# THE FLAT UNIVERSE

EXAM #3 ON THURSDAY



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- 1 hr 15 min exam in class, open book and open notes
- Things that you should DEFINITELY bring with you:
  - Writing utensil (pencil or pen – blue or black ink)
  - Calculator
- Things that you should probably bring with you:
  - Lecture notes
  - Laptop or tablet (so that you can access the WeBWorK homework problems and the "How Big is That?" sheet on the course website)
- Practice exam available on WeBWorK – email me when you want solutions
- REVIEW SESSION – **tomorrow (Wednesday), 12/3, at 7:30pm** in B&L 372

## THE FLAT UNIVERSE

Acceleration in the Universe's expansion

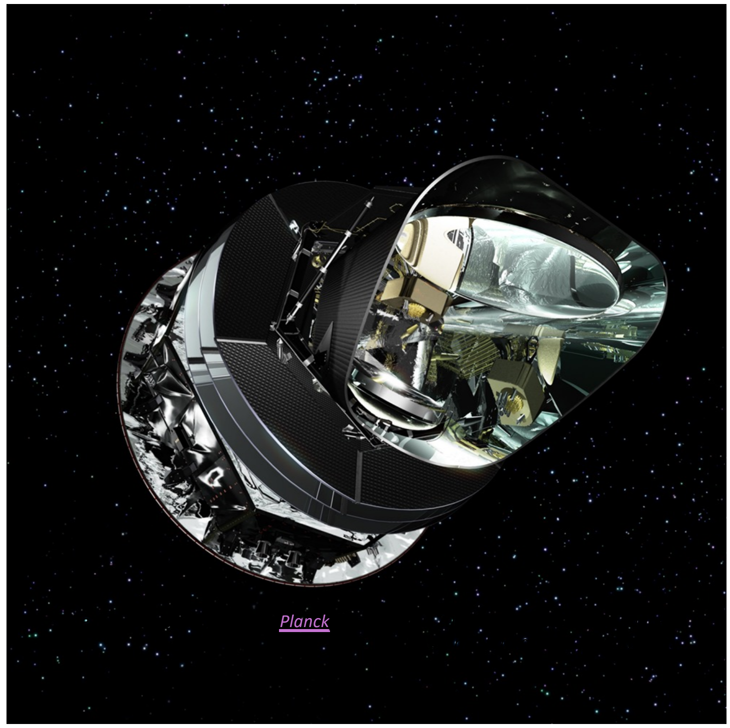
Direct measurements of the Universe's curvature: it is flat from here to decoupling

External exponential expansion driven by dark energy

The Milky Way's lonely future

Last chance to learn the Universe's origin?





*Planck*

# THE MASS-DENSITY OF THE UNIVERSE

- If the Universe is matter-dominated ($\Omega_\Lambda = 0$), then, if $\Omega_M = 0.3$, its curvature is negative, it is open, and it will continue to expand.
- It is, however, a strong theoretical prediction of many models of elementary particles and of the early Universe, especially those involving **inflation**, that $\boldsymbol{\Omega_0}$ **should be exactly 1**, and that for some unknown reasons the present measurements of $\Omega_M$ are faulty. Observers and theoreticians used to argue about this incessantly.
- There are **no good experimental results or theoretical arguments to suggest that the Universe is matter-dominated and closed**. We do not think that our Universe is a black hole.

# AGE OF MATTER-DOMINATED UNIVERSES

A general result of the solutions for matter-dominated universes is that the age is always given, in terms of the present value of the Hubble "constant," as

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

where the value of $A$ 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, and closed universes have values of $A$ smaller than 2/3.
- Jargon: $\mathrm{t} = 1/H_0$ is often called "one **Hubble time**"
- If $\Omega_M$ is assumed to be much smaller than 1, the age would be

$$t = \frac{1}{H_0} = \frac{\mathrm{s\ Mly}}{20\ \mathrm{km}} = \frac{(\mathrm{s})(10^6)(3\times10^5\ \mathrm{km/s})(\mathrm{yr})}{20\ \mathrm{km}} = 1.5\times10^{10}\ \mathrm{yr}$$



# AGE OF MATTER-DOMINATED UNIVERSES

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

$$t = \frac{2}{3}\frac{1}{H_0} = 1.0\times10^{10}\ \mathrm{yr}$$

- For the best experimental value, $\Omega_M = 1/3$, we get

$$t = 1.2\times10^{10}\ \mathrm{yr}$$

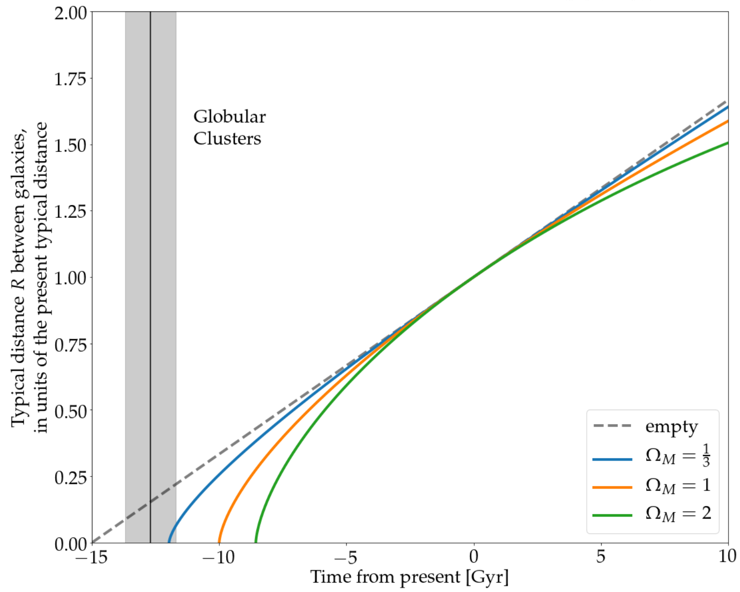
Other constraints on the age of the Universe, independent of density determinations:

- We know that the Universe must be older than the Solar System, which is $4.6\times10^9$ years old, so an age of $1.2\times10^{10}$ years would be OK here.
- The ages of white dwarf stars and globular star clusters turn out to be accurately measurable; the oldest of these are $1.2\times10^{10}$ years old ($\pm$ about $0.1\times10^{10}$ years).

**This agrees with $\boldsymbol{\Omega_M = \frac{1}{3}}$** (though smaller would be more comfortable), **and is in conflict with $\boldsymbol{\Omega_M = 1}$.**

## AGE OF MATTER-DOMINATED UNIVERSES

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

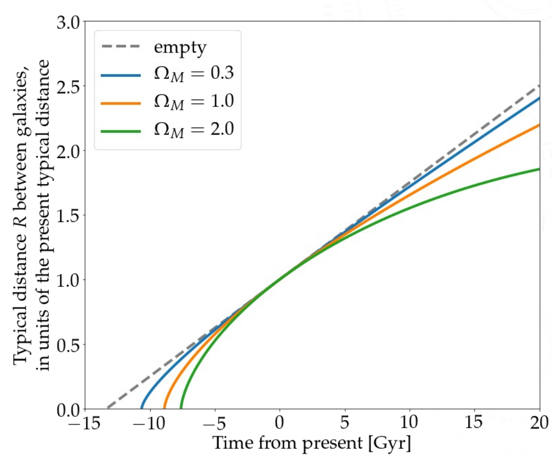





## MEASUREMENT OF THE ACCELERATION OF DISTANT GALAXIES

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

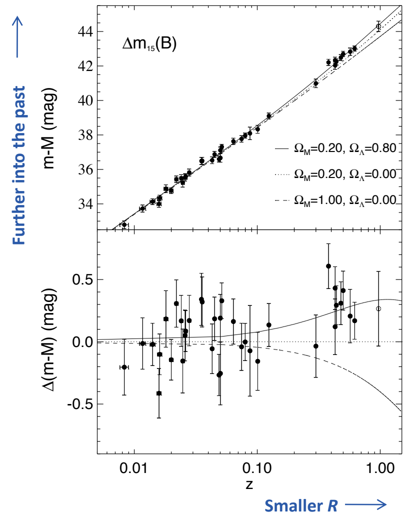
- Looking back through time at distant galaxies, the shape of $R$ vs. $t$ can be measured if the distances can be measured accurately enough.
- The **slope** of the curves ($\frac{R}{R_0}$ vs. $t$) at the present time turns out to simply be the Hubble constant.
- If the universe contains only matter ($\Omega_\Lambda = 0$), then this relationship curves 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

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

To the great surprise of most astronomers, very distant SN 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** $H_0$.

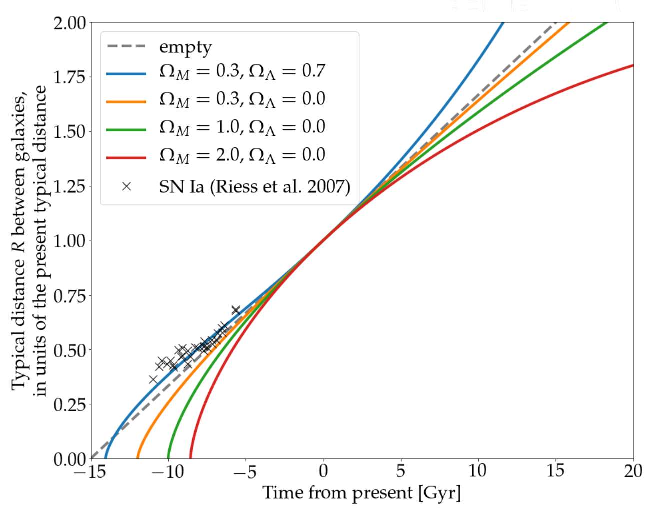



*Riess et al. (1998)*
*Perlmutter et al. (1999)*



# MEASUREMENT OF THE ACCELERATION OF DISTANT GALAXIES

Those who observed these galaxies 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.



# MEASUREMENT OF THE ACCELERATION OF DISTANT GALAXIES

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

- Most of the controversy had to do with the assumption that SN 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 you look back further into the past.
- In principle, this can alter the amount of light given off by a SN Ia, and even the direction that the light is beamed, and the physics of these blasts is sufficiently complicated that theoretical models of them have not been conclusive.



# MEASUREMENTS OF THE CURVATURE OF SPACE

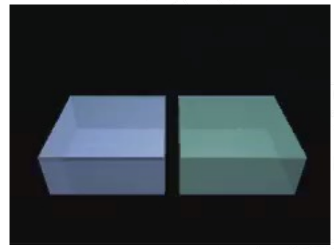
No one really fussed about the acceleration controversy too much, though, because measurements of the **curvature of space** between here/now and the epoch of decoupling were on the horizon.

- Acceleration enthusiasts and detractors alike looked forward to these new measurements as conclusive, as they would determine $k$ and $\Omega_0$ 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.
- 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.

# MEASUREMENTS OF THE CURVATURE OF SPACE

The small angular-scale anisotropies in the CMB provide the means to measure the curvature of the Universe rather directly.

- 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. 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 CMB is a snapshot of the final state of these bubbles, and the anisotropies outline these bubbles.

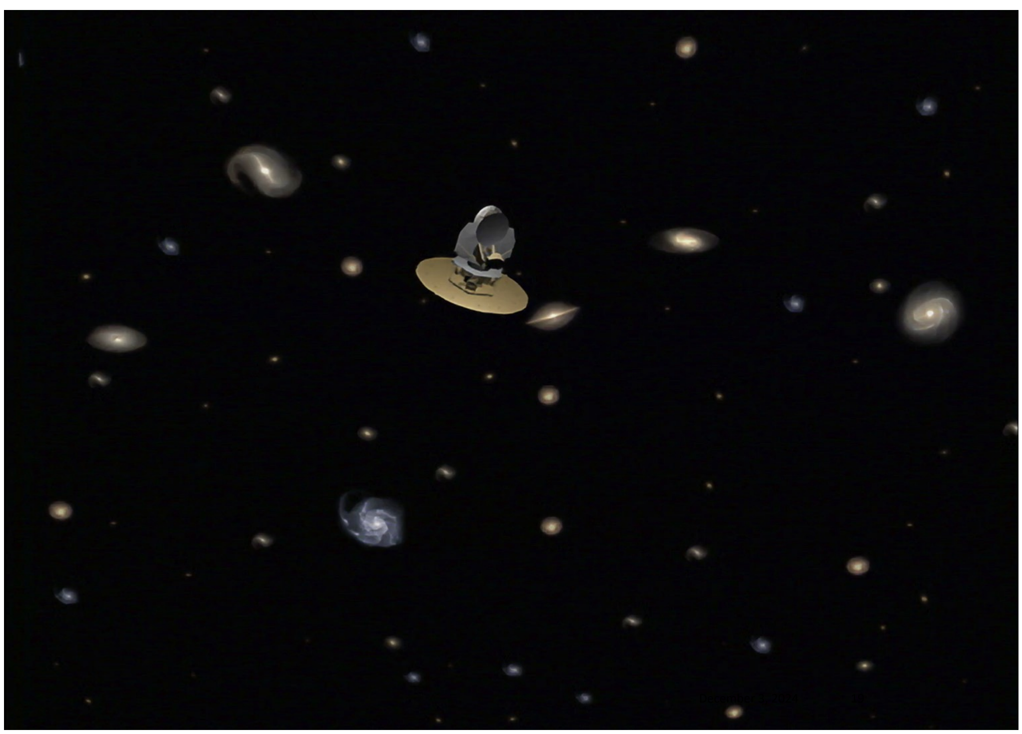


*Animation courtesy of NASA and the WMAP science team.*



# MEASUREMENTS OF THE CURVATURE OF SPACE

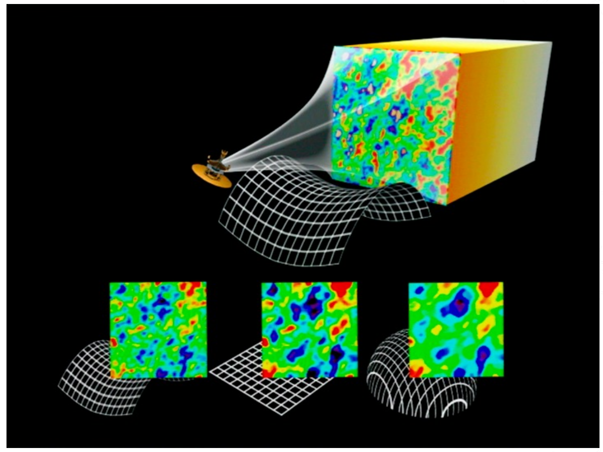
*Animation courtesy of the WMAP Science Team (NASA/GSFC).*

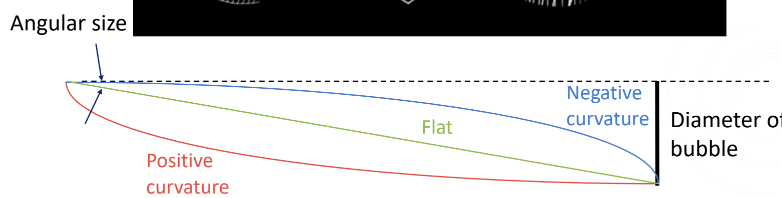


## MEASUREMENTS OF THE CURVATURE OF SPACE

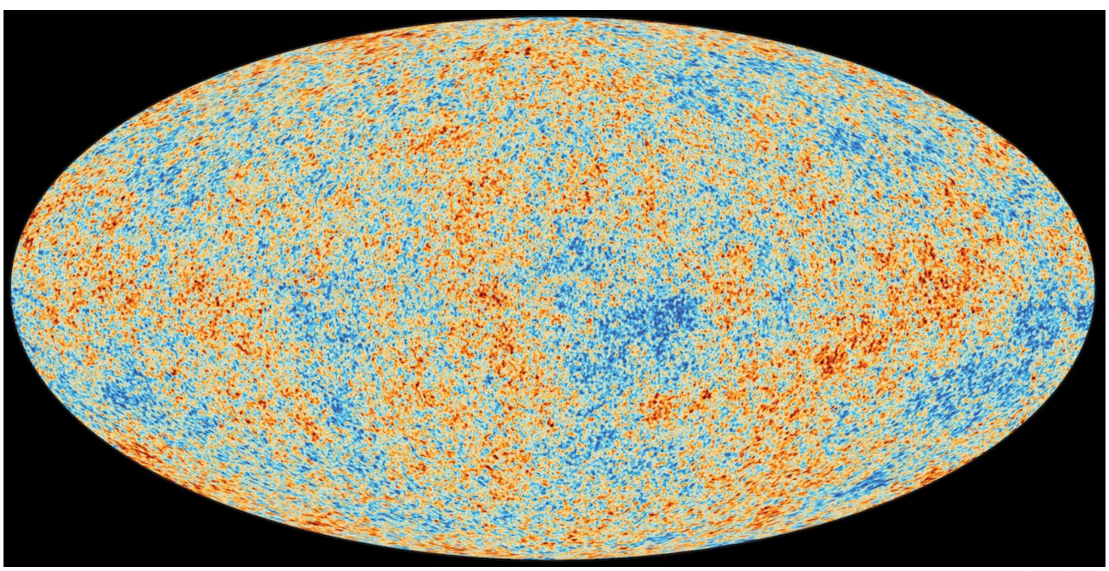
It turns out that the bubbles that are the most numerous are the ones that have only gone through half an oscillation between the Big Bang and decoupling. Their diameters can be precisely calculated (we know the speed of sound and the speed of light.)

By observing their angular size and knowing their diameters, we can determine the curvature of space between decoupling and the present.







## MEASUREMENTS OF THE CURVATURE OF SPACE

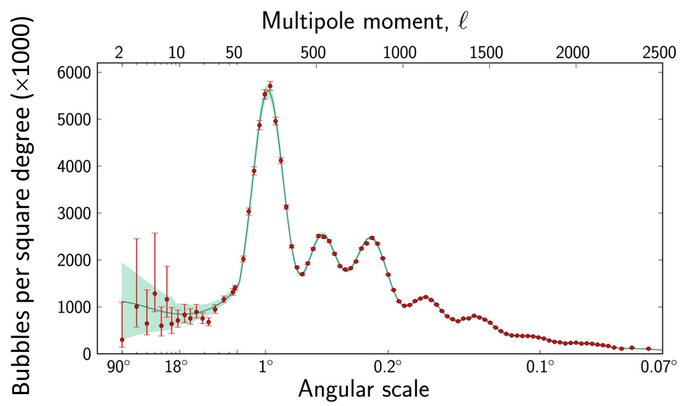
Map of the sky (plane of the Milky Way along the equator) on scales small enough to measure curvature for all current models of the Universe, by Planck.

## MEASUREMENTS OF THE CURVATURE OF SPACE

Result: $k = 0$ – **the Universe is flat** – so $\Omega_0 = \Omega_M + \Omega_\Lambda = 1$

Red points: results from Planck ($\Omega_M = 0.3$).

In **green**: expectations for $\Omega_\Lambda = 0.7$, $H_0 = 22$ km/s/Mly

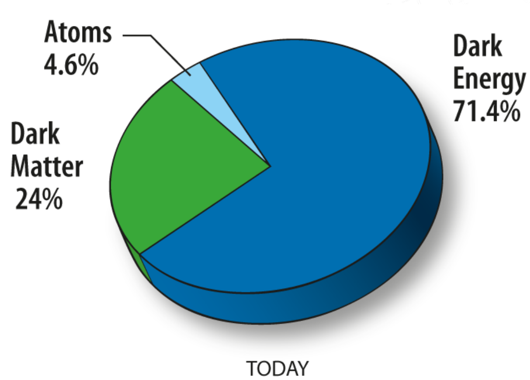





# MEASUREMENTS OF THE CURVATURE OF SPACE

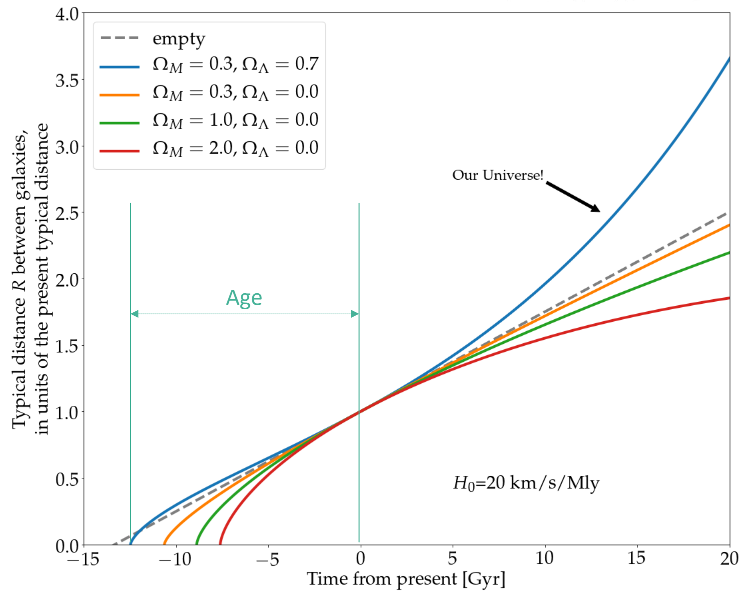
**How did the Universe come to be flat?**

- We know that $\Omega_M = \frac{1}{3}$: There is not enough matter in the Universe to make it flat.
- The **simplest** explanation seems to be dark energy, in the amount $\Omega_\Lambda = 1 - \Omega_M$.
- As discussed above, this would also account for the apparent acceleration of the Universal expansion seen in the high-redshift SN Ia results.



## AGE OF THE FLAT UNIVERSE

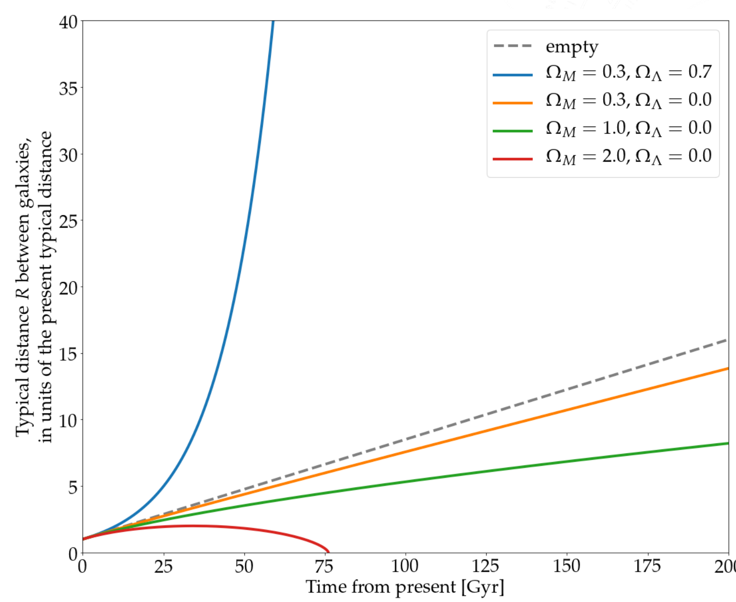
Our expanding universe compared to the matter-dominated models. Its present age turns out to be $\mathbf{1.4 \times 10^{10}}$ **years**.






## FATE OF THE FLAT UNIVERSE

The flat universe is open and expanding exponentially; in just a few Hubble times, most of the Universe that 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 $1.2\times10^{10}$ 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 $\mathbf{1.4\times10^{10}}$ years old (14 billion years).**



## 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 entire story:

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

# ASSUMING THAT THIS IS TRUE…

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, me, 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.
  - Eventually, 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.
- It will eventually be impossible to even verify the origins of the Universe.
  - The CMB will become so extremely redshifted – its temperature becoming so close to absolute zero – that it will become impossible to detect.
  - No galaxies in view: no Universal expansion to characterize.



# ASSUMING THAT THIS IS TRUE…

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 indemonstrable and come to be regarded as fables.