“The First Three Minutes”
The Big Bang’s Hot Past

• **Today:**
  – Universe is low-density and very cold (2.7 K)
  – Steadily expanding

• **~15 Gyr Ago:**
  – Universe was smaller, denser, & hotter
  – Expanding at a somewhat faster rate

• How far back can we go?
Loosing & Binding

• **Binding Energy:**
  – Energy needed to unbind (break up) matter.

• **Binding Temperature:**
  – *Temperature* equivalent to the binding energy.
  – Matter at this temperature “melts” (unbinds)

• Example:
  – In massive stars, nuclei melt at T~10 Billion K.
Typical Sizes & Binding Energies

<table>
<thead>
<tr>
<th></th>
<th>Size</th>
<th>Binding Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atoms</td>
<td>$10^{-10}$ m</td>
<td>$10^3$ K</td>
</tr>
<tr>
<td>Nuclei</td>
<td>$10^{-14}$ m</td>
<td>$10^{10}$ K</td>
</tr>
<tr>
<td>p &amp; n</td>
<td>$10^{-15}$ m</td>
<td>$10^{11}$ K</td>
</tr>
<tr>
<td>Quarks</td>
<td>$10^{-18}$ m</td>
<td>$10^{13}$ K</td>
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**Fundamental Forces of Nature**

- **Gravitation:**
  - Long-Range

- **Electromagnetic Force:**
  - Long-Range, $10^{39} \times$ stronger than gravity

- **Weak Force:**
  - Range $<10^{-17}$ meters, $10^{28} \times$ gravity

- **Strong Force:**
  - Range $<10^{-15}$ meters, $10^{41} \times$ gravity
Unification of the Forces

• **Electroweak Force:**
  – EM & Weak forces unify at high energies ($10^{15}$K)
  – Verified in particle accelerator experiments.

• **Grand Unified Theory (GUTs):**
  – Strong & Electroweak Forces unified.
  – Predicted, but no experimental basis (yet?)
“Dreams of a Final Theory”

• What about Gravity?
  – Gravity should unify with the GUTs force at very high energies.
  – Much higher than in any possible accelerator.
  – However, these energies could occur in the Early Universe.

• Problem:
  – We have no quantum theory of Gravity!
The Cosmic Timeline

• Physics gives us a framework within which to describe the Big Bang from the earliest phases to the present.
  – Particle accelerators probe matter at states similar to some of these early phases.
    • Large Hadron Collider will soon begin experiments
  – Astronomers look for evidence in the present Universe (e.g., Cosmic Background, primordial deuterium & helium, dark energy)
LHC
LHC instrument
Planck Epoch

• Before $t=10^{-43}$ sec:
  – All 4 forces unified into a single Superforce
  – 1 force rules all of physics

• Can’t say much else, as we as yet don’t have a quantum theory of gravity to guide us.
Grand Unification Epoch

• At $t=10^{-43}$ sec, $T=10^{32}$ K (???):
  – Gravity separates from the Superforce
  – Strong & Electroweak Forces still unified.

• 2 forces rule physics:
  – Gravity & GUTs

• Universe is a soup of quarks, antiquarks & photons.
Inflationary Epoch

• $t=10^{-35}$ sec (?), $T=10^{27}$ K (?):
  – Strong force separates from GUTs force
  – EM & Weak forces still unified

• 3 forces rule physics:
  – Gravity, Strong, and Electroweak forces

• Rapid separation triggers a rapid “inflation” of the Universe
The Inflationary Universe

• Universe grows by a factor of $10^{50}$ between $10^{-35}$ and $10^{-33}$ seconds!

• Expansion rate greatly slows after this brief burst of inflation.

• Helps to explain why the universe is so very smooth on large scales.
Four Forces at Last!

• $t=10^{-12}$ sec, $T=10^{15}$ K:
  – Electroweak separates into EM & Weak forces
  – All forces are now separate

• 4 forces rule physics:
  – Gravity, Strong, Weak & Electromagnetic

• Conditions becoming right for free matter to begin to exist separate from photons.
Quark Freeze-out

- At $t=10^{-6}$ sec, $T=10^{13}$ K:
  - Free quarks combine into hadrons (primarily protons & neutrons)
  - Particle-antiparticle pairs & photons in equilibrium:

\[
\begin{align*}
\text{p} + \overline{\text{p}} & \leftrightarrow \gamma + \gamma \\
\text{n} + \overline{\text{n}} & \leftrightarrow \gamma + \gamma
\end{align*}
\]
Nucleon Freeze-out

• At $t=0.01$ sec, $T=10^{11}$ K
  – protons & neutrons decouple from photons and exist as free particles.
  – electrons & positrons in equilibrium with photons
  – neutrinos & nucleons in equilibrium

• Free neutrons are stable during this epoch.
Neutrino Decoupling

• At $t=1$ sec, $T=10^{10}$ K
  – neutrinos decouple from matter
  – stream out into space freely
  – cosmic neutrino background (not yet observed)

• Free neutrons are no longer stable:
  – Decay into protons, electrons & neutrinos
  – Left with about 1 neutron for every 7 protons
Epoch of Nucleosynthesis

• $t \sim 3$ min, $T = 10^9$ K:

• Fusion of protons & remaining free neutrons:
  – Formation of $^2$H (Deuterium) & $^4$He
  – End up with $\sim 75\%$ H, 25\% He
  – Traces of D, Li, Be, B

• We cannot observe this directly, but we can look for the products of these events.
Epoch of Recombination

• $t=300,000$ yr  $T=3000$ K:

• Electrons & nuclei combine into neutral atoms
  – Universe becomes transparent
  – Photons stream out into space
  – Origin of the Cosmic Background Radiation

• Earliest we can see back *directly* using light.
The Epoch of Galaxies

• **Galaxy Formation**: \( t = 10^9 \text{ yrs}, T \sim 30 \text{ K} \)
  - Quasars
  - First generation of stars.
  - First metals from first supernovae.

• **Present**: \( t = 10^{10} \text{ yrs}, T = 2.726 \text{ K} \)
  - Galaxies, stars, planets, us...
  - Metals from supernovae of massive stars.
Cosmic Timeline
What about the Beginning?

- Our physics can not yet probe earlier than the end of the Planck Epoch ($t=10^{-43}$ sec).
- Some would say we have problems back before the Electroweak Epoch ($t=10^{-12}$ sec).
- This will be the astrophysics of the 21$^{st}$ Century (or maybe the 22$^{nd}$...
Summary:

• Physics of the Early Universe
  – Informed by experimental & theoretical physics

• The Cosmic Timeline:
  – Observations go back to \( t \approx 3 \) minutes
  – Reasonably firm physics back to \( t \approx 10^{-6} \) sec
  – Speculative back before \( t \approx 10^{-12} \) sec
  – Present theories stop at \( t \approx 10^{-43} \) sec