The Universe: What We Know and What we Don't

Fundamental Physics

- Cosmology
- Elementary Particle Physics

Elementary Particle Physics

Study of the small scale structure of the universe

- What are the basic building blocks?
- How do they interact with one another?
- Is there a smallest amount of space and time?
- Is there a theory of everything?

Cosmology

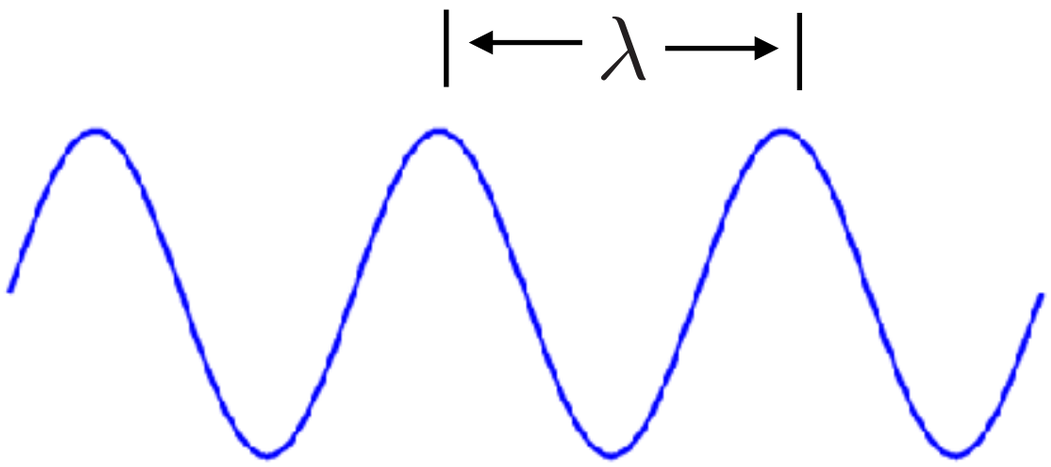
Study of the large scale structure of the universe

- How big is the universe?
- Where did the universe come from?
- What is the fate of the universe?
- Are there other universes? How many

Particle-Wave Duality

Energy inversely proportional to wavelength

$$E \propto \frac{1}{\lambda}$$

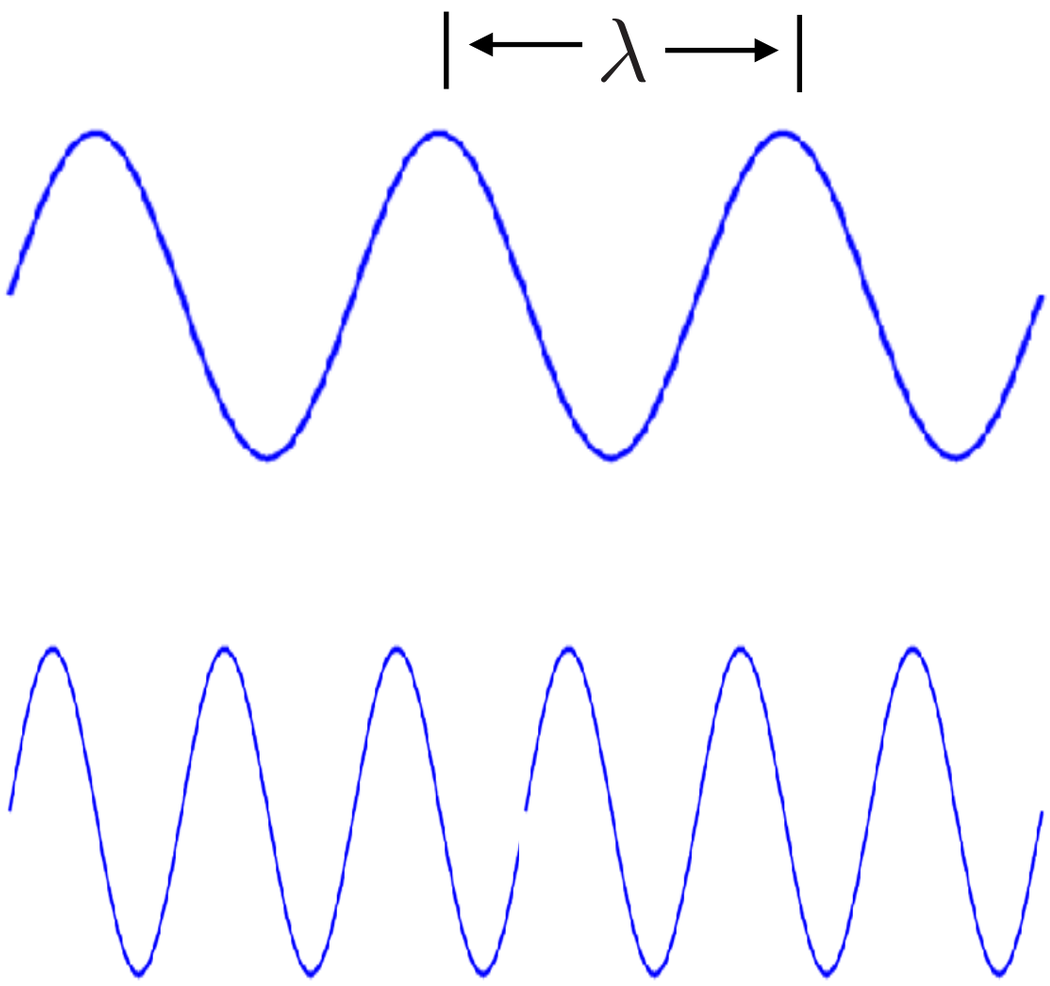


lower energy

Particle-Wave Duality

Energy inversely proportional to wavelength

$$E \propto \frac{1}{\lambda}$$



lower energy

higher energy

Large Hadron Collider

Study of small distances requires high energy probes

Large Hadron Collider

Energy scale

10^3 GeV

Distance scale

10^{-19} m

Temperature

10^{16} K

Big Bang

14 billion years ago the universe was
much denser and hotter than today

Has been expanding and cooling ever since

To know the state of the universe at
earlier and earlier times, need to know
physics at higher and higher energy
scales (smaller and smaller distances)

10^{16} K ⟶ 10^{-12} s after Big Bang

What we Know

- Physics down to a distance scale of

$$10^{-19}\ \mathrm{m}$$

- Physics down to a time of

$$10^{-12}\ \mathrm{s}$$ after the Big Bang

Fundamental Particle Physics

Fundamental Particle Physics

- What are the fundamental constituents of the universe?

Fundamental Particle Physics

- What are the fundamental constituents of the universe?
- How do they interact with each other?

How to Judge How We're Doing

Constituents

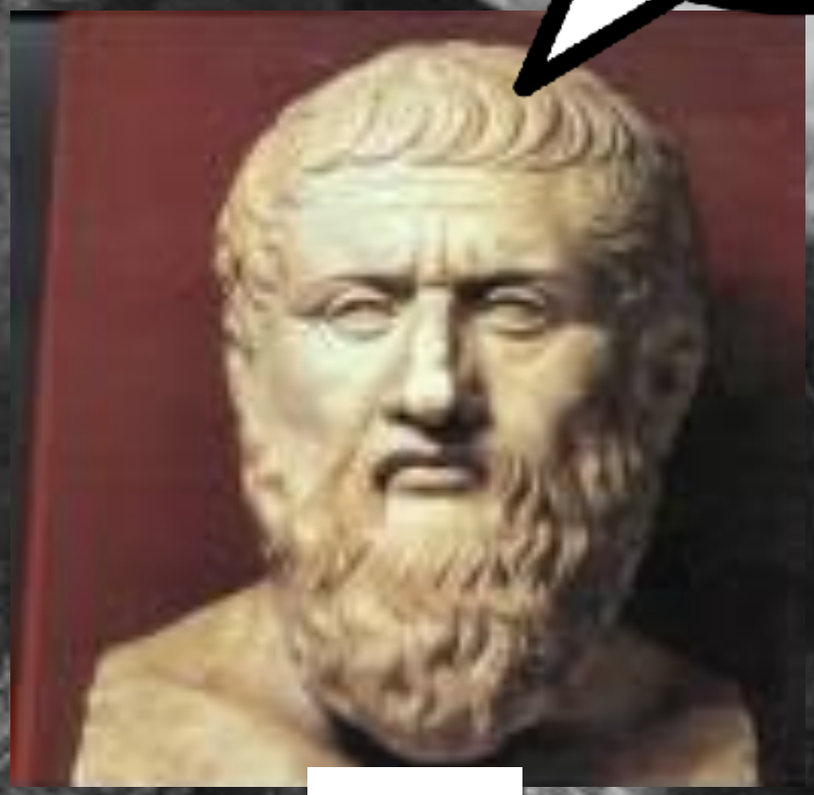
- Number: economical
- Properties: few and simple
- Point-like? (no structure)

Theory

- Mathematically consistent
- Explains all observations
- Able to make predictions

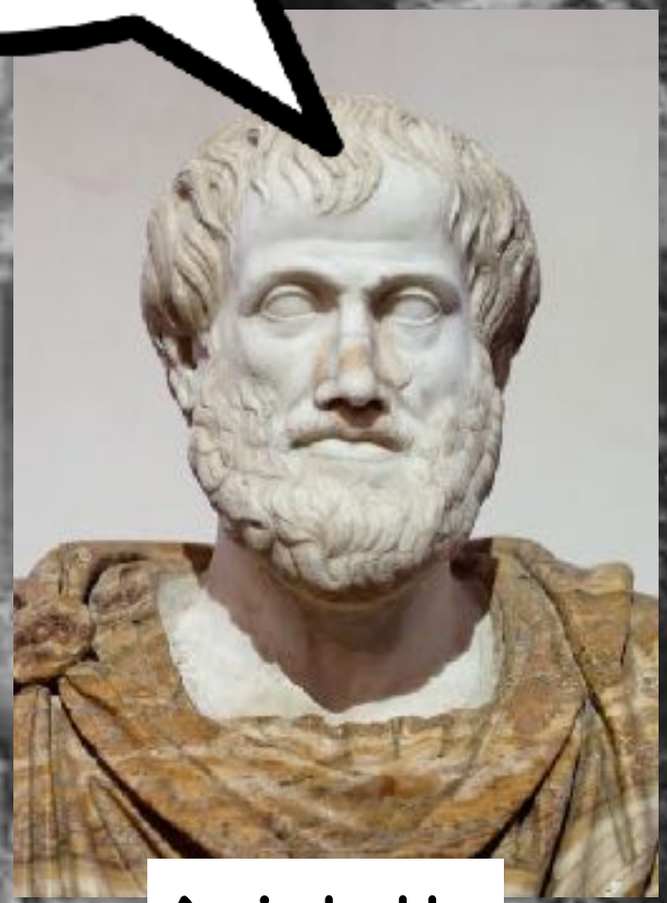
Ancient Greece

All is mathematical form



Plato

I can figure out the universe by pure thought

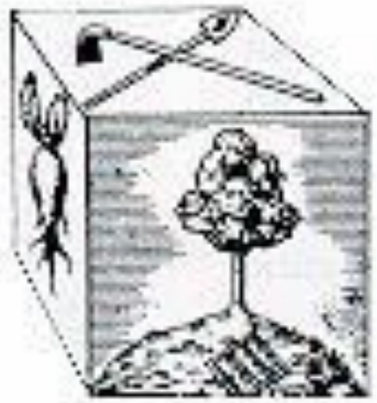


Aristotle

Fundamental Physics

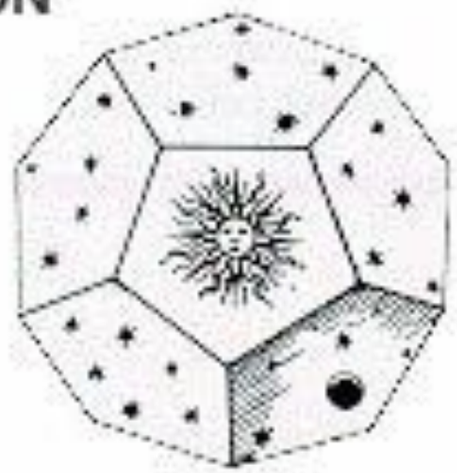
Circa 500 B.C.

OCTAHEDRON
Air



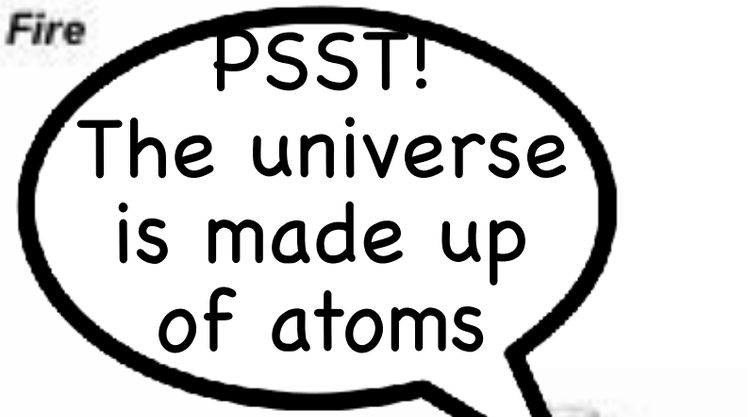
CUBE
Earth

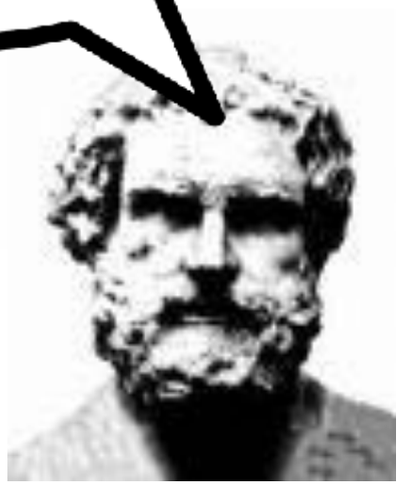
TETRAHEDRON
Fire



DODECAHEDRON
the Universe

ICOSAHEDRON
Water

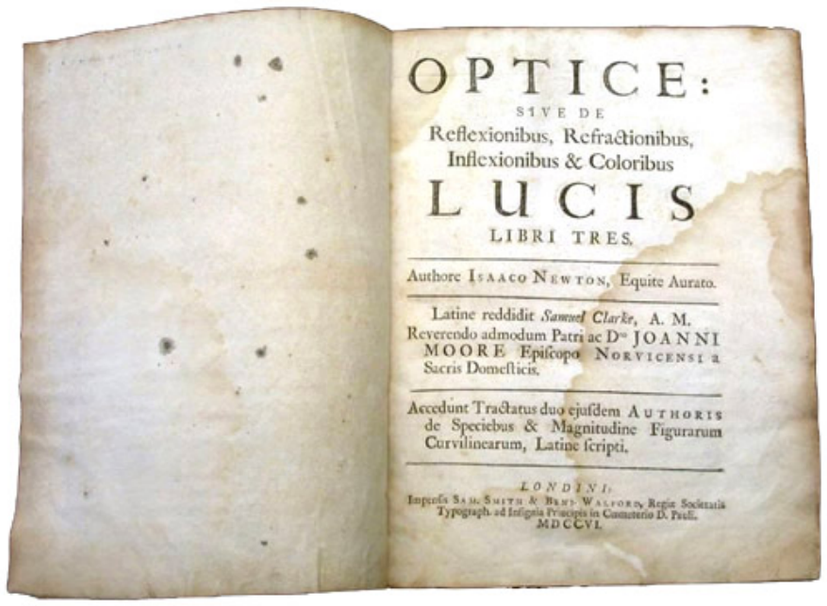




Democritus

The universe is built on the five Platonic solids

Newton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Authore ISAACO NEWTON, Equite Aurato.

Latine reddidit *Samuel Clarke*, A. M.
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Accedunt Tractatus duo ejuſdem AUTHORIS
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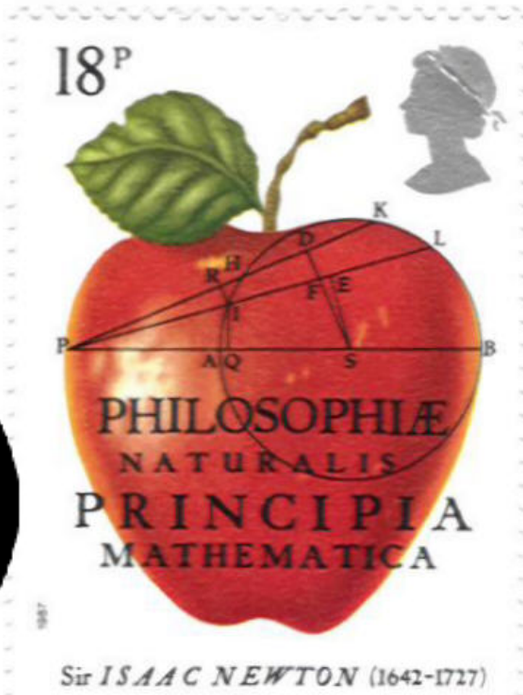
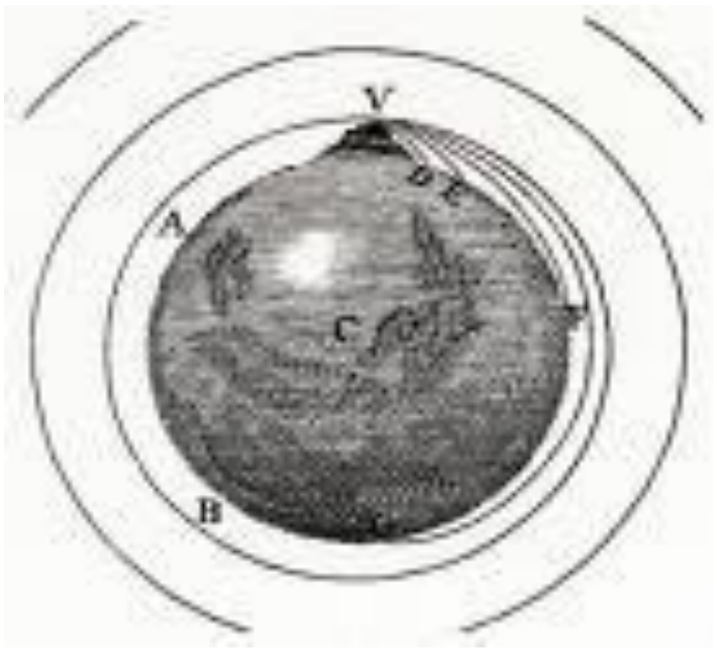
Impenſis SAM. SMITH & BENJ. WALFORD, Regiæ Societatis
Typograph. ad Inſignia Principis in Cœmeterio D. Pauli.
MDCCVI.

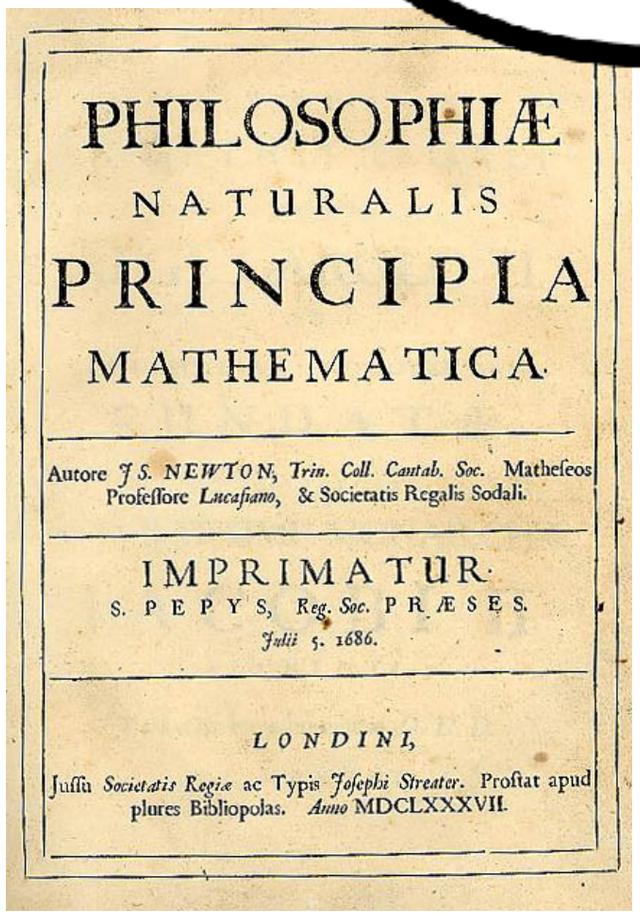
$F = ma$

The world is made of point particles



Sir ISAAC NEWTON (1642-1727)

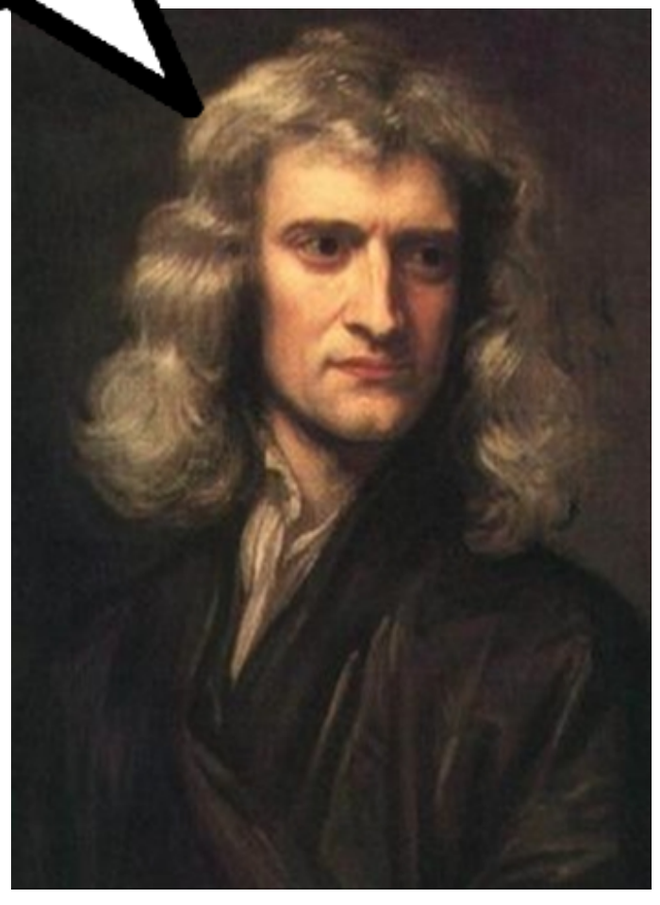



PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

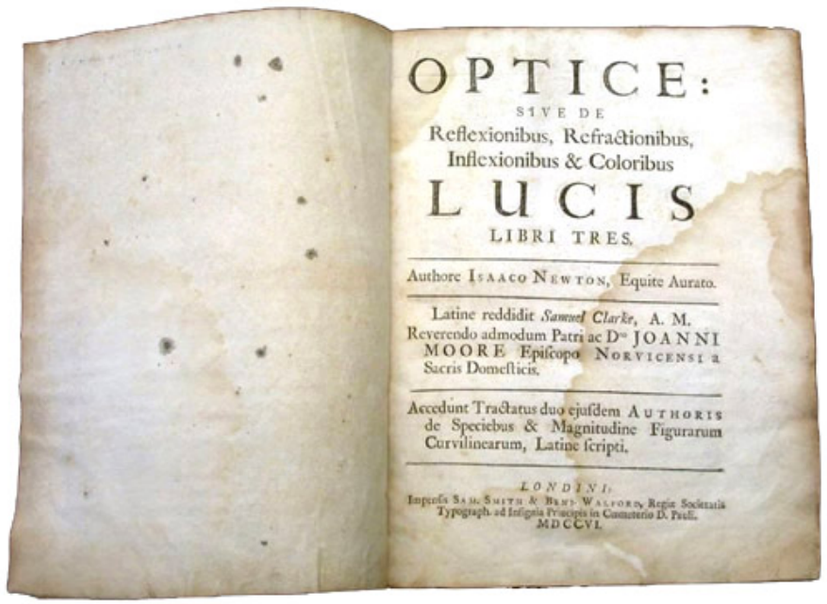
Autore *J. S. NEWTON, Trin. Coll. Cantab. Soc.* Matheſeos
Profeſſore *Lucaſiano*, & Societatis Regalis Sodali.

IMPRIMATUR.
S. PEPYS, *Reg. Soc.* PRÆSES.
Julii 5. 1686.

LONDINI,
Juſſu *Societatis Regiæ* ac Typis *Joſephi Streater*. Proſtat apud
plures Bibliopolas. *Anno* MDCLXXXVII.



Newton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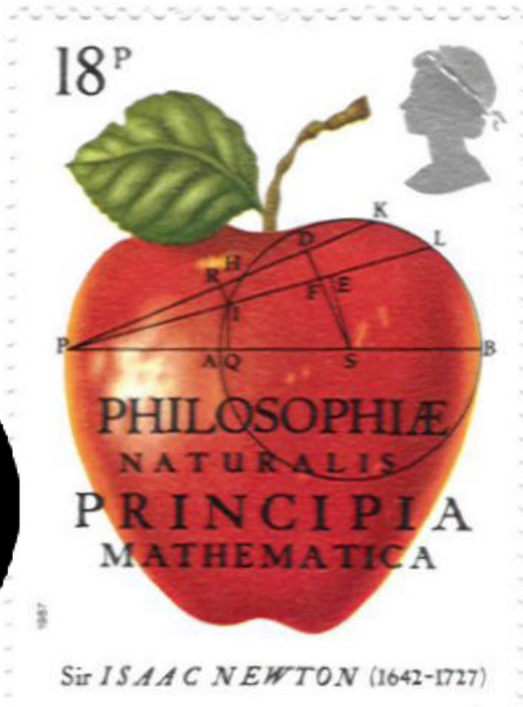
MDCCVI.

$F = ma$

I have no idea what they are



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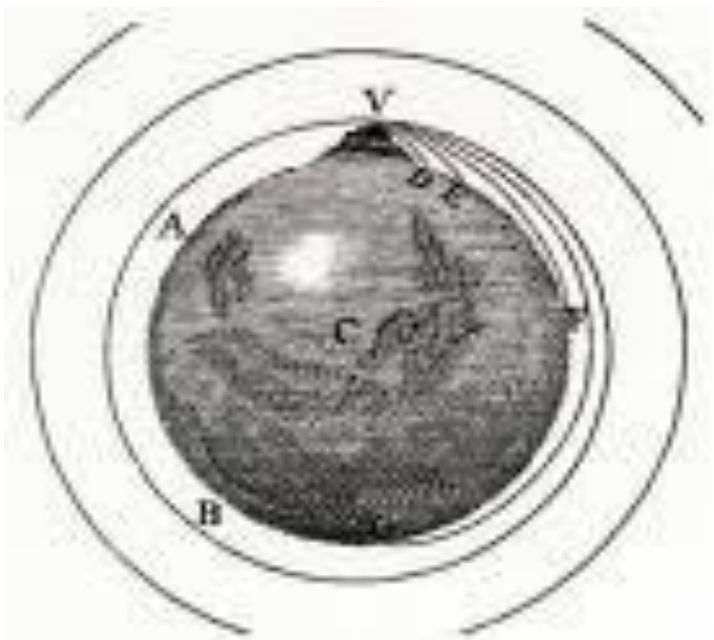

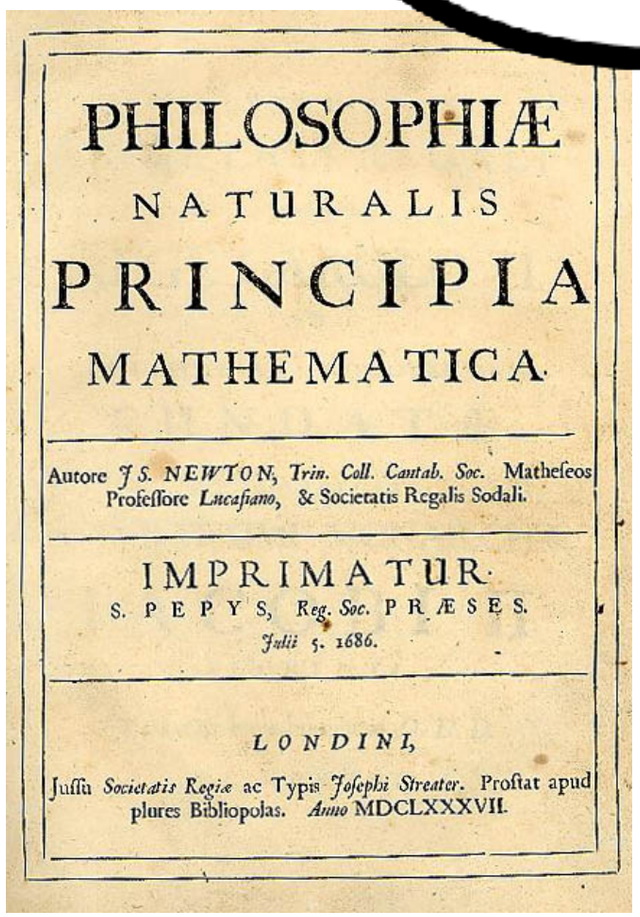
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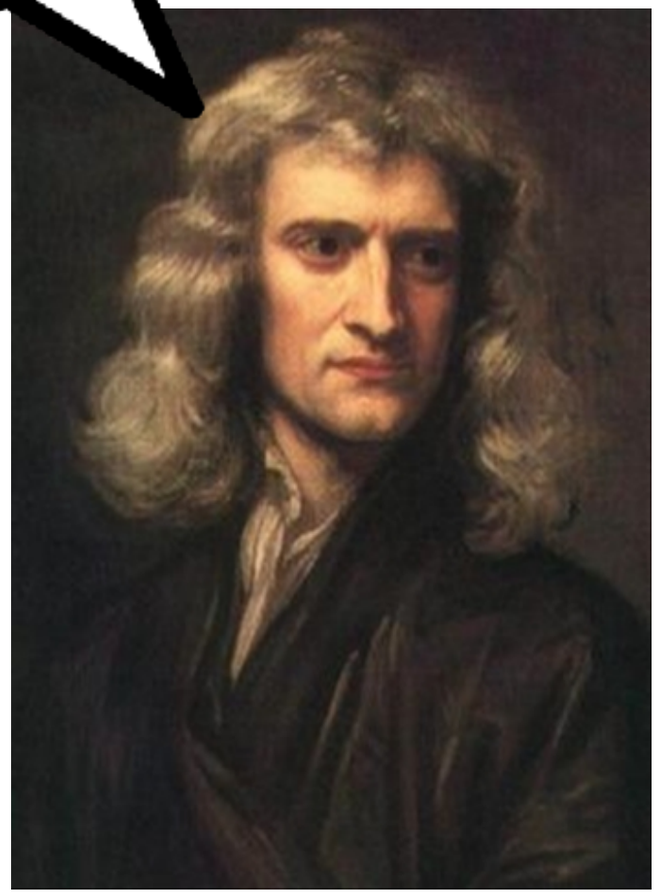
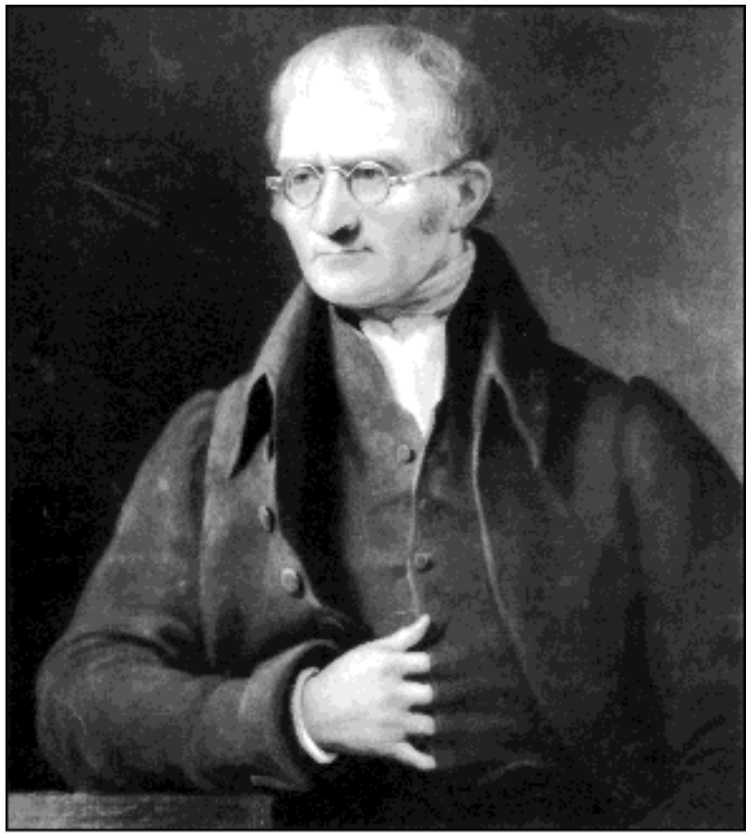


Chemists Discover Evidence for Atoms

1802



John Dalton

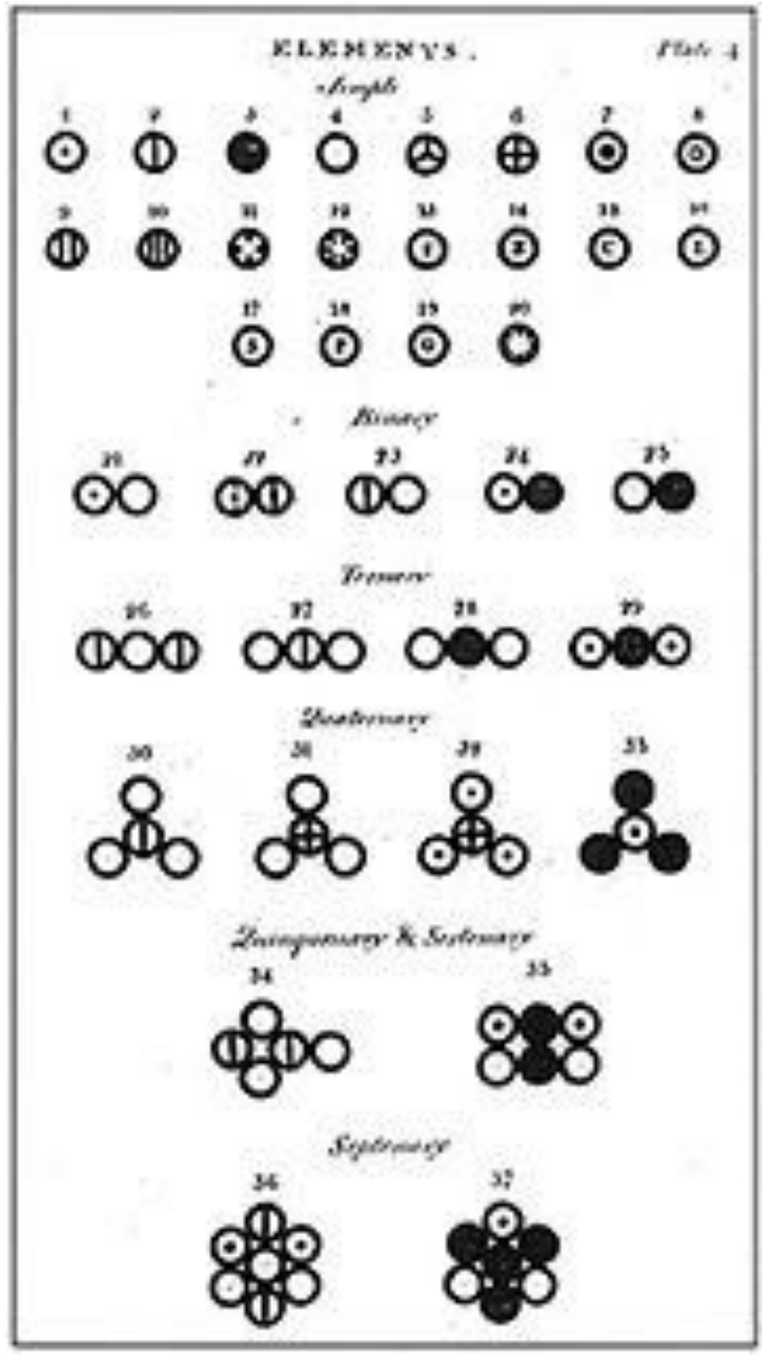
- Gay-Lussac's Law
- Boyle's Law
- Charles's Law
- Law of Multiple Proportions

NO_2

N_2O

CH_4

C_2H_4



World's First Particle Physicist

1827

Discovered Brownian Motion

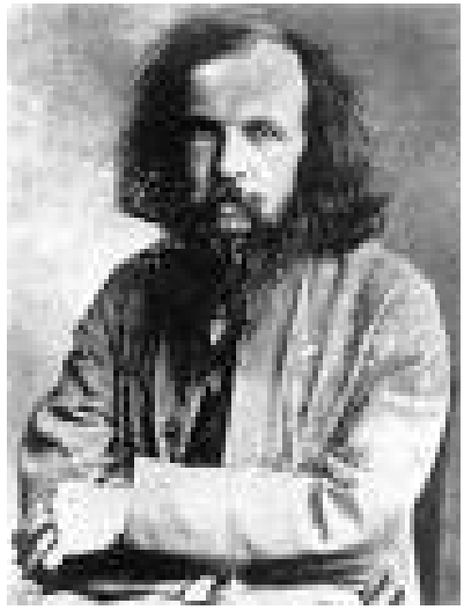
Robert Brown

Botanist

Movie of Brownian Motion

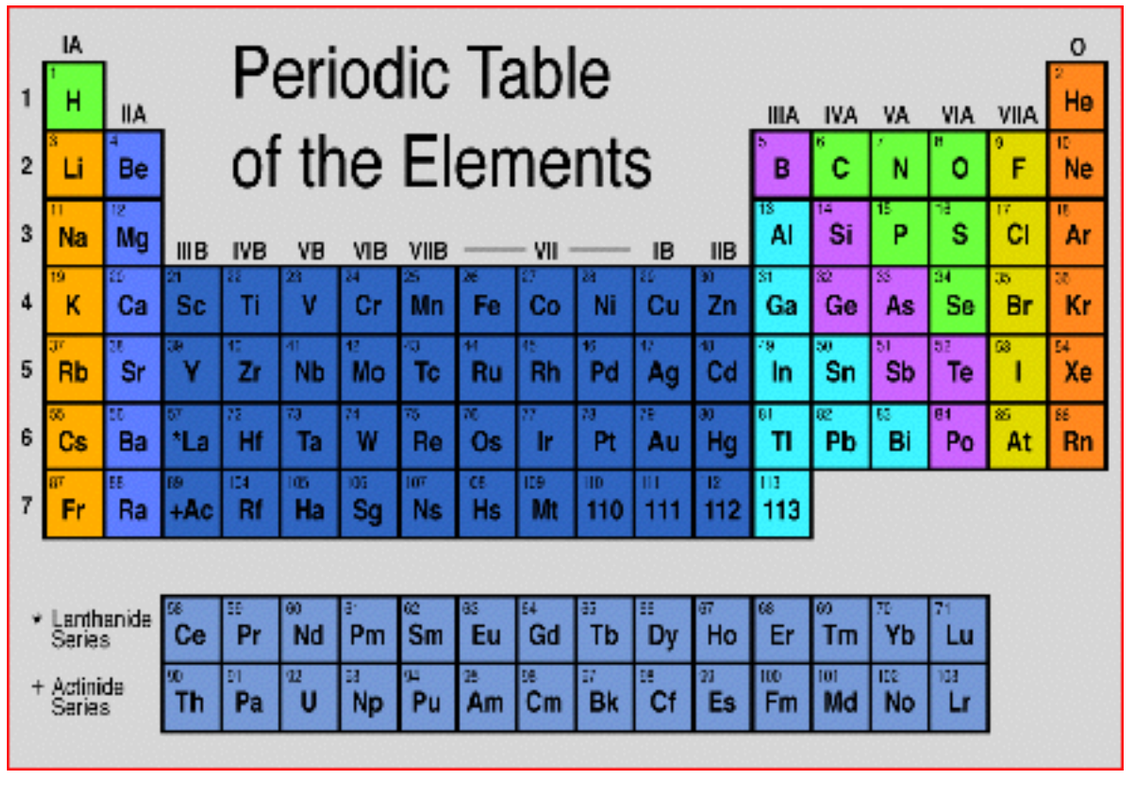
Periodic Table

1869



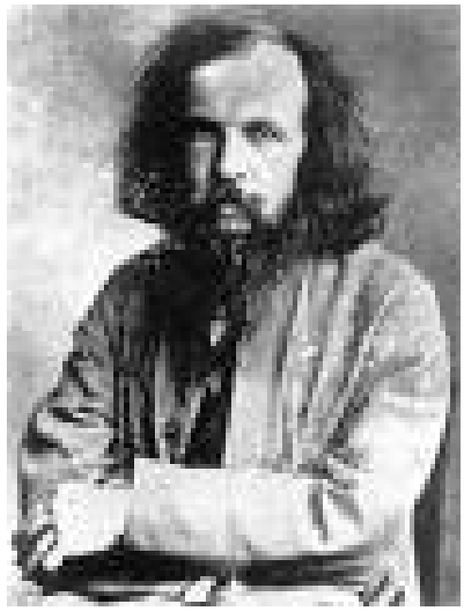
Mendeleev

a classification scheme

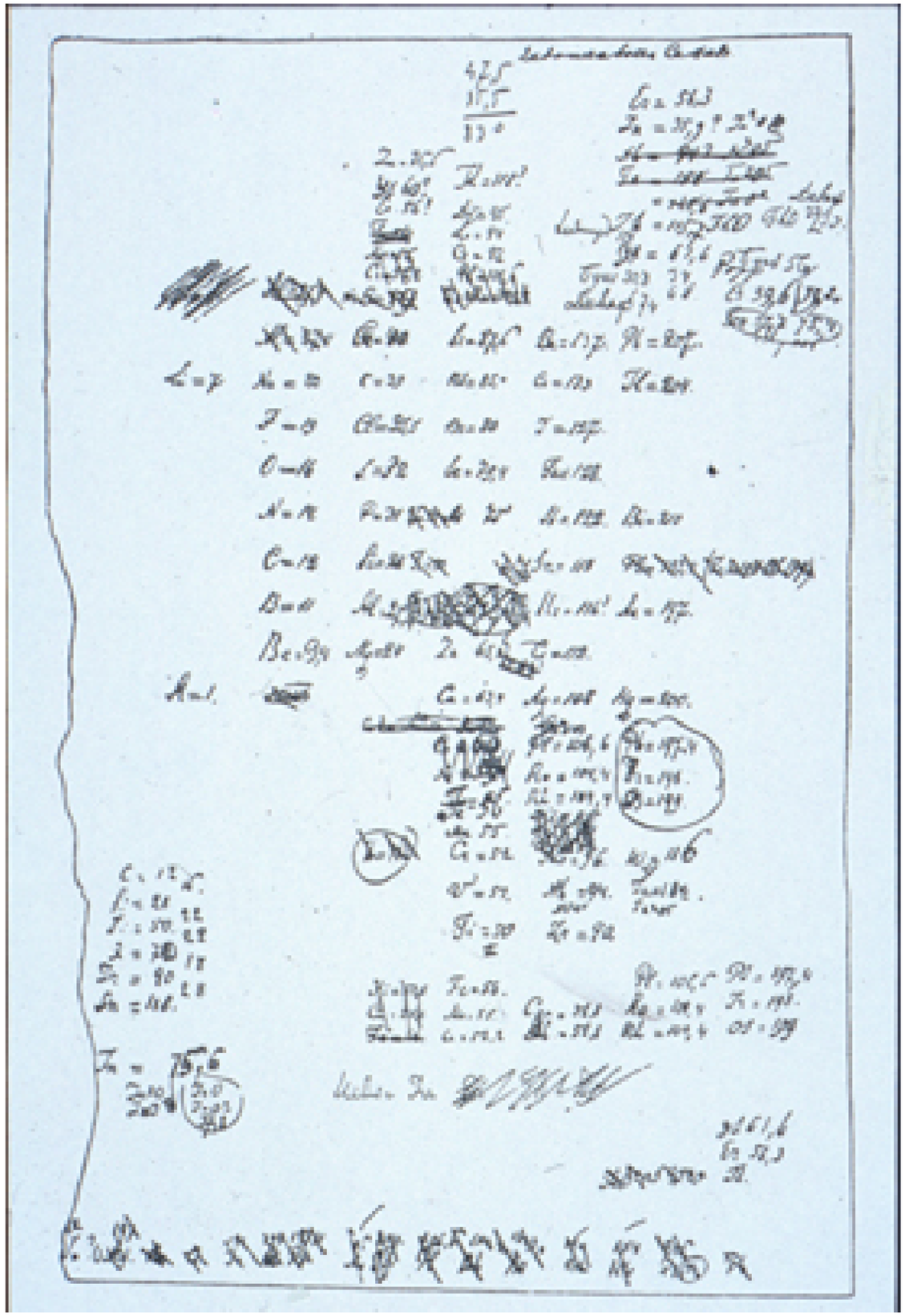


Periodic Table

1869



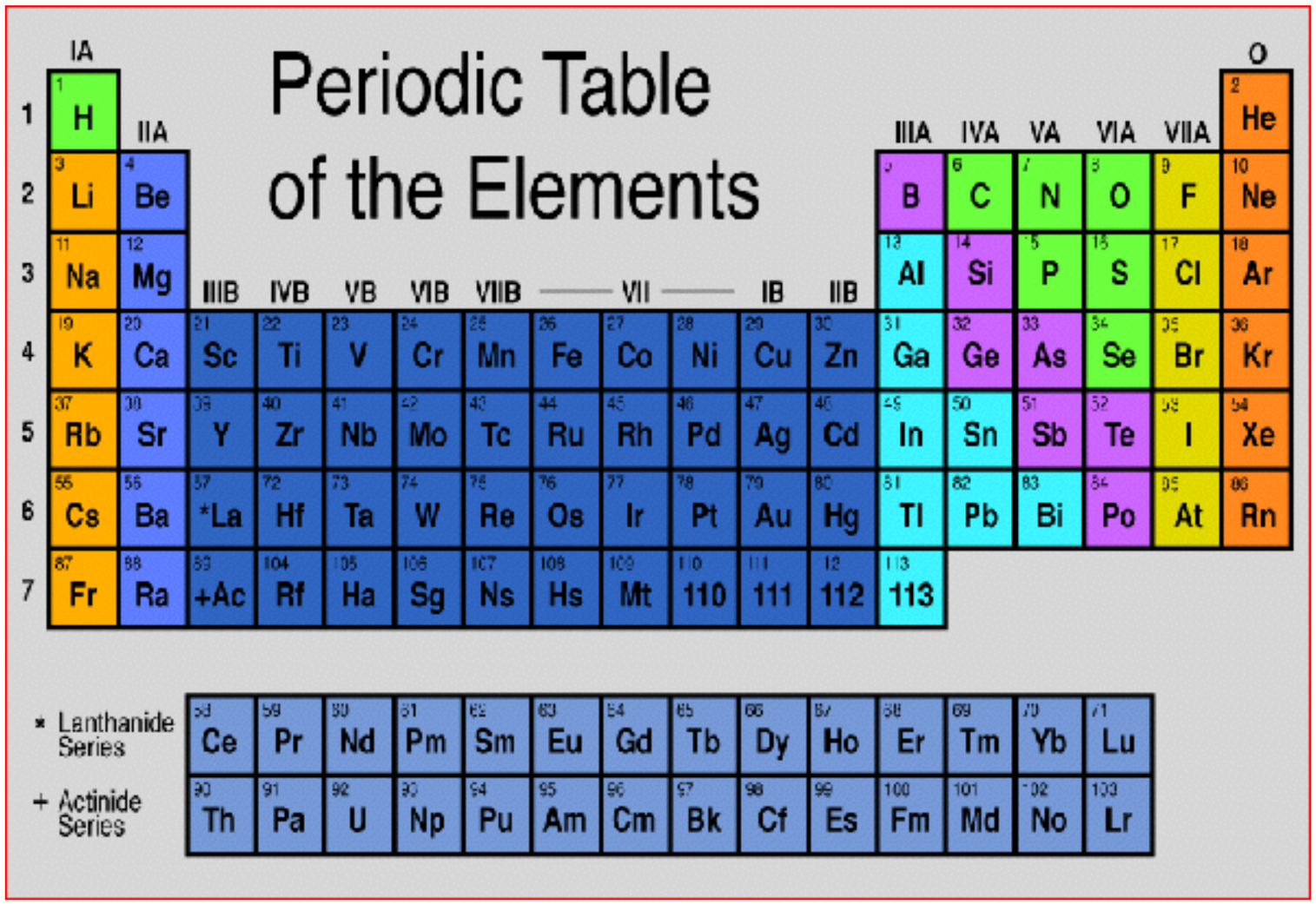
Mendeleev



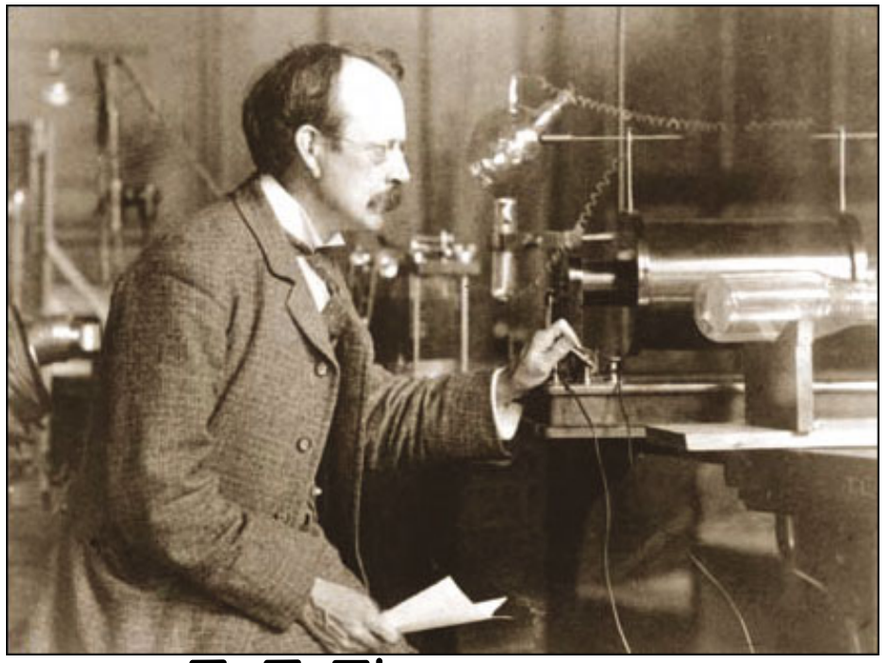
Fundamental Particle Physics

End of 19th century

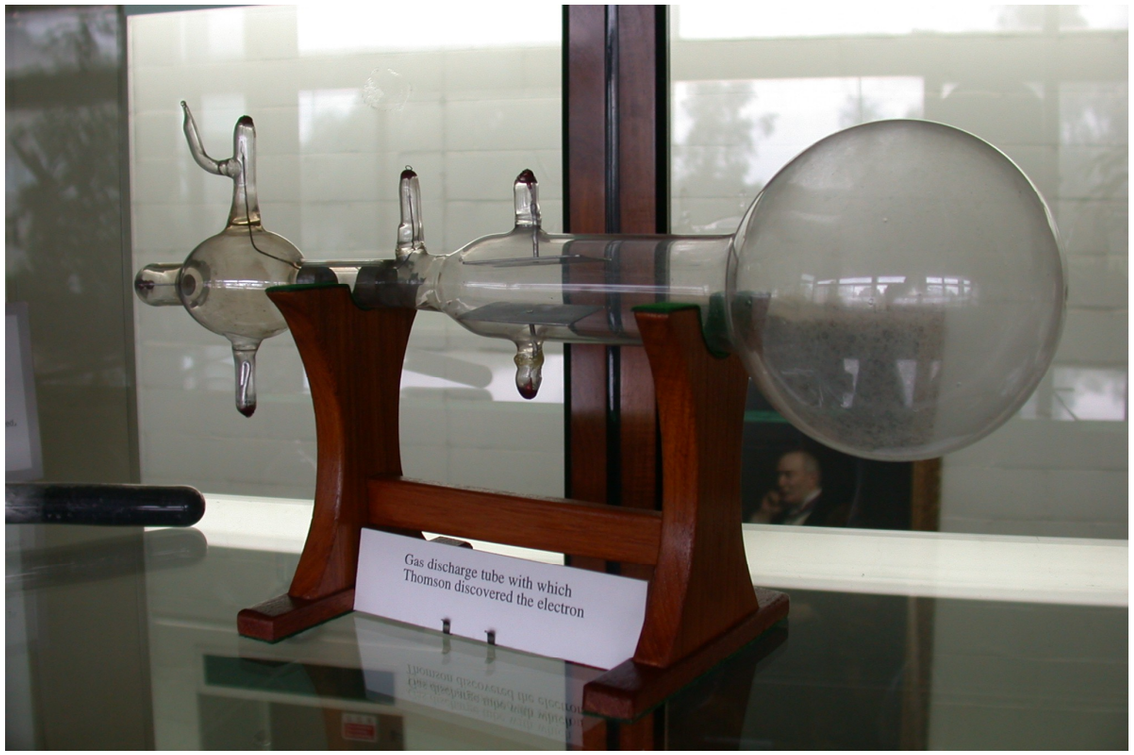
92 Atoms



Discovery of the Electron



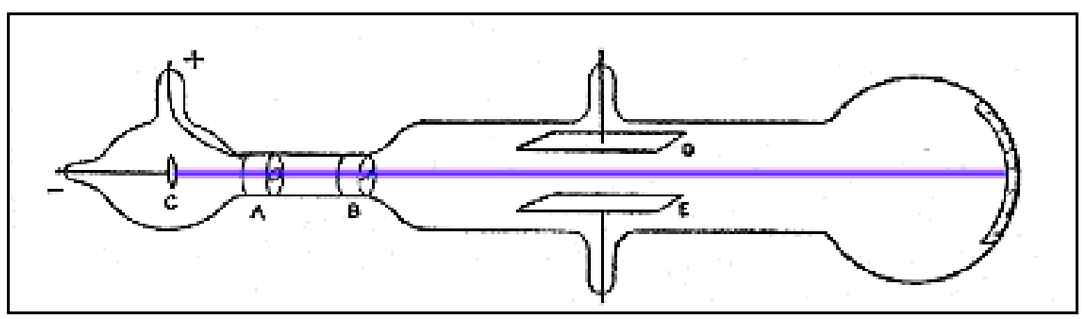
J. J. Thomson



Thomson's CRT

A new particle

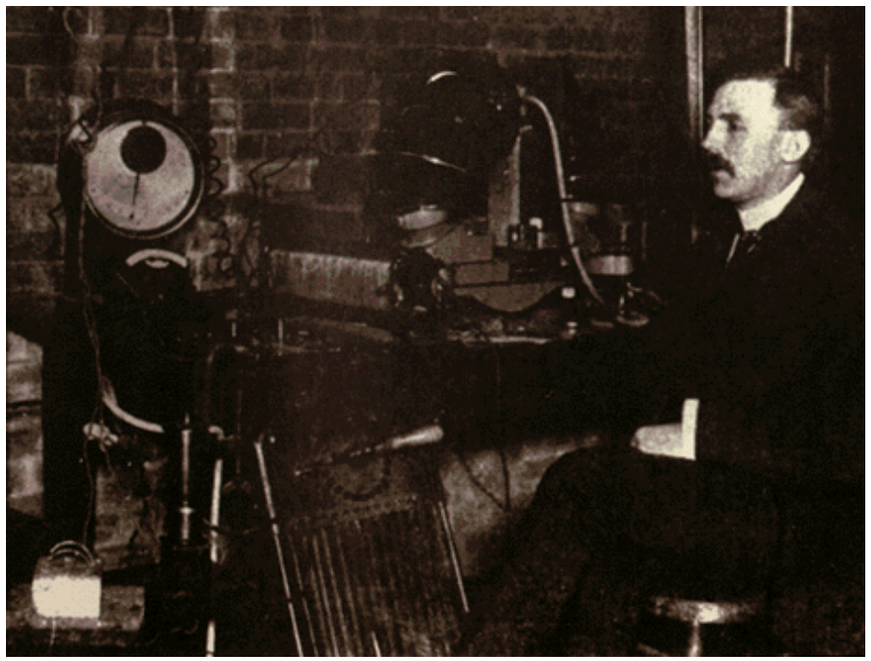
electrically charged



Lord Rutherford

World's first high energy physicist

1910

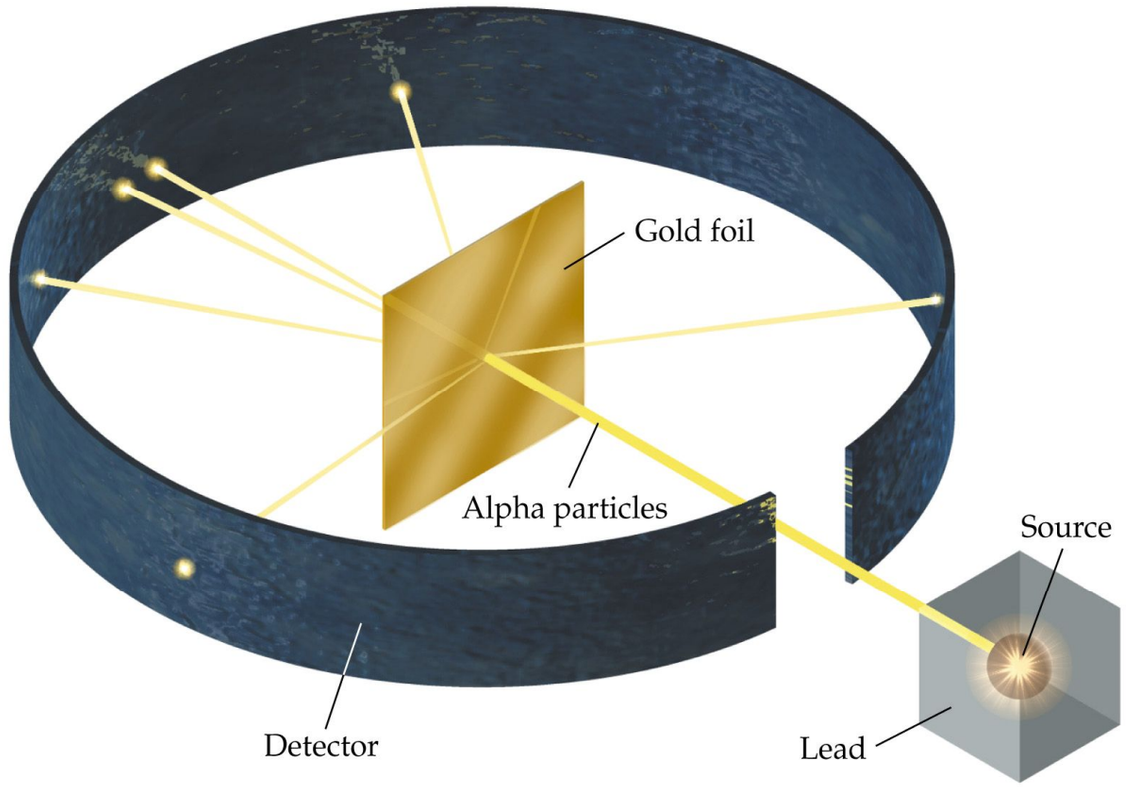


Ernest Rutherford

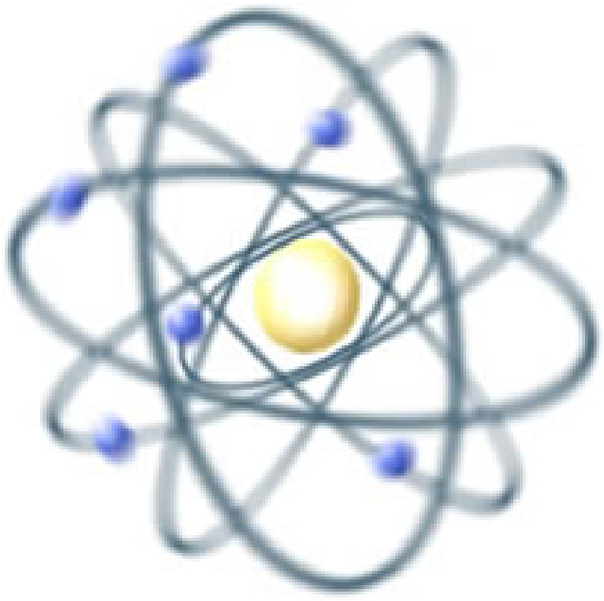
Use high energy (5 MeV) alpha particles from radium decay to study structure of the atom.

very light electrons should have no effect on the alpha's

scattering of the alpha's will indicate structure of the "pudding"



The Nuclear Atom



Nearly all of the mass of the atom concentrated in a very small positively charged nucleus.

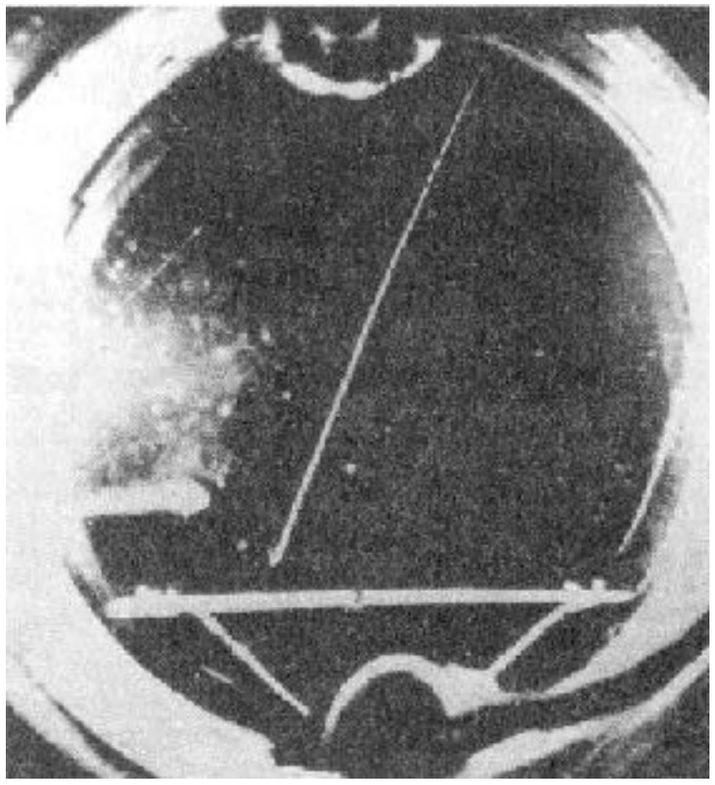
How small is the nucleus?

Discovery of the Neutron

1932

James Chadwick

Alpha particles interacting in air found to knock out neutral particles.



Rutherford had earlier discovered the proton (the nucleus of the hydrogen atom)

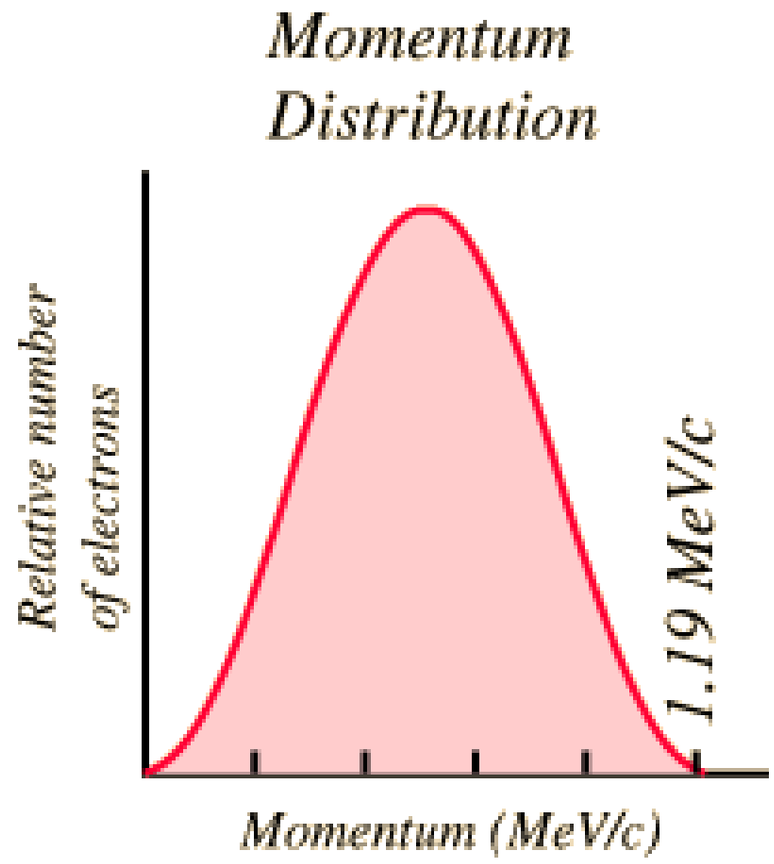
Atoms made out of:
protons, neutrons, electrons

The Neutrino

A free neutron decays
to a proton and electron
in about 15 minutes

- not a 2-body decay
- must be a third unseen particle

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



Ghost-like neutrino

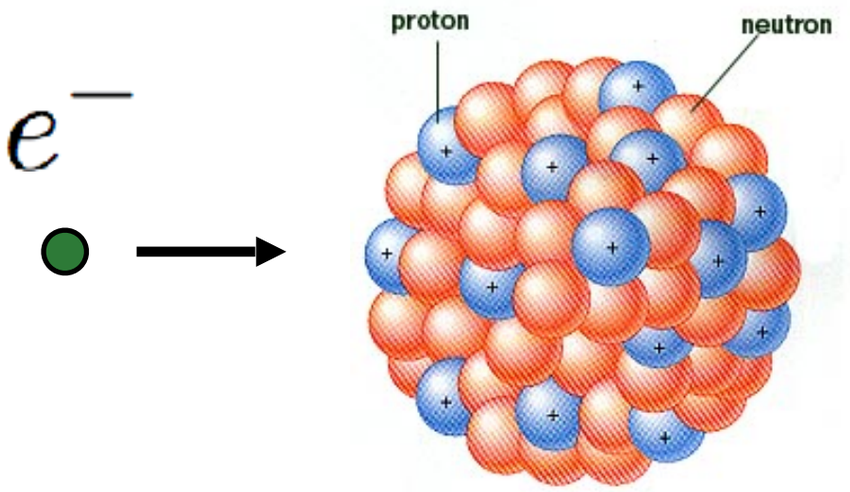
Predicted in 1930 by Pauli

Discovered in 1956 by Cowan and Reines

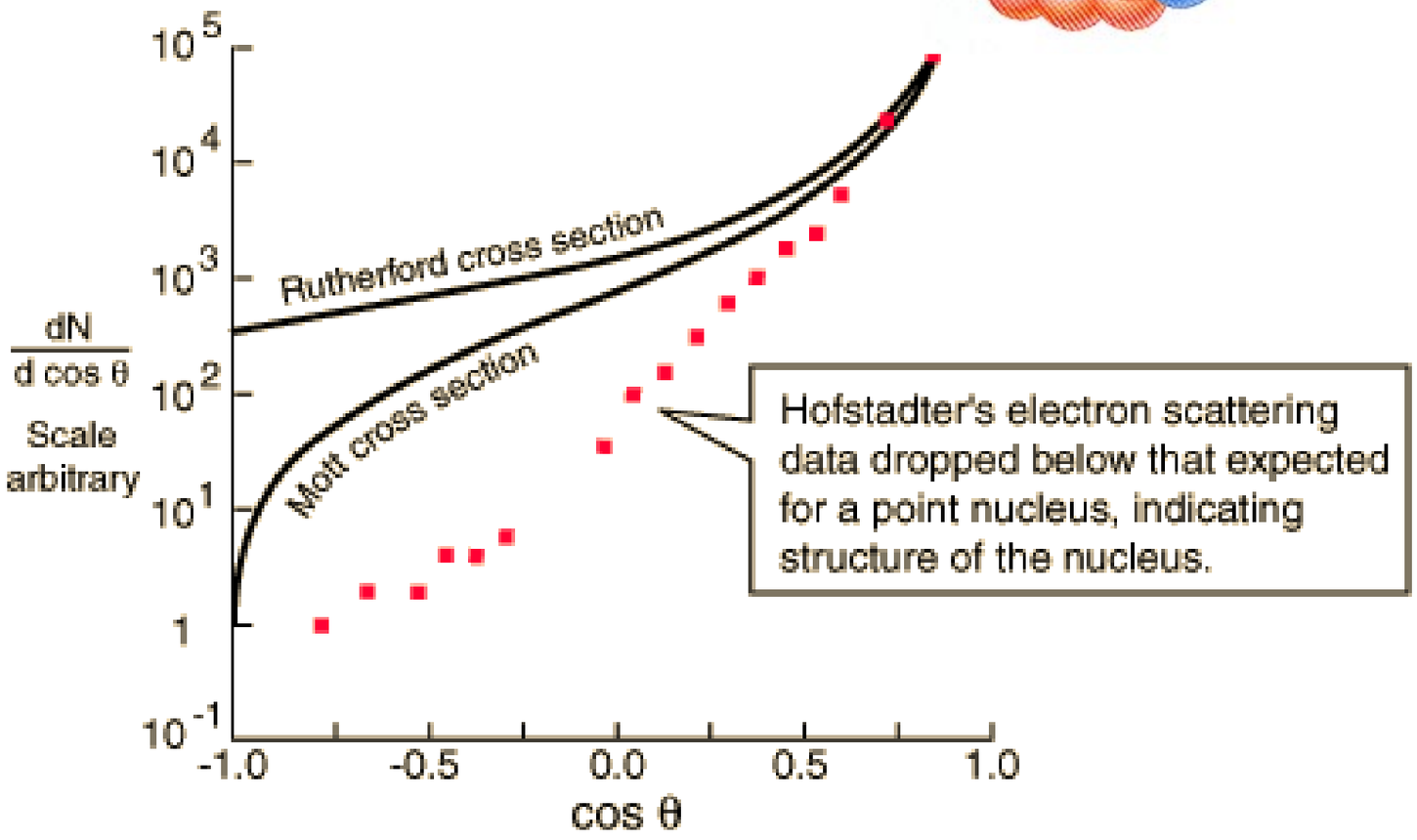
Pauli

Structure of the Nucleus

1953 Scattered 125 MeV electrons off of nuclei



Hofstadter



nuclear size: $\sim 10^{-13}$cm

Fundamental Particle Physics

1932

neutrino ν

electron e^-

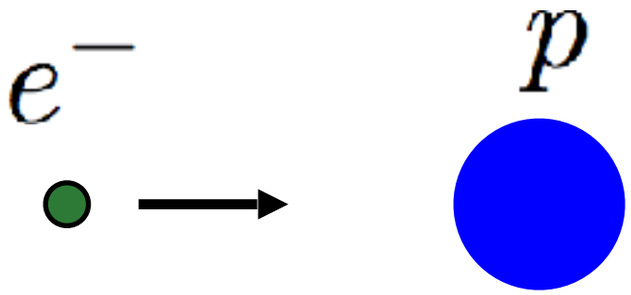
photon γ

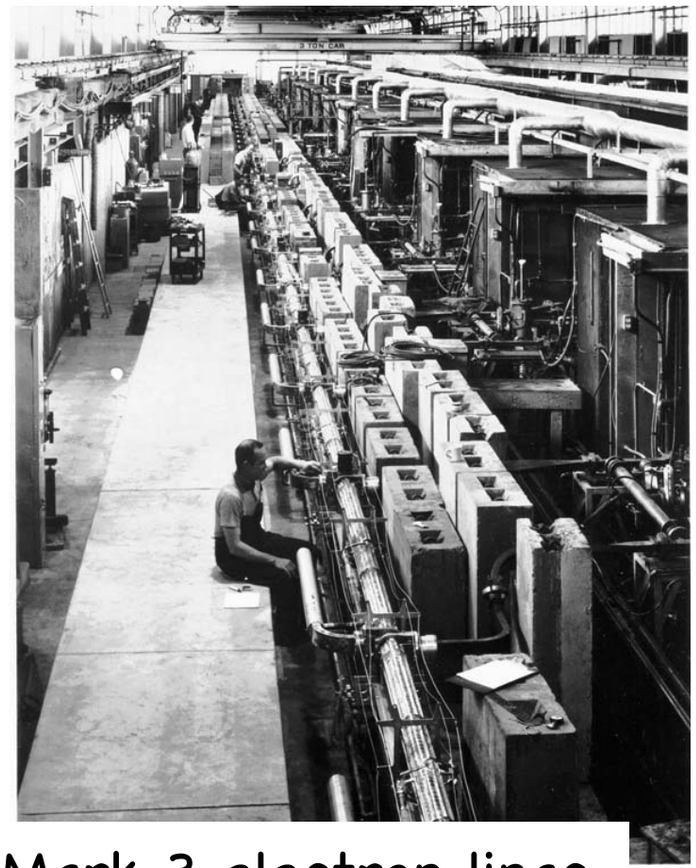
proton p

neutron n

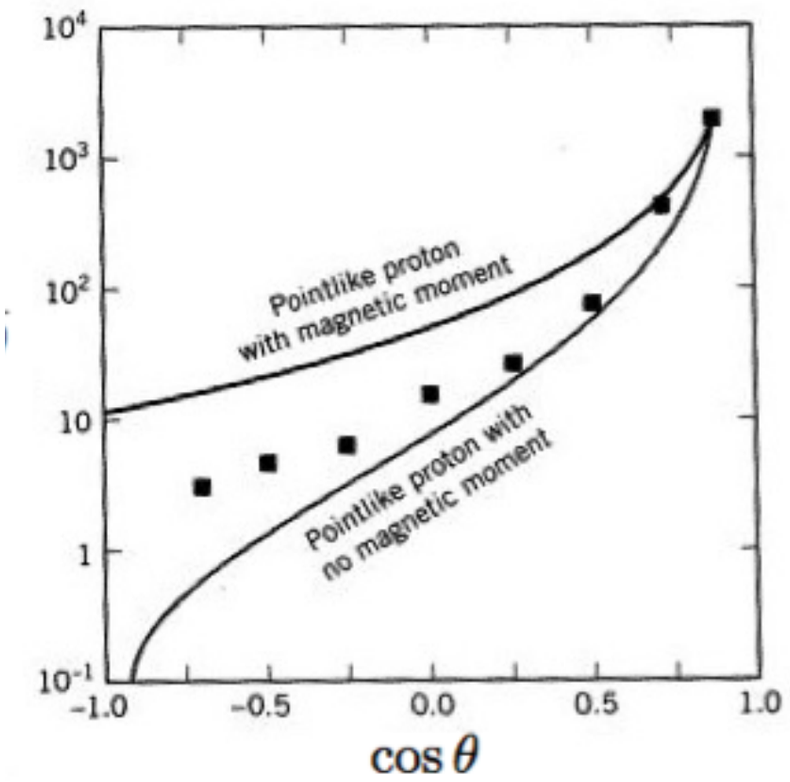
Structure of the Proton

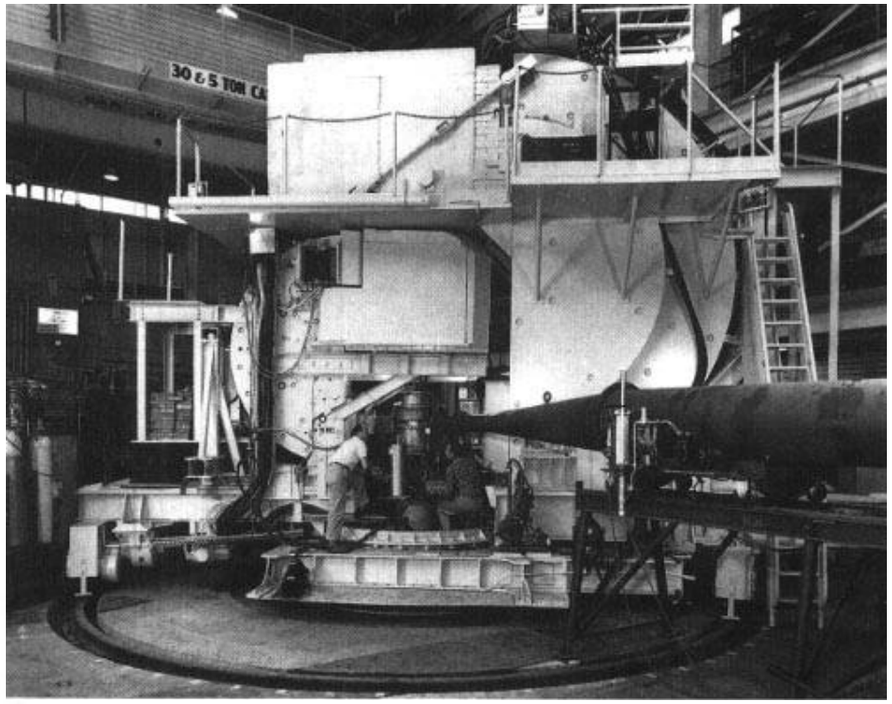
1956 Scattered 550 MeV electrons off of nuclei





Mark 3 electron linac at Stanford University



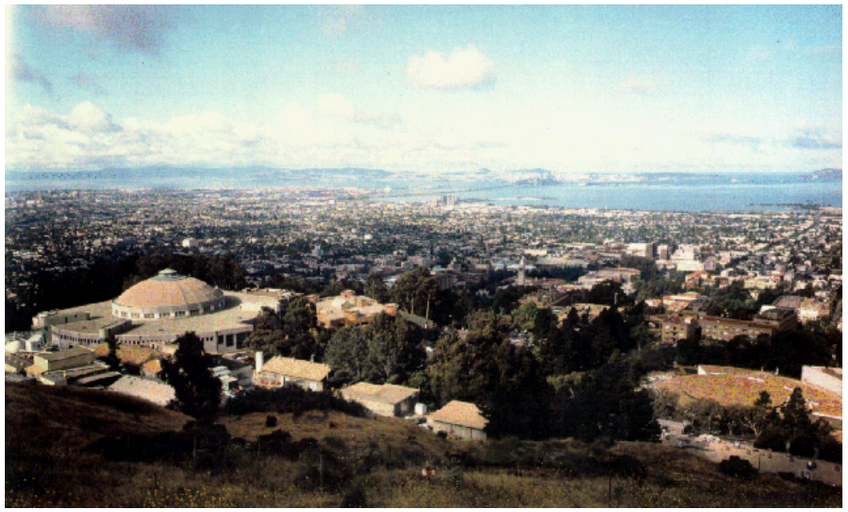


Hofstadter's spectrometer

The proton has a size
it is not a point-like object

The Bevatron

6 GeV proton synchrotron
in the hills of Berkeley



Designed to discover
the anti-proton

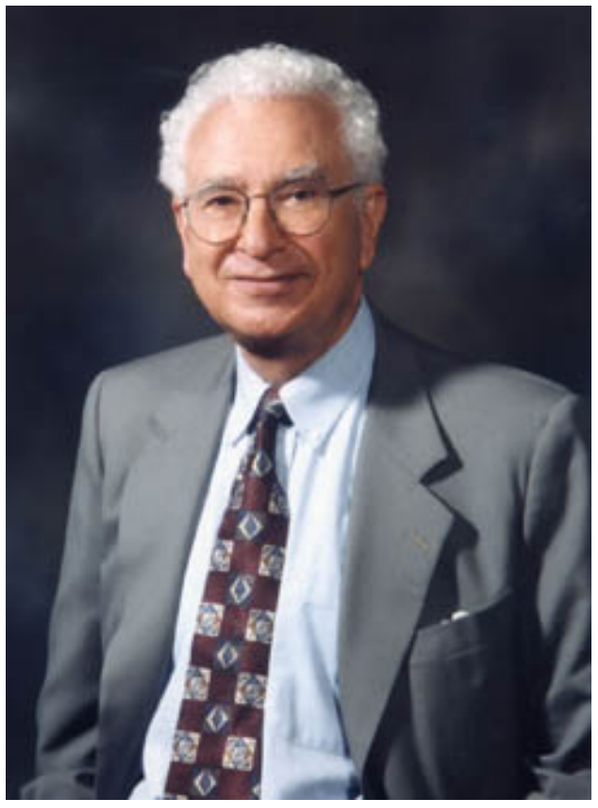
The Particle Zoo

Hundreds of new particles discovered 1955 - 1965.

What does it all mean?

Quarks

1964



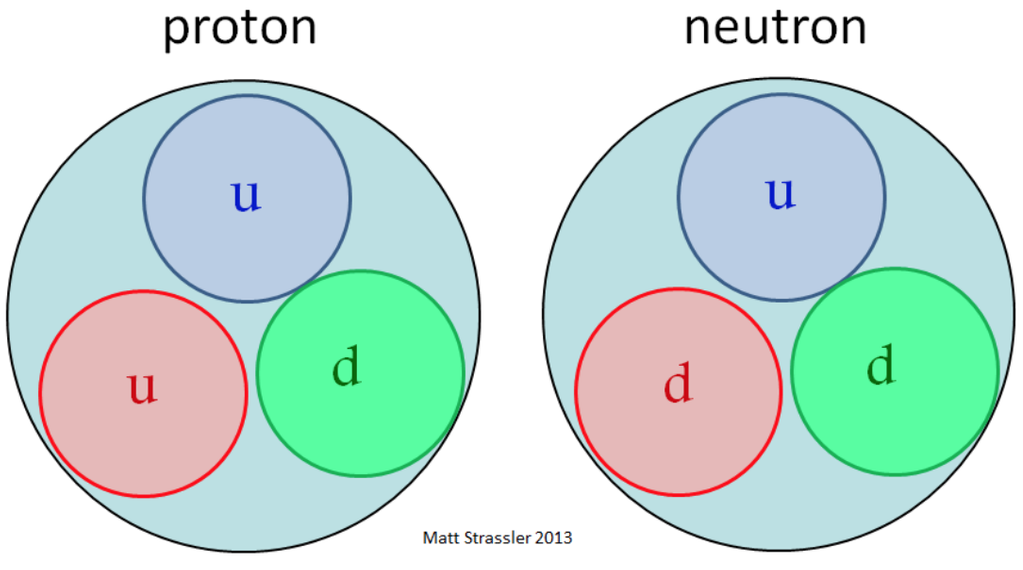
Murray Gell-Mann

Three quarks

up down strange

mesons: $q\bar{q}$

baryons: qqq



Stanford Linear Accelerator Center

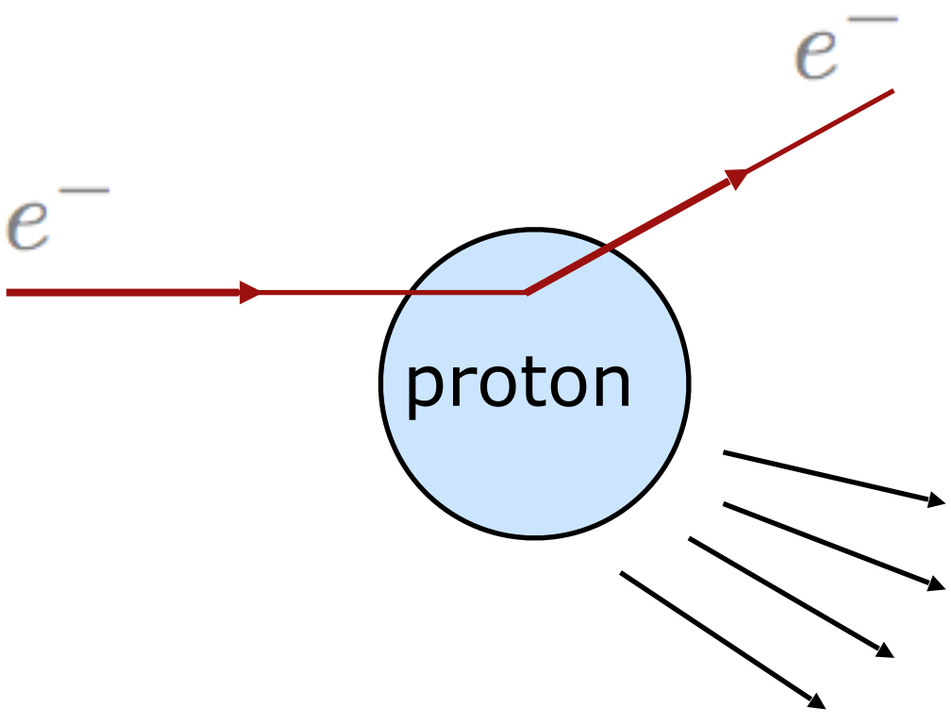
SLAC 30 GeV electrons

2-mile long linear accelerator

Inside the Proton

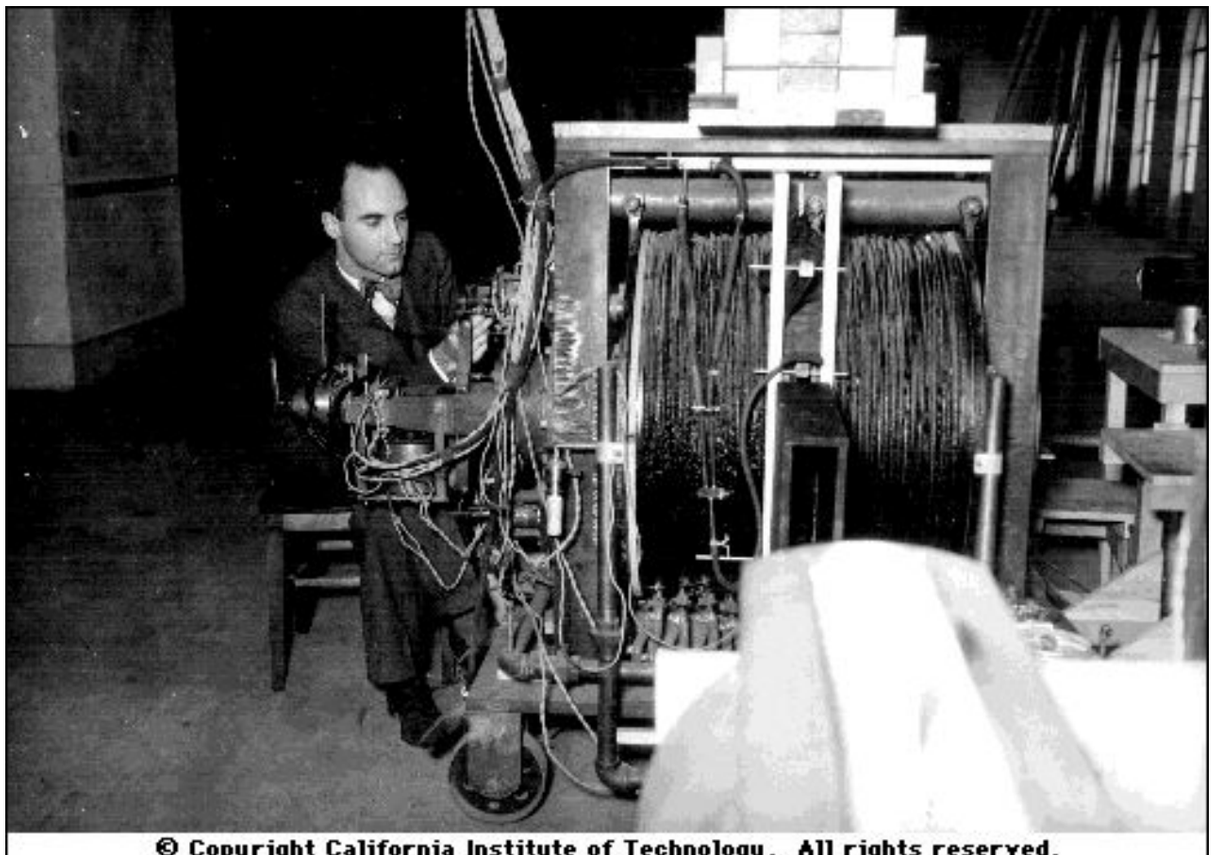
SLAC

1968



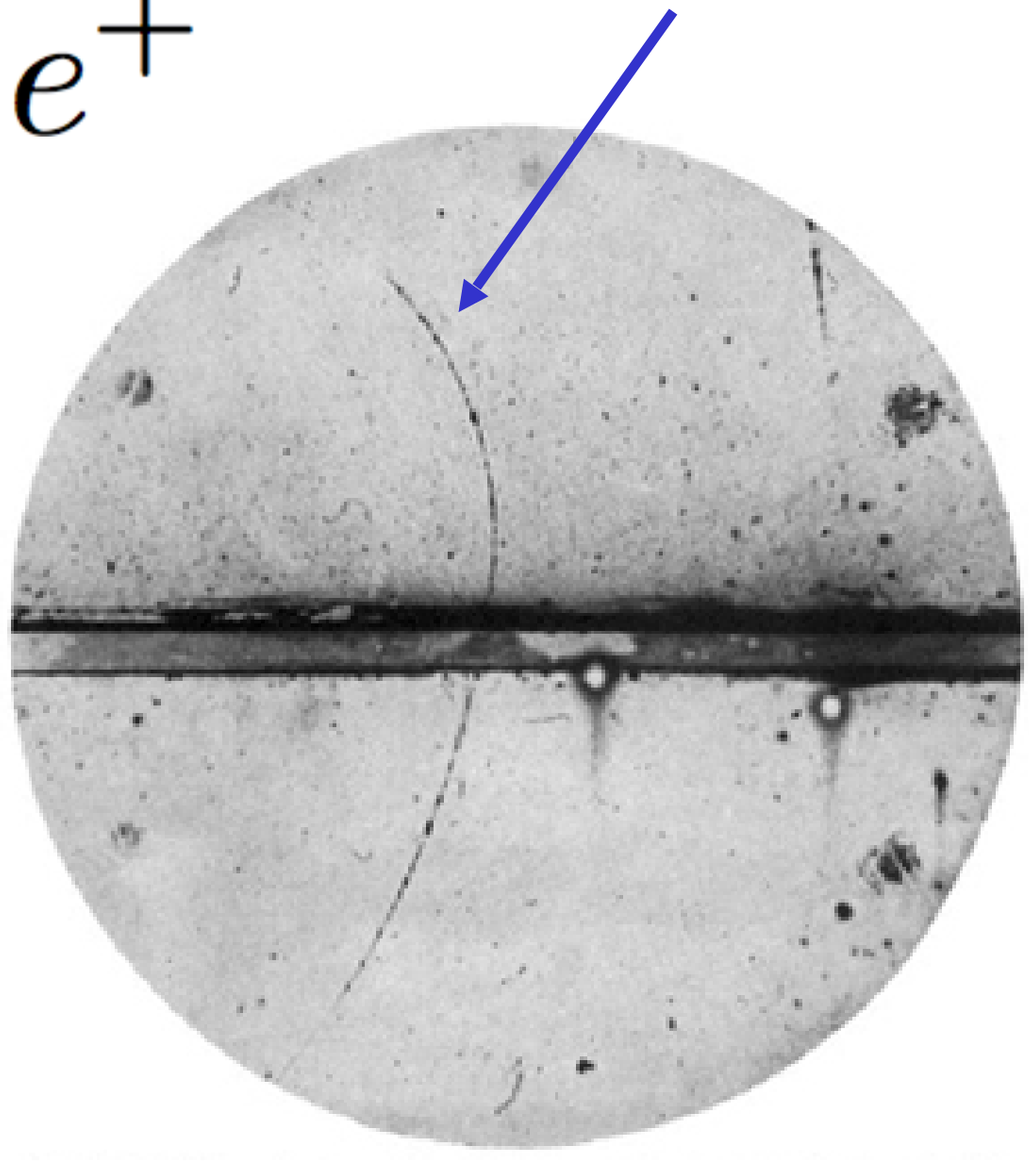
Antimatter

1932 Carl Anderson discovers anti-electrons (positrons)



e^+

positron track



Standard Model Particles

1974

neutrino ν

electron e^-

up quark u

down quark d

photon γ

gluons g

W^+ W^- Z^0

The Large Hadron Collider