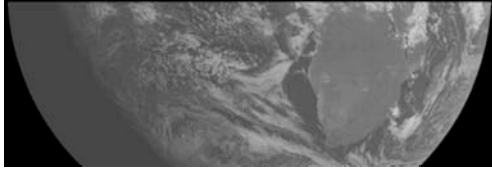


Astronomy 102.  
December 8, 2005.



Moon Shadow Moves Over Africa  
Credit and Copyright: [EUMETSAT](#)

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The age and fate of the Universe.

- The expanding Universe resembles the interior of a black hole. Is the Universe a black hole?
  - That is, is the universe open, marginal, or closed? If it's not open, it really can be thought of as a black hole.
- Related question: how old is the Universe? That is, how long has it been since the expansion (and time) began?
- If the Universe's total energy is matter-dominated (that is, if the cosmological constant is zero), the age, expansion rate, curvature and fate all turn out to be determined by one factor: how much density (mass per unit volume) there is in the Universe.
  - We usually illustrate this by general-relativistic calculation of the typical distance between galaxies as a function of time elapsed since the present day...

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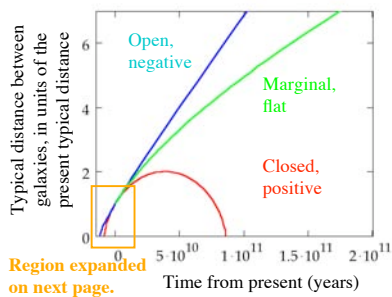
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The age and fate of the Universe.



Here are some results of such calculations, for **matter-dominated universes** with three different present-day densities. Labels indicate **boundedness** and the sign of the **space-time curvature**.

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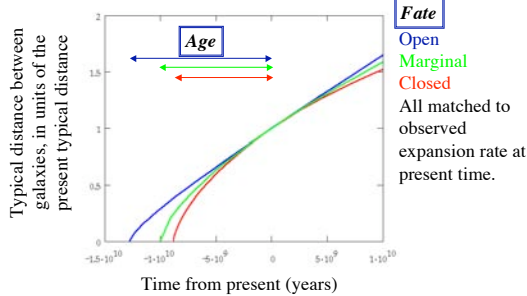
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## The age and fate of the Universe.



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## How can we tell which “universe” is our Universe?

- Several ways are possible, all with substantial and different degrees of difficulty:
  - Measure the density directly, using observations of the motions of galaxies to determine how much gravity they experience. This is much like our way of measuring black-hole masses by seeing the orbital motion of companion stars.
  - Measure the ages of the oldest objects in the Universe.
  - Measure the Universe’s curvature directly, by observing very distant objects with well-determined size and distance.
  - Measure the acceleration or deceleration of galaxies: the rate of change of the Hubble “constant.”
- The first two ways are least difficult and provide most of our data.

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## Is the Universe gravitationally bound? Matter-dominated universes.

- If the Universe is dense enough at present, the mutual gravity of its parts will eventually result in a slowing or reversal of the expansion.
- The density that would make the Universe marginal can be calculated from general relativity and is equal to
 
$$\rho_c = \frac{3H_0^2}{8\pi G} = 7.9 \times 10^{-30} \text{ gm/cm}^3$$
- This density is called the **critical density**.

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## Is the Universe gravitationally bound? Matter-dominated universes.

- Frequently, the mass density of the Universe is expressed in terms of the normalized present-day density  $\Omega_m$ . This density is defined as

$$\Omega_m = \frac{\rho}{\rho_c}$$

- The present-day density,  $\rho$  or  $\Omega_m$ , can in principle be measured, by observing the motions of galaxies by their Doppler shifts. Based on the measured value of  $\Omega_m$  we can predict the future of the Universe:
  - If  $\Omega_m < 1$ , the universe is open
  - If  $\Omega_m = 1$ , the universe is marginal
  - If  $\Omega_m > 1$ , the universe is closed.

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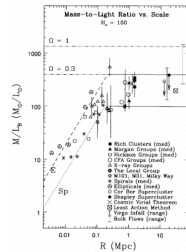
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## Is the Universe gravitationally bound? Matter-dominated universes.

- What is the present-day density of the Universe?
- Observational bounds on  $\Omega_m$ , made from "nearby" galaxy red-shift surveys over the past 15 - 20 years, consistently indicate that the current (baryonic) matter density is  $\Omega_m = 0.2 \pm 0.1$ .
- The Figure show a summary of measurements of the mass density of the Universe based on the properties of nearby galaxies (N. Bahcall, 1997).
- A more detailed analysis (Pope *et. al.*) shows that  $\Omega_m = 0.32 \pm 0.05$ .



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## Is the Universe gravitationally bound? Matter-dominated universes.

- If the Universe is matter-dominated, its curvature is negative, it is open, and it will continue to expand.
- However, many models of elementary particle physics and of the early Universe, especially those involving inflation, predict that  $\Omega_m$  should be exactly 1 and that for unknown reasons the present measurements of  $\Omega_m$  are faulty.
- There are no good experimental results or theoretical arguments to suggest that the universe is matter-dominated and closed. We don't think our Universe is a black hole.

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### Age of matter-dominated universes.

- General relativity can be used to show that the age of a matter-dominated universe is always given, in terms of the present value of the Hubble constant:

$$t = A \frac{1}{H_0}$$

where the value of the factor A depends on  $\Omega_m$ , but is less than or equal to 1:

- The factor A is equal to 1 if  $\Omega_m$  is very small compared to 1.
- The larger the value of  $\Omega_m$ , the smaller the value of A.
- Open universes have values of A between 2/3 and 1.
- A flat universe has a value of A of 2/3.
- Closed universes have values of A smaller than 2/3.

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### Age of matter-dominated universes.

- If  $\Omega_m$  is assumed to be much smaller than 1, the age would be

$$t = \frac{1}{H_0} = \frac{1}{19.6 \text{ km/s/Mly}} = 1.5 \times 10^{10} \text{ y}$$

- If  $\Omega_m$  is assumed to be 1, the factor A turns out to be exactly 2/3, and the age is

$$t = \frac{2}{3} \frac{1}{H_0} = \frac{2}{3} \frac{1}{19.6 \text{ km/s/Mly}} = 10^{10} \text{ y}$$

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### Age of matter-dominated universes.

- For the best experimental value,  $\Omega_m = 0.32$ , we get  $t = 1.2 \times 10^{10}$  years.
- Other constraints on the Universe's age, independent of density determinations:
  - We know that the Universe must be older than the solar system, which is  $4.5 \times 10^9$  years old, so an age of  $1.2 \times 10^{10}$  years would be OK.
  - The ages of white dwarf stars and globular star clusters turn out to be accurately measurable; the oldest of these are  $1.3 \times 10^{10}$  years old ( $\pm$  about  $0.1 \times 10^{10}$  years).
- This agrees with  $\Omega_m = 0.32$  (smaller would be OK too), and is in conflict with  $\Omega_m = 1$ .

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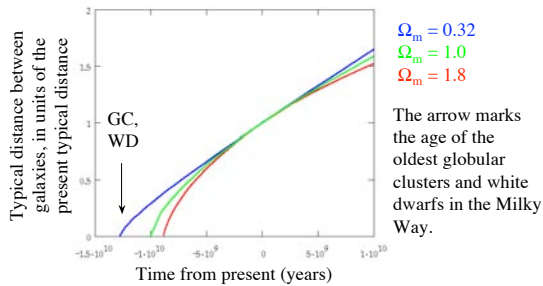
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## Age of matter-dominated universes.



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## Mid-lecture Break.

### • A final reminder/announcement:

- Final exam: Tuesday 12/20 between 4 pm and 7 pm.
- Final exam will cover Lecture 19 - 25.
- Final grades will be distributed via email by the end of the week of 12/20.



Apollo 17

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## Measurements of the Universe's space-time curvature: is it *not* matter-dominated?

- The very small fluctuations in the cosmic microwave background – a.k.a. the background anisotropies – provide the means to measure the curvature of the Universe rather directly. Reasons:
  - Before decoupling, the Universe consisted of ionized gas in equilibrium with photons. This gas-photon mixture took the form of bubbles with very slightly different densities and temperatures.
  - If a bubble were compressed by its neighbors, it heated up and pushed back on its neighbors all the harder. Thus, the bubbles could oscillate in size and temperature.
  - The cosmic microwave background is a snapshot of the final state of these bubbles, and the anisotropies outline the bubbles.

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## NASA Microwave Anisotropy Probe (MAP).



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## NASA Microwave Anisotropy Probe (MAP).

- MAP provides a very detailed picture of the anisotropies in the microwave background.
- The results of these measurements can be used to determine the cosmological constant very accurately.



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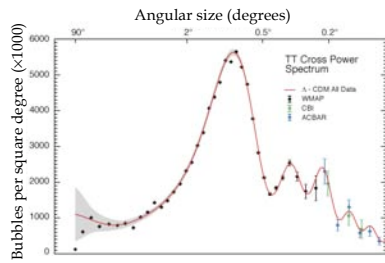
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## WMAP Results: The curvature of space-time is zero; the Universe is flat!



Black points: results from WMAP (Bennett et al. 2002). In red: expectations for a flat universe. (Courtesy of NASA and the WMAP Science Team.)

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## Measurements of the Universe's space-time curvature: it is not matter-dominated!

- If these results are true: how did the Universe come to be flat?
  - We know that  $\Omega_m = 0.32$ : there isn't enough matter in the Universe to make it flat.
  - There aren't enough photons, either. What's left?
  - The easiest way out seems to be a positive cosmological constant.
  - For the cosmological constant  $\Lambda$  one can define a relative density  $\Omega_\Lambda$ . For the Universe to be flat,  $\Omega_m + \Omega_\Lambda = 1$ . But since  $\Omega_m = 0.32$ ,  $\Omega_\Lambda = 0.68$ : the cosmological constant dominates the Universe's present mass-energy density on large scales.
- If there is an afterlife from which we can be seen, Einstein is having a really good laugh about this.

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## Measurements of the Universe's space-time curvature: it is not matter-dominated!

- This changes everything!
  - If the cosmological constant is nonzero, then there is no longer a one-to-one correspondence between curvature, boundedness and fate. For example:
    - If the value of  $\Omega_\Lambda$  were negative, the universe would collapse and end in a singularity no matter what its curvature.
    - If the value of  $\Omega_\Lambda$  were positive and large, even a positively-curved, closed universe would expand forever.
  - If  $\Omega_\Lambda = 0.68$ , distant galaxies should be seen to accelerate. This may have been confirmed, recently, in observations of distant galaxies in which supernovae have been seen.

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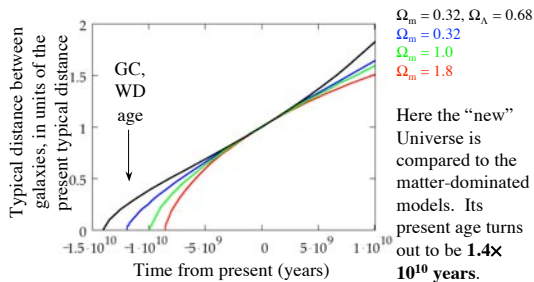
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## Age and fate of the Universe if it has a positive cosmological constant.



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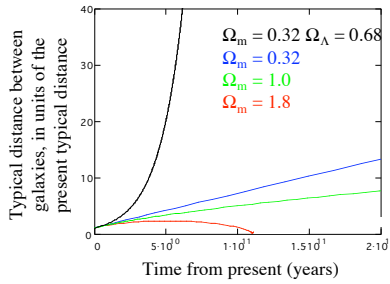
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### Age and fate of the Universe if it has a positive cosmological constant.



The expansion rate of the universe would increase tremendously; in just a few "Hubble times" most of the Universe we can see today would be red-shifted into invisibility.

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### Summary: best (experimental) determination of the state of the Universe

- The Universe has a present-day relative mass density of about  $\Omega_m = 0.32$ .
- If matter dominates its energy, the Universe is negatively-curved and open, the presently-observed expansion will continue forever, and about  $1.2 \times 10^{10}$  years (12 billion years) have elapsed since the Big Bang.
- The WMAP data show that the Universe is flat. This requires a substantial, positive cosmological constant, which dominates the present energy of the Universe:  $\Omega_\Lambda = 0.68$ . (It also requires a physical explanation for  $\Lambda$ !)

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Good luck with all your finals!  
See you on December 20, 2005.



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