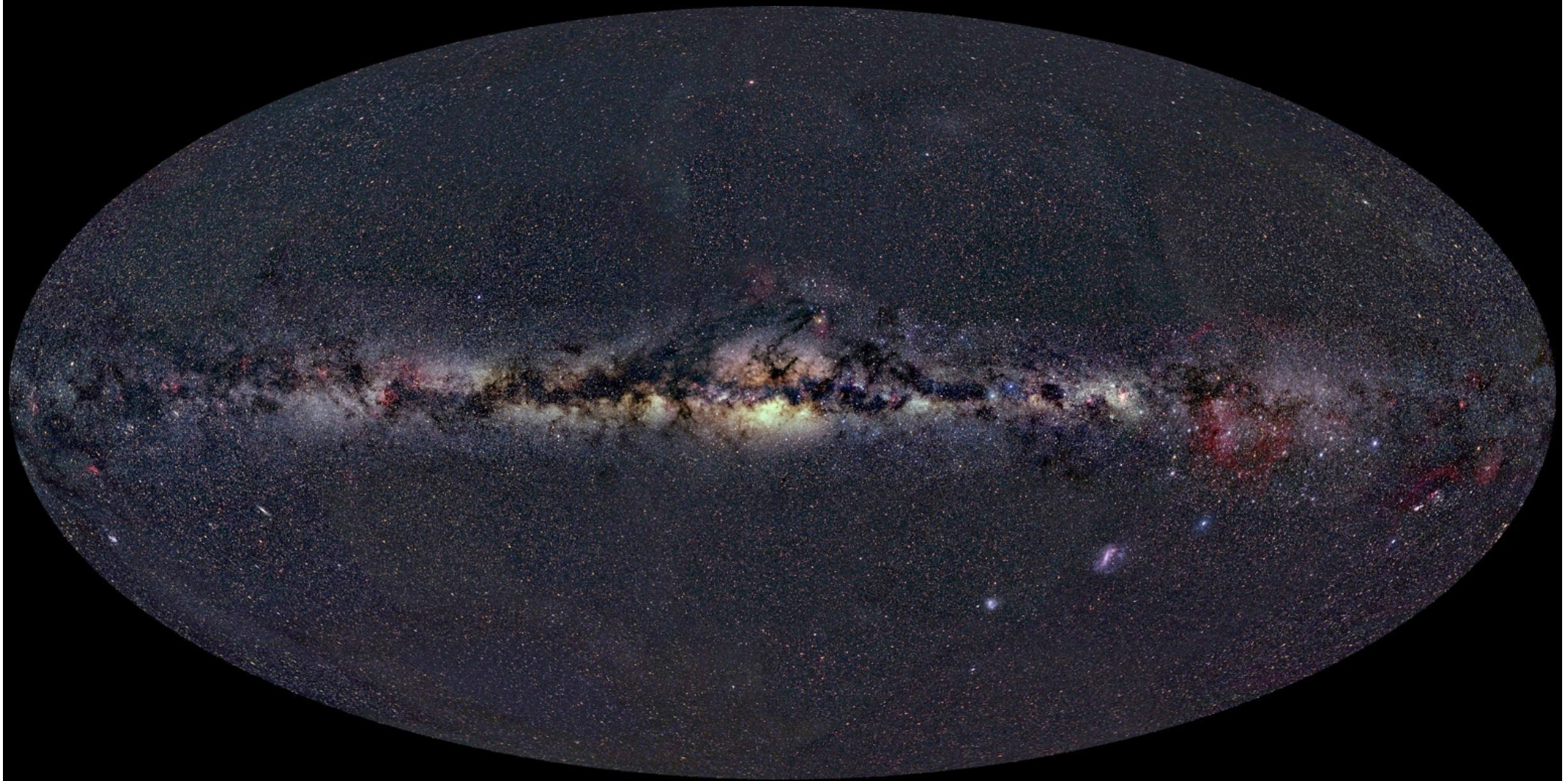


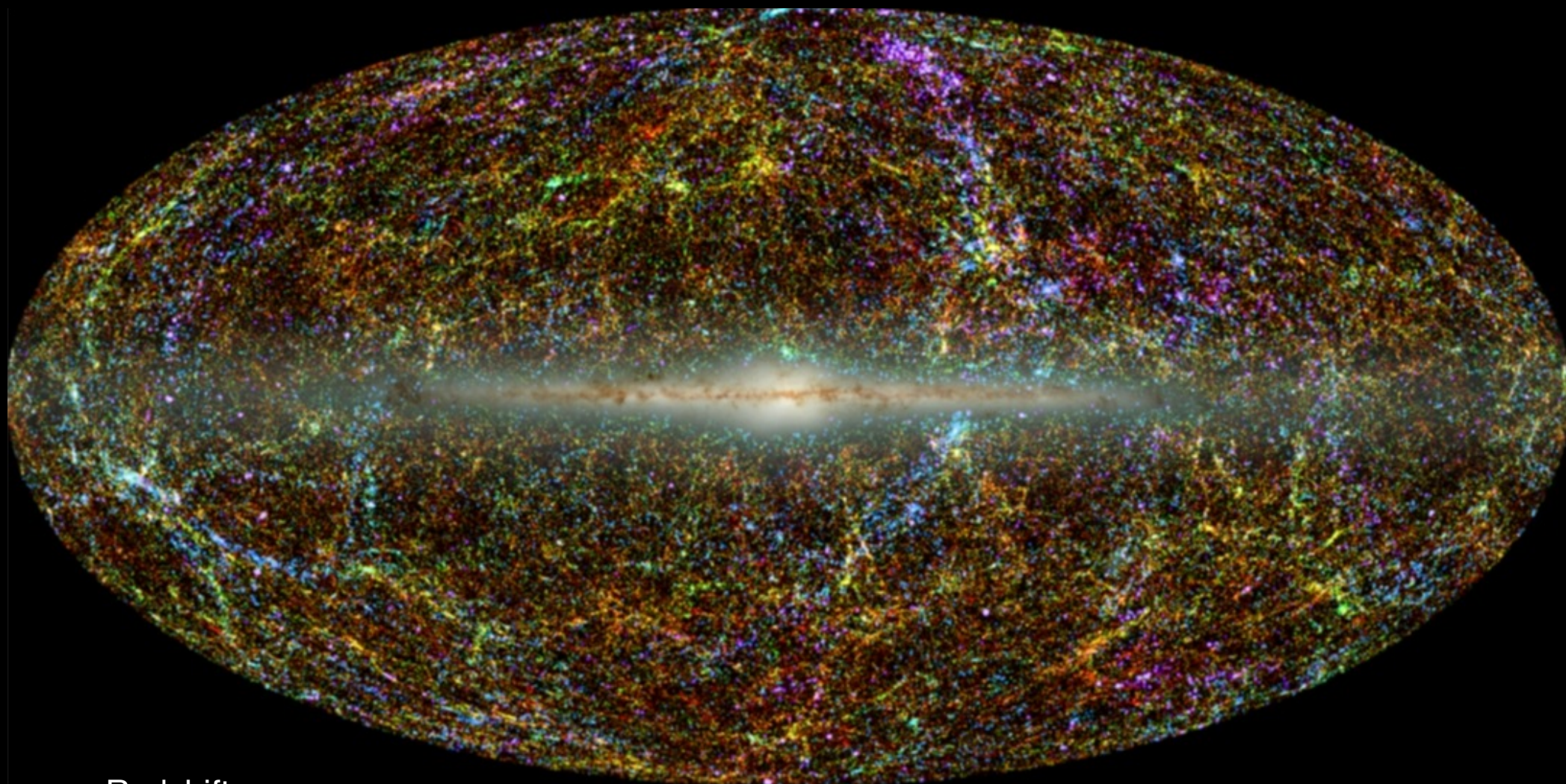
Origin and evolution of the universe

The sky as seen in the optical



Panoramic view of the near-infrared sky

(1.5 million galaxies + 0.5 billion stars)



Redshift:

blue: $z < 0.01$

green: $0.01 < z < 0.04$

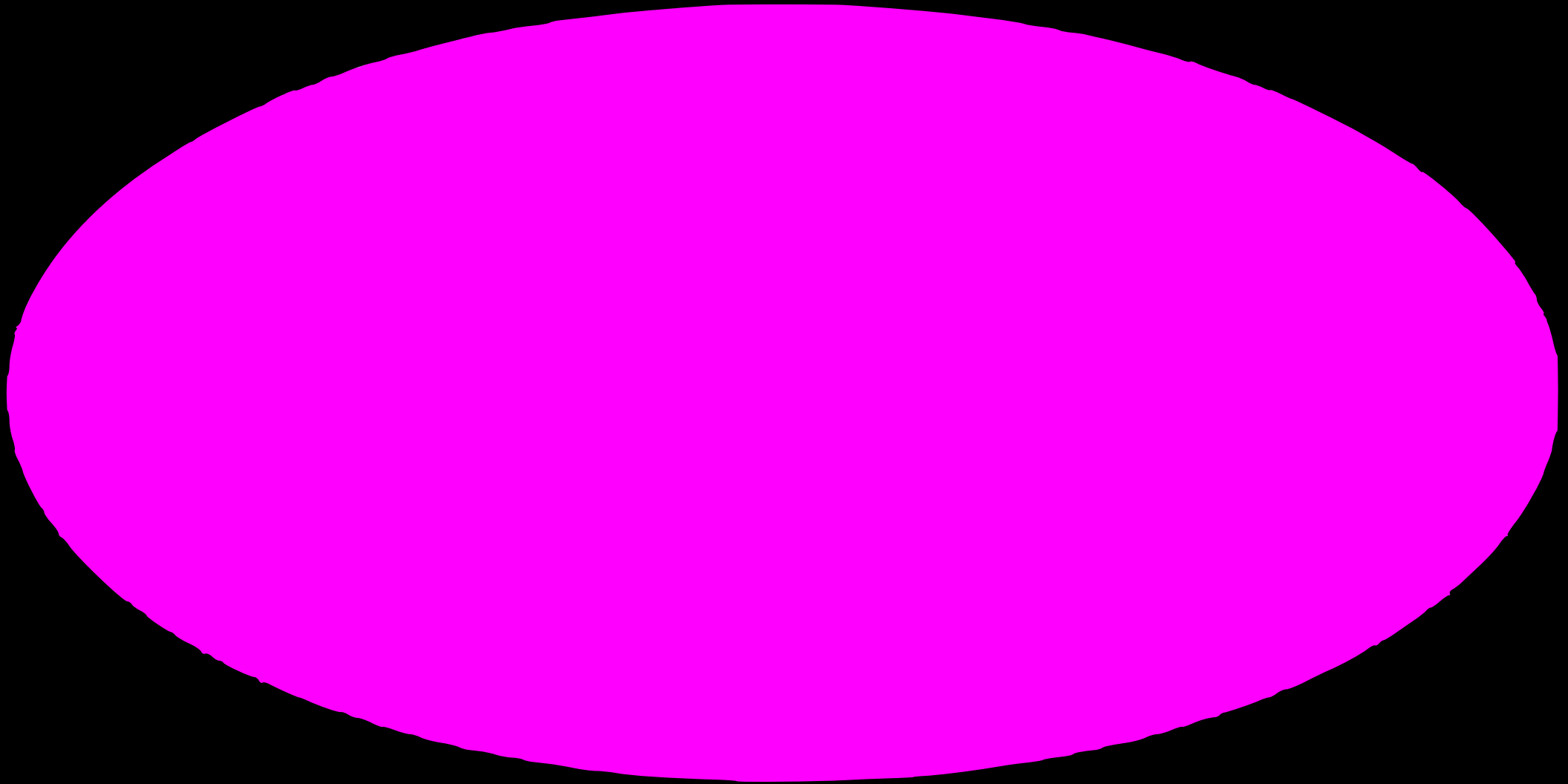
red: $0.04 < z < 0.1$

Project: *2MASS*

The sky in the microwave

Isotropy of the *cosmic microwave background* (CMB)

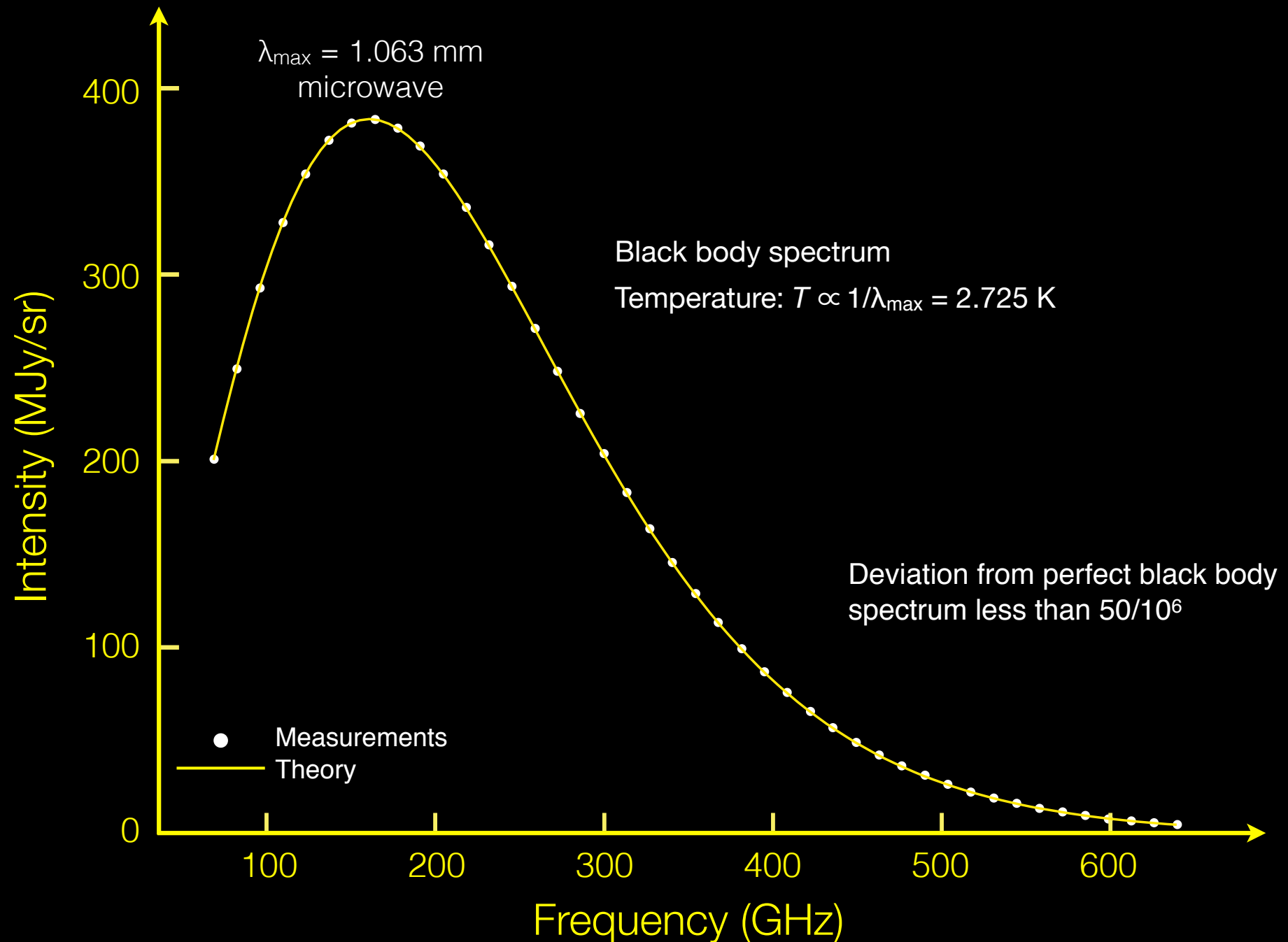
$$T = 2.72548 \pm 0.00057 \text{ K}$$



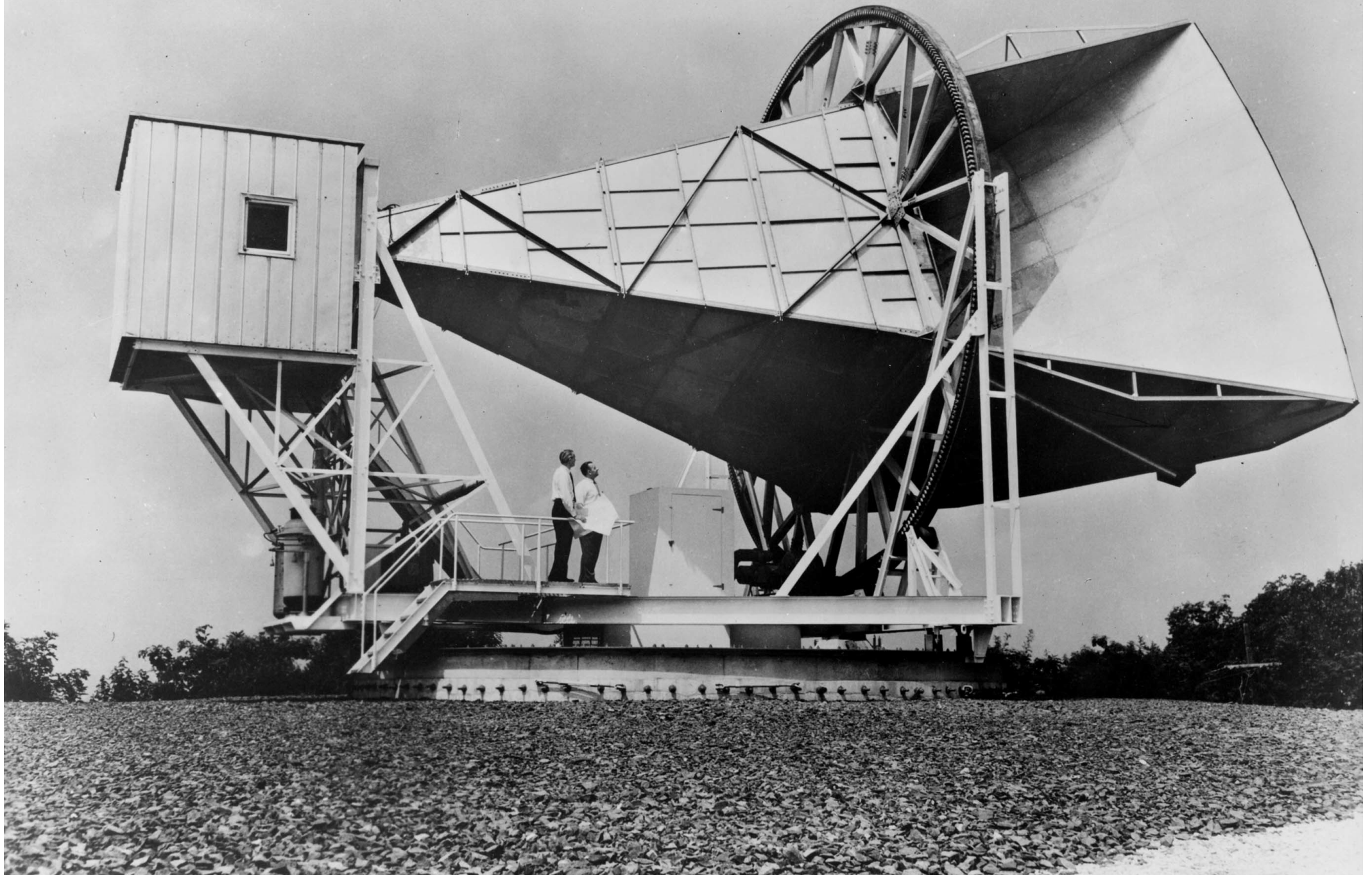
0  3.64 K

Image from satellite *COBE*

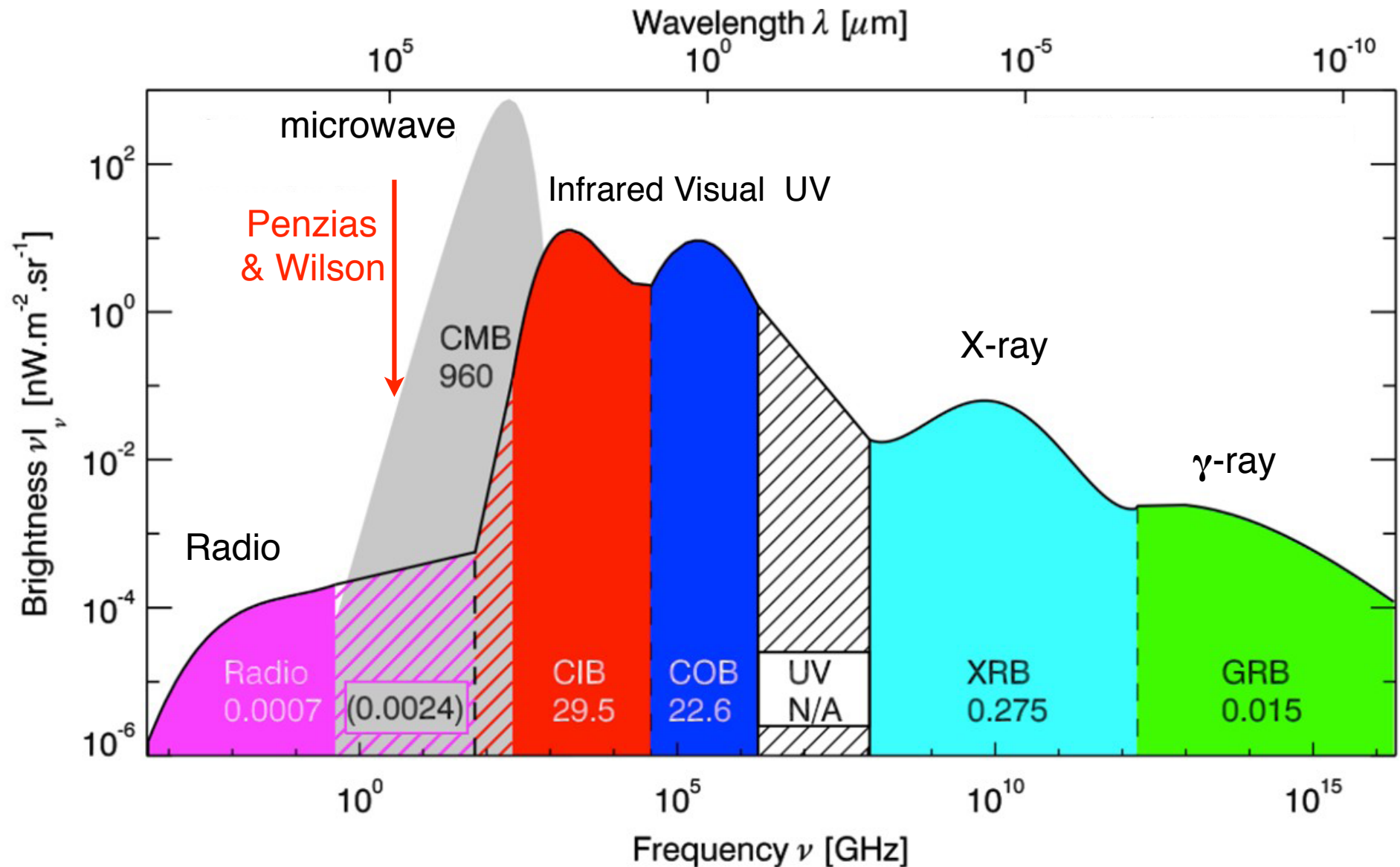
The Cosmic Microwave Background (CMB)



Accidental discovery in 1964 by physicists
Arno Penzias & Robert Wilson (Nobel prize in Physics in 1978)



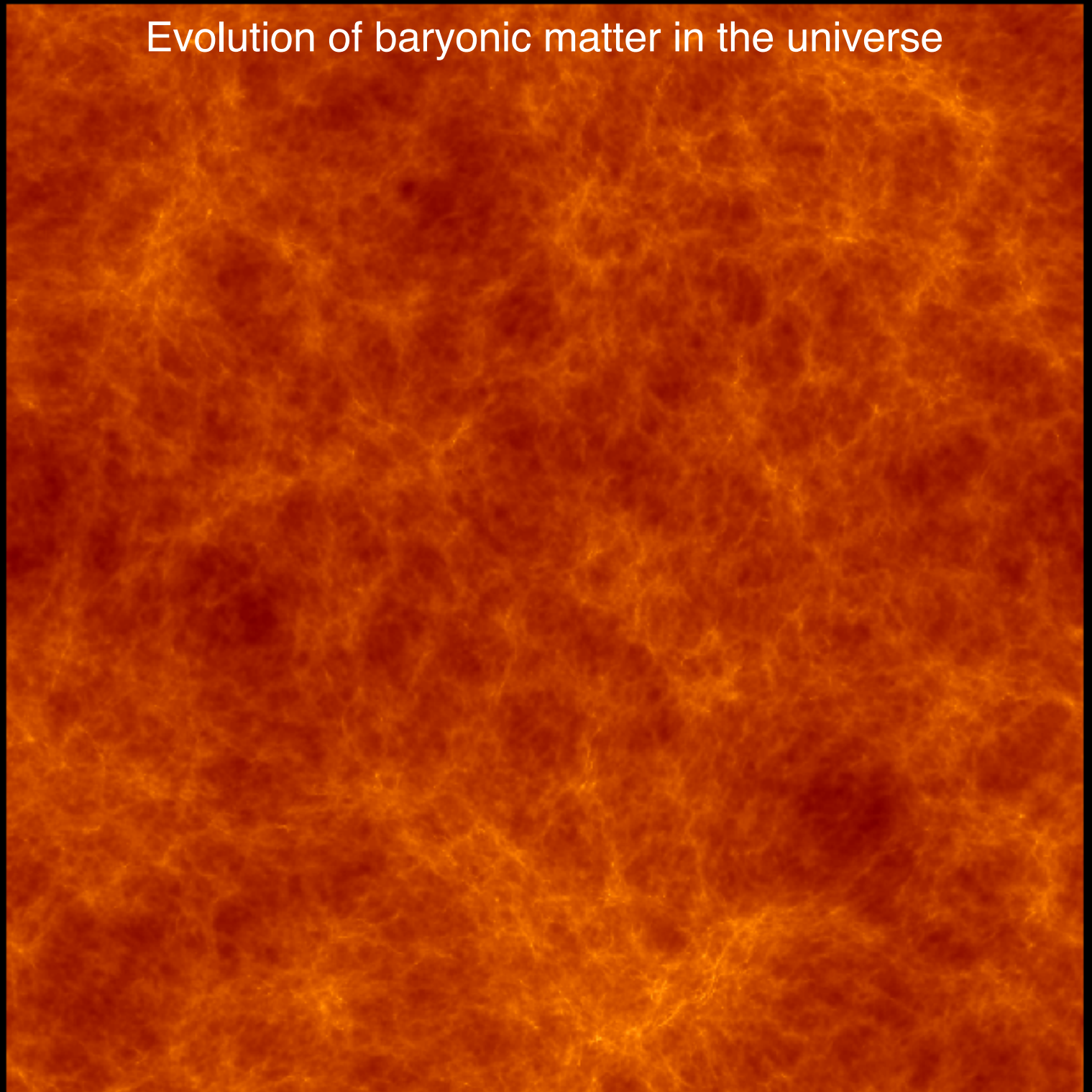
Spectral Energy Distribution of **cosmic backgrounds**



Radiation produced in the universe dominated by the **Cosmic Microwave Background (CMB)**
This is about 94% of the total

Evolution of baryonic matter in the universe

From redshift $z = 18.3$
($t = 200$ Myr after Big Bang)
to $z = 1.24$
($t = 5$ Gyr after Big Bang)



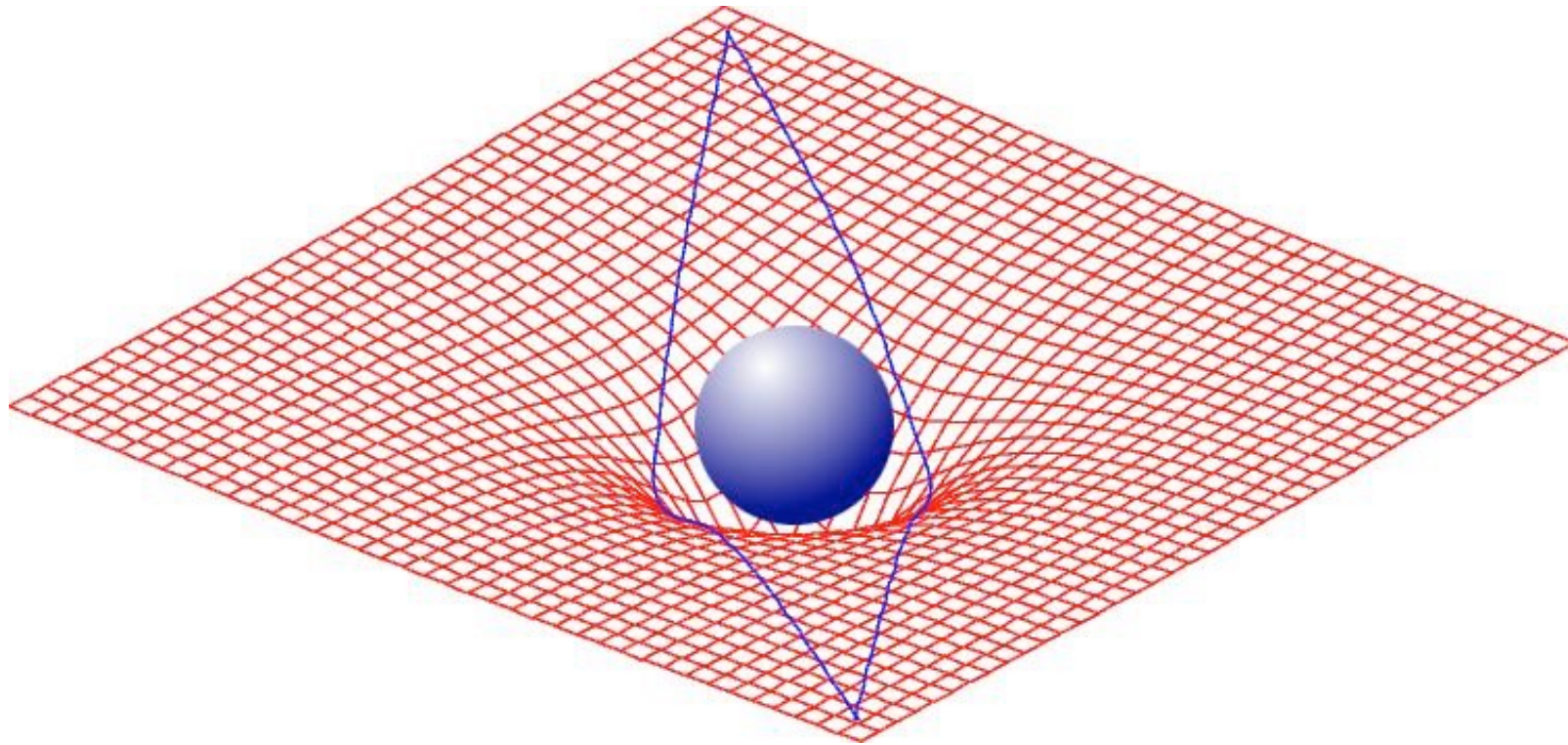
Cosmological models to describe the
origine and evolution of the universe

1915: Albert Einstein publishes the theory of General Relativity



1917: “Cosmological Considerations of The General Theory of Relativity”

In ***General Relativity*** gravitation is a **geometric theory**



Geometry is **4-dimensional** (space-time) and is affected by matter

Any object with mass deforms geometry: **curvature of space-time**

This is described by distribution of **energy and momentum**

“Cosmological Considerations of The General Theory of Relativity”

142 Sitzung der physikalisch-mathematischen Klasse vom 8. Februar 1917

Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie.

Von A. EINSTEIN.

Es ist wohlbekannt, daß die Poissonsche Differentialgleichung

$$\Delta\phi = 4\pi K\rho \quad (1)$$

in Verbindung mit der Bewegungsgleichung des materiellen Punktes die NEWTONsche Fernwirkungstheorie noch nicht vollständig ersetzt. Es muß noch die Bedingung hinzutreten, daß im räumlich Unendlichen das Potential ϕ einem festen Grenzwerte zustrebt. Analog verhält es sich bei der Gravitationstheorie der allgemeinen Relativität; auch hier müssen zu den Differentialgleichungen Grenzbedingungen hinzutreten für das räumlich Unendliche, falls man die Welt wirklich als räumlich unendlich ausgedehnt anzusehen hat.

In Einstein's model, universe is static and finite with **Cosmological Constant: $\Lambda_E = 4\pi G\rho/c^2$**

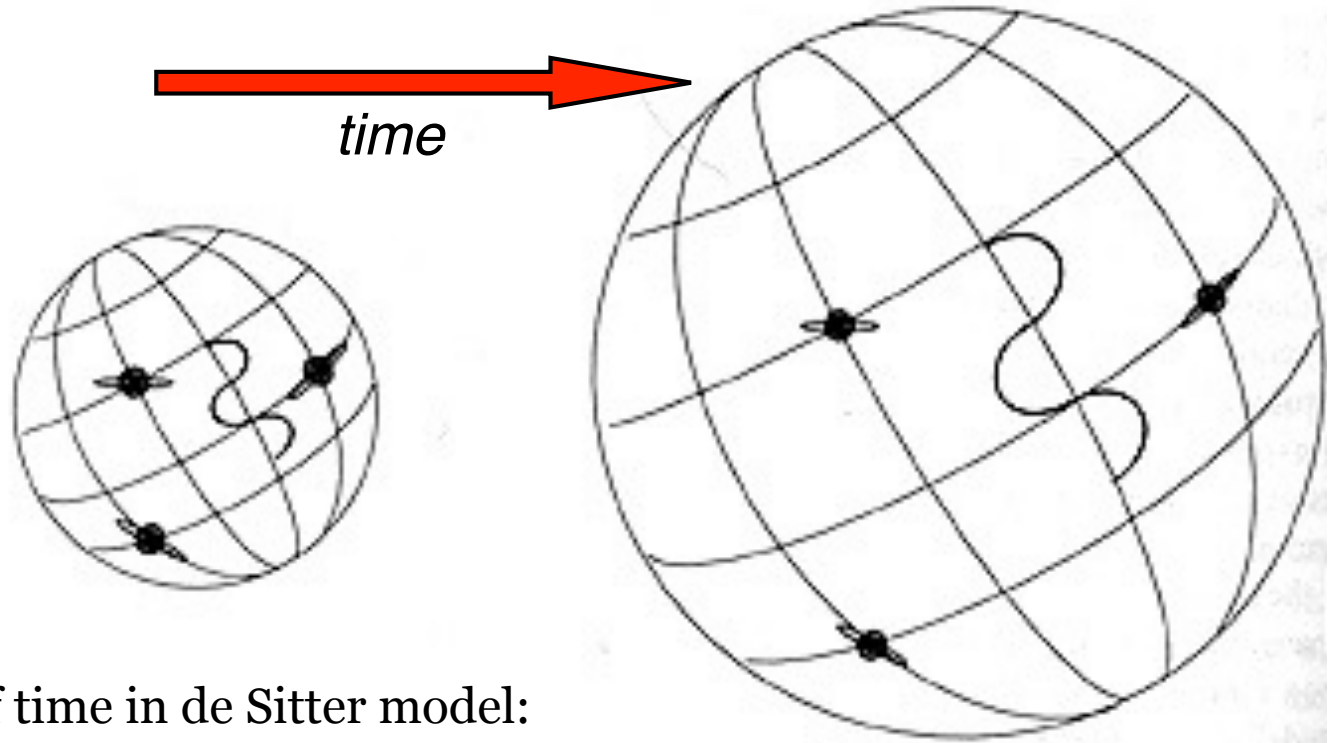
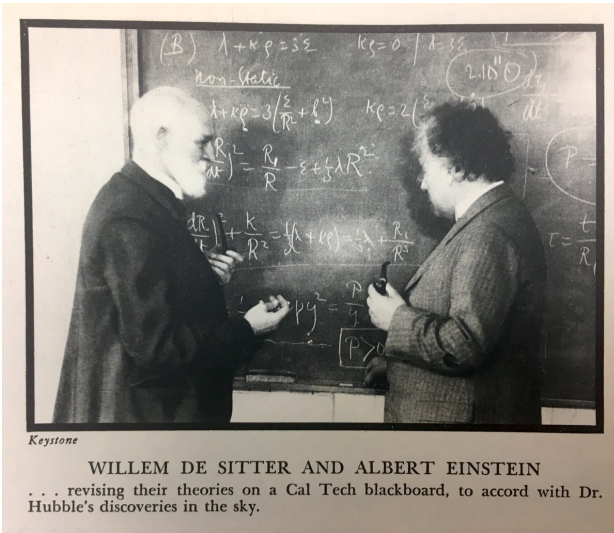
ρ : cosmic density of the universe

Λ_E : introduced to balance gravity and to make universe static (no expansion nor contraction)

de Sitter solution of Einstein equations: **the universe is expanding**

(density and pressure are neglected, universe dominated by Λ)

Expansion regulated by **scale factor $R(t)$** , which is distance between points



Scale factor as a function of time in de Sitter model:

$$R(t) \propto e^{Ht} \quad (\text{accelerated expansion})$$

$$\text{with: } H = \sqrt{\frac{\Lambda c^2}{3}} \quad (\text{constant})$$

Λ : cosmological constant

c : light speed

Friedmann-Robertson-Walker (FRW) models

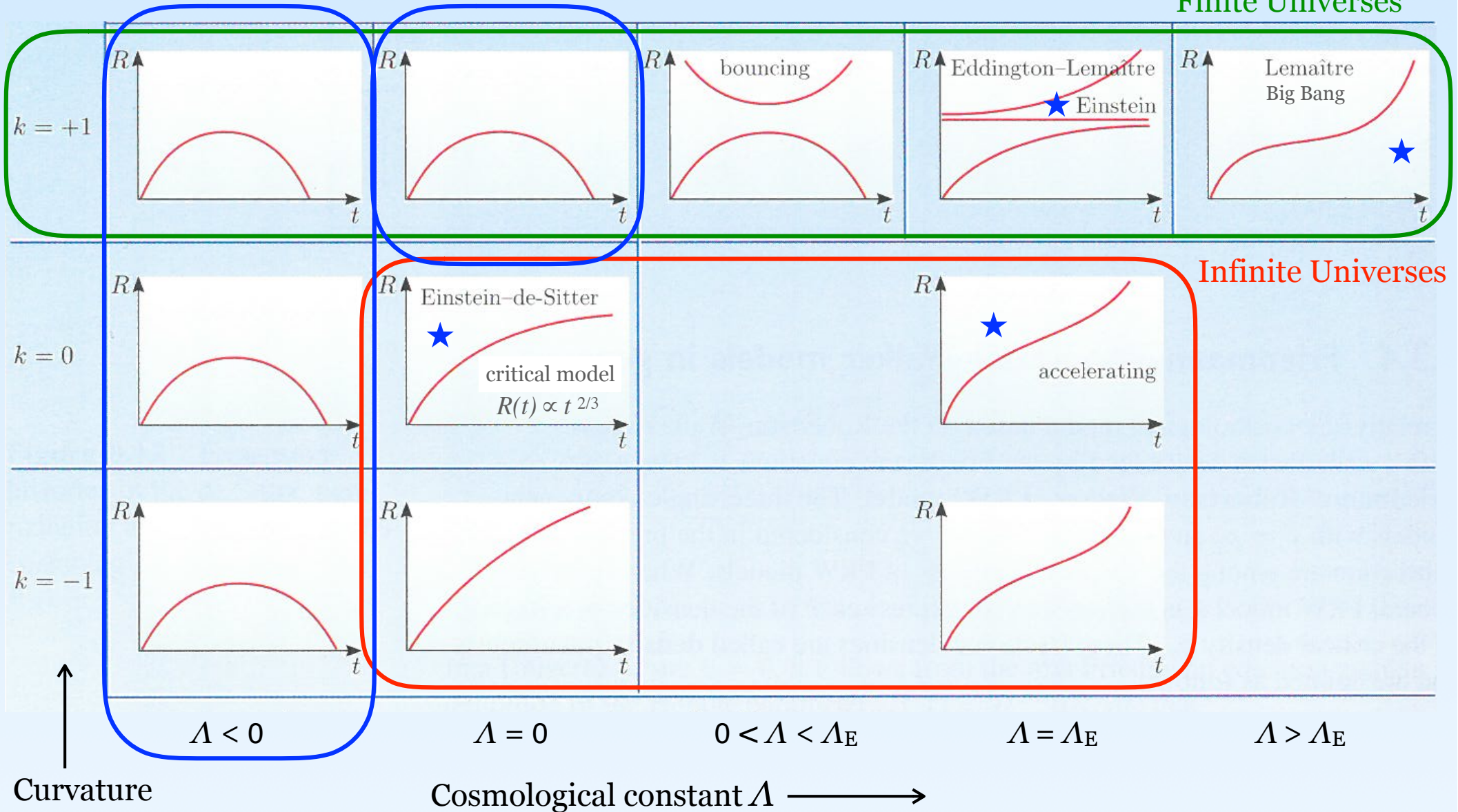
describing cosmological expansion of the universe

$R(t)$ vs. t

Big Bang is point at $R(t=0) = 0$

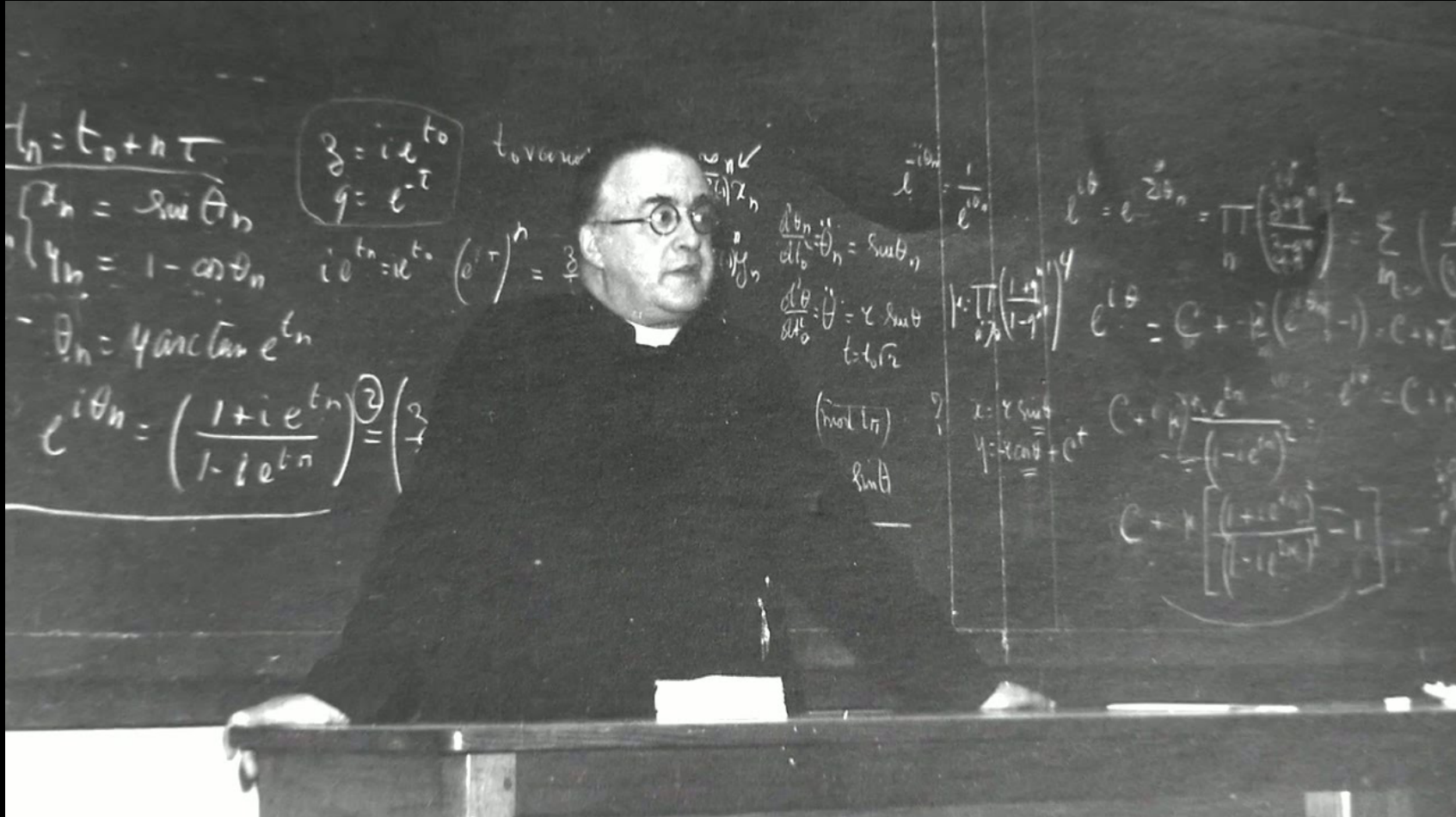
Closed Universes

Finite Universes



Lemaître (1927): $v \propto d \implies$ the universe is expanding

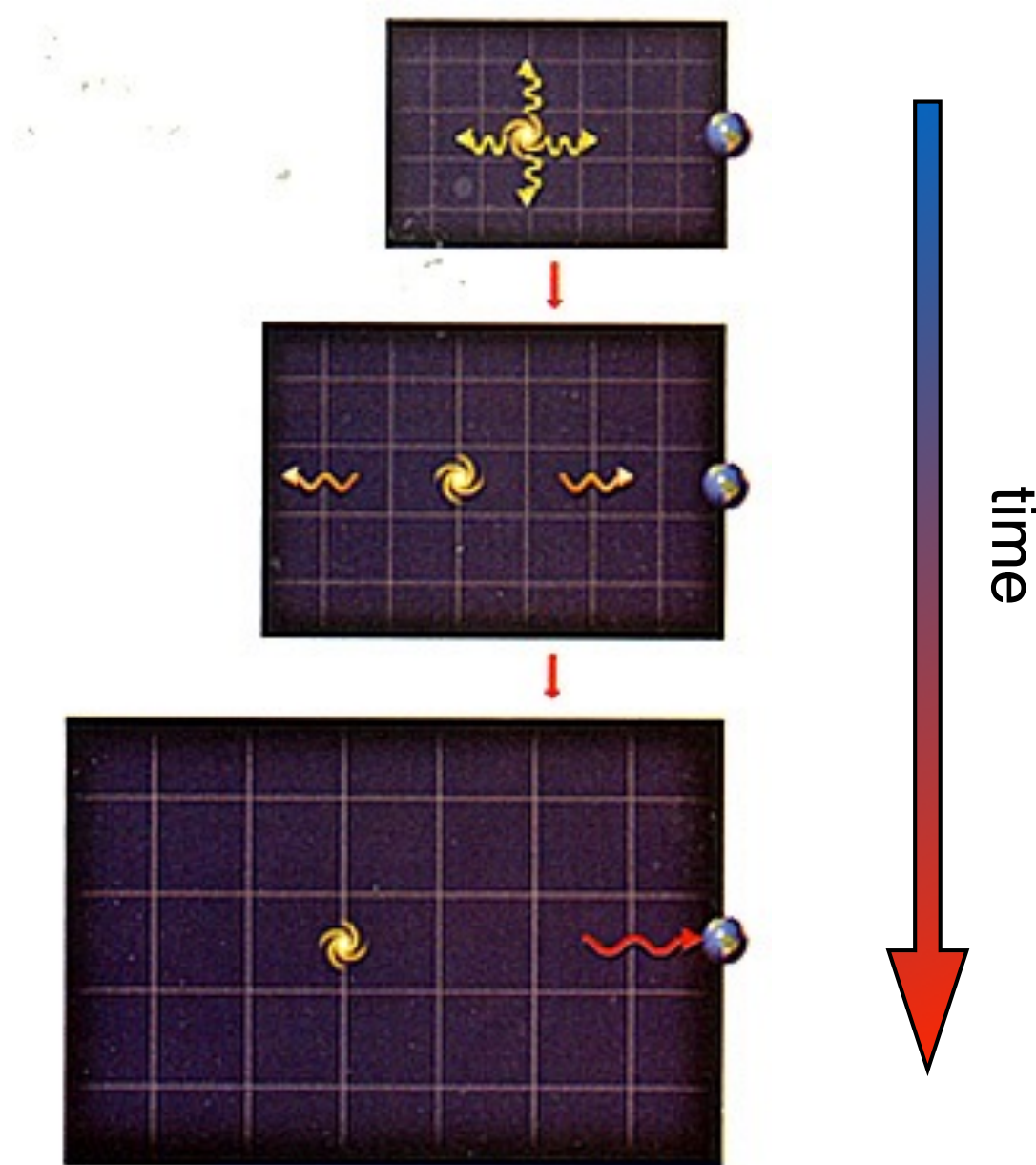
Consequence: the universe at the beginning is very **hot & dense**



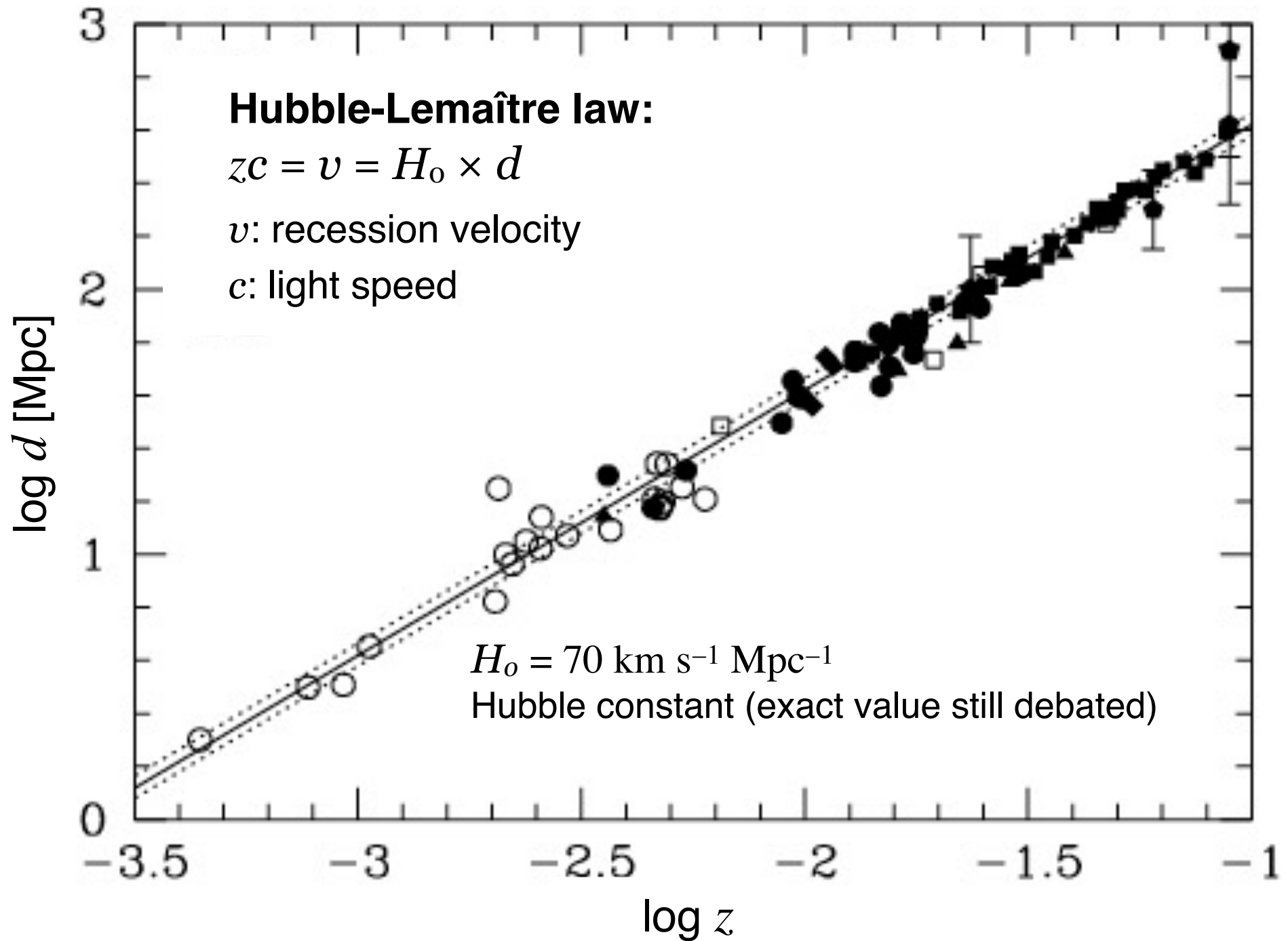
Monseigneur Georges Lemaître (July 1894 – June 1966)

Going back in time $\implies$ “Primeval Atom” or “Cosmic Egg” & **Big Bang Theory**

Distance between two points, defined by **scale factor** $R(t)$,
increases as universe expands (**redshift** z)



Lemaître (1927) & Hubble (1929):
more distant objects moving away faster $\Rightarrow$ redshift z



Curvature k : geometry of space-time

Representation in 2D

energy & mass



$$\Omega_0 > 1$$

curvature



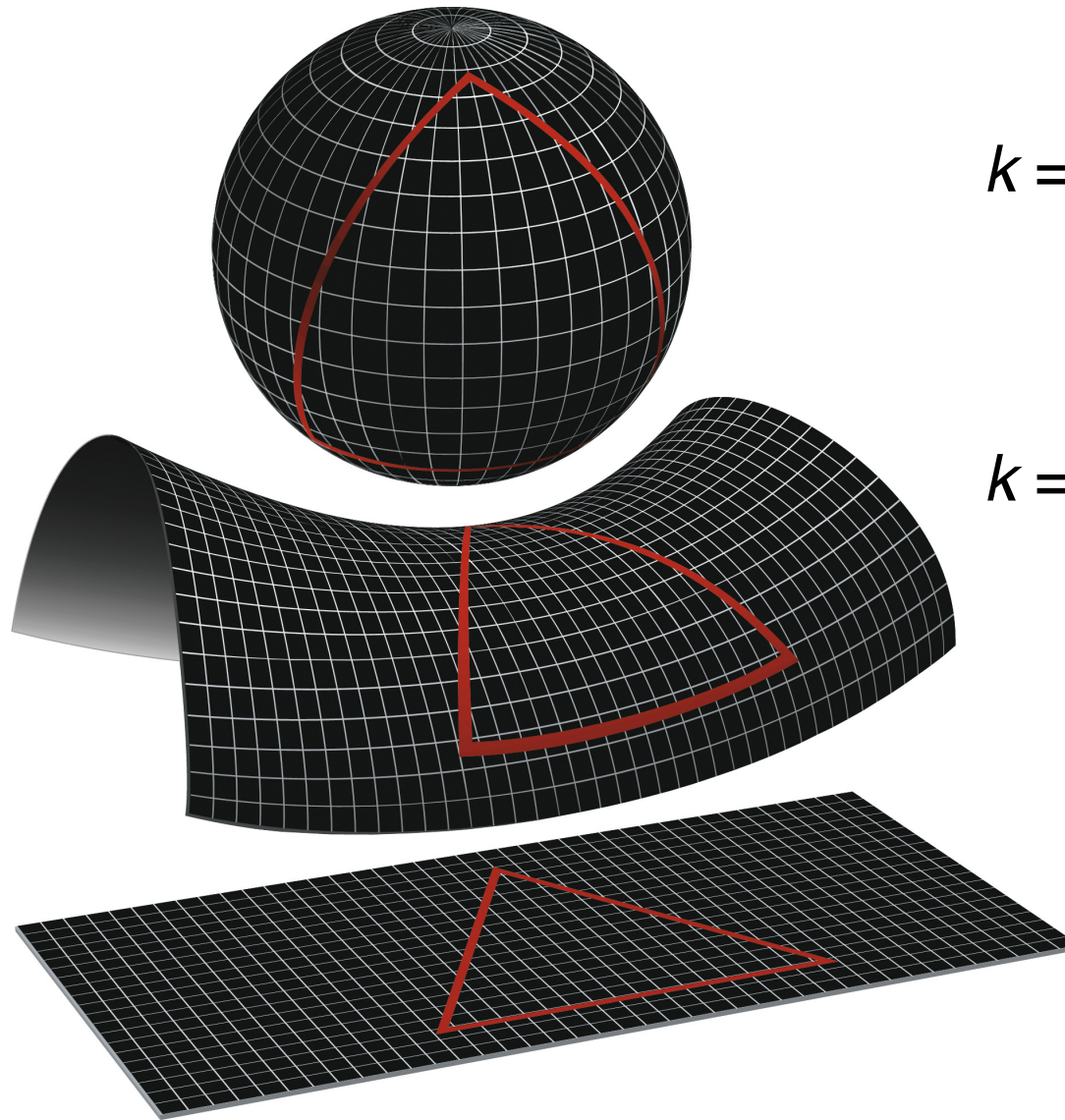
$k = +1$ closed universe

$$\Omega_0 < 1$$

$k = -1$ open universe

$$\Omega_0 = 1$$

$k = 0$ flat universe



Total matter & energy density in the universe *today* :

$$\Omega_o = \frac{\rho(t_o)}{\rho_c(t_o)} \quad \text{fraction of critical density today}$$

$$\rho = \rho_\Lambda + \rho_m + \rho_{\text{rel}} \quad \text{density of the universe today}$$

(Λ : cosmological constant, m: matter, rel: relativistic particles)

$$\rho_c = 7.9 \times 10^{-27} \text{ kg/m}^3 \quad \text{critical density today}$$

$$\Omega_o = \Omega_m + \Omega_\Lambda \quad (\rho_{\text{rel}} \text{ negligible today})$$

$$\Omega_m + \Omega_\Lambda > 1 \quad \text{for } k = +1 \quad \text{closed universe}$$

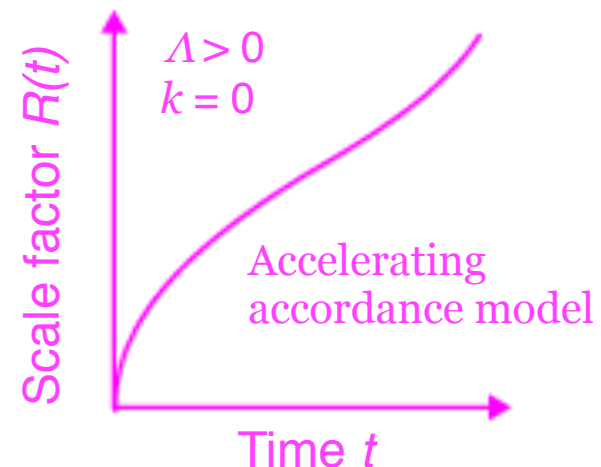
$$\Omega_m + \Omega_\Lambda = 1 \quad \text{for } k = 0 \quad \text{flat universe}$$

$$\Omega_m + \Omega_\Lambda < 1 \quad \text{for } k = -1 \quad \text{open universe}$$

Friedmann equation gives:

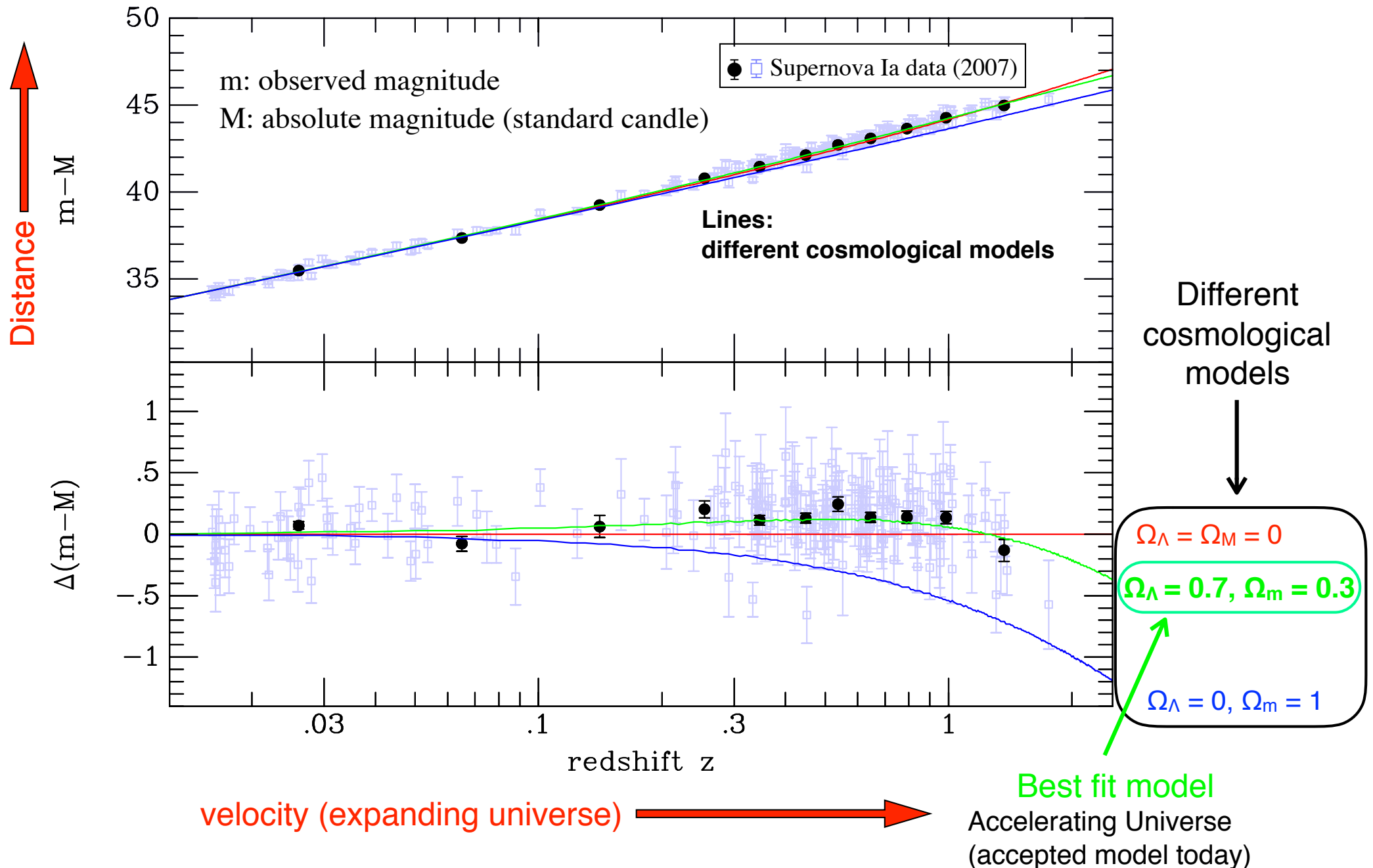
Increasing age
of the Universe
↓

1. closed model $\Lambda = 0$ & $k = +1$
2. critical model $\Lambda = 0$ & $k = 0$
3. open model $\Lambda = 0$ & $k = -1$
4. accelerating model $\Lambda > 0$ & $k = 0$



Supernovae type Ia used to find rate of expansion at different redshifts

Consequences: **today universe expansion is accelerated**



Geometry of the universe

&

Ω_m vs. Ω_Λ

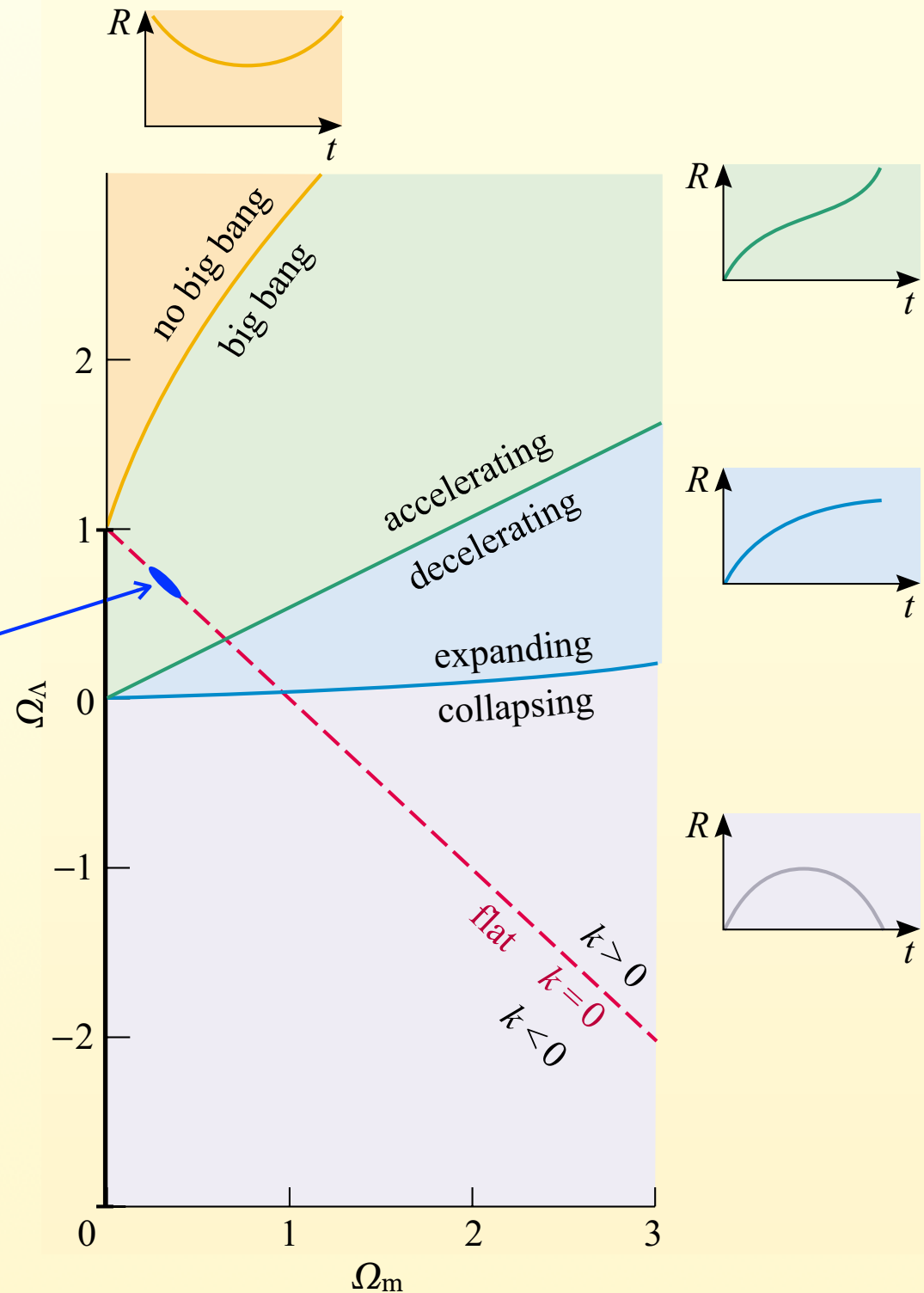
Measured values:

$$\Omega_o \approx 1$$

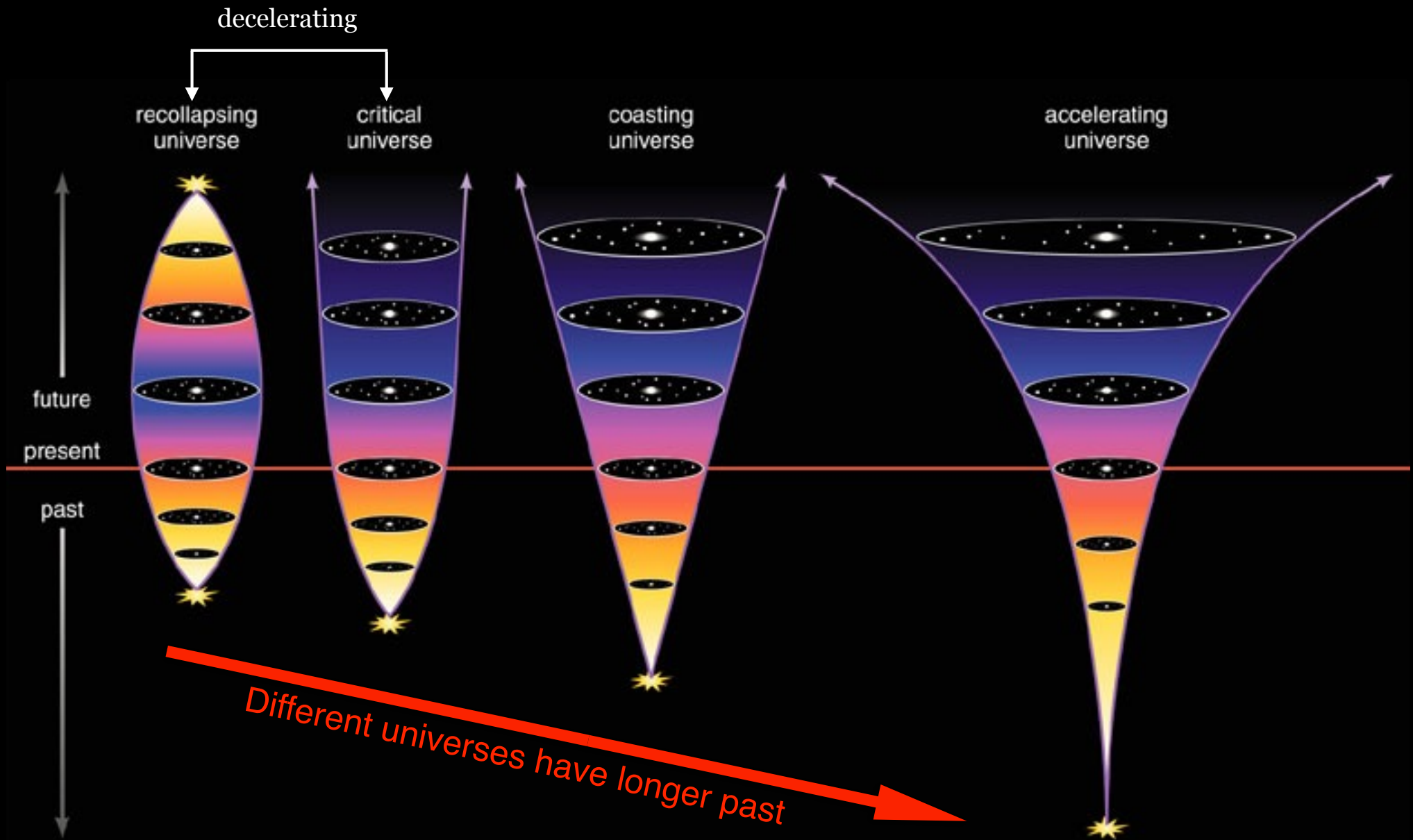
$$\Omega_m \approx 0.31$$

$$\Omega_\Lambda \approx 0.69$$

Most accepted model
of the universe today



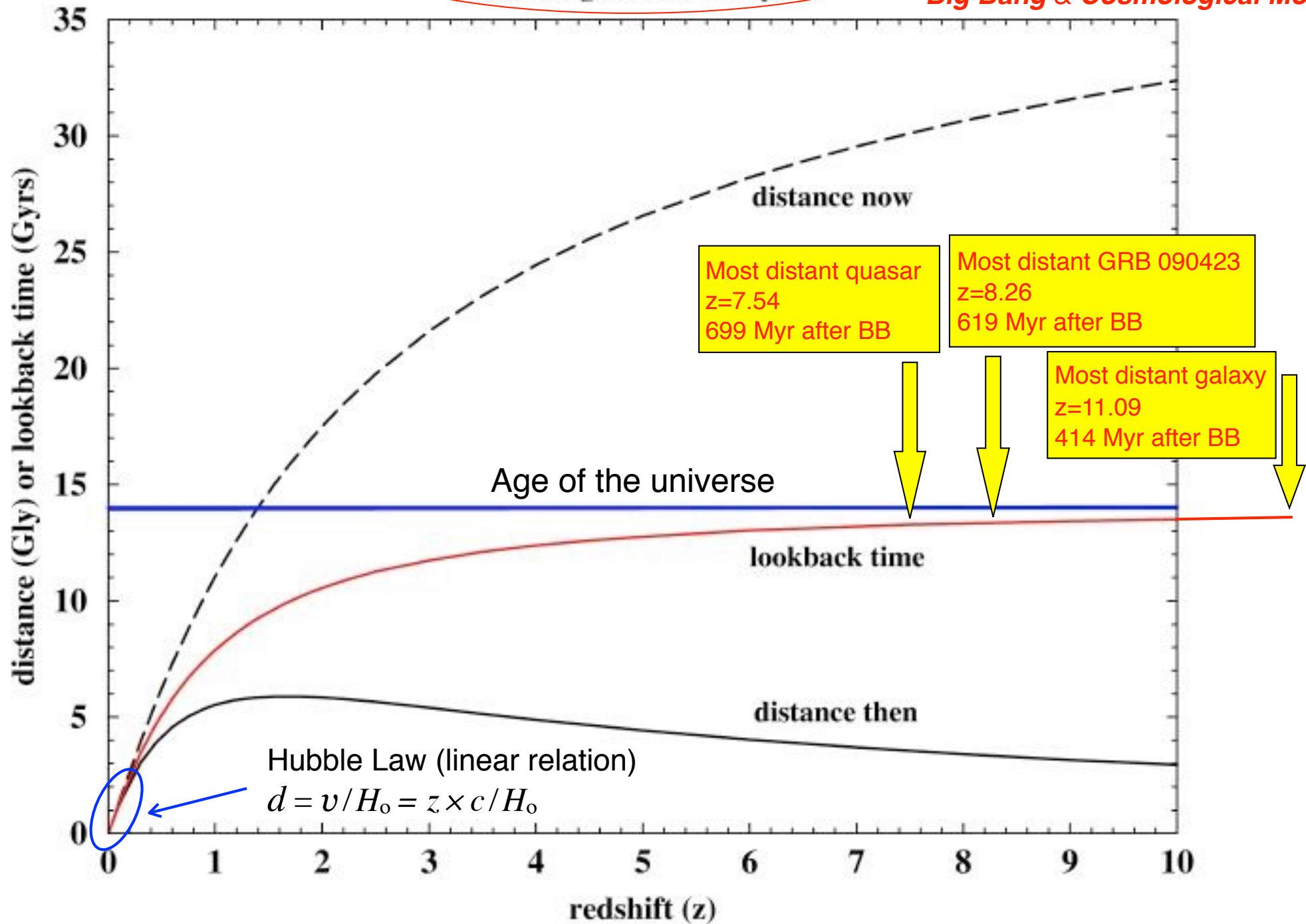
Possible models of the **expansion rate & age of the Universe**



Universe confirmed by observations of
Supernovae Ia (standard candles)
Cosmological constant Λ useful again

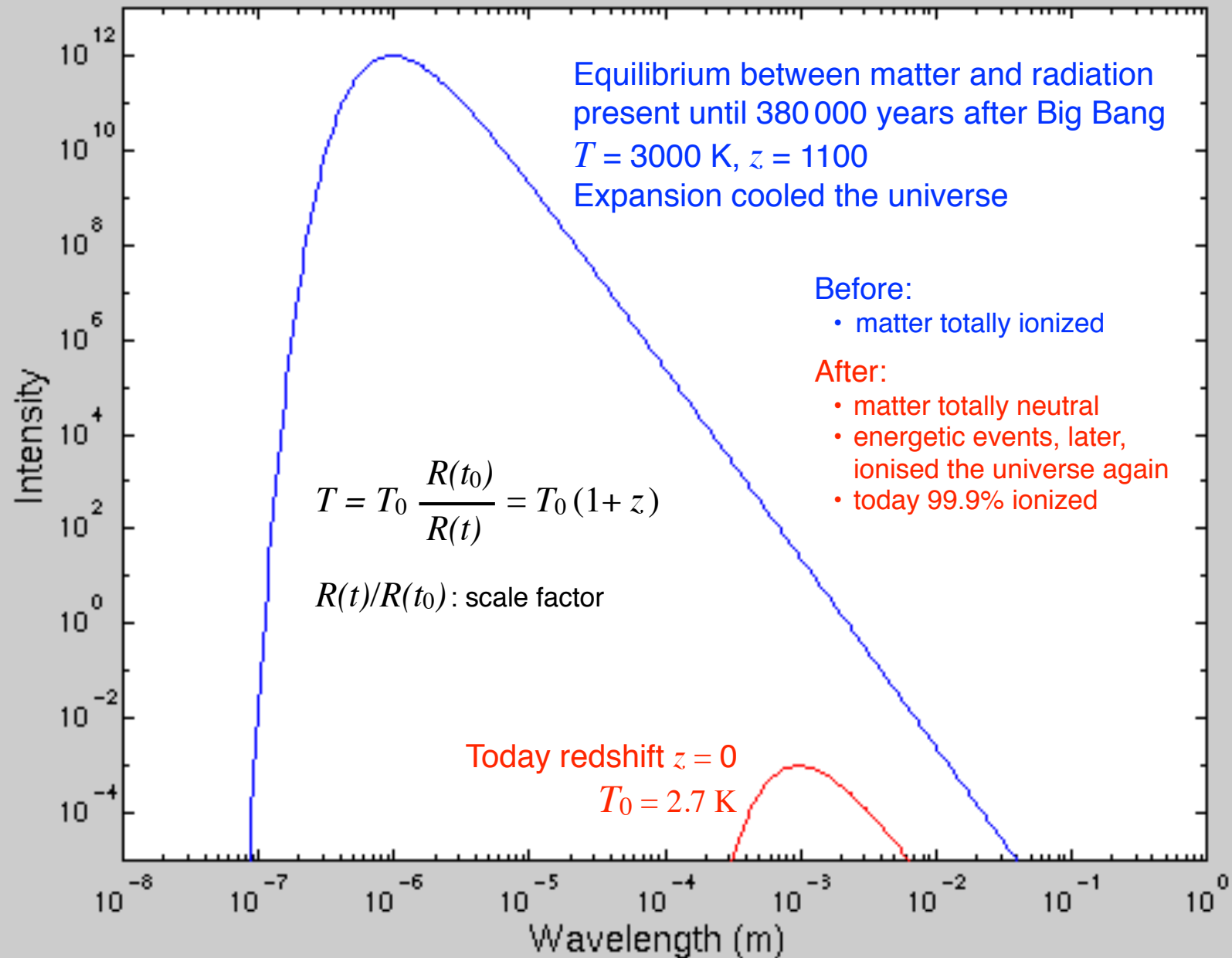
$H_0 = 70 \text{ km/s/Mpc}$, $\Omega_m = 0.26$, flat
Present Age = 14 billion years

Parameters given by
Big Bang & Cosmological Model



The Early Universe and the ***Big Bang***

Evolution of the **cosmic microwave background**



Surface of last scattering: picture of the universe 380 000 yr after Big Bang

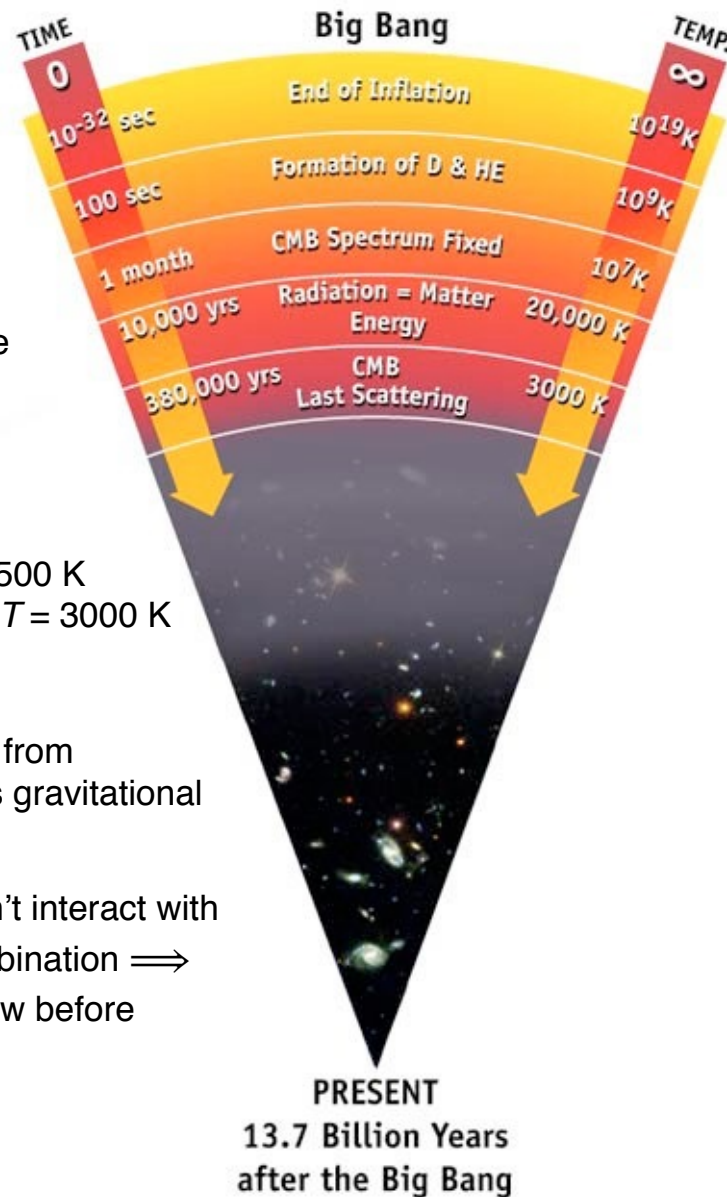
When cosmic photons were last in equilibrium with matter (black body spectrum)

Opacity of gas very high due to scattering of photons by free electrons (low energy regime: **Thomson scattering**)

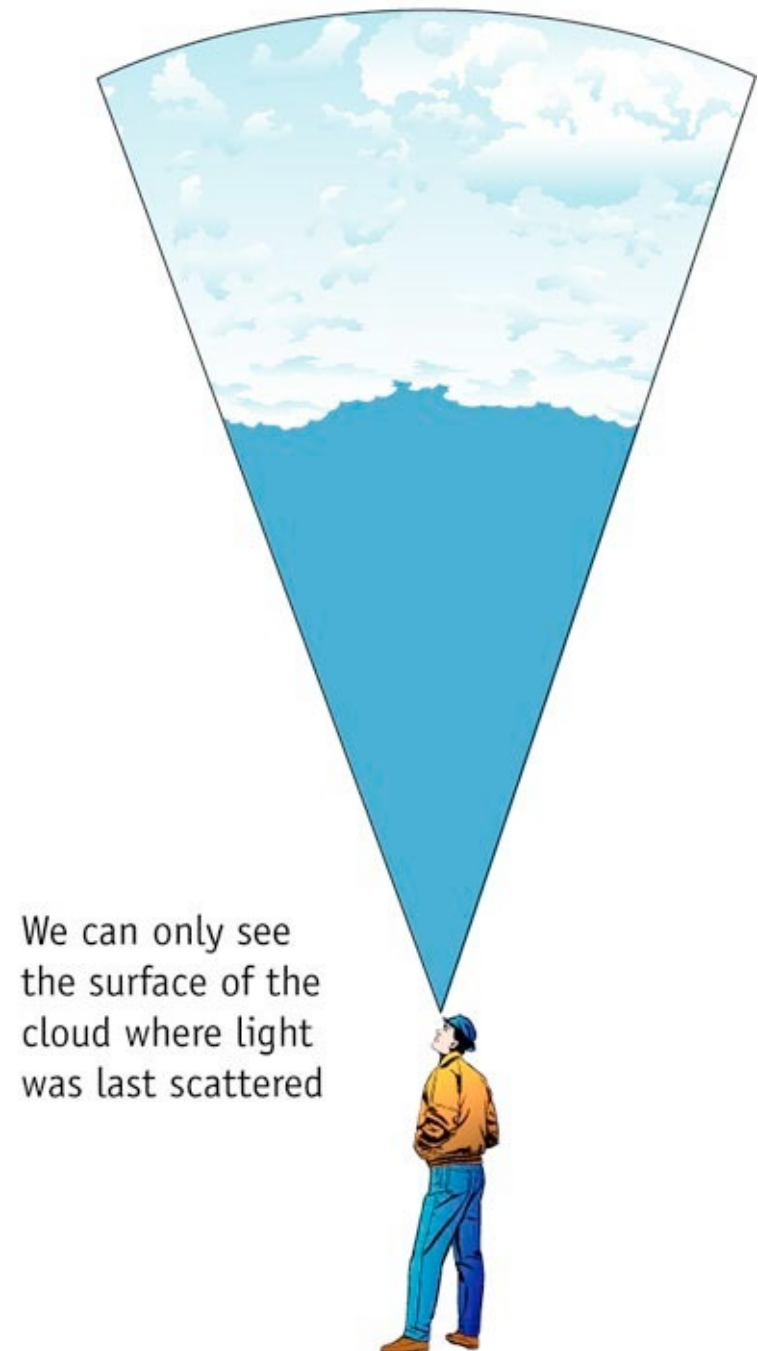
Recombination starts for $T = 4500 \text{ K}$
($t = 3 \times 10^5 \text{ yr}$ after B.B.) end by $T = 3000 \text{ K}$
($t = 3.8 \times 10^5 \text{ yr}$)

Before recombination, pressure from radiation and electrons prevents gravitational collapse to form bound objects

Cold dark matter (CDM) doesn't interact with baryons and doesn't feel recombination $\Rightarrow$ density fluctuations starts to grow before recombination

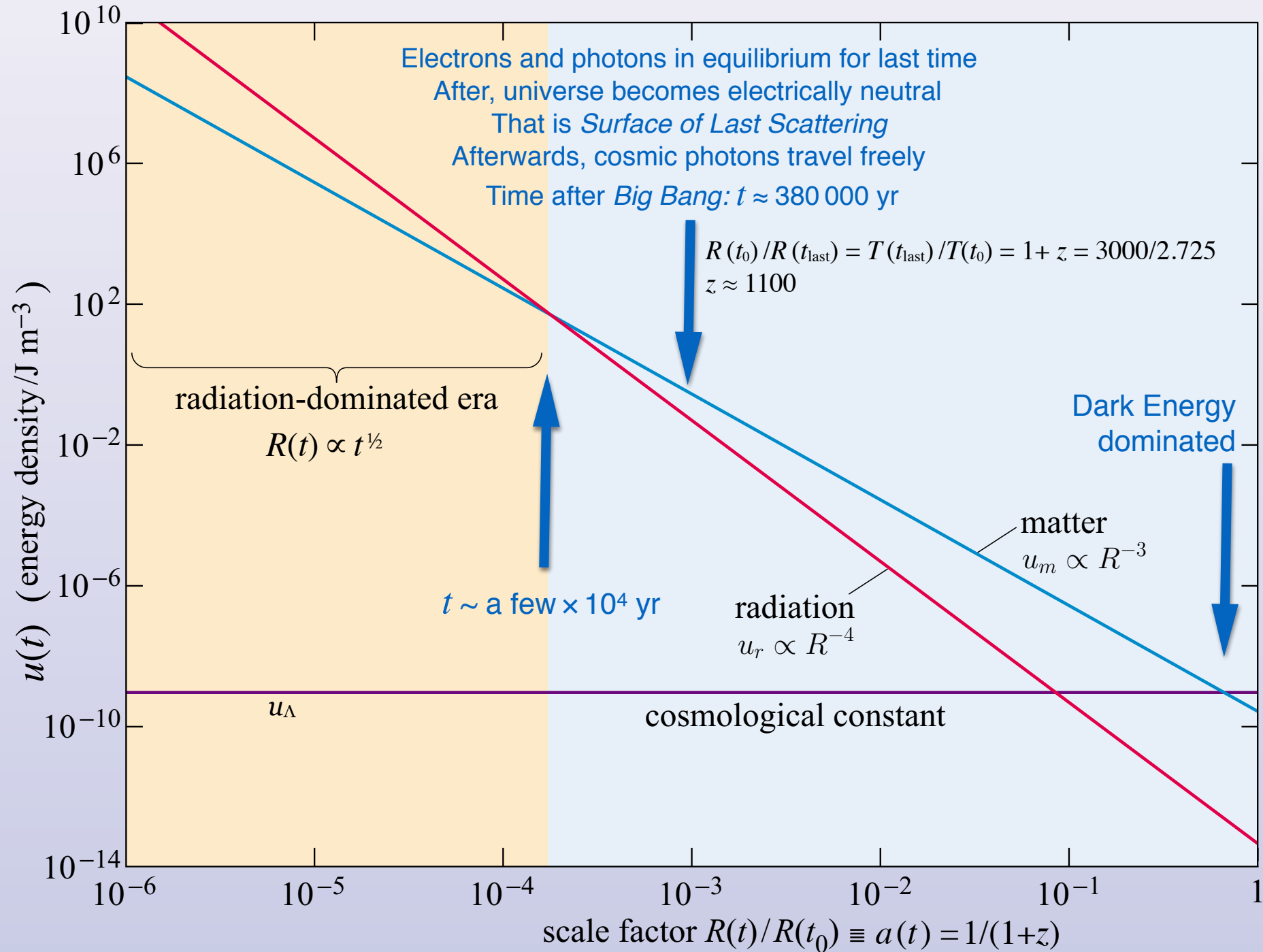


The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.



We can only see the surface of the cloud where light was last scattered

Energy densities in the expanding universe



Scale factor of the universe:

$$a(t) = \frac{R(t)}{R(t_0)} = 1/(1+z)$$

Evolution of the **temperature** of the universe:

$$T = T_0 \frac{R(t_0)}{R(t)} = T_0 (1+z)$$

Energy of particles in the **primordial** universe:

$$T \simeq E/k$$

For example: $T = 10^{14} \text{ K} \implies E \approx 9 \text{ GeV}$

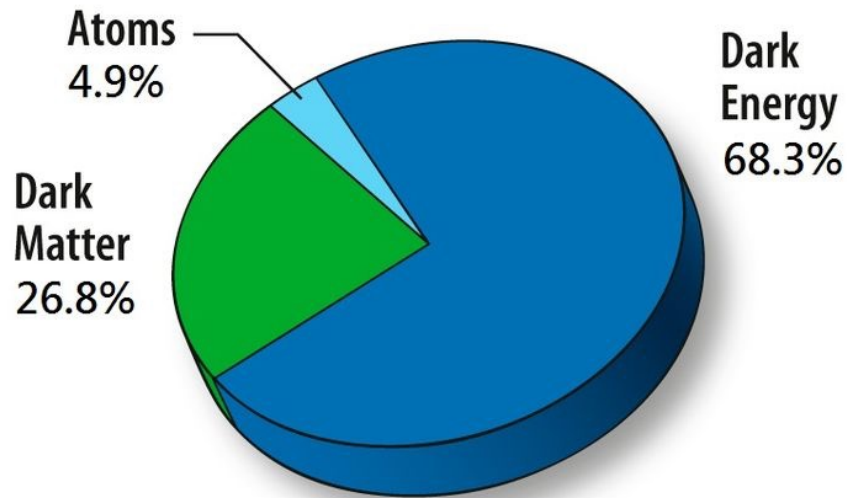
z : redshift

k : Boltzmann constant

T : temperature of CMB at time t

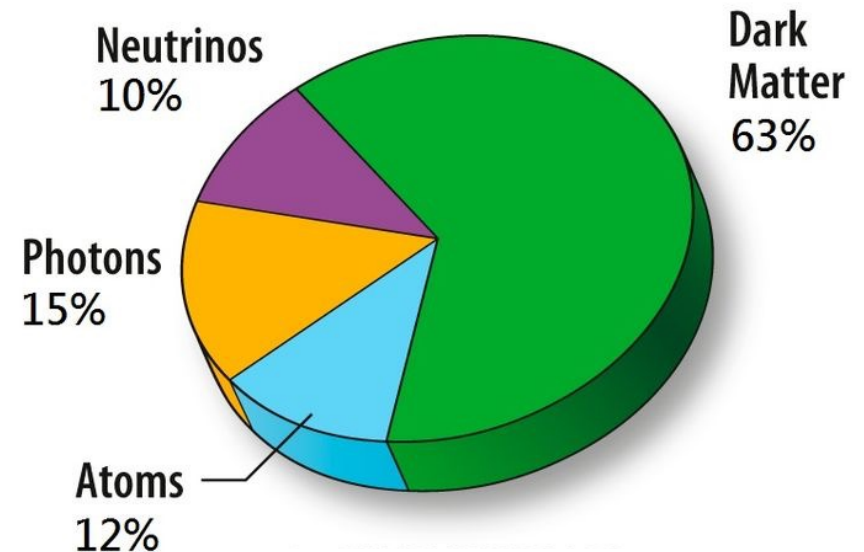
T_0 : temperature of CMB today t_0

Expansion dilutes the power of light particles
but in the past they were very important



Energy-matter distribution **today**
(relics of the Big Bang)

After CMB photons, primordial neutrinos (CNB) most numerous particles (*today* $N_\nu = 330$ per m^3), but today negligible in terms of matter density

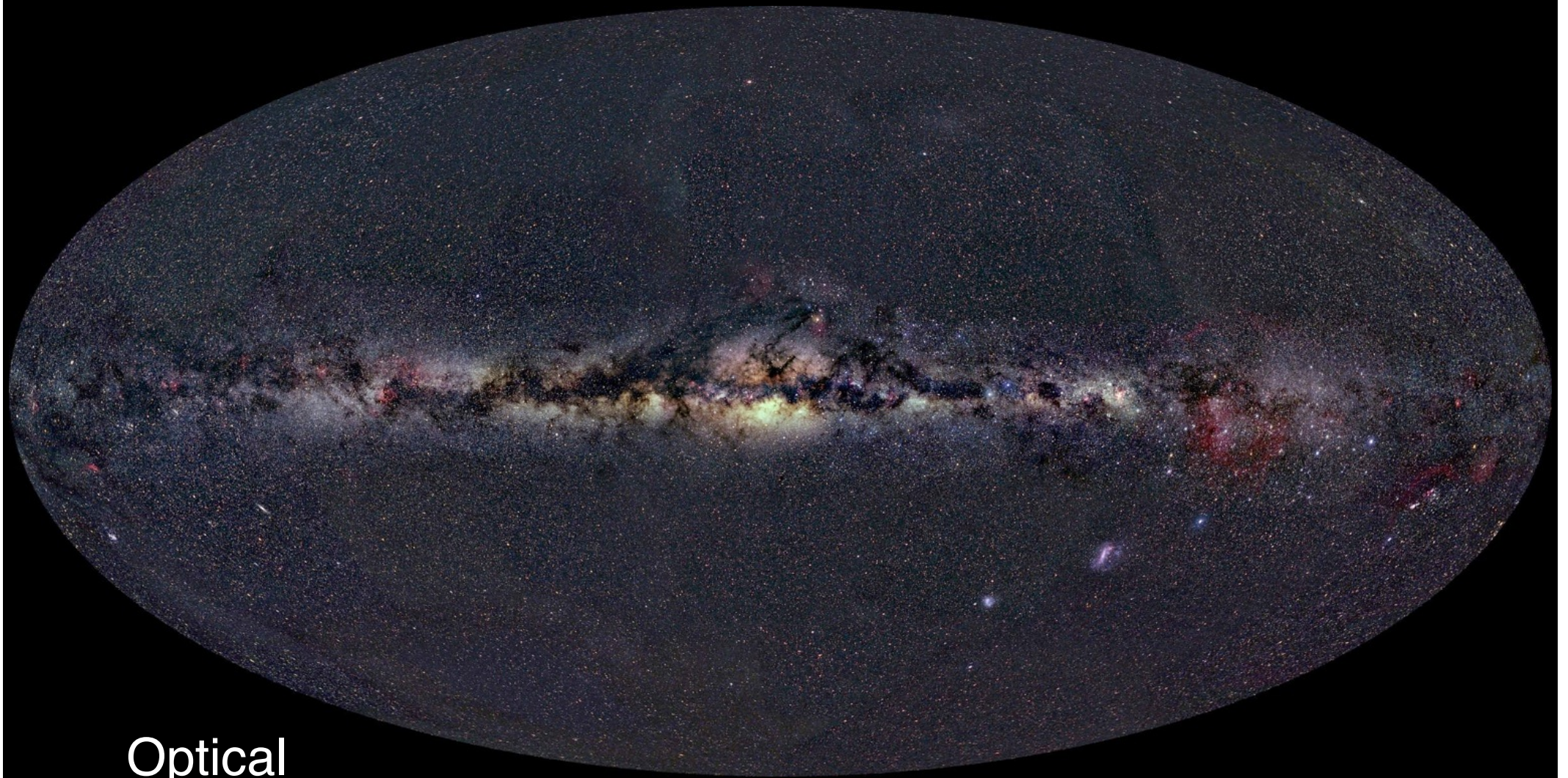


Energy-matter distribution
at time of CMB

What was the energy-matter
distributed before?

Temperature **anisotropies** in the CMB

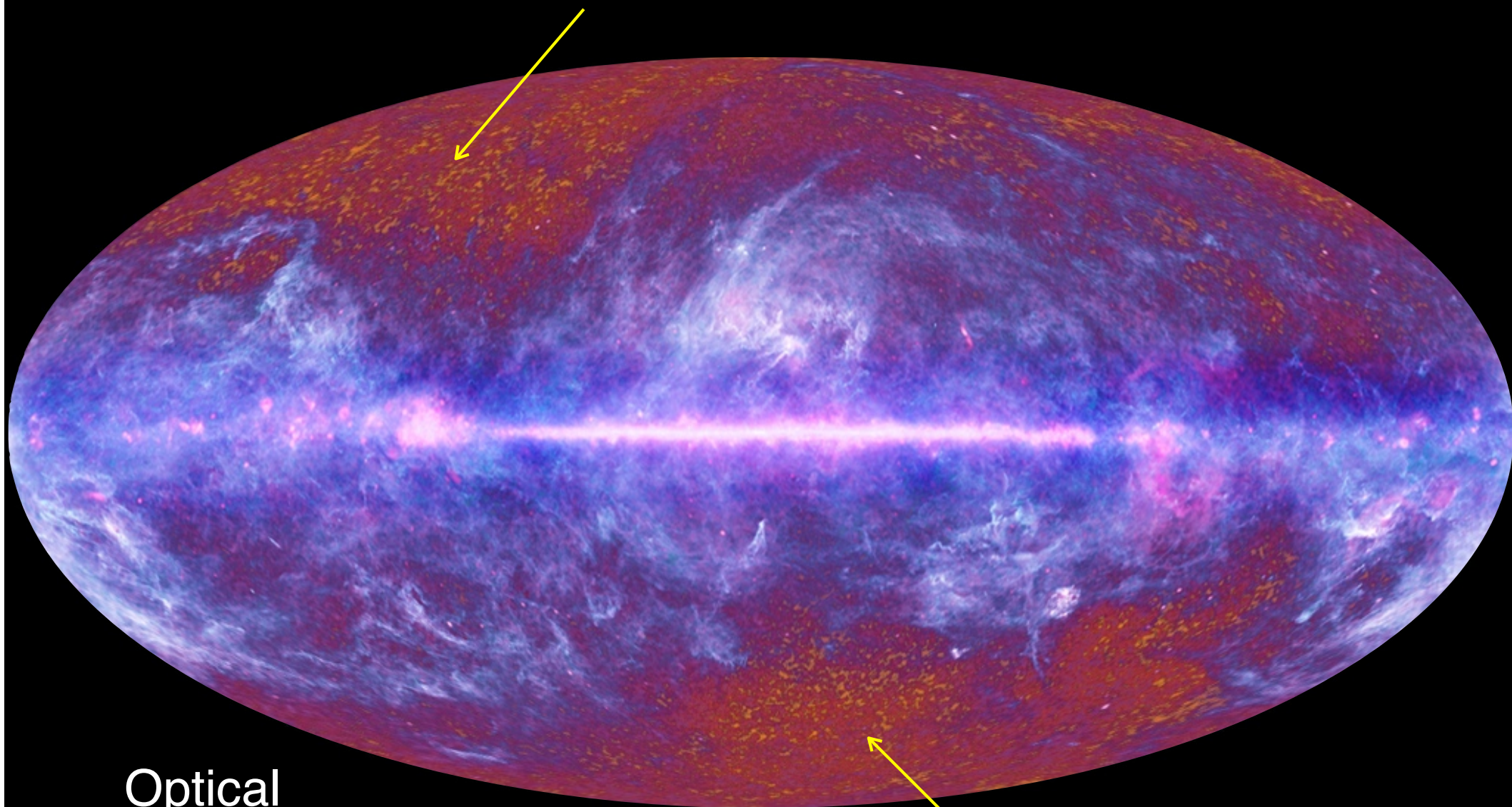
Milky Way



Optical

Milky Way

CMB anisotropies

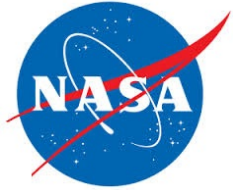


Optical

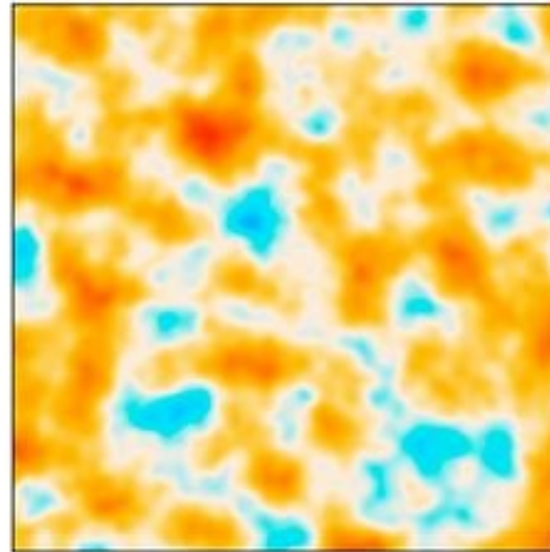
Microwave

CMB anisotropies

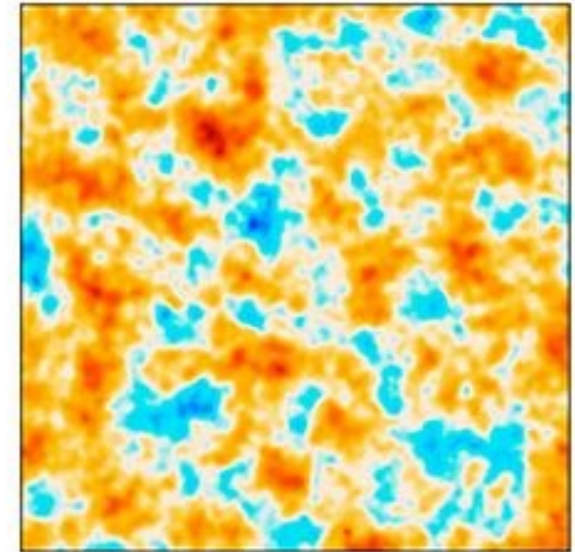
Cosmic Background Explorer (COBE) first measured anisotropies on scales larger than 0.1°



COBE



WMAP



Planck

Launch date: 1989

2001

2009

Better angular resolution

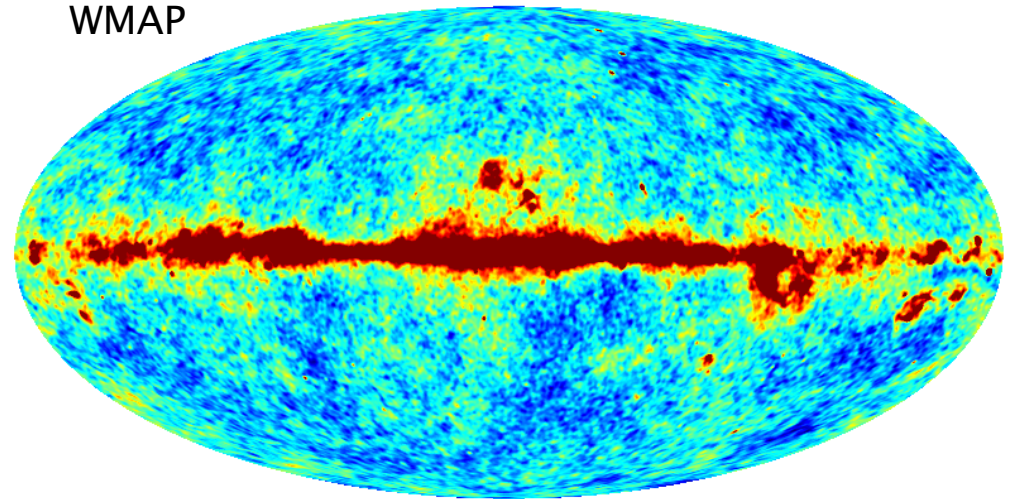
Anisotropies of Cosmic Background Radiation

COBE



$T = 2.728 \text{ K}$

WMAP

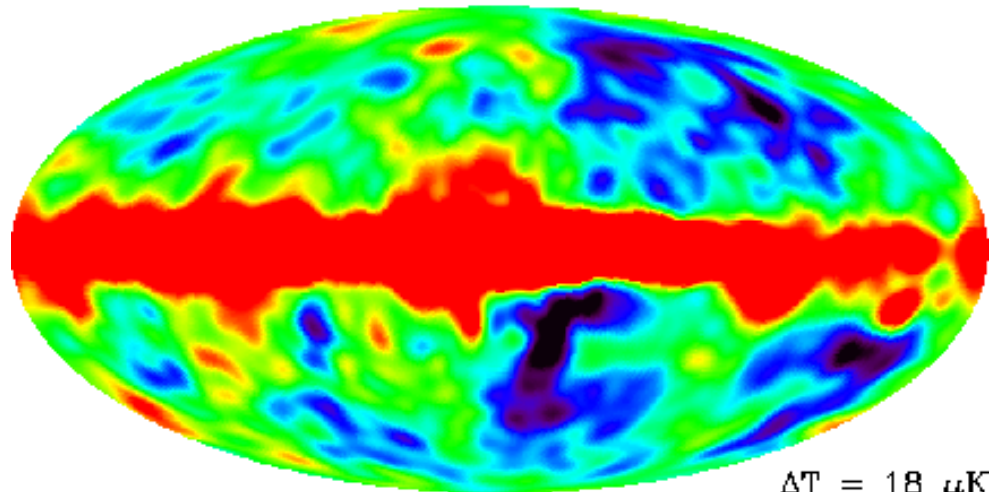


-0.234 +0.500

$\Delta T = 3.353 \text{ mK}$

Planck

44GHz



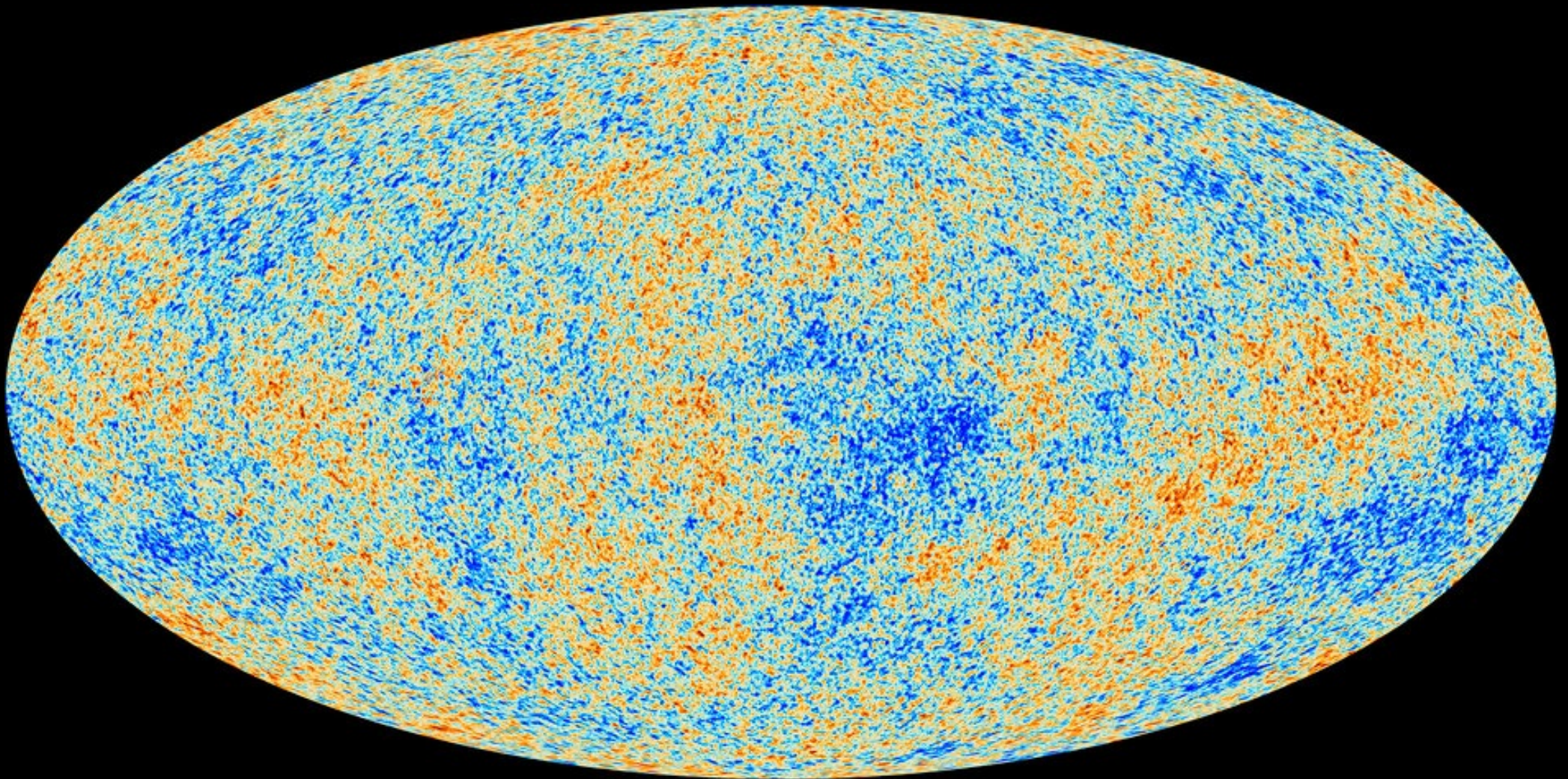
$\Delta T = 18 \mu\text{K}$

Anisotropies of Cosmic Microwave Background

Temperature anisotropies between different points in the sky

Root mean square variations of temperature: $\Delta T \approx 18 \mu\text{K}$

Consequences: primordial fluctuations of matter density also very small: $\Delta\rho / \rho \sim 10^{-5}$



All-sky surveys from ESA's *Planck Space Telescope*

The Cosmic Microwave Background

The **temperature anisotropies** tell us about:

- Geometry (curvature) of space-time in the universe
- Temperature anisotropies related to primordial fluctuations of density at time $t \sim 0$
- Small fluctuations in matter density will grow later (gravity)...
- ...and form structures (stars, galaxies, black holes) & a highly non uniform universe today

Anisotropies of CMB and geometry of space time

$$\Omega_0 = \frac{\rho}{\rho_c}$$

fraction of critical density

$$\rho = \rho_\Lambda + \rho_m + \rho_{\text{rel}}$$

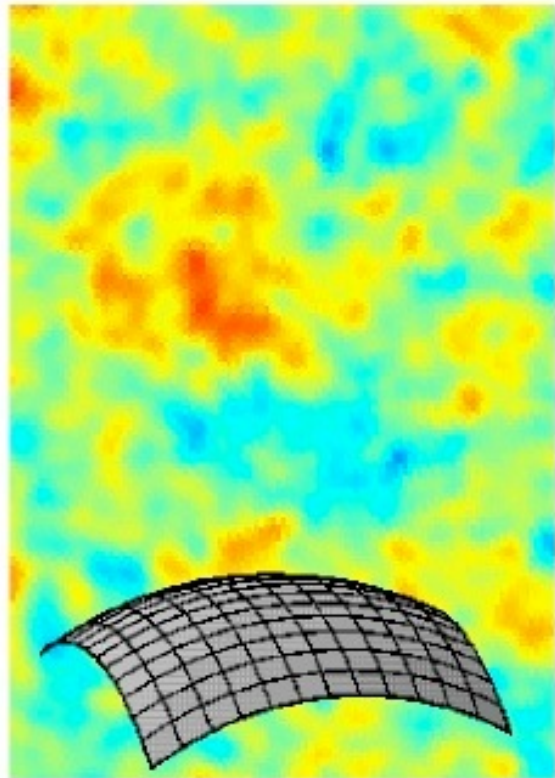
density of the universe

$$\rho_c(t_0) = 7.9 \times 10^{-27} \text{ kg/m}^3$$

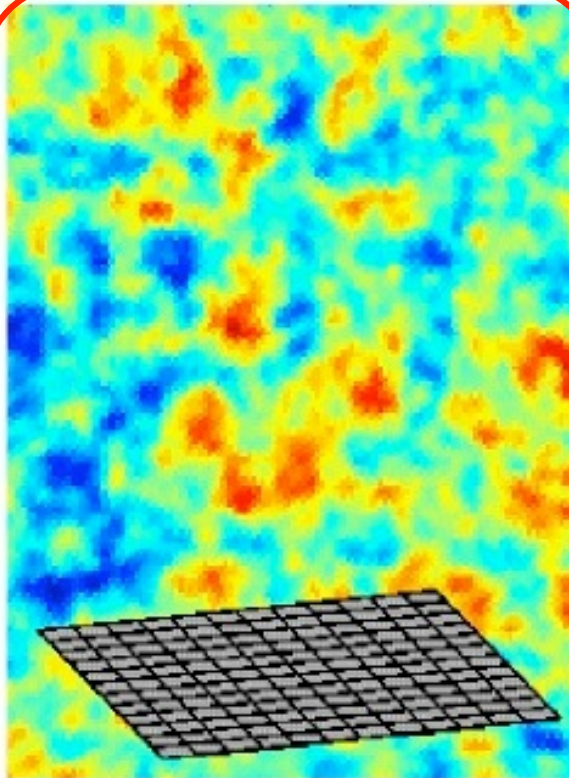
critical density **today**

Anisotropies confirmed by
observations $\Rightarrow$ flat geometry

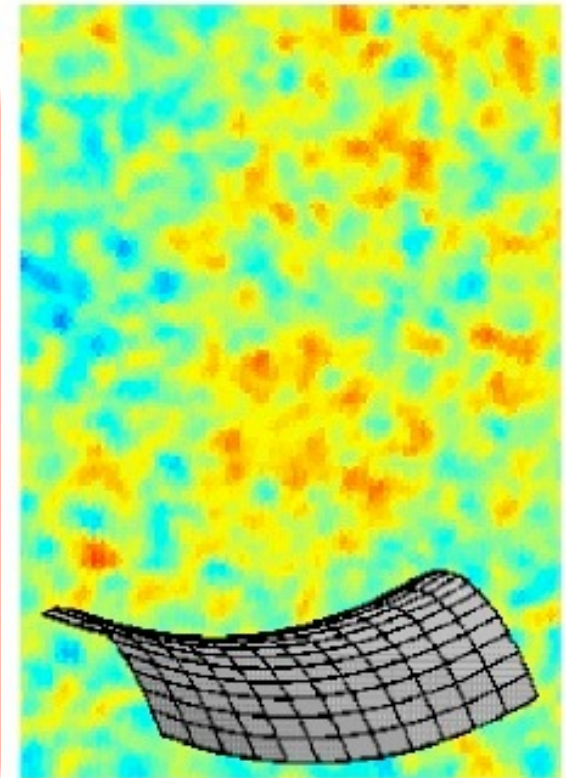
11.2°



$\Omega_0 > 1$



$\Omega_0 = 1$



$\Omega_0 < 1$

Clumpiness of CMB (anisotropy)

$\delta\rho(r)$ or $\delta(r)$: matter density perturbation (deviation from average density $\langle\rho\rangle$)

Described with Fourier transform and $k_n = 2\pi n/L$ wave number (L : length in space)

Fourier transform coefficients: $\delta_k(k)$

Clumpiness depends on scale (then k): $P(k) = \langle |\delta_k|^2 \rangle$ power spectrum

Density perturbation will grow with time

At time of inflation: quantum fluctuations are **scale invariant**

Invariance of density field per $\ln(k)$ interval: $d\sigma^2/d(\ln k) = \text{constant}$

Then: $P(k) \propto k^{n_s}$ ($n_s = 1$ spectral index)

Scale invariance breaks at end of Inflation: $n_s \simeq 1 + 2\eta - 6\varepsilon$

CMB image analysis: **Fourier transform** with spherical harmonics and Legendre polynomials

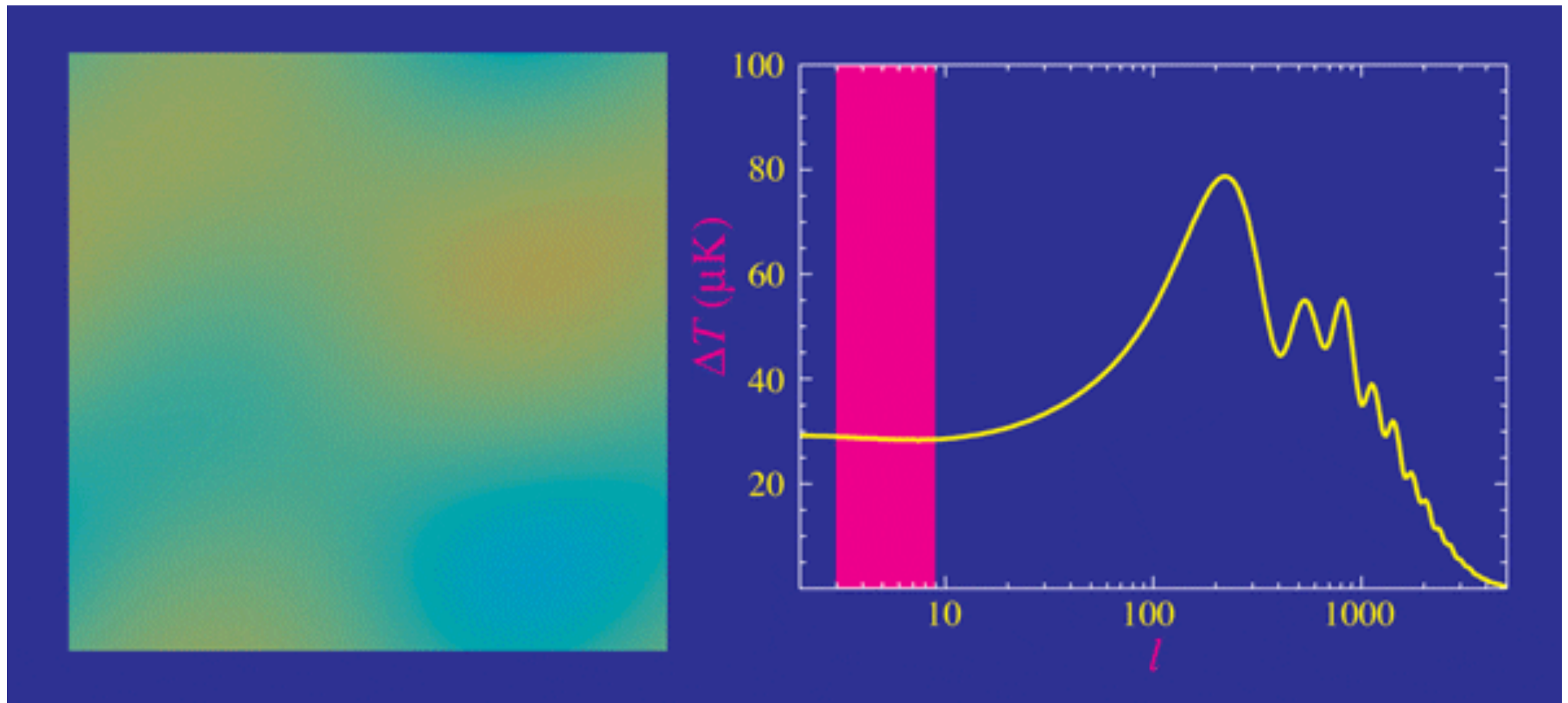
$\delta(\theta, \phi)$, with θ, ϕ angular scales and coefficients a_{lm}

Wave number: $l \sim 2\pi/\theta$ (a_{lm} monopole, dipole, quadrupole... for $l = 1, 2, 4, \dots$)

Power spectrum written in terms of $C_l = \langle (a_{lm})^2 \rangle$

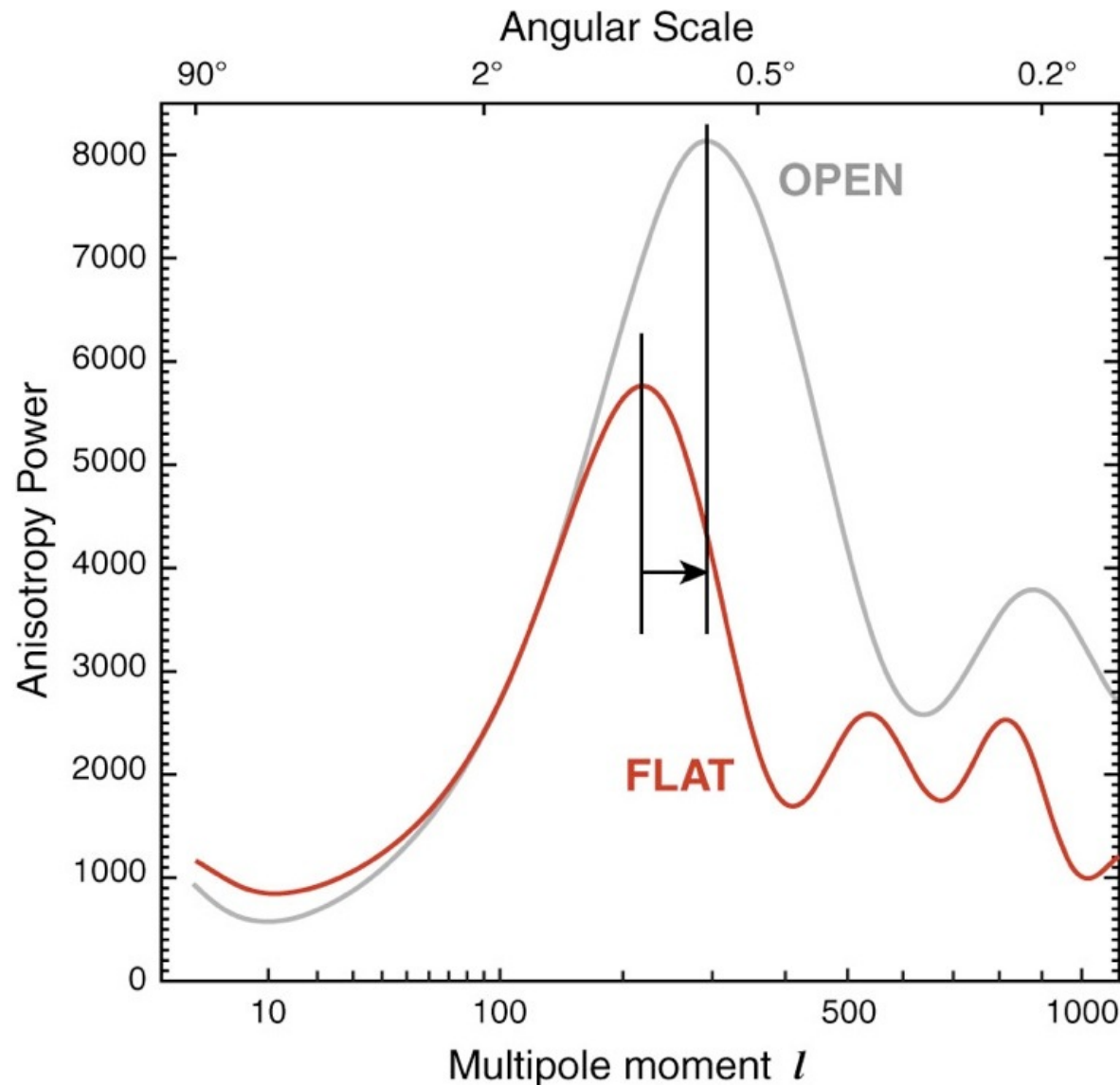
The **temperature fluctuation**: $\Delta T^2 = l(l+1) C_l \langle (T_{\text{CMB}})^2 \rangle$

Anisotropies of Cosmic Microwave Background (computer simulation)

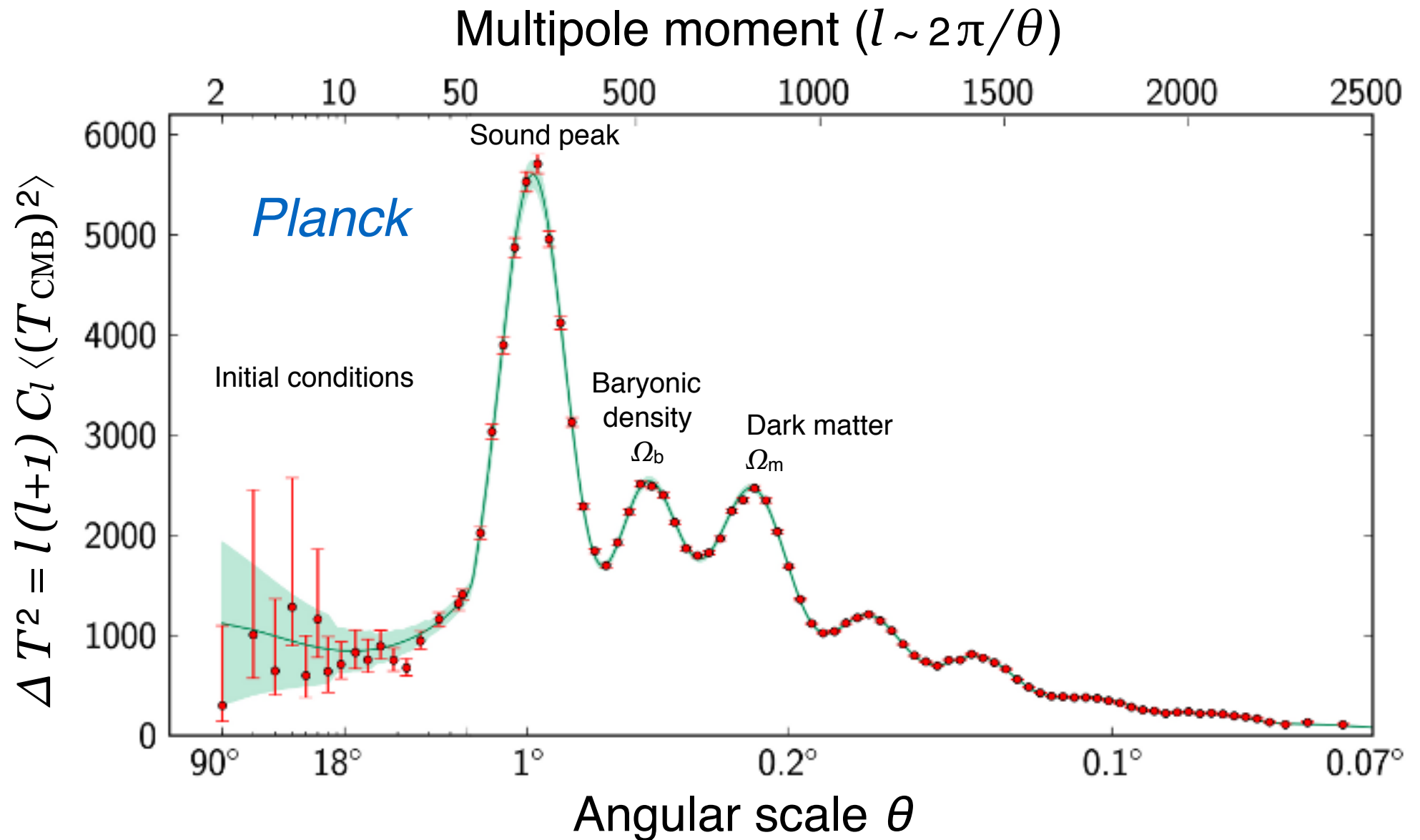


Anisotropies of CMB and **power spectrum** of temperature fluctuations

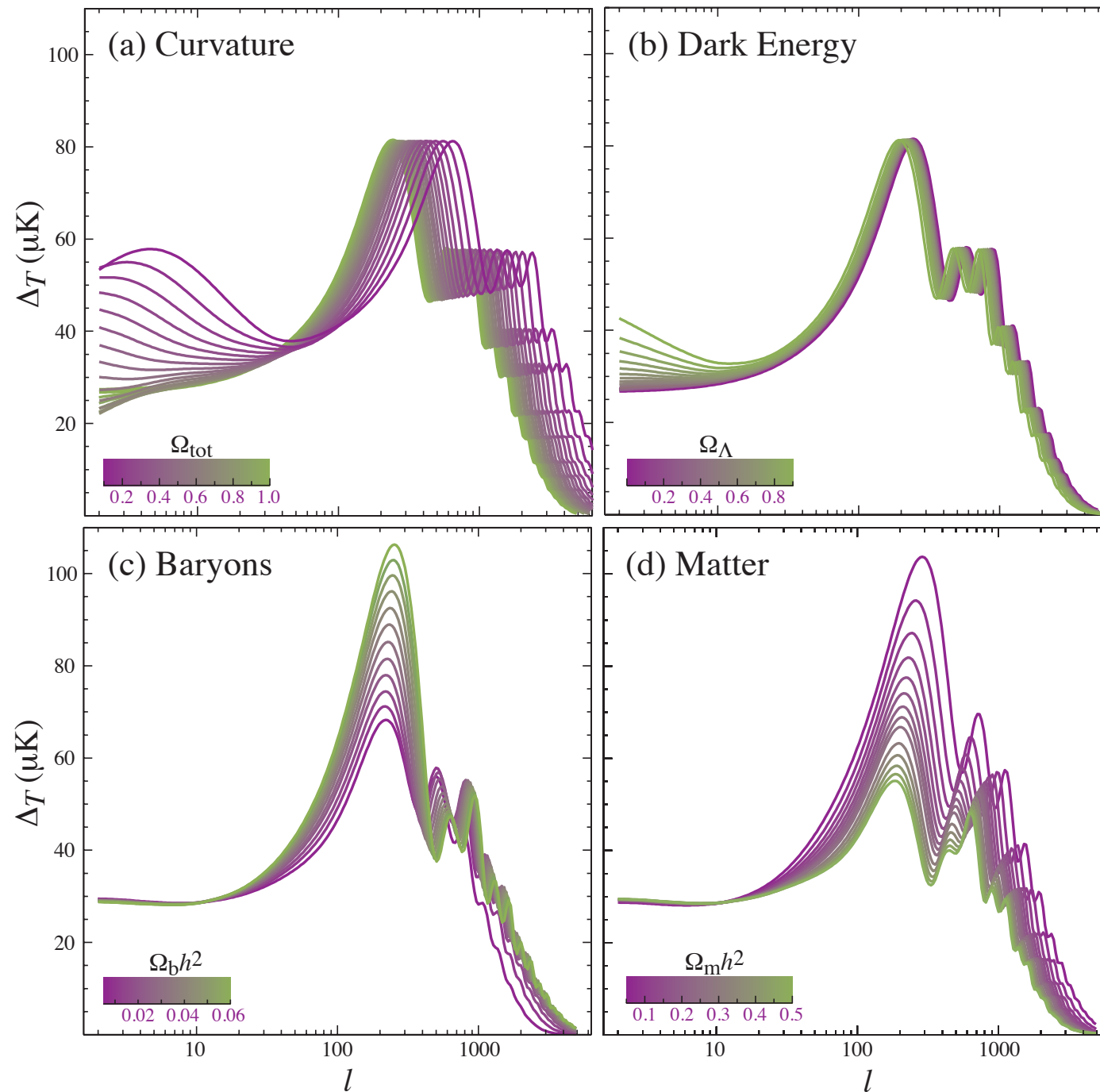
Position of the **first peak** defines curvature of the universe



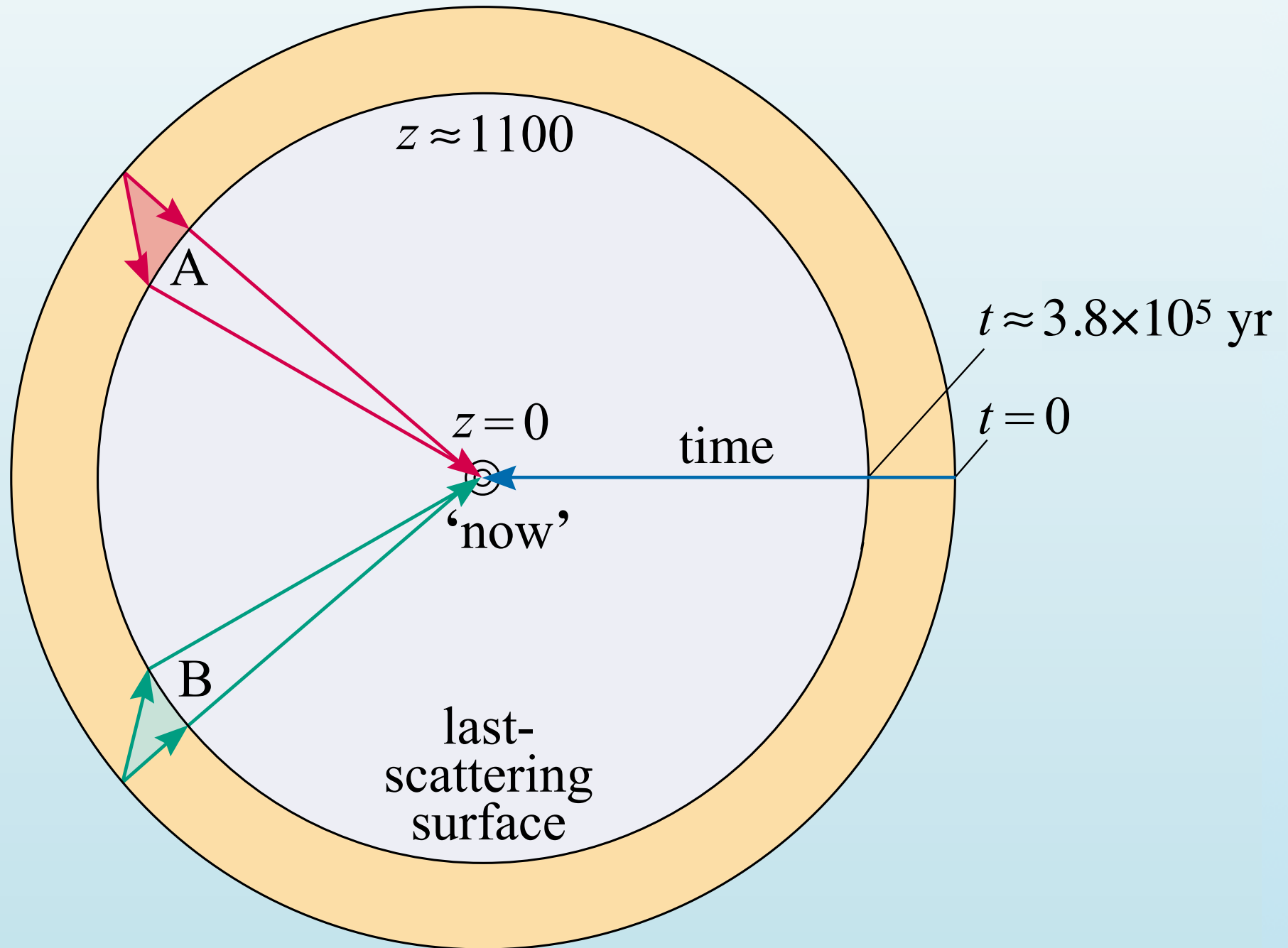
Anisotropies of CMB and **power spectrum** of temperature fluctuations



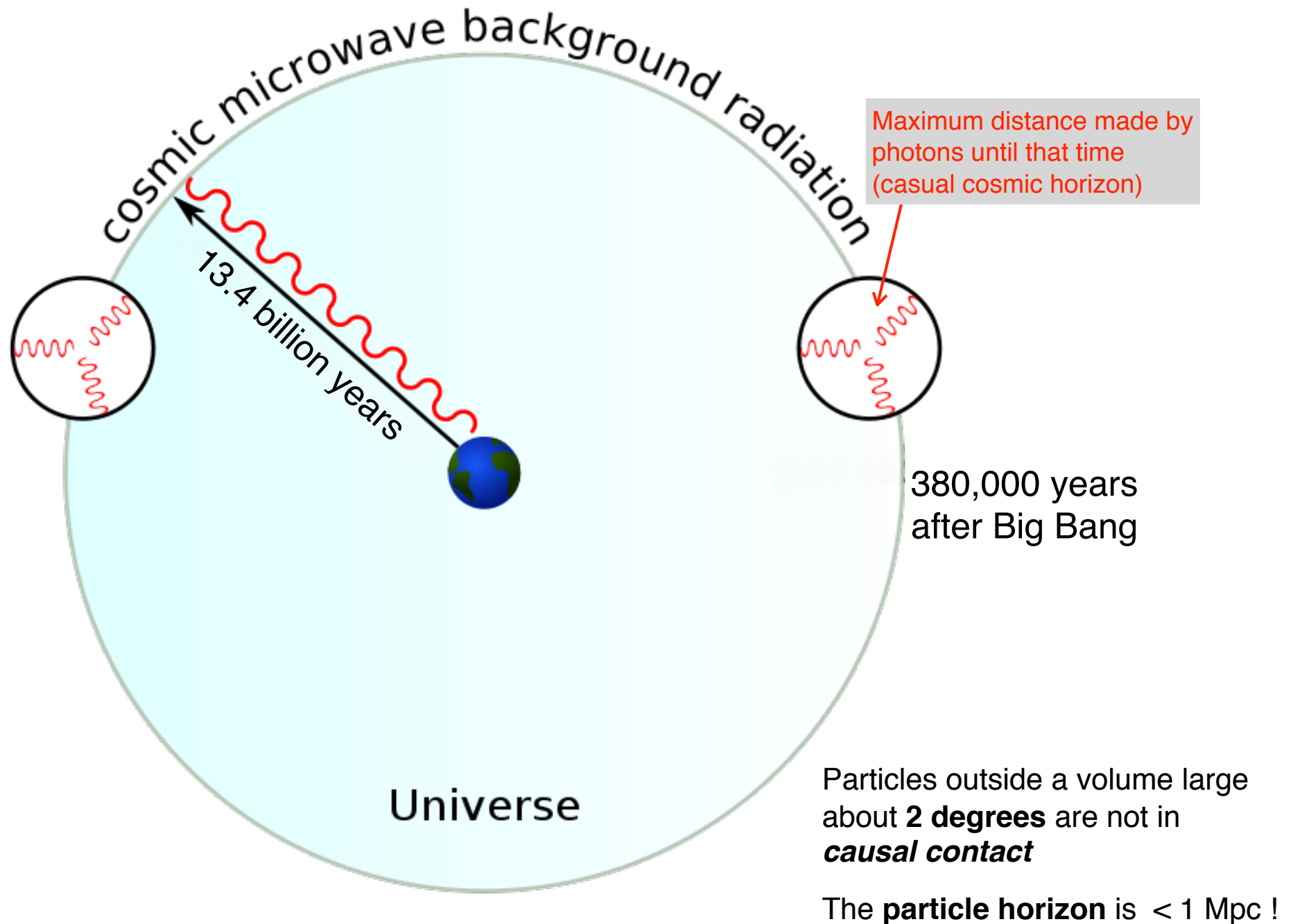
The power spectrum is **degenerate** for different initial conditions!



Surface of last scattering

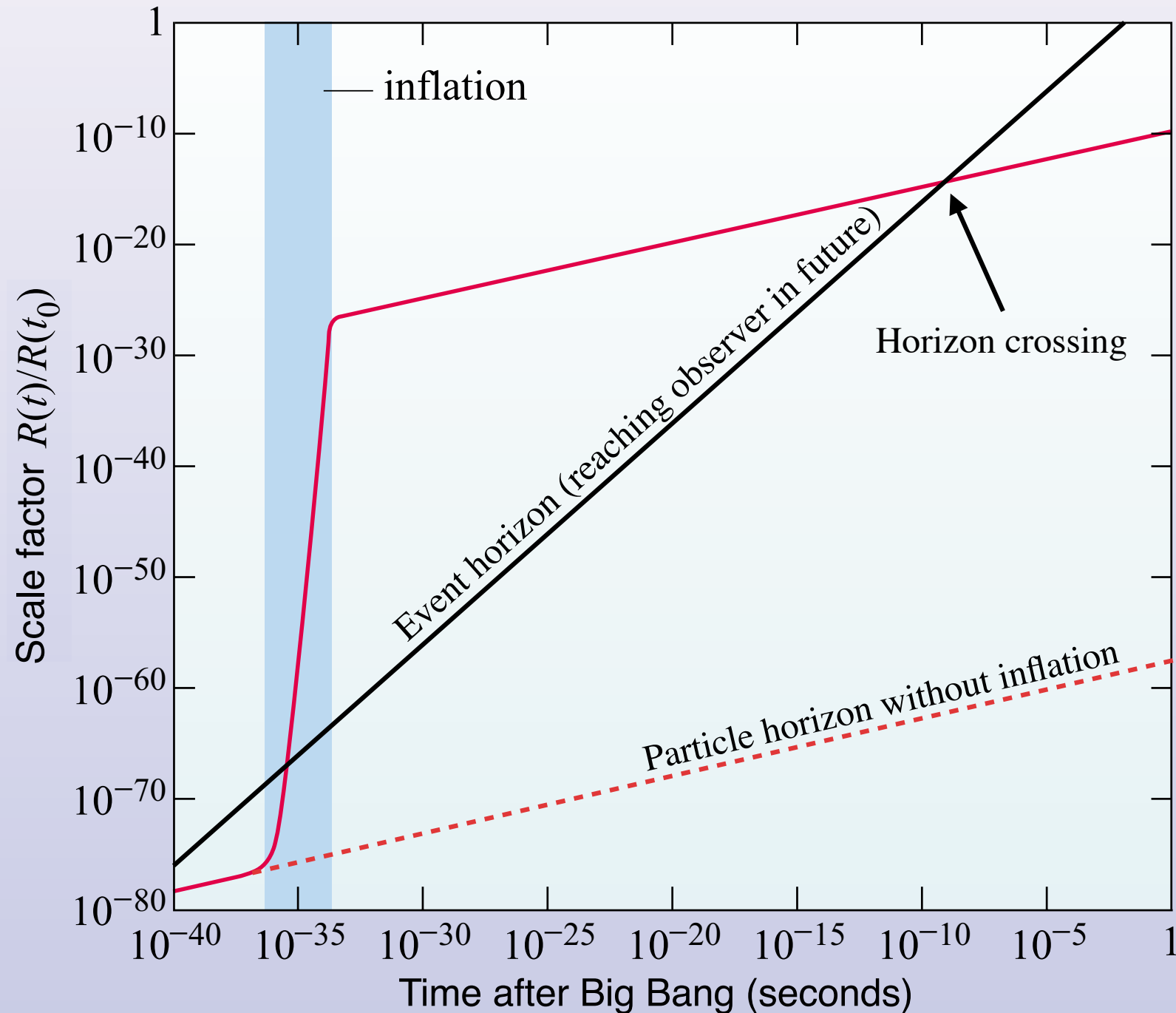


One limit of Big Ban model: the ***Horizon Problem***

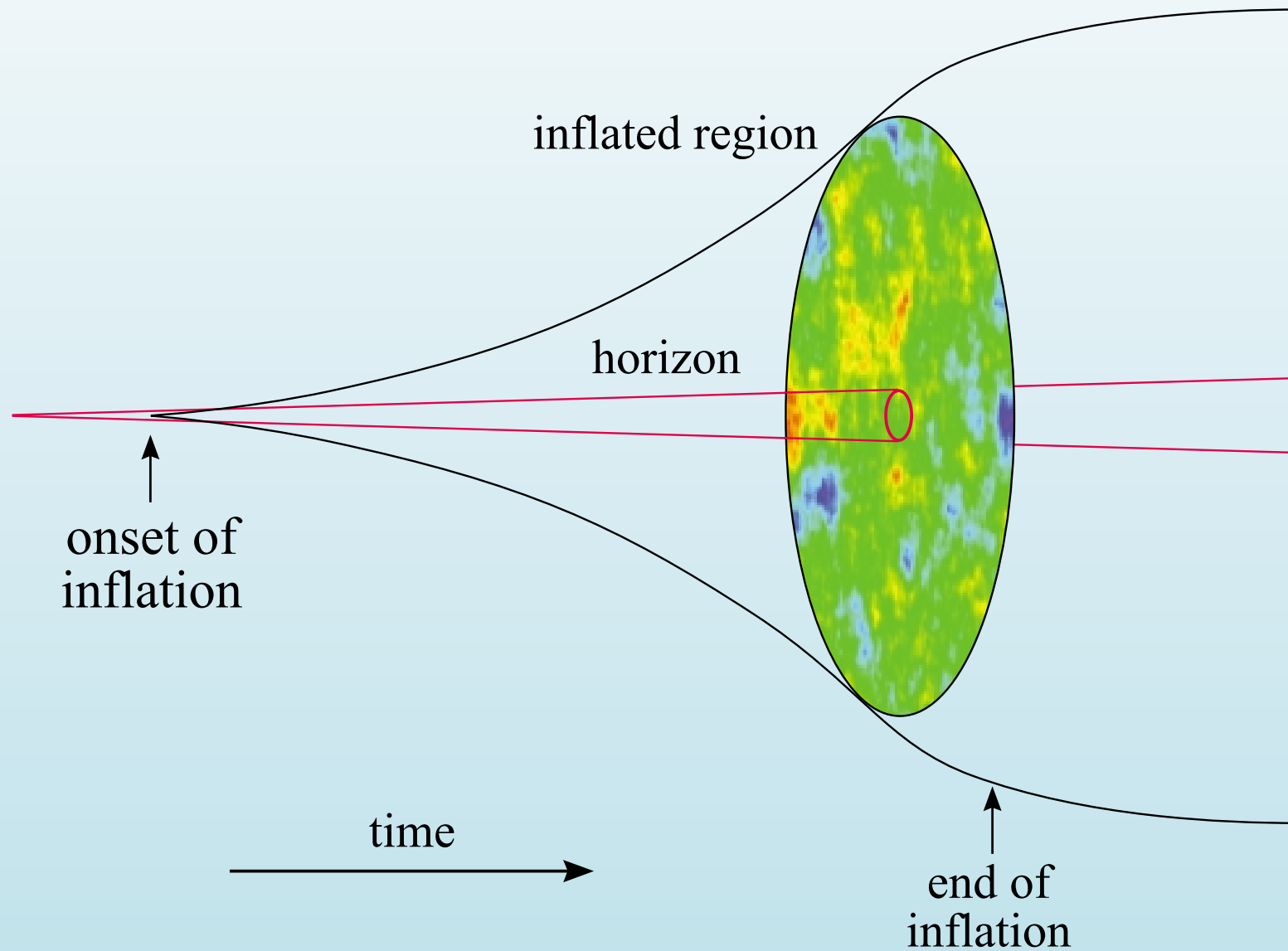


History of the universe

Inflation: exponential expansion of the universe in short time

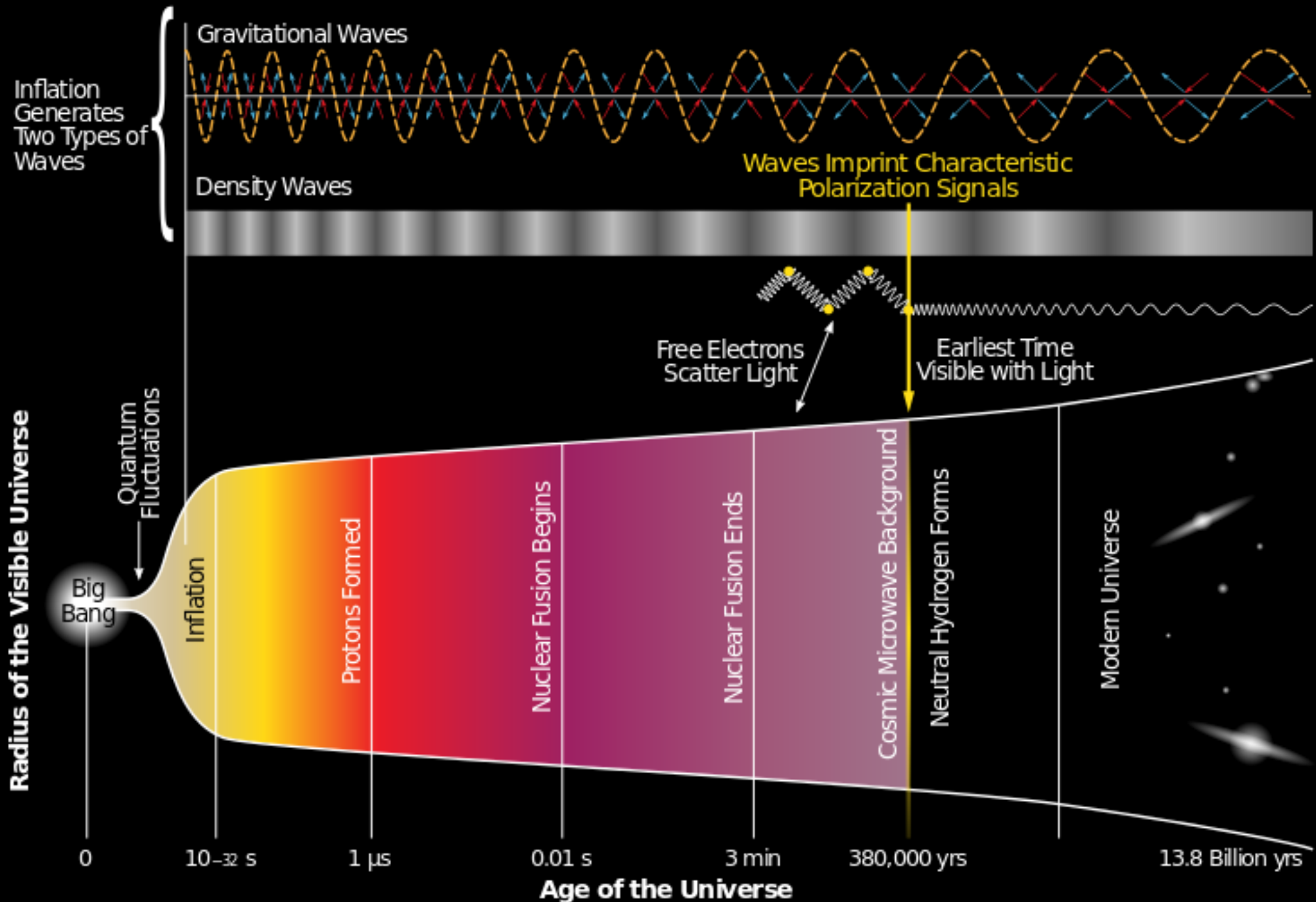


A solution: exponential expansion of the universe - ***Inflation***

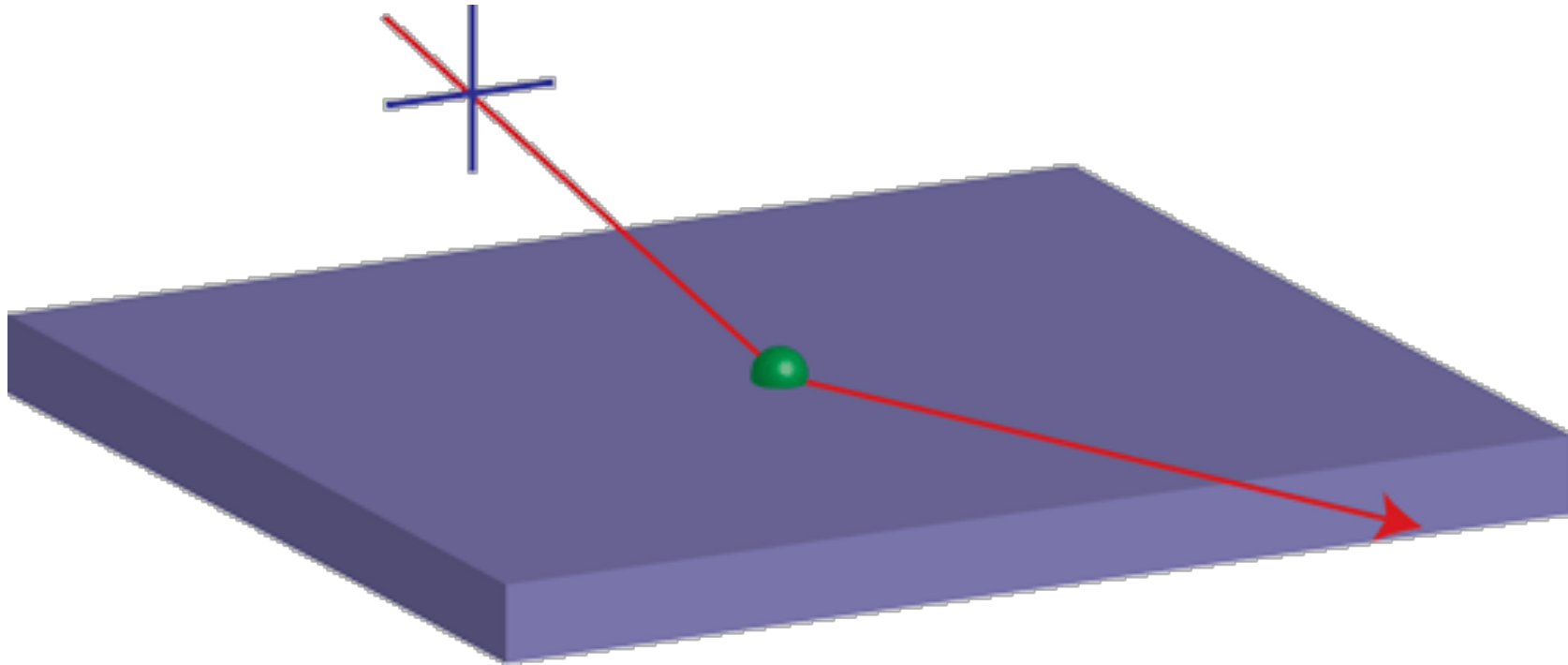


Also Inflation generates gravitational waves

Signal *today* extremely diluted by expansion of the universe, but in CMB....

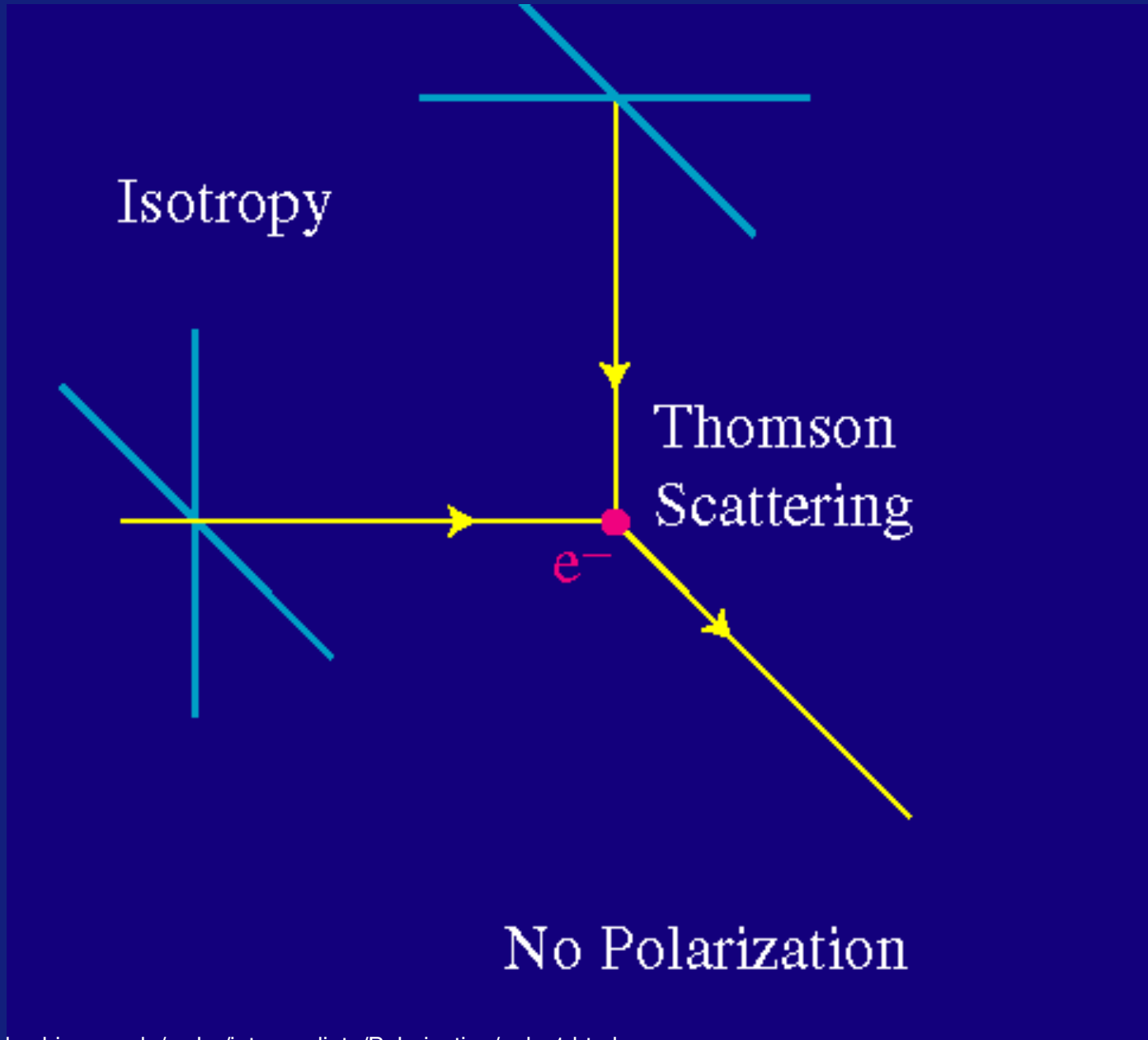


Scattered (or reflected by surface) light is polarized

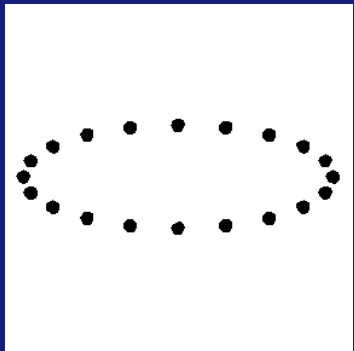


- Free electrons polarize radiation CMB has important component of polarized radiation
- But also dust polarizes radiation!

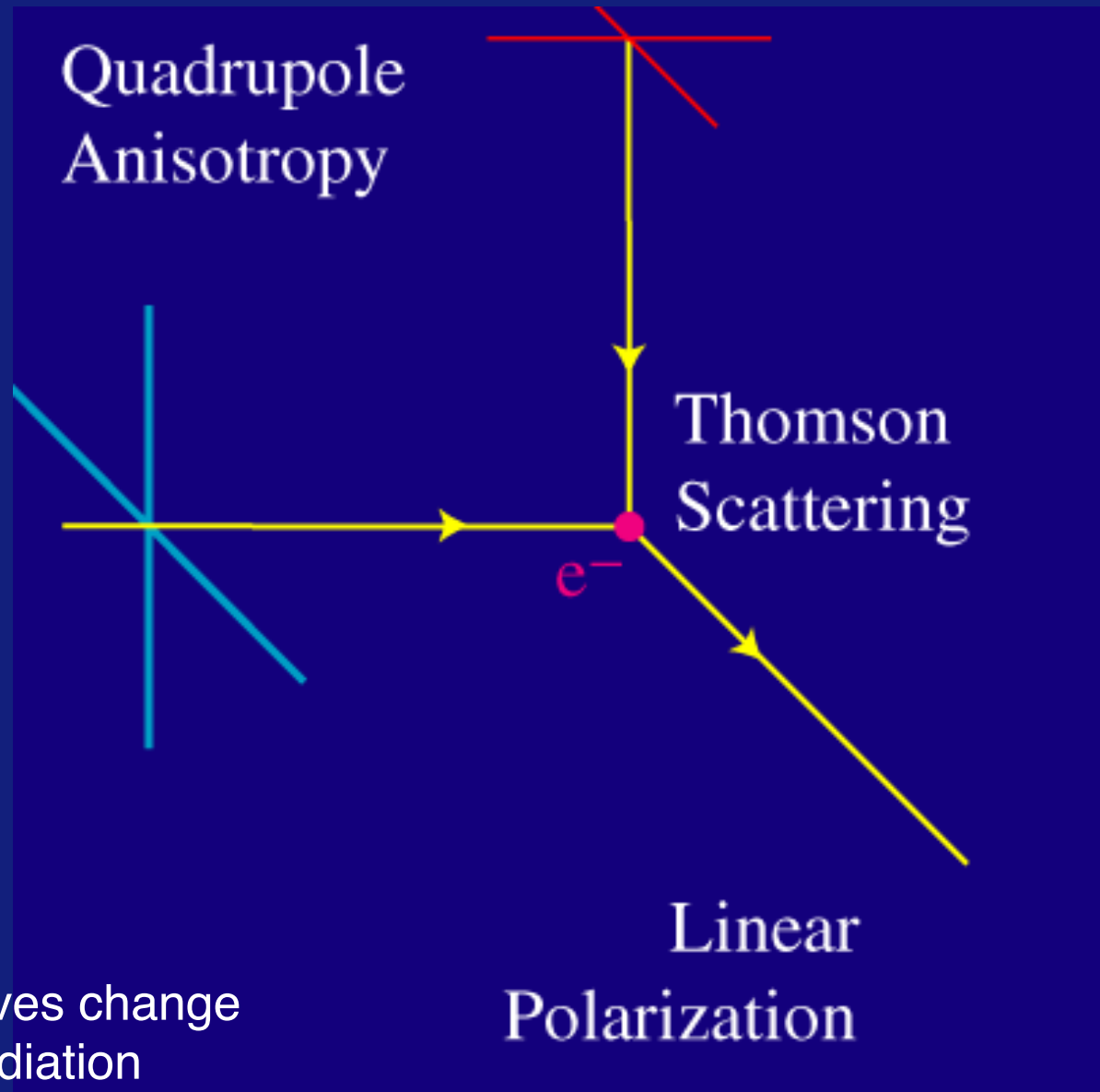
No net polarization in case of isotropy in the distribution of matter



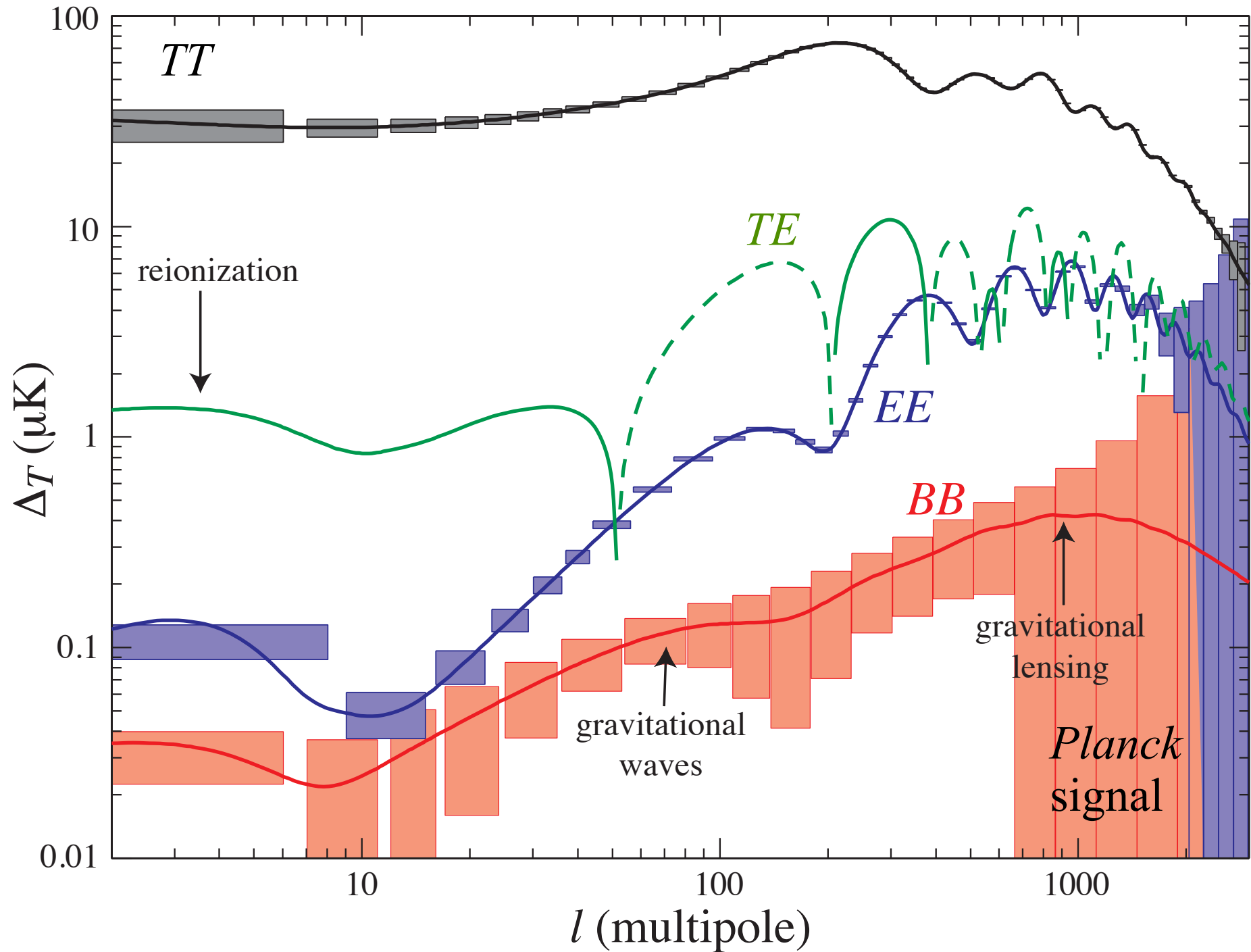
Polarization of CMB originated by “quadrupole anisotropy” of matter



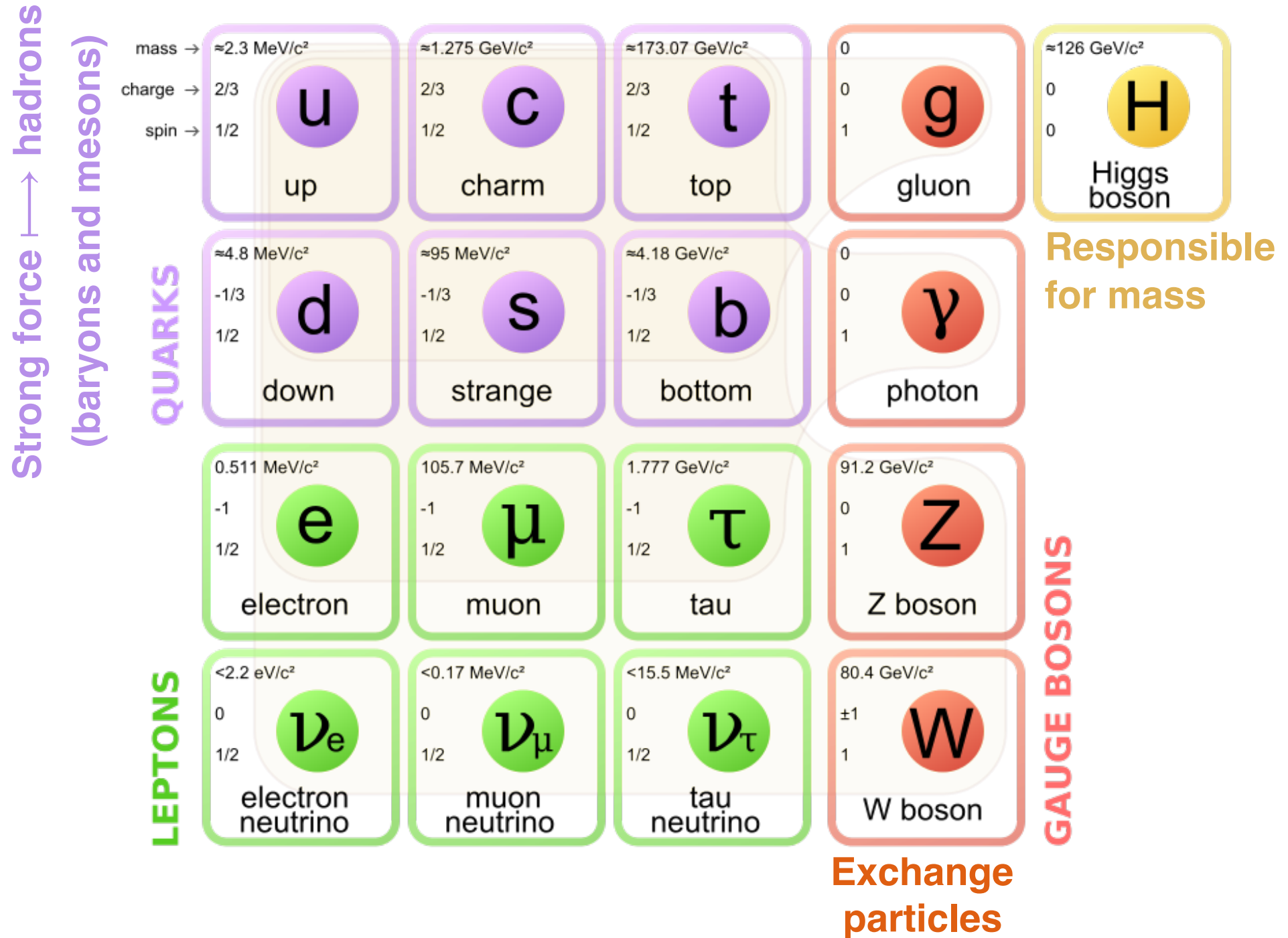
Gravitational waves change wavelength of radiation



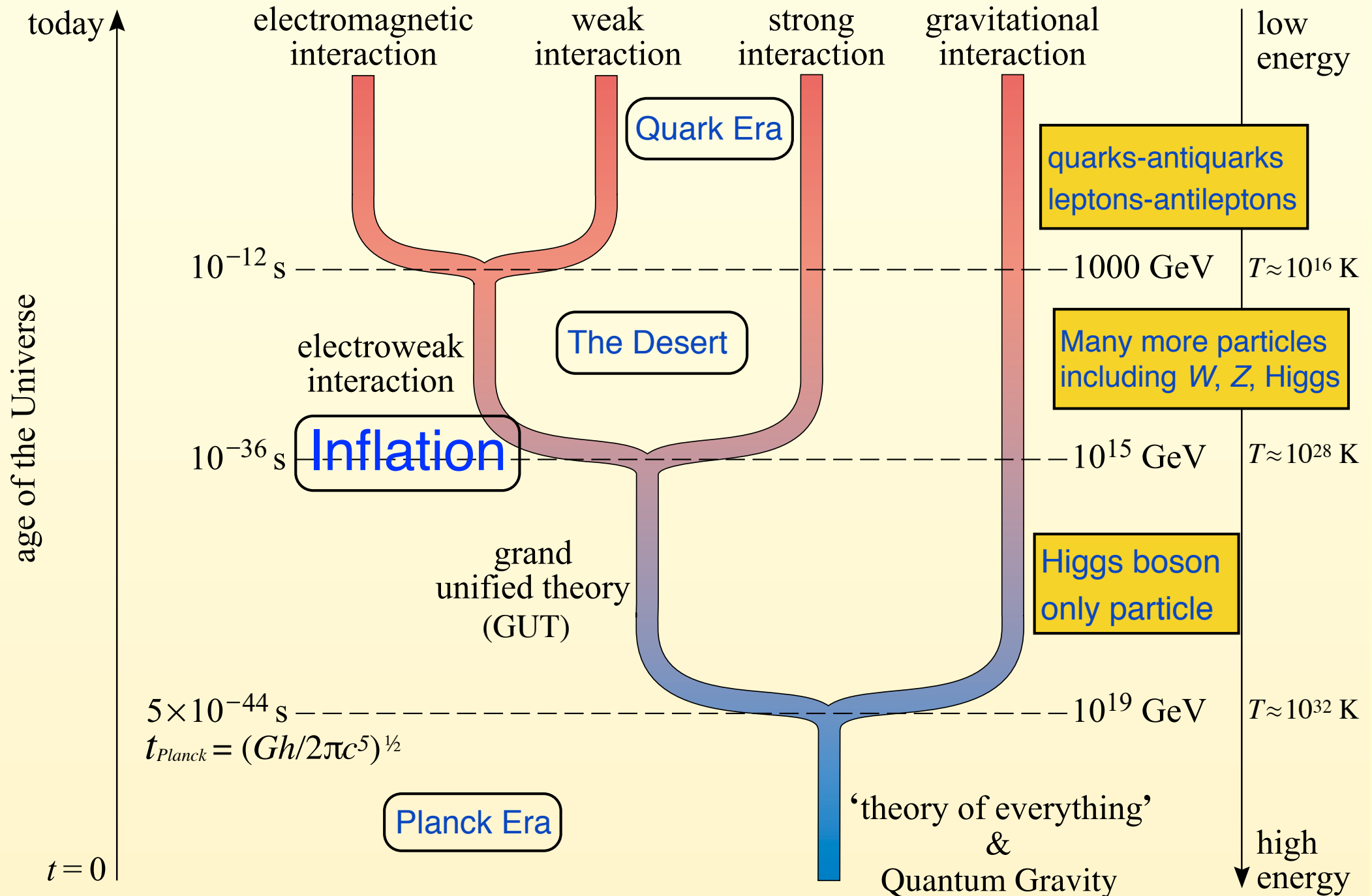
Decomposition of power spectrum and polarisation of CMB



The 17 elementary particles in the *Standard Model*

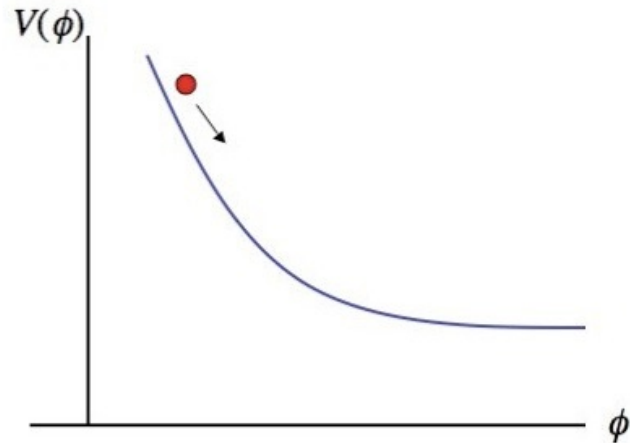
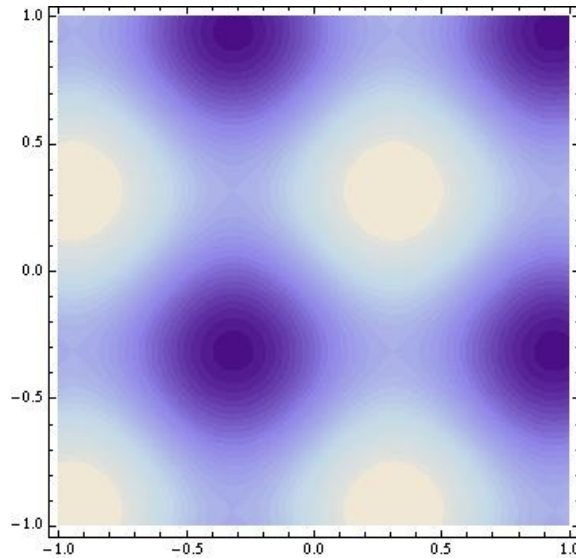


Evolution of fundamental interactions

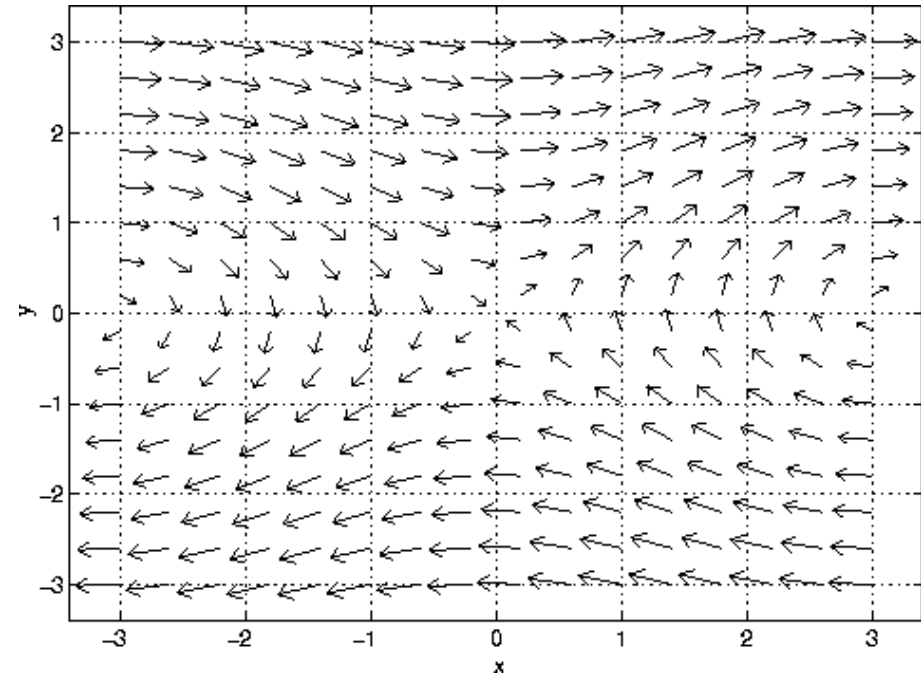


At time of *Inflation*, 3 fundamental scalar fields: **Higgs, inflaton & dark energy**

Scalar field



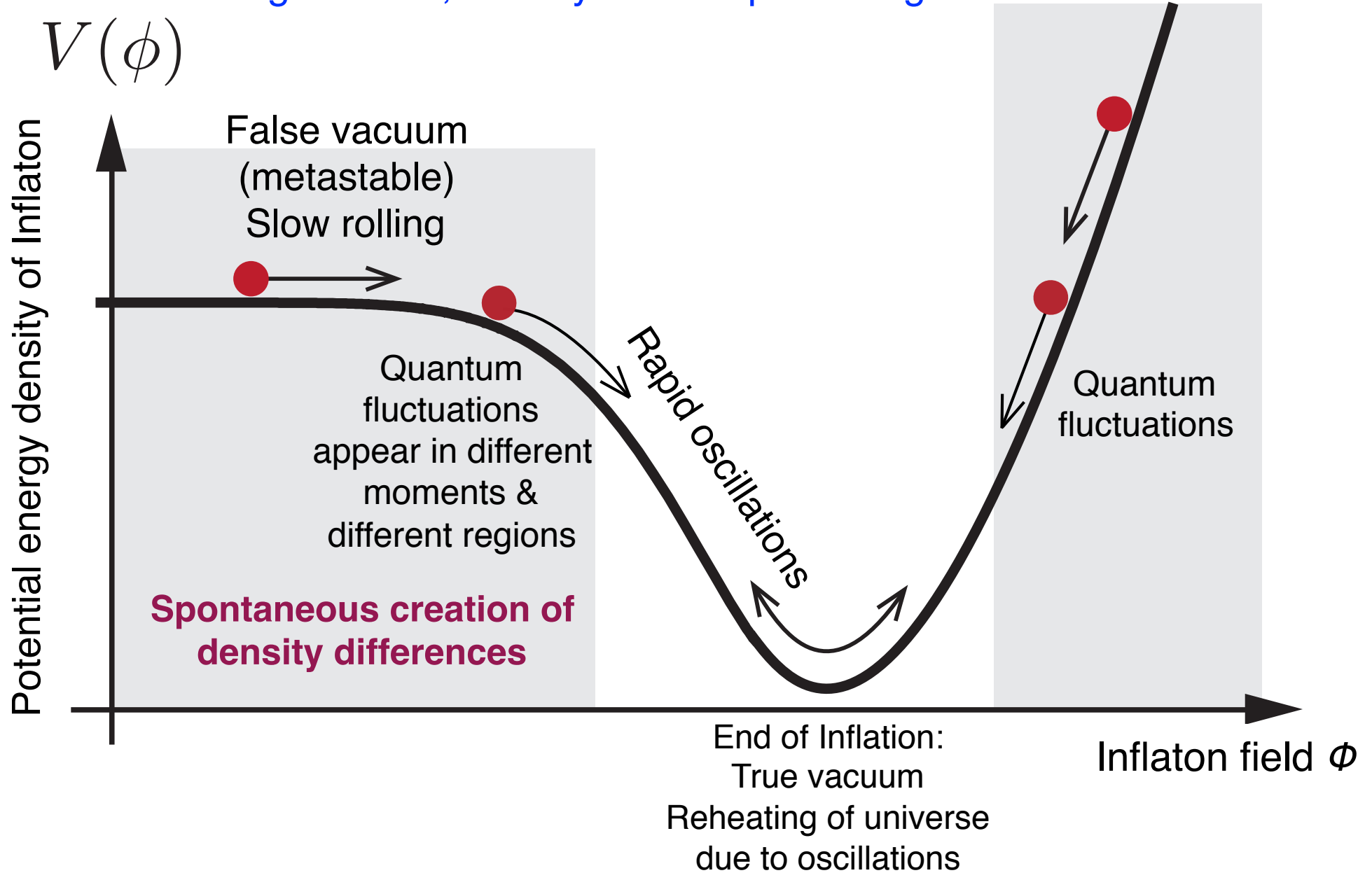
Vector field



Scalar field vs. vector field

Potential energy of inflaton field (one possible scenario)

During inflation, density anisotropies are generated



End of Inflation: universe with **asymmetry matter-antimatter** related to CP violation (called baryogenesis), **radiation and neutrinos, particles get mass** (thanks to Higgs boson)

Soon after $t = 0$, the universe has:

- Higgs bosons, which give mass to particles
- Radiation (photons)
- Primordial neutrinos (cosmic neutrino background – CNB)
- Dark matter
- Quarks (from which atoms form)
- Asymmetry matter-antimatter (strength is quantified by CMB)

Problems solved by the theory of Inflation:

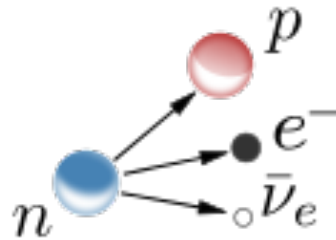
- The horizon problem
- The flatness of the universe
- Monopole problem

After initial events:

$t \sim 10^{-5} \text{ s}$, $E \sim 0.2 \text{ GeV}$, $T \sim 10^{12} \text{ K}$: **quark-hadron transition**
protons and neutrons most stable

Half-life time of protons longer than 10^{33} years

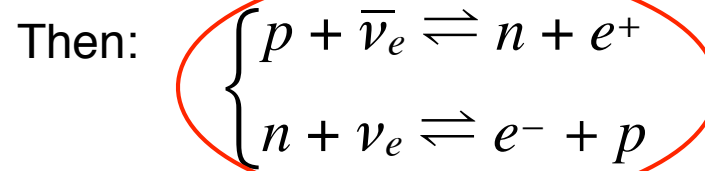
Neutrons unstable $\Rightarrow \beta^-$ decay (half-life time: $880.2 \pm 1.0 \text{ s}$)



For $10^{-5} \text{ s} < t < 10^{-2} \text{ s}$, **proton-antiproton & neutron-antineutron annihilation**

Thanks to very small excess of particles over antiparticles at GUT,
universe made of what is left of the baryons
(measured from number density of CMB photons today)

For $t = 10^{-2}$ s, large number of neutrinos, antineutrinos, electrons and positrons



Proton rest-mass energy: 938.27 MeV

Neutron rest-mass energy: 939.56 MeV

(interaction energy > 1.2 MeV)

For T high enough, equal number density of neutrons n_n and protons n_p

When T drops, neutrons start to produce more protons:

$$n_n / n_p \approx 0.9 \quad \text{at } t \sim 10^{-2} \text{ s, } E = 10 \text{ MeV}$$

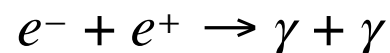
$$n_n / n_p \approx 0.65 \quad \text{at } t \sim 0.1 \text{ s, } E = 3 \text{ MeV}$$

For $t \sim 1$ s, $E \sim 1$ MeV, $T \sim 1.5 \times 10^{10}$ K, reactions above happen from right to left (called neutrino capturing, or **inverse β decay**)

Neutrinos don't interact anymore $\Rightarrow$ **Era of neutrino decoupling ($t = 0.7$ s)**

(Primordial neutrinos had more time than photons to cool $\Rightarrow$ today $T_\nu = 1.95$ K)

For $E < 1$ MeV, **electron-positron annihilation**:



Same small excess of e^- over e^+ remains

$n_n / n_p \approx 0.22$ is then frozen (no positrons available anymore for reactions above)

Number of neutrons drops only for β^- decay

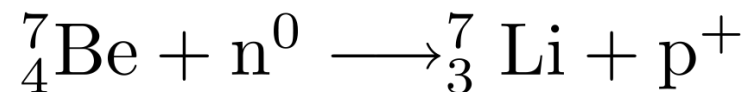
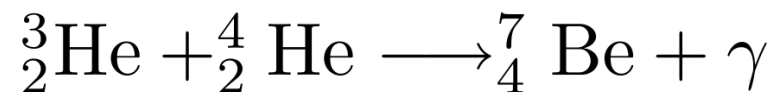
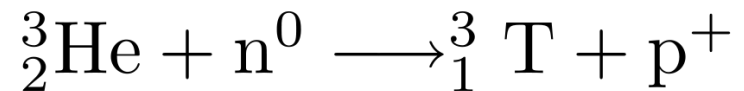
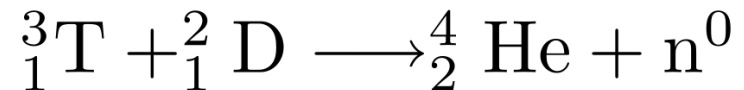
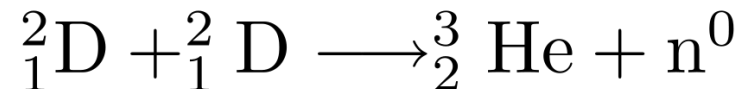
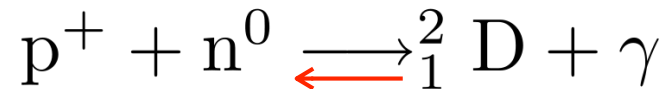
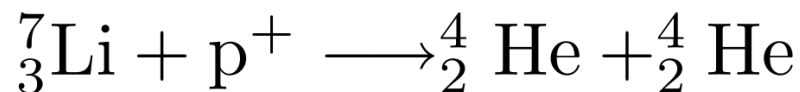
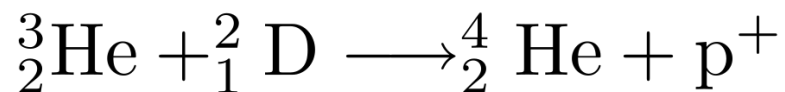
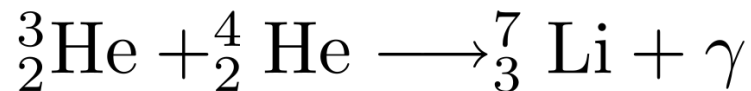
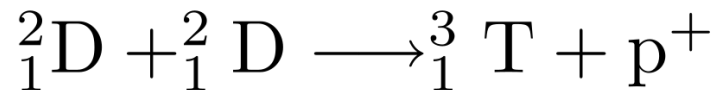
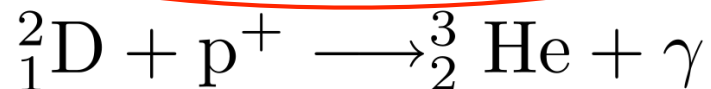
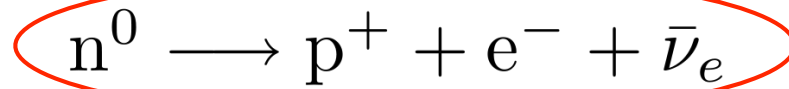
Primordial nucleosynthesis or Big Bang nucleosynthesis:

$$1 \text{ s} \lesssim t \lesssim 1000 \text{ s}$$

$$1 \text{ MeV} \gtrsim E \gtrsim 50 \text{ keV}$$

$$1 \times 10^{10} \text{ K} \gtrsim T \gtrsim 5 \times 10^8 \text{ K}$$

β^- decay



Deuterium (D) photo-disintegrates
(for $T \gtrsim 1 \times 10^9 \text{ K}$, $E > 2.23 \text{ MeV}$)

$\Longrightarrow$ few nuclear reactions

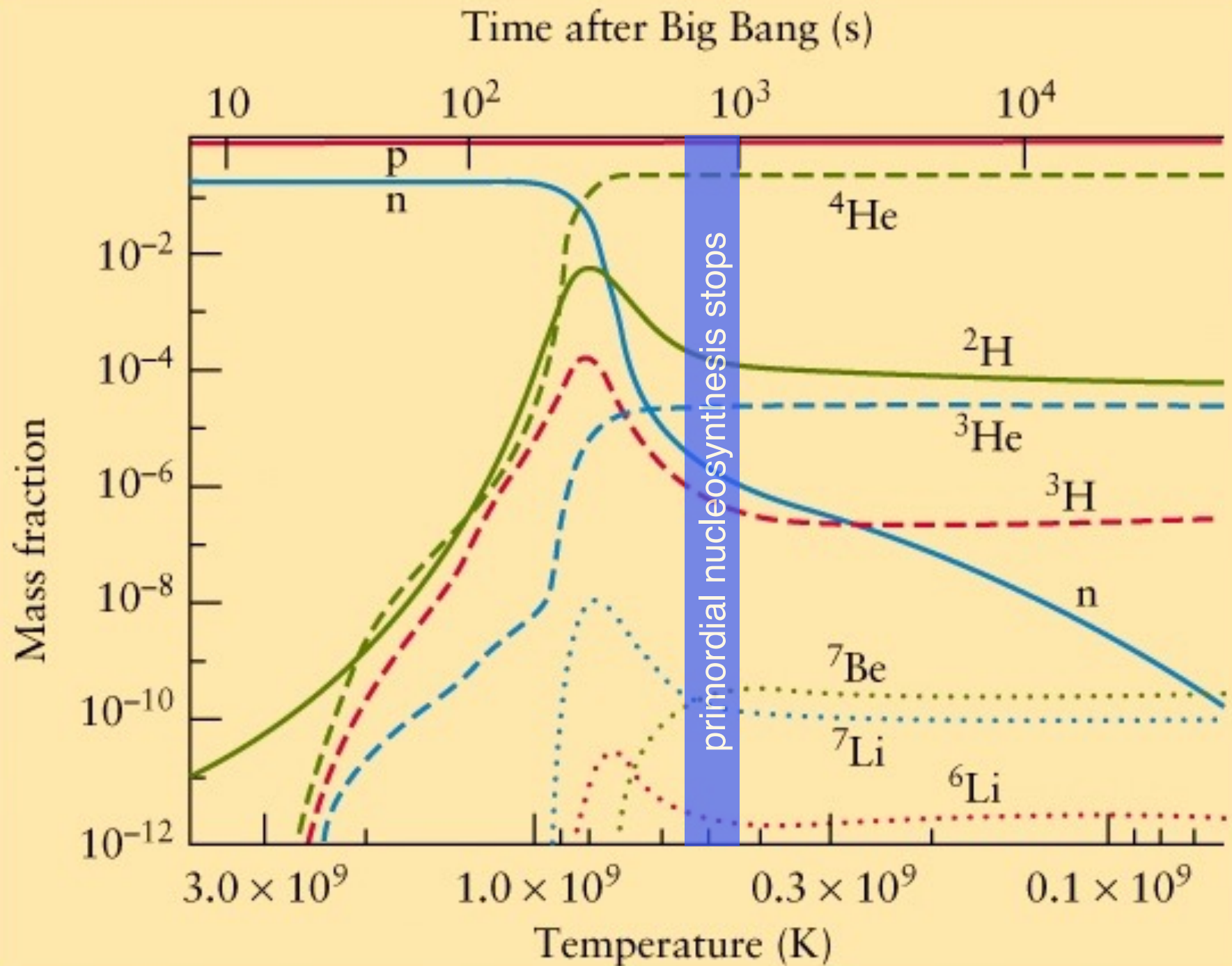
Elements created starting from neutrons and protons:

Stable: D, ${}^3\text{He}$, ${}^4\text{He}$, ${}^7\text{Li}$

Unstable: ${}^3\text{H}$ (half-life: 12 yr), ${}^7\text{Be}$ (half-life: 53.22 days)

Nucleosynthesis stops when T too low for heavier elements

History of **primordial nucleosynthesis**



Chemical composition predicted by primordial nucleosynthesis

(20 minutes after Big Bang)

Element	Mass(X) / Mass(total)
H	0.78
He	0.22
Z	$< 10^{-9}$

Z: all elements heavier than helium (called metals)

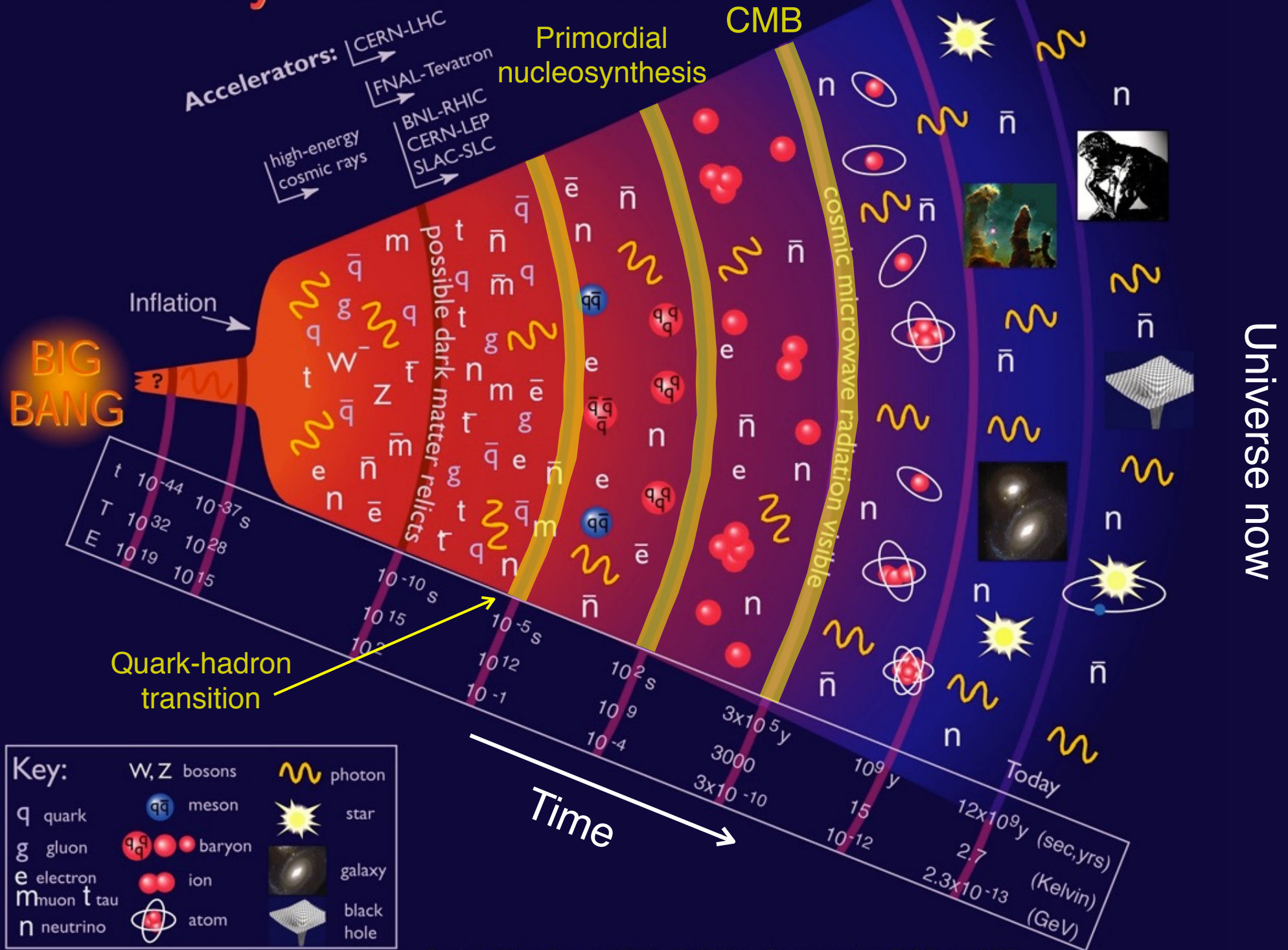
All other elements forged later in stars

Abundances of chemical elements in the Solar system (13.7 Gyr later)

Element	Mass(X) / Mass(total)
H	0.74
He	0.25
Z	0.014

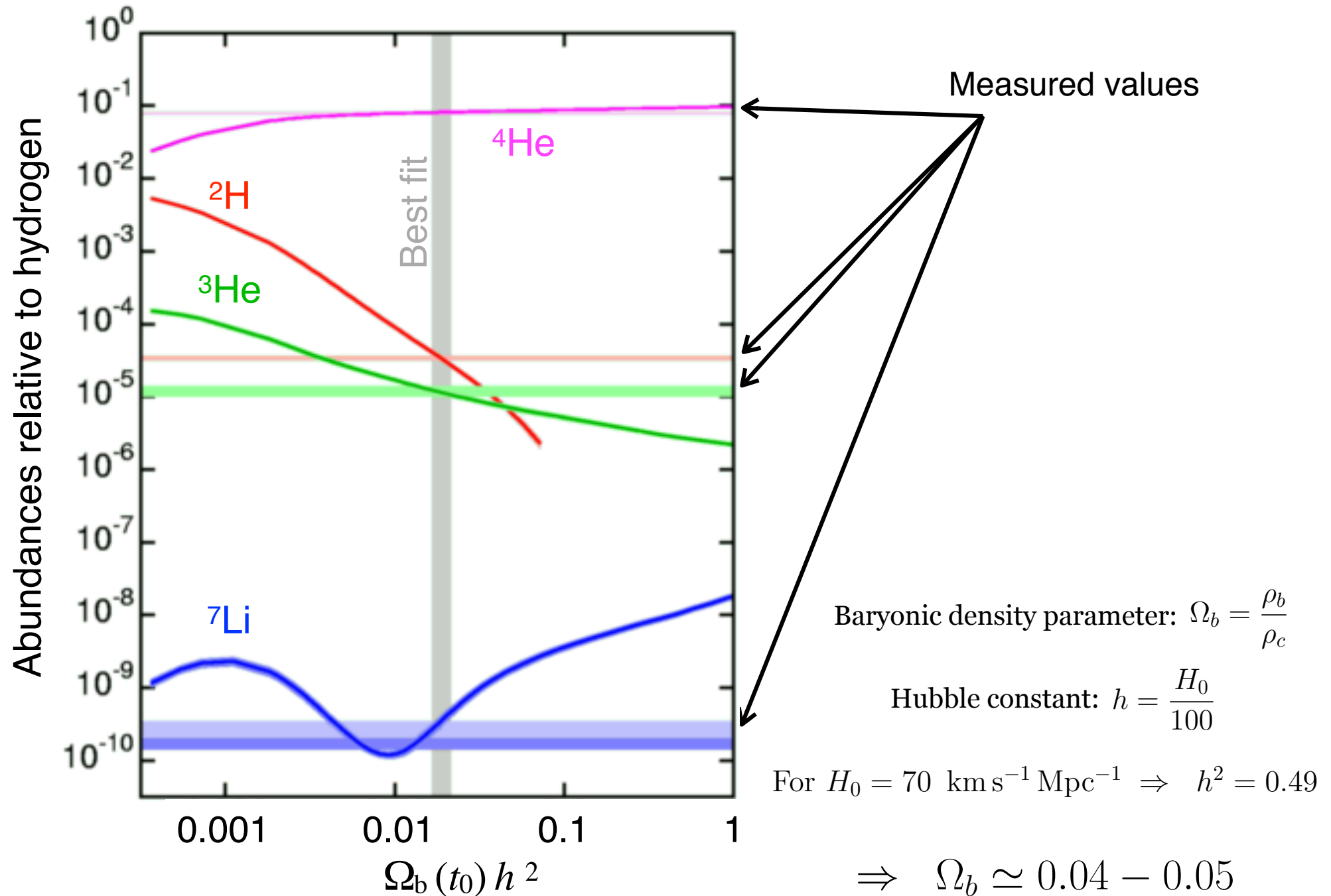
This represents the chemical composition of the Milky Way or the Local Universe

History of the Universe



Theoretical abundances of light elements during Big Bang

(all, but ^4He , very sensitive to Ω_b)



Summary of main processes in the history of the Universe

Era	Time	Size	Energy or Temperature	Relics & Observables	Events
Planck era	$< 10^{-43}$ sec	$< 10^{-50}$ cm	$> 10^{19}$ GeV	4-dimensional spacetime; cosmic expansion	Smallest unit of space-time started to expand; all forces united into one
GUT era	$< 10^{-35}$ sec	$< 10^{-47}$ cm	$> 10^{14}$ GeV	Super-heavy particles ; fundamental interactions	Separation of spacetime and matter ; gravitational, strong, and electroweak forces
Inflation	$< 10^{-32}$ sec	< 1000 cm	$> 10^{13}$ GeV	Observable universe ; large scale structures	Unstable vacuum ; quantum fluctuations
Electro-weak era	$< 10^{-10}$ sec	$< 10^{14}$ cm	> 100 GeV	Radiation; excess of matter over antimatter ; separation of force and matter fields	Radiation released in reheating; baryon-antibaryon asymmetry; separation of weak and electromagnetic forces, origin of mass
Strong era	$< 10^{-4}$ sec	$< 10^{17}$ cm	> 200 MeV	Exotic forms of dark matter	Formation of hadrons from quarks including neutrons and protons
Weak decoupling	< 1 sec	$< 10^{19}$ cm	> 3 MeV	Hydrogen nuclei domination	Neutrinos decouple, neutron/proton ratio fixed
e^-e^+ Annihilation	< 5 sec	$< 3 \times 10^{19}$ cm	> 1 MeV	Photons hotter than neutrinos today	Electron heat dumped into photons
Nucleo-synthesis	< 100 sec	$< 10^{20}$ cm	> 200 KeV	Light element abundances: D, He, Li	Nuclear reactions freeze out, stable nuclei form
Spectral decoupling	$< 10^6$ sec	$< 10^{22}$ cm	> 3 KeV	Blackbody background radiation	End of efficient photon production
Matter ~ radiation	$< 10^4$ yrs	$< 8 \times 10^{24}$ cm	> 3 eV	Mass density fluctuations	Matter density ~ radiation density
Recombination	< 0.4 My	$< 5 \times 10^{25}$ cm	$> 3000^\circ\text{K}$	CMBR	e^- and p^+ recombine into H atoms, universe transparent to light
Dark ages	< 1 Gy	$< 3 \times 10^{27}$ cm	$> 15^\circ\text{K}$	First stars , heavy elements	mass fluctuations grow, first small objects coalesce, reionization
Galaxy formation	< 2 Gy	$< 4 \times 10^{27}$ cm	$> 10^\circ\text{K}$	Stars , quasars , galaxies	Collapse to galactic systems
Bright ages	< 13 Gy	$< 9.7 \times 10^{27}$ cm	$> 2.8^\circ\text{K}$	Milky Way and Solar System	Gas consumed into stars, remnants, planets
Present era	~ 13.7 Gy	$\sim 10^{28}$ cm	$\sim 2.73^\circ\text{K}$	Supercluster	Large scale gravitational instability

Cosmological parameters

Parameter	<i>Planck</i> value	What is it?
Ω_0	1.001 ± 0.009	Total density
Ω_Λ	0.685 ± 0.007	Dark energy density
Ω_m	0.315 ± 0.007	Matter density
Ω_b	0.046	Baryonic density
ρ_c	$8 \times 10^{-27} \text{ kg/m}^3$	Critical density today
H_0	70 km/s Mpc	Hubble constant
t_0	$13.80 \pm 0.02 \text{ Gyr}$	Age of the universe

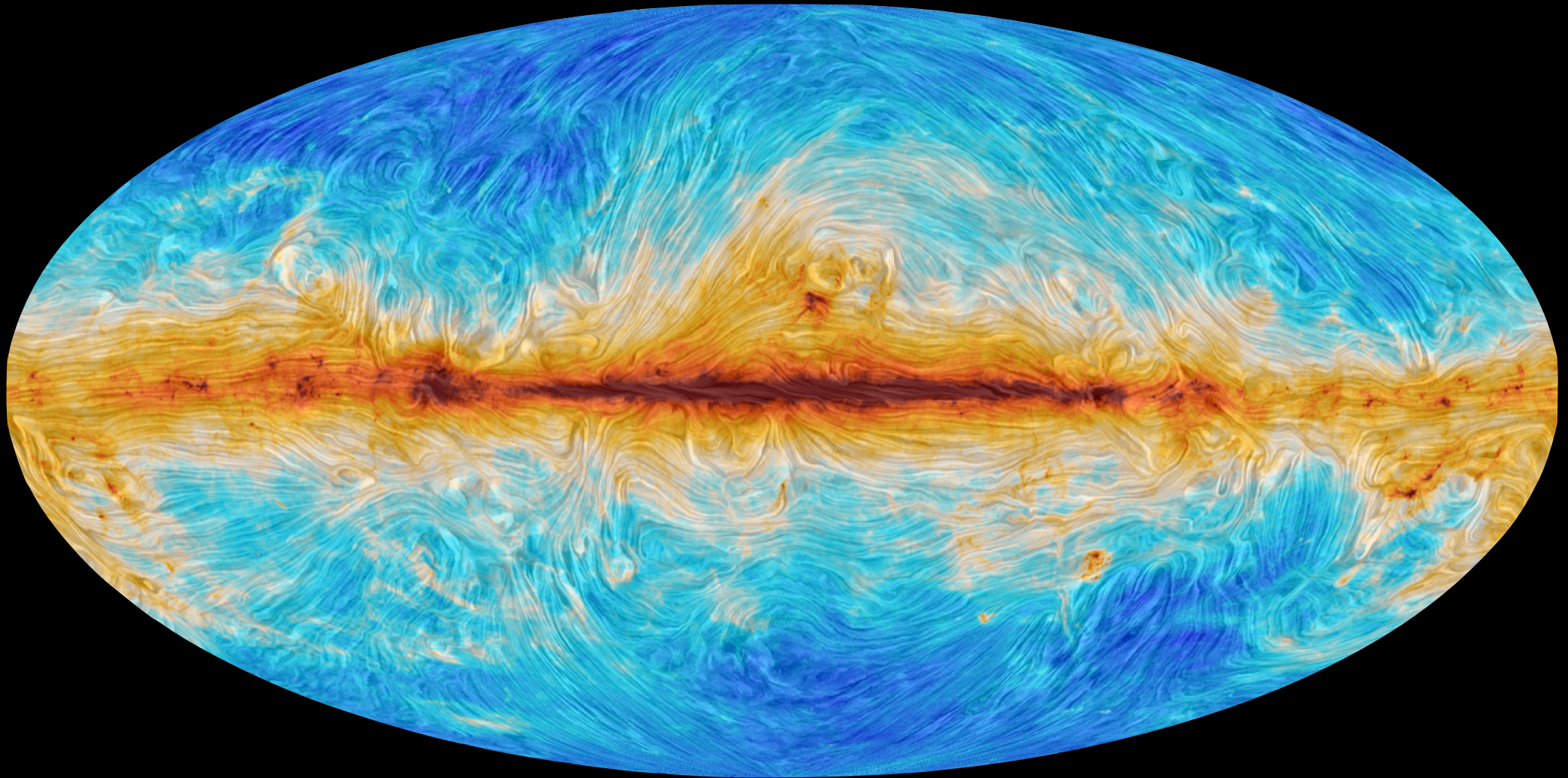
But precise values still debated and different from *WMAP*

Possible origin to accelerating universe

1. Einstein's cosmological constant
2. Dark energy (but what is it?)
3. Quantum vacuum energy
4. Quintessence
5. Negative pressure
6. Parallel universes (multiverse)
7. Modified gravity (for instance, time dependent)
8. Et cetera....

Polarized radiation detected by *Planck* satellite

Signal dominated by presence of dust (polarizing radiation) in Milky Way and nearby galaxies



All-sky surveys from ESA's *Planck* space telescope



The End

The Starry Night (Vincent Van Gogh 1889)