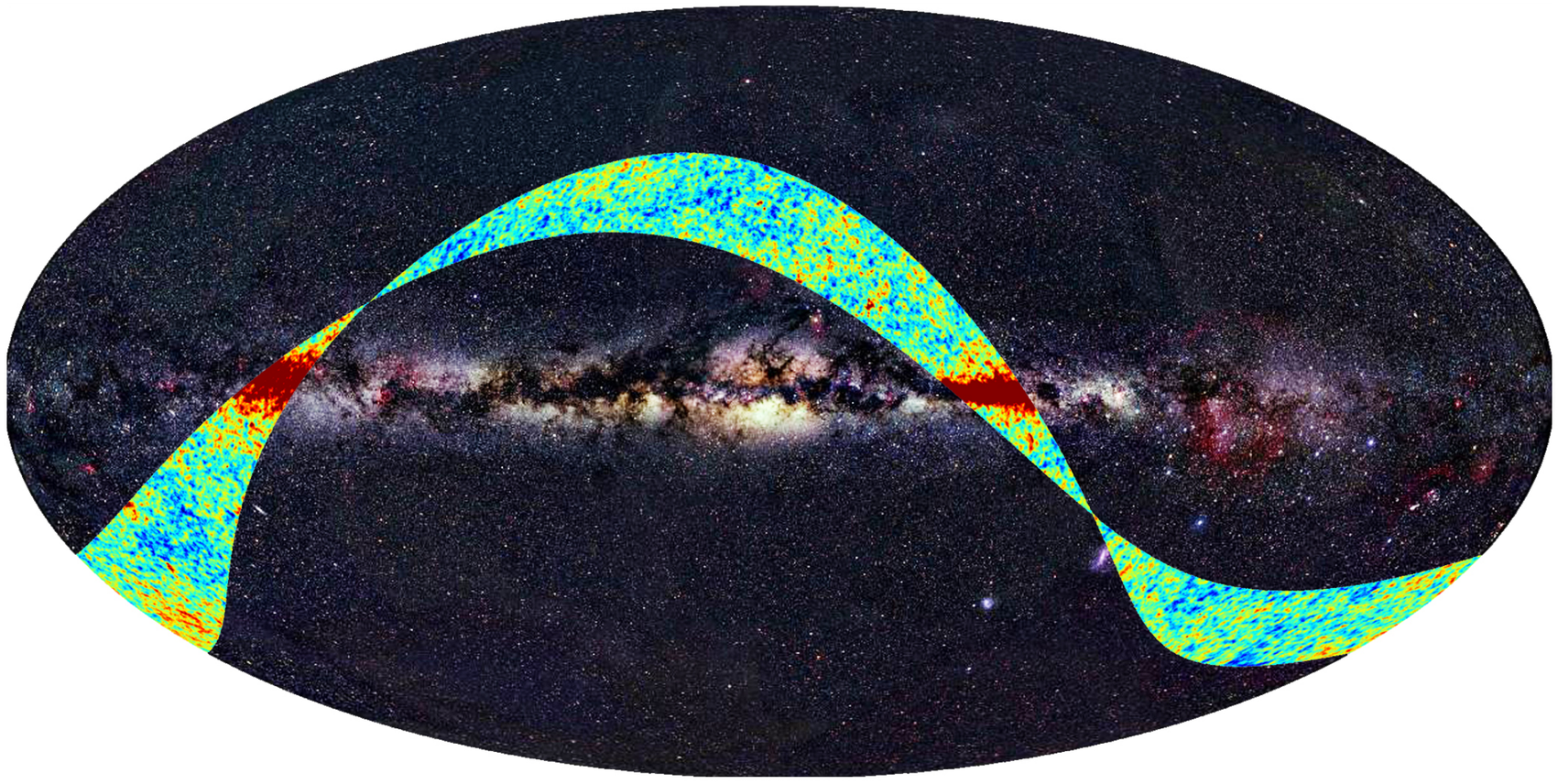
Clues from an unusual universe

from measurements to cosmology



Kevin M. Huffenberger
Assistant Professor, University of Miami

In what kind of universe do we live?

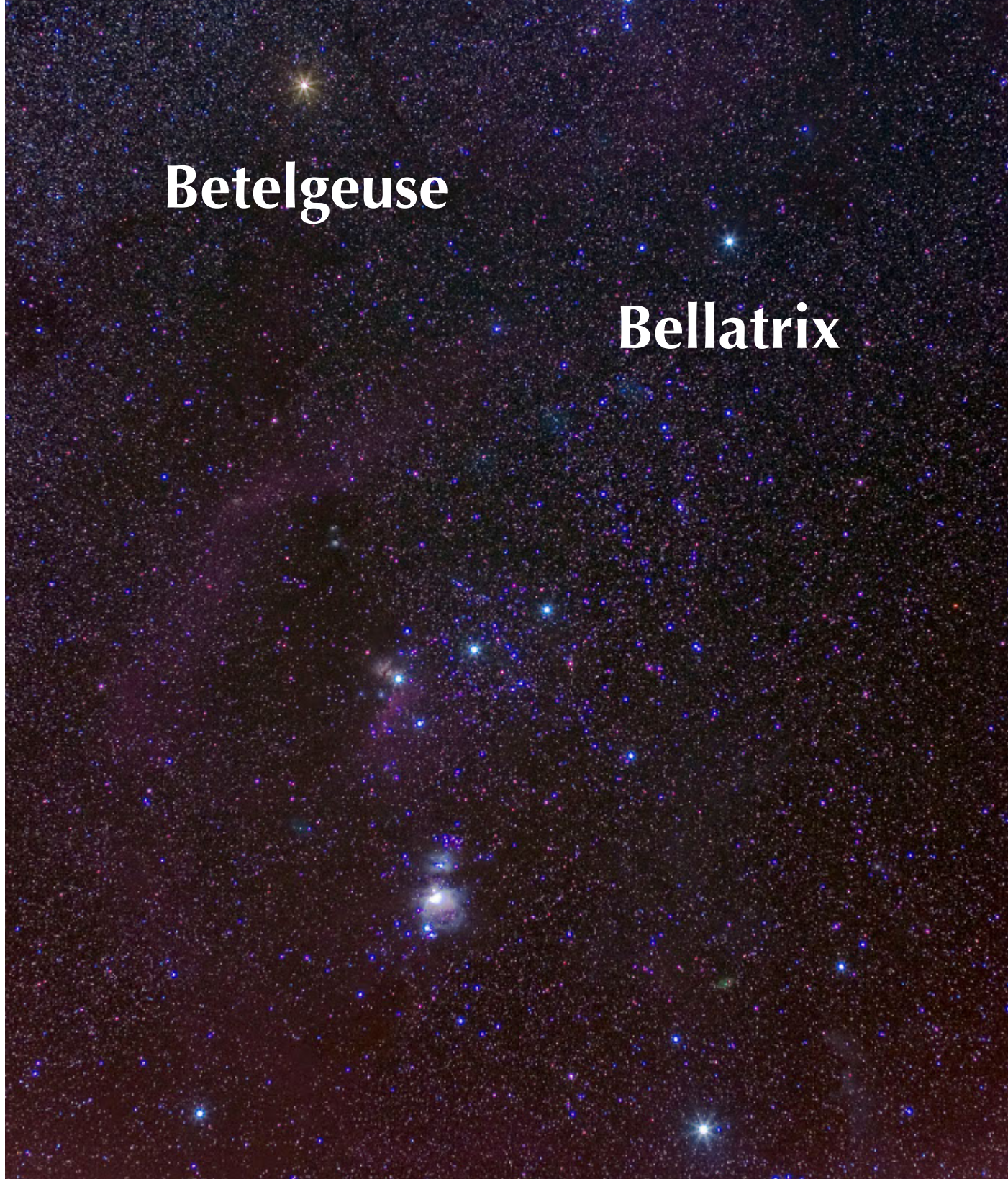
What are the contents?

What's the space-time like?

What is primordial seed of structure?

Distance problem in astronomy...

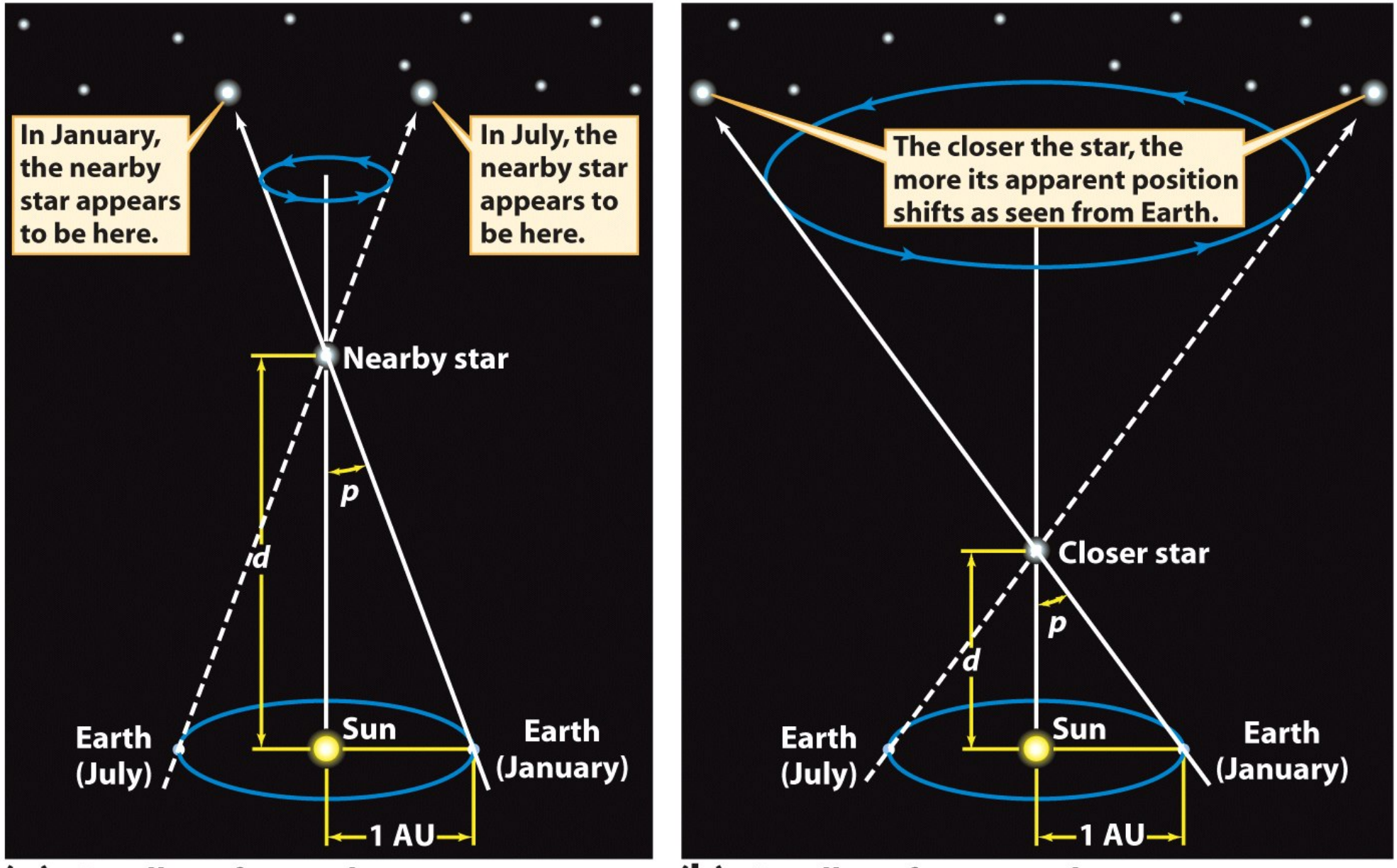
Which is further?



Figuring distance is a constant problem in astronomy.

Is a wide object actually big or just close?

Is a faint object dim or just far away?



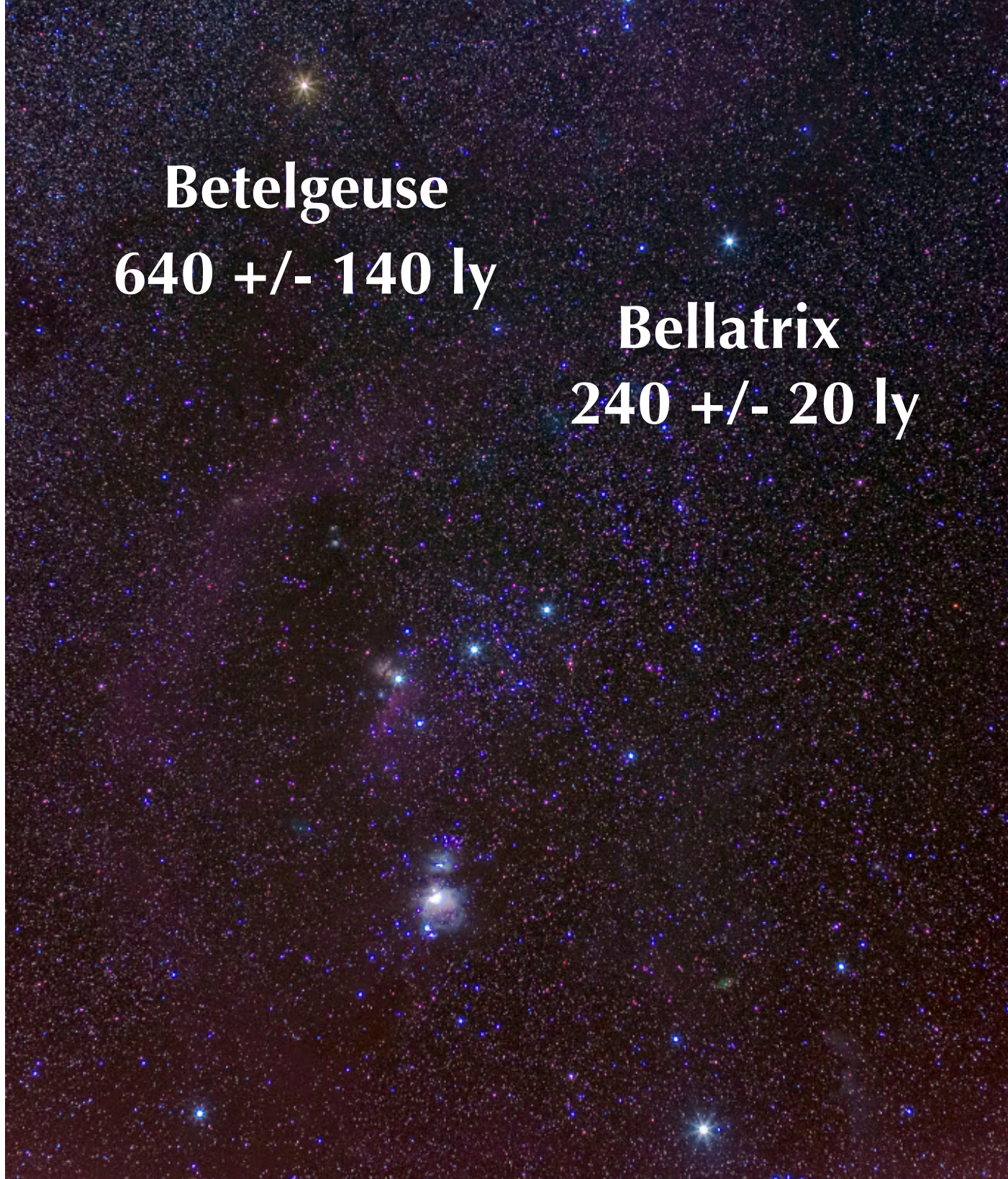
(a) Parallax of a nearby star

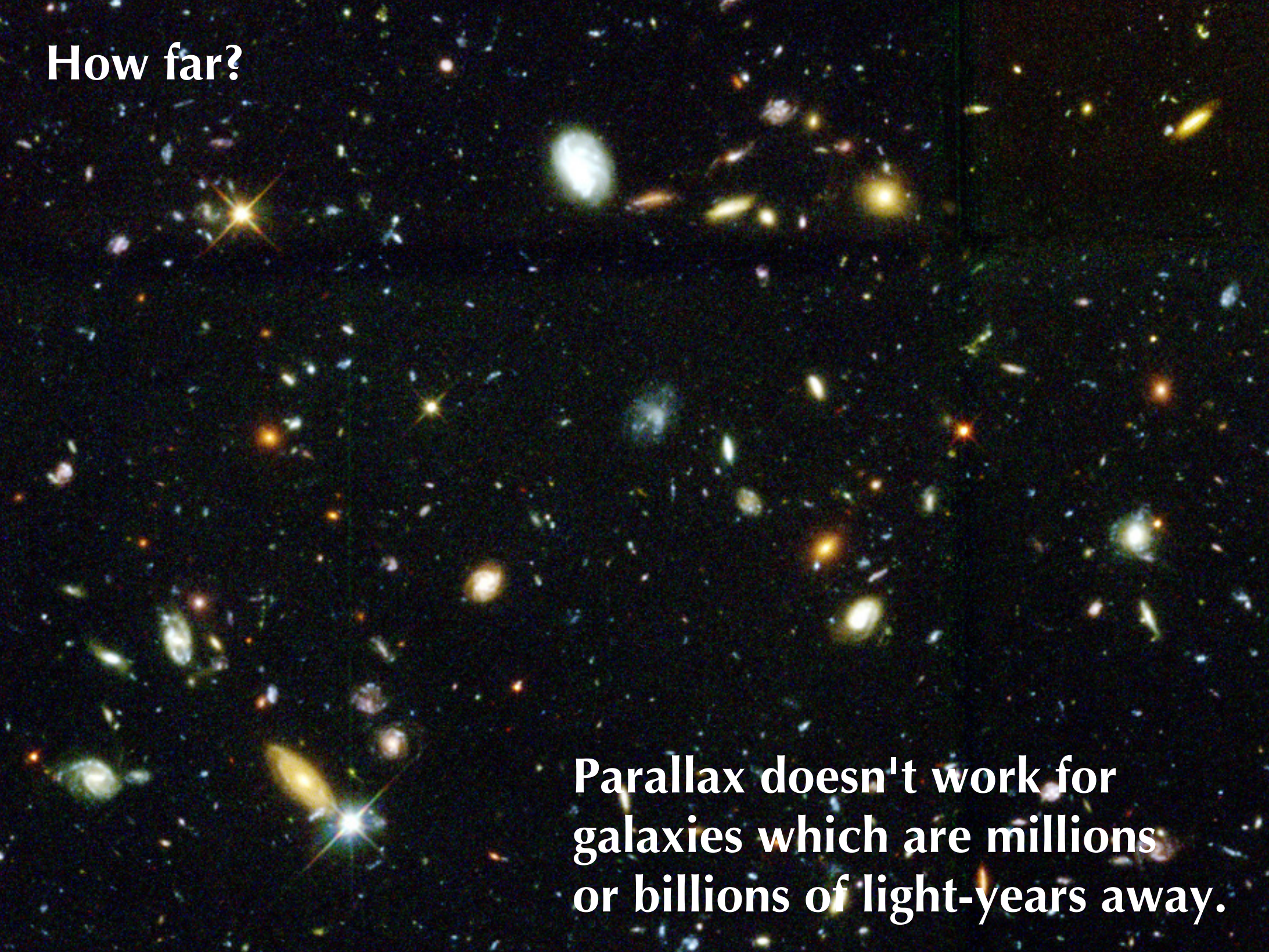
(b) Parallax of an even closer star

Figure 17-2
Universe, Eighth Edition

Distance problem in astronomy...

Which is further?




How far?
Parallax doesn't work for galaxies which are millions or billions of light-years away.

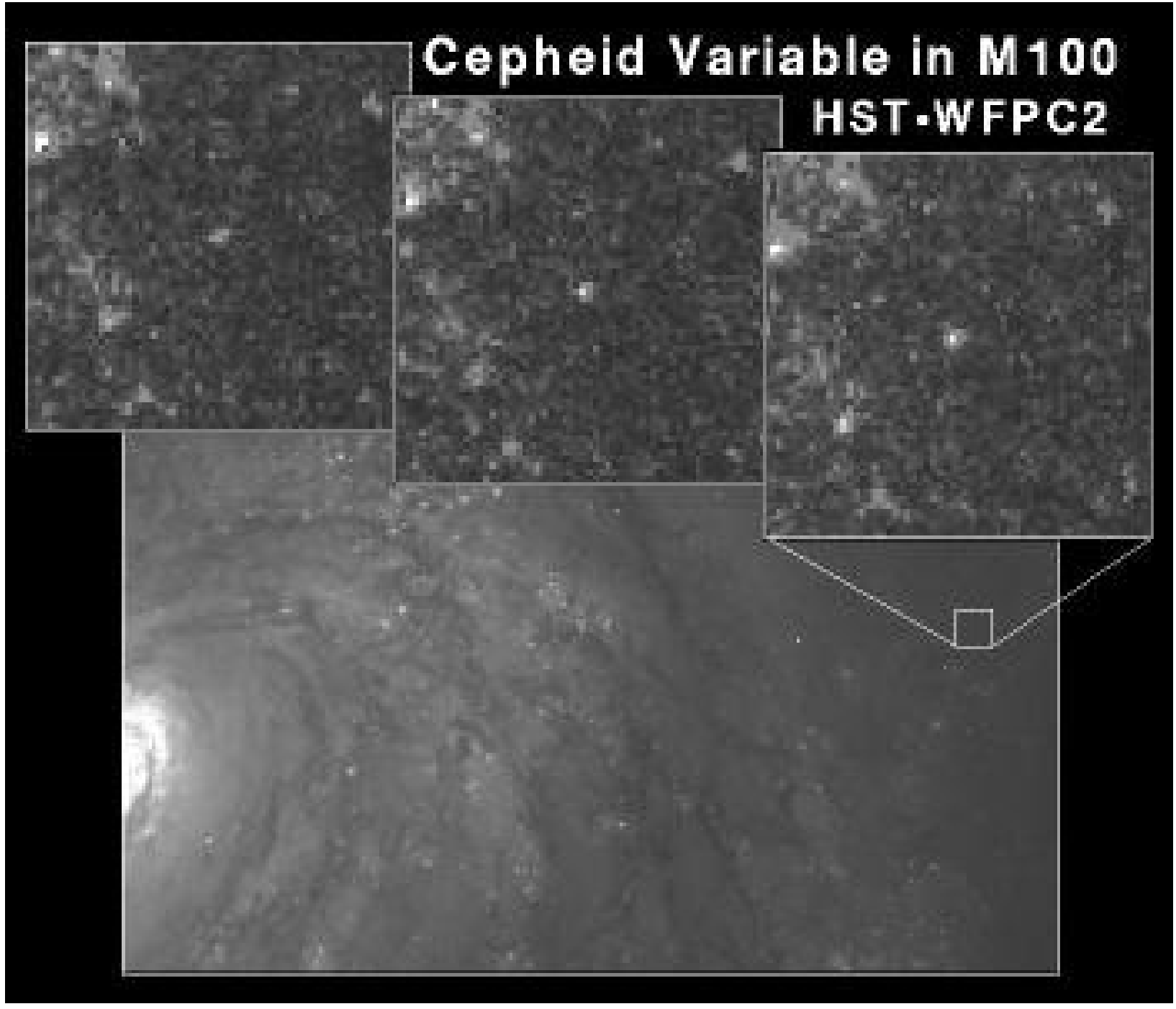
We can't figure out how far away most objects are because we don't know how bright they are.

BUT!

Cepheid variable stars are a "standard candle"

They pulsated in brightness over days/weeks

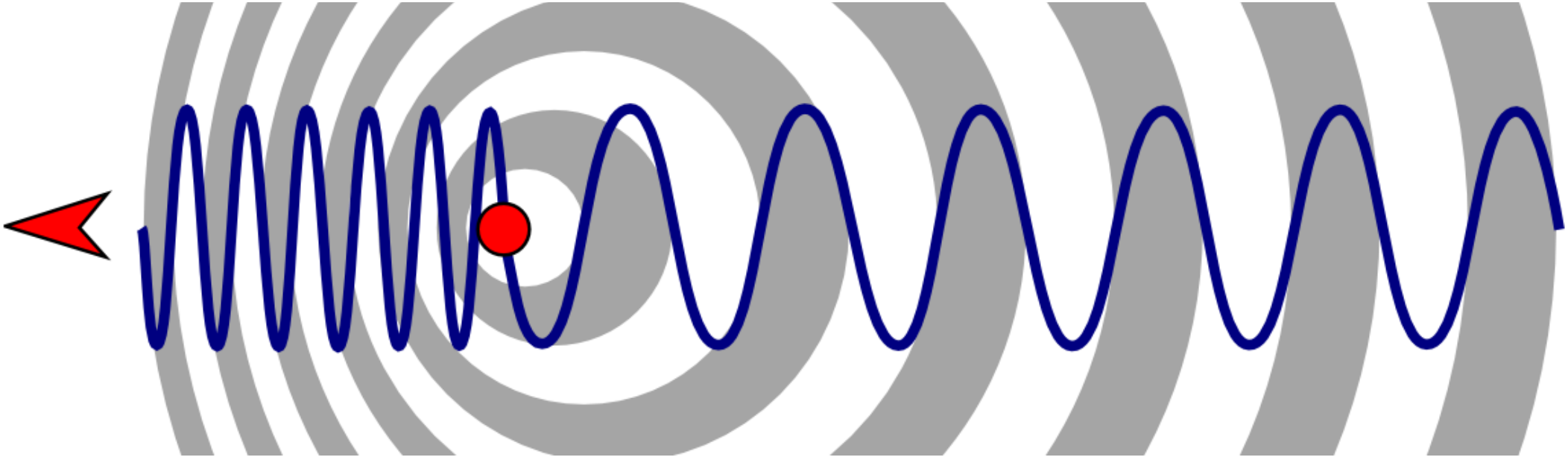
There is a *direct relationship* between luminosity and pulse period


Cepheid Variable in M100
HST•WFPC2

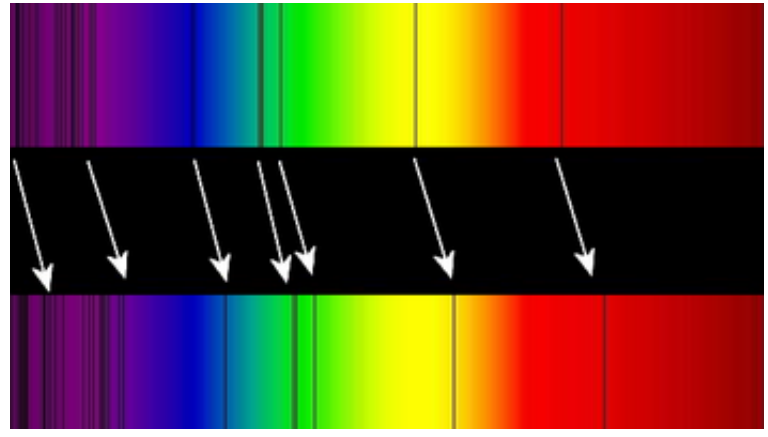
Edwin Hubble

... studied Cepheids in other galaxies during the 1920s

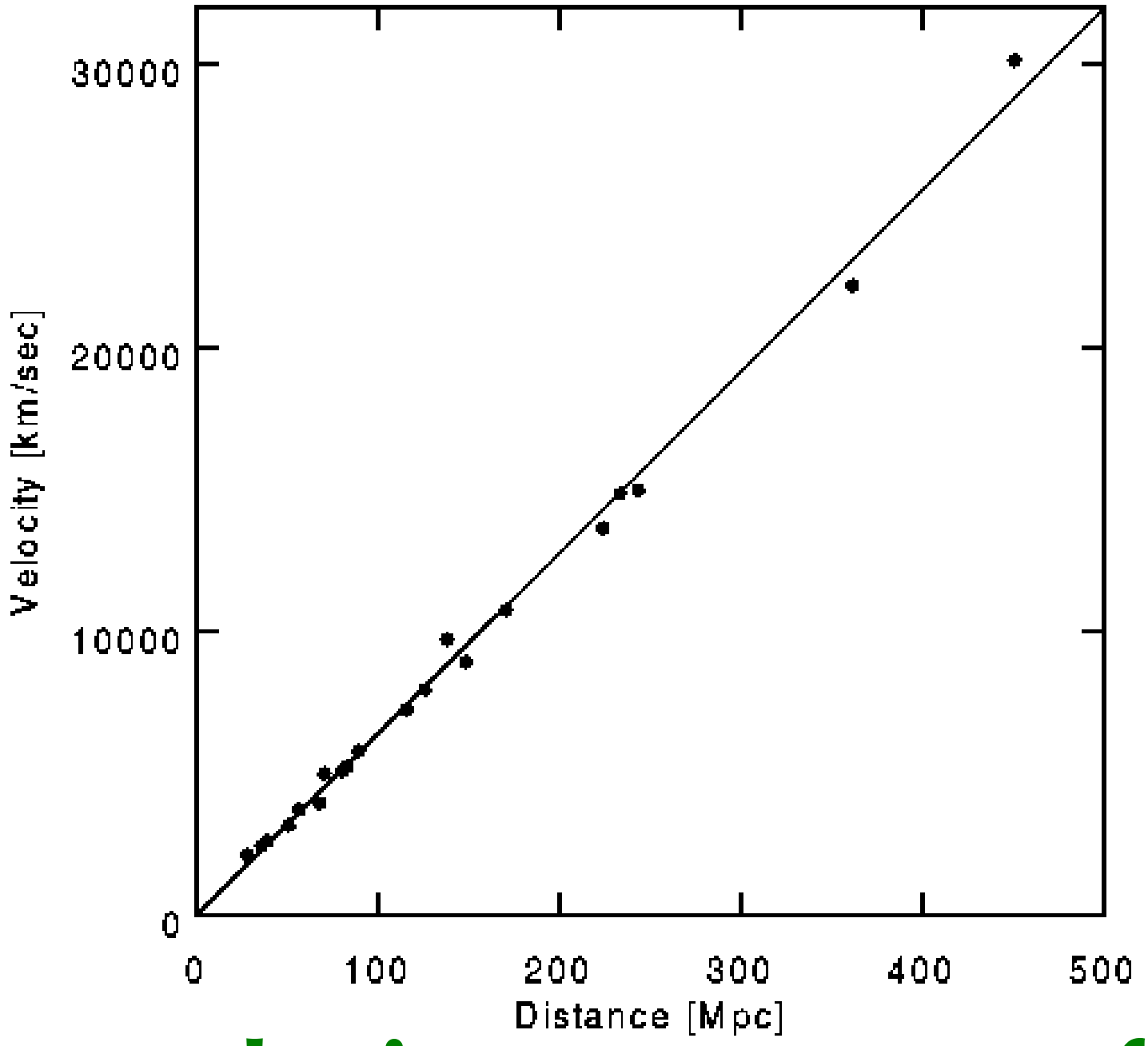
... and the motion of those galaxies with Doppler effect.



"blue-shift" **"red-shift"**



Hubble's remarkable conclusion

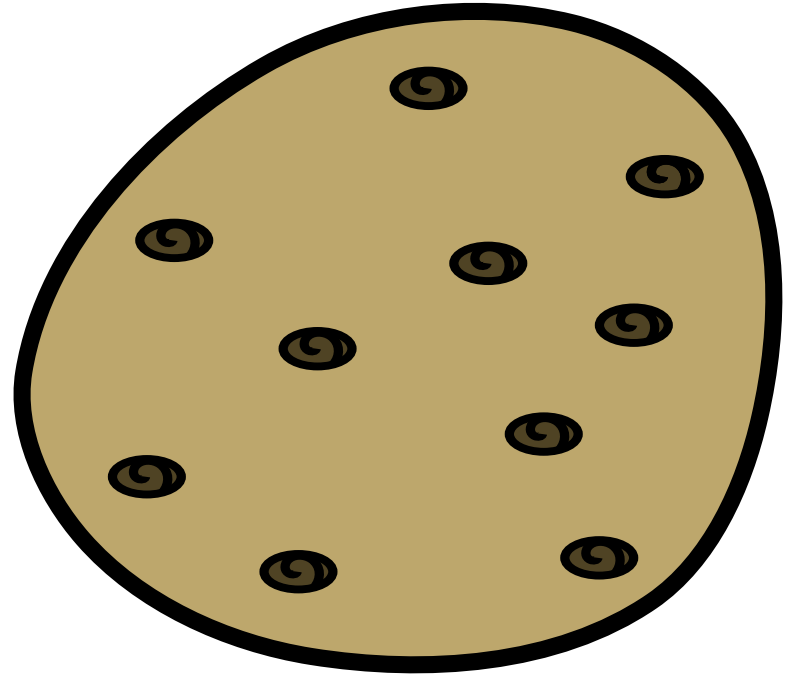


Distant galaxies move away from us!

Raisin bread metaphor

before baking:

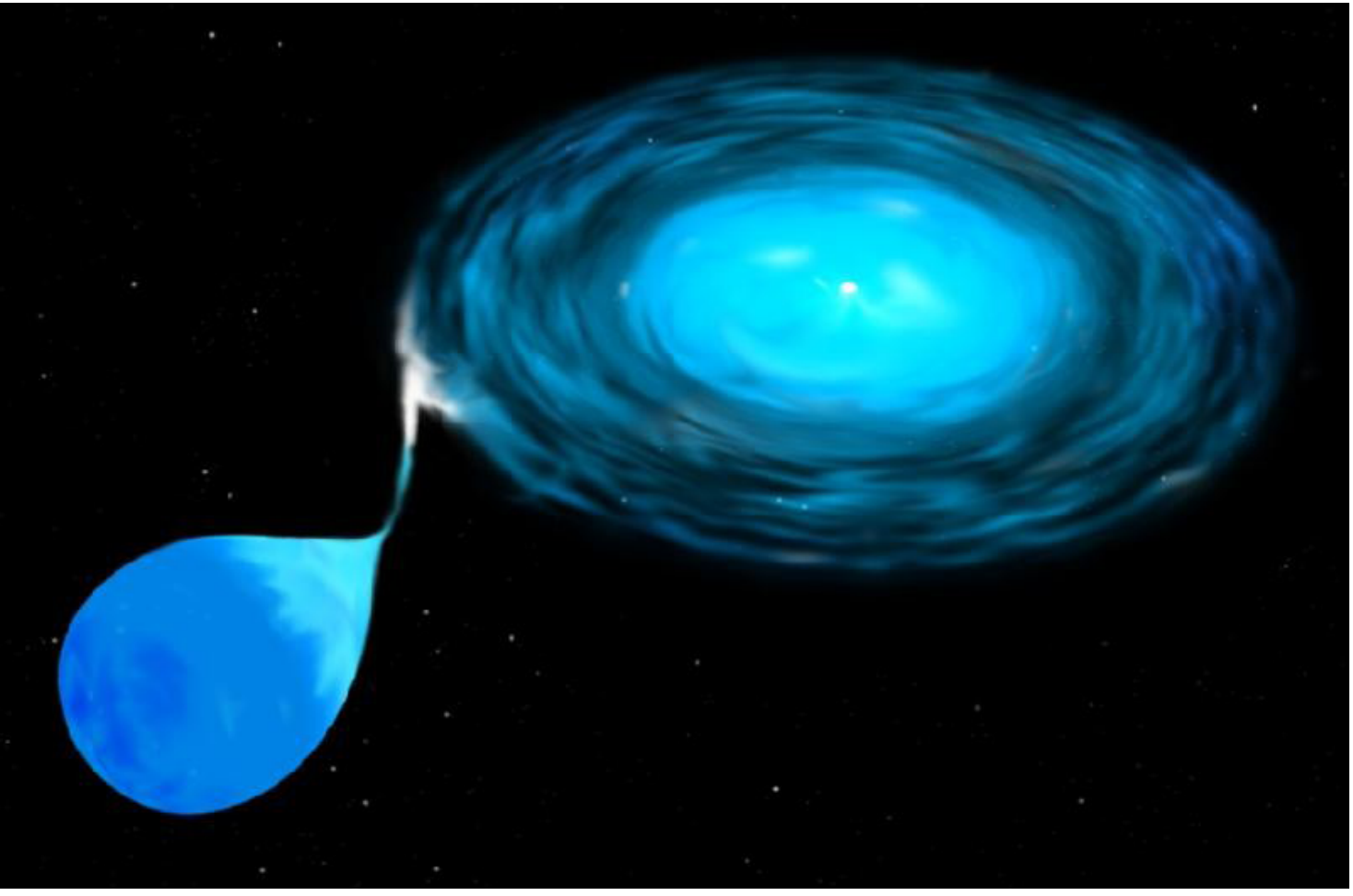
after:

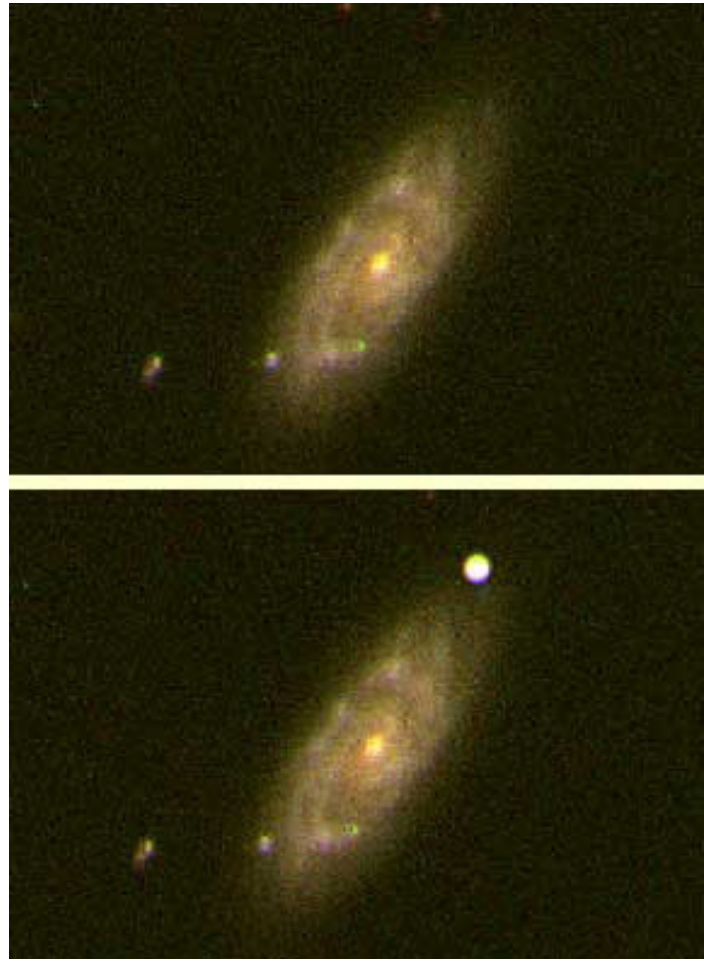


Distant raisins recede faster, just like Hubble found!

Universe is expanding!

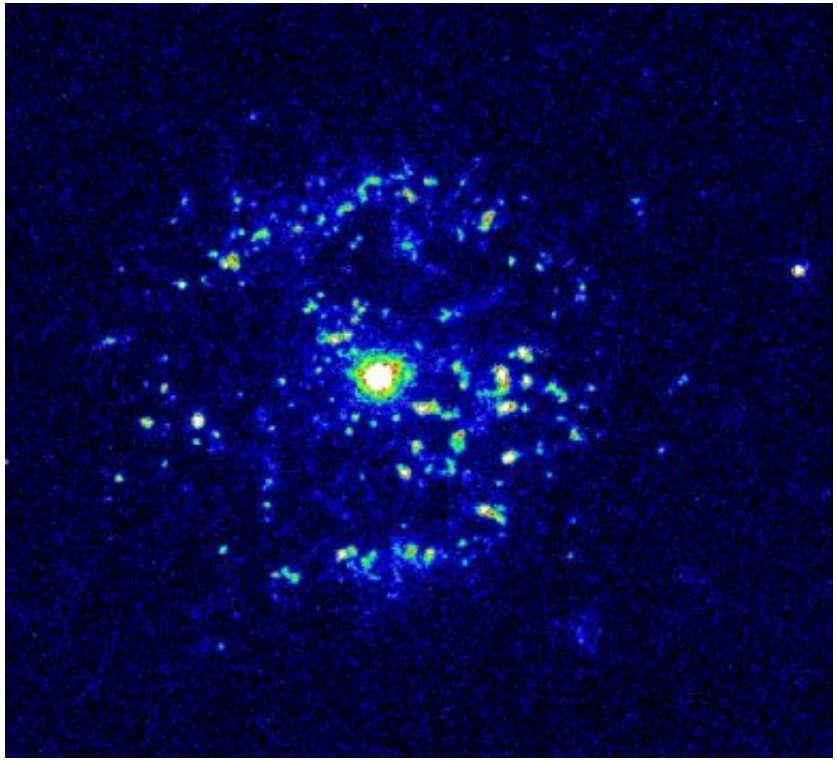
A brighter standard candle: Supernova Type 1a





1. White dwarf collects matter from companion
2. Boom!
3. Fade time gives light output, hence distance.

Nearby white dwarf T Pyxidis in the news



Used to vent (nova) every ~20 years, but not since 1966.

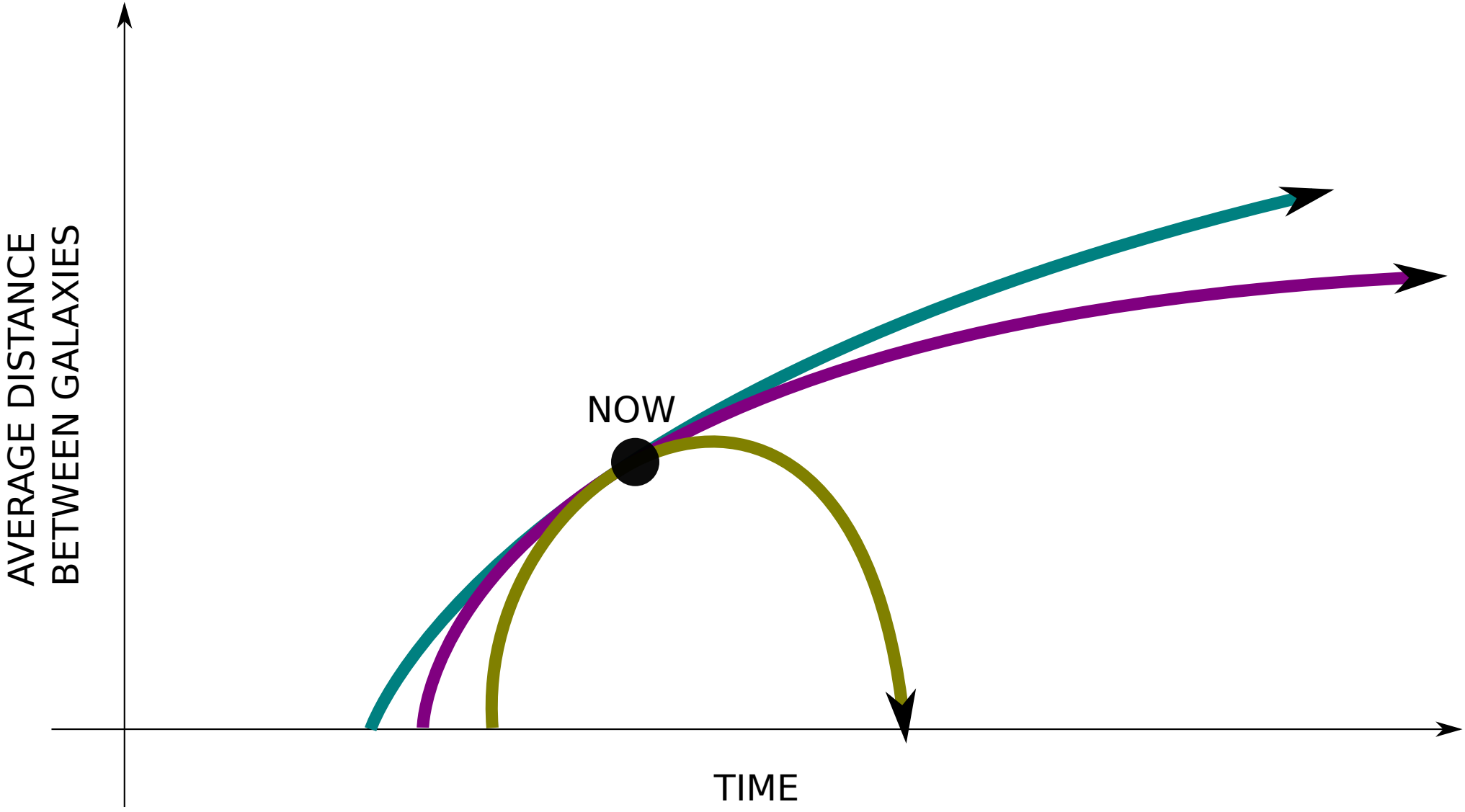
Nearby... 3200 light years.

May Supernova "soon," within ten million years.

Claims it would destroy Earth by zapping the ozone appear mistaken / exaggerated.

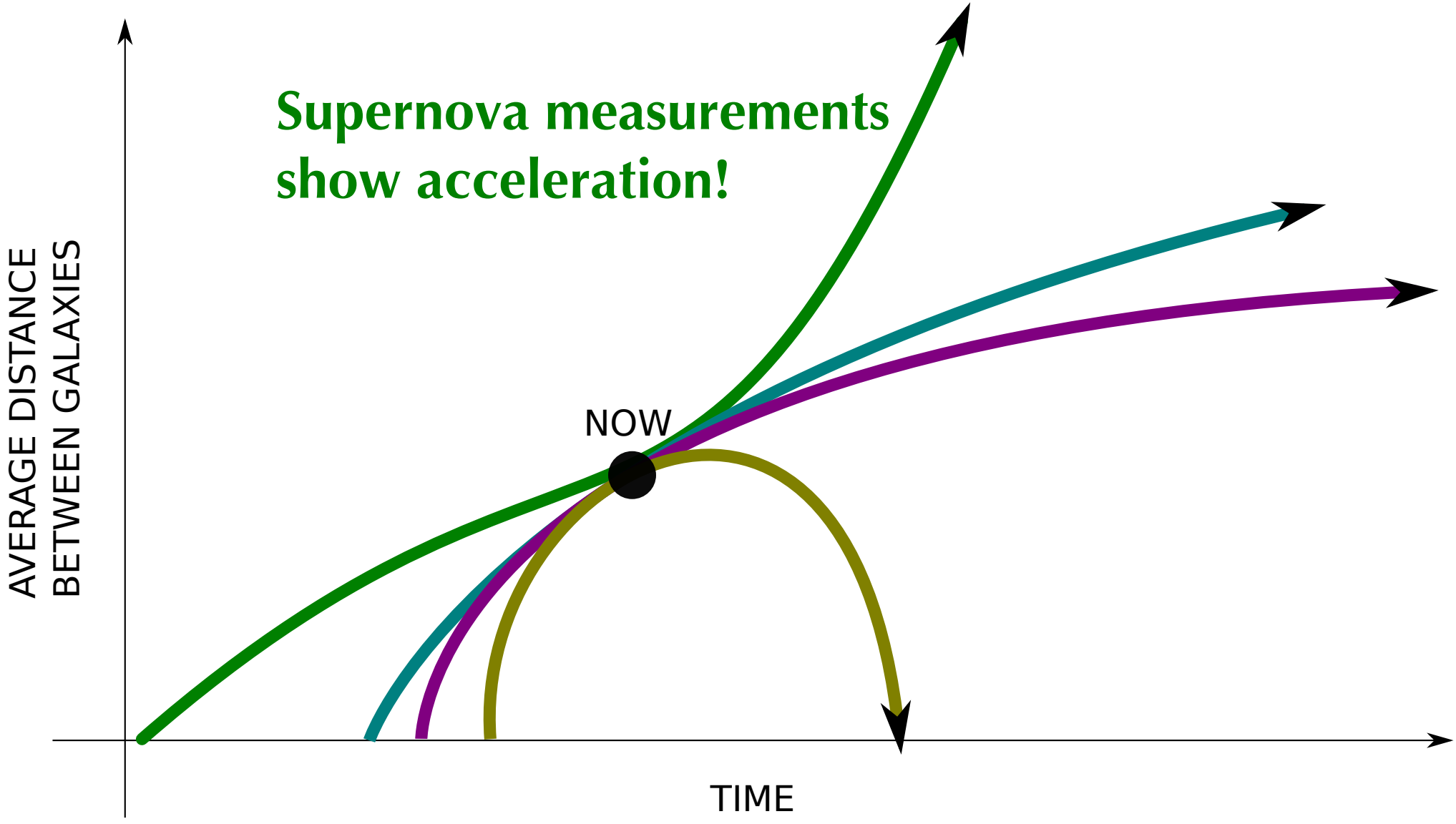
Expansion history/future

... based on Einstein's model for gravity.



Expansion history/future

... based on Einstein's model for gravity.



Type Ia SN indicate expansion is accelerating

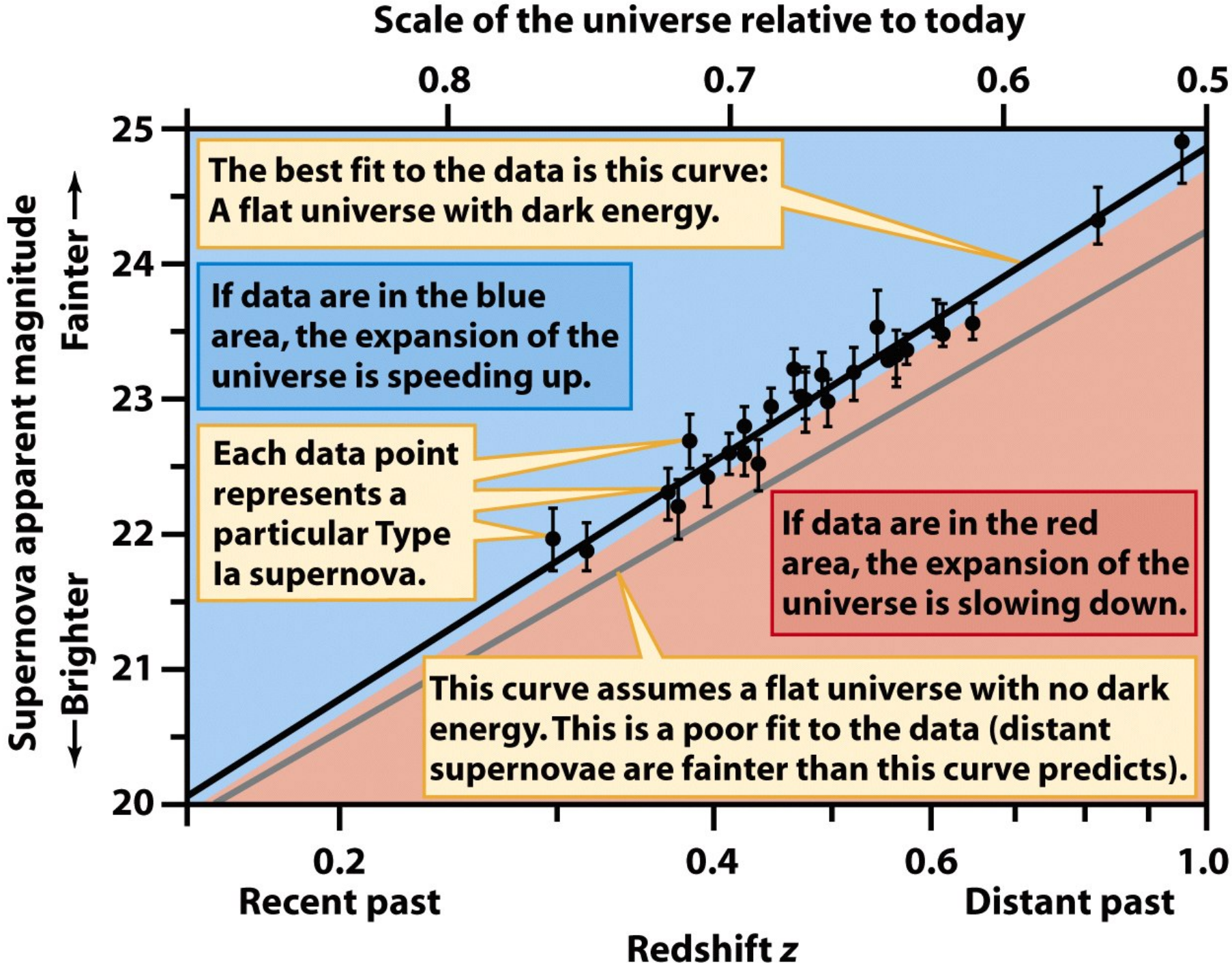
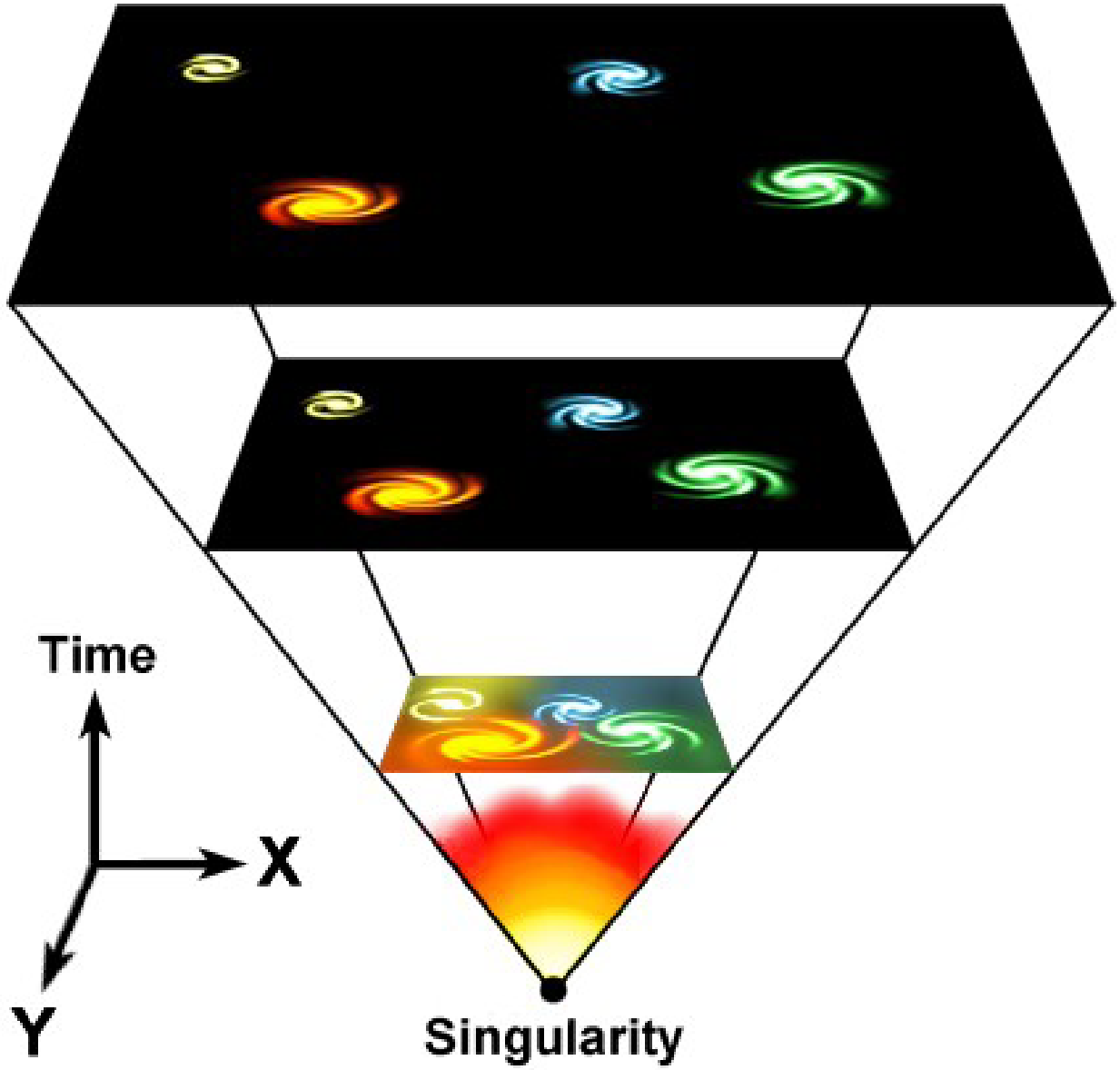


Figure 26-18

Expanding universe & the Big Bang



Thermal history of the Universe

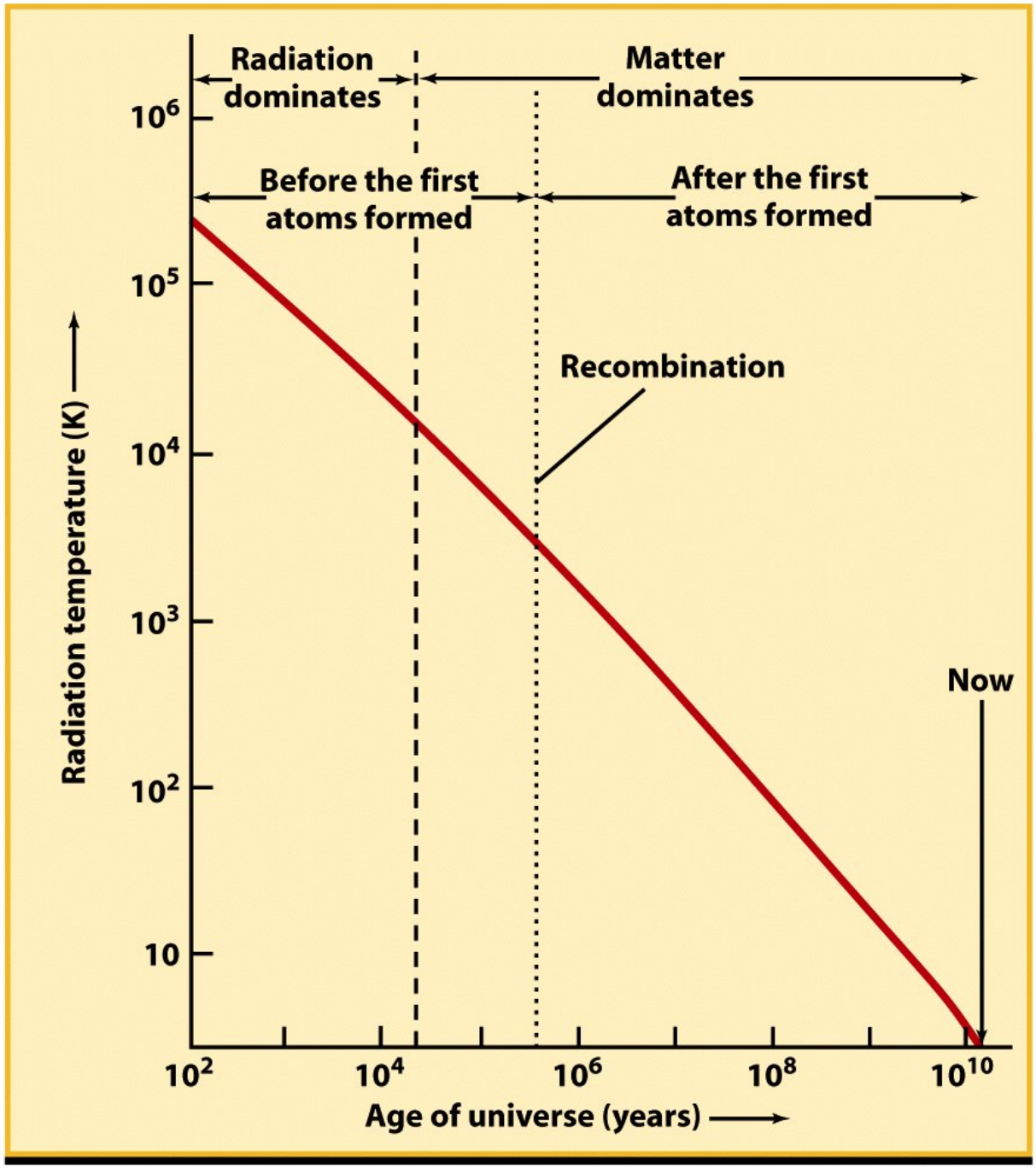


Figure 26-11
Universe, Eighth Edition

Hot, dense objects glow with a specific spectrum

Technical term: "Blackbody radiation"

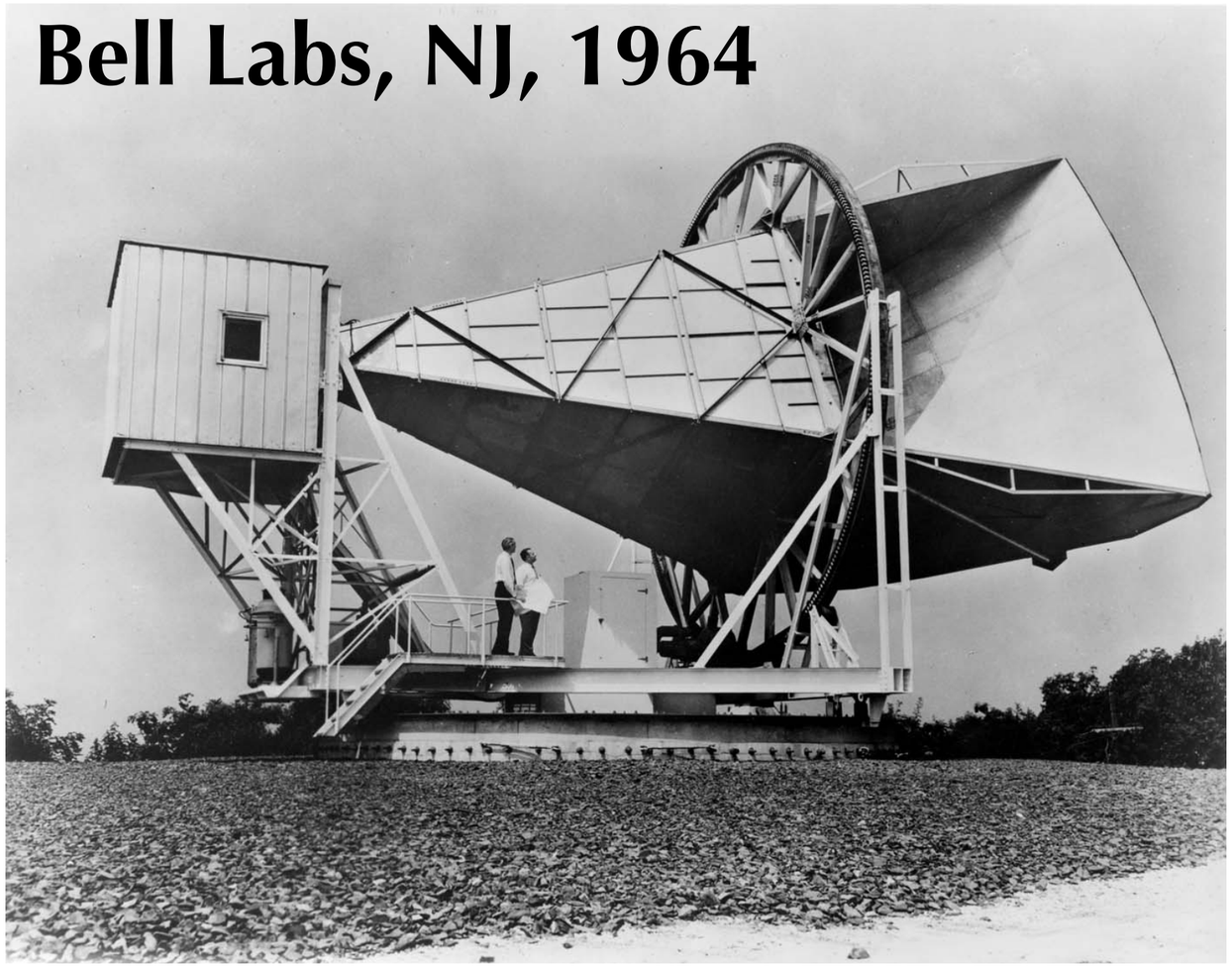
Big Bang's afterglow

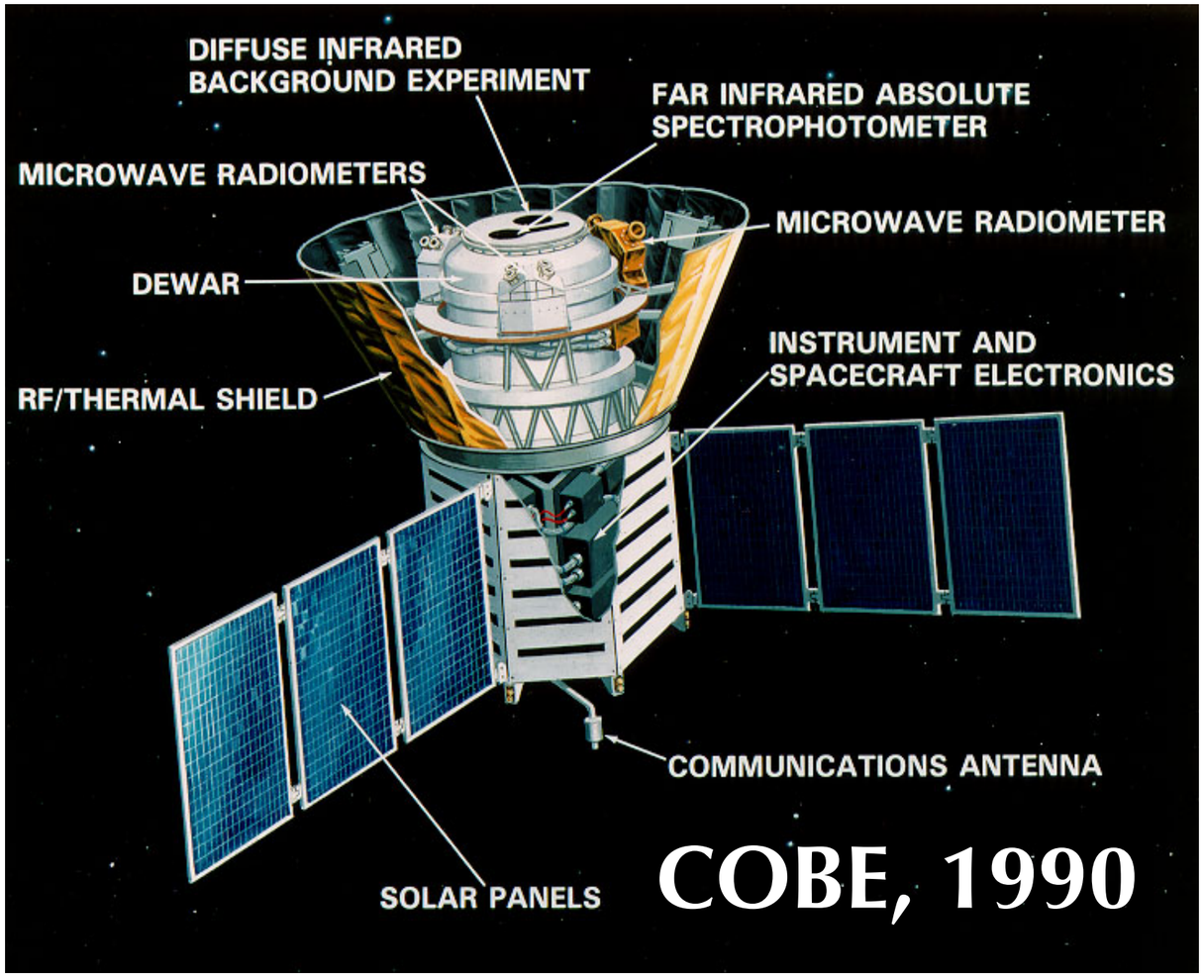
Dense, hot initial state → **Relic Background Radiation**

redshifted to microwaves.

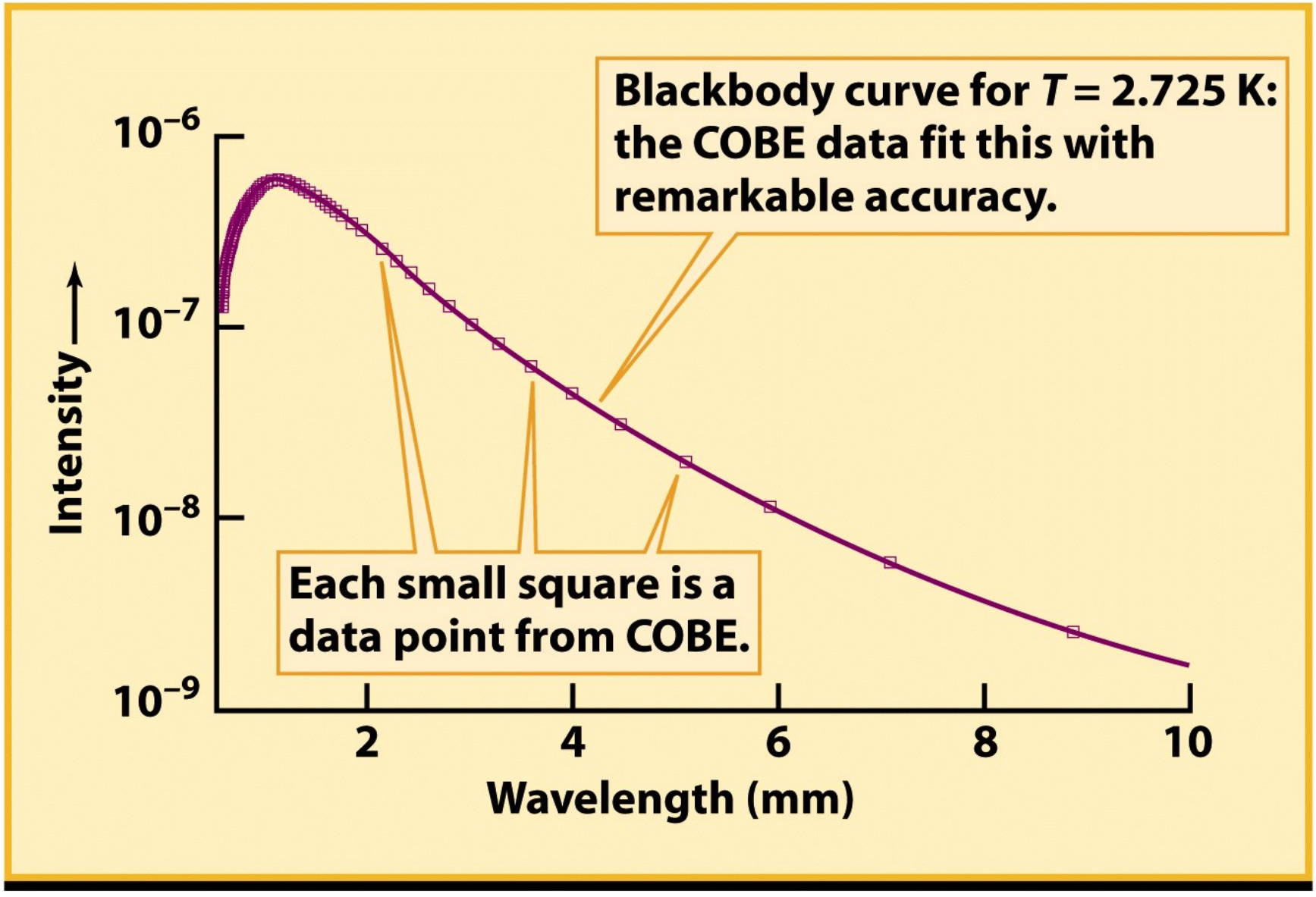
Cold: 3 K above abs. zero

Bell Labs, NJ, 1964





Each resulted in a Nobel prize!



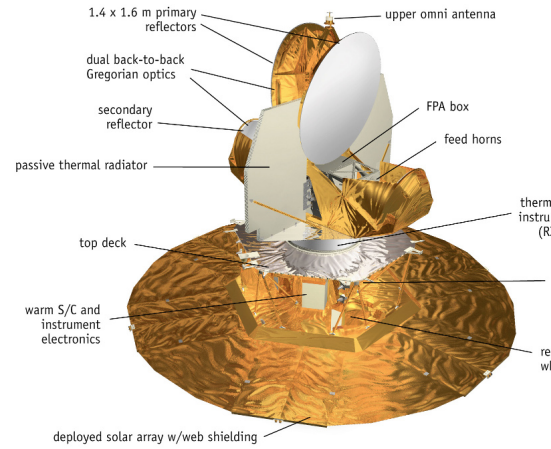
The spectrum of the cosmic microwave background

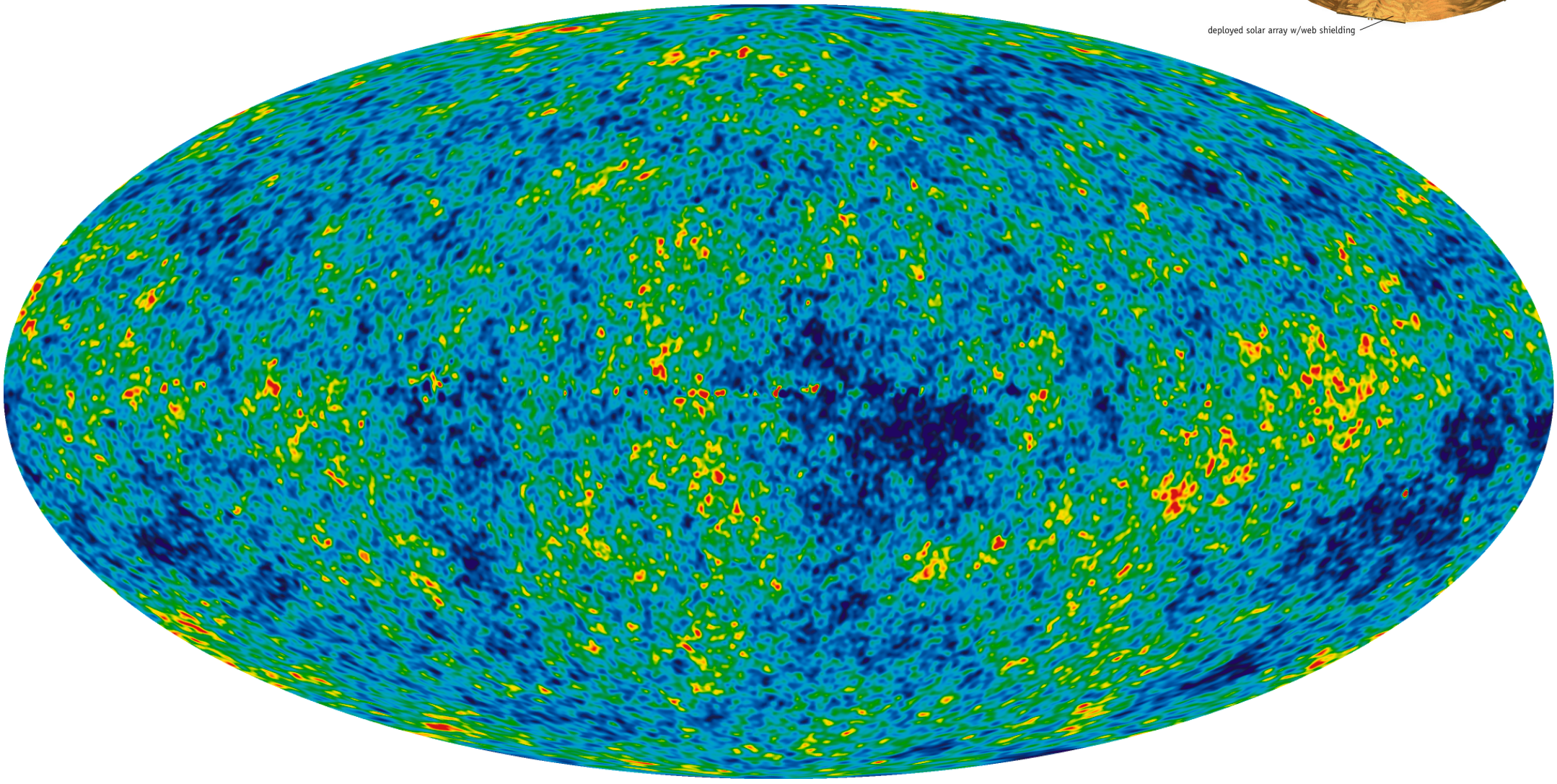
Figure 26-7b
Universe, Eighth Edition

Cosmic Microwave Background (CMB)

Very uniform!

WMAP →

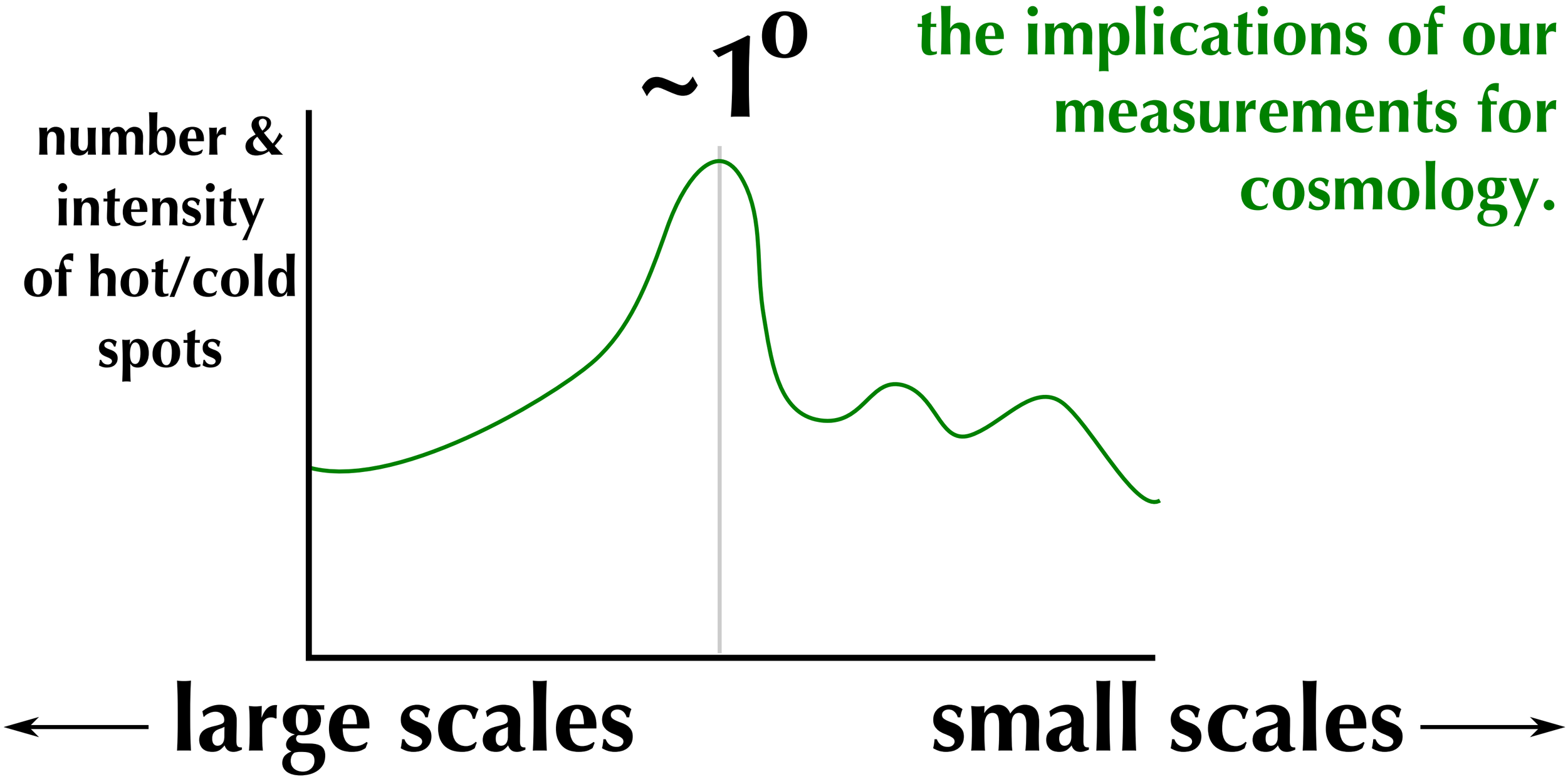




Few ten-thousands of a degree fluctuation.

CMB "power spectrum"

... our tool to understand the implications of our measurements for cosmology.



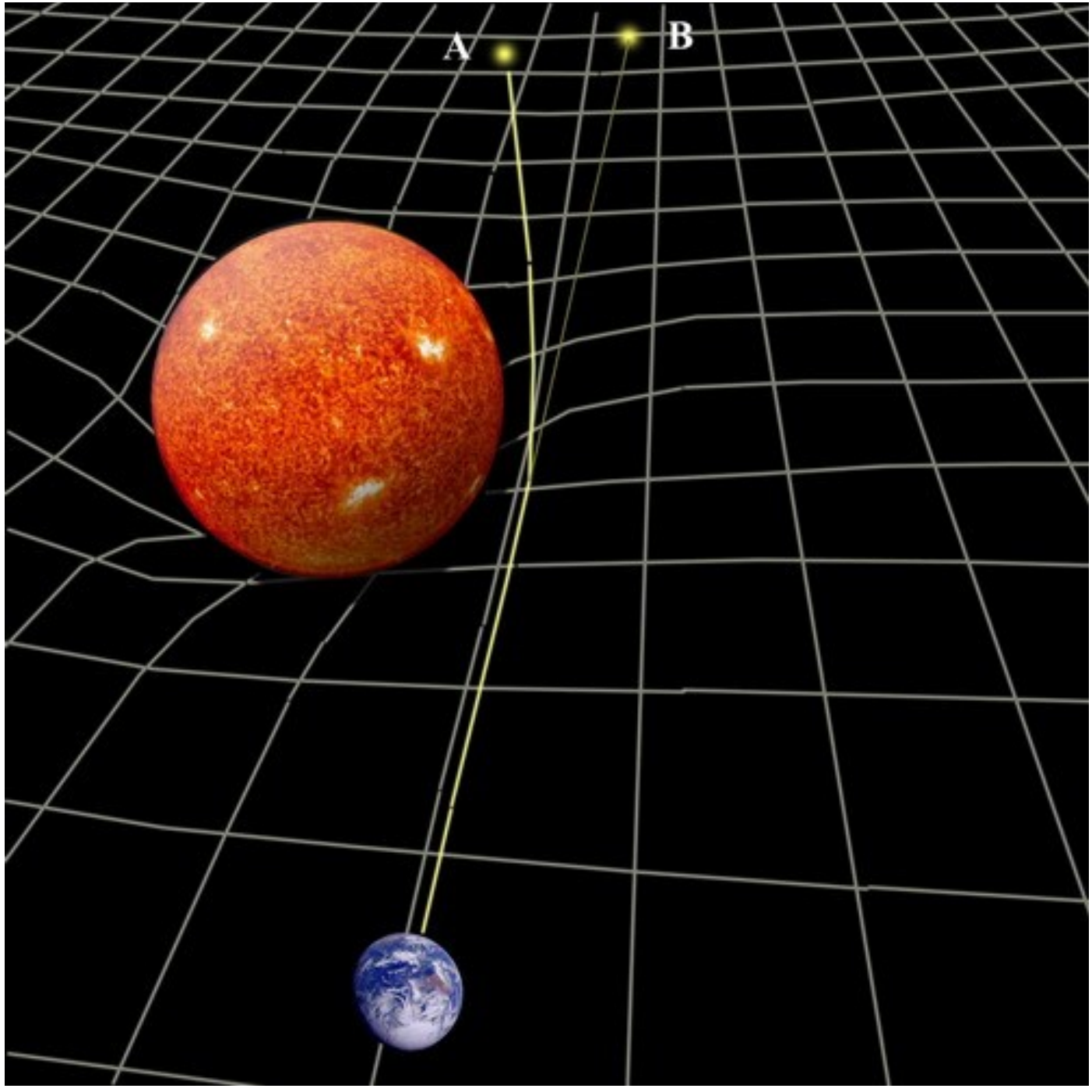
General Relativity: Einstein's theory of gravity

Field equations:

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$$\left(\begin{array}{c}\text{Curvature}\\ \text{of}\\ \text{space-time}\end{array}\right) = (\text{ constant }) \times \left(\begin{array}{c}\text{Matter}\\ \&\\ \text{Energy}\end{array}\right)$$

Gravity = curvature of spacetime.

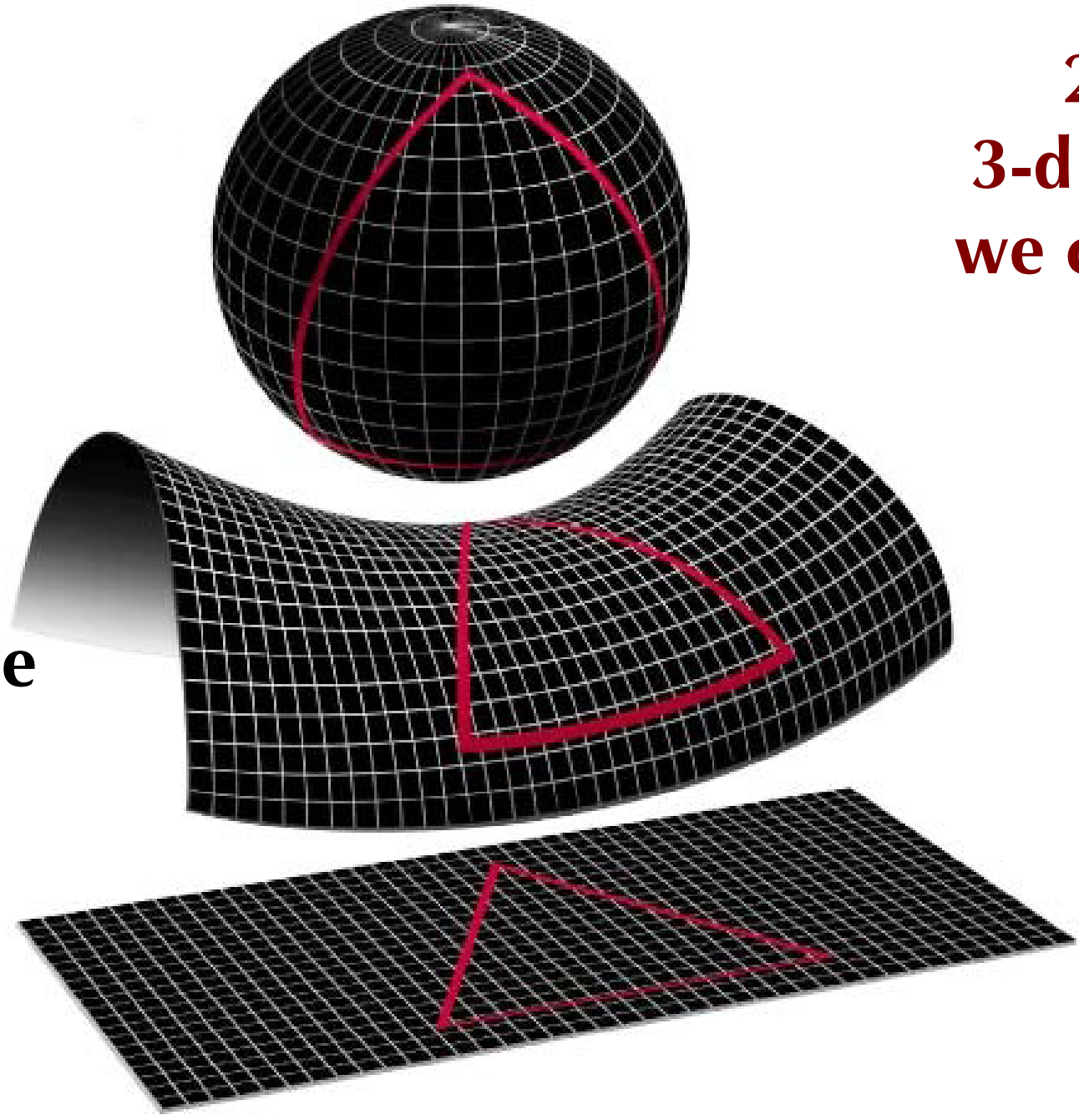


Gravity = curvature of spacetime.

ball

saddle

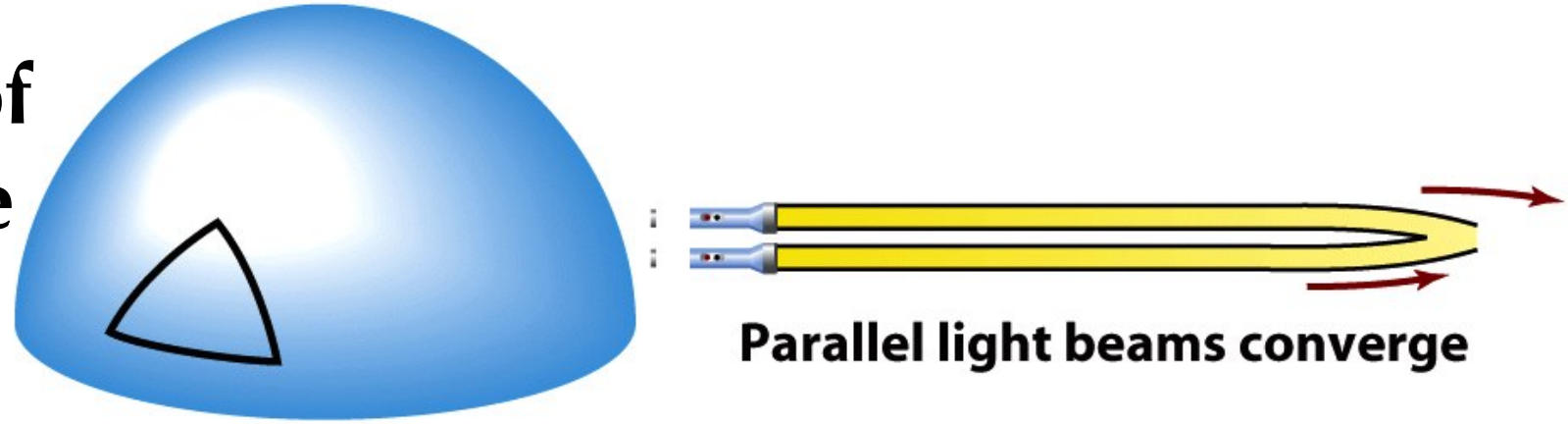
flat



2-d analogs for 3-d curved spaces we can't visualize.

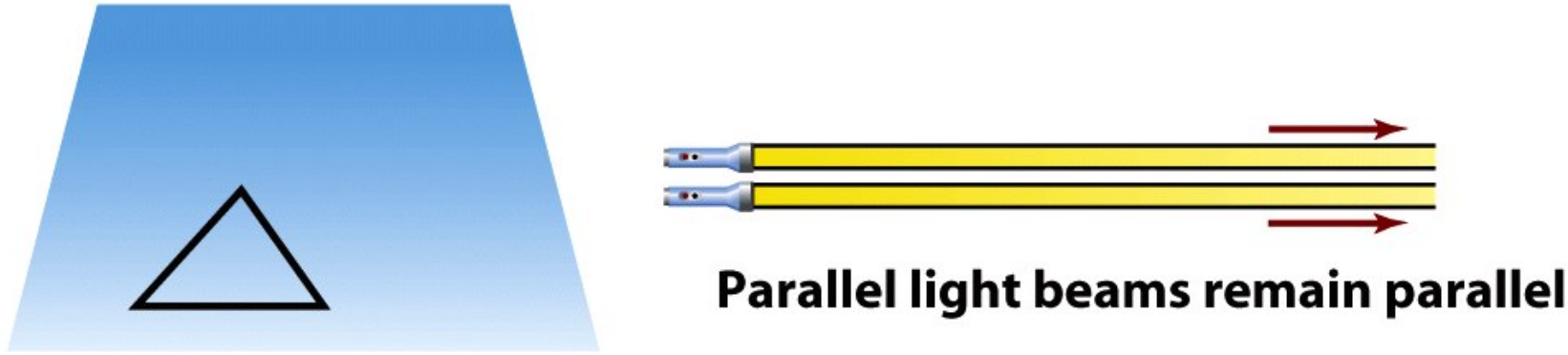
MAP990006

Geometry of the universe



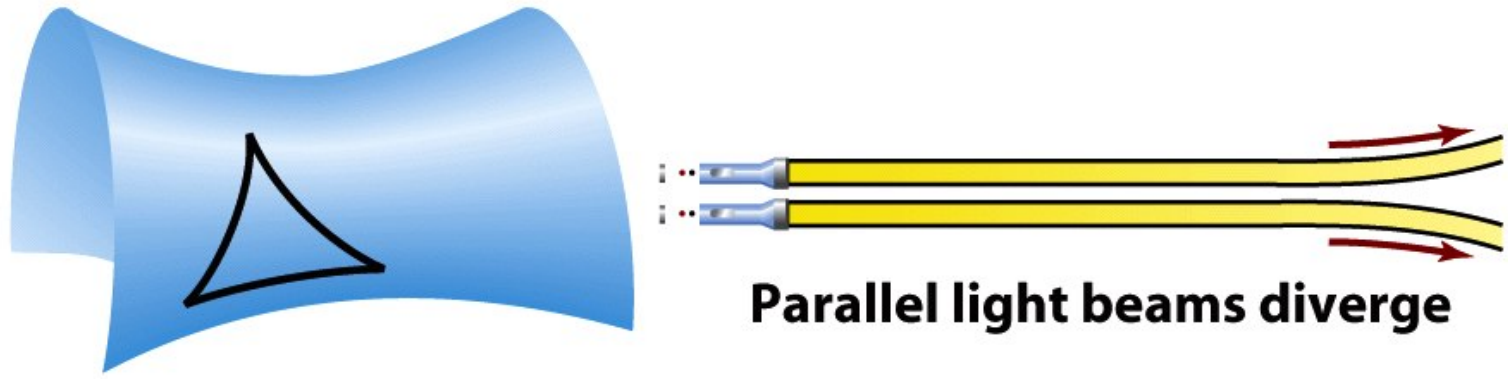
(a) Spherical space

$\rho_0 > \rho_c$, $\Omega_0 > 1$



(b) Flat space

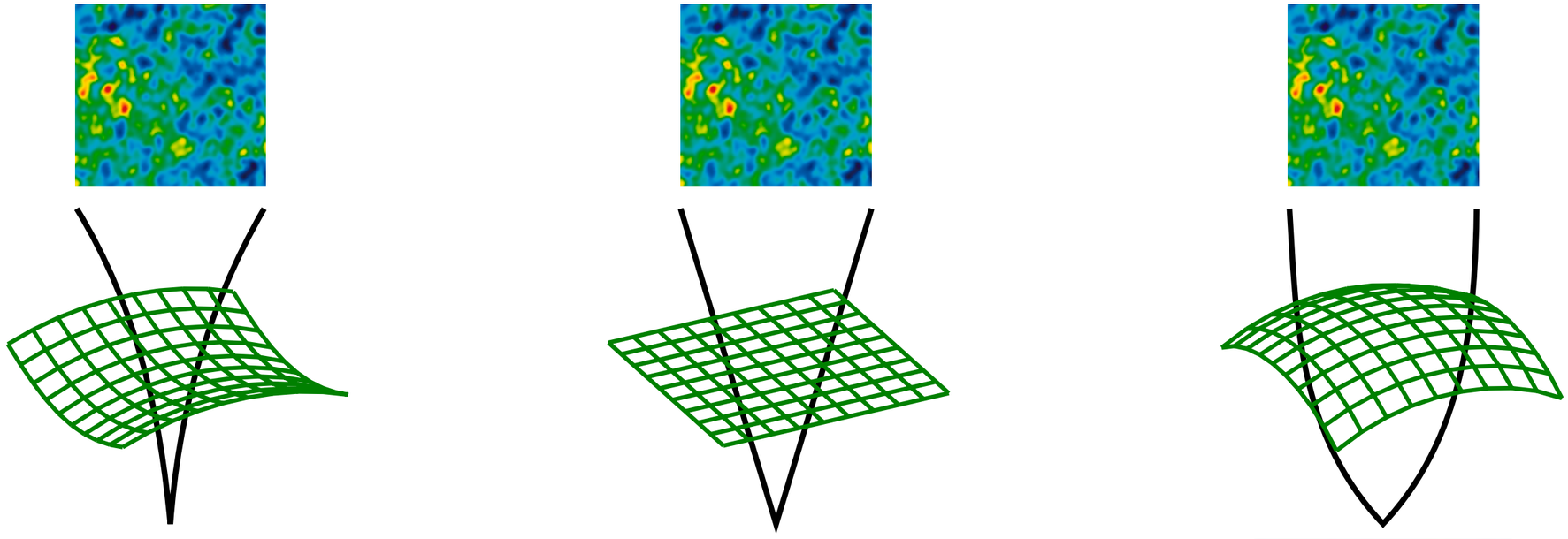
$\rho_0 = \rho_c$, $\Omega_0 = 1$



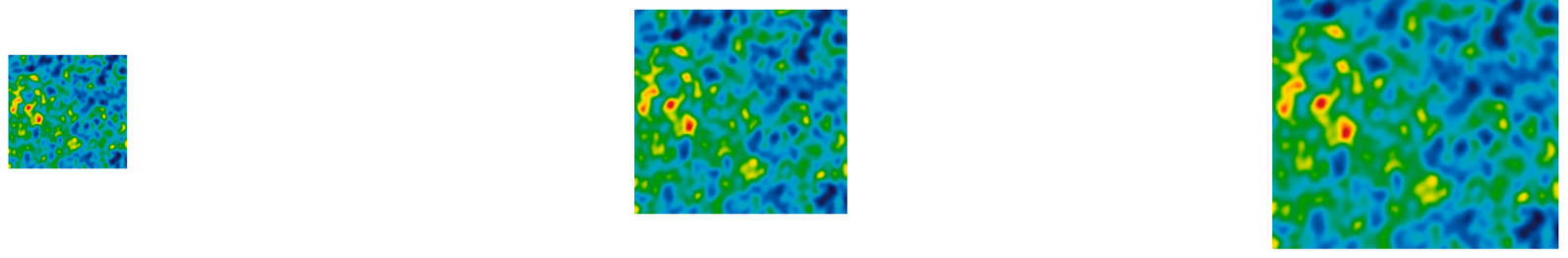
(c) Hyperbolic space

Measuring curvature

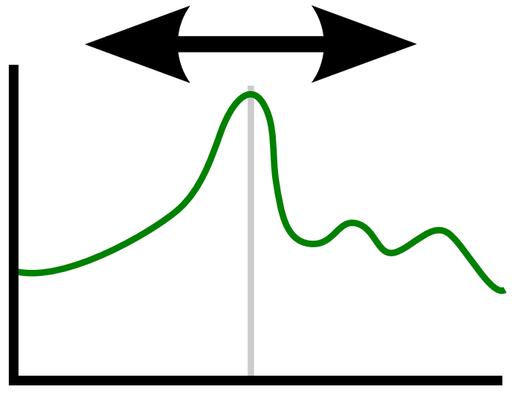
CMB surface



CMB observed



Viewing standard ruler through curved spacetime.



Universe's contents

3 components cosmologically relevant:

1. baryons, atoms, "normal matter".

2. cold dark matter, normal gravity, no pressure, no interactions.

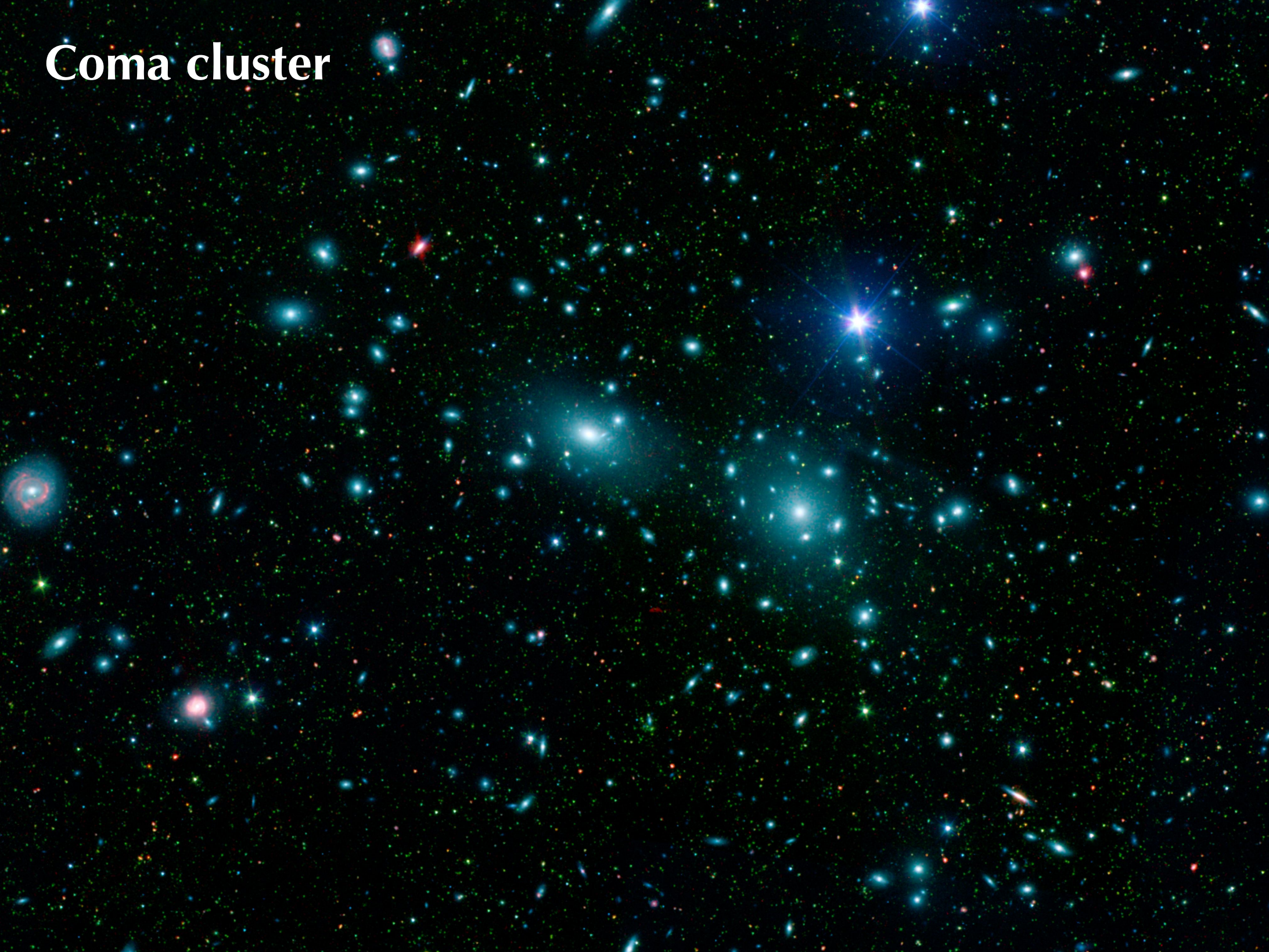
3. dark "energy", Λ = Lambda, anti-gravity, cosmological constant, acceleration.

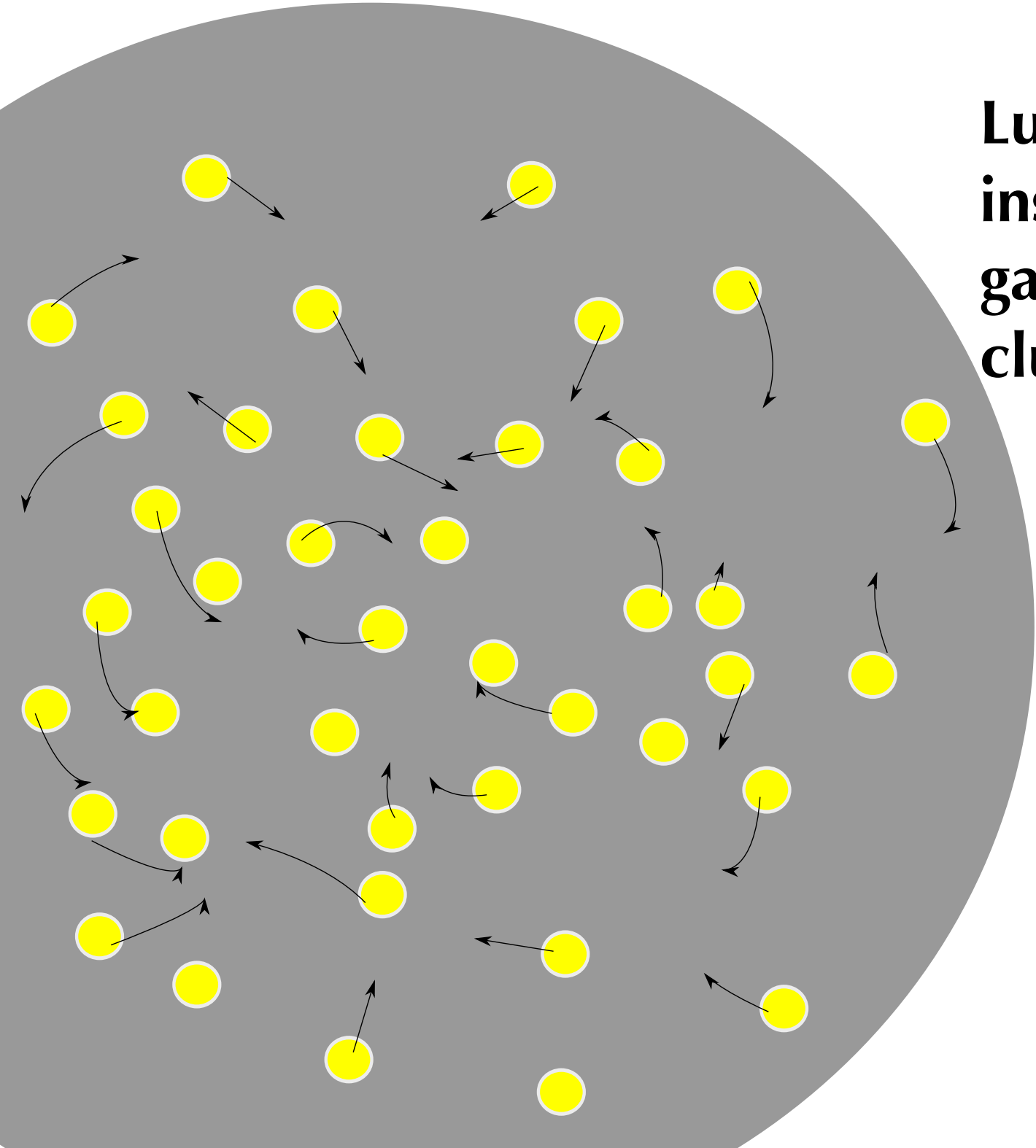
The Dark-Matter Problem

- Visible mass in *galaxies* too small for star motions.
- Visible mass *galaxy clusters* too small for galaxy motions.

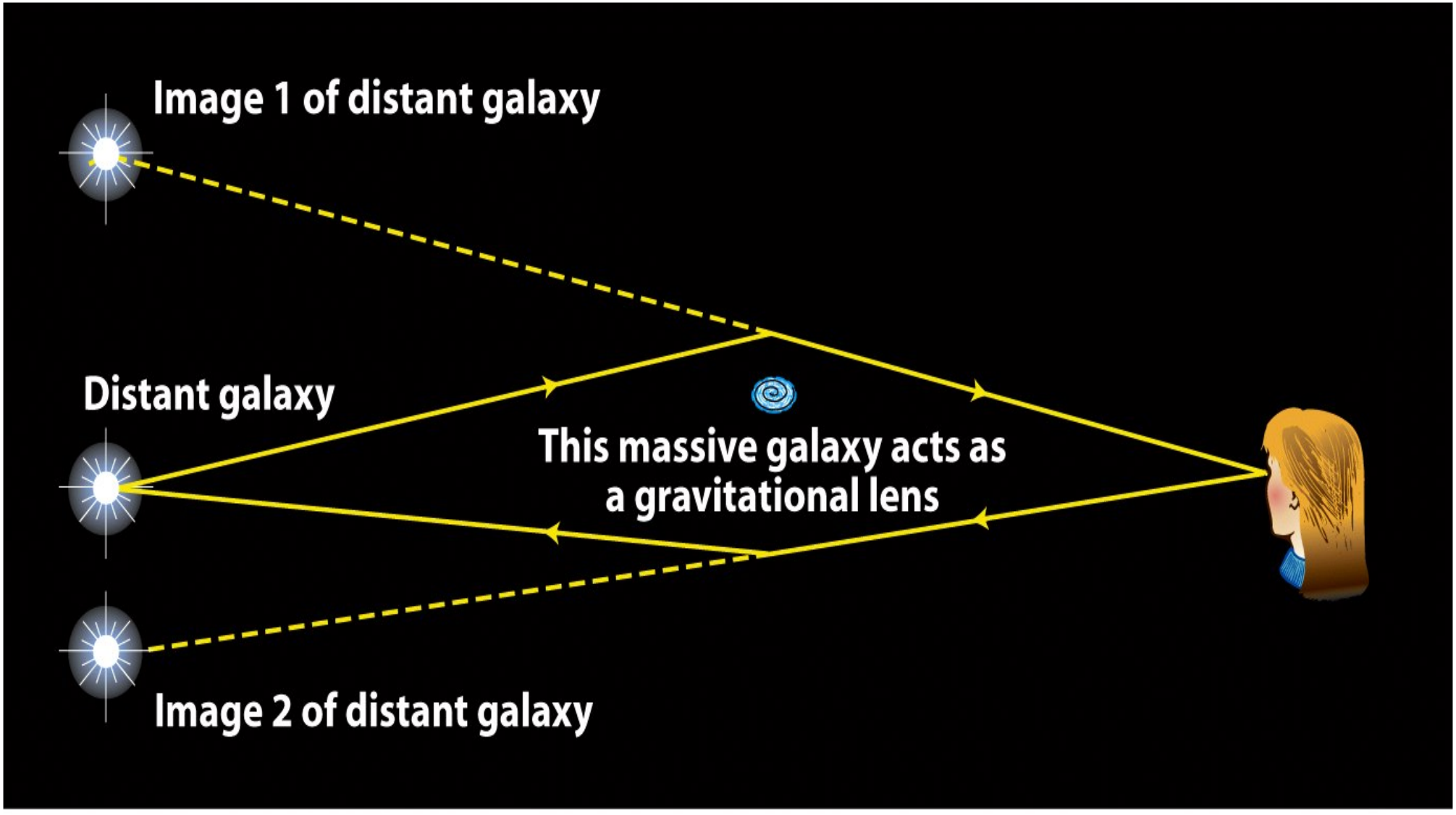
Need large amounts of **dark matter.**

Gravitational lensing by a cluster gives information about the distribution of matter in the foreground cluster.


Coma cluster



Luminous matter insufficient to explain galactic motions in clusters



How gravitational lensing happens

Figure 24-30a
Universe, Eighth Edition

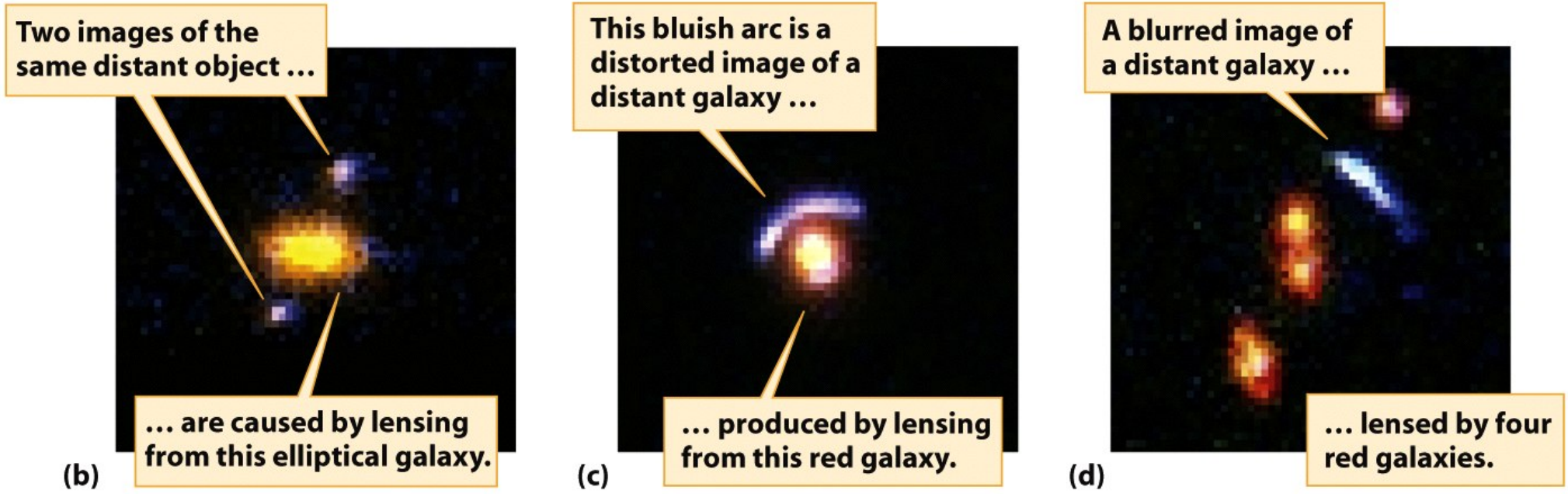
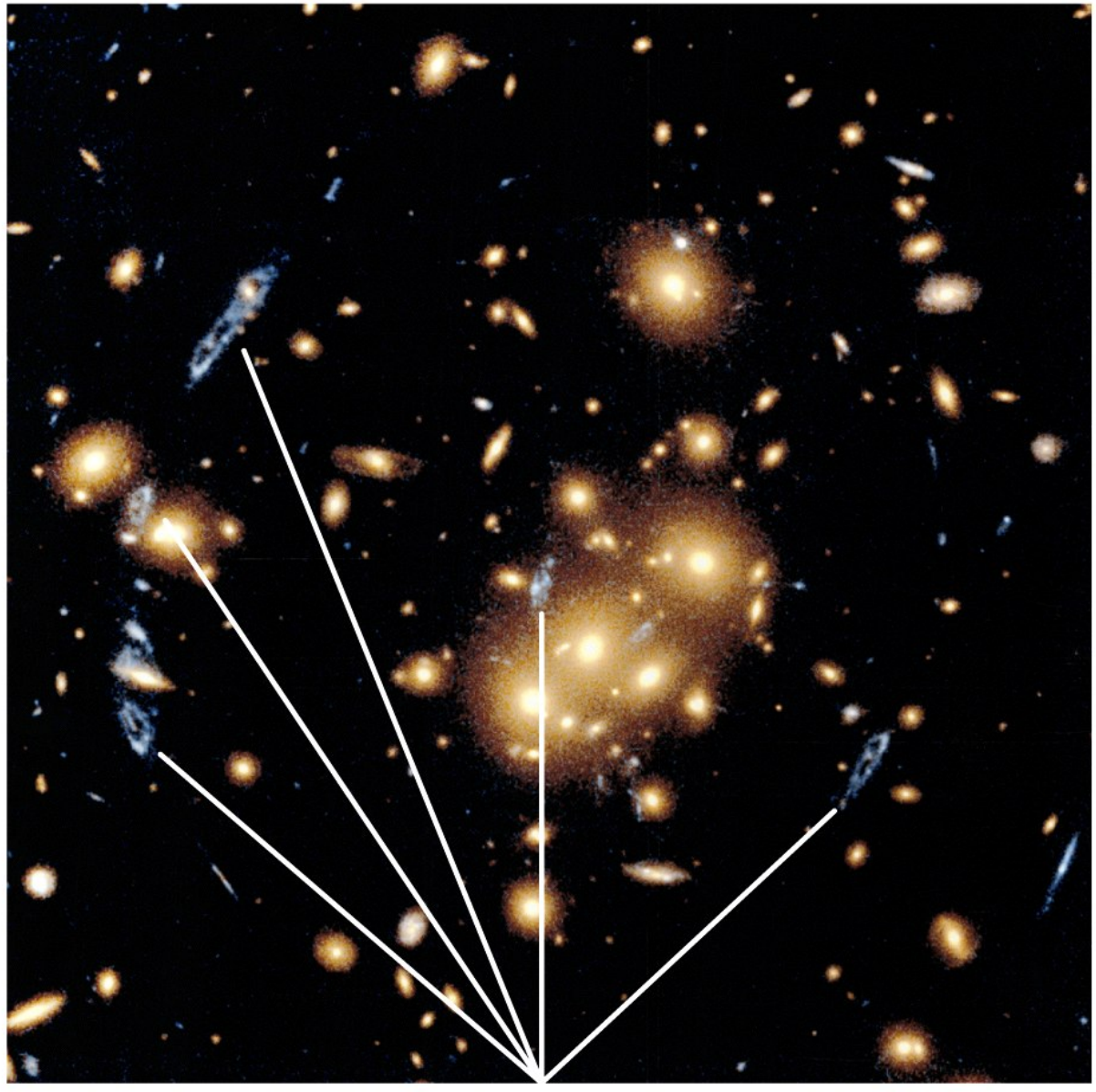


Figure 24-30bcd
Universe, Eighth Edition

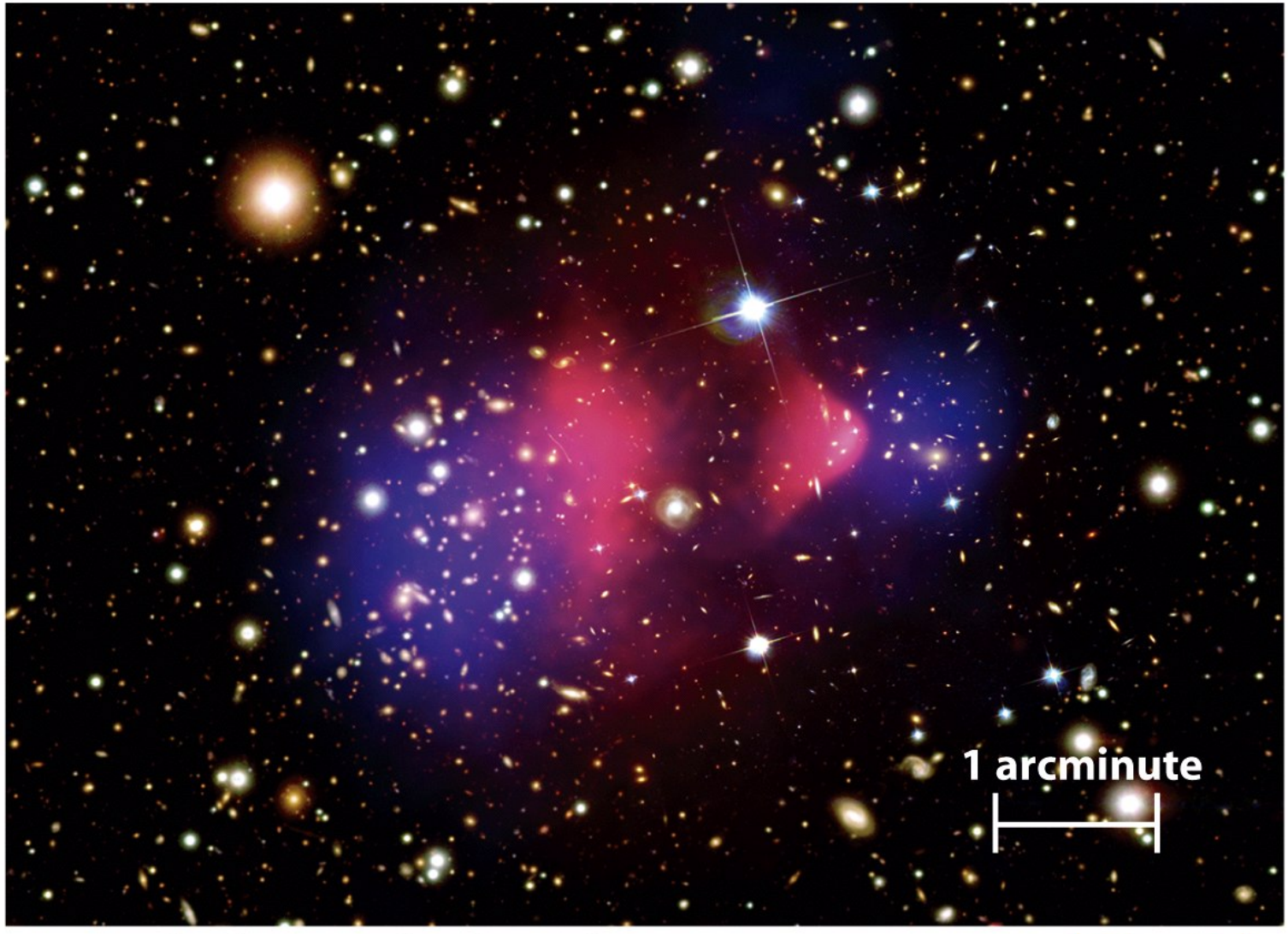
Lensing



All of these blue arcs are images of the same distant galaxy.

Figure 24-31
Universe, Eighth Edition

Bullet cluster

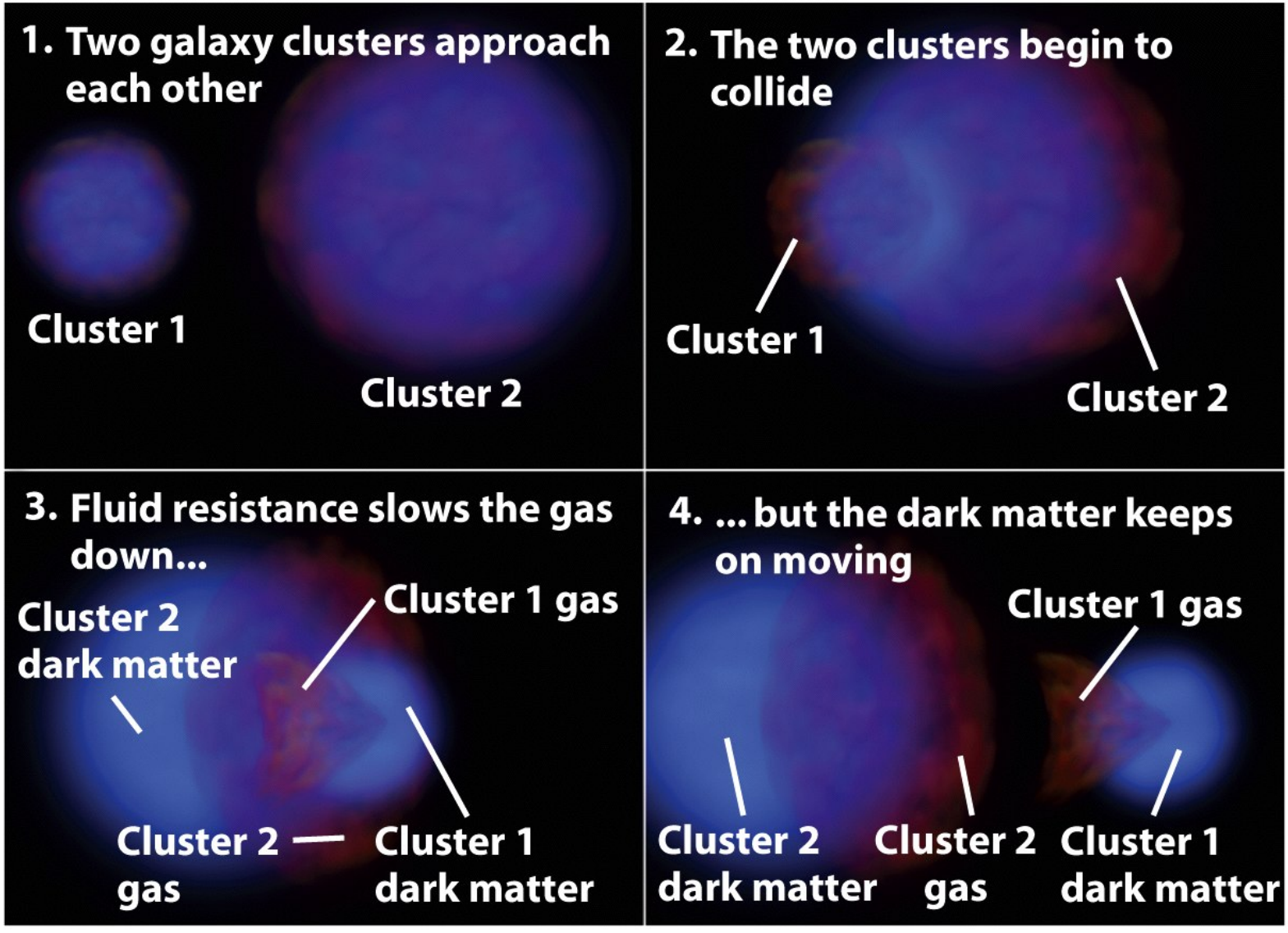


Composite image of galaxy cluster 1E0657-56 showing visible galaxies, X-ray-emitting gas (red) and dark matter (blue)

R I V U X G

Figure 24-32a
Universe, Eighth Edition

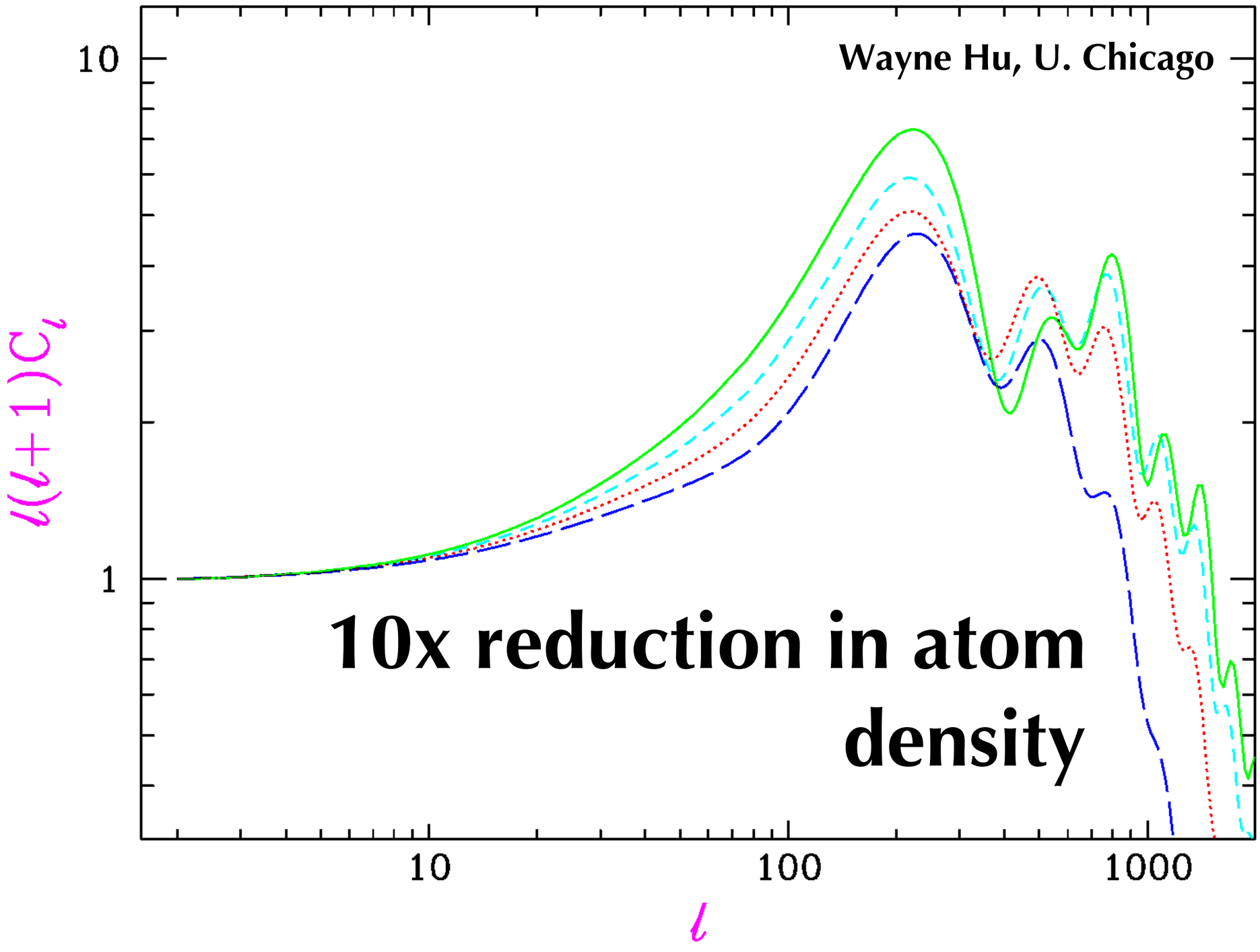
Bullet cluster model



A model of how the gas and dark matter in 1E0657-56 could have become separated

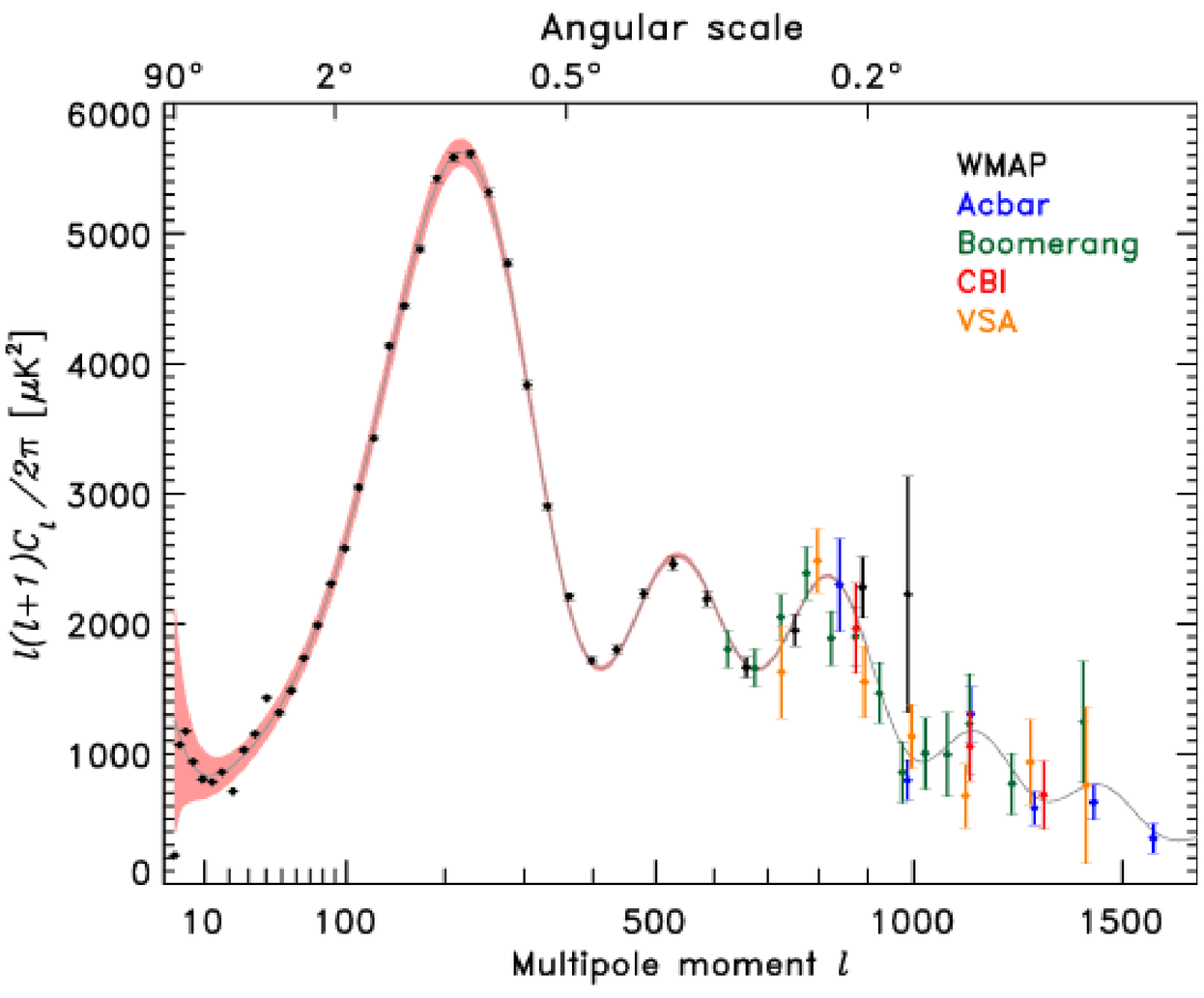
Figure 24-32b
Universe, Eighth Edition

Measuring Universe's contents



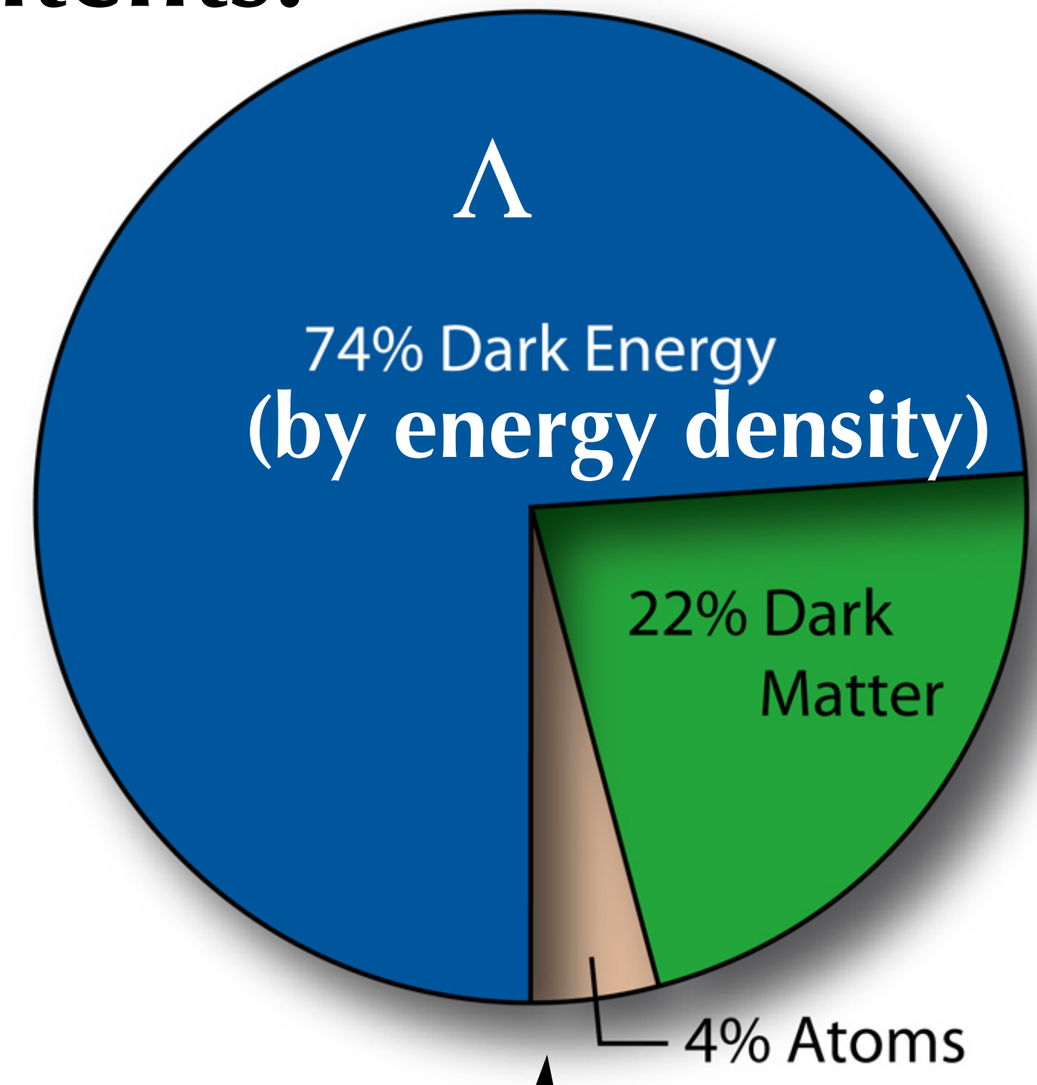
WMAP results

Data:



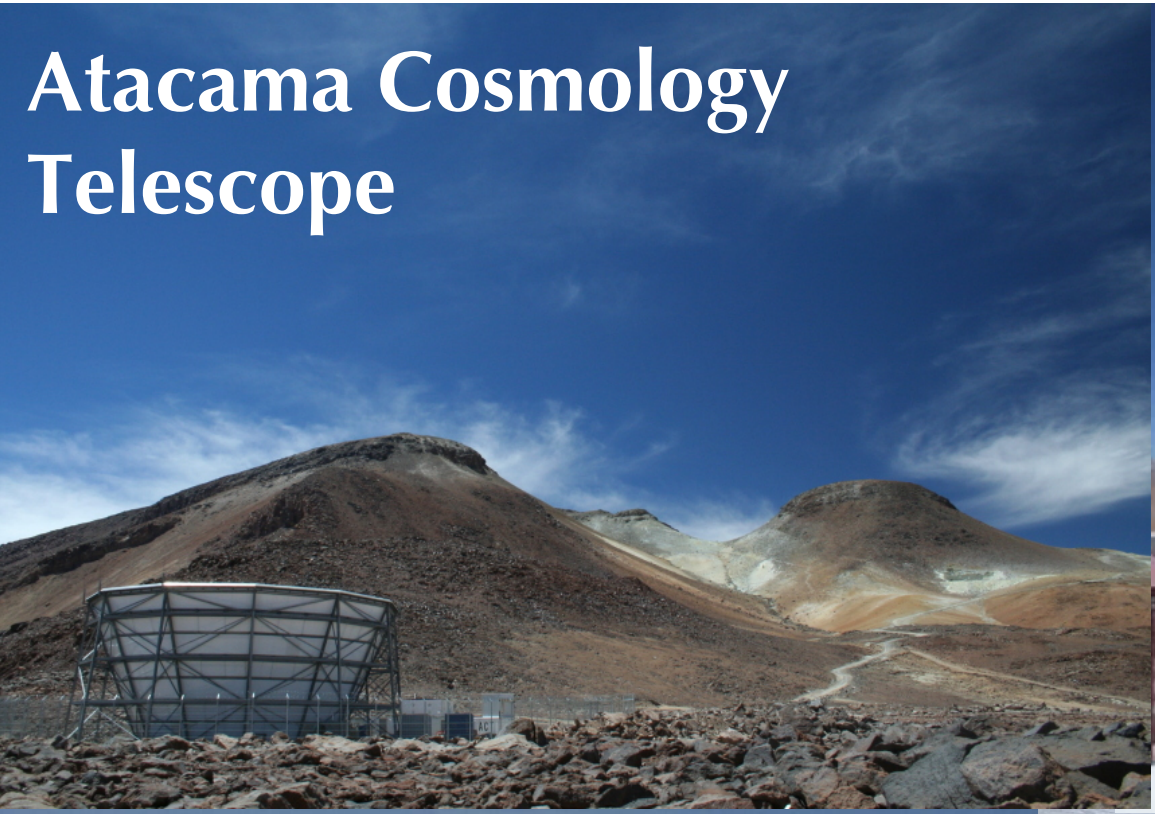
Space-time: flat +/- 2%

Contents:

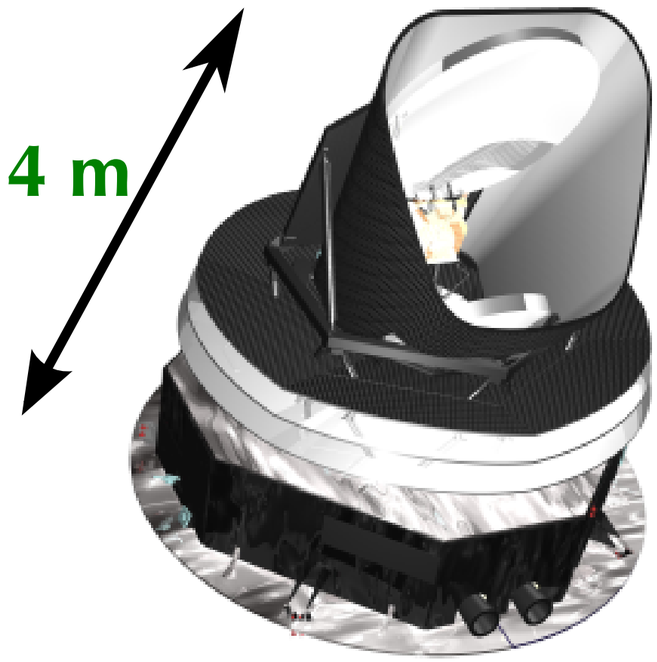


Results:

Ground / balloon based telescopes



Planck



(2008)

Next generation satellite mission.

All-sky, compared to WMAP:

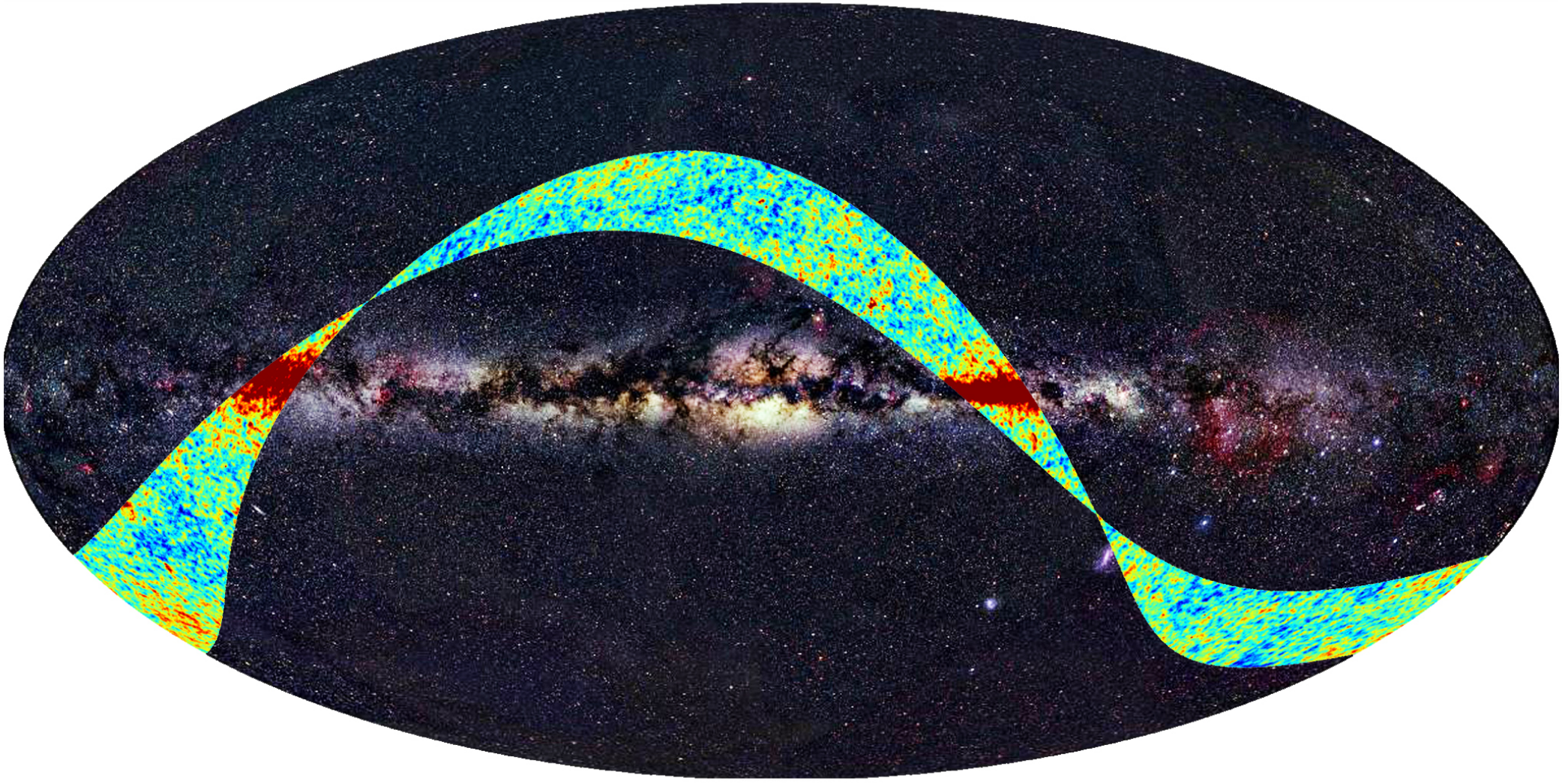
- **Wider frequency coverage.**
- **Lower noise.**
- **Higher resolution.**
- **Better polarization sensitivity.**

ESA/NASA mission, large collaboration.

Launched: May 14, 2009

Data release: 2012-2013.

Preview from Planck



Cosmic Web

On the largest scales, single galaxies, groups, and clusters are most common along filamentary structures called the **cosmic web**.

Galaxies tend to avoid the **voids**.

Structure is natural consequence of gravitational collapse from Big Bang initial conditions, and can be simulated on a computer.

Cosmic web

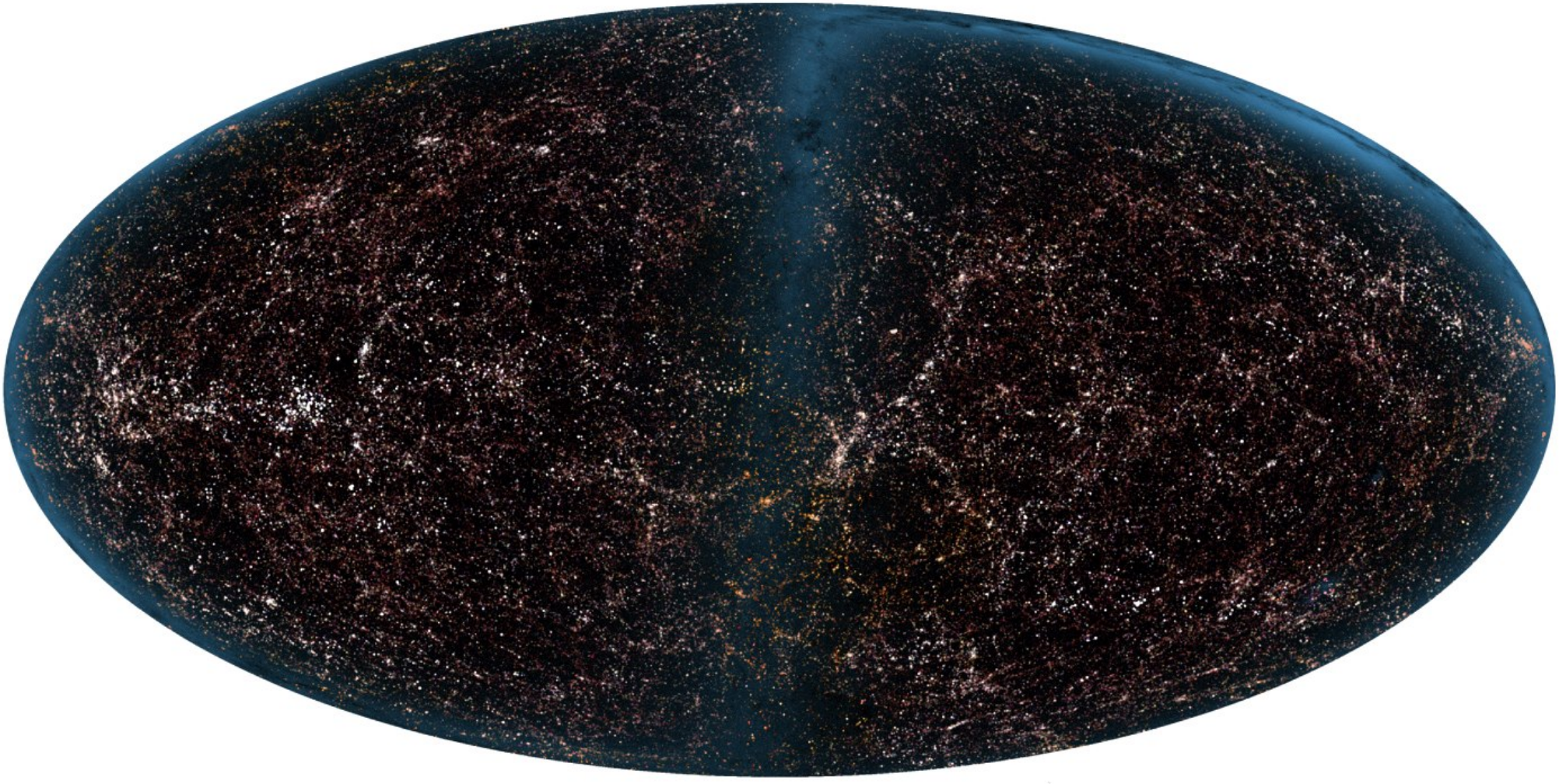
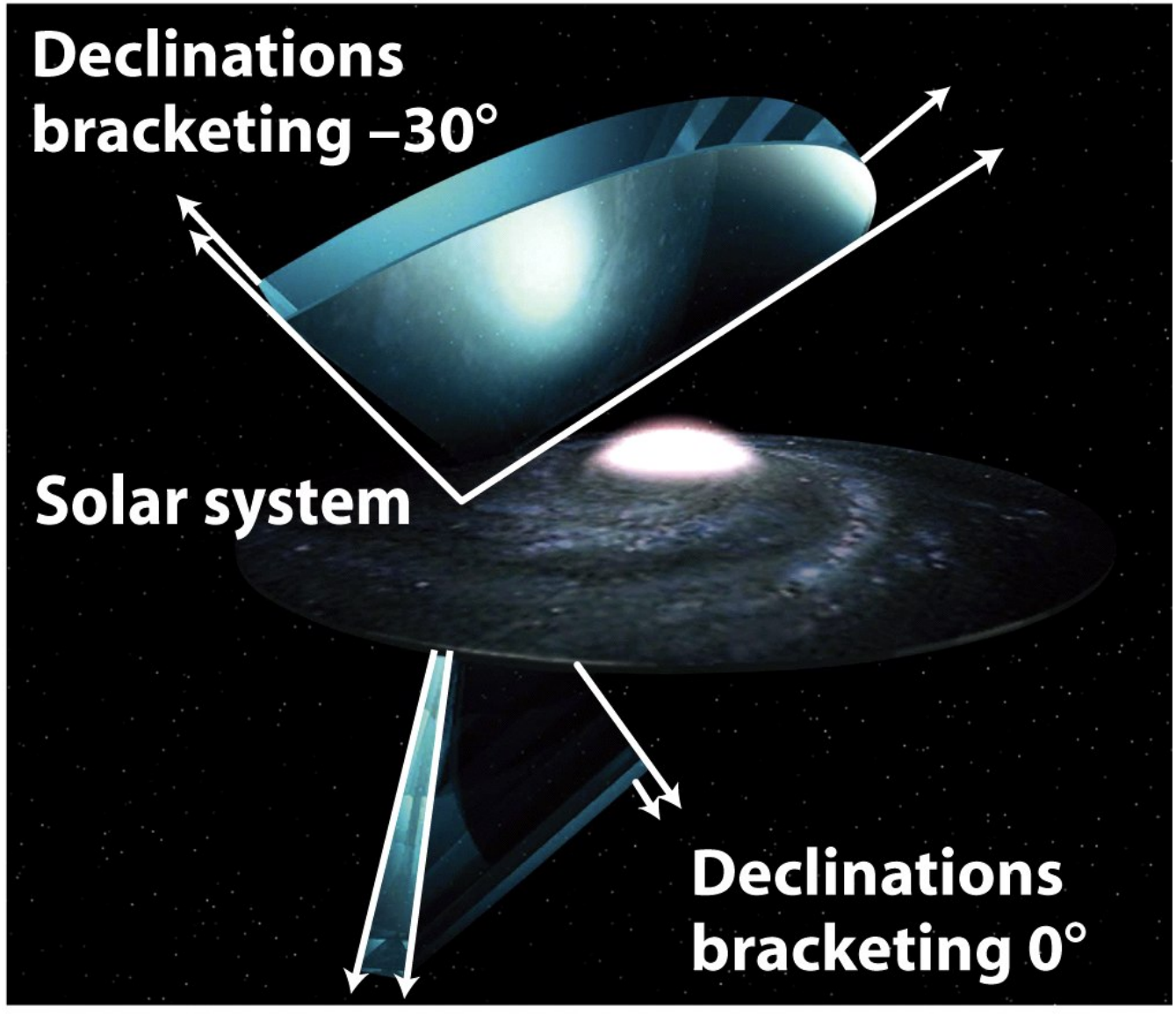


Figure 24-23
Universe, Eighth Edition

2dF survey



Fields of view in the 2dF survey

Figure 24-24b
Universe, Eighth Edition

2dF survey

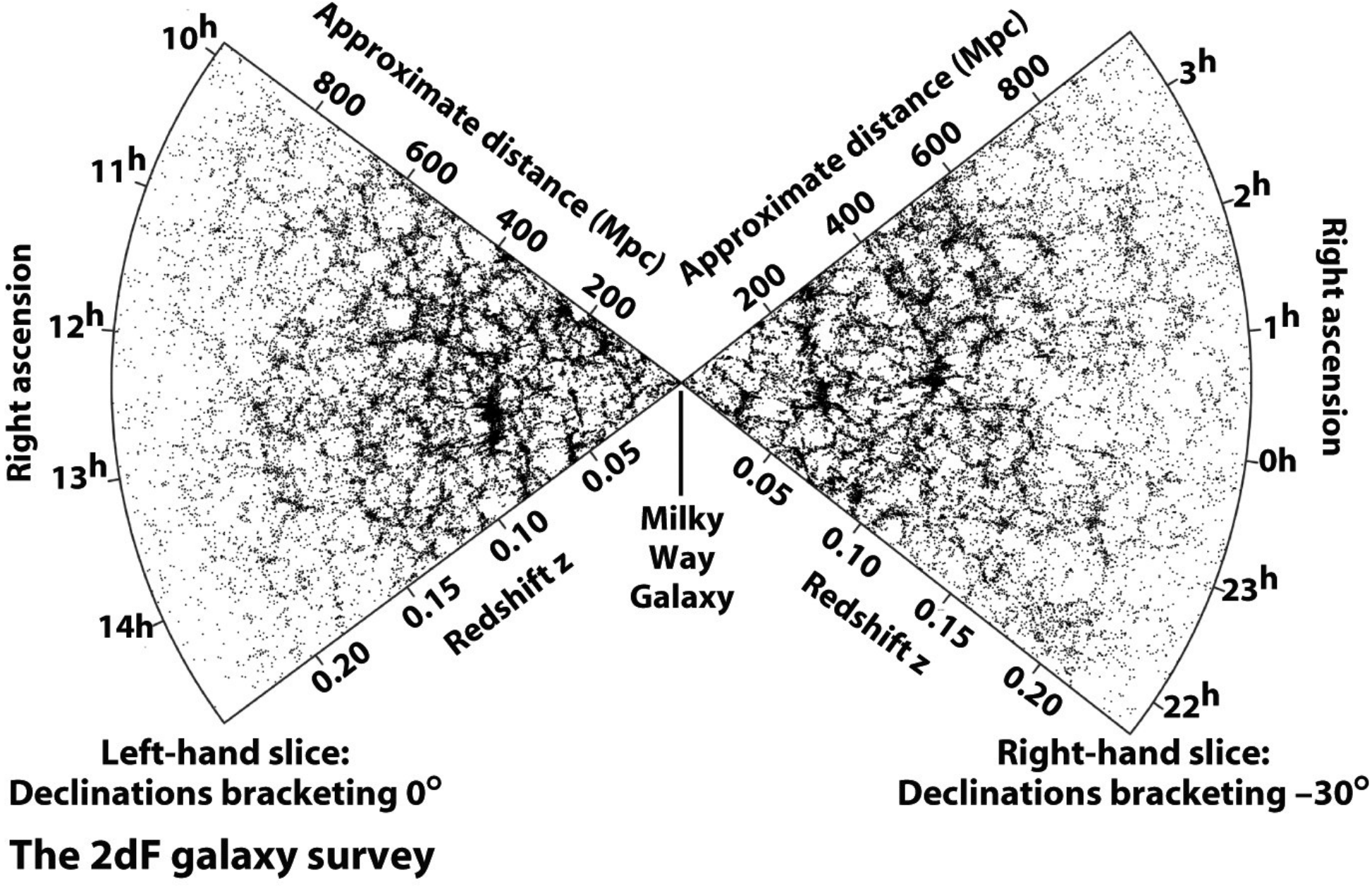
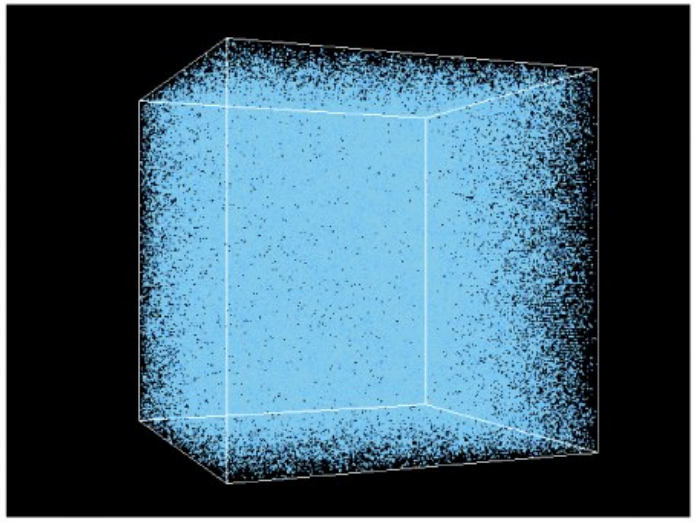
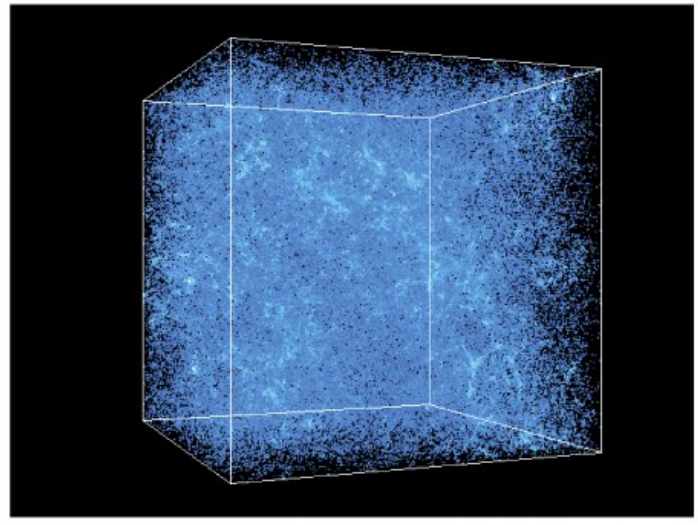


Figure 24-24a
Universe, Eighth Edition

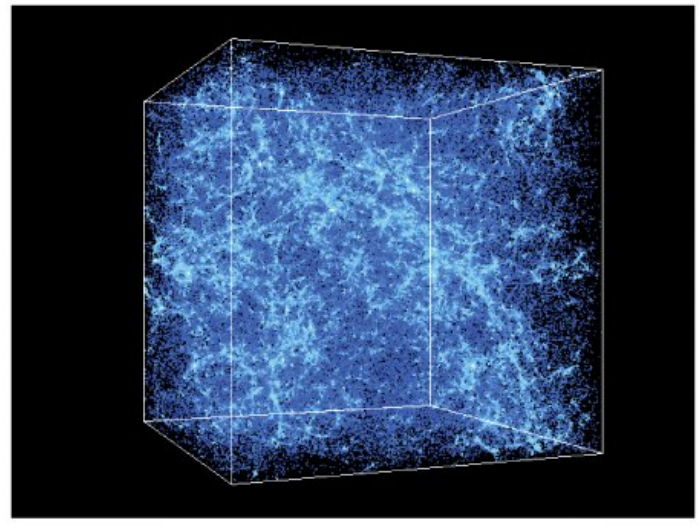
Cosmological matter simulation



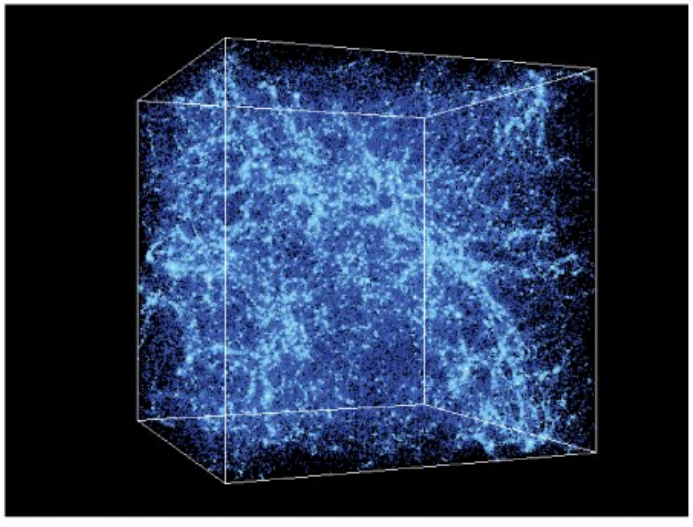
$z = 27.36$ Universe 120 million years old



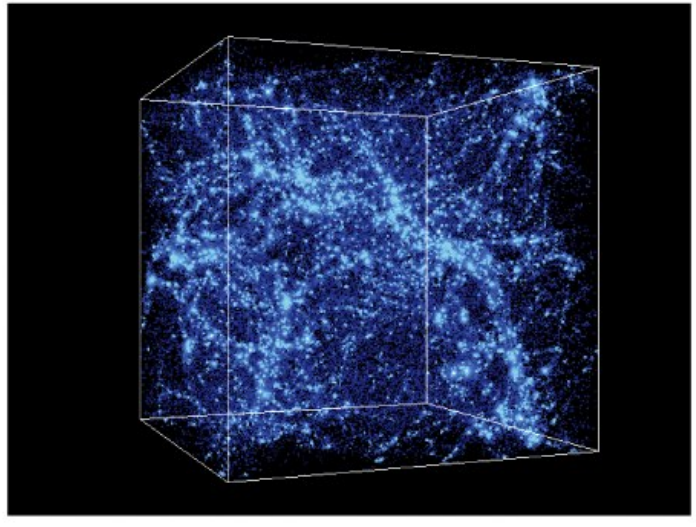
$z = 9.83$ Universe 490 million years old



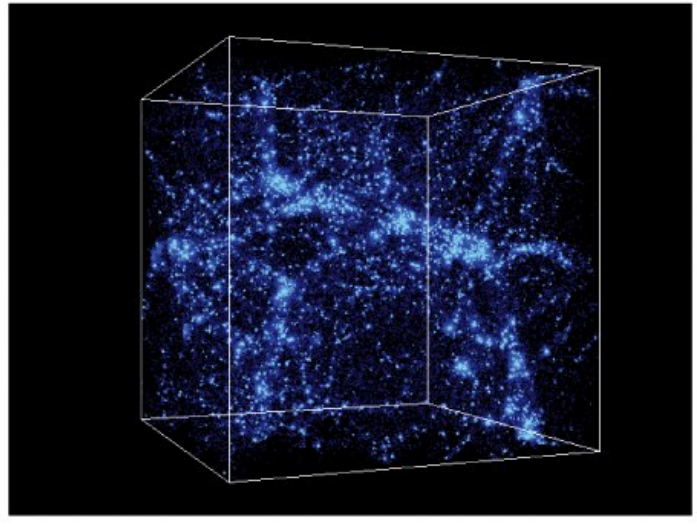
$z = 4.97$ Universe 1.2 billion years old



$z = 2.97$ Universe 2.2 billion years old



$z = 0.99$ Universe 6.0 billion years old



$z = 0.00$ Universe 13.7 billion years old

Figure 27-15
Universe, Eighth Edition

Conclusions

What are the contents?

Mostly dark energy, with some dark matter, and a small fraction of normal atoms.

But what *are* dark energy and dark matter?

What's the space-time like?

Measurements are consistent with flat.

What is primordial seed of structure?

Dense regions, like the ones we see in the CMB, collapsed gravitationally to form today's galaxies.