Introduction to Particle Physics

R. Dixon

Fermilab advances the understanding of the fundamental nature of matter and energy by providing leadership and resources for qualified researchers to conduct basic research at the frontiers of high-energy physics

Researchers come from all over the U.S. and the world to conduct their research here.

Fermilab also explores the boundaries of the universe by investigating the relationships between the very large and the very small

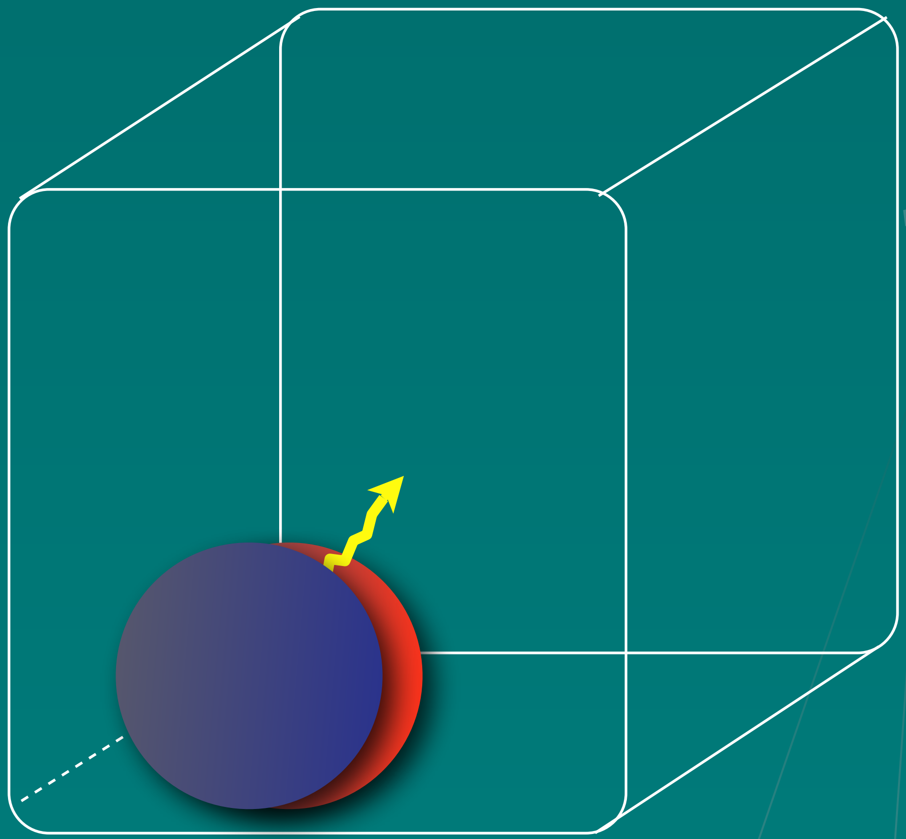
Overview

- Motivations for Science– Especially
  - Particle Physics
  - Astrophysics
- Fundamental Questions and Philosophy
  - Why is our science interesting and relevant?
- Historical Perspective
  - How did we arrive here
  - Where are we going?
- A preview of the rest of the program including examples from
  - Special Relativity
  - Quantum Mechanics

Fundamental Questions

- Why does the Universe exist?
- What is the alternative
  - Nothing
    - What is nothing?
      - That which does not exist
      - Can we get from here (existence) to nothing?
      - Fact from basic physics
        - There is no place in the known universe where there is nothing, yet many of us think we know what nothing is
      - Maybe nothing is unstable
- What are the fundamental building blocks of the Universe?

A Simple Universe



To Understand the Universe we must understand the Properties of:

Space– Shape, Dynamics
Time– What is it?
Or is it at all?

Particles– Interactions

Relationships between Space, time, and Particles!

→ Rules → Physics → Motion

What Makes up the World?

- Matter (Stuff)
  - Details
    - Complicated Stuff
      - Hot Dogs
      - Squirrels
    - Simpler Stuff
      - Molecules
      - Atoms
      - Quarks
      - Leptons
- Photons (Light)
- Space
  - 3 Dimensions
- Time
  - 1 dimension

Science/philosophical Goal: Break complex objects down to a few simple components and a few simple rules for their behavior (interactions)

How many basic ingredients do we need to make a hot dog? What role do space and time play?

What Motivates These Questions?

The Conscious Human Brain

- Curiosity
- Intellect
- Survival

Understanding how stuff is put together gives us the power to create.

- We can manipulate the structure of stuff and make it into something else; e.g., engineering, chemistry, and biology
- We can begin to ask the questions concerning how and ~~why~~ we are here

Tools for Understanding

- Human Brain
  - Philosophy
  - Logic
  - Mathematics
  - Science
  - Fantasy and Creativity
- Observations and Experiments
  - Patterns
  - Reproducibility
  - Reduction of many observations to a simple set of rules

Predictability

Stuff-- An Early Attempt

Earth

Air

Fire

Water

Pizza

Each ingredient is too complex

We need something like Legos

How many different blocks and how do they fit together?

Origins of Atomic Theory

- Democritus (or Leucippis?)
  - Atoms

All Speculation

Is it correct?

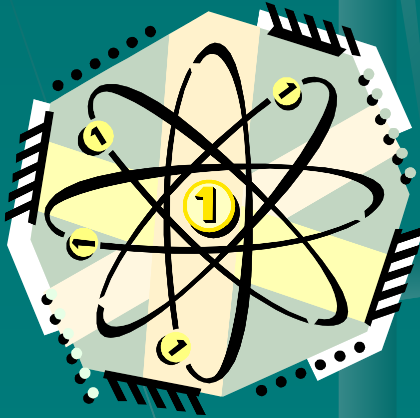
- Aristotle
  - Observations

Philosophy

Logical Thinking

Constraining Thought

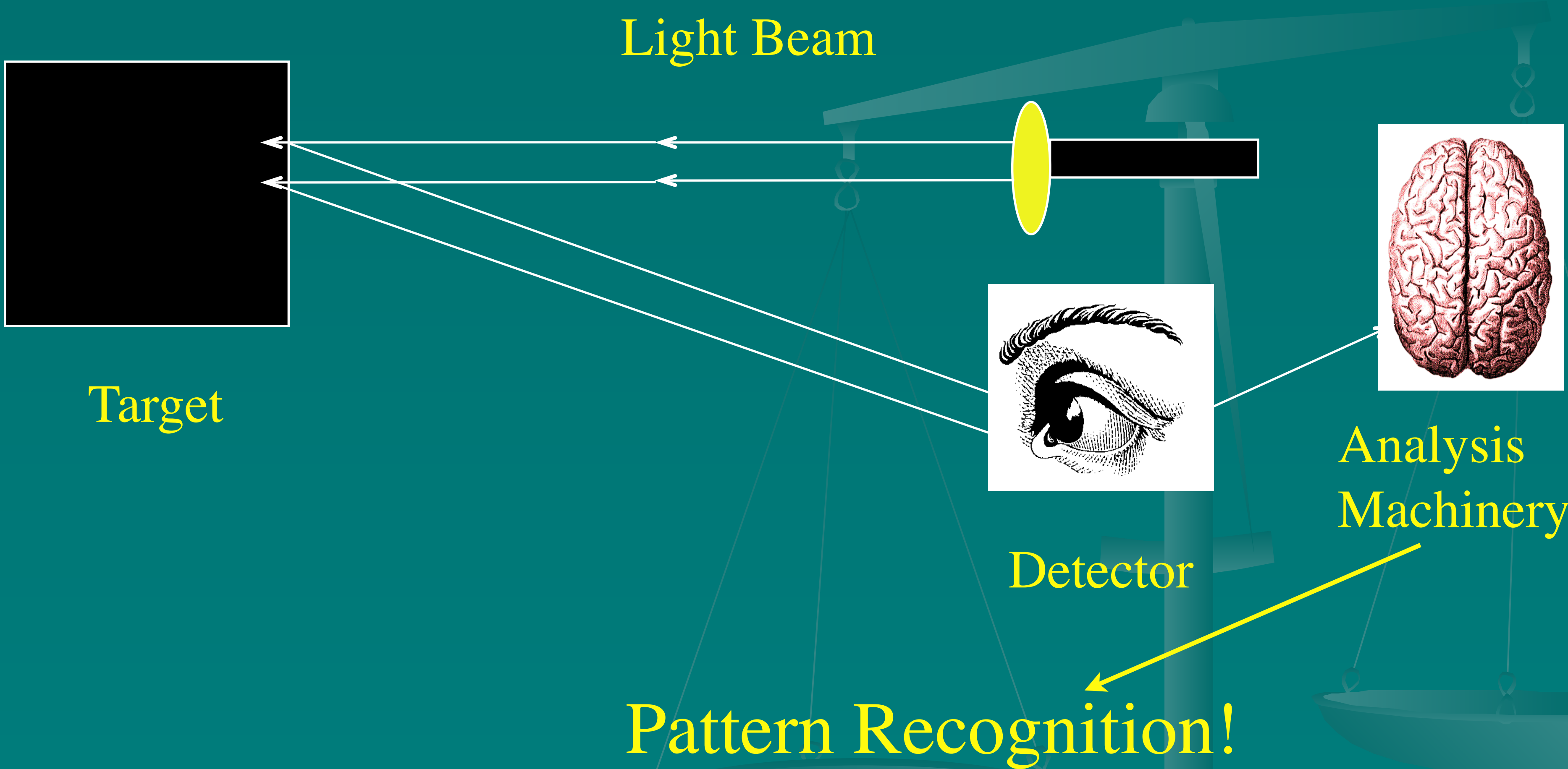
Science

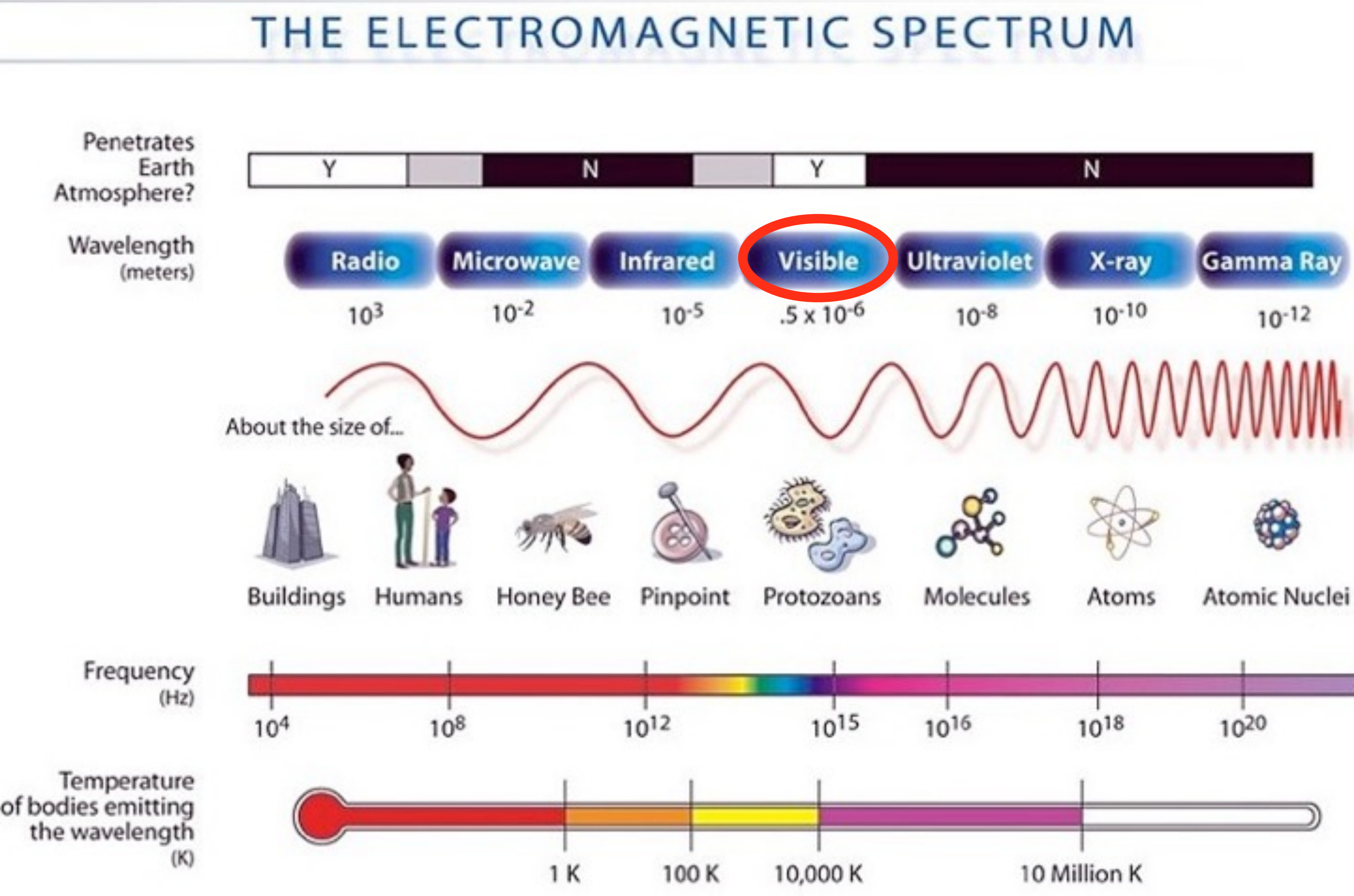


How Do We Observe?

- How does information concerning the world get into our brains?
  - Light Waves
  - Sound Waves
  - Chemical reactions on our tongues
  - Chemical reaction in our fingers
  - Chemical reactions in our noses
- Our natural detectors are
  - Eyes
  - Ears
  - Tongues
  - Skin
  - Nose

How Do We See?


Light Beam
Target
Detector
Analysis
Machinery
Pattern Recognition!


THE ELECTROMAGNETIC SPECTRUM
Penetrates Earth Atmosphere?
Y
N
Y
N
Wavelength (meters)
Radio
Microwave
Infrared
Visible
Ultraviolet
X-ray
Gamma Ray
10^3
10^-2
10^-5
.5 x 10^-6
10^-8
10^-10
10^-12
About the size of...
Buildings
Humans
Honey Bee
Pinpoint
Protozoans
Molecules
Atoms
Atomic Nuclei
Frequency (Hz)
10^4
10^8
10^12
10^15
10^16
10^18
10^20
Temperature of bodies emitting the wavelength (K)
1 K
100 K
10,000 K
10 Million K

Beams and Detectors

- Suppose we want to see something much smaller than a protozoa, how could we do it?
- Suppose we could make a better beam-- How?
  - To see more detail we would want it to have a very short wavelength or high frequency
  - Does the beam have to be a light beam?
- Suppose we could made a better detector than the eye
  - We would want it to be able to see much shorter wavelengths of light so that we can “see” more detail
  - Would we want the detector to be sensitive to something other than light-- particles for example?

Beams and Detectors

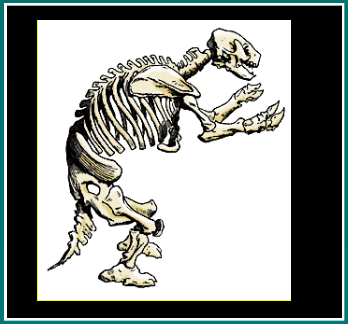
- If we change the beam from light to particles and the detector from an eye to a photomultiplier tube, are we still "seeing"?
- We still get information and we can look for patterns in it
- The process is the same
- We are simply extending the amount of information that we can get from any object
- How do we determine that the information is reliable – reproducibility

The Power of Science

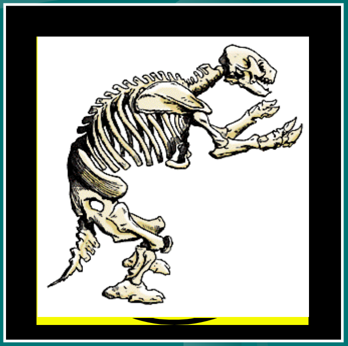
The Scientific Method

Experiments must be reproducible

This is the way we agree on what is real



Experimenter 1



Experimenter 2

Qualitative Agreement? No!

Quantitative Agreement!

Numbers

Summary

- What we need to observe the world
- Beams (Flashlights, Accelerators)
- Detectors (eyes, ears,gamma ray detectors, particle detectors . . .)
- Analysis of the information received form the detector
  - Logic and Reasoning
  - Pattern Recognition
    - Makes us think we know something
  - Numbers to quantify results in order to make detailed comparisons

In Search of Simplicity

- What do we want to look at with our improved "eyes" and beams?
  - Details of Matter
    - What do the Lego Blocks look like? (Complicated question)
    - How do they work?
    - Structure
      - Atoms,Nuclei, Protons, Neutrons, Quarks, Leptons,Bosons . . .?
        - How are they put together, or how do they interact?
        - We want to see the Lego blocks and how they fit together
  - Can we also learn something about space and time?
  - What about light? Photons

Space

- A location for stuff to be
  - Can be measured; i.e., numbers can be assigned to points in space
    - Coordinates
    - Distance
    - Mathematics-- relationships between numbers that describe the organization of space and the stuff in it
    - Volume
- How much space is there? Is this a sensible question?
- What is space? Is it nothing? Does it "do" anything?

Space is expanding!!

This lecture hall is mostly filled with empty space

Carbon

Radius of Atom = 70 x 10^{-12} m

Radius of Nucleus = 2.3 x 10^{-15} m

⇒Volume of Empty Space/Volume of Occupied Space in atom = 3 x 10^{14}

Time

- What is time?
  - Something that separates events and gives them a particular order
  - Time is what keeps everything from happening at once
  - Without time nothing would happen–it would just be
    - Makes motion (change) possible
- How much time is there?
- Did it have a beginning?
- Will it have an end?
- Is it absolute?
- Is it real; i.e. can we agree on how to measure it?
- Is it really something different than space?
- Does time really exist or is it an organizational tool of the mind?

Without change or motion what is physics?

What is Life?

Why is the clock running?

Time Measurement

- Time does not appear to hold still-- we must be clever to measure it
  - Observe regular patterns and events relative to some other event
    - The Sun and Moon
    - The seasons
- How do we make measurements quantitative?
  - Take note of regularities and define a unit of time based on a regularly occurring event
- Sundials, water clocks
- Mechanical clocks appeared in 13th century
- Atomic clocks

What if the length of the second were changing? Could we tell?

Nature of Time

- Remember time is:
  - Something that separates events and gives them a particular order
- Two Questions
  - Can every observer agree upon the amount of time that separates two events?
  - Can the order in time of the two events always be agreed upon?

Surprisingly, the answer to both questions is no!

Tested Clean for Performance Enhancing Drugs!

Albert Einstein

<u>Special Relativity</u>

No Absolute Time

<u>General Relativity</u> connects stuff to space and time

General Principles

- Principle of Relativity:
  - "The motions of bodies included in a given space are the same among themselves, whether that space is at rest or moves uniformly forward in a straight line." Isaac Newton (corollary to the laws of motion initially stated by Galileo for mechanical systems)
  - Modern version
  - The laws of physics take the same form in all frames of reference moving with constant velocity with respect to one another (all physical systems)

Note that these principles came from experience (observations)i.e.; "common sense" and from playing catch on a moving train

Additional Principle

- The velocity of light, c, is constant independent of the motion of the source or the observer

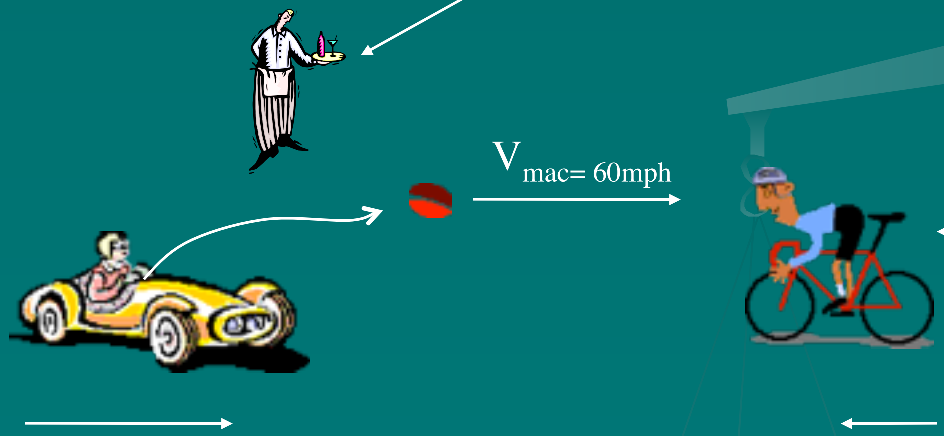
How do we come to this conclusion?

It does not appear to make common sense!

What does this mean for our observations and measurements?

Common Sense World

$V_{hamburger}$ = 60 mph (relative to car) = 120 mph to an observer standing by the road who watches the hamburger go by but is not quick enough to snatch it



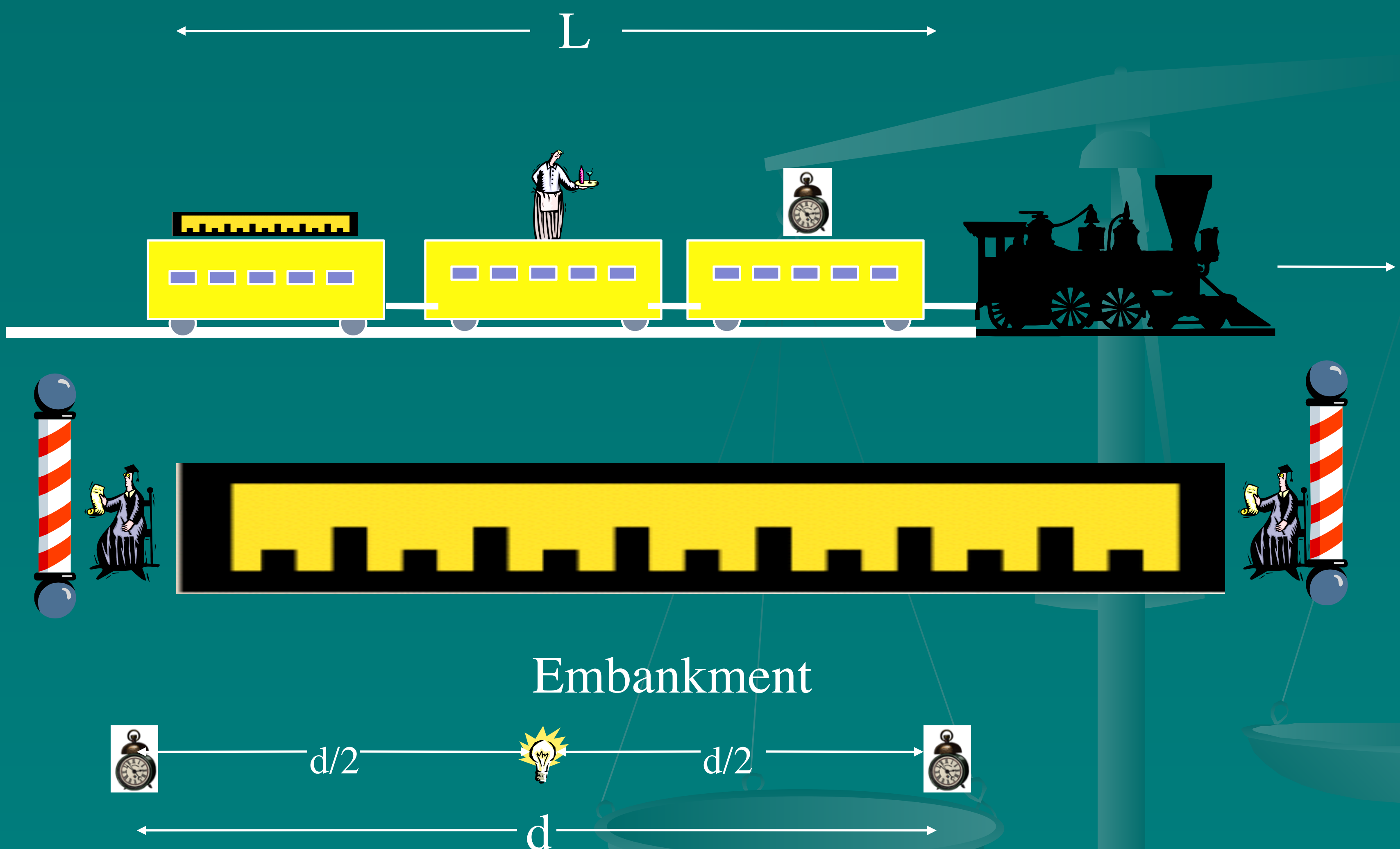
For the cyclist V = 60 +60 + 20 = 140 mph

Vcar = 60 mph

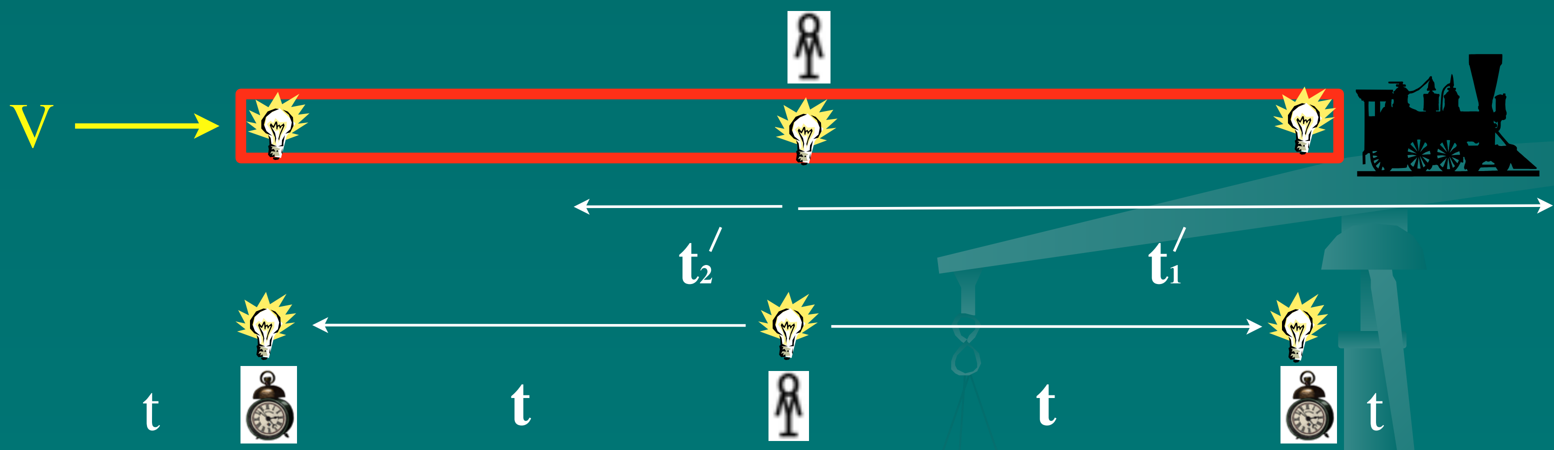
Vcyclist = 20 mph

$$V_{tot} = V_{car} + V_{mac} - (-V_{cyclist}) = 140\ mph$$

Trains and Embankments



Measurement– Embankment



$$t_2 = t_1 = t$$

$$\Longrightarrow t_1' \neq t_2'$$

Events that are simultaneous in an intertial frame are not simultaneous in a frame moving at uniform velocity in a different frame. Also has implications for measured lengths.

Common Sense World

$V_{hamburger}$ = 60 mph (relative to car) = 120 mph to an observer standing by the road who watches the hamburger go by but is not quick enough to snatch it

V_{mac}= 60mph

For the cyclist V ≠ 60 +60 + 20 = 140 mph

Vcar = 60 mph

Vcyclist = 20 mph

$$V_{tot} \neq V_{car} + V_{mac} - (-V_{cyclist}) = 140 \text{ mph}$$

Twin Paradox

Marilyn

Carolyn

Twin Paradox

Marilyn & Carolyn

Twin Paradox

← 2 Million Light Years →

Andromeda Galaxy

- The entire trip takes Carolyn about 63 years. She is fairly old when she gets back, h

Accelerate away from Earth withan acceleration of 1 g until Carolyn is halfway there and then turn around and decelerate with a deceleration of 1 g.

Marilyn has been d e than 4 million years!

The Arrow of Time

- We can change the rate that clocks run
- Some questions
  - Can we stop time?
  - Can we reverse the direction of time?
  - Did time have a beginning?
    - Big Bang
  - Will it have an end?
  - How does time get a direction?
    - On the microscopic level time runs backwards as well as forward
    - Macroscopically it only runs in one direction

The Beginning of Time?

- How do we conclude that time had a beginning?
  - Observation, Reason, the Principle of causality
    - Does the Universe change or is it static?
    - Assume the principle of causality
      - Galaxies in the Universe are flying away from one another ==>Big Bang-- time has a beginning
    - Will time go on forever?
      - Will gravity pull the Universe back together and end time in a in a very hot point?
        - Measurements have been made to determine the answer to this question, and the answer is apparently no
      - Or could time end because things just quit happening?

Time and Space Summary

- Time
  - Mysterious at best
- Space
  - Also distorted by Lorentz transformations
    - Moving train also became a shorter train as measured from the embankment

What are the Numbers

- Natural Numbers (0,1,2,3 . . .)
  - Zero used in calculations came from India
  - Most of the western world used spaces– but these were not the zeros needed for calculations
- Integers (. . . -1,0,1,2,3 . . .)
  - What does having -1 cows mean?
- Rational Numbers (a/b)
- Irrational numbers π, $\sqrt{2}$
- Imaginary Numbers $\sqrt{-1}$ or i (what would having an imaginary cow mean?)

Gerolamo Cardano and Niccolo Tartaglia

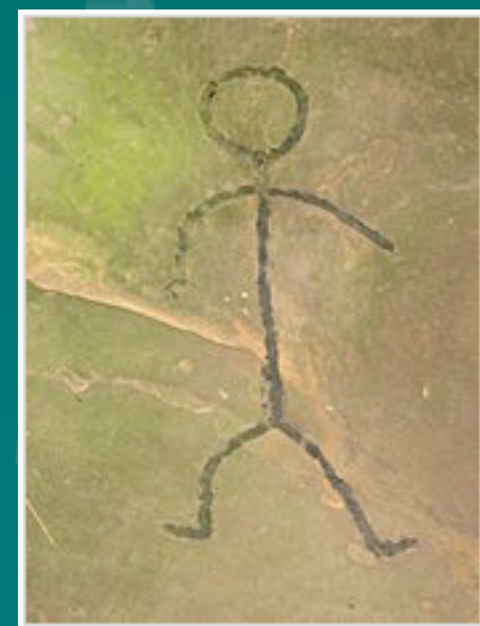
Why do we need $\sqrt{-1}$?

Niccolo Tartaglia– used in getting to Solutions to cubic equations

Scipione del Ferro

1501 - 1576

1499 - 1557



1465 - 1526

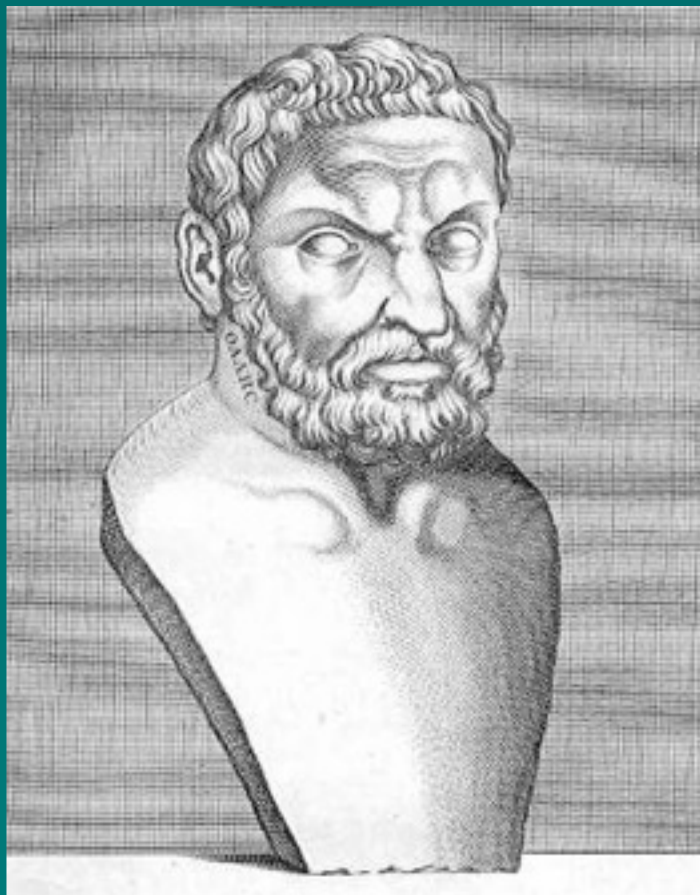
Summary so Far

- Universe
  - Matter-- Looking for the Legos (Quarks and Leptons and ?)
  - Space -- Geometry– stage or actor
  - Time-- Mysterious, orders events, tied to space through relativity (Spacetime)
- Tools for Understanding
  - Observations & Experiments using
    - Rulers
    - Clocks
    - Numbers
    - Mathematics (Reason and Logic)
    - Beams and detectors

Next: How our understanding of the physical world is evolving

Intermission

Thales of Miletus



624 BC to 546 BC Approximately

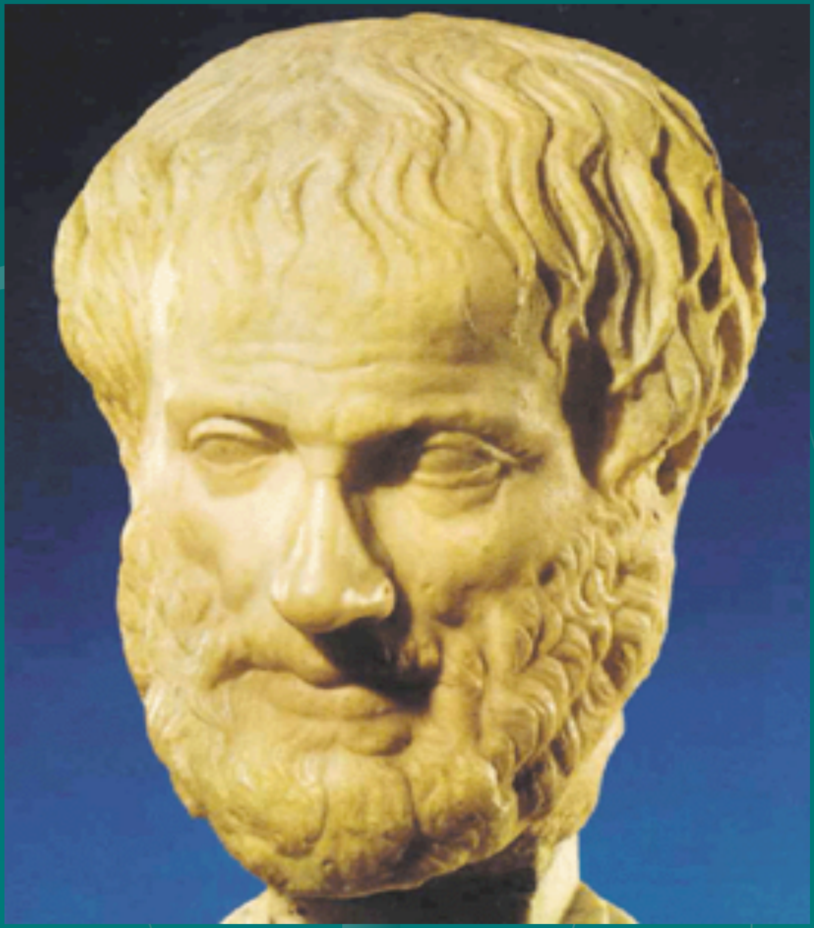
First Greek Philosopher
Attempted to explain existence without reference to mythology (birth of science)

Sought to understand the ultimate substance, change and existence

First true mathematician
Geometry– first credited mathematical discovery

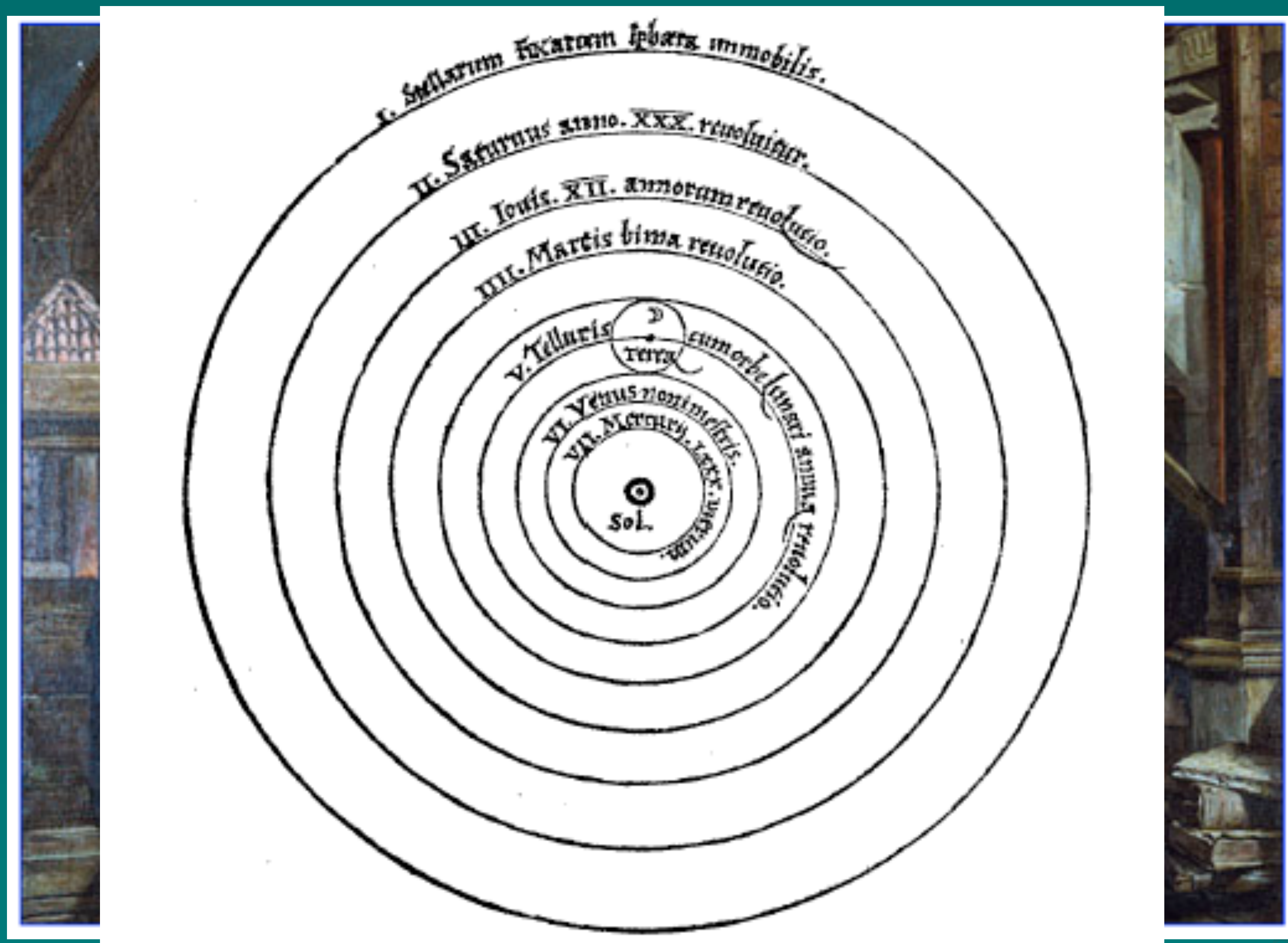
Aristotle

- Polymath
- Philosopher
- Educated at Plato's Academy
- Many contributions to civilization including
  - Categorized Species
  - Matched Explanations to Observations
- Created Physics
- Some have said he was the last person to know everything



384 BC - 322 BC

Early Dawn



1473 -1543

Nicolaus Copernicus

Johannes Kepler

1571 to 1630

Laws of Planetary Motion
Astrologer
Religious Mystic
Mother almost burned as a witch
Data from Tycho Brahe–
How did Tycho die?

Planets have elliptical orbits!

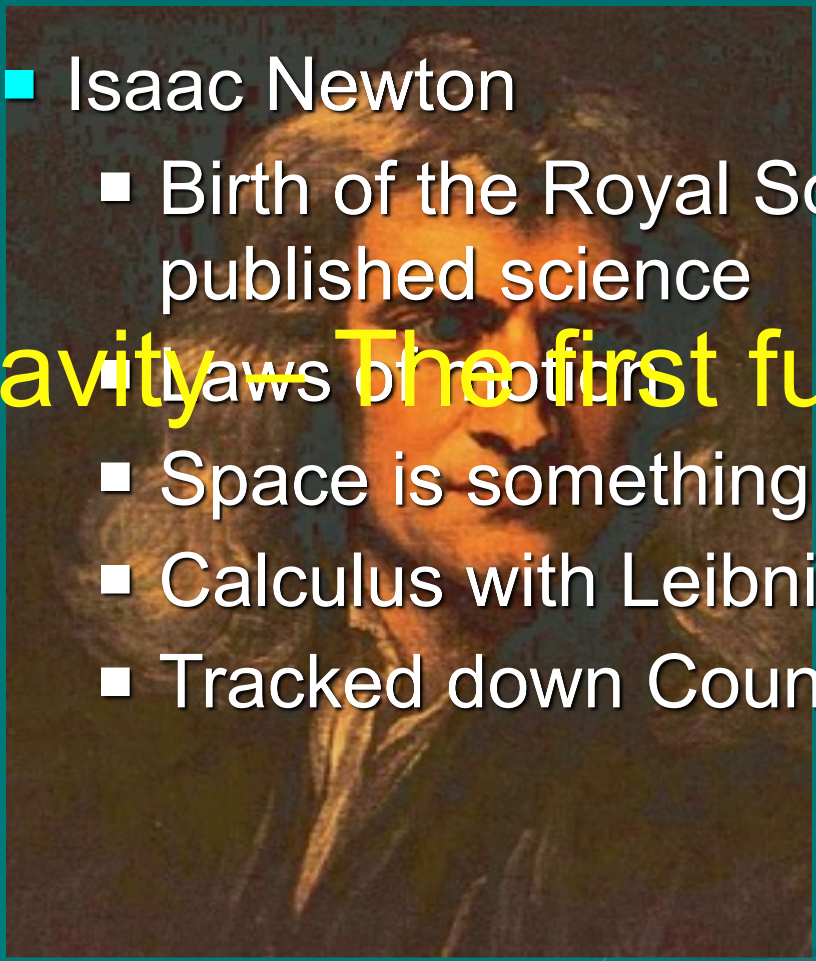
Sunrise

Galileo Galilei

lived from 1564 to 1642

Galileo Galilei formulated the basic law of falling bodies, which he verified by careful measurements. He constructed a telescope with which he studied lunar craters, and discovered four moons revolving around Jupiter.

Midmorning

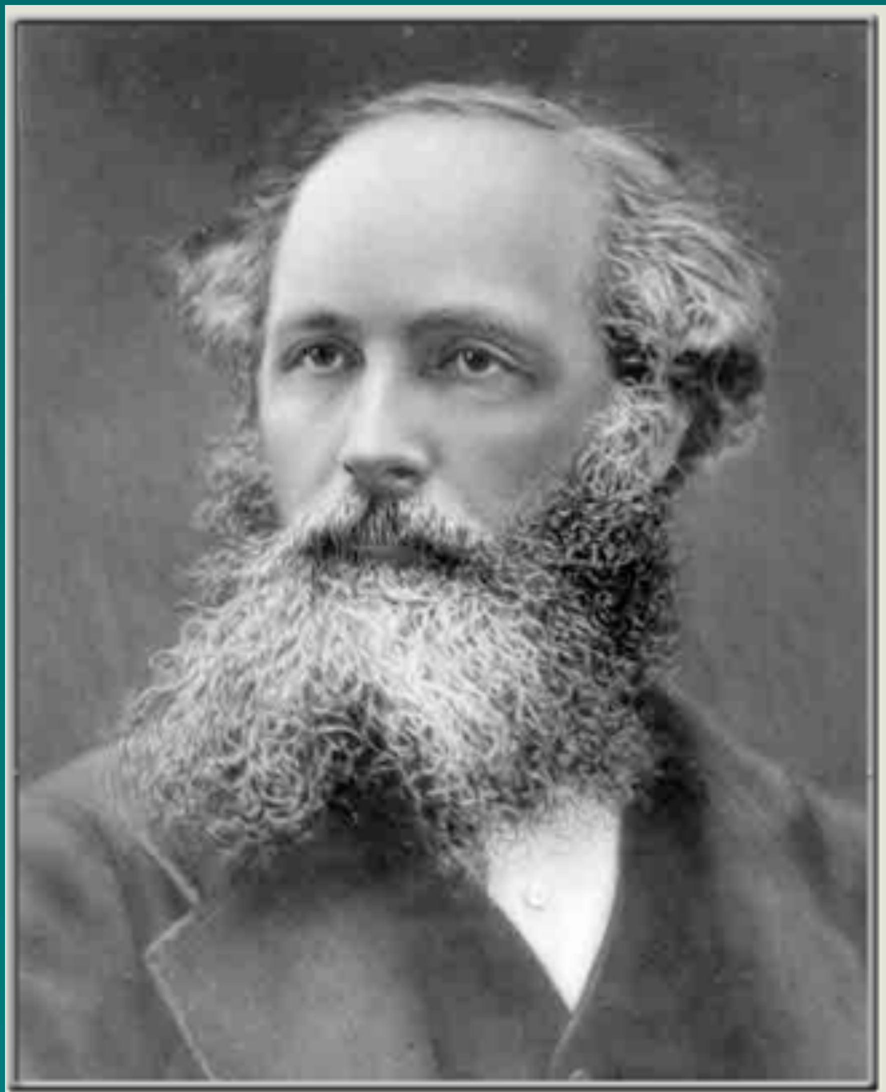


- Isaac Newton
  - Birth of the Royal Society and real published science
  - Laws of motion
  - Space is something
  - Calculus with Leibnitz
  - Tracked down Counterfeiters

Gravity – The first fundamental force!

1642 to 1727

James Clerk Maxwell



James Clerk Maxwell in his 40s.

Electromagnetic Force: the Second Fundamental Force

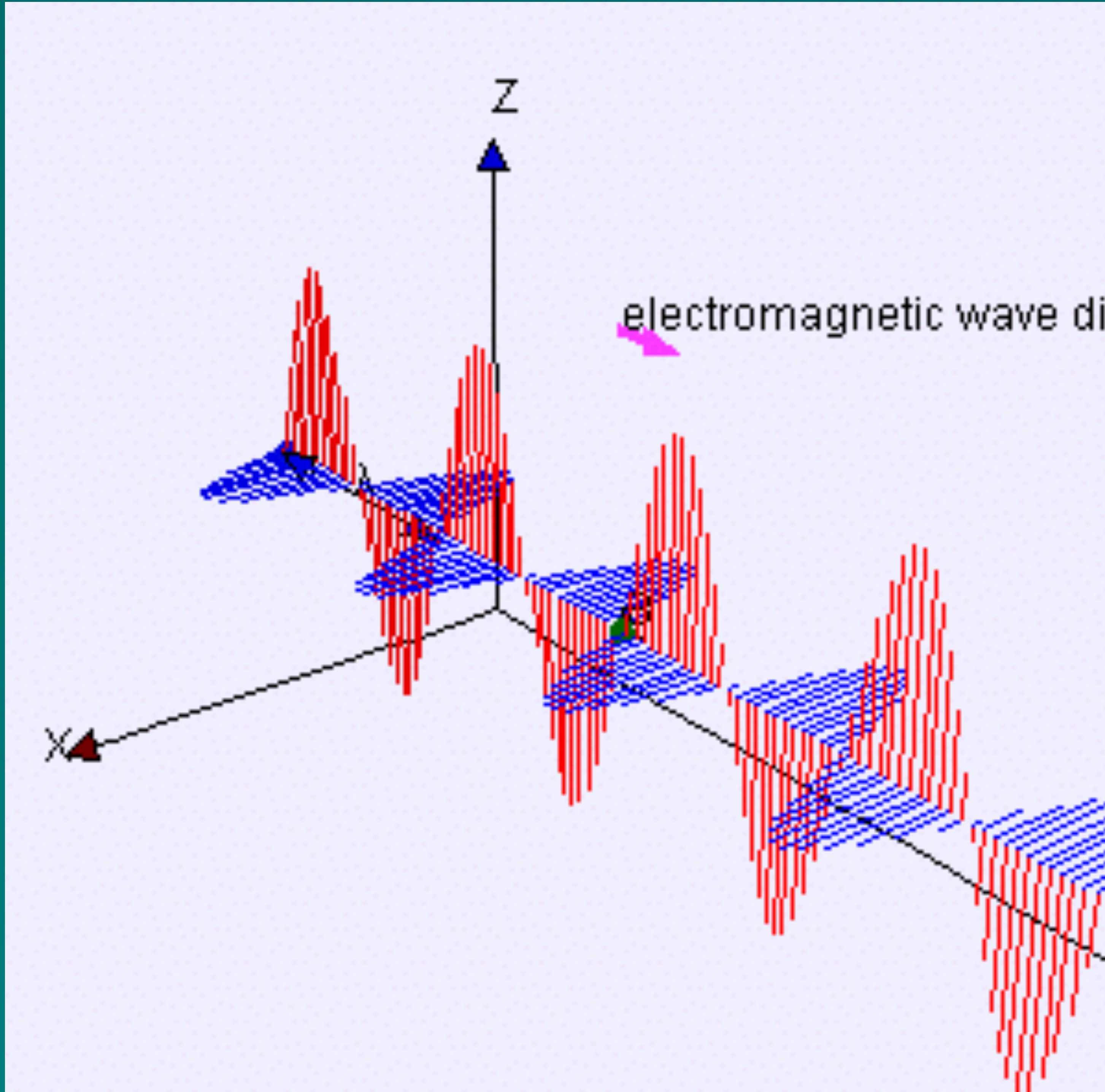
Formulation in terms of *total* charge and current[note 2]

Name	Differential form	Integral form
Gauss's law	$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$	$\oiint_{\partial V} \mathbf{E} \cdot d\mathbf{A} = \frac{Q(V)}{\varepsilon_0}$
Gauss's law for magnetism	$\nabla \cdot \mathbf{B} = 0$	$\oiint_{\partial V} \mathbf{B} \cdot d\mathbf{A} = 0$
Maxwell–Faraday equation (Faraday's law of induction)	$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$	$\oint_{\partial S} \mathbf{E} \cdot d\mathbf{l} = -\frac{\partial \Phi_S(\mathbf{B})}{\partial t}$
Ampère's circuital law (with Maxwell's correction)	$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$	$\oint_{\partial S} \mathbf{B} \cdot d\mathbf{l} = \mu_0 I_S + \mu_0 \varepsilon_0 \frac{\partial \Phi_S(\mathbf{E})}{\partial t}$

$$\nabla \cdot \mathbf{E} = 0$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \times \mathbf{B} = \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}.$$

$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}.$$

1831 to 1879


Z
electromagnetic wave di
X

Maxwell Family Portrait

Mr and Mrs James Clerk Maxwell 1869

Also worked on Statistical Mechanics, bridge engineering, and color photography

Radioactivity

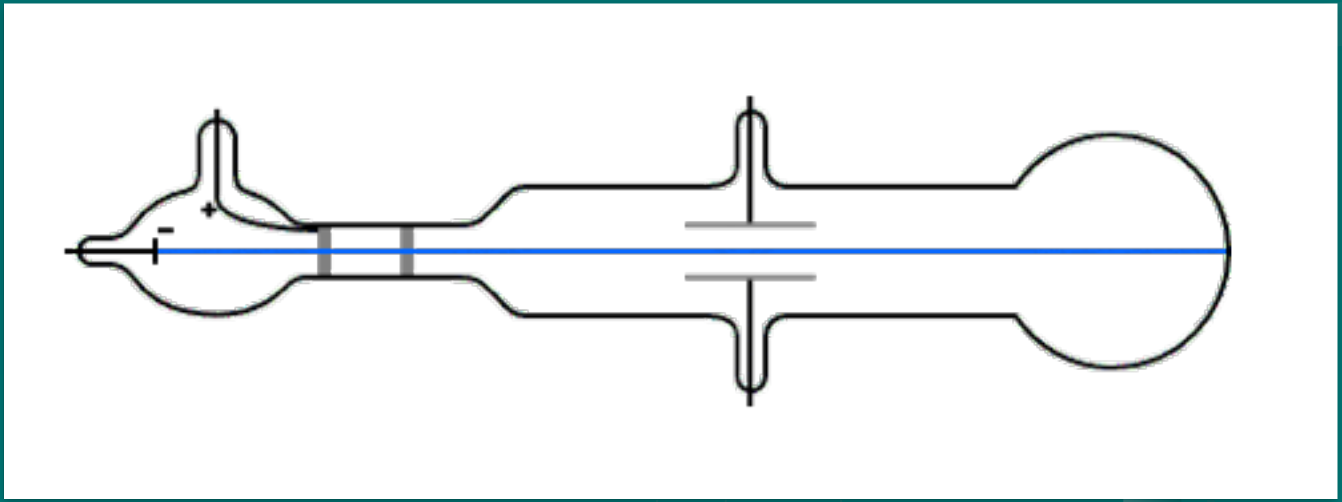
- Marie and Pierre Curie
  - Discovered and studied radioactive decay of elements (clues to internal structure of the atom and that atoms are divisible)
  - Both were awarded the Nobel Prize (along with Henri Becquerel) in 1903; Marie won a second in chemistry in 1911
  - Pierre (Marie's husband) attempted to study seances scientifically
  - Daughter, (Irene Joliot-Curie) won Nobel Prize in Chemistry in 1935
  - Pierre run over and killed by horse-drawn cart in 1906

1867 -1934 1859 -1906

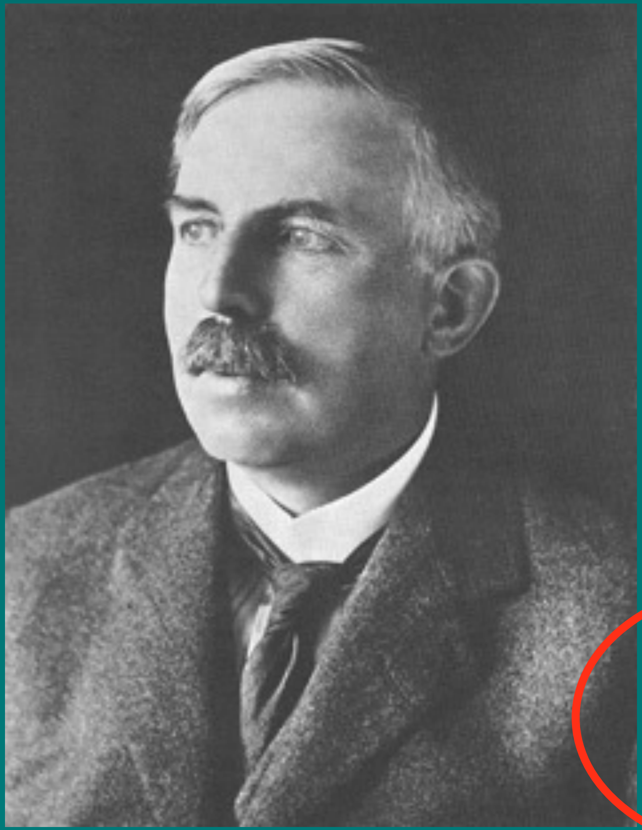
J. J.Thomson

1856 -1940

J. J. Thompson Electroscope

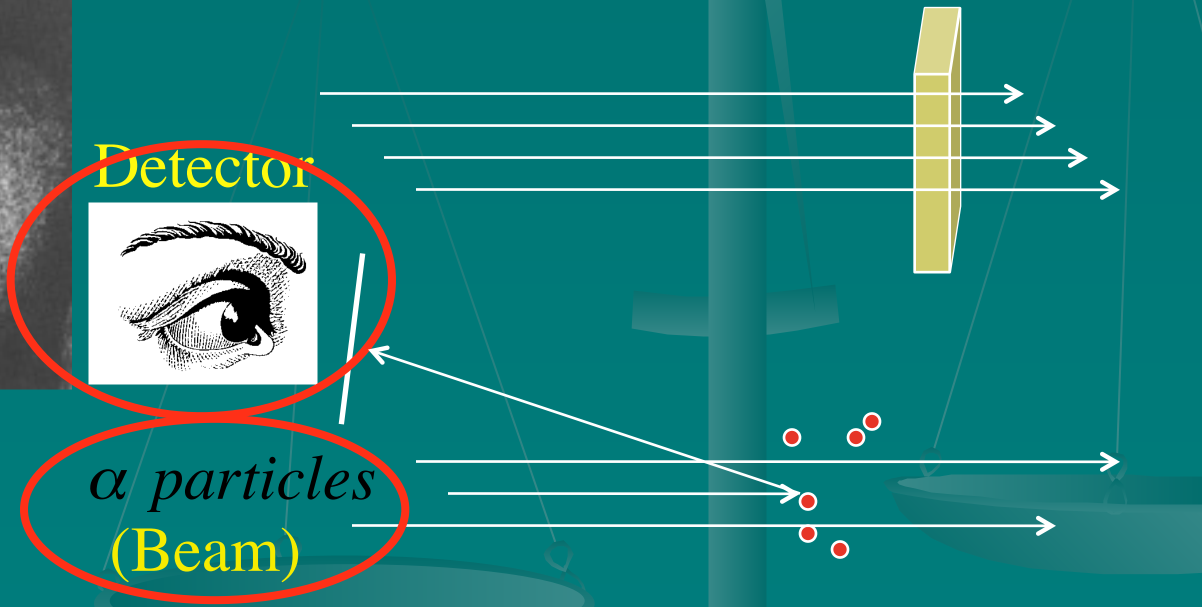


Rutherford and the Nucleus

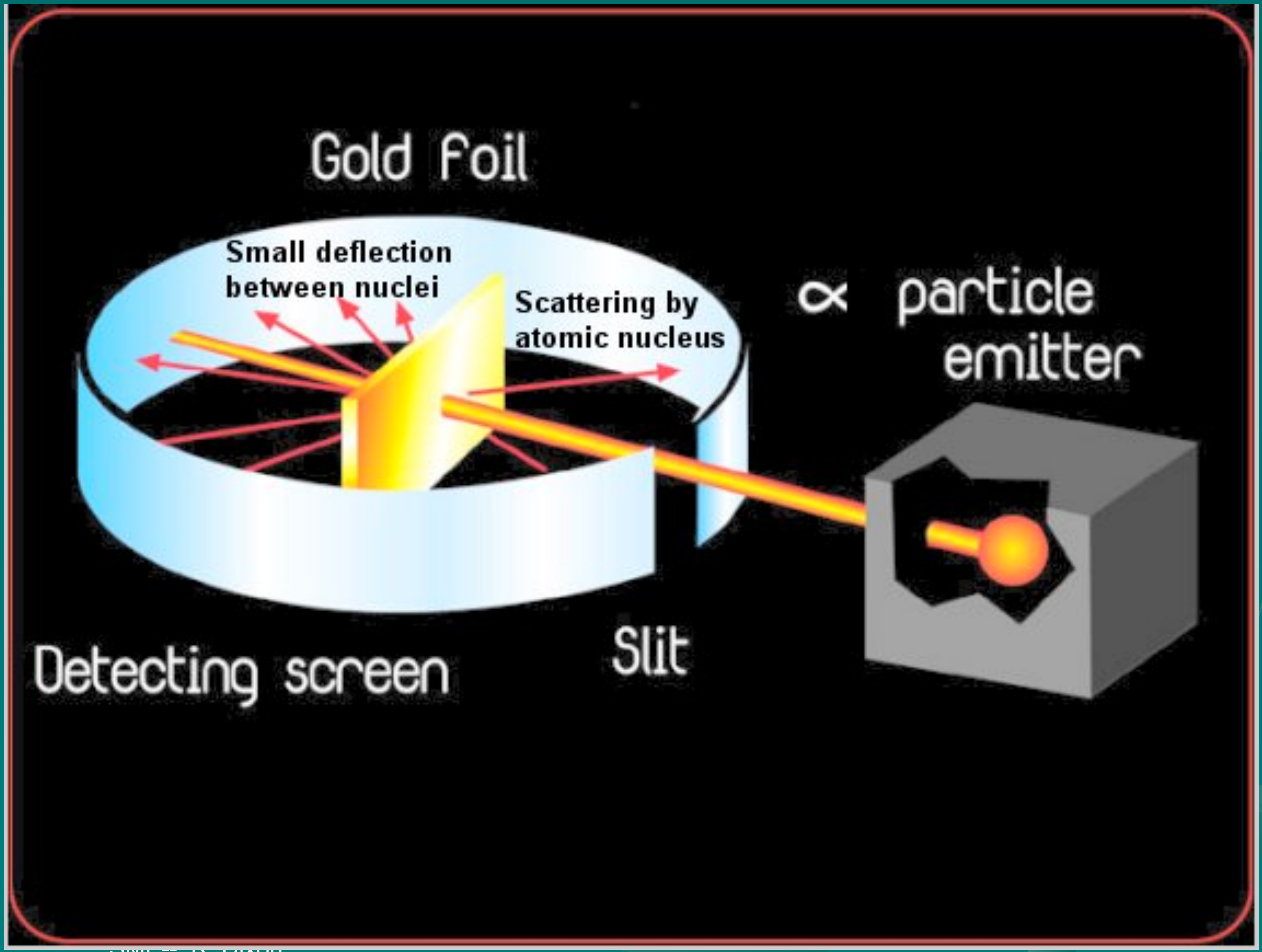


1871 -1937

- Discovery of the Nucleus (1911)



Nucleus Discover Experiment



Summary at the Time

- The elements (atoms) combine in certain ratios (Dalton)
- Electrons are part of the atom
- Atoms are electrically neutral
- Atoms have small hard core at the center
- How is an atom put together?

Confusion

- ➡ Atom consists of positive and negative charge
- Problem: How do we put this together to make an atom? How is the charge distributed? Electron orbits the central nucleus, but . . .
- Maxwell's Equations ➡ electron orbits are unstable?
- Electrons trapped in shells at different energies (Bohr), but how and why?

1905 Papers

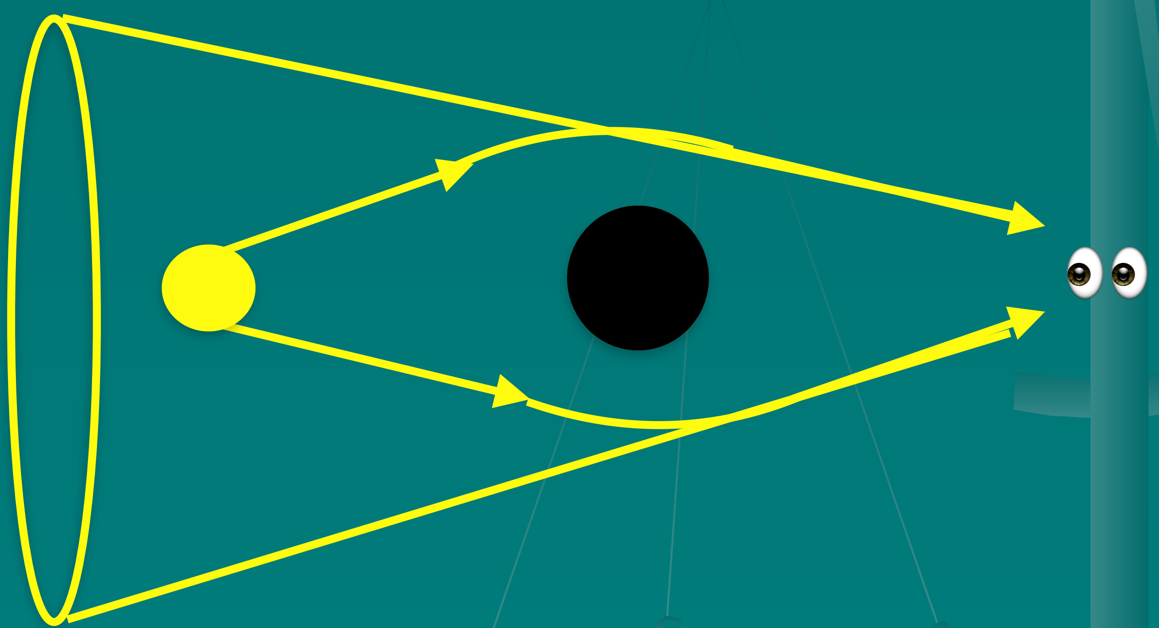
- Special Relativity
- Brownian Motion
- Photoelectric Effect
- Matter/Energy Equivalence

Mechanics?
1879 - 1955

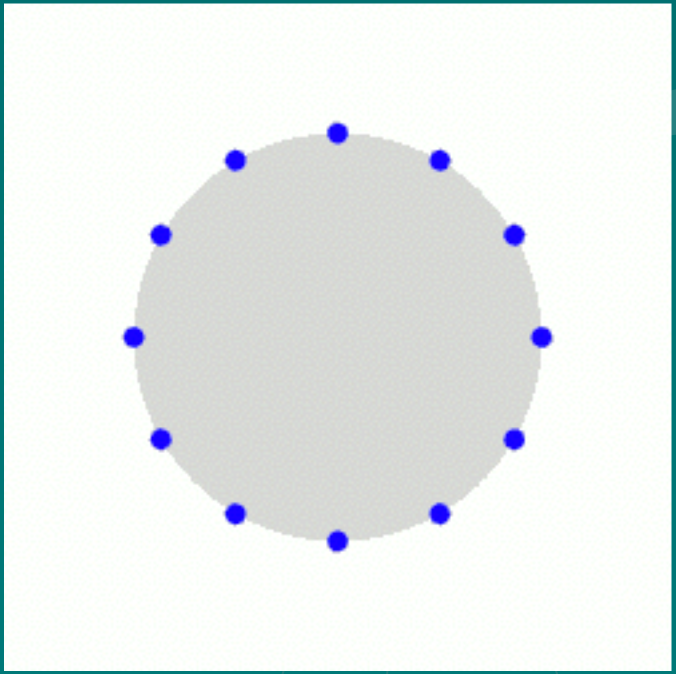
Einstein's field equations

$$G_{\mu\nu} \equiv R_{\mu\nu} - \frac{1}{2} R \, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Geometry = Energy-Momentum

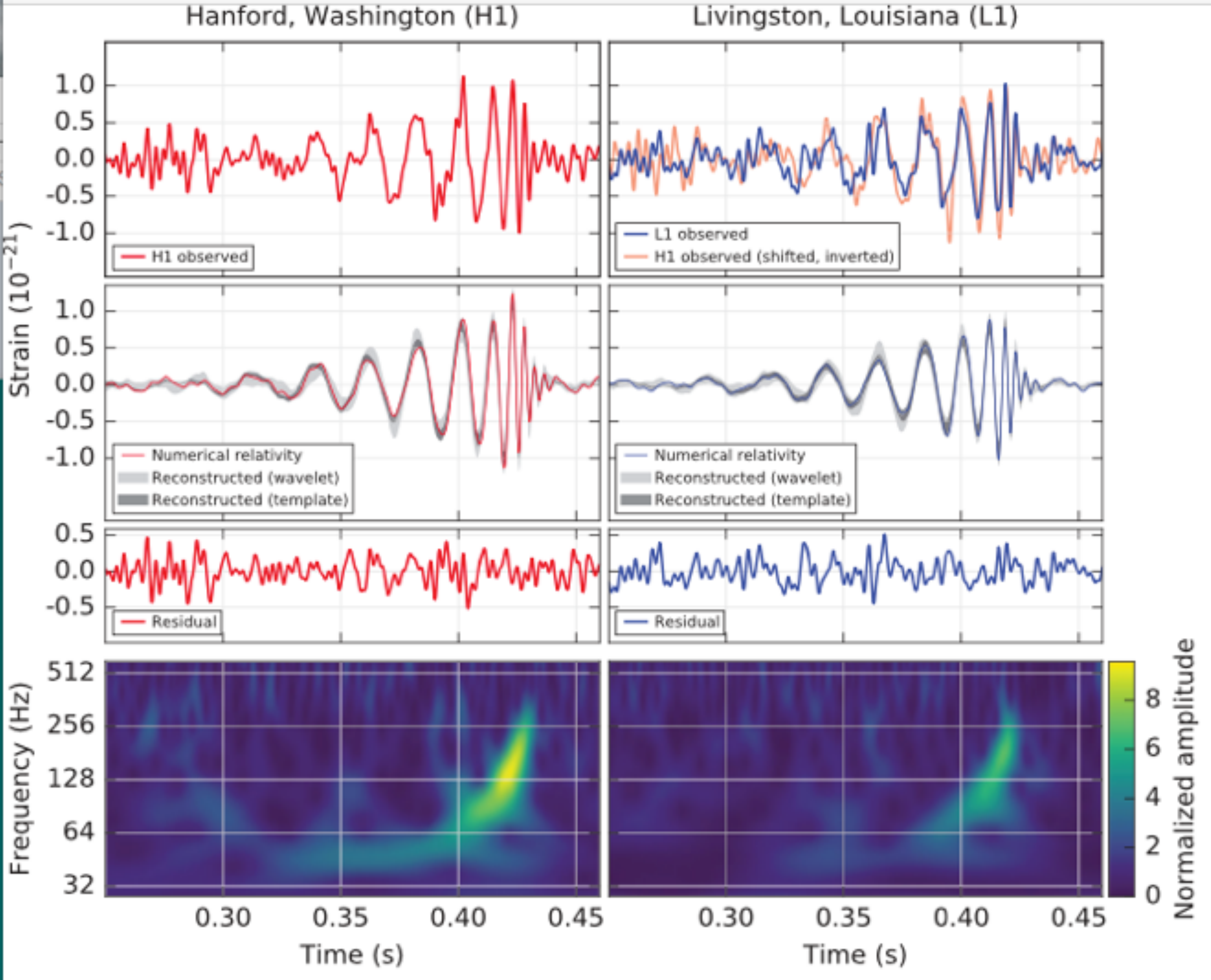


Gravitational Waves



Black Hole Merger

http://apod.nasa.gov/apod/ap160212.html



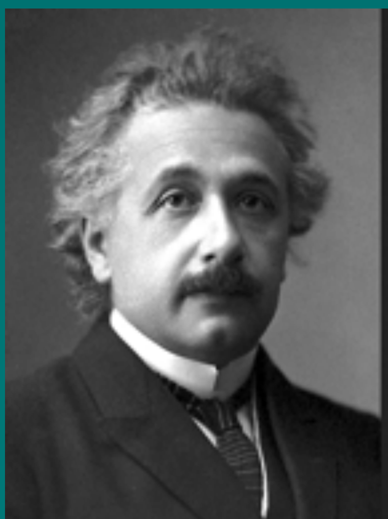
Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Frequency (Hz)
512
256
128
64
32
0.30
0.35
0.40
0.45
Time (s)
Normalized amplitude
8
6
4
2
0

LIGO Interferometers

Hanford. Washington

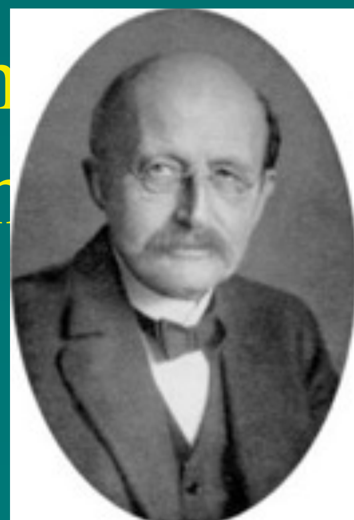
Livingston, Lousiana

Quantum Mechanics



Photoelectric Effect

Albert Einstein

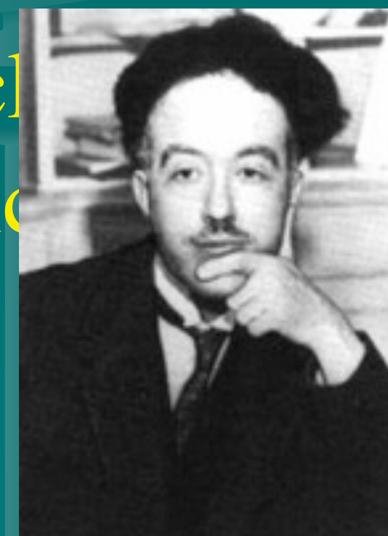


Black body Radiation

Max Planck

Solution to Atom

Neils Bohr



Particle Waves

Louis de Broglie

Quantum Mechanics (Con't.)

Werner Heisenberg

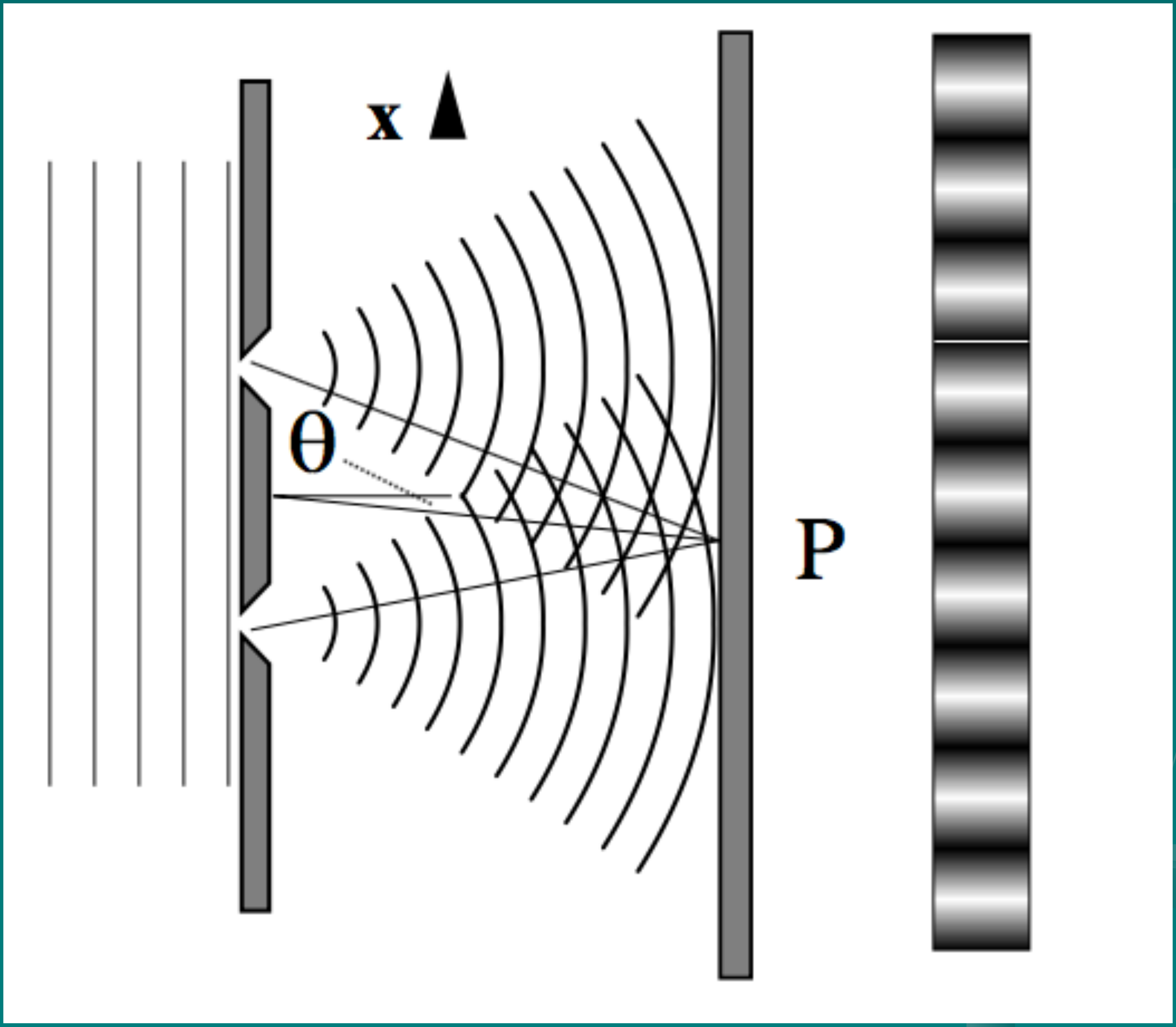
Matrix Mechanics Approach

Max Born

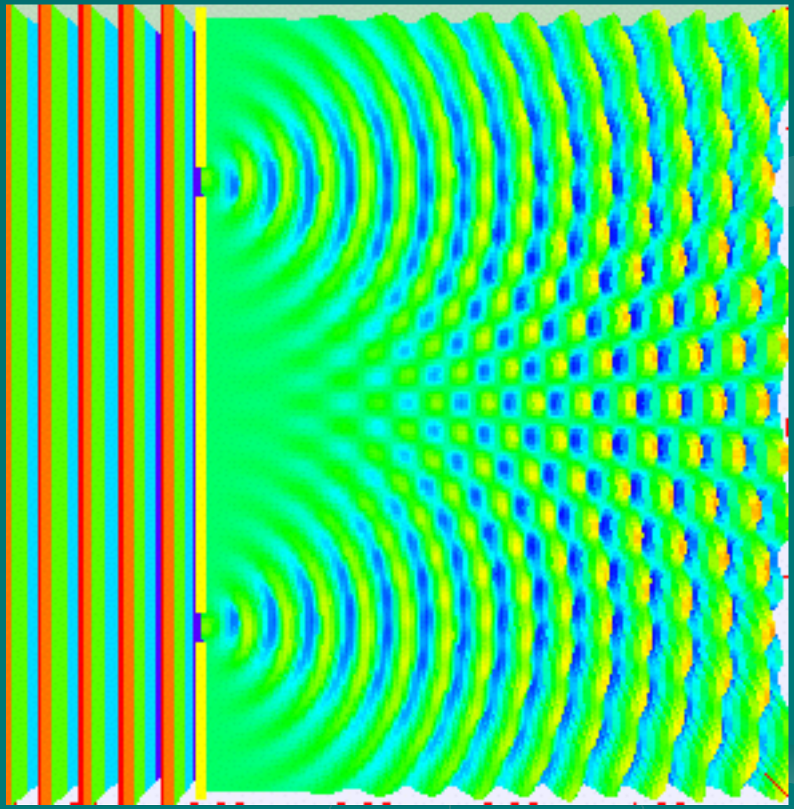
Matrix Mechanics

Erwin Schrodinger

Wave Equation Approach

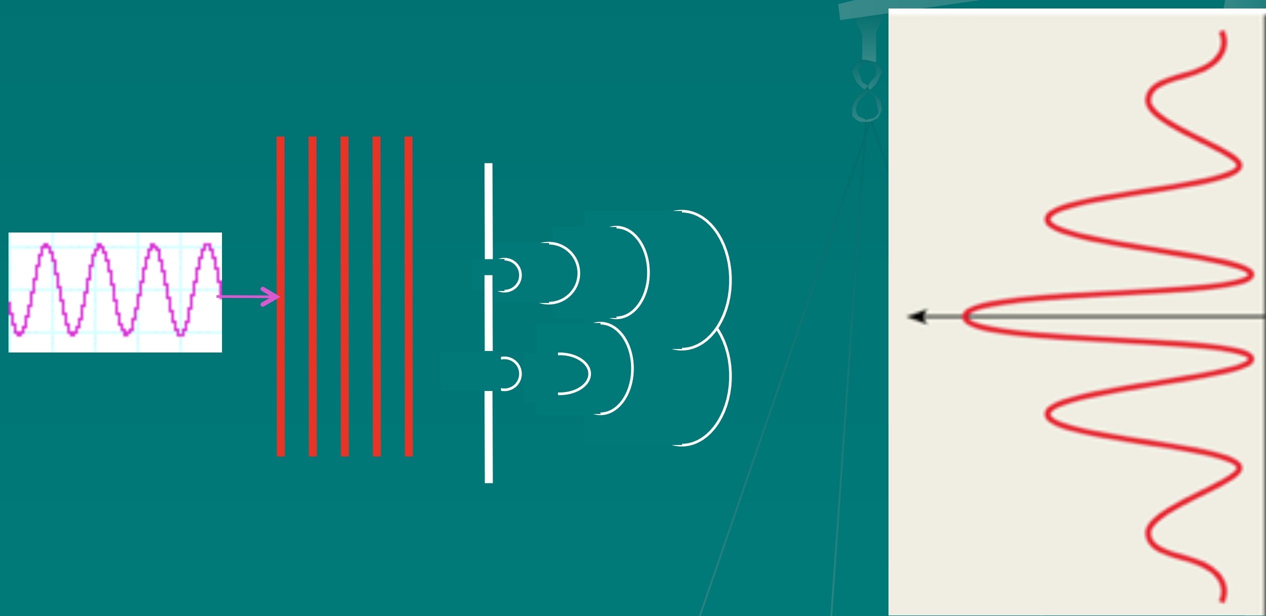

x
θ
P

Double Slit

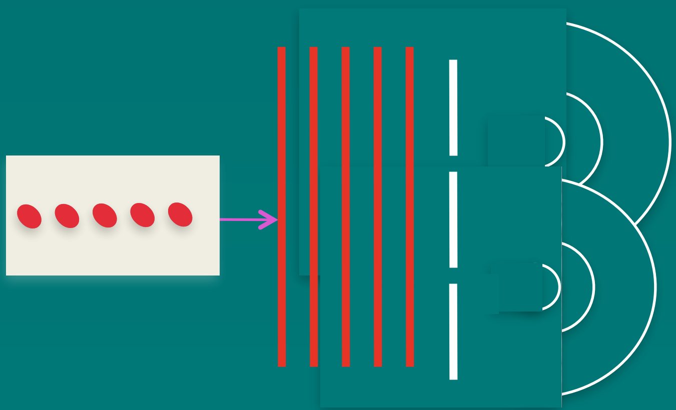


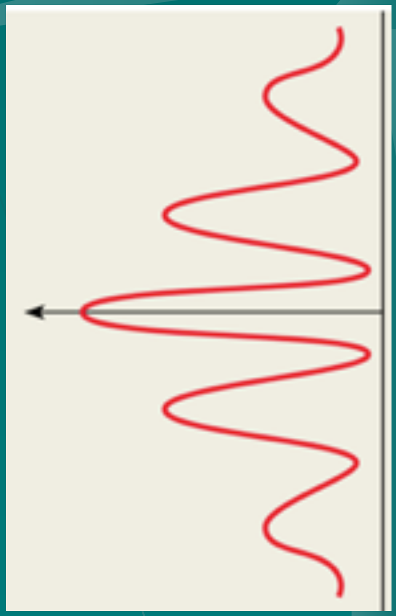
Quantum Mechanics

- Waves or Particles
  - Light Waves



Double Slit





$$\lambda = \frac{h}{p}$$

The Heisenberg Uncertainty Principle

$$\Delta X \Delta P \geq h/2\pi$$

Position and Momentum can't be precisely known at the same time. If the momentum, P, is measured precisely, then X can only be known as well as the inequality allows.
Also this uncertainty allows Particles pop in and out of existence as long as the equality below is obeyed. Such virtual particles are important to how we describe the forces.

$$\Delta E \Delta T \geq h/2\pi$$

Schrödinger Equation

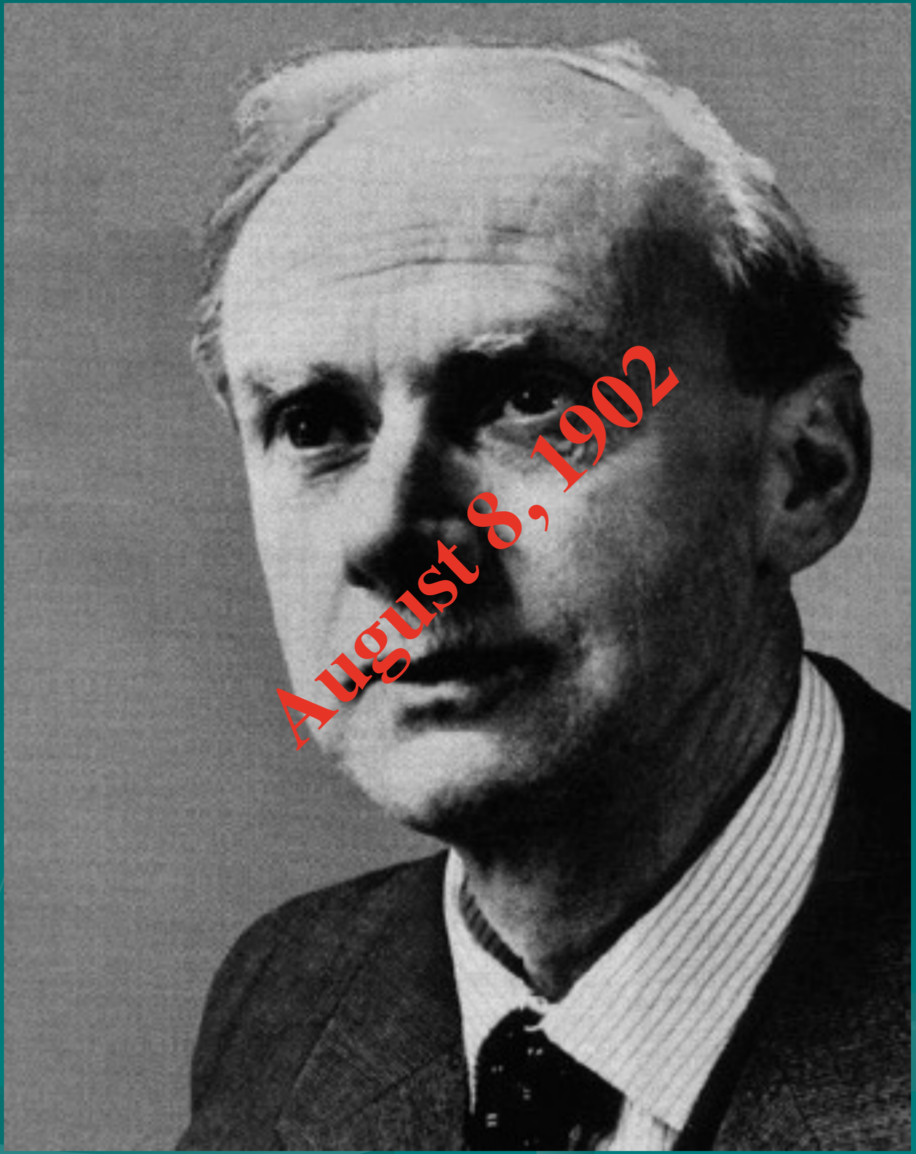
Particles are described by wave functions instead of a precise set of properties. Wave function satisfy the Schrödinger Equation:

Time-dependent Schrödinger equation *(general)*

$$i\hbar\frac{\partial}{\partial t}\Psi(\mathbf{r},t) = \hat{H}\Psi(\mathbf{r},t)$$

Antimatter

- Paul Dirac
  - Quantum Mechanics and relativity
  - ==>> Negative energy solutions to his equation predicted antimatter



1902 - 1984

Dirac Equation

$$\left(\gamma_\mu \frac{\partial}{\partial x_\mu} + \frac{mc}{\hbar}\right)\Psi = 0$$

- Attempting to make special relativity and quantum mechanics compatible — it worked
- In science one tries to tell people, in such a way as to be understood by everyone, something that no one ever knew before. But in poetry, it's the exact opposite. Quoted in H Eves *Mathematical Circles Adieu* (Boston 1977).

Accelerators

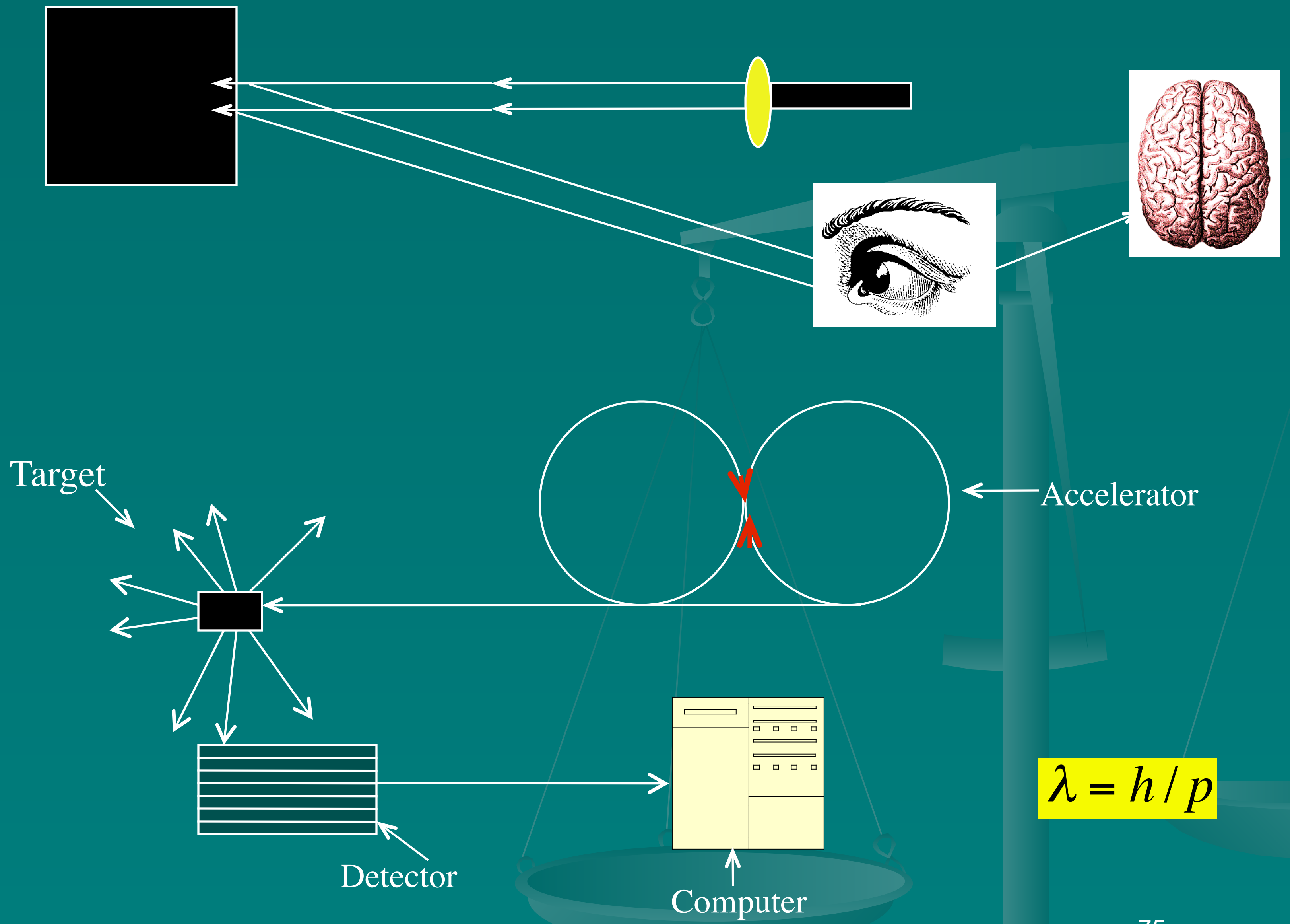
- Cockroft
  - Electrostatic generators
- Ernest Lawrence
  - Cyclotron
  - ==> Synchrotron
  - ==> Storage Rings
- Why?

$$\lambda = \frac{h}{p}$$

August 8, 1901

1901 - 1958

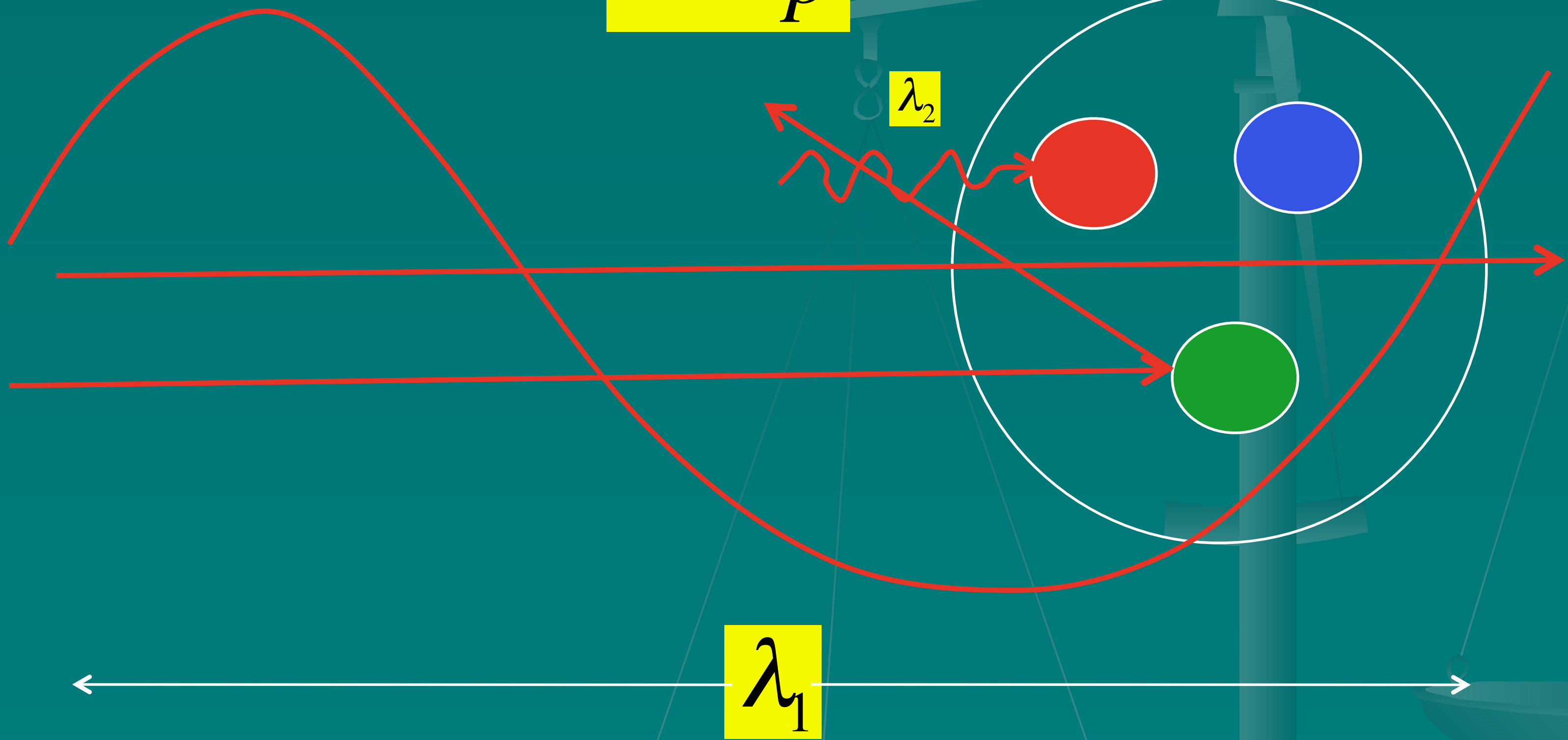
What Does an Accelerator Do?



$$\lambda = h / p$$

Structure

$$\lambda = \frac{h}{p}$$



Forces

So Far we have

- Gravity
- Electromagnetism

Study of fundamental particles has revealed two more forces that are necessary to understand the behavior of matter:

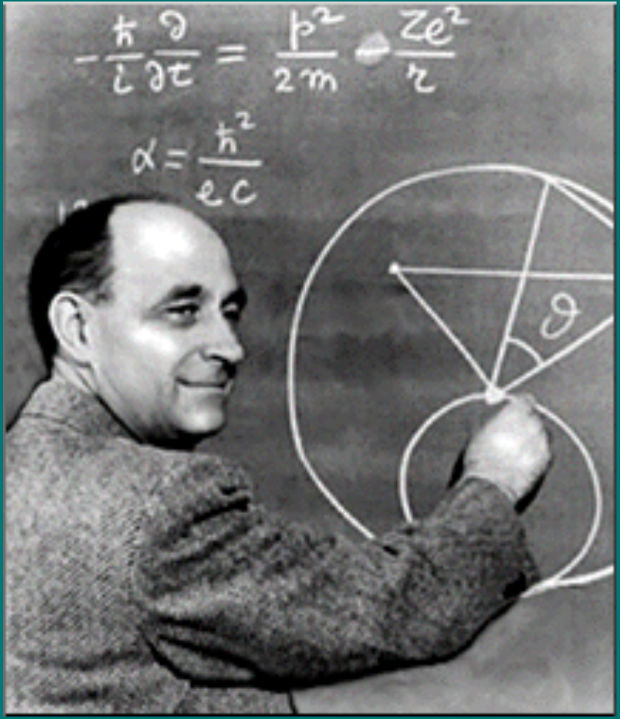
- Weak Force
- Strong Force

Forces of Nature

- Gravity
  - Keeps us off the ceiling
- Weak Force
  - Results in radioactive decays (neutron beta decays– neutrinos!!)
  - Necessary for the the Sun to shine
- Electromagnetic Force
  - Keeps atoms together
  - Runs your hair dryer
- Strong Force
  - Really makes the sunshine
  - Keeps the nucleus together

Why are these forces different?
How do they work?
Why do we think there are places (at high energies) where they are all the same?

Interactions



Enrico Fermi

1901 - 1954

Beta Decay/Weak Interactions

Richard Feynman

1918 - 1988

Quantum Electrodynamics

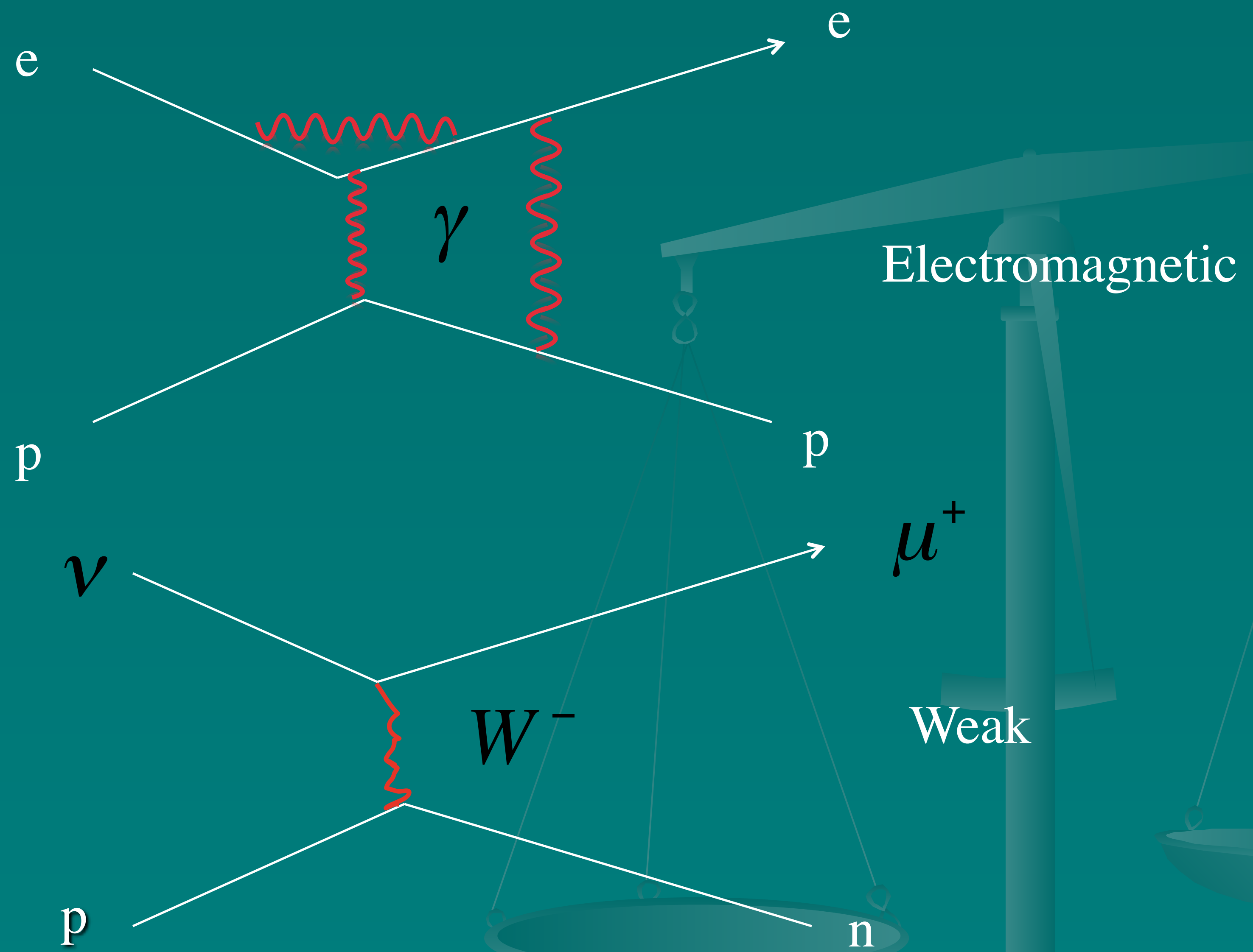
Forces Work

- Quantum Mechanics allows us to violate energy conservation for short periods of time. It is only necessary that

$$\Delta E \Delta T \geq h/2\pi$$

- This allows "virtual" particles to be exchanged between interacting particles to mediate the force
- The type of force is determined by the exchanged particle

Feynman Diagrams



Early Particle Discoveries (Looking for the Legos Blocks)

- Electron
  - Thompson 1897
- Proton
  - Rutherford??
- Neutron
  - Chadwick 1932
- Positron
  - Anderson 1932

Muon

Anderson & Neddermeyer 1936

Pi Meson or pion

Powell 1947

Predicted by Hideki Yukawa in 1935

Neutrino

1956 Reines & Cowan

Predicted 1930 by Pauli

Strange particles and more . . .

Too many more?

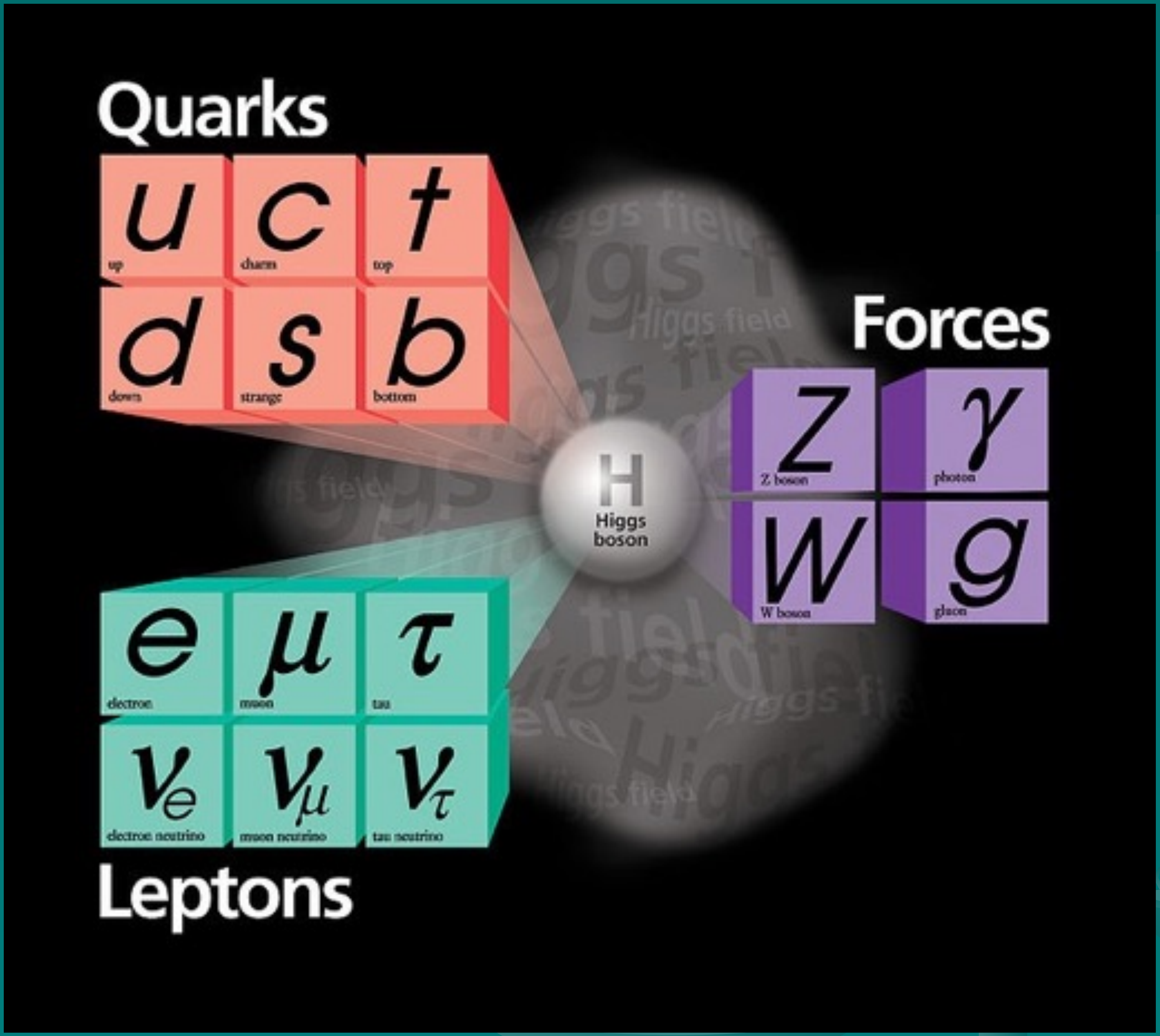
Birth of Fermilab

Modern Particle Discoveries

- Quarks -- Gellman/Zweig-- 1964
  - Baryons – 3 quarks; Mesons – 2 quarks
  - First evidence in deep inelastic scattering of electrons at SLAC
    - Bjorken -- 1970
  - Up quarks, down quarks, strange quarks
- Charm quark-- 1974 (BNL,SLAC)
- Bottom quark-- 1977 (Fermilab)
- Tau Lepton-- 1977 (SLAC)
- W and Z Bosons 1983 (CERN)
- Top Quark-- 1995 (Fermilab)
- Tau Neutrino-- 2000 (Fermilab)
- Higgs-- 2012 CERN

Standard Model
of Particle Physics

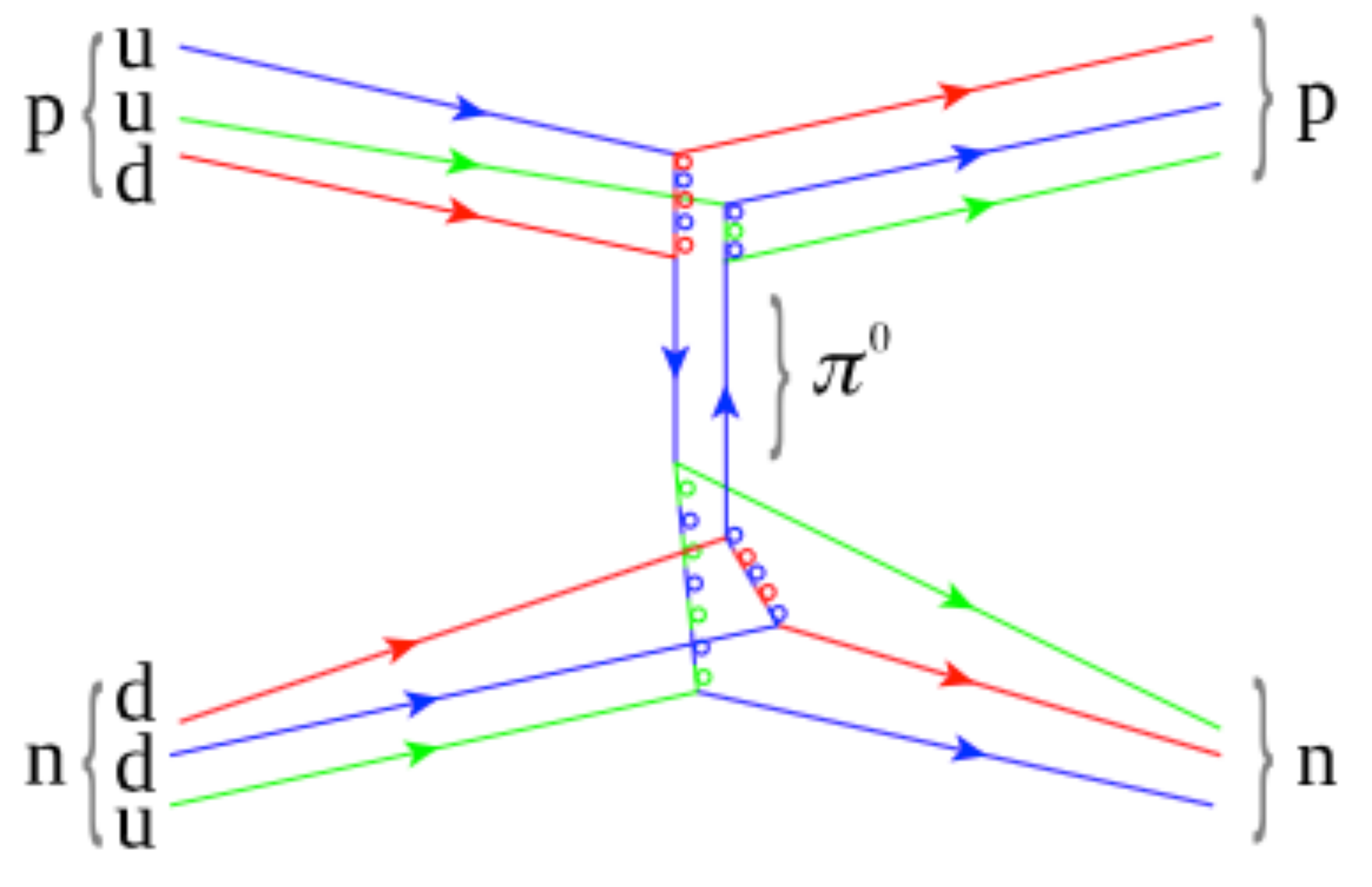
Standard Model

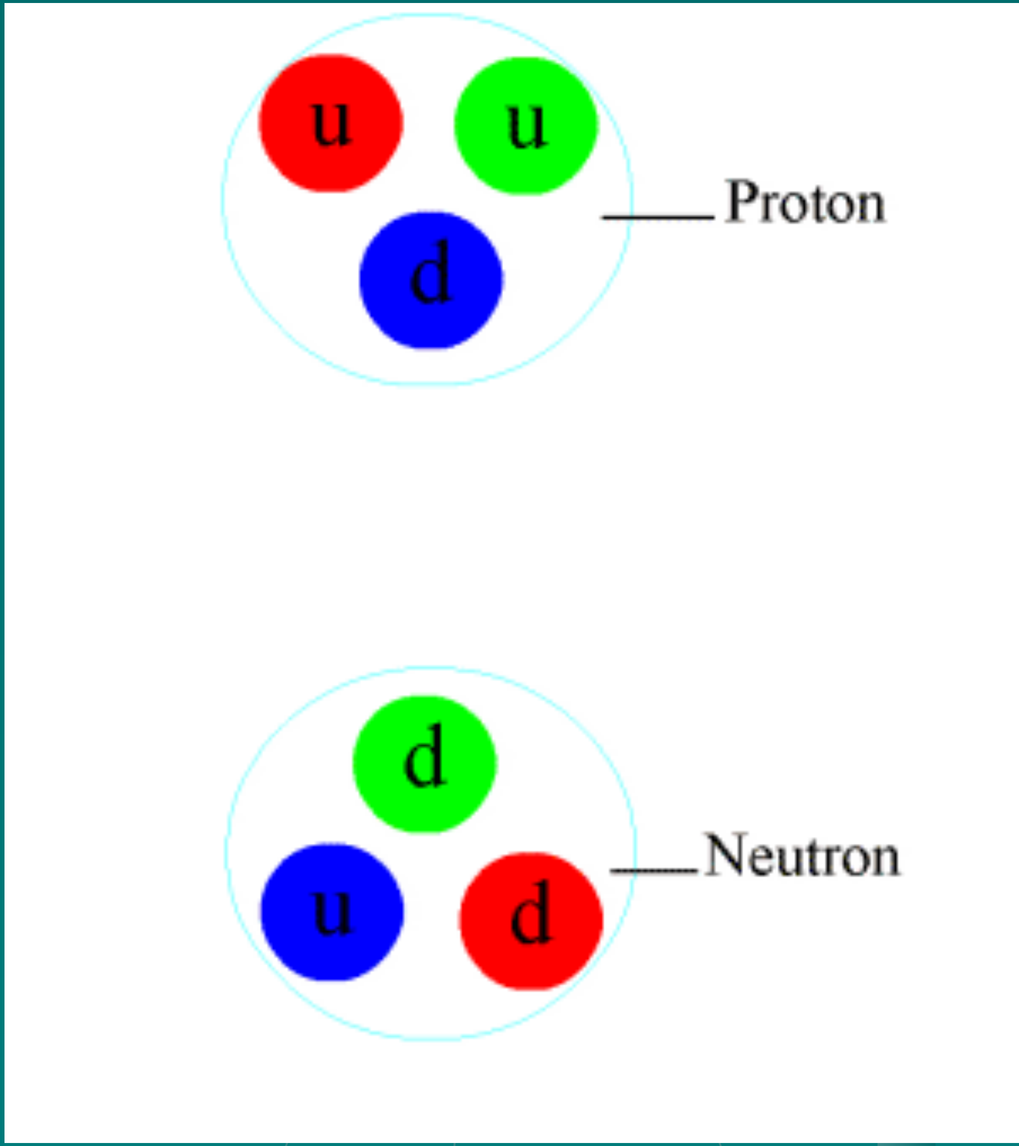


Strong Force

- Free quarks do not exist because the instead of getting weaker with distance the strong force gets stronger
- The strong force (between quarks) is mediated by gluons of different “colors”
- When a quark is knocked out of a proton the force becomes so strong that at least one more quark is created out of the vacuum to pair with it and make a standard baryon or meson

Strong Interaction Feynman Diagram




u
u
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Proton
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Neutron
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Particle Physics Summary

Study of the basic properties of

- Elementary particles
- The forces between them

Using

- Cosmic Rays
- Accelerators
- Particle Detectors
- Observations of behavior of the Entire Universe over time– Cosmology

What's Left?

- Galaxies all moving away from us
  - The farther they are, the faster they are moving-- Hubble's Law
  - Big Bang
    - Cosmic microwave background too smooth
    - Gravitational waves– Inflation?
- We don't understand the simple motions of the galaxies about one another
  - Too much mass– Dark Matter?
- Expansion of the Universe is accelerating
  - Dark Energy?
- How did the structure of the Universe come about?
  - Dark Matter?

Beyond The Standard Model

- Theory
  - Supersymmetry
  - Theory of Everything (TOF)
    - String Theory
    - Loop Quantum Gravity
    - Similar to situation with Democritus-- no technology to do the experiments
  - Spacetime
- Experiment
  - Neutrinos have mass and they oscillate – study details at Fermilab
  - Dark Matter and Dark Energy-- what are they?
  - Higgs Standard Model or not
  - Does Supersymmetry exist there==> many more particles

Summary

- Introduction to science and particle physics
  - Emphasis on fundamental questions
    - What is time?
    - What is space?
    - What is a particle?
    - How does a force work?
      - How are these objects connected?
    - How do we see (detect) them?
    - How do we think about these things?
      - Compare patterns, look for symmetries, make conjectures
      - Test the conjectures
      - Produce good explanations
- Many questinos raised, few answered-- that's my job