3.0 Neutrino Introduction

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Neutrinos

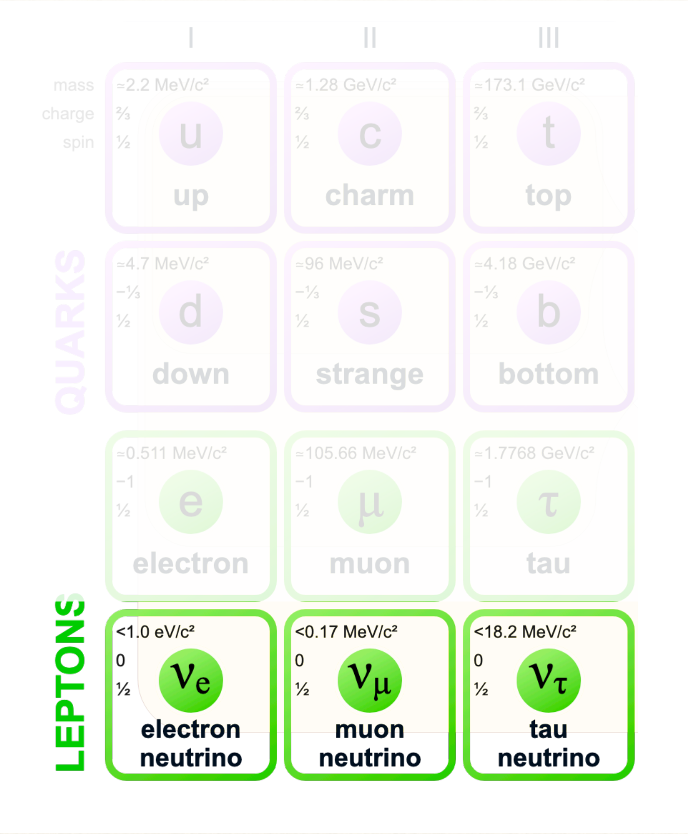
- Things I want to cover

- Cosmological neutrinos
- Solar neutrinos
- Atmospheric neutrinos
- Astrophysical neutrinos
- Neutrino interactions and oscillations

- Maybe a bit of Reactor/Geo/accelerator neutrinos

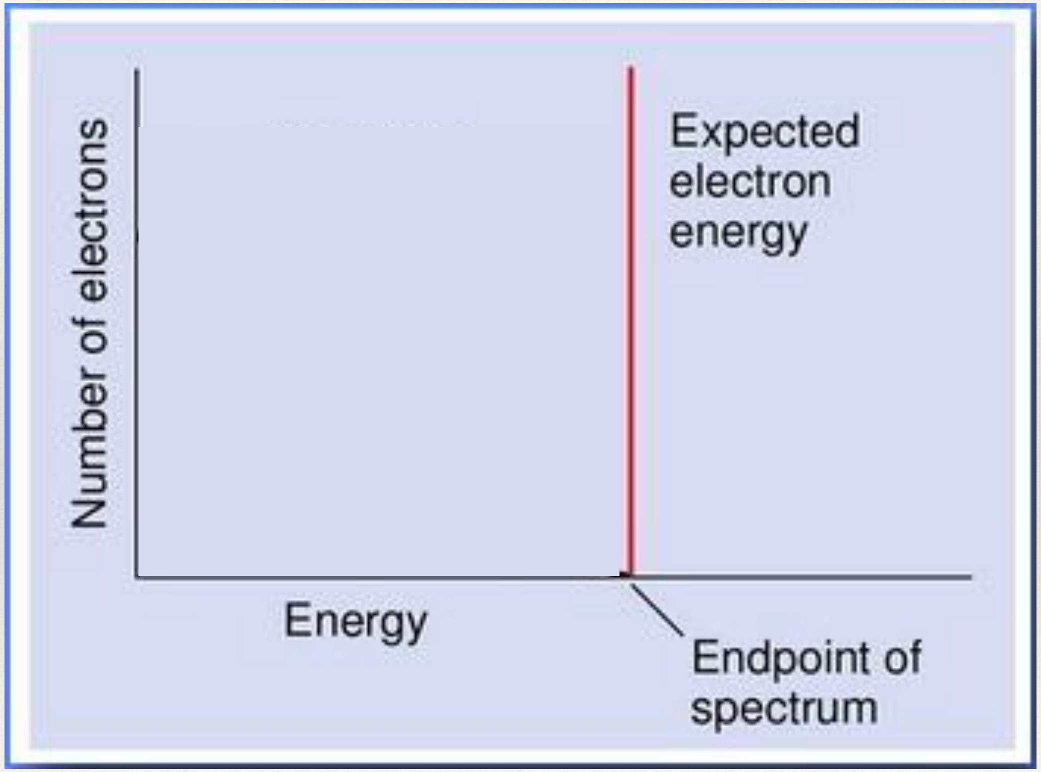
What is a neutrino

- In the standard model
- The only neutral leptons
  - No EM force
  - No Strong force
- Only participates in weak interaction



Beta decay

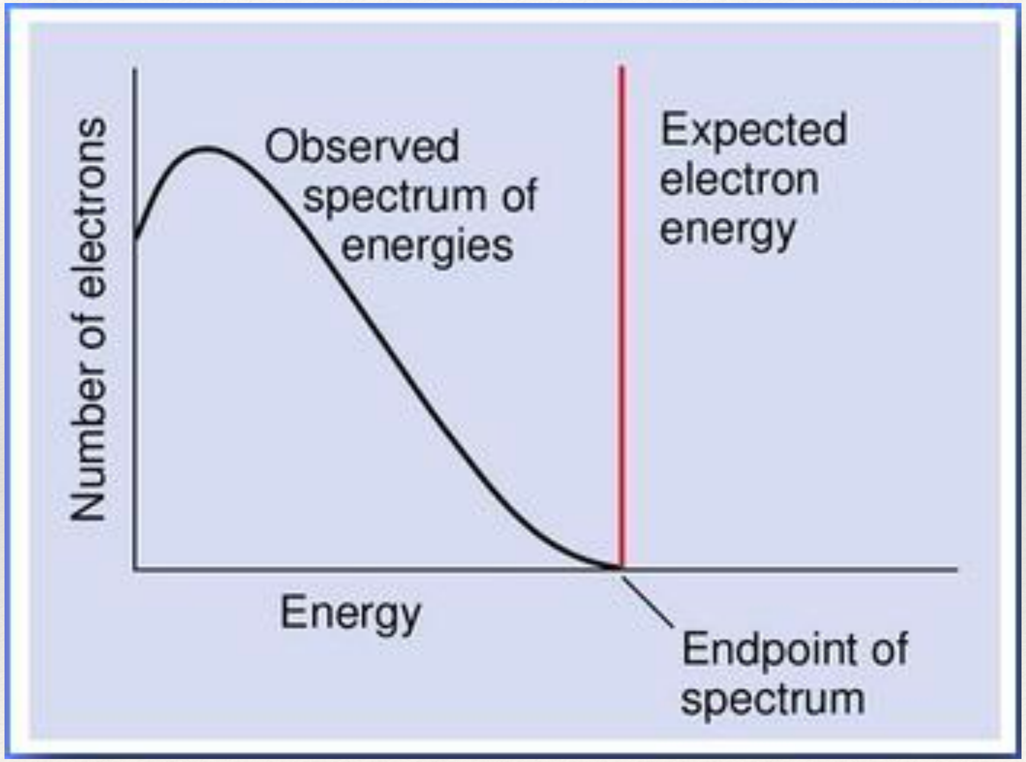
- ~ 1930 ish
- It is known that there are beta decays
- Inside a nucleus, a neutron is observed to change to a proton
- $n \to p^+ + e^- + \nu$
- What can you say about the energy of the electron?



Beta decay

I have done a terrible thing: I have postulated a particle that cannot be detected.

Wolfgang Pauli (1930)



Amaldi: Neutrino (little neutral one)

Discovery of a neutrino

- Inverse Beta Decay
- $\bar{\nu}_e + p^+ \rightarrow n + e^+$
- Now we to go to a place with lots of beta decays

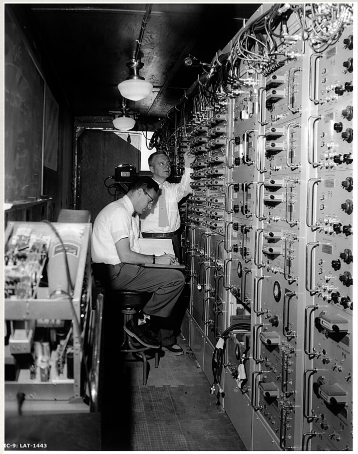


Fig. 6. Reines (seated) and Cowan in the electronics trailer for the 1956 Savannah River ne tion experiments. Courtesy of the Regents of the University of California, operators of National Laboratory.

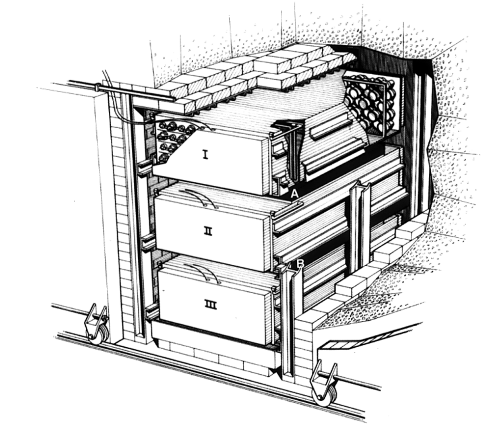
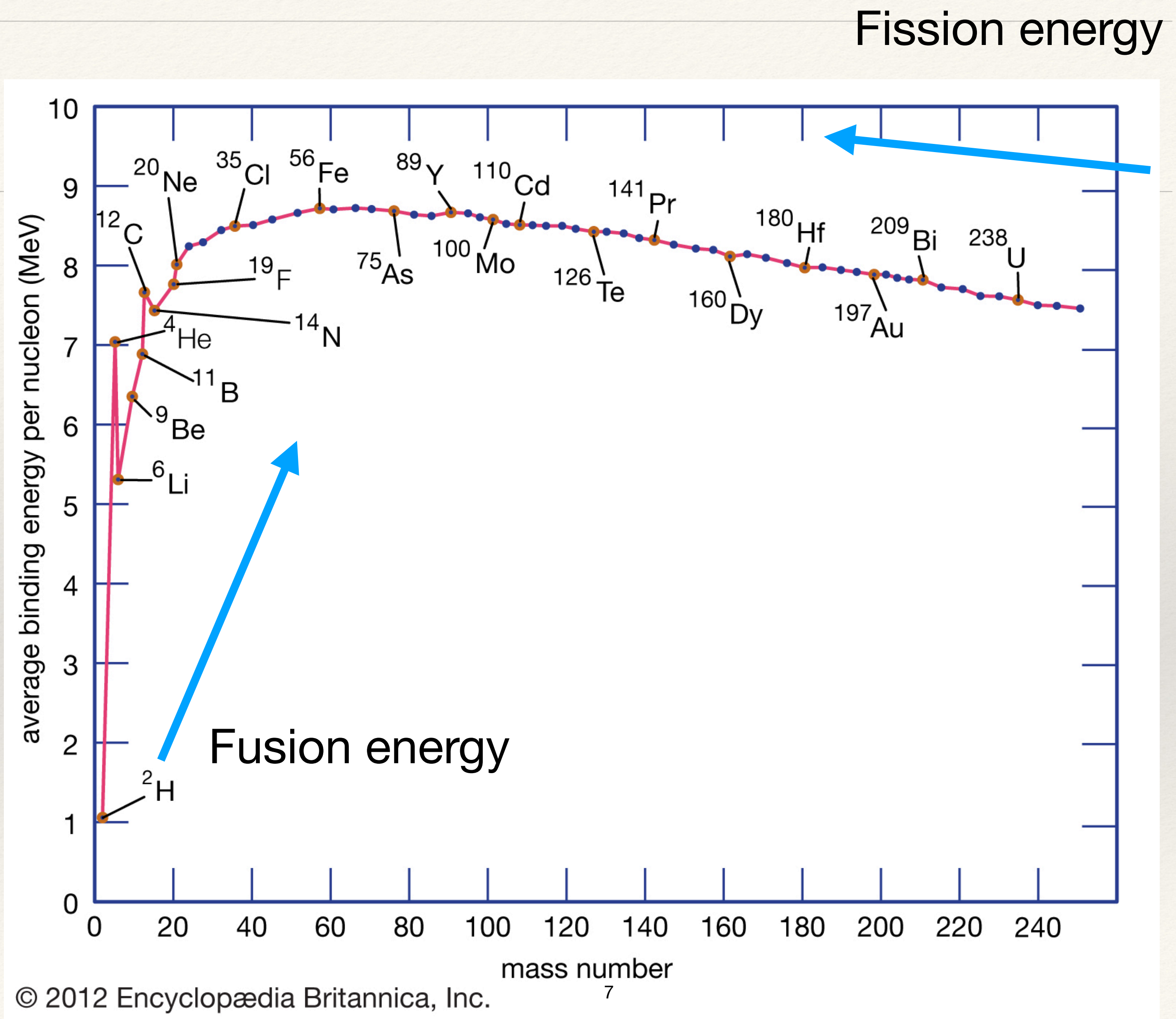


Fig. 5. The Savannah River neutrino detector. *Source:* Reines, *et al.*, "Detection of the Free Neutrino" (ref. 24), Figure 2; copyright 1960 by the American Physical Society.

Binding energy

- $m(A, Z) = Zm_p + (A - Z)m_n - B$
- Deuterium
  - $B(2,1) = 2.2$ MeV
- Helium-4
  - $B(4,2) = 28.3$ MeV

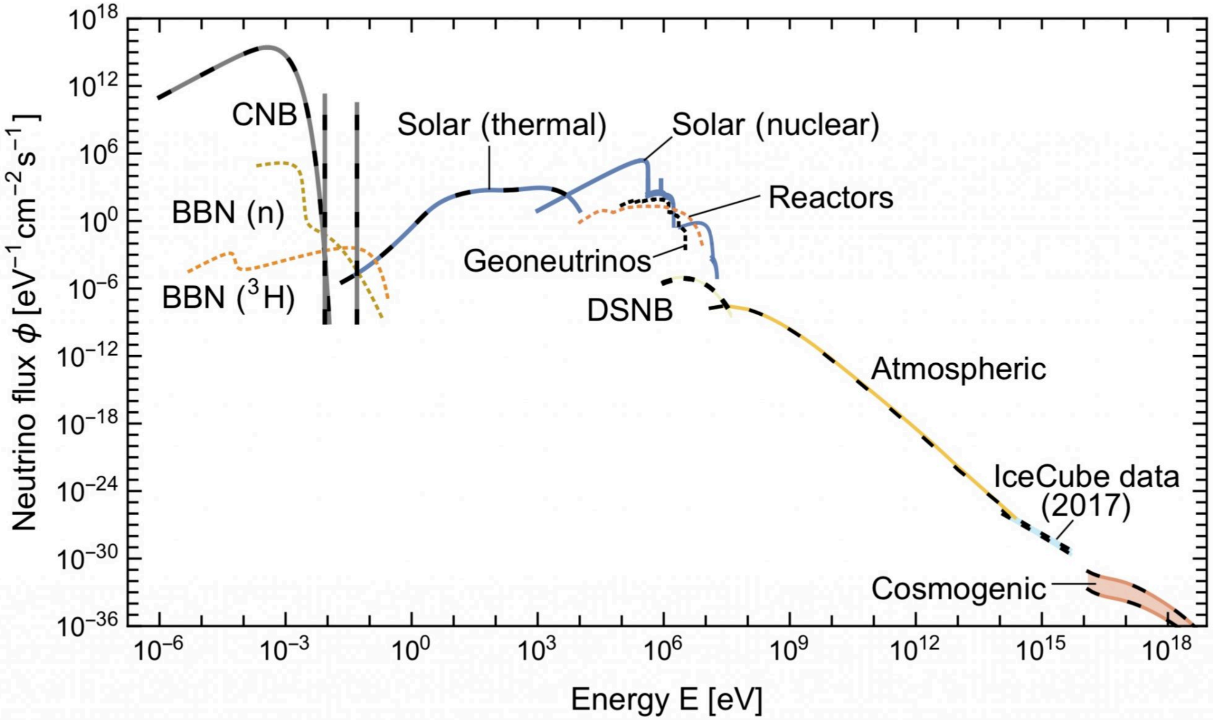


Some timelines of neutrinos

- 1898: **Radioactivity** by Becquerel
- 1900-1930: the notion of **neutron**, beta decay, and the continuum spectrum of beta decay
- 1930: Wolfgang Pauli proposes the existence of a neutral, nearly massless particle (later called the **neutrino**) to explain missing energy in beta decay, preserving conservation laws.
- 1956: Clyde Cowan and Frederick Reines experimentally confirm the existence of the **electron neutrino** in the Savannah River Experiment. Reines the 1995 Nobel Prize.
- 1962: Leon Lederman, Melvin Schwartz, and Jack Steinberger discover the **muon neutrino** at Brookhaven National Laboratory (Nobel Prize 1988).
- 1968: **Solar neutrinos** are detected by Raymond Davis Jr. in the Homestake Experiment, revealing the "solar neutrino problem", earning Davis the 2002 Nobel Prize.
- 1987: **Neutrinos from Supernova** 1987A are detected by Kamiokande and IMB detectors, confirming neutrinos' role in stellar explosions and providing insights into their properties. Koshiba Nobel 2002
- 1998: The Super-Kamiokande experiment in Japan provides evidence for **neutrino oscillations**, implying neutrinos have mass (contrary to the Standard Model). Takaaki Kajita shares the 2015 Nobel Prize for this.
- 2001-2002: The Sudbury Neutrino Observatory (SNO) in Canada resolves the solar neutrino problem, confirming n**eutrino oscillations** and flavor transformation. Arthur McDonald shares the 2015 Nobel Prize.
- 2013: The IceCube Neutrino Observatory at the South Pole detects high-energy cosmic neutrinos, opening the field of **neutrino astrophysics.**

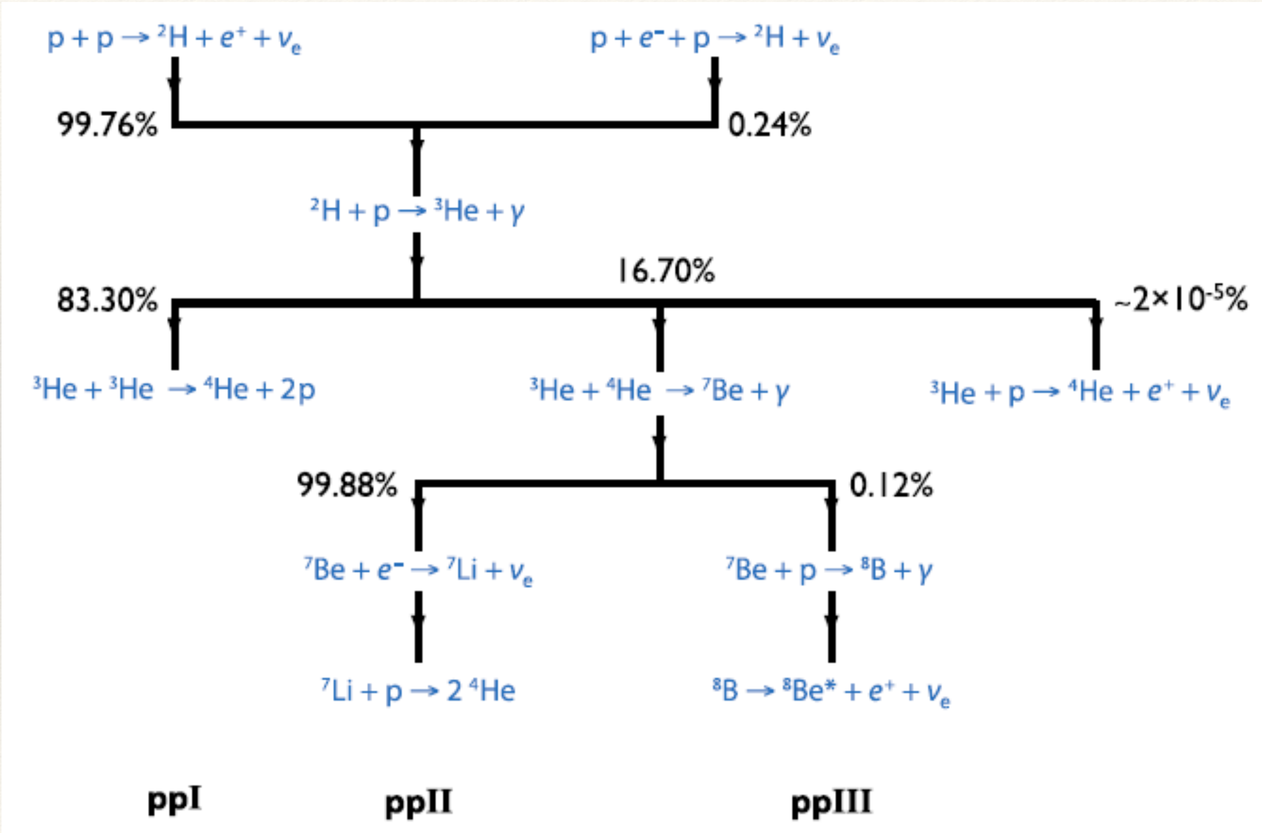
The Grand Unified Neutrino Spectrum

- Cosmic Neutrino background
  - (1e-4 to 1 eV)
- Solar neutrino (MeV)
- Supernova neutrinos (MeV)
- (Reactor neutrinos, MeV)
- Atmospheric Neutrinos
  - GeV -> TeV
- Astrophysical/Cosmogenic neutrinos
  - TeV -> PeV-> EeV



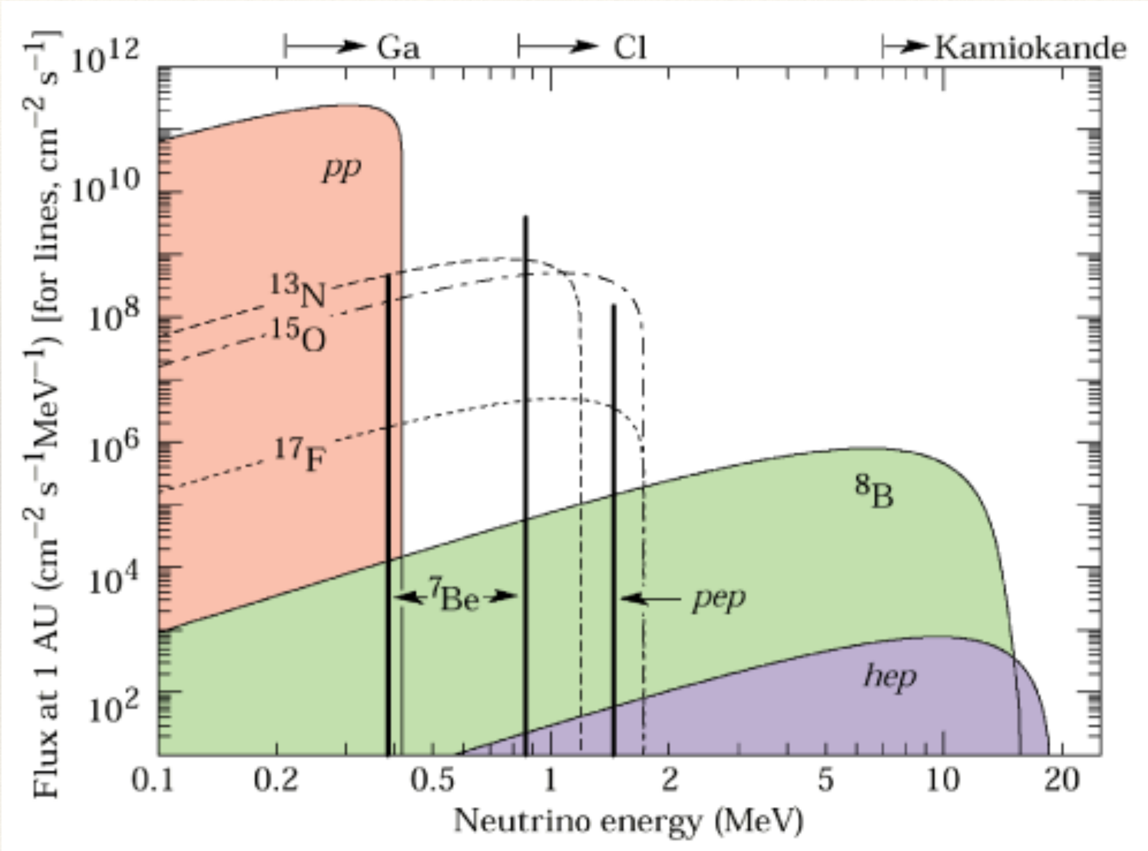
https://arxiv.org/abs/1910.11878

Place with a lot of Fusion



Solar neutrino spectrum

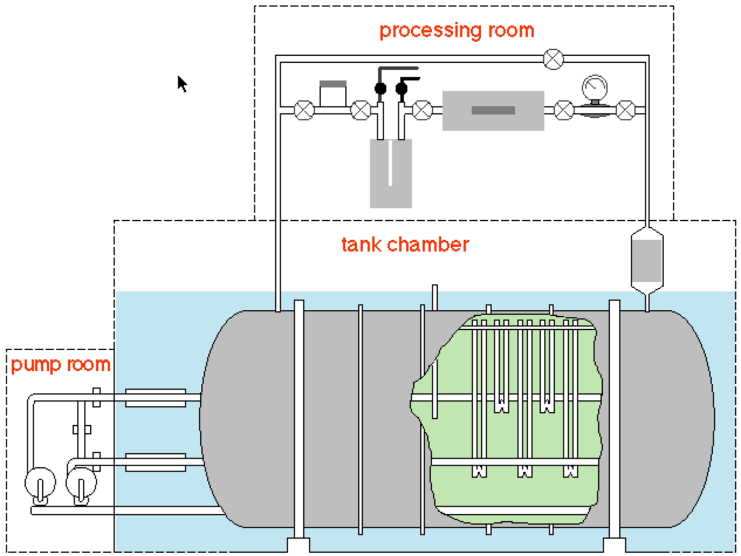
- The Sun as a ball of gas
  - + gravity
- We should be able to solve for its structure/ temperature
- + nuclear physics = energy production
- We should be able to fully understand the bulk physics of the Sun
- The physics of the core =====>



1967 Homestake experiment

- 600 tons of C_2Cl_4 (cleaning fluids)

- $\nu + ^{37}_{17}\mathrm{Cl} \rightarrow ^{37}_{18}\mathrm{Ar} + e^-$, argon-37 radioactive in 35 days



1967 Homestake experiment

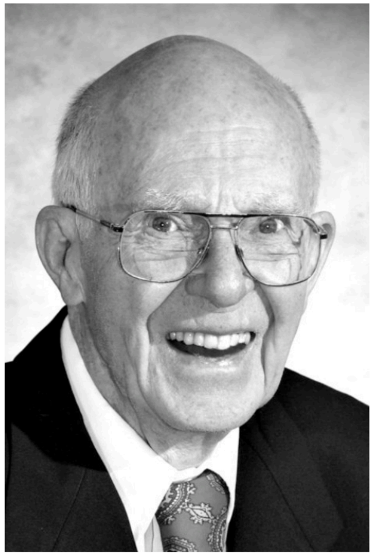


Photo from the Nobel Foundation archive.

Raymond Davis Jr.

Prize share: 1/4

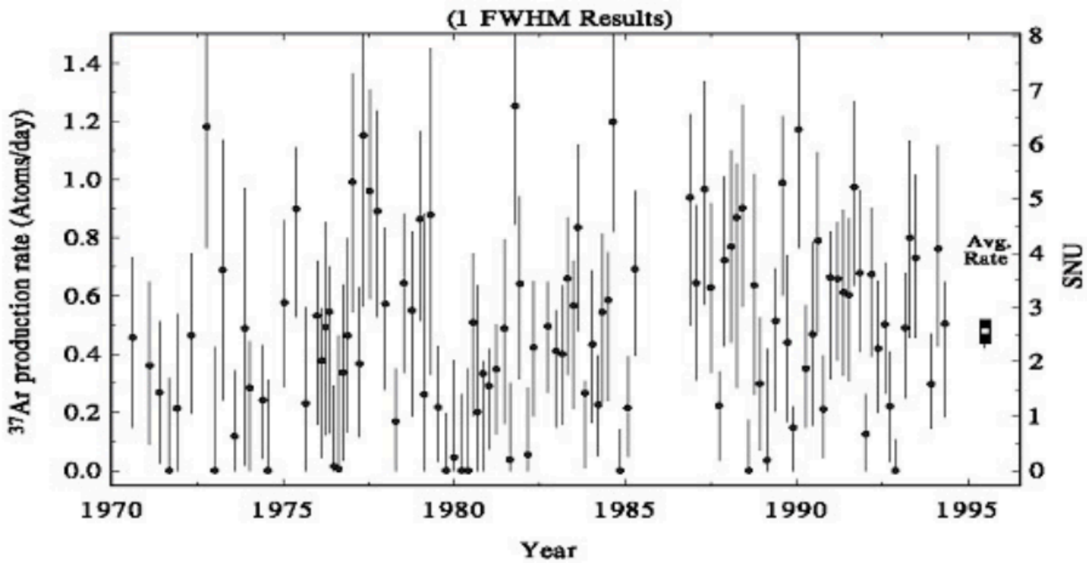


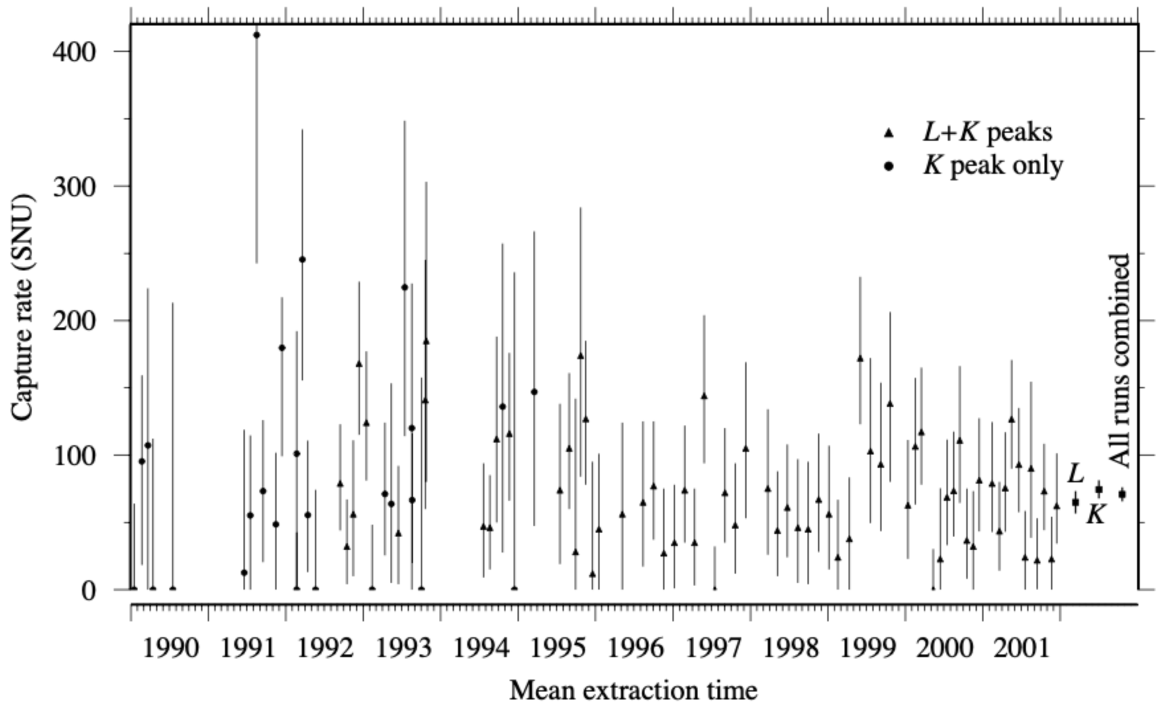
Fig. 2 Final results of Davis experiment (Cleveland et al. 1998). The average rate of about 2.5 SNU is much lower than the calculated rate of about 8.6.

The Nobel Prize in Physics 2002

- 1SNU = 10^{-36} interactions/atom/s

SAGE and GALLEX/GNO

- The Soviet–American Gallium Experiment (SAGE)
- The Gallium experiment (GALLEX/GNO)

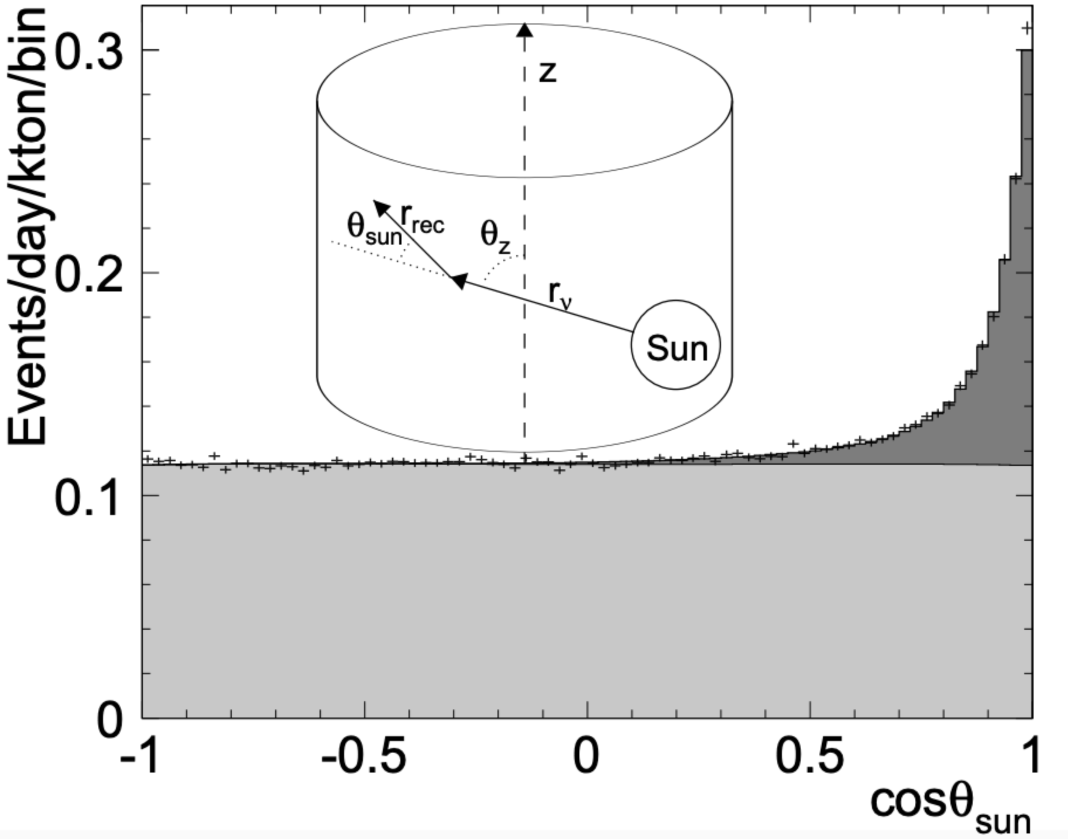


- SAGE

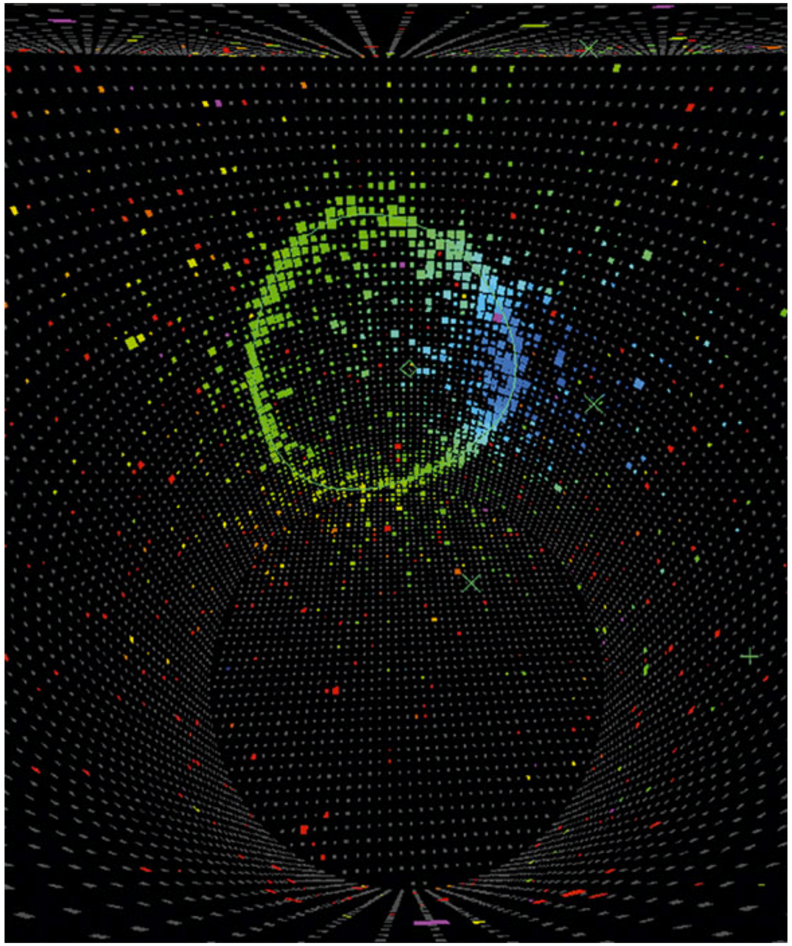
Kamiokande and Super-Kamiokande

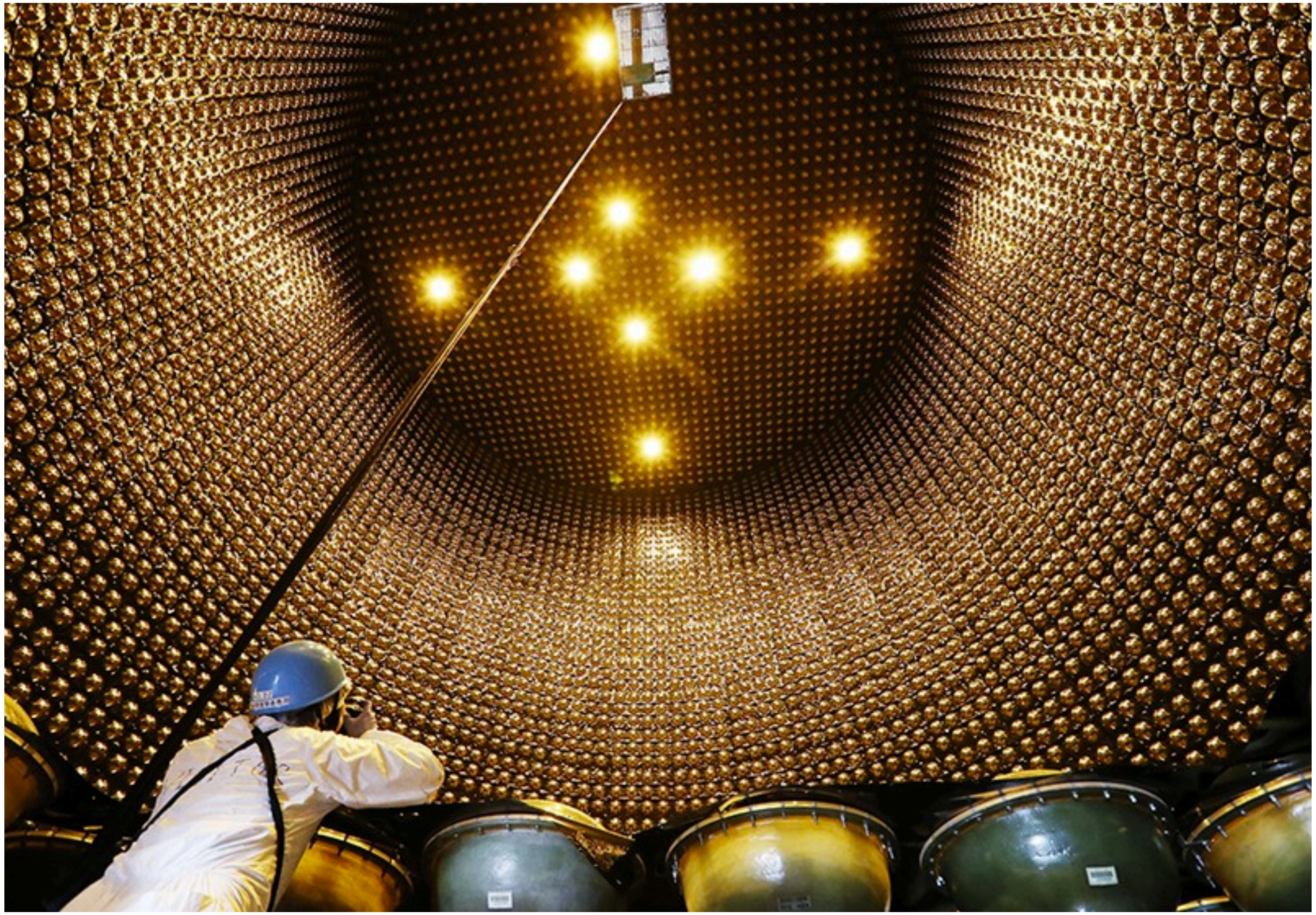
- Water Cherenkov detector
- neutrino electron scattering
- Real time event reconstruction

- Reaction has no threshold.
- But detector has,
  - Cherenkov light $\propto E_e$



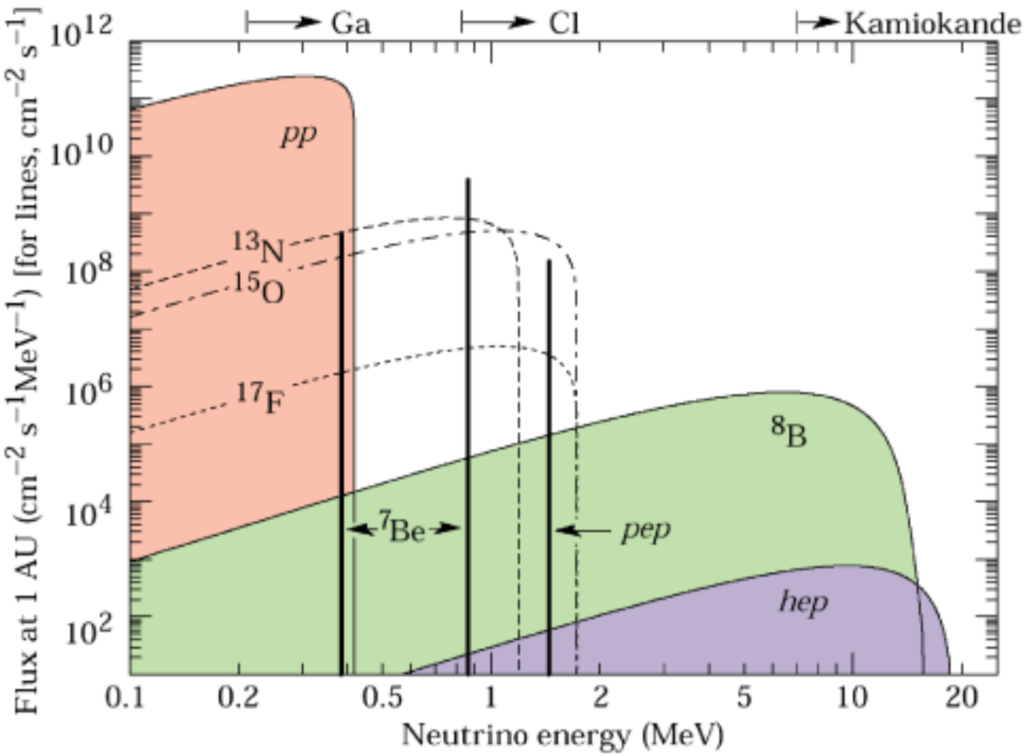
Kamiokande and Super-Kamiokande

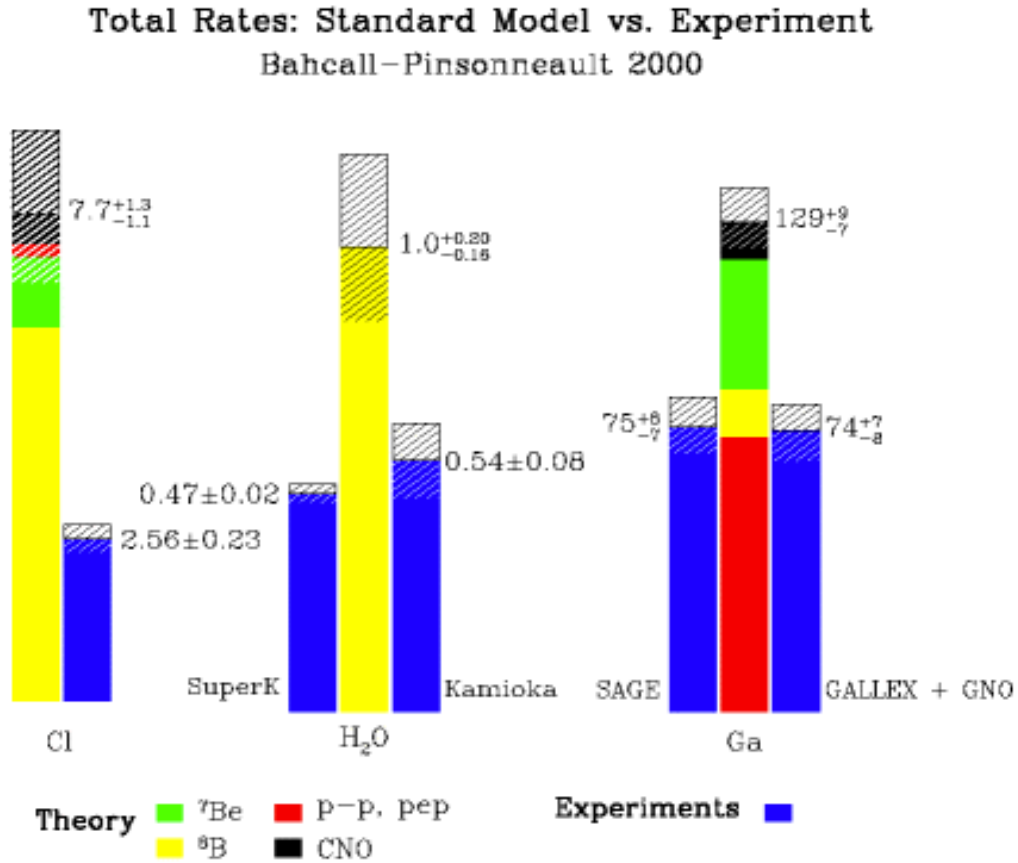




The solar neutrino problem

- Different experiment saw different amount of deficits.



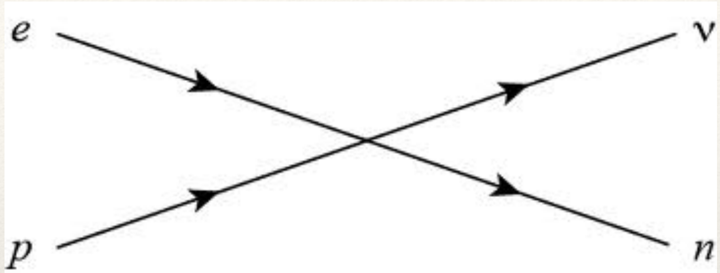


Neutrinos

- A neutral lepton that only has weak interaction
  - Very small cross section
  - Pass through many things!
- It oscillates

A quick Intro to Weak Interactions

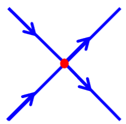
Fermi's theory of weak interaction



- There are 4 fermions in a neutron decay
- $n \rightarrow p^+ + e^- + \bar{\nu}_e$
- Fermi's theory of 4 fermion interaction

★In 1934, before the discovery of parity violation, Fermi proposed, in analogy with QED, that the invariant matrix element for β-decay was of the form:

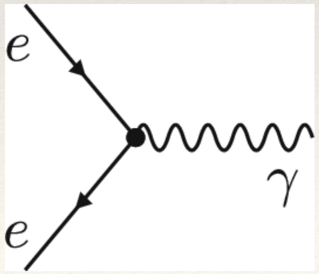
$$M_{fi} = G_F \, g_{\mu\nu} [\overline{\psi}\gamma^\mu \psi][\overline{\psi}\gamma^\nu \psi]$$



where $G_F = 1.166 \times 10^{-5}\,\mathrm{GeV}^{-2}$

•Note the absence of a propagator : i.e. this represents an interaction at a point

Compared with Electromagnetic interactions

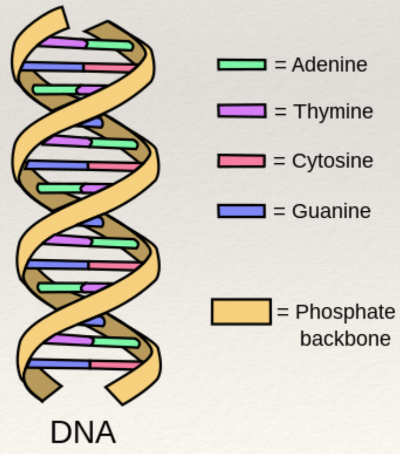


Weak Interaction vs Parity

- "Parity" as an operator to Physics
  - X -> (-X) for all spatial directions
  - Can you tell whether we live in an inverted world?

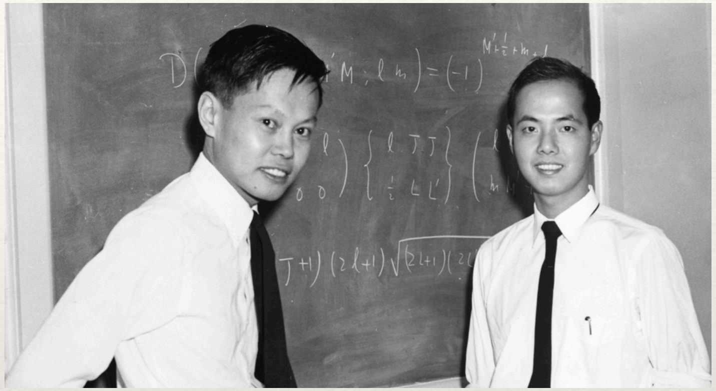
- Does physical phenomena respect parity symmetry?
- Our daily life seems say so (newtons law, gravity, EM)

- But seems not in smaller scales
  - Left-handed vs right-handed is preserved in rotation
  - Helicity/Chirality



Weak Interaction vs Parity

- Does fundamental physics respects Parity?
- Lee and Yang 1956



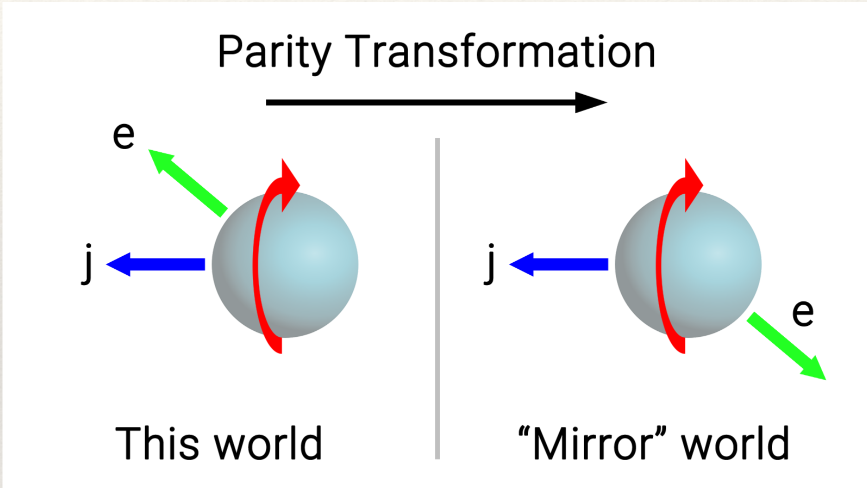
- Chien-Shiung Wu 1956
  - Experimentally proved that weak interactions violates Parity

Weak Interaction vs Parity

- Co beta decays (weak interaction)

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

- Into excited Ni, which then decay into two photons



- Under Parity
- Spin remains unchanged, the electron direction should change
- Parity conservation implies isotropic electron emission at the fundamental level

Opposite was observed

The Wu Experiment

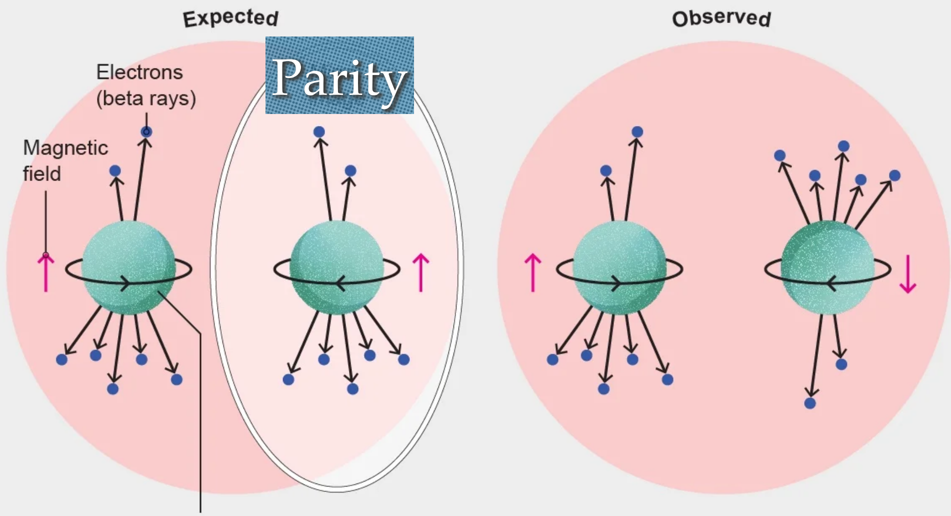
- Her nicknames include the "First Lady of Physics", the "Chinese Marie Curie" and the "Queen of Nuclear Research".

Chien-Shiung Wu
吴健雄

Chien-Shiung Wu performing experiments

Violating the Principle of Parity

Chien-Shiung Wu showed that weakly interacting particles inside an atom's nucleus do not behave symmetrically like the rest of the universe. In 1956 she devised an experiment to test the so-called principle of parity for weakly interacting particles, such as those that are produced during radioactive decay (*shown below*). When an atom has either too many protons or too many neutrons, a nucleus ejects extra electrons as it transforms from one element into another. Wu and her partners used a powerful magnet at ultracold temperatures to align the magnetic spins of cobalt 60 nuclei. Then they watched to see in which direction the electrons shot out from those nuclei. When the experimenters reversed the direction of the nuclei's spin from left to right, they expected to see a mirror image of what they had seen before. Instead the experiment revealed that parity was not conserved for weakly interacting particles: the spinning nuclei of cobalt 60 kept emitting electrons preferentially in one direction, relative to their spin. This unexpected result shocked the physics world.



Spinning cobalt 60 nuclei during radioactive decay

Quanta magazine

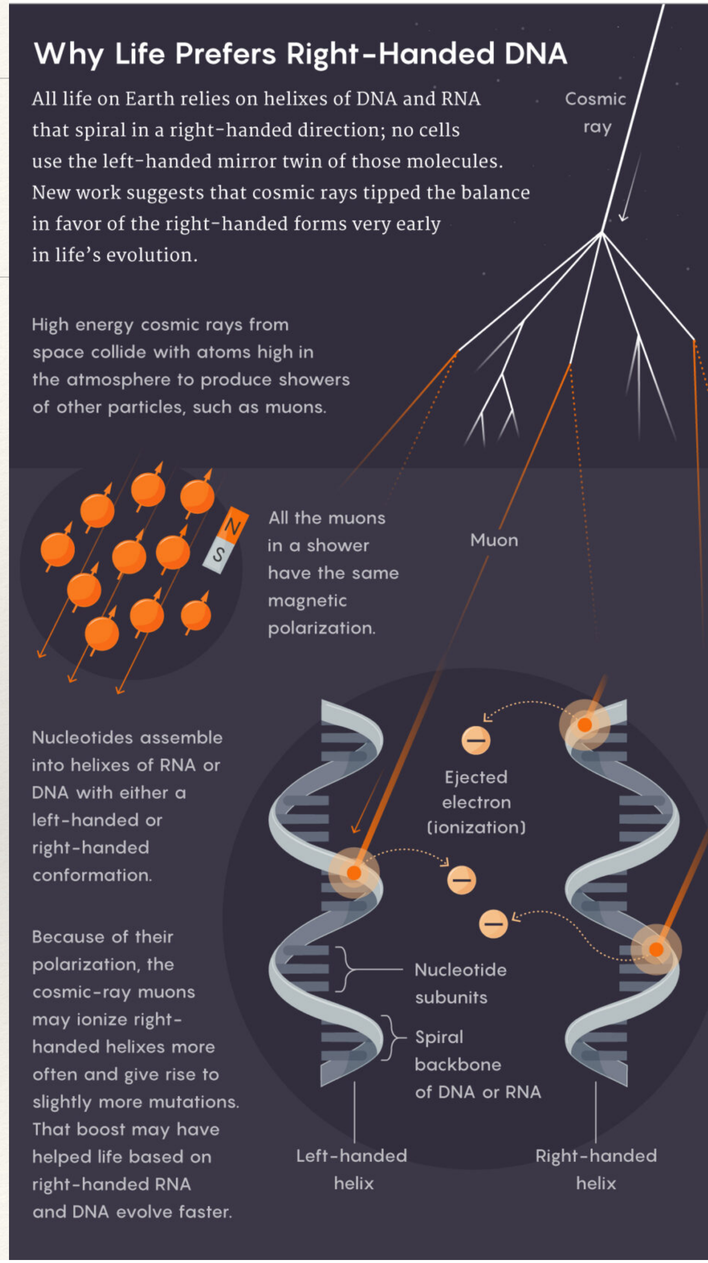
ABSTRACTIONS BLOG

Cosmic Rays May Explain Life's Bias for Right-Handed DNA

12

Cosmic rays may have given right-handed genetic helixes an evolutionary edge at the beginning of life's history.

- Really??



PHYSICAL REVIEW VOLUME 109, NUMBER 1 JANUARY 1, 1958

Theory of the Fermi Interaction

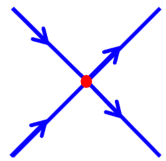
R. P. FEYNMAN AND M. GELL-MANN
California Institute of Technology, Pasadena, California
(Received September 16, 1957)

The representation of Fermi particles by two-component Pauli spinors satisfying a second order differential equation and the suggestion that in β decay these spinors act without gradient couplings leads to an essentially unique weak four-fermion coupling. It is equivalent to equal amounts of vector and axial vector coupling with two-component neutrinos and conservation of leptons. (The relative sign is not determined theoretically.) It is taken to be "universal"; the lifetime of the μ agrees to within the experimental errors of 2%. The vector part of the coupling is, by analogy with electric charge, assumed to be not renormalized by virtual mesons. This requires, for example, that pions are also "charged" in the sense that there is a direct interaction in which, say, a π^0 goes to π^- and an electron goes to a neutrino. The weak decays of strange particles will result qualitatively if the universality is extended to include a coupling involving a Λ or Σ fermion. Parity is then not conserved even for those decays like $K\to 2\pi$ or 3π which involve no neutrinos. The theory is at variance with the measured angular correlation of electron and neutrino in He^6, and with the fact that fewer than 10^{-4} pion decay into electron and neutrino.

Connection to Fermi Theory

★ **In 1934, before the discovery of parity violation, Fermi proposed, in analogy with QED, that the invariant matrix element for β-decay was of the form:**

$$M_{fi} = G_F\, g_{\mu\nu} [\overline{\psi}\gamma^\mu \psi][\overline{\psi}\gamma^\nu \psi]$$



where $G_F = 1.166 \times 10^{-5}\,\mathrm{GeV}^{-2}$

- **Note the absence of a propagator : i.e. this represents an interaction at a point**

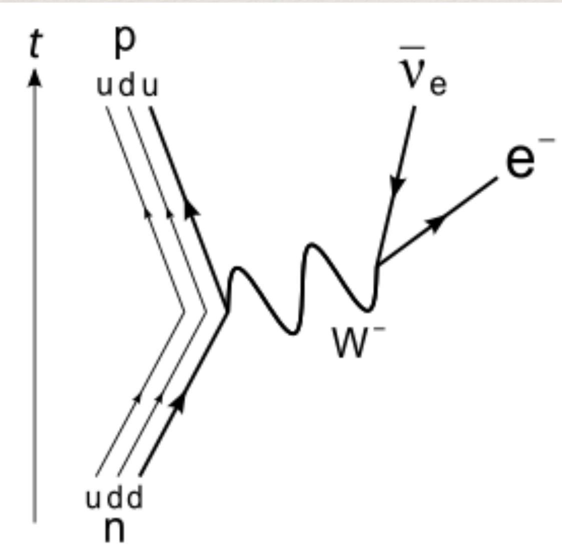
★ **After the discovery of parity violation in 1957 this was modified to**

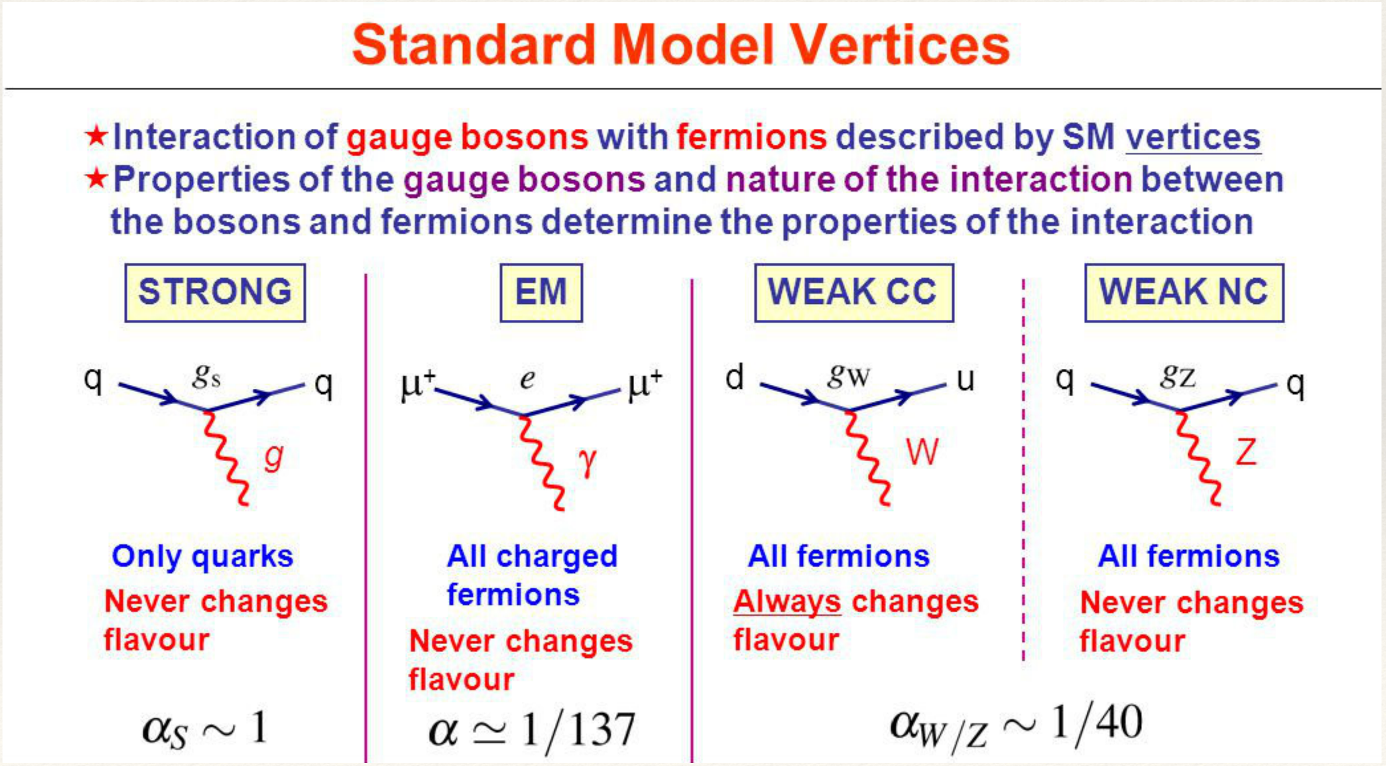
$$M_{fi} = \frac{G_F}{\sqrt{2}} g_{\mu\nu} [\overline{\psi}\gamma^\mu (1-\gamma^5)\psi][\overline{\psi}\gamma^\nu (1-\gamma^5)\psi]$$

(the factor of √2 was included so the numerical value of G_F did not need to be changed)

Weak interactions as we know it

- Neutron decay at the fundamental level





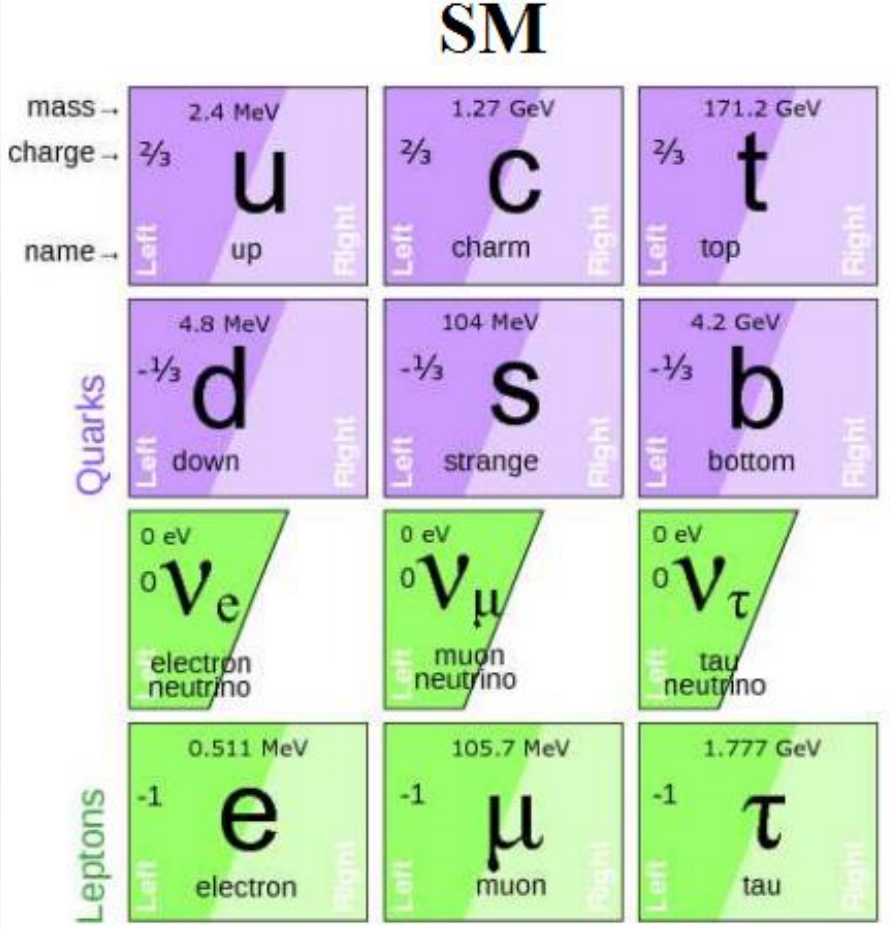
What does that mean that a particle theory breaks Parity

- Not only does weak interactions breaks Parity
- It maximally breaks the parity

- The particles can be classified as
  - Left-handed or Right-handed
  - **Weak interactions** only interacted via “Left-handed” particles

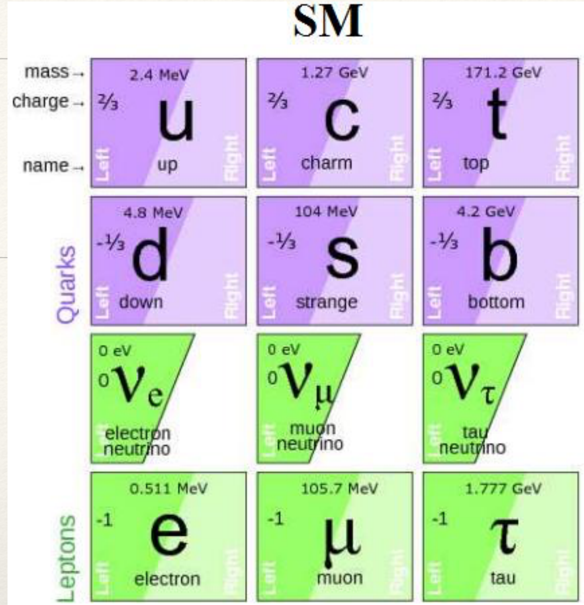
Weak interaction is "Left-handed"

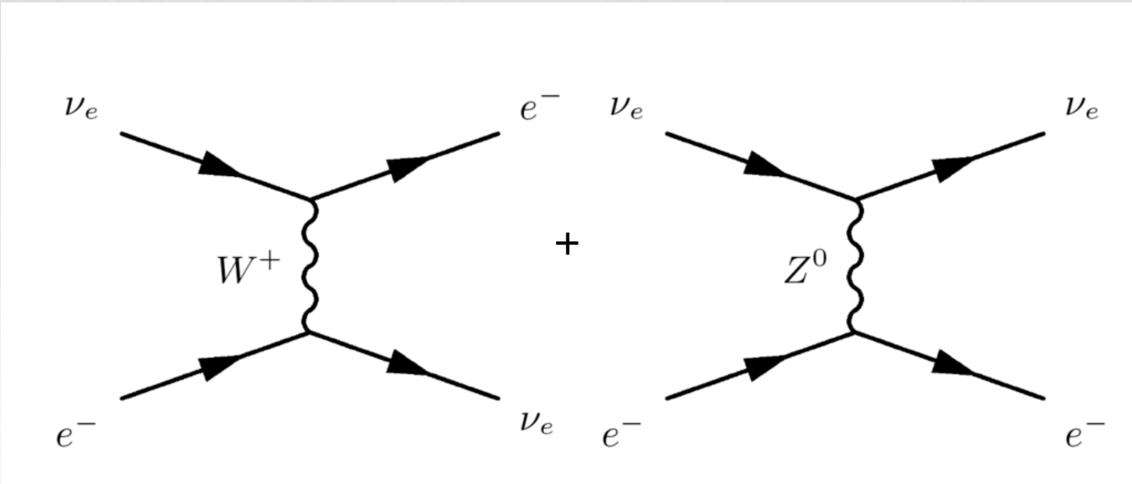
- All particles can be purely left-handed or purely right-handed, or [QM] both
- EM and Strong interactions do not care about handedness
- Only
  - **(left-handed Fermions)** and
  - **(right-handed anti-Fermions)**
- experience weak interactions
- So, only left-handed

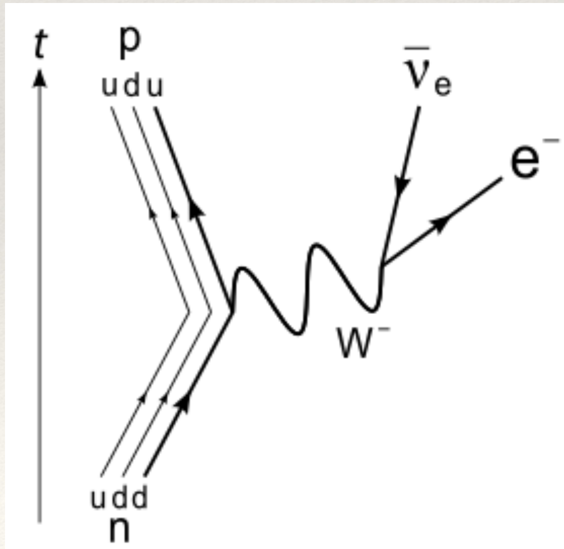


What does weak interactions do?

- If mediated by W bosons (+ or - charged), it change between (u/d) or (nu/e), as, you need to conserve charge!
- If mediated by Z boson, the particles does not change

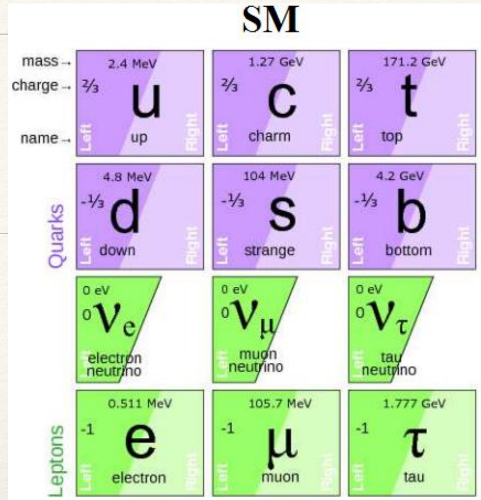






What else does RH fermions do?

- The Higgs field couples the LH fermions to the RH fermions.
  - Which becomes a mass term
- So, does neutrinos have mass?
  - And thus RH neutrinos?



$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

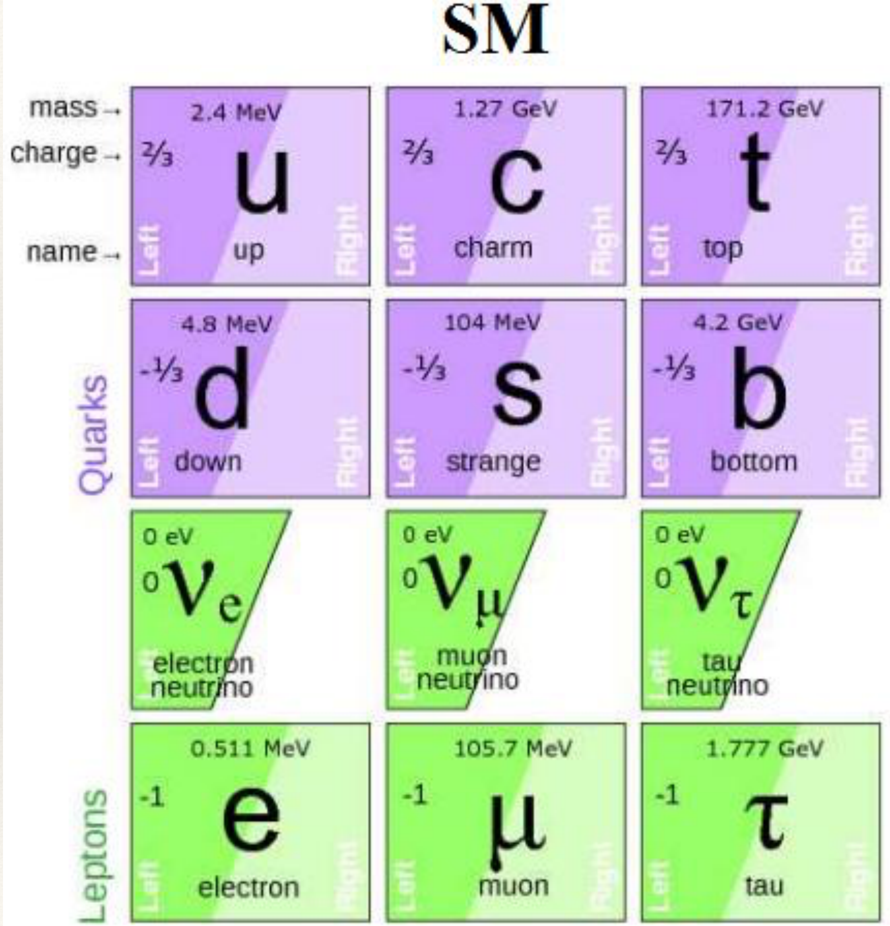
$$-\frac{\sqrt{2}}{v}\left[\underbrace{(\bar{\nu}_L, \bar{e}_L)\,\phi M^e e_R + \bar{e}_R \bar{M}^e \bar{\phi} \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}}_{\text{electron, muon, tauon mass term}}\right.$$

$$-\frac{\sqrt{2}}{v}\left[\underbrace{(\bar{u}_L, \bar{d}_L)\,\phi M^d d_R + \bar{d}_R \bar{M}^d \bar{\phi} \begin{pmatrix} u_L \\ d_L \end{pmatrix}}_{\text{down, strange, bottom mass term}}\right]$$

$$-\frac{\sqrt{2}}{v}\left[\underbrace{(-\bar{d}_L, \bar{u}_L)\,\phi^* M^u u_R + \bar{u}_R \bar{M}^u \phi^T \begin{pmatrix} -d_L \\ u_L \end{pmatrix}}_{\text{up, charmed, top mass term}}\right]$$

RH neutrinos?

- Other right-handed fermions are charged, we know they exist
- RH neutrino has no charge in all standard model forces (is undetectable particles real?)
- Old people's standard model
  - There are no RH neutrinos
  - Neutrinos have no mass (**)
    - Neutrino mass. => Breaks standard model
- Some view
  - RH neutrino may or may not exist



* * Can neutrino get mass from NOT Higgs?

- Normal fermions gets mass from Higgs
  - Same for massive bosons like W, Z
  - Somewhat proven by LHC

- Mass terms are constructed via LH-RH particle interactions
- For electrons, It must be a
  - (LH-electron X RH-positron),
  - so that (e) charged is conserved
- For neutrinos, maybe we can have
  - (LH-neutrino x RH-antineutrino) ?
  - Only neutrino can do this
  - If this term exists, neutrino can be a Majorana neutrino

$$-\frac{\sqrt{2}}{v}\left[\underbrace{(\bar{\nu}_L, \bar{e}_L)\,\phi M^e e_R + \bar{e}_R \bar{M}^e \bar{\phi} \begin{pmatrix}\nu_L \\ e_L\end{pmatrix}}_{\text{electron, muon, tauon mass term}}\right]$$

$$-\frac{\sqrt{2}}{v}\left[\underbrace{(\bar{u}_L, \bar{d}_L)\,\phi M^d d_R + \bar{d}_R \bar{M}^d \bar{\phi} \begin{pmatrix}u_L \\ d_L\end{pmatrix}}_{\text{down, strange, bottom mass term}}\right]$$

$$-\frac{\sqrt{2}}{v}\left[\underbrace{(-\bar{d}_L, \bar{u}_L)\,\phi^* M^u u_R + \bar{u}_R \bar{M}^u \phi^T \begin{pmatrix}-d_L \\ u_L\end{pmatrix}}_{\text{up, charmed, top mass term}}\right]$$

$$-\frac{1}{2}\, m_{\mathrm{M}} \left(\overline{\psi_L^c}\, \psi_L + \overline{\psi_L}\, \psi_L^c\right)$$

CPT Symmetry

History [edit]

The CPT theorem appeared for the first time, implicitly, in the work of Julian Schwinger in 1951 to prove the connection between spin and statistics.[3] In 1954, Gerhart Lüders and Wolfgang Pauli derived more explicit proofs,[4][5] so this theorem is sometimes known as the Lüders–Pauli theorem. At about the same time, and independently, this theorem was also proved by John Stewart Bell.[6][7] These proofs are based on the principle of Lorentz invariance and the principle of locality in the interaction of quantum fields. Subsequently, Res Jost gave a more general proof in 1958 using the framework of axiomatic quantum field theory.

- While Parity has been violated
- It has been found later that fundamental interactions have violated C and T and any two combinations of these symmetries.
- Parity, Charge, Time
- *Lorentz Invariant, Local, Unitary Quantum theory respects CPT*
- All known physics respects CPT symmetry
- CPT $(\bar{\nu}_e + p^+ \rightarrow n + e^-) = \nu_e + p^- \leftarrow \bar{n} + e^+$
  - Note that we have also changed handness for the neutrinos