What happened back at the Big Bang?

- The Flatness Problem:
  - NOW: Kinetic energy ~ Gravitational energy
  - But this requires incredible precision at start (t = 0).
  - kinetic exactly = gravitational energy → Critical Density
Isotropy of the Cosmic Microwave Background

- COBE satellite.

The Horizon

Current CMB emitted from sphere 13.7 billion LY in radius.

Visible universe

We will only see this part of universe sometime in future.
The Horizon

Current CMB emitted from sphere 13.7 billion LY in radius.

We will only see this part of universe sometime in future.

Visible universe

Clicker Question. Has Point A ever communicated with Point B?
A. Yes
B. No
C. Maybe

The Horizon Problem: Causality

- Points A and B have never communicated.
- How do they know how to have almost exactly the same conditions?
The solution: **Inflation**

(probably)

(maybe)

Extremely rapid expansion of universe

- due to release of energy in “phase change”.
- like ice to water.

Universe became $10^{43}$ times larger within $10^{-32}$ seconds.

[See Section 17.3]
Freezing out the forces.

Phase changes and latent heat

- Apply heat energy at a steady rate to a fixed quantity of H₂O
- How does the temperature change?
What does inflation predict for geometry of present universe?

- Predicts a flat universe
- Solves horizon problem.

Universe became $10^{43}$ times larger within $10^{-32}$ seconds.

The History of the Universe

- Quark Soup
- Inflation
- Primordial Nucleosynthesis
- Cosmic Microwave Background
- First Galaxies
- Modern Universe

Time

<table>
<thead>
<tr>
<th>Planck time</th>
<th>Inflation</th>
<th>Formation of H, He, Li</th>
<th>Decoupling of CMB</th>
<th>Galaxy Formation</th>
<th>Now</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot</td>
<td>(10^{32} K)</td>
<td>(10^{3} K)</td>
<td>(3000 K)</td>
<td>(3 K)</td>
<td>Low density</td>
</tr>
</tbody>
</table>
The Local Group

- Our Galaxy and its satellites.
- Andromeda galaxy (M31) and its satellites.
Satellite Galaxies

- Large Magellanic Cloud
- Small Magellanic Cloud
- M31, M32, NGC 205
- Milky Way
- Leo I

Galaxy Clusters
1000’s of galaxies

- Hercules Cluster
- NGC 4881 Coma Cluster
- HST - WFC2
• Local Group is in orbit about Virgo Cluster ($10^{14} \text{ M}_\odot$).
• All part of Local Supercluster ($10^{15} \text{ M}_\odot$)

• Local Group is in orbit about Virgo Cluster ($10^{14} \text{ M}_\odot$).
• All part of Local Supercluster ($10^{15} \text{ M}_\odot$)
• Local Supercluster is part of streaming motion towards “Great Attractor”
  • $10^{16-17} \text{ M}_\odot$
  • located 100 million LY away.
• Detected by extra motions superimposed on “Hubble Flow”.
The masses of galaxies

For orbits outside central mass:
- \( P^2 (M_1 + m_{\text{star}}) = a^3 \)
- Velocity = \( \frac{2\pi a}{P} \propto \frac{\sqrt{1/a}}{a} \)
- Measure Doppler shift of absorption lines & emission lines at different points in galaxy.

Inside the Central Mass

See [Fig. 16.1]

Outside the Central Mass

Dark matter

- We expected falling “Keplerian” curve out beyond outermost luminous matter.

- But curves do not drop off
  - large amounts of additional “dark matter” in outer parts of spiral galaxies.
The Milky Way’s Dark Matter “Halo”

100,000 LY

2,500,000 LY

Gravitational Lenses
Another way to measure total mass in clusters (see Fig [16.9])

The “Einstein Cross”
Galaxy at center causes 4 images of same quasar.
Gravitational Lens in Galaxy Cluster Abell 2218

- Foreground cluster distorts images of numerous background galaxies.
- Use to determine total mass of foreground cluster.
- Shows that 85% of mass is Dark Matter.

[Fig. 16.10]

The Remarkable Case of CL0024+1654

- Single distant blue galaxy.
- Lensed by foreground cluster.
- 8 different images.
- Allows detailed analysis of mass distribution in cluster.
- 83% of mass is non-luminous Dark Matter.

[see Fig 16.8]
What *is* Dark Matter?

- **Weakly-Interacting Massive Particles (WIMPs)?**
  - Current best bet.
  - Being searched for here on Earth.

*The Truth: We don’t know.*