Friday, Nov. 14

Syllabus, class notes, and homeworks are at:
www.as.utexas.edu → courses → AST 301, Lacy

Reading for next week: chapter 16

We'll go back to the old help session time and place next week: Wednesday at 5:00 in GRG 424

Topics for this week

How does the big bang theory explain Hubble's law?

How does the big bang theory explain the microwave background radiation?

Describe some of the events that occurred in the first few minutes after the big bang.

Describe how supernovae are used to measure the rate of expansion of the Universe in the past.

Describe how matter and energy cause the expansion of the Universe to accelerate or decelerate.

How can we measure the amount of normal matter, dark matter, and dark energy in the Universe? What do we find?

The Background Radiation

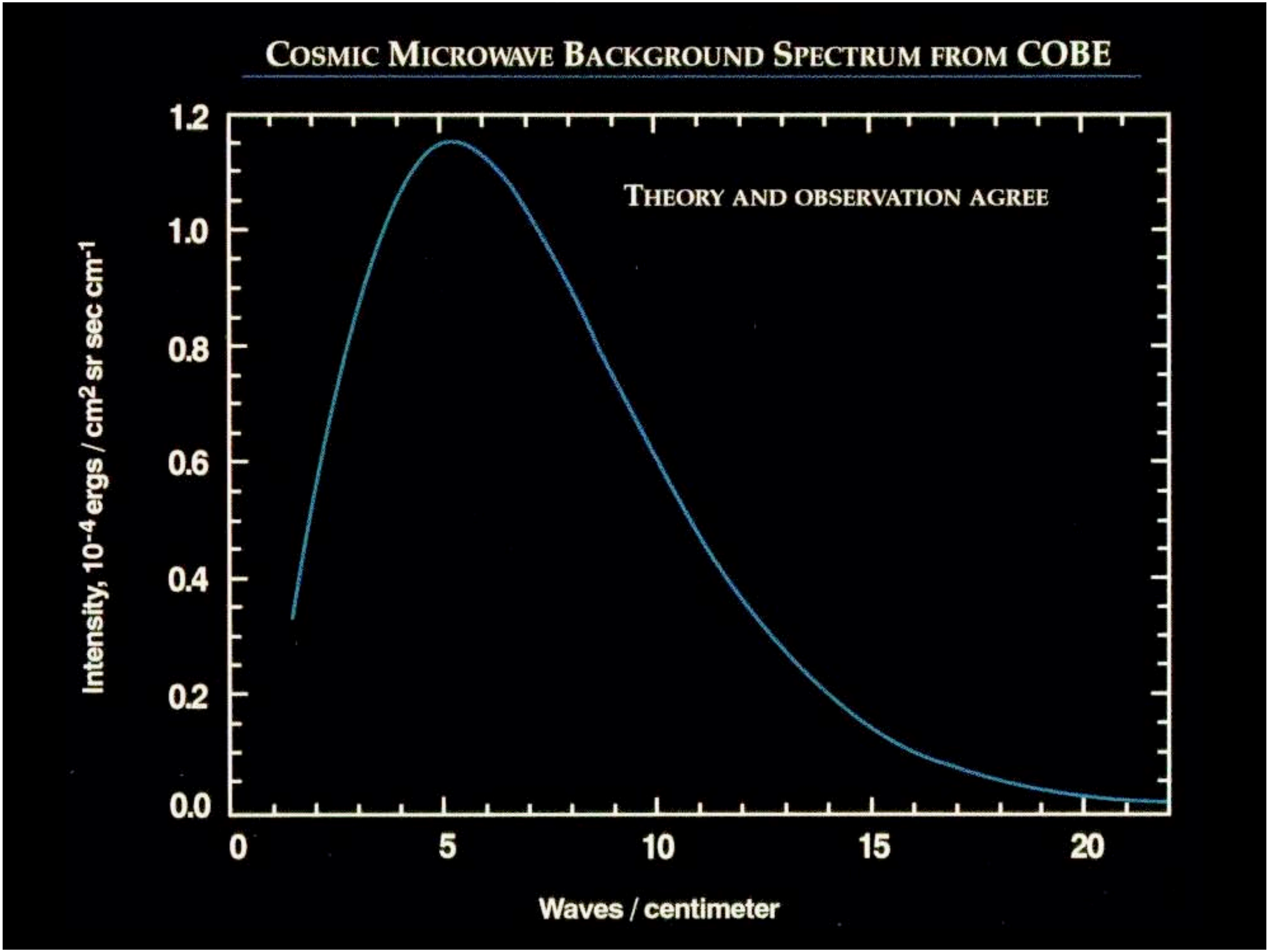
The light that is reaching us now has had its wavelengths Doppler shifted by the expansion of the Universe.

For this purpose it is easiest to look at the Doppler shift as being a stretching of wavelengths of light by the same factor as distances in the Universe have been stretched.

For 3000 K, $\lambda_{max} = 1\ \mu m$.

Stretched by a factor of 1000, this light appears now with $\lambda_{max} = 1$ mm.

It has the spectrum expected for an object at a temperature of 3 K, which would have its peak emission at 1 mm.



COSMIC MICROWAVE BACKGROUND SPECTRUM FROM COBE
THEORY AND OBSERVATION AGREE
Intensity, 10^-4 ergs / cm^2 sr sec cm^-1
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
Waves / centimeter

Thinking farther back

If the Universe has been cooling as it expanded, and it was at a temperature of 3000K 400,000 yr after the big bang, it should have been even hotter earlier.

We can ask what the temperature was at different times and what should have been happening then.

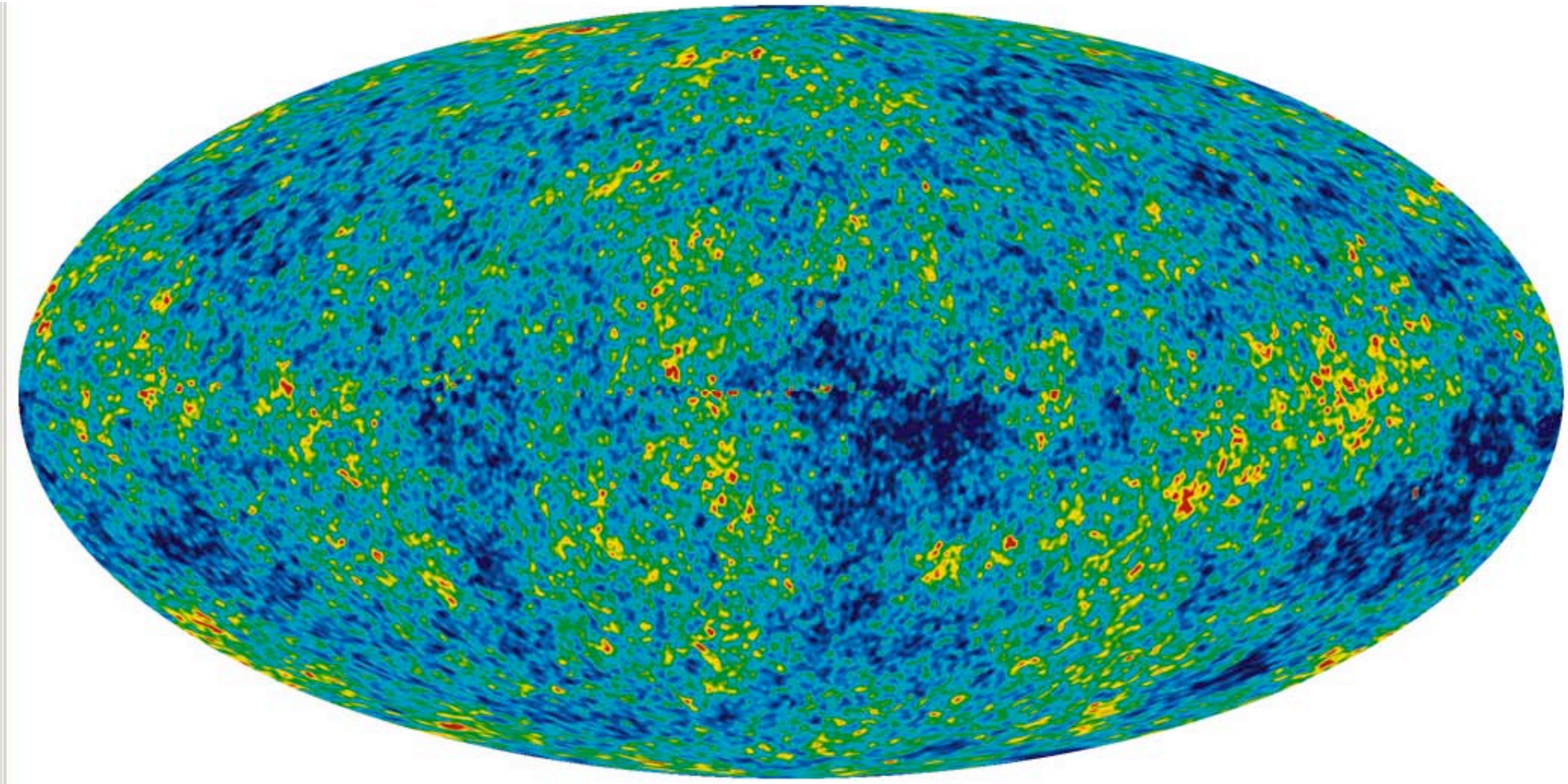
Before 400,000ABB

$t = 10^{-6}$ sec	$T \sim 10^{13}$ K	$\gamma + \gamma \leftrightarrow p^+ + p^-$
$t = 1$ sec	$T \sim 10^{10}$ K	$\gamma + \gamma \leftrightarrow e^- + e^+$
		$p^+ + e^- \leftrightarrow n + \nu$
$t = 2$ min	$T \sim 10^{9}$ K	$p^+ + n \leftrightarrow d^+$
		$d^+ + d^+ \leftrightarrow He^{++}$
		$n \rightarrow p^+ + e^- + \nu$

Heavier elements weren't formed because $^8Be \rightarrow 2\ ^4He$

Where did the elements other than hydrogen in your body come from?

A picture of the background radiation



The brightest spots are only 1.000001 times as bright as the darkest spots.

Even Earlier

The uniformity of the microwave background radiation is something of a puzzle.

The gas that emitted the radiation we see from one direction could not have communicated with the gas we see in the opposite direction (and won't for another 13 billion years).

Why were these two regions of the Universe at the same temperature?

Our favored explanation is that they were once close enough together to communicate by light, but between 10^{-35} sec and 10^{-32} sec ABB the Universe grew in size by a factor of 10^{50}.

This expansion is called inflation.

The Contents of the Universe

The gravitational attraction between galaxies can affect the expansion of the Universe.

If there is enough matter in the Universe, the attraction could stop the expansion and turn it around.

We see stars in galaxies.

How many?

We can compare the mass of stars in galaxies to the mass that would be required to have enough gravity to stop the expansion.

If we estimate the mass of stars in galaxies from the light they emit, we conclude that they have only about 1% of the mass required to stop the expansion.

Dark Matter

But we know that much of the matter in galaxies is dark.

We can measure the total mass in a galaxy from the speeds that the stars orbit at, using Kepler's 3rd law.

We find that when we include the dark matter, the mass in galaxies adds up to about 5% of the critical density (the amount of mass required to stop the expansion).

But there is also matter between galaxies in clusters of galaxies.

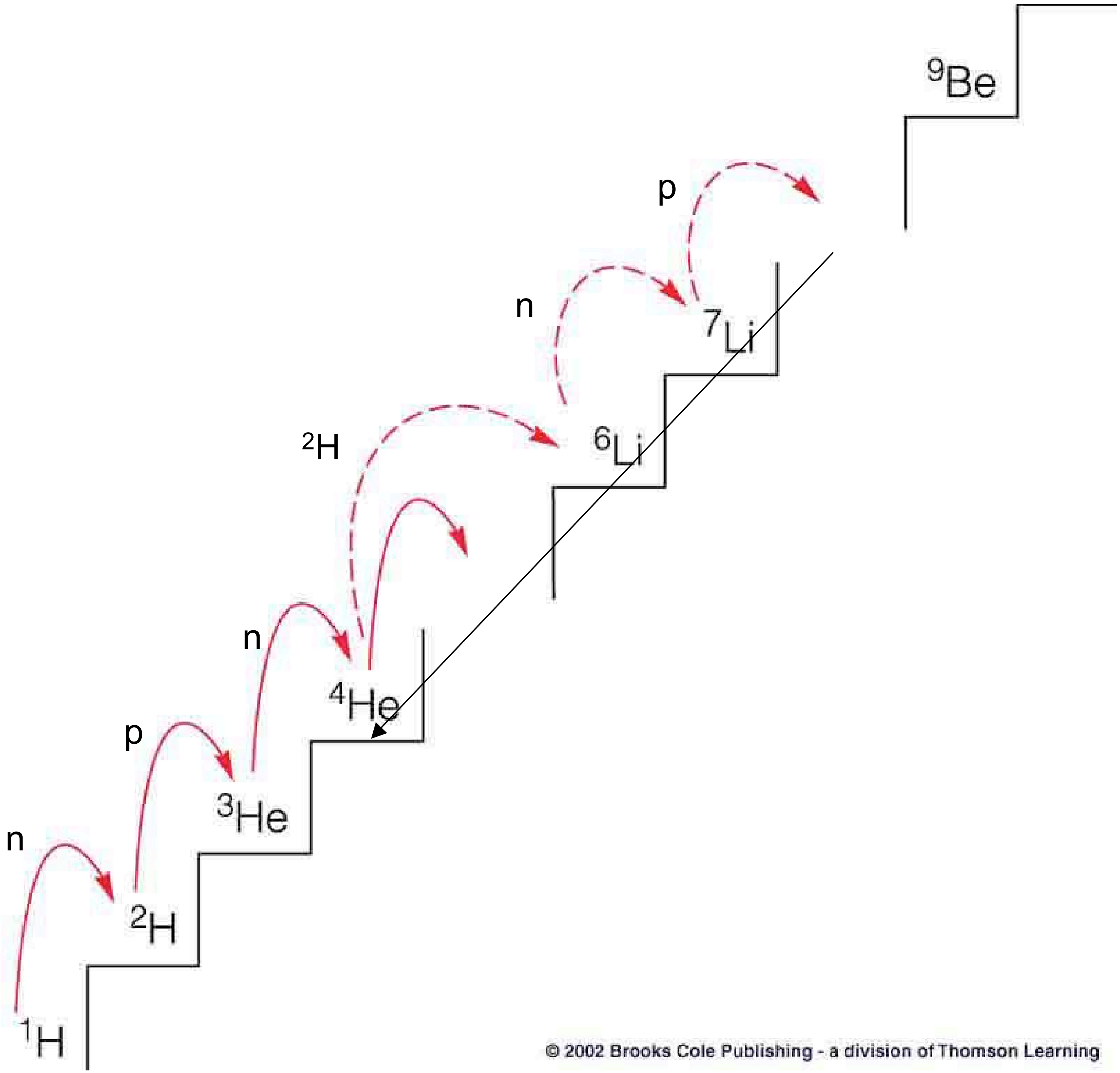
We can measure this mass from the speed at which galaxies orbit in clusters.

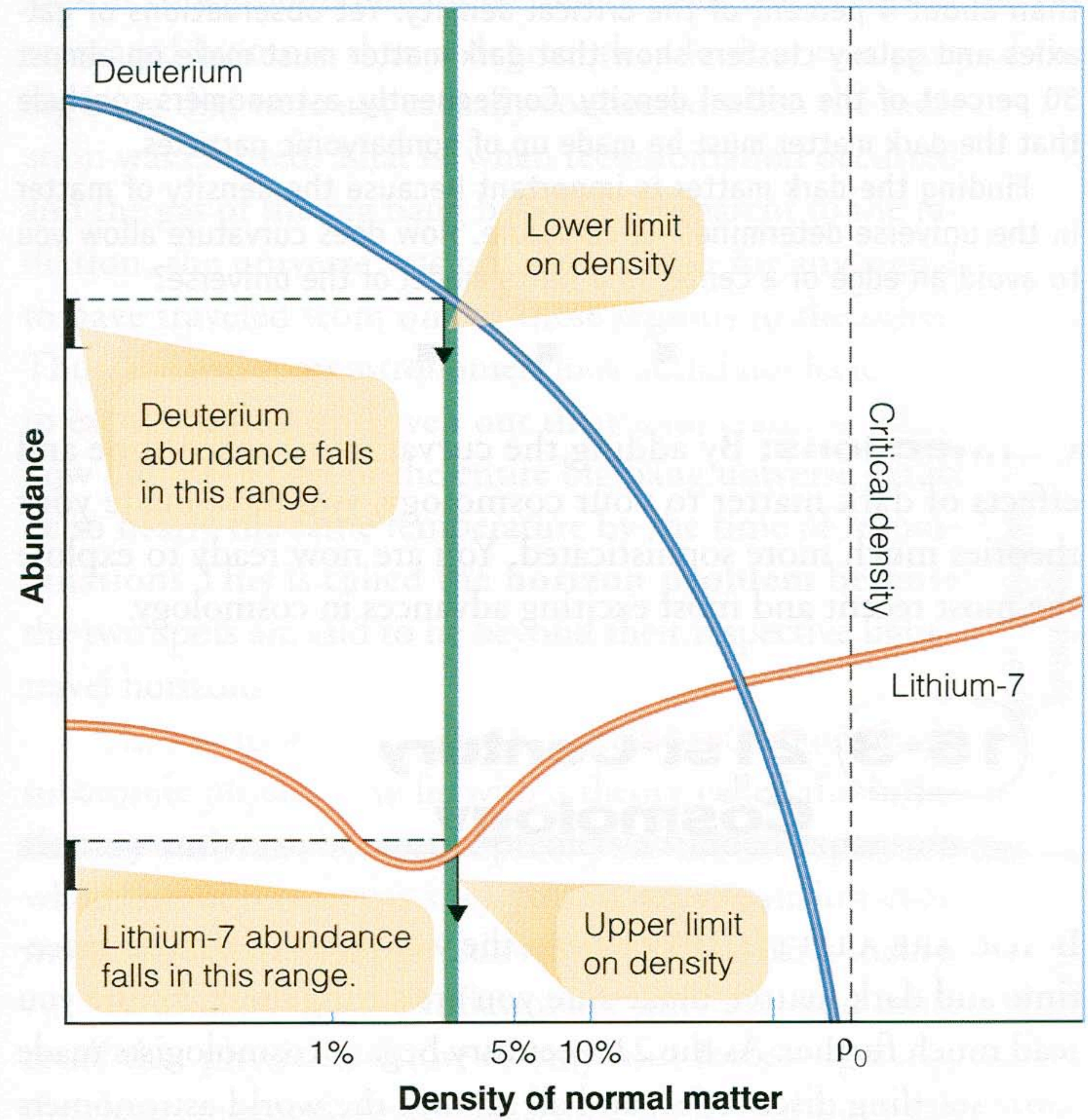
We conclude that the mass in galaxy clusters adds up to about 10% of the critical density.

Another approach

Another way to measure the amount of matter in the Universe is by asking about the fusion that occurred in the first few minutes after the big bang.

How much of the matter fused to make deuterium, helium, and lithium depended on how dense the Universe was then.


^9Be
p
n
^7Li
^2H
^6Li
n
^4He
p
^3He
n
^2H
^1H


Deuterium
Lower limit on density
Deuterium abundance falls in this range.
Abundance
Critical density
Lithium-7
Lithium-7 abundance falls in this range.
Upper limit on density
1%
5%
10%
ρ_0
Density of normal matter

Another approach

Another way to measure the amount of matter in the Universe is by asking about the fusion that occurred in the first few minutes after the big bang.

How much of the matter fused to make deuterium, helium, and lithium depended on how dense the Universe was then.

By measuring the abundances of these elements, we conclude that the matter that participated in fusion during the first few minutes adds up to 3-4% of critical density.

But this (probably) doesn’t include dark matter.

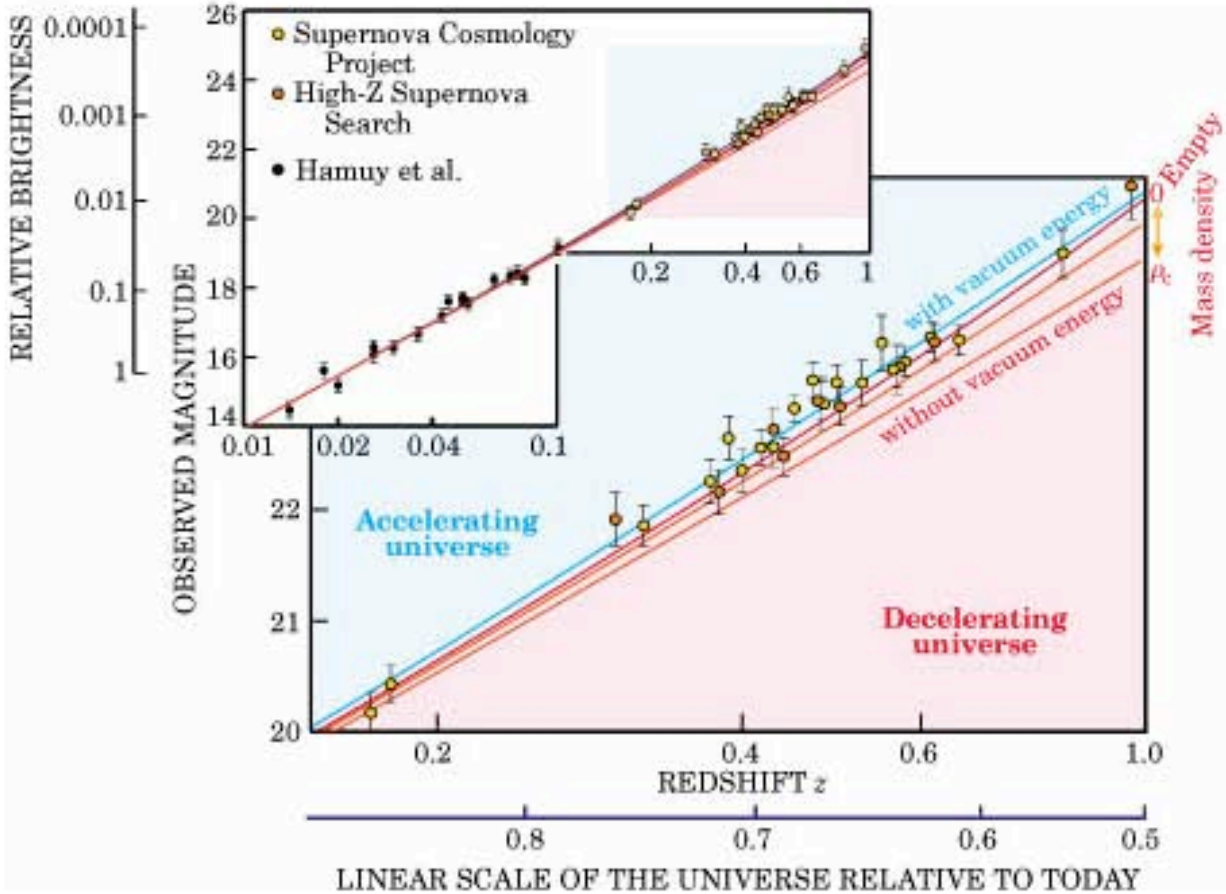
Measuring the total amount of matter

We can measure the total mass of matter in the Universe by measuring the effect of gravity on the expansion of the Universe.

We can do this by measuring the speeds of distant galaxies and asking whether those speeds are what we would expect if galaxies move with constant speed, or if instead they moved faster in the past and have been slowed down by gravity.

To do this we also have to measure the distances to the distant galaxies. We use supernovae as (very bright) standard candles for this purpose.

But we find that for the last half of the age of the Universe, the expansion has been accelerating, rather than decelerating as we expected from the effect of gravity.



Observed magnitude versus redshift is plotted for well-measured distant[12,13] and (in the inset) nearby[7] type Ia supernovae. For clarity, measurements at the same redshift are combined. At redshifts beyond $z = 0.1$ (distances greater than about 10^9 light-years), the cosmological predictions (indicated by the curves) begin to diverge, depending on the assumed cosmic densities of mass and vacuum energy. The red curves represent models with zero vacuum energy and mass densities ranging from the critical density ρ_c down to zero (an empty cosmos). The best fit (blue line) assumes a mass density of about $\rho_c/3$ plus a vacuum energy density twice that large--implying an accelerating cosmic expansion.

The measured acceleration

Instead of greater speeds in the past, as would be expected if gravity is causing the expansion of the Universe to decelerate, smaller speed were observed.

Apparently the expansion is accelerating.

There seems to be some sort of negative gravity affecting the expansion of the Universe.

According to general relativity this could happen if creation and destruction of particles in a vacuum gives the vacuum a negative pressure (like a stretched piece of rubber).

The inventory

As a fraction of the critical density, which would have enough gravity to stop the expansion:

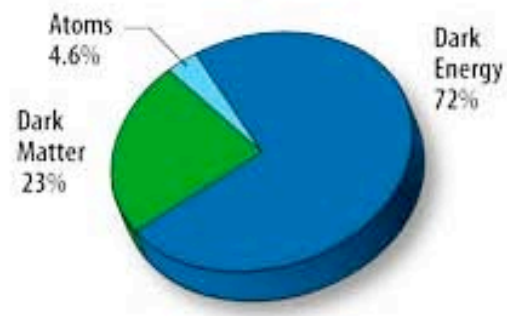
visible stars:	1%
unseen normal matter:	2%
dark matter:	24%
vacuum energy	73%

(Note: vacuum energy accelerates, rather than stops the expansion, but we include it in the inventory since the sum of these four stays constant as the Universe expands.)

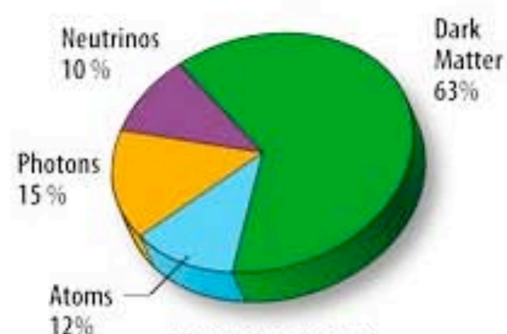
Content of the Universe

WMAP measures the composition of the universe. The top chart shows a pie chart of the relative constituents today. A similar chart (bottom) shows the composition at 380,000 years old (13.7 billion years ago) when the light WMAP observes emanated. The composition varies as the universe expands: the dark matter and atoms become less dense as the universe expands, like an ordinary gas, but the photon and neutrino particles also lose energy as the universe expands, so their energy density decreases faster than the matter. They formed a larger fraction of the universe 13.7 billion years ago. It appears that the dark energy density does not decrease at all, so it now dominates the universe even though it was a tiny contributor 13.7 billion years ago.

JPG(60 Kb) JPG(205 Kb) PNG(249 Kb) PDF(139 Kb)



TODAY



13.7 BILLION YEARS AGO
(Universe 380,000 years old)