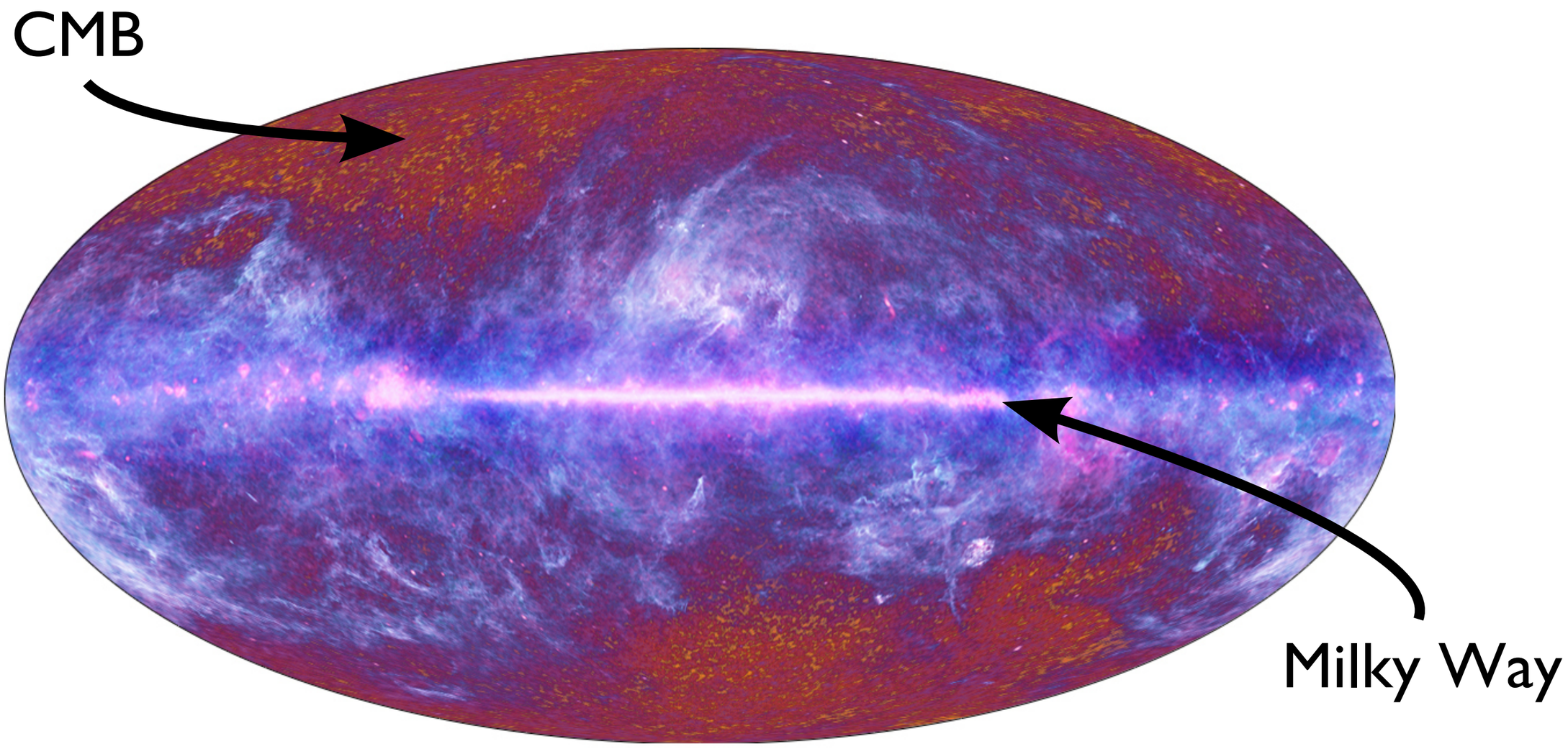
Cosmology from the Cosmic Microwave Background



Kevin M. Huffenberger, Department of Physics

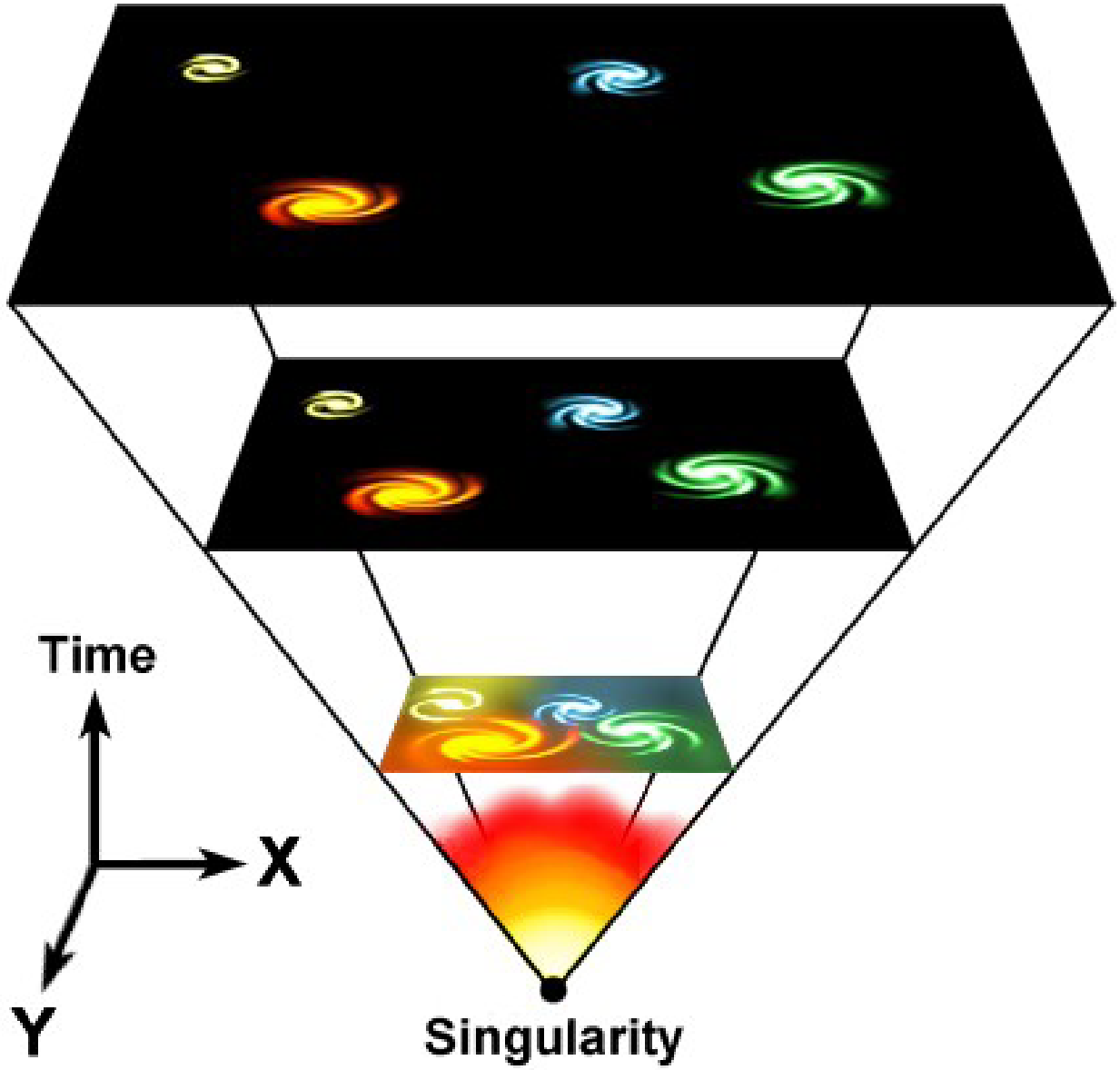
In what kind of universe do we live?

What are the contents?

What's the space-time like?

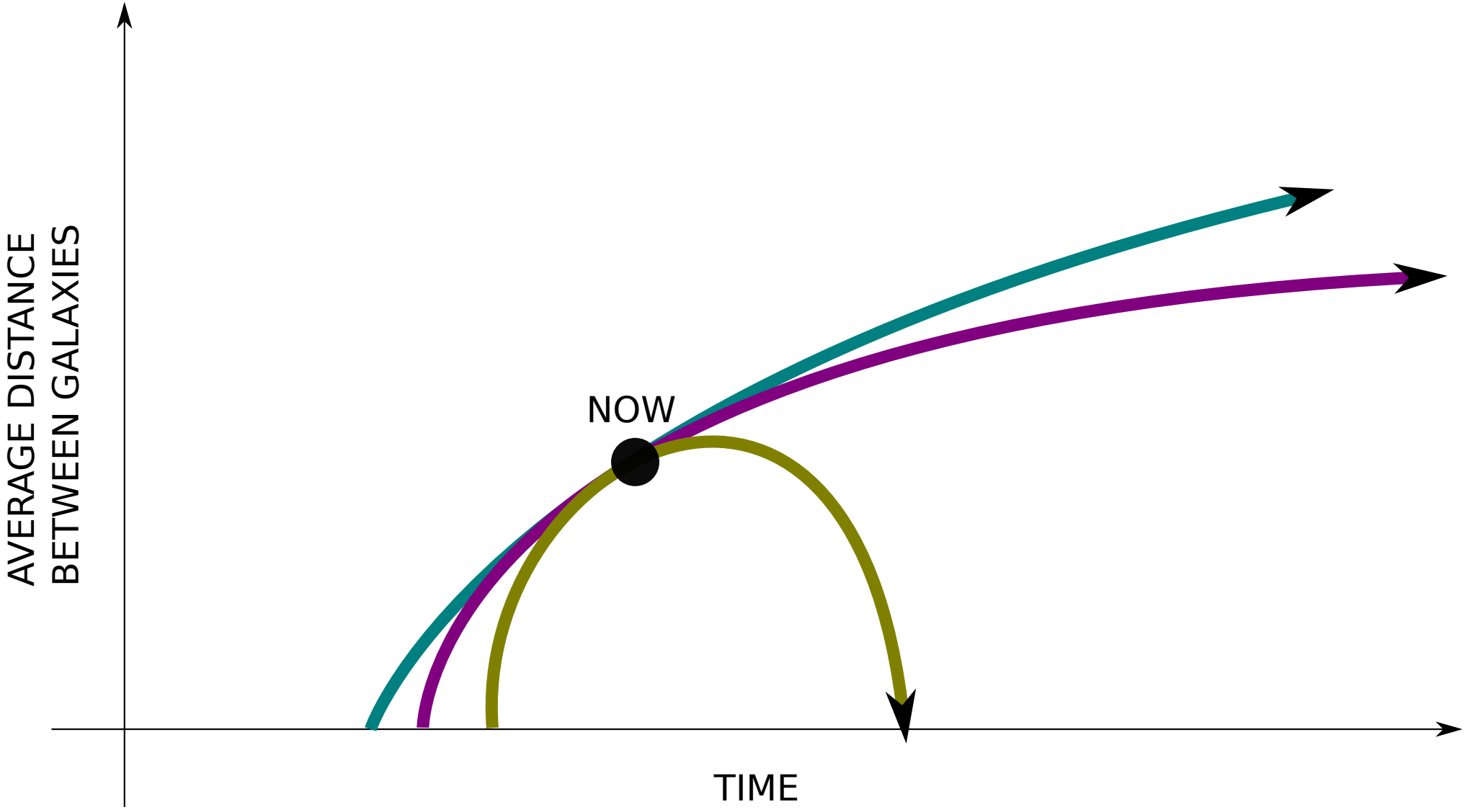
What is primordial seed of structure?

Expanding universe & the Big Bang



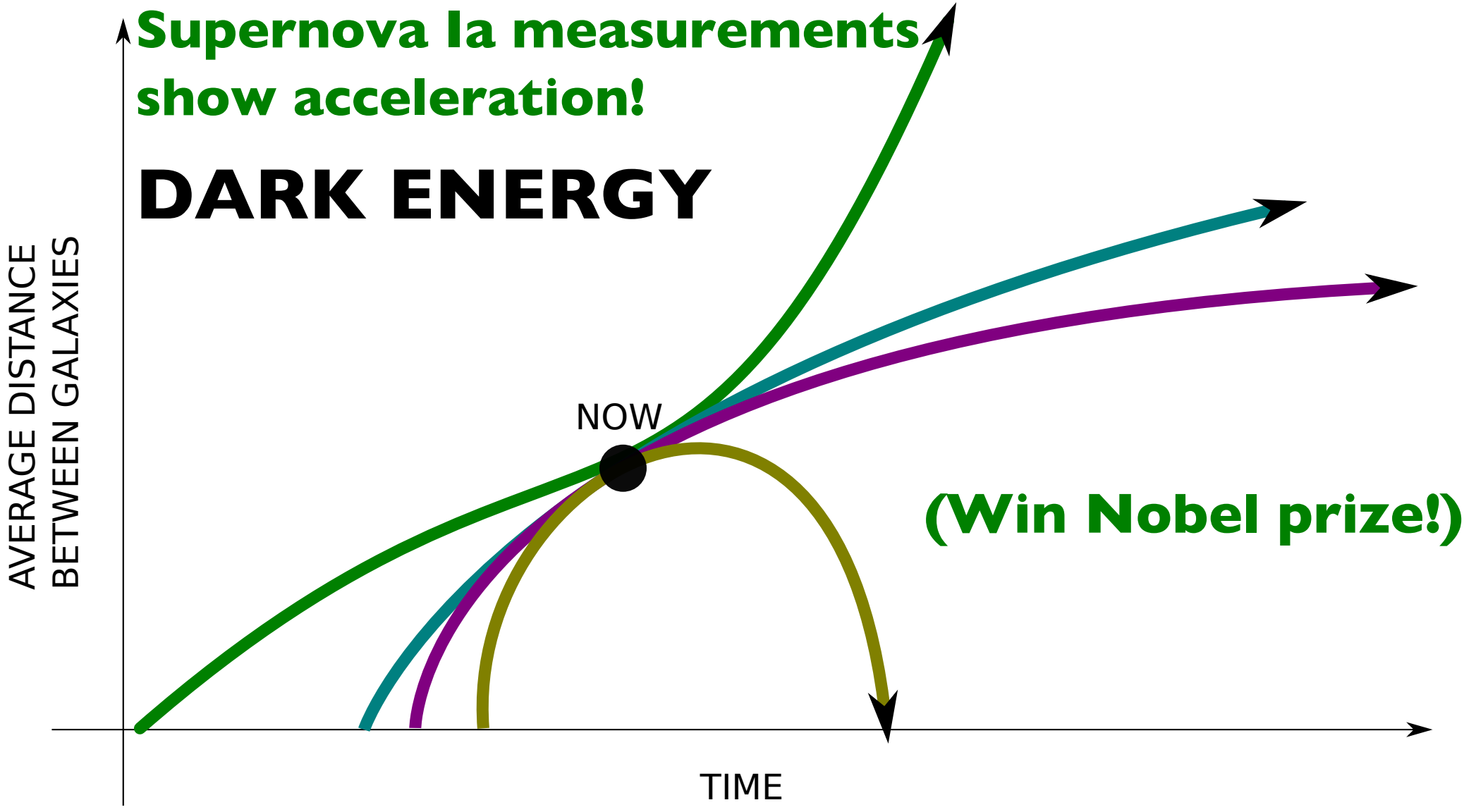
Expansion history/future

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



Expansion history/future

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



Type Ia SN indicate expansion is accelerating

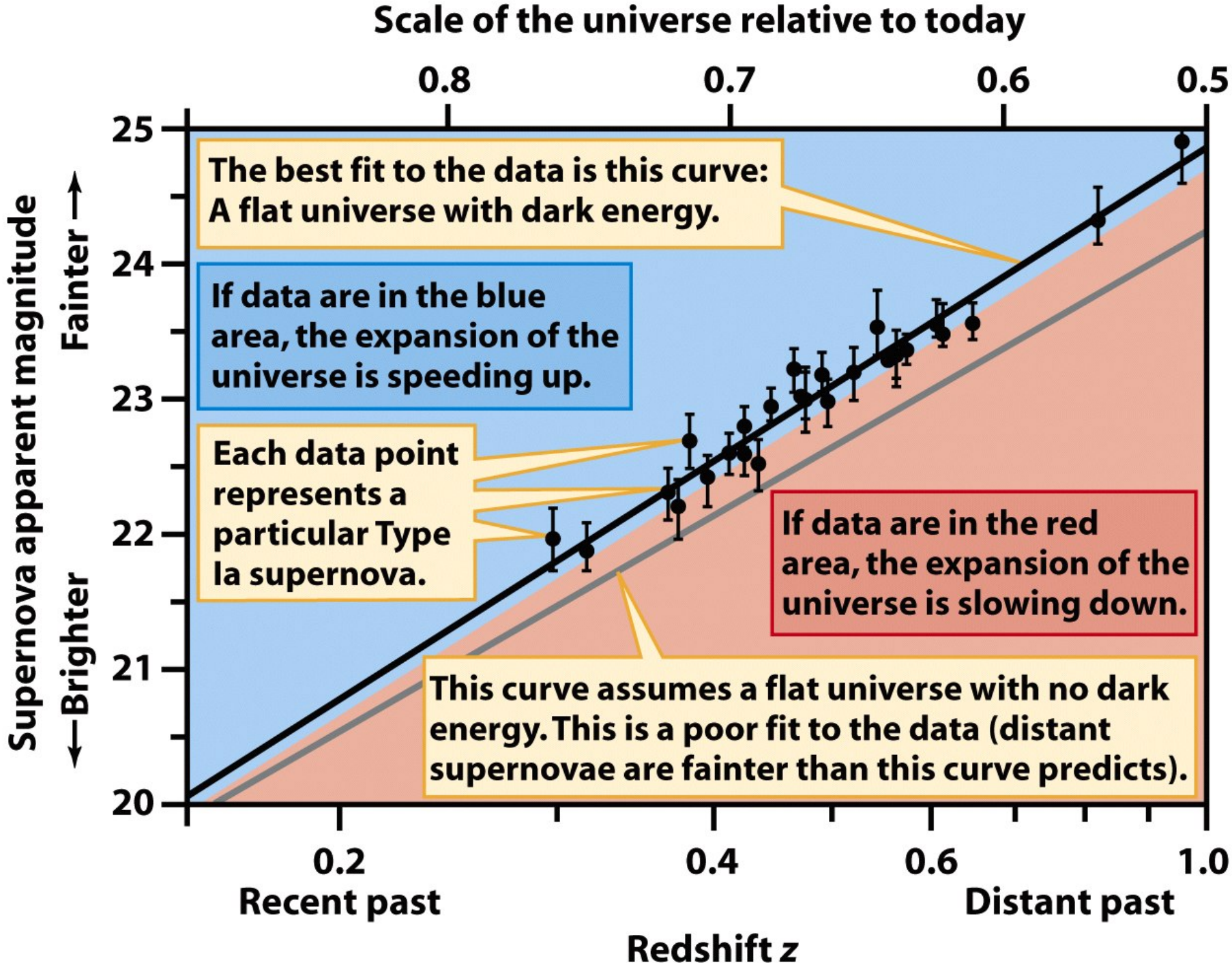


Figure 26-18

Thermal history of the Universe

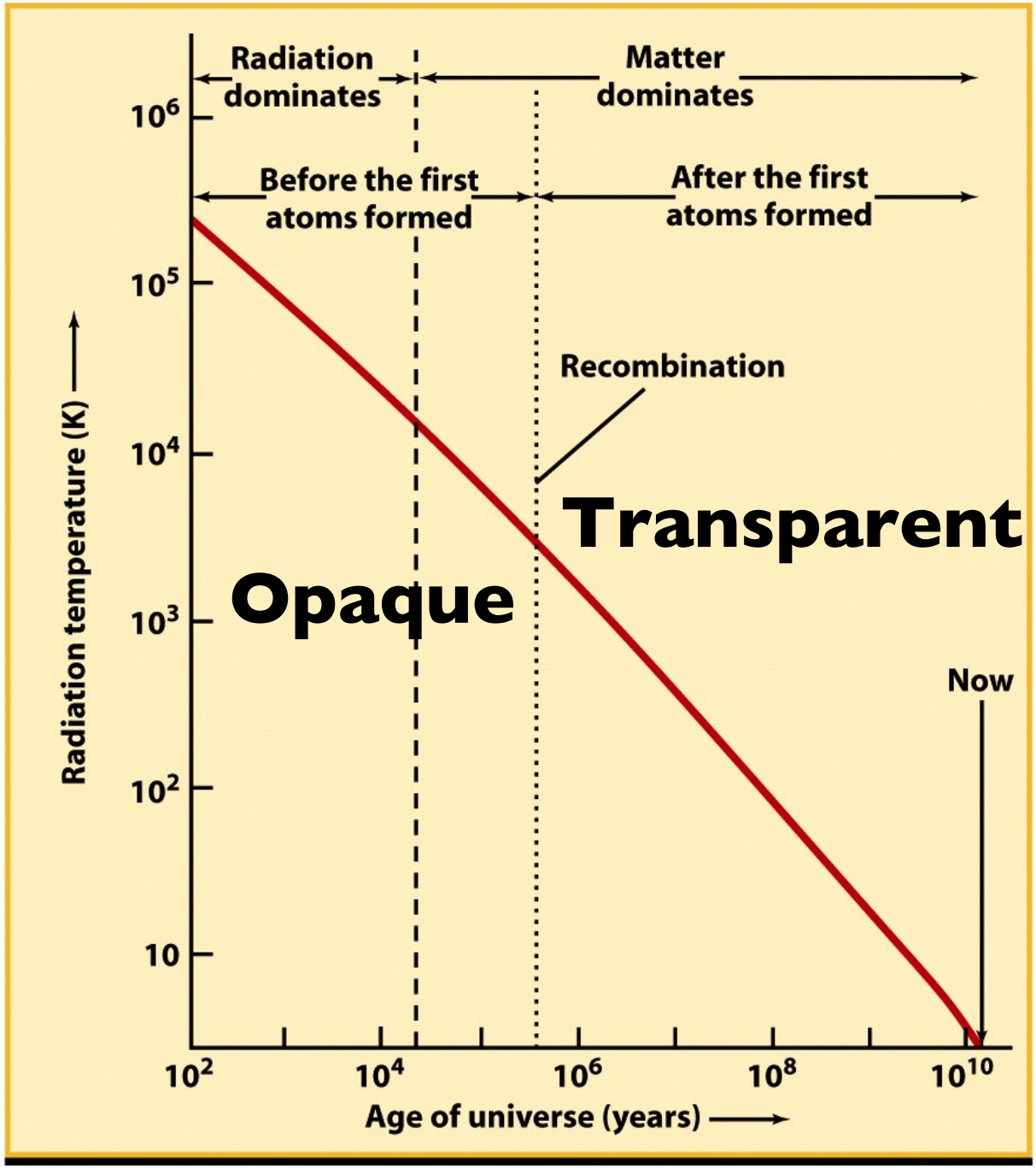


Figure 26-11
Universe, Eighth Edition

Hot, dense objects glow with a specific spectrum

Technical term: "Blackbody radiation"

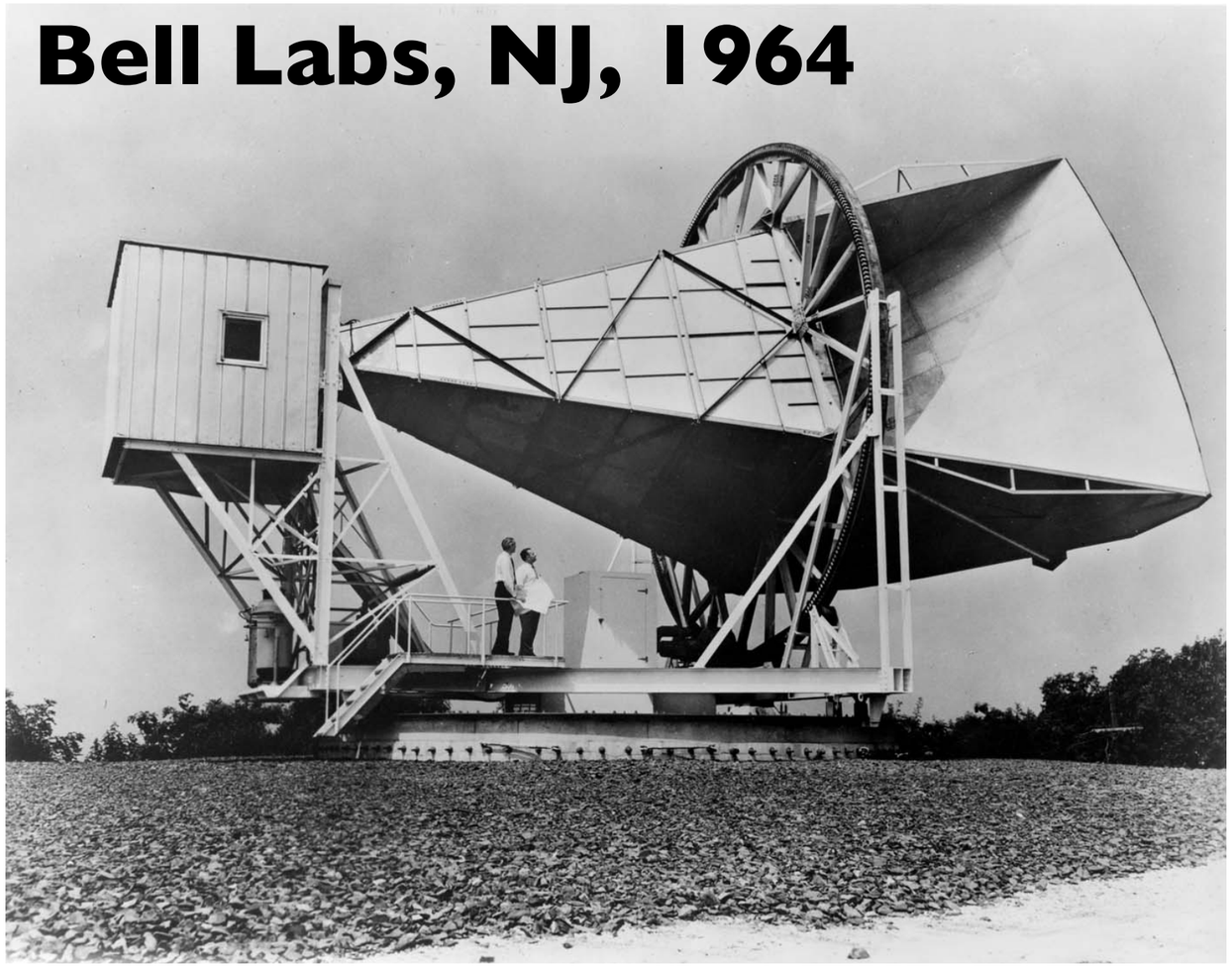
Big Bang's afterglow

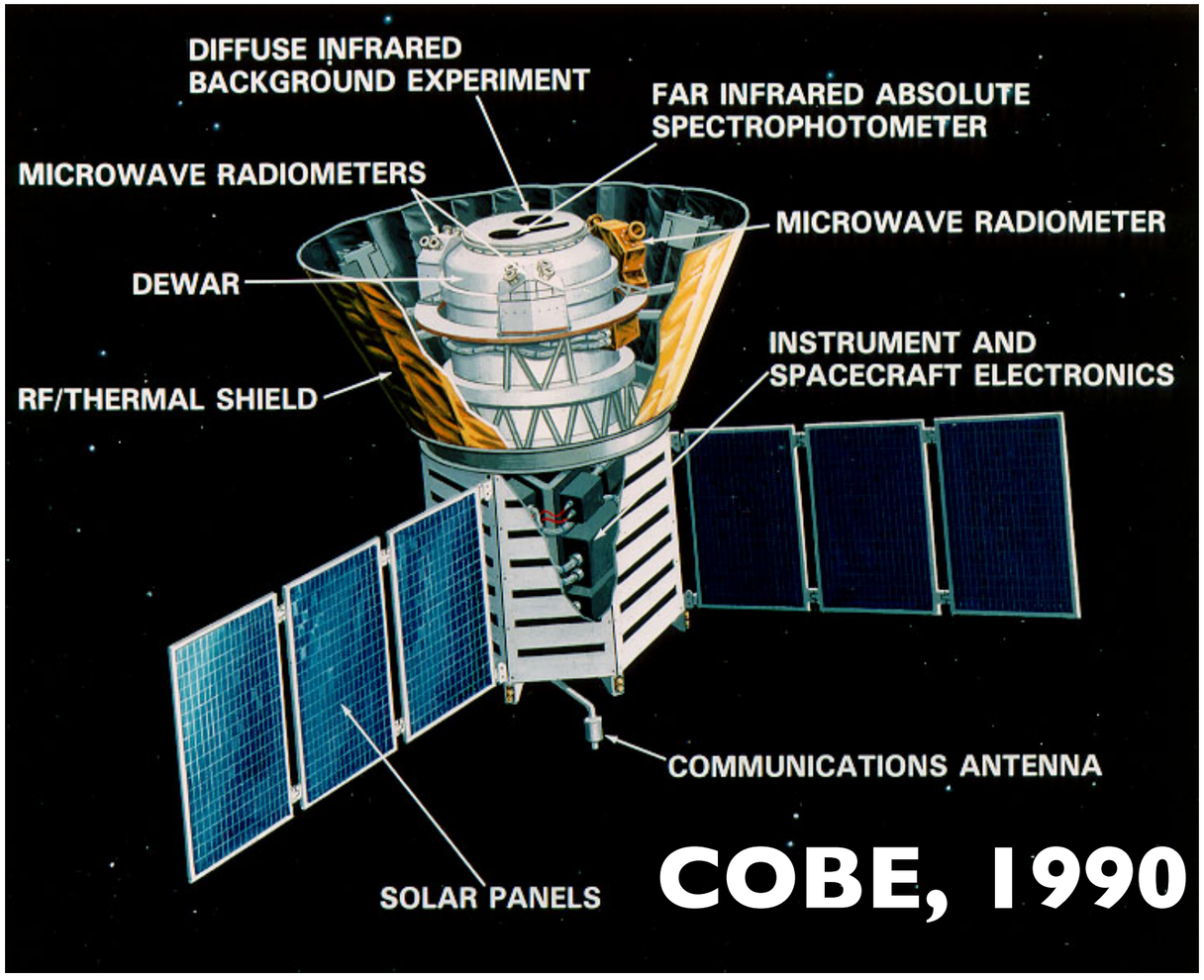
Dense, hot initial state ➡ **Relic Background Radiation**

redshifted to microwaves.

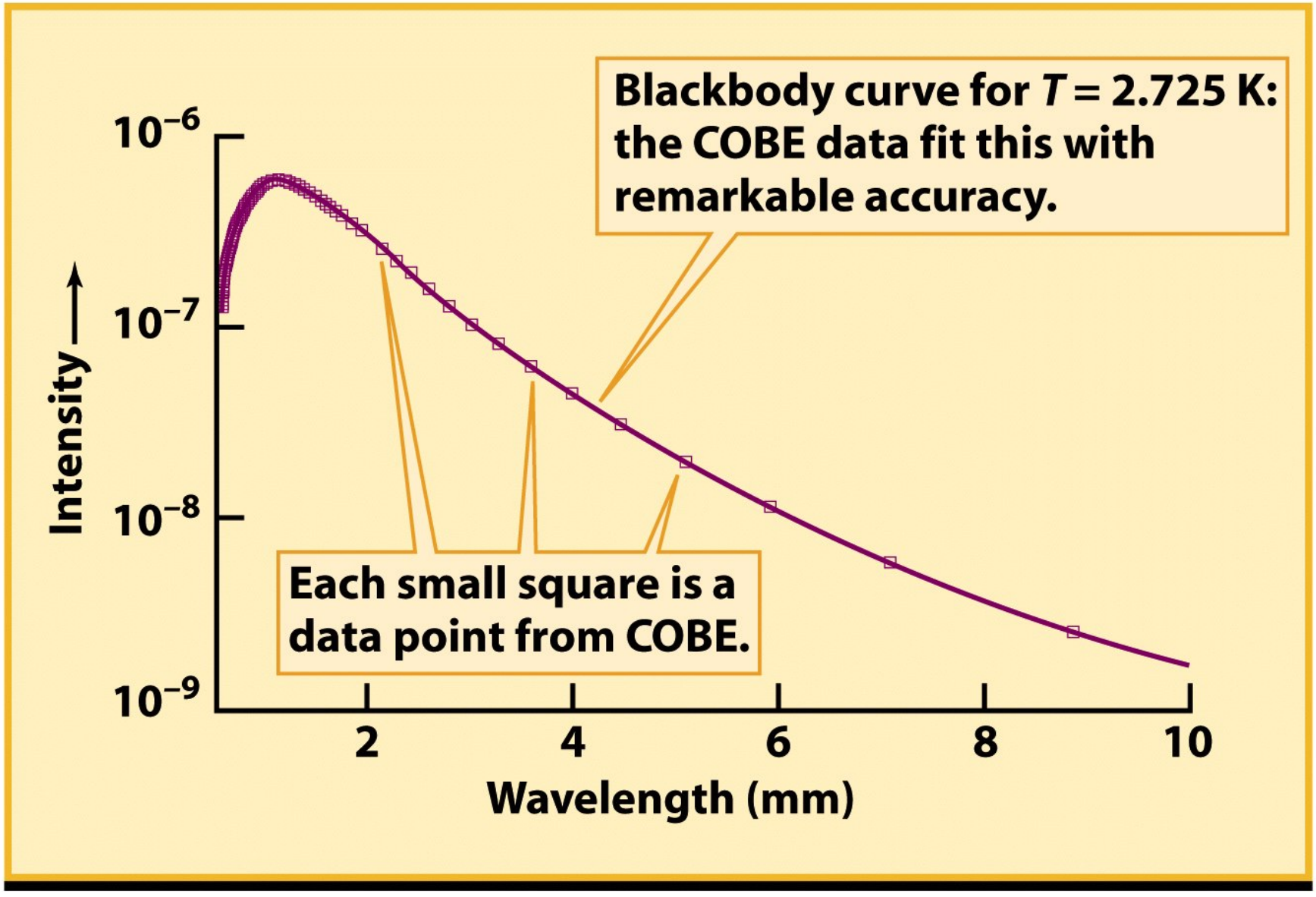
Cold: 3 K above abs. zero

Bell Labs, NJ, 1964





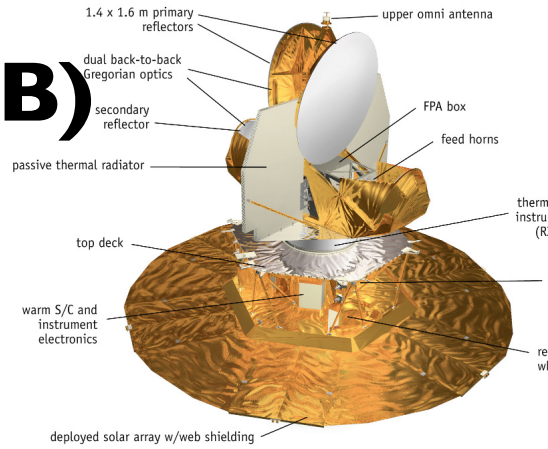
Each resulted in a Nobel prize!



The spectrum of the cosmic microwave background

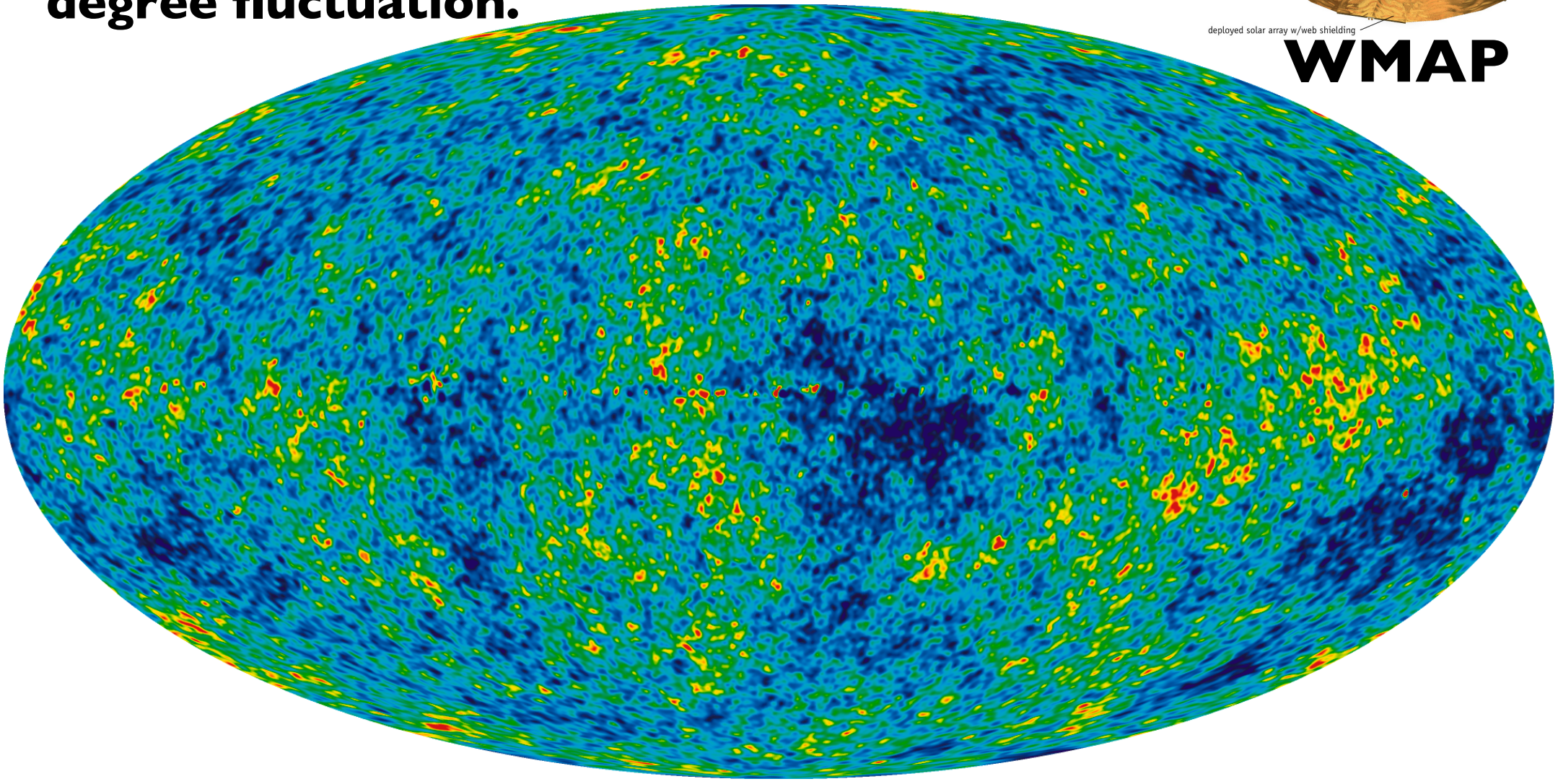
Figure 26-7b
Universe, Eighth Edition

Cosmic Microwave Background (CMB)



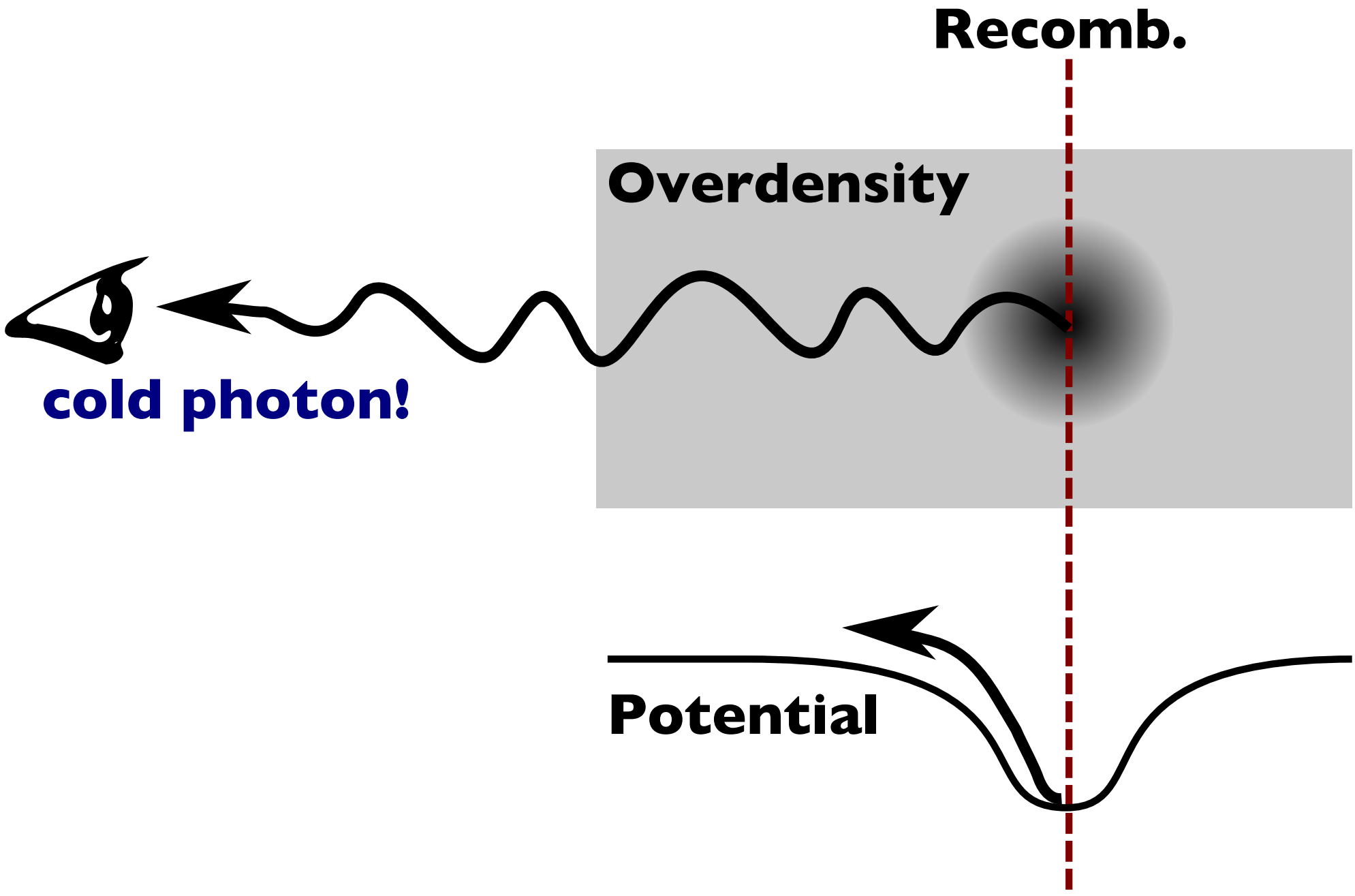
WMAP

Few ten-thousands of a degree fluctuation.

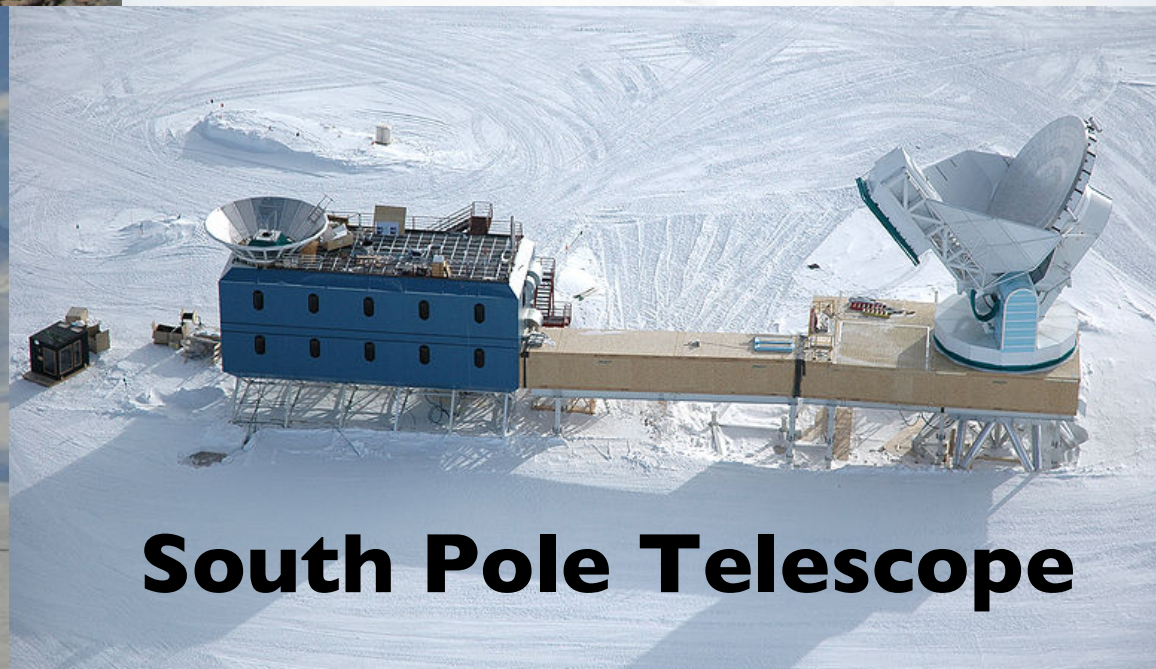


info on grav. potential @ recombination

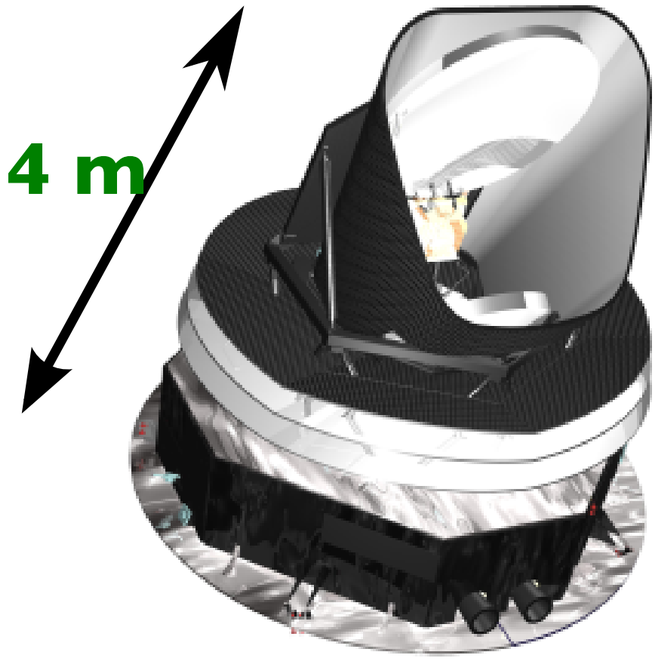
Probing gravitational potential



Ground / balloon based telescopes



Planck



Next generation satellite mission.

All-sky, compared to WMAP:

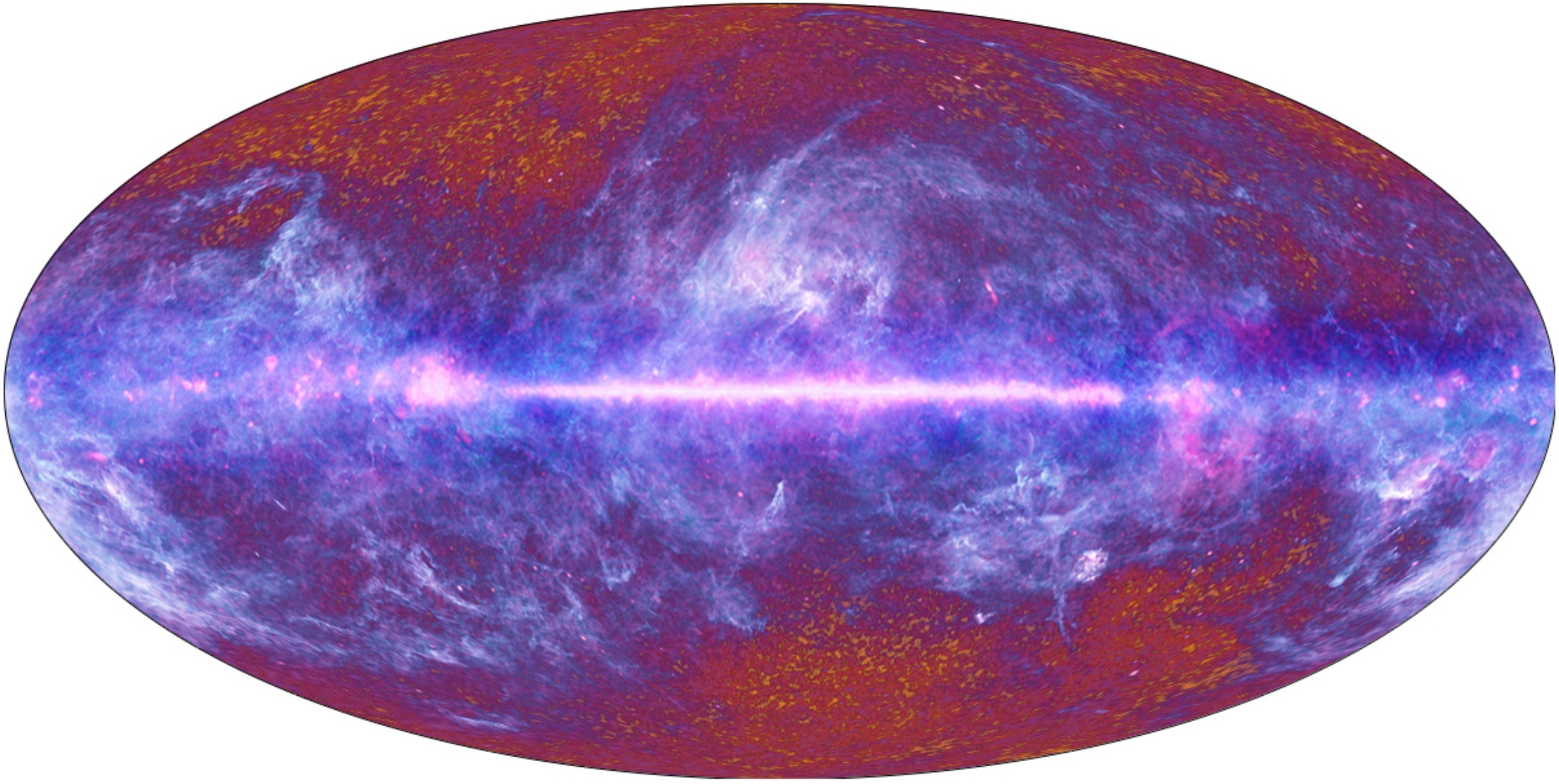
- **Wider frequency coverage.**
- **Lower noise.**
- **Higher resolution.**
- **Better polarization sensitivity.**

ESA/NASA mission, large collaboration.

Launched: May 14, 2009

Data releases: 2011-2013.

Planck's first full-sky image



Cosmology results early 2013

http://irsa.ipac.caltech.edu/

Power spectrum

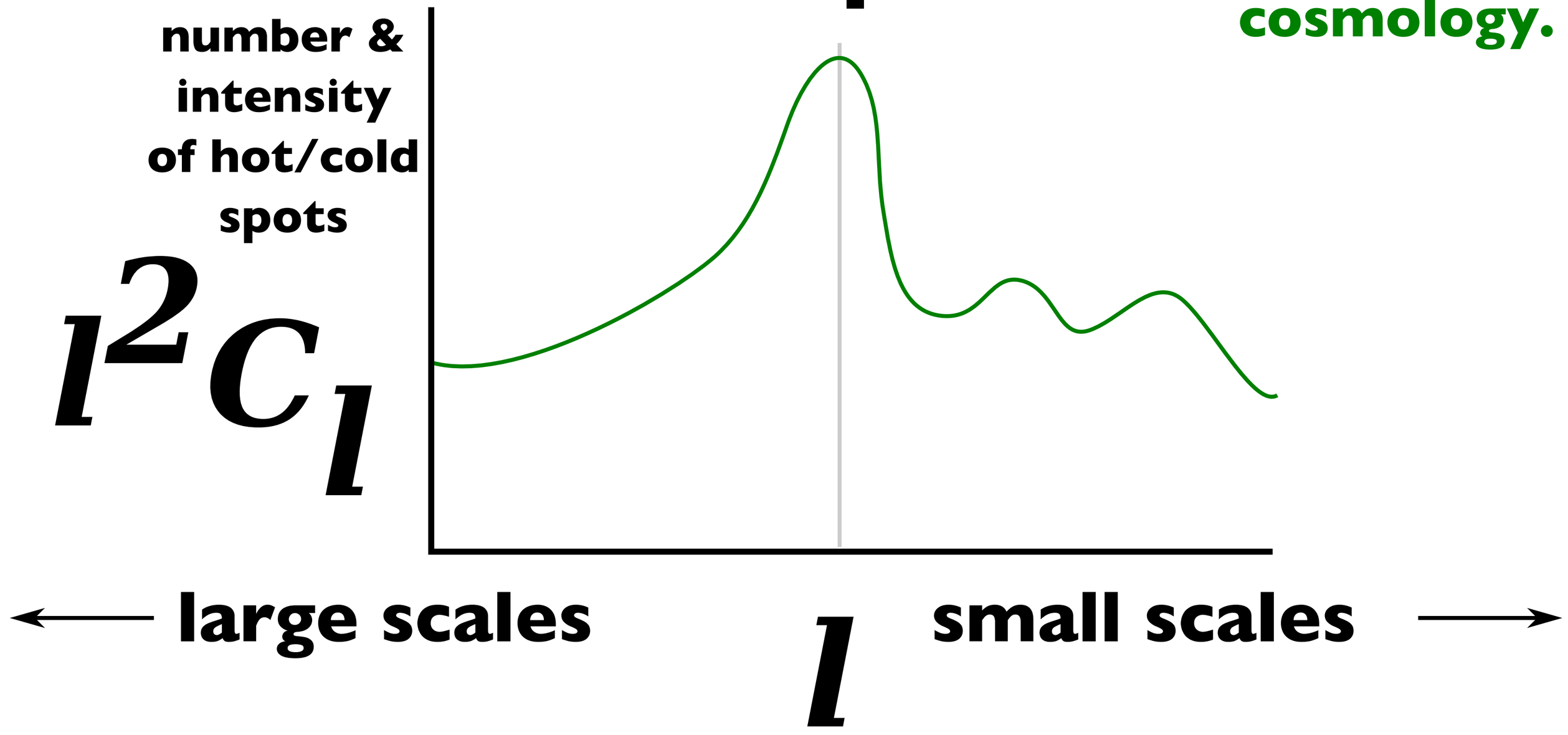
Study two-point correlation function in harmonic space

$$a_{lm} = \int d\Omega \, T(\theta, \phi) Y^*_{lm}(\theta, \phi)$$

$$\langle a_{lm} a^*_{l'm'} \rangle = C_l \delta_{ll'} \delta_{mm'}$$

CMB "power spectrum"

... fundamental tool to understand the implications of CMB measurements for cosmology.



Universe's contents

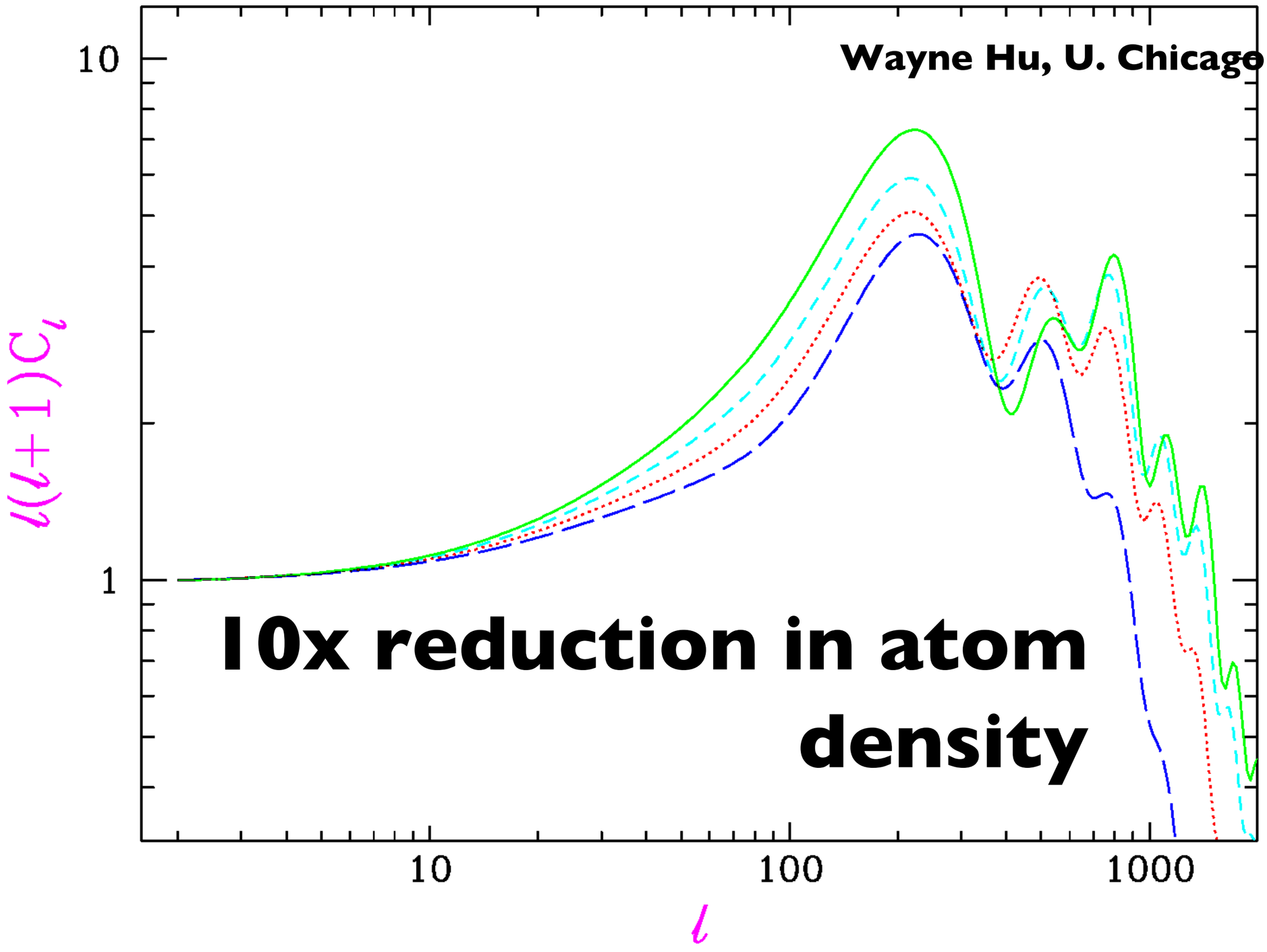
3 components cosmologically relevant:

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.

Measuring Universe's contents



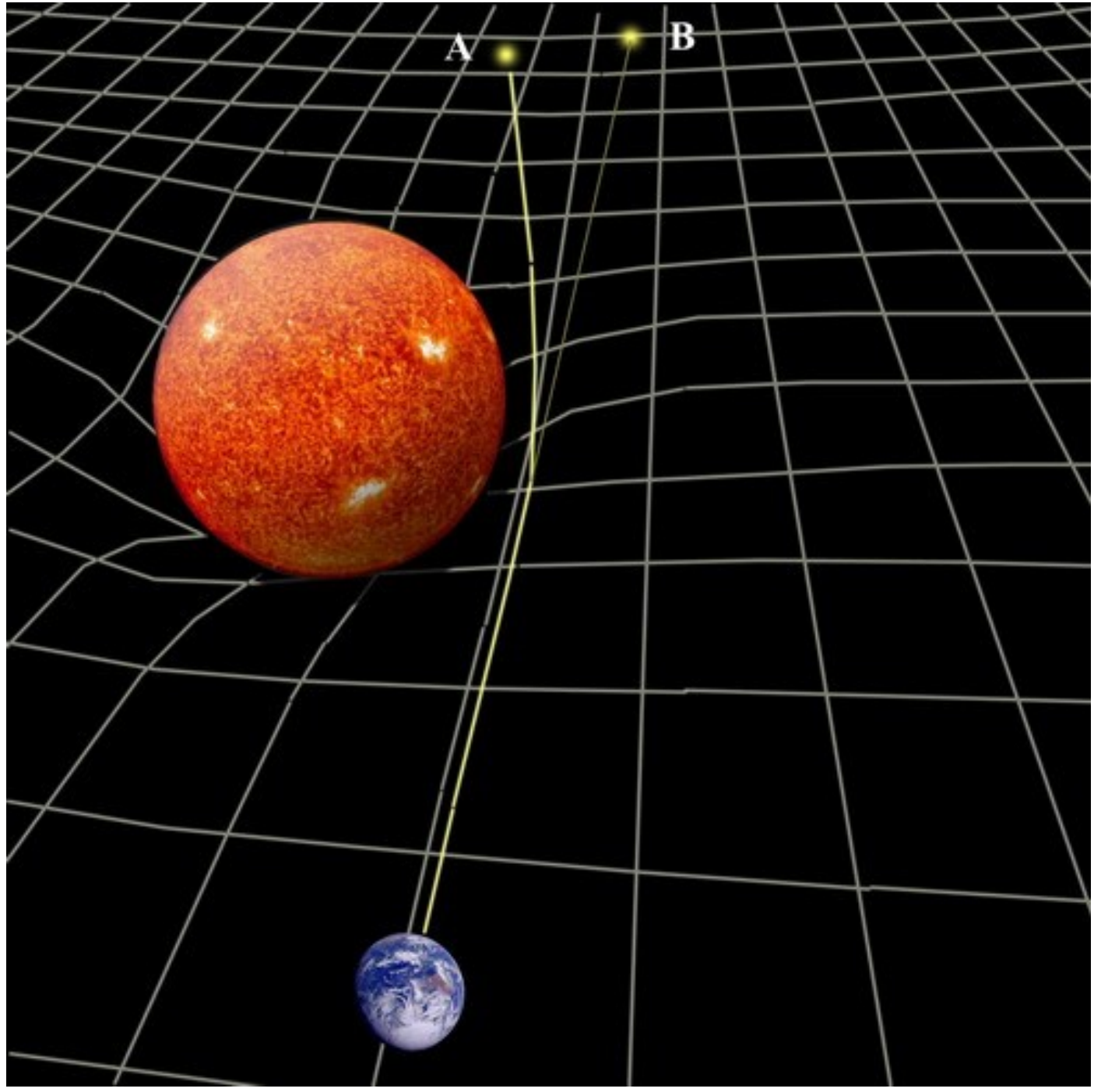
General Relativity: Einstein's theory of gravity

Field equations:

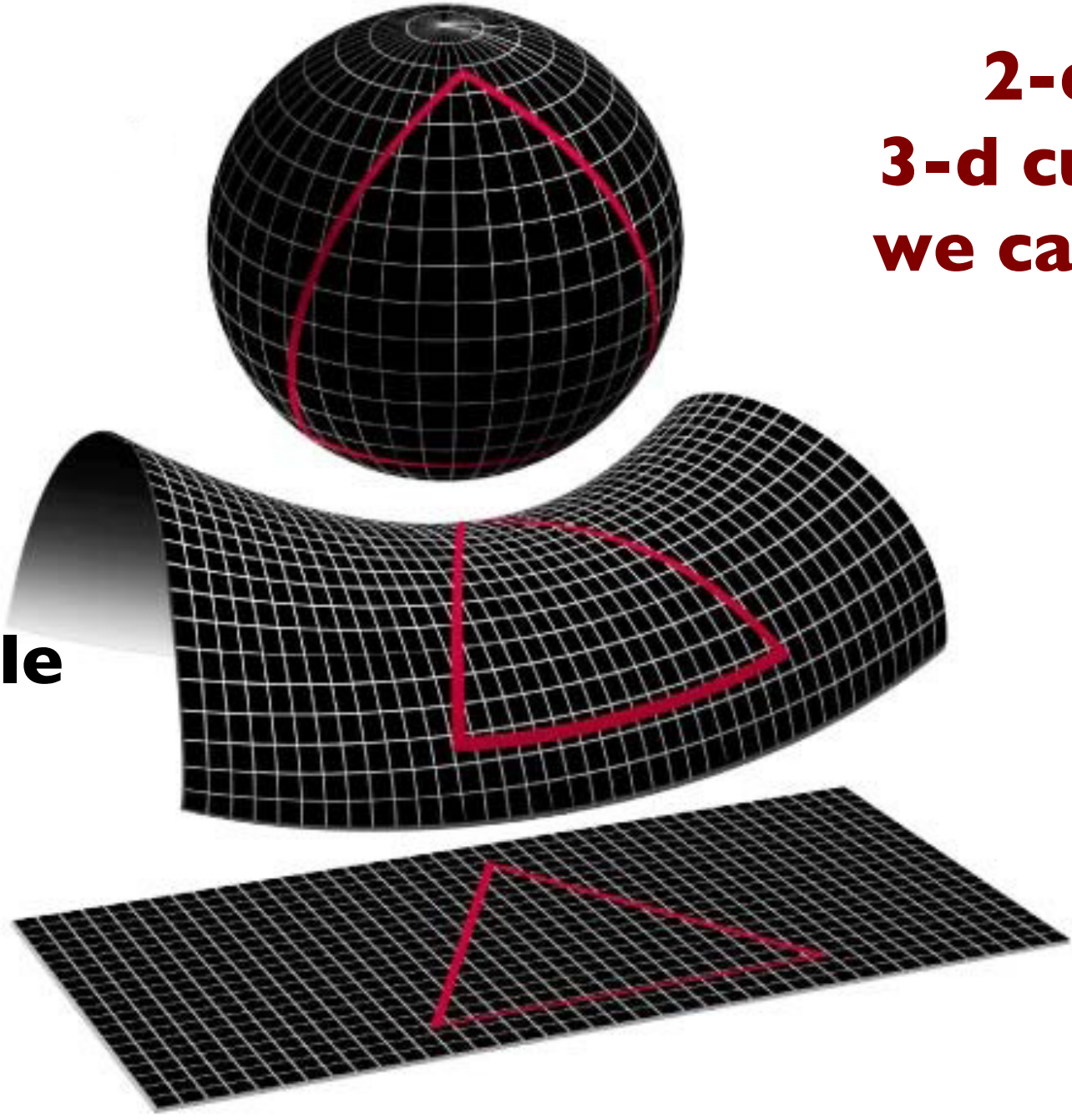
$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

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

Gravity = curvature of spacetime.



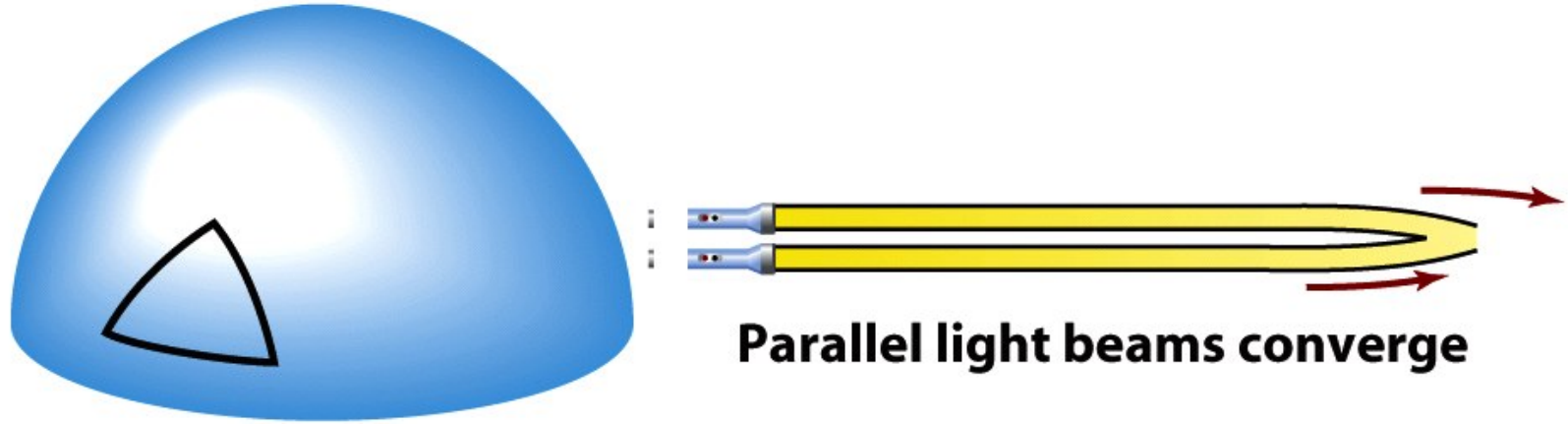
Gravity = curvature of spacetime.



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

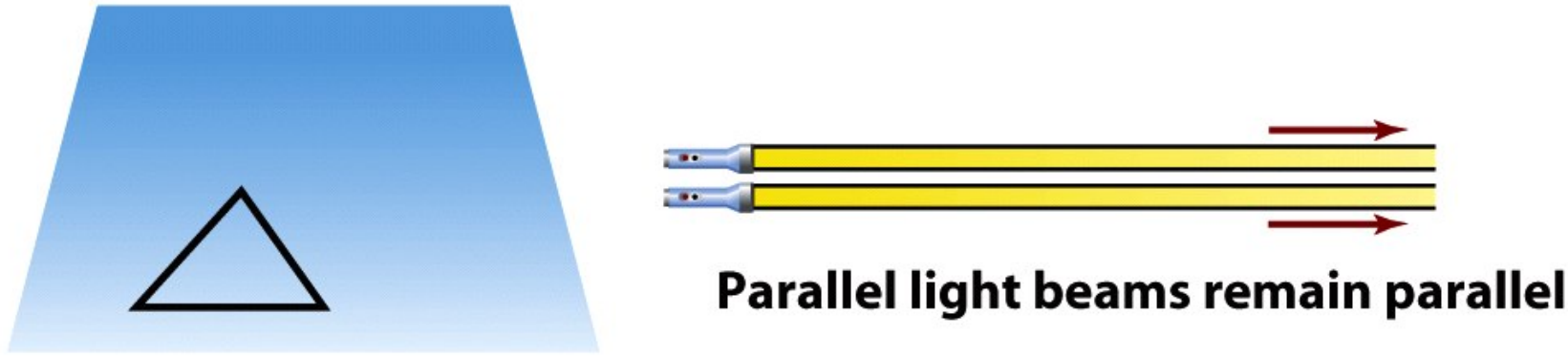
MAP990006

Geometry of the universe



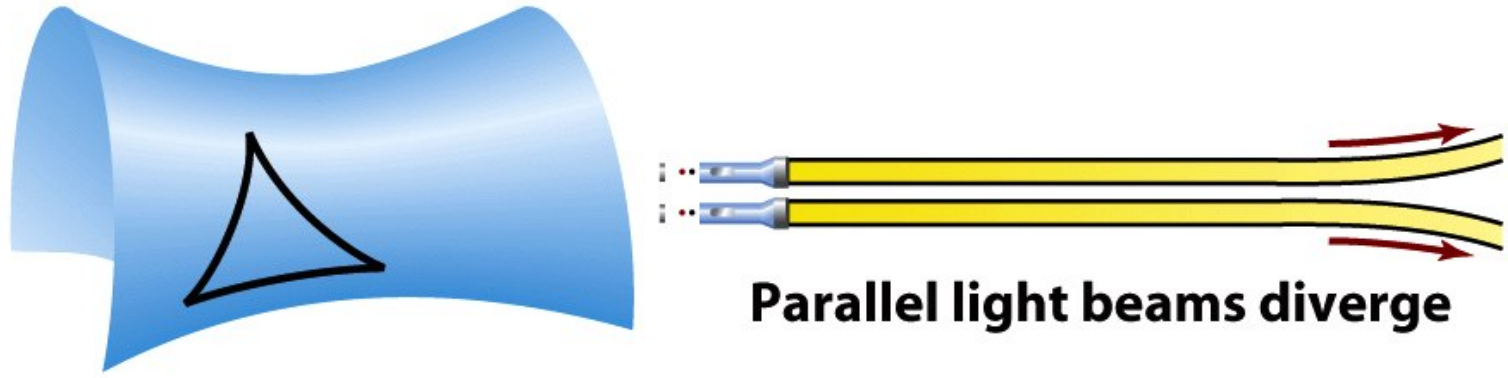
(a) Spherical space

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



(b) Flat space

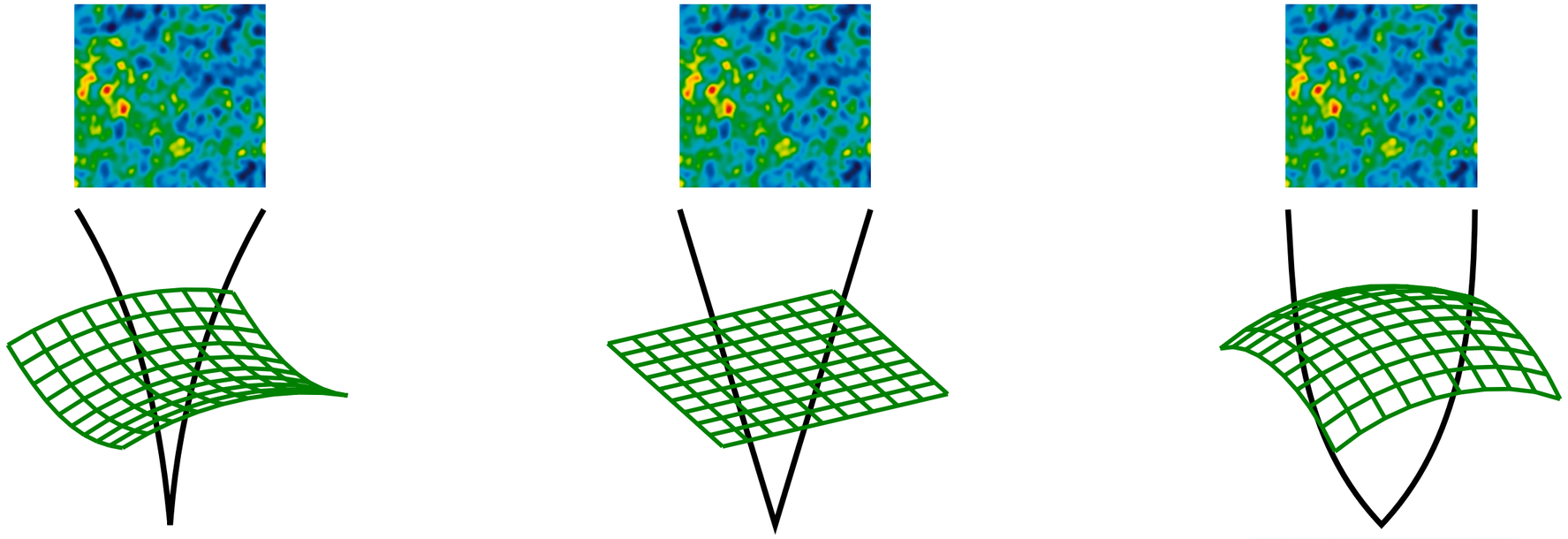
$\rho_0 = \rho_c$, $\Omega_0 = 1$



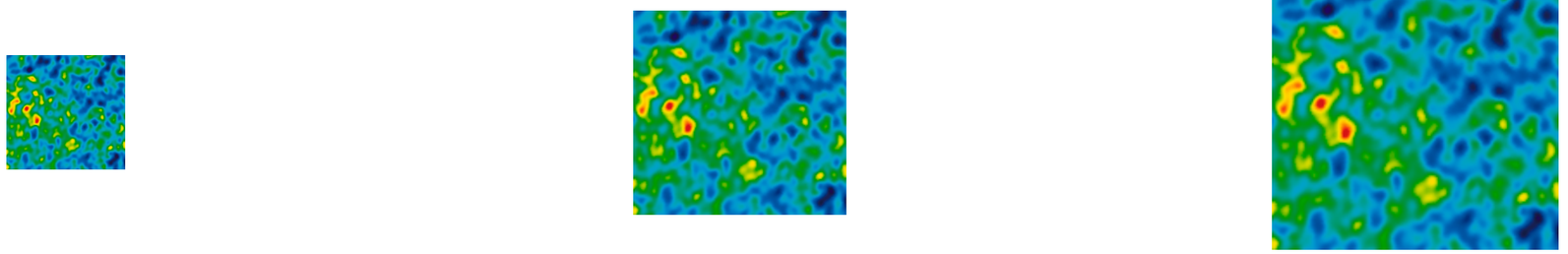
(c) Hyperbolic space

Measuring curvature

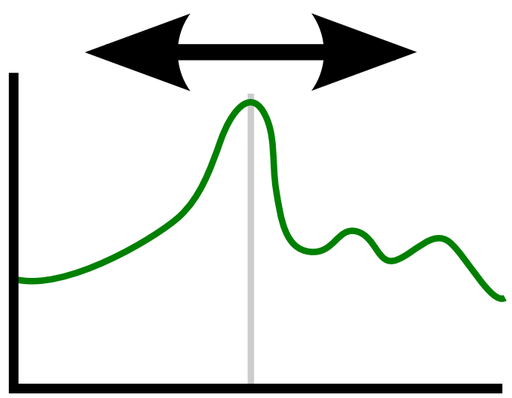
CMB surface



CMB observed



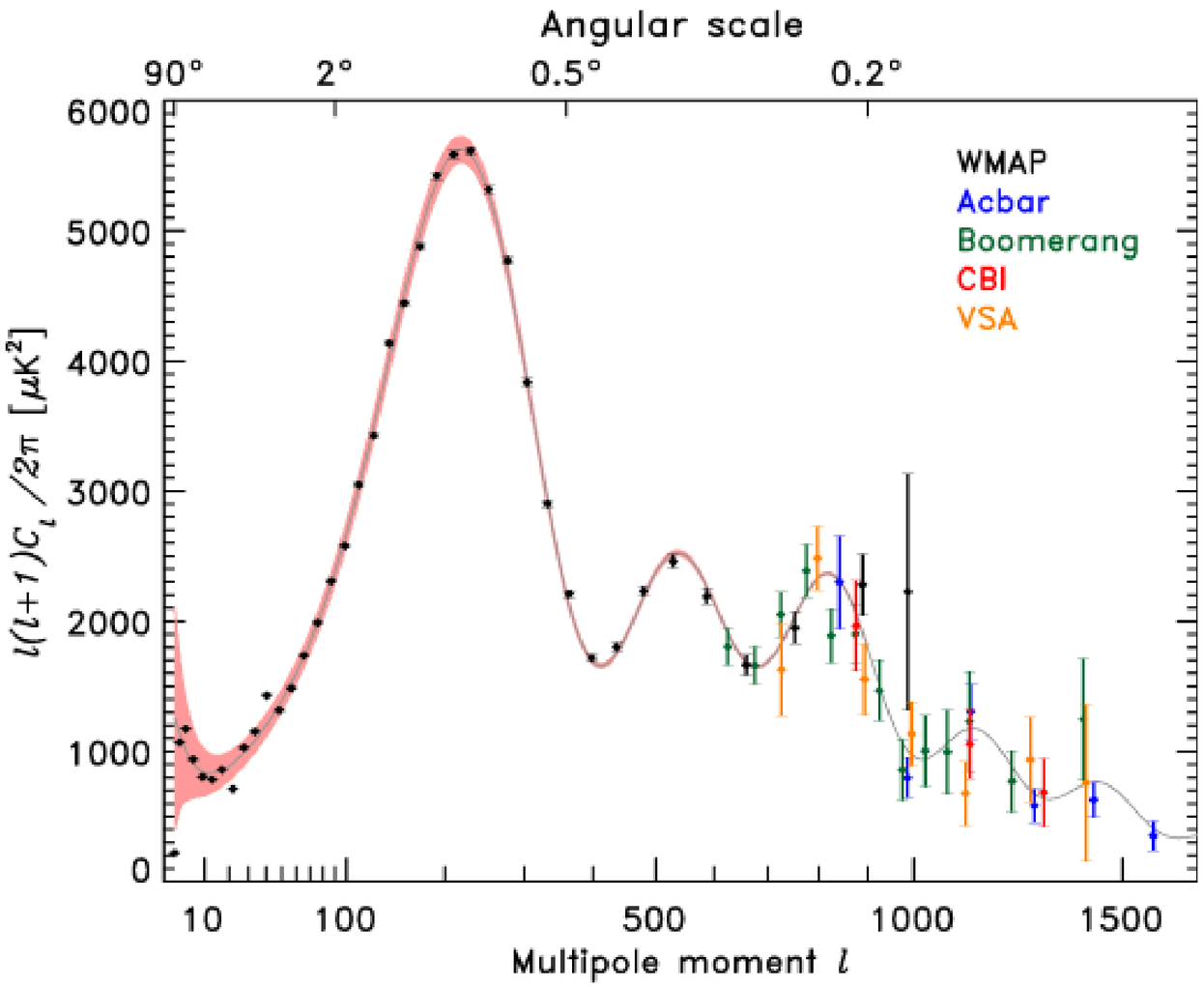
Viewing fixed sized object through curved spacetimes.



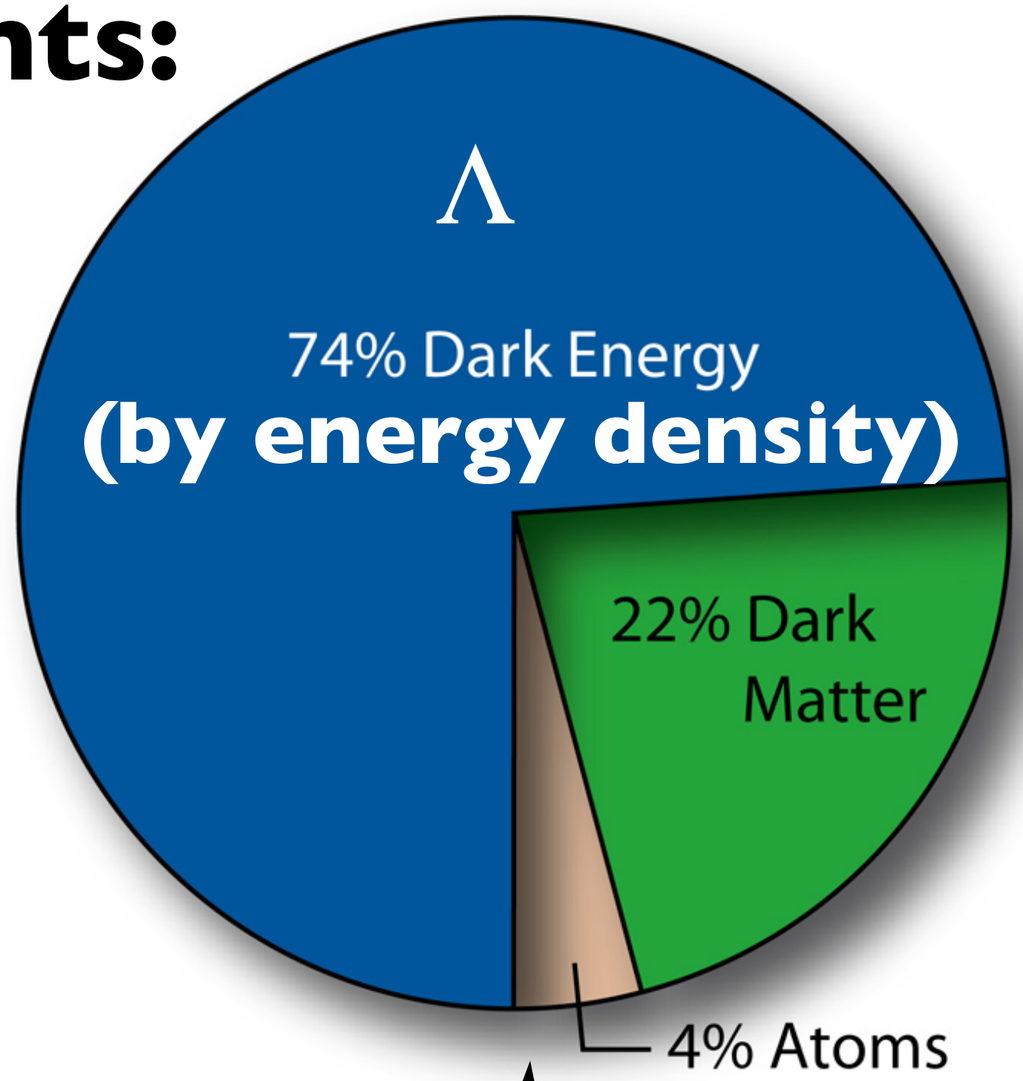
WMAP results

Space-time: flat +/- 2%

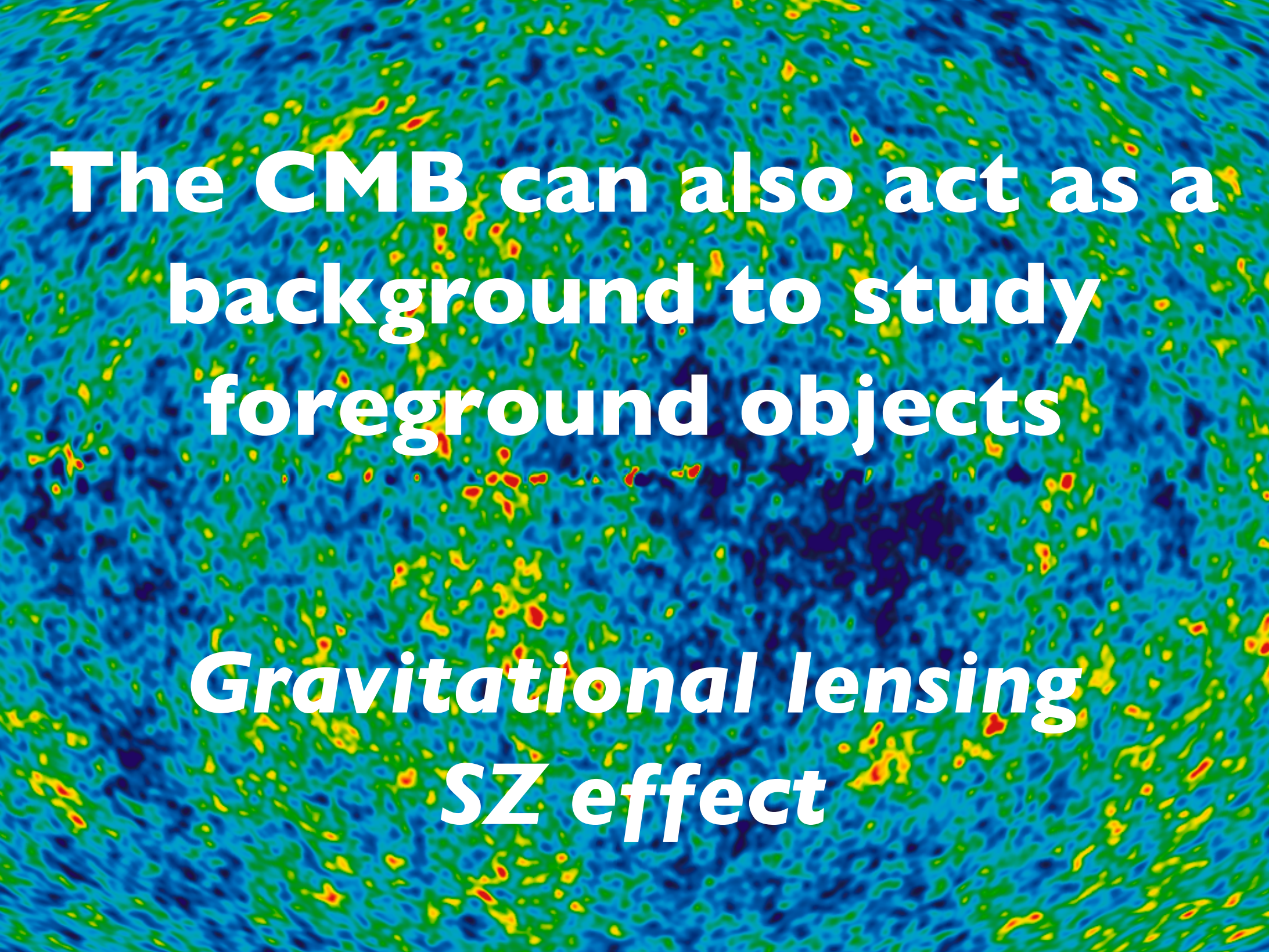
Data:



Contents:



Results:


The CMB can also act as a background to study foreground objects
Gravitational lensing
SZ effect

Cosmic web

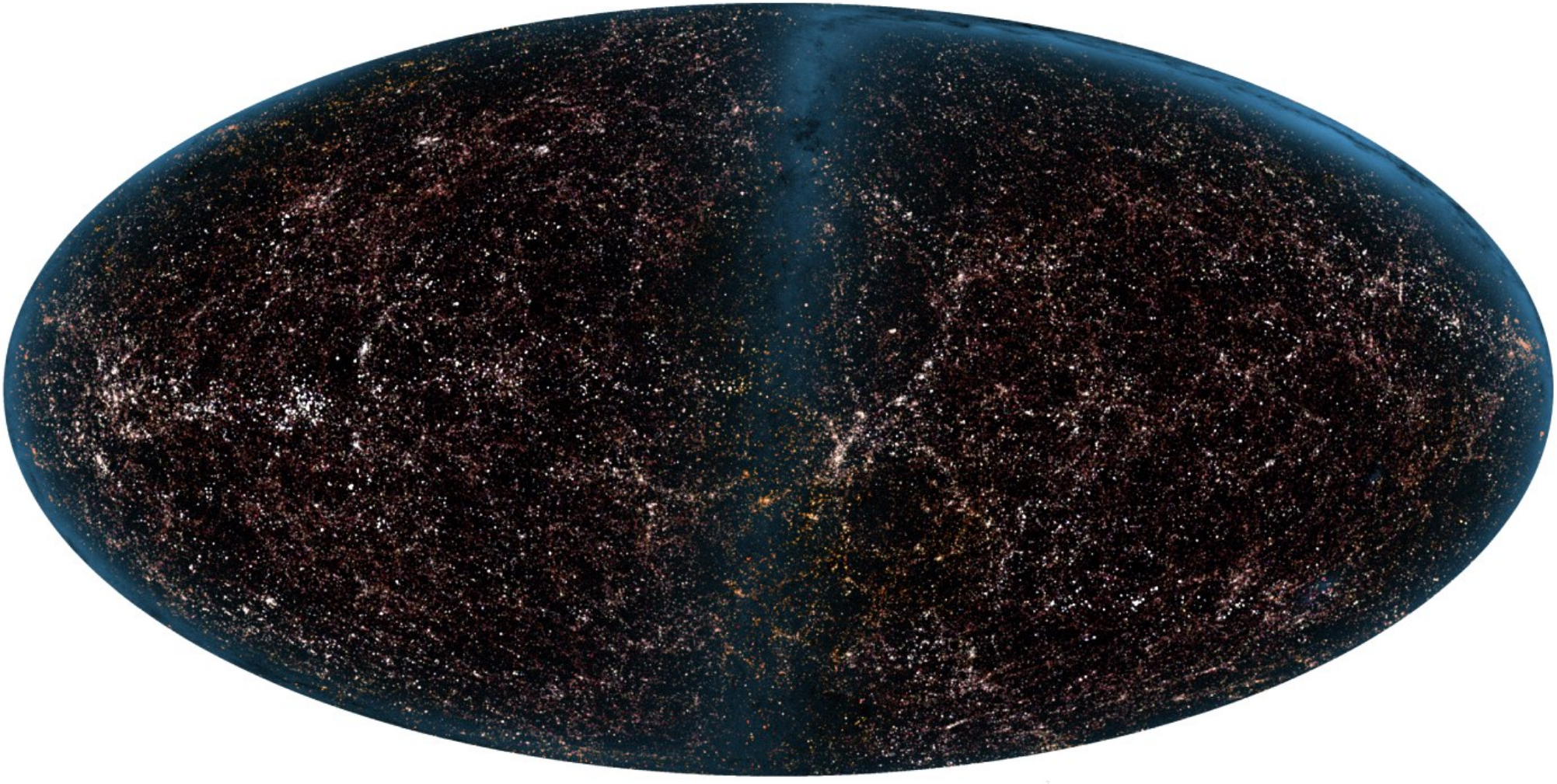
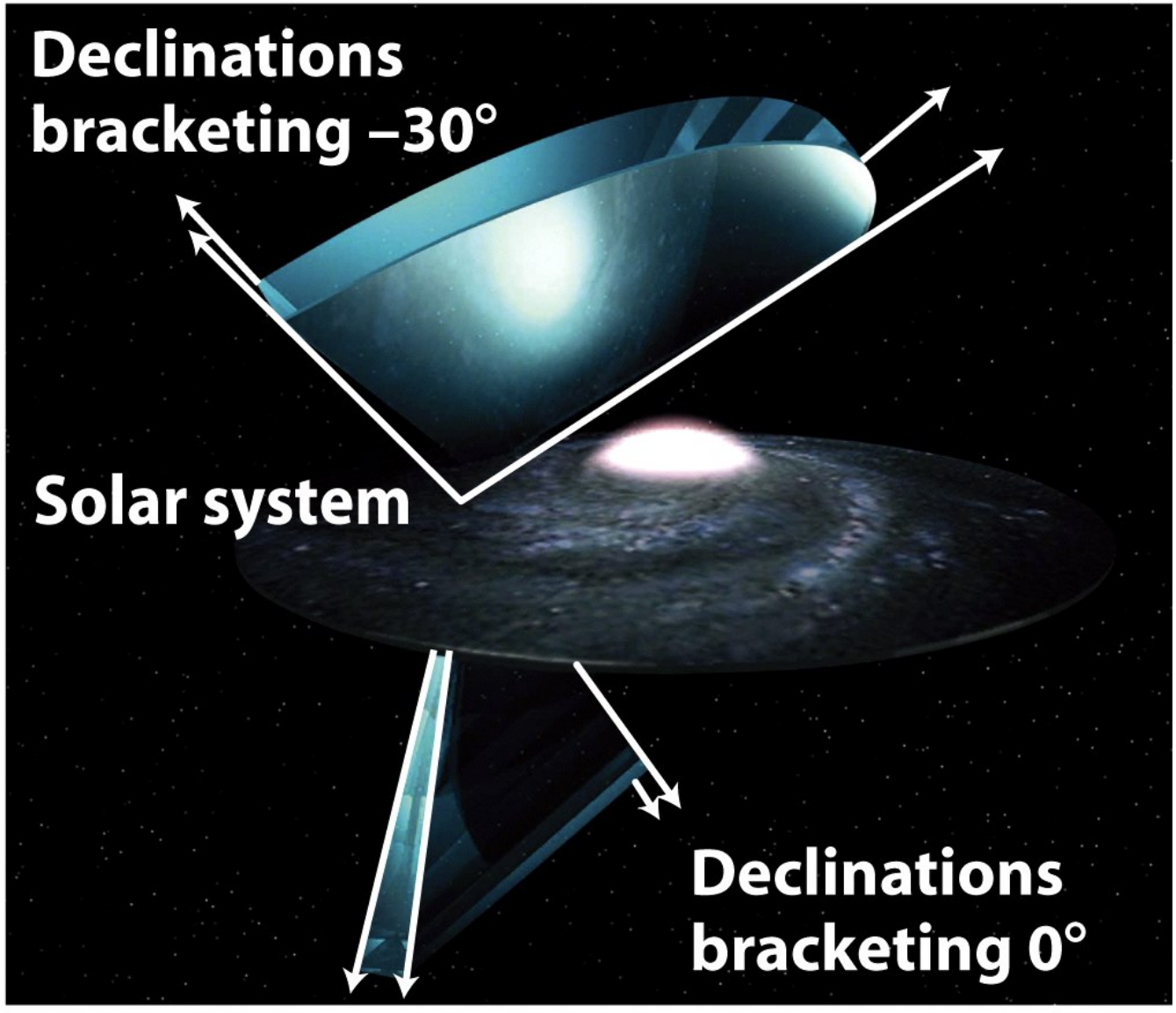


Figure 24-23
Universe, Eighth Edition

Cosmic web (2dF survey)



Fields of view in the 2dF survey

Figure 24-24b
Universe, Eighth Edition

Cosmic web (2dF survey)

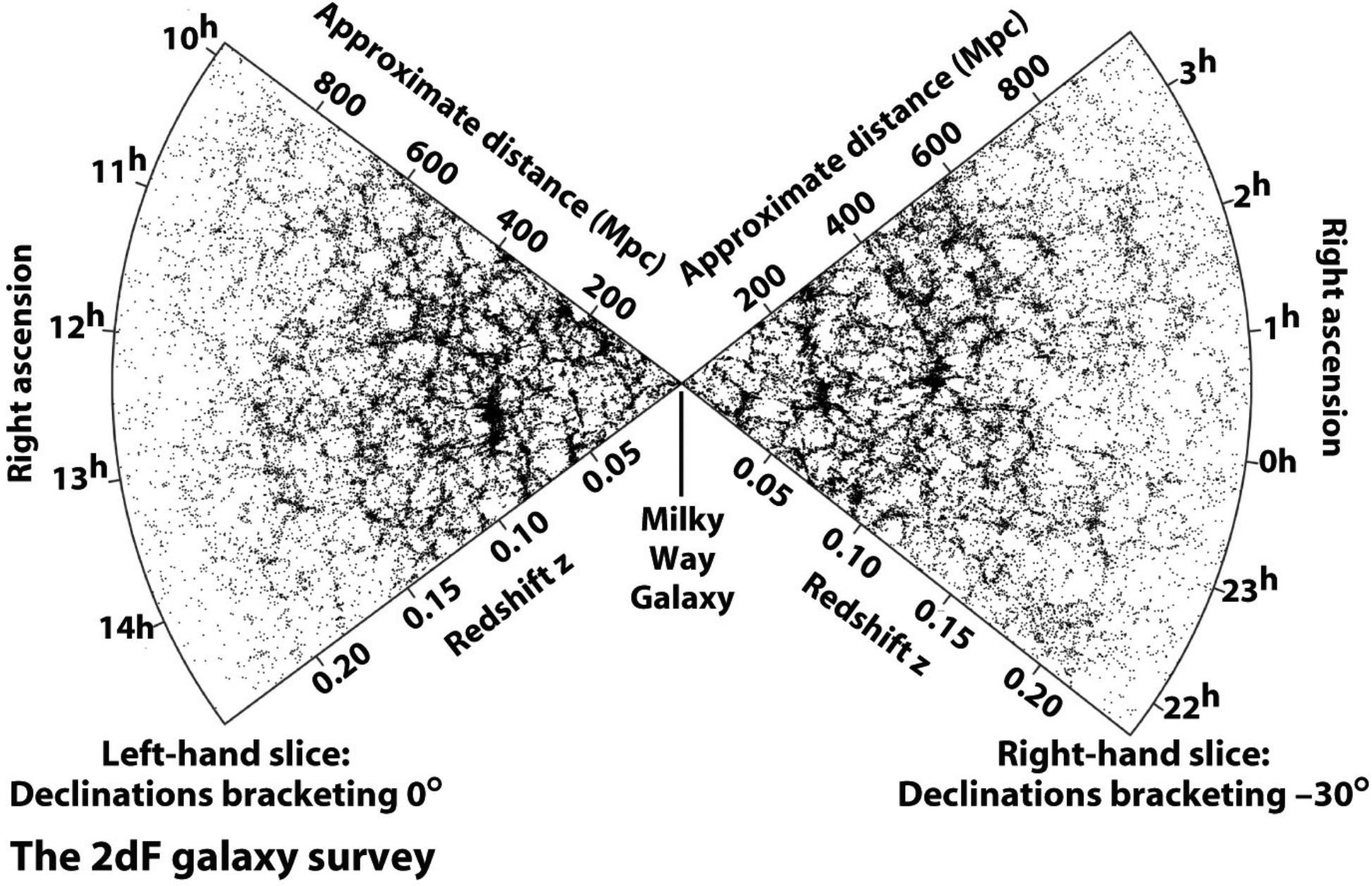
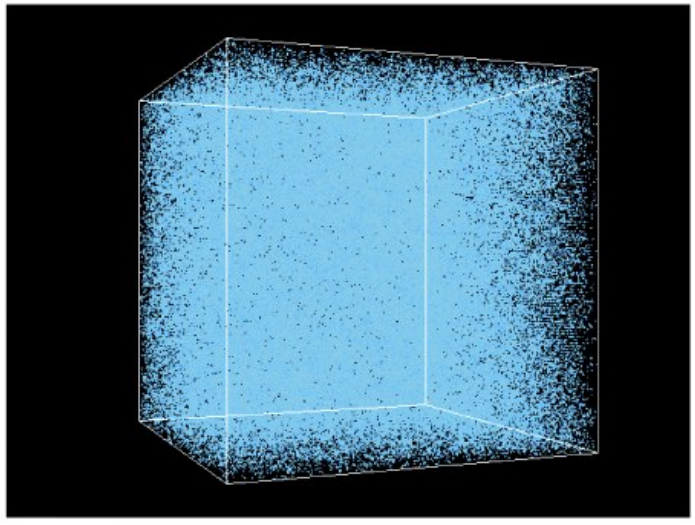
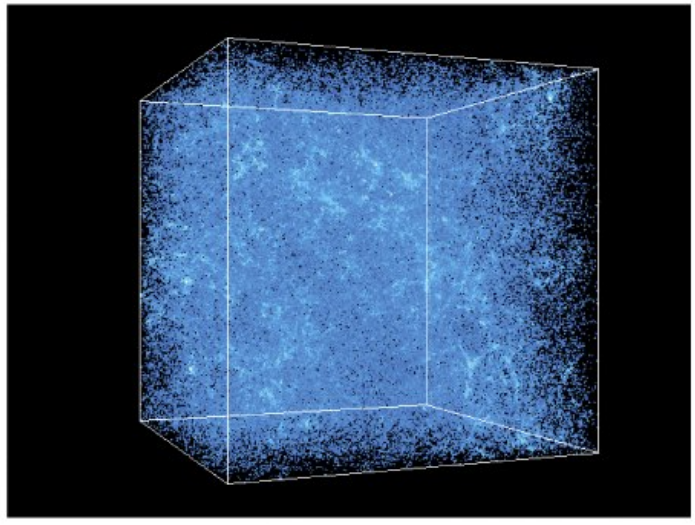


Figure 24-24a
Universe, Eighth Edition

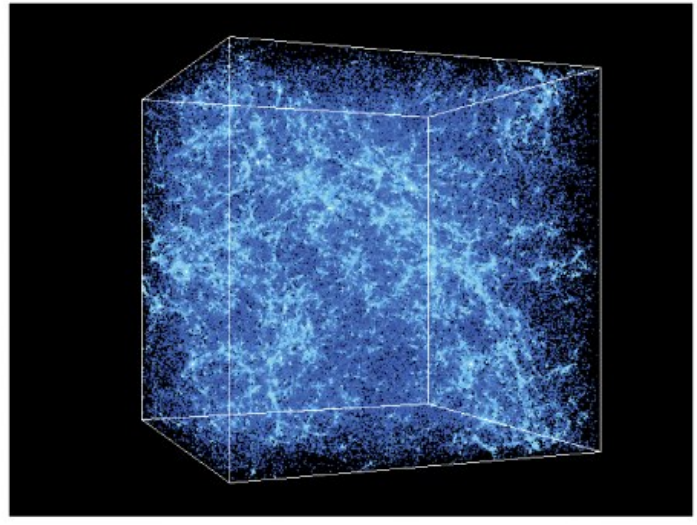
Cosmological matter simulation



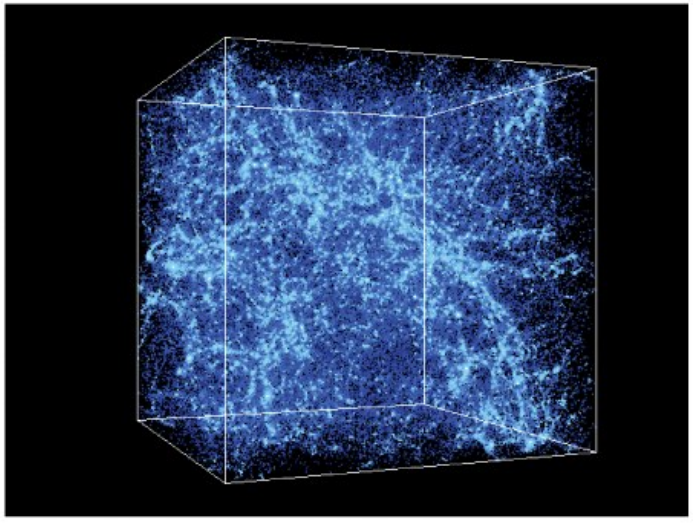
$z = 27.36$ Universe 120 million years old



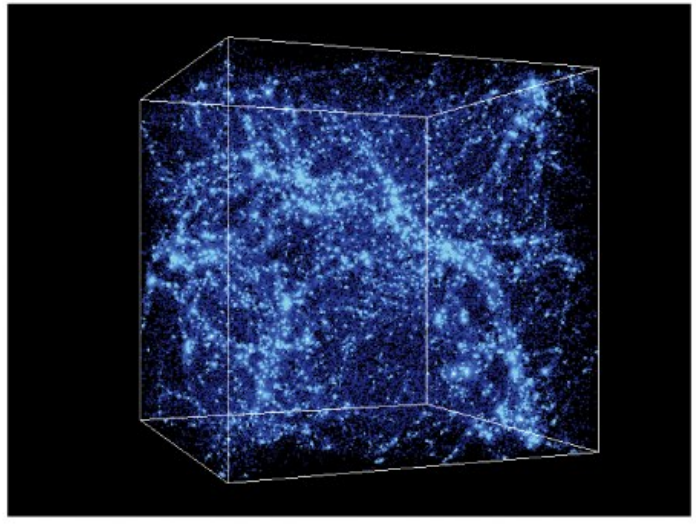
$z = 9.83$ Universe 490 million years old



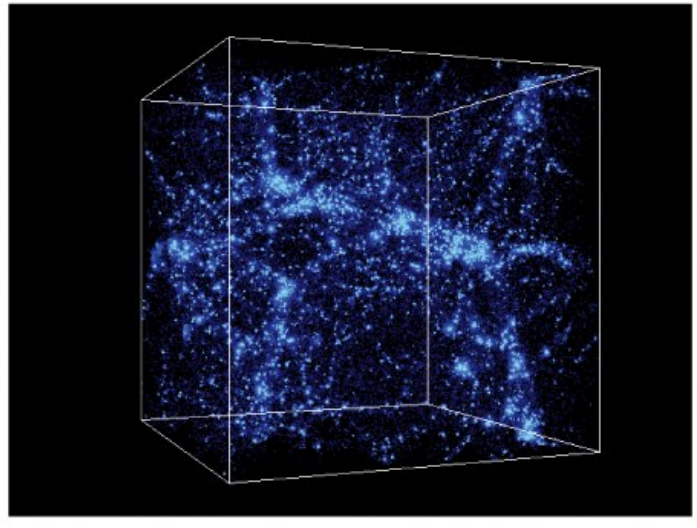
$z = 4.97$ Universe 1.2 billion years old



$z = 2.97$ Universe 2.2 billion years old



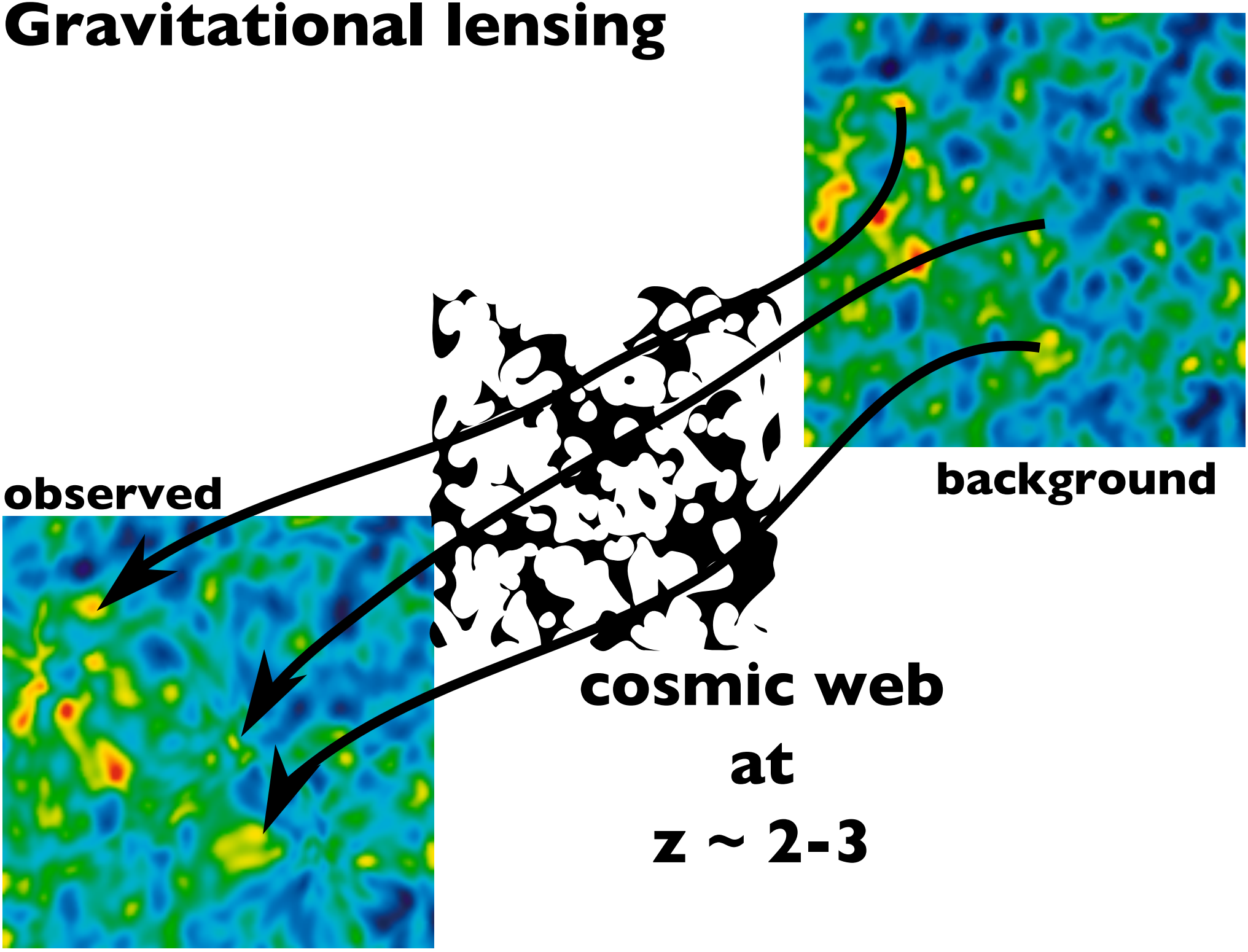
$z = 0.99$ Universe 6.0 billion years old



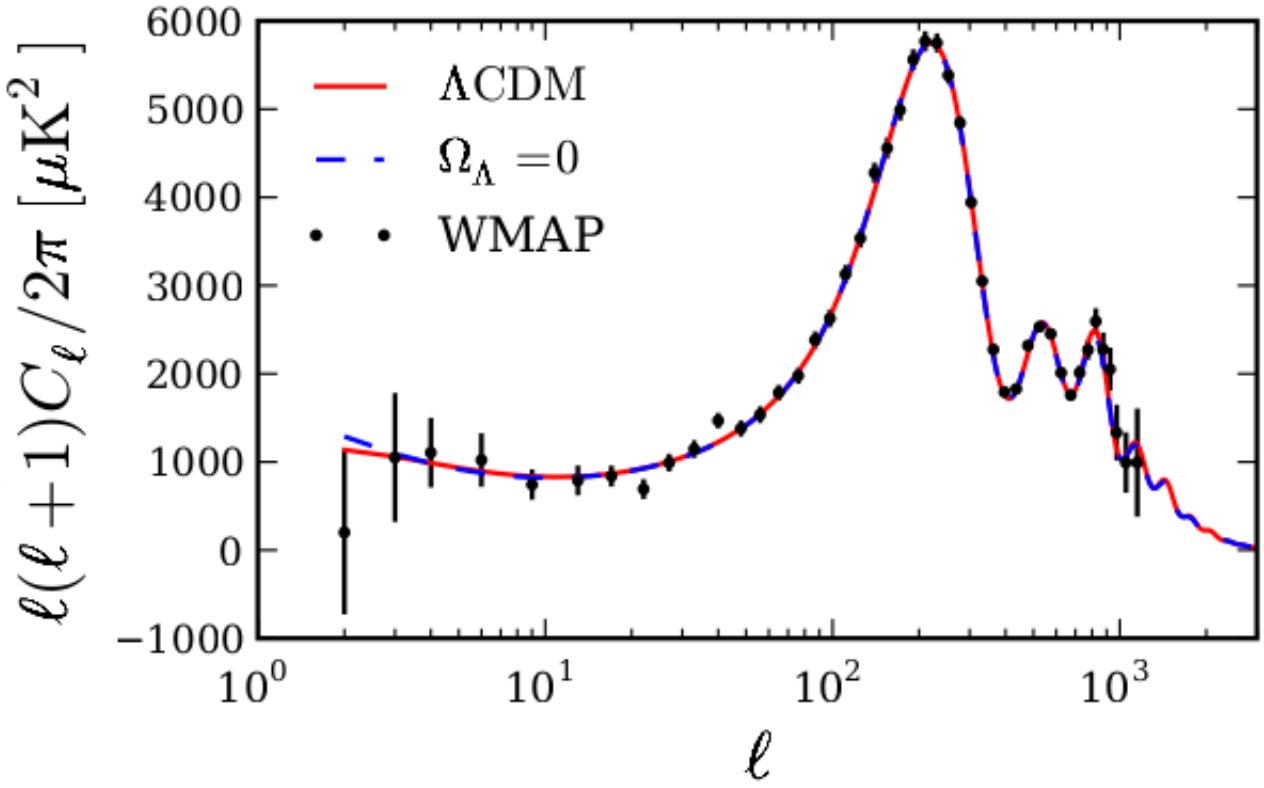
$z = 0.00$ Universe 13.7 billion years old

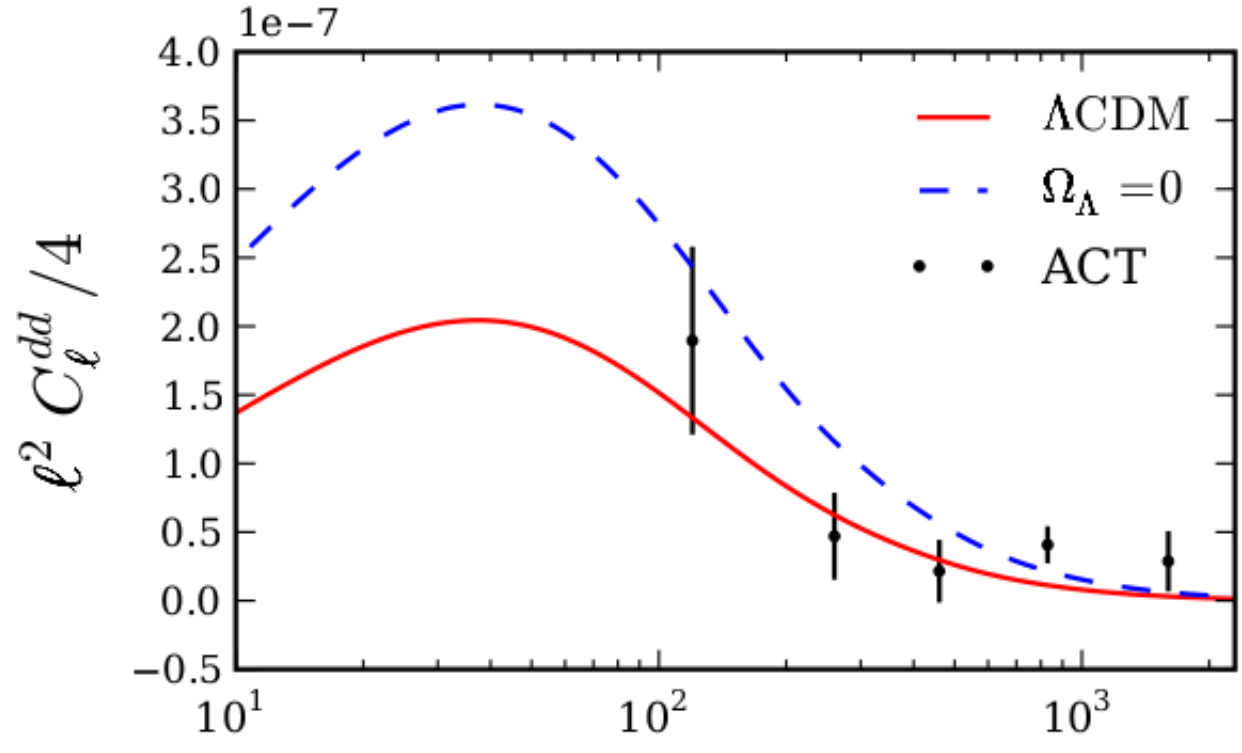
Figure 27-15
Universe, Eighth Edition

Gravitational lensing



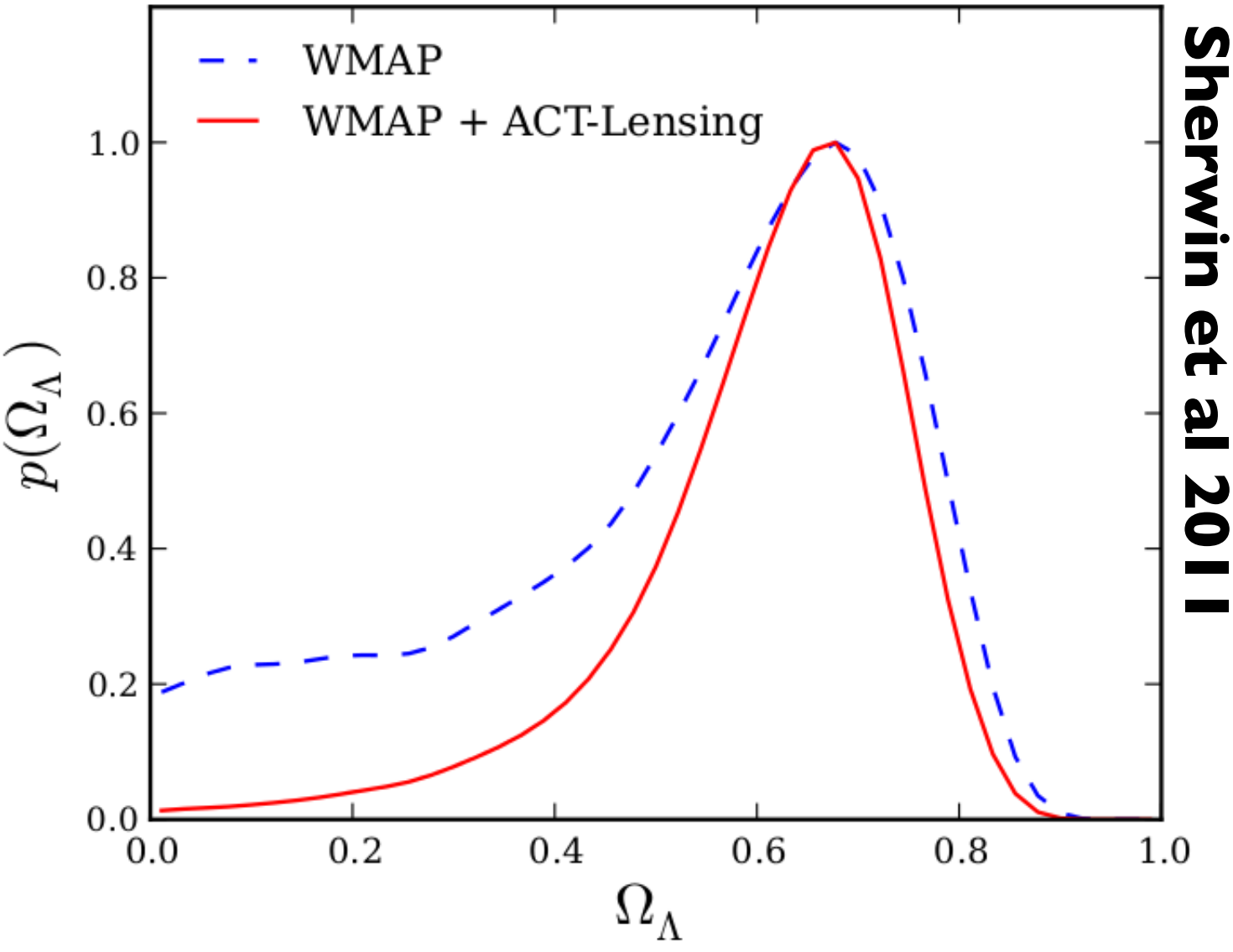
ACT CMB-lensing results





Sherwin et al 2011
Das et al 2011

ACT CMB-lensing result



Sherwin et al 2011

3.2σ evidence for Dark Energy from CMB alone (w/out SN)

Galaxy cluster (100-1000 gal.)

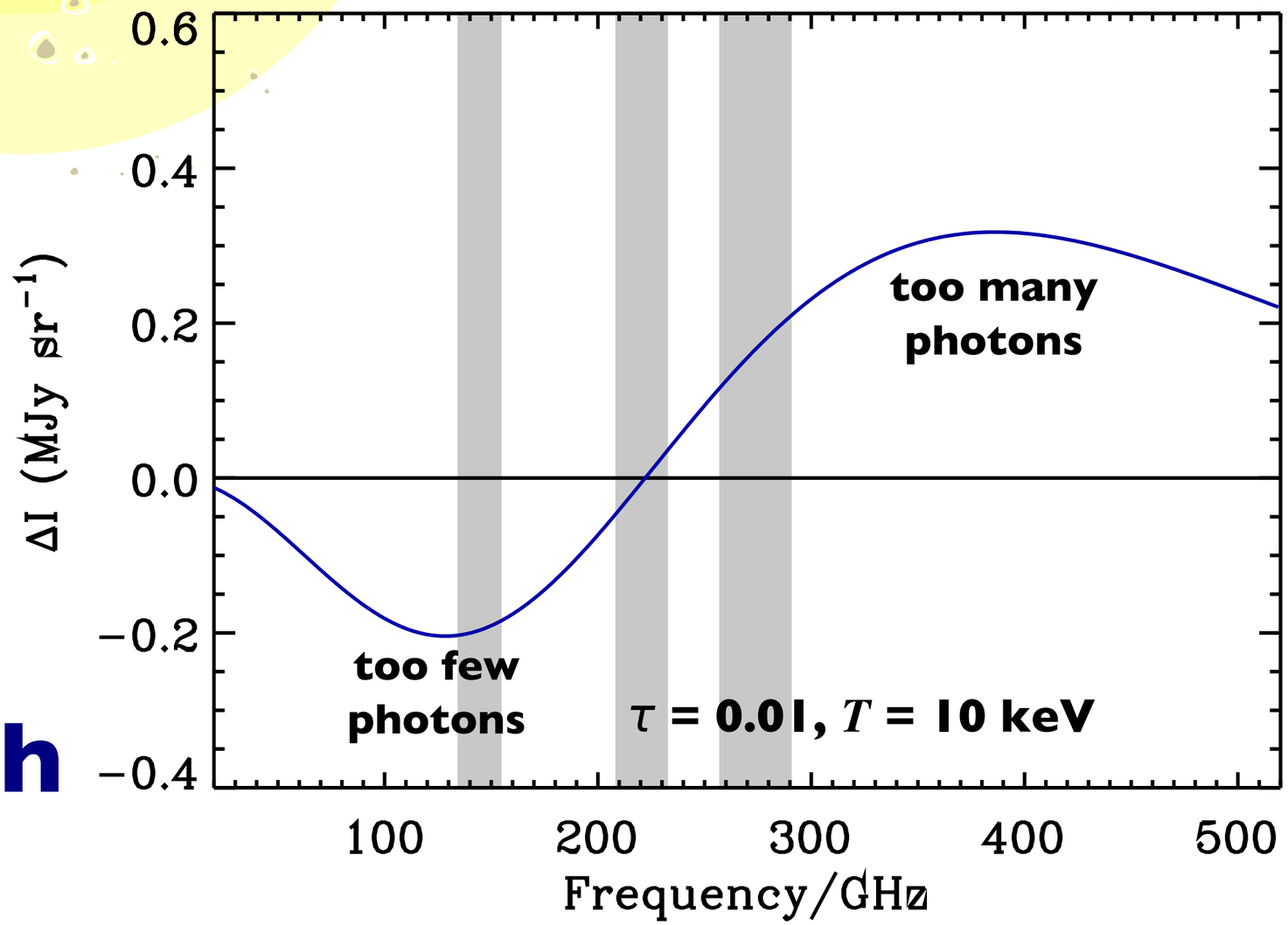
low E photon

higher E photon

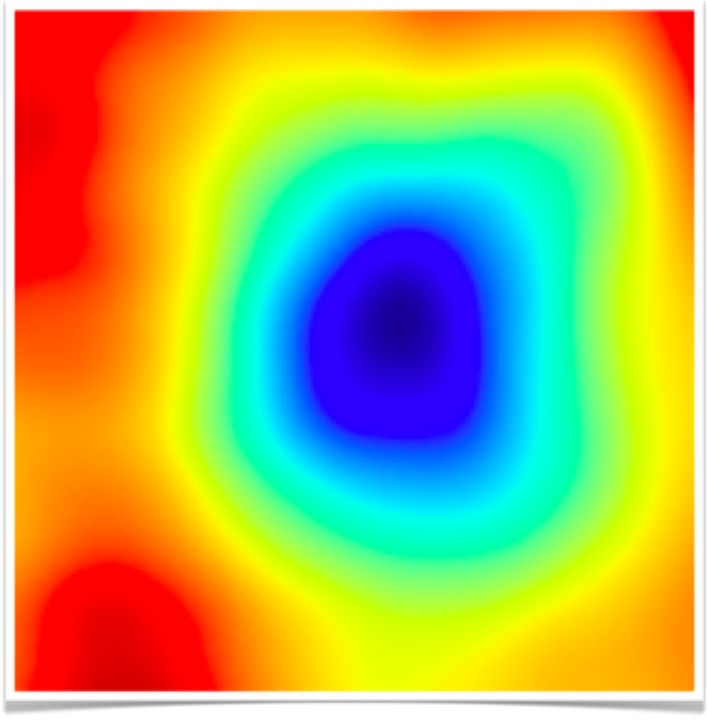
Hot gas T ~ 10^8 K

Sunyaev-Zeldovich effect

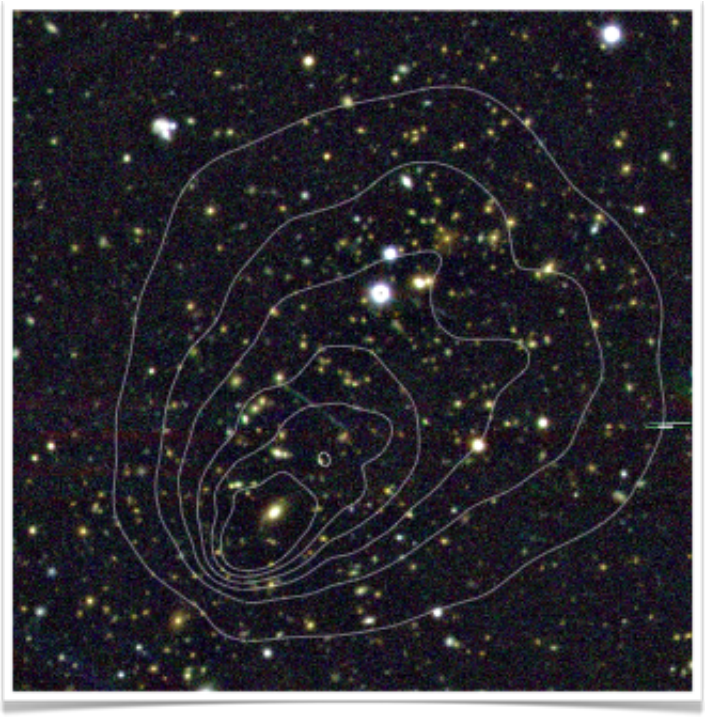
Benson et al. (2003)



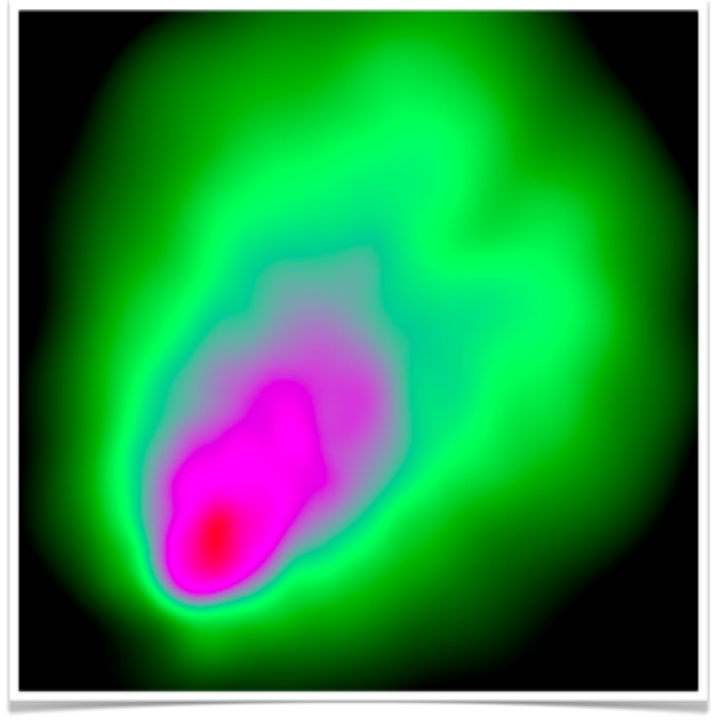
Exceptional galaxy cluster "El Gordo"



SZ



Optical

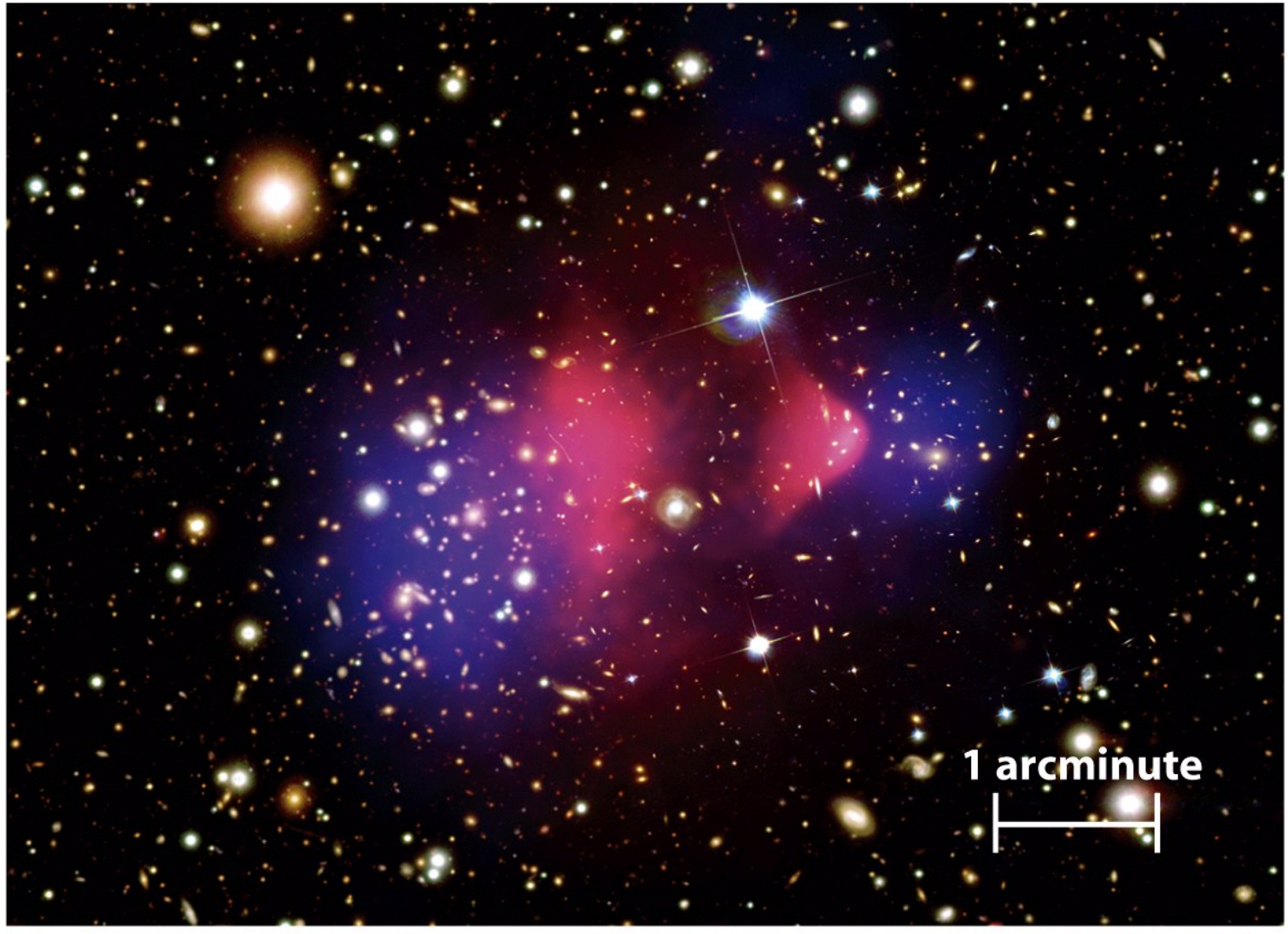


X-ray

z = 0.87, M ~ 2 x 10^{15} Msun

Highest T, Most massive at z>0.6

Bullet cluster

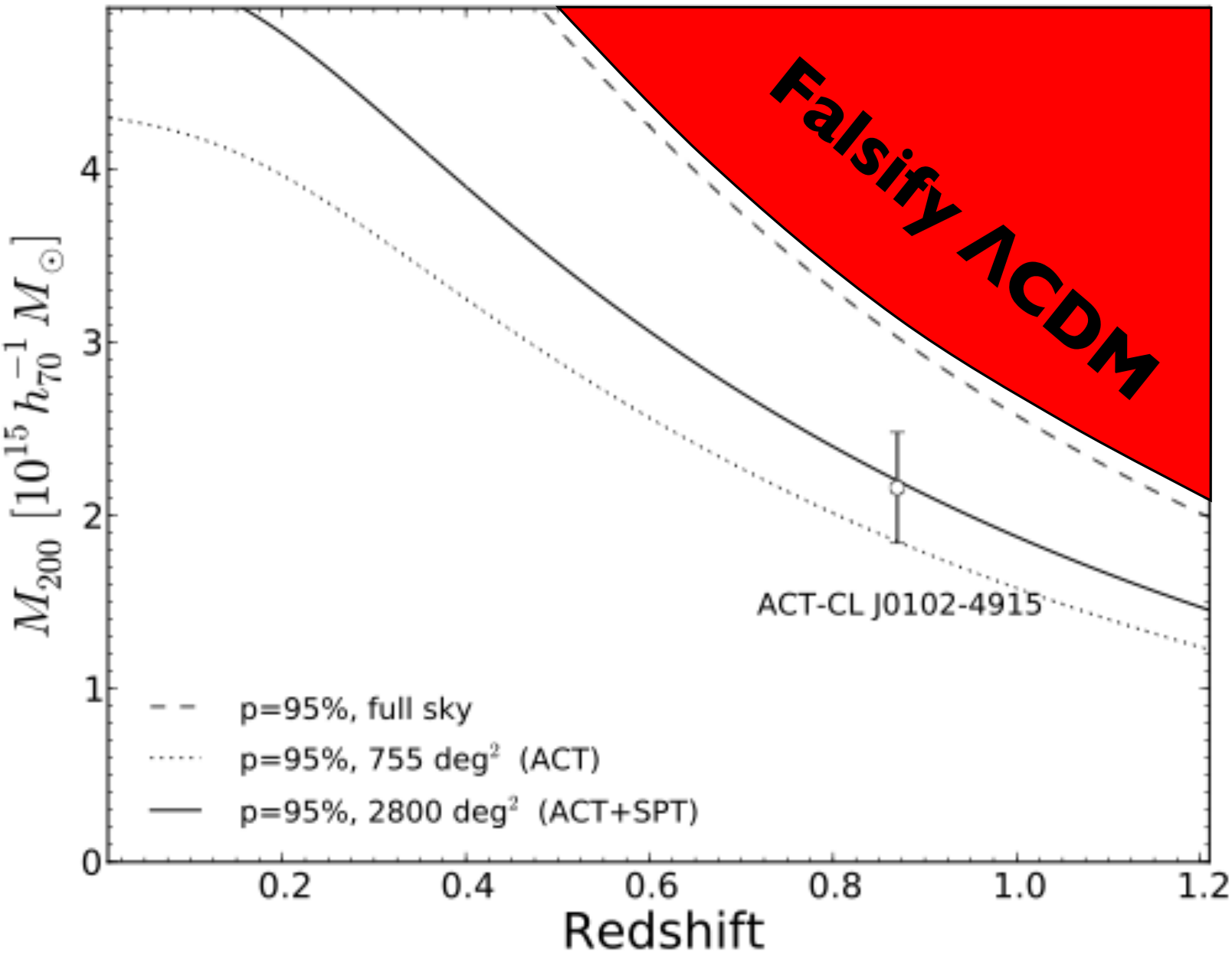


Composite image of galaxy cluster 1E0657-56 showing visible galaxies, X-ray-emitting gas (red) and dark matter (blue)

R I V U X G

Figure 24-32a
Universe, Eighth Edition

How rare is such a cluster?



Conclusions

The Universe is flat, mostly dark energy, with some dark matter, and a small fraction of normal atoms.

But what *are* dark energy and dark matter?

What is the growth rate of structure over cosmic time?

What's the precise expansion history?

Will polarization of CMB prove inflation?