Reading: Chapter 28, Section 28.3-28.5; Chapter 29, Section 29.1, 29.2-29.4
Third Exam: Tuesday, May 1 12:00-2:00

Last time: Galaxy Clusters & Superclusters - large scale structure
• Galaxies are mostly found in groups called clusters
• Clusters are further organized into superclusters
• Dark matter is needed to hold clusters together
• The large-scale structure of the visible Universe shows large voids threaded by filamentary superclusters

Today: Cosmology I - The Age of the Universe and the Big Bang
• Cosmology - answering questions about the origin of the Universe and answering them using observations
• Independent measurements all yield an age of the Universe of about 13.5 billion years
• Time began with a hot Big Bang - expansion and cooling until today
• The Big Bang makes several predictions that can be tested

Cosmology: the study of the overall structure and history of the Universe
• We live in an expanding universe
  • How long has it been expanding
  • Will it expand forever?
• We live in a very big universe
  • Is it truly infinite, or is there an “edge”?
  • Are there other Universes?
• What caused the Large Scale Structure?
  • When and how did galaxies first form?
  • When and how did clusters form?
  • What happened before there were galaxies?

These questions are all interrelated!

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• The Oldest Stars
  • use globular cluster stars in the Milky Way
  • find: age ~ 13 billion years

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• Hubble’s Law (recitation exercise)
  • how long has the Universe taken to reach its current size?
    \[ V = H_0 \times d \] (Hubble); \[ V = d/t \] (3rd grade)
  • substitute for V:
    \[ d/t = H_0 \times d \]
    so \[ 1/t = H_0 \] ... or \[ t = 1/H_0 \]
  • \( t_h < 1/H_0 \)
    • \( t_h < 15 \) billion years \( (H_0 = 65) \)
    < 19 billion years \( (H_0 = 50) \)
    < 12 billion years \( (H_0 = 77) \)
  • \( H_0 \) tells us the expansion age of the Universe
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- Conclusions to draw
  - remarkable consistency between two different measures
  - The Universe began to expand 12-19 billion years ago
  - At that time ($t=0$!) all matter was at a single point.

Looking back at time

- more distant galaxies - the universe as it was at earlier times
- we can “see” our Universe’s past by looking at large distances

Looking back through time: our best tool - HST

Assembling Galaxies
Looking back at time
the Universe was hotter in the past

The hot early Universe
energy (radiation) and mass in equilibrium

A (reverse) chronology of the Universe

<table>
<thead>
<tr>
<th>Time (since ‘0’)</th>
<th>T(K)</th>
<th>Density</th>
<th>Size</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{10}$ yr</td>
<td>3</td>
<td>$10^{-30}$</td>
<td>$1.5 \times 10^{10}$ ly</td>
<td>our world</td>
</tr>
<tr>
<td>$10^6$ yr</td>
<td>3000</td>
<td>$10^{-21}$</td>
<td>$1.5 \times 10^6$ ly</td>
<td>Hydrogen recomb.</td>
</tr>
<tr>
<td>3 minutes</td>
<td>$10^9$</td>
<td>100</td>
<td>0.3 ly</td>
<td>deuterium forms</td>
</tr>
<tr>
<td>20 sec.</td>
<td>$5 \times 10^9$</td>
<td>1000</td>
<td>0.15 ly</td>
<td>electron freeze-out*</td>
</tr>
<tr>
<td>$10^{-4}$ sec.</td>
<td>$10^{13}$</td>
<td>$10^{14}$</td>
<td>2 a.u.</td>
<td>proton/neutron freeze-out</td>
</tr>
<tr>
<td>zero</td>
<td>infinity</td>
<td>infinity</td>
<td>zero</td>
<td>The Big Bang</td>
</tr>
</tbody>
</table>

- matter + antimatter ↔ photons
- As T drops, matter freezes out:
  - high T → heavy particles
  - low T → lighter particles

\[ E = mc^2 \]
Testing the Big Bang Idea

- **Big Bang Nucleosynthesis**
  - production of light and heavy elements in the early Universe

- **Remnant radiation from primeval fireball**
  - universal background radiation

- **Origin of Cosmic Structures**
  - formation of galaxies and huge superclusters in an expanding Universe

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Big Bang Nucleosynthesis

- **Earliest minutes**
  - H, deuterium
  - He$^3$, He$^4$ (after deuterium stable)

- **Expansion and cooling**
  - halts further fusion

- **net Big Bang production**
  - ~ 75% Hydrogen
  - ~ 25% Helium
  - < 0.1% lithium, beryllium, etc.

- **Matches composition of the oldest stars!**