Nuclear and Particle Physics

An introduction

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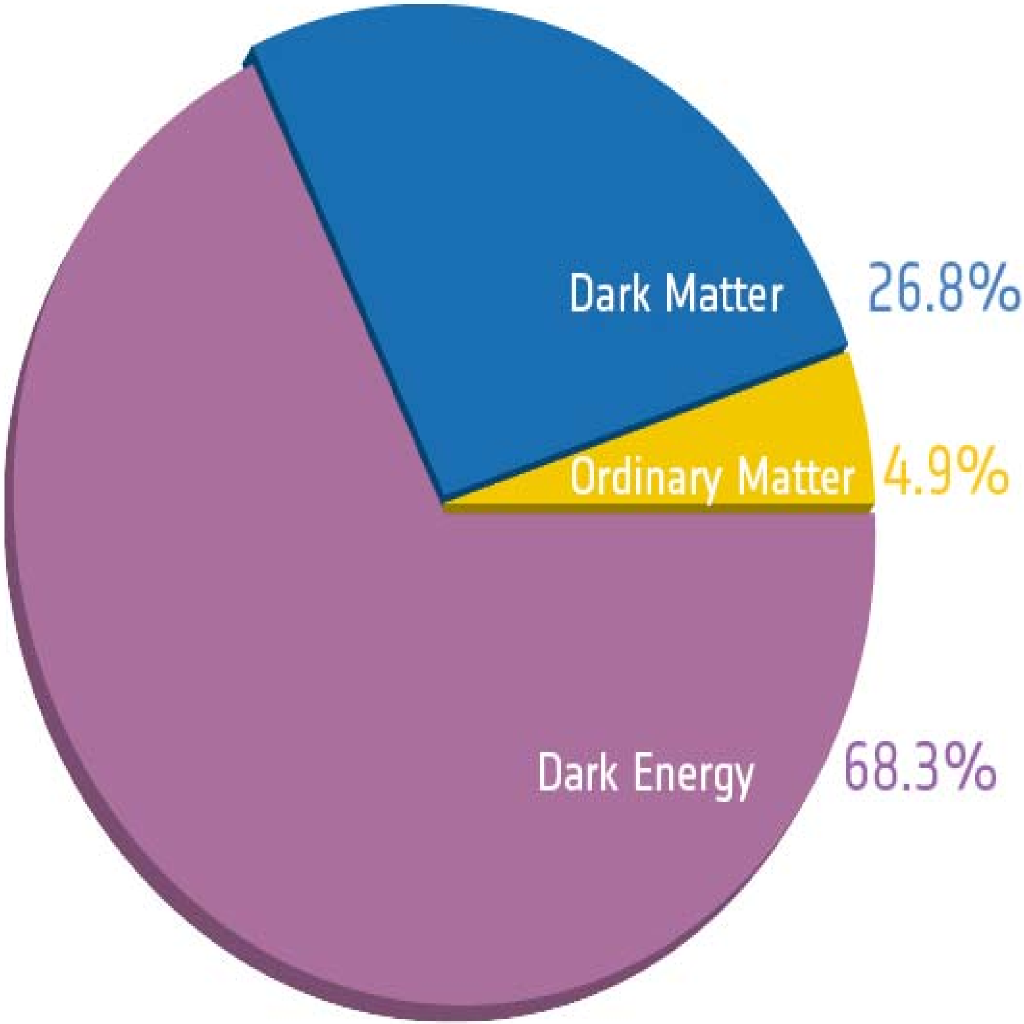
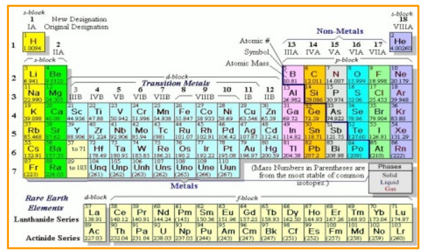
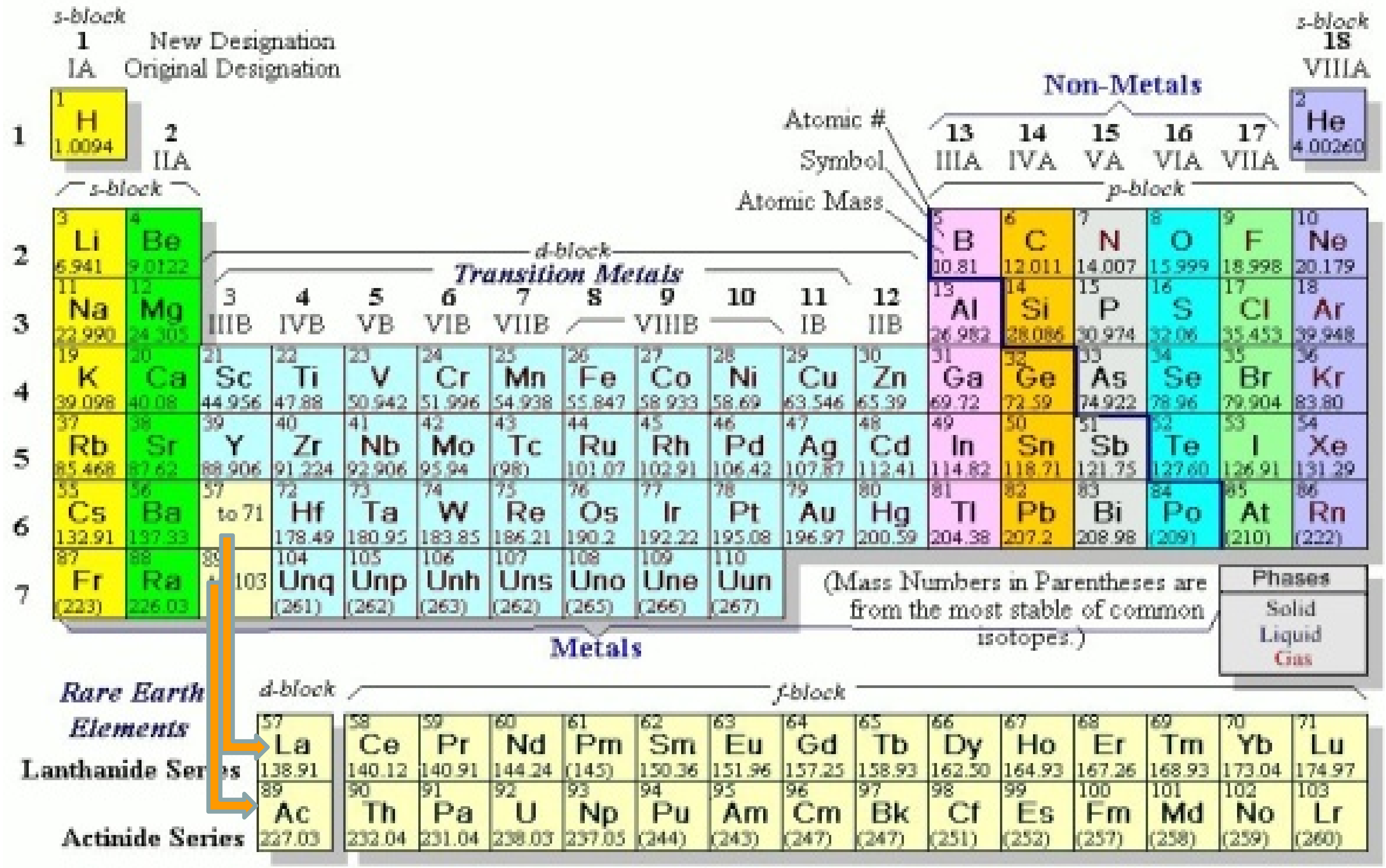
Η σύσταση του σύμπαντος

(σύμφωνα με τα δεδομένα του Planck mission-2013)

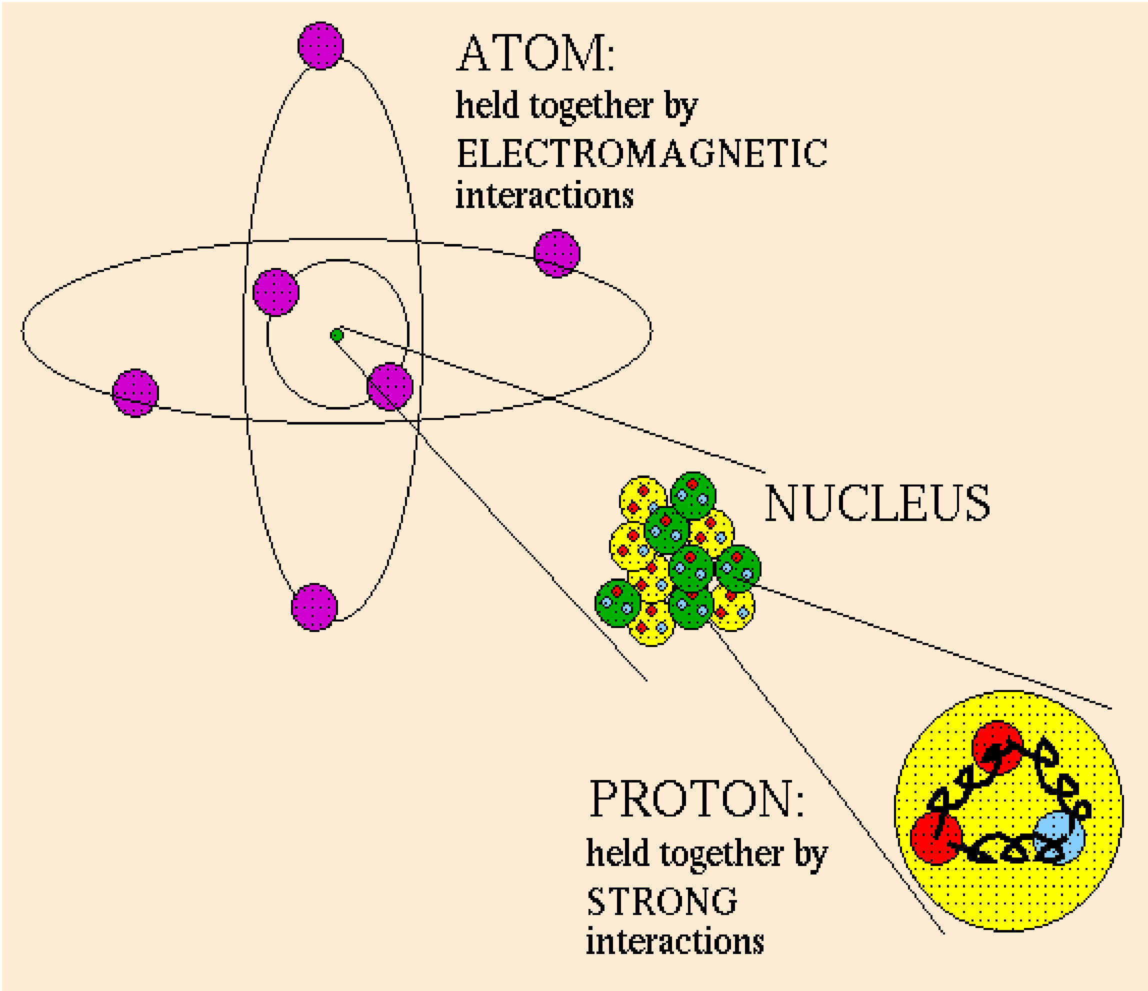




Τα δομικά στοιχεία της συνήθους ύλης (σε ατομικό επίπεδο - χημικά στοιχεία)

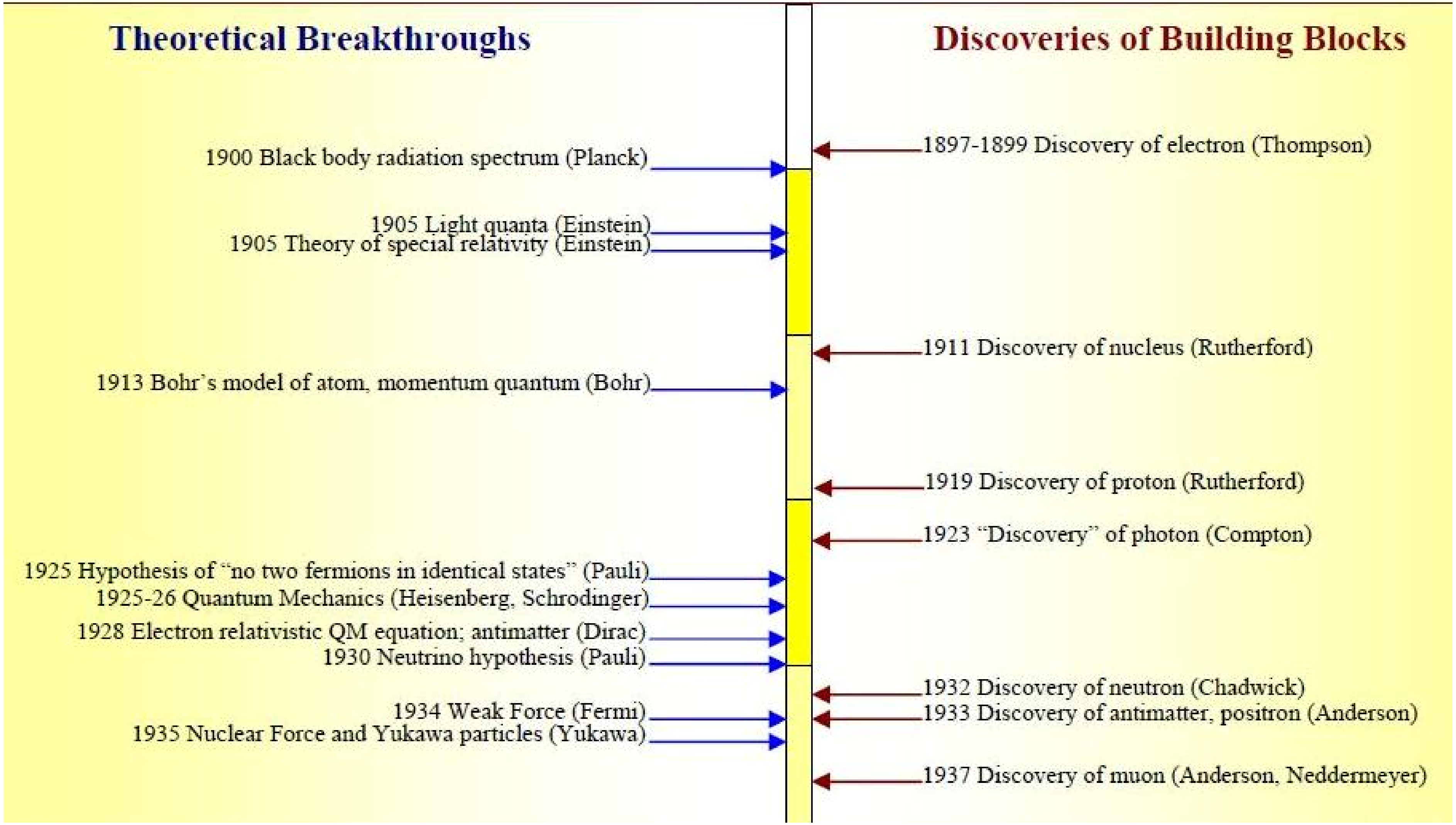


Ατομική και υπο-ατομική δόμηση της ύλης



Πώς τα ξέρουμε αυτά; Ακολουθεί λίγη ιστορία…

20th Century Elementary Particle Physics Timeline



1946 Discovery of charged pion (Perkins)
1947 Discovery of strange particles (Butler, Rochester)
1948 Quantum ElectroDynamics (Feynman; Schwinger; Tomonaga)
1956 Discovery of electron neutrino (Reines, Cowan)
1962 Discovery of muon neutrino (Lederman, Schwartz , Stein
1964 Three quarks (Gell-Mann, Zweig)
1965 Color (Greenberg)
1968 ElectroWeak Unification (Weinberg, Salam, Glashow)
1970 Charm quarks (Glashow, Iliopoulos, Maiani)
1973 Quantum ChromoDynamics
(Gross, Fritzsch, Gell-Mann, Politzer, Weinberg, Wilczek)
1974 Discovery of charm quark (Ting, Richter)
1975 Discovery of τ-lepton (Mark I, Perl)
1977 Discovery of bottom quark (Lederman)
Late 1970s Observation quark and gluon jets (TASSO, JADE)
1983 Discovery of $W^{\pm}$, Z^{0} (UA1, UA2, Rubbia)
1995 Discovery of top quark (CDF, D0)
2000 Discovery of tau-neutrino (DONUT, Lundberg)

Not shown on the time line, but still very important:

Experiment:
- Discovery of electron spin (1925)
- Discovery of Δ-resonance (1952)
- Discovery of P-violation (1957)
- Discovery of CP-violation (1964)

Nuclear Science

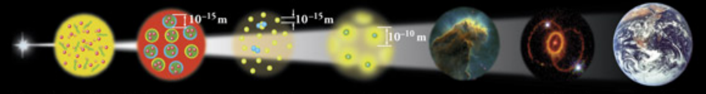
Nuclear Science is the study of the structure, properties, and interactions of the atomic nuclei. Nuclear scientists calculate and measure the masses, shapes, sizes, and decays of nuclei at rest and in collisions. They ask questions, such as: Why do nucleons stay in the nucleus? What combinations of protons and neutrons are possible? What happens when nuclei are compressed or rapidly rotated? What is the origin of the nuclei found on Earth?

Legend: proton, neutron, electron (e^-), positron (e^+), neutrino (ν), antineutrino ($\bar{\nu}$), quark, gluon field, gluon, photon (γ)

A mass number, Z atomic number: ${}^{14}_{6}C$; N neutron number $= A - Z$

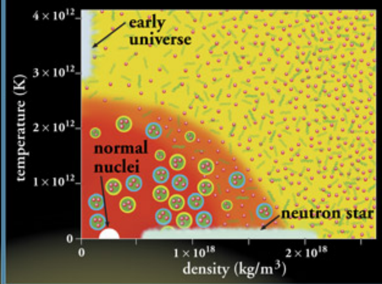
Expansion of the Universe

After the Big Bang, the universe expanded and cooled. At about 10^{-6} second, the universe consisted of a soup of quarks, gluons, electrons, and neutrinos. When the temperature of the Universe, $T_{universe}$, cooled to about 10^{12} K, this soup coalesced into protons, neutrons, and electrons. As time progressed, some of the protons and neutrons formed deuterium, helium, and lithium nuclei. Still later, electrons combined with protons and these low-mass nuclei to form neutral atoms. Due to gravity, clouds of atoms contracted into stars, where hydrogen and helium fused into more massive chemical elements. Exploding stars (supernovae) form the most massive elements and disperse them into space. Our earth was formed from supernova debris.



	Big Bang	quark-gluon plasma	proton & neutron formation	formation of low-mass nuclei	formation of neutral atoms	star formation	dispersion of massive elements	today
$T_{universe}$		$>10^{12}$ K	10^{12} K	10^{9} K	4,000 K	50 K–3 K	<50 K–3 K	3 K
time		10^{-6} s	10^{-4} s	3 min	400,000 yr	3×10^{8} yr	$>3\times10^{8}$ yr	14×10^{9} yr

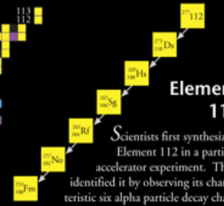
Phases of Nuclear Matter



Nuclear matter can exist in several phases. When collisions excite nuclei, individual protons and neutrons may evaporate from the nuclear fluid. At sufficiently high temperature or density, a gas of nucleons (red background) forms. At even more extreme conditions, individual nucleons may cease to have meaningful identities, merging into the quark-gluon plasma (yellow background). Current data provide hints that physicists have glimpsed the quark-gluon plasma.

Unstable Nuclei

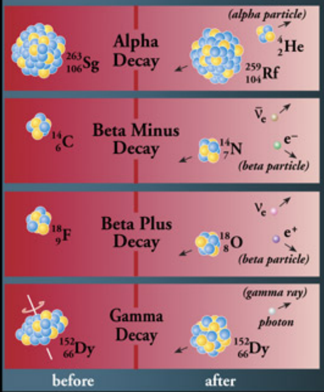
Stable nuclides form a narrow white band on the Chart of the Nuclides. Scientists produce unstable nuclides far from this band and study their decays, thereby learning about the extremes of nuclear conditions. In its present form, this chart contains about 2500 different nuclides. Nuclear theory predicts that there are at least 4000 more to be discovered with $Z \leq 113$.



Element 112

Scientists first synthesized Element 112 in a particle accelerator experiment. They identified it by observing its characteristic six alpha particle decay chain.

Radioactivity

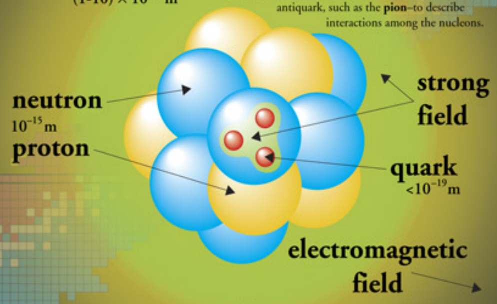


Radioactive decay transforms a nucleus by emitting different particles. In **alpha** decay, the nucleus releases a ${}^{4}_{2}$He nucleus –an alpha particle. In **beta** decay, the nucleus either emits an electron and antineutrino (or a positron and neutrino) or captures an atomic electron and emits a neutrino. A positron is the name for the antiparticle of the electron. Antimatter is composed of antiparticles. Both alpha and beta decays change the original nucleus into a nucleus of a different chemical element. In **gamma** decay, the nucleus lowers its internal energy by emitting a photon–a gamma ray. This decay does not modify the chemical properties of the atom.

The Nucleus

(1-10) $\times 10^{-15}$ m

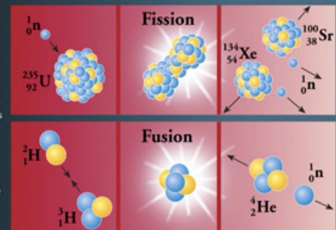
At the center of the atom is a nucleus formed from **nucleons**–protons and neutrons. Each nucleon is made from three **quarks** held together by their strong interactions, which are mediated by gluons. In turn, the nucleus is held together by the **strong** interactions between the gluon and quark constituents of neighboring nucleons. Nuclear physicists often use the exchange of mesons–particles which consist of a quark and an antiquark, such as the **pion**–to describe interactions among the nucleons.



In an atom, **electrons** range around the nucleus at distances typically up to 10,000 times the nuclear diameter. If the electron cloud were shown to scale, this chart would cover a small town.

Nuclear Energy

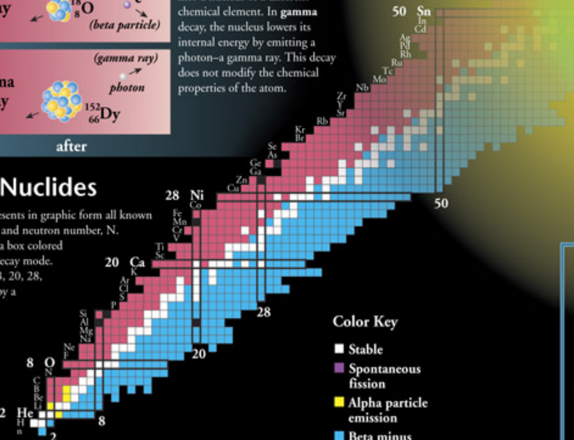
Nuclear reactions release energy when the total mass of the products is less than the sum of the masses of the initial nuclei. The "lost mass" appears as kinetic energy of the products ($E = mc^2$). In fission, a massive nucleus splits into two major fragments that usually eject one or more neutrons. In fusion, low mass nuclei combine to form a more massive nucleus plus one or more ejected particles—neutrons, protons, photons, or alpha particles.



In the early stages of stellar evolution of our sun and other stars, hydrogen fuses to form helium, releasing energy in the form of photons (light) and neutrinos. During the later stages of stellar evolution, more massive nuclei up to and beyond uranium are synthesized by fusion. By measuring the number of neutrinos that come from the Sun, scientists recently have demonstrated that neutrinos must have a mass greater than zero.

Chart of the Nuclides

The Chart of the Nuclides presents in graphic form all known nuclei with atomic number, Z, and neutron number, N. Each nuclide is represented by a box colored according to its predominant decay mode. **Magic numbers** (N or Z = 2, 8, 20, 28, 50, 82 and 126) are indicated by a rectangle on the chart. They correspond to major closed shells and show regions of greater nuclear binding energy.



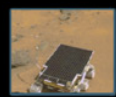
Color Key

- Stable
- Spontaneous fission
- Alpha particle emission
- Beta minus emission
- Beta plus emission or electron capture

Applications

Radioactive Dating

Naturally occurring radioactive isotopes such as ${}^{14}_{6}$C are used to date objects that were once living, such as wood. For example, from a study of artifacts found at the site, scientists determined that Stonehenge was built nearly 4,000 years ago.



Space Exploration

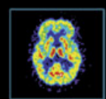
Sojourner used alpha particles to identify chemical elements present in Martian rocks. On Earth, nuclear reactions are used in many areas from criminal investigations to art authentication.

Nuclear Reactors

Nuclear reactors use the fission of ${}^{235}_{92}$U or ${}^{239}_{94}$Pu nuclei to produce electric power. Reactors and most other nuclear applications generate radioactive waste; disposal of this waste is a subject of current research.

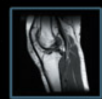
Smoke Detectors

Many smoke detectors use a small amount of the alpha emitter ${}^{241}_{95}$Am to ionize the air. Smoke entering the detector reduces the current and sets off the alarm.



Nuclear Medicine

Radioactive isotopes, such as ${}^{99m}_{43}$Tc, ${}^{60}_{27}$Co and ${}^{131}_{53}$I, are commonly used in the diagnosis and treatment of disease. Positron emitters such as ${}^{18}_{9}$F are used in Positron Emission Tomography (PET) to generate images of brain activity.



Magnetic Resonance Imaging

Magnetic Resonance Imaging (MRI) makes use of atomic transitions involving the magnetic field of a nucleus to study the local chemical environment. This technique accurately maps the density of hydrogen to produce three-dimensional images of the human body.

Astrophysical pictures courtesy NASA/JPL/Caltech and AURA/STScI.

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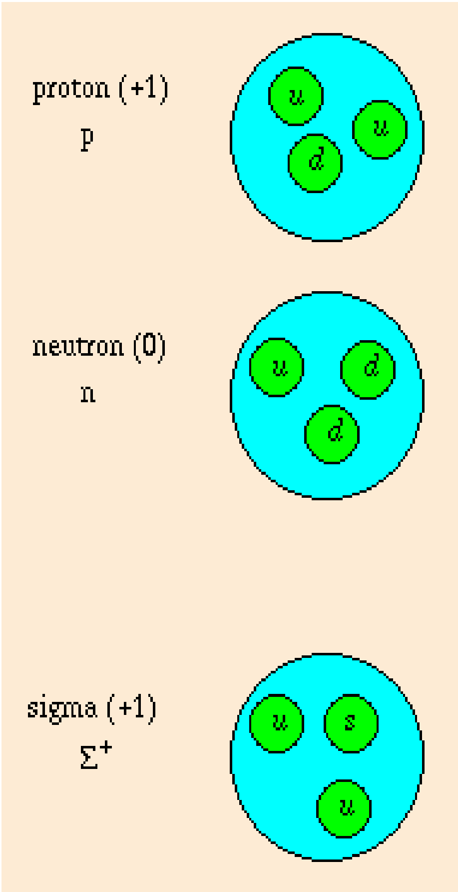
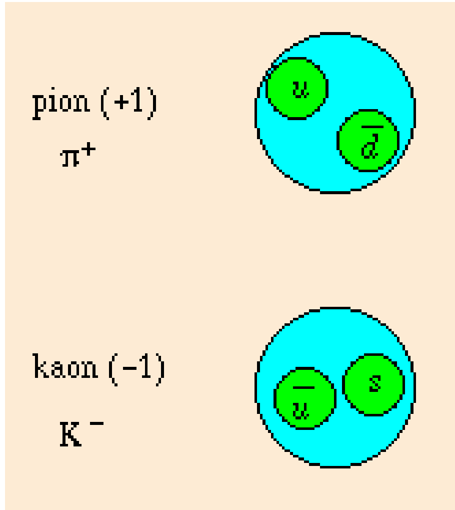
Στοιχειώδη σωματίδια με εσωτερική δομή – αδρόνια (strong interactions)

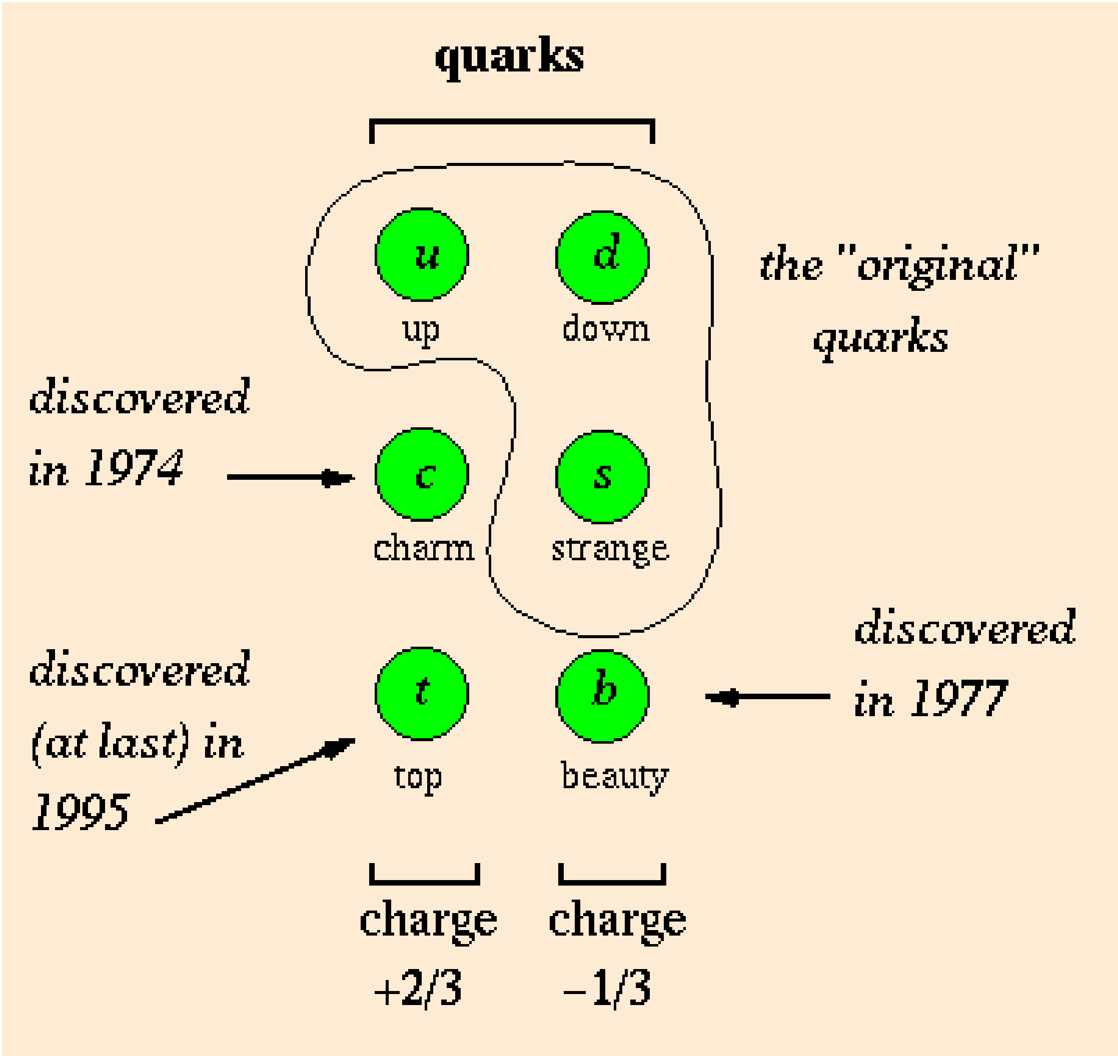




Μεσόνια:
αδρόνια με 1 quark και 1 antiquark

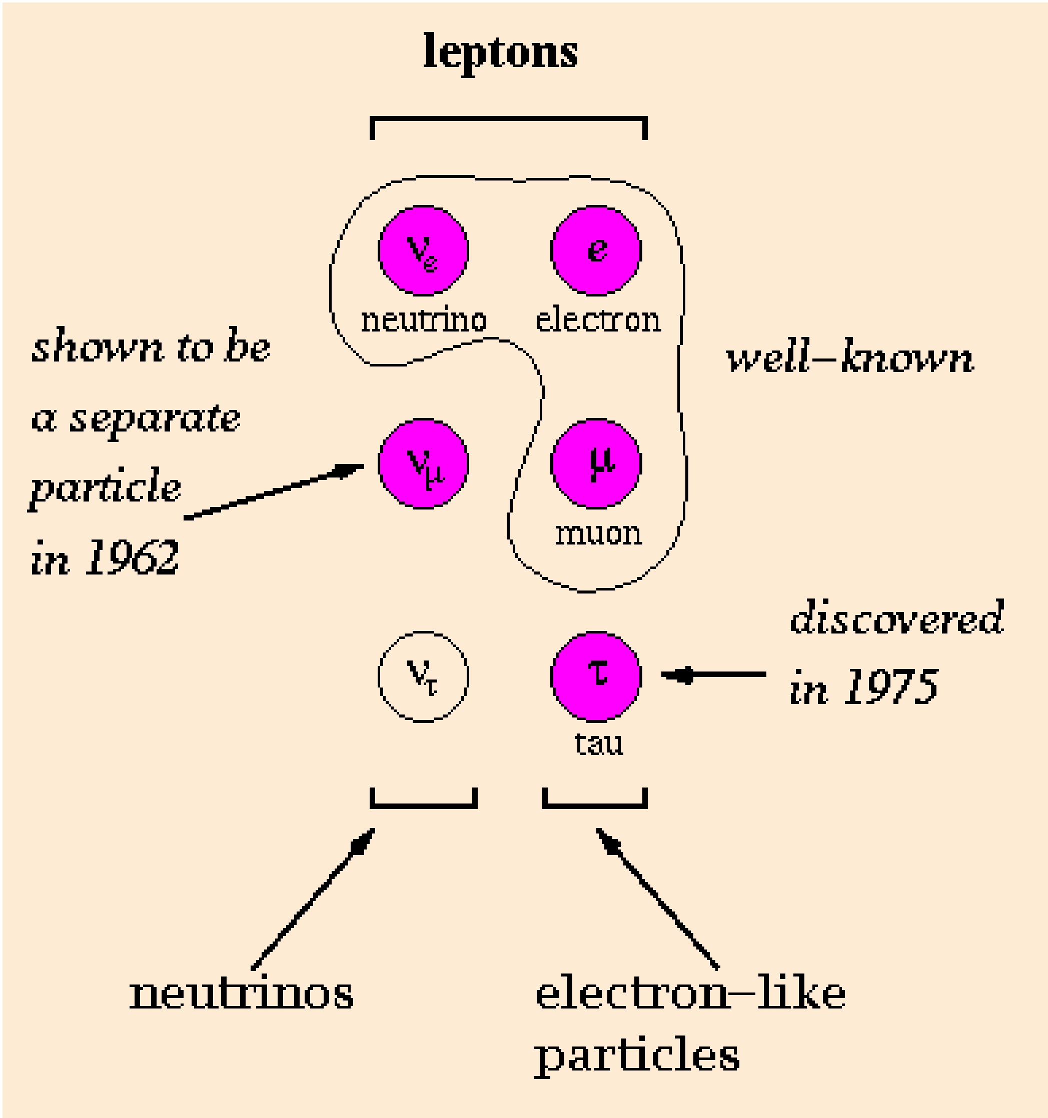
Βαρυόνια:
αδρόνια με 3 quarks ή 3 antiquark

The 6 quarks

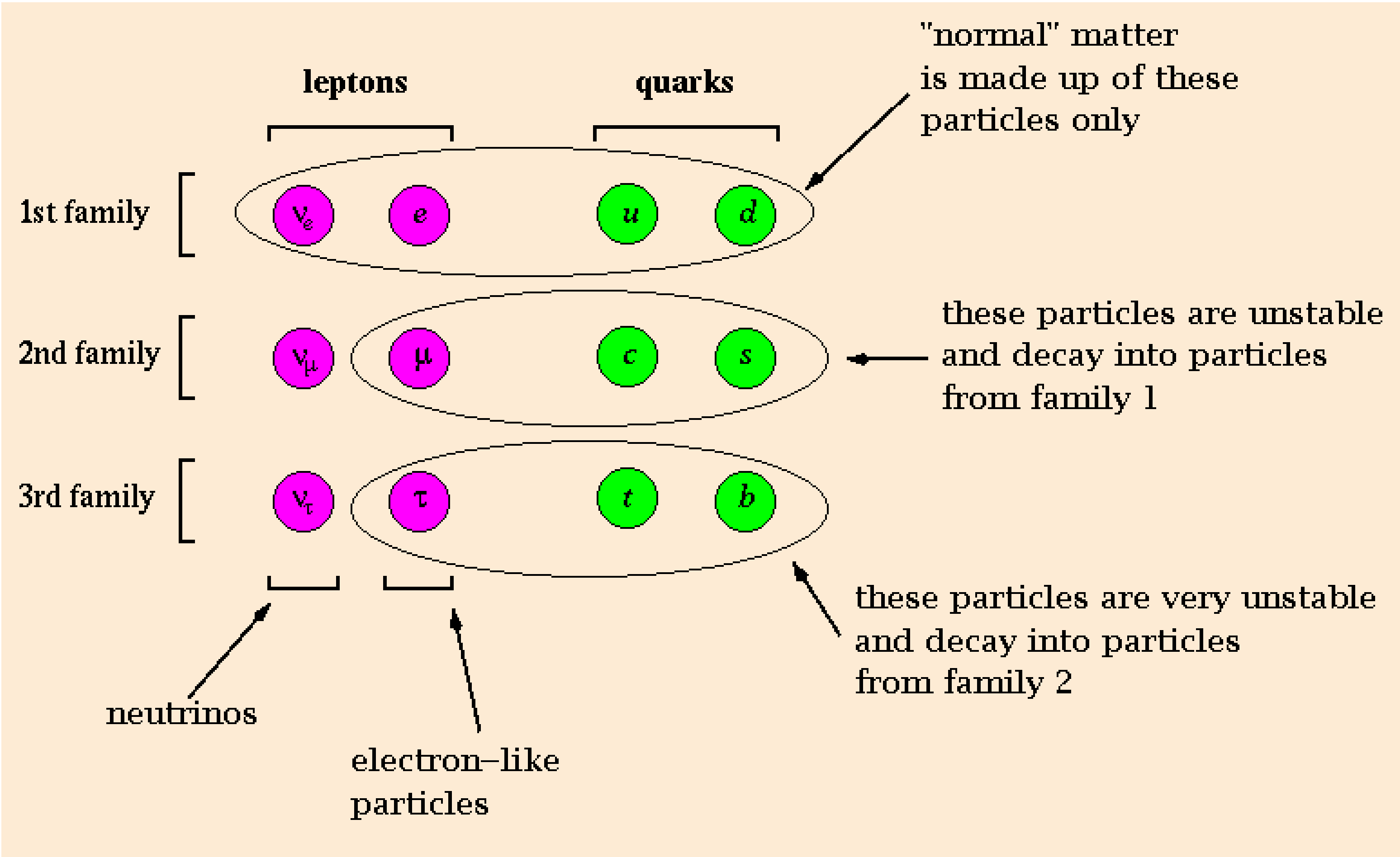


quarks
u
up
d
down
the "original"
quarks
discovered
in 1974
c
charm
s
strange
discovered
in 1977
discovered
(at last) in
1995
t
top
b
beauty
charge
+2/3
charge
−1/3

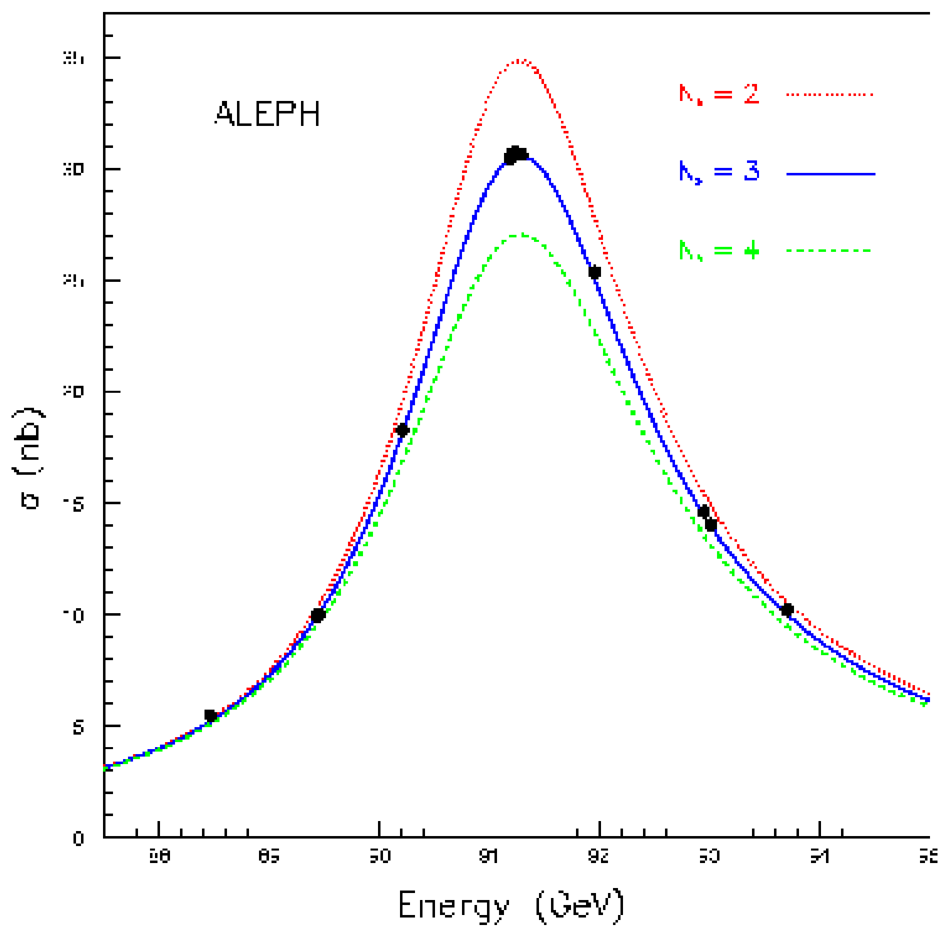
The 6 leptons



λεπτόνια και quark σε 3 οικογένειες



Measurement of Z hadronic decays, versus energy,
with predicted rates if there were 1, 2 or 3 types of neutrino
(ALEPH collaboration)



Τα δομικά στοιχεία της ύλης

(σε υποατομικό - υποπυρηνικό επίπεδο)