Overview of Particle Physics

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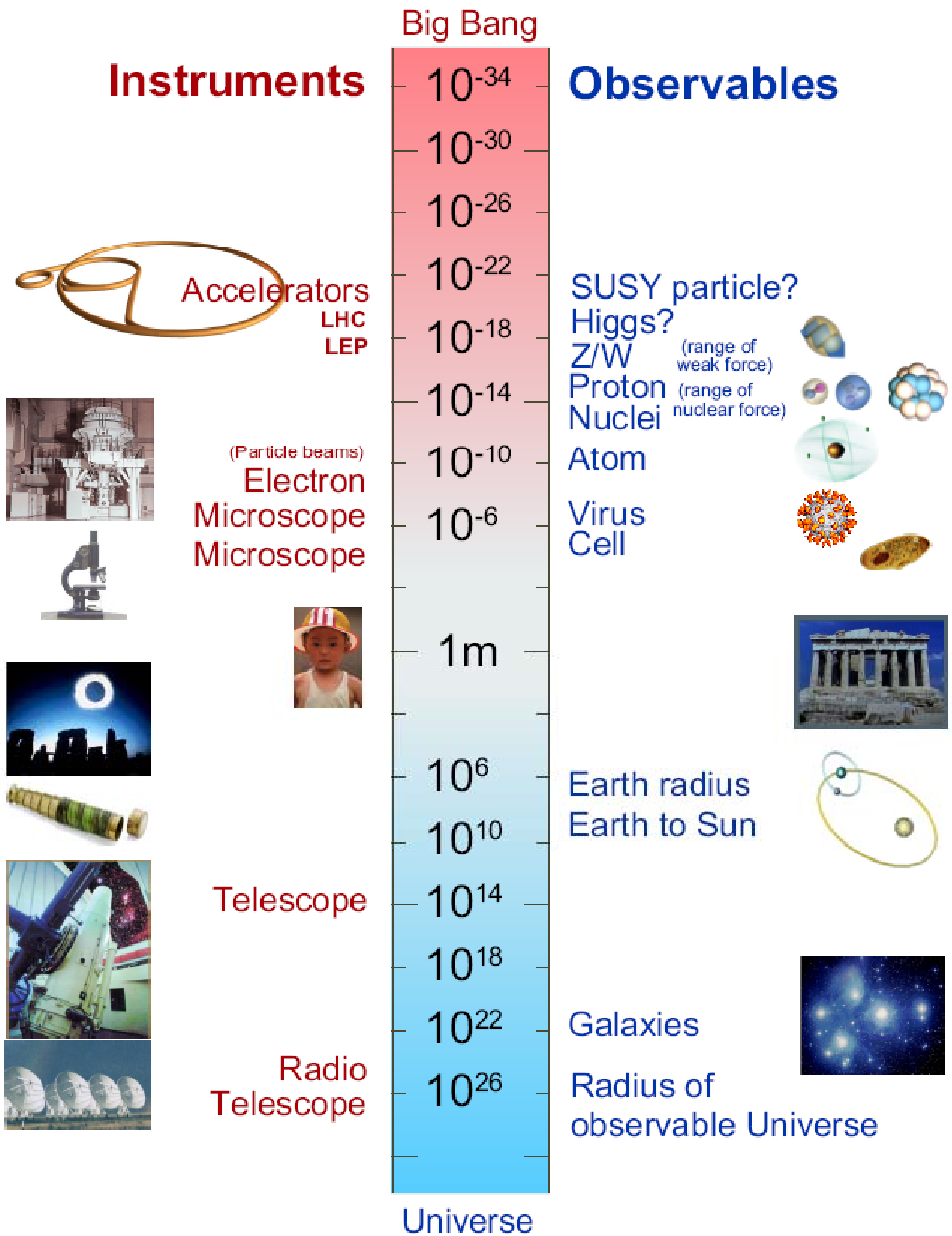
Particle Physics

- What is it?
  - Study of the elementary constituents of matter
  - And the fundamental forces that control their behavior at the most basic level
  - Connections to cosmology, i.e. study of the universe on the largest scales

The Size of Things

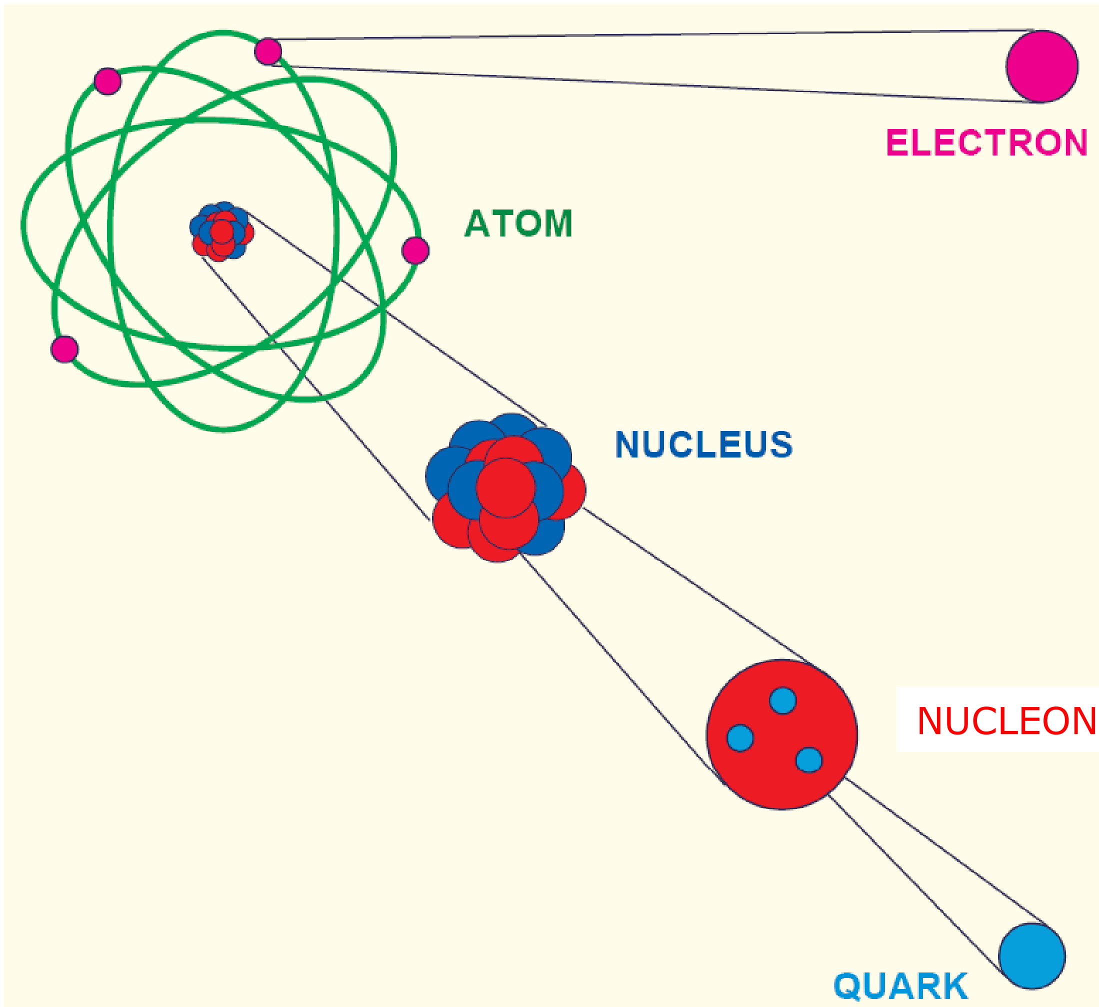


- Wavelength of probe radiation should be less than size of object probed
- de Broglie wavelength

$$\lambda = \frac{h}{p} = \frac{hc}{E}$$

- i.e. high energy probes resolve smaller sizes

Structure of the Atom



Elementary Particles

Leptons

	Electric Charge		Electric Charge
Tau	-1	Tau Neutrino	0
Muon	-1	Muon Neutrino	0
Electron	-1	Electron Neutrino	0

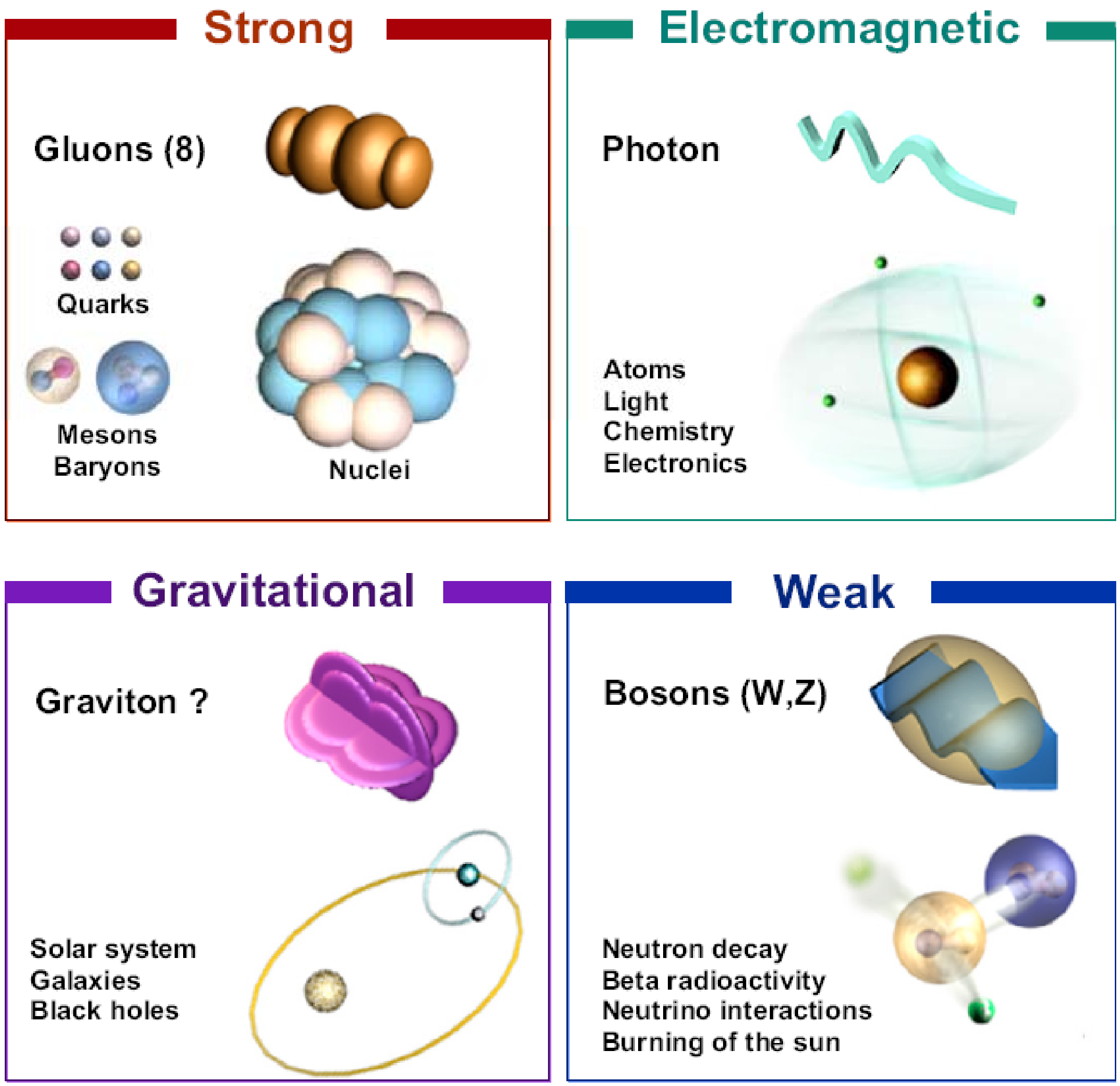
Quarks

	Electric Charge		Electric Charge
Bottom	-1/3	Top	2/3
Strange	-1/3	Charm	2/3
Down	-1/3	Up	2/3

each quark: ●R, ●B, ●G 3 colors

The particle drawings are simple artistic representations

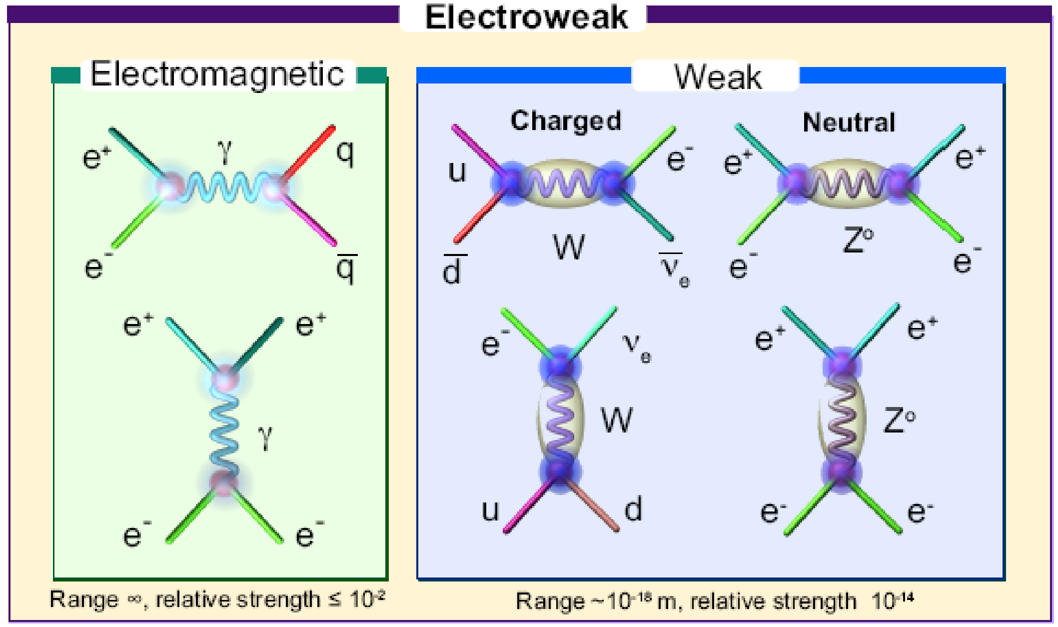
Forces



The particle drawings are simple artistic representations

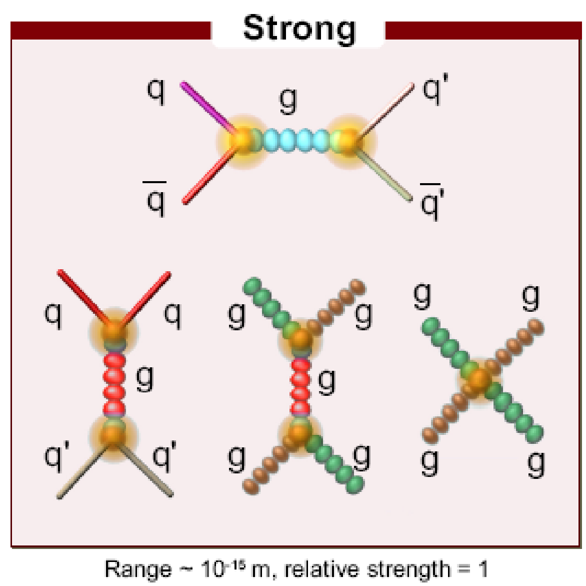
Interactions: Coupling of Forces to Matter

- Newton's law:
  - Action at a distance



- Maxwell's equations:
  - Interaction by fields

- Quantum Field Theory:
  - Forces are produced by the exchange of "messengers" or "gauge bosons"



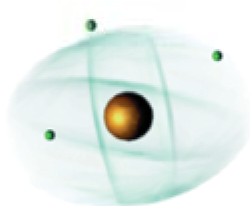
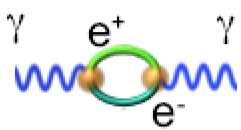
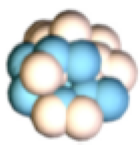
Aside: Units of Energy and Mass

- Physicists usually express energy in units of electron volts (eV), where one eV is the energy accquired by an electron accelerated through a potential of 1 Volt

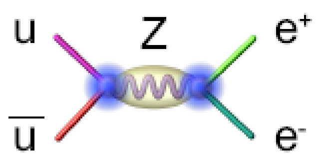
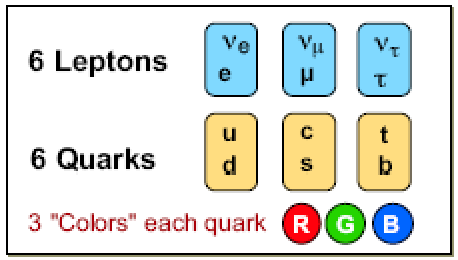
- 1 eV = 1.6×10^{-19} J

- Masses are usually expressed in terms of eV/c^2 using Einstein's relation $E = m\,c^2$
  - Example: Rest mass of electron
    - Use $E = m\,c^2 = (9.11 \times 10^{-32}\ \text{kg})\ (3 \times 10^8\ \text{m/s}^2) = 8.2 \times 10^{-14}$ J
    - Convert to eV: $E = 0.511$ MeV
    - So, $m_e = 0.511$ MeV/c^2

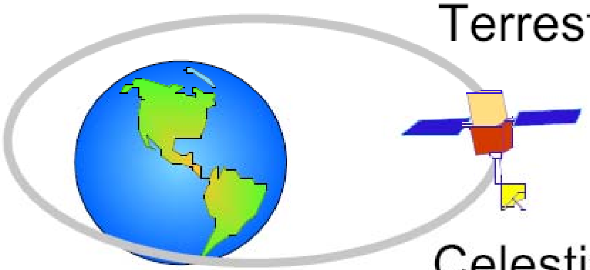
More on Sizes

	$\lambda = h / p$		$T \approx t^{-1/2}$	1900....
	10^{-10} m	$\leq$ 10 eV	>300000 Y	**Quantum Mechanics** **Atomic Physics**
				1940-50 **Quantum Electro Dynamics**
	10^{-15} m	MeV - GeV	$\approx$ 3 min	1950-65 **Nuclei, Hadrons** **Symmetries** **Field theories**
	10^{-16} m	>> GeV	$\approx 10^{-6}$ sec	1965-75 **Quarks** **Gauge theories**

More on Sizes

	10^{-18} m	≈ 100 GeV	≈ 10^{-10} sec	**SPS, $p\bar{p}$ 1970-83** ElectroWeak Unification, QCD
				**LEP 1990** 3 families **Tevatron 1994** Top quark
Origin of masses The next step...	10^{-19} m	≈ 10^{3} GeV	≈ 10^{-12} sec	**LHC 2005** Higgs ? Supersymmetry ?
Proton Decay ?	10^{-32} m	≈ 10^{16} GeV	≈ 10^{-32} sec	**Underground Labs** GRAND Unified Theories ?
The Origin of the Universe	10^{-35} m	≈ 10^{19} GeV (Planck scale)	≈ 10^{-43} sec	?? Quantum Gravity? Superstrings ?

Unification of the Forces



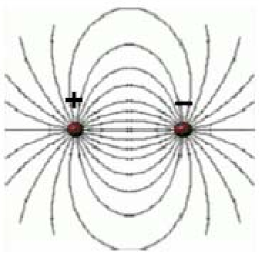
Terrestrial mechanics

Celestial mechanics

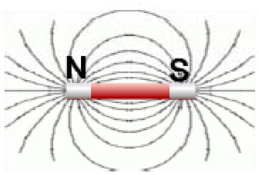
Universal Gravitation

Inertial vs. Gravitational mass

(I. Newton, 1687)



Electricity



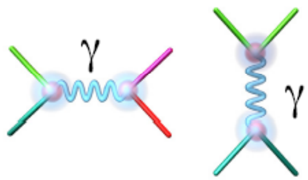
Magnetism

Electromagnetism

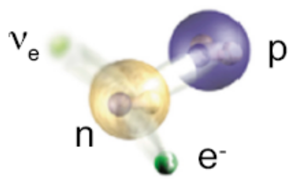
Electromagnetic waves (photon)

(J.C. Maxwell, 1860)

Unification of the Forces



Electromagnetism



Weak force

Electroweak

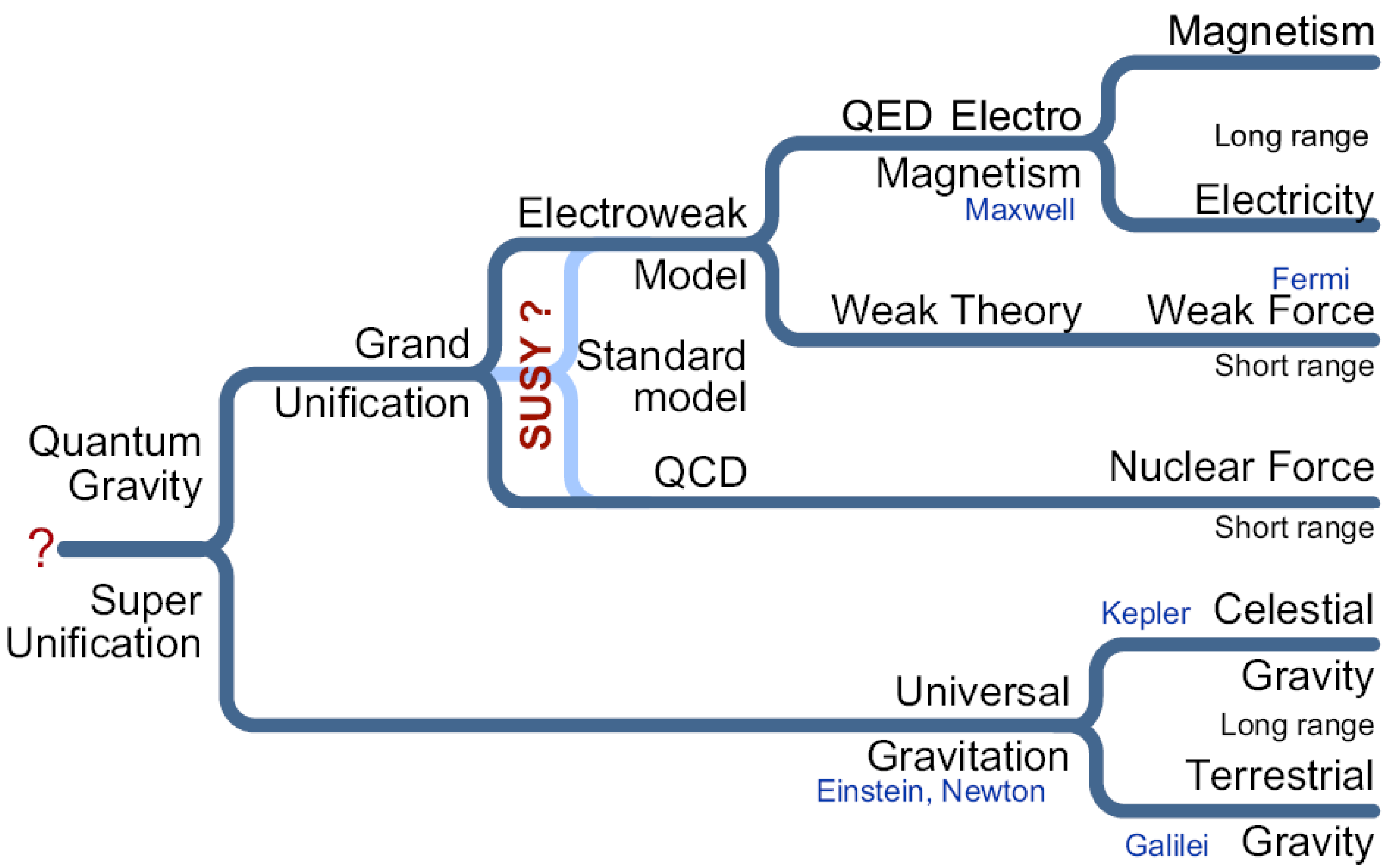
Intermediate bosons W, Z
(1970-83)

?

Probing shorter distances
reveals
deeper regularities

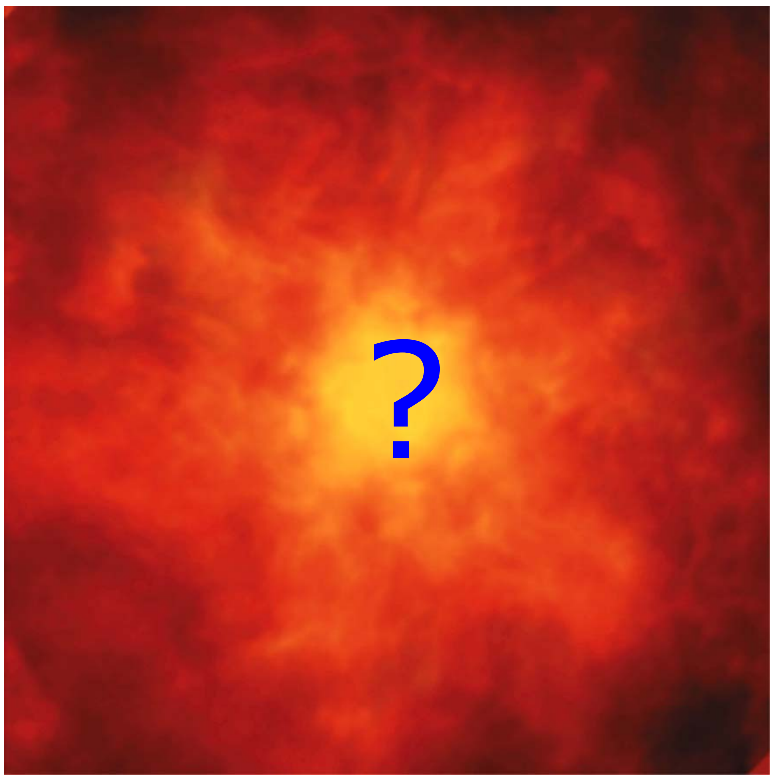
UNIFIED DESCRIPTIONS

The Standard Model and Beyond



Quantum Gravity Era

- 10^{-43} sec after big bang
- Gravity separates as a force, the other forces remain as one (Grand Unification)



- $t < 10^{-43}$ s: The Big Bang
  - Universe expands from single point with infinitely high energy density (infinite T)
- $T \approx 10^{-43}$ s, 10^{32} K
  - 10^{19} GeV, 10^{-24} m
  - All particle types and their anti-particles in thermal equilibrium (created and annihilated at same rate)
  - Phase transition: gravity "freezes out" and became distinct from the other forces
  - Other 3 forces cannot be distinguished from one another in their interactions with quarks and leptons

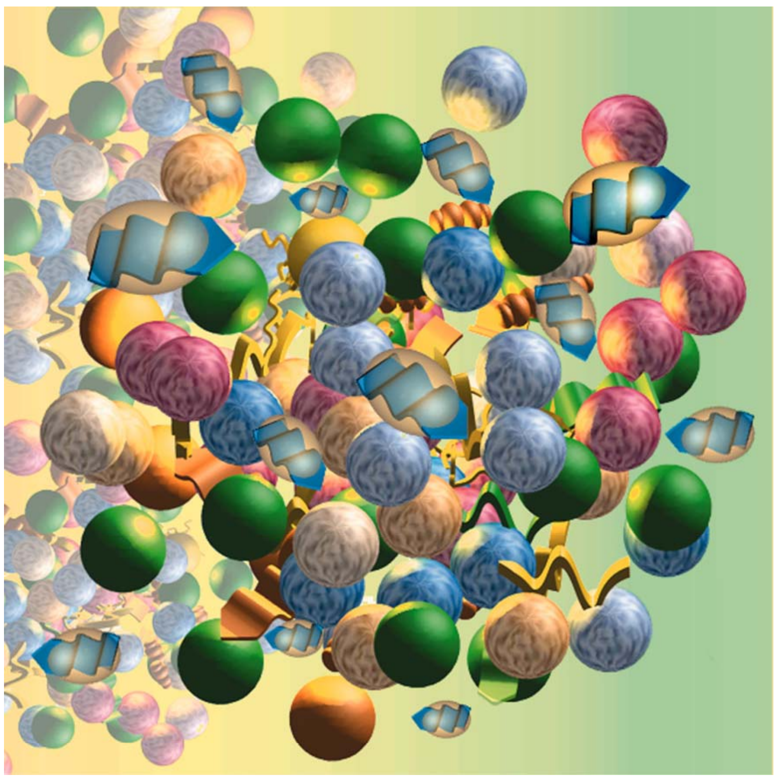
Grand Unification Era

- 10^{-35} sec after big bang
- Inflation ceases, expansion continues
- Strong and electroweak forces become distinguishable

- $t \approx 10^{-35}$ s, 10^{27} K: Inflation
  - 10^{16} GeV, 10^{-32} m
  - Rate of expansion increases exponentially for a short time
  - Universe doubled every 10^{-32} s
  - Presently observable universe only 3 m in size after inflation
  - Solves horizon and flatness problem
- $T \approx 10^{-32}$ s, Strong force freezes out
  - Via another phase transition
  - Slight excess of matter over anti-matter develops (1 ppb) sufficient to yield presently observed excess of matter over antimatter
  - Too hot for quarks and gluons to bind together: they form a quark-gluon plasma

Electroweak Era

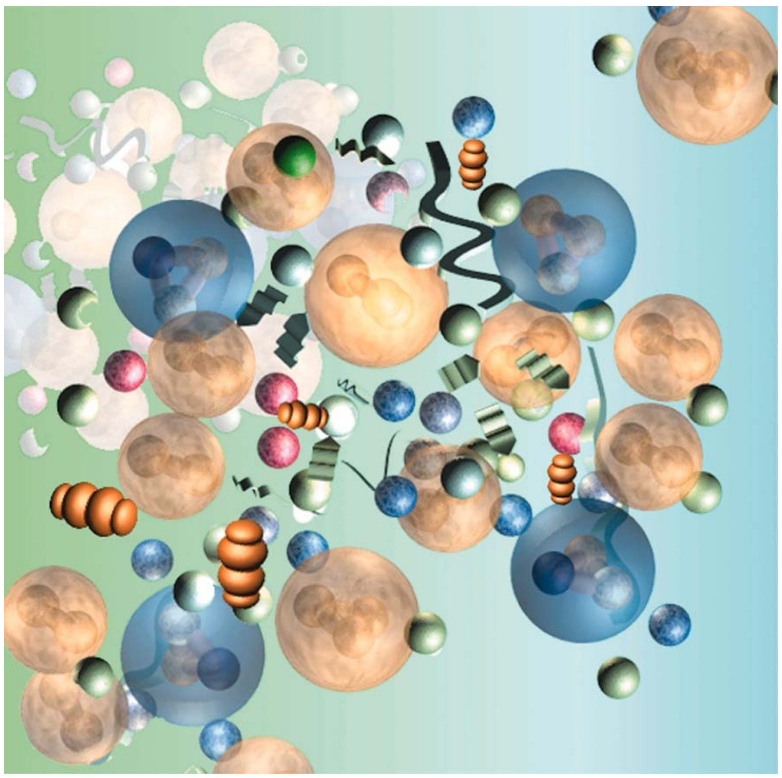
- 10^{-10} sec after big bang
- Electroweak force splits



- $t \approx 10^{-10}$ s, 10^{15} K: Electromagnetic and weak forces separate
  - 100 GeV, 10^{-18} m
  - Weak force "freezes out" via another phase transition
  - All four forces become distinct in their actions
  - Anti-quarks annihilate with quarks leaving a residual excess of matter
  - W and Z bosons decay

Protons and Neutrons Form

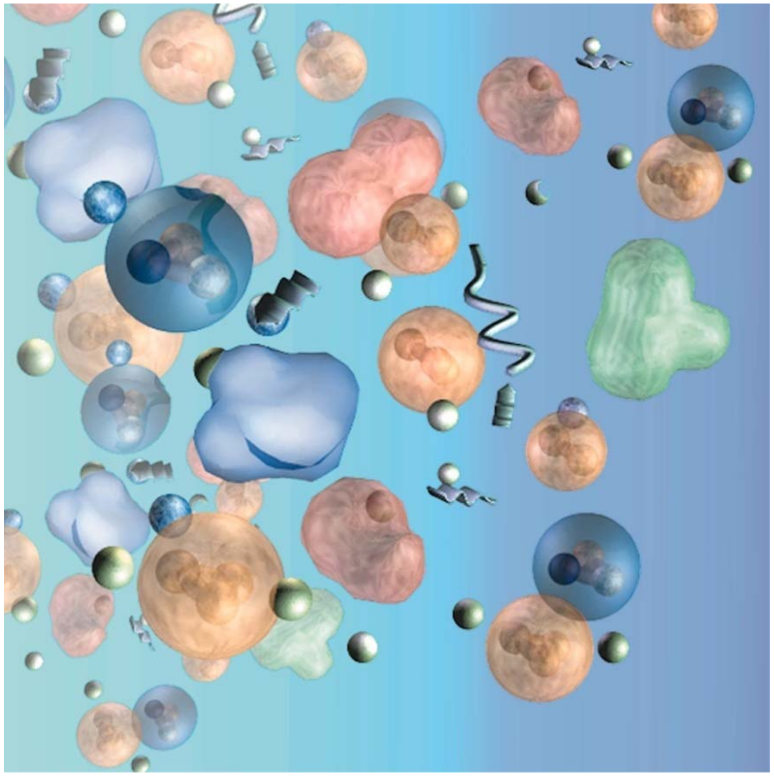
- 10^{-4} sec after big bang
- Quarks combine to make protons and neutrons



- $t \approx 10^{-4}$ s, 10^{13} K: Protons and neutrons form
  - 1 GeV, 10^{-16} m
  - Universe has grown to the size of our solar system
  - As T drops, quark-antiquark annihilation stops and the remaining quarks combine to make protons and neutrons
- $t \approx 1$ s, 10^{10} K: Neutrinos decouple
  - Neutrinos become inactive (essentially do not participate in interactions)
  - Electrons and positrons annihilate and are not recreated: an excess of electrons is left

Nuclei Form

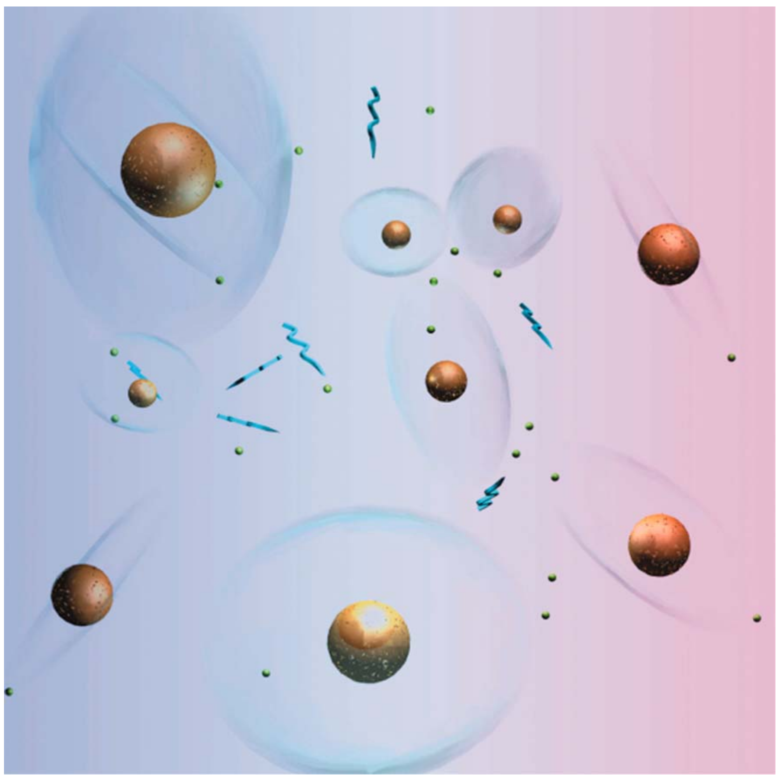
- 100 sec after big bang
- Protons and neutrons combine to form helium nuclei



- t ≈ 3 min, 10^9 K: Nuclei are formed
  - 0.1 MeV, 10^{-12} m
  - T now low enough to allow nuclei to form
  - Conditions are similar to those in a star today or in thermonuclear bomb
  - Neutron-proton ratio drops to 13:87
  - The bulk consitution of the universe is now in place: mostly protons (75%) and helium nuclei
  - T is still too high for atoms to form and electrons form a gas of free particles

Era of Atoms and Light

- 300,000 years after big bang
- The universe become transparent and fills with light



- t ≈ 300,000 years, 6000 K: Atoms are created
  - 0.5 eV, 10^{-10} m
  - Electrons and nuclei bind together
  - Atoms of hydrogen, helium and lithium are created
  - Radiation (light, photons) is no longer energetic enough to break atoms
  - The universe becomes transparent to photons
  - Matter density dominates
  - Astronomy/astrophysics can study the evolution of the Universe back to this time (COBE, WMAP, PLANCK)

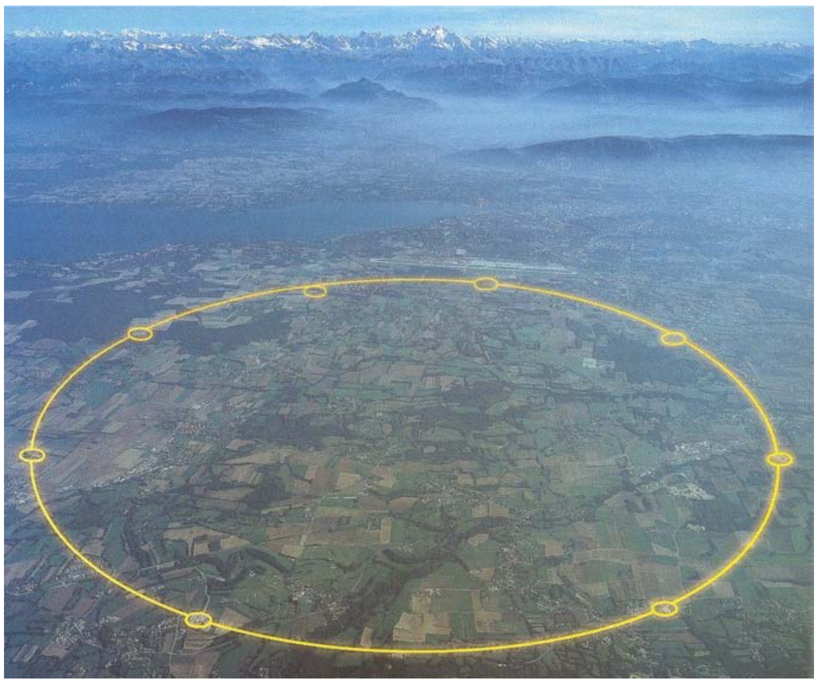
Galaxy Formation

- 1000 years after big bang

- $t \approx 10^9$ years, 18 K: Galaxy formation
  - Local mass density fluctuations act as seeds for stellar and galaxy formation
  - Nucleosynthesis, the synthesis of nuclei such as carbon up to iron, starts to occur in stars
  - Heavier elements are synthesized and dispersed in stellar collapse and supernovae explosions

Today

- 13.7 billion years after big bang



- $t \approx 13.7 \times 10^9$ years, 3 K: Humans evolve on earth
  - Chemical process link atoms to form molecules, DNA, life
  - Humans build COBE, Hubble, Tevatron, LHC etc. to figure it all out

Credits

- CMS Brochure 2003
  - http://cmsinfo.cern.ch/outreach/CMSdocuments/CMSbrochure/CMS-Brochure03.pdf

- T. Virdee, Inaugural Lecture
  - http://cmsinfo.cern.ch/outreach/CMSdocuments/JimInaugural/JimInaugural_index.html