Unification of Forces

Newton: Earth-gravity with celestial motion

Faraday etc

Pre-Maxwell: Electricity + Magnetism

Einstein: Space & Time

Quantum Theory: Wave & Particle
Bohr, de Broglie, Schrödinger, Heisenberg

Weak + EM:
Weinberg et al '70
Nobel '79
(with Salam, Glashow)

Problem: what 'mediates' β-decay

Answer: $\gamma \rightarrow \{ Z^0, W^+, W^- \}$
Mixing same particles

photon is not what we think

Reason: Vacuum proportional to has structure!
100 + 'elementary', strongly interacting particles

\[
\begin{align*}
\{ & \text{up quark } u, \\
\{ & \text{down quark } d, \\
\{ & \text{strange quark } s, \\
\{ & \text{charmed quark } c, \\
\{ & \text{bottom quark } b
\end{align*}
\]

Baryons: p, n, ..., bound by

Mesons: π, K, ... 

\[q\bar{q} \rightarrow \text{new interactions}
\]

G Gluon like photon \ QCD

Puzzle:

How to bring together

Electro-Weak with Strong

Very nice attempts FAILED

\[\Rightarrow \text{your chance!}\]
Vacuum and Laws of Physics

- Quantum fluctuations fill ‘space devoid of matter’ = VACUUM
- Quantum vacuum is polarizable: see atomic level shifts
- Quantum vacuum state has quantum structure: glue condensate

\[ \langle V | G | V \rangle = 0 \]

\[ 0.5 \text{fm} \rightarrow \langle V | \frac{\alpha_s}{\pi} G^2 | V \rangle \approx (2.3 \pm 0.3) \times 10^{-2} \text{GeV}^4 = [390 \pm 12 \text{ MeV}]^4 \]

\[ 
\langle V | G^a_{\mu\nu} | V \rangle = 0, \quad G^2 = \sum_a G^a_{\mu\nu} G^a_{\mu\nu} = 2 \sum_a [\vec{B}_a^2 - \vec{E}_a^2]
\]

- Vacuum determines inertial mass of all matter particles?

\[ m_i = g_i \langle V | h | V \rangle, \quad h = \bar{\psi} \psi ? \]
When matter dissolves

<table>
<thead>
<tr>
<th>TEMPERATURE (DEGREES KELVIN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{15}$</td>
</tr>
<tr>
<td>$10^{13}$</td>
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<td>$10^{9}$</td>
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<tr>
<td>$10^{6}$</td>
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<td>$10^{3}$</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>TIME AFTER BIG BANG (SECONDS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-9}$</td>
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<td>$10^{-6}$</td>
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<td>$10^{15}$</td>
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<td>$10^{18}$</td>
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<tr>
<td>$10^{21}$</td>
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</tbody>
</table>

- QUARK-GLUON PLASMA
- HADRONIZATION
- NUCLEOSYNTHESIS
- ATOMS FORMED
- NOW

RECREATING THE EARLY UNIVERSE IN LABORATORY

**Micro-Bang**

- Energy Density: $\sim 1-5 \text{GeV/fm}^3 = 1.8-9 \times 10^{15} \text{g/cc}$
- Latent Vacuum Heat: $\sim 0.1-0.4 \text{GeV/fm}^3 \approx (166-234 \text{MeV})^4$
- Pressure: Relativistic matter $= \frac{1}{3} \epsilon = 0.52 \times 10^{30} \text{barn}$
- Temperature: $T_0, T_f = 300-250, 175-145 \text{ MeV}; 300 \text{MeV} \approx 3.5 \times 10^{12} \text{K}$

**Big-Bang**

- Time: $\tau \sim 10-50 \mu s$
- Baryon/Antibaryon Ratio: $N_B/N \sim 10^{-10}$

**S-Ag Reaction at 200A GeV (by NA35)**
RHIC Complex

RHIC depends on many of Brookhaven's world-class physics machines, which make and accelerate the RHIC beam.

Click the picture or the index to learn more about the many Brookhaven physics facilities that make up the RHIC complex.
**Cosmology**
- density fluctuations during QCD phase transition
- dark matter / large scale structure

**Astrophysics**
- compressibility of matter
- neutron stars / supernovae
All matter made of quarks: $u$, $d$, $s$ & electrons

<table>
<thead>
<tr>
<th></th>
<th>$u$</th>
<th>$d$</th>
<th>$s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q$</td>
<td>+$\frac{2}{3}$</td>
<td>$-\frac{1}{3}$</td>
<td>$-\frac{1}{3}$</td>
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<tr>
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<td>$\frac{1}{2}$</td>
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</tr>
<tr>
<td>$m$</td>
<td>5-10 MeV</td>
<td>5-10 MeV</td>
<td>130-180 MeV</td>
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<tr>
<td>$m$</td>
<td>5-10 MeV</td>
<td>1300-1800 MeV</td>
<td>4500-5000 MeV</td>
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<tr>
<td>$m$</td>
<td>5-10 MeV</td>
<td>174 GeV</td>
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</tbody>
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Heavy flavours

MST: Glue causes abundant production of strangeness
FORMATION OF STRANGENESS DENSE PHASE

In thermal QGP phase strangeness is produced by gluon fusion reactions $GG \rightarrow s\bar{s}$

(Rafelski/Müller, PRL48 (1982) 1066). ⇒ Excess of strangeness and STRANGE ANTIBARYONS

WA97-SPS/CERN Results

![Graph showing yield per participant relative to p-Pb vs number of participants.](image)