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From Quarks to the Cosmos

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Storyline

- Aside: HARBOR
- The Fundamental Forces of Nature
- The Standard Model
- The Universe and Particle Accelerators
- Connecting Quarks to the Cosmos

http://www.quarkstothe.cosmos.org/
HARBOR

High Altitude Reconnaissance Balloon for Outreach and Research

- Student flight opportunities to near space (80,000 ft to 120,000 ft)
- High altitude weather balloons, parachute recovery
- GPS track via ham radio and APRS
- First flight was Monday 28 July 2008
- Max Altitude: 79,056 ft
- Camera (ARIES), Temperature/Pressure (PASCAL)

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http://space.weber.edu/harbor/
There are 4 fundamental forces in Nature

### The Forces of Nature

<table>
<thead>
<tr>
<th>Name</th>
<th>Range</th>
<th>Affects</th>
<th>Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Color</td>
<td>∞</td>
<td>Colored particles</td>
<td>1</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>∞</td>
<td>Charged particles</td>
<td>1/137</td>
</tr>
<tr>
<td>Weak Nuclear</td>
<td>$10^{-17}$ m</td>
<td>Quarks, leptons</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>Gravity</td>
<td>∞</td>
<td>Everything</td>
<td>$10^{-42}$</td>
</tr>
</tbody>
</table>

Everything we’ve observed happen, can be explained in terms of these forces.
There are 3 kinds of fundamental particles: mediators, leptons, and quarks.

### The Particles of Nature

<table>
<thead>
<tr>
<th>Name</th>
<th>Associated Force</th>
<th>Lepton</th>
<th>Quark</th>
</tr>
</thead>
<tbody>
<tr>
<td>W, Z</td>
<td>Weak</td>
<td>e</td>
<td>u</td>
</tr>
<tr>
<td>Gluon</td>
<td>Color</td>
<td>ν_e</td>
<td>d</td>
</tr>
<tr>
<td>Photon</td>
<td>EM</td>
<td>μ</td>
<td>s</td>
</tr>
<tr>
<td>Graviton</td>
<td>Gravity</td>
<td>ν_μ</td>
<td>c</td>
</tr>
<tr>
<td></td>
<td></td>
<td>τ</td>
<td>t</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ν_τ</td>
<td>b</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Charge</th>
<th>Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1</td>
<td>+2/3</td>
</tr>
<tr>
<td>0</td>
<td>-1/3</td>
</tr>
<tr>
<td>-1</td>
<td>-1/3</td>
</tr>
<tr>
<td>0</td>
<td>+2/3</td>
</tr>
<tr>
<td>-1</td>
<td>-1/3</td>
</tr>
</tbody>
</table>

### The Standard Model

Anti-particles are the same, but with opposite charge.
**Composite Particles**

- Leptons can exist by themselves, and can be directly detected by particle experiments.
- Quarks are “confined”, and cannot be seen alone, only in groups of 2 or 3.
  - **Mesons**: particles with 1 quark + 1 antiquark
  - **Baryons**: particles with 3 quarks

<table>
<thead>
<tr>
<th>Proton</th>
<th>Neutron</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u+u+d$</td>
<td>$d+u+d$</td>
</tr>
<tr>
<td>$\pi^+$</td>
<td>$\pi^-$</td>
</tr>
<tr>
<td>$u+d$</td>
<td>$d+u$</td>
</tr>
</tbody>
</table>
Because everything is made of quarks and leptons, and there are only 6 of each

There are a finite number of possible combinations! We should be able to predict what can be found!

By the end of the 1960s, we had predicted the existence of charmonium (c+c) mesons.

In 1974, Burton Richter at SLAC and Samuel Ting at MIT independently discovered this particle (J/ψ)

This is called the November Revolution, and in 1976, Ting and Richter received the Nobel Prize in Physics
Okay, quarks. Cosmos?

- What does this have to do with astrophysics?
- The basic idea of *Quarks to the Cosmos* is that understanding particle physics can help us better understand the Cosmos, and understanding the Cosmos can help us better understand particle physics. *Sometimes*.
- The extremely macroscopic is intimately connected to the extremely microscopic
  - The *forces of Nature* govern everything
  - The nature of particles affects the *composition and structure* of big things
  - Big things can *emit particles* as a consequence of physical processes
Many have suggested that the dark energy could be a cosmological constant.

Particle physics has good limits on possible cosmological constants.

Supposed we ask everyone “how much cosmological constant is there?” and compare.

Measure “how much” by density (amount/volume).

\[
\frac{\rho_{astro}}{\rho_{part}} \sim 10^{120}
\]

Too big!
We make particles in accelerators by smashing things together, making them hot and dense.

Anywhere you get hot and dense in the Cosmos, you can also get all these exotic particles.
Quark Star

- A (theoretical) denser cousin of neutron stars
- Denser, so it is smaller
THE BIG BANG

Time Since Big Bang
- Present: 15 billion years
- 1 billion years
- 300,000 years
- 3 minutes
- 0.001 seconds
- $10^{-10}$ seconds
- $10^{-35}$ seconds
- $10^{-43}$ seconds

Era of Galaxies
Era of Atoms
Era of Nuclei
Era of Nucleosynthesis
Particle Era
Electroweak Era
GUT Era
Planck Era
Seeing the Universe

- Virtually everything you know about the Cosmos was learned from a single source: light
- We can also watch the Universe in particles

Neutrino Astronomy

Cosmic Ray Astronomy
Neutrinos are naturally generated during nuclear fusion when neutrons are changed back and forth into protons.

\[ n \rightarrow p^+ + e^- + \bar{\nu}_e \]

\[ p^+ \rightarrow n + e^+ + \nu_e \]

Lots of fusion in stars, so there are lots of neutrinos!

They are extremely hard to detect, because they do not easily interact with matter.
To detect neutrinos, you watch for occasional interactions with ordinary atoms.

- Rare events, so you can watch 1 atom for a long time, or watch a lot of atoms for a much shorter time.

- The first was in the Homestake Mine in South Dakota, built in the late 1960s by Ray Davis.
Others have followed, most notably SNO (Sudbury Neutrino Observatory) and Super-Kamiokande (Super-K)
In any supernova explosion, there should be a burst of neutrinos associated with the cataclysmic nuclear explosion.

Q: How many neutrinos did we see from SN 1987A?
A: 12 (we expected ~10); 24 total from all the world’s detectors

Q: How many papers have been written about those 12 neutrinos?
A: ~3220
Cosmic rays are simply high energy particles that are accelerated by astrophysical events. They enter the Earth’s atmosphere, they hit molecules and generate more particles in a cosmic ray shower.
A variety of ways exist to detect cosmic rays. One of the world’s leading cosmic ray observatories is in Utah!
Future efforts in particle physics depend on new accelerators. The newest is the **Large Hadron Collider**

- Located on the Swiss-French border, it will be the most powerful collider ever built (16.5 miles around)
Quarks cannot exist as isolated particles

At high enough pressure and temperature, they can dissolve into a soup known as the **Quark-Gluon plasma**

This soup is reminiscent of the earliest moments after the **Big Bang**, when quarks were free to do as they wished!
The Holy Grail in particle physics is the **Higgs Boson** – the only particle in the Standard Model that has not been detected.

- We believe the LHC should be able to detect it.

- Leon Lederman once wrote: “If the Universe is the Answer, what is the Question?”

- The Higgs defines the energy scales of particle physics, and as a result, the properties of all the other particles.
Will the LHC create microscopic black holes? **Possibly.**

Should I be worried? **Probably not.**

WHY NOT?

A simple argument: collision energy is ~14 TeV = 1400 GeV

At these energies, about $2 \times 10^{13}$ cosmic rays hit the Earth’s atmosphere every second

In every square meter, 4 cosmic rays of this energy strike every 100 seconds.

Nature is already doing it!
Last Thoughts...

- There are deep connections between particle physics and astrophysics that we are just now beginning to understand.

- Astrophysical systems are like giant particle accelerators in space.

- Particle accelerators are like small pockets of astrophysics that we can look at up close in the lab.