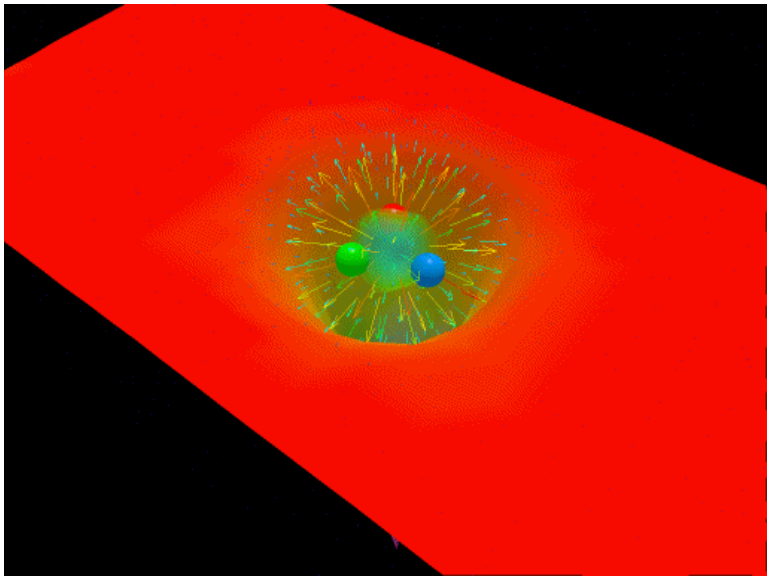
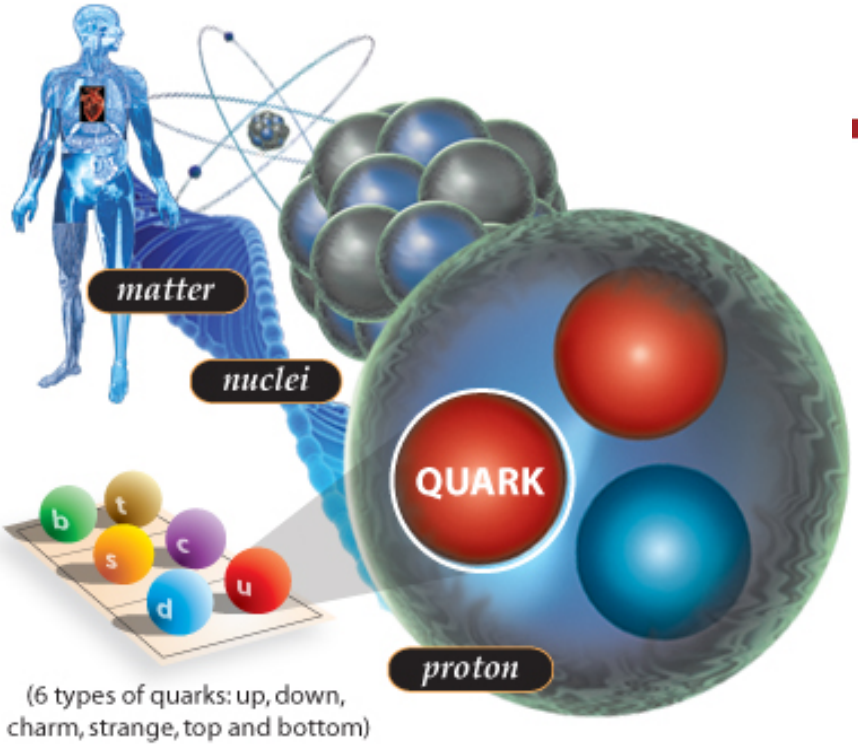


Nuclear Physics

Exploring the Heart of Matter

Mark Dalton
Jefferson Lab, Newport News VA, USA

With slides from Latifa Elouadrhiri, David Lawrence and Alex Barnes



Part I
Introduction to the structure of matter

The Greek Revolution

Atomic theory first originated with Greek philosophers about 2500 years ago. This basic theory remained unchanged until the 19th century when it first became possible to test the theory with more sophisticated experiments.

The atomic theory of matter was first proposed by **Leucippus,** a Greek philosopher who lived at around 400BC. He called the indivisible particles, that matter is made of, atoms (from the Greek word atomos, meaning “indivisible”).

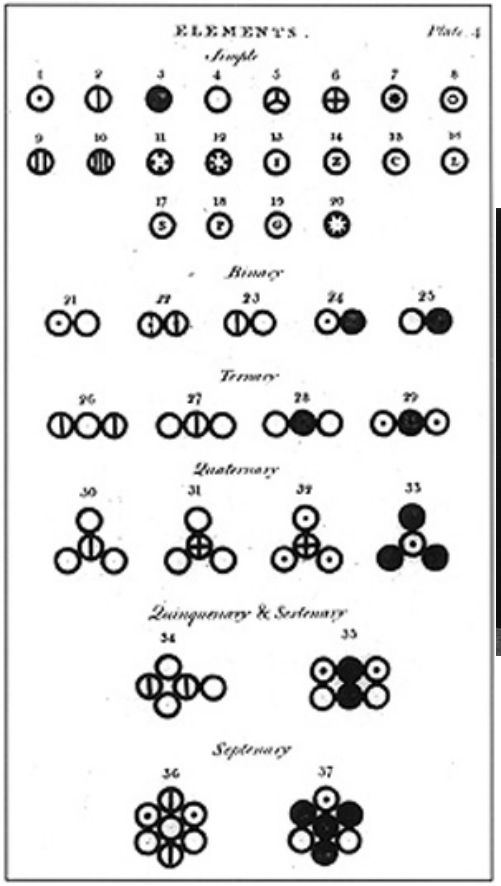
Leucippus's atomic theory was further developed by his disciple, **Democritus.**

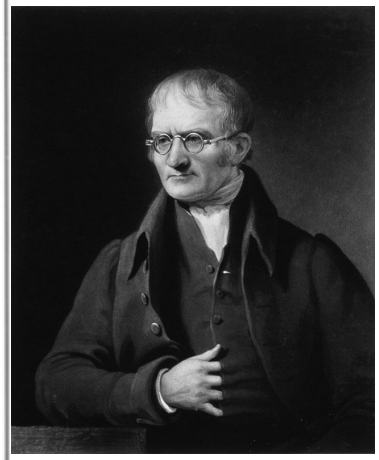
Aristotle and **Plato** favored the ***earth, fire, air*** *and* ***water*** approach to the nature of matter.

The Atom

The birth of atomic theory was revived in the nineteenth century, with the birth of modern science.

In 1803 **J. Dalton** postulated the existence of **the chemical elements (atoms!)** To explain the variety of compounds known



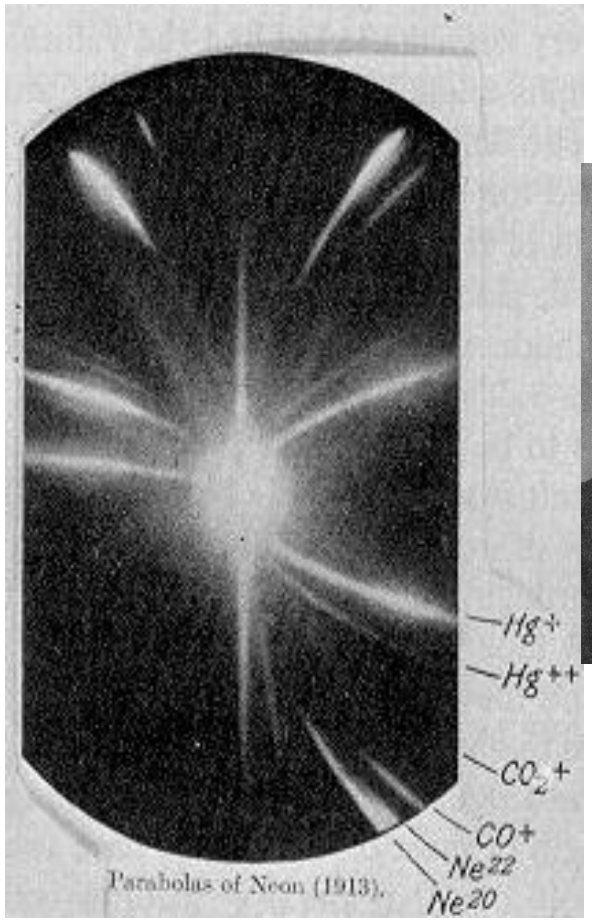


The Atom

Our current knowledge of the structure of the atom is the result of the work of many scientists and their discoveries

In 1803 **J. Dalton** postulated the existence of **the chemical elements (atoms!)** To explain the variety of compounds known

In 1897, **JJ. Thomson**, with his studies on cathode rays and the discovery of the **electron**, destroyed the concept of the atom as an indivisible particle



The Atom

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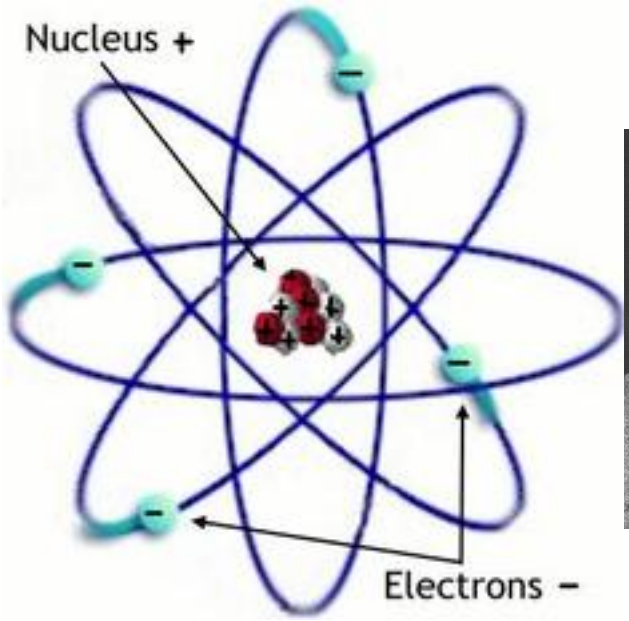
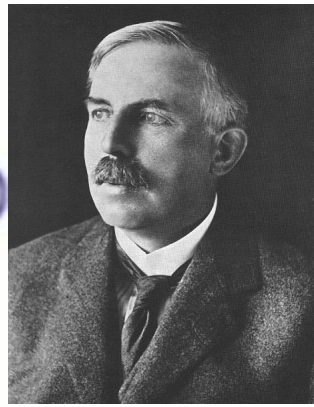
In 1897, **JJ. Thomson**, with his studies on cathode rays and the discovery of the **electron**, destroyed the concept of the atom as an indivisible particle

In 1911, **E. Rutherford's** experiment and the development of **quantum mechanics** led to the **modern atomic models**





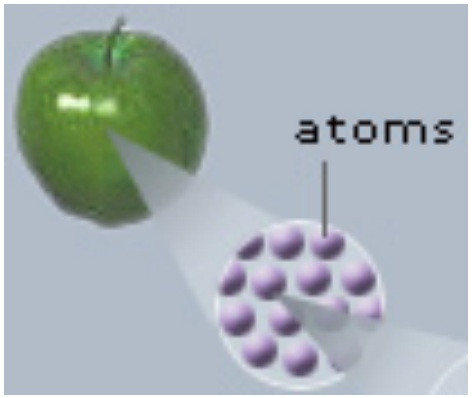
We and all things around us are made of atoms

The Son of Man - René Magritte

Human Hair

~ 50 μm = 50 10^{-6} m

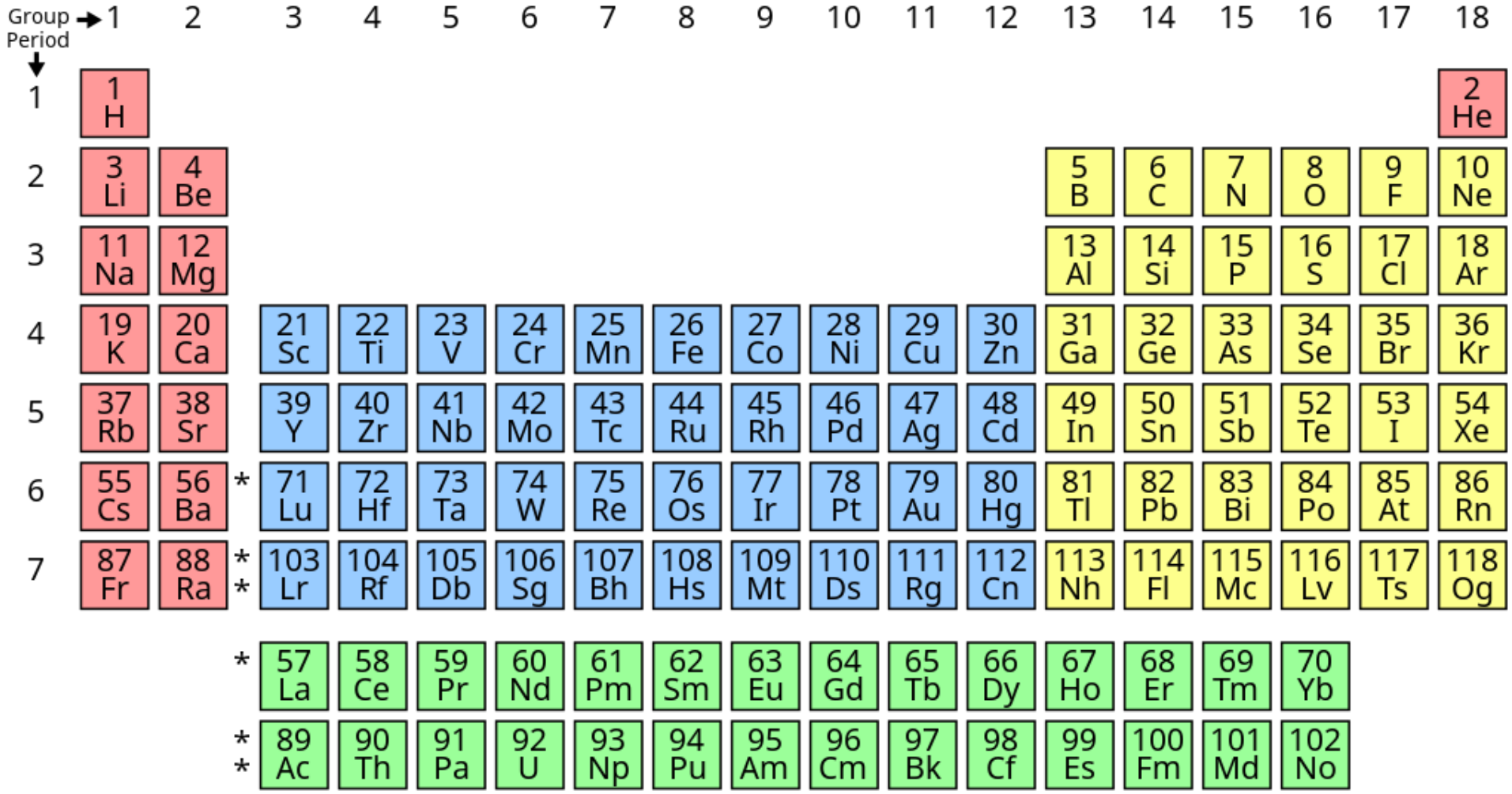
= 0.000050 m



Atom ~ 10^{-10} m

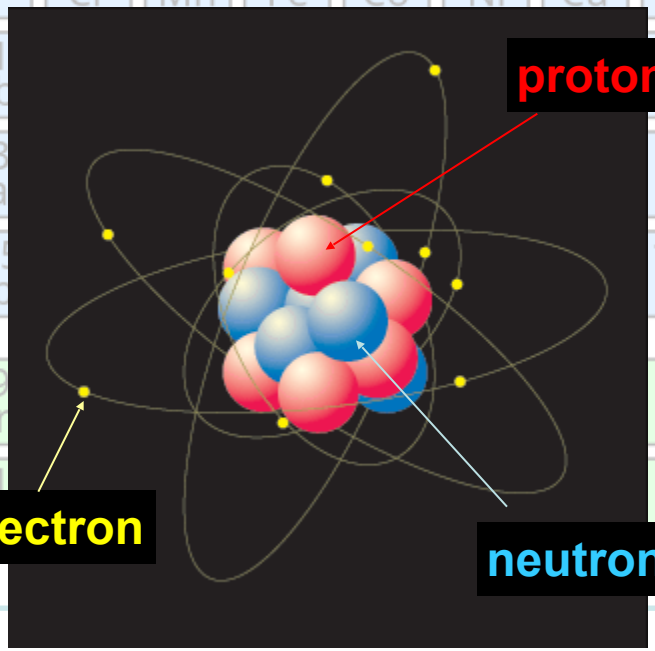
= 0.0000000001 m

Atoms


Group
Period
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
1 H He
2 Li Be B C N O F Ne
3 Na Mg Al Si P S Cl Ar
4 K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Ge As Se Br Kr
5 Rb Sr Y Zr Nb Mo Tc Ru Rh Pd Ag Cd In Sn Sb Te I Xe
6 Cs Ba * Lu Hf Ta W Re Os Ir Pt Au Hg Tl Pb Bi Po At Rn
7 Fr Ra * * Lr Rf Db Sg Bh Hs Mt Ds Rg Cn Nh Fl Mc Lv Ts Og
* La Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb
* * Ac Th Pa U Np Pu Am Cm Bk Cf Es Fm Md No

Atoms

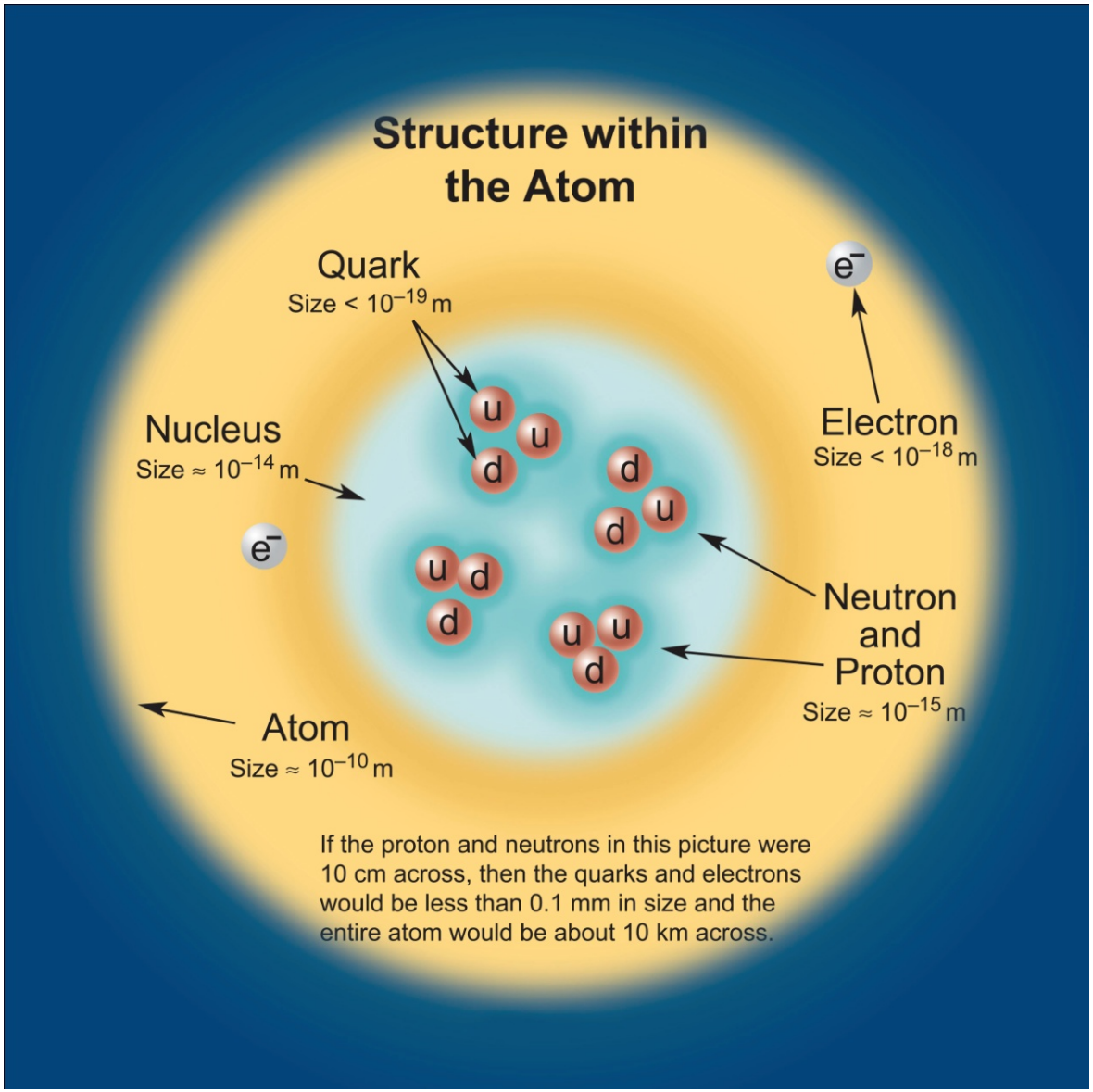
Atoms are all similarly made of:
- protons and neutrons in the nucleus
- electrons orbiting around



The electron was the first elementary particle to be discovered (JJ Thomson 1897)

Protons, neutrons are made up of quarks

From the Atom to the quark



Atoms and sub-atomic particles are much smaller than visible light wave-length
Therefore, we cannot really "see" them (all graphics are artist's impressions)
To learn about the sub-atomic structure we need particle accelerators

Quarks

- Quarks are elementary particles, ie, indivisible, and there are 6 different types, called flavors
- Have electric charge and a new type of call charge **color**(***R***, ***G***, ***B***)

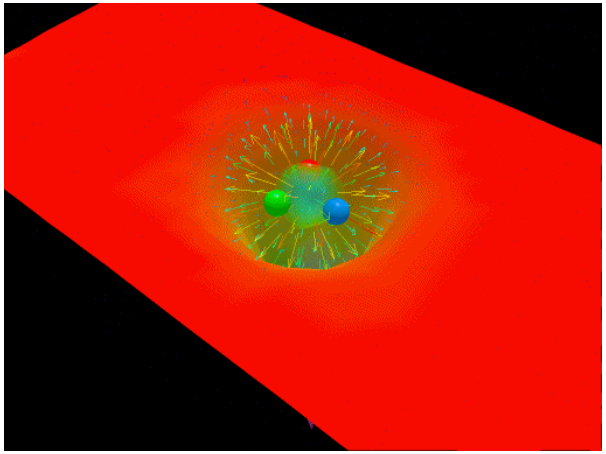
6 flavors:
up, down, strange,
charm, bottom, top

Electric charge
± 1/3, ± 2/3

Charge color(***R***, ***G***, ***B***)

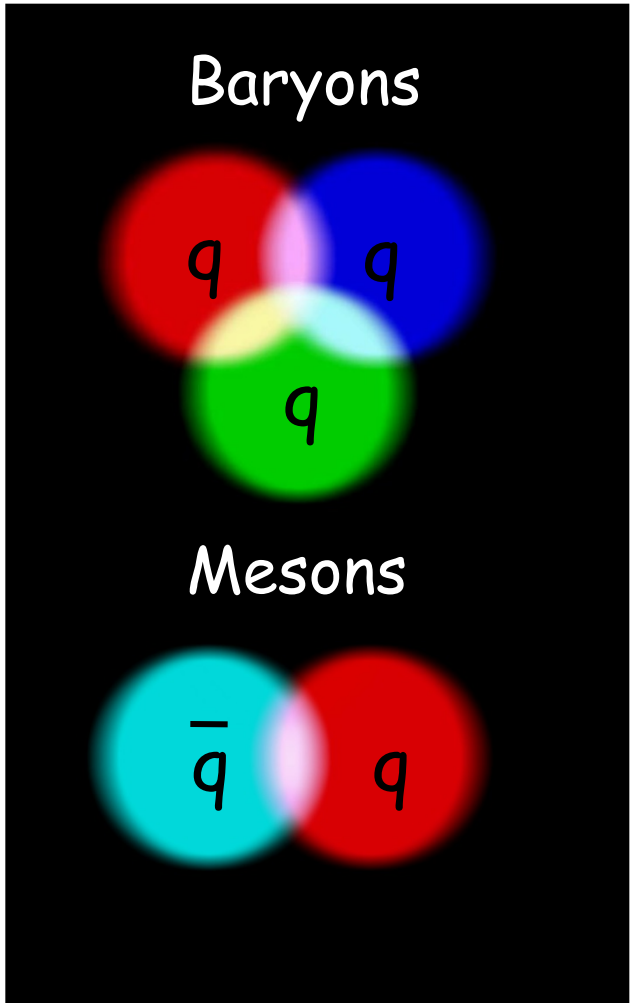
Quarks

- Quarks are elementary particles, ie, indivisible, and there are 6 different types, called flavors
- Have electric charge and a new type of call charge **color**(***R***, ***G***, ***B***)
- The quarks interact via the **strong nuclear force**, which manifests itself through the exchange of force carriers called gluons

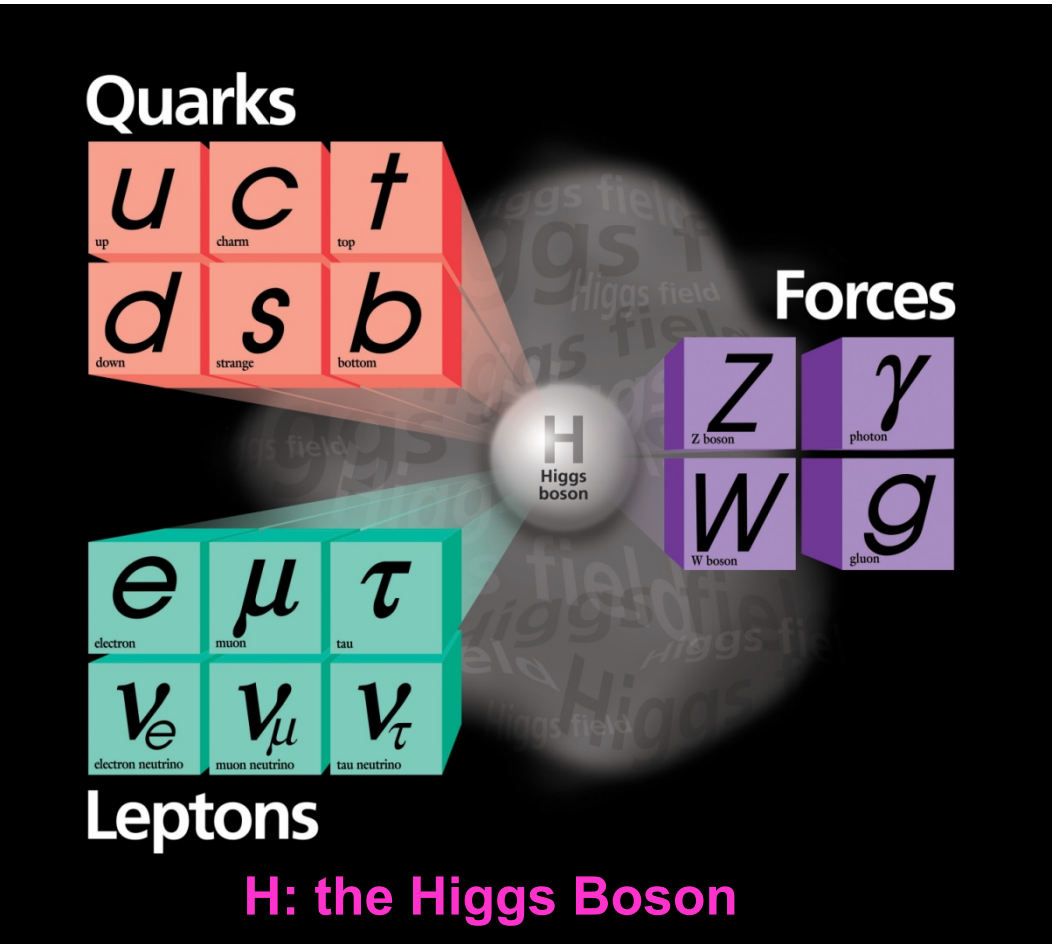


Hadrons

- Quarks are elementary particles, ie, indivisible, and there are 6 different types, called flavors
- Have electric charge and a new type of call charge **color**(***R***, ***G***, ***B***)
- The quarks interact via the **strong nuclear force**, which manifests itself through the exchange of force carriers called gluons
- A Free quark has never been observed. (A property called “confinement” that is still a bit mysterious)
- Quarks combine to form objects colorless "white" object called **hadrons**: **baryons** are known configurations (3q) and **mesons** (qq)



The Standard Model



Framework which includes:

Matter
- 6 quarks
- 6 leptons

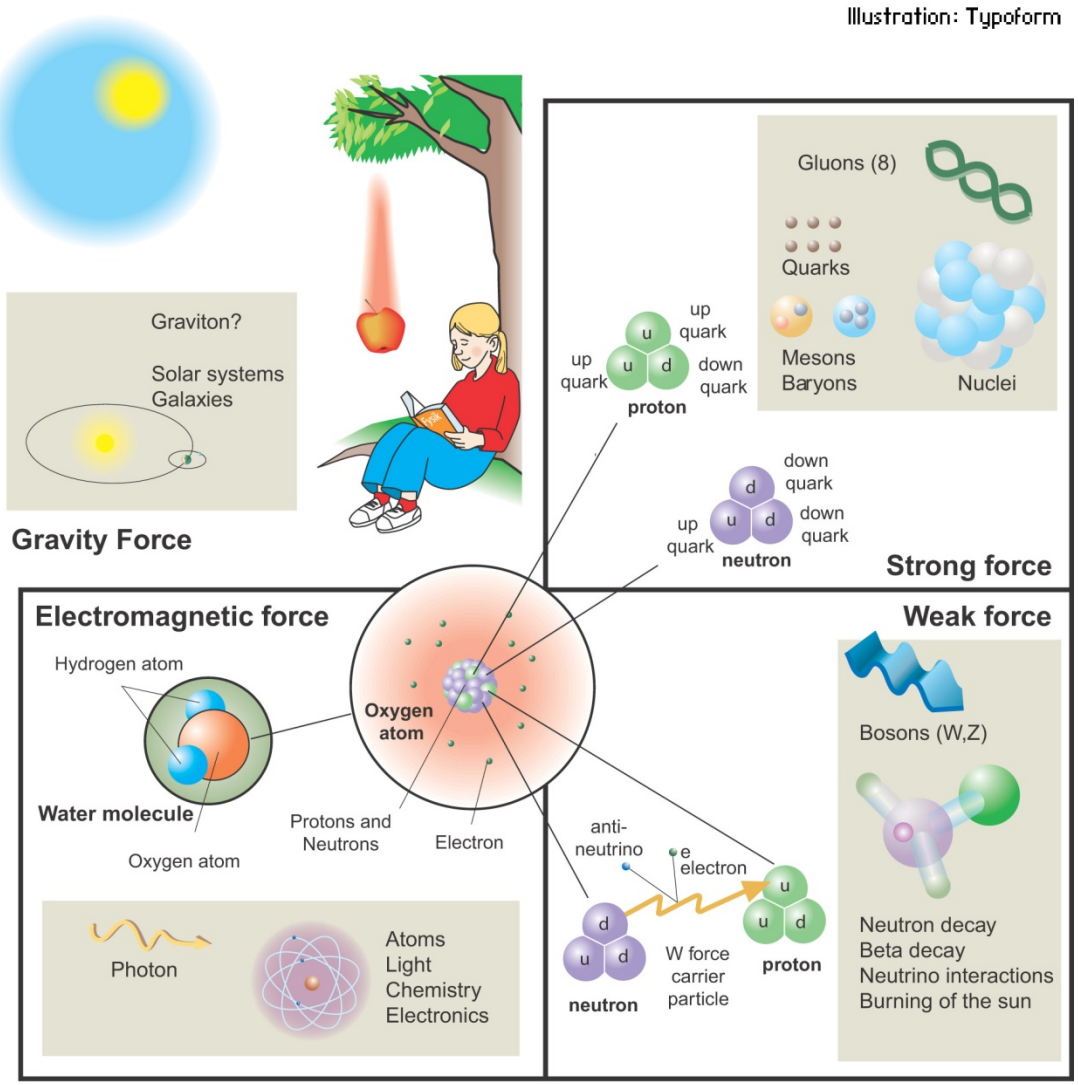
Grouped in three generations

Forces
- Electroweak:
  - γ (photon)
  - Z^0, $W^{\pm}$
- Strong
  - g (gluon)

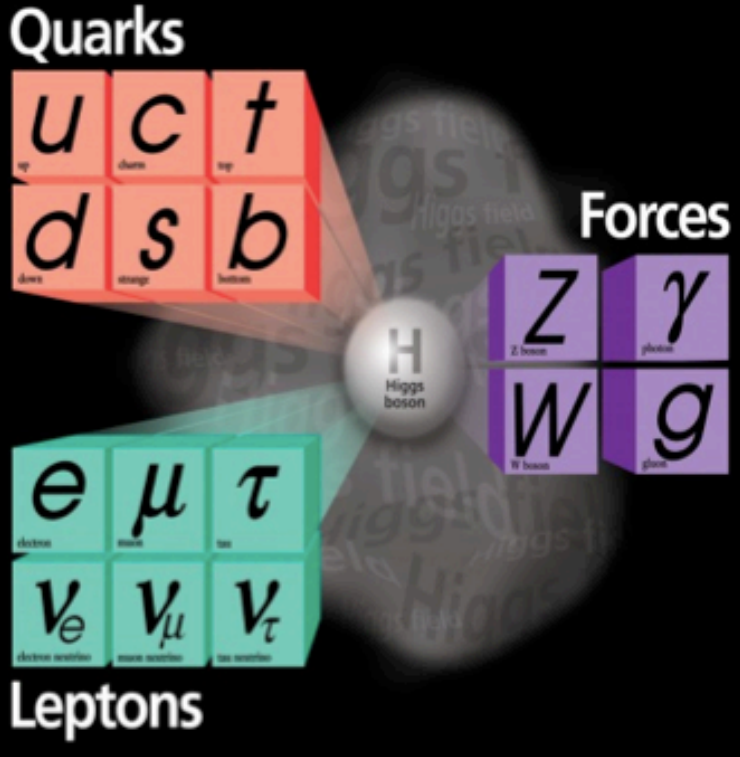
Not gravity! No quantum field theory of gravity yet..

Simple and comprehensive theory that explains hundreds of particles and complex interactions

The Four Fundamental Forces



The Standard Model and our world



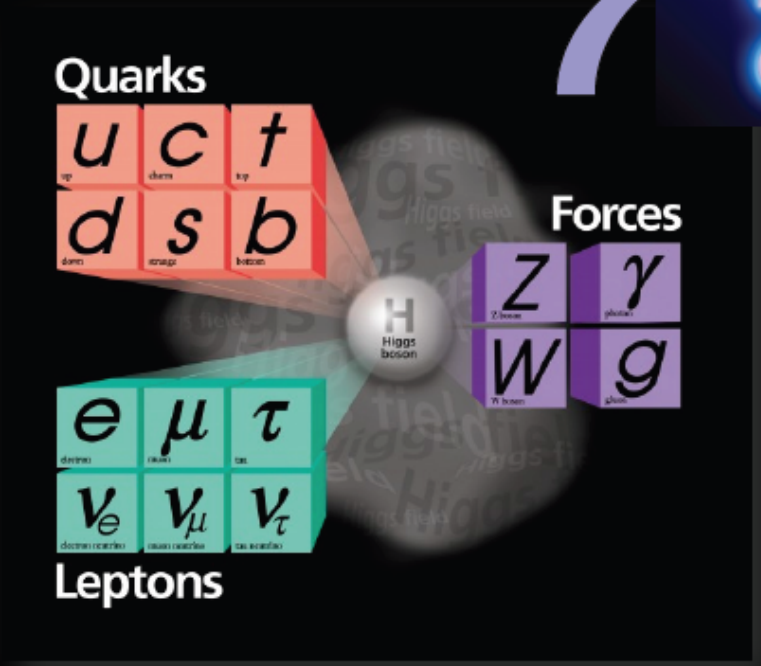
From the D. Gross Nobel Lecture (2004):

"It is sometimes claimed that the origin of mass is the Higgs mechanism that is responsible for the breaking of the electroweak symmetry that unbroken would forbid quark masses.

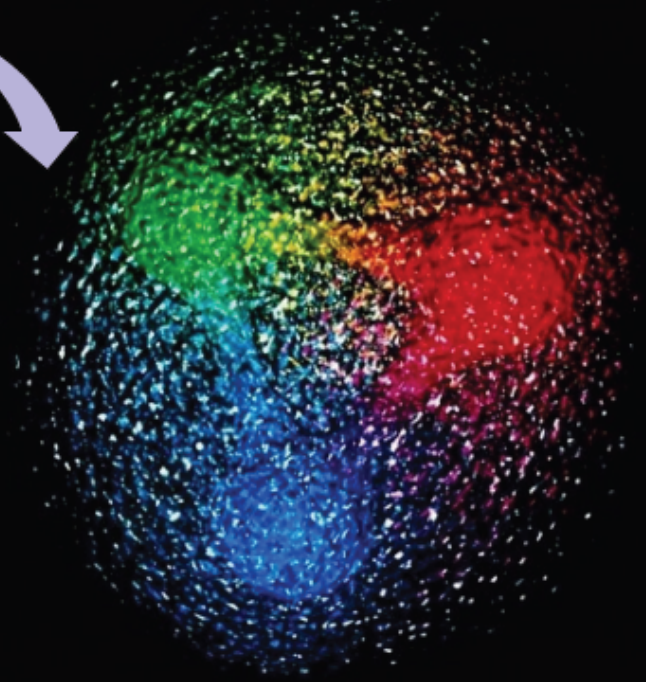
This is incorrect. **Most, 99%, of the proton mass is due to the kinetic and potential energy of the massless gluons and the essentially massless quarks, confined within the proton."**

The Standard Model & the QCD

Elementary Particles



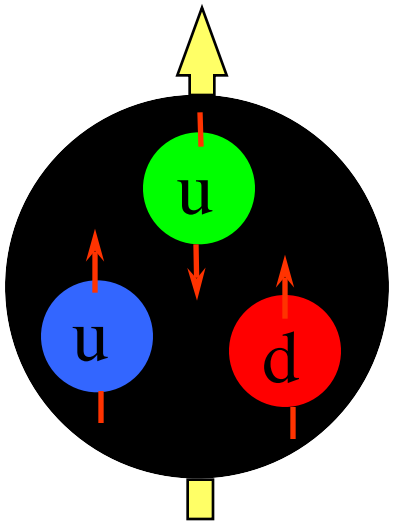
Nucleon



Proton Mass » M(up) + M(up) + M(down)
~ 10 MeV

Proton Spin : Only 25% of the proton spin is carried by the quarks

Constituent Quark model



The proton is built from three quarks of spin s = 1/2
and having masses m_q ~ 300 MeV*

actual u,d quark masses are ~2-5MeV

M. Gell-Mann, 1964
G. Zweig, 1964

- Proton mass: $m_p \approx 3m_q$
- Proton spin: $S = \frac{1}{2} \oplus \frac{1}{2} \oplus \frac{1}{2}$

Solely built from the quark spins!

Tremendously successful model in description of

- Hadron mass spectra

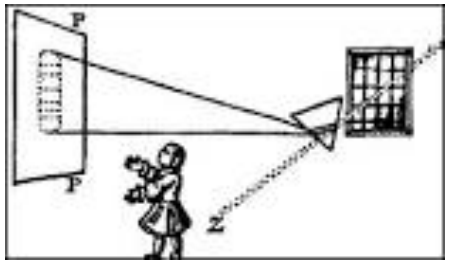
Spectrum of the hydrogen atom

- Much of what we know about the structure of the hydrogen atom we know from the excitation spectrum created by its constituents: proton, electron, and the electromagnetic field generating sharp energy levels.

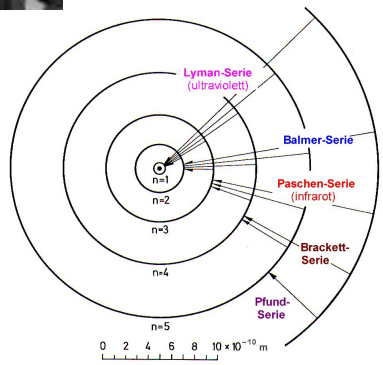
- Much of the structure of the proton is revealed by the excitation spectrum of its constituents.

- The proton constituents are strongly interacting particles (quarks, gluons), giving rise to very broad energy levels that are difficult to isolate.

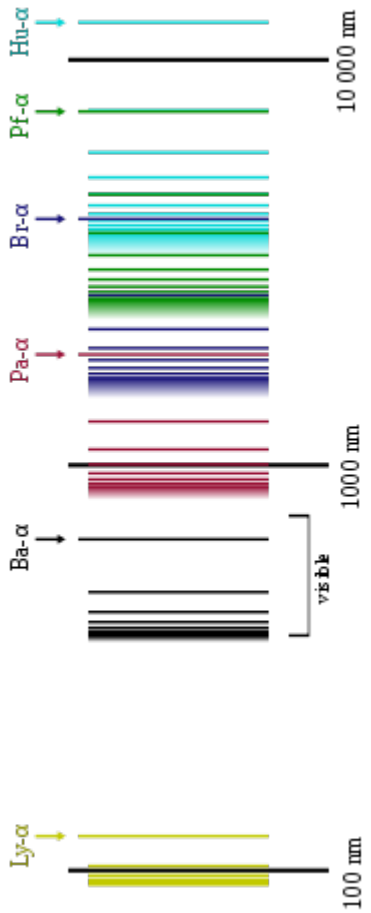
I. Newton, 1666



N. Bohr
1913



Spectral series of hydrogen, today



Nuclear Shell Model

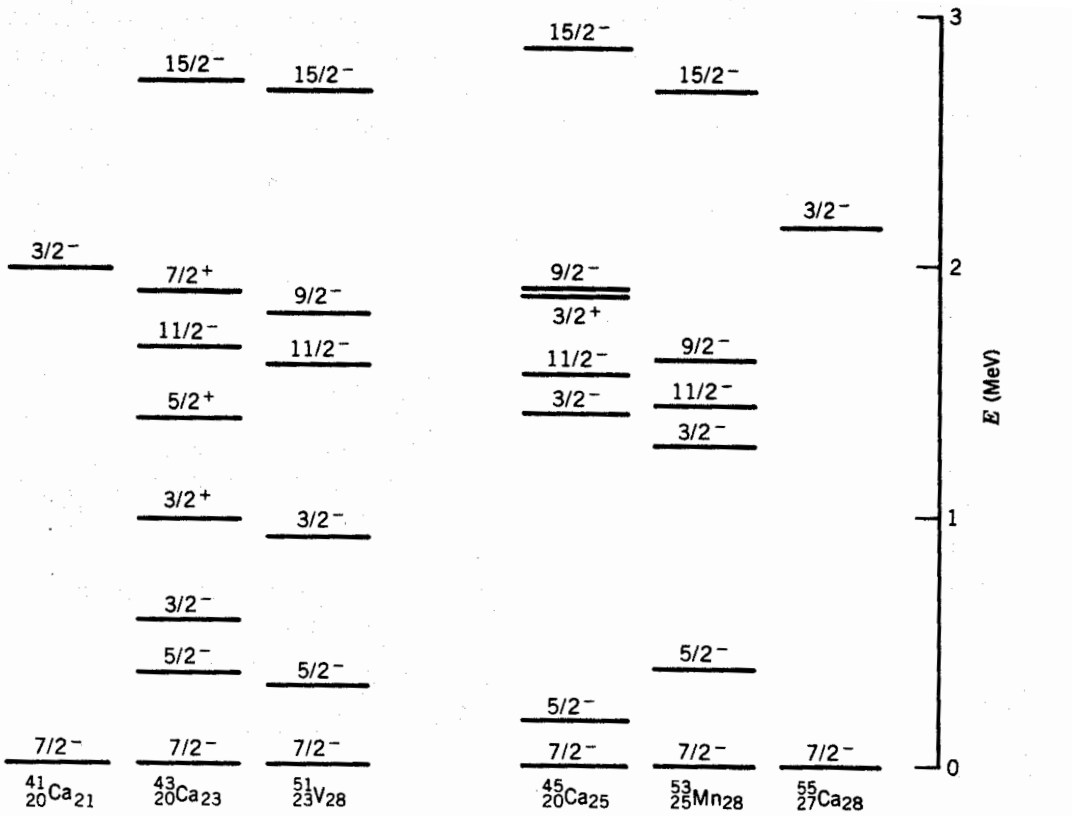
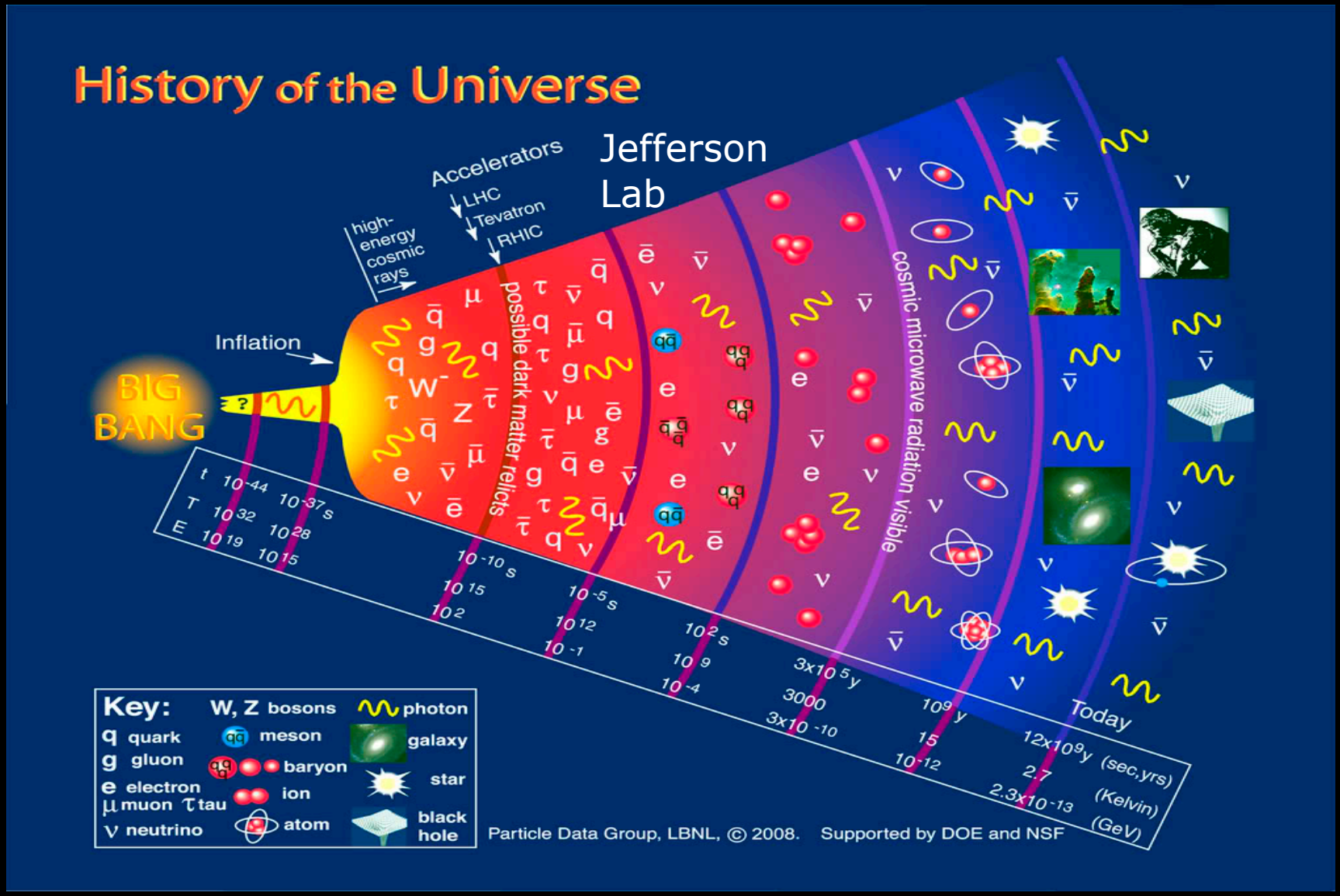


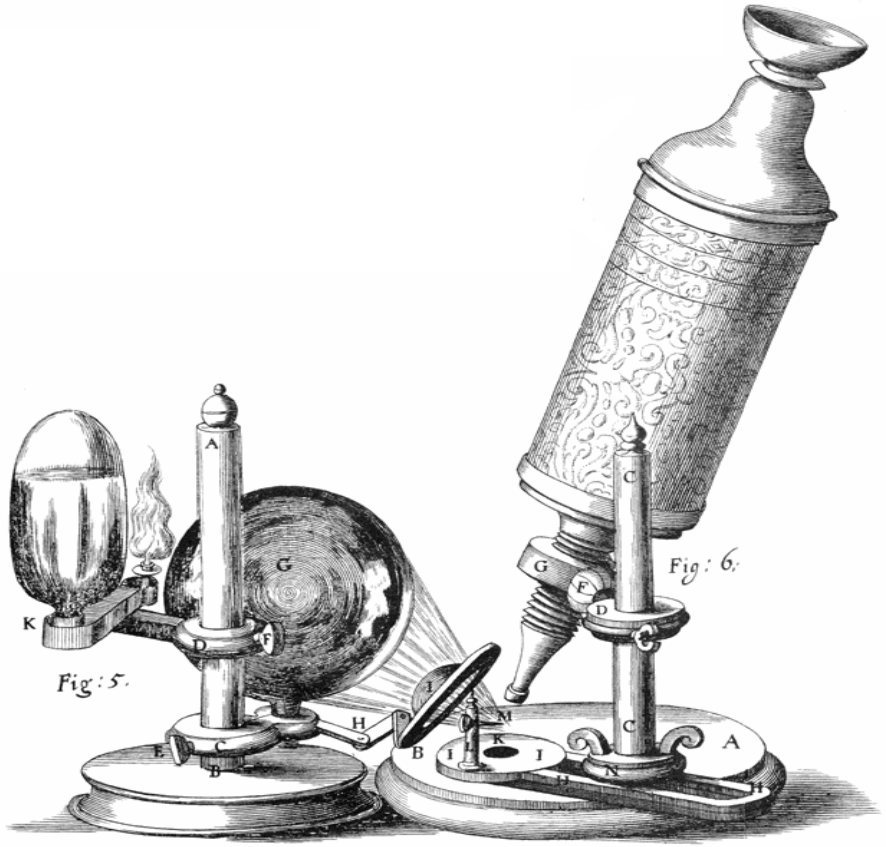
Figure 5.25 Excited states of some nuclei with valence particles in the $f_{7/2}$ shell. All known levels below about 2 MeV are shown, and in addition the $\frac{15}{2}^-$ state is included.

From "Introductory Nuclear Physics", Kenneth S. Krane, 1988 Wiley Publishing

The Nuclear Shell model can describe excitation energies of nuclei where the protons and neutrons act in a similar role as the electrons in the Atomic Shell model.

This pattern of excitation energies is determined by the physical forces binding the nucleons in the nucleus.

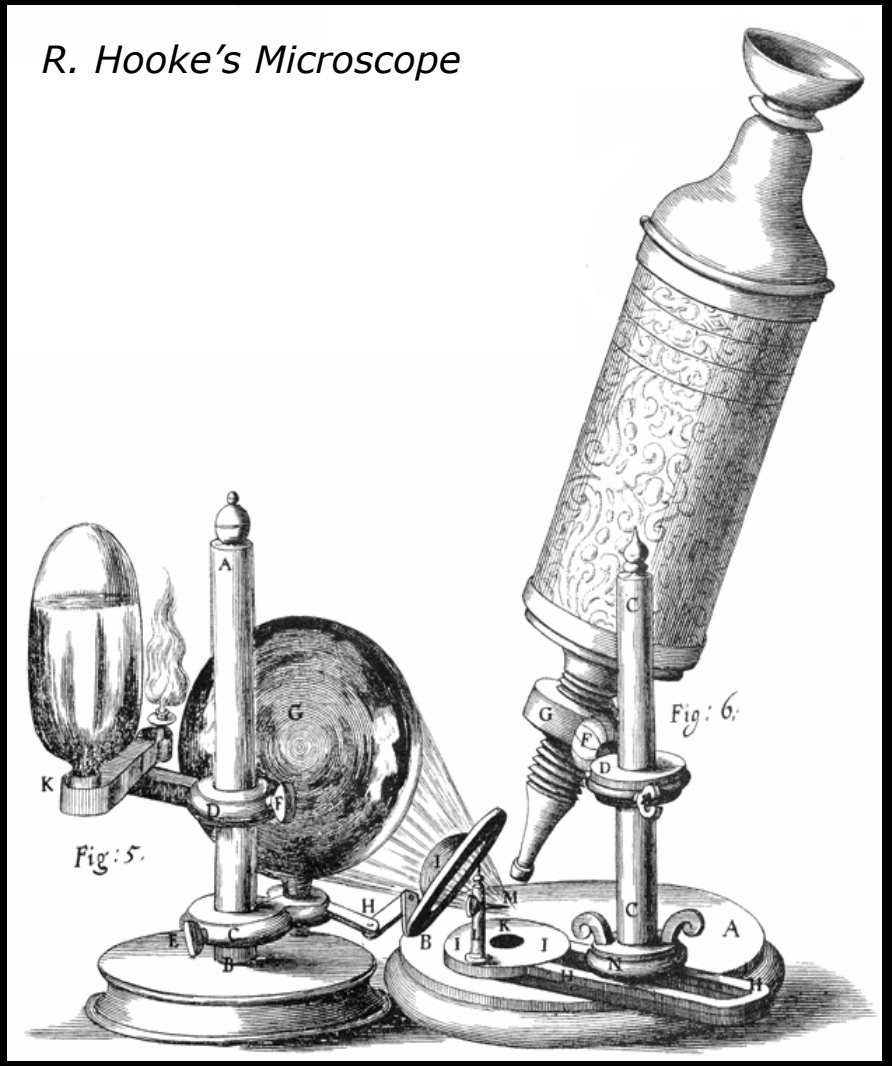

History of the Universe
Jefferson Lab
Accelerators
LHC
Tevatron
RHIC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
Today
Key:
W, Z bosons
photon
q quark
meson
galaxy
g gluon
baryon
star
e electron
ion
μ muon τ tau
atom
black hole
ν neutrino
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF
(sec,yrs)
(Kelvin)
(GeV)



Part –II
Particle Scattering Microscope on the world of quarks

The Microscope

In the past, scientists tried to study microscopic objects invisible to the human eye, using magnifying glasses first and then ever more sophisticated tools



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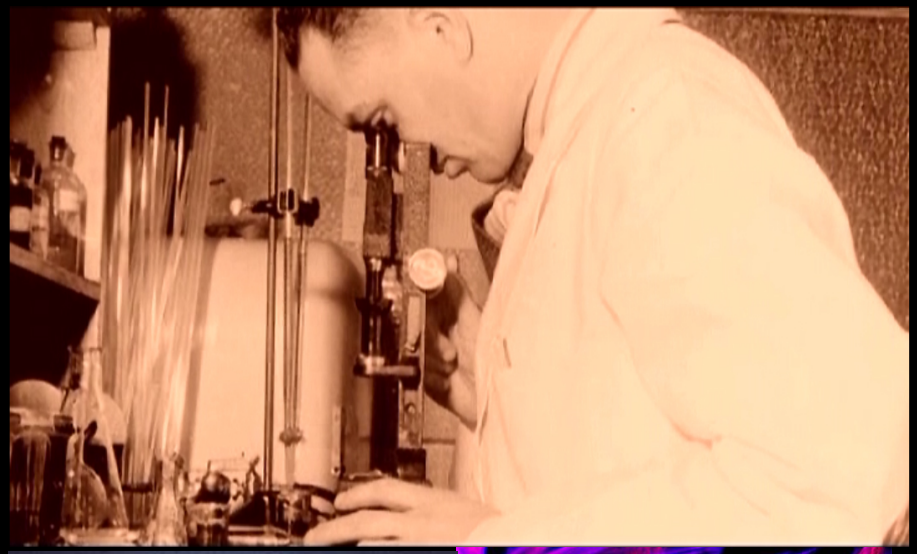
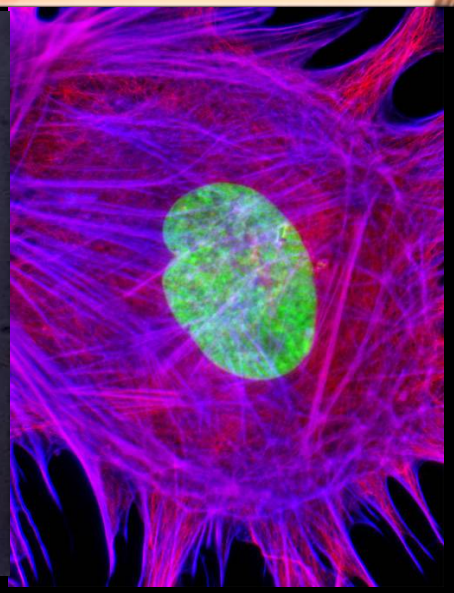
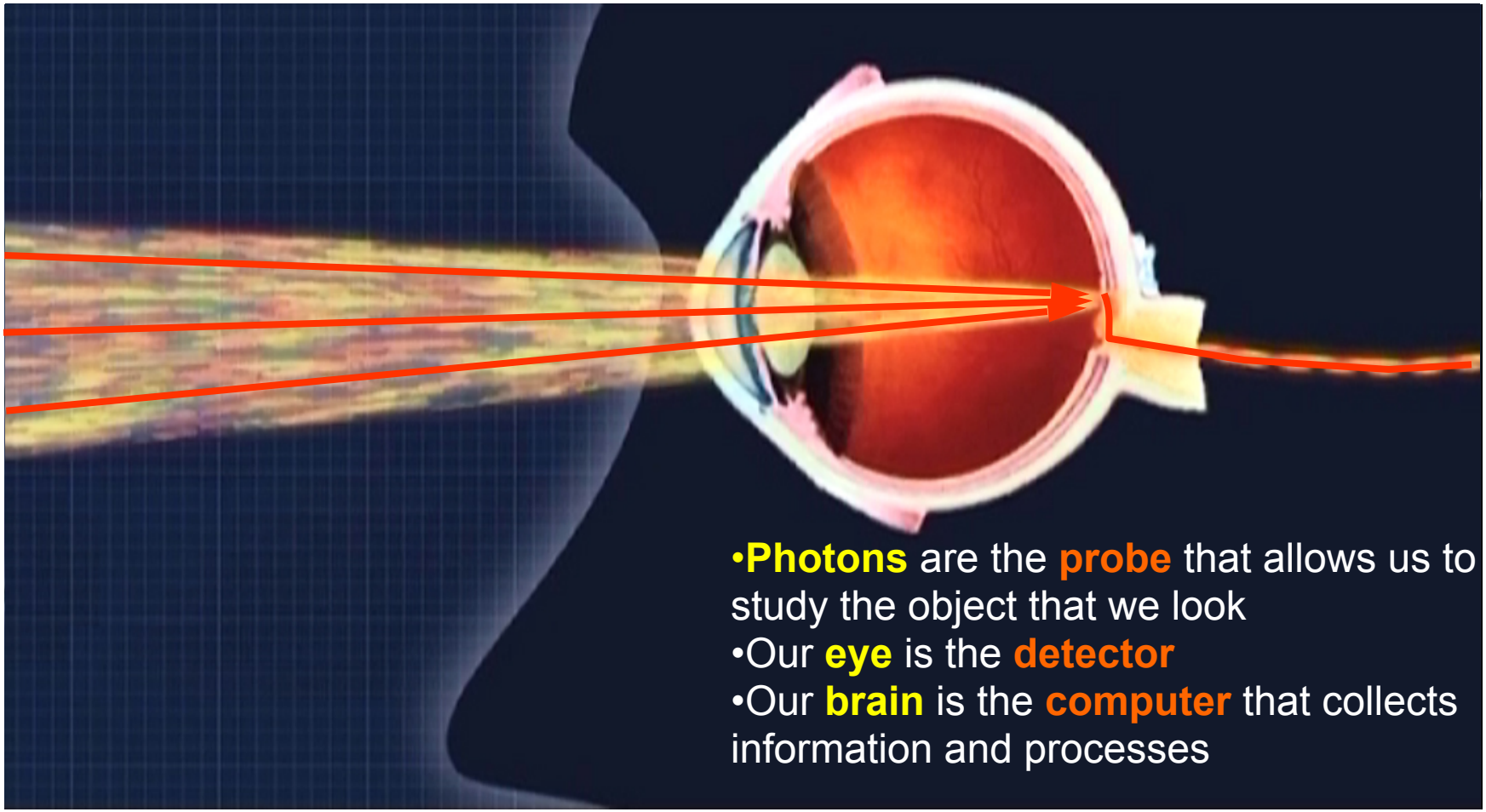


The optical microscope allowed the discovery of the existence of microscopic organisms and to study the organic fabric

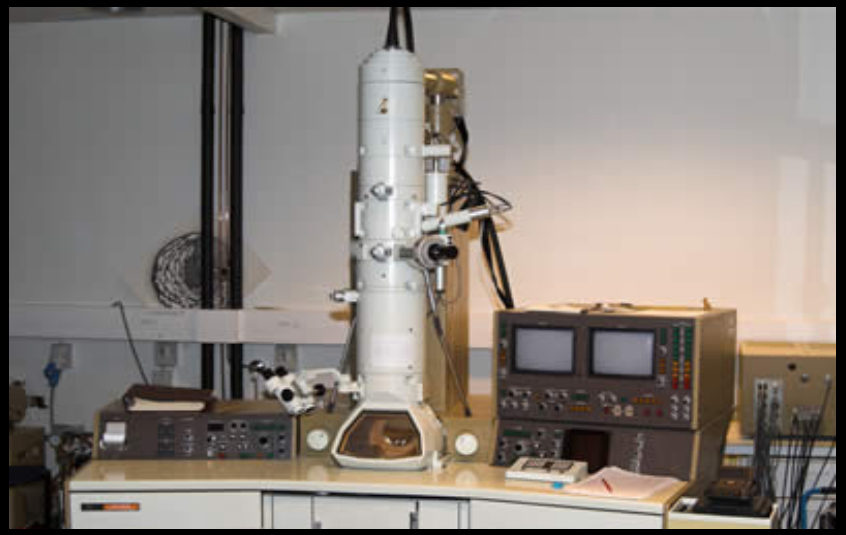


The Microscope

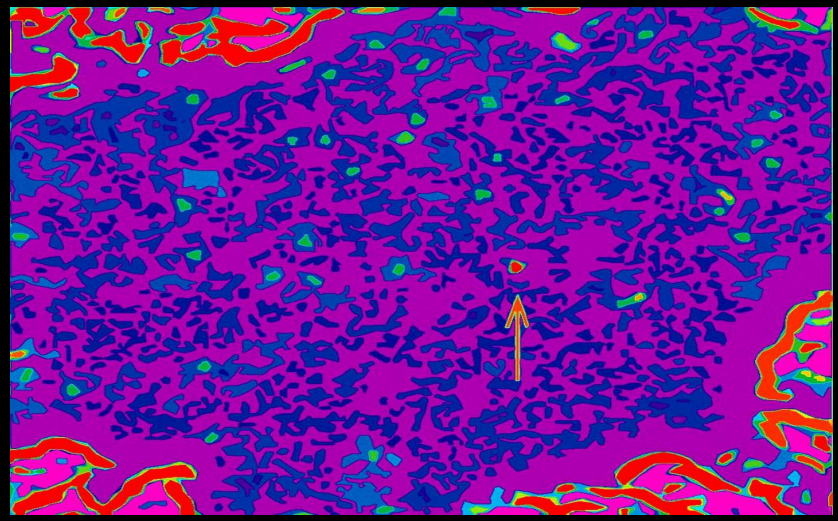


The Microscope

Today, more sophisticated microscopes achieved a very high resolution



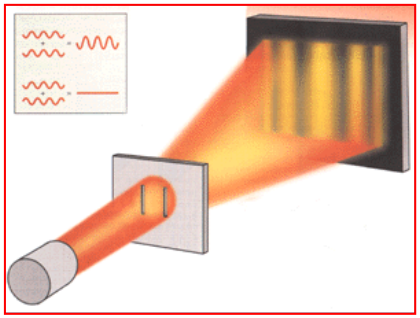
the electron microscope allows you to see objects the size of the atom

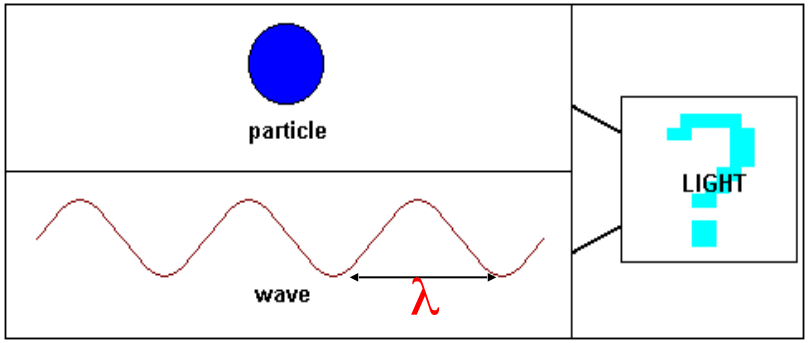


But how can we get to "see" quarks?

Wave-particle duality of Nature

Central concept of quantum mechanics:
all particles present wave-like properties





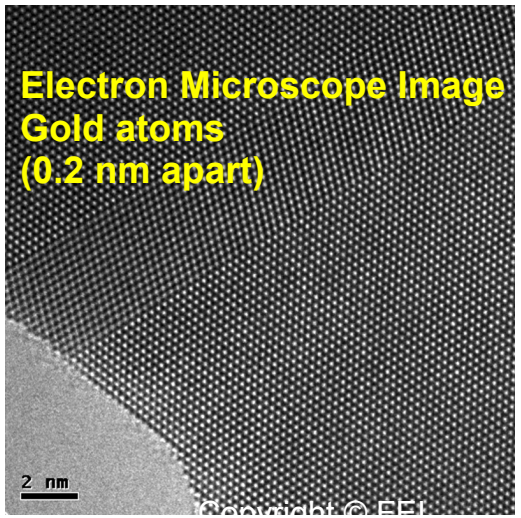
Not only light has a dual nature

De Broglie showed that moving particles have an equivalent wavelength λ

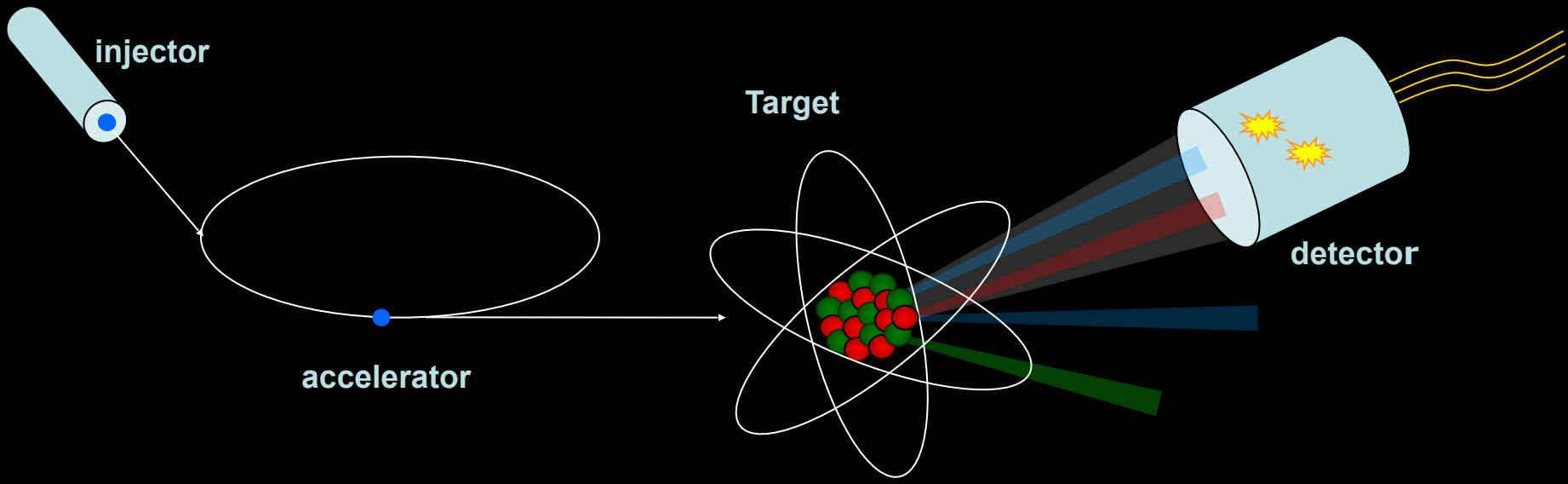
$$\lambda \propto \frac{1}{p}$$

So high momentum gives us short wavelengths so we can make out small details

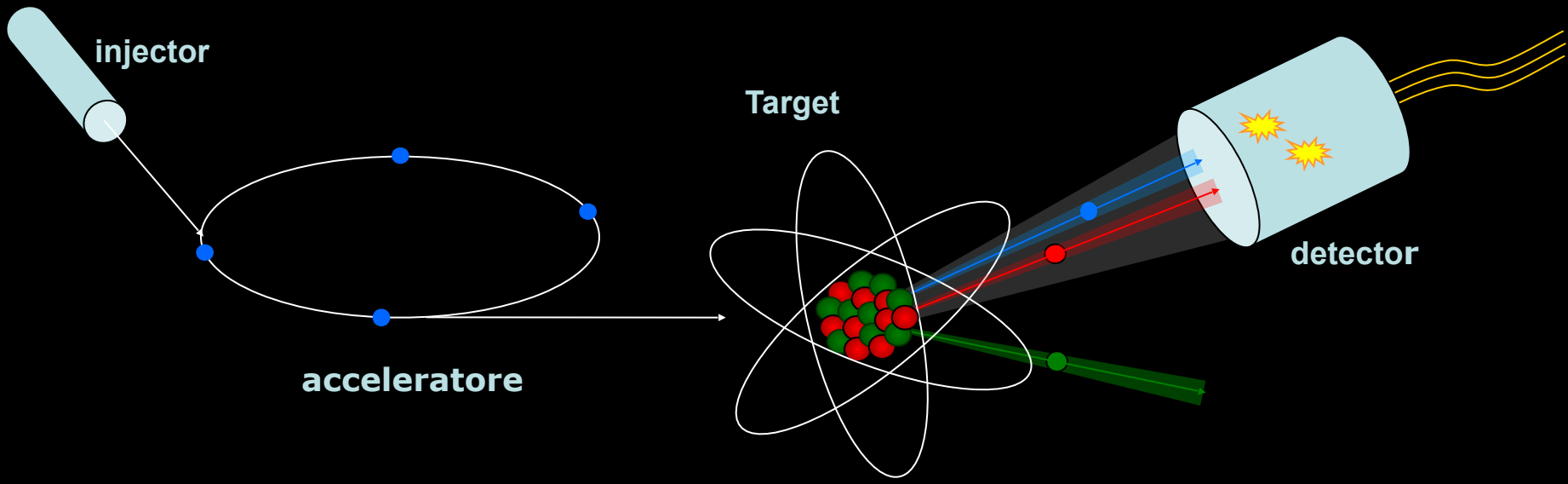
Example: electron microscope



Electron Scattering

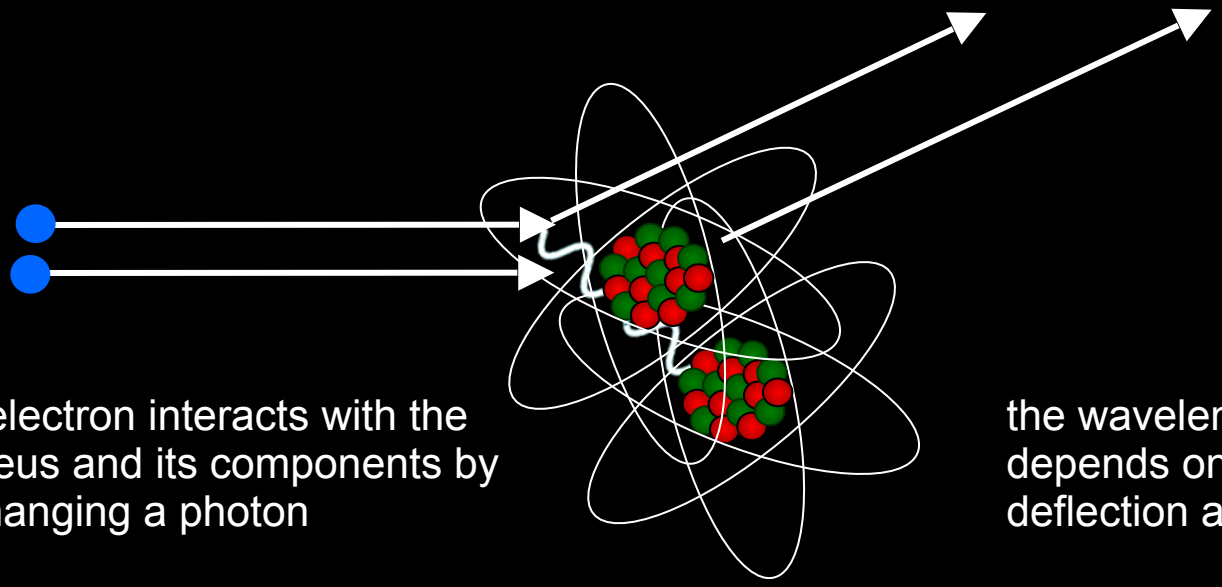


Electron Scattering



but what happens when an electron interacts with the nucleus and with the protons and neutrons inside?

Electron Scattering

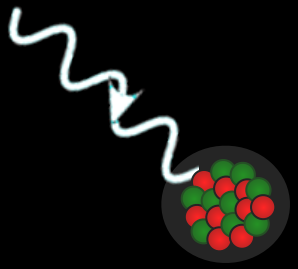


the electron interacts with the nucleus and its components by exchanging a photon

the wavelength of the photon depends on the energy and the deflection angle of the electron

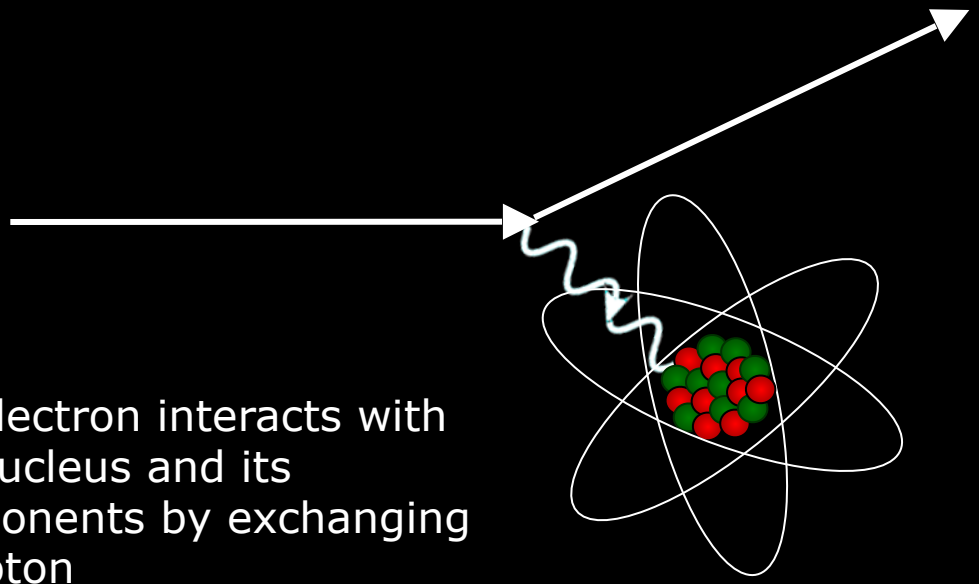
At wavelengths comparable to the size of the nucleus

$\lambda >> 10^{-15}$ m



the photon interacts with the entire core and it is not possible to distinguish its components

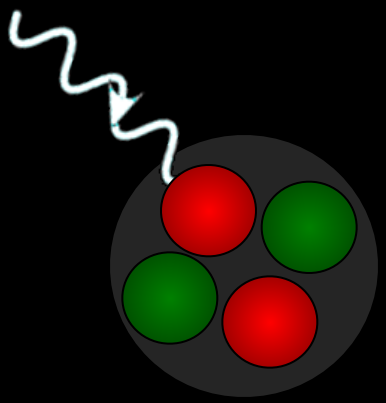
Electron Scattering



the electron interacts with the nucleus and its components by exchanging a photon

the wavelength of the photon depends on the energy and the angle of the electron

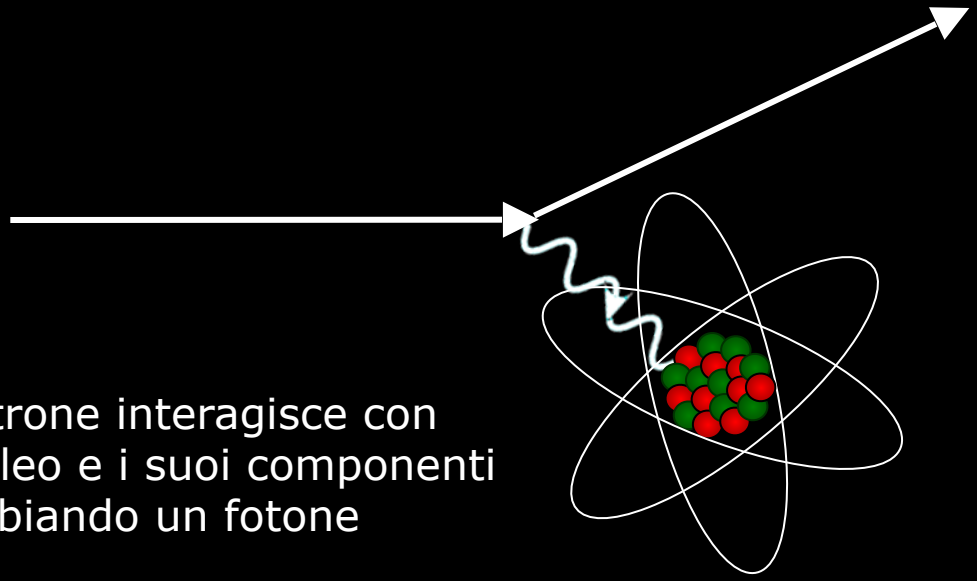
At intermediate wavelength the order of the size of the nucleon



the photon interacts with the individual protons and neutrons that make up the nucleus

$\lambda \sim 10^{-15}$ m

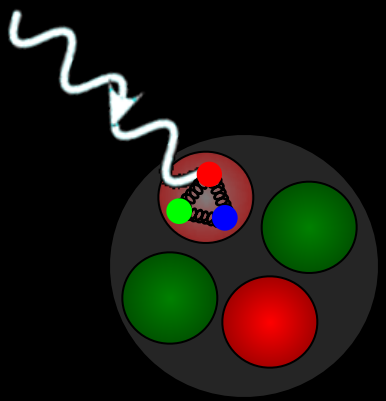
Electron Scattering



l'elettrone interagisce con
il nucleo e i suoi componenti
scambiando un fotone

the wavelength of the photon
depends on the energy and the angle
the electron

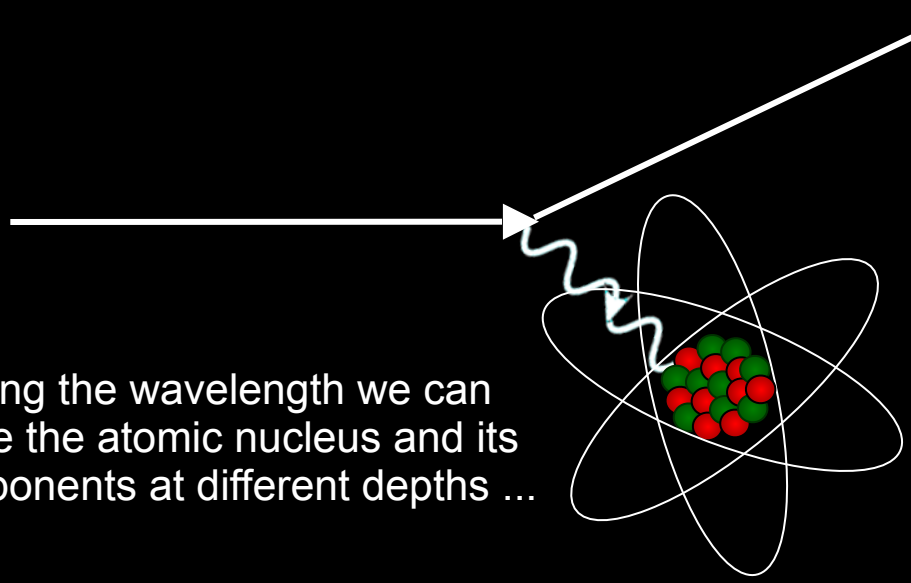
At short wavelength, smaller
than the size of the proton



the photon interacts with the
constituents of the individual
nucleons, ie quarks and gluons

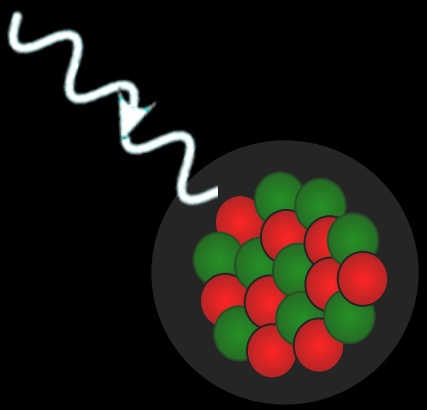
$\lambda << 10^{-15}$ m

Electron Scattering

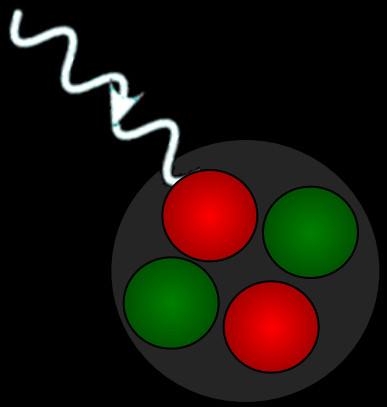


Varying the wavelength we can probe the atomic nucleus and its components at different depths ...

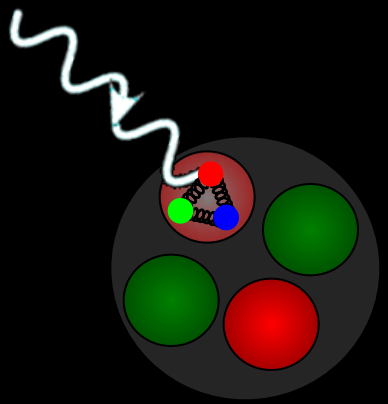
And ... study how quarks and gluons form nucleons and nuclei



$\lambda >> 10^{-15}$ m



$\lambda \sim 10^{-15}$ m



$\lambda << 10^{-15}$ m

Aerial photon taken April 6, 2012

Electron beam accelerator

- continuous-wave (1497MHz, 2ns bunch structure in halls)
- Polarized electron beam
- Upgraded to 12GeV (from 6GeV)
- 70 μA max @ 12Gev (200μA max @ 6GeV)

Aerial p
taken Apr

Hall-D (

Electron beam
- continuou
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  structure in
- Polarized (
  beam
- Upgraded
  (from 6GeV
- 70 μA ma
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