History: Discoveries and realizations, shifts of paradigms

Class Schedule

Date	Topic	
Week 1 (9/22/18)	Introduction	YJ
Week 2 (9/29/18)	History of Particle Physics	YJ
Week 3 (10/6/18)	Special Relativity	Ed
Week 4 (10/13/18)	Quantum Mechanics	Ed
Week 5 (10/20/18)	Experimental Methods	Ed
Week 6 (10/27/18)	The Standard Model - Overview	YJ
Week 7 (11/3/18)	The Standard Model - Limitations	YJ
Week 8 (11/10/18)	Neutrino Theory	Ed
Week 9 (11/17/18)	Neutrino Experiment	Ed
Week 10 (12/1/18)	LHC and Experiments	YJ
Week 11 (12/8/18)	The Higgs Boson and Beyond	YJ
Week 12 (12/15/18)	Particle Cosmology	Ed

Class Policy

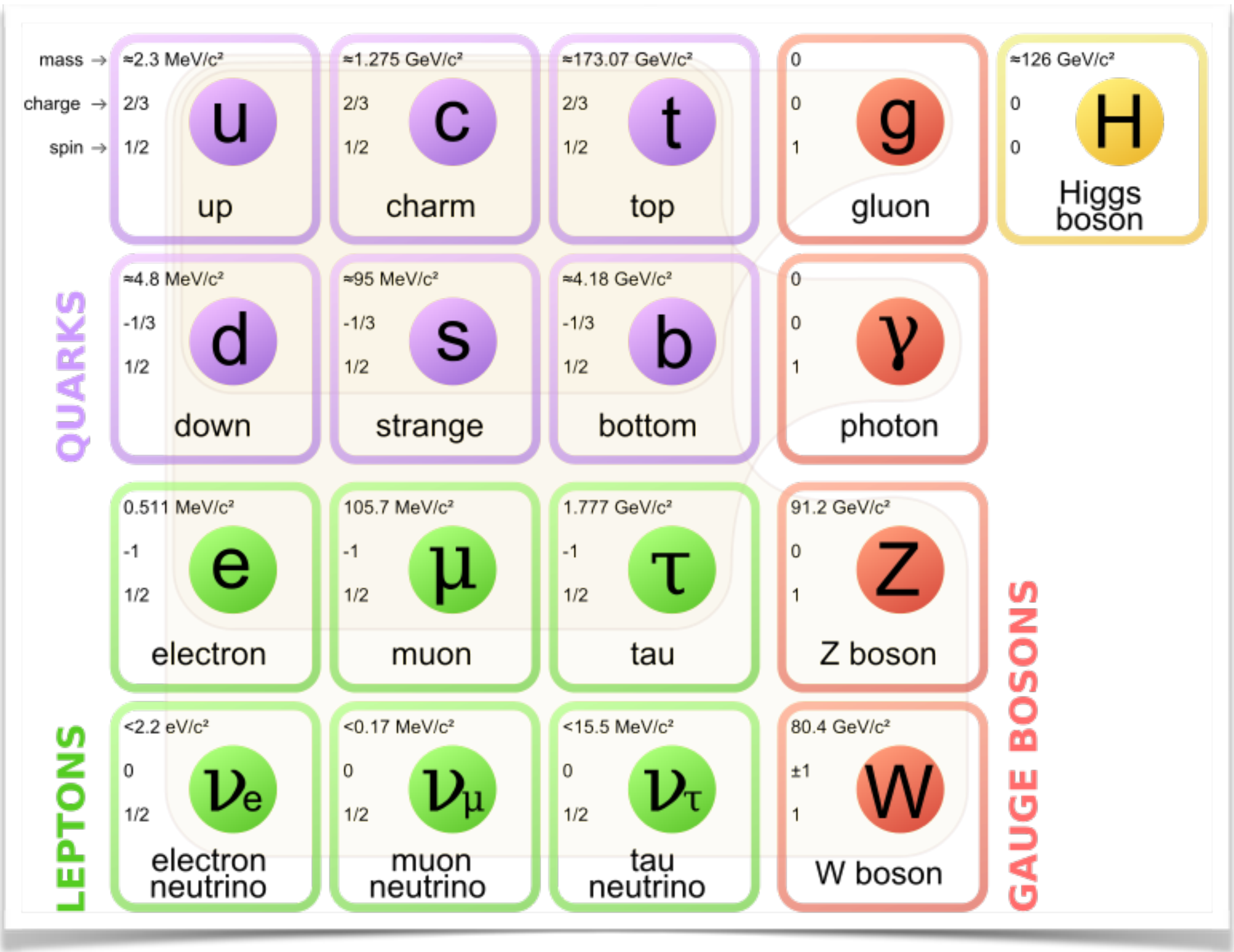
- Classes from 10:00 AM to 12:30 PM (10 min break at ~ 11:10 AM).
- Attendance record counts.
- Up to four absences
- Lateness or leaving early counts as half-absence.
- Send email notifications of all absences to shpattendance@columbia.edu.

Class Policy

- No cell phone uses during the class.
- Feel free to step outside to the hall way in case of emergencies, bathrooms, starvations.
- Feel free to stop me and ask questions / ask for clarifications.
- Resources for class materials, Research Opportunities + Resources to become a particle physicist

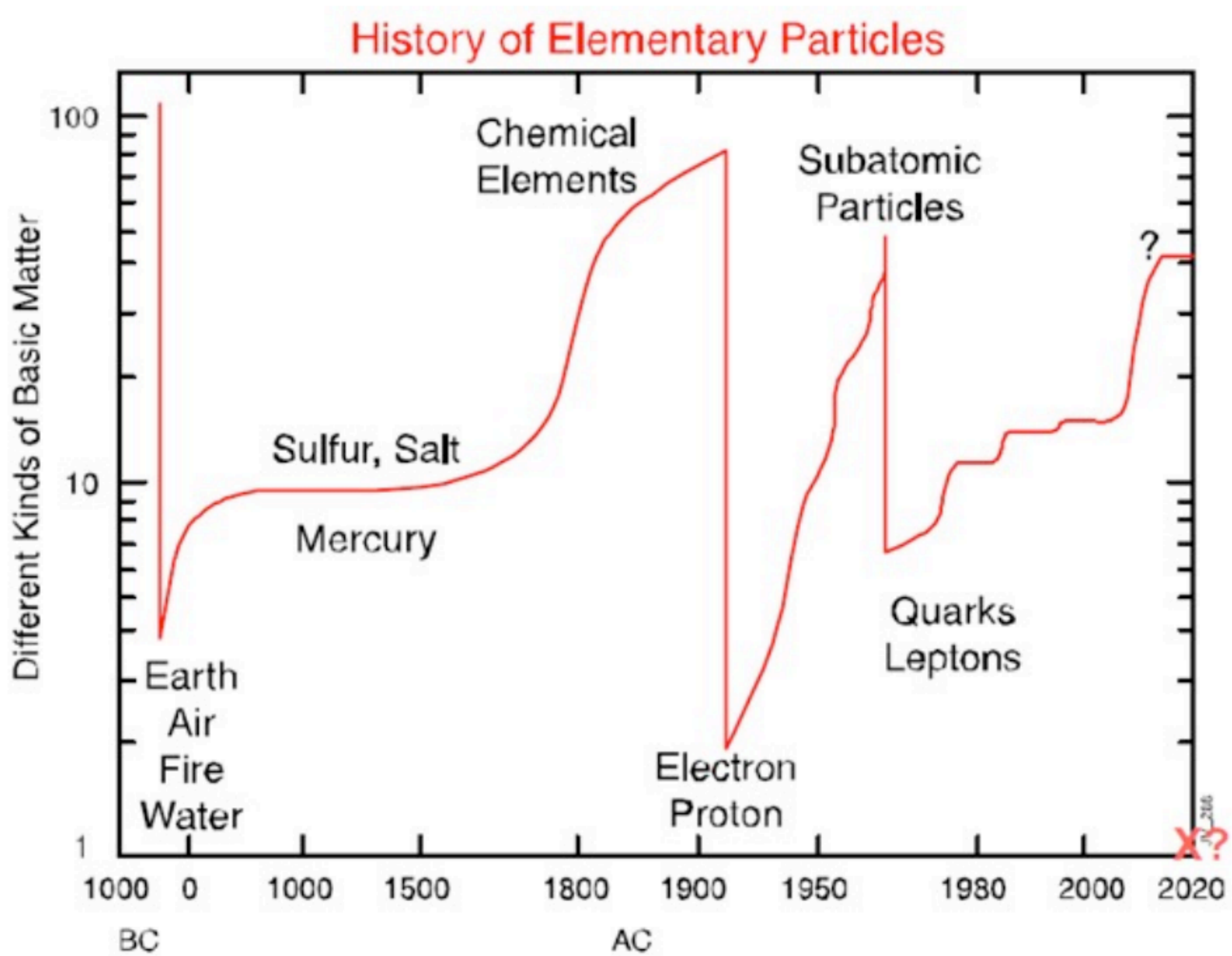
https://twiki.nevis.columbia.edu/twiki/pub/Main/ScienceHonorsProgram

The Big Picture (today)

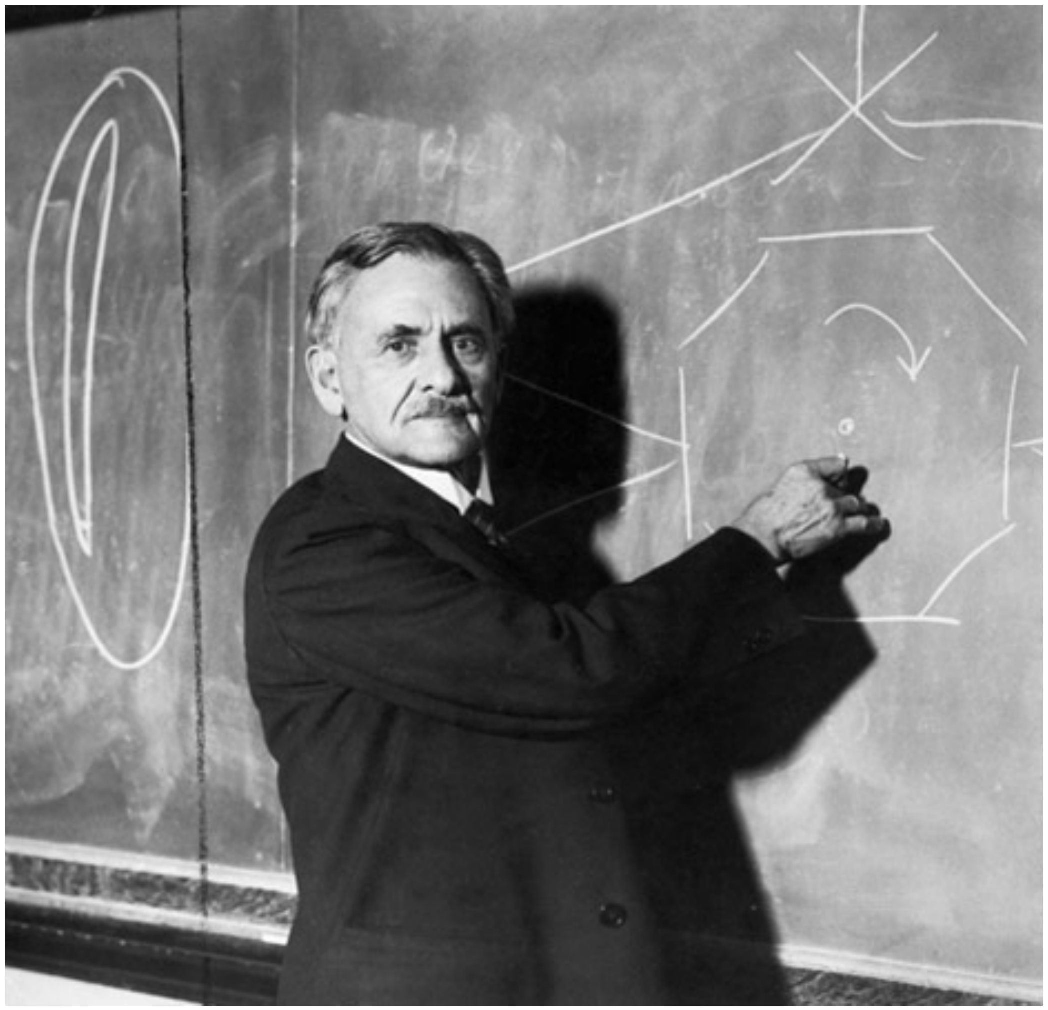


The Standard Model
The orthodox of modern physics
Not perfect
Yet incredibly accurate
.
How did we get here

History of the number of elementary particles



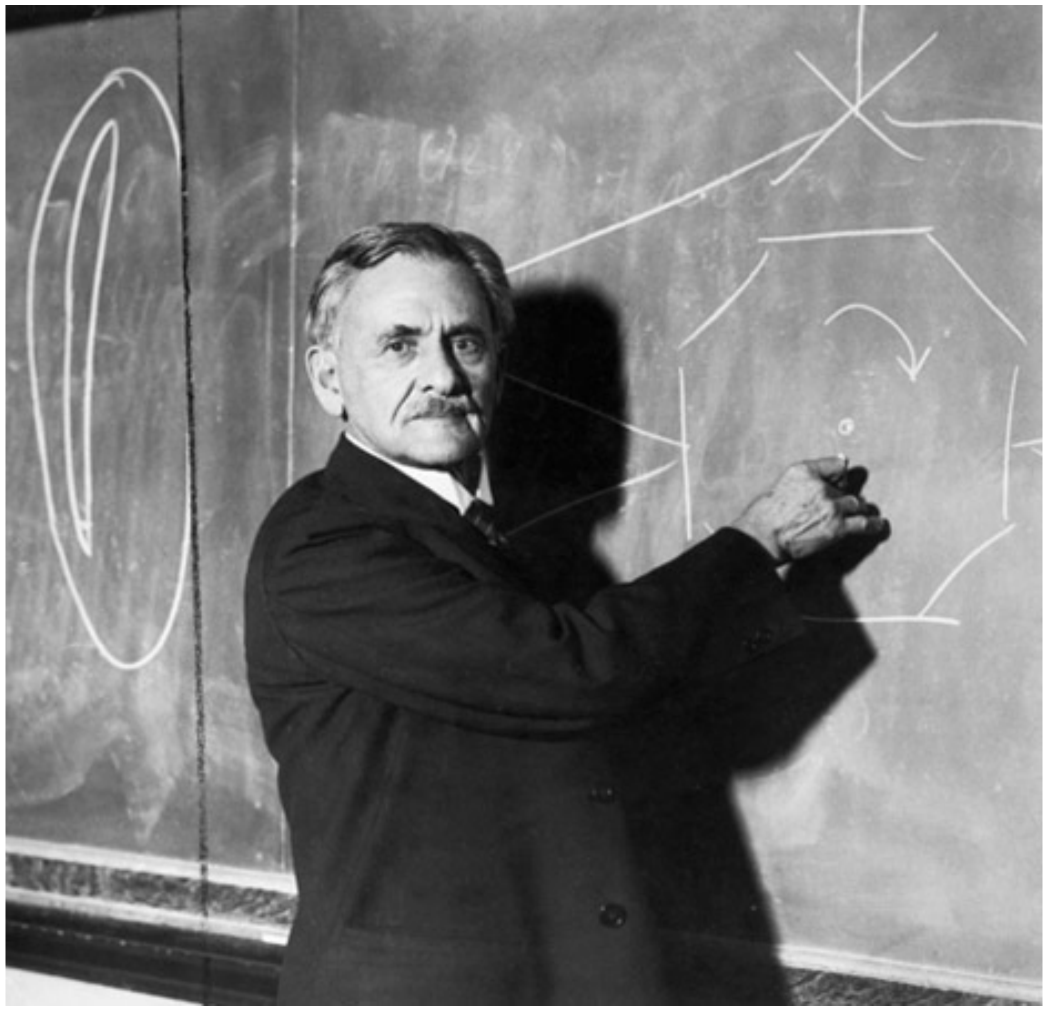
Late 1800's (The end of physics)



"The more important fundamental laws and facts of physical science have all been discovered, and these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote. (…) Our future discoveries must be looked for in the sixth place of decimals."

Albert Abraham Michelson, 1894

Late 1800's (The end of physics)



"The more important fundamental laws and facts of physical science have all been discovered, and these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote. (…) Our future discoveries must be looked for in the sixth place of decimals."

Albert Abraham Michelson, 1894

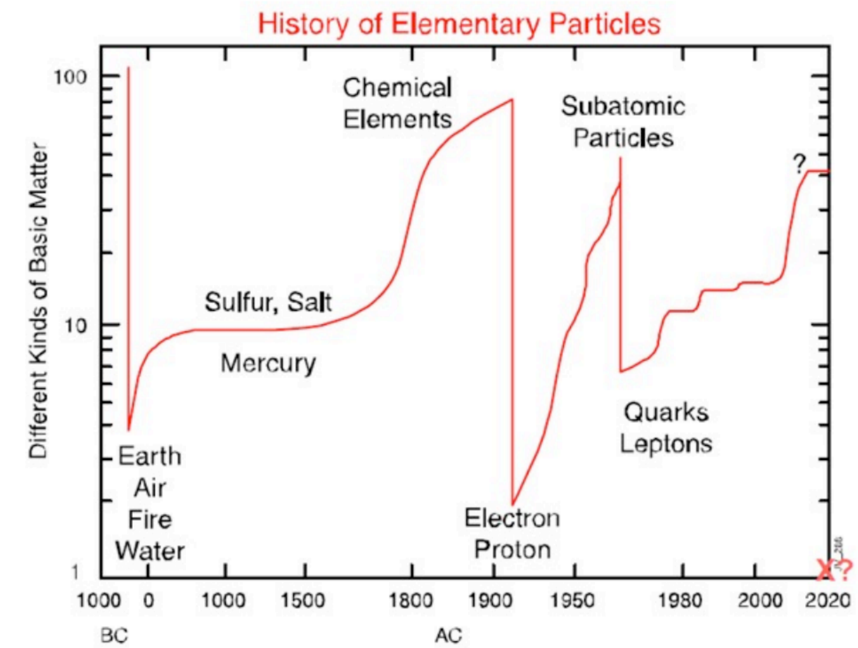
By the way,
Michelson measured the speed of light,
Michelson interferometer is used for LIGO for gravitational wave detection.

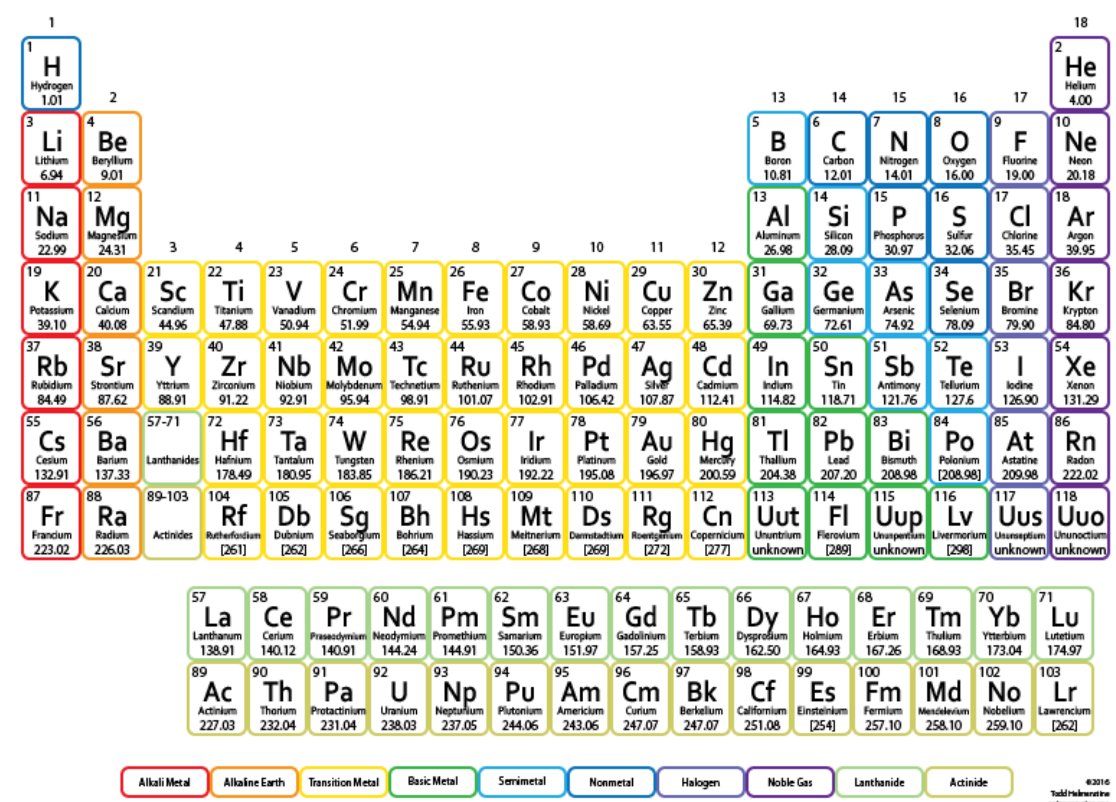
Late 1800's

- **Atoms were the fundamental particles of nature.**

- Mendeleev's Periodic Table summarizes patterns and scientists used these patterns to search for "missing" elements.

- Chemists and physicists were classifying the known (and yet-to-be discovered) elements according to their chemical properties.



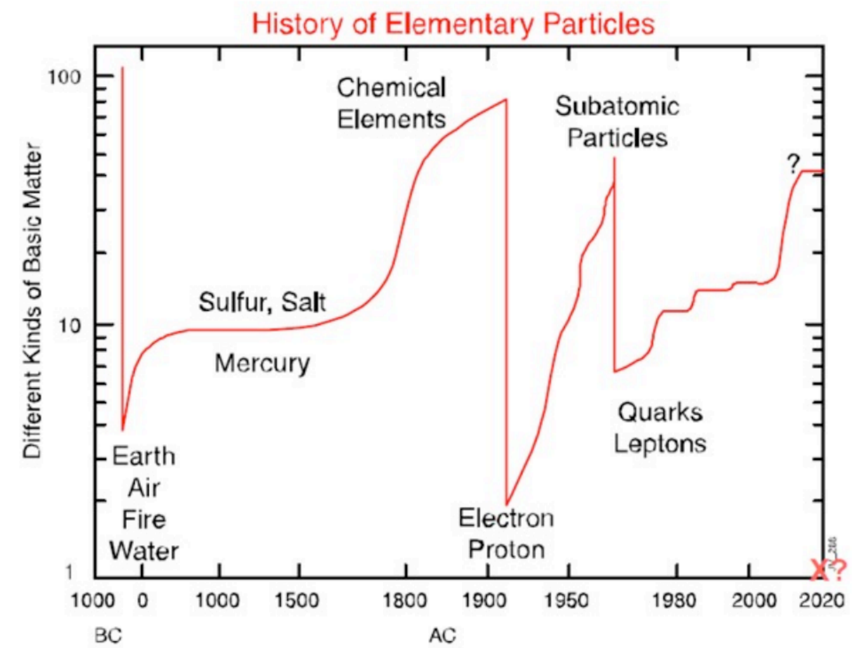


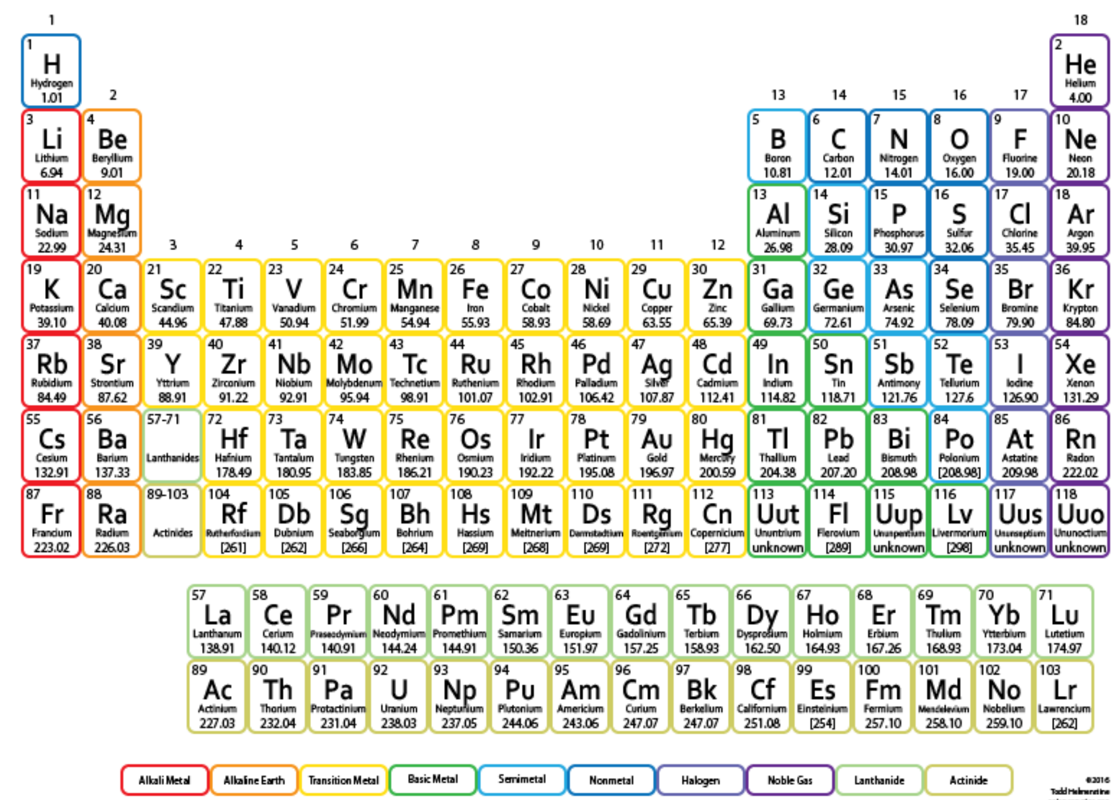
Late 1800's

- **Atoms were the fundamental particles of nature.**

- *Trends* in the periodic table suggest some underlying atomic structure, i.e., atoms are composites of smaller, more *"fundamental"* particles that determine chemical behavior.

- Are these the smallest Lego blocks? Or a manifestation of smaller Lego blocks?





The 1890's

- New, unstable elements (radioactivity) were being investigated by M. Curie, P. Curie, E. Rutherford, et al.
- Radioactivity: describes the emission of particles from atomic nuclei as a result of nuclear instability.
- The fact that atoms seemed to spontaneously split apart also suggests they are not fundamental particles.

Pierre and Marie Curie

Marie Curie Facts

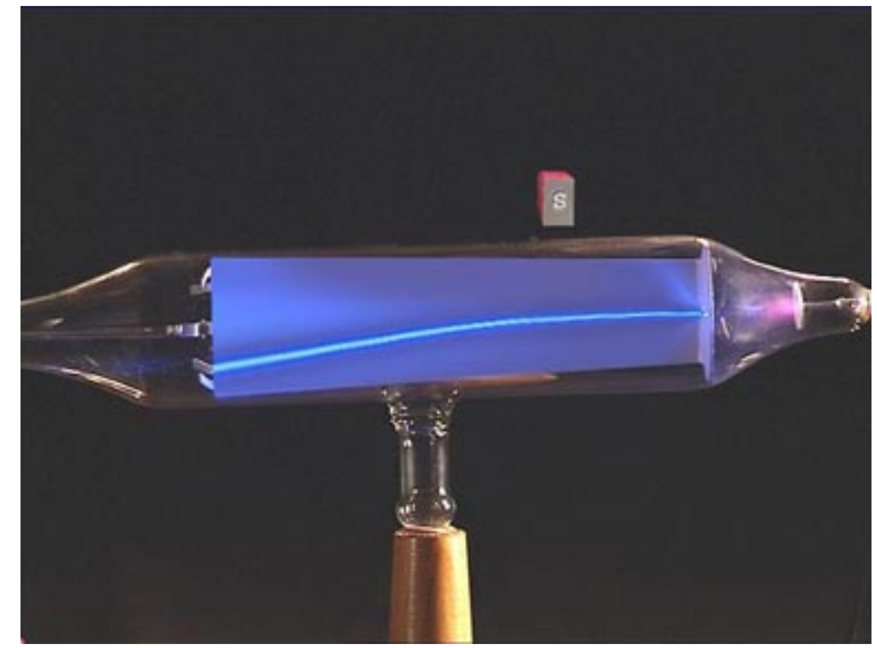
- She helped save a million soldiers during world war 1. (http://theinstitute.ieee.org/tech-history/technology-history/how-marie-curie-helped-save-a-million-soldiers-during-world-war-i)
- Albert Einstein reportedly remarked that she was probably the only person who could not be corrupted by fame.

The Classical Era (1897-1932)

Discovery of the electron (1897)

- For a number of years, scientists had generated "cathode rays" by heating filaments inside gas-filled tubes and applying an electric field.
  - Cathode rays have electric charge, because they can be deflected by magnetic fields.
  - Question: Are cathode rays some kind of charge fluid, or are they made of charge particles (like ions)?

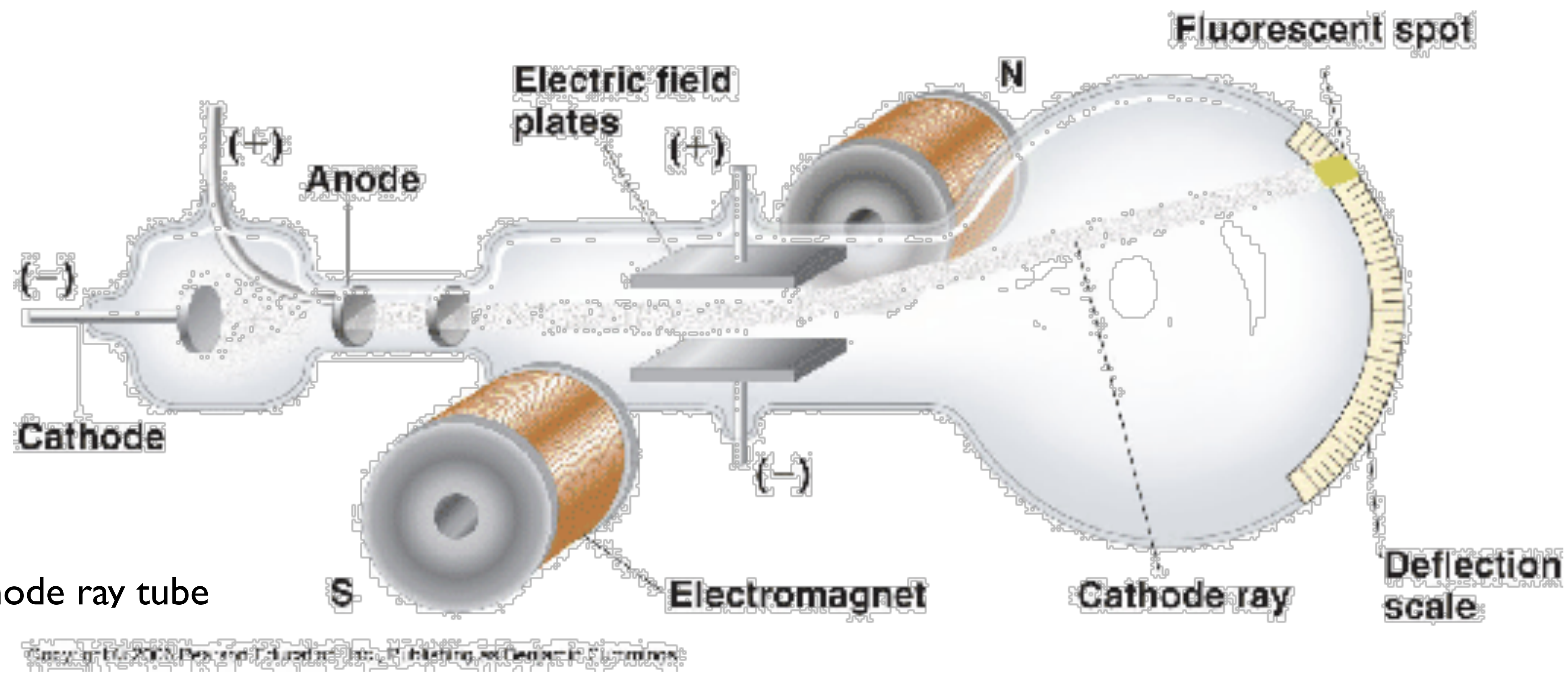
- In 1897, J.J. Thompson attempted a measurement of the charge/mass ratio of cathode rays to see if they were particles.



J. J. Thompson

Discovery of the electron (1897)

- Put a cathode ray into a known electric magnetic field.
- Measure the cathode ray's deflection.



Thompson's cathode ray tube

- If cathode rays are composed of discrete charges, their deflection should be consistent with the Lorentz Force Law:

$$\vec{F} = q\,(\vec{v} \times \vec{B} + \vec{E})$$

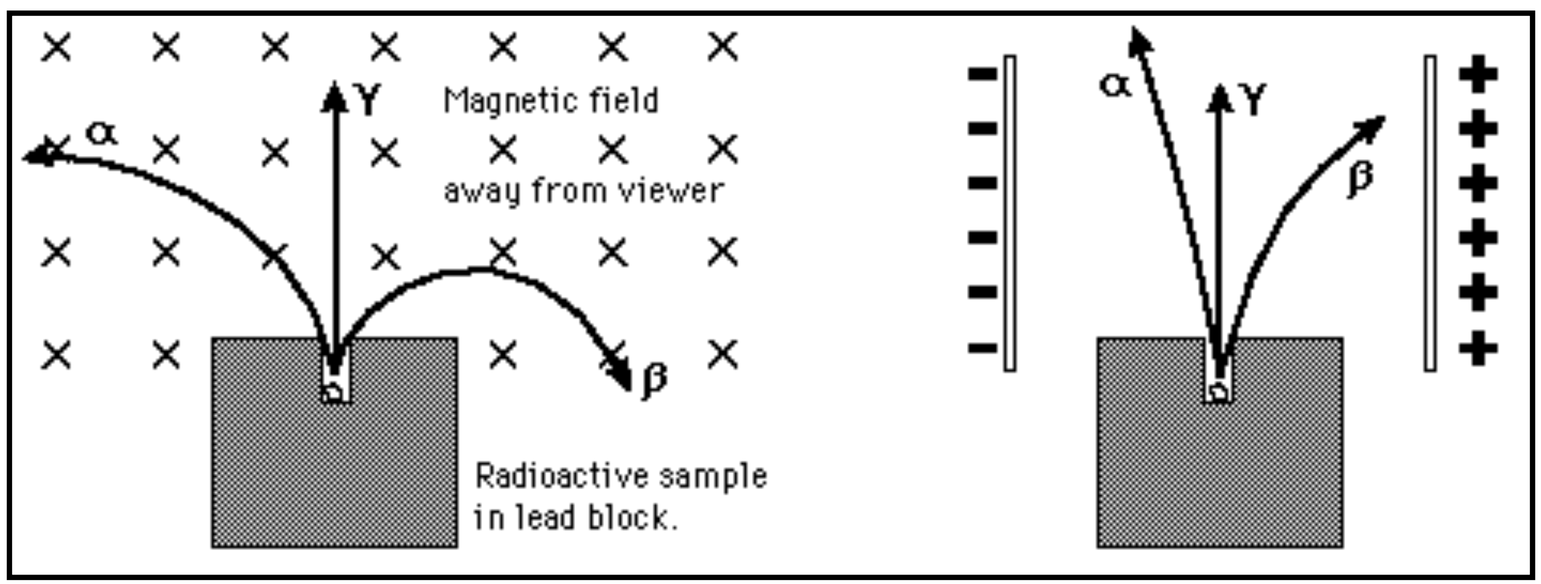
Discovery of the electron (1897)

- Thomson found that cathode ray deflections were consistent with the Lorentz Force, and could be particles ("corpuscules") after all.
- The charge to mass ratio e/m was significantly larger than for any known ion (over 1000x e/m of hydrogen). This could mean two things:
  1. **The charge e was very big.**
  2. **The mass m was very small.**
- Independent measurements of e/m (oil drop experiment) suggested that, in fact, cathode rays were composed of extremely light, negatively charged particles.
- Thomson called his corpuscle's charge the **electron** (from the Greek "amber"); eventually, this term was applied to the particles themselves, whose mass is:

$$m_e = 0.511 \text{ MeV}/c^2$$

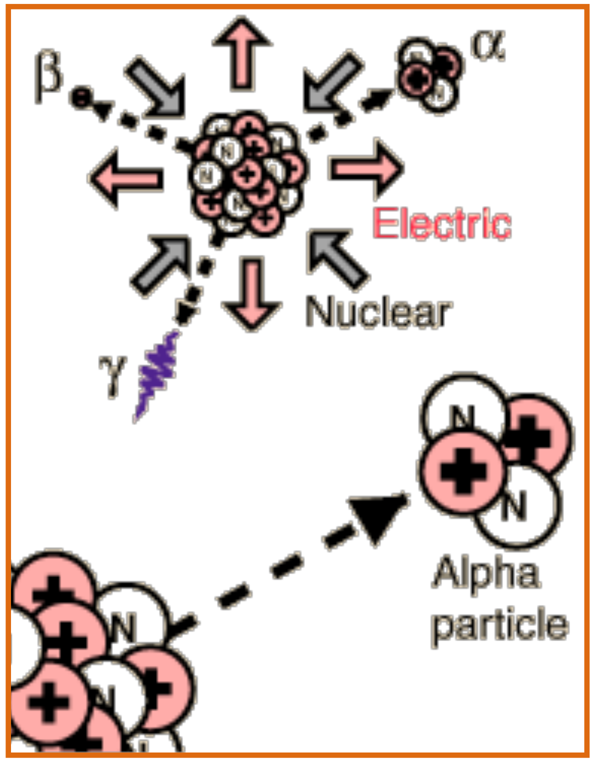
The 1890's

- At the time, it was known that unstable elements tended to emit three types of particles, which were differentiated by their electric charge.



1) **Alpha particles (α):** +2 electric charge; about 4x proton mass
2) **Beta particles (β):** -1 electric charge; about 1/1800 proton mass
3) **Gamma particles (γ):** electrically neutral;

The 1890's



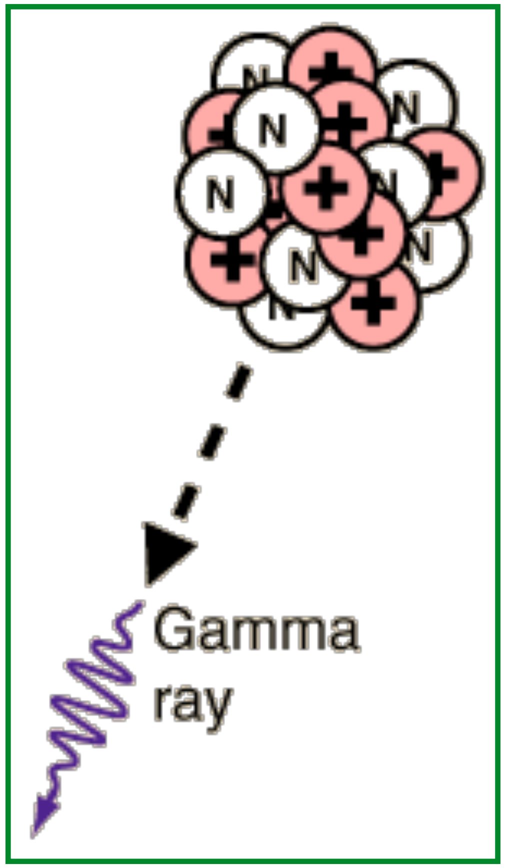
- The α-particle, as it turns out, is just He^{+2}, the nucleus of a helium atom. It is emitted in decays like:

$$^{218}_{84}Po \rightarrow ^{214}_{82}Pb + \alpha$$

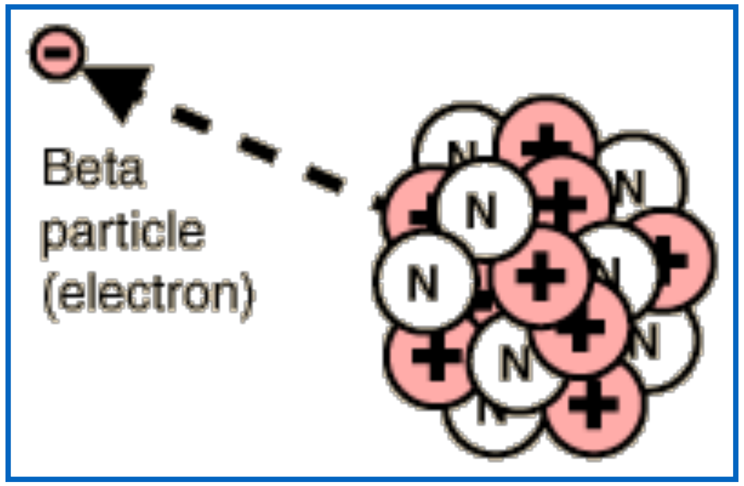
- The β-particle is an electron (not known until 1897). A beta-decay example:

$$^{234}_{90}Th \rightarrow ^{234}_{91}Pa + \beta$$

- The γ-particles are photons, emitted in such decays as:

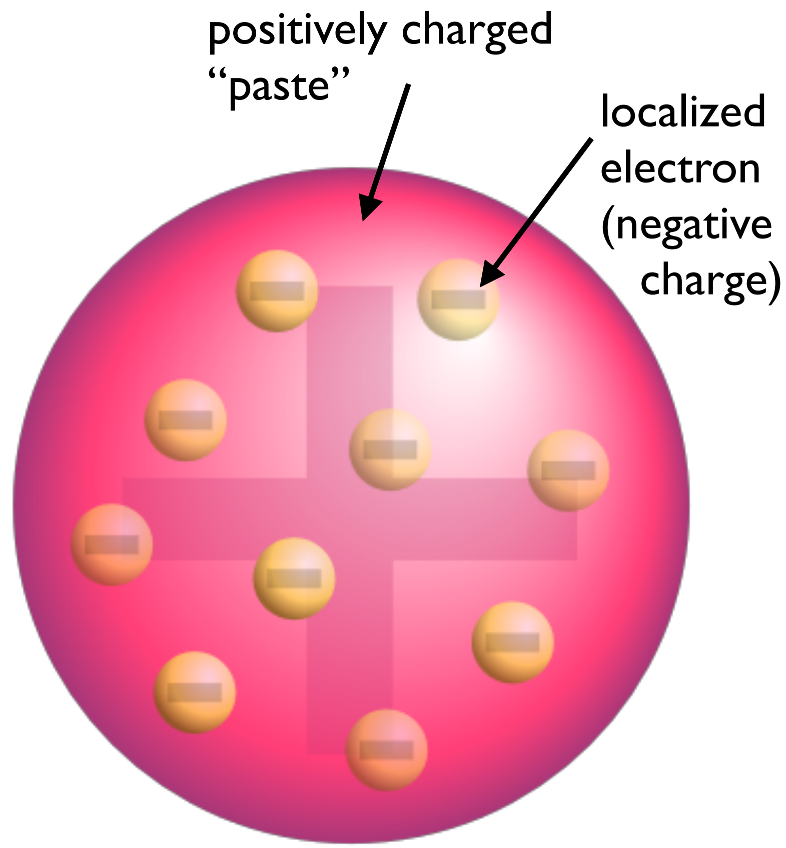


$$^{137}Ba^{*} \rightarrow ^{137}Ba + \gamma$$



Discovery of the electron (1897)

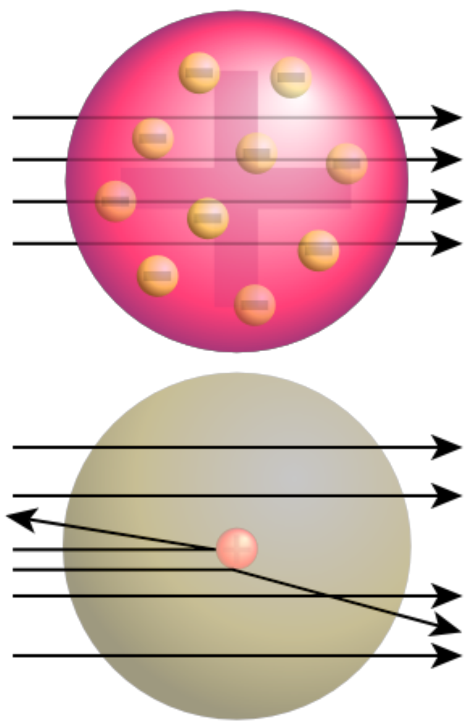
- Thompson correctly believed that electrons were fundamental components of atoms (e.g. responsible for chemical behavior).
- Because atoms are electrically neutral, he concluded that the negatively charged point-like electrons must be embedded in a "gel" of positive charge such that the entire atoms is neutral.
- Thompson: electrons are contained in can atom like "plums in a pudding".



Thomson's plum-pudding model of the atom.

Rutherford Experiment

- Test of Thompson's theory of atomic structure (1909-1913):

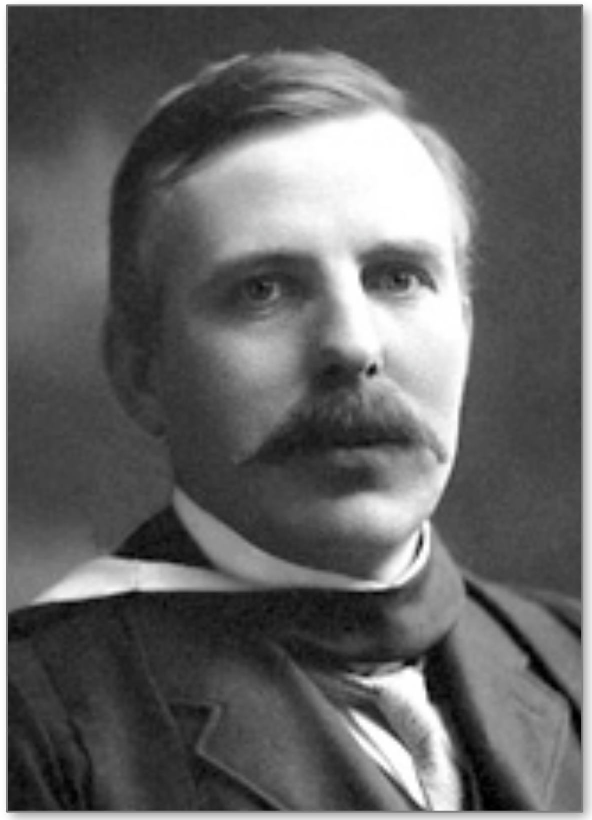


Thompson's model of atom

Rutherford's model of atom

Image: Wikipedia.org

Scattering two particles and measuring the deflection gives information about particle structure and interaction.



E. Rutherford
Image: NobelPrize.org

Rutherford Experiment

- Gold-foil experiment:

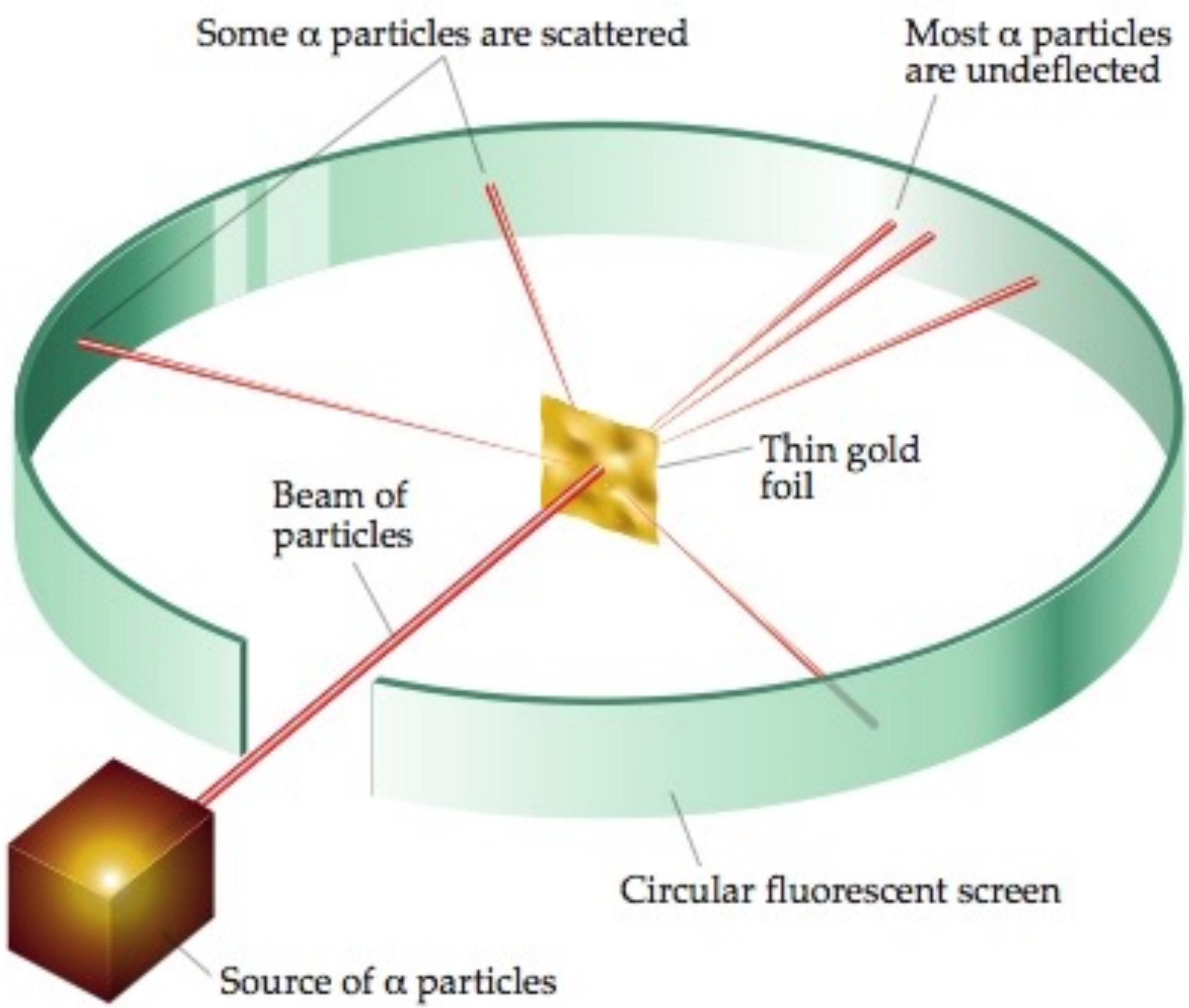
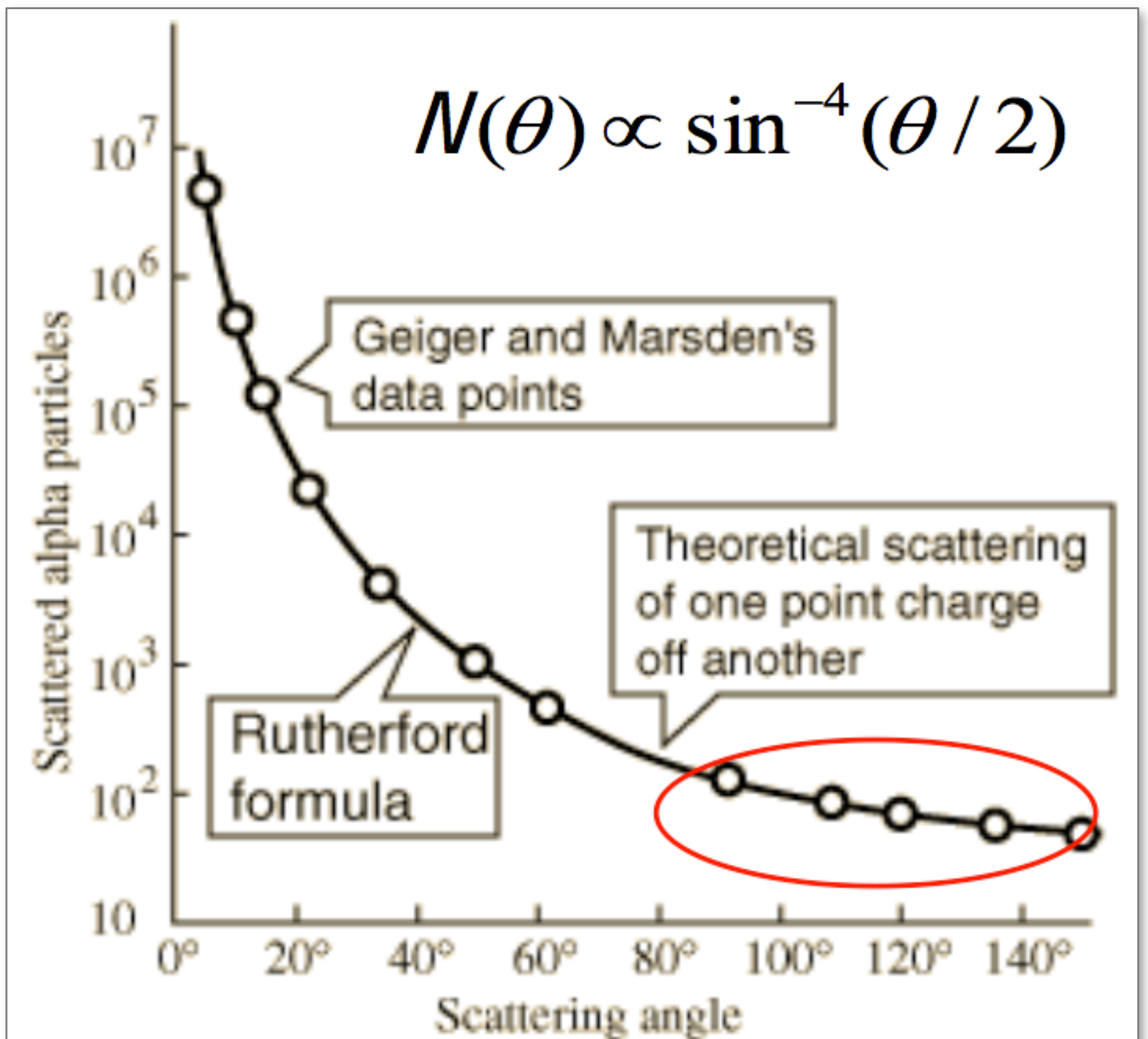


Image: highered.mcgraw-hill.com

Rutherford Experiment

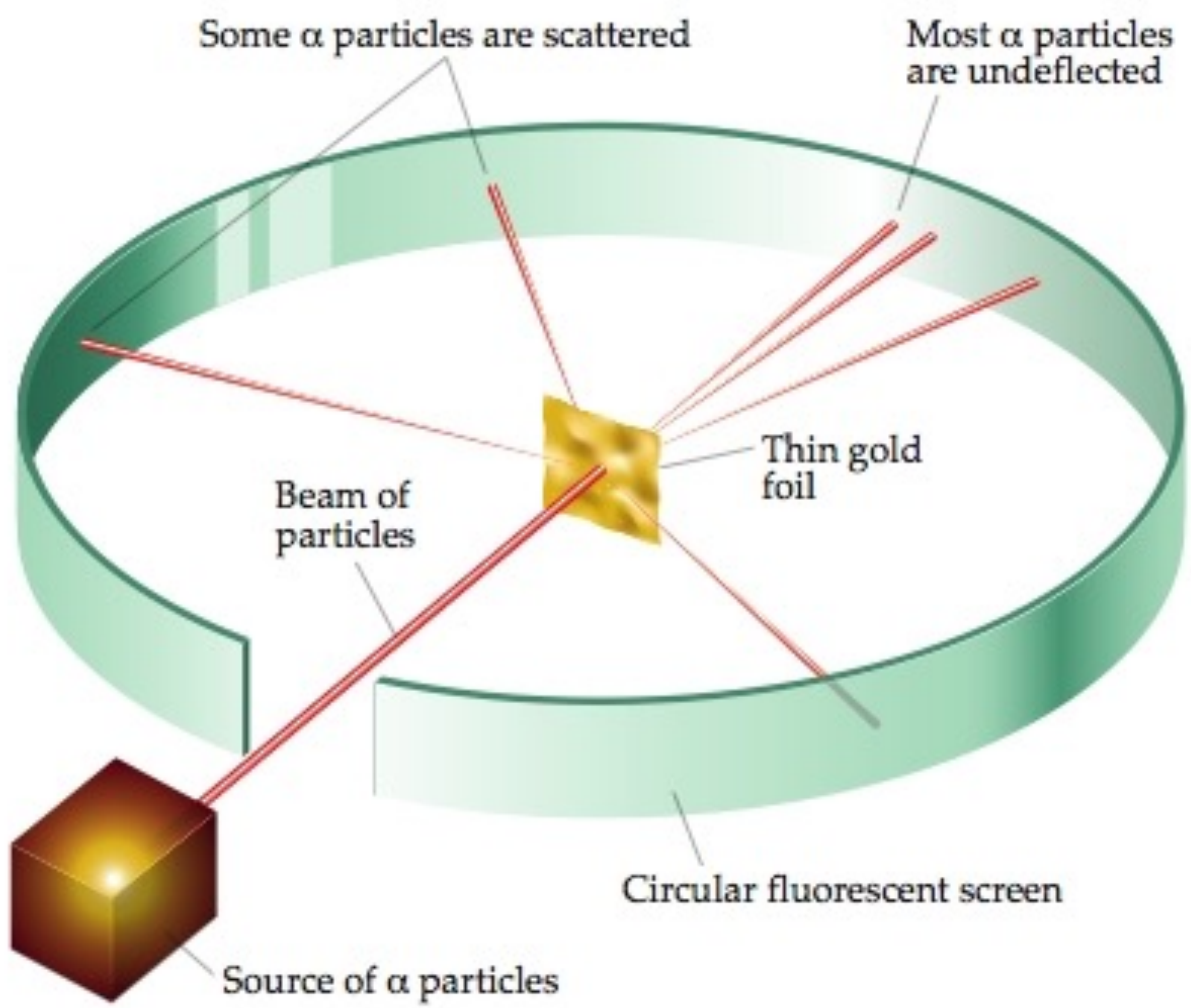
- Gold-foil experiment:



- Most α-particles were not scattered at all, but a few were scattered through angles of 90° or more!!

Rutherford Experiment

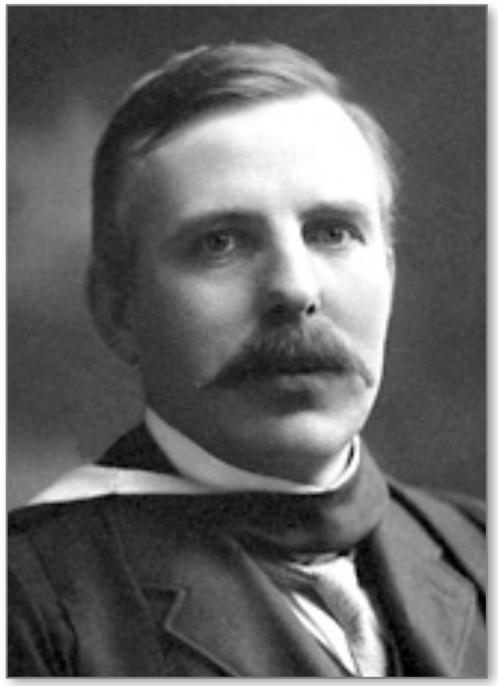
- Gold-foil experiment:



- Most α-particles were not scattered at all, but a few were scattered through angles of 90° or more!!
- Rutherford: large-angle scattering is exactly consistent with Coulomb repulsion of two small, dense objects.
- **Conclusion:** scattered particle beam is evidence of a dense, compact, positively-charged structure, located at the center of the atom.

Image: highered.mcgraw-hill.com

E. Rutherford
Image: NobelPrize.org



Discovery of the nucleus (1911)

- Rutherford's efforts formed one of the truly great experiments of modern physics.
- He quickly understood that he had discovered a new nuclear model of the atom, saying of the result:

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

- In a later experiment (1919), he identified the nucleus of the hydrogen atom as an elementary particle present in all other nuclei: **the Proton**.

J. Chadwick
Image: NobelPrize.org

Discovery of the Neutron (1932)

- In the Bohr atomic model, atoms consisted of just protons and electrons.
- However, there was a major problem: most elements were heavier than they should have been.
  - He charge is +2e, but weighs $4m_p$;
  - Li charge +3e, but weighs $7m_p$; etc.
- To account for the missing mass in heavier elements, nuclei had to contain other particles comparable in mass to the proton (1 GeV/c^2), but with no electric charge.
- The mysteries massive, neutral particle inside atomic nuclei eluded detection until 1932, when J. Chadwick observed the neutron in an α-Be **scattering experiment**.

P. Dirac
Image: NobelPrize.org

Initiation of anti-matter (1927)

- P. Dirac attempted to combine quantum mechanics with the relativistic energy formula:

$$E^2 - (\vec{p}c)^2 = (mc^2)^2$$

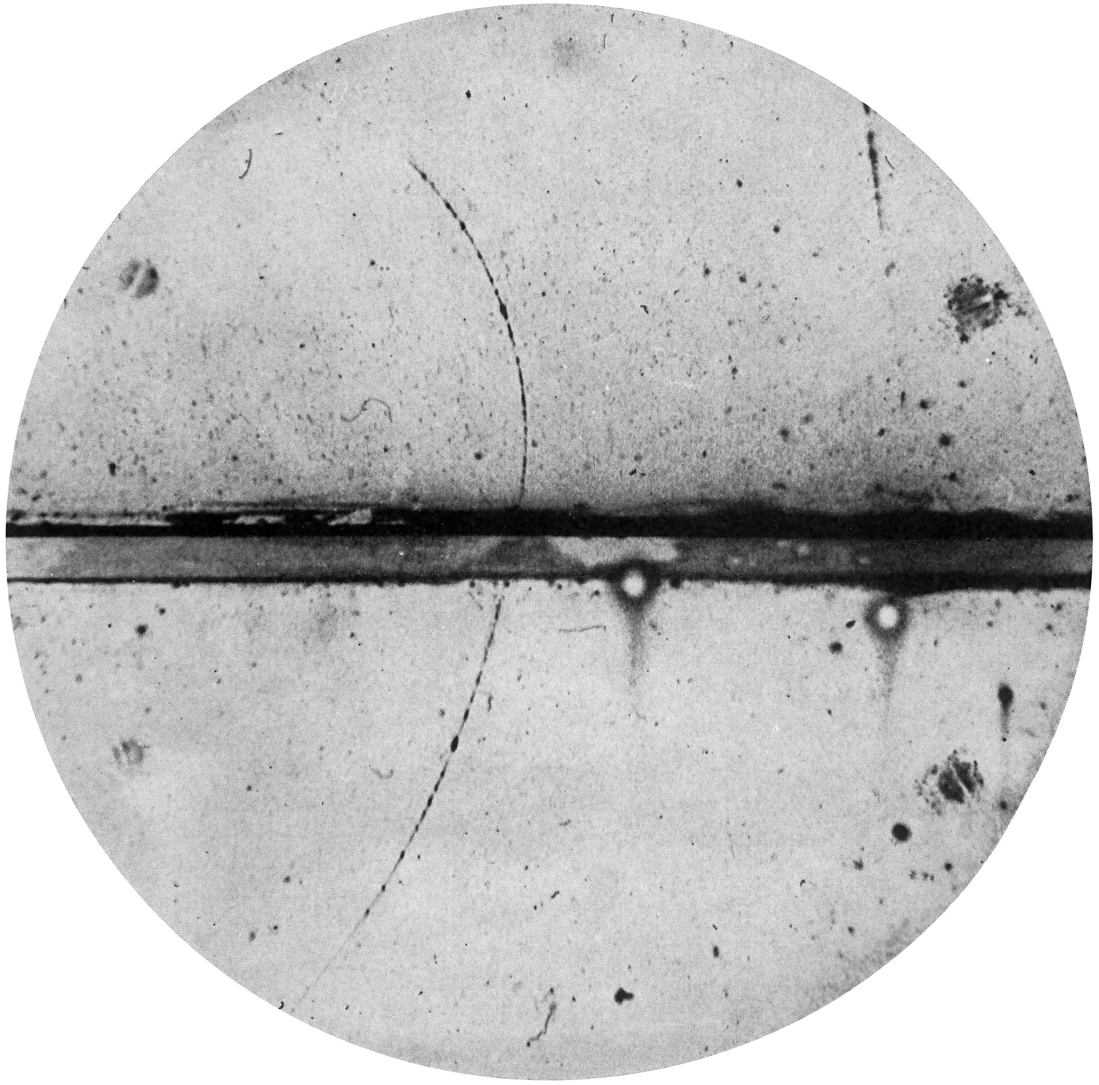
- **Problem:** the theory allows both positive and negative energy solutions!

$$E_+ = +\sqrt{p^2c^2 + m^2c^4}$$
$$E_- = -\sqrt{p^2c^2 + m^2c^4}$$

- **Dirac's interpretation:** the positive solutions are ordinary particles; the negative solutions are anti-matter
- But was anti-matter real, or just a mathematical artifact?

Discovery of antimatter (1932)

- In 1932, C. Anderson observed the anti-electron (positron), validating Dirac's theory.
- The chamber was placed in a magnetic field (pointing onto the page) which caused the particle to travel in a curve.
- But was it a negative charge traveling downward, or a positive charge traveling upward? From the curvature of the track, and from its texture, Anderson was able to show that the mass of the particle was close to that of electron.

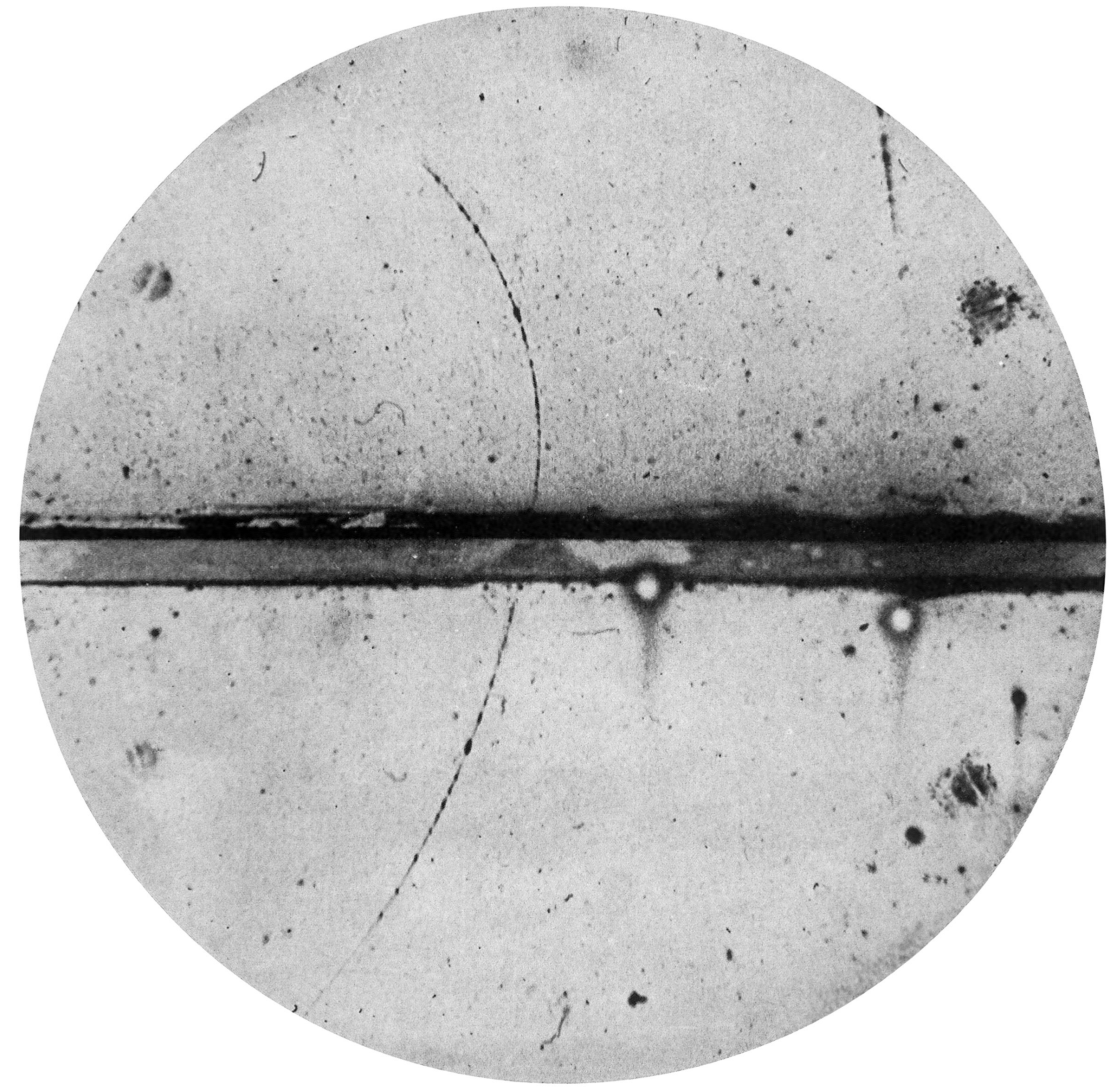


Discovery of the positron in a cloud chamber by C. Anderson

Image: J. Griffiths, *Intro to Elementary Particles*

Discovery of antimatter (1932)

- Feynman's explanation of negative energies: they are the positive energy states of anti-particles!
- Anti-matter is a universal feature of quantum field theory: all particles have matching anti-particles.
- Anti-particles have the same mass as their particle partners, but opposite quantum numbers (charge, lepton number, etc.).



Discovery of the positron in a cloud chamber by C. Anderson

Image: J. Griffiths, *Intro to Elementary Particles*

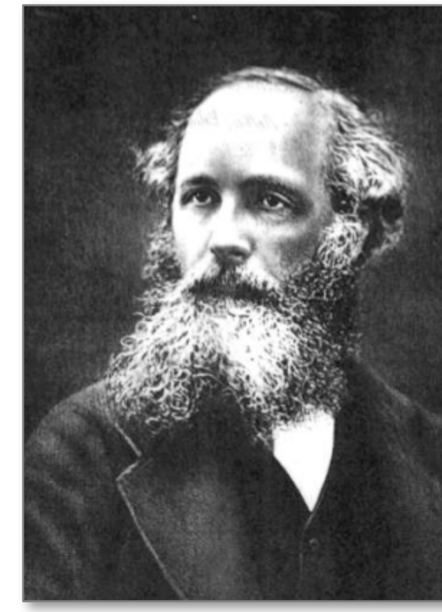
Notation: Particle e^-, p

Antiparticle $e^+, \bar{e}, \bar{p}$

In the mean time (1900-1924)

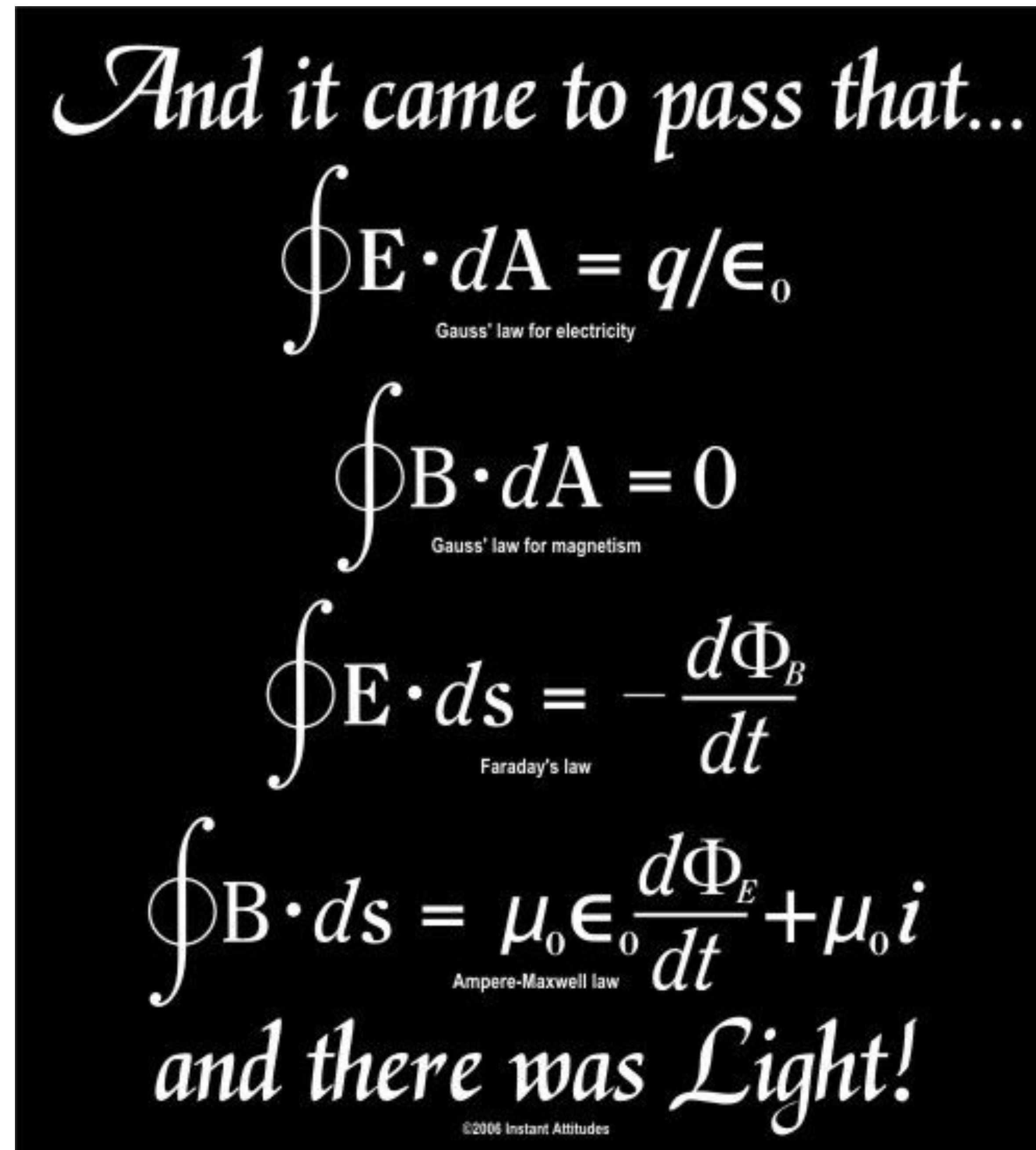
- **A new particle, the electromagnetic field quantum**
- The discovery of the **photon**, the quantum of the electromagnetic field, marked a major departure from classical physics.
- As with the developing picture of the atom, it took several decades (and several incontrovertible experiments) before physicists accepted the existence of the photon.
- But, before we get into that, let's talk about what classical physics actually had to say about electromagnetism.

J.C. Maxwell
The University of York

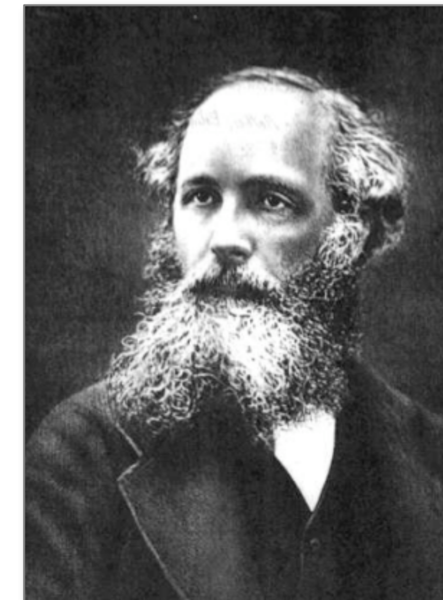


Classical Electrodynamics

- Work by J. C. Maxwell in the mid/late 1800s:
  - The electromagnetic (EM) field could be understood in terms of four equations.
- These are Maxwell's equations in the vacuum, relating the electric and magnetic field.

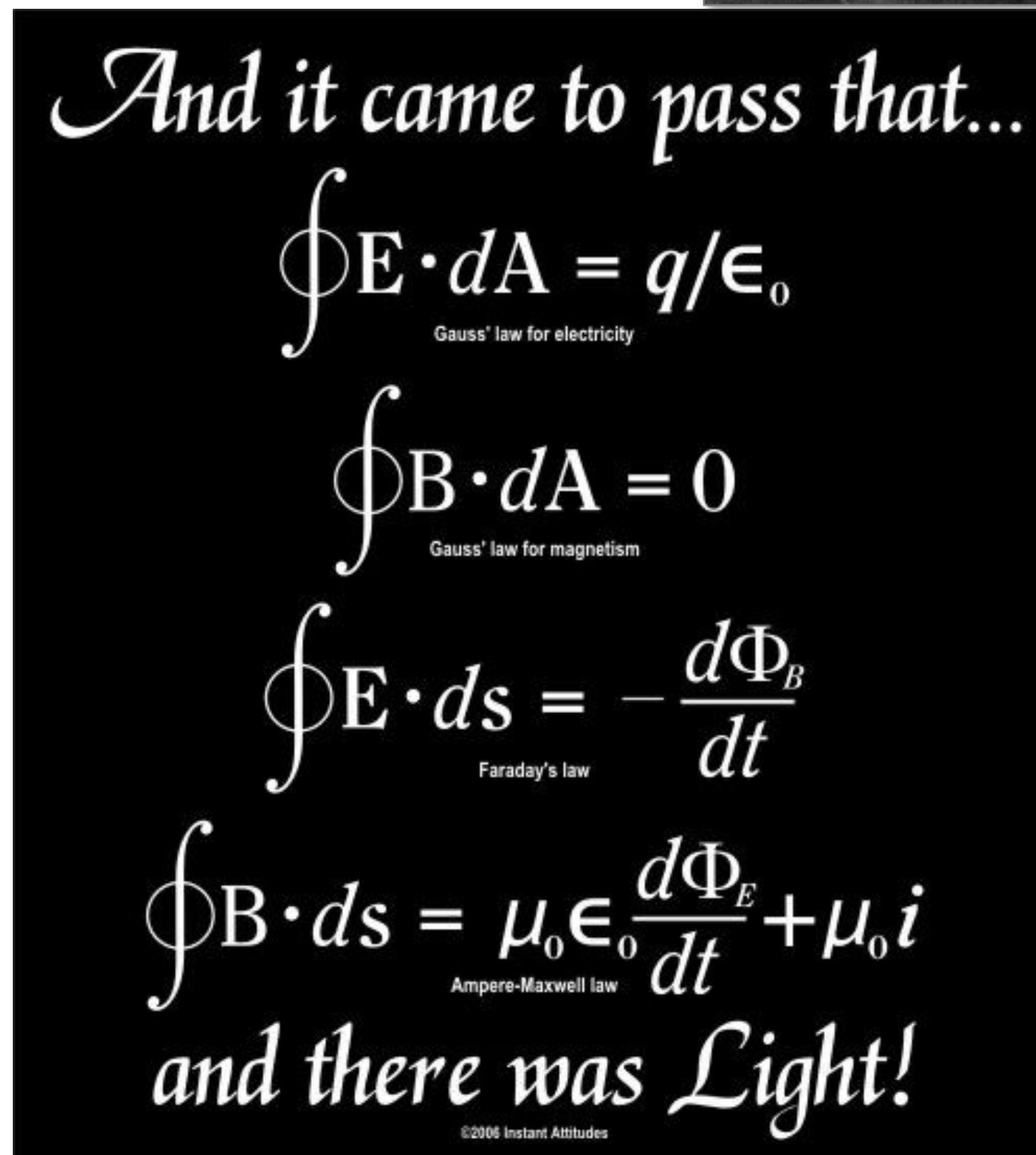


J.C. Maxwell
The University of York



Classical Electrodynamics

- Gauss's law: the electric flux leaving a volume is proportional to the charge inside.
- Gauss's law for magnetism: there are no magnetic monopoles; the total magnetic flux through a closed surface is zero.
- Faraday's law of induction: the voltage induced in a closed circuit is proportional to the rate of change of the magnetic flux it encloses.
- Ampere's circuital law: the magnetic field induced around a closed loop is proportional to the electric current plus displacement current.



Classical Electrodynamics

- Maxwell's equations predict self-propagating, transverse, electric and magnetic (electromagnetic) waves, aka light, which travel at speed $c=3x10^8$m/s and have frequency $f=c/\lambda$

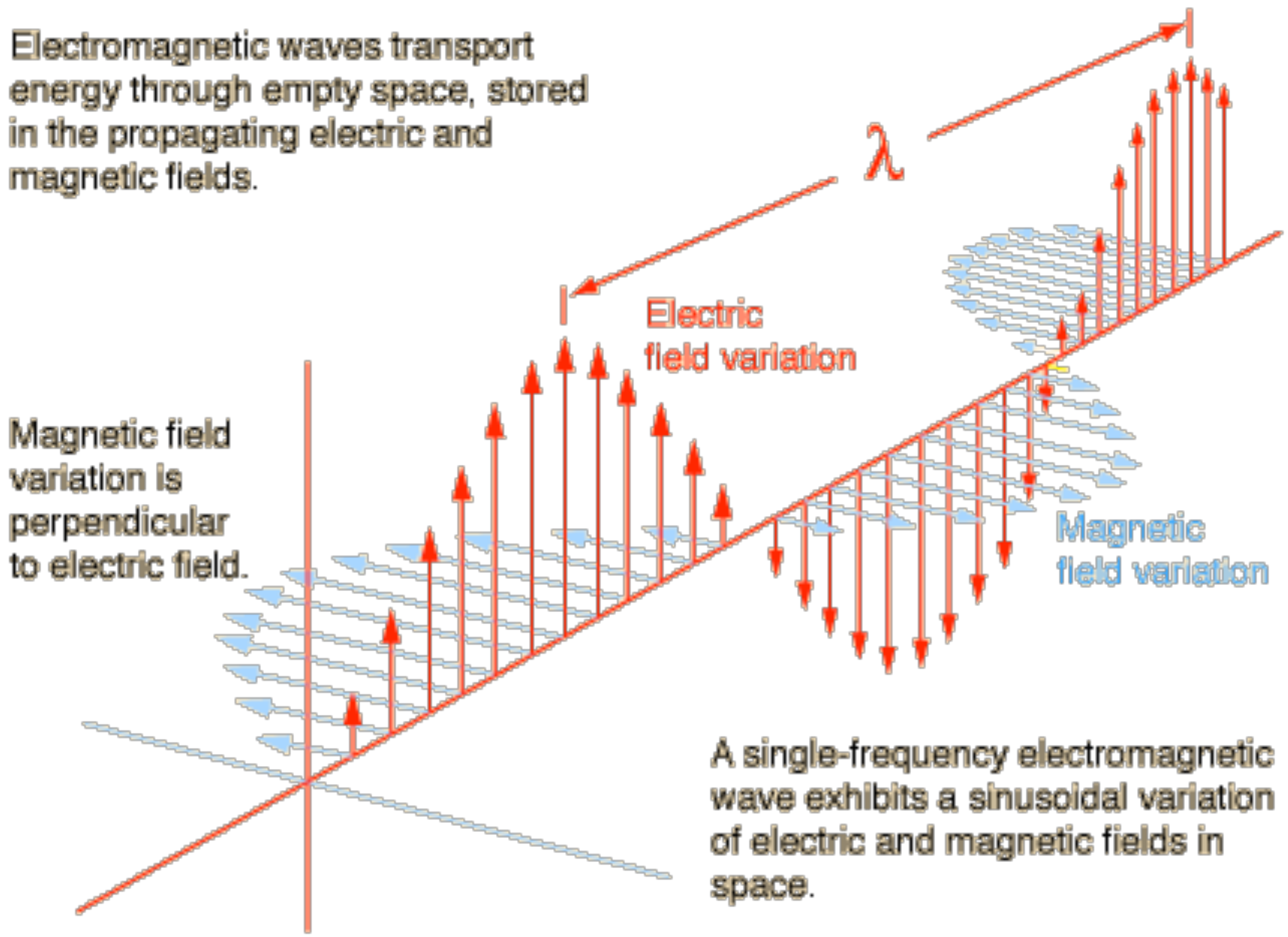


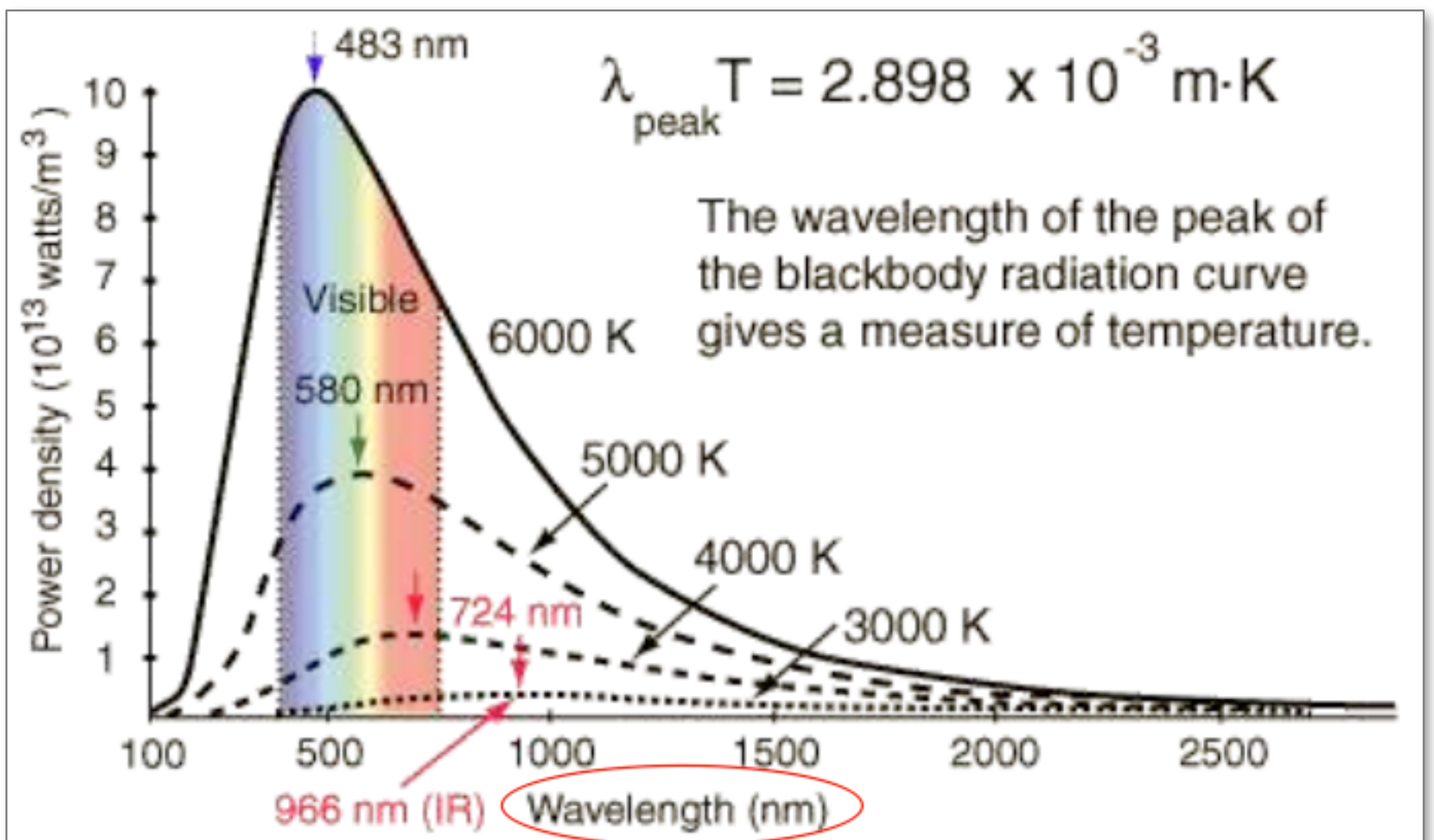
Image: HyperPhysics.com

Classical Electrodynamics

- **A beautiful theory…**
  - The implications of the Maxwell Equations – namely, the appearance of electromagnetic fields to observers in different inertial reference frames – inspired scientists (Poincaré, Einstein) to develop special relativity.
- **But…**
  - When trying to explain thermal radiation (light emitted by hot objects), the theory completely fails!

Failure of classical electrodynamics

- When light is emitted by hot objects, the intensity of the light always varies continuously with the wavelength - unlike atomic spectra - and the spectrum has a characteristic shape.



- This so-called **blackbody** spectrum always peaks at a wavelength that depends on the surface temperature of the body.
- Examples of blackbodies: stars, light filaments, toaster coils, the universe itself!

Failure of classical electrodynamics

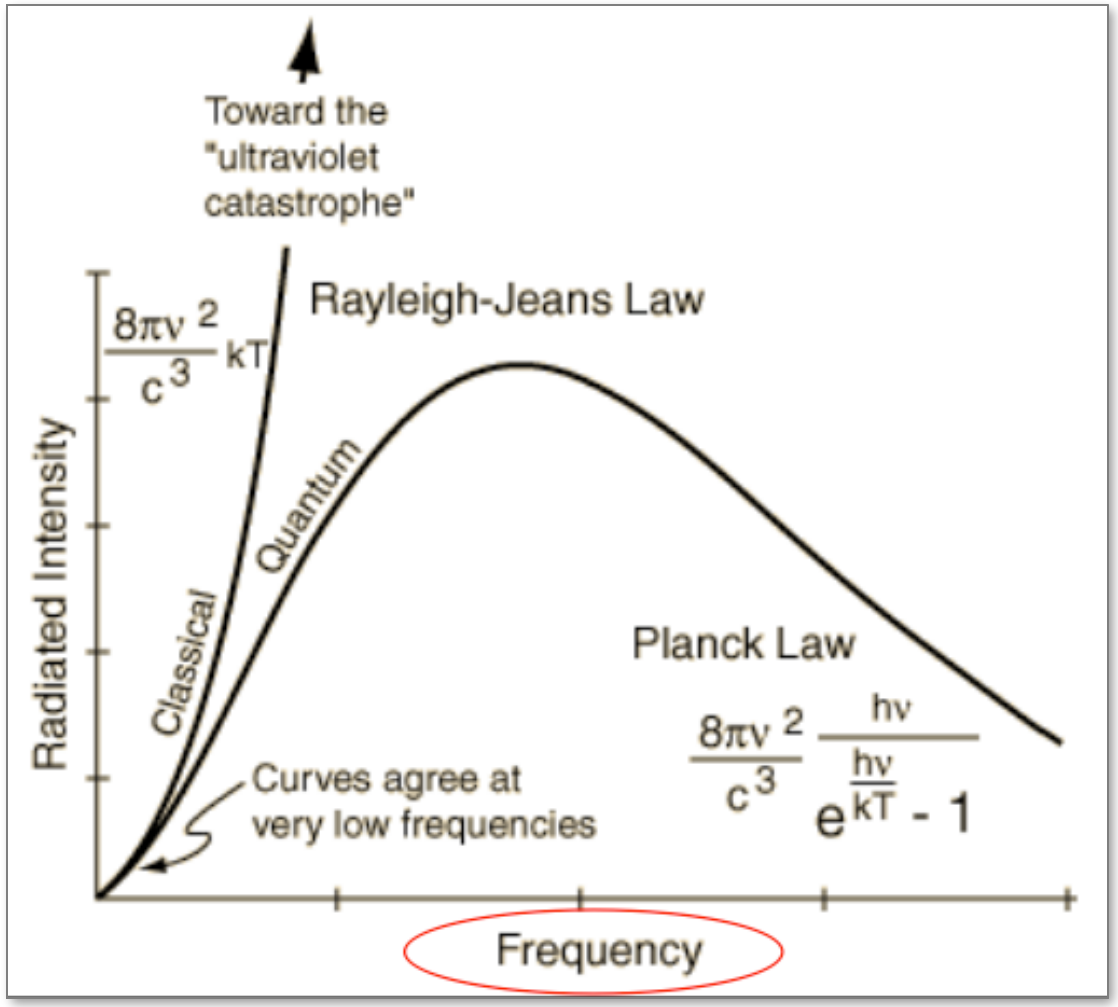
"Ultraviolet catastrophe"

https://www.youtube.com/watch?v=FXfrncRey-4

- A study of blackbody radiation with classical EM and statistical mechanics (the Rayleigh-Jeans Law) predicts that the emitted intensity varies with frequency and temperature as:

$$I_\nu(T) \propto \frac{k_B T}{c^3}\nu^2$$

- This means that as the light frequency increases into the UV, the intensity becomes infinite!
- This nonsensical answer was such an embarrassment for the theory that physicists called it the "ultraviolet catastrophe".



Planck's solution: light quanta

- In 1900, using arguments from statistical mechanics (the theory of bodies in thermal equilibrium), M. Planck derived a theoretical curve that fit the blackbody spectrum perfectly:

$$I_\nu(T) \propto \frac{h}{c^3}\frac{\nu^3}{e^{h\nu/k_BT}-1}$$

- However, to get this result, Planck had to assume that thermal radiation is quantized; that is, it's emitted in little "packets" of energy, **photons**, proportional to the frequency ν: $E = h\nu$

- The quantity h, called Planck's constant, was determined from the fit to the blackbody spectrum. It turned out to be a fundamental constant of nature, and has the value: $h = 4.1357\times10^{-15}\ \mathrm{eV\cdot s}$

M. Planck
NobelPrize.org

Are photons real?

- In order to explain blackbody emission spectra, Planck needed to assume that thermal radiation is emitted in bundles whose energy comes in integral multiples of hν.
- This suggested that light could actually be quantized (it's a **particle**). But most of the experimental evidence (and Maxwell's Equations) at the time said that light is a **wave**.
- So is light a particle, or a wave? As it turns out, light can behave like a particle if you are performing the right kind of experiment!
- At first, Planck did not really believe in the light quantum, and most physicists did not accept its existence until faced with undeniable evidence from two phenomena:

1) The photoelectric effect

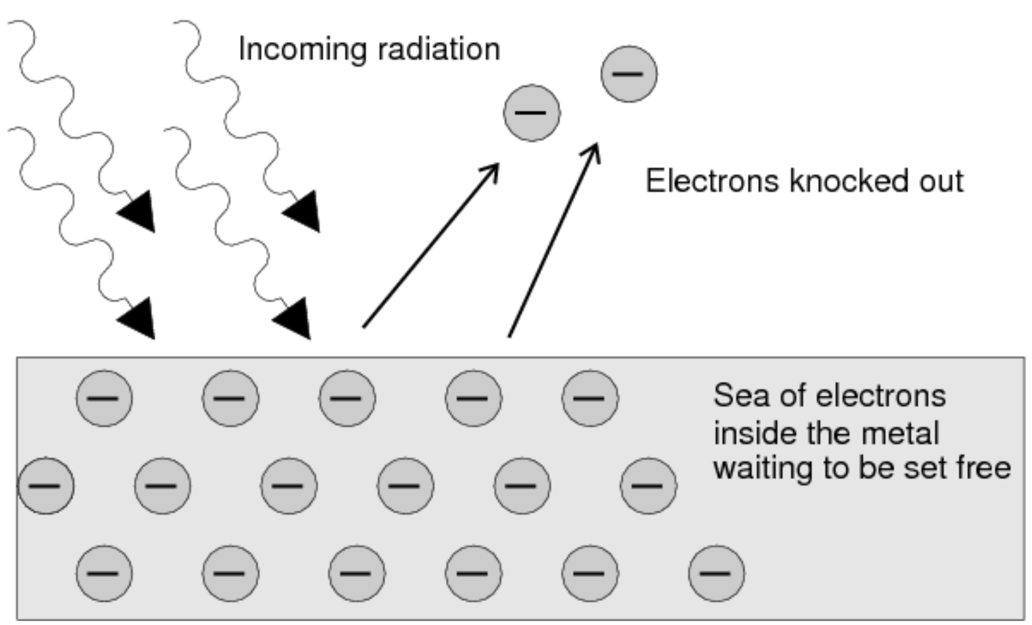
2) Compton scattering

→ Evidence for particle nature of light!

Photoelectric effect (1905)

- In the 1800's, it was discovered that shining light onto certain metals liberated electrons from their surface.
- Experiments on this photoelectric effect showed odd results:

1. Increasing the intensity of the light increased the number of electrons, but not the maximum kinetic energy of the electrons.
2. Red light did not liberate electrons, no matter how intense it was!
3. Weak violet light liberated few electrons, but their maximum kinetic energy was greater than that for more intense long-wavelength beams!



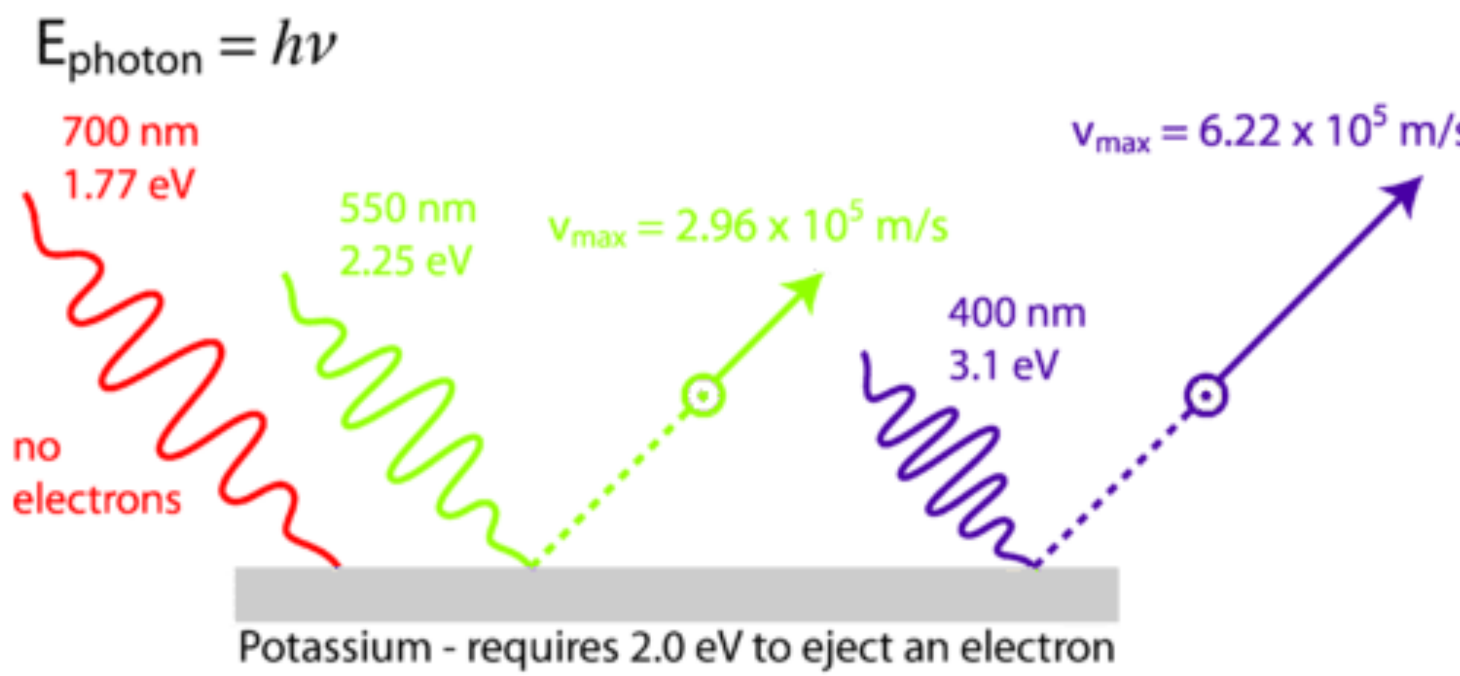
Photoelectric effect (1905)

A. Einstein
NobelPrize.org

- In 1905, A. Einstein showed that these results made perfect sense in the context of quantization of the EM field, where photon energy is proportional to frequency. If photons of energy E=hν strike electrons in the surface of the metal, the freed electrons have a kinetic energy:

$$K = h\nu - \phi$$

- The work function ϕ is a constant that depends on the metal.

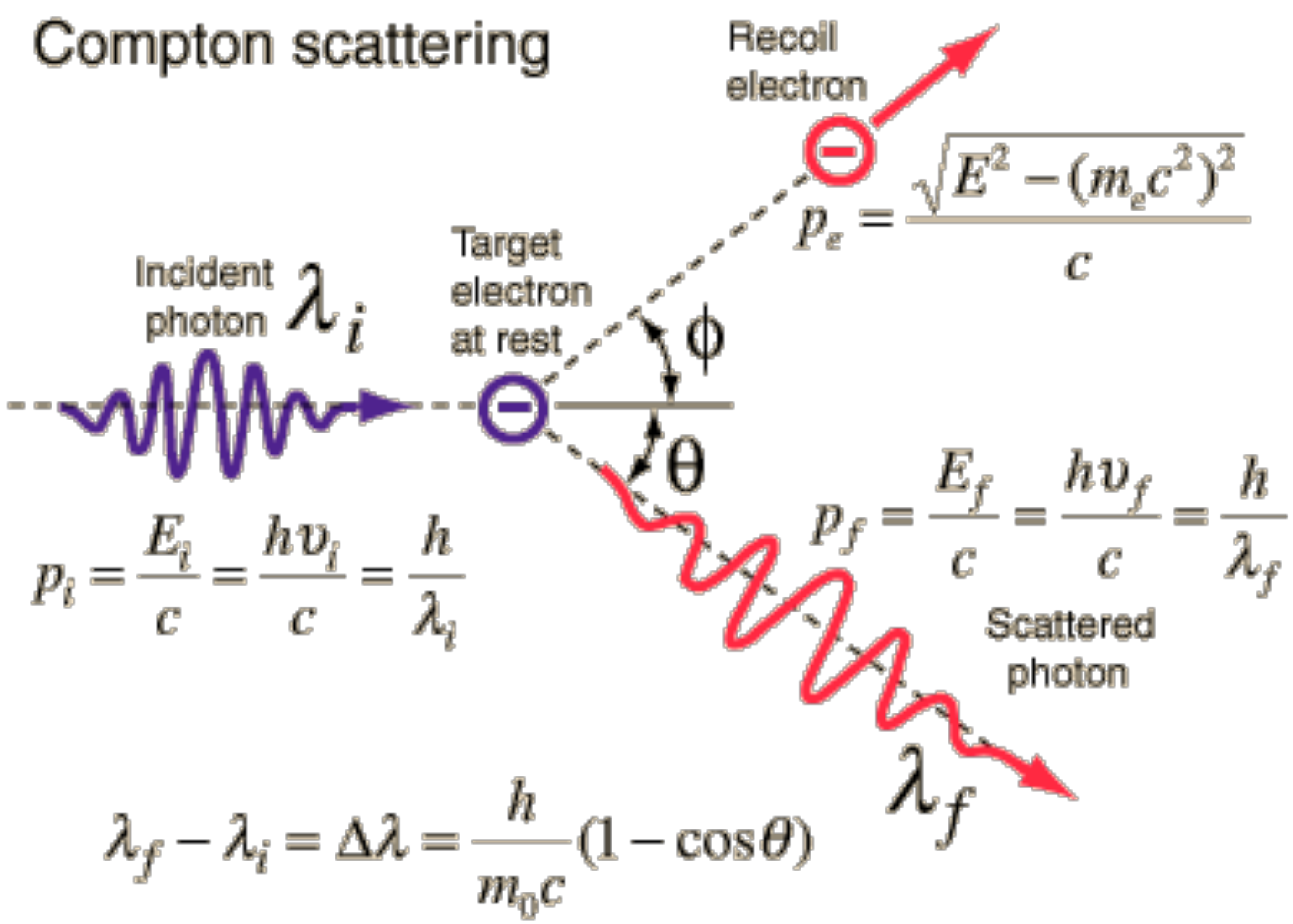


Compton Scattering (1923)

A. H. Compton
NobelPrize.org

- In 1923, A. H. Compton found that light scattered from a particle at rest is shifted in wavelength by an amount:

$$\lambda_f - \lambda_i = \lambda_c(1-\cos\theta)$$



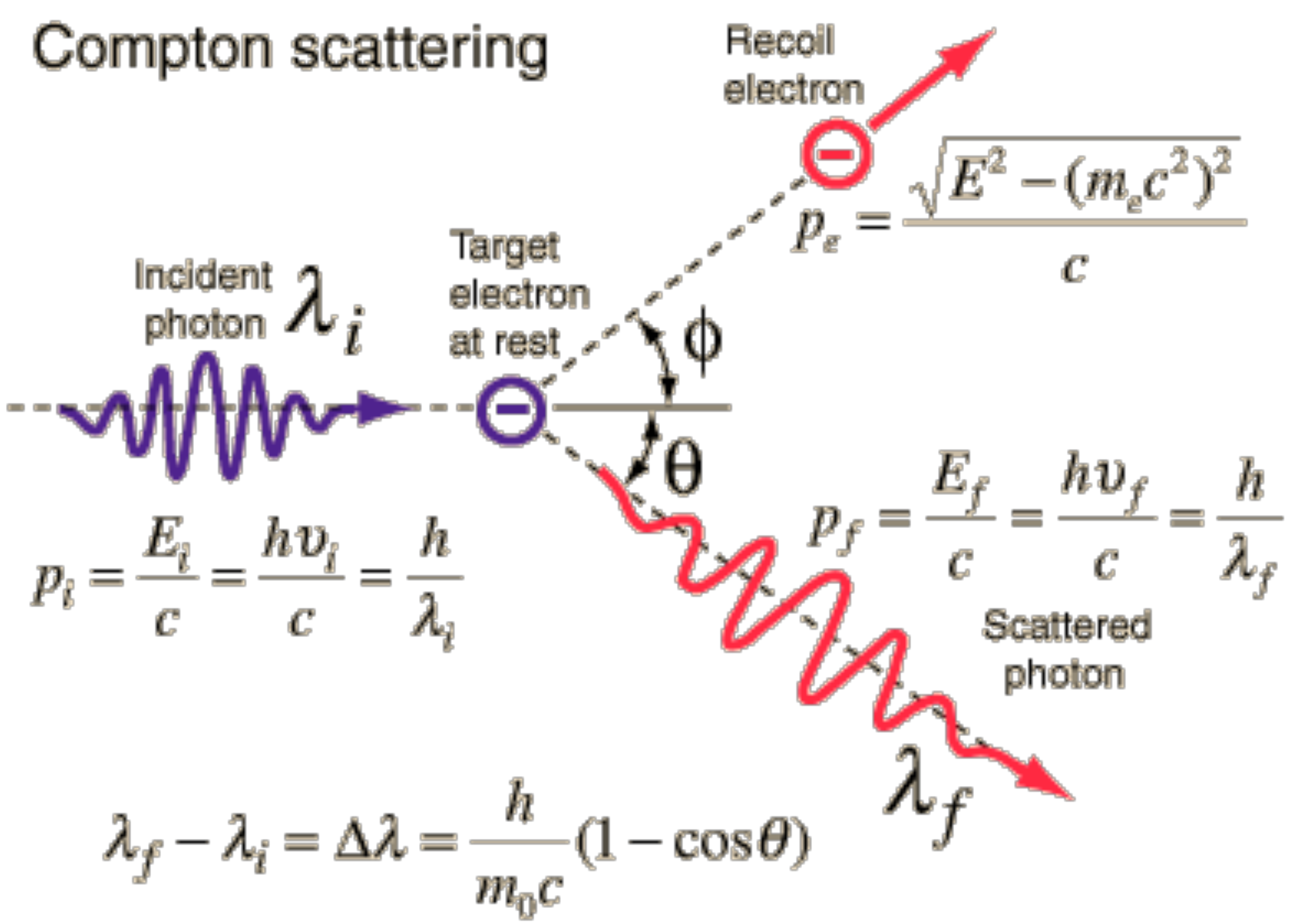
- Here, λc = h/mc is the Compton wavelength of the target mass m.

Compton Scattering (1923)

A. H. Compton
NobelPrize.org

- In 1923, A. H. Compton found that light scattered from a particle at rest is shifted in wavelength by an amount:

$$\lambda_f - \lambda_i = \lambda_c(1-\cos\theta)$$



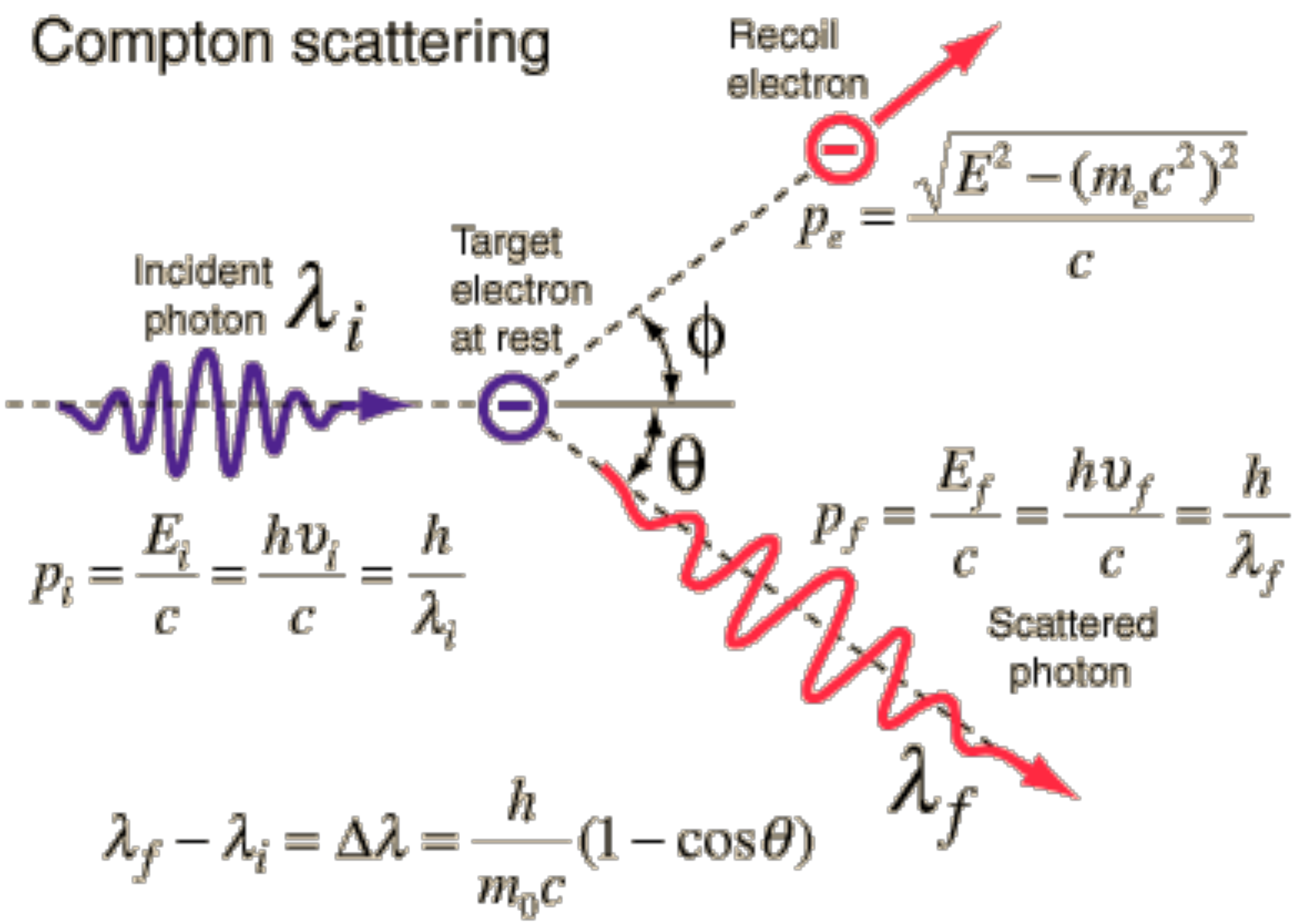
- Here, λc = h/mc is the Compton wavelength of the target mass m.
- There is no way to derive this formula if you assume light is a wave.
- If you treat the incoming light beam as a particle with energy E=hv, Compton's formula comes right out!

Compton Scattering (1923)

A. H. Compton
NobelPrize.org

- In 1923, A. H. Compton found that light scattered from a particle at rest is shifted in wavelength by an amount:

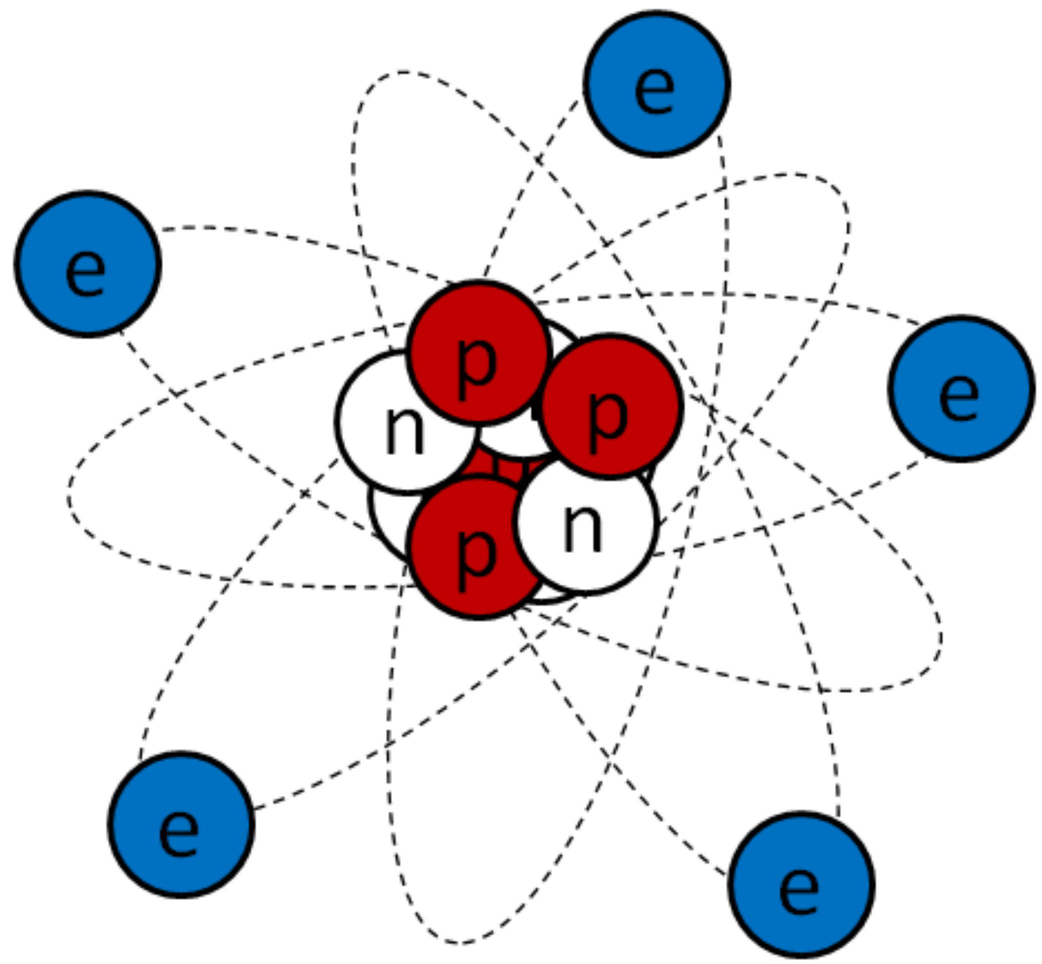
$$\lambda_f - \lambda_i = \lambda_c(1 - \cos\theta)$$



On to the particle zoo (1932-1960)

Field quantization in nuclear physics

- Field quantization, once accepted for the electromagnetic field, was quickly applied to other calculations.
- One was the physics of the atomic nucleus, which gets very complicated after hydrogen.
- **Question:** How are protons in heavy atoms bound inside the 1 fm "box" of the nucleus?
- Shouldn't the electrostatic repulsion of the protons blow the nucleus apart?
- What holds protons together in such a packed state? (https://youtu.be/LraNu_78sCw)



Matt Strassler 2012

H. Yukawa
Image: NobelPrize.org

Nuclear force model (1934)

- Evidently, some force is holding the nucleus together:
  - **The "strong force"**
- Inside the nucleus, the strong force has to overwhelm the EM force, but outside, on the atomic scale, it should have almost no effect.
- **How to accomplish this?**

H. Yukawa

Image: NobelPrize.org

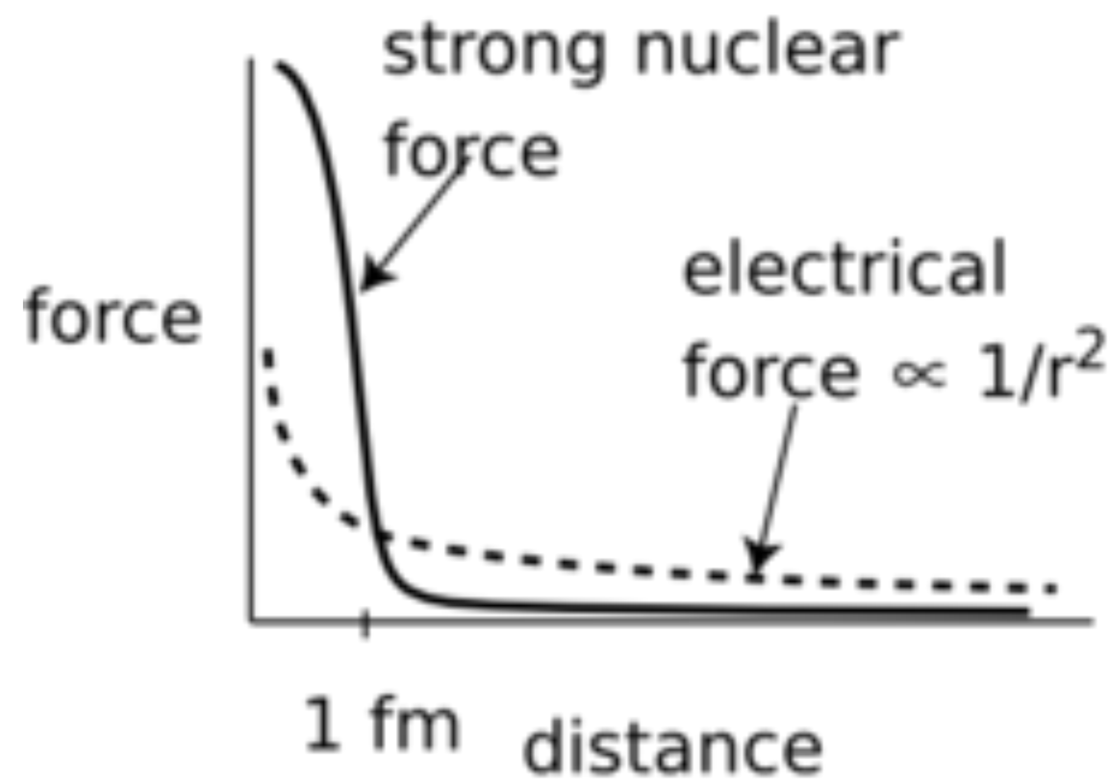
Nuclear force model (1934)

- Assume the strong force has a very short range, falling off rapidly to zero for distances greater than 1 fm(10^{-15}m).

- H. Yukawa: force may vary as

$$F_{\text{strong}} \propto -\frac{1}{r^2} e^{-r/a}$$

where a >> 1 fm is the range.



H. Yukawa
Image: NobelPrize.org

Nuclear force model (1934)

- Yukawa's Model: the proton and neutron are attracted to each other by some sort of field, just like the electron is attracted to the proton by the electromagnetic field.
- The nuclear field should be quantized; that is, it is mediated by an exchanged quantum, as the electromagnetic field is mediated by the photon.
  - So there should be a new detectable particle!

H. Yukawa
Image: NobelPrize.org

Nuclear force model (1934)

- An interesting issue: because the range of the nuclear field is so small, the exchanged quantum of the strong force must be massive.
    - This is due to the Uncertainty Principle - more on this later…

- Yukawa calculated the mass of the strong mediator, and found it to be about $300m_e$, or $m_p/6$.

- Because its mass fell between that of the proton and electron, he called it a *meson* (Greek = “middle-weight”), distinguished from the electron (*lepton* = “light-weight”) and the neutron and proton (*baryon* = “heavy-weight”).

Estimate of Yukawa meson mass

- Use Heisenberg's uncertainty principle:

$$\Delta E \Delta t = \hbar, \quad \hbar = h/2\pi$$

to estimate the Yukawa meson mass.

Estimate of Yukawa meson mass

- When two protons in a nucleus exchange a meson (mass m), they temporarily violate energy conservation.
- The Heisenberg Uncertainty Principle says this is OK, as long as the amount of energy borrowed is "paid-back" in a time such that:

$$\Delta E \Delta t = \hbar, \quad \hbar = h / 2\pi$$

- In this case, we need to "borrow" an energy large enough for the meson to make it across the nucleus from one proton to another.
- Since the meson will probably travel at some substantial fraction of the speed of light, the time it takes to cross the nucleus is roughly:

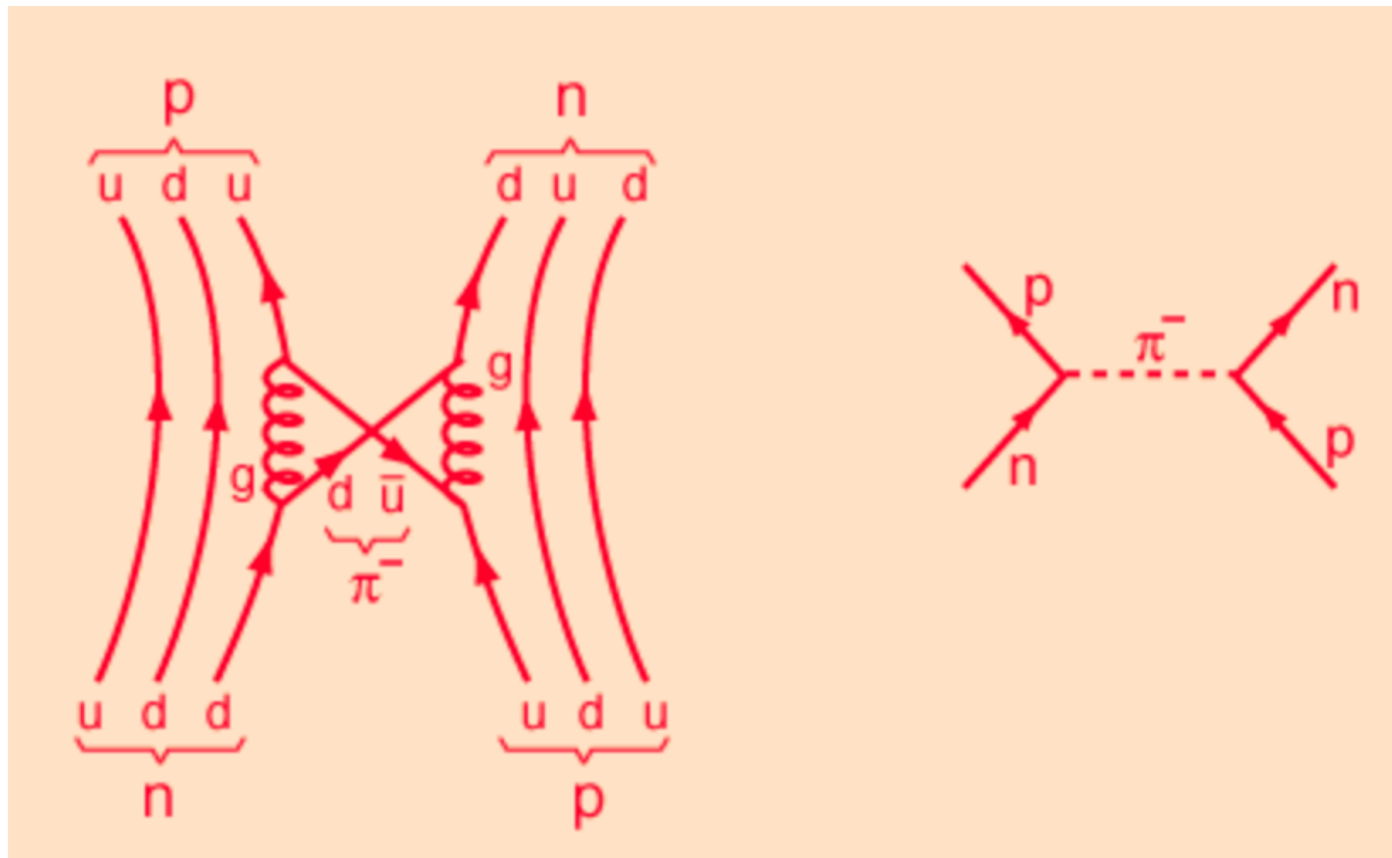
$$\Delta t = r_0 / c, \quad r_0 \approx 1\,\mathrm{fm}$$

- So, the meson mass is: $m = \hbar / (r_0 c) \approx 150\,\mathrm{MeV}/c^2$

Discovery of Yukawa's meson?

- In 1937, two groups studying cosmic ray air showers found particles of approximately the mass predicted by Yukawa.
- Did this confirm Yukawa's theory of strong interactions?
  - Not exactly…
  - It turned out the particles observed had too long lifetimes and too little masses…
- By 1947, physicists realized that the cosmic ray particles were not the expected nuclear meson, but rather a completely unexpected elementary particle: **the muon μ**
- **Theorists were not happy. Rabi: "Who ordered that?"**
- About the same time, however, other short-lived particles known as pions were also discovered.

Estimate of Yukawa meson mass



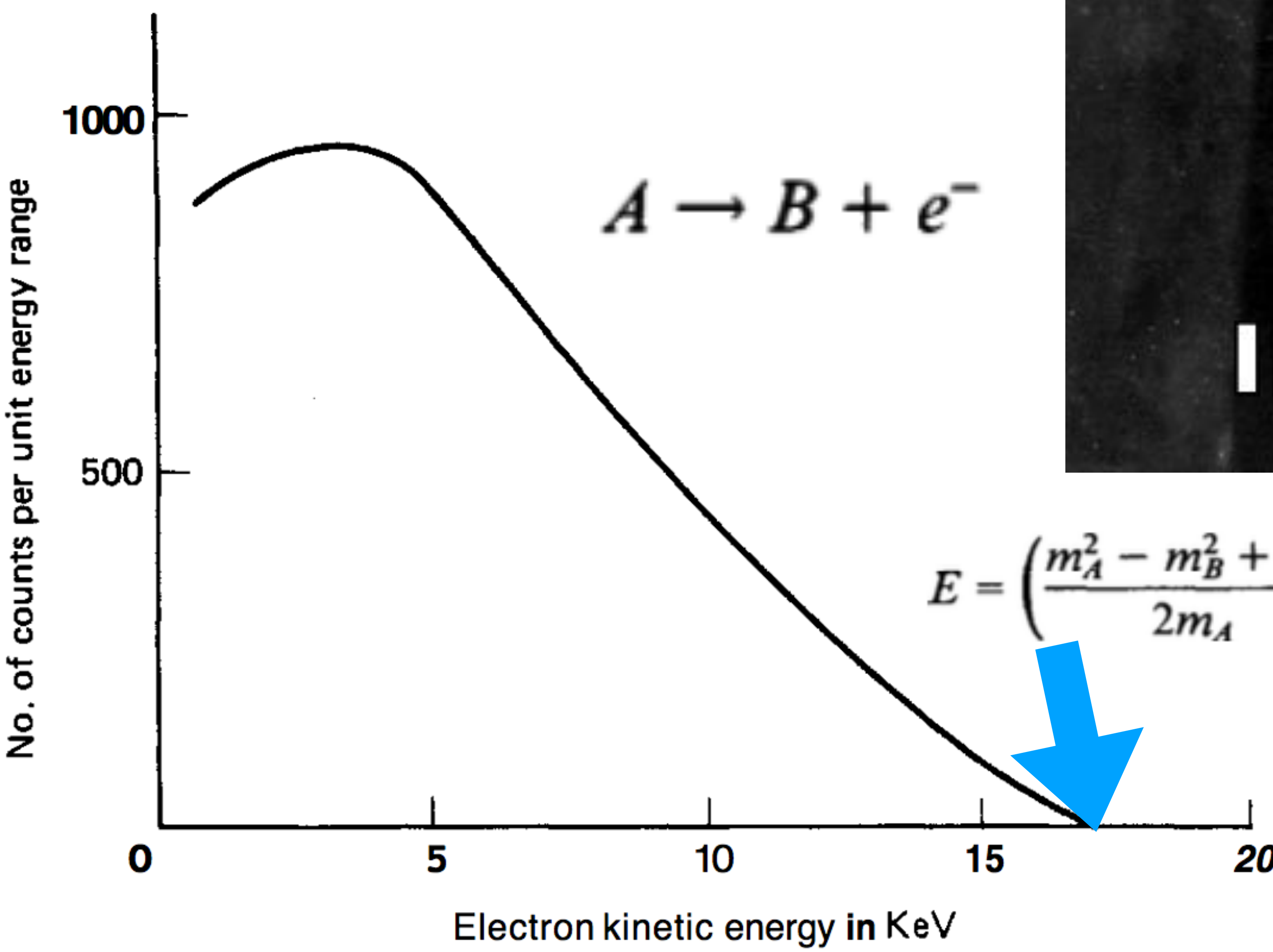
One of many forms the gluon interaction between nucleons could take, this one involving up-antiup pair production and annihilation and producing a π^- bridging the nucleons.

The particle spectrum extends…

- Proton, electron, neutron
- Photon
- Muon
- Pions
- + antiparticles

… plus Neutrinos!

$$n \rightarrow p + e^- + \,?$$



$$A \rightarrow B + e^-$$

$$E = \left(\frac{m_A^2 - m_B^2 + m_e^2}{2m_A}\right)c^2$$

W. Pauli

… plus Neutrinos!

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

Postulated to save conservation of energy!

- In the study of radioactive decays (beta-decay), physicists found that many reactions appeared to violate energy conservation.
- Conclusion 1 (Bohr): nuclear decays do actually violate energy conservation.
- Conclusion 2 (Pauli): missing energy is carried off by another neutral particle which hadn't been detected (as of 1930).
- In 1932, E. Fermi incorporated Pauli's idea into his theory of nuclear decays. He called the missing particles ***neutrinos***.
- Major assumption: neutrinos almost never interact with ordinary matter, except in decays.

W. Pauli

E. Fermi

NobelPrize.org

Discovery of neutrinos (1950s)

C. Cowan and F. Reines
Image: CUA

- By introducing neutrinos (symbol ν) to radioactive decay, conservation of energy was restored. Decay reactions started to look like this:

$$n \rightarrow p + e^- + \bar{\nu}$$
$$\pi \rightarrow \mu + \nu$$
$$\mu \rightarrow e + 2\nu$$

- By 1950, there was compelling theoretical evidence for neutrinos, but no neutrino had ever been experimentally isolated.
- Finally, in the mid-1950s, C. Cowan and F. Reines came up with a method to directly detect neutrinos using "inverse" β-decay: $\bar{\nu} + p \rightarrow n + e^+$
- **A difficult experiment.** Cowan and Reines set up a large water tank outside a commercial nuclear reactor, expecting to see evidence of the above reaction only 2 to 3 times per hour, which they did. **Conclusion: (anti-) neutrinos exist!**

Anti-neutrinos?

- Because all particles have anti-particles, physicists assumed that neutrinos must have corresponding *anti-neutrinos*.
- But does anything distinguish a neutrino from a anti-neutrino?
- From the results of Cowan and Reines, the reaction below must occur:

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

- If anti-neutrinos are the same as neutrinos, the anti-neutrino version of this reaction must also occur:

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

- In fact, in the late 1950s, R. Davis and D.S. Harmer found that the anti-neutrino reaction does not occur. Therefore, something is different about the anti-neutrino that forbids the process. But what?

A new conservation law

- **A rule of thumb (R. Feynman): a reaction will be observed unless it is expressly forbidden by a conservation law.**
- So what conservation law does the anti-neutrino reaction violate?
  - Conservation of energy and electric charge are obeyed, so it must be something else.
- In 1953, E.J. Konopinski and H.M. Mahmoud proposed the existence of a new quantum number that explained why certain reactions worked while others did not.
- They assigned a lepton number L=+1to the electron, muon, and neutrino, and L=-1to the positron, antimuon, and antineutrino. All other particles got L=0. In any reaction, this lepton number had to be conserved.

Lepton number conservation

- To apply conservation of lepton number, just add up the lepton numbers on each side of the reaction and see if they agree.
- The neutrino reaction occurs because:

$$\nu + n \rightarrow p + e^{-}$$
$$L: 1 + 0 = 0 + 1$$

- The antineutrino reaction doesn't occur because:

$$\bar{\nu} + n \rightarrow p + e^{-}$$
$$L: -1 + 0 \neq 0 + 1$$

- In view of lepton number conservation, the charged pion and muon decays should actually be written:

$$\pi^{+} \rightarrow \mu^{+} + \nu \qquad \mu^{+} \rightarrow e^{+} + \nu + \bar{\nu}$$
$$\pi^{-} \rightarrow \mu^{-} + \bar{\nu} \qquad \mu^{-} \rightarrow e^{-} + \nu + \bar{\nu}$$

Lepton FLAVOR number conservation

- Experimentally, the following decay (though it obeys energy, charge, and lepton number conservation) has not been observed (so far):

$$\mu^- \rightarrow e^- + \gamma$$

- Why?

Lepton FLAVOR number conservation

- Experimentally, the following decay (though it obeys energy, charge, and lepton number conservation) has not been observed (so far):

$$\mu^- \rightarrow e^- + \gamma$$

- Apparently, the absence of this reaction suggests a law of conservation of "mu-ness," but that alone wouldn't explain why muons can decay like this:

$$\mu \rightarrow e + \nu + \bar{\nu}$$

- Conclusion: something about the ν's in the second reaction makes it occur.

Lepton FLAVOR number conservation

- Experimentally, the following reaction (though it obeys energy, charge, and lepton number conservation) never occurs:

$$\mu^- \rightarrow e^- + \gamma$$

- **The Answer:** there are two kinds of neutrinos: one associated with the electron (νe), and one with the muon ($\nu \mu$).
- Therefore, we now have an electron number L_e and a muon number L_μ to account for all forbidden and allowed processes.
- Lepton conservation becomes electron number and muon number conservation.

Decays and lepton flavor conservation

- In the context of L_e and L_μ conservation, we can now account for all forbidden and allowed decays…

$n \rightarrow p + e^- + \bar{\nu}_e$	$L_e : 0 = 0 + 1 - 1$
$\pi^+ \rightarrow \mu^+ + \nu_\mu$	$L_\mu : 0 = -1 + 1$
$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$	$L_\mu : 0 = +1 - 1$
$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$	$L_e : 0 = -1 + 1 + 0$ $L_\mu : -1 = 0 + 0 - 1$
$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$	$L_e : 0 = +1 - 1 + 0$ $L_\mu : +1 = 0 + 0 + 1$

- Note how all of the decays conserve charge and energy as well as lepton flavor.

But is this a fundamental or accidental symmetry? More on this later…

The particle spectrum extends…

- Proton, electron, neutron
- Photon
- Muon
- Pions
- + antiparticles
- + neutrinos

The particle spectrum extends…

- Proton, electron, neutron
- Photon
- Muon
- Pions
- + antiparticles
- + neutrinos
- + strange particles

Discovery of strange particles (1947)

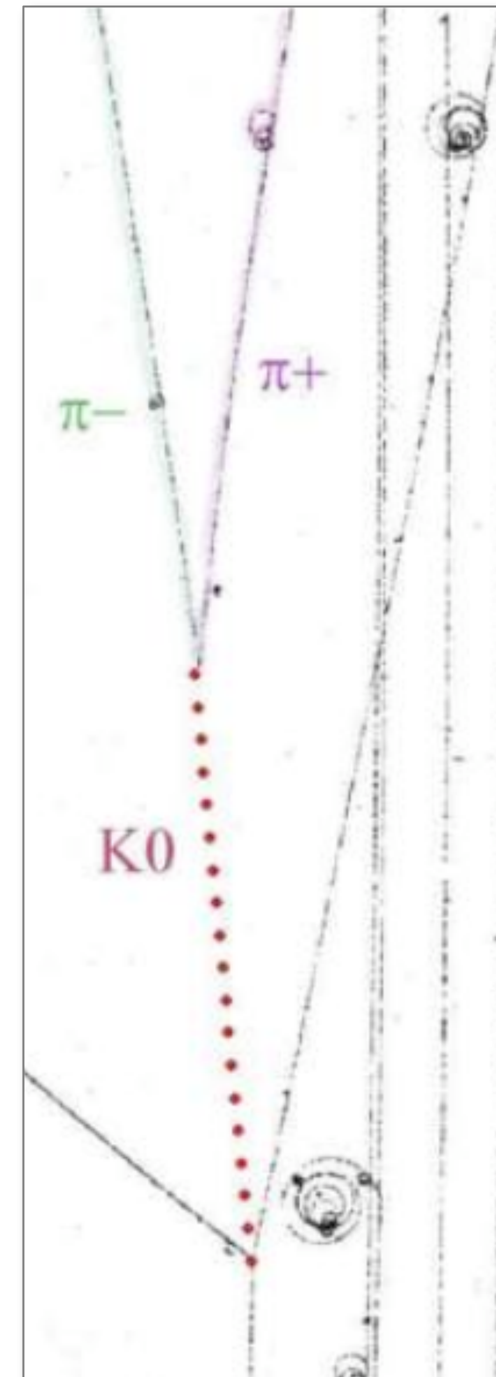
- By 1947, the catalog of elementary particles consisted of the p, n, π, μ, e, and the ν (and the anti-particles). The overall scheme seemed pretty simple.
- However, at the end of that year, a new neutral particle was discovered: the K0 (“kaon”):

$$K^0 \rightarrow \pi^+ + \pi^-$$

- In 1949, a charged kaon was found:

$$K^+ \rightarrow \pi^+ + \pi^+ + \pi^-$$

- The K’s behaved somewhat like heavy π’s, so they were classified as mesons (“mass roughly between the proton and electron mass”).
- Over the next two decades, many more mesons were discovered: the η, the φ, the ω, the ρ’s, etc.



Bubble chamber photo of kaon decay (U of Birmingham)

More strange particles (1950)

- In 1950, C. Anderson observed another particle that looked like the K, but decayed via the reaction:

$$\Lambda \rightarrow p + \pi^-$$

- The Λ is heavier than the proton, making it a baryon like the p and n.
- Over the next decade, as particle accelerators started to increase in energy, many more (increasingly heavy) baryons were discovered: the Σ's, the Ξ's, the Δ's, etc.
- Struggling to fit new particles into existing theories, physicists viewed the growing groups of mesons and baryons with increasing dismay…

More strange particles (1950)

When Nobel prizes were first awarded in 1901, physicists knew something of just two objects which are now called "elementary particles": the electron and the proton…. I have heard it said that "the finder of a new elementary particle used to be rewarded by a Nobel Prize, but such a discovery now ought to be punished by a $10,000 fine."

-W. Lamb, Nobel Prize Acceptance Speech, 1955

... and a new conservation law

- QUESTION: Experiments in the 1950s showed that there were many unstable baryons, but the proton was not one of them. Why didn't the proton decay?

$$p \rightarrow e^{+} + \gamma \quad ?$$

- In 1938, Stückelberg proposed an explanation of the proton's stability. The method is familiar: he introduced a new quantum number, and assumed that it was conserved in all interactions.
- The new quantum number, often written A, is called the baryon number. The baryons get A=+1, and the antibaryons get A=-1; all other particles get A=0.

… and a new conservation law

- Baryon number conservation explains why β-decay works, and p-decay does not:

$$n \rightarrow p + e^- + \bar{\nu}_e, \qquad A: 1 = 1 + 0 + 0$$

$$p \rightarrow e^+ + \gamma, \qquad A: 1 = 0 + 0$$

- NOTE: no known reaction seems to conserve meson number, so we don't have to worry about conservation of mesons.

… and yet another:

- "Strange" behavior: the new mesons and baryons discovered during the 1950s all had the following properties:

  1) They are produced on short timescales (10^{-23}s)

  2) But they decay relatively slowly (10^{-10}s)

- This suggests the force causing their production (strong force) differs from the force causing their decay (weak force).

Strangeness (S)

- In 1953, M. Gell-Mann and K. Nishijima introduced a new quantum number, strangeness (S), to explain this behavior.

- According to this scheme, strangeness is conserved in strong interactions, but not conserved (violated) in weak decays.

- **Important point:** In addition, particles with non-zero S are always produced in pairs – no interaction produces just one strange particle.

Conservation of strangeness

- A p-π collision may produce the following products (here S is conserved):

$$\pi^- + p \rightarrow \begin{cases} K^+ + \Sigma^- \\ K^0 + \Sigma^0 \\ K^0 + \Lambda \end{cases}$$

- The K's have S=+1, the Σ's and Λ have S=-1, and the π, p, and n have S=0.
- When these particles decay, S is not conserved: $\Lambda \rightarrow p + \pi^-$

$$\Sigma^+ \rightarrow \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases}$$

- Strong processes conserve S; weak processes do not!

Summary of particle zoo (1960)

- **Leptons:** e, μ, ν_e, ν_μ. Lightest particles. Lepton number is conserved in all interactions.
- **Mesons:** π, η, φ, ω, ρ, … Middle-weight particles. There is no conserved "meson number".
- **Baryons:** p, n, Σ, Ξ, Λ, … Heaviest particles. Baryon number A is always conserved. Strangeness S is conserved sometimes (strong interactions) but not always (weak decays).

Summary of particle zoo (1960)

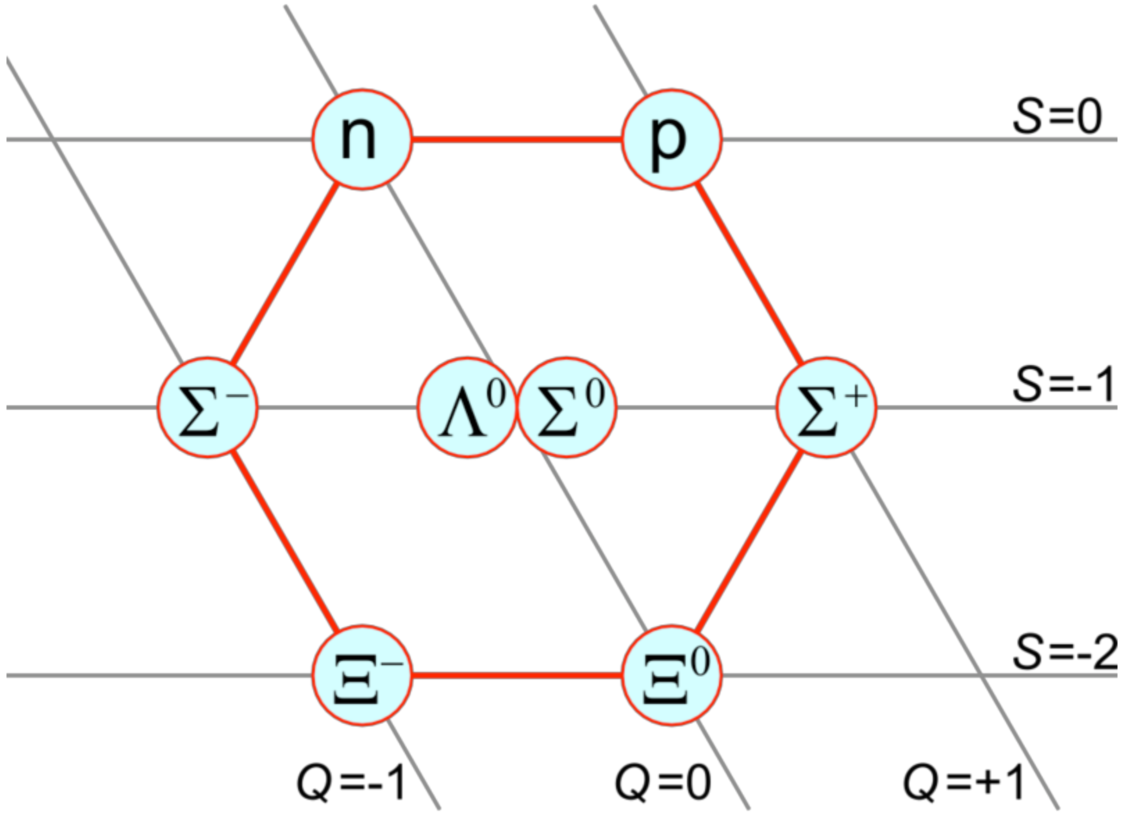
- The point: things seemed like a real mess! No one knew how to predict particle properties. New conservation laws were invented to explain reactions.

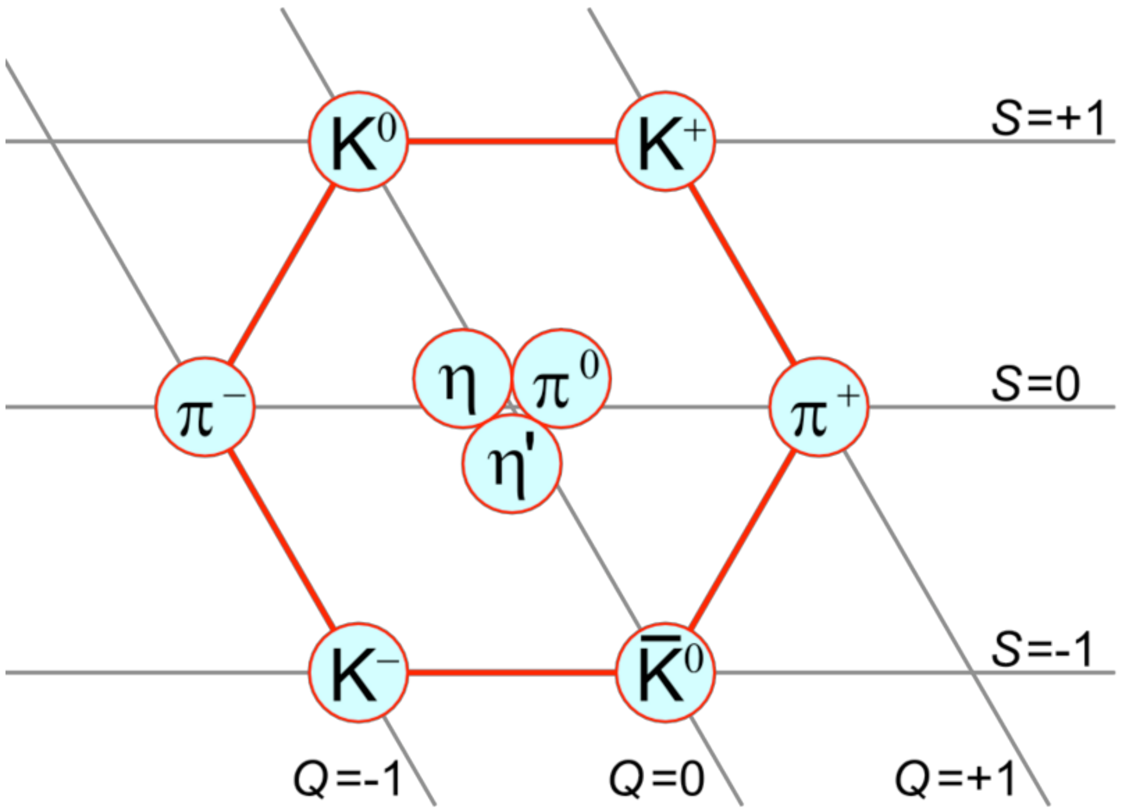
The Quark Era (1960 - 1978)

M. Gell-Mann
Image: NobelPrize.org

The Eightfold way

- Finally, in 1961, Gell-Mann brought some order to the chaos by developing a systematic ordering of the elementary particles.
- He noticed that if he plotted the mesons and baryons on a grid of strangeness S vs charge Q, geometrical patterns emerged.
- The lightest mesons and baryons fit into hexagonal arrays:



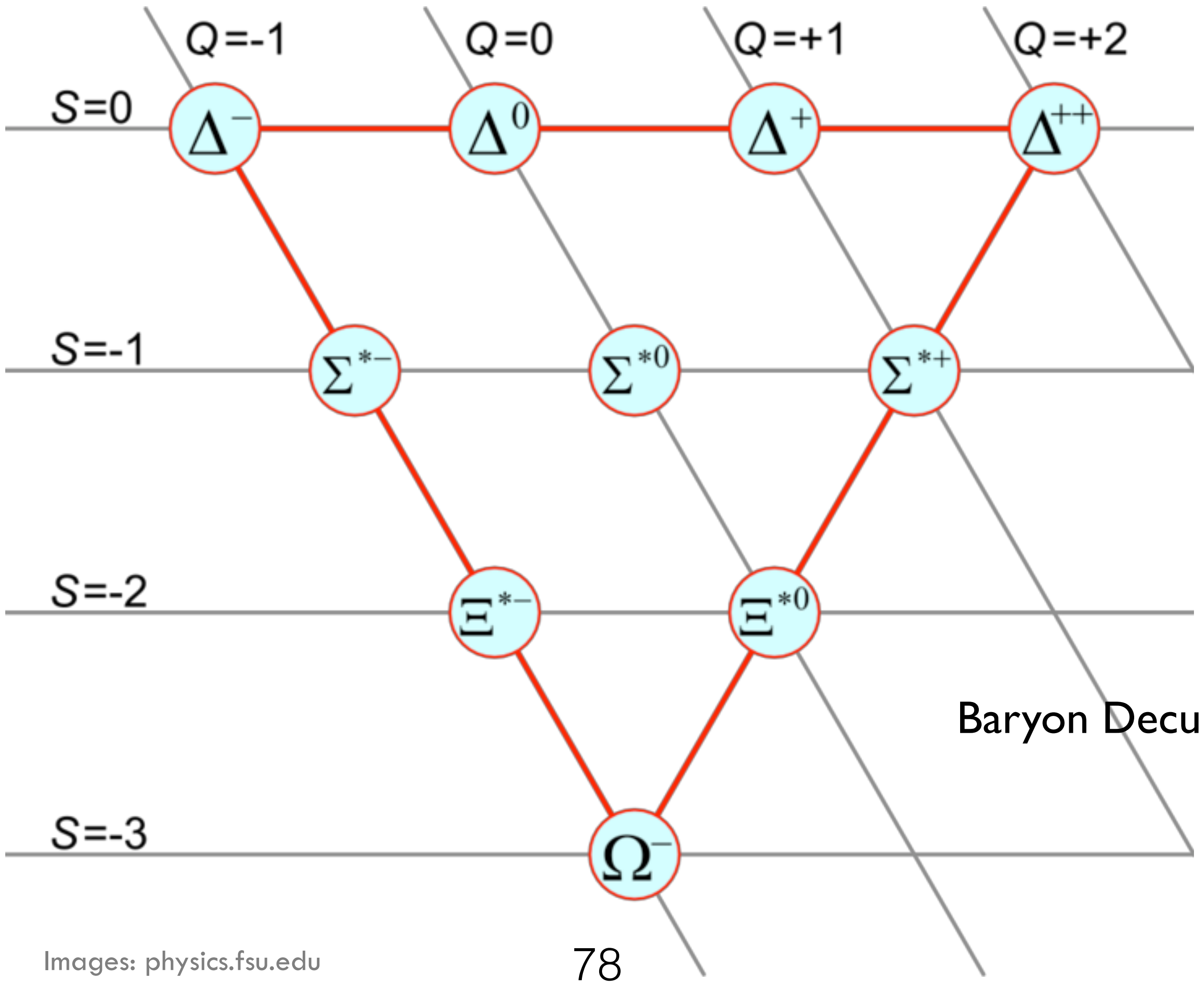


Images: physics.fsu.edu

M. Gell-Mann
Image: NobelPrize.org

The Eightfold way

- Gell-Mann called his organizational scheme the "Eightfold Way".
- Note that other figures were allowed in this system, like a triangular array incorporating 10 of the heavier baryons:



Baryon Decuplet

Images: physics.fsu.edu

Prediction of new baryons (1964)

- Like the Periodic Table of the elements, the Eightfold Way yields simple relations between the hadrons.
- Gell-Mann/Okubo mass formula: relates masses of the members of the baryon octet:

$$2(m_{p/n} + m_{\Xi}) = 3m_{\Lambda} + m_{\Sigma}$$

- Similarly, a mass formula for the baryon decuplet:

$$M_{\Delta} - M_{\Sigma^*} = M_{\Sigma^*} - M_{\Xi^*} = M_{\Xi^*} - M_{\Omega}$$

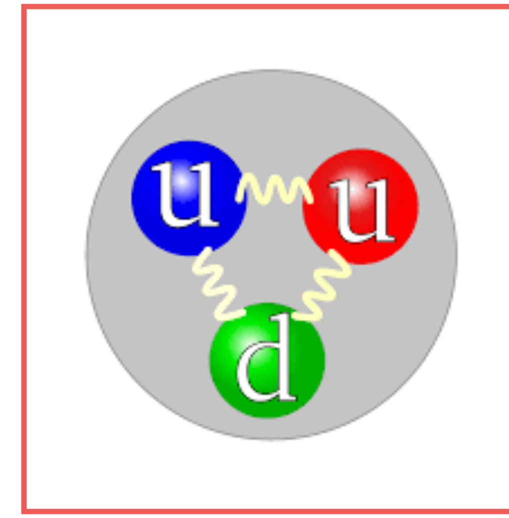
- Key point: in 1963, the Ω- had not yet been observed. Gell-Mann used the Eightfold Way to predict its mass, charge, and strangeness.
  In 1964, the Ω- was found, and had exactly the properties predicted!

The quark model (1964)

- The patterns of the Eightfold Way evoke the periodicities of the Table of the Elements.
- In 1964, Gell-Mann and G. Zweig proposed an explanation for the structure in the hadron multiplets: all hadrons are composed of even more fundamental constituents, called quarks.
- According to their quark scheme, quarks came in three types, or "flavors": **up (u), down (d), and strange (s)**.
- To get the right hadronic properties, Gell-Mann gave his quarks fractional electric charge:

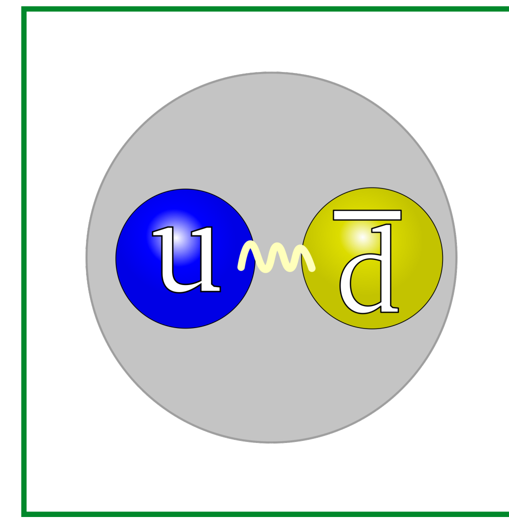
Quark Flavor	Charge (Q)	Strangeness (S)
Up: u	2/3	0
Down: d	-1/3	0
Strange: s	-1/3	-1

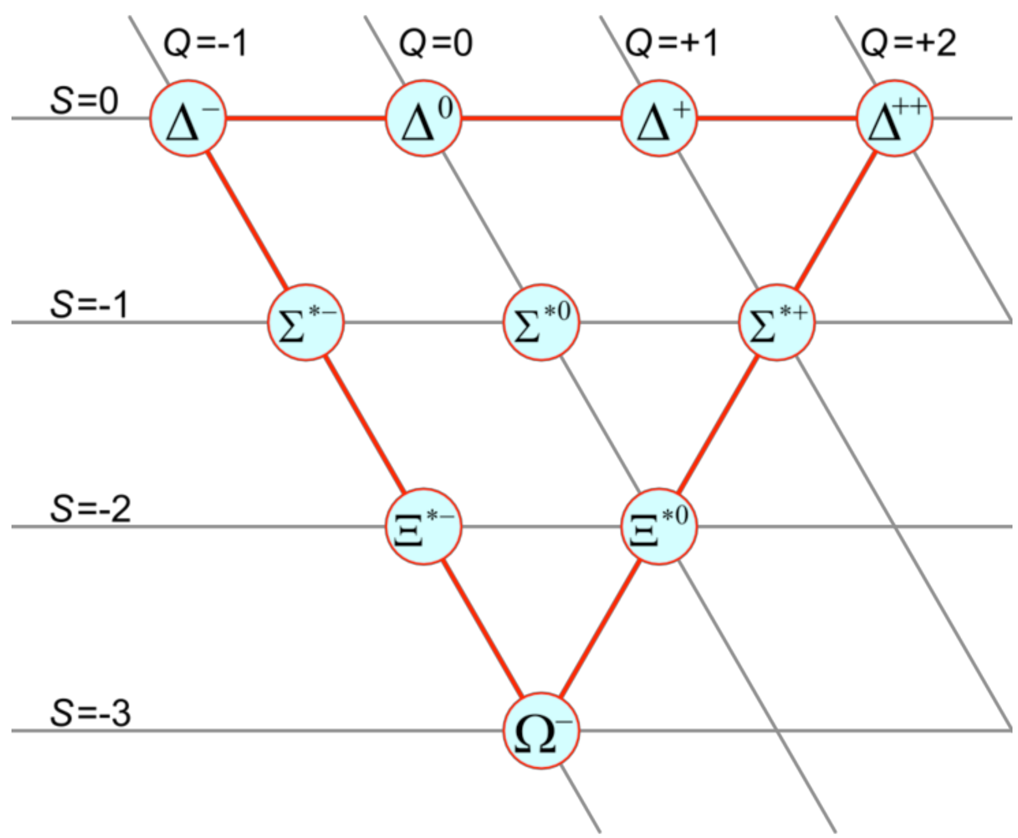
The quark model (1964)



- The quark model has the following conditions:

1. Baryons are composed of three quarks; antibaryons are composed of three antiquarks.
2. Mesons are composed of quark-antiquark pairs.

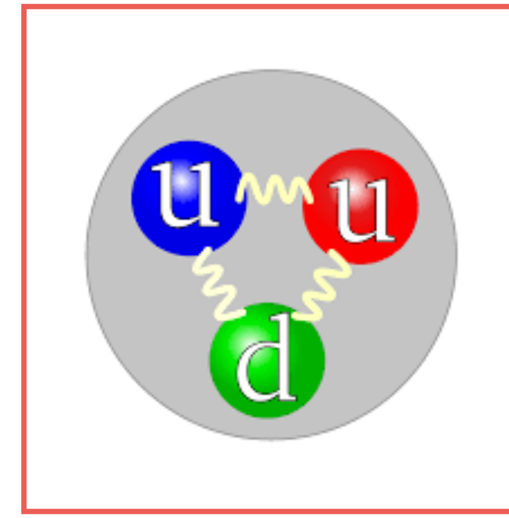




Baryon decuplet

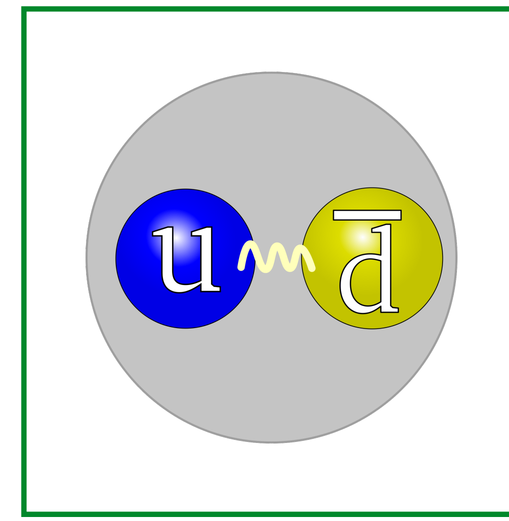
- Using these rules, the hadronic multiplets are easily constructed…

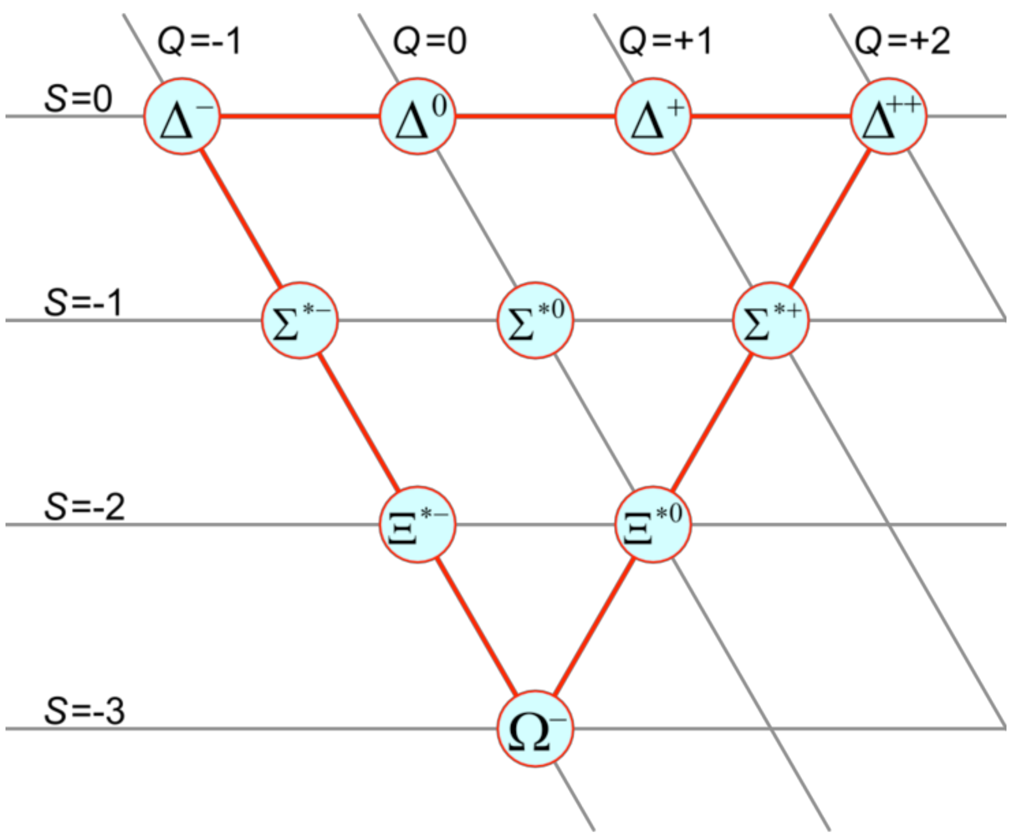
The quark model (1964)



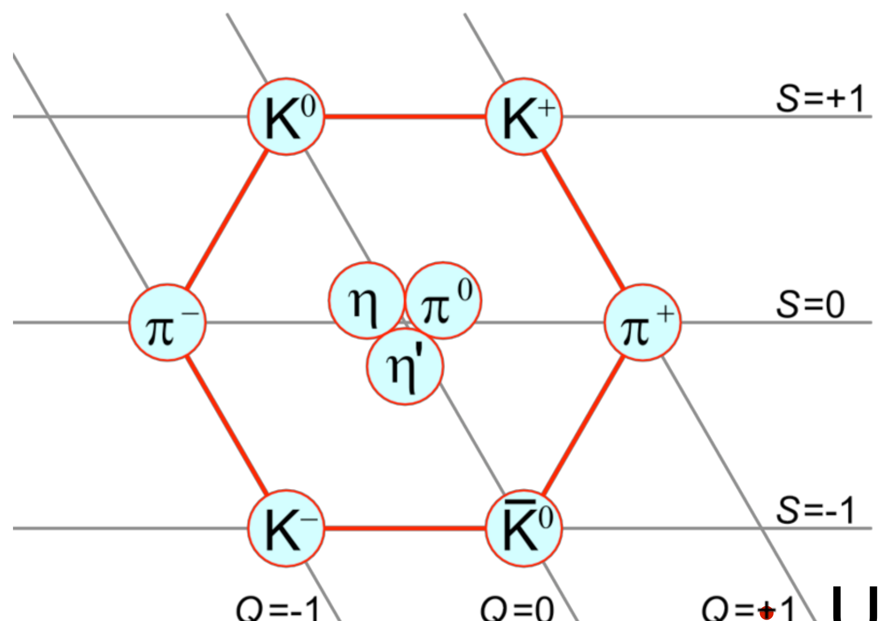
- The quark model has the following conditions:

1. Baryons are composed of three quarks; antibaryons are composed of three antiquarks.
2. Mesons are composed of quark-antiquark pairs.





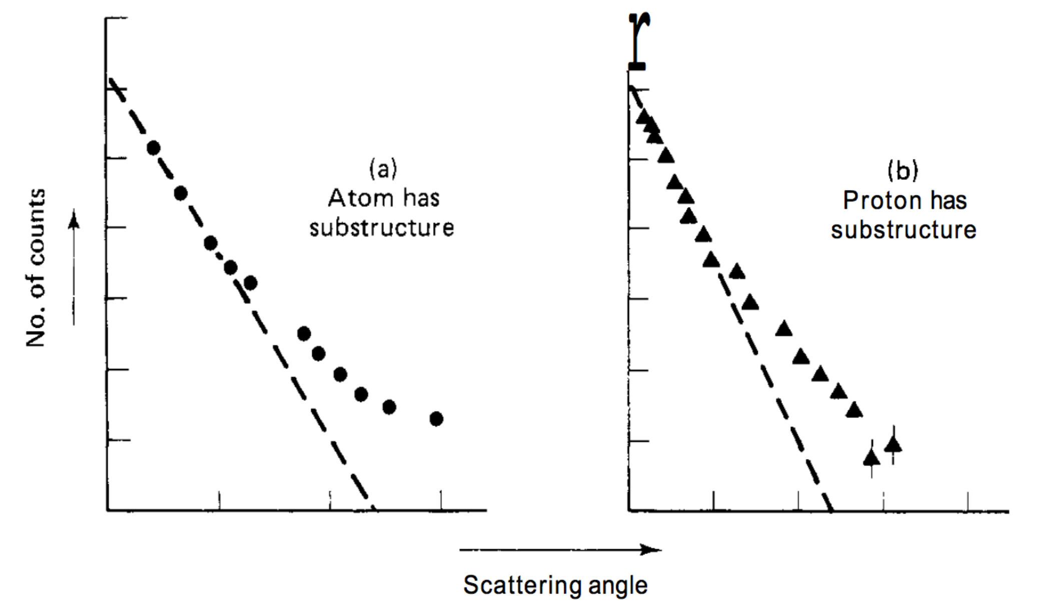
Baryon decuplet



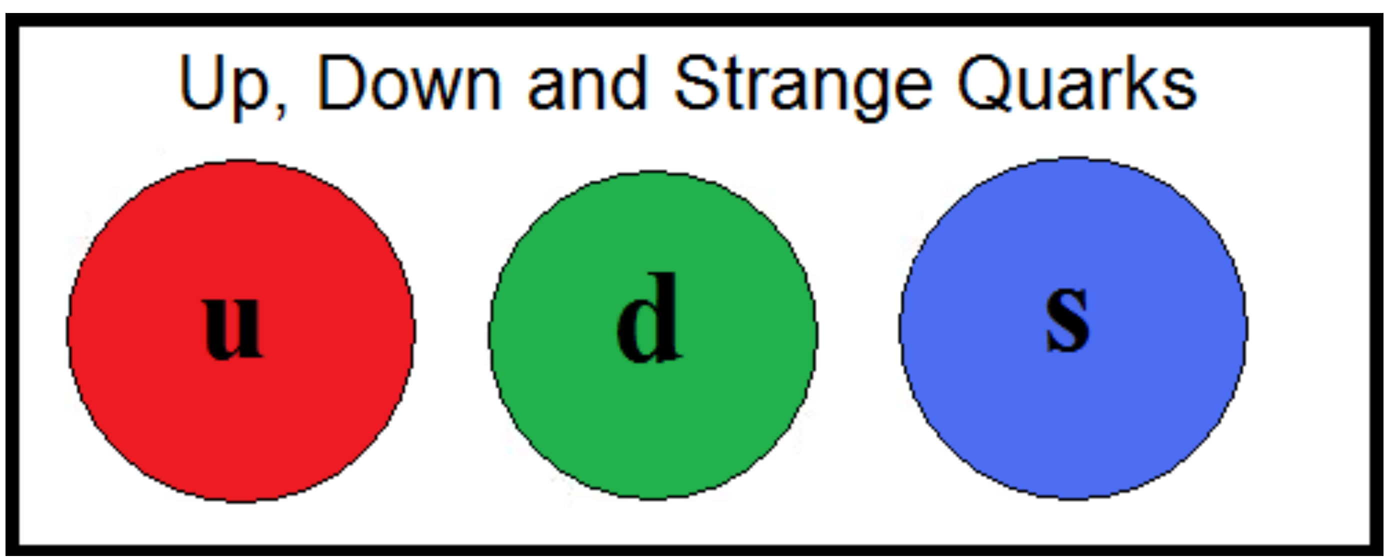
Using these rules, the hadronic multiplets are easily constructed…

The quark model (1964)

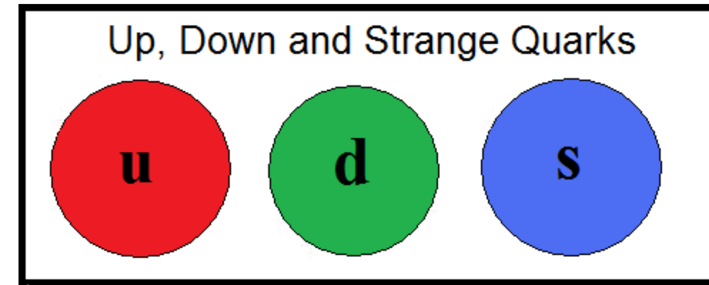
- Note: quarks have never actually been observed
- There is no such thing as a free quark (more on this later…).

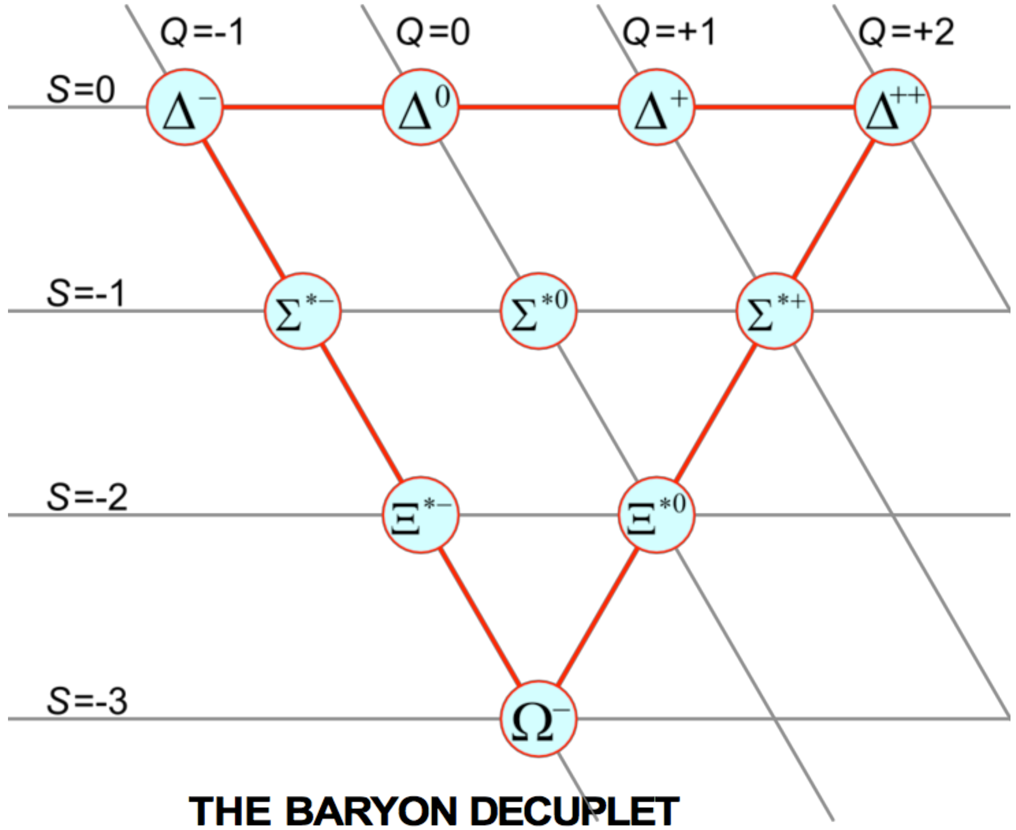


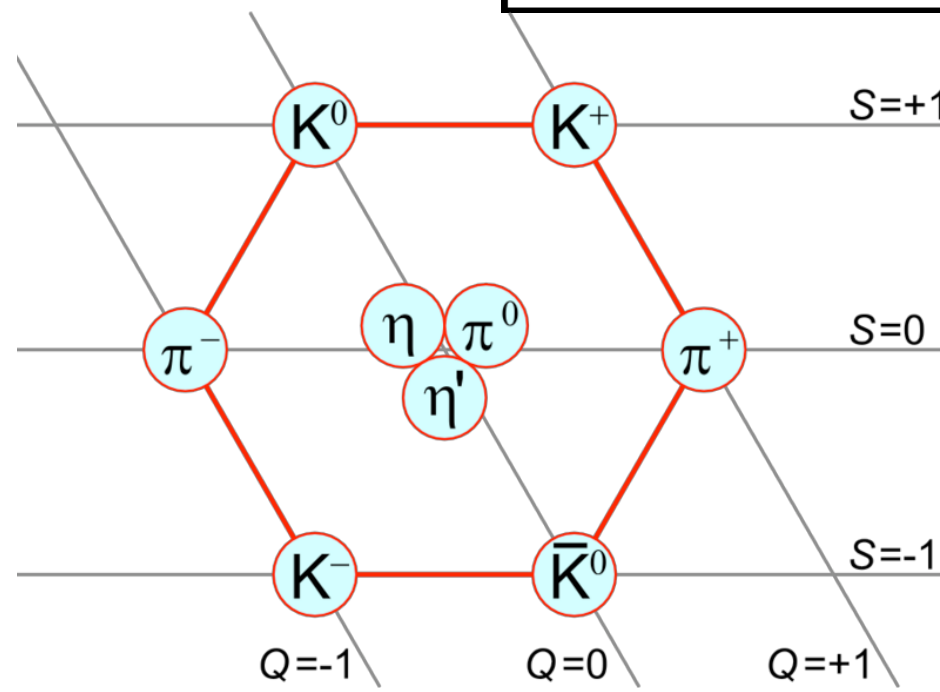
- However, scattering experiments indicate that hadrons do have a substructure (analogous to Rutherford scattering of atoms).



The quark model (1964)







THE BARYON DECUPLET

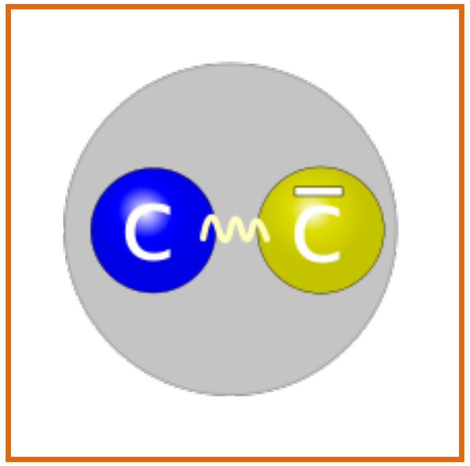
444	Q	S	Baryon
uuu	2	0	A++
uud	1	0	A+
udd	0	0	Δ^0
ddd	−1	0	Δ^-
uus	1	−1	Z*+
uds	0	−1	Σ^{*0}
dds	−1	−1	Σ^{*-}
uss	0	−2	Ξ^{*0}
dss	−1	−2	Ξ^{*-}
sss	−1	−3	R–

THE MESON NONET

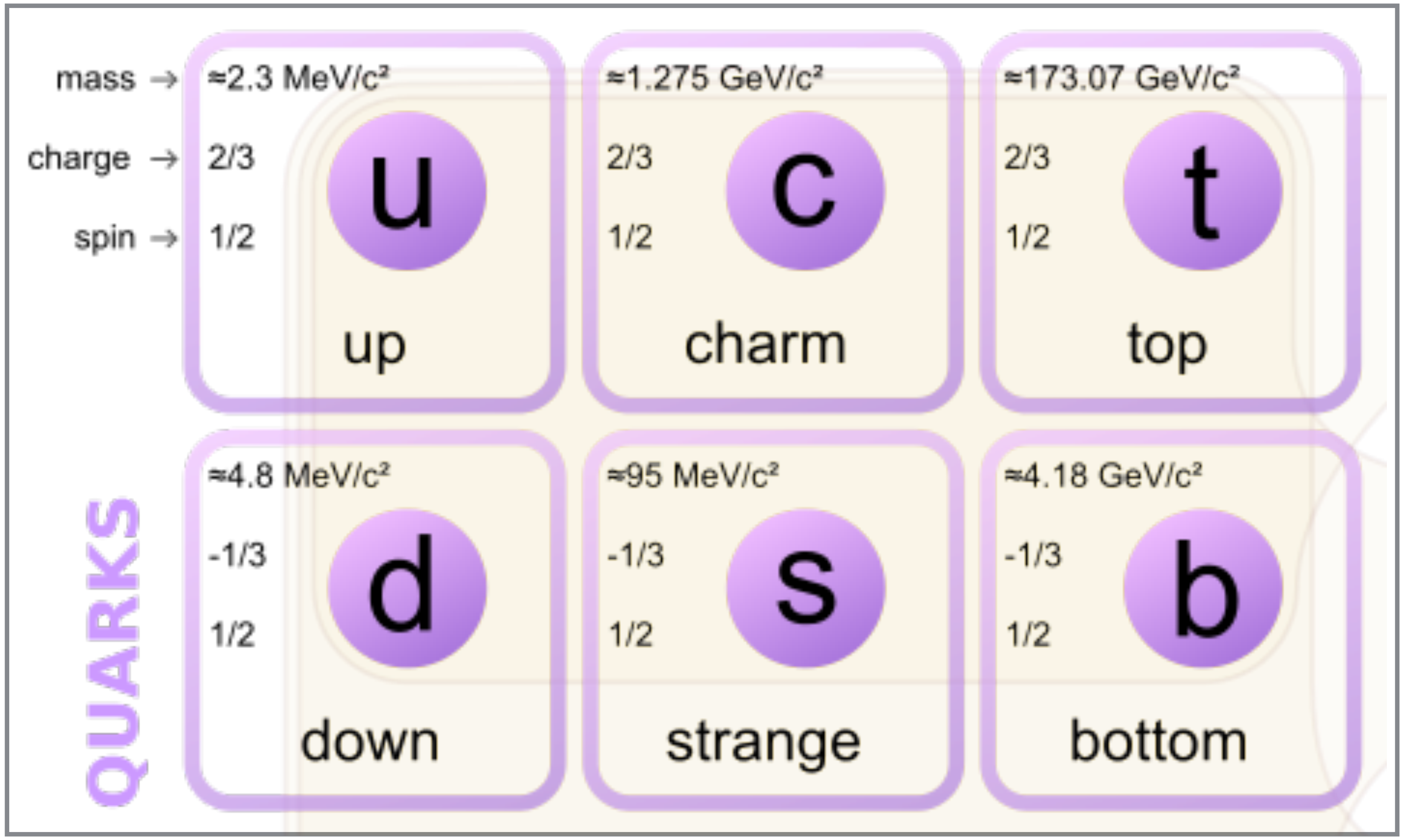
$q\bar{q}$	Q	S	Meson
$u\bar{u}$	0	0	π^0
$u\bar{d}$	1	0	7r+
$d\bar{u}$	−1	0	π^-
$d\bar{d}$	0	0	η
U S	1	1	K^+
$d\bar{s}$	0	1	K^0
$s\bar{u}$	− 1	−1	K^-
$s\bar{d}$	0	− 1	$\bar{K}^0$
$s\bar{s}$	0	0	??

The quark model (1964)

- Until the mid-1970s, most physicists did not accept quarks as real particles.
- Then, in 1974, two experimental groups discovered a neutral, extremely heavy meson called the J/ψ.
  - The J/ψ had a lifetime about 1000 times longer than other hadrons in its mass range.
  - A simple way to explain its properties uses the quark model.
- A new quark, called charm (c), was introduced; and the J/ψ was shown to be a bound state of a charm-anticharm pair (sometimes called "charmonium").



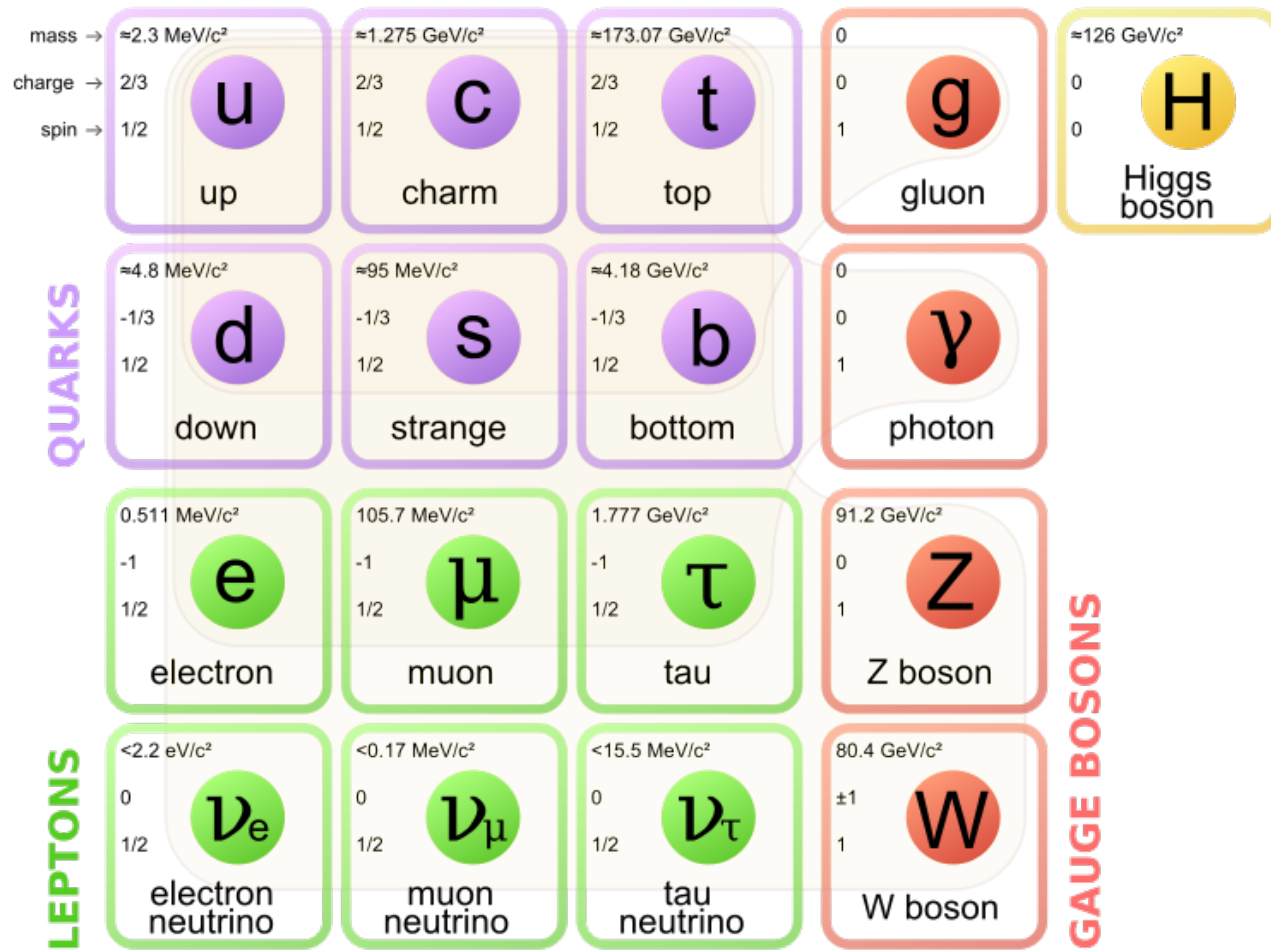
The quark model



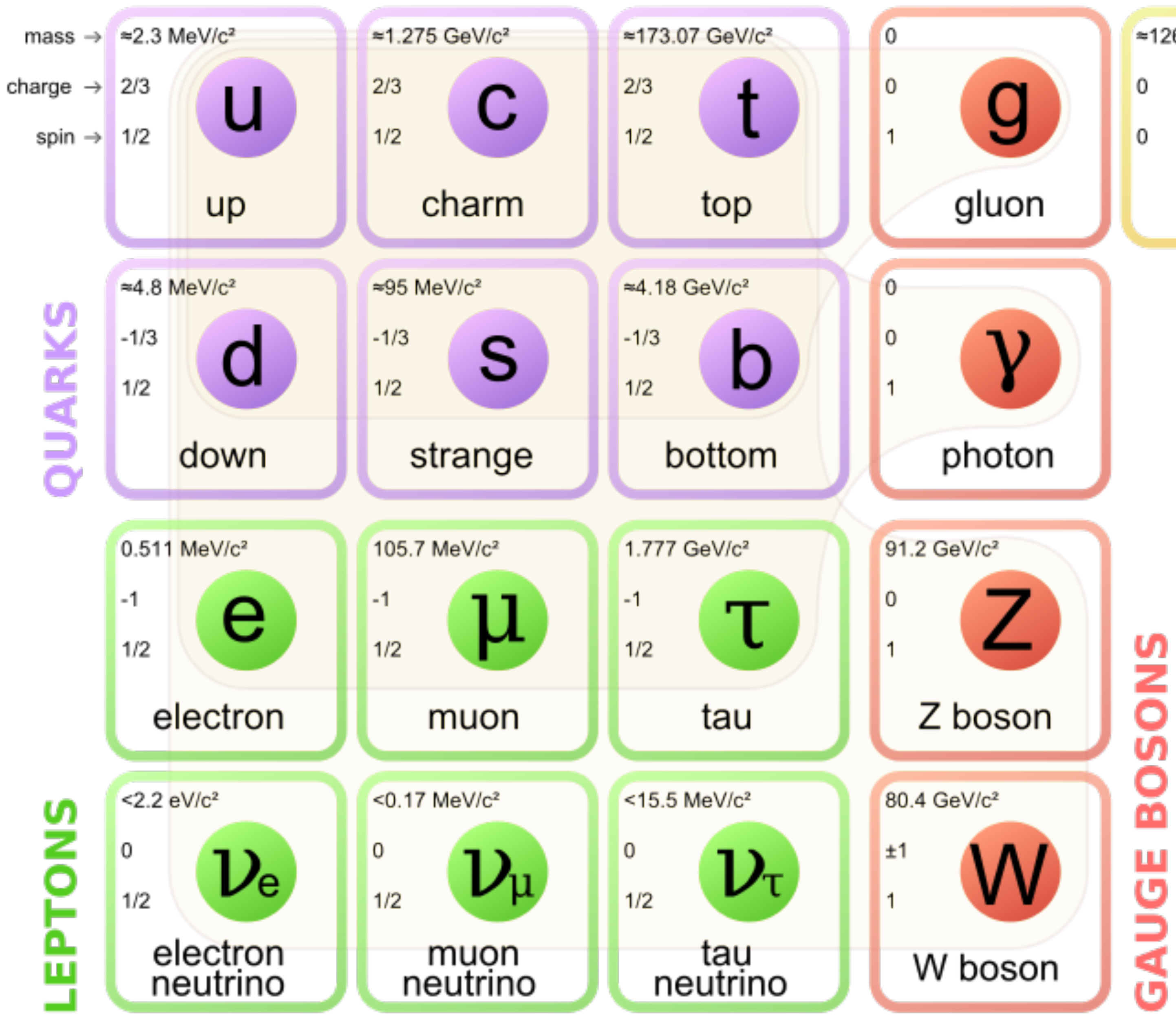
- **We have since discovered the bottom (beauty) quark, in 1977, and the top (truth) quark, in 1995.**

The Standard Model Now

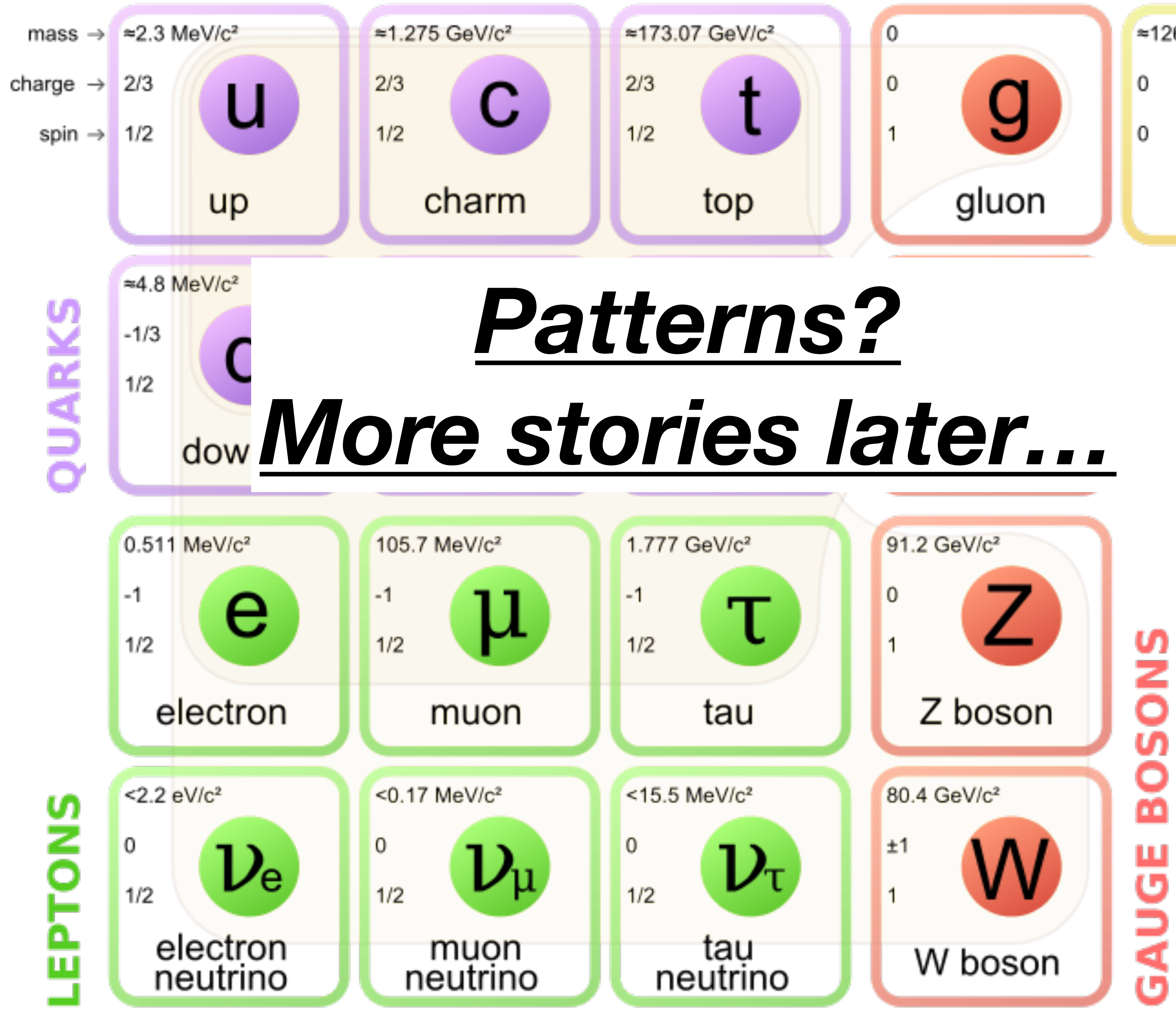
The Standard Model now



The Standard Model now



The Standard Model now



Patterns?

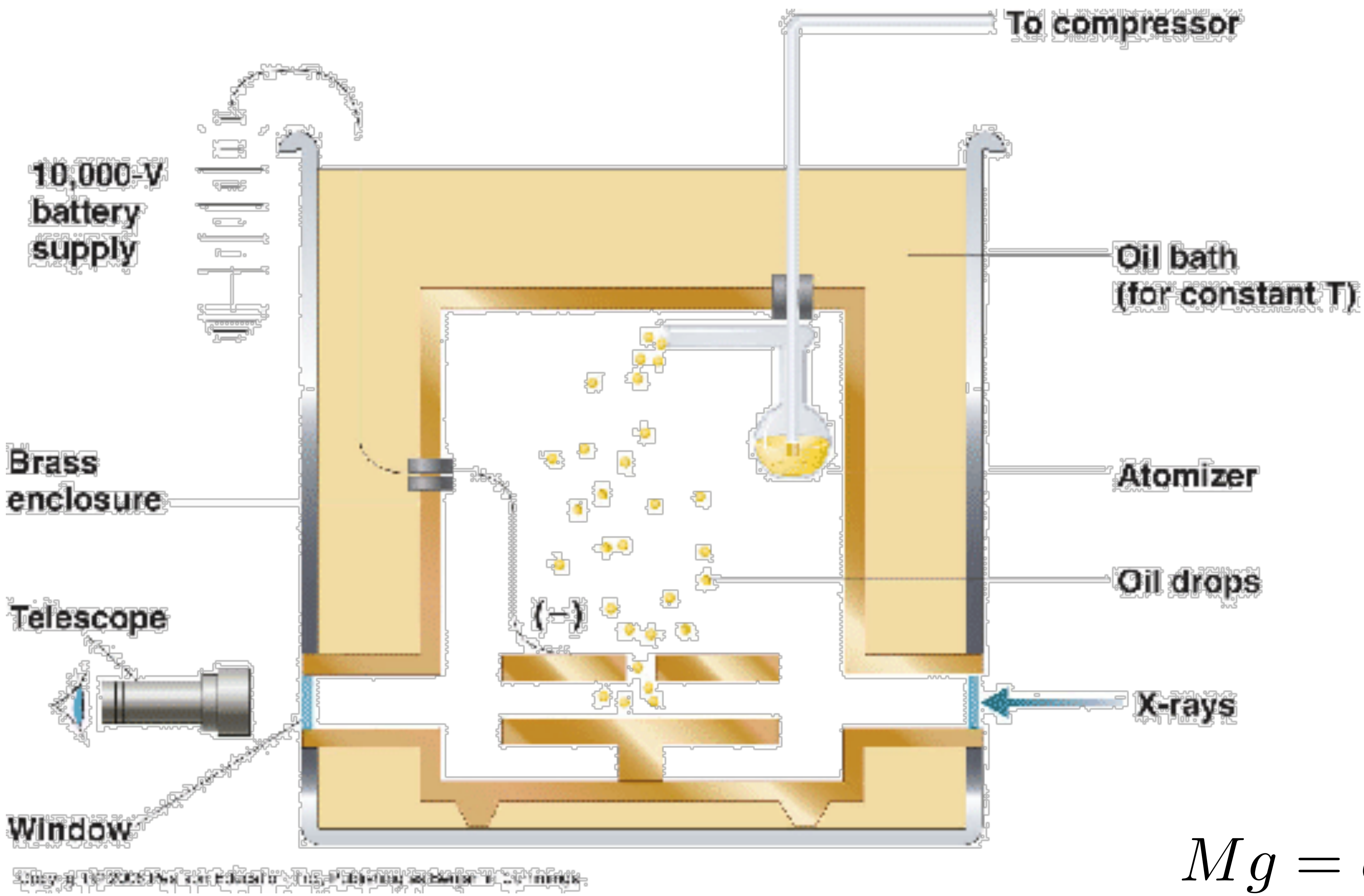
More stories later…

That's all for this week…

- **Next week:** Special Relativity

Bonus

- Robert Milikan's oil drop experiment (1906):



$$Mg = qE$$

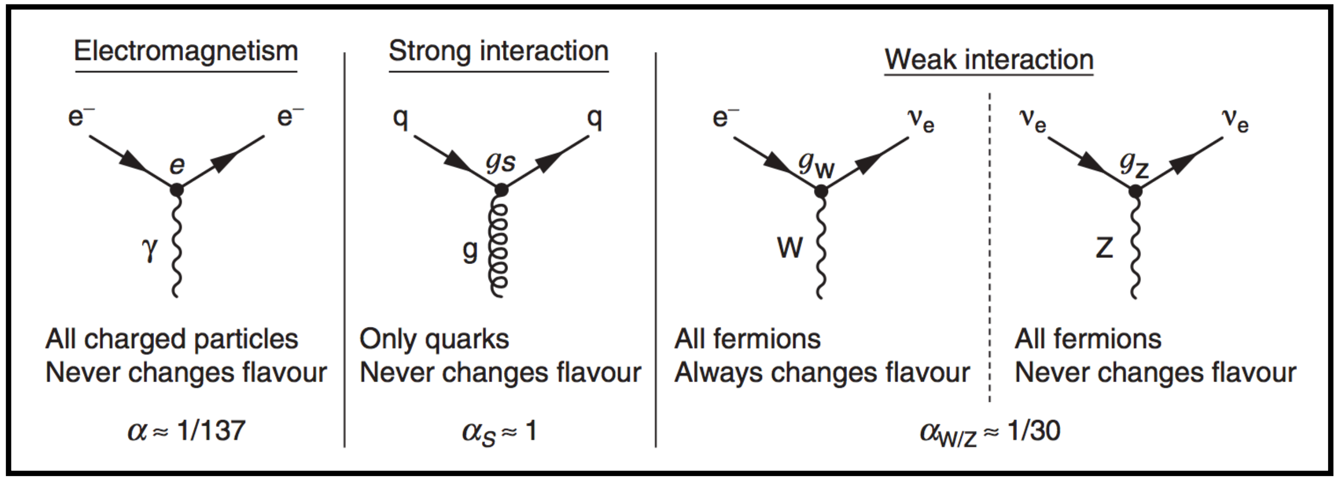
P violation in 60Cu

Recap and survey

Unfinished business

How matter interacts

- Examples of Feynman diagrams

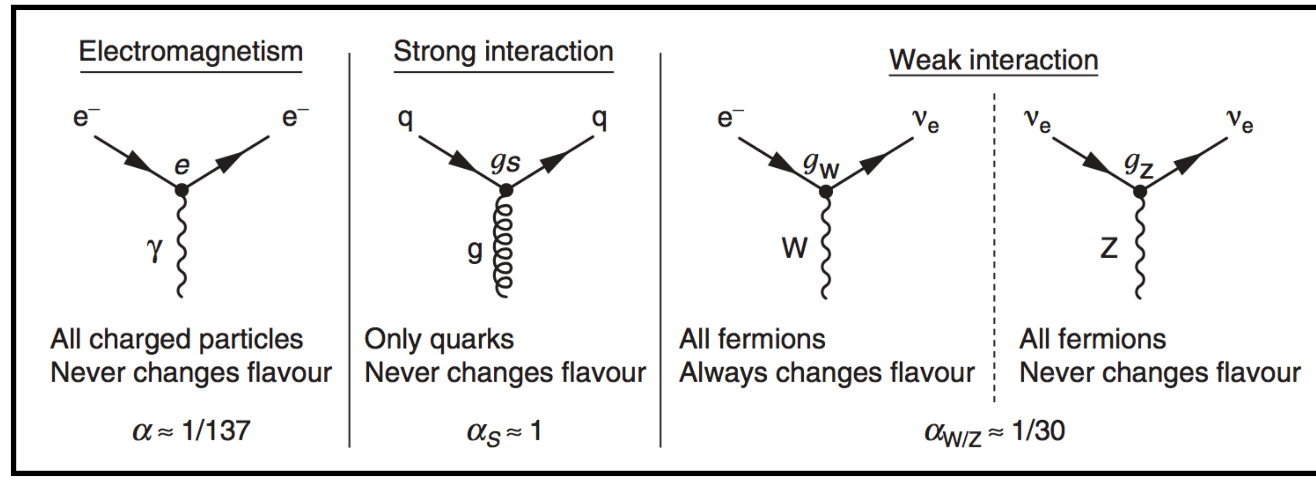


Beta decay
Neutron -> Proton + electron + neutrino

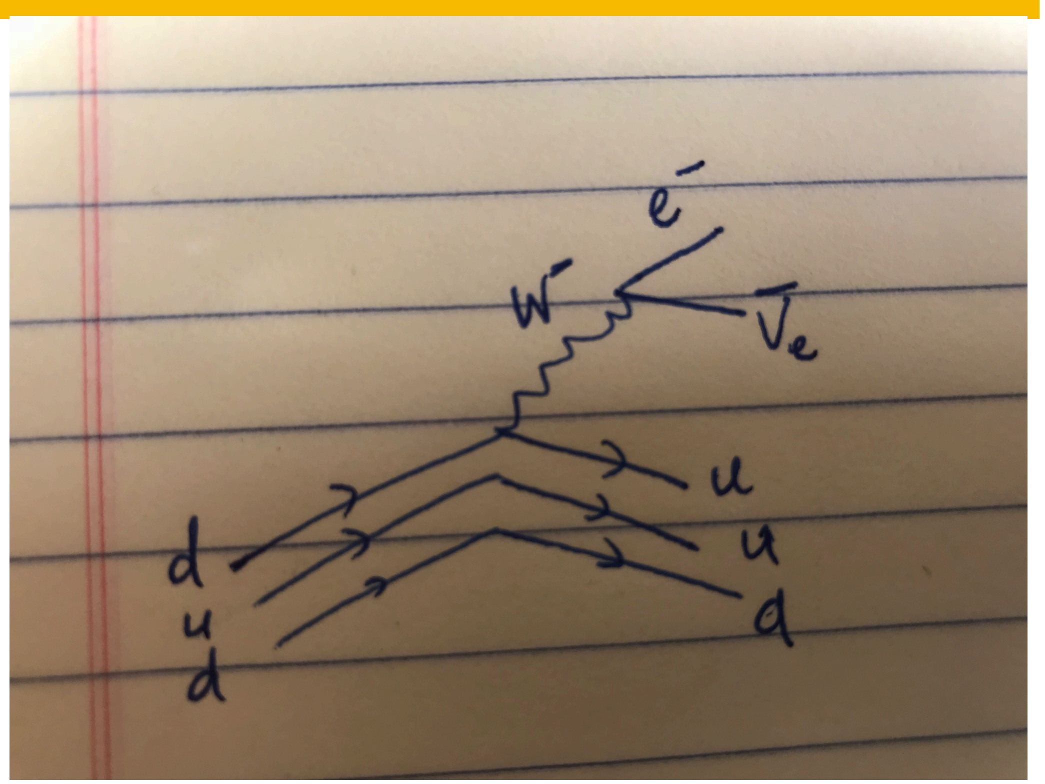
Hint:
Neutron has 1 up quark (+2/3 e), 2 down quark (-1/3 e).
Proton has 2 up quarks and 1 down quark.
Electromagnetic charge should be conserved.

How matter interacts

- **Examples of Feynman diagrams**



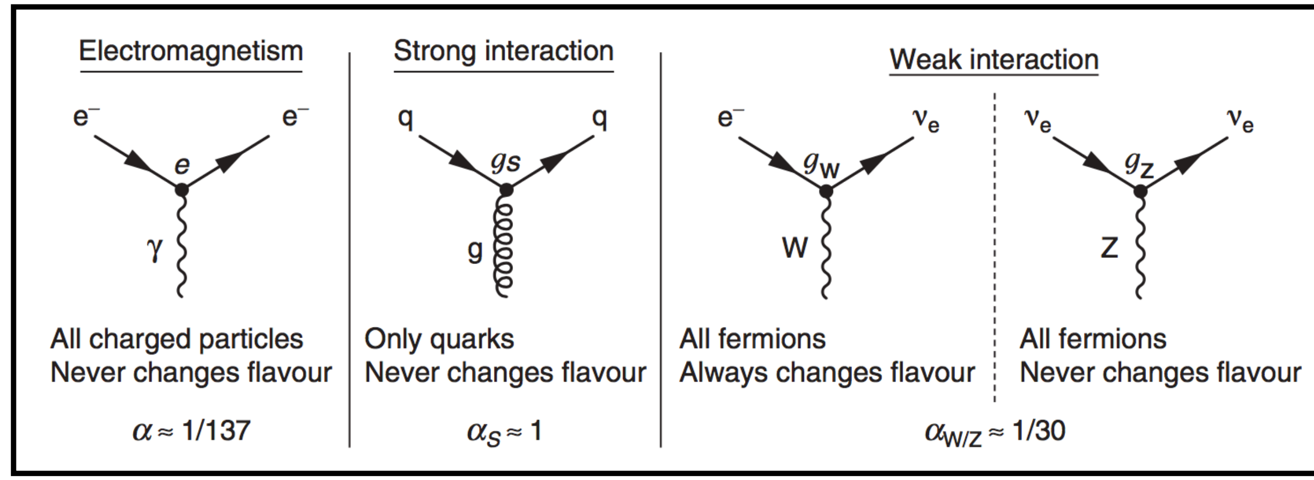
Beta decay
Neutron -> Proton + electron + neutrino



Hint:
Neutron has 1 up quark (+2/3 e), 2 down quark (-1/3 e).
Proton has 2 up quarks and 1 down quark.
Electromagnetic charge should be conserved.

How matter interacts

- **Examples of Feynman diagrams**

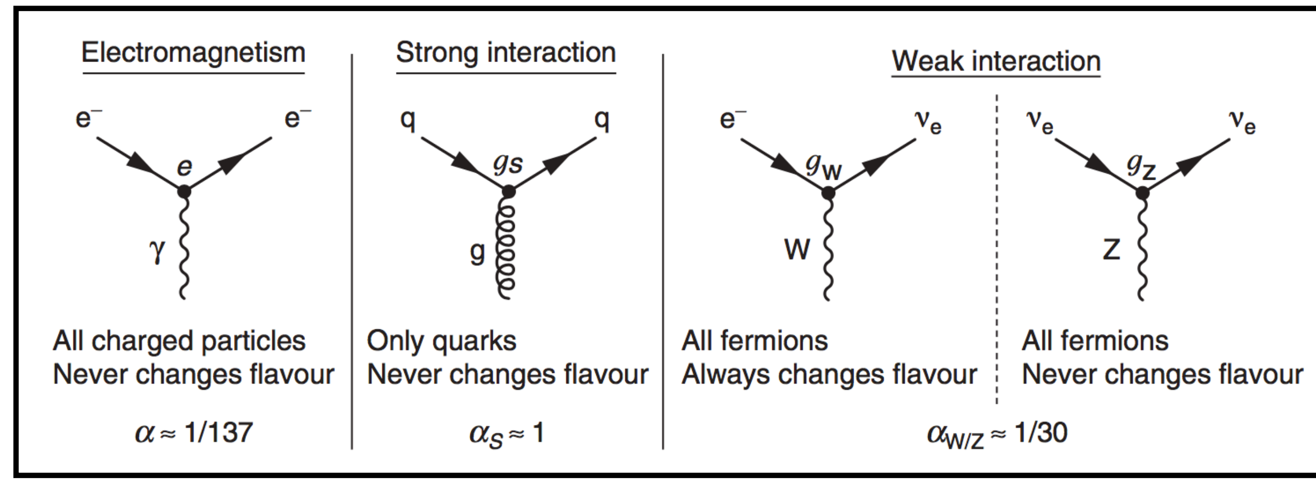


e+, e- pair annihilation

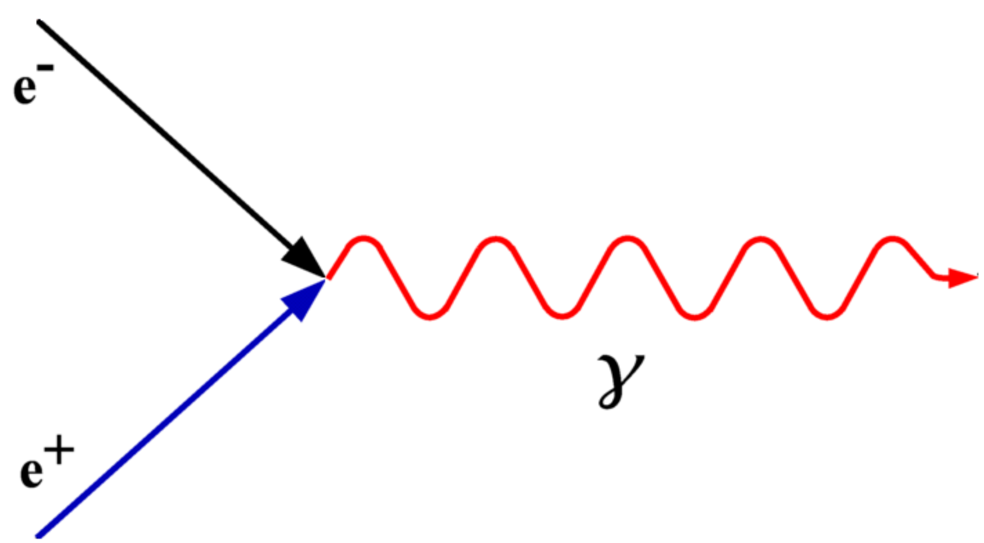
Hint:
Elementary particle and its anti-particle can annihilate

How matter interacts

- **Examples of Feynman diagrams**



e+, e- pair annihilation



Hint:
Elementary particle and its anti-particle can annihilate

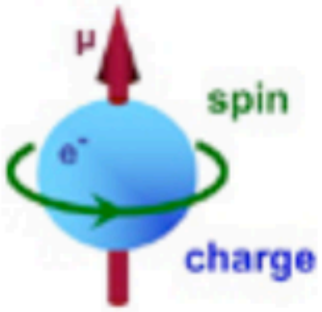
Foundations of Particle Theory

- Particle physics is the study of the smallest constituents of matter.
- At these size scales, matter behaves quite differently than in the macroscopic world.
  - Here, particles obey the rules of quantum mechanics.
  - Moreover, to observe the smallest size scales, we must accelerate particles to very high energies, near the speed of light, **c**. At these speeds, Newtonian mechanics is superseded by special relativity.
- Elementary particle physics describes objects that are both *very small and very fast*.
- Physicists developed a theoretical framework that incorporates relativistic and quantum principles: **Quantum Field Theory**.

Field Theory and the Standard Model

- Quantum field theory (QFT) is the sophisticated mathematical infrastructure of particle physics. It tells us the dynamics of elementary particles - that is, how to use force laws to describe subatomic behavior.
- While QFT is itself quite challenging, its main product - the Standard Model of particle physics - is conceptually straightforward.
- Some parts of the Standard Model perform incredibly well, for example, Quantum Electrodynamics. Its predictions match experiment with stunning accuracy!
  - Actually, these are the most precise predictions and measurements in Science.

$\mu_{electron}$= 1.00115965219 ±0.000000000001 μ_B (measured)
$\mu_{electron}$= 1.00115965217 ±0.000000000003 μ_B (QED prediction)
(PDG, 2002)



Quiz: Interactions

- Name 4 interactions
- Name the mediating particles for those interactions
- Classify them to fermions or bosons

Class Survey

- Name / Year
- Favorite subject
- What made you register for SHP particle physics?
- What are you most excited to learn from this class?
- What is the most exciting thing in physics for you?
- Any physics/ research in physics related questions? (Optional)