Cosmology in 5 Easy Pieces

- Cosmology with Newton
- The Cosmic Microwave Background and the Early Universe.
- Cosmology with Einstein: General Relativity and the Cosmological Constant
- Observational Cosmology: The Supernova Result
- The (Very) Early Universe

Eras and Events in the Early Universe

<table>
<thead>
<tr>
<th>Era or Event</th>
<th>Time</th>
<th>Temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planck era</td>
<td>$&lt; 5 \times 10^{-43}$ s</td>
<td>$&gt; 10^{37}$ GeV</td>
</tr>
<tr>
<td>Planck transition</td>
<td>$5 \times 10^{-43}$ s to $10^{-16}$ s</td>
<td>$10^{37}$ GeV to $10^{32}$ GeV</td>
</tr>
<tr>
<td>Grand unification</td>
<td>$10^{-16}$ s to $10^{-10}$ s</td>
<td>$10^{57}$ GeV</td>
</tr>
<tr>
<td>Electroweak era</td>
<td>$10^{-10}$ s to $10^{-4}$ s</td>
<td>$10^{57}$ GeV to $100$ GeV</td>
</tr>
<tr>
<td>Electroweak transition</td>
<td>$10^{-4}$ s</td>
<td>$100$ GeV</td>
</tr>
<tr>
<td>Quark era</td>
<td>$10^{-3}$ s to $10^{-1}$ s</td>
<td>$100$ GeV to $200$ MeV</td>
</tr>
<tr>
<td>Quark-hadron transition</td>
<td>$10^{-1}$ s</td>
<td>$200$ MeV</td>
</tr>
<tr>
<td>Neutrino decoupling</td>
<td>$0.1$ s</td>
<td>$3$ MeV</td>
</tr>
<tr>
<td>Electron-positron annihilation</td>
<td>$1.3$ s</td>
<td>$1$ MeV</td>
</tr>
</tbody>
</table>

(Table 16.2)
Why We Believe the Hot Big Bang Cosmology

- Makes specific predictions, verified by observation.

1) **Hubble Law**: Predicts velocity proportional to distance, as observed for galaxies.

2) **Cosmic microwave background radiation**: Predicts a thermal (black-body) spectrum released at "recombination" epoch \( t = 380,000 \text{ yrs}, \ T = 3000 \text{ K} \), now cooled by a factor of \( \sim 1000 \) \( T = 3 \text{ K} \). CMB discovered in 1965, with properties in perfect agreement with predictions.

3) **Abundances of elements**: Primordial nucleosynthesis calculations predict a Universe made up of \( \sim 25\% \) He and \( \sim 75\% \) H by mass, as observed.

Two Problems with "Standard" Big Bang

1) **Flatness problem**: Why is the Universe so nearly flat? That is, why is \( \Omega_{\text{tot}} \) so close to 1.0?

   - To be anywhere near unity today, it must have started out with a value exceedingly close to unity in the beginning.

2) **Horizon problem**: Why does the Universe have the same average temperature in all directions, even though widely separated regions could never have been in thermal equilibrium with each other since they are beyond each other's horizon?

Examining the CMB: Preliminaries

What is the angular diameter distance to the surface of last scattering \((z \sim 1100)\)?

For a flat universe:

\[
d_A = \frac{14.6 \text{ Gpc}}{z} = \frac{14.6 \text{ Gpc}}{1100} \\
\]

\[d_A \approx 13 \text{ Mpc}\]

What is the largest region of space that could have been in sonic communication at the time of recombination?
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Adiabatic perturbations in a gas/fluid of pressure $P$ and energy density $u$ travel at a sound speed given by:

$$c_s^2 = c^2 \frac{dP}{du}$$

but, since $P = wu$, $c_s = \sqrt{w}c$ : the sound speed is proportional to the speed of light.

Assuming the photon - baryon fluid to have $w = 1/3$, $c_s = \frac{c}{\sqrt{3}}$. Recombination occurs well into the matter era, during which $d_s = 3ct$. Since the sound speed is proportional to the speed of light:

$$d_{\text{sound}} = \frac{3ct}{\sqrt{3}} = 0.2 \text{ Mpc}$$

Two Problems with “Standard” Big Bang

1) Flatness problem: Why is the Universe so nearly flat? That is, why is $\Omega_{\text{tot}}$ so close to 1.0?

To be anywhere near unity today, it must have started out with a value exceedingly close to unity in the beginning.

2) Horizon problem: Why does the Universe have the same average temperature in all directions, even though widely separated regions could never have been in thermal equilibrium with each other since they are beyond each other’s horizon?
**Inflation to the Rescue!**

**Inflation**: The theory that, early in the history of our universe, a brief period of extraordinarily rapid, accelerated expansion occurred.

Accounts for both the horizon problem and the flatness problem:

- Before inflating, the tiny initial Universe could have achieved a uniform temperature:

  ![Graph showing temperature change over time](image1)

- Inflation flattens out any initial curvature the Universe may have had, like a balloon inflating:

  ![Balloon inflating](image2)