Announcements

- Grades for midterm 3 posted on D2L
  - Average 83%, scantron forms here
  - Answers on D2L under Content, Course handouts
- **Quiz 13 on Chapter 17 due Monday** – last regular quiz
- Today: More on Chapter 17, Cosmology
- Upcoming schedule
  - Finish Chapter 17 Friday
  - Chapter 18: Friday, Monday (covered by **extra credit quiz** – available tonight, due May 12 10 am, at least 85% (12/14) to pass, +1% on final grade)
  - Wednesday May 7: review for final exam
  - **Final exam Monday May 12, 10 am - noon**

Announcements

- **More extra credit**
- **Extra credit quiz: Math problems**
  - available tomorrow until May 12 (date of final exam)
  - 15 questions
  - similar to questions involving math on previous quizzes
  - 3 attempts allowed, 80% needed for credit (at least 12/15)
  - will show which questions wrong, but correct answers won't be given
  - +1% on final grade

Astronomy 103

Cosmology

Please read chapter 17

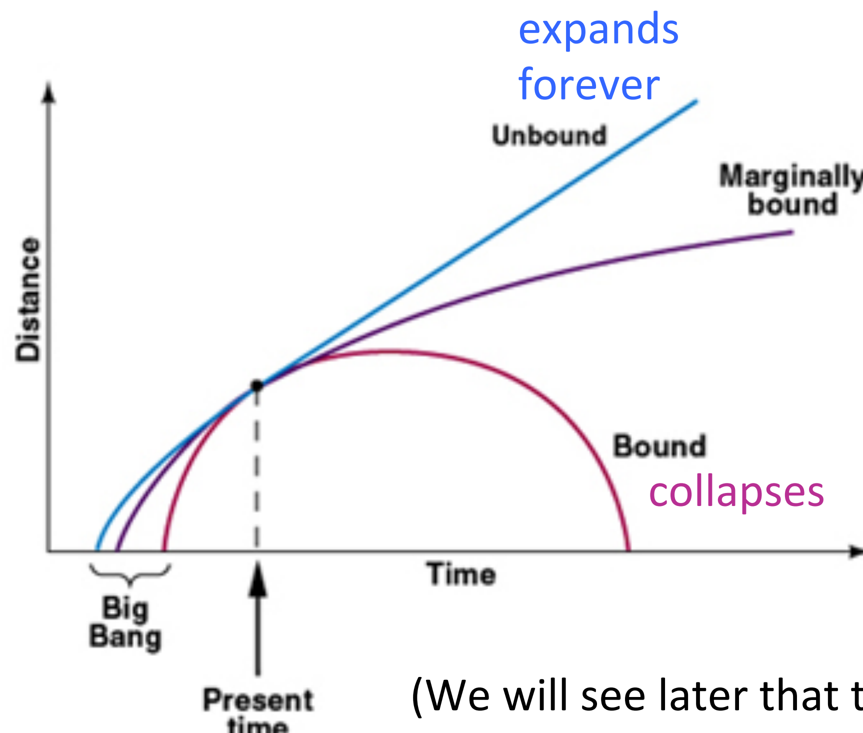
The Fate of the Cosmos

There are two possibilities for the universe in the far future:

1. It could keep expanding forever.

2. It could collapse.

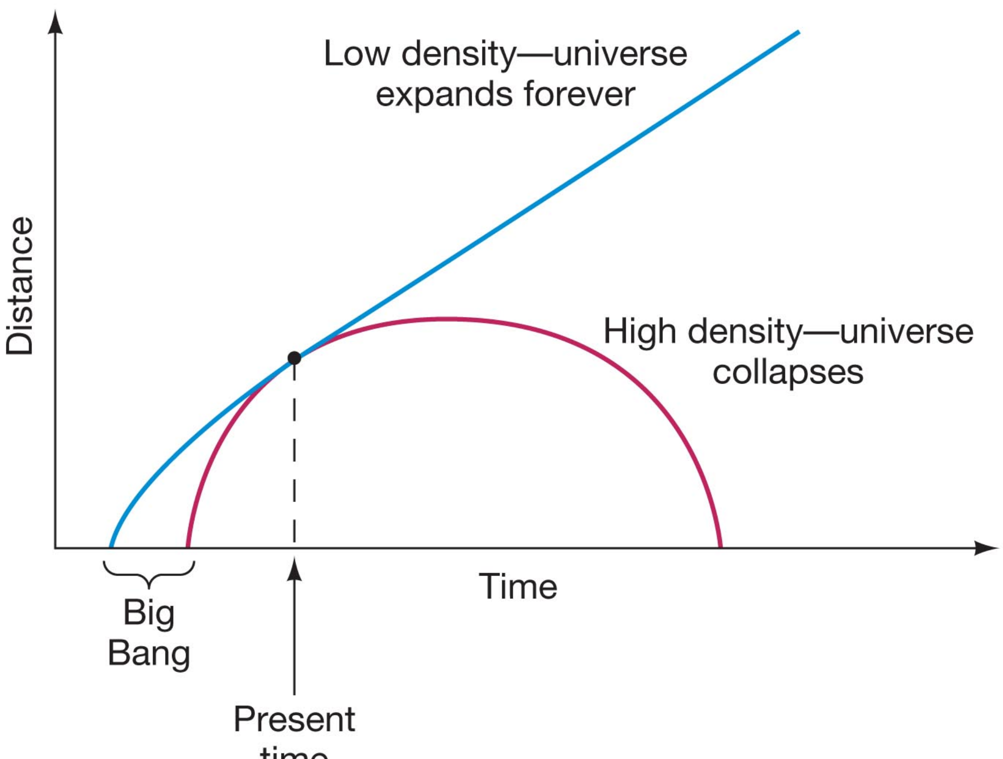
Assuming that the only relevant force is gravity, which way the universe goes depends on its density: how much matter there is.



(We will see later that the story is actually more complicated than this, and gravity is probably not the only relevant force.)

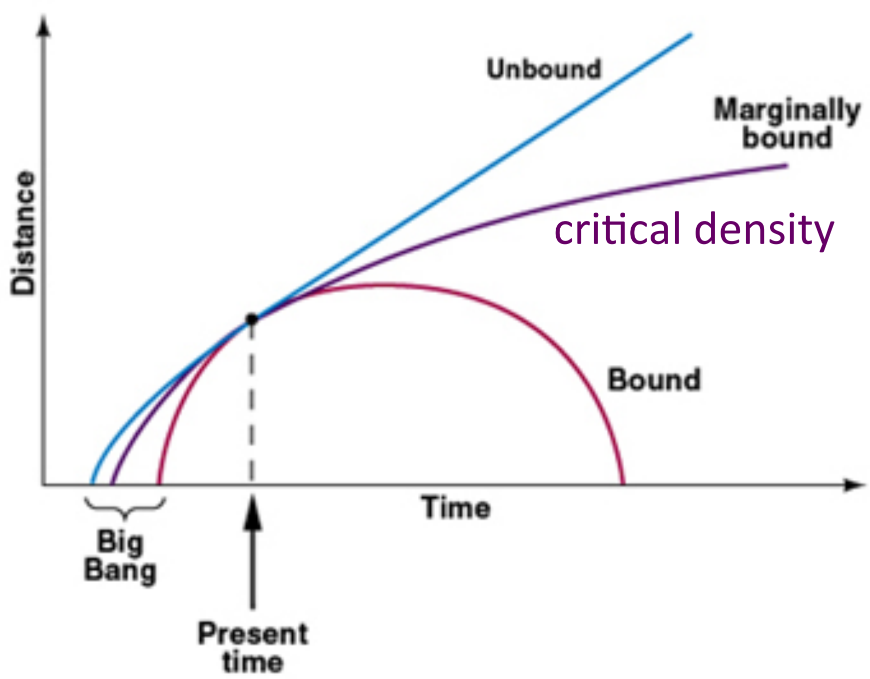
The Fate of the Cosmos

If the density is low, the universe will expand forever. If it is high, the universe will ultimately collapse. This is just a battle between the initial energy of expansion from the Big Bang and gravity.



The Fate of the Cosmos

If the density is low, the universe will expand forever. If it is high, the universe will ultimately collapse. The density that separates these two possibilities is the critical density.



What is the critical density?
About 9×10^{-27} kg/m^3: five hydrogen atoms per cubic meter, or 0.1 Milky Way galaxies per cubic megaparsec.

Cosmic Dynamics and the Geometry of Space

These possibilities for the future of the universe are related to the curvature of space. According to general relativity, space is curved, and the curvature is determined by the total density of the universe.

Note that total density includes everything: both matter (including dark matter) and energy, which are related by $E=mc^2$.

Cosmic Dynamics and the Geometry of Space

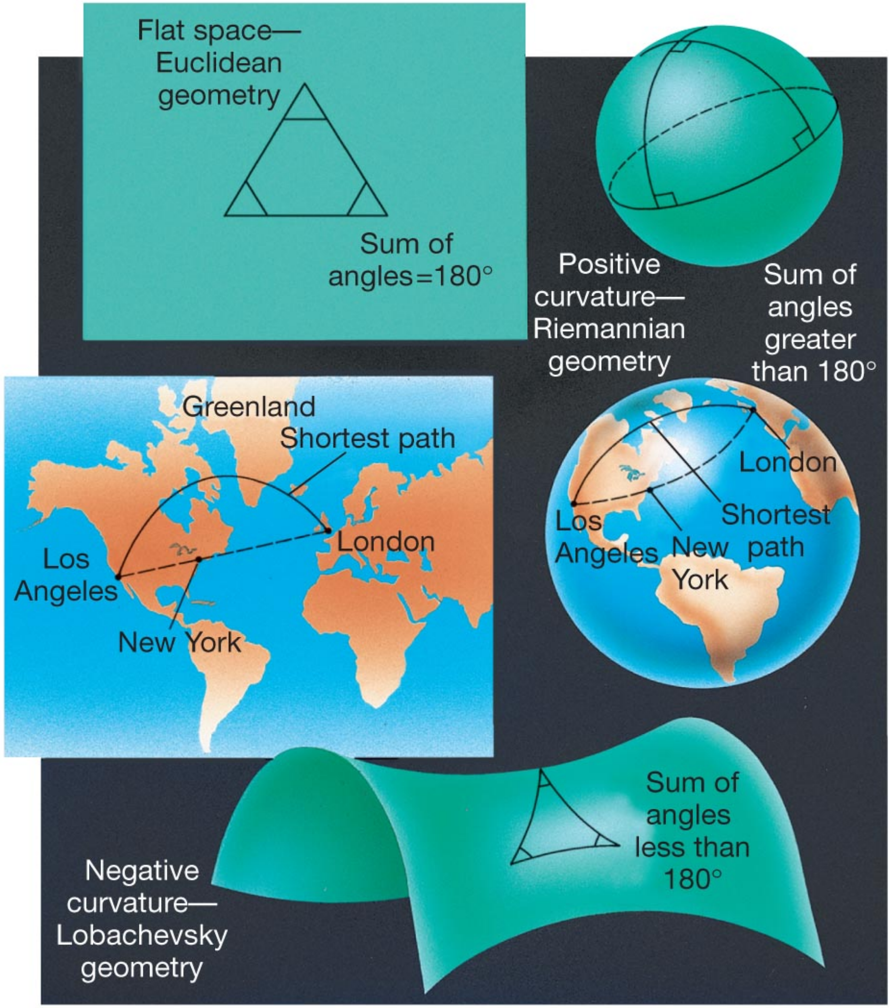
There are three ways that space can be curved, and they are related to the ultimate fate of the universe:

1. Closed – this is the geometry that leads to ultimate collapse

2. Flat – this corresponds to the critical density: exactly the right amount of matter and energy to make the universe flat

3. Open – expands forever

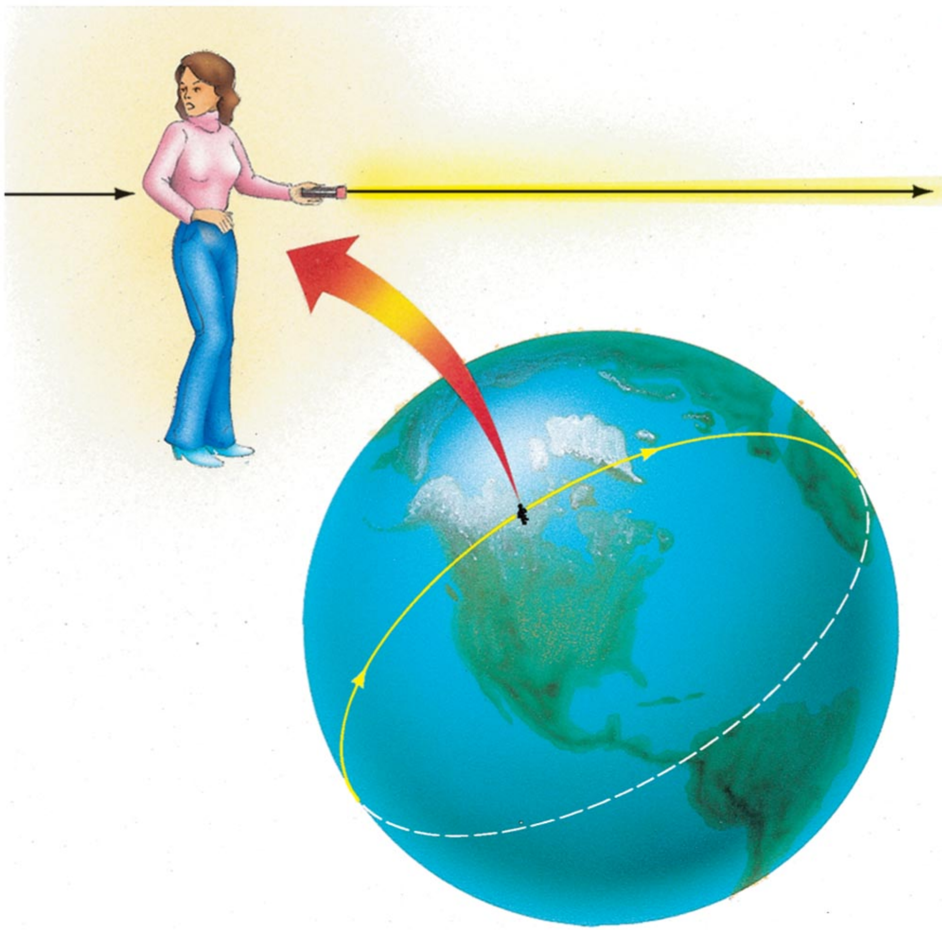
The Geometry of Space



Space can be curved: it can be closed, flat or open.

These three possibilities are illustrated here. The closed geometry is like the surface of a sphere; the flat one is flat; and the open geometry is like a saddle.

Cosmic Dynamics and the Geometry of Space



In a closed universe, you can travel in a straight line and end up back where you started.

Cosmic Dynamics and the Geometry of Space

How can we figure out what kind of universe we live in?

Try to measure how much matter and energy there is, and see how it compares to the critical density.

Measure the curvature! The apparent brightness and apparent sizes of distant objects will be different for different geometries.

The Fate of the Cosmos

The ultimate fate of the universe depends on its actual density of matter and energy.

Measurements of luminous matter suggest that the actual density is only a few percent of the critical density.

But – we know there must be large amounts of dark matter. However, the best estimates for the amount of dark matter needed to bind galaxies in clusters, and to explain gravitational lensing, still only bring the observed density up to about 0.3 times the critical density, and it seems very unlikely that there could be enough dark matter to make the density critical.

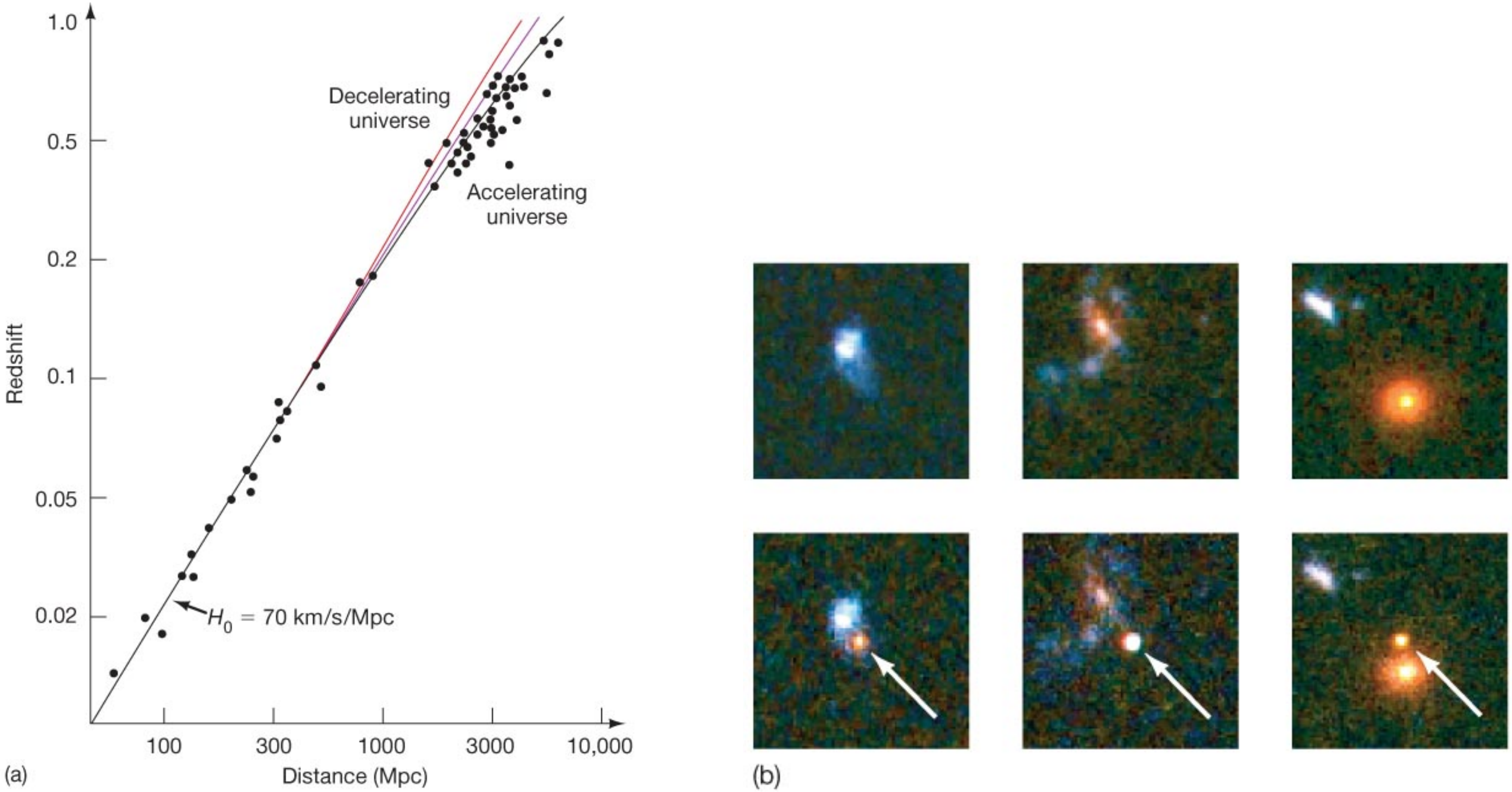
The Fate of the Cosmos

So measurements of the matter density suggest that the universe is open, with less than the critical density. But this is not the full story…

Type I supernovae can be used to measure the behavior of distant galaxies.

If the expansion of the universe is decelerating, as it would be if gravity were the only force acting, the farthest galaxies had a more rapid recessional speed in the past, and will appear as though they were receding faster than Hubble's law would predict.

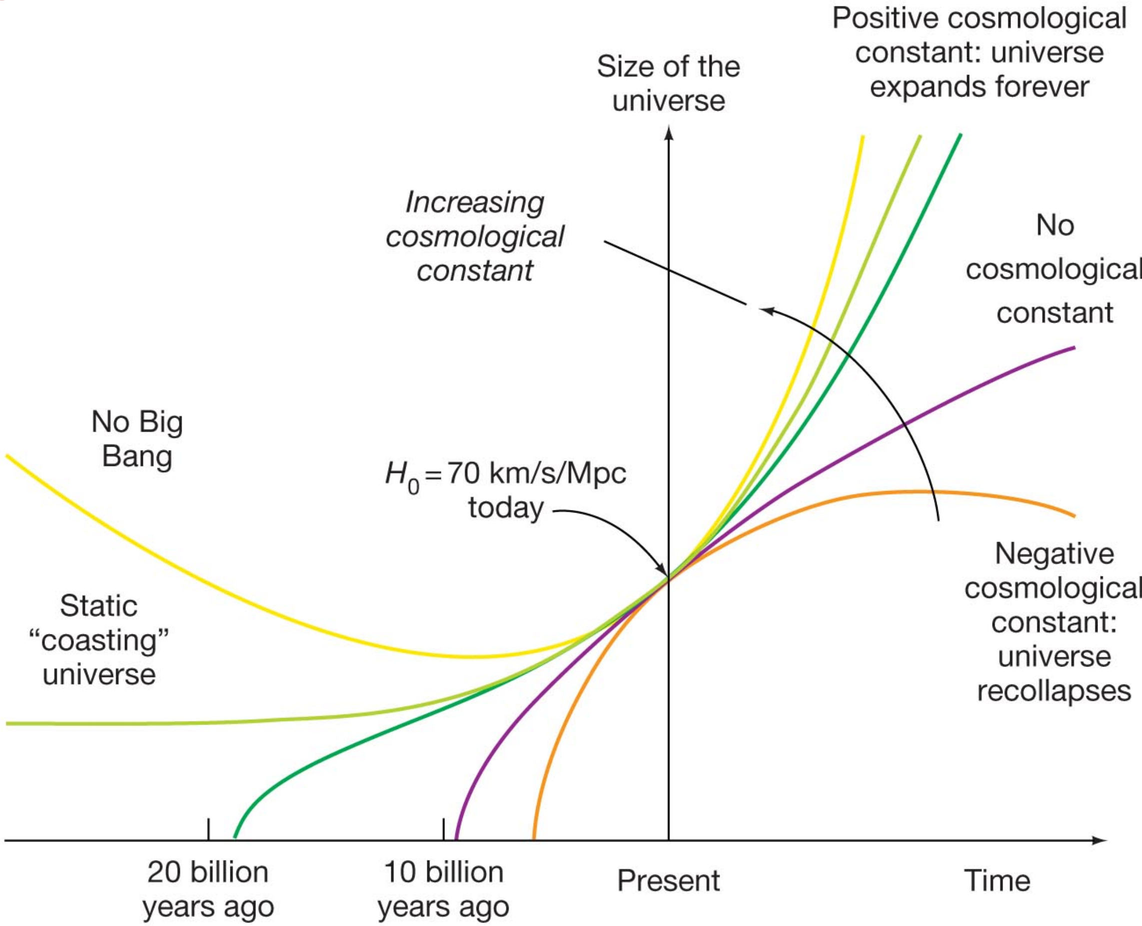
The Fate of the Cosmos



However, when we look at the data, we see that it corresponds not to a decelerating universe, but to an accelerating one!

The Fate of the Cosmos

Possible explanation for the acceleration: Vacuum pressure (cosmological constant), also called dark energy.



The Nobel Prize in Physics 2011
Saul Perlmutter, Brian P. Schmidt, Adam G. Riess

Photo: Roy Kaltschmidt. Courtesy: Lawrence Berkeley National Laboratory

Saul Perlmutter

Photo: Belinda Pratten, Australian National University

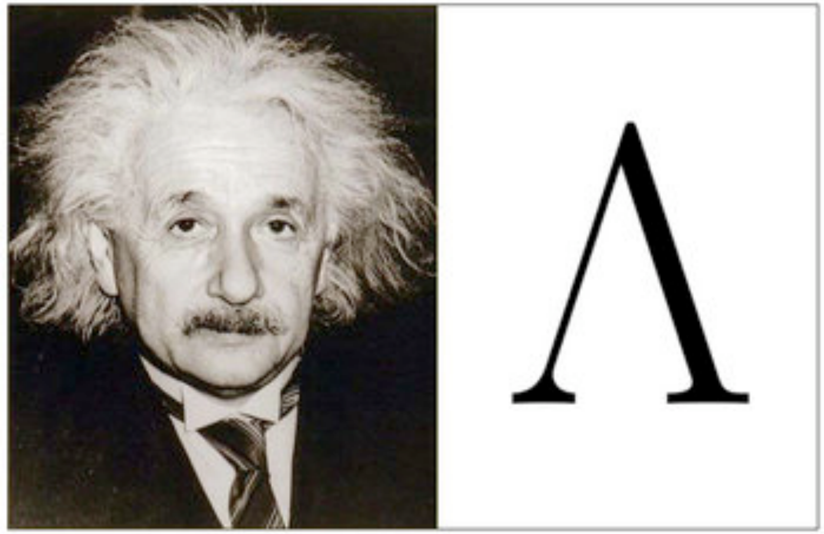
Brian P. Schmidt

Photo: Homewood Photography

Adam G. Riess

The Nobel Prize in Physics 2011 was divided, one half awarded to Saul Perlmutter, the other half jointly to Brian P. Schmidt and Adam G. Riess *"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"*.

Einstein and the Cosmological Constant



The cosmological constant is symbolized with the capital Greek letter lambda.

- **1915: Einstein's general theory of relativity predicts expanding universe...**
- **…but Einstein doesn't believe it, adds "cosmological constant" to make universe static**
- **"Einstein's biggest blunder"**
- **But it seems we need it after all!**

The Fate of the Cosmos

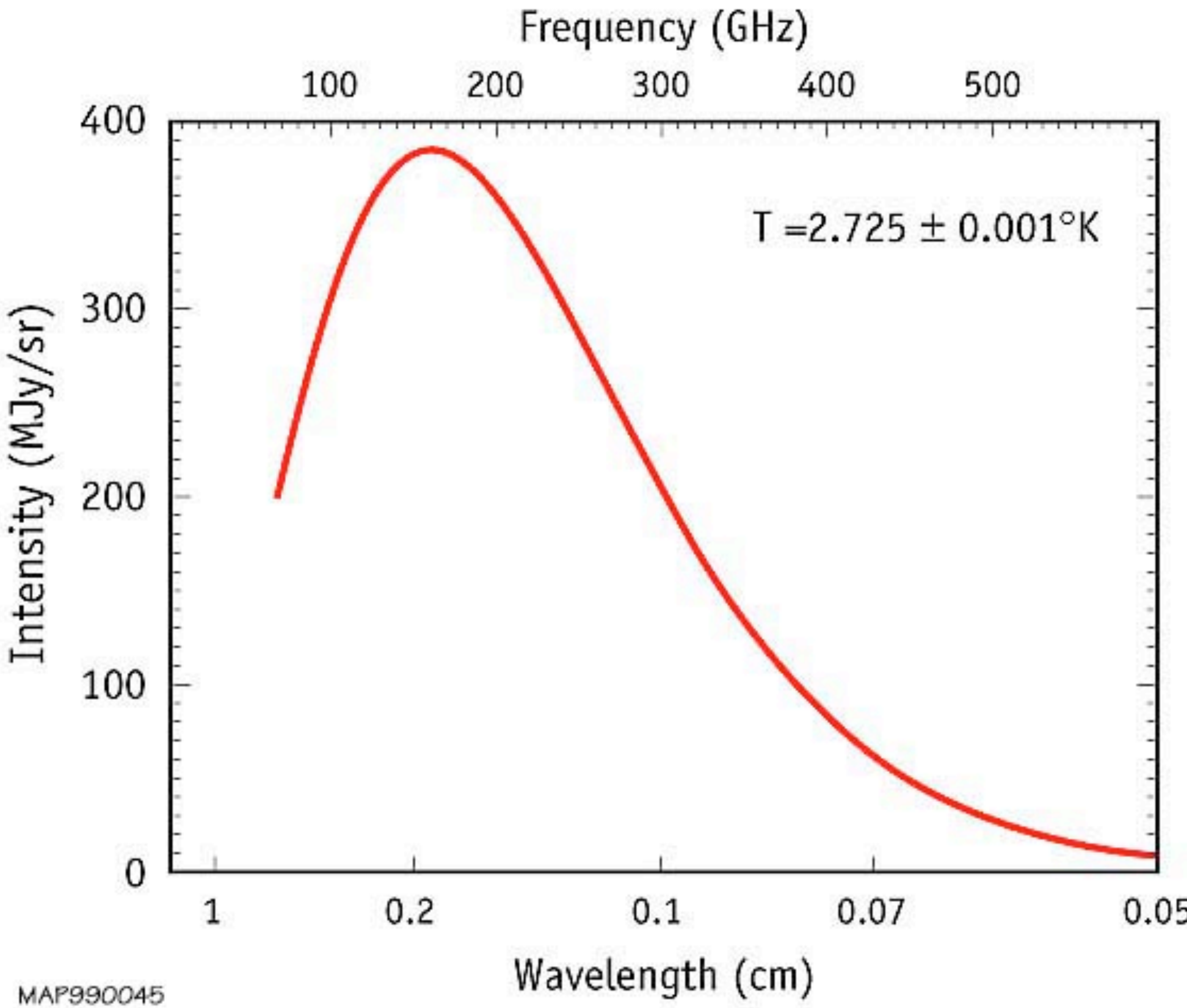
So measurements of the matter density suggest that the universe is open, with less than the critical density.

But measurements of Type I supernovae indicate that there is something else in the universe as well, something that provides a repulsive force and causes the expansion to accelerate. We call this dark energy, but we don't know what it is. It is not satisfactorily predicted or explained by any current theory of physics.

What does this mean for the actual geometry and fate of the universe?

The Cosmic Microwave Background

Again



Leftover radiation from the Big Bang

Almost perfect blackbody spectrum with temperature T=2.725 K

The Cosmic Microwave Background

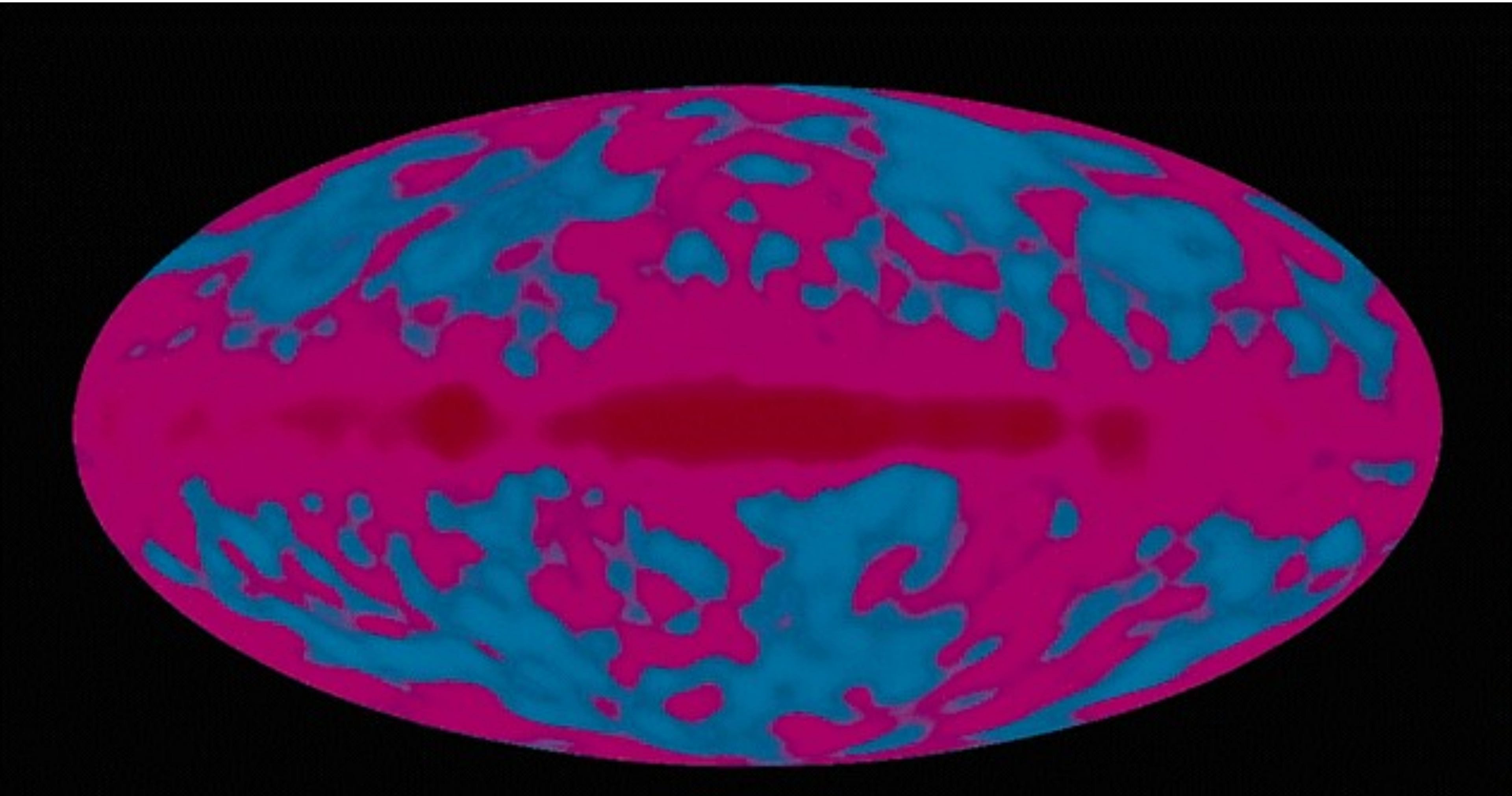
Again

Recent measurements by the COBE, WMAP and Planck satellites have revealed a nearly exact symmetry in all directions and a spectrum that matches the predicted blackbody spectrum to better than 1 part in 100,000.

The very small fluctuations in the temperature of the cosmic microwave background tell us about the small fluctuations in density in the early universe.

Careful measurement of these fluctuations can tell us about the content and ultimate fate of the universe!

This COBE Satellite (Cosmic Microwave Background Explorer) picture reveals the slight differences in density in the very early universe that must later have formed clusters of galaxies

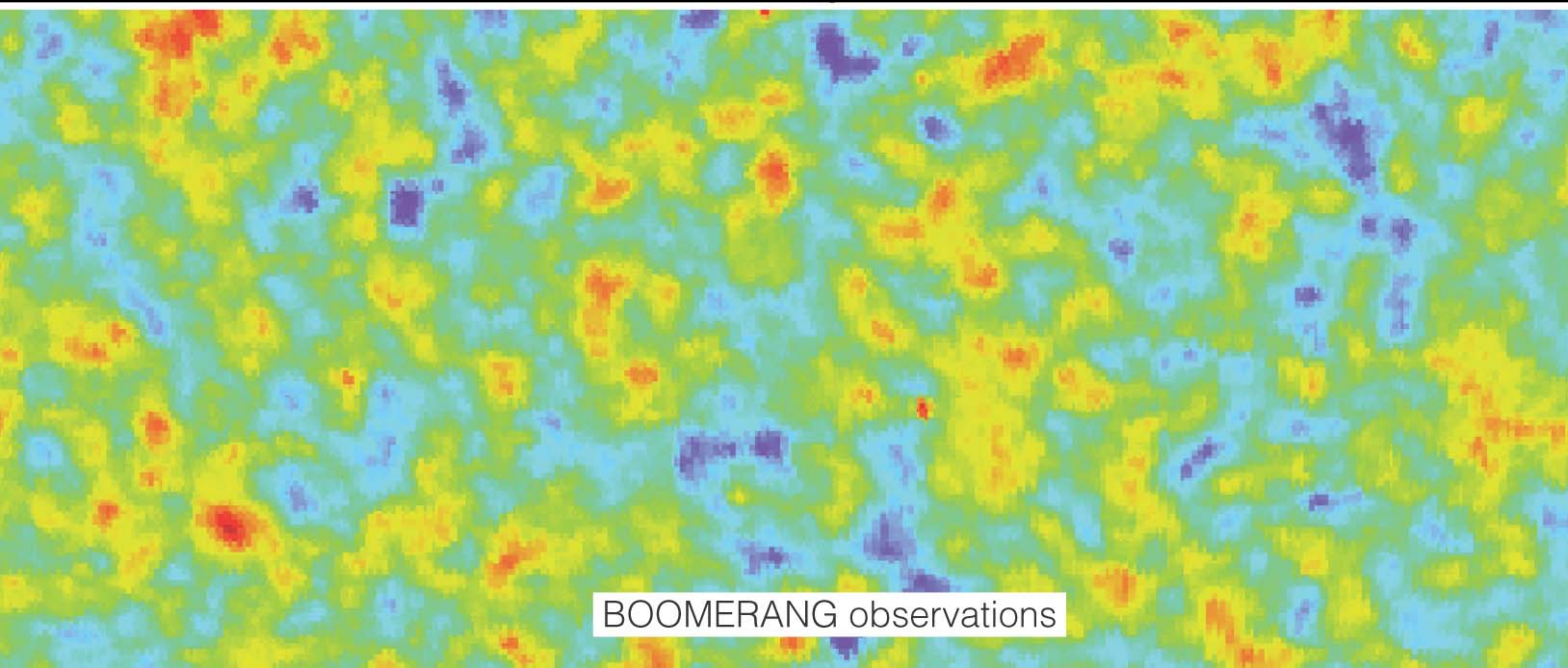


Tiny differences in temperature greatly enhanced (The differences are about 10^{-5} K)

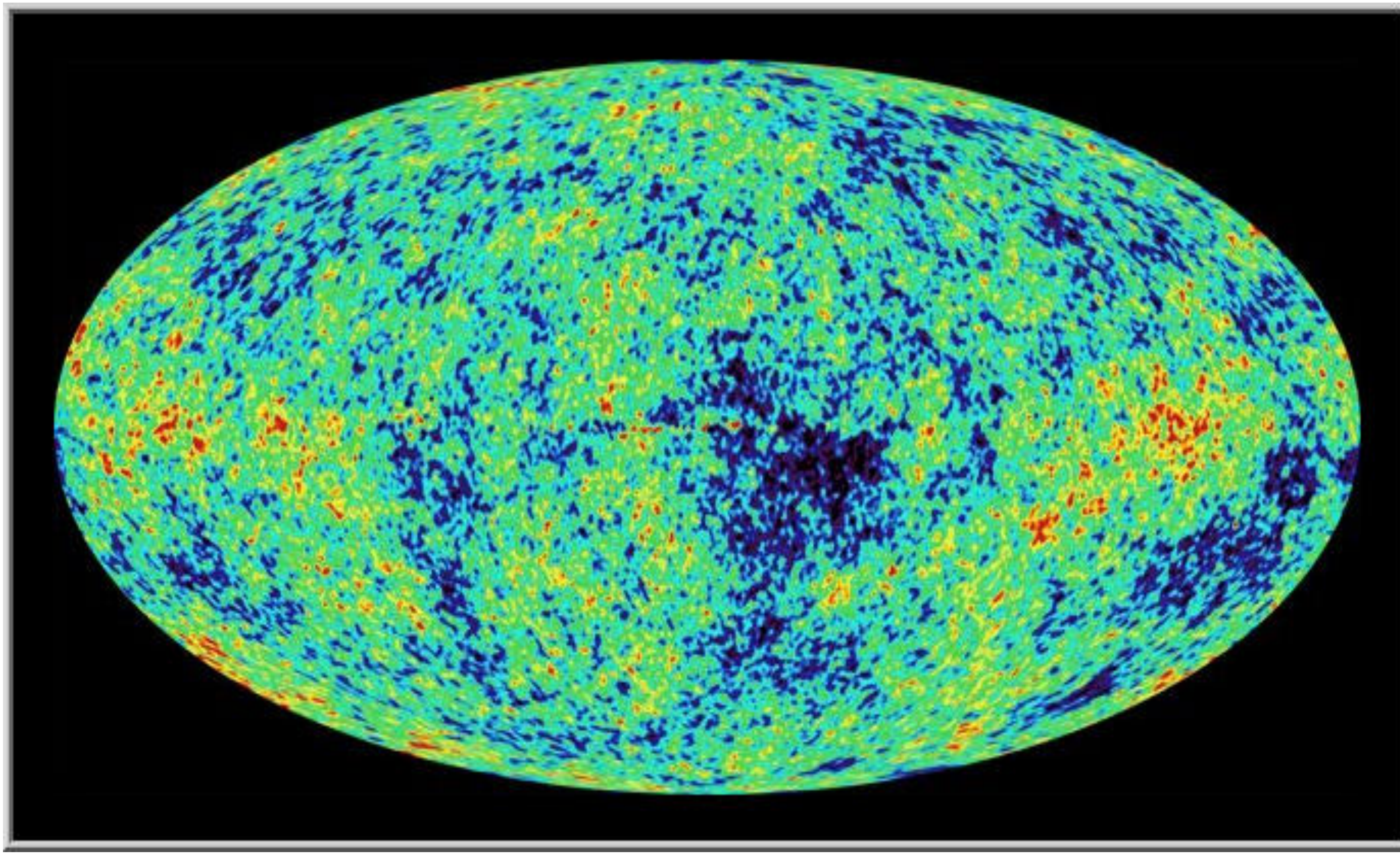
2.73 +.00001 K

2.73 -.00001 K

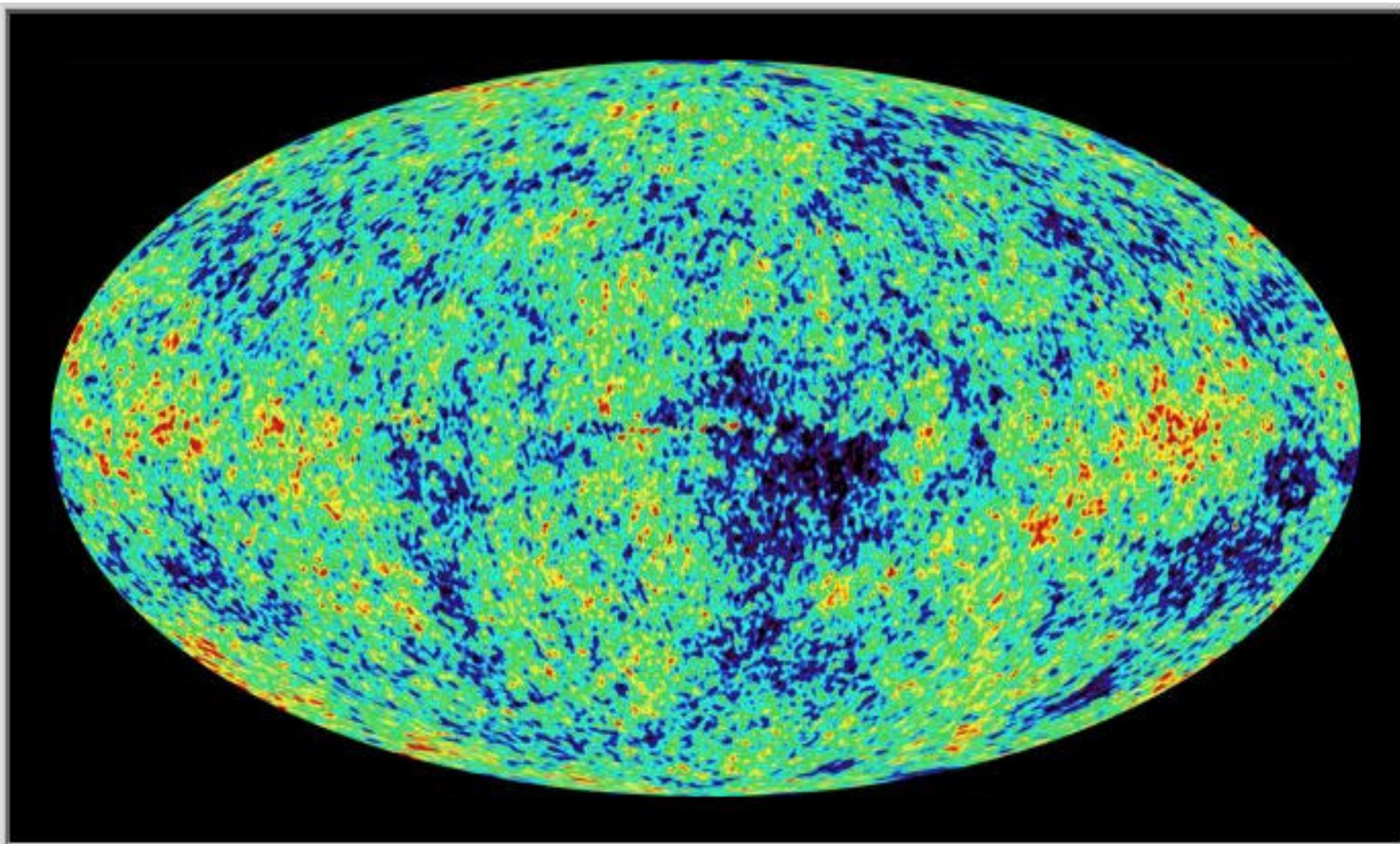
[redacted]



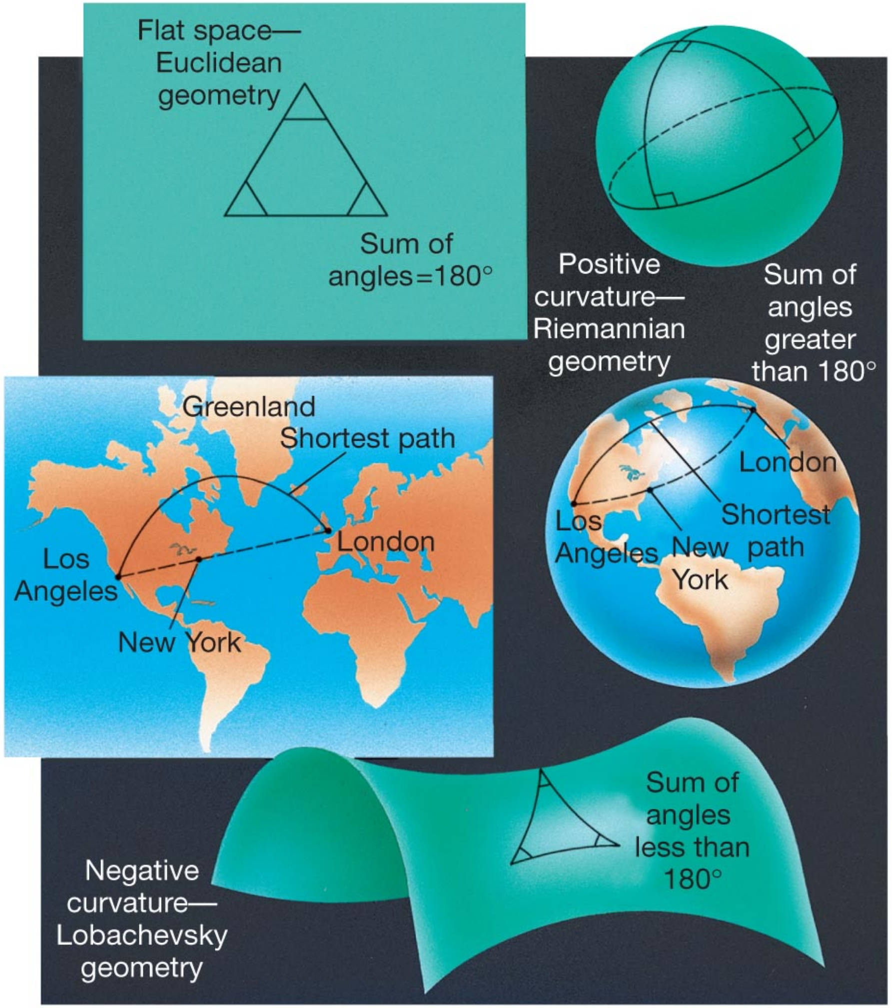
A still more accurate map of the microwave background (WMAP)



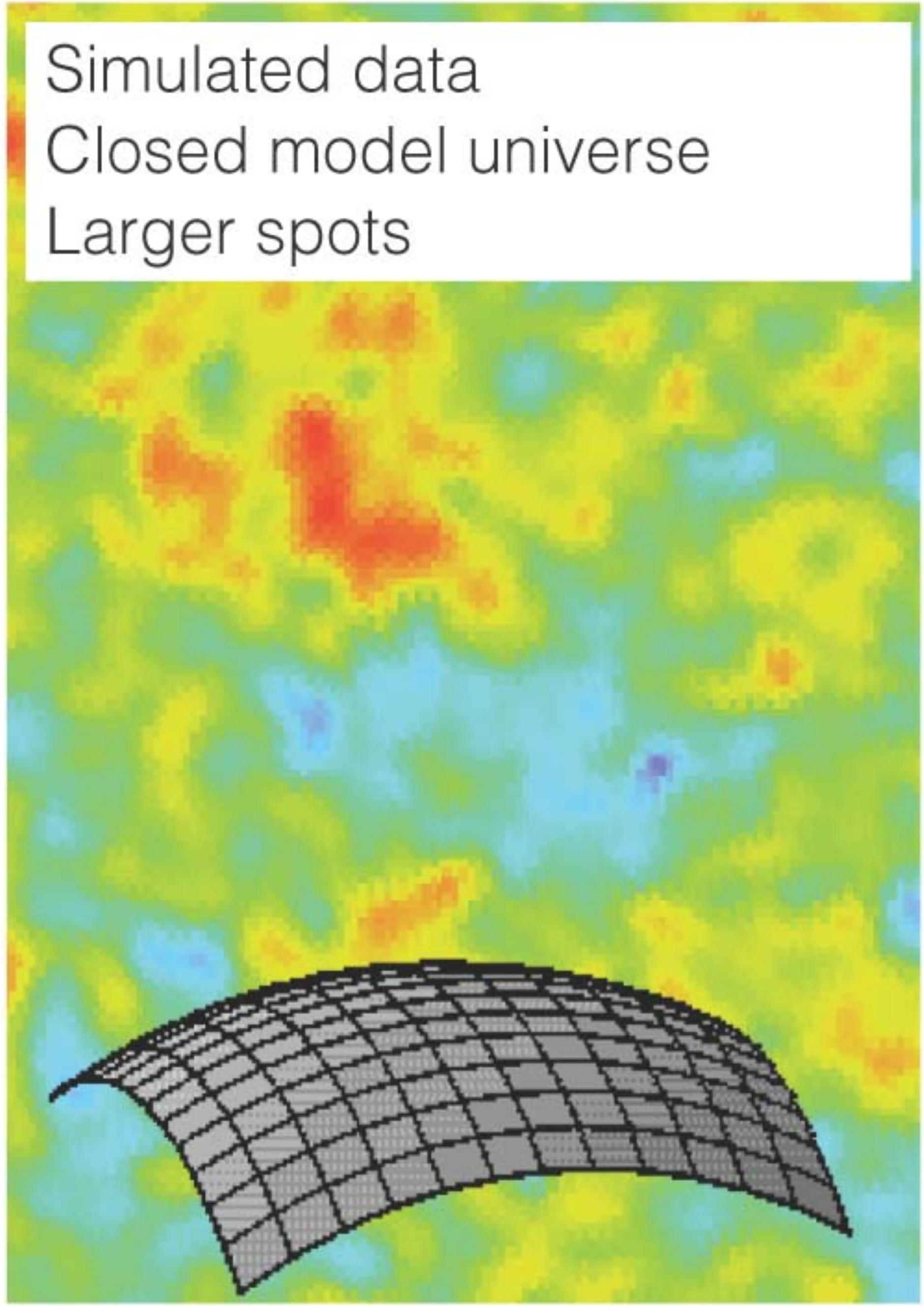
The size of the hotter and cooler spots depends on the **geometry of the universe.**

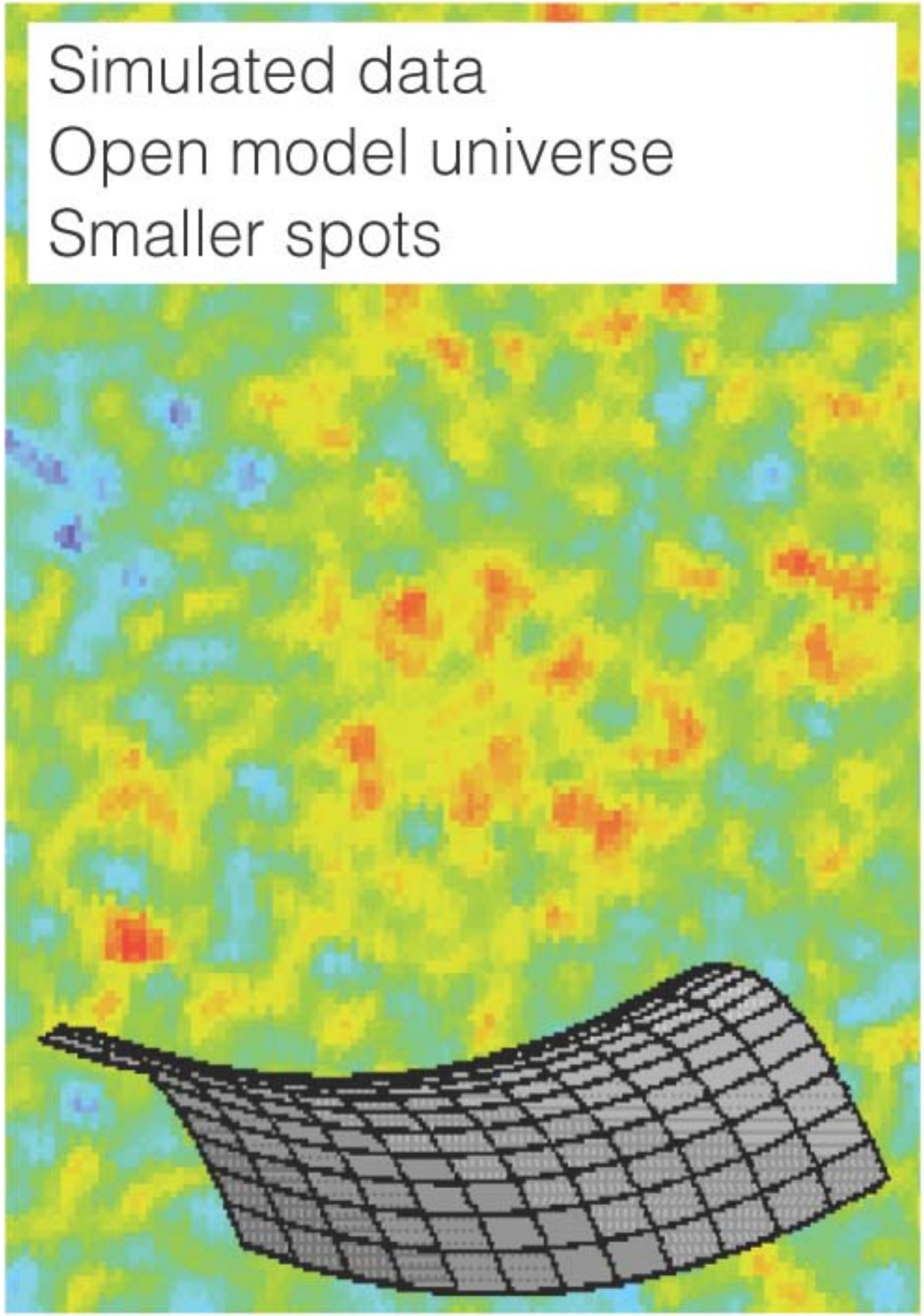


The Geometry of Space

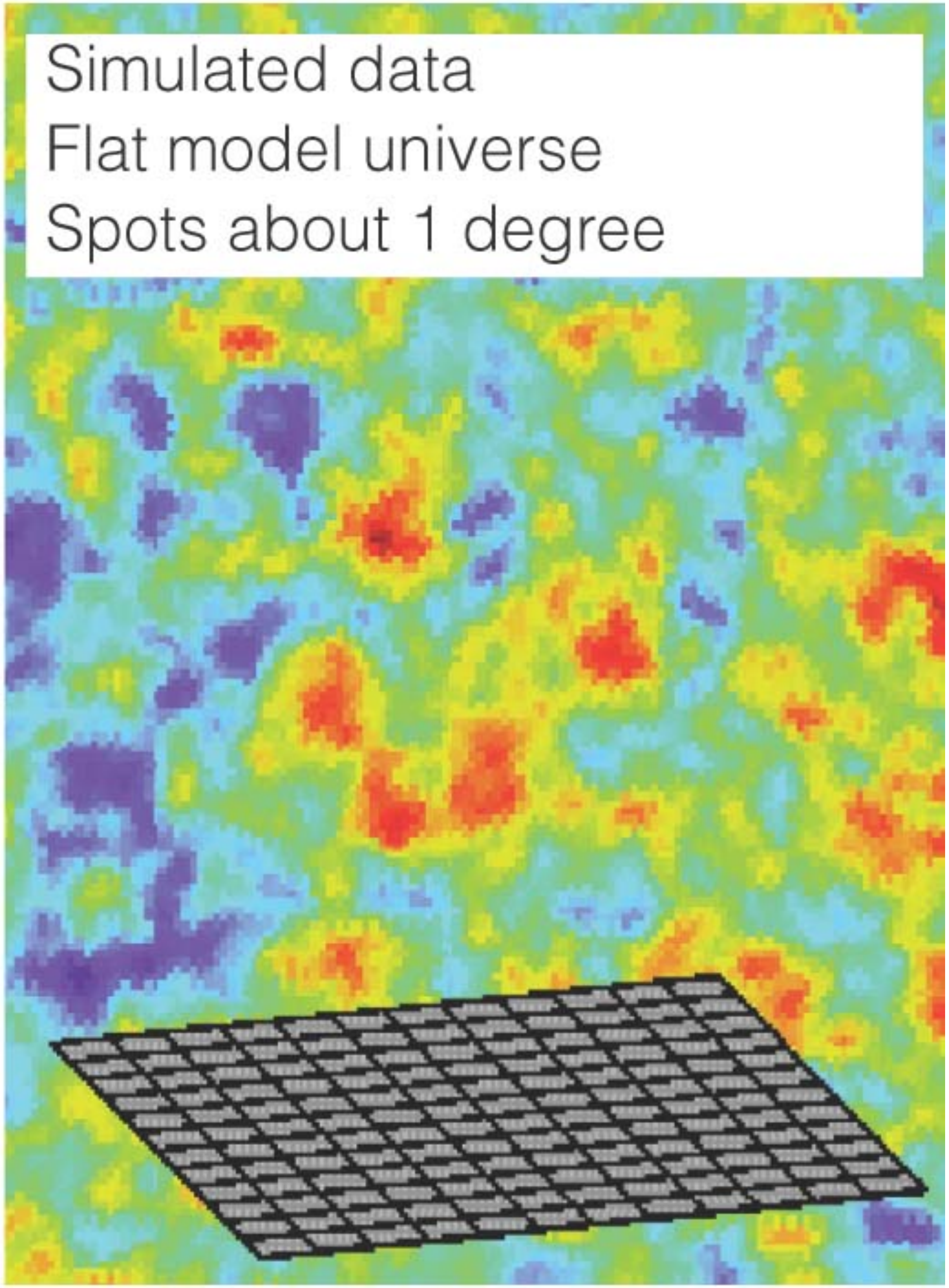


The temperature variations in the cosmic microwave background will appear to have a different size depending on the geometry of the universe, so by measuring the CMB we can tell if the universe is open, closed or flat.


Simulated data
Closed model universe
Larger spots


Simulated data
Open model universe
Smaller spots

Our observations match the flat model universe – the universe is flat!

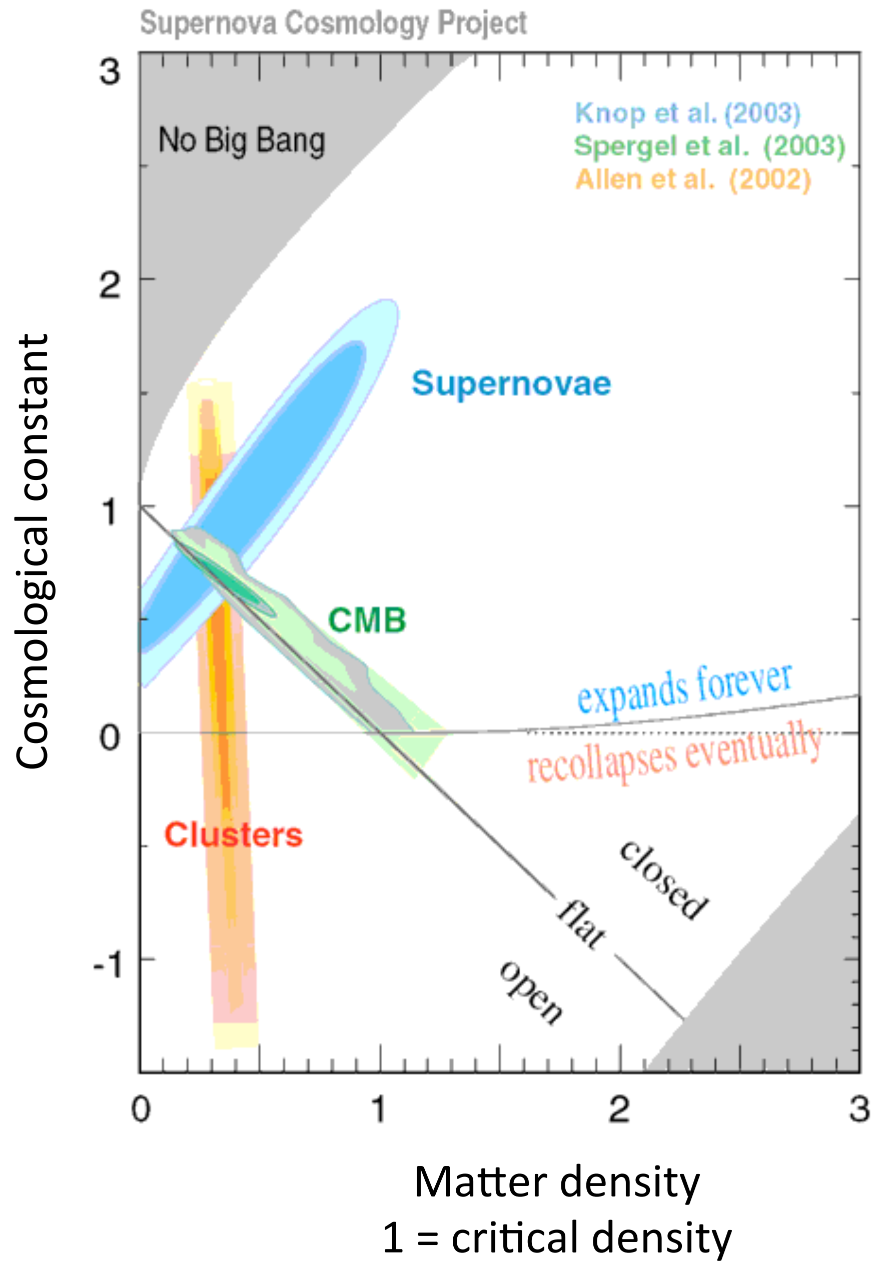


The Contents of the Universe

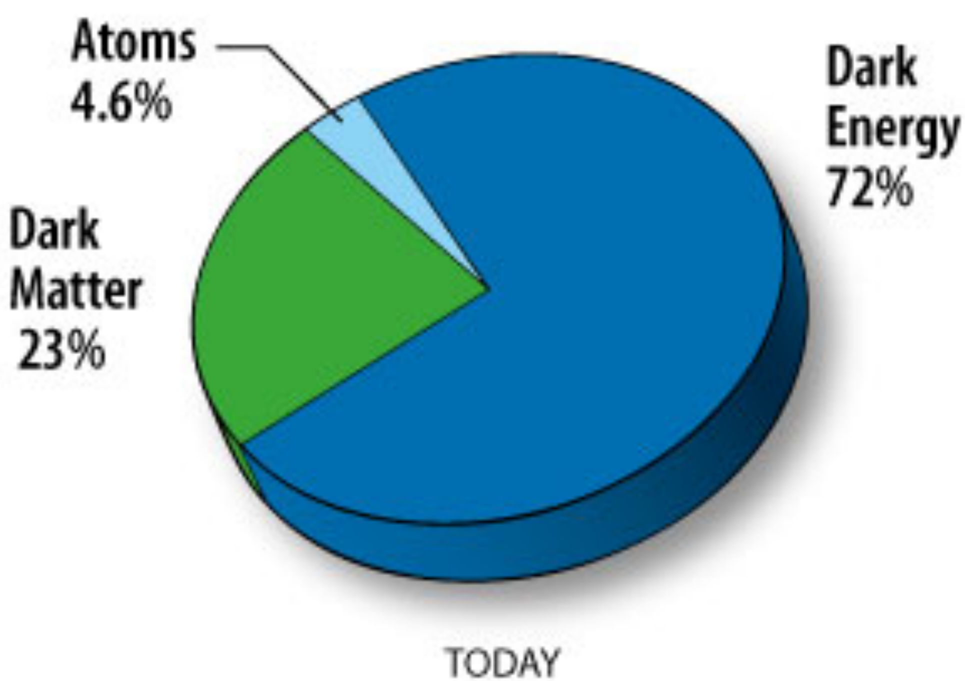
Observations of the cosmic microwave background tell us that the universe is flat: the total density is equal to the critical density.

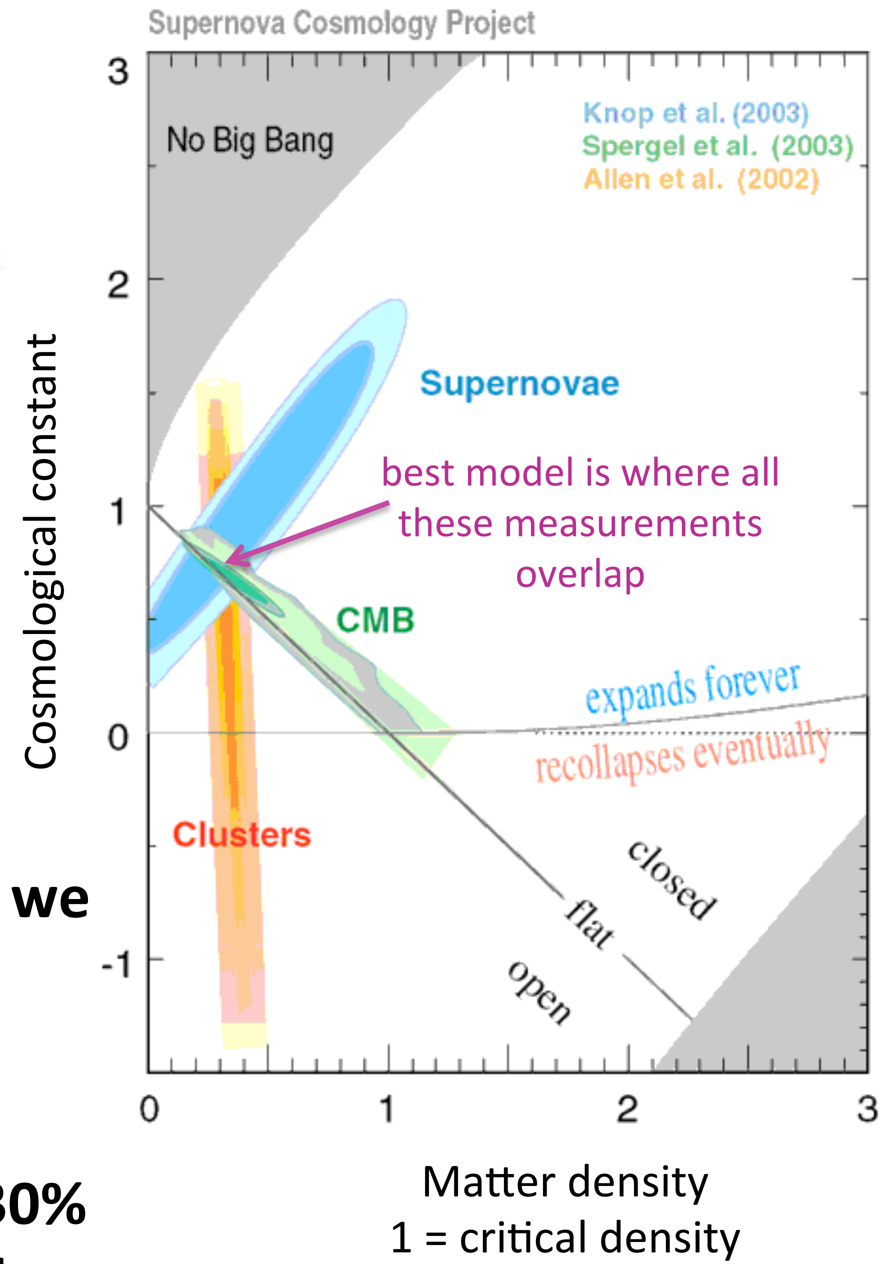
Type Ia supernovae tell us that there is a cosmological constant and the universe is accelerating.

Counting galaxy clusters tells us that the total matter density is low, about 30% of the critical density.



The Contents of the Universe

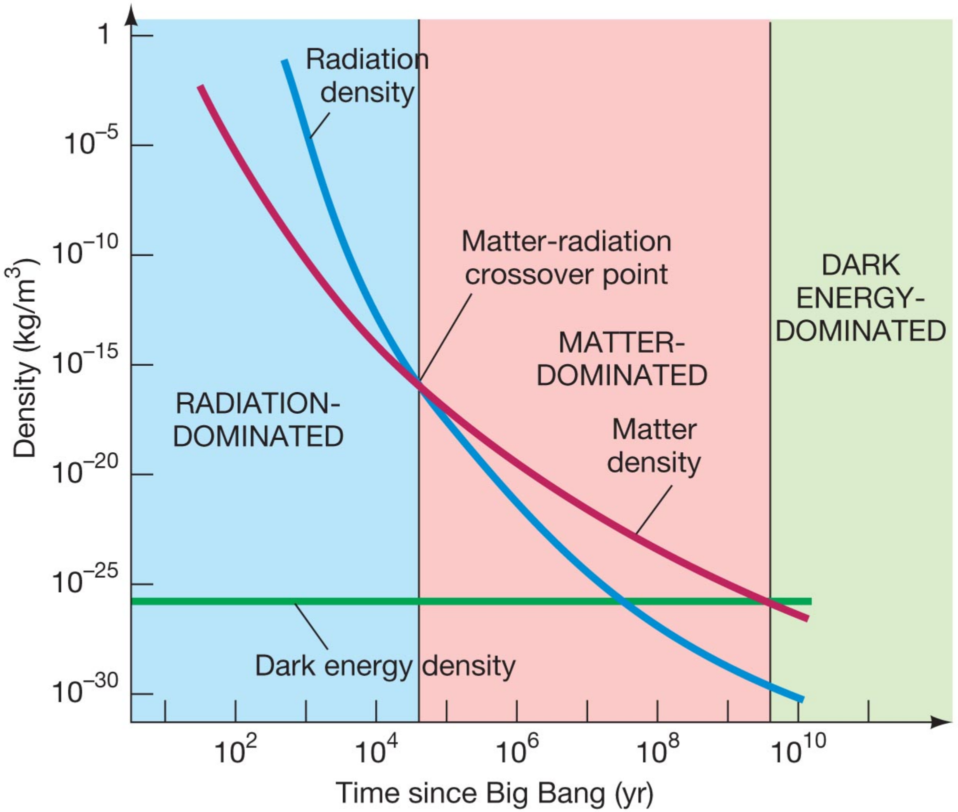




Combining all these measurements, we find that the universe is flat with density equal to the critical density. About 70% of the energy in the universe is dark energy, and about 30% is matter. Most of the matter is dark.

The Content of the Universe and the Fate of the Cosmos

What does this mean for the ultimate fate of the universe?



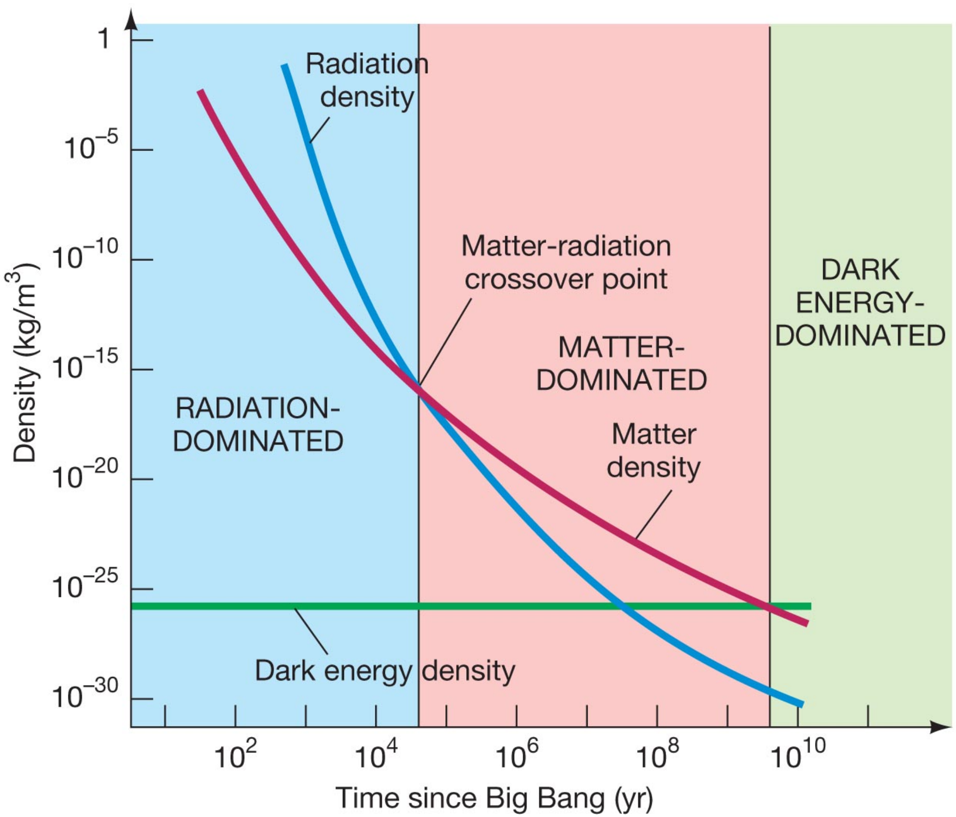
The total energy of the universe consists of matter, radiation, and dark energy.

At early times, radiation dominated, then matter took over.

The matter density decreases as the universe expands, but the density of dark energy is constant.

The Content of the Universe and the Fate of the Cosmos

What does this mean for the ultimate fate of the universe?



Since the density of dark energy is constant while the matter density decreases, dark energy will eventually take over.

This has already happened.

The universe is dominated by dark energy and will expand forever.

Recap: The Standard Model

The universe began with the Big Bang: a point of infinite density and temperature, which then expanded and cooled.

Evidence: the observed expansion of the universe, the leftover light from the Big Bang (the cosmic microwave background), the agreement between independent measurements of the age of the universe.

The universe is flat, containing radiation, (mostly dark) matter, and dark energy. Evidence from the size of the temperature fluctuations in the cosmic microwave background, from Type Ia supernovae, and from counting galaxy clusters.