Reading: OpenStax, Chapter 29, Sections 29.1-29.6 (for this lecture and next)

Exam 3: Monday, November 23rd (details to follow)

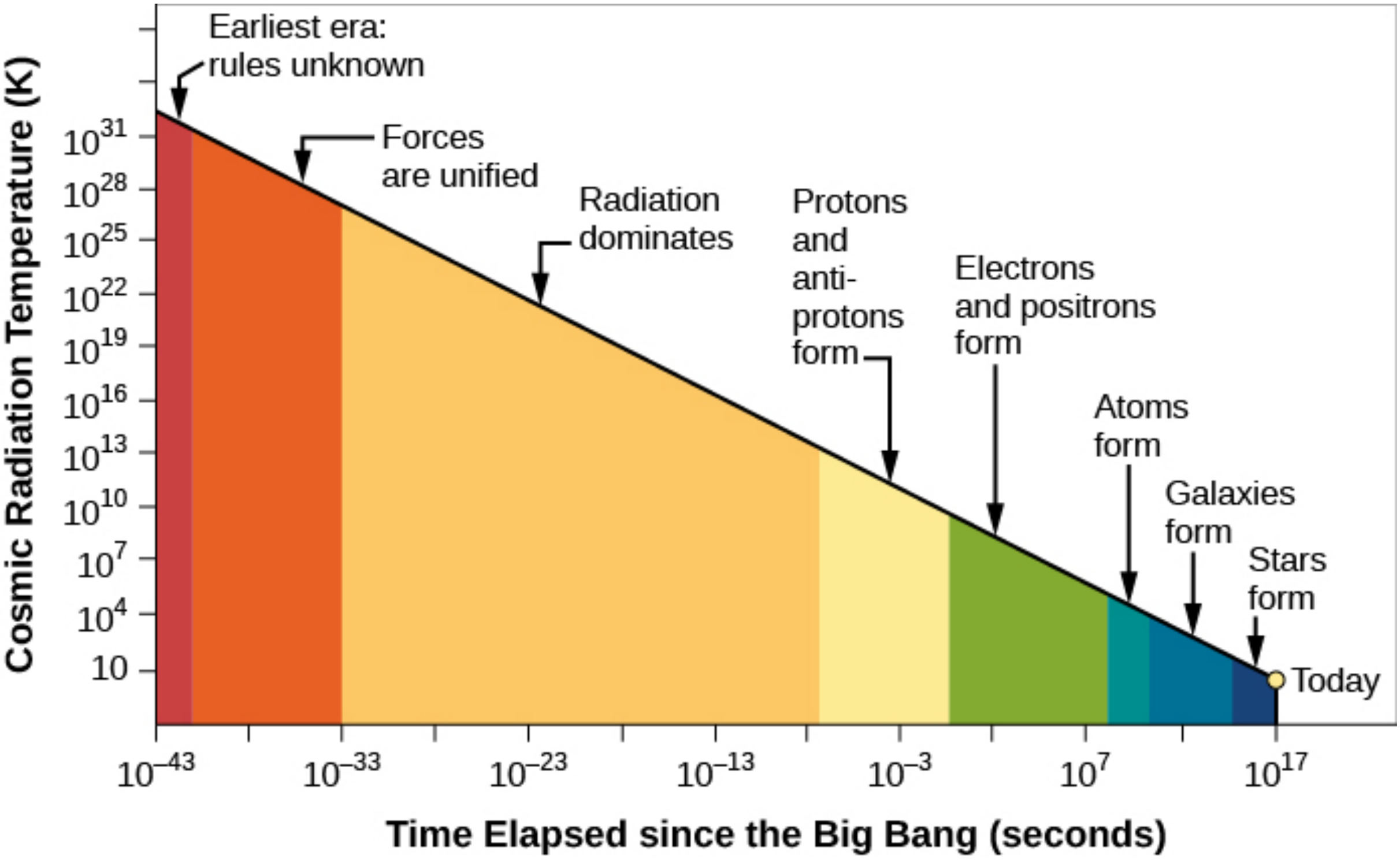
Previously: **Cosmology I - The Age of the Universe and the Big Bang**

- Cosmology - answering questions about the origin of the Universe and answering them using observations
- Independent measurements all yield an age of the Universe of about 13.5 billion years
- Time began with a hot Big Bang - expansion and cooling until today
- The Big Bang makes several predictions that can be tested

Today: **Cosmology II - The Big Bang and its aftermath**

- Remnant radiation produces a cosmic microwave background
- Small density fluctuations needed to make galaxy clusters were present in the very early universe
- A very “Inflation” epoch is needed to make the post-Big Bang expanding universe look like what we see today

The earliest moments of the Big Bang



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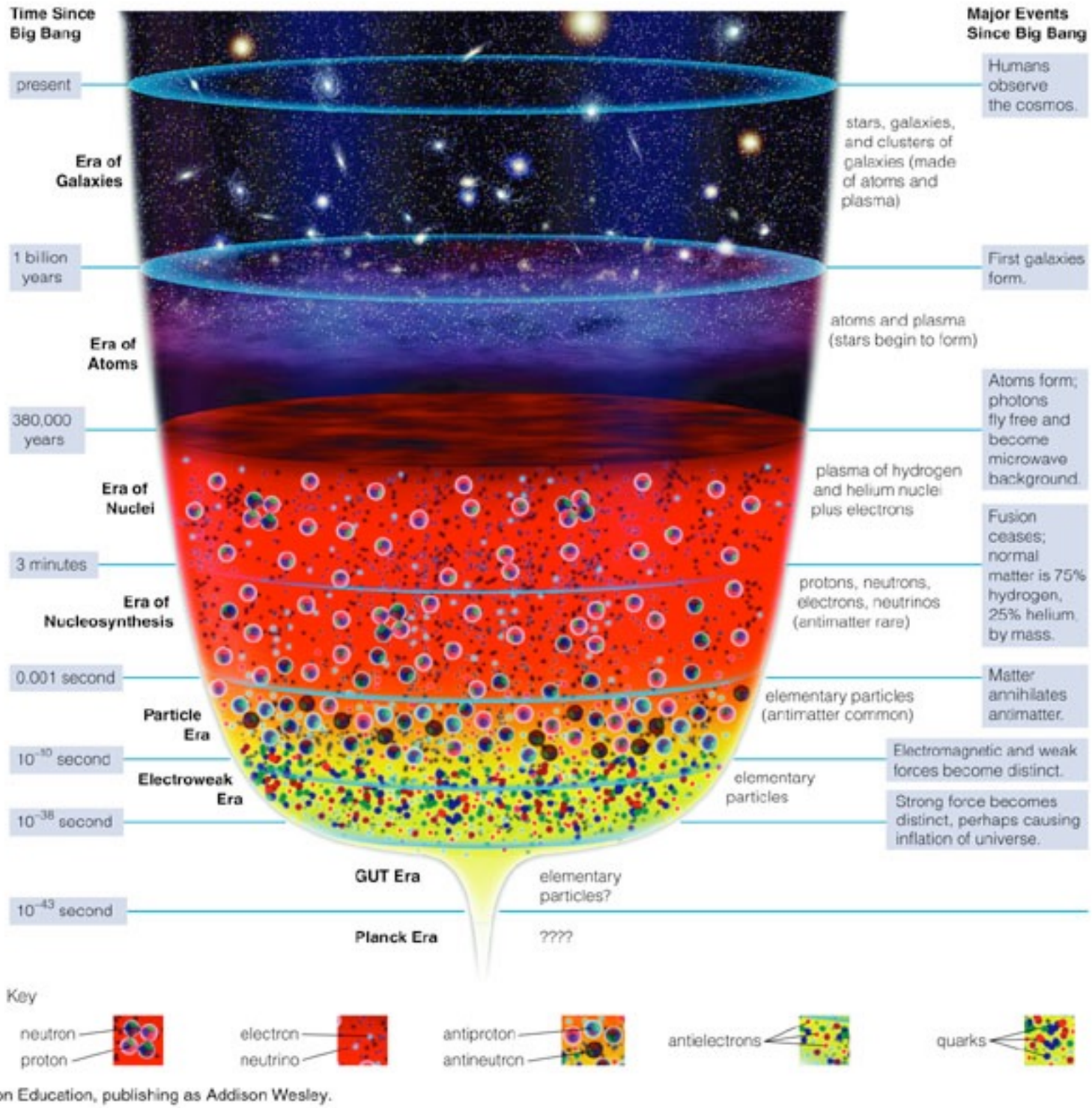
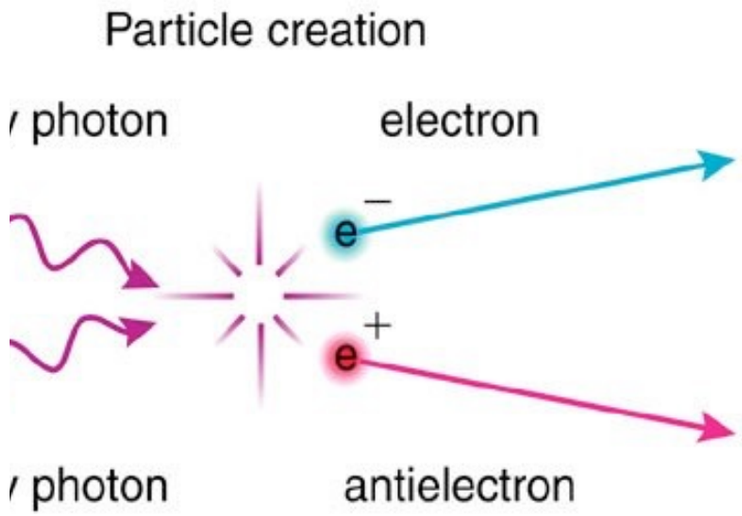
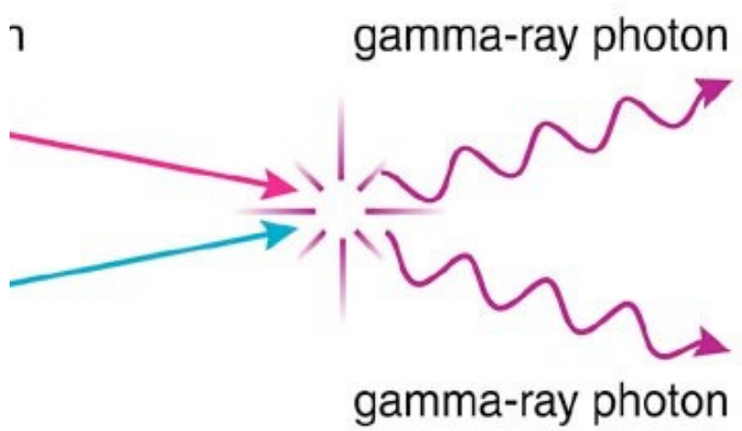






Energy (radiation) and mass were in equilibrium

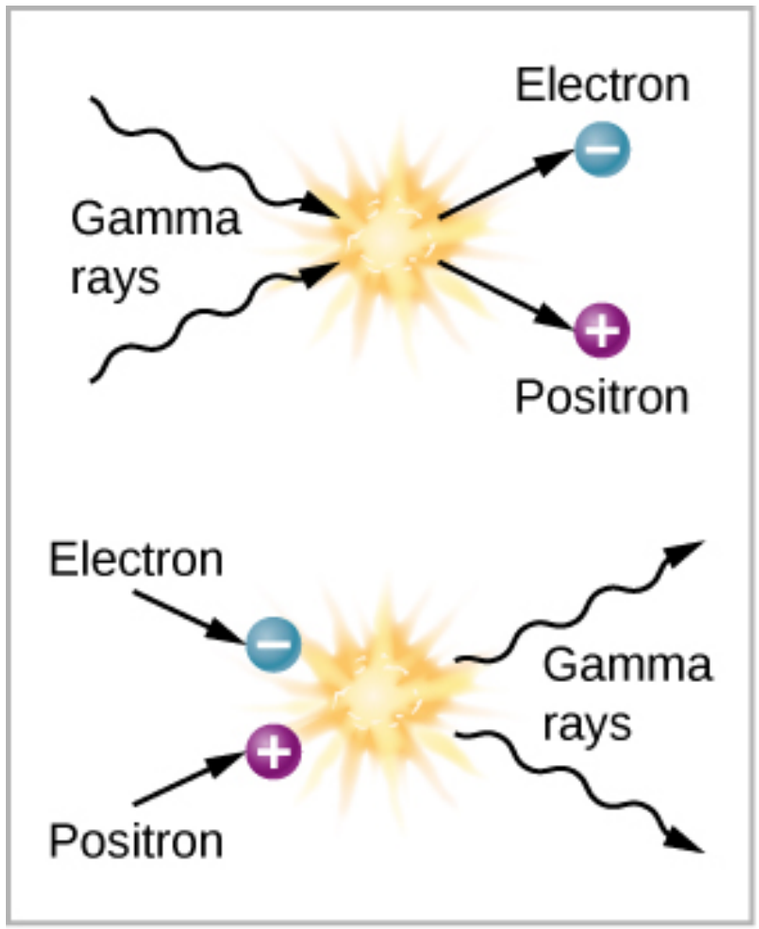
Testing the Big Bang Idea

- **Big Bang Nucleosynthesis**
  - production of light elements in the early Universe

- **Remnant radiation from primeval fireball**
  - universal background radiation

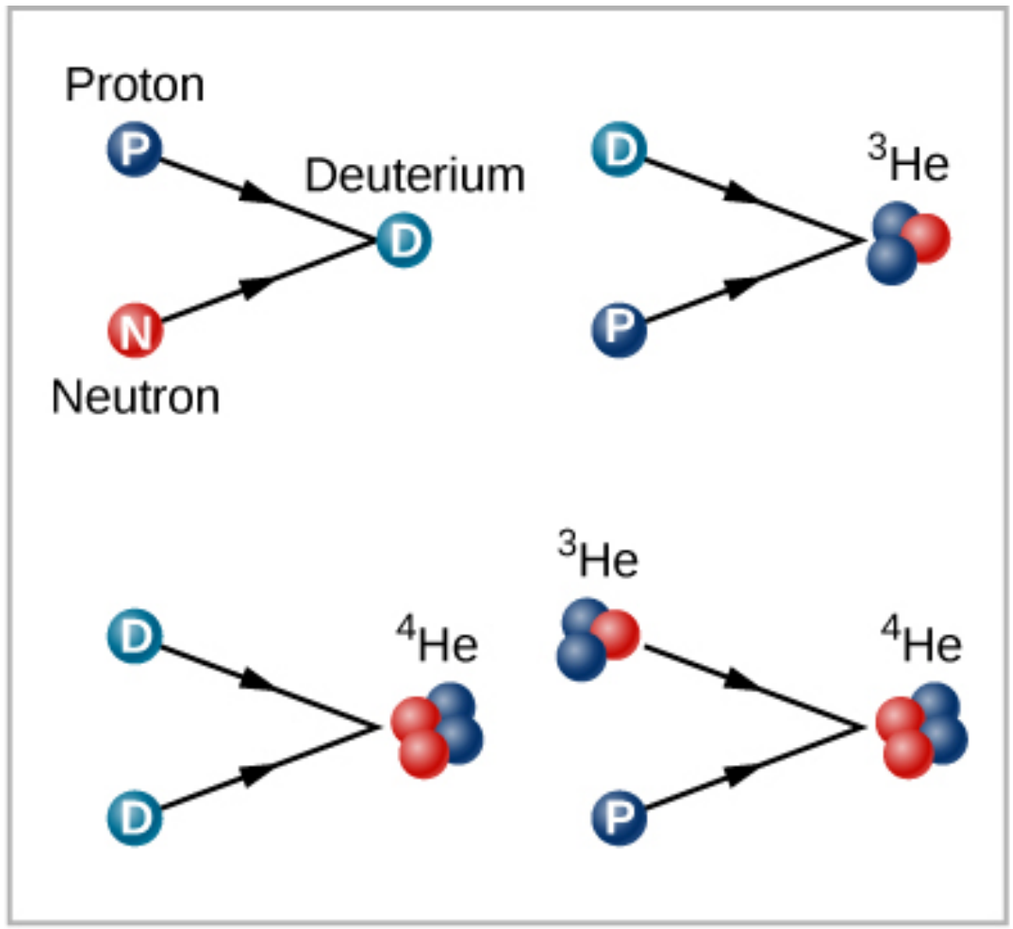
- **Origin of Cosmic Structures**
  - formation of galaxies and huge superclusters in an expanding Universe

Big Bang Nucleosynthesis



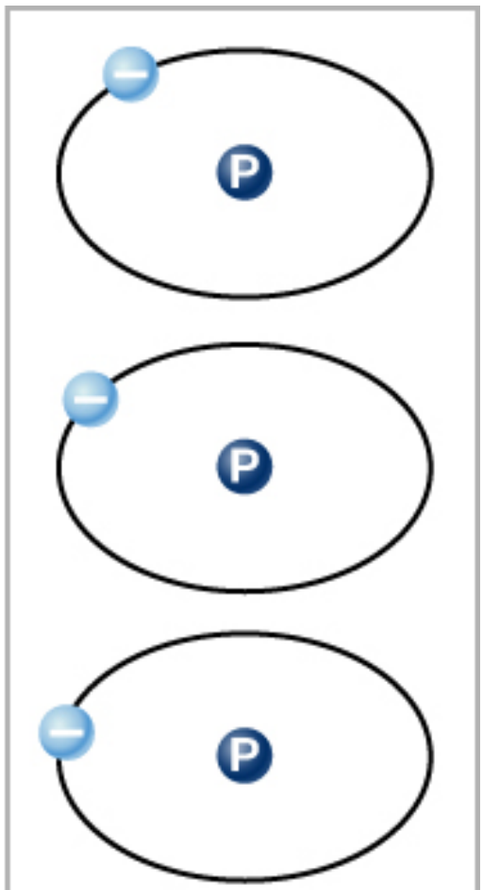
10^{-2} seconds

(a)



3 minutes

(b)

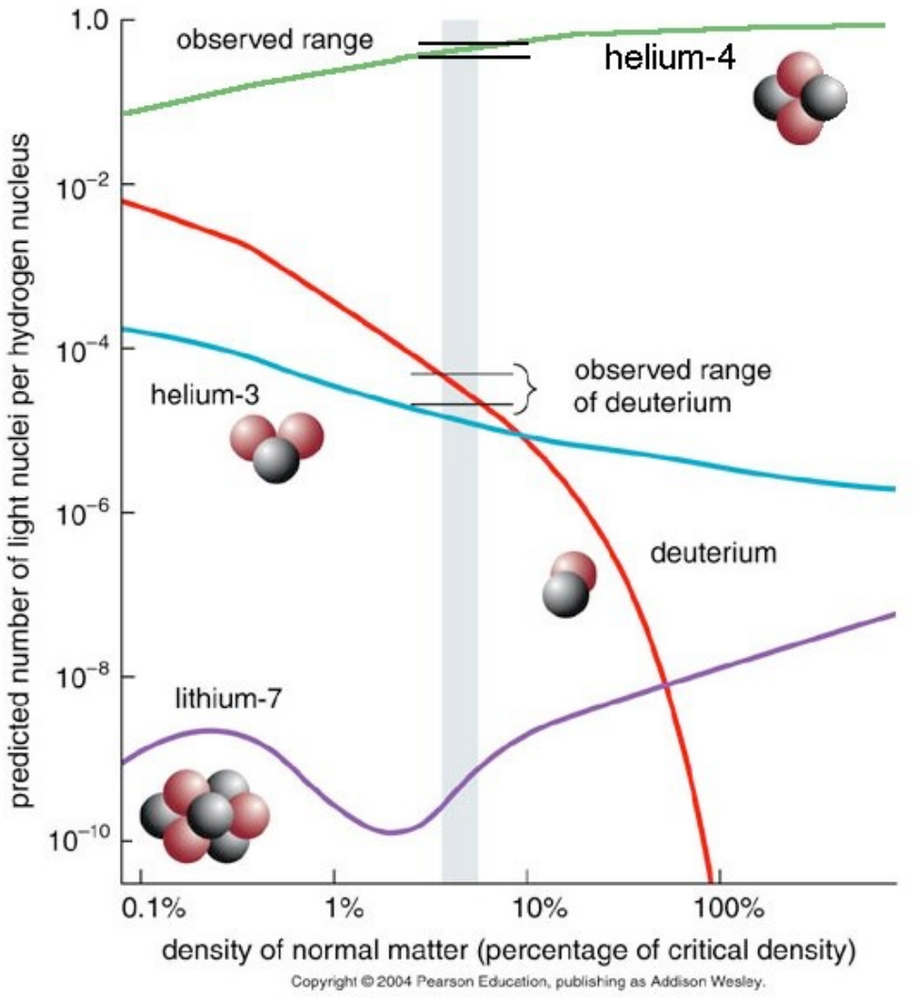


300,000 to 700,000 years

(c)

Big Bang Nucleosynthesis

- **Earliest minutes**
  - H, deuterium
  - He^3, He^4
- **Expansion and cooling**
  - halts further fusion
- **net Big Bang production**
  - ~ 75% Hydrogen
  - ~ 25% Helium
  - < 0.1% lithium, beryllium, etc.
- **Matches composition of the oldest stars!**



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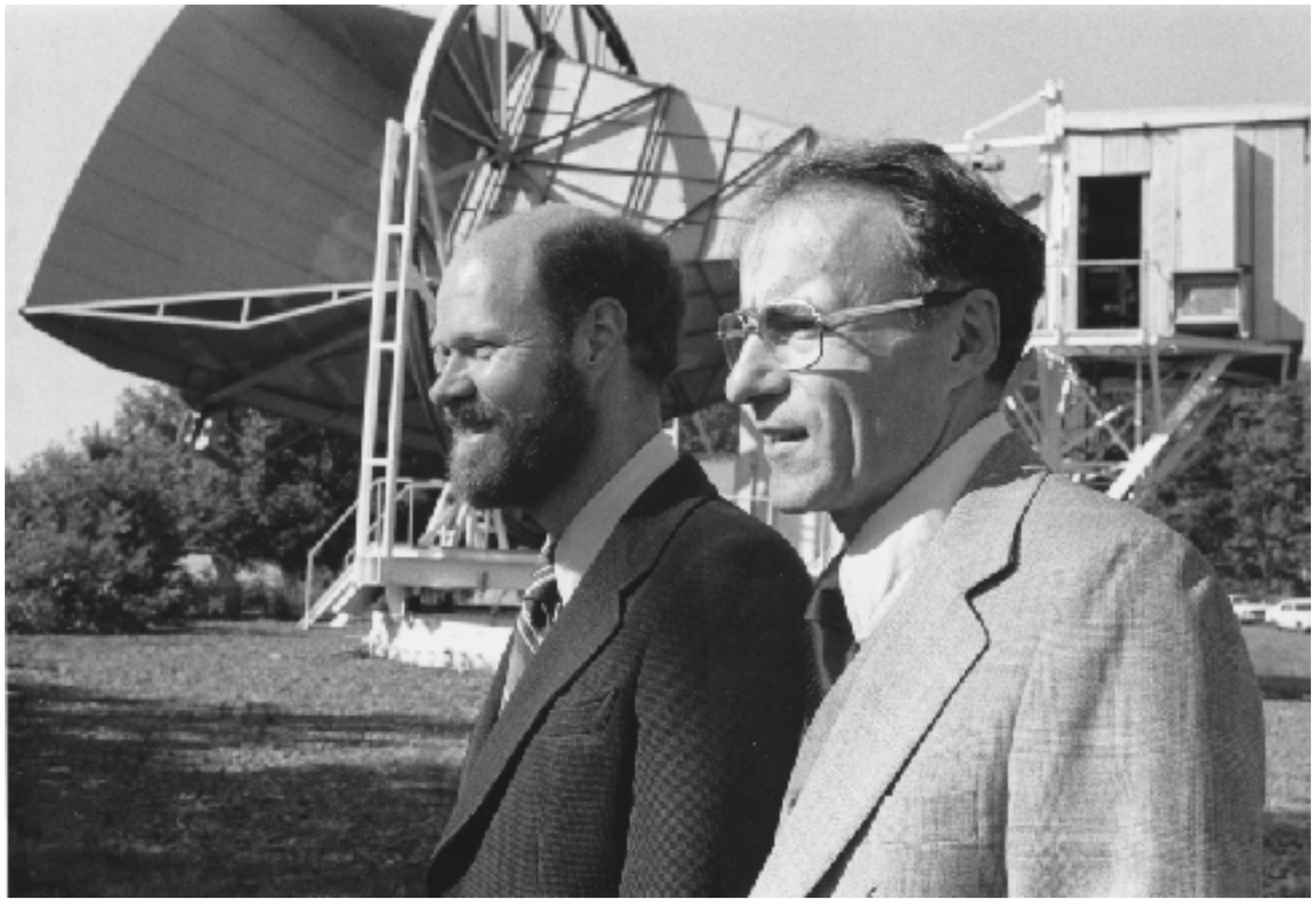
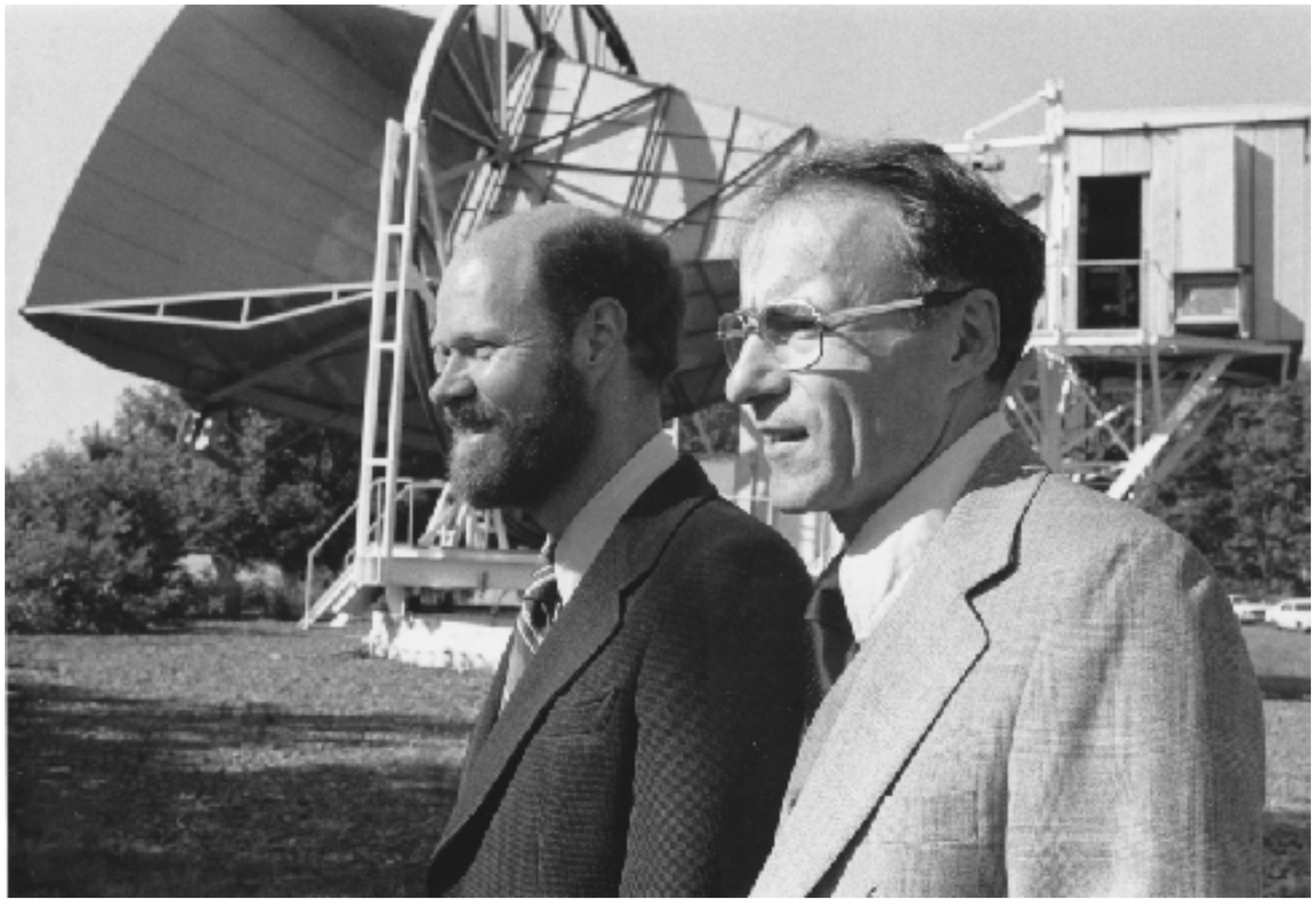
Discovery of the Big Bang



- Found strange radio radiation
- Pointed telescope in many directions and found same thing (cosmological principle)
- Thought it was pigeon poo
- Radiation was consistent with a blackbody at T ~ 3 K

Discovery of the Big Bang



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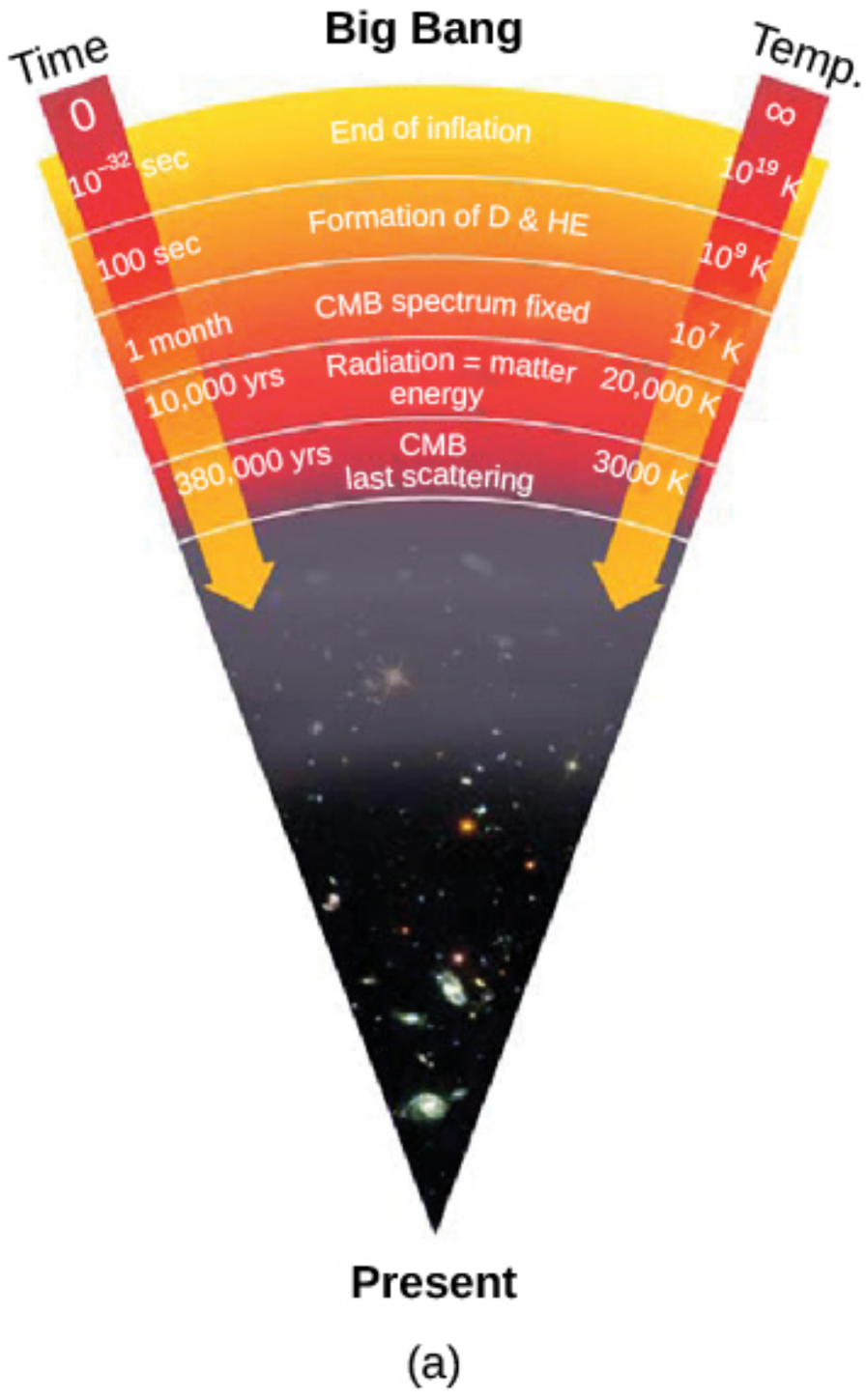
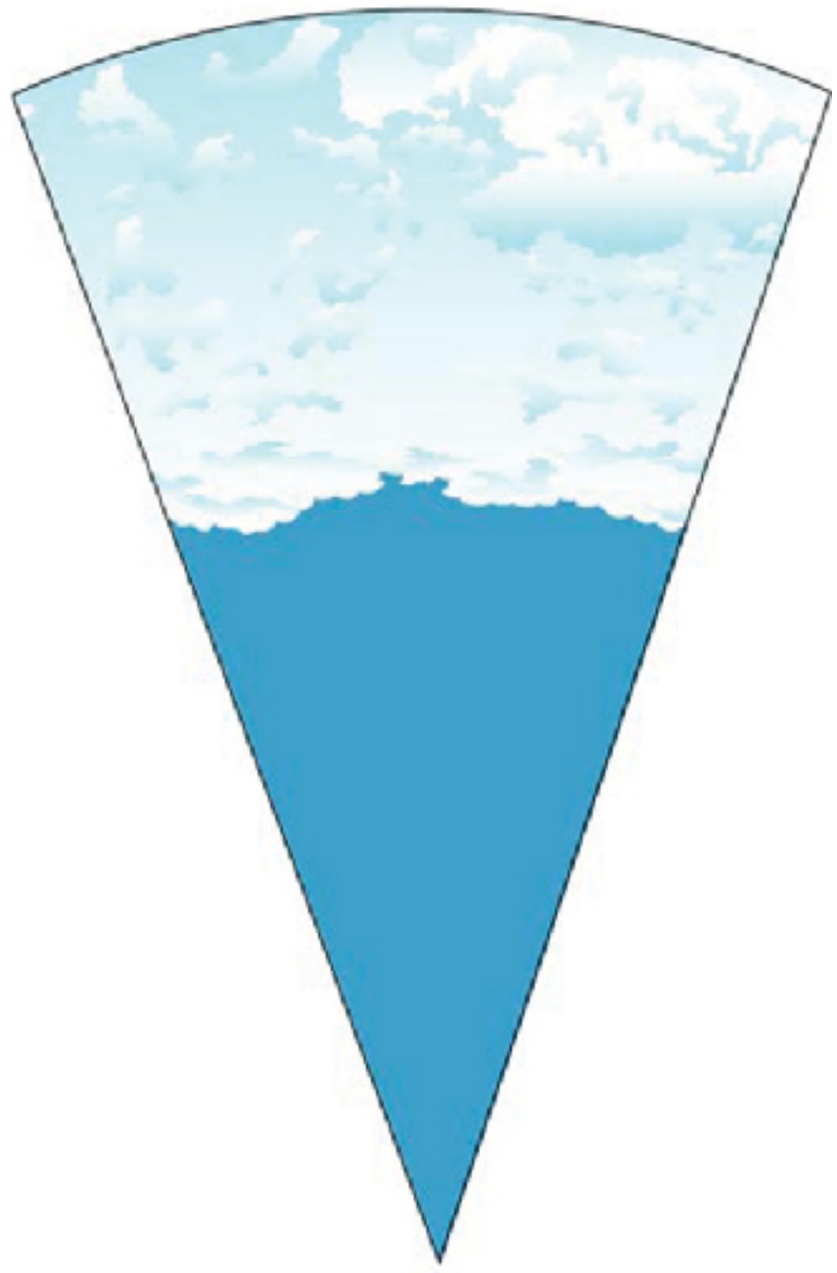
Won Nobel Prize in 1987!

The Universe was opaque until about 380,000 years



(a)



(b)

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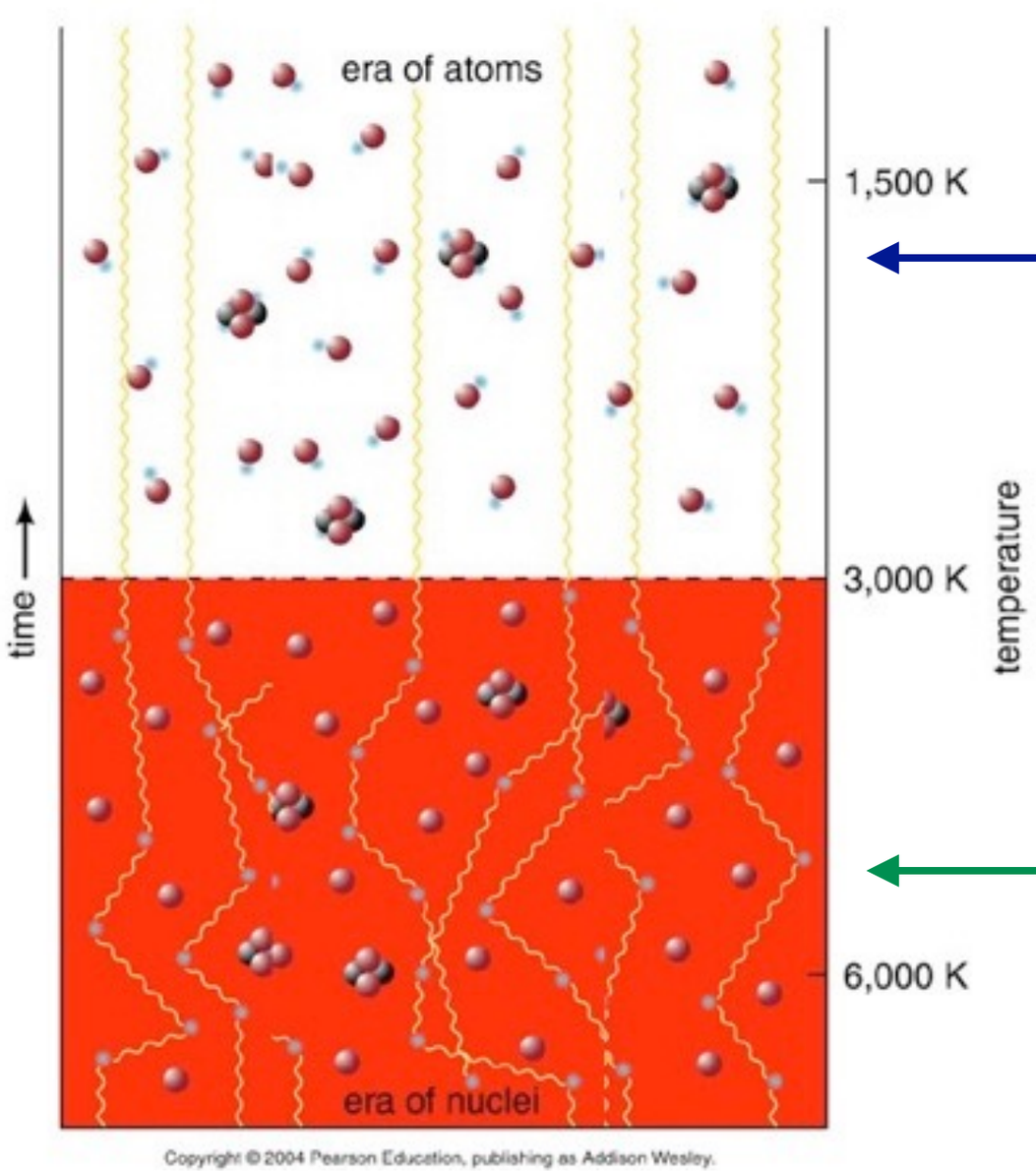
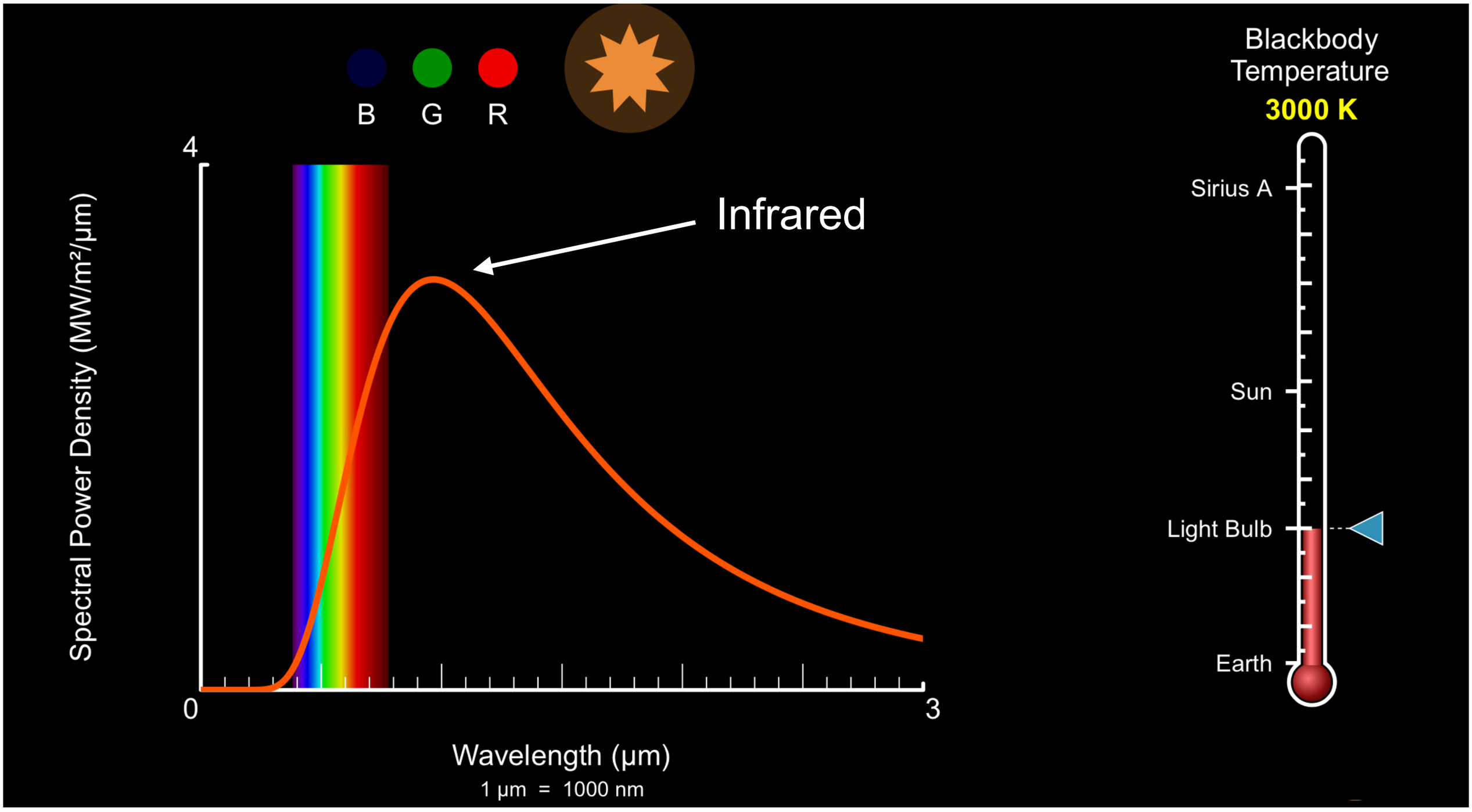


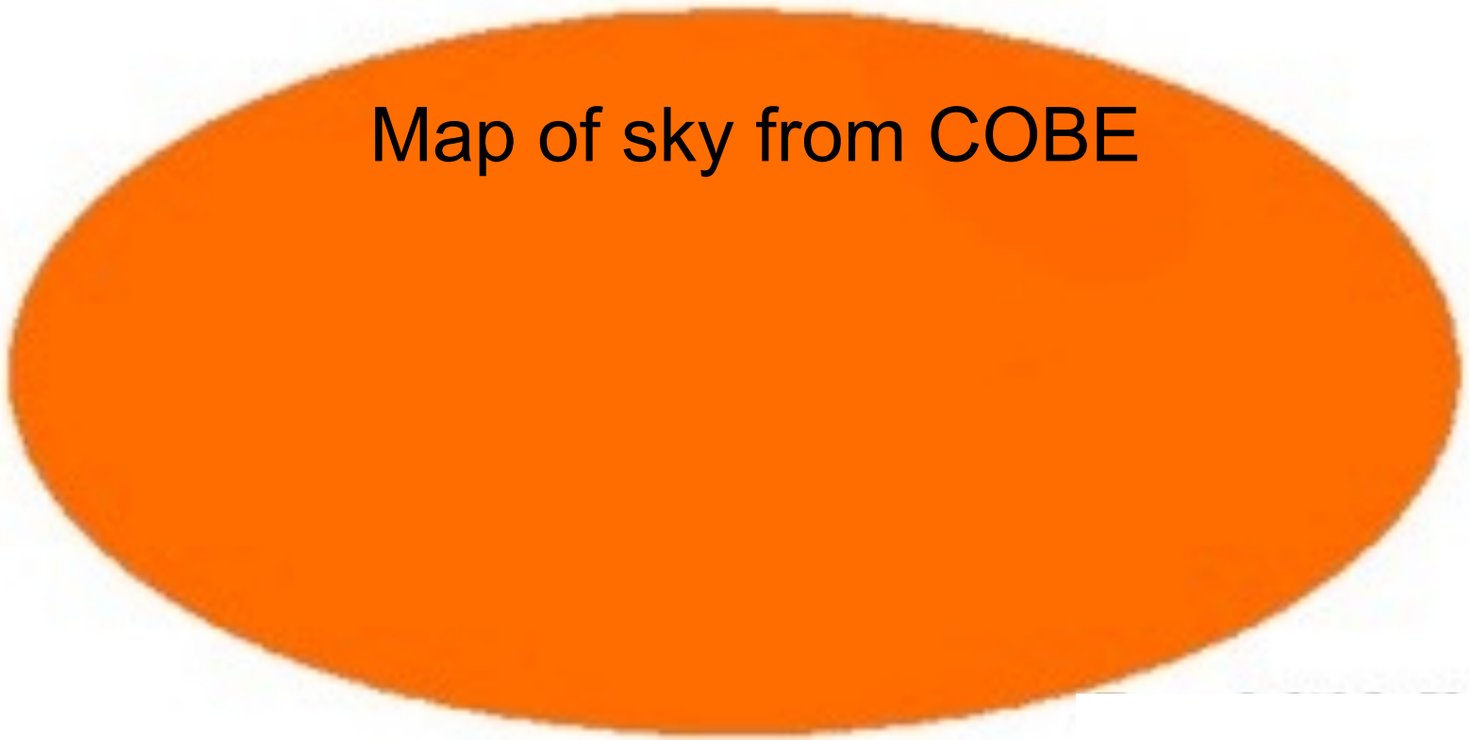
- Universe cooled down
- Hydrogen recombined
- Universe was transparent
- Exterior to star — light moves freely

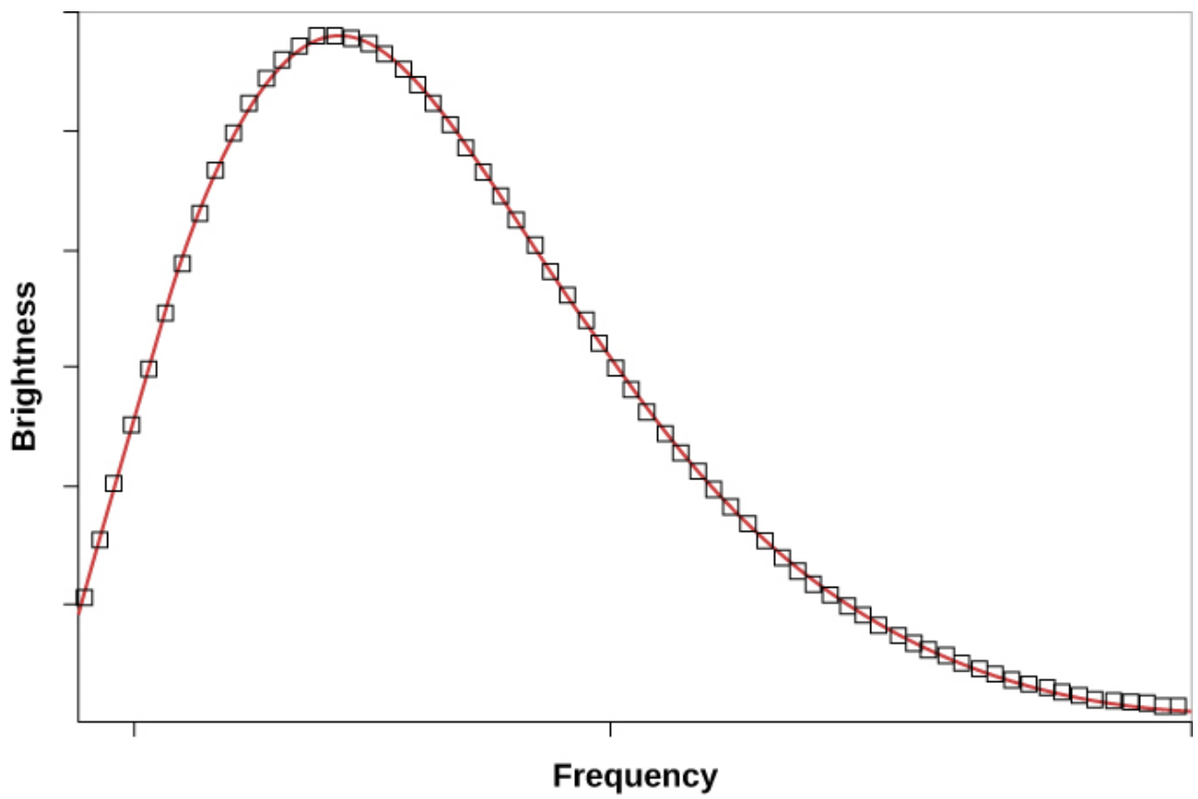
- Universe was hot
- Hydrogen was ionized
- Universe was opaque
- Kind of like the interior of a star

At 380,000 years, Universe was a blackbody of T = 3000K



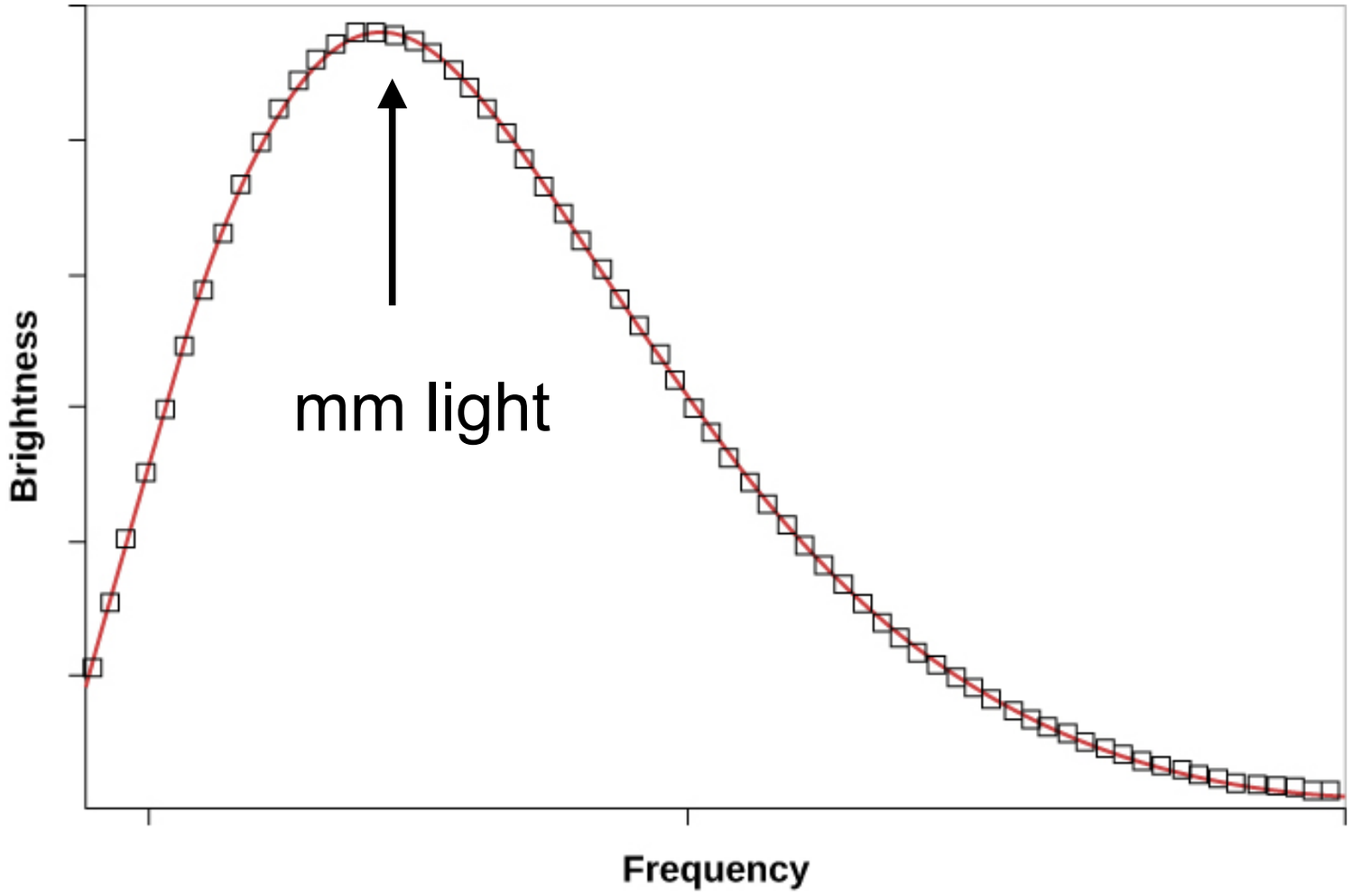
Cosmic Background Explorer (COBE)





- **Launched in 1990 to observe CMB from space**
- **Found that the CMB Is a blackbody to 1 part in 100,000)**
- **T = 2.728 K**

CMB observed by COBE is at a much lower temperature

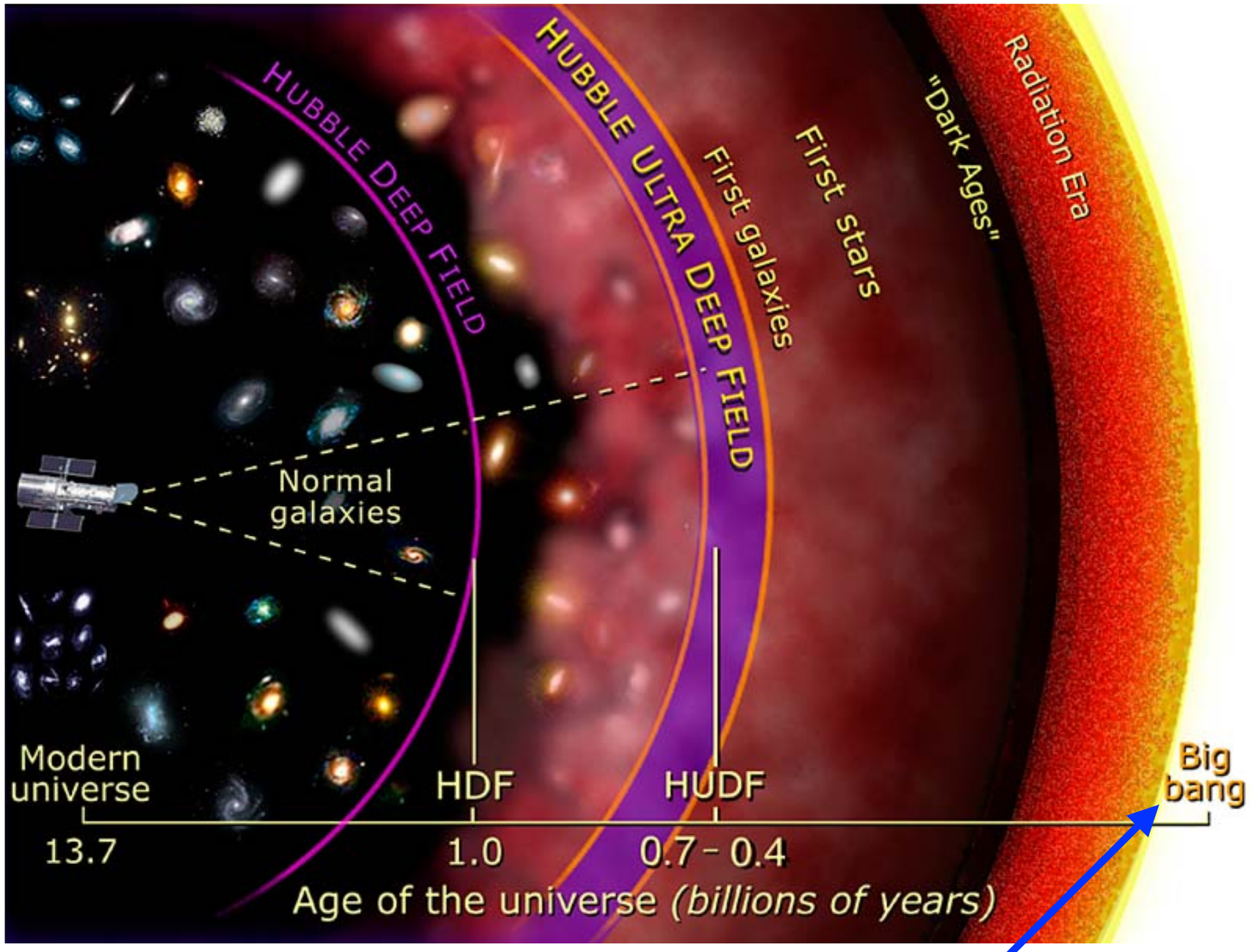


A quiz question!

- ***If the Universe was 3000 K (and emitted at infrared wavelengths) at 380,000 years of age, why is it now observed to be 2.73 K (microwave)?***

Can again address the "edge" of the Universe

- **The Edge (or Horizon)**
  - back in space = back in time
  - beyond ~14 billion light years → no stars, but CMB
  - is this a physical edge? No
  - viewed from anywhere, R_{univ} = 14 billion ly



Opaque

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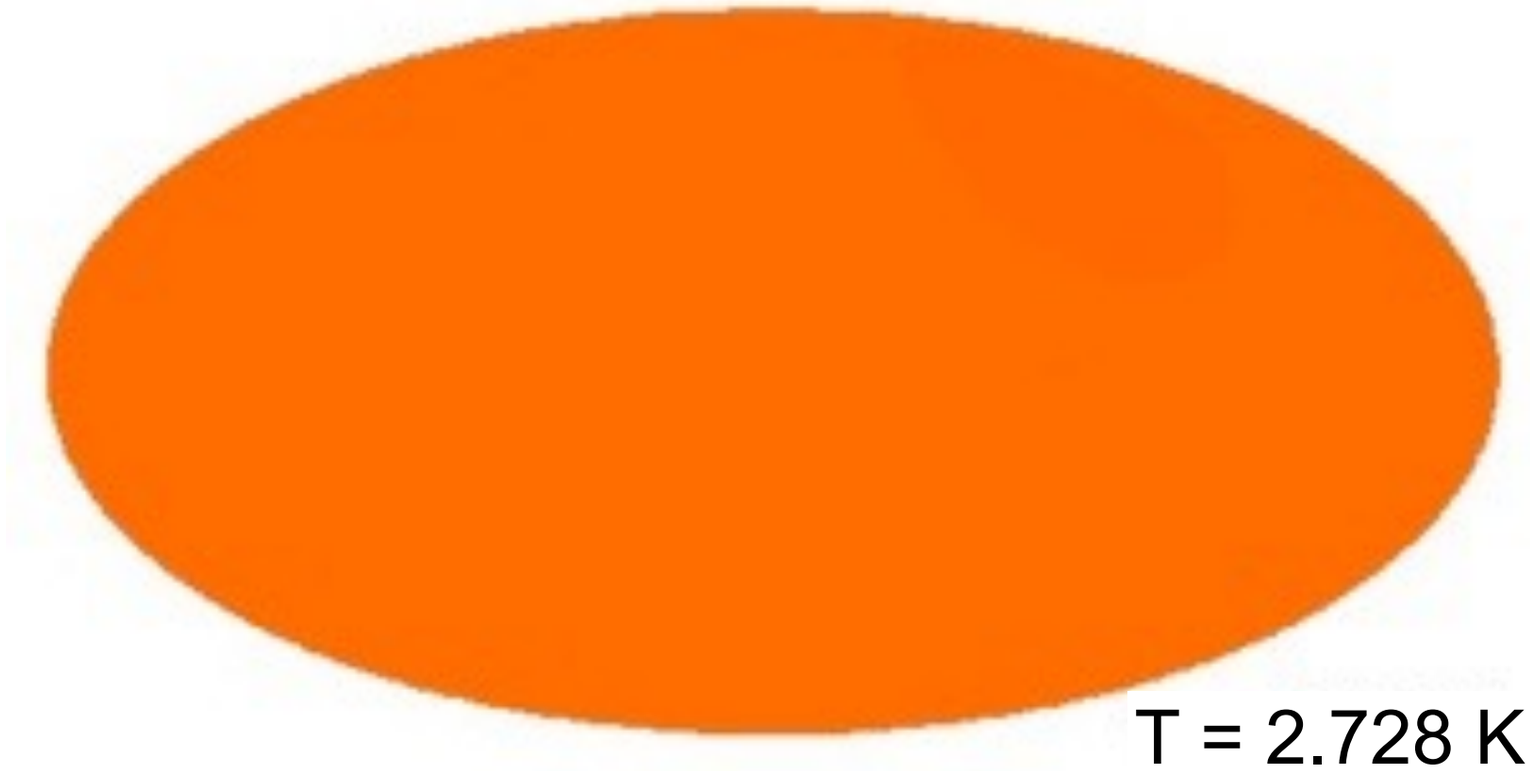
The CMB is remarkably uniform!

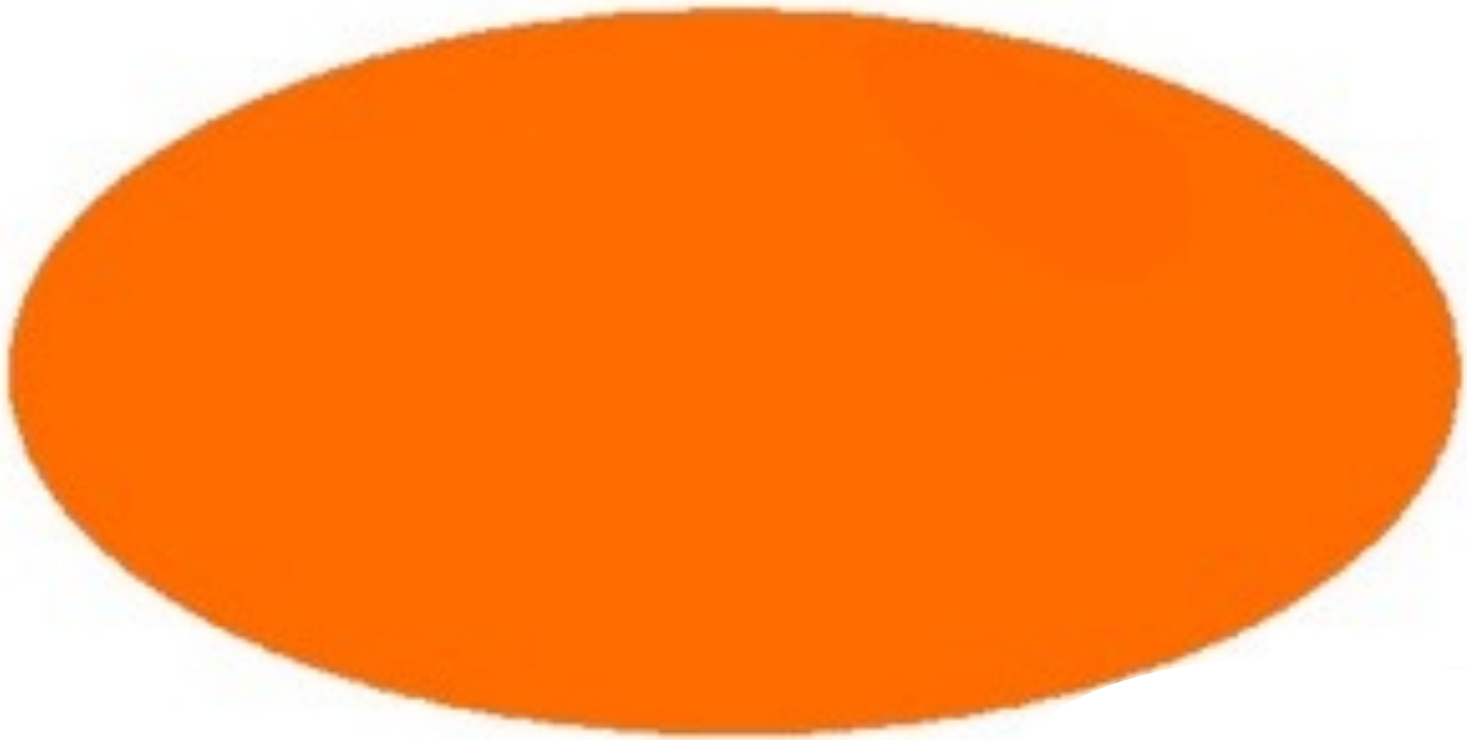
Map of sky from COBE



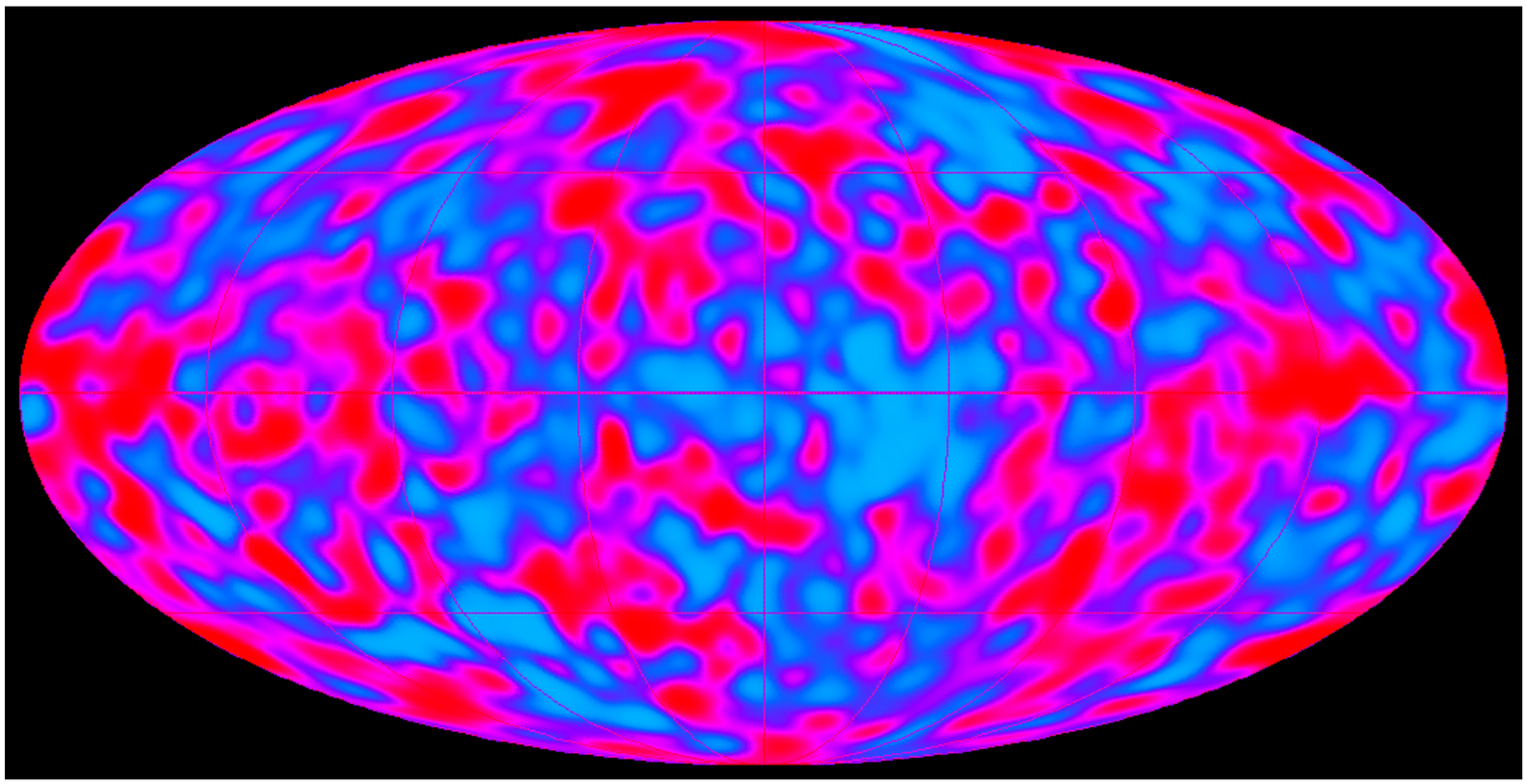
T = 2.728 K

Confirms the cosmological principle that the Universe is homogenous and isotropic

But, if we look closer at the COBE data…

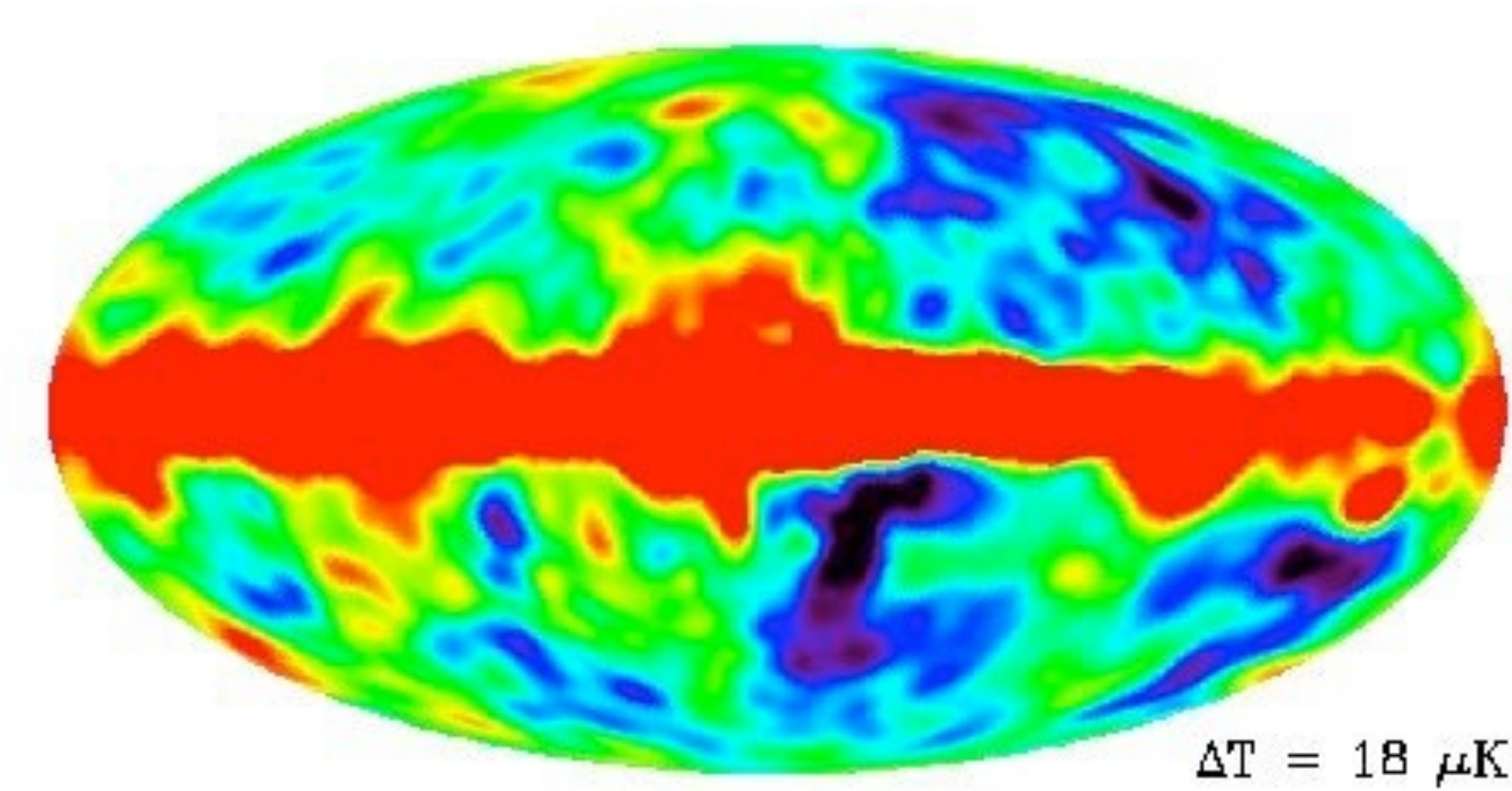


- Differences at the 0.3 mK level
- Not quite a blackbody! (but still very close)



From COBE to WMAP

(1992) (2010)



WMAP - Wilkinson Microwave Anisotropy Probe

From COBE to WMAP

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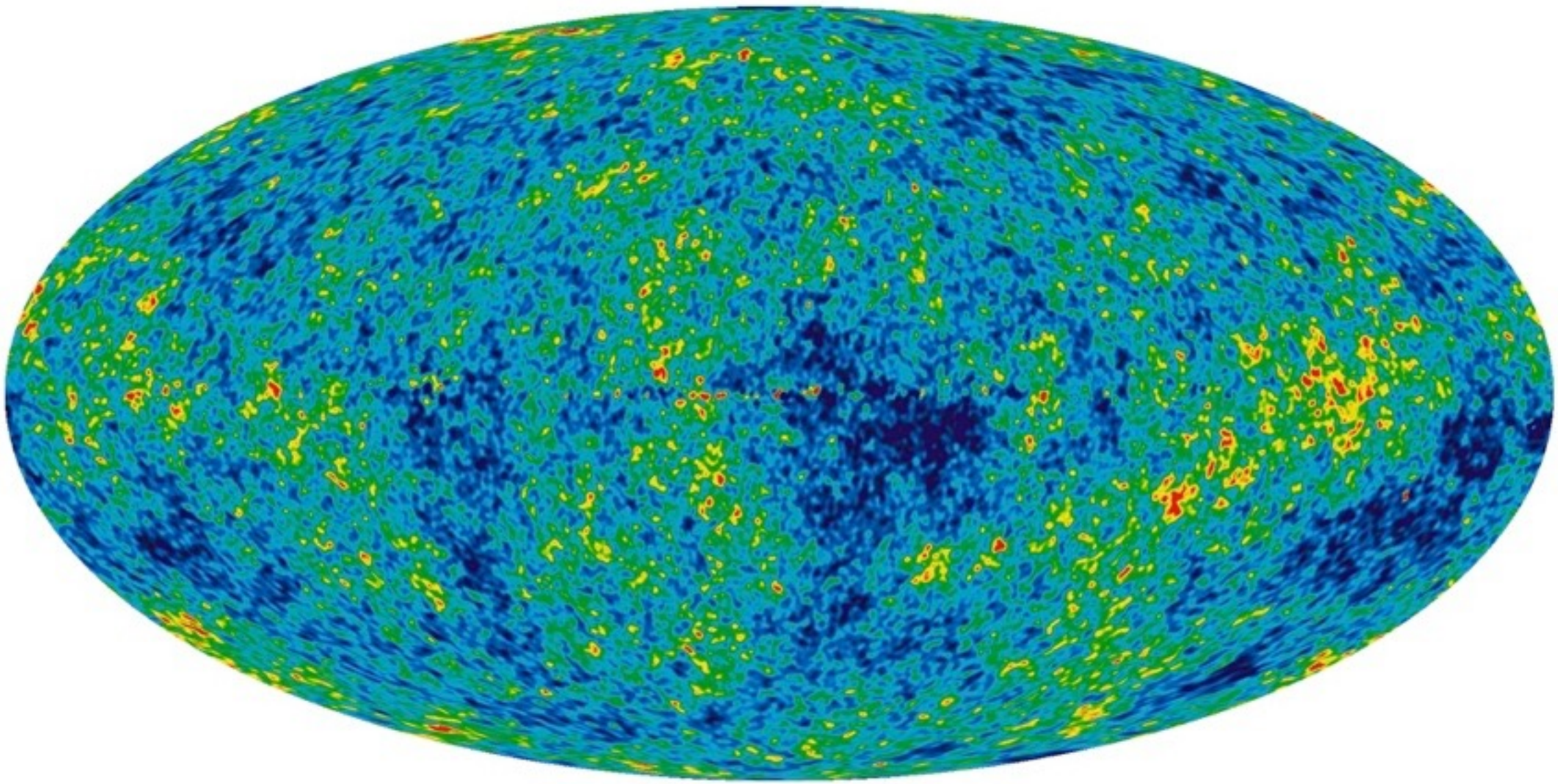
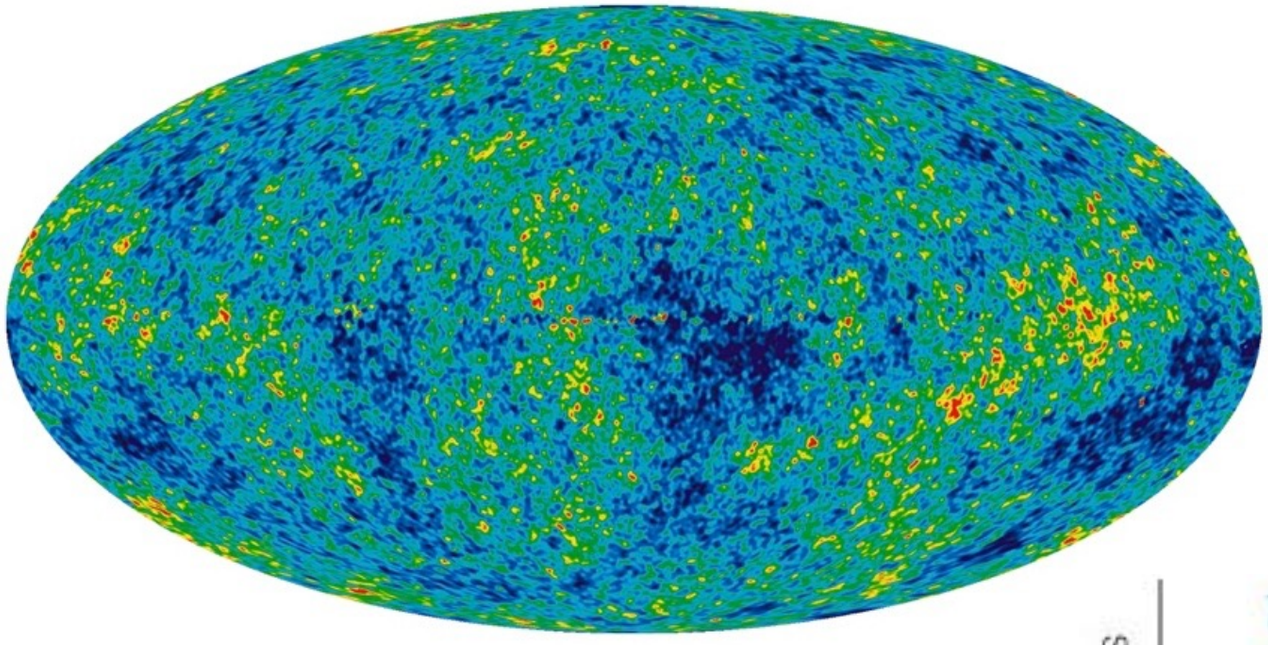
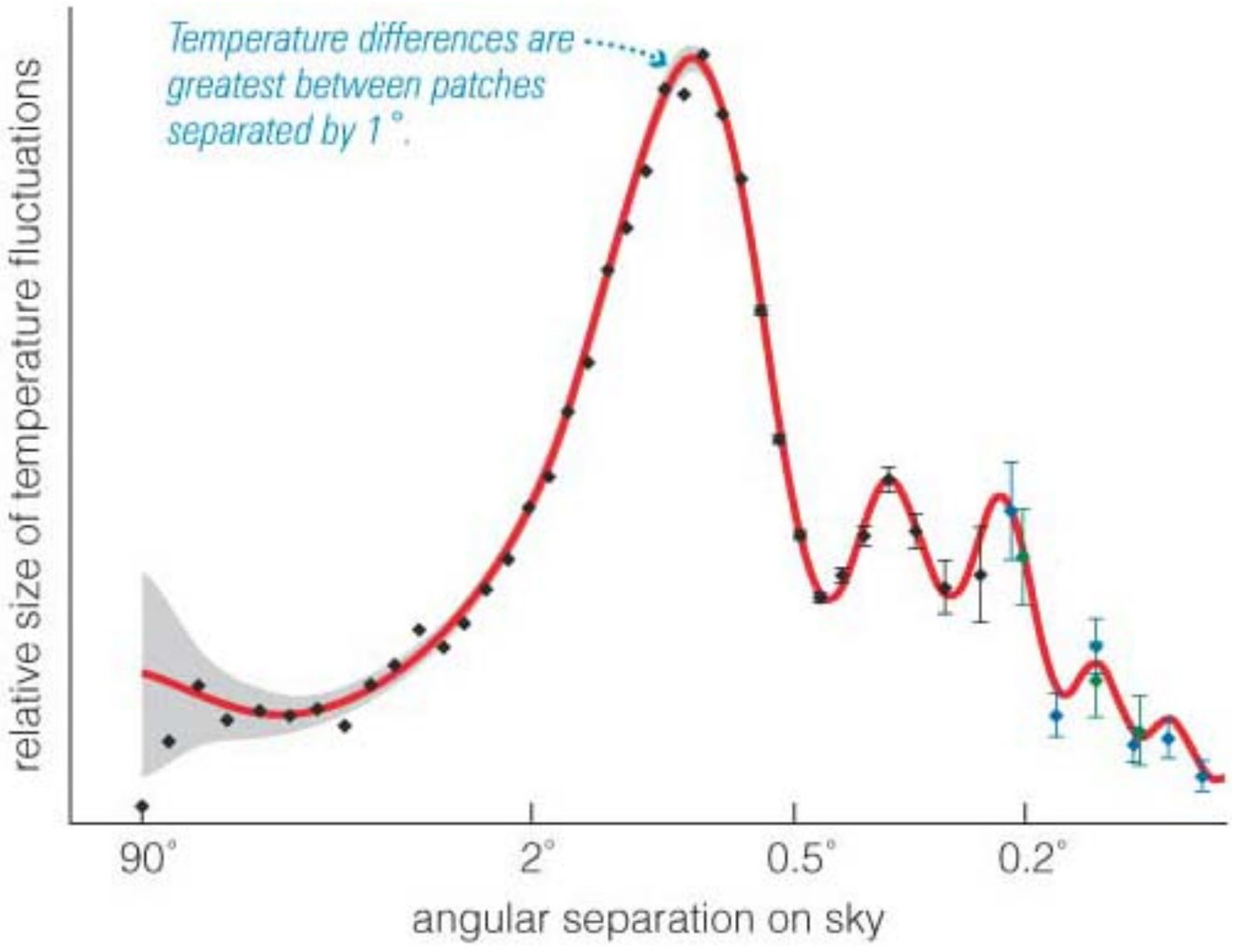


WMAP - Wilkinson Microwave Anisotropy Probe

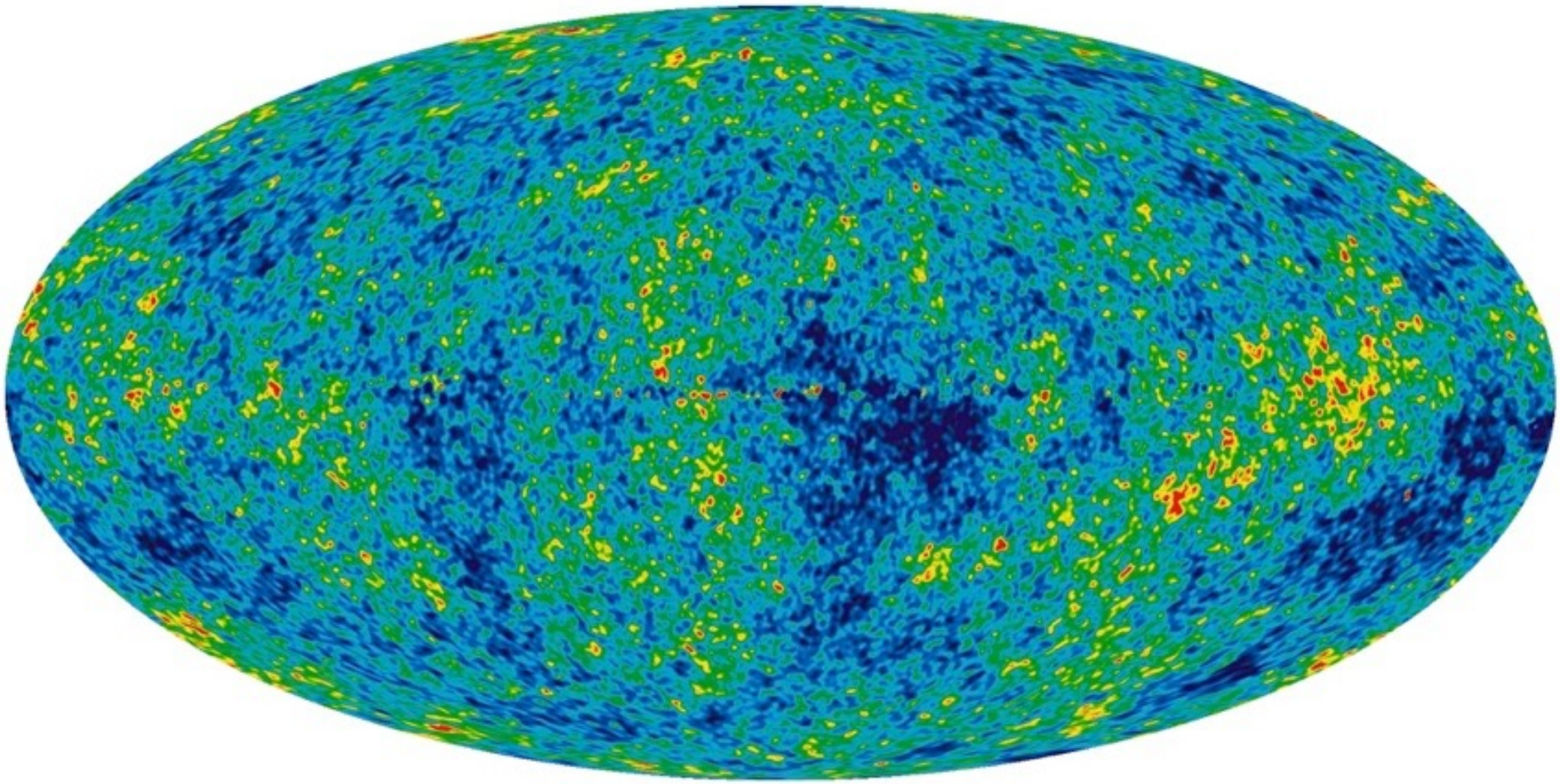
The “scale” of ‘bumps’ is not uniform...





From WMAP to Planck

(2010) (2013)



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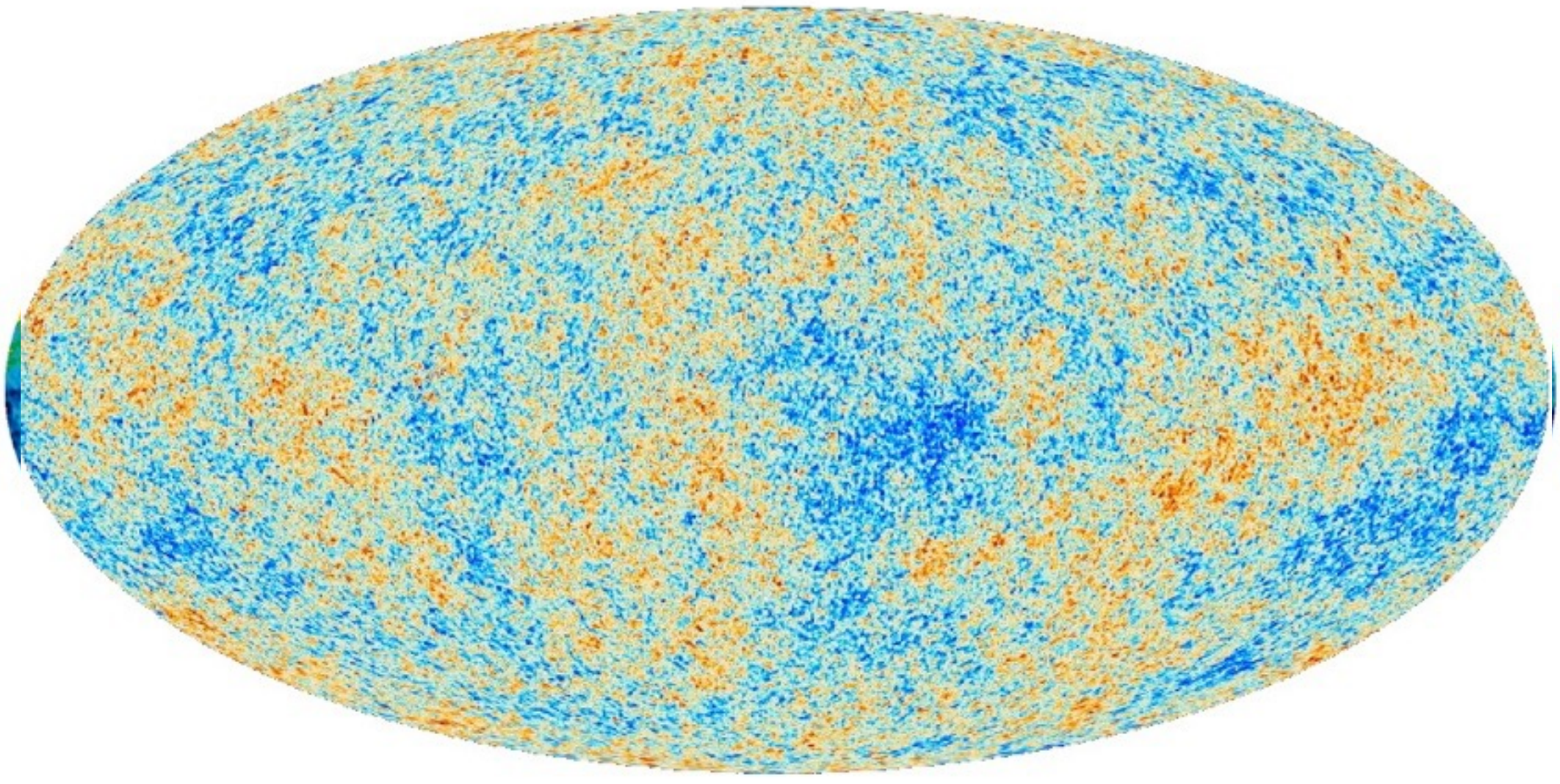
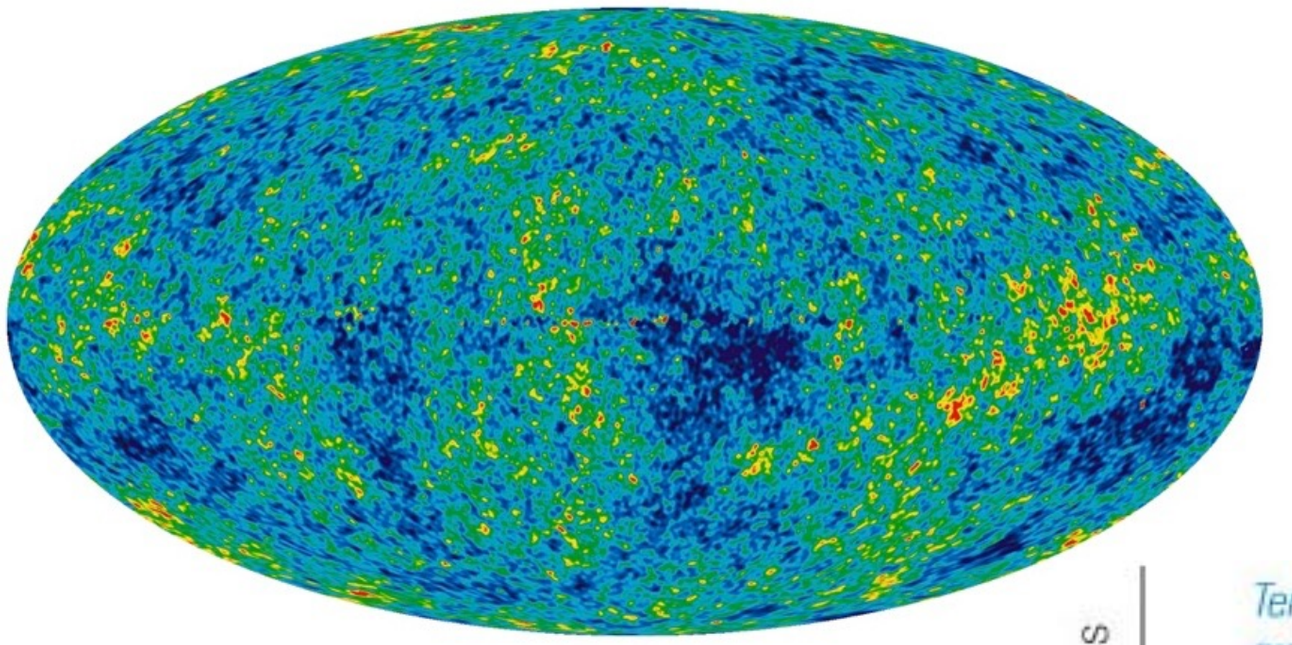
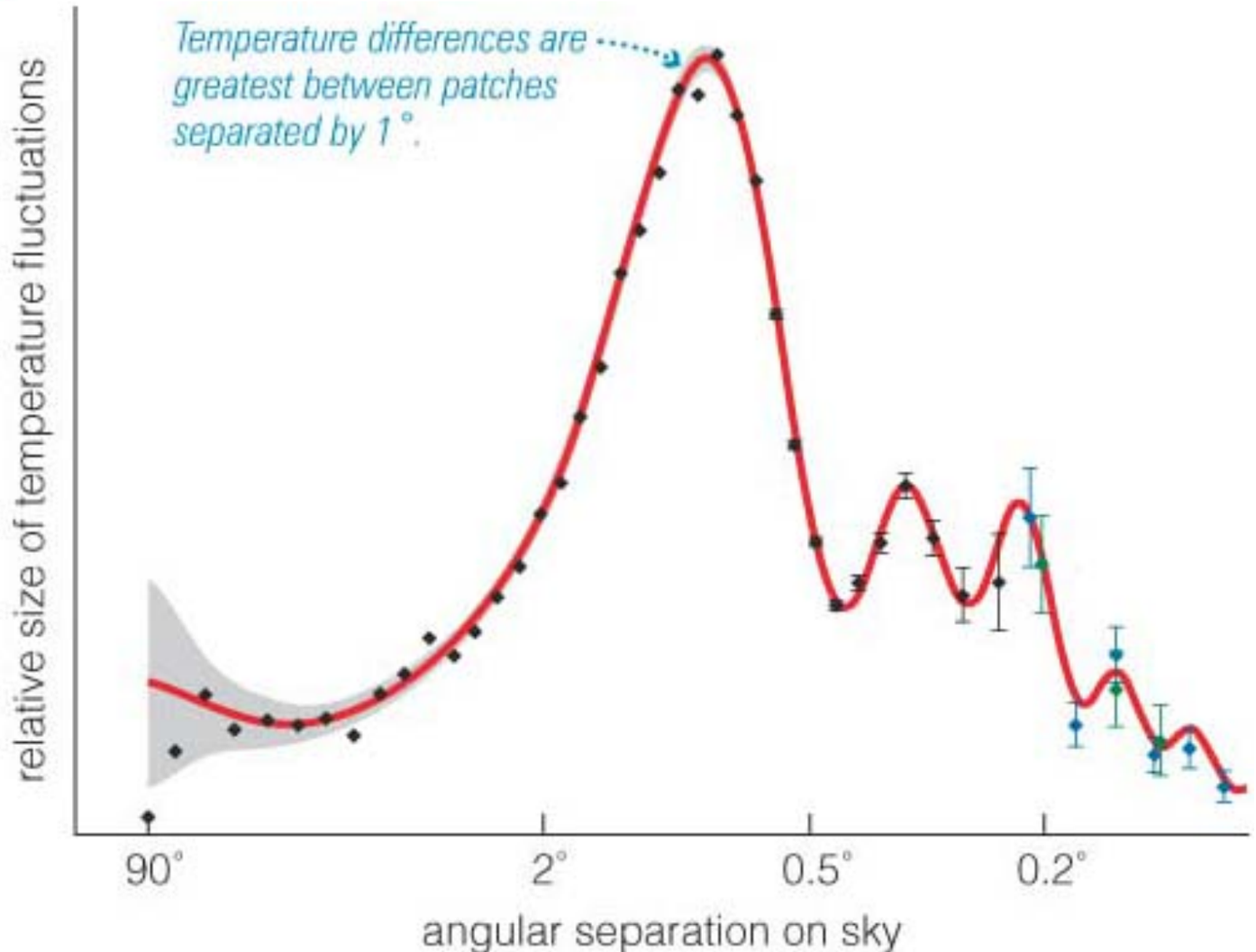


Further refinement!





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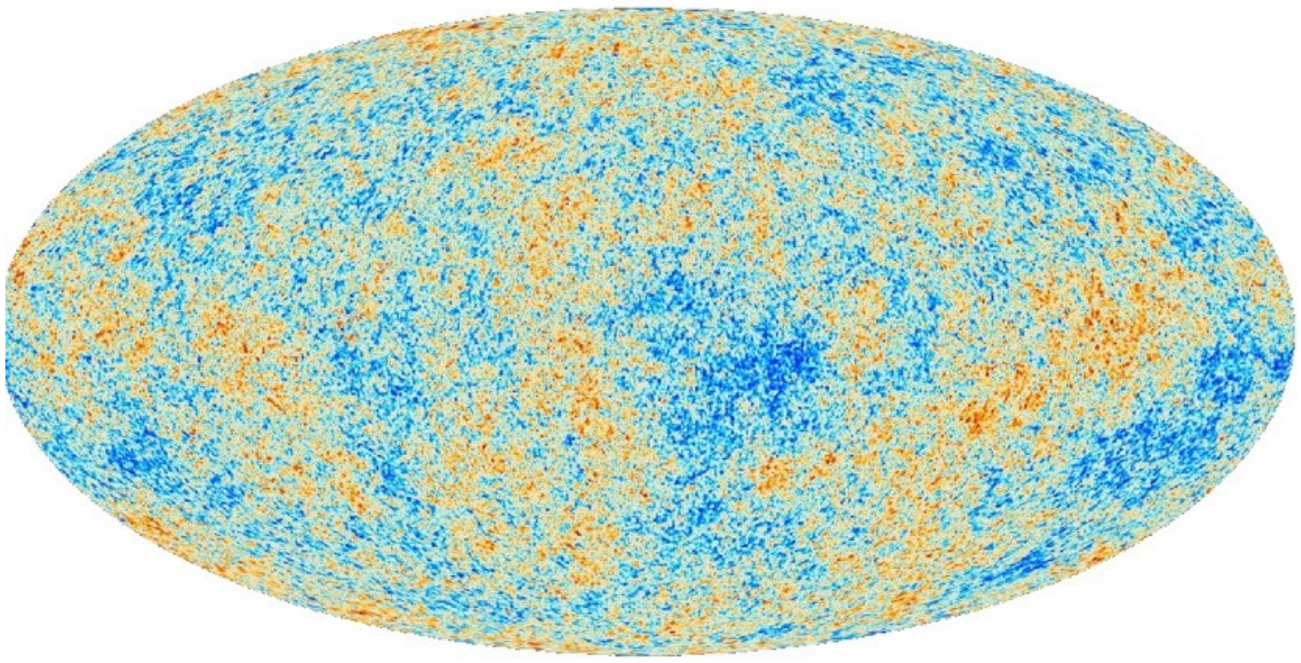

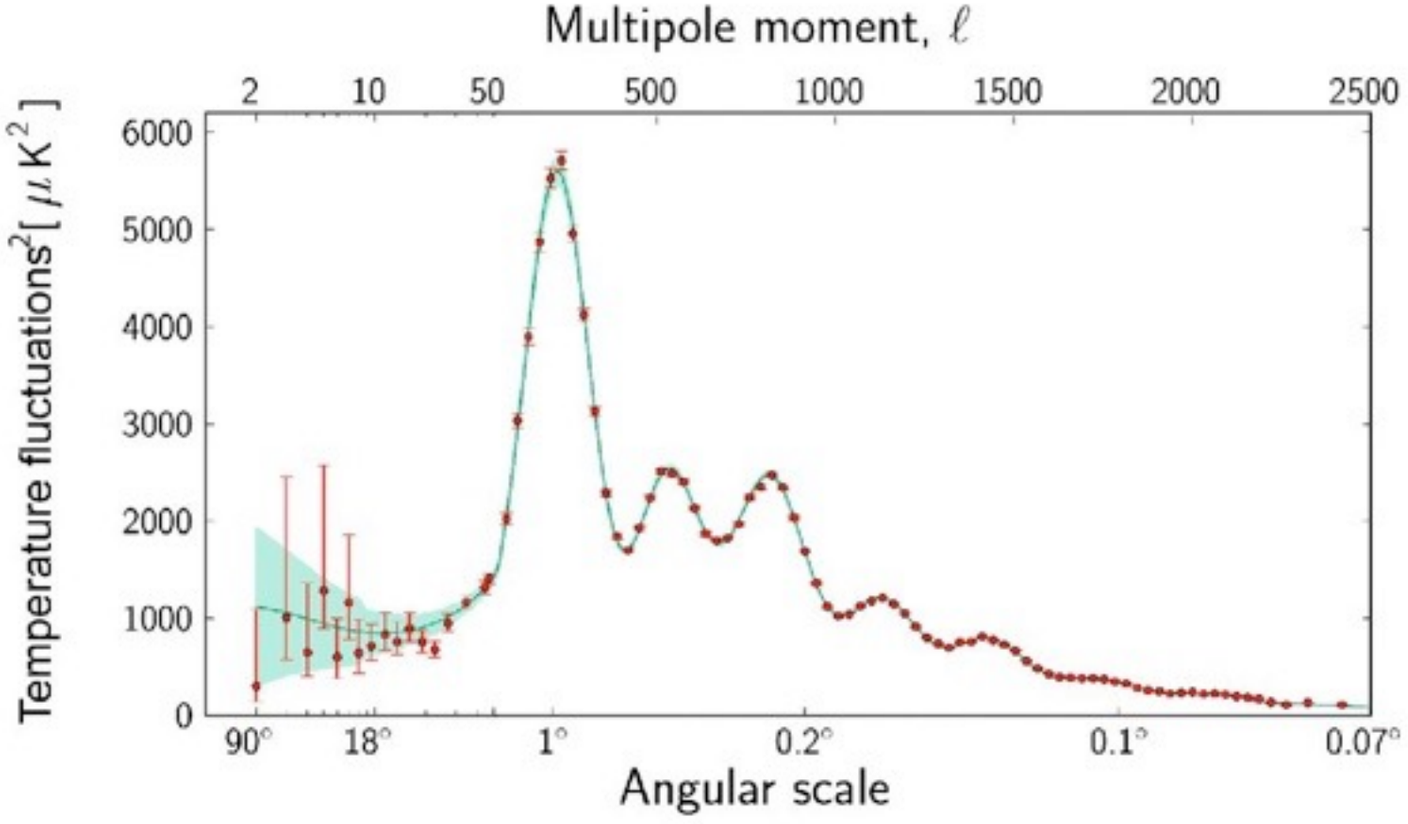

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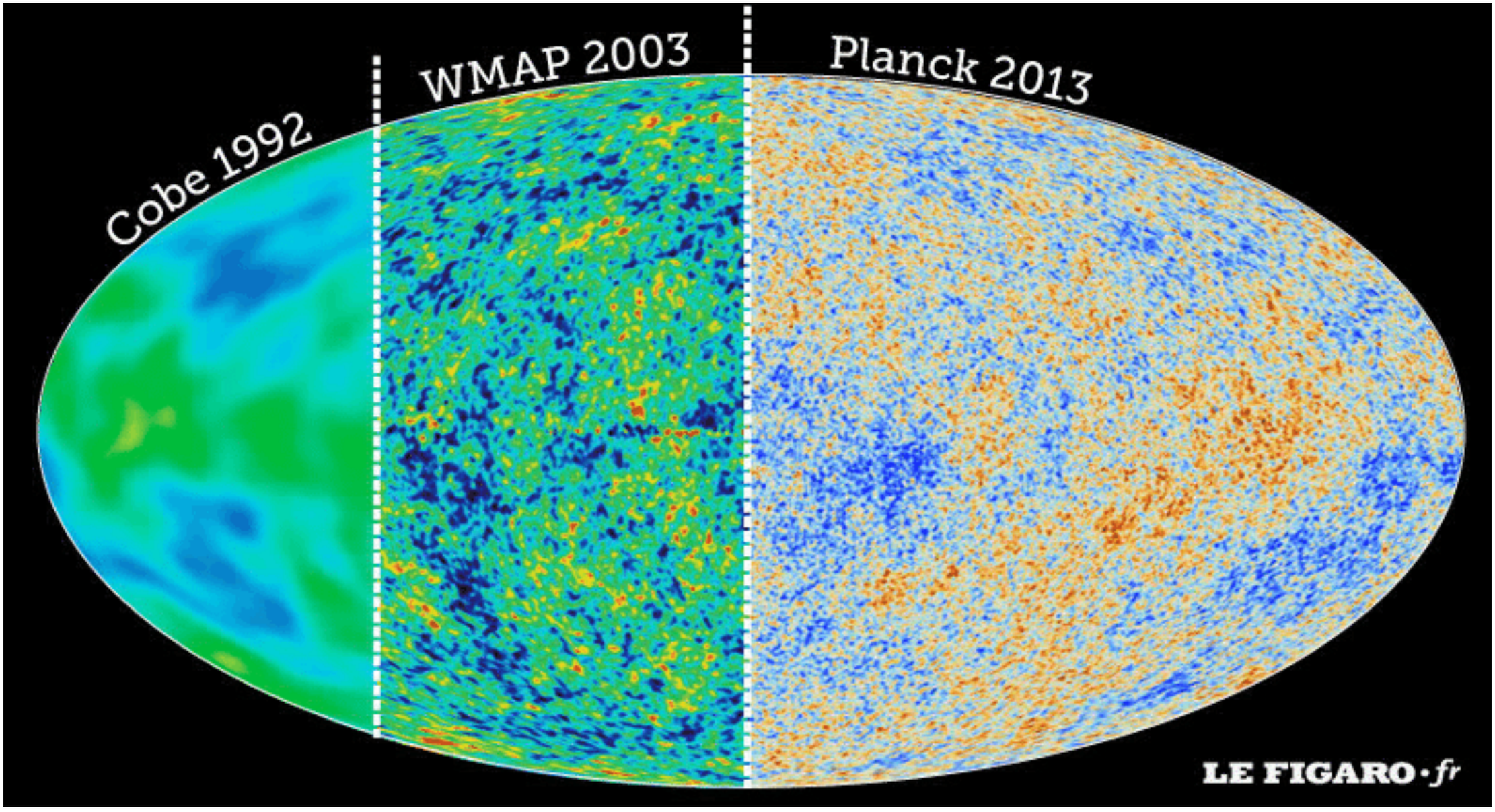
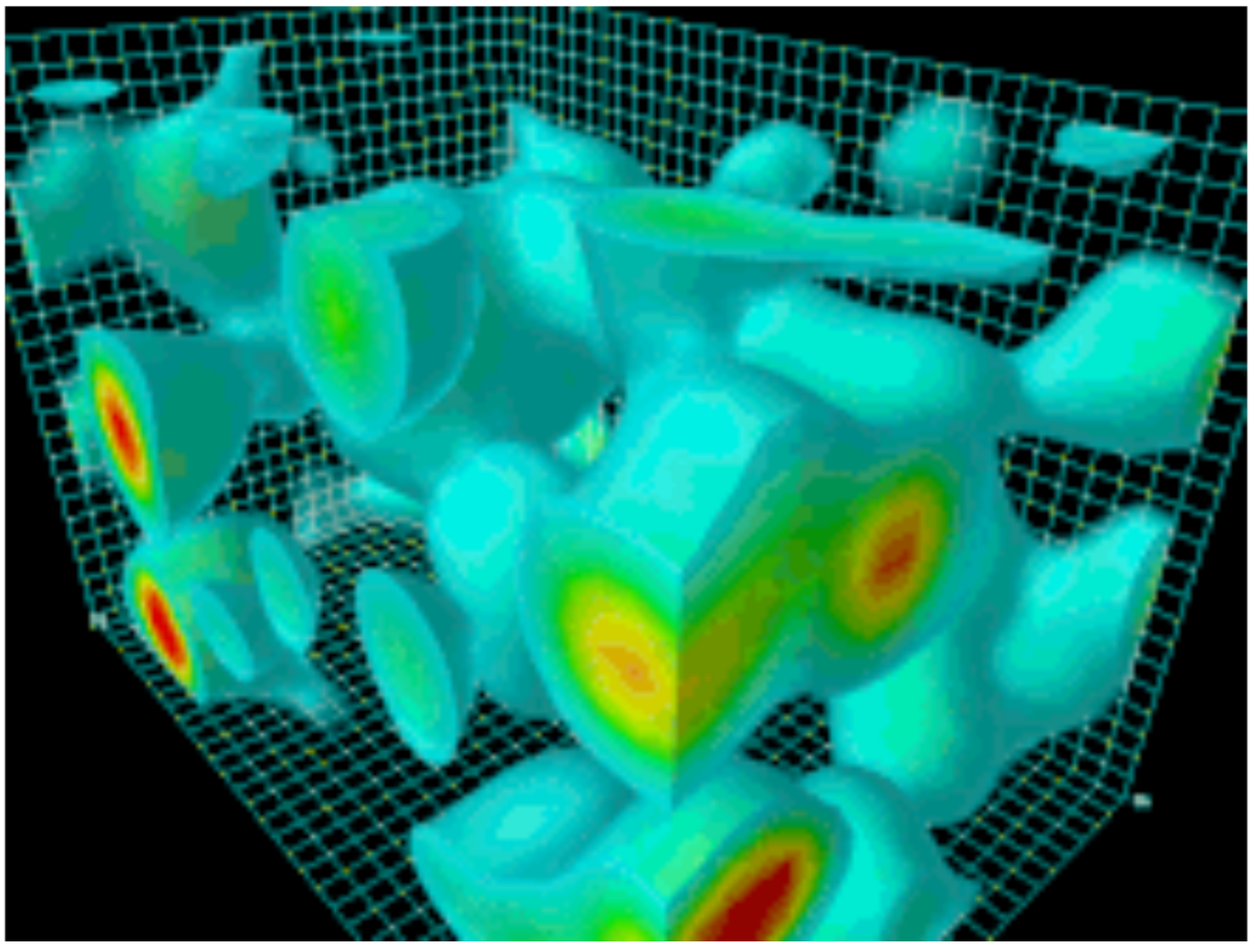


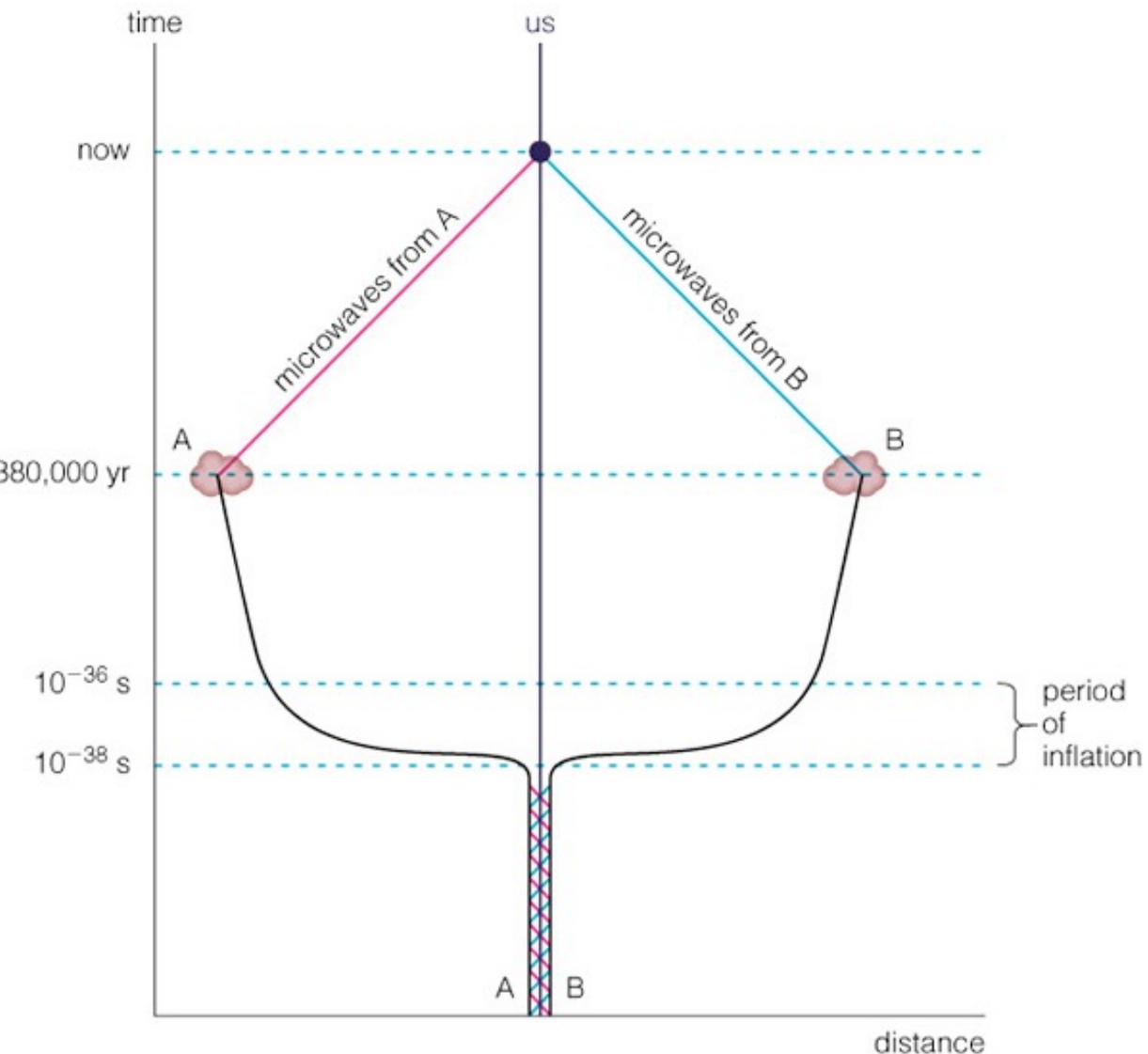
What are these fluctuations?

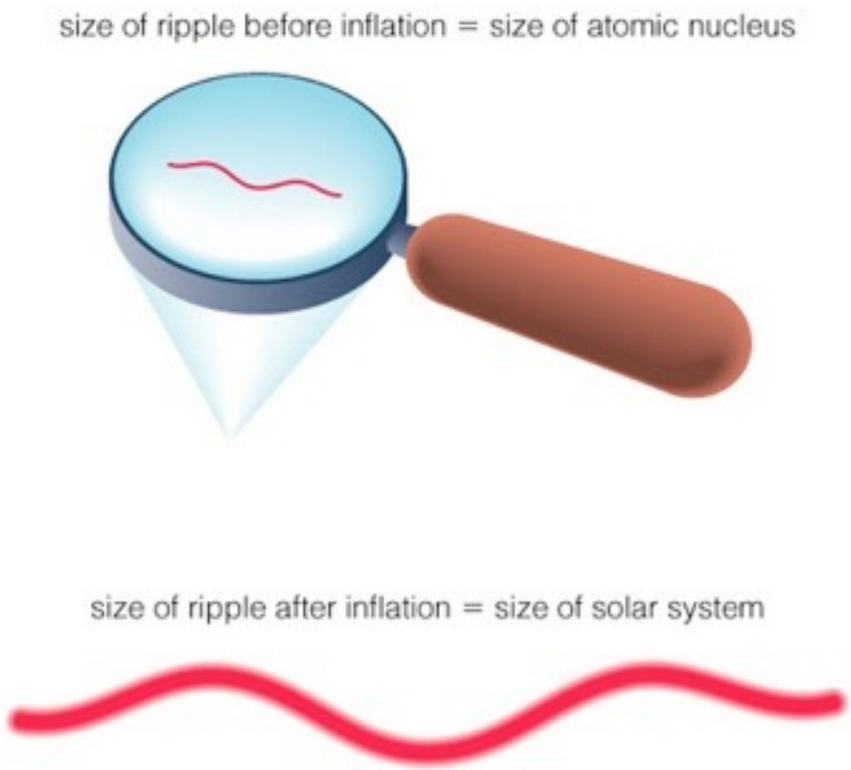


- On VERY small scales, quantum mechanics dominates
- Quantum mechanics states that energy can fluctuate randomly on these small scales
- In the CMB, these fluctuations are manifested as temperature and density variations

Small scale fluctuations get amplified by *Inflation*

- t ~ 10^{-37}sec
  - gravity repulsive
  - brief accelerated expansion
- before inflation: all points in space could communciate
- after inflation: too distant for further contact





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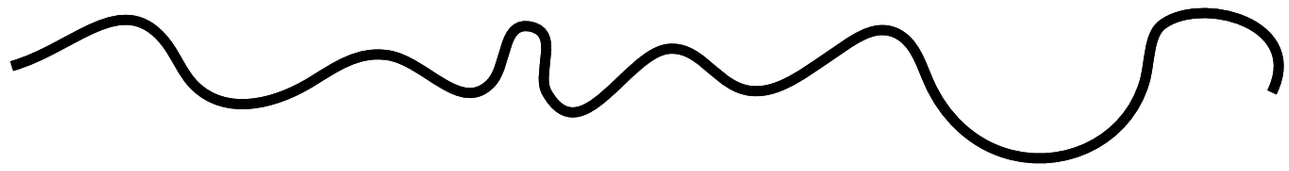
Photons



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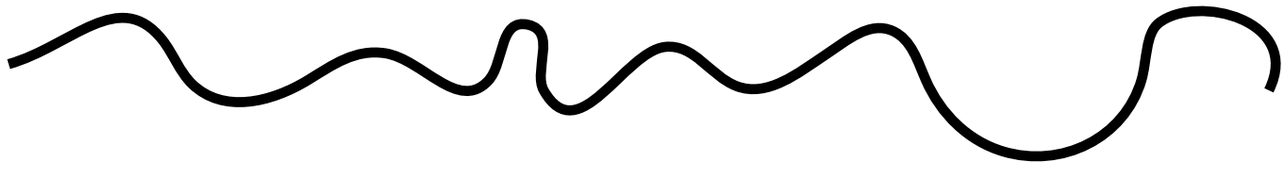
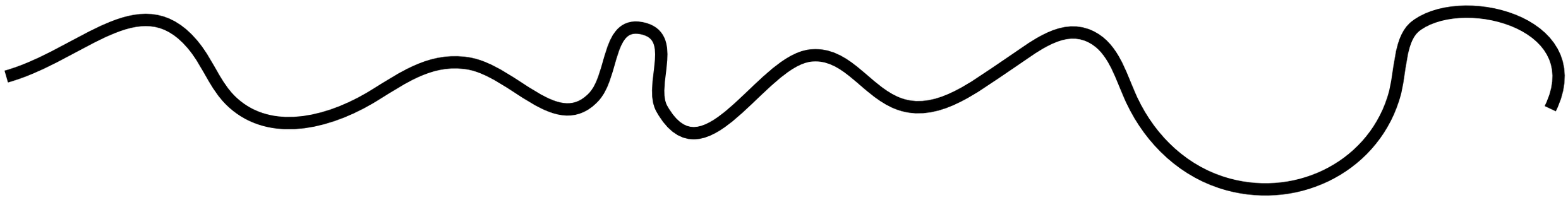


Not to scale….



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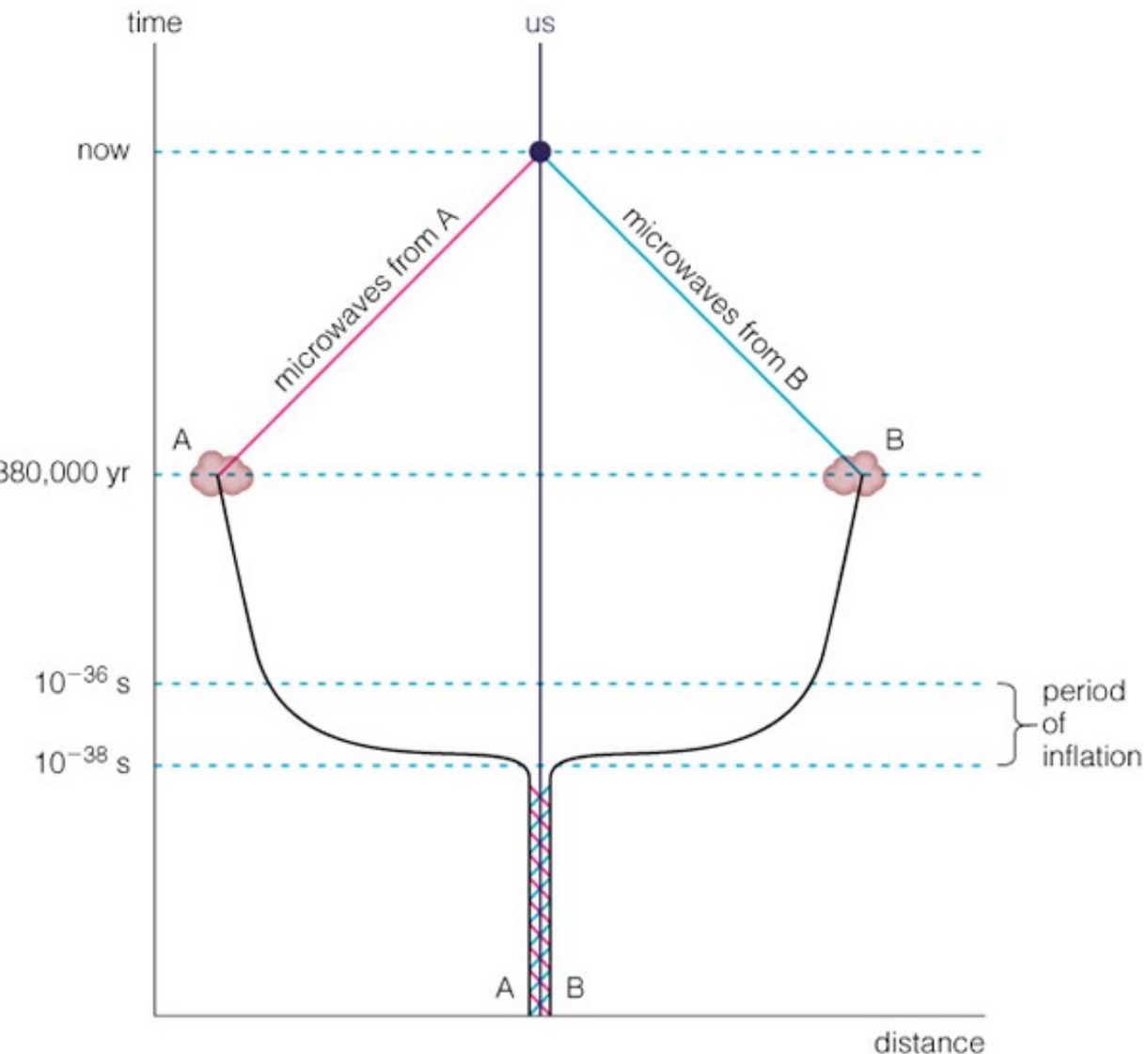
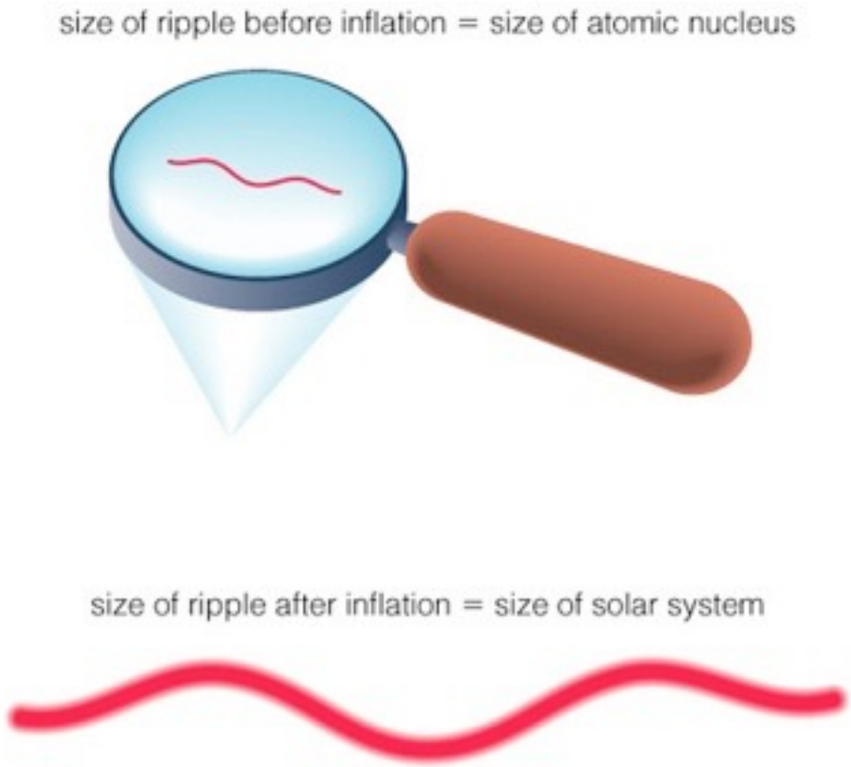
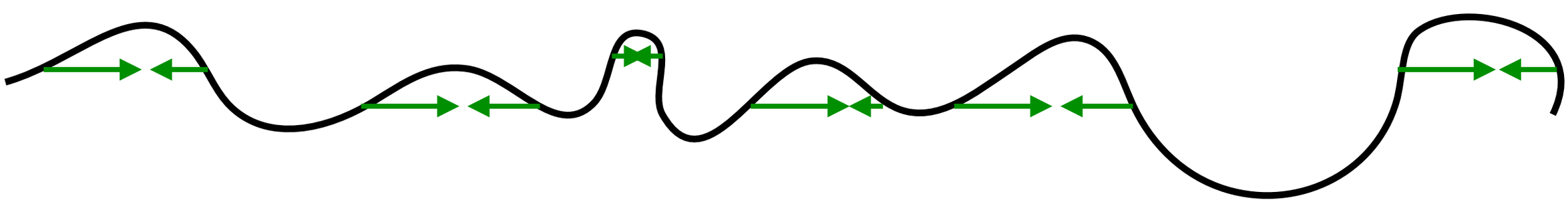
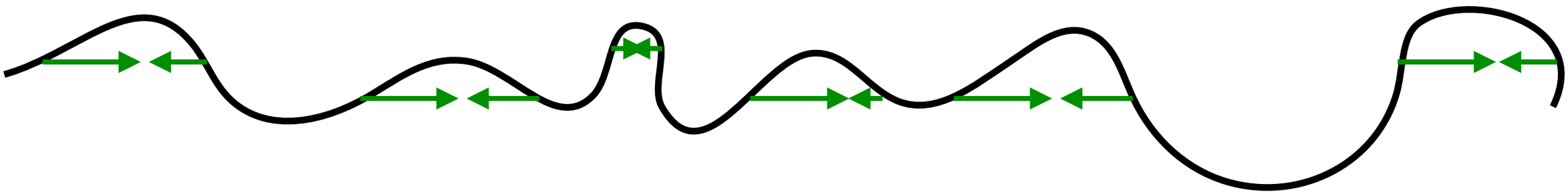


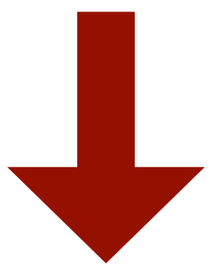


Regions of higher density begin to collapse



These fluctuations become the seeds of superclusters





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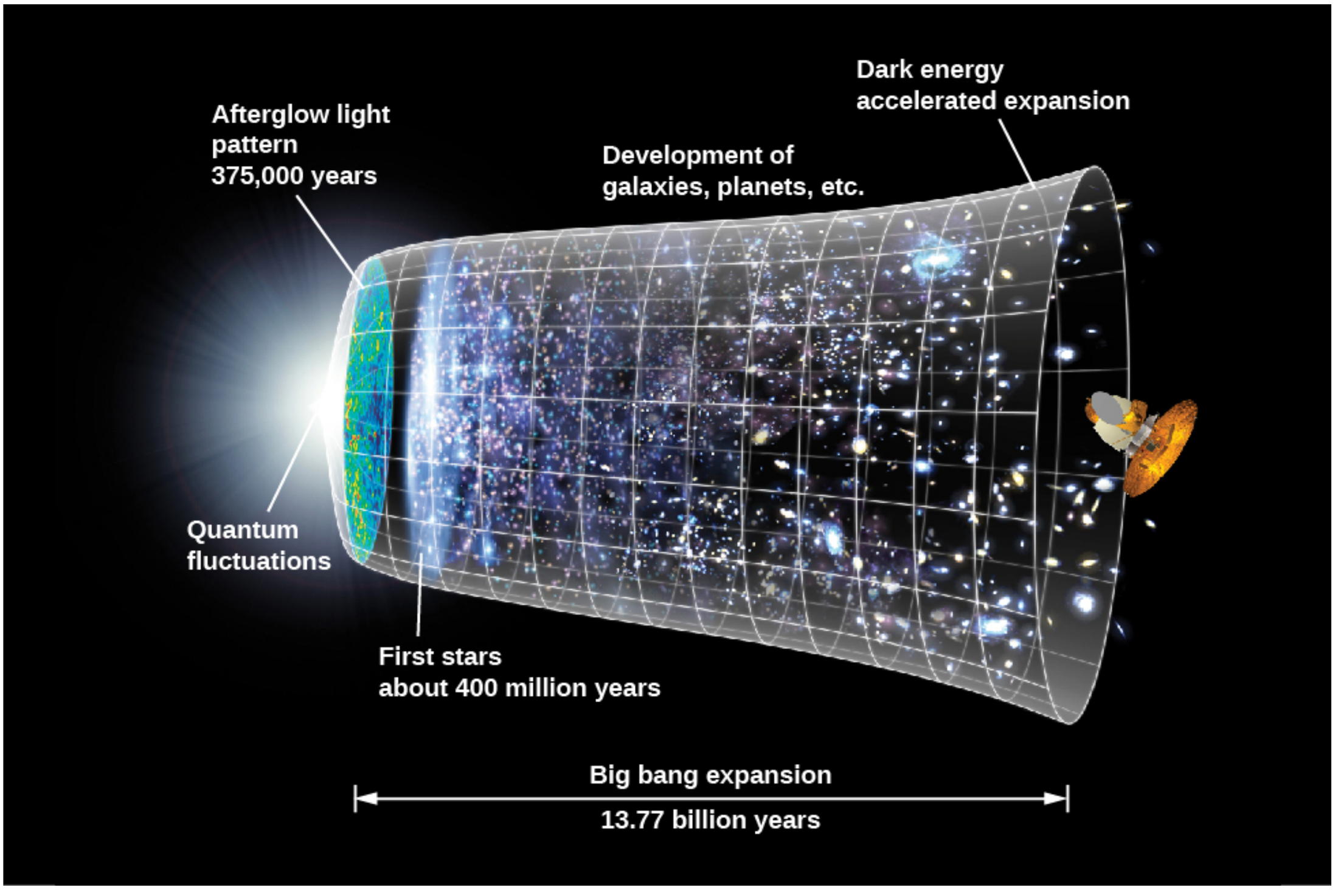
What exactly this "inflation" is is still somewhat mysterious!

Summary so far (in one picture)



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