Historical Perspective

A lightning introduction to
Modern Nuclear and Particle Physics
Or
Subatomic Physics: The First 100 years

An Atomic Model

- *Matter is composed of atoms (molecules):*
  - A nucleus of mass A has Z protons, A-Z neutrons
  - Z electrons surround the nucleus to make the atom
  - Different Z determines chemistry
  - Differing A gives rise to isotopes

Birth of Atomic Physics

- *1895: X-rays observed from CRTs (science leads to fame and fortune!)*
- *1896: Uranium emits radiation*
- *1897: e/m measured for charged cathode rays (electrons); plum pudding model*
- *1898: new radioactive elements*
- *1900: Planck's radiation law*
- *1905: Photoelectric effect*
- *1911: Rutherford scattering: nucleus forms a tiny, heavy core*
- *1914: Bohr model for hydrogen*

Relativistic Quantum Mechanics

- *1923: Compton scattering*
- *1924-27: Birth of Quantum Mechanics*
- *Late 1920s: Fermions and Bosons*
- *1930: Dirac Equation*
- *1932: Discovery of the neutron*
- *1932: Discovery of the positron*

Electrons, protons, neutrons, photons and positrons established: photons are the mediators of the electromagnetic force

Møller scattering, Bhabha scattering, Mott scattering…

Some Outstanding Issues

- *How is the nucleus held together?*
  - New "strongly interacting" particles: Yukawa
- *Antiparticles*
  - Dirac Equation
- *Nuclear beta decay*
  - Neutrinos: Pauli and Fermi

Birth of Subatomic Physics

- *Early 1930s: Cosmic ray studies to get to "high" energy*
- *Mid 1940s: The first accelerators (WWII technology)*
- *Muon and pion discovered*
- *Muon is "electron-like"*
- *Three pions, strongly interacting*

Lepton: "light-weight"
Meson: "middle-weight"
Baryon: "heavy-weight"

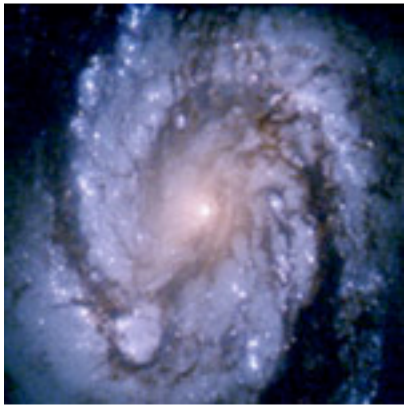
More Discoveries, Mysteries

- *Late 1940s: A bunch of new, unstable particles observed and characterized*
- *Strange particles: produced copiously, decays slowly*
- *Mid 1950s: Antiparticles for every particle, including baryons!*
- *1955: neutrino interaction seen*
- *1957: mirror-symmetry not obeyed in beta decay*
- *1961: Quark model introduced (not accepted!)*
- *1962: Two species of neutrinos established*
- *1963: Matter-Antimatter symmetry not universal*

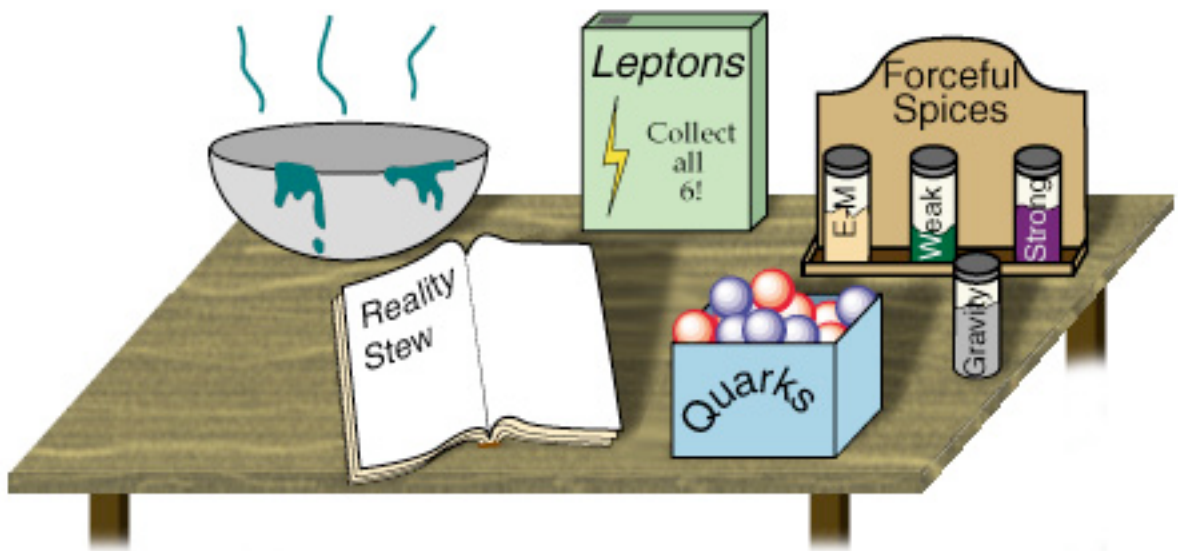
Modern Subatomic Physics

- *1960s: Proton has substructure; made up of hard, point-like objects*
- *1972: "neutral" weak interaction observed*
- *1974: Discovery of heavy quarks*
- *Mid 70s: Quark Model and QCD*
- *Late 1970s: Standard Model established*
- *1983: W and Z bosons directly observed*
- *1990s: Neutrinos have mass*

Progress over 2000 years



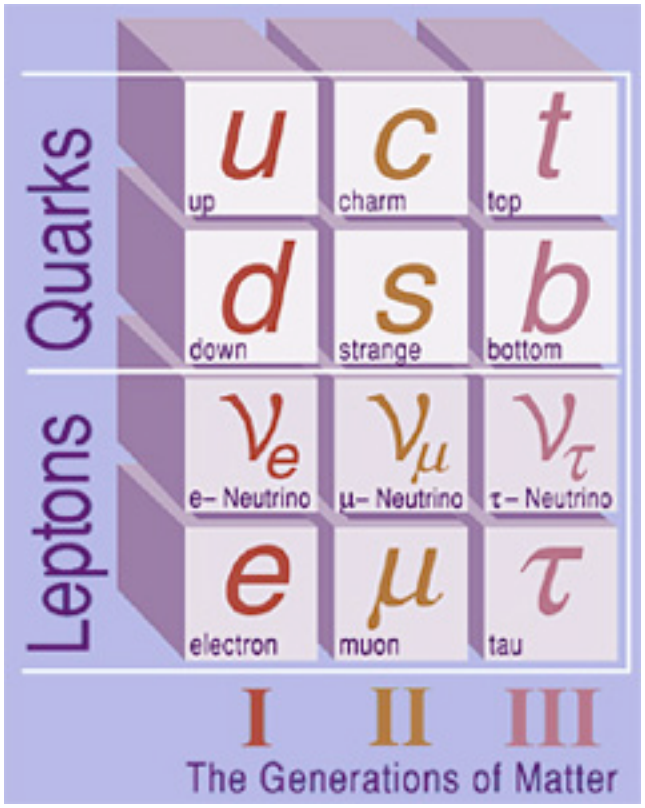
What are we made of?
What holds us together?



Fermions and Bosons

- *Particles possess spin: Intrinsic Angular Momentum*
- *Rest frame property: no classical analog*
- *Particles with integral spin are Bosons*
  - symmetric under identical particle interchange
- *Particles with half-integral spin are Fermions*
  - antisymmetric under identical particle interchange
  - Pauli's exclusion principle
- *Matter particles are Fermions*
- *Carrier particles are Bosons*

Particle (Fermion) Zoo (2007)



Visible matter made up of first generation quarks and leptons

Dark Matter?
Dark Energy??!!

Forces and Carriers (Bosons)

	Gravity	Weak (Electroweak)	Electromagnetic	Strong
Carried By	Graviton (not yet observed)	W^+ W^- Z^0	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and W^+ W^-	Quarks and Gluons
	10^{-43}	10^{-14}	10^{-3}	1

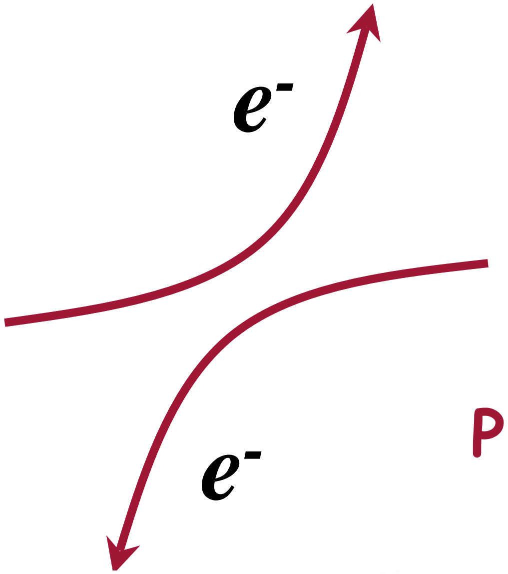
Gravity and Electromagnetic

Infinite range

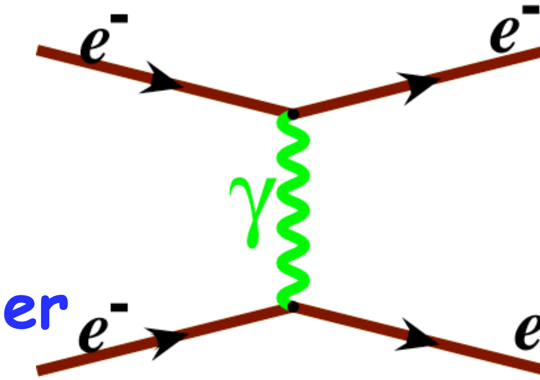
Strong and Weak

10^{-15} meter

Picture of an Interaction

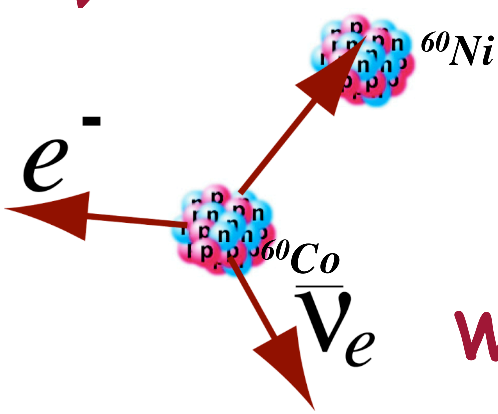


Electromagnetic interaction characterized by electric charge

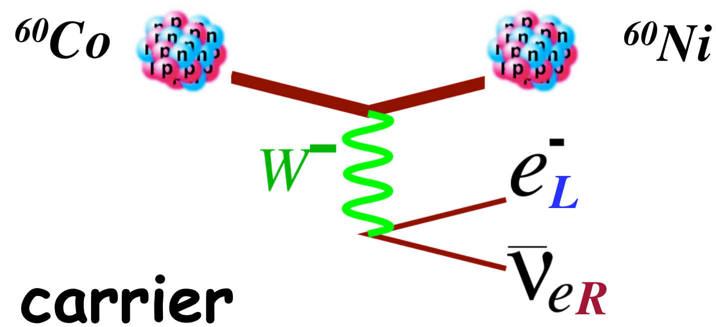


Photon is the force carrier

Weak interaction characterized by weak charge



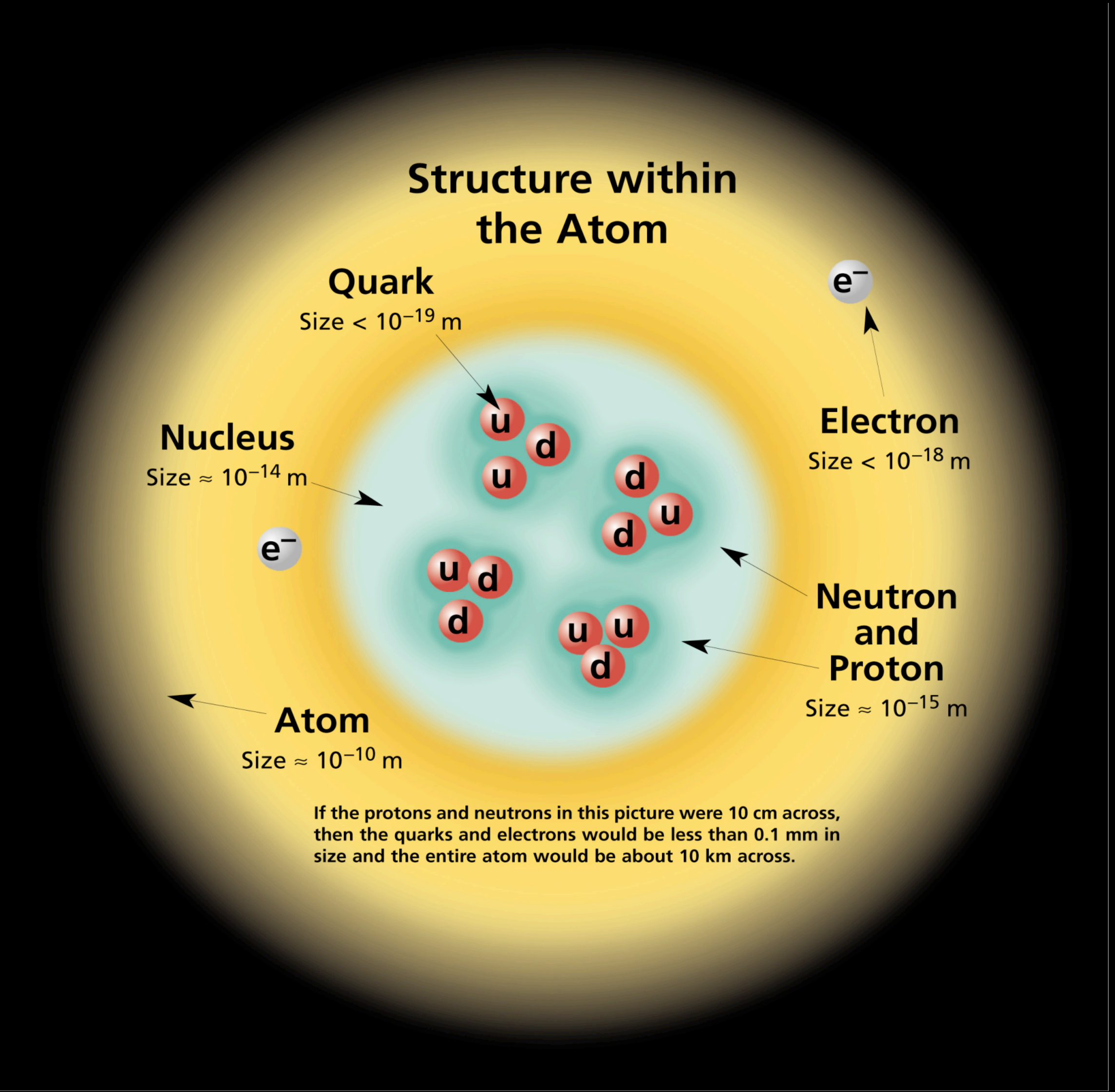
Radioactive decay of ^{60}Co Nucleus



W boson is the force carrier

Likewise, quarks carry strong charge (color), and exchange gluons

A Sense of Scale



History of Time

attometers

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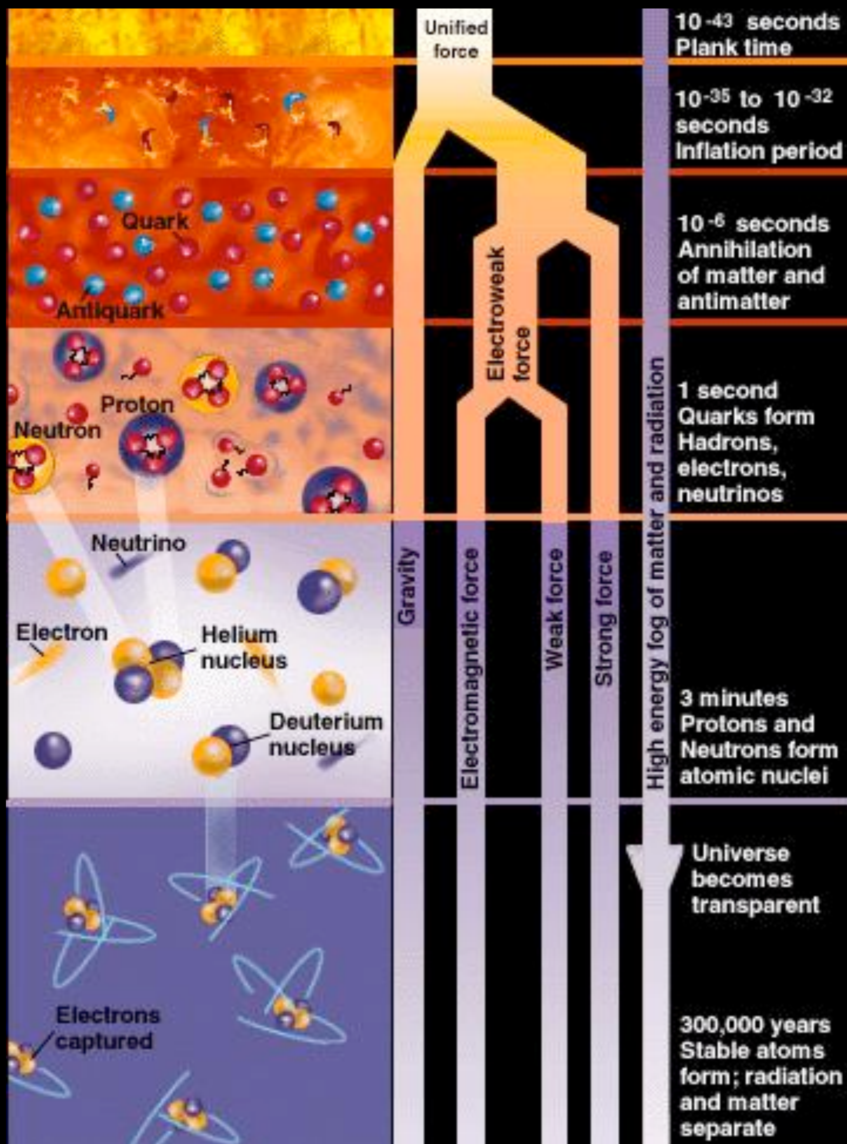
femtometers



femtometers

↓

picometers

Femtoscience

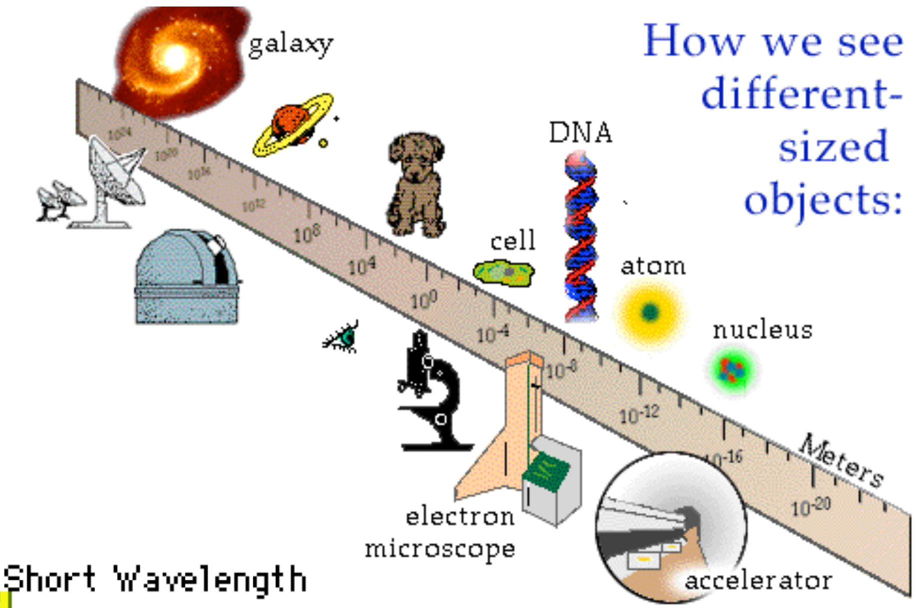
Resolving objects at 10^{-15} m (femtometer) requires special instrumentation

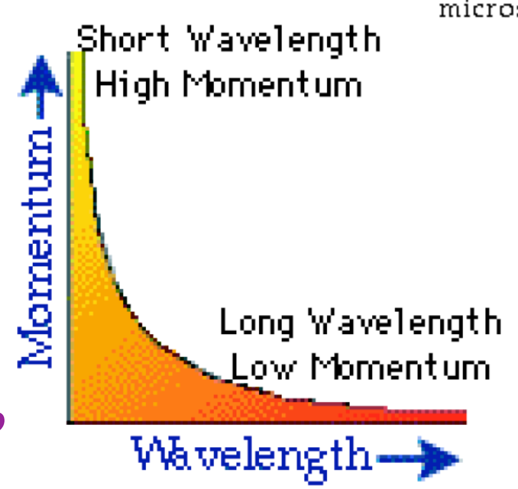
Particles are waves at nuclear scales

quantum mechanics

How to produce femtometer wavelengths in the laboratory?

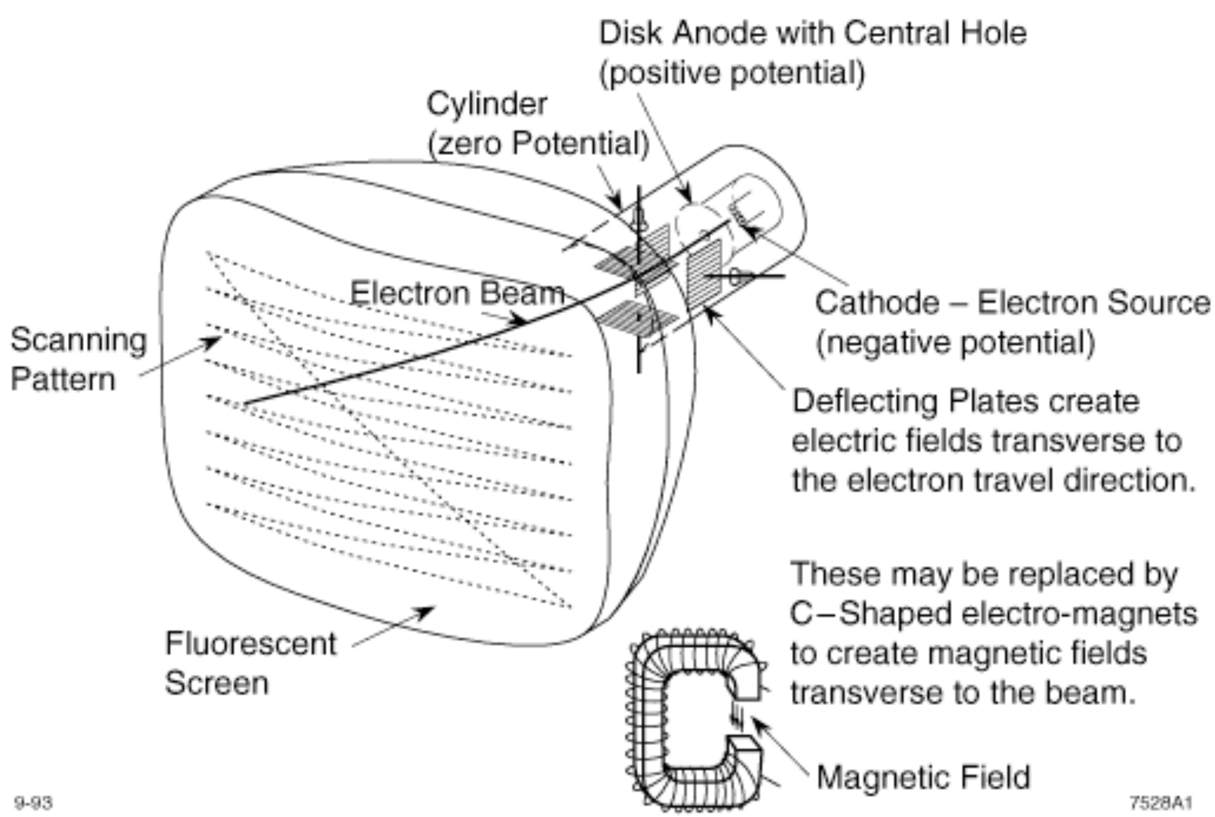
How we see different-sized objects:



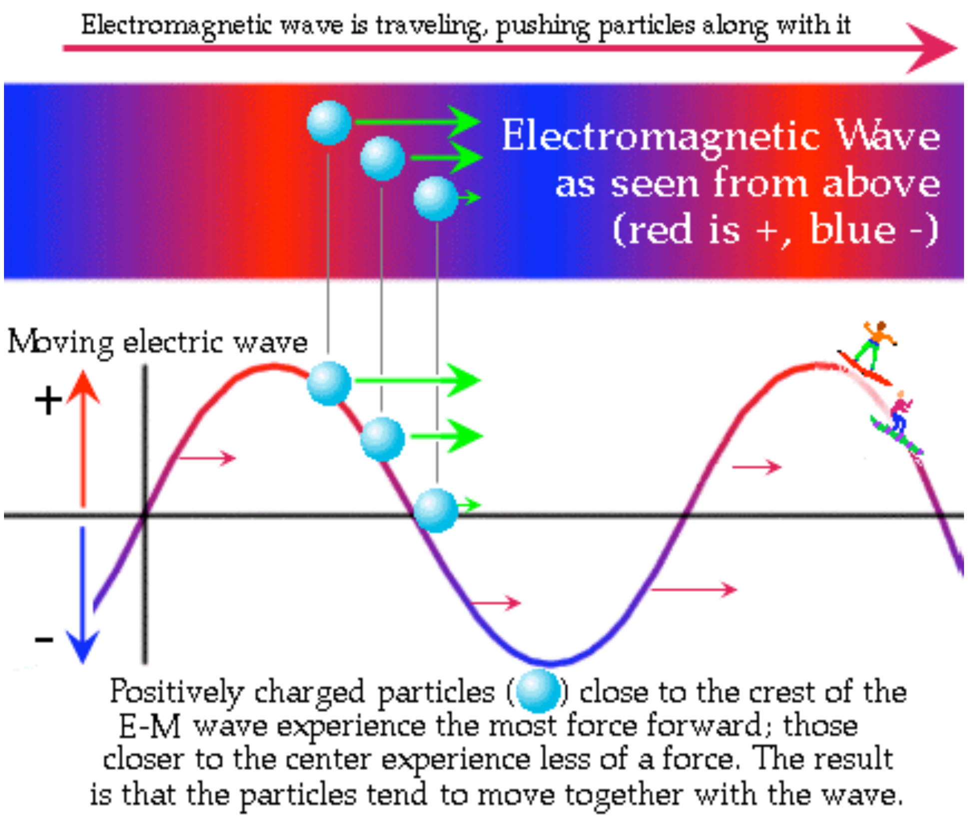


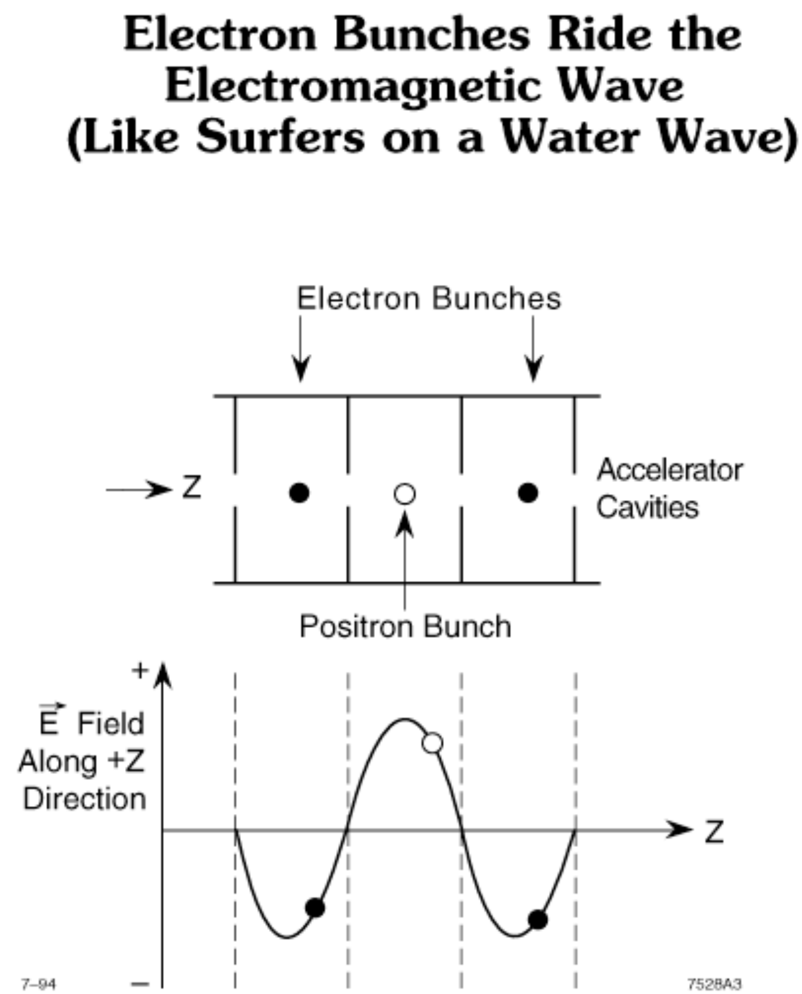
Particle Accelerator

Your TV is an Accelerator Too!

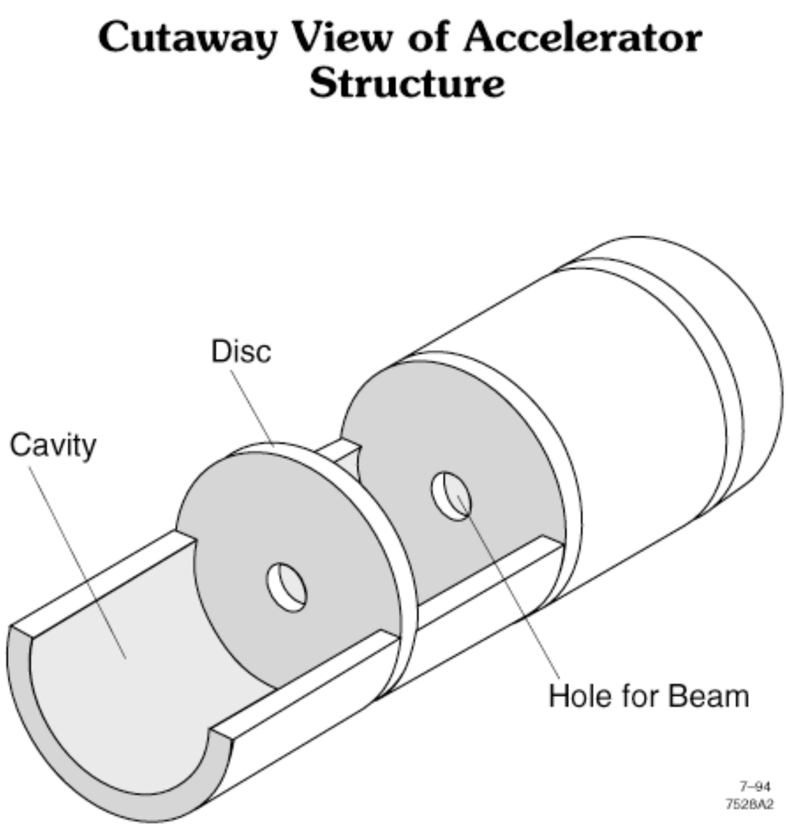


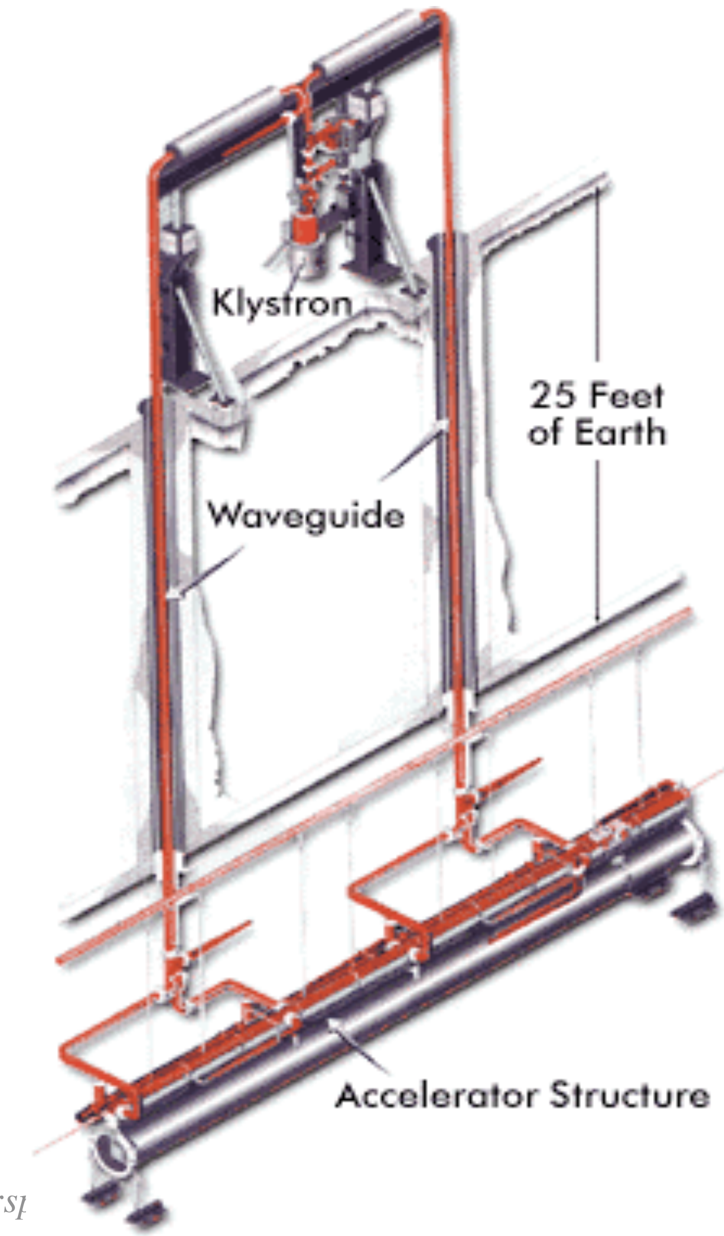
Particle Accelerator





Accelerating Structures





Energy, Momentum & Mass

Newton: Kinetic energy $K = 1/2\ mv^2 = p^2/2m$

Einstein: Total energy $E = [p^2c^2 + m^2c^4]^{1/2}$

Kinetic Energy = Total Energy - Rest Energy = $E - E_0$

Rest Energy $E_0 = mc^2$

$$K = \sqrt{p^2c^2 + E_0^2} - E_0$$

when $pc \ll E_0$: $K \approx \dfrac{p^2}{2m} = \dfrac{p^2c^2}{2E_0}$.

Rest Mass in Electron Volts

Joule is an incovenient unit for rest energy

Electron mass: 9×10^{-31} kg $\qquad E_0 = mc^2 = 0.511$ MeV

Convenient energy unit: eV, keV, MeV, GeV, TeV

Convenient mass unit: MeV/c^2 $\qquad$ Convenient momentum unit: MeV/c

If energy and momentum are of roughly equal or greater value than the rest mass, the particle is relativistic: speed close to the speed of light

***Example**: $p = 1.50$ MeV/c, $pc = 1.50$ MeV. If $E_0 = 0.511$ MeV, then $E = [1.50^2 + 0.511^2]^{1/2} = 1.58$ MeV, $K = E - mc^2 = 1.07$ MeV. In this case, the speed is 94.94% of the speed of light.*

Wide Range of Masses!

Neutrino	*~ meV/c^2 ?*
electron	*0.511 MeV/c^2*
Muon	*105 MeV/c^2*
Proton	*938 MeV/c^2*
Z Boson	*91 GeV/c^2*
Top Quark	*175 GeV/c^2*