Symmetry and Particle Physics

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Summer Student Lecture

I. Matter, Particles, and the Standard Model

A. What are Particles?

B. The Standard Model

C. The Big Bang

II. Symmetry and Conservation

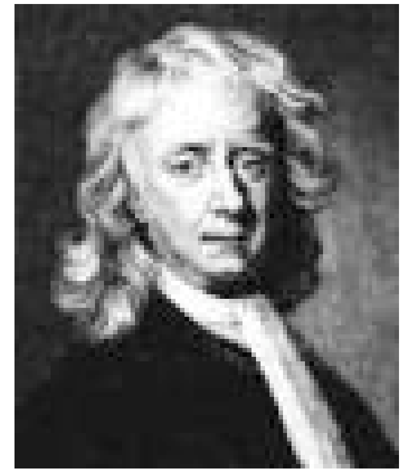
A. Conservation Laws

B. History of CP Violation

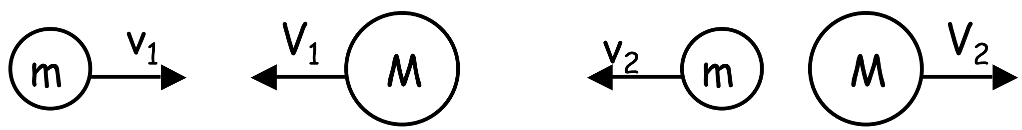
C. Connection to Antimatter

III. Experimental Progress

Classical laws of motion



- "Natural philosophy" – Isaac Newton
  - Beginning of mathematical physics
  - Foundation in observing nature
- Conservation of Energy
- Conservation of (Linear) Momentum
- Conservation of Angular Momentum

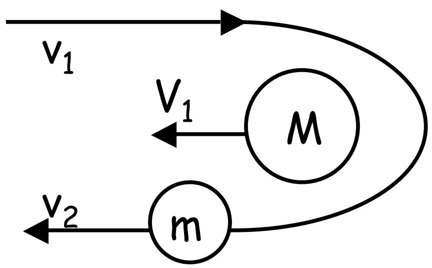


Conservation of Energy: $\_\ mv_1^2 + \_\ MV_1^2 = \_\ mv_2^2 + \_\ MV_2^2$

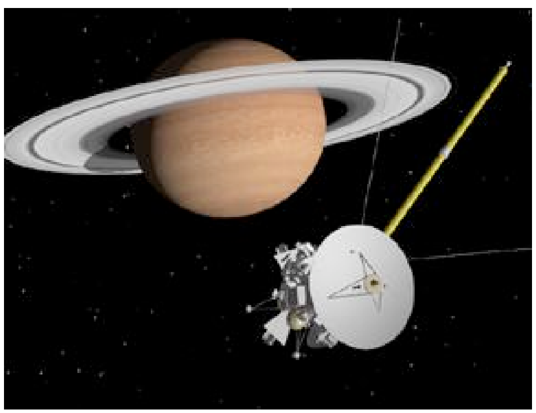
Conservation of Momentum: $m\vec{v}_1 + M\vec{V}_1 = m\vec{v}_2 + M\vec{V}_2$

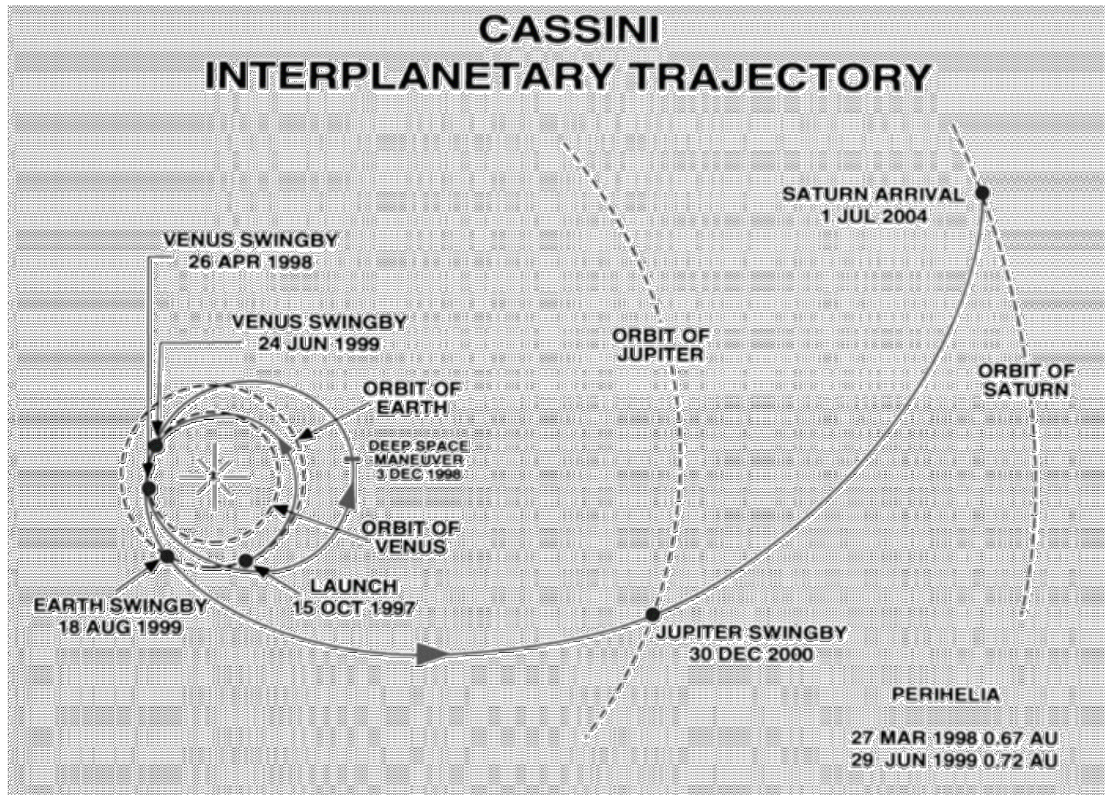
Slingshot effect

Elastic collision and gravity are both conserving



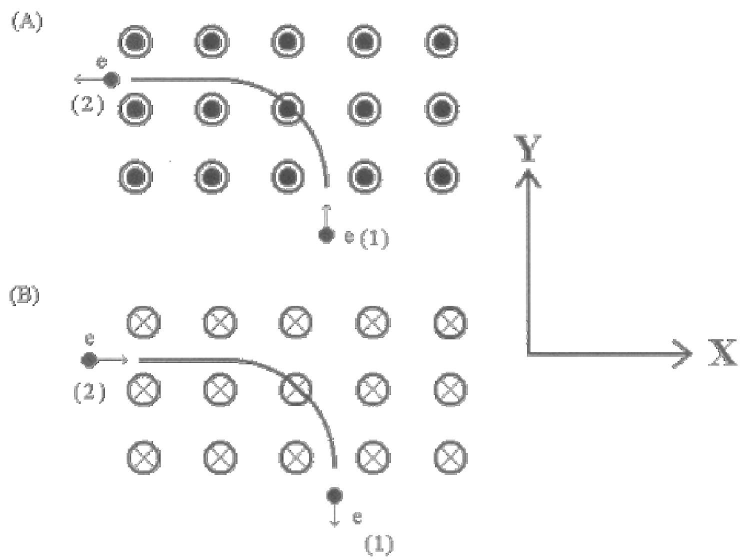
$$v_2 = 2V_1 + v_1 \quad (M >> m)$$





Lorentz Force

- Charged particle bends in a magnetic field
- Is momentum conserved?



- Understanding conservation laws tells you something about the interaction

Great Moments in Physics

1687	Newton discovers the Law of Gravitation
1787	Coulomb discovers the Law of Electrostatic Attraction and Repulsion
1803	Dalton's Atomic Theory
1865	Maxwell's Equations of Electromagnetism
1870	Periodic Table of the Elements
1897	J. J. Thomson discovers the "electron"
1911	Rutherford shows that the atom has a nucleus or center, where the positive charge and most of the mass is concentrated.
1914	Rutherford discovers the "proton"
1926	Schrödinger Equation- Quantum Mechanics
1926- 1930	More understanding of atomic structure and the emission and absorption of light by atoms.
1932	Chadwick discovers the neutron (neutral component of the nucleus)

Fundamental Building Blocks of Matter

- Forces Between Particles (Bosons)

Force	Relative Strength	Range	Typical Decay time
Nuclear	10^{3}	10^{-13} cm	10^{-23} sec
Electromagnetic	1	$1/r^{2}$ (long range)	10^{-20} sec
Electroweak	10^{-11}	10^{-16} cm (very short)	10^{-10} - 10^{-6} sec-> several min..
Gravitational	10^{-39}	$1/r^{2}$ (long range)	-----

Noether’s Theorem

- Conservation laws and symmetries are closely related. (Emmy Noether 1915)
  - o Mathematical proof was praised by Einstein

- Energy conservation < > Time symmetry
- Momentum conservation < > Displacement symmetry
- Angular momentum < > Rotational symmetry

Continuous Symmetries

i. Translational (x,y,z >> 3 degrees of freedom)

.........Momentum (P_x, P_y, P_z ....)

ii. Temporal (T>>> 1 degree of freedom)

....Energy (E>>1 degree of freedom)

iii. Rotational (θ_1, θ_2, θ_3 >> 3 degrees of freedom)

For these Continuous symmetries there exist a

Conservation Law

Conservation Laws

Dynamical Conservation Laws

I. Conservation of Linear Momentum

II. Conservation of Energy

III. Conservation of Angular Momentum

IV. Other Discrete Conservation Laws

a. Charge

b. Baryon and Lepton number

c. Parity, CP, CPT,......

Should Symmetry be included ?

What goes in……….is…………What comes out

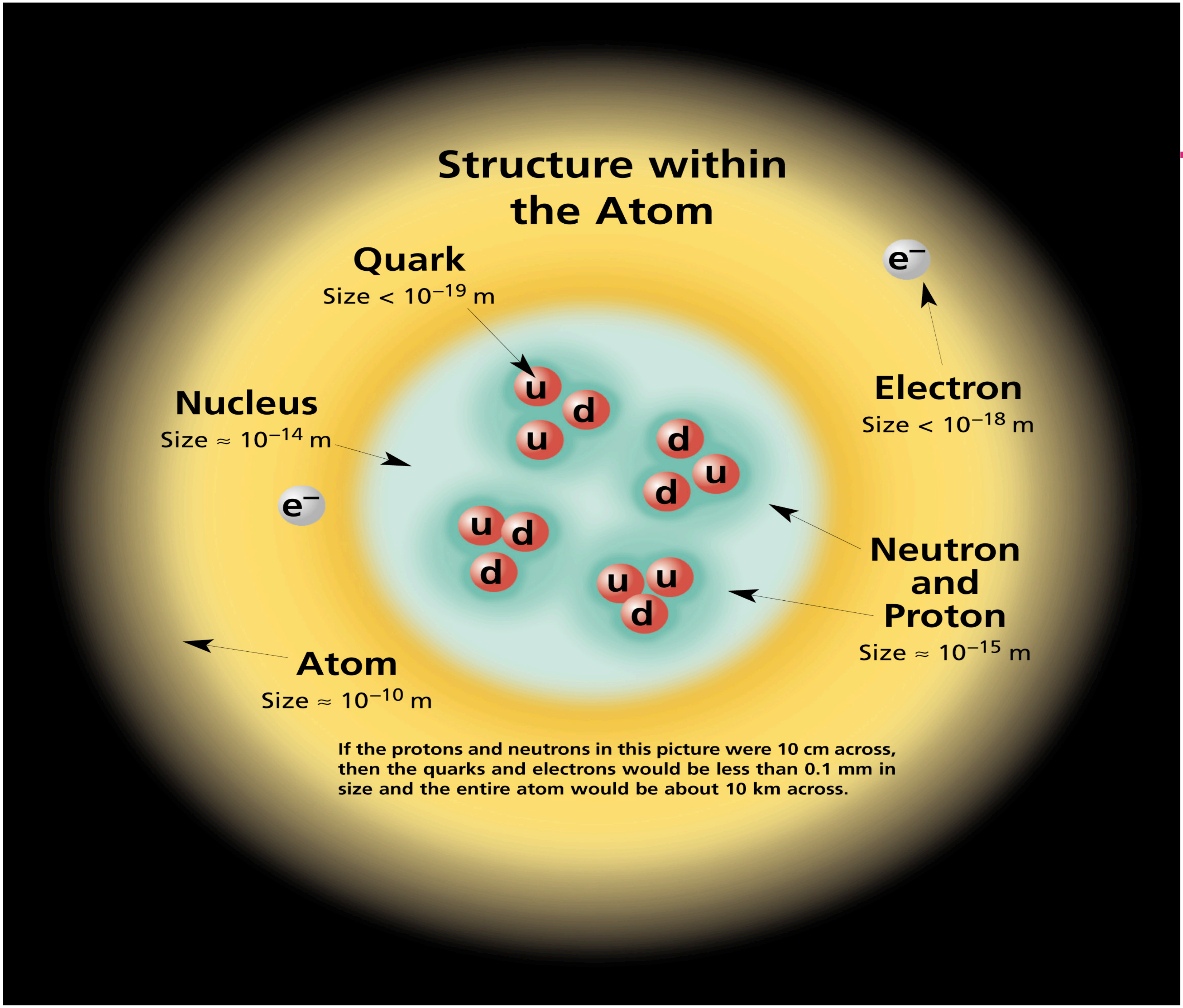
Observed Patterns

- Patterns on properties of the elements lead to the periodic table
- The periodic table lead to the atom

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Unq	105 Unp	106 Unh	107 Uns	108 Uno	109 Une	110 Unn								

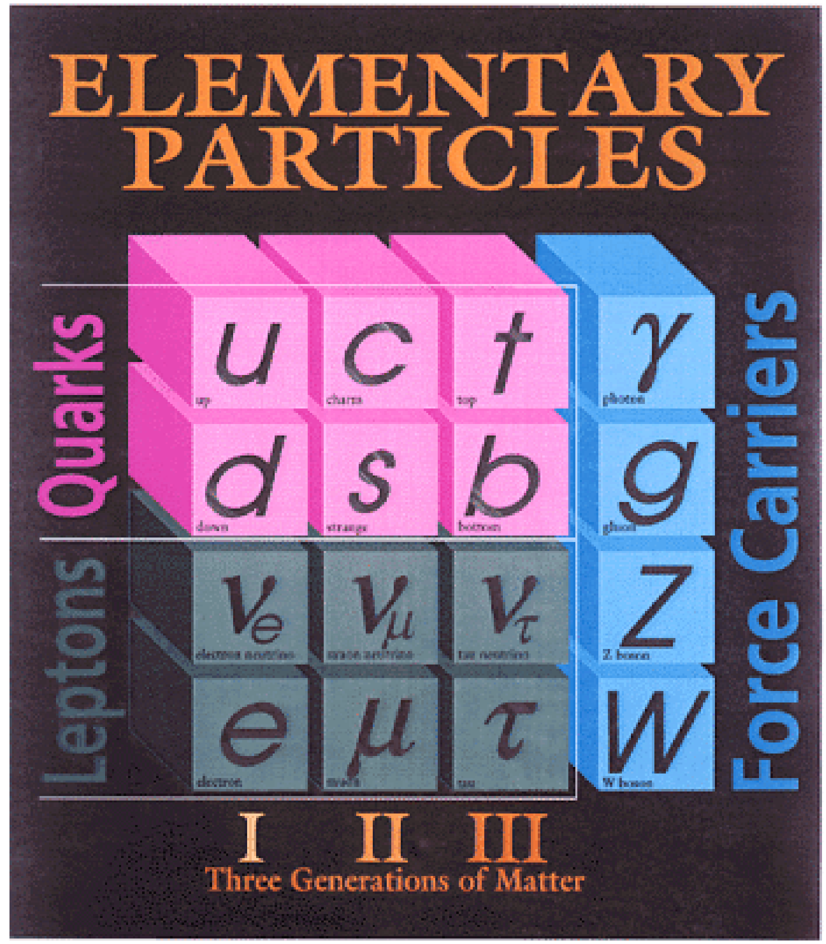
58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Dmitri Mendeleev


Structure within the Atom
Quark
Size < 10^{-19} m
e⁻
Electron
Size < 10^{-18} m
Nucleus
Size ≈ 10^{-14} m
u
d
u
d
u
d
e⁻
u
d
d
u
u
d
Neutron and Proton
Size ≈ 10^{-15} m
Atom
Size ≈ 10^{-10} m
If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

Particles

- Discoveries
  - top quark 1995
  - bottom quark 1977
  - ν_τ (tau neutrino) 2000
  - direct CP violation (with CERN) 1999
- Some critical measurements
  - *t* and *W* mass 1998
  - QCD at highest energies 1988-now
  - proton structure 1984-95
  - charm lifetimes 1985-95



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	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

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
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Fundamental Symmetries of Nature

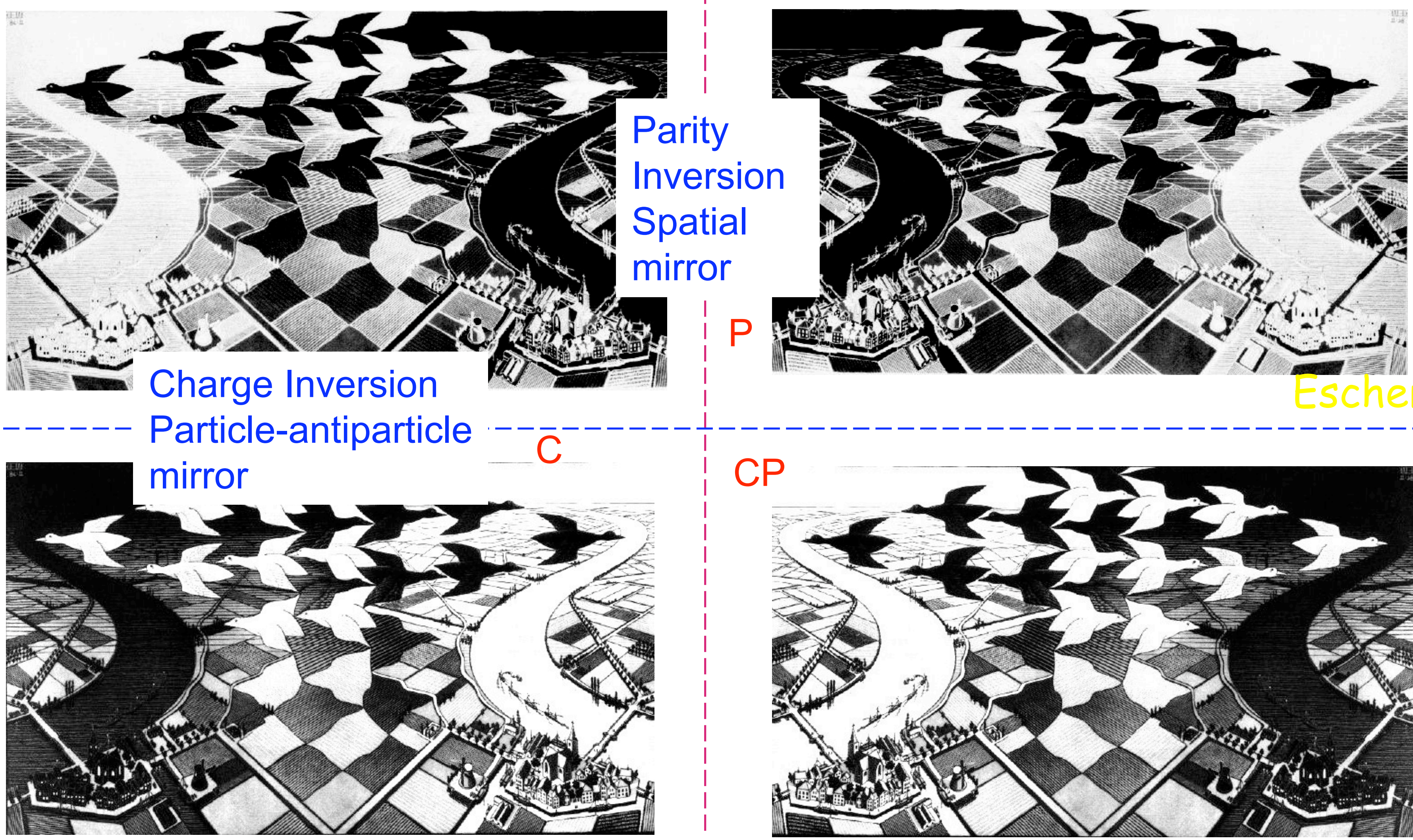
A Brief Summary

C	Charge Conjugation	(Antimatter World)
P	Parity Reversal	(Mirror World)
CP	C and P Together	(Antimatter Mirror World)
T	Time Reversal	(World Running Backward)
CPT	C and P and T	(Backward Running Antimatter Mirror World)

C	Strong	Electromagnetic	Weak
P	Strong	Electromagnetic	Weak
CP	Strong	Electromagnetic	Weak ?
CPT	Always Good	(Pauli)	
T	Strong	Electromagnetic	Weak ? (Indirect)

Experimentally, with Kaons and B Mesons: P CP CPT ?

Discrete Symmetries



Broken Symmetry

- Many symmetries in nature are not perfect

- We study these broken symmetries in particle physics

Why is there more matter than anti-matter in the universe?
This requires CP violation!

Why do the force carriers have vastly different masses?
This may require some sort of Higgs particle!

Anti-Matter

WHAT IS ANTI-MATTER ?

Every "particle" has a partner called an "anti-particle" .

The two have the same mass and the same lifetime (if it decays).

The main difference is that they have OPPOSITE electric charge.

Anti-Matter

• Examples:	Year of discovery
• Electron	(1897)
• Positron	(1932)
• Proton	(1919)
• Anti-Proton	(1955)
• Neutron	(1932)
• Anti-Neutron	(1956)

Matter (●) and Anti-Matter (❍) annihilate into other energy (~) particles and vice versa.

Pair Annihilation

● ❍ ➡ ~ ~

Pair Production (always created in pairs)

~ ~ ➡ ● ❍

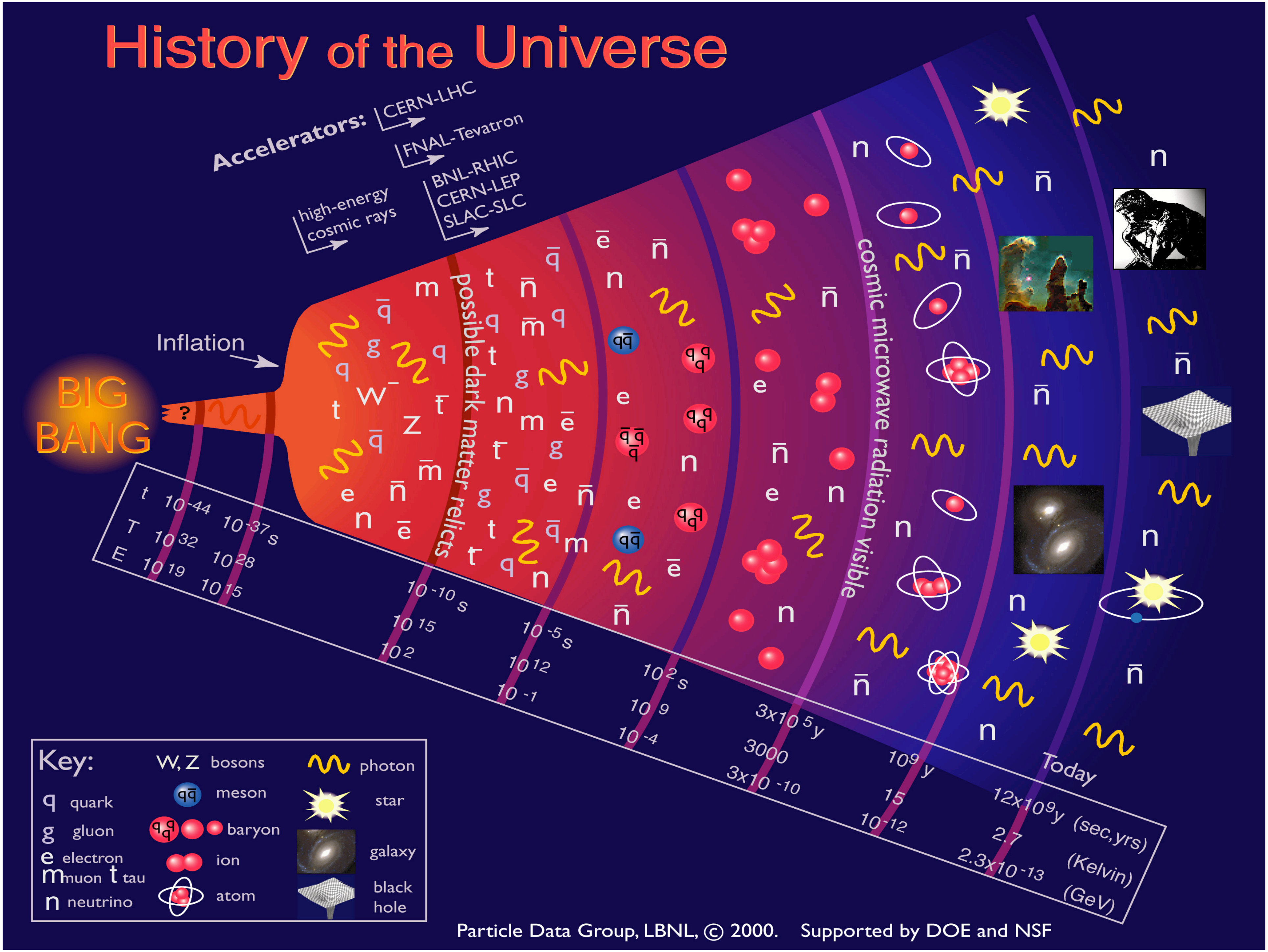
Anti_Hydrogen in the only anti-atom seen so far

(a few events at CERN and more than 50 events studies here at Fermilab)

No anti-Atoms in Cosmic rays are observed so far

Symmetry from the Beginning

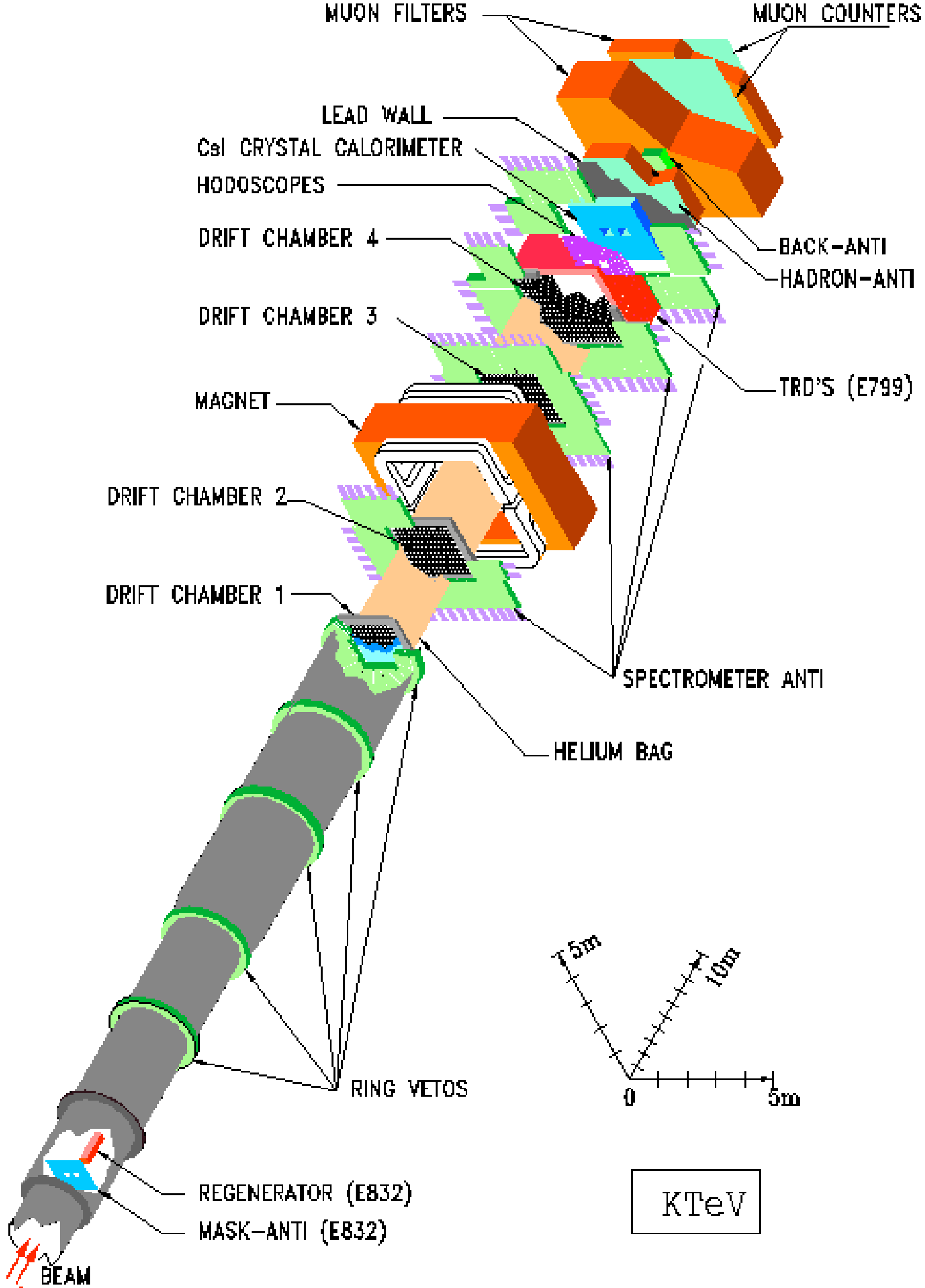
- Equal numbers of matter, anti-matter and Photons existed.
- Matter and Anti-matter annihilations p-photon pair production maintain a balance (for a while)
- A small asymmetry develops between the matter and anti-matter (origins unknown)
- As the Universe expands and cools the pair production stops (not enough energy for the reaction), and the matter annihilation continues until the anti-matter is depleted (as far as we know).
- The matter left over makes up the matter Universe (Stars, galaxies and Us)



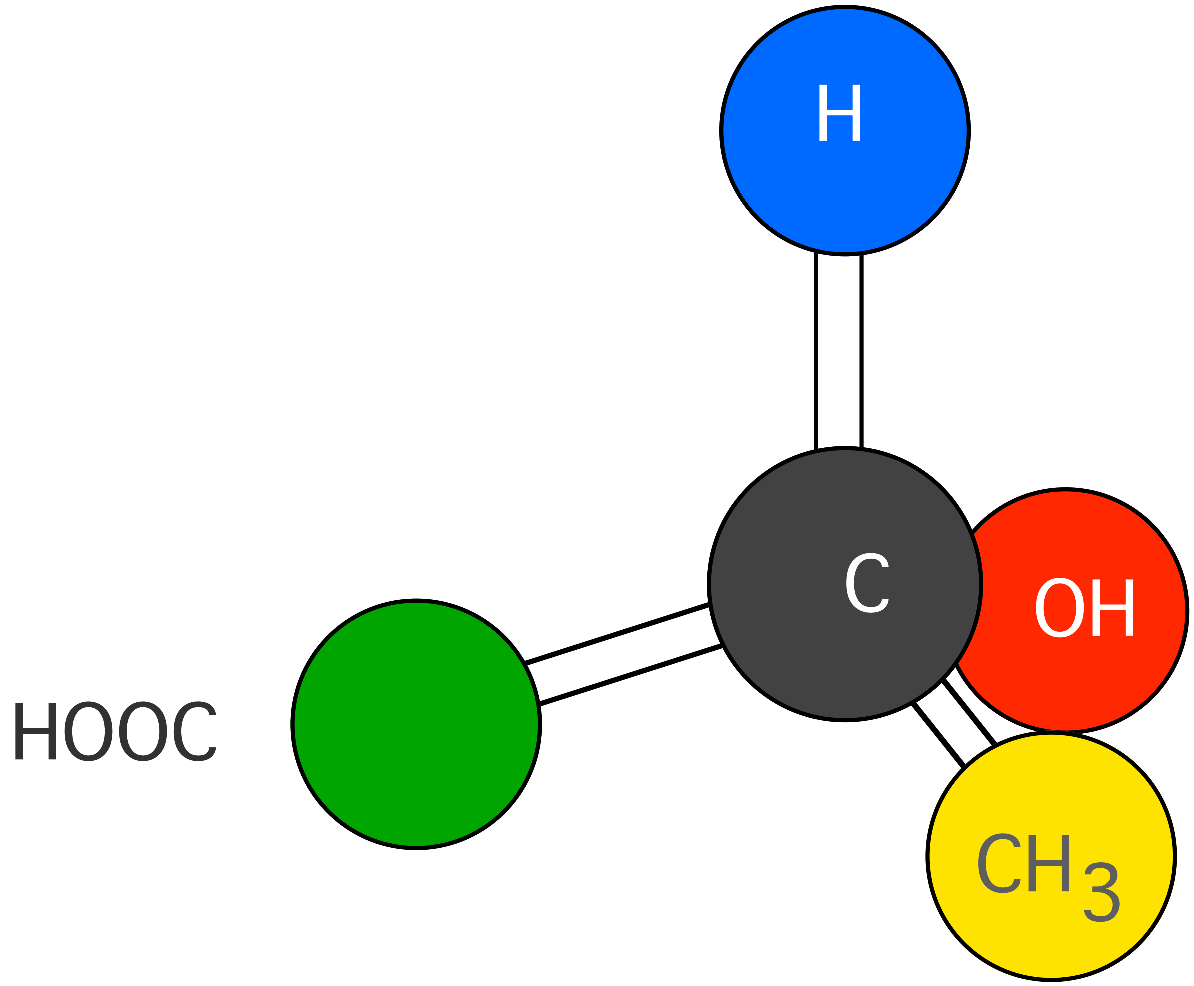
History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
10 -10 s
10 15
10 2
10 -5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10 -12
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

KTeV

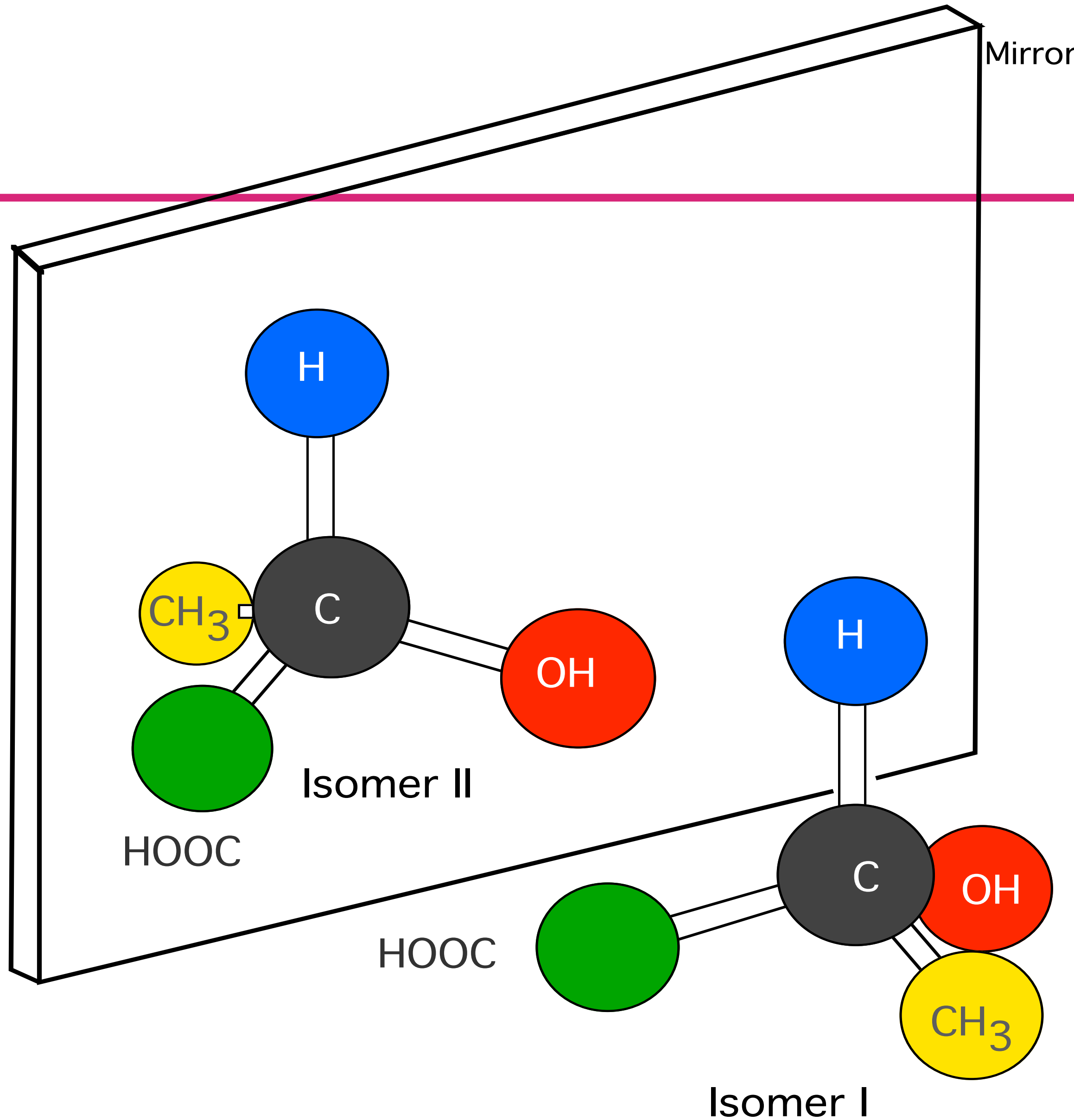
Creation Movie


MUON FILTERS
MUON COUNTERS
LEAD WALL
CsI CRYSTAL CALORIMETER
HODOSCOPES
DRIFT CHAMBER 4
BACK-ANTI
HADRON-ANTI
DRIFT CHAMBER 3
TRD'S (E799)
MAGNET
DRIFT CHAMBER 2
DRIFT CHAMBER 1
SPECTROMETER ANTI
HELIUM BAG
RING VETOS
5m
10m
0
5m
REGENERATOR (E832)
MASK-ANTI (E832)
BEAM
KTeV

INPUT



Isomer I



Lactic Acid

Conclusions

- Noether's Theorem: Conservation laws are related to symmetries
- Conservation laws in classical and modern physics
- Experiments reveal the symmetries, which often lead to theoretical ideas and better understanding of nature.
- Experiments reveal broken symmetries, which lead to an even more questions and answers