QuarkNet Summer Session for Teachers: The Standard Model and Beyond

Allie Reinsvold Hall

Summer 2024

Plan for today

- Staff introductions, logistics, expectations
- Introduce yourselves in breakout rooms

- Lecture: History of the Standard Model

- 10 minute break

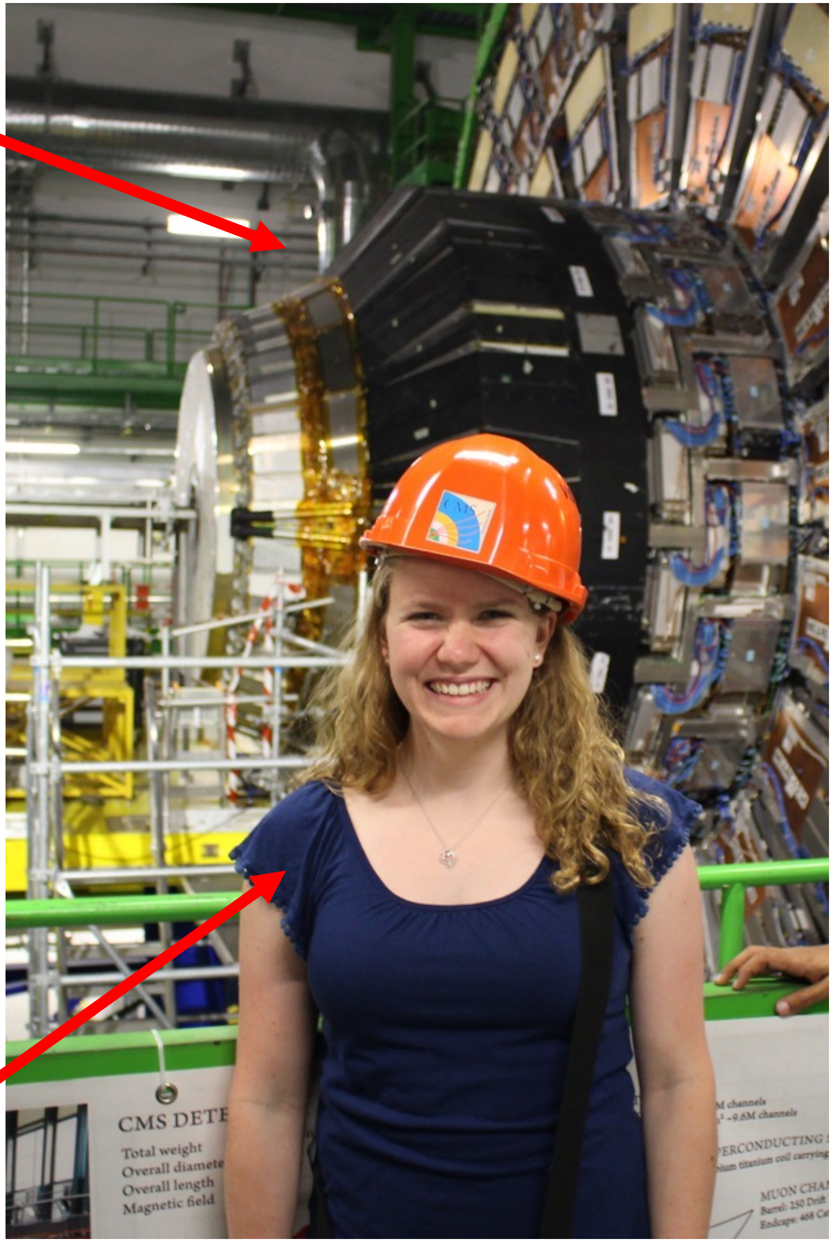
- Lecture: History of the Standard Model
- Homework discussion in breakout rooms

- Final logistics, plan for next week

A little about me

- Highschool in Des Moines, Iowa
- Majored in Physics at the College of St. Benedict in Minnesota
- Ph.D. in experimental particle physics from the University of Notre Dame in Indiana
  - Graduated 2018
  - Dissertation: search for supersymmetry using the CMS experiment
- Postdoc at Fermilab, 2018 – 2021
- Assistant Professor at the US Naval Academy, Annapolis, MD, 2021 – Present
  - Teaching undergraduate physics, working on dark matter searches using CMS and scientific computing R&D

CMS Detector



CMS Physicist

Course overview

What are the fundamental building blocks that make up our universe?

Mission: overview of the past, present, and future of particle physics

1. History of the Standard Model, Part 1: Chemistry to Quantum Mechanics
2. History of the Standard Model, Part 2: Particle zoo and the Standard Model
3. Particle physics at the Large Hadron Collider (LHC)
4. Beyond the Standard Model at the LHC
5. Neutrino physics
6. Dark matter and cosmology

Zoom etiquette

- Join a few minutes early so the meeting can start on time.
- Have your video on if possible.
  - Low bandwidth/bad connection may be an exception in order to maintain connectivity.
- Find a quiet space with minimal distractions.
- Be present in the meeting. Avoid other tasks including checking email, working on your phone, etc.
- Mute your microphone when not talking.
- When speaking, begin by stating your name.
- Try to avoid talking at the same time as other participants.
- Avoid monopolizing the conversation; both in large groups and in the breakout rooms.

Useful information

- Lots of important information on the course website:

https://quarknet.org/content/quarknet-summer-session-teachers-2024

- Sign up for college credit here (2 credits): https://myusf.stfrancis.edu/portal/real/apply/202430/30599

- Class times: **7:30 – 9:30pm Eastern time on Tuesdays**
  - June 18, June 25, July 2, (break on July 9), July 16, July 23, July 30
  - One hour of lecture, one hour of discussion based on homework activities
- Zoom sessions will be recorded and posted

- QuarkNet support from Ken Cecire, Shane Wood, Spencer Pasero
  - Thank you!

Expectations

Homework

- Approximately 1 hour per week
  - I will often include > 1 hour's worth of material: choose what is most beneficial to fit your experience level
- Will also be posted on the course website
- Each class will include breakout sessions to discuss the homework activities

Weekly survey

- Used to self-report attendance and homework participation
  - Professional development certificate will reflect the number of hours you report
- Tell me what you liked/disliked about each session and if you have any questions

Homework and survey will be sent via email on **Thursdays**

→ If you don't get it, let me know!!

Introductions

Thank you for filling out a slide introducing yourself! Get to know each other by looking at the slides here.

Zoom breakout rooms:

- Name
- School/QuarkNet Center
- Any specific QuarkNet programs you are involved in
- A little about you: What's your favorite particle?

History of the Standard Model: Part 1

Nothing exists except atoms and empty space;
everything else is opinion.

- Democritus of Abdera, 420 BC

Learning objectives

Objectives: Understand the driving motivations and important events in the history of particle physics and quantum field theory

- Part 1: Chemistry to Quantum Mechanics
- Part 2: Particle zoo and the Standard Model

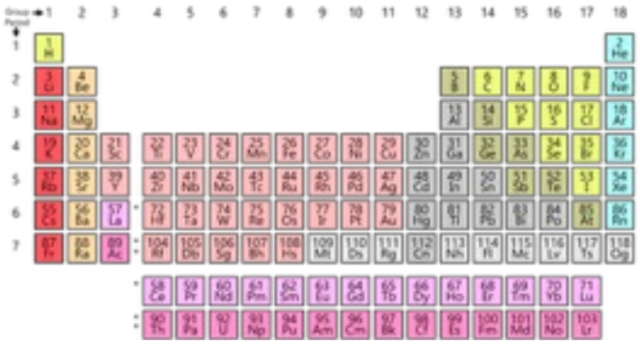
Biased history, inspired by *The God Particle* by Leon Lederman, 1988 Nobel Laureate and former Fermilab director

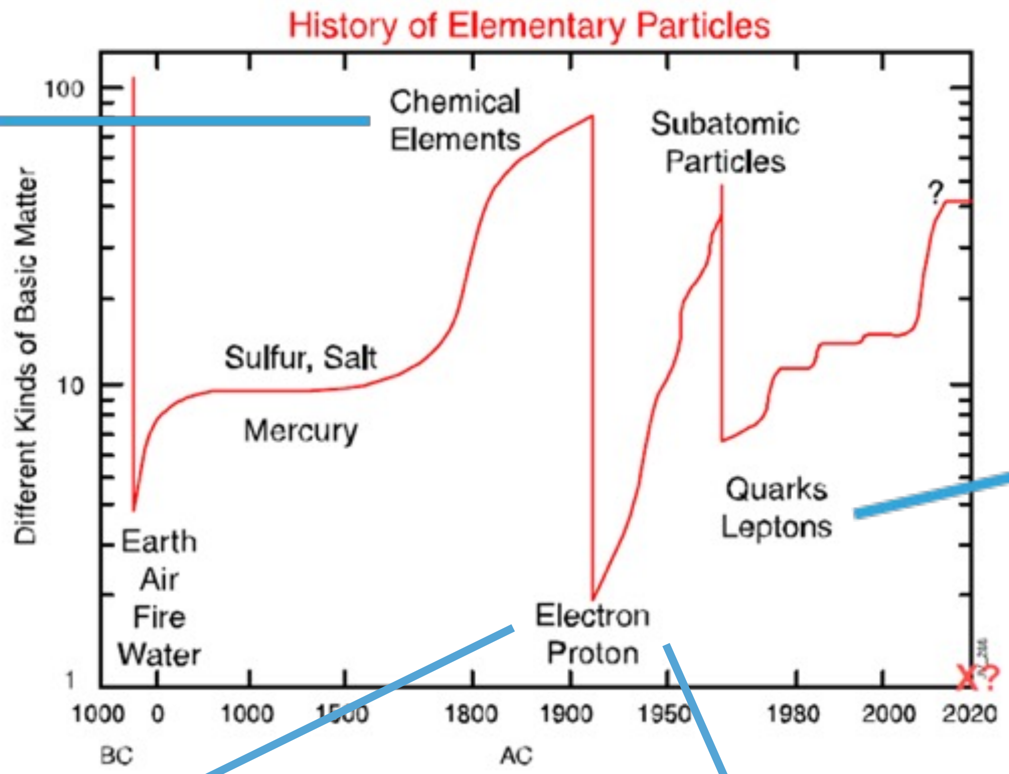
- I am not a science historian, but I'll do my best!

What is particle physics?

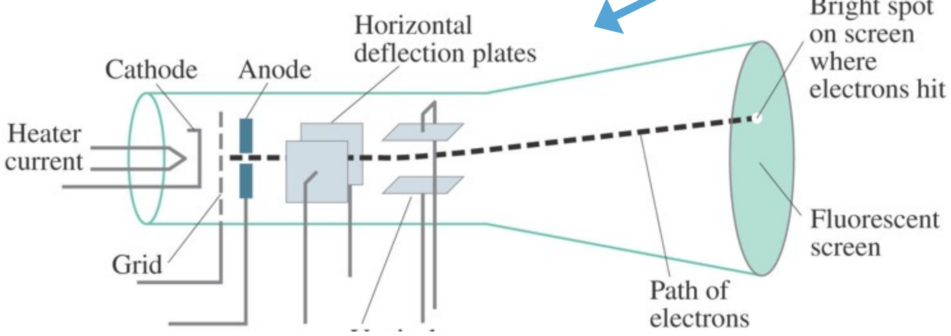
- Trying to understand the basic building blocks of our universe •
- “Fundamental” or “elementary” particles
  - Cannot be divided into any smaller pieces
  - No internal structure
- Origin of the idea: Ancient Greeks (Democritus, 420 BC) coined the term “a-tom”

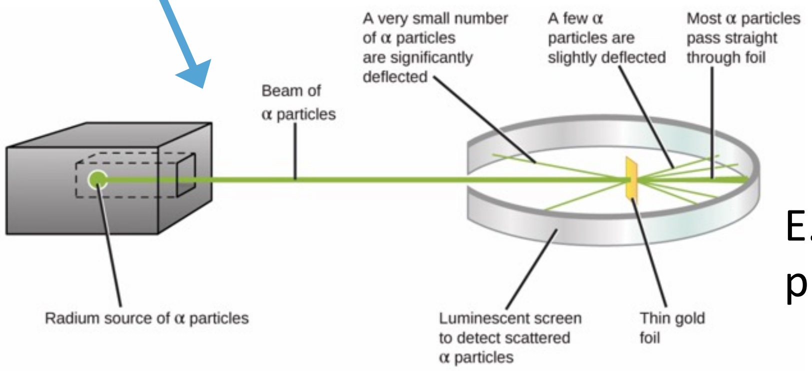
2500 years of particle physics





J.J. Thompson: electron (1897)





E. Rutherford: proton (1909)

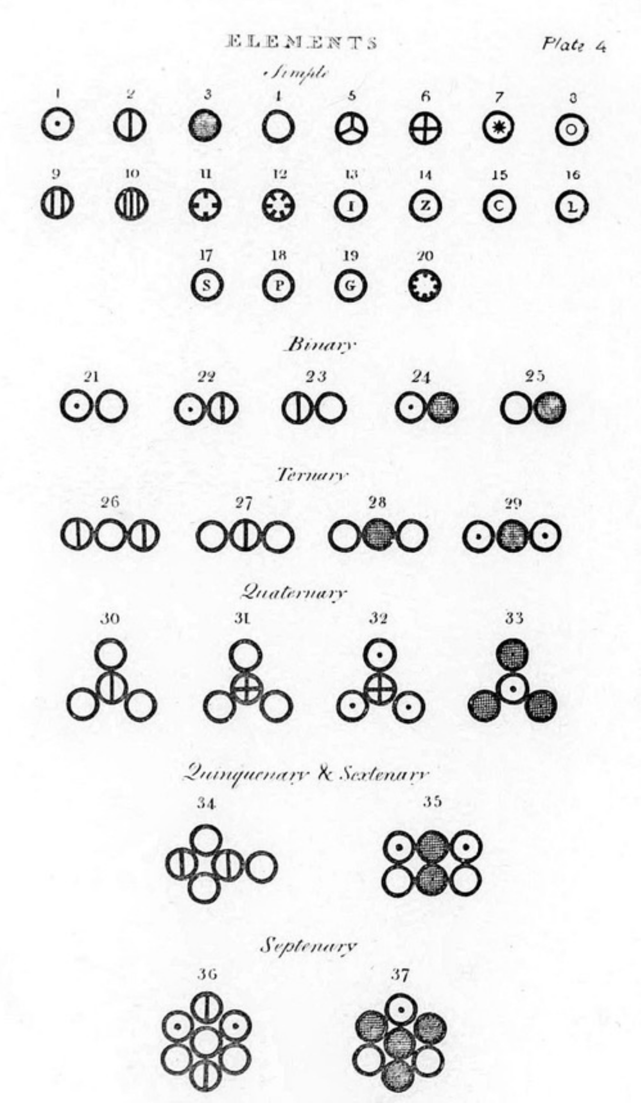
Chemical atoms (1700s – 1800s)

- Late 1700s: Well-known that splitting chemicals always gave same ratio of elements by weight
  - Water: 8 parts oxygen, 1 part hydrogen by weight

John Dalton (1766 – 1844)

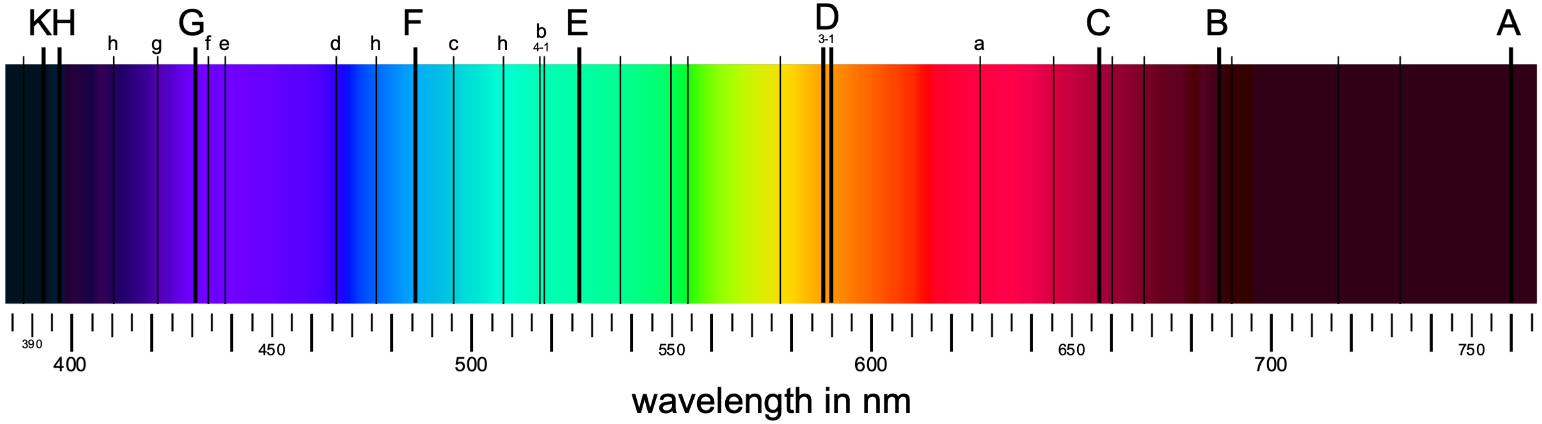
- Proposed the chemical atom as the basic unit of chemicals, 1804-1817
- Atoms are defined based on weight
  - Structureless, indivisible
  - Atoms of a given element are indistinguishable
  - Chemical reactions can combine or separate atoms

Dmitri Mendeleev (1834 – 1907) organized atoms into the Periodic Table in 1867



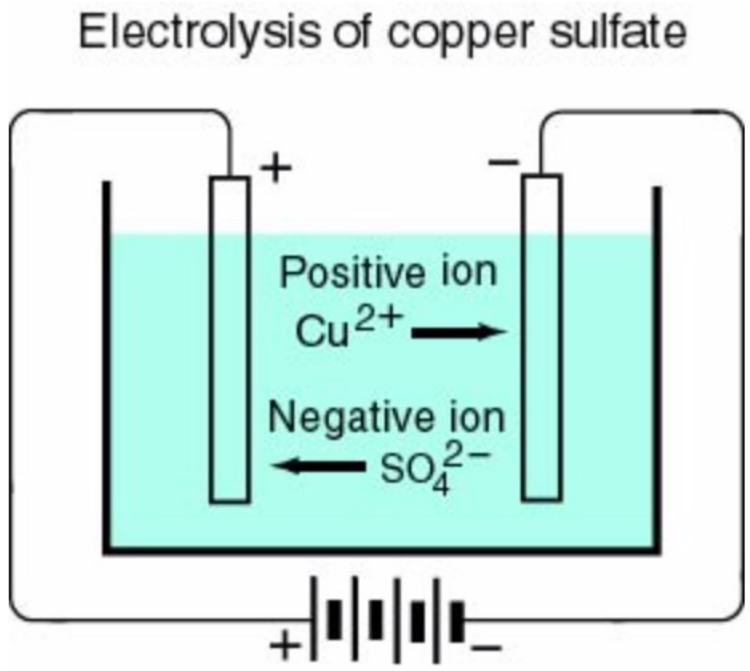
Physics at the turn of the century (1900)

- Mechanical paradigm: all physical phenomena could be described using principles of mechanics
- Maxwell's equations had been written in their familiar form and experimentally verified by Oliver Heaviside (1850 – 1935) and Heinrich Hertz (1857 – 1894)
- **Signs of trouble**
    - X-rays
    - Radioactivity
    - Spectral lines from the sun



Are chemical atoms fundamental?

- **Michael Faraday (1791 – 1867):** Laws of Electrolysis (published 1833) indicated that there were *particles of electricity*
  - Mass of chemical released is proportional to the total amount of electricity that passed through the liquid
  - Mass liberated by a fixed quantity of electricity is proportional to the atomic weight multiplied by the number of atoms in the compound

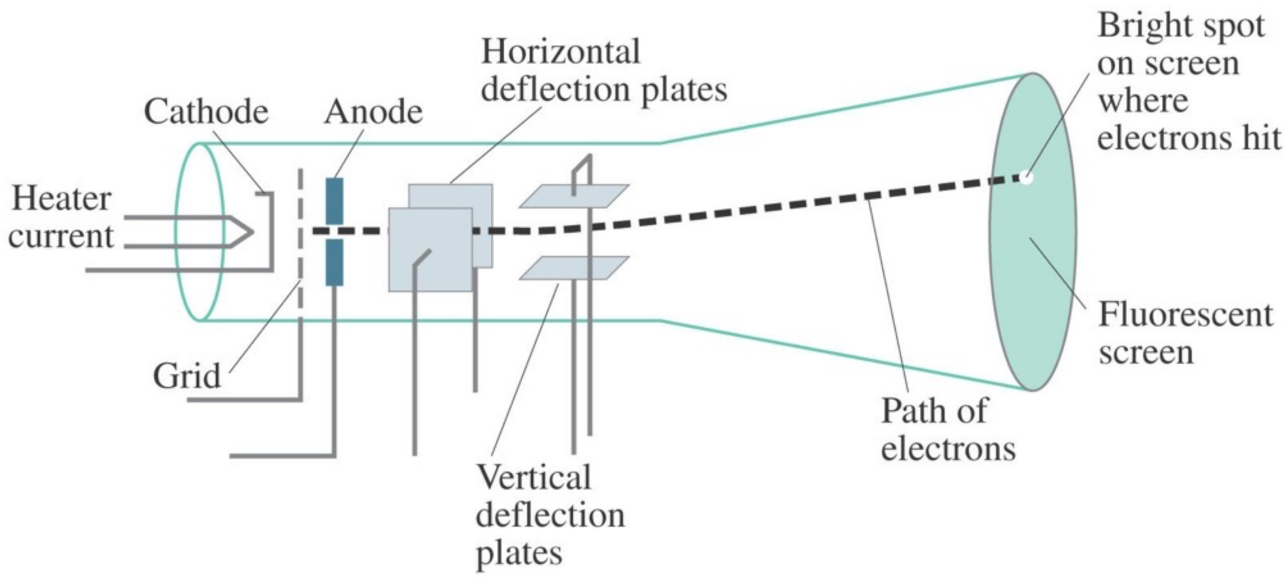


Discovery of the electron

- **J.J. Thomson (1856– 1940):** explored cathode rays in an evacuated glass tube

- What is the beam?
  - Massless electromagnetic vibrations in the aether?
    - Beam was deflected by electric fields = negatively charged particles!
  - Charged gas molecules?
    - Applied known E and B fields, measured e/m ratio
    - Same measured value of e/m even for different gas and cathode materials

  → 1897: **New fundamental particle** that is present in all atoms!

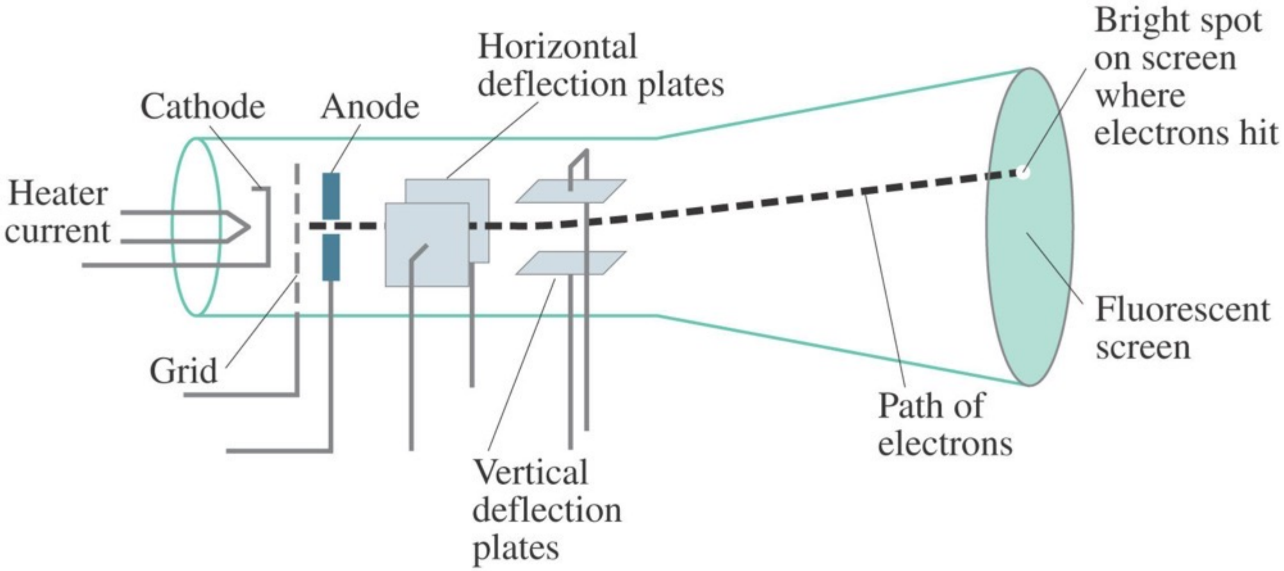


- Thomson measured e directly using a cloud chamber in 1898

Discovery of the electron

J.J. Thomson (1856 - 1940)

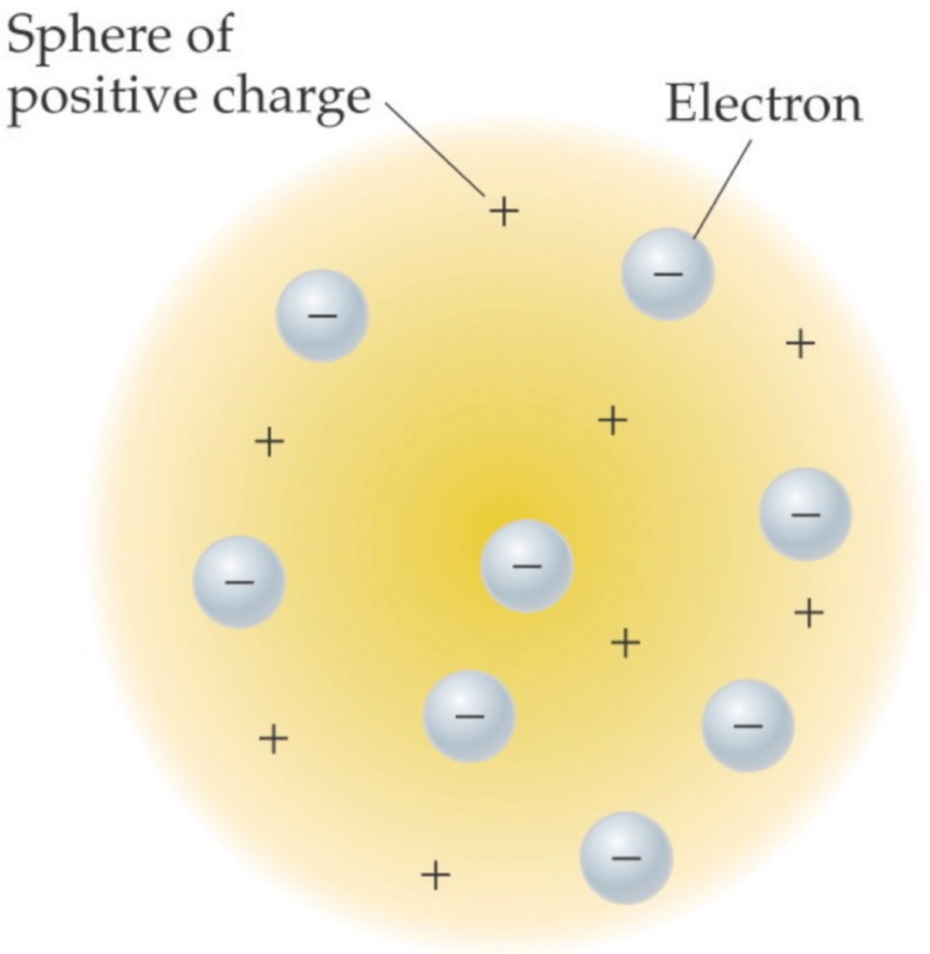
1906 Nobel Prize



First solid evidence that the chemical atom was not the structureless, uncuttable fundamental particle that scientists thought!

Plum Pudding Model of the Atom

Proposed by **J.J. Thomson** in 1904



Electrons are embedded in a positively charged atom like plums in a pudding

Rutherford Scattering

- **Ernest Rutherford (1871 – 1937):** Sent α particles toward a thin gold foil
- Surprisingly, 1 in 8000 α's were deflected back towards the source.

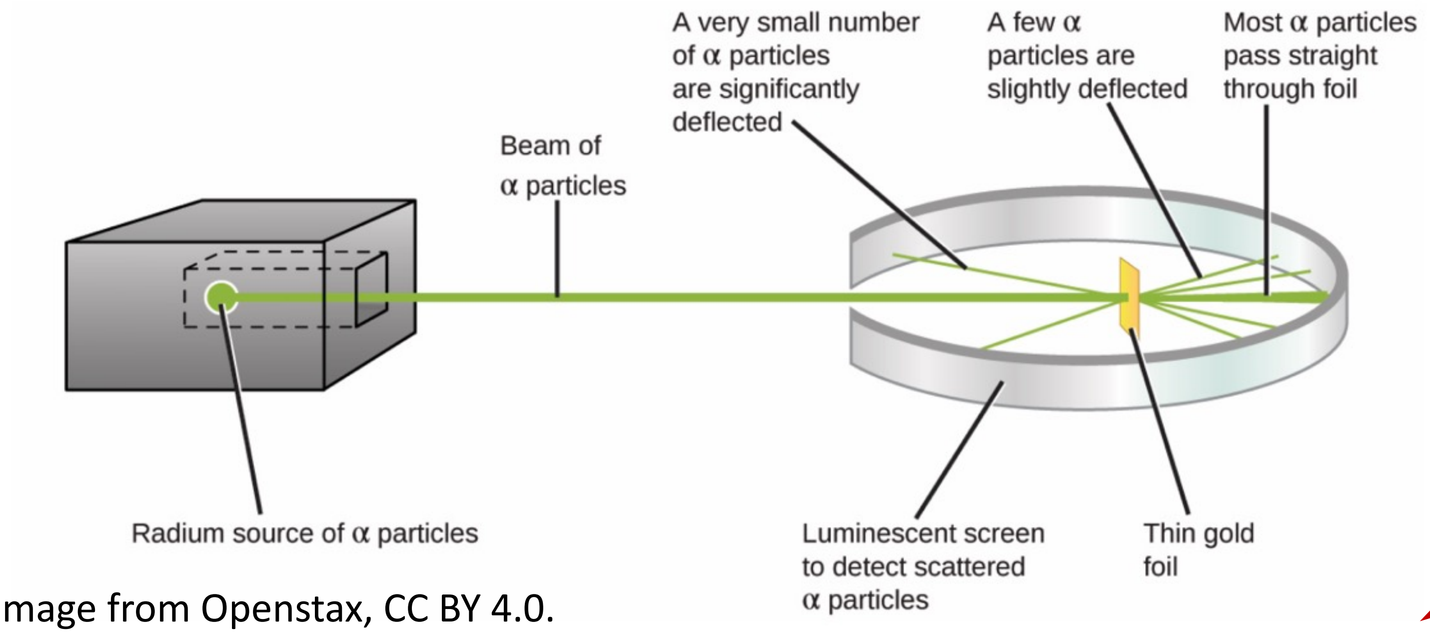


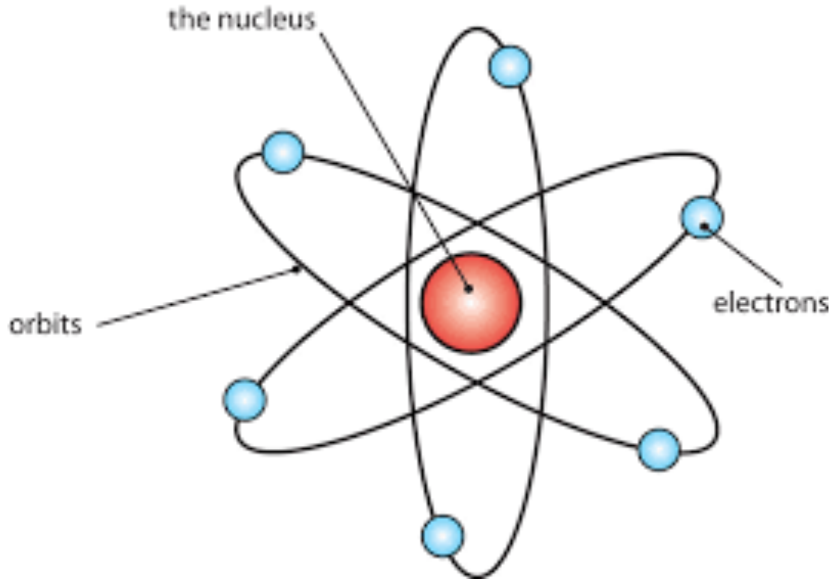
Image from Openstax, CC BY 4.0.

> "It was quite the most incredible event that has ever happened to me in my life. It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you.

E. Rutherford (1909)

- Conclusion: positive matter is concentrated in an incredibly small volume (10^{-13} cm)

Planetary Model of the Atom



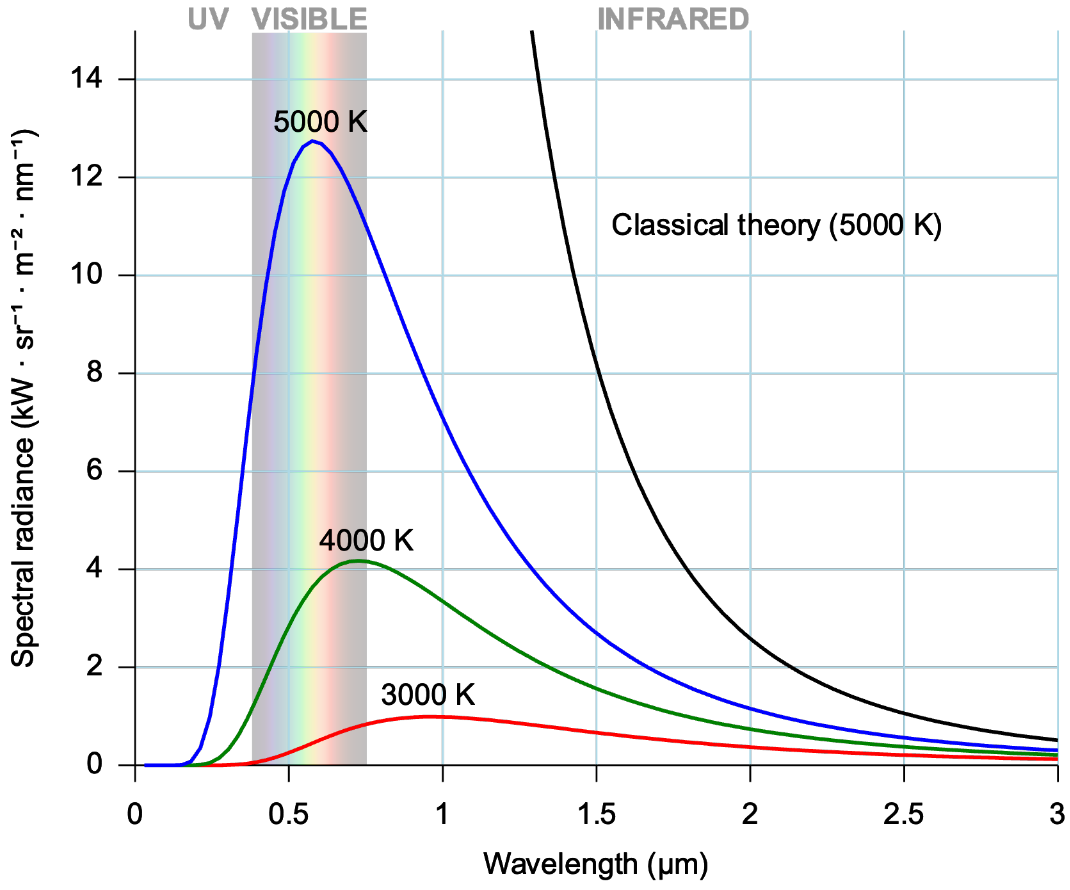
- Planetary model was proposed by **Rutherford** in 1911
- Atomic structure:
  - Central positive charge in a small volume
  - Surrounded by a cloud of orbiting electrons
- **Niels Bohr** in 1913 proposed ad hoc rules for orbits that correctly described hydrogen's spectral lines

1922 Nobel Prize

Thoroughly dispelled idea that chemical atoms were the basic building blocks

Ultraviolet catastrophe

- Blackbody: object that absorbs all incoming light and emits thermal radiation
- Predictions for the light emitted by a blackbody
  - Classical theory: infinite amount of light emitted at low wavelengths
- **Max Planck (1858 – 1947)** guessed the correct mathematical form to fit the data in 1900
  - Blackbodies could only emit light in discrete quantities
  - Each quanta has an energy dependent on frequency: $E = hf$
  - Shorter wavelengths "cost" more energy to radiate

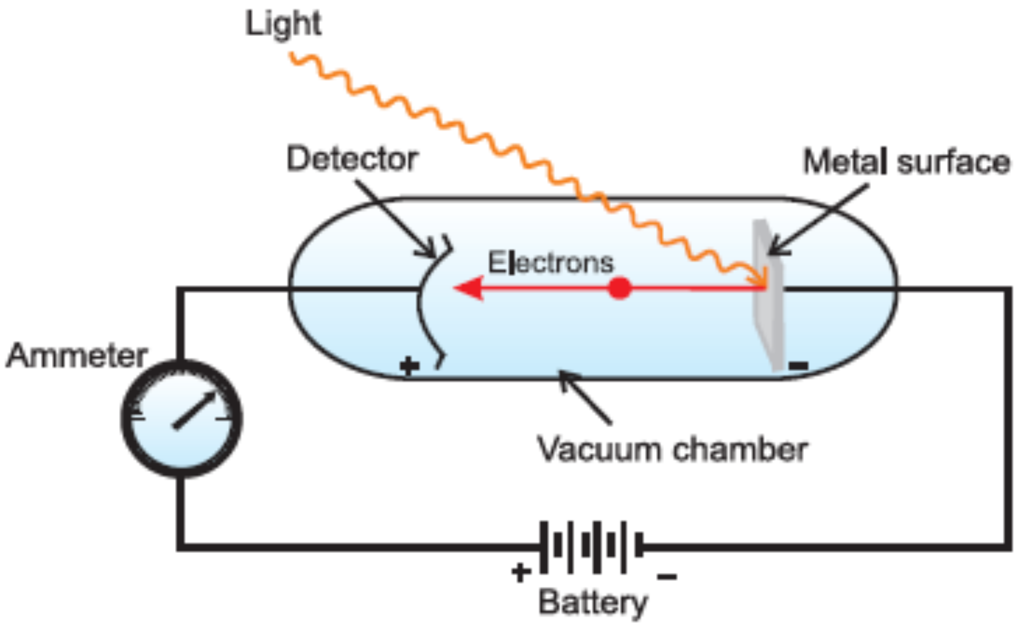


Photoelectric effect

- First observed by Hertz in 1887
- Shining light on a metal surface leads to measurable current ("photoelectrons")

Observations:

1. Higher intensity leads to more photoelectrons
2. There is no time interval between light's arrival and the emission of photoelectrons
3. No photoelectrons released if $f < f_{crit}$
4. Above f_{crit}, higher frequency means the photoelectrons have a higher E_{max}



Explained by **Albert Einstein (1879 – 1955)** in 1905, building off Planck's light quanta:

$$hf = KE_{max} + \varphi \text{ where } \varphi = h\, f_{crit}$$

1921 Nobel Prize

De Broglie waves

- **Louis de Broglie (1892 – 1987)** posited in his PhD thesis that particles have wave properties
- **Symmetry at work:** If light waves can be particles, then particles can be waves
  - In hydrogen, electron's wavelength determines the allowed radii
  - Explained the Fraunhofer solar spectral lines, previously explained ad hoc by the **Bohr** model

$$\lambda = h/p = h/\gamma m v$$

1929 Nobel Prize

- Experimentally confirmed at Bell Labs by Clinton Davisson & Lester Germer and at the Cavendish Lab by George Thomson in 1927

1938 Nobel Prize

- De Broglie was also the first to call for the creation of a united European laboratory, today known as CERN

Schrödinger's equation

$$i\hbar \frac{\delta}{\delta t}\Psi(x,t) = \left[\frac{-\hbar^2}{2m}\frac{\delta^2}{\delta x^2} + V(x)\right]\Psi(x,t)$$

$$\mathrm{E}\,\psi(x) = \left[\frac{-\hbar^2}{2m}\frac{d^2}{dx^2} + V(x)\right]\psi(x)$$

1933 Nobel Prize

- Published in January 1926 by **Erwin Schrödinger (1887 – 1961)**
  - Used de Broglie's wave concept as a foundation
  - Consistent with the matrix formalism developed by **Werner Heisenberg (1907– 1976)** a few months earlier, but easier to use
- Originally Ψ was interpreted as an actual matter wave
  - **Max Born (1882– 1970)**: Stated in 1926 that $|\Psi^2|$ is proportional to the **probability** of a particle to be found at a given point
  - Huge paradigm shift from the deterministic worldview championed by Newton

1954 Nobel Prize

Heisenberg Uncertainty Principle

- Mathematical consequence of the **Schrödinger** equation
- Proposed by **Heisenberg** in 1927
- Limit to the precision with which we can predict complementary variables

$$\Delta p \, \Delta x \geq \frac{\hbar}{2}$$

$$\Delta E \, \Delta t \geq \frac{\hbar}{2}$$

1932 Nobel Prize

- Arises from the wave-like nature of particles
  - **Not** a consequence of flaws in our equipment; even with unlimited funding, we can never know both!

Homework discussion

- Data from 2001 experiment on the Heisenberg uncertainty principle

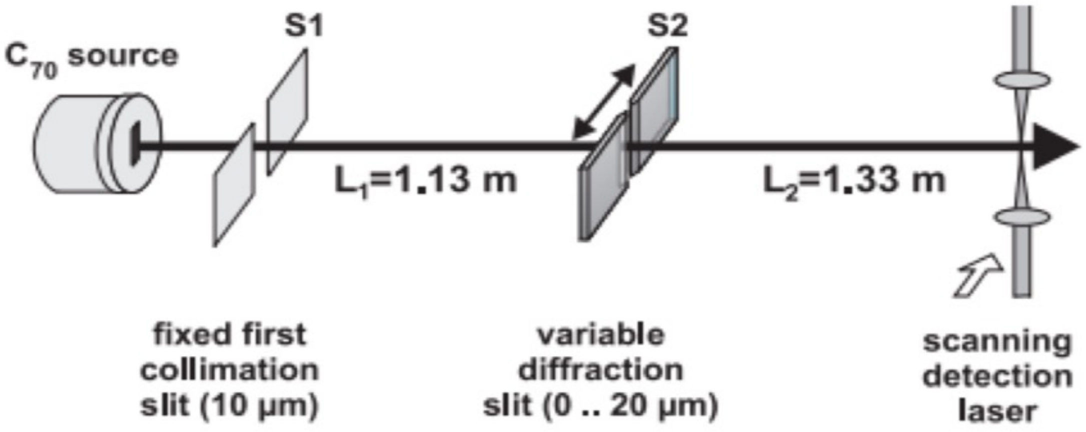


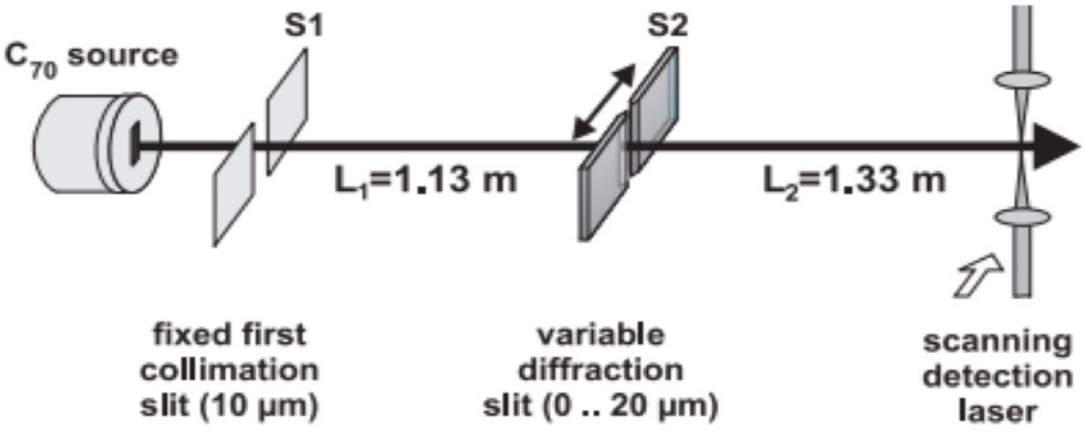
Figure 2: *Experimental setup made by Nairz, Arndt, and Zeilinger, 2001,* *https://arxiv.org/abs/quant-ph/0105061*.

Breakout discussions

1. What happens to Δx when Δp increases? (Can you describe it mathematically?)
2. How does your mathematical model support or contradict Heisenberg's uncertainty principle? Describe your reasoning.
3. How would improving the experimental setup change these results and your claims?
4. If you've done this activity with your students before: what went well? What would you do differently? Would you recommend this activity to other teachers?

Homework discussion

- Data from 2001 experiment on the Heisenberg uncertainty principle



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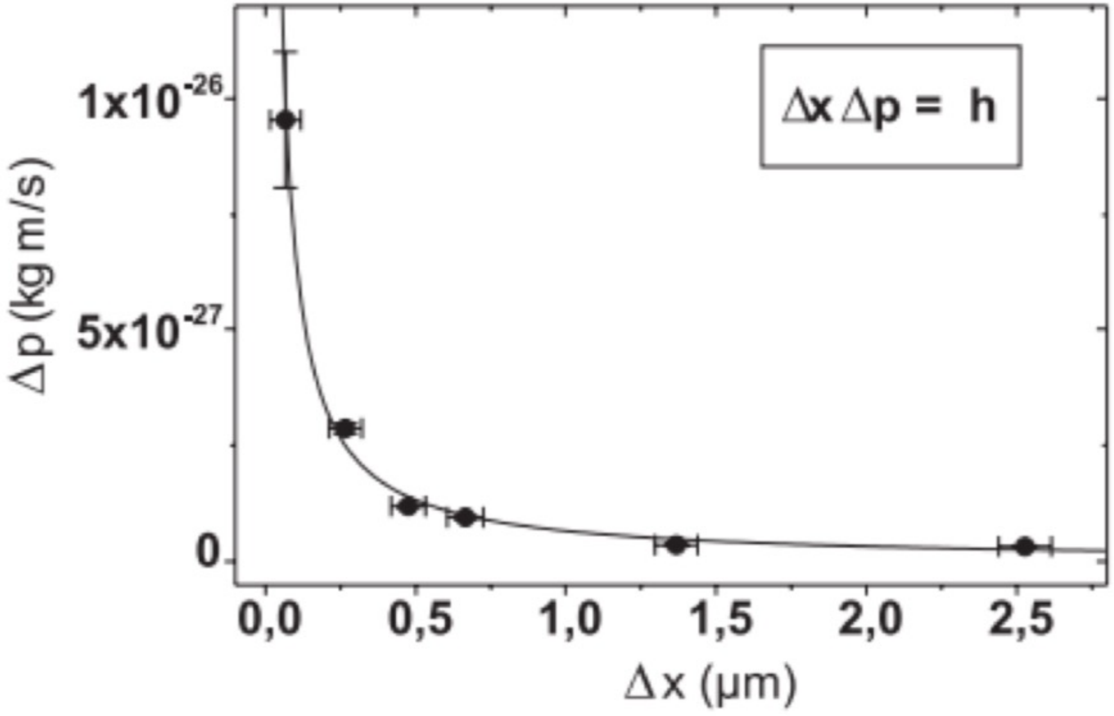

Homework discussion

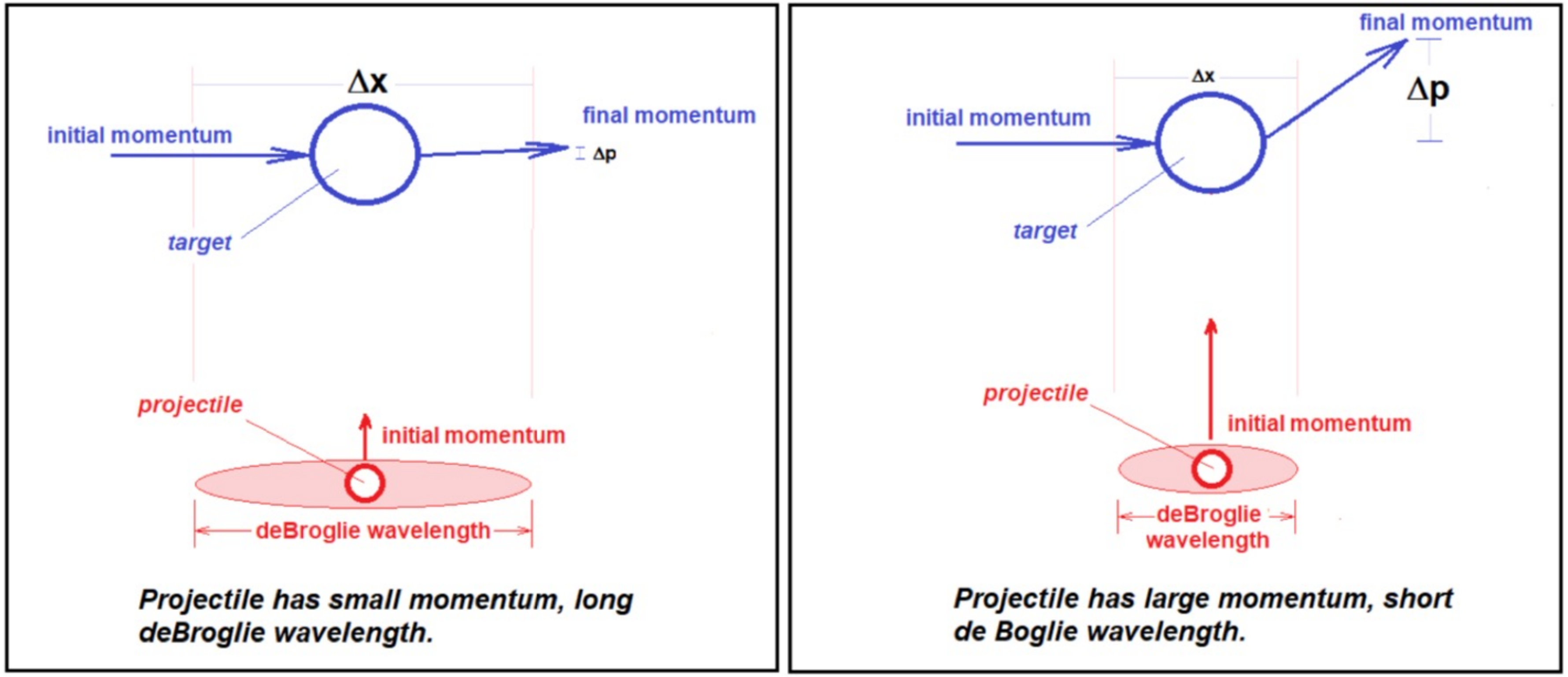

Figure 1: Relationship between momentum and de Broglie wavelength.

Fundamental property of quantum systems and **not** a statement about the current ability of our experimental apparatus

Mass-energy equivalence (and units)

- Einstein's famous equation $E = m\,c^2$
  - **Symmetry** between energy and mass
- **Paul Dirac (1902 – 1984)** expanded the mass-energy equivalence in 1928 to include momentum:

$$E^2 = p^2c^2 + m^2\,c^4$$

- E is in units of eV (keV, MeV, GeV, TeV)
- 1 eV = energy an electron gains passing through a voltage difference of 1 V
- **Natural units:** Planck's constant = speed of light = 1
- $E^2 = p^2c^2 + m^2\,c^4 \rightarrow E^2 = p^2 + m^2$

  → Momentum and mass are also measured in eV

  → If p is close to m, then the particle is moving relativistically

Dirac equation

- 1927: **Paul Dirac (1902 – 1984)** wanted to merge quantum theory and special relativity for electrons (spin 1/2 particles)
  - Spin = intrinsic angular momentum
- Result: Dirac equation (natural units)

$$(i\,\gamma^{\mu}\delta^{\mu} - m)\psi = 0$$

where μ goes from 0 to 3

- ψ is a **spinor** with four components – two spin states (±1/2) for **two particles**
- Implications:
  - Describes particles that have spin $1/2 * \hbar$
  - Two solutions – one with positive charge, one with negative charge

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Simplified explanation:

- $x^2 = 4$ has two solutions, ±2
- So does $E^2 = p^2c^2 + m^2\,c^4$

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1933 Nobel Prize

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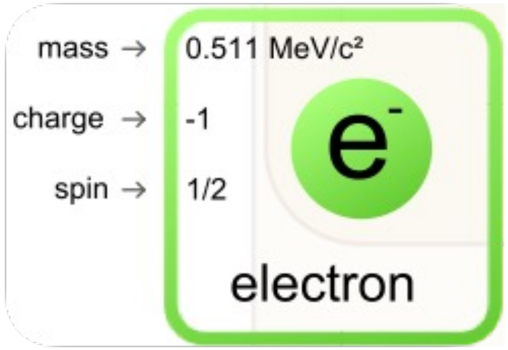
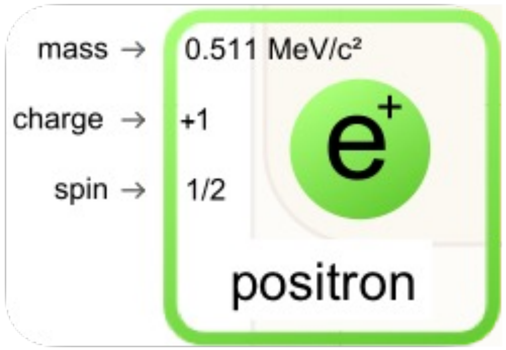
- Implications:
  - Describes particles that have spin $1/2 * \hbar$
  - Two solutions – one with positive charge, one with negative charge
- Original idea: positive particles were protons – only known option at the time
- 1932: Carl Anderson recorded a positron track in a cloud chamber

1936 Nobel Prize

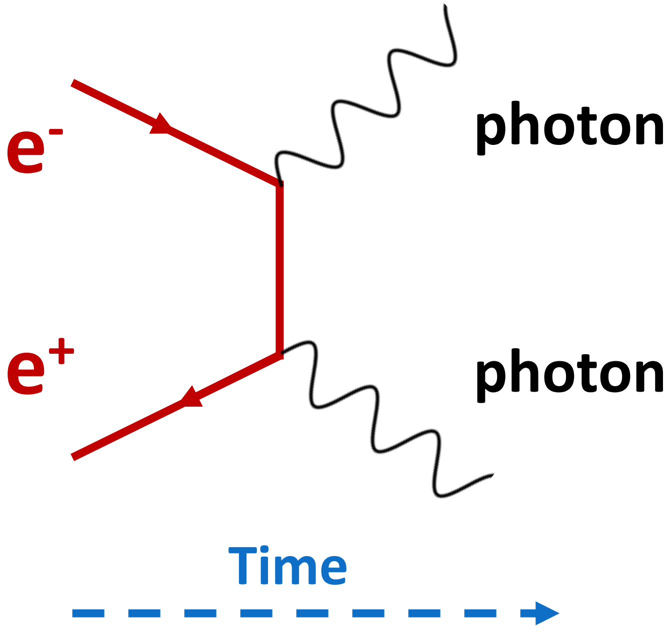
Antimatter

- Antimatter is exactly the same as matter except one attribute is flipped: the *charge*



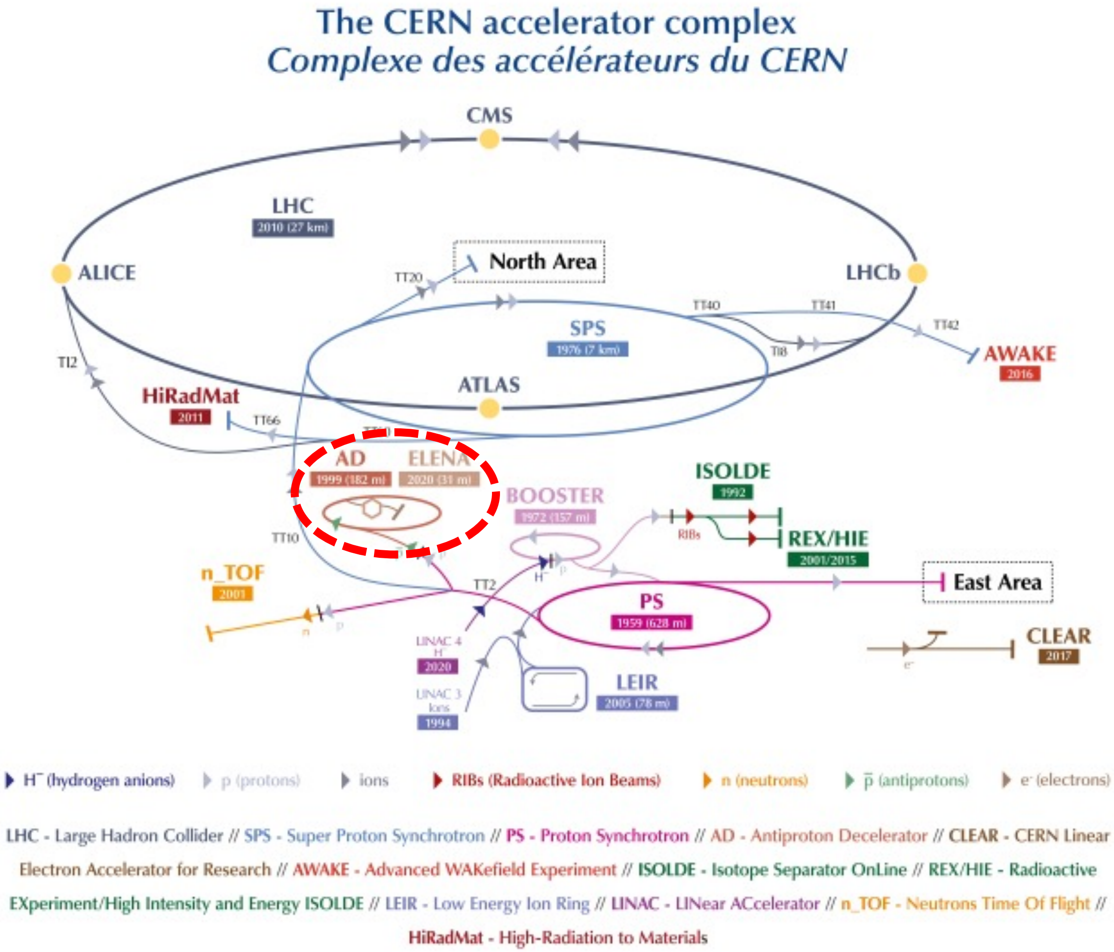


- A particle and its antiparticle can annihilate into a pair of light particles (*photons*)
  - Often use a bar to denote antiparticles: $\bar{e}$
  - In Feynman diagrams, antiparticles are shown as particles moving *backward* in time



How do we make antimatter?

At the antimatter factory of course!

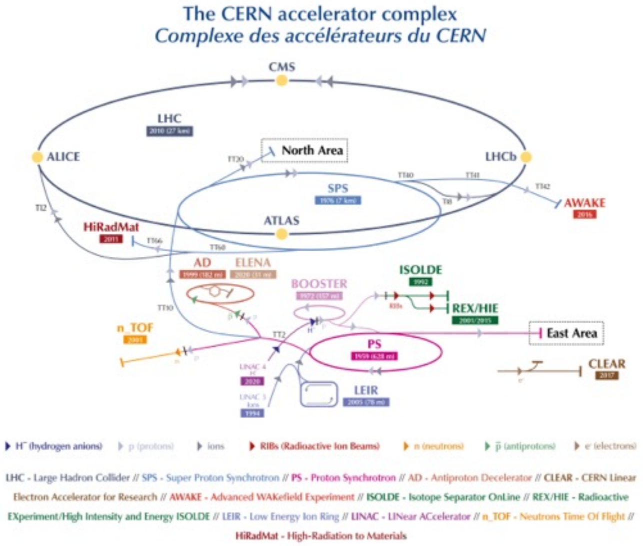


How do we make antimatter?

Some antimatter is easier to produce than others…

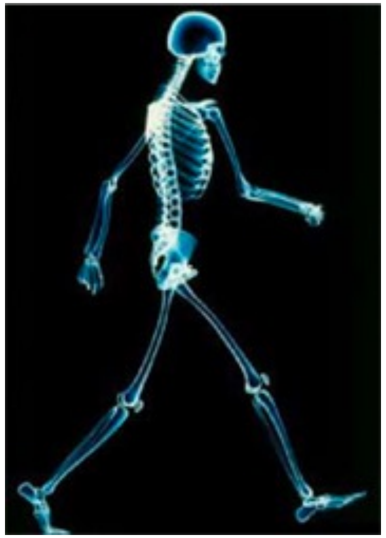
Antiprotons from high energy collisions of a proton beam on a fixed target of metal

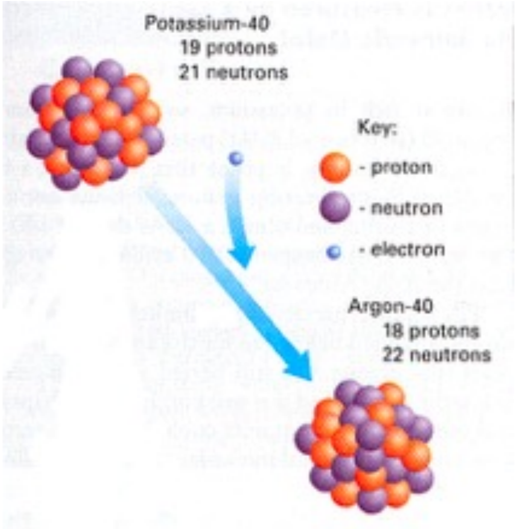
$$p + p \rightarrow \bar{p} + p + p + p$$



Positrons from Potassium-40: your body produces about 180 positrons per hour!

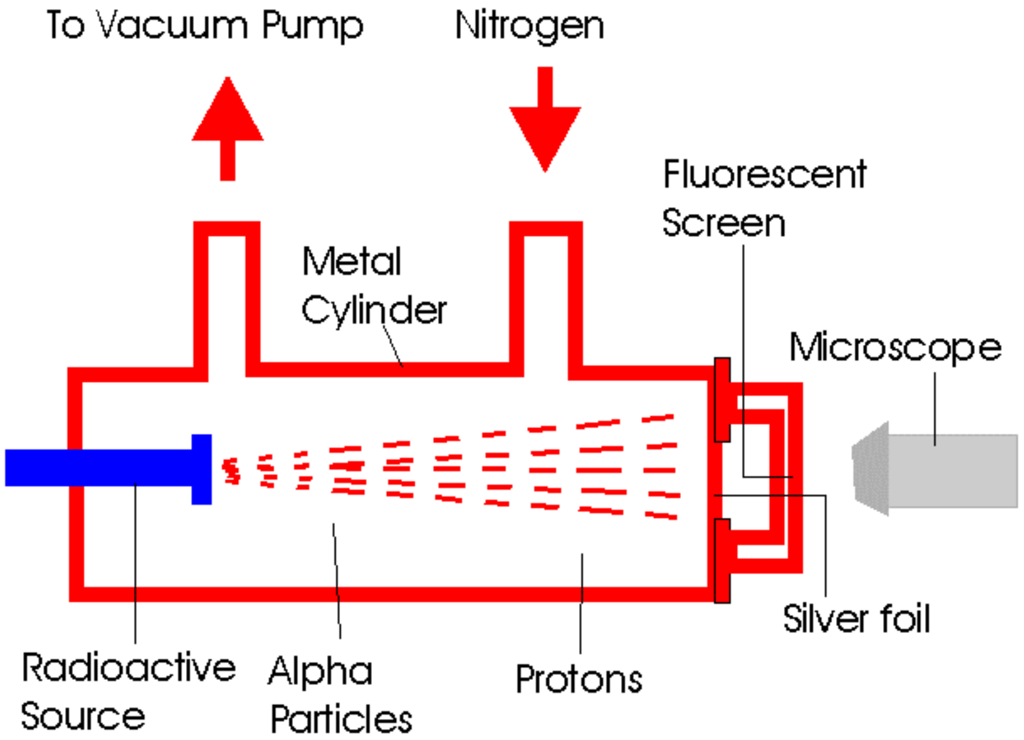
$$^{40}_{19}\mathrm{K} \rightarrow ^{40}_{18}\mathrm{Ar} + e^{+} + \nu_e$$





Observation of the proton

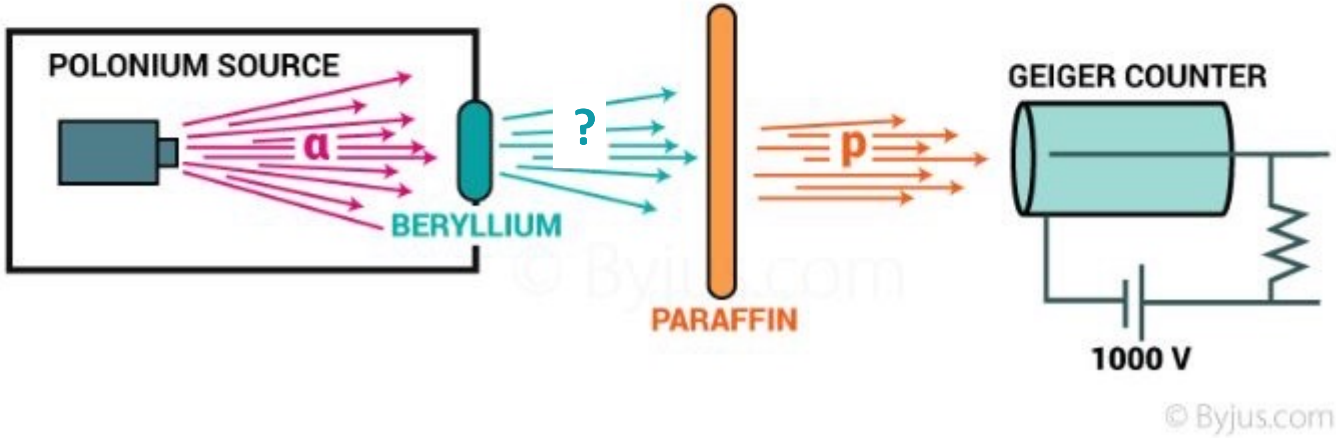
- First proposed by **William Prout** in 1815
  - Asserted that all atoms are made of hydrogens
- **Rutherford** proved in 1917 that nitrogen contains hydrogen nuclei using the reaction ${}^{14}N + \alpha \rightarrow {}^{17}O + p^{+}$



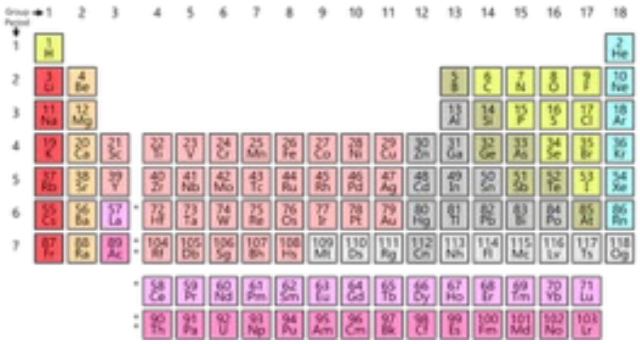
Observation of the neutron

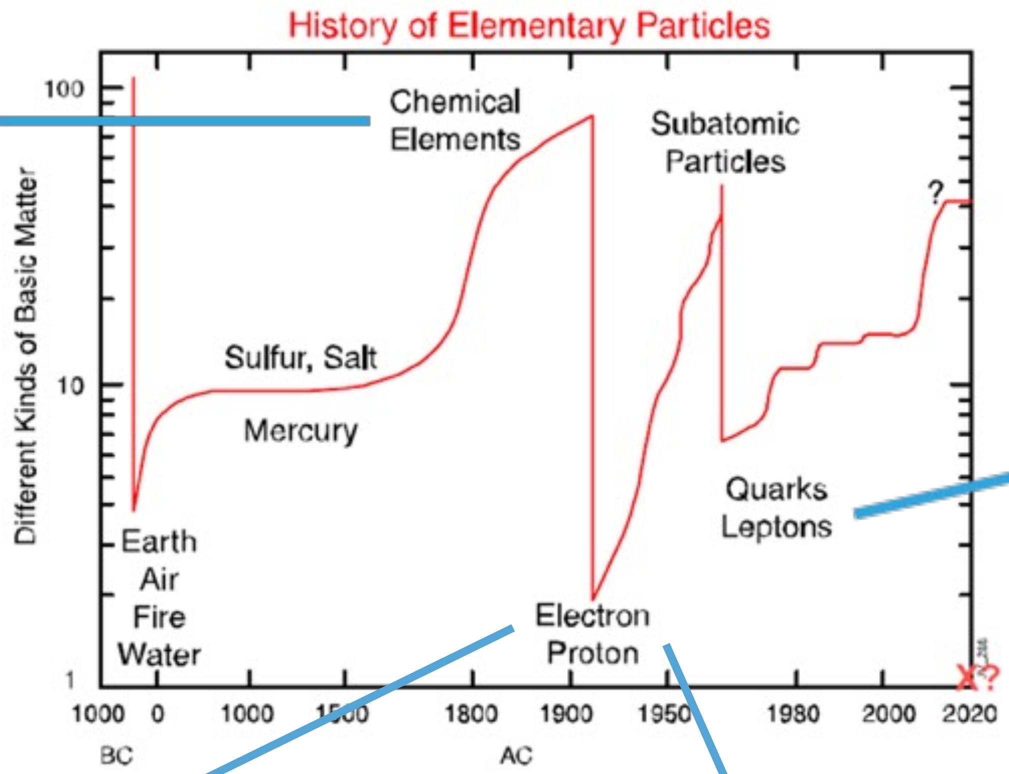
- Already known that the nucleus contained more than just protons
  - Mass of helium was 4, but it had an atomic number of 2
  - **Rutherford**: extra mass comes from combining extra protons and electrons in the nucleus
- **Irene Joliet-Curie** and **Frederic Joliet** in 1930 produced high energy protons from unknown Be radiation on paraffin wax
  - Hypothesis: radiation from Be was high energy photons
- **James Chadwick** (1891 – 1974) in 1932: radiation was a **new neutral particle, the neutron**
  - Mass just above that of the proton

1935 Nobel Prize



2500 years of particle physics





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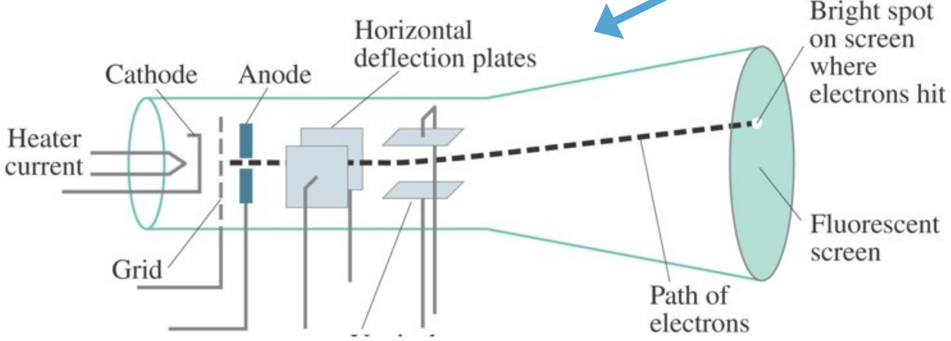
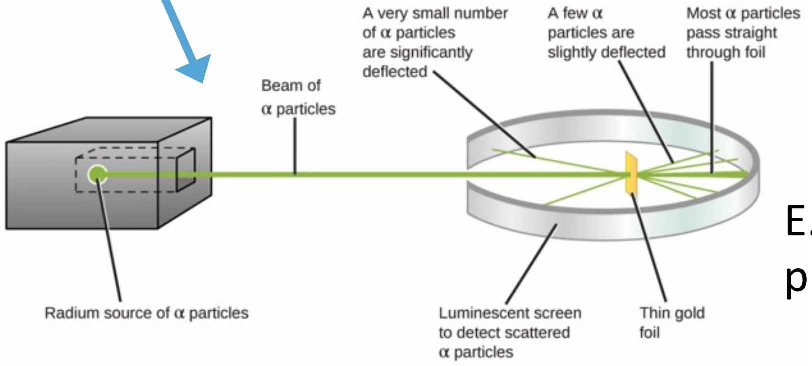




E. Rutherford: proton (1909)

Conclusions – Part 1

- Whirlwind tour from the beginning of modern chemistry up to 1930s
- Particle physics is the search for simplicity and the underlying principles
  - Symmetry and conservation laws

- Standard Model of 1933: Schrödinger equation, Dirac equation, Maxwell’s equation, and Einstein’s theory of relativity
- Elementary particles so far: photon, proton, neutron, electron, positron

- Next week: many new particles, leading to modern particle physics and the birth of the Standard Model

Homework: due June 25

1. Complete D0 activity

2. Watch Steven Pollock's lecture on the 1974 November Revolution (30 minutes)

3. Fill out weekly survey

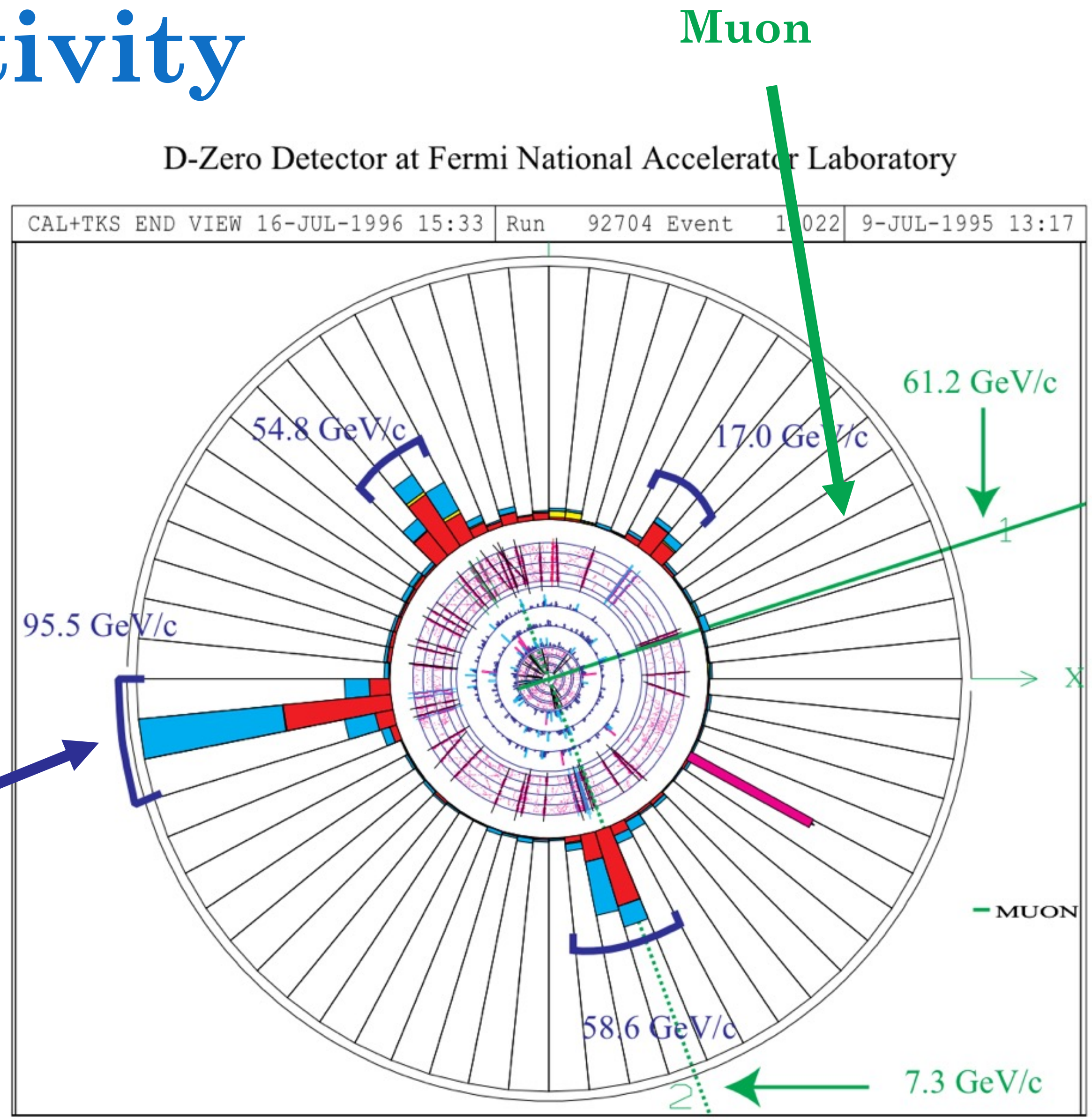
- Should take about an hour! Additional, optional resources are posted to the course website

- Email me with any concerns or questions

Homework 1: D0 activity

- Fermilab Tevatron collider
  - Operated from 1983 – 2011
  - Collided protons and anti-protons at a center-of-mass energy up to 2 TeV

- Jargon:
  - Event: one collision between "bunches" of particles
  - Transverse plane: plane perpendicular to the beam
  - **Jets:** collimated spray of particles from the decay of quarks.
  - **Muons:** Heavier version of the electron



Homework 2: November revolution

- Watch Steven Pollock's lecture on the November revolution (30 minutes)

Historical context:

- Many new "fundamental" particles discovered in the 1950s and 1960s
- **Quarks:** proposed by Gell-Mann and Zweig in 1964 to explain them all
- Mathematical framework or the way the world actually works?
    - Are there real quarks?
      If so, why haven't we seen them?

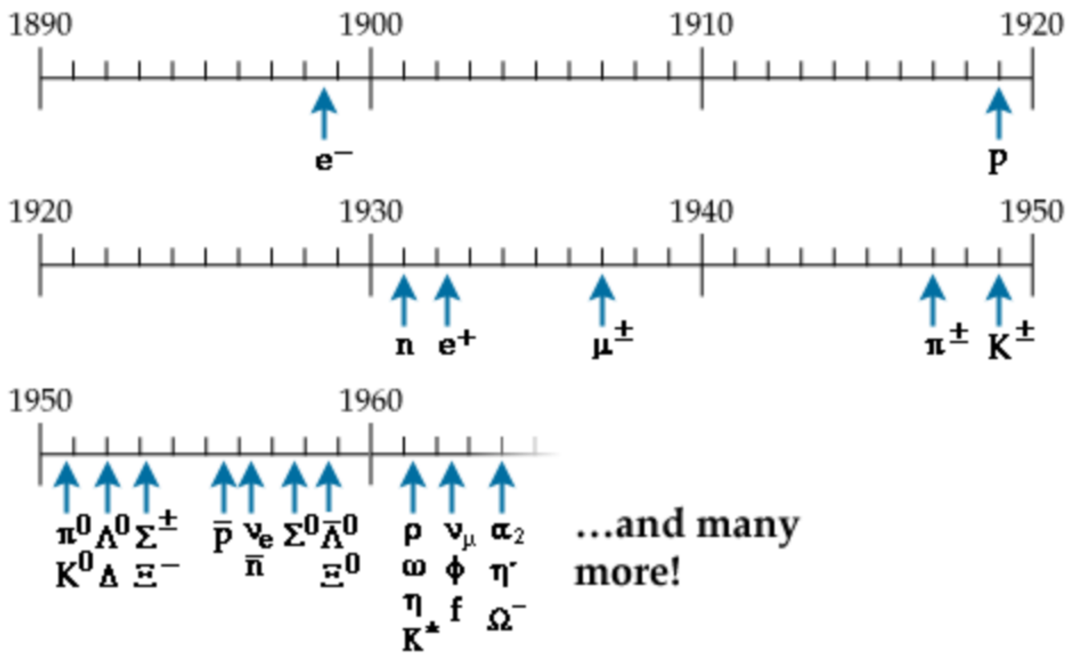
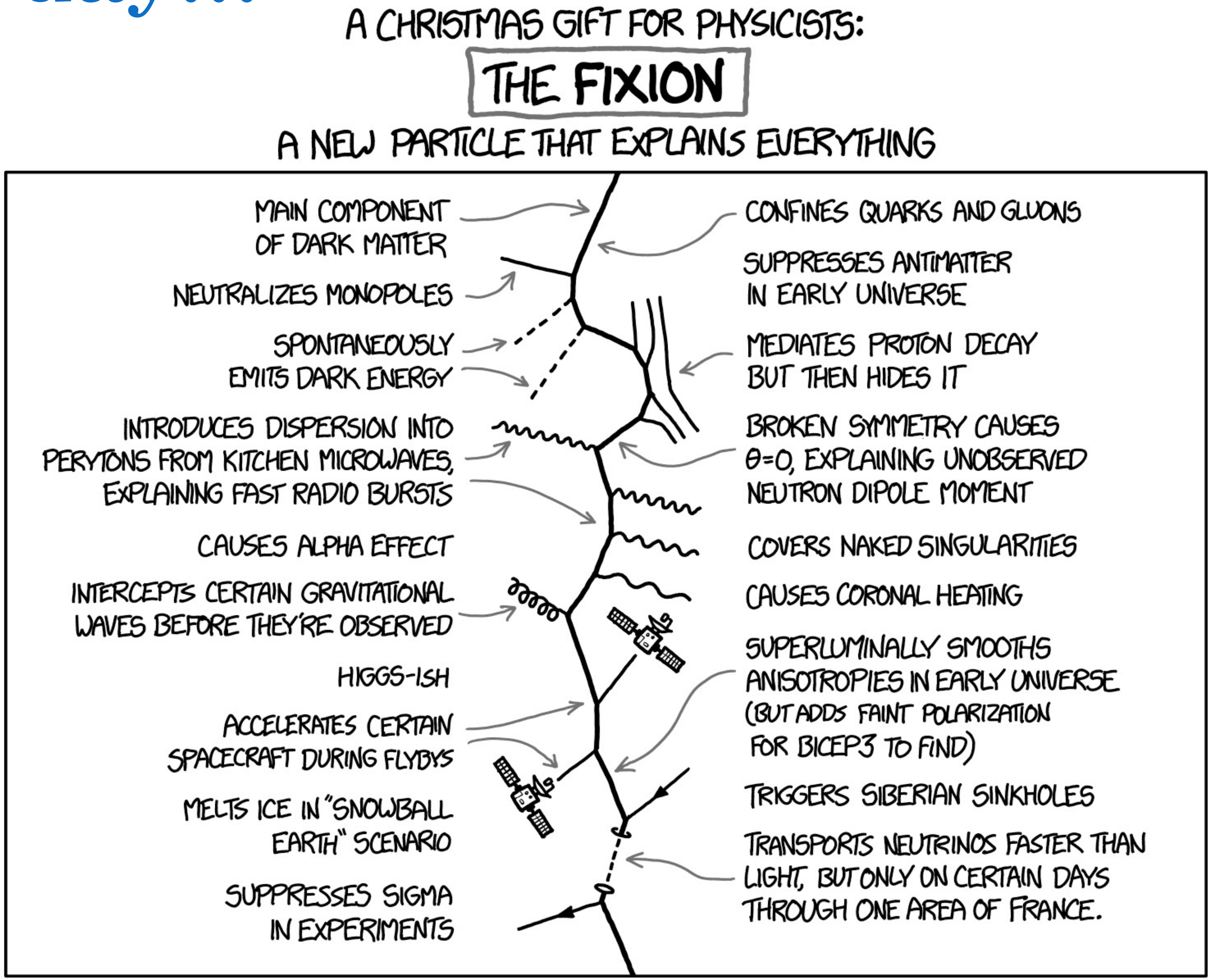


Image from the particle adventure

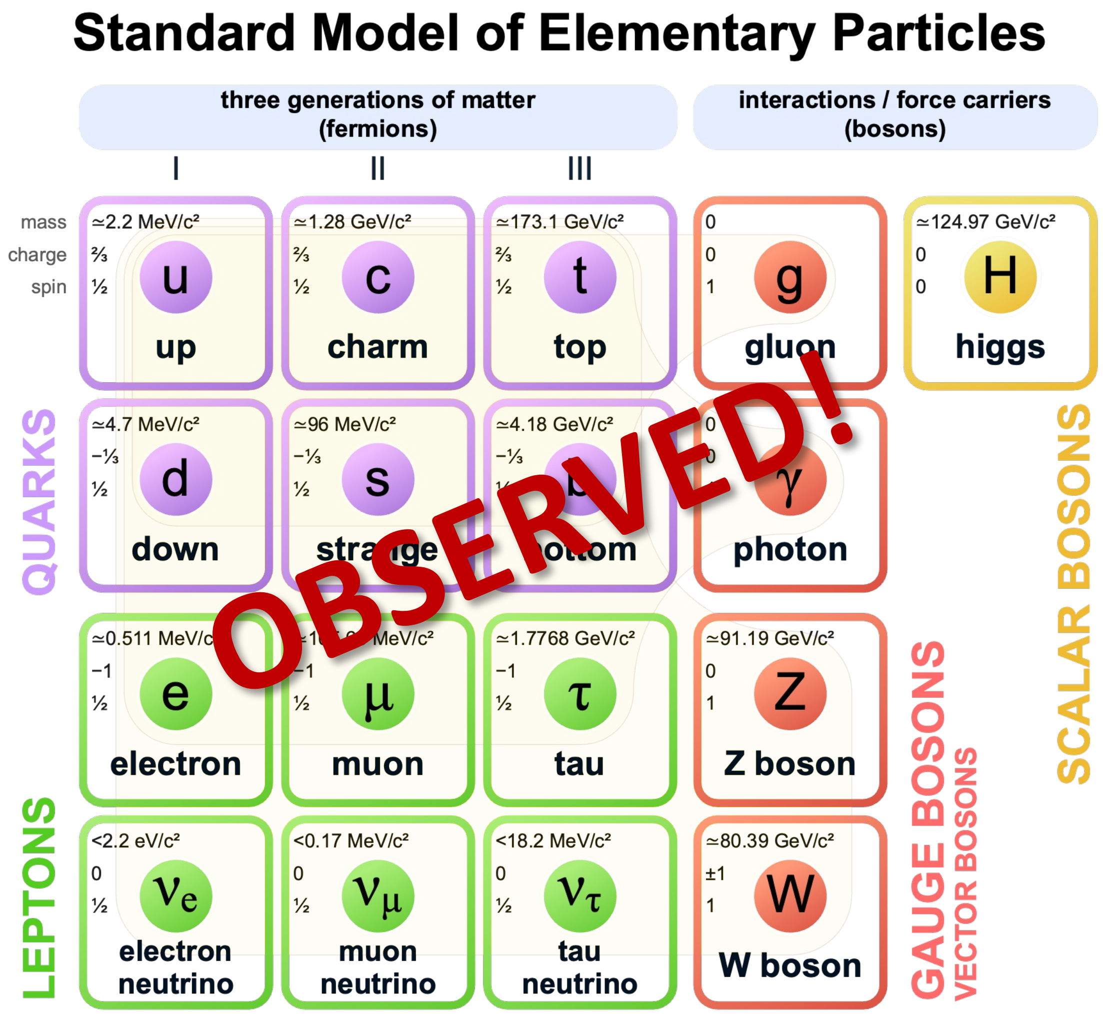
End of Part 1

Some day…



https://xkcd.com/1621/

Preview: Standard Model

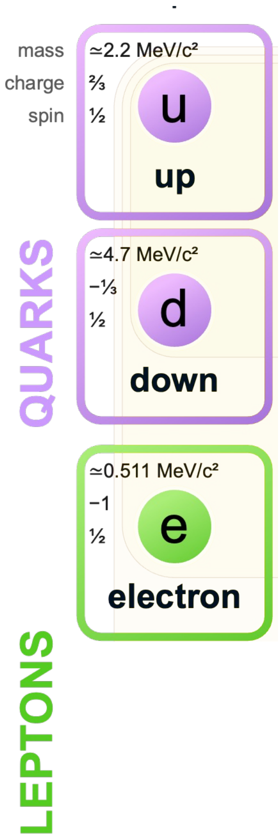


Observations:

- electron: 1897 by JJ Thomson
- muon: 1937 by Anderson & Neddermeyer
- electron neutrino: 1956 by Cowan & Reines
- muon neutrino: 1962@BNL
- up, down, strange quark: 1968@SLAC
- charm quark: 1974@SLAC, BNL
- tau lepton: 1975@SLAC
- bottom quark: 1977@FNAL
- gluon: 1979@DESY
- W and Z bosons: 1983@CERN
- top quark: 1995@FNAL
- tau neutrino: 2000@FNAL
- Higgs boson: 2012@CERN

Earth's building blocks

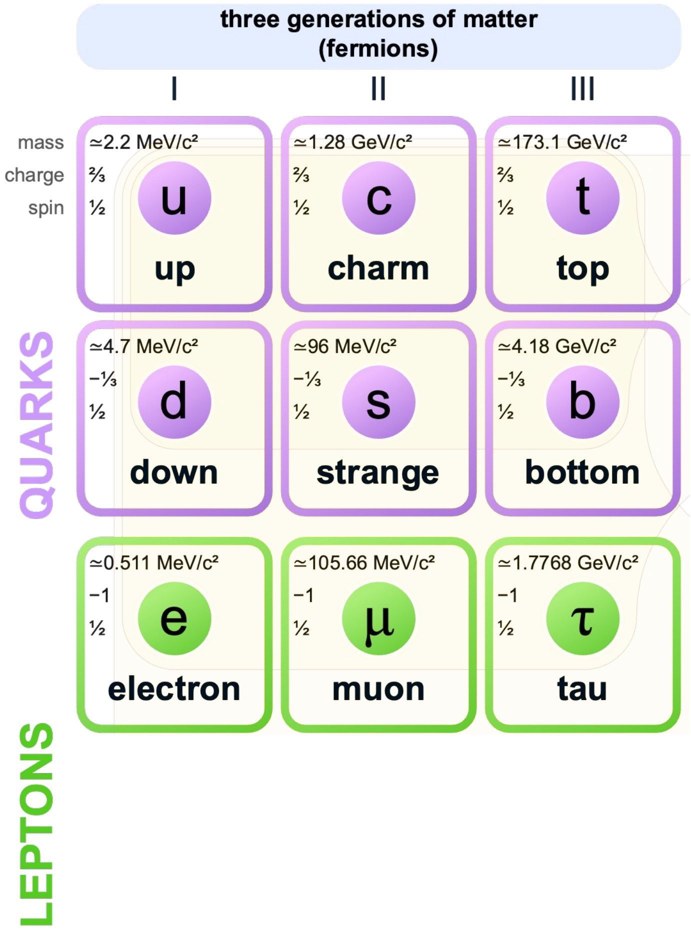
Standard Model of Elementary Particles



- All ordinary matter is made from **up quarks**, **down quarks**, and **electrons**

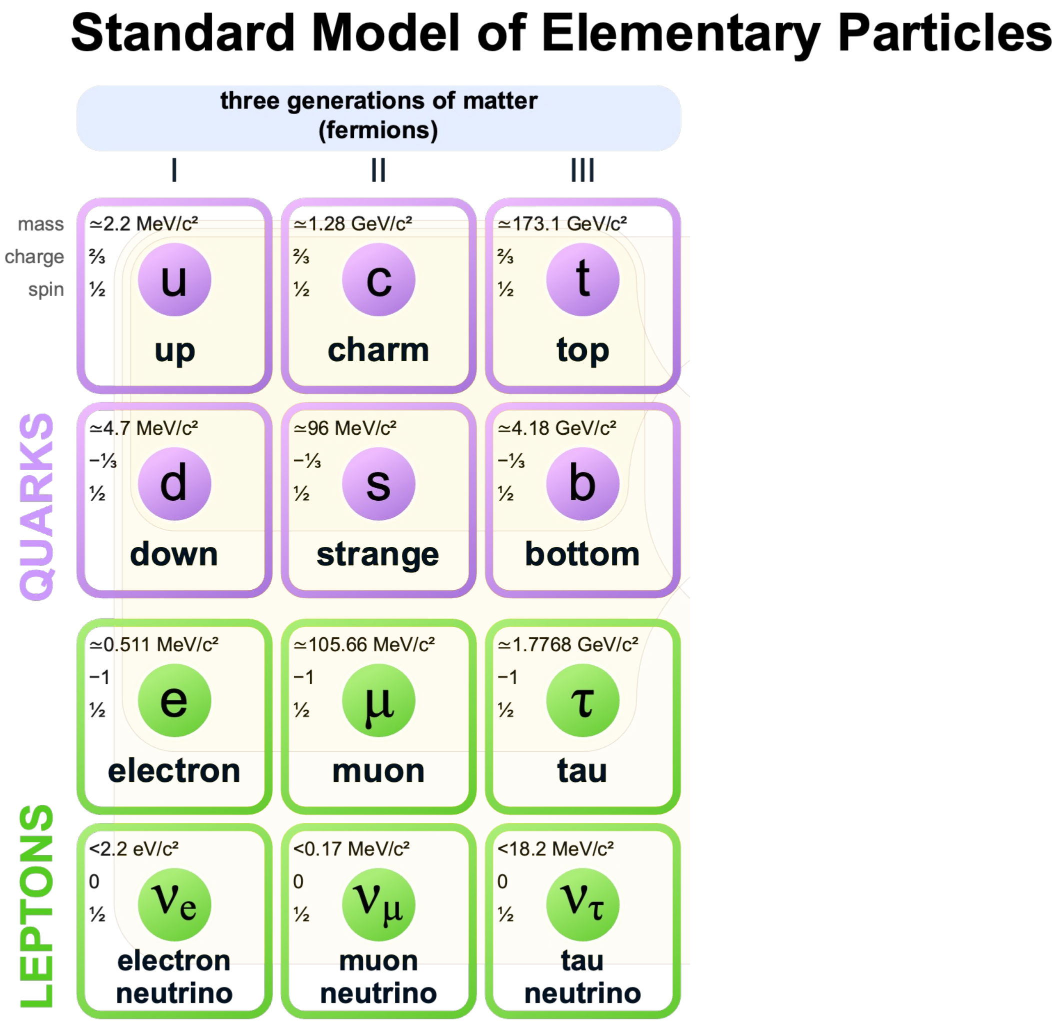
Three generations

Standard Model of Elementary Particles



- All ordinary matter is made from **up quarks**, **down quarks**, and **electrons**
- There are three copies, or *generations*, of quarks and leptons
  - Same properties, only heavier

Neutrinos

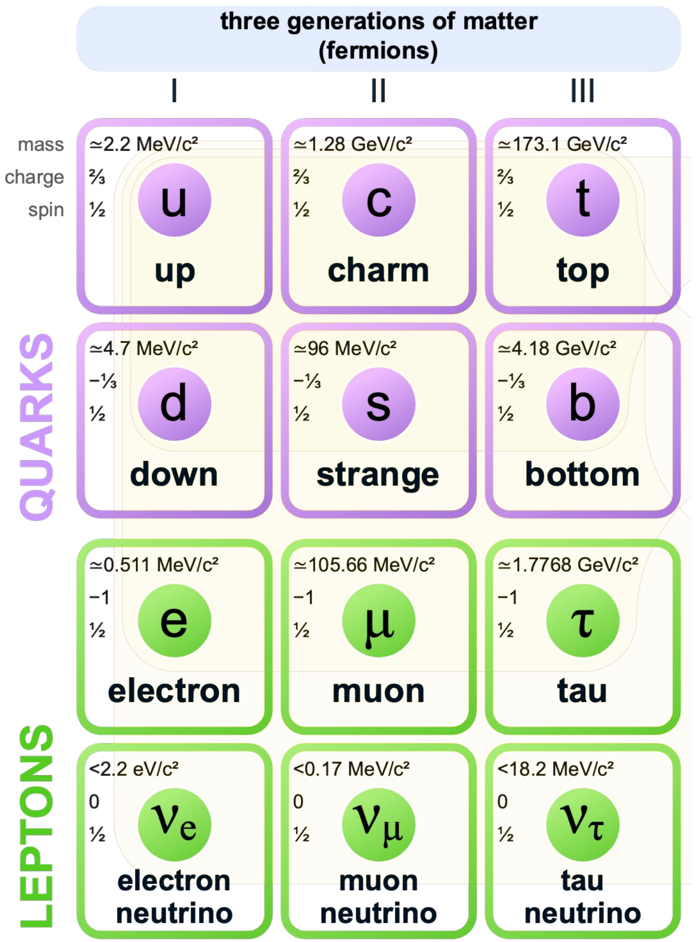


- All ordinary matter is made from **up quarks**, **down quarks**, and **electrons**
- There are three copies, or *generations*, of quarks and leptons
  - Same properties, only heavier
- Leptons also include **neutrinos**, one for each generation
  - Neutrinos have non-zero masses can **oscillate** between flavors– Lecture 5

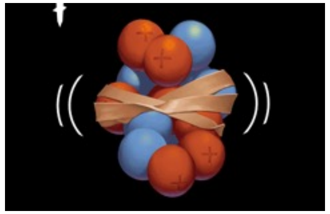
All of these *matter* particles are **fermions:** they have **half integer spin**

Force carriers

Standard Model of Elementary Particles

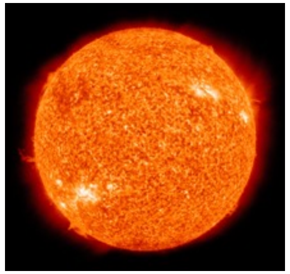


- The other group of particles in the Standard Model are **bosons:** particles with **integer spin**
- These are the force carriers



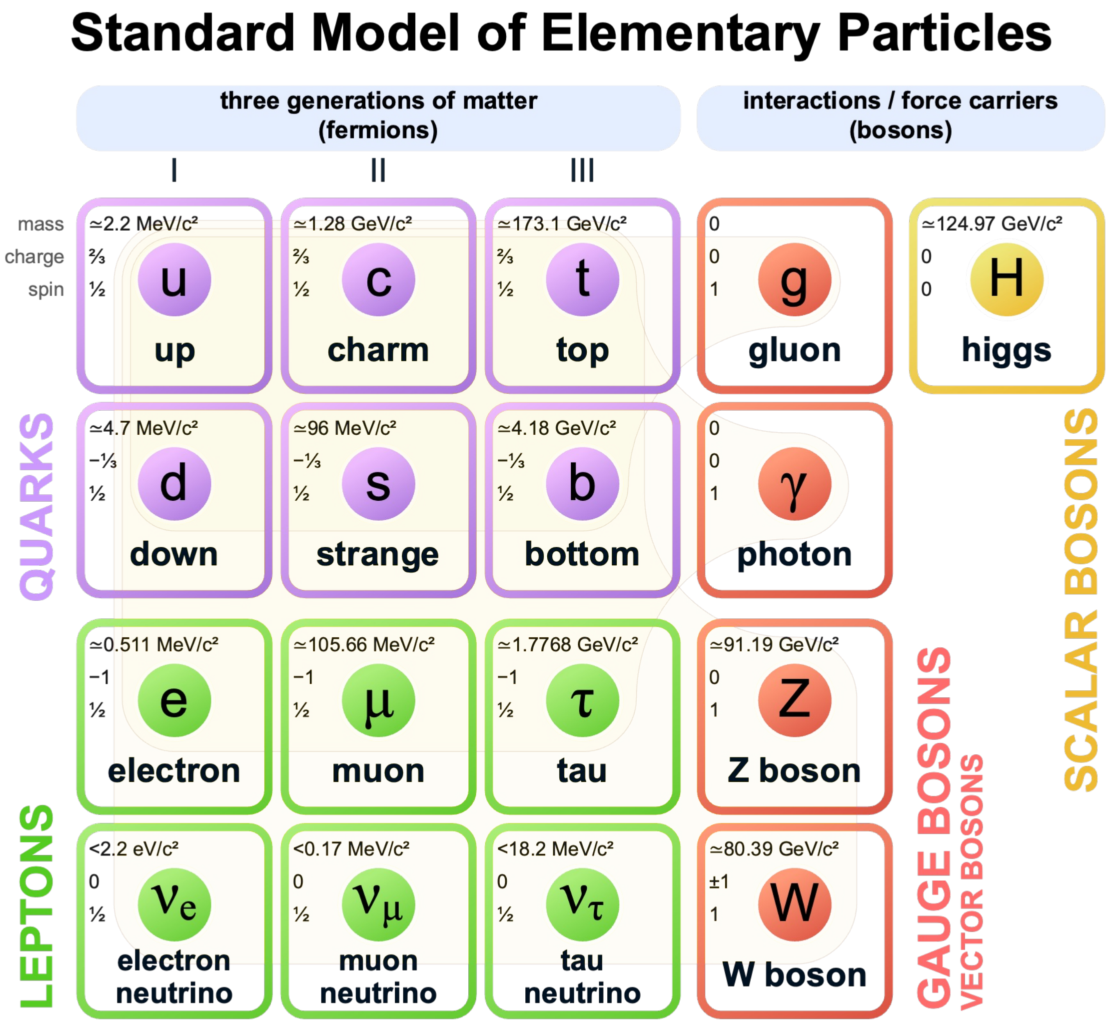
Strong force

Electromagnetic force



Weak force

Higgs boson



Higgs boson

- Spin 0: first fundamental scalar
- Higgs mechanism describes how particles get their mass