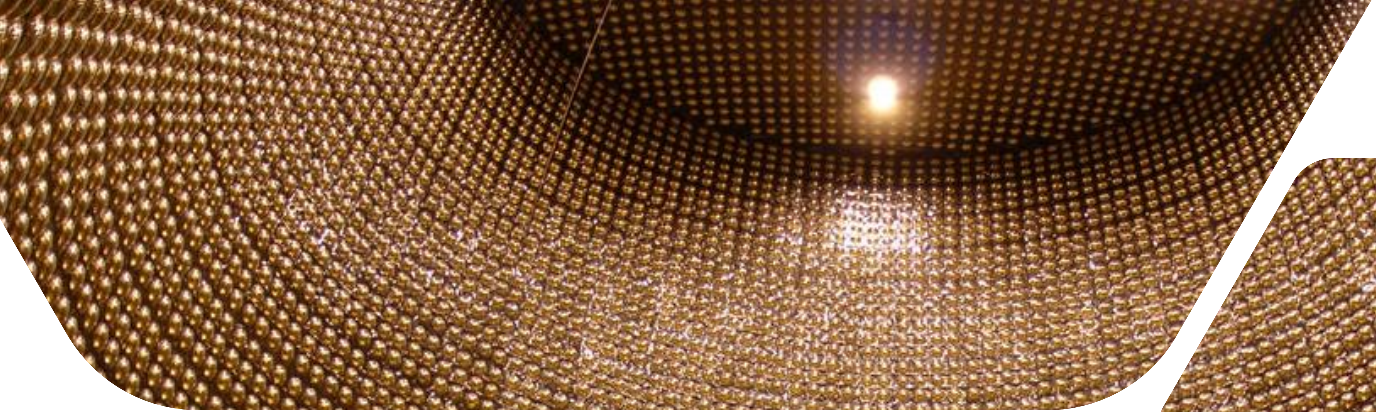
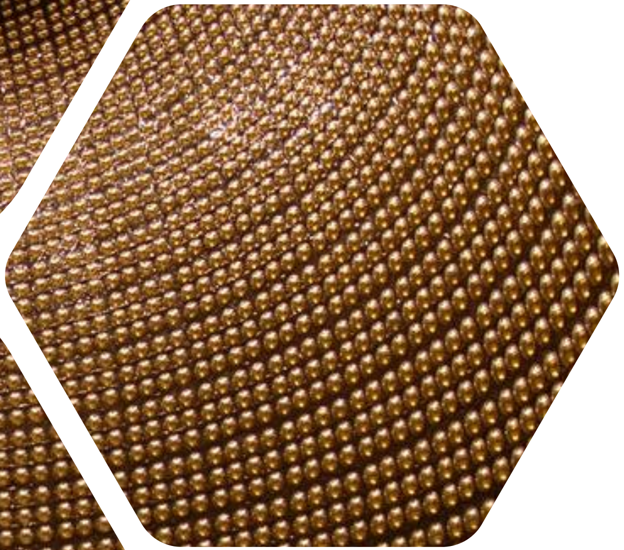
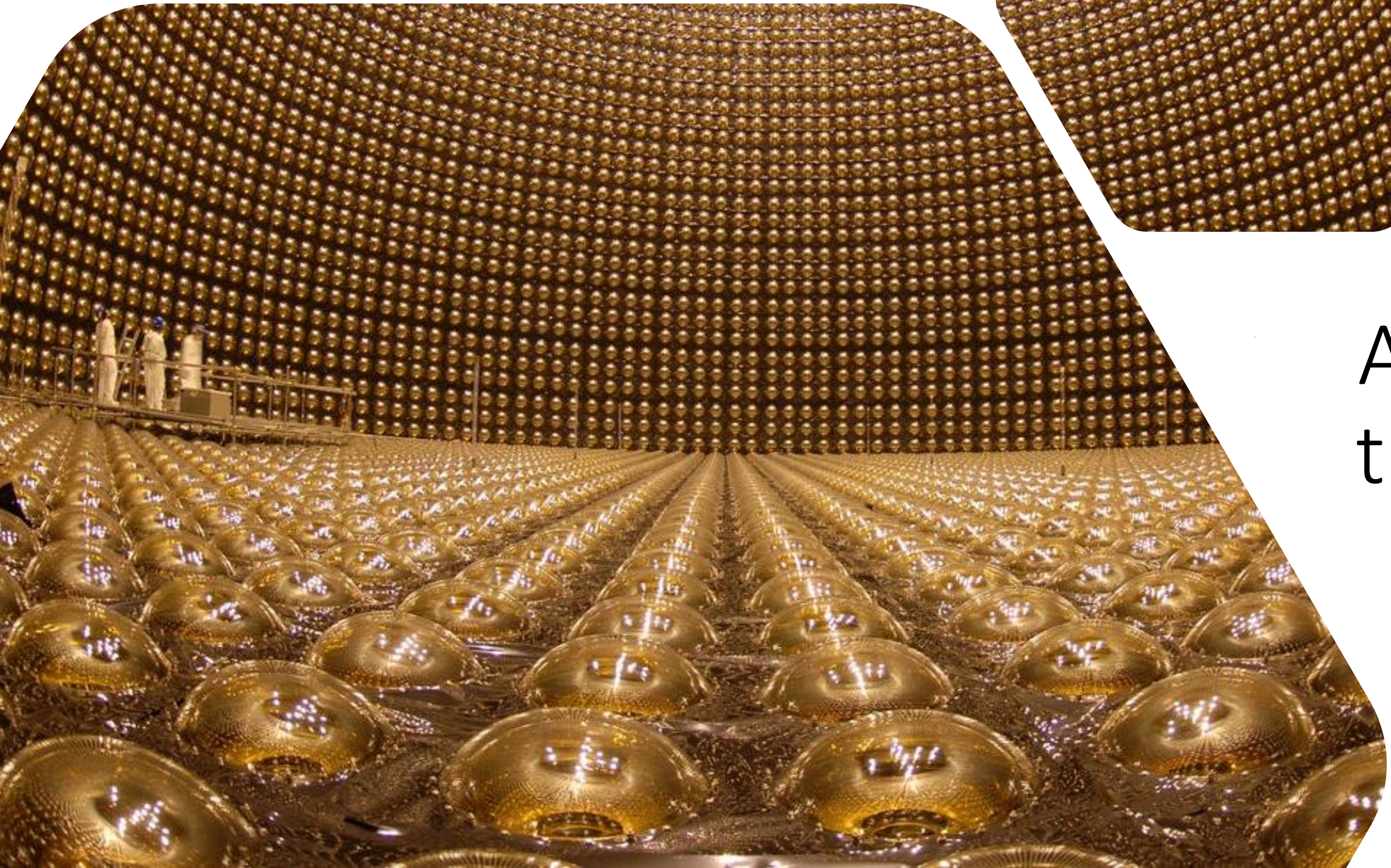


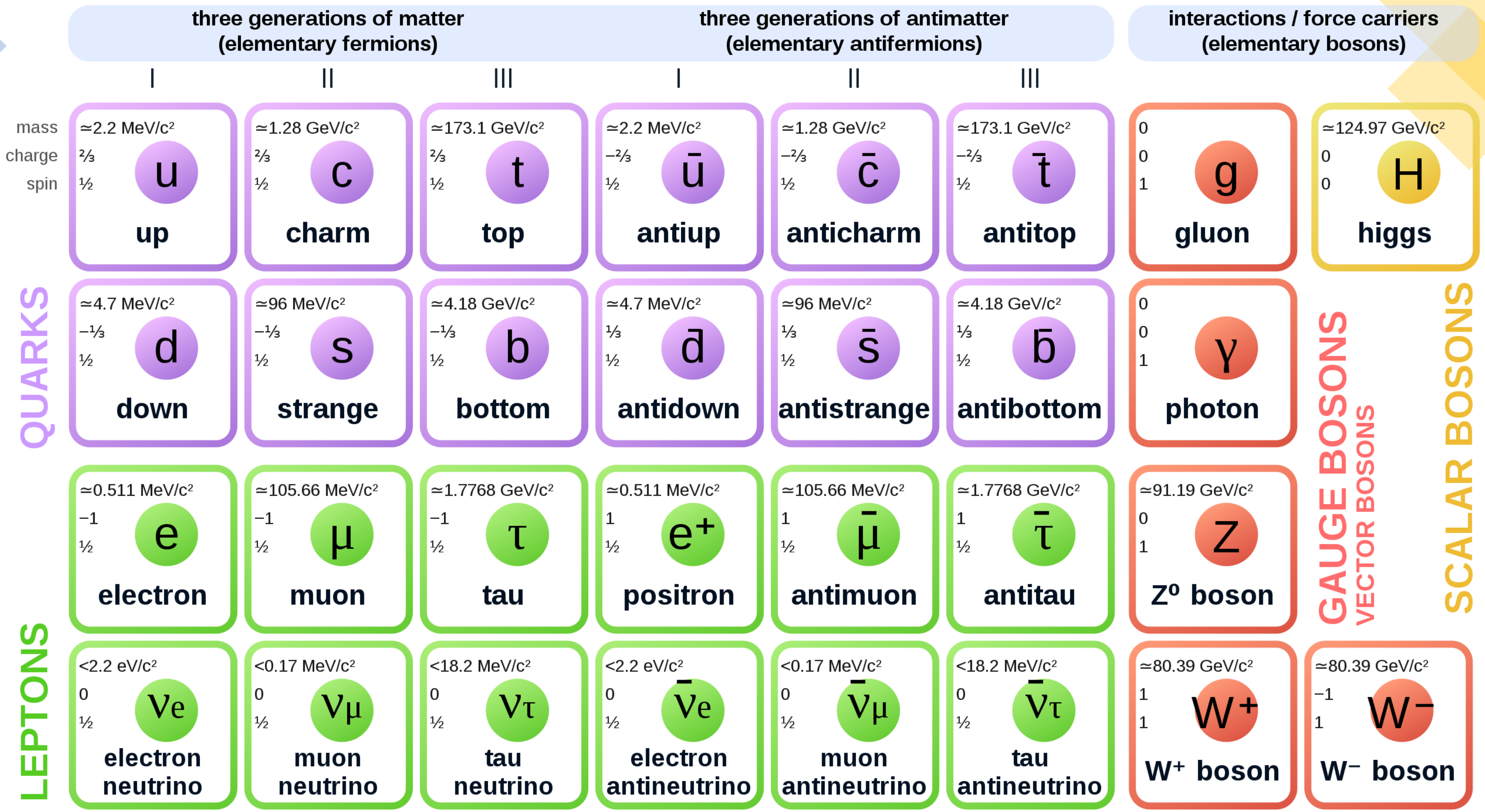




-Neutrinos-
A brief overview of the ‘ghost particle’.

By Jaiden Parlone

Standard Model of Elementary Particles



1 proton : 1 electron : 1 neutron : 1 billion neutrinos

Abundance 2nd only to photons!

Bananas emit around 1,000,000 neutrinos per day, mostly from Potassium-40 beta decay.

You emit around 300,000,000 per day as well.

Both are these are nothing compared to the sun's output, which leads to around 100,000,000,000,000 (100 trillion) passing through your body every second.

However…

There is only about a 1 in 4 chance of a neutrino interacting within your body within your lifetime.

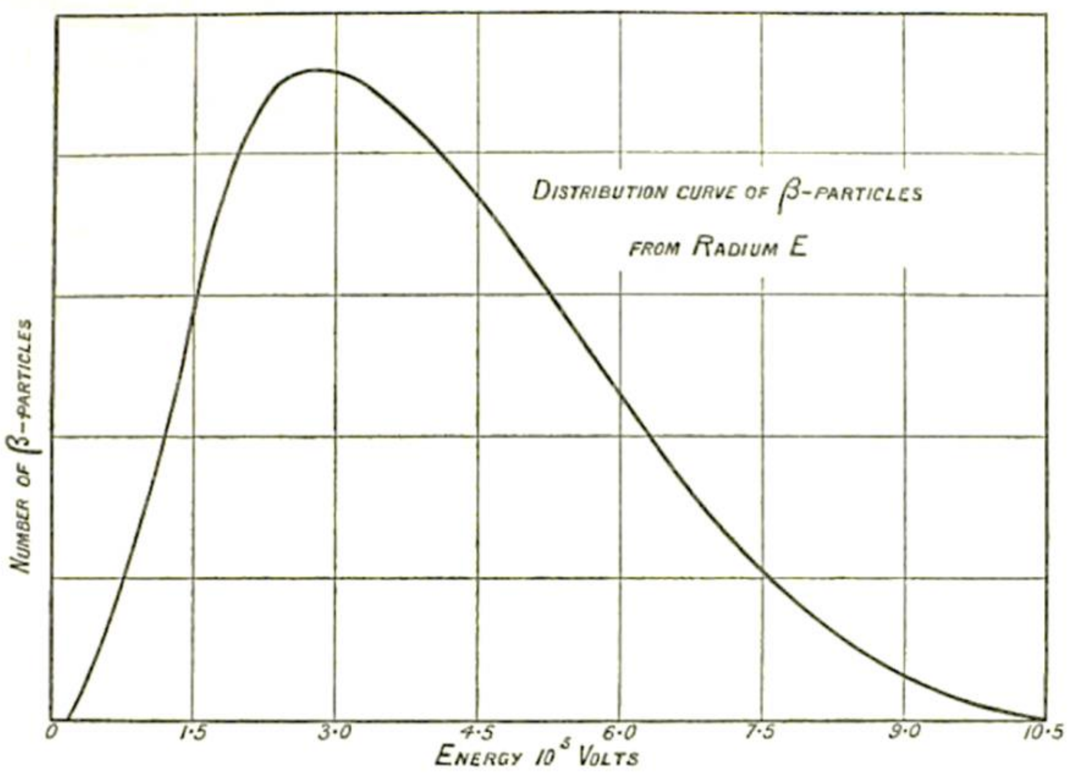
And if you were holding a banana, it would take about 2 billion years before a neutrino from it interacted with you.

In the early 20th Century, beta decay was thought to be a two body process, described by:

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

In 1914 James Chadwick discovered that the energy spectrum of electrons emitted during beta decay of radium was continuous as opposed to discrete, apparently in violation of conservation of energy.

This type of decay would have also violated later laws of angular momentum and lepton number conservation.



Note that this diagram is actually from a confirmation paper from 1927; Doi: 10.1098/rspa.1927.0168.

In 1930 Pauli first postulated a neutral, spin-$\frac{1}{2}$ particle with negligible mass that was also produced in this process. This he named ‘neutron’ but it was later renamed to ‘neutrino’ (the Italian equivalent of "little neutral one") after Chadwick’s discovery of the atomic neutron. This particle would later be fully realised as the electron antineutrino.

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

However, due to this particle’s properties Pauli famously stated:

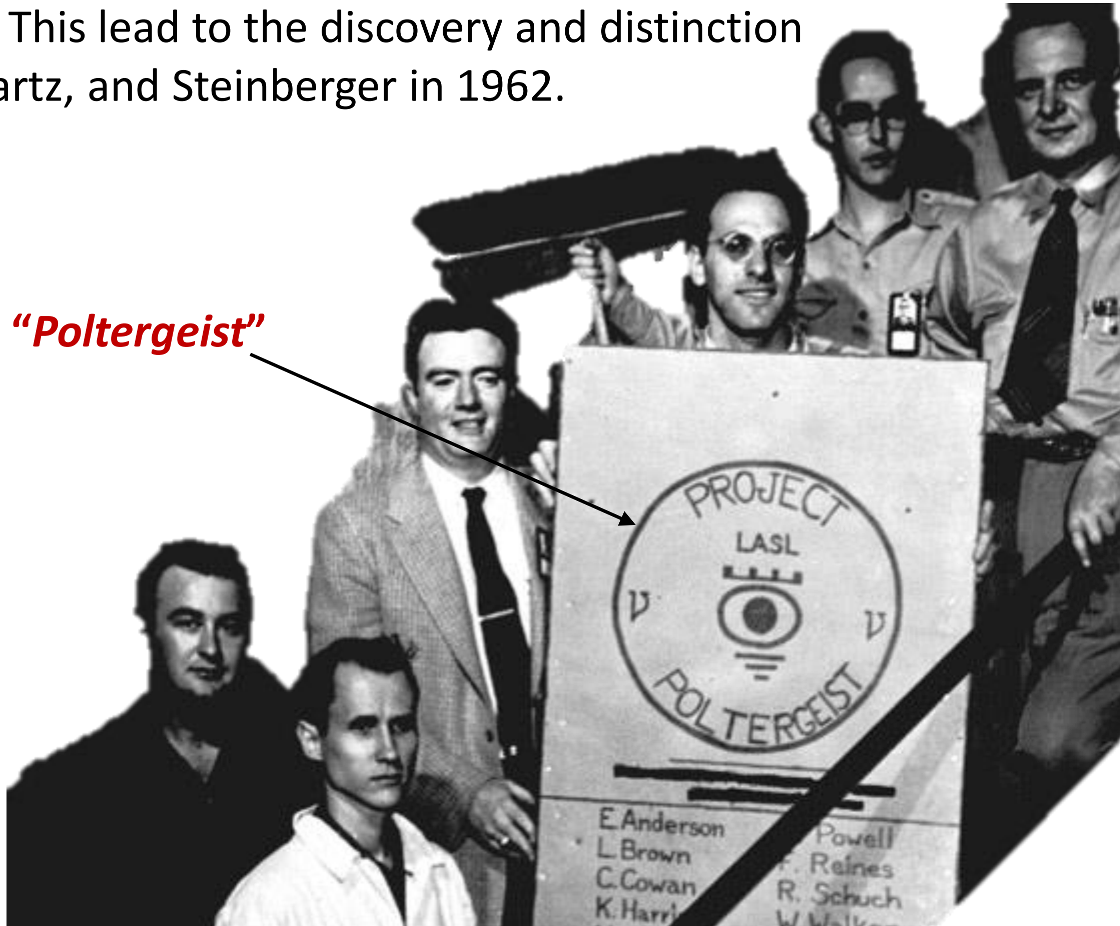
In 1956 the team working on the Cowan-Reines neutrino experiment published results utilised antineutrinos created in a nuclear reactor to induce a process known as ‘inverse beta decay’:

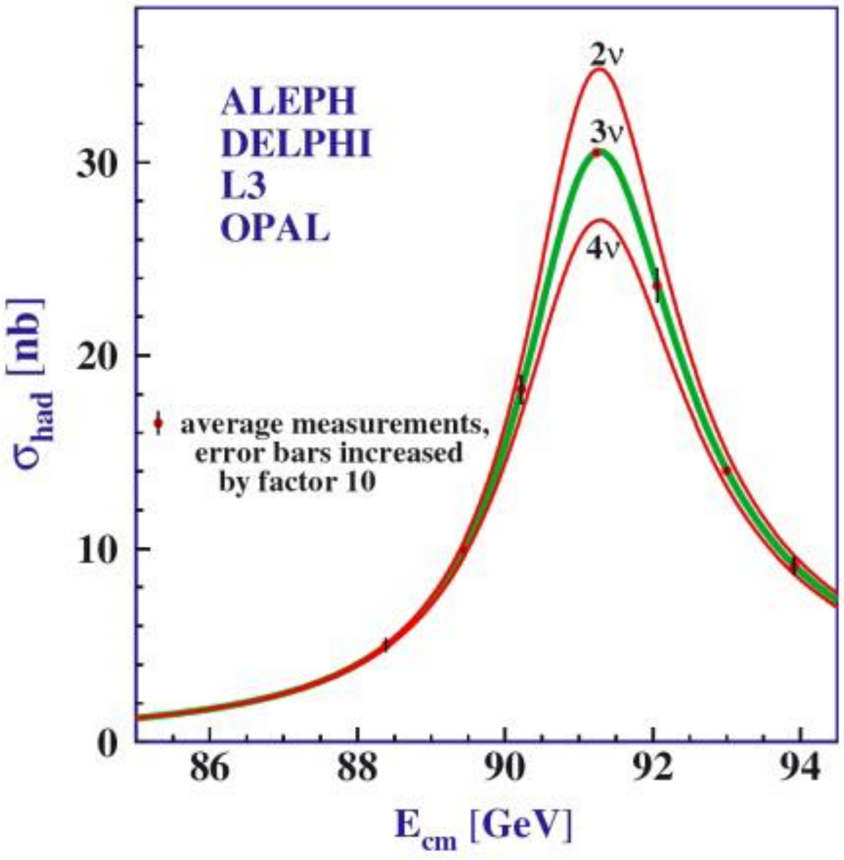
$$\bar{\nu}_e + p \rightarrow n + e^-$$

This effort was awarded a Nobel Prize in 1995, almost 45 years later.

However, open questions still remained. These neutrinos had only been observed to produce electrons in interactions, whereas there was now another known lepton, the muon. This lead to the discovery and distinction of the muon neutrino, ν_μ, by Lederman, Schwartz, and Steinberger in 1962.

Project “*Poltergeist*”





Studies of Z^0 boson decay allows for the number of light active neutrinos to be determined. This is done through the decay mode;

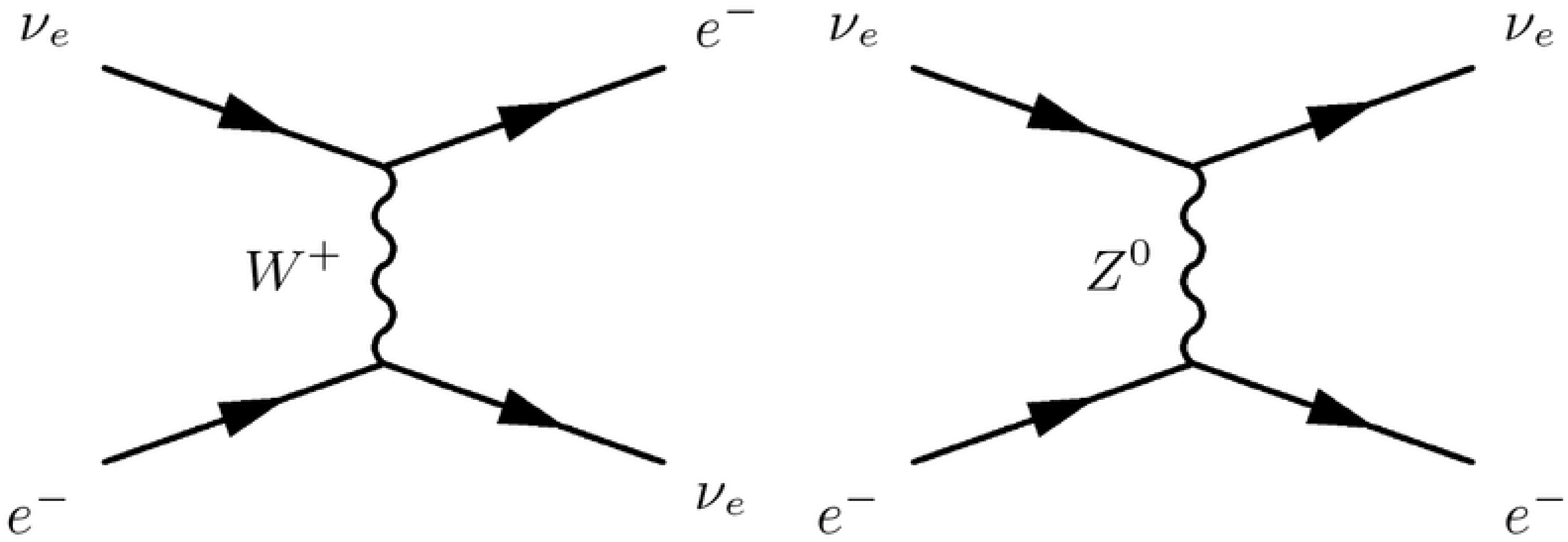
$$Z^0 \rightarrow \nu_l + \bar{\nu}_l$$

Where each neutrino flavour contributes to the decay width.

From this, the results from LEP determined to the number of light, active neutrino species to be: $N_\nu = 2.984 \pm 0.008$

This was achieved before the DONUT collaboration discovered the tau neutrino, ν_τ, in July 2000.

Because they have no colour charge, or electric charge, neutrinos interact only through the Weak Force.

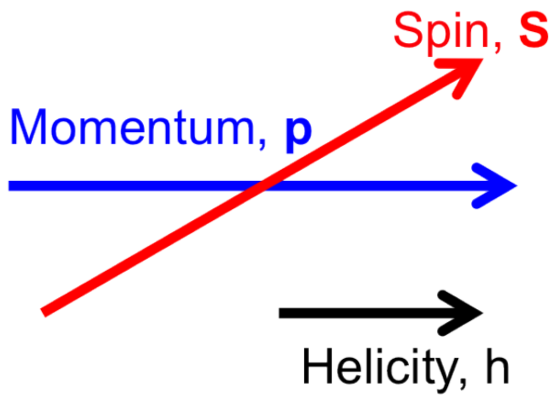


$W^{\pm}$mediated interactions are the only known flavour changing interaction, and are referred to as the ‘Charged Current’ in many sources.

The fact that the $W^{\pm}$ and Z^0 are massive are a result of symmetry breaking in the Higgs Field, the derivation of which tends to be covered in the 3rd or 4th year ‘Gauge Theories’ course.

Whilst this next bit is contained within the electroweak theory, it’s good to describe its origins:

Helicity is defined as the projection of the spin on to the direction of the particle's momentum.



$$h = \frac{\sigma \cdot \mathbf{p}}{|p|}$$

Right helicity $=$ spin aligned with direction of momentum. $\vec{\sigma} \uparrow\uparrow \vec{p}$

Left helicity $=$ spin anti-aligned with direction of momentum. $\vec{\sigma} \uparrow\downarrow \vec{p}$

Chirality is a bit more abstract, and is best thought about in terms of transformations (i.e. a reflection of a chiral object is not the same), but in the relativistic limit, helicity and chirality become equivalent.

When a parity operation (flip coordinates) is performed on helicity:

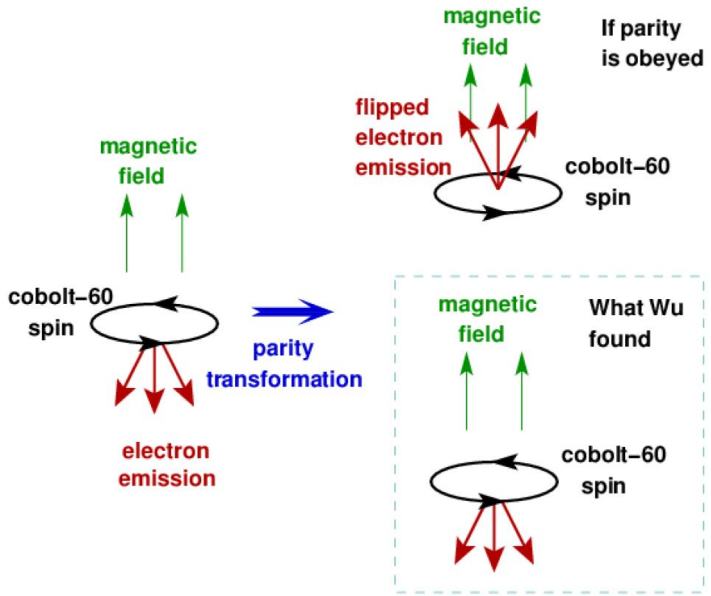
Momentum: Polar vector, changes sign: **p** → -**p**
Spin: Axial vector, $\sigma \rightarrow \sigma$

Therefore helicity should always change under parity transformation... right?

C.S. Wu checked this was correct for Weak interactions and in 1957 found that it simply wasn't. Parity was violated, apparently maximally. This understandably traumatised many physicists.

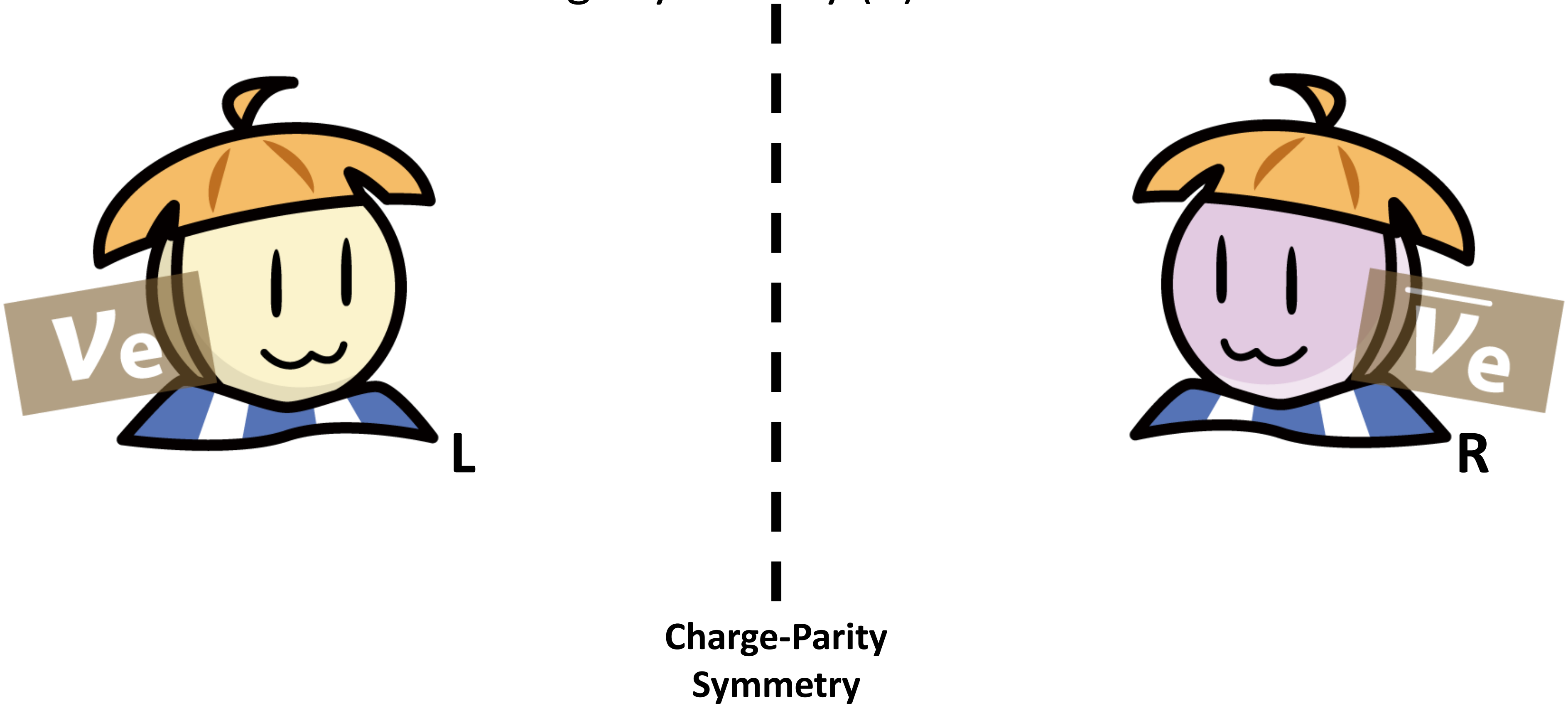
$$^{60}_{27}\mathrm{Co} \rightarrow ^{60}_{28}\mathrm{Ni}^* + e^- + \bar{\nu}_e$$
$$^{60}_{28}\mathrm{Ni}^* \rightarrow ^{60}_{28}\mathrm{Ni} + 2\gamma$$

- Apply magnetic field
- Cool apparatus to 0.01 K
- High proportion of ^{60}Co spins are aligned with the magnetic field
- Examine distribution of emitted electrons and photons.



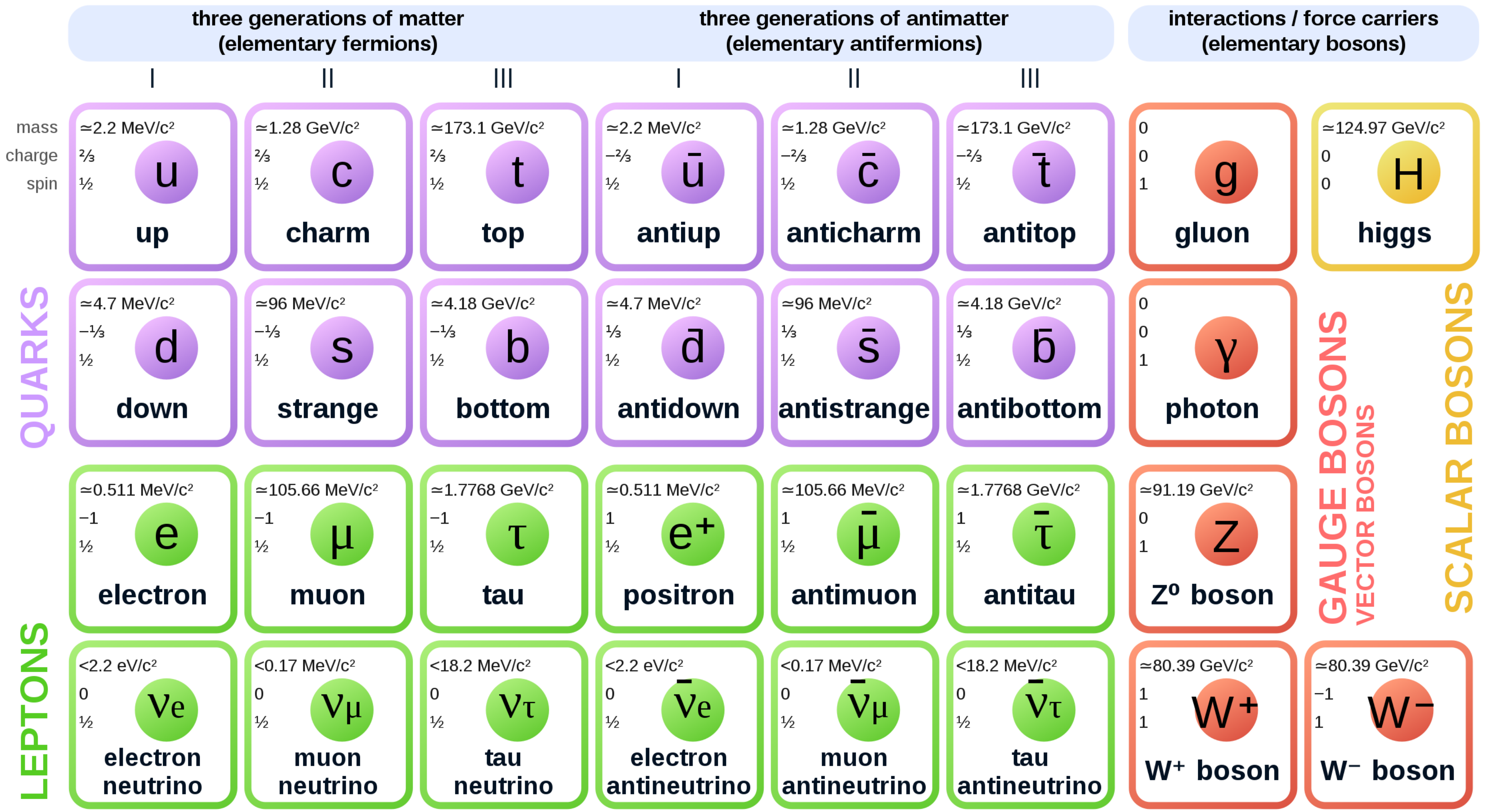
Lee and Yangs' contributions to the theory of Parity violation were rewarded with a Nobel prize in that same year. Though Wu's role was mentioned, she unfortunately wasn't officially honoured until 1978 with the Wolf Prize.

The charged weak bosons only couple to left handed particles, and right handed antiparticles. As neutrinos can only interact weakly, only left-handed neutrinos and right-handed antineutrinos exist, but their opposite chiral partners do not (in the standard model). This also means that Charge symmetry (C) is broken.



A note is that charge conjugation reverses all internal quantum numbers as well as reversing electric charge.

Standard Model of Elementary Particles



With this revelation of broken symmetries, the unified electroweak theory is fully within the standard model. So all is well! Neutrinos are massless, neutral, spin-$\frac{1}{2}$, chiral elementary fermions. Unless….

Solar neutrino problem

In the late 1960s Raymond Davis, a chemist by trade, knew that electron neutrinos interacting with chlorine would produce a radioactive isotope of argon:

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

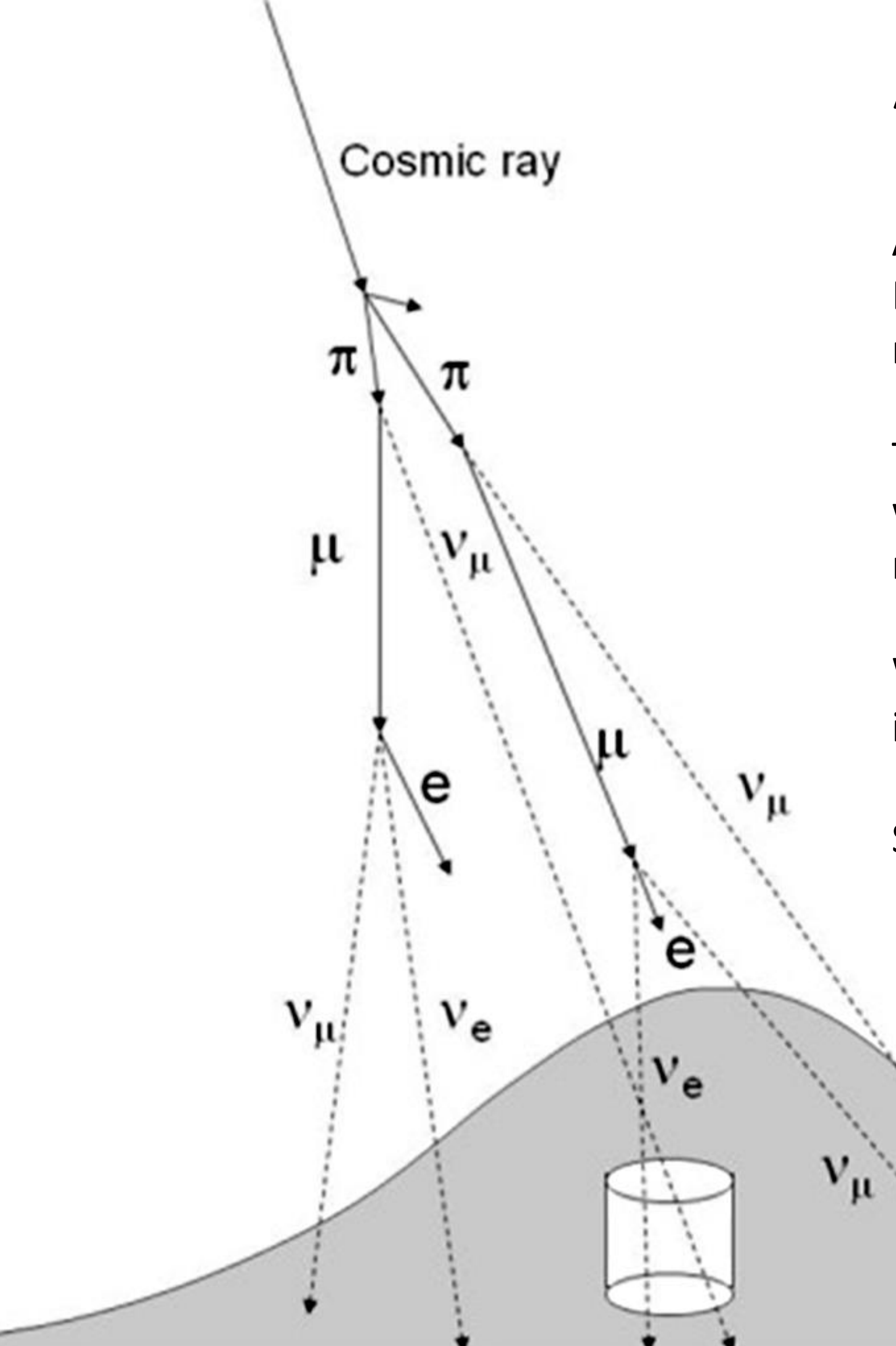
The idea was to fill a 380 cubic meter tank with perchloroethylene (dry-cleaning fluid), place it 1,478 meters underground to shield from cosmic rays, and count solar neutrinos (produced by fusion chains) by extracting and measuring the resulting argon.

With a week's operation, the experiment could expect to create 10 atoms of argon, compared to the 9×10^{30} chlorine atoms present in the tank.

However Davis did not find the expected 10 atoms, but instead 3. Many thought this to be experimental error, or an inaccurate prediction, but many later experiments confirmed this result.

This came to be known as the 'solar neutrino problem'.

Atmospheric neutrino problem



Atmospheric neutrinos are typically produced about 15 kilometres above the Earth's surface. When a cosmic ray (usually a proton) interact with an atomic nucleus in the atmosphere, it forms a cascade of particles.

Through many decays of the unstable products (here be a great relativity worked question on the lifetime of muons), neutrinos are produced with a ratio of 2:1 of muon:electron flavour.

When measured, this ratio was different to the prediction. Many experiments indicated a disappearance of ν_μ and an appearance of ν_e.

Something was clearly going on.

A possible solution?

Inspired by Kaon oscillations proposed by Gell-Mann and Pais, Bruno Pontecorvo proposed a possibility that another neutral particle, neutrinos, might oscillate between two states.

The three proposals he made were;

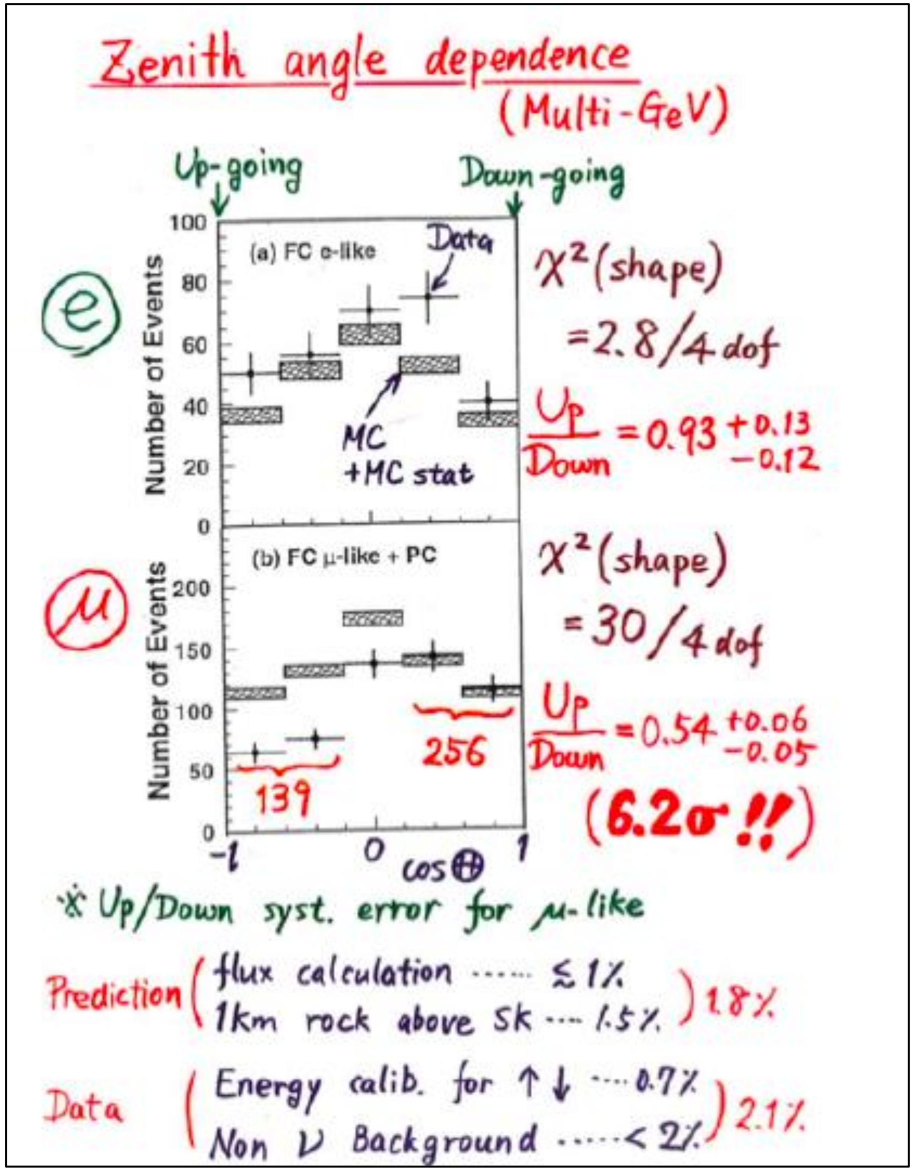
- $\nu \leftrightarrow \bar{\nu}$ oscillations, enabling neutrinos to be their own anti-particle (named Majorana particles).
- $\nu_L \leftrightarrow \bar{\nu}_L$ and $\nu_R \leftrightarrow \bar{\nu}_R$ where a neutrino changes handedness, enabling access to those neutrinos unable to take part in Weak interactions. These are dubbed ‘sterile’ neutrinos.
- $\nu_e \leftrightarrow \nu_\mu$, allowing a neutrino to violate lepton flavour conservation, changing between the two lepton flavours known at the time.

These proposals can all be found in: Soviet Physics JETP. 7: 172. 1958.

A complete confirmation

In 1998, the Super-Kamiokande water Cerenkov detector achieved the first measurement of atmospheric neutrino flavour disappearance, with the energy dependant pattern expected of oscillation phenomena.

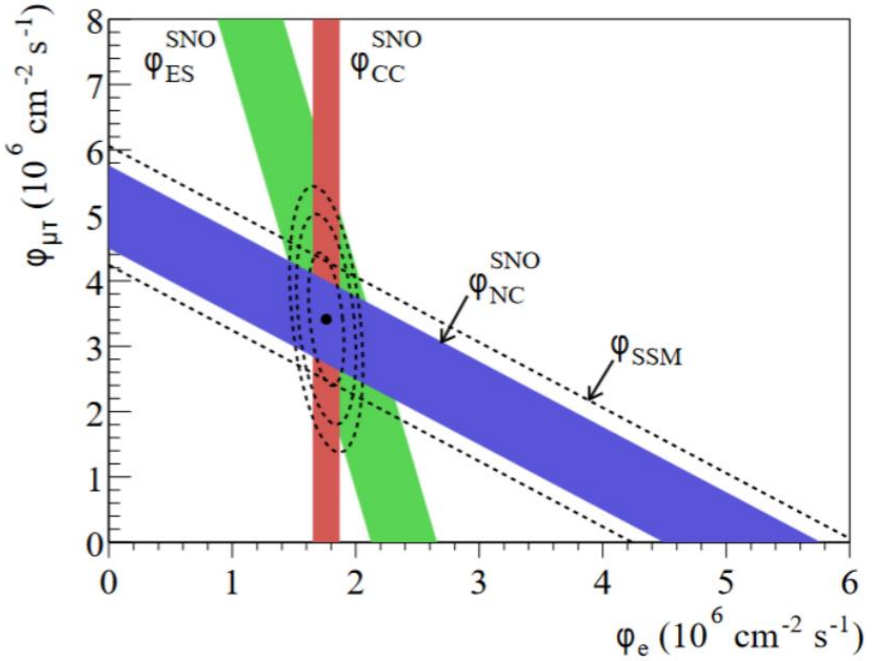
On the right is shown the dependence on zenith angle (i.e. the angle the neutrino entered the detector from with from below being $\cos\Theta = -1$ and above $\cos\Theta = 1$) and therefore the distance travelled by the neutrino (from atmosphere above or through Earth as well).



SNO place like home.

In 2002 the Sudbury Neutrino Observatory, a kiloton heavy water Cerenkov detector announced that it had measured solar neutrinos using three different interaction channels.

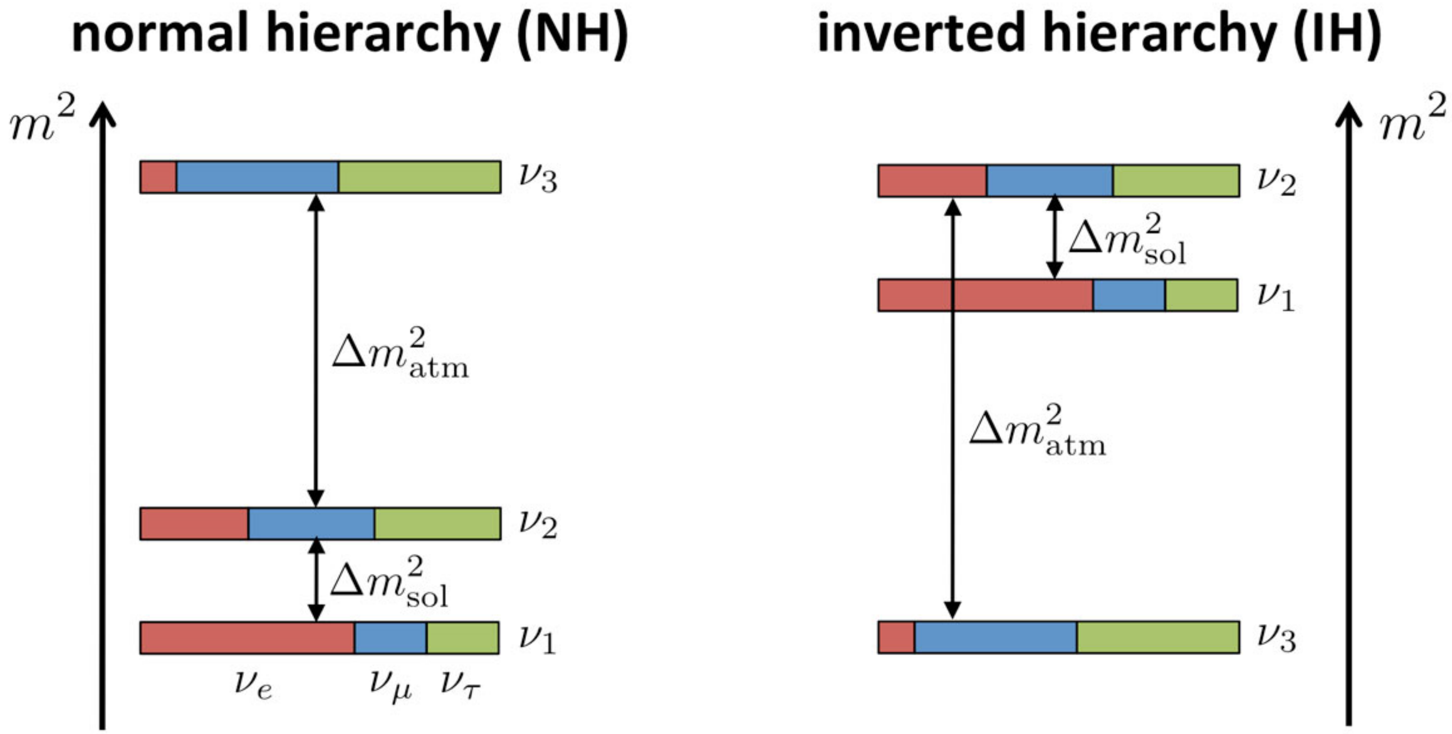
- The first, a charged current interaction, was sensitive to only ν_e. This saw the deficit Davis had at the Homestake experiment.
- The second, a neutral current interaction, was sensitive to all ν. This saw neutrino flux matching that predicted by the solar model.
- The third, an Elastic Scattering interaction, primarily sensitive to ν_e but had sensitivity to other flavours. This mostly gave directional info.



With these detections, the community was sure that neutrino flavour oscillations were occurring! However this realisation came with a troubling conclusion. Neutrinos had mass.

Well, kinda. What they actually required in theory was a mass difference between three, set, well defined states. And then each set neutrino flavour must be a transformation from these states, each flavour ending up as a mix of the three masses. This transformation is given by a rotation (contained in a matrix) from the mass states to the flavour states (or visa versa).

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

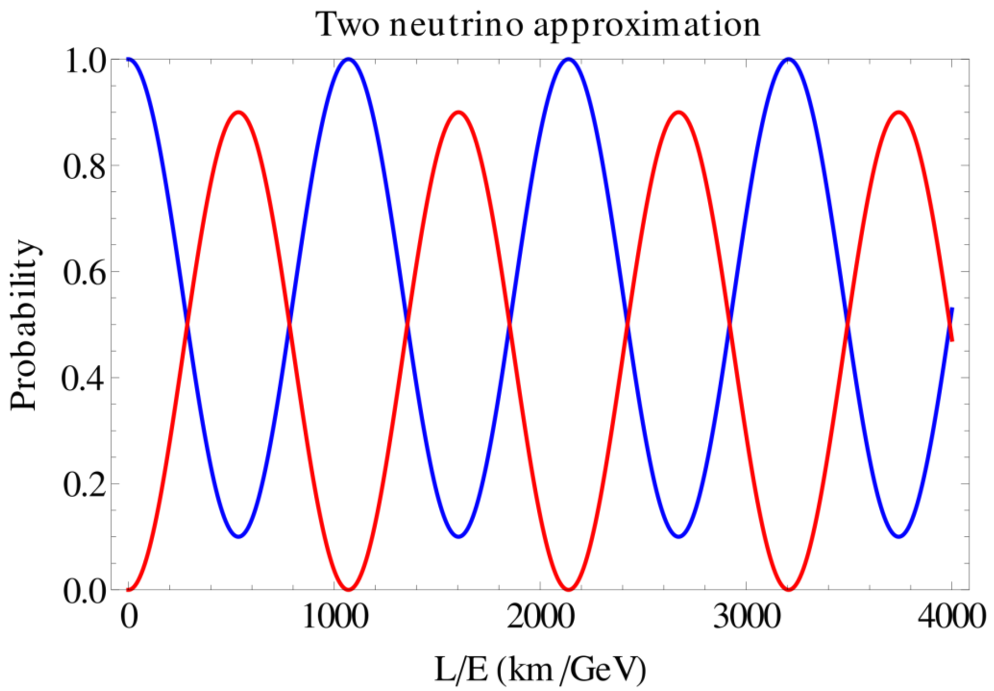


If we start off in a two flavour world, this rotation matrix becomes familiar;

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

And the survival probability of a flavour can be derived to be;

$$P(\nu_e \to \nu_e) = 1 - \sin^2 2\theta \sin^2 \left[\frac{(m_2^2 - m_1^2)x}{2E}\right]$$
$$= 1 - \sin^2 2\theta \sin^2 \left[\frac{1.27\Delta m^2 L}{E}\right]$$



From here we can see a couple of things;

- If the mass difference is 0, no oscillations can occur.
- Theta, named the mixing angle, defines how different the flavour states are from mass states. This determines amplitude of oscillation and is maximal at $\frac{\pi}{4}$.
- There are two free parameters that are either set for us by nature, or we can freely control;
  - ❖ Length, L, is the distance a neutrino will propagate.
  - ❖ Energy, E, is the energy of that neutrino.

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\text{CP}}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$
$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{\text{CP}}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{\text{CP}}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{\text{CP}}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{\text{CP}}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{\text{CP}}} & c_{23}c_{13} \end{bmatrix}.$$

$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \text{Re}\left(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right)\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right) + 2\sum_{i>j} \text{Im}\left(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right)\sin\left(\frac{\Delta m^2_{ij}L}{2E}\right),$$

With 3 flavour oscillations, things get more complex (no pun intended), but remain familiar;

- There are now 2 mass differences, the large and the small; Δm^2_{32} & Δm^2_{21}. Note that because of the squared mass terms, the signs are not detectable without extra effects.
  - ❖ $\Delta m^2_{21} = 7.53 \times 10^{-5} eV^2$
  - ❖ $\Delta m^2_{32} \approx \Delta m^2_{13} = 2.45 \times 10^{-3} eV^2$
- There are 3 mixing angles; θ_{12}, θ_{23}, and θ_{13}. These values (shown below in terms of $\sin^2(\theta)$) are large, especially θ_{23} which is nearly maximal.
  - ❖ $\sin^2(\theta_{12}) = 0.307$
  - ❖ $\sin^2(\theta_{23}) = 0.546$
  - ❖ $\sin^2(\theta_{13}) = 0.0220$

The value for θ_{13} was found to be surprisingly large (though still smaller than the others) and opened up a whole new possibility; measuring the CP-violating phase factor, δ_{CP}.

Parameter values taken from PDG interactive listings, shown without error.

CP violation would mean: $P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$

The magnitude of CP effect is given by the Jarlskog Invariant:

$$J_{CP}^{PMNS} = \frac{1}{8}\, sin2\theta_{12}\; sin2\theta_{13}\; sin2\theta_{23}\; cos\theta_{13}\; sin\delta_{CP}$$

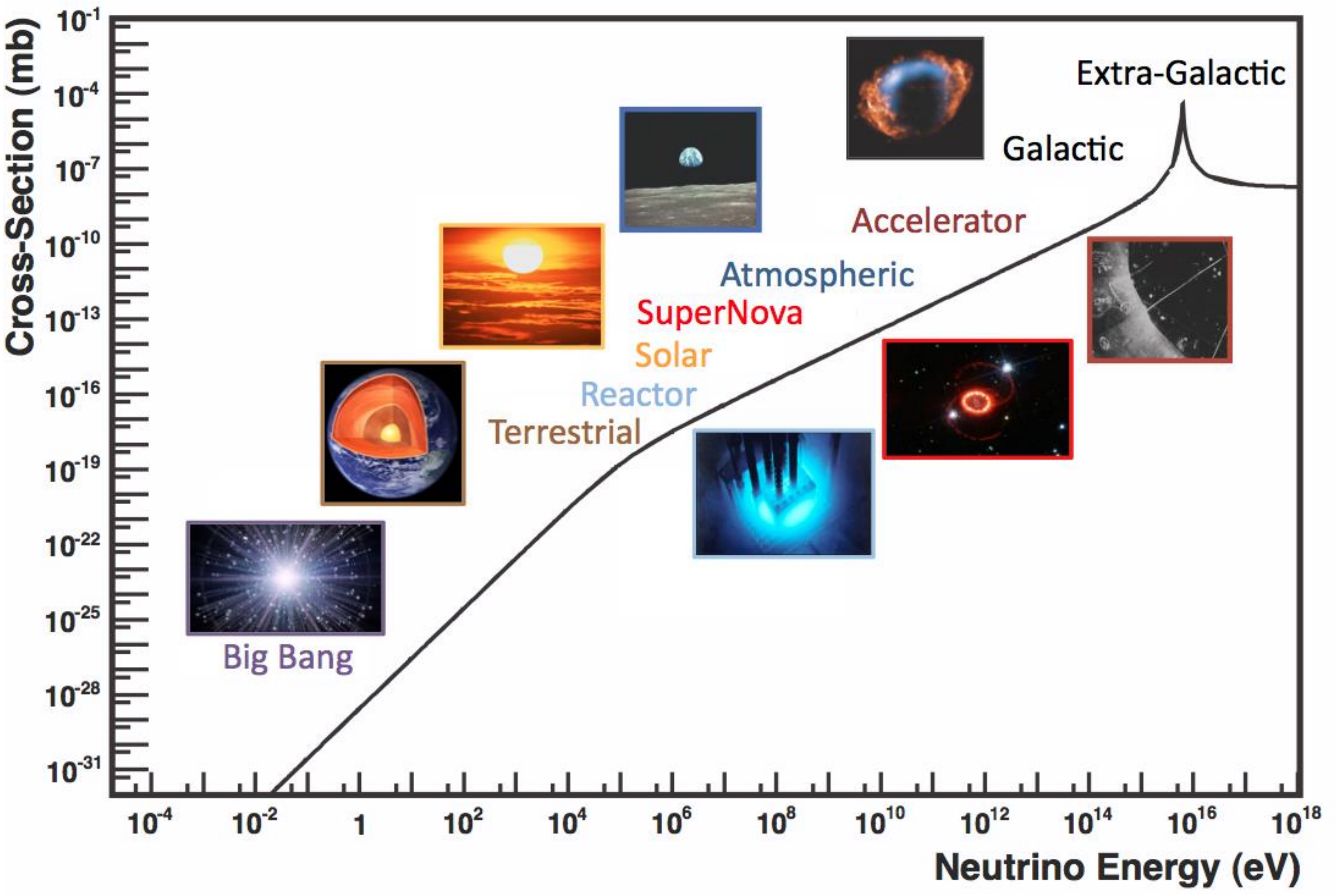
$$J_{CP}^{PMNS} = 0.035\; sin\delta_{CP}$$

$$J_{CP}^{CKM} \approx (3 \pm 1) \times 10^{-5}$$

Indications that the value of δ_{CP} is actually near maximal, and thus leptonic CP violation is large. This could explain the matter-antimatter asymmetry!

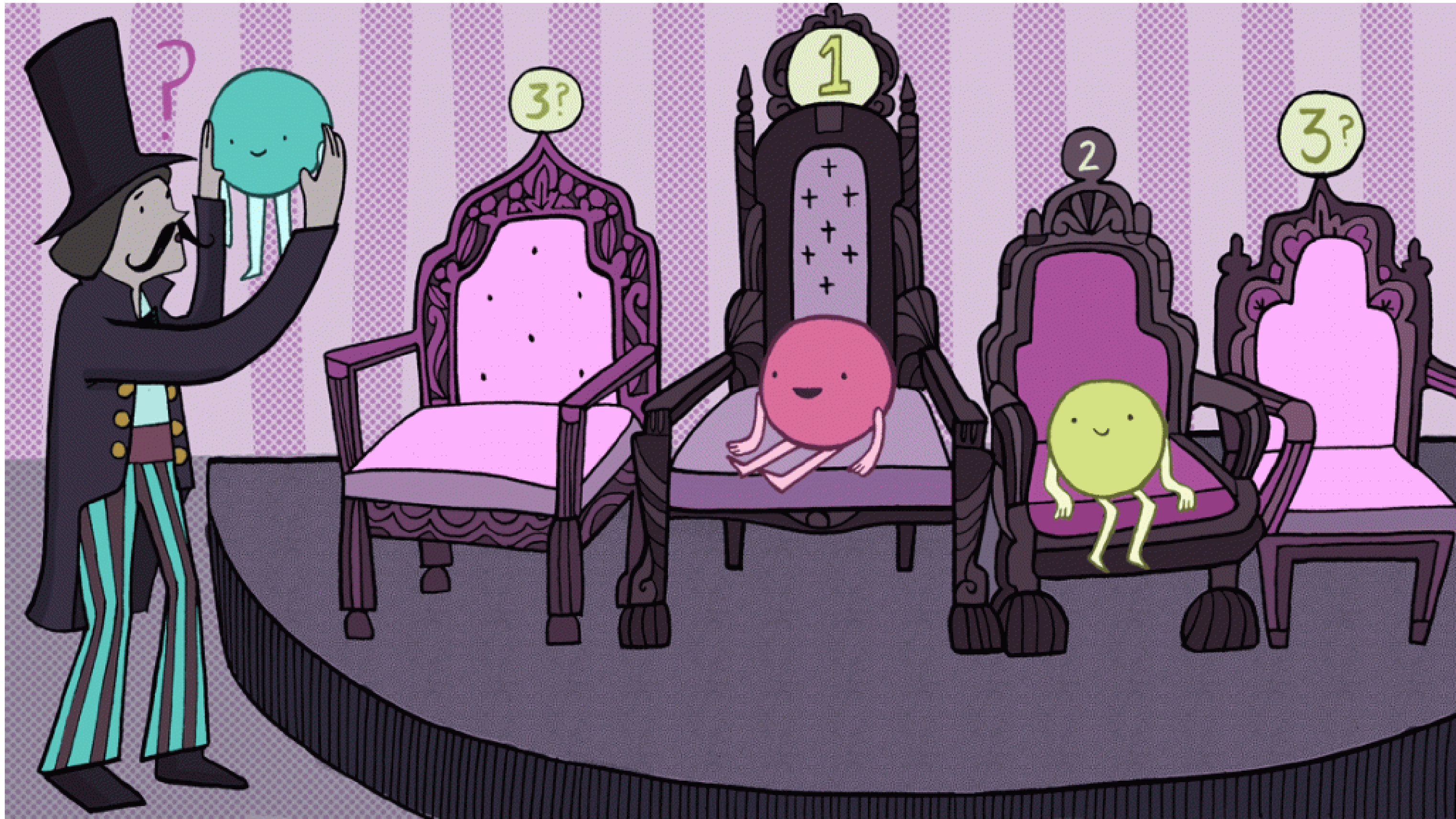
And this is perhaps only one of the most famous questions…

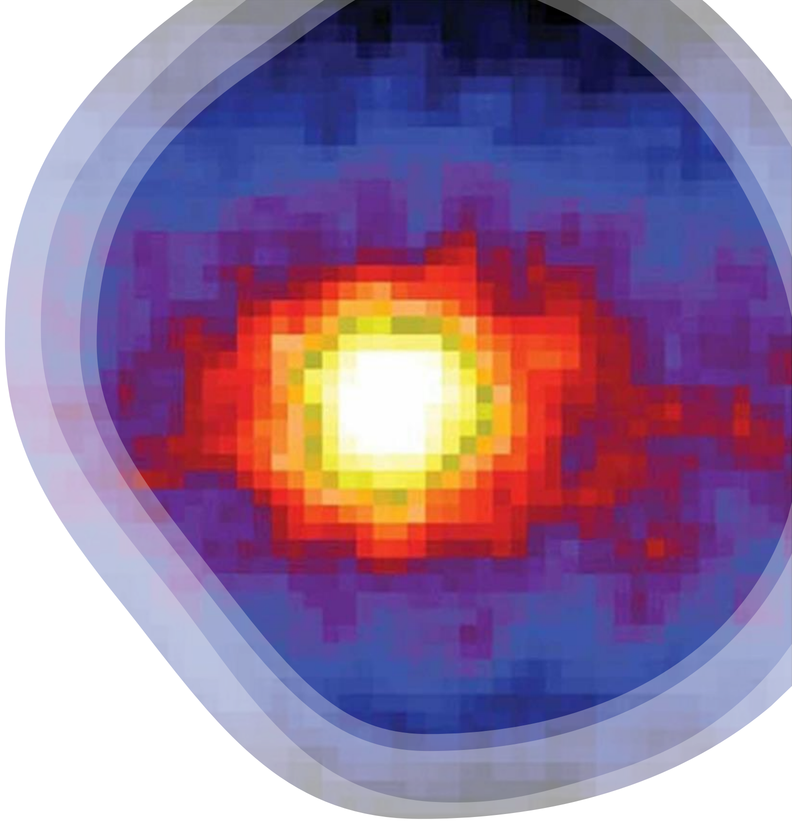
- Our neutrino detection capabilities span an incredible range of energies, with many neutrino experiments trying to achieve many different measurements.



Other open questions

- Neutrinos have mass, where does this come from? (Neutrinoless double beta decay)
- Which order are these masses in? This is called neutrino mass ‘hierarchy’. (Matter effects)
- Can neutrinos oscillate their handedness? (Short baseline experiments)
- Is θ_{23} maximal or which side of $\frac{\pi}{4}$ does it lie.
- What is a neutrino’s speed? Looking at you OPERA.





Neutrino Astronomy

Is it not a strange fate that we should suffer so much fear and doubt for so small a thing?- Boromir