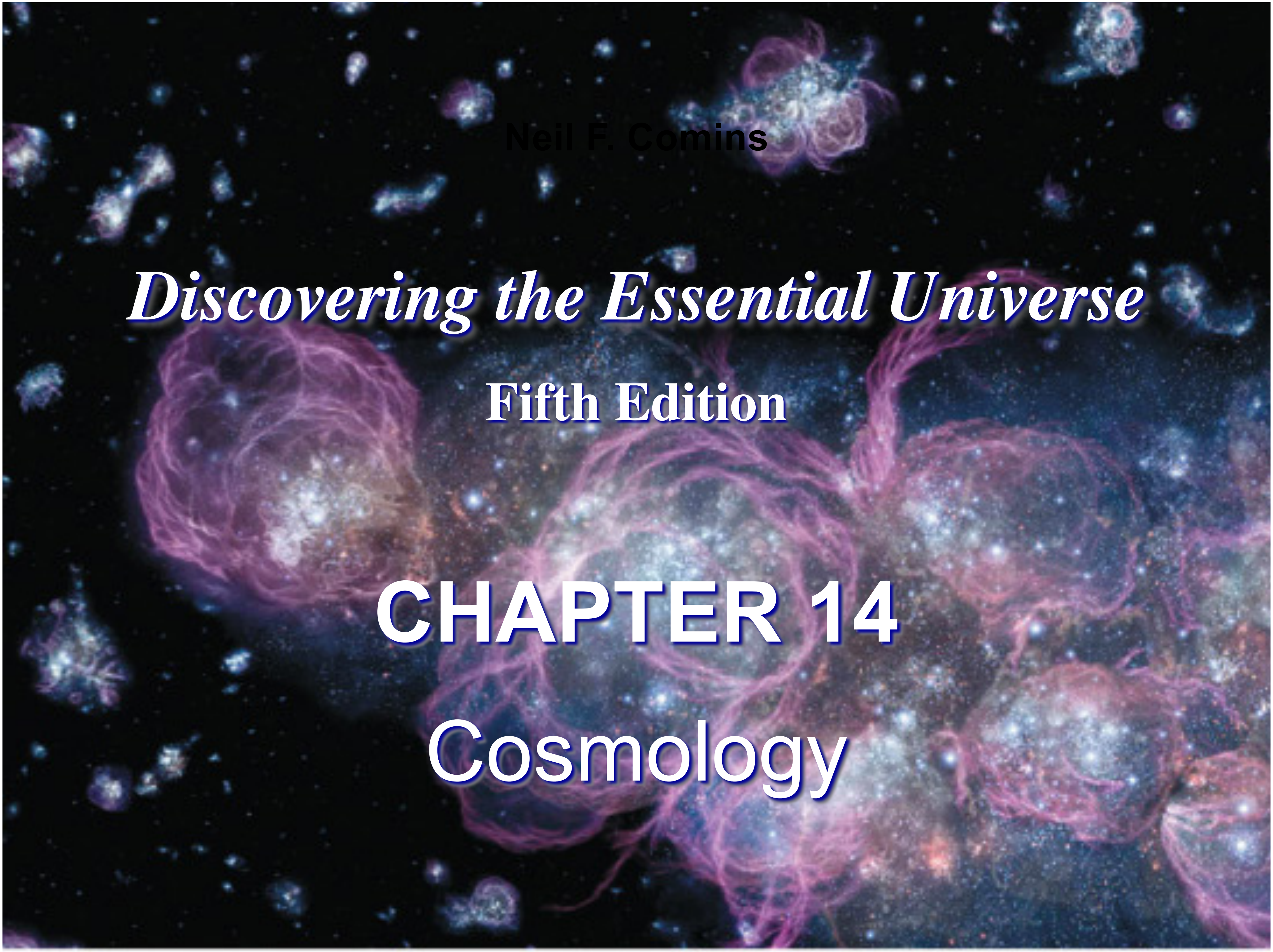


Neil F. Comins

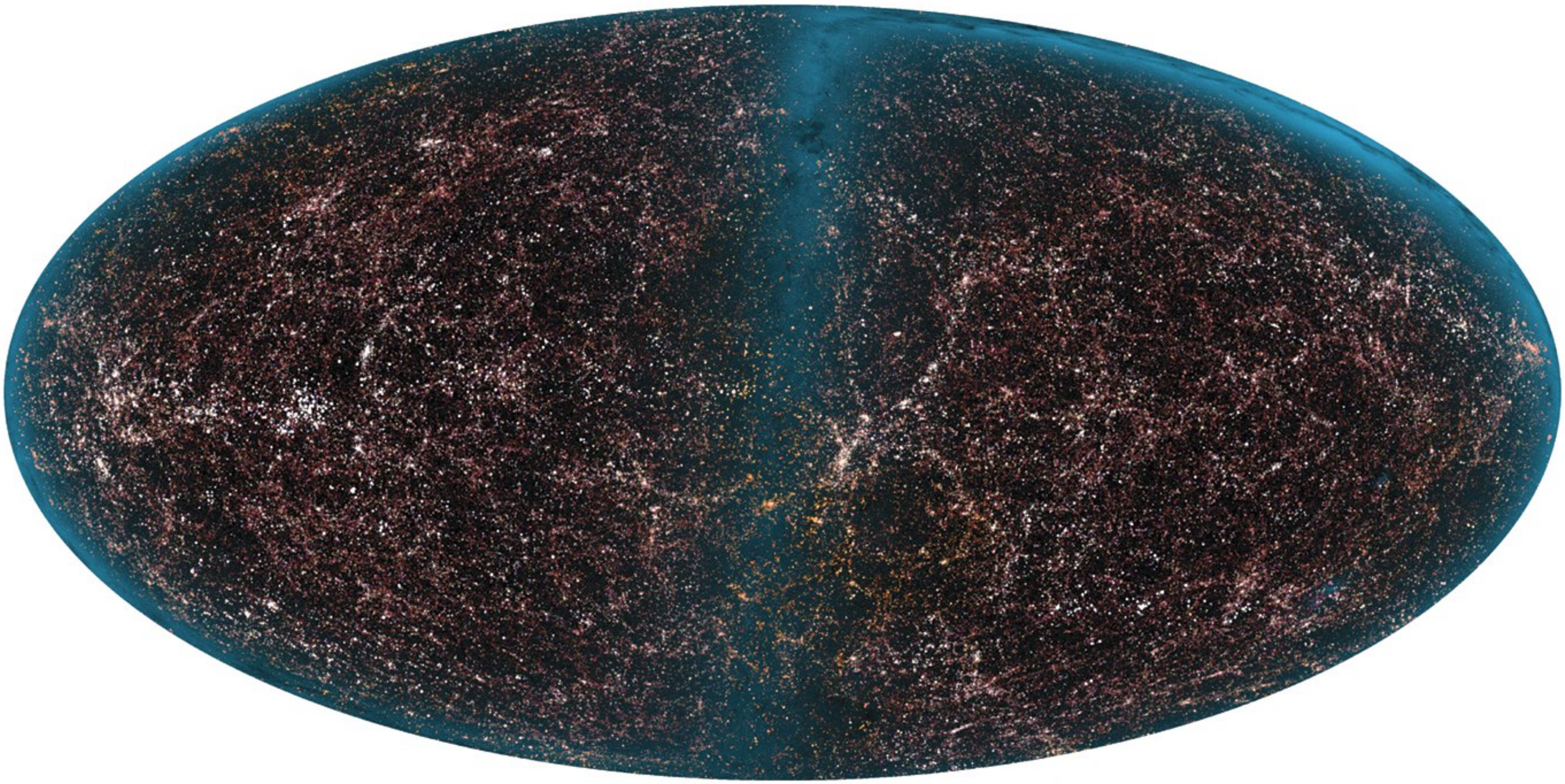
Discovering the Essential Universe

Fifth Edition

CHAPTER 14

Cosmology

Einstein's theory of general relativity predicts a contracting or expanding universe - but not a static universe



Einstein did not believe the prediction and "fudged" his theory. Later he said that that was his biggest blunder!

Discovery of the 3 K cosmic microwave background radiation (CMB)

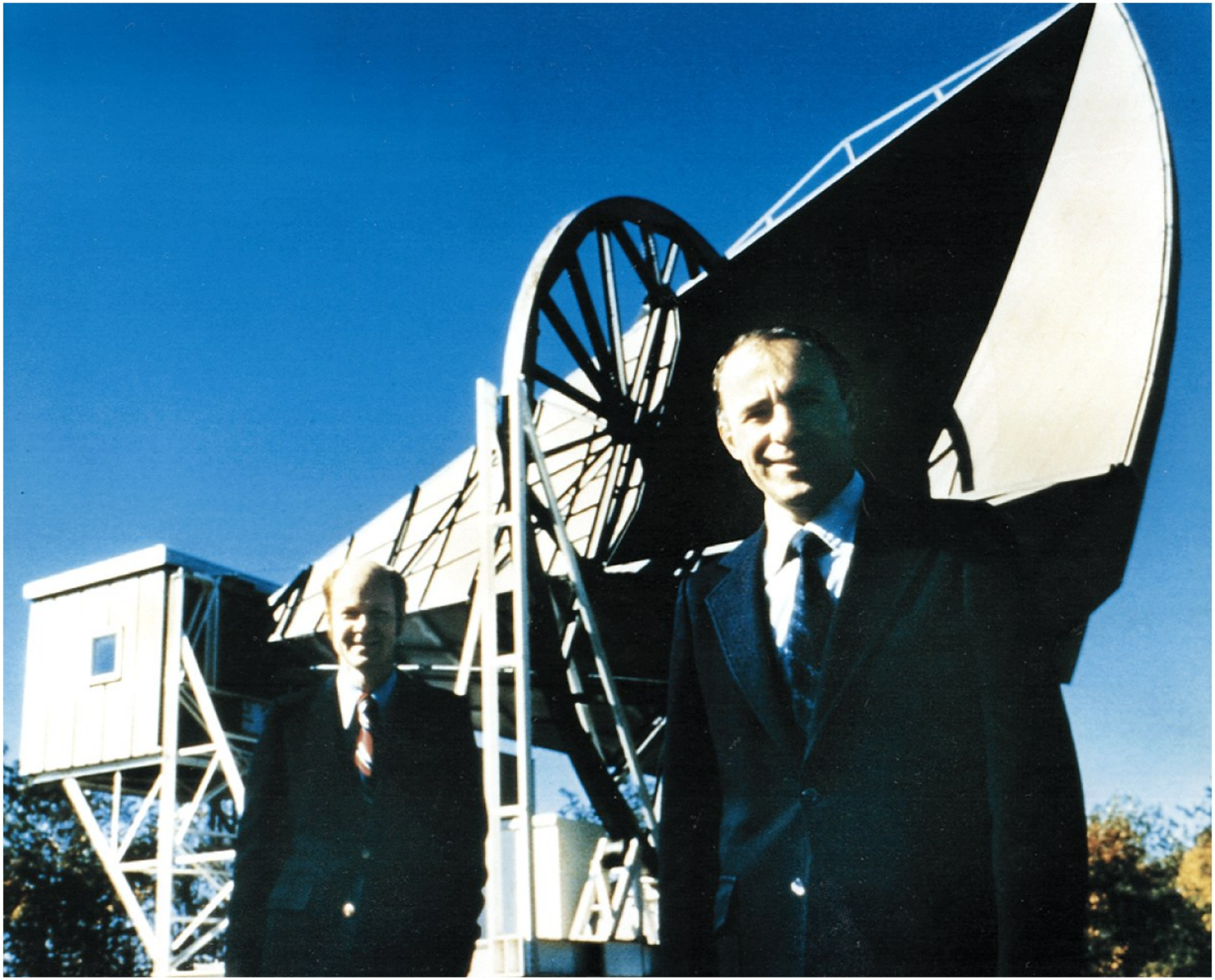


Figure 18-2
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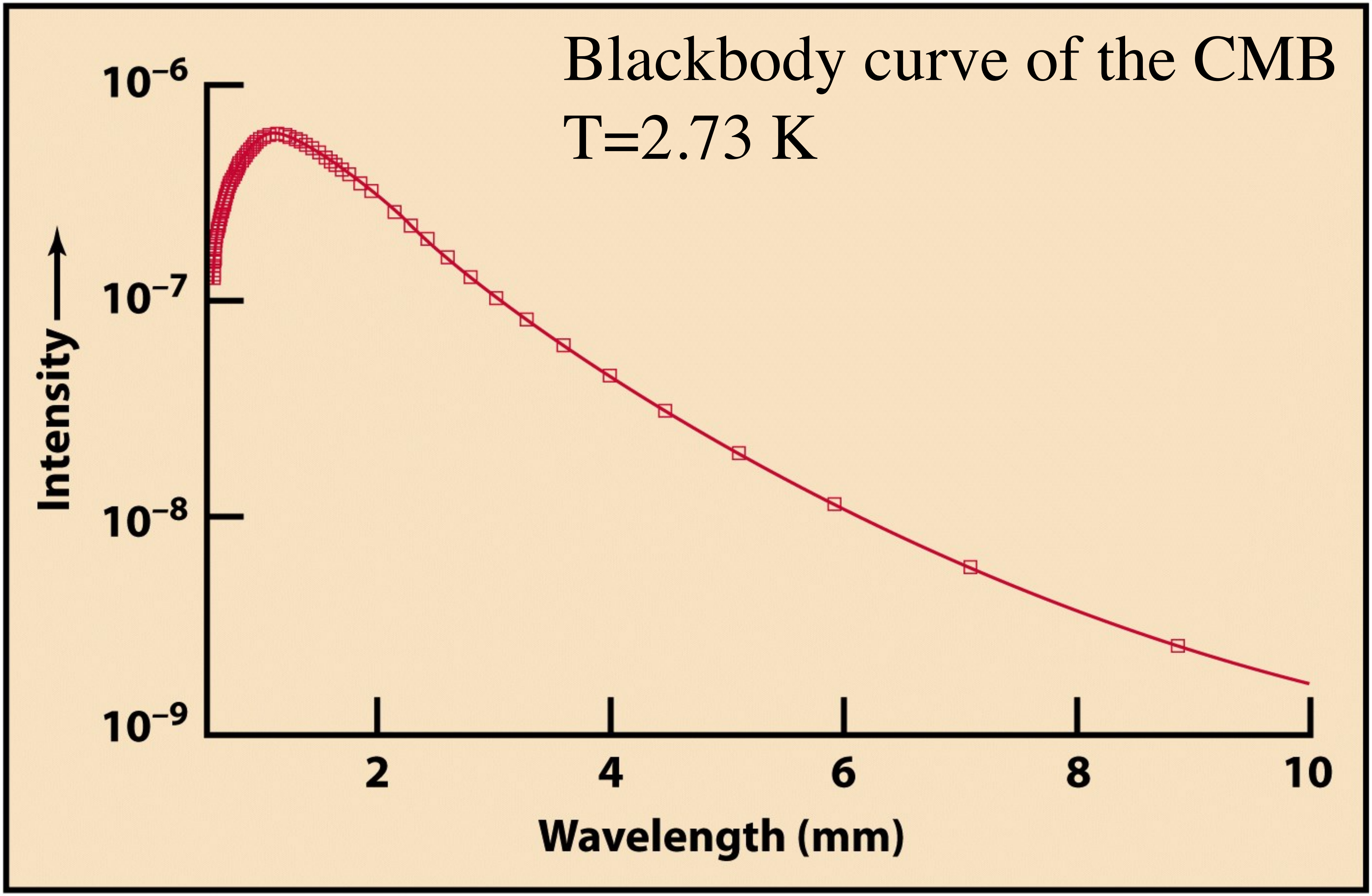


Figure 18-4
Discovering the Universe, Eighth Edition

Cosmological redshift

Hubble discovered the
expansion of the universe

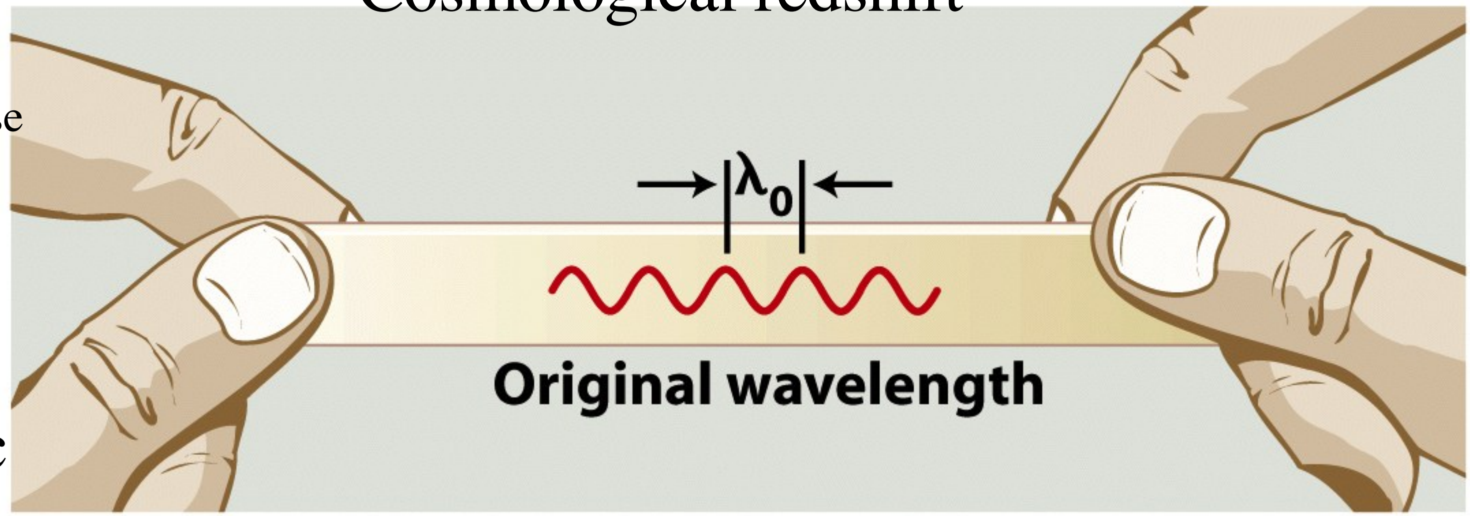
$H_0 = v/d$

$= 71$ km/s/Mpc

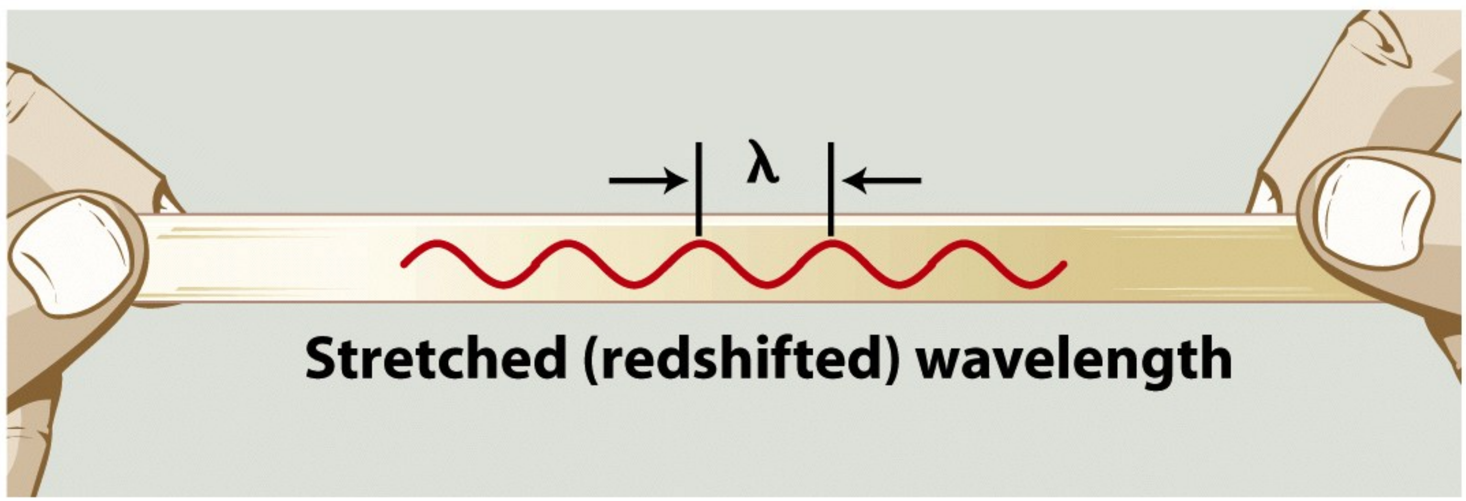
$1/H_0 = d/v$

$= 13.7 \ 10^9$ yr

==> Big Bang



a A wave drawn on a rubber band …



b … increases in wavelength as the rubber band is stretched.

Figure 18-1
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Cosmic microwave background - CMB

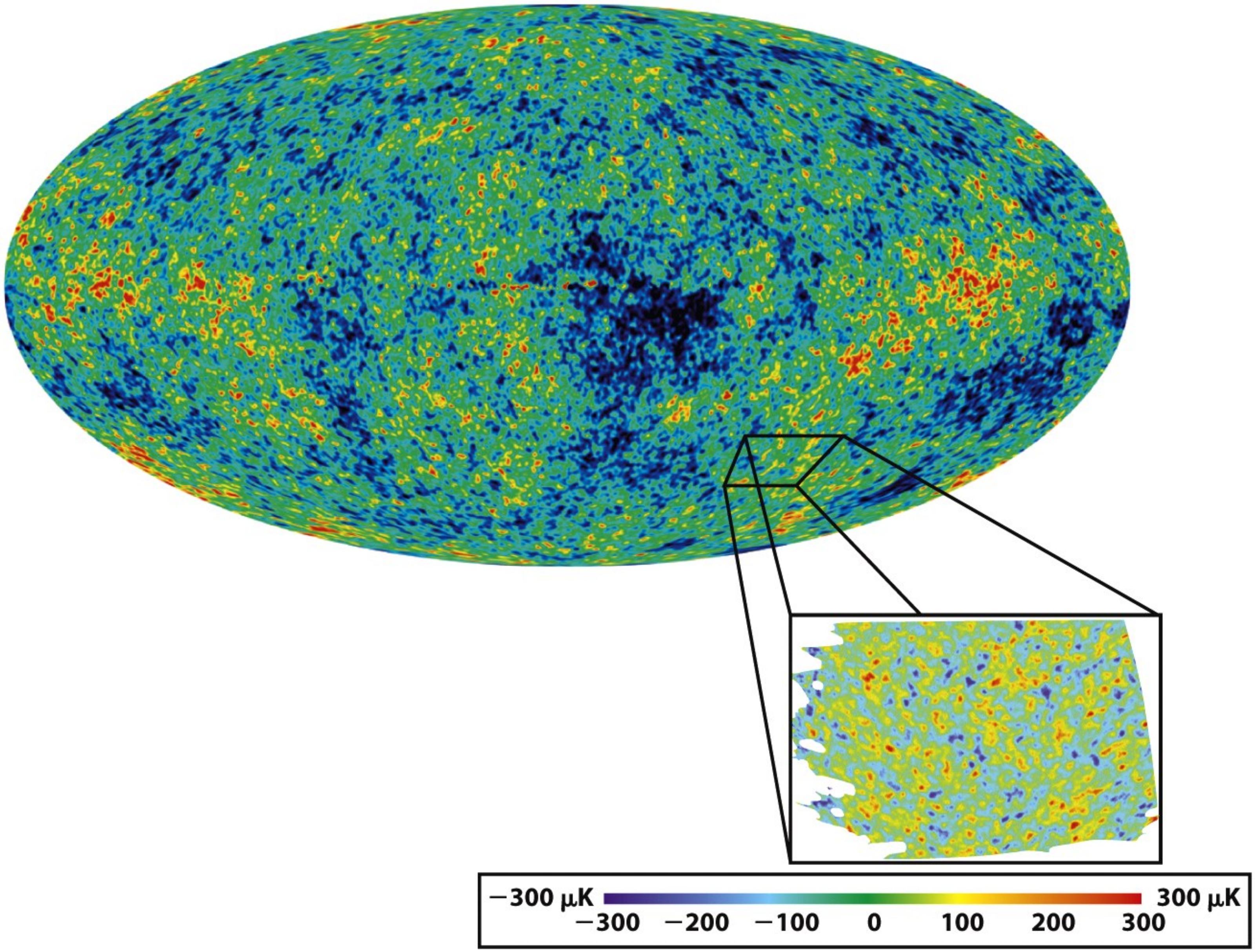

Figure 18-15
Discovering the Universe, Eighth Edition

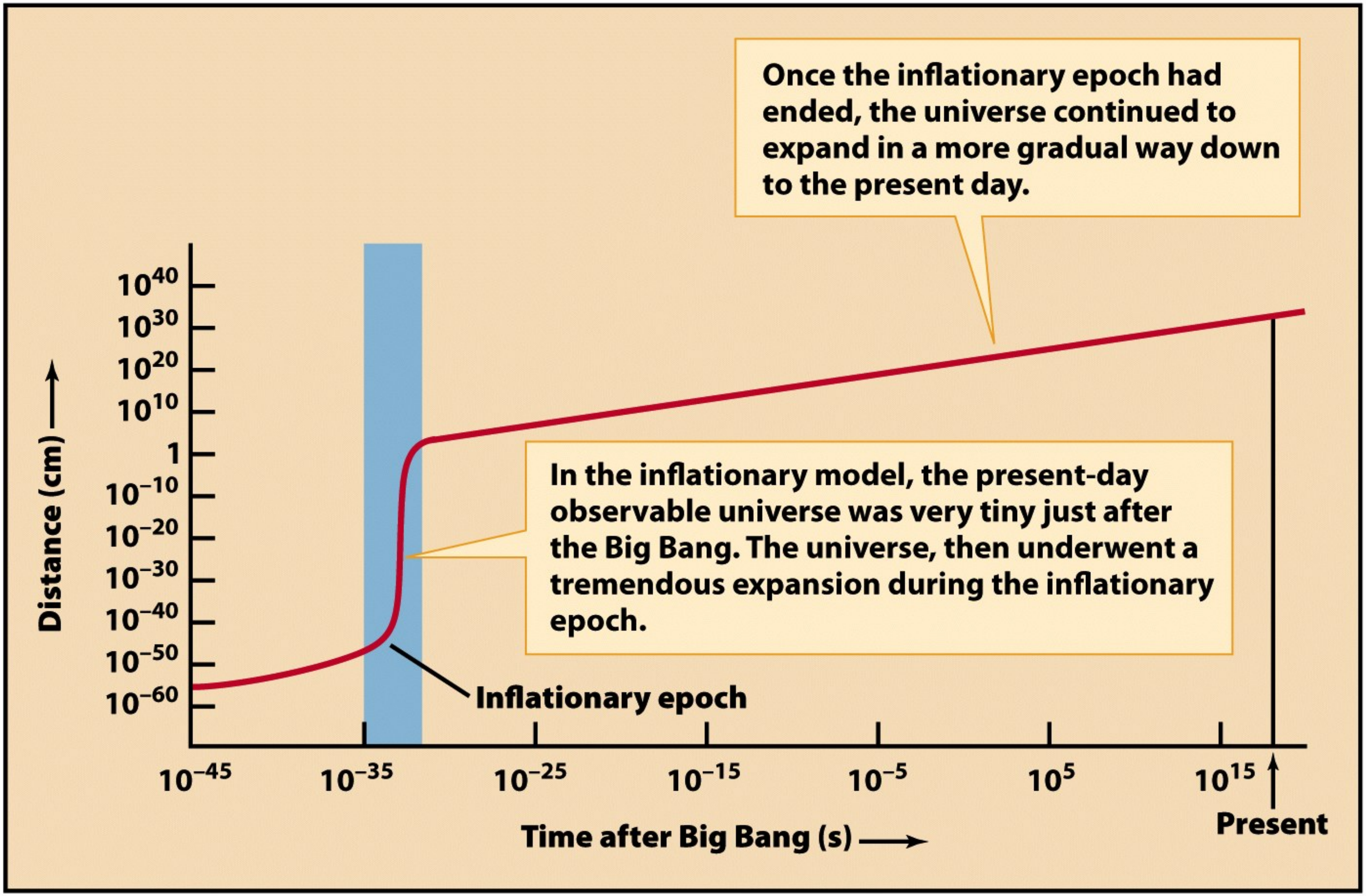

Figure 18-10

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The four forces of nature

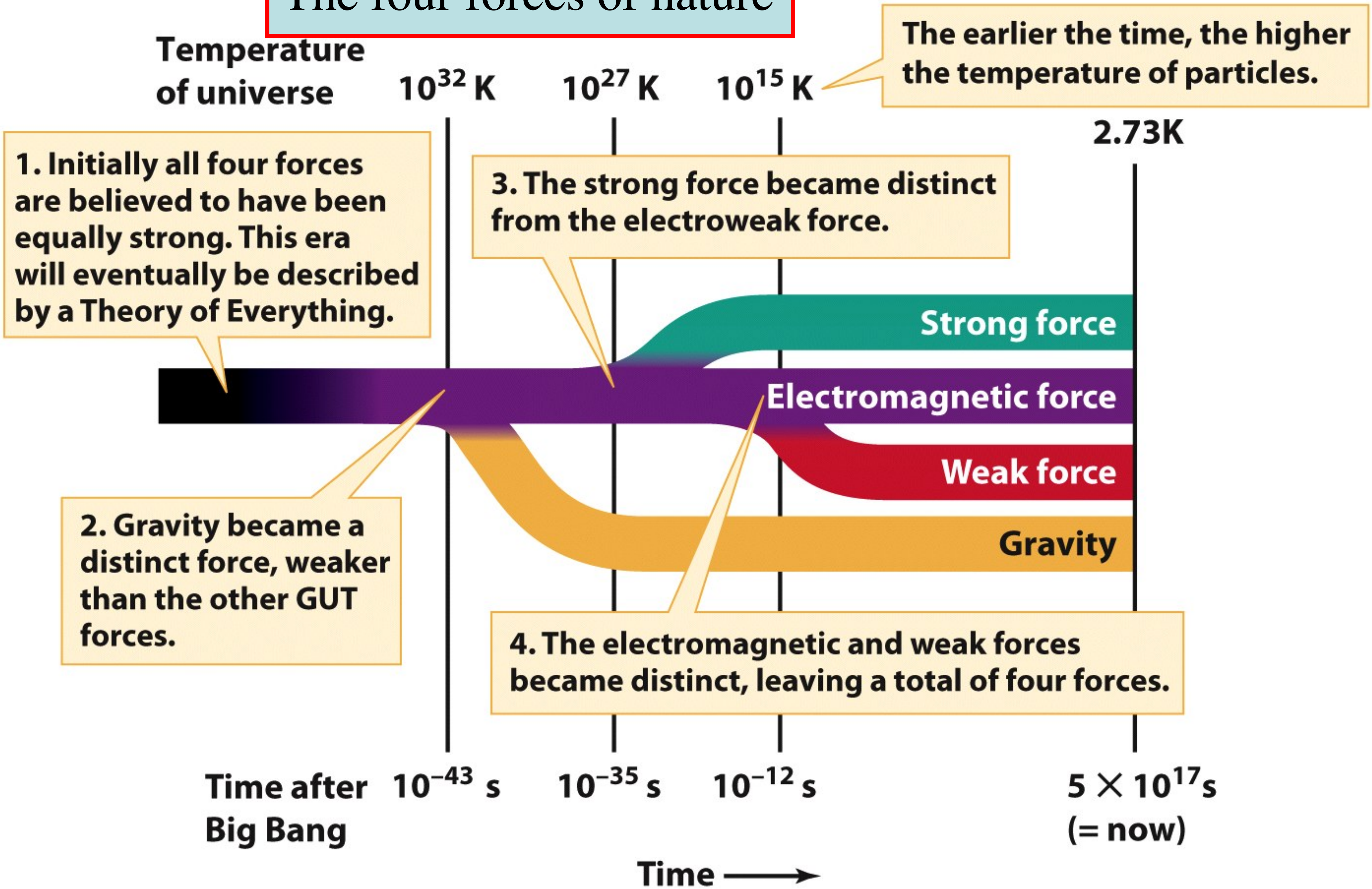

Figure 18-7
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Mysteries Needing Explanation

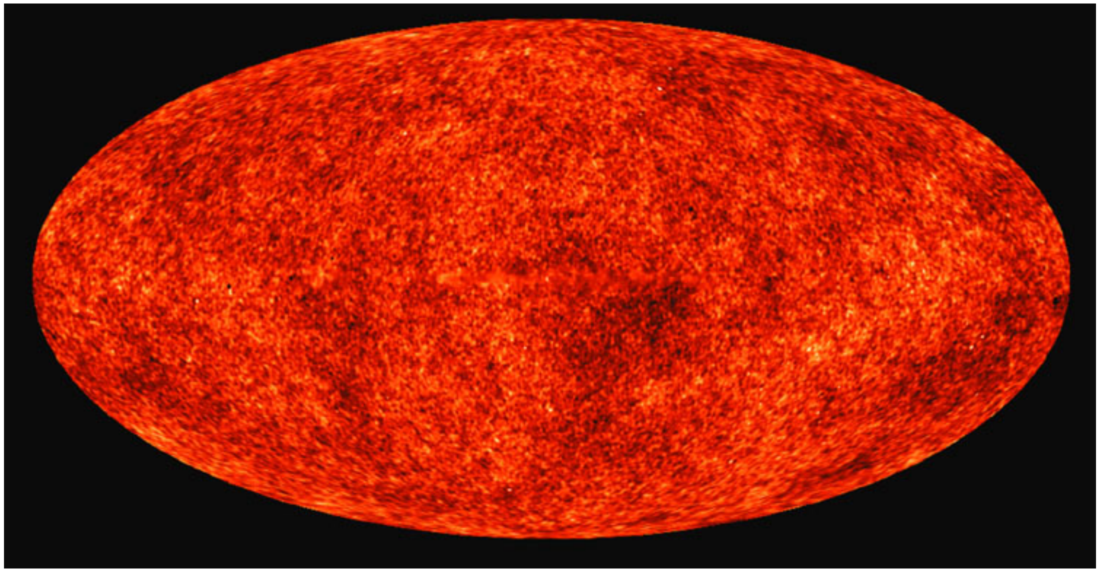
1. Where does structure come from?

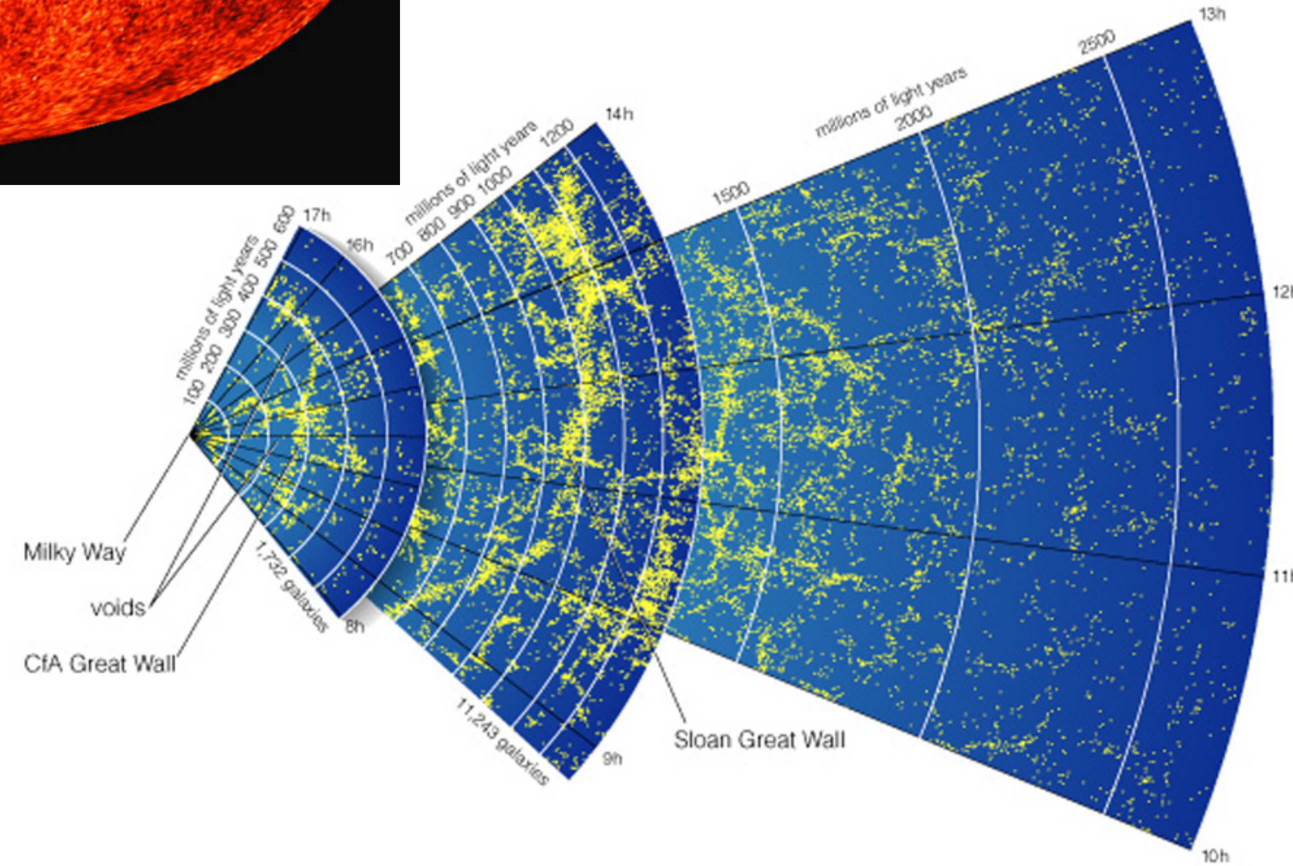
2. Why is the overall distribution of matter so uniform?

3. Why is the density of the universe so close to the critical density?

Inflation explains these features of the universe

- Structure: Giant quantum fluctuations
- Uniformity: equal temperatures and densities
  before inflation
- Density: with matter and dark energy
  => density = critical density

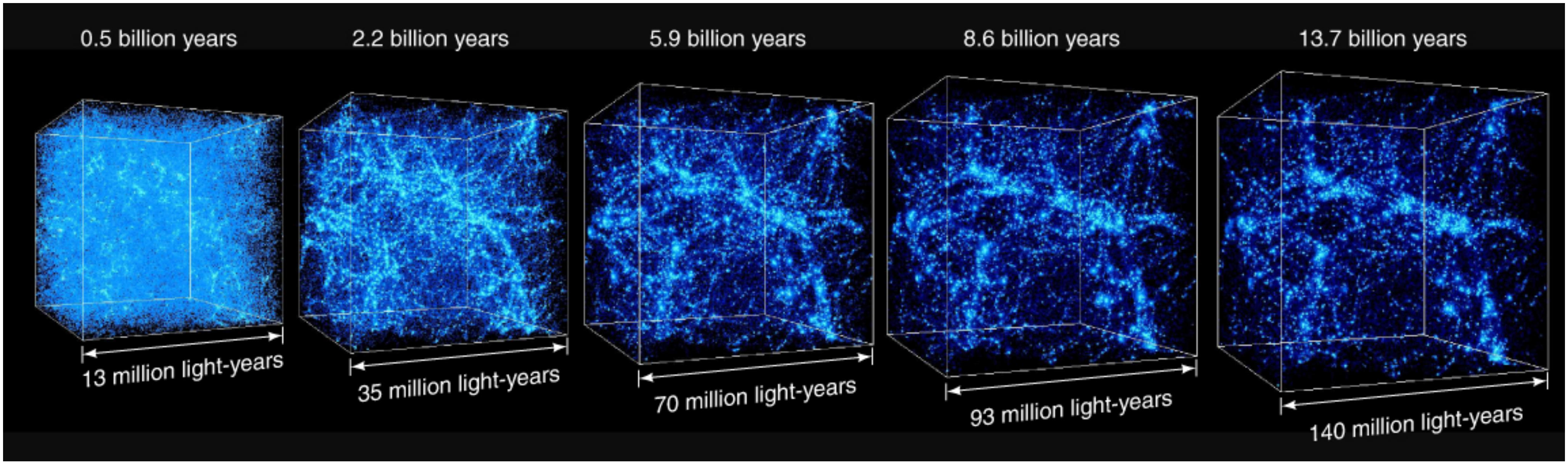




Maps of galaxy positions reveal extremely large structures: ***superclusters*** and ***voids.***

Time in billions of years

0.5 2.2 5.9 8.6 13.7



13 35 70 93 140

Size of expanding box in millions of light-years

Models show that the gravity of dark matter pulls mass into denser regions — universe grows lumpier with time.

The observable universe – out to 13.8 billion lightyears

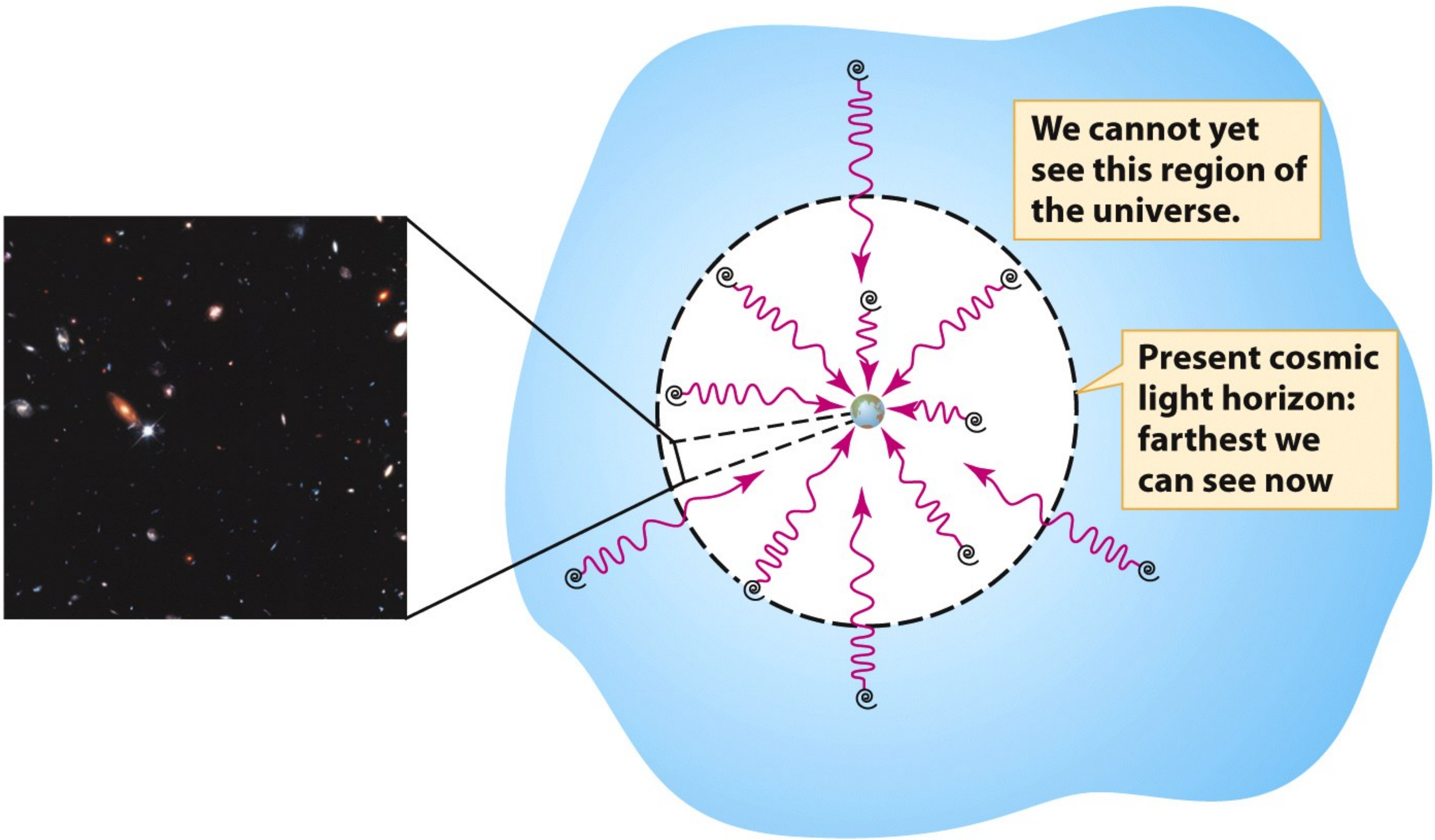


Figure 18-11
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Evolution of radiation and matter density

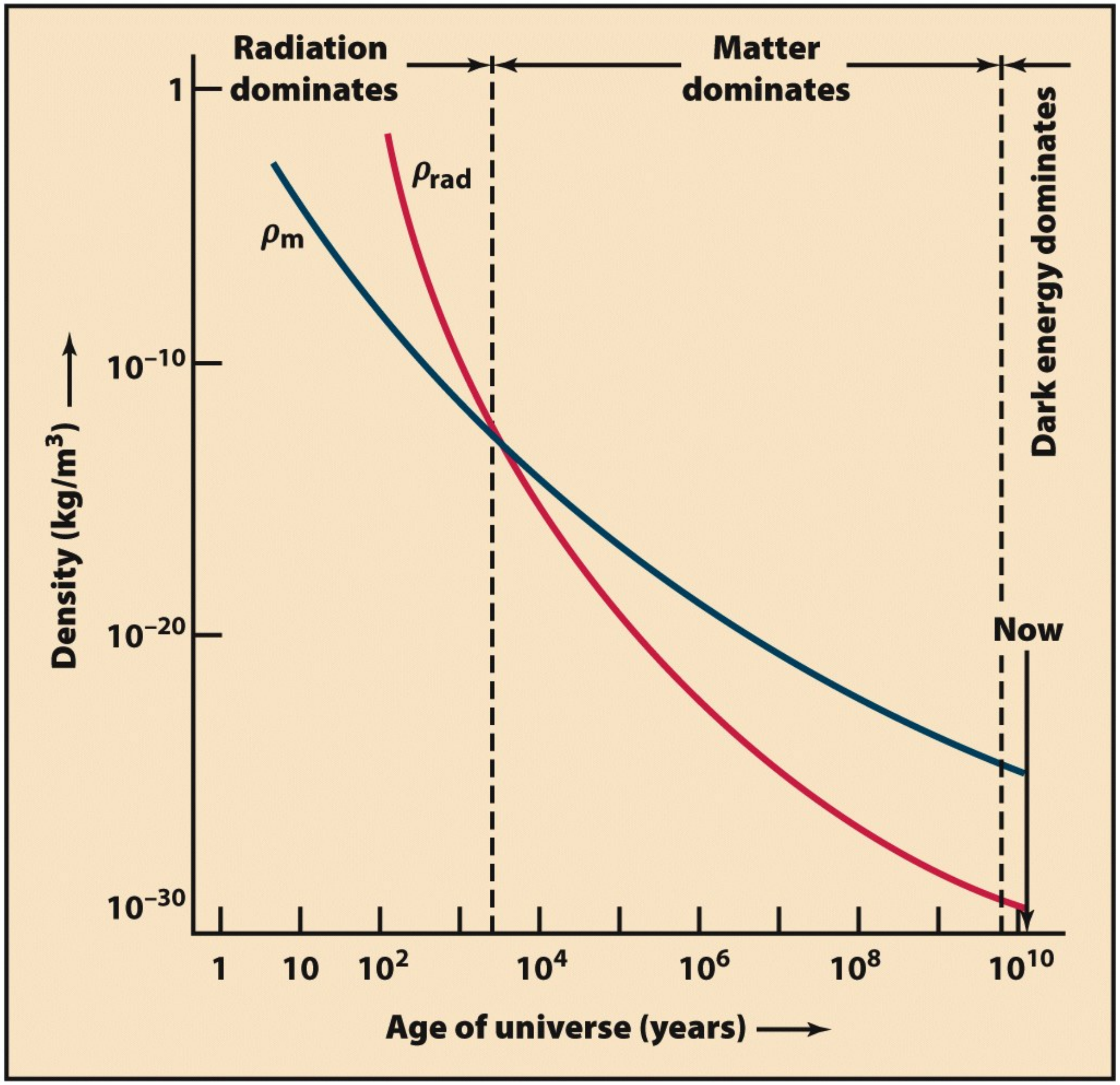

Figure 18-13
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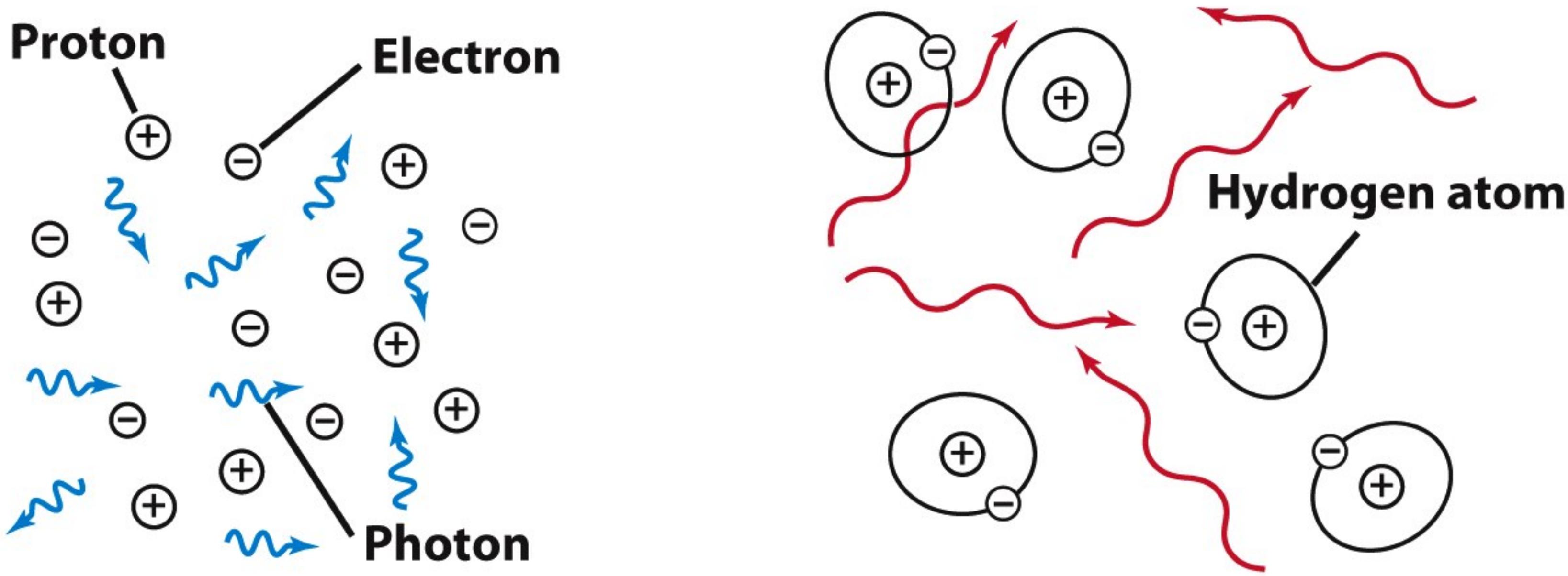
The universe was opaque during the first 380,000 years
Dark Ages



a Before recombination:
- Temperatures were so high that electrons and protons could not combine to form hydrogen atoms.
- The universe was opaque: Photons underwent frequent collisions with electrons.
- Matter and radiation were at the same temperature.

b After recombination:
- Temperatures became low enough for hydrogen atoms to form.
- The universe became transparent: Collisions between photons and atoms became infrequent.
- Matter and radiation were no longer at the same temperature.

Figure 18-14
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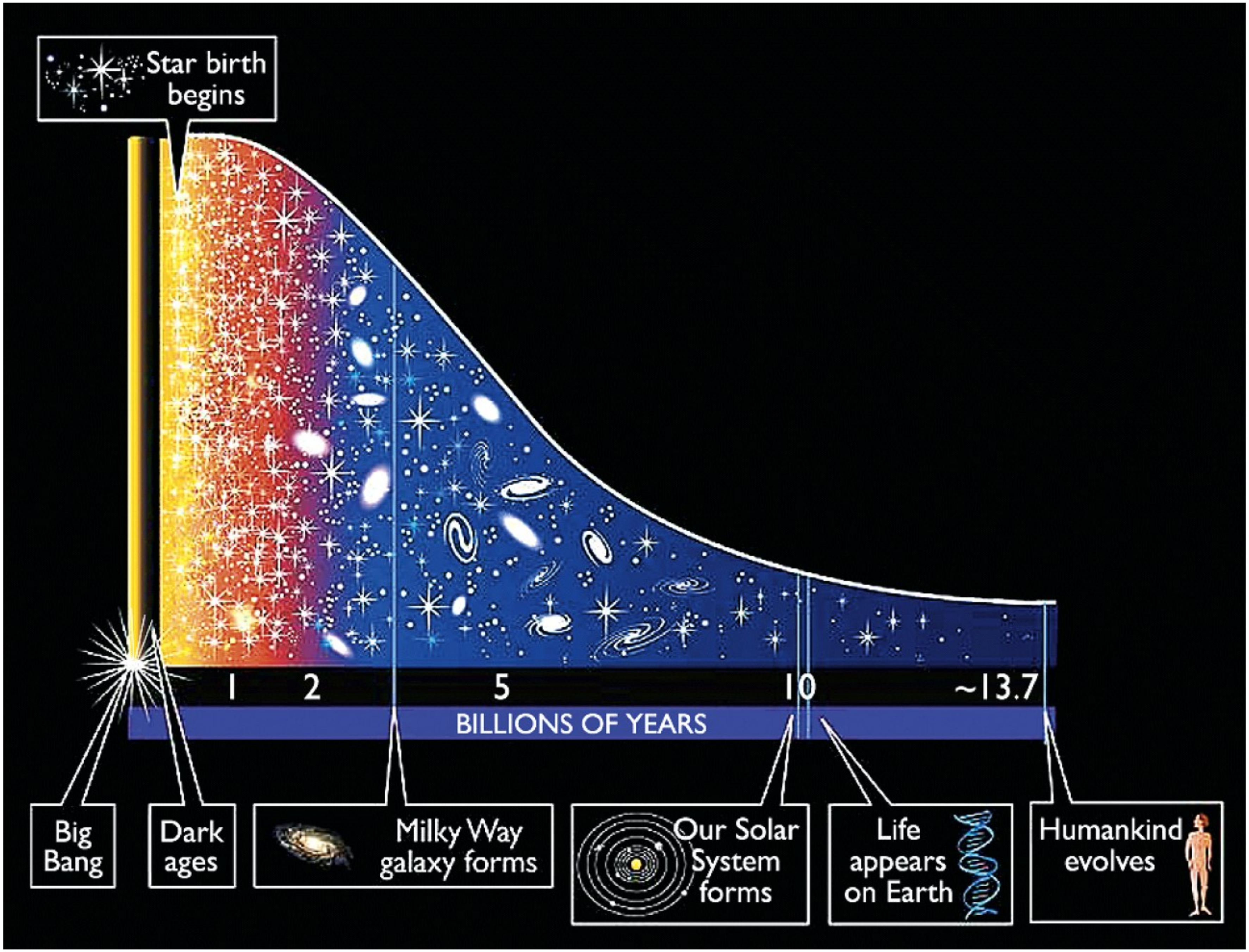

Figure 18-17a
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The cosmic timeline

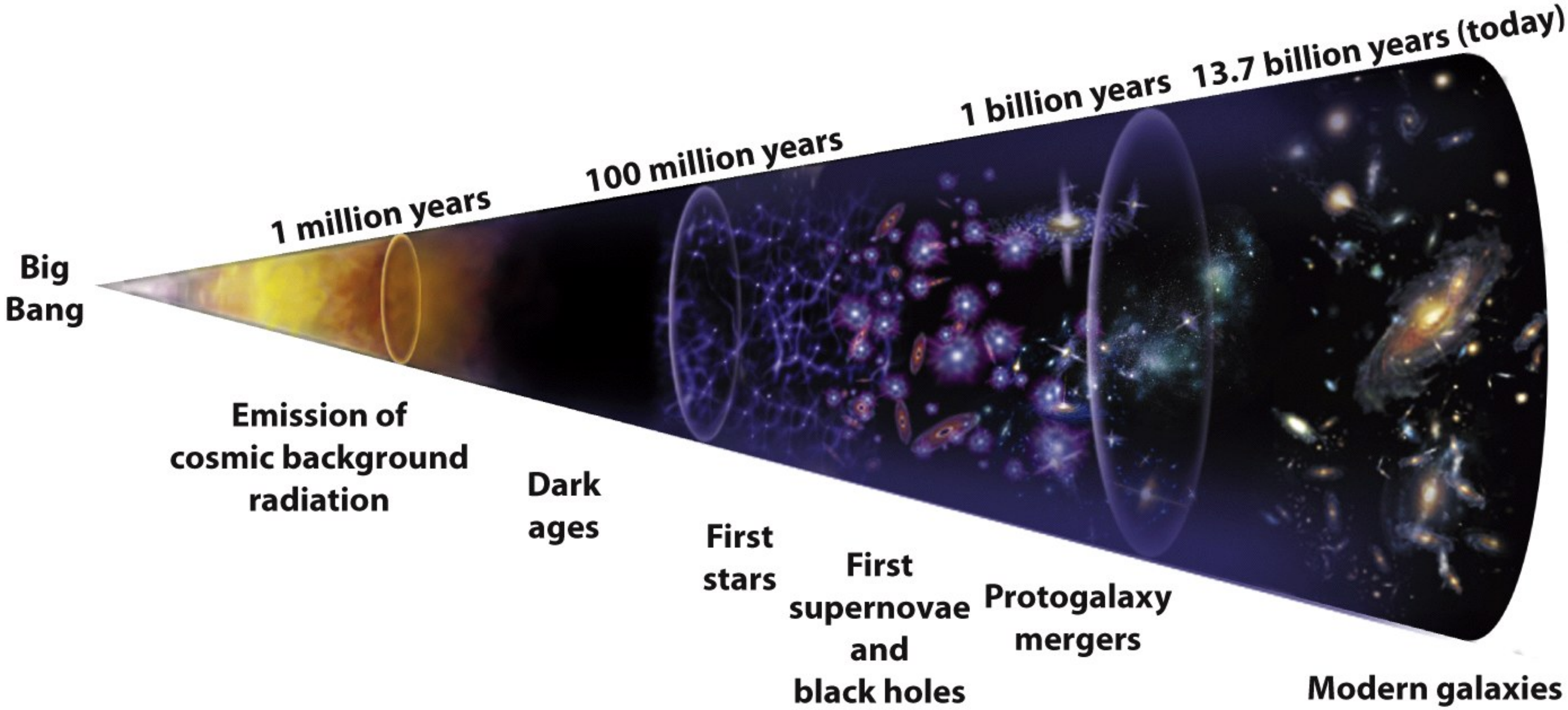
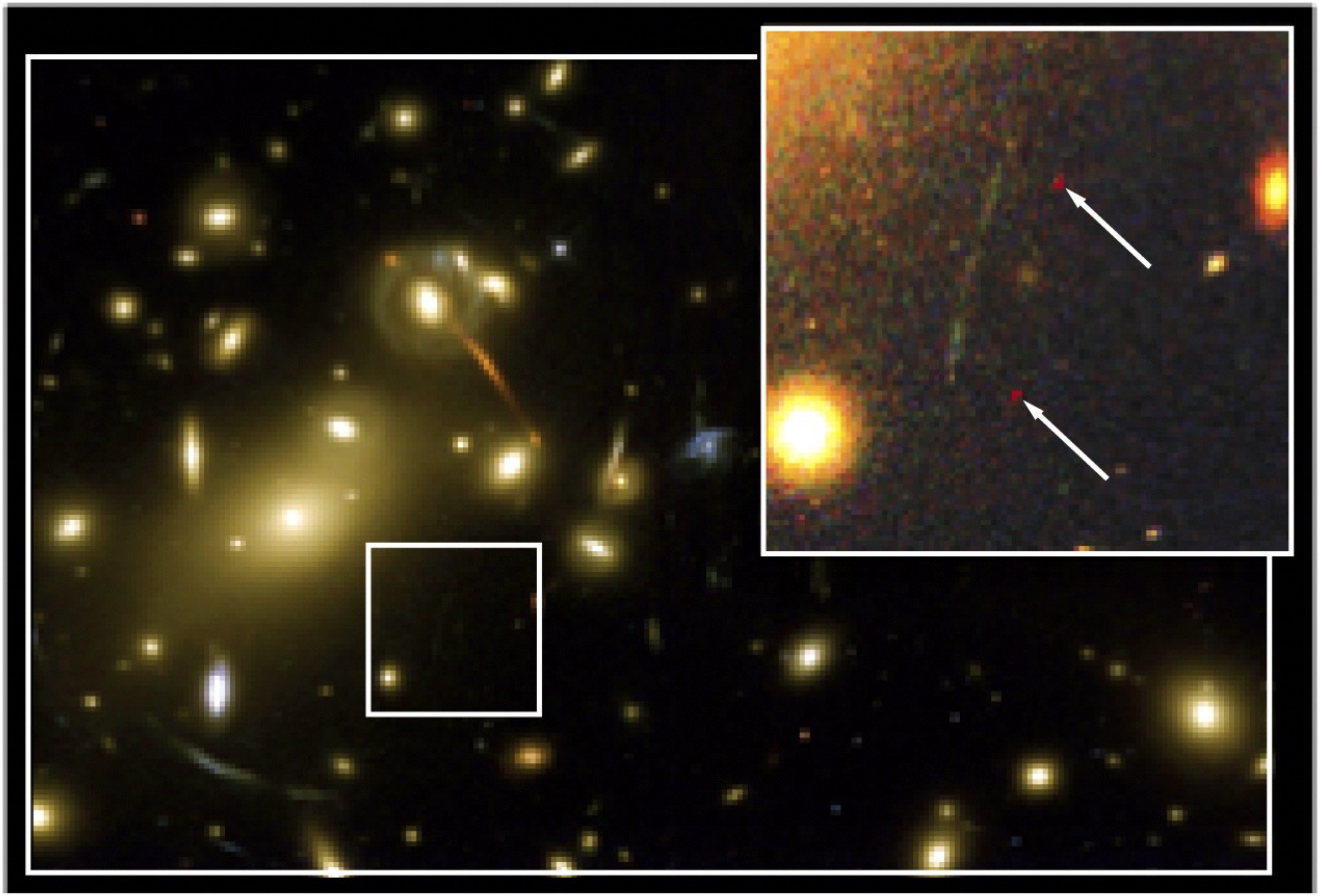


Figure 18-19
Discovering the Universe, Eighth Edition



Arrows indicate galaxies beginning to form 13.4 billion years ago

Figure 18-16b
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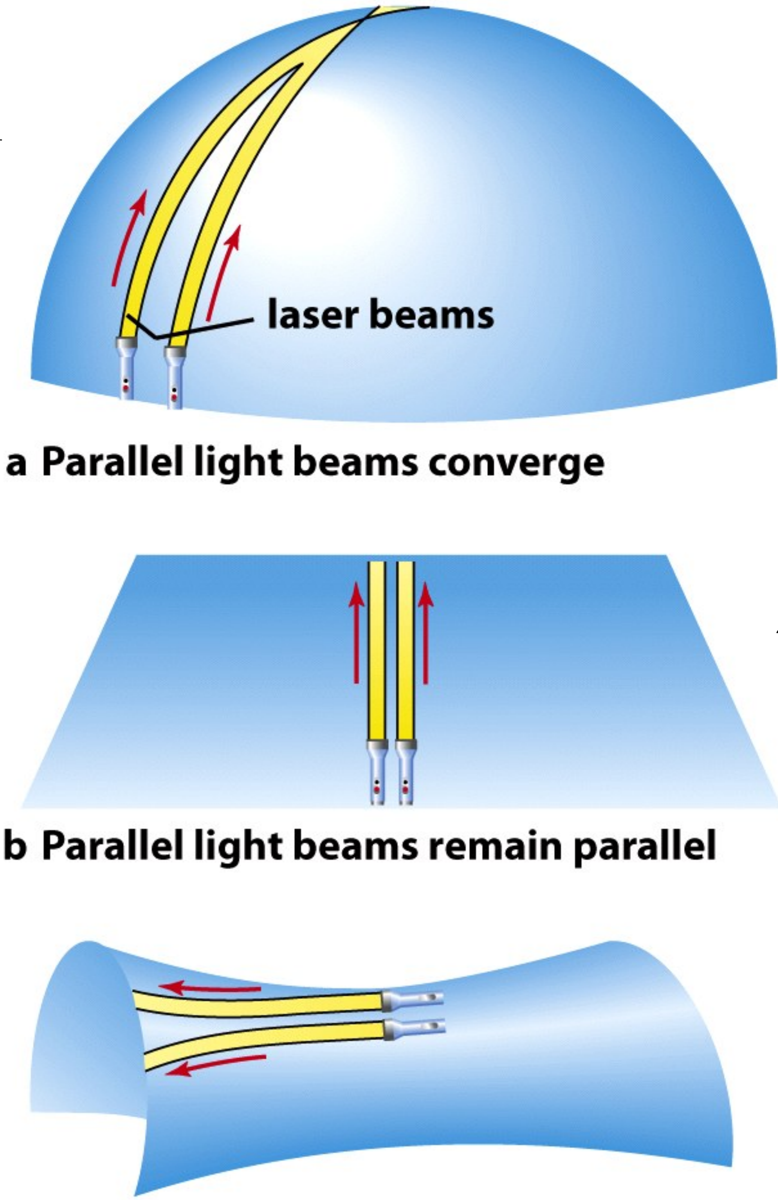
Possible shapes of space

ρ_0 :density, ρ_c: critical density, $\Omega_0 = \rho_0 / \rho_c$



a Parallel light beams converge

b Parallel light beams remain parallel

c Parallel light beams diverge

Figure 18-21

$\rho_0 > \rho_c$: $\Omega_0 > 1$

positive curvature of space

closed universe

⇨ **Big Crunch**

$\rho_0 = \rho_c$: $\Omega_0 = 1$

zero curvature of space

flat universe

⇨ **expansion for ever (just barely)**

$\rho_0 < \rho_c$: $\Omega_0 < 1$

negative curvature of space

open universe

⇨ **expansion for ever**

Structure of the early universe

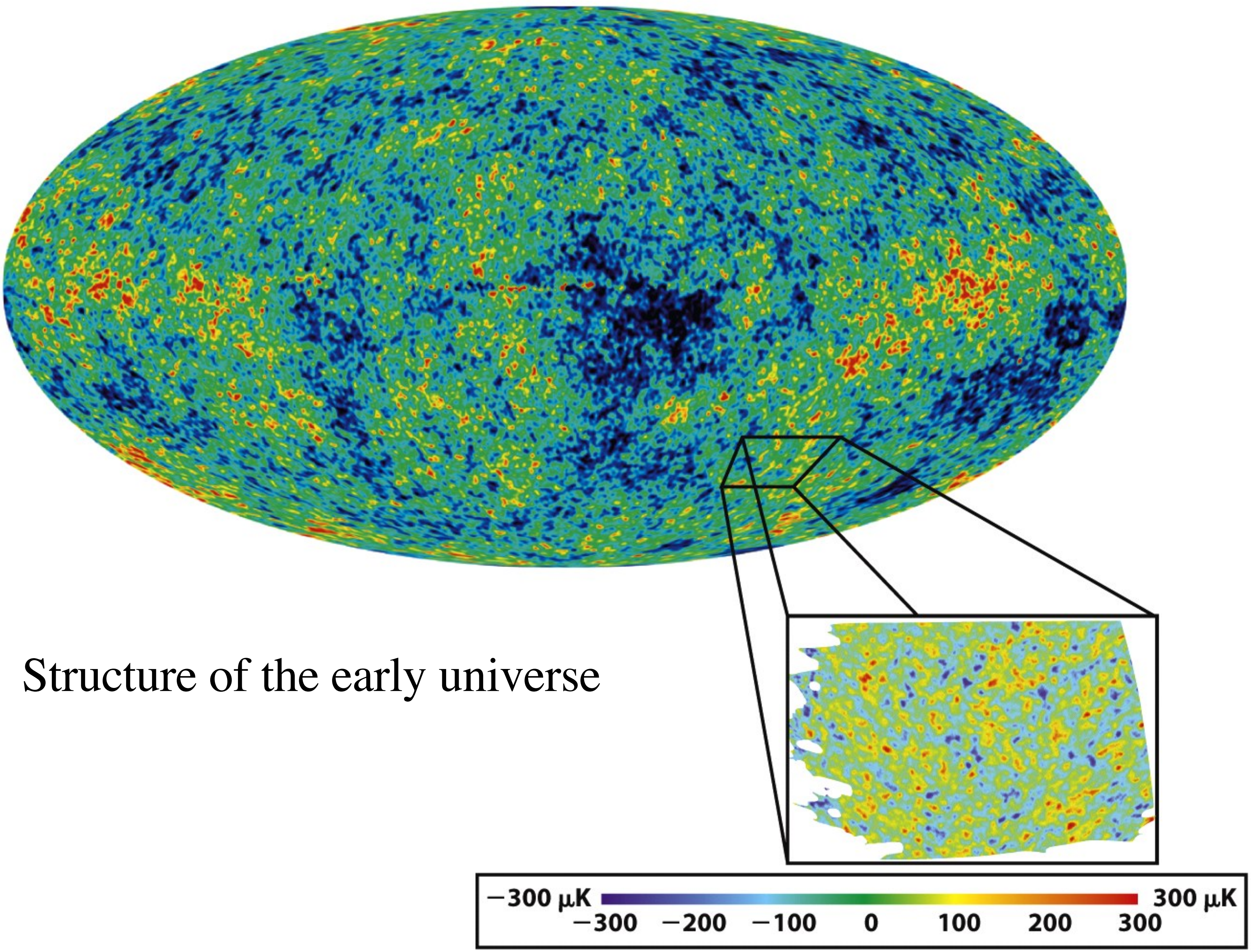


Figure 18-15
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CMB and the curvature of space

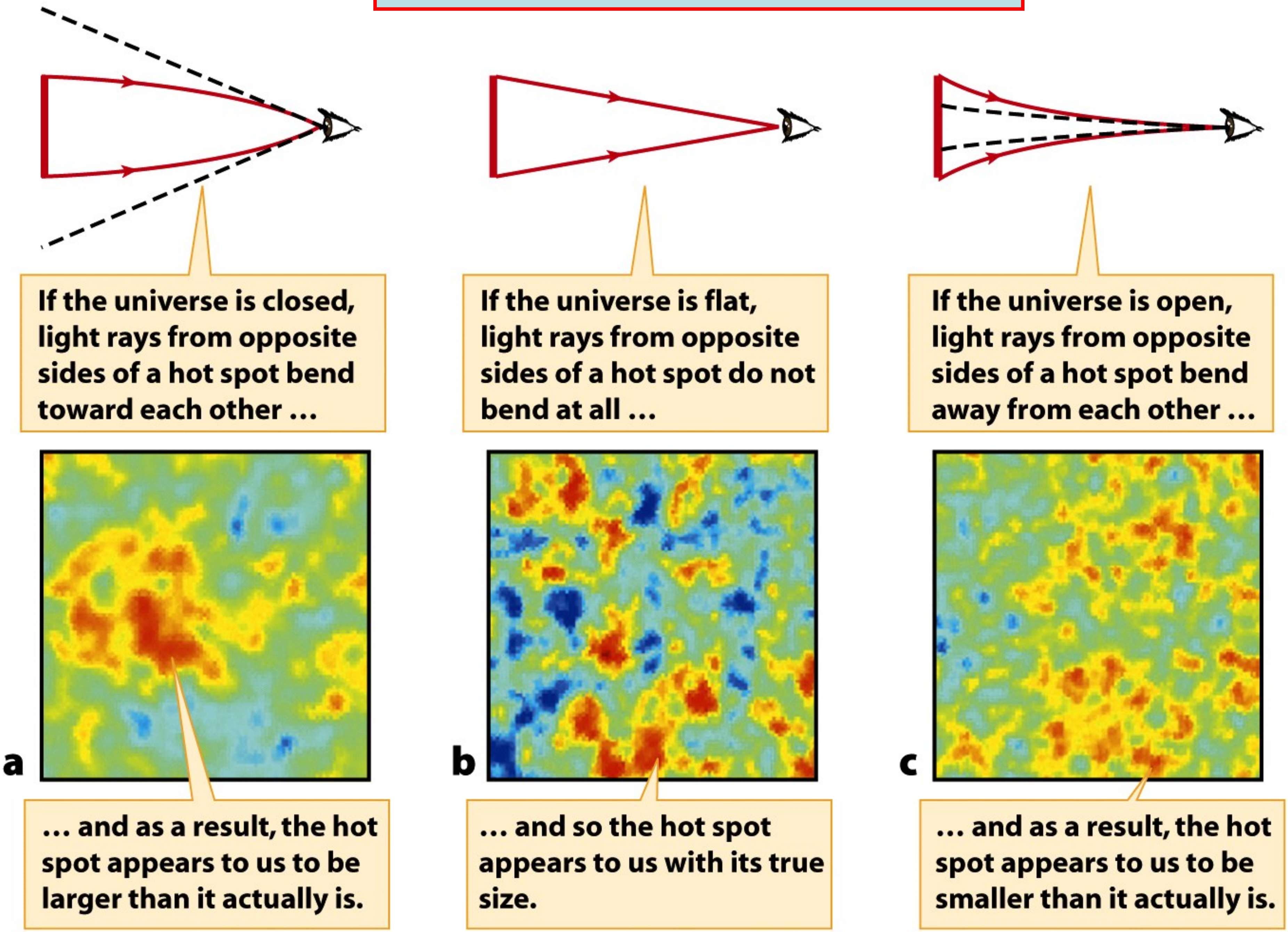

Figure 18-22
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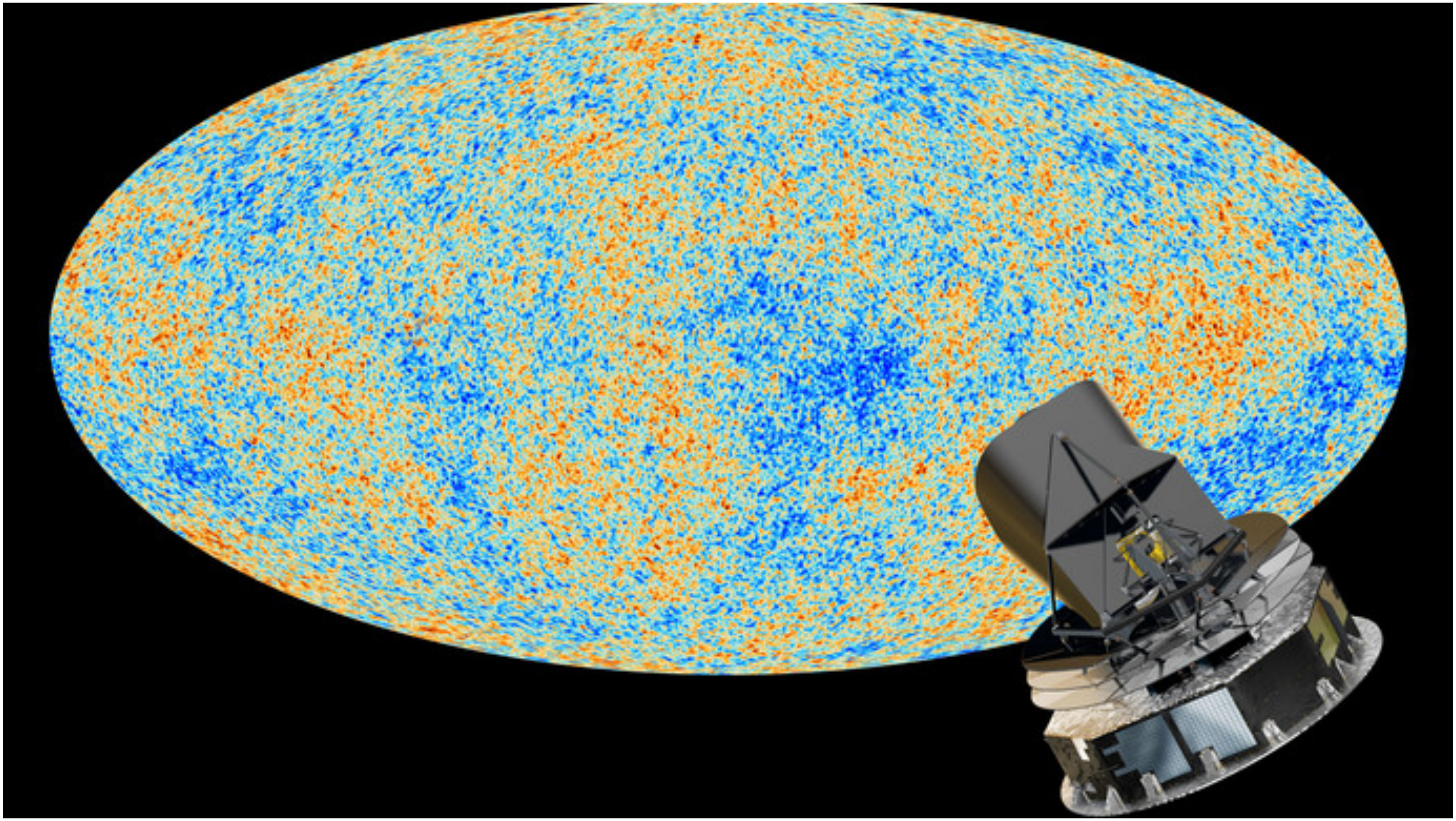
CMB with Planck satellite - 2013



Esa.int

Type Ia supernova

The supernova is dimmer than expected, indicating that the distance to it is greater than it would be if the expansion of the universe were slowing down.

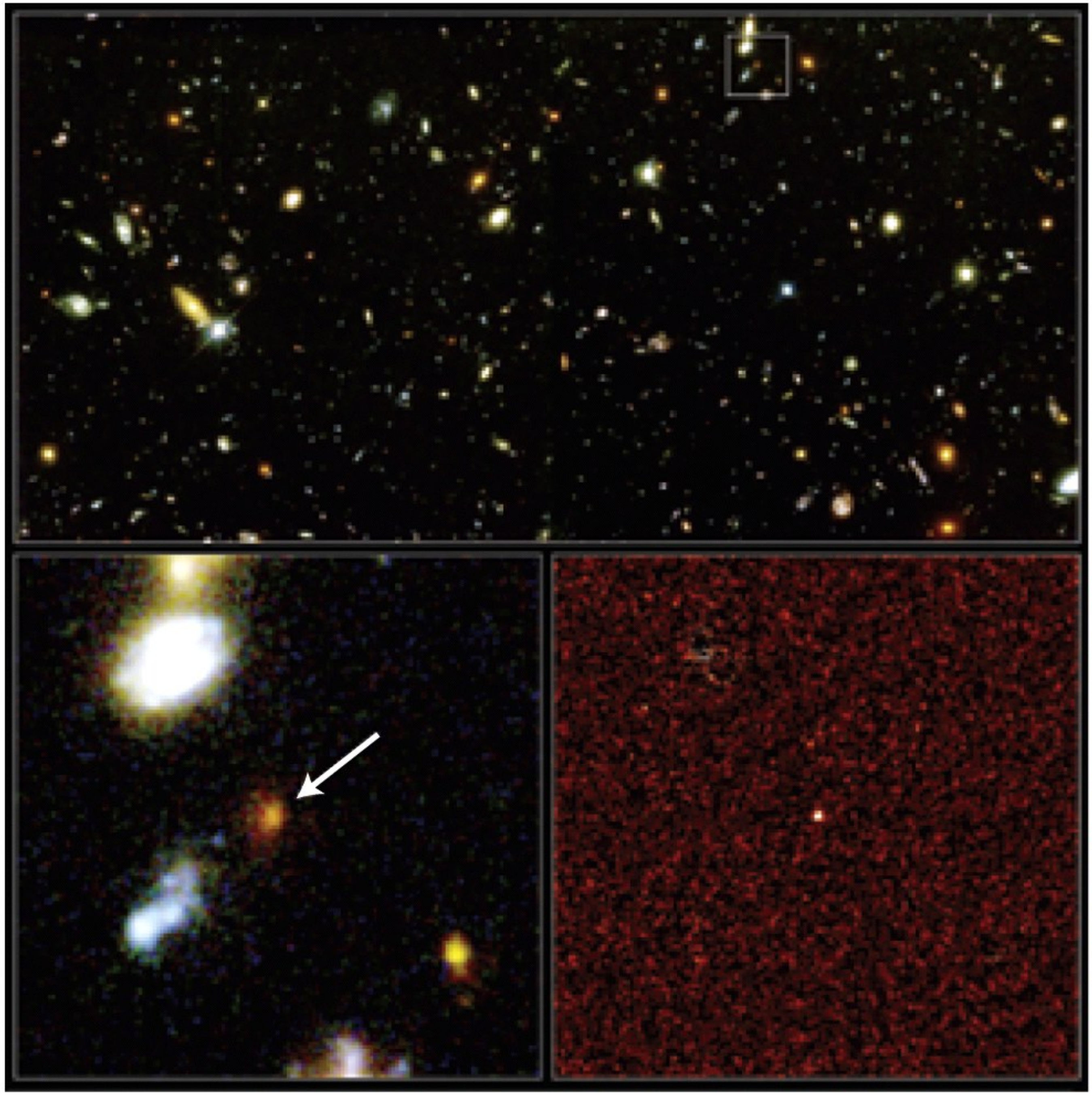


Figure 18-23a
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There must be an outward cosmological force! ==>Dark Energy

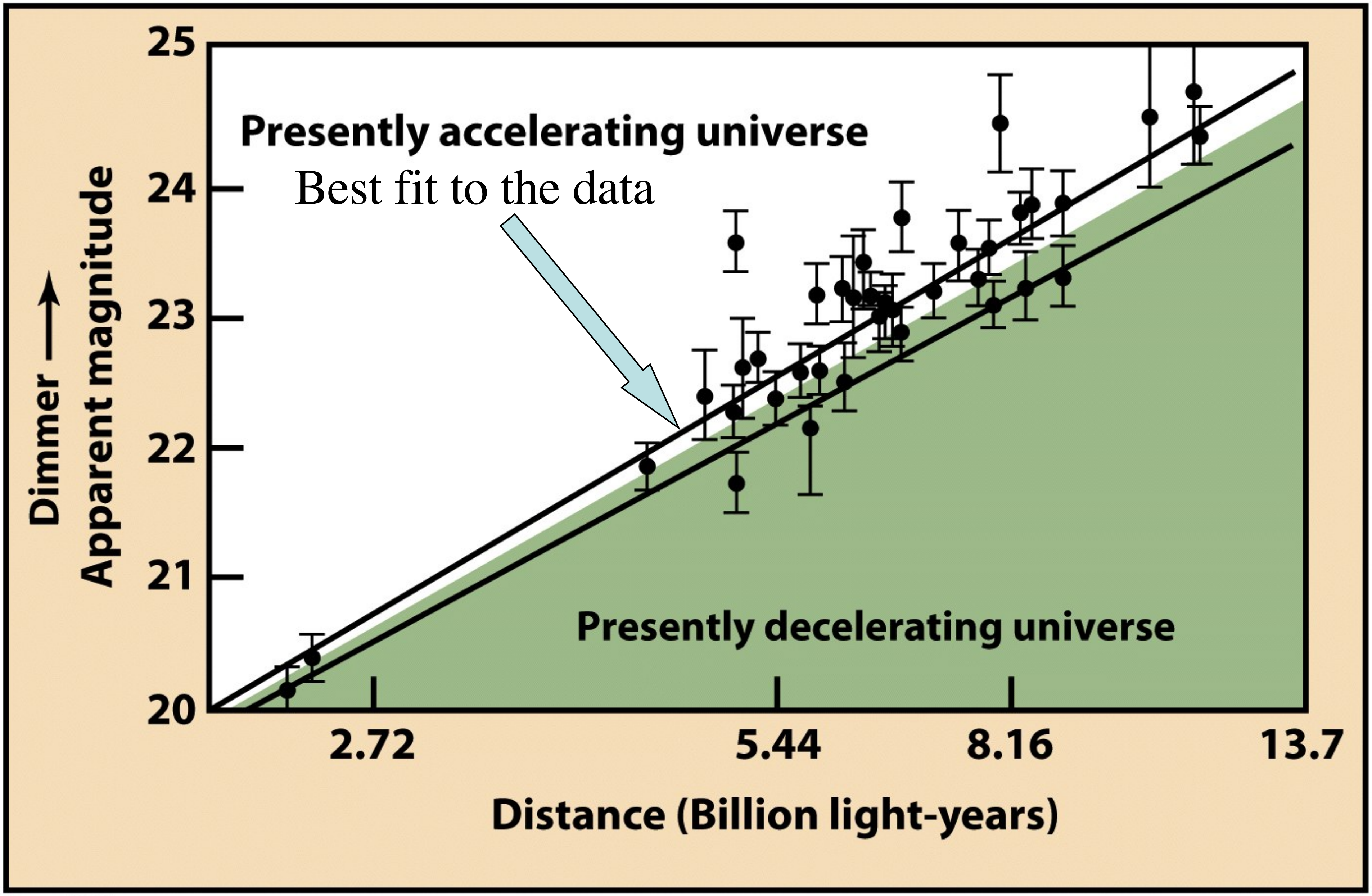

Figure 18-23b
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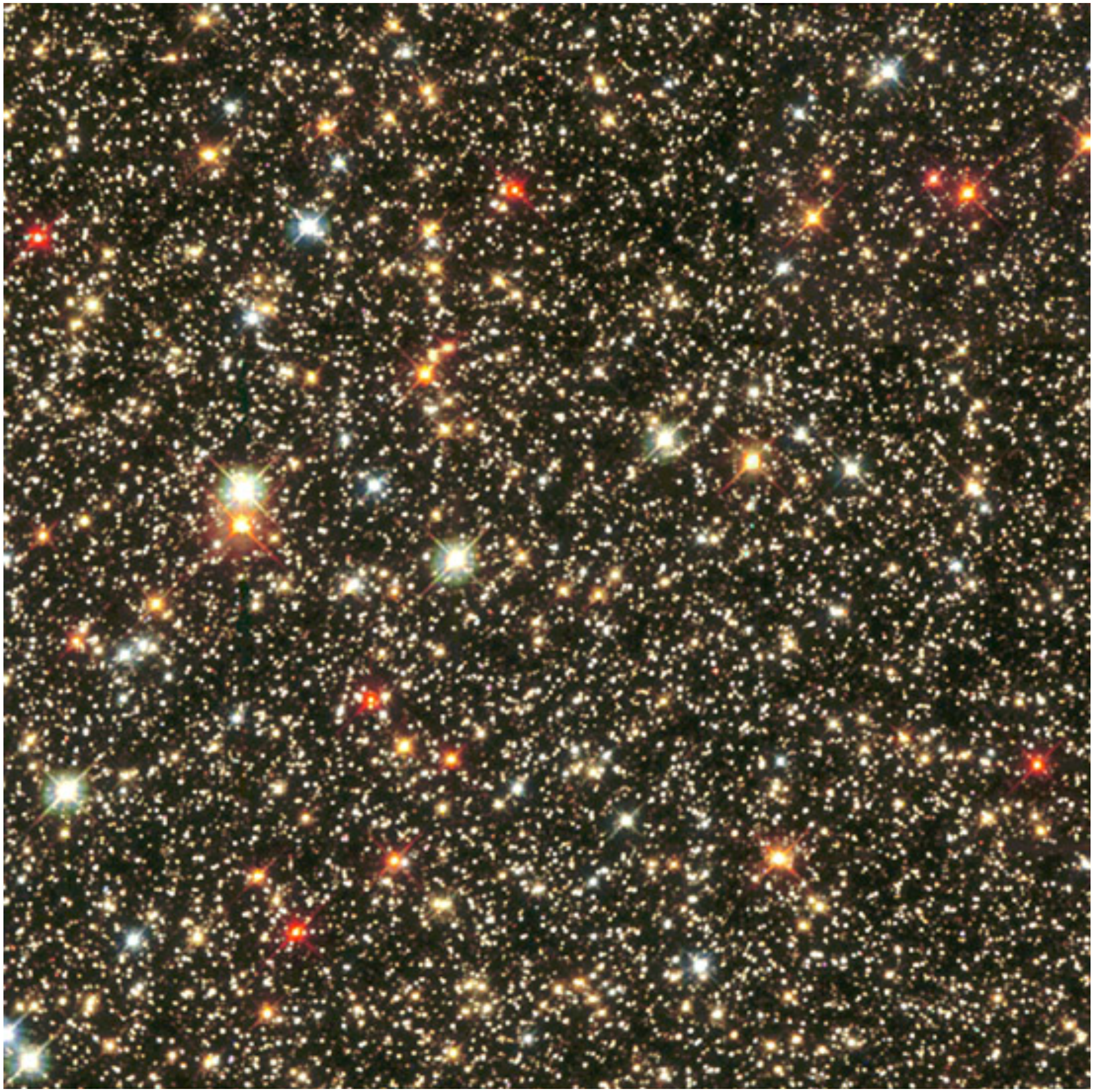
The major components of the Universe

5%	normal matter
27%	dark matter
68%	dark energy

$$\Omega_{0,\,M} + \Omega_{0,\,\Lambda} = \Omega_0 = 1$$

Why is it so dark in the night?



Olbers' Paradox

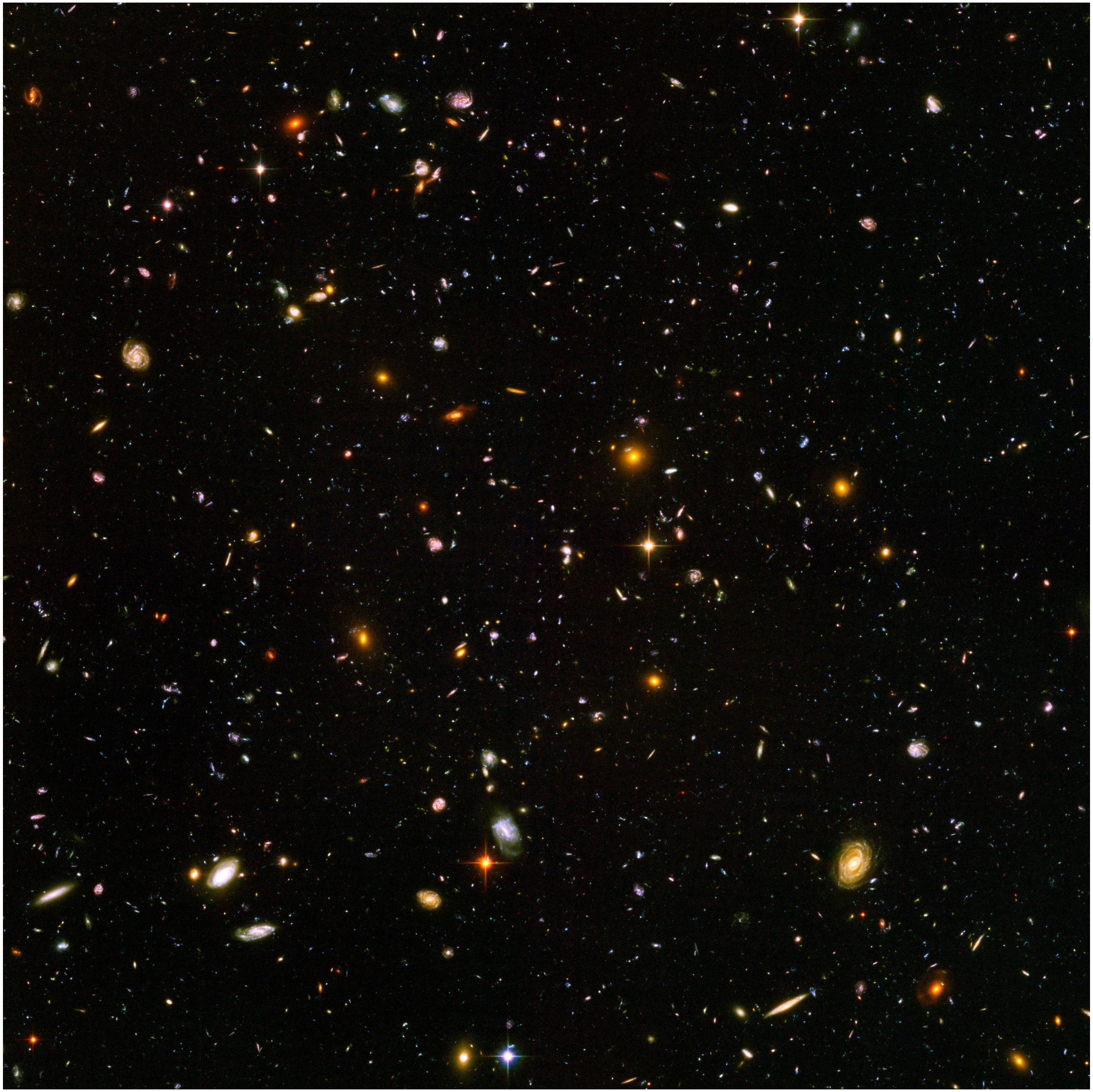
If the universe were

1. infinite

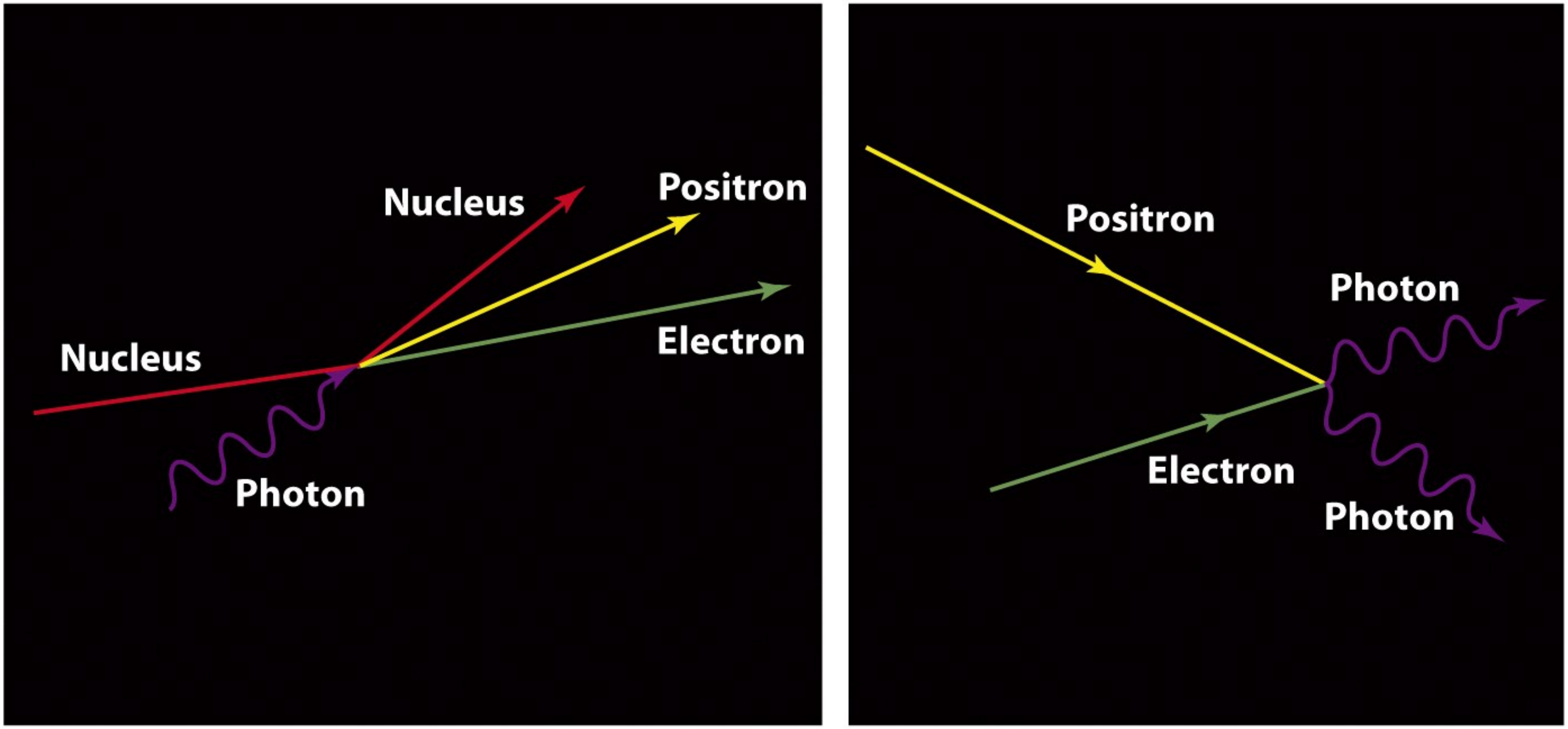
2. unchanging

3. everywhere the same

then stars would cover the night sky.



The night sky is dark because we see only the observable universe up to 13.8 billion light years distance.



a Nucleus collides with photon and creates positron-electron pair

b Positron and electron annihilate each other and create two photons

Time ⟶

Time ⟶

Figure 18-12
Discovering the Universe, Eighth Edition