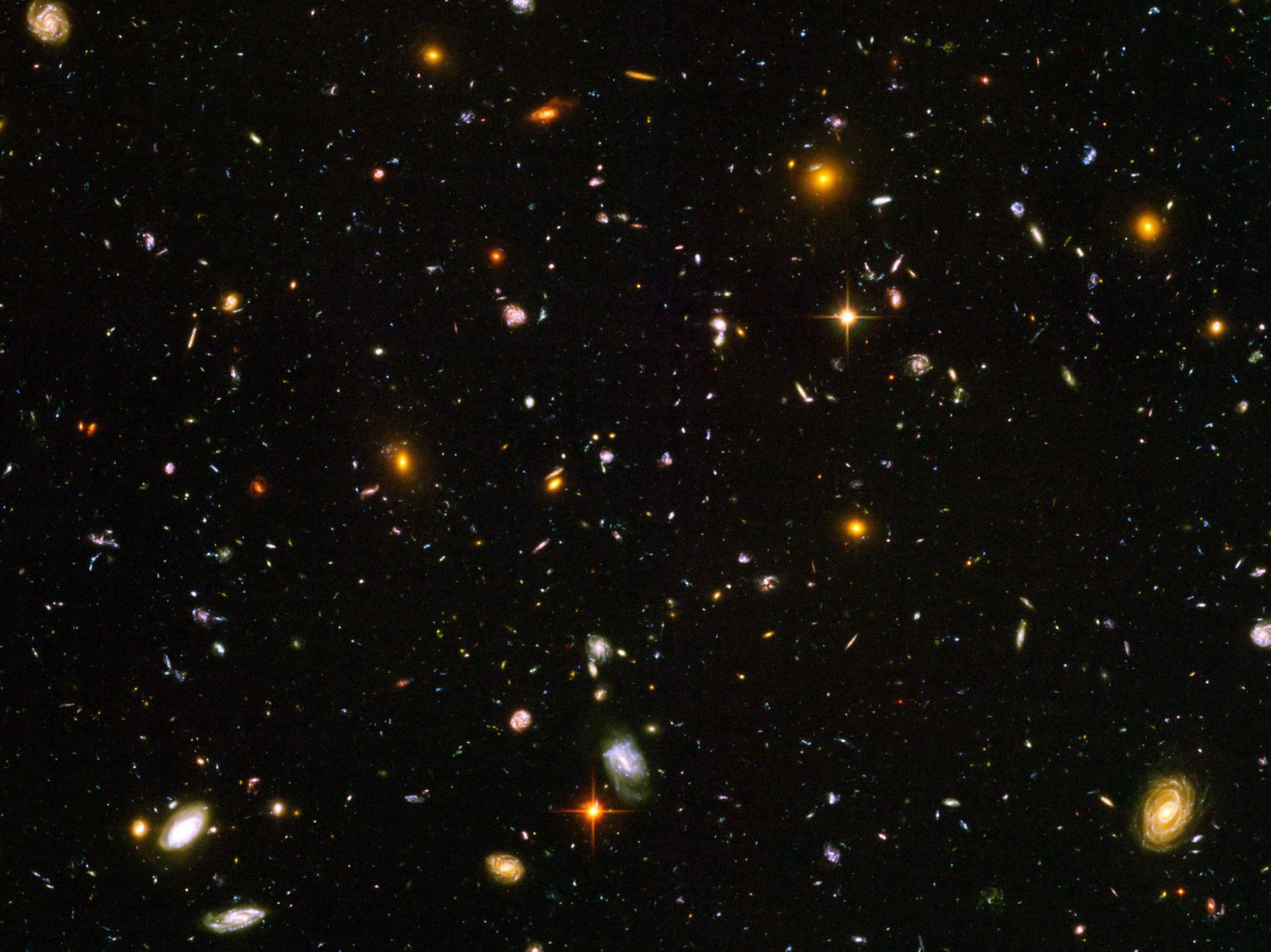
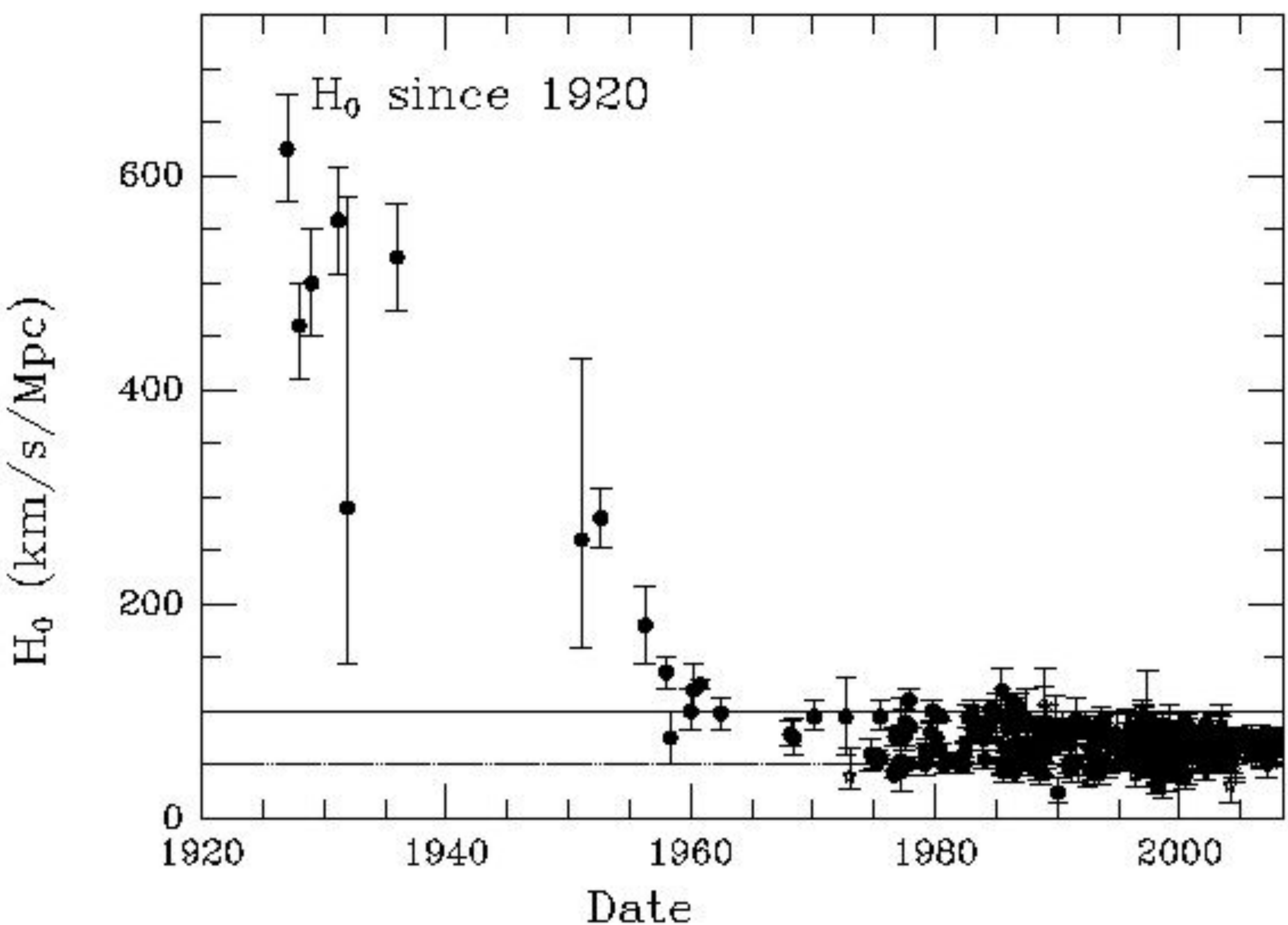
ASTR368

Cosmology

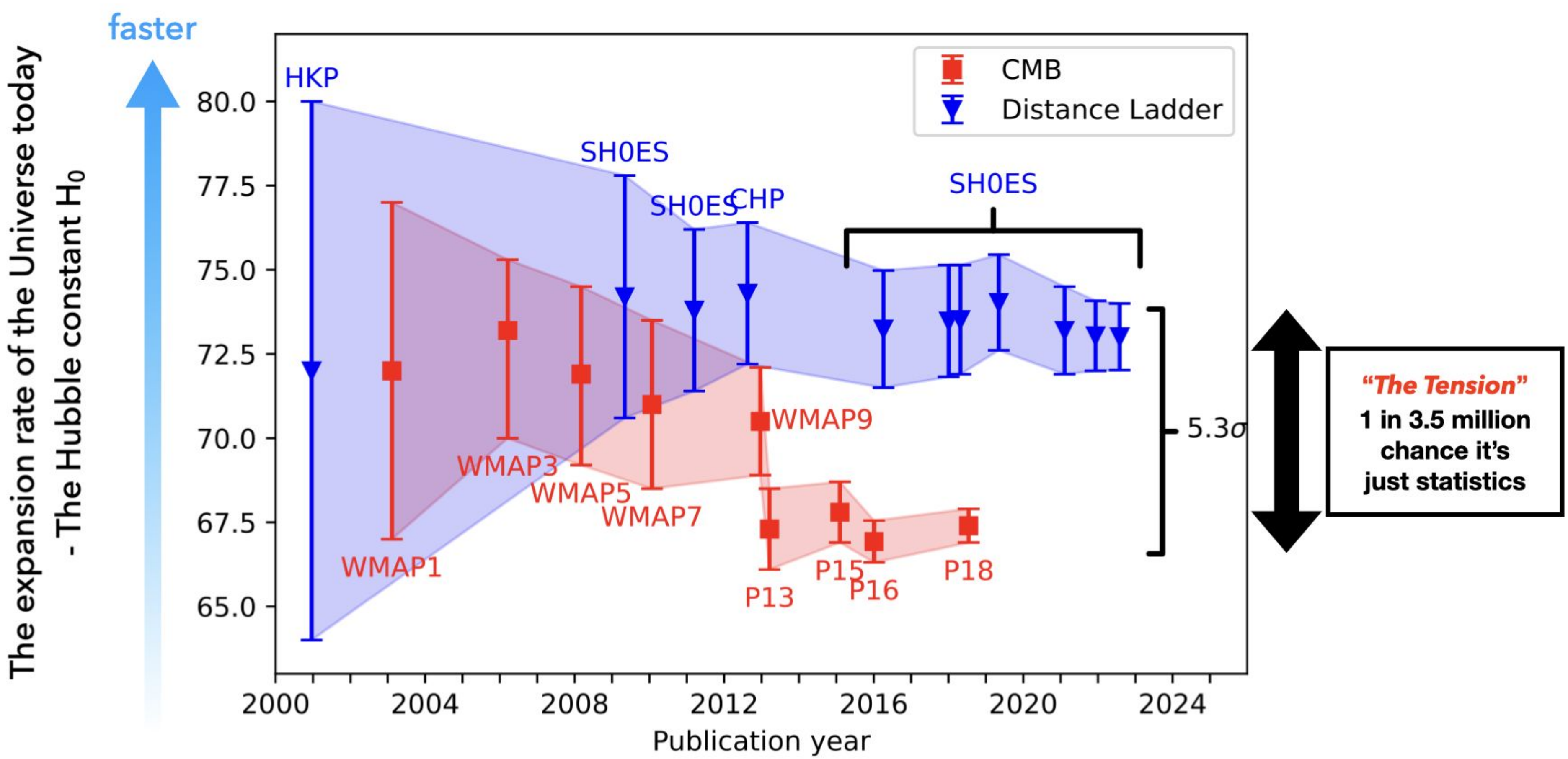
Because light has a finite speed, when we look at distant objects, we are seeing them as they looked in the past.

High redshift=large distance=far back in time

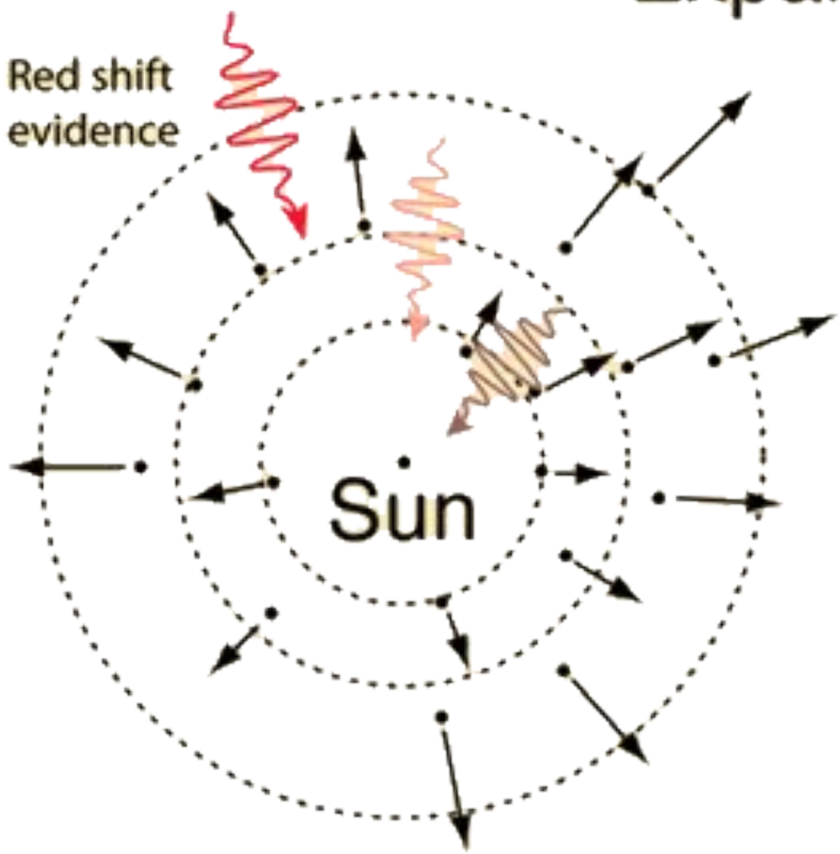



H$_0$ since 1920
H$_0$ (km/s/Mpc)
0
200
400
600
1920
1940
1960
1980
2000
Date

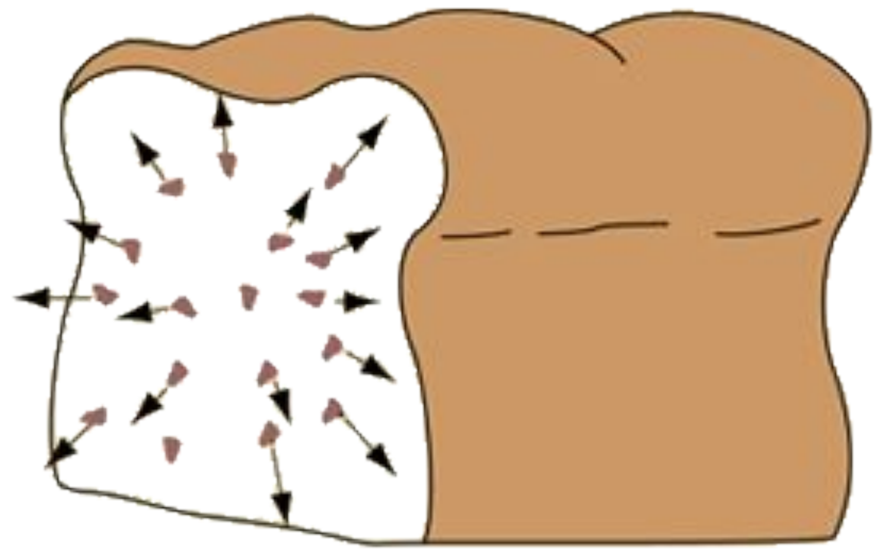
An emerging problem in Physics



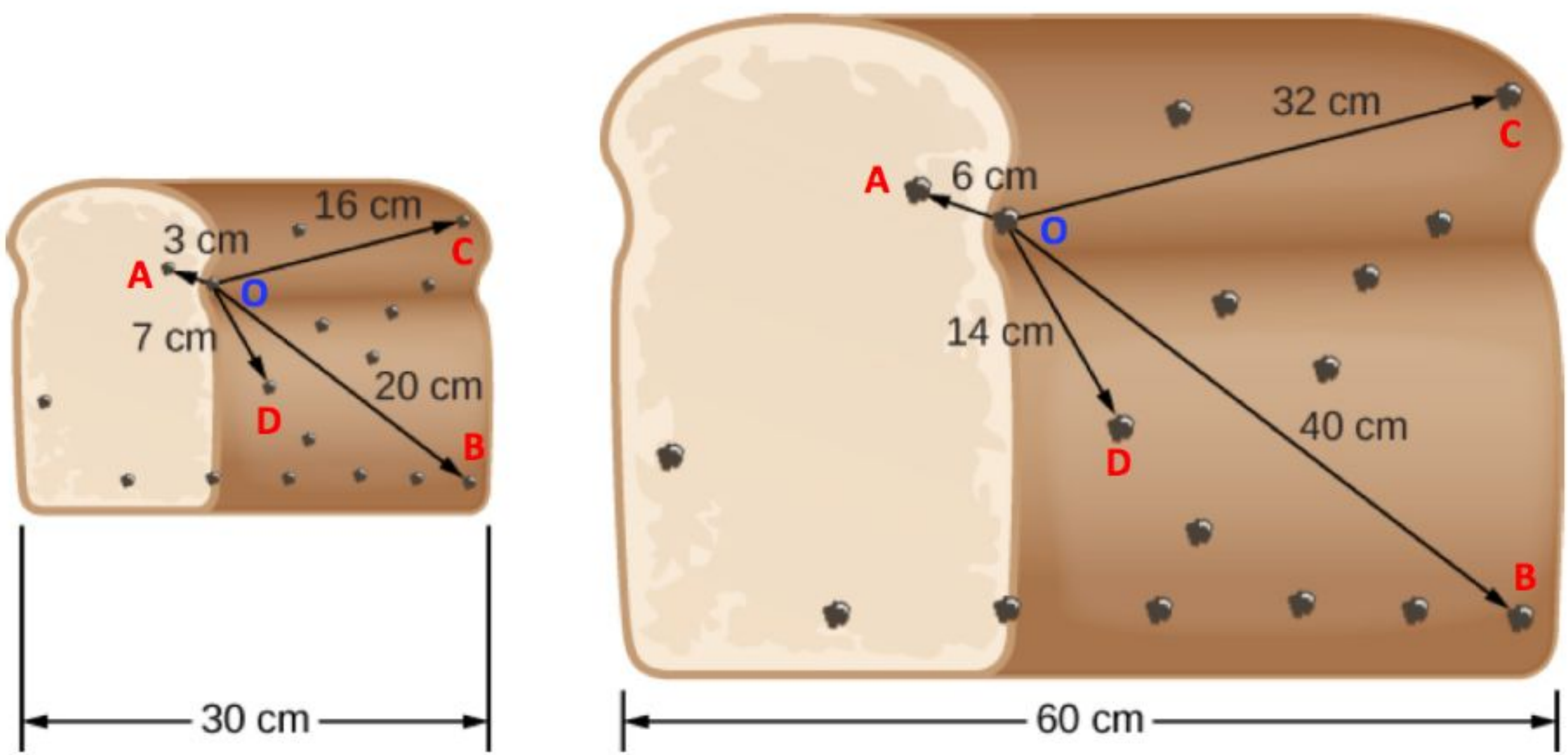
Expanding universe

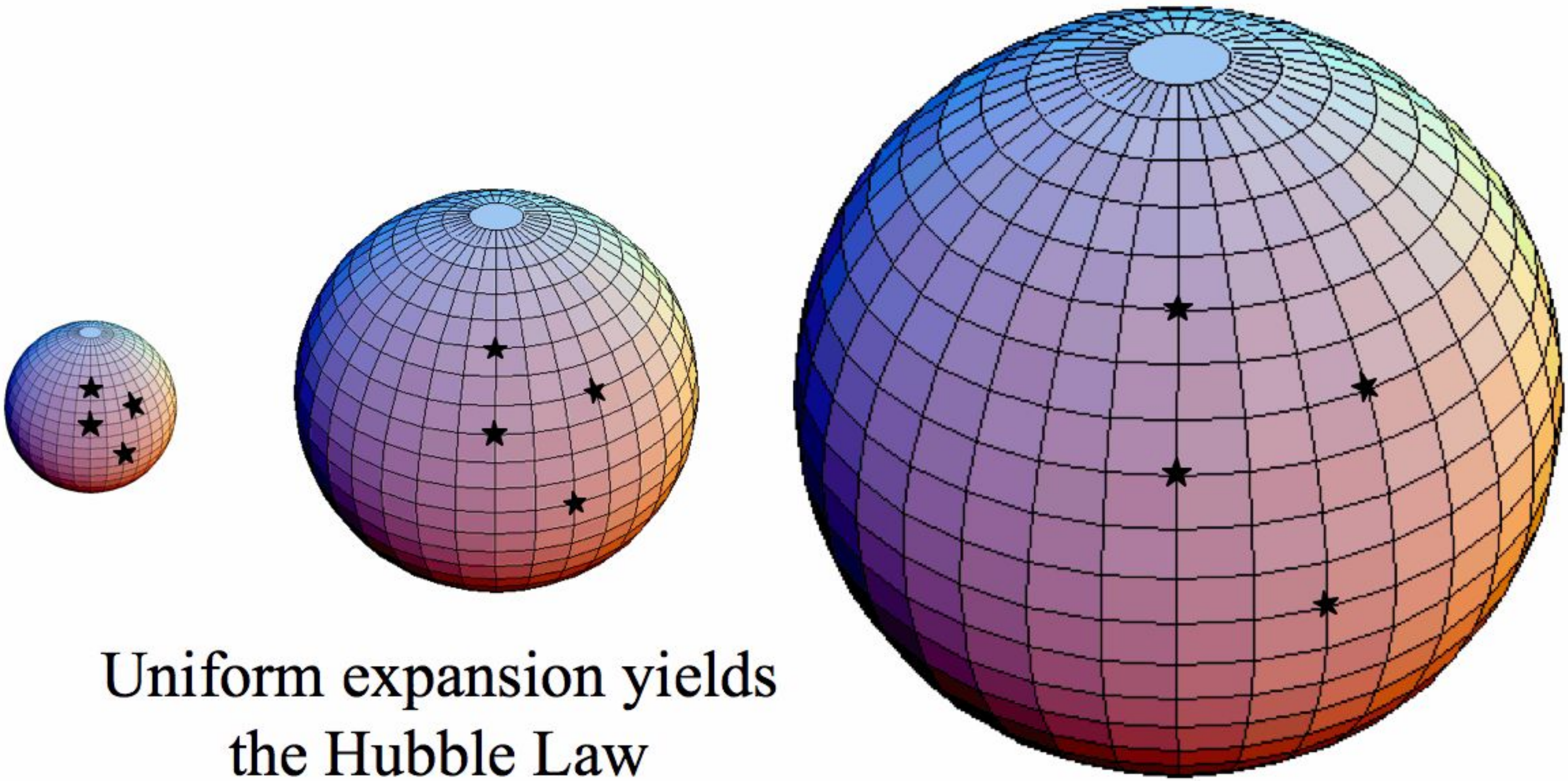


H = 71 km/s/Mpc



Every raisin in a rising loaf of raisin bread will see every other raisin expanding away from it.


16 cm
3 cm
A
O
C
7 cm
20 cm
D
B
30 cm
32 cm
C
A
6 cm
O
14 cm
40 cm
D
B
60 cm



Uniform expansion yields
the Hubble Law

$$v = H_0 d$$

$$t_H = d/v = 1/H_0$$

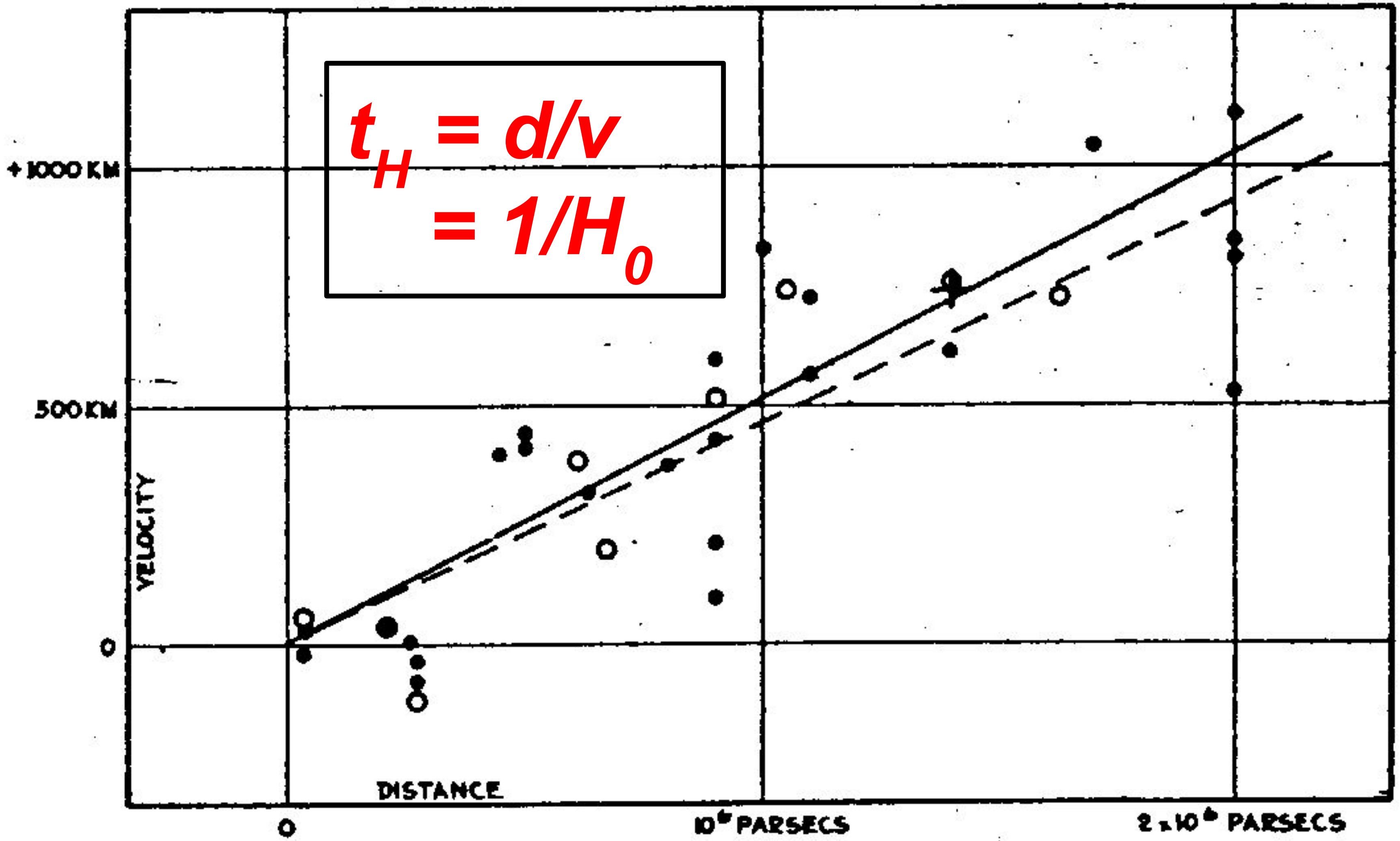
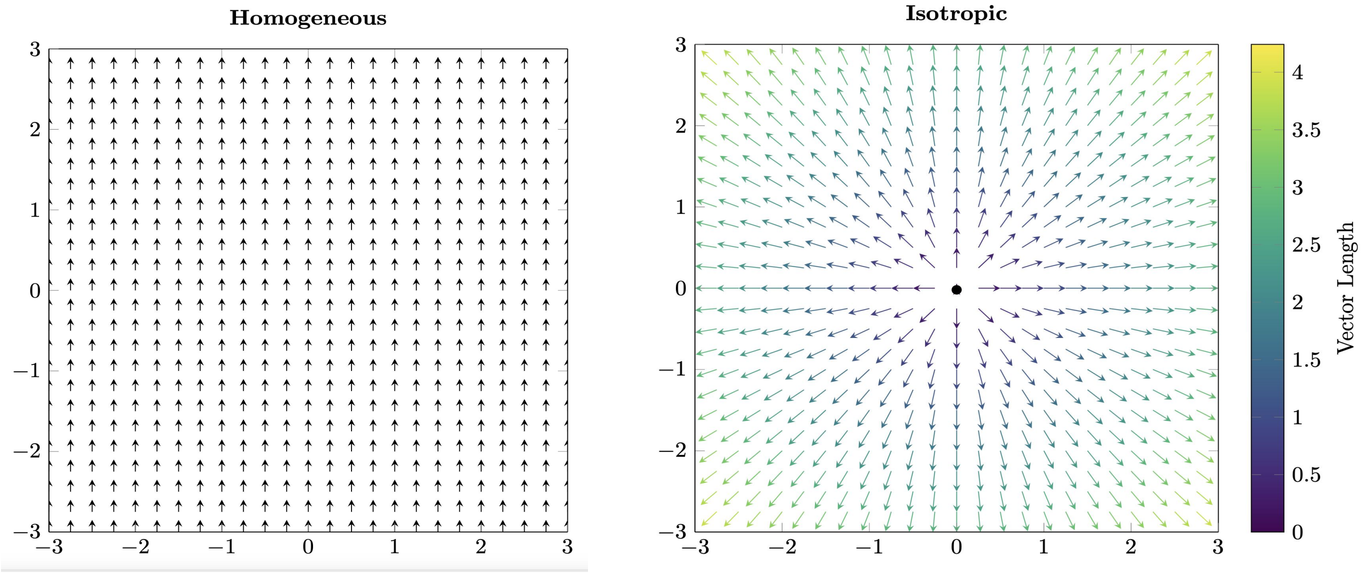


FIGURE 1

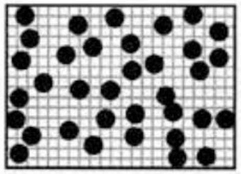
The Cosmological Principle

The Universe is *homogeneous* (there is no preferred location) and *isotropic* (the same in all directions) on “large enough” scales. In other words, the Universe that we can observe is a fair sample.

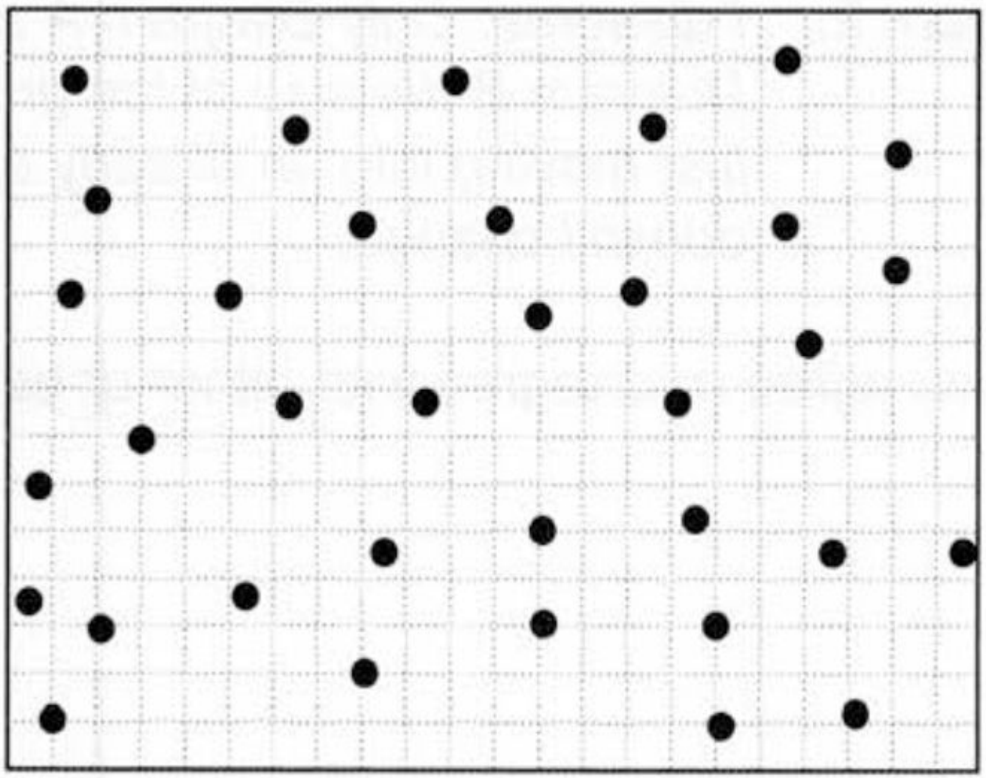


Credit: Joseph Kania thesis, WVU, 2023

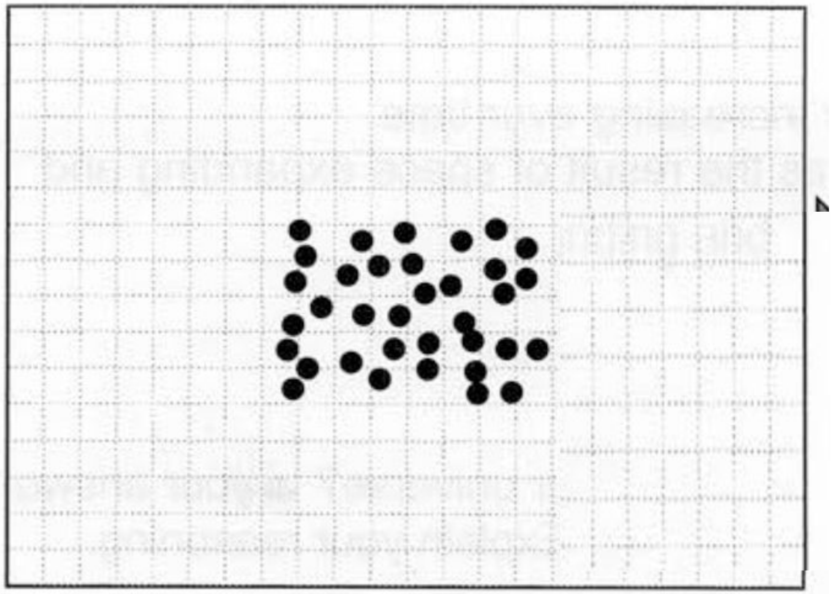
Past - Version A



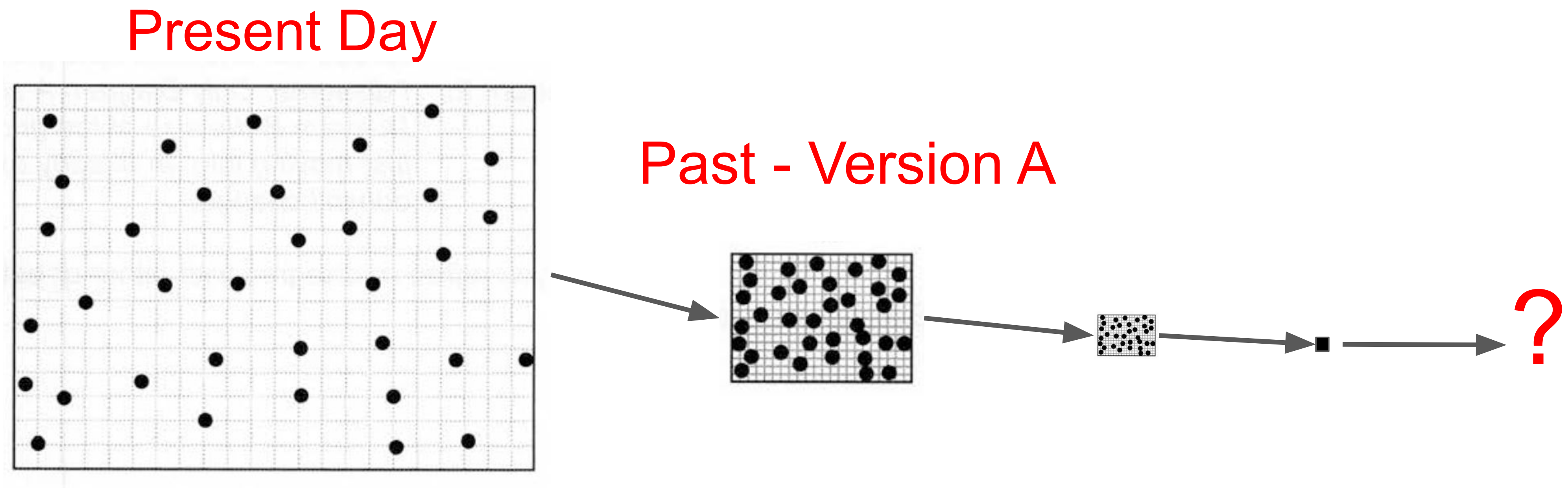
Present Day

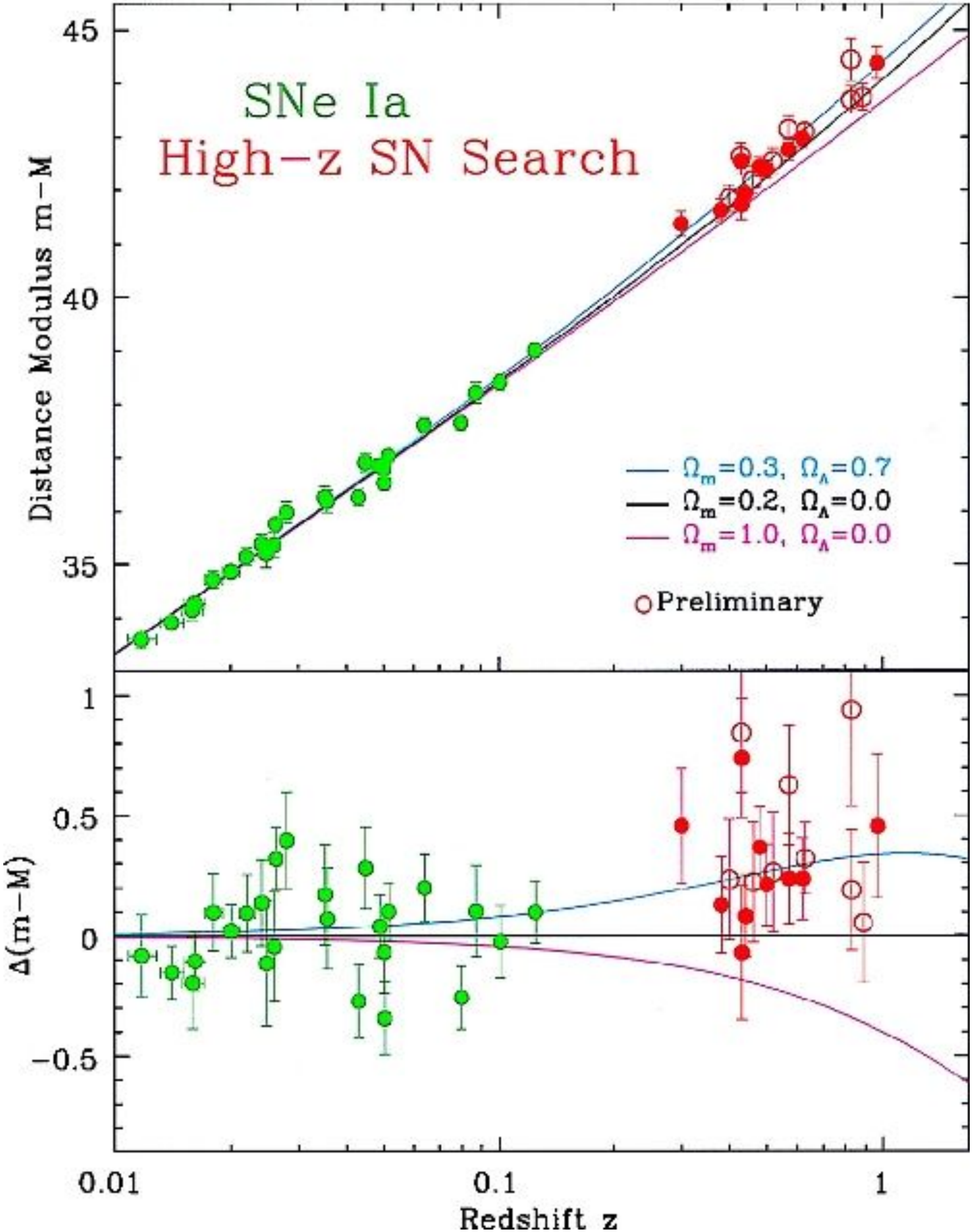


Past - Version B



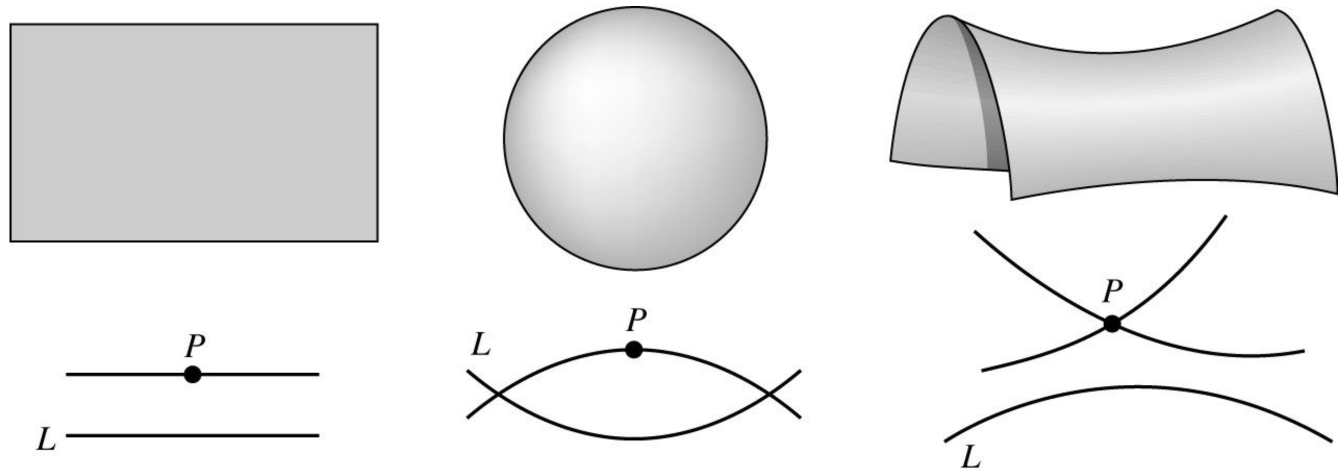
Space Itself is Expanding!


Present Day
Past - Version A
?

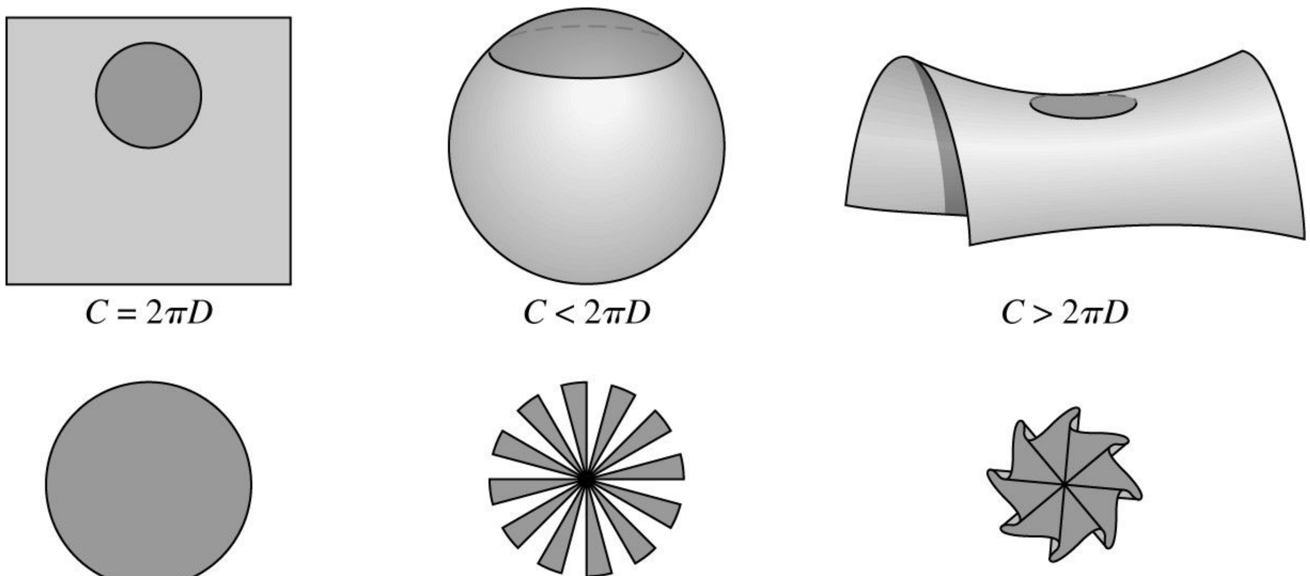


SNe Ia
High-z SN Search
Distance Modulus m−M
45
40
35
Ω_m=0.3, Ω_Λ=0.7
Ω_m=0.2, Ω_Λ=0.0
Ω_m=1.0, Ω_Λ=0.0
Preliminary
Δ(m−M)
1
0.5
0
−0.5
0.01
0.1
1
Redshift z

Geometries



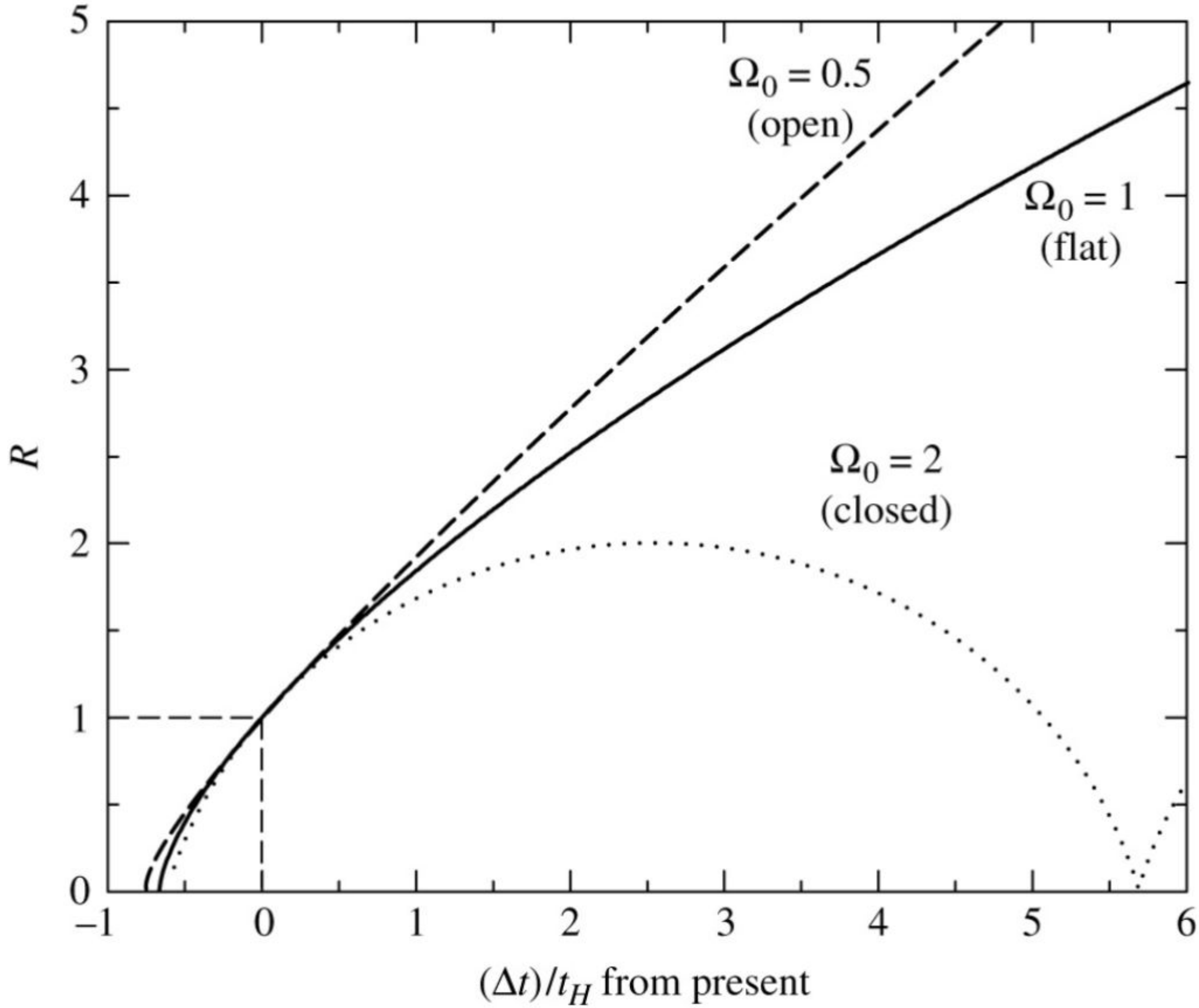
(a) (b) (c)



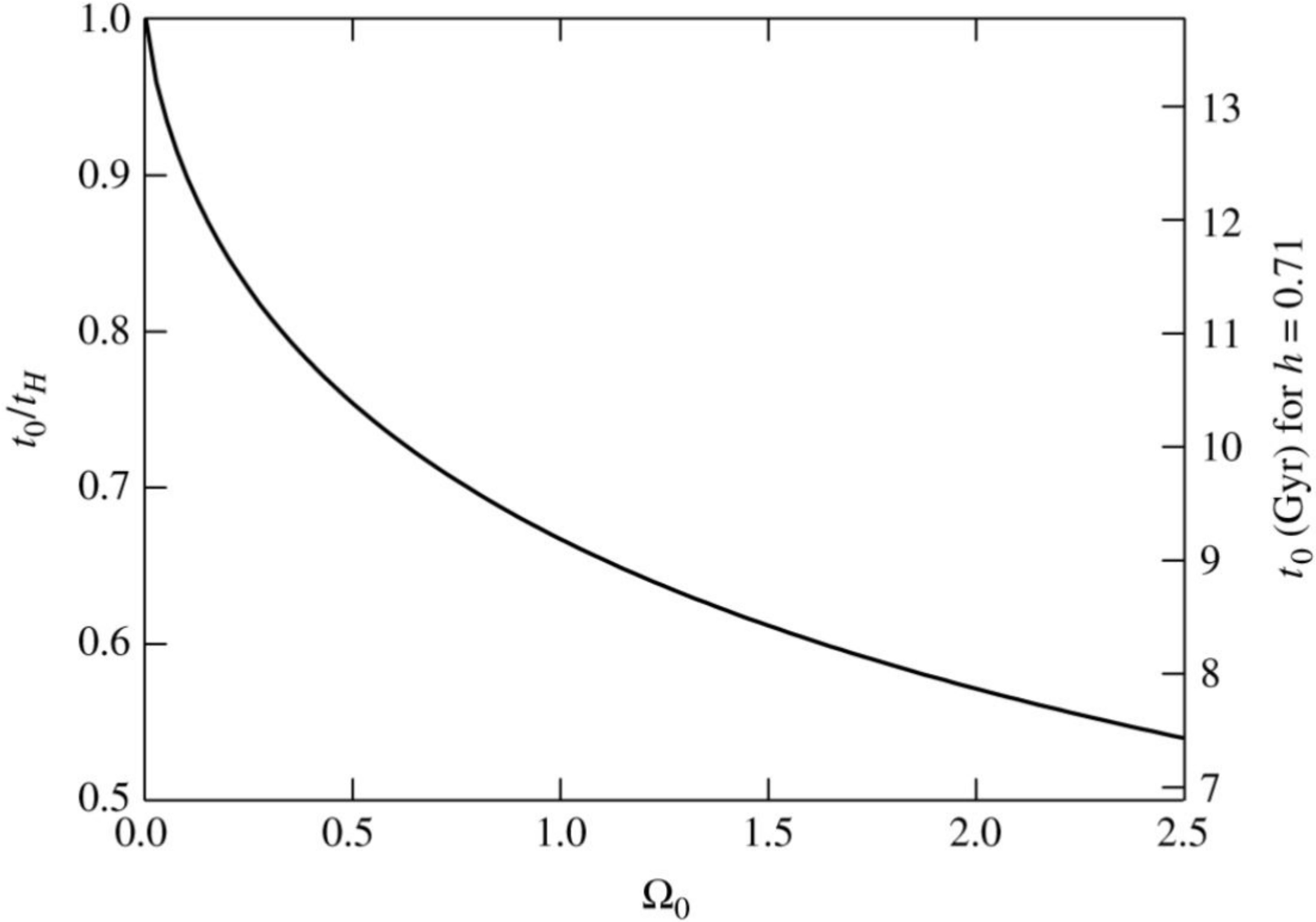
Zero curvature (a)

Positive curvature (b)

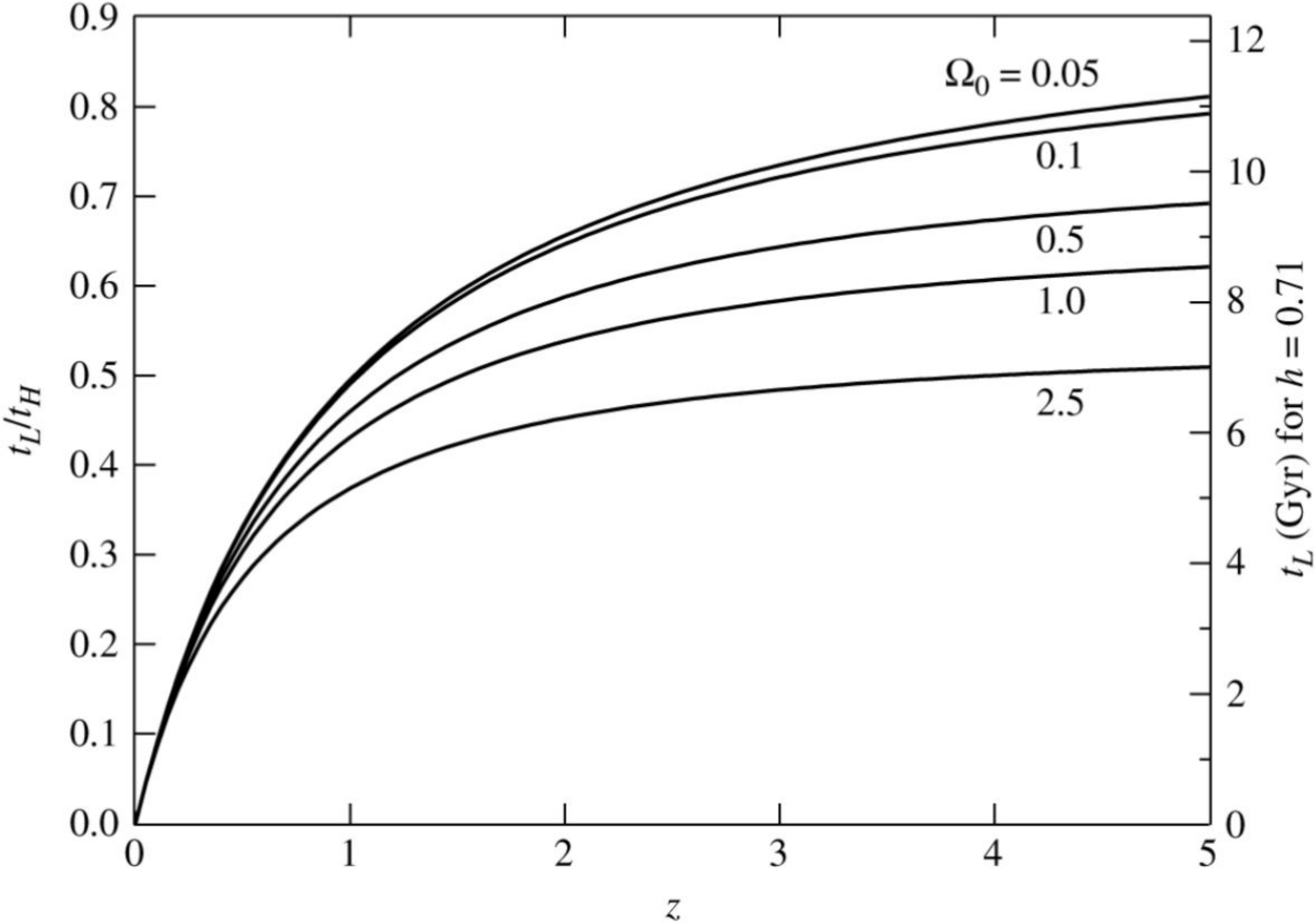
Negative curvature (c)



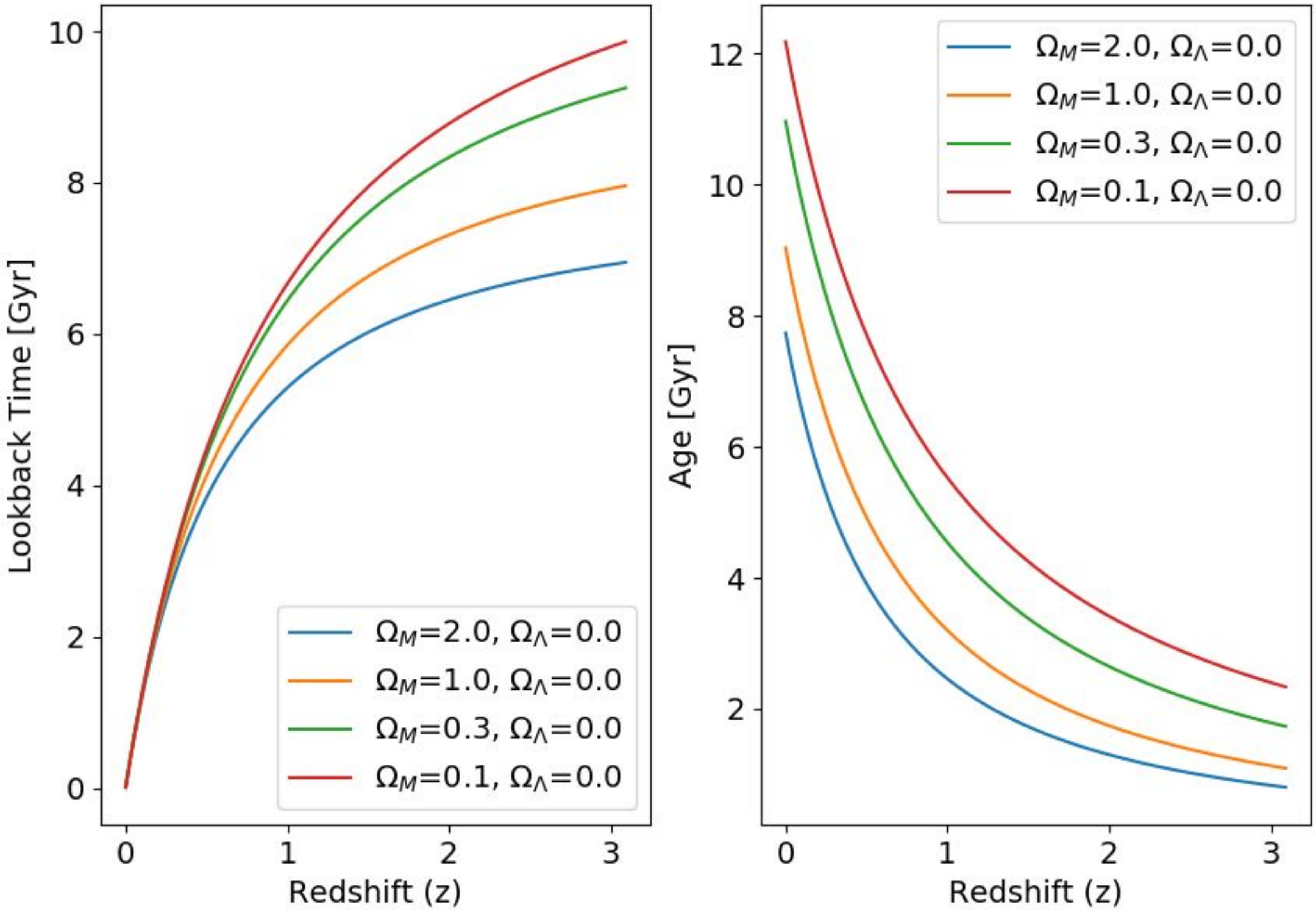
$\Omega_0 = 0.5$
(open)
$\Omega_0 = 1$
(flat)
$\Omega_0 = 2$
(closed)
R
$(\Delta t)/t_H$ from present
0
1
2
3
4
5
−1
6



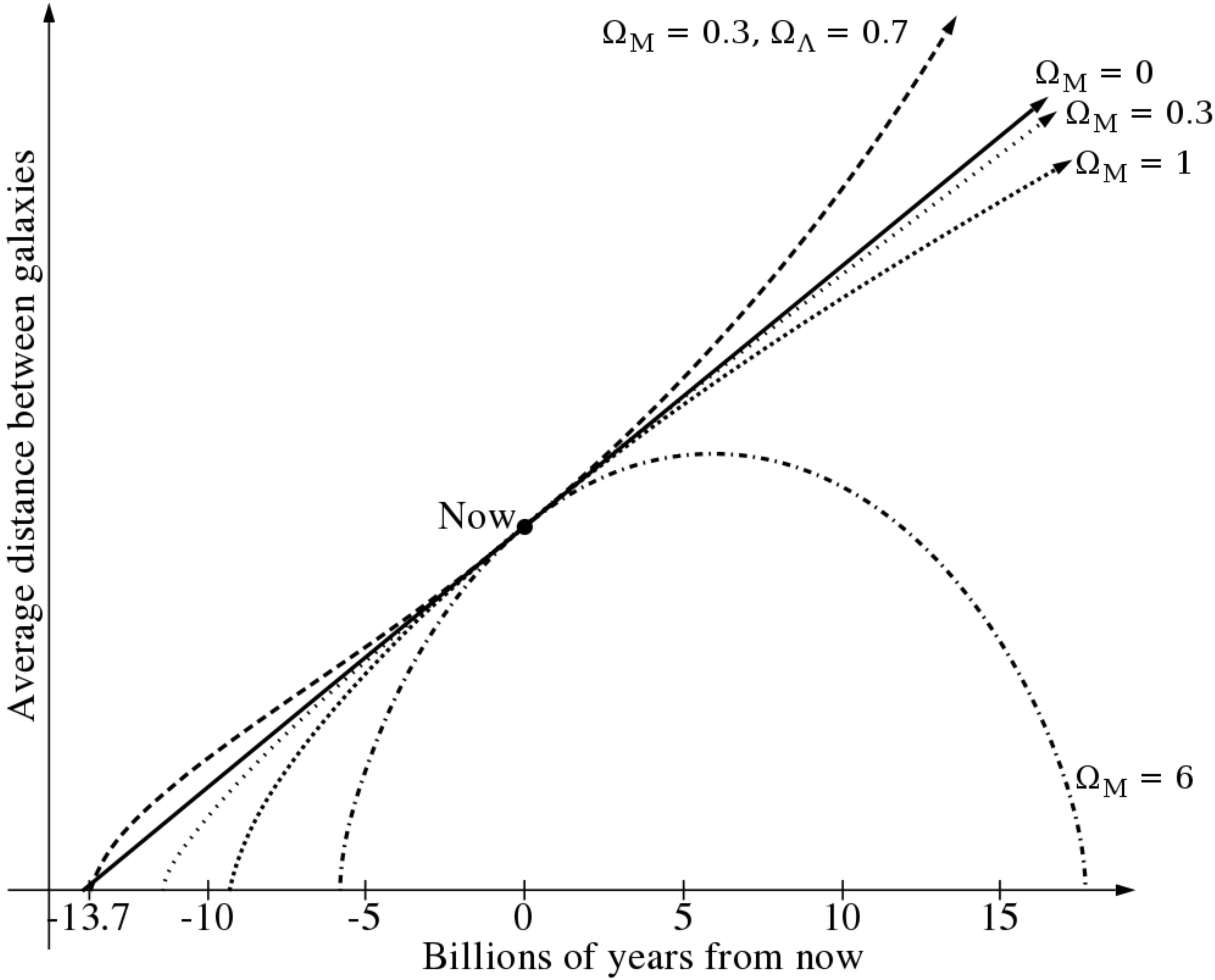
1.0
0.9
0.8
0.7
0.6
0.5
t_0/t_H
13
12
11
10
9
8
7
t_0 (Gyr) for $h = 0.71$
0.0
0.5
1.0
1.5
2.0
2.5
Ω_0



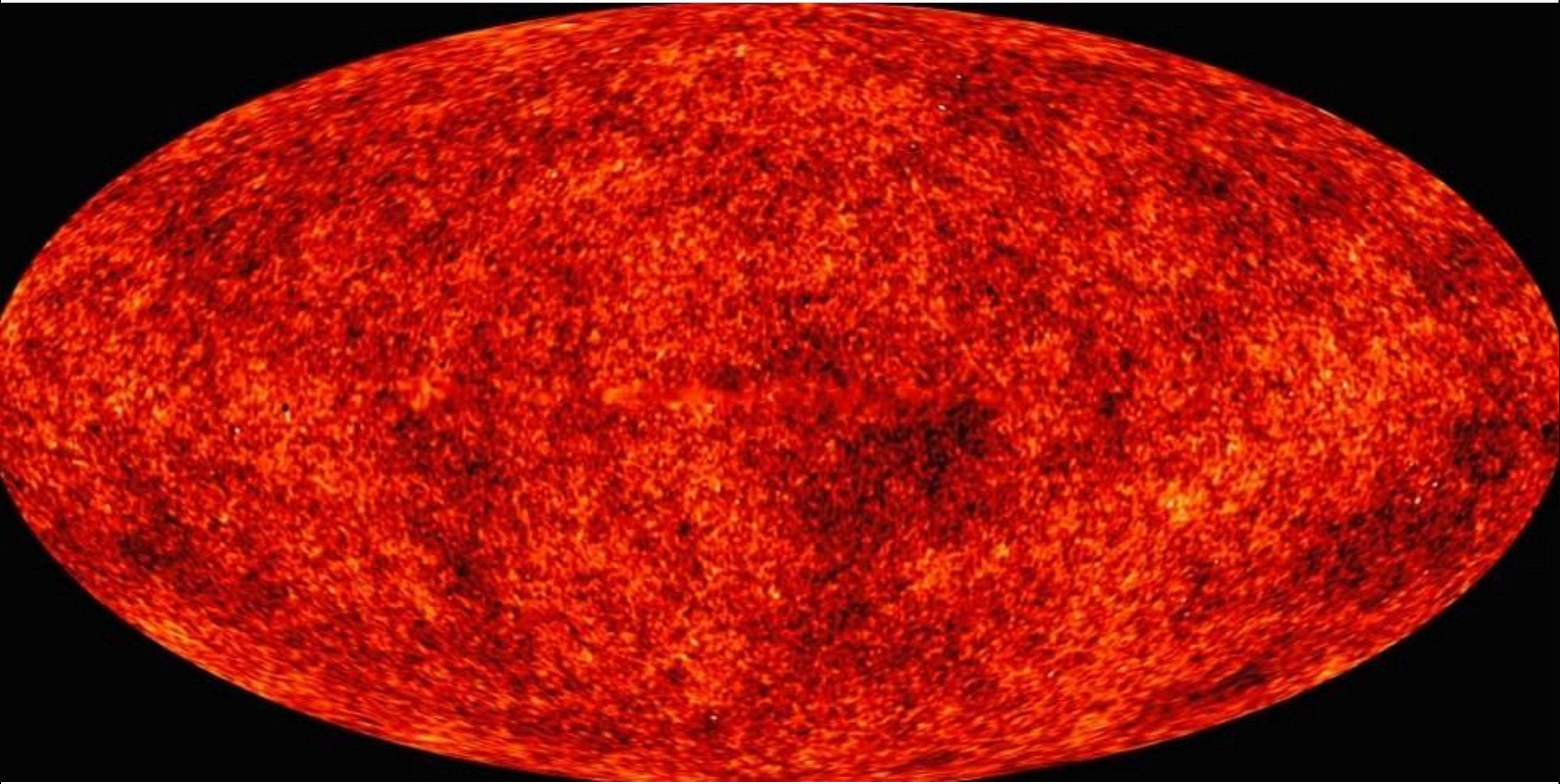
$\Omega_0 = 0.05$
0.1
0.5
1.0
2.5
t_L/t_H
t_L (Gyr) for $h = 0.71$
z
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0
1
2
3
4
5
0
2
4
6
8
10
12

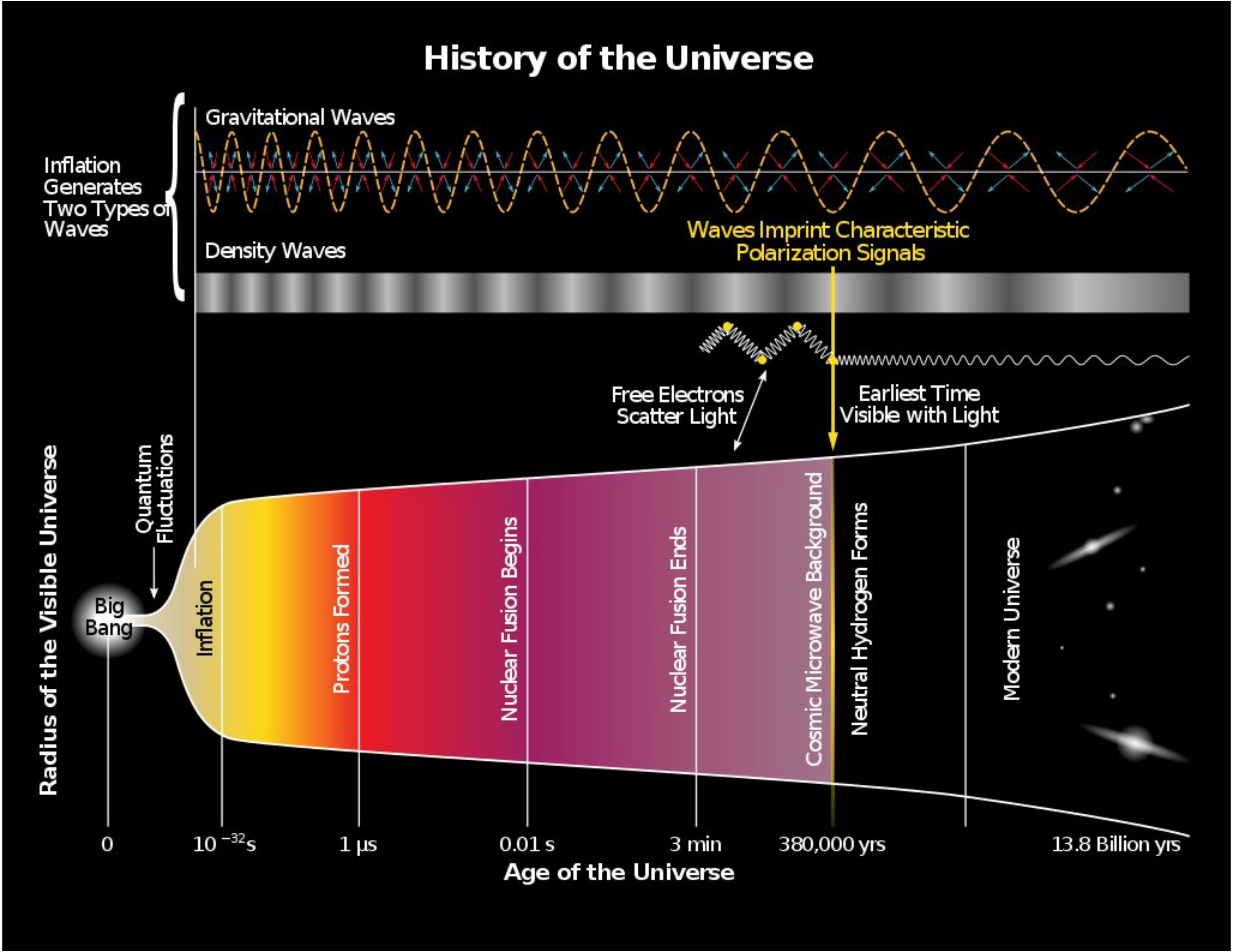


Lookback Time [Gyr]
Redshift (z)
Ω_M=2.0, Ω_Λ=0.0
Ω_M=1.0, Ω_Λ=0.0
Ω_M=0.3, Ω_Λ=0.0
Ω_M=0.1, Ω_Λ=0.0
Age [Gyr]
Redshift (z)
Ω_M=2.0, Ω_Λ=0.0
Ω_M=1.0, Ω_Λ=0.0
Ω_M=0.3, Ω_Λ=0.0
Ω_M=0.1, Ω_Λ=0.0

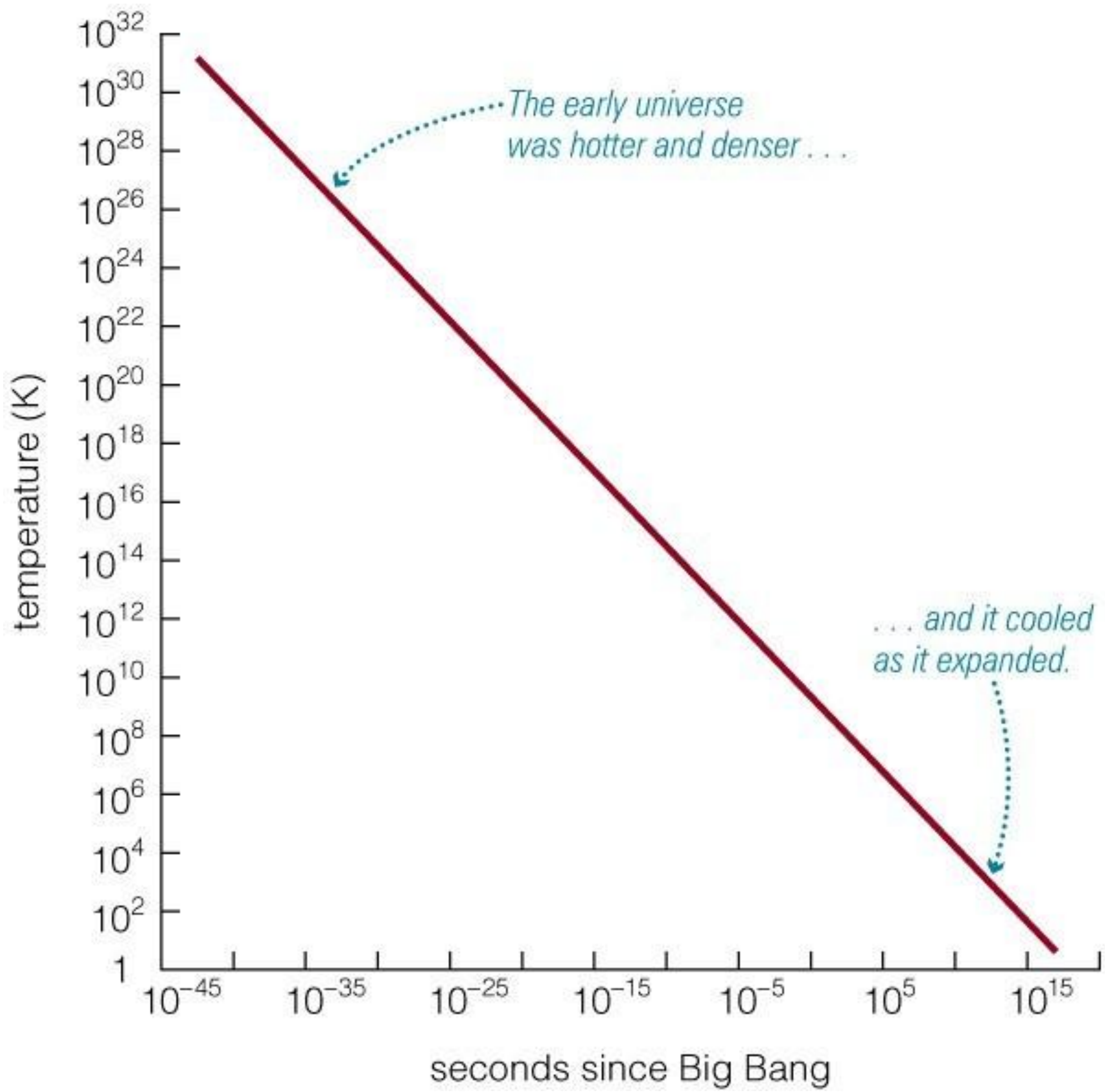


$\Omega_M = 0.3, \Omega_\Lambda = 0.7$
$\Omega_M = 0$
$\Omega_M = 0.3$
$\Omega_M = 1$
Now
$\Omega_M = 6$
Average distance between galaxies
-13.7
-10
-5
0
5
10
15
Billions of years from now




History of the Universe
Gravitational Waves
Inflation Generates Two Types of Waves
Density Waves
Waves Imprint Characteristic Polarization Signals
Free Electrons Scatter Light
Earliest Time Visible with Light
Radius of the Visible Universe
Quantum Fluctuations
Big Bang
Inflation
Protons Formed
Nuclear Fusion Begins
Nuclear Fusion Ends
Cosmic Microwave Background
Neutral Hydrogen Forms
Modern Universe
0
10 −32 s
1 μs
0.01 s
3 min
380,000 yrs
13.8 Billion yrs
Age of the Universe

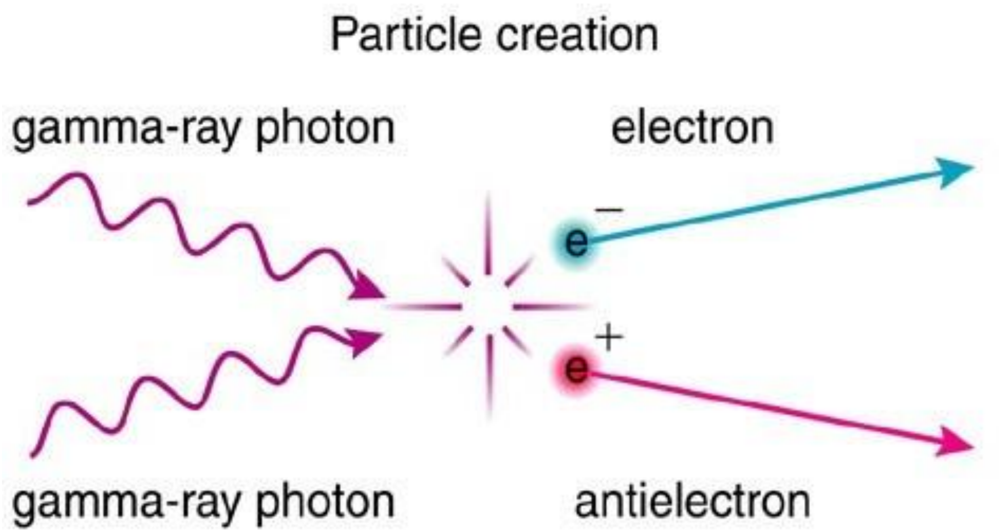
Density, temp of Early Universe



The early universe must have been extremely hot and dense, and everything was packed close together.

Like a star, the temperature increases with increasing density

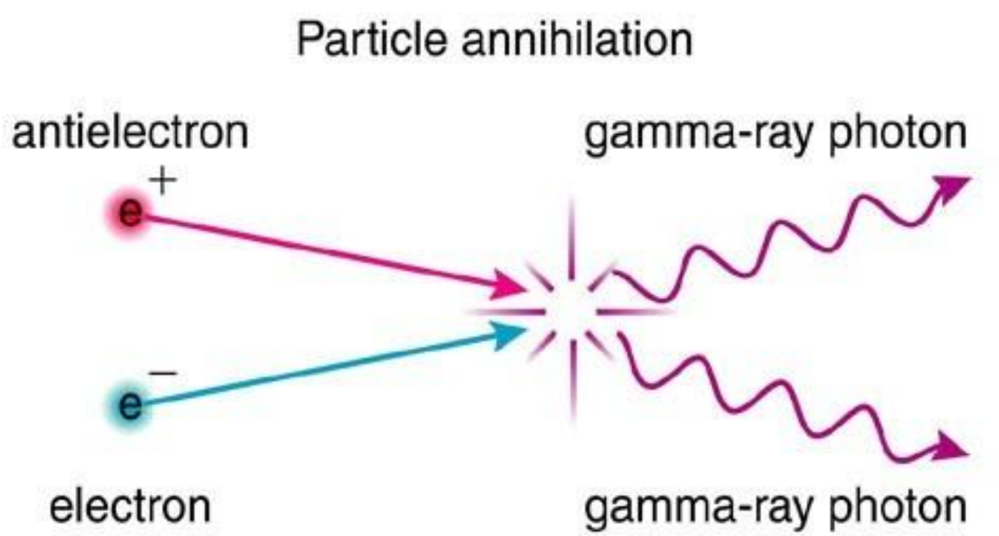
How did we get Matter?



Photons converted into particle-antiparticle pairs and vice-versa

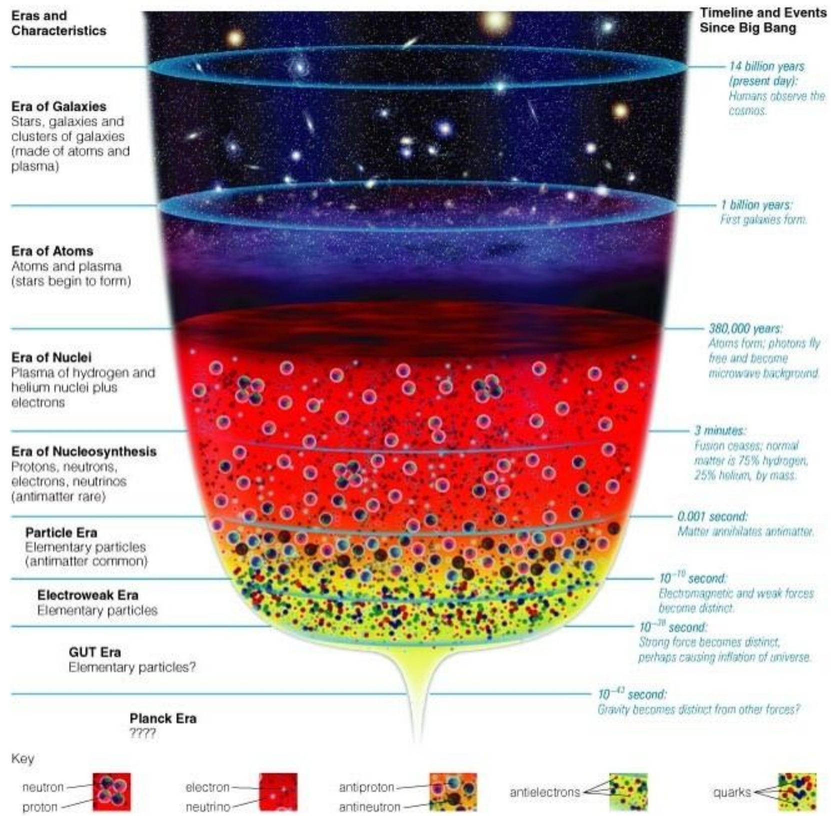
Works both ways!

$$E = mc^2$$



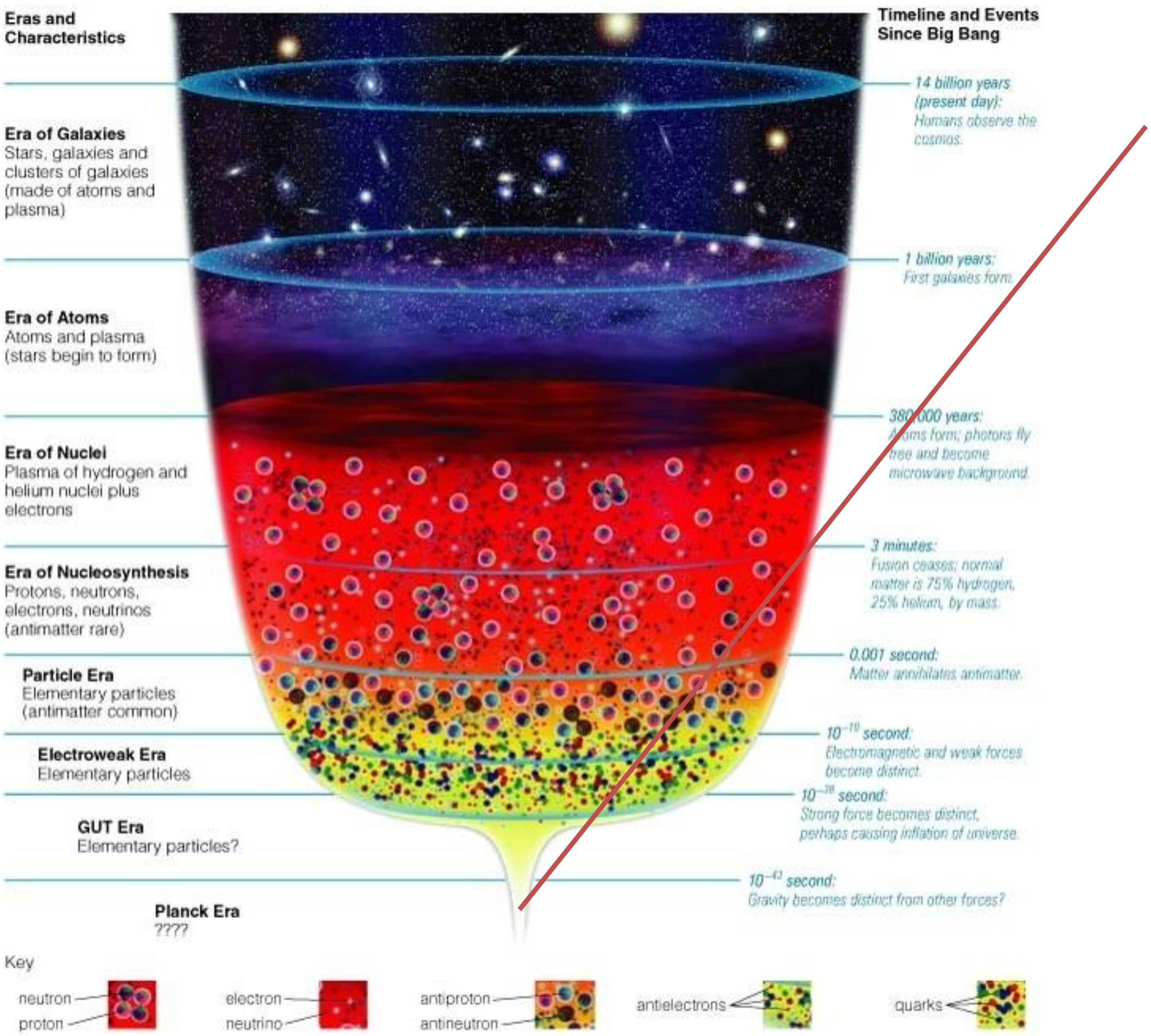
Early universe was full of particles and radiation because of its high temperature

Big Bang Timeline



All changes are due to the cooling of the Universe, and the decreasing density. Remember: density and temperature are linked!!

Big Bang Timeline (Planck Era)

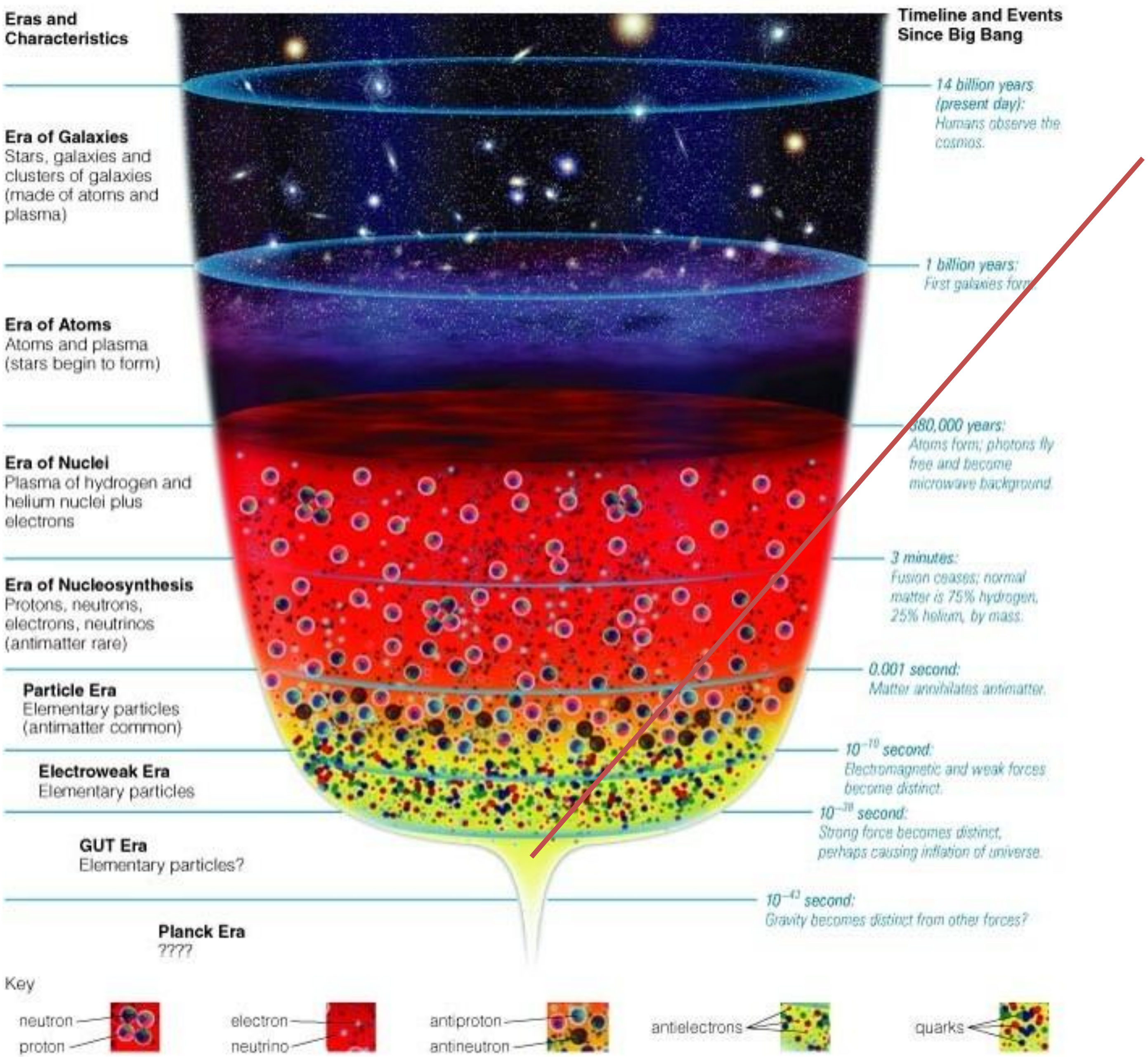


Before 10^{-43} s

????

No one knows

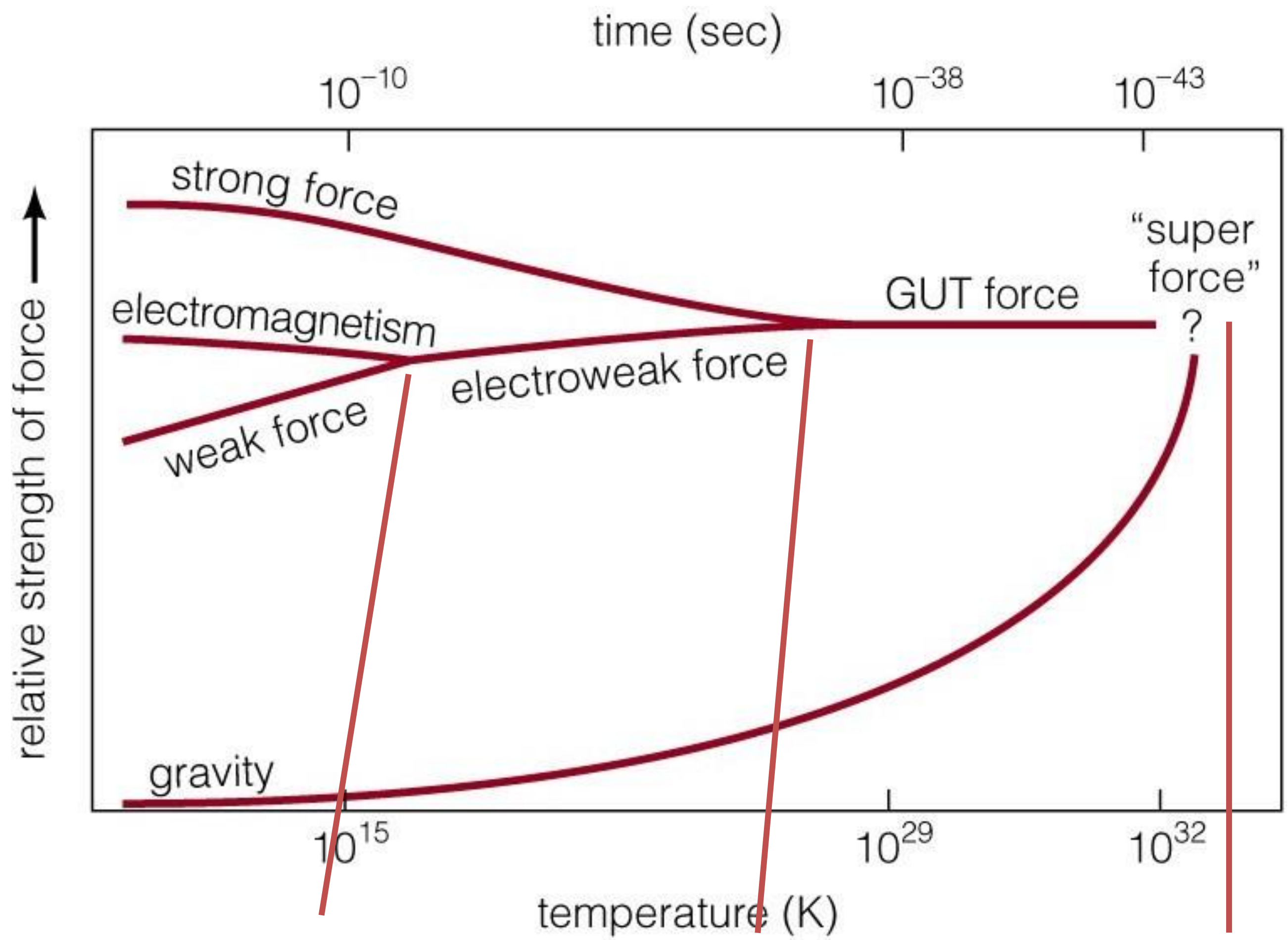
Big Bang Timeline (GUT Era)



Lasts from Planck time (~10^{-43} sec) to end of GUT force (~10^{-38} sec)

Forces united (except gravity) into one force – possibly elementary particles

Forces at High Temperature



Four known forces in universe:

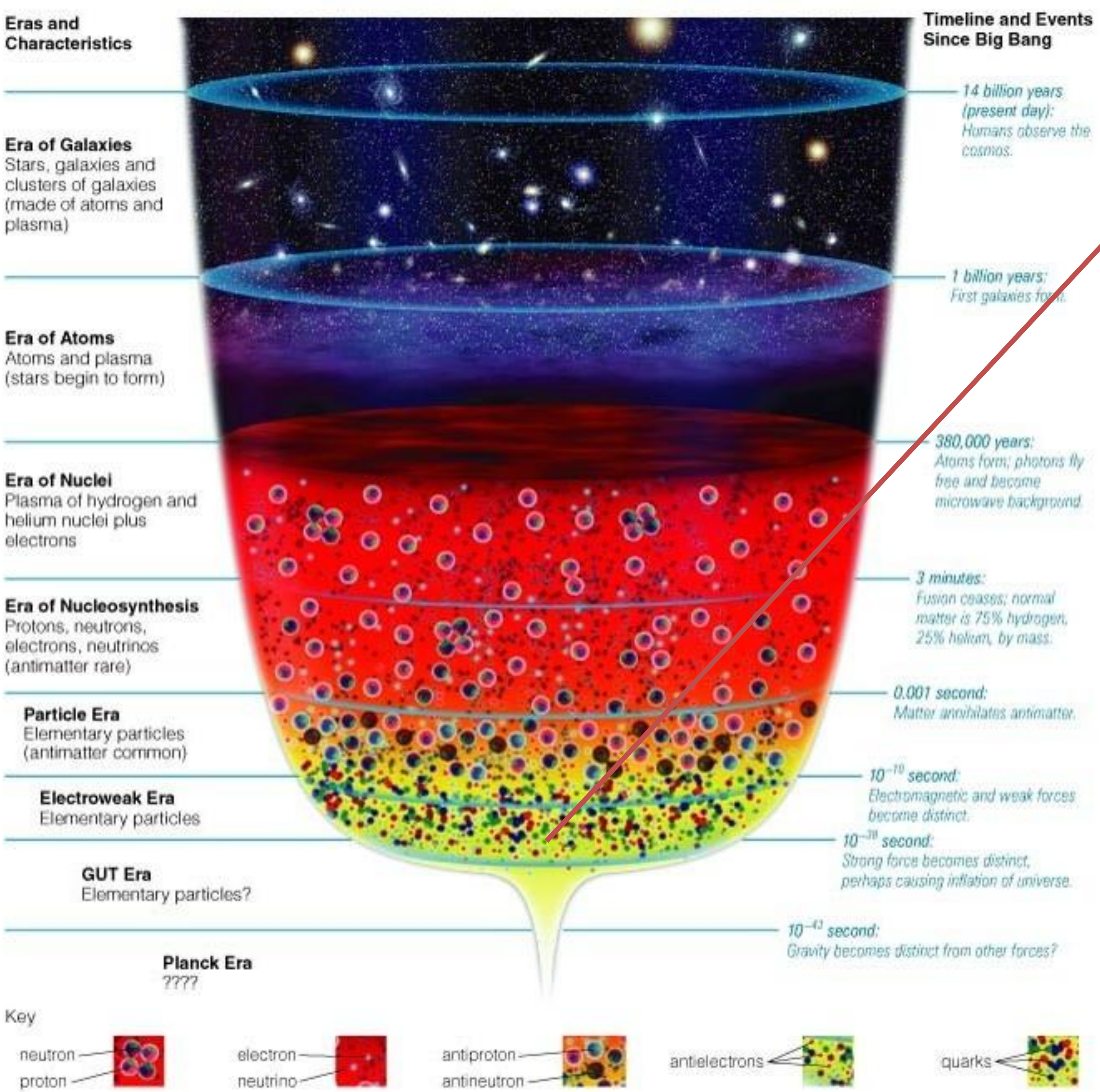
Strong Force

Electromagnetism

Weak Force

Gravity

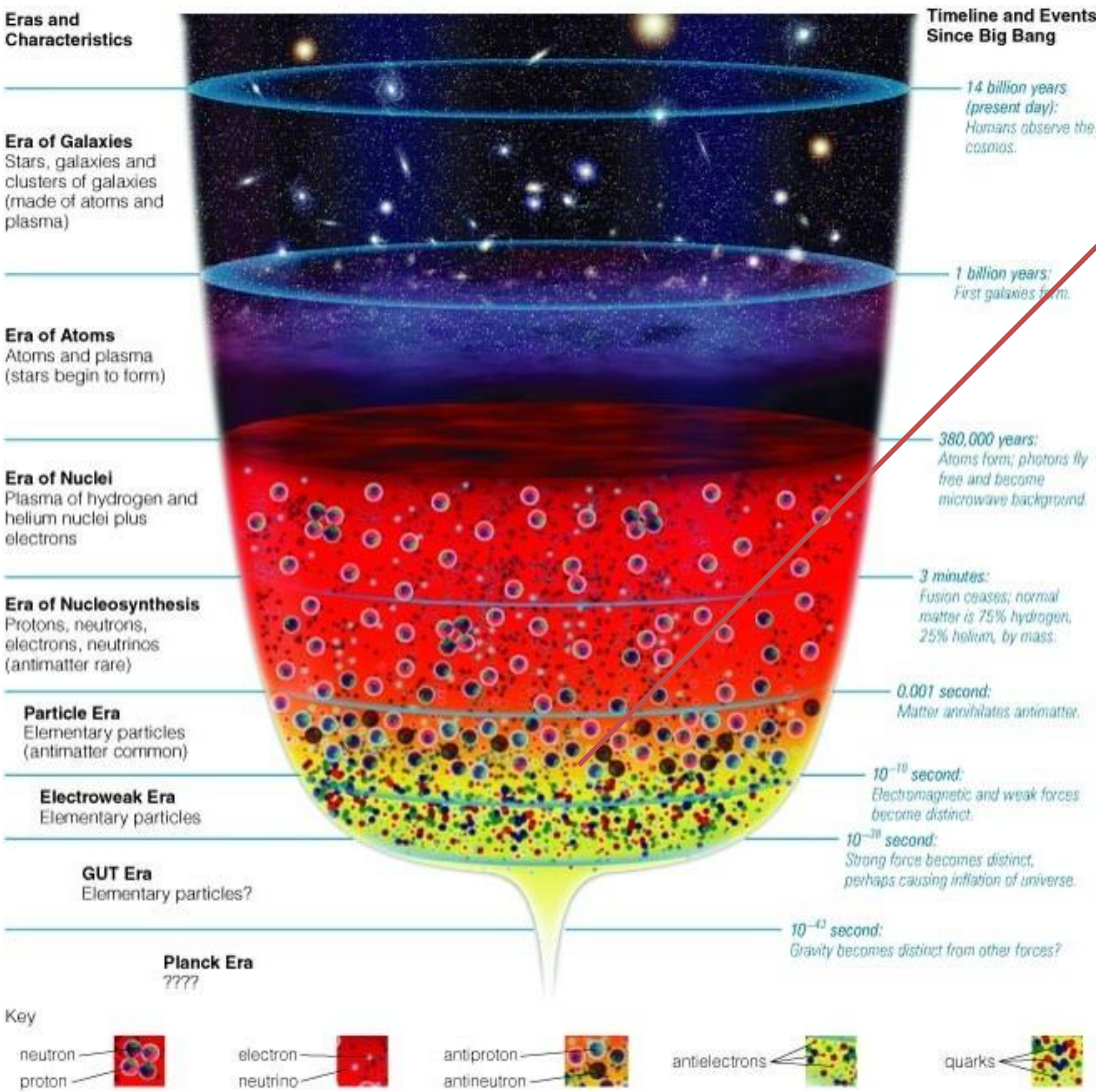
Big Bang Timeline (Electroweak Era)



Lasts from ~10^{-38} sec to ~10^{-10} sec

Elementary particles

Big Bang Timeline (Particle Era)

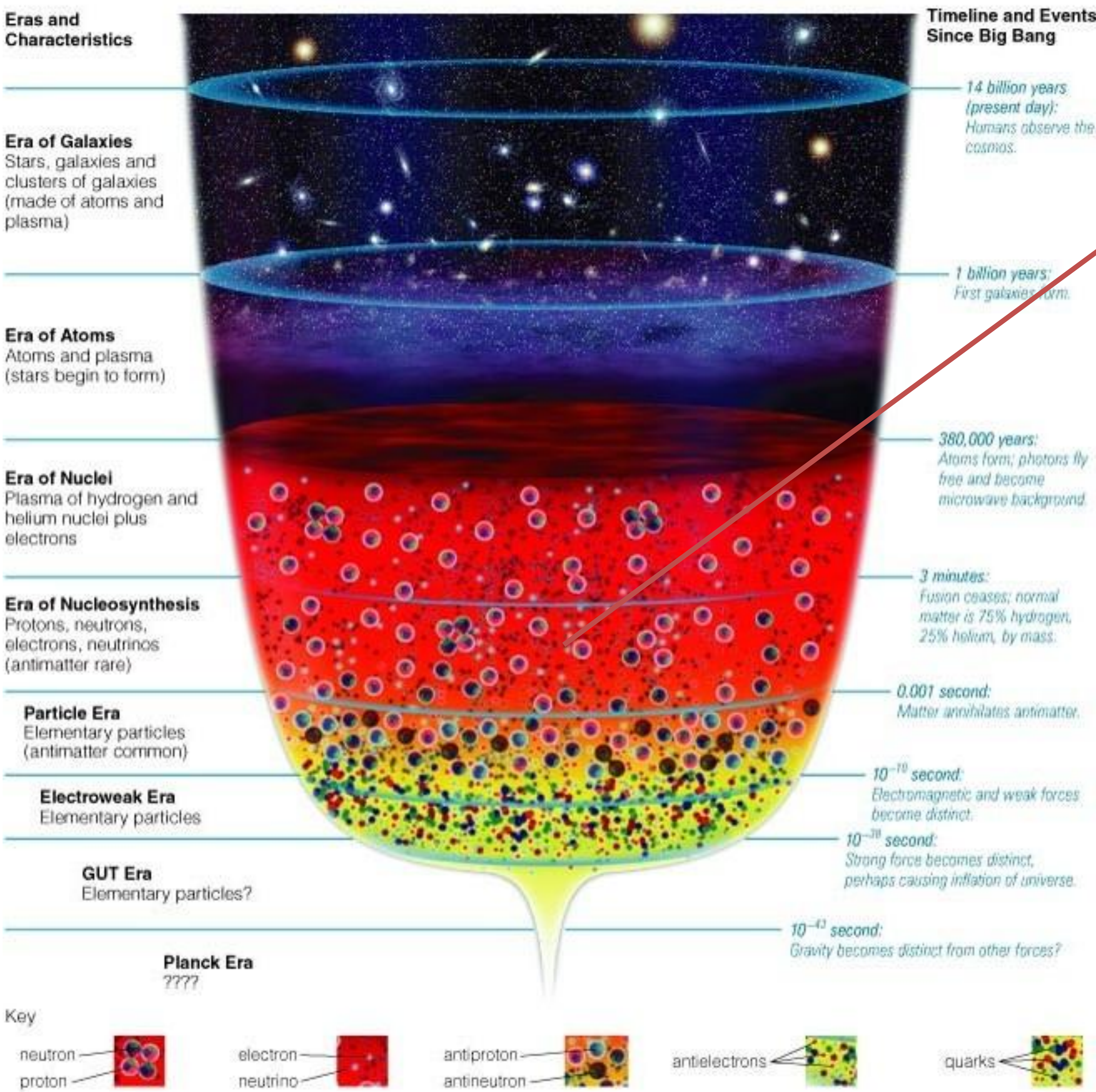


10^{-10} s to 0.001 s

Amounts of matter and antimatter nearly equal

(Roughly 1 extra proton for every 10^9 proton-antiproton pairs)

Big Bang Timeline (Era of Nucleosysthesis)

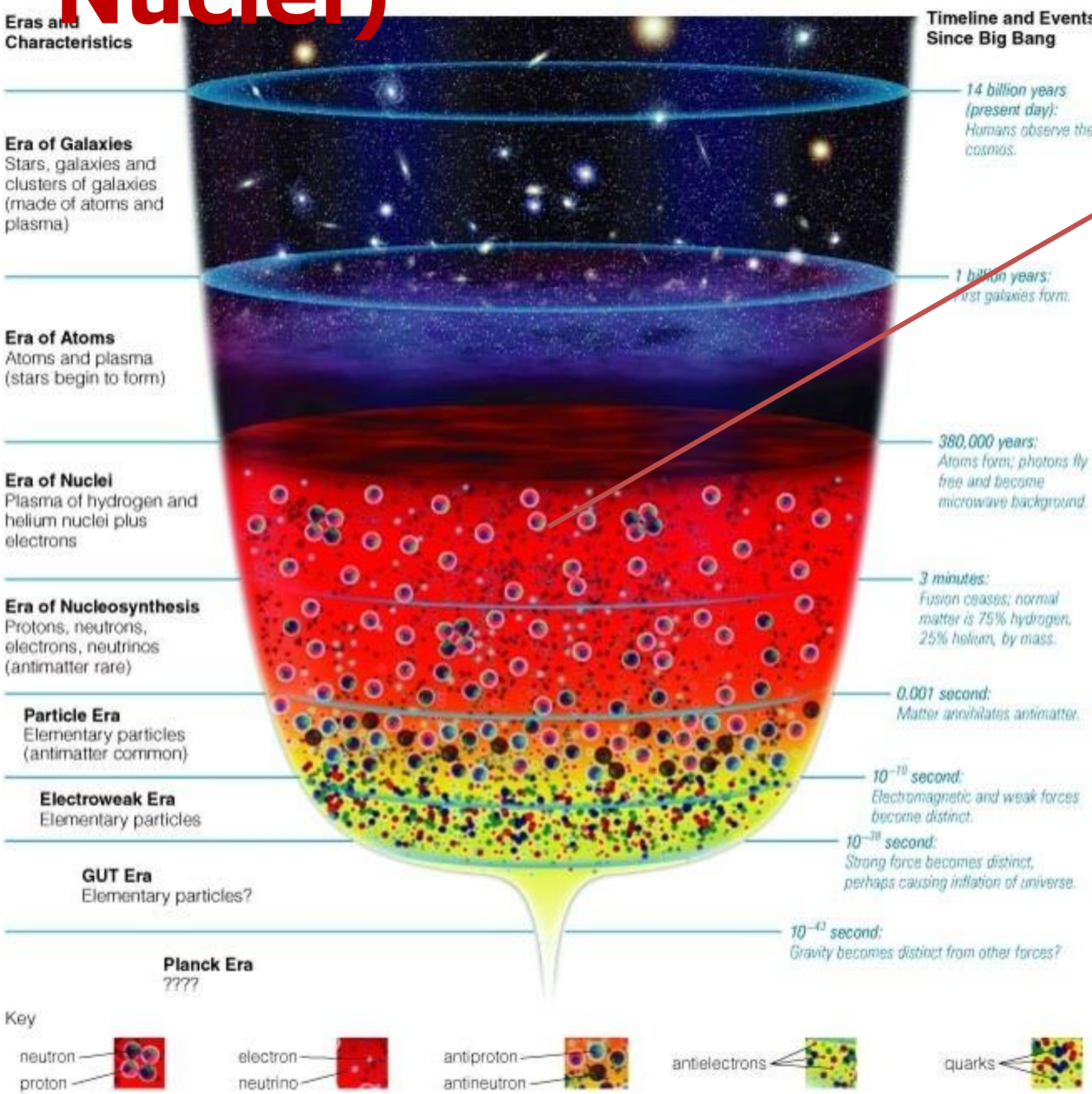


0.001 s to 3 min Nucleosysnthesis : The creation of atomic neclei (matter)

Nuclei begin to fuse

Universe is a plasma of H, He neclei

Big Bang Timeline (Era of Nuclei)

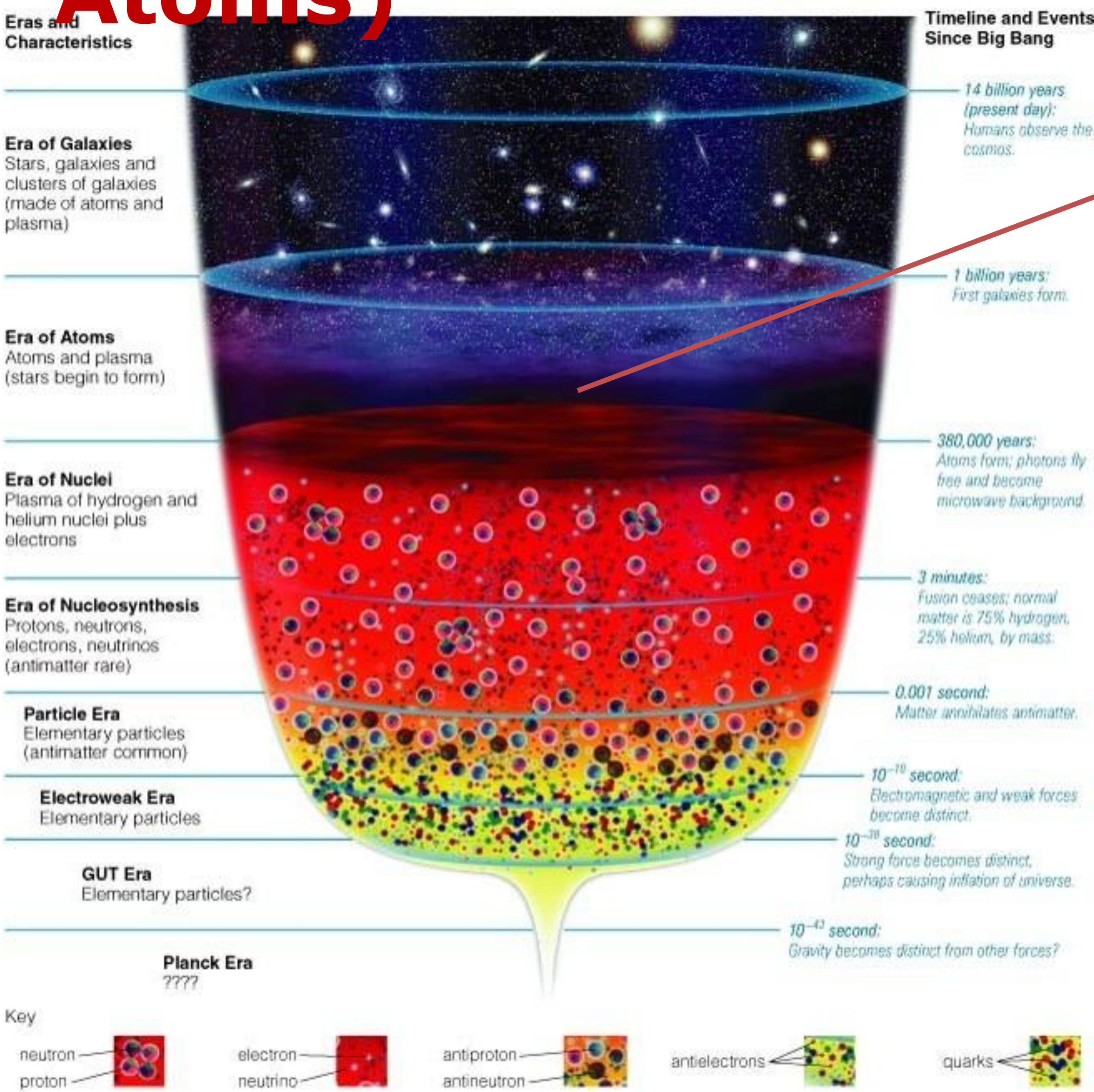


3 min to 300,000 years

Helium nuclei form at age ~ 3 minutes

Universe has become too cool to blast helium apart

Big Bang Timeline (Era of Atoms)

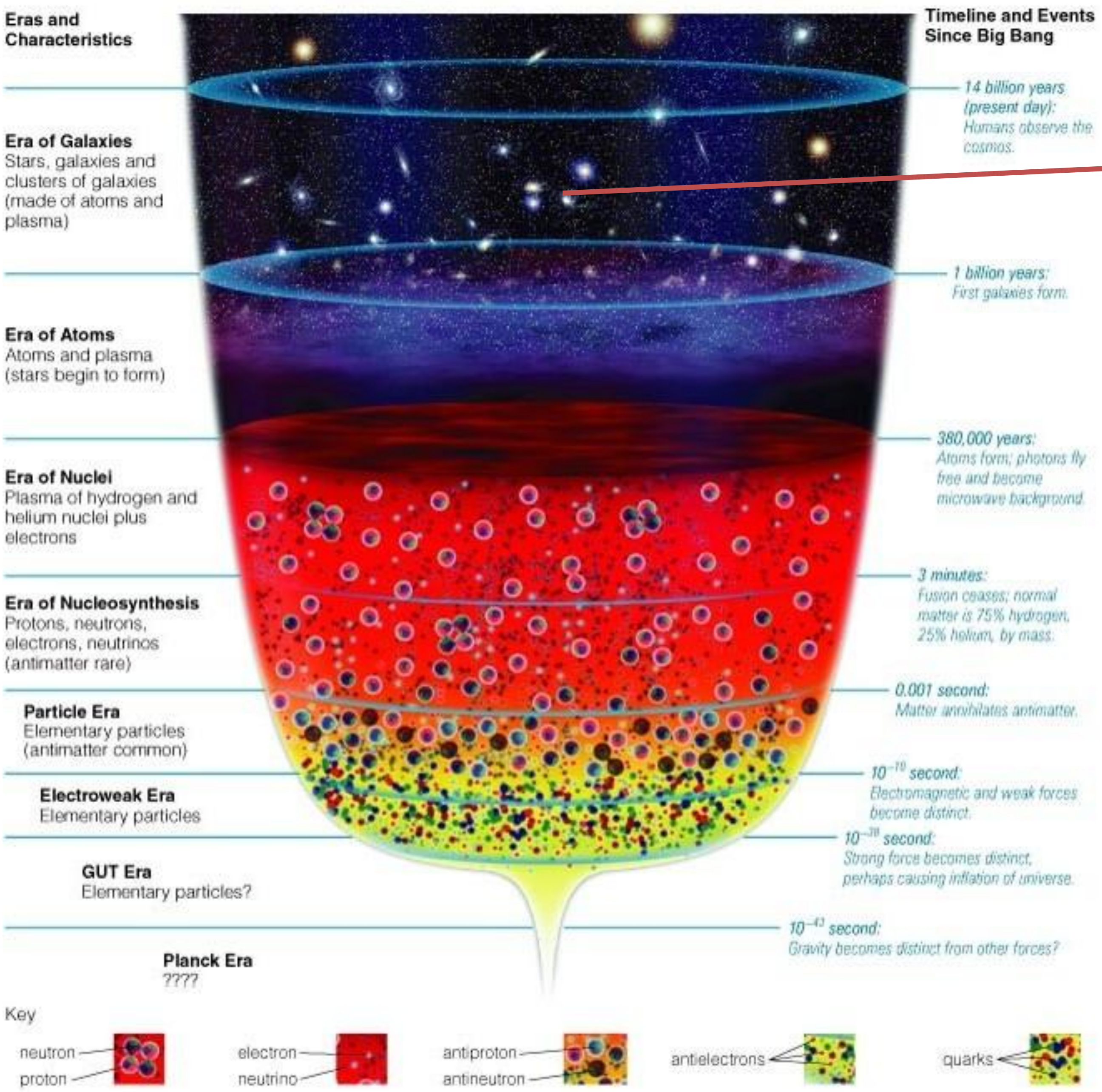


300,000 to 1 billion years

Atoms form at age ~ 300,000 years

Background radiation released (more later)

Big Bang Timeline (Era of Galaxies)

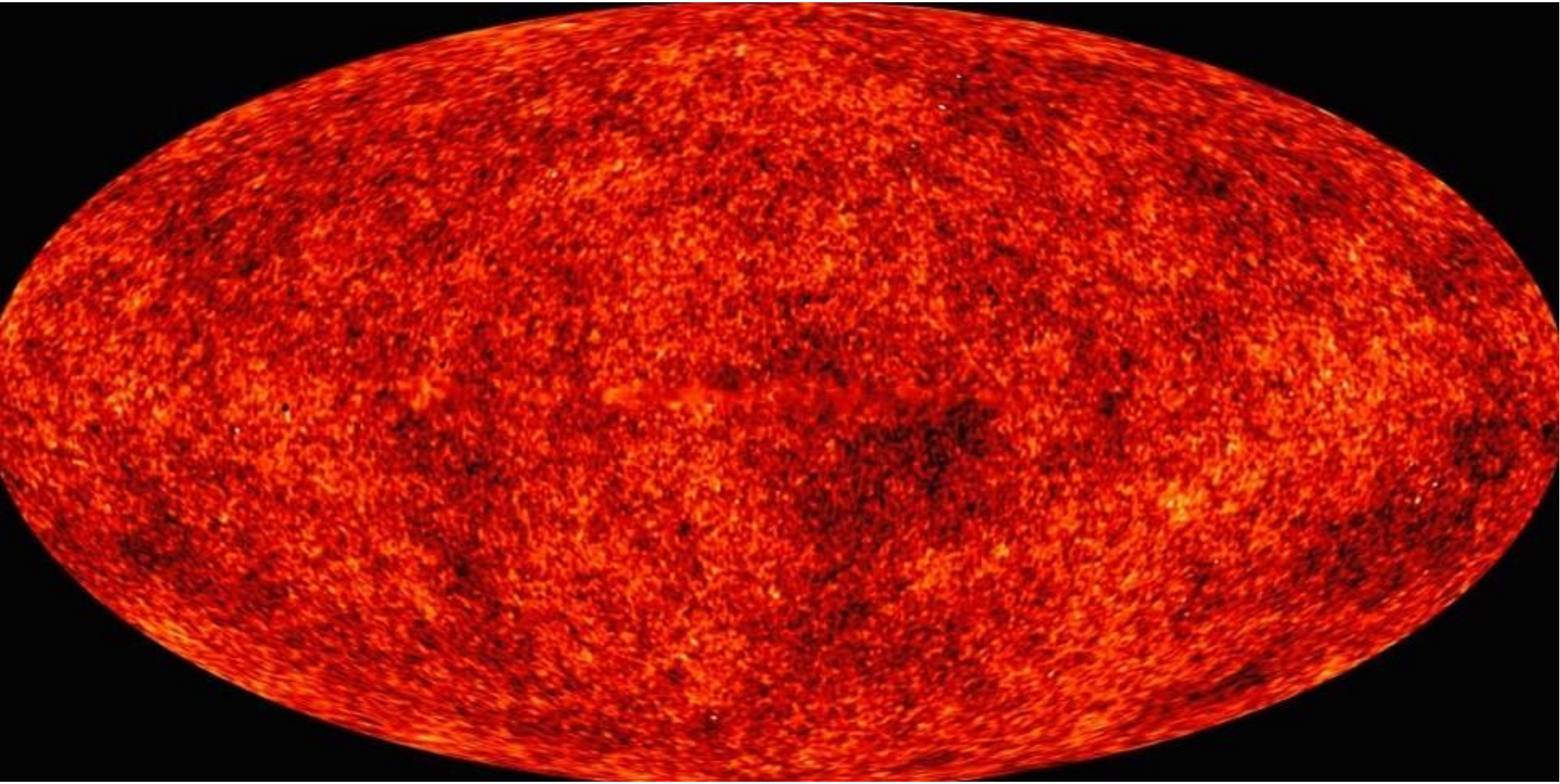


Galaxies form at age ~ 1 billion years

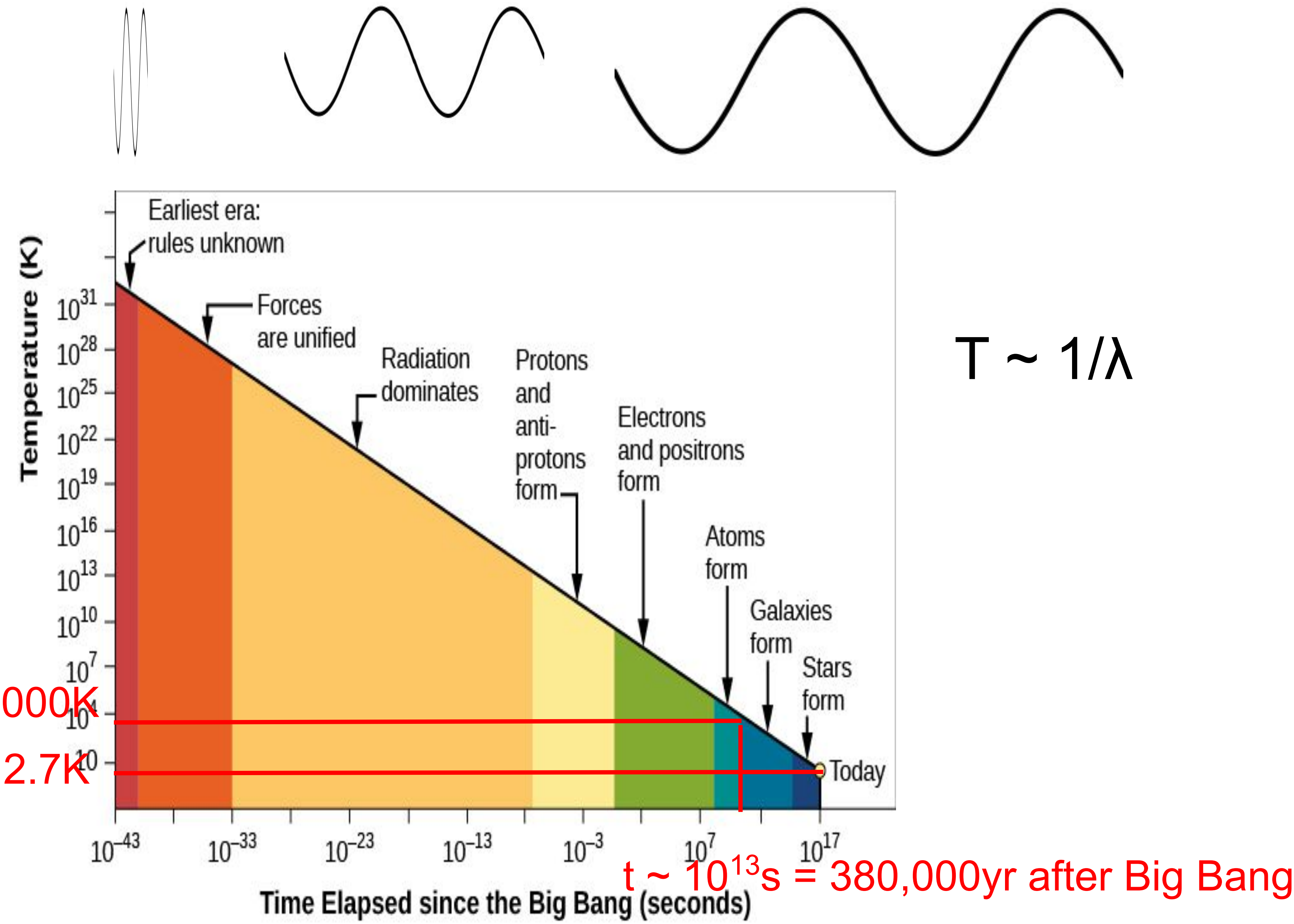
What is the Evidence for the Big Bang?

1) Radiation from the Big Bang still detected today
2) The elemental abundances that we measure agree with that expected
3) Darkness of the night sky

1) Radiation from the Big Bang

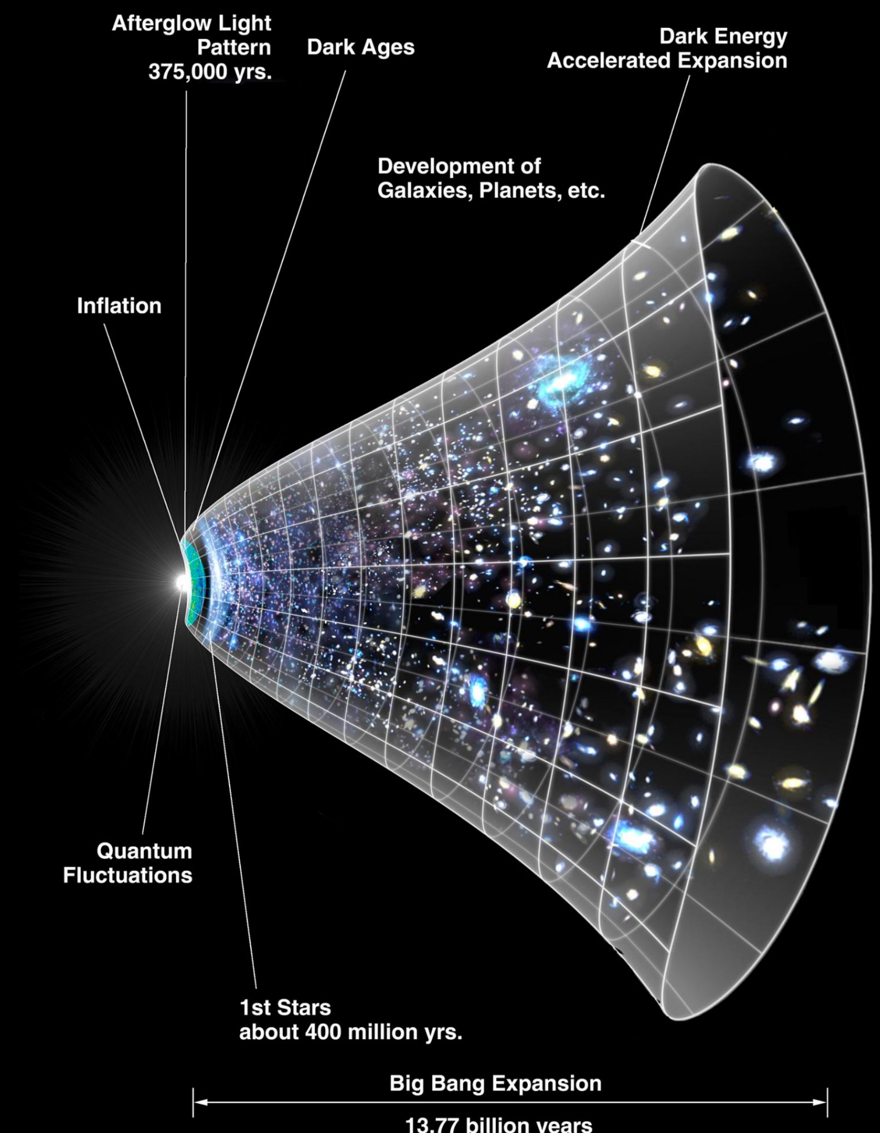


"Cosmic Microwave Background" (CMB)!

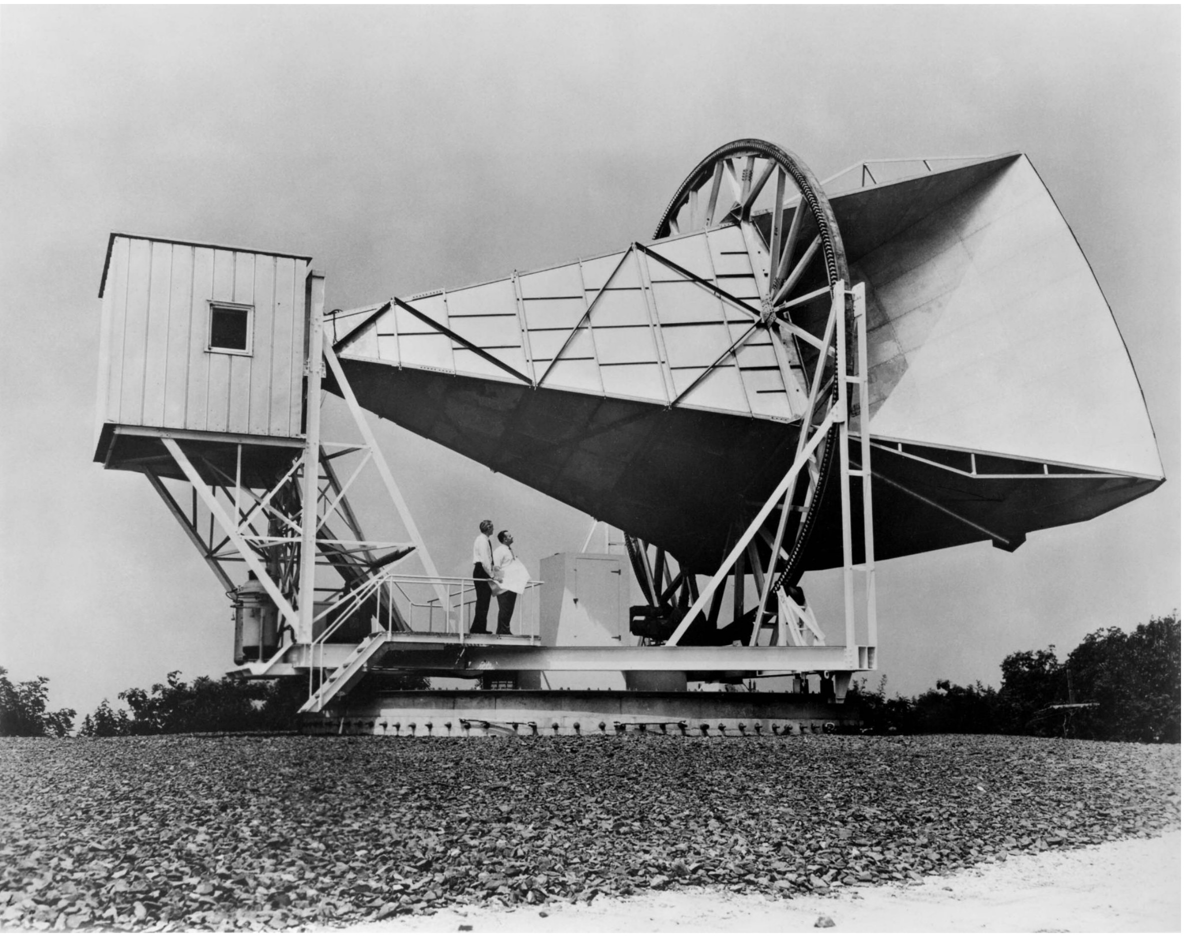


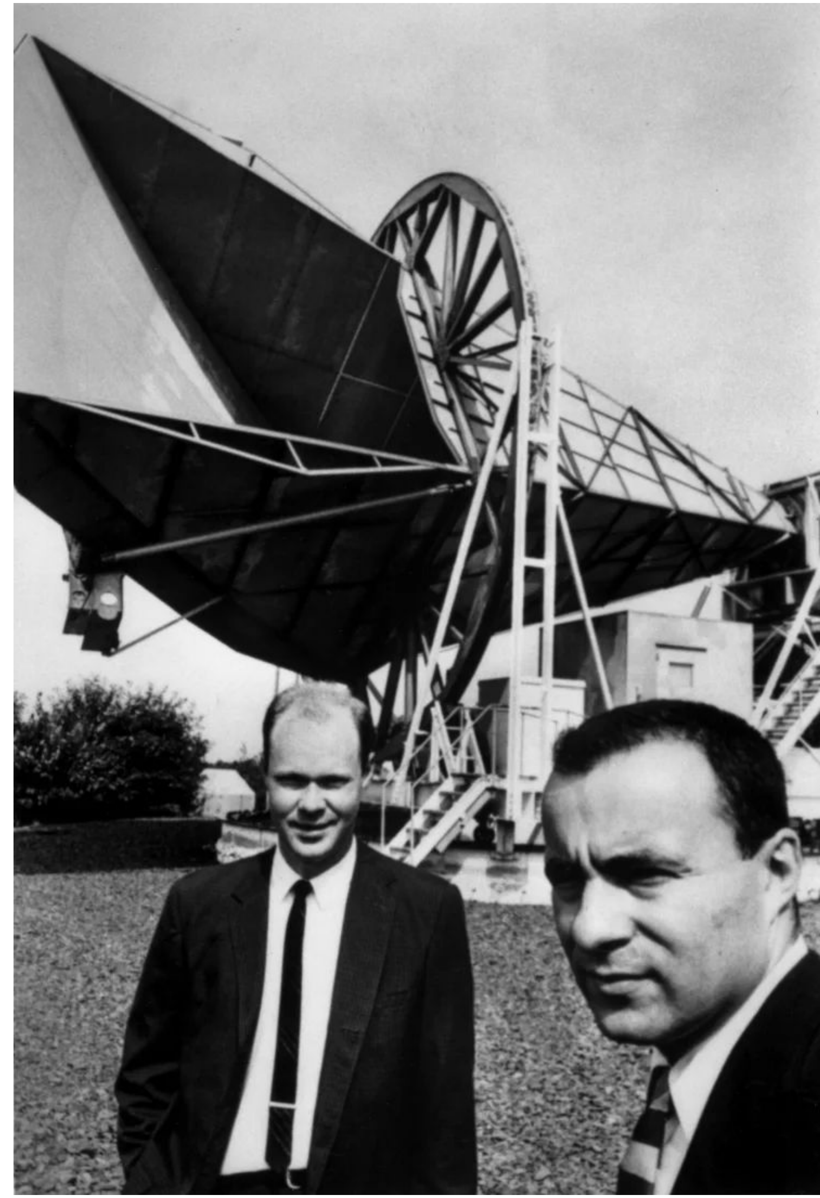
$T \sim 1/\lambda$

Credit:
https://pressbooks.online.ucf.edu/astronomybc/chapter/29-3-the-beginning-of-the-universe/


Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Dark Energy
Accelerated Expansion
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years

Detection of the CMB - The Bell Labs Horn Antenna

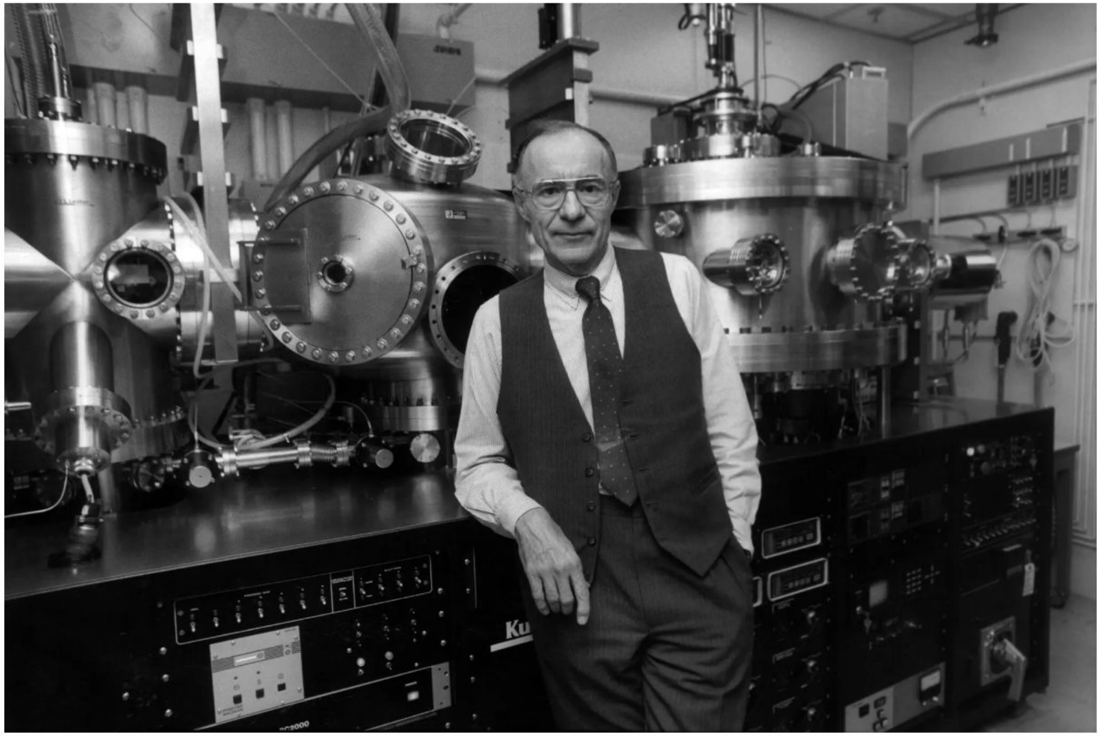




The New York Times

Arno A. Penzias, 90, Dies; Nobel Physicist Confirmed Big Bang Theory

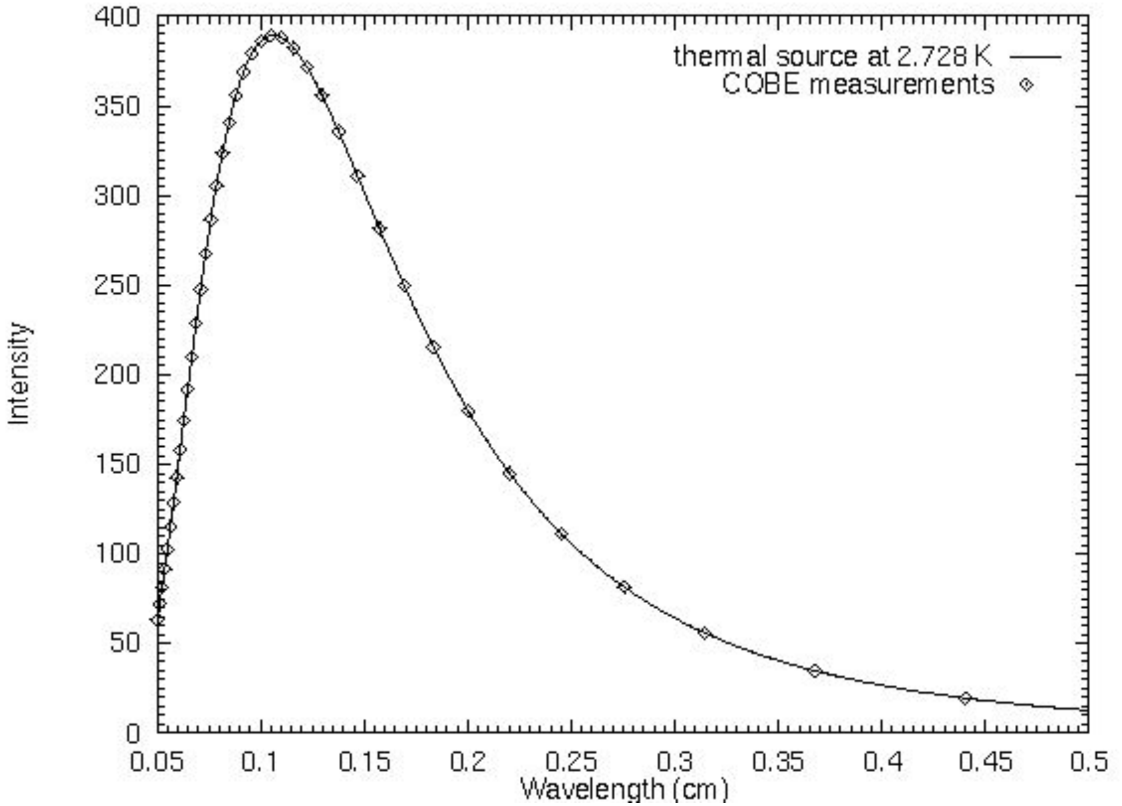
His 1964 discovery with Robert W. Wilson settled a debate over the origin and evolution of the universe.



Dr. Arno A. Penzias in a 1991 photo at Bell Laboratories in New Jersey. He and Dr. Robert W. Wilson were researchers there in 1964 when they discovered cosmic microwave background radiation, remnants of the Big Bang. Frank C. Dougherty

Cosmic Microwave Background (Radiation) - the CMB(R)

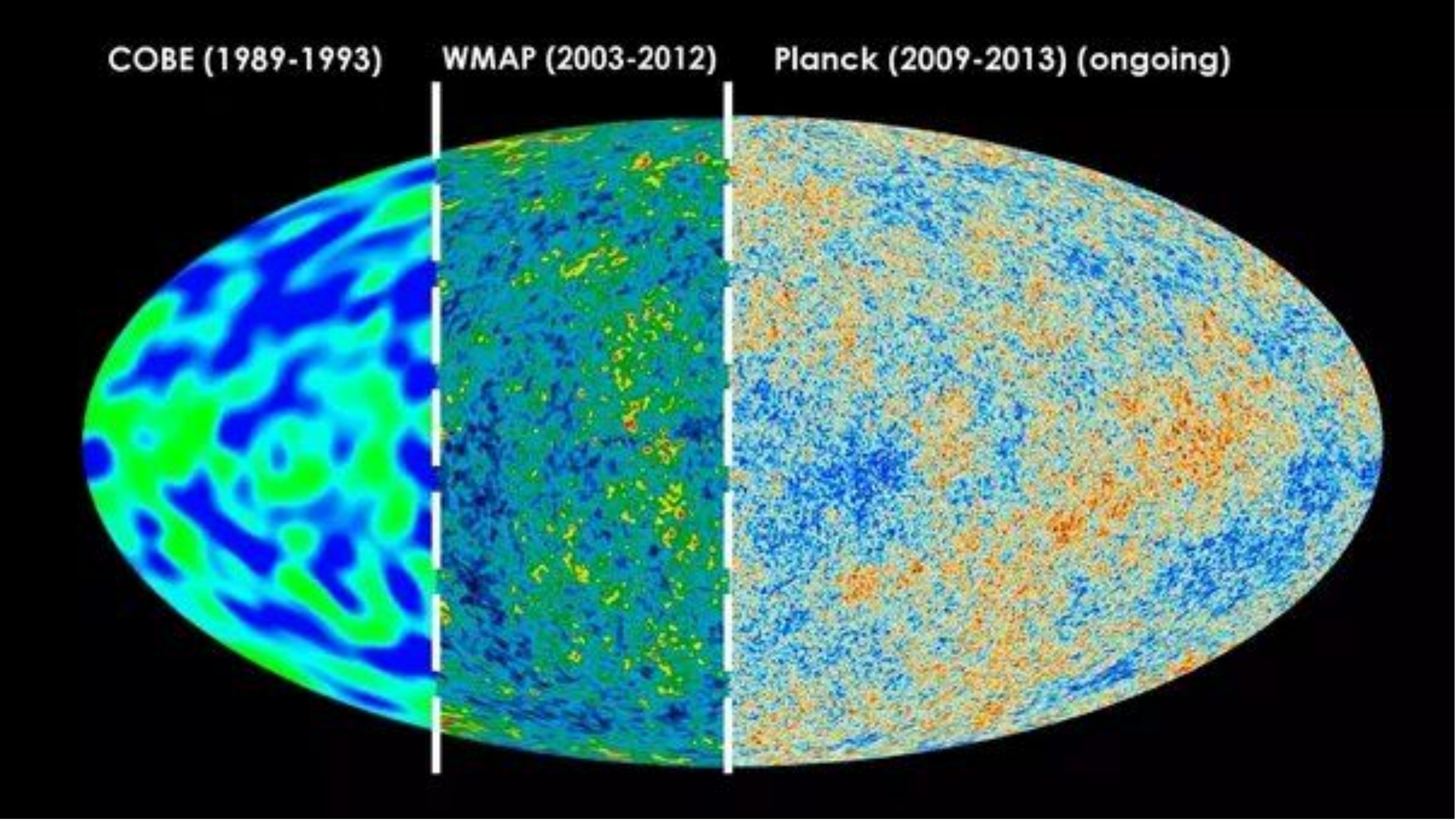
T = 2.72548±0.00057 K



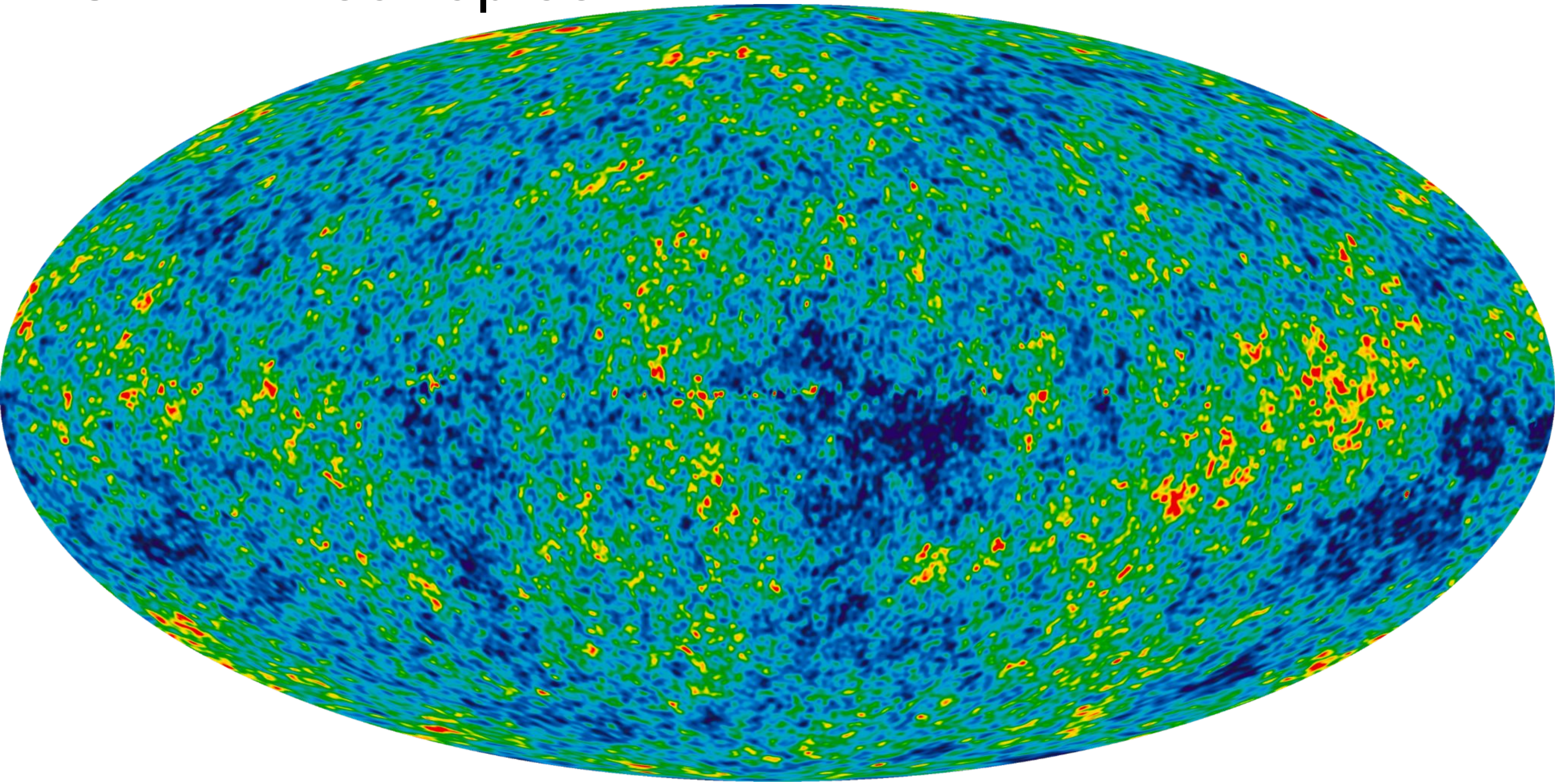
In 1978, Penzias and Wilson were awarded the Nobel Prize for Physics for their joint measurement. There had been a prior measurement of the cosmic background radiation (CMB) by Andrew McKellar in 1941 at an effective temperature of 2.3 K using CN stellar absorption lines observed by W. S. Adams.[5] Although no reference to the CMB is made by McKellar, it was not until much later[6] after the Penzias and Wilson measurements that the significance of this measurement was understood.

Over two decades later, working at a Bell Telephone Laboratories facility atop Crawford Hill in Holmdel, New Jersey, in 1964, Arno Penzias and Robert Wilson were experimenting with a supersensitive, 6 meter (20 ft) horn antenna originally built to detect radio waves bounced off Echo balloon satellites.[2] To measure these faint radio waves, they had to eliminate all recognizable interference from their receiver. They removed the effects of radar and radio broadcasting, and suppressed interference from the heat in the receiver itself by cooling it with liquid helium to −269 °C, only 4 K above absolute zero.

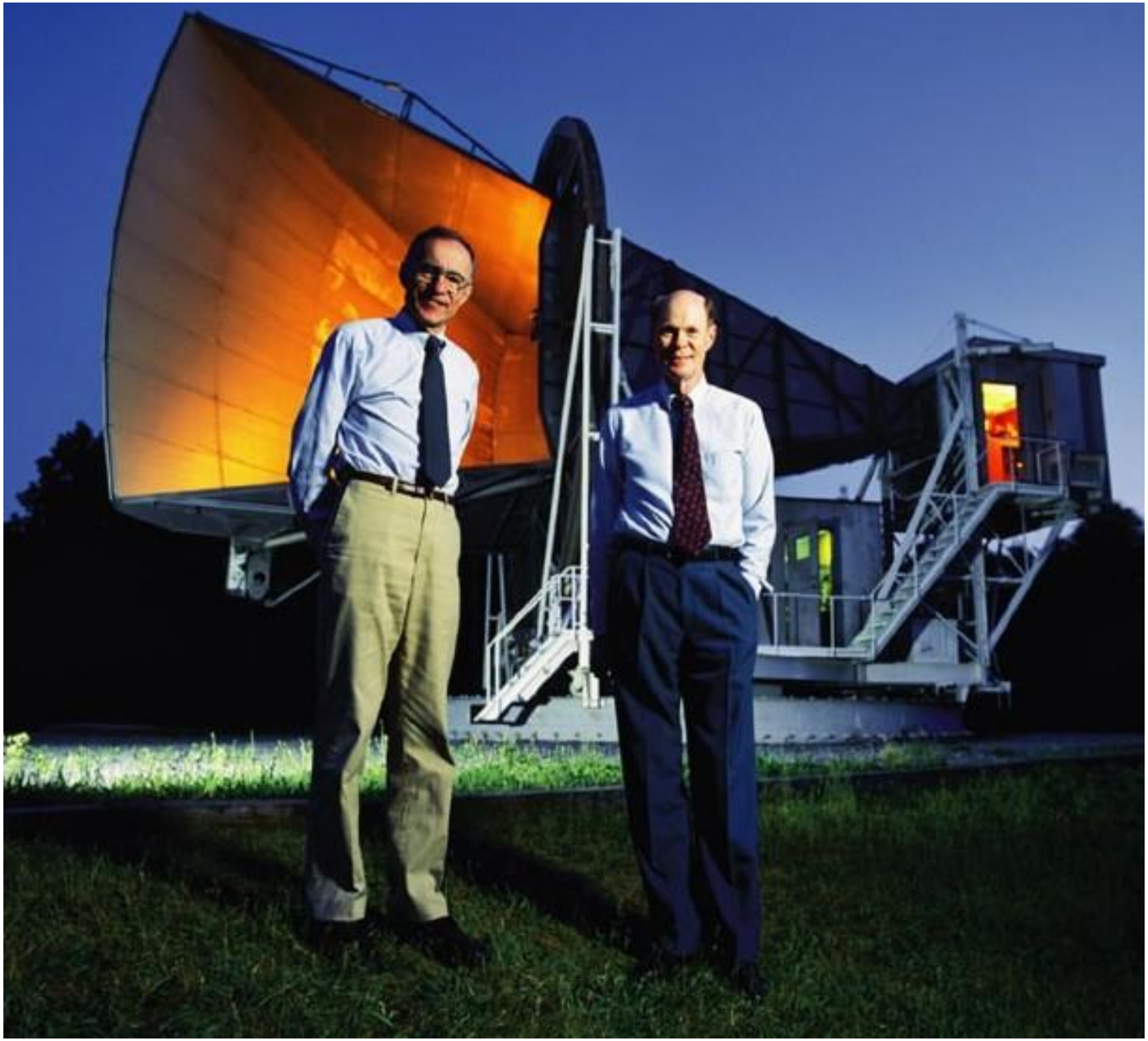
When Penzias and Wilson reduced their data, they found a low, steady, mysterious noise that persisted in their receiver. This residual noise was 100 times more intense than they had expected, was evenly spread over the sky, and was present day and night. They were certain that the radiation they detected on a wavelength of 7.35 centimeters did not come from the Earth, the Sun, or our galaxy. After thoroughly checking their equipment, removing some pigeons nesting in the antenna and cleaning out the accumulated droppings, the noise


COBE (1989-1993)
WMAP (2003-2012)
Planck (2009-2013) (ongoing)

CMB Anisotropies



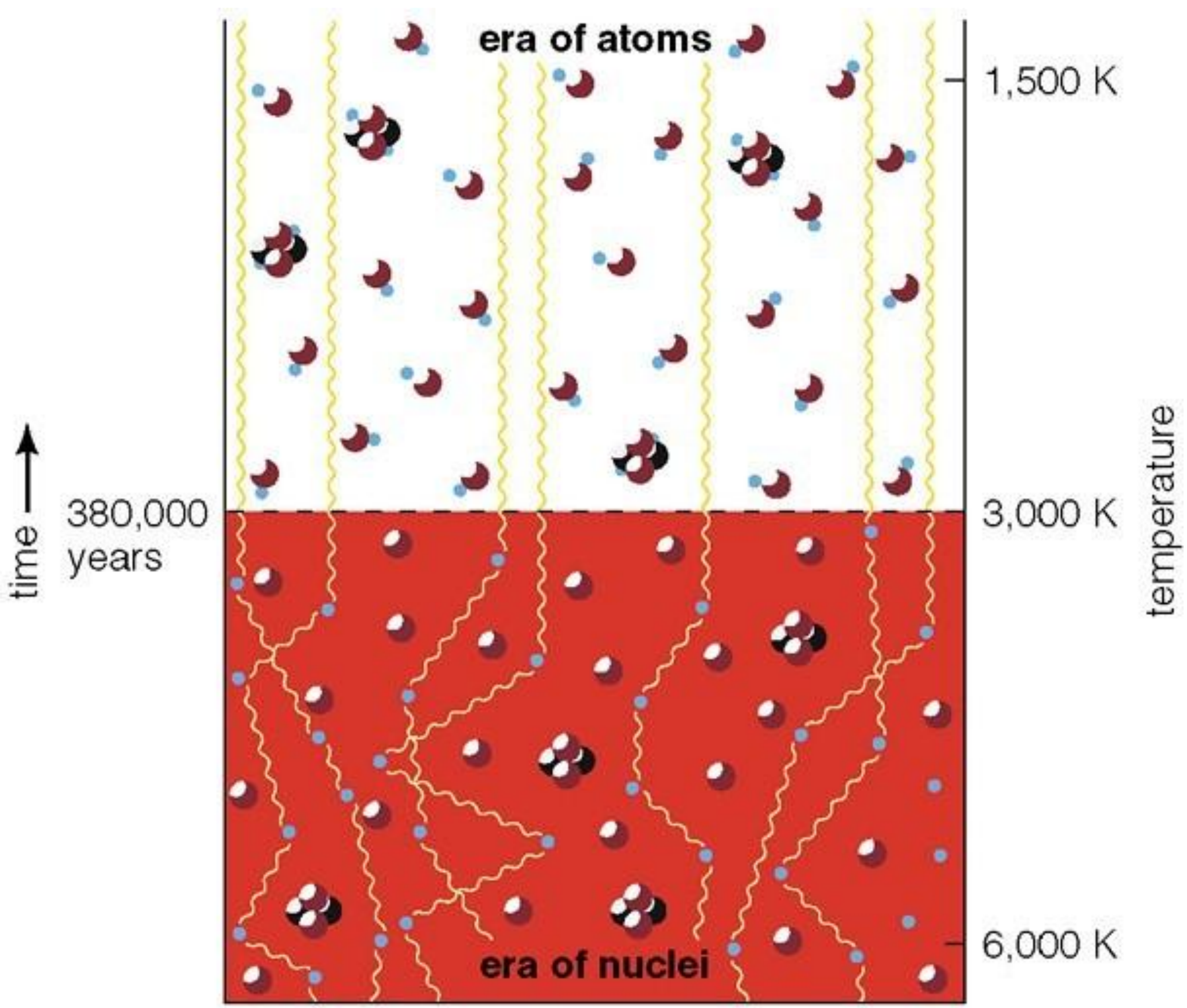
Cosmic Microwave Background (CMB)



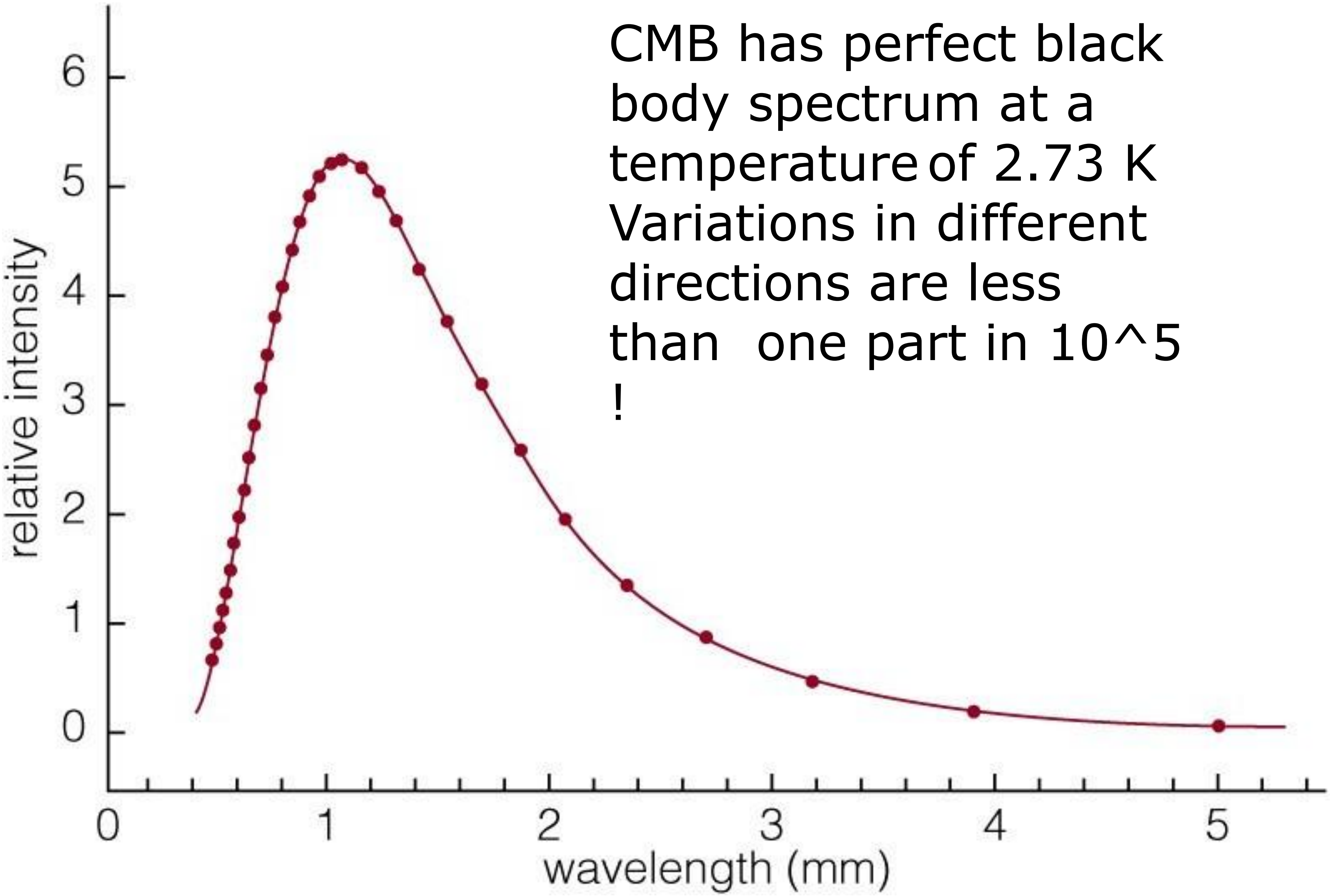
The cosmic microwave background – the radiation left over from the Big Bang – was detected by Penzias & Wilson in 1965 (Nobel Prize)

This is a few percent of the noise in an analog TV signal.

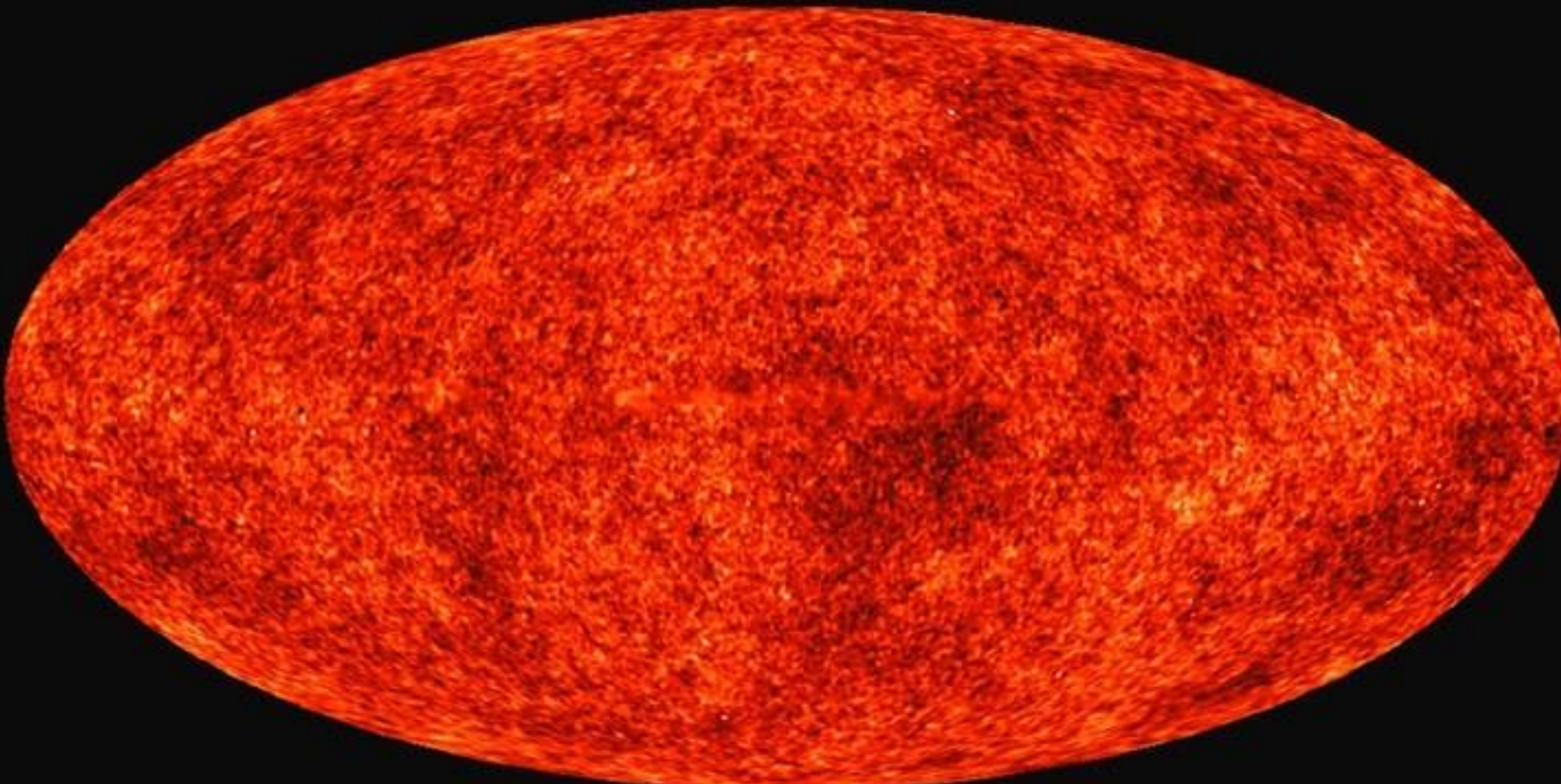
Where does the CMB come From?

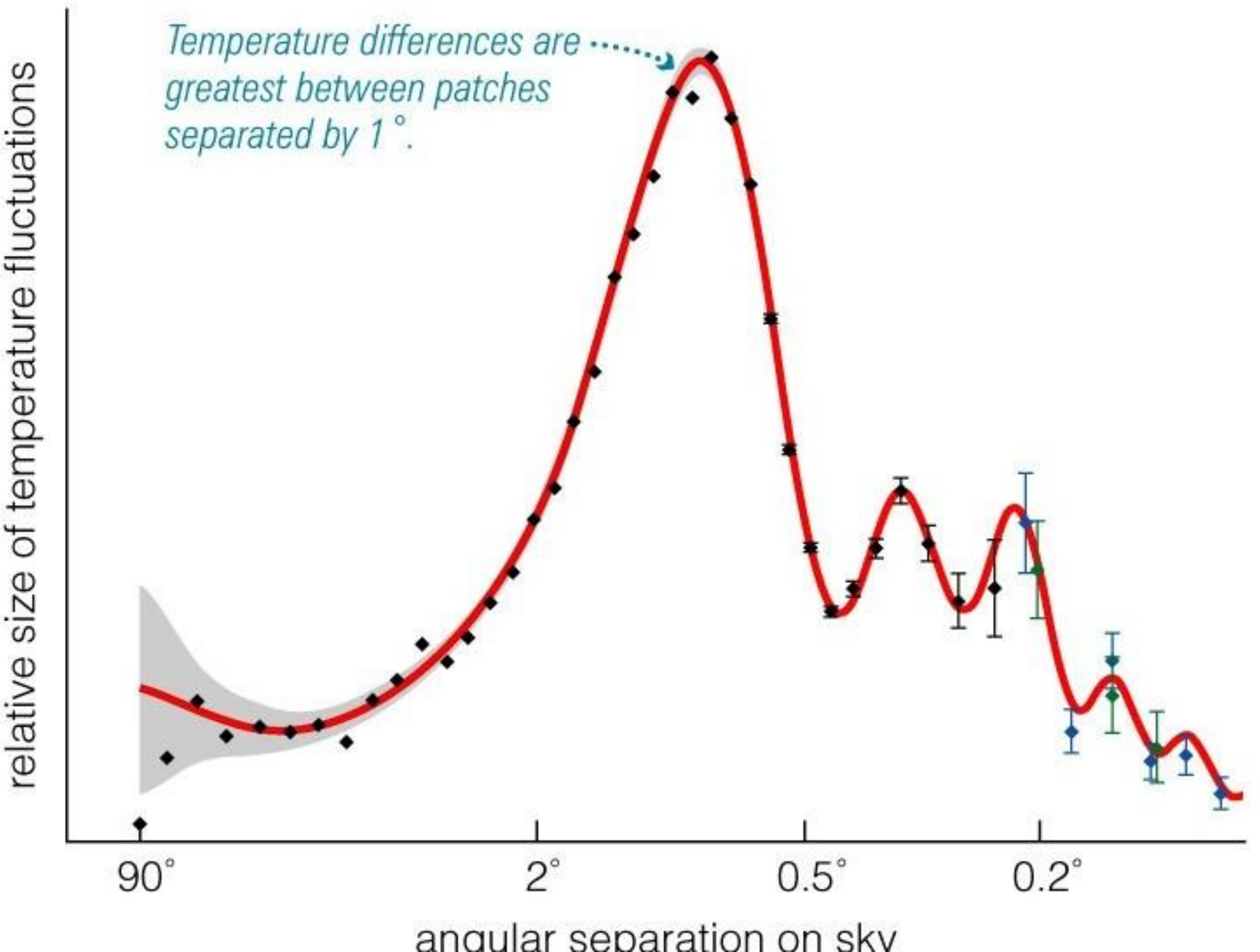


Background radiation from Big Bang has been freely streaming across universe since atoms formed at a temperature ~ 3,000 K.



CMB has perfect black body spectrum at a temperature of 2.73 K Variations in different directions are less than one part in 10^5 !



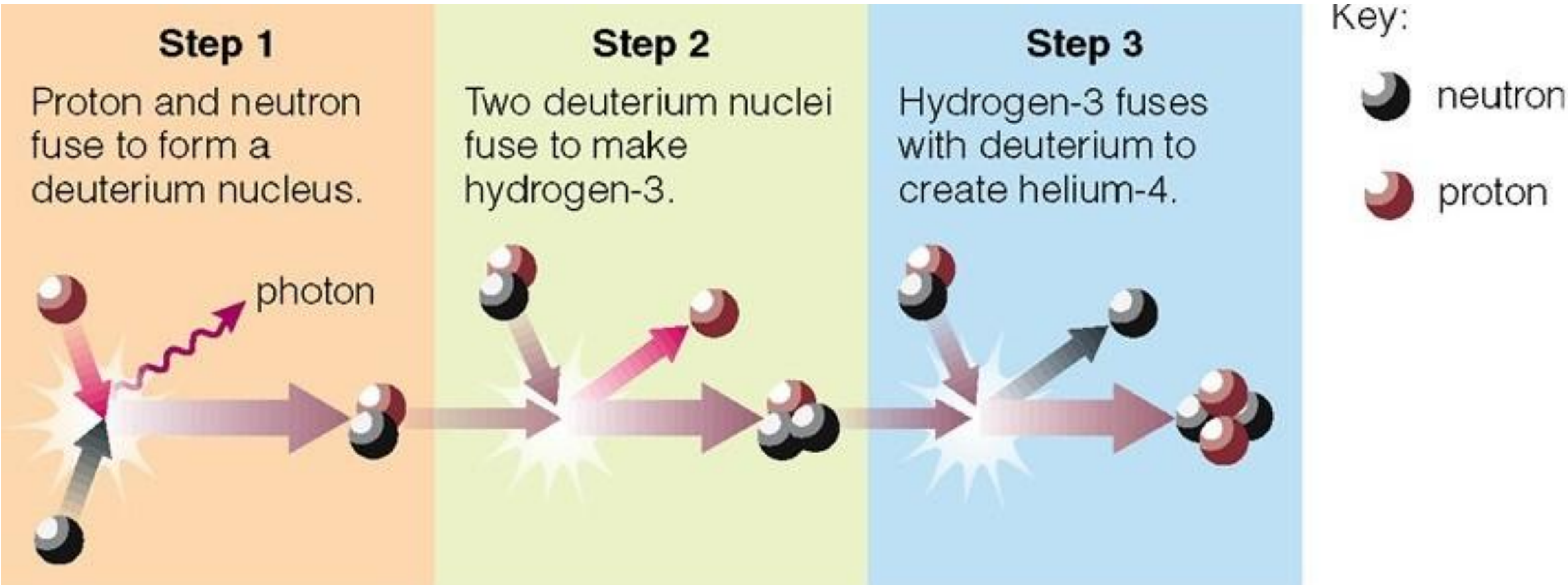

Temperature differences are greatest between patches separated by 1°.
relative size of temperature fluctuations
90°
2°
0.5°
0.2°
angular separation on sky

"Seeds" Inferred from CMB

- Overall geometry is flat
  - Total mass+energy has critical density
- Ordinary matter ~ 4.4% of total
- Total matter is ~ 27% of total
  - Dark matter is ~ 23% of total
  - Dark energy is ~ 73% of total
- Age of 13.7 billion years

In excellent agreement with observations of present-day universe and models involving inflation and WIMPs!

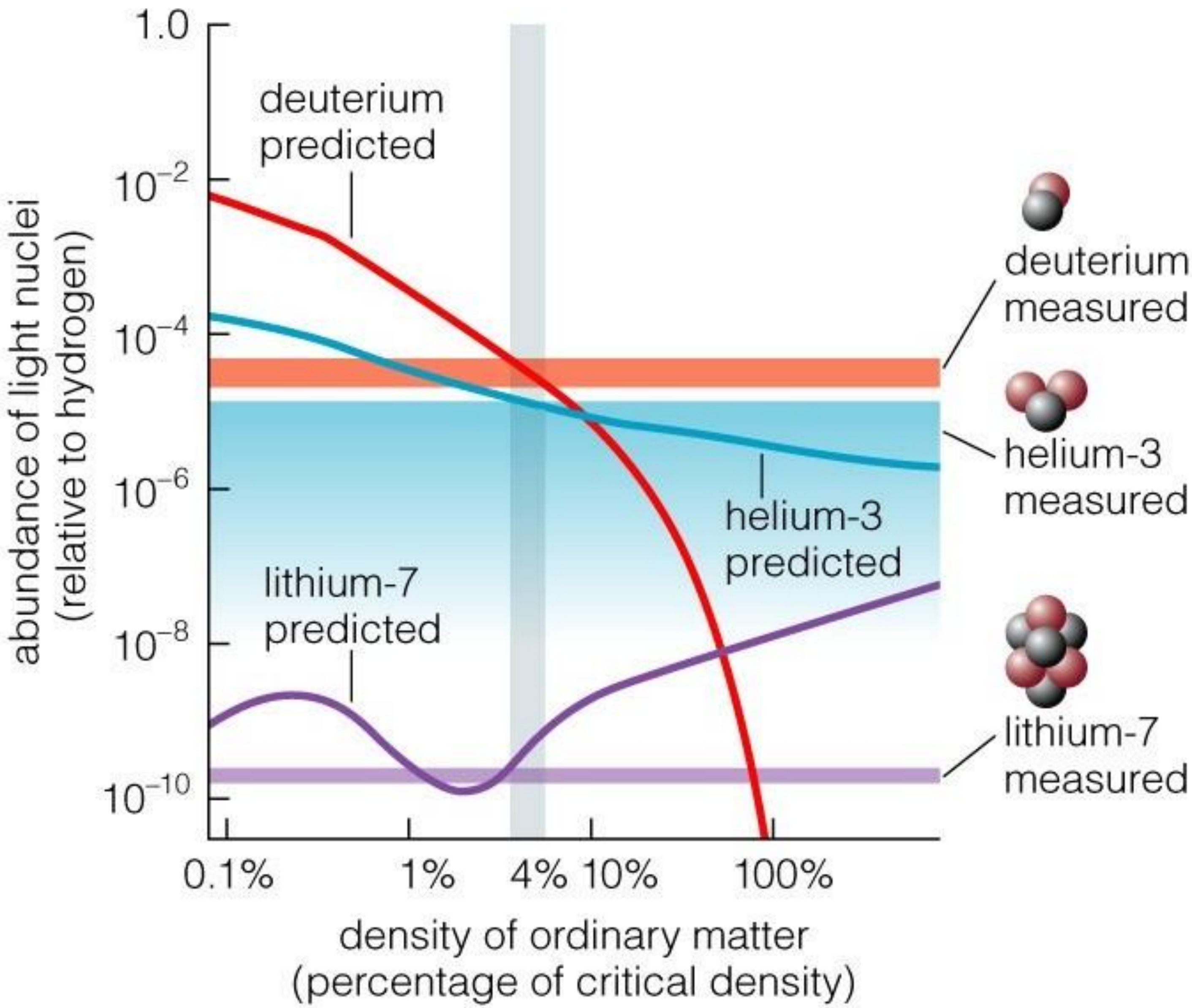
2) The abundances of elements



Protons and neutrons combined to make long- lasting helium nuclei when universe was ~ 3 minutes old

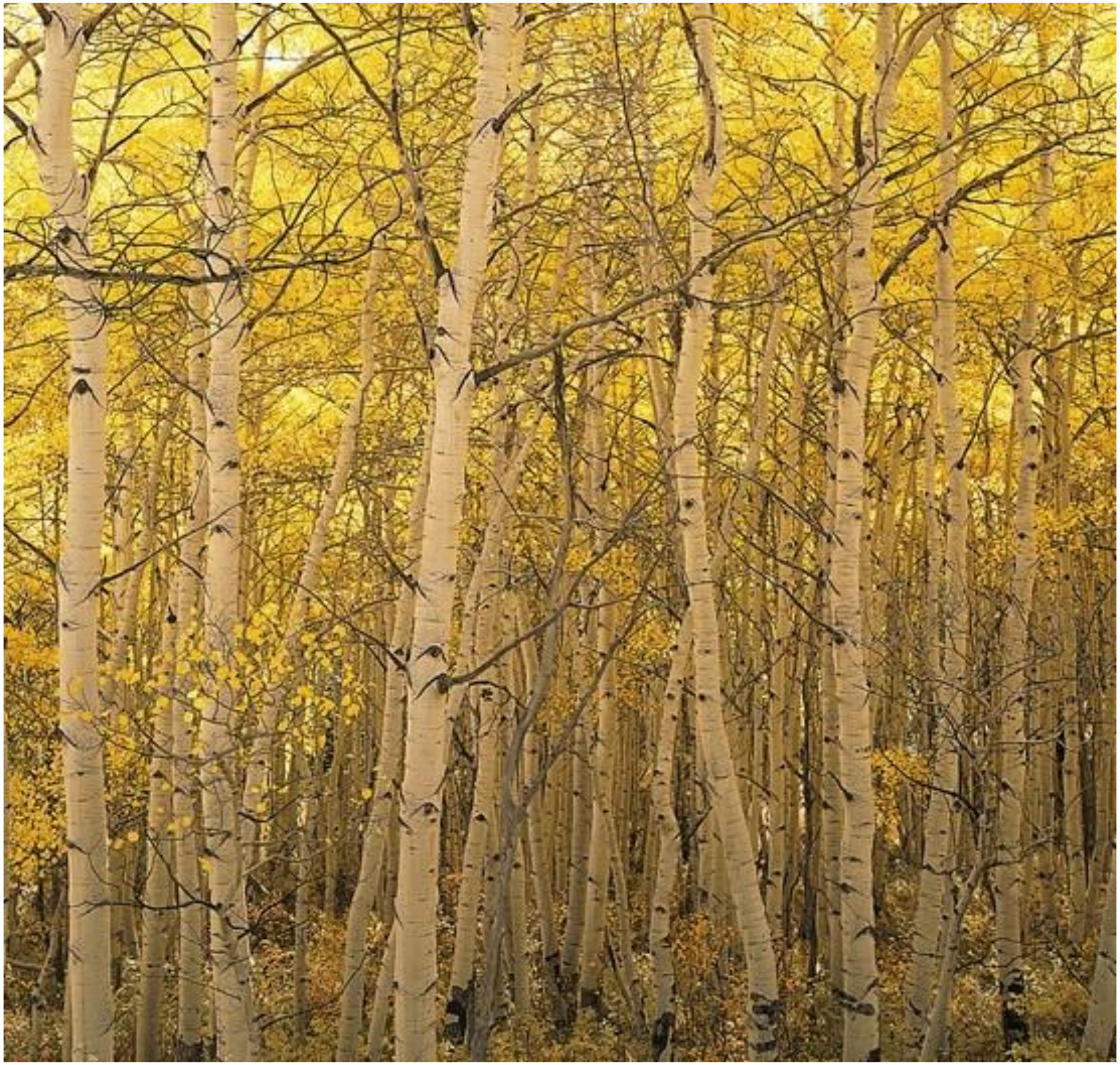
Big Bang theory prediction: 75% H, 25% He Matches observations!

Cosmic Abundances

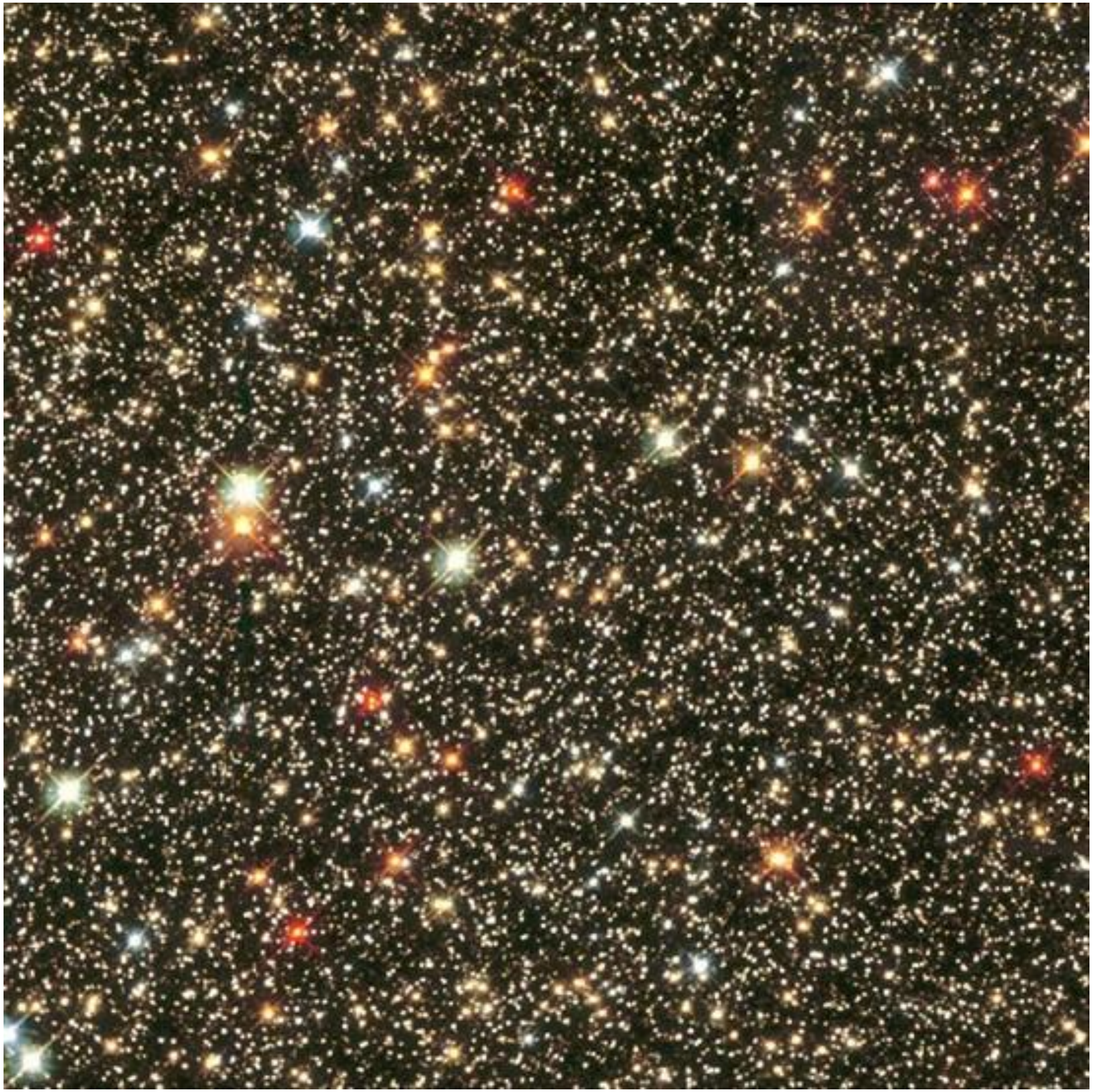


Abundances of other light elements agree with Big Bang model having 4.4% normal matter (the rest being dark matter and dark energy)

3) Darkness of Night Sky



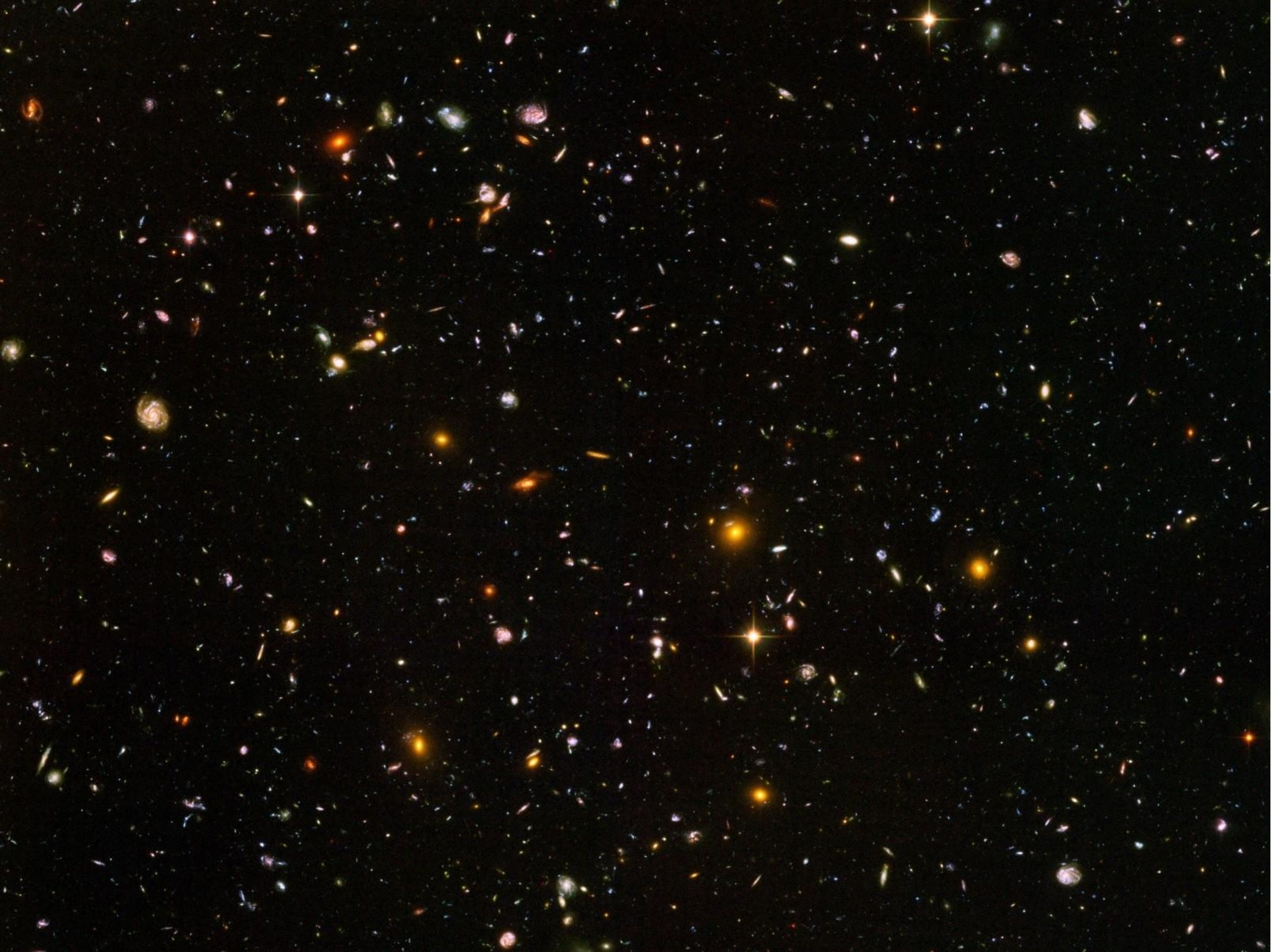
Olbers' Paradox

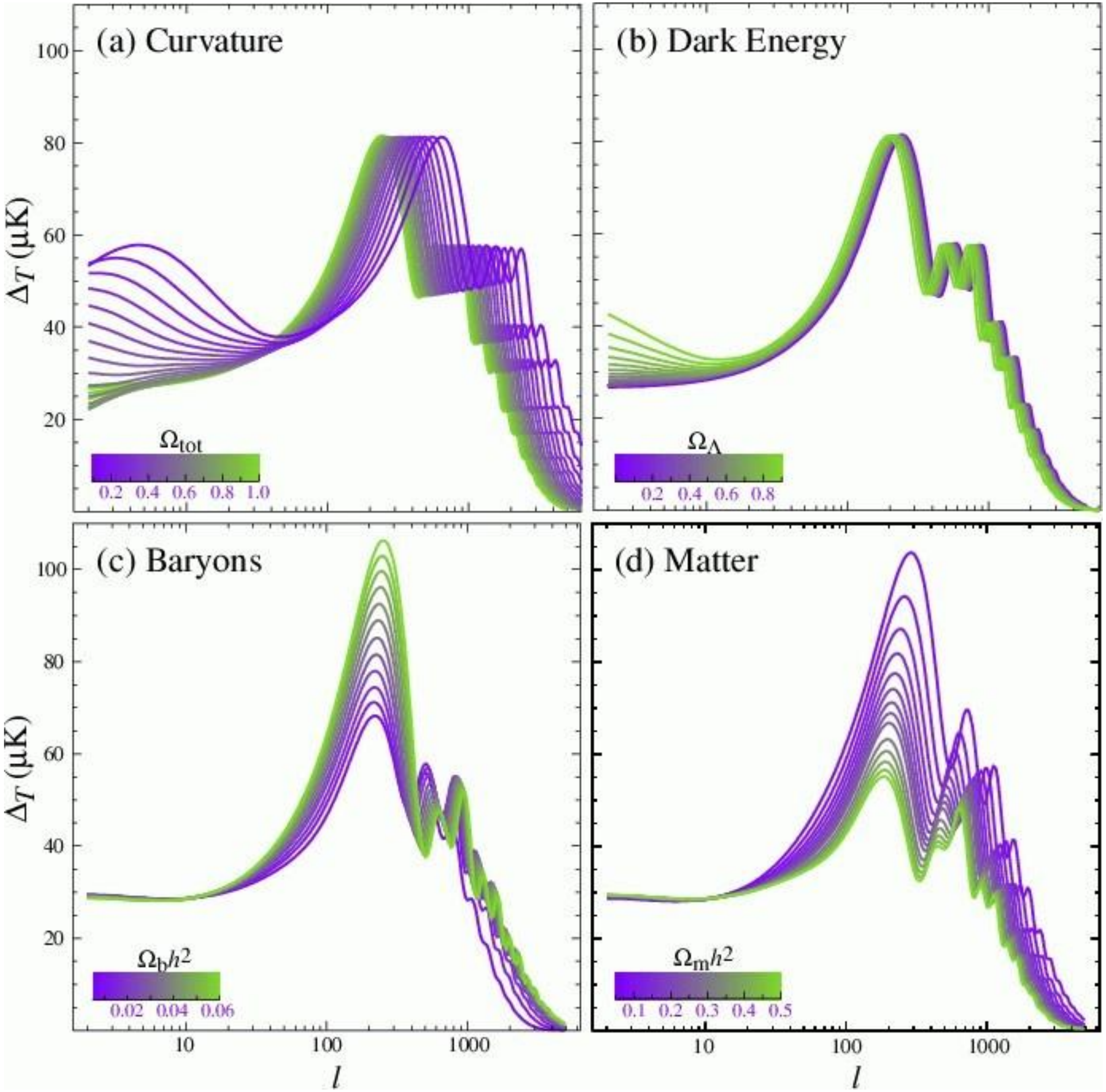


If universe were

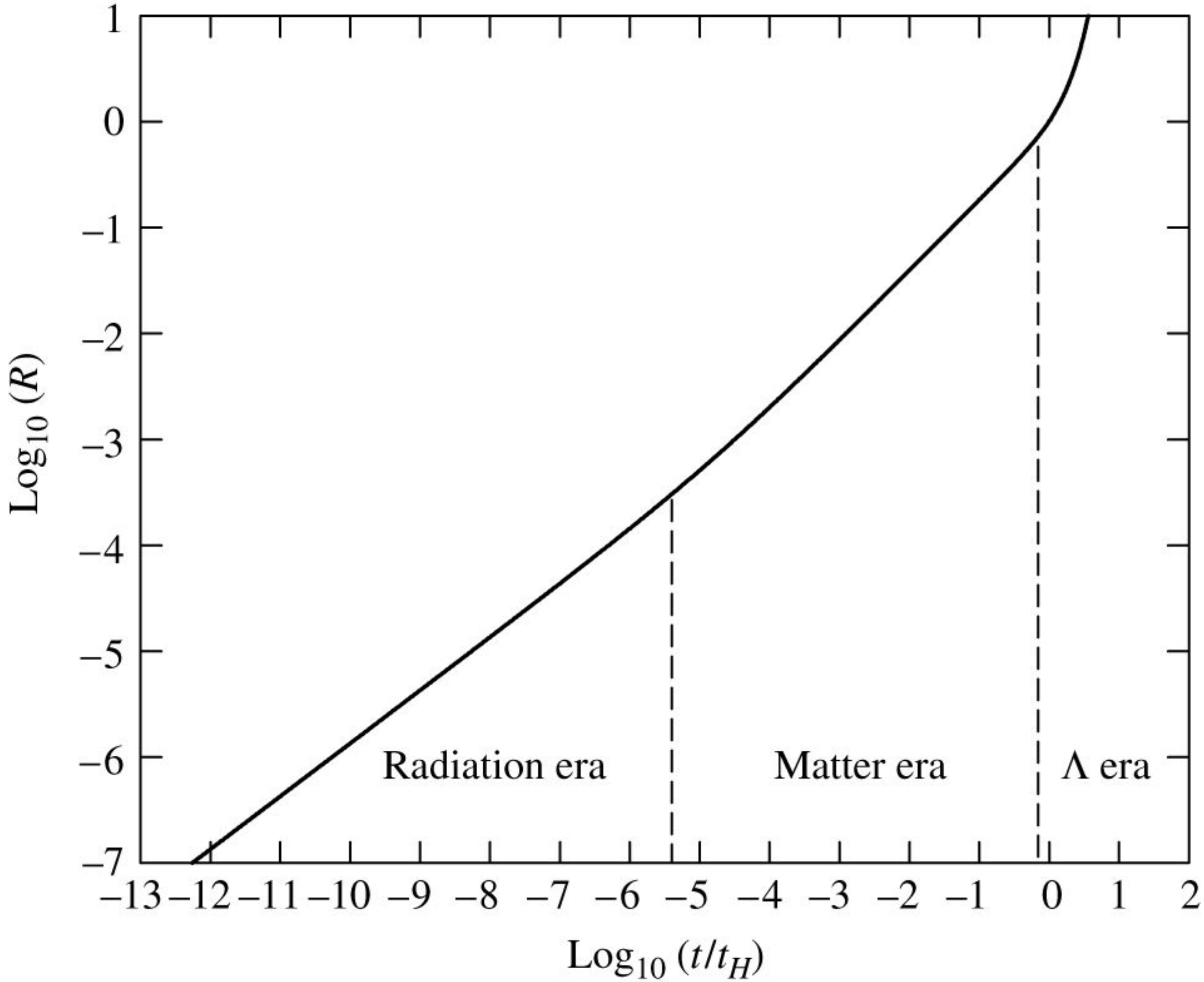
1) infinite
2) unchanging
3) everywhere the same

Then, stars would cover the night sky, and it would be as bright as the Sun



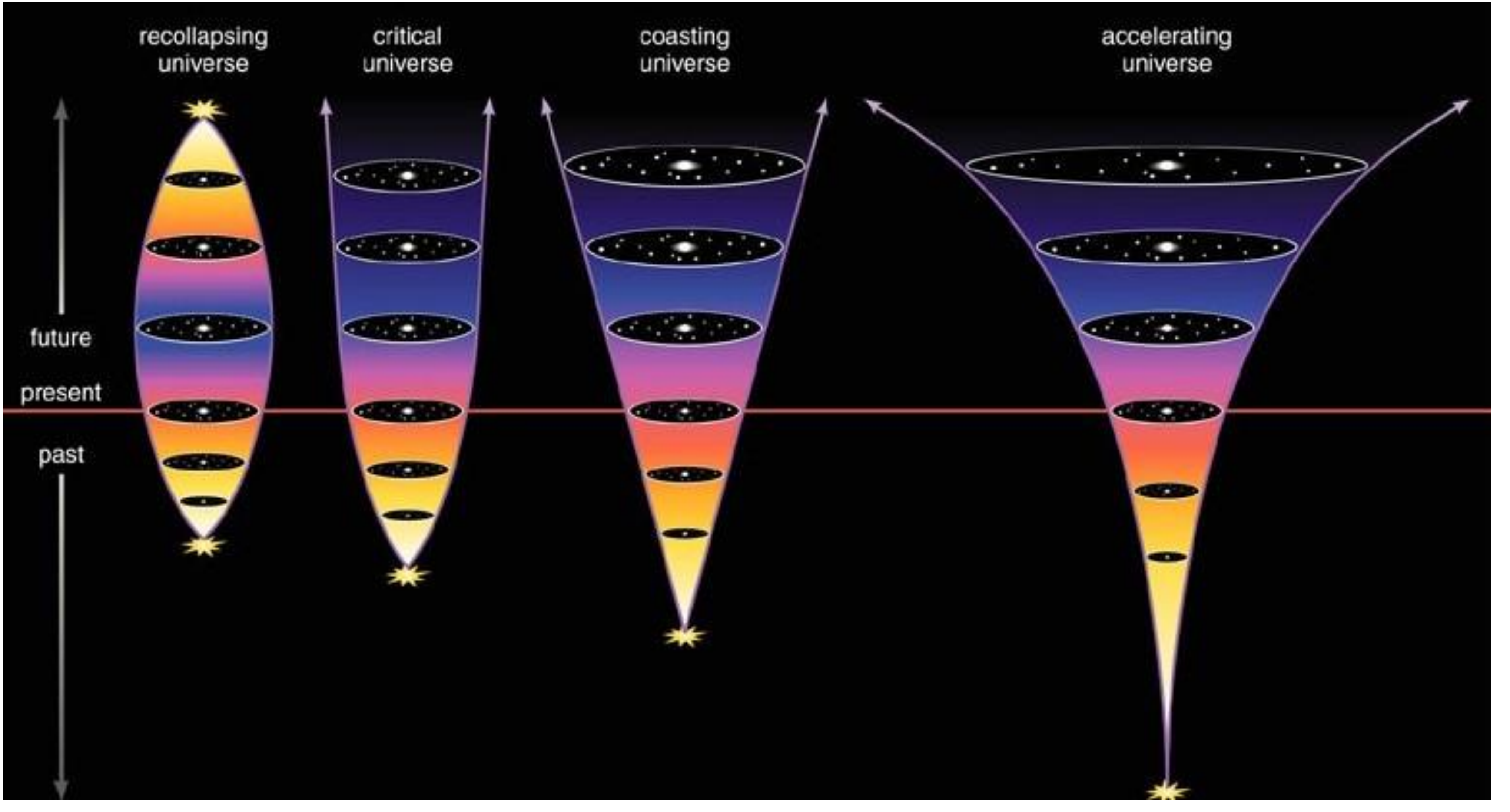


(a) Curvature
(b) Dark Energy
(c) Baryons
(d) Matter
Δ_T (μK)
l
Ω_{tot}
0.2 0.4 0.6 0.8 1.0
Ω_Λ
0.2 0.4 0.6 0.8
$\Omega_b h^2$
0.02 0.04 0.06
$\Omega_m h^2$
0.1 0.2 0.3 0.4 0.5
20 40 60 80 100
10 100 1000



1
0
–1
–2
–3
–4
–5
–6
–7
Log10 (R)
Radiation era
Matter era
Λ era
–13 –12 –11 –10 –9 –8 –7 –6 –5 –4 –3 –2 –1 0 1 2
Log10 (t/tH)

Fate of the Universe



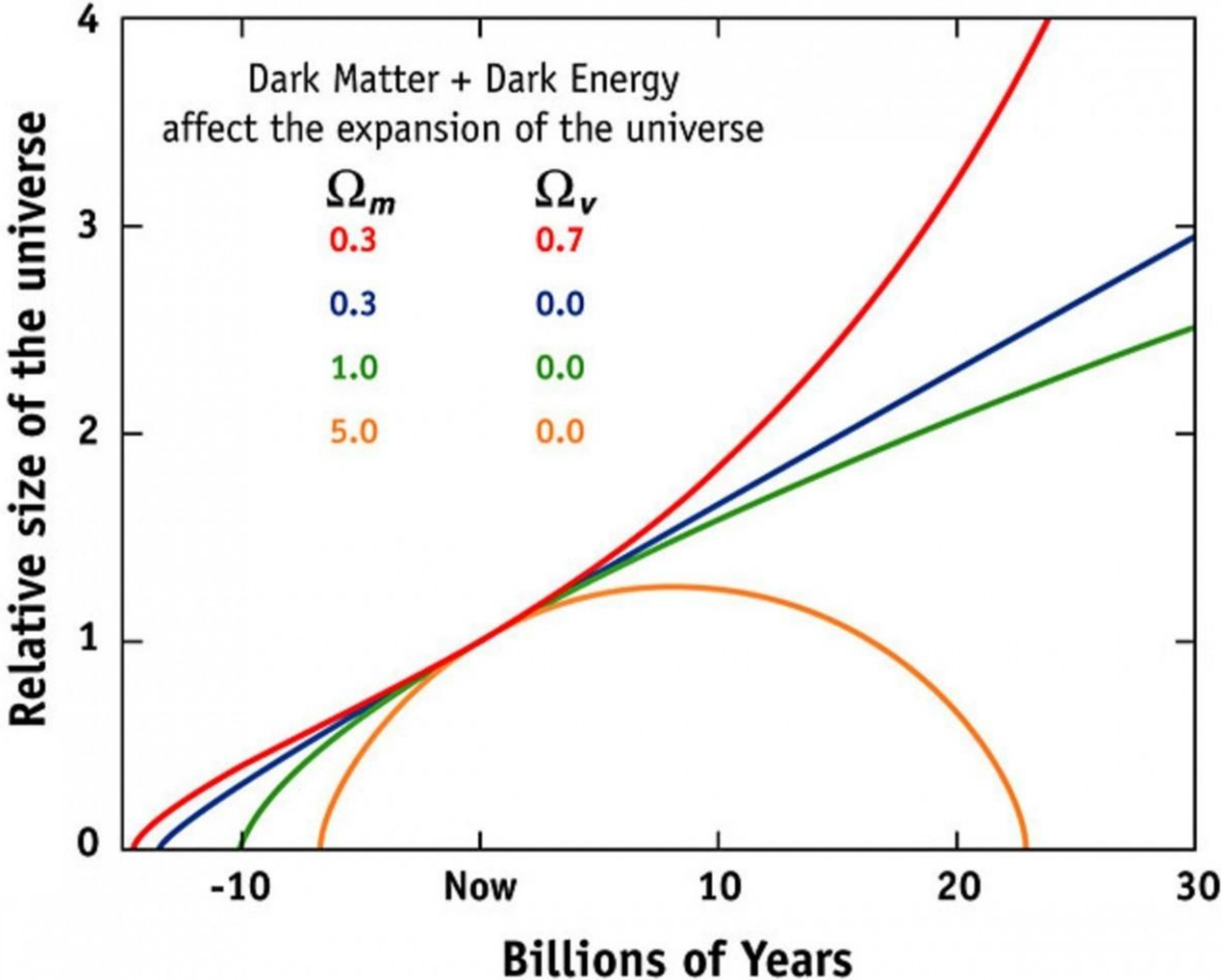
Recollapse

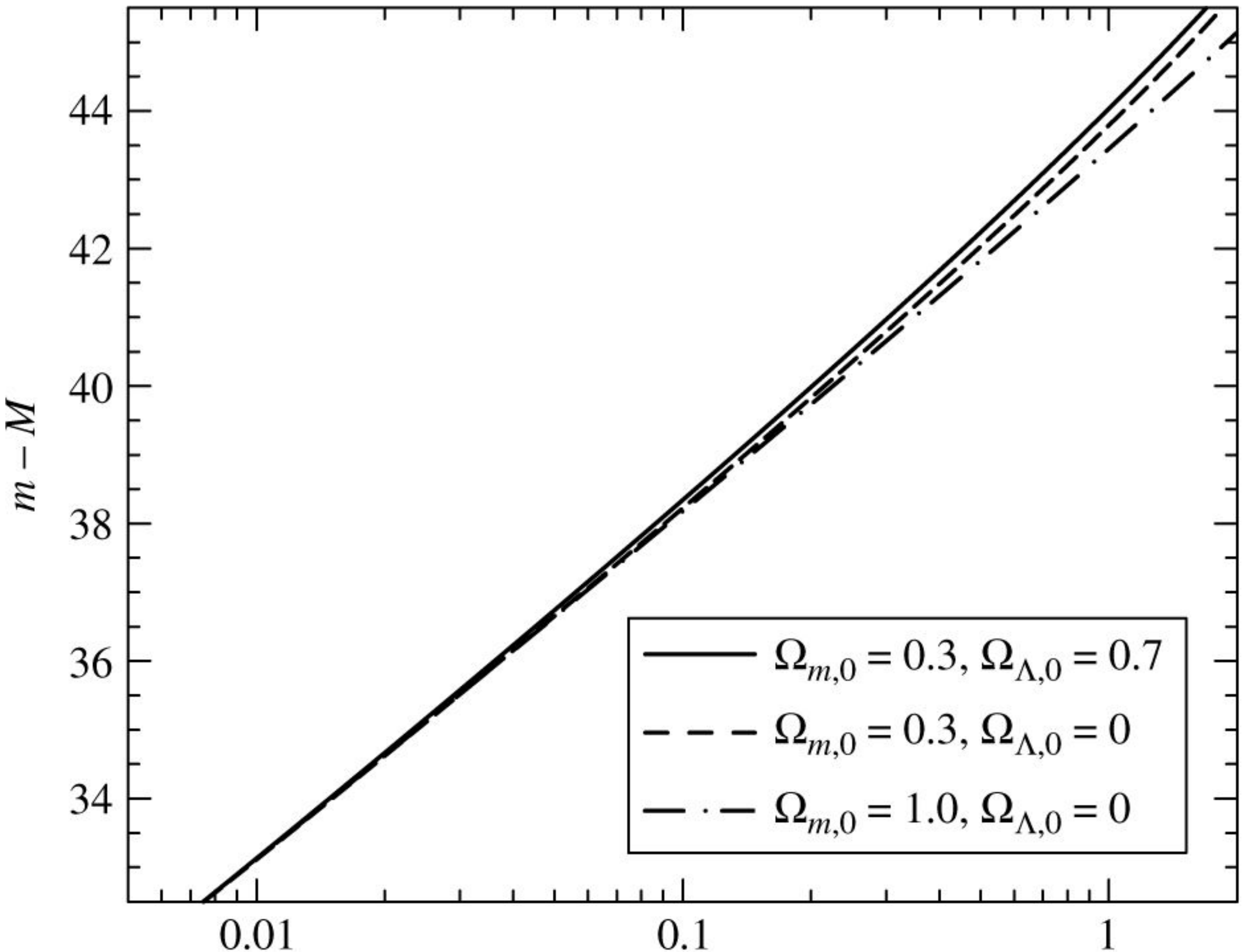
Eventual stop to expansion

Expansion forever

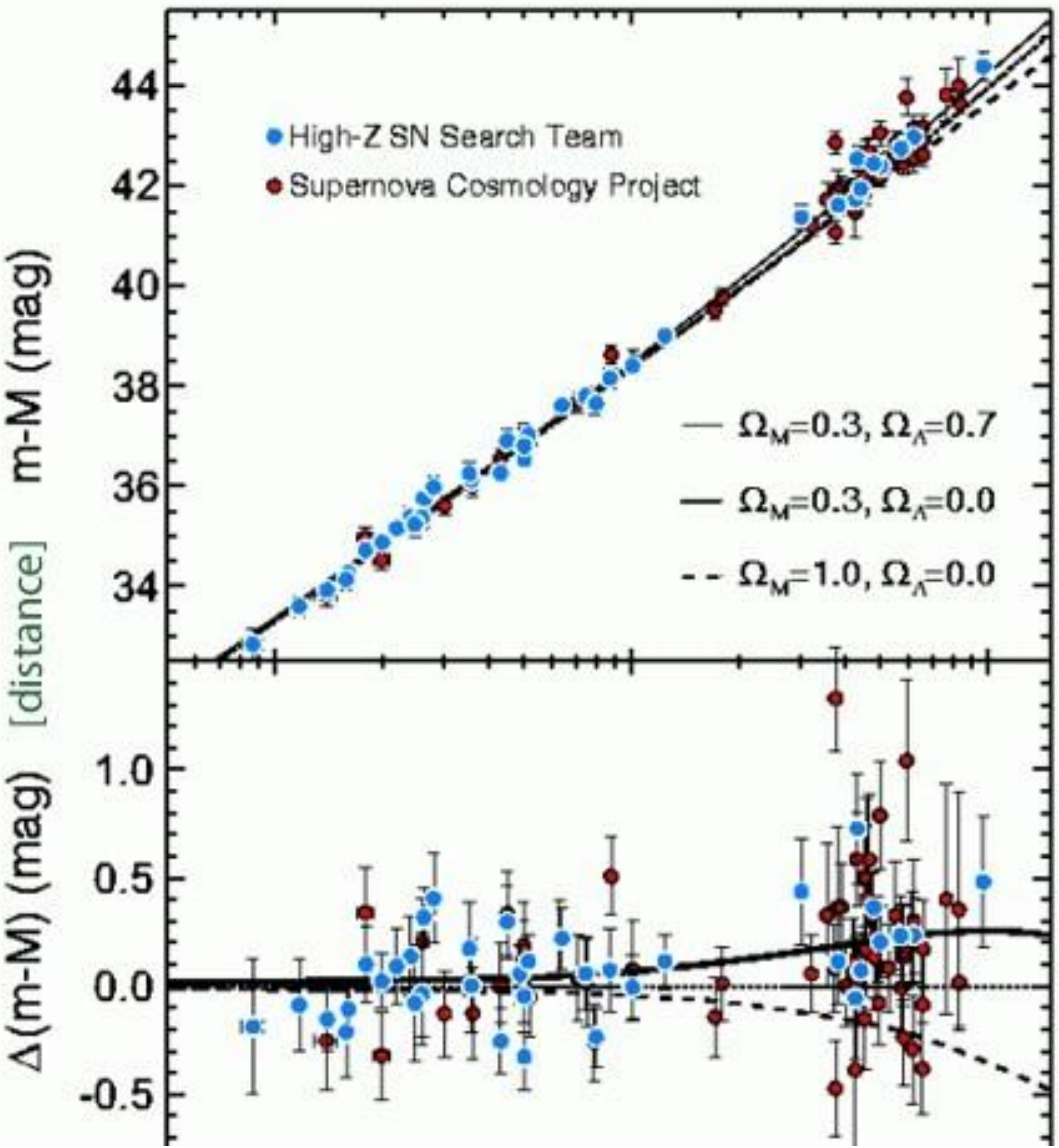
Expansion forever, but increasingly fast

EXPANSION OF THE UNIVERSE



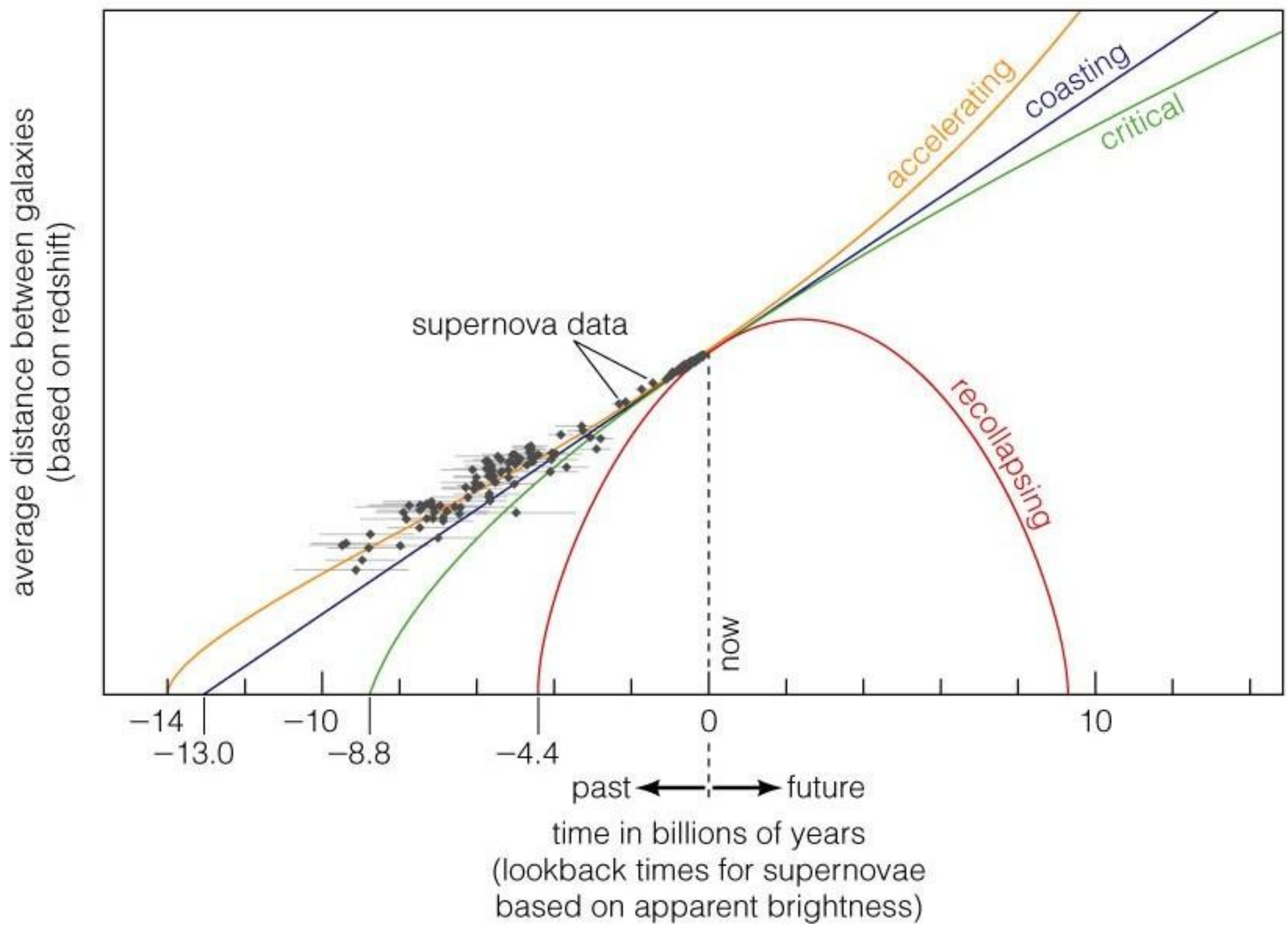


$m - M$
44
42
40
38
36
34
0.01
0.1
1
$\Omega_{m,0} = 0.3,\ \Omega_{\Lambda,0} = 0.7$
$\Omega_{m,0} = 0.3,\ \Omega_{\Lambda,0} = 0$
$\Omega_{m,0} = 1.0,\ \Omega_{\Lambda,0} = 0$



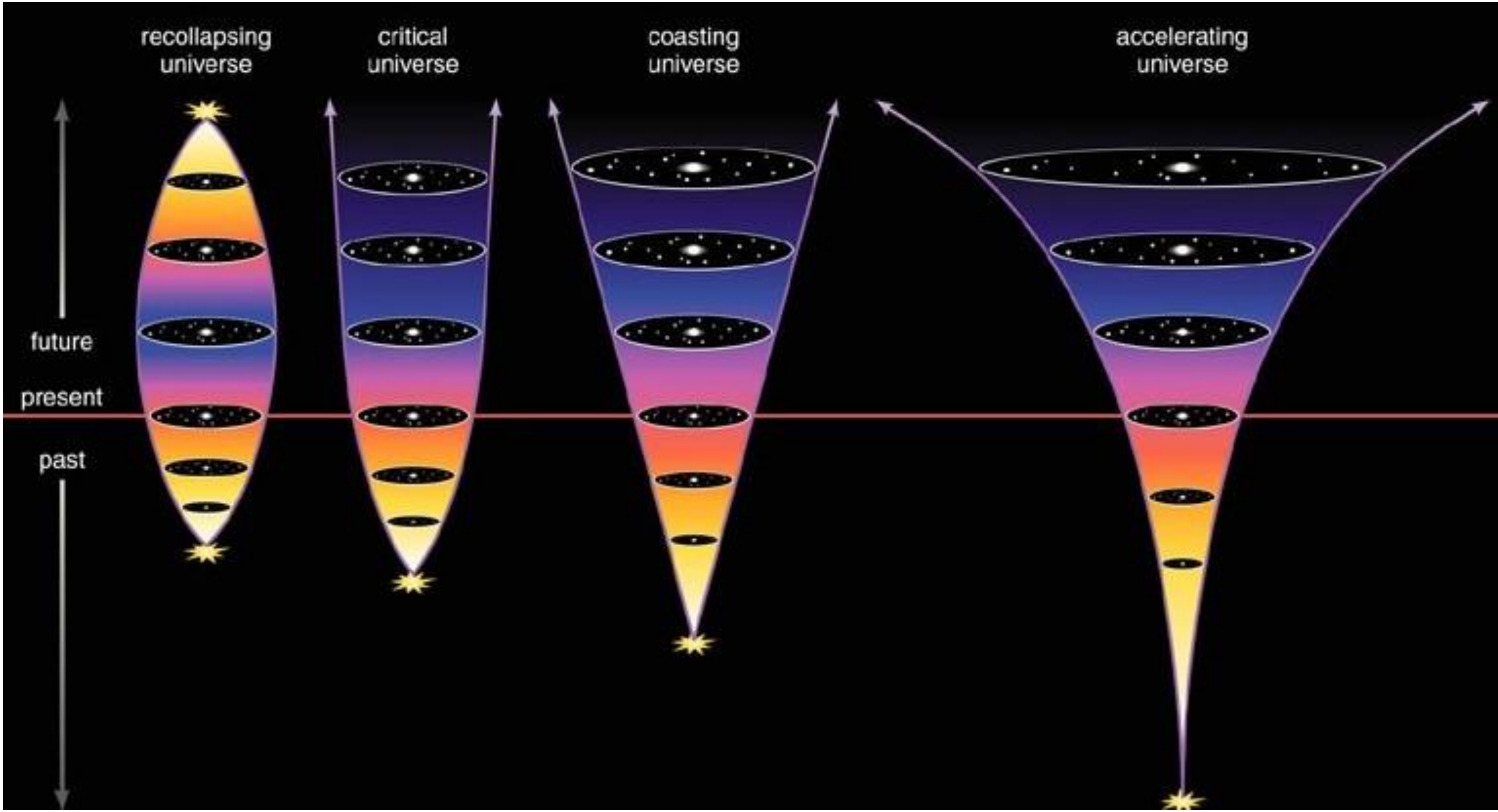
High-Z SN Search Team
Supernova Cosmology Project
m-M (mag)
[distance]
Δ(m-M) (mag)
Ω_M=0.3, Ω_Λ=0.7
Ω_M=0.3, Ω_Λ=0.0
Ω_M=1.0, Ω_Λ=0.0
44
42
40
38
36
34
1.0
0.5
0.0
-0.5

The Accelerating Universe



Accelerating universe is best fit to supernova data

Fate of the Universe

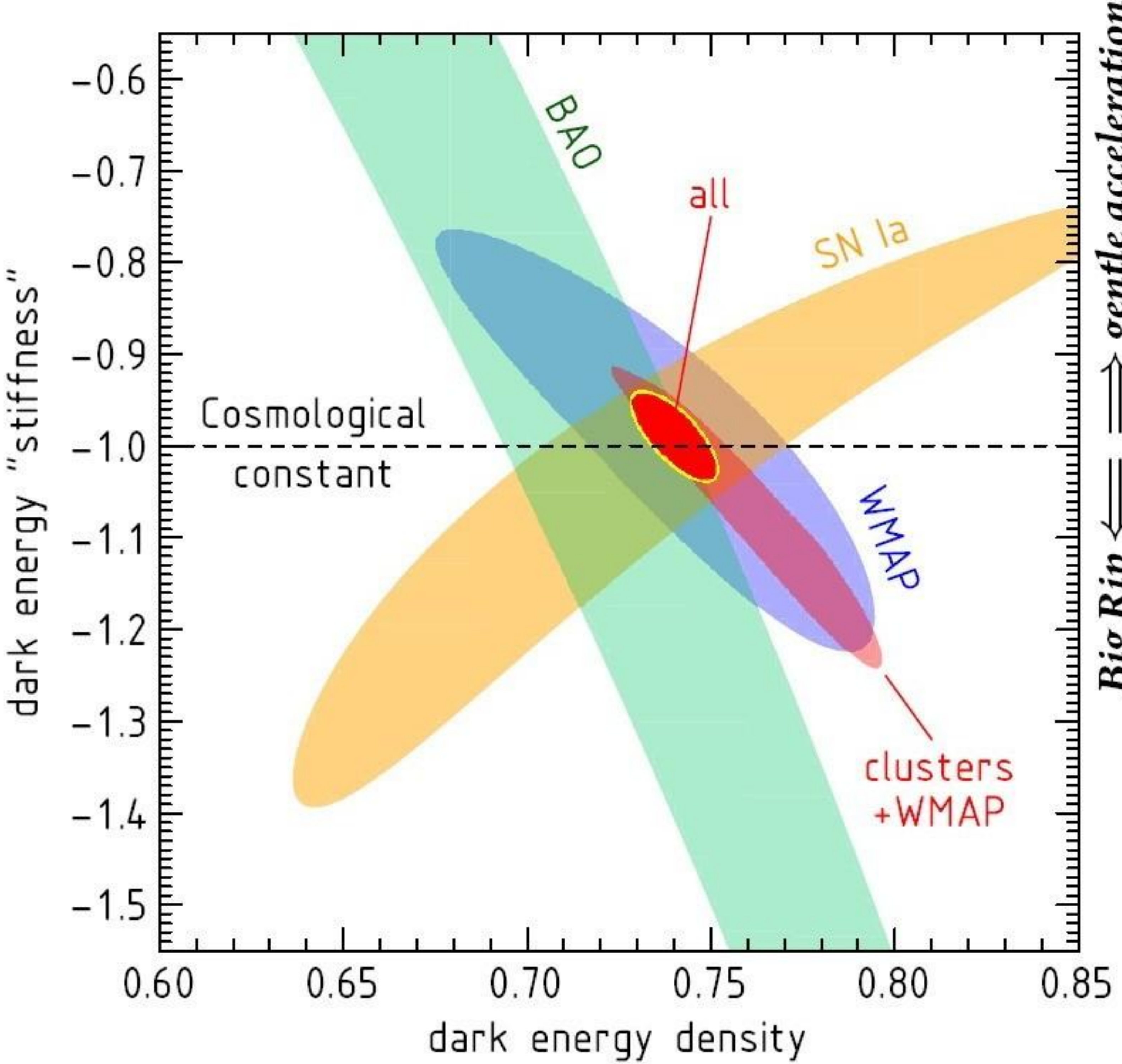


Recollapse

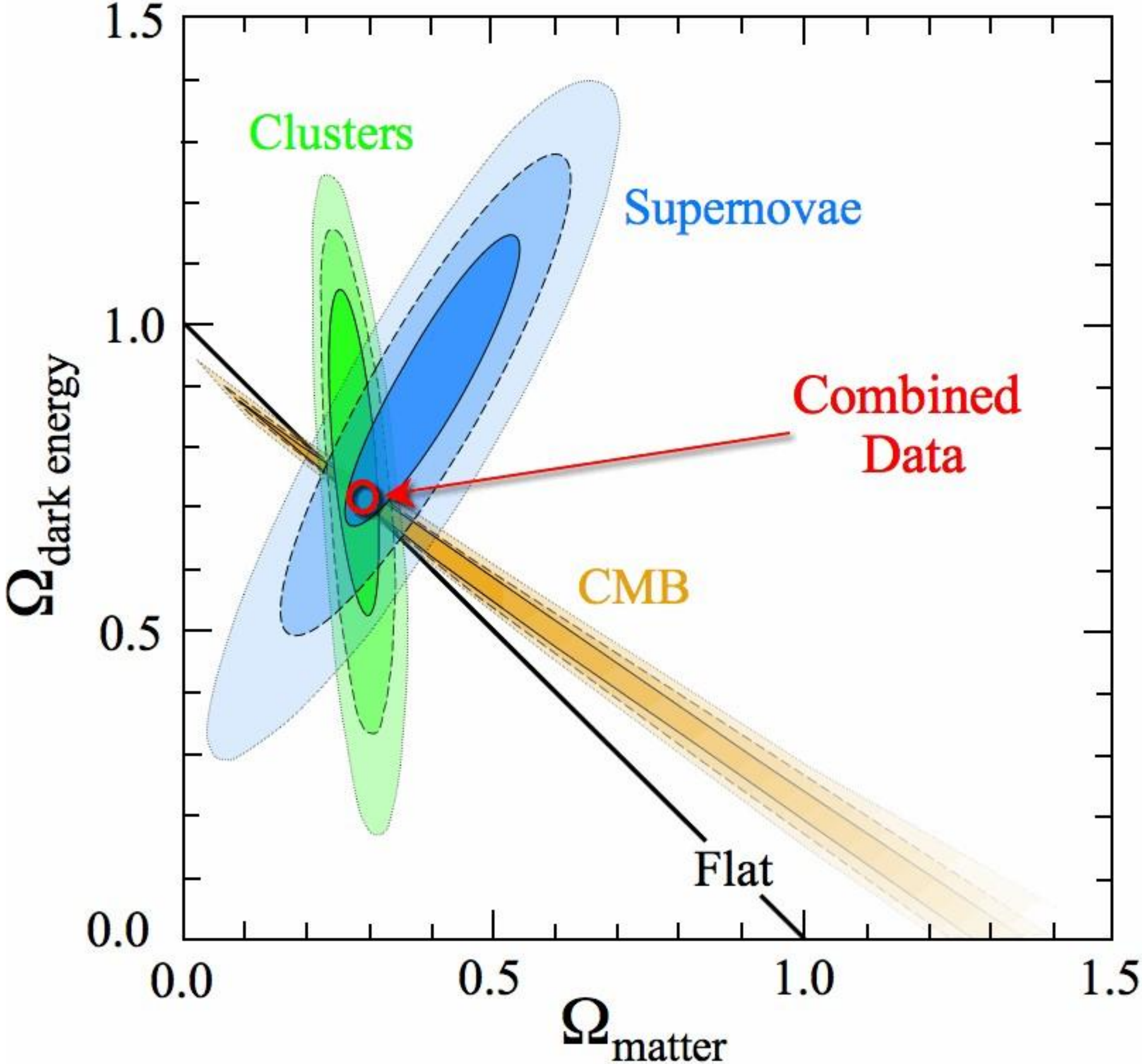
Eventual stop to expansion

Expansion forever

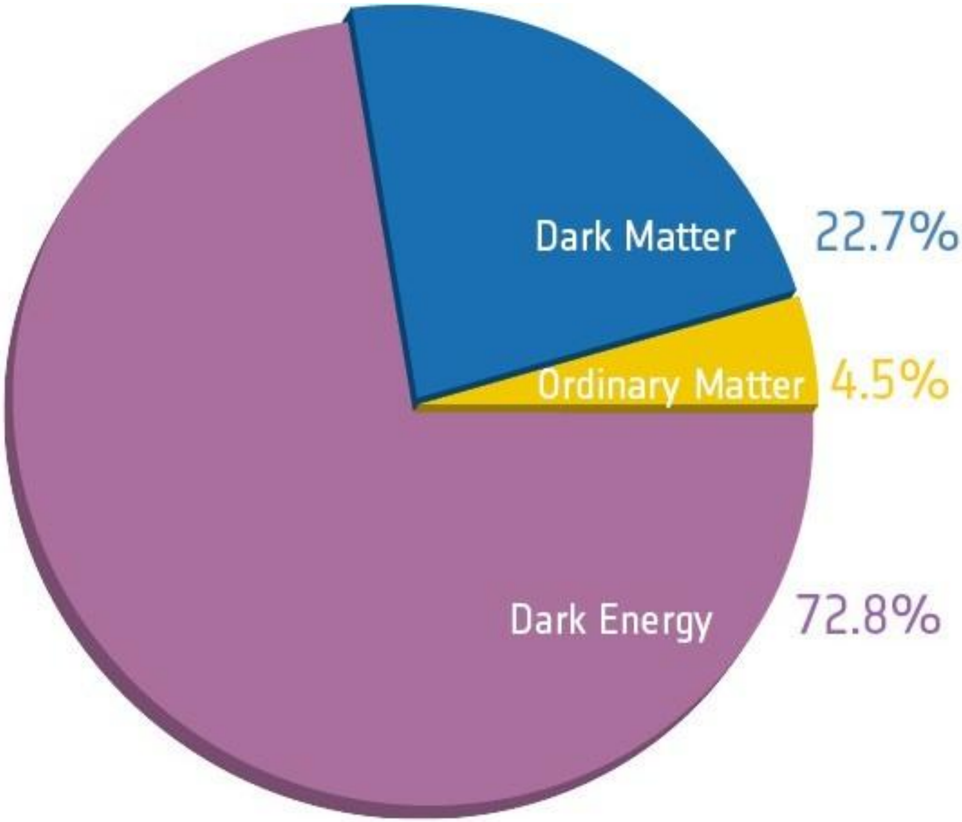
Expansion forever, but increasingly fast



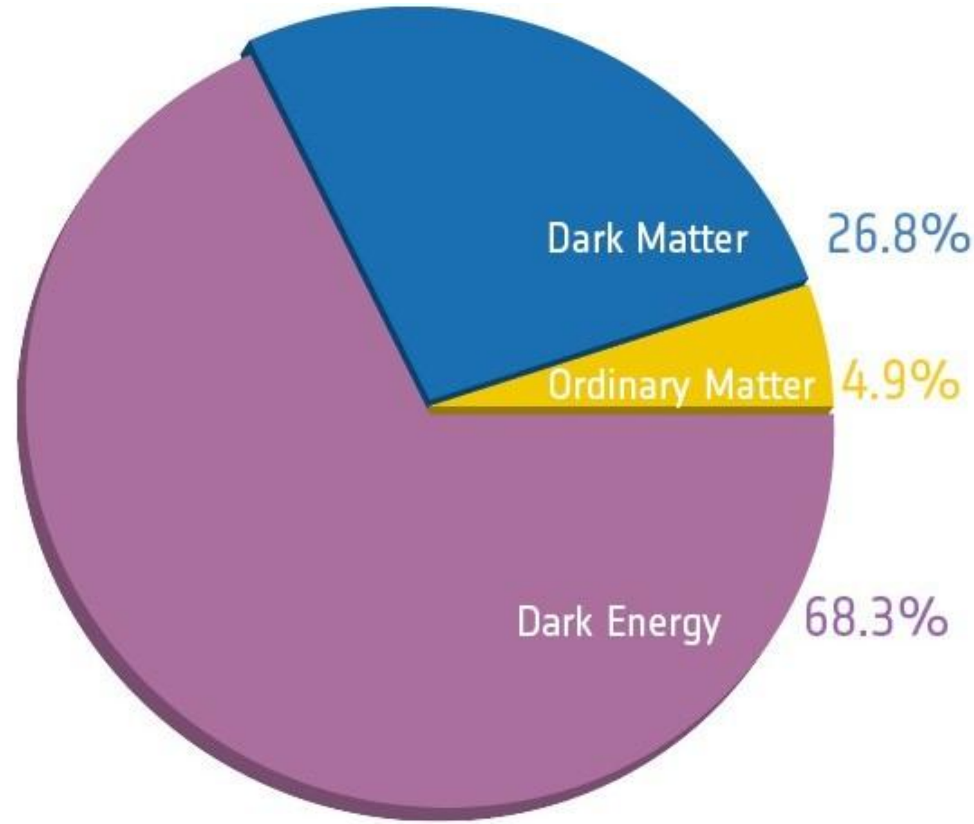
dark energy "stiffness"
dark energy density
-0.6
-0.7
-0.8
-0.9
-1.0
-1.1
-1.2
-1.3
-1.4
-1.5
0.60
0.65
0.70
0.75
0.80
0.85
BAO
all
SN Ia
Cosmological constant
WMAP
clusters +WMAP
Big Rip ⟸ ⟹ gentle acceleration



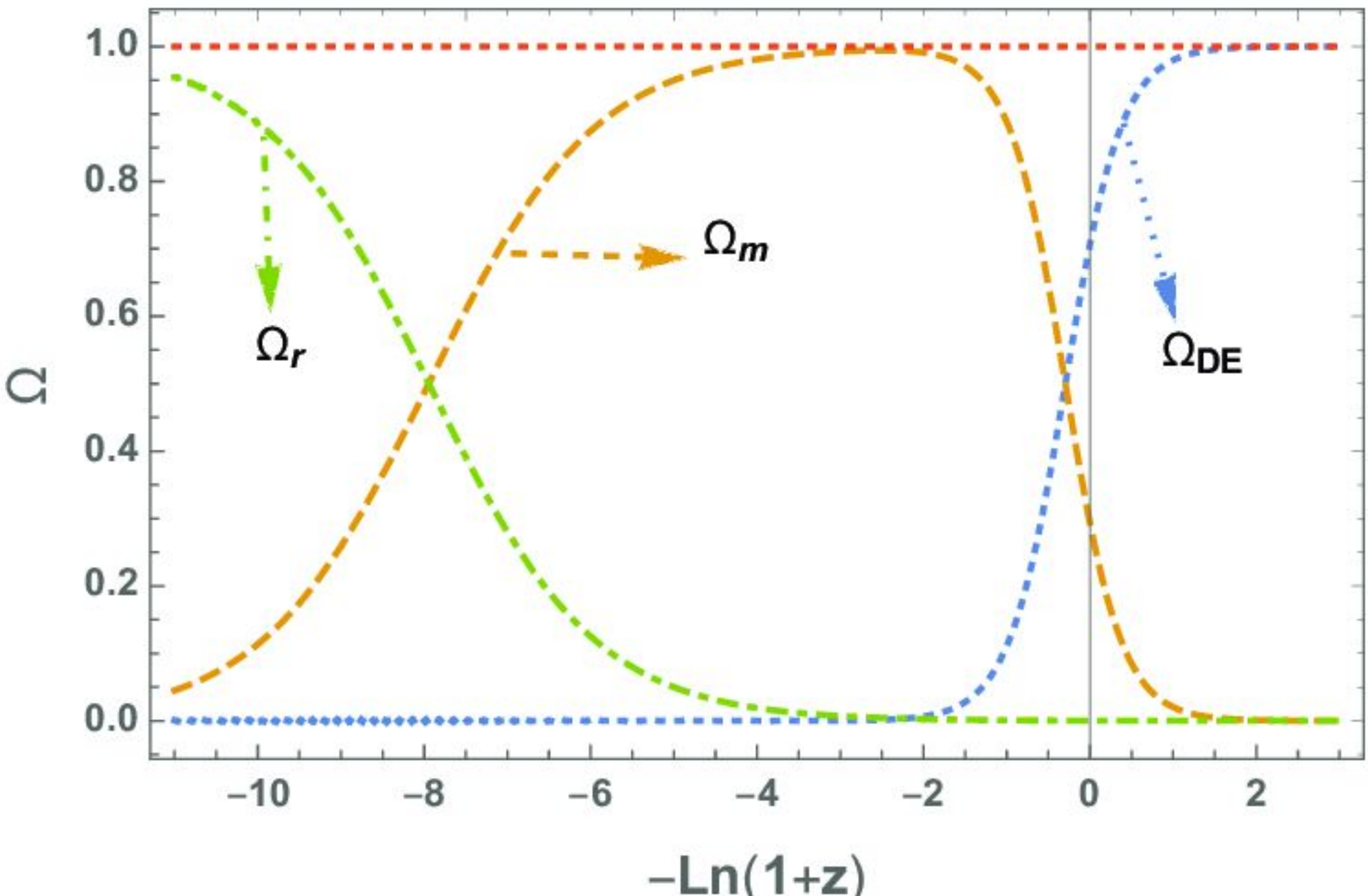
1.5
1.0
0.5
0.0
0.0
0.5
1.0
1.5
Ω dark energy
Ω matter
Clusters
Supernovae
Combined
Data
CMB
Flat



Before Planck



After Planck



1.0
0.8
0.6
0.4
0.2
0.0
Ω
Ω_r
Ω_m
Ω_{DE}
−10
−8
−6
−4
−2
0
2
−Ln(1+z)