The Standard Model – Part 1:
”Cut the Shackles ... Changed My Name”

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PROGRAMME

- Part 1:
  ”Cut the Shackles …
  Changed My Name”
- Part 2:
  ”This Way to Gold”
- Part 3:
  ”I Came So Far to
  Get Lost at Sea…”

”So I cut the shackles and changed my name
And I shed my past like skin on a snake
But I came so far to get lost at sea
Oh, where the hell am I supposed to be?

And the sirens scream down every road
While the signs light up, ‘This way to gold’
But I'm attached to my worst enemy
Oh, who the hell am I supposed to be?”

Alice Merton, “Run Away Girl”

An Incredible Era

- It is an incredible era in which to be studying the universe.
- The tools have never been sharper.
- The ideas have never been more powerful.
- There has never been more data.
- There are just a few mysteries to be resolved.

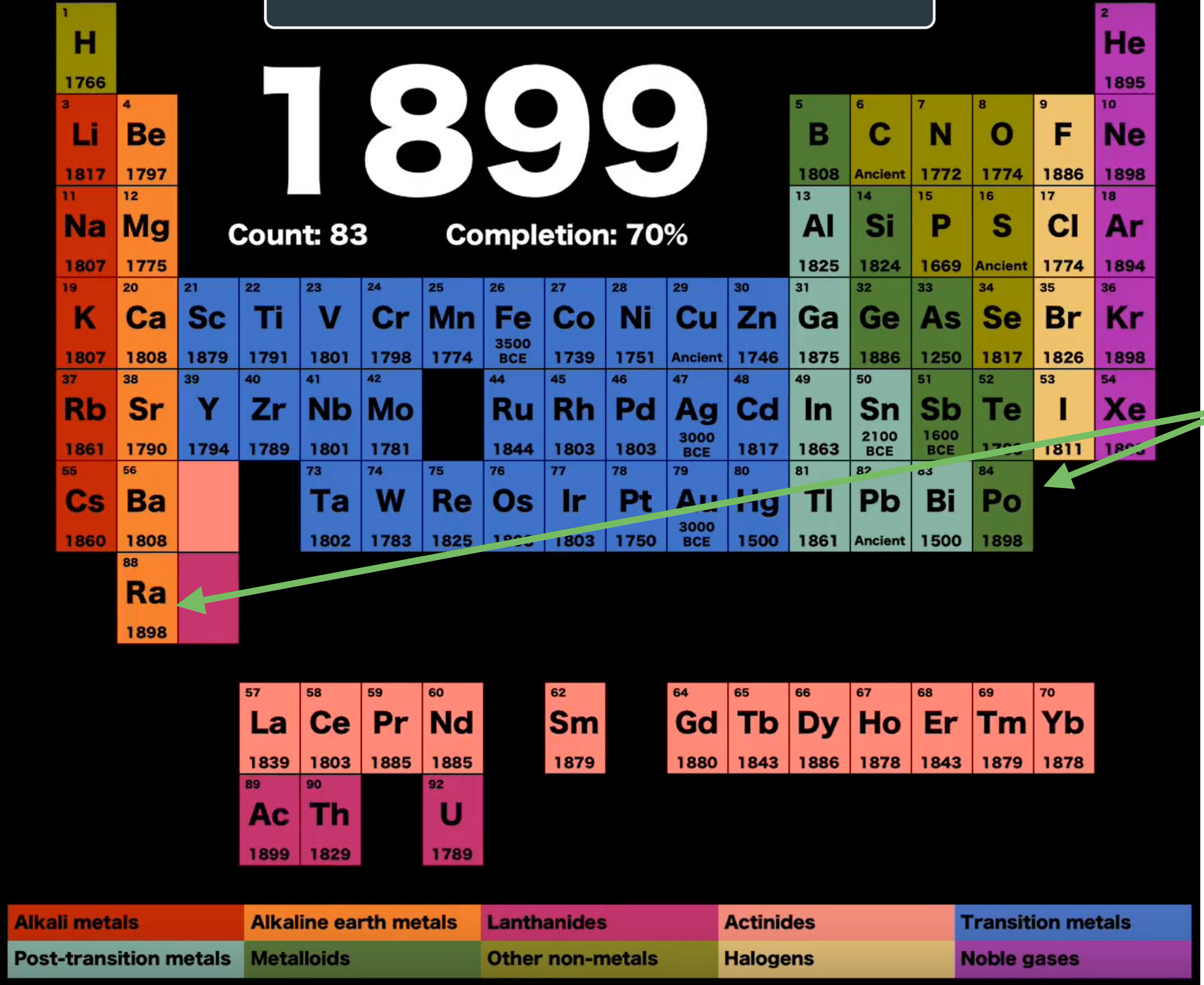
What era am I describing?

1899

PART 1
Cut the Shackles … Changed My Name

Physics, ca. 1899

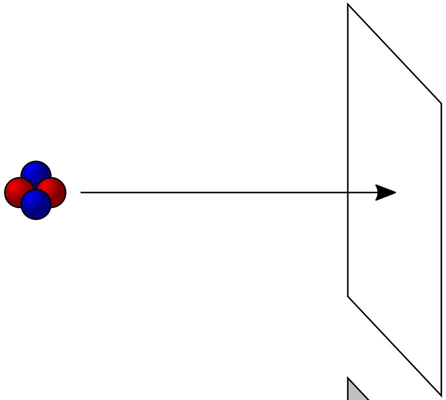
- Mechanics was well-established as a description of motion and forces, including mechanical energy.
  - **Problem: there appeared to be a new form of energy – radiation from natural elements – that defied conservation laws.**
- Thermodynamics was recently established as a description of heat energy (1st and 2nd laws of thermodynamics are established)
  - **Problem: the blackbody radiation spectrum not fully described and understood.**
- Electromagnetism is also recently established in its more modern form (Maxwell's Equations).
  - **Problems: laws not invariant under a Galilean transformation and Maxwell's Equations predict a speed of light but don't specify the reference frame in which this number is measured.**



Marie (right) and Pierre (left) Curie

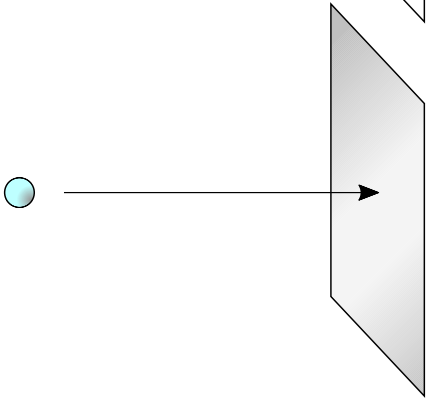
1898: a banner year for the discovery of noble or radioactive elements

α



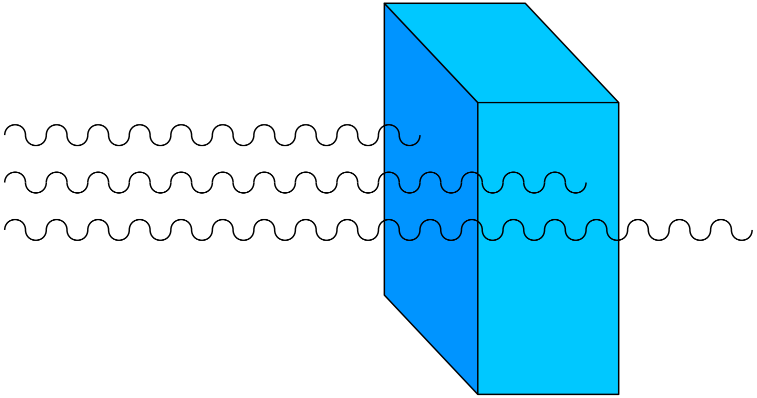
Least-penetrating radiation, later understood to be helium nuclei (late 1800s/early 1900s)

β



Intermediate-penetrating radiation, understood by charge-to-mass ratio (1900) to be electrons (cathode rays)

γ



Highly penetrating radiation, understood to be high-energy light (1914), discovered using radium in 1900.

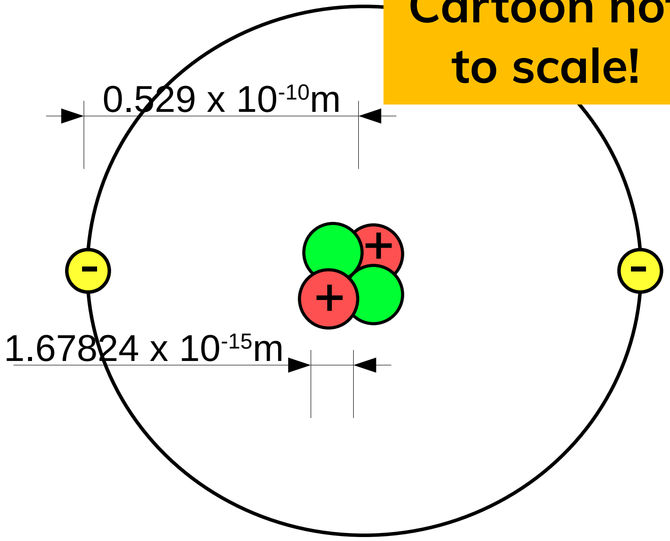
Age of the Atom

- Einstein's 1905 paper explaining Brownian motion "seals the deal" on the atomic hypothesis.
- Thomson identified "cathode rays" as made from constituents, electrons, in 1897. Builds a model of an atom using electrons.
- Geiger, Marsden, and Rutherford use scattering experiments to identify a positively charged core inside gold atoms, 10,000 times smaller than the overall atomic size. The "Rutherford model" is born in 1911 from this data.
- Attempts to explain other atomic phenomena (spectra) require a model of the atom, and the Bohr-Rutherford model is the first "quantum model" of the atom to explain discreteness of atomic spectra. Atomic spectra and other new atomic data would drive the development of quantum mechanics for 2 decades.
- Nuclear physics would drive quantum mechanics as well. The neutron is discovered in 1932 by Chadwick, completing the understanding of the traditional atom.

The Energy Scale of the Nucleus (10’)

- Estimate, using only classical physics [mechanics, EM], the energy scale (in eV) associated with nuclear processes.
- Bonus: estimate the wavelength of a photon that could be released from a nuclear process, using this model. What class of photon is this? (radio, infrared, visible, UV, x-ray, gamma ray)

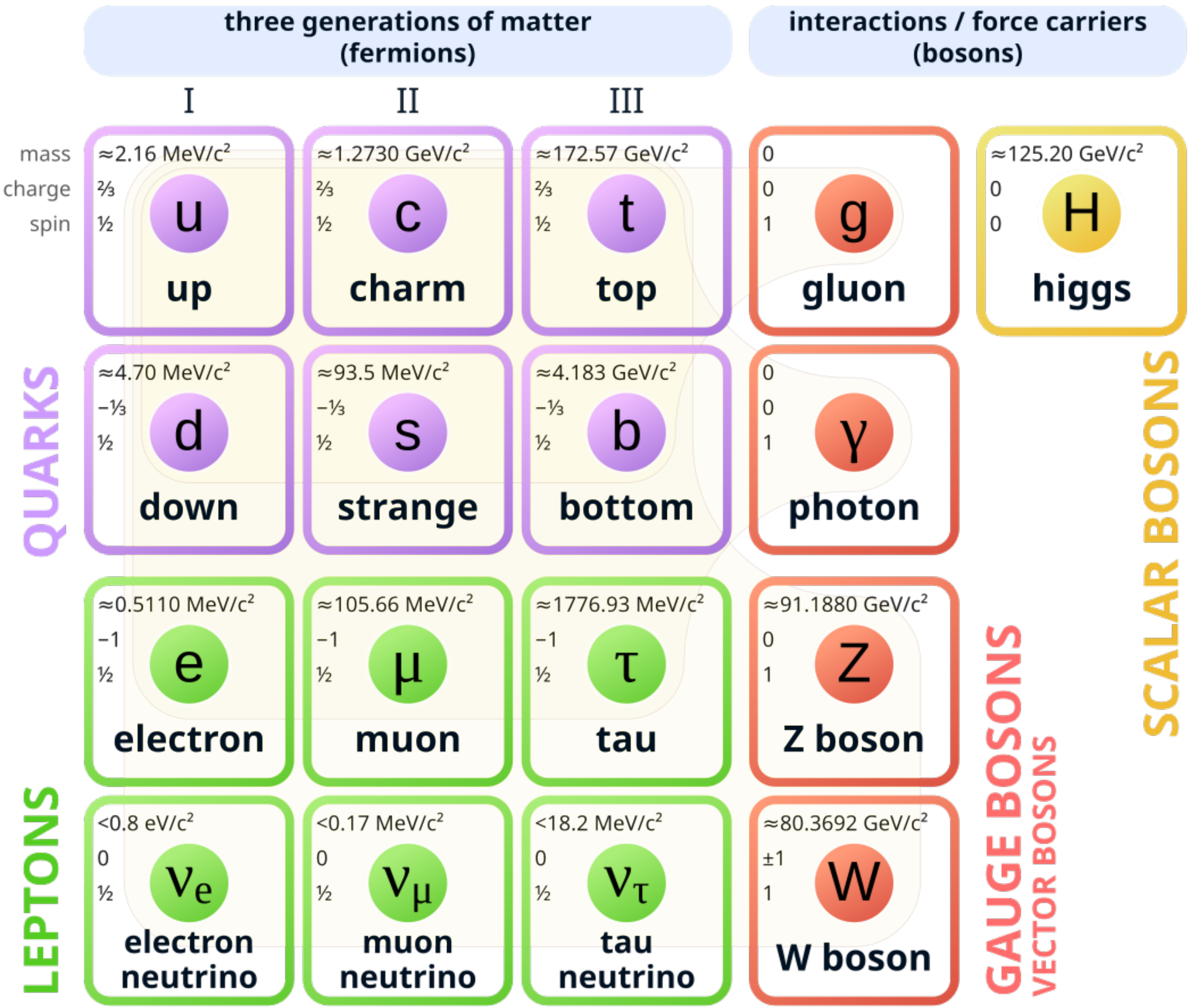
Cartoon not to scale!



Useful Information

1 eV = 1.609×10^{-19} J
$\varepsilon_0 = 8.85419 \times 10^{-12}$ C/kg/m^3/s^2
1 fm = 10^{-15}m

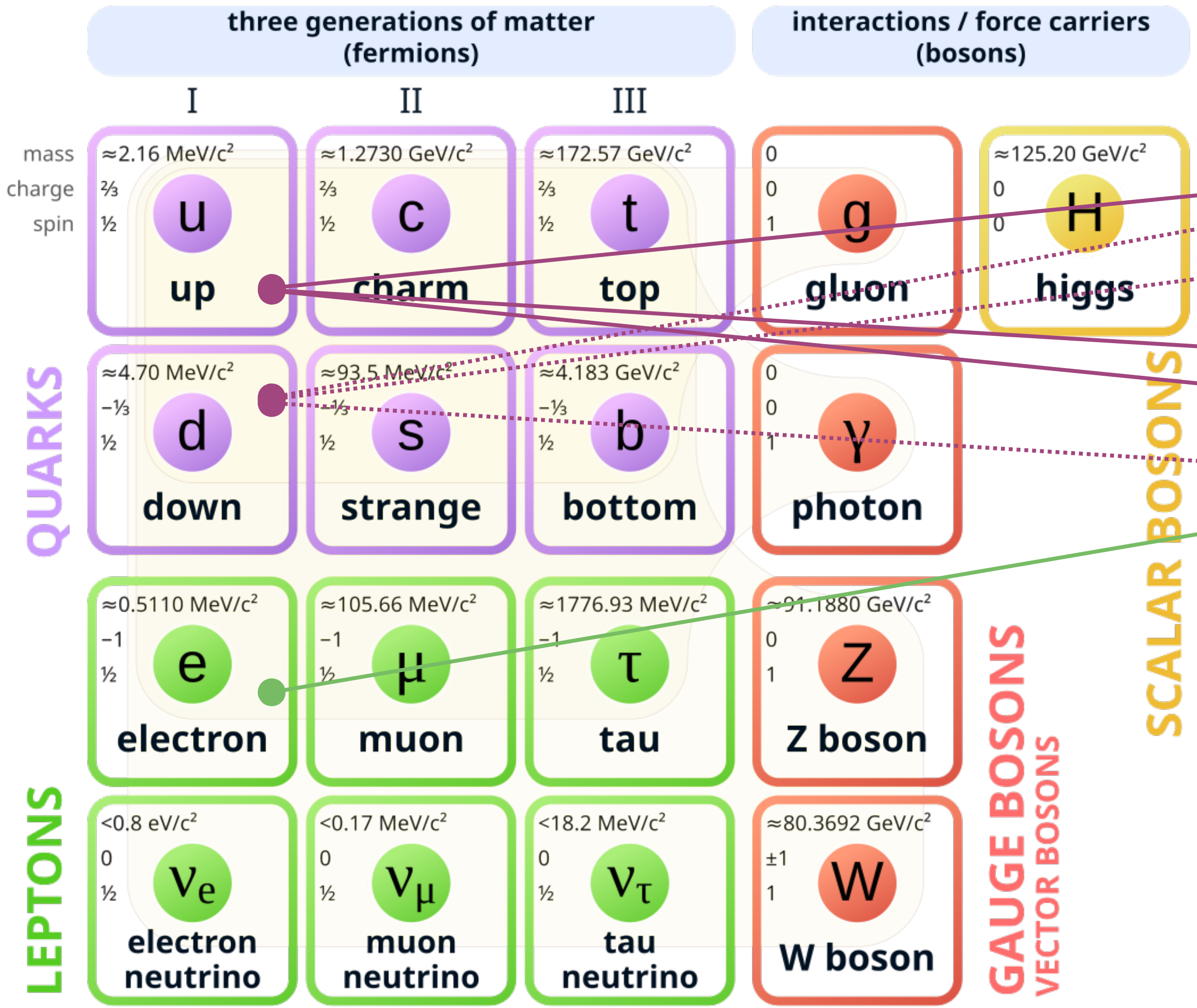
Standard Model of Elementary Particles

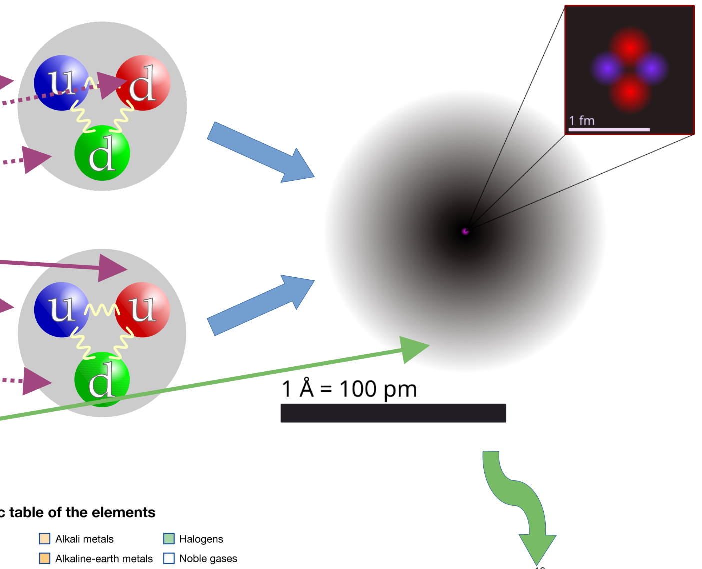


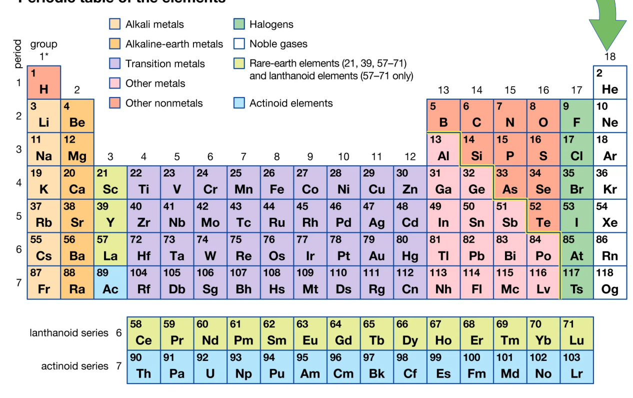
The modern understanding, based on a century of discovery.

- Two families of matter particles, describable by quantum mechanics.
- Three distinct interactions (forces), also describable by quantum mechanics.
- Matter “charged” under forces → determines how they interact.
- Mathematical symmetries whose obeyance/breaking defines the character of physical behaviour.

Standard Model of Elementary Particles







period	1*	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og

lanthanoid series 6	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
actinoid series 7	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

*Numbering system adopted by the International Union of Pure and Applied Chemistry (IUPAC).

The Tools of Physics ca. 1930

Classical Mechanics/Lagrangian and Hamiltonian Dynamics

$$L \equiv T - V$$
$$H \equiv T + V$$

T = kinetic energy
V = potential energy

$$\frac{d}{dt}\left(\frac{dL}{d\dot{q}_i}\right) - \frac{dL}{dq_i} = 0 \qquad \dot{q}_i \equiv \frac{dq_i}{dt}$$

Lagrange's Equations →
Equations of Motion

The above applies to a system with discrete components (e.g., particles!) but can be readily generalized to systems with continuous coordinates (classical field theory!)

Classical Theory of Electromagnetism/Maxwell's Equations

$$\vec{\nabla} \cdot \vec{E} = \rho \qquad \vec{\nabla} \times \vec{E} + \frac{\partial \vec{B}}{\partial t} = 0$$
$$\vec{\nabla} \cdot \vec{B} = 0 \qquad \vec{\nabla} \times \vec{B} - \frac{\partial \vec{E}}{\partial t} = \vec{j}$$

This is the form when in empty space ("vacuum")

Light is an electromagnetic wave that moves at speed c:

$$c = \lambda f$$

The Tools of Physics ca. 1930

Special Relativity/A Theory of Invariants

$$t' = \gamma(t - \beta x)$$
$$x' = \gamma(x - \beta c t)$$
$$y' = y$$
$$z' = z$$

A frame S is treated as being "at rest" (with coordinates x,y,z,t) and a frame S' as being "in motion relative to S" with its own coordinates x',y',z',t'. S' is in motion relative to S with a velocity v along x such that $\beta = v/c$.

$$\gamma \equiv (1-\beta^2)^{-\frac{1}{2}}$$

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

The relationship between mass (inertia), motion (momentum), and total energy.

$$c = 2.998 \times 10^8 \text{ m/s}$$

Schroedinger's Equation (Non-Relativistic Quantum Theory)

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

1-dimensional form of the equation, with $\Psi(x,t)$ being the wave function, which in the Born interpretation results in a probability density for finding the system at position x at time t by computing $|\Psi(x,t)|^2 = \Psi^*(x,t)\Psi(x,t)$.

$$E = hf = \hbar\omega, \quad p = h/\lambda = \hbar k$$
$$\hbar = h/2\pi$$

$$h = 6.626 \times 10^{-34} \text{ J}\cdot\text{s}$$

The Tools of Physics ca. 1930

Symmetry and Conservation Laws

Noether's theorem (1918), born from a quest to prove/disprove the validity of the General Theory of Relativity, gave us deep insight into the nature of conservation laws:

A physical system with conservative forces

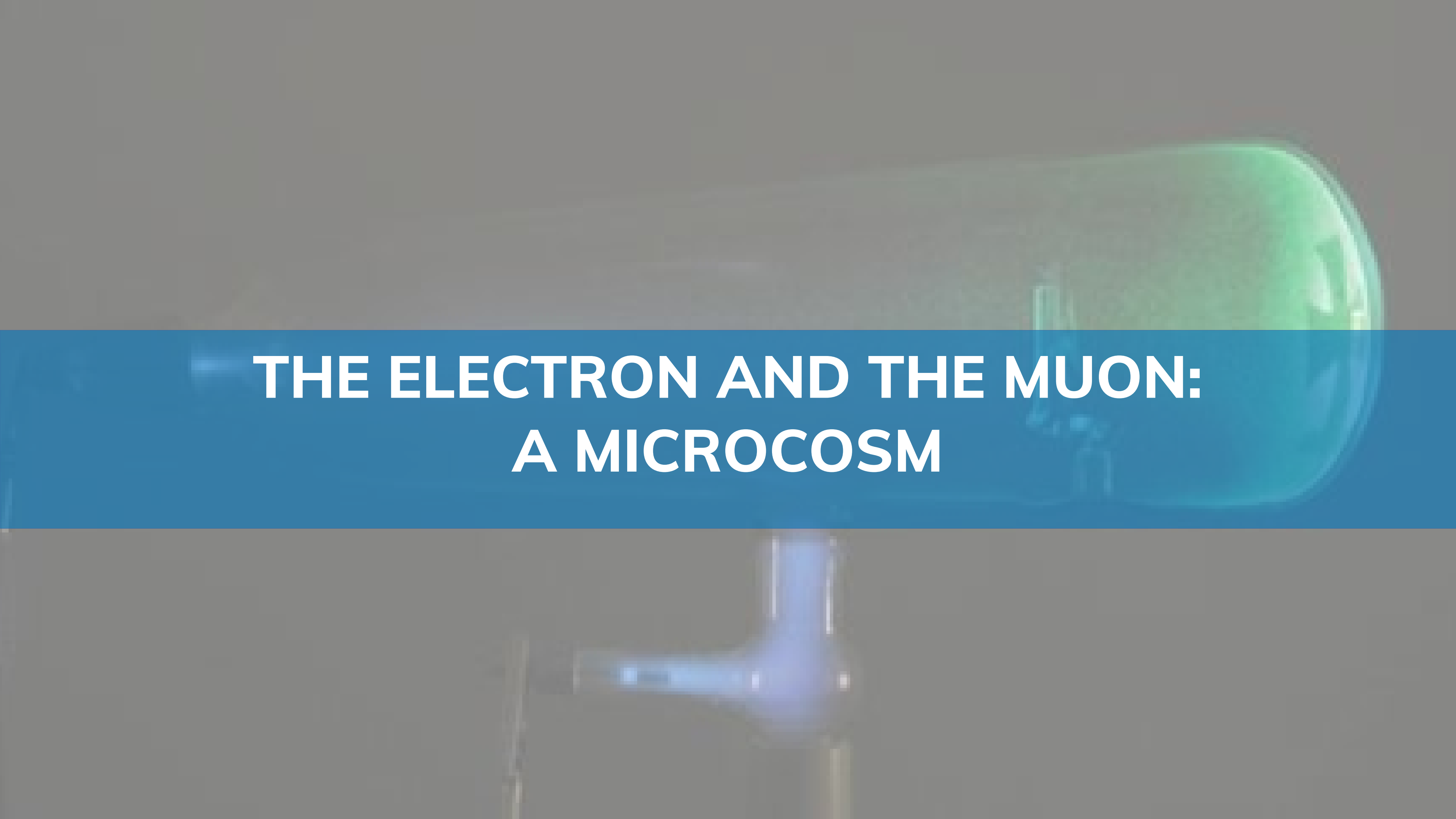
A Continuous Symmetry ⟷ A Conserved Quantity

$$\left(\frac{dL}{d\dot{\vec{q}}_i}\cdot\dot{\vec{q}} - L\right)T_r - \frac{dL}{d\dot{\vec{q}}_i}\cdot\dot{\vec{Q}}_r$$

where T_r ($\mathbf{Q}_r$) is the generator of time (space) evolution

Amalie Emmy Noether

THE ELECTRON AND THE MUON: A MICROCOSM

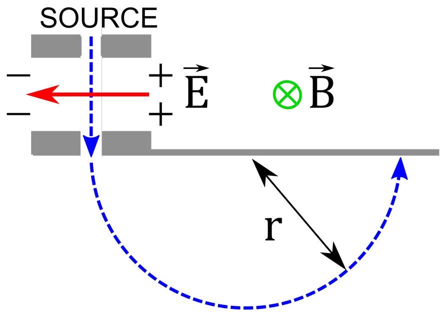


Why the Muon?

- We'll begin with the electron – its discovery and properties
- We'll look at some of the early evolution of particle detector technology
- The discovery of the muon was the first step into the matter picture of the standard model ("generations" of matter)
- Lessons from the muon will help us to understand all the rest of the Standard Model particles

Discovery of the Electron

- “Cathode Rays” observed and studied by multiple scientists (1859-1876).
- J.J. Thomson (1897) determines they are made from particles with charge-to-mass ratio different from hydrogen ions. Millikan’s 1909 experiment established the elementary charge, and from this the electron mass could be determined.

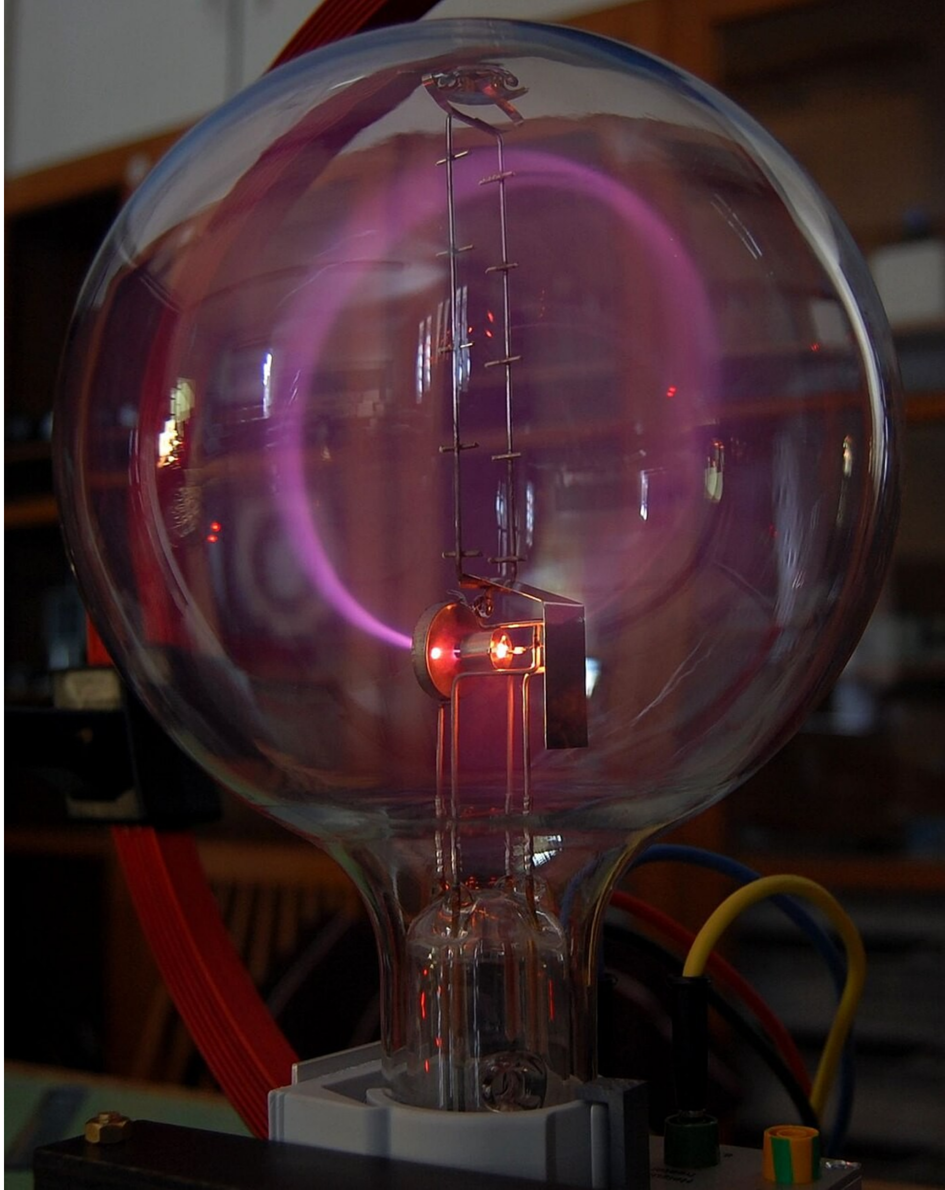


$$\frac{Q}{m} = \frac{E}{B^2 r}$$

$$|\vec{F}_E| = |\vec{F}_B|$$

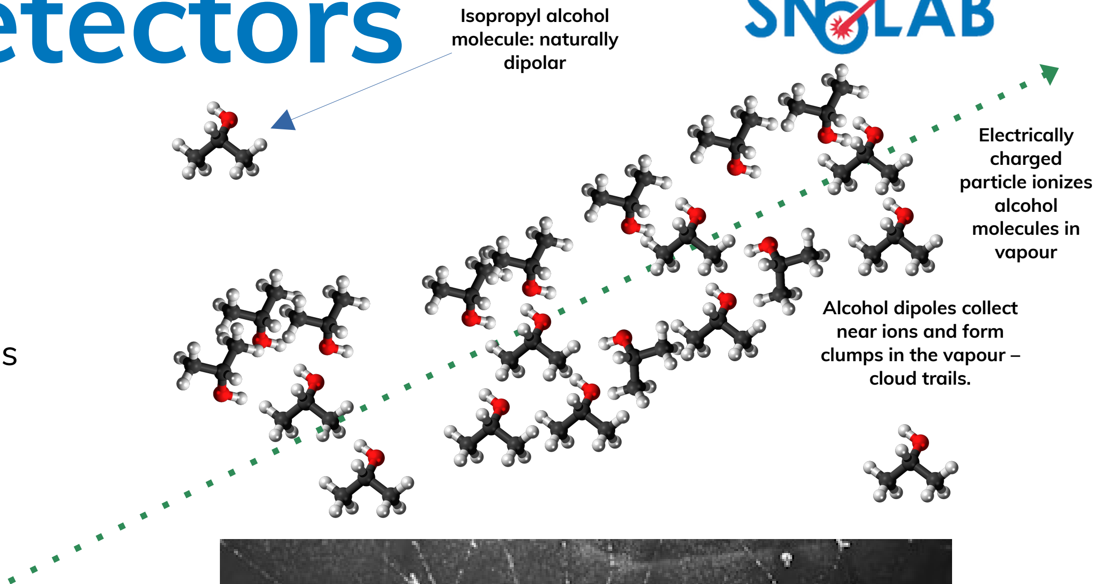
$$e = 1.602 \times 10^{-19}\,\mathrm{C}$$

$$m_e = 9.109 \times 10^{-31}\,\mathrm{kg} = 511.0 \times 10^{3}\,\mathrm{eV/c^2}$$



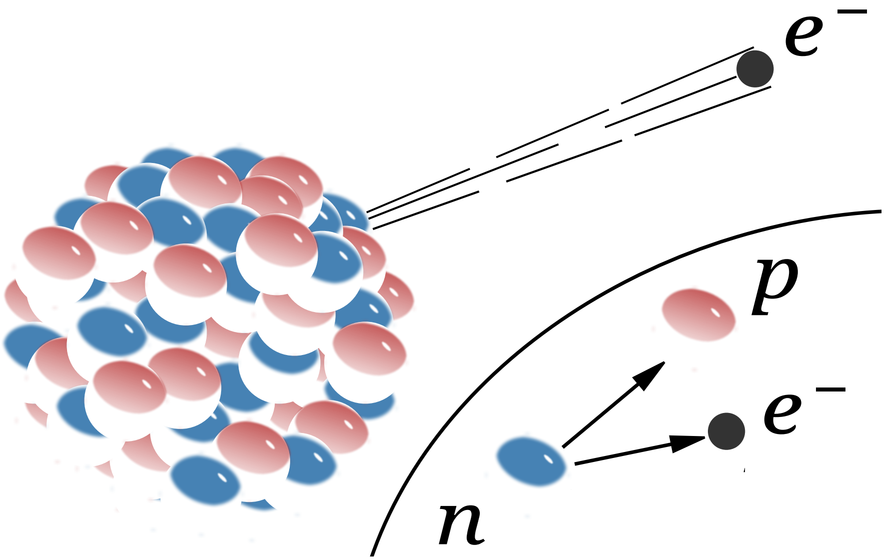
Early Particle Detectors

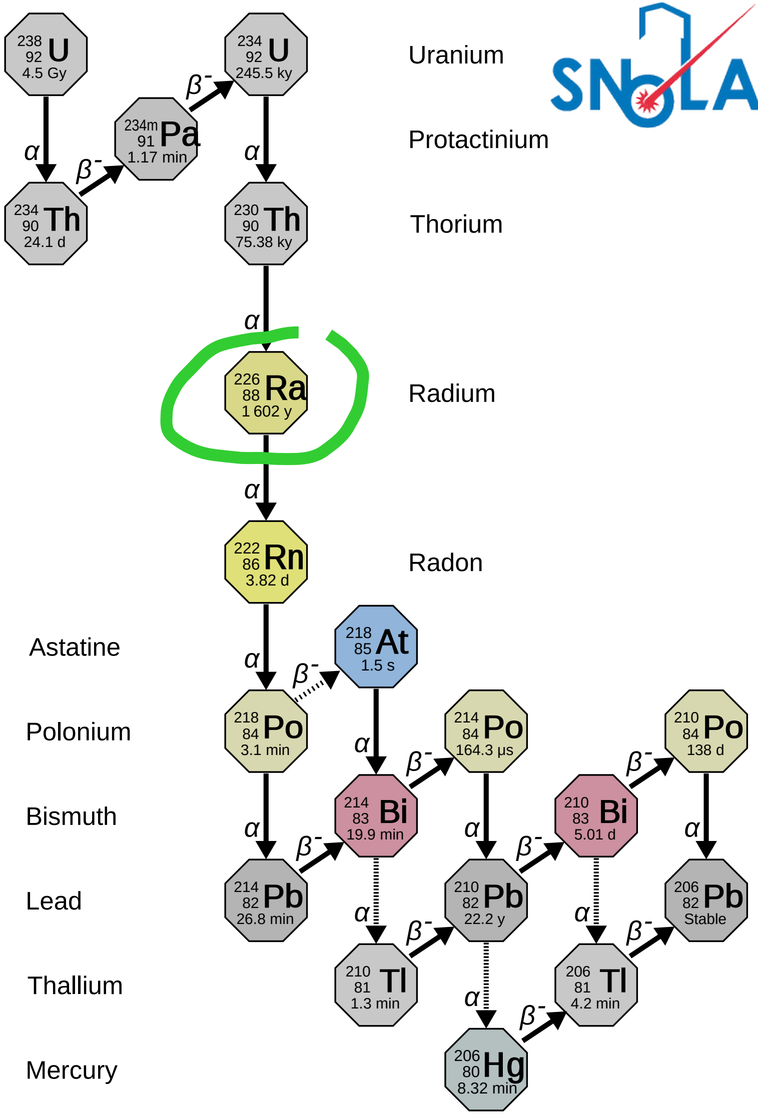
- Chemical photography developed in the early 1800s
  - Photographic plates became the earliest particle detectors, one purpose and sometimes accidentally (c.f. Becquerel's accidental discovery of natural radioactivity when he detected Roentgen's "x-rays" coming from uranium salts)
- The Cloud Chamber was invented in the early 1900s (Charles Wilson) and was a staple of atomic and subatomic physics until the bubble chamber was invented in the 1950s. Combined with photography this allowed capture of the trajectories of particles.



Describe the radiations you see in this cloud chamber movie.

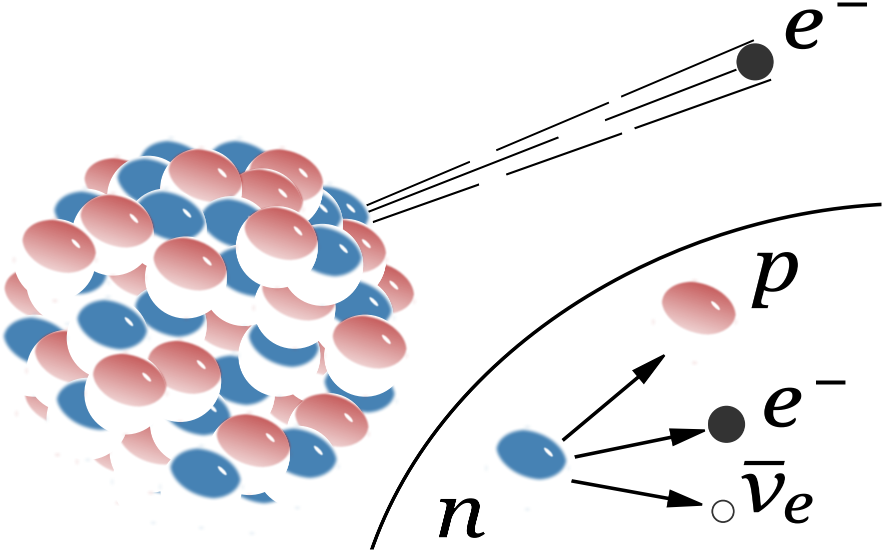
Beta Decay

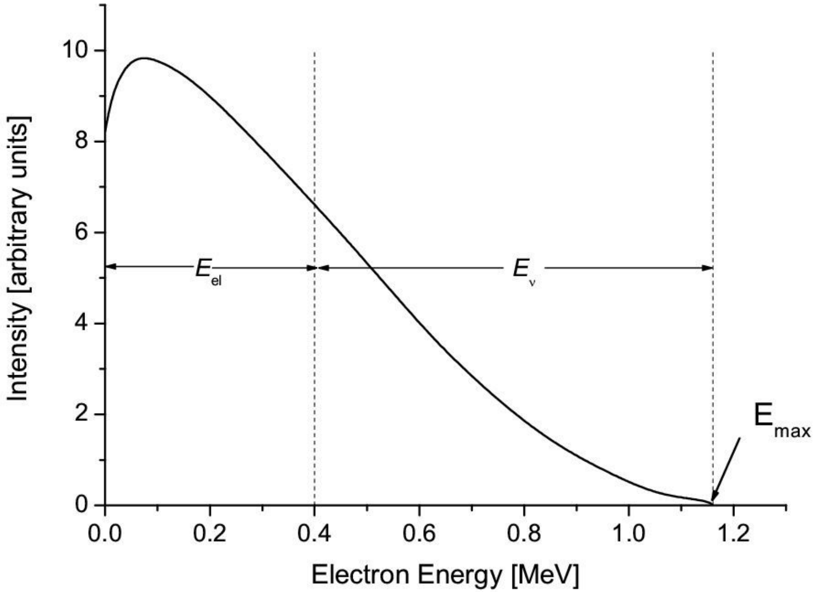




Exercise: using the simple model depicted above and relativistic mechanics, predict the kinetic energy of the electron assuming the neutron started at rest.

Beta Decay



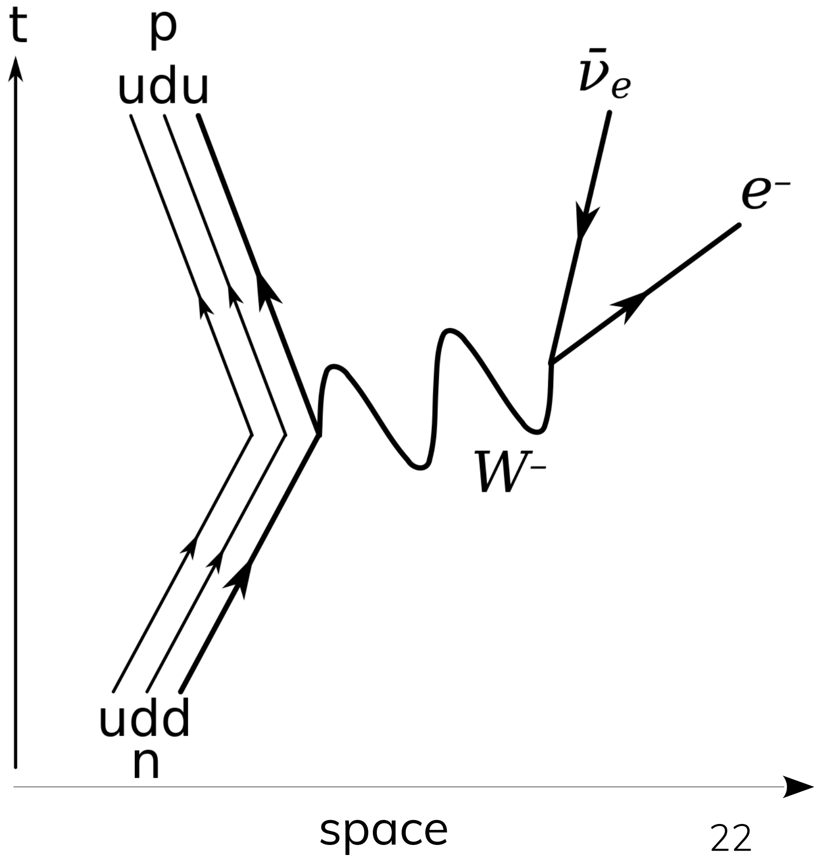


The actual beta decay spectrum of the electron implies at least one of two hypotheses: an additional "unseen" particle is also produced in beta decay (a 3-body problem) OR energy is not conserved in (some? all?) nuclear reactions.

The former hypothesis won out: the neutrino was observed in 1956 by reversing the beta decay process using a nuclear reactor as a source of anti-neutrinos.

The Weak Nuclear Force

- The existence of beta decay implied a secondary nuclear force in addition to the one that "guarantees nuclear stability". As it results in rarer processes, it would appear weaker than that force … implying a "weak nuclear force" in addition to a "strong nuclear force".
- The weak force has the ability to transmute neutrons and protons, while the strong nuclear force has the ability to bind neutrons and protons.

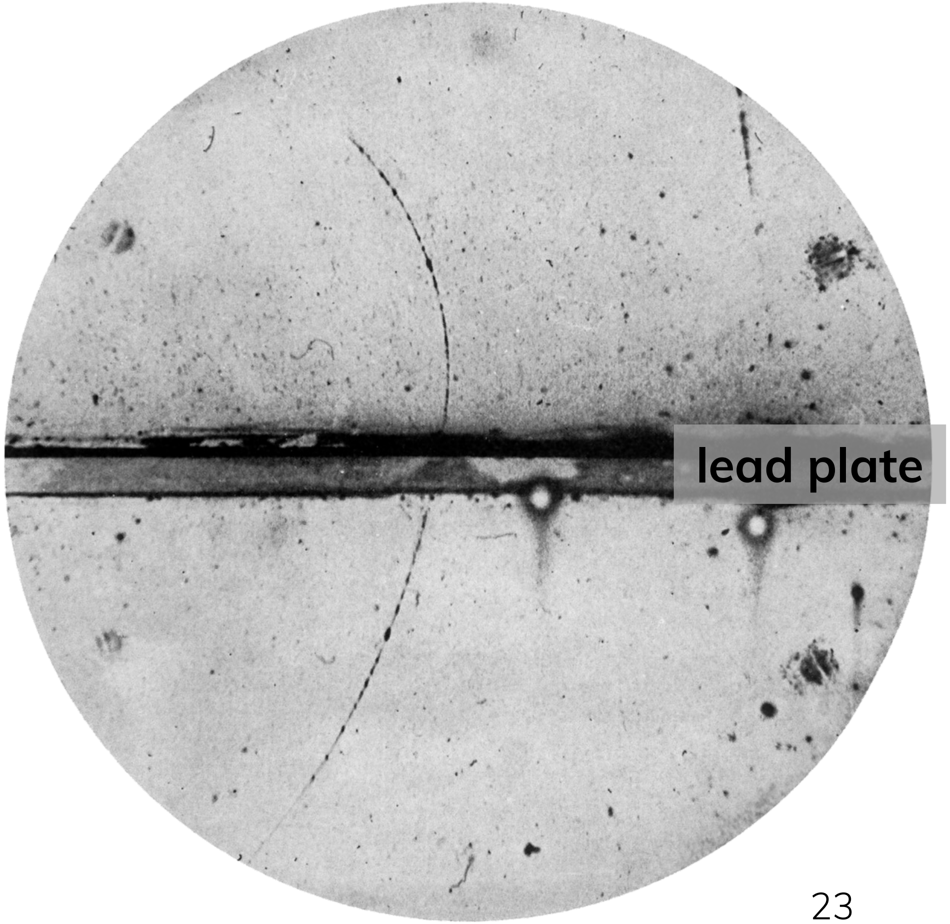


Discovery of the Positron

- The hard work of many physicists culminated in the famous work of Paul Dirac in 1928 in successfully combining quantum mechanics and special relativity. This was the birth of relativistic quantum mechanics (and the Dirac Equation).

- The Dirac Equation describes fermions (spin-1/2 particles like the electron) but admits what appear to be negative-energy solutions. Weyl demonstrated they would have mass equal to the positive-energy counterparts. Dirac interpreted these as a new form of matter – antimatter – and postulated the existence of the positron, the antimatter counterpart of the electron.

- The discovery of the positron is credited to cloud chamber experiments overseen by Carl Anderson in 1932. A cloud chamber outfitted with a magnetic field can detect particles that are electron-like but bend in the wrong direction.



Taking Stock of Matter and Forces (ca 1935)

- Electromagnetism
  - Light (photons) are the force-carrying particles, infinite in range in free space and massless. Acts between electric charges only. Cannot explain nuclear stability.
- Weak nuclear force
  - Estimated to be too weak to explain the stability of nuclei (proton repulsion), but plays clear roles in nuclear physics (beta decay). Short-ranged, implying a force carrier with mass (Yukawa theory).
- Strong nuclear force
  - Hideki Yukawa estimated the mass of the nuclear force-carrier based on its range (see right). While Yukawa theory has validity, the strong force turned out to be much stranger. However, this elevated interest in a new particle of mass O(100) MeV/c^2 that could explain this force.

$$V(r)_{\mathrm{nucl}} \propto \frac{e^{-r/r_0}}{r}$$

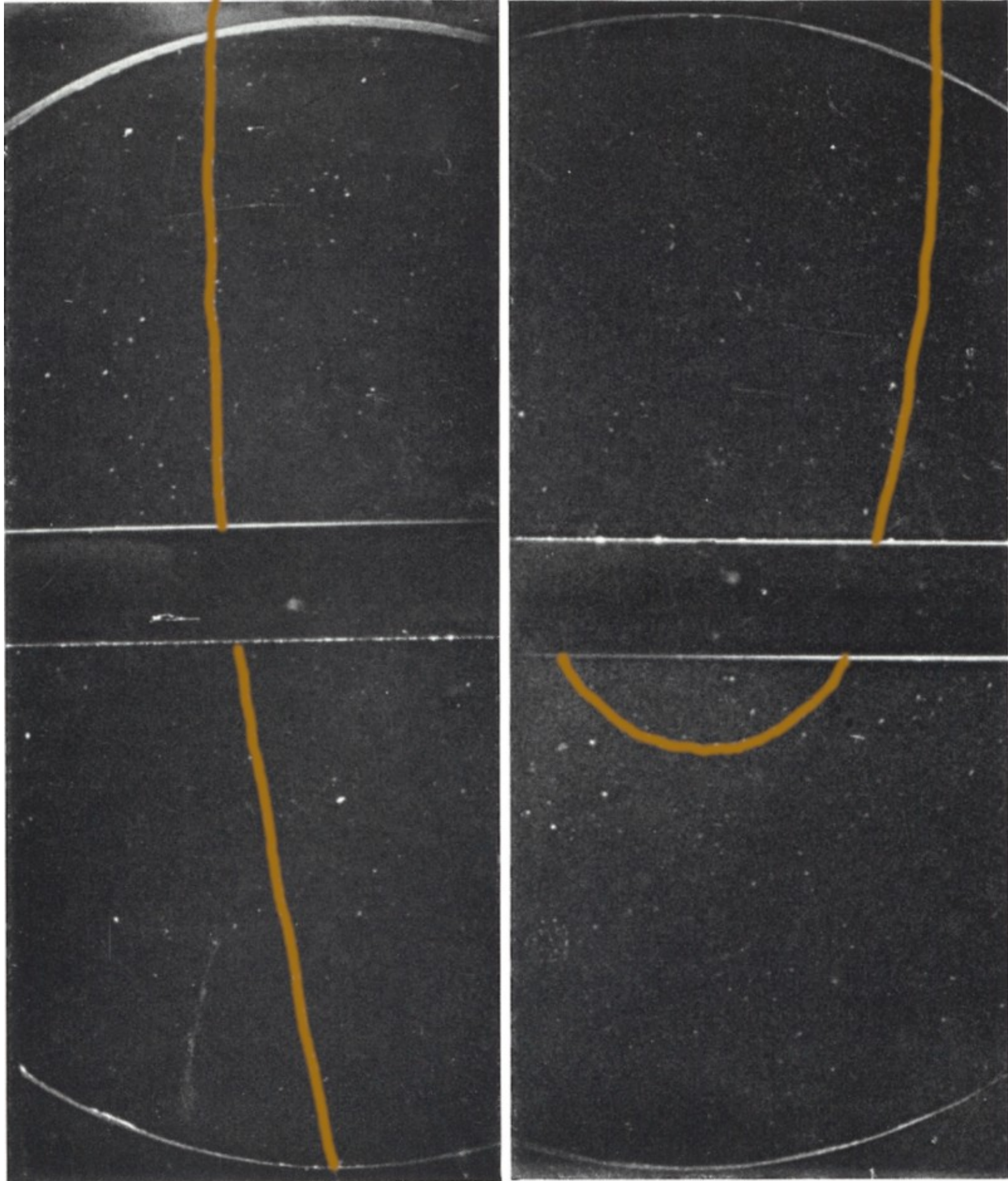
r_0 is the nuclear scale, so ~1.2fm. The range of an interaction involving a force carrier of mass *m* is given by the Compton wavelength, $\hbar/mc$, so we can estimate that

$m=\hbar/r_0c \sim 160\,\mathrm{MeV}/c^2$.

Discovery of the Muon

Cosmic ray (showers) were discovered in 1912 and have been a valuable environment in which to look for new particles/phenomena. Positrons were discovered using these showers and cloud chambers.

Strong evidence of a heavy particle emerged in cloud chambers in 1936, with a mass ~207 times that of the electron.

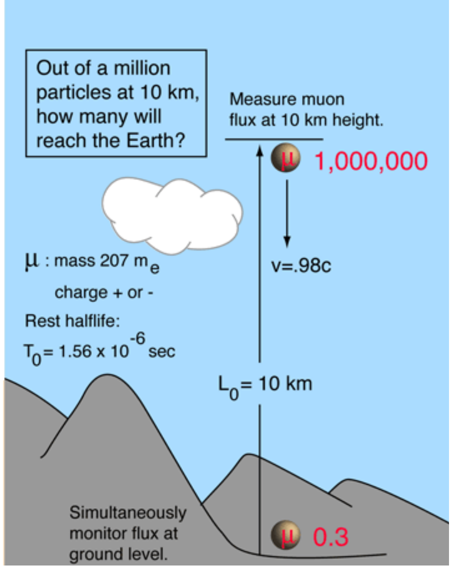


Properties of the Muon

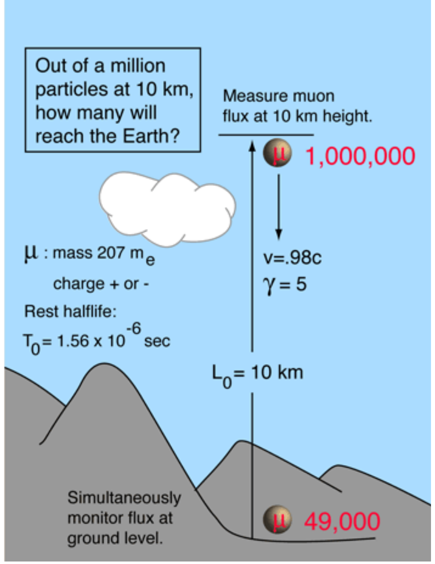
Extensive work over decades revealed its properties:

- mass of 106 MeV/c^2
- spin-1/2
- same charge magnitude as the electron
- comes in matter (-) and antimatter (+) varietals
- unstable, with lifetime (half-life) of 2.1969811 μs (1.5228312 μs)
- decay produces electrons and neutrinos
- *(it is not the particle predicted by Yukawa theory)*

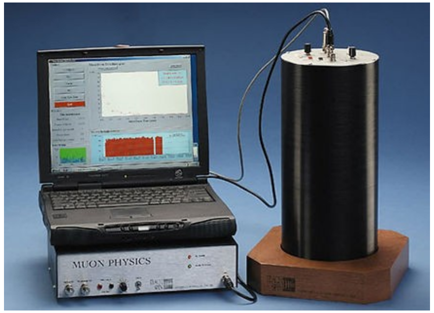
In fact, the muon was the first unexpected gift from nature after all the successes of quantum theory and relativity. It was not “needed” by any previous physical or mathematical discovery. This famously led the physicist Isidor Isaac Rabi to quip, “Who ordered that?”



Classical Physics Prediction



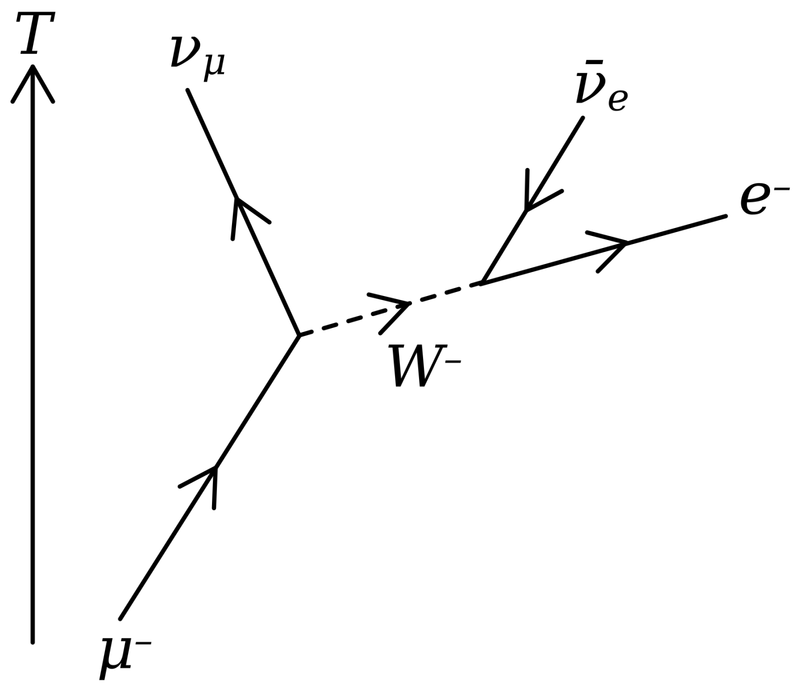
Modern Physics Prediction



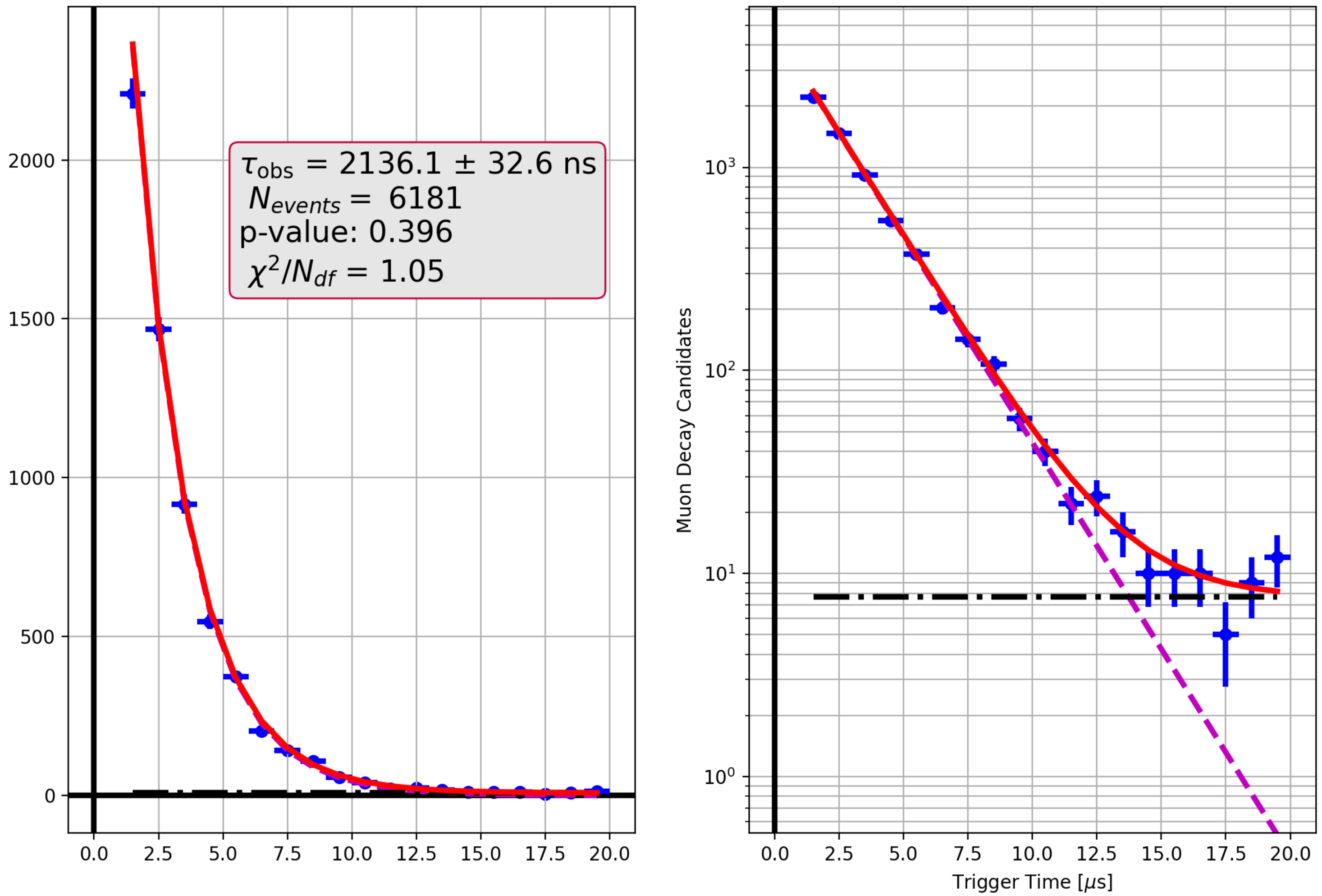
Muons with <160 MeV of kinetic energy can be stopped (through interactions with matter) in a small volume of scintillator (e.g., polyvinyltoluene). The slowing/stopping results in a pulse of scintillation light; the decay of the muon results in a second pulse.

Exercises with the Muon

- The Muon as the first laboratory for the special theory of relativity
- The Muon as a laboratory for unstable particle behaviour and the inference of particle properties



https://github.com/stephensekula/trisep2024-sm-inputs

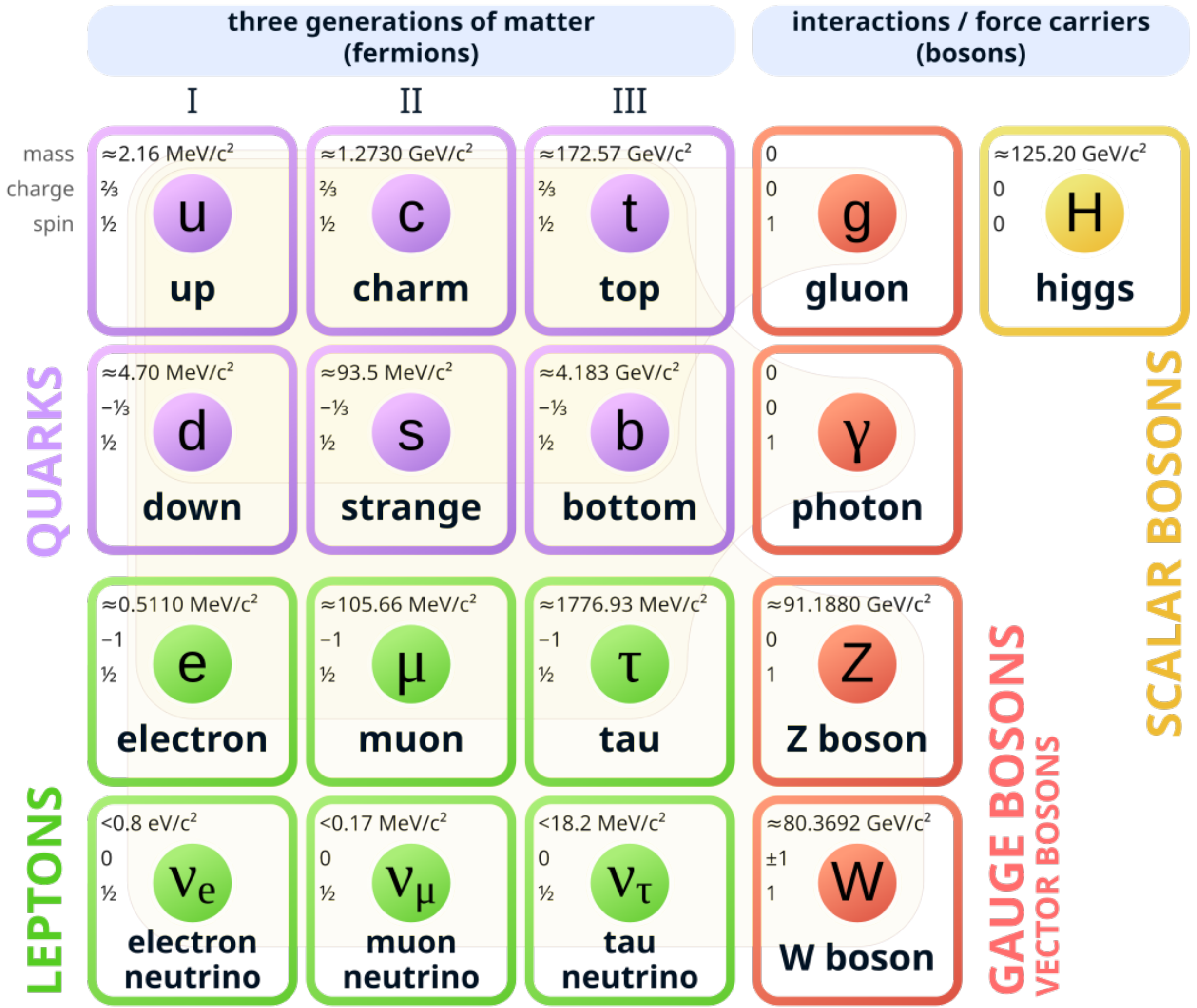


Accepted value:

2196.9811 ns

About 2.5σ low. This is caused by real nuclear physics, which we can discuss in lecture if there is time.

Standard Model of Elementary Particles



The modern understanding, based on a century of discovery.

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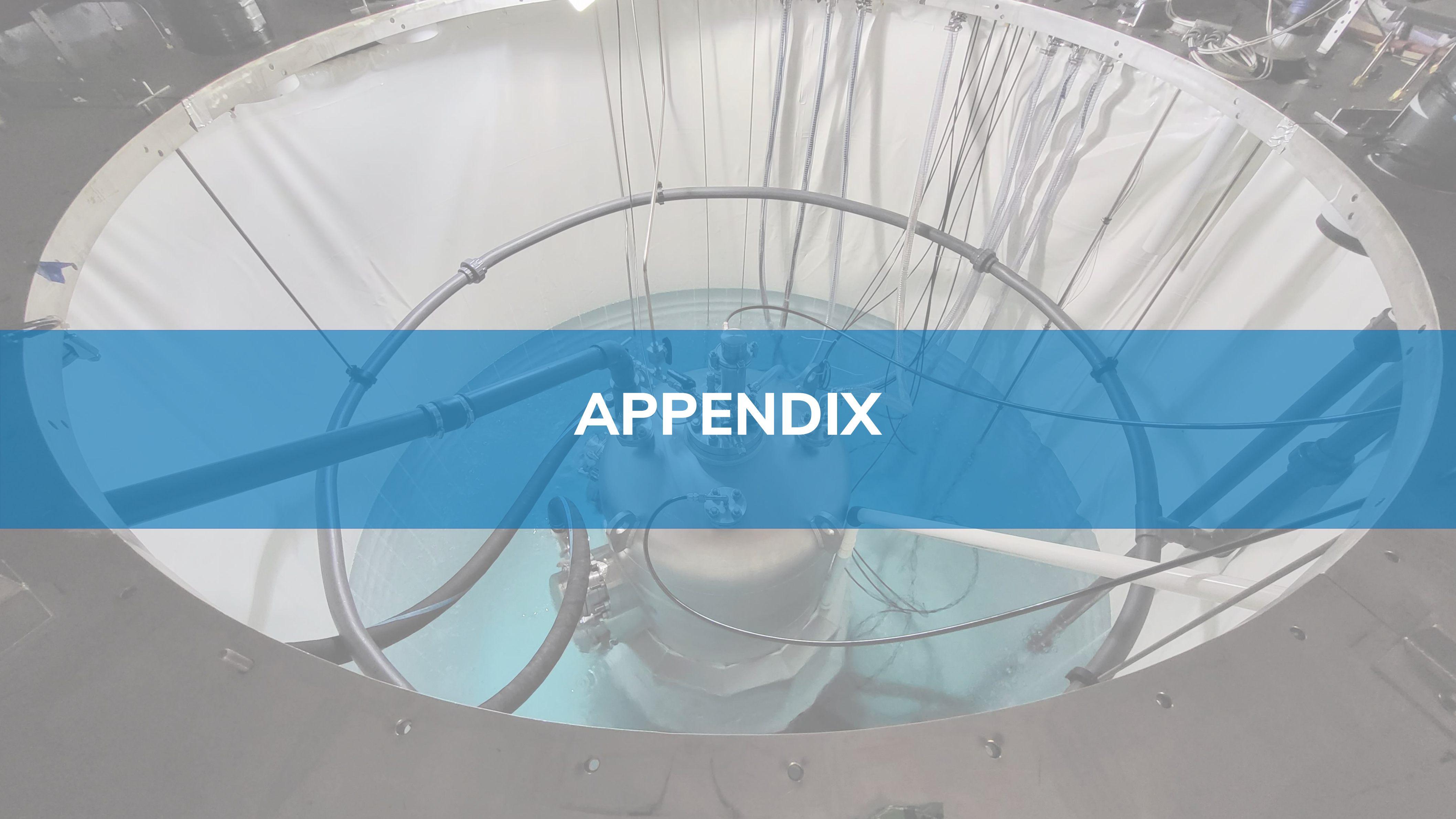
- Mathematical symmetries whose obeyance/breaking defines the character of physical behaviour.

Next Steps

- Quantum theory and relativity in the early 20th century were united and provided a powerful, predictive framework for atomic and subatomic physics.
- These were built on the old ideas of mechanics, E&M, and thermodynamics … but extended those frameworks, pulled them together, and in doing so largely resolved the problems of the old theories … but …
- New technology led to the discovery of things "beyond the atom" or "outside the atom" whose very existence meant it was necessary to expand/extend relativistic quantum theory:
  - *New forms of matter (we'll see more next time)*
  - *New interactions besides electromagnetism*
- Matter has a generational structure, with the 1st generation being "stable" and the 2nd (and 3rd) generation decaying down to the 1st. The muon-electron relationship is one example of this.

APPENDIX



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