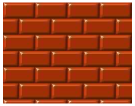
Cogne 2003

Two Lectures on Physics

1. *The Large Scale Structure of the World*
2. *The Small Scale Structure of the World*

The Large Scale Structure of the World

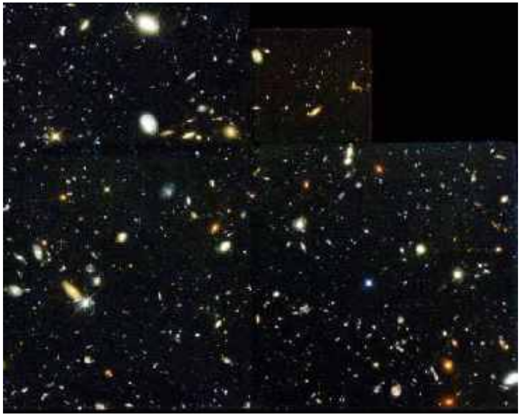
The goal of physics is to understand the universe

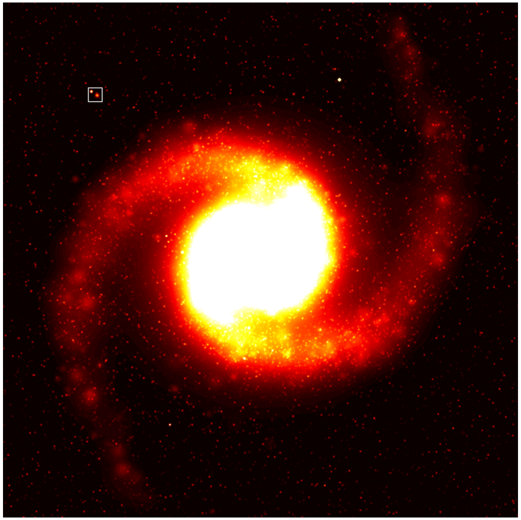


⋆ what are the building blocks

⋆ what are the laws

The universe is made of galaxies

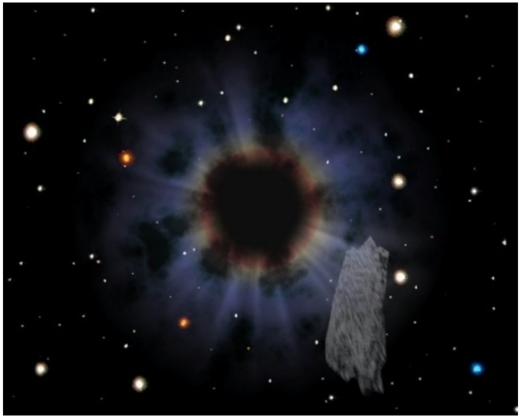




each galaxy is made of stars

... and many things you people wouldn’t believe...

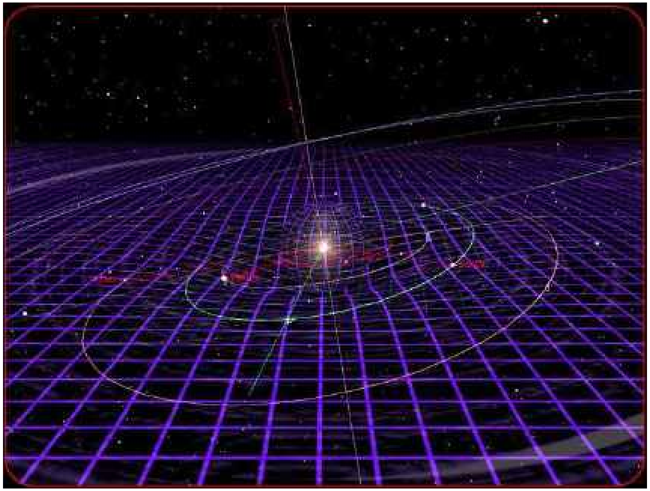
blackholes ...

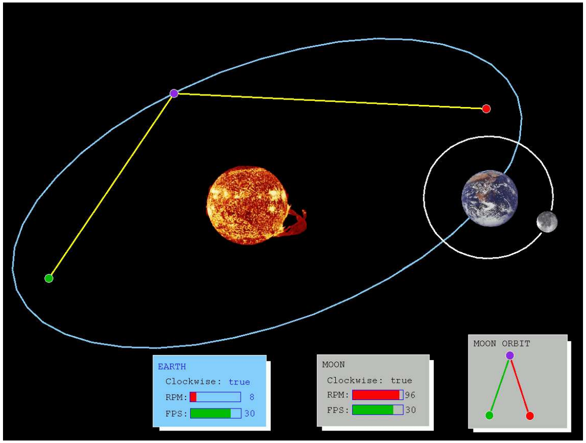


... and gamma ray bursts ...

“I’ve seen things you people wouldn’t believe. Attack ships on fire off the shoulder of Orion. I watched C-beams glitter in the dark near the Tannhauser gate. All those moments will be lost in time, like tears in rain. Time to die. ”

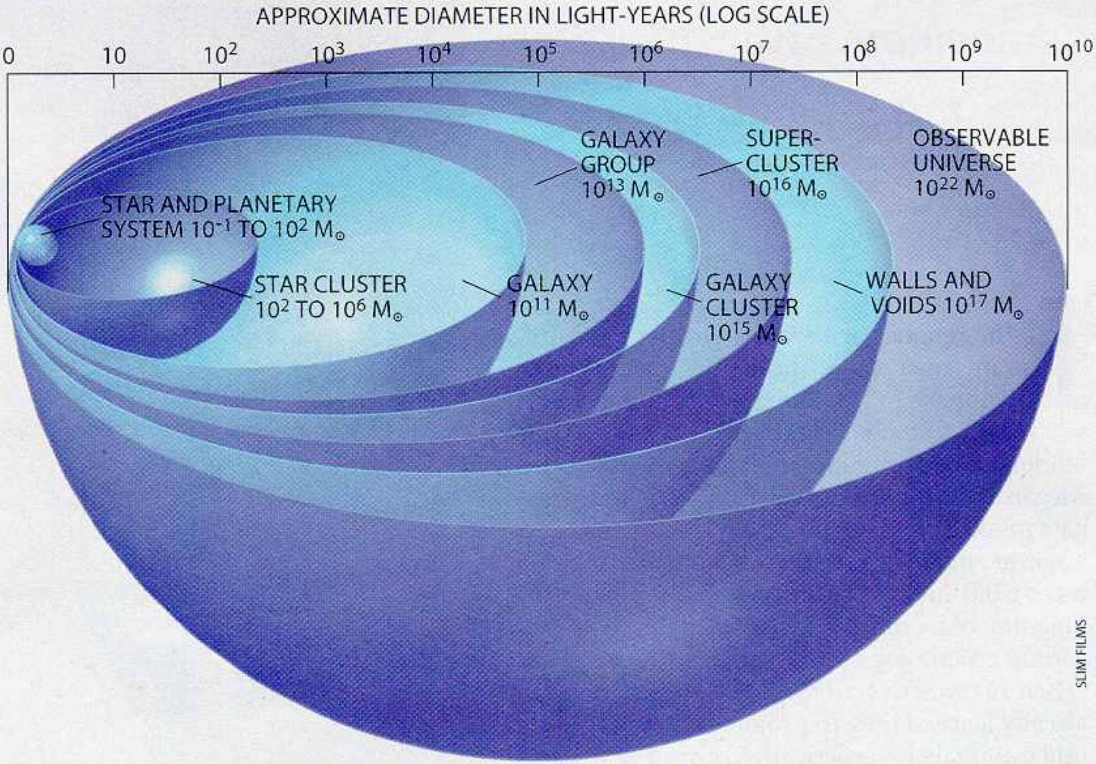
... the more familiar solar system $\longrightarrow$





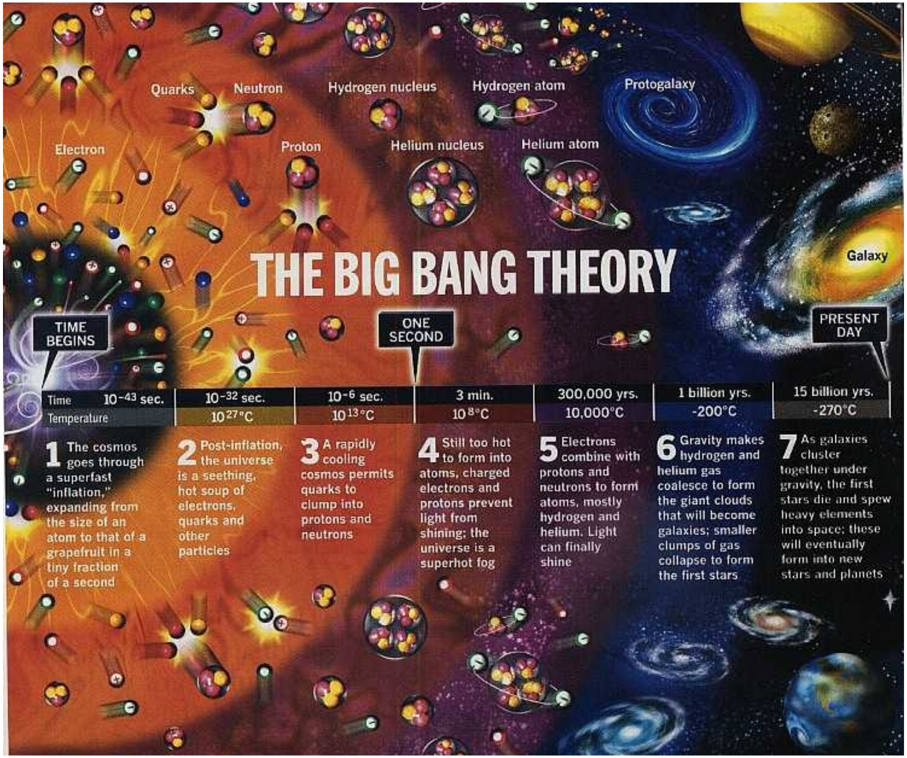
$\longleftarrow$ ... and even more familiar, the Moon ...

1 LIGHT-YEAR = 9.46$\times 10^{15}$ m $\longrightarrow$



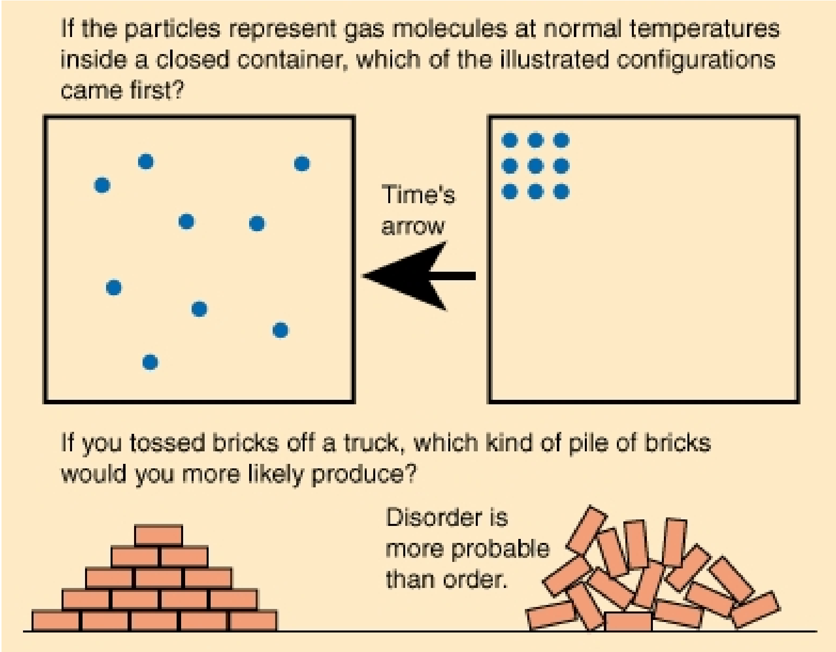
HIERARCHY OF COSMIC STRUCTURES ranges from stars and planets to the universe itself. The largest objects held together by gravity are galaxy clusters with masses up to 10^{15} times that of the sun (denoted as $M_\odot$). Although there is a higher level of organization consisting of superclusters and great walls, these patterns are not bound gravitationally. On even larger scales, the universe is featureless. Astronomers think most of these structures form from the progressive agglomeration of smaller units.

The Big-Bang


Quarks
Neutron
Hydrogen nucleus
Hydrogen atom
Protogalaxy
Electron
Proton
Helium nucleus
Helium atom
THE BIG BANG THEORY
Galaxy
TIME BEGINS
ONE SECOND
PRESENT DAY
Time
Temperature
10-43 sec.
10-32 sec.
10 27°C
10-6 sec.
10 13°C
3 min.
10 8°C
300,000 yrs.
10,000°C
1 billion yrs.
-200°C
15 billion yrs.
-270°C
1 The cosmos goes through a superfast "inflation," expanding from the size of an atom to that of a grapefruit in a tiny fraction of a second
2 Post-inflation, the universe is a seething, hot soup of electrons, quarks and other particles
3 A rapidly cooling cosmos permits quarks to clump into protons and neutrons
4 Still too hot to form into atoms, charged electrons and protons prevent light from shining; the universe is a superhot fog
5 Electrons combine with protons and neutrons to form atoms, mostly hydrogen and helium. Light can finally shine
6 Gravity makes hydrogen and helium gas coalesce to form the giant clouds that will become galaxies; smaller clumps of gas collapse to form the first stars
7 As galaxies cluster together under gravity, the first stars die and spew heavy elements into space; these will eventually form into new stars and planets

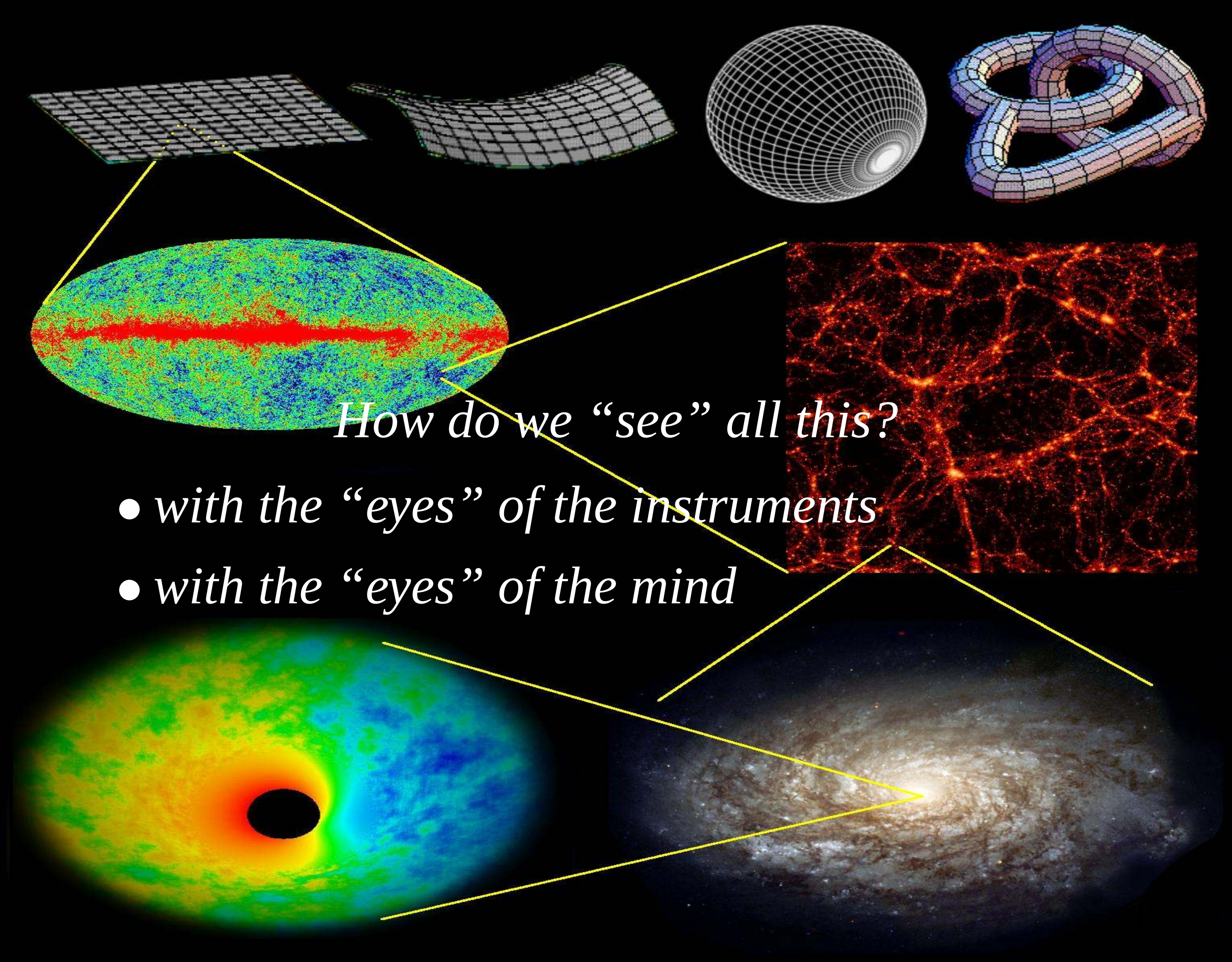

Big Bang
Big Bang Plus Tiniest Fraction of a Second (10-43)
Inflation
COBE Sky Map
Big Bang Plus 300,000 Years
Light From First Galaxies
Big Bang Plus 15 Billion Years

The II Law of Thermodynamics

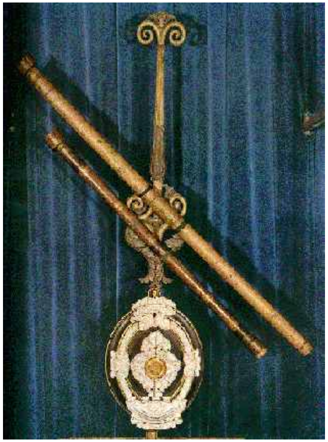


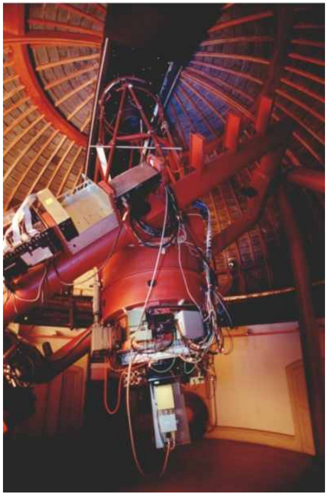
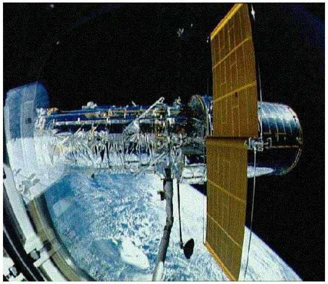
ORDER $\rightarrow$ DISORDER

$\Delta S > 0$ (entropy increases)


How do we “see” all this?
• with the “eyes” of the instruments
• with the “eyes” of the mind

instruments: telescopes, radiotelescopes, ...

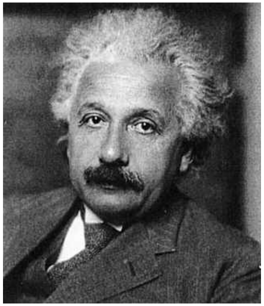


.... with the “eyes” of mind: Mathematics ....

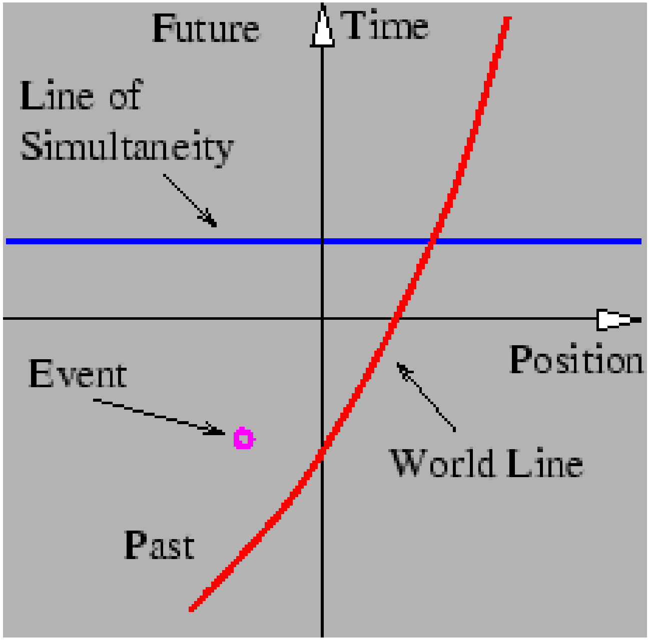
“The book of Nature is written in the language of Mathematics”
Galileo Galilei (1564-1642)

“Nature is the realization of the simplest conceivable mathematical ideas”
Albert Einstein (1879-1955)

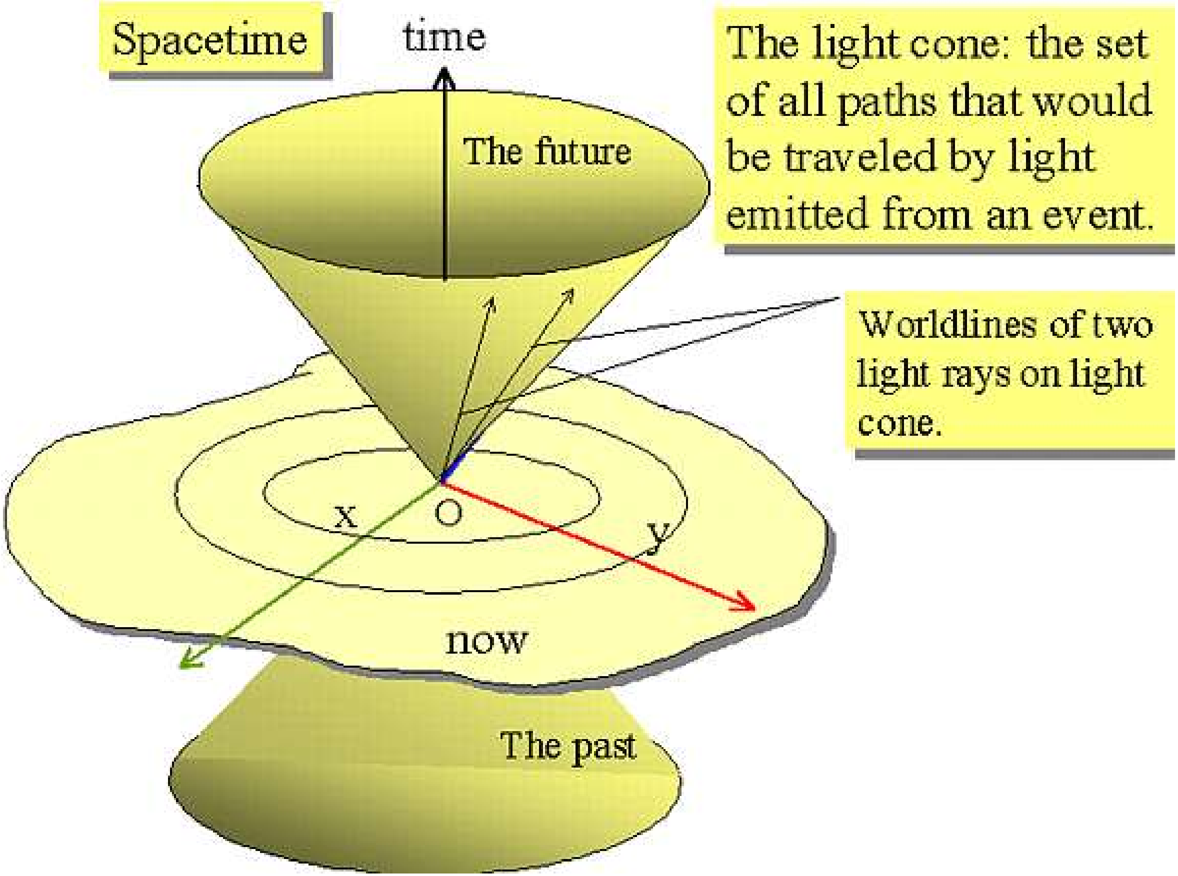


- We represent the building blocks of our universe in terms of mathematical entities
- The physical laws are expressed by mathematical relations between these entities
- The most basic building block of our universe: space-time

A moving particle is represented by a curve in Spacetime (World Line)



LOCAL STRUCTURE OF SPACE-TIME



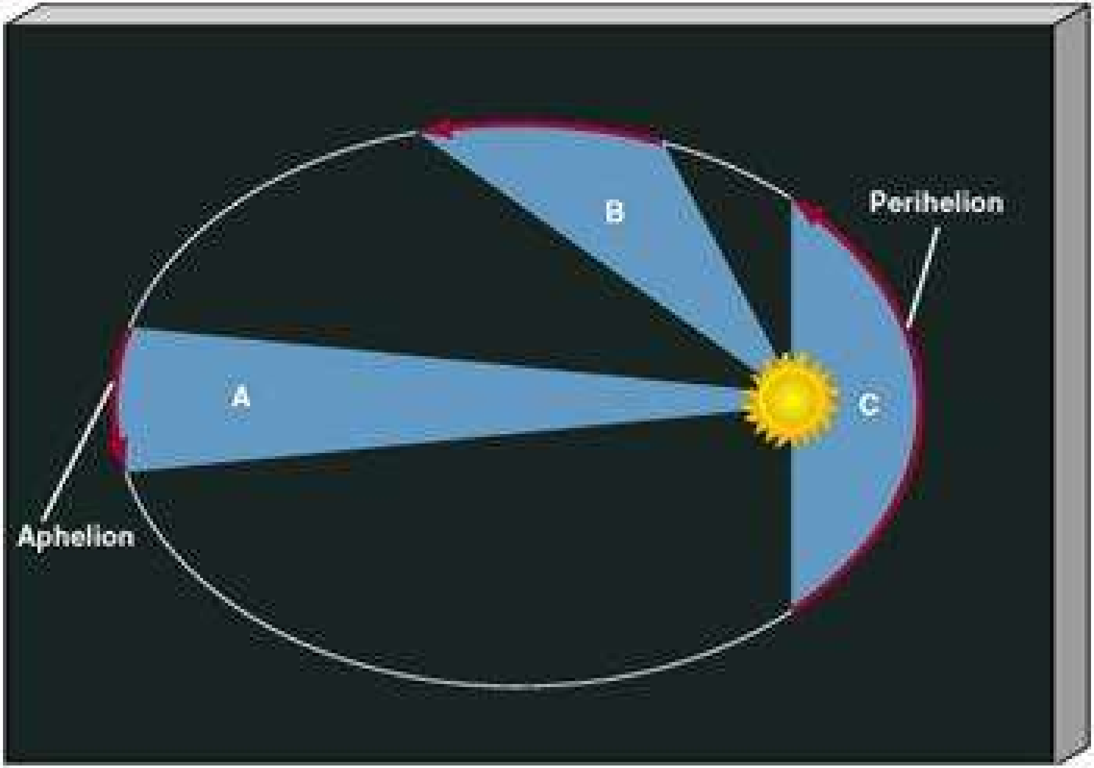
GRAVITY

The apple and the Moon are falling according to the same law

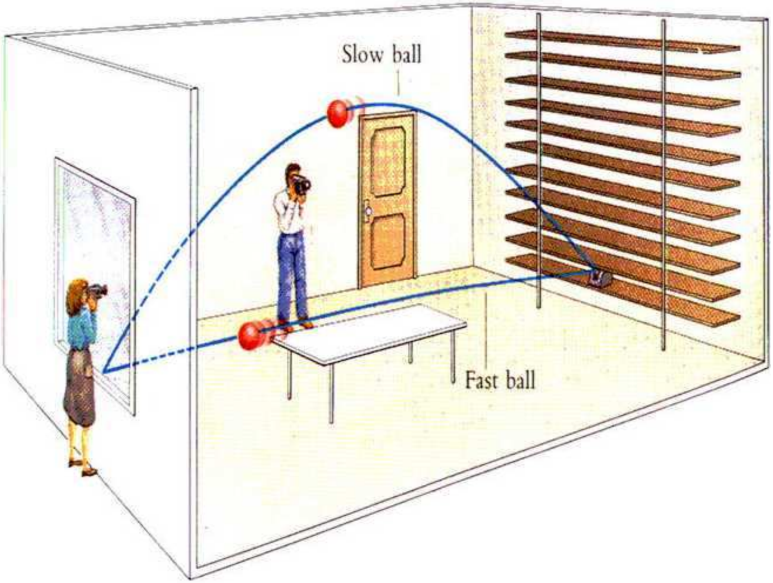
$$m\frac{d^2\mathbf{r}}{dt^2} = G\frac{Mm}{r^2}\mathbf{e}_r$$

Isaac Newton (1642-1727)

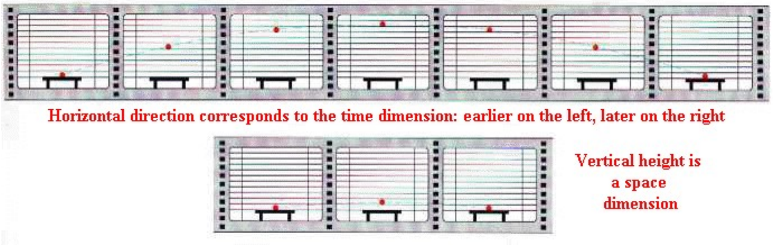
KEPLER'S MARVELOUS LAWS



GRAVITY = SPACETIME CURVATURE (4-D)



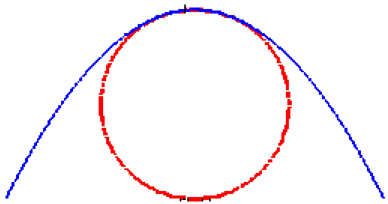
NOT JUST CURVATURE OF SPACE IN 3-D



FROM GALILEO TO EINSTEIN

x_3 vertical height in 3D
$x_4 = ct$ time coordinate in 4D
$c = 3 \times 10^8$ m/s velocity of light
$g = 9.8$ m/s^2 gravity acceleration at the surface of Earth

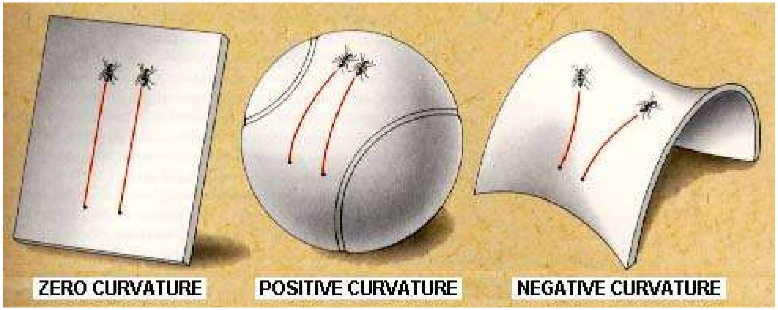
$$x_3 = -\frac{1}{2}\frac{g}{c^2}x_4^2$$

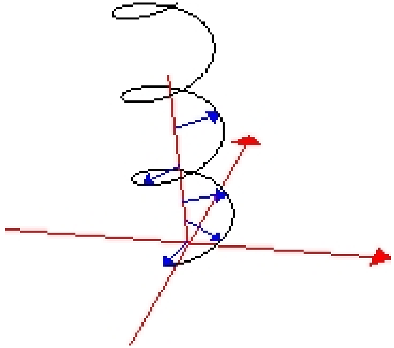


osculating circle

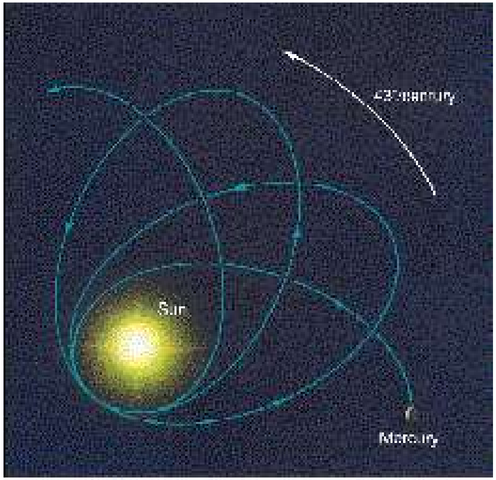
Radius of curvature $= c^2/g \sim 1$ LIGHT-YEAR

MOTION = GEODESIC IN 4D

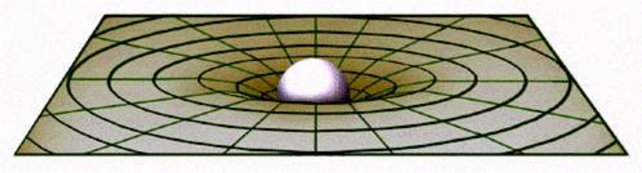


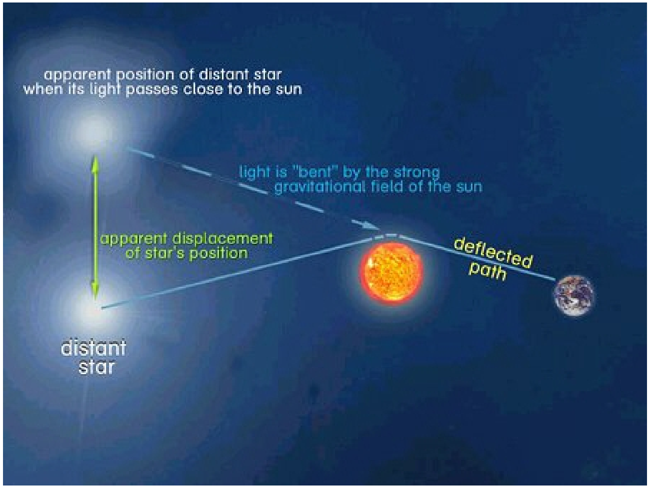


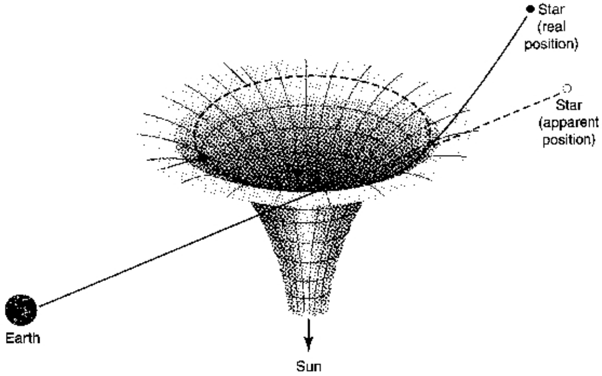
$$m\frac{d^2\mathbf{r}}{dt^2} = G\frac{Mm}{r^2}\mathbf{e}_r + \text{corrections}$$

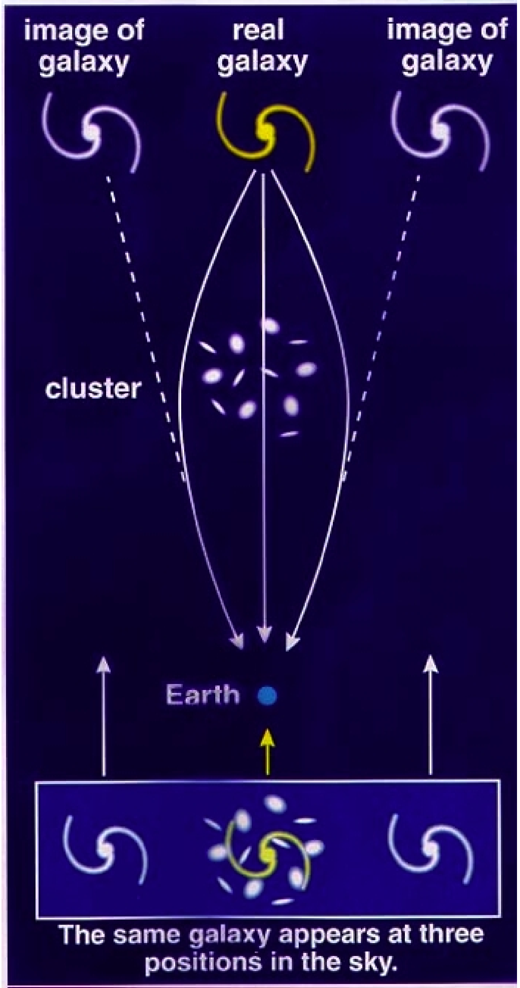


Gravity is a distortion the fabric of spacetime. Matter determines the curvature of spacetime. Particles follow geodesic paths.

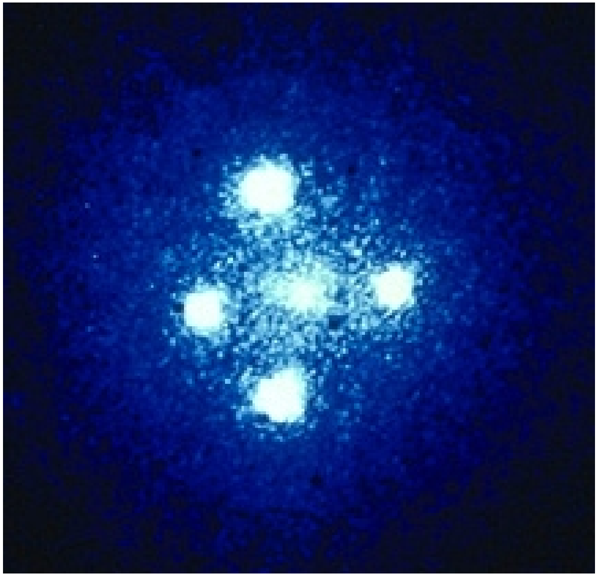








Gravitational lensing Light from a very distant galaxy that passes a cluster of galaxies can be bent to produce double (rarely triple) images.



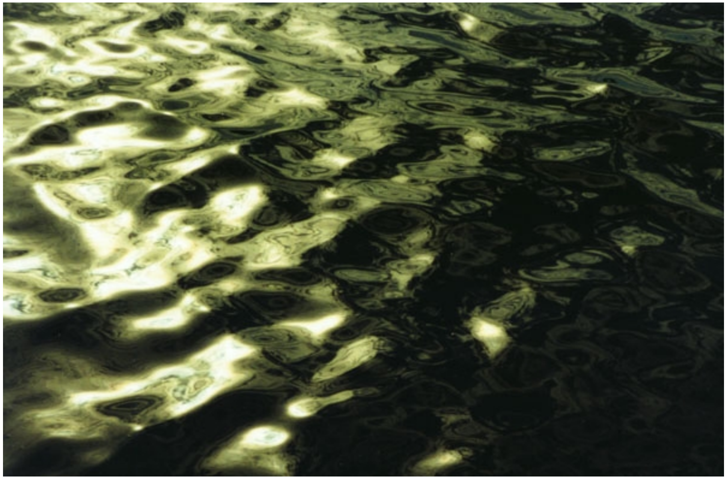
The most ”spectacular” display of gravitational lensing is the Einstein Cross: a quasar image (G2237-0305, as seen by the Hubble Space Telescope) is repeated 4 times.

Mathematical description of gravity

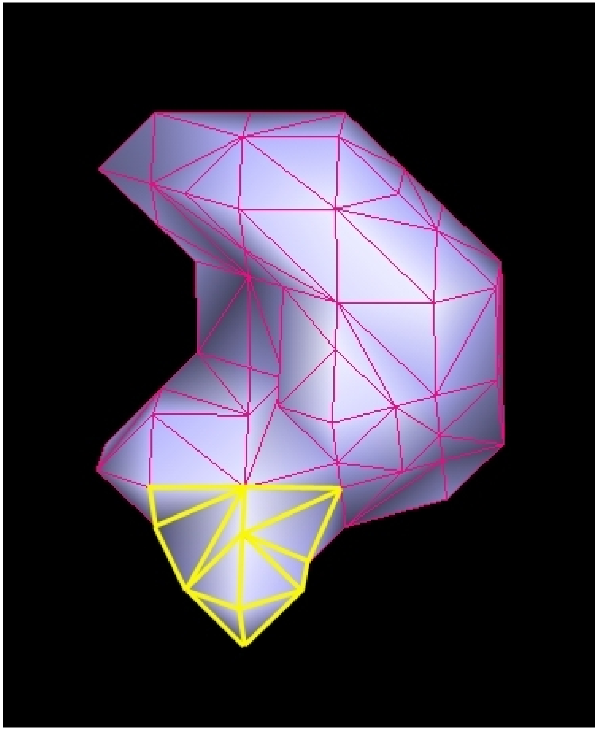
The mathematical notion of “field”:

$$\text{FIELD} : (\mathbf{r}, t) \longrightarrow \text{FIELD}(\mathbf{r}, t)$$

FIELD$(\mathbf{r}, t)$ can be a number, a vector, or a more complicated mathematical entity “sitting” at the point $(\mathbf{r}, t)$



2D WATER FIELD:
WATER$(\mathbf{r}, t)$ is the height of water with respect to a plane, at the point $\mathbf{r} \in$ plane and at time t



The metric field METRIC gives the metrical relations at the different points of spacetime (as the length of a vector “sitting” at the point $(\mathbf{r}, t)$)

CURVATURE = function of METRIC

Einstein’s equation:

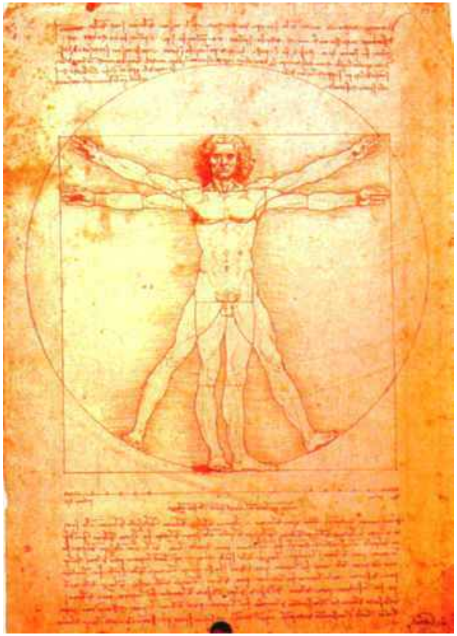
CURVATURE $=$ MASS-ENERGY

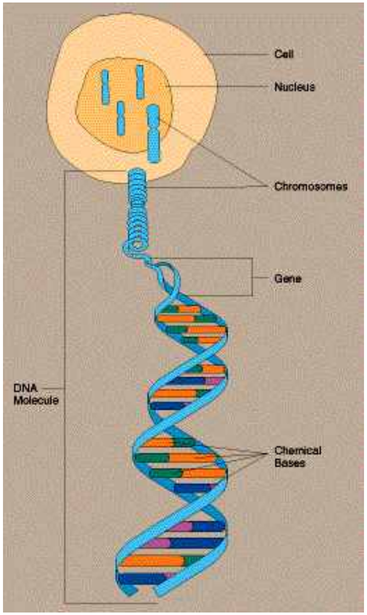
which extends Newton-Poisson equation

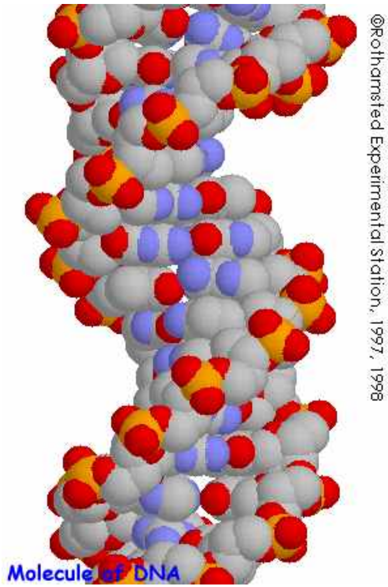
$$-\Delta V = \rho$$

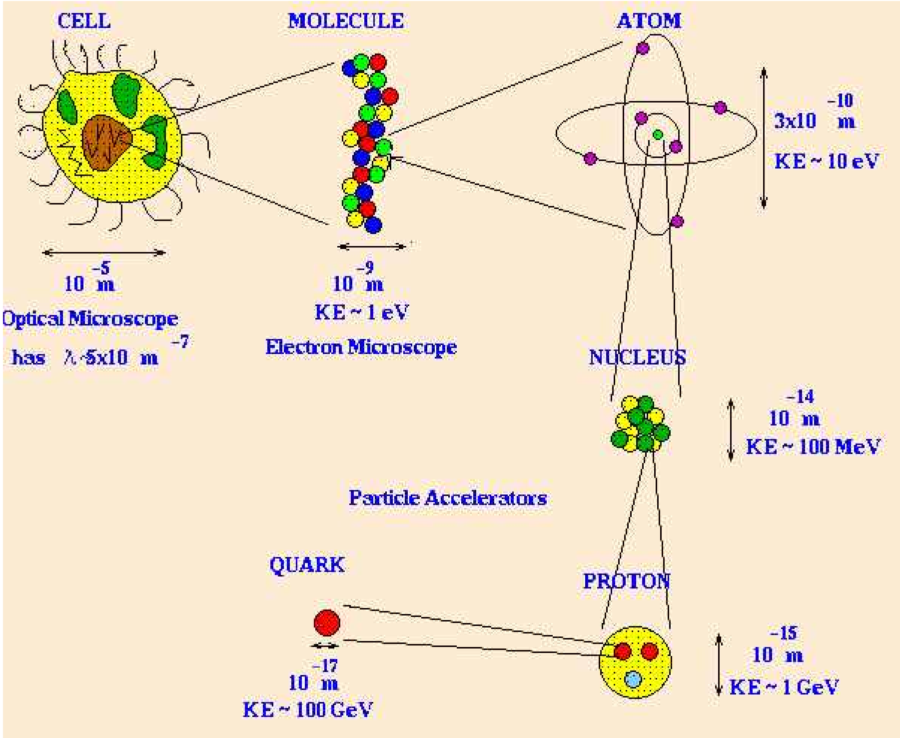
The Small Scale Structure of the World

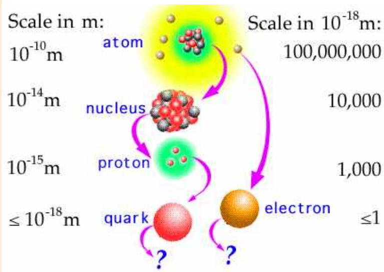
Is Man The Measure Of All Things ?











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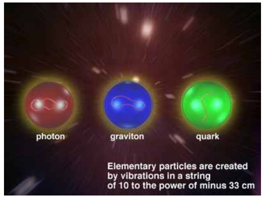
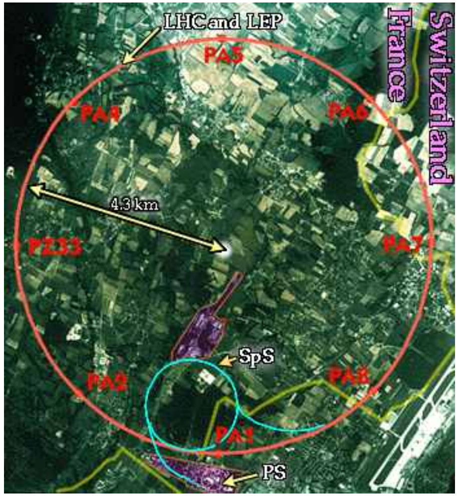


How do we “see” all this?

with microscopes...

very big “microscopes”



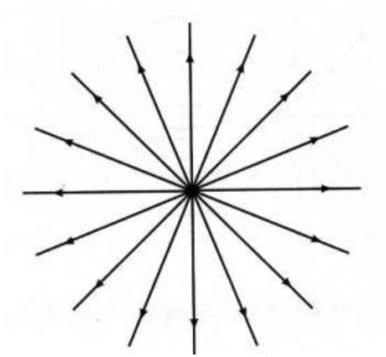
.... and with mathematics ....

recall the notion of field:

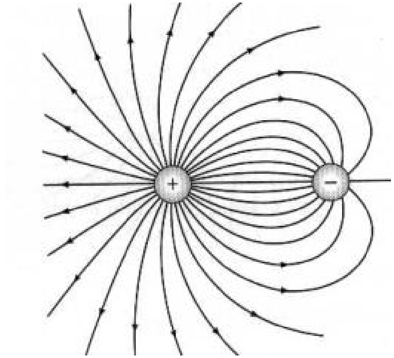
$$\text{FIELD} : (\mathbf{r}, t) \longrightarrow \text{FIELD}(\mathbf{r}, t)$$

$\text{FIELD}(\mathbf{r}, t)$ can be a number, a vector, or a more complicated mathematical entity “sitting” at the point $(\mathbf{r}, t)$

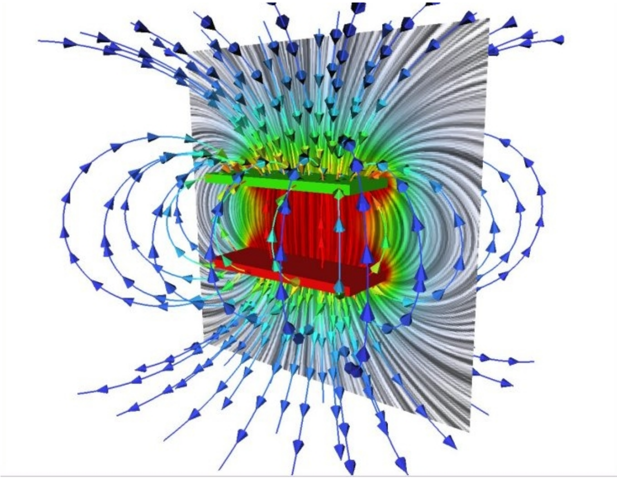
ELECTROMAGNETIC FIELDS: $\mathbf{E} = \mathbf{E}(\mathbf{r}, t)$ and $\mathbf{B} = \mathbf{B}(\mathbf{r}, t)$

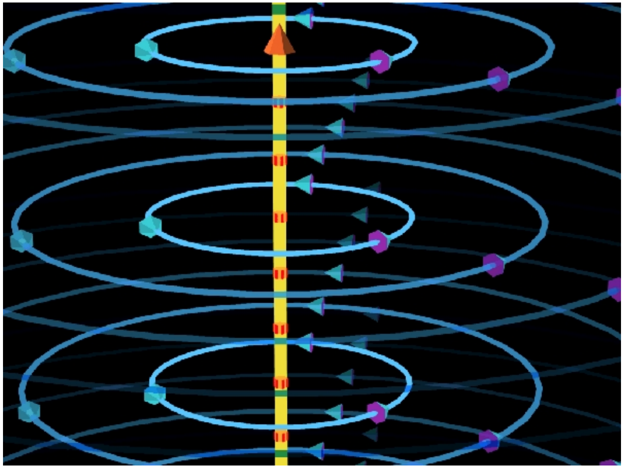


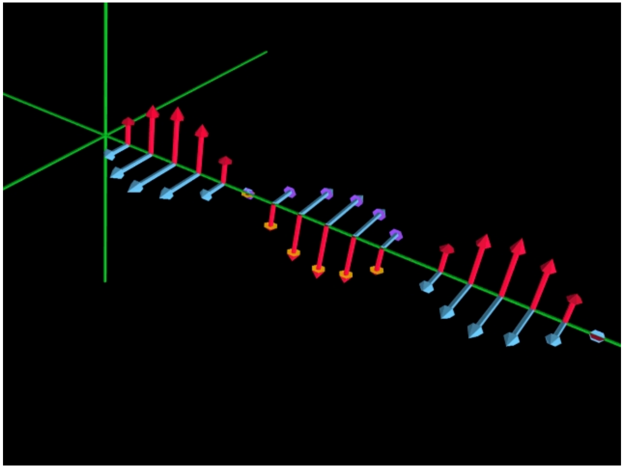
electric field $\mathbf{E}$ generated by a positive charge



electric field $\mathbf{E}$ generated by a positive charge and a negative charge

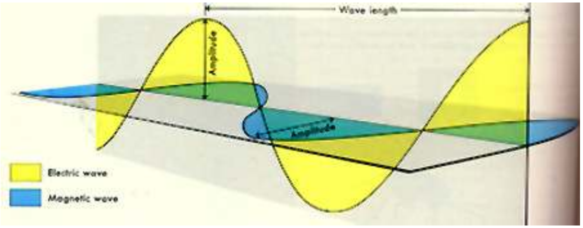


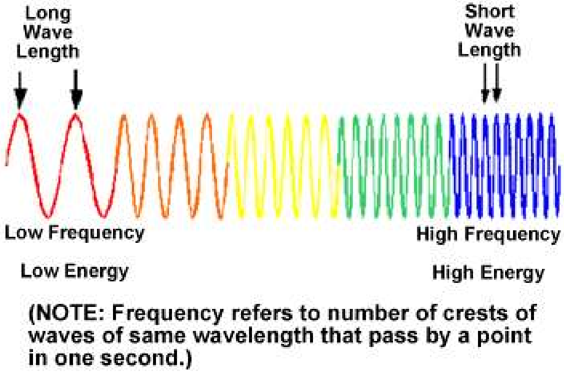


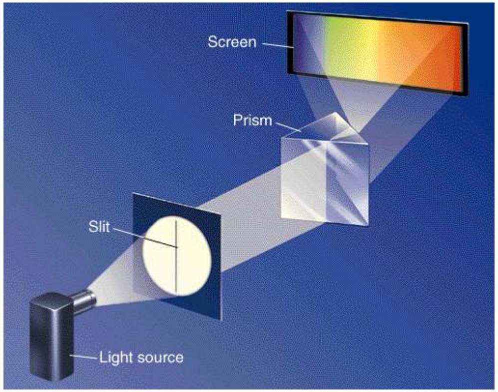


↑ $\mathbf{E}$ around a condenser
↗ $\mathbf{B}$ around a wire
→ $\mathbf{E}$ and $\mathbf{B}$ of an electromagnetic wave

Electromagnetic waves







Young's double slit experiment

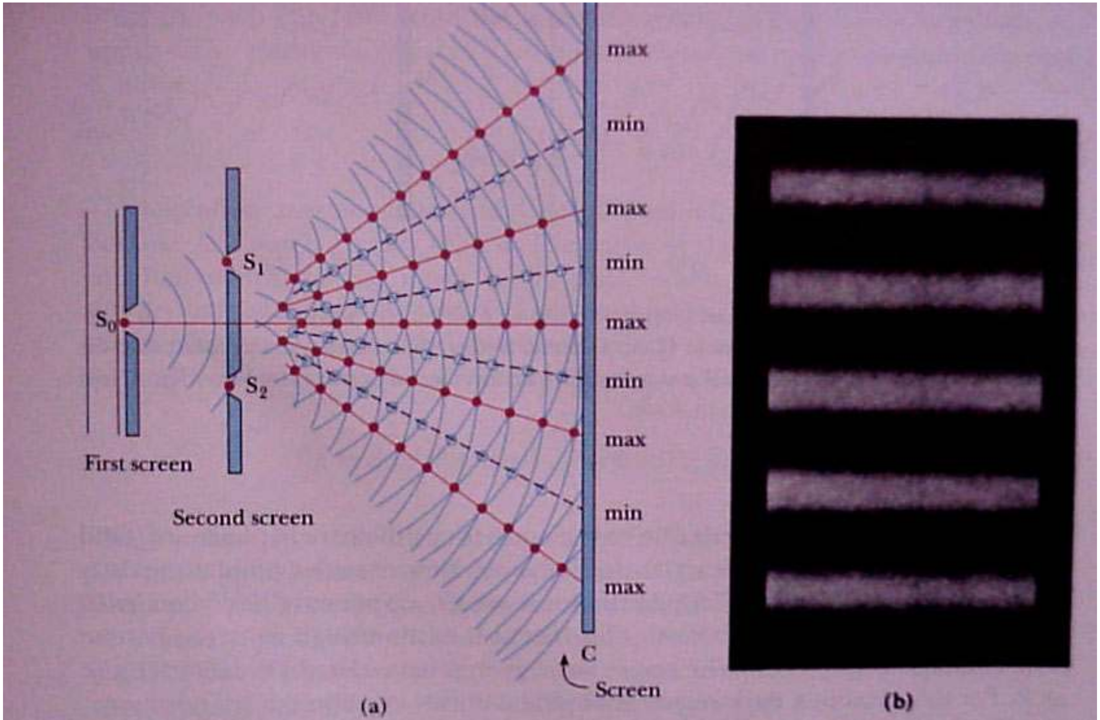
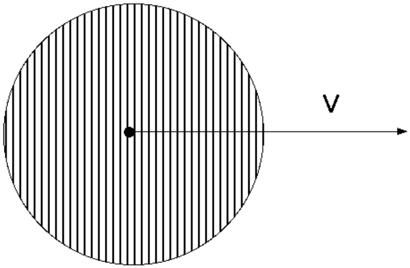


FIGURE 37.1 (a) Schematic diagram of Young's double-slit experiment. The narrow slits act as wave sources. Slits S_1 and S_2 behave as coherent sources that produce an interference pattern on screen C. (Note that this drawing is not to scale.) (b) The fringe pattern formed on screen C could look like this.



QUANTUM FIELD: with a particle of mass m moving with speed v is associated a WAVE FIELD Ψ with wavelength

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

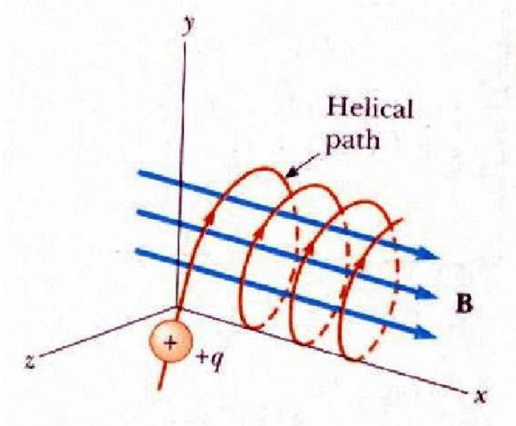
$h = 6.63 \times 10^{-34}$ is Planck constant

L = length scale of variation of the electromagnetic fields

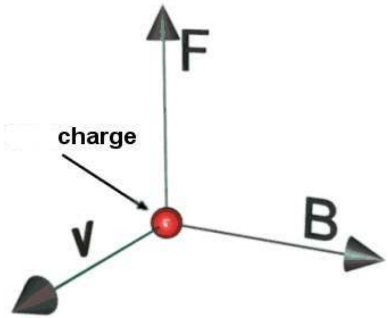
- If $\lambda \ll L$ the law of motion of the electron is the Newton-Lorentz law

$$m\frac{d^2\mathbf{r}}{dt^2} = e\mathbf{E} + e\mathbf{v} \times \mathbf{B}$$

For example



Remember the Lorentz force:



- Electron of 100 eV (K.E.)

$$v = \sqrt{\frac{2\,\text{K.E.}}{m}} = \sqrt{\frac{(2)(100\ \text{eV})(1,6 \times 10^{-19}\ \text{J/ eV})}{9.1 \times 10^{-31}\text{Kg}}} = 5.9 \times 10^{6}\ \text{m/s}$$

$$\lambda = \frac{h}{mv} = 1.2 \times 10^{-10}\ \text{m} = 1.2\ \text{Å}$$

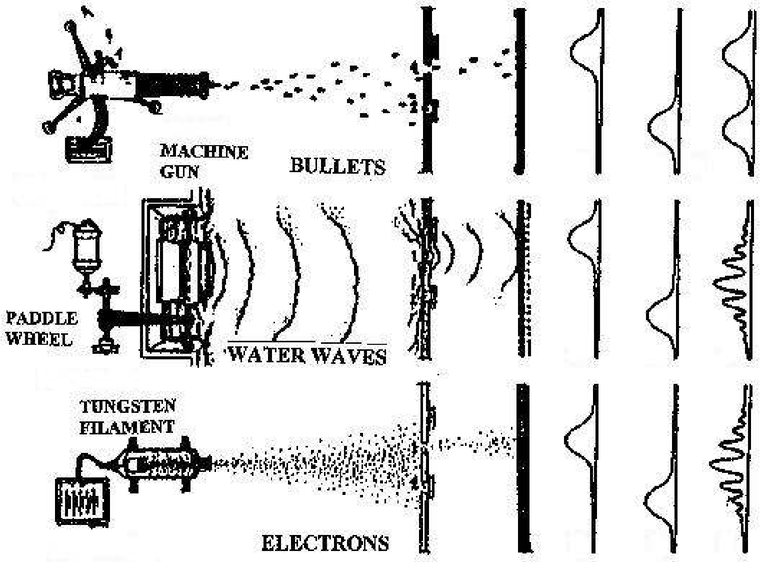
- Ultrarelativistic electron (v=c)

$$\lambda = \frac{h}{mc} \sim 10^{-13}\ \text{m}$$

- Ball of 1 Kg moving at 1 m/s

$$\lambda = 6.63 \times 10^{-34}\ \text{m}$$

- If $\lambda \sim L$ there are new QUANTUM LAWS OF MOTION



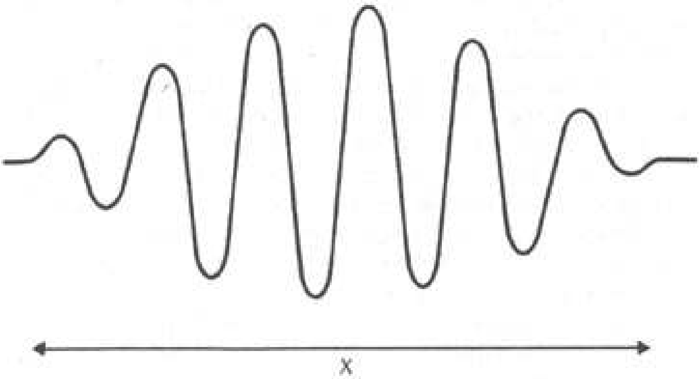
$\lambda \ll L$ (classical motion)

$\lambda \sim L$ (quantum motion)

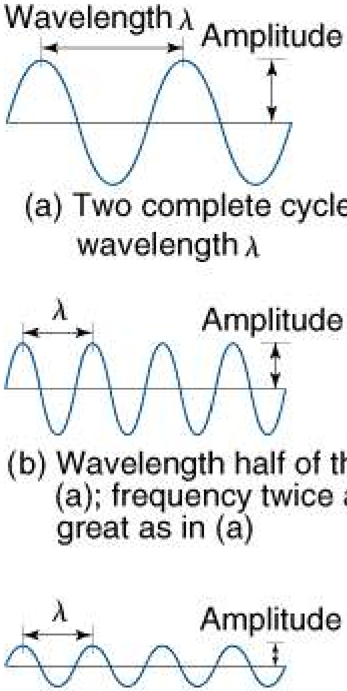
If $\lambda \sim L$ the quantum field Ψ produces strong deviations from classical motion

$|\Psi(\mathbf{r})|^2$ = intensity of electrons at the screen (= probability that a single electron hits the screen at the point $\mathbf{r}$)

Ψ is a “wave” and the particle is somewhere in the region where the intensity of the wave is high



a wave packet corresponding to a particle located somewhere in the region X



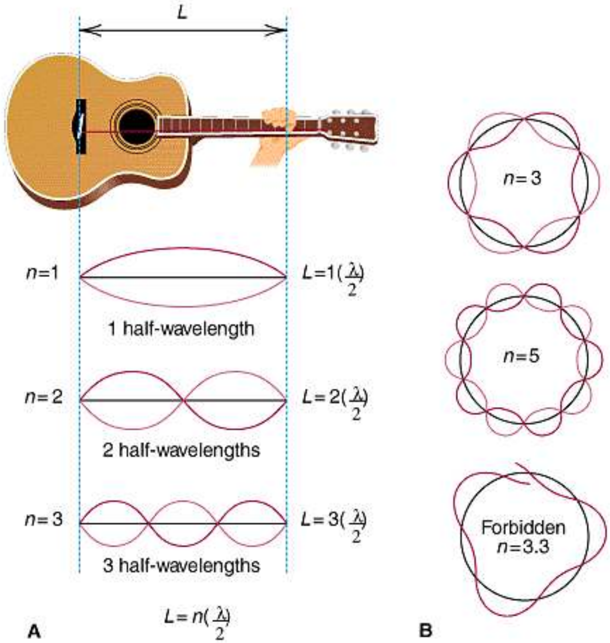
(a) Two complete cycles of wavelength λ

(b) Wavelength half of that in (a); frequency twice as great as in (a)

(c) Same frequency as (b), smaller amplitude

$|\Psi(\mathbf{r})|^2$ = probability that the the particle is in the point $\mathbf{r}$

Inside Hydrogen atom ($L \sim 1$ Å)



$$2\pi r = n\frac{h}{mv}$$

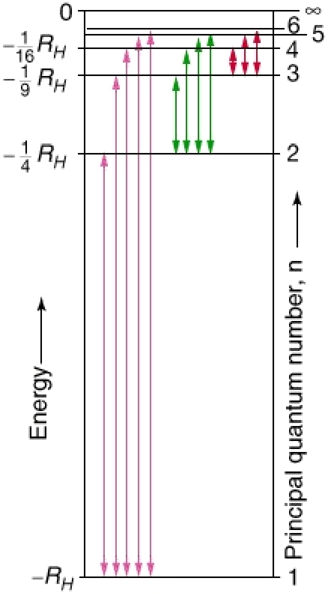
$$r = n\frac{\hbar}{mv}$$

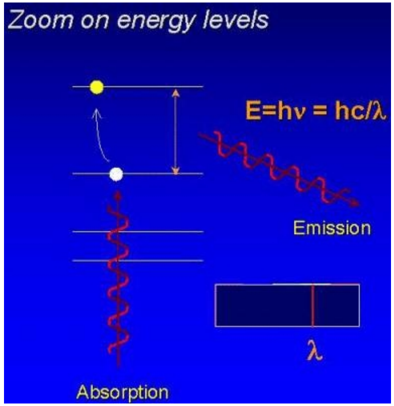
$$\frac{mv^2}{r} = \frac{e^2}{r^2}$$

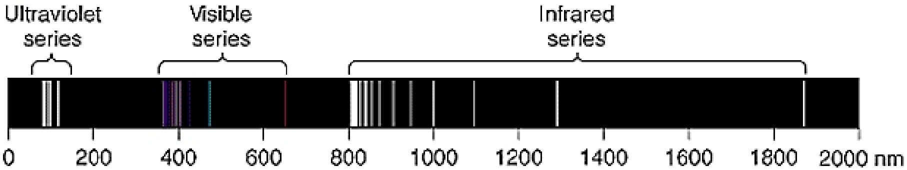
$$r = n\frac{\hbar^2}{me^2}$$

$$E = \frac{1}{2}mv^2 - \frac{e^2}{r} = -\frac{1}{2}\frac{e^2}{r} = -\frac{1}{2}\left(\frac{me^4}{\hbar^2}\right)\left(\frac{1}{n^2}\right)$$

$$\Delta E = E_n - E_{n'} = \frac{1}{2}\left(\frac{me^4}{\hbar^2}\right)\left(\frac{1}{n'^2} - \frac{1}{n^2}\right)$$







$$R_H = \frac{me^4}{4\pi\hbar^3 c} = 109737,31\text{cm}^{-1}$$

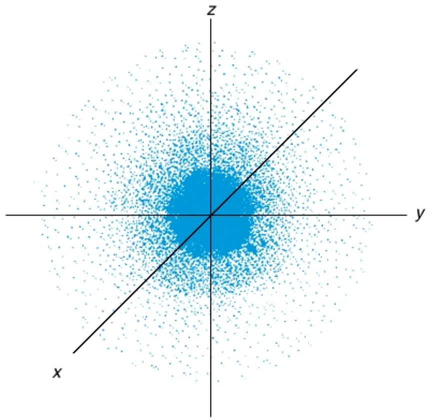
In general the Ψ-FIELD is solution of Schrödinger equation

$$i\hbar\frac{\partial\Psi}{\partial t} = -\frac{\hbar^2}{2m}\Delta\Psi + V$$

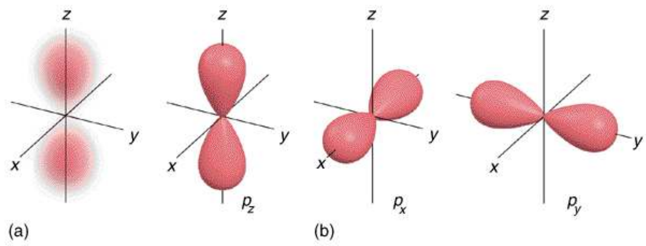
and the particle evolves according to Bohm's law

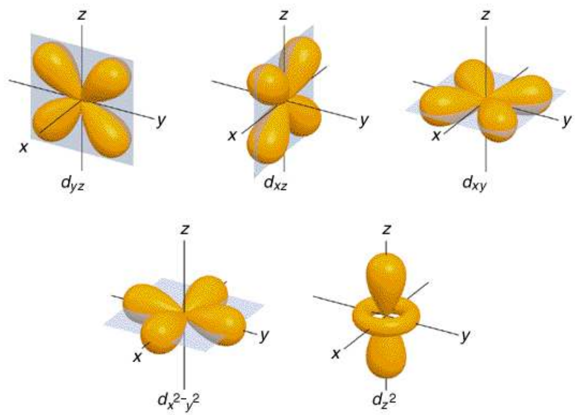
$$\frac{d\mathbf{r}}{dt} = \frac{\hbar}{m}\,\mathrm{Im}\,\frac{\nabla\Psi}{\Psi}$$

Ψ-FIELD of lowest energy

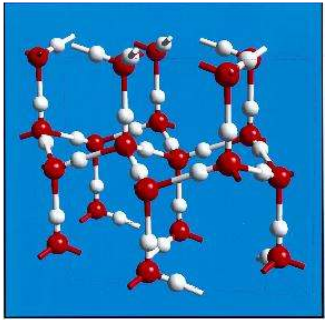


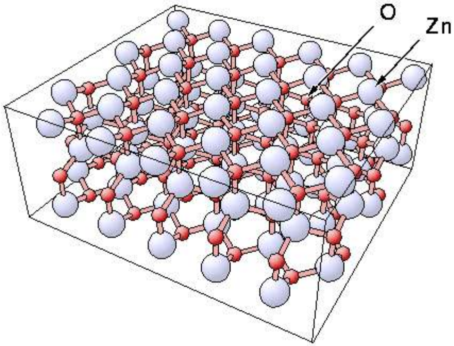
Ψ-FIELDS of higher energy



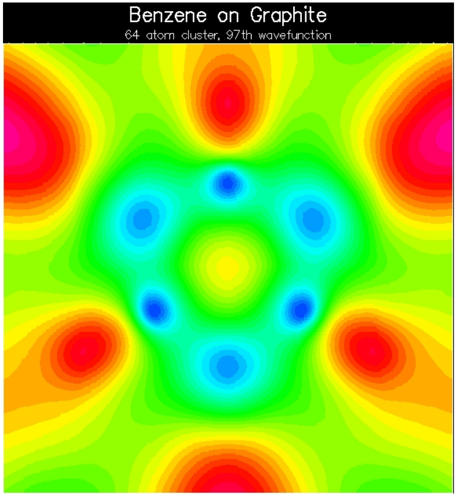


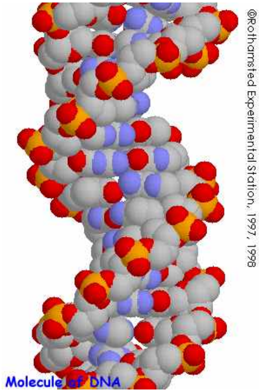
The quantum laws determine the structure of matter ... and life



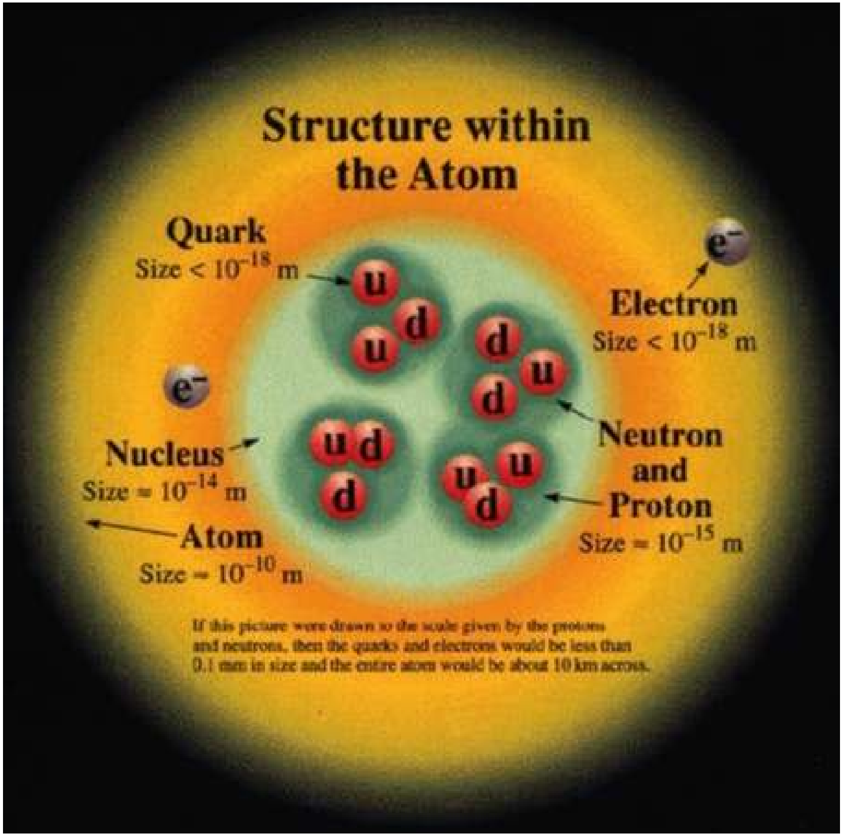


ZnO(000-1)|(-1-1-1) (wurtzite) surface





Inside the nucleus



Standard Model of

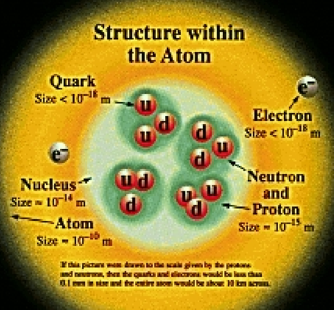
FUNDAMENTAL PARTICLES AND INTERACTIONS

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2,...

Leptons spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$< 2 \times 10^{-8}$	0
e electron	5.1×10^{-4}	−1
ν_μ muon neutrino	$< 3 \times 10^{-4}$	0
μ muon	0.106	−1
ν_τ tau neutrino	$< 4 \times 10^{-2}$	0
τ tau	1.784	−1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	4×10^{-3}	2/3
d down	7×10^{-3}	−1/3
c charm	1.5	2/3
s strange	0.15	−1/3
t top (not yet observed)	> 89	2/3
b bottom	4.7	−1/3



BOSONS

force carriers
spin = 0, 1, 2,...

Unified Electroweak spin = 1	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.6	−1
W^+	80.6	+1
Z^0	91.16	0

Strong or color spin = 1	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge

Confinement

Residual Strong Interactions

PROPERTIES OF THE INTERACTIONS

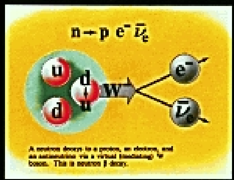
Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength for two u quarks at: 10^{-18} m (relative to electromagnetic)	10^{-41}	0.8	1	25	Not applicable to quarks
Strength for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

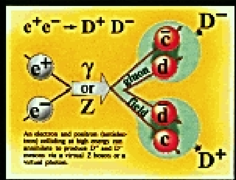
Sample Fermionic Hadrons					
Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$					
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	−1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	−1	1.672	3/2

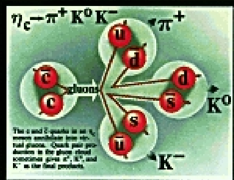
Sample Bosonic Hadrons					
Mesons $q\bar{q}$					
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	−1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
D^+	D+	$c\bar{d}$	+1	1.869	0
η_c	eta-c	$c\bar{c}$	0	2.980	0

Matter and Antimatter

Figures



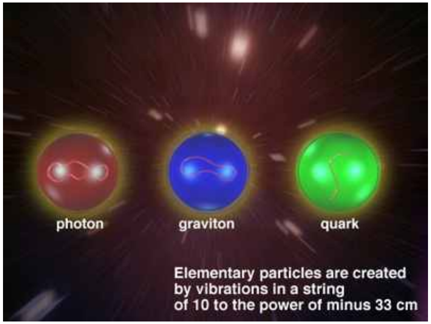




Contemporary Physics Education Project

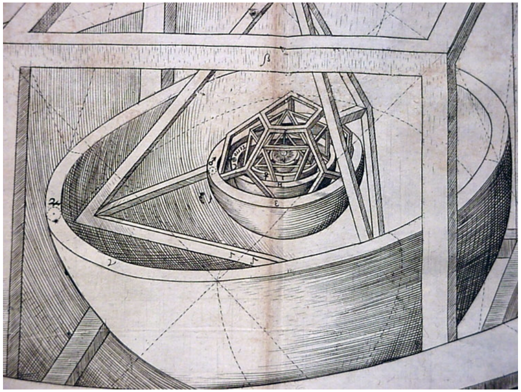
U.S. DEPARTMENT OF ENERGY
LAWRENCE BERKELEY LABORATORY
STANFORD LINEAR ACCELERATOR CENTER
SUPERCONDUCTING SUPER COLLIDER LABORATORY
CERN-MICROCOSM
IBM
ROCKWELL INTERNATIONAL
MARTIN MARIETTA ASTRONAUTICS GROUP
AMERICAN ASSOCIATION OF PHYSICS TEACHERS
BURLE Electron Tubes

What about $\lambda < 10^{-18}$ m ?



unfortunately, no experiments...

Back to the origin of the universe ...



The great Kepler and the fallacies of pure reason ...

Physics of creation?