Universe at 400,000 yr: Weighing the universe—2 Dec

- Homework 10 will not be accepted after the last day of classes (Fri, 11th). Answers will be posted after class.
- Final exam: Mon, 14th in 1410 (next door)

- Cosmic background radiation is not completely isotropic.
  - Hotter by 0.004K in one direction and cooler in opposite direction. \( \Rightarrow \) We move.
  - Largest fluctuations (0.0002K) are at an angular scale of 1°.
- Use fluctuations to weigh the universe (determine the mass density).

Remove motion

- Remove motion and show with increased contrast
- Largest fluctuations are at an angular scale of 1°.

Temperature fluctuations: Light & dark mottling
Fluctuations at an angular scale of 1°

- Largest fluctuations are at an angular scale of 1°.
- Fluctuations are dense & sparse regions
  - Dense regions are hotter by 0.0002K.
  - Sparse regions are cooler.

How fluctuations work

- Largest fluctuations are at an angular scale of 1°.
- Fluctuations are growing dense & sparse regions
  - Dense regions are hotter by 0.0002K.
  - Sparse regions are cooler.
- What happened to fluctuations at smaller scales?
  - Radiation dominates. Radiation from a hotter region warms up a cooler region.
  - At smaller scales, temperature is more uniform.
- Why does warming cooler regions not work on large scales?
  - Effects of warming can only go as fast as speed of light. Universe was not old enough to average out large scales.
How fluctuations work

- What happened to fluctuations at smaller scales?
  - Radiation dominates. Radiation from a hotter region warms up a cooler region.
  - At smaller scales, temperature is more uniform.
  - Why does warming cooler regions not work on large scales?
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  - A denser region grows by gravity.

1. Why are there no dense, hot regions having a very large size?
   A. They cooled off.
   B. The universe was not old enough.
   C. They are difficult to observe.

- Effect of gravity can only go as fast as speed of light. Universe was not old enough to grow at large scales.
- Size of largest fluctuations is
  \[ \frac{1}{3} \times \left( \frac{\text{Age of universe}}{\text{speed of light}} \right) \]

What sprouts from this kernel?

Astronomical Weighing

- Principle for astronomical weighing:
  - Define a motion
  - Time the motion
  - If the motion takes longer, the mass is less.

- To find mass of sun, measure period T & size R of a planet’s orbit.
  - Under influence of the gravity of the sun, a planet moves a given distance. If the time is short, the mass of the sun is greater.

- To find mass of a galaxy, measure the speed of gas in orbit & radius of orbit.
  - Under influence of the gravity of the galaxy, a gas cloud moves a given distance. If the time is short, the mass of the galaxy is greater.

<table>
<thead>
<tr>
<th>Mass</th>
<th>Test object</th>
<th>Motion</th>
<th>Behavior if more massive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun</td>
<td>Earth</td>
<td>An orbit</td>
<td>Year is shorter</td>
</tr>
<tr>
<td>Galaxy</td>
<td>Gas cloud</td>
<td>An orbit</td>
<td>Speed is faster</td>
</tr>
</tbody>
</table>
Effect of gravity on expansion of the universe

- We assumed the force of gravity had a negligible effect on the expansion of the universe, so that the speed of galaxies remained the same. Now we include the force of gravity.
- How to think about the effect of gravity on the expansion of the universe.
  - We are at the center of a big sphere. Many galaxies (and other stuff) fill the sphere. Even more galaxies are outside the sphere.
  - A galaxy is on the edge of the sphere.
  - Sphere expands and galaxy moves because universe expands.
  - Present speed & present distance are fixed by Hubble’s Law.
  - Newton says: The galaxy feels the pull only of the mass inside the sphere.
  - If there is much mass, the galaxy will slow down, and the expansion of the U will slow down too. (The galaxy is a marker for the expansion of the U.

1. Consider H’s constant $H = \frac{v}{D}$. If there is little mass in the sphere, $v$ was constant and $D$ was smaller in the past. If there is more mass, would Hubble’s constant in the past be ___?
   A. bigger yet
   B. same as with little mass
   C. not as big

Effect of gravity on expansion of the universe

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Weighing Universe

- Principle for astronomical weighing:
  - Define a motion
  - Time the motion
  - If the motion takes longer, the mass is less.
- Consider a big sphere centered on us, which contains many galaxies
- Mass inside sphere pulls on galaxy & slows expansion.
- Present speed & present distance are fixed by Hubble’s Law.
- To find mass density of the universe, measure the time it takes for the U to expand by a factor of 2 by looking at galaxies for which the wavelength has expanded by a factor of 2. (Other factors are OK too.)

5. Consider now & time when radius of sphere is $1/2$ present radius. If the time to expand by a factor of 2 is long, the mass density of the U is ___. Explain your reasoning.
   A. high.
   B. low.

Summarizing questions

- What are the important observable events in the history of the universe?
- In what sense is the cosmic background radiation a snapshot of the universe?
- Why is the cosmic background radiation hotter in a certain direction and cooler in the opposite direction?
- What determines the physical size of the fluctuations of the cosmic background radiation?
- Why does the angular size of the fluctuations determine the mass density of the universe?