

9 Feb

16 Feb 2012

- Announcements
  - Homework 4 (long) is due on Feb 28.
- Outline
  - Is space created and destroyed?
  - Evidence that the vacuum energy density is significant to cause the expansion to accelerate.
  - Cosmic background radiation

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## Is space created and destroyed?

### ■ Space near a star

Recall the Schwarzschild metric

$$ds^2 = -\left(1 - 2\frac{M}{r}\right) dt^2 + \left(1 - 2\frac{M}{r}\right)^{-1} dr^2 + r^2(d\theta^2 + \sin^2\theta d\phi^2)$$

We derived the path of a planet by figuring out how the curvature of space and the distortion of time affect the planet's 4 momentum. The planet feels the curvature and distortion and moves accordingly.

Newton said the planet feels the force of gravity and changes its velocity. Space is flat, and time is not distorted.

Who is right?

Q: Due to the presence of the sun, there is more volume in the solar system. How can you figure that out?

As the solar system was assembled, the volume in the solar system increased. If the sun exploded, the volume would decrease.

Space can be created and destroyed.

Q: Are you willing to discard  $\vec{F} = m\vec{a}$  and all of your intuition about motion, because they are not correct?

### ■ Space in the universe

Recall the R-W metric

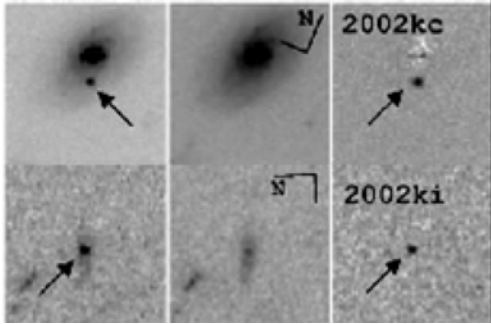
$$ds^2 = -dt^2 + a(t)^2 \left[ \frac{dr^2}{1 - \left(\frac{r}{r_0}\right)^2} + r^2(d\theta^2 + \sin^2\theta d\phi^2) \right].$$

Q: Over time, is there more space between us and some distant galaxy?

Q: Is the distant galaxy moving?

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## Measuring the flux of type I supernovae

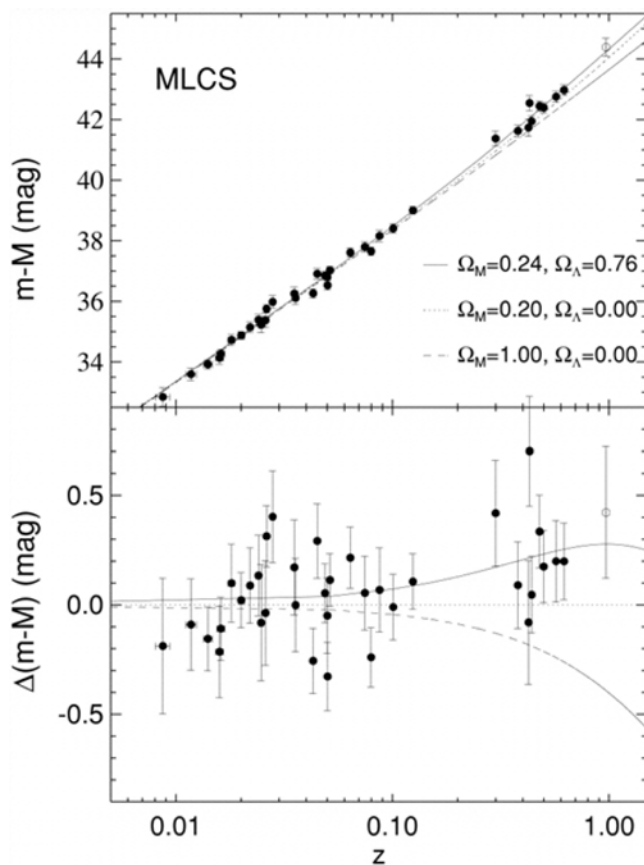


Riess et al, 2004, ApJ 607, 665.

- Type I supernovae do not have hydrogen in the spectrum. Type II supernovae do have hydrogen.
- A Type II supernova is a massive star that explodes when it runs out of fuel and pressure is insufficient to counter gravity. The hydrogen is from the outermost part of the star.
- A Type I supernova is a white dwarf that explodes.  
A WD and giant orbit each other.  
Mass moves from the giant to the WD.  
WD explodes when it gets so much mass from the giant that degeneracy pressure can no longer oppose gravity.
- Type I supernovae are approximately “standard candles.” They have the same luminosity.
- How to find supernovae  
Look at many galaxies.  
Look again later. Find objects that were not there earlier.
- Measuring the flux  
Measure the flux over time. Identify the peak flux and the rate of flux decrease.  
Report the peak flux corrected by an empirical correlation between peak flux and the rate of decrease.

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## Observations



Upper plot: magnitude  $m$  vs redshift  $z$ .  $M$  is the magnitude at 10pc.

Magnitude  $m$  and flux  $F$  are related by

$$m - M = -2.5 \log_{10} F / F(10 \text{ pc})$$

Q: How much fainter are the supernovae at  $z = 0.1$  compared with those at  $z = 0.01$ ? Explain why this is not unexpected.

More on magnitudes:

$$\begin{aligned} m &= -2.5 \log_{10} F \\ &= -2.5 / \log 10 \log F \\ &= -1.0857 \log F \\ dm &= -1.09 dF / F \\ &\approx dF / F \end{aligned}$$

If magnitude differs by +0.1, the flux is approximately 10% fainter.

Lower plot: difference between  $m - M$  and a model with  $\Omega_0 = 0.2$  for pressureless matter.

Other models:  $\Omega_{0,\text{matter}} = 1, \Omega_{0,\Lambda} = 0$  ( $\Lambda$  stands for cosmological constant or vacuum)

$\Omega_{0,\text{matter}} = 0.24, \Omega_{0,\Lambda} = 0.76$

Supernovae are fainter than that for a universe with 0.2 of the critical density. Recall: to put supernovae at a given redshift farther, remove mass from the universe to get universe to expand slower in the past. Reiss et al say supernovae are too faint even if there is no mass. Need the negative pressure of the vacuum to accelerate the expansion.

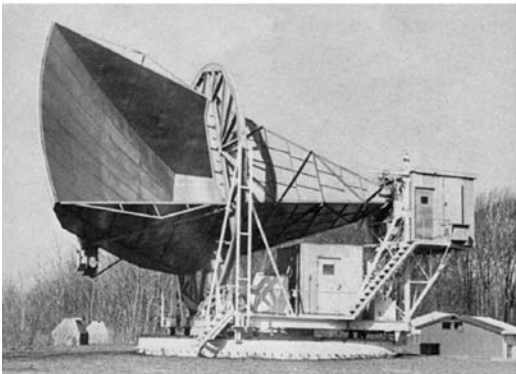
Conclusion:

The universe has significant vacuum energy to make the expansion faster than it was in the past.

# The cosmic microwave background radiation

- Discovery in 1965
- Penzias & Wilson

Out[7]=



Right picture: Picture of Penzias & Wilson's equipment in Deutsches Museum, Munich, Germany (Thanks to Joel Adelsberg)

Arno Penzias & Bob Wilson, post-docs at Bell Labs in Holmdel, NY, measured the noise of the horn & receiver left over from the Echo Project.

Their results:

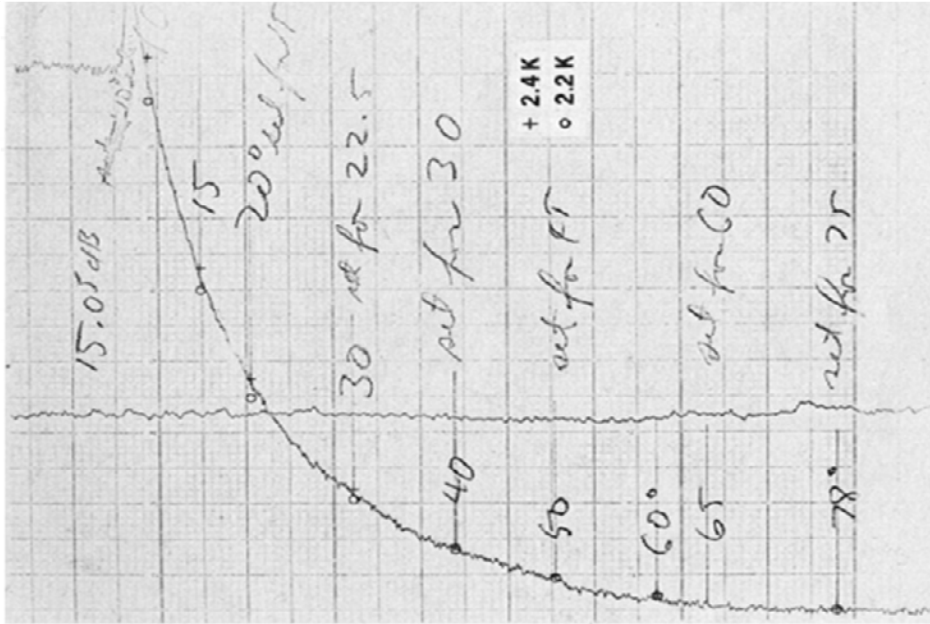
Source	K
Total	6.7
Atmosphere	2.3
Antenna	<u>0.9</u>
Unaccounted	3.4

Penzias & Wilson, 1965, "A measurement of the excess antenna temperature at 4080Mc/s," ApJ 142, 419  
 "The excess temperature is ... isotropic, unpolarized, and free from seasonal variation."

Q: Why would the radiation from the Big Bang be isotropic and free from seasonal variation? Give an example of some astrophysical source of radiation that is not isotropic.

How did they measure the radiation from the atmosphere? You cannot shut it off.

■



### ■ Dicke's interpretation

Dicke, Peebles, Roll, & Wilkinson, 1965, "Cosmic Black-body Radiation," ApJ 142, 414.

"Could the universe have been filled with black-body radiation from this possible high-temperature state?"

### ■ Plot

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## Why the cosmic background radiation is important for the history of the universe

### Black-body radiation

A wavelength characterizes black body radiation

$$\lambda = \frac{hc}{kT}$$

Alternatively, Wien's Law. Peak of the spectrum in wavelength is

$$\lambda_{\text{peak}} = 2.9 \text{ mm} \frac{\text{K}}{T}$$

Because wavelengths expand with the universe, the wavelength of the black-body radiation increases with time and the temperature decreases.

The temperature of the radiation changes as  $a^{-1}$ .

Q: When a very distant gamma-ray burster sent its light out ( $z = 8$ ), was the radiation hot enough to melt ice?

Why is this significant for the history of the universe?

The temperature and characteristic energy in the past was very high. Processes that are not possible today were possible at one time.

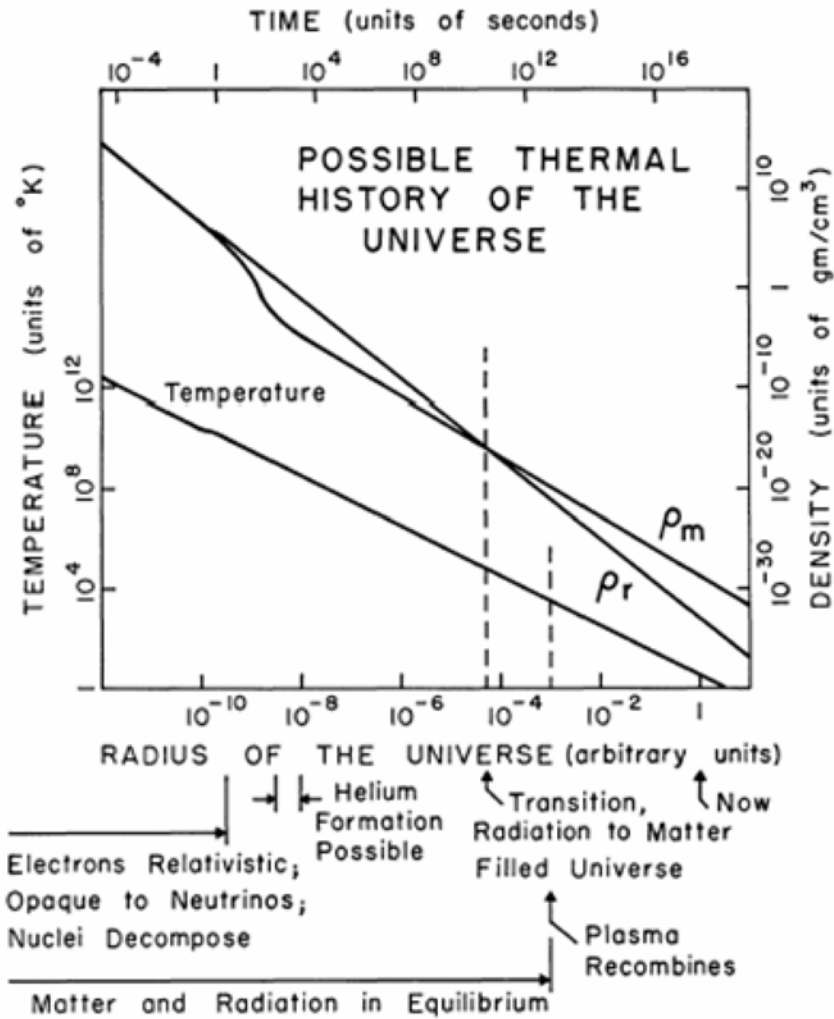
The mass-energy density changes

$$\rho_{\text{radiation}} \sim a^{-4}$$

whereas

$$\rho_{\text{pressureless matter}} \sim a^{-3}$$

$a^{-4}$  always beats  $a^{-3}$  for small enough  $a$ . At early times, the radiation determines the expansion history of the universe.



## Important events in the history of the universe

- "Recombination"

Universe changes from ionized to neutral at  $T=3000\text{K}$ .  $p + e^- \rightarrow \text{H}$

- Q: What is the expansion parameter at recombination?
- Q: The ionization energy of hydrogen is  $13.6\text{eV} = 13.6 \times 11600\text{K/eV} = 160,000\text{K}$ . Why does recombination occur at such a low temperature?
- The cross section for scattering for free electrons is much higher than for bound electrons.

- The universe was opaque before recombination.

The cosmic microwave background is a snapshot of the universe at recombination at 400, 000 years.

- Helium forms. The early universe was too hot for nuclei (other than n and p) to exist.
  - At  $a = 10^{-9}$ , the universe became cool enough for  $n + p \rightarrow {}^2\text{H}$ . Then  ${}^4\text{He}$  and trace amounts of  ${}^7\text{Li}$  and  ${}^3\text{He}$  form.

$$2.7 / 11\,600 \times 10^{*^9}$$

$$2.32759 \times 10^6$$

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## Initialization