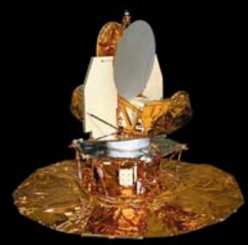
Today in Astronomy 102: the new flat Universe

- Acceleration in the Universe's expansion.
- Direct measurements of the Universe's curvature: it's flat from here to decoupling.
- Eternal exponential expansion driven by dark energy:
  - The Milky Way's lonely future
  - Last chance to learn the Universe's origins?

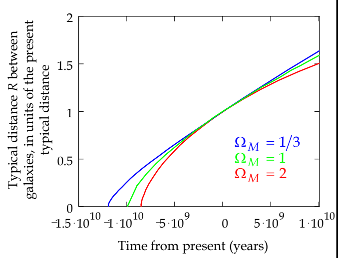


The NASA Wilkinson Microwave Anisotropy Probe (WMAP), launched in 2001, which obtained definitive images of cosmic background fluctuations .

The third method: measurement of the acceleration of distant galaxies

The third way of finding which Big Bang model fits our Universe best is the measurement of acceleration of distant galaxies.

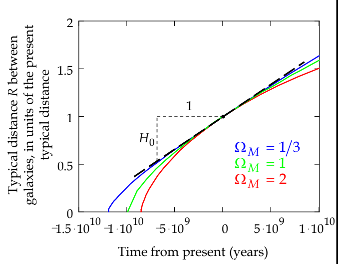
- Looking back through time at distant galaxies, one should be able to measure the shape of R vs. t if one can measure distances accurately enough.



Measurement of the acceleration of distant galaxies (continued)

The **slope** of the curves we've been plotting (R/R_0 vs. t), at the present time, turns out simply to be the Hubble constant.

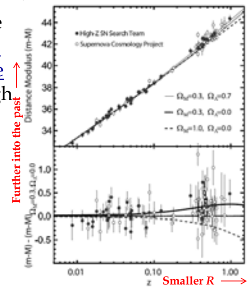
The matter-dominated models curve away from the straight-line Hubble law at large distances, in the direction of larger values of H_0: **deceleration** of the Universal expansion.



Measurement of the acceleration of distant galaxies (continued)

In the late 1990s it became possible to measure distances and redshifts for galaxies containing supernovae of type Ia, at distances large enough to reveal departure from the straight-line Hubble law.

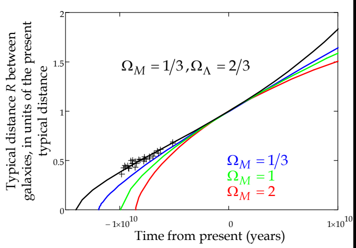
To the great surprise of most astronomers, very distant SNe Ia were fainter than expected – from which it is inferred that they are significantly more distant than expected. The curve bent in the direction of **smaller** H_0.



Riess, Fillipenko et al. 1998, Perlmutter et al. 1999

Measurement of the acceleration of distant galaxies (continued)

Those who observed these supernovae were quick to point out that the bend in the curve was in the direction of **acceleration** of the Universal expansion, rather than the anticipated deceleration, which implies substantial **dark energy** in the Universe as well as matter.



SN Ia -galaxy observations by Riess et al. (2007), transposed onto matter-dominated (blue +) and accelerating (black +) models.

Measurement of the acceleration of distant galaxies (continued)

Because the effect being measured is small, and because the supernovae and galaxies being observed are so distant, these results were a bit controversial.

- Most of the controversy had to do with the assumption that SNe Ia have the same "yield" – give off the same amount of light – whether they happened recently or ten billion years ago.
- The abundance of elements heavier than helium decreases substantially as one looks back further in the past.
- This in principle can alter the amount of light given off by a SN Ia, and even the direction the light is beamed, and the physics of these blasts is sufficiently complicated that theoretical models of them have not been conclusive.

Measurement of the acceleration of distant galaxies (continued)

Reaction typical, though physicist famous:

…I encountered a hard-bitten veteran gravitation physics colleague in the elevator of the Princeton physics building and asked him if he believed the purported evidence of accelerating expansion. "No," he replied. Neither do I. Why not? Two reasons: (1) Because the speed-up argument relies too trustingly on the supernovae being standard candles. (2) Because such an expansion would, it seems to me, contradict a view of cosmology too simple to be wrong.

- John Archibald Wheeler (who preferred the closed Universe with $\Omega_M > 0,\ \Omega_\Lambda = 0$)

A fourth method: measurement of the curvature of space

Nobody really fussed about the acceleration controversy too much, though, because measurements of the **curvature of space** between here/now and the epoch of Decoupling were on the horizon.

- Acceleration enthusiasts and detractors alike looked forward to these new measurements as conclusive, as they would determine k and Ω_{total} independent of observations of supernovae and galaxies.
- The curvature of space in the nearby Universe is too small to measure in the foreseeable future, but observations of the small-scale structure ("**anisotropies**") of the cosmic microwave background (CMB) offer a way to measure the curvature on a grand scale.

Measurement of the curvature of space (continued)

- Recall that the anisotropies are very small; none differ by more than 0.001% in brightness from the average brightness of the CMB.
- The COBE satellite could not detect small enough angular scales to solve this problem.
- Astronomers had been trying for two decades to detect anisotropies on angular scales to measure curvature, using ground-based telescopes, but without much success. Fluctuation in atmospheric transmission, and civilization-created radio interference, kept ruining the observations.
- Finally in the late 1990s and early 2000s the problems were overcome by leaving the absorbing part of the atmosphere:

Measurement of the curvature of space (continued)

- Observations from extremely dry sites, like the South Pole (e.g. ACBAR) or the high Atacama desert in Chile (e.g. CBI).
- Long-duration observations from high-altitude balloons.
  - Several-day flights give useful results (e.g. MAXIMA), but better observations are enabled, and made uniquely difficult, by steady circumpolar winds in the arctic and antarctic: with luck, the balloon blows around to its starting point in about a month. Best example is BOOMERANG.
- Satellite observations, à la COBE: the Wilkinson Microwave Anisotropy Probe (WMAP), launched in 2001. These measurements turned out to be definitive.

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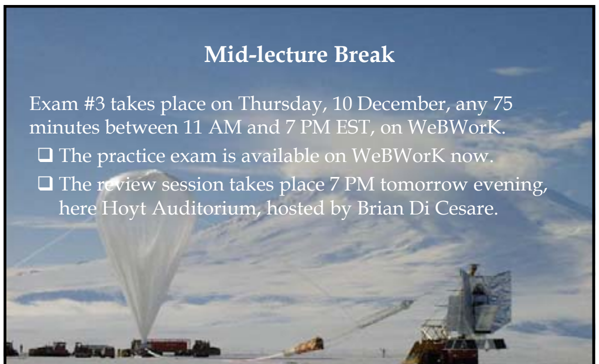

Mid-lecture Break

Exam #3 takes place on Thursday, 10 December, any 75 minutes between 11 AM and 7 PM EST, on WeBWorK.

- The practice exam is available on WeBWorK now.
- The review session takes place 7 PM tomorrow evening, here Hoyt Auditorium, hosted by Brian Di Cesare.

Deployment of the balloon-borne BOOMERANG cosmic-background anisotropy experiment in Antarctica; Mt. Erebus in the background.

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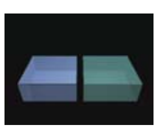
Measurements of the Universe's space curvature

The small-angular-scale anisotropies in the cosmic microwave background 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 speed with which these bubbles oscillate is limited by the **speed of sound** in the gas.
- The cosmic microwave background is a snapshot of the final state of these bubbles, and the anisotropies outline the bubbles.



Animation courtesy of NASA and the WMAP Science Team. See map.gsfc.nasa.gov.

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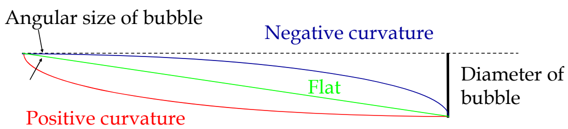
Measurements of the Universe's space curvature (continued)

- It turns out that the bubbles that are the most numerous are the ones that have only gone through half an oscillation between the Big Bang and decoupling. Their diameters can be calculated precisely. (We know the speed of sound *and* the speed of light.)
- By observing their angular size and knowing their diameters we can determine the curvature of space between decoupling and here-and-now.

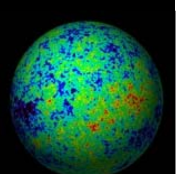


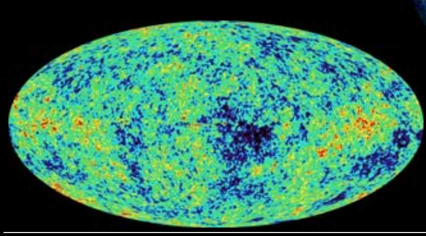
Measurements of the Universe's space curvature (continued)

Animation courtesy of the WMAP Science Team (NASA/GSFC). See map.gsfc.nasa.gov .

Measurements of the Universe's space curvature (continued)

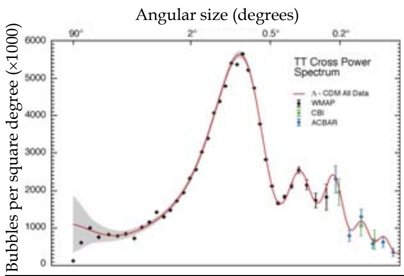
Map of the sky (plane of Milky Way along the equator) on scales small enough to measure curvature for all current models of the Universe, by WMAP.





Measurements of the Universe's space curvature (continued)

Result: $k = 0$ – **the Universe is flat** – and $\Omega = \Omega_M + \Omega_\Lambda = 1$.



Black points: results from WMAP (Bennett et al. 2003). In **red**: expectations for $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7, H_0 =$ 22 km sec^{-1}Mly^{-1}.

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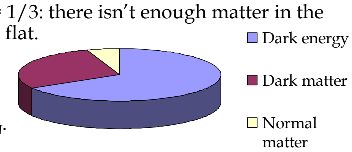
Measurements of the Universe's space curvature (continued)

How did the Universe come to be flat?

- We know that $\Omega_M = 1/3$: there isn't enough matter in the Universe to make it flat.
- The **simplest** way out seems to be dark energy, in the amount $\Omega_\Lambda = 1 - \Omega_M$.
- This, as discussed above, would account for the apparent acceleration of the Universal expansion, seen in the high-redshift SN Ia results.



If there is an afterlife from which we can be seen, Einstein is having a really good laugh about this.

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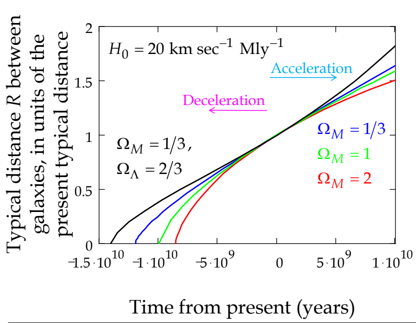
Age of the new flat Universe



Here the "new" Universe is compared to the matter-dominated models. Its present age turns out to be **1.4×10^{10} years**.

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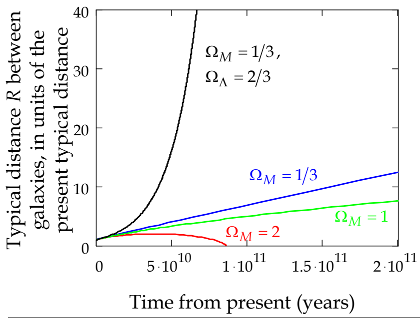
Fate of the new flat Universe



The new Universe is open and expanding exponentially; in just a few Hubble times most of the Universe we can see today will be redshifted into invisibility.

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

- The Universe has a present-day relative mass density of about $\Omega_M = 1/3$, not nearly enough to close the Universe.
- If matter were to dominate its energy, the Universe would be negatively-curved and **open**, and about 1.2×10^{10} years (12 billion years) would have elapsed since the Big Bang.
- But the cosmic background small-scale anisotropies indicate that the Universe is **flat** between here and the decoupling surface. Easiest to explain if $\Omega_\Lambda = 2/3$; the Universe's dynamics are dominated by dark energy.
- Thus, the **Universe is open**, the present expansion will continue and will increase dramatically over time, and **the Universe is about 1.4×10^{10} years (14 billion years) old**.

Caveats

There are still doubters, though; they might even be in the majority. Two substantial reasons to doubt that this – a dark-energy dominated Universe – is the whole story:

- *How much do you trust Occam's razor?* This is the simplest model that explains the observations, but begs the question of what dark energy actually is, and stands unique among complex systems in the simplicity of its description. (A Universe simpler than a star or planet?)
- *If the model is true, we're in a privileged position.* We now find ourselves poised on the boundary between the matter-driven and dark-energy-driven eras of Universal expansion. Ask Copernicus what we risk by thinking we live at the center of the Universe…

Let's assume it's true, though. What's next?

Within a few tens of billions of years:

- The rapidly-increasing Universal expansion will not soon result in the expansion of compact, tightly-bound things like you, the Earth, or the Milky Way.
- But the exponential expansion will render invisible parts of the Universe that are currently visible.
  - As space expands more rapidly, widely separated parts that light could currently travel between within the age of the Universe, can no longer make the trip. We will lose sight of our surroundings, beginning with the most distant galaxies.

What's next? (continued)

  - The Milky Way and its closest companions will be all that can be seen of the Universe of galaxies. It will die alone, as eventually its matter is converted to black holes and radiation.
- Eventually it will be impossible even to verify the origins of the Universe.
  - The Cosmic Microwave Background will become redshifted so extremely – its temperature becoming so close to absolute zero – that it will become impossible to detect.
  - No galaxies in view: no Universal expansion to characterize.

What's next? (continued)

This makes our current position seem even more privileged: we can still **demonstrate** that the Universe began in the explosion of a mass-density singularity, that the ensuing expansion has been in progress for 14 billion years, and that the Universe is spatially flat and open. In another 100 billion years, those experimental facts could become undemonstrable, and come to be regarded as fables.

NASA/WMAP Science Team