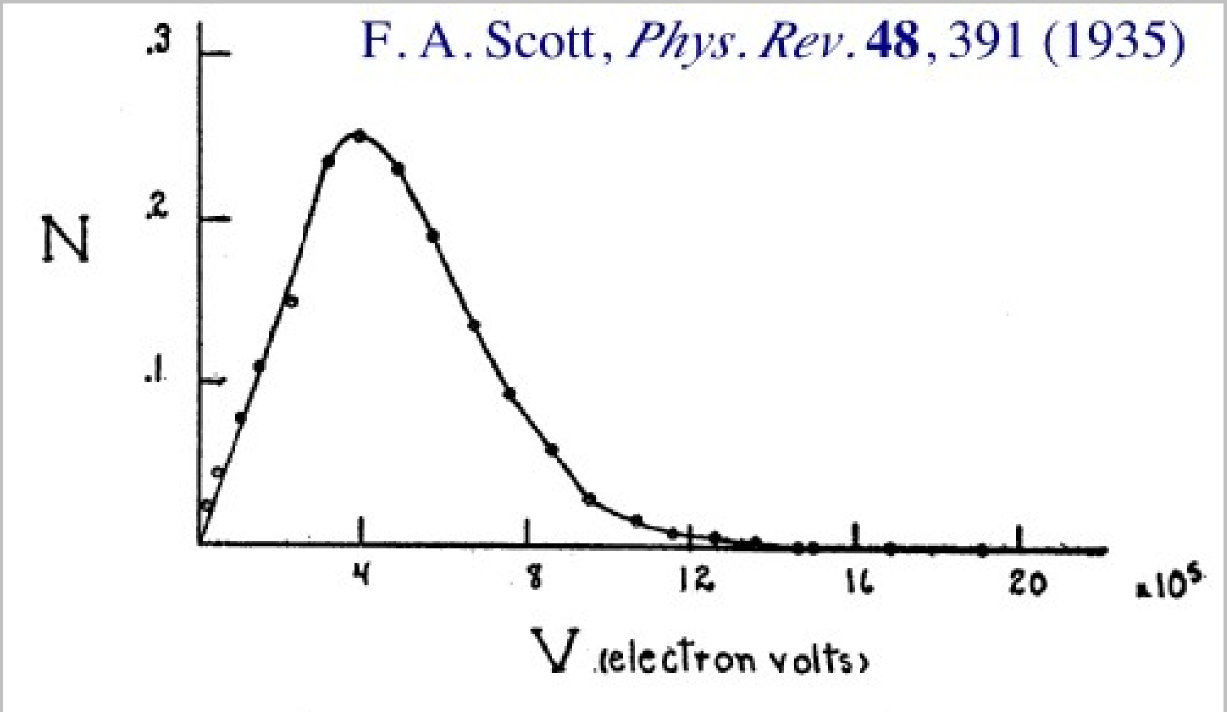


FIG. 5. Energy distribution curve of the beta-rays.

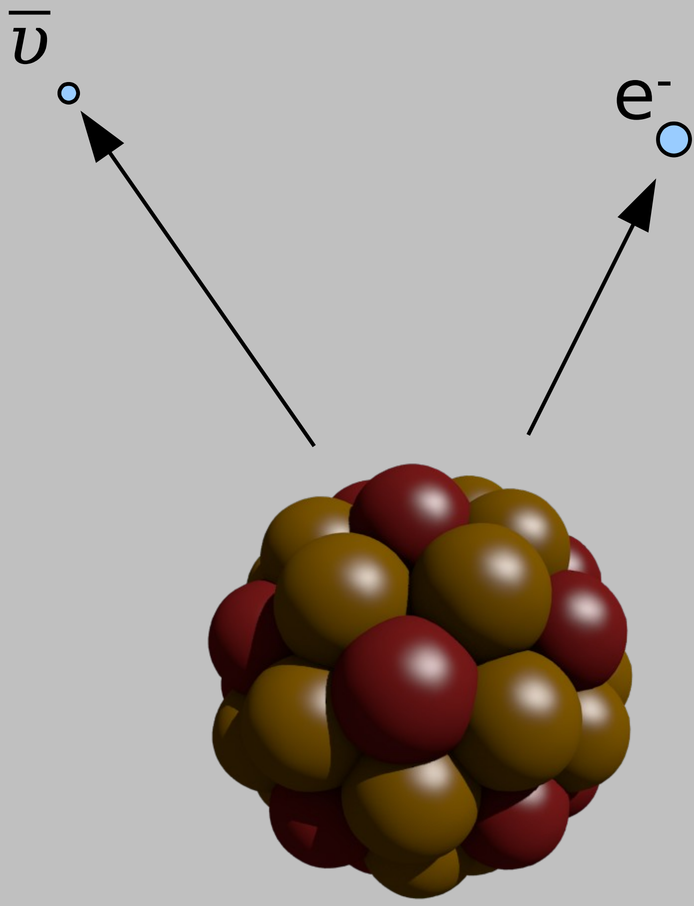
- A continuous spectrum
- Hard to reconcile with quantized nuclear states!

Three guiding principles of physics:

- conservation of momentum
- conservation of angular momentum
- conservation of energy

1930's : Beta Decay had physicists following a suggestion from Niels Bohr; they entertain the idea that energy is *not* conserved in (some) elementary processes.

Pauli's Alternative



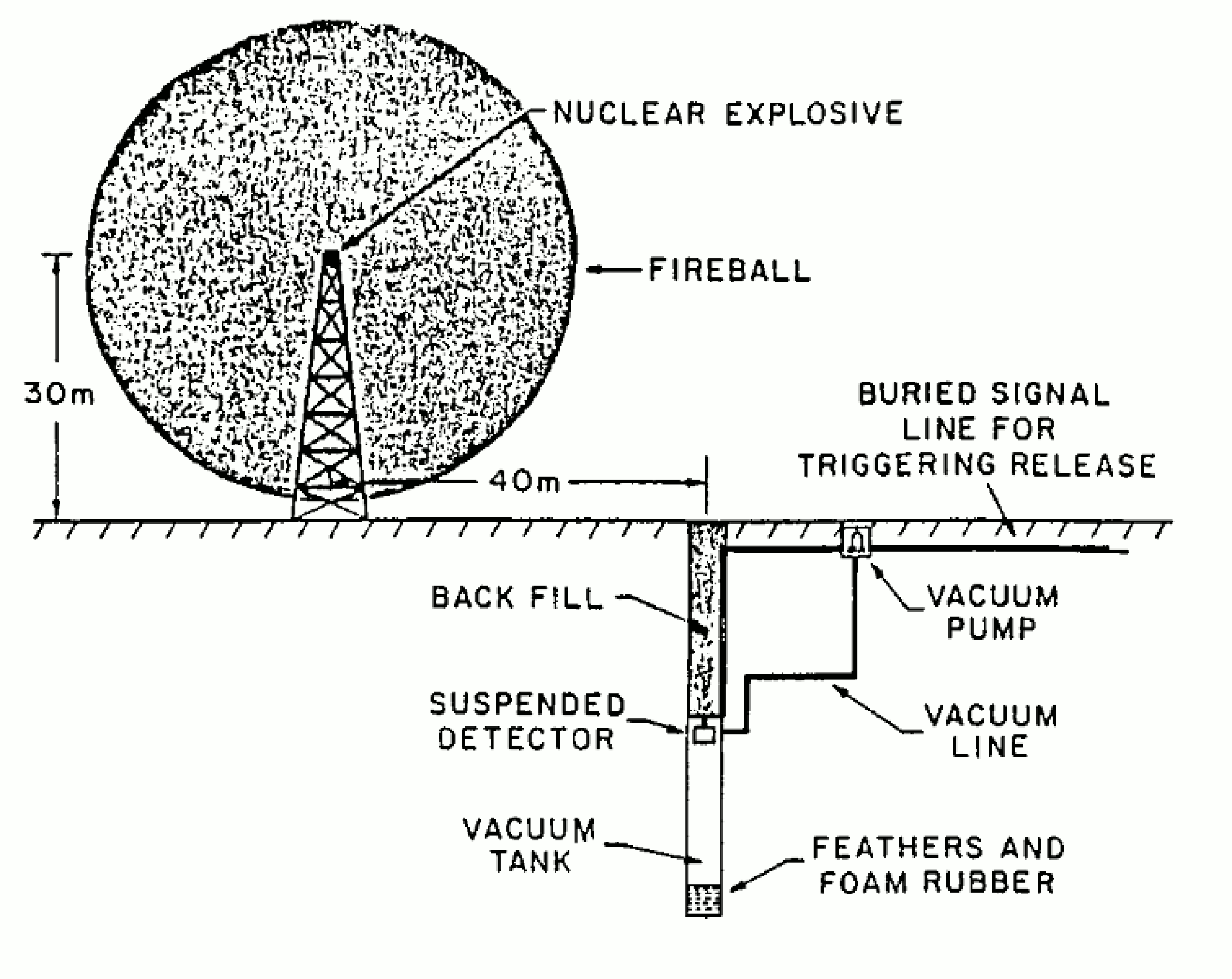
$$n \rightarrow p + e^- + \bar{\upsilon}$$

I admit that my expedient may seem rather improbable from the first, because if [neutrinos] existed they would have been discovered long since. Nevertheless, nothing ventured nothing gained . . . We should therefore be seriously discussing every path to salvation.'

- Pauli, 1930

From Reines, 1996, Rev. Mod. Phys, 68, 317

Discovering the Neutrino

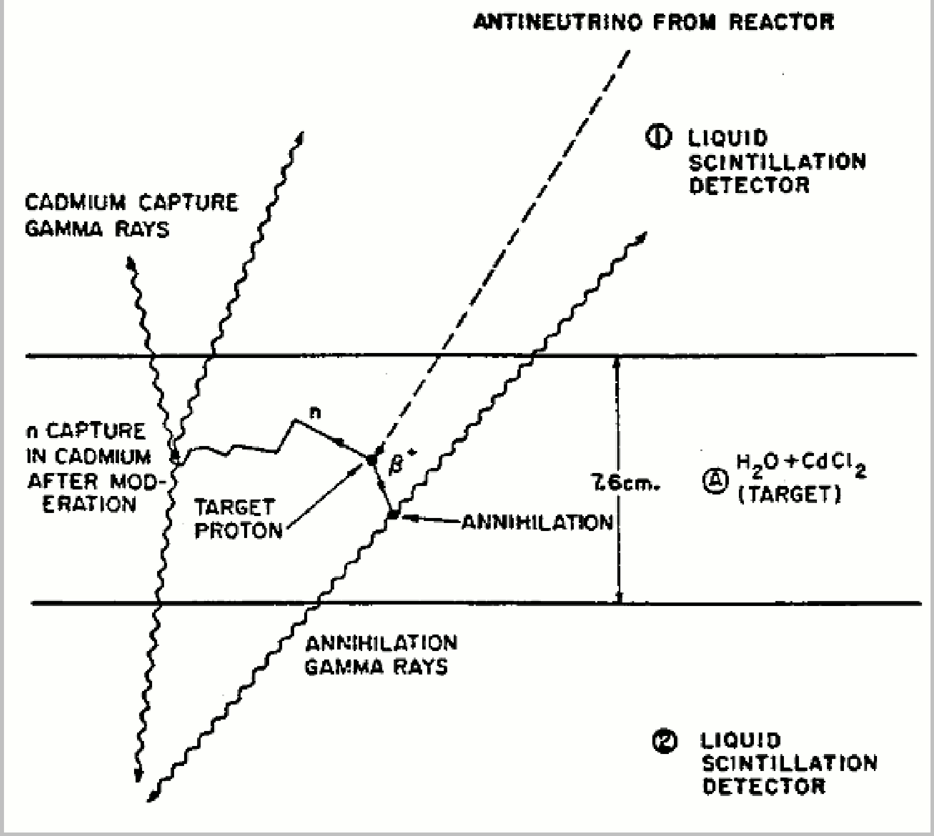


Proposed (and approved) experiment to detect:

$$n + e^{+} \rightarrow p + \bar{\upsilon}$$

Reines 1996

Near the Savannah River, NC Nuclear Reactor, 1956

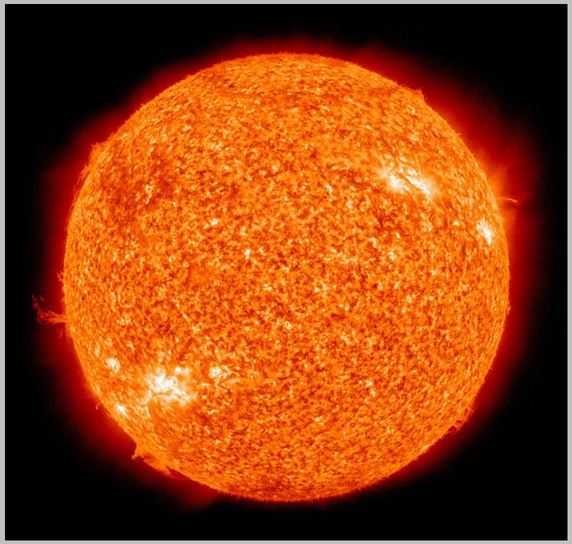


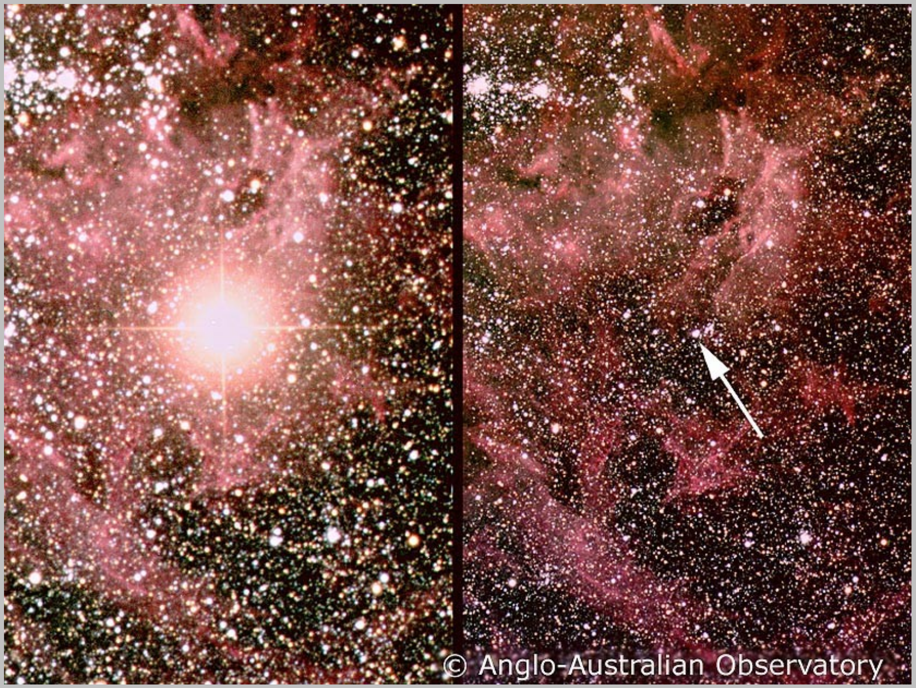
Neutrinos discovered, 26 years after they were hypothesized.

Cowan et al., 1956, *Science*, 124, 103

Image: Reines 1996

Neutrino Astronomy

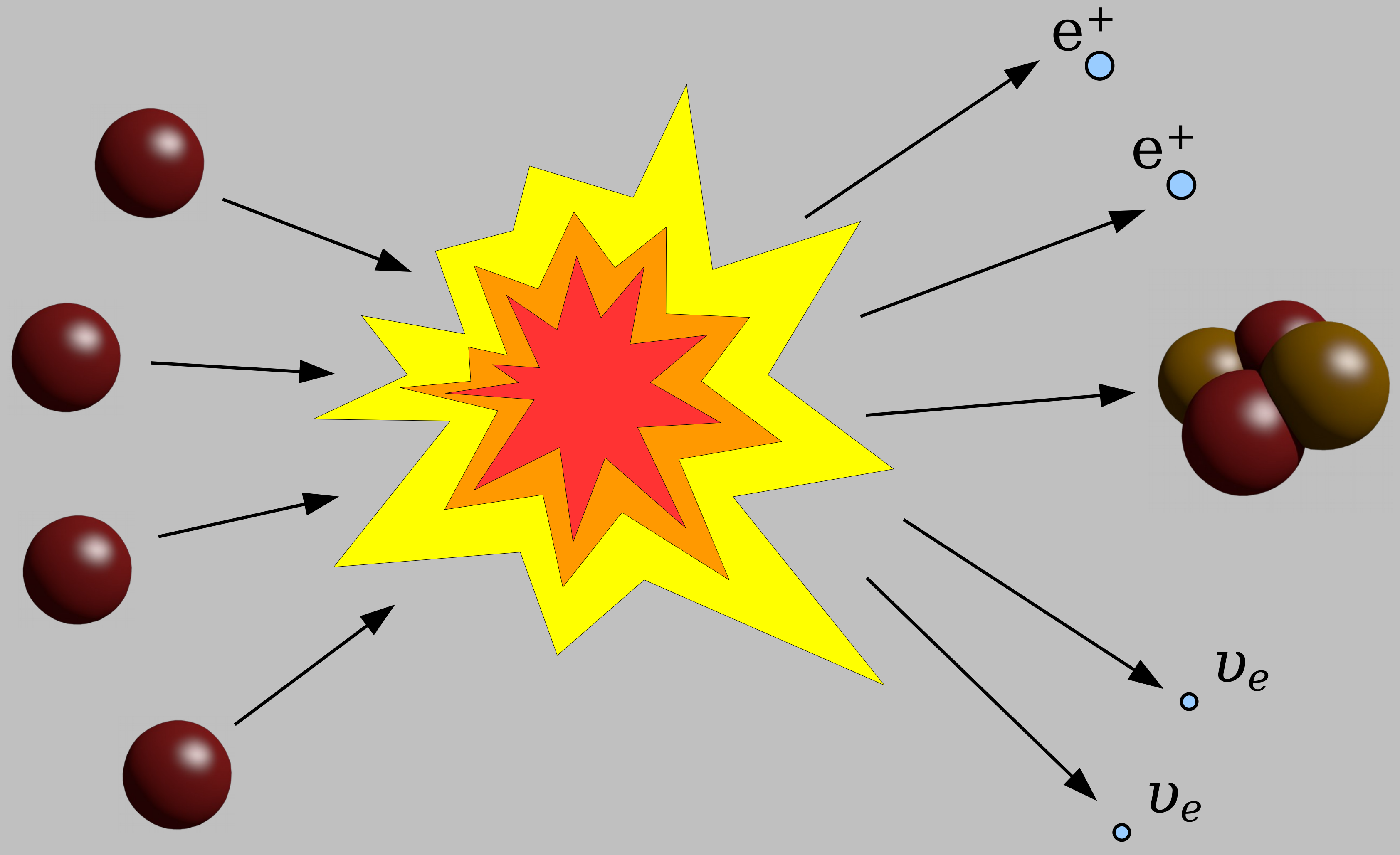




So far: two individual objects

Ultra-high-energy neutrinos: IceCube, 2013
(diffuse background? Source unknown!)

Neutrinos from the Sun



$$4p \rightarrow \alpha + 2\,e^{+} + 2\,\upsilon_e$$

Detecting Solar Neutrinos

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

John Bahcall & Ray Davis at the Homestake Mine, 1964

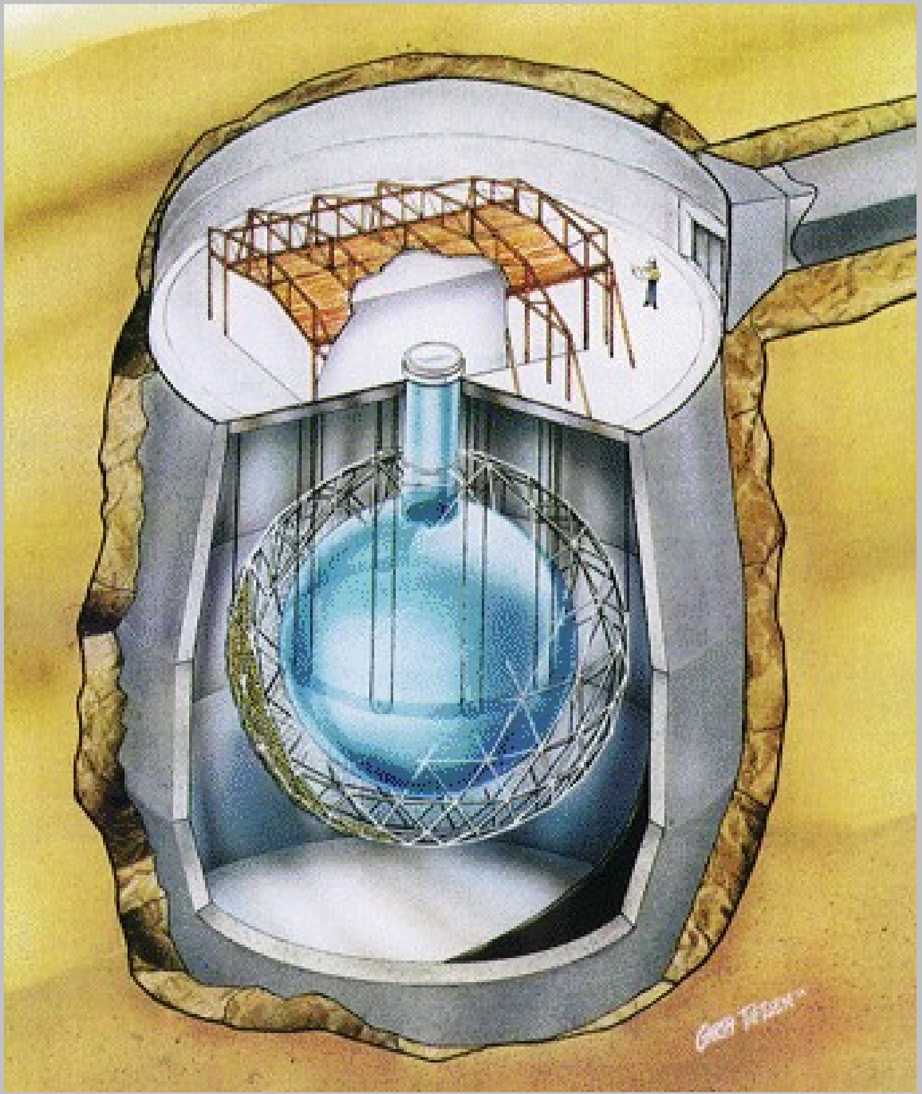
Solving the Solar Neutrino Problem

Problem: the observed flux of neutrinos from the sun is only 1/3 what's expected!

Possible solutions:

- Something is weird about the Sun
- Something is weird about neutrinos

http://www.sno.phy.queensu.ca/



The Sudbury Neutrino Observatory

Neutrinos (and other particles) come in flavors

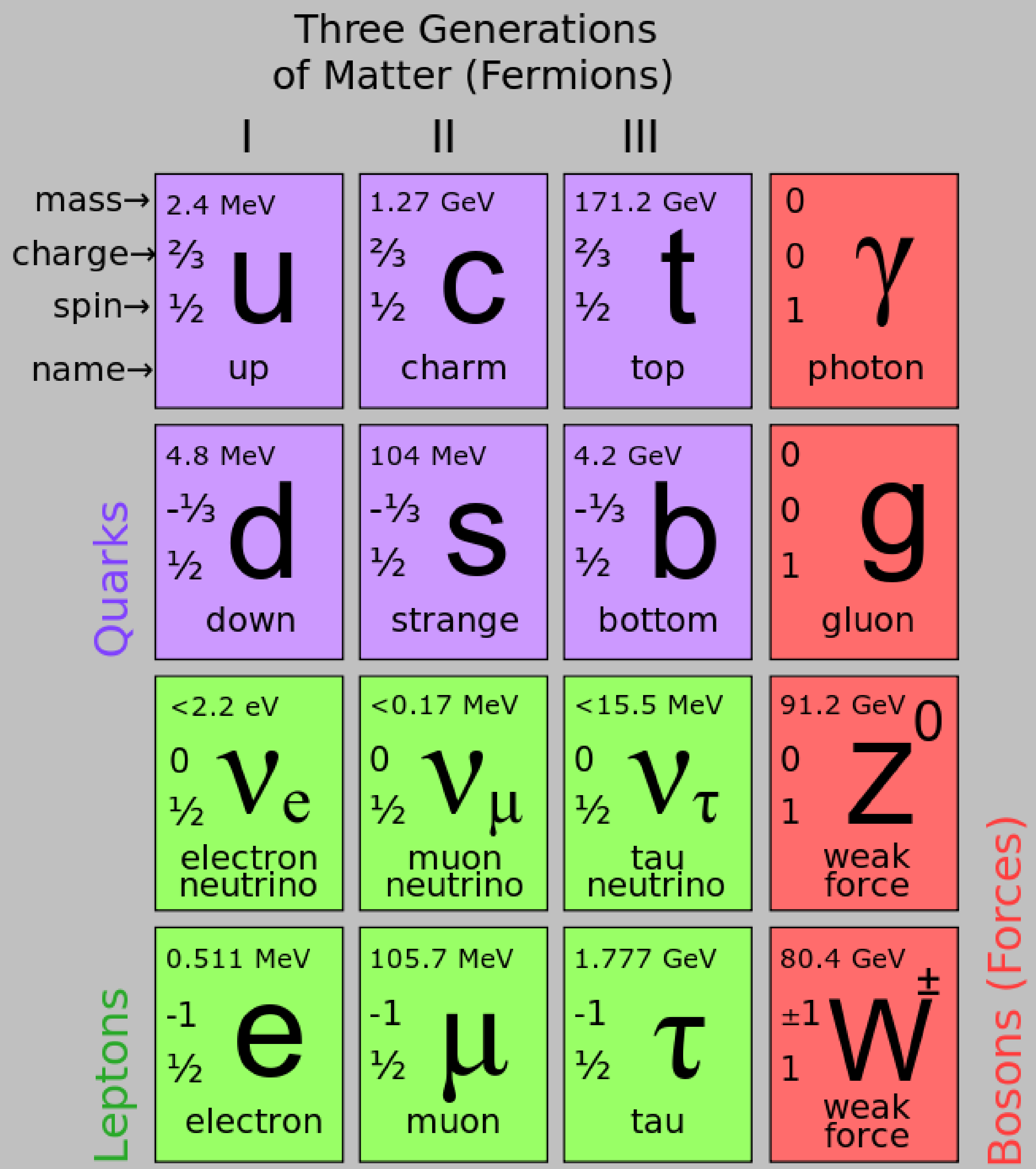
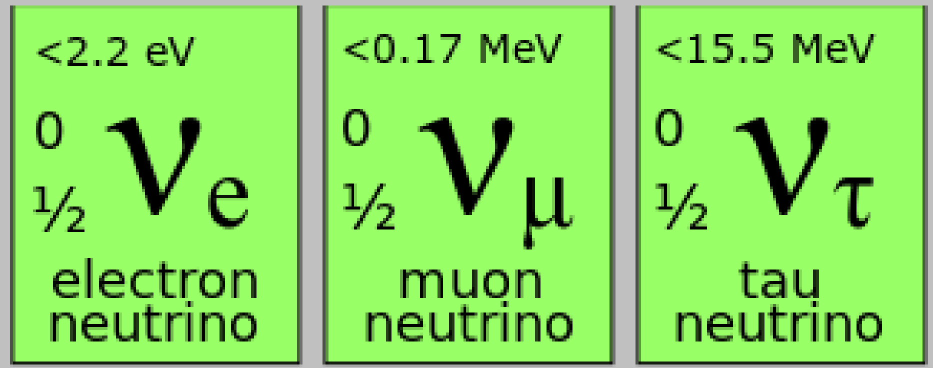


Image: Wikimedia Commons MissMJ

Measuring more types of neutrinos

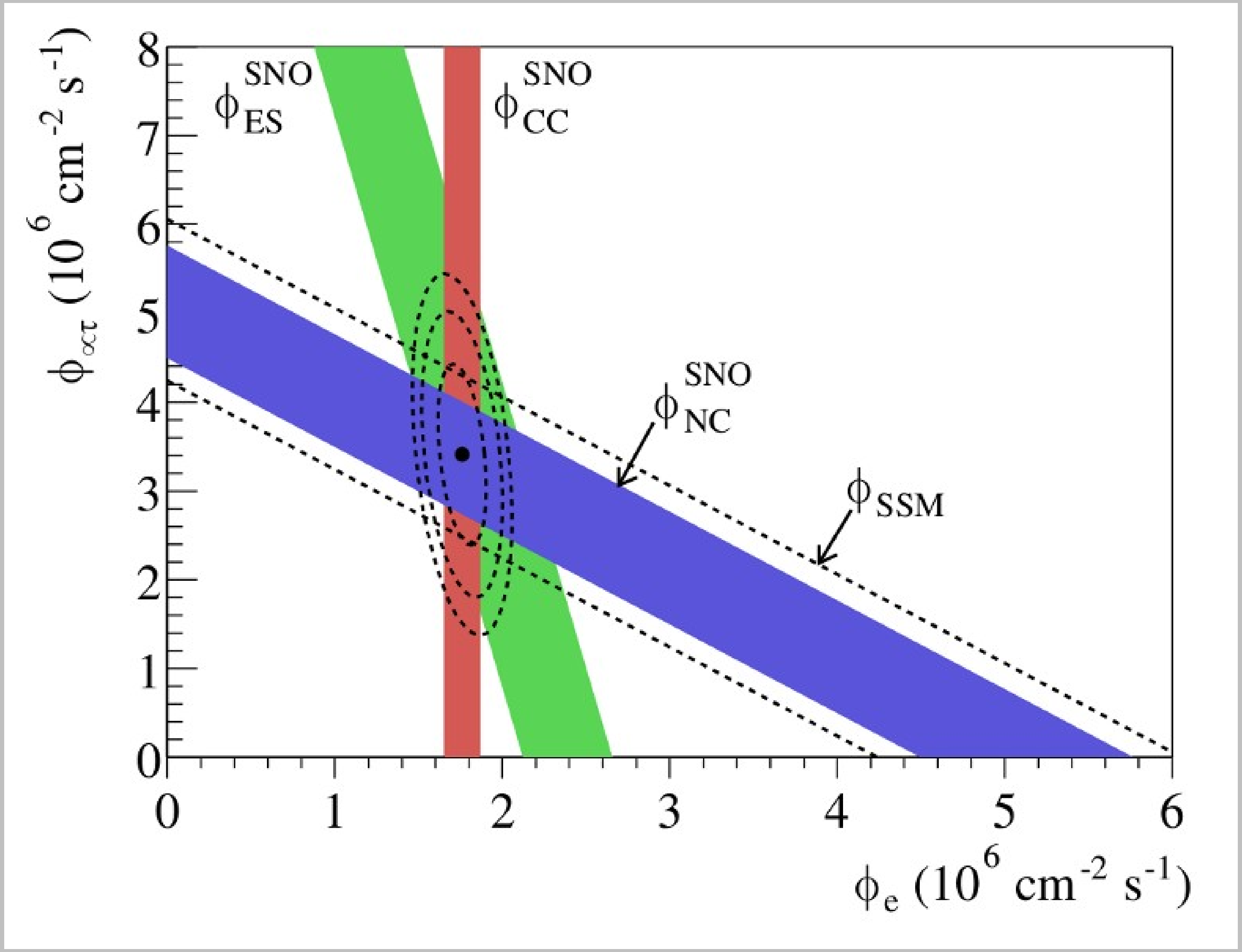


$\upsilon_e + d \rightarrow p + p + e^-$ "Charged Current (CC)"

$\upsilon_x + d \rightarrow p + n + \upsilon_x$ "Neutral Current (NC)"

$\upsilon_x + e^- \rightarrow \upsilon_x + e^-$ "Elastic Scattering (ES)"

Detection of Neutrino Oscillations



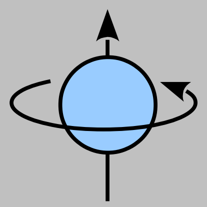
Discovery: Ahmad et al., 2001, PhRvL, 87g, 1301

Image: Ahmad et al., 2002, PhRvL, 89a, 1301

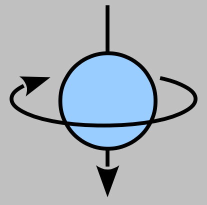
Quantum Properties

Many fundamental measurements can only have a finite number of "quantized" possible values.

e.g. the angular momentum (rotation) of an electron:



Rotating counter-clockwise ("spin up")



Rotating clockwise ("spin down")

Quantum Properties

An individual electron may be in a *mixture* of states

$$\frac{1}{\sqrt{2}}\left|\uparrow\right\rangle + \frac{1}{\sqrt{2}}\left|\downarrow\right\rangle$$

This means "if you measure the spin of this electron, there is a 50% chance you will measure up, and a 50% chance you will measure down."

After you measure the electron, its state changes; it is either

$$\left|\uparrow\right\rangle$$

or

$$\left|\downarrow\right\rangle$$

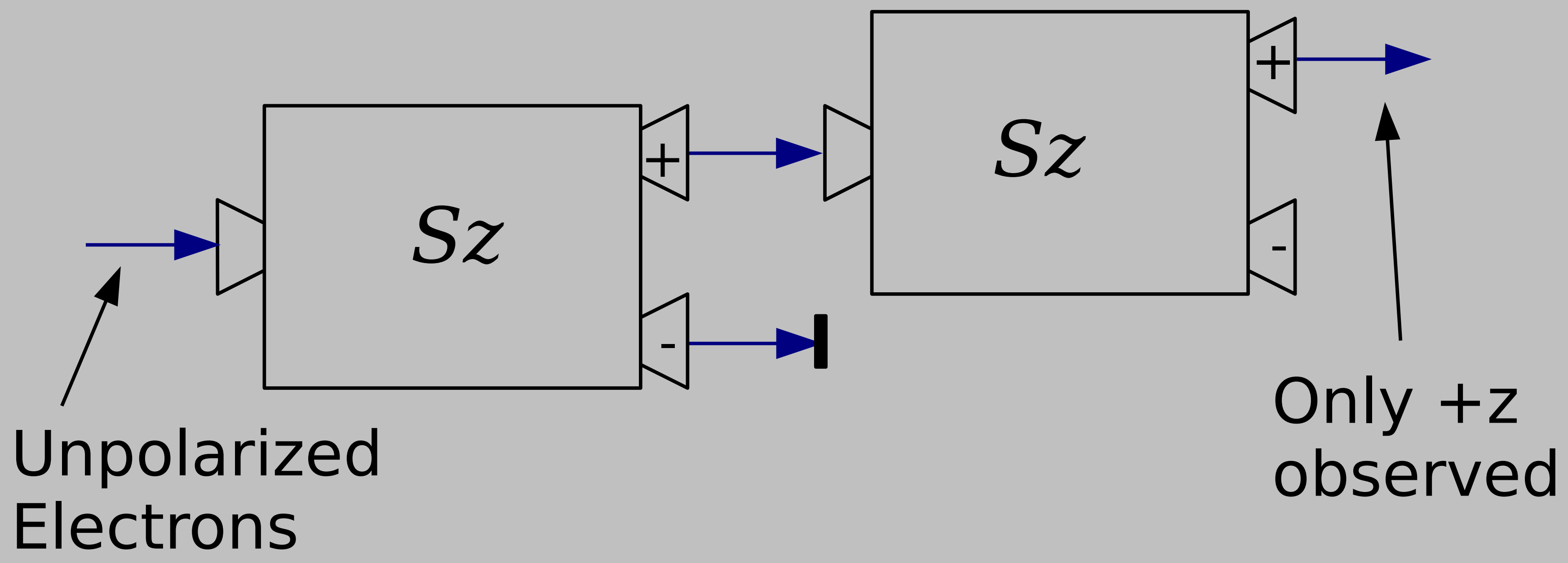
These things are the "z-spin *eigenstates*"

Y-spin eigenstates are not the same as Z-spin eigenstates!

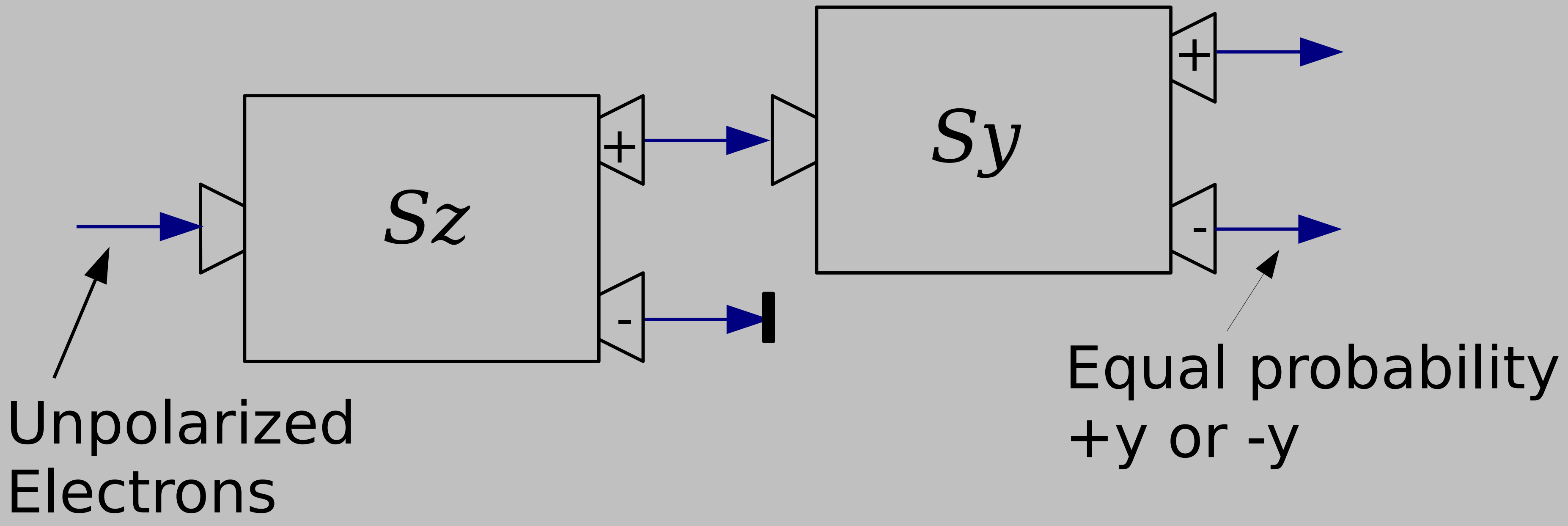
$$|\rightarrow\rangle = \frac{1}{\sqrt{2}}|\uparrow\rangle + \frac{1}{\sqrt{2}}|\downarrow\rangle$$

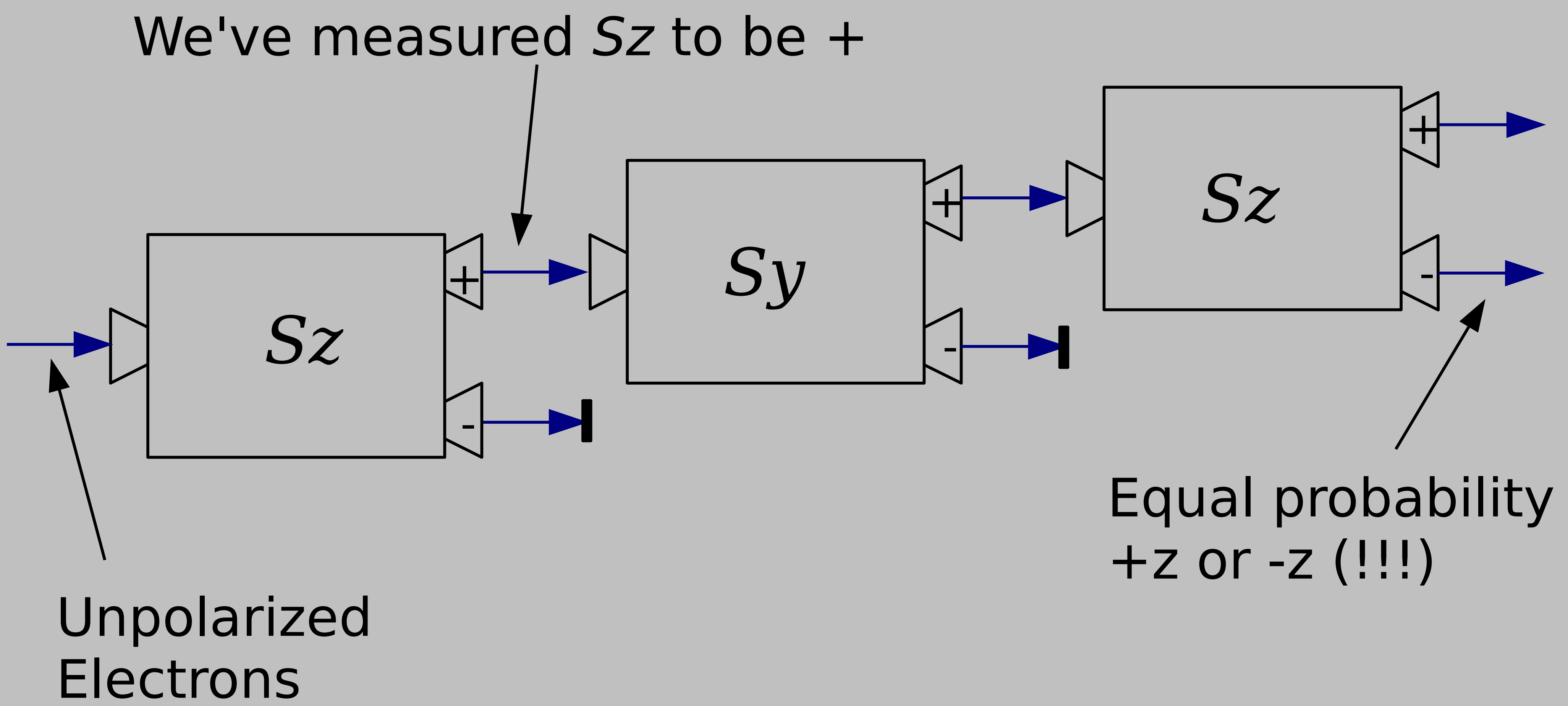
$$|\leftarrow\rangle = \frac{1}{\sqrt{2}}|\uparrow\rangle - \frac{1}{\sqrt{2}}|\downarrow\rangle$$

We say that the y-spin eigenstates are each a *mixture* of the z-spin eigenstates.



Sz
Sz
+
-
+
-
Unpolarized Electrons
Only +z observed


Sz
+
-
Sy
+
-
Unpolarized
Electrons
Equal probability
+y or -y



Spin about the z-axis and spin about the y-axis are *orthogonal*. A spin-z eigenstate is *not* a spin-y eigenstate!

Production of Neutrinos in the Sun

$$p + p \rightarrow d + e^{+} + \nu_{e}$$

They are produced as a *flavor* eigenstate

Propagation of Neutrinos to the Earth

Mass states are what propagates… the things flying through space are then probabilistically one of the three masses of neutrinos

Detection of Neutrinos

Flavor eigenstates are detected. The propagating mass-eigenstate neutrino probabilistically becomes one of the three flavors of neutrinos.