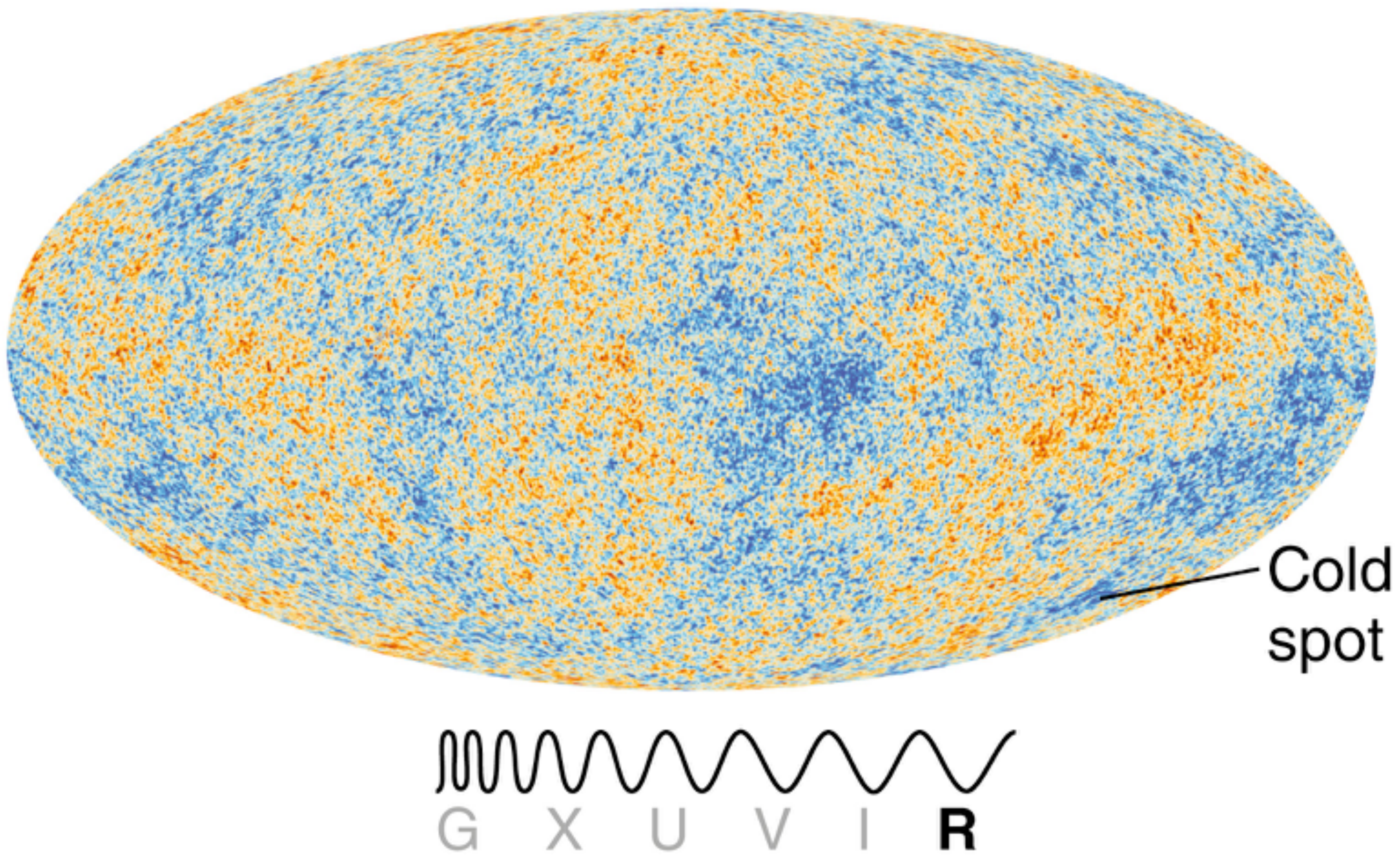
Chapter 16: The Evolution of our Universe

Ch. 16 Reading Assignment due now!

EC write-ups accepted anytime



What IS the Big Bang?

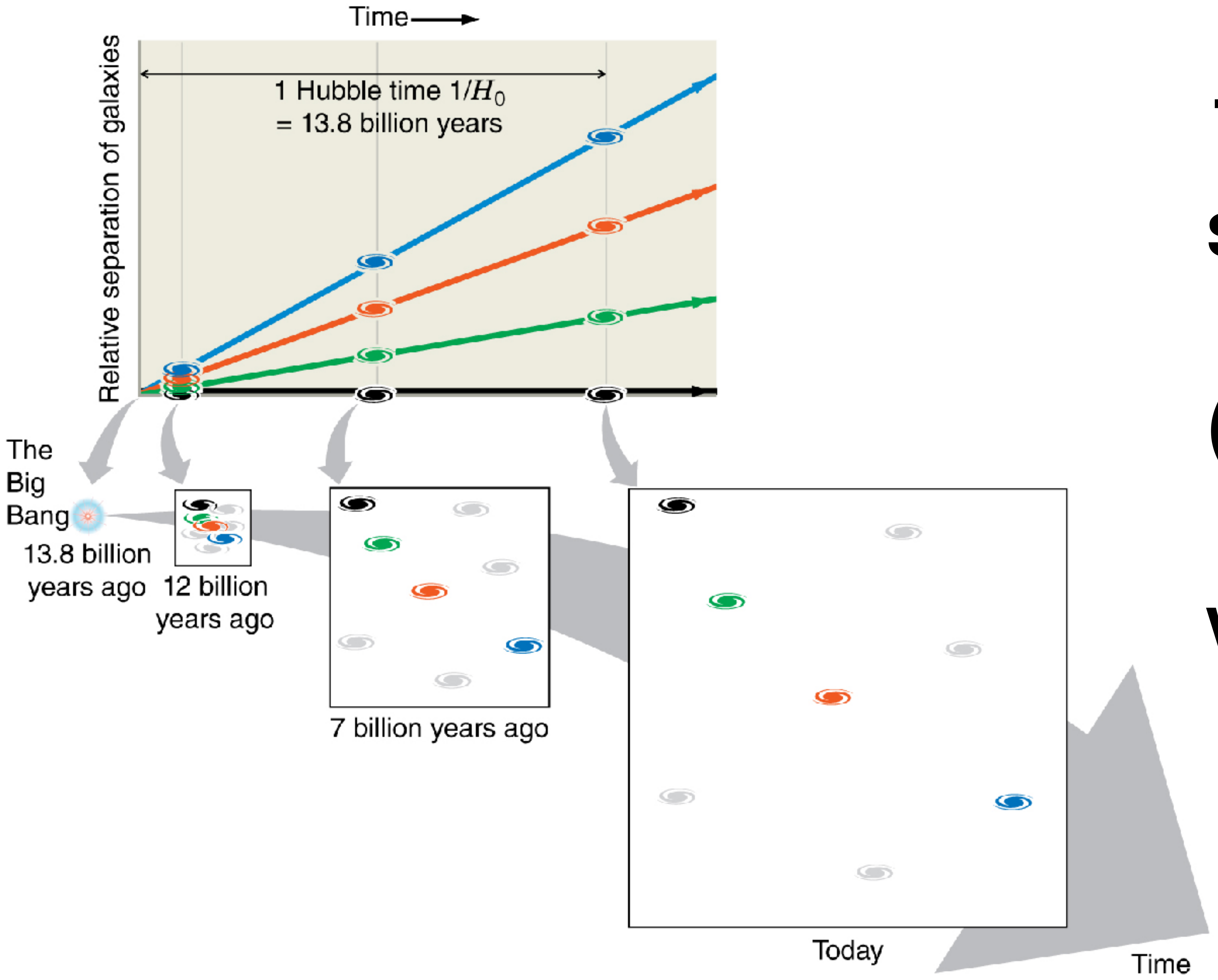
A) A part of space that exploded to become the universe

B) A bubble of spacetime that expanded from the multiverse

C) Expanding spacetime that starts very hot and dense in a singularity

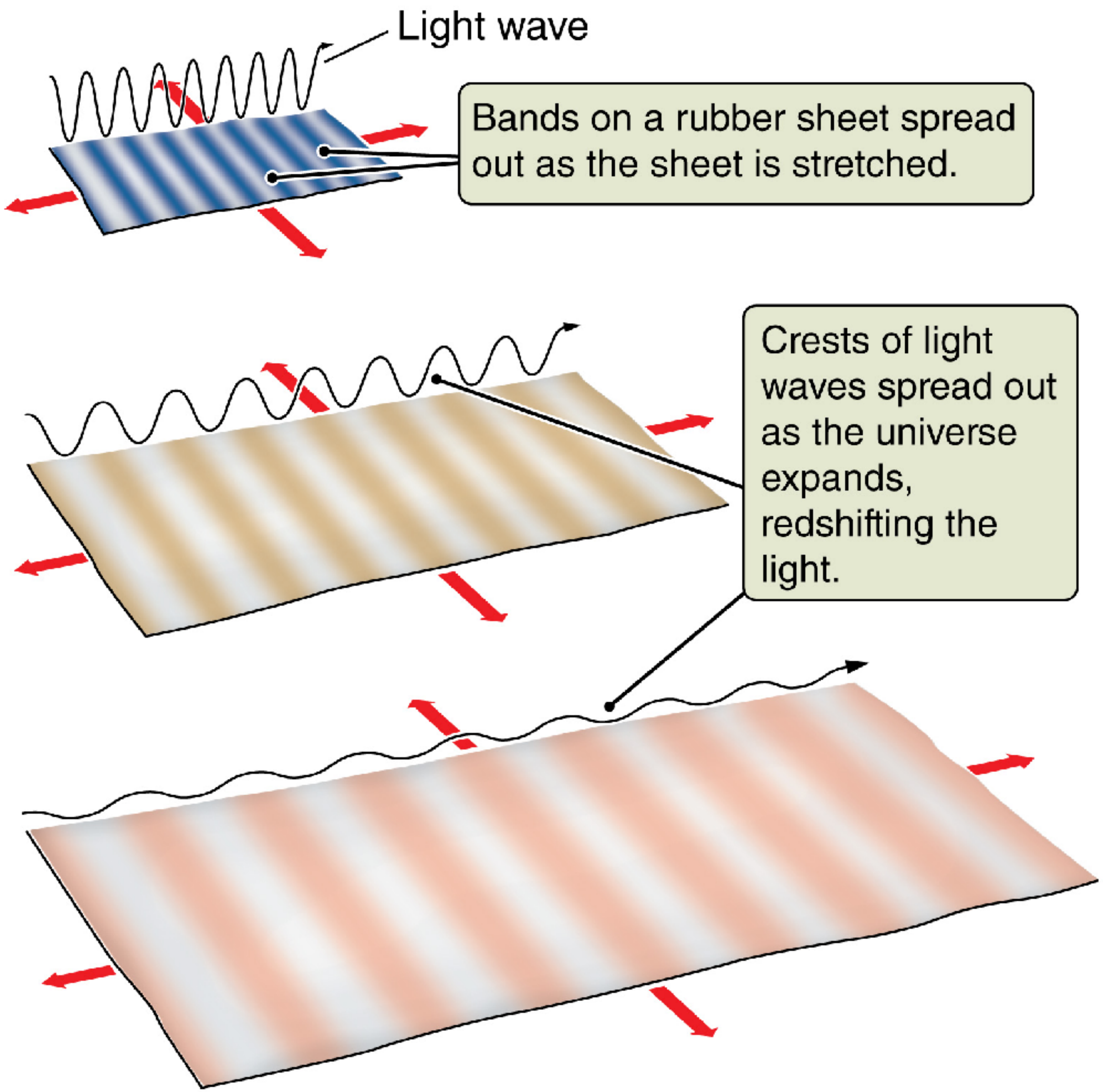
D) Expanding spacetime that starts very hot and dense as if from a singularity

Where did the Big Bang happen?



The expansion of space, evidenced by Hubble's law (galaxy redshifts), implies galaxies were much closer together in the past

Light gets redshifted because it's "tied" to space and expands with it



Chapter 16: The Evolution of our Universe

No office hours today

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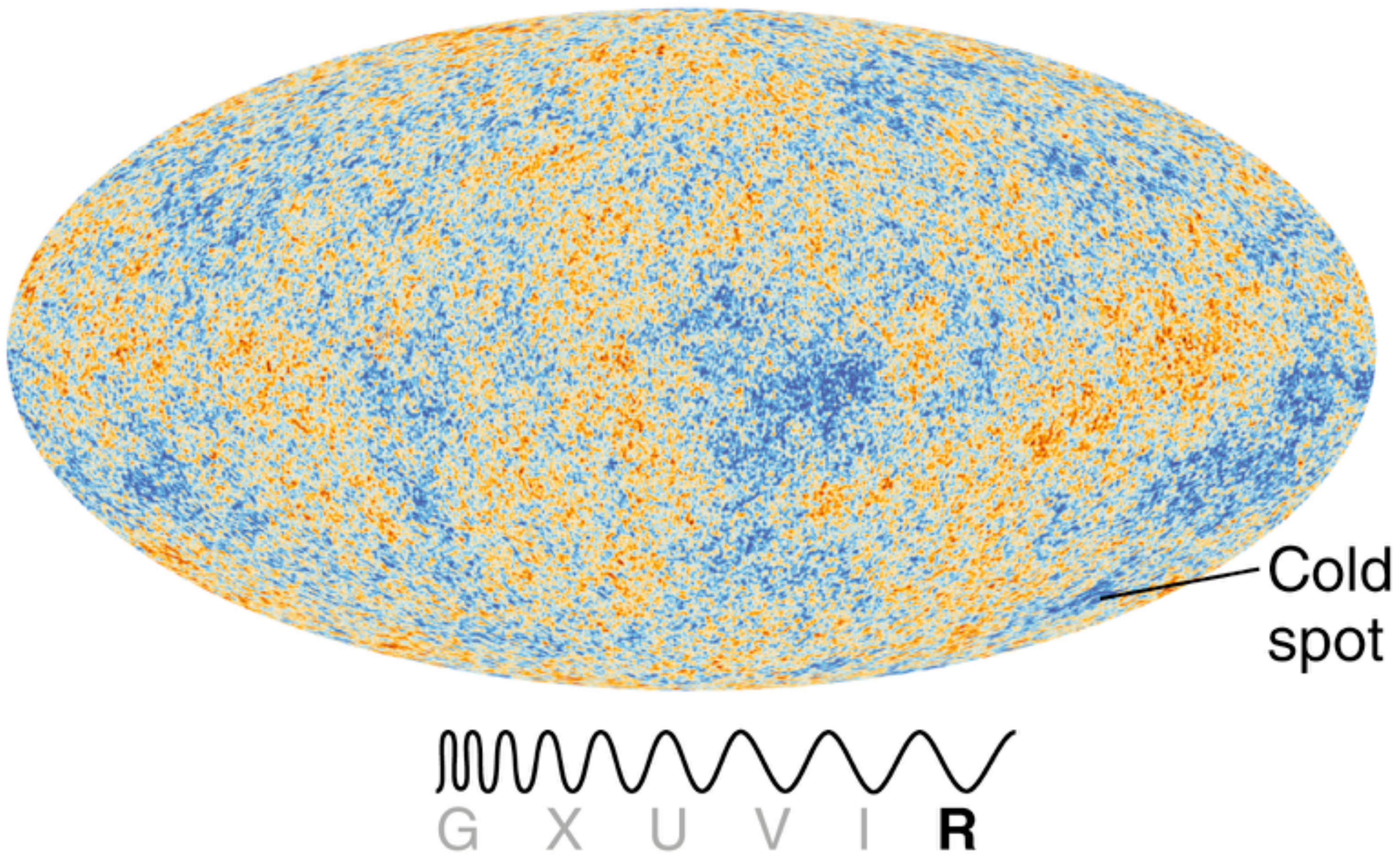
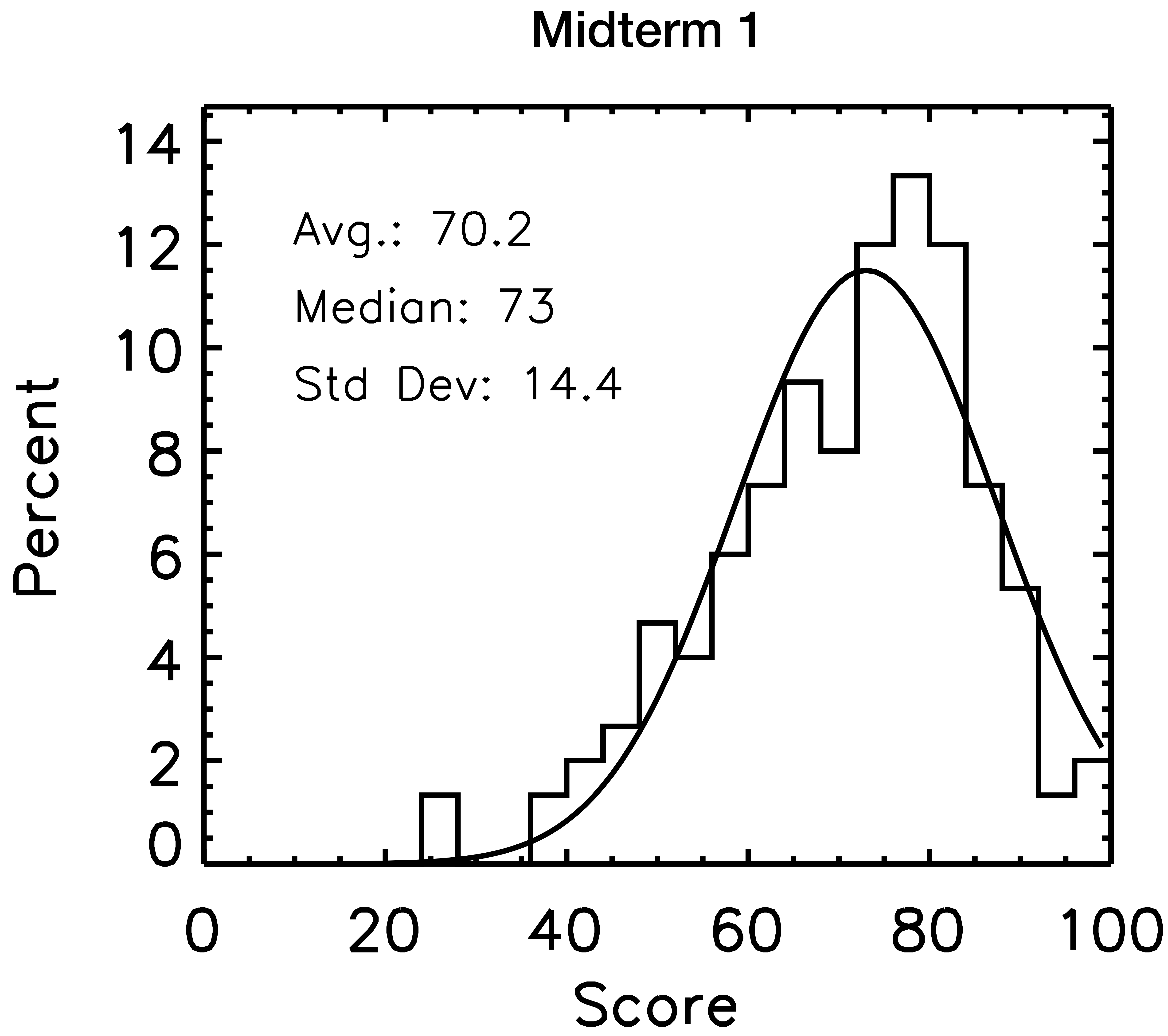
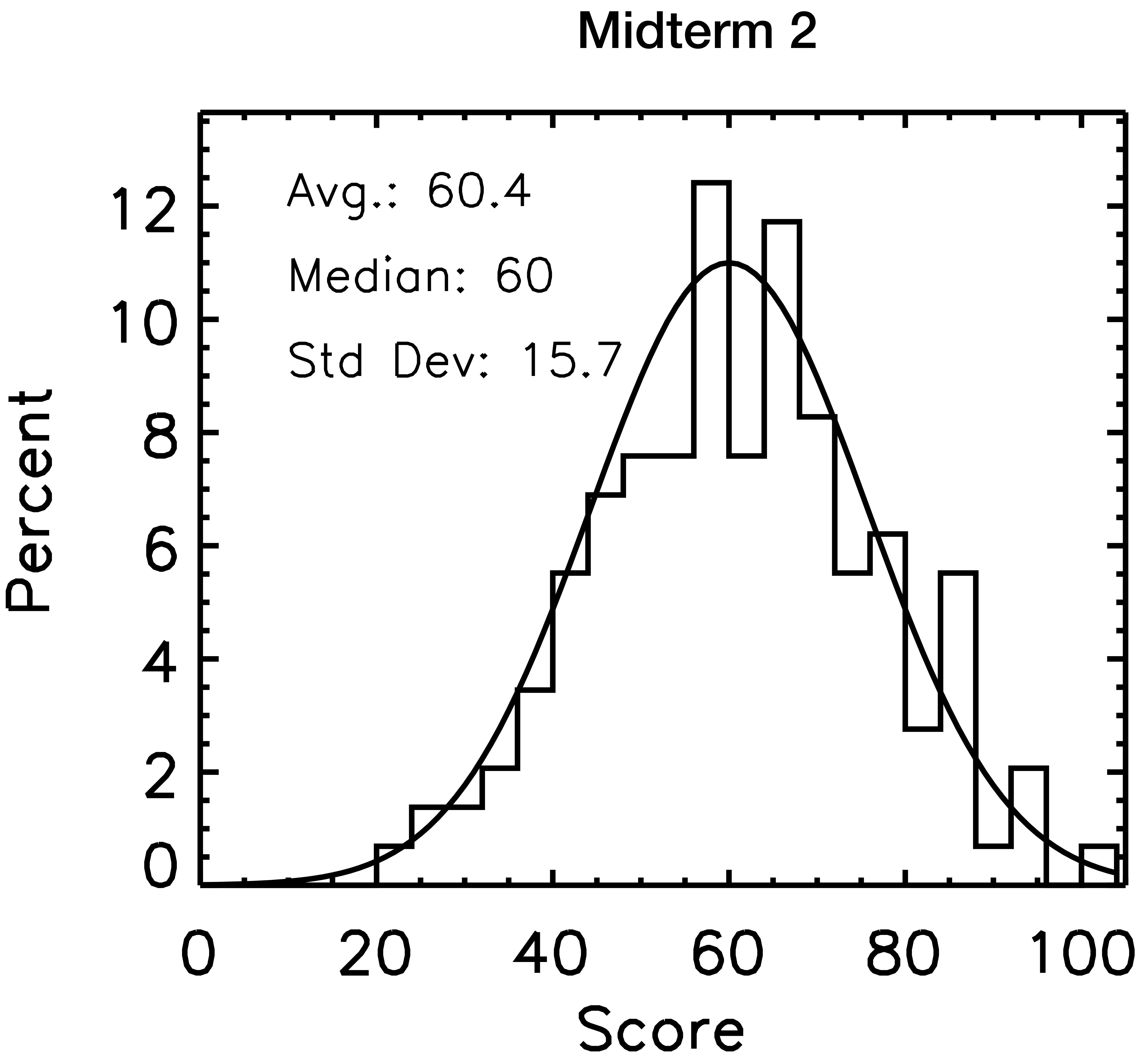
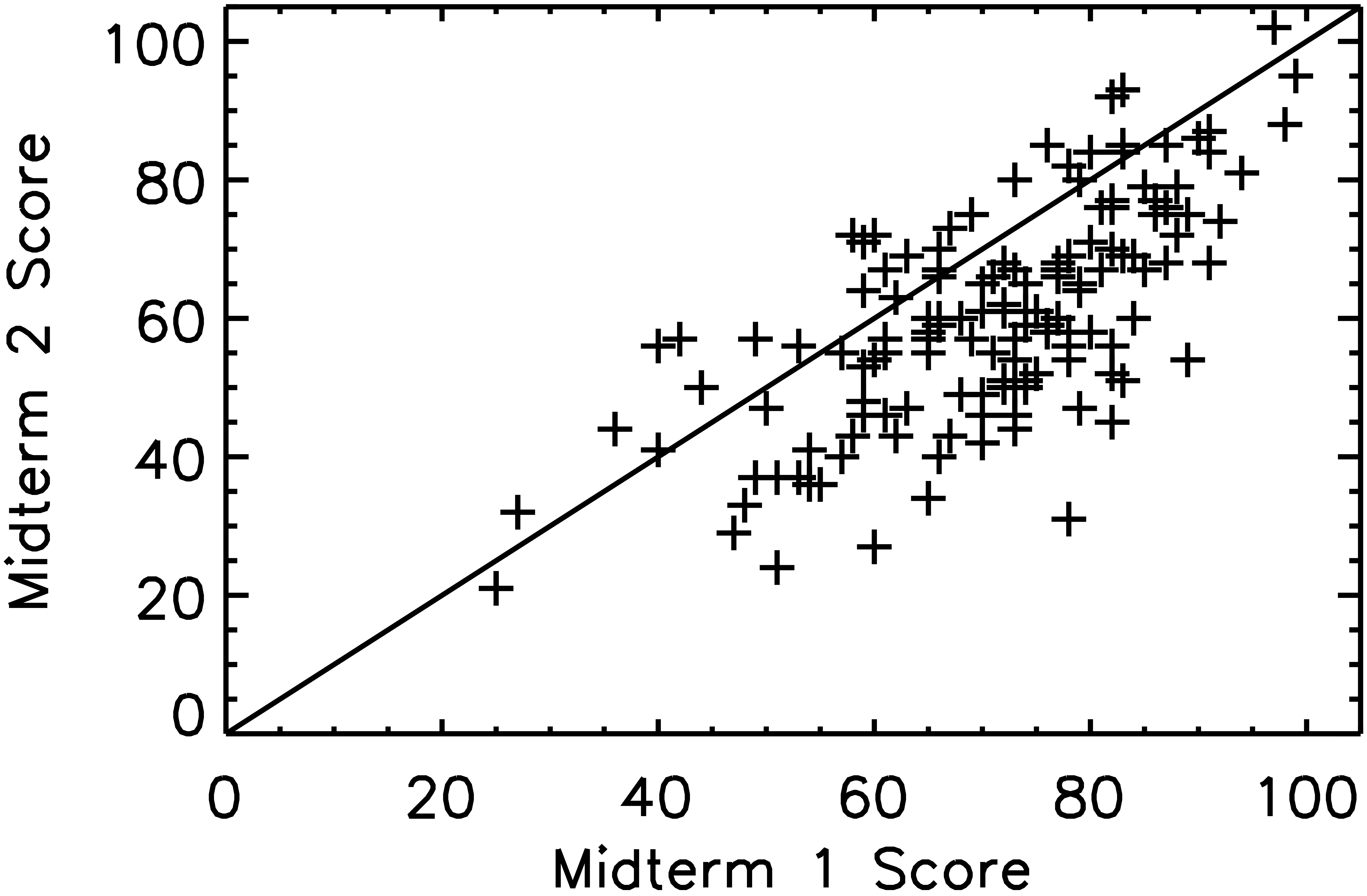
Check your grades in Canvas!



Midterm 2 results are in






Midterm 2 Score
0
20
40
60
80
100
Midterm 1 Score
0
20
40
60
80
100

Only 1 question more than 1/4th got incorrect

(on second thought, I agree it's a bad question)

What would happen if mass were continually added to a 2 $M_\odot$ neutron star?

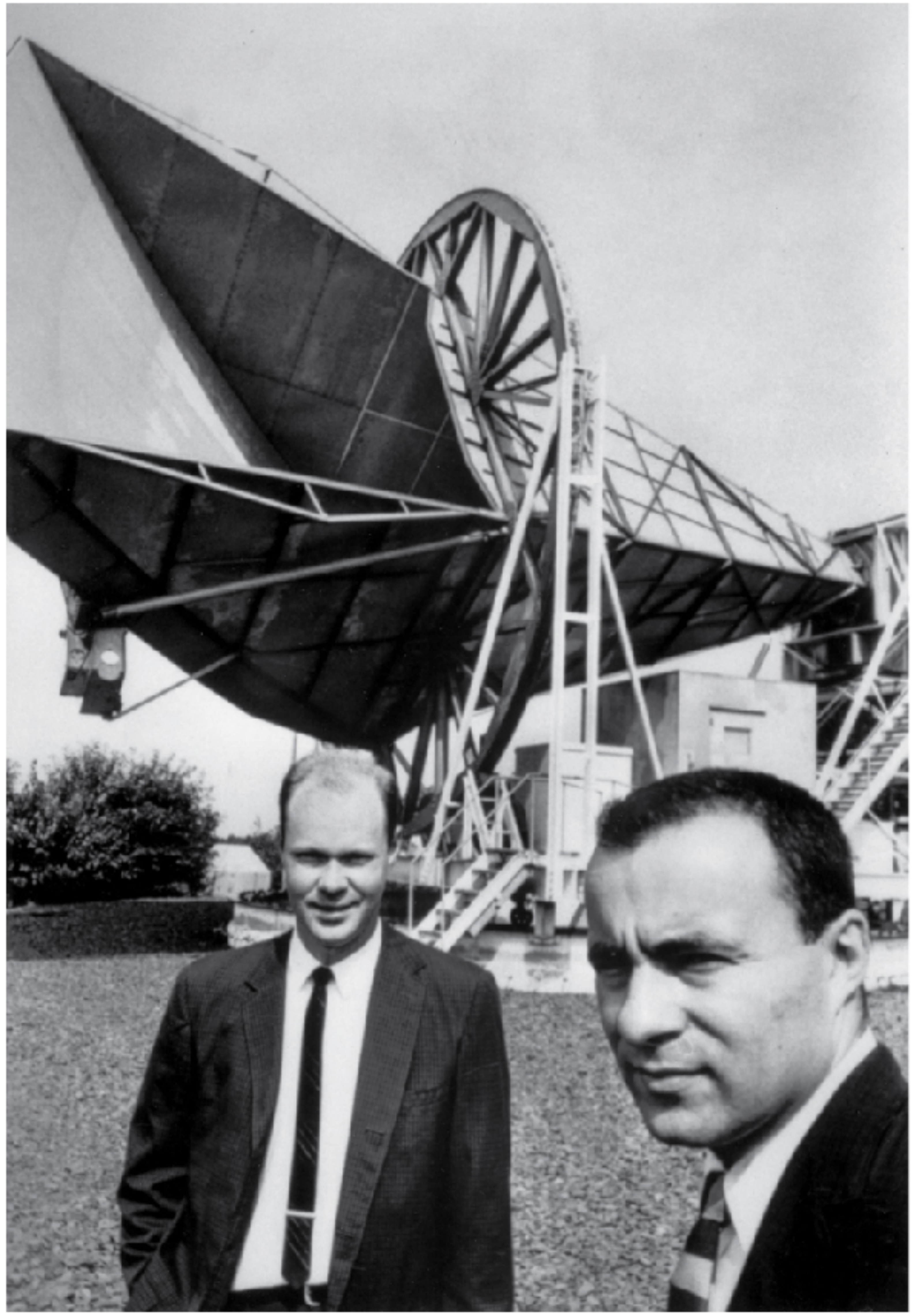
A. The star would erupt as a nova.

B. The star's radius would increase.

C. The star would eventually become a black hole.

D. All of the above would occur.

Evidence of the Big Bang was confused with pigeon poo



Penzias and Wilson worked at Bell Labs, were trying to reduce noise in a radio receiver

“Eliminated" pigeons as a source of noise, realized it must be cosmic

Meanwhile, smarty-pantses at Princeton were like, “let’s build a telescope to search for this early universe radiation Gamow, Alpher, and Bethe suggested might exist”

Bell Labs guys came back with, “don’t bother, found it already — Nobel Prize please”

They got it, for the discovery of the Cosmic Microwave Background

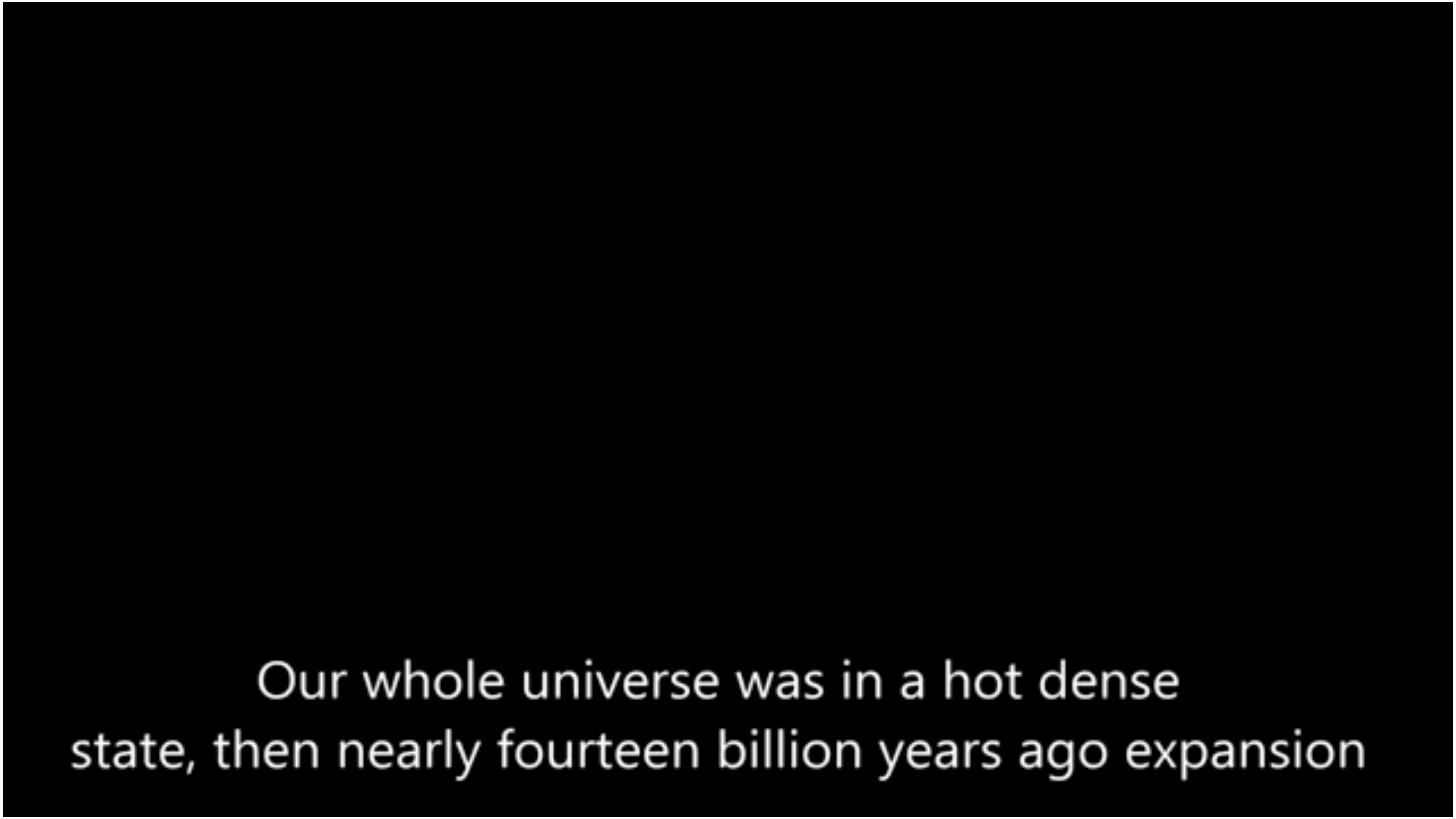
What is the CMB?

A) Leftover particles from the Big Bang

B) Leftover radiation (gamma rays) from the Big Bang

C) Leftover radiation (microwaves) from the Big Bang

D) Leftover cosmic rays from the Big Bang



https://www.youtube.com/watch?v=CMSYv_Z4SI8

Story time: when the universe was a baby

In the early universe, many interactions between particles (just like at the LHC)
quarks, electrons, photons, neutrinos all transform into each other

As universe expands, densities decrease and protons/electrons/photons dominate baryon soup

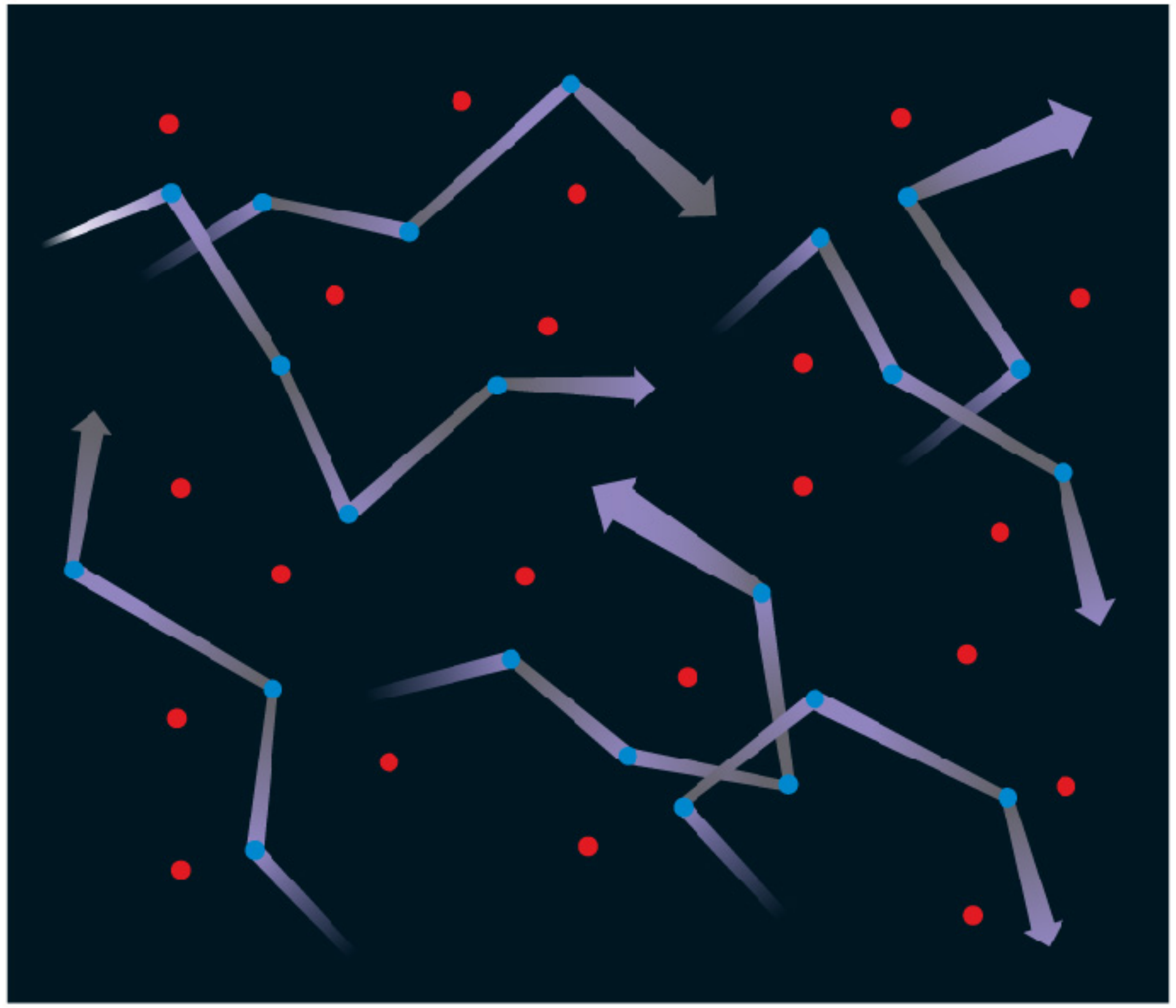
Eventually, electrons can be captured by protons to form atoms that are not immediately broken up by energetic photons
—> <u>recombination</u>

Soon thereafter, the density of free electrons is too low to scatter photons, and the universe becomes transparent
—> <u>photon decoupling</u>

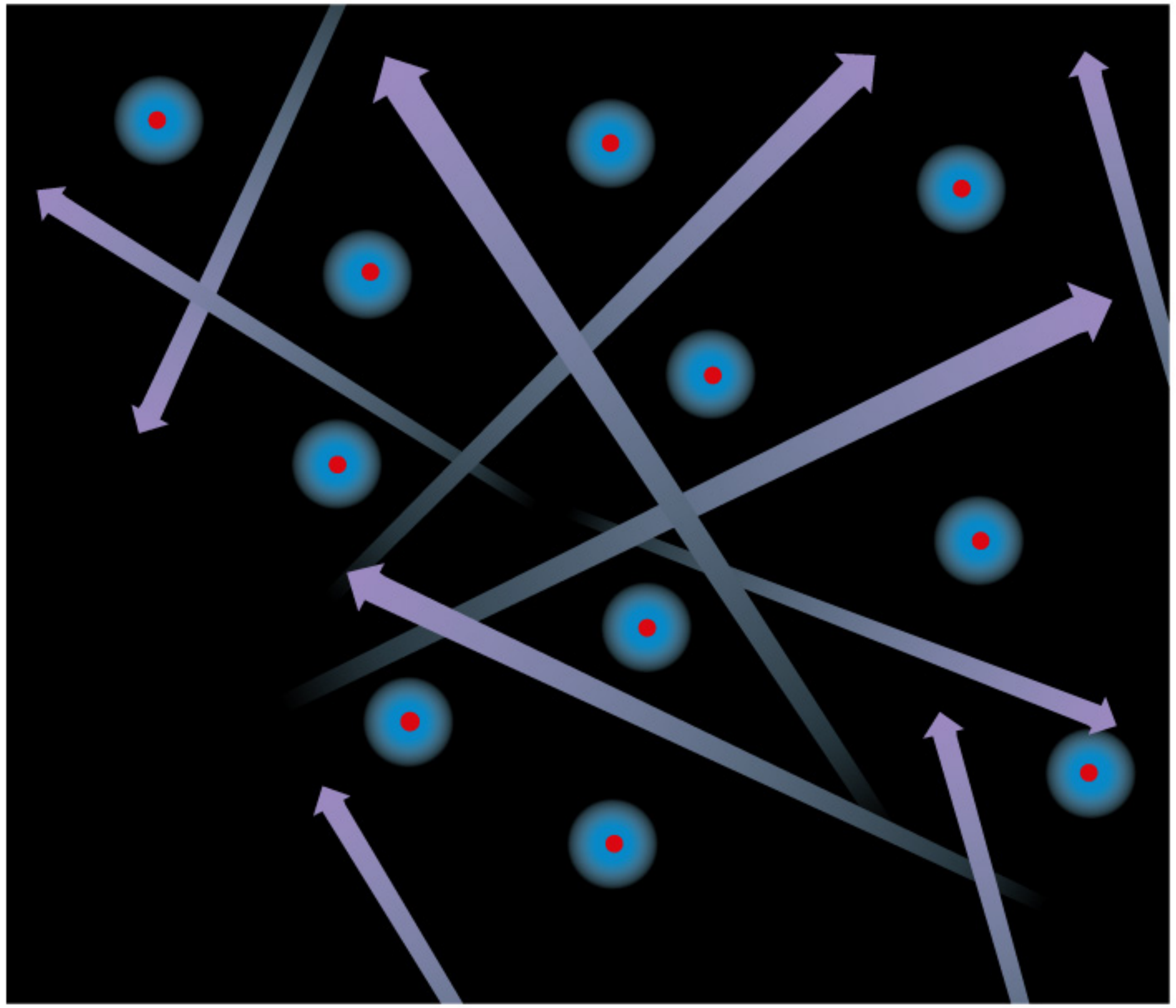
As the universe expands further, a time comes when a CMB photon scatters off an electron for one last time
—> <u>last scattering</u>

In the ionized early universe, light was trapped by free electrons. Radiation had a blackbody spectrum.

At this time, it was as though the universe was filled with a thick fog.



KEY • Proton • Electron Path of photon

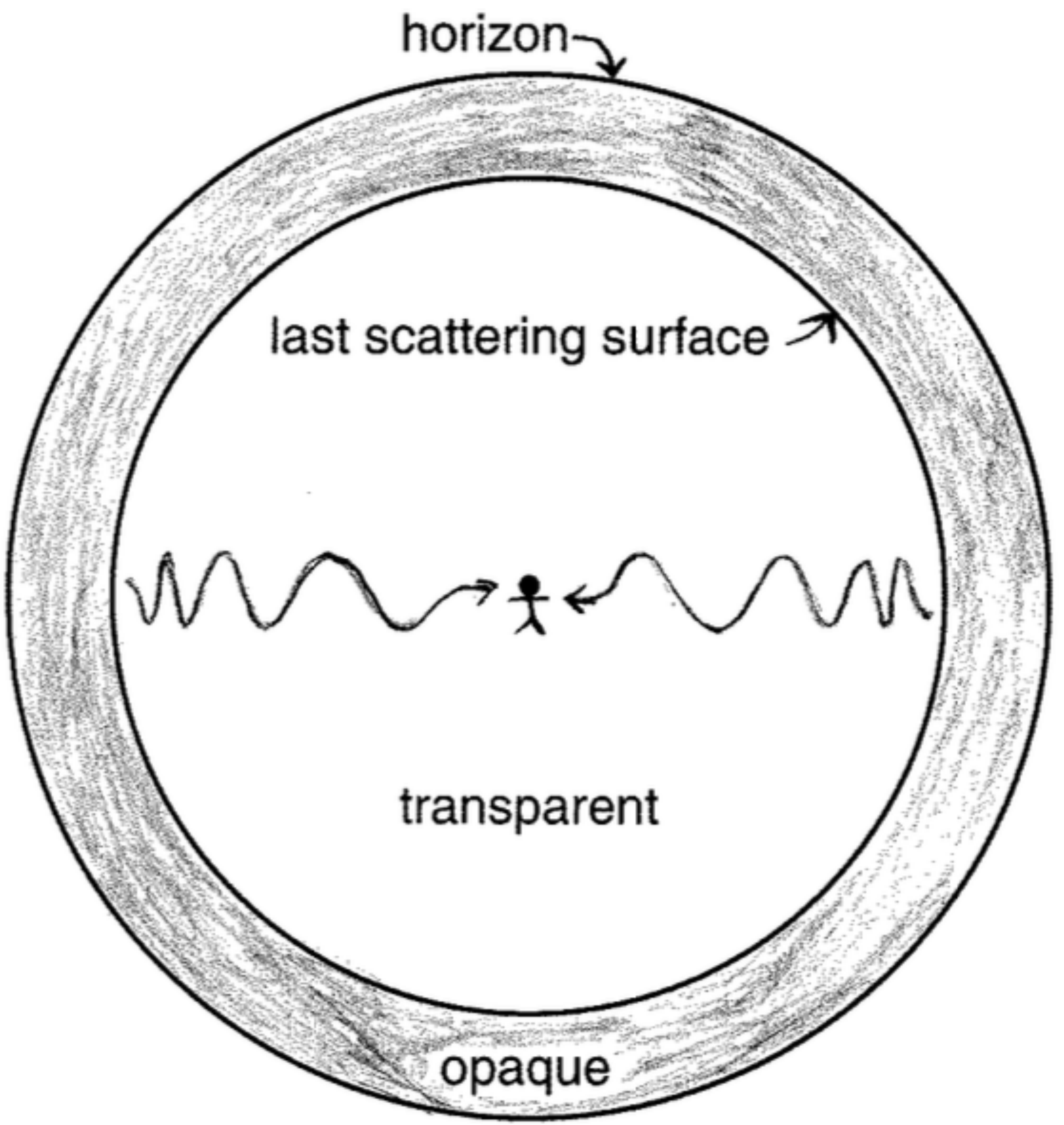


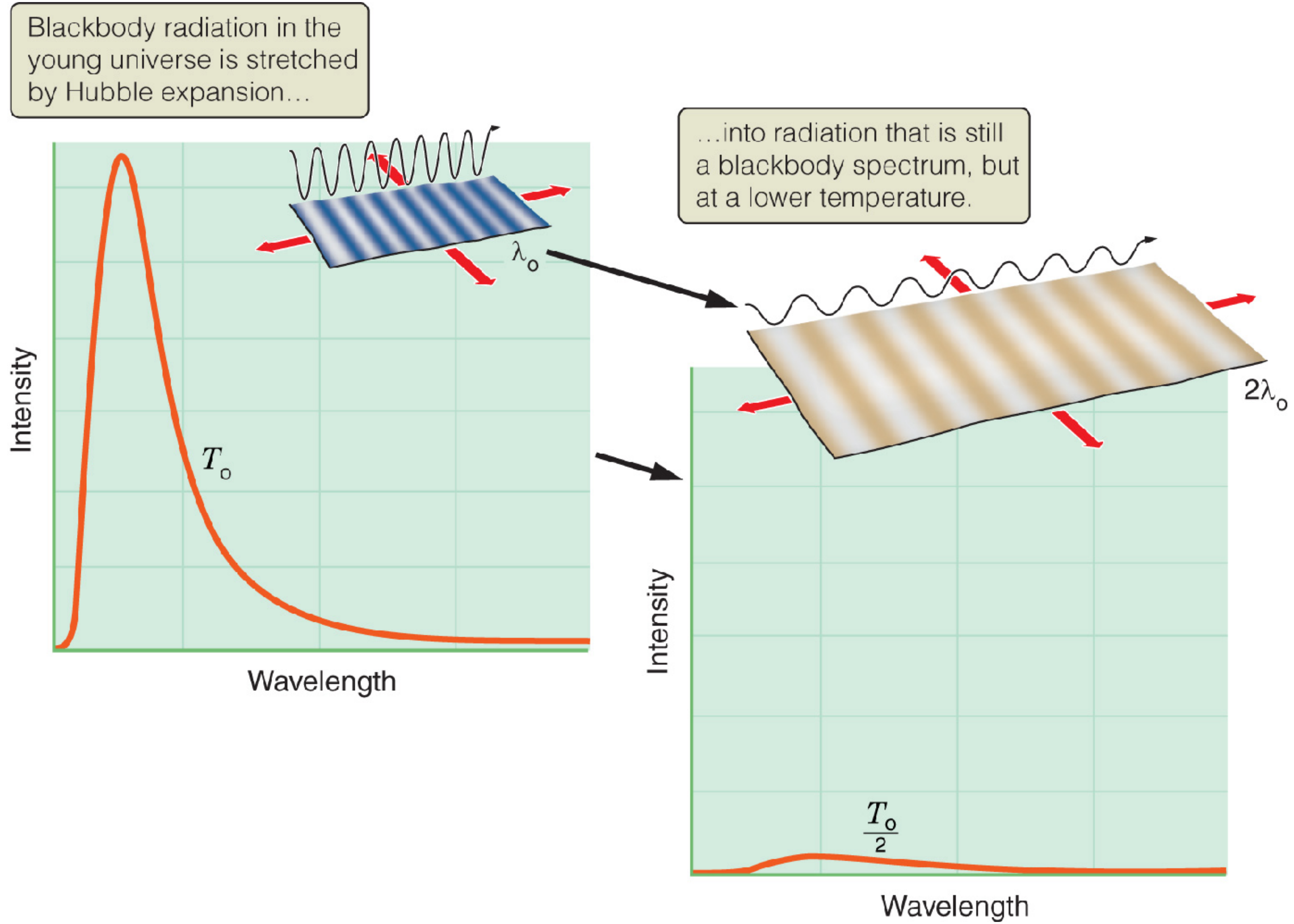
When the universe recombined, it became transparent, and the blackbody radiation traveled freely through the universe.

Recombination was like the fog suddenly clearing.

The CMB is like looking into the Sun — you can only see as far as the last time a photon got scattered

“the surface of last scattering”

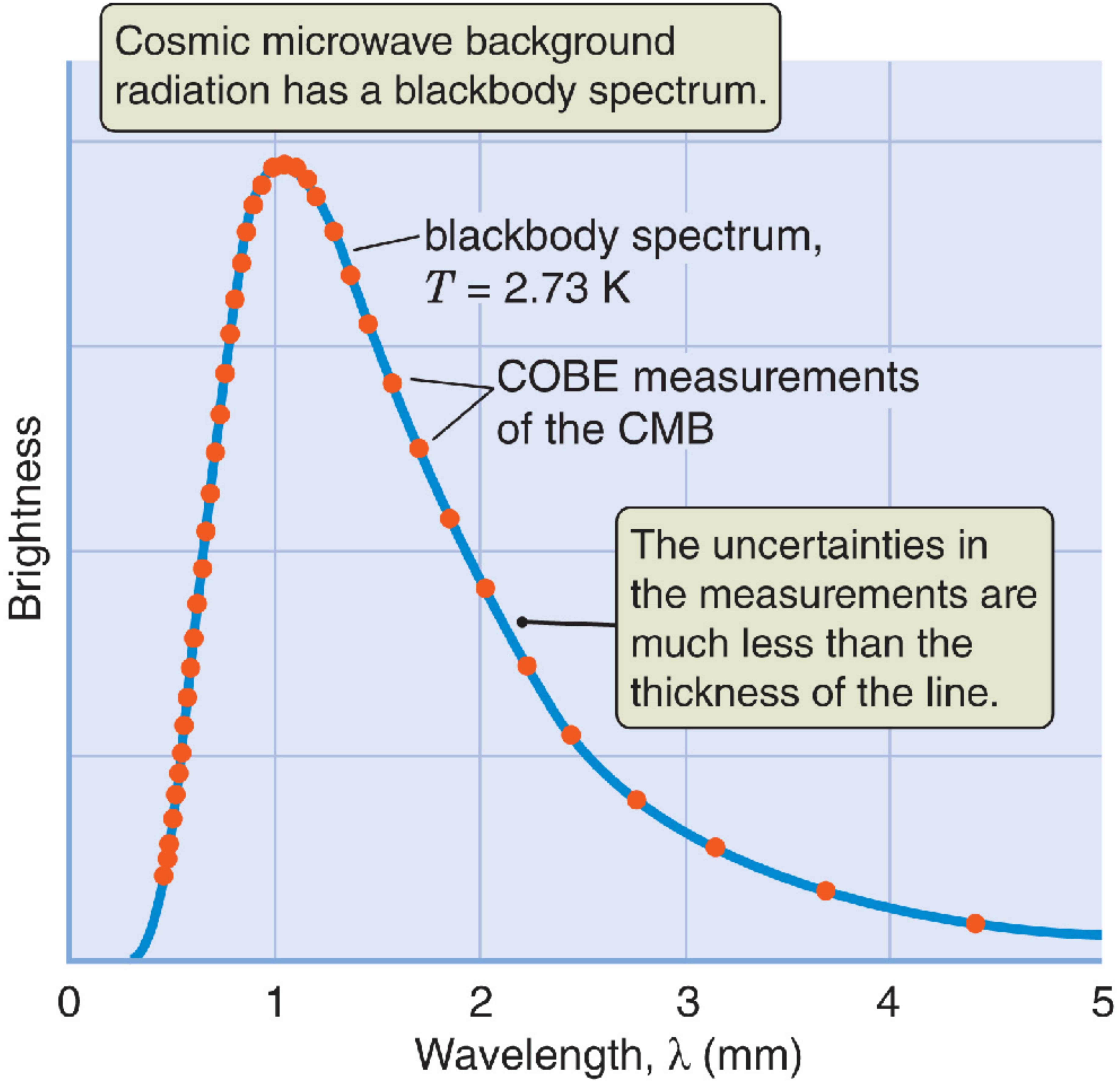



Blackbody radiation in the young universe is stretched by Hubble expansion…
…into radiation that is still a blackbody spectrum, but at a lower temperature.
Intensity
Wavelength
T_o
λ_o
$2\lambda_o$
Intensity
Wavelength
$\frac{T_o}{2}$

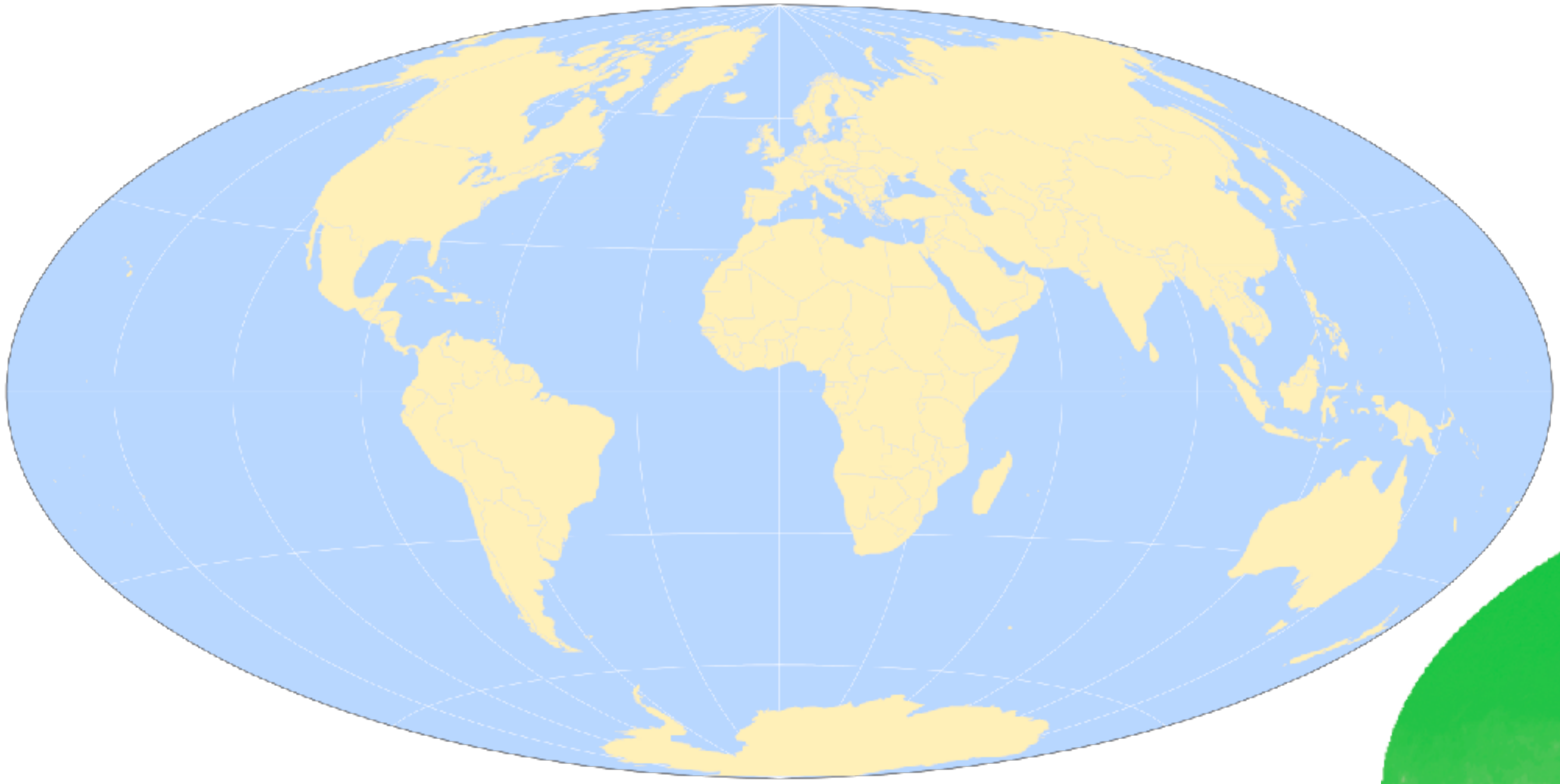
Error bars are too small to show on this plot

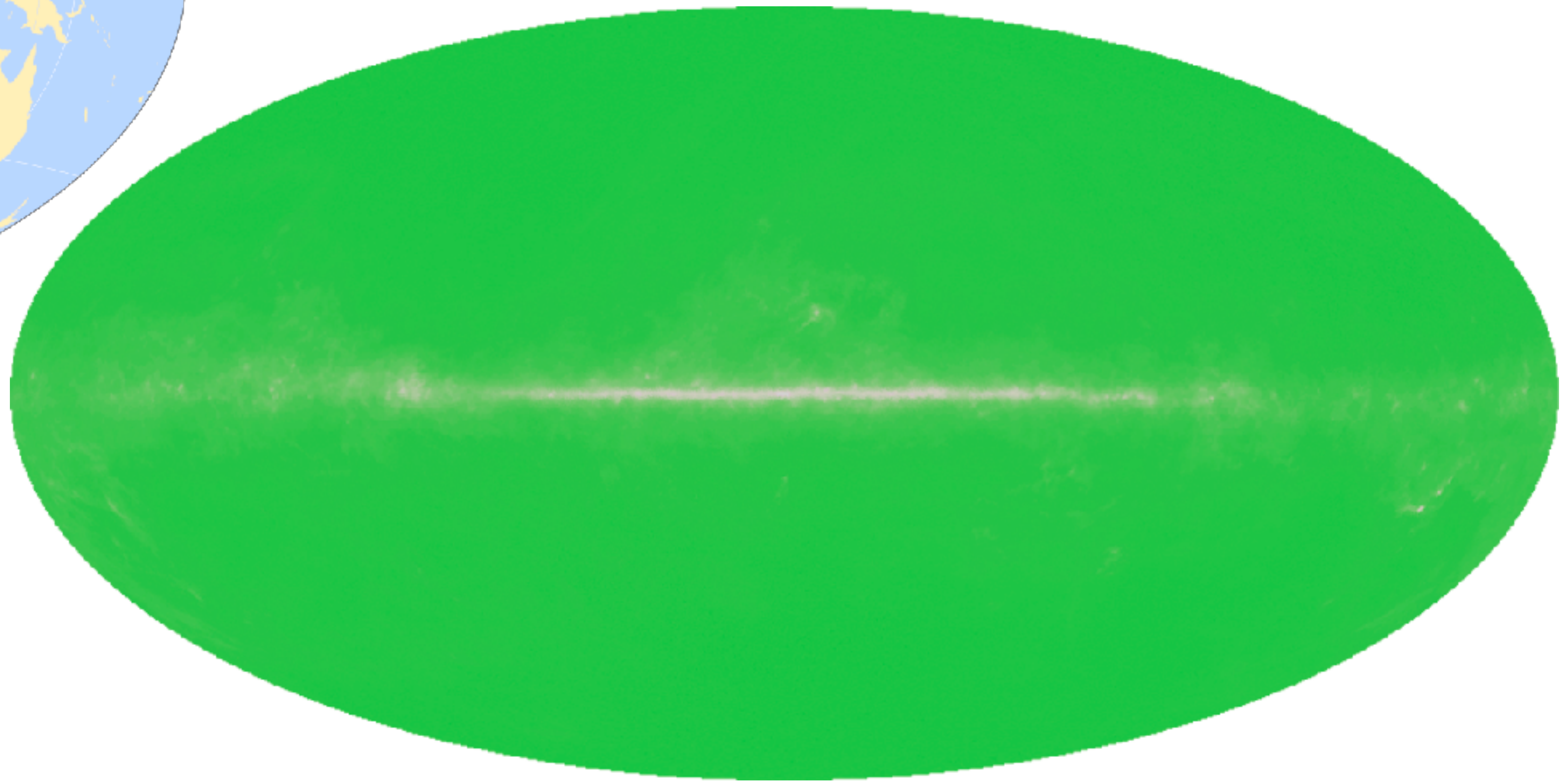
Measurement had to be in space to confirm entire spectrum was a blackbody (atmosphere absorbs light near the peak)

Received a standing ovation when shown at a meeting of the American Astronomical Society in the early 1990s

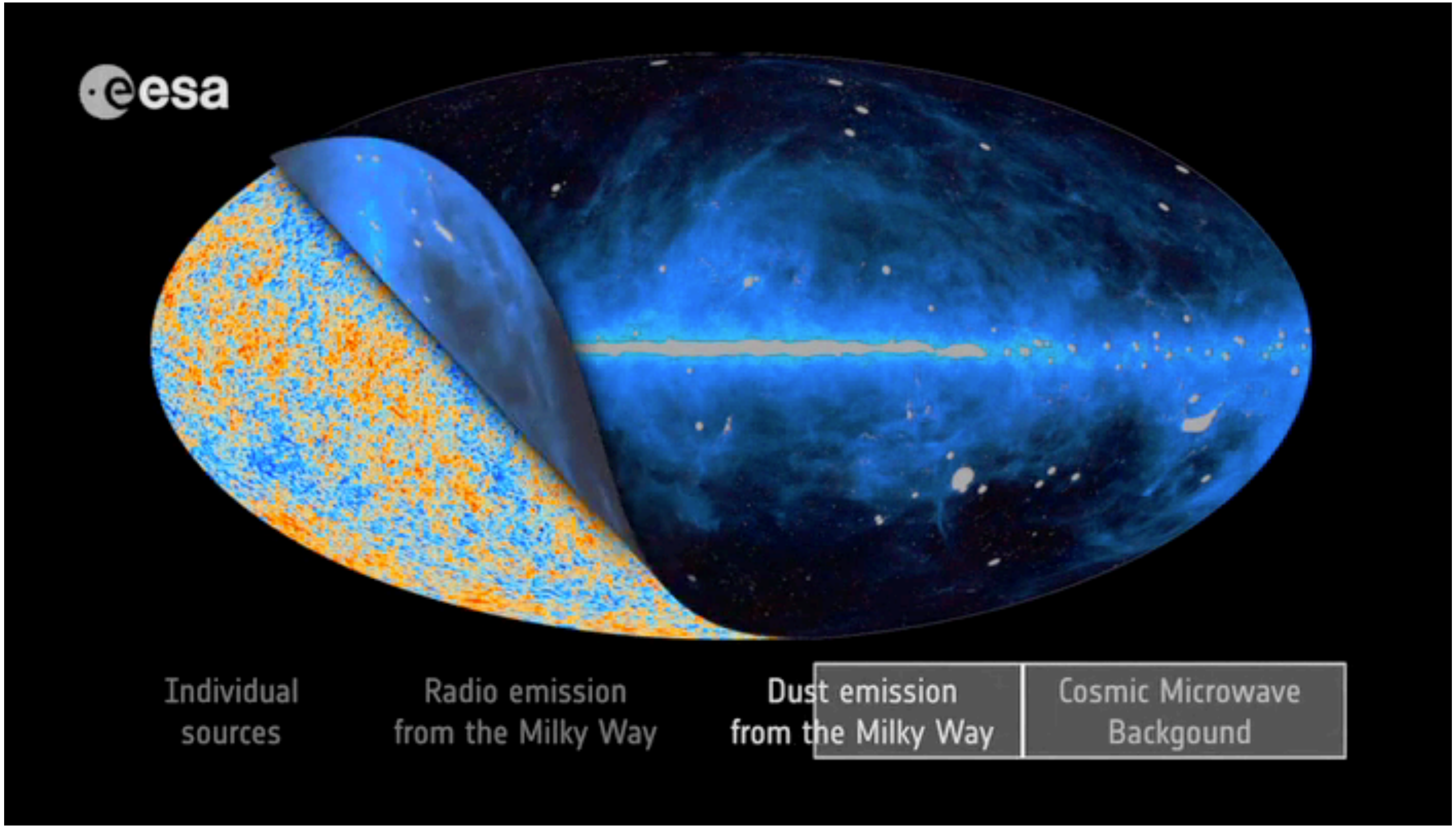


Every direction you look, the sky has the same temperature (2.73 degrees above absolute zero)



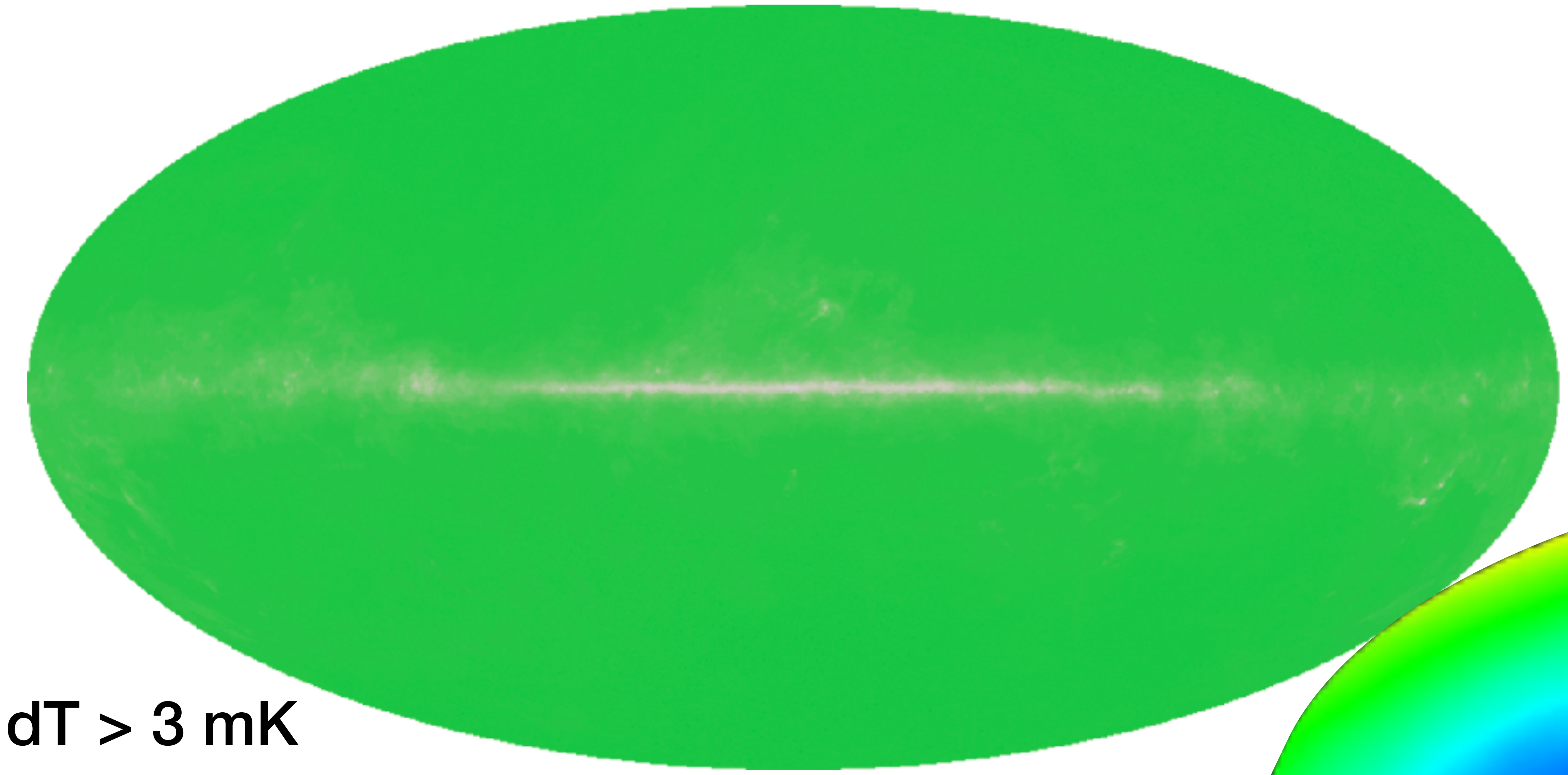


Removing features reveals new structures

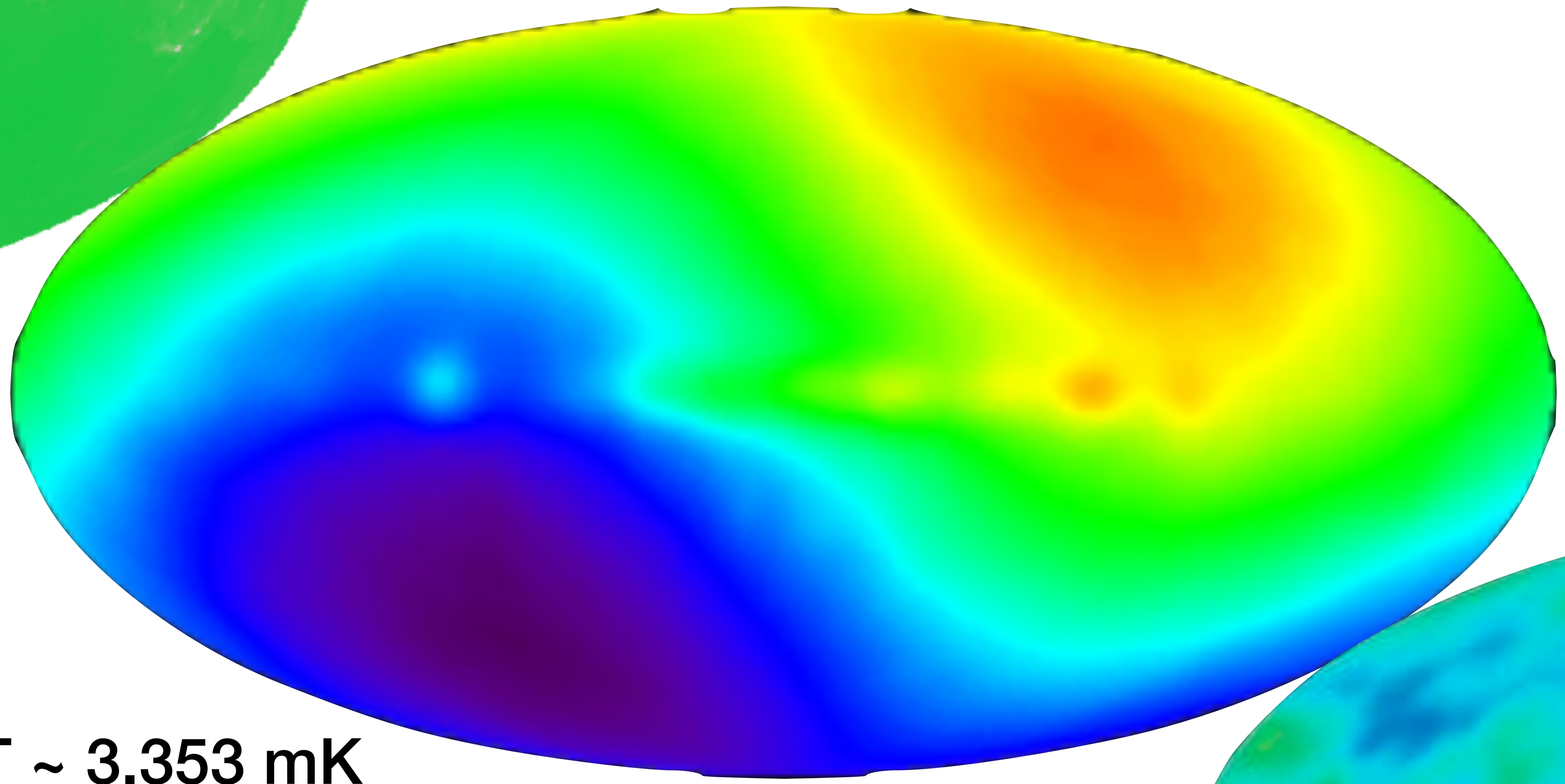


Removing features reveals new structures

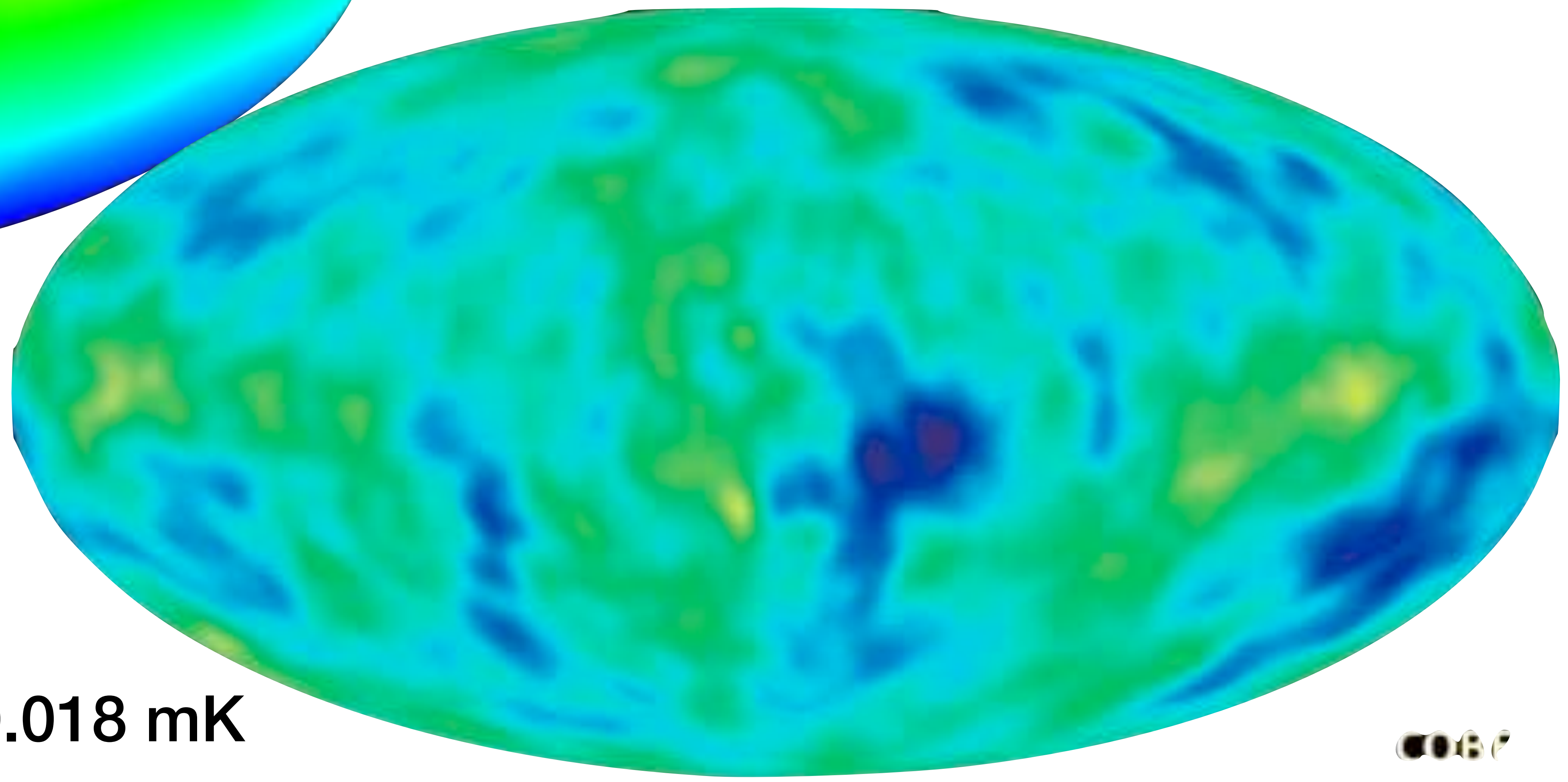
COBE measurements



dT > 3 mK

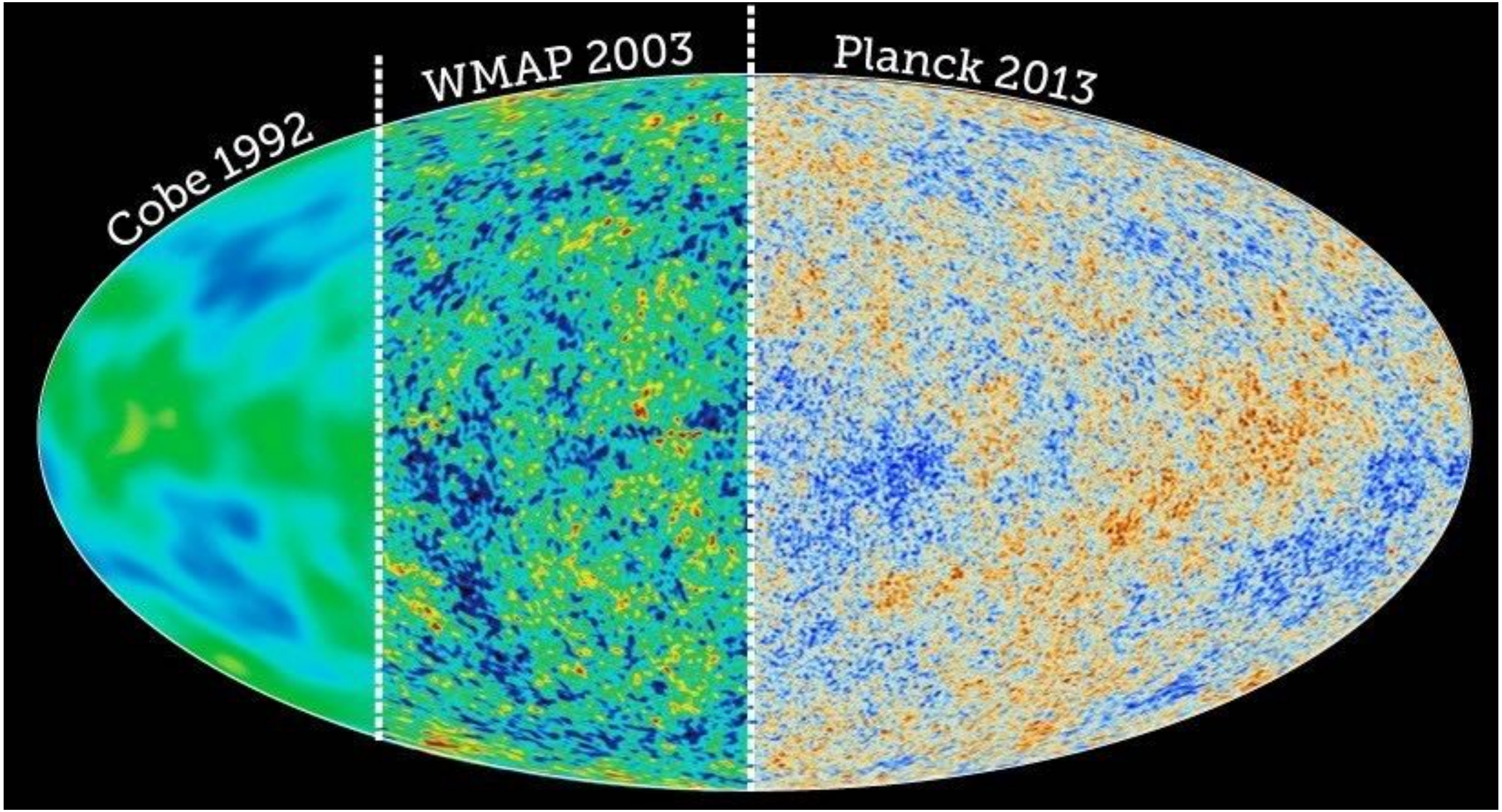


dT ~ 3.353 mK



dT ~ 0.018 mK

Over 25 years, refine spatial resolution



Chapter 16: The Evolution of our Universe

Class on Wednesday!

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Midterm 2 up front

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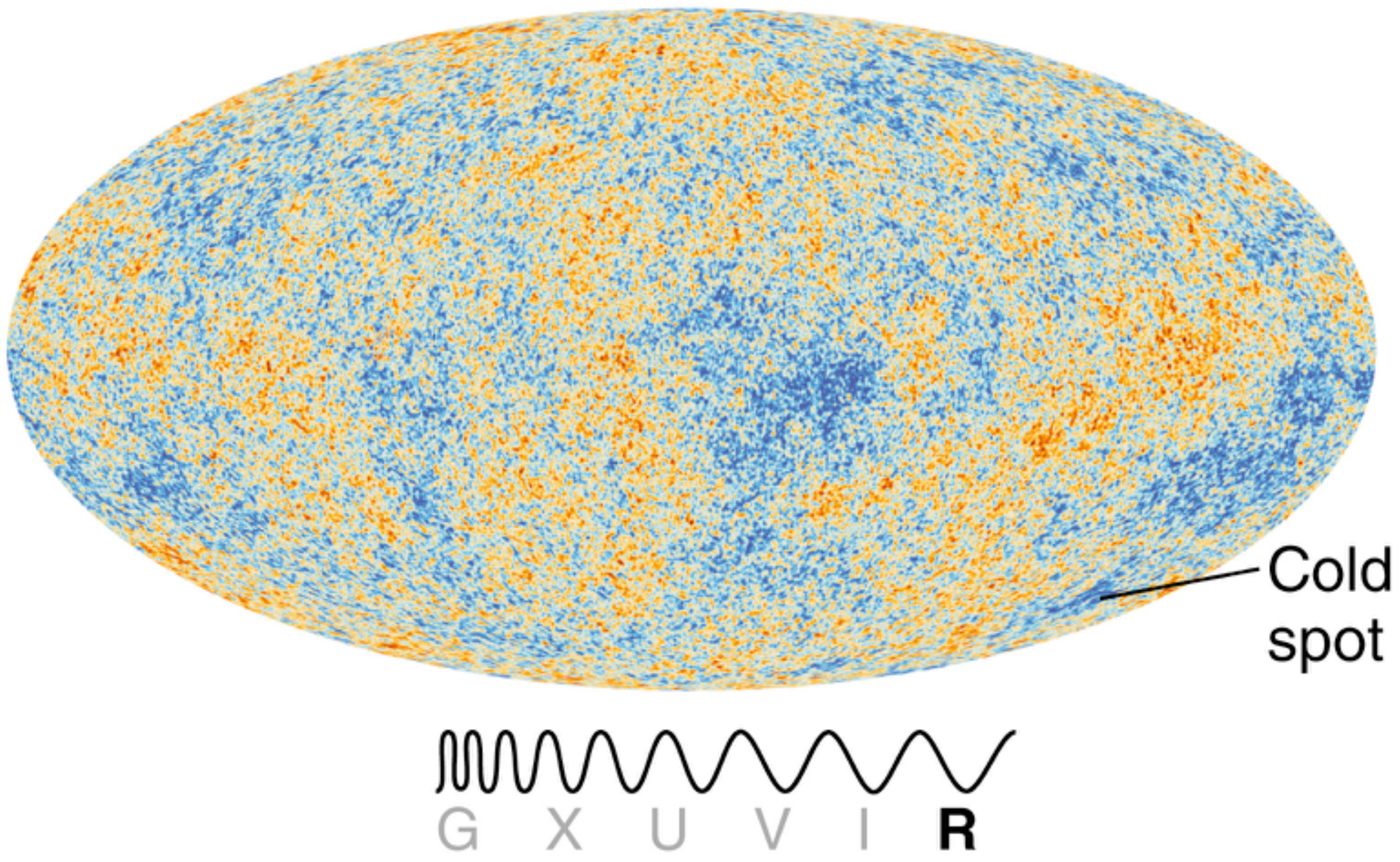
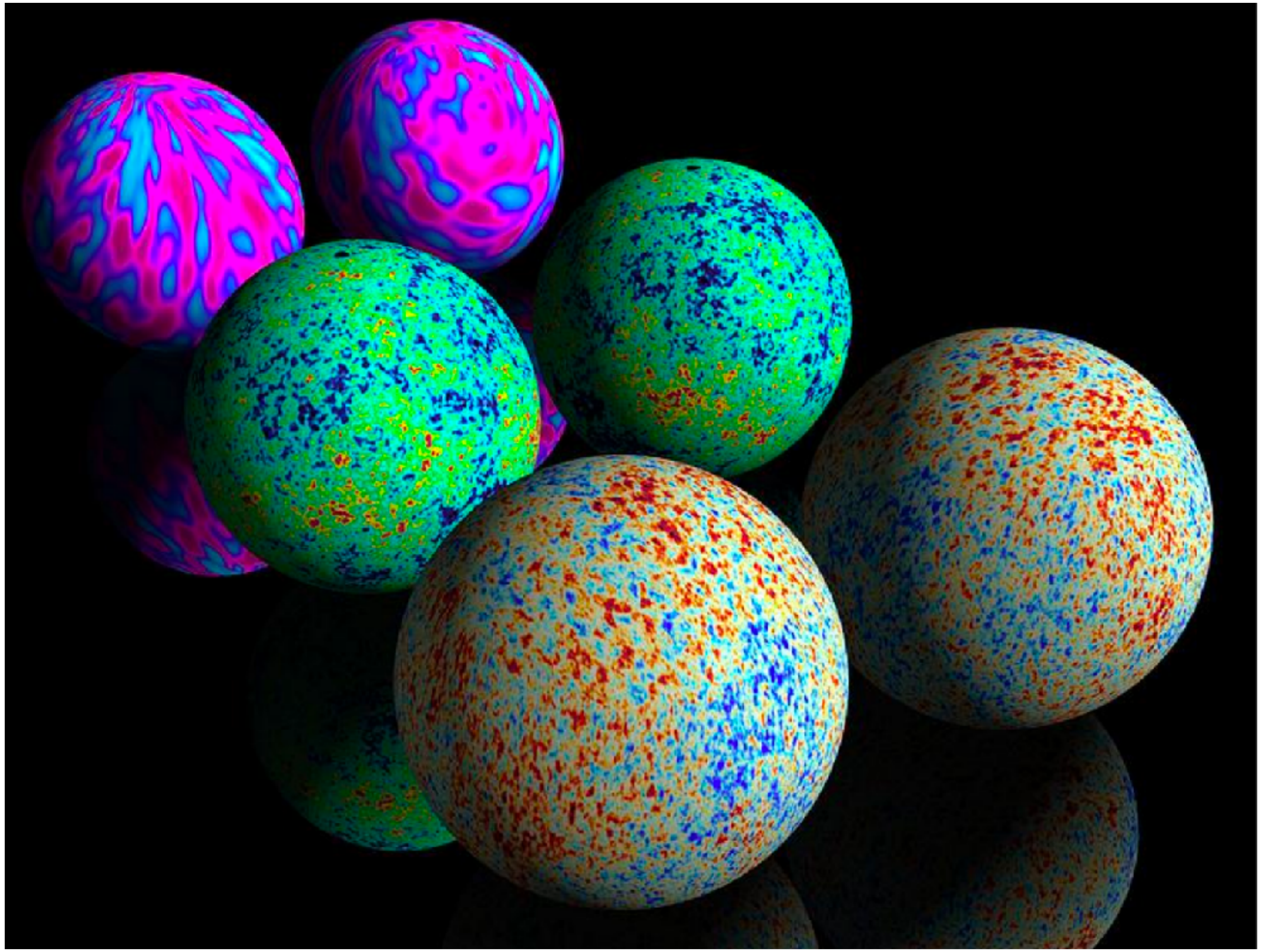


Reminder: these maps are projections of the celestial sphere

COBE
1990

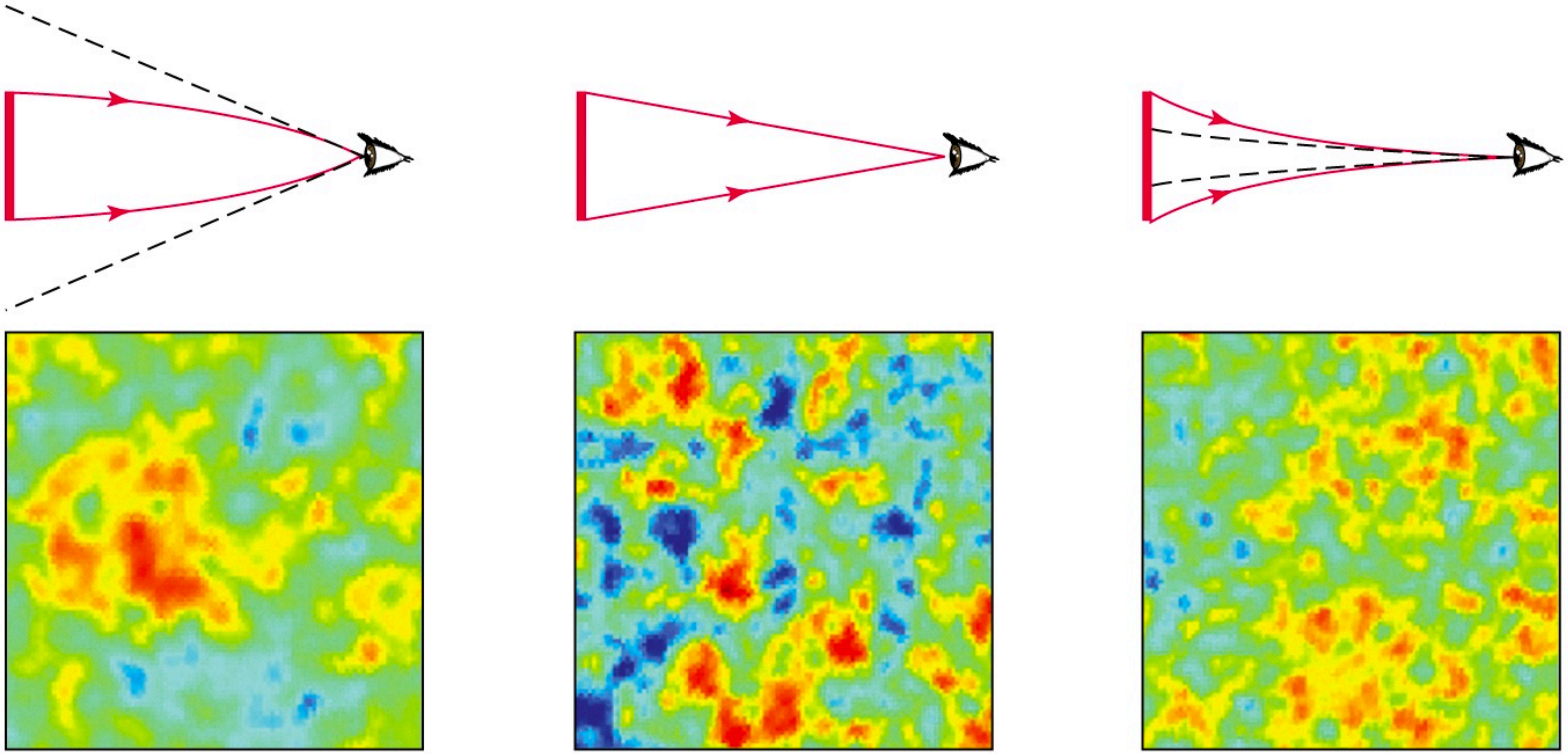
WMAP
2003

Planck
2013



https://fineartamerica.com/featured/cosmic-microwave-background-radiation-carlos-clarivan.html

CMB provides a giant triangle of known size!

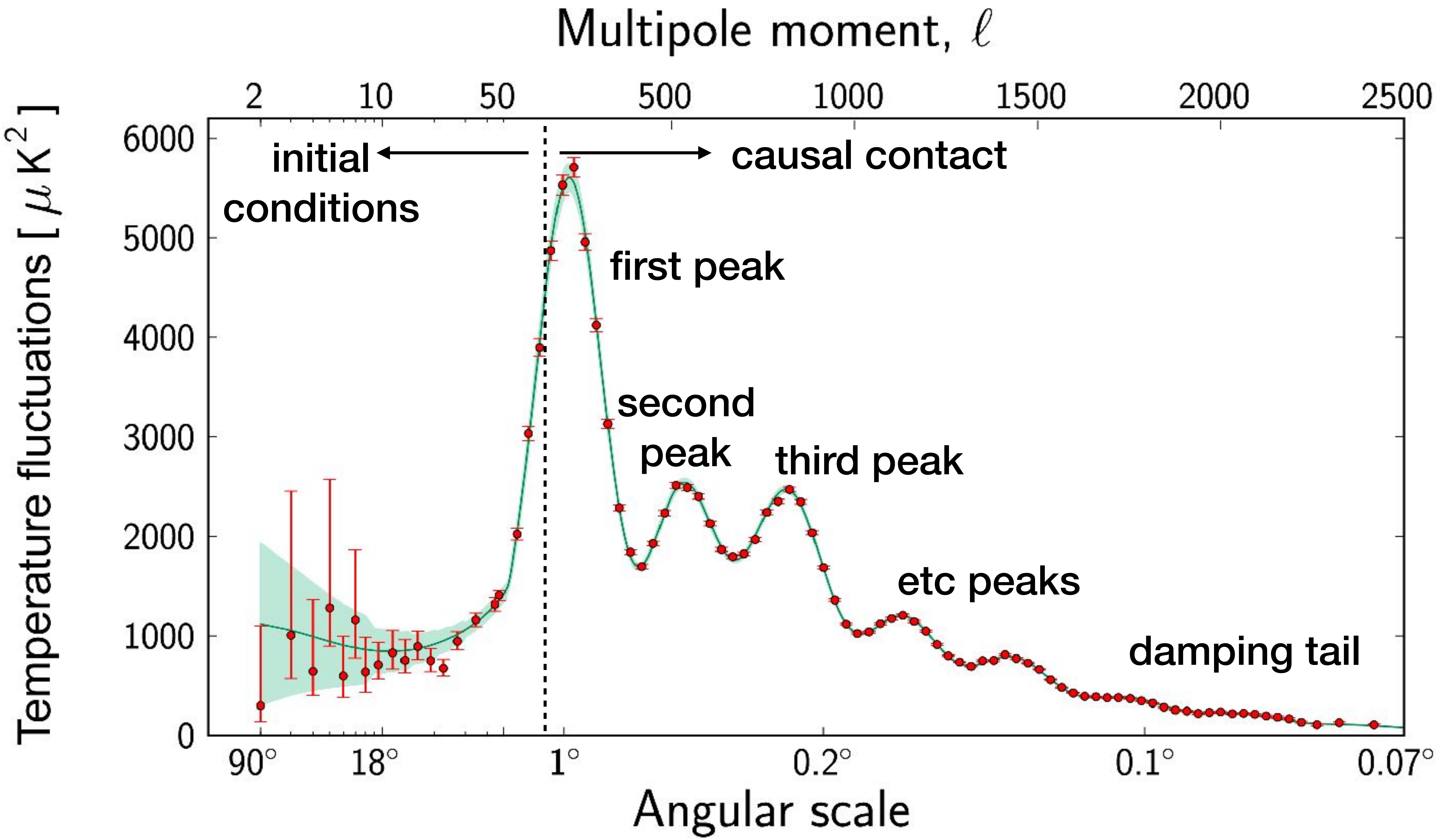


a If universe is closed, “hot spots” appear larger than actual size

b If universe is flat, “hot spots” appear actual size

c If universe is open, “hot spots” appear smaller than actual size

Acoustic peaks



First peak:
spatially flat

Second peak:
existence of "dark baryons"

Third peak:
amount of dark matter

Damping tail:
photons can cross entire grav. fluct., wipes out signal

What determines how the expansion of space changes?

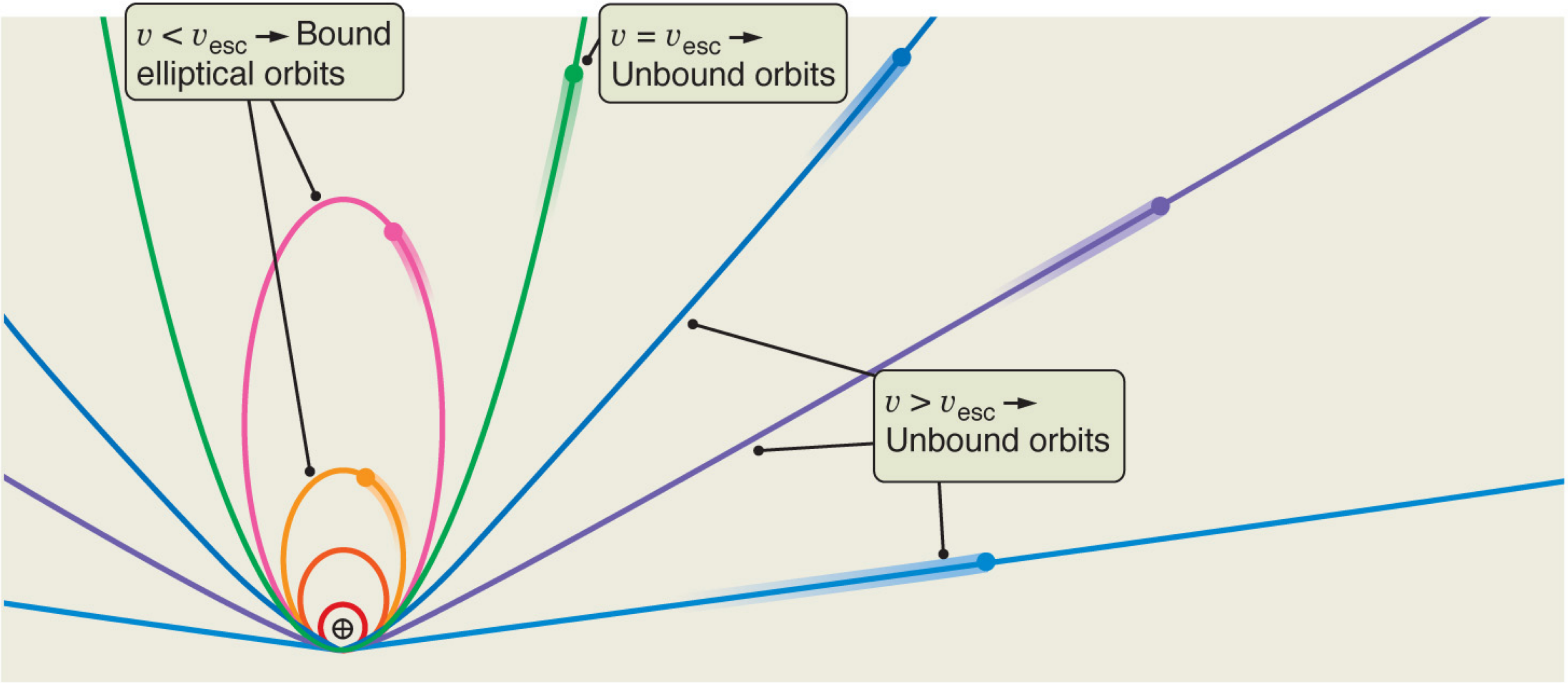
A) Its initial speed of expansion

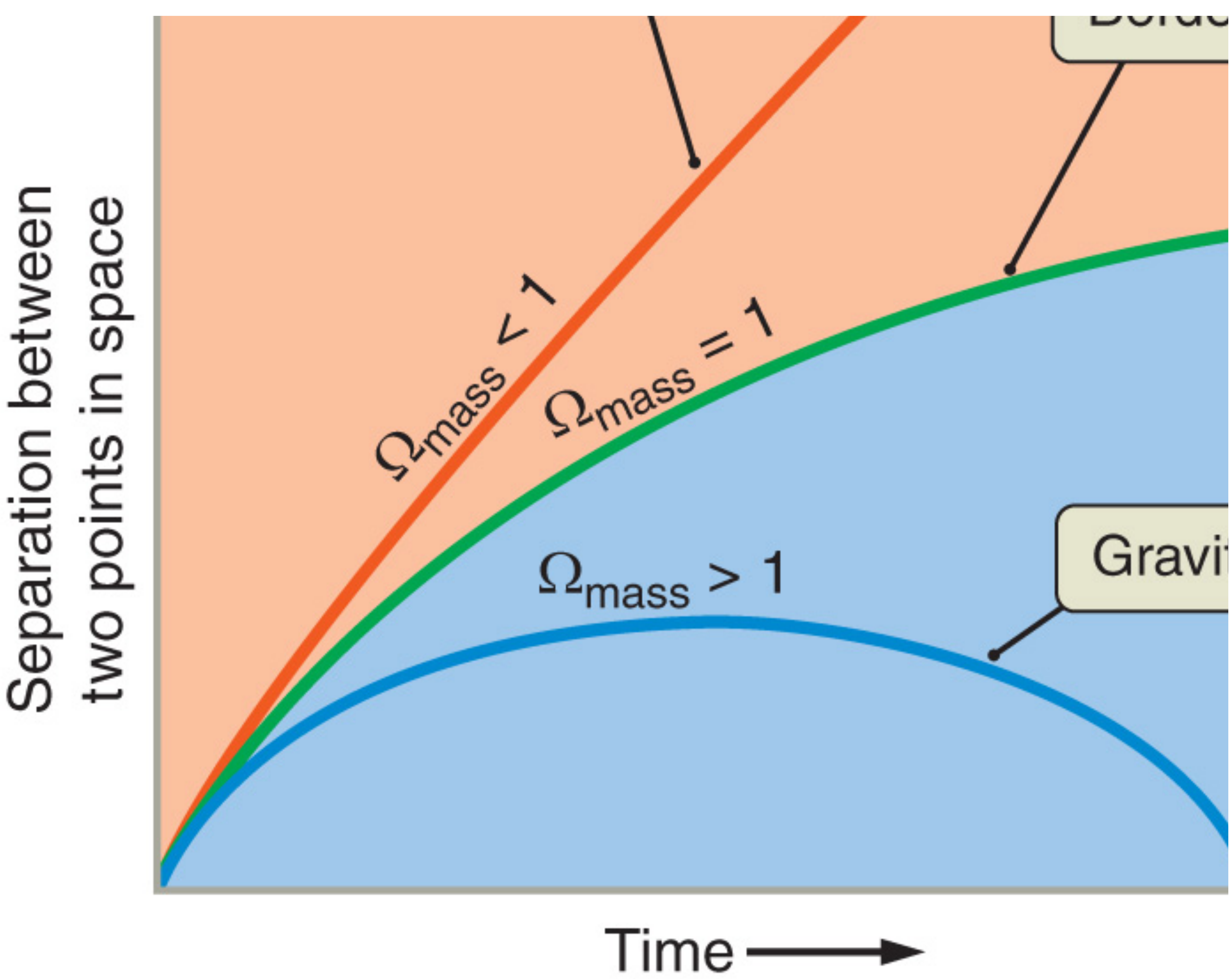
B) How many large structures form

C) The density of mass

D) The density of radiation

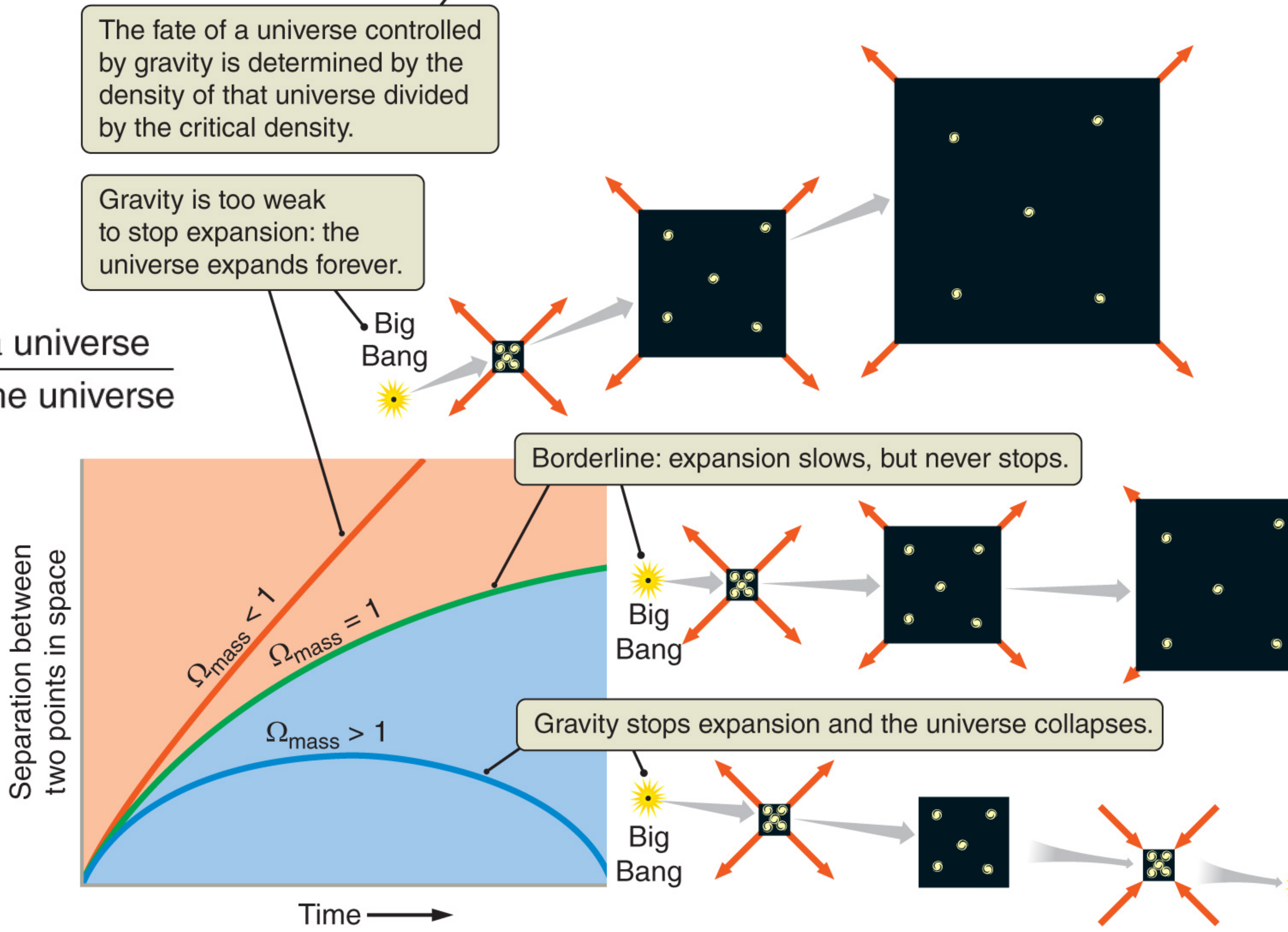
Escape Velocity - works for the expansion of the universe (in analogy)




Separation between two points in space
Time
Ωmass < 1
Ωmass = 1
Ωmass > 1
Gravit

$$\Omega_{mass} = \frac{\text{Actual density of a universe}}{\text{Critical density of the universe}}$$

since the 1920s, astronomers have been trying to figure out which universe we live in



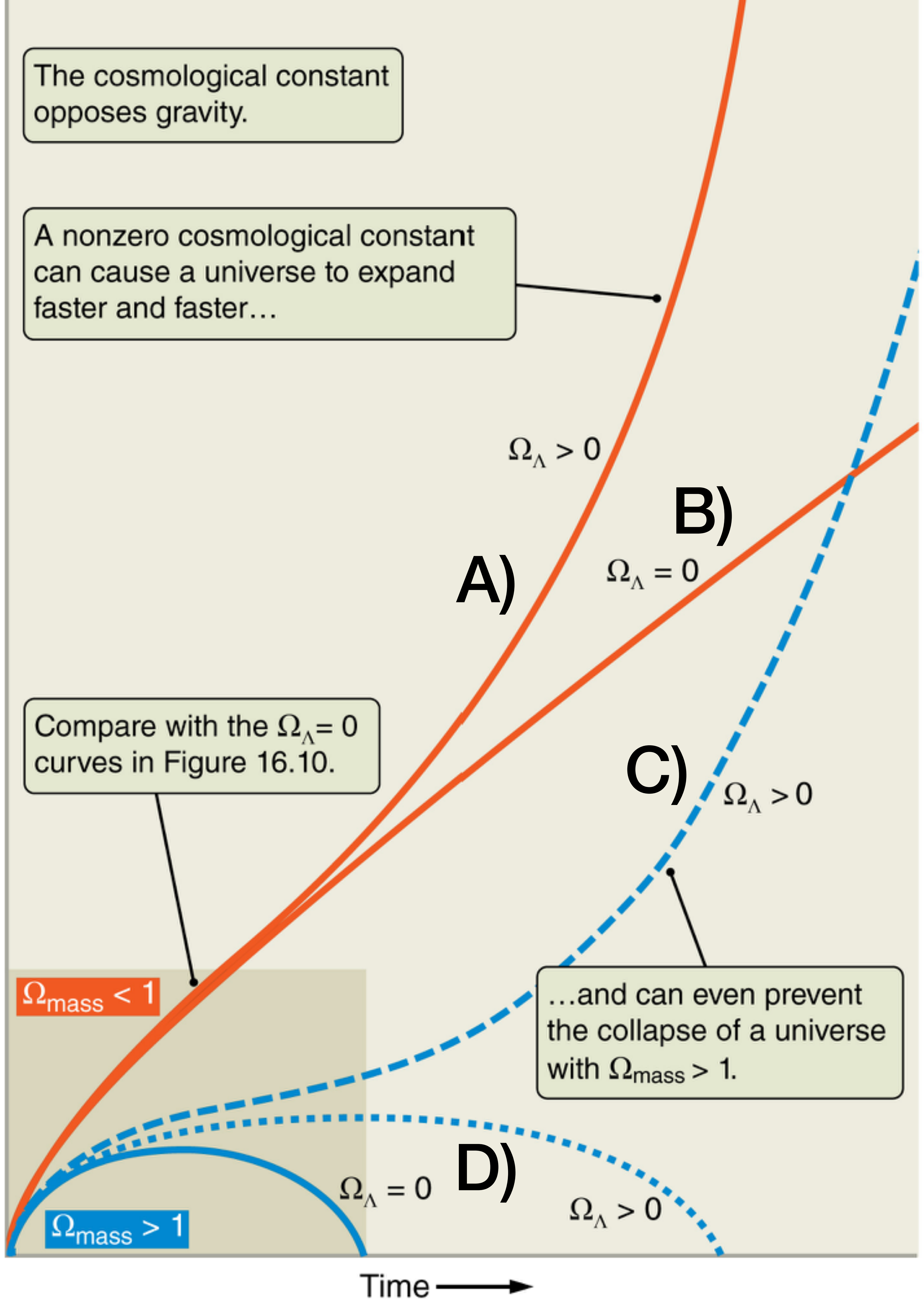
What is the fate of our universe?

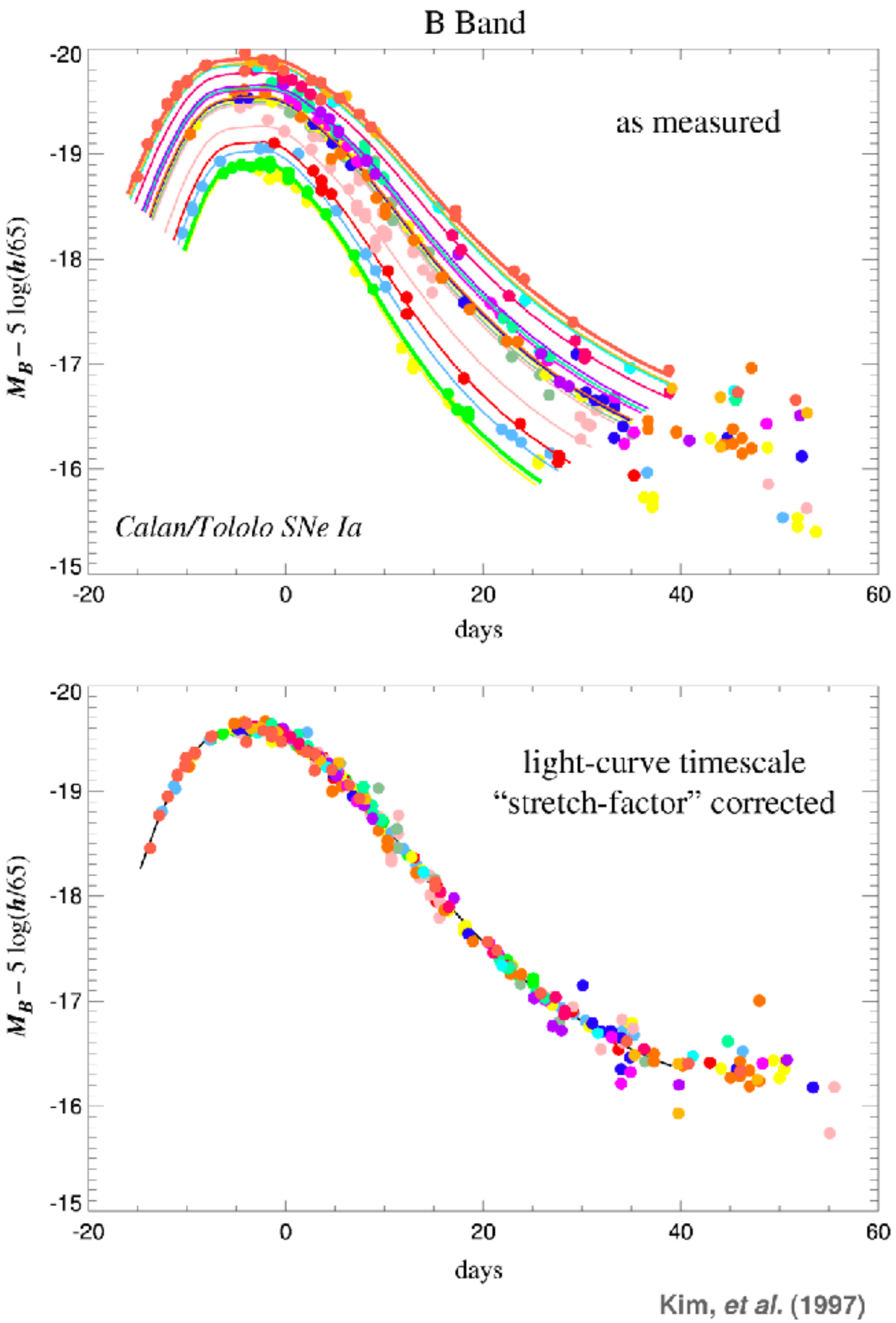
A) It will expand forever, gradually slowing down due to gravity

B) It will eventually stop expanding and recollapse

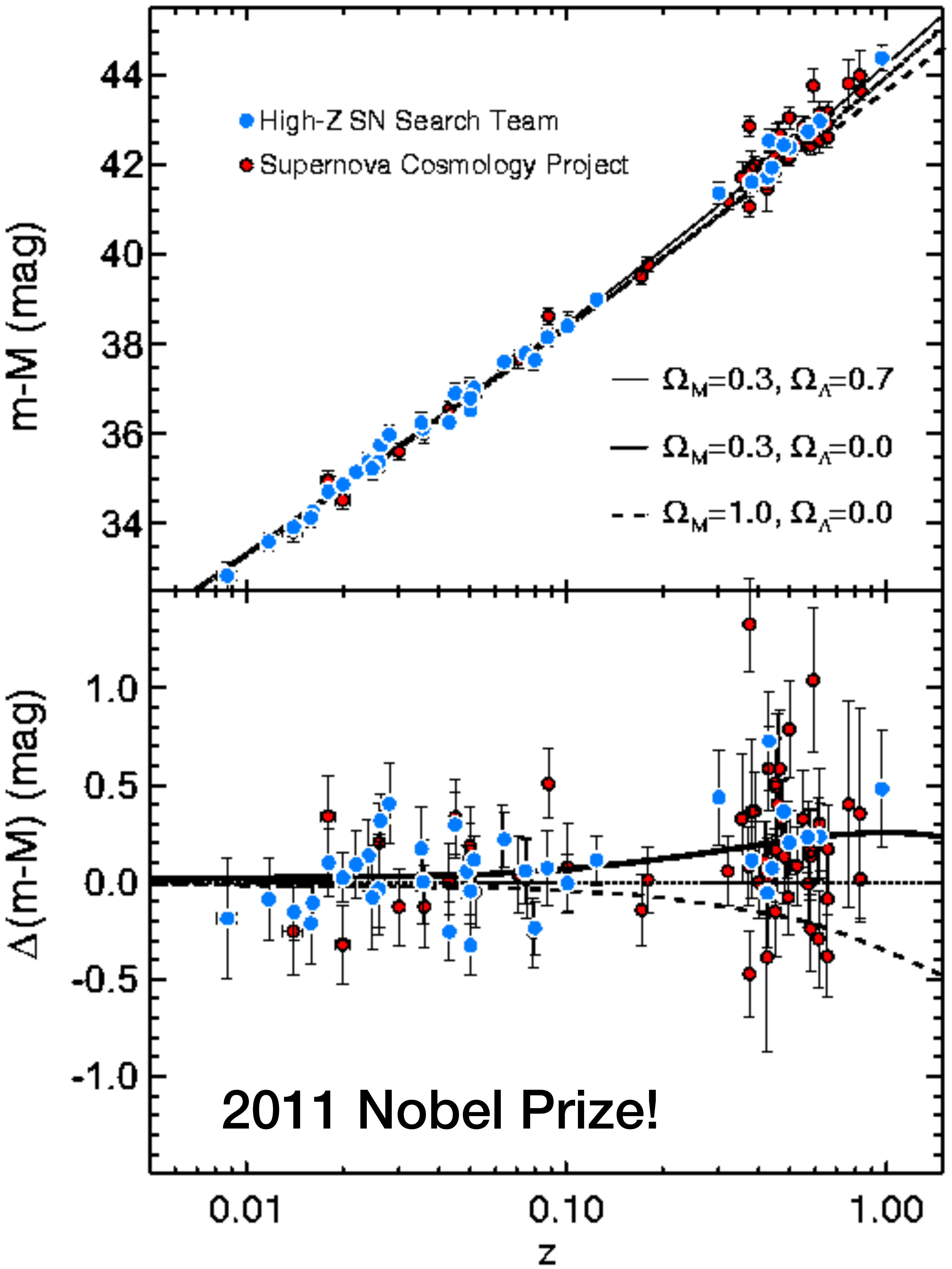
C) None of the above

Which universe do we (think) we live in?



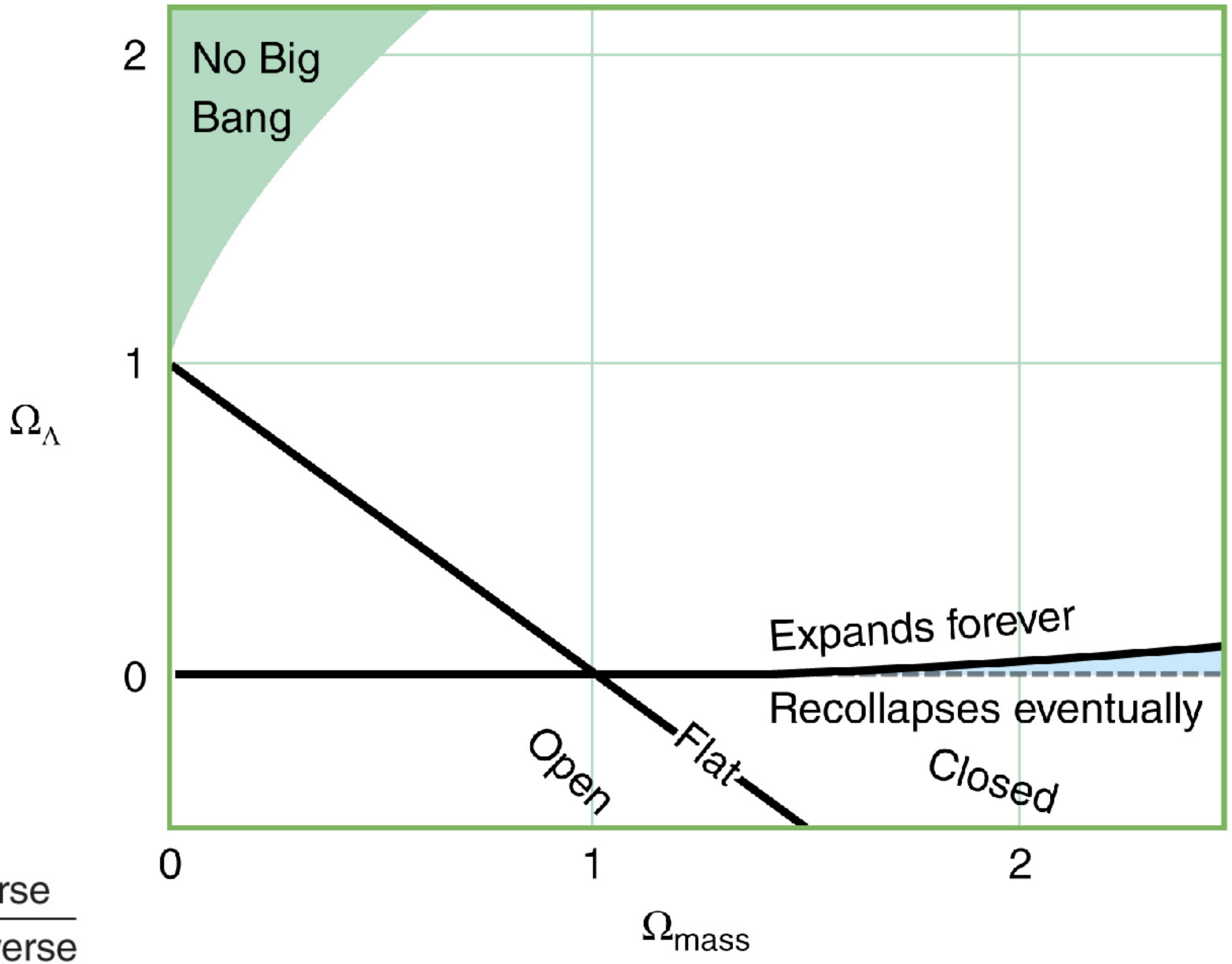


B Band
as measured
Calan/Tololo SNe Ia
$M_B - 5\log(h/65)$
days
light-curve timescale
“stretch-factor” corrected
$M_B - 5\log(h/65)$
days
Kim, et al. (1997)



High-Z SN Search Team
Supernova Cosmology Project
m-M (mag)
Ω_M=0.3, Ω_Λ=0.7
Ω_M=0.3, Ω_Λ=0.0
Ω_M=1.0, Ω_Λ=0.0
Δ(m-M) (mag)
2011 Nobel Prize!
z

Amount of matter (normal plus dark) and dark energy determine the fate AND CURVATURE of the universe



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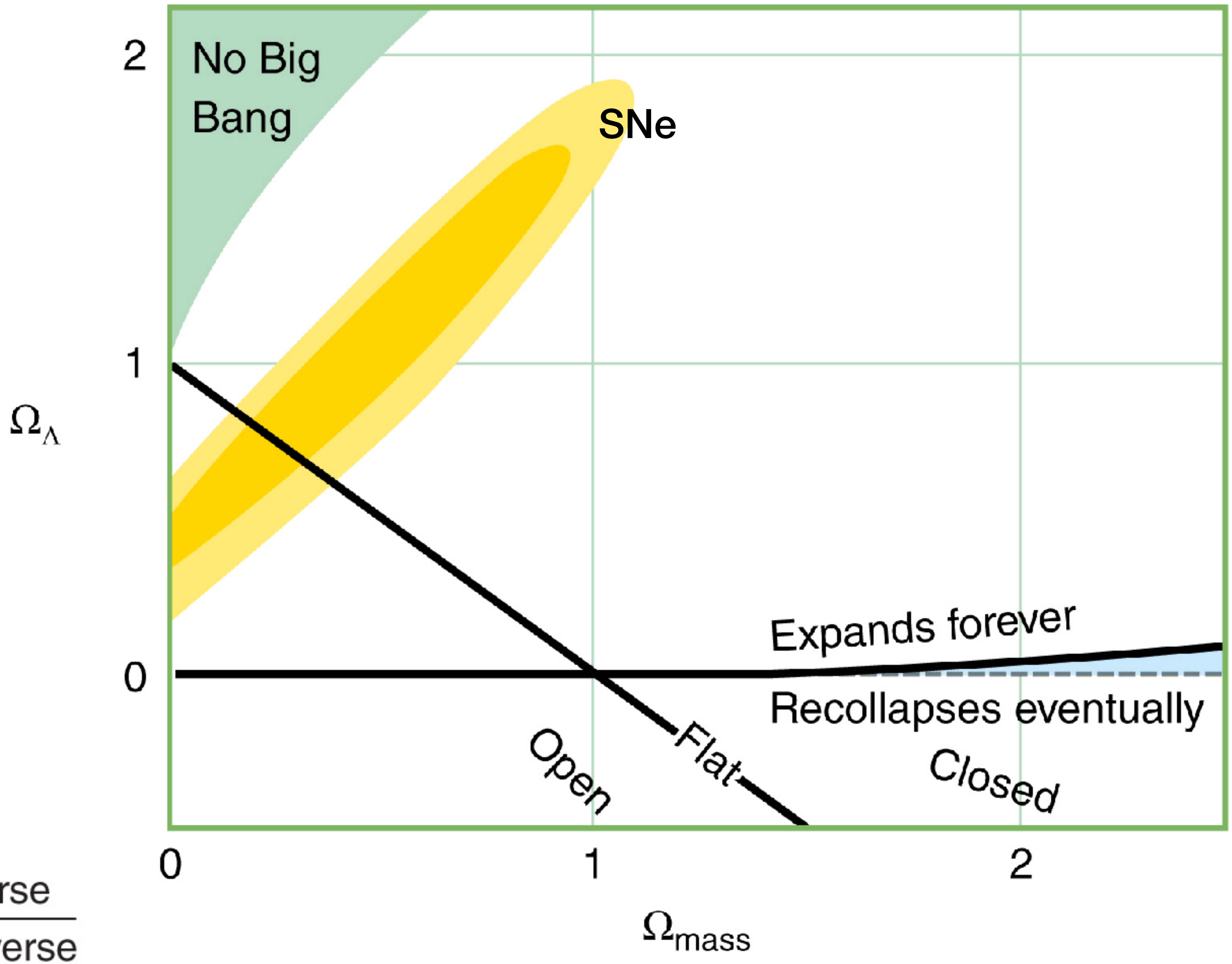
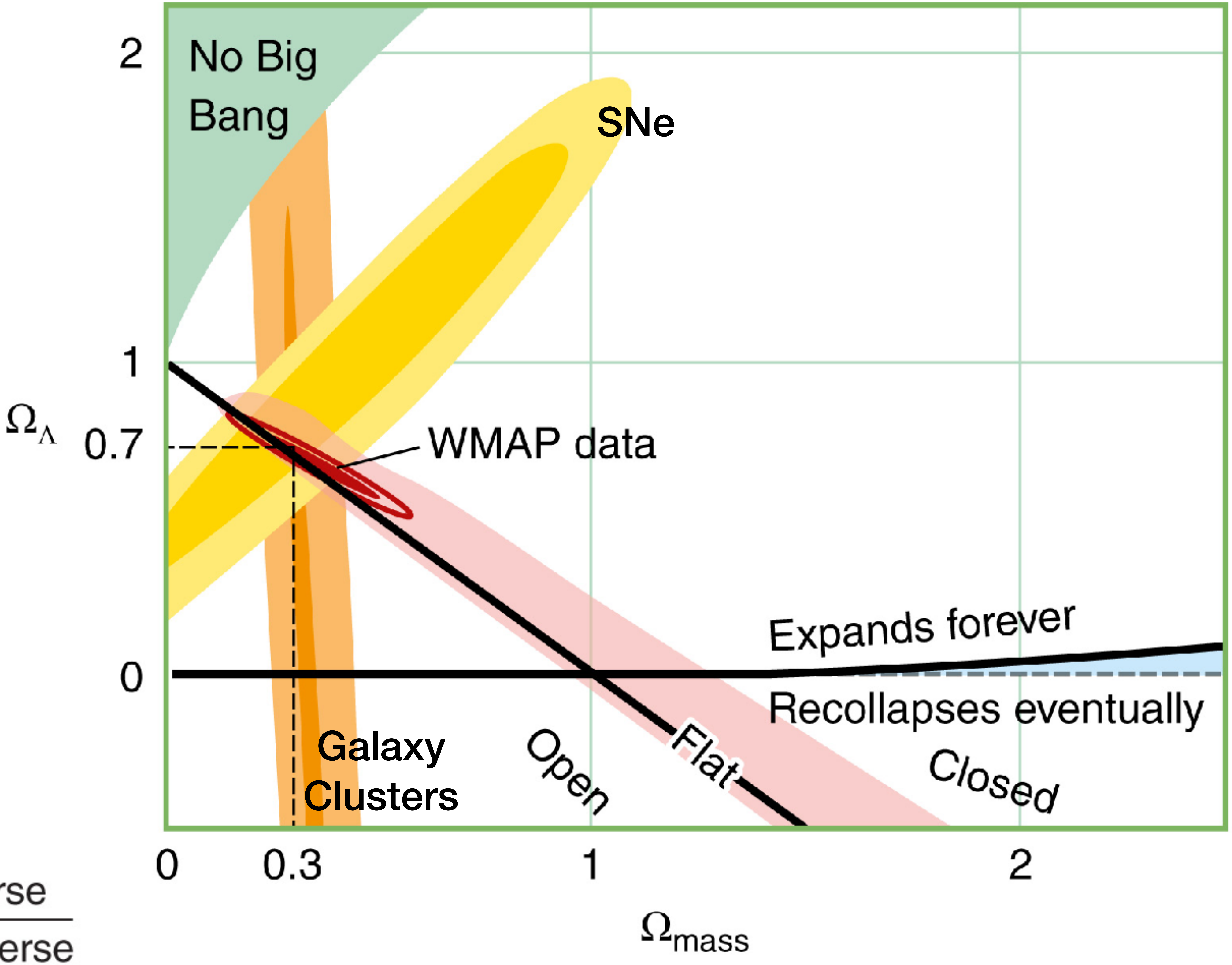


$$\Omega_{mass} = \frac{\text{Actual density of a universe}}{\text{Critical density of the universe}}$$

Amount of matter (normal plus dark) and dark energy determine the fate AND CURVATURE of the universe



$$\Omega_{mass} = \frac{\text{Actual density of a universe}}{\text{Critical density of the universe}}$$

Parameters that determine the evolution of the universe

Matter	Dark Energy	Radiation (CMB)	Curvature

$$\Omega_m + \Omega_\Lambda + \Omega_r + \Omega_k = 1$$

~0.3	~0.7	$\sim 9\times10^{-5}$	~0

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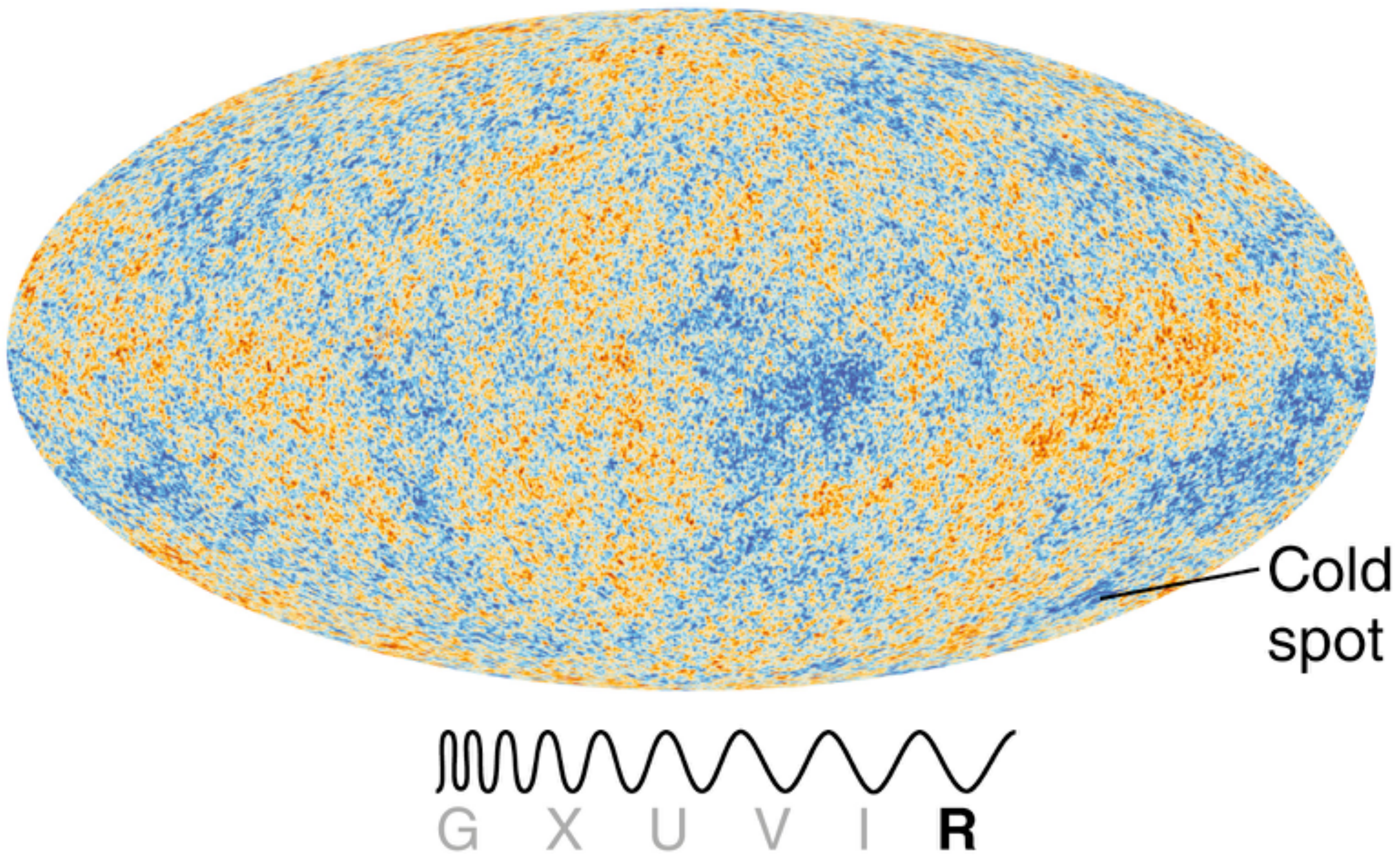
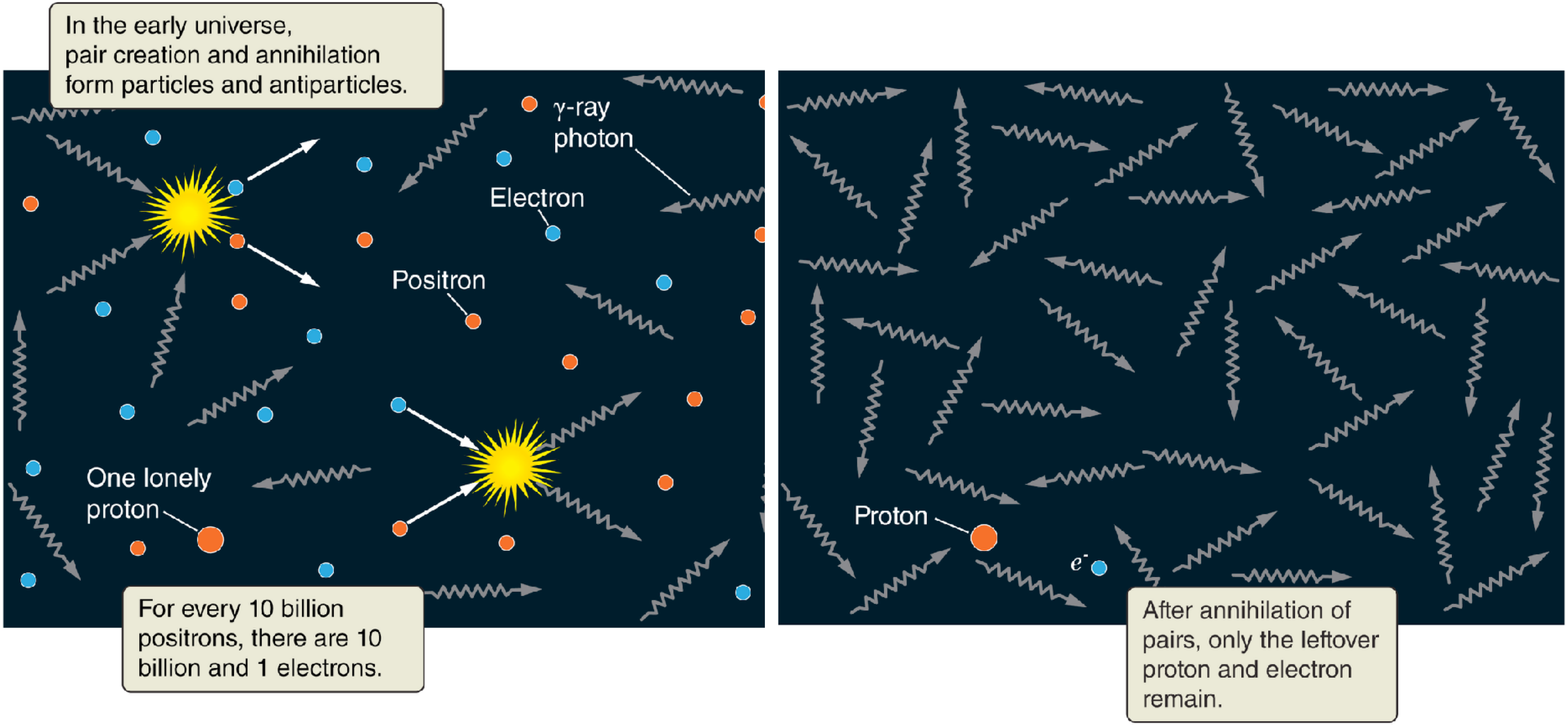


Origin of matter and the CMB



Two features we would like to explain

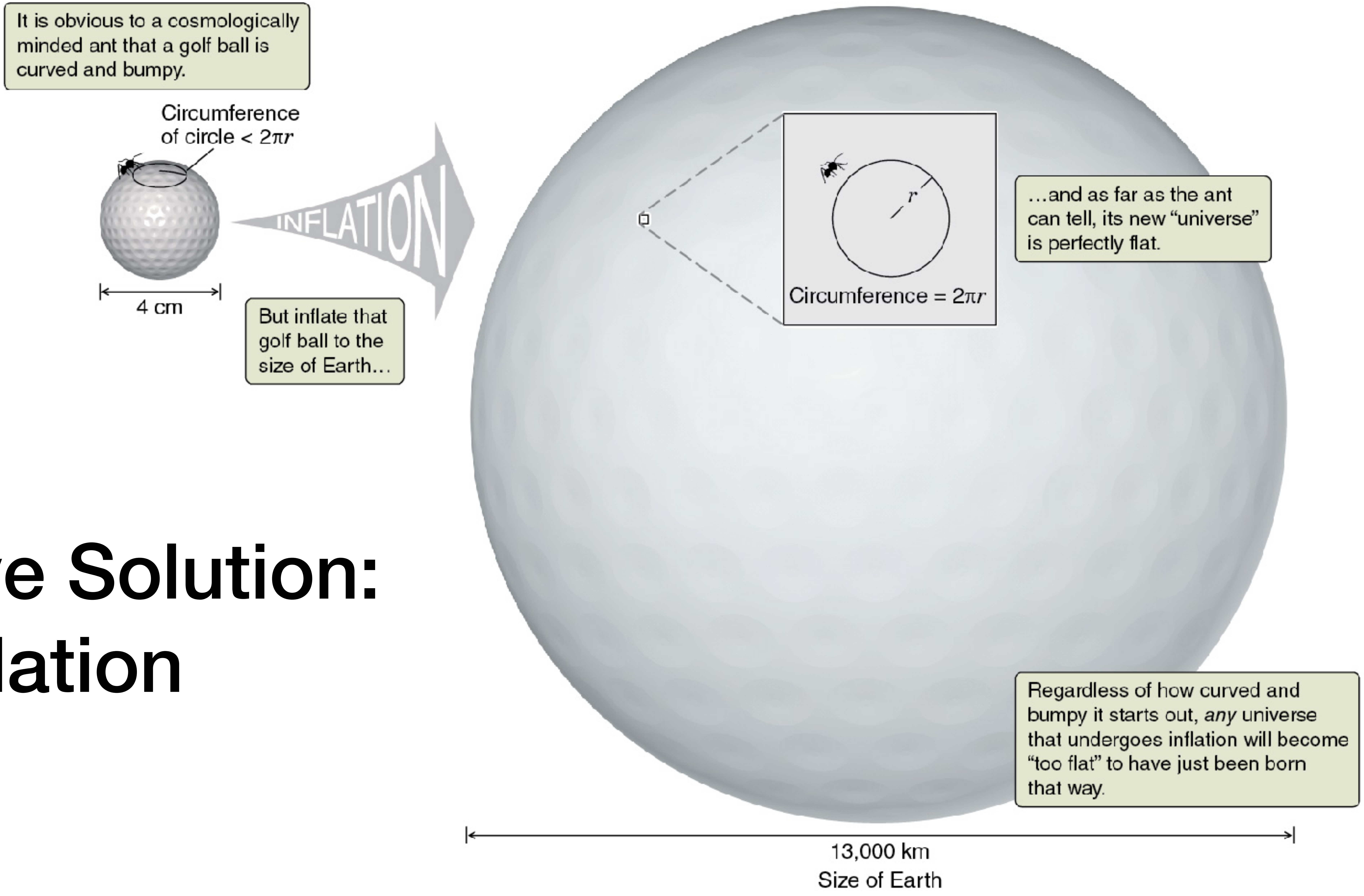
The Flatness Problem

Why is the universe flat when that is the least likely curvature the universe could have?

The Horizon Problem

Why is the temperature of the CMB the same on opposite sides of the universe?

Attractive Solution: Inflation



String theory, the multiverse, etc., are not scientific theories

But, for better or worse, scientists work on them and talk about them, so tautologically they are science