Neutrinos

Nature's Mysterious Messengers

Jyotsna Osta

February 15, 2014

Saturday Morning Physics Lecture at Fermilab

Some trivia on Neutrinos

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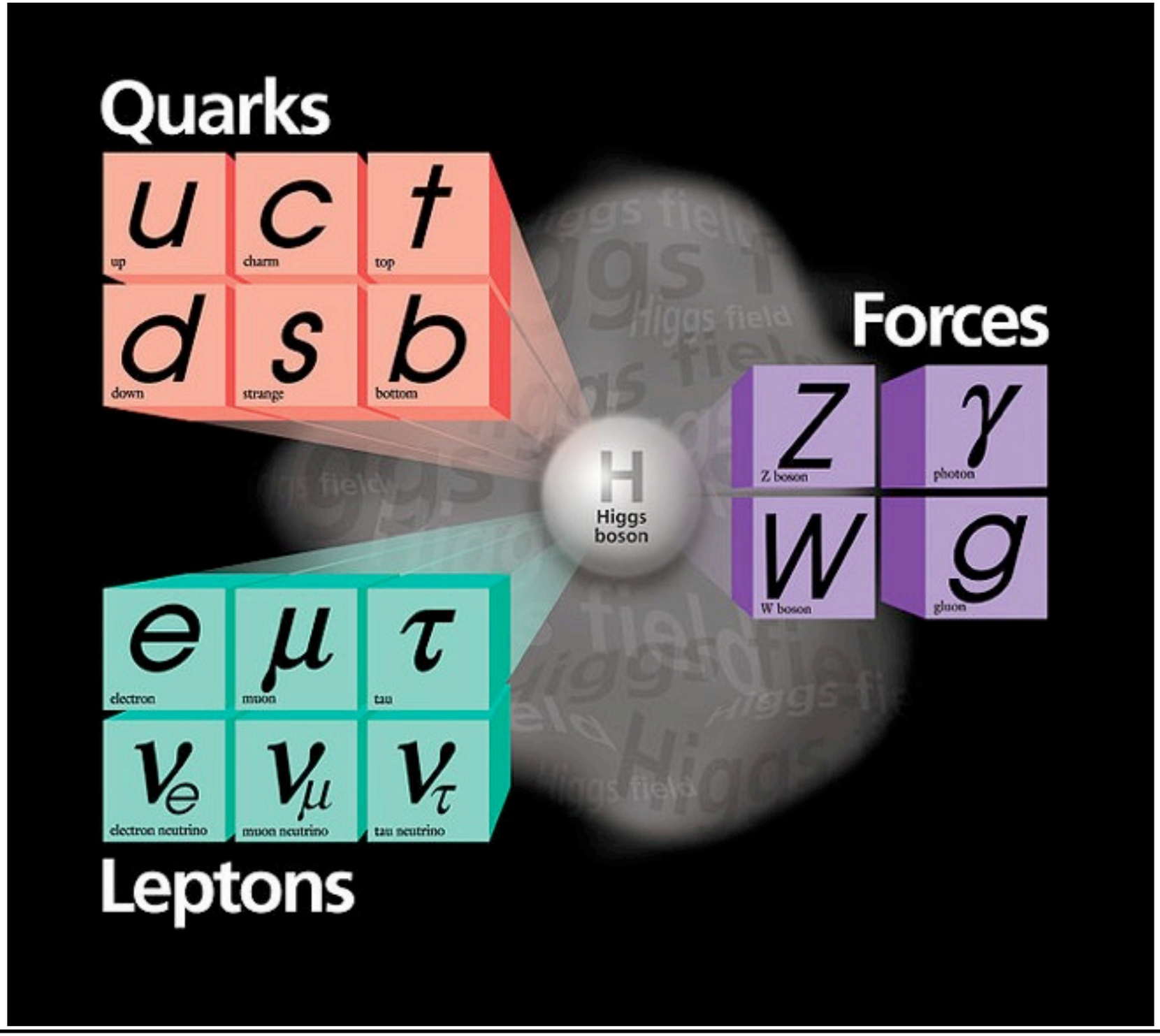
At the coldest lab temperatures ever achieved, neutrinos could still move at ~300 m/s, MORE THAN 20 TIMES AS FAST AS Usain Bolt at top speed !

The Standard Model



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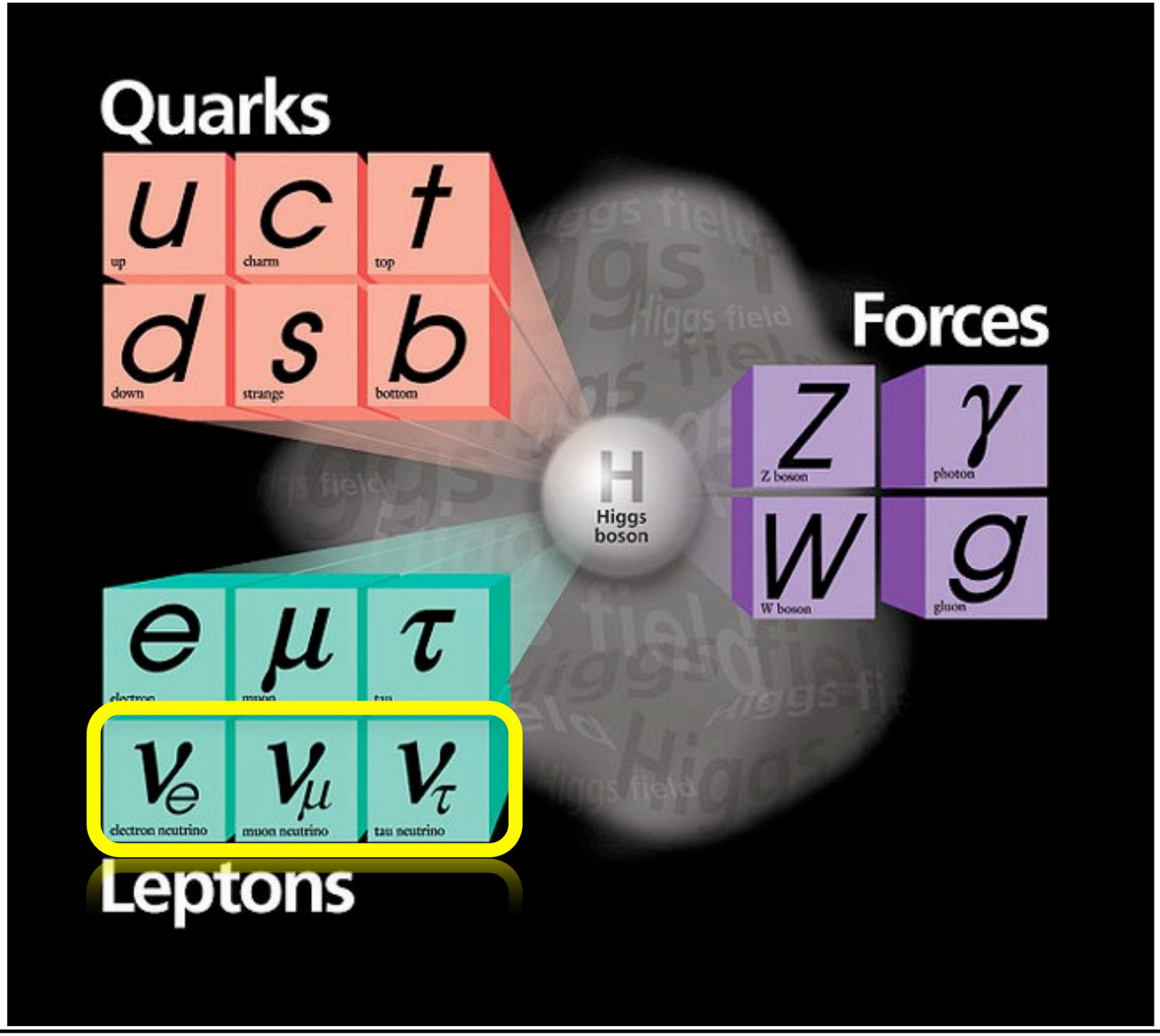

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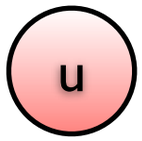
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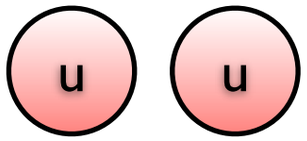
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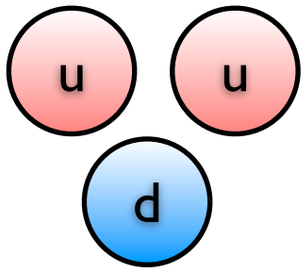
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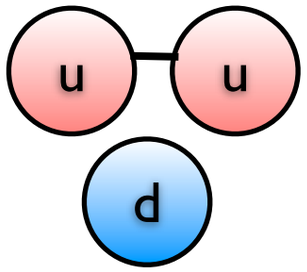
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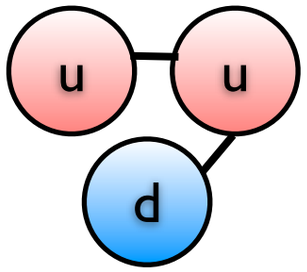
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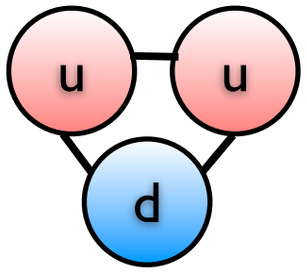
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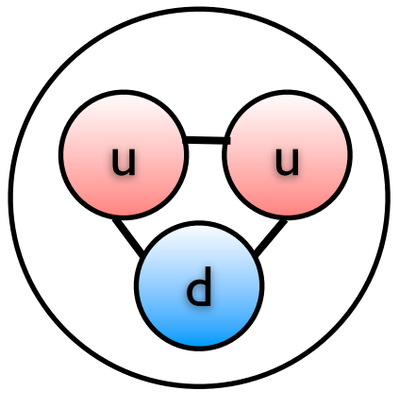
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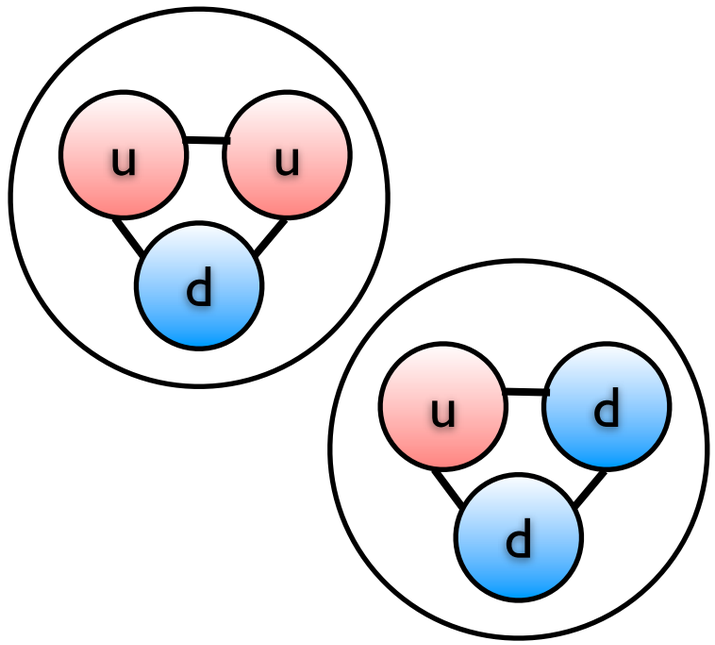
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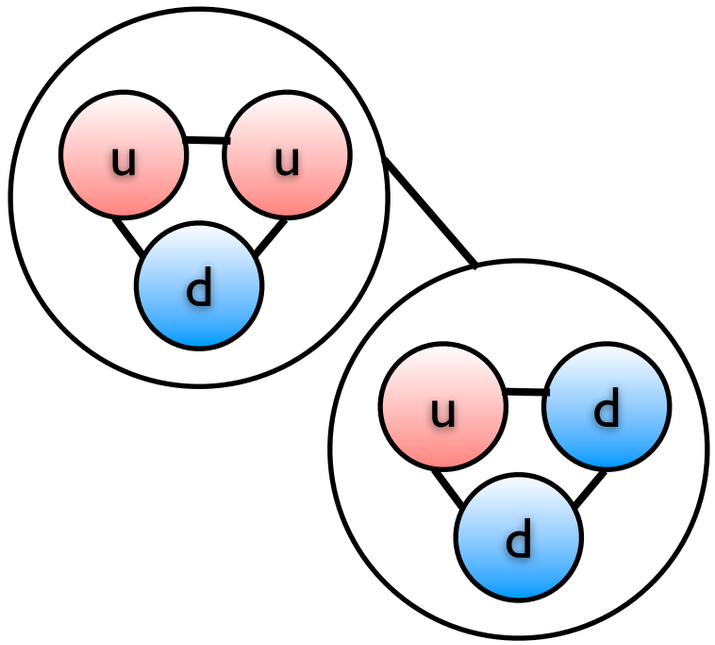
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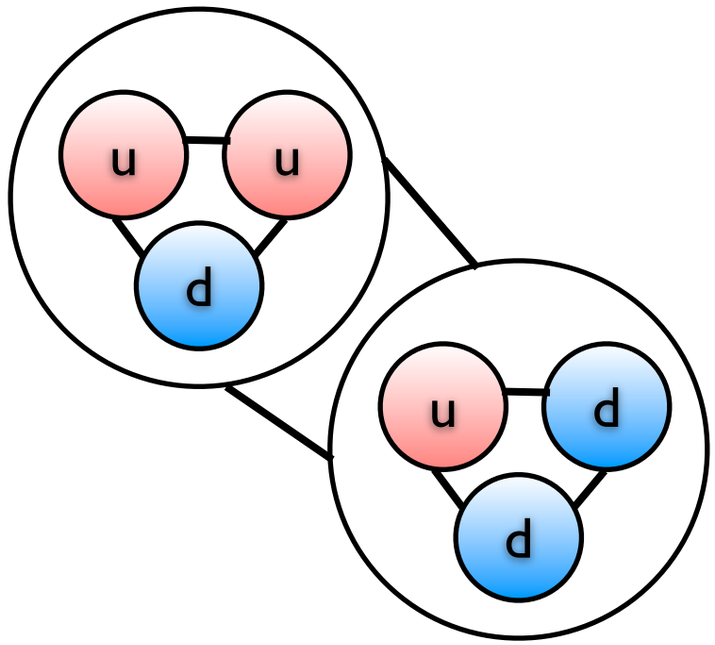
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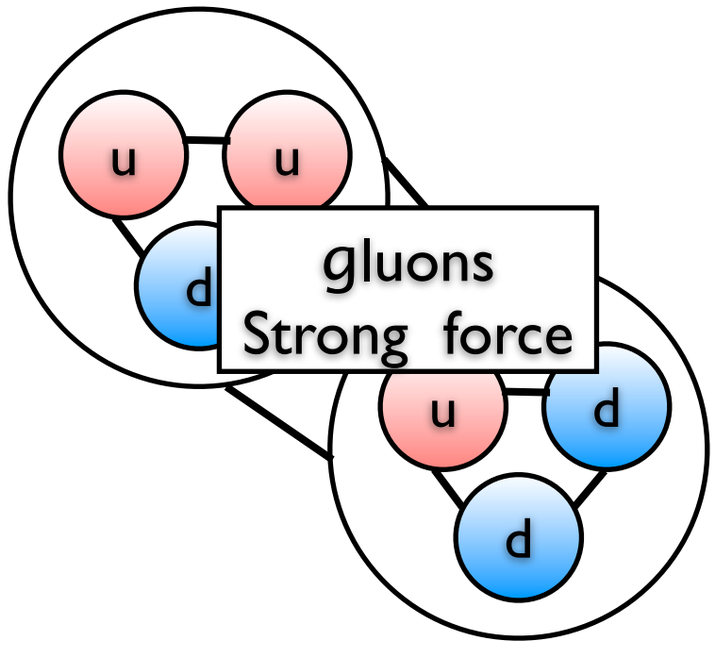
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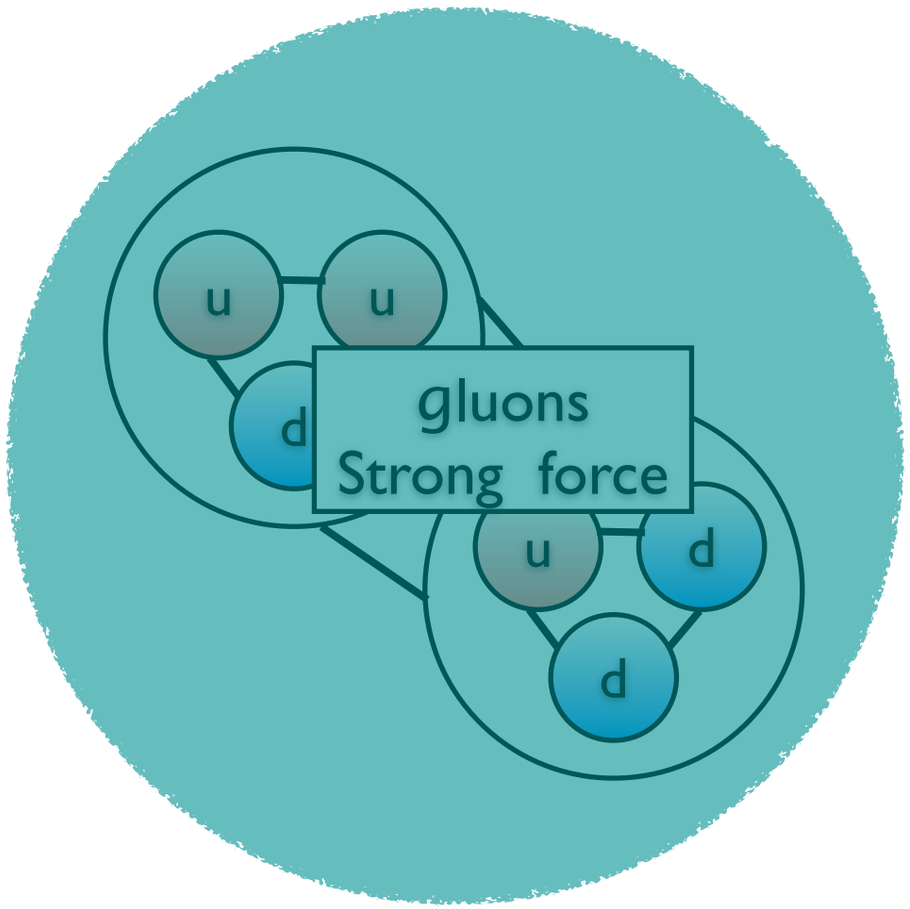
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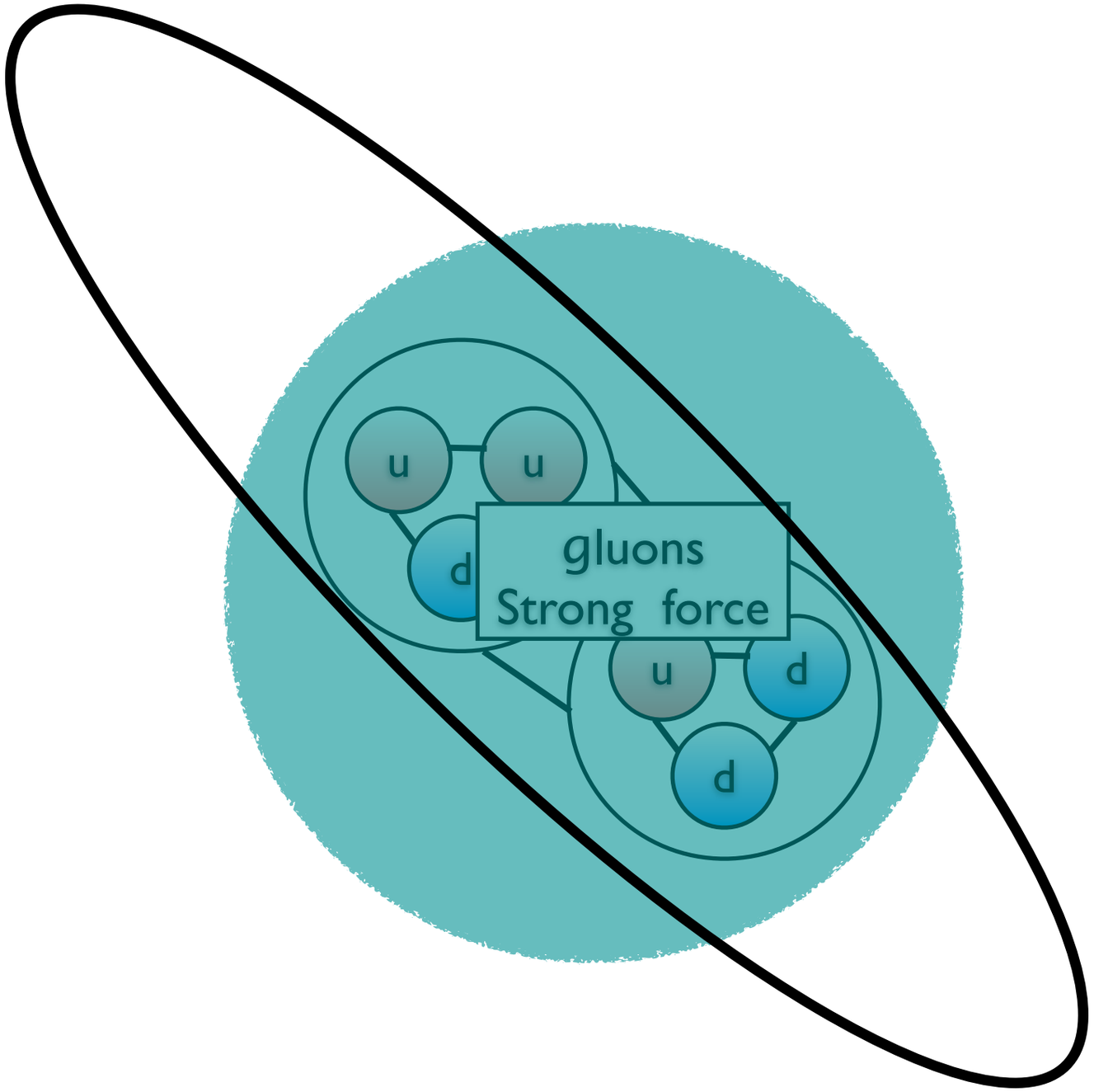
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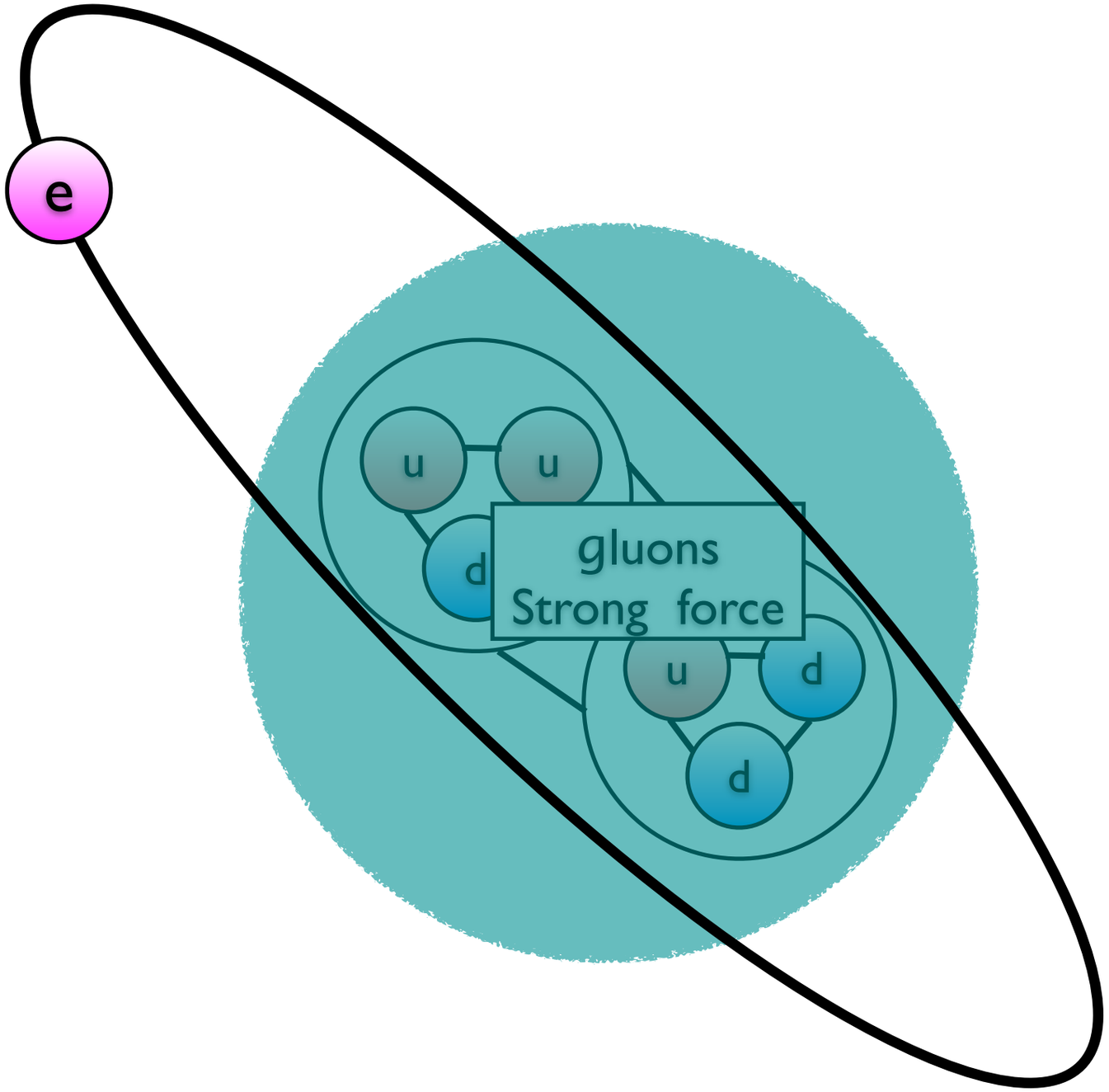
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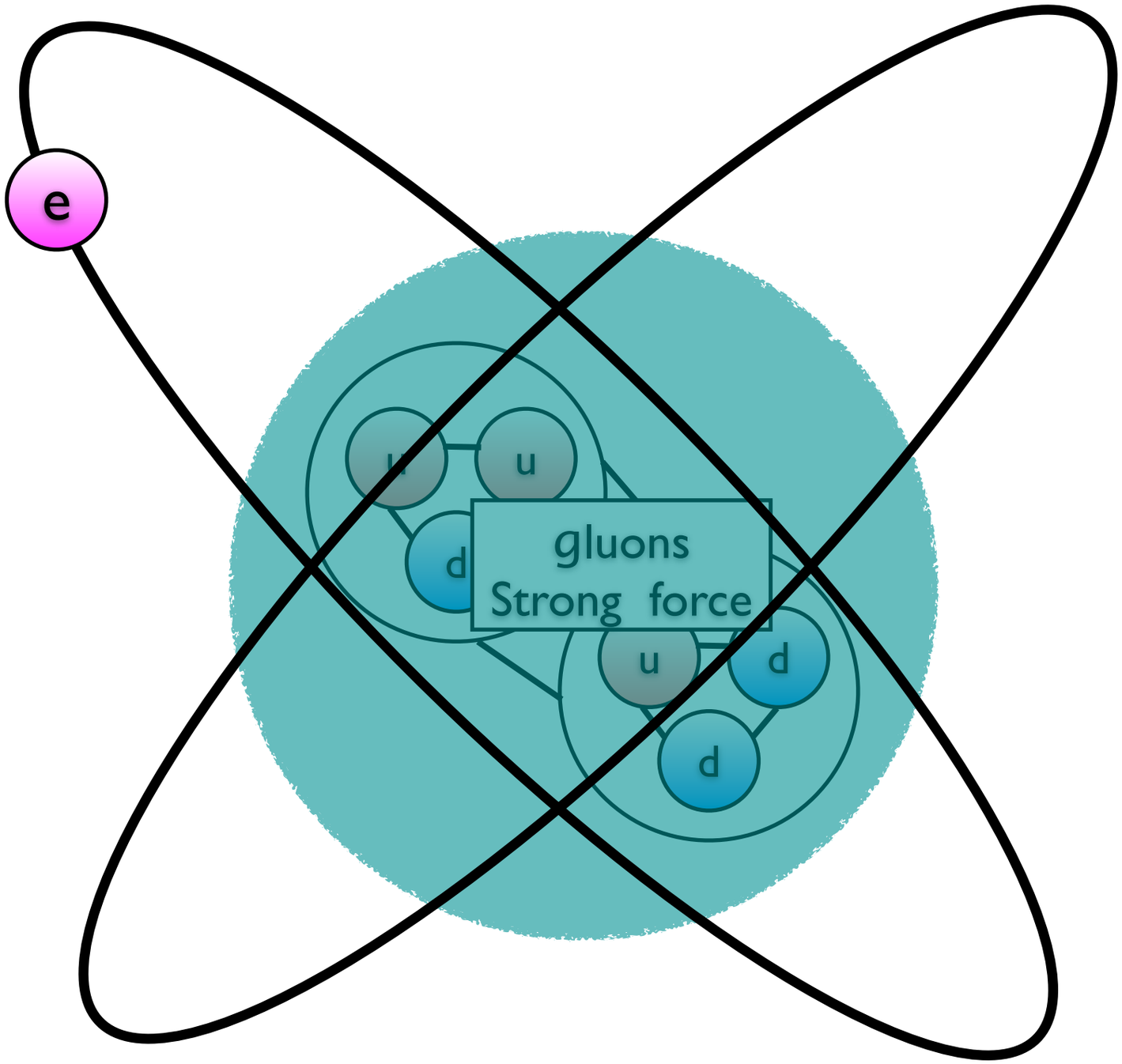
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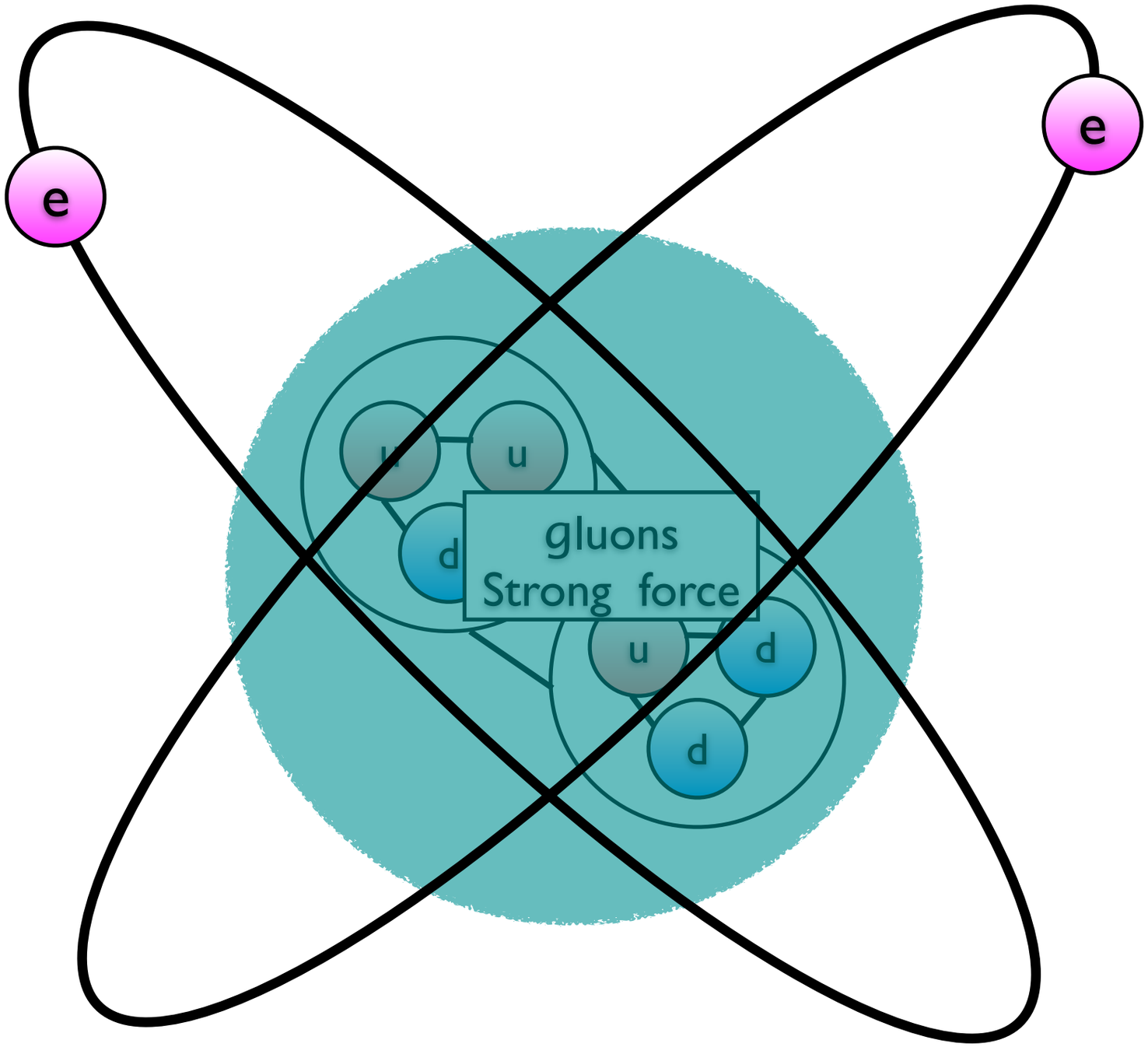
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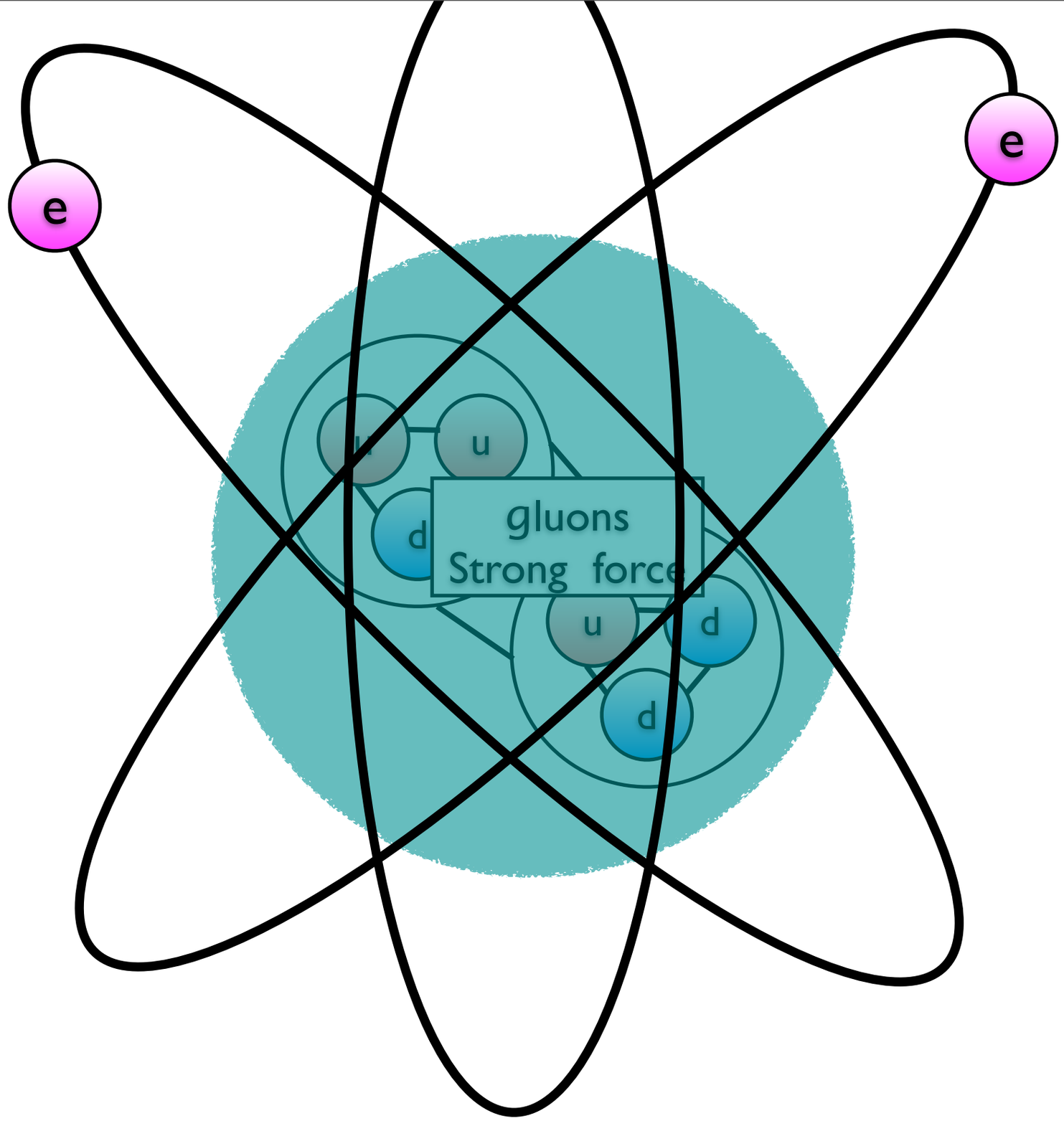
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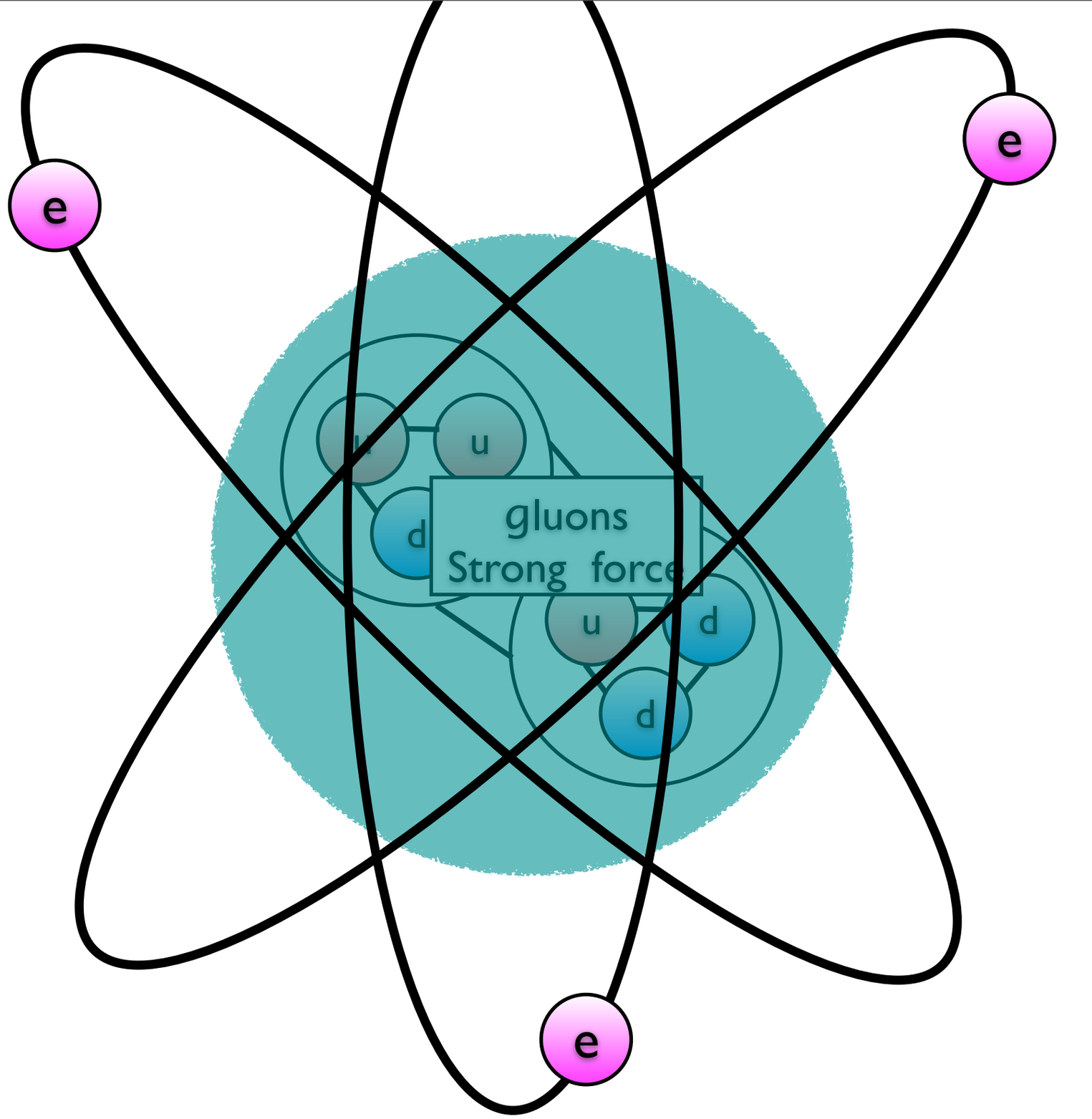
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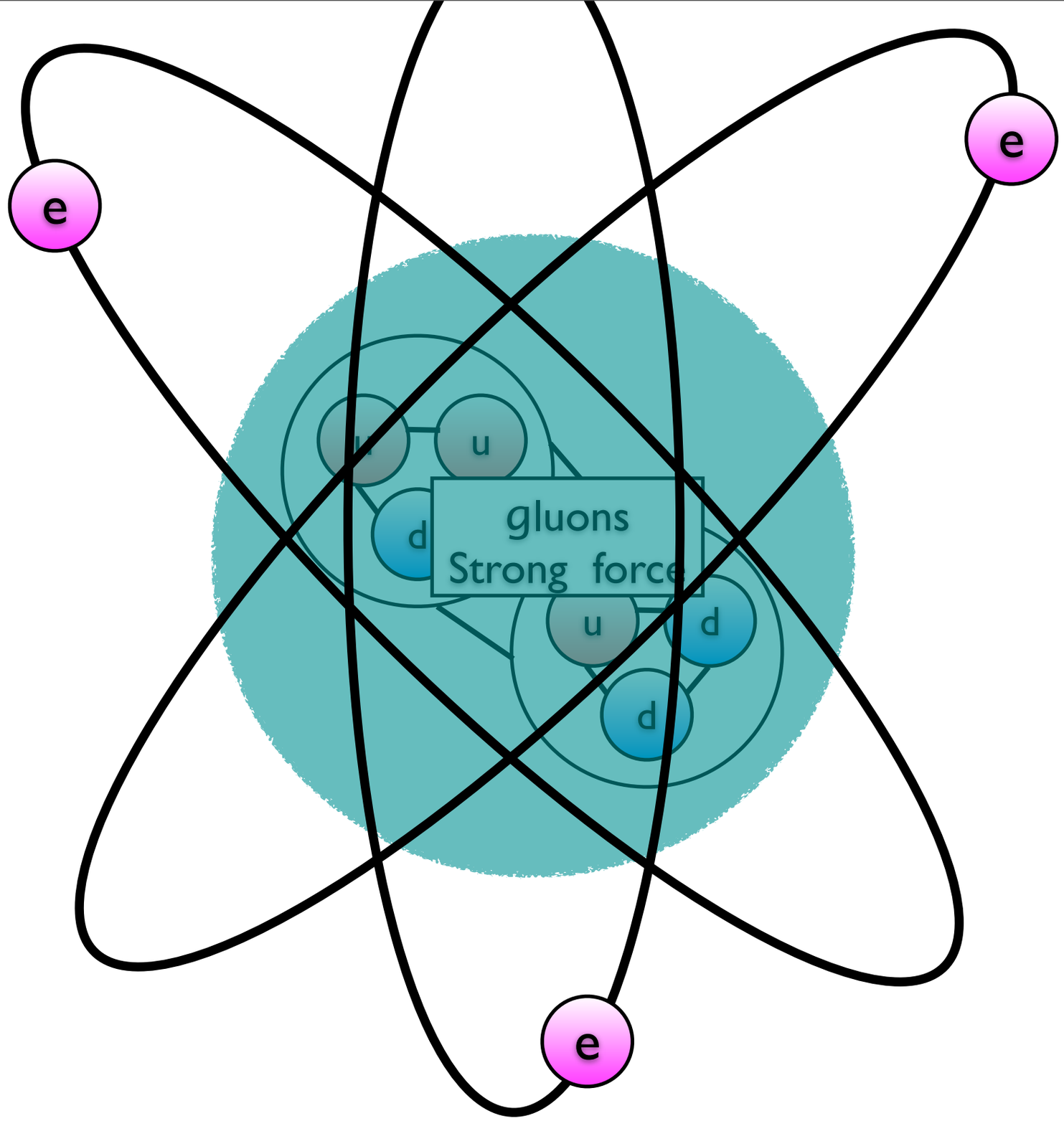
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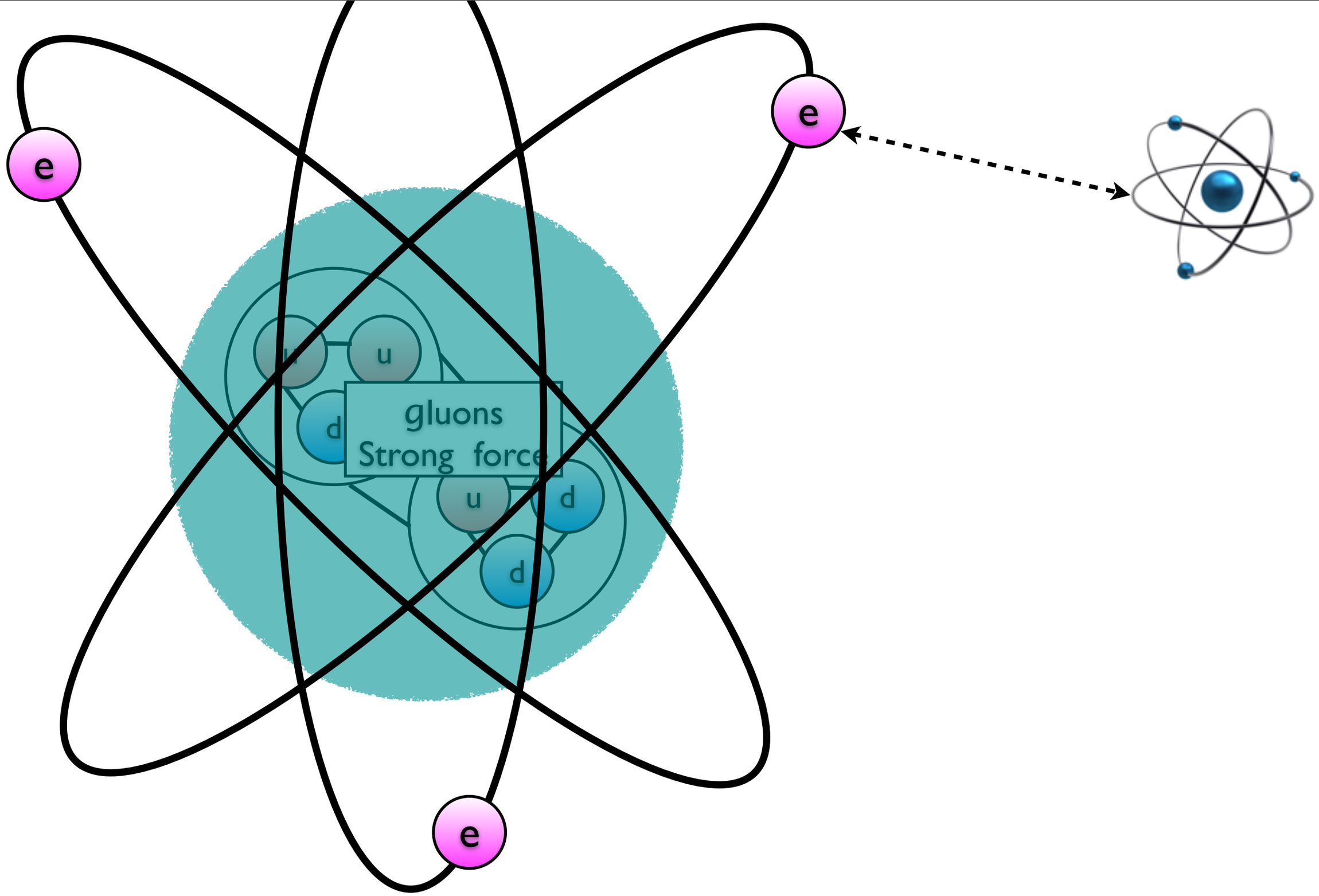
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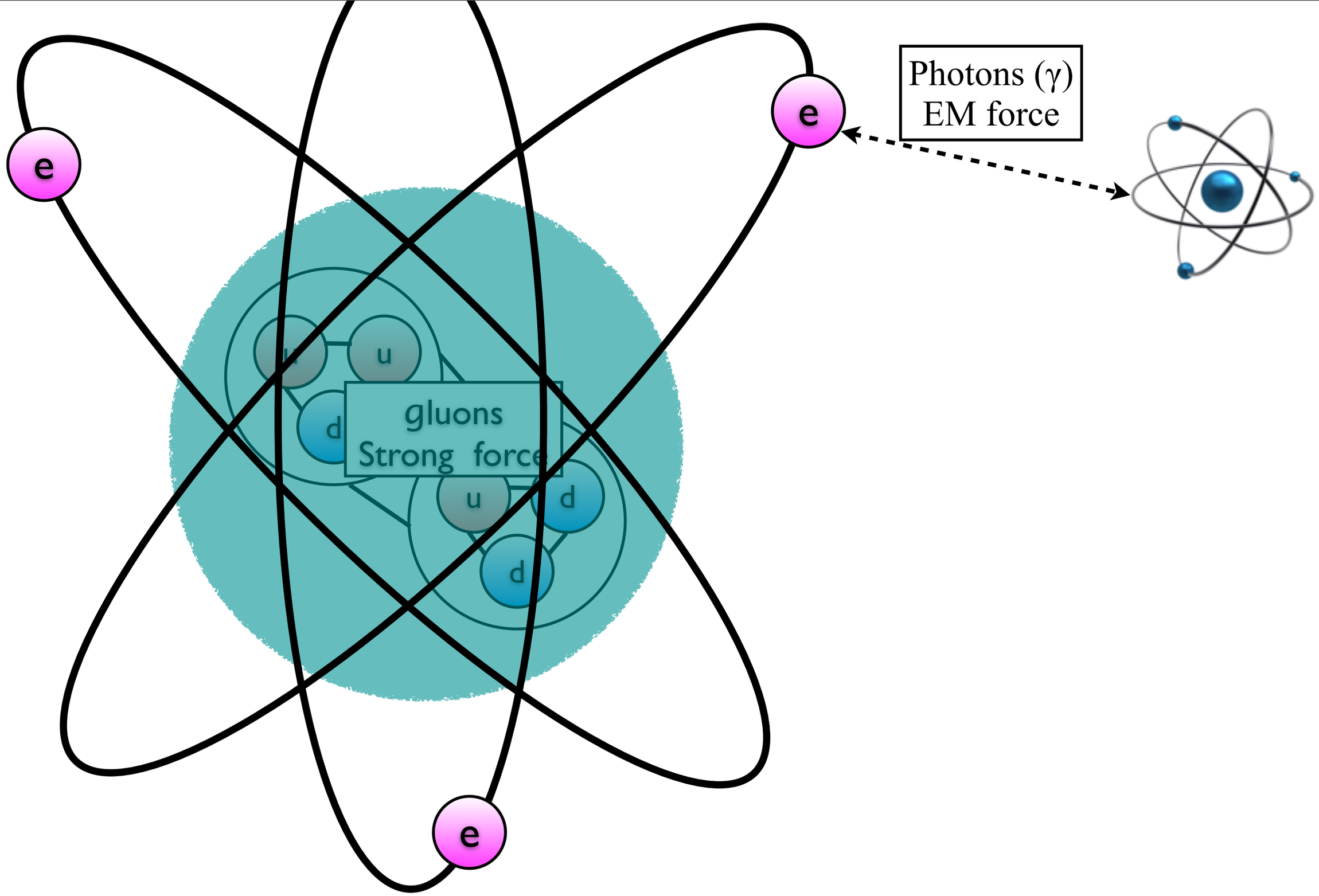
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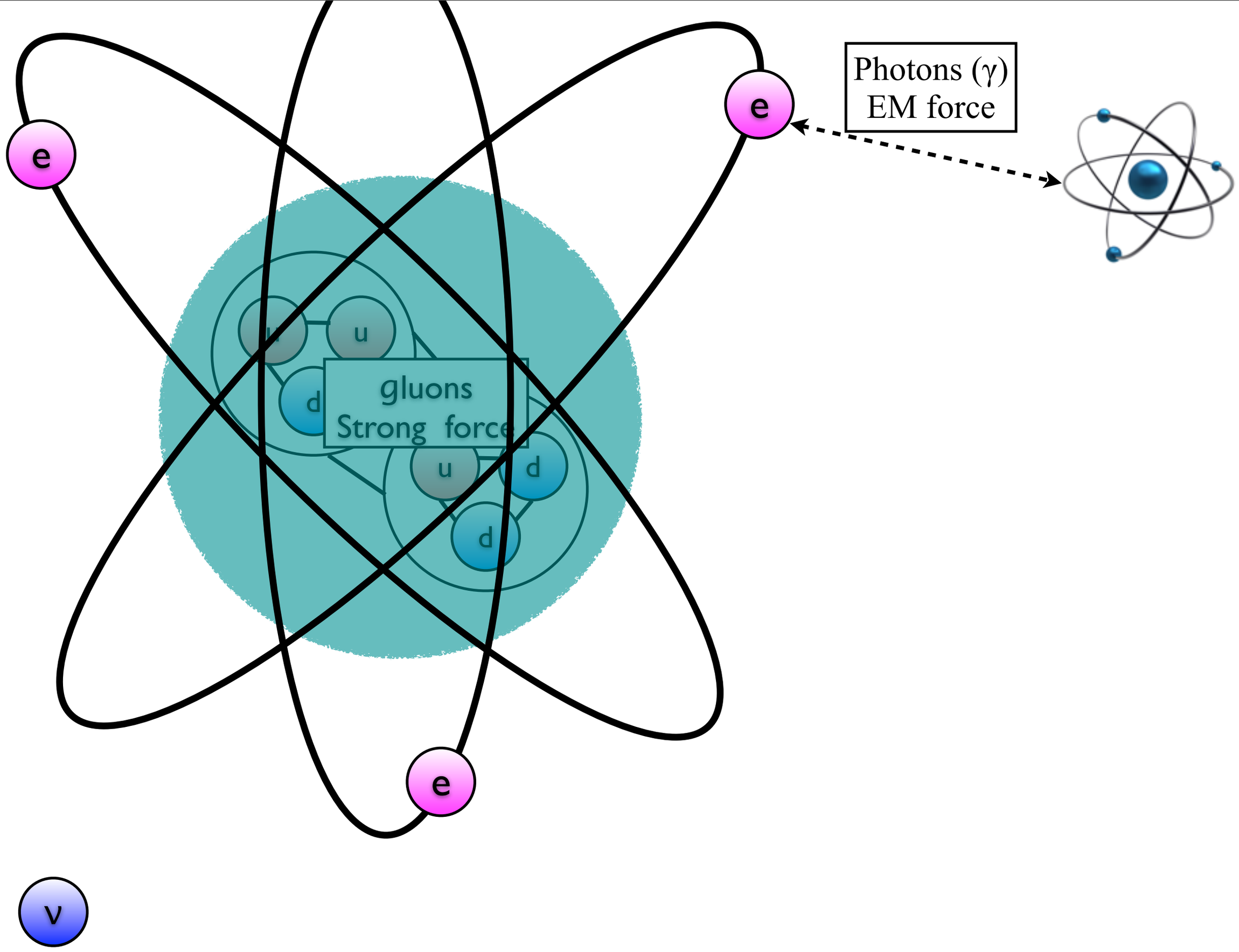
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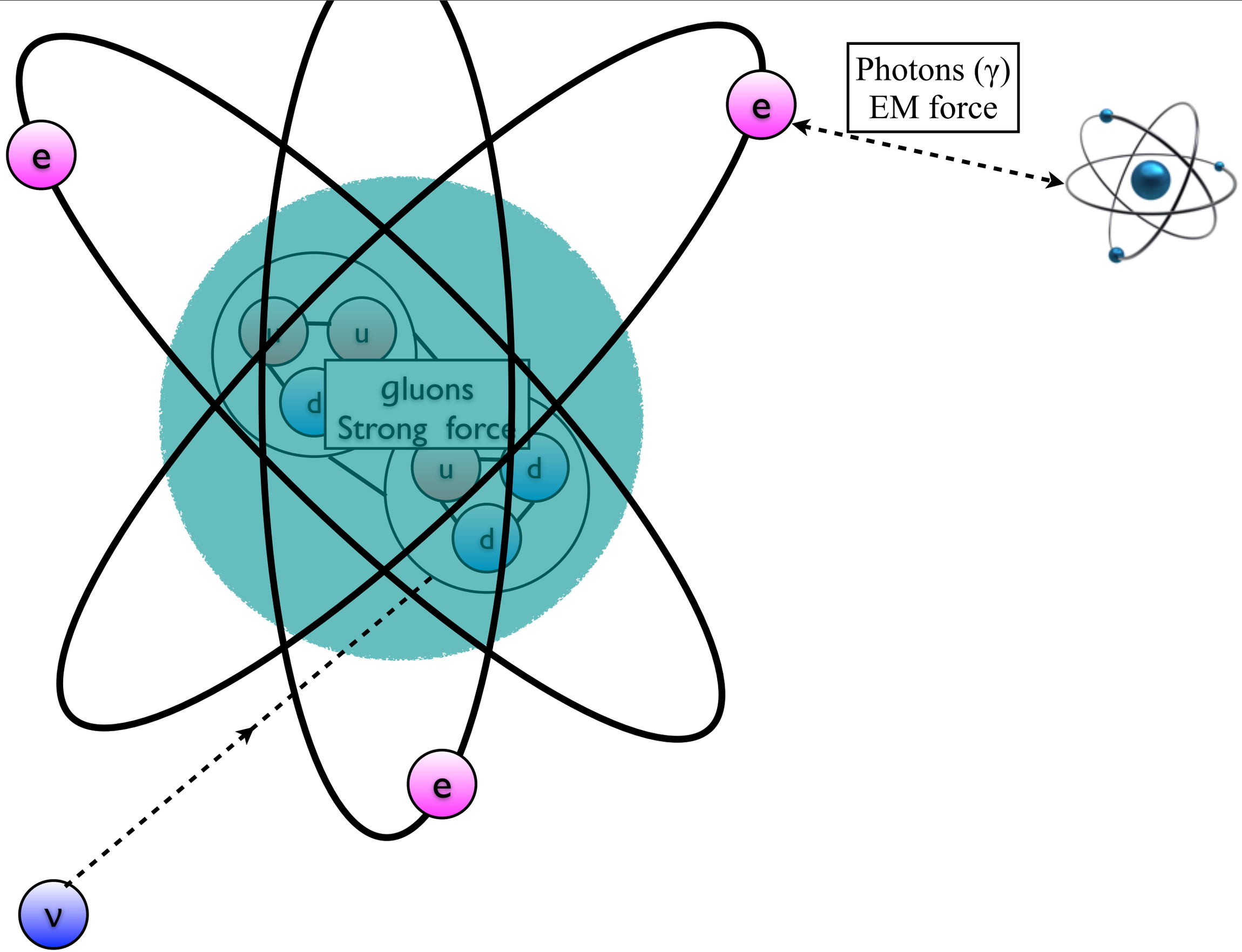
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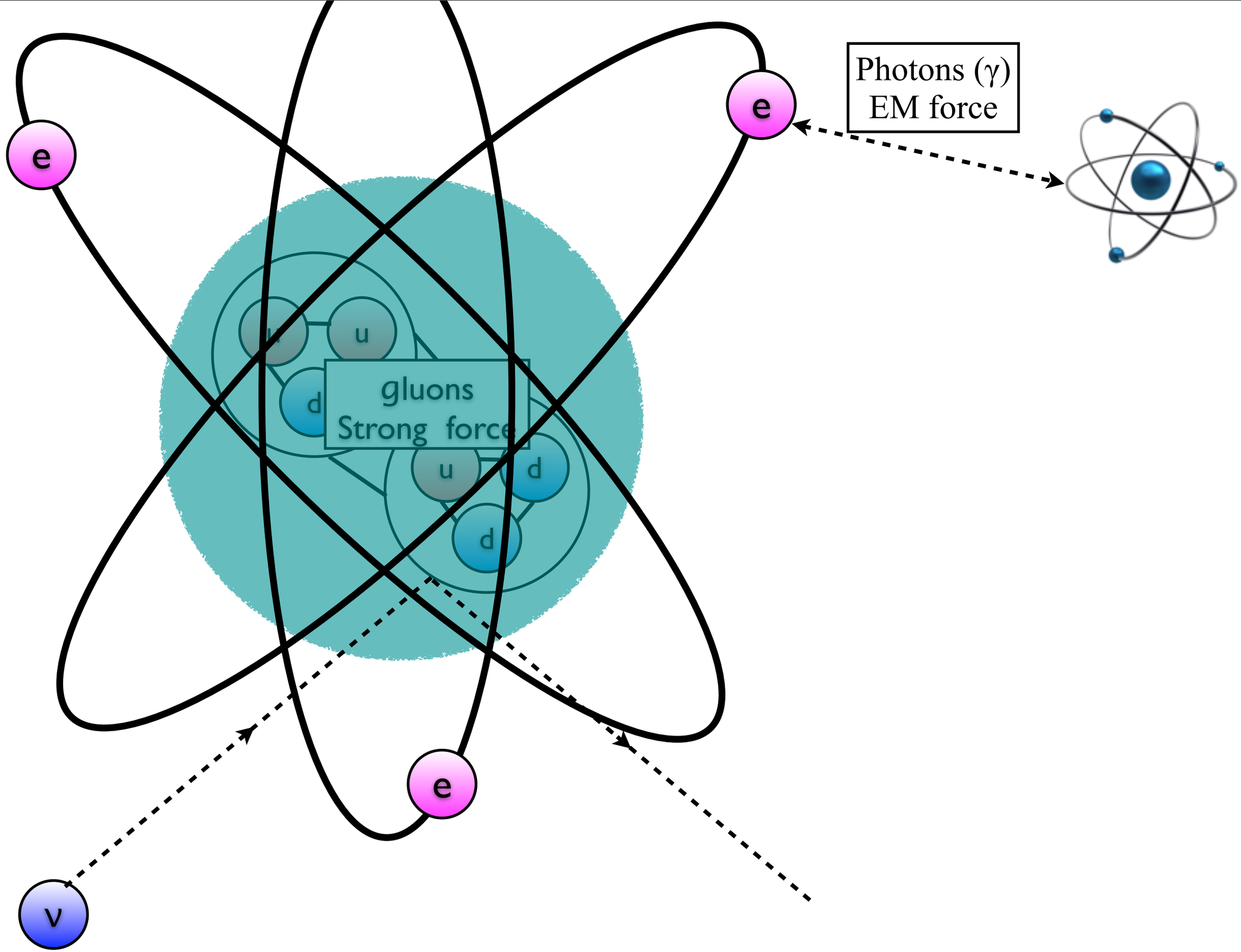
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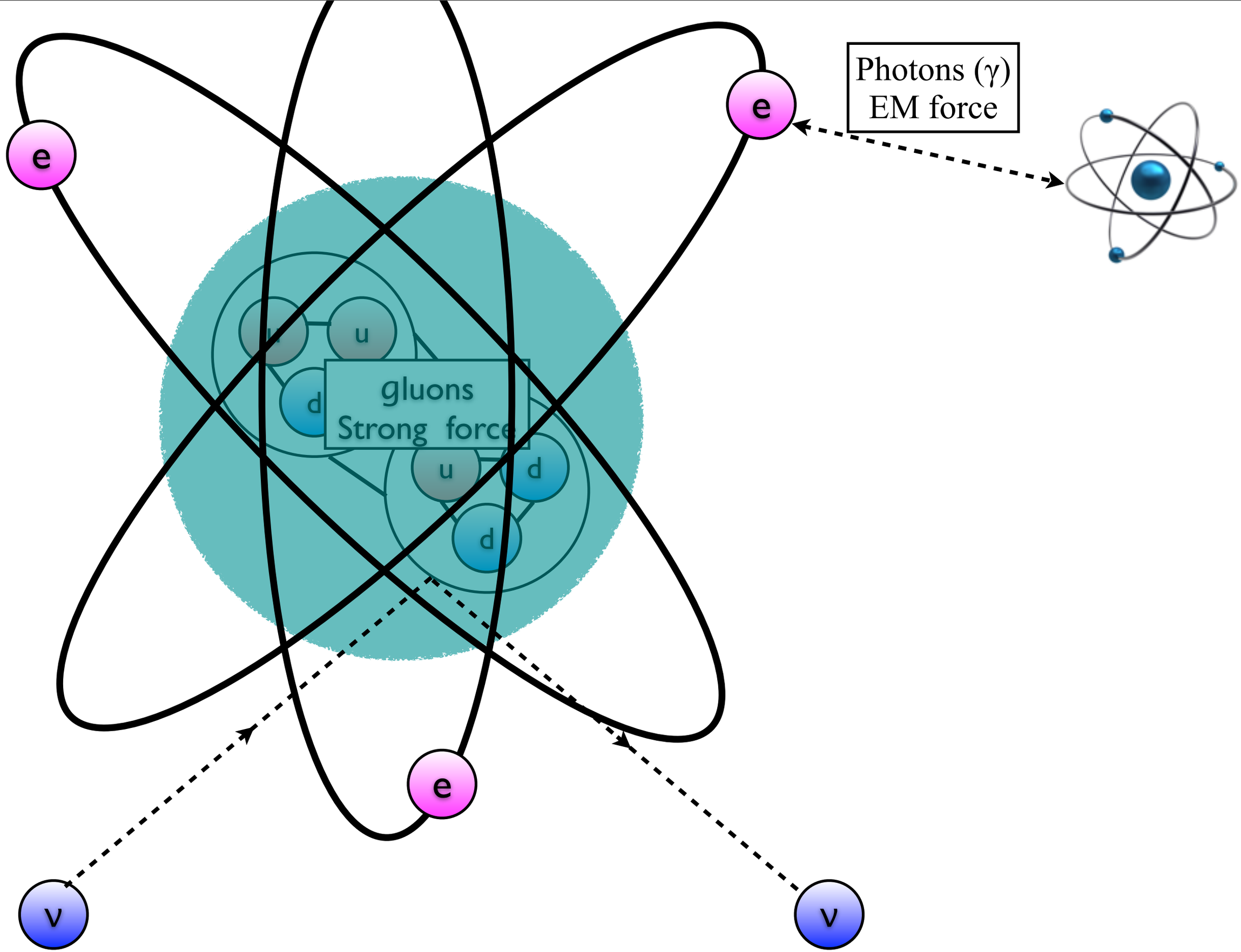
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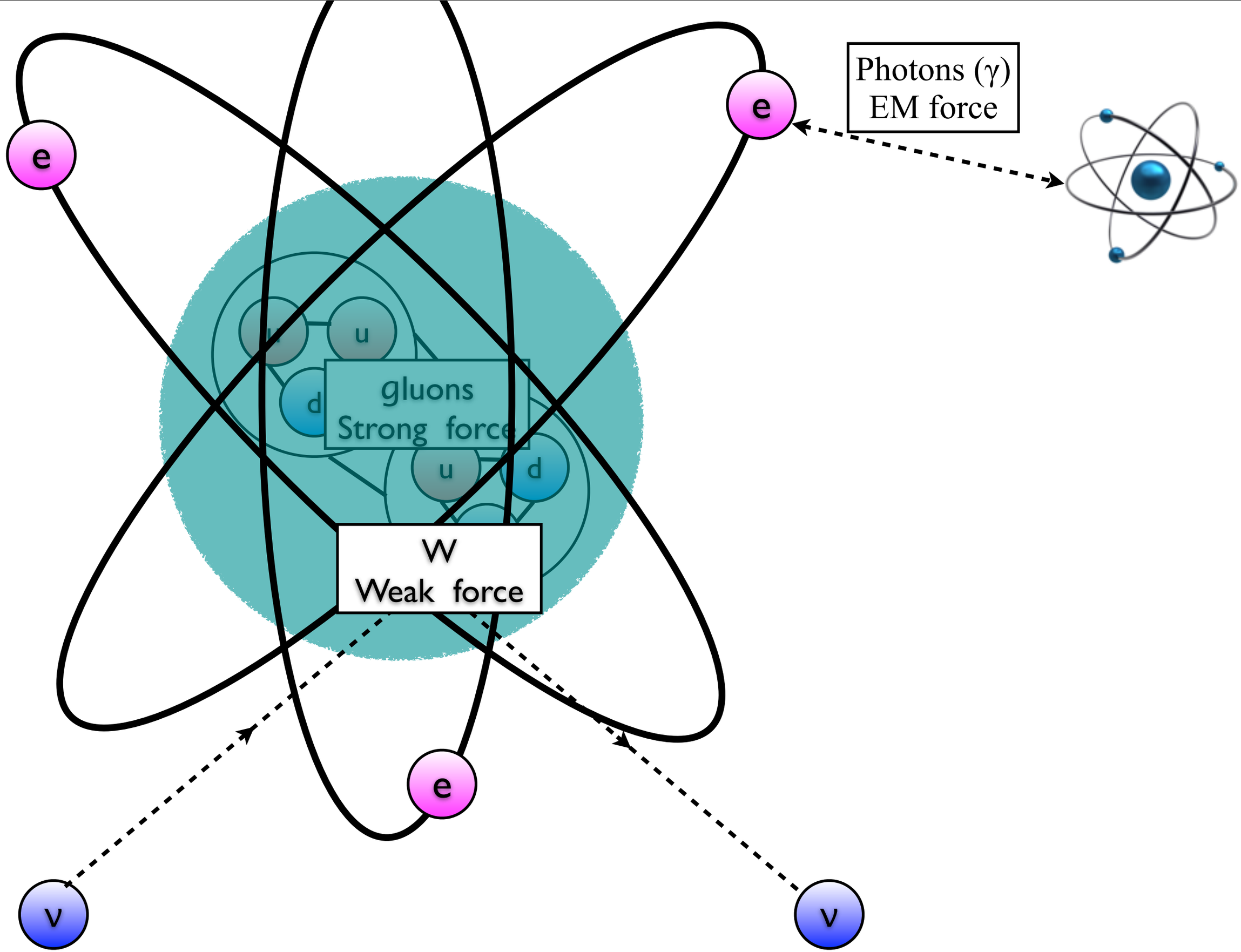
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BIG
QUESTIONS

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BIG QUESTIONS

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DOES THE HIGGS GIVE MASS TO NEUTRINOS?

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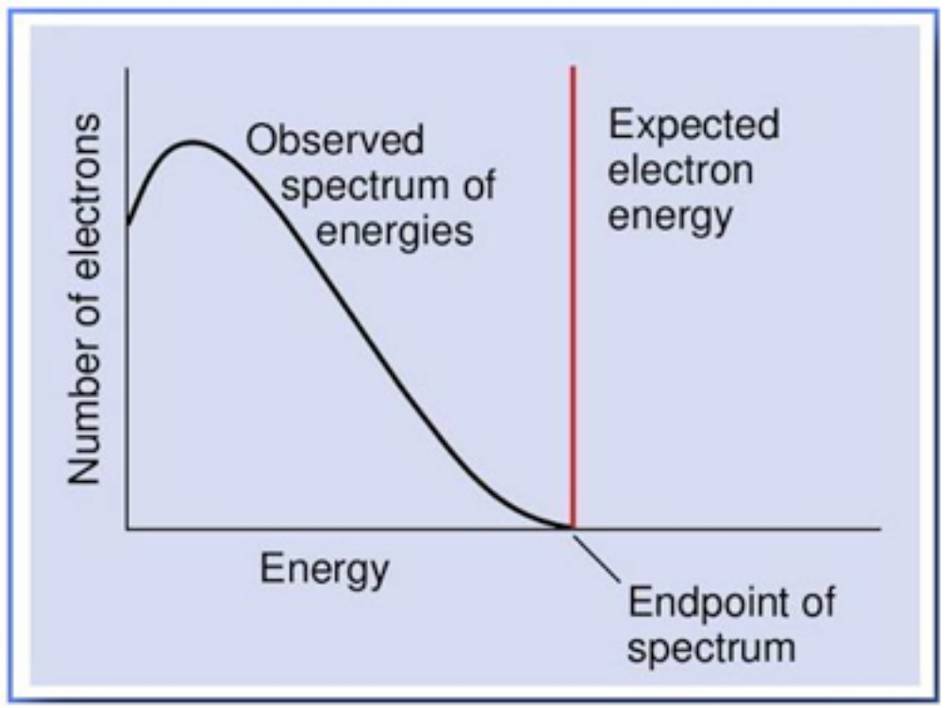
A Brief Recap

- February 1896: Henri Becquerel discovered radioactivity from phosphorescence of uranium in absence of light.
- In 1898: Marie and Pierre Curie succeeded in isolating 2 new radioactive elements from pitchblende , Polonium (Po) and Radium (Ra)
- In 1903: Becquerel and Curies awarded Nobel Prizes in Physics
- In 1899: Ernest Rutherford was studying ionization of gases by radiation from uranium. He identified:
  - Alpha(α) radiation ➜ 2 protons, 2 neutrons (^{4}He). Absorbed by a single sheet of paper.
  - Beta(β) radiation ➜ electrons, penetrates several mm of Al, Cu.
- In 1900: Villard discovered Gamma(γ) radiation
  - They are EM radiation but have shorter wavelengths and higher energies
  - Can penetrate 20 cm of iron, several cm of lead !
- In 1905: Albert Einstein announced his Theory of Special Relativity !

Beta decays

- Energy-mass relation: **$E = mc^2$**
  - Energy is conserved overall.
  - Profound way of storing and transforming energy.
- Energy conservation principle seemed to work for alpha and gamma decays, but for not beta decays !
- In 1914, James Chadwick discovered that energy spectrum of beta electrons was continuous, rather than a single value !



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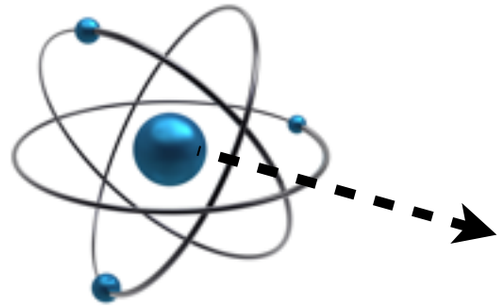

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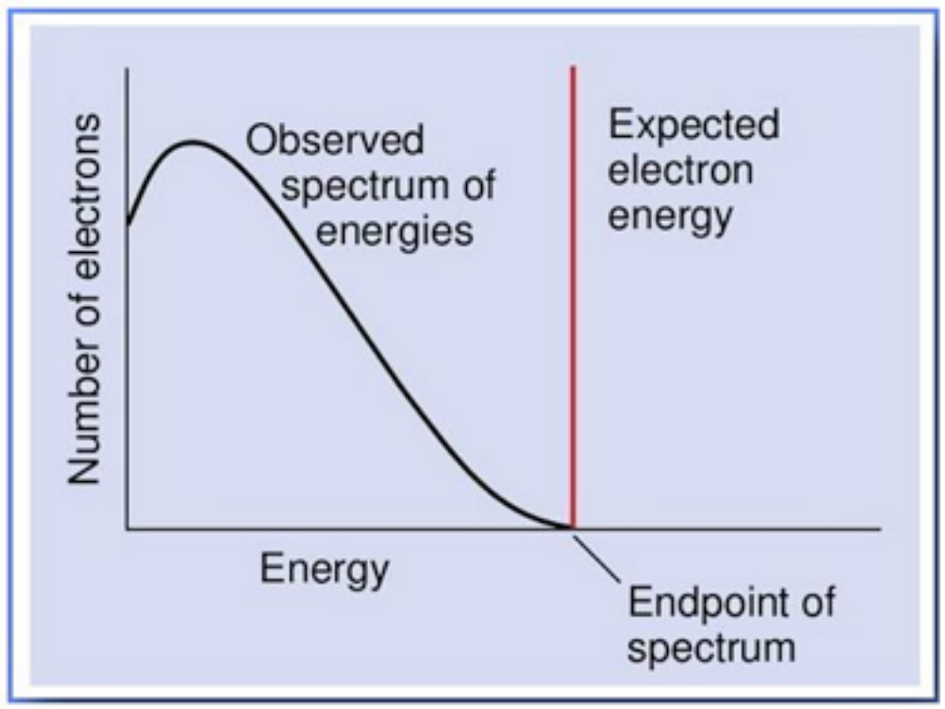

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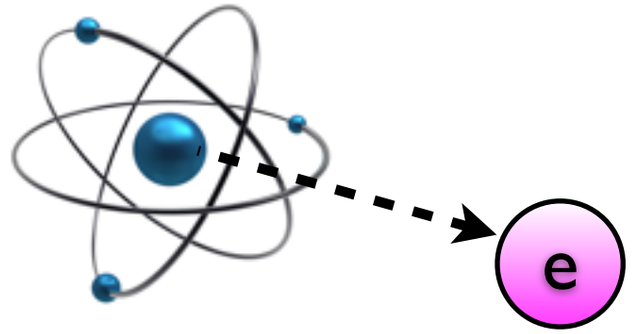

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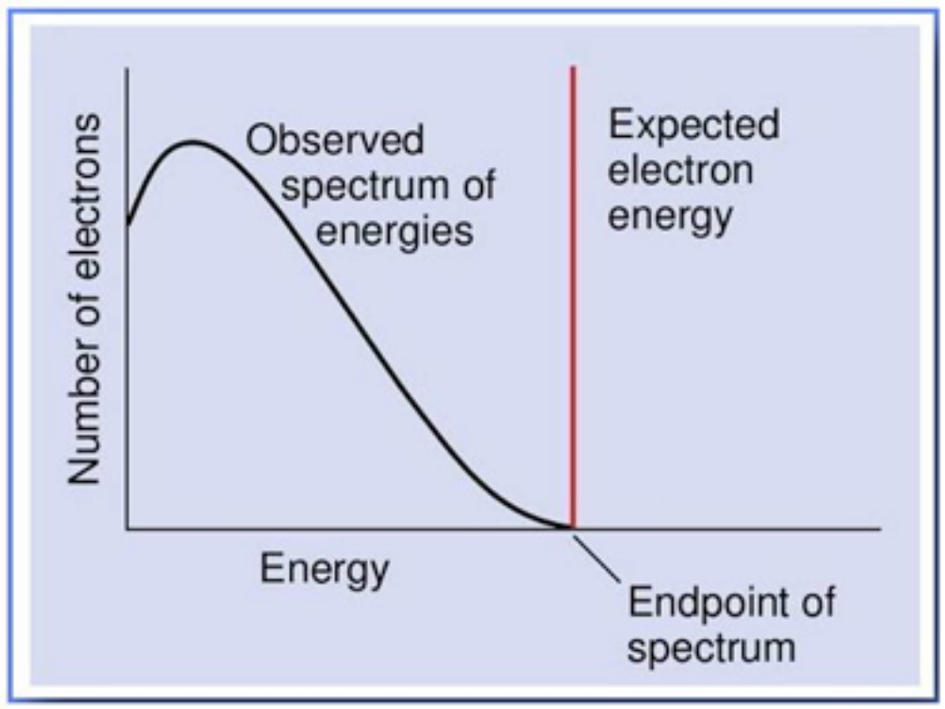

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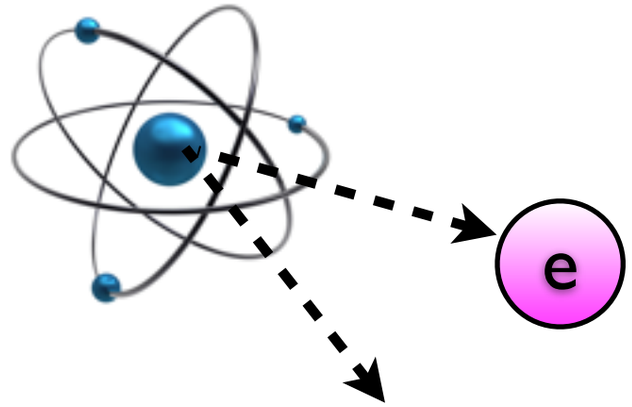

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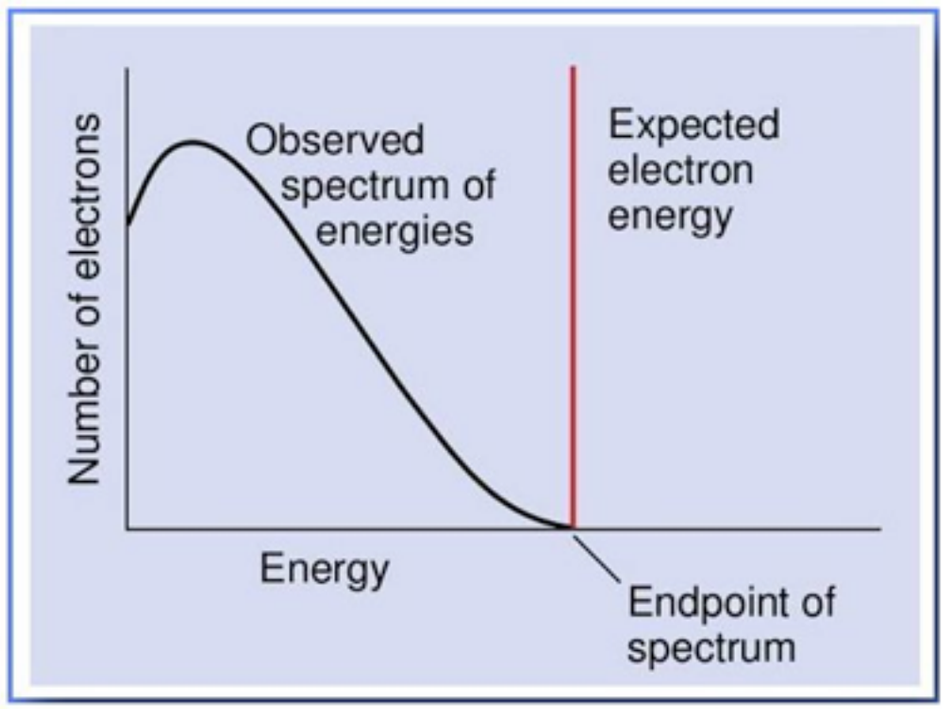

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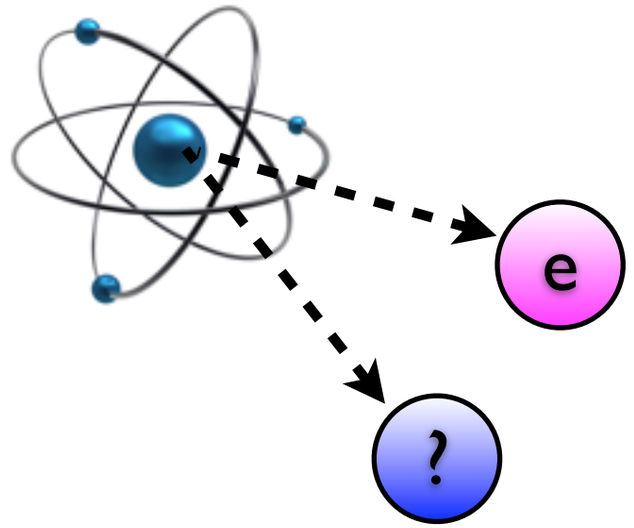

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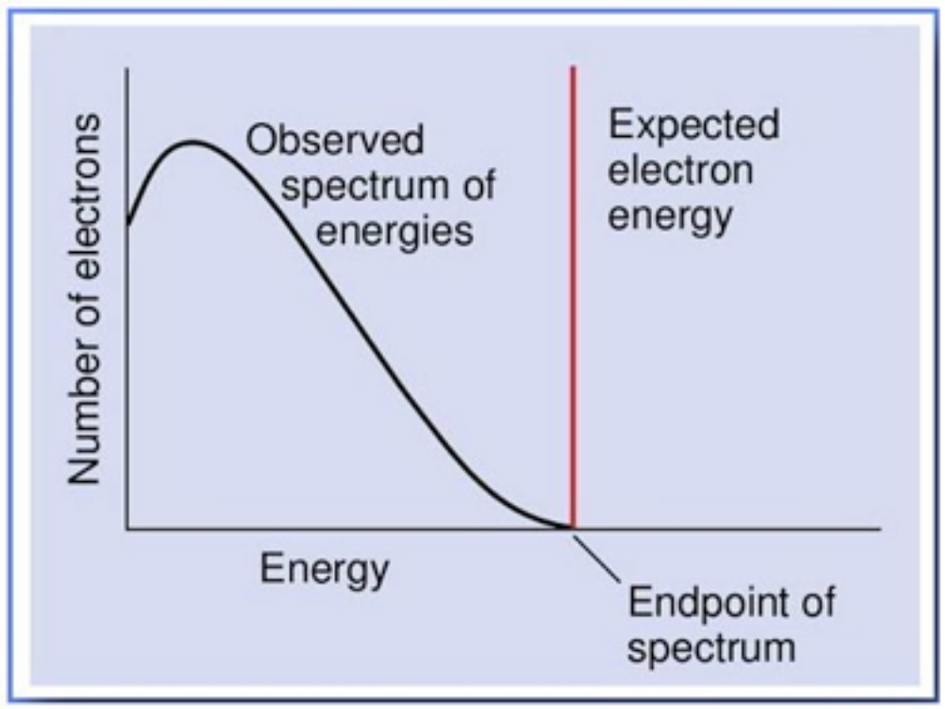

Enter ..... Wolfgang Pauli !

(1945 Nobel Prize in Physics)

Discovered Pauli's Exclusion Principle and was also the first to postulate existence of the neutrino !

Pauli on vacation, 1931

A Desperate Remedy

circa 1930

- Pauli's saving grace :
  - In beta(β) decays the electron is accompanied by an additional neutral particle.
  - So, energy is conserved - it is just shared - between visible electron and invisible neutral partner.
- Pauli's intention was to solve 2 puzzles :
  - Understand nuclear properties. Nuclei are made up of protons and neutrons. Neutrons are exactly like protons, except electrically neutral.
  - This neutron is produced in β decay along with electron.

- Pauli's enthusiasm quickly died. He realized that proposed particle in β decay should be massless, but one proposed for nucleus should be massive !
- In 1932, James Chadwick discovered the neutron !
  - Neutron (massive) was not the solution for β decay puzzle !

Offener Brief an die Gruppe der Radioaktiven bei der
Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Dear Radioactive Ladies and Gentlemen,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst ansuhören 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 Grössenordnung 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.

Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

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gez. W. Pauli

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Dear Radioactive Ladies and Gentlemen,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst ansuhören 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

"I have done a terrible thing. I have postulated a particle that cannot be detected." (W. Pauli, 1931)

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Fermi expressed interest in Pauli's idea and called the proposed neutral particle "neutrino" (little neutron in Italian)

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Enter ..... Enrico Fermi !

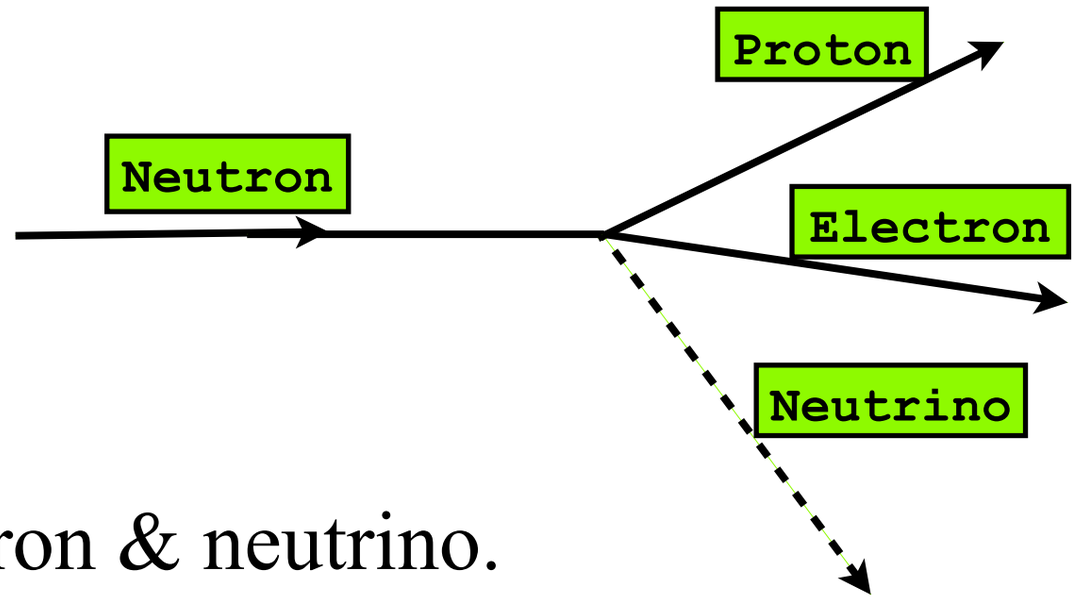
(1938 Nobel Prize in Physics)

Fermi statistics(Fermions) → team leader on Manhattan Project → Univ. of Chicago → FNAL !

Fermi on a boat, Isola d'Elba (1954)

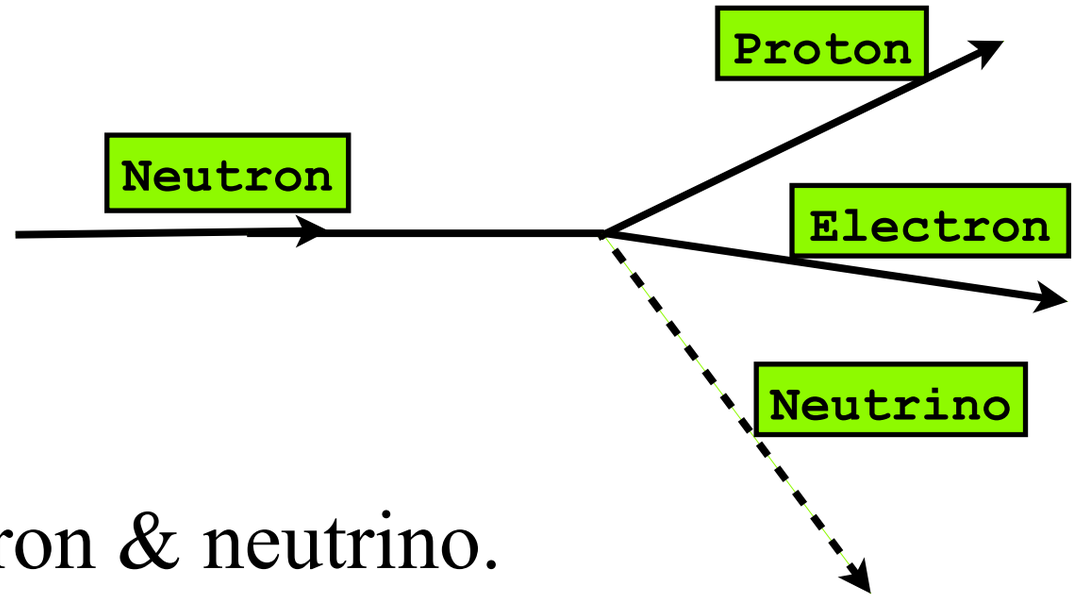
Fermi, 1923

Radioactivity & Beta-decay



- Fermi's model of beta decay
  - A neutron turns into a proton, electron & neutrino.
  - He assumed that the 4 particles could occur at the same point in space and time.
- Using this theory Fermi calculated energy spectrum of electrons in beta decay. They matched experimental data.
- Lack of enthusiasm for neutrino topics in physicists !
- Fermi wrote a paper in 1934 titled "Tentative theory of beta rays" and sent it for publishing.
  - Nature rejected it ! Published elsewhere in Italian and German first.

Radioactivity & Beta-decay



- Fermi's model of beta decay
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Fermi despaired, gave up theorizing about neutrinos, instead started experimenting with neutrons (nuclear fission) !

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Enter ..... Bruno Pontecorvo !

Often a central actor and yet, somehow, never quite reaching the pantheon of the immortals .....

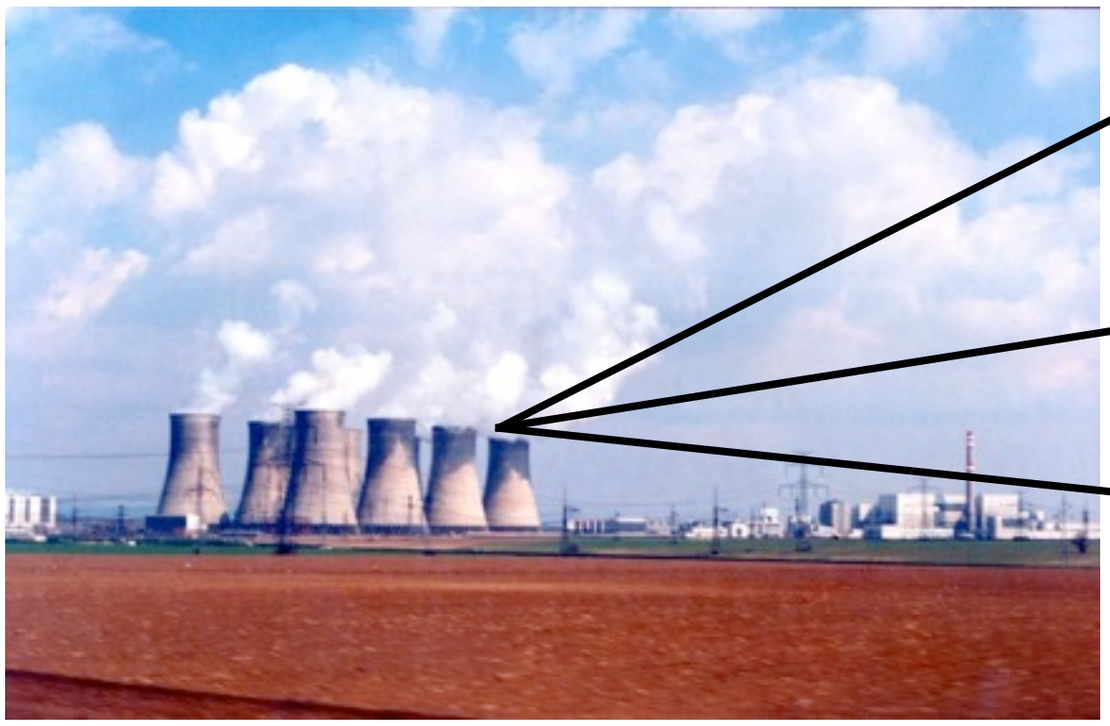
Pontecorvo was the first to postulate that there might be different "types" of neutrinos !

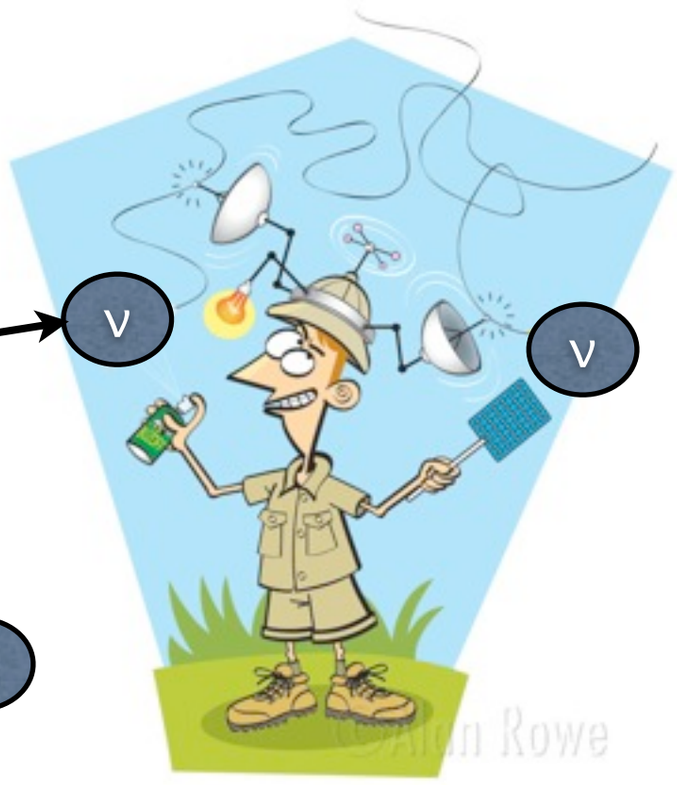
Pontecorvo's insight for detecting neutrinos

- Chances of detecting an individual neutrino were "miniscule" .....
- But, if you have an intense source of neutrinos, producing billions of them each second, one or two might get detected occasionally !

- A uranium reactor should be producing about **ten million billion neutrinos per second** in the act of producing nuclear power !

- You need patience and the right kind of detector to catch at least a few neutrinos !





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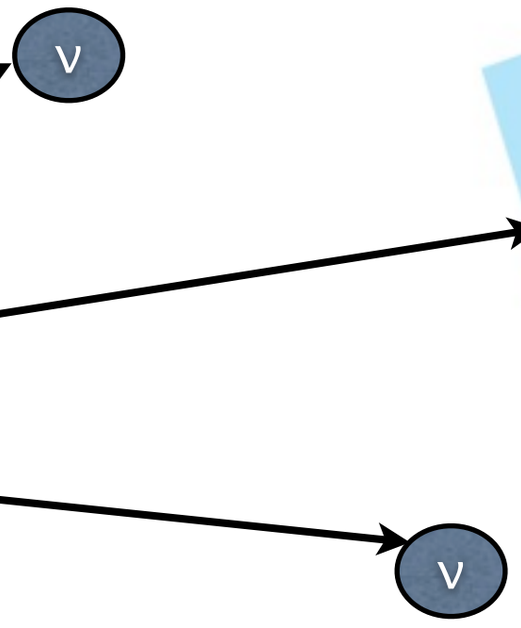
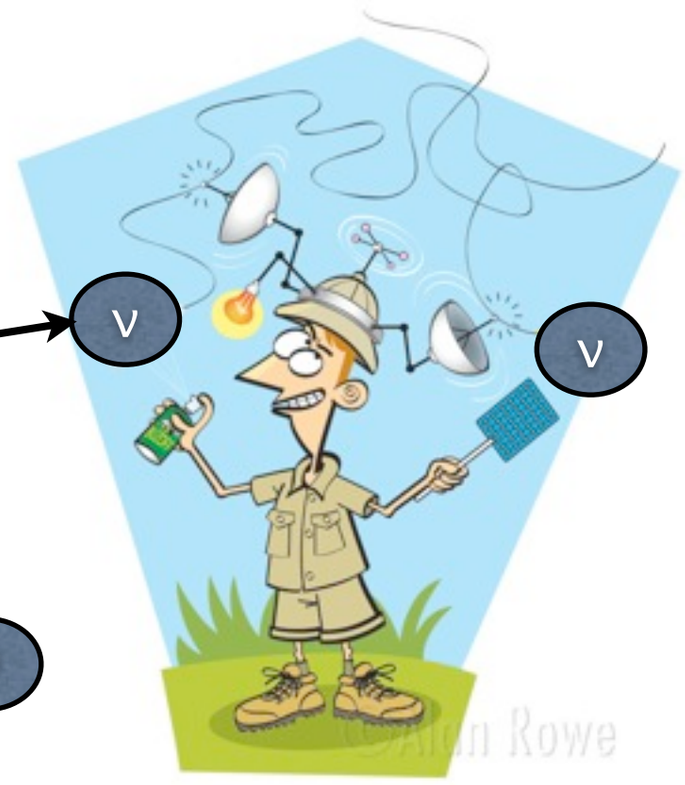
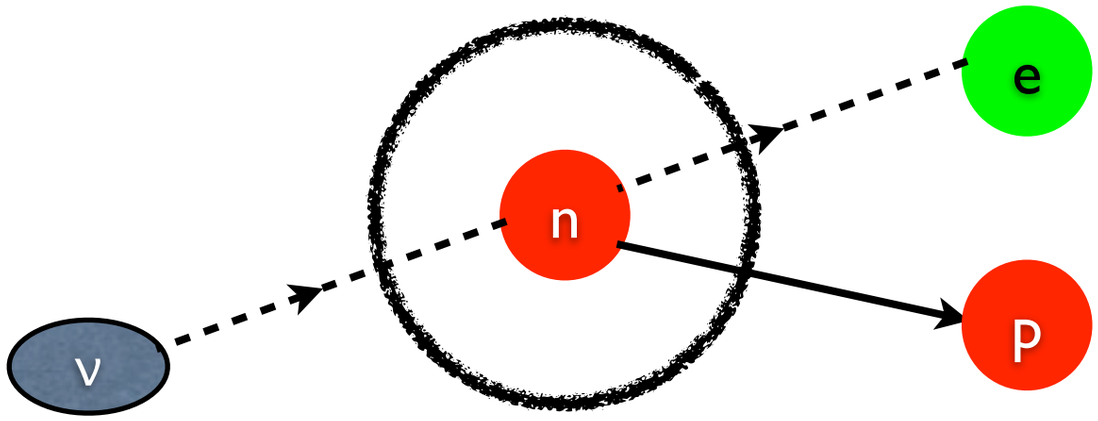
This is like winning the lottery !!!





Pontecorvo's "how to detect a neutrino !"

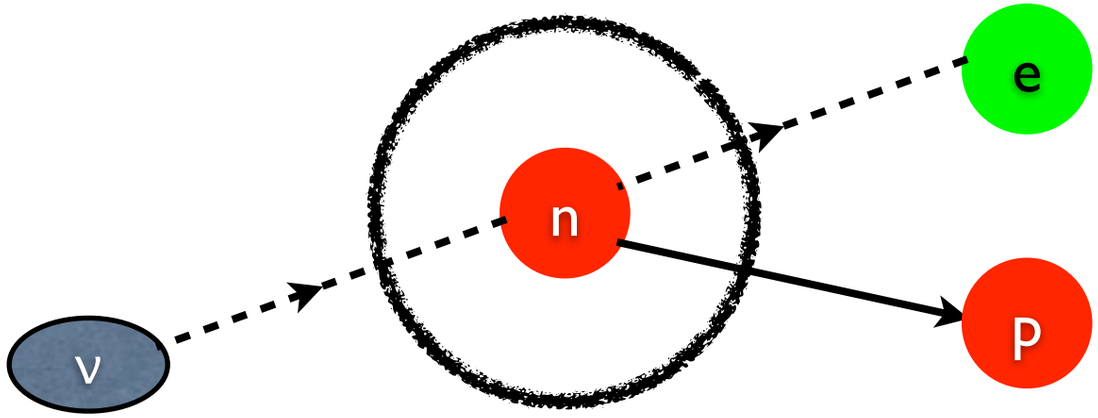
circa 1947



- **Neutrino bumps into matter and creates an electron !**
- This creates an extra proton in the relevant atomic nucleus !
- Now this nucleus would attract the electron !
- Turns into an atom of another element
  - One rung up in the Periodic Table !

Pontecorvo's "how to detect a neutrino !"

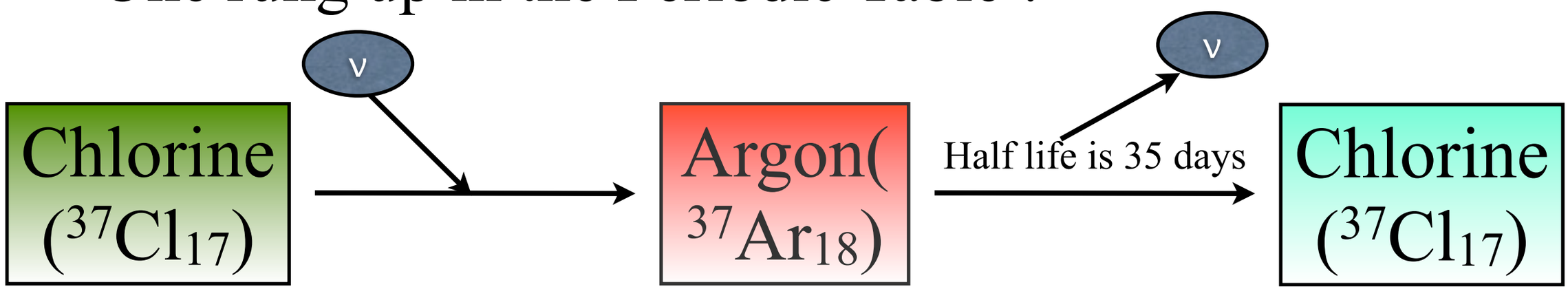
circa 1947



- **Neutrino bumps into matter and creates an electron !**
- This cr[illegible]ic nucleus !
- Now th[illegible]
- Turns i[illegible]

Use Cl as detecting medium
(large vat of cleaning fluid)
Extract Ar atoms by boiling !

  - One rung up in the Periodic Table !



Enter ..... Raymond Davis Jr. !

(2002 Nobel Prize in Physics)

Eventually turned Pontecorvo's dream into reality but had to wait to understand neutrinos ..... call it fate or oversight .....

Ray Davis with a quizzical look, inside the Homestake mine circa 1966

Ray and Radiochemistry

circa 1952

- Ray Davis's background in radiochemistry helped him:
  - Pontecorvo's idea: Neutrinos pick up charge when interacting with matter !
  - Easy separation of Argon atoms from a Chlorine solution.
  - Detect radiation by use of electrical signals from ionization of Argon gas.

- Built first neutrino detector at Brookhaven National Laboratory.
- Tank had 4000 liters of carbon tetrachloride (CCl_4) - waited for Argon atoms to accumulate.
  - Observed nothing in addition to the results of cosmic ray interactions !

Davis exposed about 4000 liters of carbon tetrachloride to (anti)neutrinos at the Brookhaven Graphite Research Reactor

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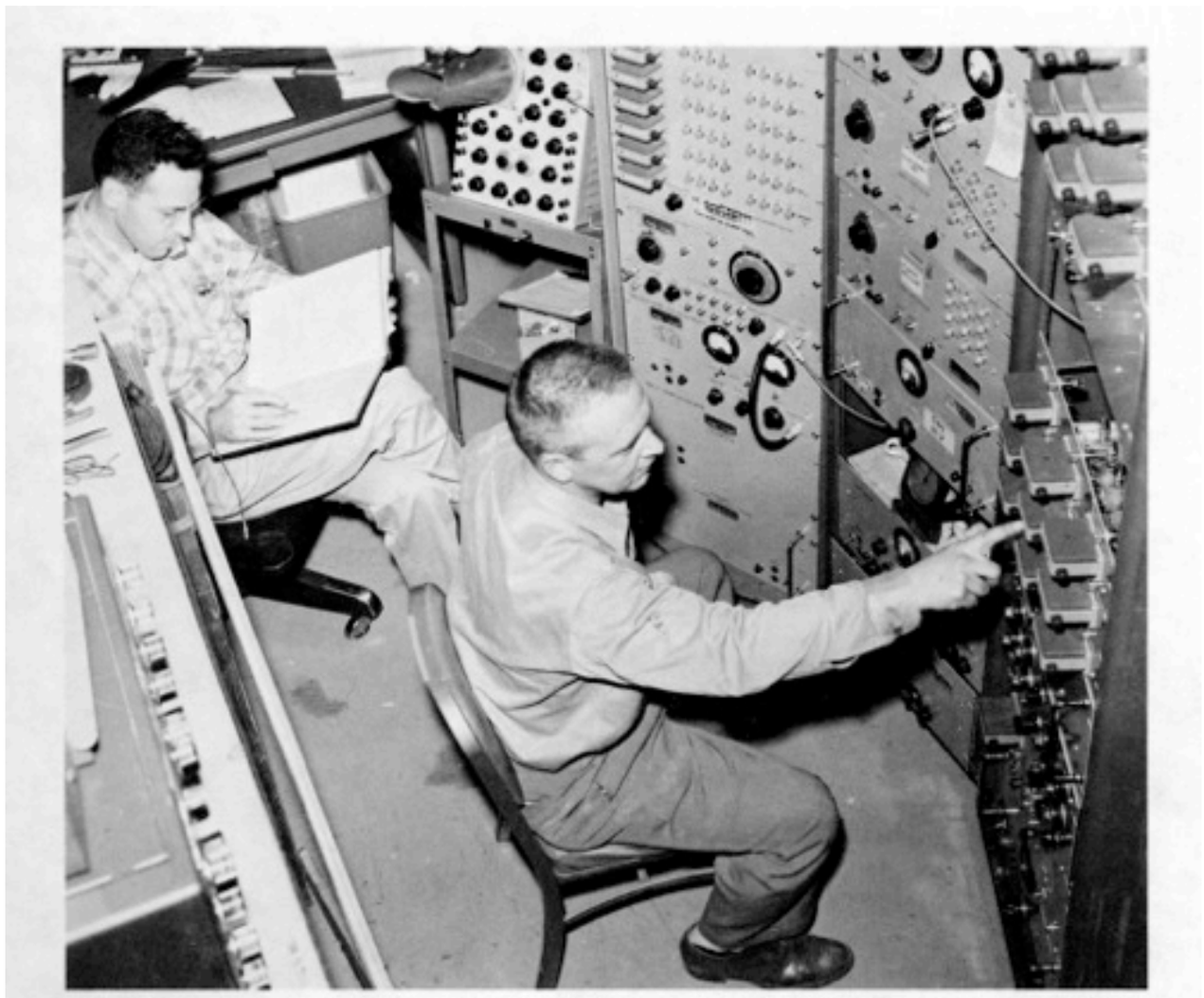
He would have to come to the Homestake mine (SD) to be able to see neutrinos !

Davis exposed about 4000 liters of carbon tetrachloride to (anti)neutrinos at the Brookhaven Graphite Research Reactor

Enter ..... Fred Reines and Clyde Cowan !

(1995 Nobel Prize in Physics)

Let's try to detect neutrinos by exploding an atom bomb !

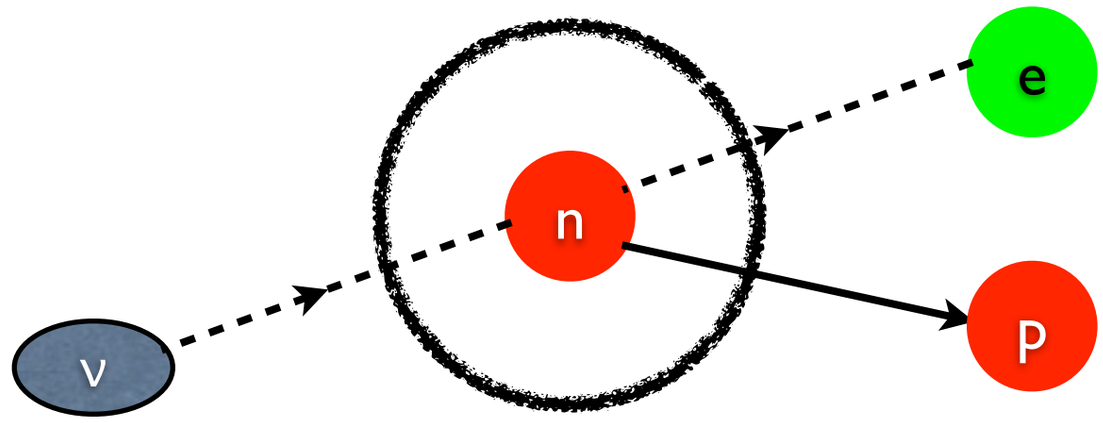


Frederick Reines (left) and Clyde L. Cowan, Jr. with the control equipment used in their first tentative observations of the neutrino at Hanford, Washington, in 1953. Their definitive detection of the (anti) neutrino was performed at Savannah River, Georgia, three years later. (Courtesy General Electric Co.)

Nuclear reactors would suffice

USE THIS !

- Hans Bethe convinced them that there was a better way to do this experiment.
  - Controlled nuclear power from a nuclear reactor !
- A nuclear reactor emits 10 trillion *anti*neutrinos, per square centimeter, per second.
  - Should be enough !

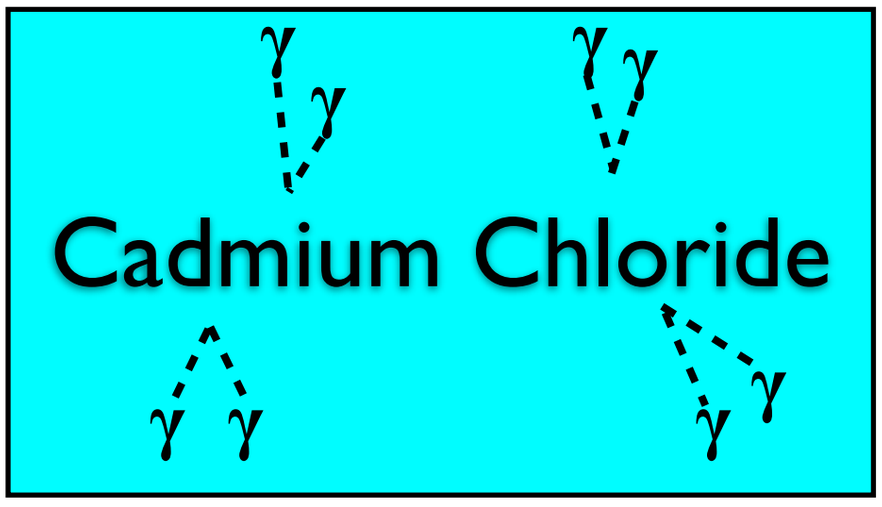


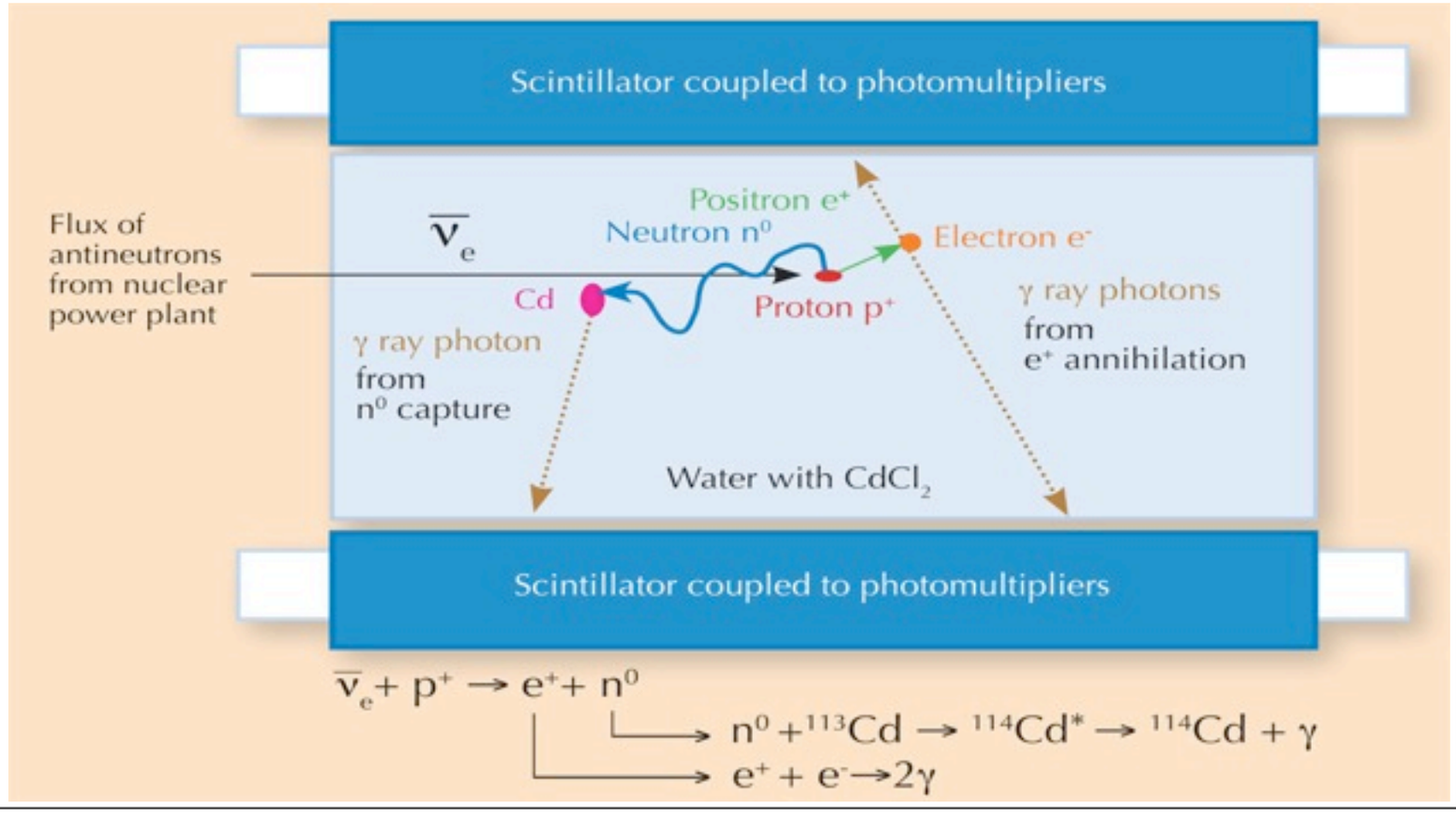
- Experiment seemed much simpler.
- Could be repeated any number of times.
- Reines and Cowan knew that if neutrinos exist conservation of electric charge would produce a positron and a neutron.
- They were unaware of the distinctions between neutrinos and anti-neutrinos then.
- Good enough for scheme to work !

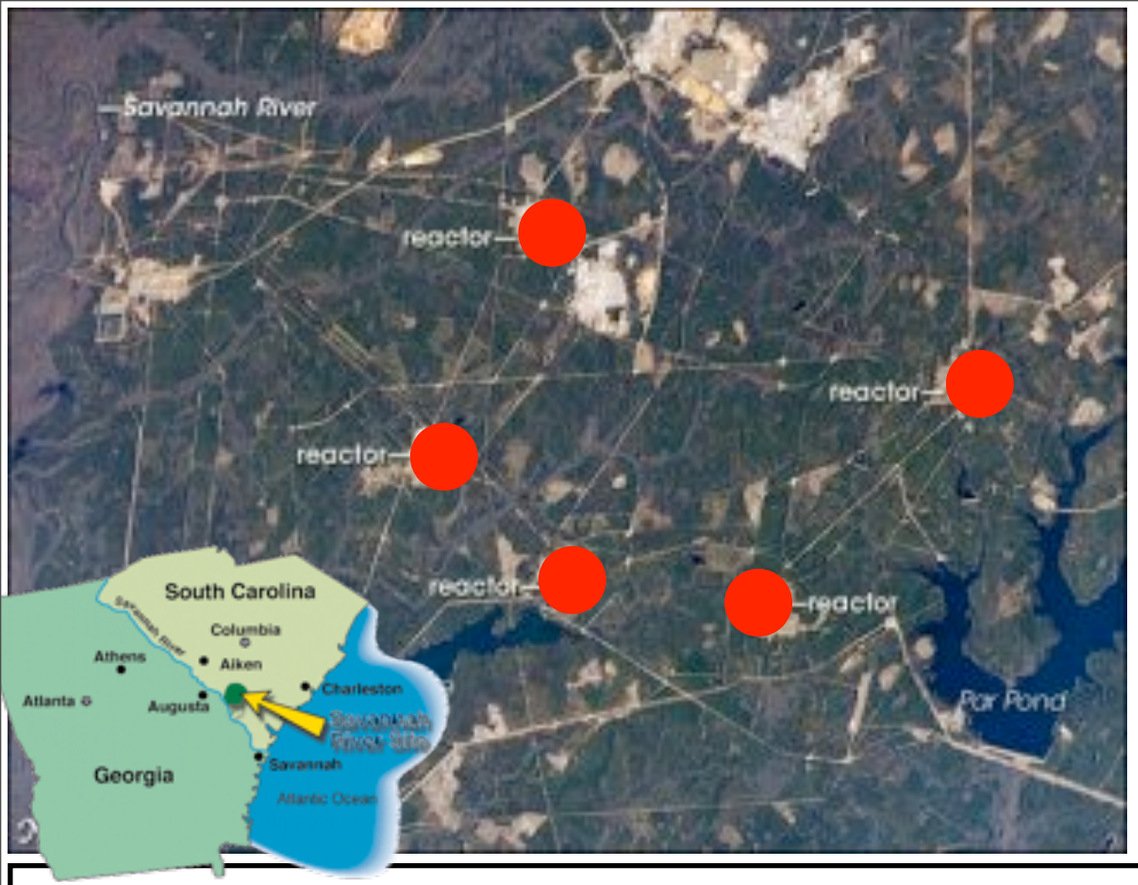
Project Poltergeist

circa 1953

- A small prototype detector located at nuclear reactor at Hanford in WA.
  - Saw first hints of signal, though needed more shielding from cosmic rays.
- Built larger version of detector and installed it 12 m underground at Savannah River Site (SRS), SC.
- Detecting medium: Cadmium chloride ($CdCl_2$). → well separated signatures !
- Event signature: Two separate gamma (γ) ray bursts, occurring 5 microseconds apart !







Reactors at Savannah River nuclear site

The P-Reactor at Savannah River site

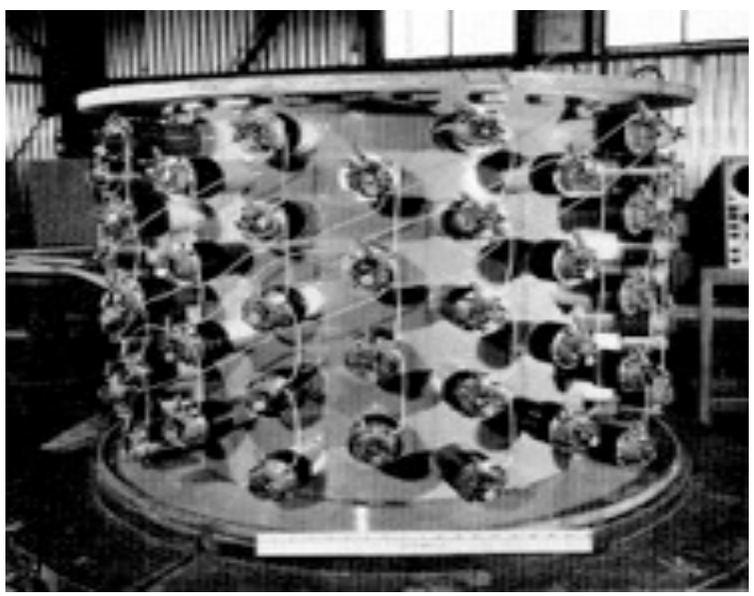
Blowing up the K cooling tower at SRS

Dealing with radioactive nuclear fuel at SRNS

Observations of first *(anti)*neutrinos

circa 1956

- Summer of 1956:
  - Poltergeist recorded gamma ray bursts, 5.5 microseconds apart !
    - Minimal background from cosmic rays.
  - Cowan and Reines sent Pauli a telegram announcing the discovery of the "neutrino" on June 14, 1956.
- Years later:
  - Reines reminded Bethe about his 1934 pronouncement with Peierls that "there is no practically possible way of observing the neutrino !"
  - Bethe's reply: "Well, you shouldn't believe everything you read in the papers."
- Ray Davis and Pontecorvo were still waiting to see neutrinos using their detector !



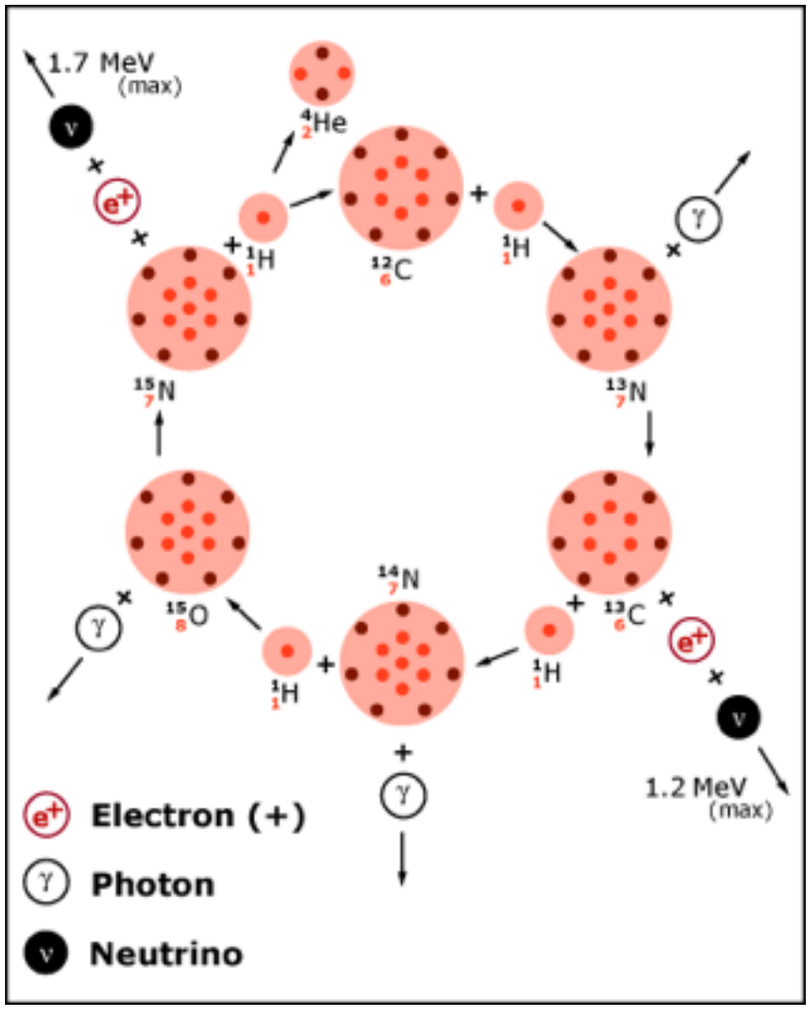
Detector used by Reines and Cowan

Fred Reines Clyde Cowan

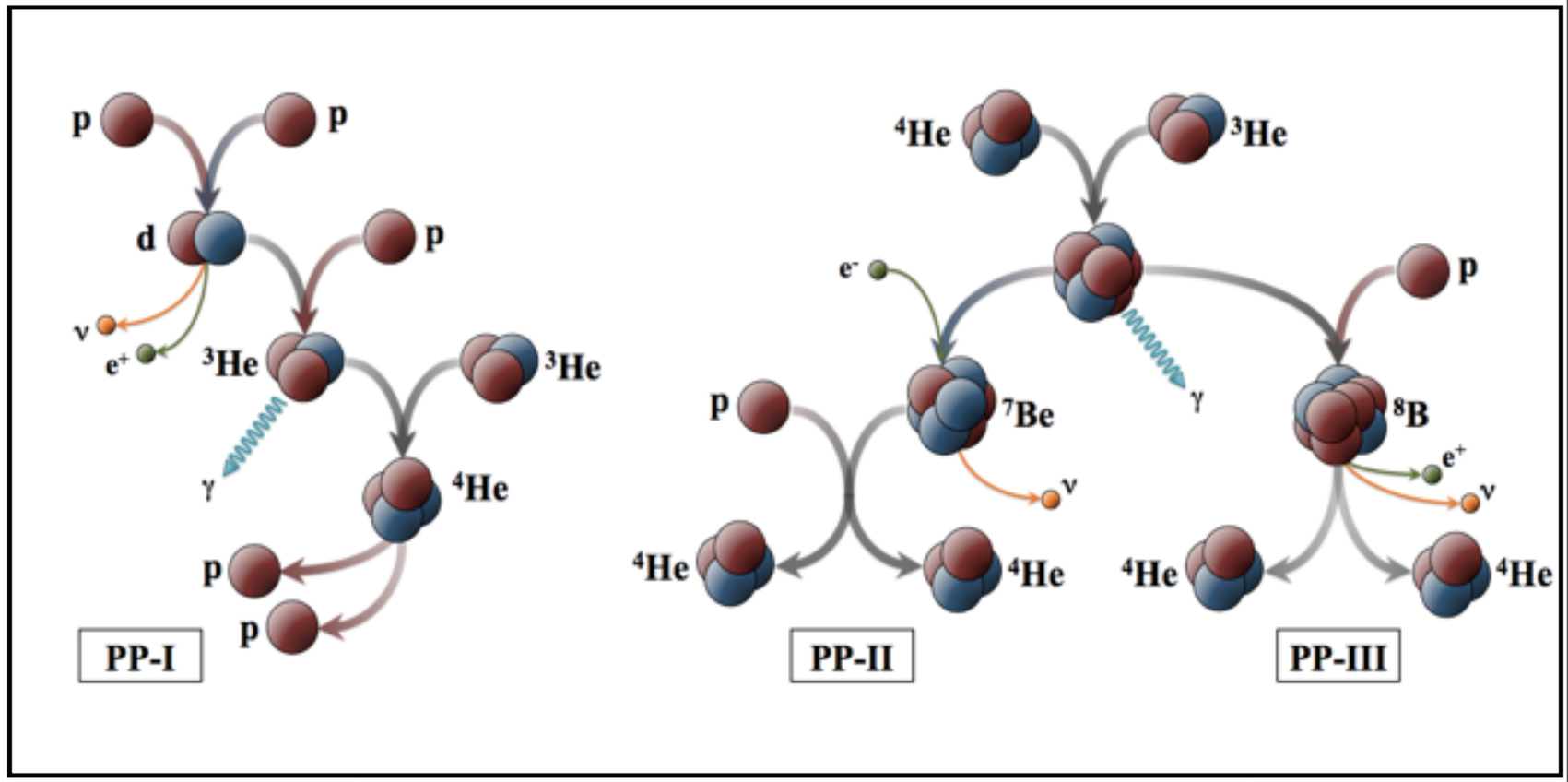
Project Poltergeist team at Hanford

Why does the Sun shine ?

- Rutherford : nuclear transmutations in the sun produce a lot of energy for a trifling amount of mass.
- Arthur Eddington : Sun generates light by burning hydrogen and turning it into helium
- Hans Bethe discovered the CNO and *pp* fusion chain cycles



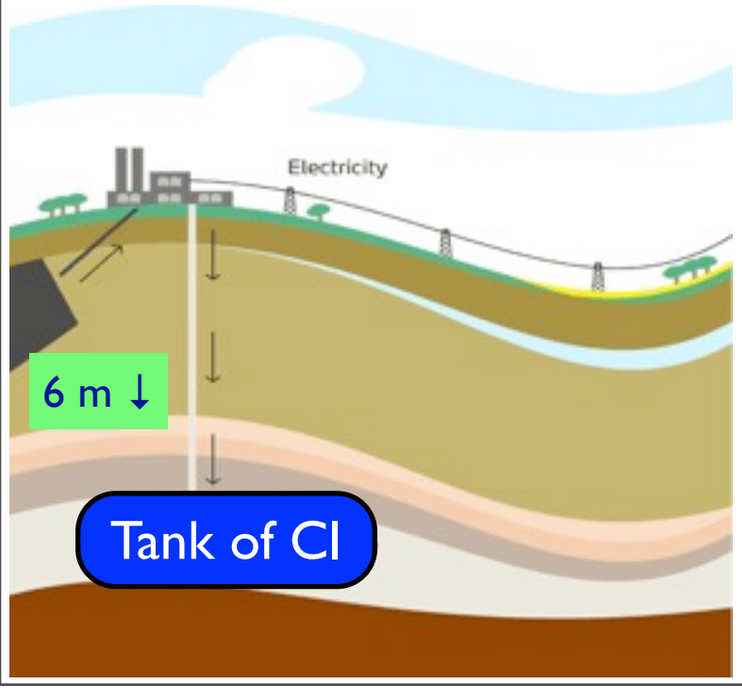
CNO Cycle for bigger stars



pp fusion chain reaction in Sun

Looking into the heart of the Sun

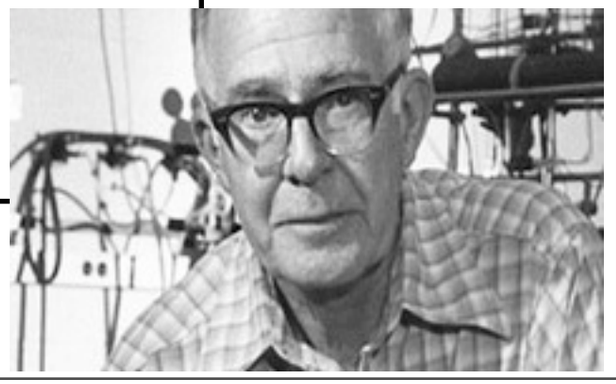
- Bethe's theory of nuclear fusion in stars implied that the Sun should produce not just heat but vast numbers of neutrinos !
- Davis thought, "If I can look at these neutrinos, I can look into the Sun !"
- Neutrinos from *pp* fusion (dominant in Sun) not energetic enough for interacting with chlorine !
- Neutrinos from CNO cycle (dominant in bigger stars) have high enough energy for chlorine !
- While experimenting at BNL, he always hoped to capture solar neutrinos too !
  - Important verification of the CNO cycle !



No neutrinos from the Sun detected !

Production rate of neutrinos in CNO cycle must be very low !

Or no solar neutrinos !



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- Neutrinos fro
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- While experim
  - Important v

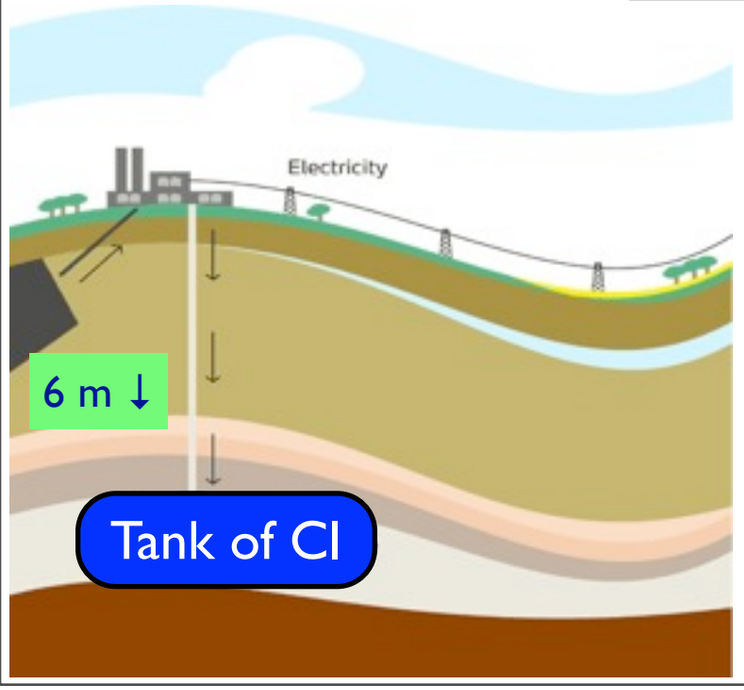
Willy Fowler suggested that the Sun might indeed produce neutrinos from ^{8}B !

Might be energetic for detection by chlorine !

Davis saw evidence of neutrinos at SRS, but insufficient to distinguish solar from cosmic !

os too !

h



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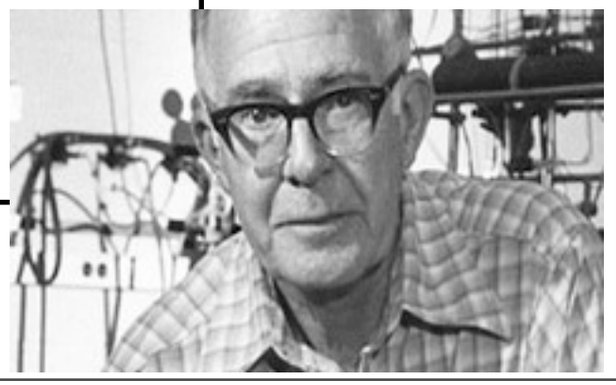

Enter ..... John Bahcall !

The Philosophy grad student who fell in love with Physics !

John Bahcall, Homestake mine, Chlorine Solar Neutrino Experiment, SD, 1964

Beta decay and electron capture

Beta decay and electron capture

Beta Decay

Beta decay and electron capture

Beta Decay

$$n \rightarrow p + e^- + \nu$$

Beta decay and electron capture

Beta Decay

$n \rightarrow p + e^- + \nu$

Inverse Beta Decay

Beta decay and electron capture

Beta Decay

$$n \rightarrow p + e^- + \nu$$

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$$\nu + n \rightarrow p + e^-$$

Beta decay and electron capture

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Electron Capture

Beta decay and electron capture

Beta Decay

$$n \rightarrow p + e^- + \nu$$

Inverse Beta Decay

$$\nu + n \rightarrow p + e^-$$

Electron Capture

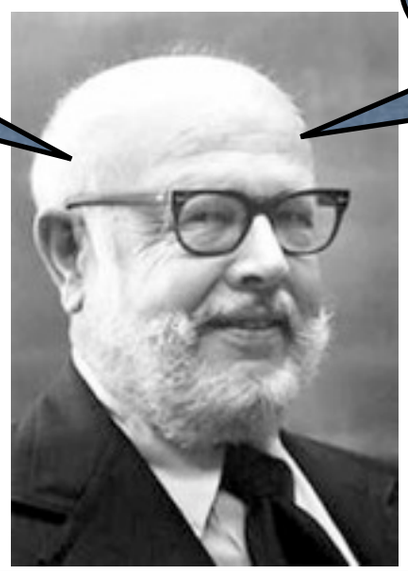
$$e^- + p \rightarrow \nu + n$$

Bahcall's calculations

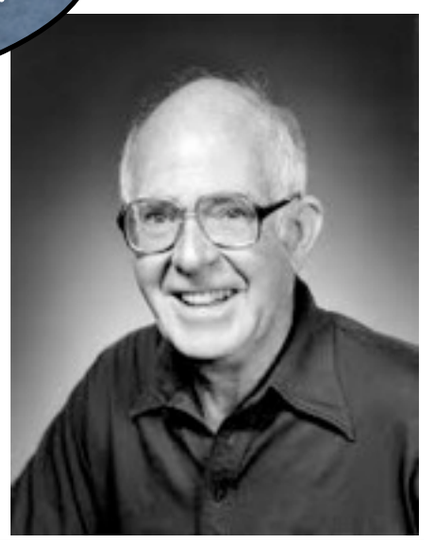
circa 1962

- Bahcall's calculations on electron capture ($e^- + p \rightarrow \nu_e + n$) did not make experimental sense !
  - Electron capture rates in earthly matter (trapped orbits) seemed different from that in plasma of a star (free flow) !
  - Popular literature on element formation (Fowler was an author) in stars assumed same rates !
- He wrote a paper on his calculations, it was published in Physical Review.
- Fowler happened to be the paper referee !
  - Asked Bahcall and Davis to join him at Caltech !

"Come, work with me at Caltech !"

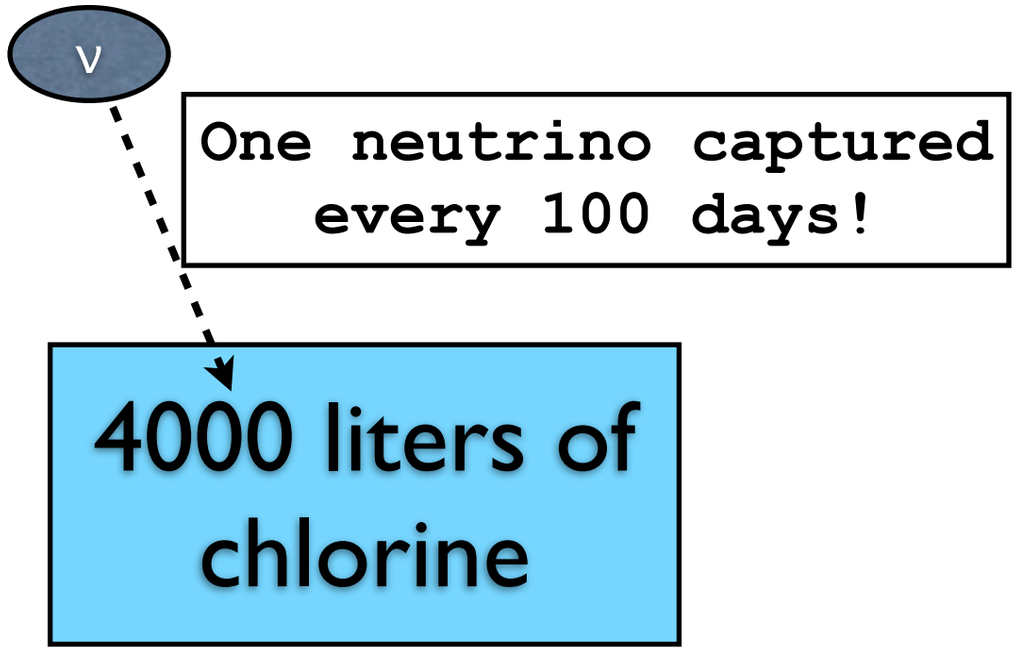


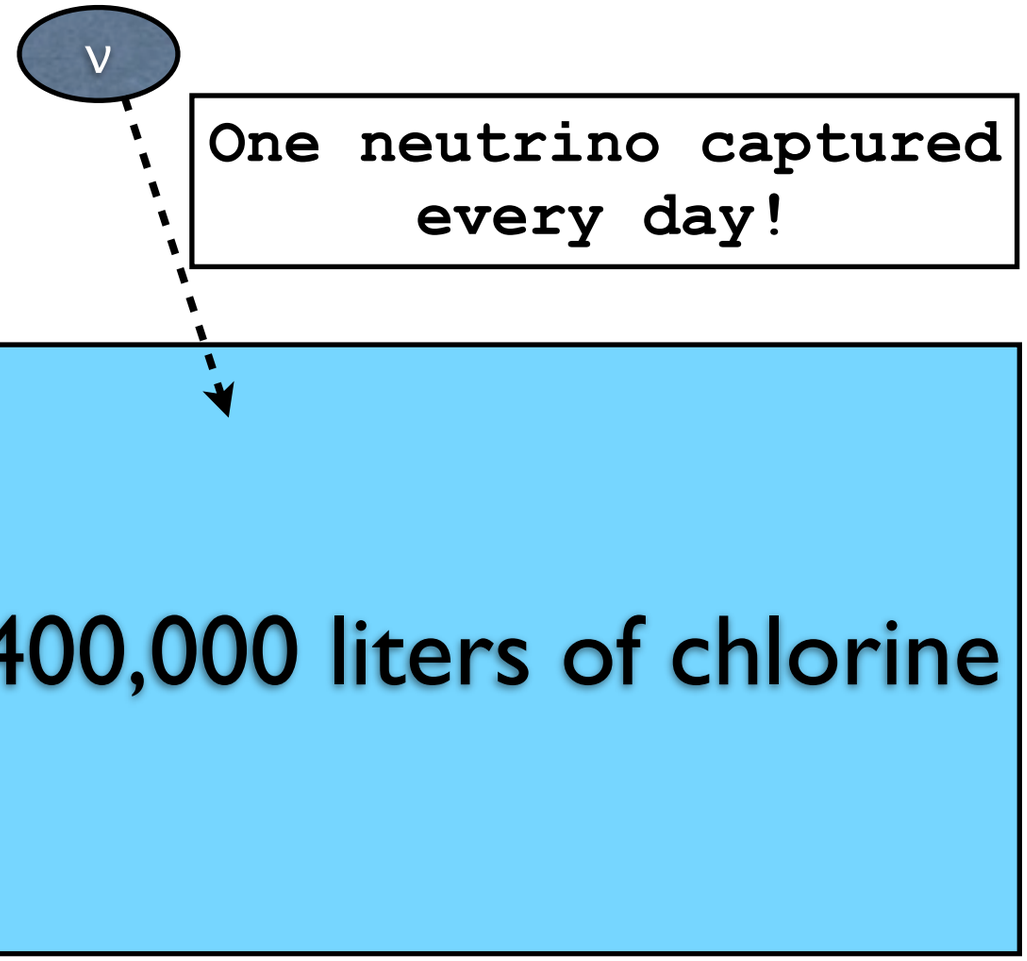
"There's a guy in IN who knows how to calculate how nuclear physics works in the Sun ! Come to Caltech !"



Davis, Bahcall and Neutrinos

- Bahcall was asked to compute what his calculations implied for producing neutrinos in the Sun !
- Bahcall showed that there was a difference between measurements on earth and what should happen in the Sun !
  - Did not sound encouraging !





Davis, Bahcall and Neutrinos

- Bahcall was asked to compute what his calculations implied for producing neutrinos in the Sun !
- Bahcall showe measurements on earth and w
  - Did not sou

ν

One neutr rino captured every ery day!

4000 liters chlorine

400,000 liters of chlorine

Search for an underground cavern

- Ray Davis was upbeat ! Wanted to build a 400,000 litres experiment !
- He felt he could extract even the very few Argon atoms !
  - "Smoking gun" for solar neutrinos !
- Major worry was interference from cosmic rays, produce Argon atoms.
- Concluded that detector would have to be at least 1220 m underground.

Anaconda Copper Mine
Butte, MT
1280 m deep
Excavation cheap
Cavern too small

Homestake Gold Mine
Lead, SD
1480 m deep
Excavation expensive
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Sunshine Silver Mine
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1640 m deep
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No money/funding agency available for their proposal initially!

Lots of convincing and persuasion needed to get some funds from BNL !

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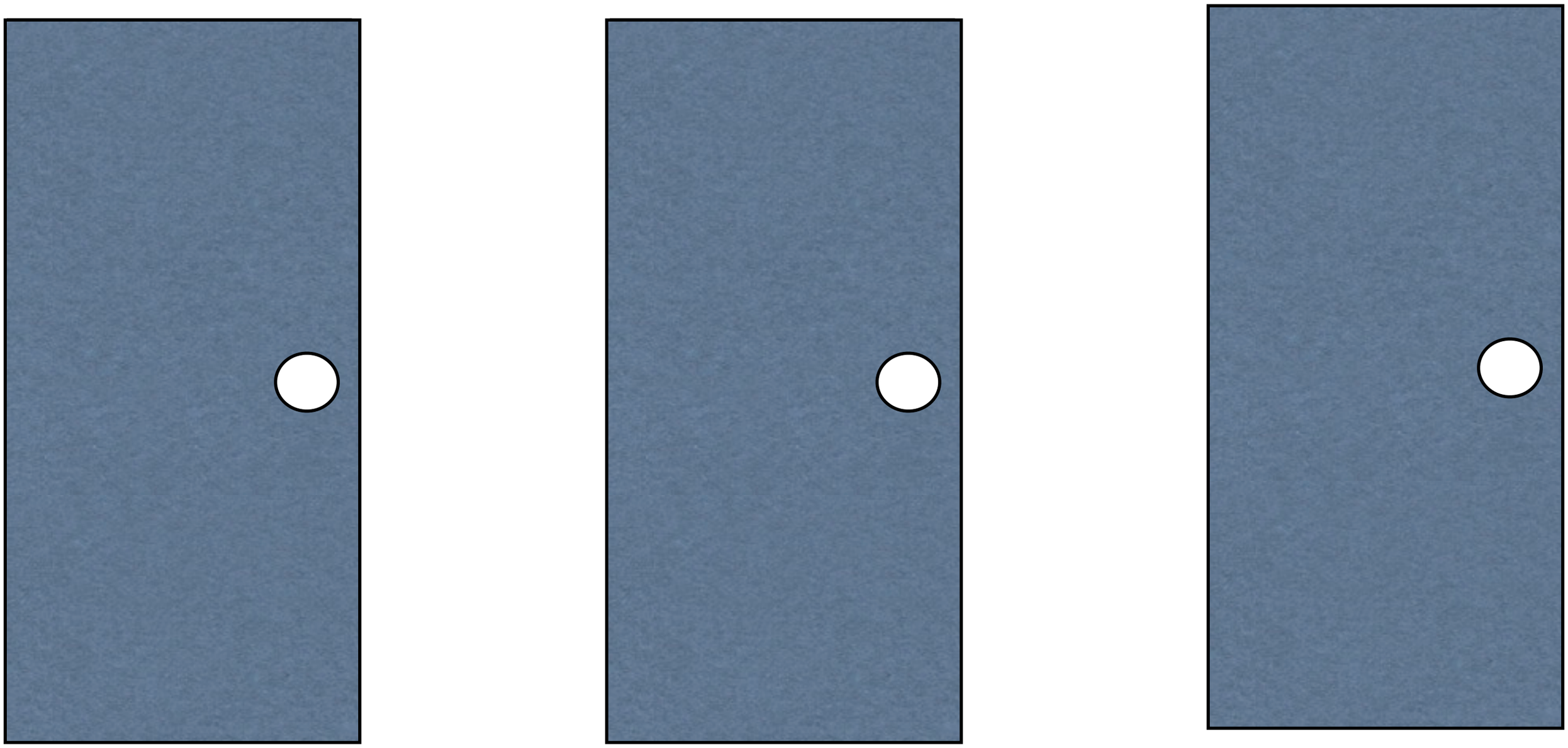
How many neutrinos were they expecting to find ?

- By end of Summer 1966, experiment was ready to start at Homestake mine !
- Bahcall had improved the precision of his calculations.
- 66 billion solar neutrinos cross a cm^2 (about size of your eye socket) each sec !
- Which ones would Davis's detector (chlorine atoms) be able to capture ?



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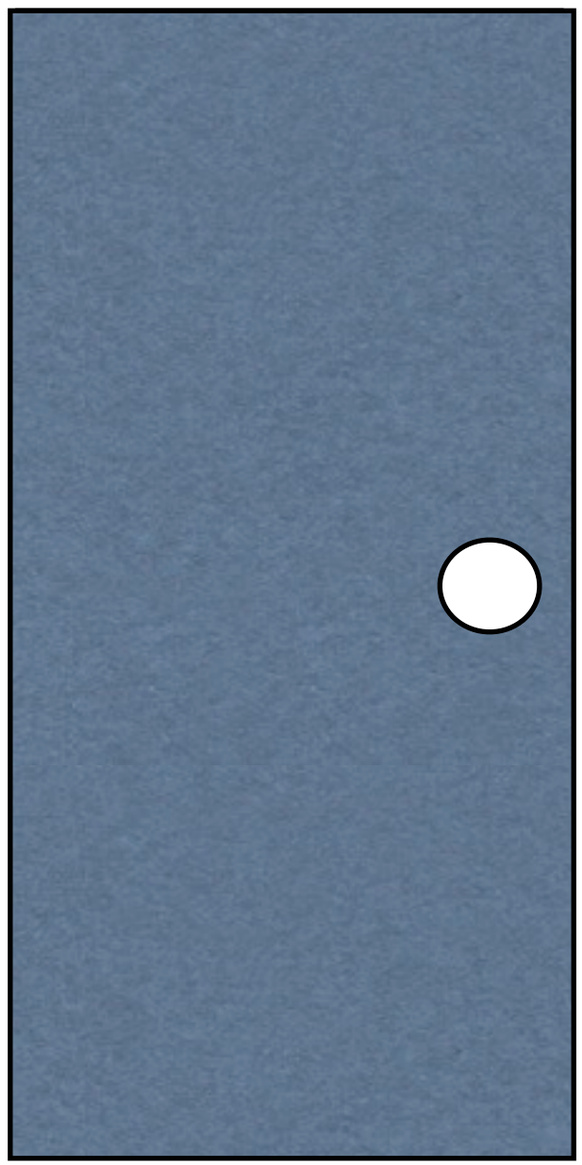
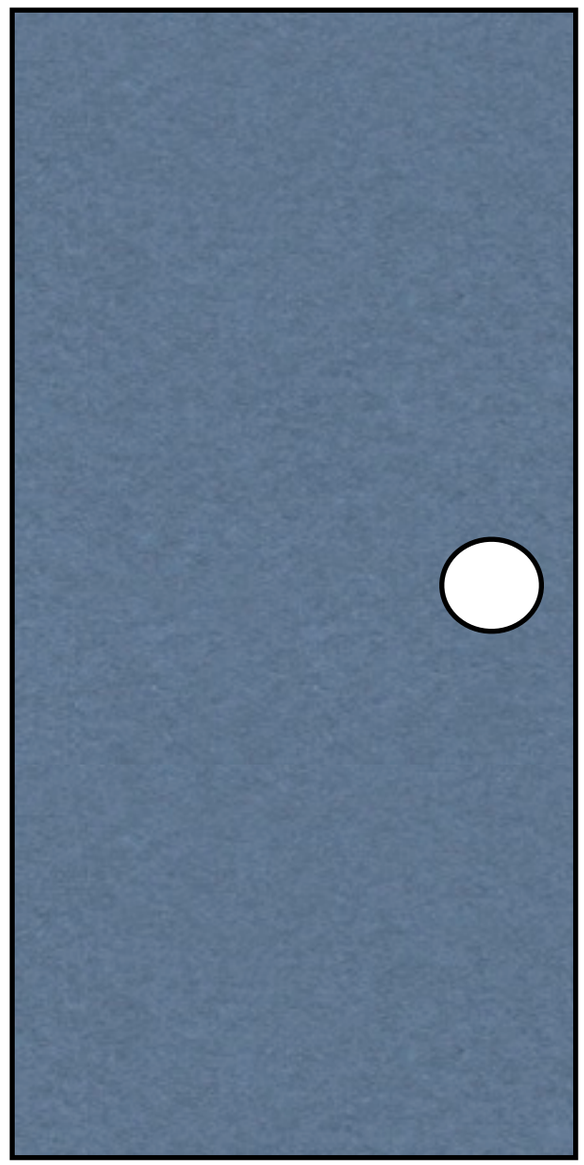
Sixty billion born this way !

Not energetic enough to activate chlorine !





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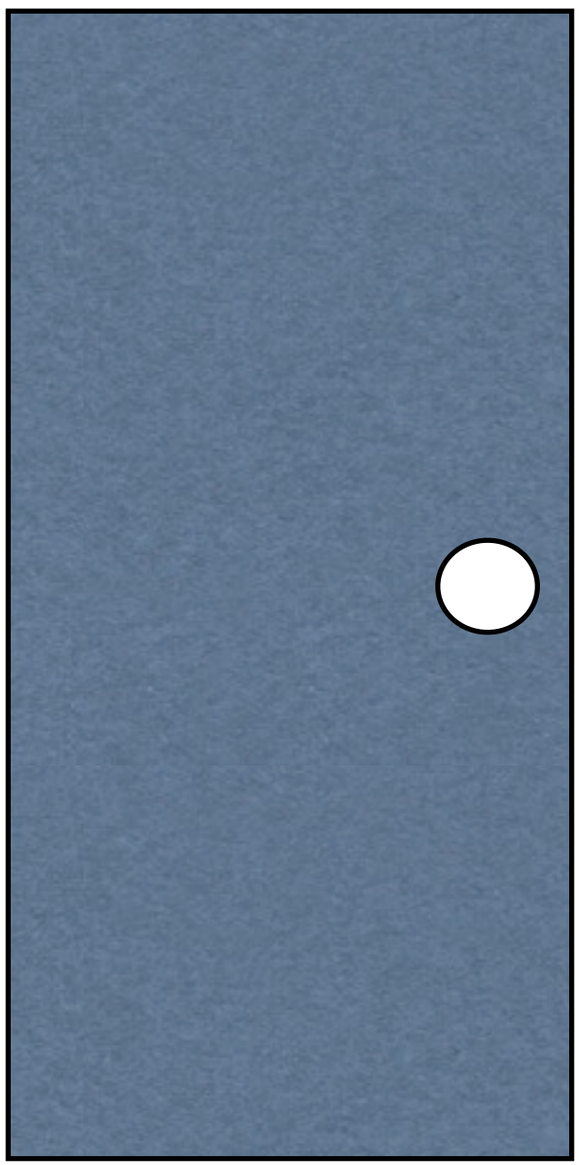

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$p+p \rightarrow {}^4He$	$^3H+{}^4He \rightarrow {}^7Be$	$^7Be+p \rightarrow {}^8B$
Sixty billion born this way !	Five billion born this way !	0.5 million born this way !
Not energetic enough to activate chlorine !	Still not energetic enough to activate chlorine !	Energetic enough, might activate chlorine !

What is a Solar Neutrino Unit (SNU) ?

- For a neutrino **born along with ^{8}B**, chance of it hitting a ^{37}Cl was 1 in 10^{36} atoms per second
  - It means, wait **10^{36} seconds** before a 50:50 chance of capturing a neutrino !
- This capture rate : 1 Solar Neutrino Unit (SNU)

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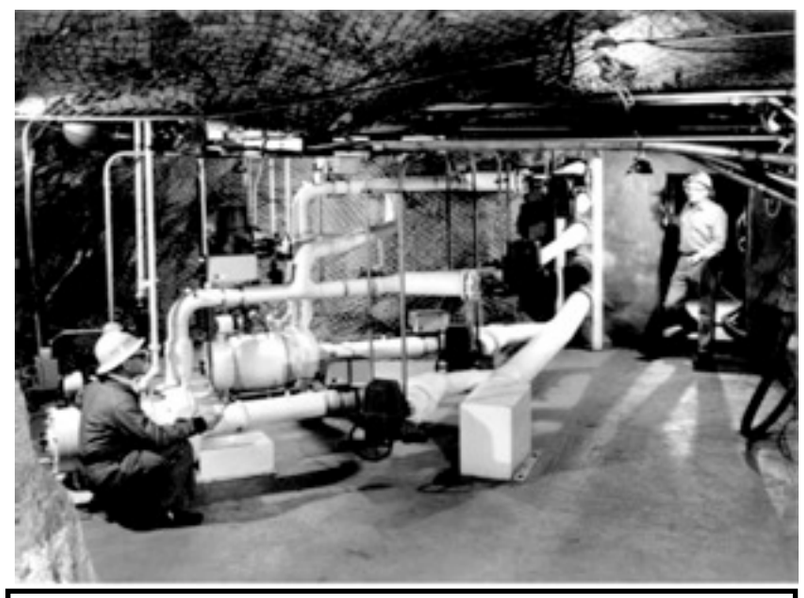
Compare to age of universe in seconds ?

Bahcall's predictions & Davis's results

circa 1968

- 400,000 litres of cleaning fluid contains 2×10^{30} atoms of ^{37}Cl
- Average waiting time for a single capture is about 6 days !
- Bahcall's predicted rate:
  - Best model for solar interior, nuclear reaction cross-sections, Cl capture mechanism suggested by Ben Mottelson
  - 80 % of this expected rate would be from radioactive ^{8}B decay neutrinos !
- Neutrinos detected by Davis:
  - More than a factor of 2 less !

Davis atop the 400,000 chlorine tank



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Davis and Bahcall at Homestake detector

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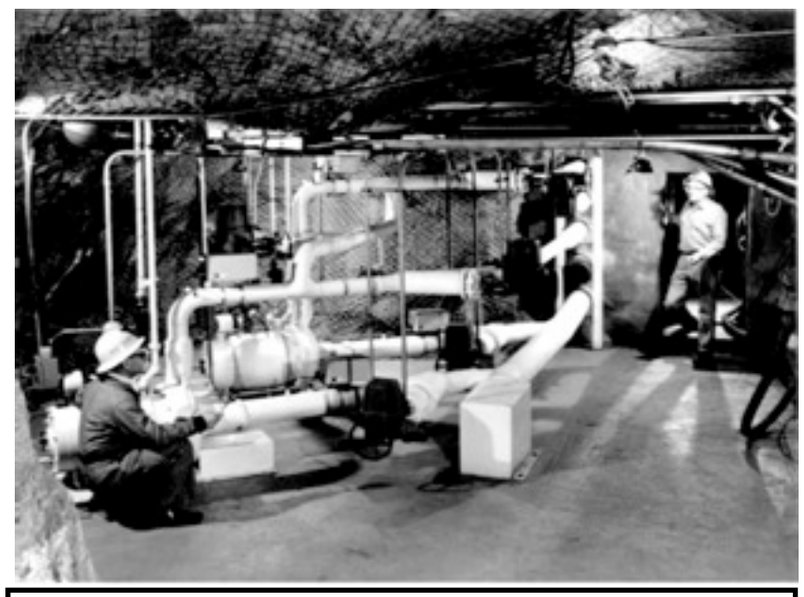

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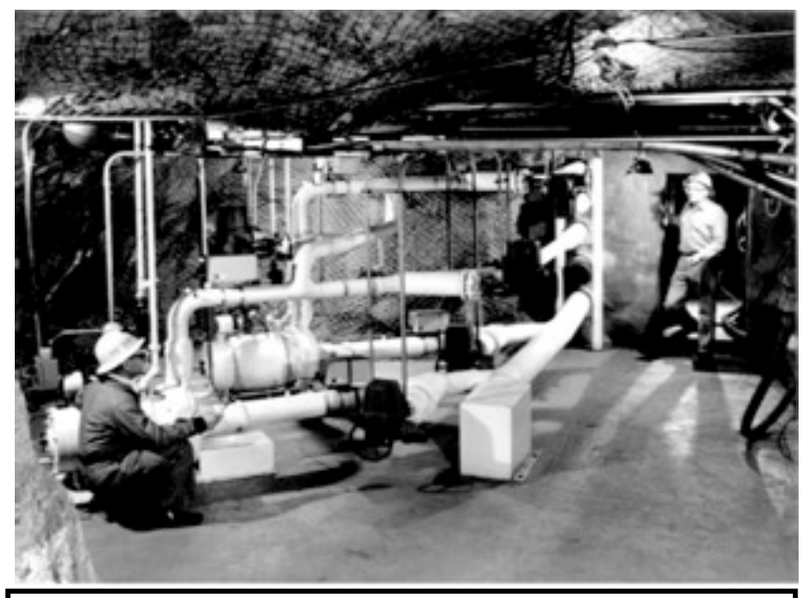

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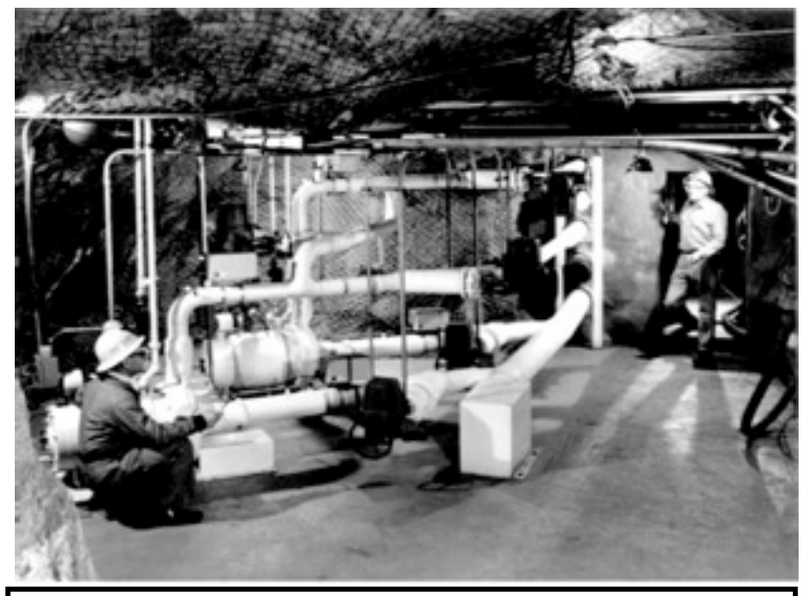

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  Remember Davis was sensitive to the high energy neutrinos from ^{8}B stage that can interact with chlorine

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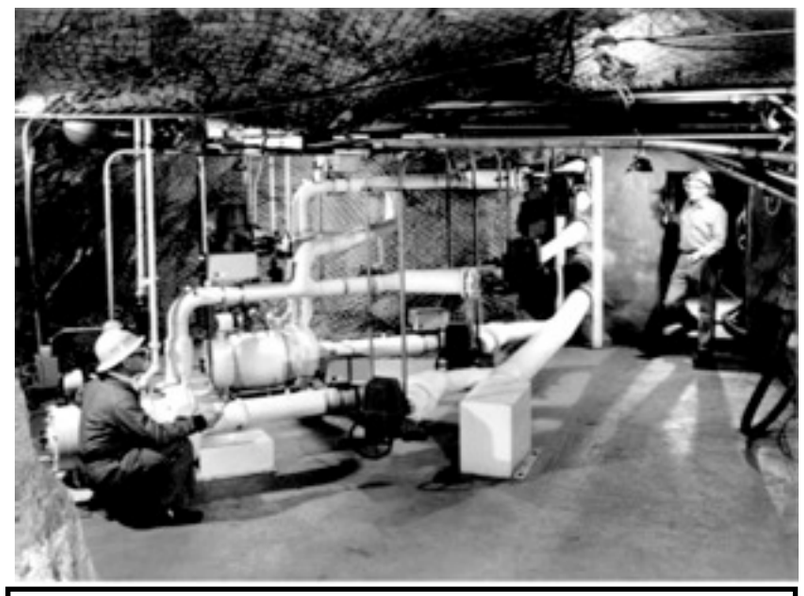

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Lots of questions !

- Davis's experiment was the only one to claim to have seen solar neutrinos, but there was a lot of confusion .....
  - Was method convincing enough ? Small numbers in a vast assembly!
  - Was Davis sure that he was measuring solar neutrinos ?
  - How hermetic was the detector ? Argon leaking in from outside or extra produced inside ?
  - Some convinced experiment was right, but disagreed on what it all meant !
  - Non-astrophysicists decided that solar model could not be trusted !
    - Davis's data showed that Sun produced fewer neutrinos than standard model predicted !
  - Astrophysicists argued solar model was right, something else was wrong !
  - Background from cosmic rays seemed small - but signal was small too !

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  - Was method convincing enough ? Small numbers in a vast assembly!
  - Was Davis sure that he was measuring solar neutrinos ?
  - How hermetic was the detector ? Argon leaking in from outside or extra produced inside ?
  - Only 1 atom of ^{37}Ar a month (from cosmic rays) allowed !

Next step: Reduce background noise further !

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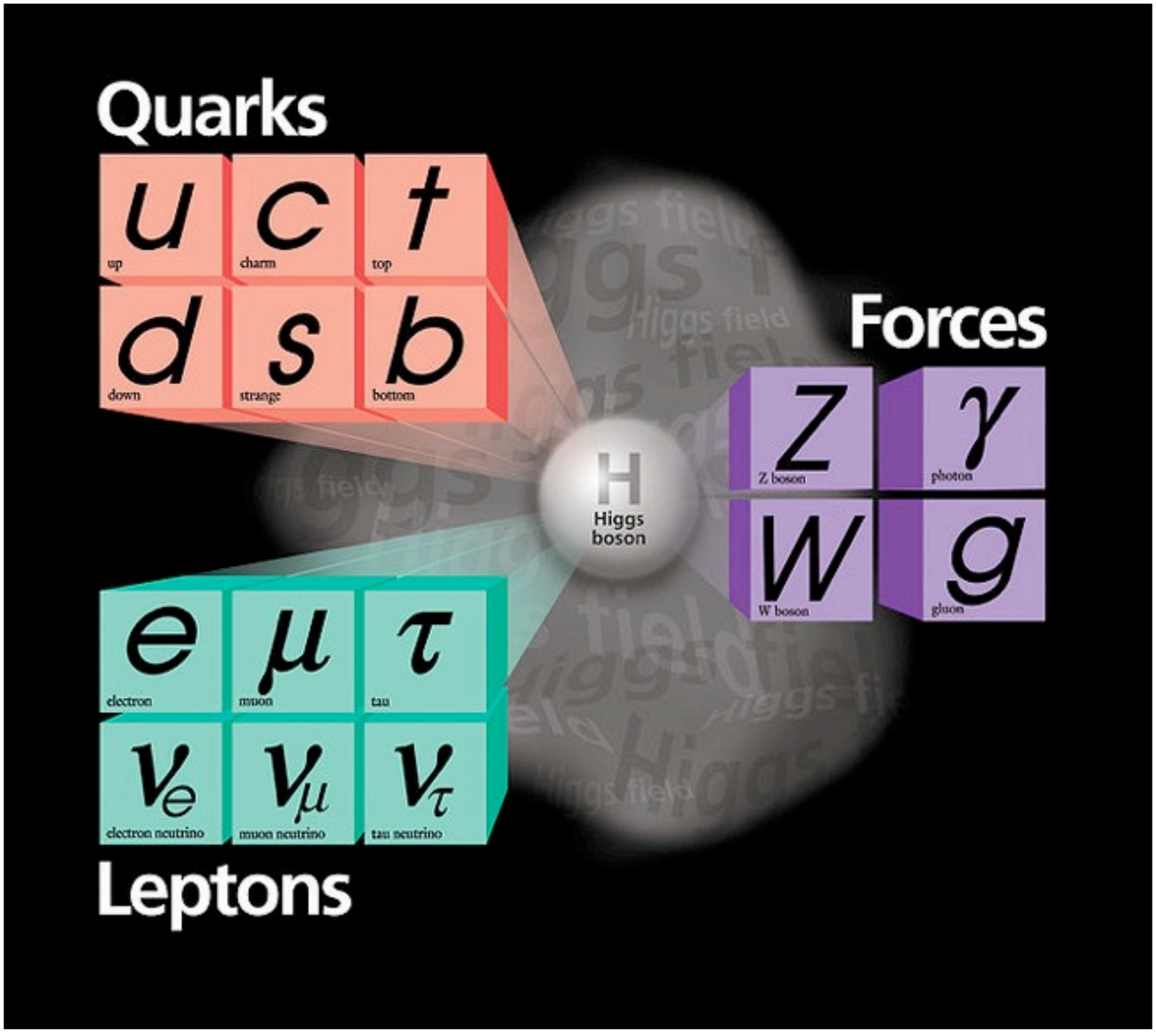
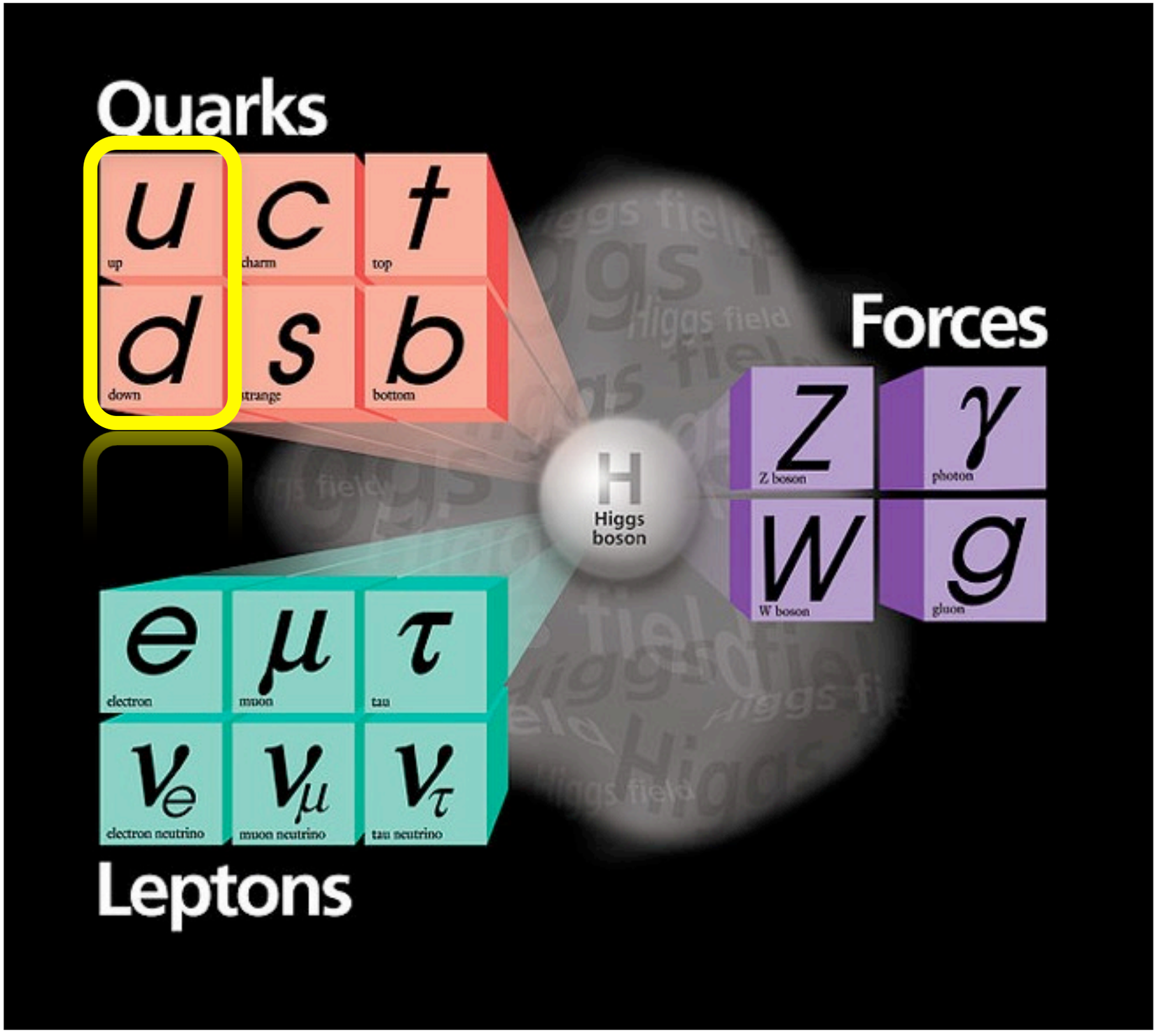
A brief diversion from the solar neutrino story .....
we will come back to it later on again !

The Standard Model



Pions are of meson family. They are made of 2 quarks each.
Muons are heavier cousins of electrons.

The Standard Model



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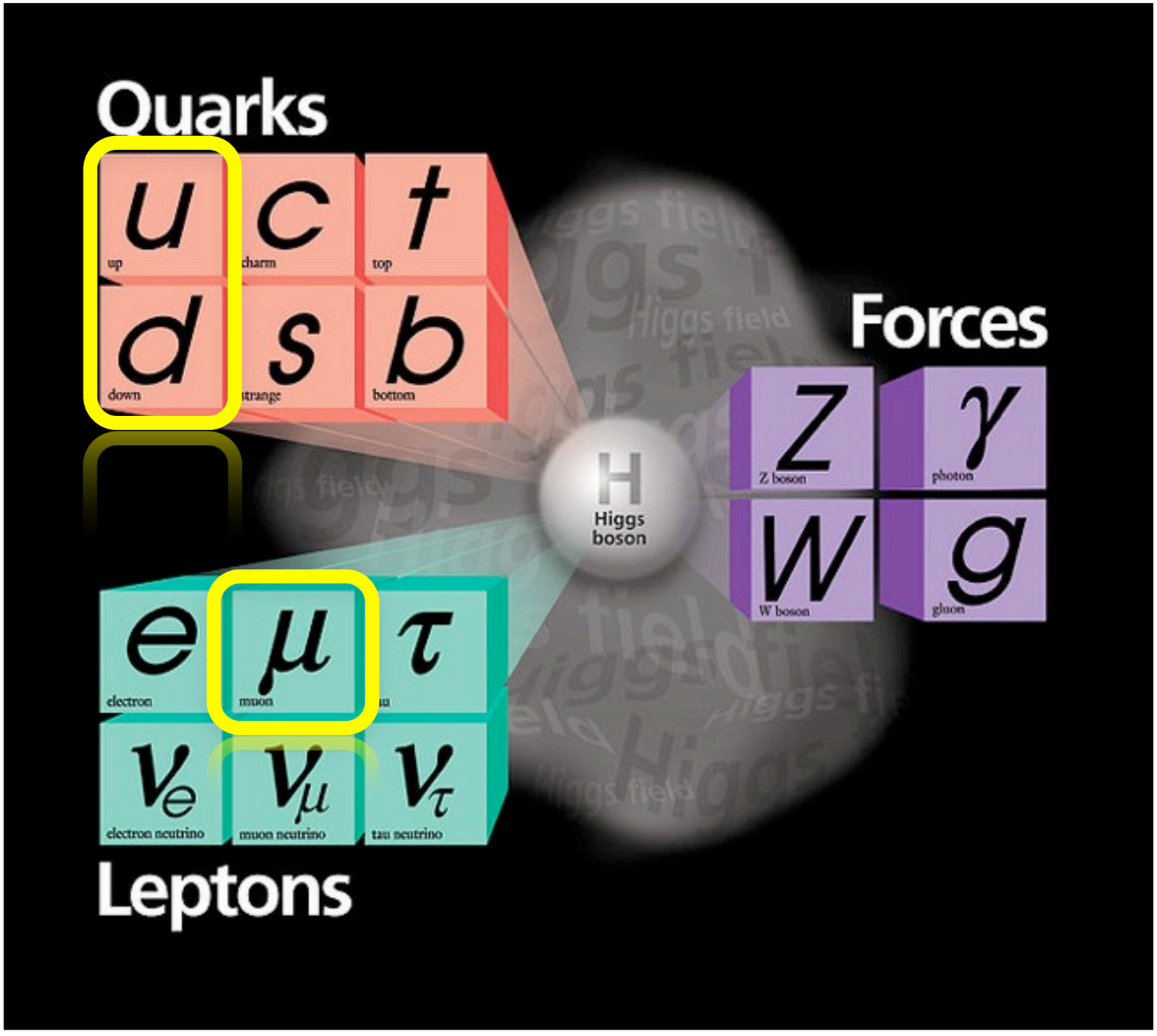

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Muons and Pions

- Physicists had postulated the existence of the pion first
  - Strong nuclear force makes a pion in proton-neutron collision
- Muon was discovered first (1937) from cosmic radiation
  - Seemed a lot like a heavier cousin of the electron
  - It decayed to an electron, remaining energy carried away by neutral radiation
  - Was the "neutral radiation" a photon ? $\mu \rightarrow e + \gamma$? Why not ?
  - Jack Steinberger was to show that this is not the case !
- Pion was discovered later (1947) from cosmic rays
  - Pion decays via weak force to muon and neutrino in 0.01 μsec

Enter ..... Jack Steinberger !

(1988 Nobel Prize in Physics)

Germany → Chicago → World War II → Physics

Jack Steinberger in front of the Pupin Laboratories, Columbia University

A Tale of Two Neutrinos

circa 1959

- Fermi suggested muon might decay into electron and 2 more particles
- Steinberger (Fermi's student) confirmed his conjecture by experiment !
  - The 2 "missing" particles should have no charge and near zero mass - but they're not photons !

- Pontecorvo was also fascinated by idea that $\mu \rightarrow e + \gamma$ does not exist !
  - He wondered if the muon is more than just a "heavy electron"
    - It has some special "muon-ness" about it. Same for electron.
  - He also explored if a lepton and a neutrino could make pairs
- He proposed that all this could be tested by looking at neutrino interactions with matter

Making Neutrinos and Detecting them

Accelerators (cyclotrons) → High Energy Protons → Target

Target → High Energy Pions

High Energy Pions → Muons

High Energy Pions → Neutrinos

Muons → Thick Steel Shield

Neutrinos → Thick Steel Shield

Thick Steel Shield → Artificial neutrino beam

Artificial neutrino beam → Massive Target Detector

Massive Target Detector → Neutrino reveals itself by picking up charge from atoms

Making Neutrinos and Detecting them

Accelerators (cyclotrons) → High Energy Protons → Target → High Energy

If all neutrinos are alike :
equal numbers of muons and electrons produced !

If neutrinos of different types :
different numbers produced !

means "neutrinos carry identity" !

Artificial neutrino beam → Massive Target Detector → Neutrino reveals itself by picking up charge from atoms

Enter ..... Leon Lederman !

(1988 Nobel Prize in Physics)

Muon Neutrino ..... FNAL ..... IMSA ..... coiner of “God Particle”

Grad student Leon Lederman looking into a cloud chamber at Columbia University

Enter ..... Melvin Schwartz !

(1988 Nobel Prize in Physics)

Rewriting the Neutrino lexicon with Steinberger & Lederman

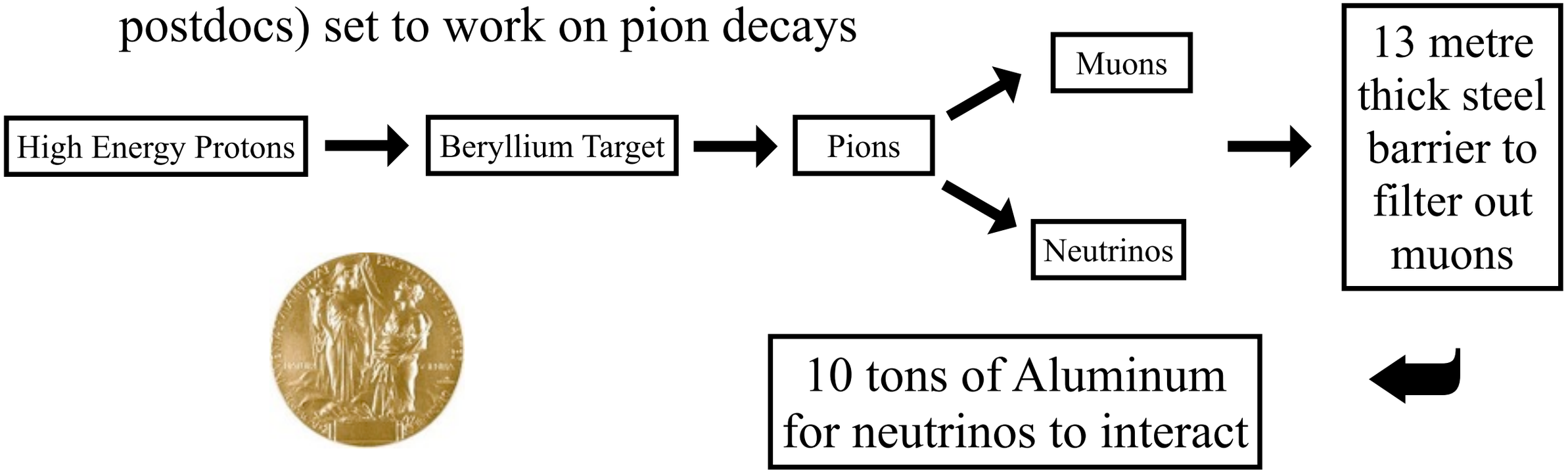
Schwarz with a spark chamber used in the discovery of the muon neutrino

Time for a break ??? !!!

Discovery of the Muon Neutrino

circa 1962

- At the new AGS (Alternating Gradient Synchrotron) facility at Brookhaven National lab:
- Team of seven (Schwartz, Steinberger, Lederman, four students and postdocs) set to work on pion decays



- More than 10^{14} neutrinos passed through detector
  - **Only 51 hit the aluminum and resulted in a muon !**
  - **None gave an electron !**
- Proved that muon-neutrinos and electron-neutrinos were distinct !

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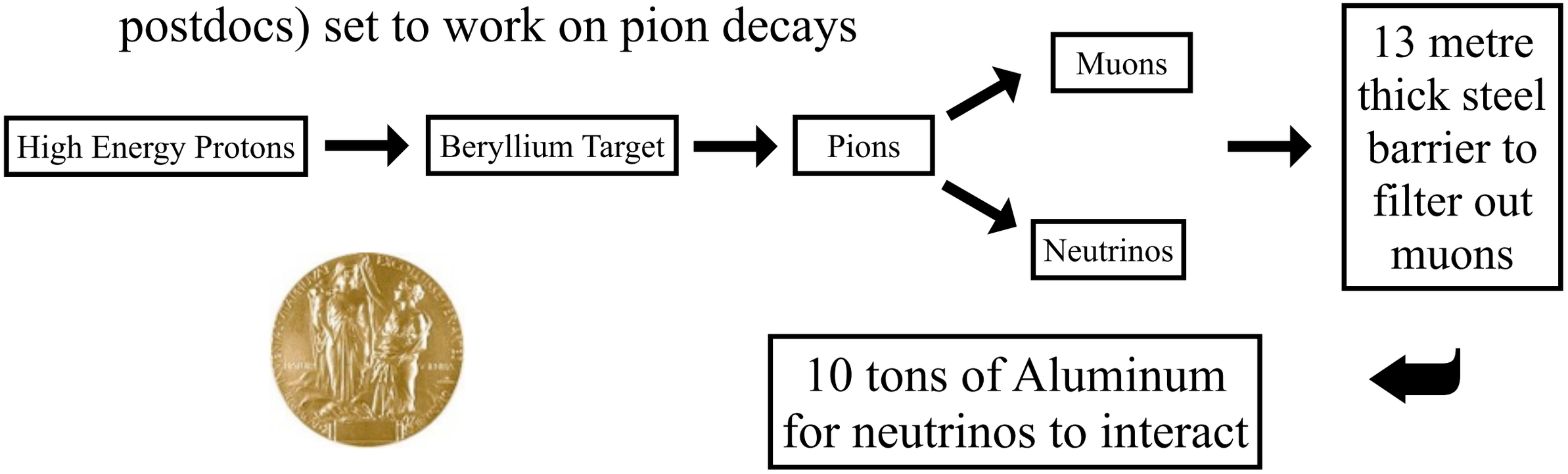

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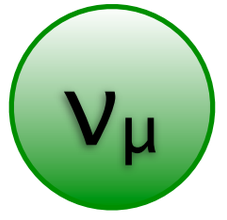

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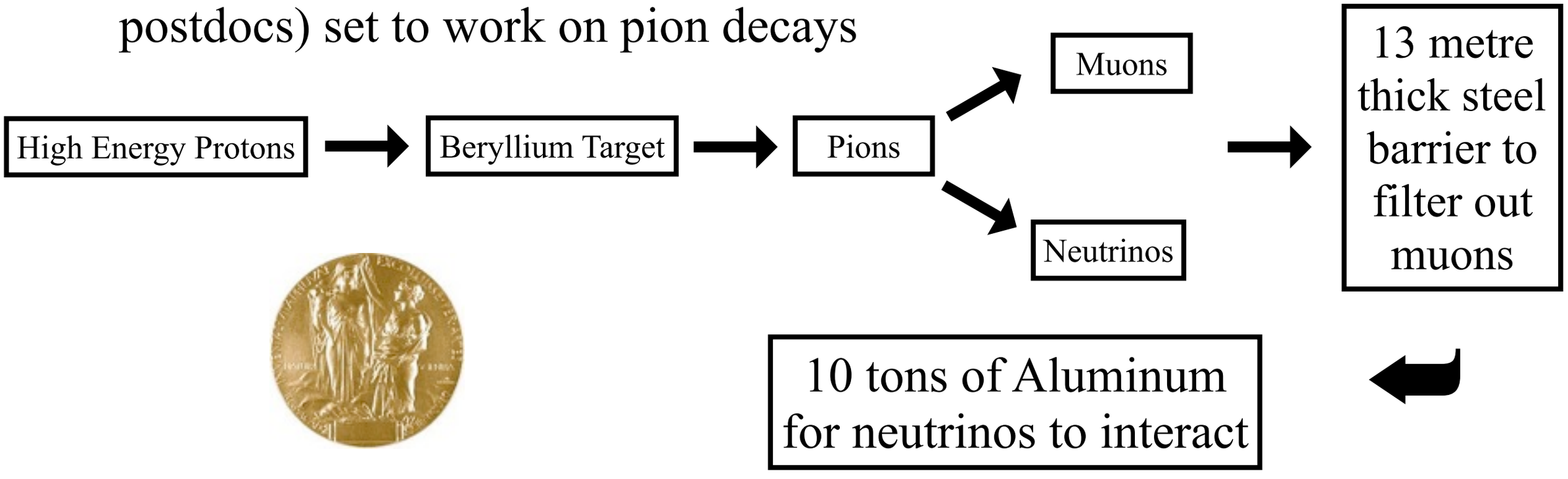

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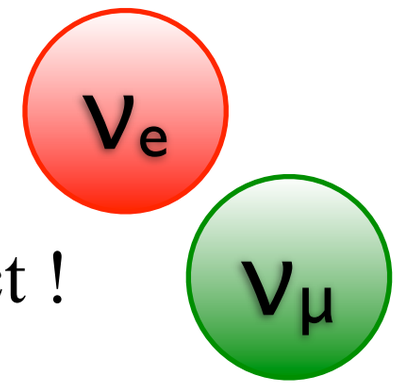


Alternating Gradient Synchrotron
(1960 - present)

AGS control room, circa 1966

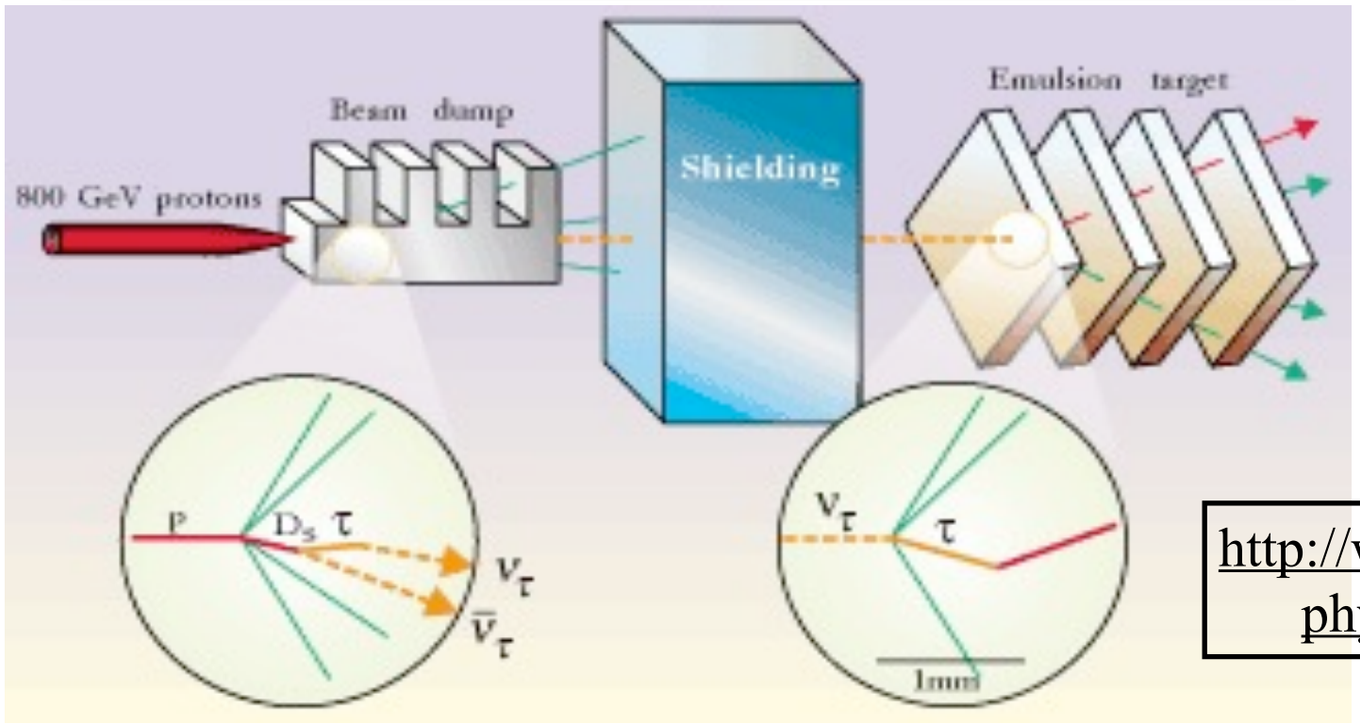
Building the AGS in the 1950s

- Built on the innovative concept of alternating gradient
- Design energy of 33 GeV reached in July 1960
- Highest energy accelerator in the world until 1968
- AGS discoveries earned researchers three Nobel Prizes
- Still serves as injector for Brookhaven's Relativistic Heavy Ion Collider
- For more information: www.bnl.gov/about/history/accelerators.php

Three Neutrino types ?

- In 1976, Martin Perl discovered the "tau (τ)" lepton
  - Tau is an even heavier cousin of the electron
- Standard Model stipulates that every charged lepton has a neutral partner !
  - Tau-neutrino (ν_τ) was predicted, but hard to detect !
  - Tau-neutrino converts into tau particle, tau decays into muons and electrons in < 10^{-9} seconds !
- Discovered in 2000 by DONUT experiment at Fermilab !

Direct Observation of the NeUtrino Tau



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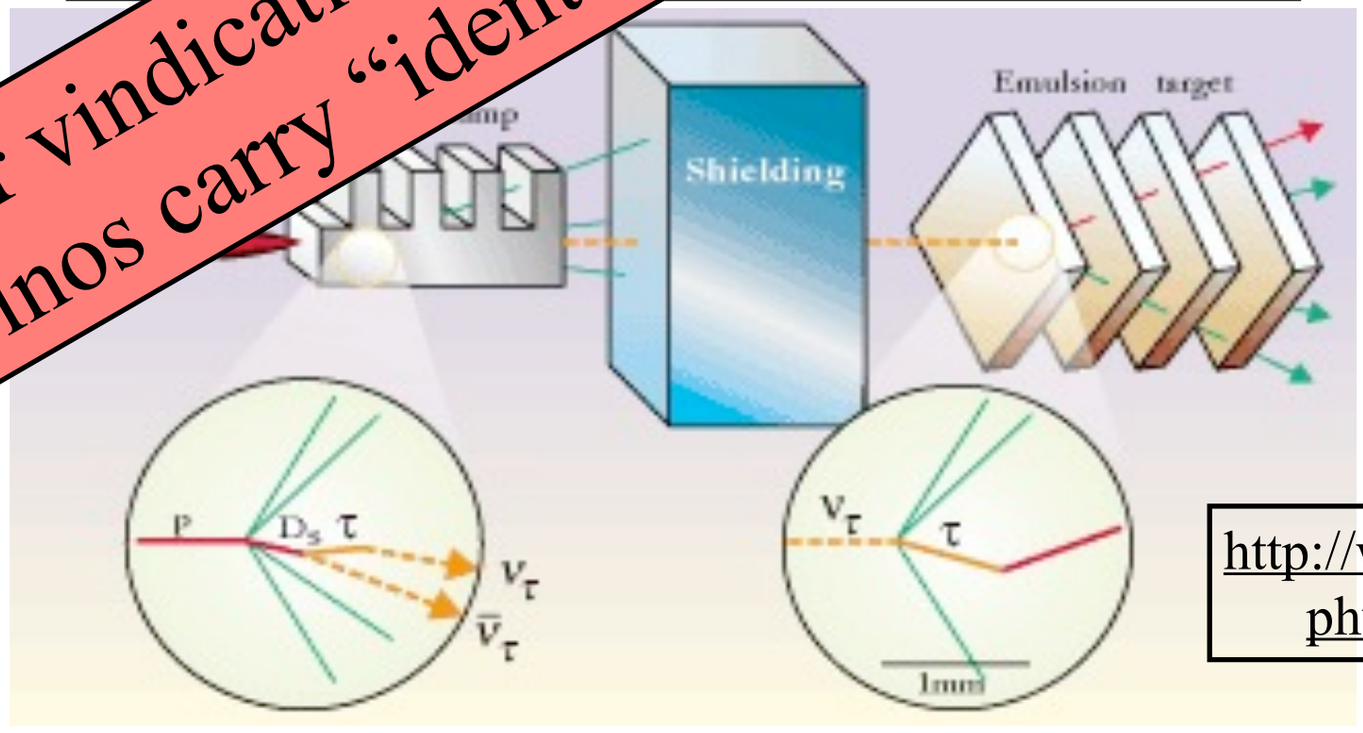
ν_T

Further vindication to Pontecorvo's 1959 paper that neutrinos carry "identity cards" ("flavor" today) !

Direc… the NeUtrino Tau



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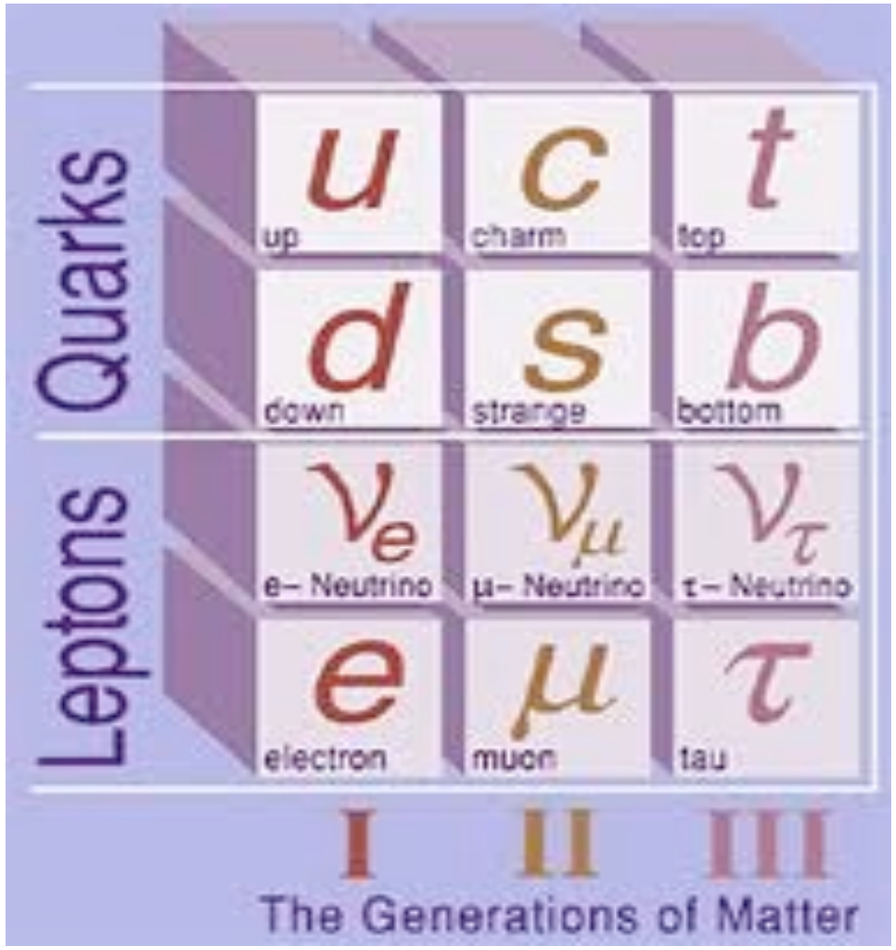
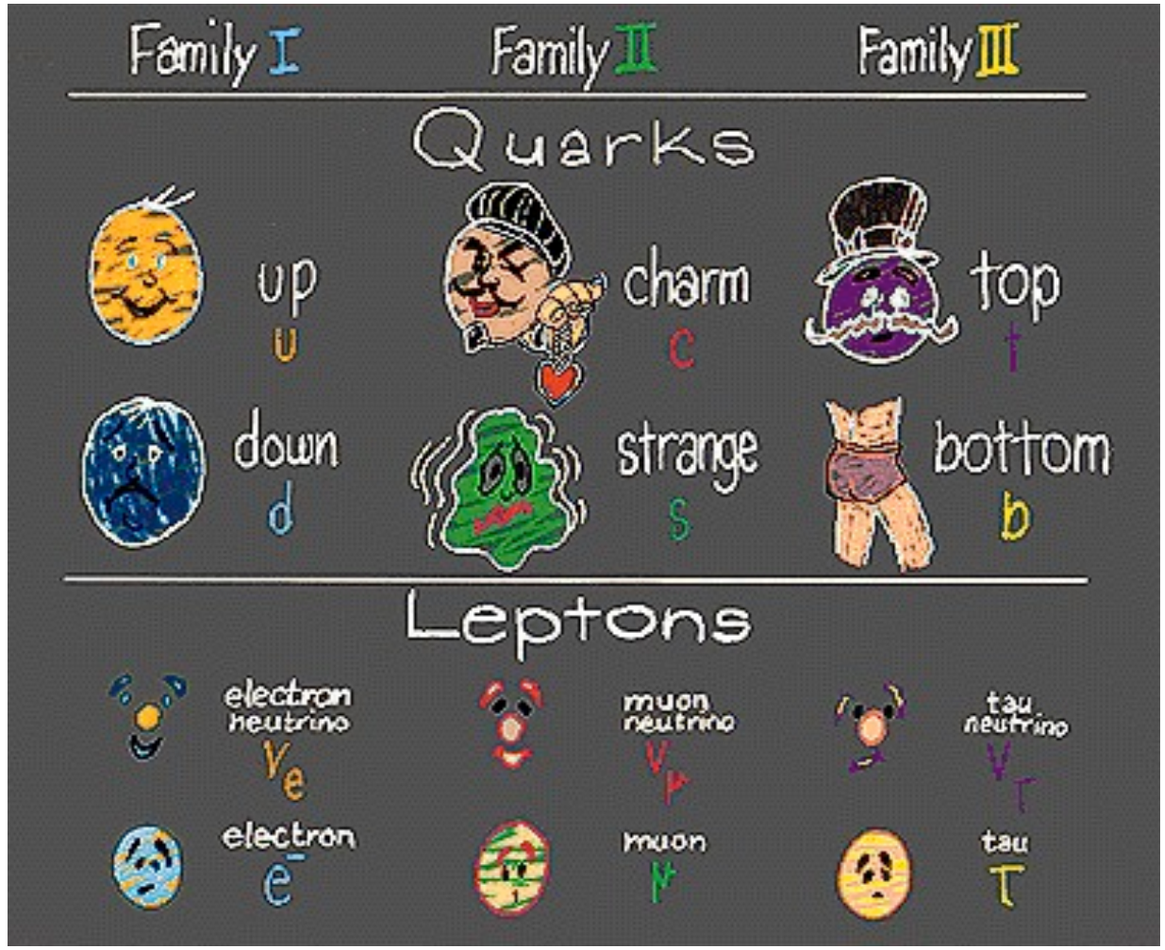
Some parting thoughts on flavors .....

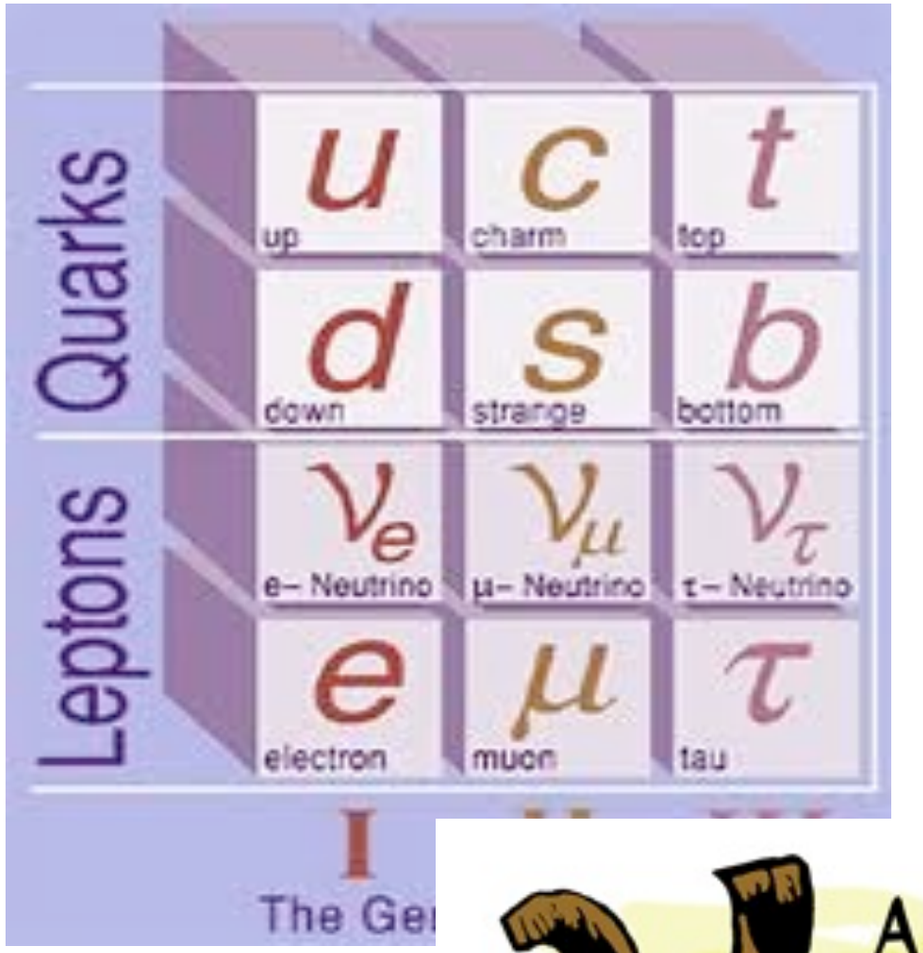


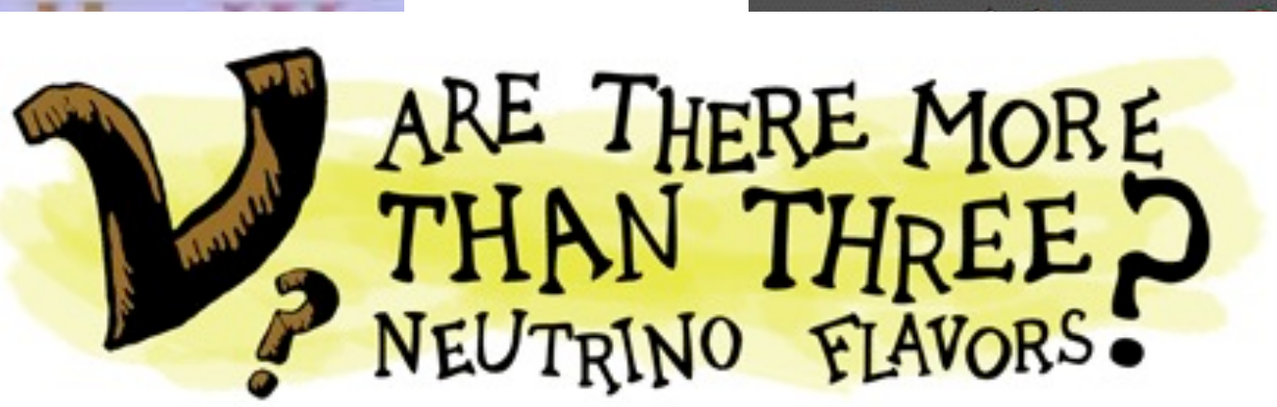


SM: Six leptons partnered by six varieties of quarks

- Why are there only three generations each, for quarks and leptons ?
  - Is there an interaction changing one into the other ?
- Are there any other neutrino types ?
  - Maybe, maybe not ! No one knows as yet !
- Pontecorvo postulated that the existence of more than one neutrino plays a major part in the solar neutrino mystery !

Some parting thoughts on flavors .....





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Back to the solar neutrino story .....

A Gallium detector ?

- By 1978, more precise results from Davis:

- Bahcall's solar neutrino prediction:
- Let's see if this is also the case with neutrinos from the dominant *pp* fusion process ! But they are low energy !
- Gallium has a higher capture rate for low energy neutrinos !
- Bahcall's predictions for gallium (Ga) as detecting medium:
  - Total capture rate of solar neutrinos was 132 SNU !
  - 74 of these could come from basic *pp* fusion process !
  - 50 of these could come from ^{7}Be and ^{8}B stages of the solar chain !
- By 1990, SAGE (U.S.S.R.) and GALLEX (Italy) experiments started up !

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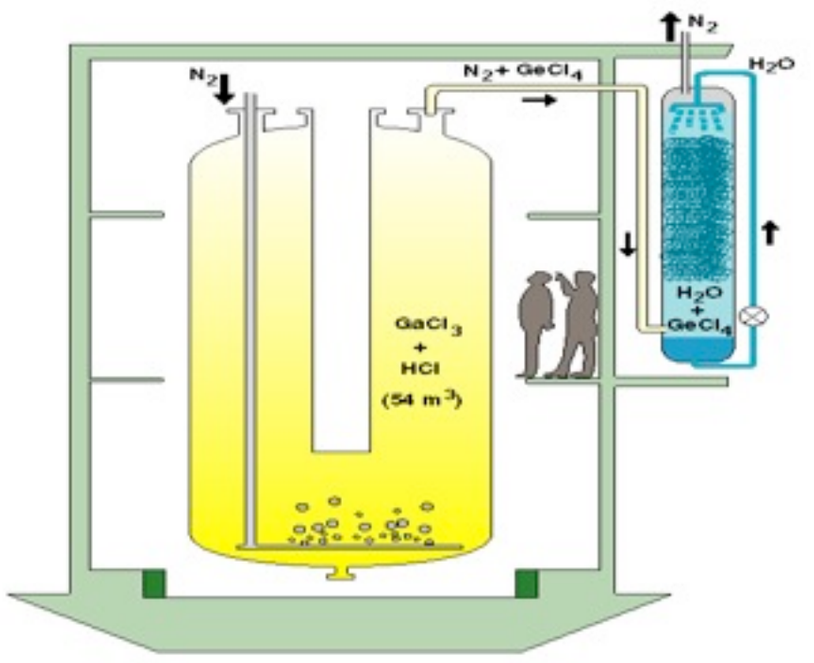
Baksan Neutrino Observatory at depth of 3500 m

Tunnel connecting 2 caverns inside Andyrchi Mountain

Part of the Baksan Underground Scintillation Telescope sensors

Gran Sasso National Lab, GALLEX is housed here

GALLEX solar neutrino experiment



Schematic of GALLEX detecting tank full of Ga

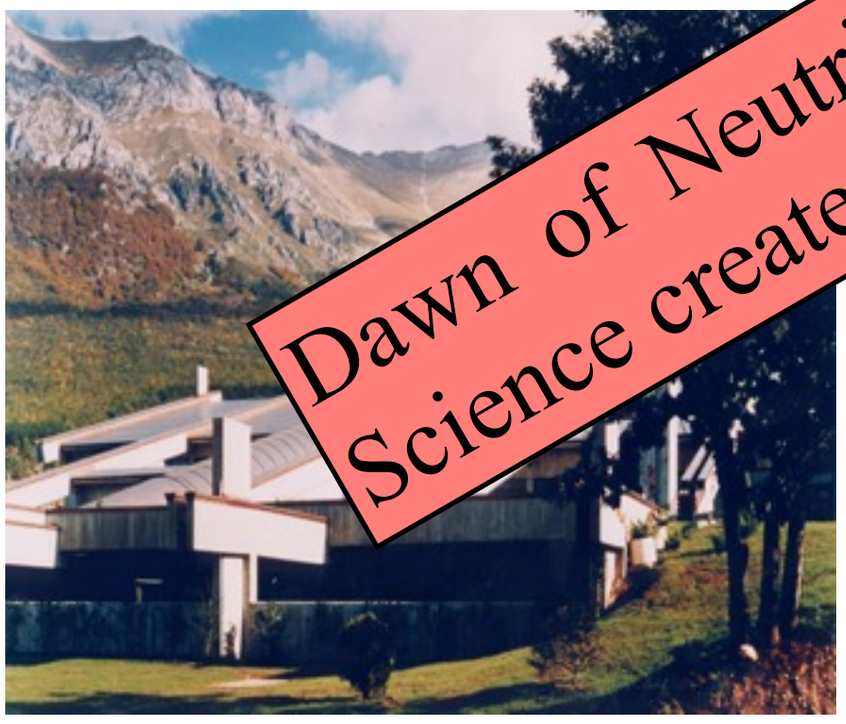
Baksan Neutrino Observatory at depth of 3500 m

Tunnel connecti
inside Andy

t of the Baksan Underground Scintillation Telescope sensors

Astronomy - a new branch of
evolutionize the field !

Dawn of Neutrino Astr
Science created - would revo



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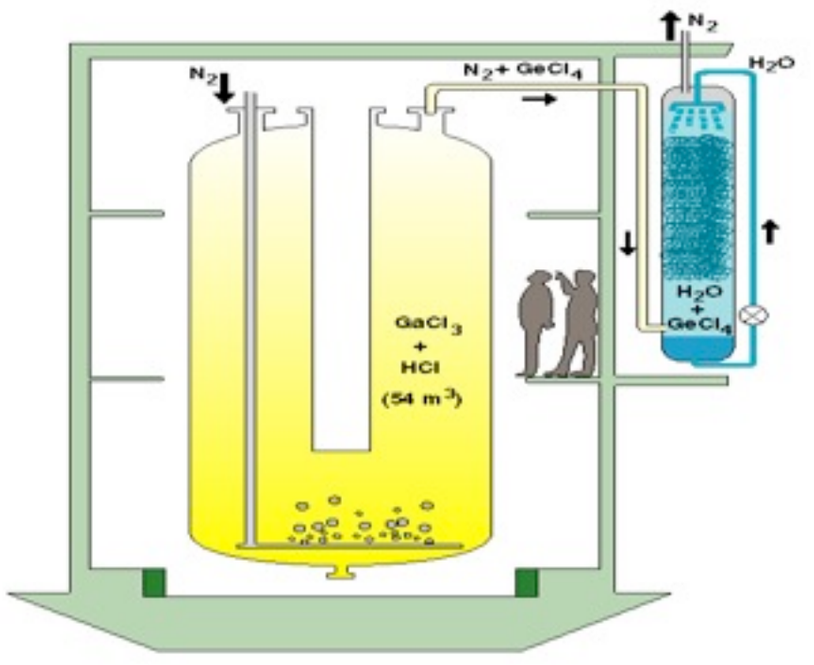


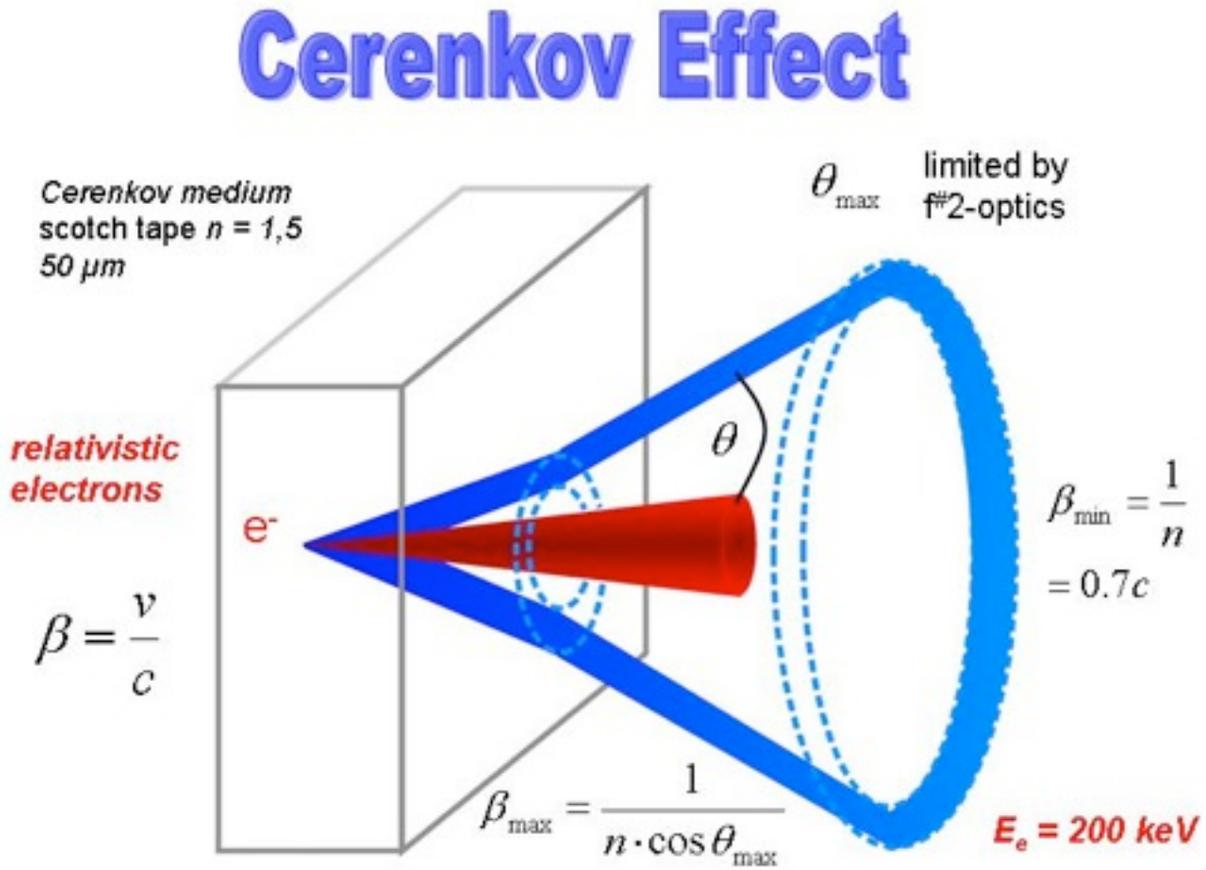
Schematic of GALLEX detecting tank full of Ga

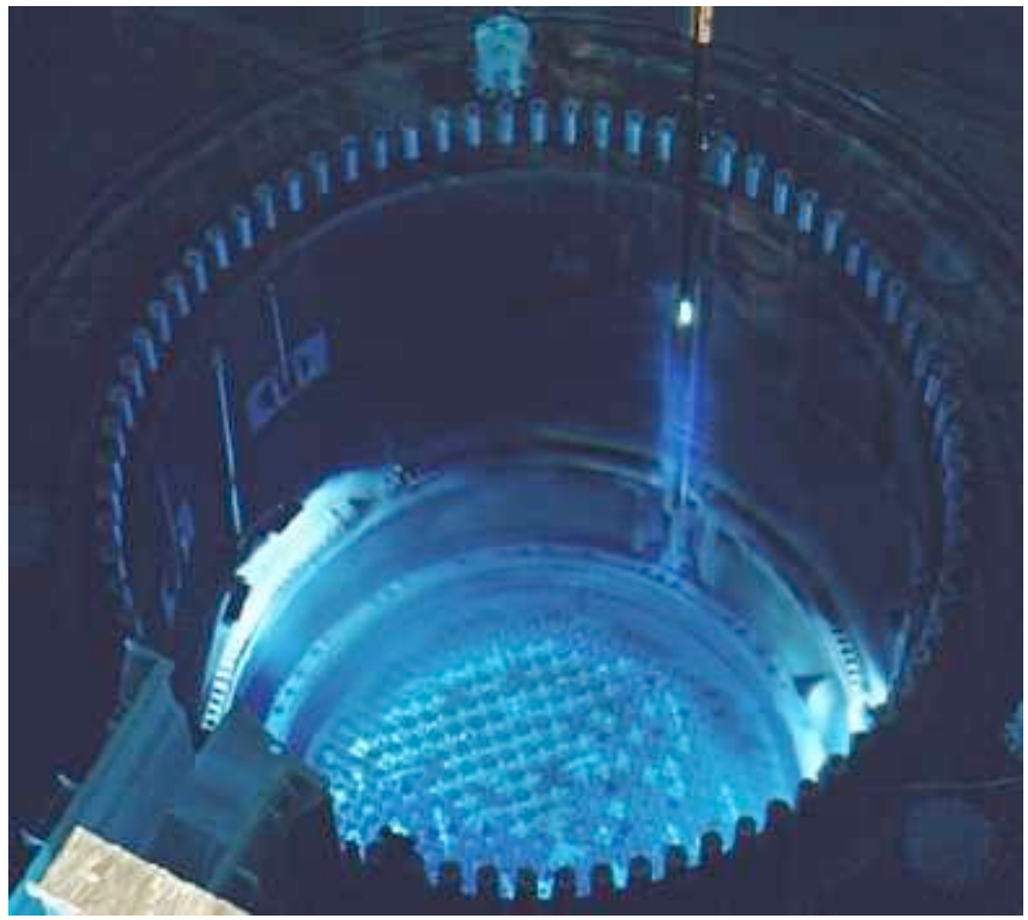
A Novel Idea: Capture Neutrinos "Online" !

- Physicists realized the importance of capturing neutrinos one at a time, as they happened !
  - Why accumulate and infer on a monthly basis ?
- The IMB (Lake Erie) and Kamioka (Japan) mine experiments had been looking for proton decays
- They had built huge tanks of ultra pure water surrounded by PMTs (photo multiplier tubes)

Cerenkov light from super luminal speeds → PMT → Electric current

Cerenkov Radiation





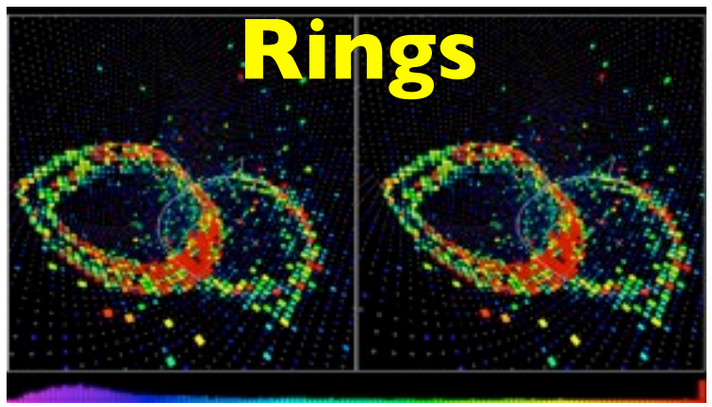
Cerenkov light in the core of a nuclear reactor

- What is Cerenkov radiation ?
- Charged particles (e, p, π) can travel through water faster than light
- There is a luminous boom (like sonic boom)
- A cone of pale blue light radiates out, centered around flight path
- Light cone is detected by PMTs

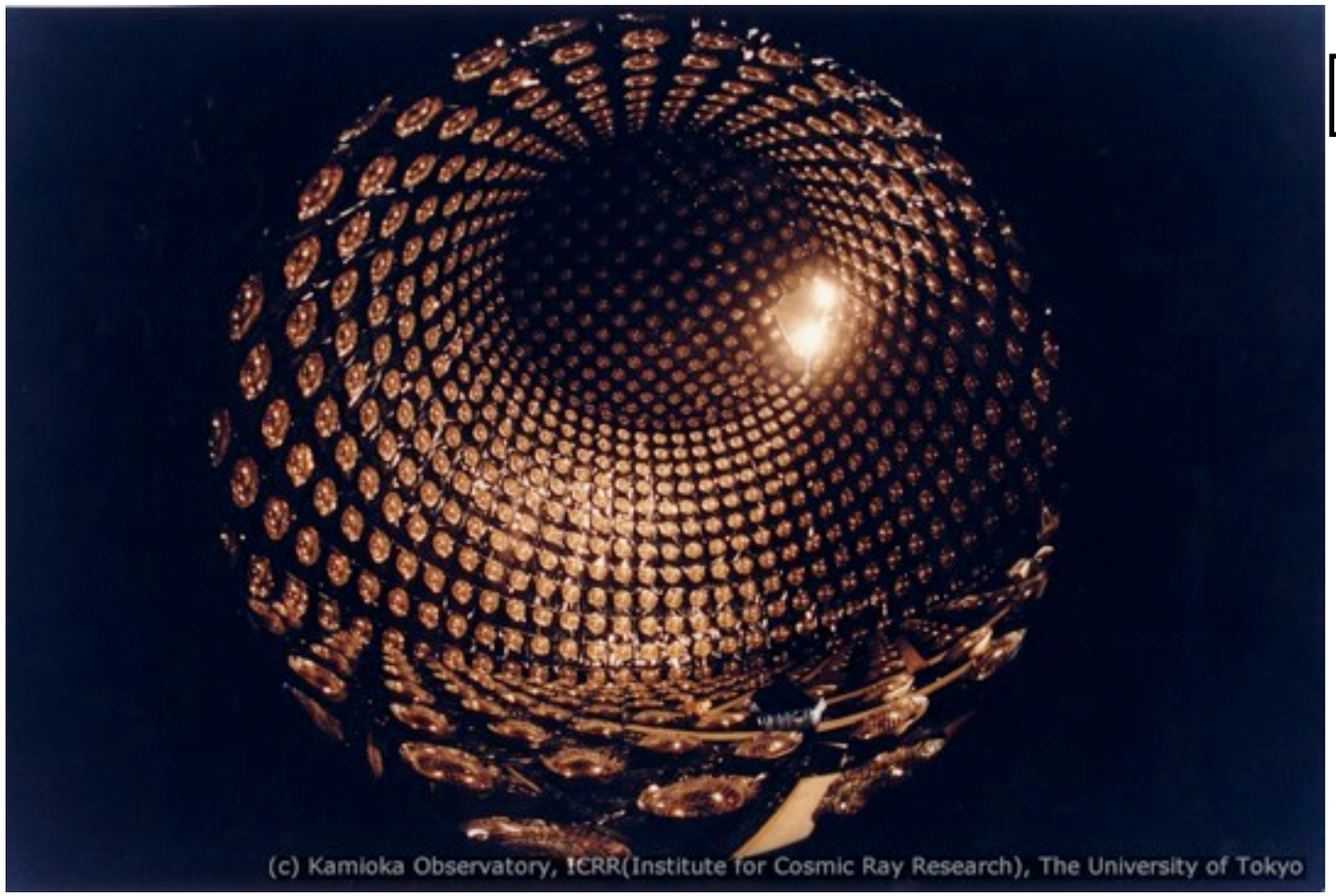
Use it for Neutrinos !

- It dawned gradually that protons decay very rarely !
- Use these huge detectors for looking at neutrinos (the unwanted backgrounds) !
- Kamioka team modified their detector to increase sensitivity to low energy neutrinos

Solar neutrinos → electrons → Cerenkov radiation → PMTs →



- Size of ring ➜ speed of electron ➜ energy of neutrino !
- Shape of ring ➜ flavor of neutrino (sharp/fuzzy)
- Time of arrival of Cerenkov light ➜ direction of neutrino
- Kamioka could make a “neutrinograph” of the Sun !



Kamiokande detector from bottom

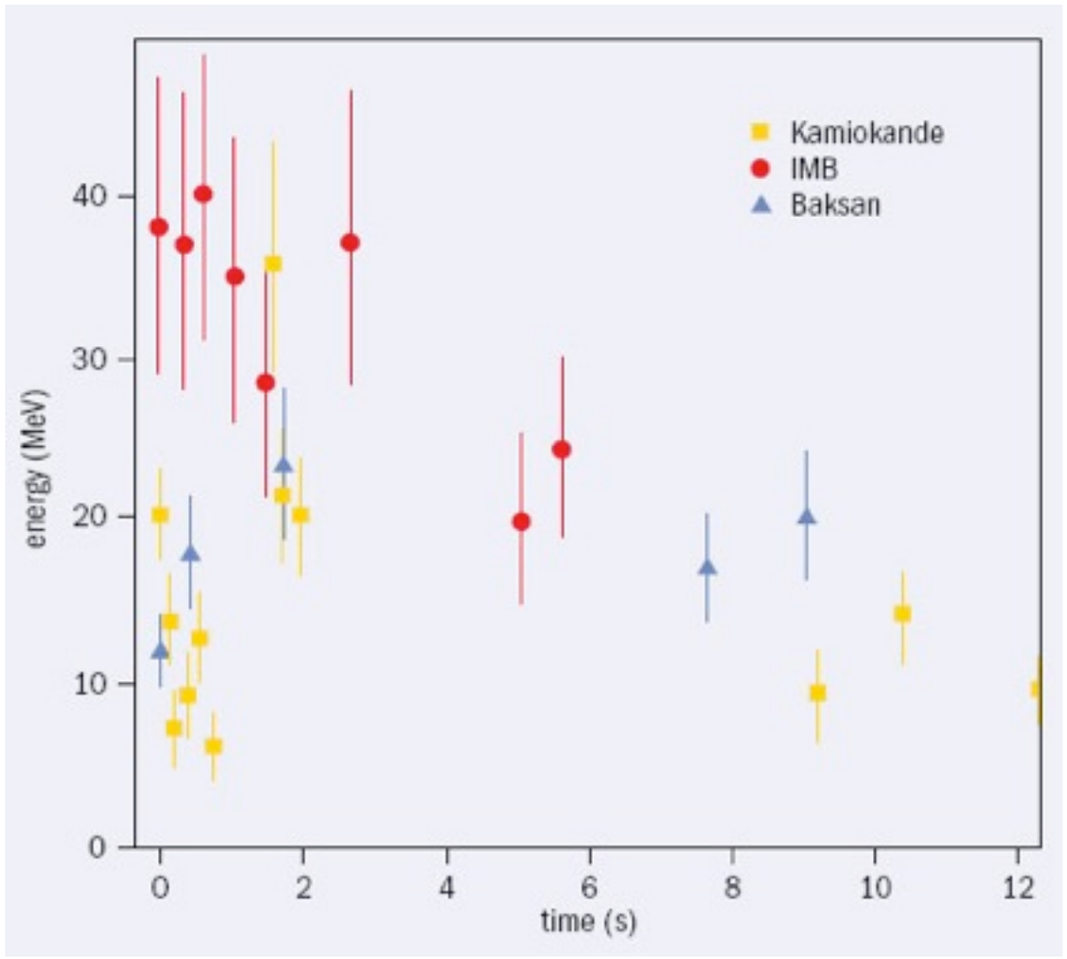
http://www-sk.icrr.u-tokyo.ac.jp/kam/index.html

http://www.nu.to.infn.it/exp/all/kamiokande/

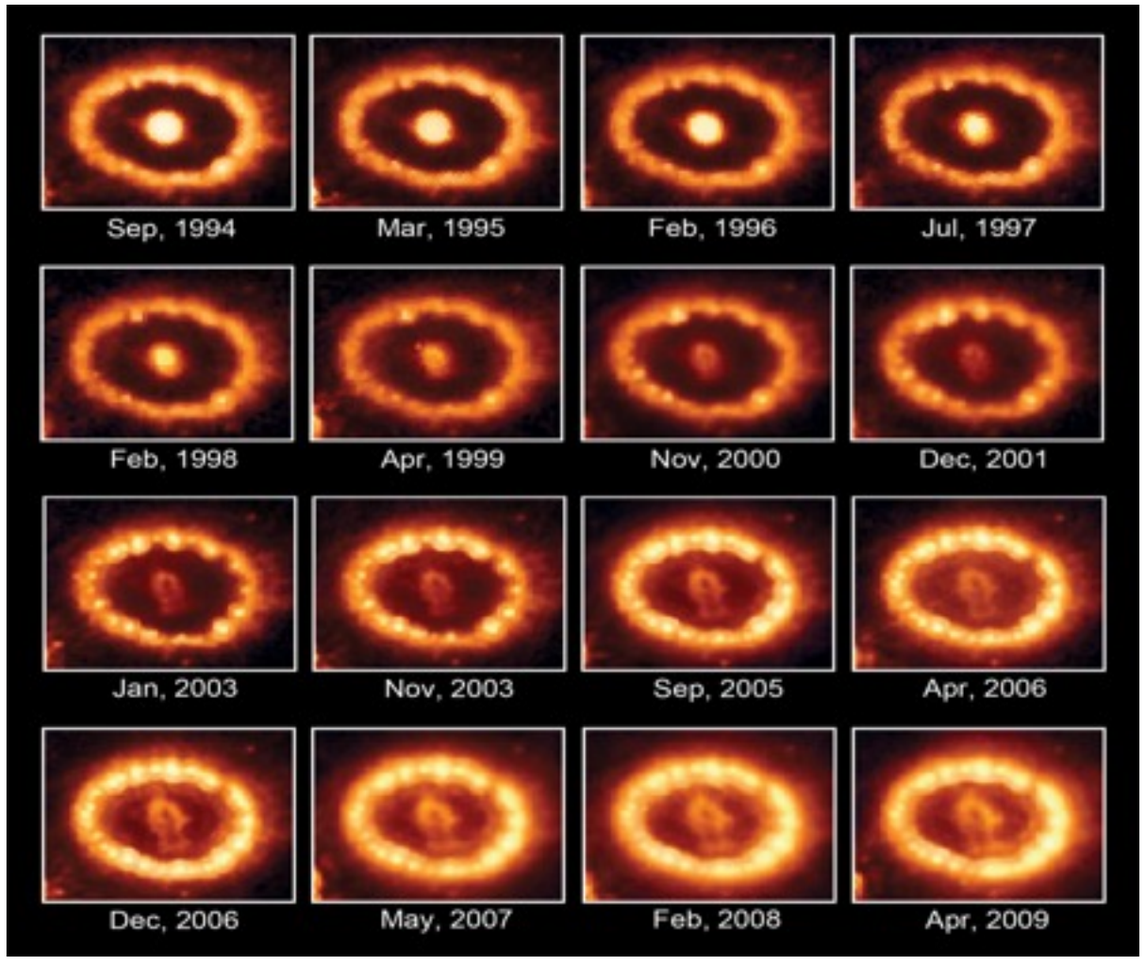
- Kamiokande located 1,000 m underground, tank contained 3,000 tons of pure water.
- Kamiokande had 1,000 PMTs.
- Detector could tell a lot about the neutrino: its energy, when it hit, direction it came from.

PMT repair work inside Kamiokande

A stroke of luck !



Supernova 1987A detection by 3 experiments



Changes in the equatorial ring over time

- Kamiokande (Kamioka Nucleon Decay Experiment) finished detector revisions by end of 1986
- On February 23, 1987, they detected 11 neutrinos that passed through the Earth for about 15 seconds !
- These were coming from a supernova in the Large Magellanic Cloud (a satellite galaxy of Milky Way)
- They had been traveling for the past 170,000 years !
- The IMB experiment also detected 6 neutrinos from supernova 1987A.

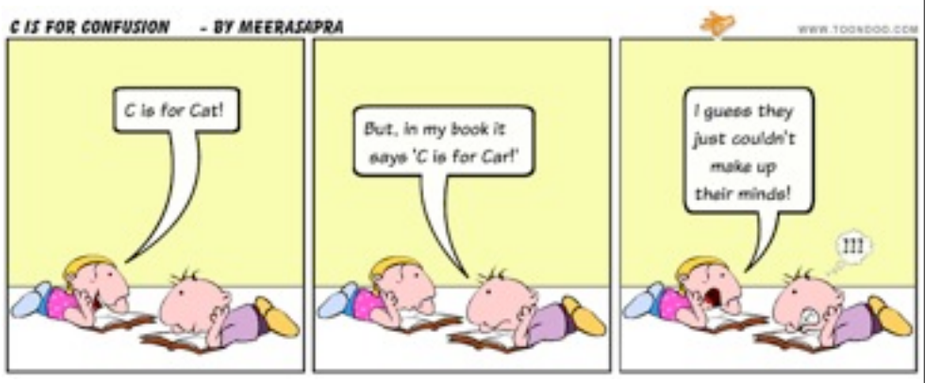
Missing neutrinos everywhere !

- Kamiokande detected neutrinos from 1987-1995. These were the high energy ones from ^{8}B production.
- Number of solar neutrinos decreased as their energy increased !
  - In agreement with Bahcall's prediction for ^{8}B solar neutrinos !
- Total number detected stubbornly less than 1/2 from prediction !

- First Davis and now Kamiokande .....
- Certain that neutrinos from rare solar processes were fewer than expected
- But what about those from the dominant *pp* process ?

Neutrinos ..... prime suspects ?

- SAGE made ~100 measurements of solar neutrino flux from 1990-2000
- Both SAGE and GALLEX found same answer:
  - 70 to 80 SNU detected !
- Prediction: 130 SNU ! Shortfall of 50% ..... again !



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- Independent experiments gave similar results; were sending common message
- Sun was not the culprit either !
- Data on helioseismology also confirmed Bahcall's assumptions about the inner workings of the Sun

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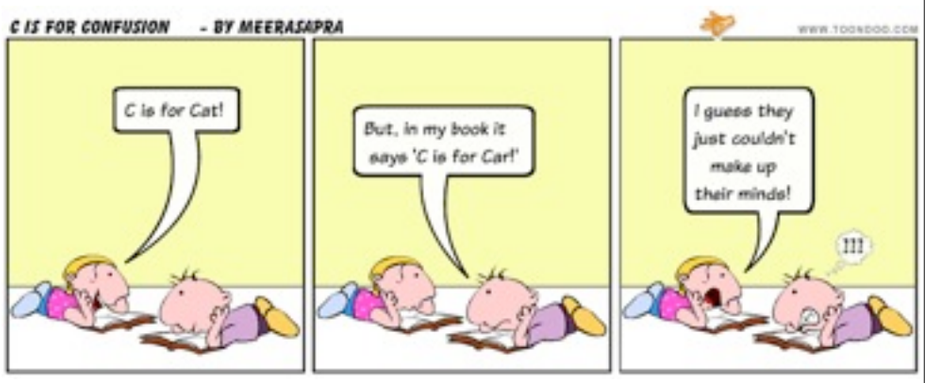

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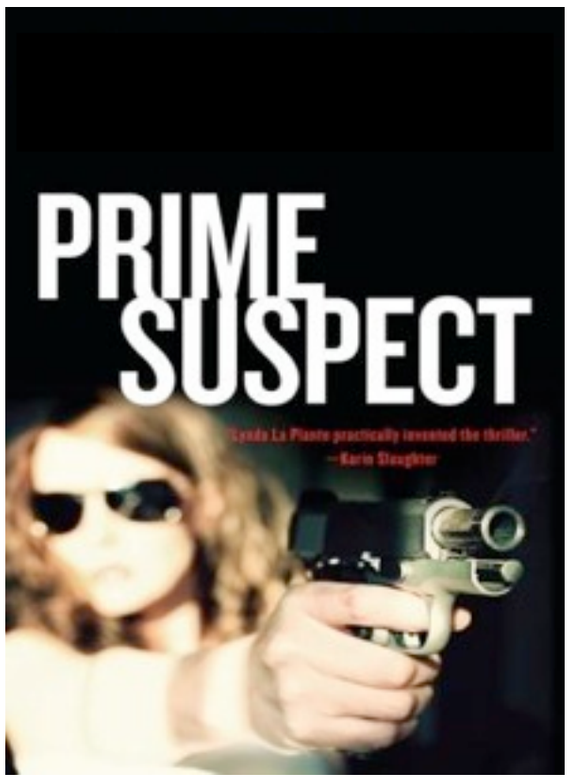

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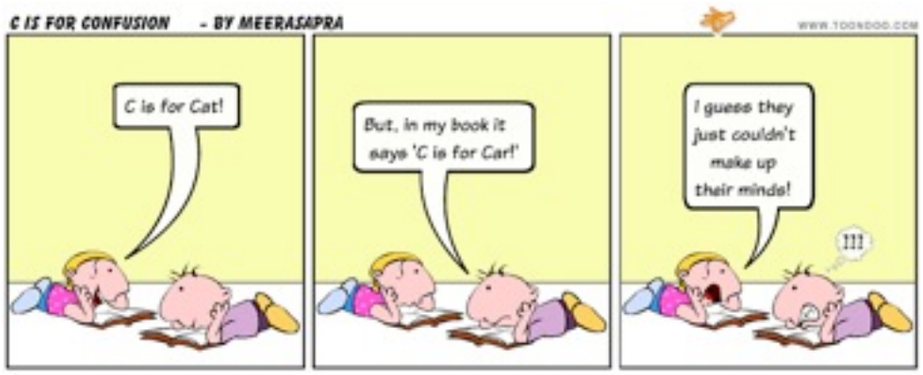

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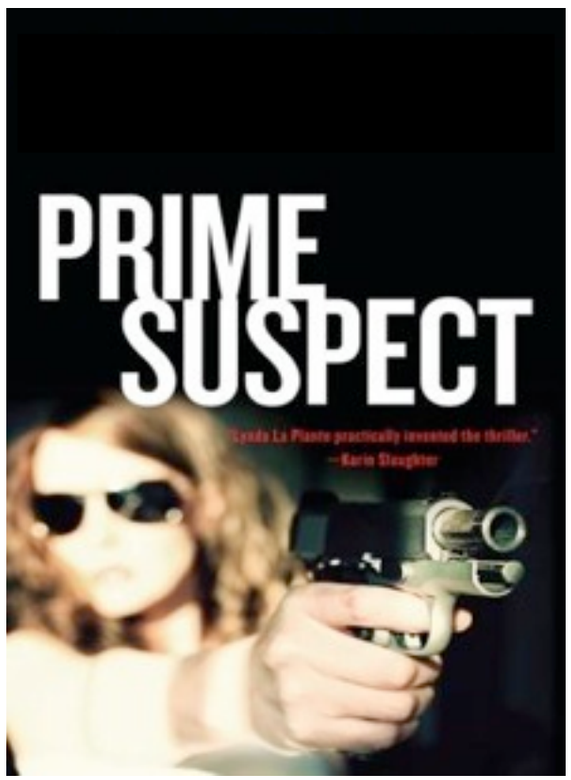
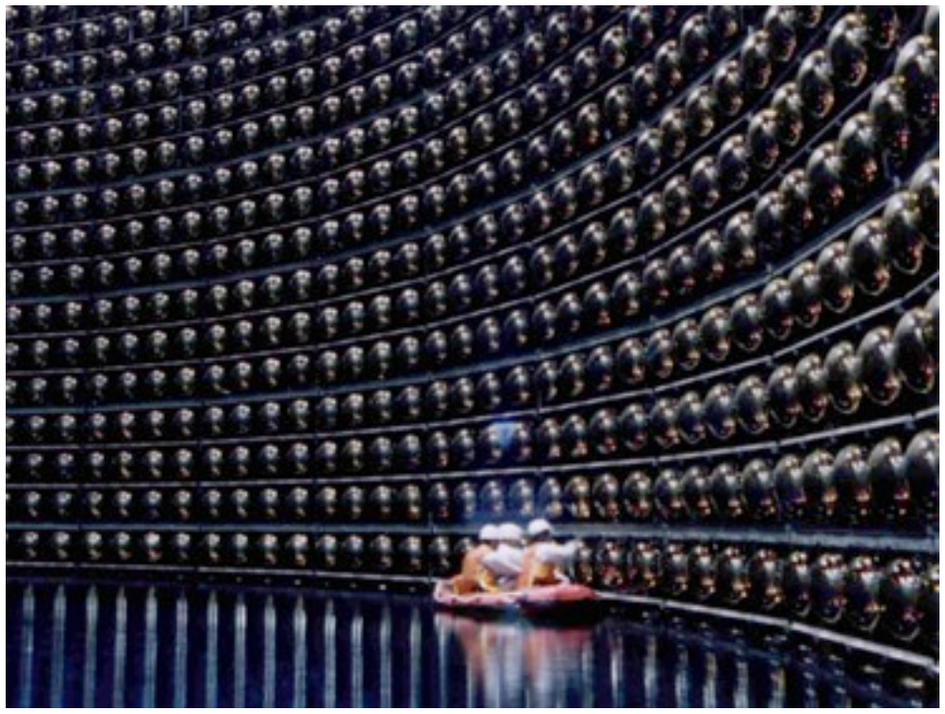
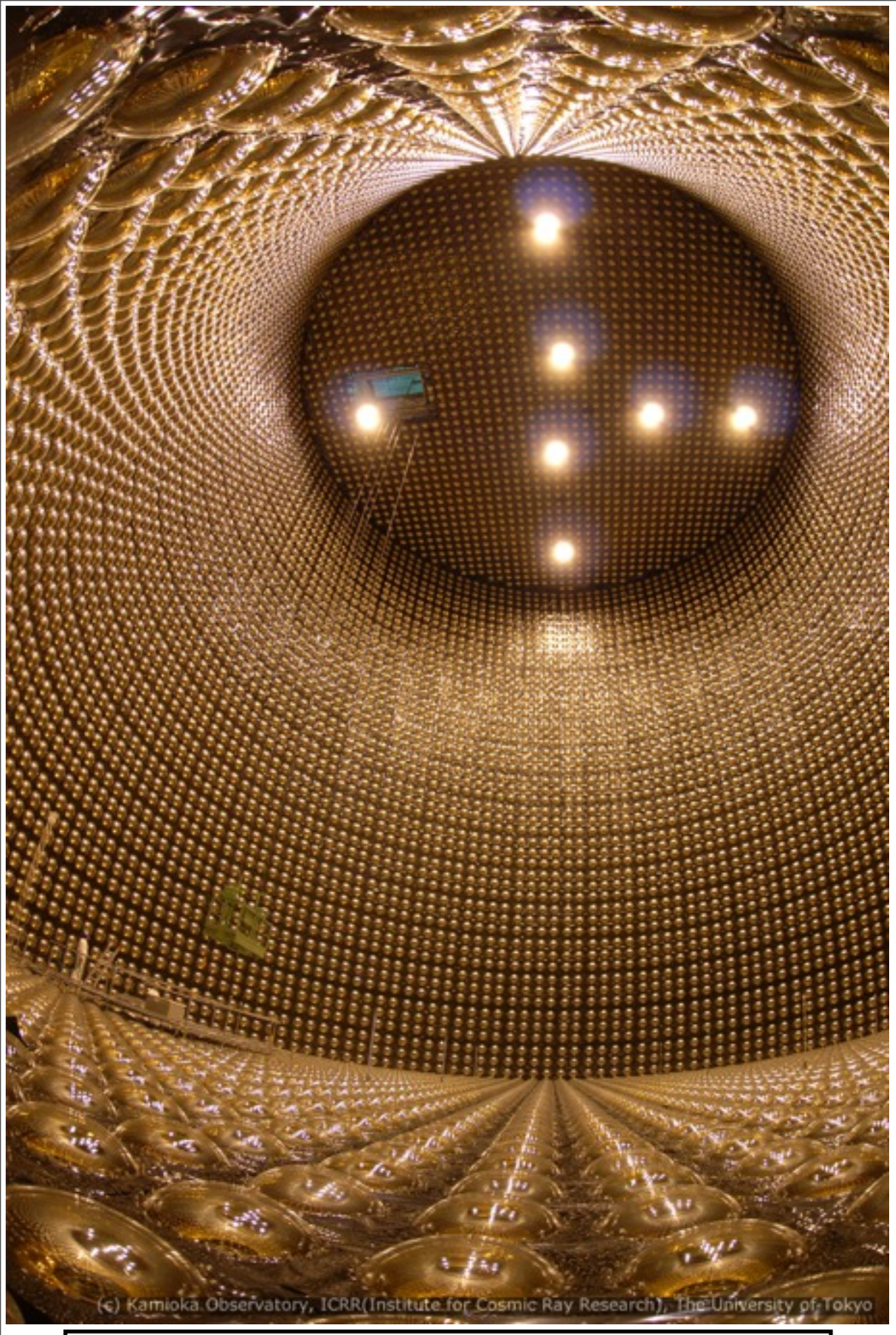
Could neutrinos be the prime suspects here ???



Onwards to SuperK

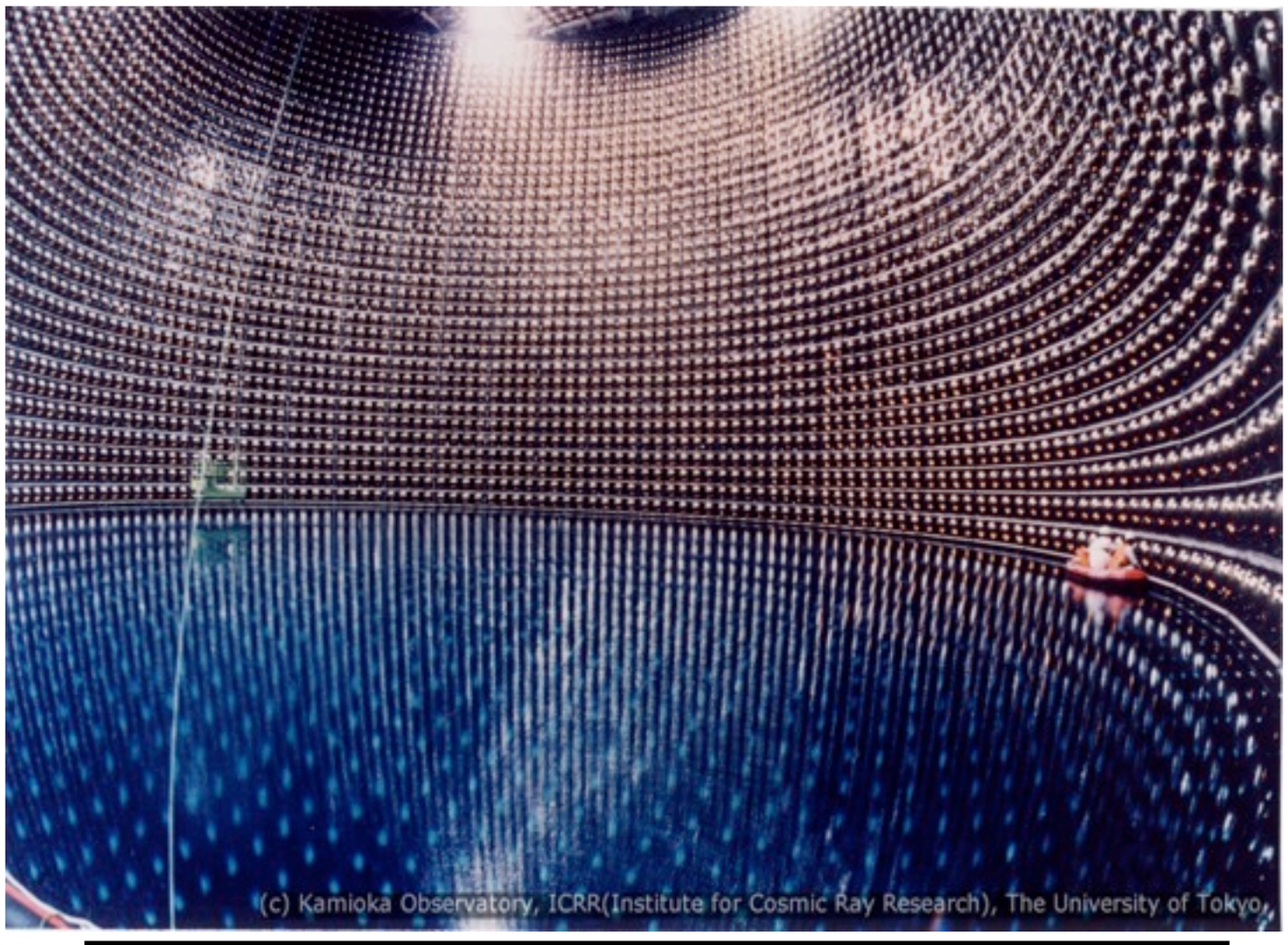


- By 1996, Kamiokande was ready for an upgrade
- With 10 times more water and PMTs than before, the detector was renamed SuperKamiokande (SuperK) !
- SuperK could also detect atmospheric neutrinos (from debris of cosmic rays hitting the upper atmosphere, producing showers of neutrinos) !
- SuperK was ready to remove all doubts about the solar neutrino puzzles !
- A whole wealth of surprises lay in wait with atmospheric neutrinos too !



SuperK with nearly all PMTs - 2006

- SuperK located 1,000 m underground, huge stainless steel tank contains 50,000 tons of ultra pure water.
- SuperK had 13,000 PMTs covered an entire acre on its surface.
- Electronics designed to tell direction of neutrino, 20 km above Japan or 13,000 km through the Earth entering detector from bottom
- Purpose of SuperK was to reveal neutrino properties through observation of solar, atmospheric and man-made neutrinos.



Filling SuperK tank with pure water - 1996

So where did the neutrinos go ?

- SuperK results showed neutrinos from cosmic rays were ν_e:ν_μ = 1:1 ..... expected ratio is 1:2 ..... muon neutrinos seemed to disappear !
- More remarkably, the deficit was greater for neutrinos traveling through the earth than those arriving from overhead !
  - The further the muon-neutrino traveled, the more likely it was to disappear !
- By 1980s, IMB experiment also concluded that ν_e:$\nu_\mu \approx$ 1:1, rather than expected value of 2 !
- This became known as

- Davis's conclusions with solar neutrinos had been similar !
- Could solar neutrinos be disappearing too ?
  - After all they had travelled 150 million kilometers from the Sun !

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- This became known as **"atmospheric neutrino anomaly"**

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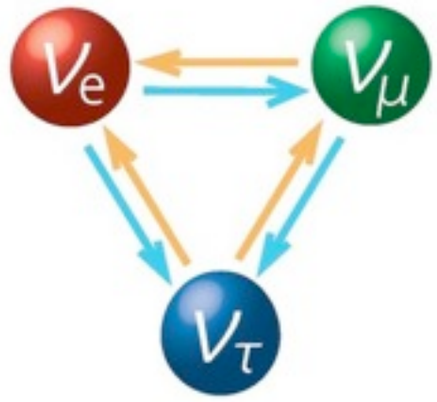
Do Neutrinos oscillate ?

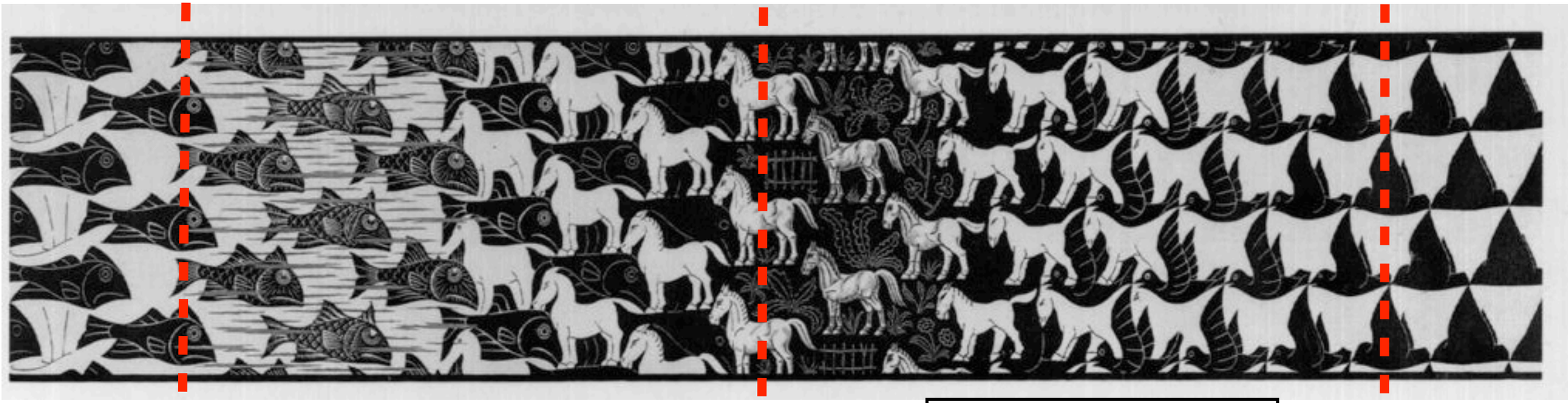


- Neutrinos are produced in 3 flavors:
  - electron(e), muon(μ) and tau(τ)
- Did they remember their origin over longer time scales ?
  - Solar neutrinos traveled for more than 150 million km !
- Could an **electron-neutrino (ν_e)** born in the Sun somehow "change identity" into a **muon-neutrino (ν_μ)** during its journey ?
  - If yes, Davis would detect only those electron-neutrinos that had not switched their identity !

Neutrinos ..... and mass

- "Changing their identity" could explain the 2-3 SNU that Davis observed versus Bahcall's prediction of 6 SNU
- However, this idea was highly controversial !
  - How can neutrinos have this "personality disorder" unless they have mass ?
  - Standard Model said neutrinos are massless and travel with the speed of light !
- Pontecorvo had noticed that Quantum Mechanical laws allowed neutrinos to "oscillate from one state to another" only if they had some mass (even if triflingly small) !
- In 1969, he and Vladimir Gribov published their theory. Hypothesis was that there are two varieties of neutrinos, with different masses.

Metamorphosis



Artist: M.C. Escher

- Davis's measurement showed an apparent shortfall of neutrinos because the originally emitted neutrino had "metamorphosed" into something else !
- Not everyone ignored the idea of neutrino oscillations
- Neutrinos are not massless after all !
- Atmospheric neutrino anomaly and Davis's results showed a clear deficit of solar neutrinos, made people wonder about neutrino mass !

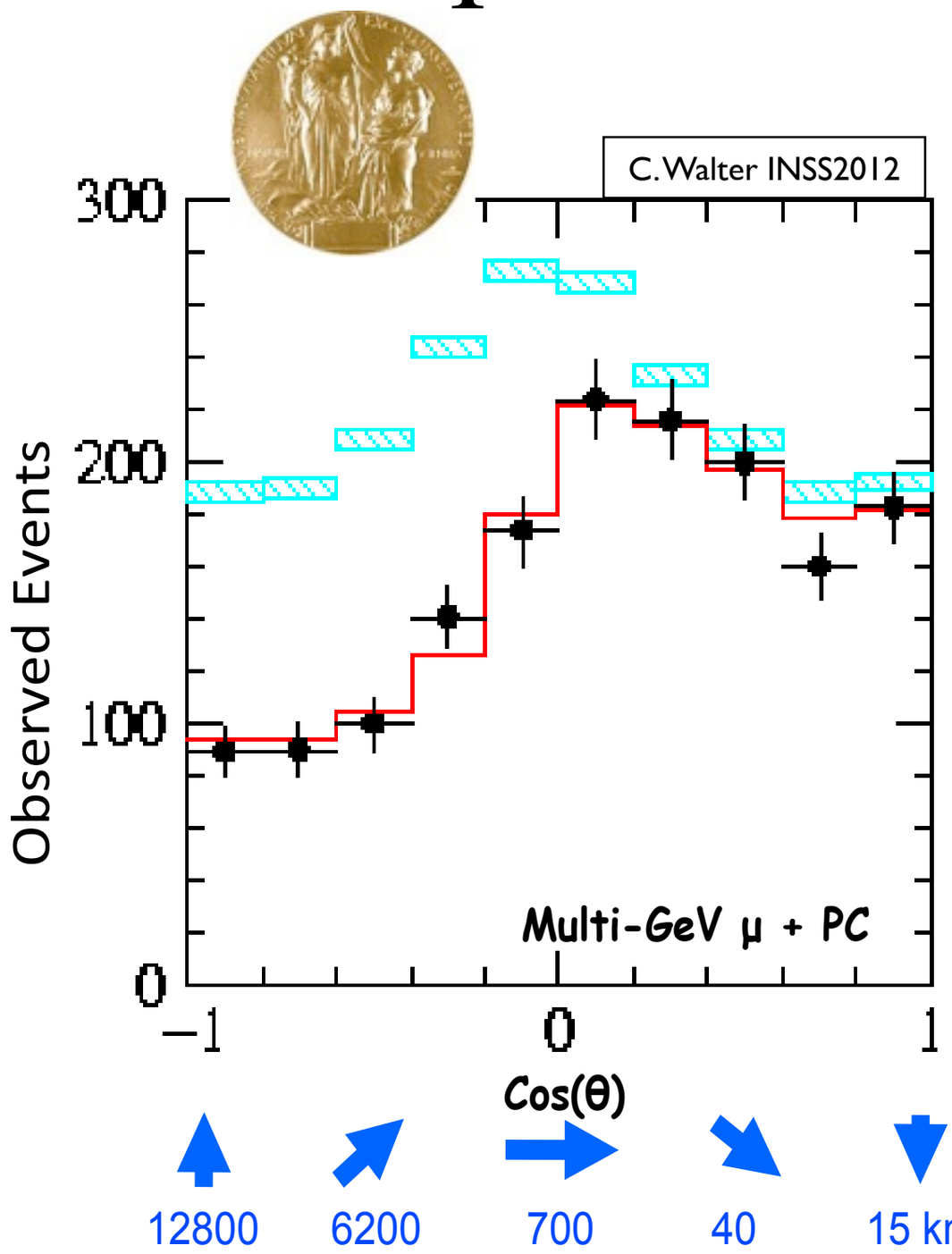
More precise results from SuperK

- By 1998, SuperK announced that observed atmospheric neutrino deficit was a function of
  - Distance travelled by the neutrino
  - Energy of the neutrino

- According to the theory of relativity, the oscillations were faster for lower energy neutrinos than for higher energy ones

- This is exactly what data showed !

- It had taken 30 years but Pontecorvo had been vindicated !



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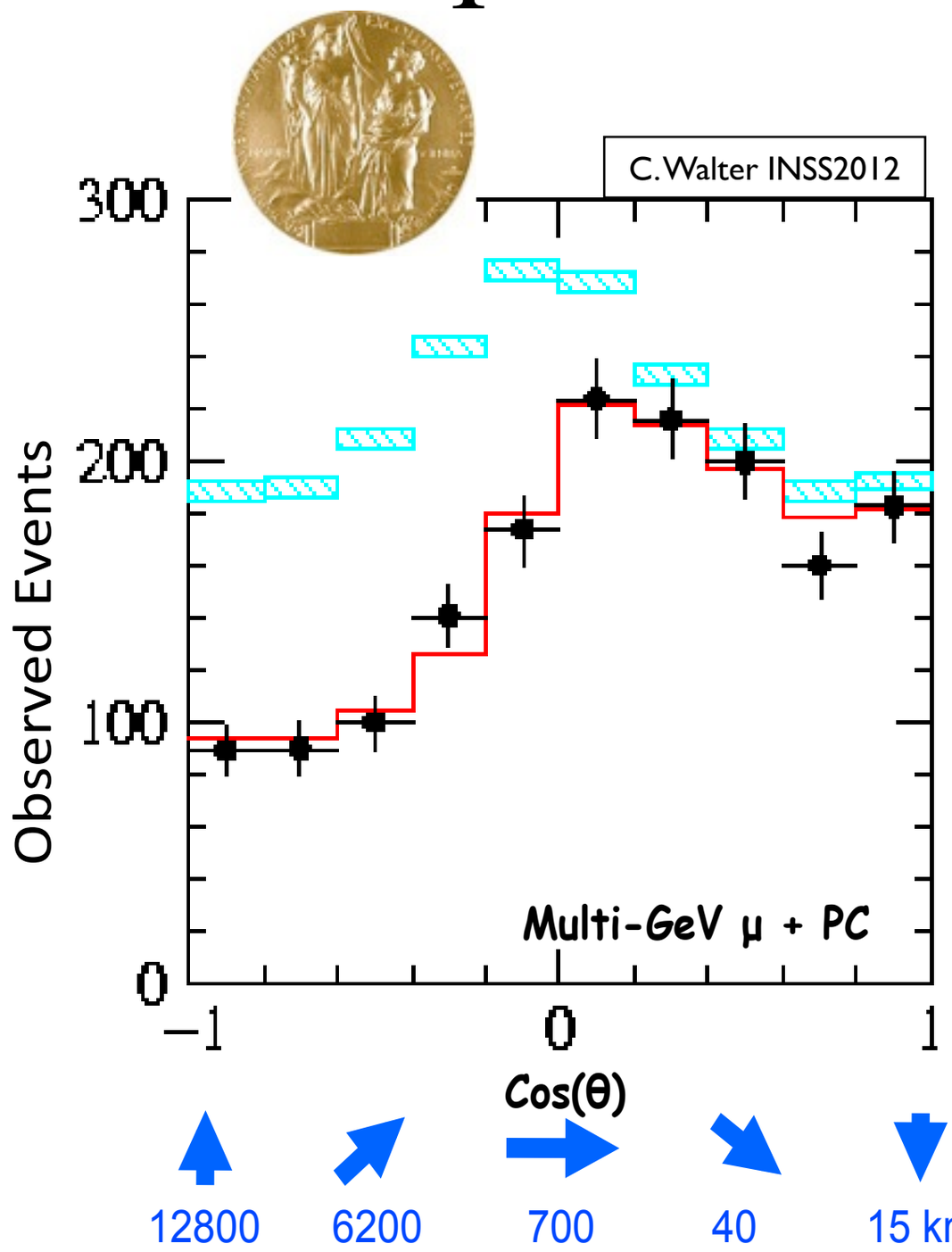
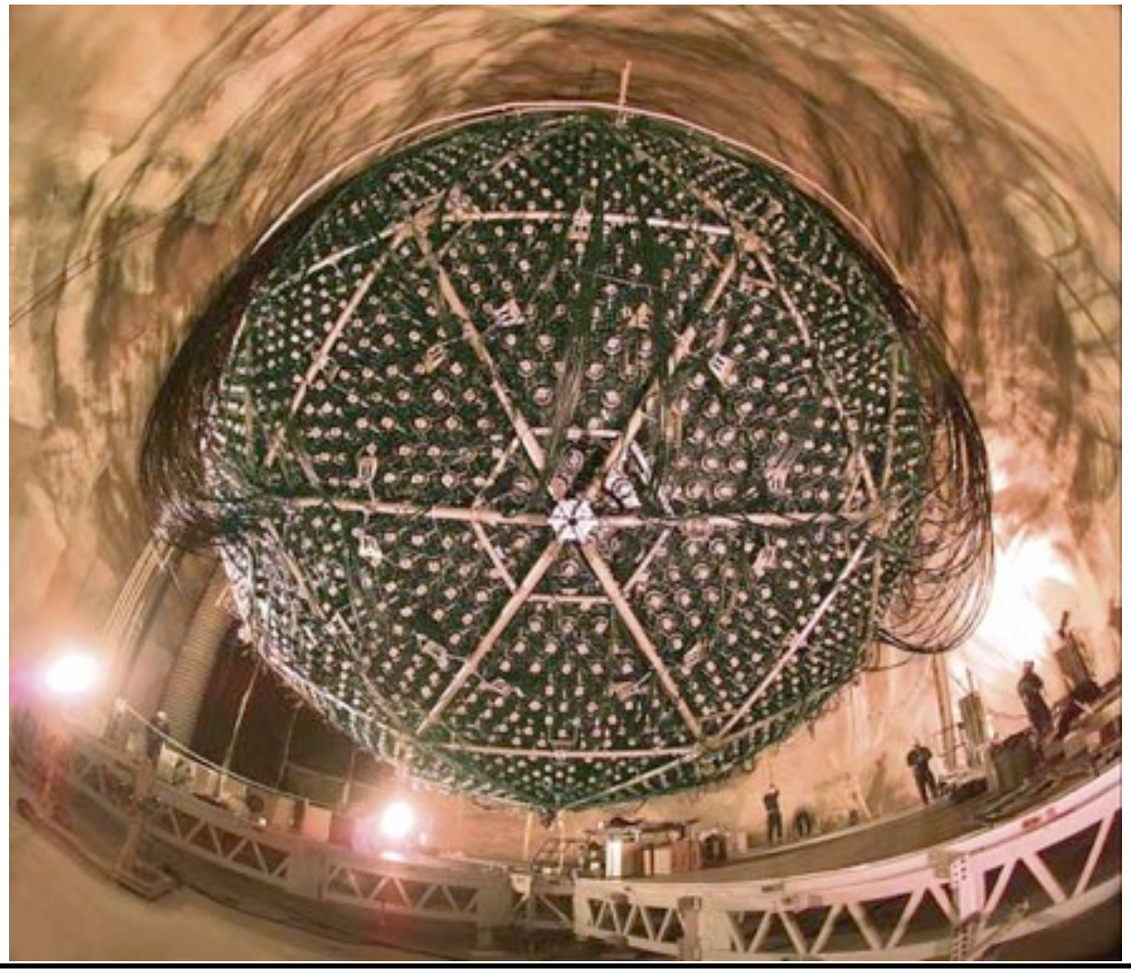
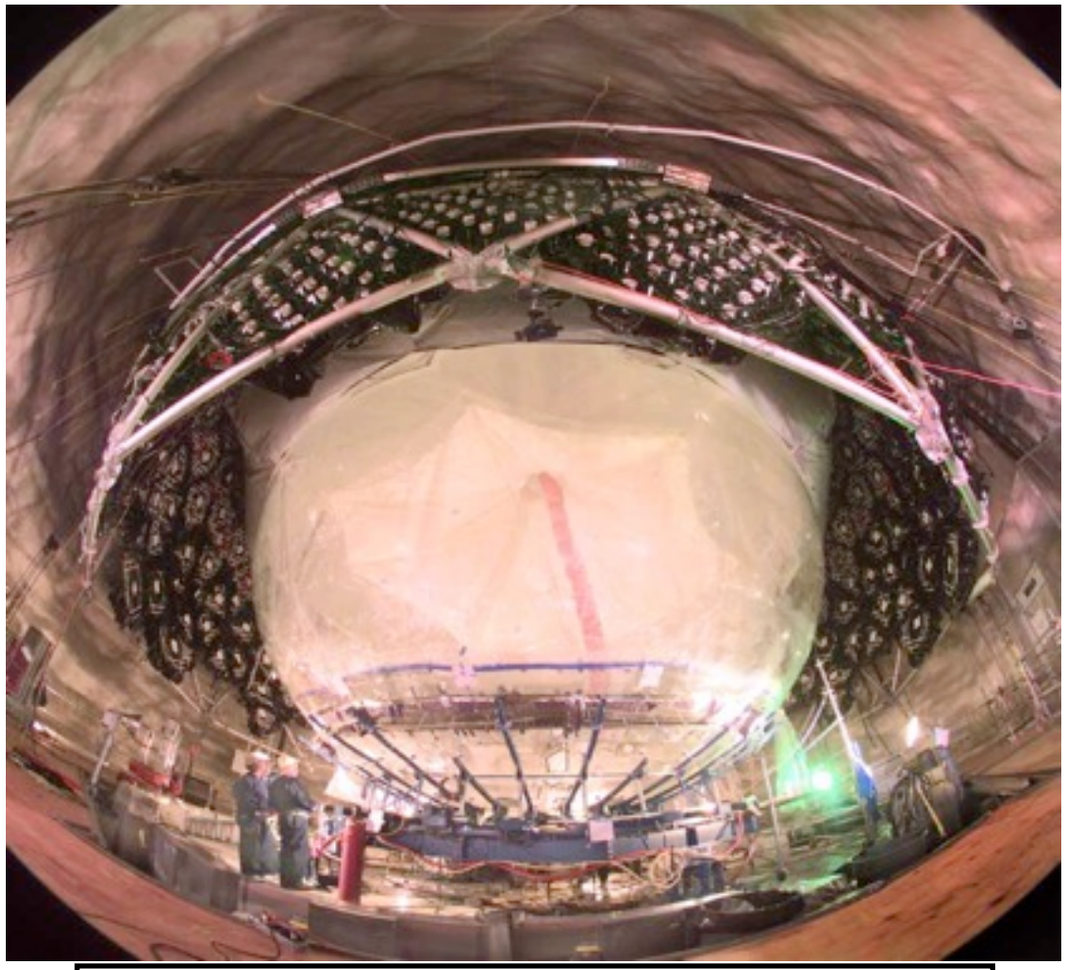


Would it be the same for Davis and Bahcall ?

Sudbury Neutrino Observatory (SNO)



Geodesic sphere with light sensors on it

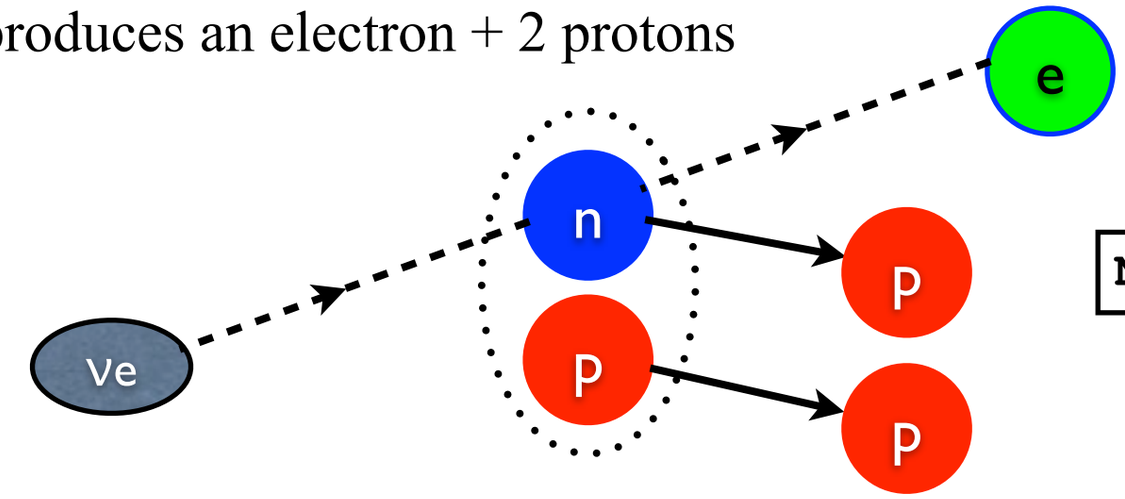


Heavy water acrylic tank at SNO

- Designed to solve solar neutrino problem. High energy neutrinos (0.01 of 1% of whole)
- Detector as big as a ten storey building. Began taking data in 1999
- Contained 1000 tons of heavy water (D_2O) in an acrylic container 12 m in diameter
- Container surrounded by geodesic sphere, diameter 18 m.10,000 light sensors mounted on it
- Cavern is 34 m high, 22 m across, 2 km below ground, in an old nickel mine
- SNO intercepted ~10 neutrinos a day. Capable of detecting all neutrino types (ν_e,ν_μ,ν_τ)

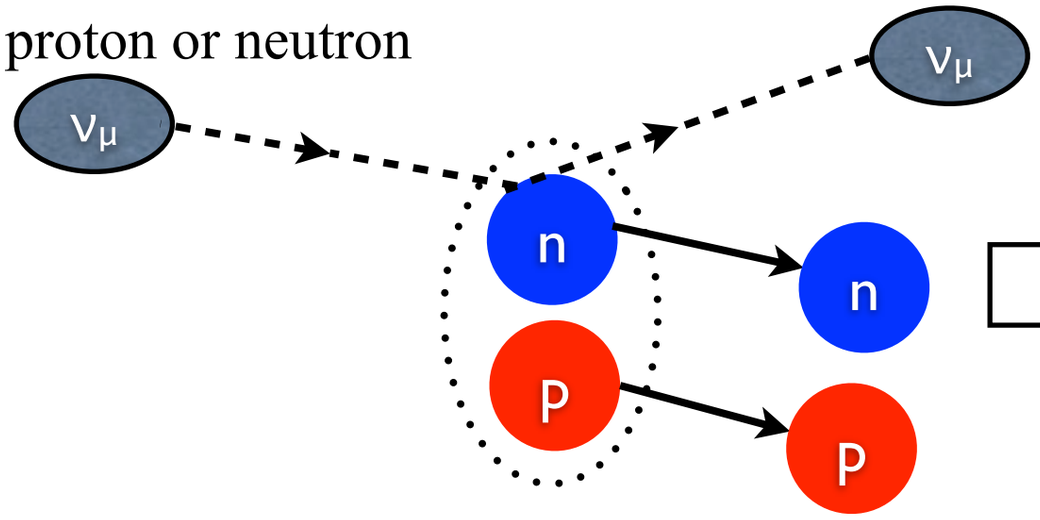
Total and electron neutrinos

- Herb Chen outlined ideas for interpreting the results from heavy water (D_2O)
- Electron neutrino produces an electron + 2 protons



Number of electron neutrinos

- Most muon and tau neutrinos would just bounce off either nucleon, kick it out from the deuterium but leave it unchanged
- Result: No electron + 1 proton or neutron



Total number of neutrinos

- By comparing the above 2 categories SNO could measure total neutrino flux and fraction of electron-neutrinos
- Summer 2002: SNO added 2 tons of pure salt to heavy water for intercepting more solar neutrinos !
  - Better discrimination between different types of neutrinos !

Herb Chen died in 1987, could not see the results of his inspired ideas.

New results from SNO

- Declared on September 7, 2003 !
  - Number of electron-neutrinos: 1.75×10^6 per cm^2 per second
    - Same as an earlier result in 2001.
  - Total neutrino flux: 5.21×10^6 per cm^2 per second.
    - This agreed with earlier combined (SNO+SuperK) results !
    - Electron neutrinos are about 1/3 of total !

- Davis had always measured the number of solar neutrinos that are still "electron type" as they reached his detector, correctly !
- Bahcall's calculation of solar neutrino production was also correct !
  - In Bahcall's words "the agreement is so close that it's embarrassingly close !"

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Electron-neutrinos here were changing to other types of neutrinos, which could again transform into a different type !

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Bahcall was considered as "the guy who wrongly calculated the flux of neutrinos from the Sun" !

He had been been right all along !

On receiving news of being vindicated he said, "I feel like dancing, I am so happy !"

Evolution of Neutrino Astronomy

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Bahcall's calculations showed that number of neutrinos are sensitive to Sun's core temperature, multiplied by itself 25 times !

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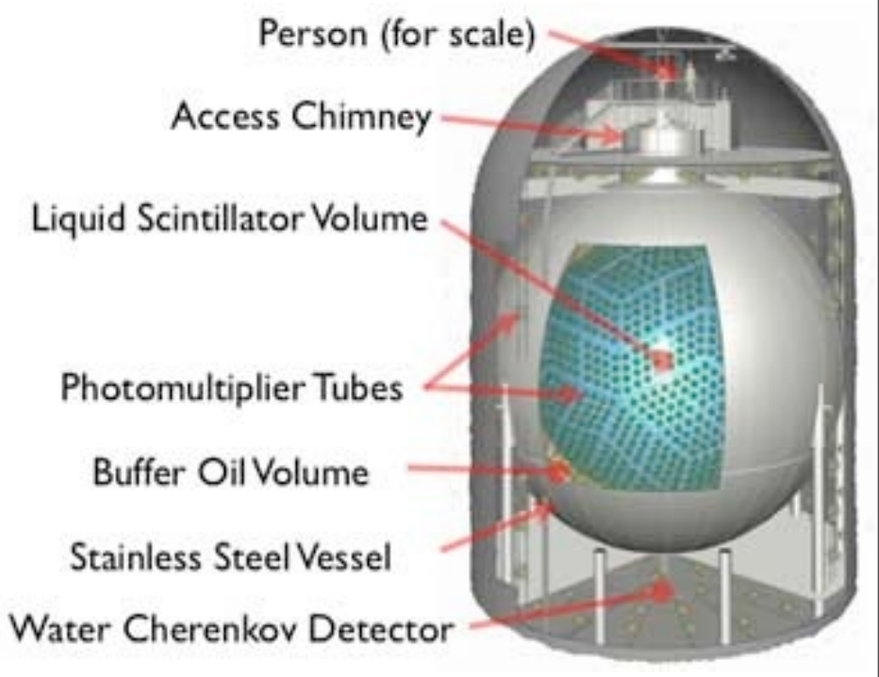
Neutrino astronomy became a quantitative science with SuperK and SNO solving the solar neutrino mystery !

Neutrino astronomy could now lead to discoveries !

Neutrinos "change identities" ?

- SNO and SuperK had proved that neutrinos "oscillate" (change flavors) as they travel
  - How rapid are the oscillations ?
  - If one variety of neutrinos disappear, which variety is created ?

- KamLAND (Kamioka Liquid-scintillator Anti-neutrino Detector) sensitive to anti-neutrinos from 53 Japanese commercial nuclear reactors
- It is at a flux weighted average distance of ~180 km from the reactors



- KamLAND showed that rise and fall in intensity depended on time of flight of anti-neutrino

$$\text{Time of flight of the neutrino} \propto \frac{\text{Distance travelled by the neutrino (L)}}{\text{Energy of the neutrino (E)}}$$

Neutrino masses

- The mathematics of oscillation probabilities gives a measure of the mass differences in the $(\text{mass})^2$
  - 10^{-5} eV^2 (very small number)

- How massive is each neutrino ?
  - One massless, the other has mass of about 10^{-2} eV ?
  - Both masses around 1 eV ?
  - Which is the heaviest neutrino, which is the lightest one ?
  - What about the masses of the anti-neutrinos ?

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Puzzle: Why do neutrino masses seem so similar, yet not quite identical !

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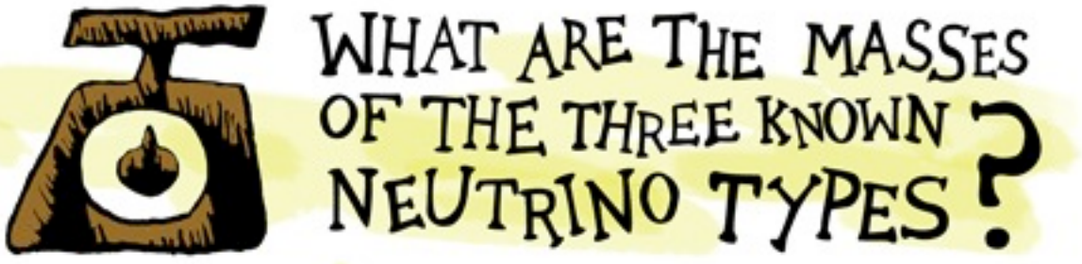
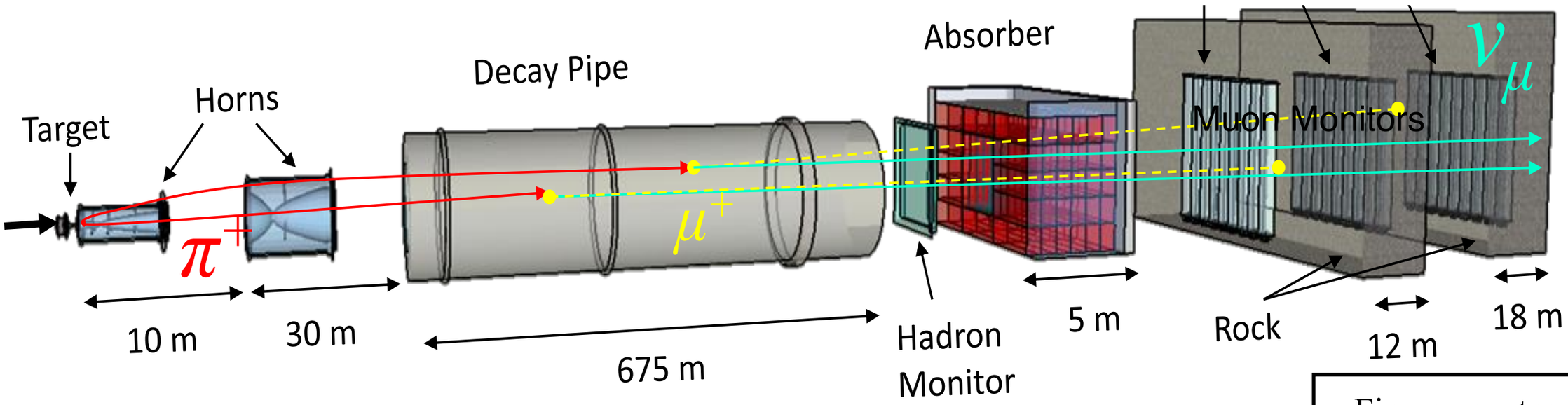


Building a Neutrino Beam

NuMI (Neutrinos at the Main Injector) beam line at Fermilab

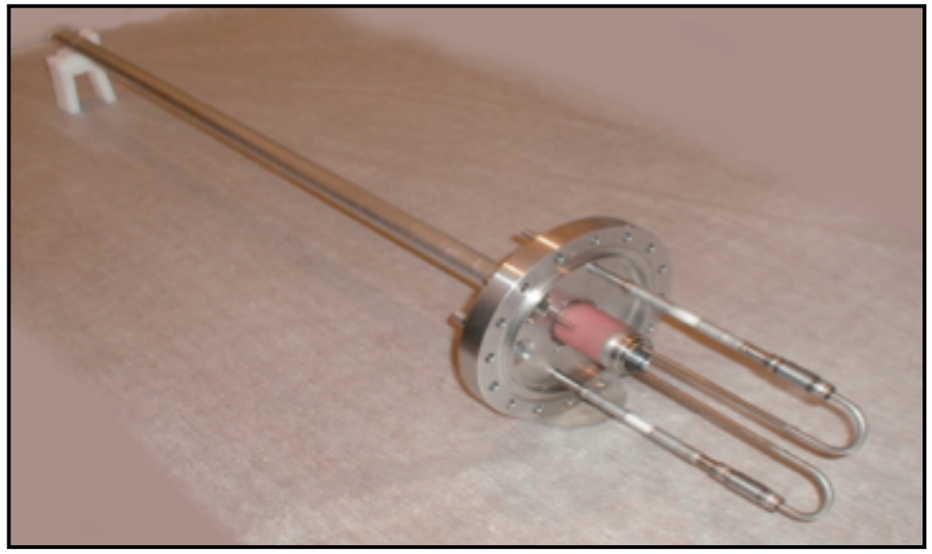


MINOS

Figure courtesy Ž. Pavlović

- Neutrinos produced in an accelerator can be customized in energy and type
- High energy protons are slammed into a carbon target
- Charged pions produced are focussed into a parallel beam
- Travel along the tunnel where they decay into muons and muon-neutrinos
- The rock-face absorbs all charged particles, leaving just a beam of neutrinos
- Due to curvature of earth, beam is directed downwards at an angle of 3 degrees
- Neutrino detector at Soudan mine in MN, 735 km from Fermilab, looking for evidence of oscillation

MI delivering protons to NuMI target



NuMI graphite target

Decay pipe tunnel for NuMI beam

Main Injector tunnel at Fermilab

NuMI horn for focusing particles

Decay pipe installation

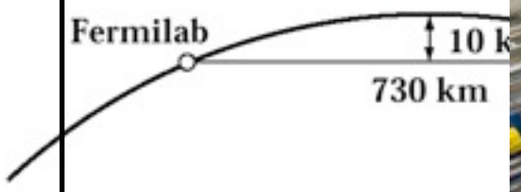
NuMI beamline during construction

NuMI tunnel boring machine

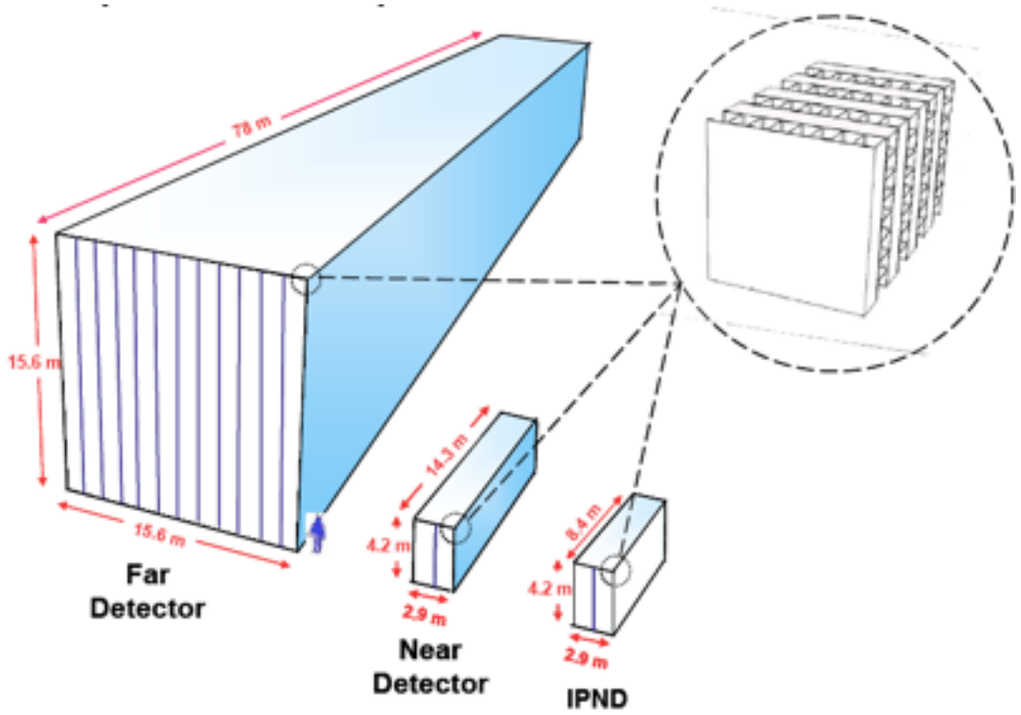
Muon Monitor fabrication at UT

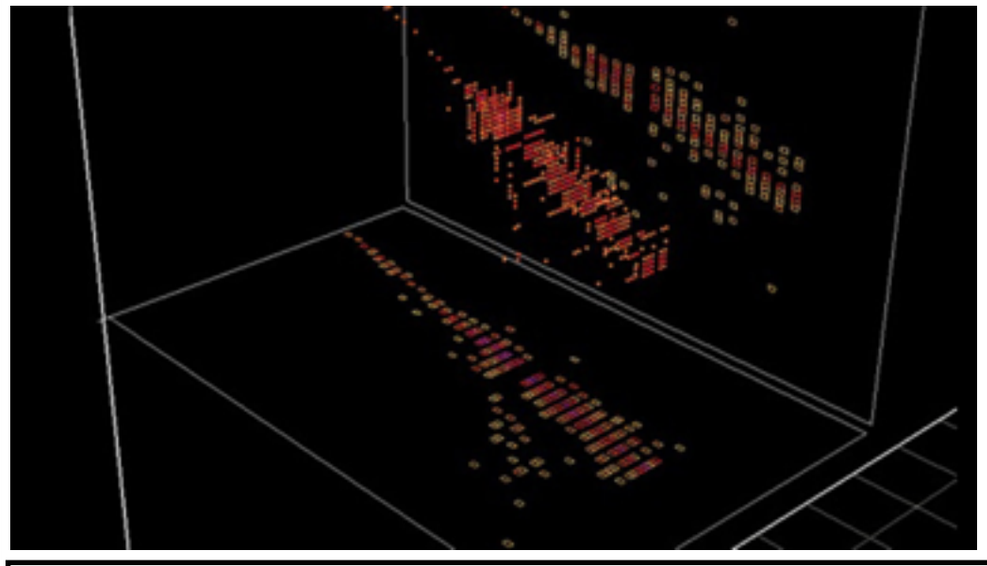
Main Injector Neutrino Oscillation Search (MINOS)

- Long base line experiment, neutrinos have to travel 735 km from near to far detector !
- Time of flight is ~ 2.5 ms !
- Near and far detector count muons from the neutrinos that oscillate
- MINOS started taking data in 2005
- 1-2 neutrinos detected at Soudan per day
- By 2006, a clear deficit of neutrinos was observed



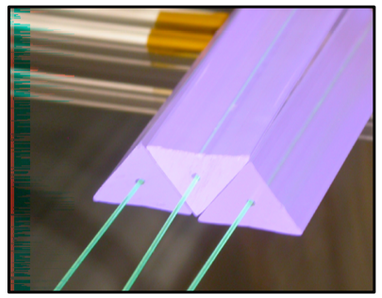
NOvA

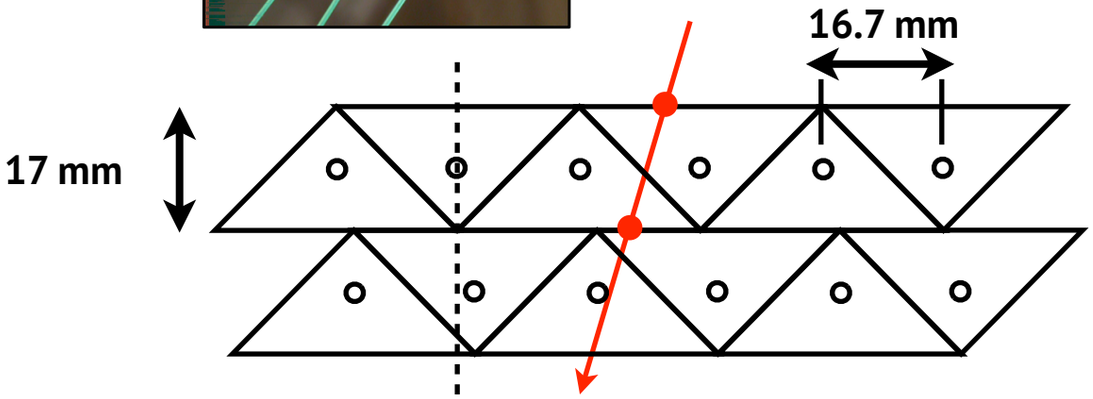




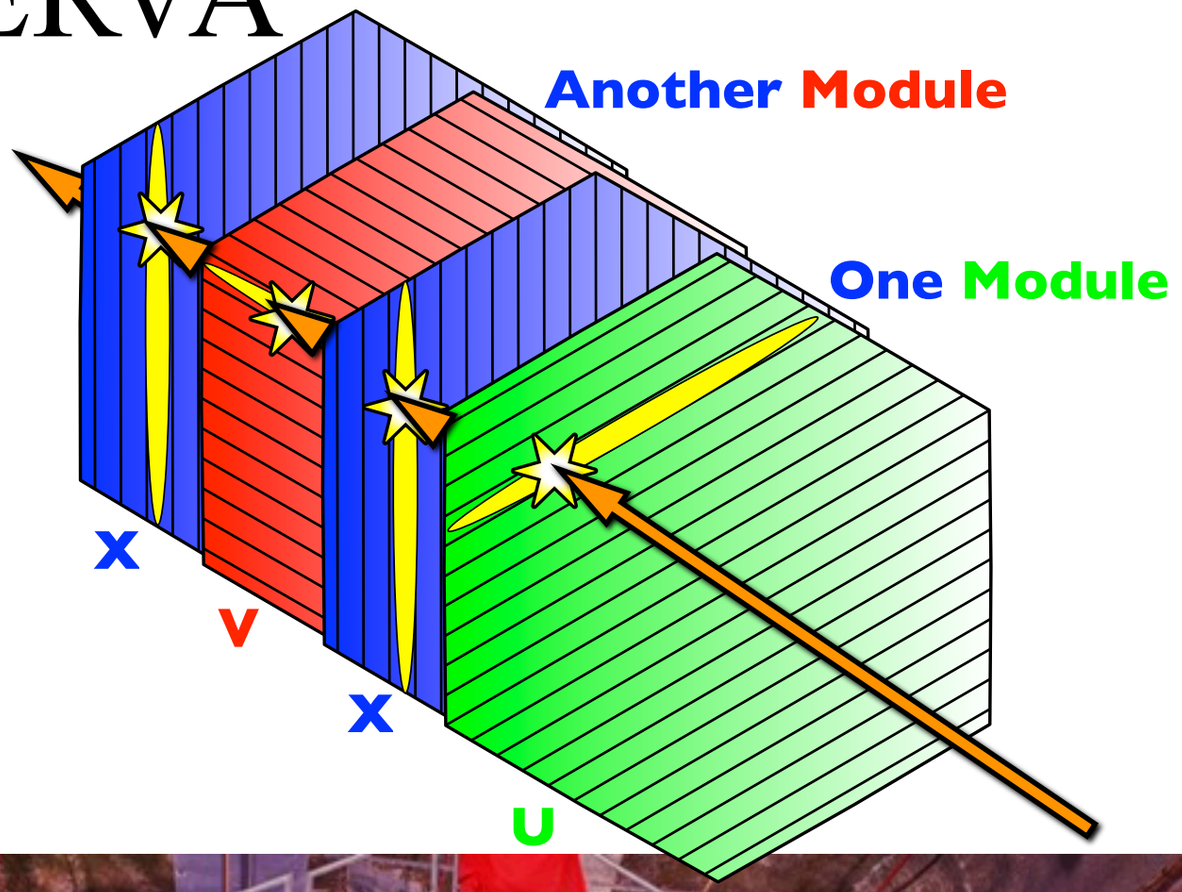
Cosmic ray shower at NovA far detector

MINERvA

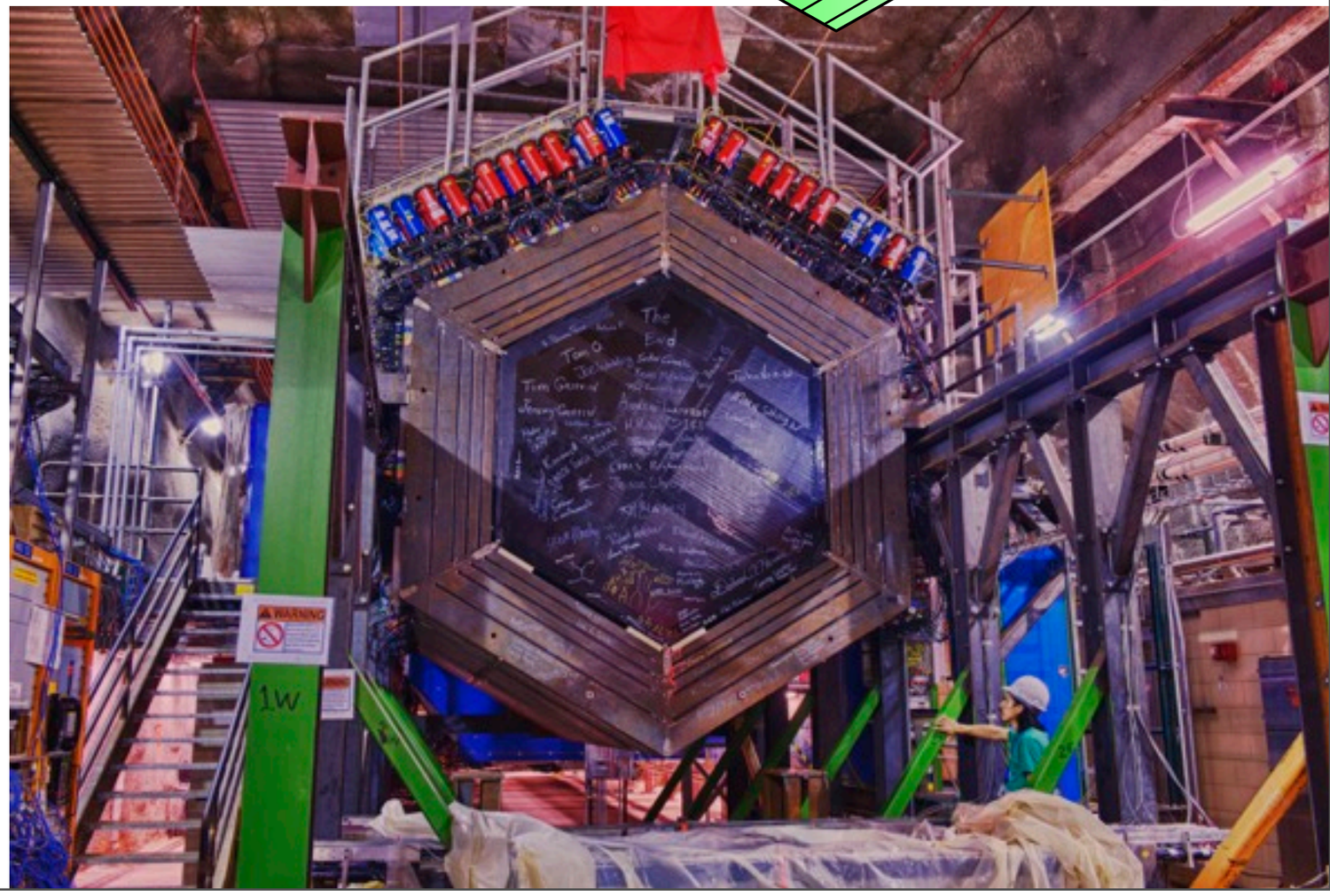




Charge sharing for improved position resolution (~3 mm) and alignment



Helium target at MINERvA



Matter anti-matter asymmetry

- Neutrino experiments these days detect both neutrinos and anti-neutrinos
  - Will show if both have the same properties (oscillate, interact) !
- If they are different then we can tell something about the origins of the universe !
  - How did our matter dominated world emerge from the symmetric matter anti-matter universe that resulted from the Big Bang ?
- If same, then are neutrinos their own anti-particles ?

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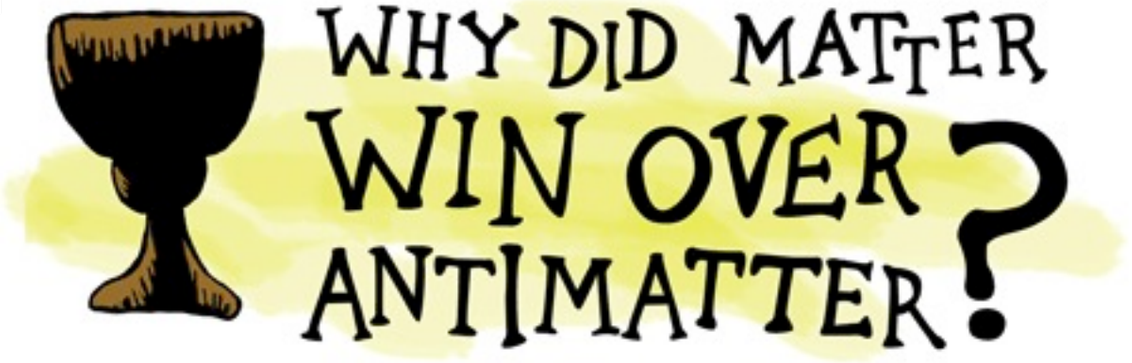

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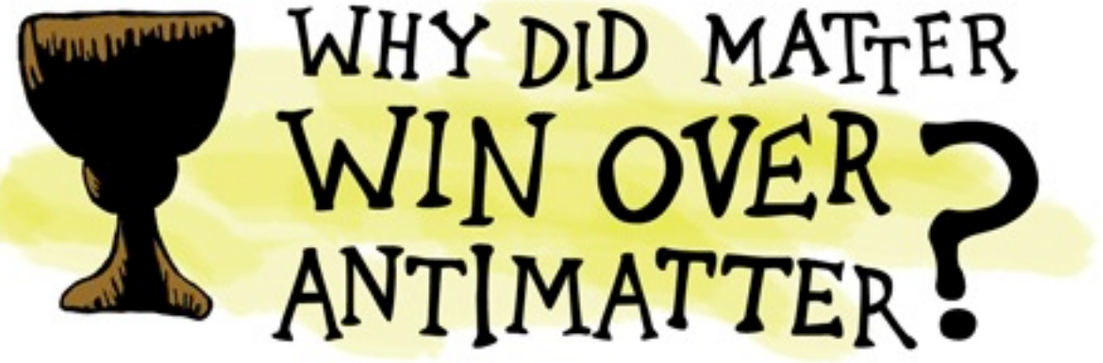

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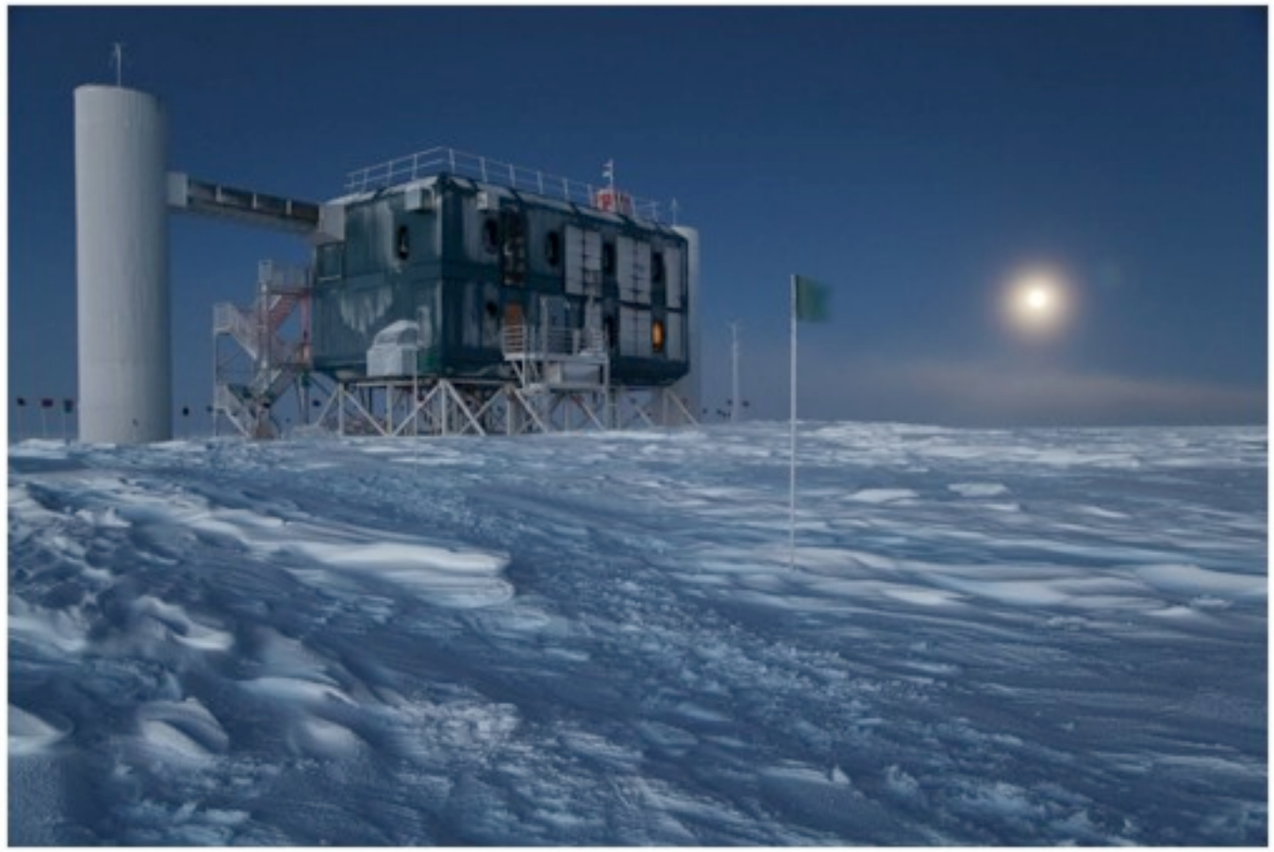
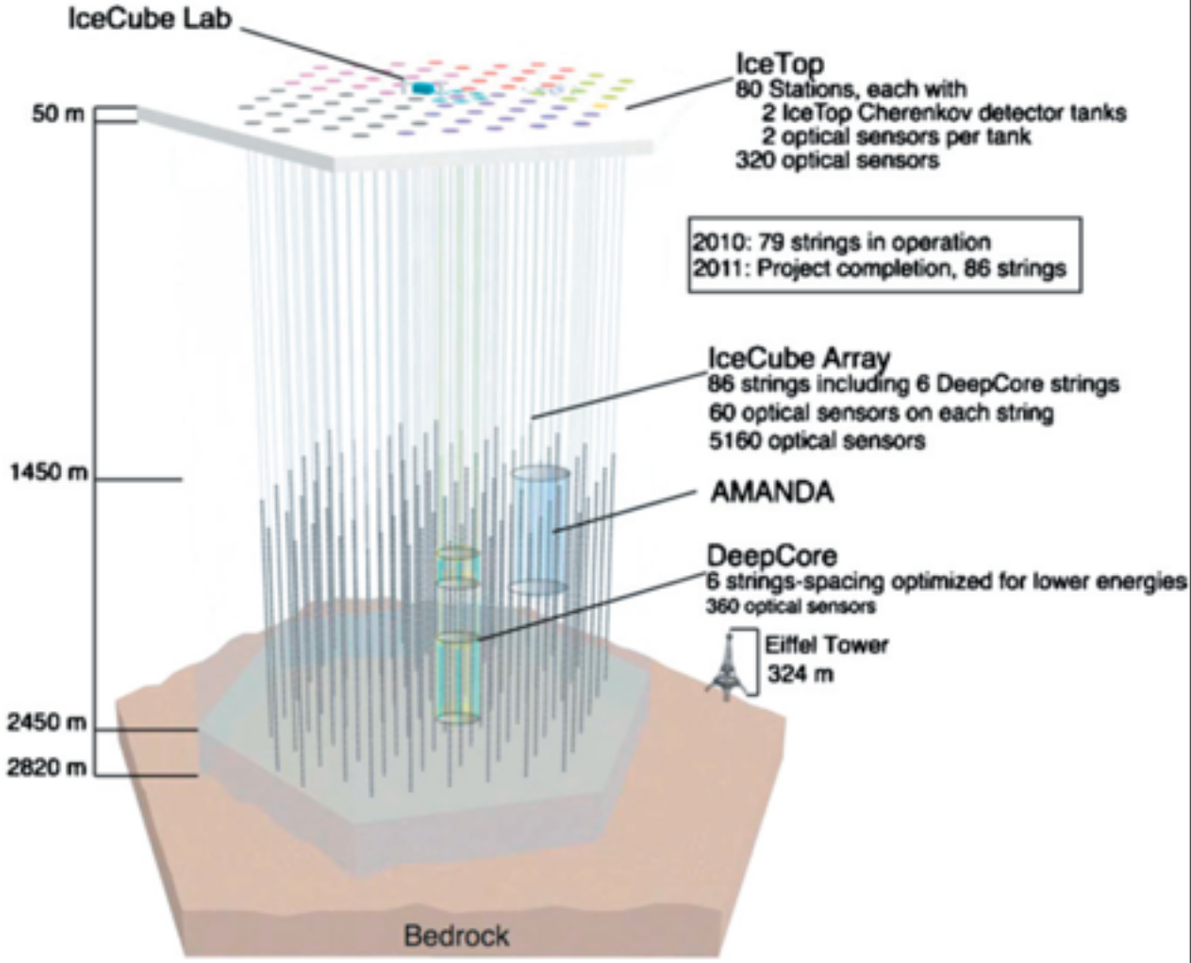
IceCube and Extra Galactic Neutrinos

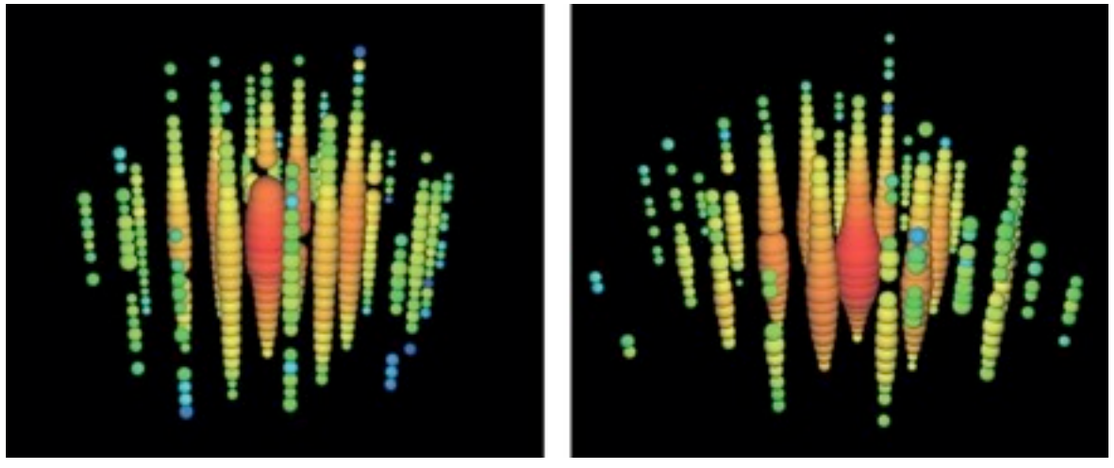


Above ground measuring station for IceCube



Schematic of the entire detector

- Designed to look for high energy neutrinos coming from our own or other galaxies
- Spherical optical sensors (DOMs) deployed on "strings" at depths of 1.5-2.5 km at the Amundsen-Scott South Pole station
- Thousands of sensors distributed over a cubic km of volume under the Antarctic ice
- November 2013, IceCube announced detection of 28 events that likely originated outside solar system !

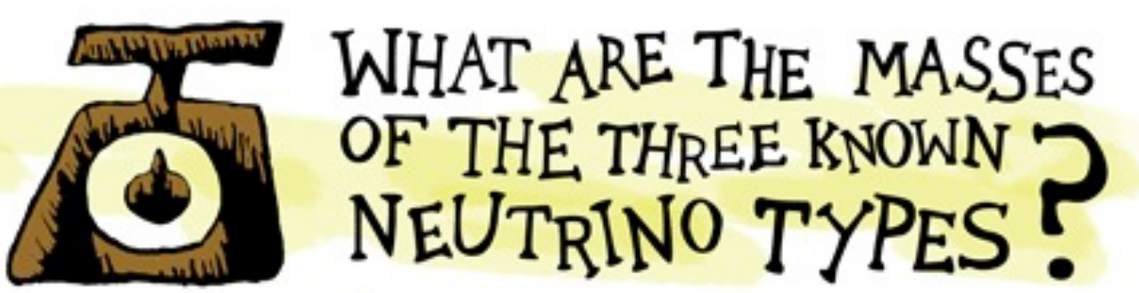


Two observed events


BIG
QUESTIONS

$\nu_?$ ARE THERE MORE THAN THREE NEUTRINO FLAVORS?

BIG QUESTIONS



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Some References

- Books :
  - “Neutrino” by Frank Close (Oxford University Press)
  - “Neutrino Astrophysics” by John Bahcall (Cambridge University Press)
  - “Solar Neutrinos” by Bahcall, Davis and others (Westview Press)
  - “Neutrino Physics” by Kai Zuber (Institute of Physics, London)
  - “Introduction to the Physics of Massive and Mixed Neutrinos” by Samoil Bilenky (Springer)

- Journals/Articles :
  - “The Evolution of Neutrino Astronomy”, J. Bahcall and R. Davis, Jr., (http://arxiv.org/abs/astro-ph/9911486)
  - “Solving the Mystery of the Missing Neutrinos”, J. Bahcall, (http://arxiv.org/abs/physics/0406040)
  - “Measurement of the Solar Neutrino Capture Rate by the Russian-American Gallium .....”, SAGE Collaboration (http://arxiv.org/abs/astro-ph/0204245)

- Web links :
  - Fermi National Accelerator Laboratory
  - Brookhaven National Accelerator Laboratory
  - http://www.nu.to.infn.it/ (Neutrino Unbound)
  - http://www-sk.icrr.u-tokyo.ac.jp/index-e.html (Kamioka Observatory)

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"There may be surprises awaiting us that will turn out to be even more sensational than anything that has happened so far !"

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BACKUP SLIDES

Long wait to see neutrinos .....

circa 1955

- Ray built a larger detector located at the nuclear reactor near Savannah River in SC.
- Same result as before - no evidence of neutrinos !
- What was actually missing ?
  - Nuclear reactors actually produce *anti*neutrinos not neutrinos ! Tank full of anti chlorine needed for their detection.
  - Antineutrinos are the antimatter analogue for neutrinos.
- Davis had implicitly proved that neutrinos and antineutrinos are different !
- However, he would have to come to the Homestake mine (SD) to be able to see neutrinos !