ASTR 340: Origin of the Universe

Prof. Benedikt Diemer

Lecture 17 • The cosmic microwave background

11/02/2021

Next week

Time	Monday	Tuesday	Wednesday	Thursday	Friday
11:00-12:00	TA office hours			~~Office hours~~	
12:00-12:30					
12:30-1:45		Lecture		Lecture on zoom!	
1:45–3:00					
3:00-4:00			~~Office hours~~		
4:00-11:59					
11:59			Tue quiz due		Thu quiz due

- No office hours (no homework due)
- Thursday lecture on zoom!

Recap

Participation: Recap #1

TurningPoint:
Roughly how long after the Big Bang was nucleosynthesis complete?

Session ID: diemer

30 seconds

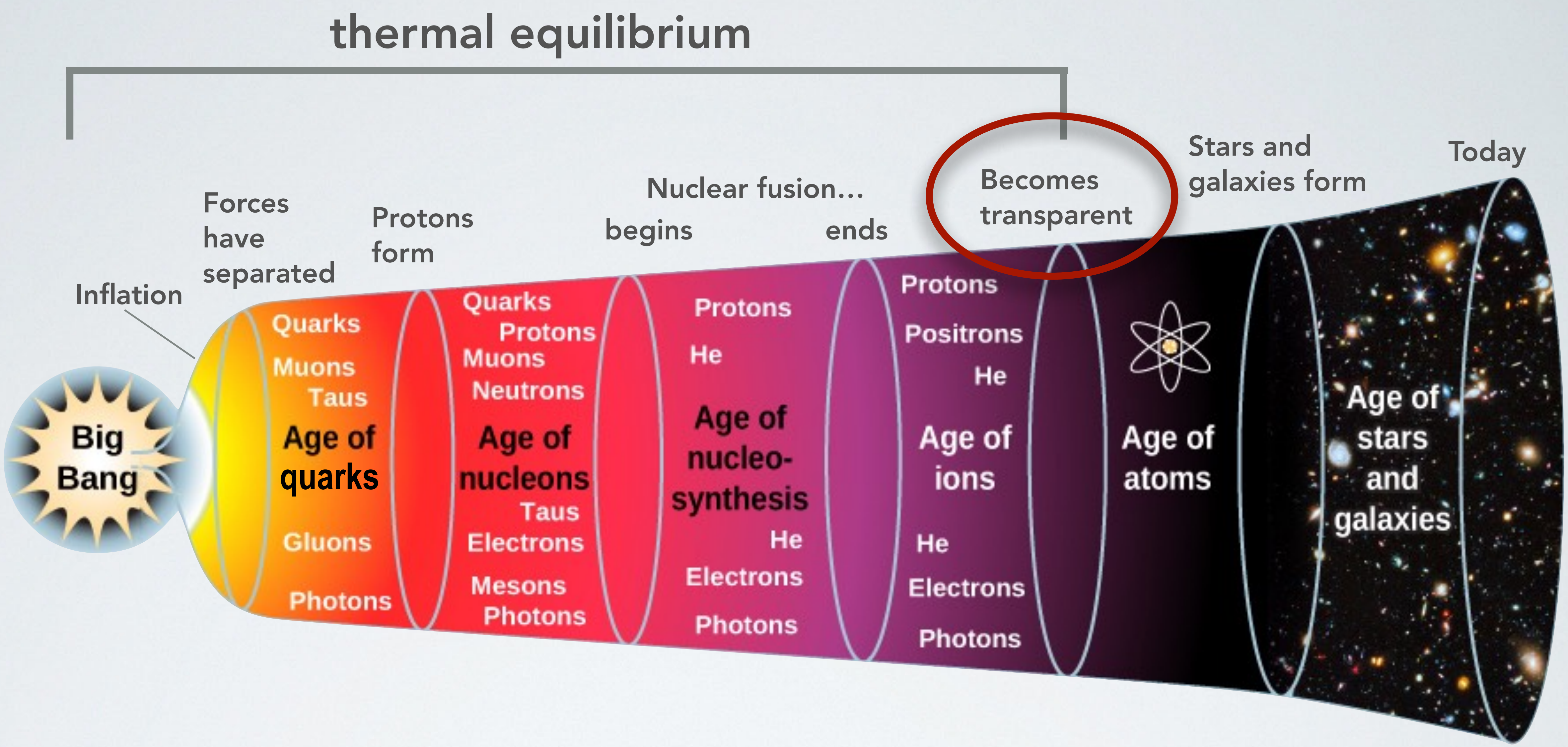
Participation: Recap #2

TurningPoint:
What are the most abundant particles after nucleosynthesis?

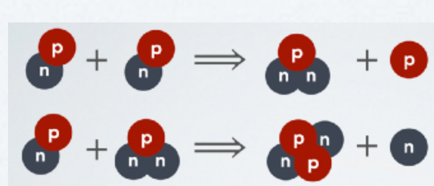
Session ID: diemer

30 seconds

History of the Universe



Time	0	10^{-12} s	10^{-6} s	15 s	30 min	380,000 yr	$\approx$ 100 Myr?	13.8 Gyr
Temperature (K)	∞	10^{15}	10^{13}	5×10^9	3×10^8	3000		2.725



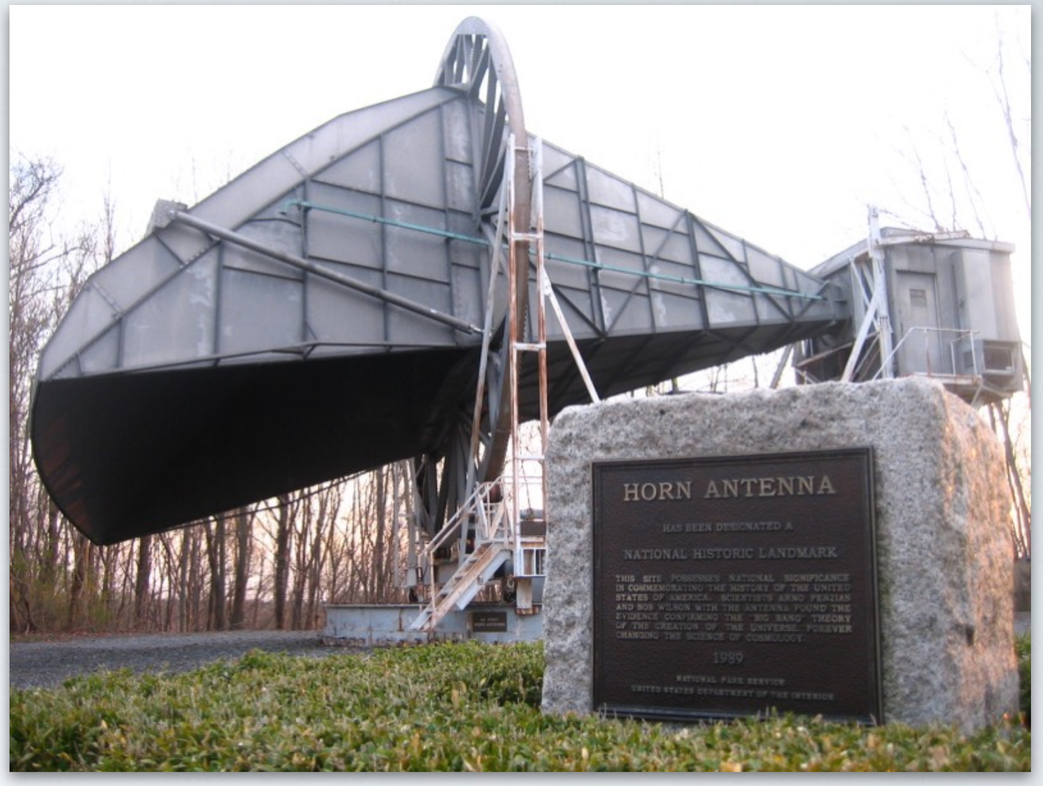
Today

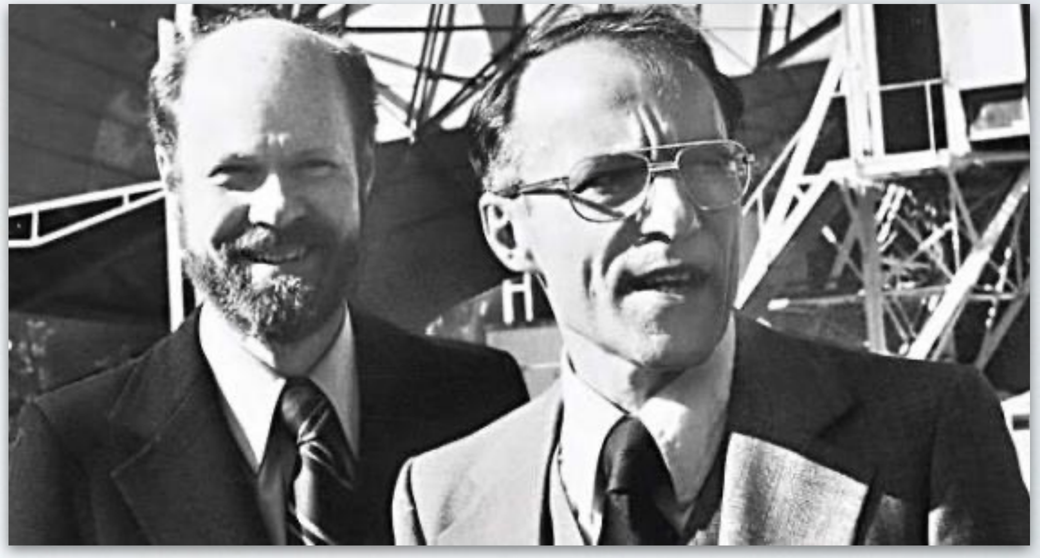
- Recombination and the CMB
- COBE and the blackbody spectrum
- Fluctuations in the CMB
- What we can learn from the CMB

Part 1: Recombination and the CMB

Discovery of the Cosmic Microwave Background

- In 1964/65, Arno Penzias & Robert Wilson tried to study radio emission from the Milky Way
- They were plagued by a constant “noise” that came from all directions (isotropic)
- Isotropy means it has to be of cosmic origin!
- Gamow et al. had predicted relic radiation from hot early universe in the 1940’s, and some scientists were actually looking for it
- Penzias & Wilson got 1978 Nobel Prize for discovery





Bell Labs / Wikipedia

Participation: Nobel Prize

TurningPoint:
Was the Penzias and Wilson Nobel for the discovery of the CMB deserved?

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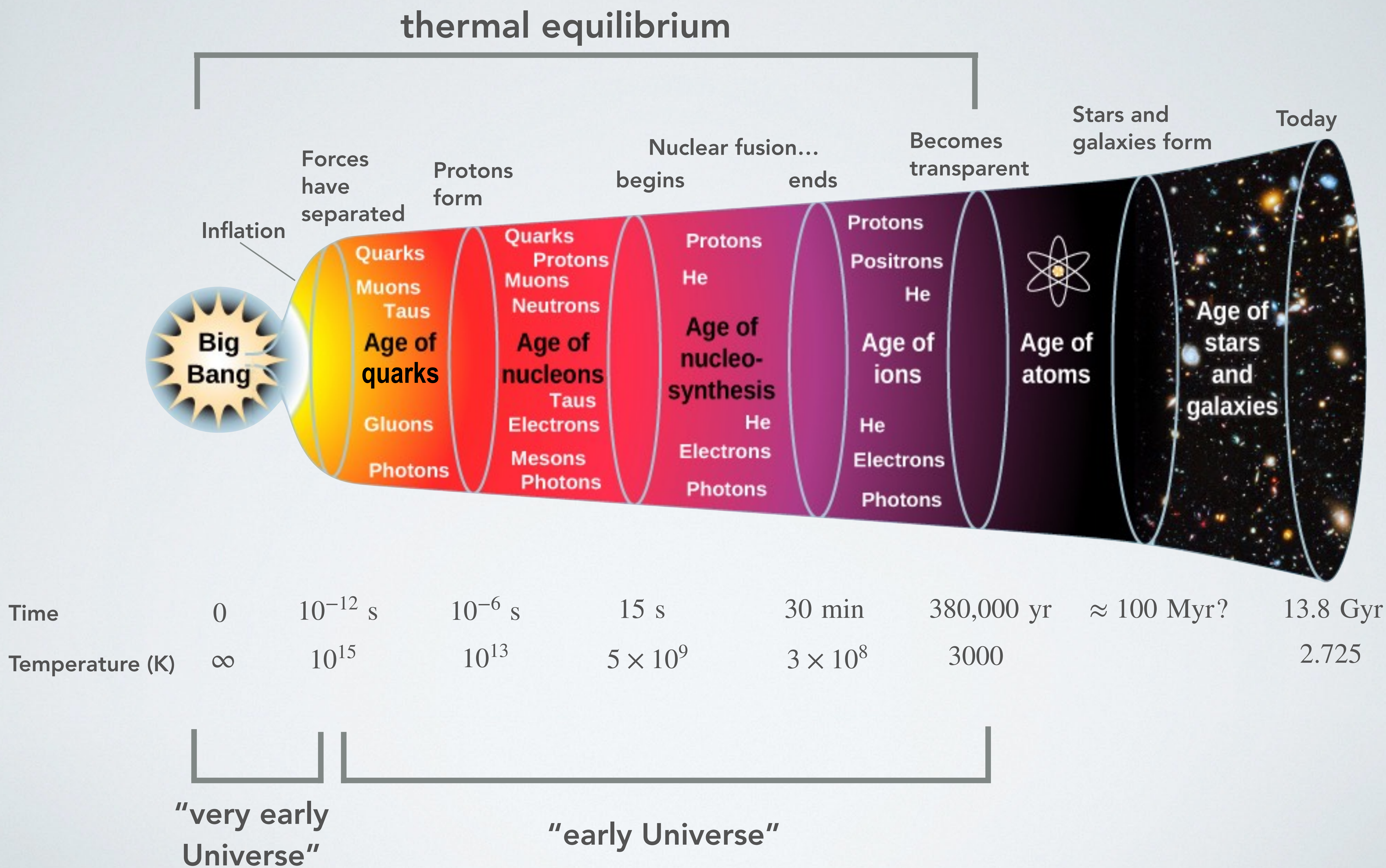
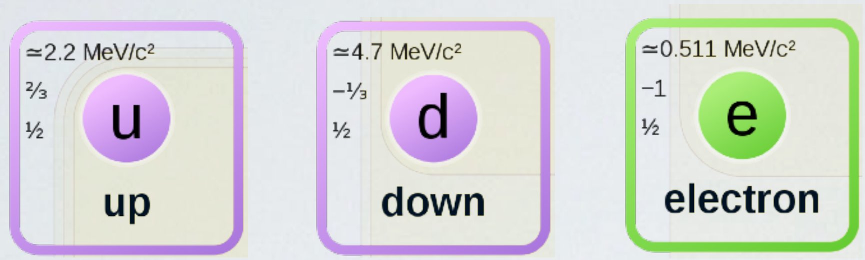
30 seconds

History of the Universe

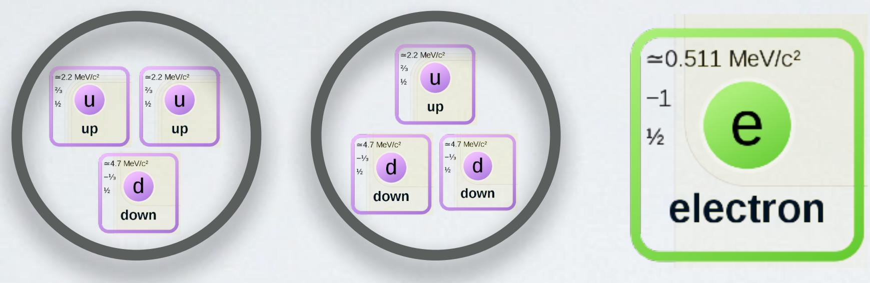


Hierarchy of particle structure



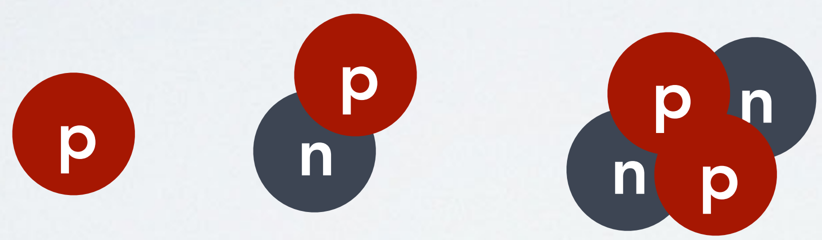
elementary particles: quarks, electrons…

$t \geq 10^{-6}$ s



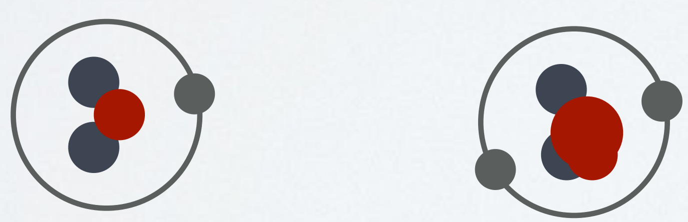
protons, neutrons, electrons…

$t \geq 3$ min



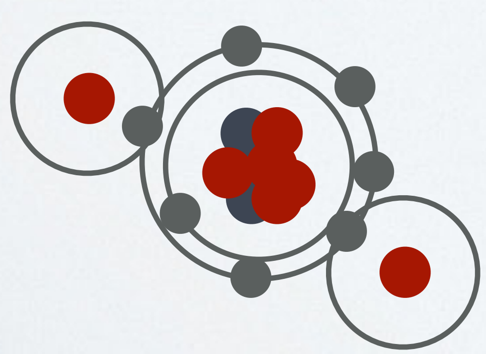
simple nuclei: H, D, He, Li (w/o elect.)

$t \geq 380{,}000$ yr



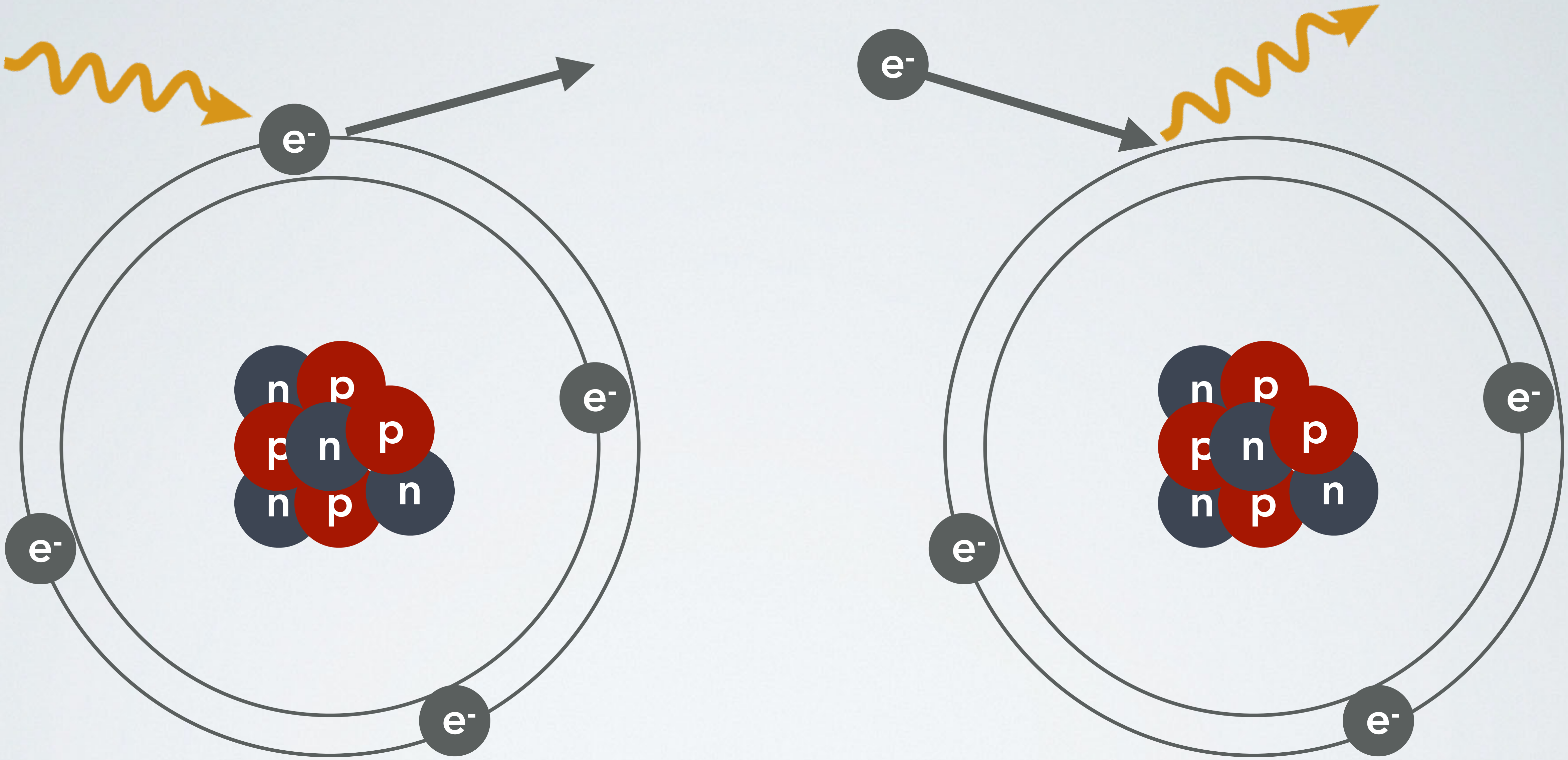
atoms (nuclei and bound electrons)

$t \geq$ few 100 Myr?

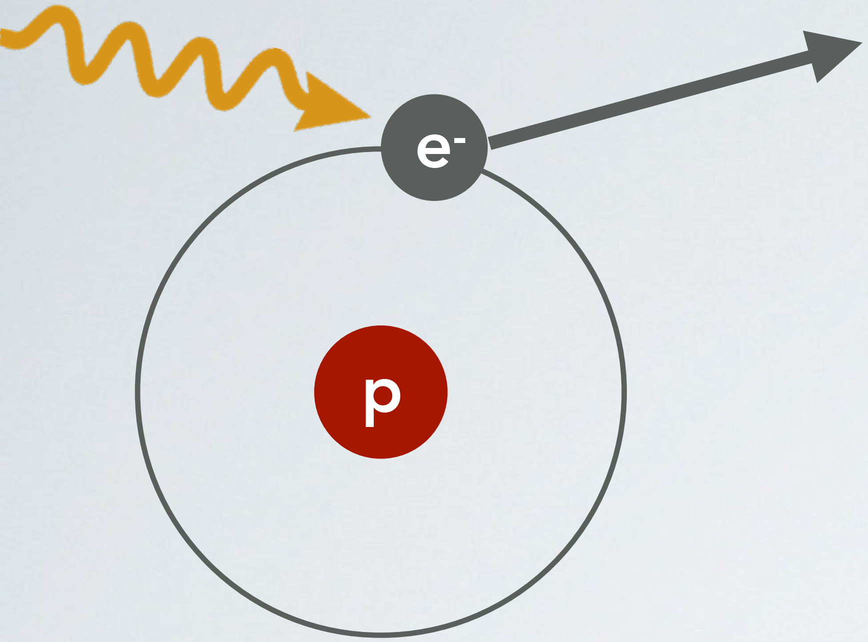


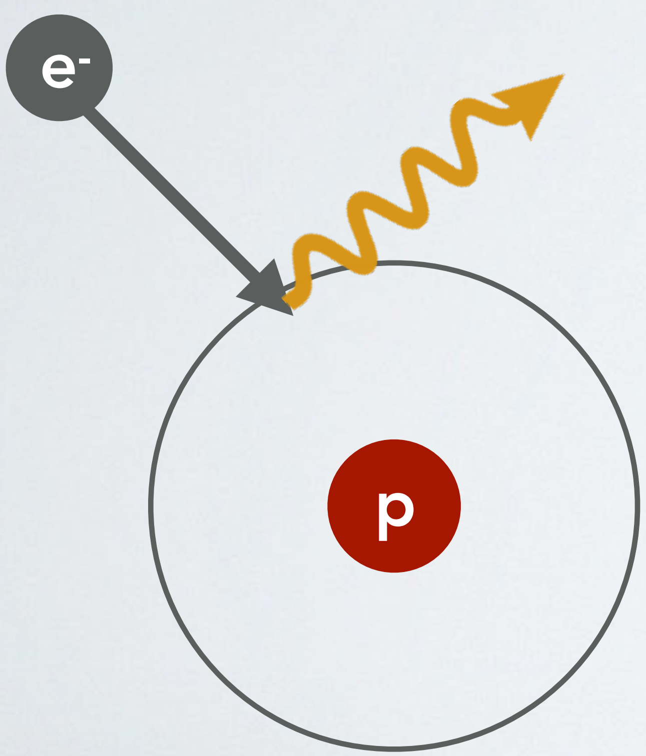
molecules (multiple atoms)

Ionization



Ionization



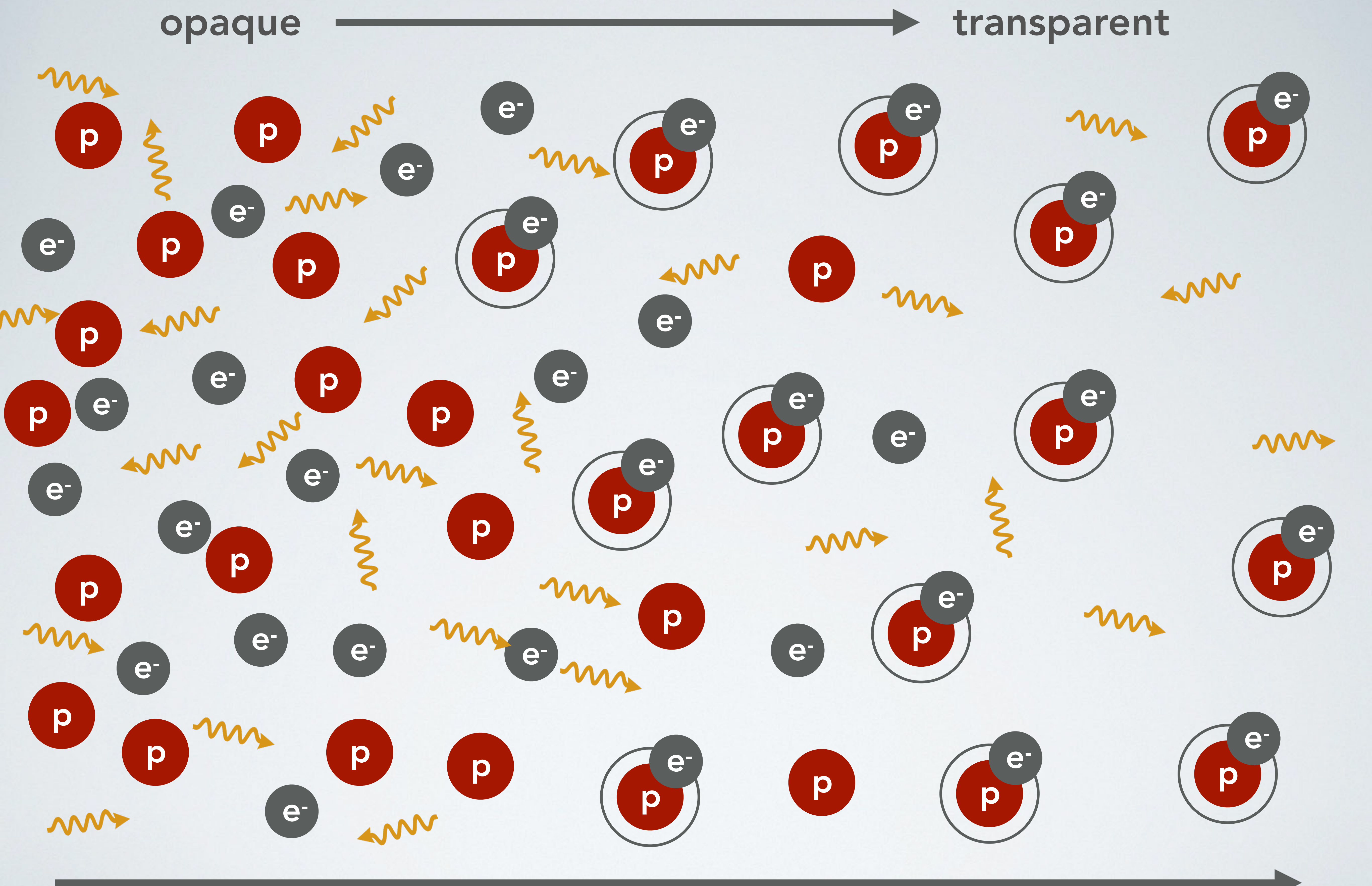


$$E_{\text{ion,H}} = 13.6\ eV = 2.2 \times 10^{-11}\ \text{erg}$$

$$\langle E \rangle = \frac{3}{2} k_{\text{B}} T$$

$$\Longrightarrow \quad T_{\text{ion,H}} \approx 10^5\ \text{K}$$

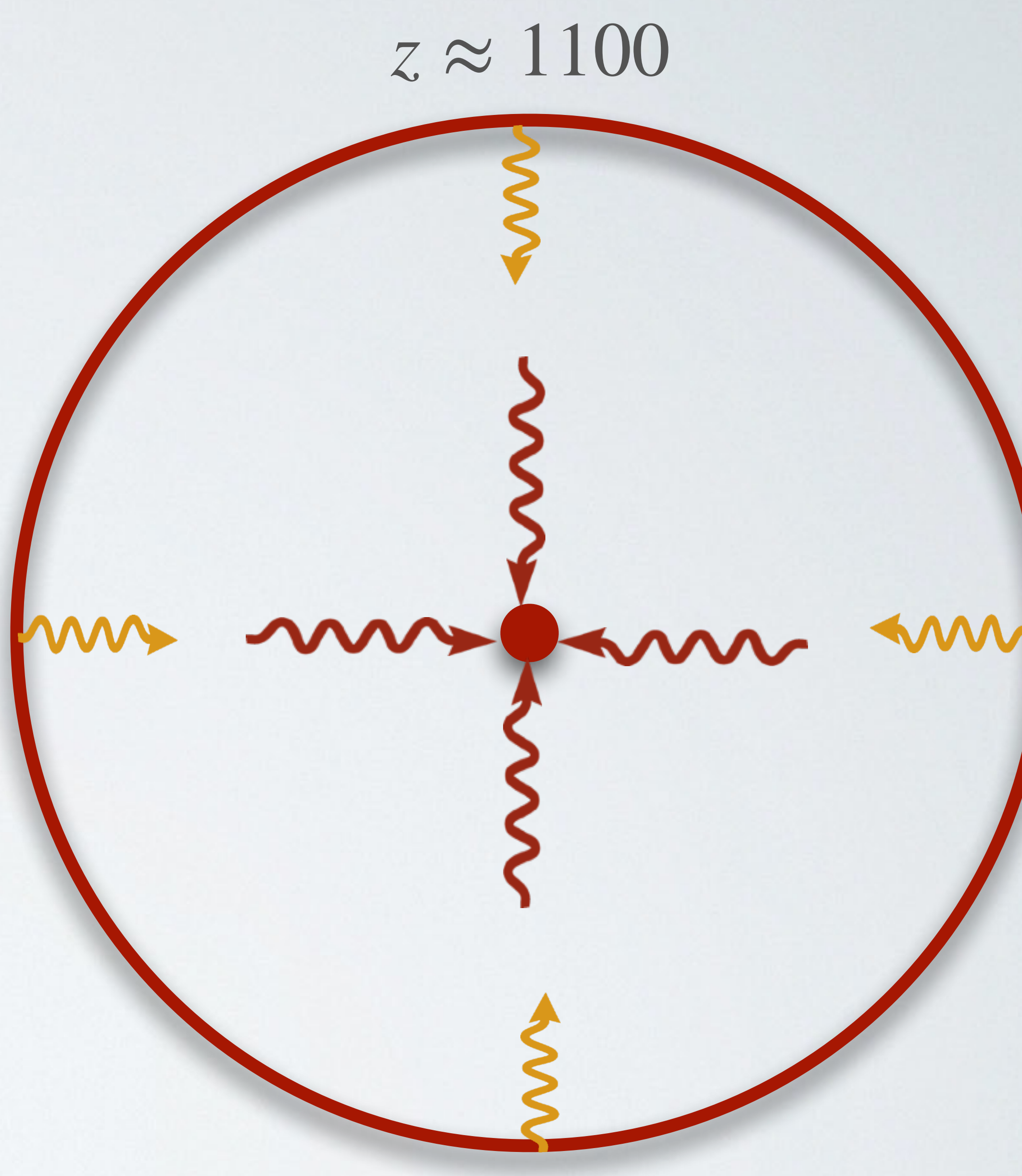
- However, this calculation uses the **average** energy at a given temperature
- Even a small number of particles that have enough energy can ionize lots of atoms
- The real temperature where **hydrogen gets ionized** is about **3000 K**
- Atom is lower-energy state, meaning that electrons want to combine with protons! But if the temperature is too high, they keep getting kicked off again
- When temperature drops below 3000 K, electrons are captured and hydrogen atoms form



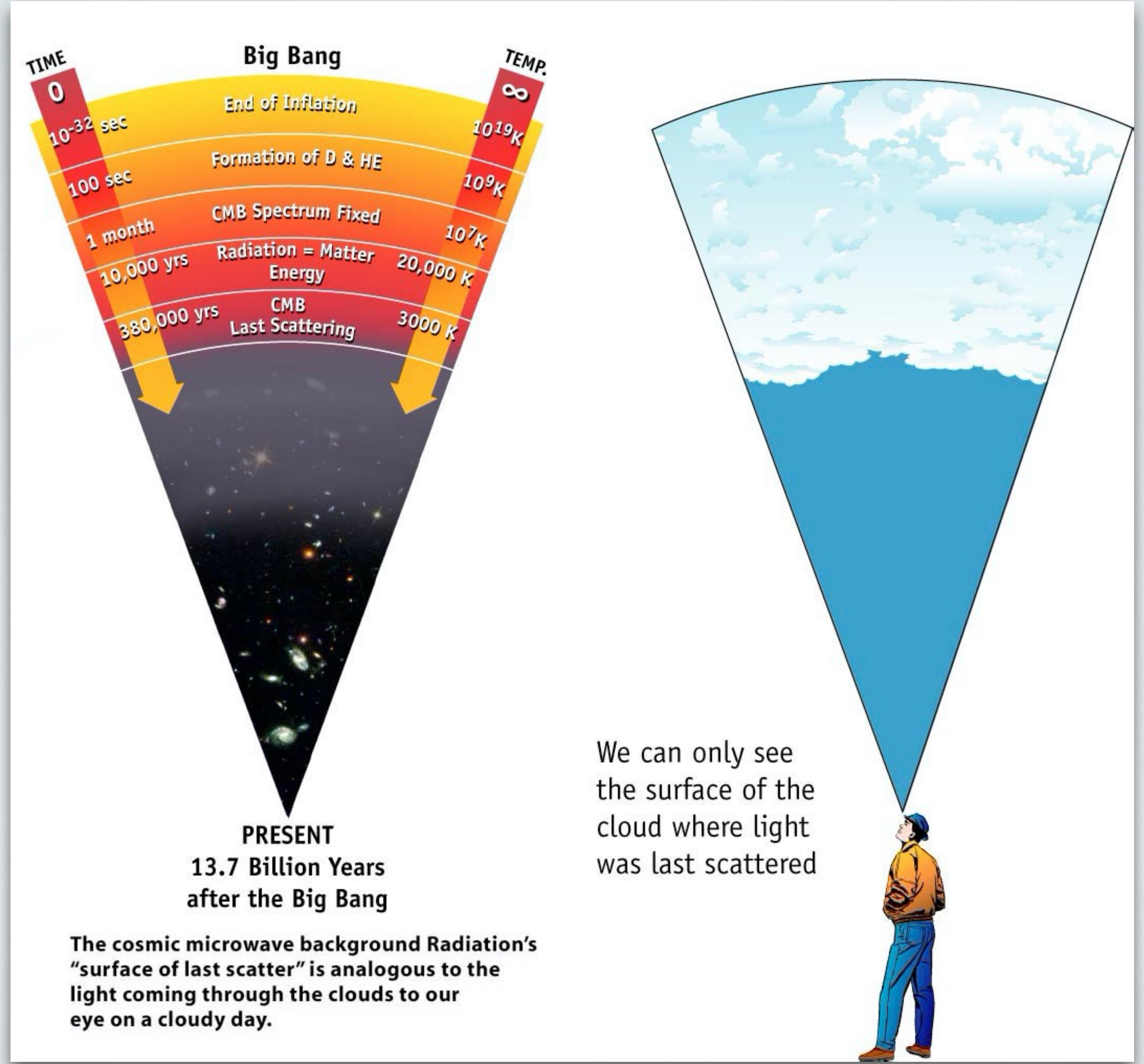
$T \approx 3000$ K
$t \approx 380{,}000$ yr

Recombination and the CMB

- Formation of atoms is called "**recombination**"
- **Photons interact less with bound electrons** than free electrons, so radiation began to stream freely after recombination ("**decoupling**")
- After decoupling, radiation has been **free-streaming** through the Universe
- Light is emitted everywhere in the Universe at recombination, and travels in all directions
- When we observe the CMB, we are looking at "**surface of last scattering**": the sphere from which light happens to be reaching us today after traveling for nearly 14 billion years (in expanding Universe)
- CMB is the **redshifted remnant** of radiation that was last "in contact" with matter at z~1100
- Each photon has lost energy as the Universe expands
- **Temperature** at surface of last scattering would have been ~3000 K, now 3000 K / 1100 = 2.725 K



Surface of last scattering



The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.

Part 2: COBE and the blackbody spectrum

Participation: Blackbody

TurningPoint:

What is the blackbody temperature of sunlight?

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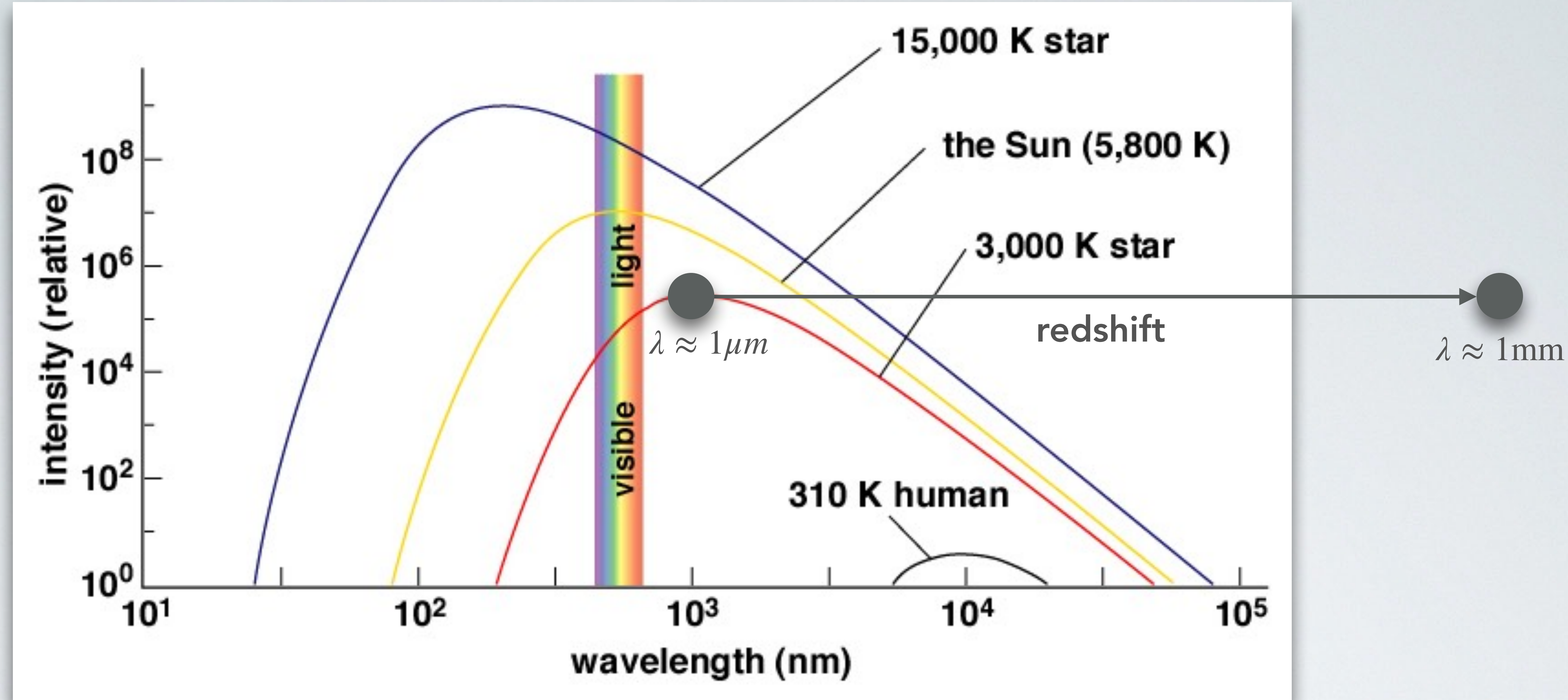
30 seconds

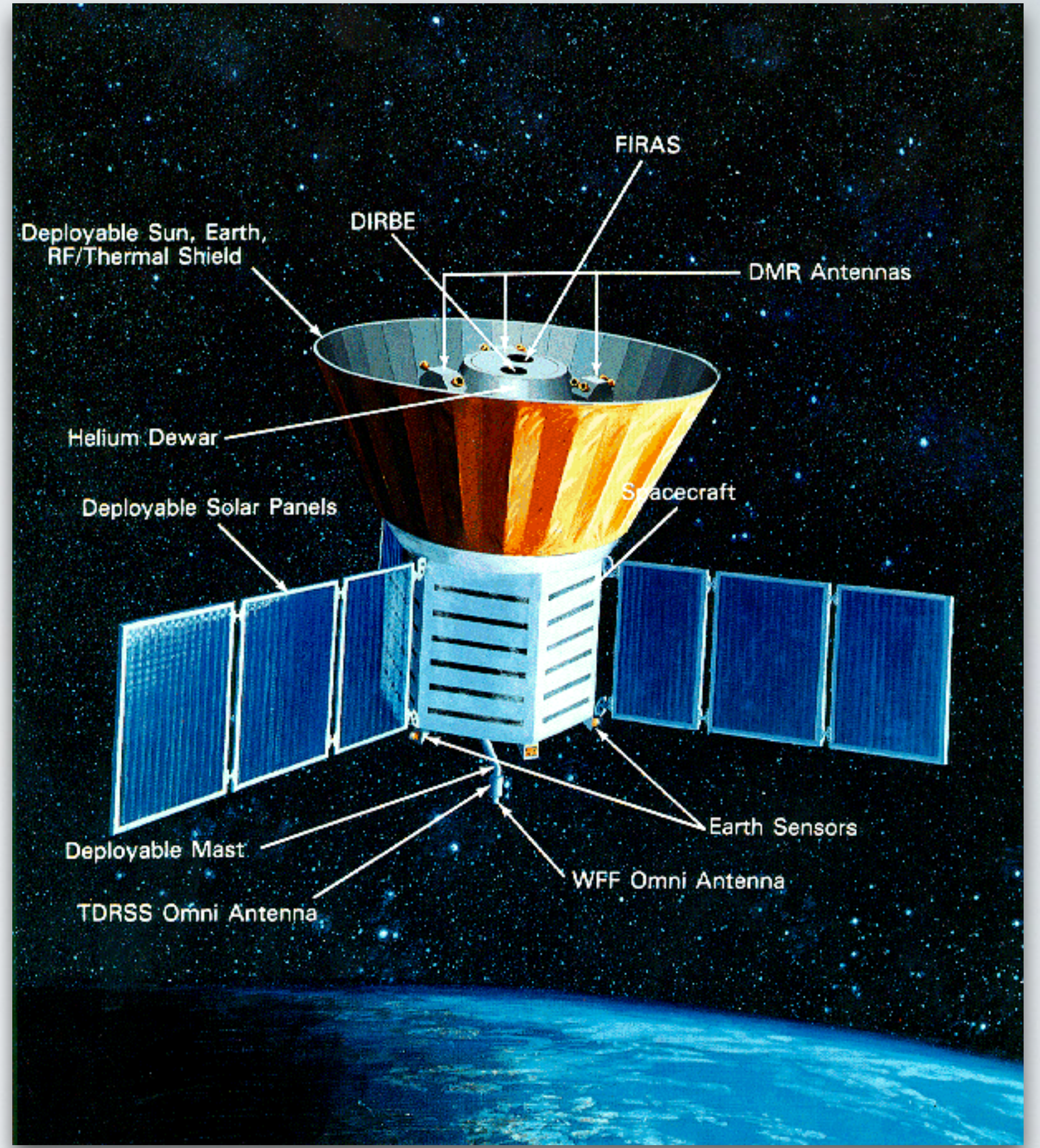
Blackbody Spectrum



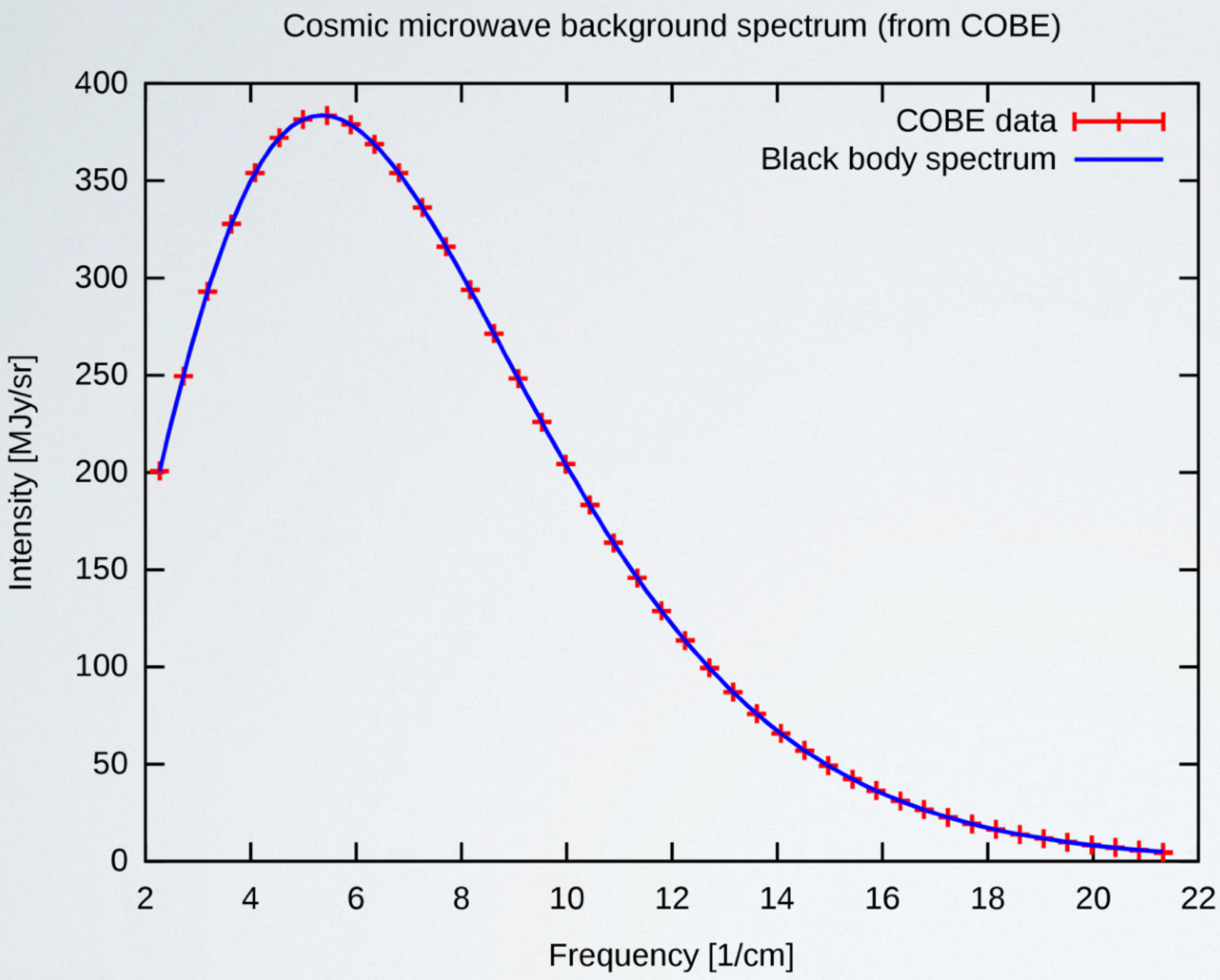
- What do we mean by the **temperature of light?**
- Any body in thermal equilibrium emits a **blackbody spectrum** that depends on its temperature (e.g. infrared cameras see heat emitted by humans)
- **Shape of spectrum** is expected to be **unchanged** over cosmic time because all photos get stretched equally
- Redshifted to microwave frequencies
- Cannot observe this spectrum properly from the ground because atmosphere is opaque over large part of wavelength range

COBE satellite

- Through late 1980s, observations were from balloons or rockets
- Cosmic Background Explorer (COBE) launched in 1989
- Built by NASA Goddard Space Flight Center
- Primary goals:
  - measure the **spectrum** of the CMB
  - measure any **variations** in the CMB with direction



COBE spectrum



- Shape of blackbody spectrum within 0.03%
- Characteristic temperature of 2.725 K within ±0.002K
- Evidence that CMB is indeed relic radiation from Big Bang

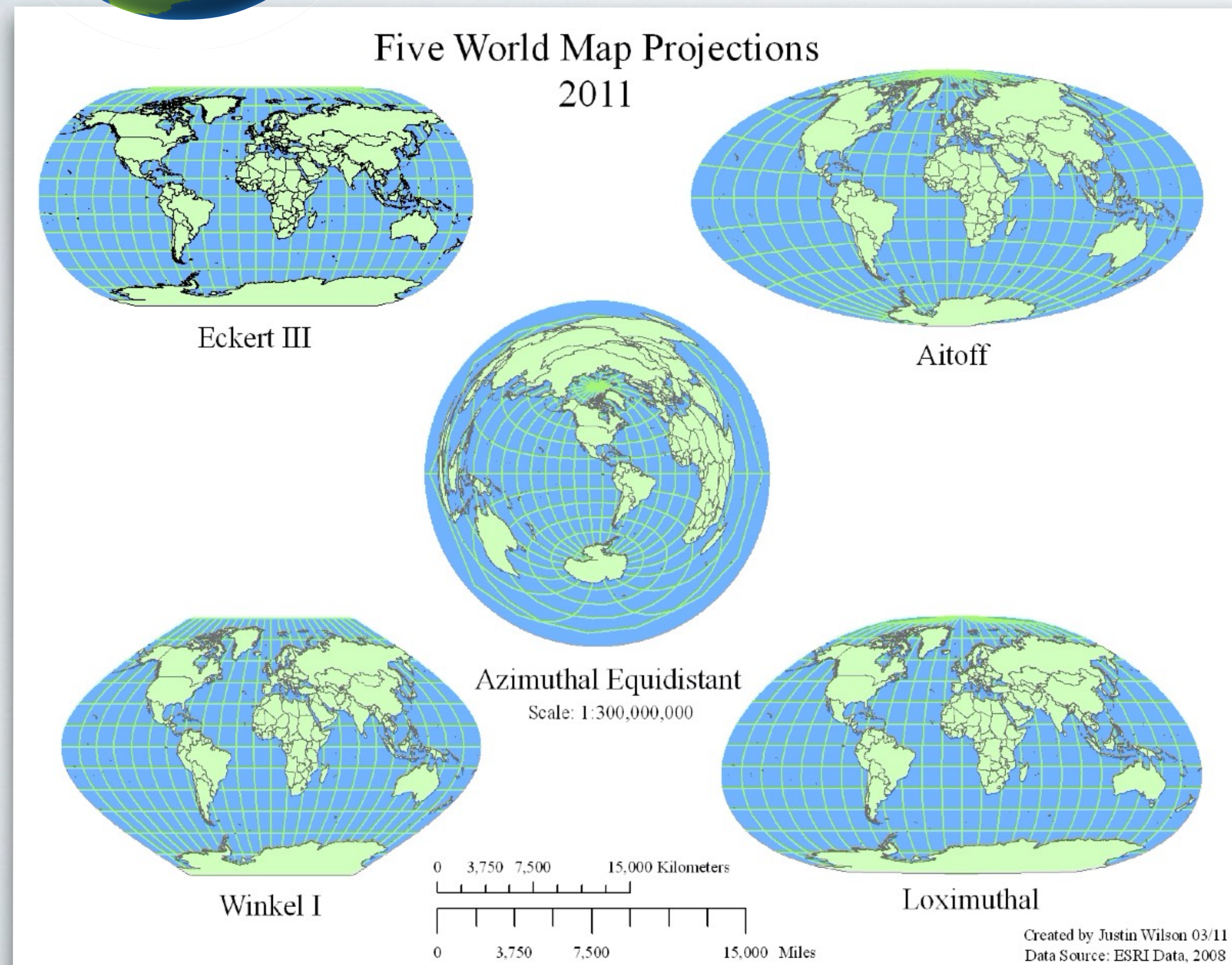
Nobel Prize 2006

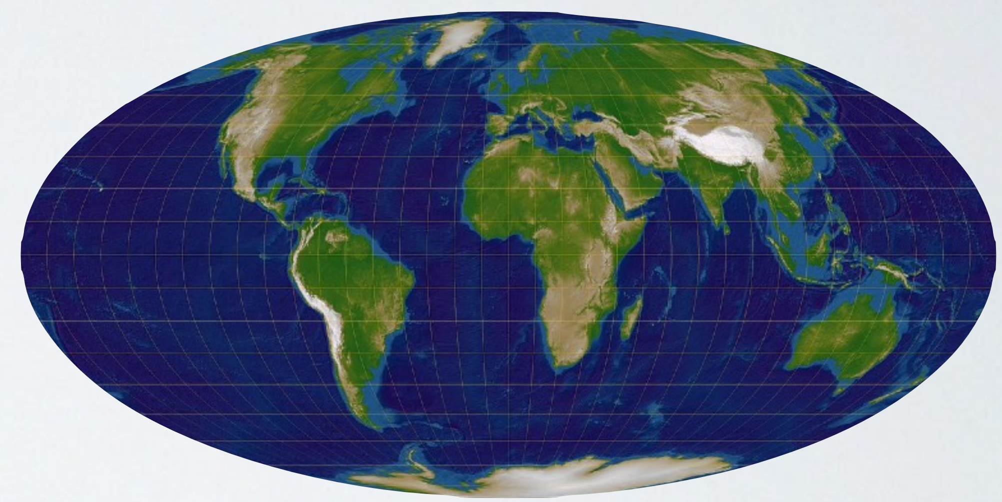
- Awarded to John Mather (GSFC & UMD) and George Smoot (UC Berkeley)
- "…for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation"
- COBE team involved more than 1000 scientists and engineers!

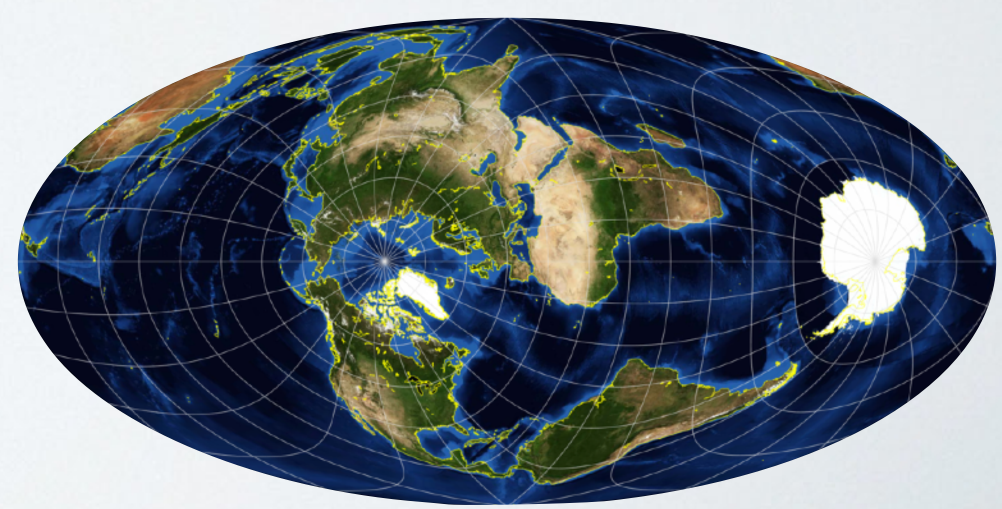
Part 3: Fluctuations in the CMB

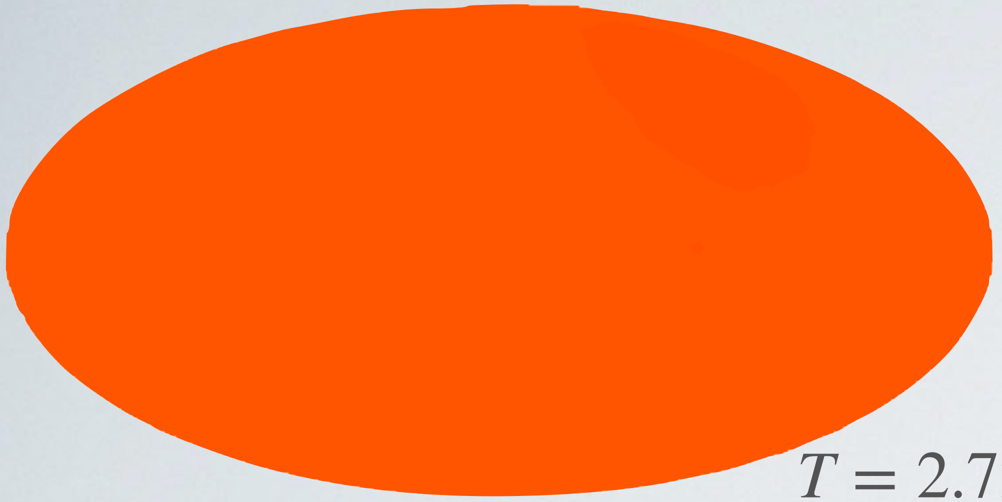
Map projections

- There are many (imperfect) ways to project a sphere onto a 2D image
- For the CMB, we use the so-called Mollweide projection, which makes an ellipsoid-like shape



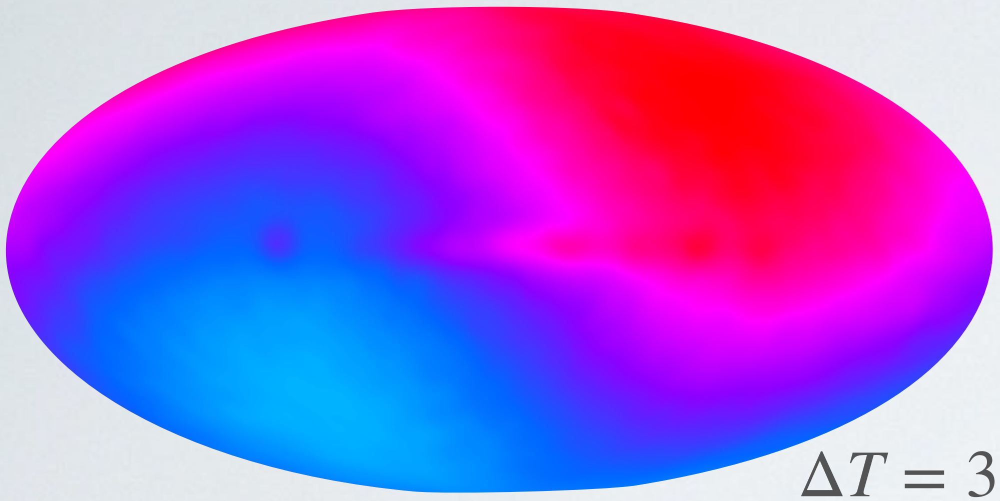






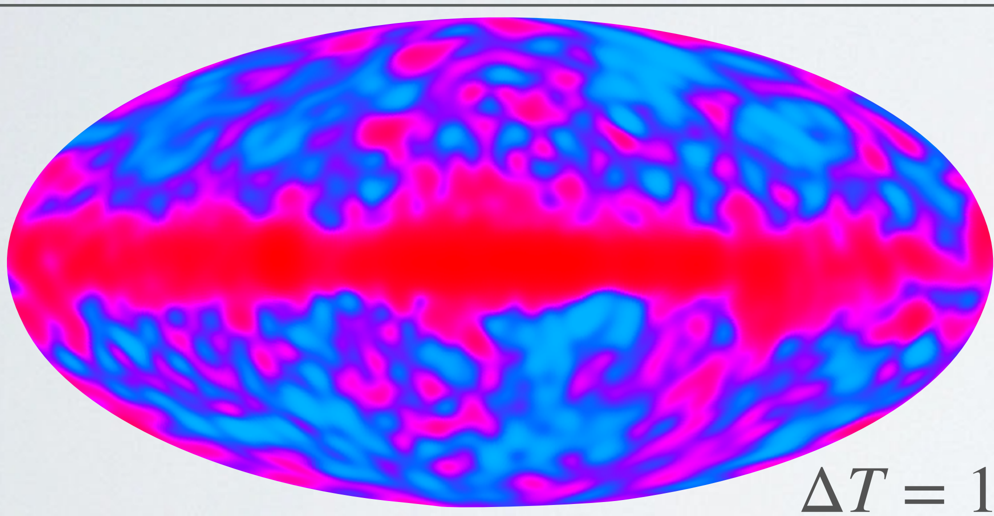
$T = 2.725\ \mathrm{K}$

- Projections of temperature over the whole sky
- At first sight, CMB is isotropic (same temperature in all directions)
- We subtract this average temperature to look for differences



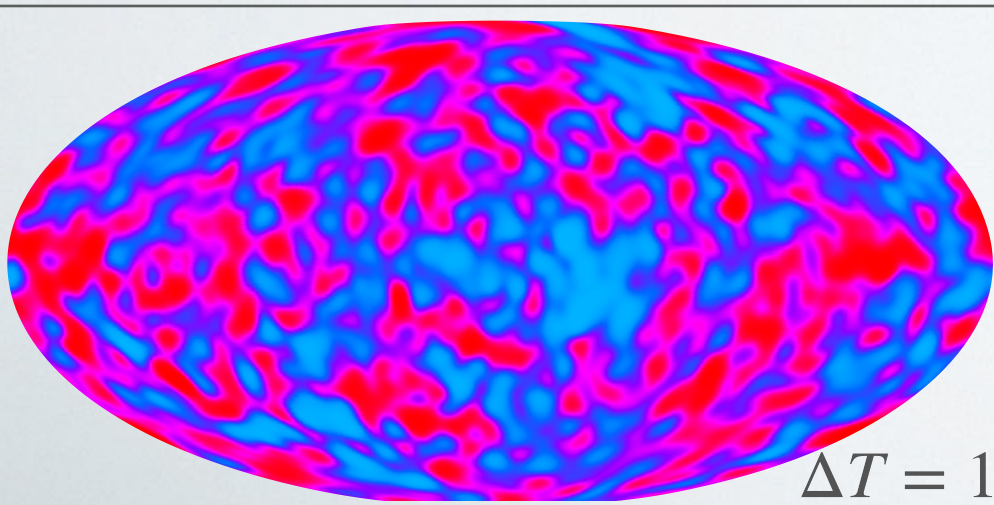
$\Delta T = 3.4\ \mathrm{mK}$

- But there are small differences: a "dipole" of blue/redshift in the direction of **Earth's motion**
- Total velocity is **390 km/s relative to CMB**
    - 30 km/s from Earth's orbit around Sun
    - 220 km/s from Sun's orbit around Galaxy
    - Motion of Milky Way in large-scale structure



$\Delta T = 18\ \mu\mathrm{K}$

- We **subtract the dipole** to look for differences in the actual CMB temperature
- Red band is from our Galaxy (which emits at the frequency range of the CMB)
- **Variations are at a level of 10^{-5}** of the average temperature

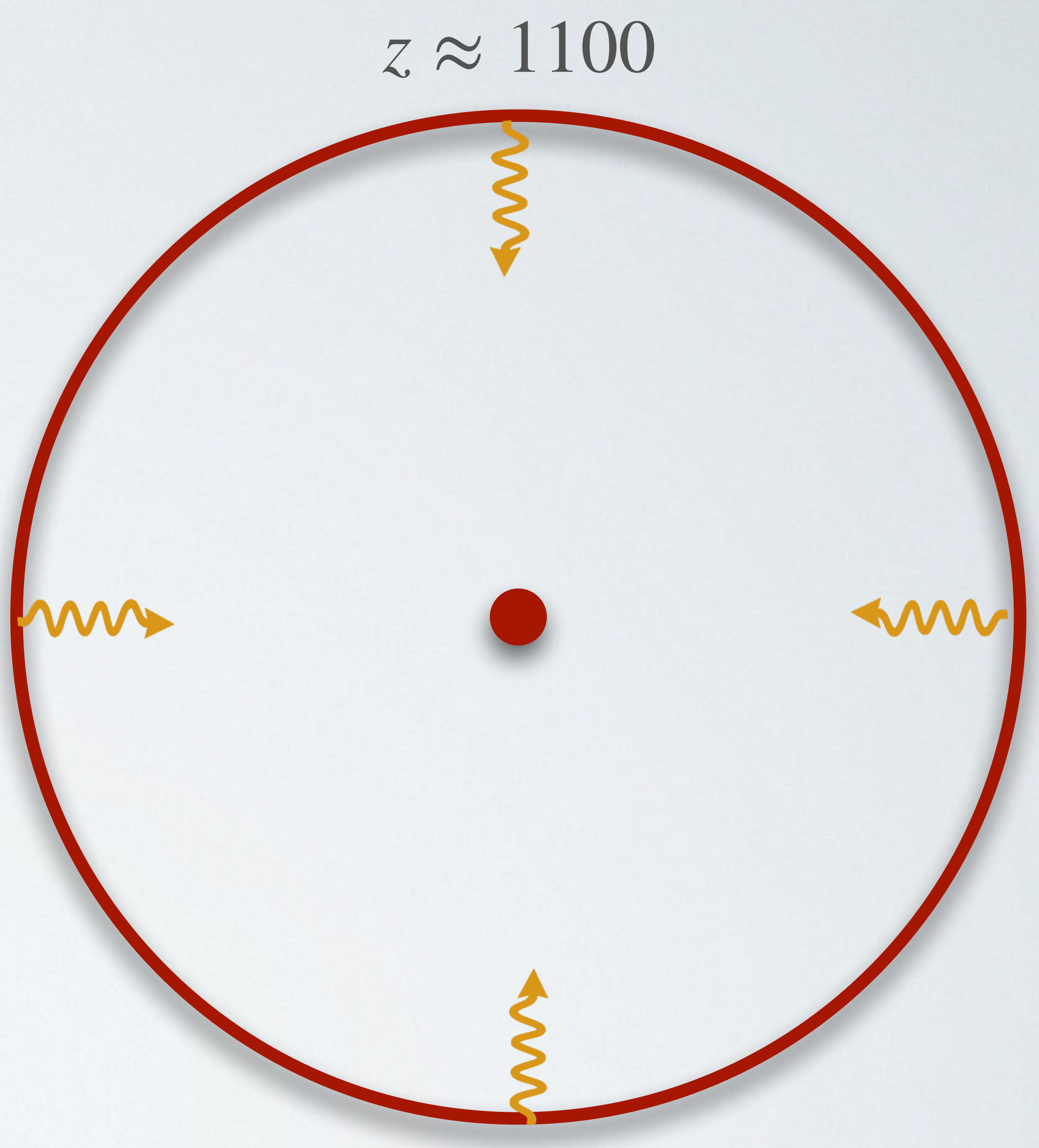


$\Delta T = 18\ \mu\mathrm{K}$

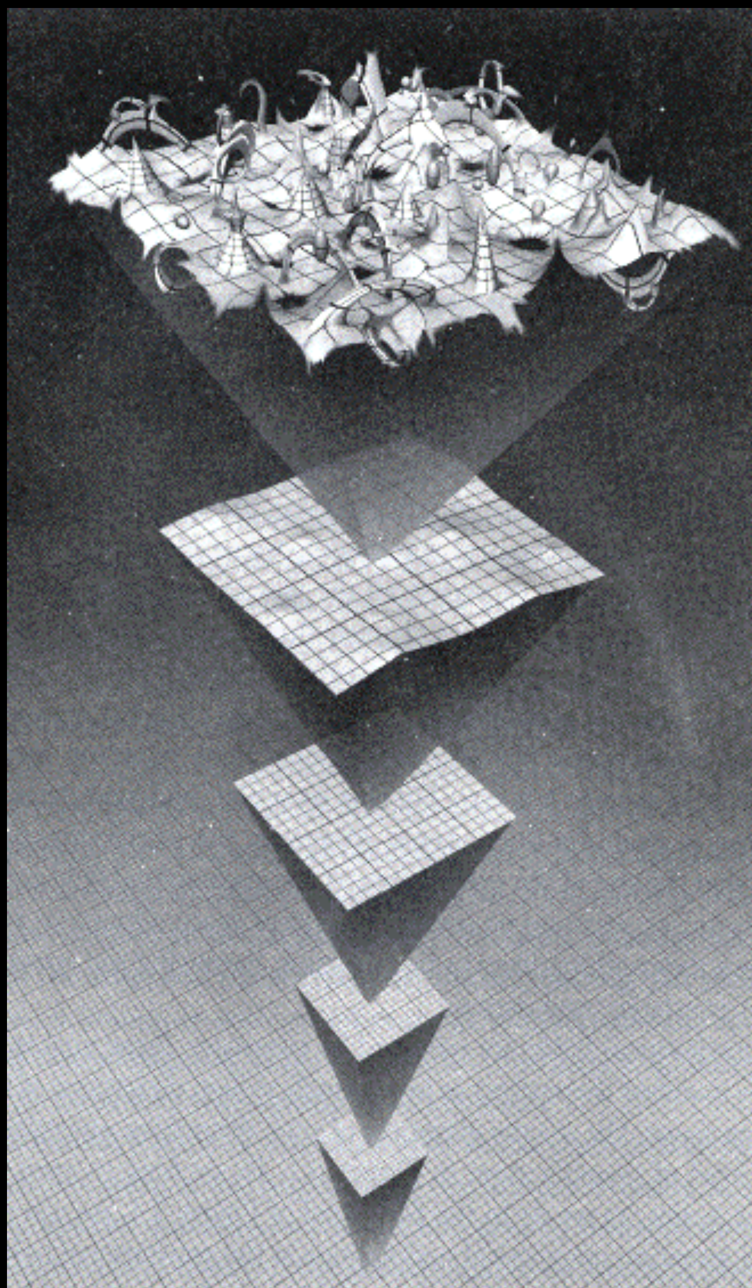
- Use observations at other frequencies to model the galactic emission
- **Subtract galactic emission** from measurement to get actual CMB

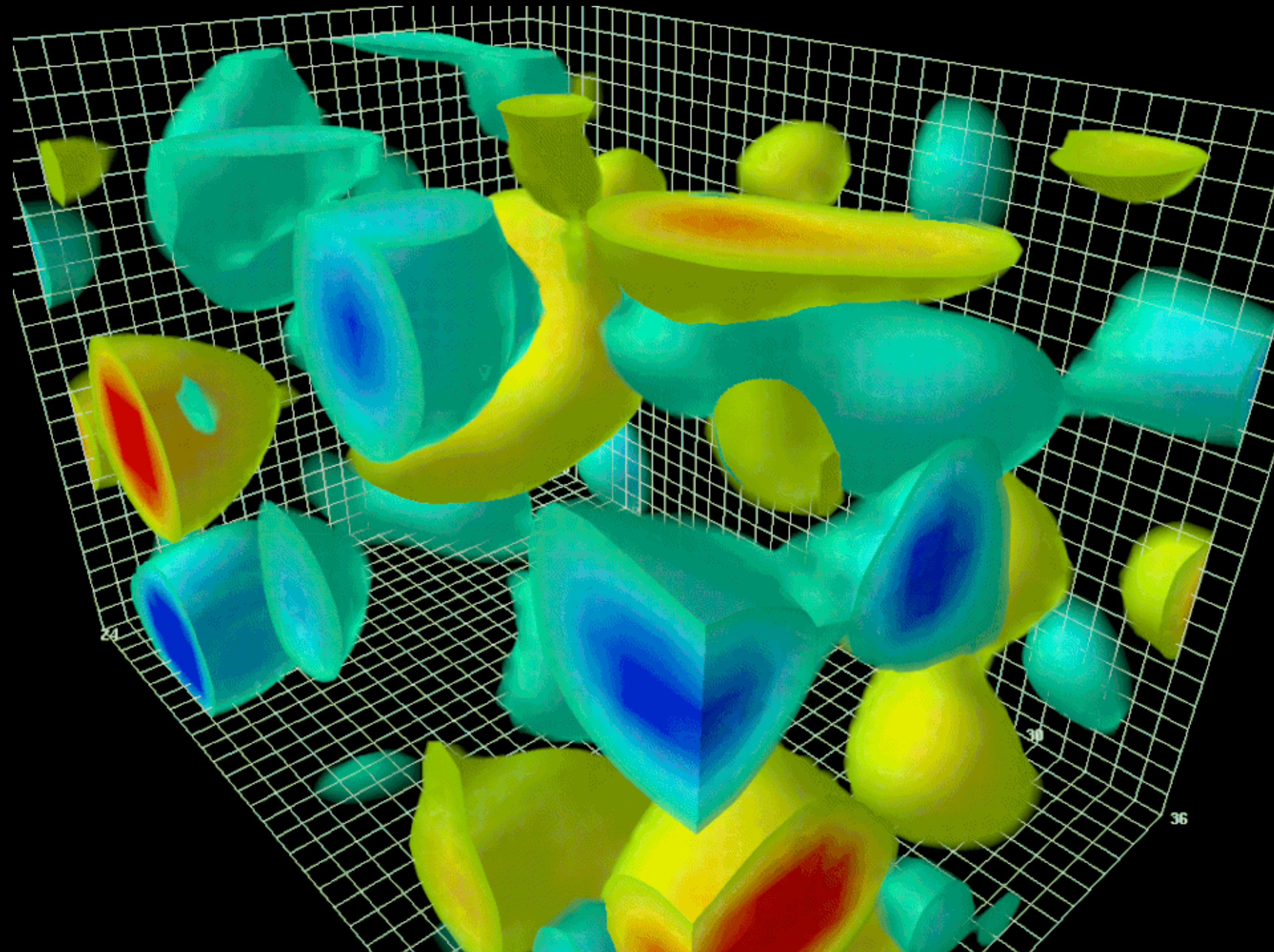
Is the CMB a special frame of reference?

- From the CMB dipole, we measure the motion of the Earth relative to the average frame of matter in the Universe
- In General Relativity, we would say that the CMB frame is free-falling in the large-scale gravitational field of the Universe
- This does not pose a problem for Special Relativity: we are free to define such a frame, but it is not physically special



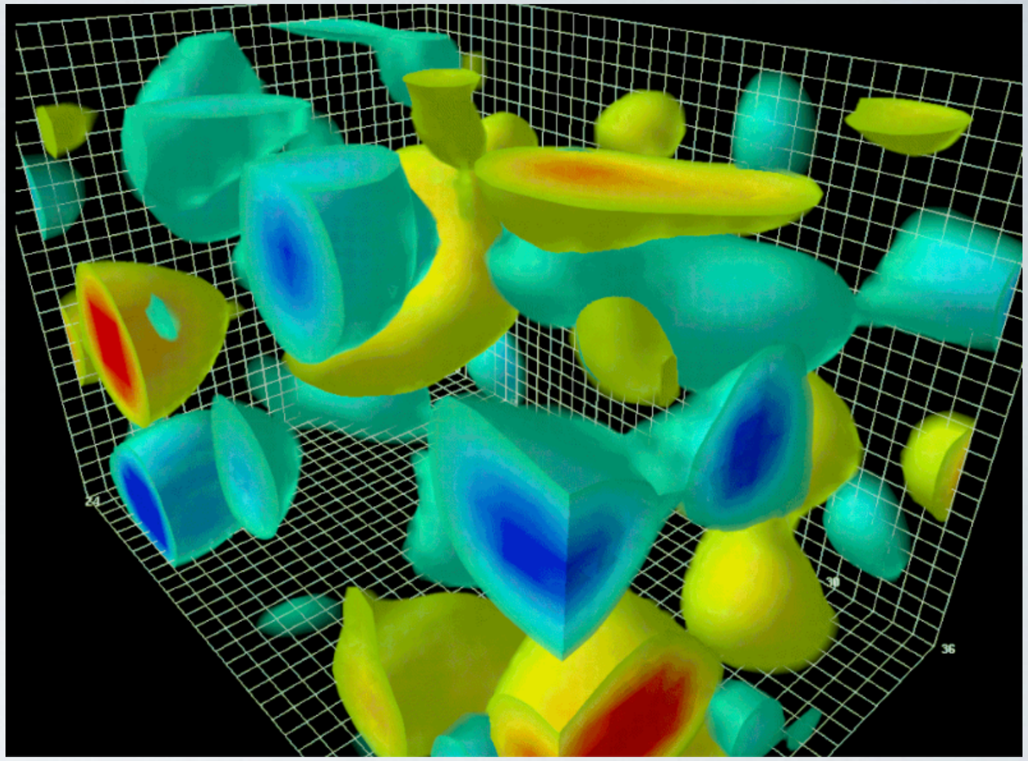
What are the fluctuations?



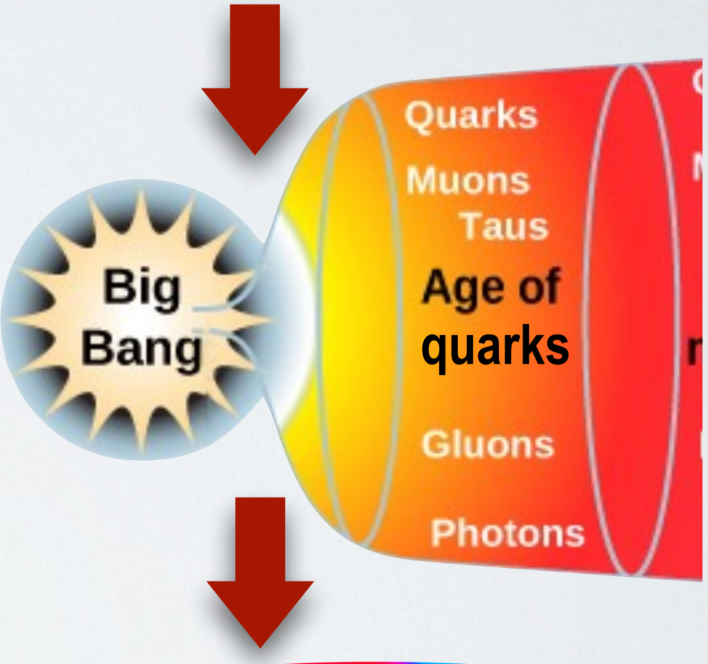


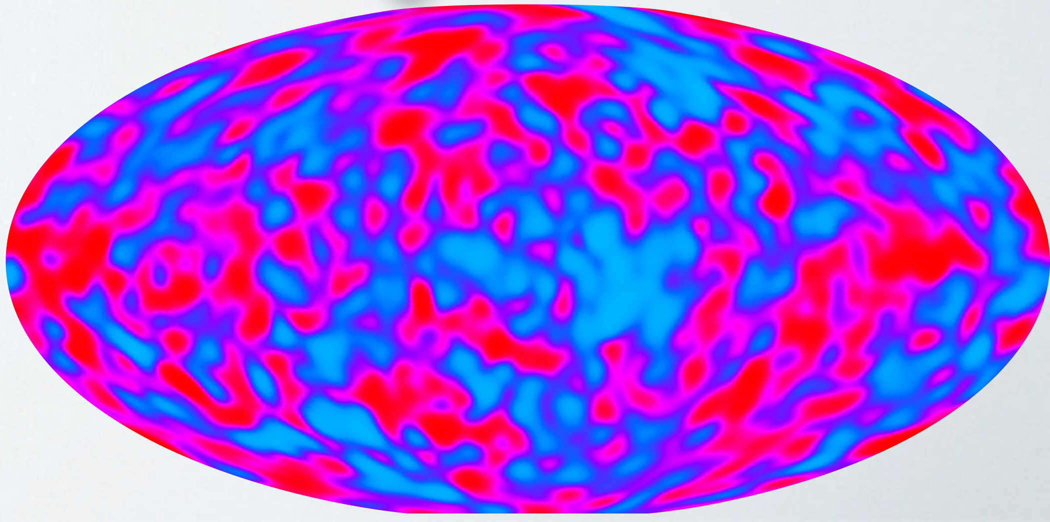
- We expect random quantum fluctuations during the Planck epoch

What are the fluctuations?



- Overall, extremely isotropic CMB supports the idea that the Universe is isotropic (cosmological principle)
- Quantum fluctuations from Planck epoch are amplified during inflation
- Inflation expands the Universe so quickly that afterward, patches are out of causal contact and thus out of thermal equilibrium
- Some patches are slightly denser/hotter and some less dense/cooler
- Pattern is complicated by dynamics of photon-matter fluid in early Universe
- Small over/underdensities are the seeds of all structure in the Universe

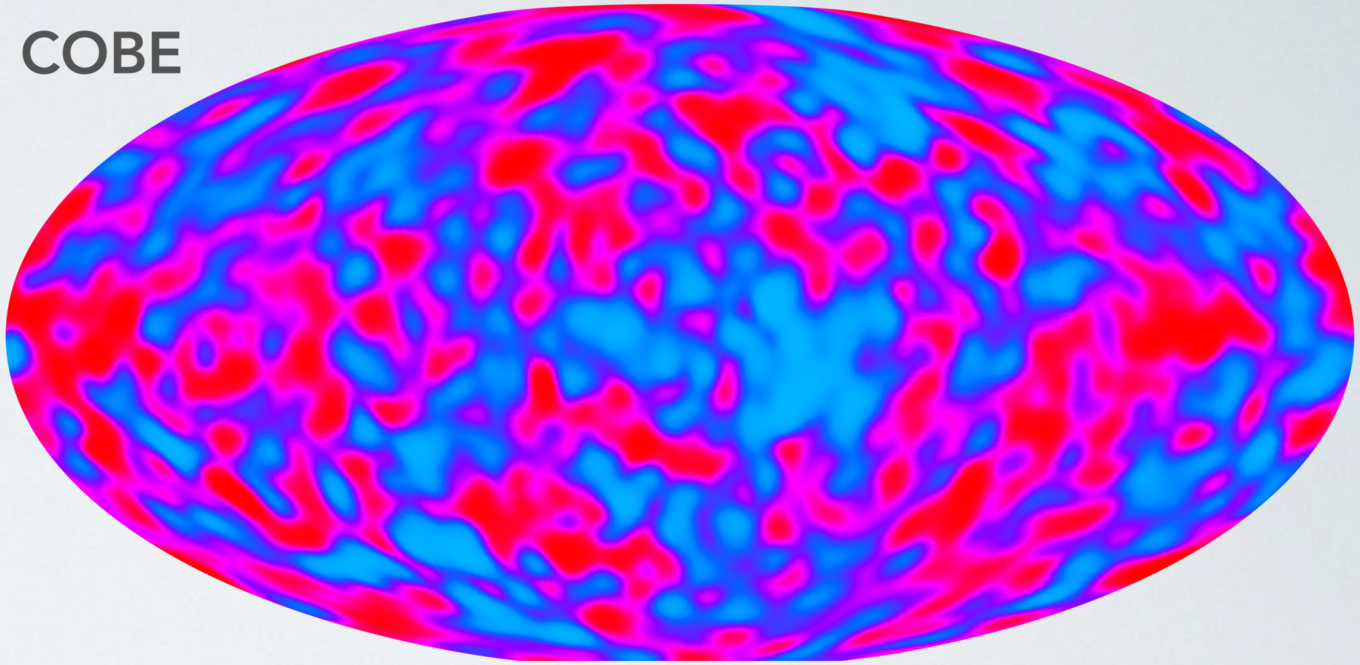


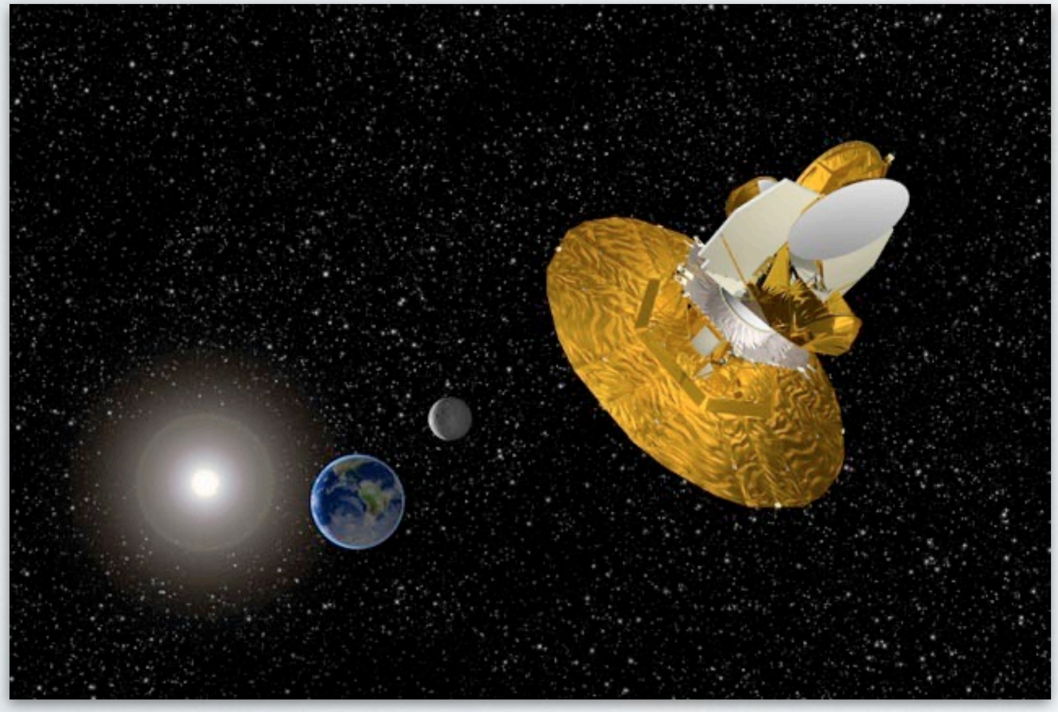


Measuring the fluctuations

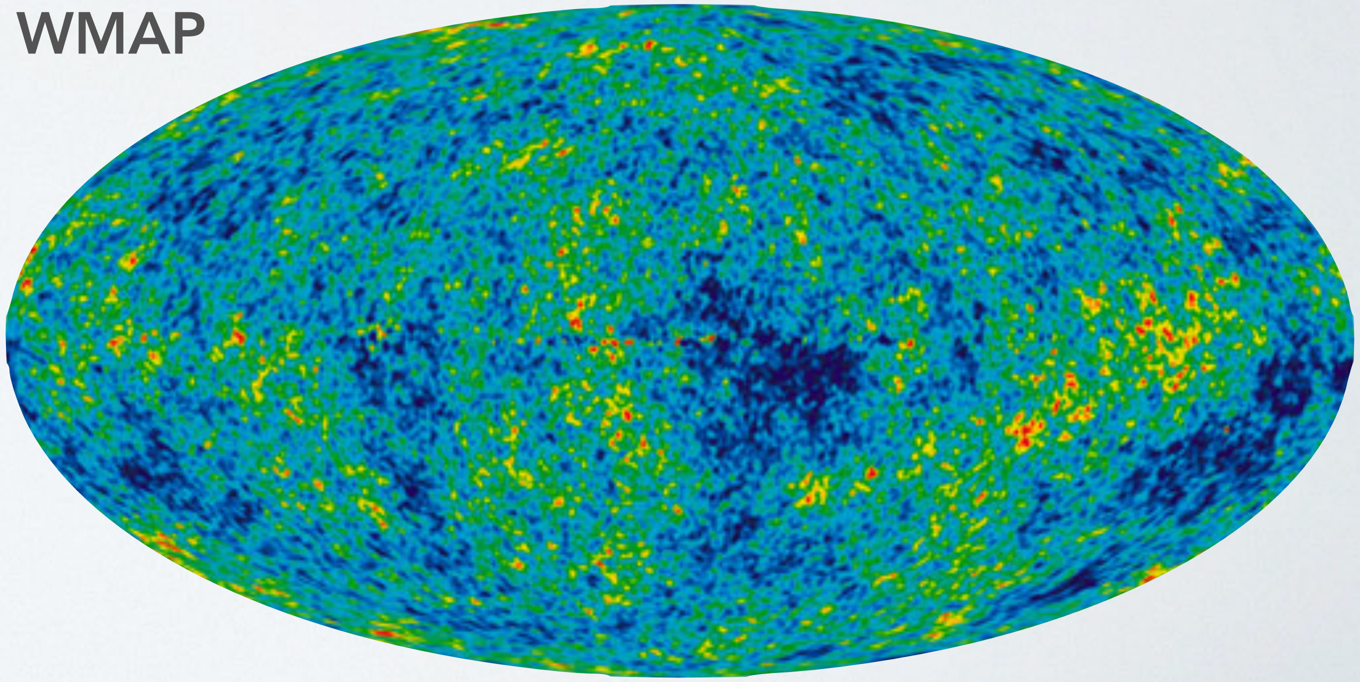
- WMAP: Satellite launched in 2001
- Much higher spatial resolution (0.2°) than COBE (7°)

COBE





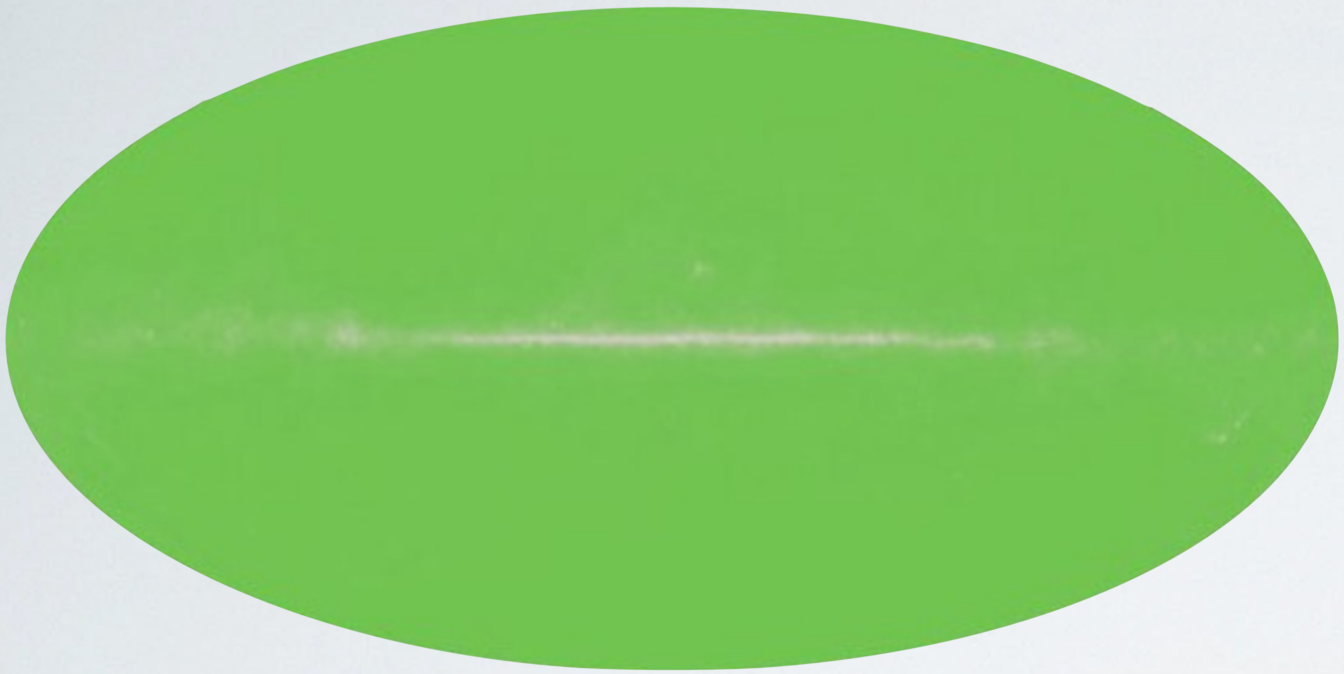
WMAP



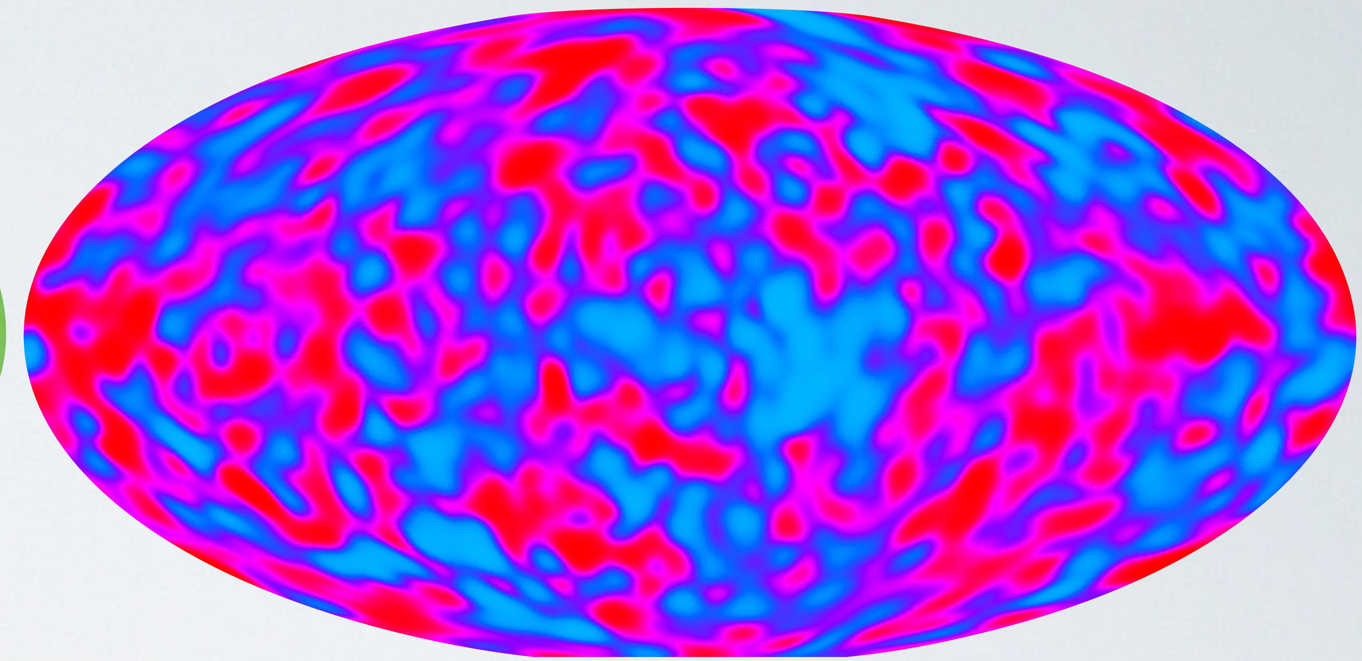
NASA / WMAP

Measuring the fluctuations

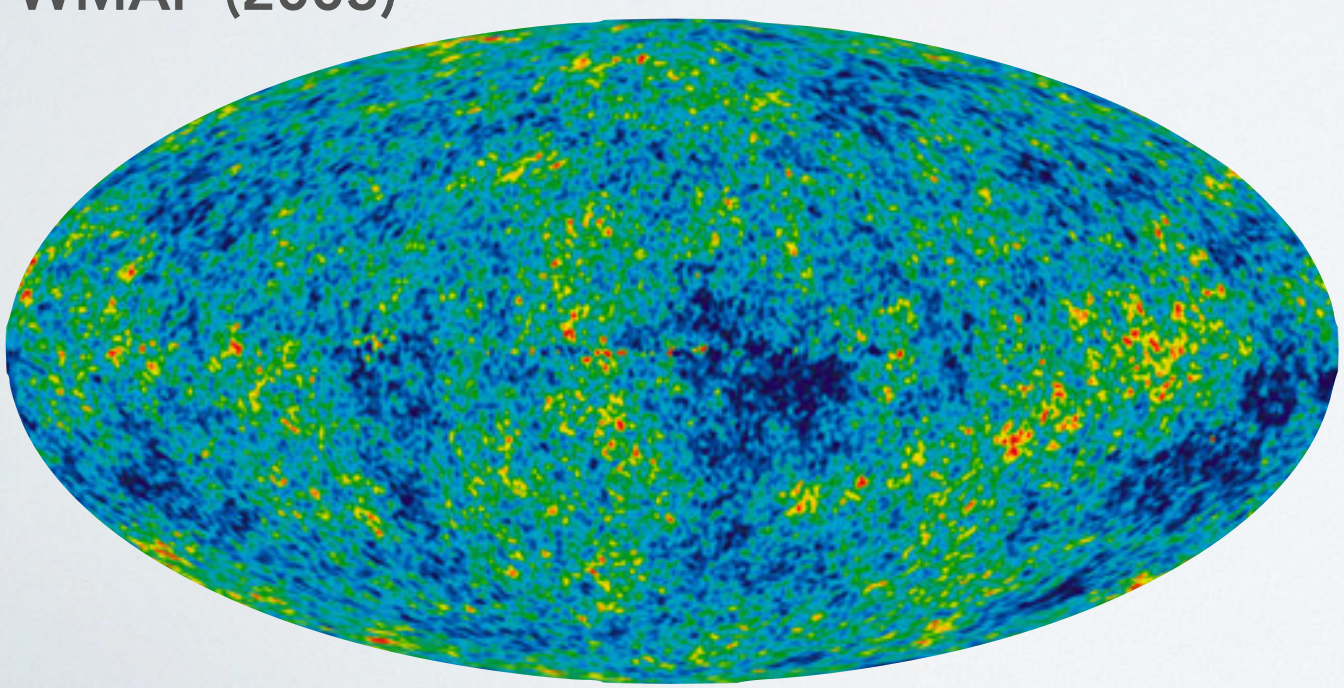
Penzias & Wilson (1965)



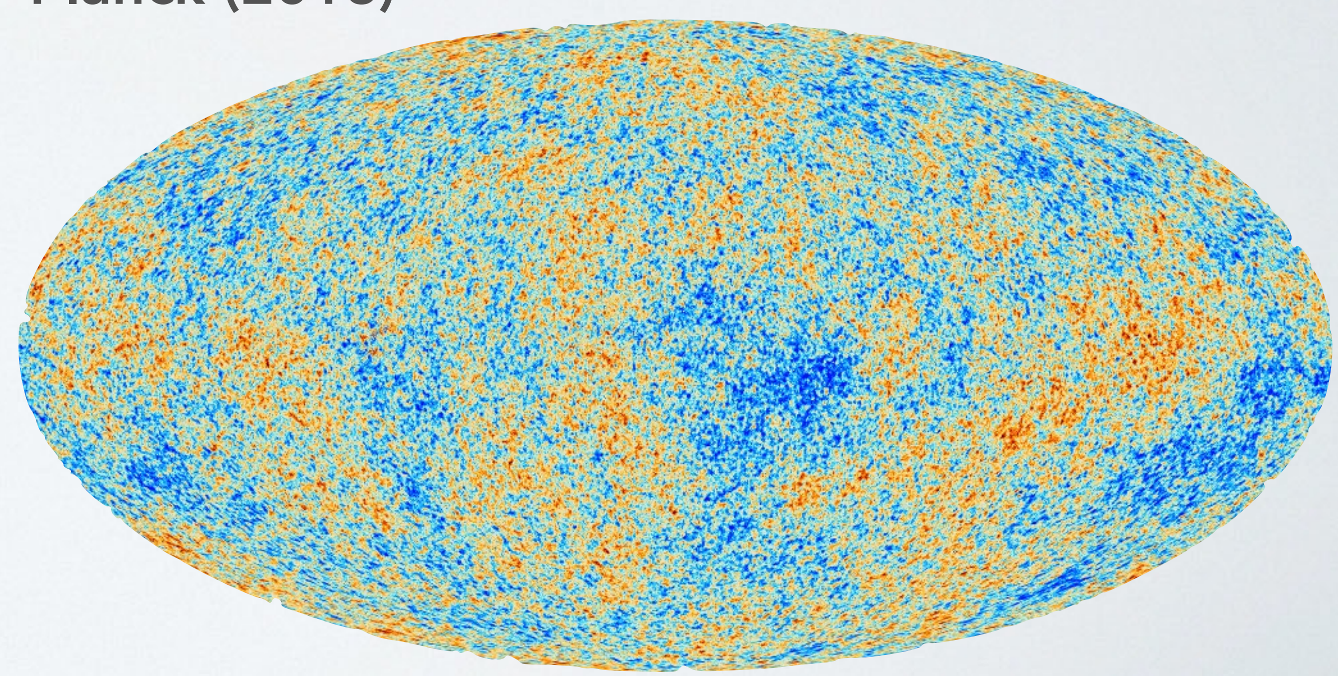
COBE (1992)



WMAP (2003)

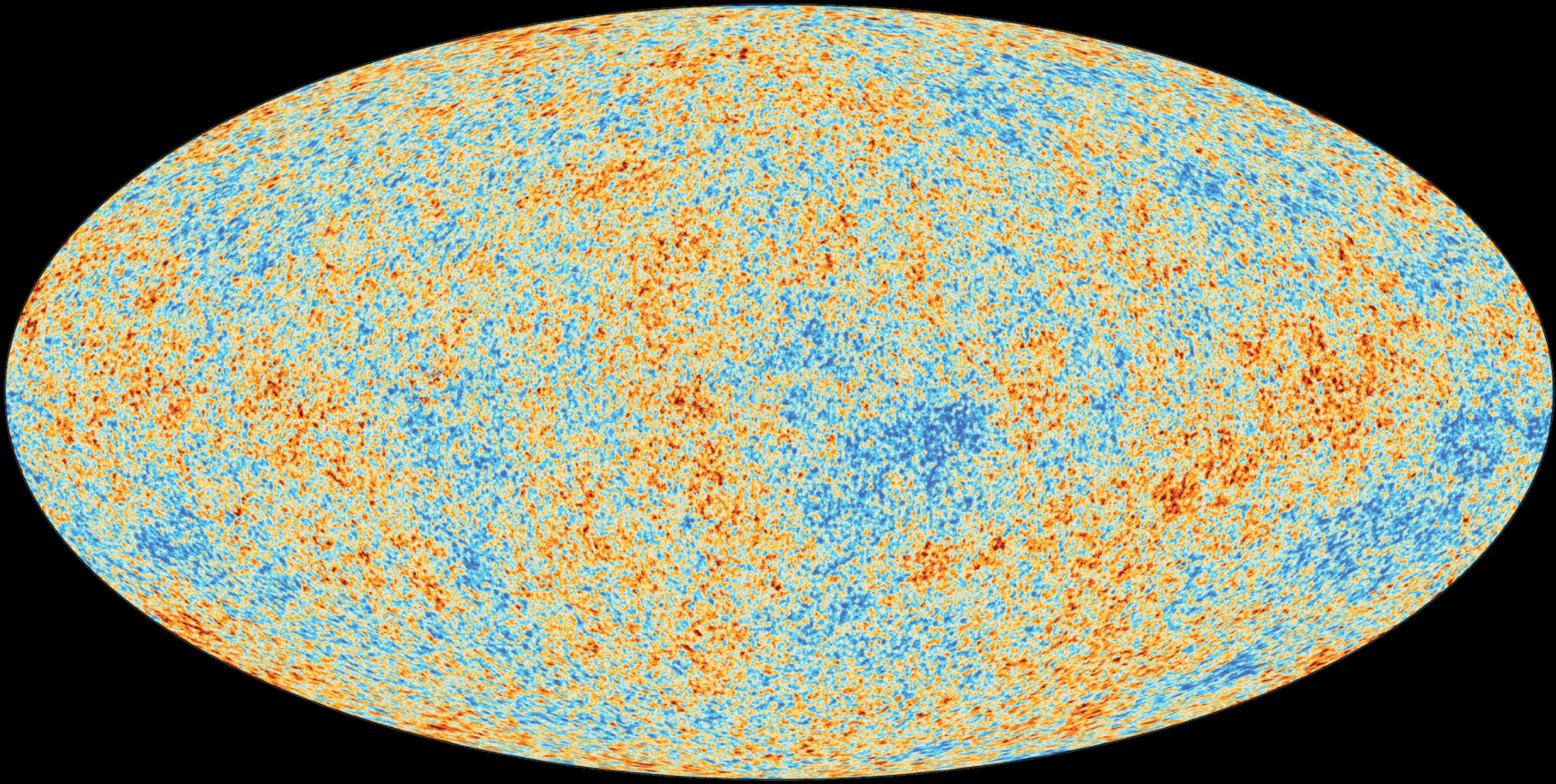


Planck (2018)



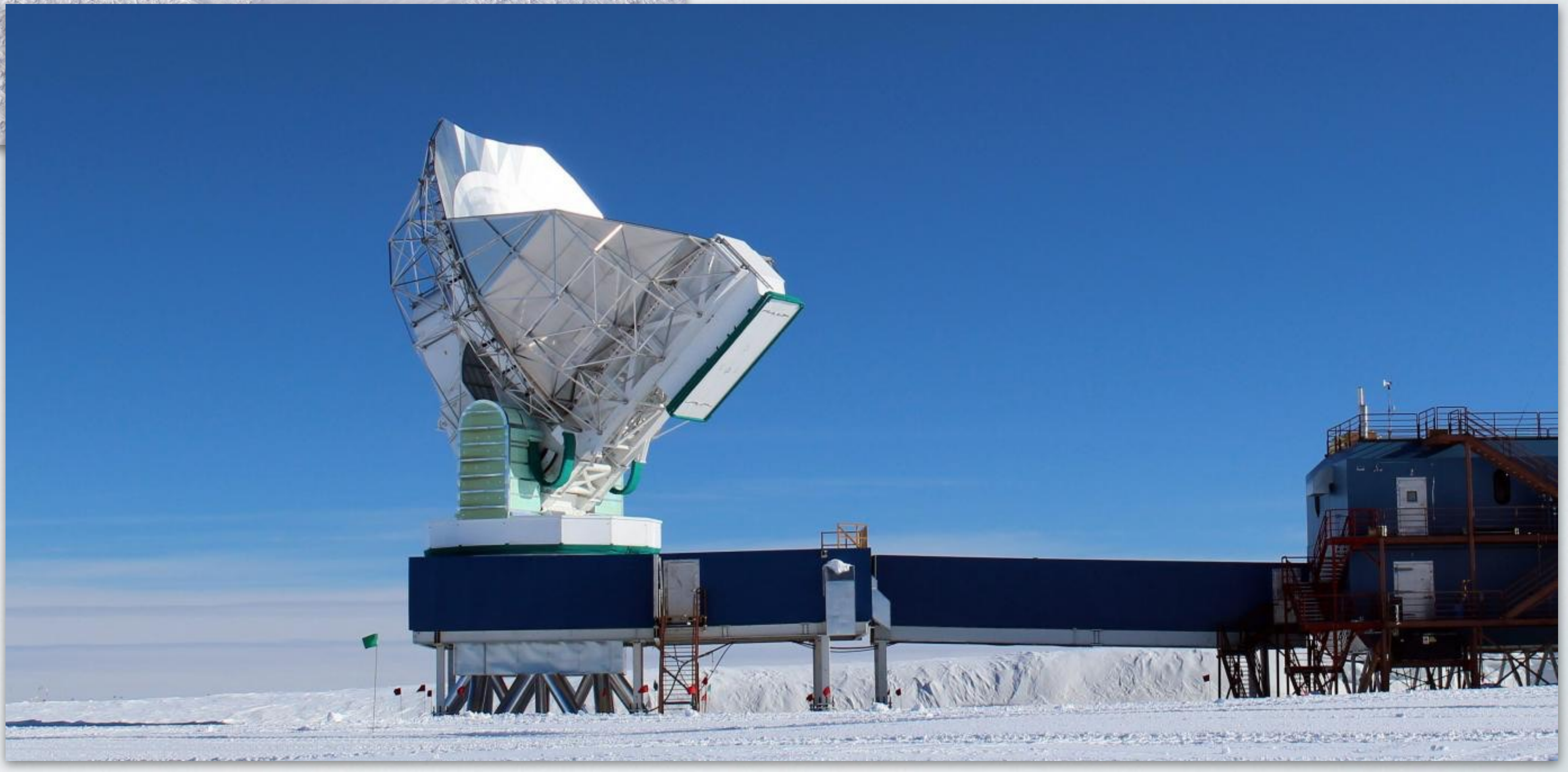
NASA / WMAP / Planck

Planck CMB Map



ESA / Planck

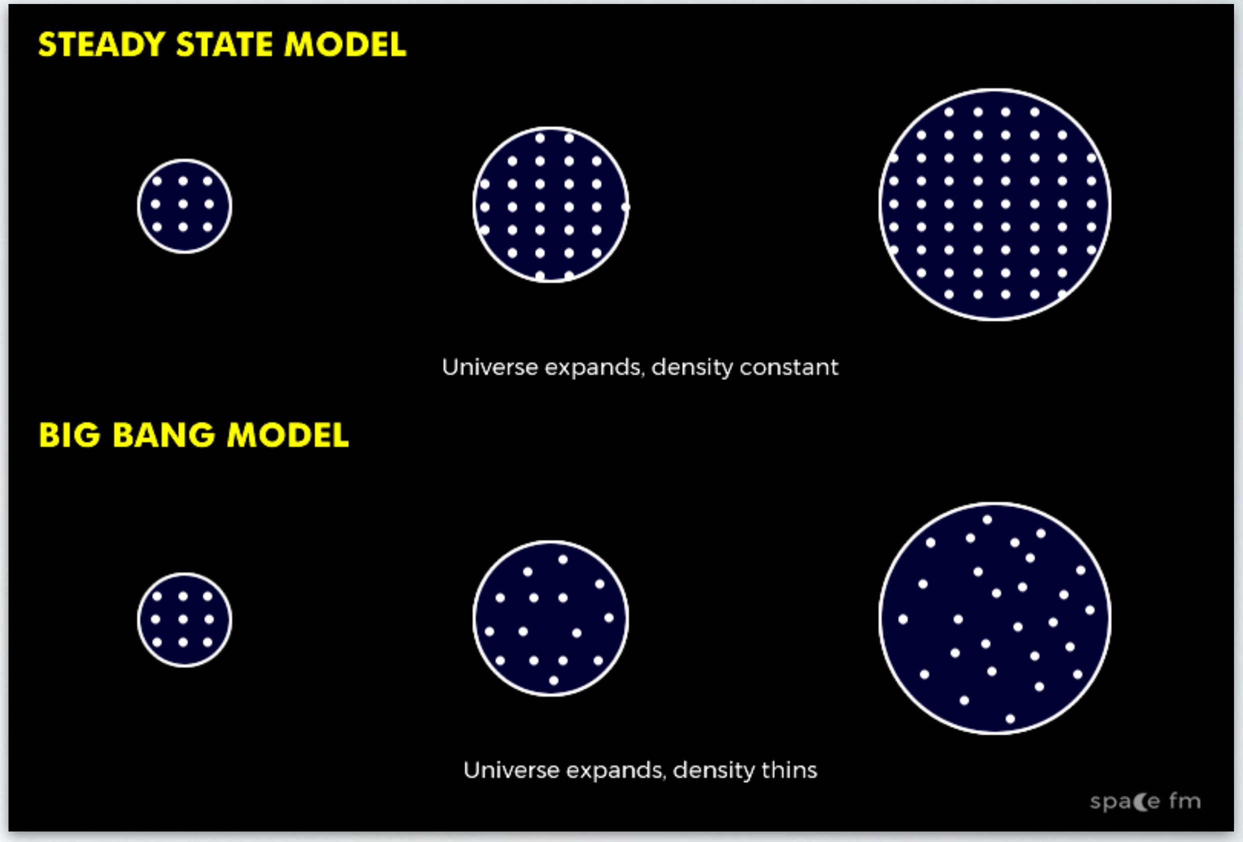
South Pole Telescope



Part 4: What we can learn from the CMB

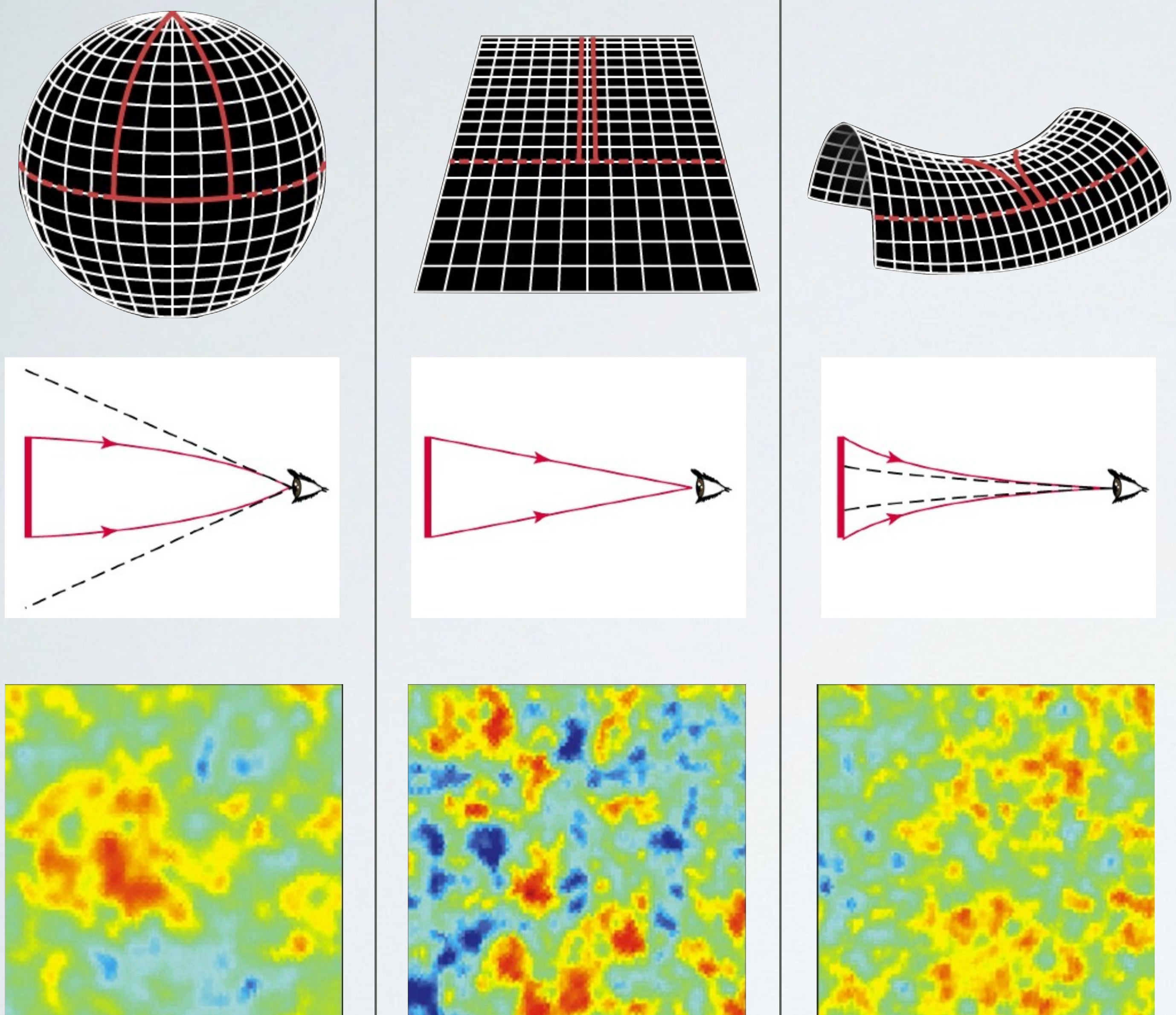
Steady State Theory

- In the 50s and 60s, steady state model was a serious competitor
- Matter (e.g., hydrogen atoms) is continuously created as space expands
- Obeys cosmological principle
- Fred Hoyle in 1949:
  "These theories were based on the hypothesis that all the matter in the universe was created in one big bang at a particular time in the remote past."
- CMB was predicted by Big Bang, and is very hard to explain in steady-state cosmology



NASA / WMAP

Curvature of the Universe



Closed ($k > 0$), spots appear larger

Flat (spots appear in actual size)

Open ($k < 0$), spots appear smaller

- We understand the physics of the CMB patches very well, so we know what size they should be
- If the Universe was strongly curved, the apparent size of the patches would change
  - Larger if positively curved, because lines converge
  - Smaller if negatively curved, because lines diverge
- All CMB measurements are compatible with $k = 0$ (flat)

Take-aways

- **Recombination** (transformation from ionized to atomic hydrogen) takes places at about **3000 K**

- Universe becomes **transparent** to photons; CMB consists of **redshifted** photons from this epoch (z = 1100)

- CMB is almost perfectly **isotropic**, but it's tiny fluctuations tell us about the over- and underdensities in the early Universe that **seeded structure**

Next time…

We’ll talk about:

- How we know about dark matter and dark energy

Assignments

- Post-lecture quiz (by tomorrow night)
- Homework #4 (by Thursday 11/11)

Reading:

- H&H Chapter 13