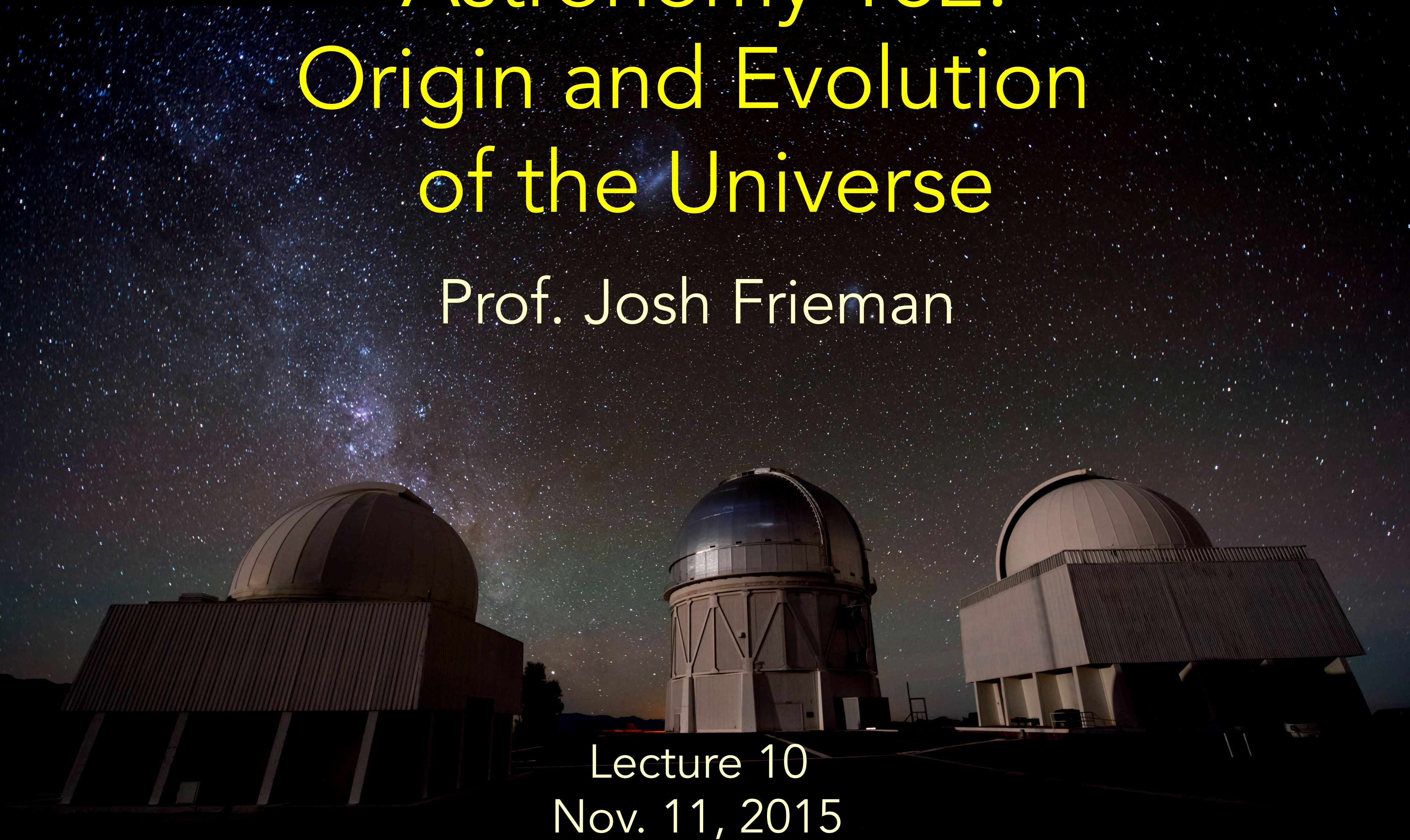
Astronomy 182: Origin and Evolution of the Universe

Prof. Josh Frieman



Lecture 10

Nov. 11, 2015

Today

- Hot Big Bang I: Cosmic Microwave Background

Assignments

- This week: read Hawley and Holcomb, Chapter 12 .
- This Fri., Nov. 13: Essay 3 due on HH, Chapter 13. Optional re-write of Essay 1 on Chap. 10 due.

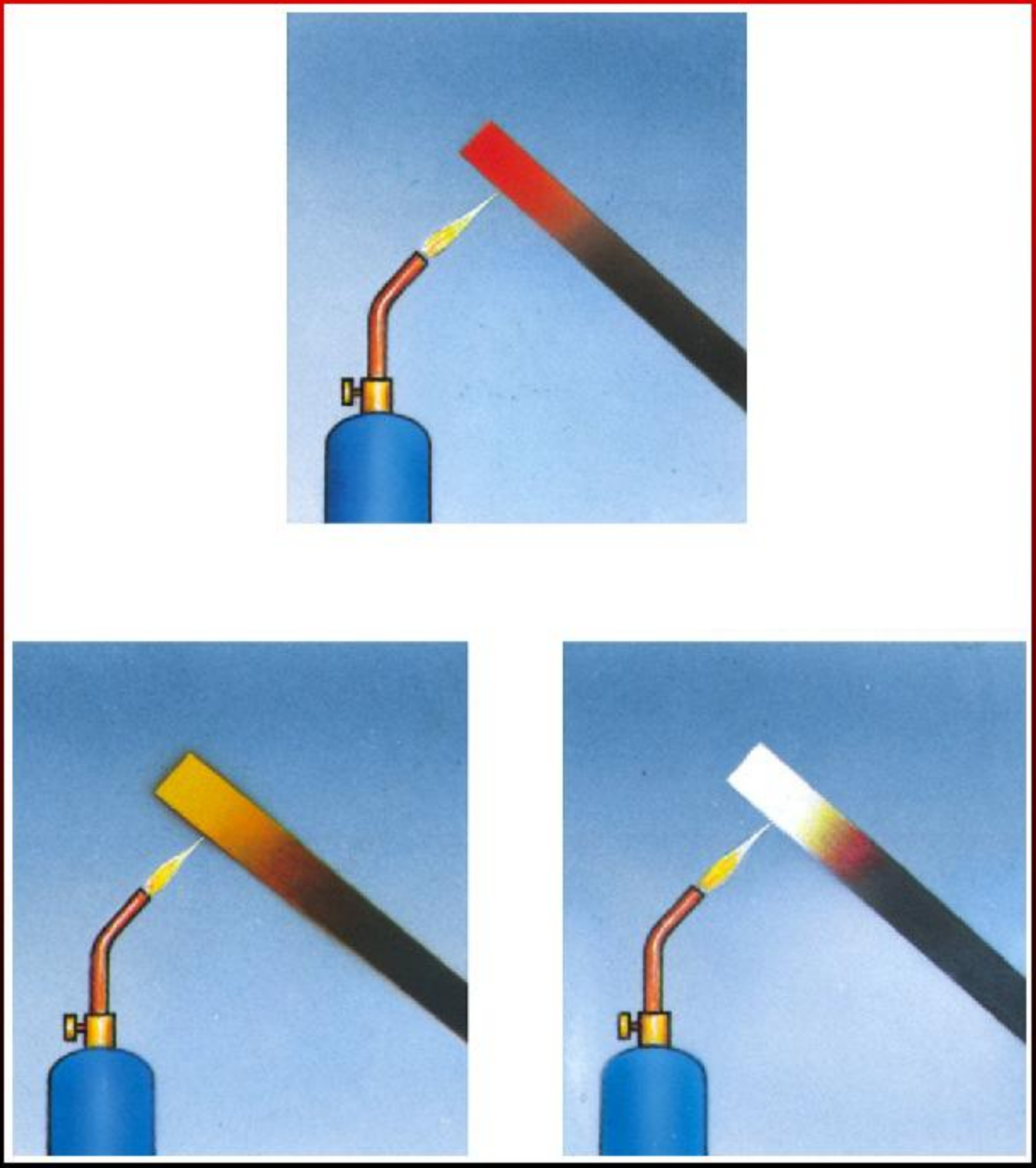
The Big Bang Theory

- The Universe has been expanding from a hot, dense beginning 13.7 billion years ago.
- This paradigm provides a successful framework for interpreting all cosmological observations to date.
- Three Classical Observational Pillars of the Big Bang:
  - Hubble's law of expansion
  - Cosmic Microwave Background (today)
  - Big Bang Nucleosynthesis (next time)

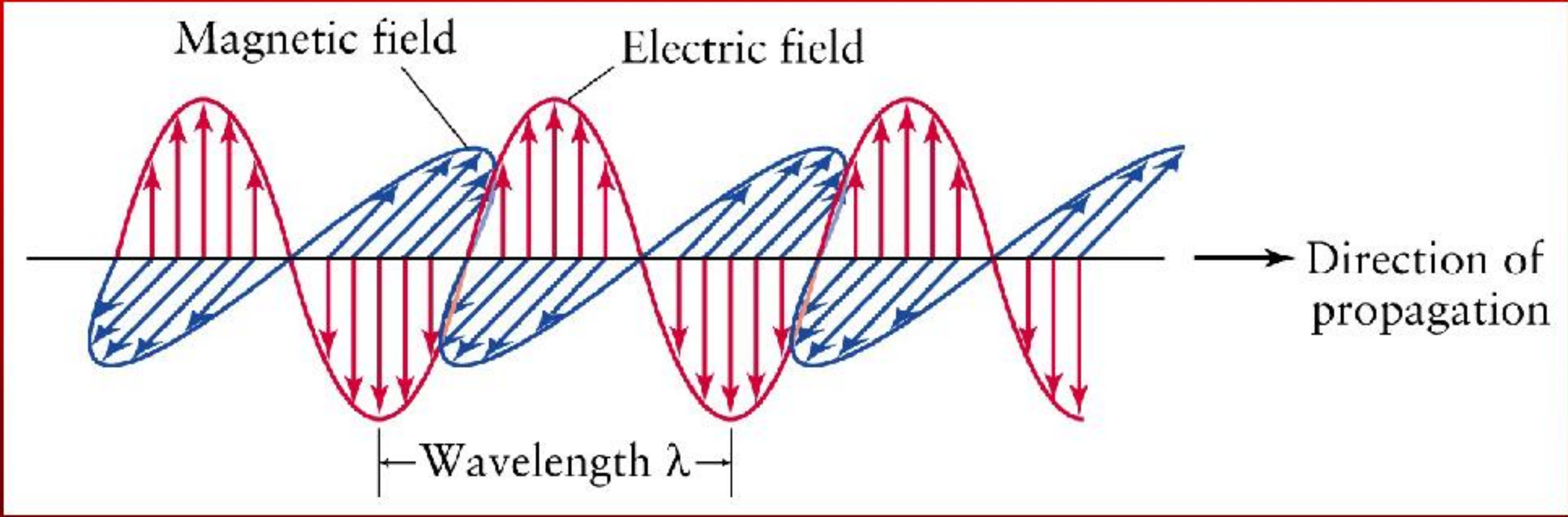
The Expanding Universe

Run it backward: Universe heats up and becomes denser

Hot Objects Emit Light

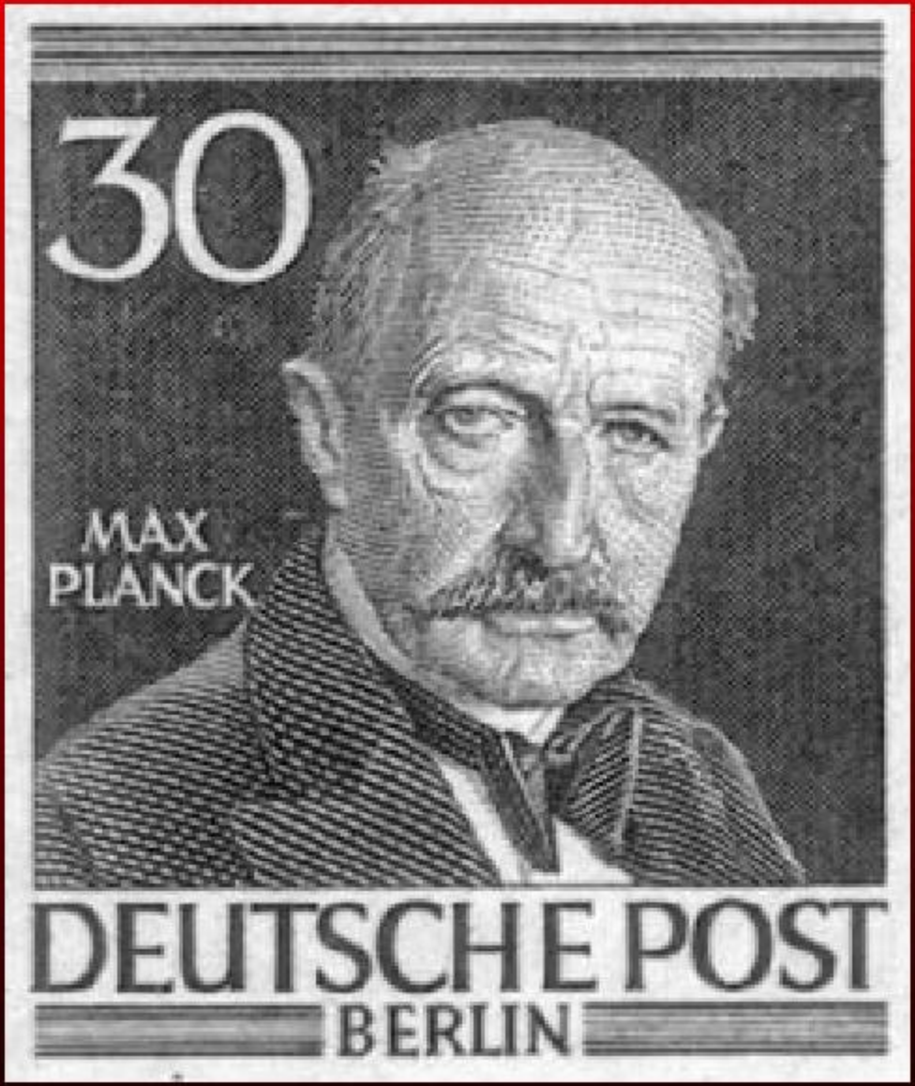


What is Light?



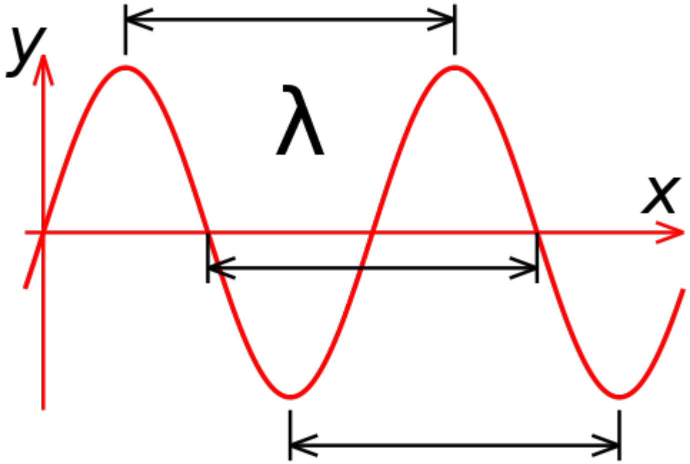
- Light is an electromagnetic wave. (For the current discussion anyway!)
- It moves forward always at the same speed - 186,000 miles per second.
- The distance from one peak to the next is called the *wavelength*.

Max Planck



In 1900 explained the spectrum of light from a hot object. ⇒ The birth of Quantum Mechanics!

Light is both an Electromagnetic Wave and a Particle (Photon)



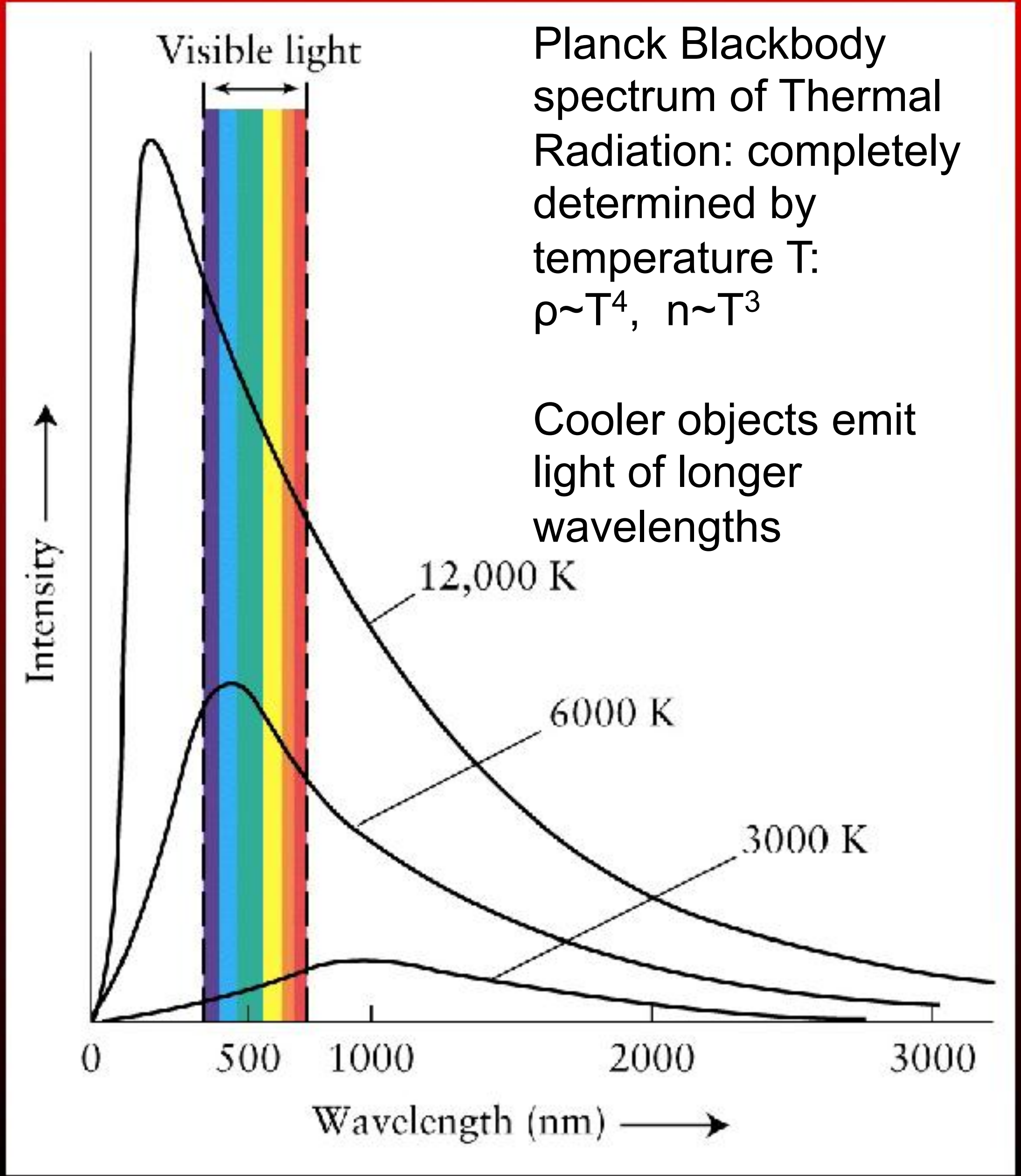
λ – wavelength – distance between wavecrests

$\lambda\nu = c$
(speed of light)

ν – frequency
$\nu = 1/\Delta t =$
1/period (time between passing wavecrests)
Unit: Hz = 1/second

Energy per photon (quantum):
$E_\gamma = h\nu = hc/\lambda$
h is Planck's constant

Spectrum of Light from a Hot Object



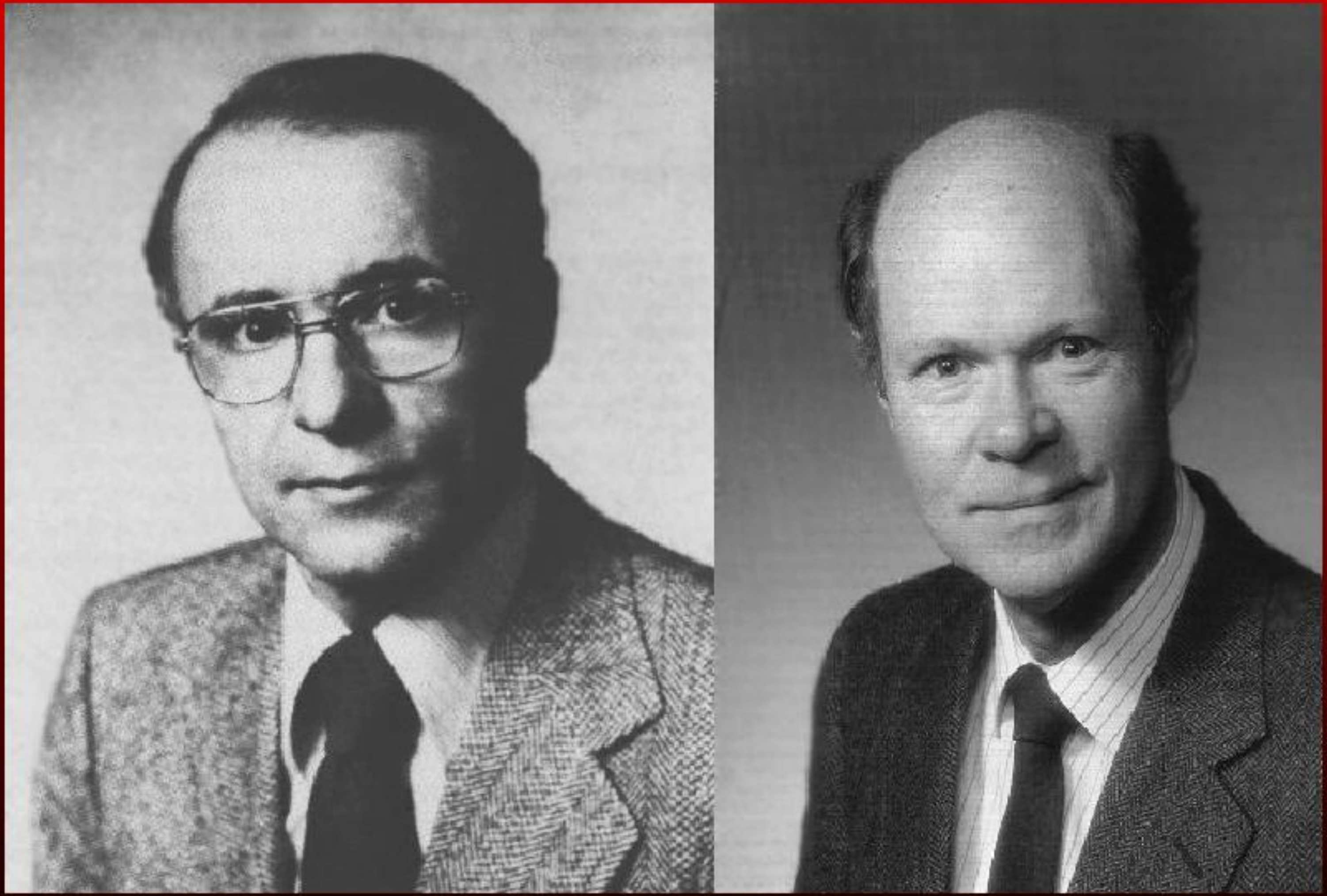
Planck Blackbody spectrum of Thermal Radiation: completely determined by temperature T:
$\rho \sim T^4$, $n \sim T^3$

Cooler objects emit light of longer wavelengths

Prediction and Observation of the Cosmic Microwave Background

- 1940's: Gamow, Alpher and Hermann were developing theories of dense, hot early Universe.
- 1960's: Princeton University crew were building experiment to look for this "relic light" left over from early times.
- 1965: Down the road Penzias and Wilson at Bell Labs were puzzling over excess noise in their microwave receiver… which was isotropic (not from Earth or the Galaxy)

Penzias and Wilson

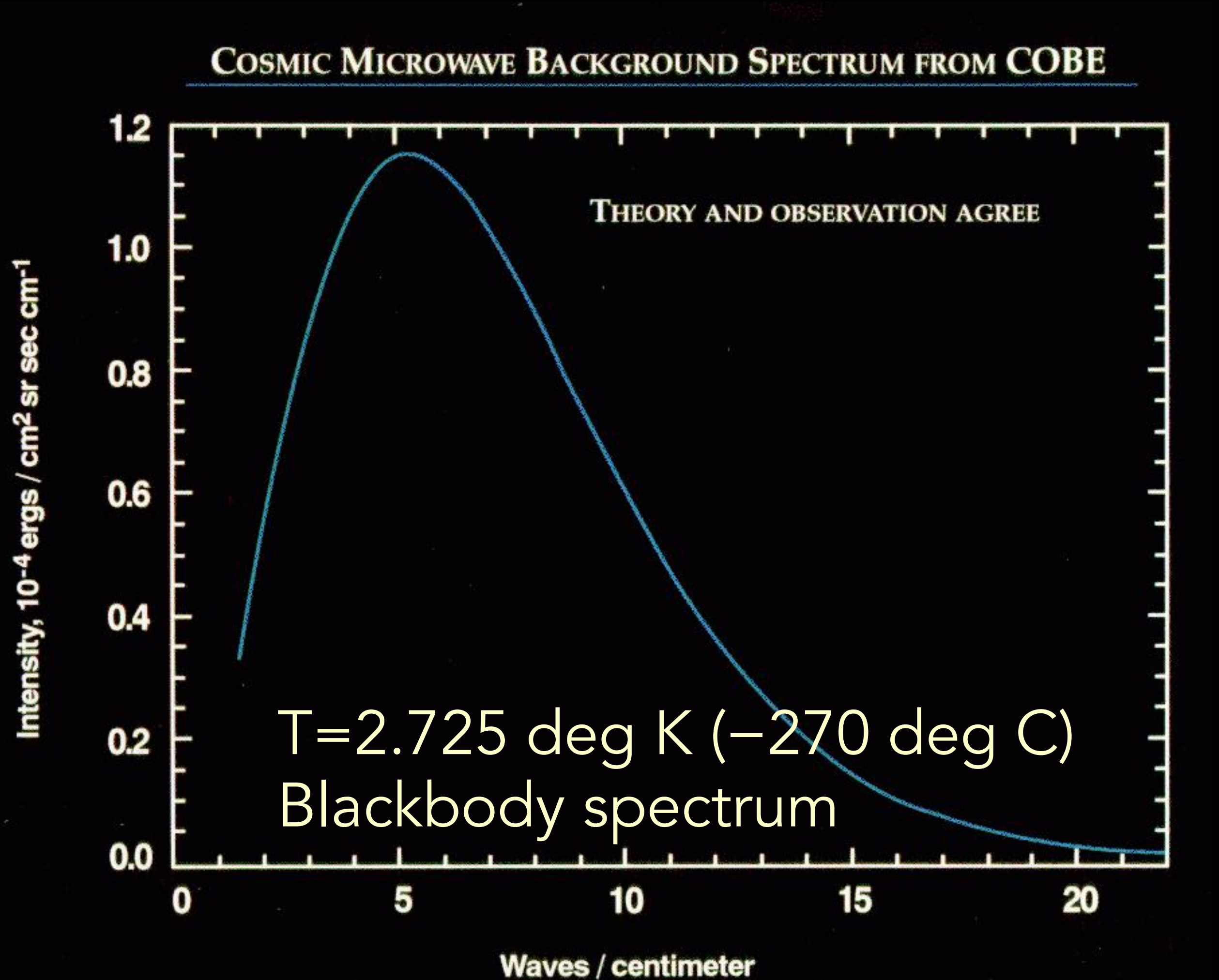


1978 Nobel Prize for discovery of the CMB

Bell Labs Horn Antenna

Cosmic Microwave Background

- Universe is filled with thermal electromagnetic radiation: the Cosmic Microwave Background (CMB) radiation, remnant from the hot early Universe.



ν – frequency

Cosmic Microwave Background

- Universe is filled with nearly isotropic, thermal electromagnetic radiation: the Cosmic Microwave Background (CMB) radiation, remnant from the hot early Universe, with precisely Blackbody spectrum at T=2.725 deg K.
- Number density of CMB photons: $n \sim T^3 = 400/cm^3$
- Most CMB photons have mm-cm wavelengths
- Responsible for ~1% of the 'snow' in old TVs

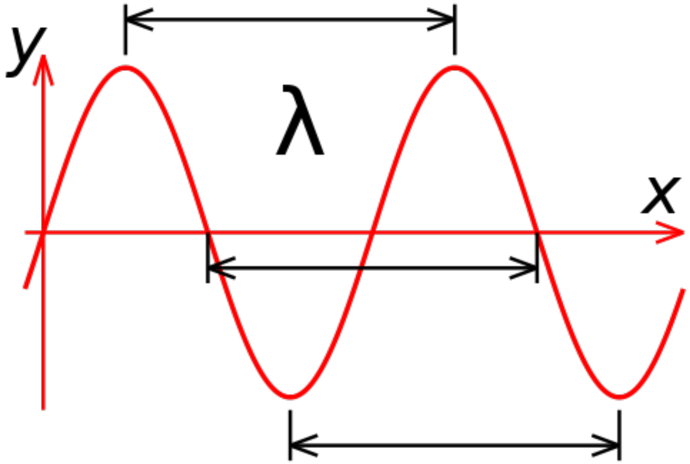
Nature of Planck Spectrum

- Theory predicts not just the spectral shape, but also the intensity of light at given wavelength.

- FIRAS measured exactly the expected amount, at every wavelength, as if we are inside a glowing object whose temperature is 2.7 degrees Kelvin (4.9 F above absolute zero).

- The Universe has clearly expanded a lot since it was hot and dense!

Light is both an Electromagnetic Wave and a Particle (Photon)



λ – wavelength – distance between wavecrests

$\lambda\nu = c$
(speed of light)

ν – frequency
$\nu = 1/\Delta t =$
1/period (time between passing wavecrests)
Unit: Hz = 1/second

Energy per photon (quantum):
$E_\gamma = h\nu = hc/\lambda$
Since expansion stretches wavelength, $\lambda \sim a(t)$ (redshift), it follows that photon energy redshifts: $E_\gamma \sim 1/a(t)$

Photons in the Expanding Universe

- Assume that photons are not created or destroyed. Then the total number of photons in a volume V is fixed:

$$N = nV = \text{constant}$$

- Thus the number density of photons obeys

$$n \sim 1/V$$

- In the expanding Universe, the volume $V \sim a^3$ so that

$$n \sim 1/a^3$$

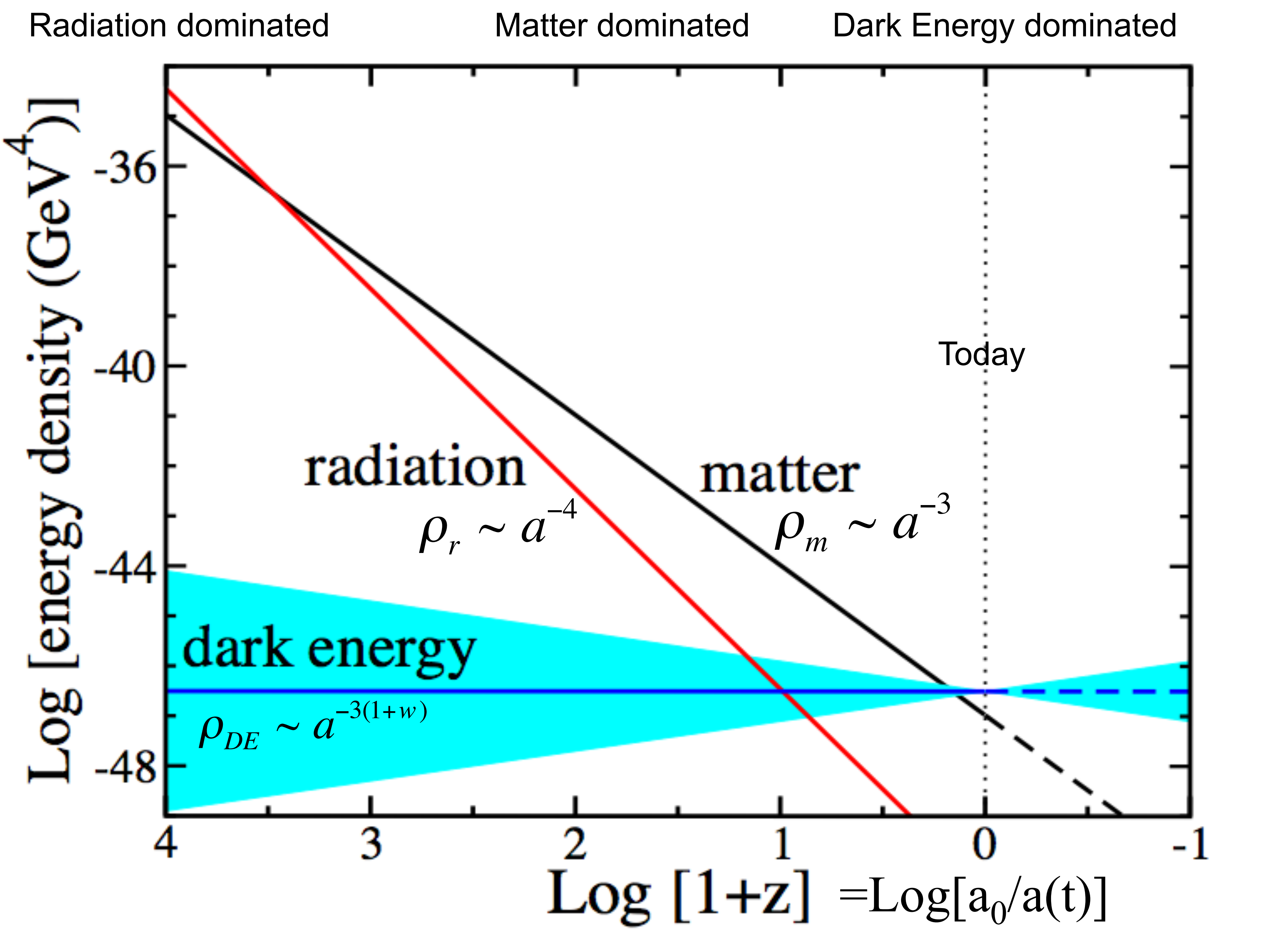
and therefore the density of a photon 'gas' obeys:

$$\rho = nE_\gamma \sim (1/a^3)(1/a) \sim 1/a^4$$

- For thermal radiation, $\rho \sim T^4 \rightarrow T \sim 1/a$

Why is the CMB Microwaves?

- Hot objects glow primarily in visible light.
  - The night sky is dark.
  - But it's glowing brightly in microwaves...
- Why? Because the CMB photons have "stretched" with the expansion of the Universe.
  - They have been cosmologically Doppler shifted way down through the infra-red into the microwave...



Radiation dominated
Matter dominated
Dark Energy dominated
Log [energy density (GeV^4)]
-36
-40
-44
-48
radiation
$\rho_r \sim a^{-4}$
matter
$\rho_m \sim a^{-3}$
Today
dark energy
$\rho_{DE} \sim a^{-3(1+w)}$
4
3
2
1
0
-1
Log [1+z] =Log[a_0/a(t)]

Where do the CMB Photons Come From?

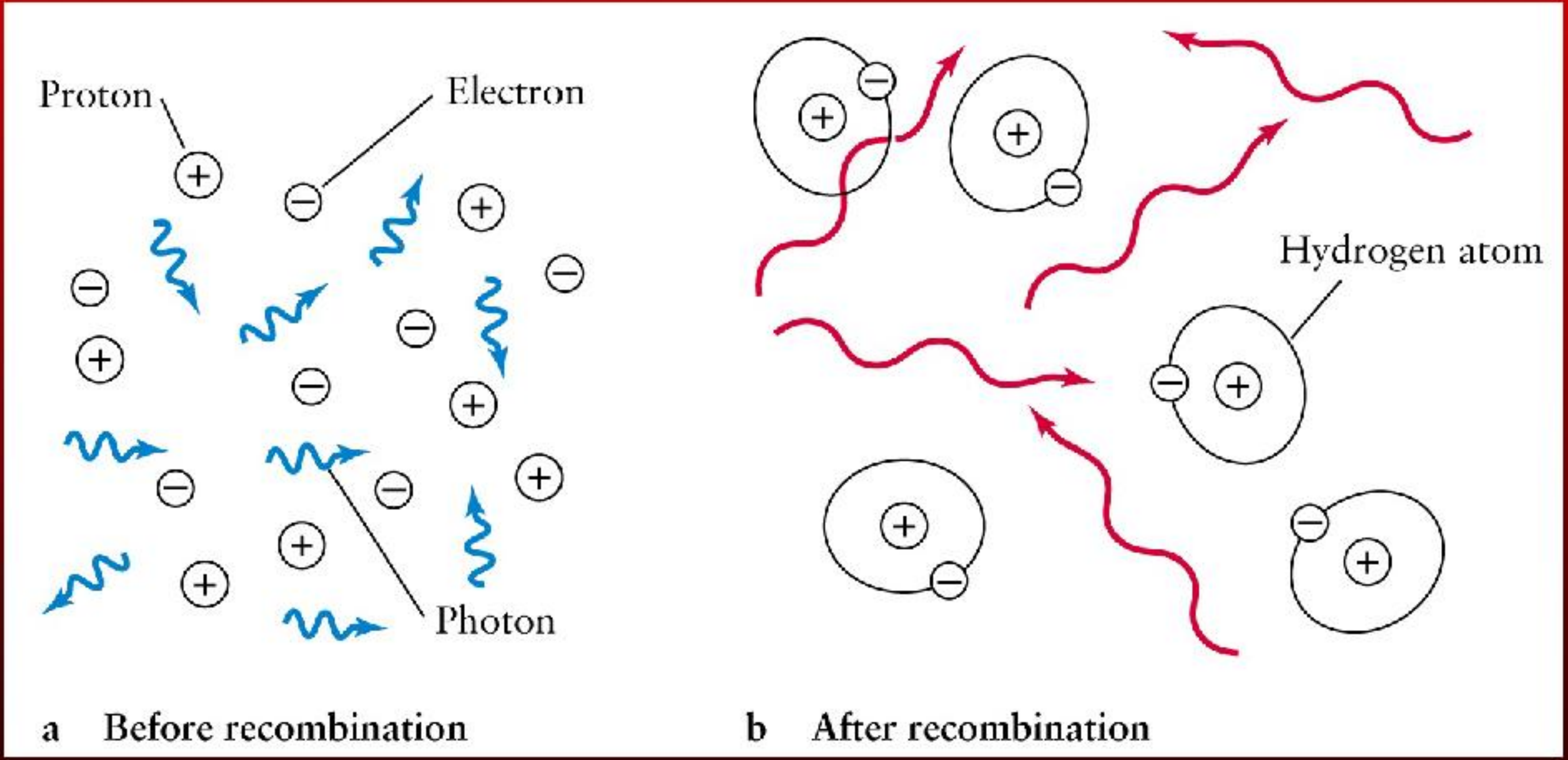
- Back in time denser / hotter.

- Eventually hot enough that atoms become ionized:
  - Plasma - The Fourth State of Matter

- Three familiar states of matter:
  - Solid - atoms are bonded together rigidly
  - Liquid - atoms are bonded less rigidly
  - Gas - atoms move fast and freely

- Fourth state:
  - Plasma - atoms slam together so hard electrons are knocked free.
  - Becomes a "soup" of nuclei, electrons and photons.

Plasma Universe was Opaque



In a plasma light rays constantly bump into electrons which changes their directions.

These frequent collisions establish thermal equilibrium and thermal BB spectrum.

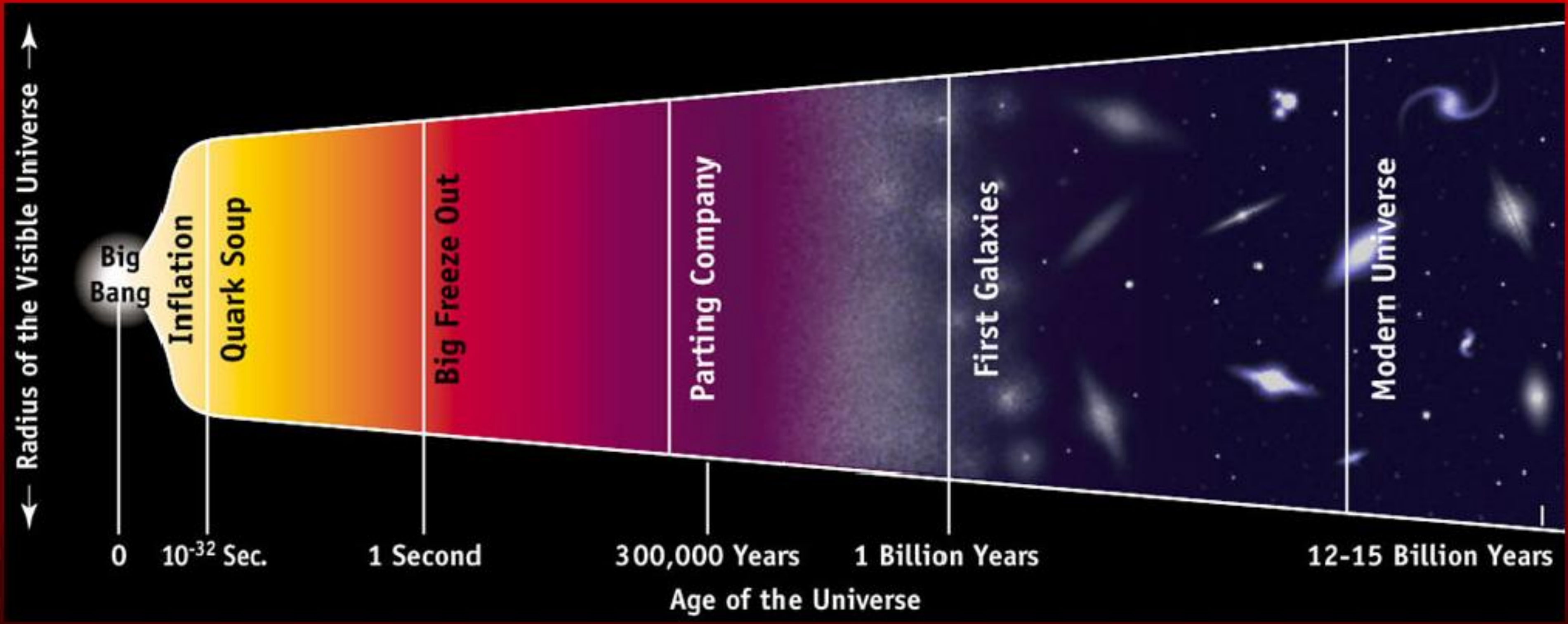
Atomic Recombination

- When the expanding plasma cooled to T~3000 deg, when the Universe was 380,000 years old, and the Universe was about 1/1000th its present size, typical CMB photons were no longer energetic enough to knock electrons out of Hydrogen atoms.
- Electrons and protons "recombined" from plasma to form neutral Hydrogen atoms at this time.

Recombination and Decoupling

- Prior to Hydrogen recombination, CMB photons interacted rapidly (scattered) with free (charged) electrons in the plasma.
- Once recombination occured, the scattering rate of photons dropped precipitously: rate of photon interaction with neutral atoms is much smaller: Photon Decoupling
- CMB photons have travelled freely since then. Maps of the CMB thus provide a (redshifted) snapshot of the Universe when it was 380,000 years old.
- Cosmic Weather report: Universe was ‘foggy’ before decoupling, clear since then.

Cosmic Timeline



Theory, laboratory measurements, and knowledge of the composition and current expansion rate allow us to wind the clock back to a tiny fraction of a second after the big bang!

Logarithmic view of Cosmic History

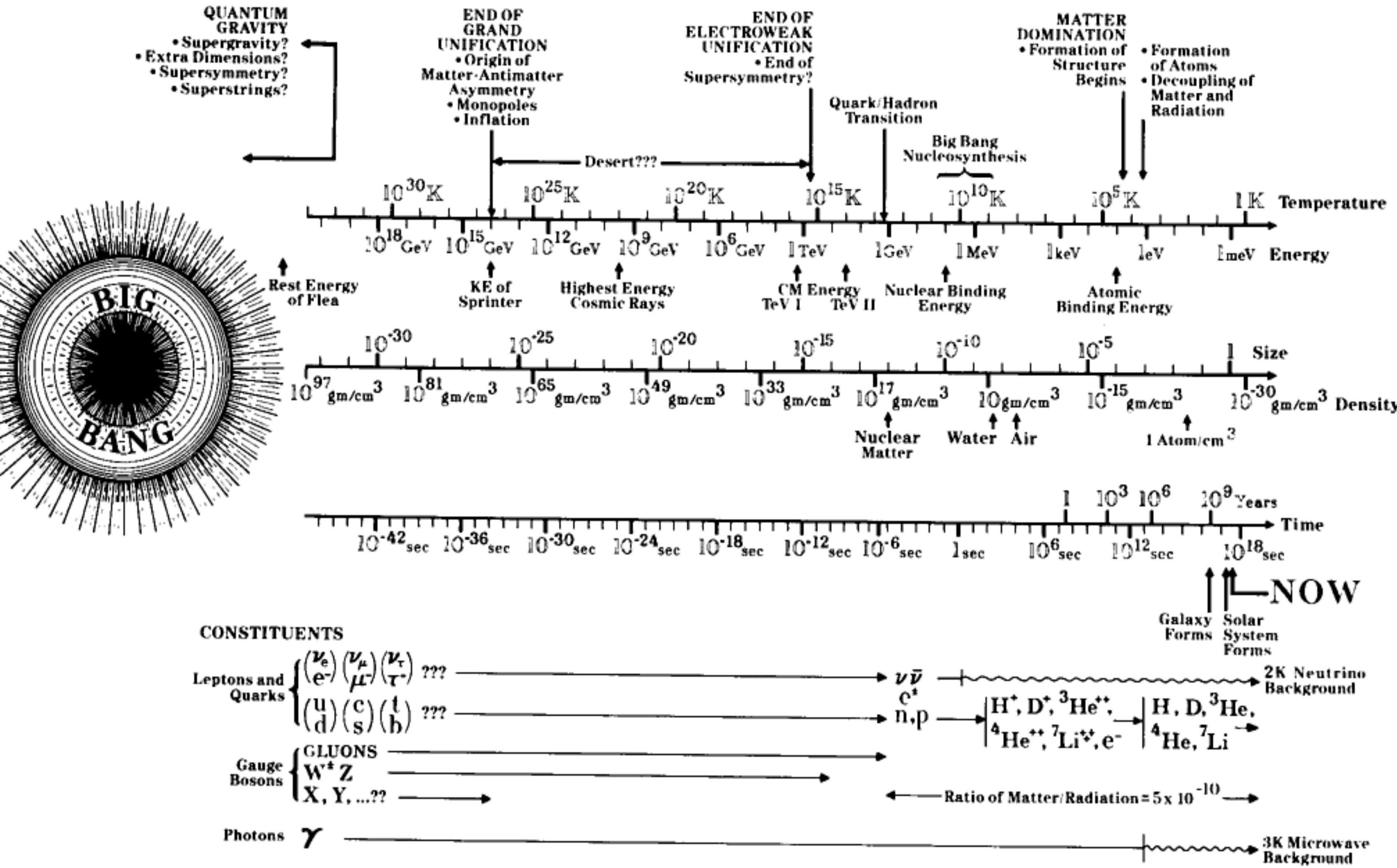
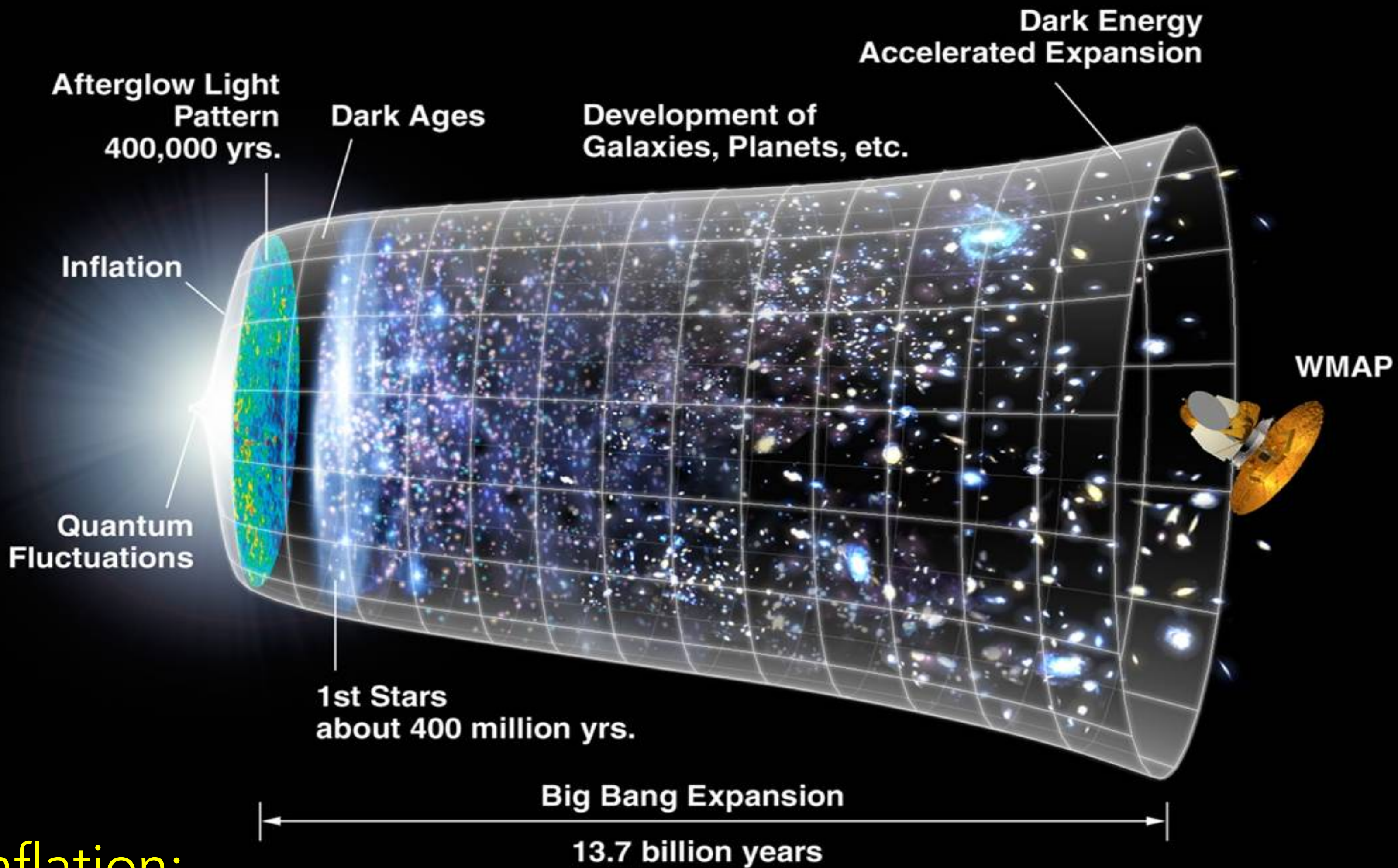
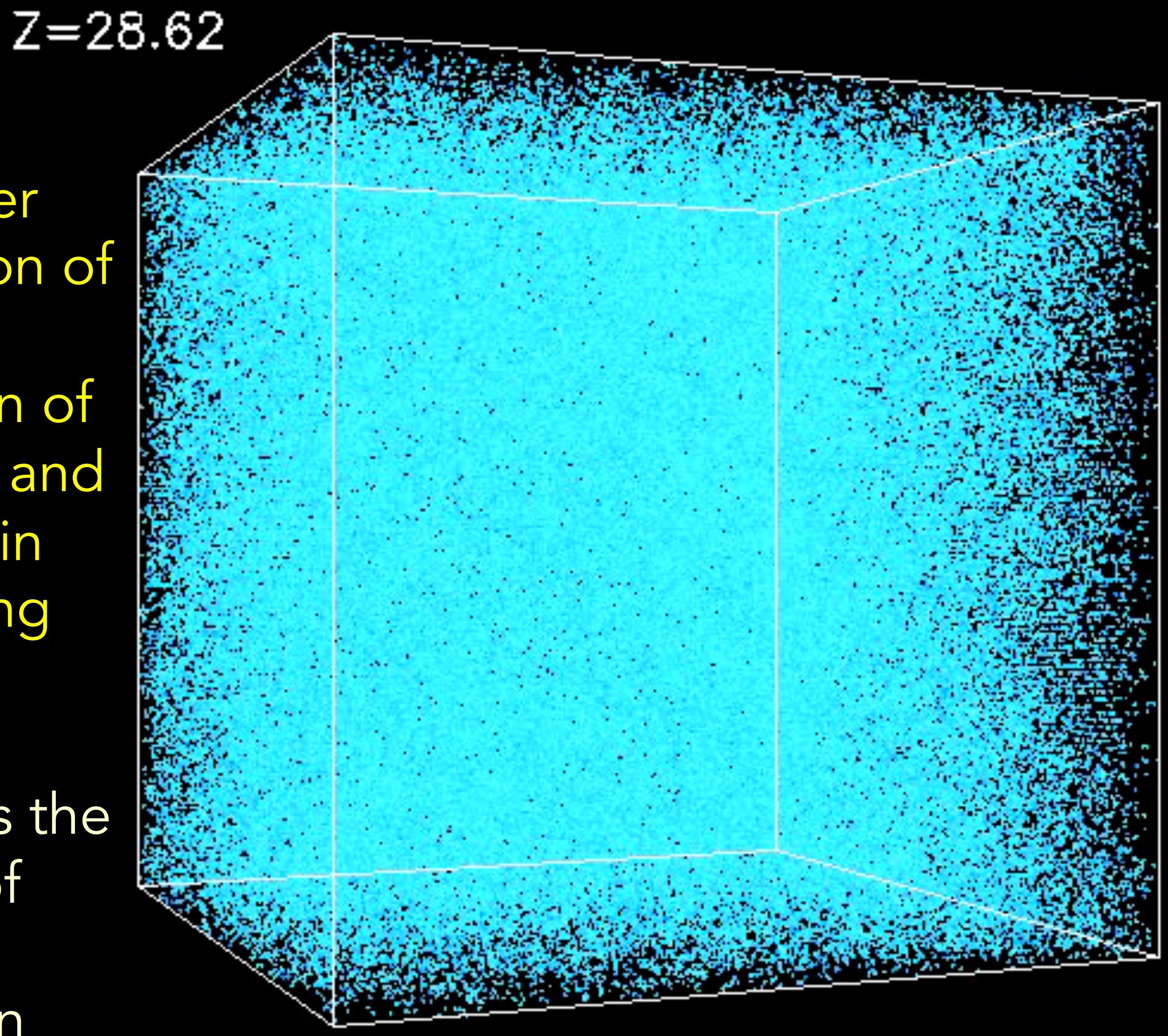


Fig. 1.5.

Brief History of the Universe



Inflation:
burst of rapid expansion a tiny fraction of a second after the Big Bang



Computer Simulation of the formation of Galaxies and Clusters in Expanding Universe

Gravity is the engine of structure formation

Z=40.52

Formation of a (lumpy) halo of Dark Matter

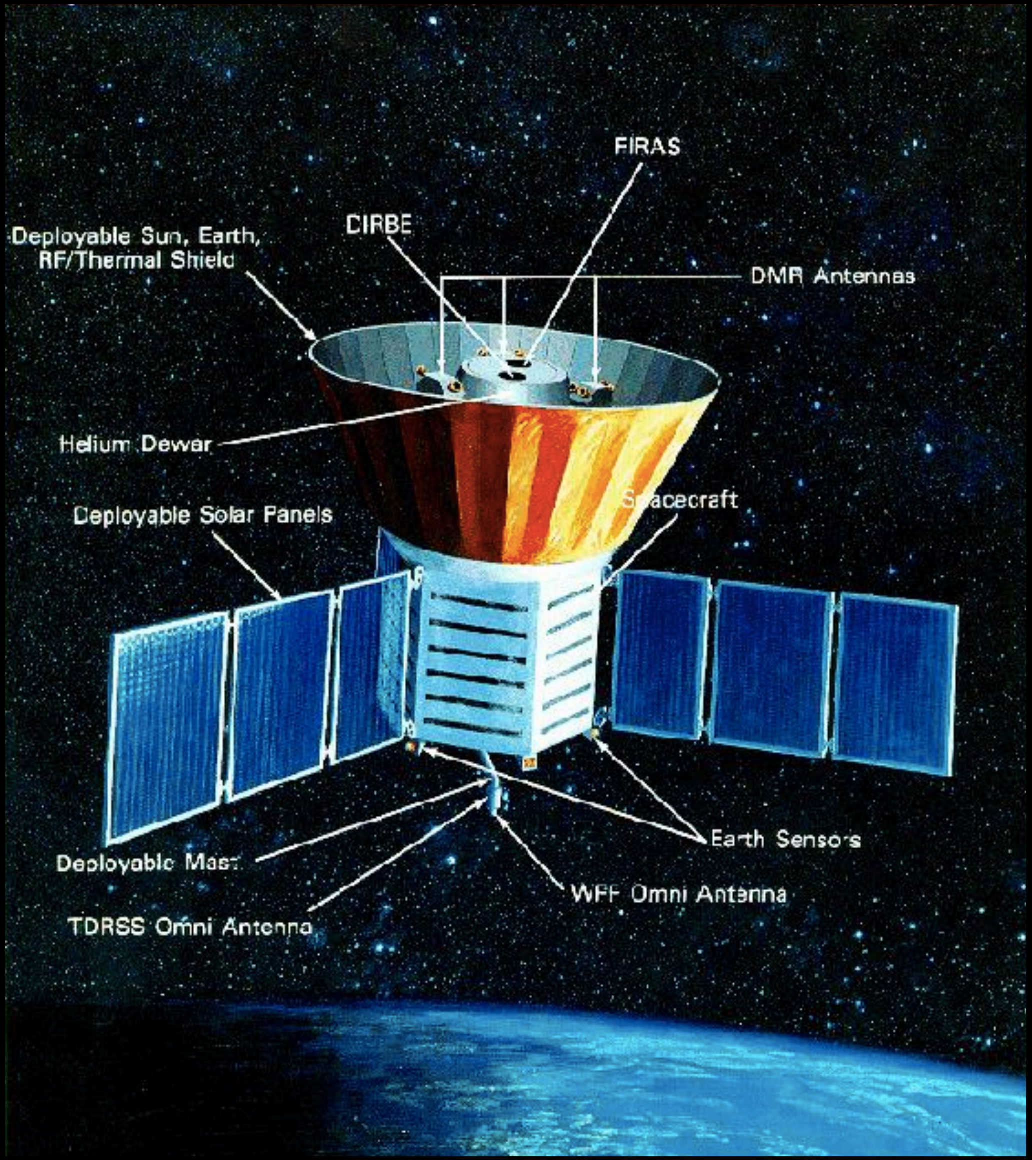
Kravtsov

COBE Satellite (Cosmic Background Explorer)

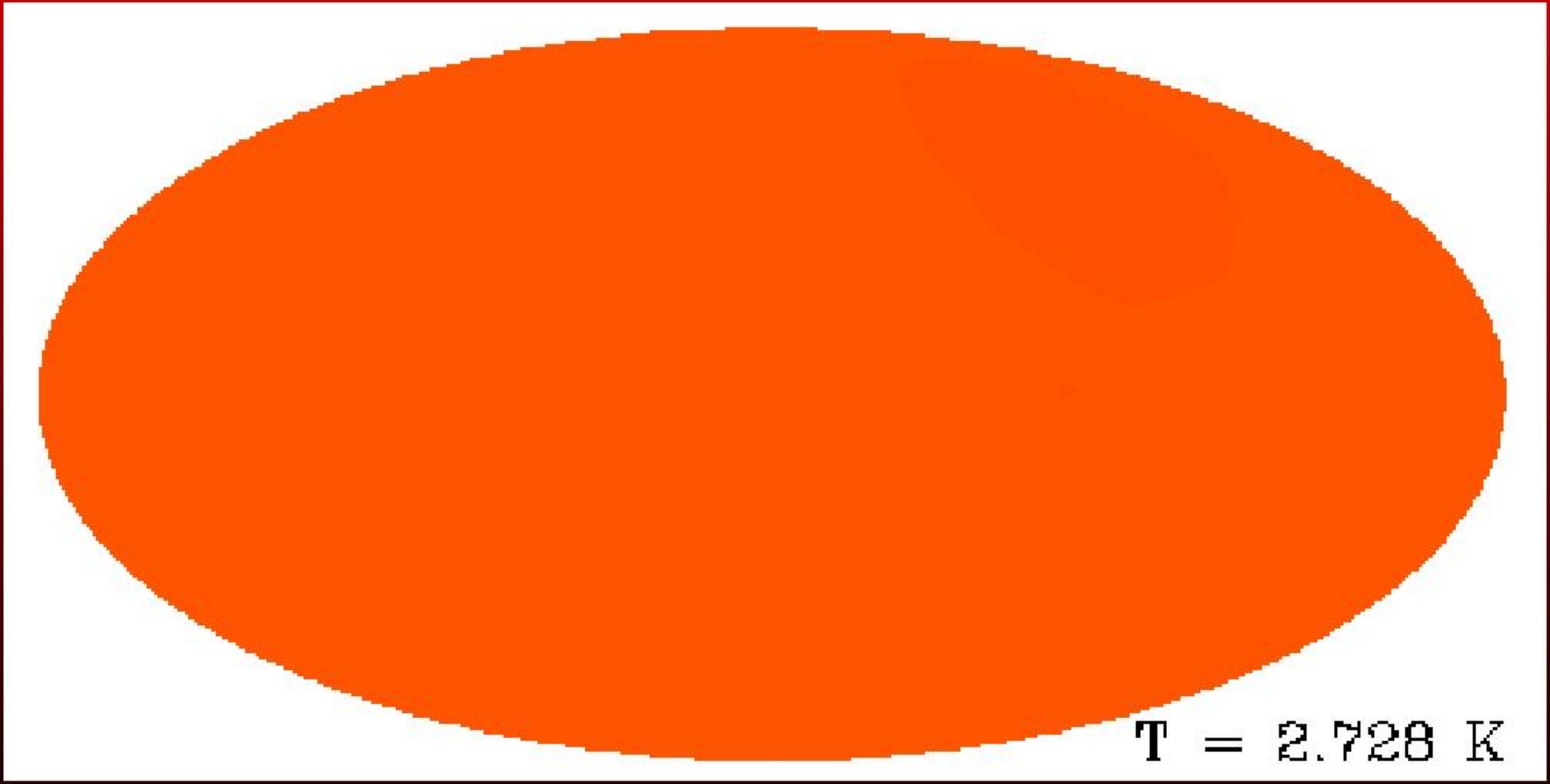
Launched by
NASA 1990

Precision measurement
of CMB Blackbody
spectrum

First clear detection
of CMB anisotropies
(Temperature
differences across
the sky)

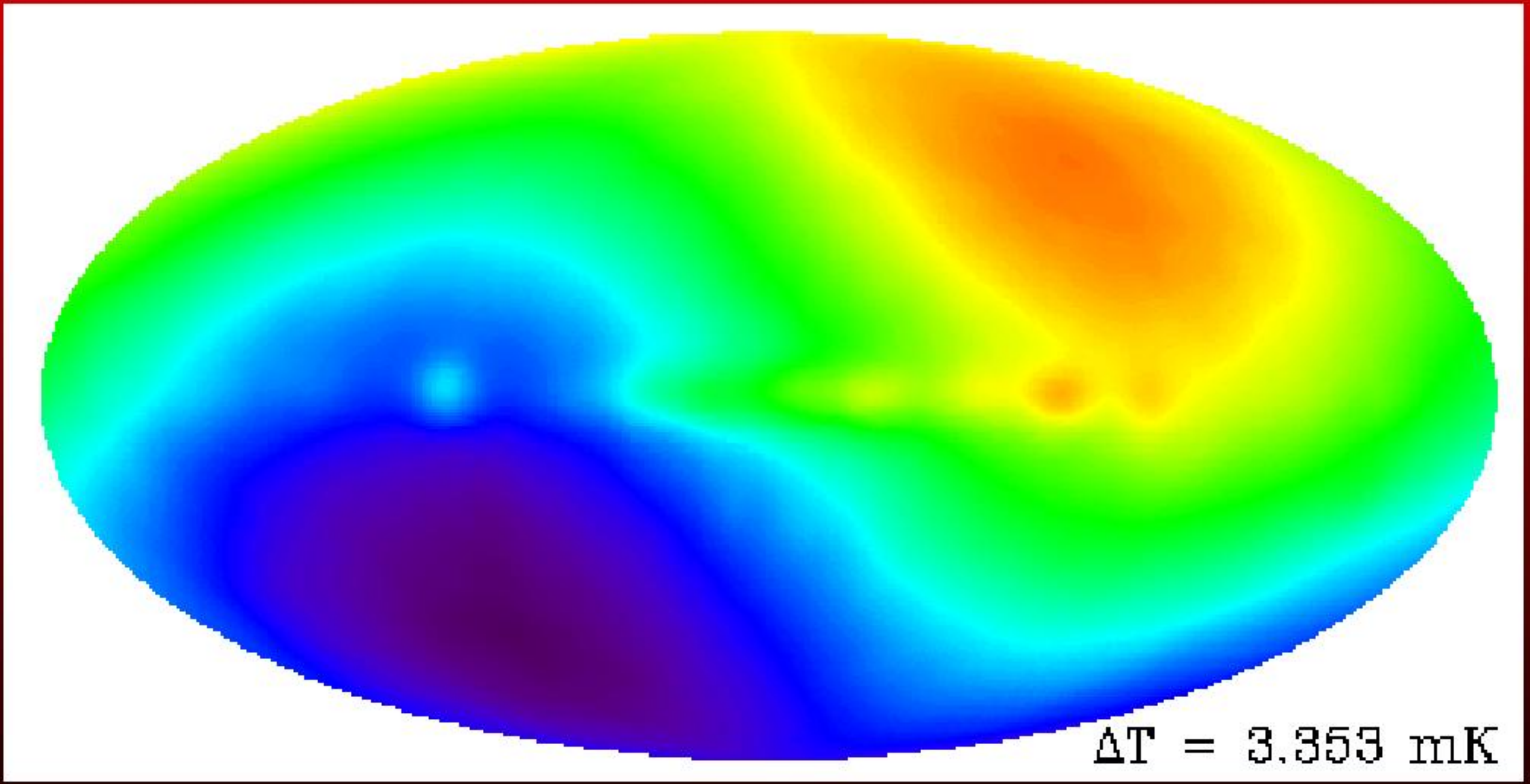


II: CMB Has Equal Brightness in All Directions



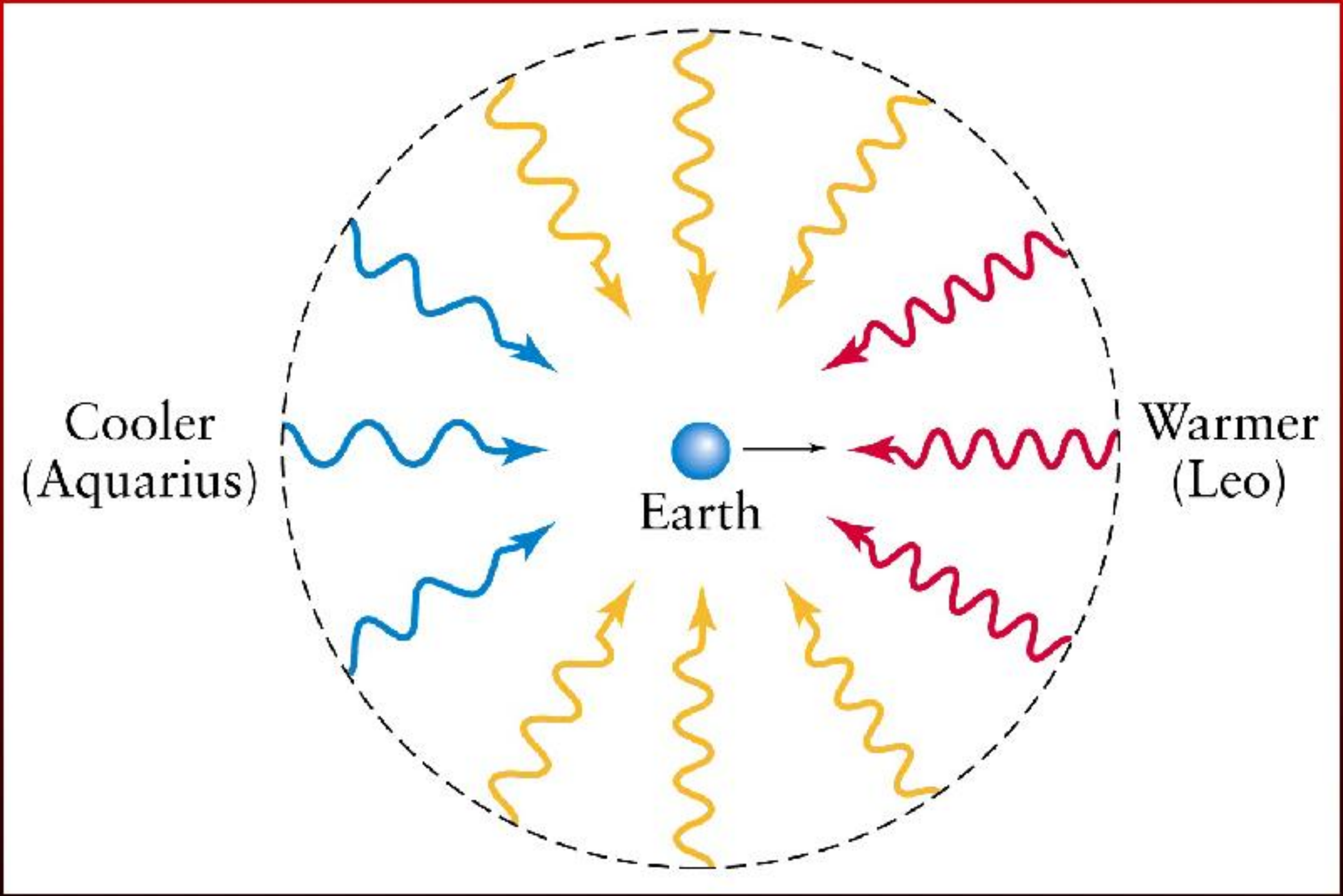
Well *nearly* equal brightness - The plasma was very smooth!

Our Motion Through the CMB



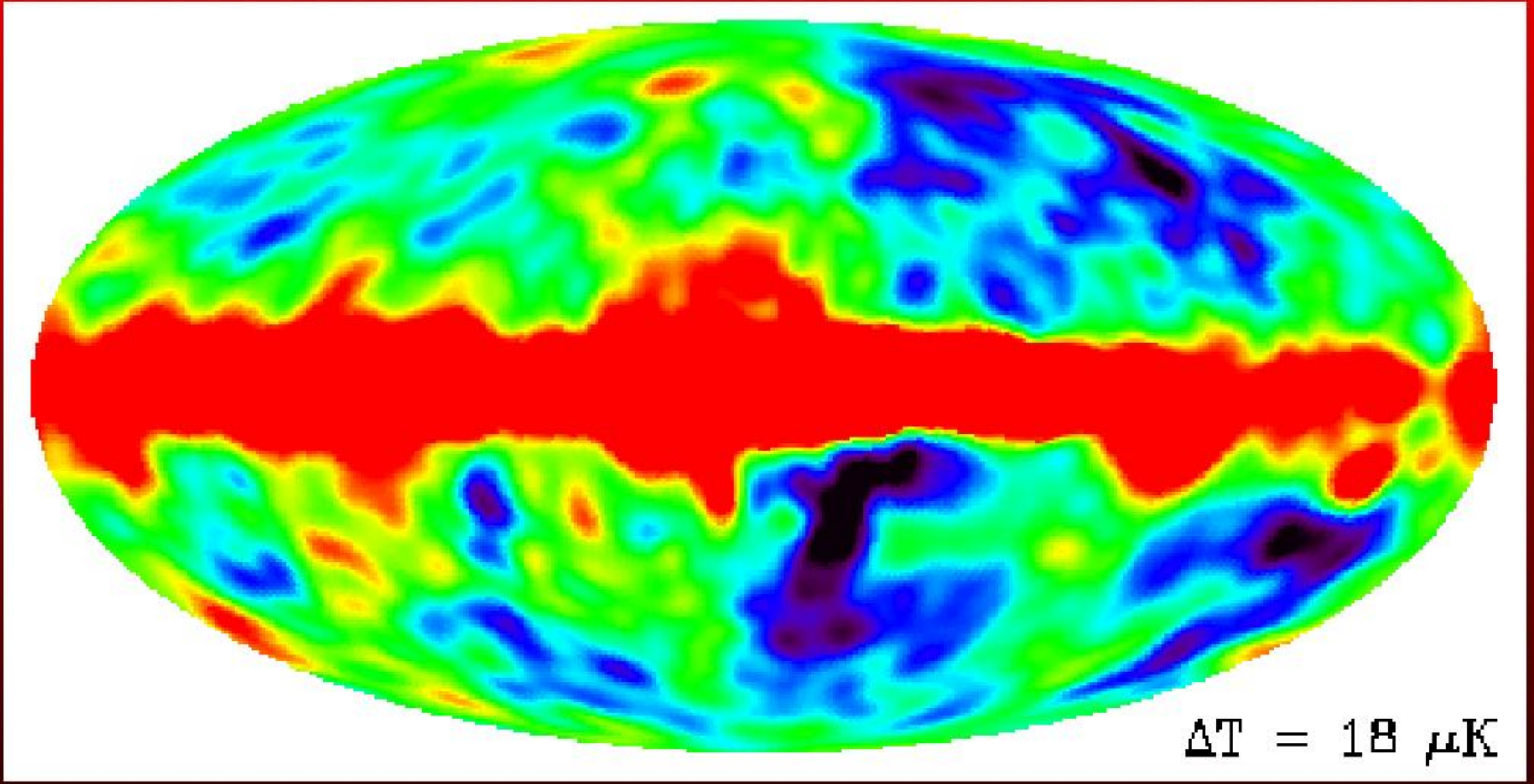
1 part in a thousand (standard) Doppler shift

Our Motion Through the CMB



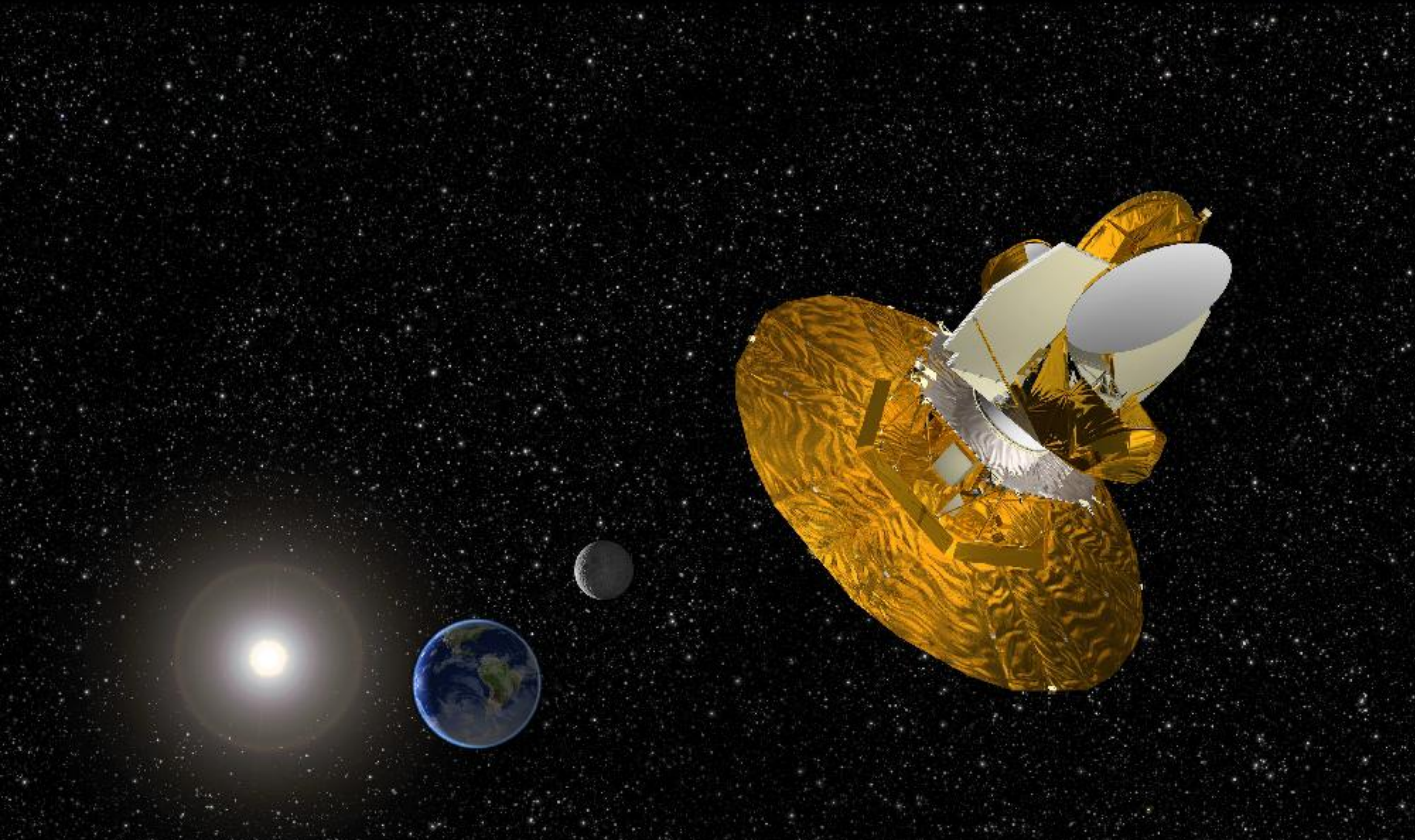
We are moving at 370 km per second through the CMB

III: Unevenness of the CMB



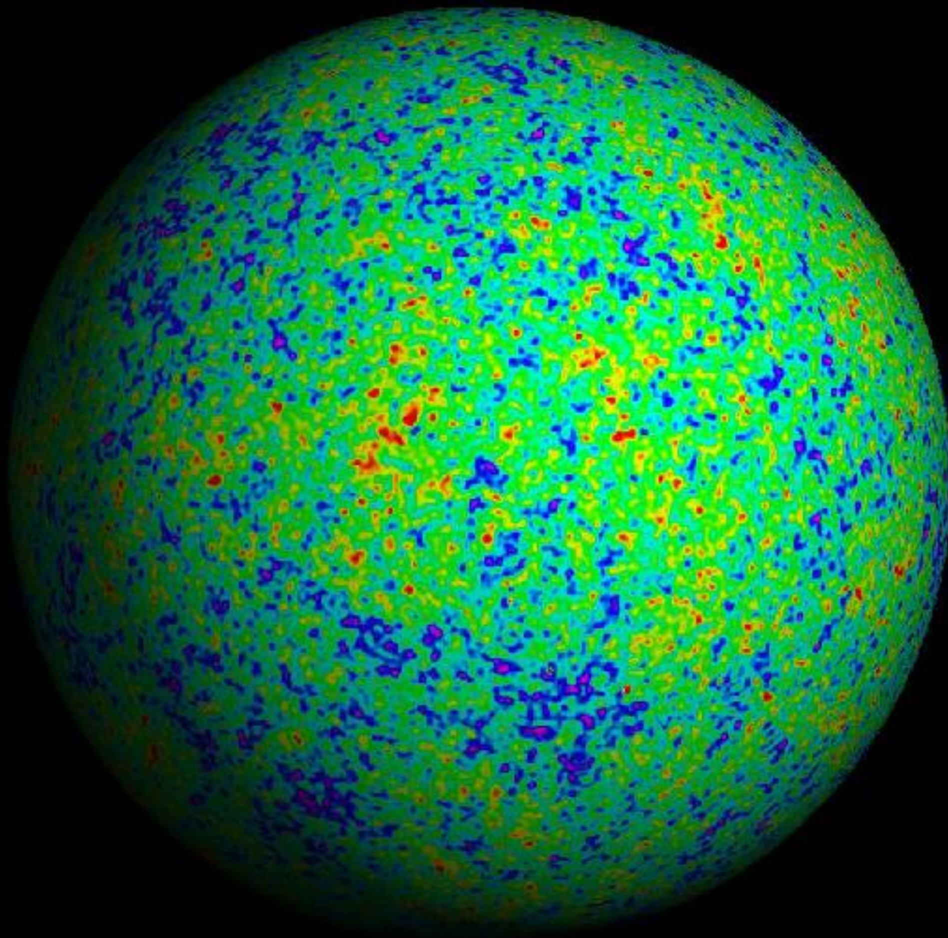
Removing the effect of our motion reveals tiny residual unevenness in the brightness of the CMB.

WMAP Spacecraft



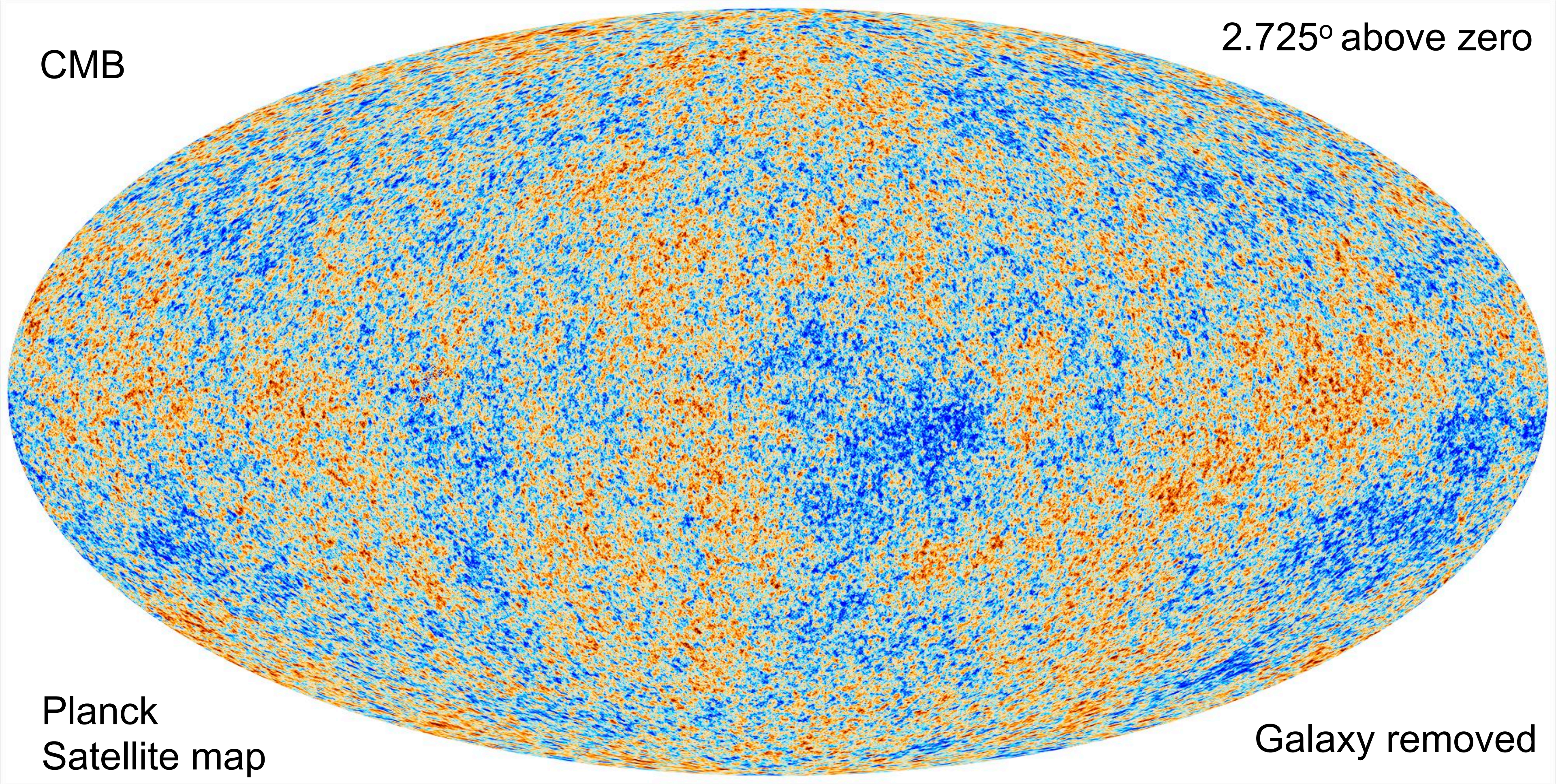
Launched by NASA 2001, more sentitive and finer angular resolution than COBE

CMB Sky as Measured by WMAP



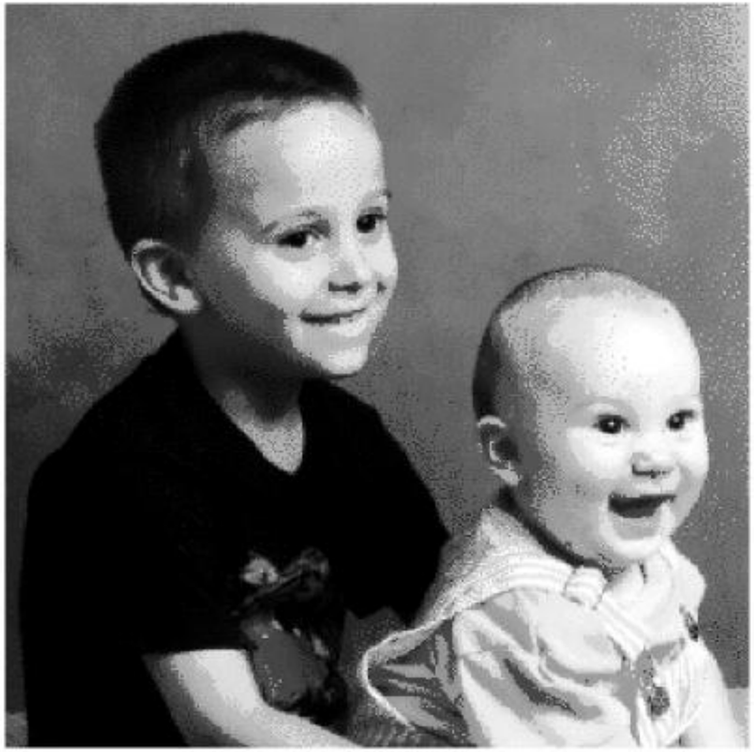
CMB is a sample of the density structure on a shell cut through the 300,000 year old Universe.

Planck CMB Map



Snapshot of the Universe when it was only 380,000 years old
Temperature varies by only 0.00001 deg across the sky.

Image and Its Power Spectrum I



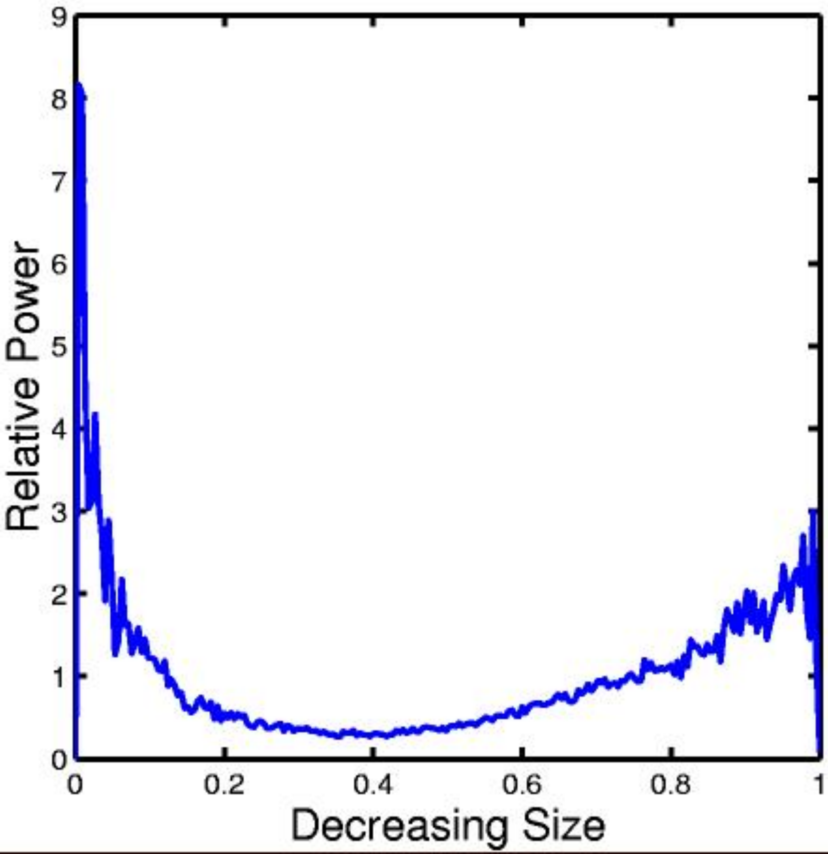
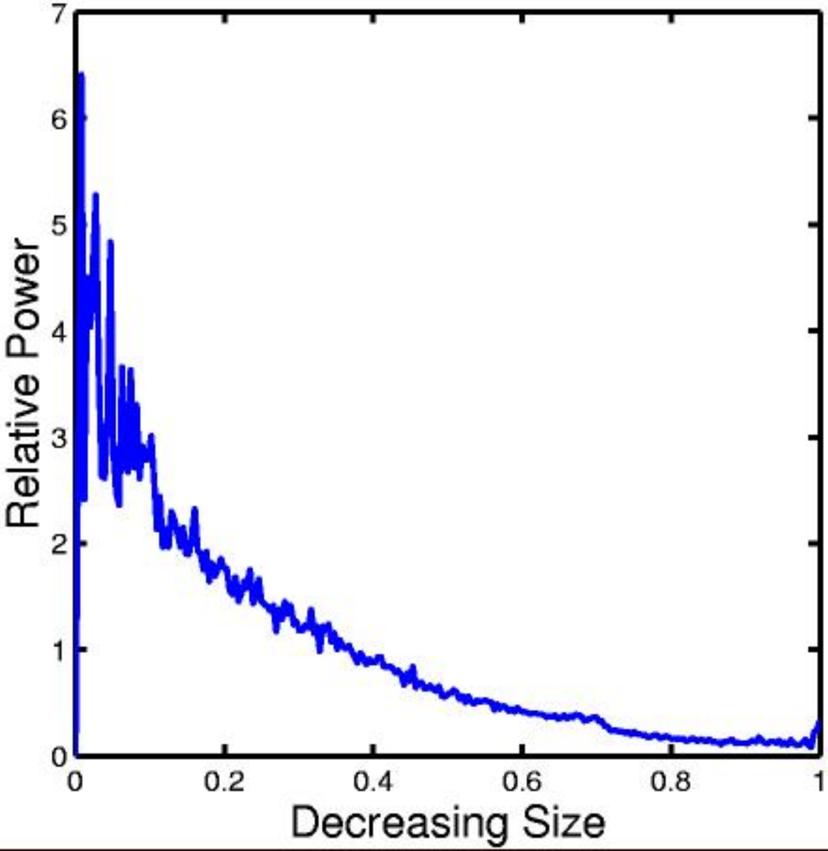
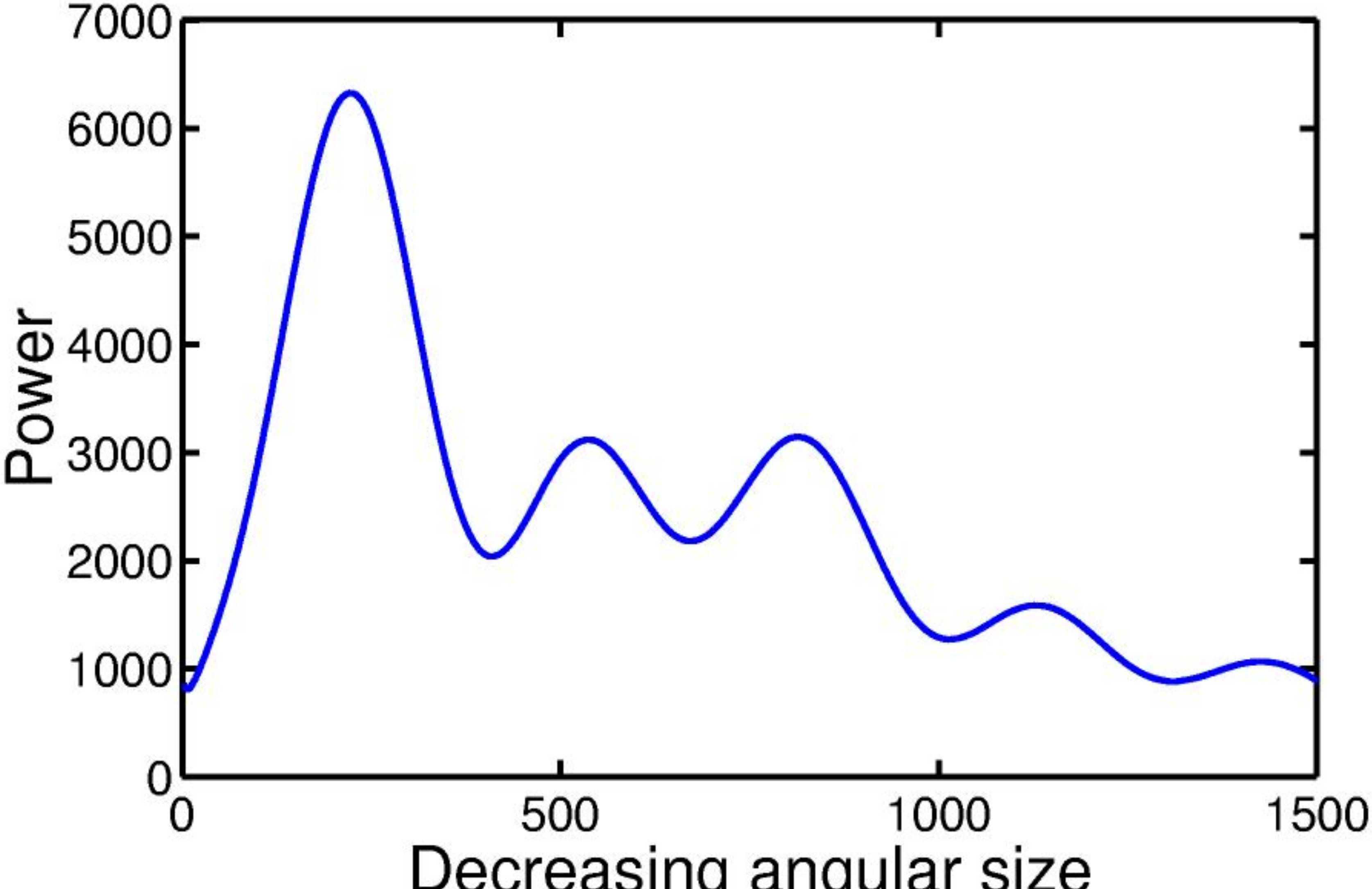


Image and Its Power Spectrum II



Favored CMB Power Spectrum...



Theoretical dependence of CMB anisotropy on the baryon density