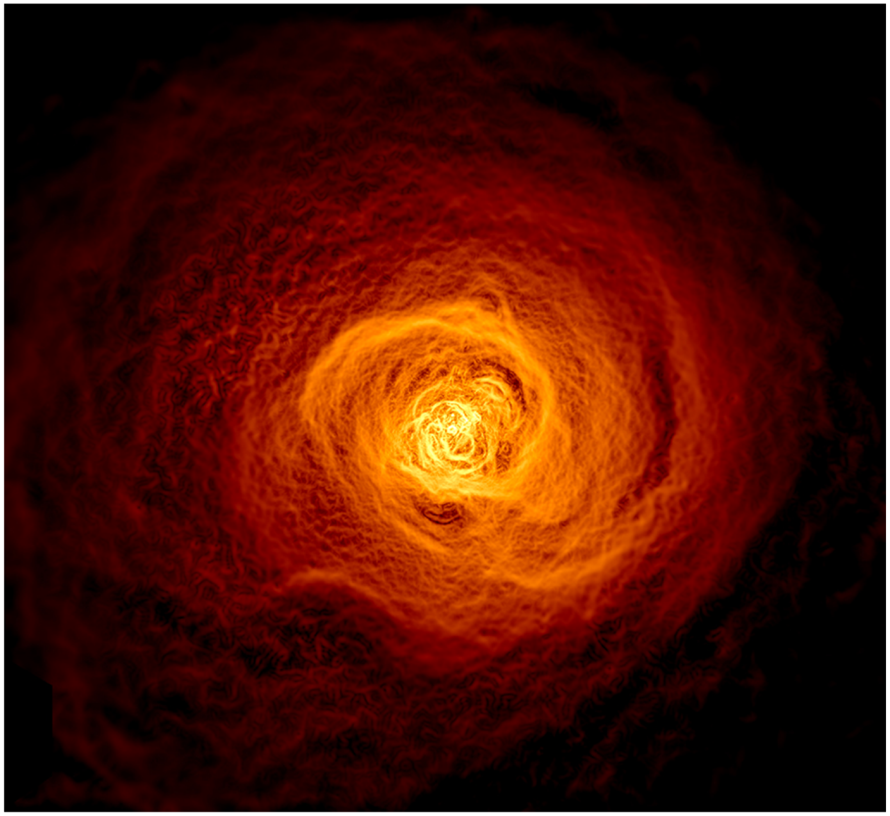
[27] Dark Energy and the Fate of the Universe (5/10/18)

Upcoming Items

1. Review for final: tomorrow (Friday), 1-3 PM, normal classroom
2. Final exam: 8-10 AM Saturday, May 12, normal classroom
3. Good luck!

APOD 5/4/17

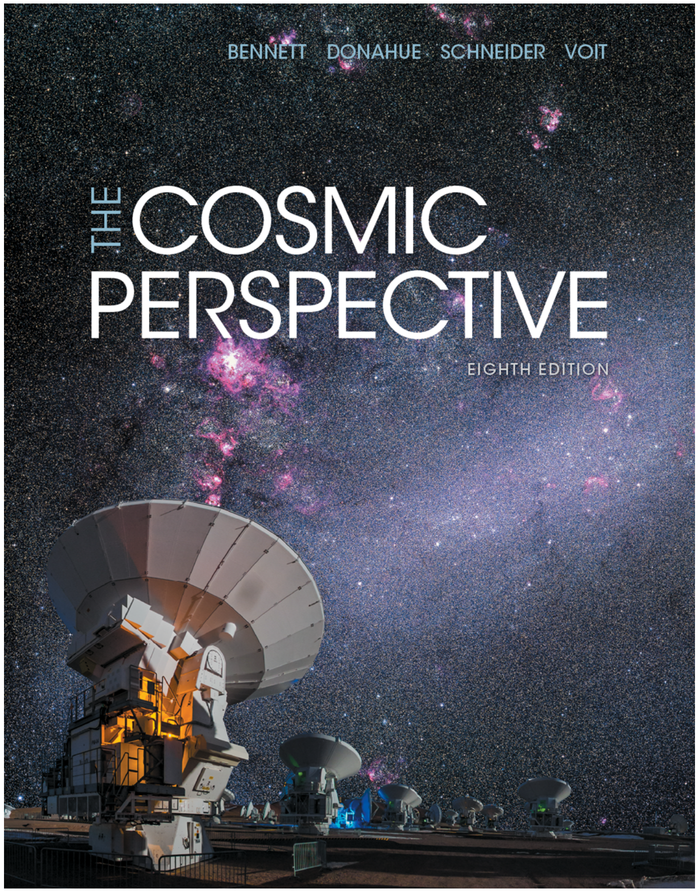


LEARNING GOALS

Ch. 23.4

For this class, you should be able to…

- … *deduce the scale factor of the universe given a redshift and vice versa;*
- … *sketch how the scale factor varies with time in the four expansion models (recollapsing, critical, coasting, and accelerating), and order the models by relative age of the universe at the present time;*
- … *describe the evidence for an accelerating universe and the need for "dark energy";*
- … *predict the fate of our universe based on its dark matter and dark energy content.*



Any astro questions?

Dark Energy and the Fate of the Universe

- Evolution of universe determined by competition between cosmological expansion and gravitational attraction.
  1. Recollapsing universe (“Big Crunch”), youngest age.
  2. Critical universe (matter dominated, density = critical density).
  3. Coasting universe (expansion continues without slowing).
  4. Accelerating universe (implies dark energy), oldest age.
- Formalize expansion models by considering scale factor, Hubble parameter, critical density, and density parameter.
- White dwarf supernovae imply expansion was slower in the past ➔ dark energy. But what is it?
- Will the universe end in darkness?…

You'll be sort of surprised what there is to be found
Once you go beyond Λ *and start poking around.*

—adapted from Dr. Seuss, "On Beyond Zebra"

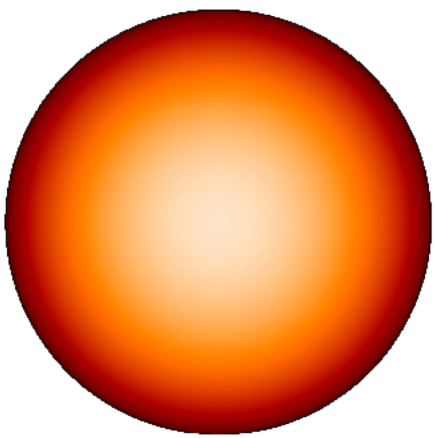
The Big Questions about Our Universe

- What are the contents of our universe?
  - What is the average density?
  - How much normal matter, dark matter, radiation, etc. is there?
- What is the geometry of our universe?
  - Spherical, flat, or hyperbolic?
  - What does that even mean?

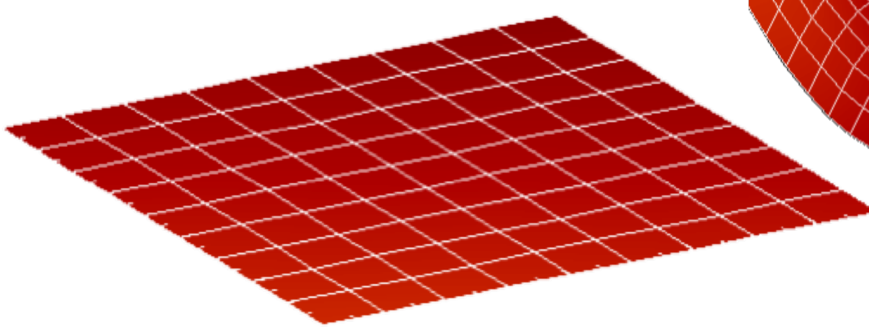
  From previous lectures, the answer appears to be: flat.
- What is the history of our universe?
  - How does the size (scale factor) change with time?
  - How old is our universe?
  - What is its eventual fate?

Review: The Geometry of Space

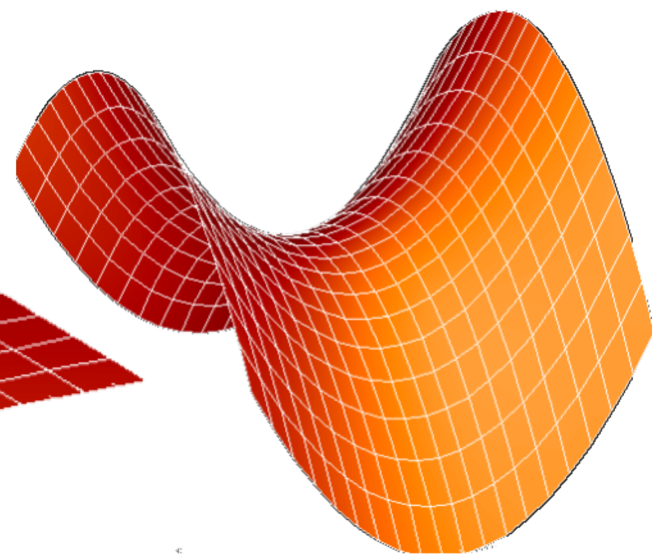
- There are only three possibilities for the geometry of space: spherical, flat, and hyperbolic.
  - In order to visualize it, we cannot think of the 3-D curved space… we need to "project" it down to 2-D.



Spherical
(finite volume)



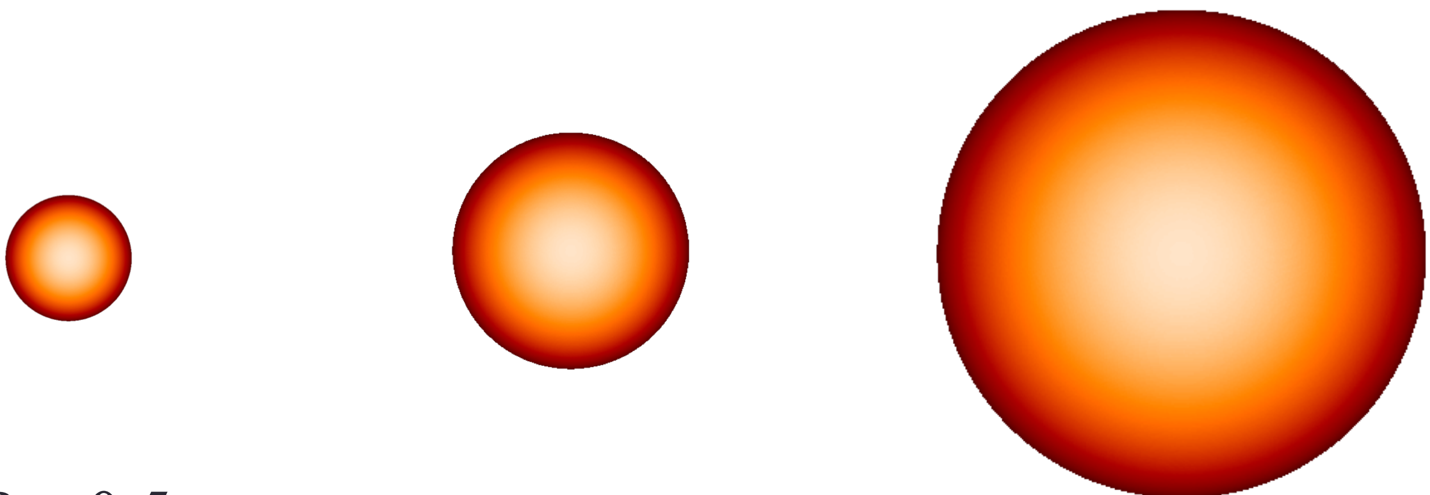
Flat
(infinite volume)



Hyperbolic
(infinite volume)

The Cosmological Scale Factor

- The scale factor R tells you how "stretched out" space is.
  - Allows you to talk about expansion and contraction of the universe (even if universe is infinite).
- Simplest example is the spherical case.
  - Scale factor is just the radius of the sphere.



$R = 0.5$ $\quad$ $R = 1$ $\quad$ $R = 2$

Recall Hubble's Law Within the Standard Cosmological Models

- Fundamentally new way to look at Hubble's law…
  - *Redshift is not due to speed of galaxies.*
  - Galaxies are (approximately) stationary in space…
  - **Galaxies get further apart because the space between them is stretching (expanding)!**
  - The expansion of space also affects the wavelength of light… as space expands, the wavelength expands and so there is a redshift.

- So, cosmological redshift is due to cosmological expansion of wavelength of light, not the regular Doppler shift from galaxy motions.

Relation Between z and $R(t)$

- The redshift of light from a galaxy is given by

$$z = \frac{\lambda_{\text{obs}} - \lambda_{\text{emit}}}{\lambda_{\text{emit}}}.$$

- Using the cosmological view of redshift, we write

$$\lambda_{\text{obs}} = \left(\frac{R_{\text{now}}}{R_{\text{then}}}\right)\lambda_{\text{emit}}.$$

- So, we have…

$$z = \frac{R_{\text{now}}}{R_{\text{then}}} - 1.$$

Hubble's Constant Revisited

- The "Hubble parameter" is given by

$$H = \frac{\text{speed}}{\text{distance}} = \frac{1}{R}\frac{\Delta R}{\Delta t} = \frac{1}{R}\frac{dR}{dt} = \frac{\dot{R}}{R}.$$

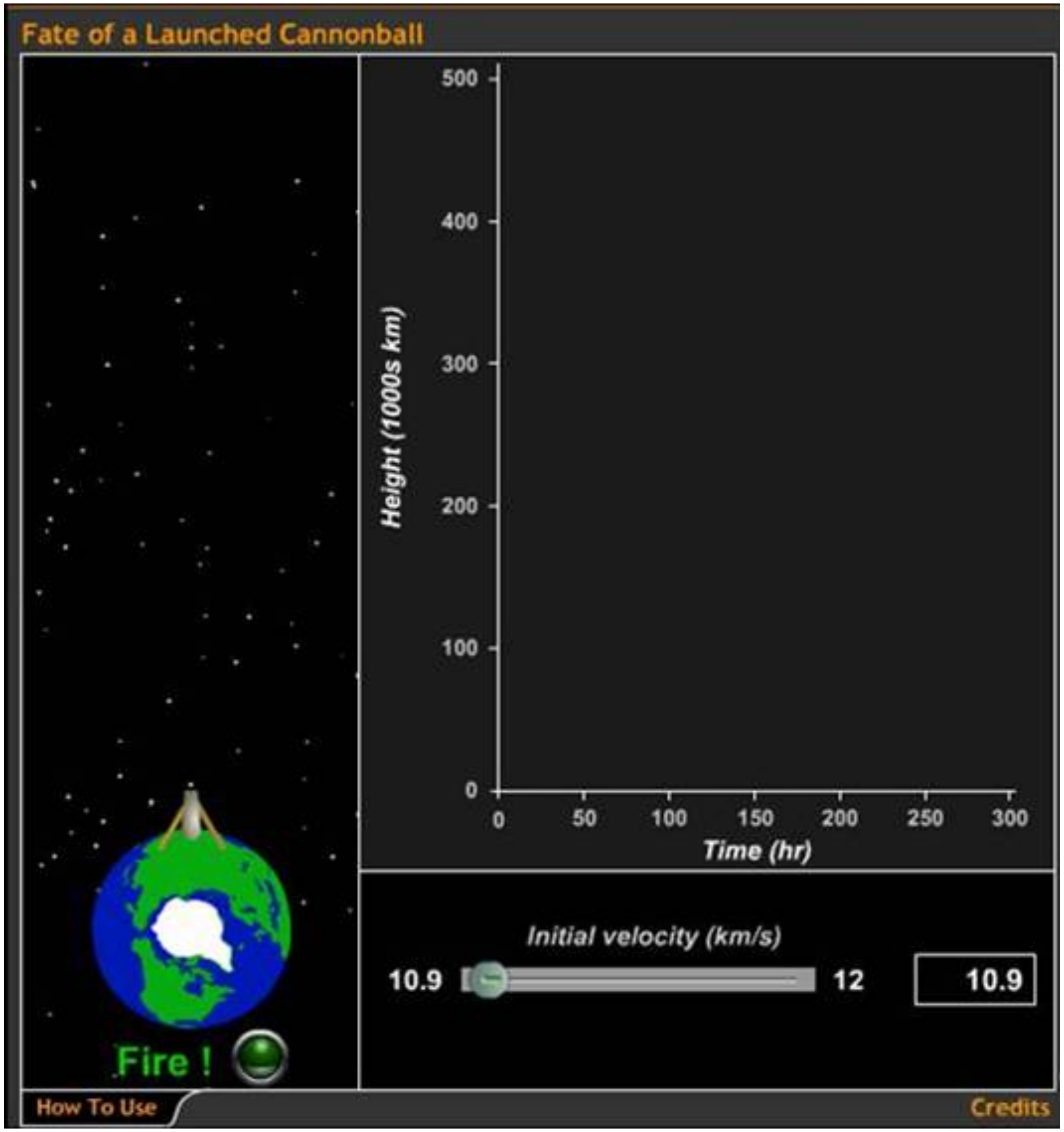
- The value of the Hubble parameter today, H_0, is the Hubble constant.
- Hubble's law lets us translate redshift ("velocity") to lookback time (distance), but it only holds while the expansion rate is constant.
- To determine distances for higher redshifts, we need to know $R(t)$…

Einsteinian Cosmology

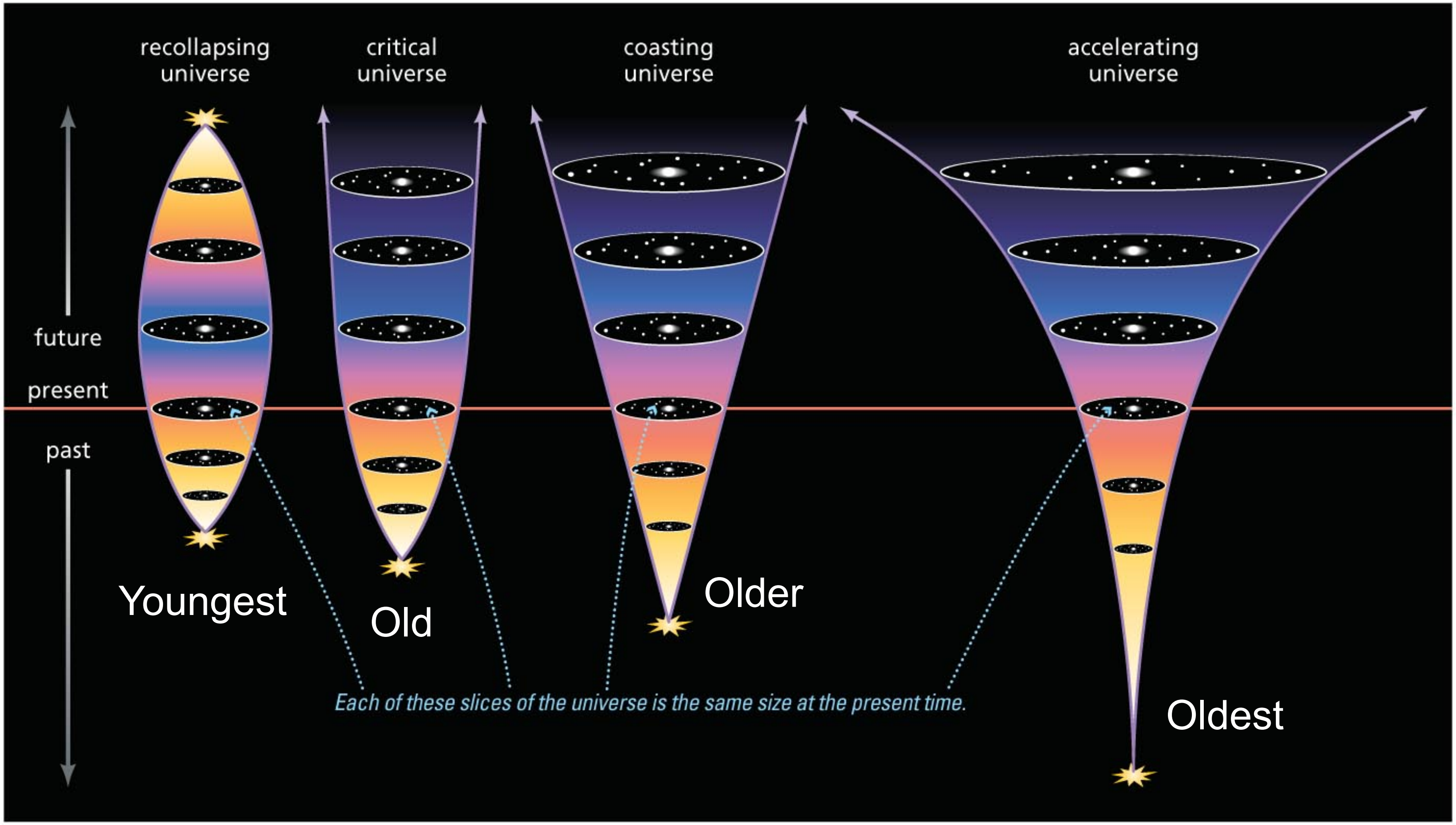
- What determines the geometry and how the universe expands or contracts?
  - Einstein's general relativity equations show that the geometry depends upon the total density of the universe.
  - Given a geometry, Einstein's equations predict how the scale factor changes with time, i.e., they determine the function $R(t)$.

Einsteinian Cosmology

- So what did Einstein find?
  - He managed to find a solution to his equations that were both homogeneous and isotropic.
  - BUT he found that any such solution represented a universe that was either in a state of collapse or expansion!
- Then Einstein made a mistake…
  - He could have predicted that the universe was either expanding or contracting several years before Hubble found it.
  - But, he let himself be led by the “common knowledge” that the universe was static (so something must hold it up against its own gravity).
  - He modified his equations (adding the “cosmological constant”) to make such a static solution possible.
  - Later called this his “greatest mistake.”
- However, Einstein did lay the foundations for all modern **cosmological models**.



Does the universe have enough kinetic energy to escape its own gravitational pull?



- The fate of the universe and its estimated age depend on the abundances of matter and dark energy.

The Critical Density

- Combining GR with the cosmological principles gives the density that determines the geometry of the universe:

$$\rho_{crit} = \frac{3H^2}{8\pi G}.$$

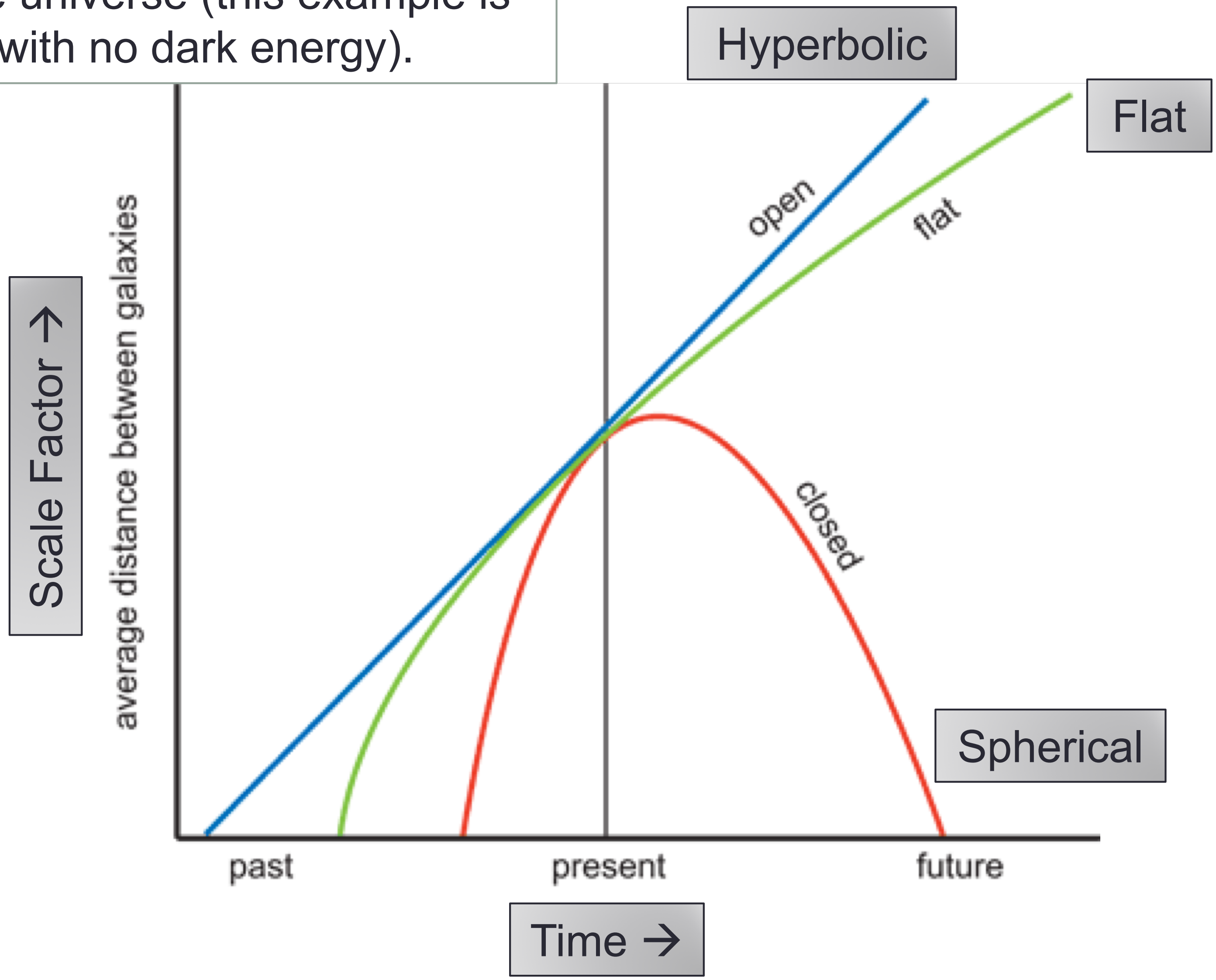
For $H = H_0 \sim 70$ km/s/Mpc, $\rho_{crit} \sim 1.0\times10^{-26}$ kg/m^3.

- Define the "density parameter" as the true density of the universe divided by the critical density:

$$\Omega = \frac{\rho}{\rho_{crit}}.$$

- $\Omega > 1 \Rightarrow$ Spherical (and recollapsing if no dark energy).
- $\Omega = 1 \Rightarrow$ Flat (and asymptotic if no dark energy).
- $\Omega < 1 \Rightarrow$ Hyperbolic (and coasting if no dark energy).

A plot of scale factor vs. time shows the history of the universe (this example is for the case with no dark energy).



The Observations

- Let’s take a census of mass in the universe… we will phrase all densities as fractions of the critical density.
- Normal (“baryonic”) matter…
  - Primordial nucleosynthesis $\Rightarrow \Omega_B \sim 0.05$ (saw this previously).
  - Stars account for 10–25% of this.
  - Rest of the baryonic mass is in gas.
- Dark matter…
  - Galaxy dark matter halos, and dark matter in groups and clusters: $\Omega_{DM} \sim 0.25$.
  - This is much more than the density of baryonic matter allowed from primordial nucleosynthesis… so most of the dark matter must be non-baryonic.
- So… best guess is that $\Omega \approx 0.3$.

What about the radiation density?

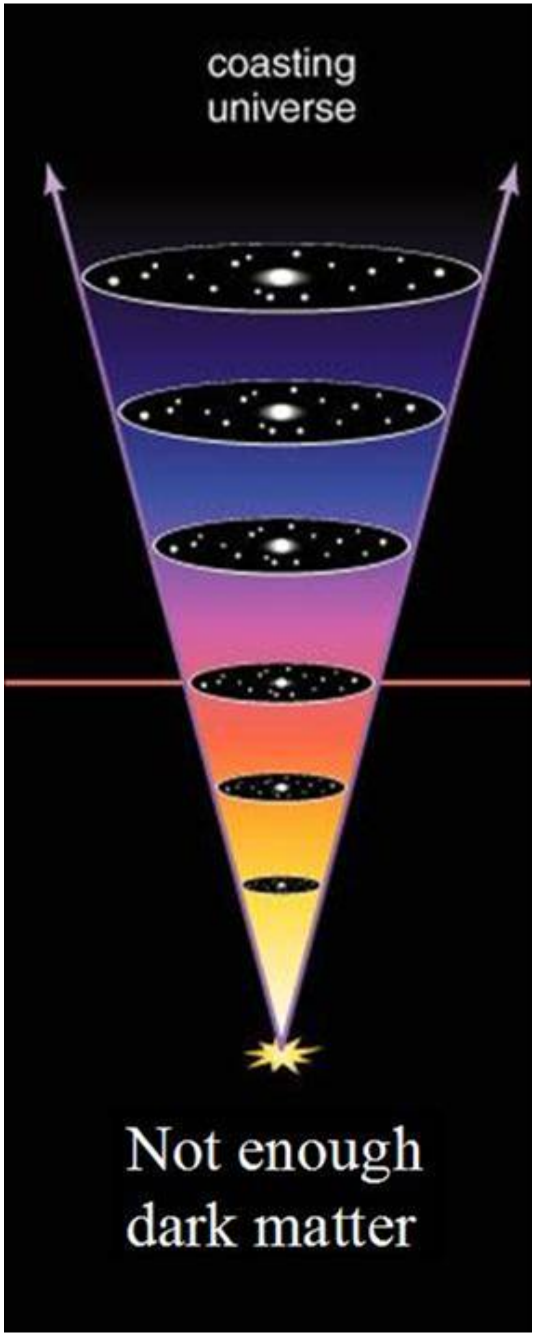
- From $E = mc^2$, we know energy is equivalent to mass, so it should contribute to the total matter density.
- From the Stefan-Boltzmann law, the radiated power from a given volume is related to the energy density by

$$F = \sigma T^4 = \frac{c}{4} \times (\text{energy density}).$$

(the factor of $c/4$ comes from geometrical considerations).

- So mass density $\rho = (\text{energy density})/c^2 = 4\sigma T^4/c^3$.
- The present temperature of the universe is $T = 2.725$ K (microwave background), giving $\rho_{\text{rad}} = 4.6\times10^{-31}$ kg/m^3.
- Compare this to $\rho_{\text{matter}} \sim 4\times10^{-28}$ kg/m^3 (only about 0.2 H atoms per cubic meter!) ➔ ρ_{rad} irrelevant today.

- Since the density of matter is ~30% of the critical density, we expect the expansion of the universe to overcome its gravitational pull.

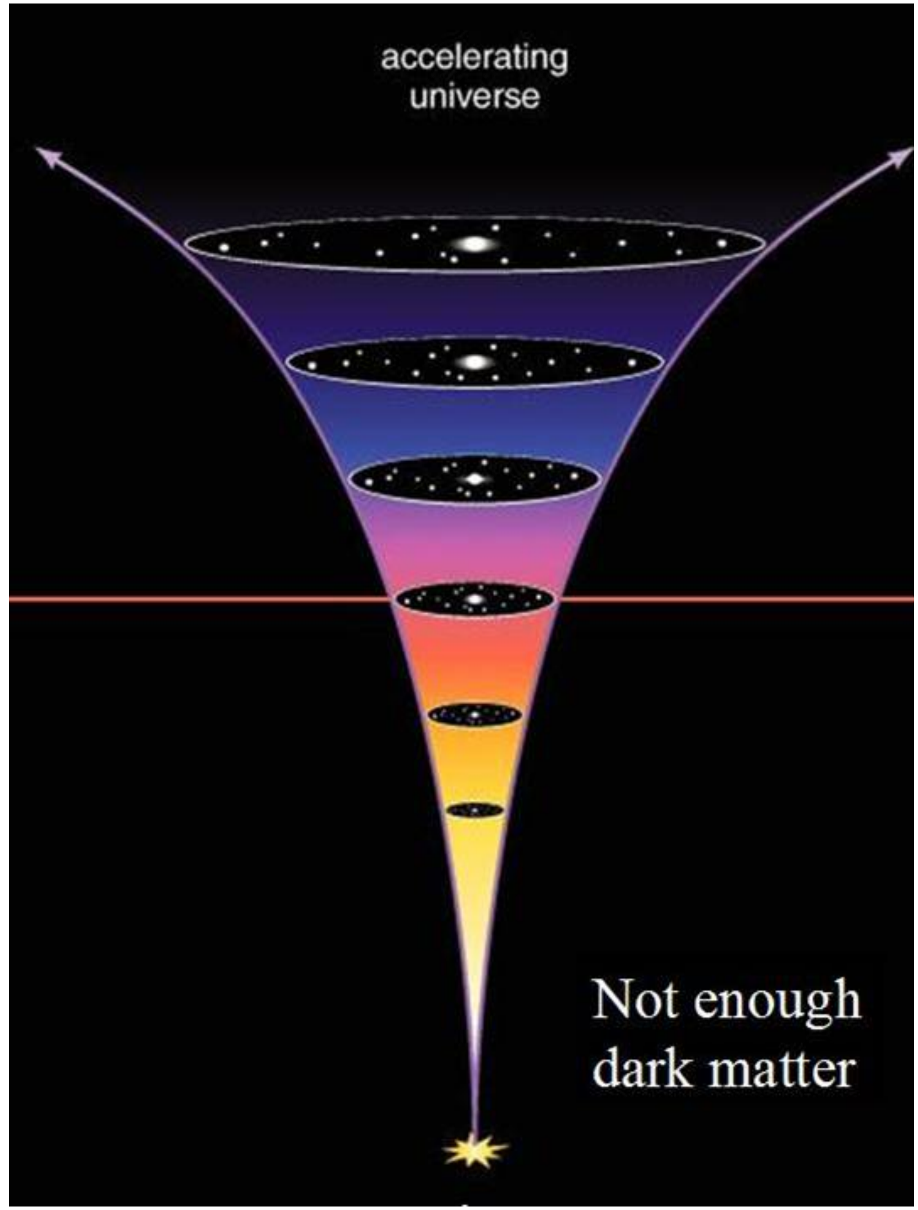


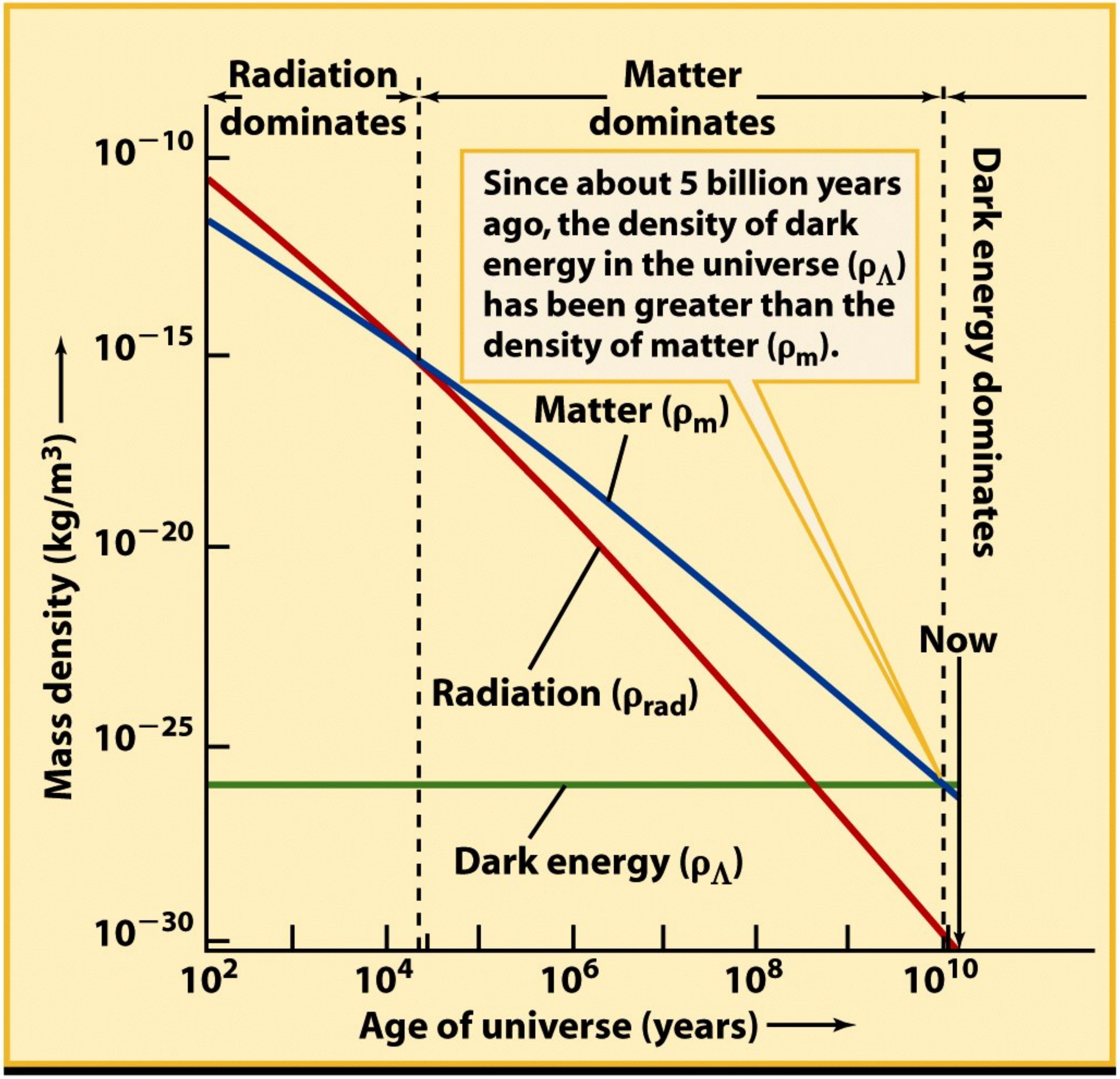
The Acceleration of the Universe

- Another way of looking at this:
  - As we saw previously, observations of the universe suggest it has a flat geometry (meaning parallel lines stay parallel), with density parameter $\Omega = 1.00 \pm 0.01$.
- So, we seem to have a problem…
  - Our census of the mass that we see in the universe gives $\Omega \approx 0.3$.
  - But the geometry of the universe is flat, suggesting that $\Omega \approx 1.0$.
  - Something is wrong/missing!
- The missing ingredient was discovered in the late 1990s.
- Observations of distant white-dwarf supernovae (SN1a) showed that the expansion of the universe is accelerating: a new component to Ω.

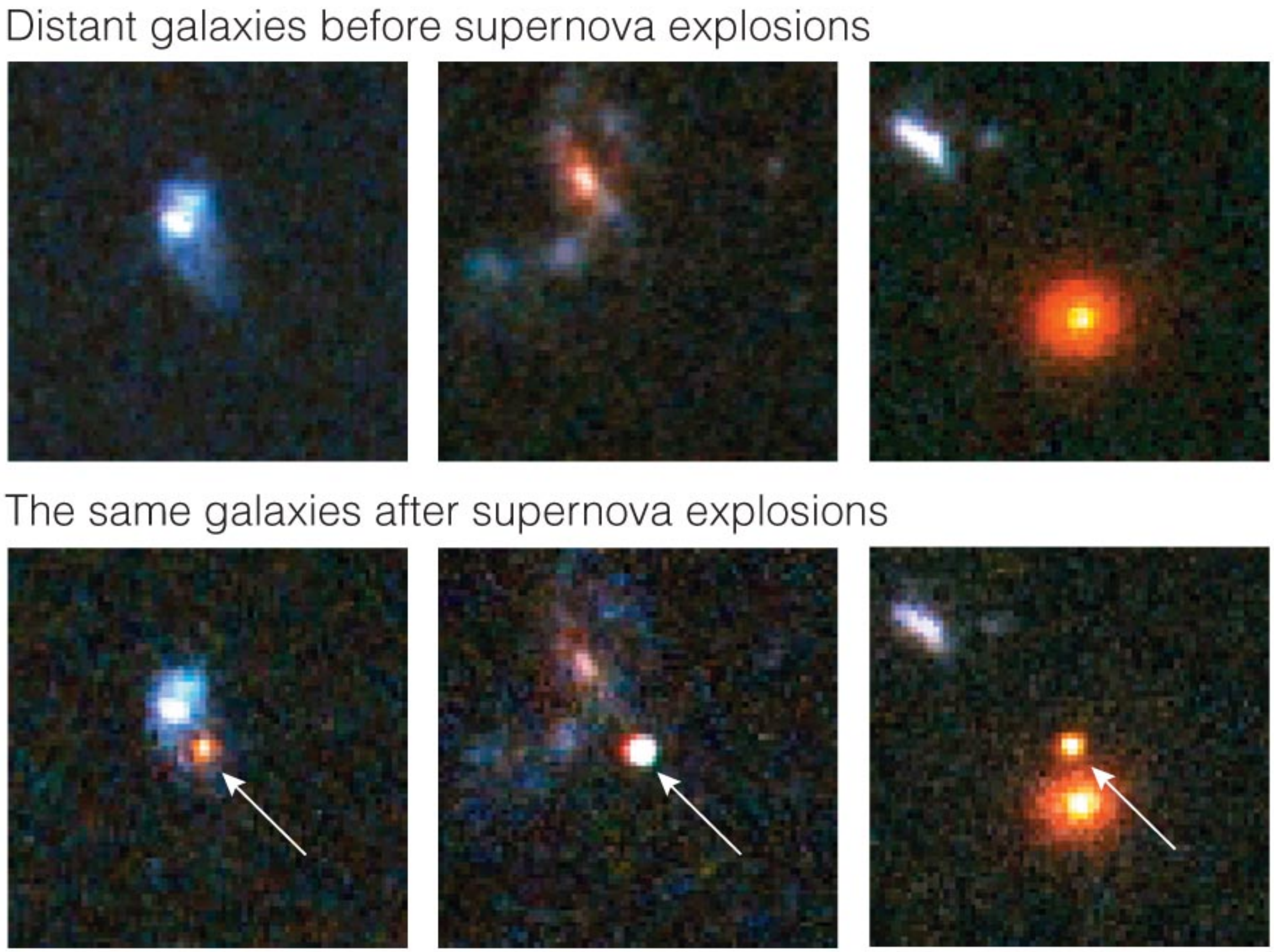
In fact, the expansion appears to be speeding up!

Dark energy?



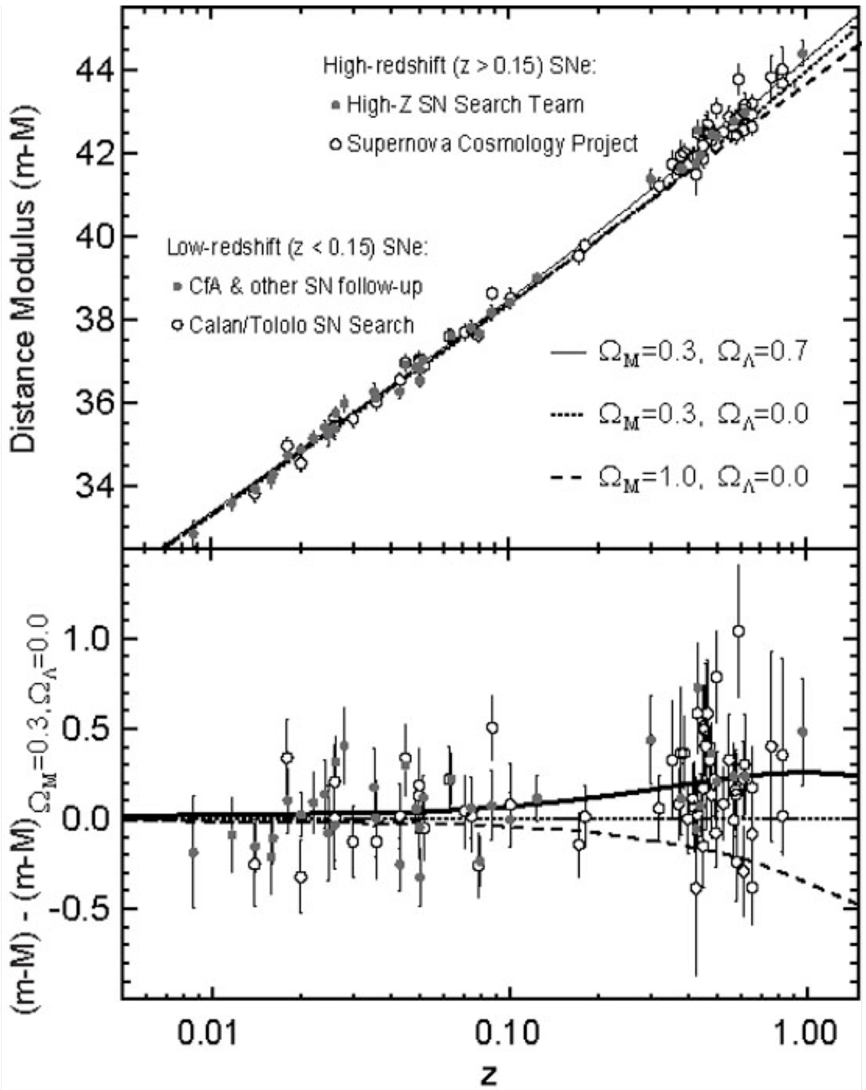


Radiation dominates
Matter dominates
Dark energy dominates
Since about 5 billion years ago, the density of dark energy in the universe (ρ_Λ) has been greater than the density of matter (ρ_m).
Matter (ρ_m)
Radiation (ρ_{rad})
Dark energy (ρ_Λ)
Now
Mass density (kg/m^3)
10^{-10}
10^{-15}
10^{-20}
10^{-25}
10^{-30}
10^2
10^4
10^6
10^8
10^{10}
Age of universe (years)

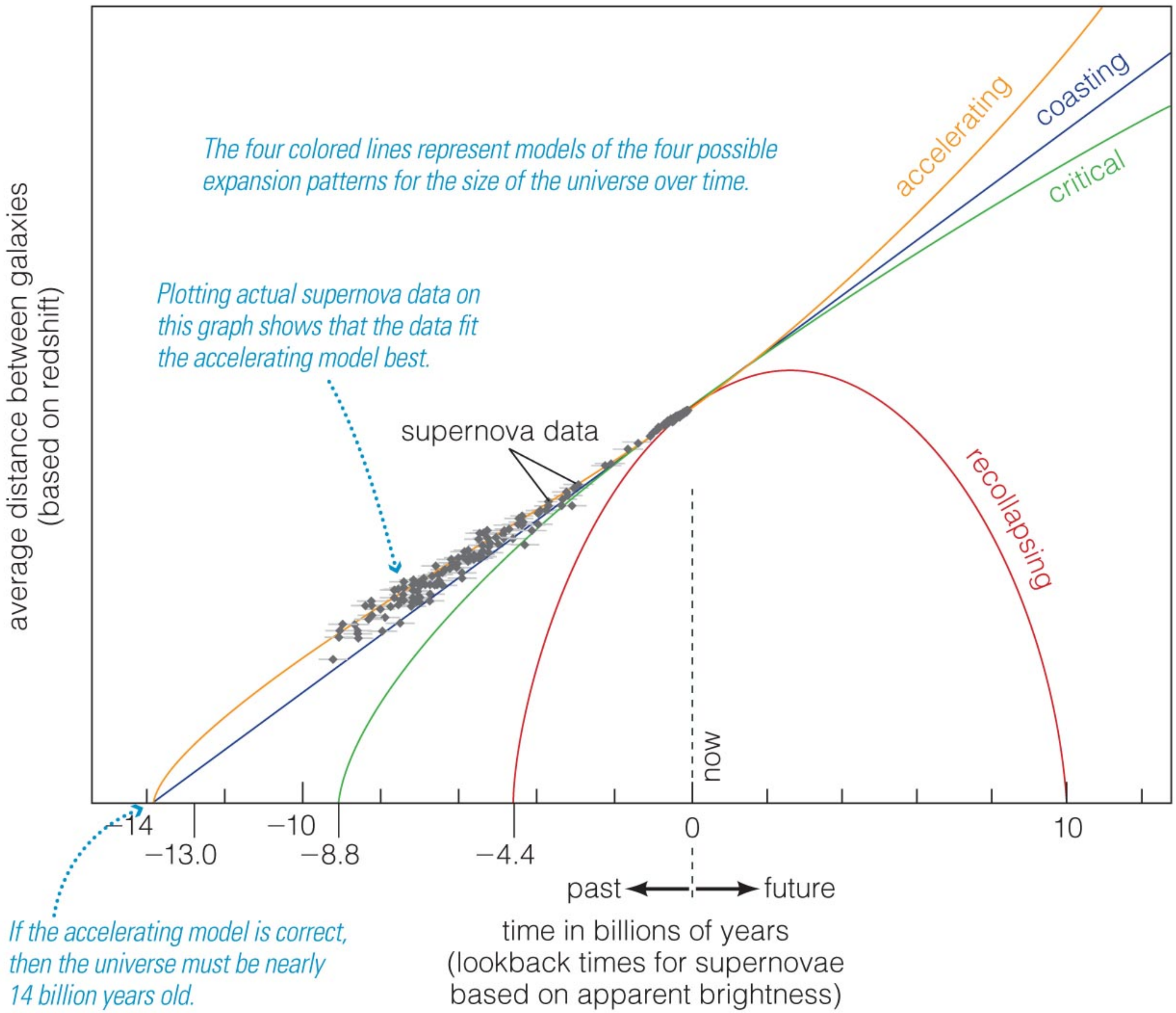


The brightness & z of distant white dwarf supernovae tell us how much the universe has expanded since they exploded.

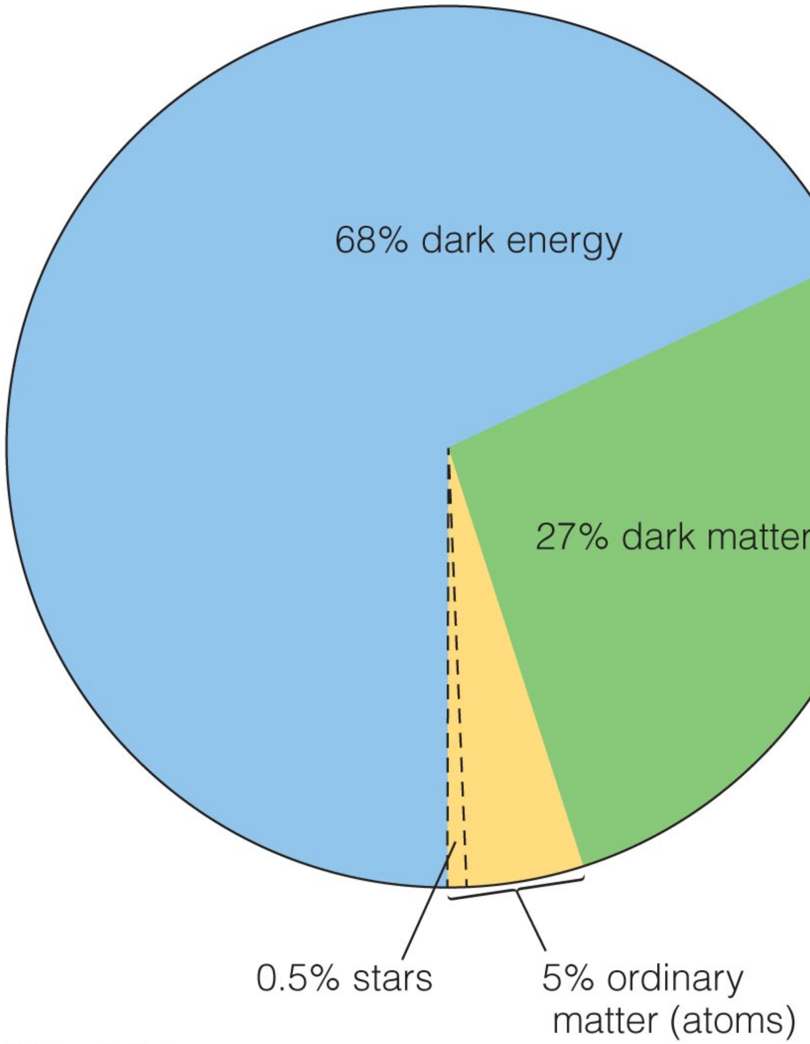
White-dwarf Supernovae Data



- Photons from the most distant supernovae are less redshifted than we would expect from today's expansion rate.
- The universe was expanding at a *slower* rate in the past.



- An accelerating universe best fits the supernova data.

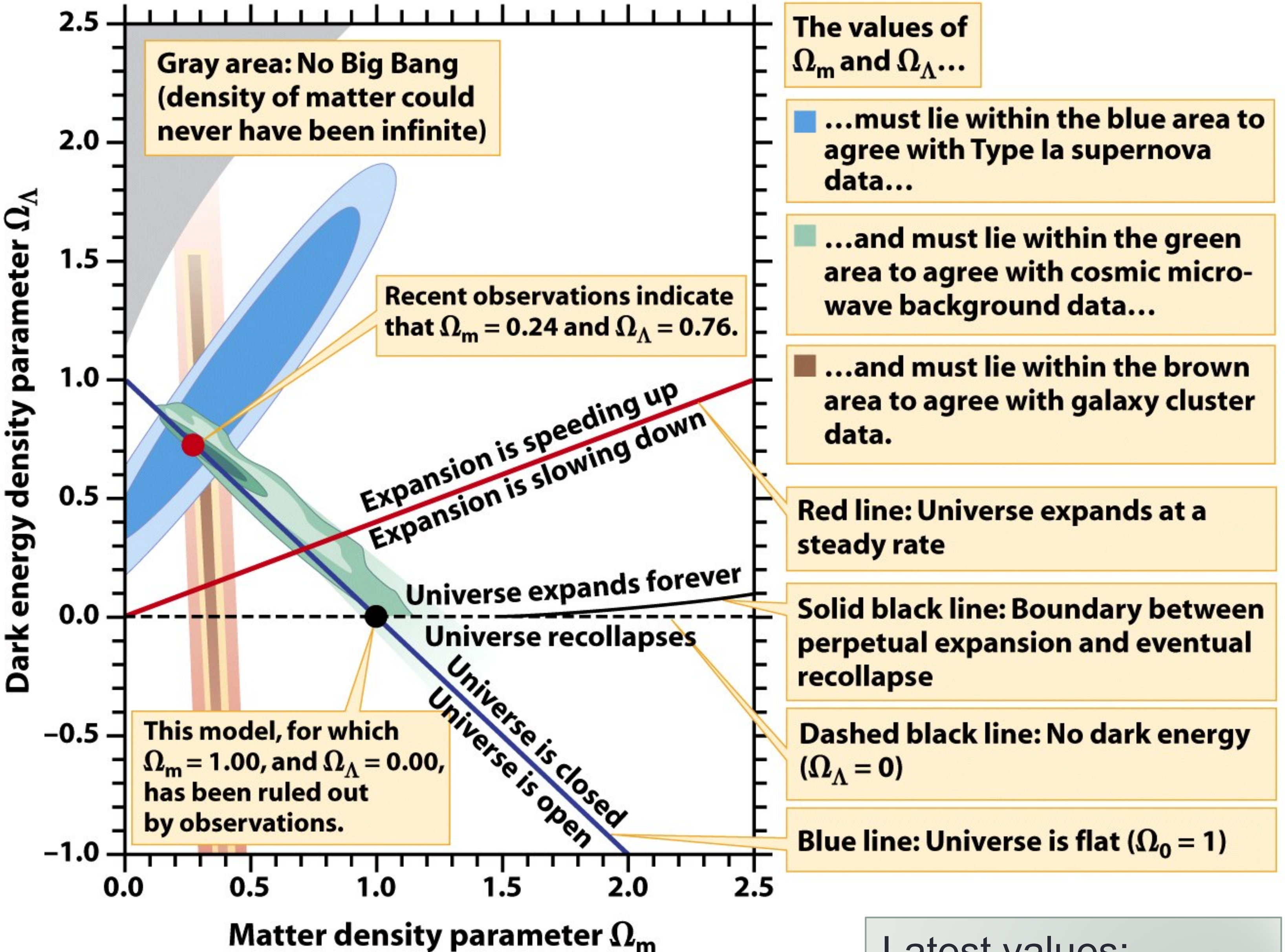


- Measurements of the cosmic microwave background indicate that the universe has a flat geometry, thus dark energy is needed to fill out the remaining mass-energy.

The Acceleration of the Universe

- What's causing the acceleration? Two possibilities…
  1. Our understanding of gravity is wrong, and GR needs to be modified on cosmological scales.
  2. There is a new kind of "stuff" that is pushing the universe apart (***dark energy***).

- If you work out the mass equivalent of the required amount of dark energy, get $\Omega_{\mathrm{DE}} \approx 0.7$.
  - Adding in the contribution from matter, $\Omega_{\mathrm{m}} \approx 0.3$, this is just the right amount to make the universe flat.
  - The basic nature of dark energy is a profound mystery. If it's due to the cosmological constant Λ, $\Omega_{\mathrm{DE}} = \Omega_{\Lambda}$.



Latest values:
$\Omega_m = 0.31$, $\Omega_\Lambda = 0.69$.