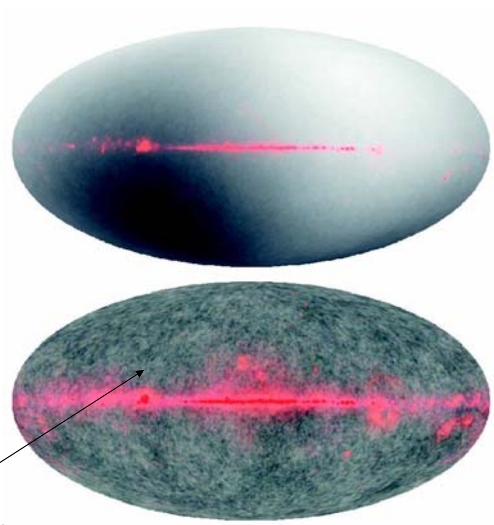
Universe at 400,000yr: Weighing the universe—2 Dec

- 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 1º.
- Use fluctuations to weigh the universe (determine the mass density).

Remove motion

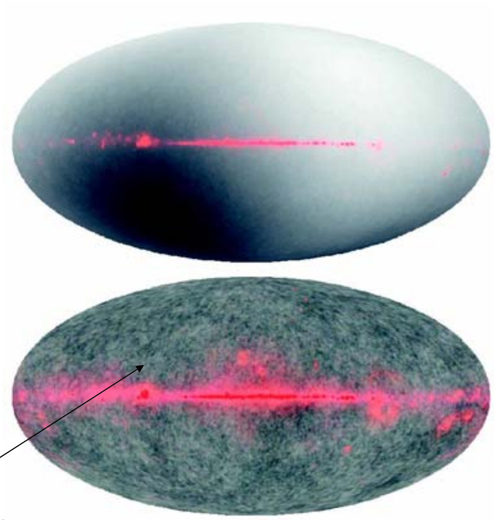
- Remove motion and show with increased contrast
- Largest fluctuations are at an angular scale of 1º.



Temperature fluctuations:
Light & dark mottling

Fluctuations at an angular scale of 1°

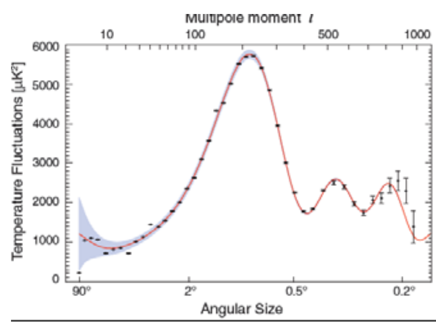
- Largest fluctuations are at an angular scale of 1°.
- Fluctuations are dense & sparse regions
  - Dense regions are hotter by 0.0002K.
  - Sparse regions are cooler.



Temperature fluctuations: Light & dark mottling

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.



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How fluctuations work

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  - Radiation dominates. Radiation from a hotter region warms up a cooler region.
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- Why does warming cooler regions not work on large scales?
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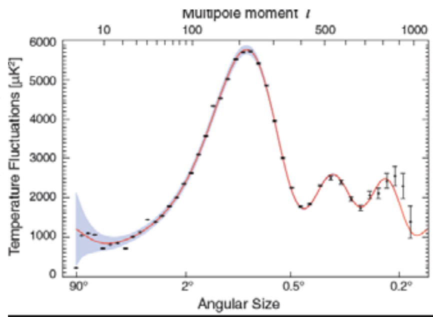
- A denser region grows by gravity.

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
  1/3 (Age of universe)×(speed of light)



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What sprouts from this kernel?

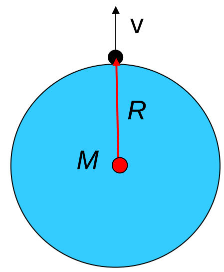
Astronomical Weighing

- 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.

Mass	Test object	Motion	Behavior if more massive
Sun	Earth	An orbit	Year is shorter
Galaxy	Gas cloud	An orbit	Speed is faster

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) fills 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.



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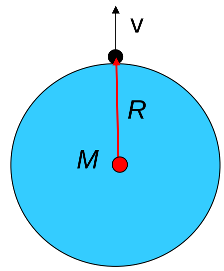
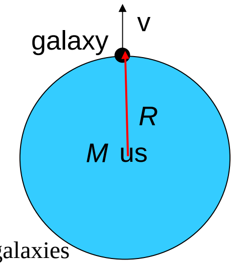
1. Consider H's constant H=v/D. If there is little mass in the sphere, v was constant and D was smaller in the past. If there is more mass, would Hubble's constant in the past be ___?
   A. bigger yet
   B. same as with little mass
   C. not as big

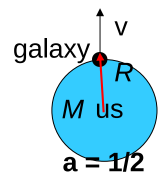


Weighing Universe



- 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 ½ 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?