Saturday Morning Physics -- Texas A&M University

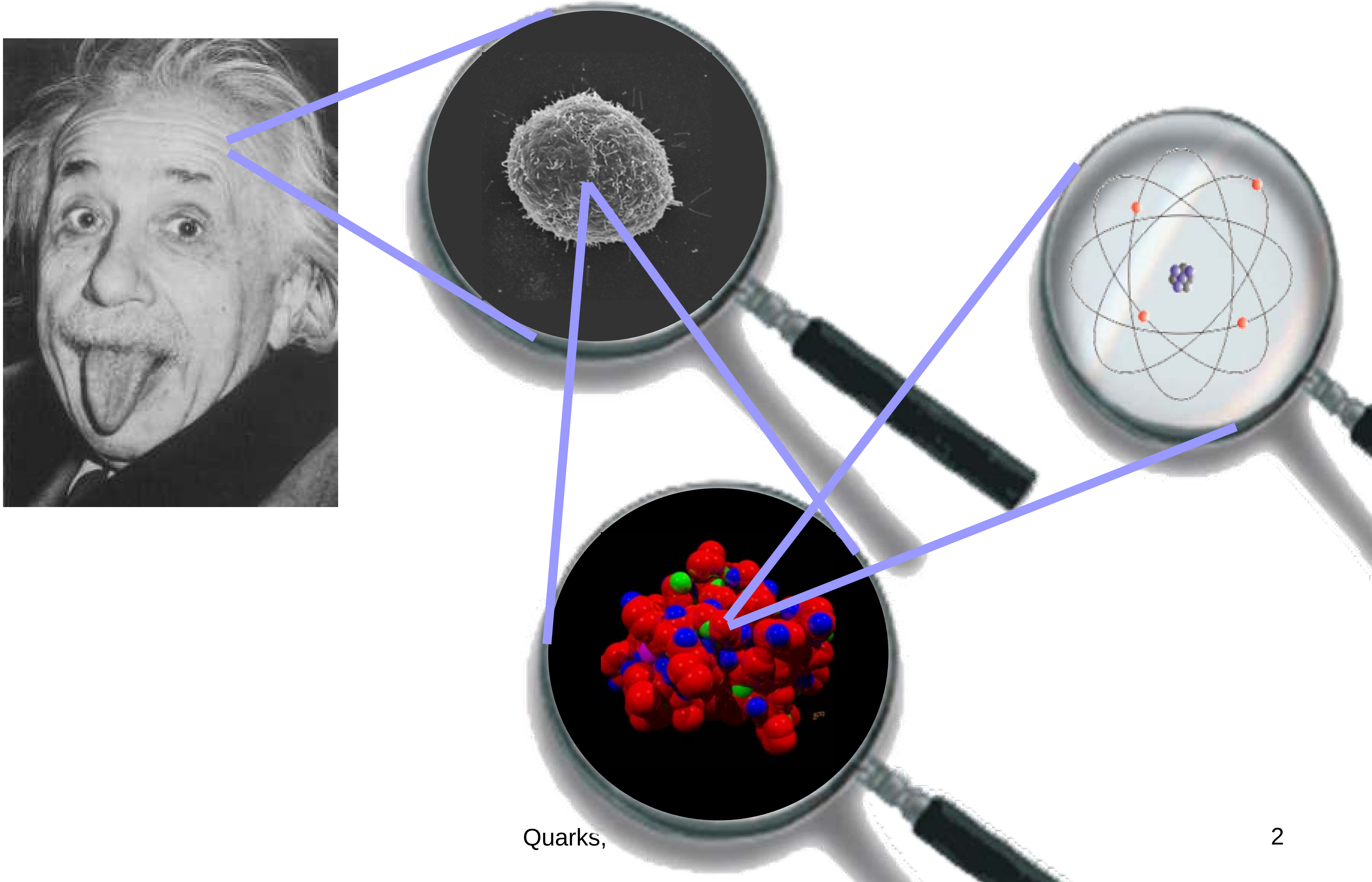
Quarks, Gluons, and Co.

Meet the Quirky Inhabitants of the Proton

Dr. Rainer J. Fries

February 21, 2009

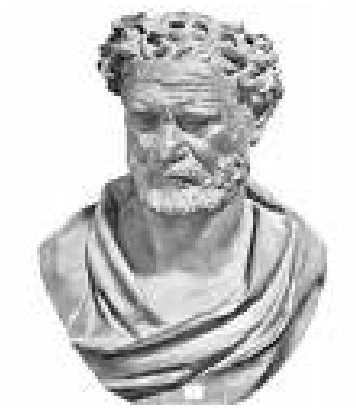
Zooming in on the World around us



Atoms

19th century chemistry confirms:
there are only 92 different 'elements', from hydrogen H to uranium U.

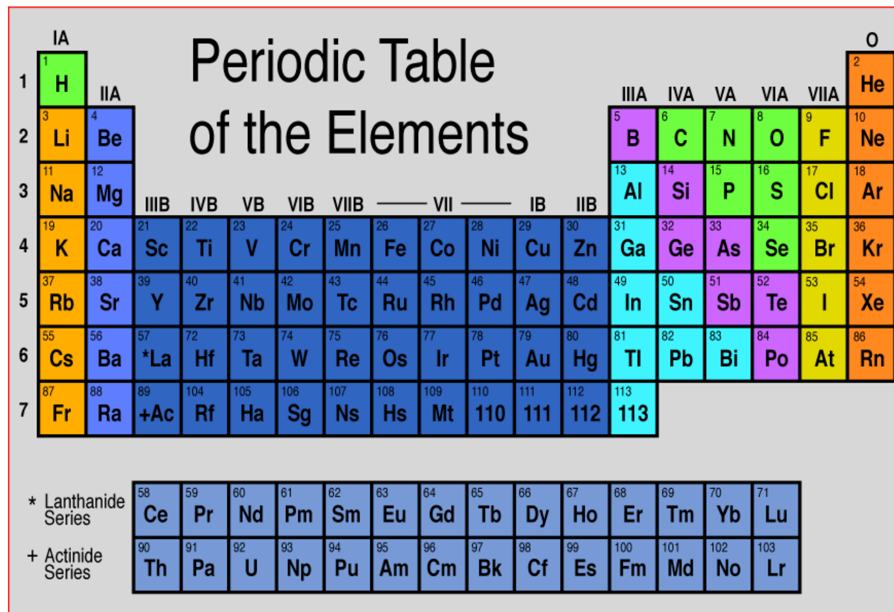
Everything around us is built from combinations of these elements.



Democritus, Greek philosopher ~ 400 B.C:

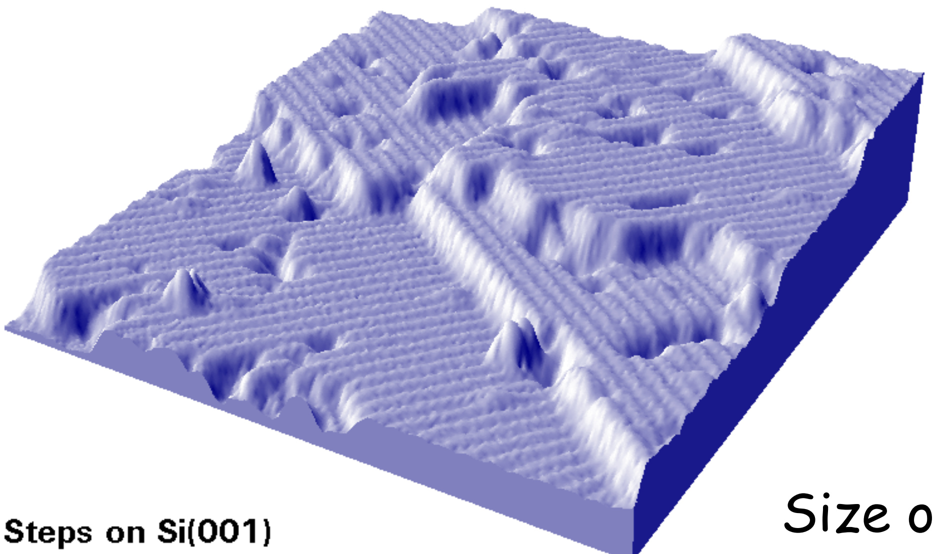
"All matter is made up of very small indivisible elements"

He called them 'atomos'.

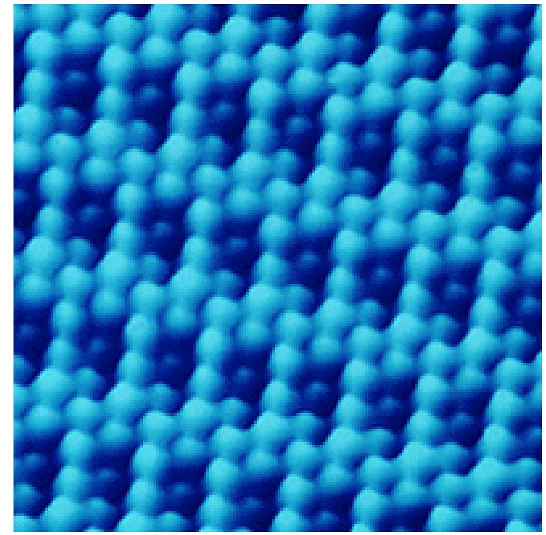


Atoms

Today: we can make atoms visible



Steps on Si(001)
B. S. Swartzentruber
Sandia National Lab



U of Oregon Chemistry

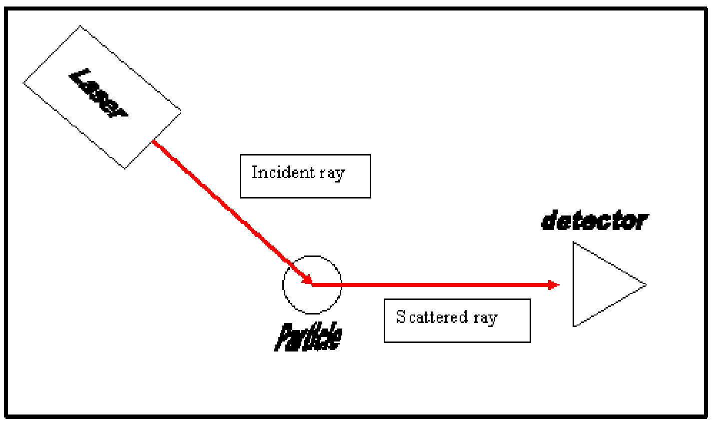
Size of the smallest atom (hydrogen):

0.000 000 000 1 m (meter)
= 10^{-10} m = 1 Angstrom

How is it possible to see such tiny structures?

Scattering Experiments

Our vision: the eye collects light reflected from objects and our brain processes the information

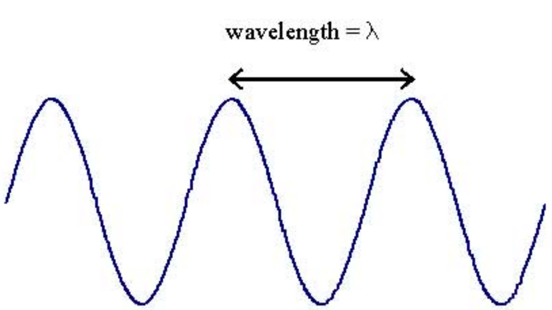


Light: wavelength 4000 - 7000 Angstrom, too large to see an atom.
Better: X-rays, electrons

Use this principle:
Shoot a ray of light or particles at an object.
Measure the scattered rays with a detector.

Resolution of the probe (light, particle) is important:

The wavelength must be smaller than the size of the structure to probe.



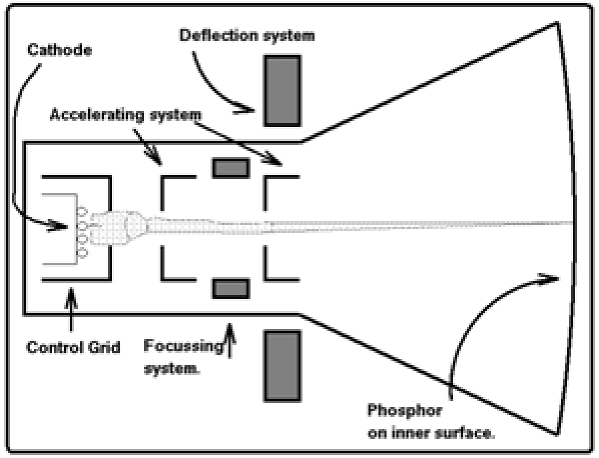
Electrons

What is electric current?

In wires there seems to be a flow of very small quantities of negative electric charge carried by tiny particles.

They are called electrons e^-.

In fact these 'quanta' can be extracted from metals by heating them up → cathode rays.



Basic properties of electrons, measured around 1900:

Electric charge is –e. e = 1.6×10^{-19} C is called the fundamental charge.

Mass = 1/2000 u = 511 keV. 1 u is the mass of the hydrogen atom.

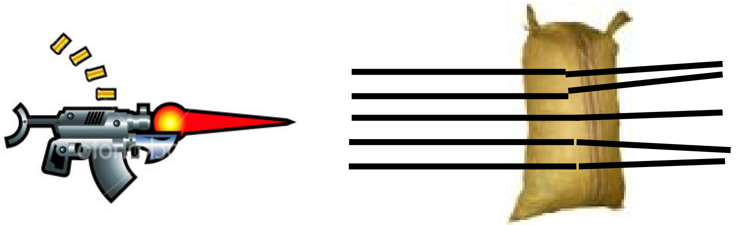
J. J. Thomson (1897): Electrons are small parts of atoms.
The first 'subatomic' particle was discovered.

Taking a Look inside an Atom

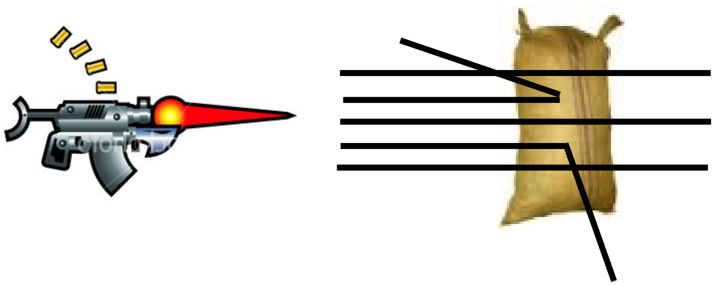
Atoms are neutral. If they contain electrons there must be an equal amount of positive charge. How does an atom look on the inside?

Compare the following two "scattering experiments":

Professional scientist, closed lab, do not attempt!

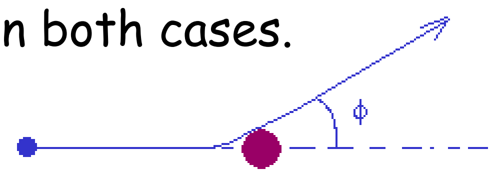


1) Shooting at a bag of beans



2) Bag of equal weight but stuffed with cotton and a few small lead beads

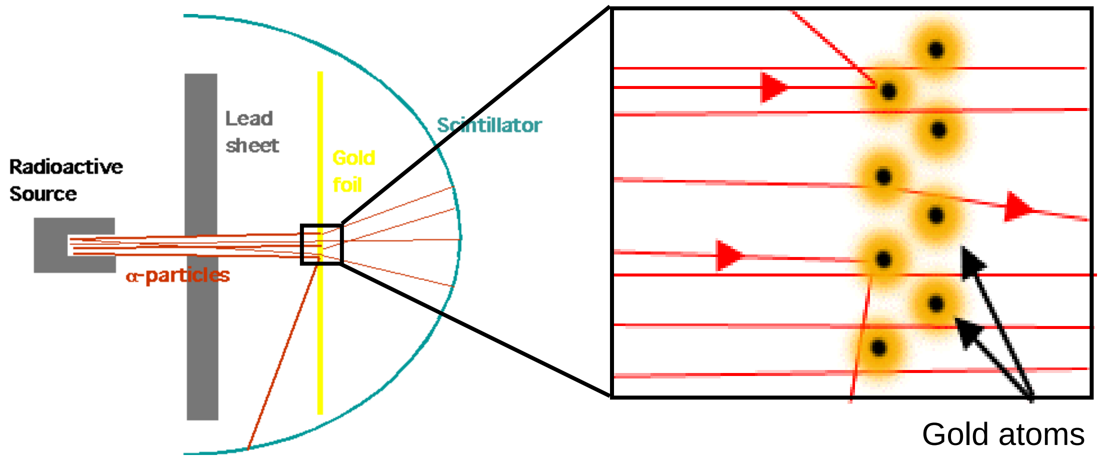
Obviously the possible scattering angles of the bullets are different in both cases.



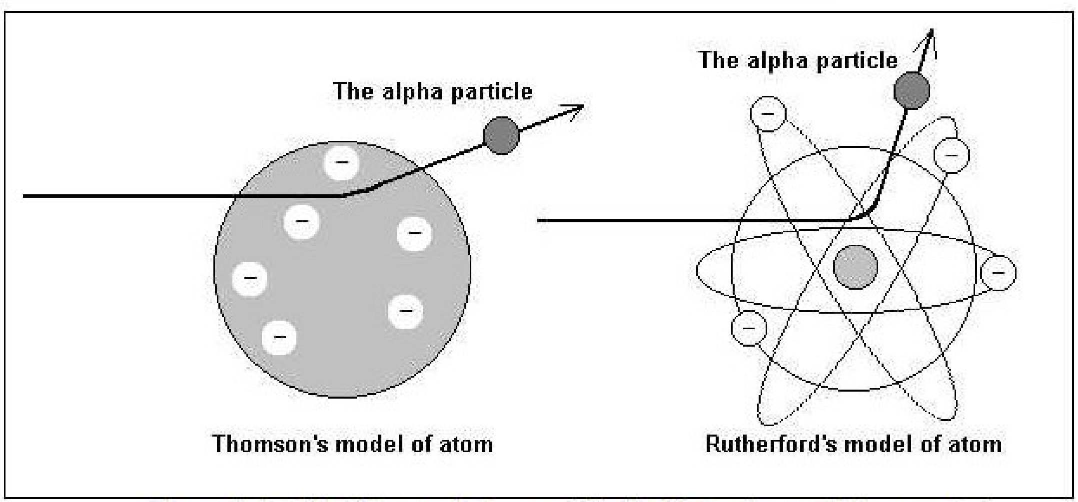
1) Only small angles possible.
2) Some bullets are scattered at large angles.

Taking a Look inside an Atom

In 1911 E. Rutherford did this famous experiment with α-particles instead of bullets. His target were gold atoms.



Rutherford's result was similar to the second scenario!



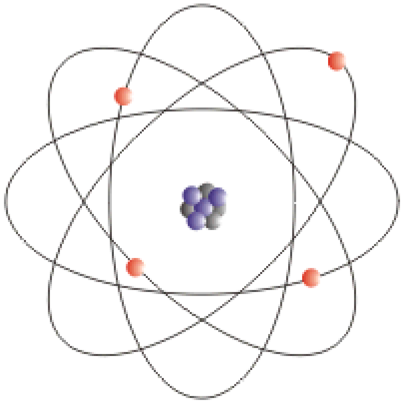
The models of the Thomson's atom and Rurtherford's atom; and the expected aberrations of alpha particle in both cases.

The positive charge in an atom and most of its mass is concentrated in a tiny, very dense center, the nucleus.

Co.

The Nucleus

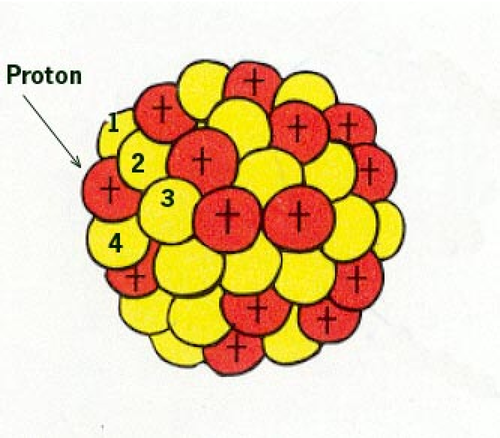
More than 99% of the mass of an atom is in the nucleus, which is more than 10,000 times smaller than the atom, about 1 – 10 fm (Fermi).
1 fm = 10^{-5} Angstrom = 10^{-15} m.



A cloud of electrons orbits the nucleus, held in place by the mutual attraction of the electric charges.

Most of the atom is just empty space!
But with a strong electromagnetic field present.

Nuclei are made up of two particles:
Protons p: positive charge +e, mass ≈ 1u
Neutrons n: neutral, roughly the same mass as p



Protons and neutrons are kept together by a new force: the *strong force.*

Particles

We distinguish particles by their …

participation in strong interactions
YES: they are called *hadrons*
e.g. proton, neutron
NO: they are called *leptons*
e.g. electron

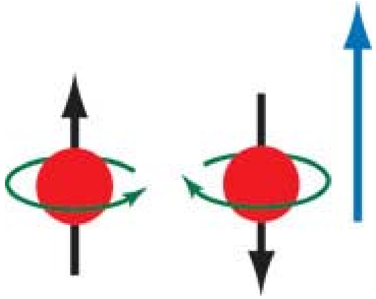
electric charge
positive or negative
usually in multiples of e

mass
usually measured in electronvolts (eV)
1 u ≈ 0.939 GeV (Gigaelectronvolts, Giga = Billion)

spin
= Quantized angular momentum
(can take values $0\hbar$, $\frac{1}{2}\hbar$, $1\hbar$, $3/2\hbar$, $2\hbar$, etc)
Electrons, protons, neutrons: spin $\frac{1}{2}\hbar$

Particles with integer spin are called *bosons*.

Particles with half-integer spin are called *fermions*.



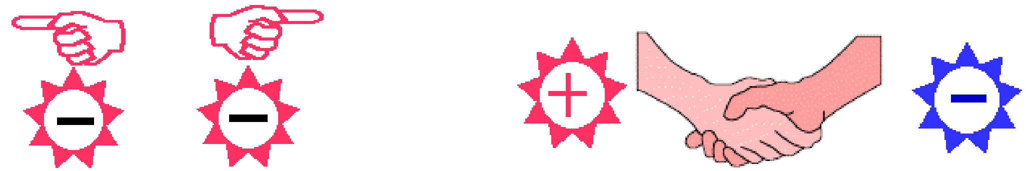
Electrons, protons and neutrons are fermions.

Electromagnetism

Electric phenomena:

Two kind of charges:
plus and minus

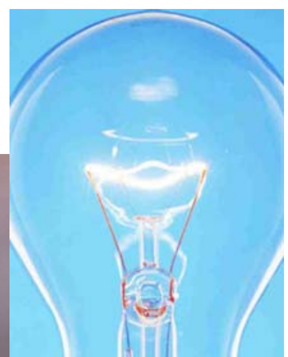
The forces between them lead to electric currents.

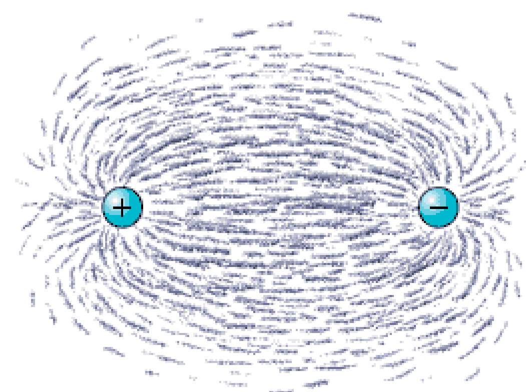


Equal charges repel each other
Opposite charges attract each other

Electric force acts over a distance even in empty space:

→ Electric field

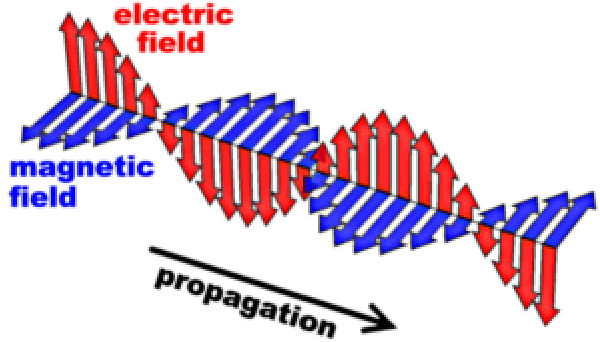


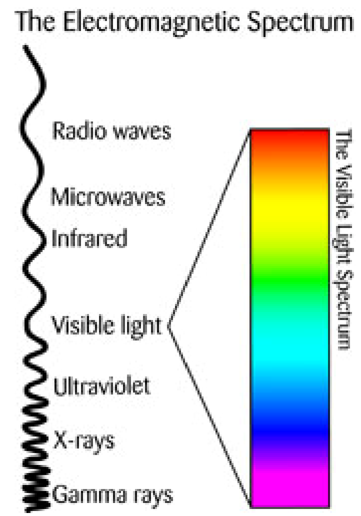


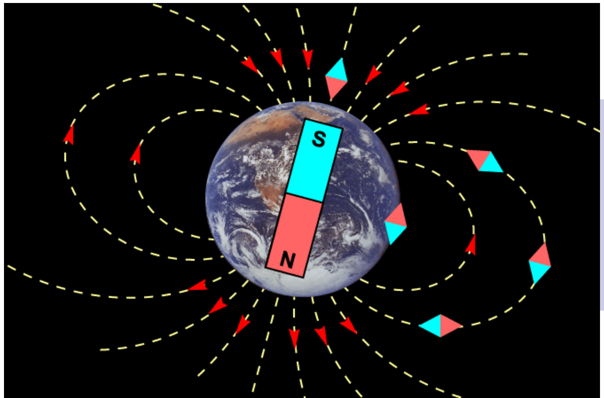
Electromagnetism

Moving electric charges produce magnetic fields.
Accelerated electric charges produce electromagnetic waves.

Electromagnetic waves = a special combination of electric and magnetic fields that can travel over long distances (e.g. radio waves, light, X rays)







Electromagnetism describes electricity, magnetism and light

Quarks, Gluons and Co.

From Forces to Quantum Fields

M. Planck (1900) suggested that energy in light comes in small packets called 'quanta'.

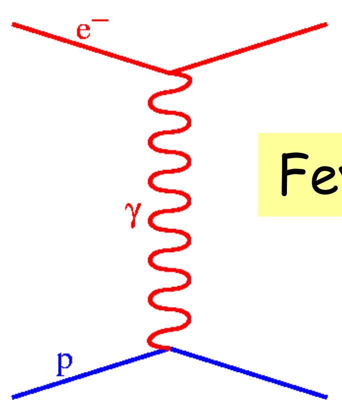
Energy of one quantum $E = h\nu$

ν = frequency

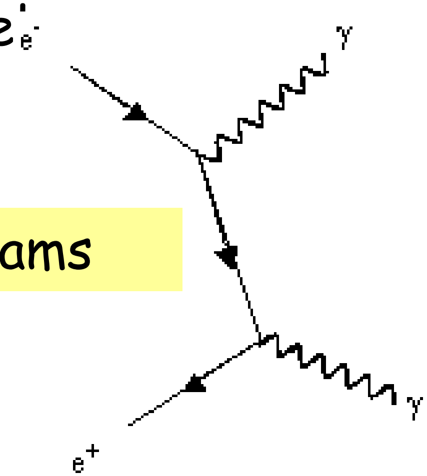
These quantum packets behave like particles.
The electromagnetic field can be described by the action of these force carrier particles, called *photons* γ.

Photons are bosons with spin 1 and they are massless. They 'couple' to electric charges and have no electric charge themse

Force carriers transmit forces by being exchanged between particles.



Feynman diagrams

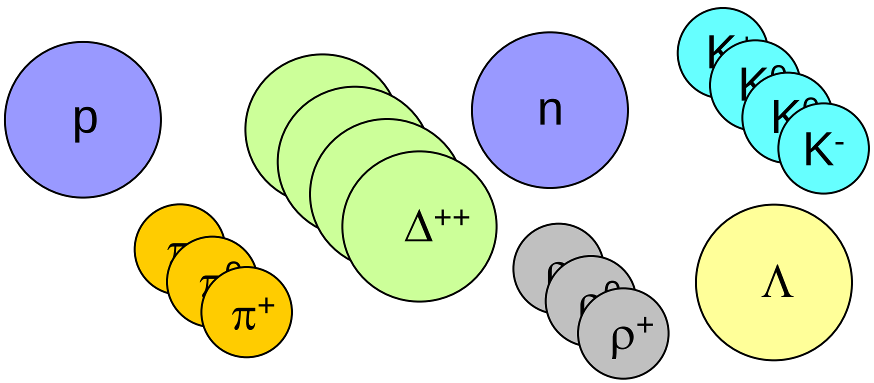


Electron + proton interacting

Electron-positron annihilation $e^+ + e^- \rightarrow 2\gamma$

The Hadron Zoo

In 1940 only 5 elementary particles were known: proton, neutron, electron, muon and positron. Only proton and neutron are hadrons (strong force acts on them).



With the advent of accelerators at the end of the decade a big 'zoo' of hadrons was discovered: Pions, kaons, rhos, … many more

Too many! Maybe hadrons are not elementary particles after all?

They could be grouped into one of two categories:

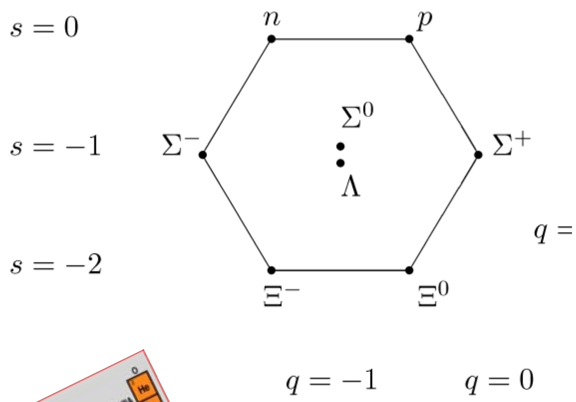
❖ Heavier ***baryons***, whose total number is always conserved.
E.g. protons, neutrons

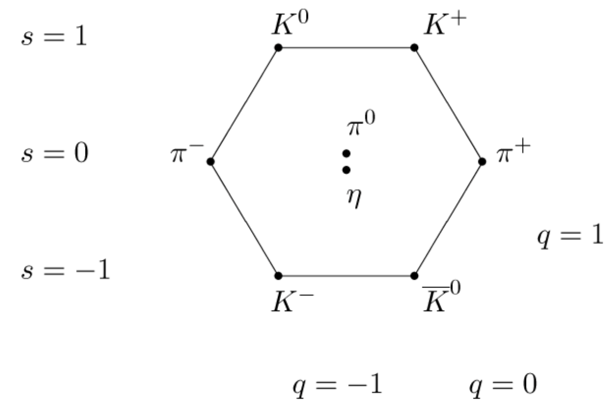
❖ Lighter ***mesons***, which can decay into particles which are not hadrons.
E.g. pions, kaons

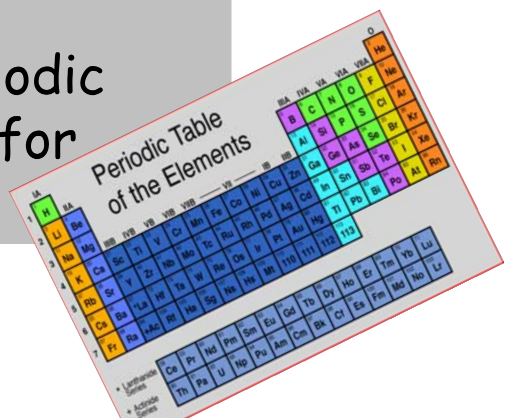
The Hadron Zoo

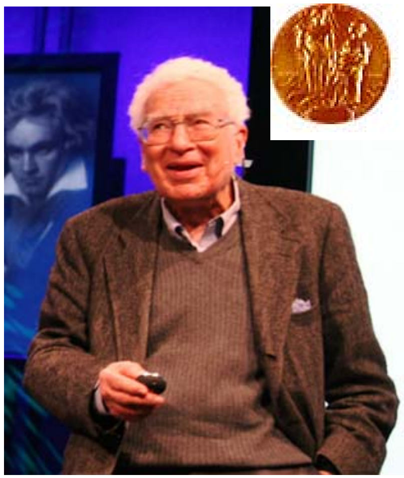
Eventually it was found that hadrons with similar properties can be grouped into multiplets.

Similar to the periodic table of elements for atoms.









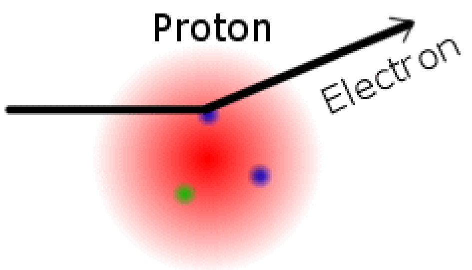
Gell-Mann & Zweig (1964): the systematics of hadrons could be understood if hadrons consisted of combinations of smaller, more fundamental particles. Those must be fermions (spin-$\frac{1}{2}$) and have fractional charges.

Gell-Mann called them *quarks*. Nobody believed them.

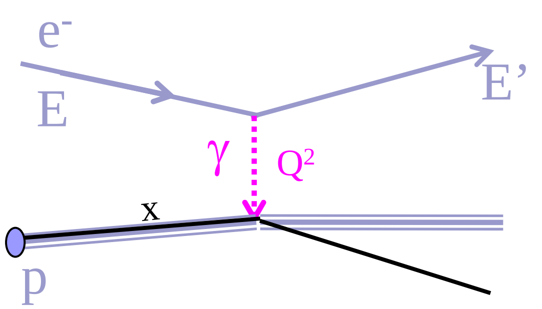
Deep-Inelastic Scattering (DIS)

How could this hypothesis be tested?
A new Rutherford experiment with better resolution!

Deep-inelastic scattering (DIS):
shoot electrons at protons with E_{cm} > 1 GeV



Measurement:
deflection angle θ
final electron energy E'



E.g. proton as a whole: x=1.

If it consisted of three equal parts with the same energy, each of those would have x = 1/3.

θ and E' can be rewritten as two quantities known as x and Q^2.

x = fraction of the proton energy carried by what is hit inside the proton.
Q^2 = resolution of the photon.

Deep-Inelastic Scattering (DIS)

DIS scattering formula:
(cross section as function of θ and E′)

$$\frac{d\sigma}{dE'd\Omega} = \left(\frac{\alpha\hbar}{2E\sin^2(\theta/2)}\right)^2 \left[\frac{2F_1(x,Q^2)}{M}\sin^2(\theta/2) + \frac{2MxF_2(x,Q^2)}{Q^2}\cos^2(\theta/2)\right]$$

"Structure functions" F_1 and F_2 know about the structure of the proton.

Different predictions had been made.

For the quark model (i.e. proton is a loose collection of point-like spin-½ fermions):

1) F_1, F_2 don't depend on Q^2 (Bjorken scaling)

2) F_1, F_2 are not independent: $2xF_1 = F_2$ (Callan-Gross relation)

The Discovery of Quarks

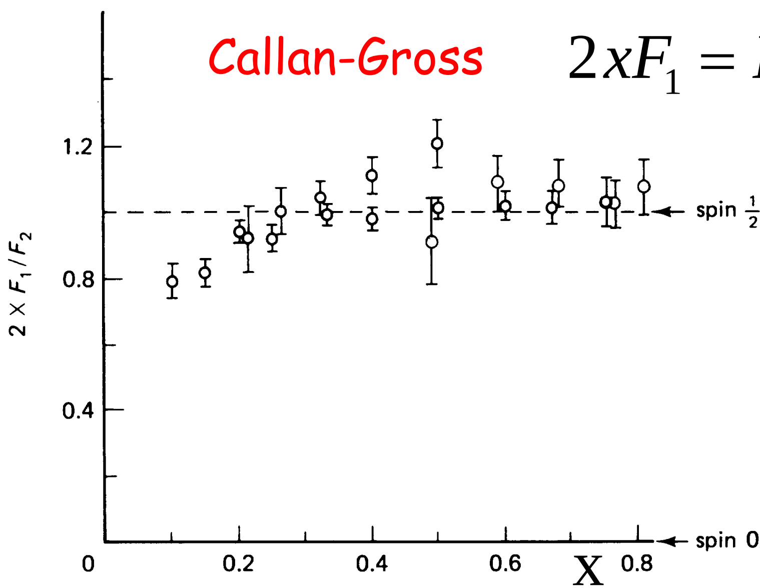
The verdict (SLAC, 1968)
SLAC = Stanford Linear Accelerator Center

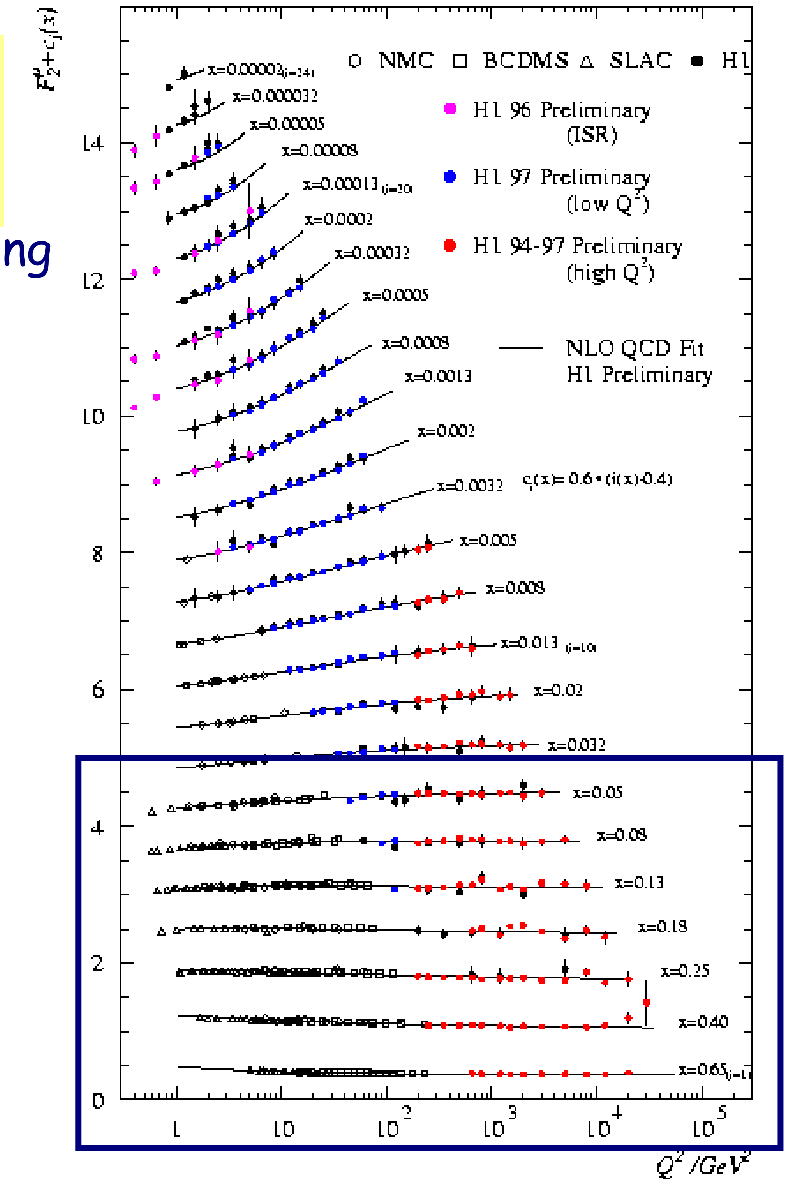
The Winner is …

Quarks!

Bjorken scaling

Callan-Gross $2xF_1 = F_2$

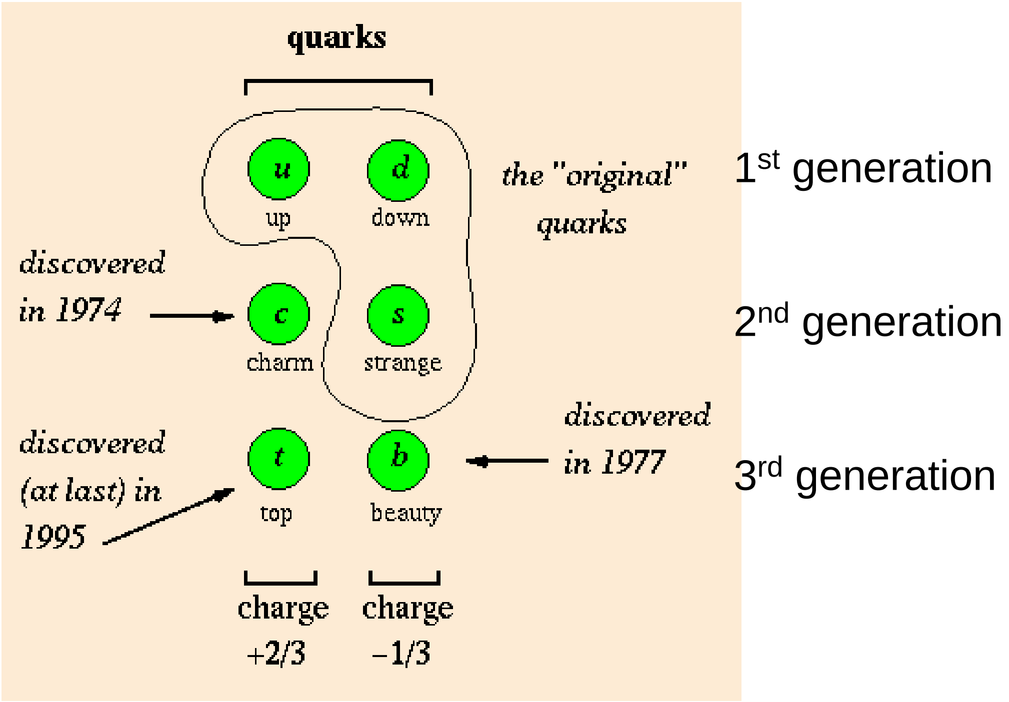




Quarks, Gluons and

Quarks

3 different quarks were initially found: Up, Down and Strange. Three more were found later on.



We know that there are only six quarks in 3 generations:
[up down]
[charm strange]
[top bottom]

+ their six antiquarks

Increasing mass from 0.002 GeV (up) to 174 GeV (top).

Surprise: they do have fractional electric charges +2/3 or -1/3. They feel both the weak and strong force.

Quantum Chromodynamics

How do quarks interact and bind together?

Careful: this is not the same as color in common language!

Experimental result: each quark seems to exist in three varieties. The strange new feature was called color.

Each quark has one of three colors: 'red', 'green' or 'blue'
(+ 3 anti colors for antiquarks)

u u u

1972: the theory of *Quantum Chromodynamics* is born:

Quarks interact through a new kind of particle, called the *gluon*. The gluon transmits the strong force, just as photons transmit the electromagnetic force.

It was realized that gluons can be described by a strange theory already written down in 1955 by Yang and Mills (above).

Gluons

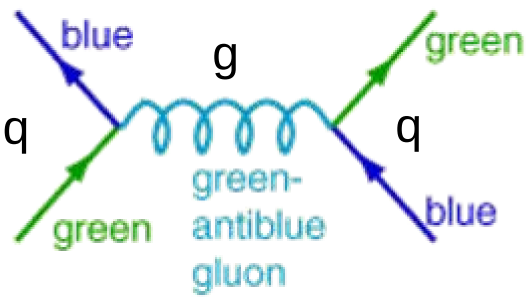
Color is the 'charge' for the strong force, i.e. gluons couple to this color charge

(just as photons couple to electric charge to transmit the electromagnetic force)

Gluons themselves also carry color. Thus gluons couple to themselves!

This is a direct result of the Yang-Mills theory.

There are 8 different color charges possible for a gluon
(3 color)x(3 anti-color)-'white'



Color is conserved in the coupling.

The Standard Model

BOSONS
force carriers
spin = 0, 1, 2, …

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

6 fermions and 6 leptons come in 3 identical generations
(only masses are different)
Plus they have antiparticles.

FERMIONS
matter constituents
spin = 1/2, 3/2, 5/2, …

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

Leptons and quarks feel the weak force. Only quarks have color charges and feel the strong force.

Now You Can Own the SM to Hug!

6 fermions and 6 leptons come in 3 identical generations
(only masses are different)
Plus they have antiparticles.

Also on sale: custom particles. Convenient for theorists.

Standard Model and Beyond

- Beyond the Standard Model:
  - Higgs Boson ?
  - Supersymmetry ??
  - Graviton ??
  - Dark Matter ??
  - Dark Energy ??
  - Strings and Branes ?????

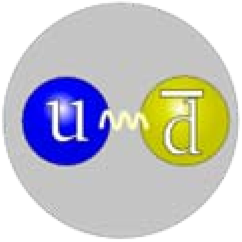
- More on the "Strong" Sector of our Universe: the strange behavior of quarks and gluons.

Hadrons = Bound States

Experimental fact: all hadrons are color neutral.

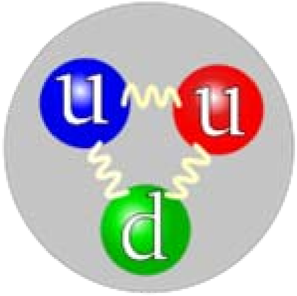
I.e. the color of the quarks and gluon inside has to add up to 'white'.

- Meson = quark + antiquark



π^+

- Baryon = 3 quarks



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Those quarks are called the valence quarks of a hadron.

E.g. the valence quark structure of the proton is *uud*

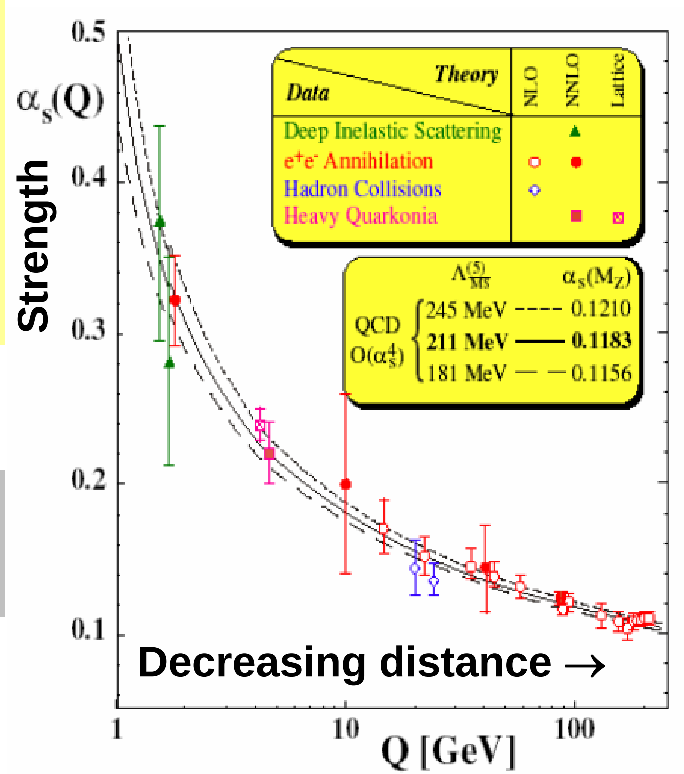
Asymptotic Freedom

Puzzle: if the strong force is “strong”, why do we “see” quarks inside a proton (e.g. in deep-inelastic scattering)?

Gross, Wilczek, Politzer (1974):
The strong force is *asymptotically free*.

The closer you come to a color charge the weaker the strong force becomes!

For electric forces it’s just the other way around.

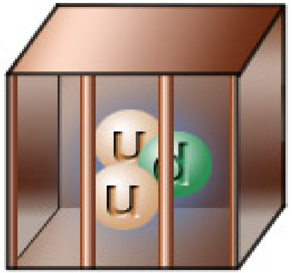


So to see quarks, hit a proton with something with small wave length, or high energy.

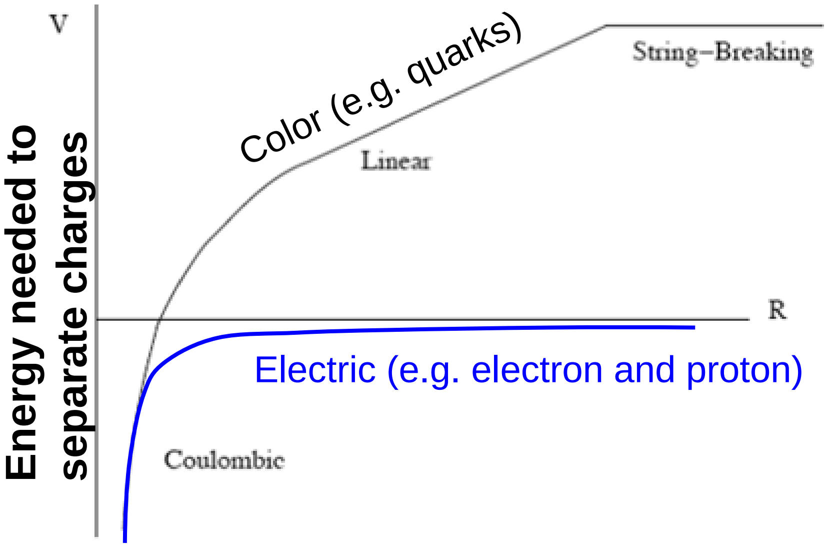
Confinement

QCD exhibits another fantastic feature: confinement. No free color charge can exist in the vacuum (remember hadrons are all color neutral.

Energy needed to separate two quarks is infinite.



Quarks and gluons have <u>never</u> been observed in the vacuum.



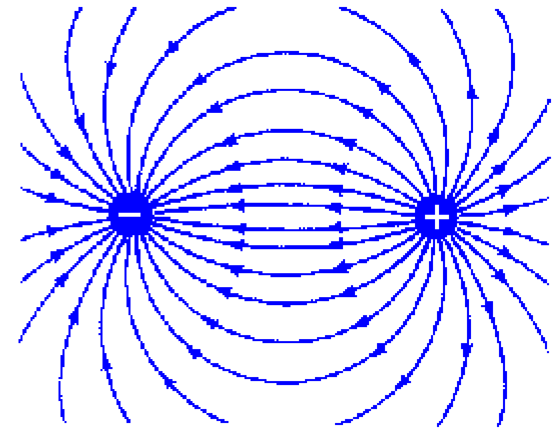
Confinement has not yet been fully understood.

It has been named one of the outstanding mathematical problems of our time. The Clay Foundation will pay you $1,000,000 if you prove it!

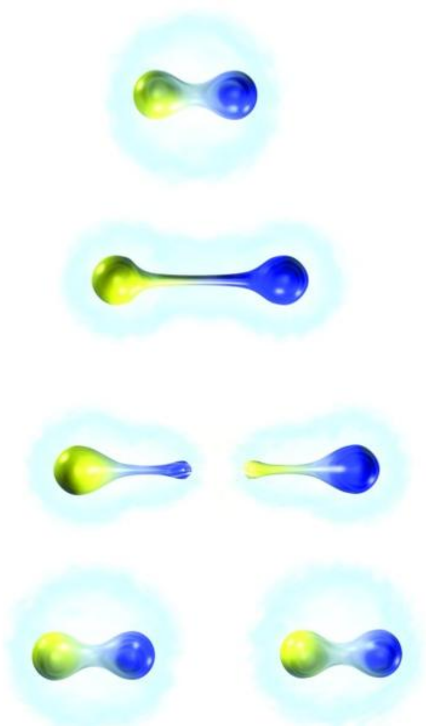
http://www.claymath.org/

Confinement

- The QCD vacuum is very special. It repels field lines. They are squeezed into flux tubes.
- If enough energy is pumped into such a "gluon string" it breaks and a quark-antiquark pair is created.

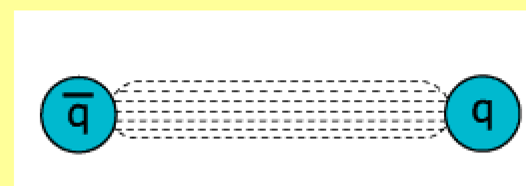


Compare: two electric charges



Breaking of a flux tube: create a new $q\bar{q}$ pair, never single quarks

Gluons moving over large distances form 'flux tubes' between quarks which act like rubber bands.



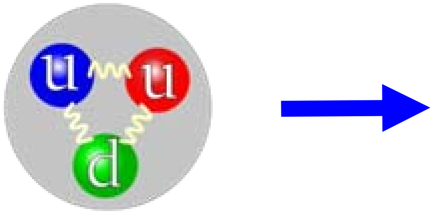
To pull this quark-antiquark pair apart you need to spend more and more energy.

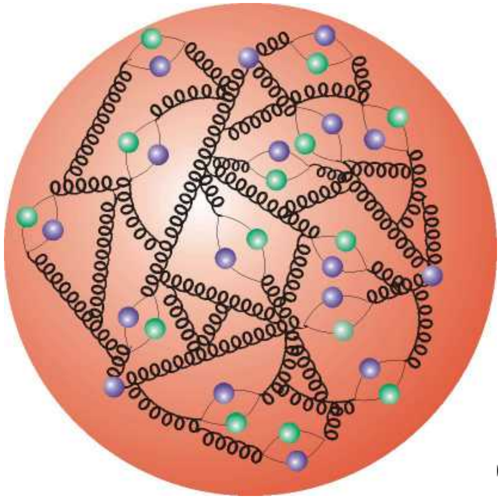
The Modern Picture of Hadrons

Scattering experiments on the proton tell us:
there is an unlimited number of quarks and gluons
in a proton at any given time.

They come from quantum fluctuations.

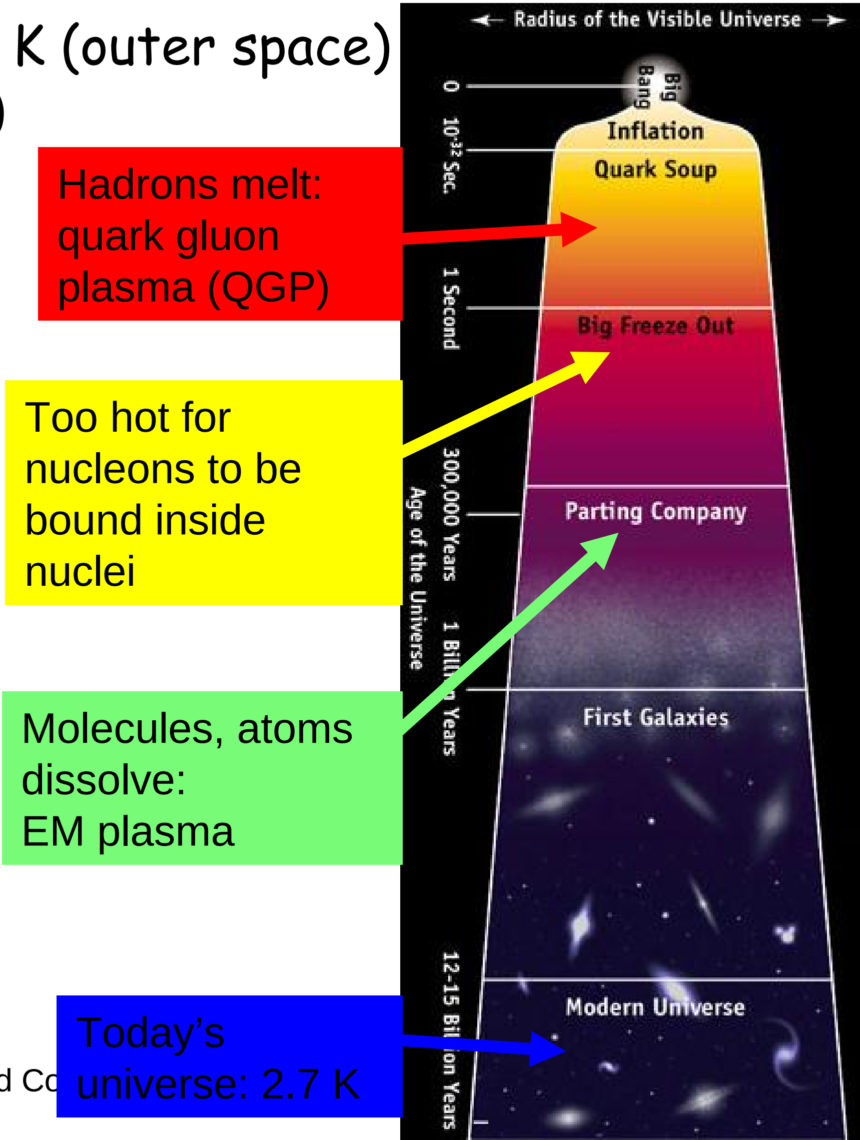
1919: Proton
Ca. 1970: Proton = uud
2009: Proton = uud + gluons + quark-antiquark pairs





The Era of Quarks and Gluons

- Our universe today: temperature 3 K (outer space) to ~ 100,000,000 K (inside the sun)
- Quarks and gluons seem to be confined into protons and neutrons everywhere we look.
- But: protons and neutrons melt at T ~ 1,000,000,000,000 K !
- The universe just microseconds after the big bang was that hot!



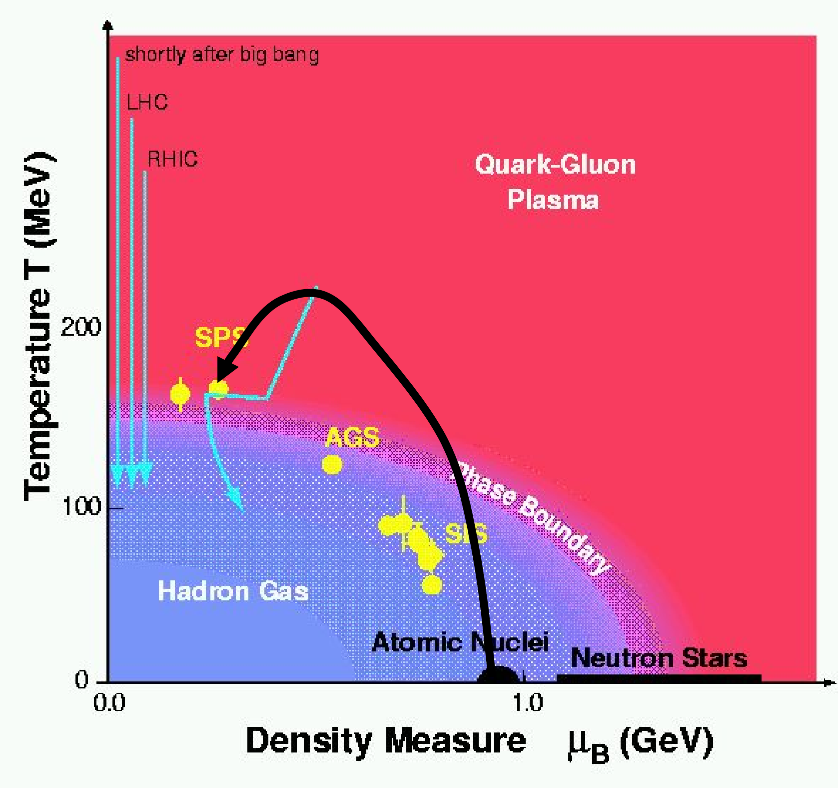
Exploring Quark-Gluon Plasma

What happens at the critical temperature of 10^{12} K?

Just as liquid suddenly turns into vapor, or ice turns into water at a certain temperature, hadrons turn into QUARK GLUON PLASMA.

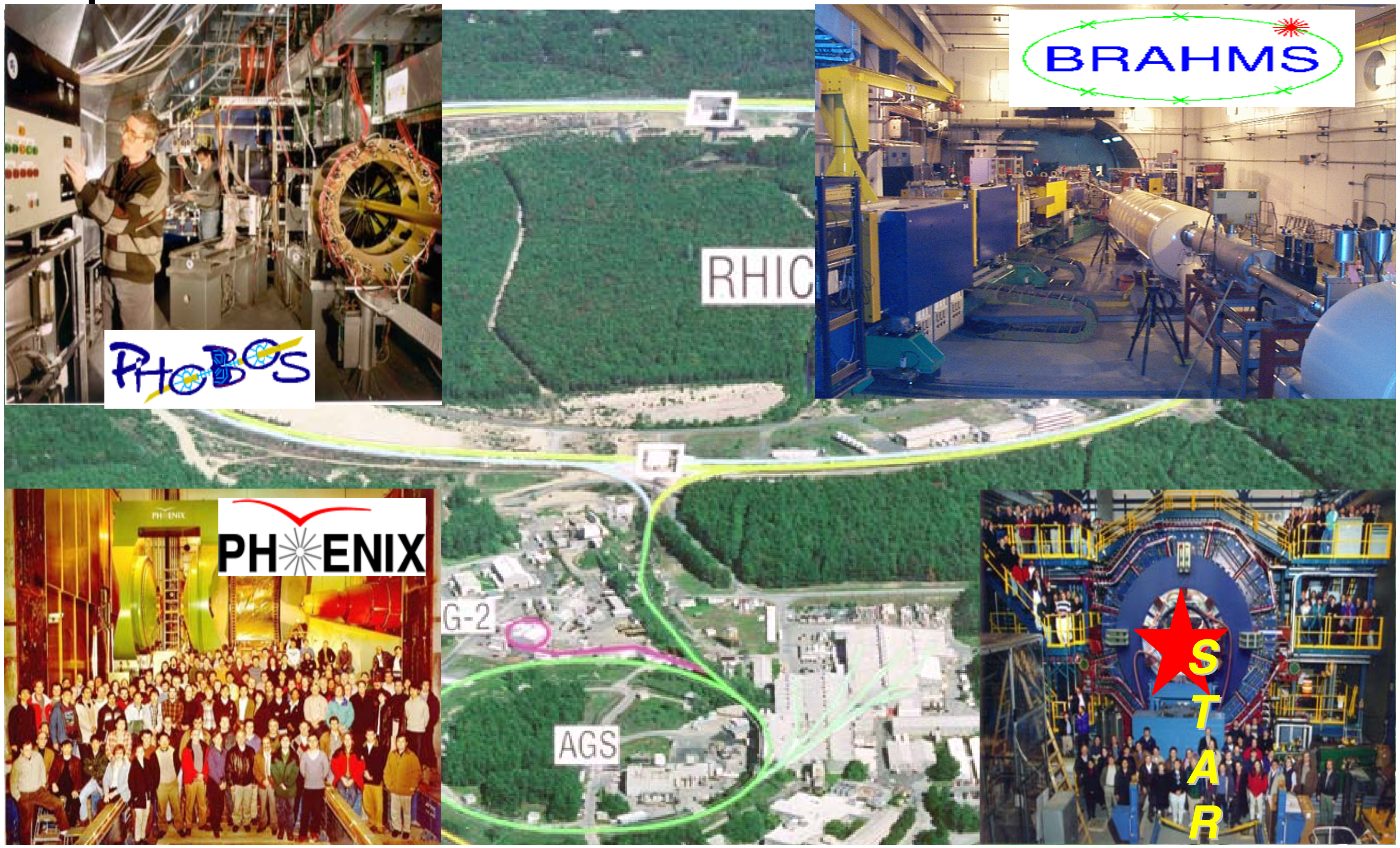
In nature: not observed in the last 13 billion years

Quark-gluon droplets can be created in collisions of nuclei at very high energy.



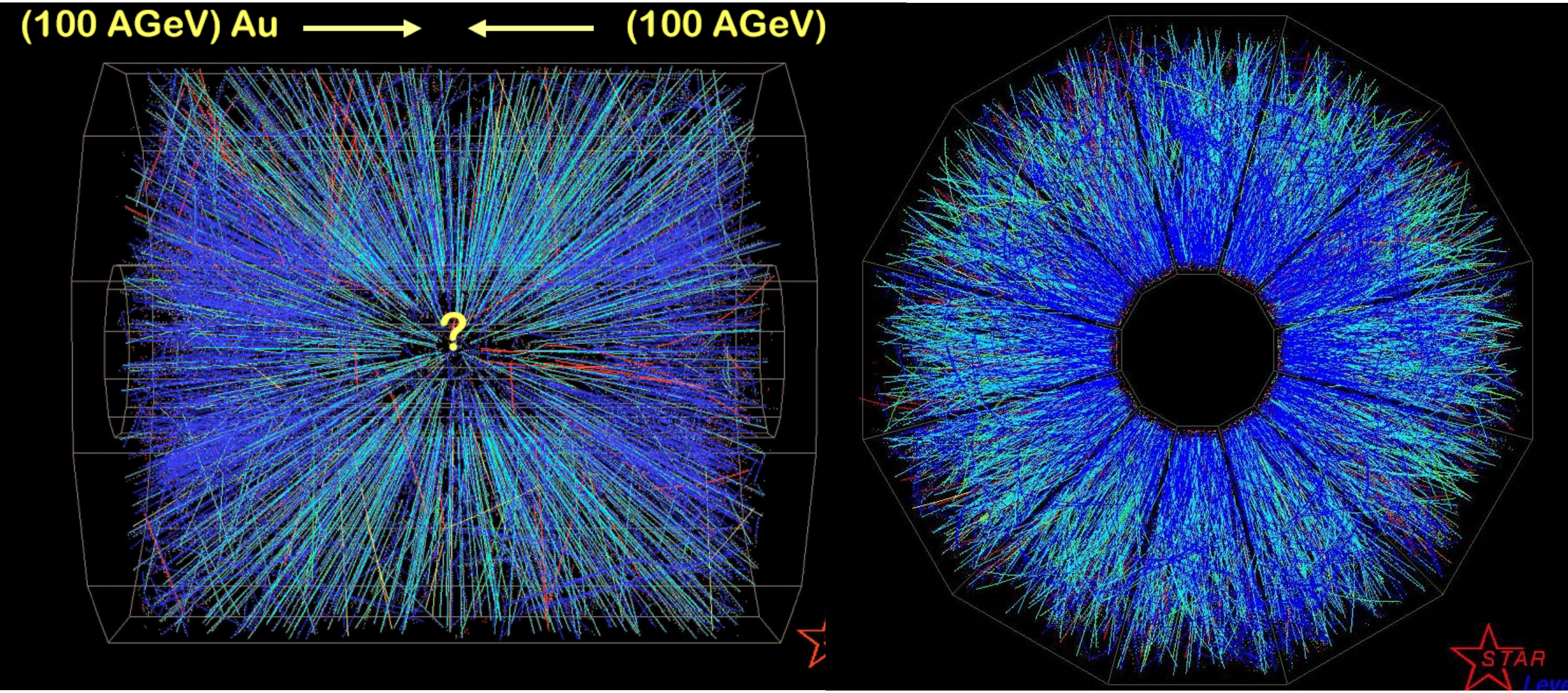
The Relativistic Heavy Ion Collider

- Collider for p+p, p+A, A+A at Brookhaven
- 4 Experiments



Au+Au Collisions

Thousands of particles created!

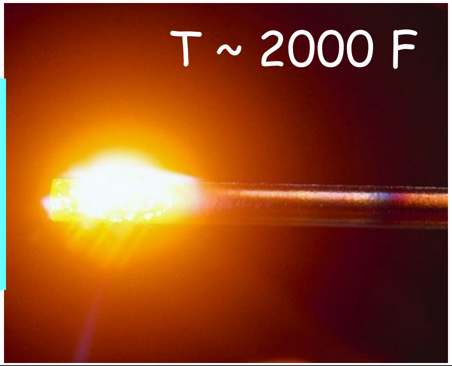


Follow the particle tracks back: they emerge from a very hot and dense fireball much smaller than an atom.

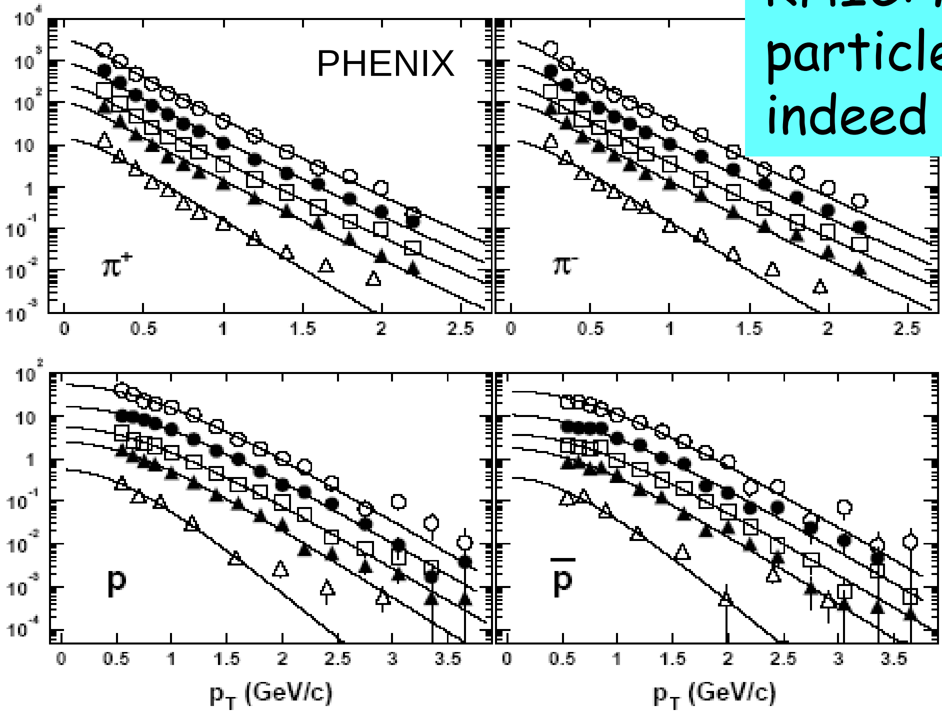
RHIC: Temperature

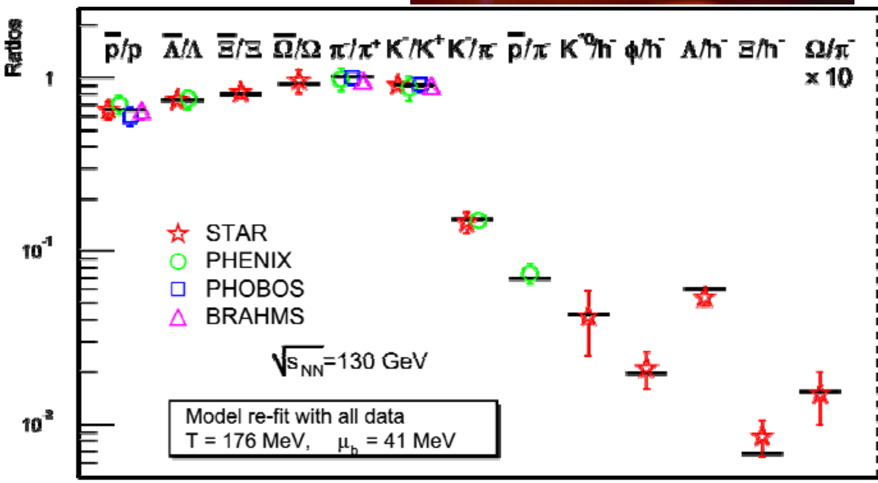
We can measure the temperature of an object through the particles it emits.

Often done with photons (infrared, light). The hotter the object, the more energetic the particles on average.



RHIC: Measurements of particle spectra indicate indeed T ~ 10^{12} K.



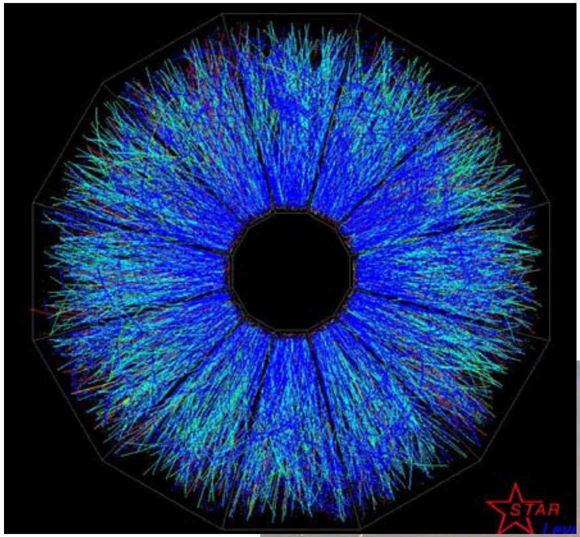


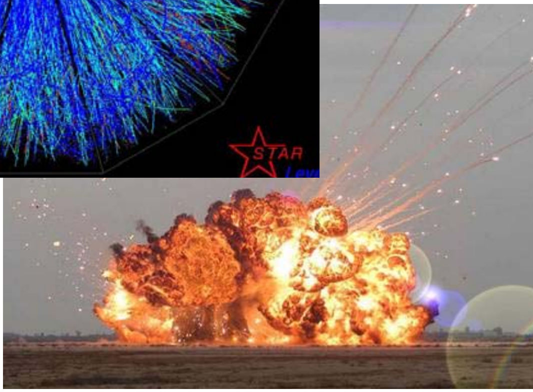
Braun-Munzinger et al., PLB 518 (2001) 41

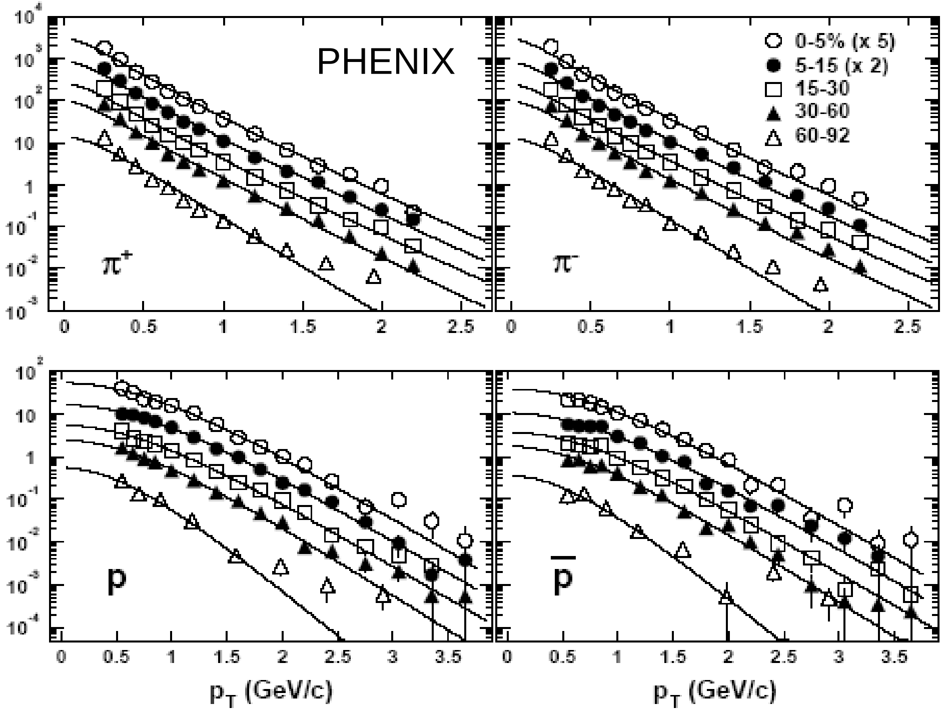
RHIC: Exploding Quark Droplets

What else can we learn from particle spectra?

The quark-gluon droplets explode with almost the speed of light.



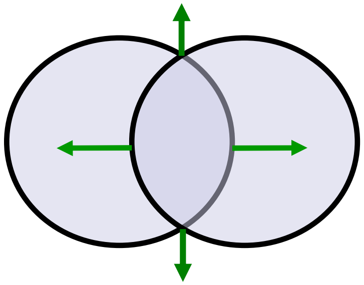


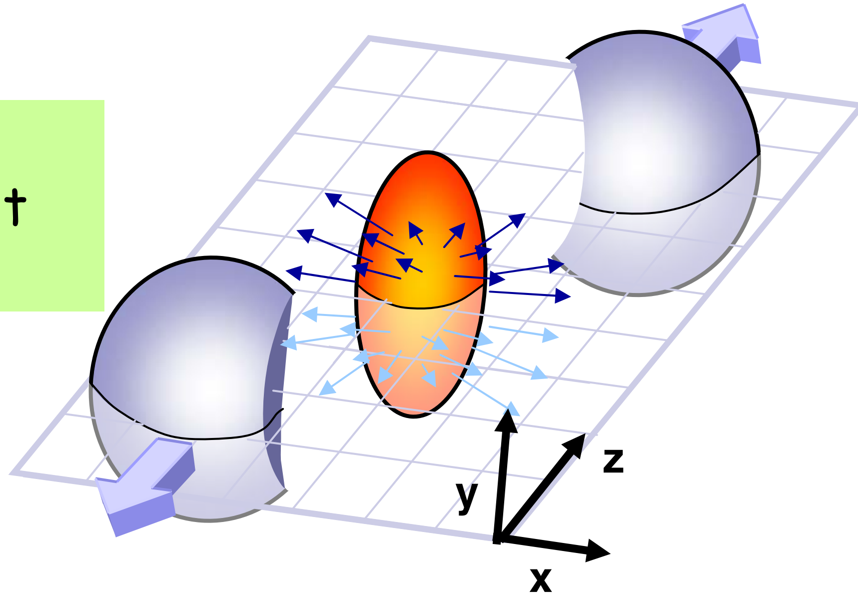


How this explosion works in detail depends on the properties of the particles involved:
Pressure inside the drop?
Viscosity of quark matter?

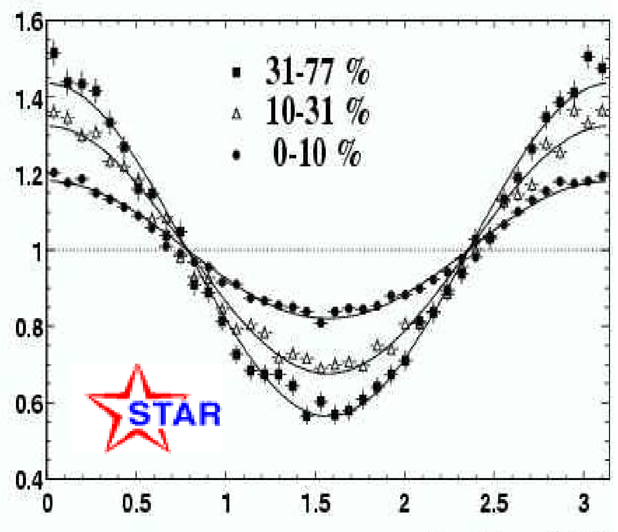
RHIC: Elliptic Flow

Most of the collisions don't happen head-on. Then the quark droplet is not round but elliptical.





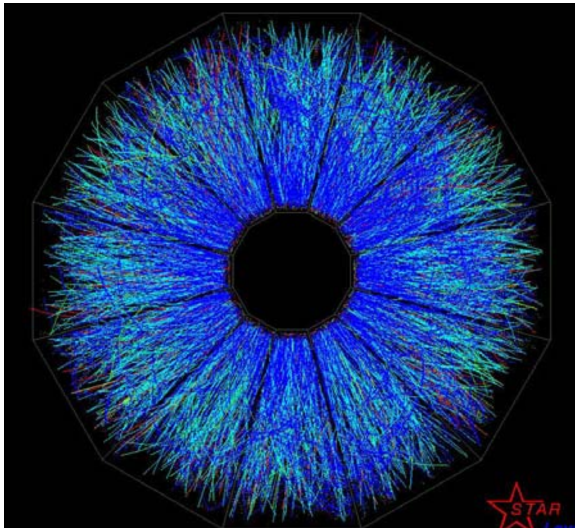
The pressure inside will accelerate particles more in the direction where the drop is narrower: "elliptic flow".

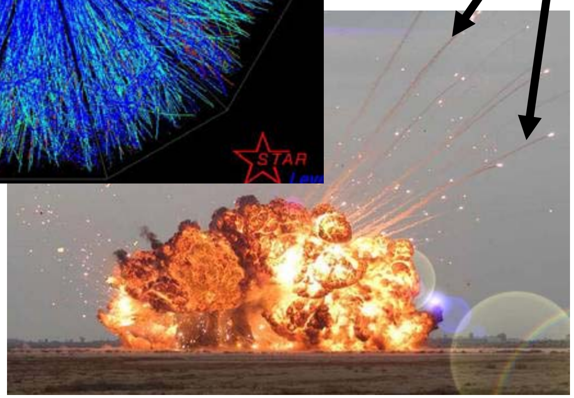


Walk halfway around the fireball ⟶

Elliptic flow measurements are a very sensitive barometer.

Hard Probes



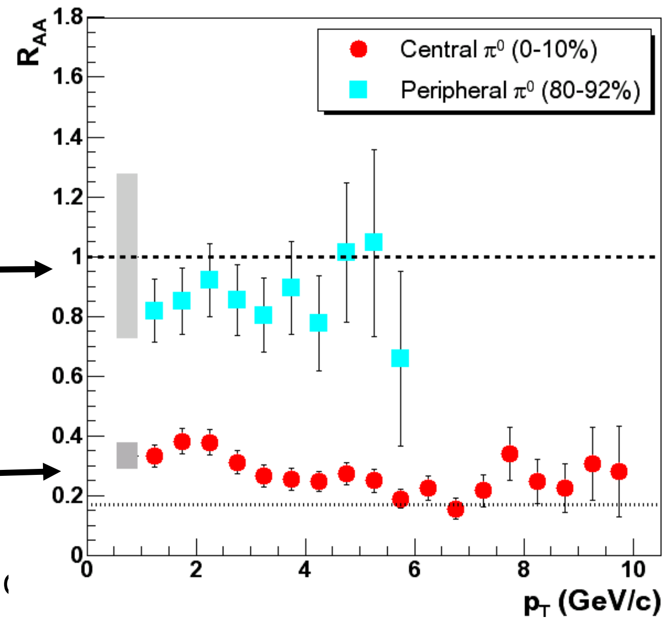


Some of the stuff coming out of an explosion is much faster than the rest.

We can use these highly energetic particles as probes. They tell us how transparent or opaque the hot quark droplet is.

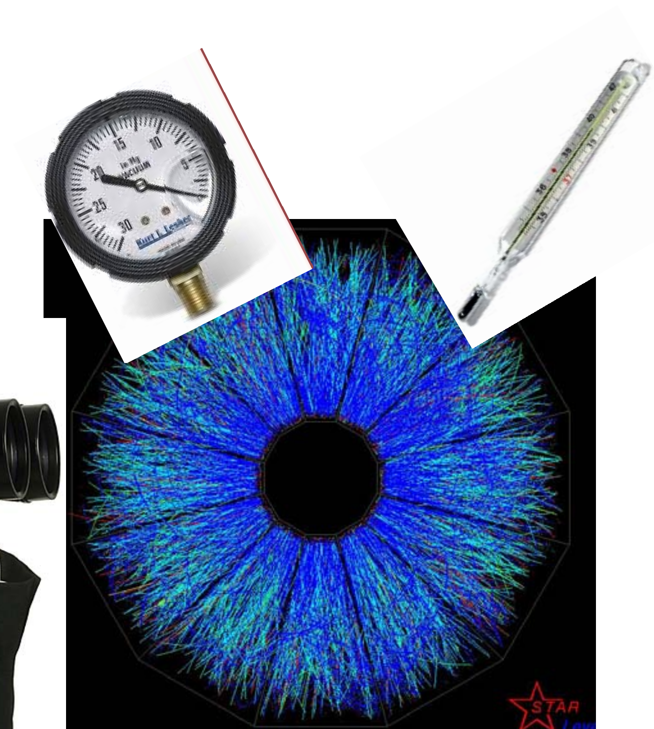
Expected this many fast particles

Only observed that many at RHIC



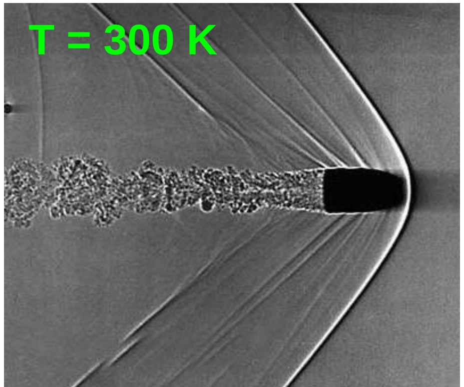
What Have We Learned?

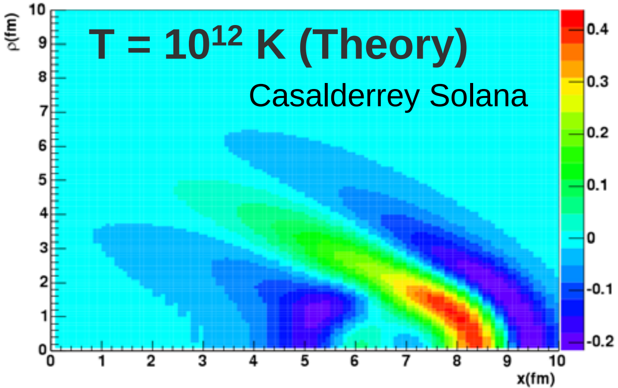
- We reached the temperatures we expected
- We have strong indications that quark and gluons are free!
- Quark gluon plasma is at least 10 times as opaque as a nucleus.
- Quark gluon plasma seems to flow like a nearly perfect liquid.
- More exciting stuff ahead!

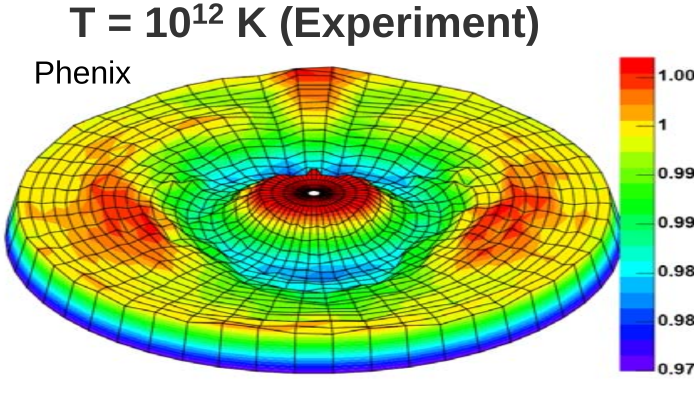


Sonic Booms in the QGP?

- Sonic booms = shock wave if something travels with more than the speed of sound.
  - At RHIC: speed of the quark/gluon ~ c
- Opening angle of the Mach cone related to speed of sound: $\cos\theta_M = c_s$
- Indications that those very fast particles we use as probes make sonic booms in the QGP at RHIC.







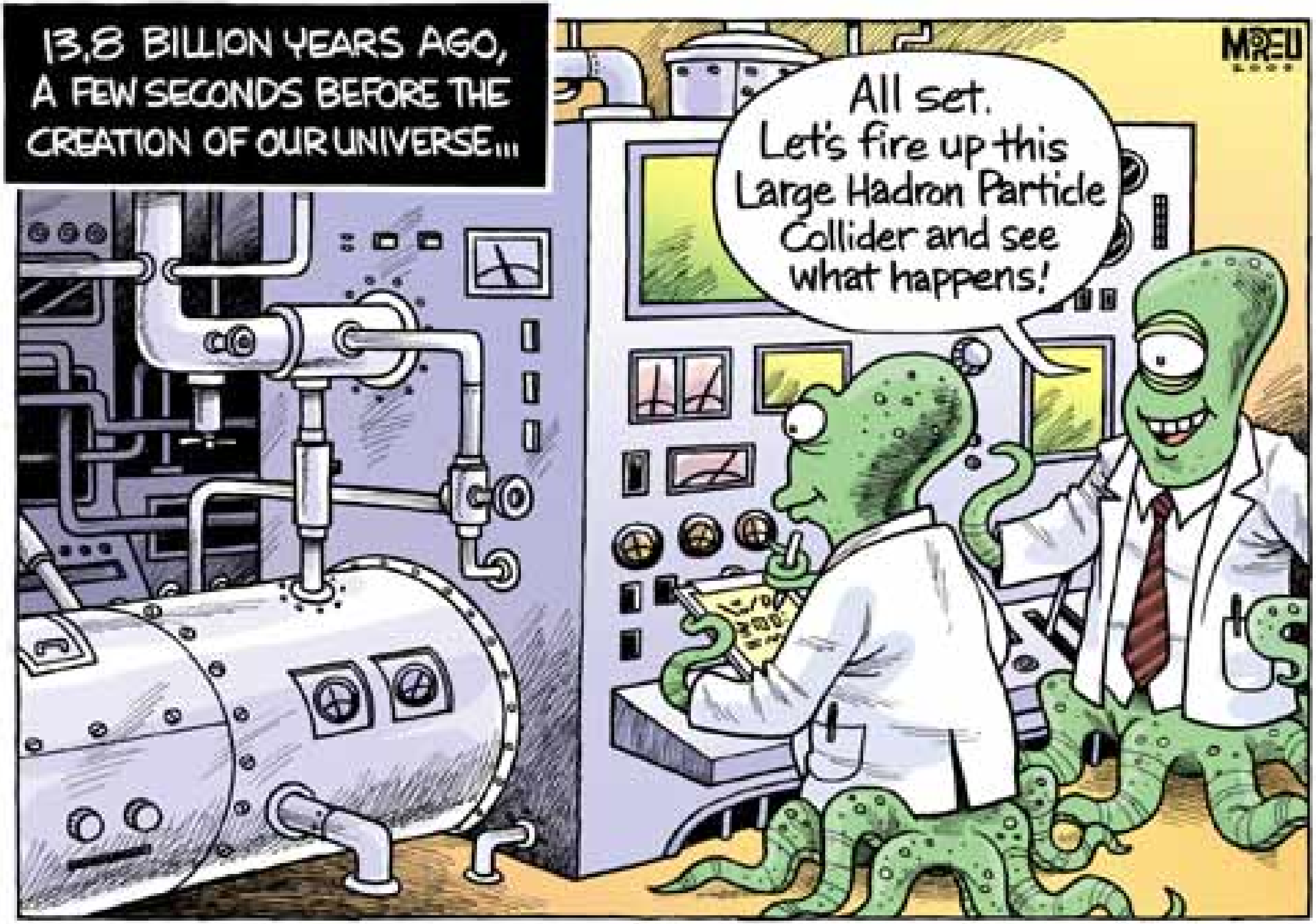
Quarks and Gluons at LHC

See Prof. Toback's talk (Jan 24): the next energy frontier.

Collides proton, but in principle it is a gluon collider. Hope to find new particles (Higgs, SUSY, etc.), but all will have to come from collisions of gluons (and quarks).

Will also collide lead nuclei and create Quark Gluon Plasma at even higher temperatures.

LHC will also teach us lots about the Strong Force.


13.8 BILLION YEARS AGO, A FEW SECONDS BEFORE THE CREATION OF OUR UNIVERSE...
All set. Let's fire up this Large Hadron Particle Collider and see what happens!
MREU

The End

The animation *Secret Worlds: The Universe Within* can be found on the website of the National High Magnetic Field Laboratory at Florida State University.

http://micro.magnet.fsu.edu/primer/java/scienceopticsu/powersof10/

Credit: Florida State University. A Java plugin for the browser is necessary to watch the animation.