Today in Astronomy 102: the age, and fate, of the Universe

- Matter-dominated universes, and measurements of the mass density of the Universe: an open Universe?
- Direct measurements of the Universe's curvature: a flat Universe?
- Time without end: the Universe does **not** appear to be a black hole, is probably **open**, and will probably expand forever.

The NASA Microwave Anisotropy Probe (MAP), launched this year, which may obtain the definitive images of cosmic background fluctuations .

From last time: the cosmic microwave background is almost *too* isotropic.

One theoretically-popular way out of this problem is to postulate a brief period of **inflation** early in the Universe's history. Briefly, this is thought to happen as follows.

- Shortly after the Big Bang, the **vacuum** could have had a much larger energy density, in the form of virtual pairs, than it does today. This possibility is allowed under certain theoretical models of numbers and interactions of elementary particles.
- At some time during the expansion, the vacuum underwent a **phase transition** (like freezing or condensing) to produce the lower-energy version we have today.

Inflation: the cosmic microwave background is almost *too* isotropic (continued).

- While the vacuum was in its high-energy-density state, it gave a large additional impulse to Universal expansion.
  - Recall: vacuum fluctuation energy density is actually **negative** in strongly curved spacetime; virtual pairs were **exotic** in the newborn Universe. Thus the vacuum acts "anti-gravitationally" early in the expansion.
- Accounting for the vacuum's influence in general relativity leads to a **very much smoother and faster expansion**. During this period, spacetime's radius of curvature increases more like a bubble blowing up, than like a blast wave - hence the name **inflation** for the process.
  - During inflation, the vacuum would appear in the field equations as a **cosmological constant**.

Inflation: the cosmic microwave background is almost *too* isotropic (continued).

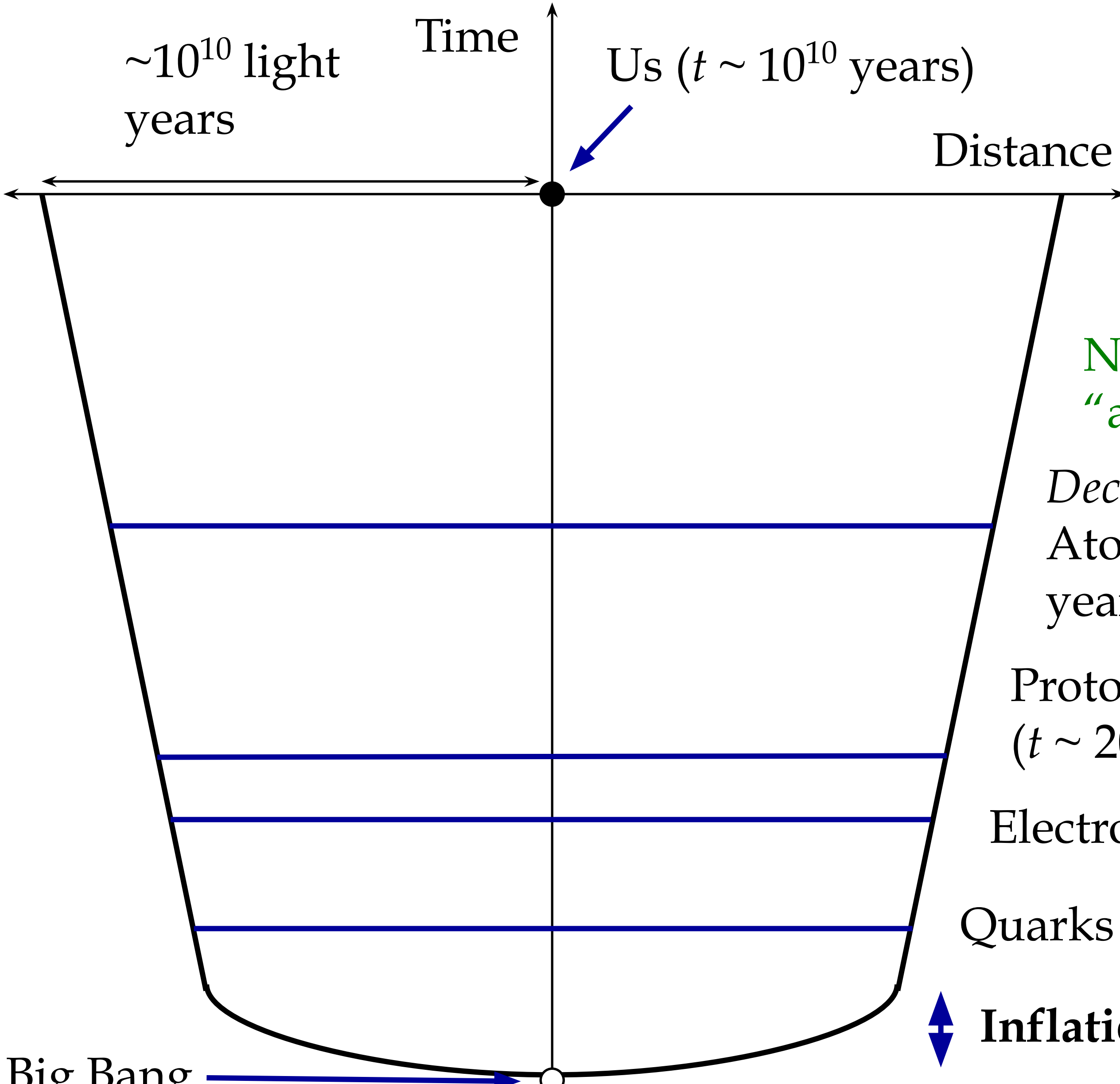
The inflationary era would have been relatively brief, much shorter than the time between Big Bang and decoupling.

- If it lasted through 100 doublings of the Universe's size, that would do it, and this takes only about 10^{-35} seconds.
- During the remaining "normal" expansion between the end of inflation (decay of the vacuum to its low energy density state) and decoupling, the bumps and wiggles normally present in blast waves still wouldn't have had enough time to develop.

We know of course that the Universe has become much less smooth since decoupling. The seeds for inhomogeneities like galaxies, stars and people were not sown before decoupling, however.

Expansion of an inflationary Universe

Note: "~" means "approximately equals."



Decoupling: Atoms (t ~ 2×10^{5} years)

Protons, neutrons, nuclei (t ~ 200 sec)

Electrons (t ~ 1 sec)

Quarks (t ~ 10^{-6} sec)

Inflation (first ~10^{-35} sec)

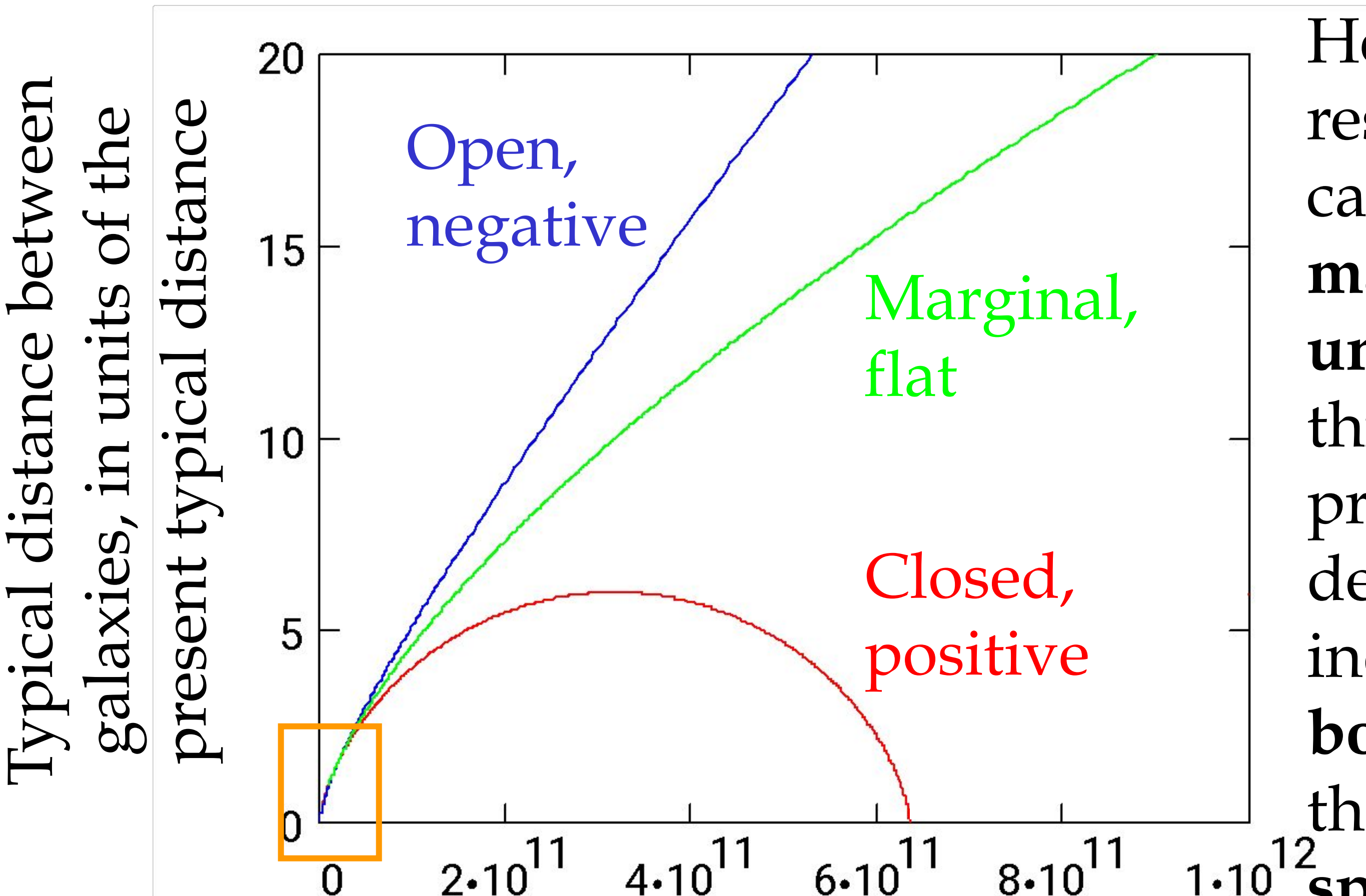
The age and fate of the Universe

- 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…

The age and fate of the Universe (continued)

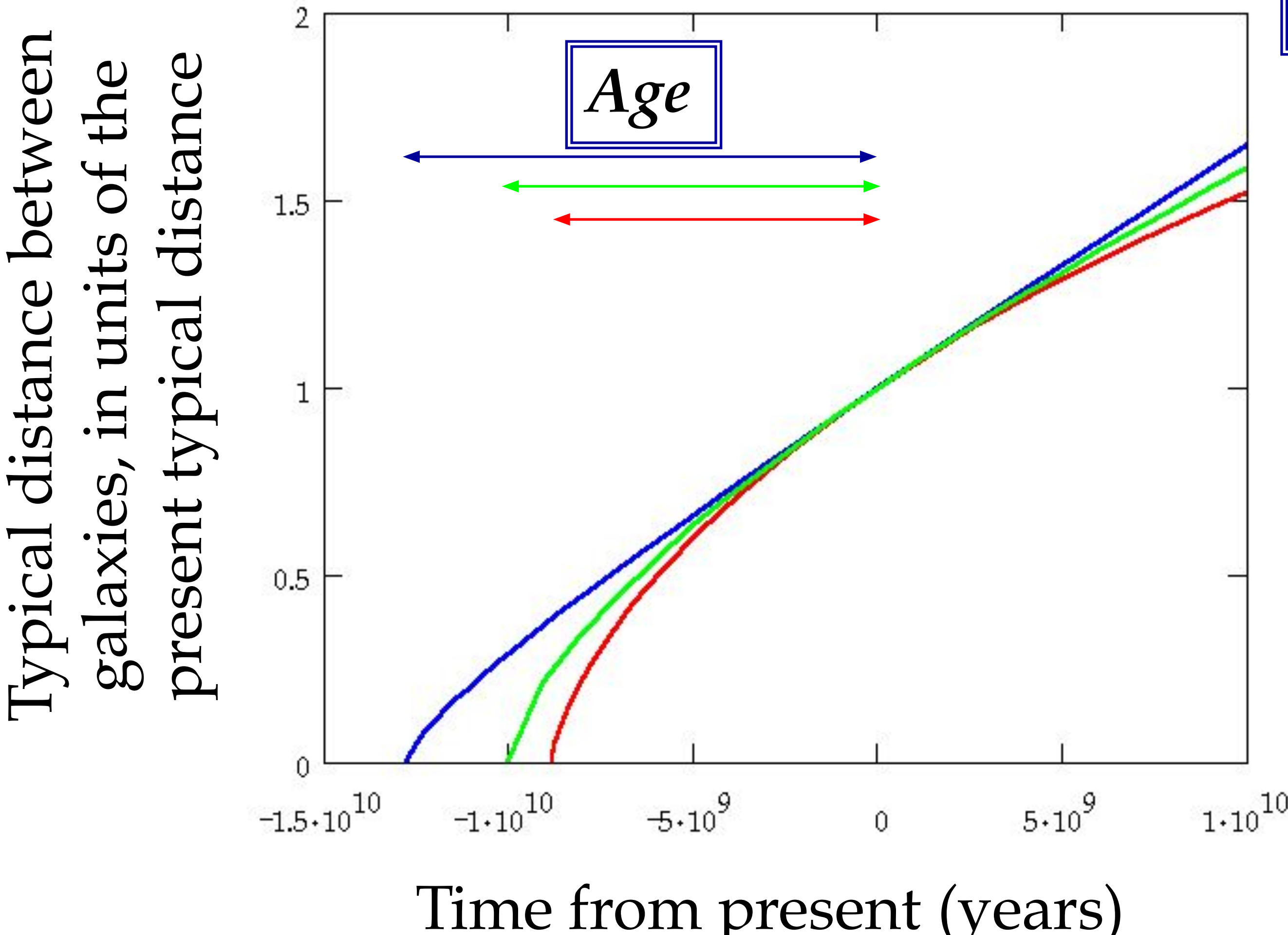


Time from present (years)

Region expanded on next page.

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 **spacetime curvature.**

The age and fate of the Universe (continued)



Fate

Open

Marginal

Closed

All matched to observed expansion rate at present time.

How can we tell which "universe" is our Universe?

Several ways are possible, all with substantial and different degrees of difficulty:

1. Measure the **density** directly, using observations of the motions of galaxies to determine how much gravity they experience. (Much like our way of measuring black-hole masses by seeing the orbital motion of companion stars.)
2. Measure the **ages of the oldest objects** in the Universe.
3. Measure the Universe's **curvature** directly, by observing very distant objects with well-determined size and distance.
4. 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. In order…

1. 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

$$\rho_C = \frac{3H_0^2}{8\pi G} = 7.9 \times 10^{-30}\ \mathrm{gm\ cm^{-3}}$$ Critical density

$$\Omega_m = \frac{\rho}{\rho_C}$$ Normalized present-day density (“omega”)

The present-day density, ρ or Ω_m, can in principle (but with difficulty!) be measured, by observing the motions of galaxies by their Doppler shifts. **If $\Omega_m < 1$, the universe is open; if $\Omega_m = 1$ it is marginal; if $\Omega_m > 1$, it is closed**.

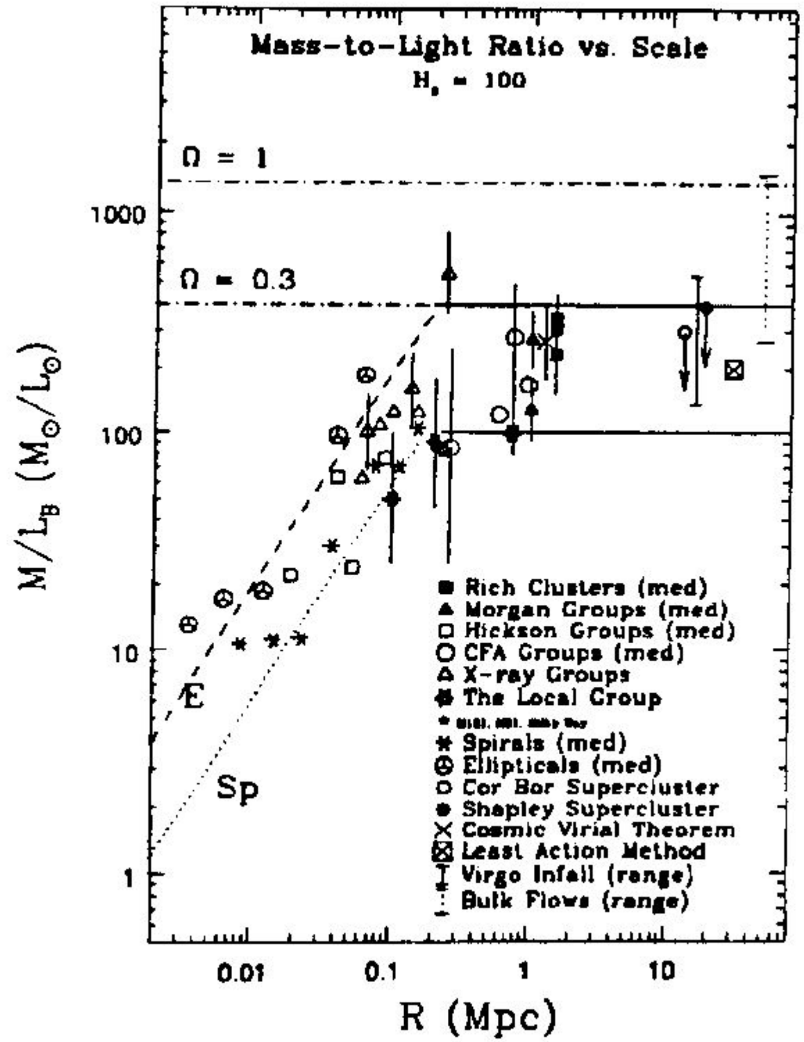
1. Is the Universe gravitationally bound? Matter-dominated universes (continued).

So what is the present-day density of the Universe?

- Observational bounds on Ω_m, made from "nearby" galaxy redshift surveys over the past 15-20 years, consistently indicate that

$$\Omega_m = 0.2 \pm 0.1$$

Right: summary of measurements of the Universe's mass density (N. Bahcall 1997)



1. Is the Universe gravitationally bound? Matter-dominated universes (continued).

- So if the Universe is matter-dominated, its curvature is negative, it is open, and it will continue to expand.
- It is, however, a strong theoretical prediction many models of elementary particles and of the early Universe, especially those involving **inflation**, that **Ω_m should be exactly 1**, and that for unknown reasons the present measurements of Ω_m are faulty. Observers and theoreticians used to argue incessantly about this.
- 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.

Mid-lecture break

Homework #7 is due on Friday at 11 PM.

Exam #3 takes place Thursday, 20 December 2001, 4-5:15 PM, right here.

- ❑ The TAs are scheduling a review session: stay tuned to your e-mail.
- ❑ Don't forget the practice exam, available on the AST 102 Web site.

Image: Deployment of the balloon-borne BOOMERANG cosmic-background anisotropy experiment in Antarctica, with Mt. Erebus in the distance (Caltech/UCSB/U. Rome/NASA).

2. 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", as

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

where the value of the factor A depends on Ω_m, but is less than or equal to 1.

- The factor A is equal to 1 if Ω_m is very small compared to 1. The larger the value of Ω_m, the smaller the value of A. Open universes have values of A between 2/3 and 1, and closed universes have values of A smaller than 2/3.
- Jargon: $t = 1/H_0$ is often called "one Hubble time."

2. Age of matter-dominated universes (continued)

- If Ω_m is assumed to be much smaller than 1, the age would be

$$t = \frac{1}{H_0} = \frac{1}{20 \dfrac{\text{km}}{\text{sec} \times \text{Mly}} \left(\dfrac{\text{ly}}{9.46 \times 10^{12} \text{ km}} \right)}$$

$$= 4.73 \times 10^{17} \text{ sec} \left(\frac{\text{year}}{3.16 \times 10^{7} \text{ sec}} \right) = 1.5 \times 10^{10} \text{ years}$$

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

$$t = \frac{2}{3} \frac{1}{H_0} = 1.0 \times 10^{10} \text{ years}$$

2. Age of matter-dominated universes (continued)

For the best experimental value, $\Omega_m = 0.2$, we get

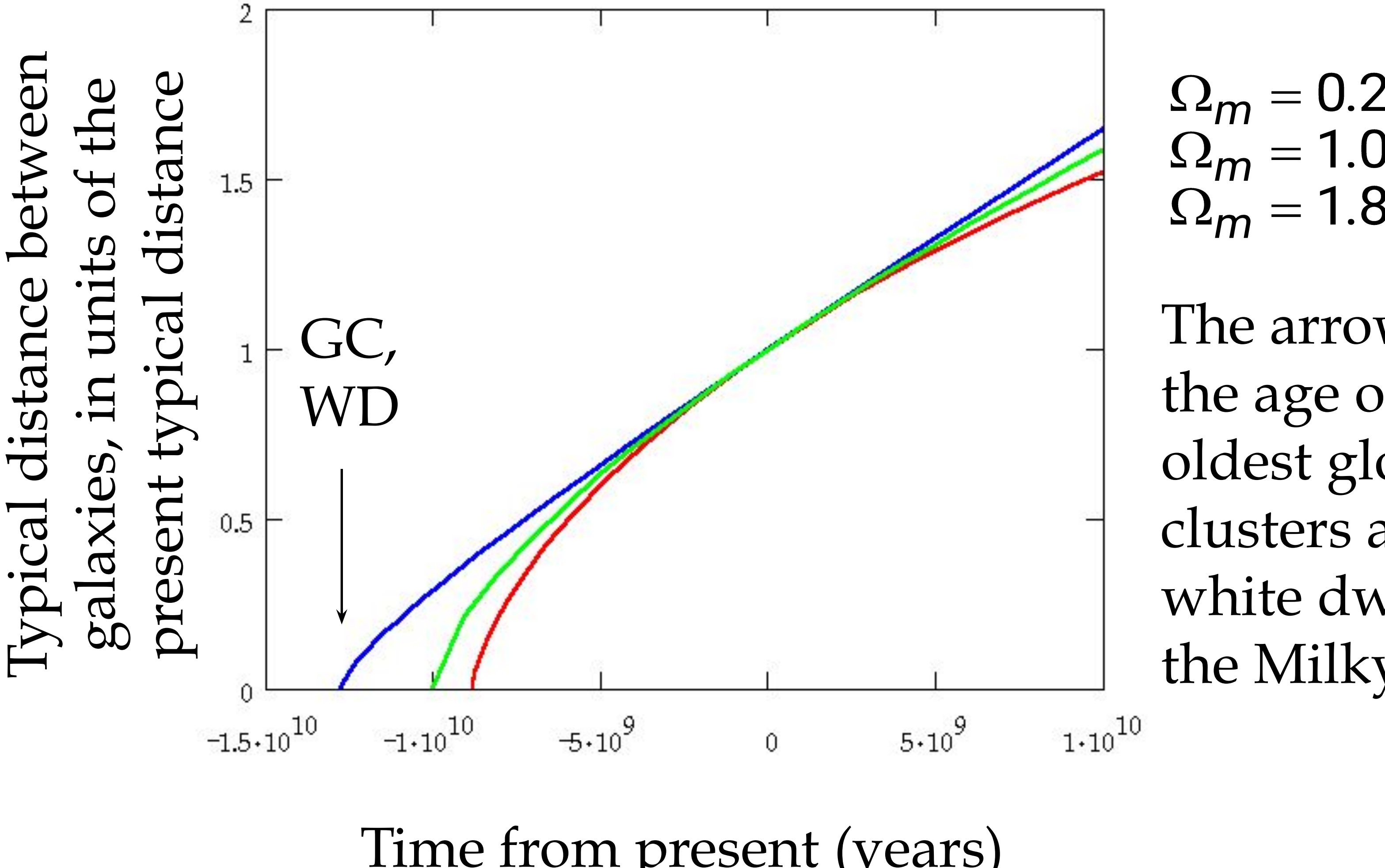
$$t = 1.3 \times 10^{10} \text{ years}$$

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 4.5×10^9 years old, so an age of 1.3×10^{10} years would be OK on this score.
- ❑ The ages of white dwarf stars and globular star clusters turn out to be accurately measurable; the oldest of these are 1.3×10^{10} years old ($\pm$ about 0.1×10^{10} years).

This agrees with $\Omega_m = 0.2$ (smaller would be OK too)**, and is in conflict with $\Omega_m = 1$.**

2. Age of matter-dominated universes (concluded)



The arrow marks the age of the oldest globular clusters and white dwarfs in the Milky Way.

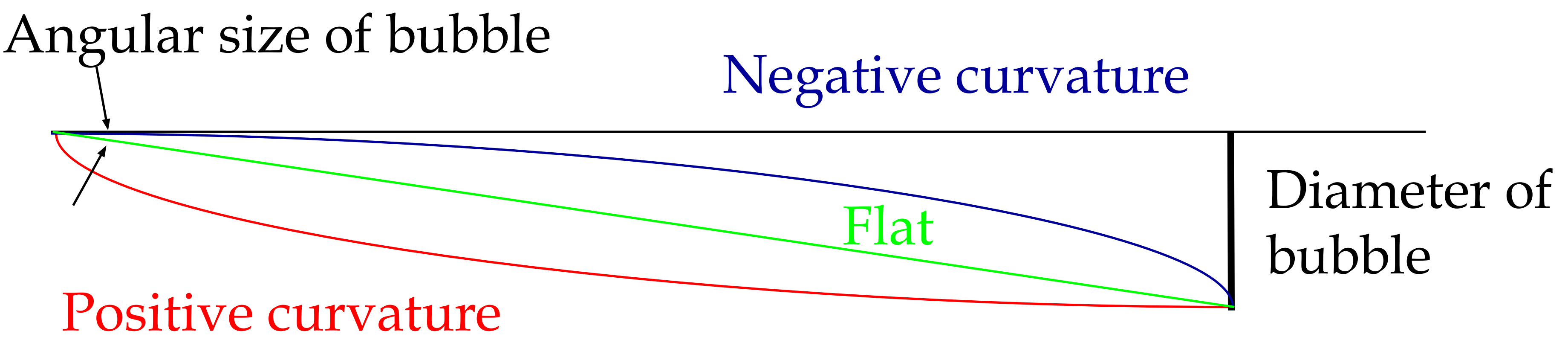
3. Measurements of the Universe's spacetime curvature: is it *not* matter-dominated?

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.

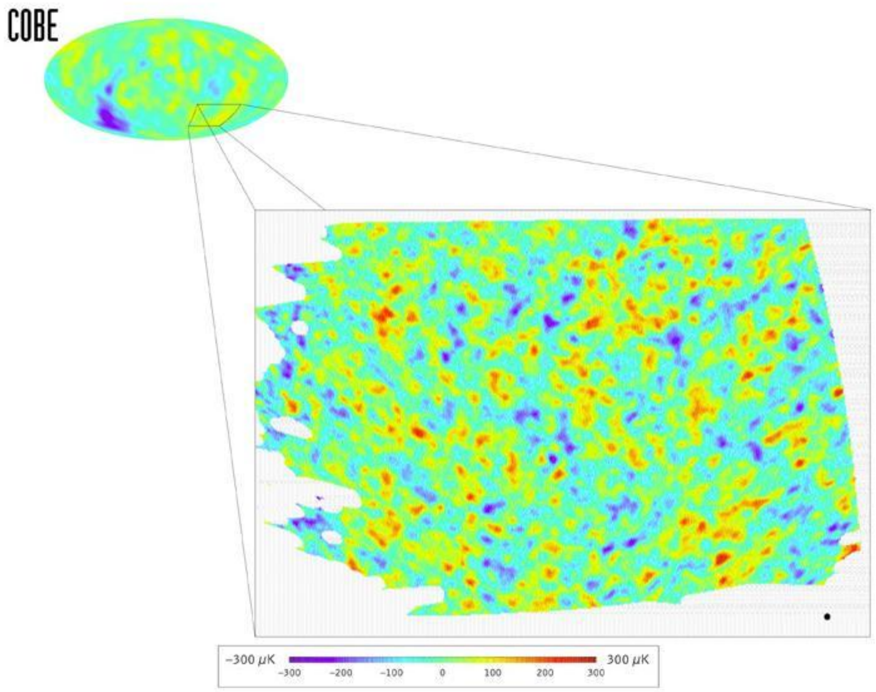
3. Measurements of the Universe's spacetime curvature: is it *not* matter-dominated? (continued)

- 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.
- By observing their angular size and knowing their diameters we can determine the **curvature of spacetime** between decoupling and here-and-now.



3. Measurements of the Universe's spacetime curvature: is it *not* matter-dominated? (continued)

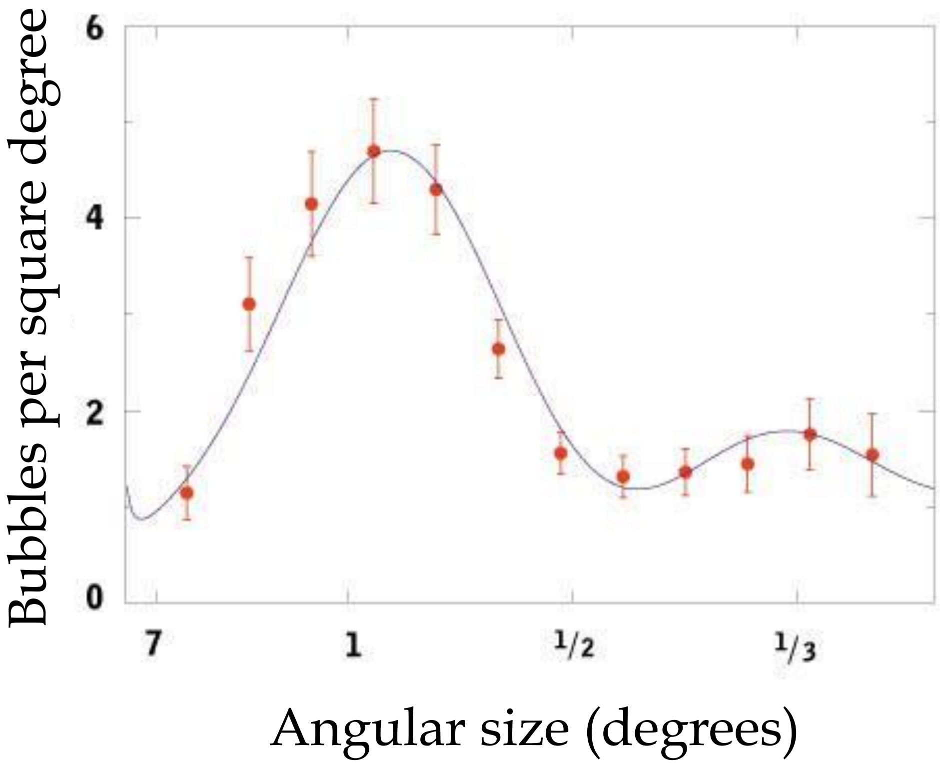
- Detection of cosmic background anisotropies on the scale of these bubbles has become possible in the last few years, in high-altitude balloon-borne measurements by the MAXIMA and BOOMERANG instruments.



Results from BOOMERANG (Caltech/ UCSB/ U. Rome/ NASA)

3. Measurements of the Universe's spacetime curvature: is it *not* matter-dominated? (continued)

- Result: the curvature between decoupling and here/now is zero – **a flat Universe!**



In **red**: results from BOOMERANG: P. de Bernardis *et al.* 2000, *Nature* **404**, 955,. (Caltech/ UCSB/ U. Rome/ NASA)
In **blue**: expectations for a flat universe.

3. Measurements of the Universe's spacetime curvature: is it *not* matter-dominated? (continued)

If these results are true: how did the Universe come to be flat?

- We know that $\Omega_m = 0.2$: 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**. (See lecture, 4 December 2001.)
- For the cosmological constant Λ one can define a relative "density" Ω_Λ. For the Universe to be flat, $\Omega_m + \Omega_\Lambda = 1$. But $\Omega_m = 0.2$, so $\Omega_\Lambda = 0.8$; **the cosmological constant dominates the Universe's present mass-energy density on large scales.**

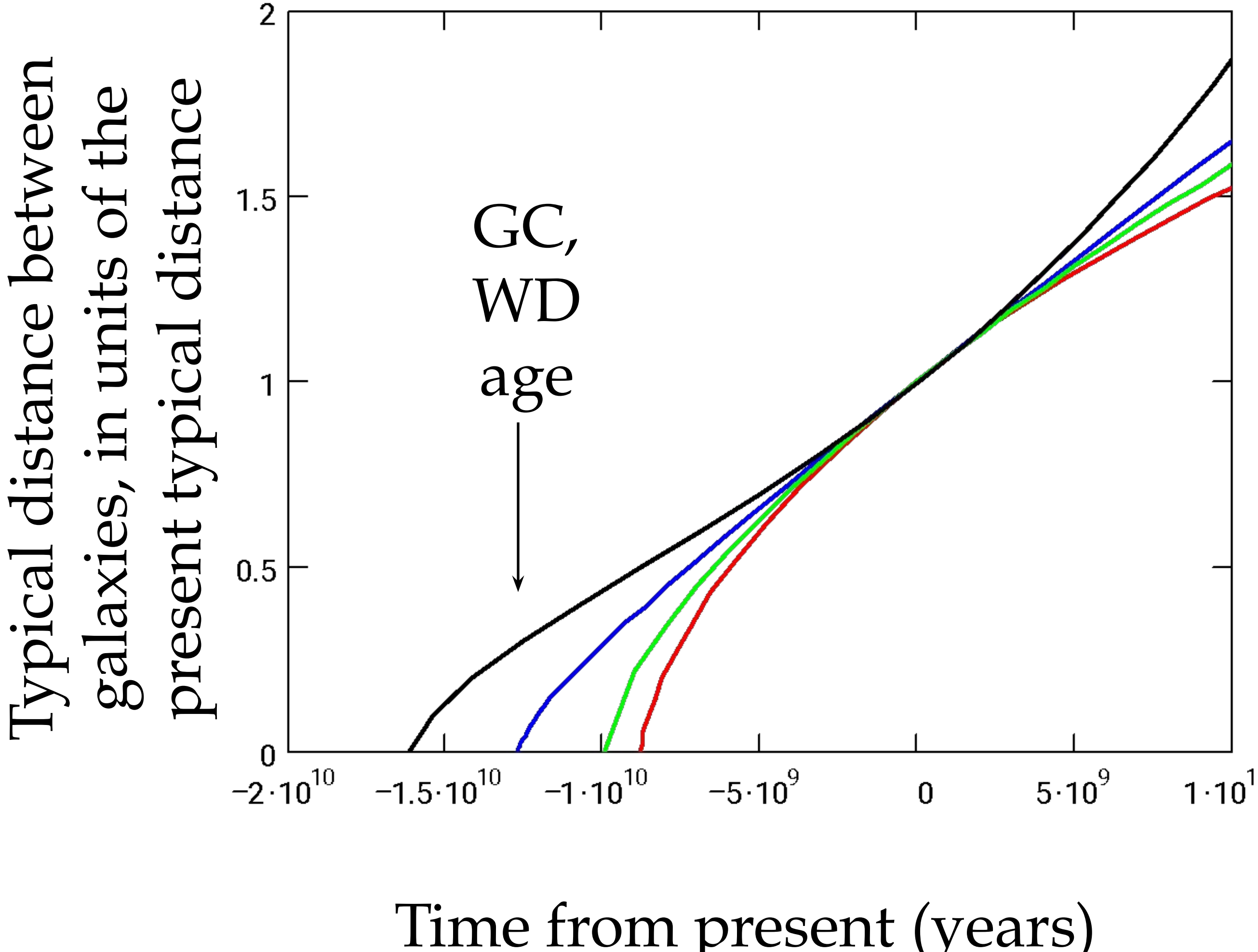
If there is an afterlife from which we can be seen, Einstein is having a really good laugh about this.

3. Measurements of the Universe's spacetime curvature: is it *not* matter-dominated? (continued)

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 Ω_Λ were negative, the universe would collapse and end in a singularity no matter what its curvature.
  - If the value of Ω_Λ were positive and large, even a positively-curved, closed universe would expand forever.
- **(4.)** If $\Omega_\Lambda = 0.8$, distant galaxies should be seen to **accelerate**. This may have been confirmed, recently, in observations of distant galaxies in which supernovae have been seen.

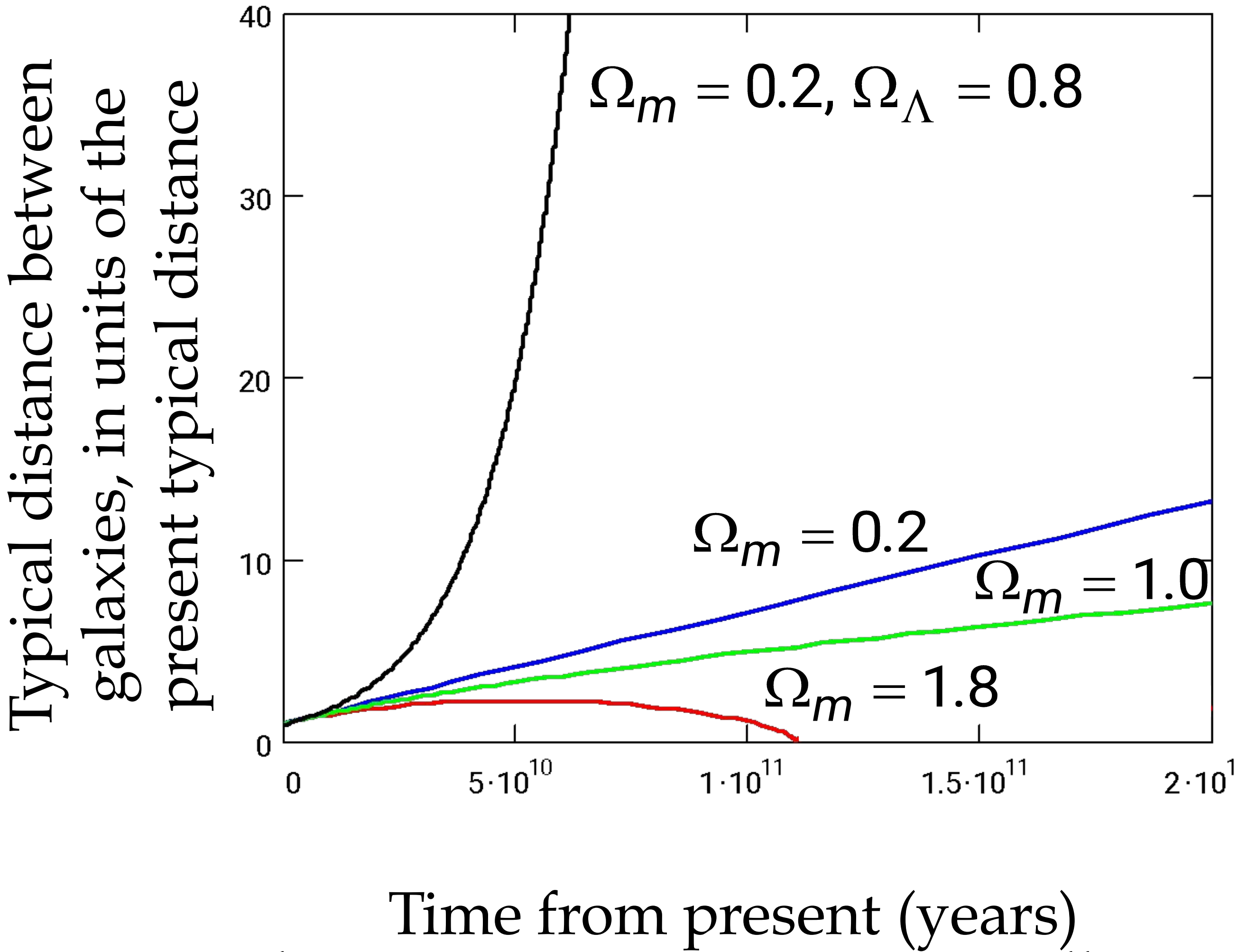
Age and fate of the Universe if it has a positive cosmological constant



$\Omega_m = 0.2, \Omega_\Lambda = 0.8$
$\Omega_m = 0.2$
$\Omega_m = 1.0$
$\Omega_m = 1.8$

Here the "new" Universe is compared to the matter-dominated models. Its present age turns out to be **1.6×10^{10} years**.

Age and fate of the Universe if it has a positive cosmological constant (continued)



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 redshifted into invisibility.

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

- The Universe has a present-day relative mass density of about Ω_m = 0.2.
- If matter dominates its energy, the Universe is negatively-curved and **open,** the presently-observed expansion will continue forever, and about 1.3×10^{10} years (13 billion years) have elapsed since the Big Bang.
- There are indications, in experiments which need to be reproduced, that the Universe is **flat**. This requires a substantial, positive cosmological constant, which dominates the present energy of the Universe: $\Omega_\Lambda = 0.8$. (It also requires a physical explanation for Λ!)
- If this is true, the Universe is open, the present expansion will continue and will increase dramatically over time, and the Universe is about 1.6×10^{10} years (16 billion years) old.

The NASA MAP satellite, launched this year and just beginning its mission, will settle the cosmological-constant issue once and for all. Stay tuned; the final answer may appear in the next few years.