How did the universe begin?

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Kavli IPMU, University of Tokyo

Tokyo Woman's Christian University
07/July/2023

Image:NASA, ESA, CSA, and STScI

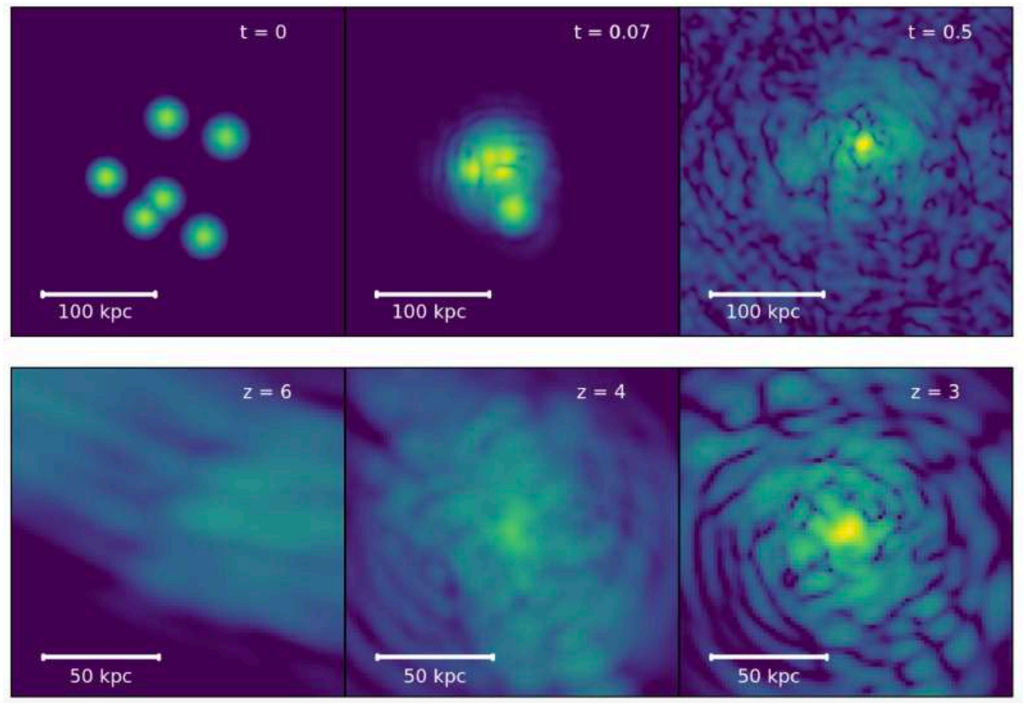
A little bit about me…

Undergrad and masters ⟶ IFUSP (Brazil)

PhD ⟶ Universidade McGill (Canada)

Postdoc ⟶ Max Planck Institute for Astrophysics (Germany)

Currently: Professor at the **Kavli Institute for the Physics and Mathematics of the Universe** and University of São Paulo, Brazil.



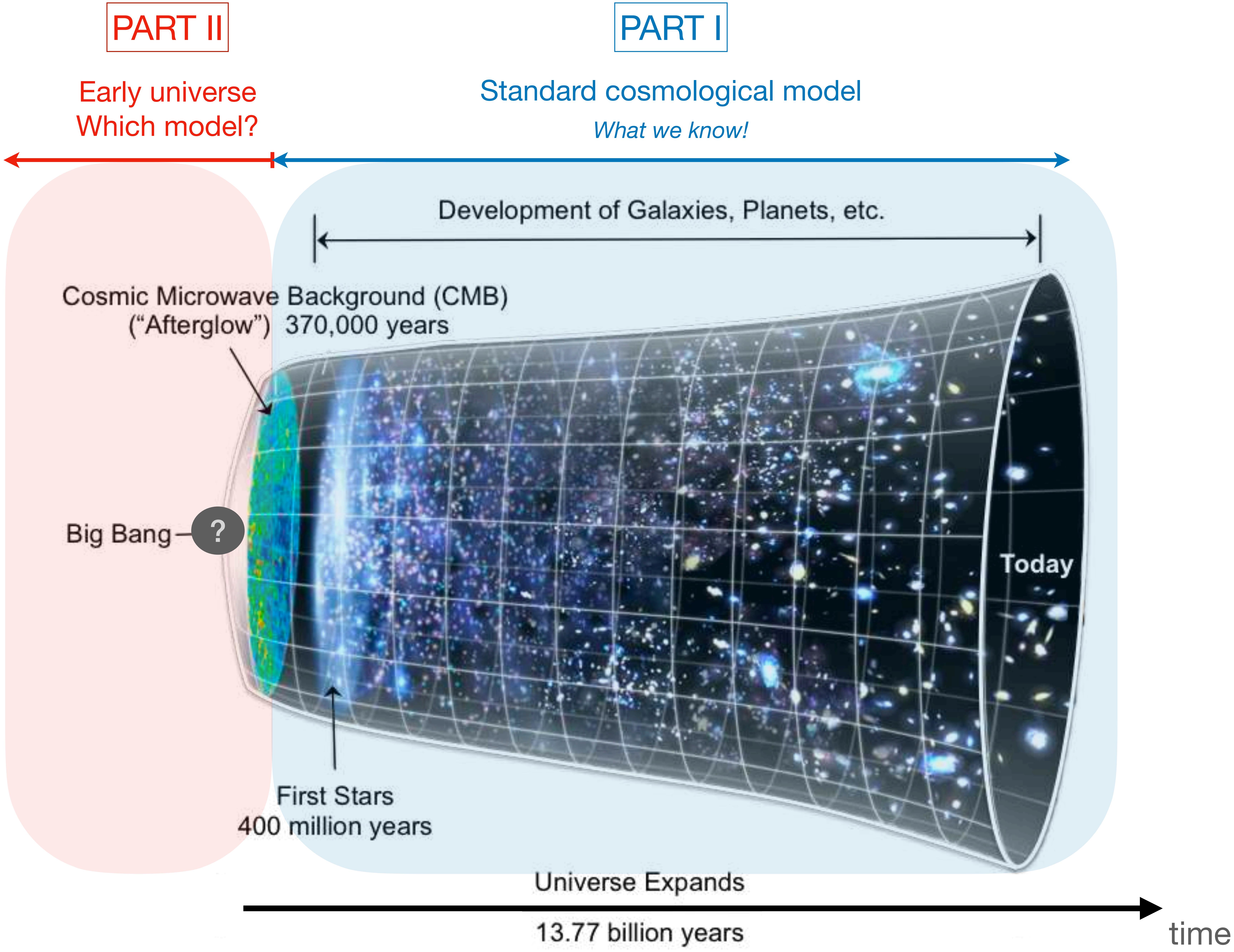
<u>My research:</u>

Theoretical cosmology

- Early universe
- Dark energy
- Dark matter
    - Ultra-light DM, axions

I also use observational data to test cosmological models and simulations.

Overview



PART II
Early universe
Which model?
PART I
Standard cosmological model
What we know!
Development of Galaxies, Planets, etc.
Cosmic Microwave Background (CMB)
("Afterglow") 370,000 years
Big Bang
?
Today
First Stars
400 million years
Universe Expands
13.77 billion years
time

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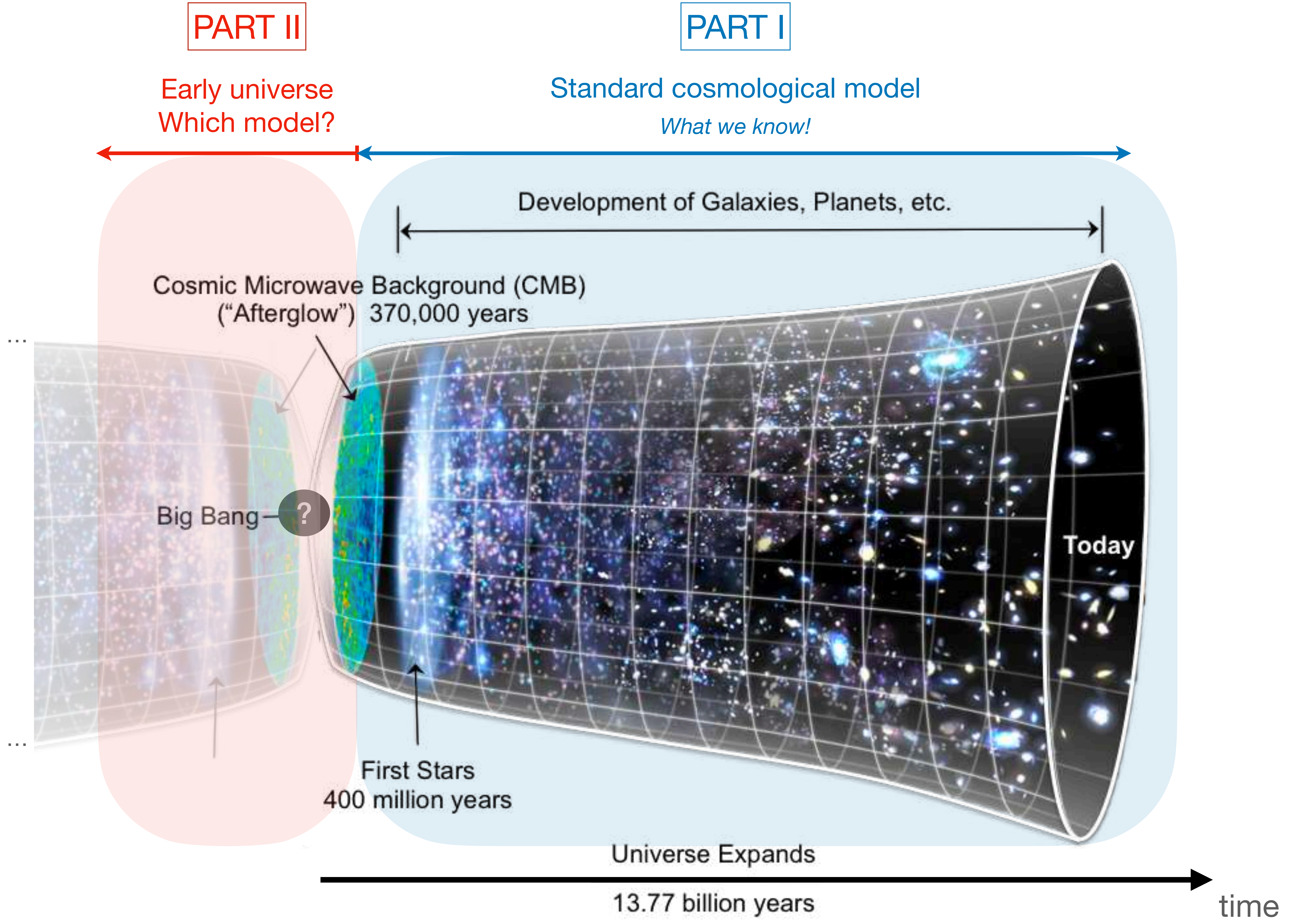

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PART I

The standard cosmological model

Cosmology

- Cosmology studies the evolution and composition of the universe

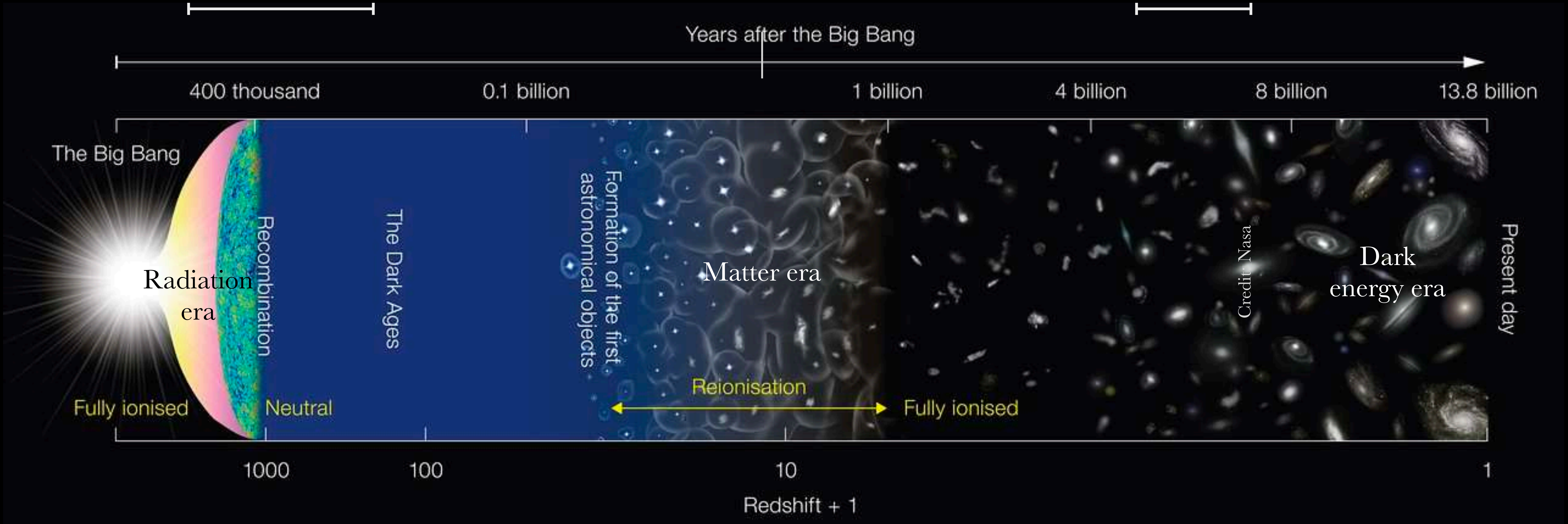
Cosmology

- Cosmology studies the evolution and composition of the universe
- Huge success! Cosmology became a precision science. (~30 years)
- ΛCDM: standard model, 6 parameters measured with precision ~1%

Early universe- IC

Dark matter- CDM
Structure formation

Dark energy - Λ
Accelerated expansion



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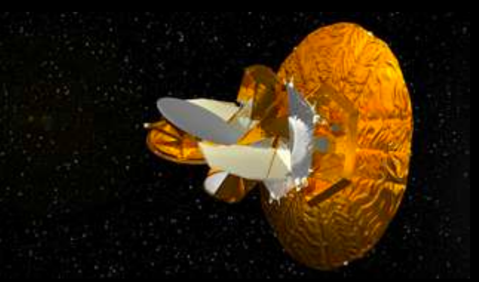
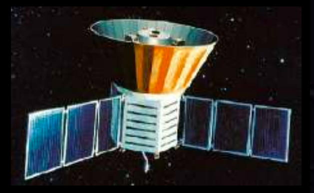
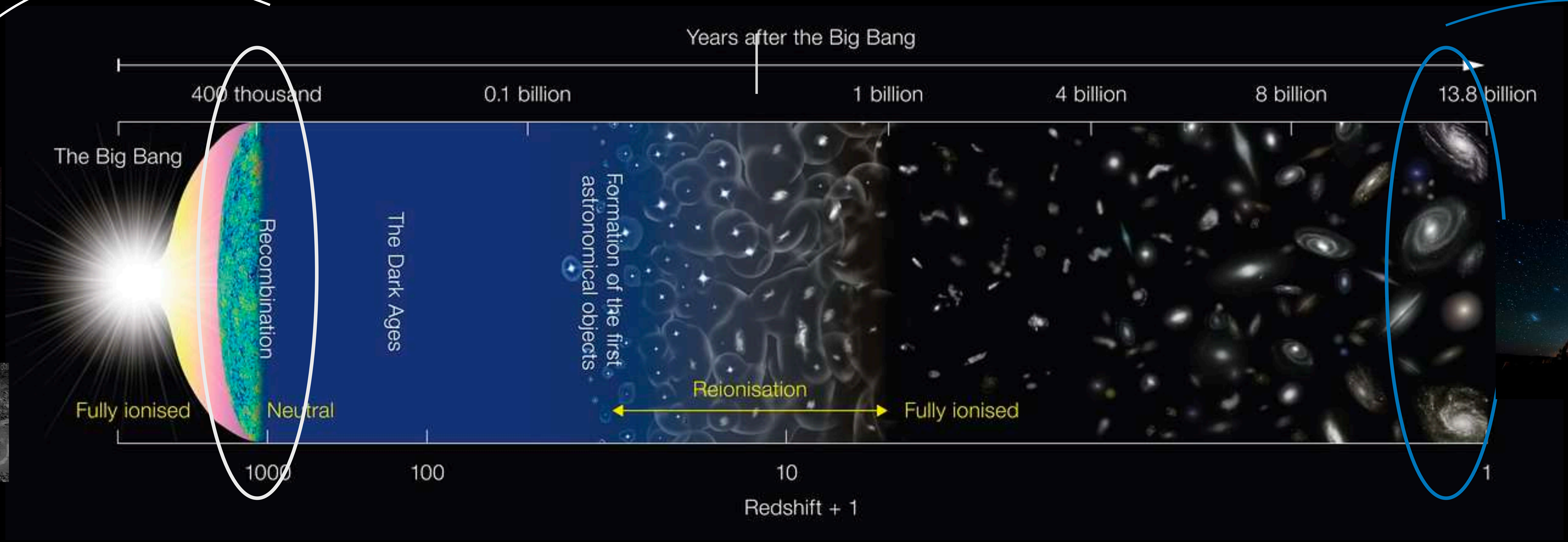





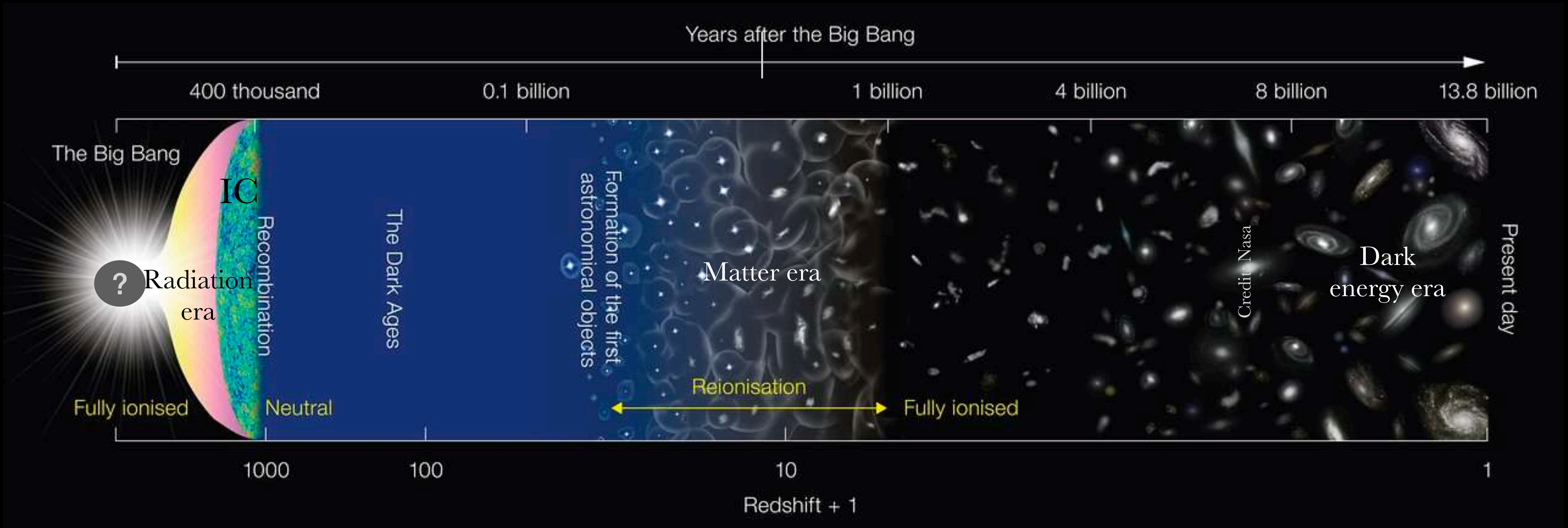
- Theoretical advances
- Observations with growing precision

MANY fundamental open questions

Early universe
Big Bang? What is the physics of the early universe?

Dark matter p
What is the dark matter?

Dark energy -
What is the dark energy?



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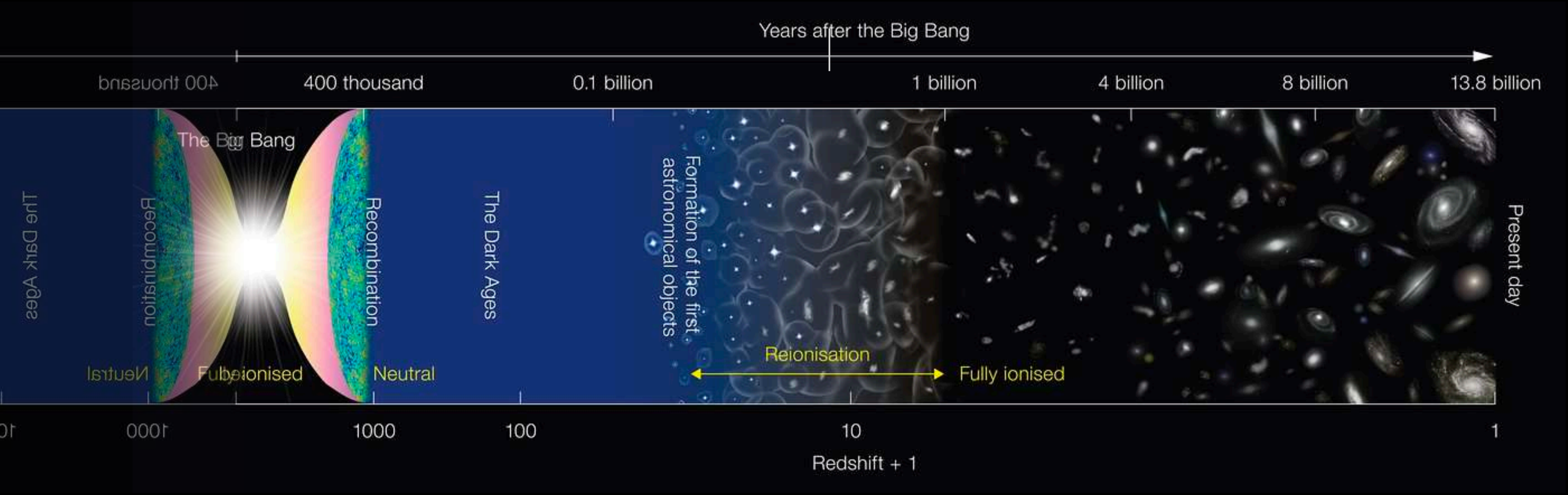

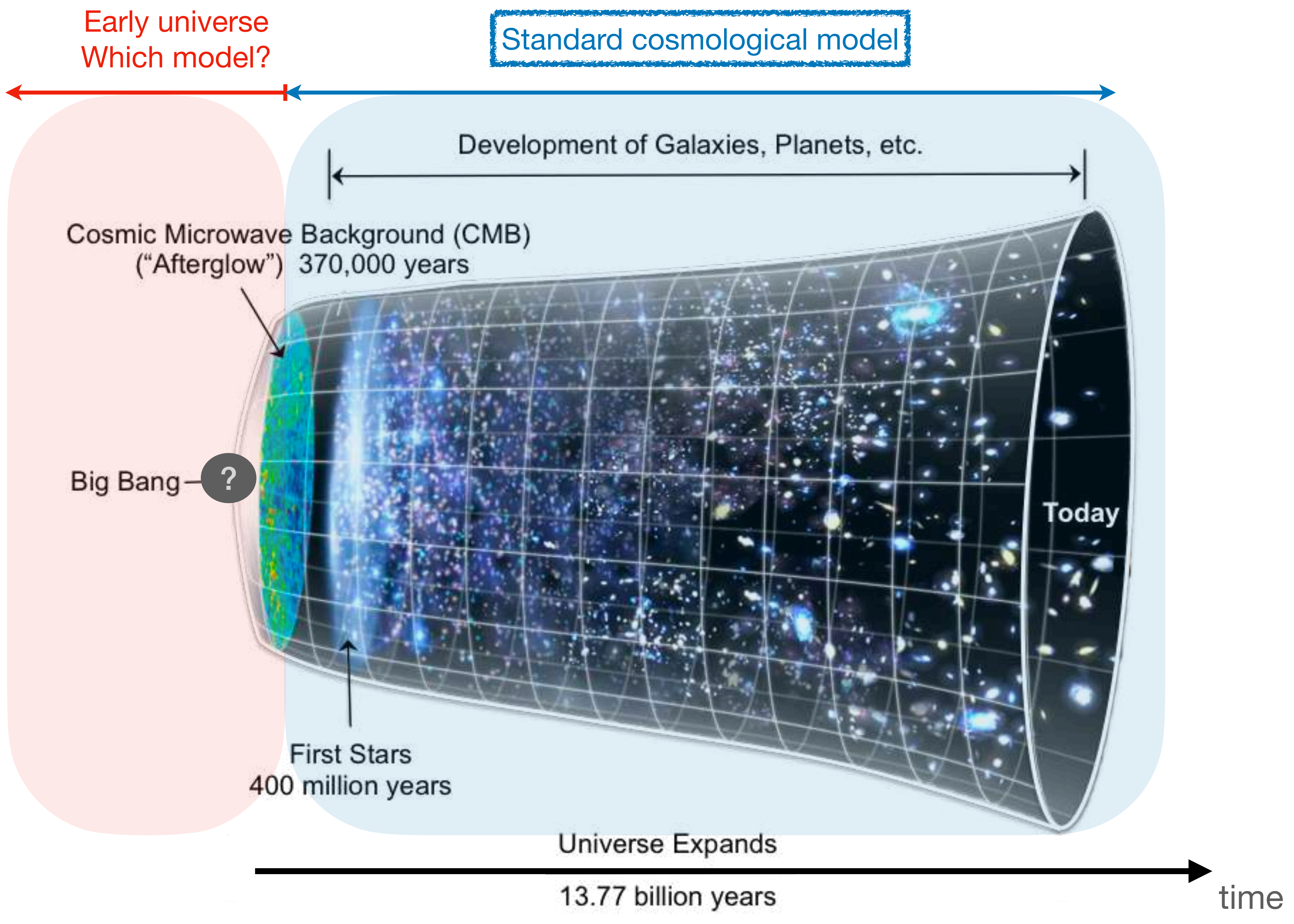
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Standard cosmological model

a.k.a. ΛCDM model

Parametrization: 6 parameters

The SCM describes the structure, evolution and composition of our universe. It also explains what we see and have in our universe today. It includes, then, the standard model of elementary particles, and explains the evolution and formation of the particles and structures we have today.

2 theoretical Pilars:

- GR
- Cosmological principle

3 observational pilars:

- Hubble - Lemaître Law
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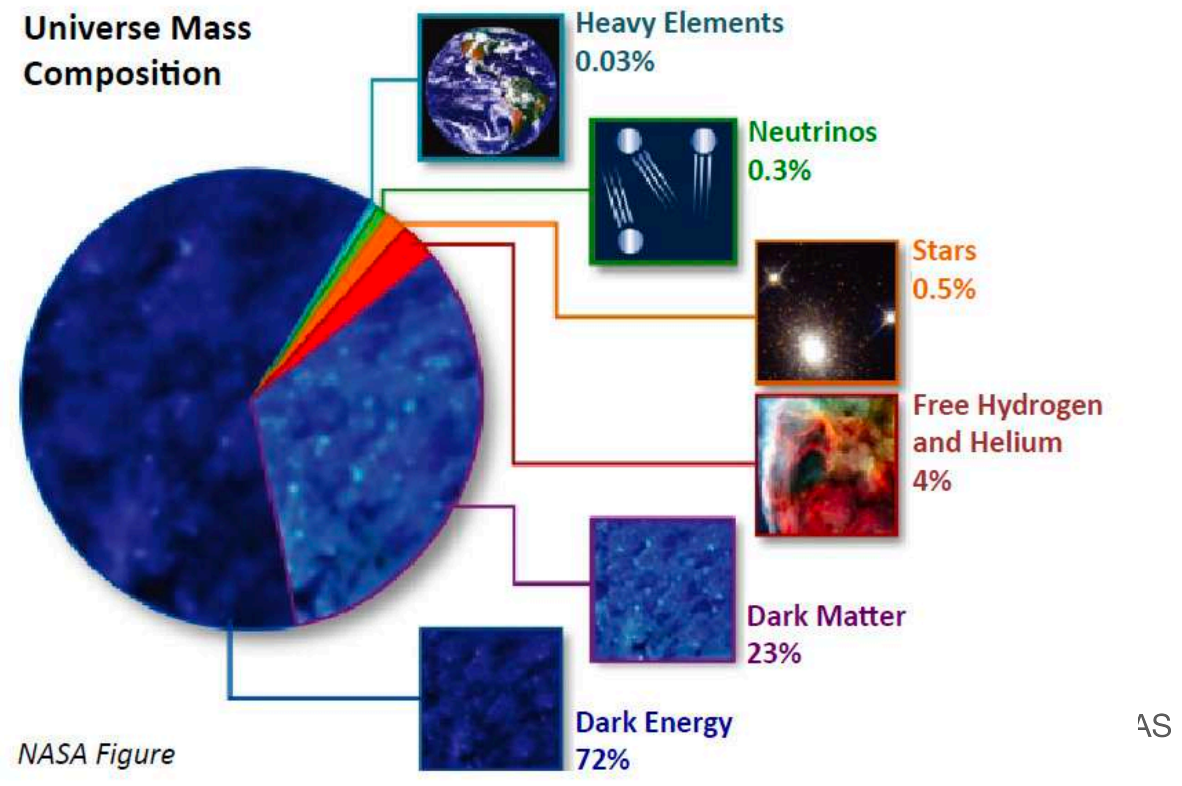

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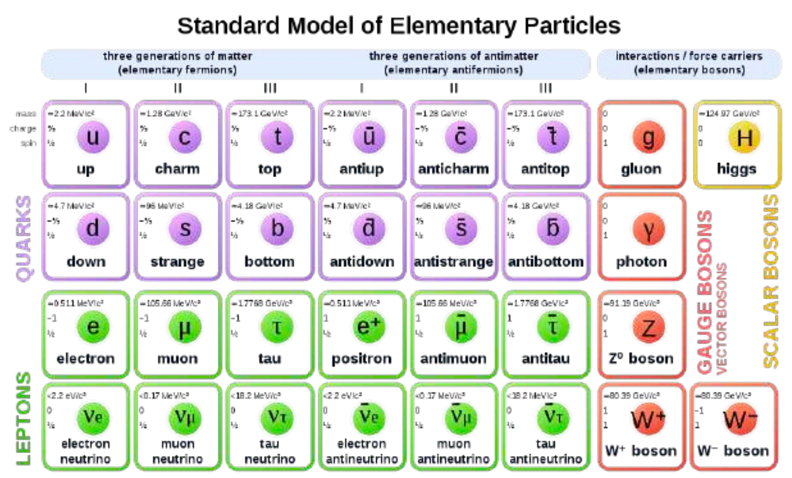
Standard model of elementary particles



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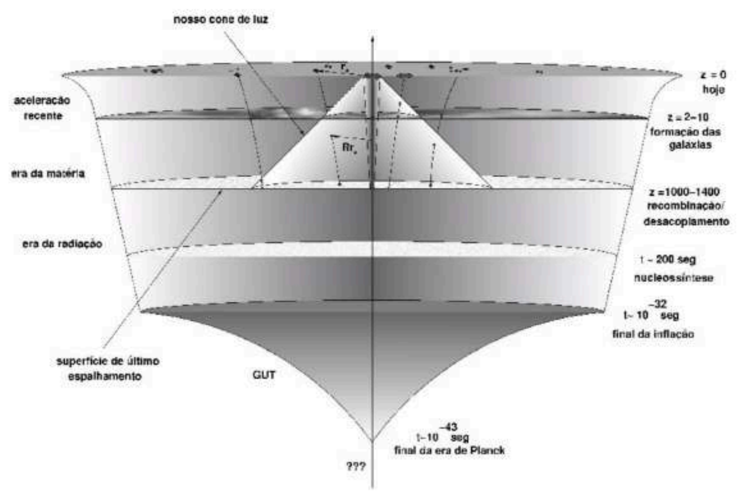
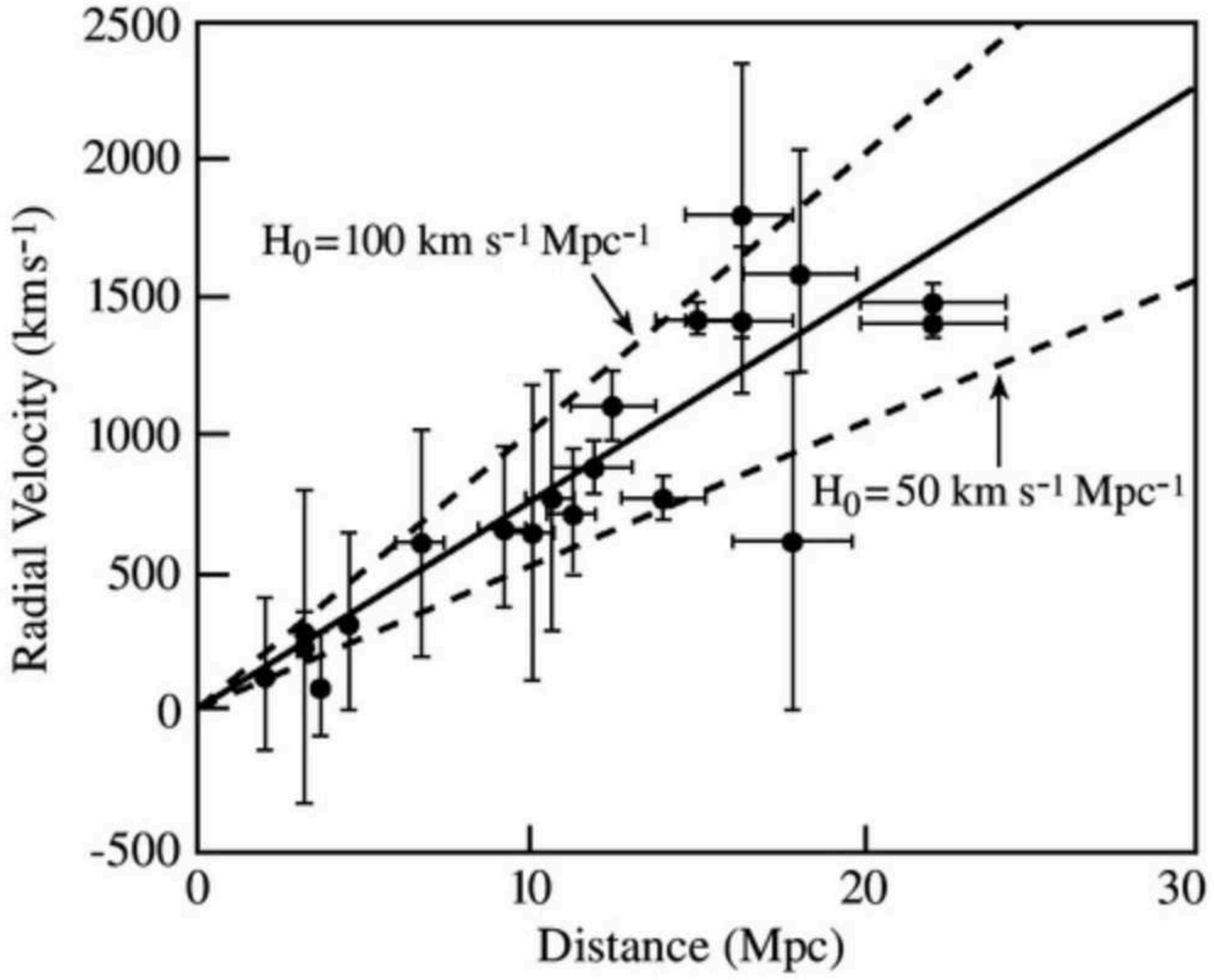
Thermal history



Expanding universe: Hubble-Lemaitre law

Hubble, in 1929, and Lemaître, in 1927, discovered the relation between the recession velocity of galaxies and their distances.

Kenneth R. Lang



$$v = H_0 R$$

Velocity: redshift

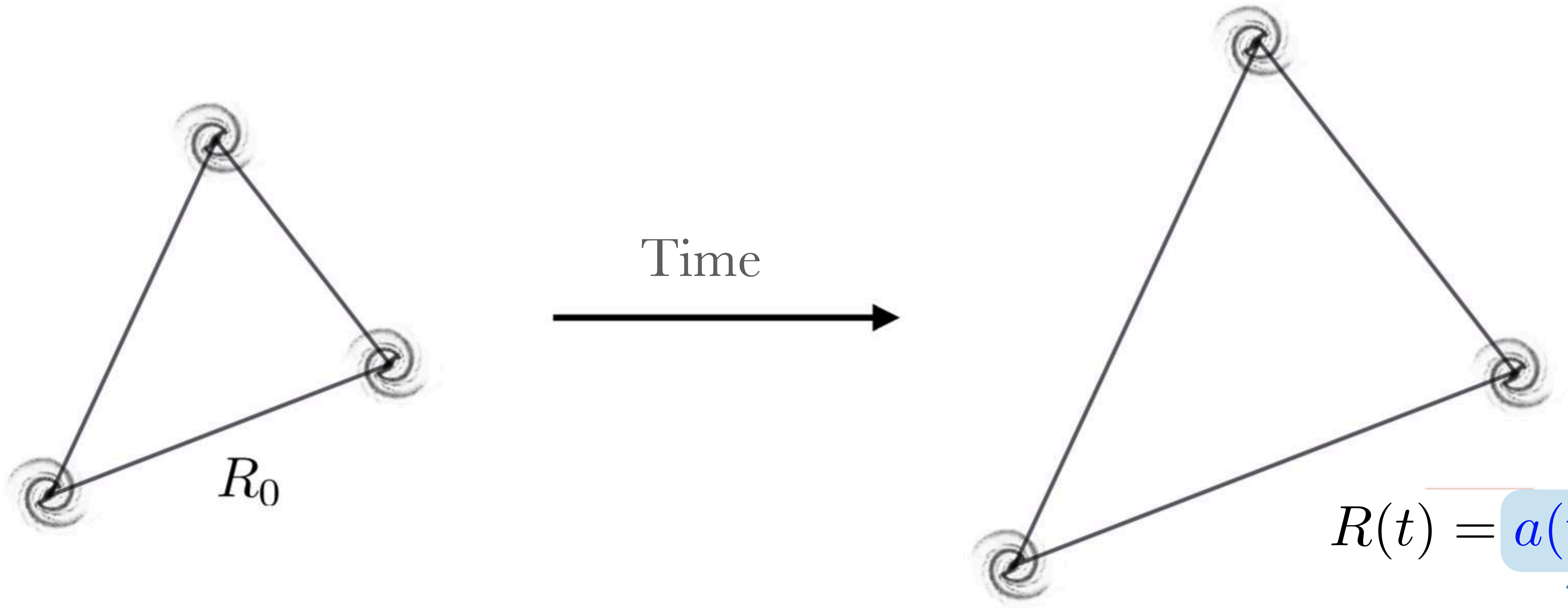
distance: luminosity

H_0 - current rate of expansion

Expanding universe: Hubble-Lemaitre law

In general relativity, we interpret this as the universe expanding. An expansion of the space between galaxies.

Crédito: D. Baumann



$$R(t) = a(t) R_0$$

Scale factor

$$v \equiv \dot{R} = \frac{\dot{a}}{a} \equiv H_0 R$$

Hubble parameter (constant): current expansion rate of the universe

Dynamics - Friedmann equations

We need to define the **evolution of the scale factor**.

That is determined by *content of the universe*

This description is made using **general relativity**

$$\underbrace{G_{\mu\nu}}_{\text{Geometry- How universe expands}} = 8\pi G \underbrace{T_{\mu\nu}}_{\text{Components}}$$

The dynamics and kinematics of our universe are determined by Einstein's general relativity, where its field equations, valid in all points of the universe, tell us how the content of the universe affects its dynamics.

Dynamics - Friedmann equations

Geometry-
How universe expands

Friedmann equations (or Friedmann - Lemaître)

Components

Rate of expansion ←

$$\left(\frac{\dot{a}}{a}\right)^2 = H^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2}$$

Second derivative of a(t) ←

$$\frac{\ddot{a}}{a} = \dot{H} + H^2 = -\frac{4\pi G}{3}(\rho + 3P)$$

Components described as a perfect fluid:

ρ Energy density

P Pressure

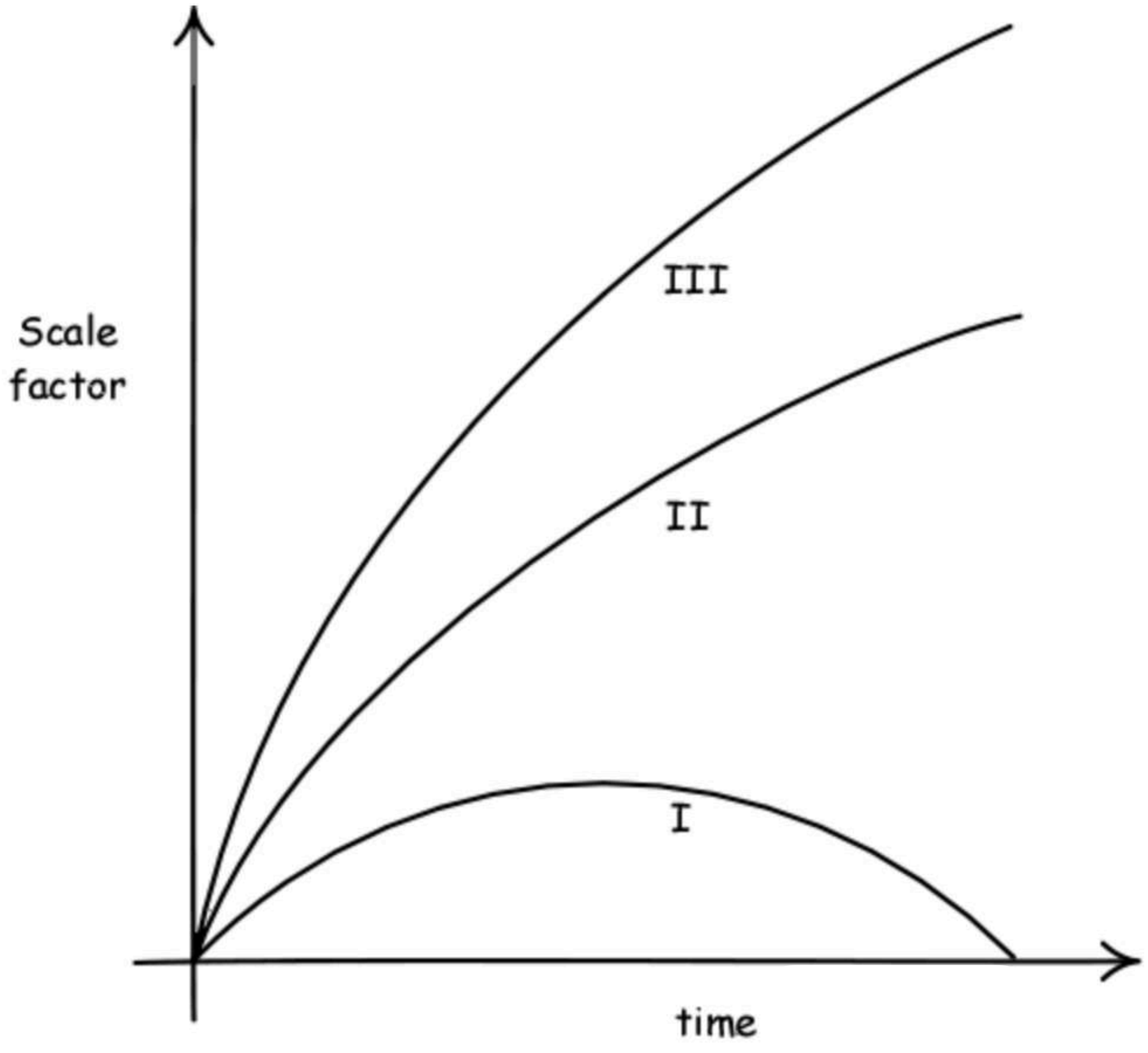
The components in the universe drives the dynamics and expansion of the universe!

Combining both equations:

$$\dot{\rho} + 3H(\rho + P) = 0$$

Continuity equation
(Conservation of the energy density)

Dynamics - Friedmann equations



Crédito: J. D. Horton

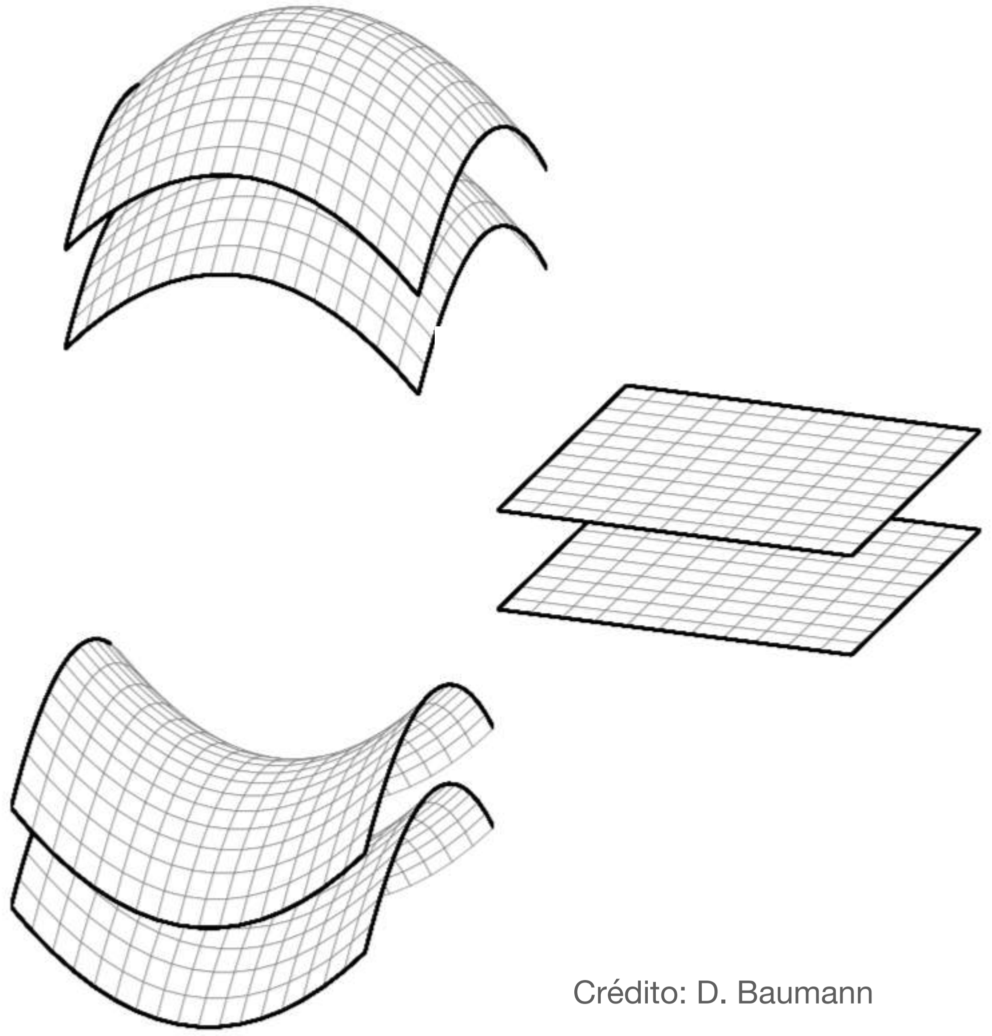
We can also rewrite the 1st Friedmann equation as:

$$1 = \Omega_{tot} - \frac{k}{a^2 H^2}$$

where

$$\Omega_{tot} = \sum_i \Omega_i \,, \qquad \text{and} \qquad \Omega_i = \frac{\rho_i}{\rho_{crit}}$$

I	$\Omega_{total} > 1 \Leftrightarrow k = +1\,,$	Closed universe
II	$\Omega_{total} = 1 \Leftrightarrow \quad k = 0\,,$	Flat universe
III	$\Omega_{total} < 1 \Leftrightarrow k = -1\,,$	Open universe



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Components of the universe

To describe a homogenous universe, we use perfect fluids, following the equation:

$$\dot{\rho} + 3H\left(\rho + P\right) = 0$$

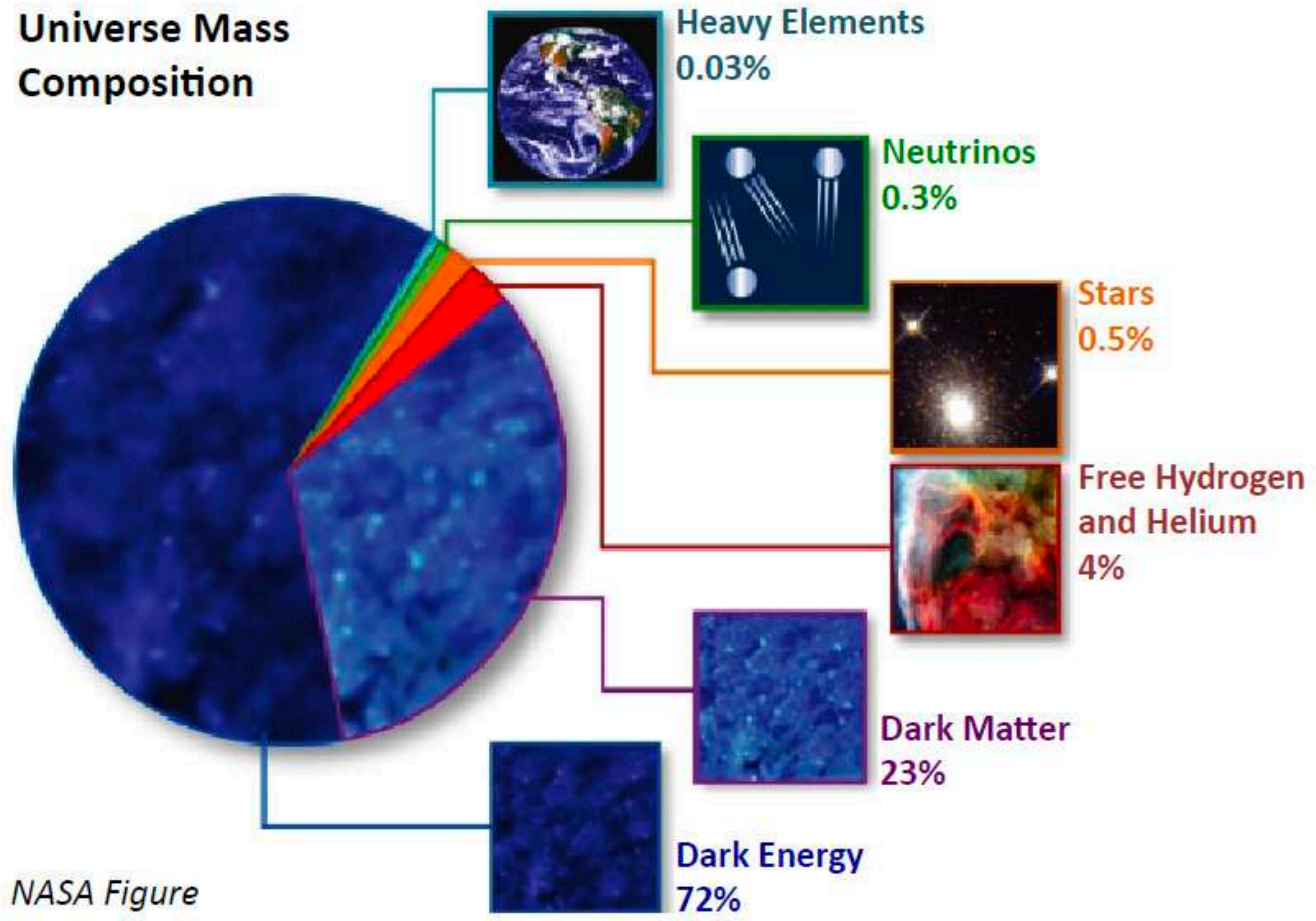
Cosmological fluids are described by a constant ***equation of state (EoS)***

$$\omega = \frac{P}{\rho}$$

Leading to:

$$\frac{\dot{\rho}}{\rho} = -3(1+w)\frac{\dot{a}}{a} \longrightarrow \boxed{\rho \propto a^{-3(1+w)}}$$

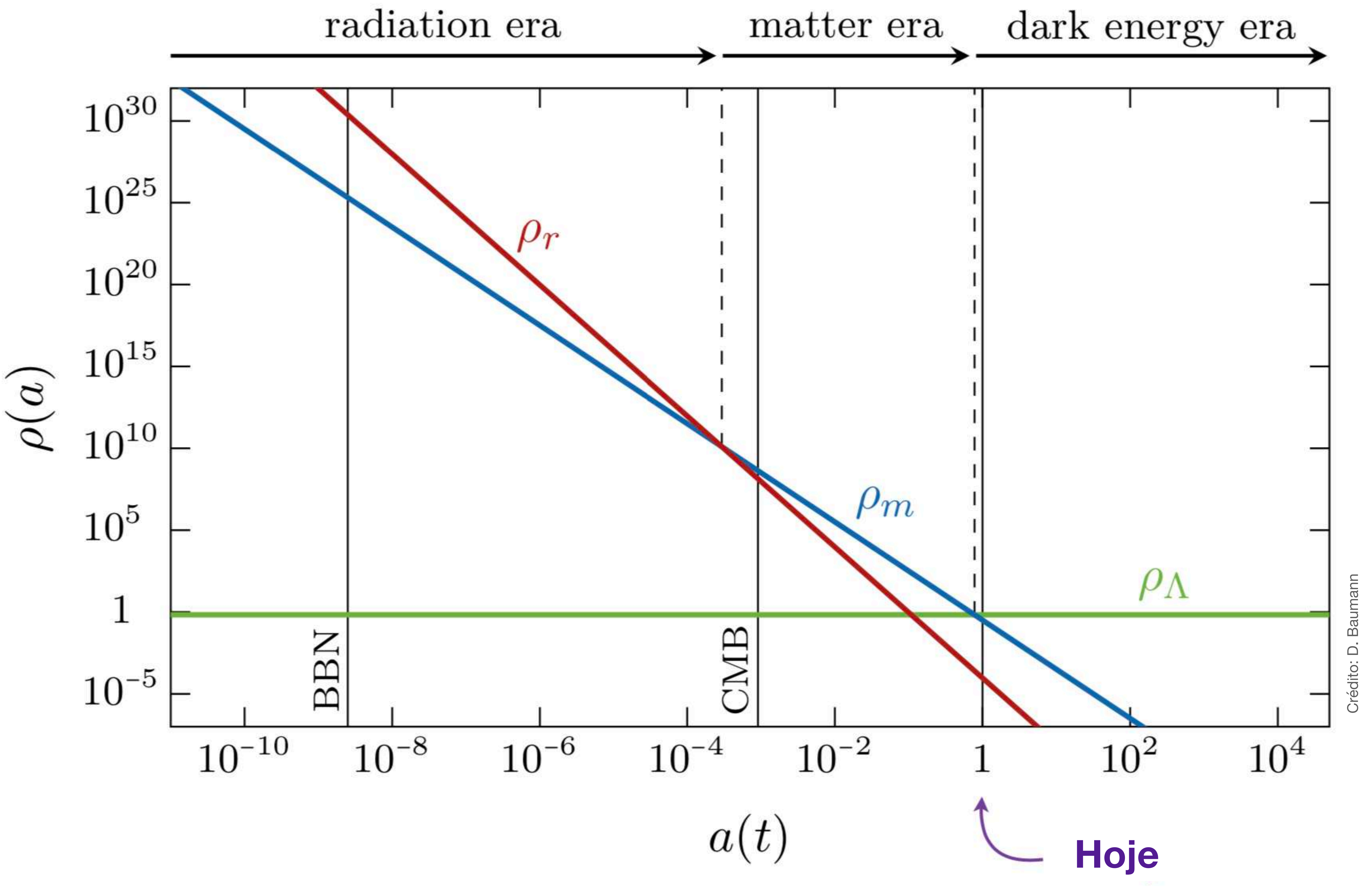
Components of the universe



Each component evolves and leads to a different expansion of the universe.

Lets study how each component evolves

Matter, radiation and dark energy



$$\dot{\rho} + 3H\left(\rho + P\right) = 0$$

Matter is a fluid with zero pressure ($\omega = 0$):

$$\left(\frac{\dot{a}}{a}\right)^2 \propto \rho \propto a^{-3}$$

Radiation is a relativistic fluid ($\omega = 1/3$):

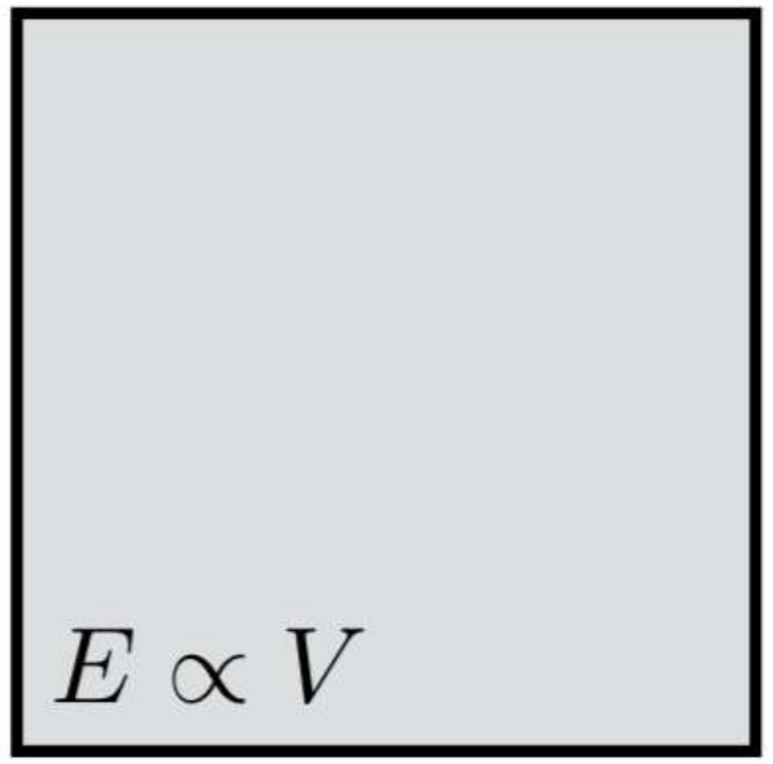
$$\left(\frac{\dot{a}}{a}\right)^2 \propto \rho \propto a^{-4}$$

Dark Energy: $\omega < -1/3$

$$\left(\frac{\dot{a}}{a}\right)^2 \propto \rho = \text{const}$$

Dark energy

Observational data indicates that the universe is expanding in an **accelerated** way $\ddot{a} > 0$



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Acceleration

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) > 0$$

Diceleration

$$\Rightarrow \quad w = \frac{p}{\rho} < -\frac{1}{3}$$

The component which is the source of this accelerated expansion we call dark energy

<u>Cosmological constant</u>

Cosmological const.

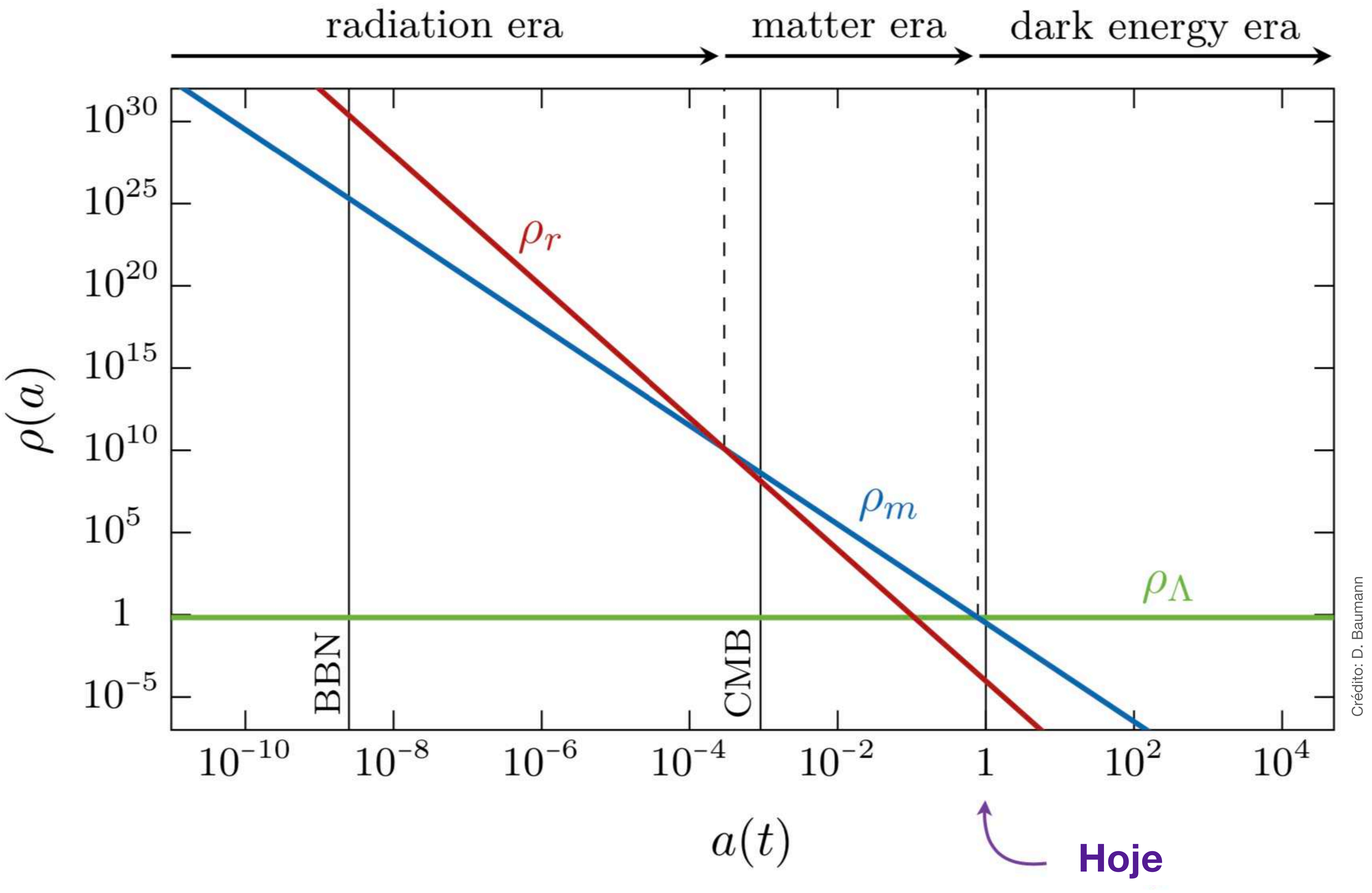
$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) + \frac{\Lambda}{3} \quad + \quad w = -1 \quad \Longrightarrow \quad \left(\frac{\dot{a}}{a}\right)^2 \propto \rho = \text{const}$$

accelerates expansion

$$\downarrow$$

$$a \propto e^{H_0 t}$$

Matter, radiation and dark energy



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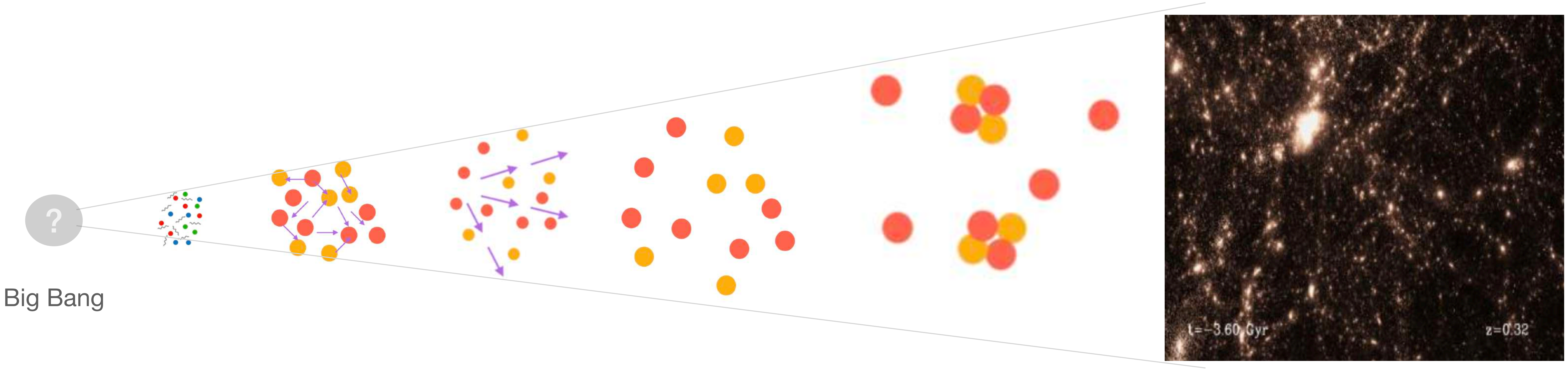
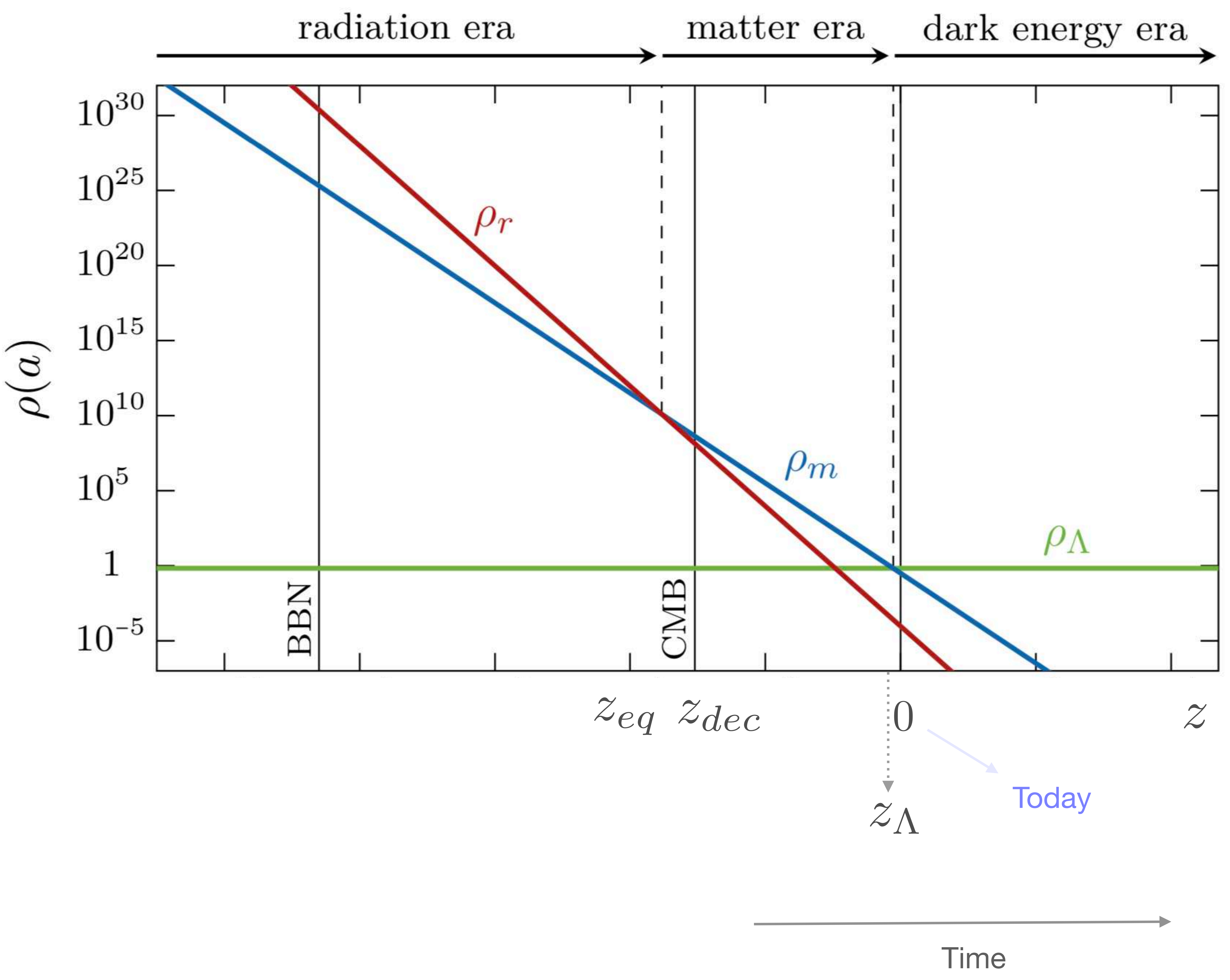
Standard cosmological model - Hot Big Bang model



If the universe is expanding, this means that before its energy was contained in a small, hot and **dense** region.

Standard cosmological model

$$\begin{cases} \Omega_m = \Omega_m^0 (1+z)^3, & \text{matéria,} \\ \Omega_{rad} = \Omega_{rad}^0 (1+z)^4, & \text{radiação,} \\ \Omega_\Lambda = \Omega_\Lambda^0 (1+z)^{3(1+\omega)}, & \text{energia escura,} \end{cases}$$



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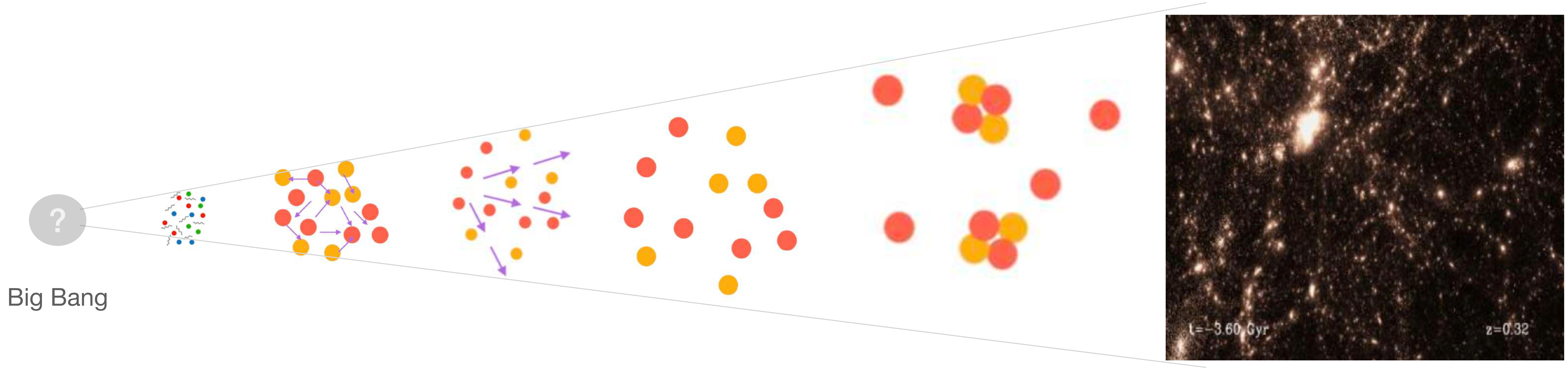

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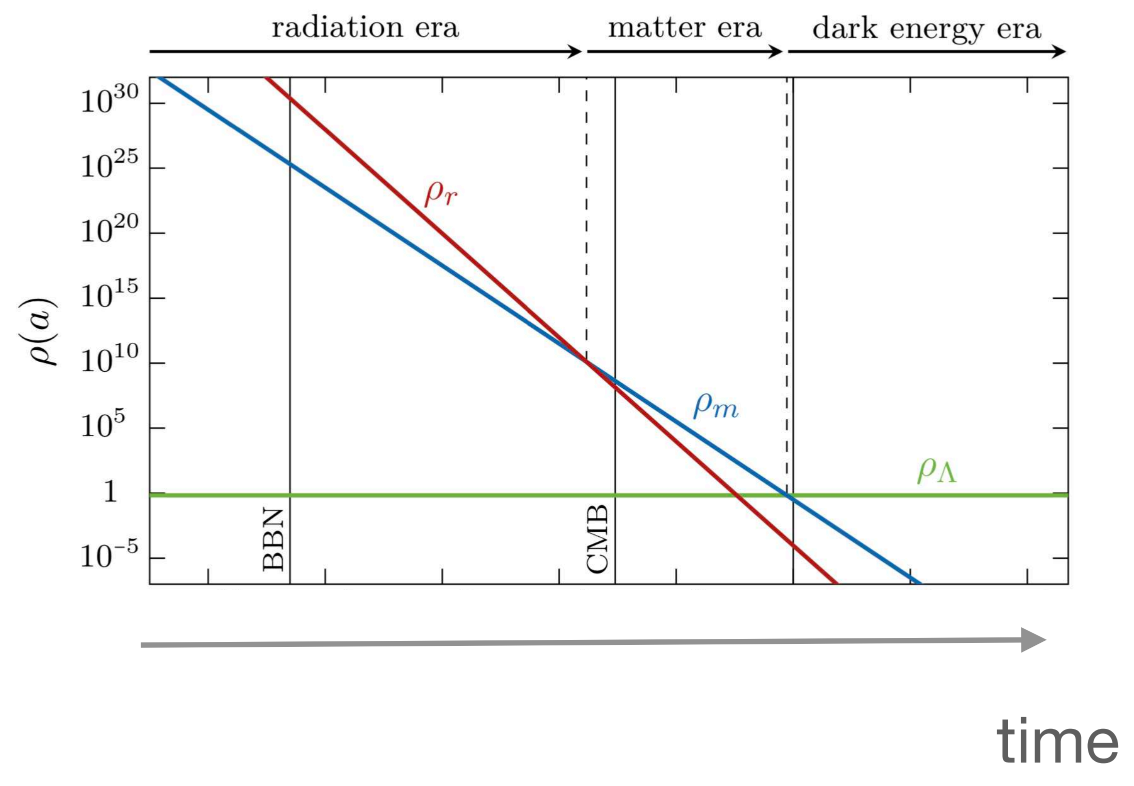
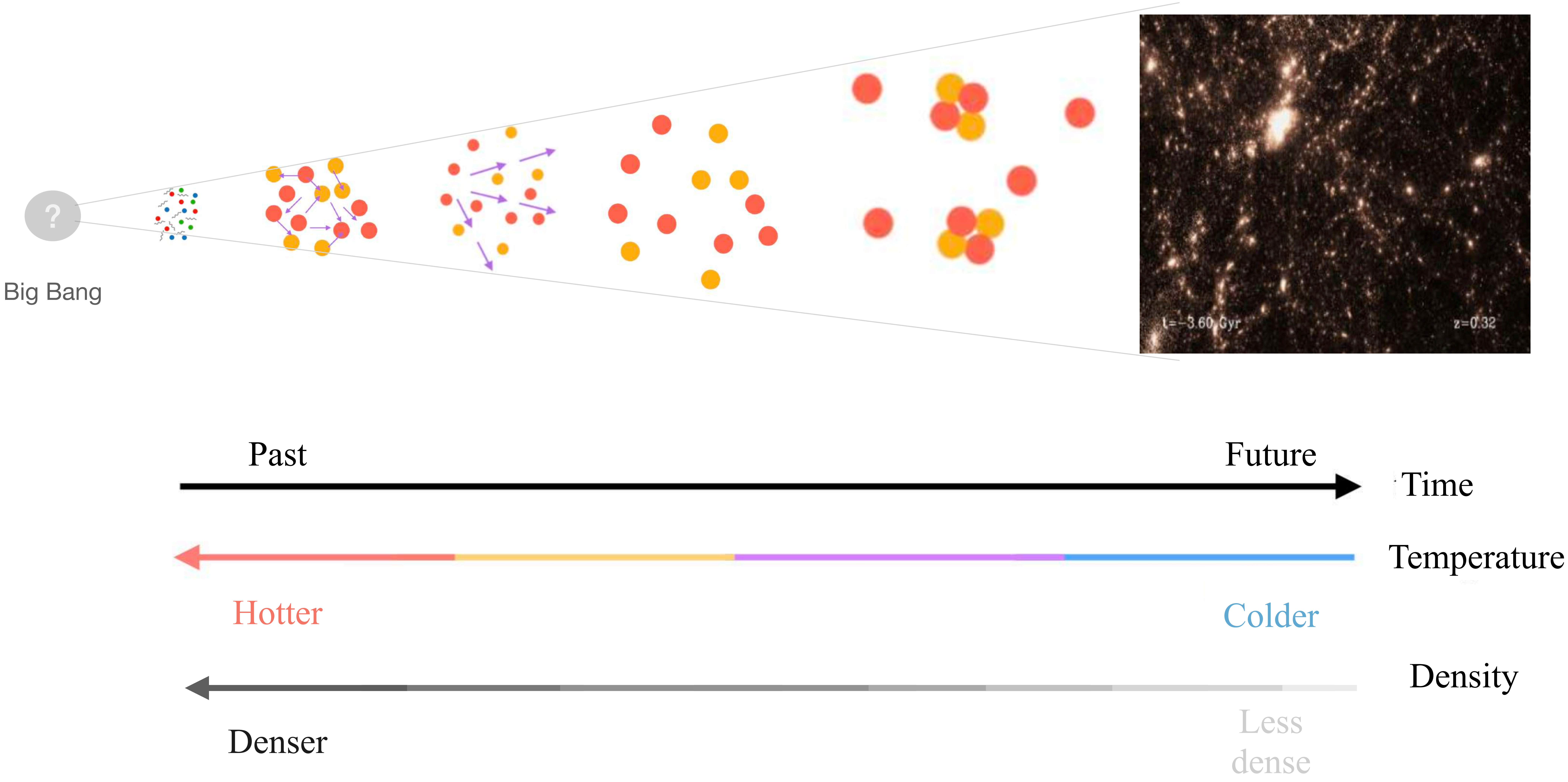


$$\rho_{rad}(T) = \sum_{i=1}^{n} \alpha_i g_i \left(\frac{\pi^2}{30}\right) T^4 \longrightarrow \boxed{T_{rad}(z) = T^0_{rad}(1+z)}$$

$$\downarrow t \quad \uparrow z \quad \uparrow T$$

Standard cosmological model - Hot Big Bang model



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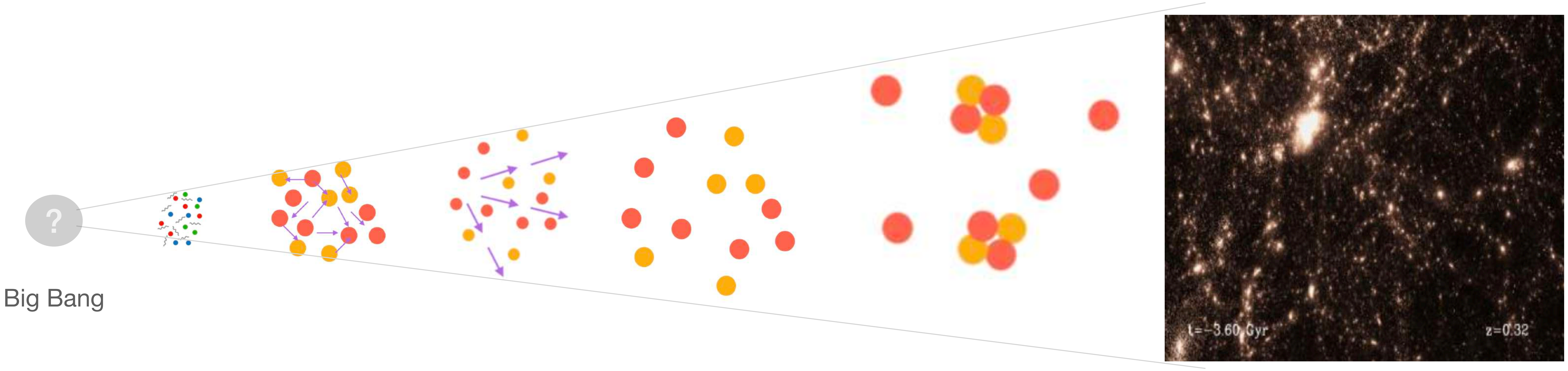
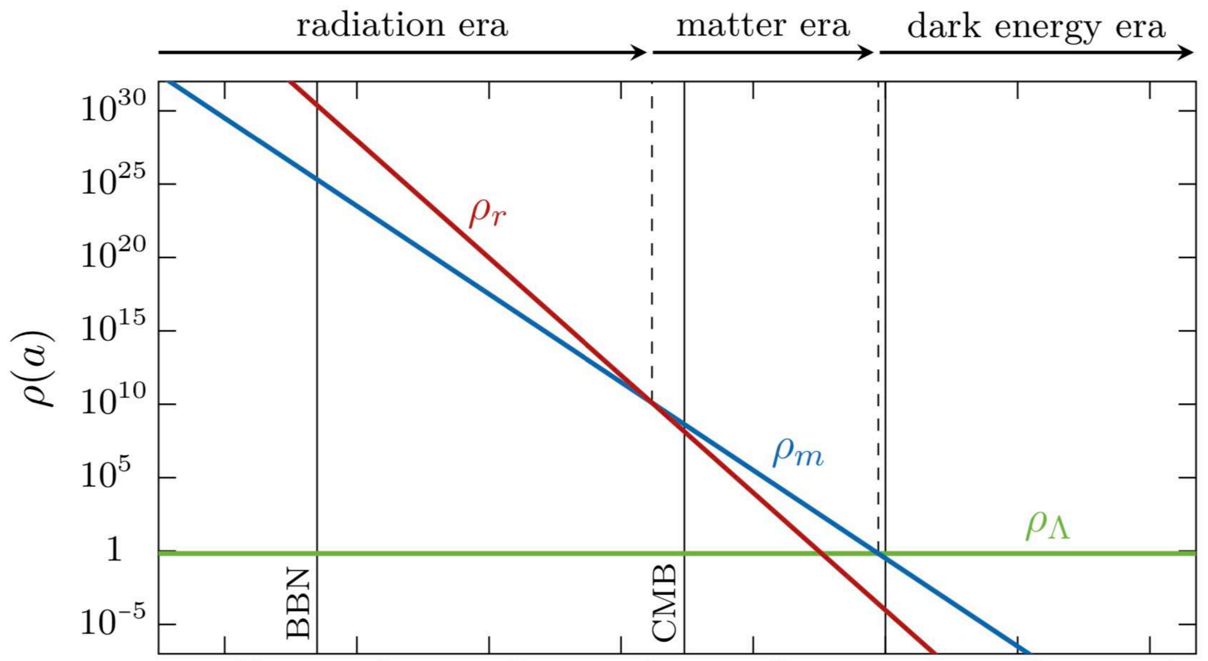


Universe started hot and dense (Big Bang) and is expanding and cooling

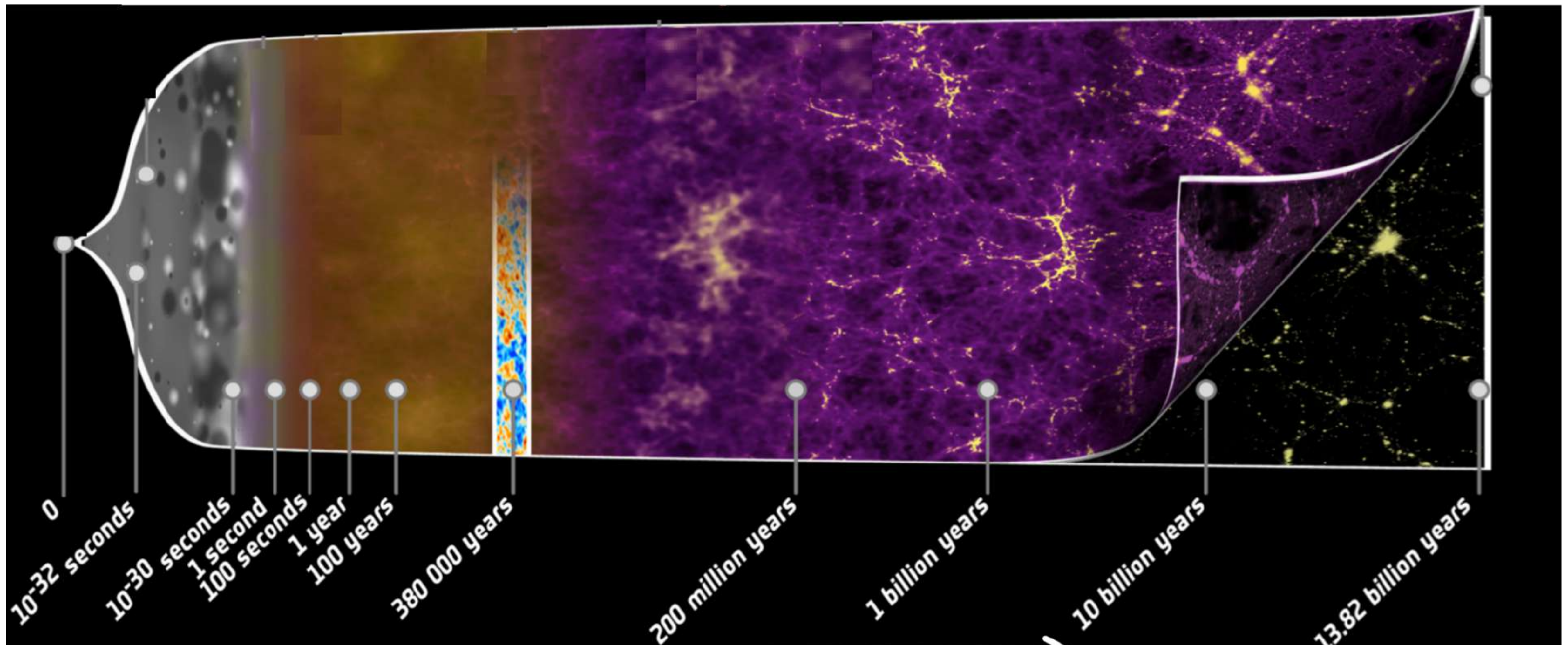


Explains the evolution from ***small*** perturbations to the large macroscopic objects we see today (galaxies, stars, …)

Explains all the ordinary matter in the universe (SM) + extra components

ΛCDM: parametrizes all these components with only 6 parameters!

Thermal history of the universe



Credit: Nasa

Past — Future — Time

Temperature

Hotter — Colder

Density

Denser — Less dense

Size

Small — Large

Standard cosmological model

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a.k.a. ΛCDM model

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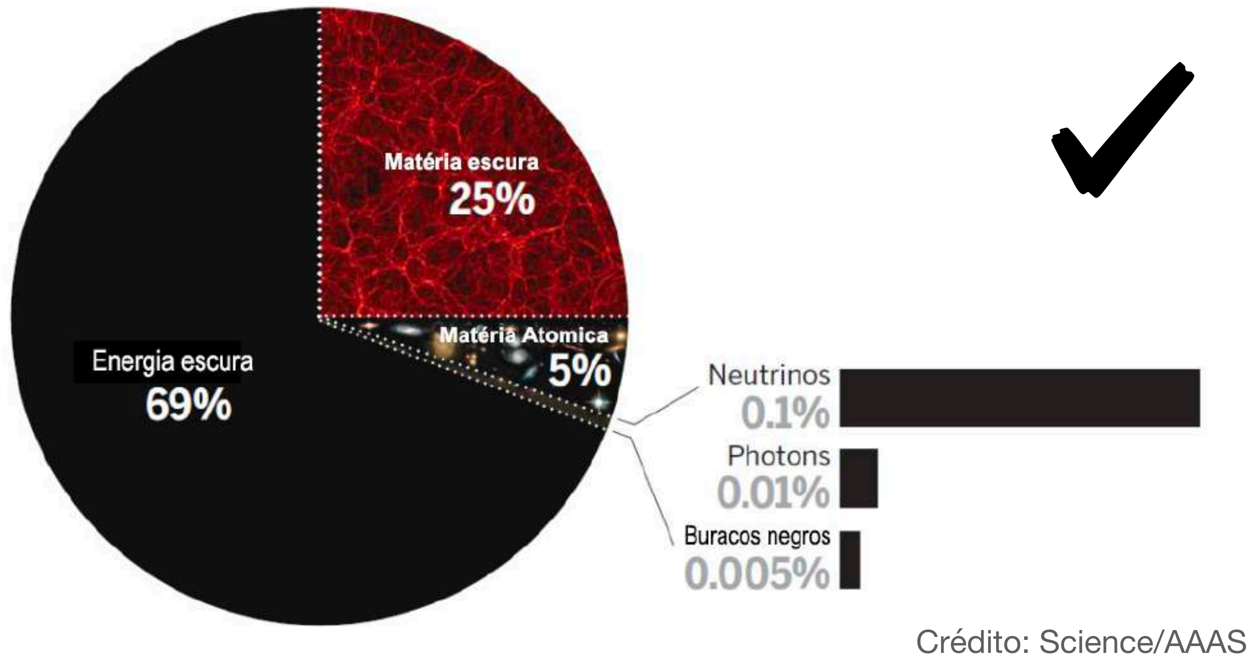

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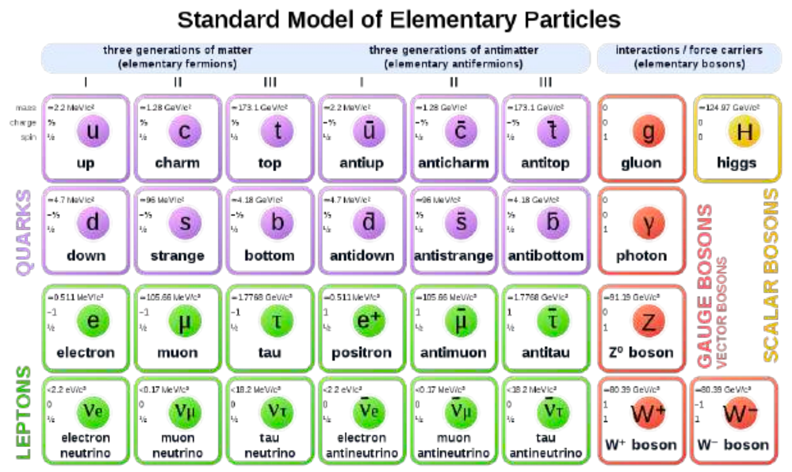
Standard model of elementary particles



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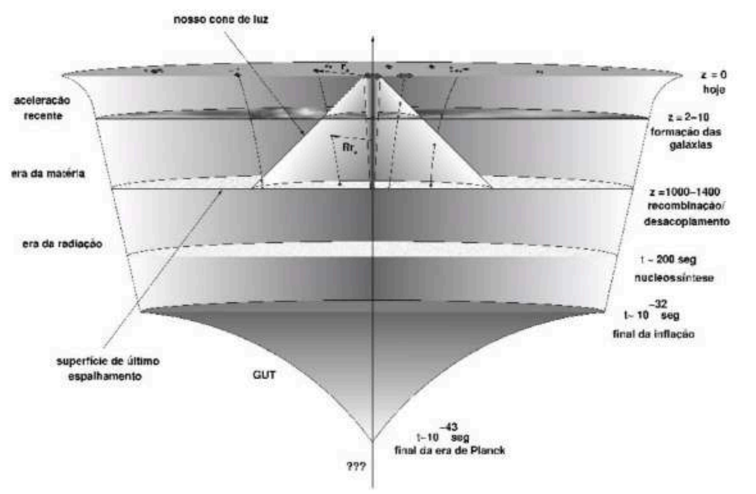
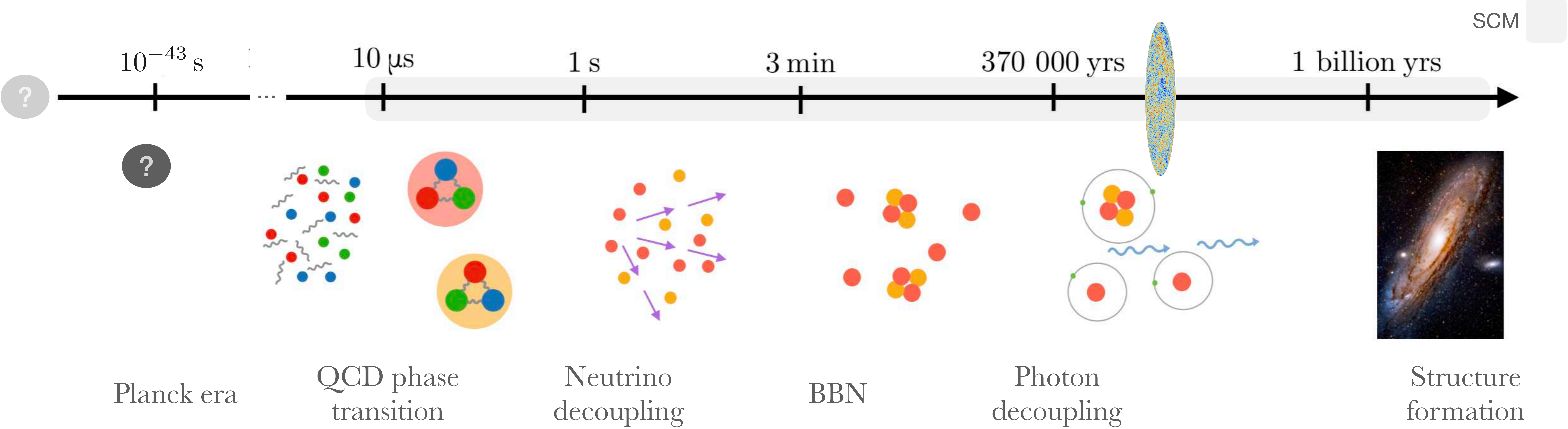
Thermal history



Thermal history of the universe

The universe“started" hot e **dense** → as it cools, the structures we know start to form



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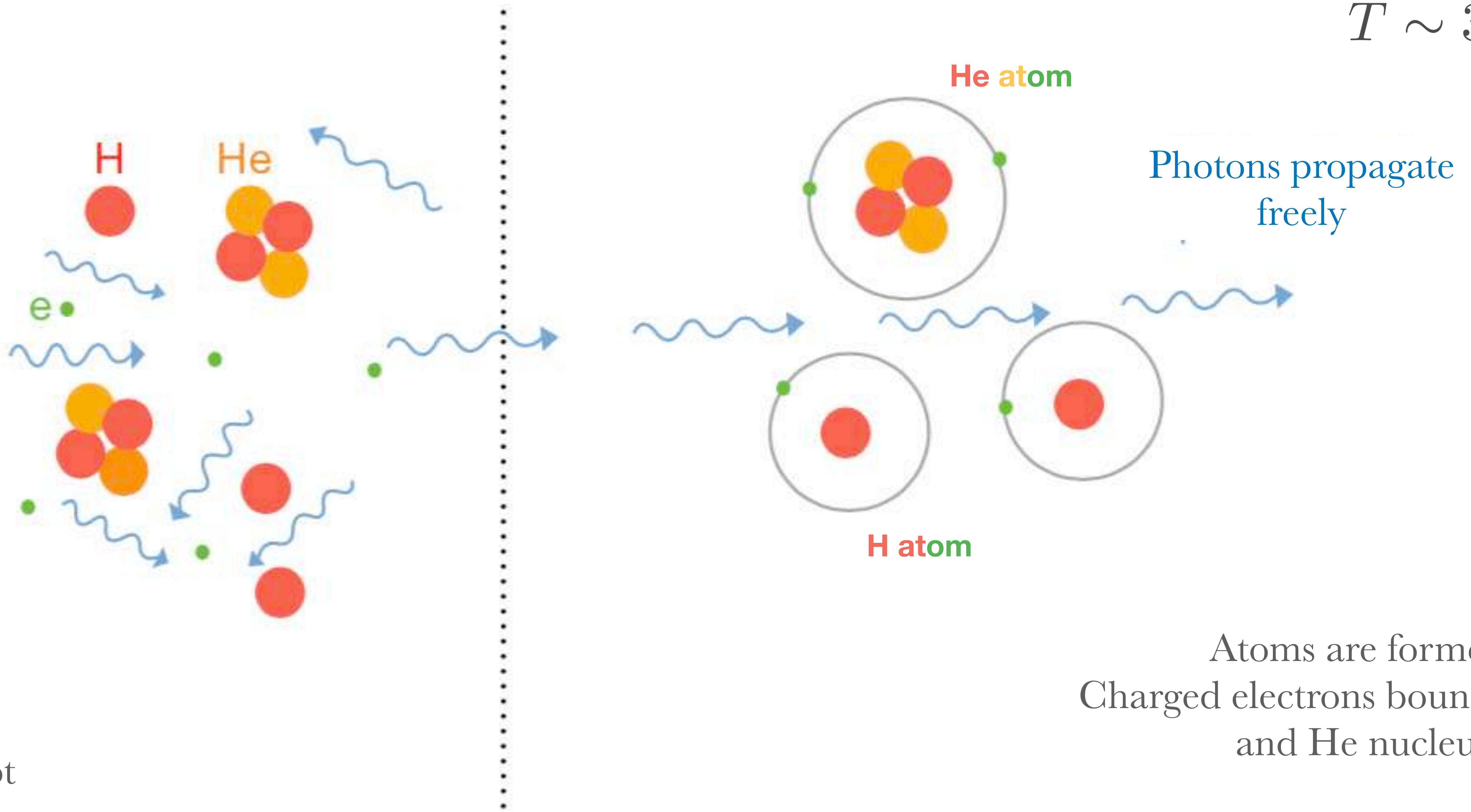
Recombination and photon decoupling

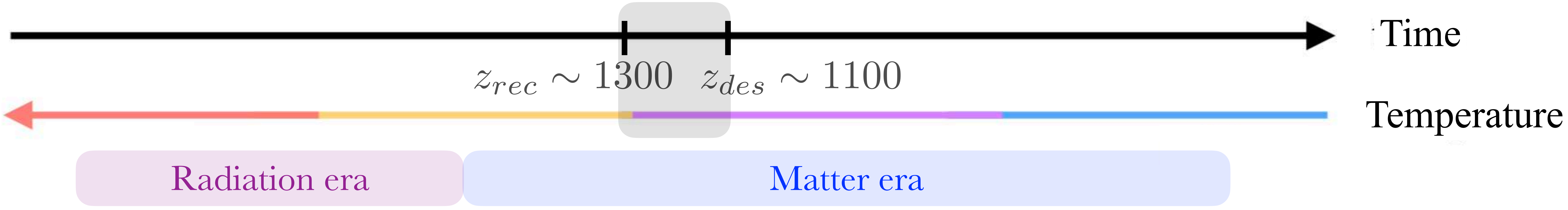
$t \sim 370000\,\text{yrs}$

$T \sim 3000\,\text{K}$



Plasma ("soup") of coupled H, He, elétrons and radiation - thermal equilibrium
- universe is opaque: radiation cannot scape!

Atoms are formed!
Charged electrons bound with n H and He nucleus



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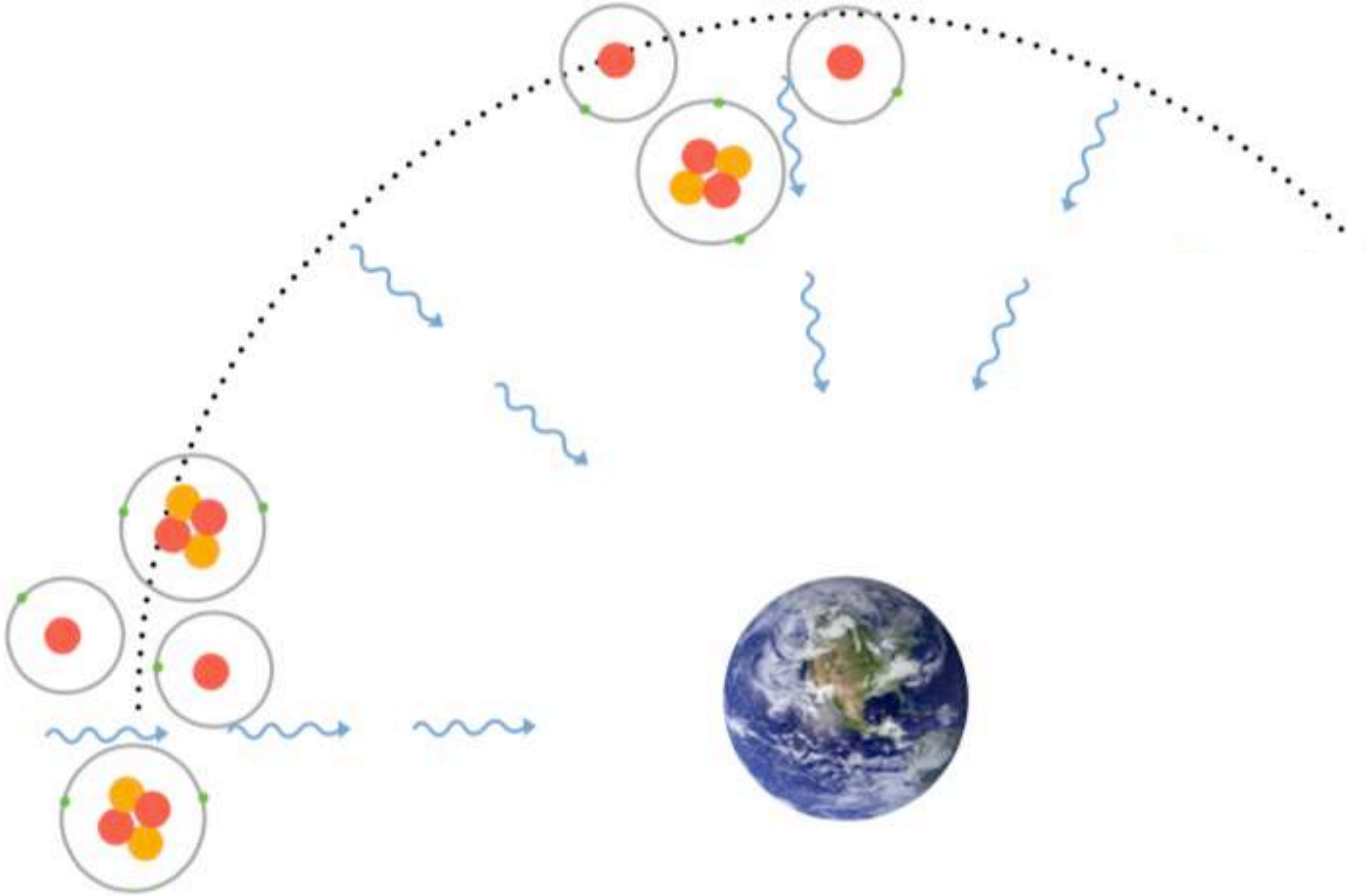
These photons are the first light of our universe…



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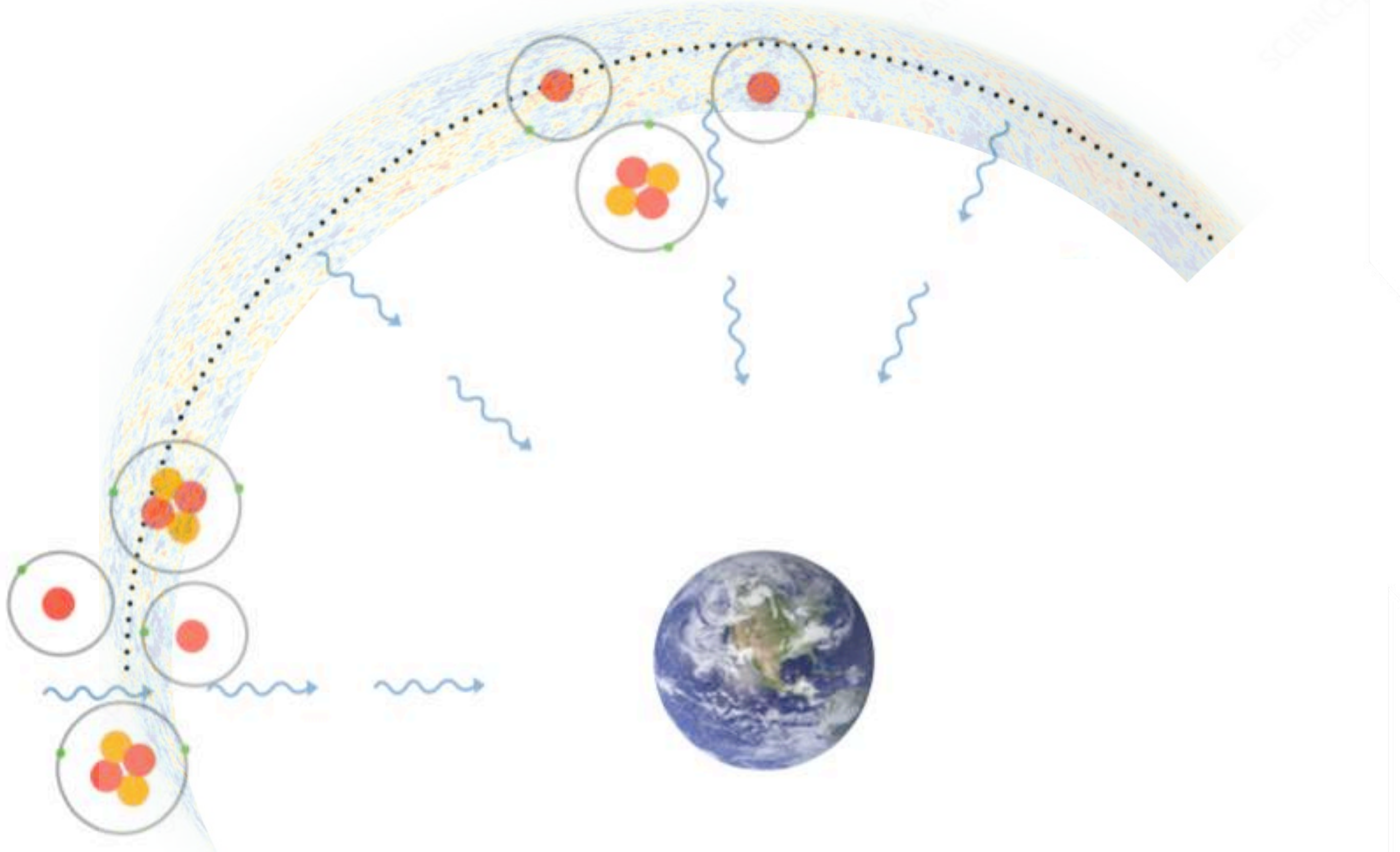
… e tell us how the universe was at early times.

Cosmic **M**icrowave **B**ackground *(CMB)*



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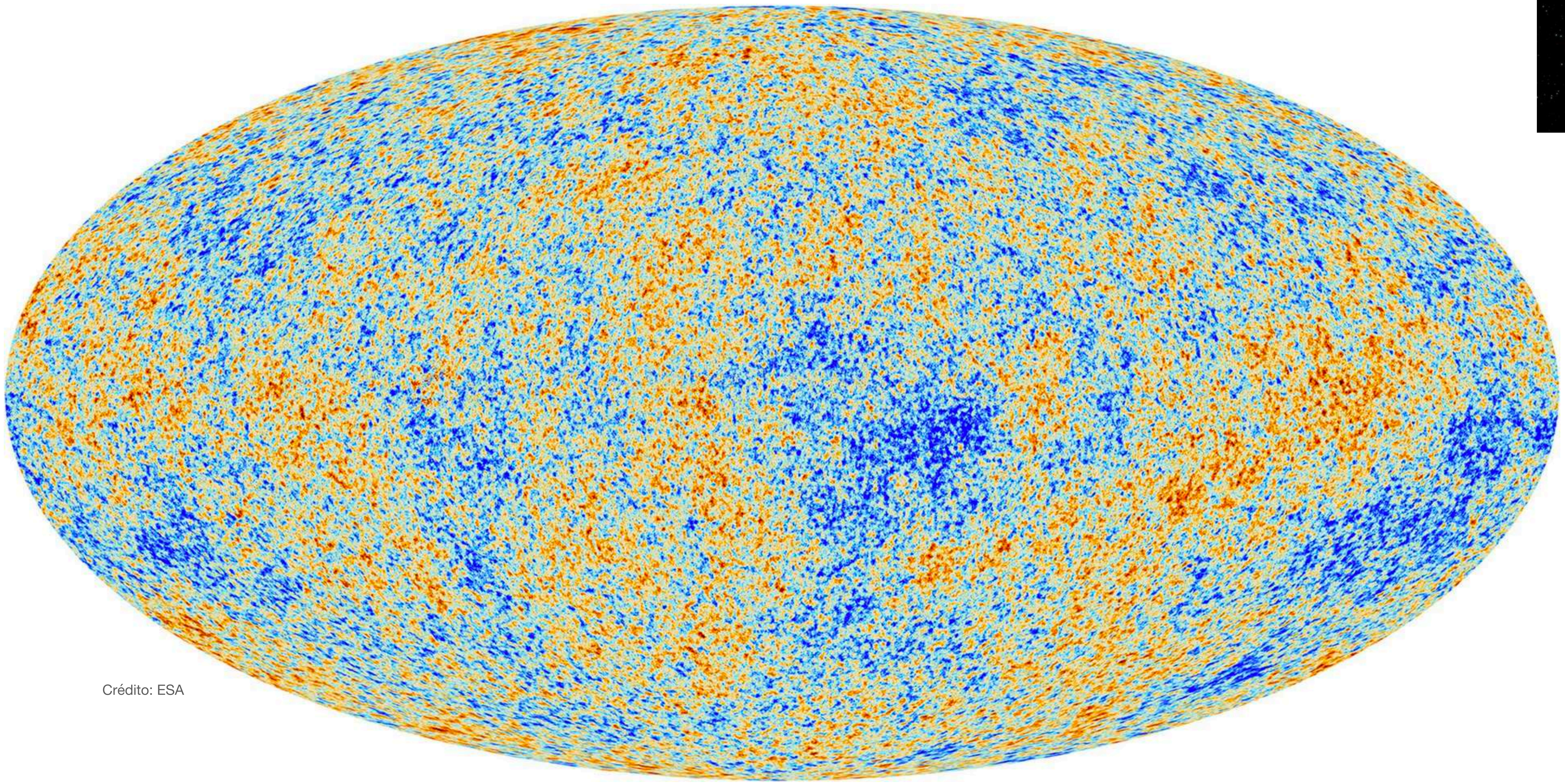
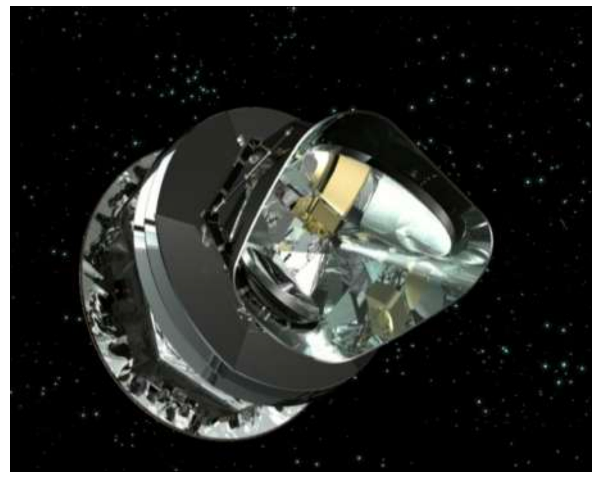
Given the expansion of the universe, we observe these photons in microwave.

Cosmic **M**icrowave **B**ackground *(CMB)*





Planck satellite

SCM pillar!

Temperature 2.7 K. Small fluctuations - initial condition for the structures of our universe

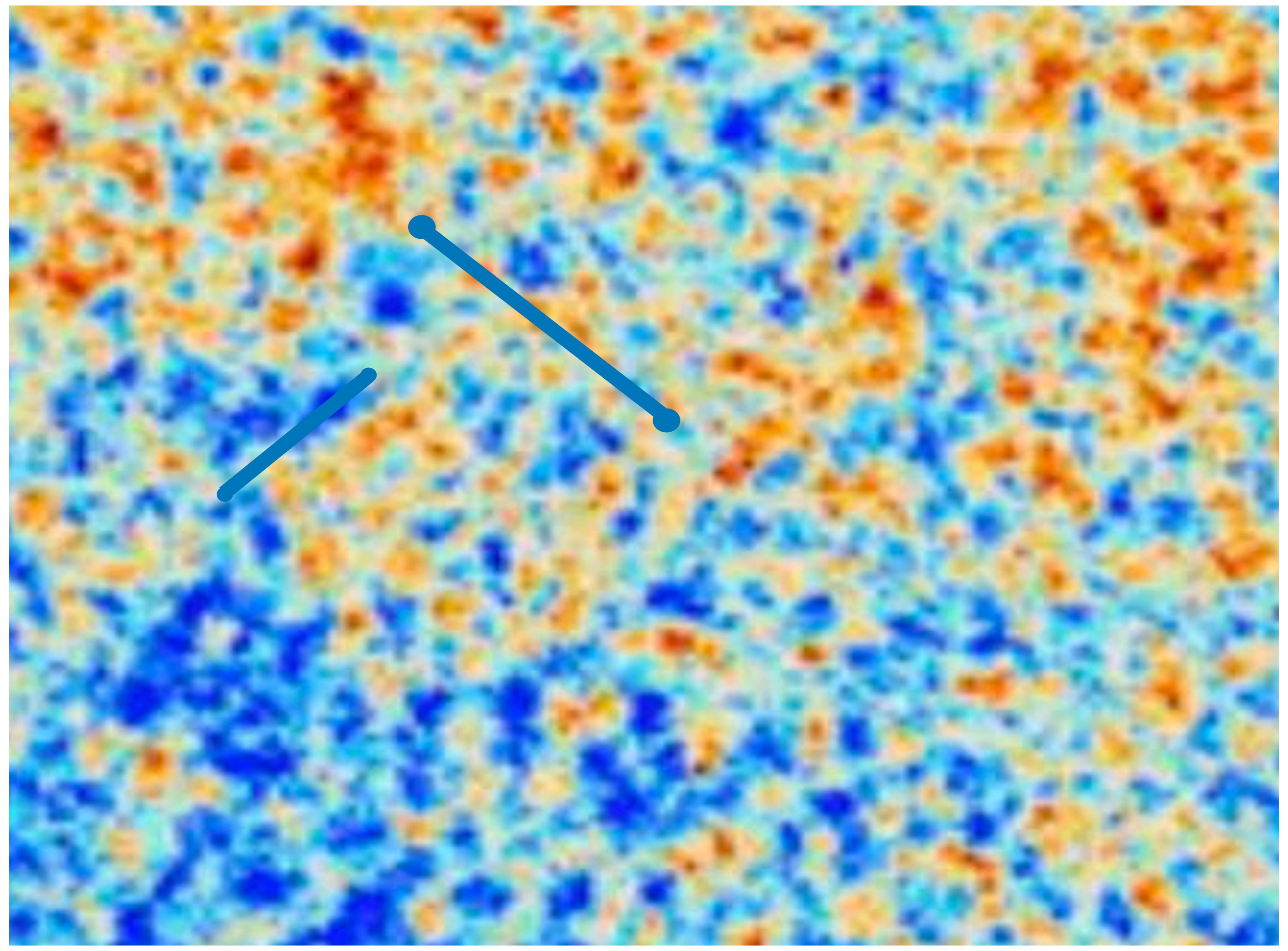
Cosmological parameters

Standard cosmological model - LCDM model

$$\{\Omega_b,\ \Omega_m\ ,\Omega_\Lambda\ ,n_s\ ,A_s\ ,\tau\}$$

Using CMB and other LSS probes, can constraint the parameters with incredible precision.

Planck 2018



$\Omega_b = 0.0484 \pm 0.0003 \longrightarrow$ Amount of visible/ordinary matter

$\Omega_m = 0.308 \pm 0.012 \longrightarrow$ Amount of dark matter

$\Omega_\Lambda = 0.692 \pm 0.012 \longrightarrow$ Amount of dark energy

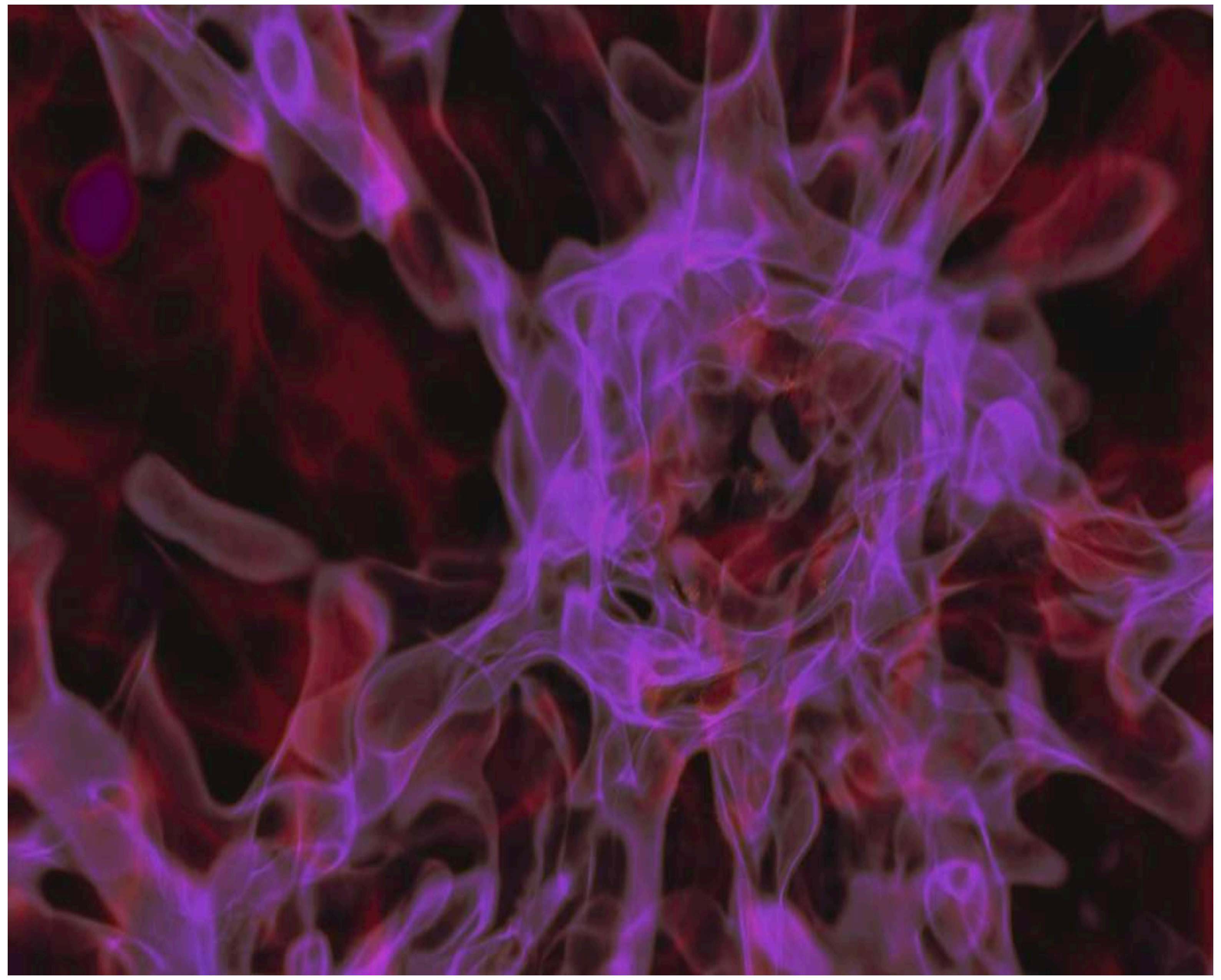
$\mathrm{n}_s = 0.9626 \pm 0.0057 \longrightarrow$ Scale dependence of the initial fluctuations

$10^9\, A_s = 2.092 \pm 0.034 \longrightarrow$ Amplitude of the initial fluctuations

$\tau = 0.0522 \pm 0.0080 \longrightarrow$ Optical depth

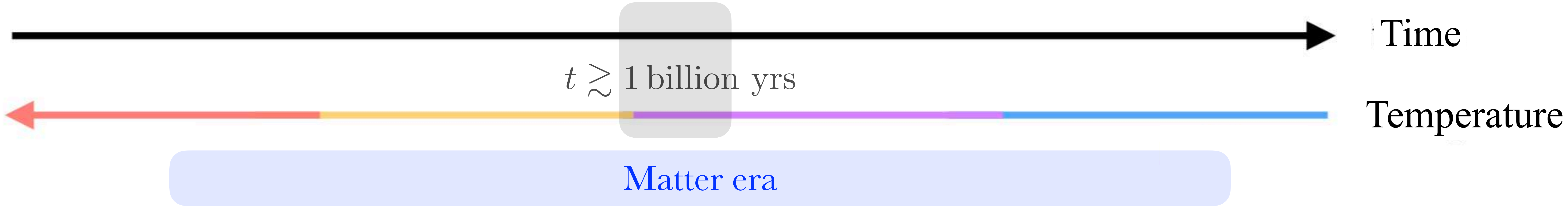
Formation of stars and galaxies

$t \gtrsim 1$ billion yrs



Credit: AARON SMITH/TACC/UT-AUSTIN

Credit: NASA and ESA



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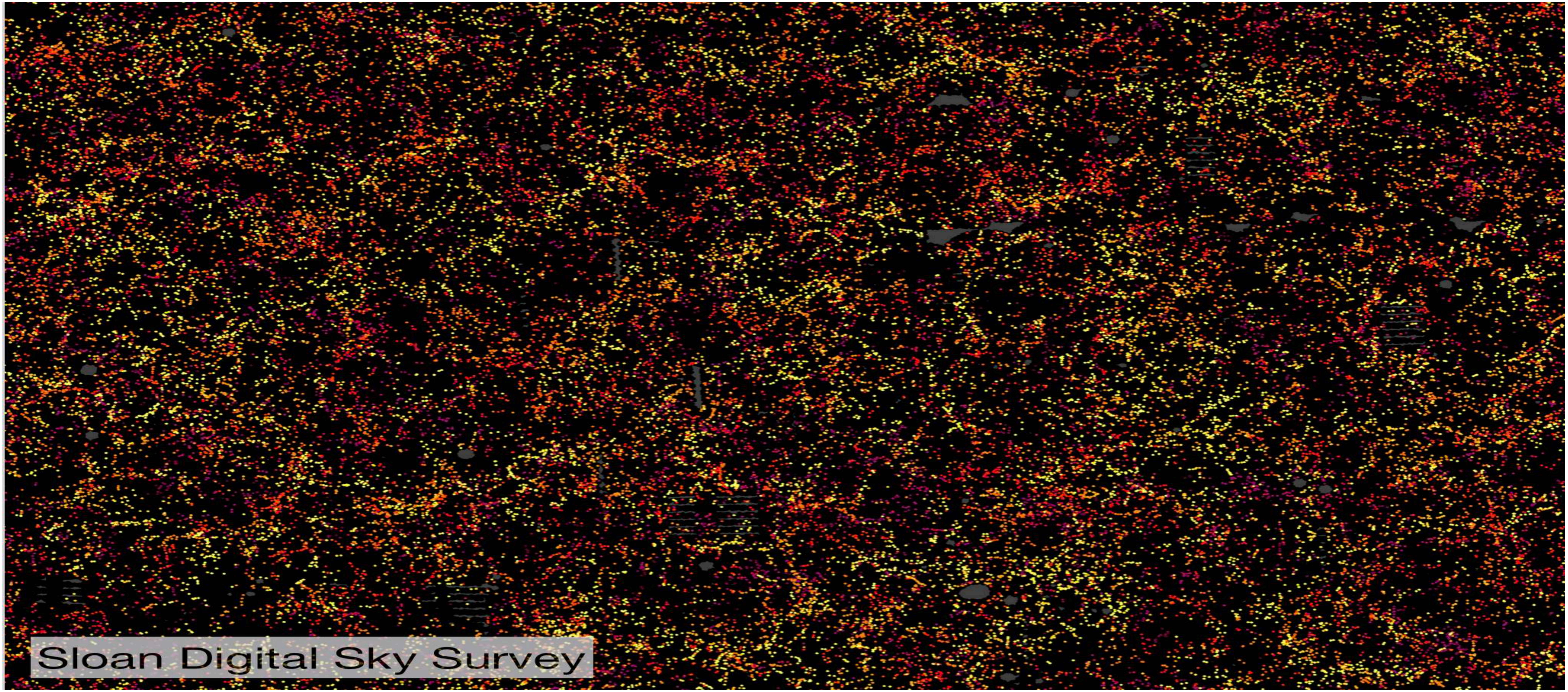
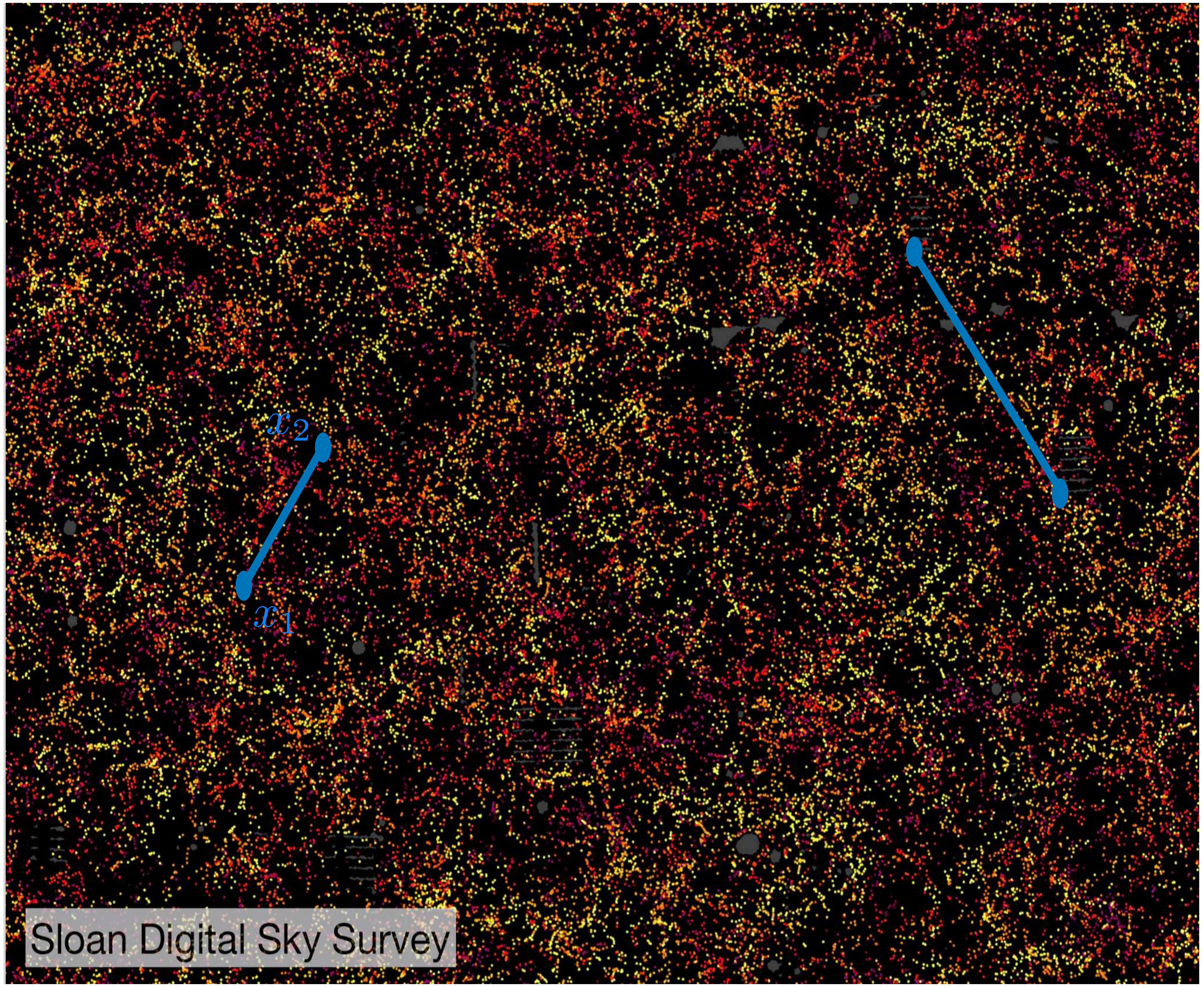
Large scale structure



How to measure the structures



2 point correlation function:

$$\langle \delta(x_1)\delta(x_2)\rangle$$

If we decompose the density contrast into Fourier modes:

$$\delta(x) = \sum_k \delta_k \sin(kx + \phi_k)$$

$$k = 2\pi/\lambda$$

$$\Longrightarrow \quad \boxed{P(k) = |\delta_k|^2}$$

Power spectrum

One of the main objects in cosmology!

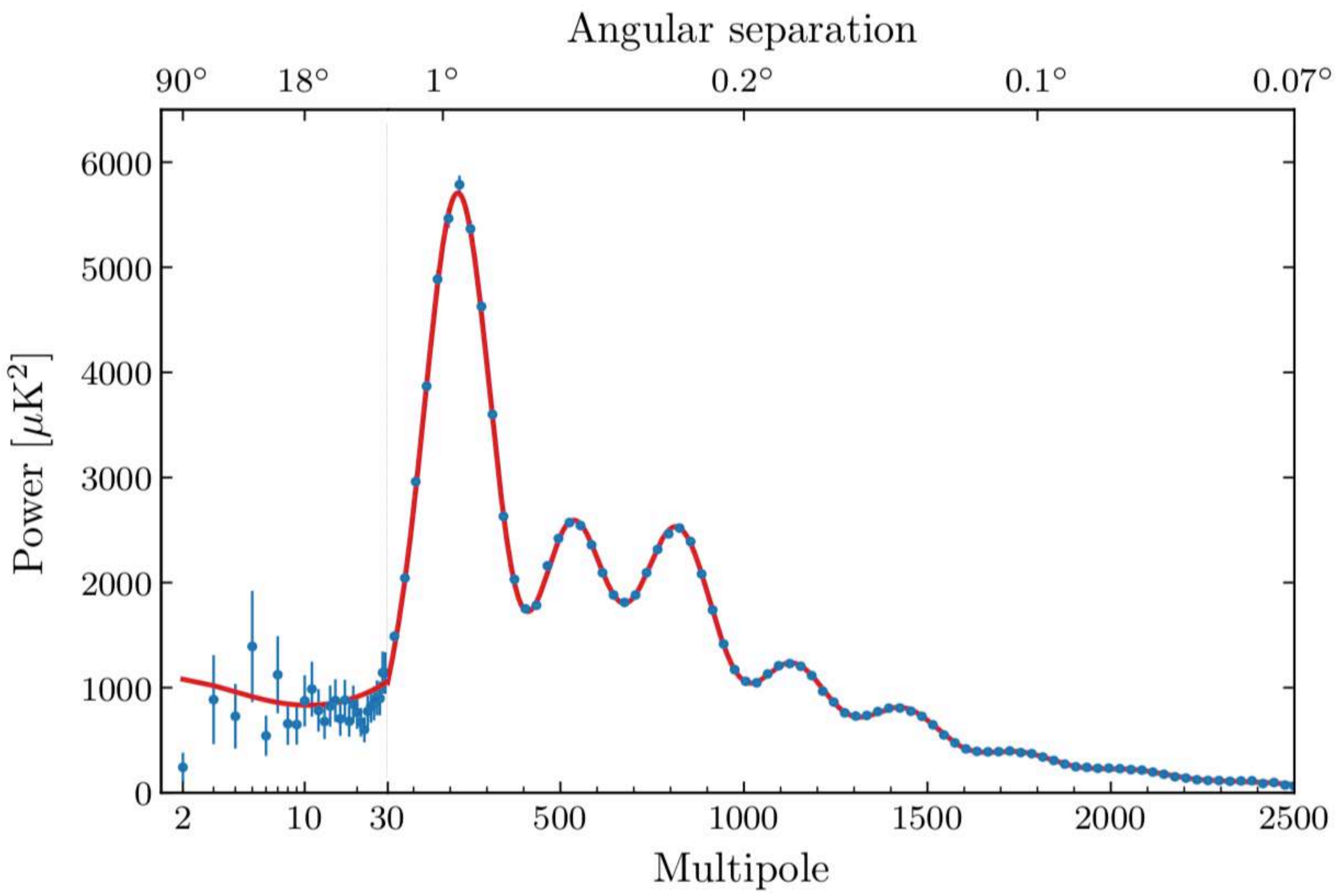
How to measure the structures

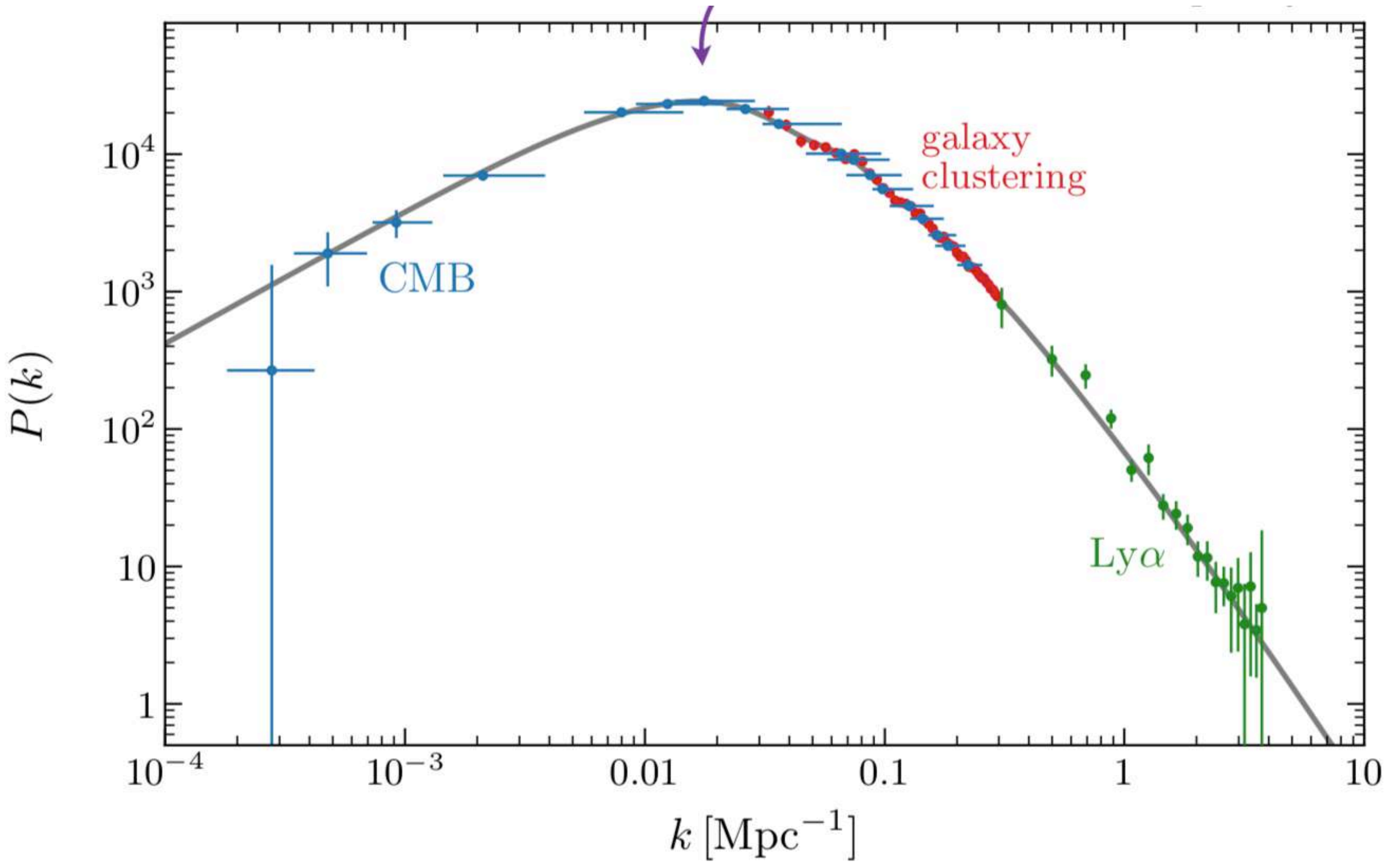
LCDM model

$$\{\Omega_b, \Omega_m, \Omega_\Lambda, n_s, A_s, \tau\}$$

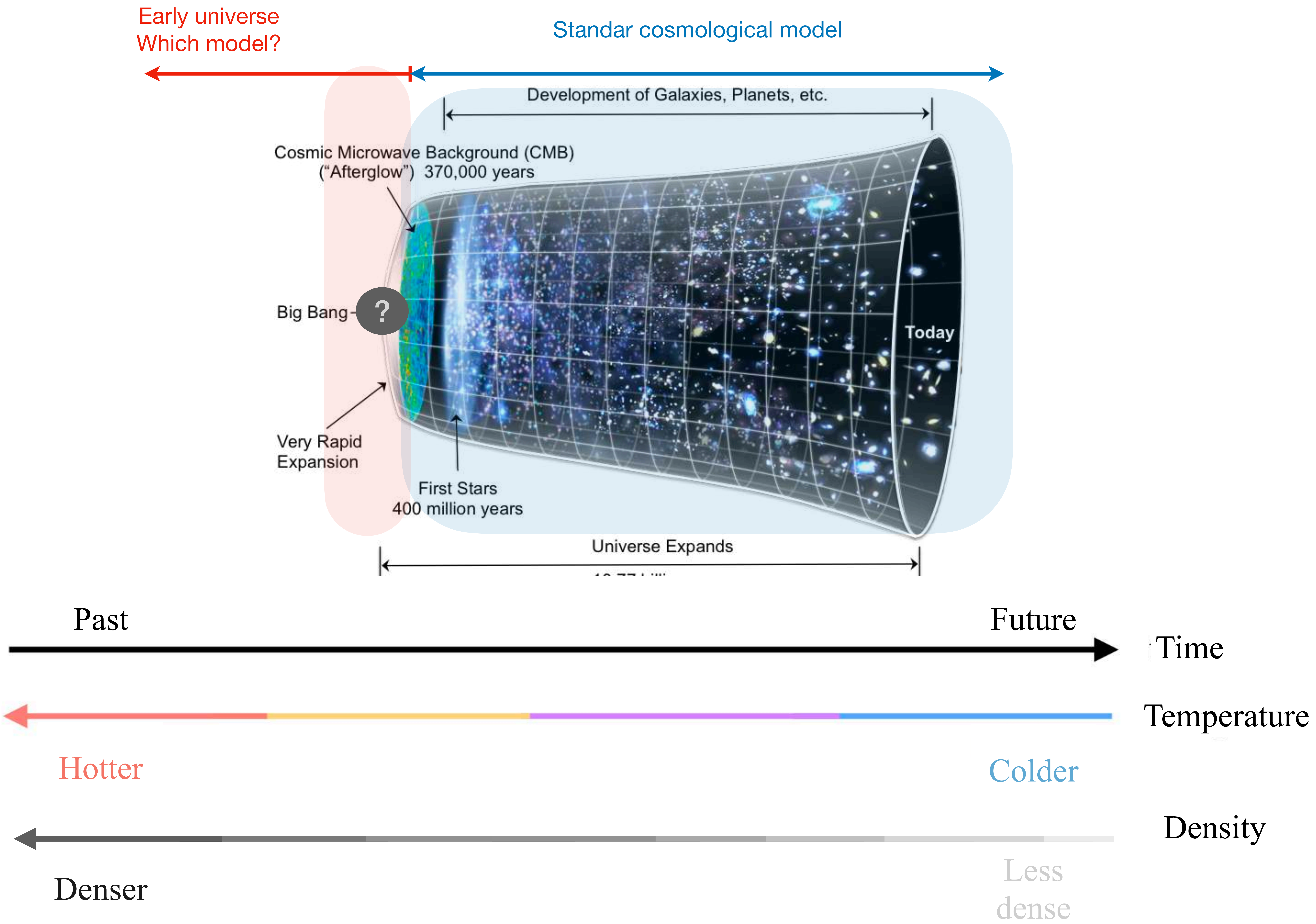
Cosmic Microwave Background

LSS





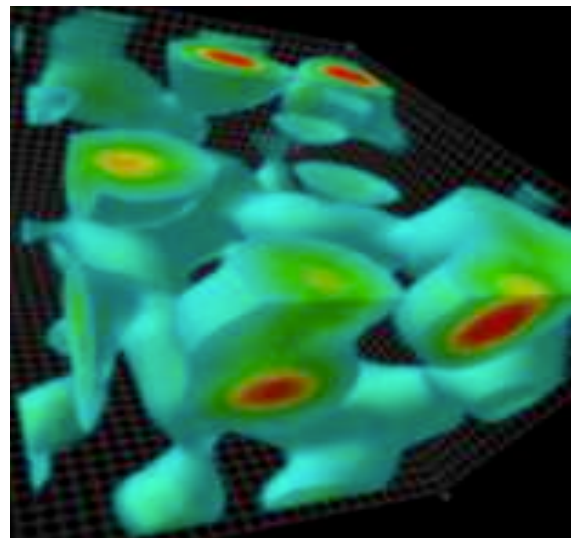
$$f(\theta, \varphi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} C_\ell^m \, Y_\ell^m(\theta, \varphi)$$


Early universe
Which model?
Standar cosmological model
Development of Galaxies, Planets, etc.
Cosmic Microwave Background (CMB)
("Afterglow") 370,000 years
Big Bang
?
Today
Very Rapid
Expansion
First Stars
400 million years
Universe Expands
Past
Future
Time
Temperature
Hotter
Colder
Density
Denser
Less
dense

Where everything we see comes from?

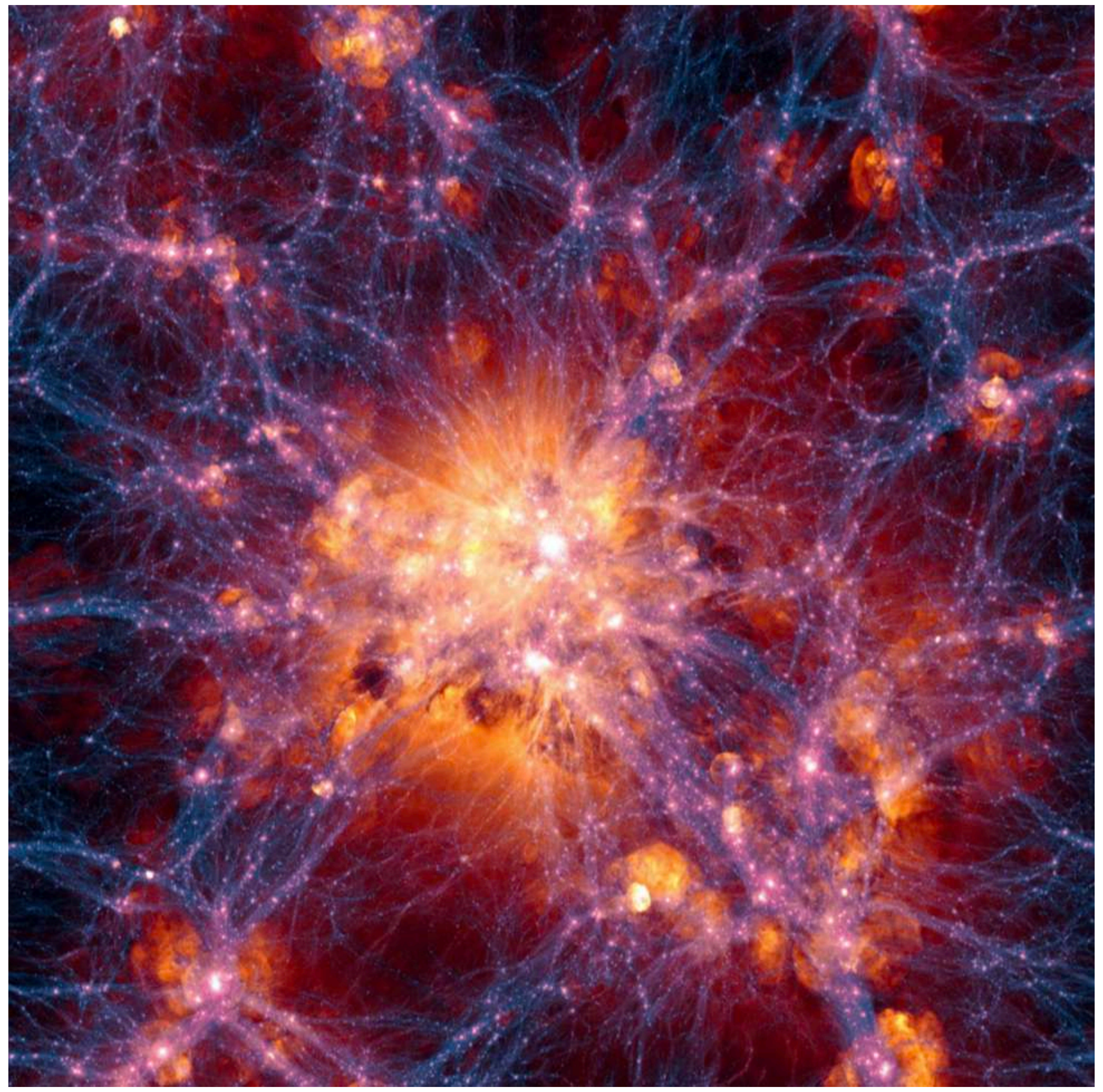
The answer comes from the interesting connection between the really small and really large…

?What is the origin of the initial density fluctuations?



Initial conditions
Initial perturbations

10^{-30} m

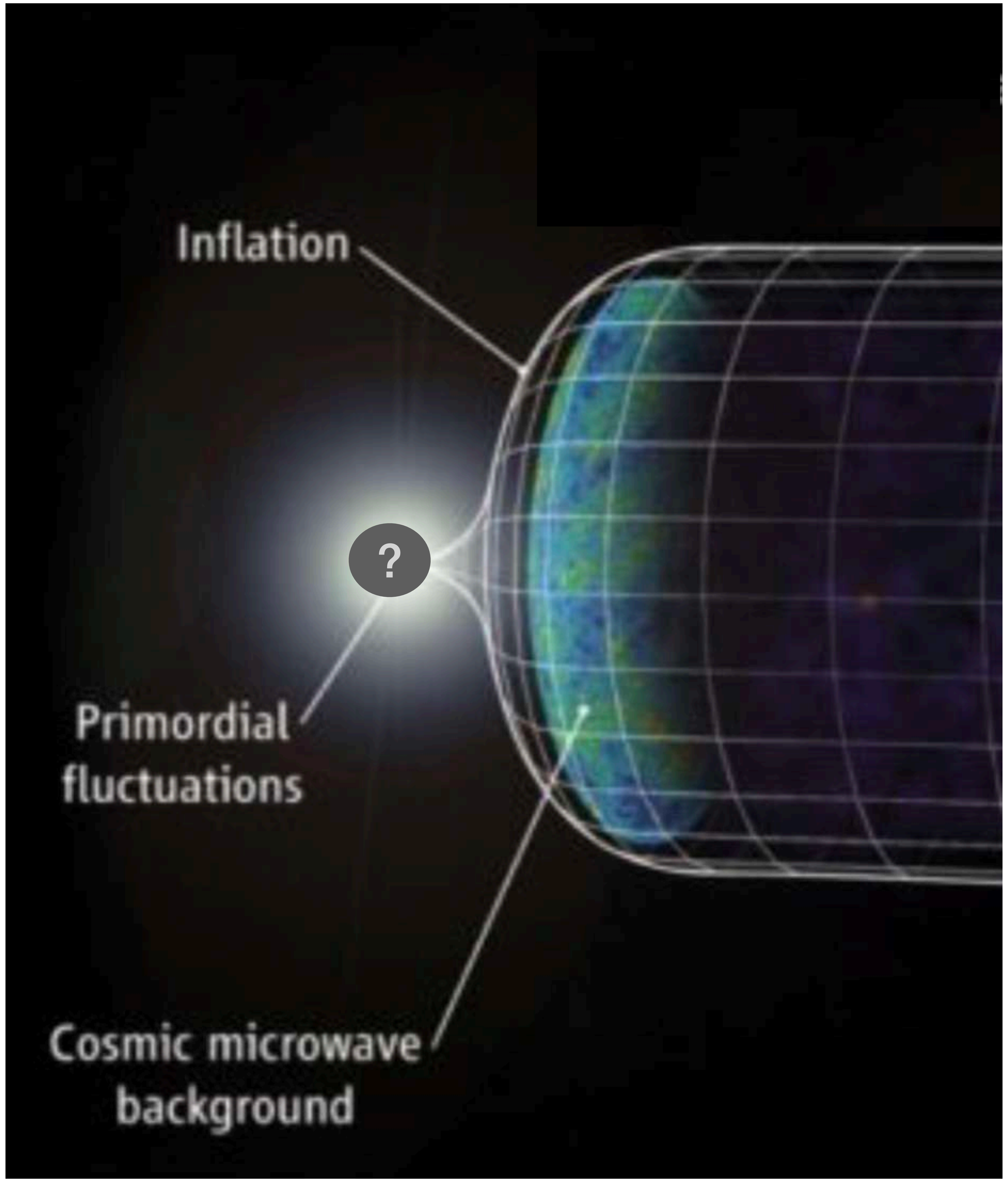


Structures of the universe

10^{25} m

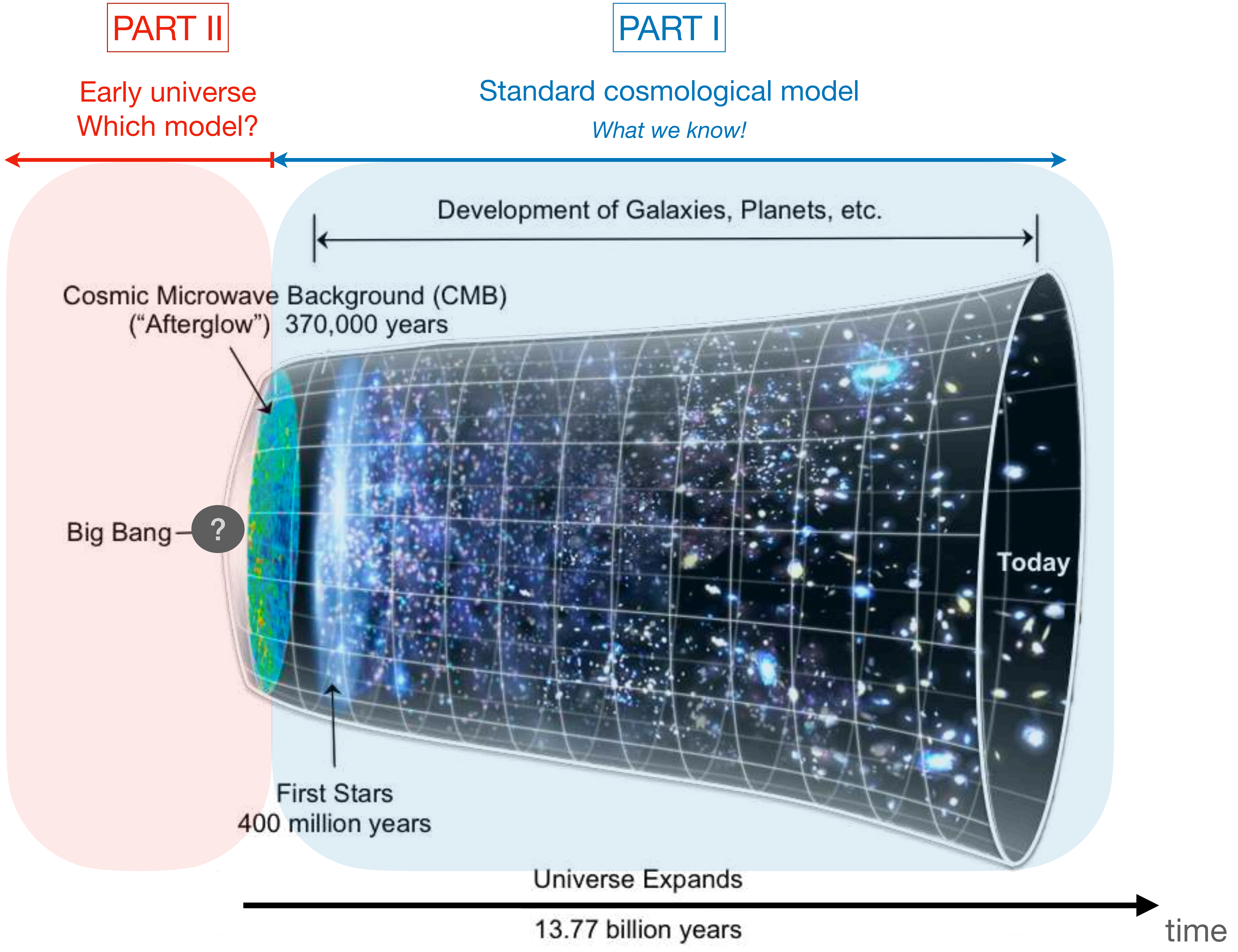
Crédito: D. Baumann

This is going to depend on how was the evolution of the early universe…



PART II

Early universe



Problems of the standard cosmological model

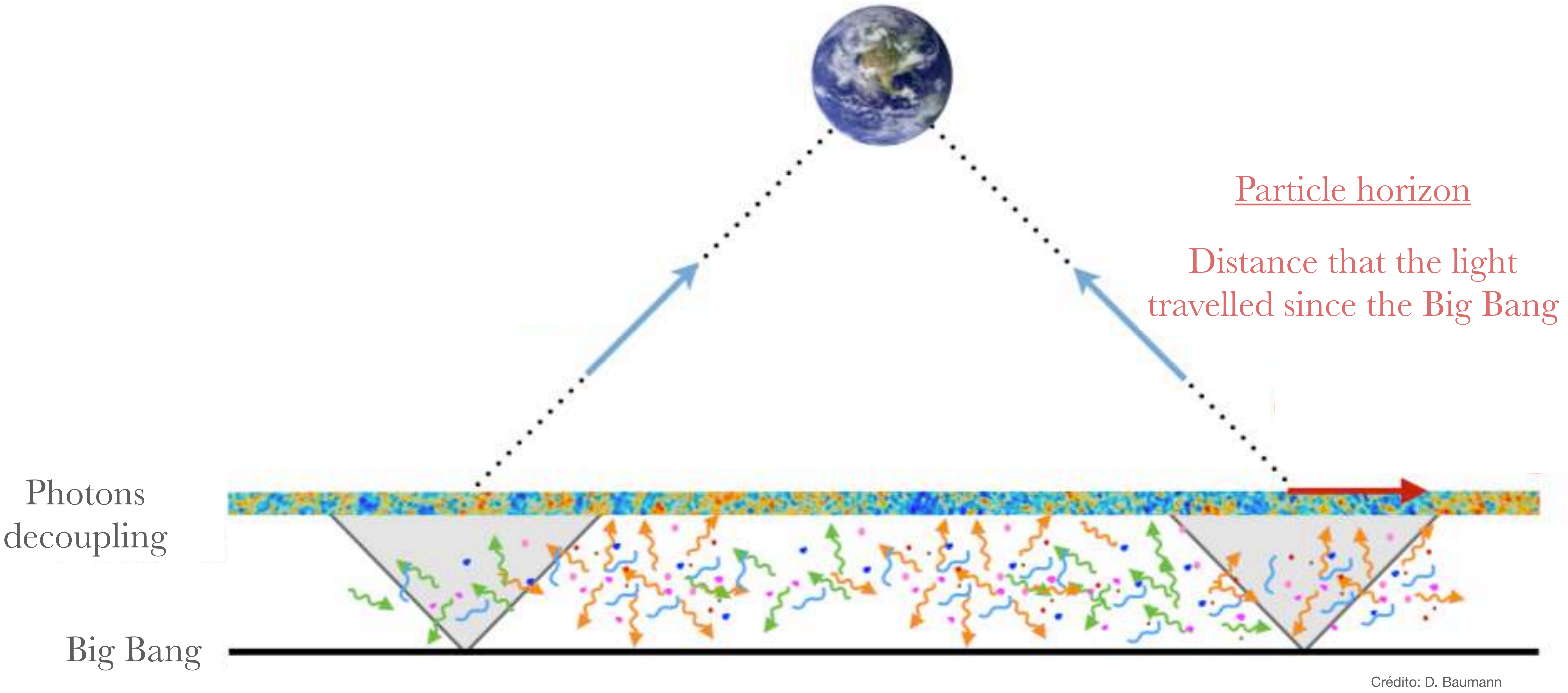
- Horizon problem
- Problem of the origin of structures
- Flatness problem
- Problem of the magnetic monopoles
- Initial singularity
- DM and DE

Horizon problem

Crédito: D. Baumann

Horizons in cosmology

Since the speed of light is constant and the universe is expanding, there is a limit for what is accessible to an observer in the universe.

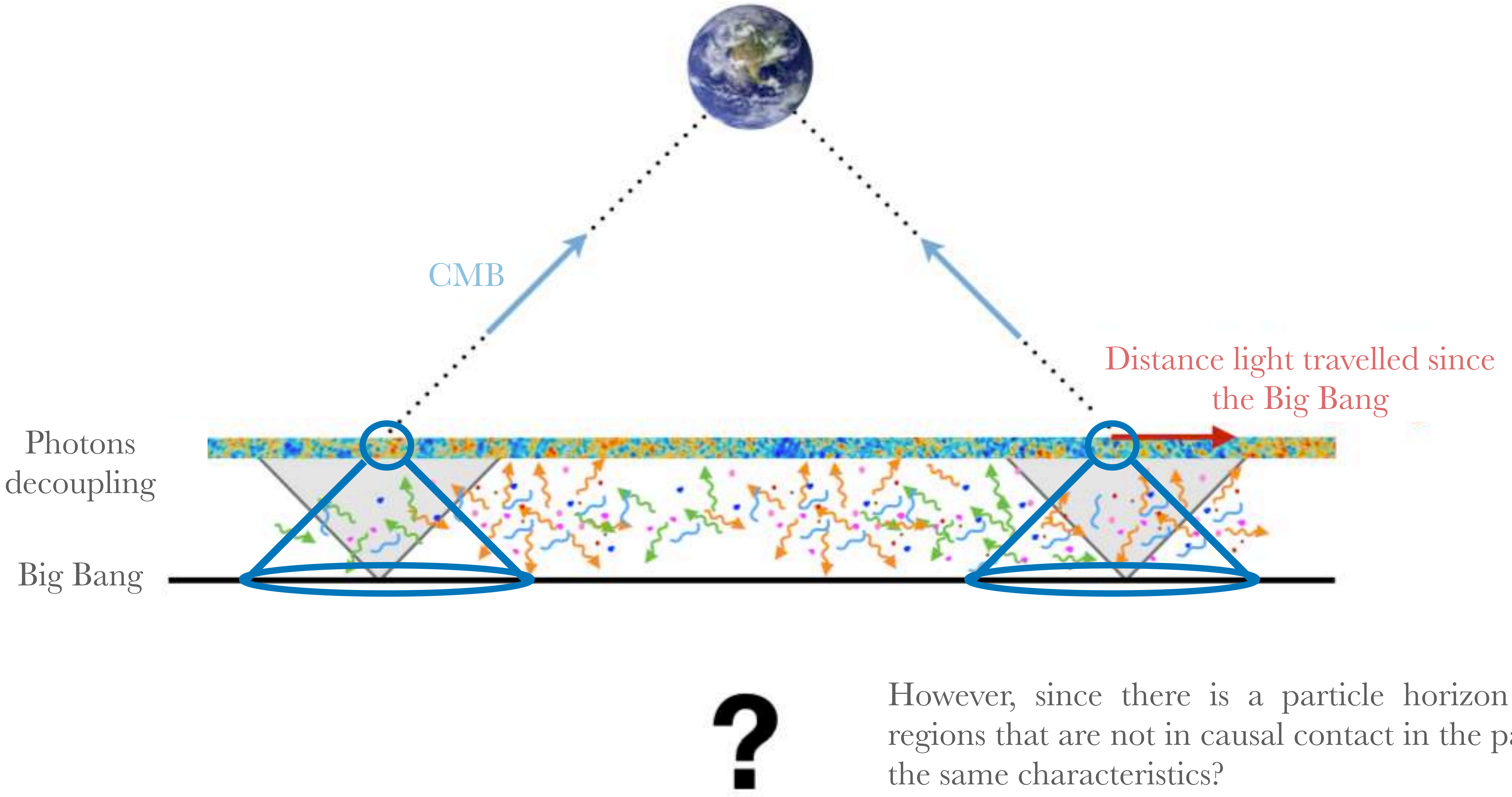


This limit of what can be observed is known as horizon.

Horizon problem

also known as homogeneity and isotropy problem

As we saw, the CMB presents the same temperature in every point of the observable universe, except from small deviations

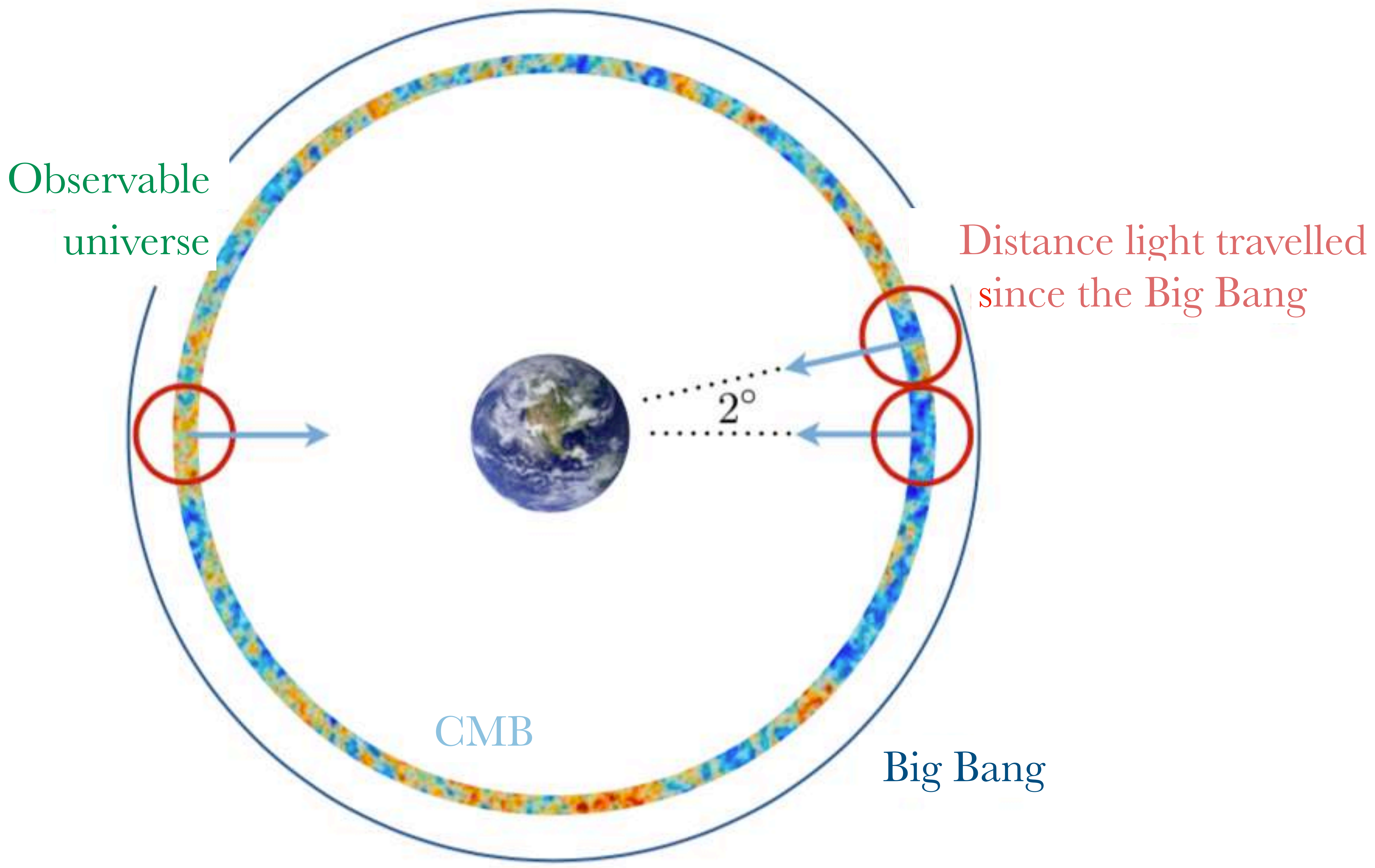


However, since there is a particle horizon today, HOW regions that are not in causal contact in the past can present the same characteristics?

Crédito: D. Baumann

Horizon problem

also known as homogeneity and isotropy problem



The CMB is made of $10^4 - 10^6$ causally disconnected regions, yet it is observed to be almost perfectly uniform!?

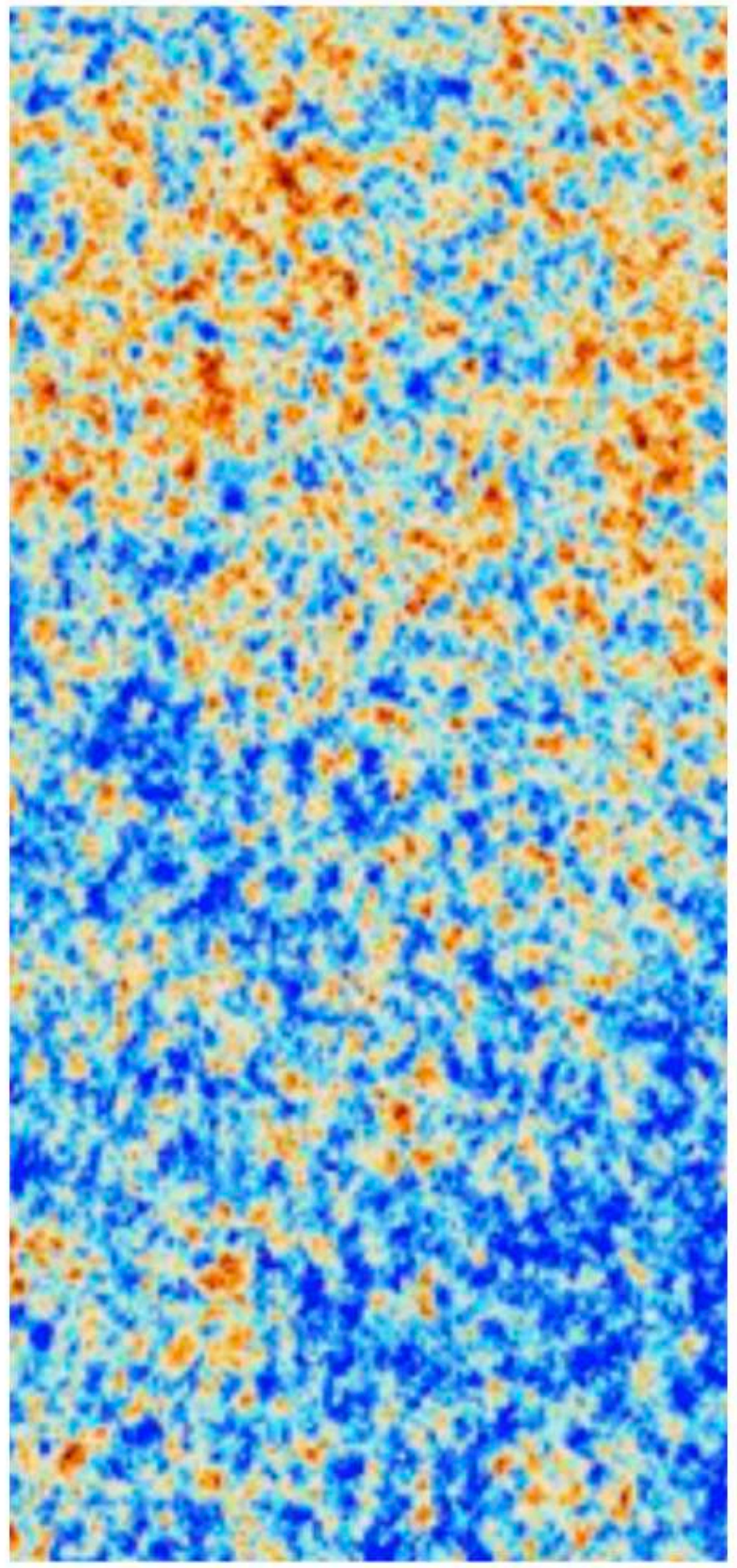
= horizon problem!

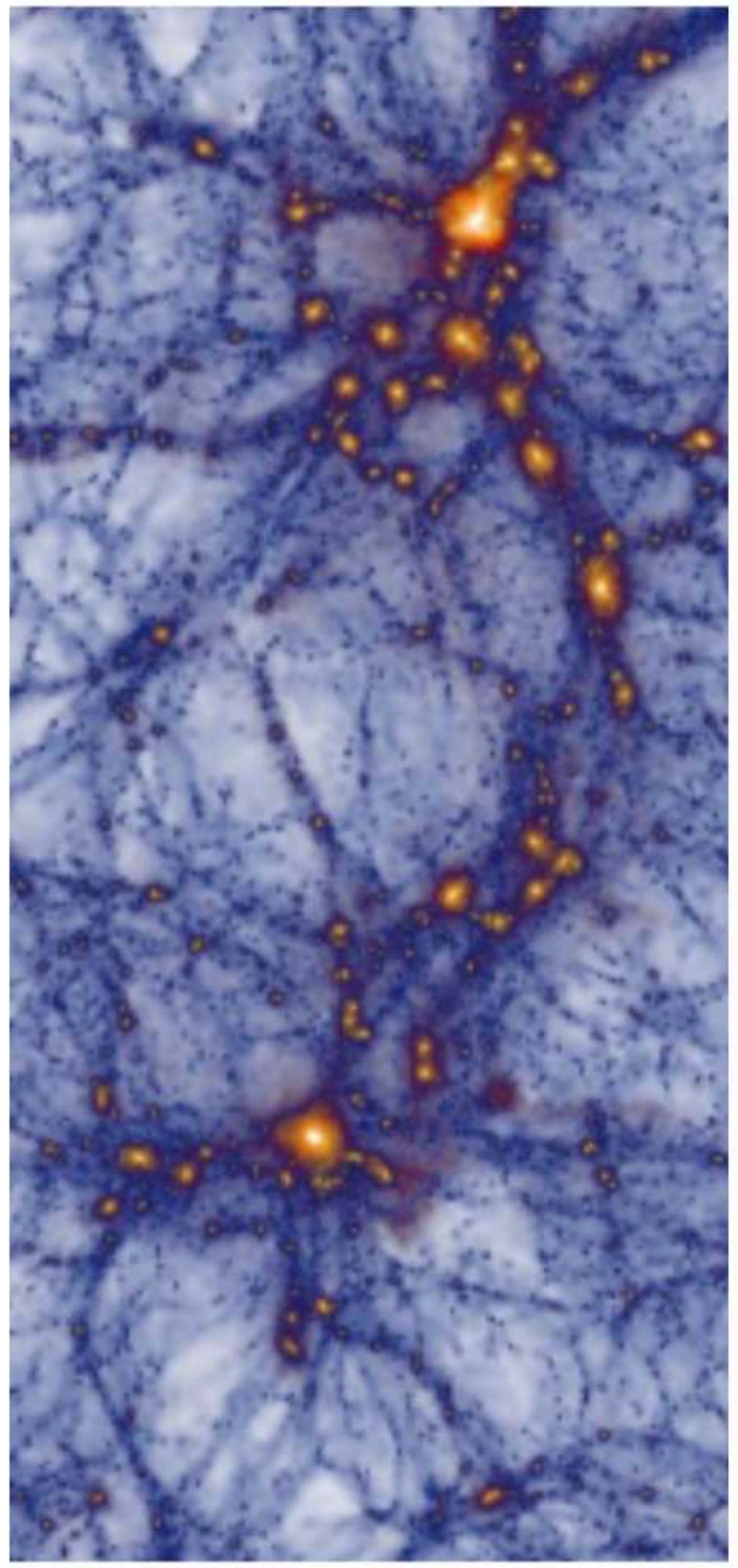
Crédito: D. Baumann

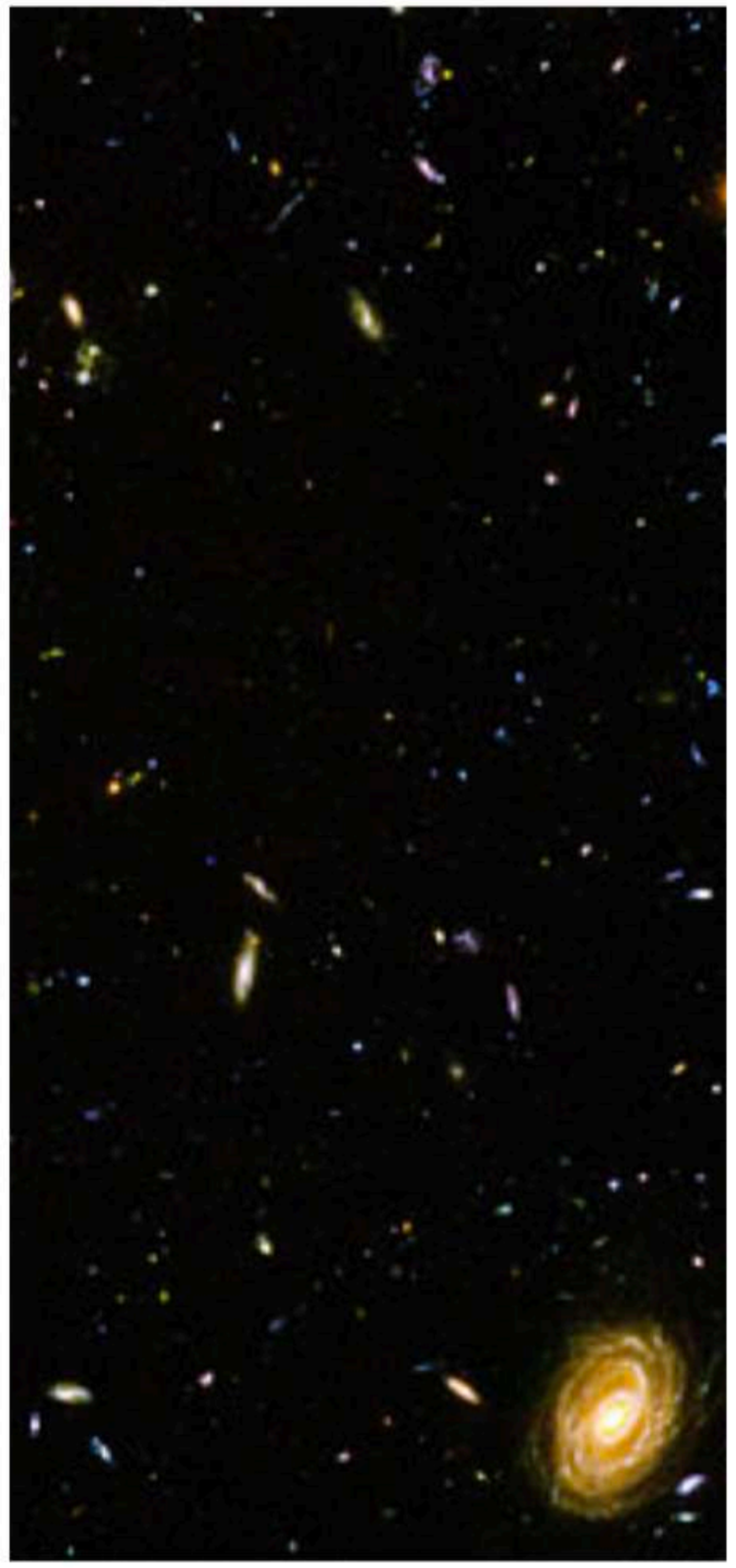
Problem of the *origin of structures*

Origin of the small perturbations → Small perturbations → Macroscopic structures

$\delta\rho \sim 10^{-5}\,\bar{\rho}$



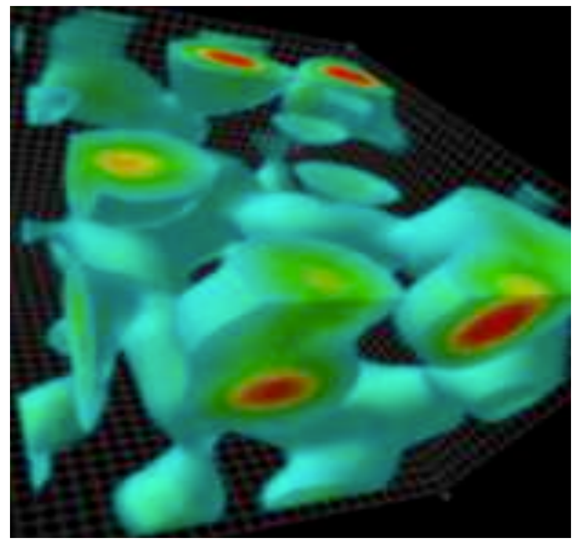




10^{-32} s | 380.000 years | 13.8 billion of years

Crédito: D. Baumann

Problem of the origin of structures



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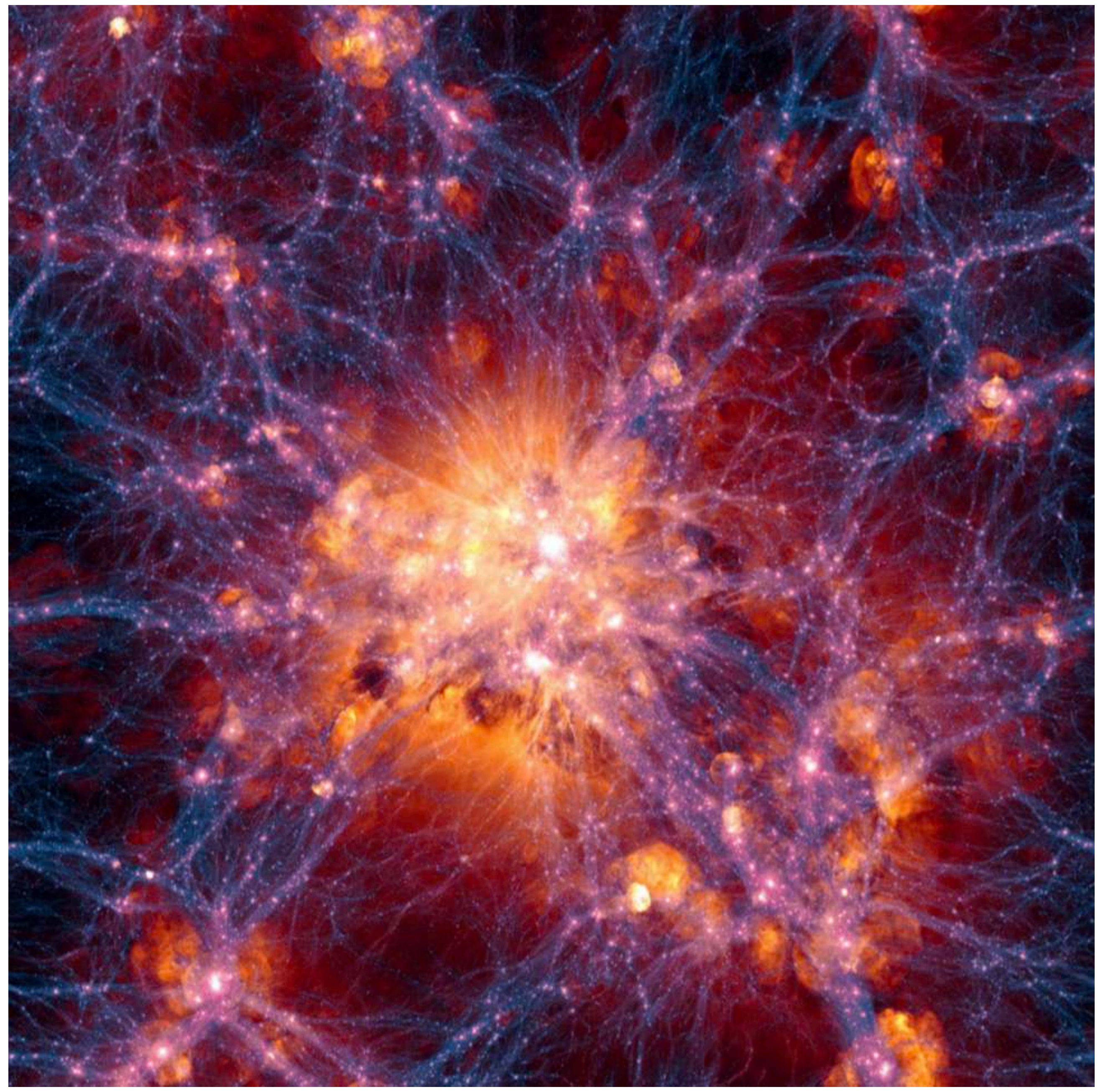
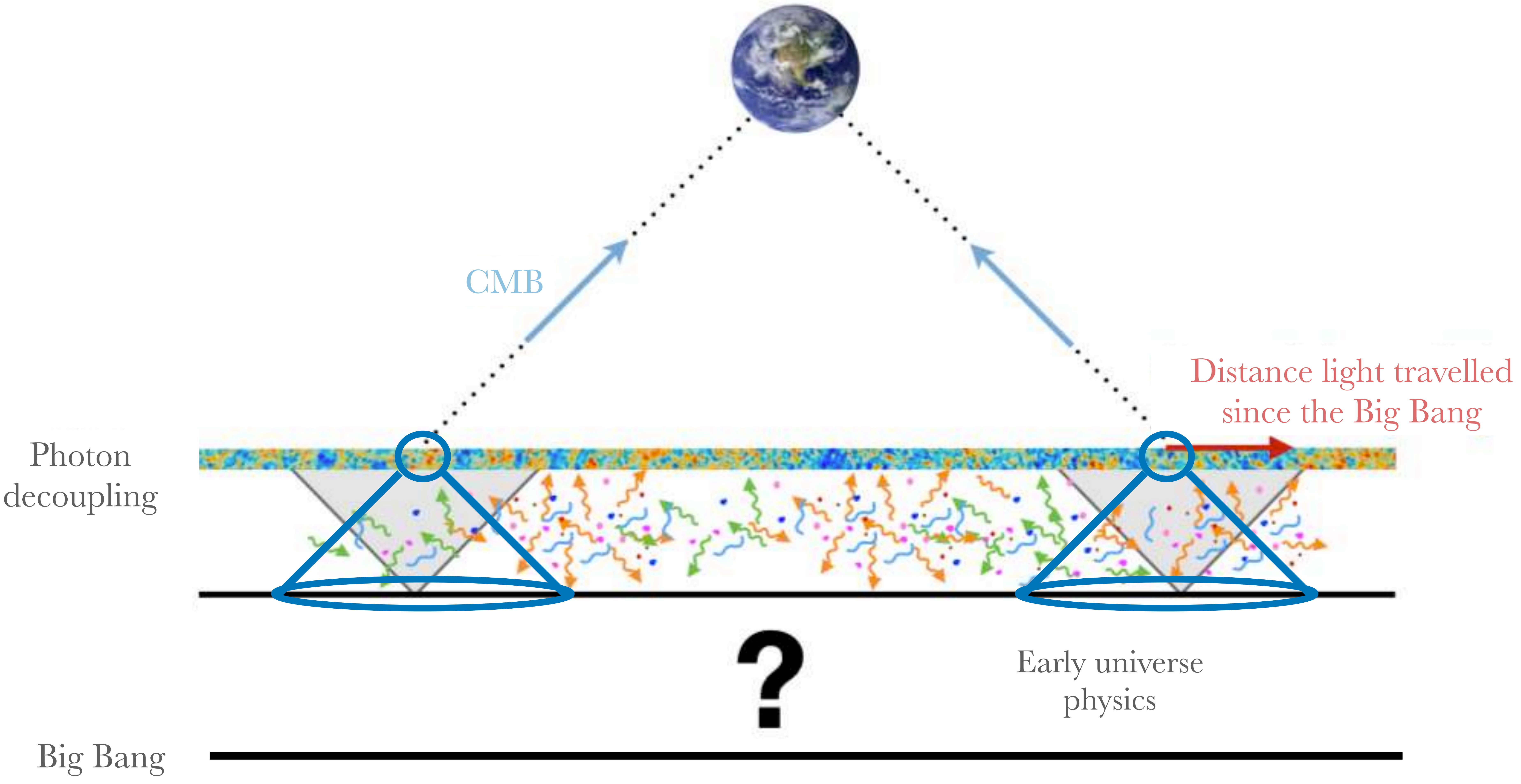


Structures of the universe

10^{25} m

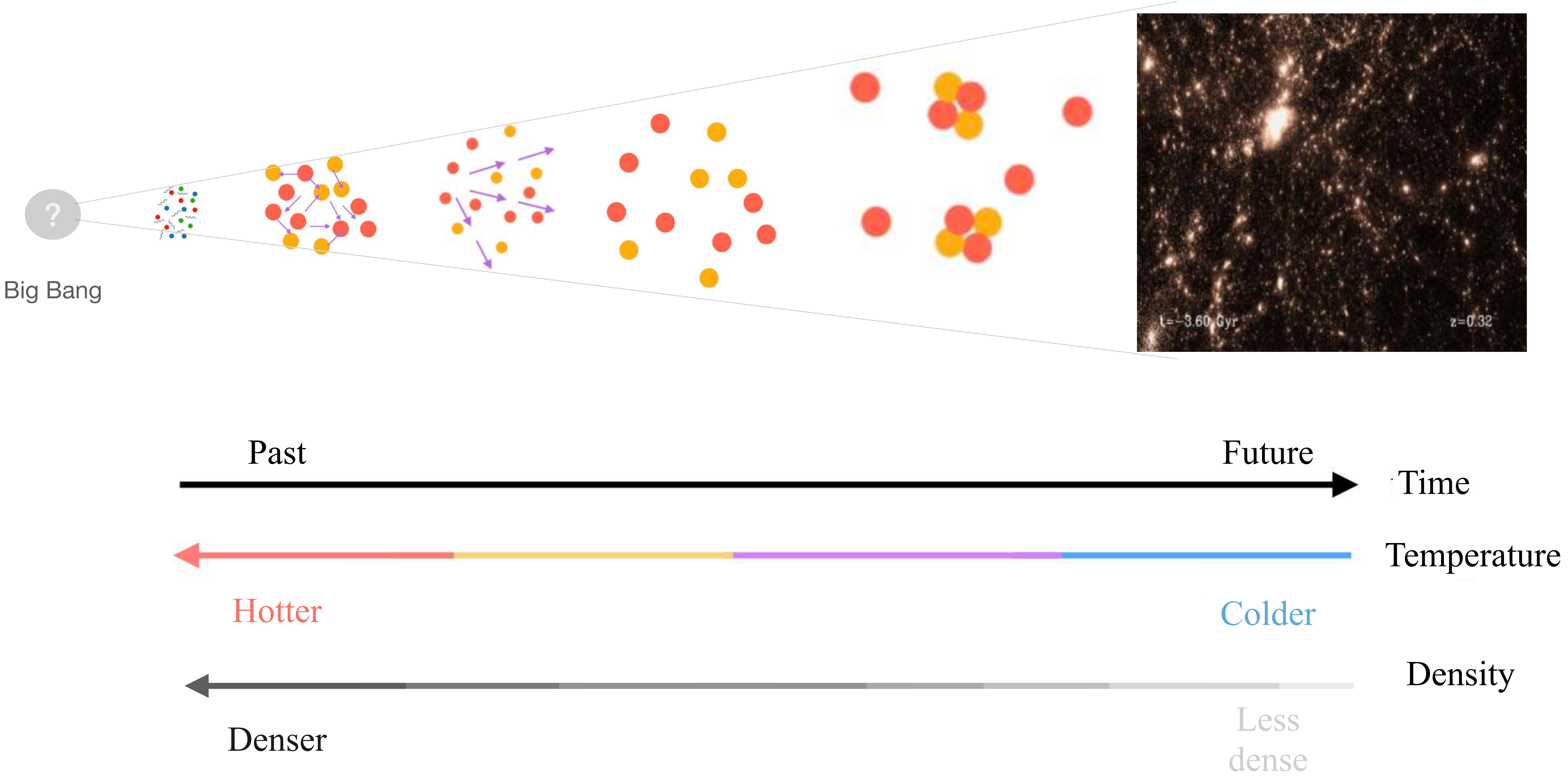
Crédito: D. Baumann

We need to understand the primordial universe, explain the origin of the initial fluctuations and make predictions to test these theories of the early universe evolution



Crédito: D. Baumann

Singularity problem



Crédito: D. Baumann

Early universe models

solving the SCM problems

Inflation

Motivation: solve the SCM problems

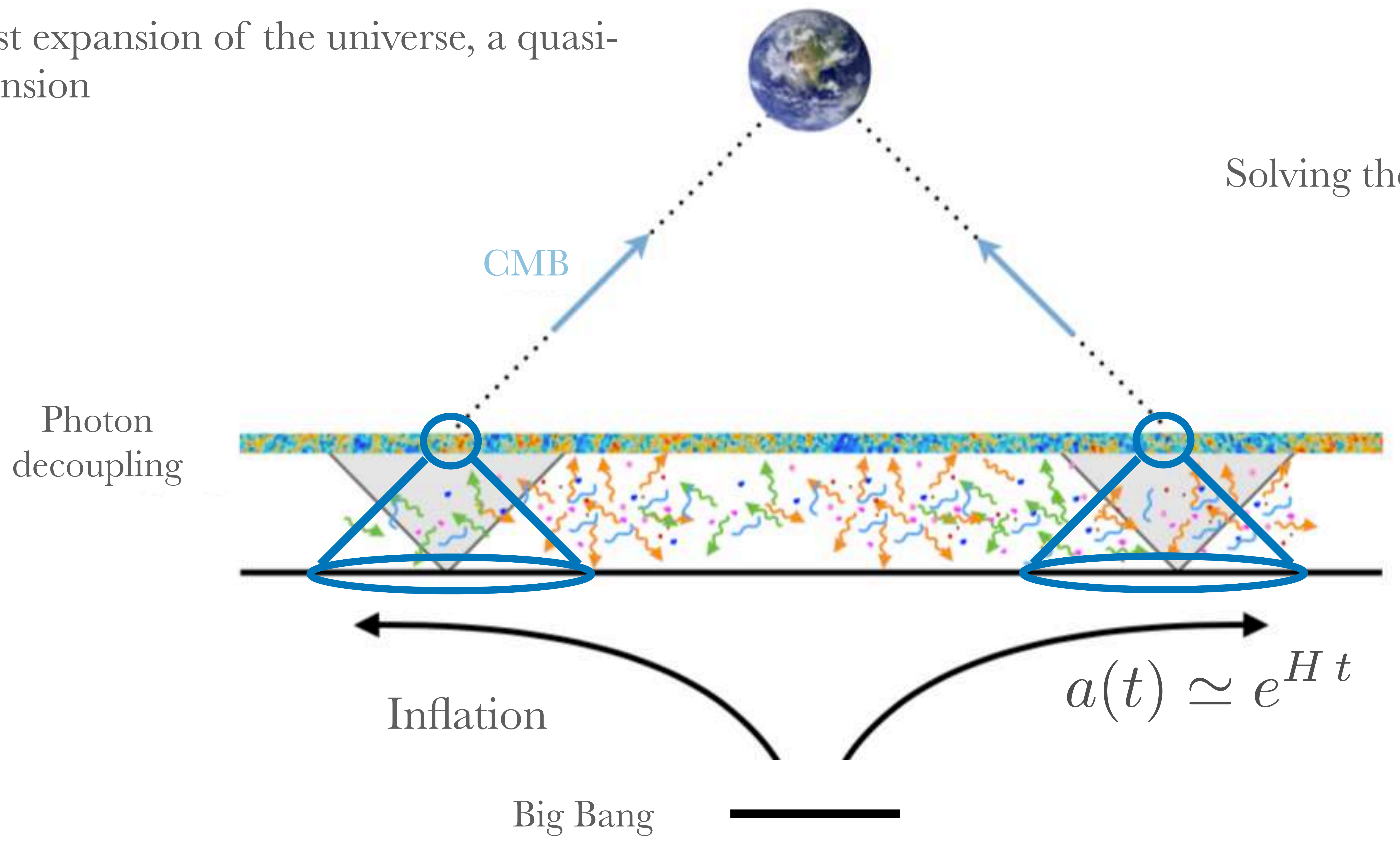
Crédito: D. Baumann

Inflation

Guth (1980)
Linde(1982)
Albrecht e Steinhardt (1982)

Period of very fast expansion of the universe, a quasi-exponential expansion

Solving the horizon problem



Originally (Guth 1980) - to solve the magnetic monopoles problem

Crédito: D. Baumann

Acceleration

How can we obtain such an expansion of the universe?

Remember:

- Dark Energy

acceleration

Dark energy

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left[(\rho(t) + p(t))_{R,M} + \rho_{EE}(t)\right] \qquad + \qquad w < -\frac{1}{3}$$

decelerates the expansion

Implementing the inflationary mechanism

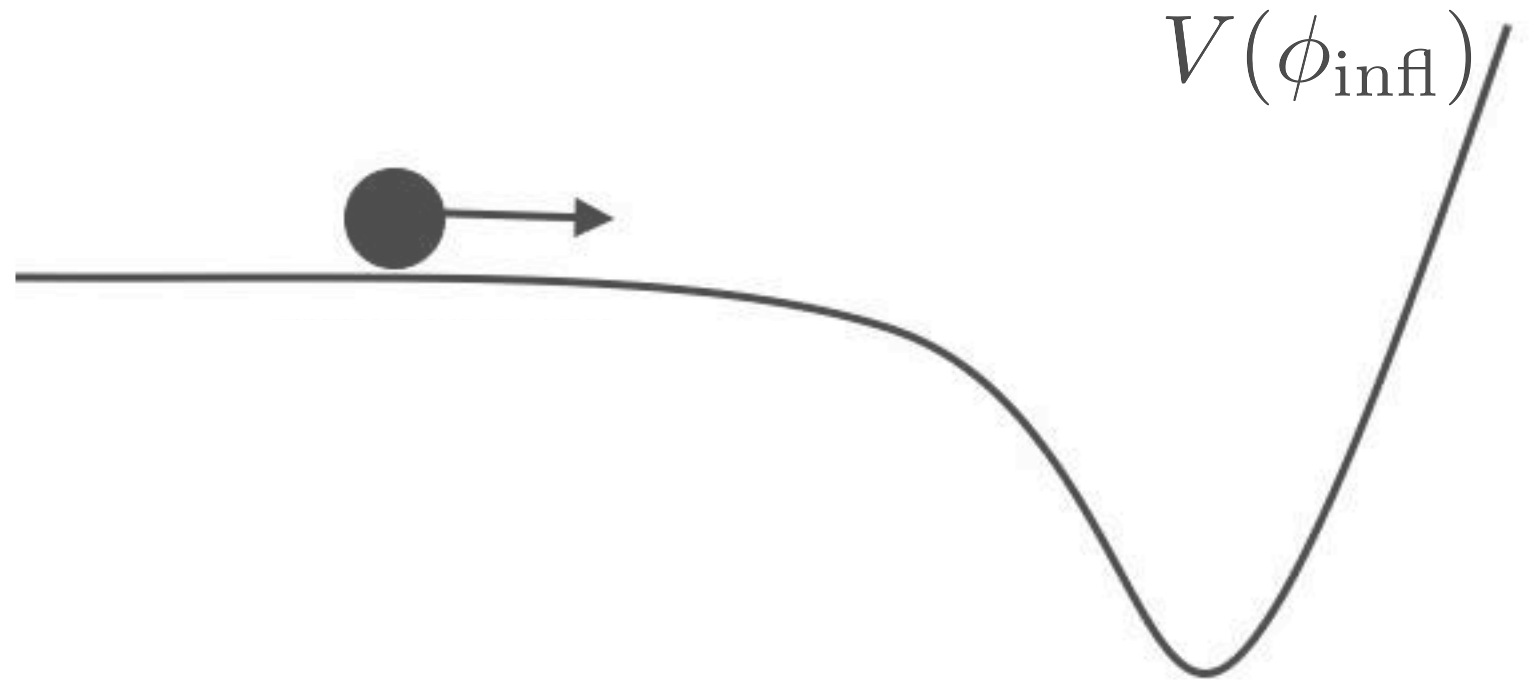
How can we implement a microphysical model of the accelerated

- Adding one (or many) new components that dominate the universe at its begining with $w < -\frac{1}{3} \implies \ddot{a} > 0$

$$\rho_{\rm infl}\,,\ \ p_{\rm infl}$$

We call this new component the *inflaton*

To cause this acceleration, this new component has to have a potential with this shape



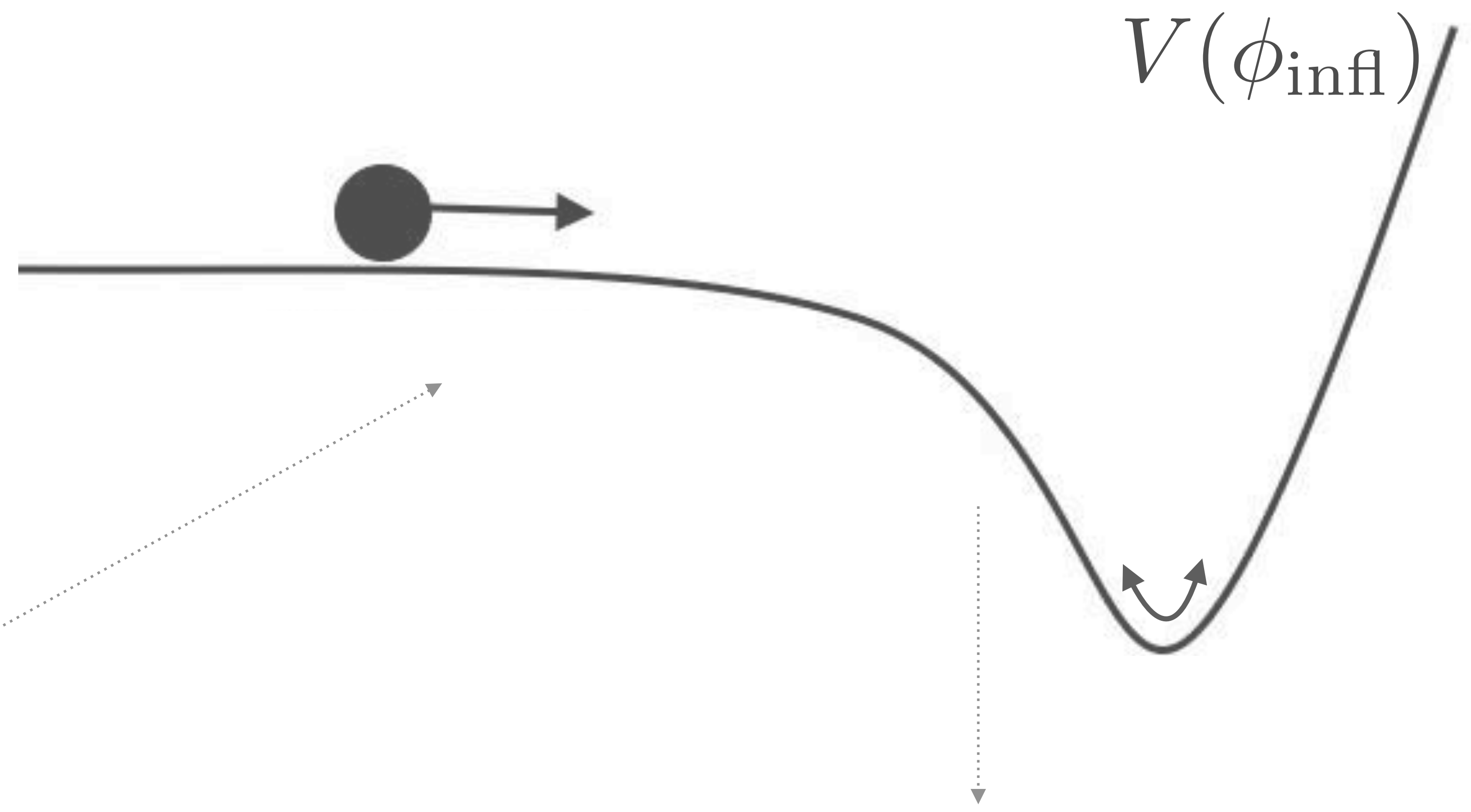
(like for dark energy) it has to have a almost constant energy density

Inflation

TOY MODEL:

Scalar field (*inflaton*) $\phi(t)$ in a FRW background

To cause the acceleration, the potential has to have the form:



Causes the accelerated expansion - quasi-exponential

$$\epsilon \equiv -\frac{\dot{H}}{H^2} < 1$$

However, inflation has to end, so the era of radiation begins - ***graceful exit***

$$\epsilon \sim 1$$

Inflation

For the experts

Single scalar field inflation

$$S = -\int d^4x\sqrt{-g}\,\mathcal{L} = -\int d^4x\sqrt{-g}\,\left[\frac{1}{2}\partial_\mu\phi\partial^\mu\phi + V(\phi)\right]$$

$-g$: metric determinant of $g_{\mu\nu}$

Energy momentum tensor: $$T_{\mu\nu} = \partial_\mu\phi\partial_\nu\phi - g_{\mu\nu}\left(\frac{1}{2}g^{\alpha\beta}\partial_\alpha\phi\partial_\beta\phi - V(\phi)\right)$$

$$\Rightarrow \quad \rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$
$$p_\phi = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

Potential energy

dominates

kinetic energy =

$p_\phi < -\rho_\phi/3$

Inflation models

Many models!!!

Name	Parameters	Sub-models	$V(\phi)$
HI	0	1	$M^4\left(1-e^{-\sqrt{2/3}\phi/M_{\rm Pl}}\right)$
RCHI	1	1	$M^4\left(1-2e^{-\sqrt{2/3}\phi/M_{\rm Pl}}+\frac{A_{\rm I}}{16\pi^2}\frac{\phi}{\sqrt{6}M_{\rm Pl}}\right)$
LFI	1	1	$M^4\left(\frac{\phi}{M_{\rm Pl}}\right)^p$
MLFI	1	1	$M^4\frac{\phi^2}{M_{\rm Pl}^2}\left[1+\alpha\frac{\phi^2}{M_{\rm Pl}^2}\right]$
RCMI	1	1	$M^4\left(\frac{\phi}{M_{\rm Pl}}\right)^2\left[1-2\alpha\frac{\phi^2}{M_{\rm Pl}^2}\ln\left(\frac{\phi}{M_{\rm Pl}}\right)\right]$
RCQI	1	1	$M^4\left(\frac{\phi}{M_{\rm Pl}}\right)^4\left[1-\alpha\ln\left(\frac{\phi}{M_{\rm Pl}}\right)\right]$
NI	1	1	$M^4\left[1+\cos\left(\frac{\phi}{f}\right)\right]$
ESI	1	1	$M^4\left(1-e^{-q\phi/M_{\rm Pl}}\right)$
PLI	1	1	$M^4e^{-\alpha\phi/M_{\rm Pl}}$
KMII	1	2	$M^4\left(1-\alpha\frac{\phi}{M_{\rm Pl}}e^{-\phi/M_{\rm Pl}}\right)$
HF1I	1	1	$M^4\left(1+A_1\frac{\phi}{M_{\rm Pl}}\right)^2\left[1-\frac{2}{3}\left(\frac{A_1}{1+A_1\phi/M_{\rm Pl}}\right)^2\right]$
CWI	1	1	$M^4\left[1+\alpha\left(\frac{\phi}{Q}\right)^4\ln\left(\frac{\phi}{Q}\right)\right]$
LI	1	2	$M^4\left[1+\alpha\ln\left(\frac{\phi}{M_{\rm Pl}}\right)\right]$
RpI	1	3	$M^4e^{-2\sqrt{2/3}\phi/M_{\rm Pl}}\left\lvert e^{\sqrt{2/3}\phi/M_{\rm Pl}}-1\right\rvert^{2p/(2p-1)}$
DWI	1	1	$M^4\left[\left(\frac{\phi}{\phi_0}\right)^2-1\right]^2$
MHI	1	1	$M^4\left[1-\mathrm{sech}\left(\frac{\phi}{\mu}\right)\right]$
RGI	1	1	$M^4\frac{(\phi/M_{\rm Pl})^2}{\alpha+(\phi/M_{\rm Pl})^2}$
MSSMI	1	1	$M^4\left[\left(\frac{\phi}{\phi_0}\right)^2-\frac{2}{3}\left(\frac{\phi}{\phi_0}\right)^6+\frac{1}{5}\left(\frac{\phi}{\phi_0}\right)^{10}\right]$
RIPI	1	1	$M^4\left[\left(\frac{\phi}{\phi_0}\right)^2-\frac{4}{3}\left(\frac{\phi}{\phi_0}\right)^3+\frac{1}{2}\left(\frac{\phi}{\phi_0}\right)^4\right]$
AI	1	1	$M^4\left[1-\frac{2}{\pi}\arctan\left(\frac{\phi}{\mu}\right)\right]$
CNAI	1	1	$M^4\left[3-(3+\alpha^2)\tanh^2\left(\frac{\alpha}{\sqrt{2}}\frac{\phi}{M_{\rm Pl}}\right)\right]$
CNBI	1	1	$M^4\left[(3-\alpha^2)\tan^2\left(\frac{\alpha}{\sqrt{2}}\frac{\phi}{M_{\rm Pl}}\right)-3\right]$
OSTI	1	1	$-M^4\left(\frac{\phi}{\phi_0}\right)^2\ln\left[\left(\frac{\phi}{\phi_0}\right)^2\right]$
WRI	1	1	$M^4\ln\left(\frac{\phi}{\phi_0}\right)^2$
SFI	2	1	$M^4\left[1-\left(\frac{\phi}{\mu}\right)^p\right]$
II	2	1	$M^4\left(\frac{\phi-\phi_0}{M_{\rm Pl}}\right)^{-\beta}-M^4\frac{\beta^2}{6}\left(\frac{\phi-\phi_0}{M_{\rm Pl}}\right)^{-\beta-2}$
KMIII	2	1	$M^4\left[1-\alpha\frac{\phi}{M_{\rm Pl}}\exp\left(-\beta\frac{\phi}{M_{\rm Pl}}\right)\right]$
LMI	2	2	$M^4\left(\frac{\phi}{M_{\rm Pl}}\right)^\alpha\exp\left[-\beta(\phi/M_{\rm Pl})^\gamma\right]$
TWI	2	1	$M^4\left[1-A\left(\frac{\phi}{\phi_0}\right)^2e^{-\phi/\phi_0}\right]$
GMSSMI	2	2	$M^4\left[\left(\frac{\phi}{\phi_0}\right)^2-\frac{2}{3}\alpha\left(\frac{\phi}{\phi_0}\right)^6+\frac{\alpha}{5}\left(\frac{\phi}{\phi_0}\right)^{10}\right]$
GRIPI	2	2	$M^4\left[\left(\frac{\phi}{\phi_0}\right)^2-\frac{4}{3}\alpha\left(\frac{\phi}{\phi_0}\right)^3+\frac{\alpha}{2}\left(\frac{\phi}{\phi_0}\right)^4\right]$
BSUSYBI	2	1	$M^4\left(e^{\sqrt{6}\frac{\phi}{M_{\rm Pl}}}+e^{\sqrt{6}\gamma\frac{\phi}{M_{\rm Pl}}}\right)$
TI	2	3	$M^4\left(1+\cos\frac{\phi}{\mu}+\alpha\sin^2\frac{\phi}{\mu}\right)$
BEI	2	1	$M^4\exp_{1-\beta}\left(-\lambda\frac{\phi}{M_{\rm Pl}}\right)$
PSNI	2	1	$M^4\left[1+\alpha\ln\left(\cos\frac{\phi}{f}\right)\right]$
NCKI	2	2	$M^4\left[1+\alpha\ln\left(\frac{\phi}{M_{\rm Pl}}\right)+\beta\left(\frac{\phi}{M_{\rm Pl}}\right)^2\right]$
CSI	2	1	$\frac{M^4}{\left(1-\alpha\frac{\phi}{M_{\rm Pl}}\right)^2}$
OI	2	1	$M^4\left(\frac{\phi}{\phi_0}\right)^4\left[\left(\ln\frac{\phi}{\phi_0}\right)^2-\alpha\right]$
CNCI	2	1	$M^4\left[(3+\alpha^2)\coth^2\left(\frac{\alpha}{\sqrt{2}}\frac{\phi}{M_{\rm Pl}}\right)-3\right]$
SBI	2	2	$M^4\left\{1+\left[-\alpha+\beta\ln\left(\frac{\phi}{M_{\rm Pl}}\right)\right]\left(\frac{\phi}{M_{\rm Pl}}\right)^4\right\}$
SSBI	2	6	$M^4\left[1+\alpha\left(\frac{\phi}{M_{\rm Pl}}\right)^2+\beta\left(\frac{\phi}{M_{\rm Pl}}\right)^4\right]$
IMI	2	1	$M^4\left(\frac{\phi}{M_{\rm Pl}}\right)^{-p}$
BI	2	2	$M^4\left[1-\left(\frac{\phi}{\mu}\right)^{-p}\right]$
RMI	3	4	$M^4\left[1-\frac{c}{2}\left(-\frac{1}{2}+\ln\frac{\phi}{\phi_0}\right)\frac{\phi^2}{M_{\rm Pl}^2}\right]$
VHI	3	1	$M^4\left[1+\left(\frac{\phi}{\mu}\right)^p\right]$
DSI	3	1	$M^4\left[1+\left(\frac{\phi}{\mu}\right)^{-p}\right]$
GMLFI	3	1	$M^4\left(\frac{\phi}{M_{\rm Pl}}\right)^p\left[1+\alpha\left(\frac{\phi}{M_{\rm Pl}}\right)^q\right]$
LPI	3	3	$M^4\left(\frac{\phi}{\phi_0}\right)^p\left(\ln\frac{\phi}{\phi_0}\right)^q$
CNDI	3	3	$\frac{M^4}{\left\{1+\beta\cos\left[\alpha\left(\frac{\phi-\phi_0}{M_{\rm Pl}}\right)\right]\right\}^2}$

Inflation: a mechanism, not a unique theory!

Encyclopædia Inflationaris J. Martin, et al (2013)

Case study

Inflation $\longrightarrow$ graceful exit $\longrightarrow$ SCM evolution
(quasi-exp. expansion)

Many models!!!

CHAOTIC INFLATION

Linde(1982)

Conditions

- Single field
- Potential that has a slow-roll region
- Graceful exit
- General initial conditions

$\Rightarrow \quad \phi_i \gg m_{pl}$

(Large field)

Types of potential:

- Polinomial $V(\phi) \propto \phi^p$
- Power law $V(\phi) \propto 1 + \cos(\phi/f)$
- Intermediary inflation $V(\phi) \propto \phi^{-\beta}$
- Natural inflation $V(\phi) \propto \exp(\phi/m_{pl})$

Models of inflation

Inflation: a mechanism, not a unique theory!

SLOW-ROLL INFLATION

Large field inflation: $\Delta\phi \gg m_{pl}$

In large-field models the field moves over a large (super-Planckian) distances.
Predicts: amplitude of the gravitational waves produced during inflation is large

Small field inflation: $\Delta\phi \ll m_{pl}$

In small-field models the field moves over a small (sub-Planckian) distance.
Small-field models predicts: amplitude of the gravitational waves produced during inflation is too small to be detected.

The potentials that give rise to such small-field evolution often arise in mechanisms of *spontaneous symmetry breaking*, e.g., Higgs-like potential

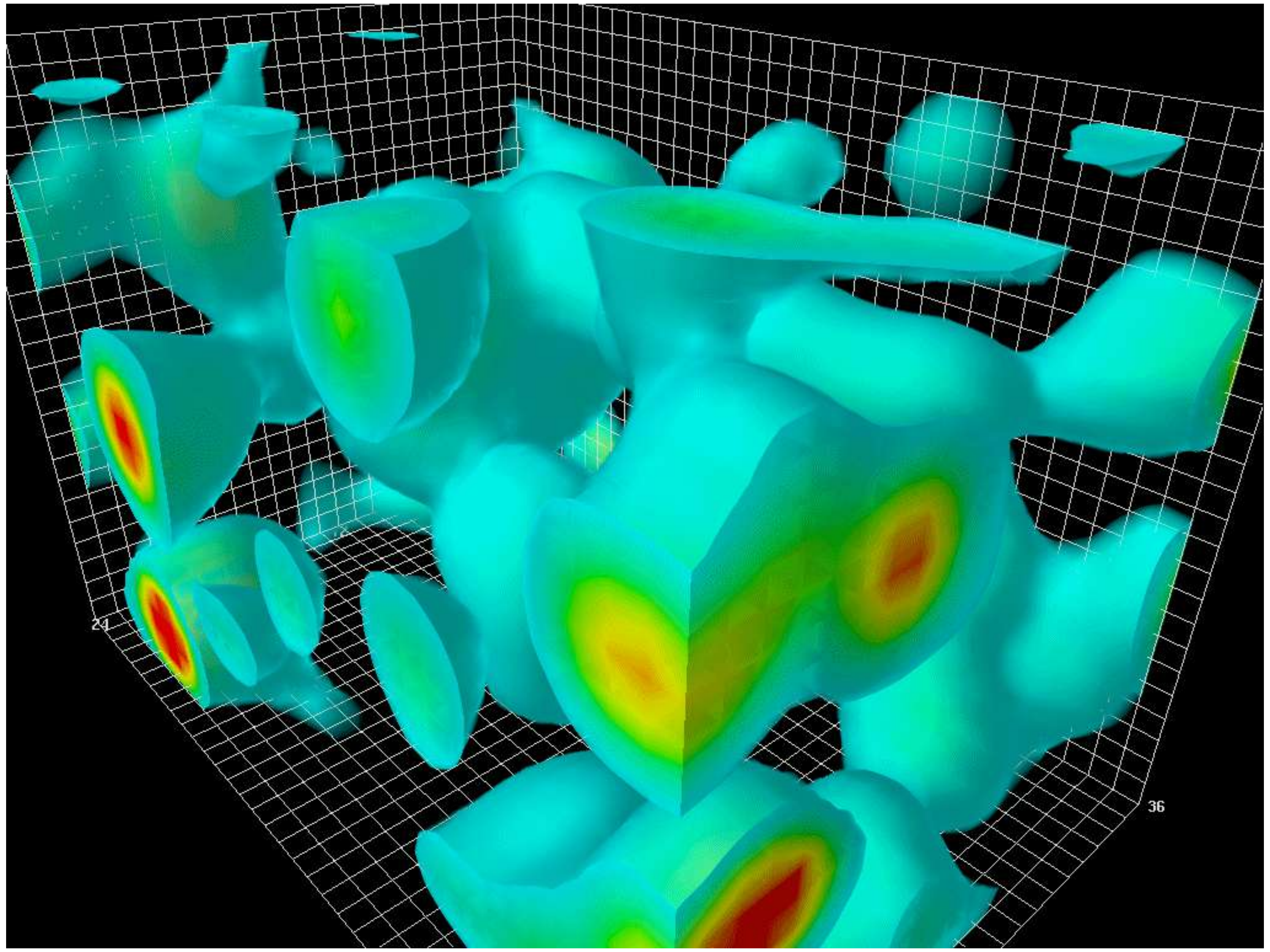
$$V(\phi) = V_0 \left[1 - \left(\frac{\phi}{\mu}\right)^2\right]^2 (+\dots)$$

BEYOND SLOW-ROLL INFLATION

- Non-minimal coupling to gravity
- Modified gravity
- Non-canonical kinetic term
- Multifield inflation

Inflation - Origin of structures

In quantum mechanics the vacuum or empty space if full of fluctuations



Uncertainty principle

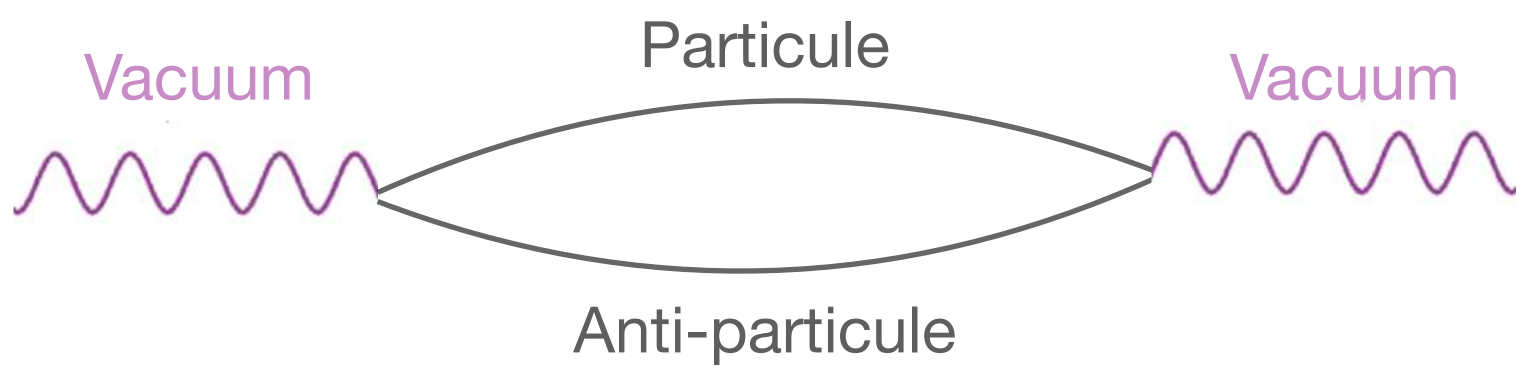
$$\Delta x \Delta p \geq \hbar$$

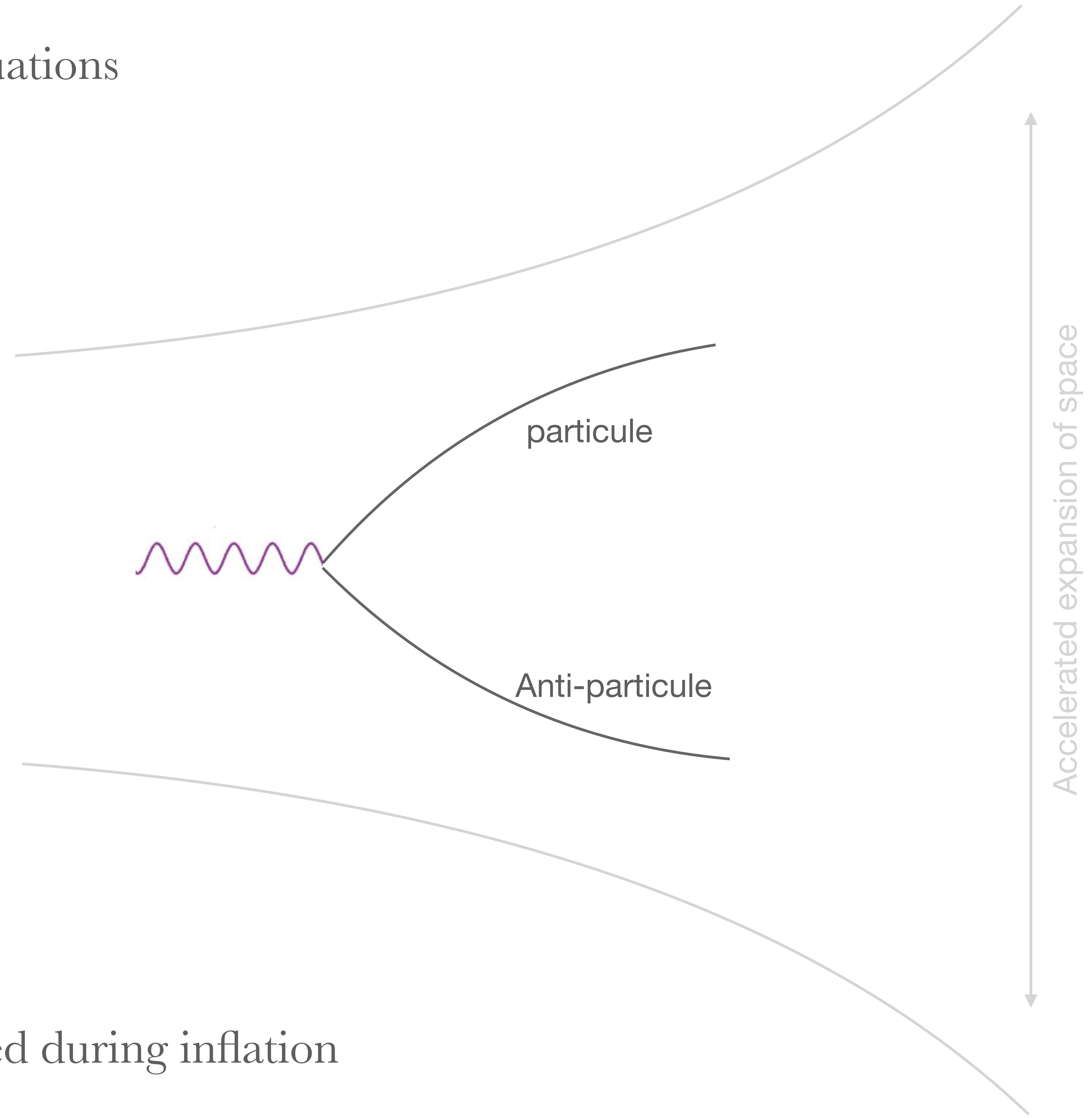
These fluctuations are real and present in our universe. But their effects are very small.

Inflation - Origin of structures

In quantum mechanics the vacuum or empty space if full of fluctuations

Pictorially:

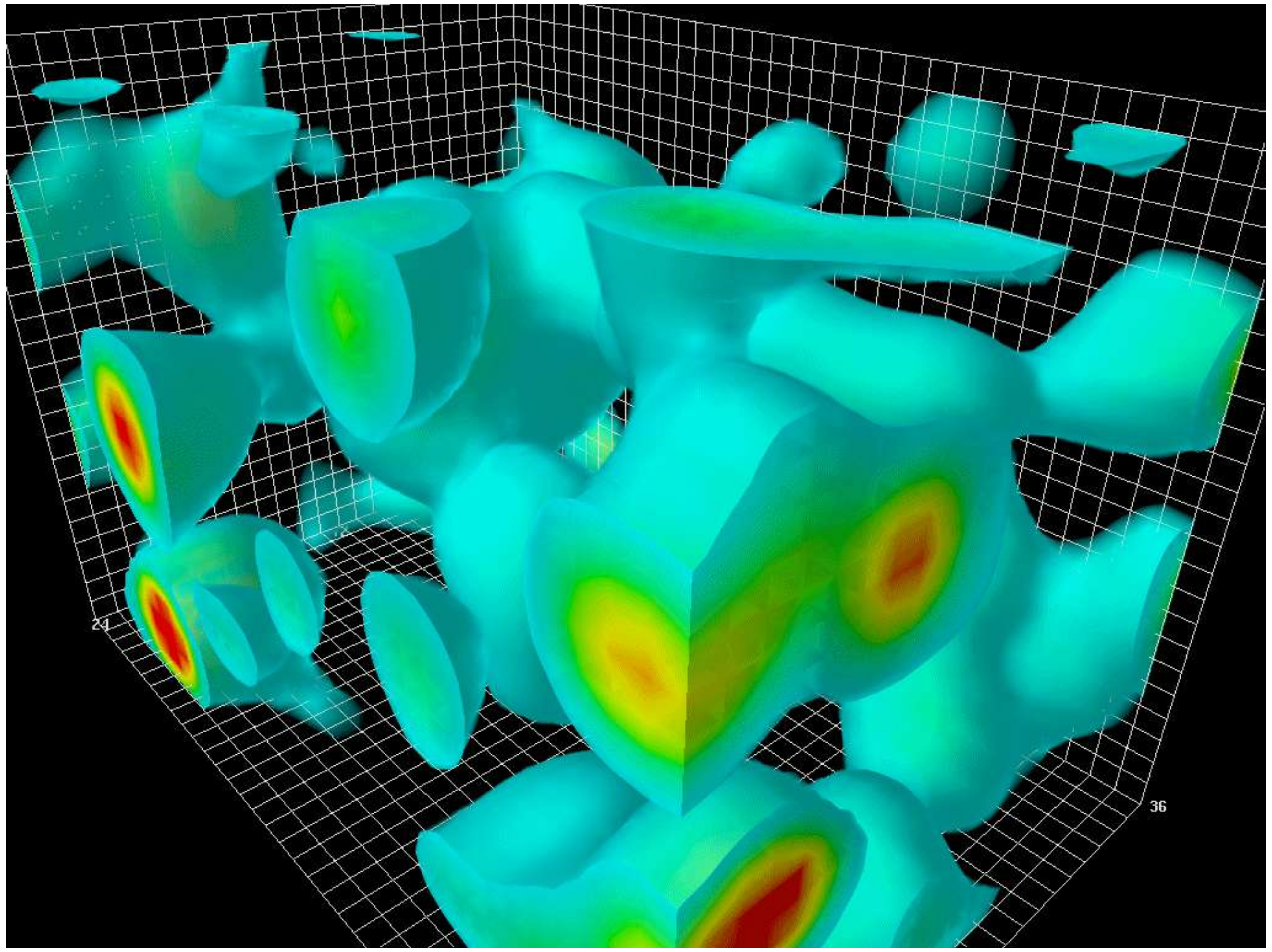




These particles describe the quantum perturbations that are generated during inflation

Inflation - Origin of structures

The initial perturbation have a quantum origin in the beginning of the universe, during inflation *

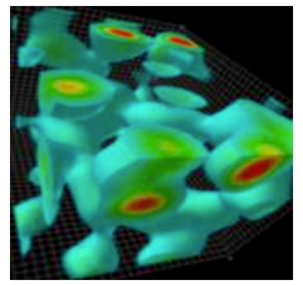


Possible since inflation puts all the regions in the universe in causal contact

Inflation - Origin of structures

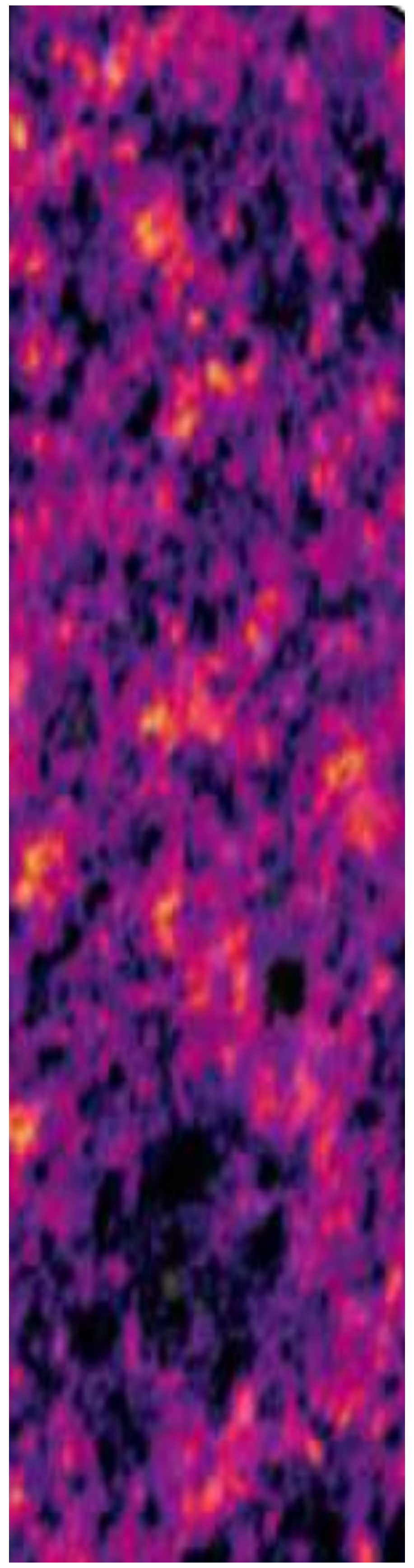
In $\sim 10^{-32}$ seconds, the universe grew exponentially in size

Perturbations are amplified
and stretched during *inflation*



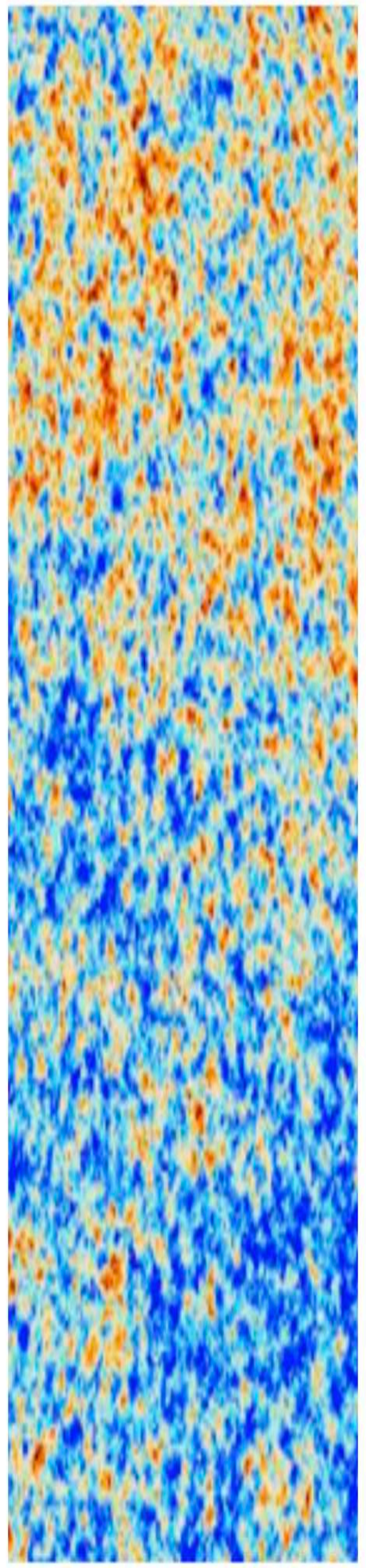
Microscopic initial
perturbations

$$a(t) \simeq e^{H\,t}$$



Classical and
macroscopic
perturbations

Radiation
era



CMB

Inflation - Origin of structures

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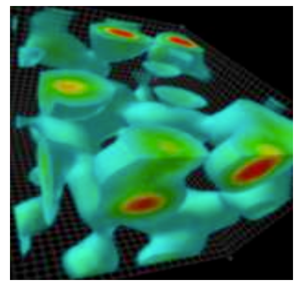

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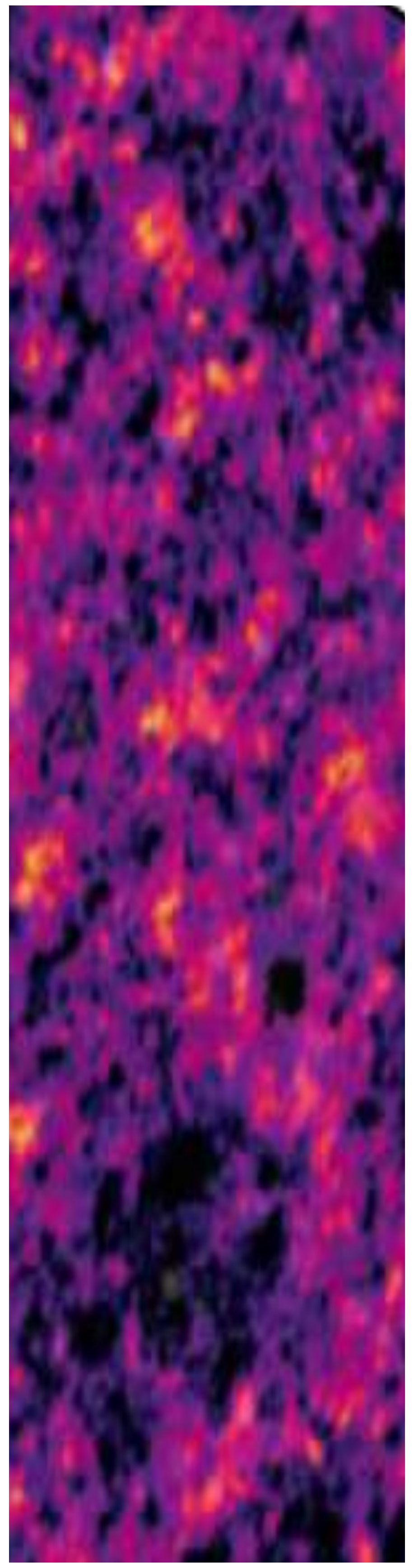

Classical and
macroscopic
perturbations

Radiation
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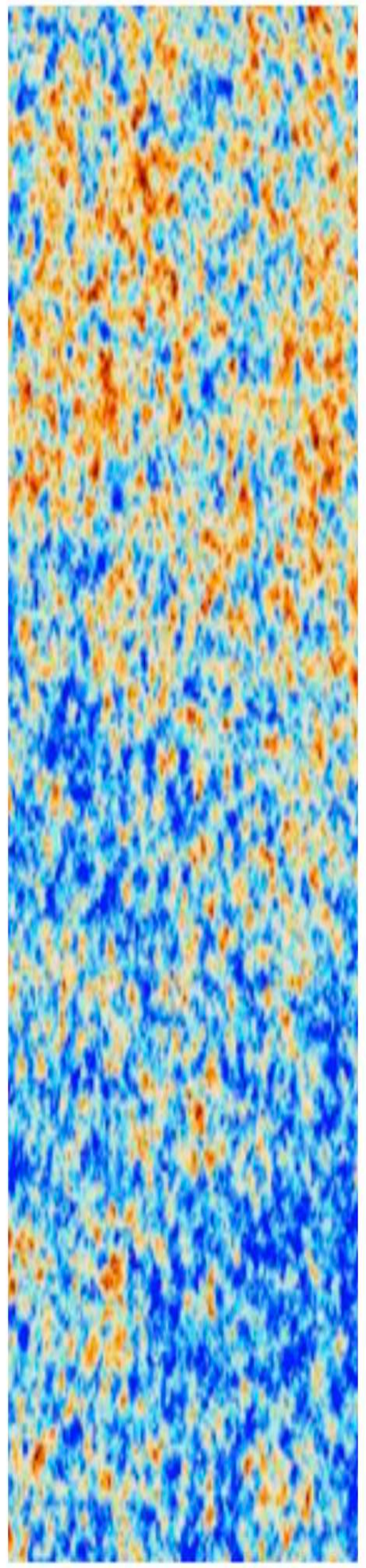
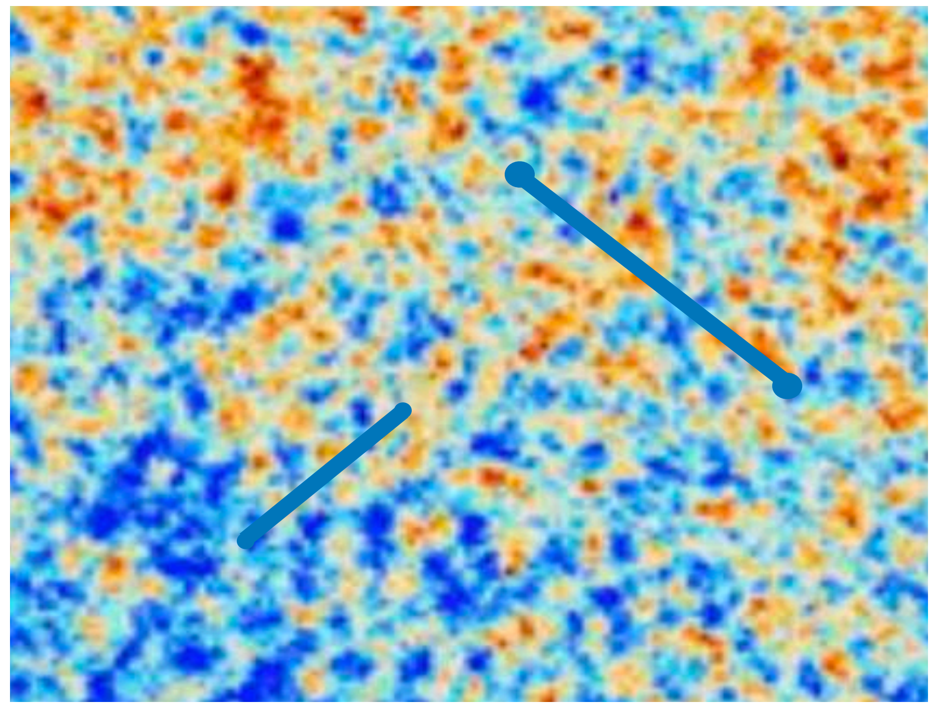


CMB

✔ Solves the formation of structure problem

What we measure?

The inflationary perturbations create perturbations with an almost scale invariant spectrum



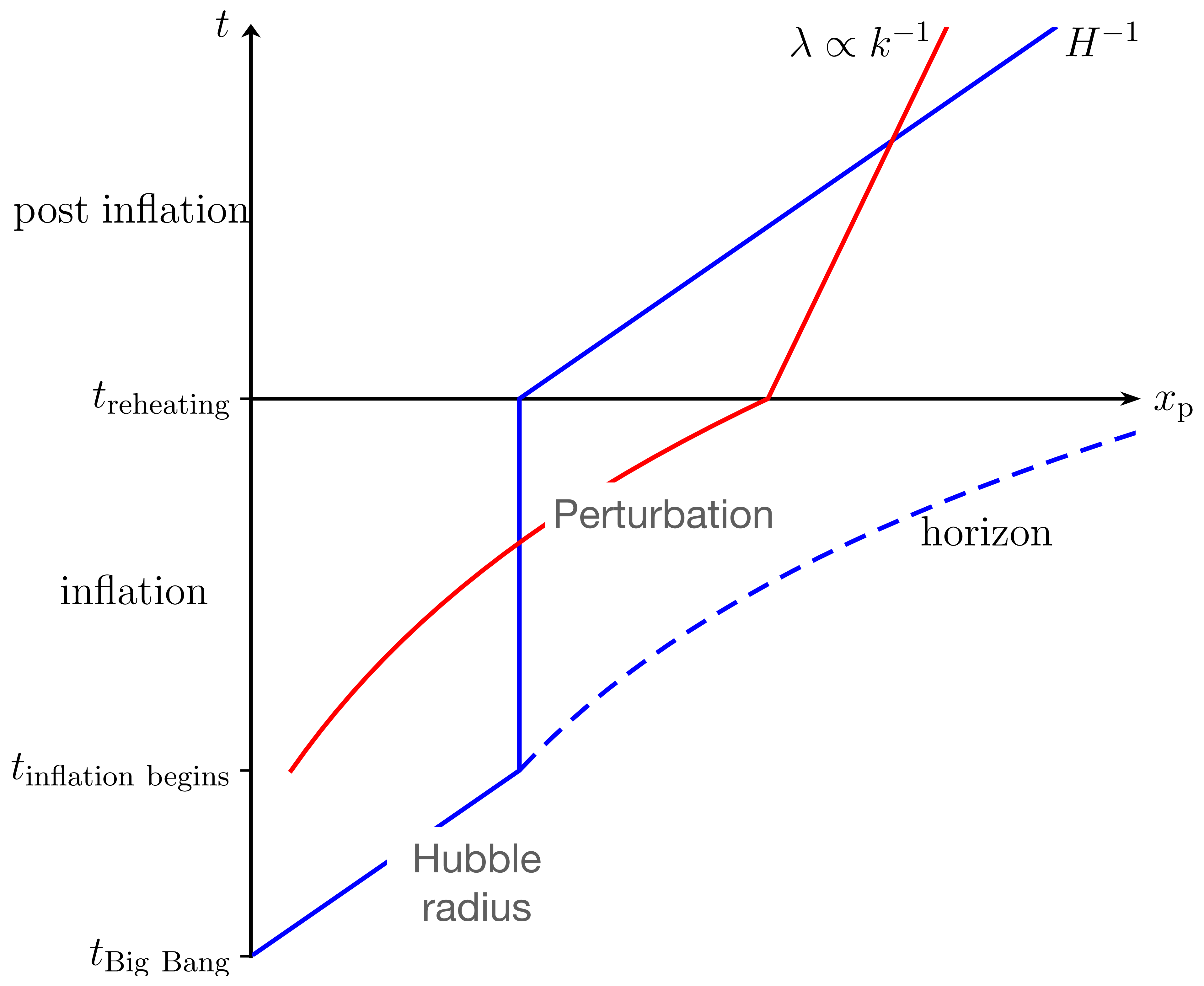
$$P(k) = A_S \left(\frac{k}{k_*}\right)^{n_S - 1}$$

$n_s \longrightarrow$ Scale dependence of the initial fluctuations
$A_s \longrightarrow$ Amplitude of the initial fluctuations

Predictions in accordance with what is measured in the CMB!

$\Omega_b = 0.0484 \pm 0.0003 \longrightarrow$ Amount of visible/ordinary matter
$\Omega_m = 0.308 \pm 0.012 \longrightarrow$ Amount of dark matter
$\Omega_\Lambda = 0.692 \pm 0.012 \longrightarrow$ Amount of dark energy
$n_s = 0.9626 \pm 0.0057 \longrightarrow$ Scale dependence of the initial fluctuations
$10^9 A_s = 2.092 \pm 0.034 \longrightarrow$ Amplitude of the initial fluctuations
$\tau = 0.0522 \pm 0.0080 \longrightarrow$ Optical depth

Inflation - Origin of structures



Problems with inflation

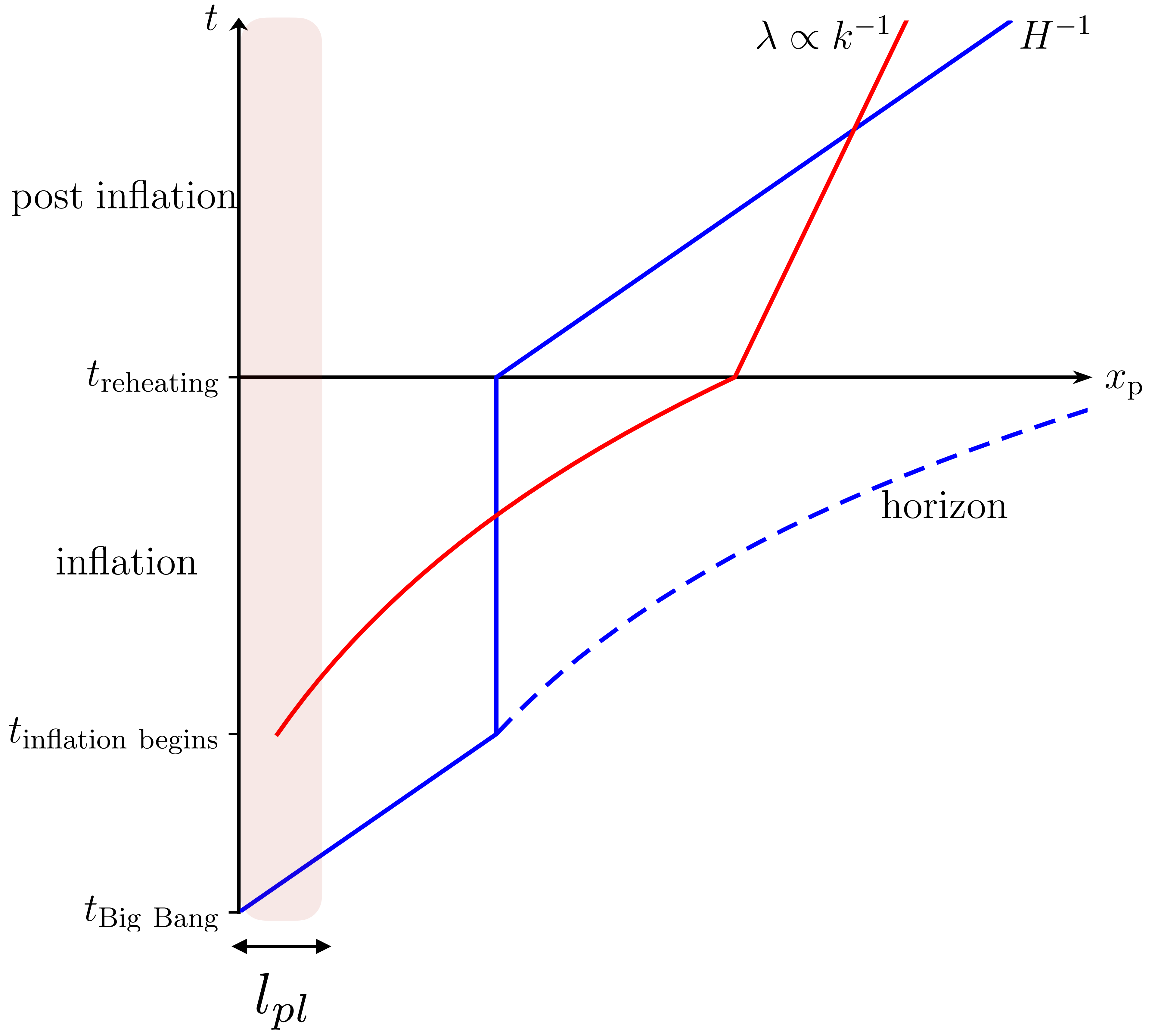
- Initial singularity
- Transplanckian problem
- Measure problem
- Hierarchy problem
- …

Inflation also has problems!

* still highly debated in the literature

Problems of inflation

- Inicial singularity
- Transplanckian problem
- Measure problem
- Hierarchy problem
- …



Alternatives to inflation

Alternatives to inflation

Scenarios:

Matter bounce
Ekpyrotic model

Pre-Big Bang model

Classical bounce
geodesic completeness

Bounce

Cyclic universe

Cyclic

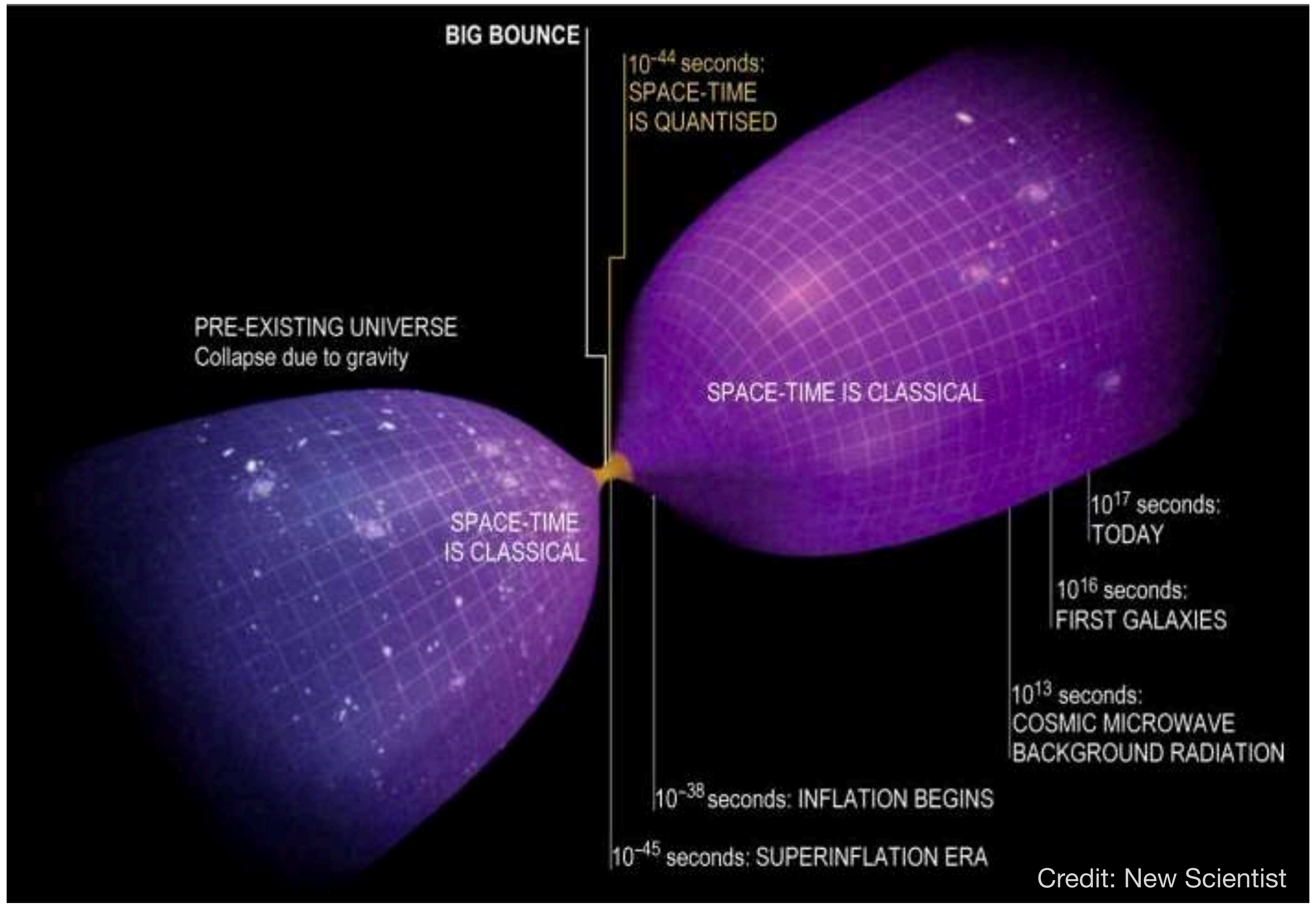
String Gas Cosmology
…

Emergent

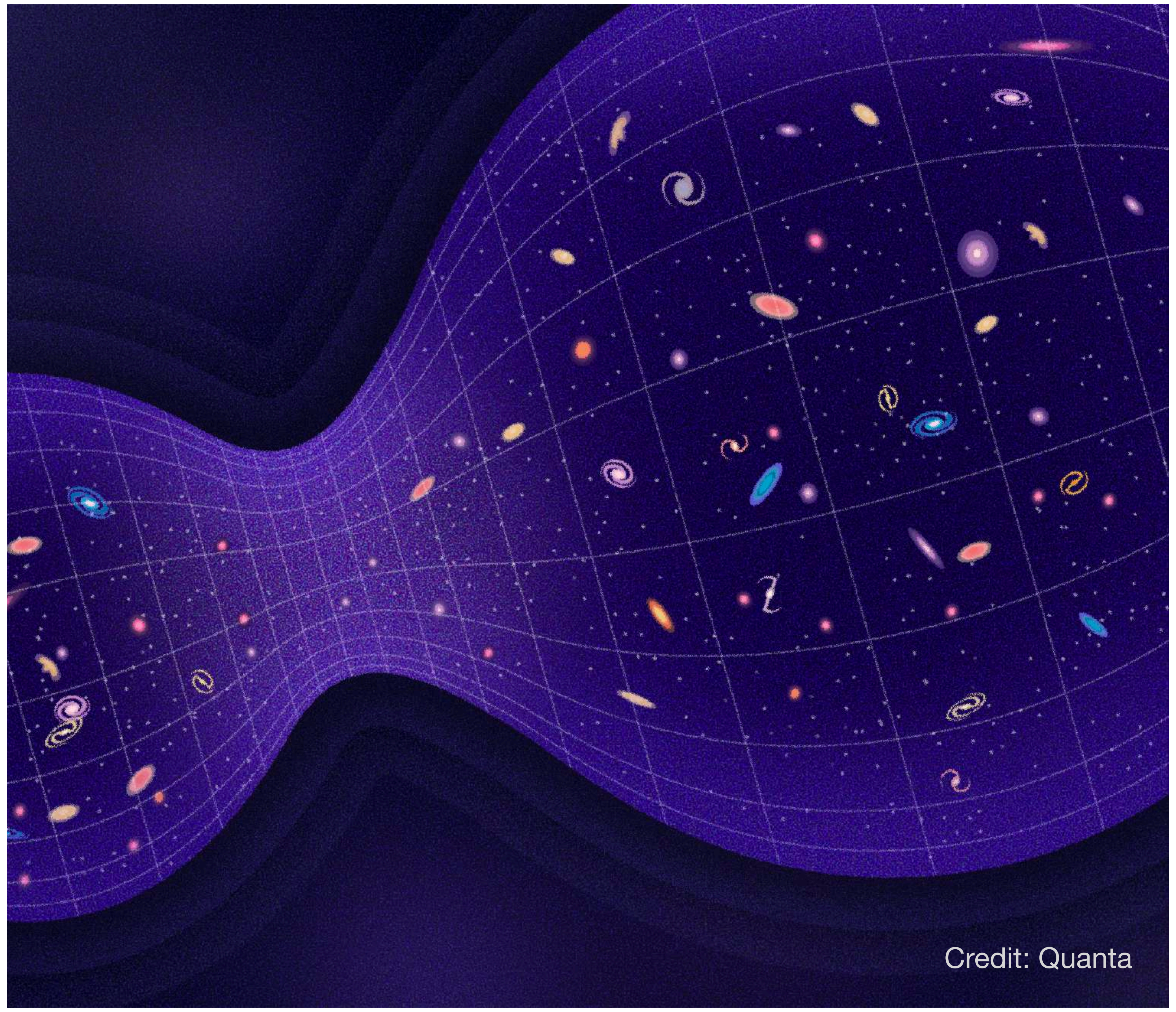
Bouncing models

Robert Brandenberger, Patrick Peter,
"Bouncing Cosmologies: Progress and Problems",
1603.05834

What if the universe did not have a beginning, but came from a previous phase of contraction, followed by the SCM



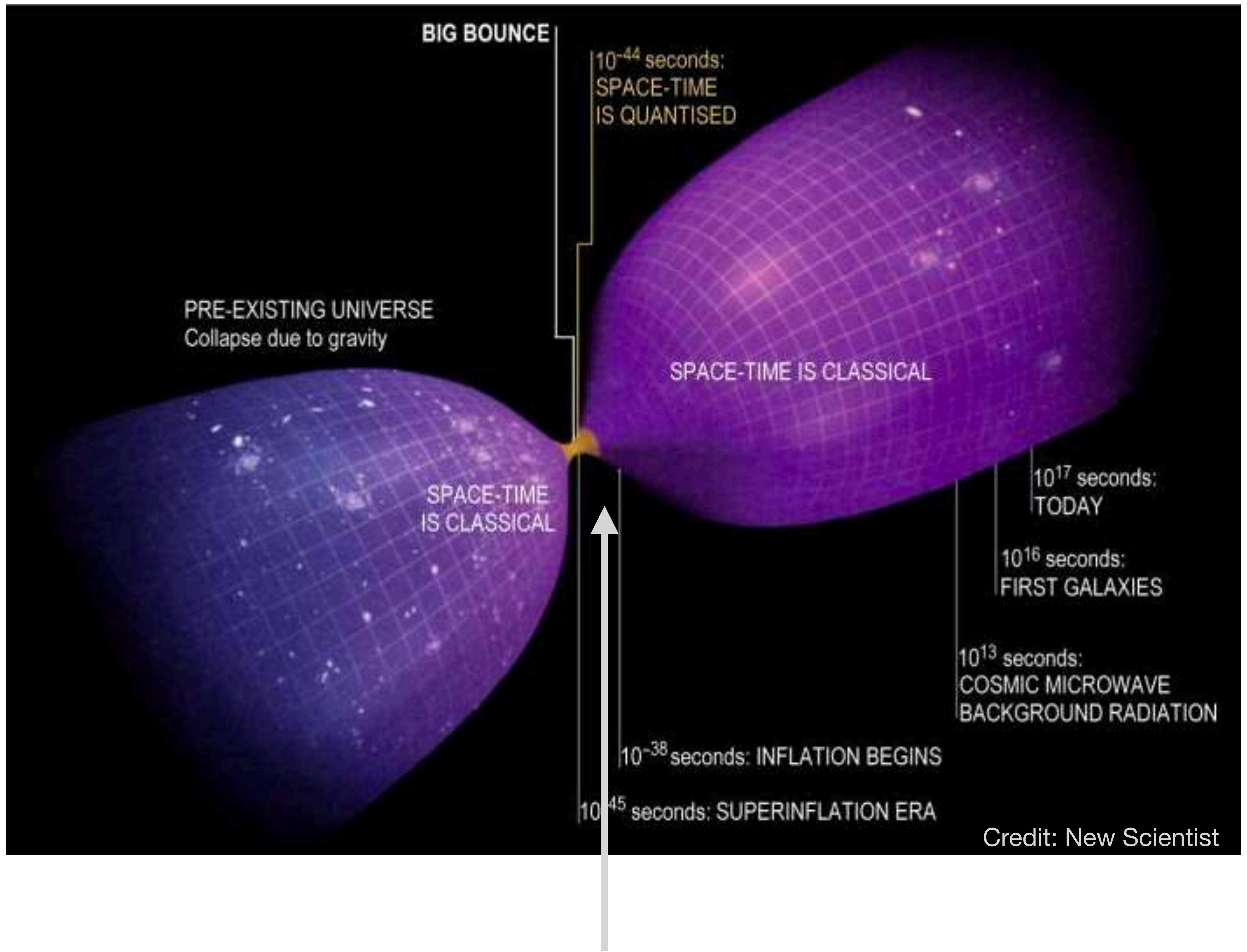
Credit: New Scientist


Credit: Quanta

Bouncing models

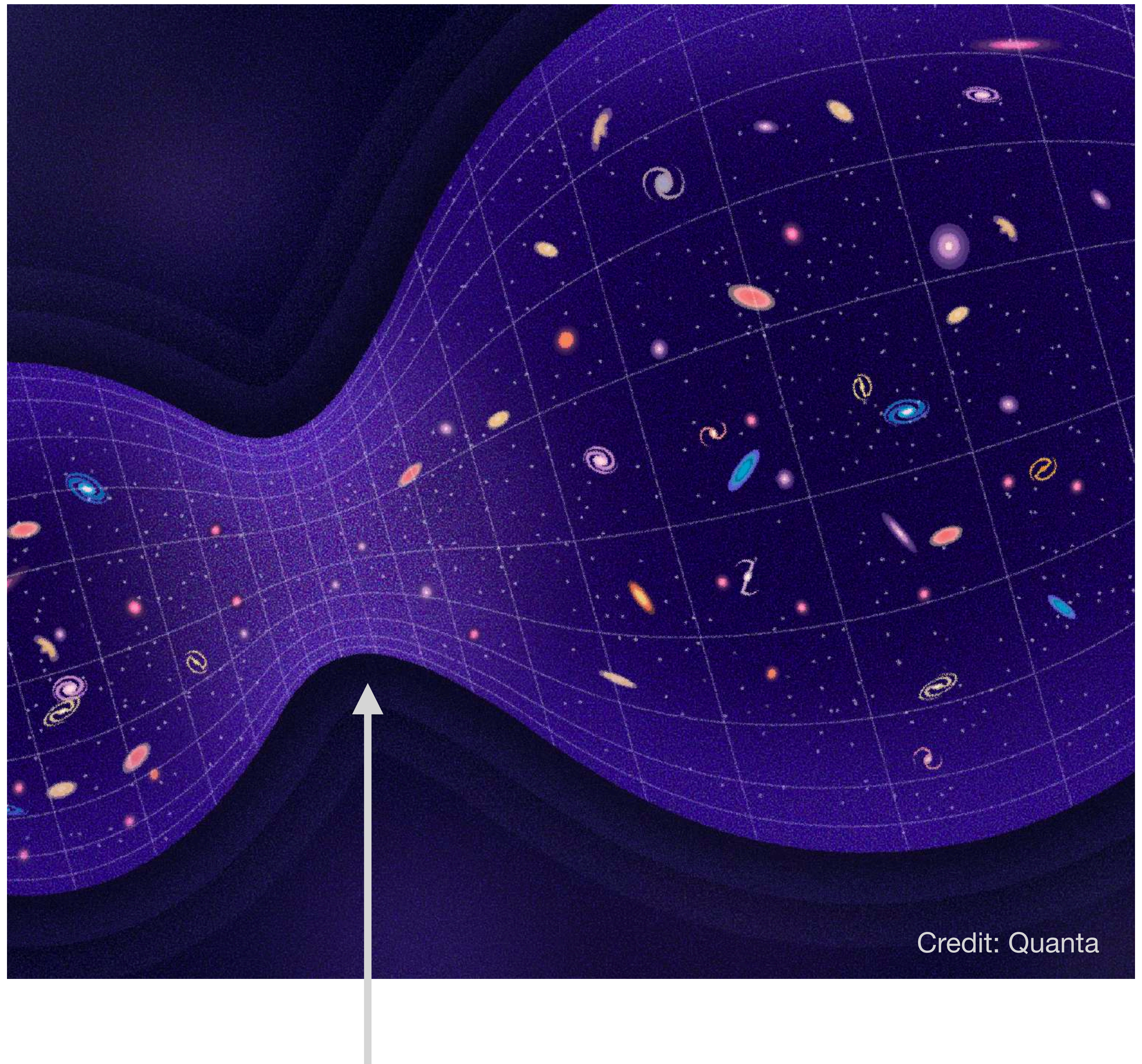
This *bounce* can occur in two ways:

<u>Singular bounce</u>



Singularity Big Bang/Big Crunch

<u>Non-singular bounce</u>



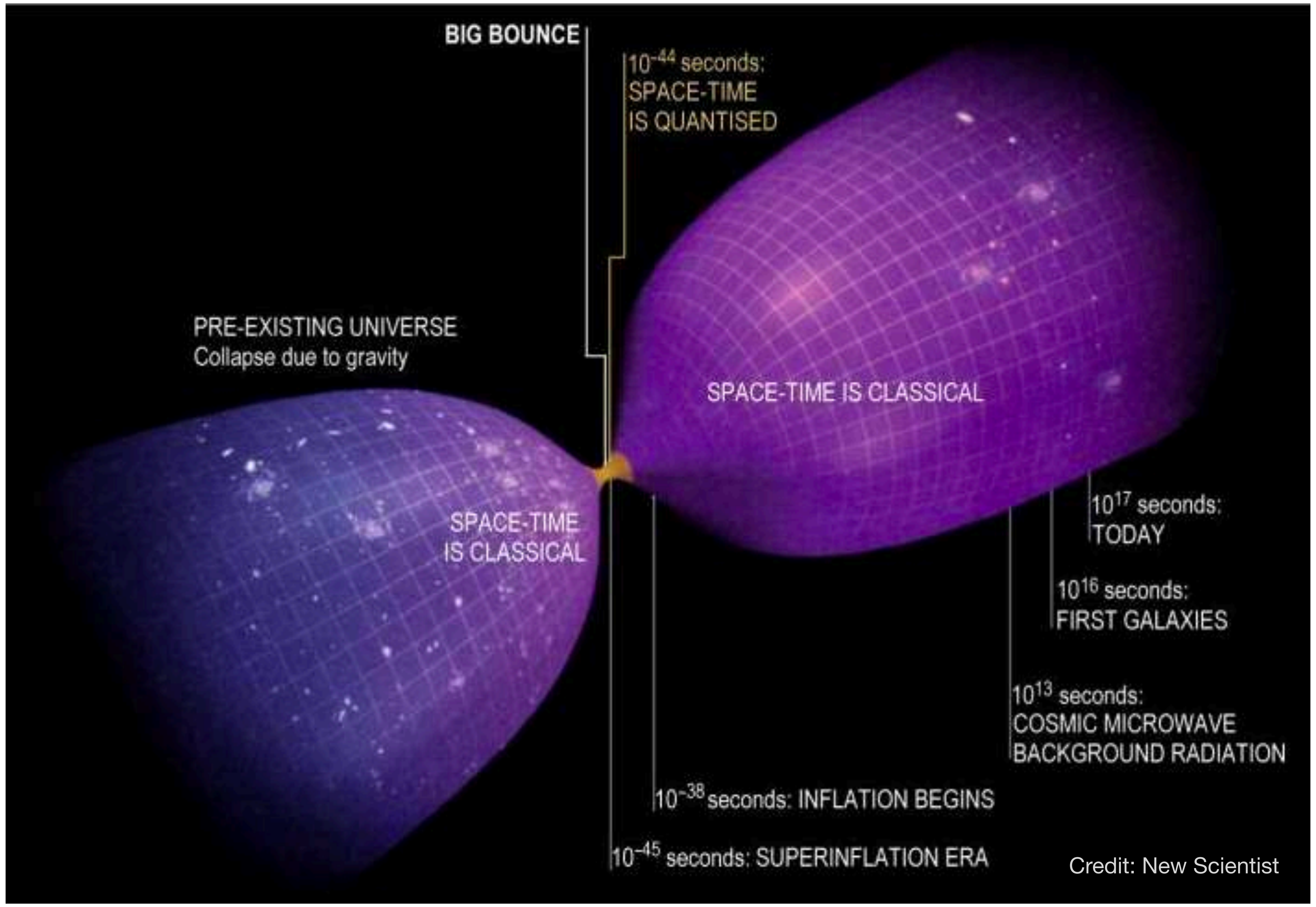
Classical bounce

Bouncing models

How is it possible to have these models?

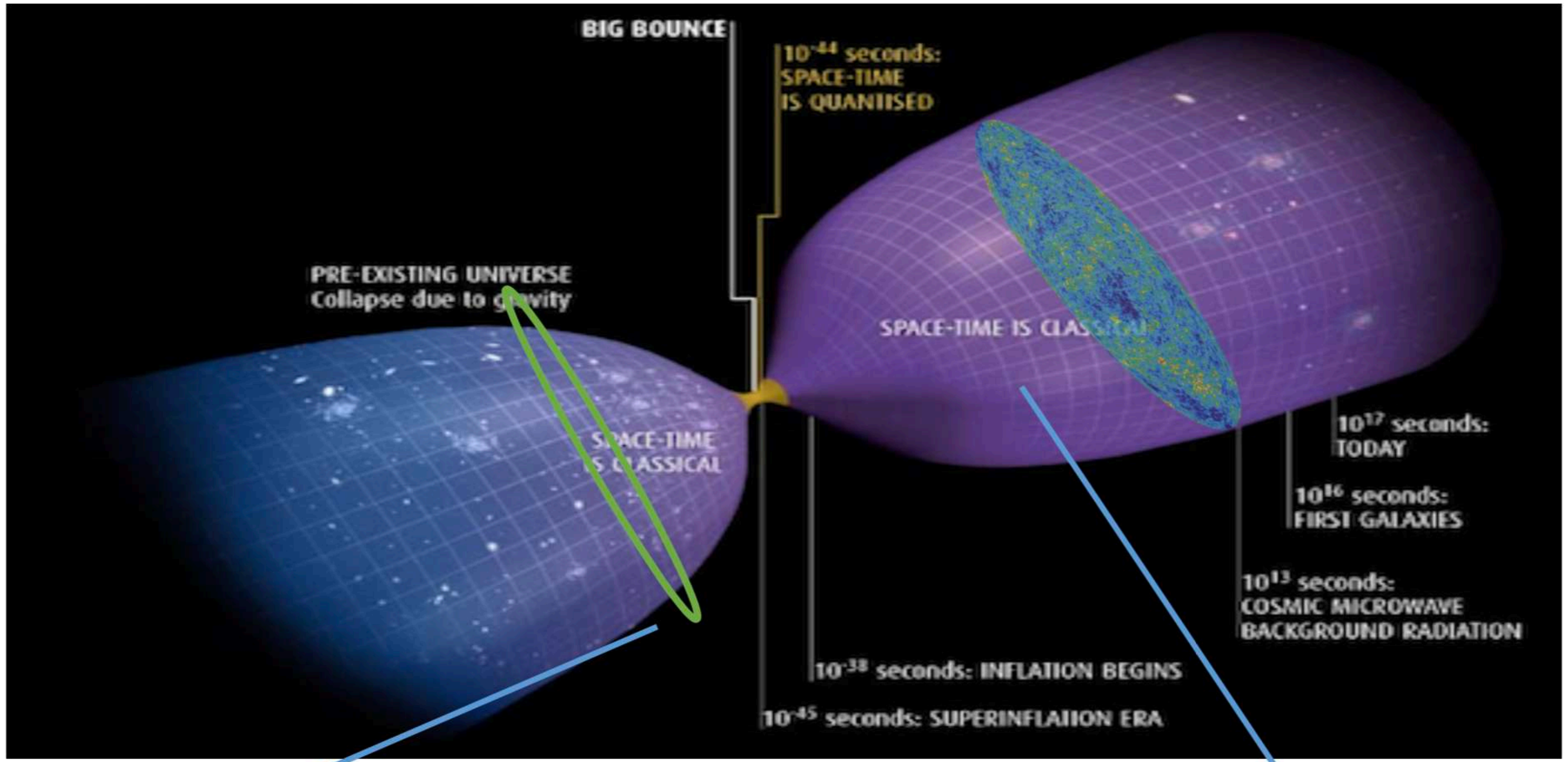
New physics

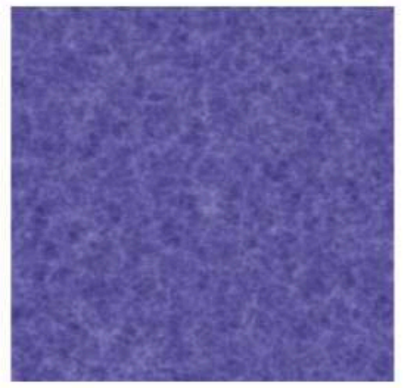
- Modified gravity theories
- New components dominate the universe during the contraction phase that make the universe have this dynamics → violates *null energy condition* $\rho + p > 0$
- …



Bouncing models

Solving the SCM:





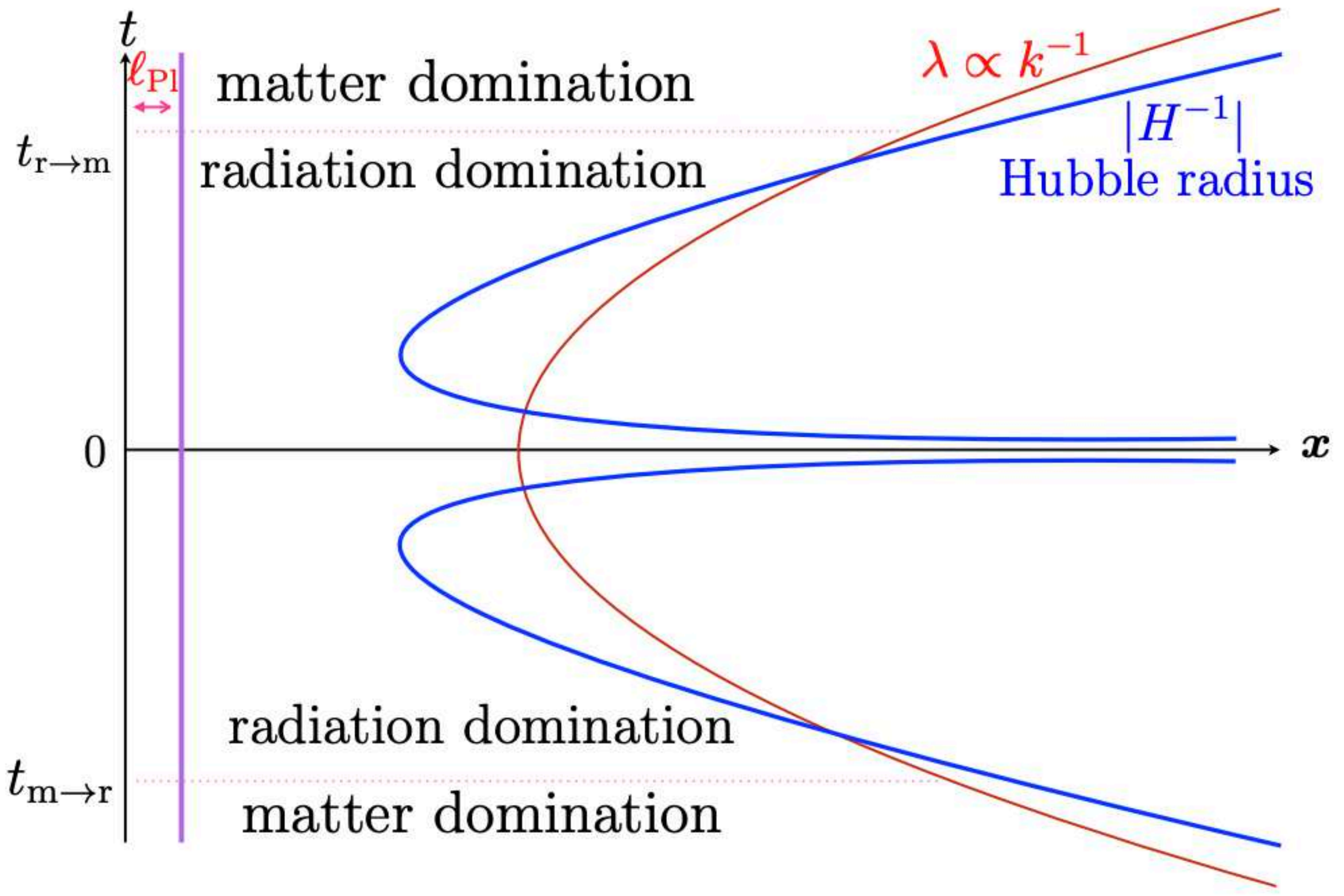
Smoothes and leaves the universe flat
Generates the same scale invariant spectrum

SCM

Bouncing models

Example: Matter bounce

Symmetric bounce



Bouncing cosmologies: scales of cosmological interest originate on sub-Hubble scales at early times in the contracting phase, in the same way that they originate on sub-Hubble scales early in inflation. It is possible to have a causal generation mechanism for fluctuations, as in inflation.

The nature of this structure formation mechanism depends on the specific bouncing model being considered

Alternatives to inflation

Scenarios:

Matter bounce

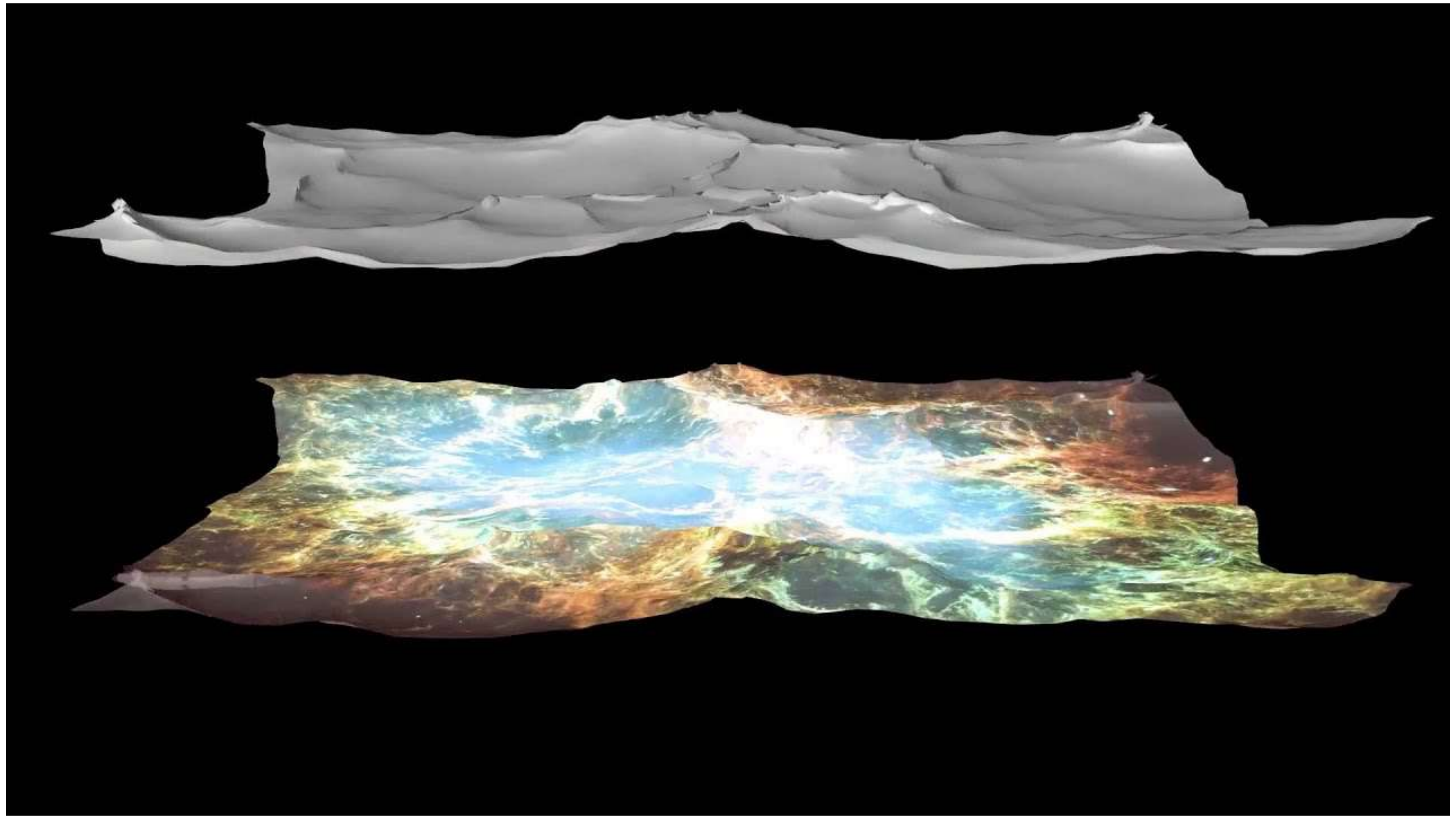
Ekpyrotic model

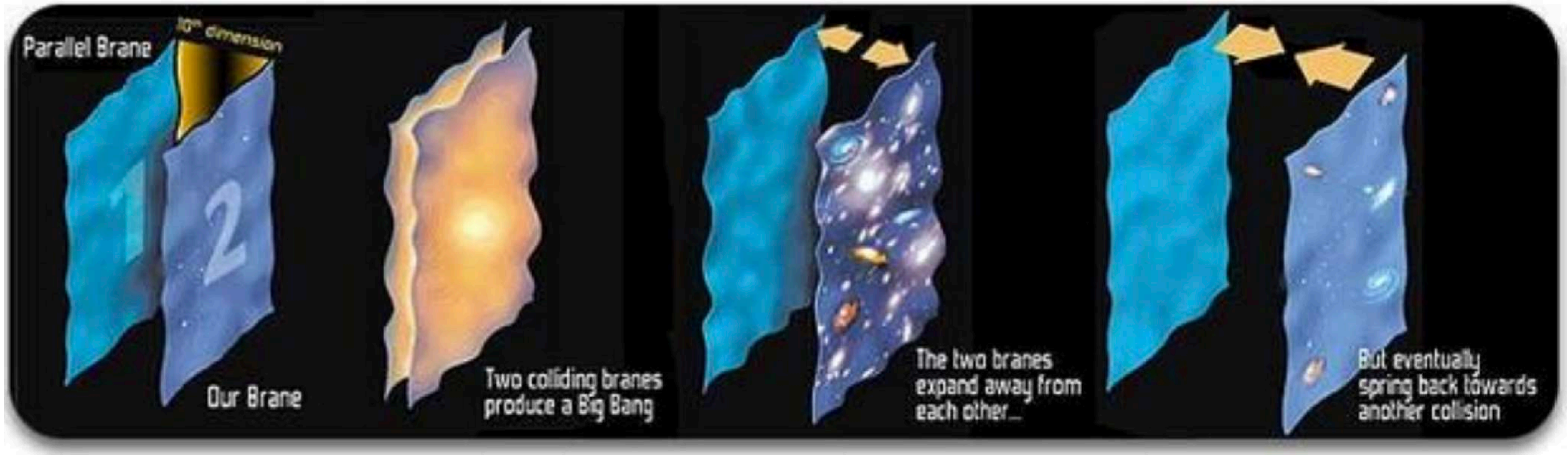
Pre-Big Bang model

Classical bounce

geodesic completeness

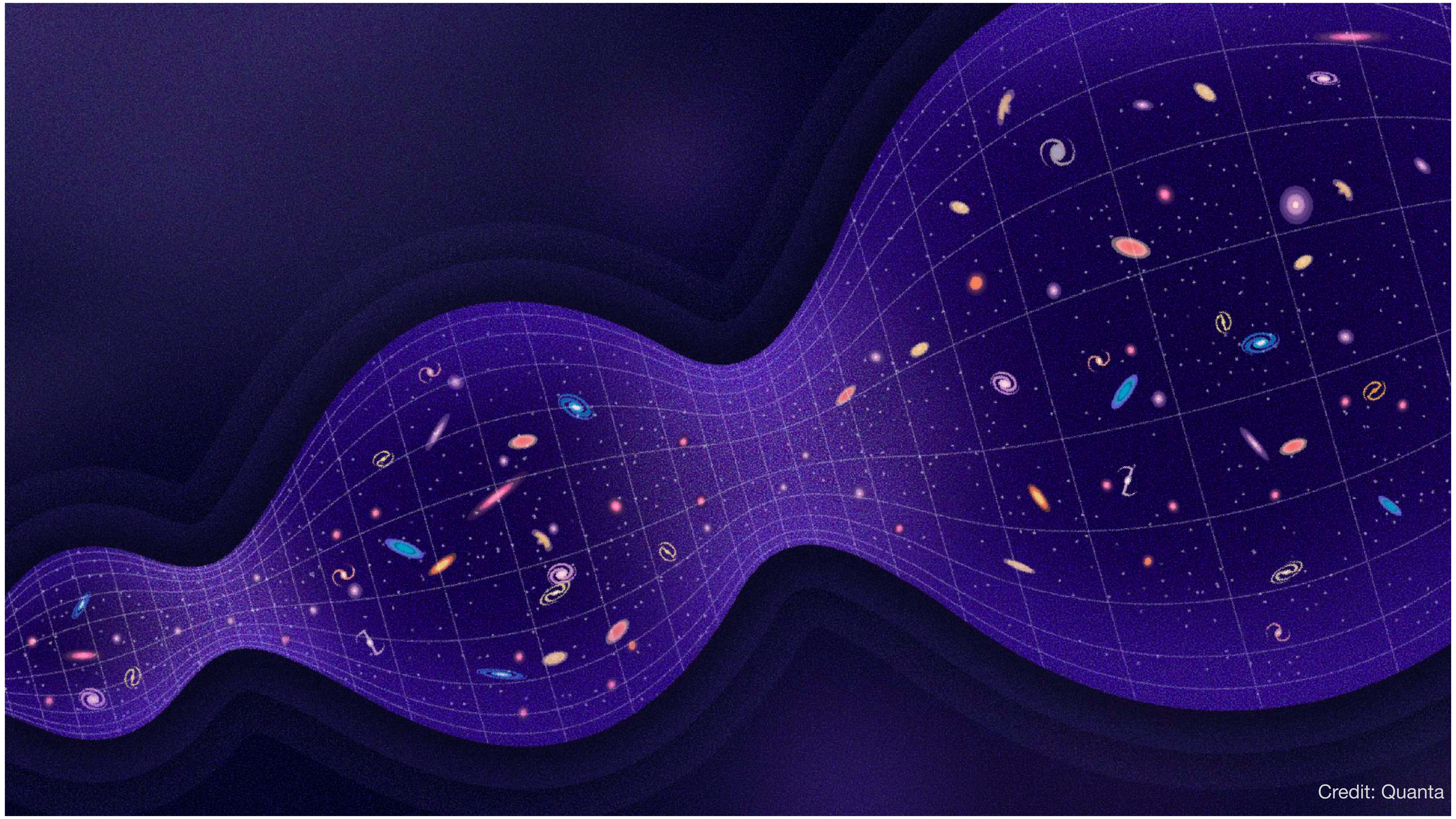
String Gas Cosmology



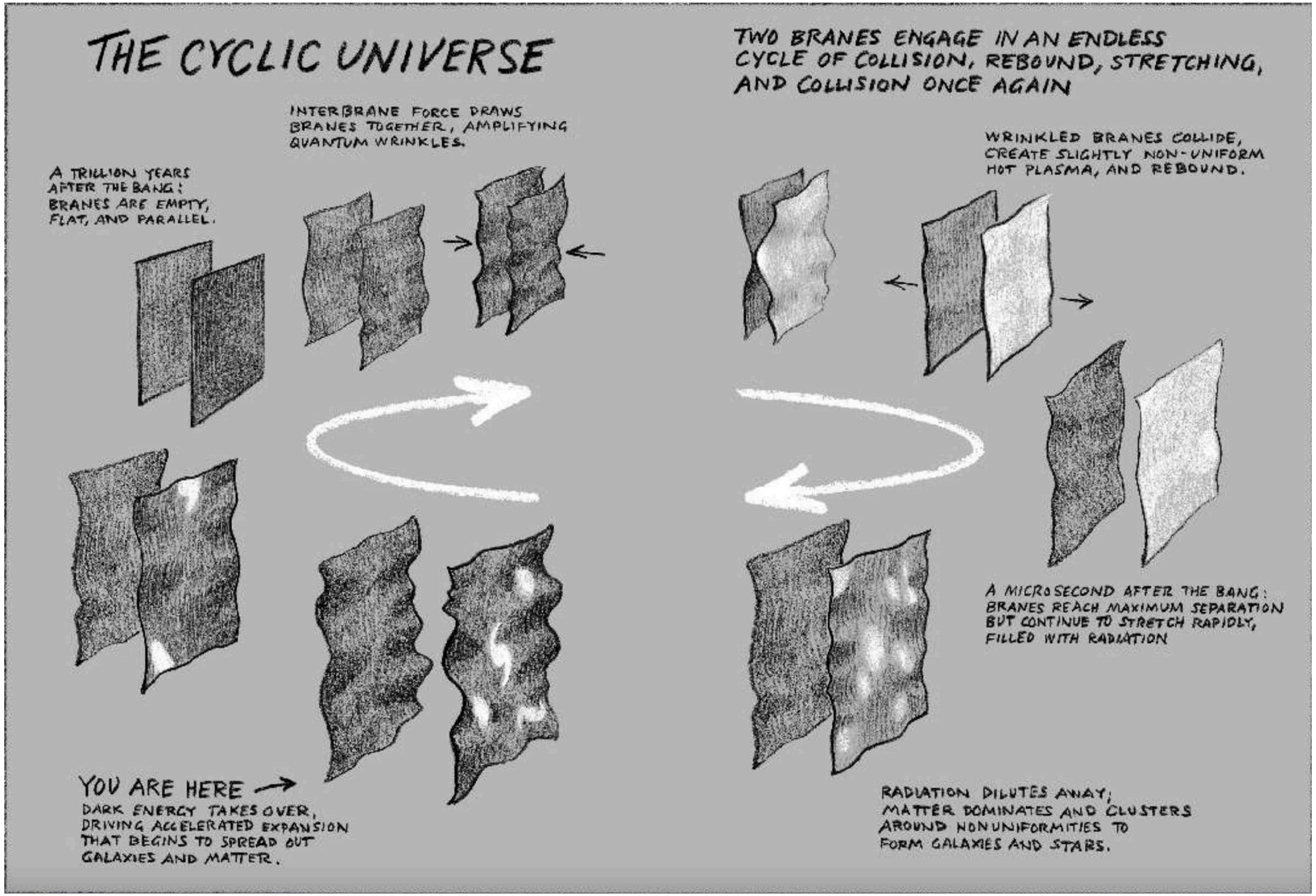


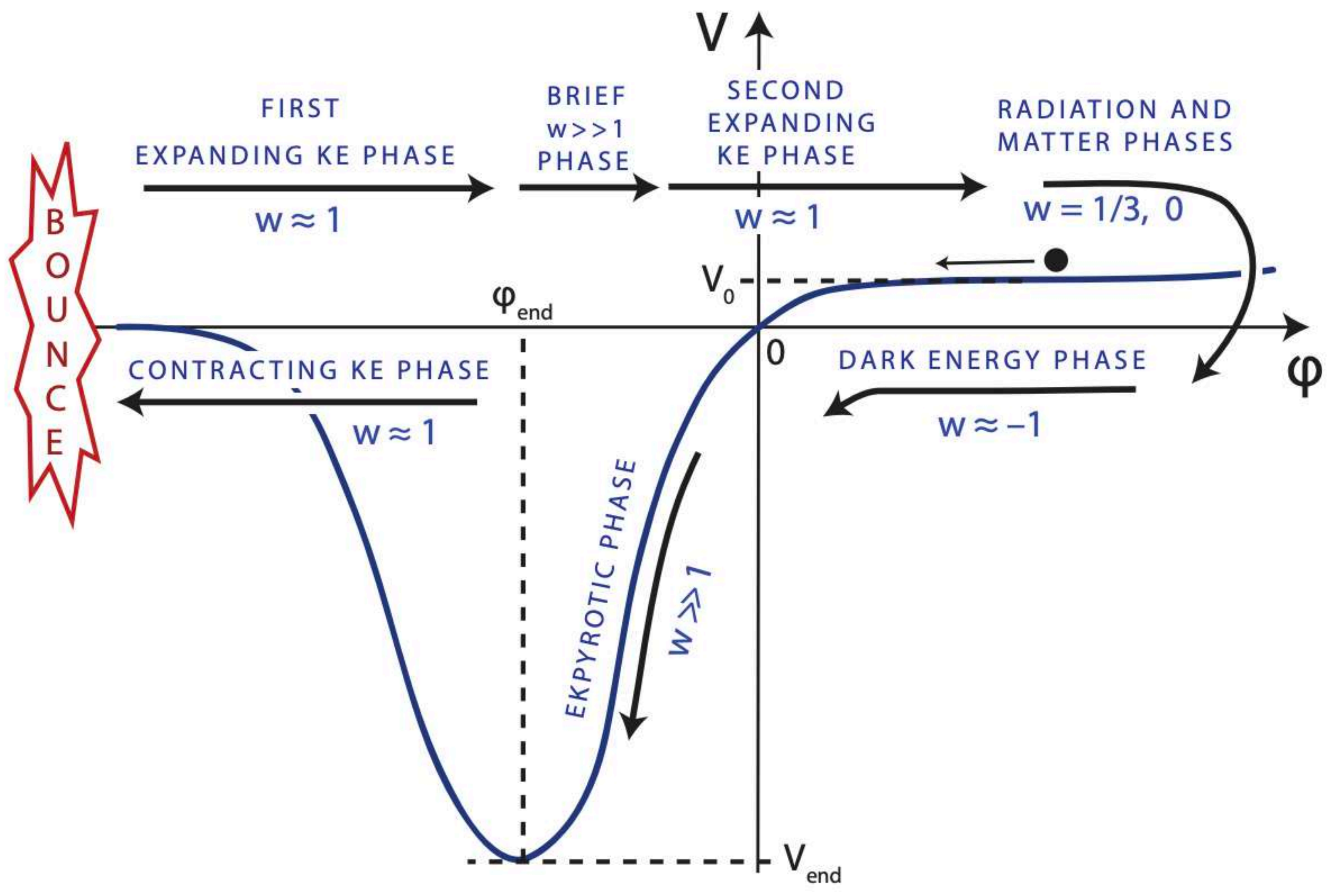
Cyclic *models*

Succession of periods of contraction and expansion



Cyclic models





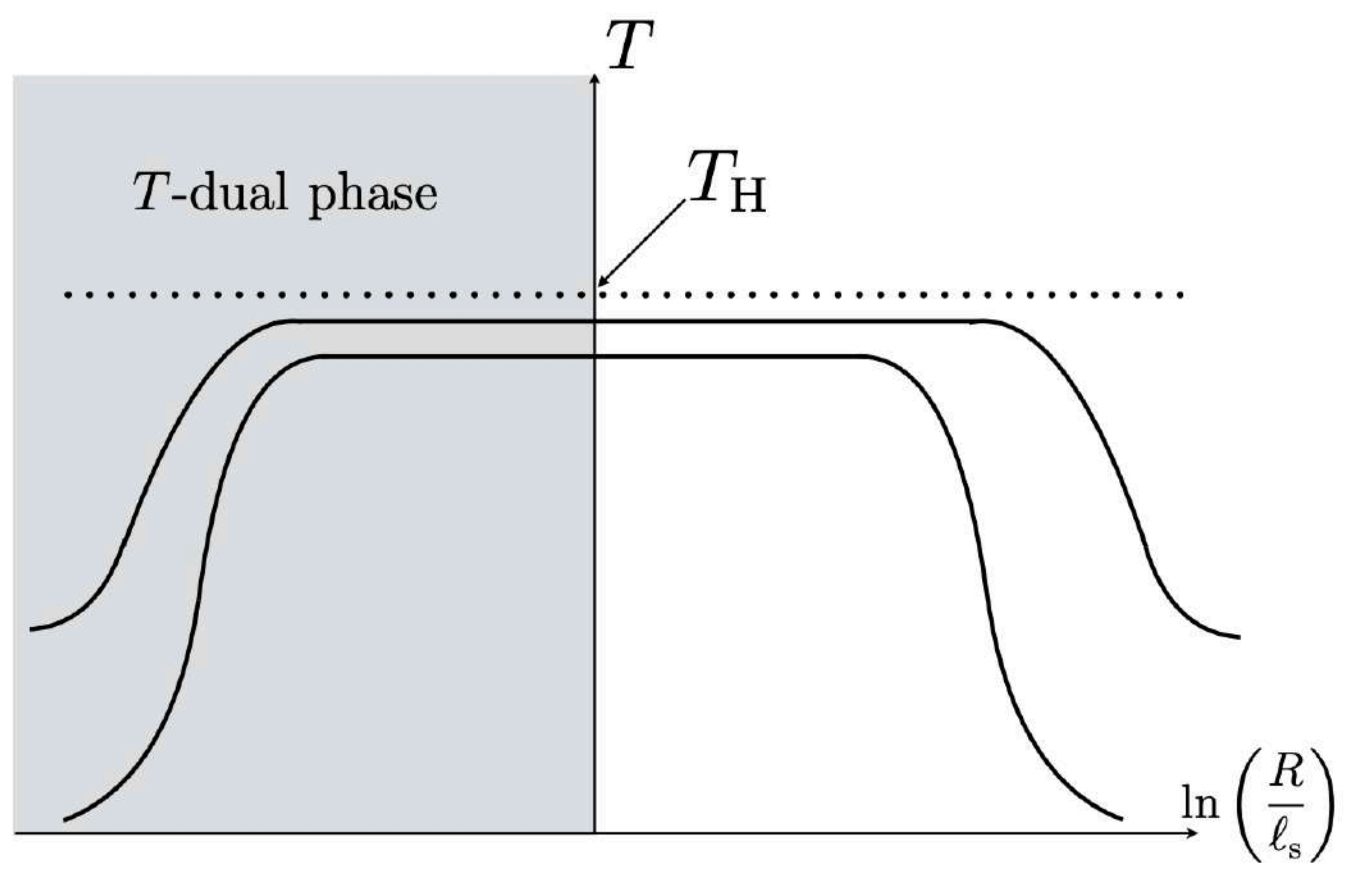
Credit: Paul Steinhardt

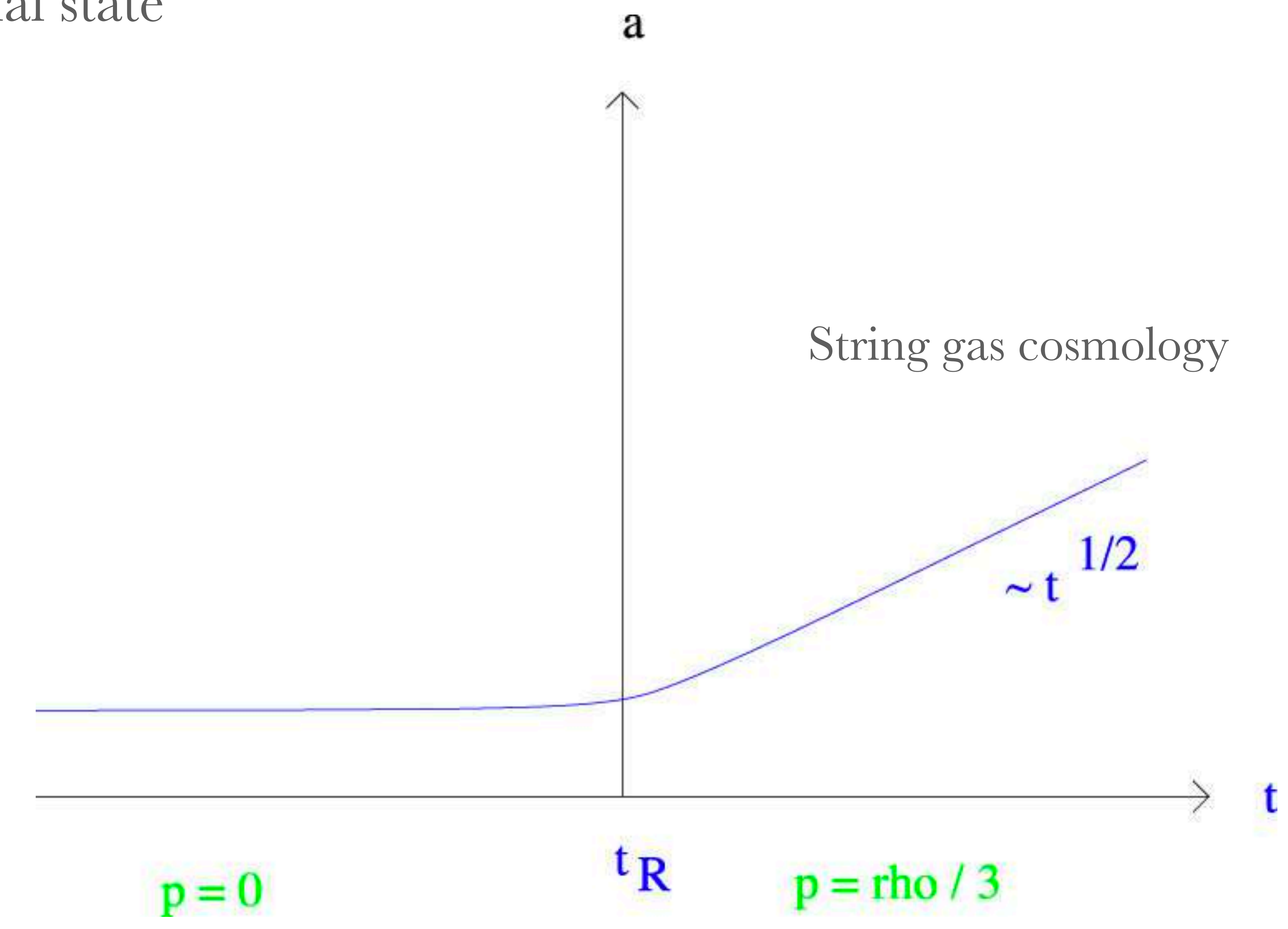
Emergent universe models

There is no initial singularity and the universe emerges from a initial state

For example:

- Initial stage
- *String gas cosmology*





Temperature T of a gas of closed strings in a box of radius R as a function of radius. T: never exceeds the Hagedorn temperature TH.

R. Brandenberger (2015)

The extent of the plateau of the T(R) curve depends on the total entropy of the system - the larger the entropy the wider the plateau

Emergent universe models

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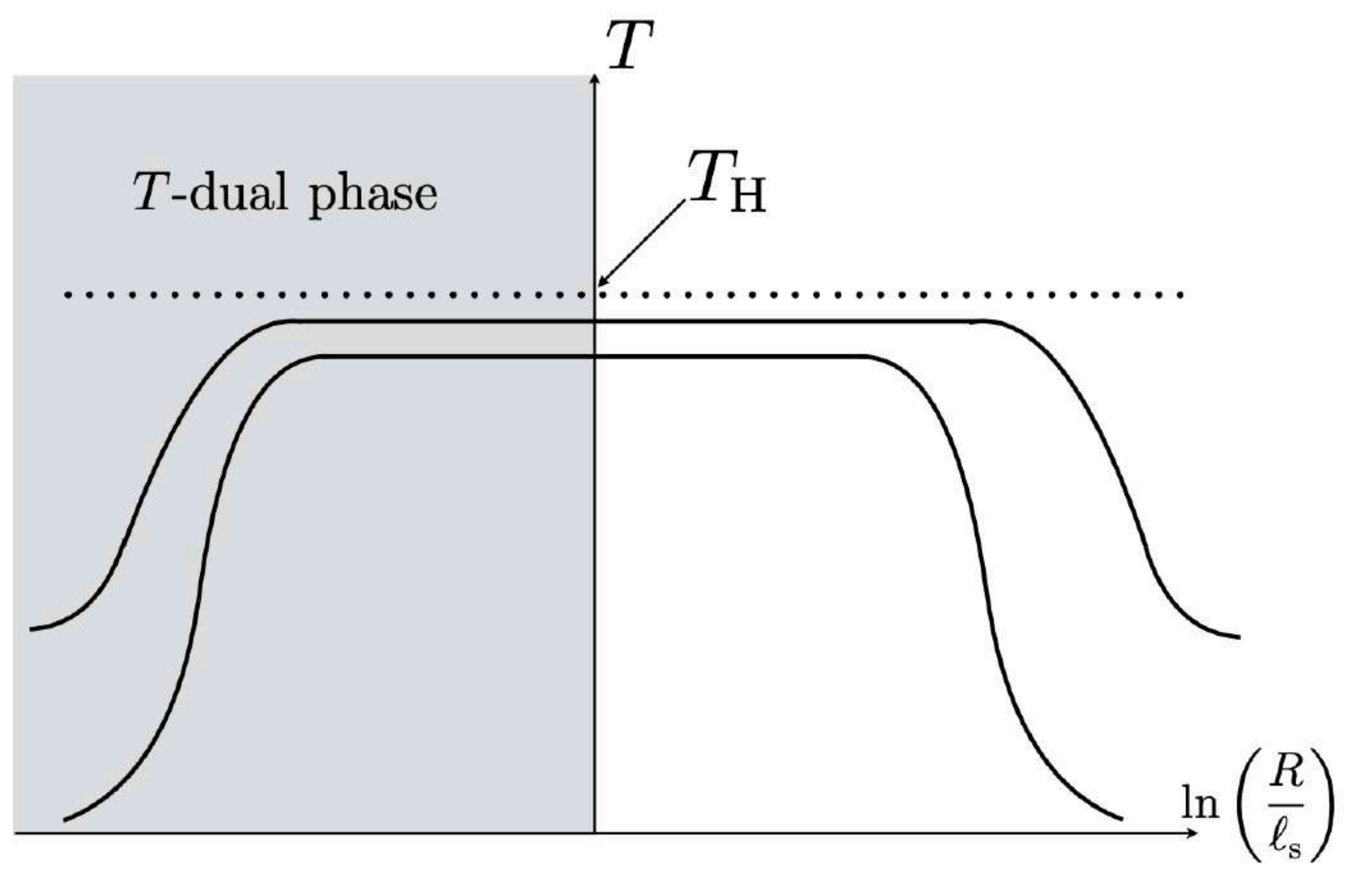

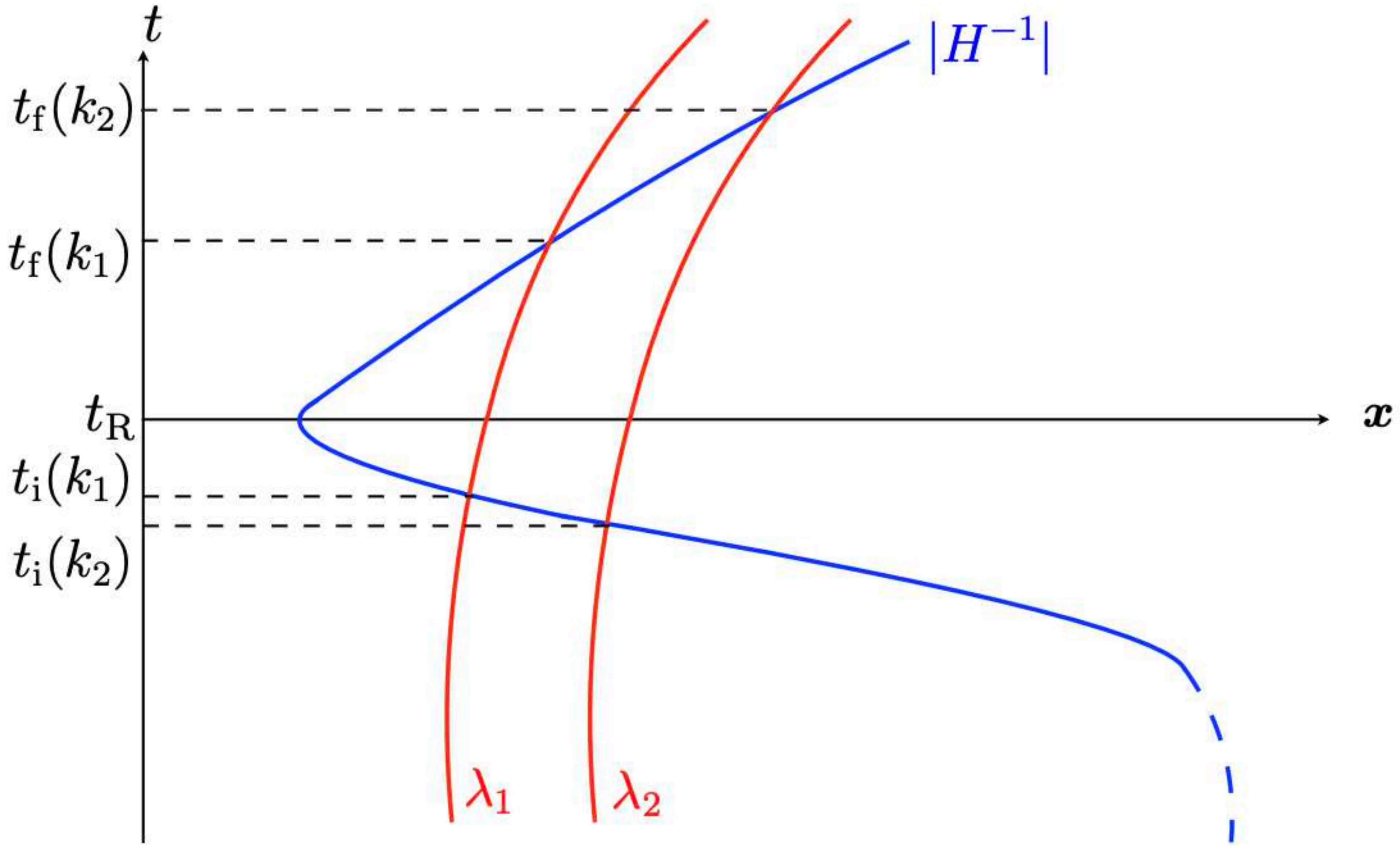

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Alternatives to inflation

Origin of the perturbations:

Matter bounce

Ekpyrotic model

Pre-Big Bang model

Quantum fluctuations

String Gas Cosmology

…

Thermal initial fluctuations

How to distinguish between models?

Can we falsify or rule out inflation or alternatives?

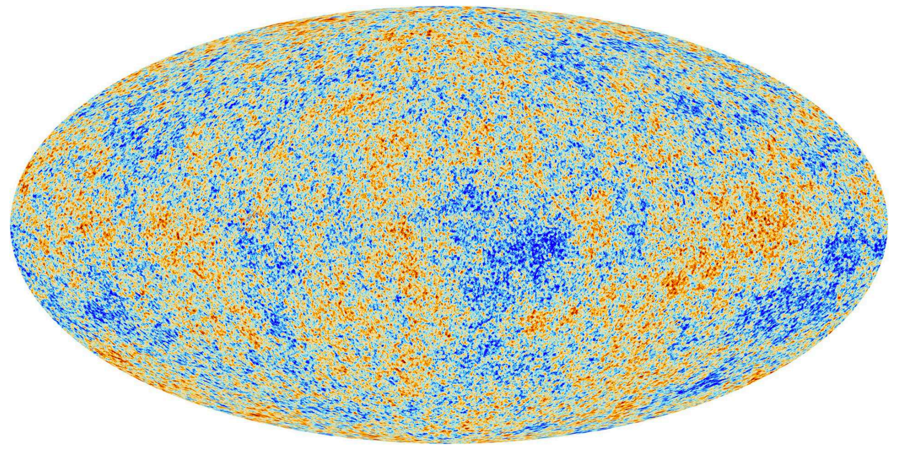
Very important question!!

Is it possible?

How to distinguish between models?

ALL of these models have predictions that are in agreement with the CMB (and LSS)

$\rightarrow \quad (n_S, A_S)$



Then how can we distinguish between these models?

We need to search for predictions that are distinct

Models of inflation

Name	Parameters	Sub-models	$V(\phi)$
HI	0	1	$M^4\left(1-e^{-\sqrt{2/3}\phi/M_{\rm Pl}}\right)$
RCHI	1	1	$M^4\left(1-2e^{-\sqrt{2/3}\phi/M_{\rm Pl}}+\frac{A_{\rm I}}{16\pi^2}\frac{\phi}{\sqrt{6}M_{\rm Pl}}\right)$
LFI	1	1	$M^4\left(\frac{\phi}{M_{\rm Pl}}\right)^p$
MLFI	1	1	$M^4\frac{\phi^2}{M_{\rm Pl}^2}\left[1+\alpha\frac{\phi^2}{M_{\rm Pl}^2}\right]$
RCMI	1	1	$M^4\left(\frac{\phi}{M_{\rm Pl}}\right)^2\left[1-2\alpha\frac{\phi^2}{M_{\rm Pl}^2}\ln\left(\frac{\phi}{M_{\rm Pl}}\right)\right]$
RCQI	1	1	$M^4\left(\frac{\phi}{M_{\rm Pl}}\right)^4\left[1-\alpha\ln\left(\frac{\phi}{M_{\rm Pl}}\right)\right]$
NI	1	1	$M^4\left[1+\cos\left(\frac{\phi}{f}\right)\right]$
ESI	1	1	$M^4\left(1-e^{-q\phi/M_{\rm Pl}}\right)$
PLI	1	1	$M^4e^{-\alpha\phi/M_{\rm Pl}}$
KMII	1	2	$M^4\left(1-\alpha\frac{\phi}{M_{\rm Pl}}e^{-\phi/M_{\rm Pl}}\right)$
HF1I	1	1	$M^4\left(1+A_1\frac{\phi}{M_{\rm Pl}}\right)^2\left[1-\frac{2}{3}\left(\frac{A_1}{1+A_1\phi/M_{\rm Pl}}\right)^2\right]$
CWI	1	1	$M^4\left[1+\alpha\left(\frac{\phi}{Q}\right)^4\ln\left(\frac{\phi}{Q}\right)\right]$
LI	1	2	$M^4\left[1+\alpha\ln\left(\frac{\phi}{M_{\rm Pl}}\right)\right]$
RpI	1	3	$M^4e^{-2\sqrt{2/3}\phi/M_{\rm Pl}}\left\|e^{\sqrt{2/3}\phi/M_{\rm Pl}}-1\right\|^{2p/(2p-1)}$
DWI	1	1	$M^4\left[\left(\frac{\phi}{\phi_0}\right)^2-1\right]^2$
MHI	1	1	$M^4\left[1-\mathrm{sech}\left(\frac{\phi}{\mu}\right)\right]$
RGI	1	1	$M^4\frac{(\phi/M_{\rm Pl})^2}{\alpha+(\phi/M_{\rm Pl})^2}$
MSSMI	1	1	$M^4\left[\left(\frac{\phi}{\phi_0}\right)^2-\frac{2}{3}\left(\frac{\phi}{\phi_0}\right)^6+\frac{1}{5}\left(\frac{\phi}{\phi_0}\right)^{10}\right]$
RIPI	1	1	$M^4\left[\left(\frac{\phi}{\phi_0}\right)^2-\frac{4}{3}\left(\frac{\phi}{\phi_0}\right)^3+\frac{1}{2}\left(\frac{\phi}{\phi_0}\right)^4\right]$
AI	1	1	$M^4\left[1-\frac{2}{\pi}\arctan\left(\frac{\phi}{\mu}\right)\right]$
CNAI	1	1	$M^4\left[3-\left(3+\alpha^2\right)\tanh^2\left(\frac{\alpha}{\sqrt{2}}\frac{\phi}{M_{\rm Pl}}\right)\right]$
CNBI	1	1	$M^4\left[\left(3-\alpha^2\right)\tan^2\left(\frac{\alpha}{\sqrt{2}}\frac{\phi}{M_{\rm Pl}}\right)-3\right]$
OSTI	1	1	$-M^4\left(\frac{\phi}{\phi_0}\right)^2\ln\left[\left(\frac{\phi}{\phi_0}\right)^2\right]$
WRI	1	1	$M^4\ln\left(\frac{\phi}{\phi_0}\right)^2$
SFI	2	1	$M^4\left[1-\left(\frac{\phi}{\mu}\right)^p\right]$
II	2	1	$M^4\left(\frac{\phi-\phi_0}{M_{\rm Pl}}\right)^{-\beta}-M^4\frac{\beta^2}{6}\left(\frac{\phi-\phi_0}{M_{\rm Pl}}\right)^{-\beta-2}$
KMIII	2	1	$M^4\left[1-\alpha\frac{\phi}{M_{\rm Pl}}\exp\left(-\beta\frac{\phi}{M_{\rm Pl}}\right)\right]$
LMI	2	2	$M^4\left(\frac{\phi}{M_{\rm Pl}}\right)^\alpha\exp\left[-\beta(\phi/M_{\rm Pl})^\gamma\right]$
TWI	2	1	$M^4\left[1-A\left(\frac{\phi}{\phi_0}\right)^2e^{-\phi/\phi_0}\right]$
GMSSMI	2	2	$M^4\left[\left(\frac{\phi}{\phi_0}\right)^2-\frac{2}{3}\alpha\left(\frac{\phi}{\phi_0}\right)^6+\frac{\alpha}{5}\left(\frac{\phi}{\phi_0}\right)^{10}\right]$
GRIPI	2	2	$M^4\left[\left(\frac{\phi}{\phi_0}\right)^2-\frac{4}{3}\alpha\left(\frac{\phi}{\phi_0}\right)^3+\frac{\alpha}{2}\left(\frac{\phi}{\phi_0}\right)^4\right]$
BSUSYBI	2	1	$M^4\left(e^{\sqrt{6}\frac{\phi}{M_{\rm Pl}}}+e^{\sqrt{6}\gamma\frac{\phi}{M_{\rm Pl}}}\right)$
TI	2	3	$M^4\left(1+\cos\frac{\phi}{\mu}+\alpha\sin^2\frac{\phi}{\mu}\right)$
BEI	2	1	$M^4\exp_{1-\beta}\left(-\lambda\frac{\phi}{M_{\rm Pl}}\right)$
PSNI	2	1	$M^4\left[1+\alpha\ln\left(\cos\frac{\phi}{f}\right)\right]$
NCKI	2	2	$M^4\left[1+\alpha\ln\left(\frac{\phi}{M_{\rm Pl}}\right)+\beta\left(\frac{\phi}{M_{\rm Pl}}\right)^2\right]$
CSI	2	1	$\frac{M^4}{\left(1-\alpha\frac{\phi}{M_{\rm Pl}}\right)^2}$
OI	2	1	$M^4\left(\frac{\phi}{\phi_0}\right)^4\left[\left(\ln\frac{\phi}{\phi_0}\right)^2-\alpha\right]$
CNCI	2	1	$M^4\left[\left(3+\alpha^2\right)\coth^2\left(\frac{\alpha}{\sqrt{2}}\frac{\phi}{M_{\rm Pl}}\right)-3\right]$
SBI	2	2	$M^4\left\{1+\left[-\alpha+\beta\ln\left(\frac{\phi}{M_{\rm Pl}}\right)\right]\left(\frac{\phi}{M_{\rm Pl}}\right)^4\right\}$
SSBI	2	6	$M^4\left[1+\alpha\left(\frac{\phi}{M_{\rm Pl}}\right)^2+\beta\left(\frac{\phi}{M_{\rm Pl}}\right)^4\right]$
IMI	2	1	$M^4\left(\frac{\phi}{M_{\rm Pl}}\right)^{-p}$
BI	2	2	$M^4\left[1-\left(\frac{\phi}{\mu}\right)^{-p}\right]$
RMI	3	4	$M^4\left[1-\frac{c}{2}\left(-\frac{1}{2}+\ln\frac{\phi}{\phi_0}\right)\frac{\phi^2}{M_{\rm Pl}^2}\right]$
VHI	3	1	$M^4\left[1+\left(\frac{\phi}{\mu}\right)^p\right]$
DSI	3	1	$M^4\left[1+\left(\frac{\phi}{\mu}\right)^{-p}\right]$
GMLFI	3	1	$M^4\left(\frac{\phi}{M_{\rm Pl}}\right)^p\left[1+\alpha\left(\frac{\phi}{M_{\rm Pl}}\right)^q\right]$
LPI	3	3	$M^4\left(\frac{\phi}{\phi_0}\right)^p\left(\ln\frac{\phi}{\phi_0}\right)^q$
CNDI	3	3	$\frac{M^4}{\left\{1+\beta\cos\left[\alpha\left(\frac{\phi-\phi_0}{M_{\rm Pl}}\right)\right]\right\}^2}$

Encyclopædia Inflationaris J. Martin, et al (2013)

How to distinguish between models?

- GWs
- Non-Gaussianities
- Features in the power spectrum
- Birefringence
- …

How to distinguish between models?

Gravitational waves

Besides creating density fluctuations, models of the early universe evolution create gravitational waves.

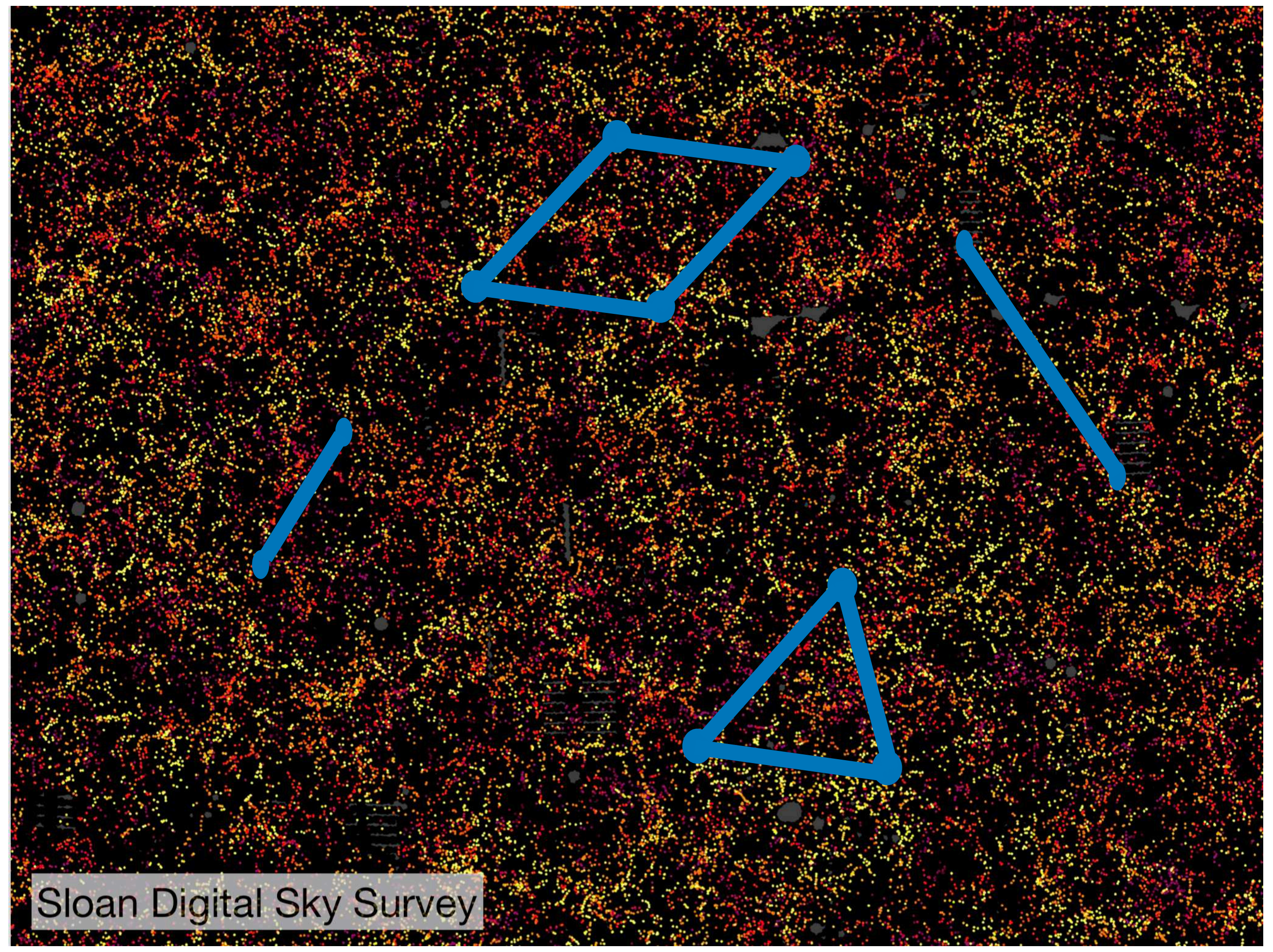
Different models, like inflation and bouncing, have different predictions. Within inflation and other models, we have different predictions.

If we take into account (p)reheating we can have extra GWs.

When we measure the primordial GWs, this would allow us to distinguish between some of these models.

Non-gaussianities

If the distribution is Gaussian, all the information is contained in the 2 point function. If not, we have to calculate the n-point correlation function:



$$\langle \delta\delta\delta \rangle$$

$$\langle \delta\delta\delta\delta \rangle$$

$$\langle \delta \ldots \delta \rangle$$

Different inflationary models (and alternative models) can predict different NG signatures.

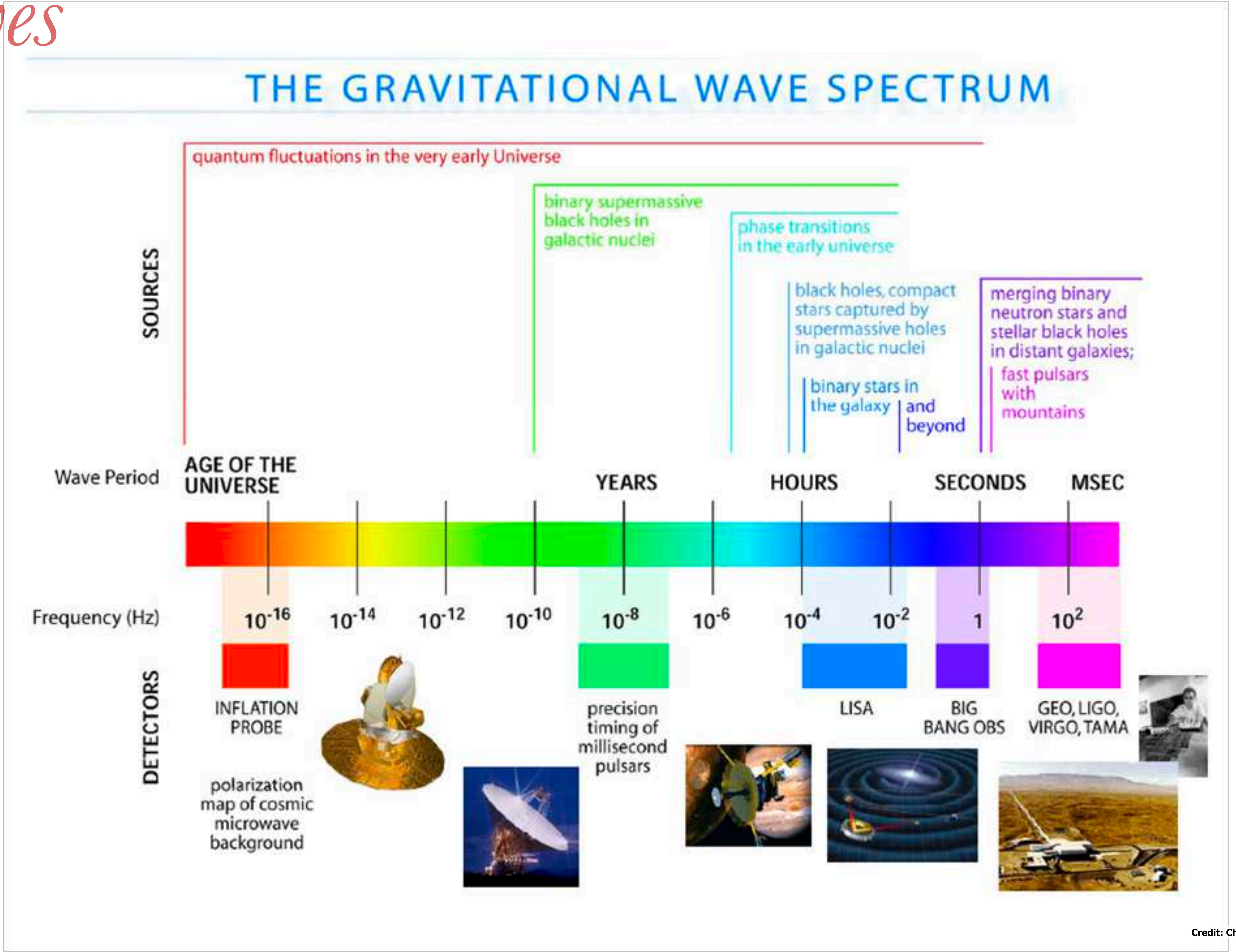
Gravitational waves

VACUUM GWs

SOURCED GWs
(secondary GWs)

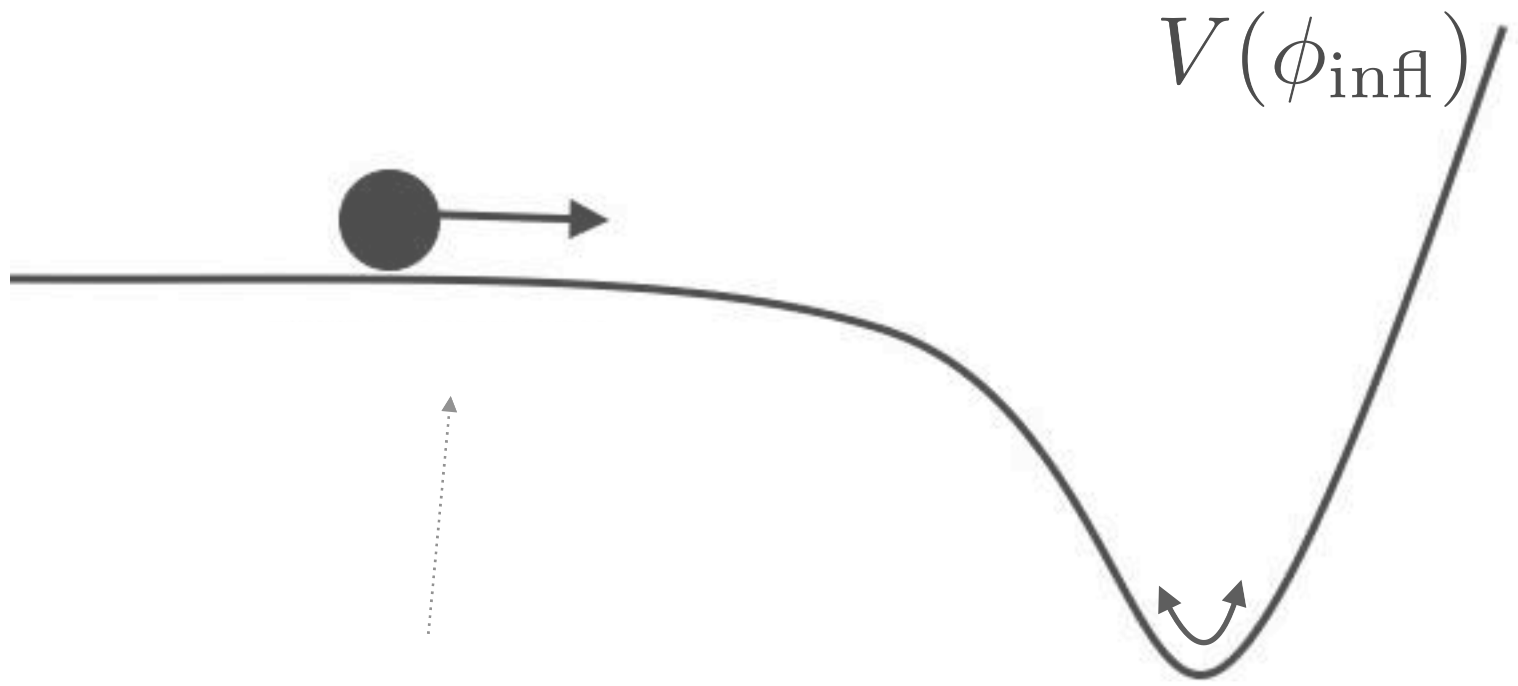
From topological defects

…



Credit: Chris Henze

After inflation - (p)reheating

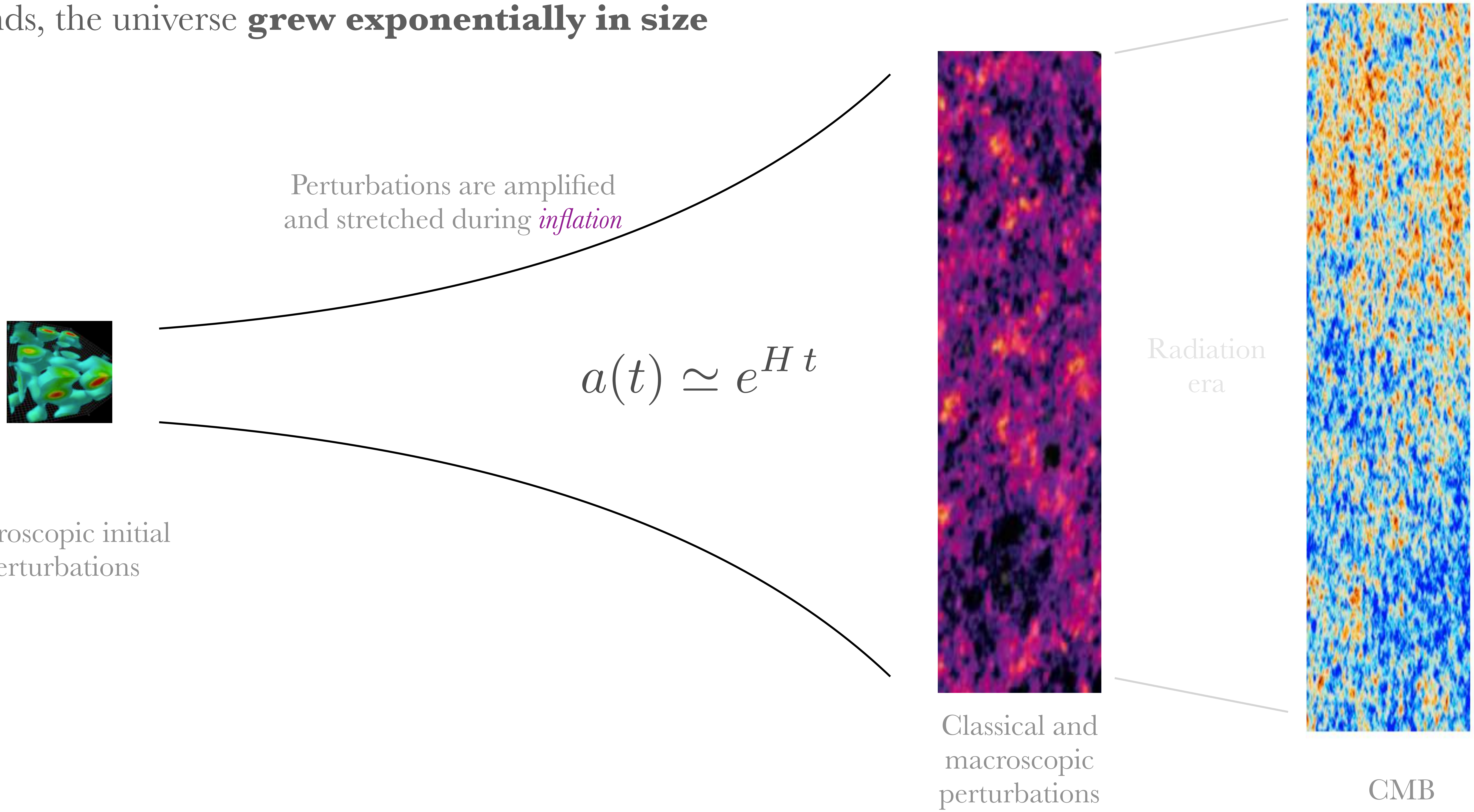


Causes the accelerated expansion - quasi-exponential

Leaves the universe empty!!

Inflation - inflates the universe

In $\sim 10^{-32}$ seconds, the universe **grew exponentially in size**



$$a(t) \simeq e^{H\,t}$$

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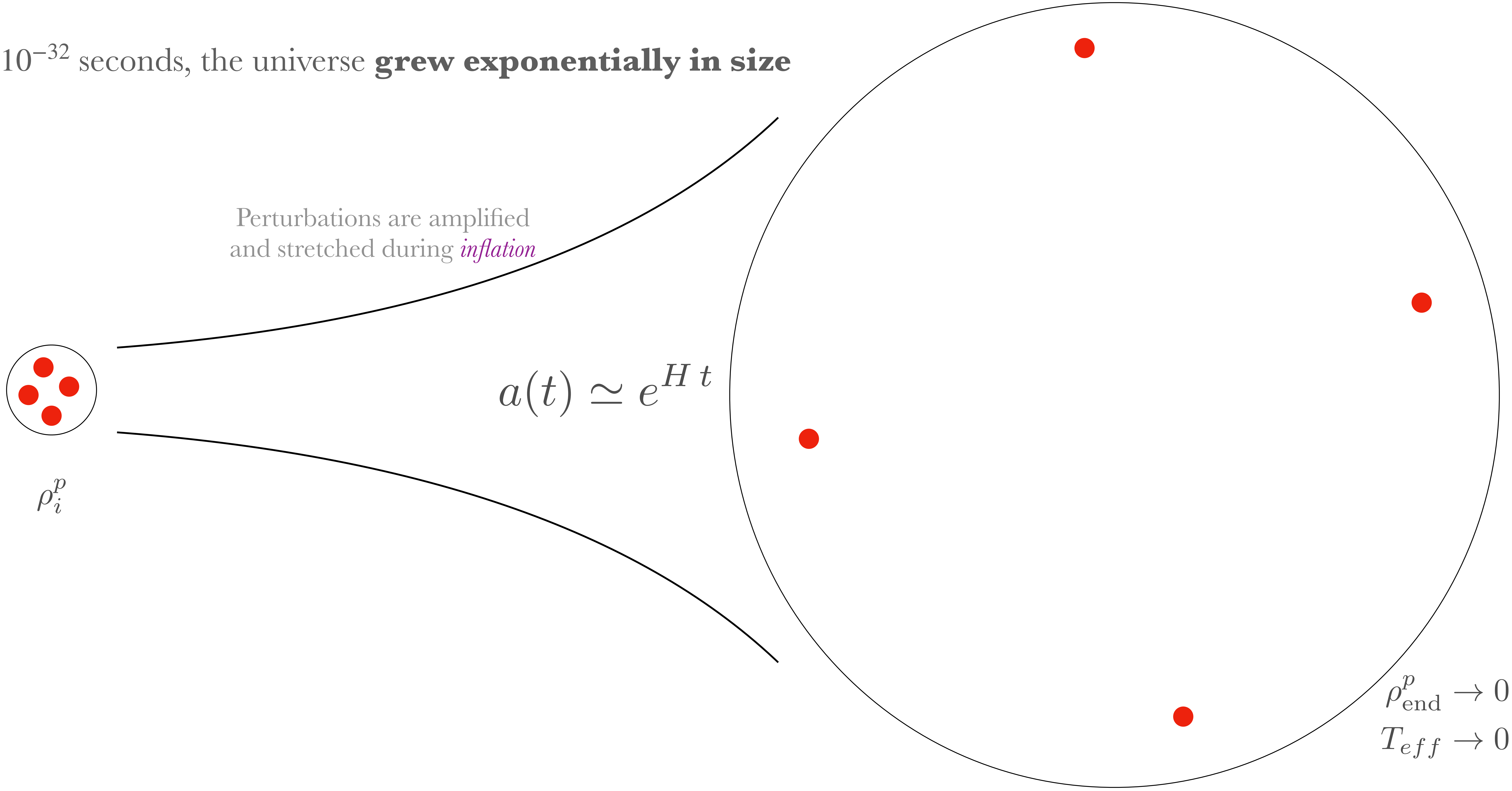

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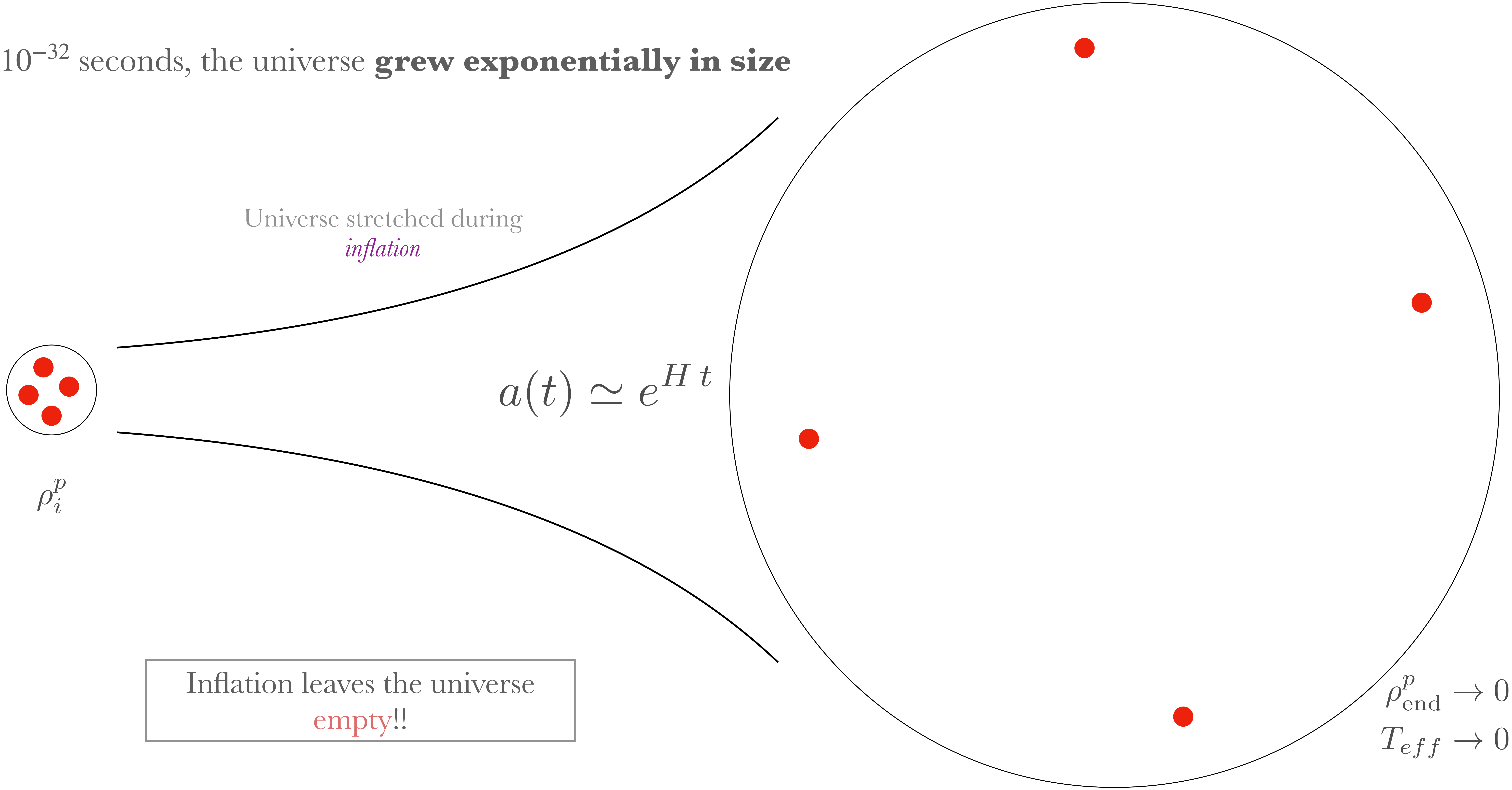

Inflation leaves the universe
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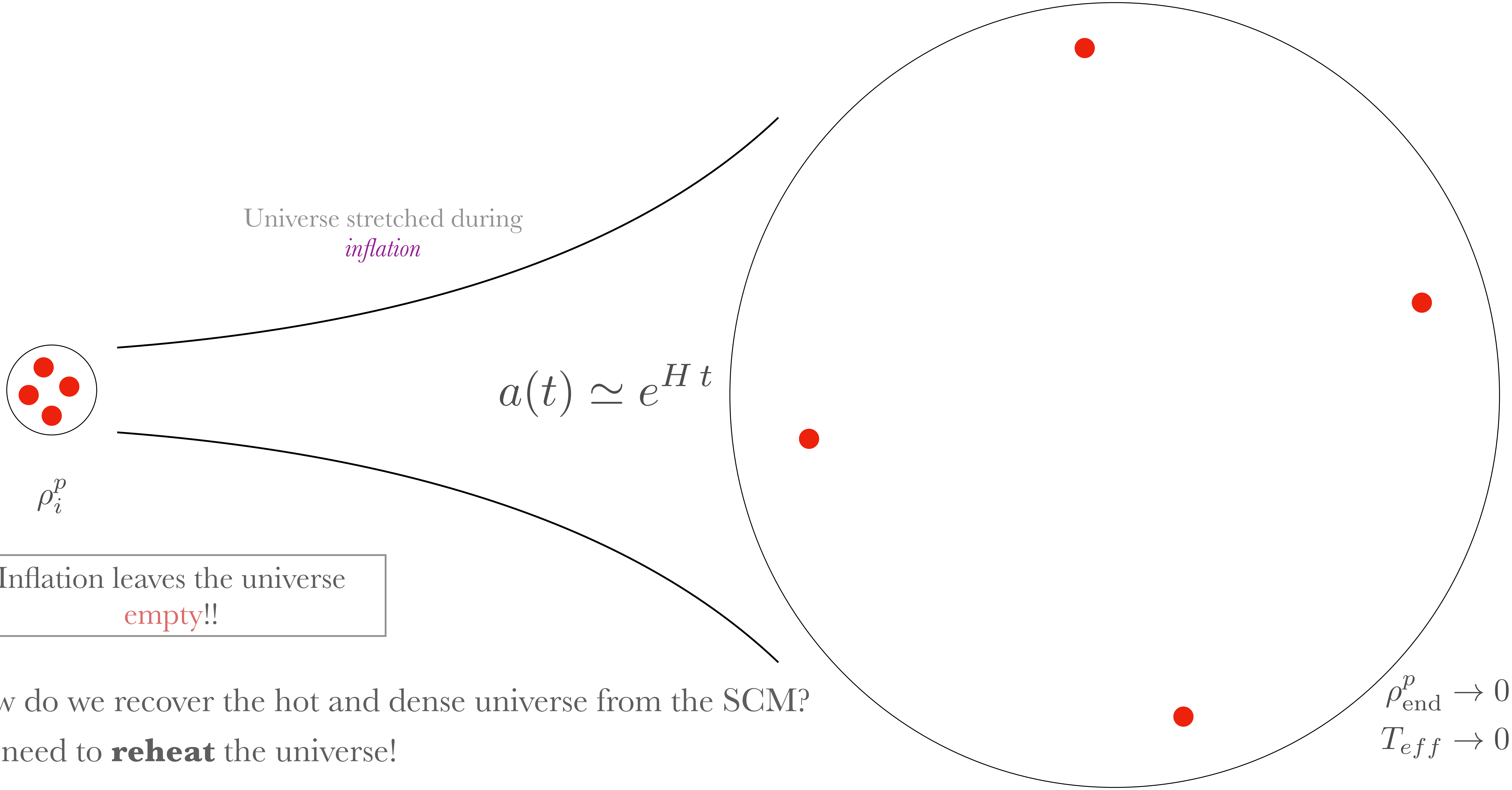
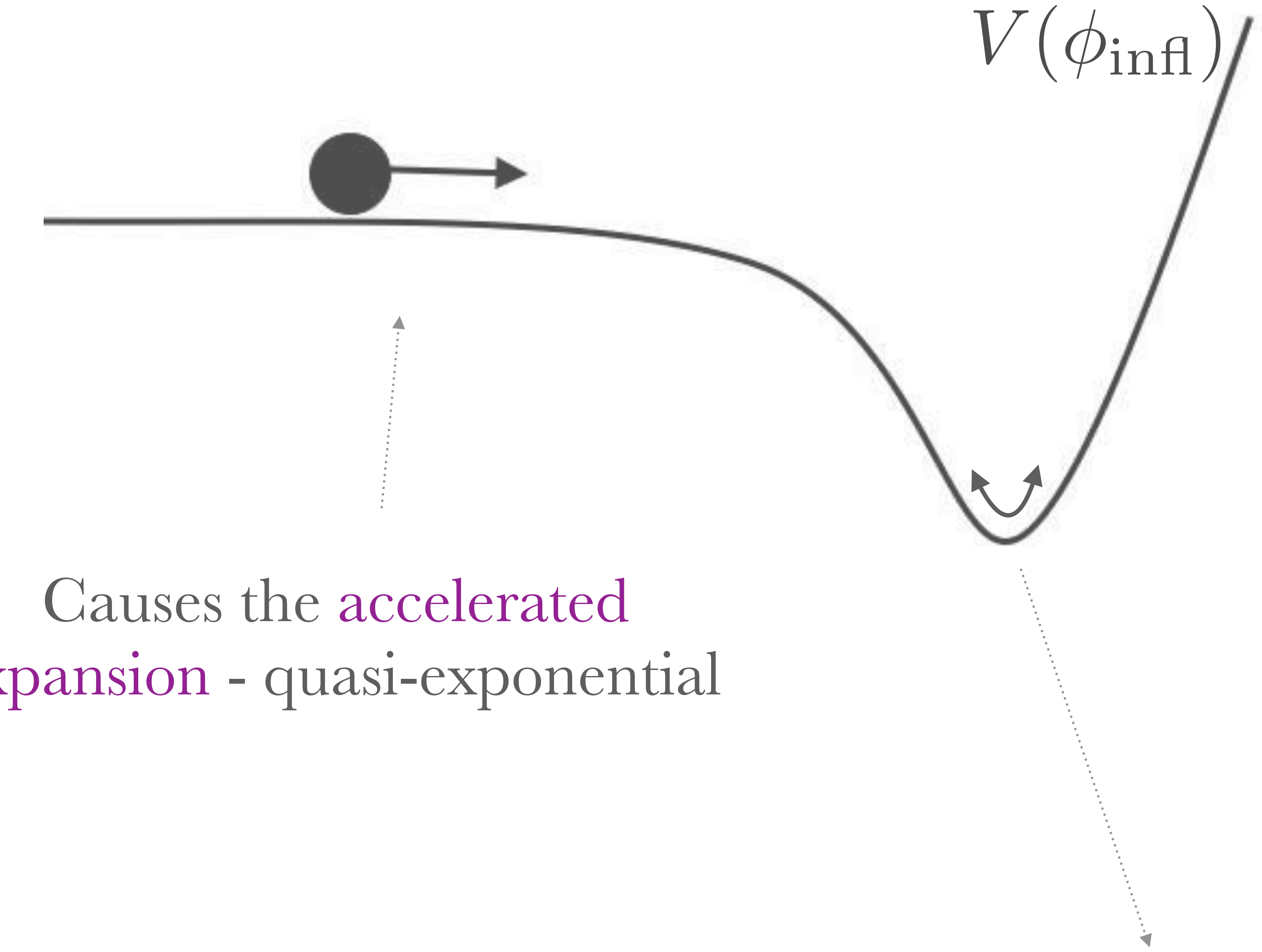


Inflation leaves the universe empty!!

How do we recover the hot and dense universe from the SCM?

We need to **reheat** the universe!

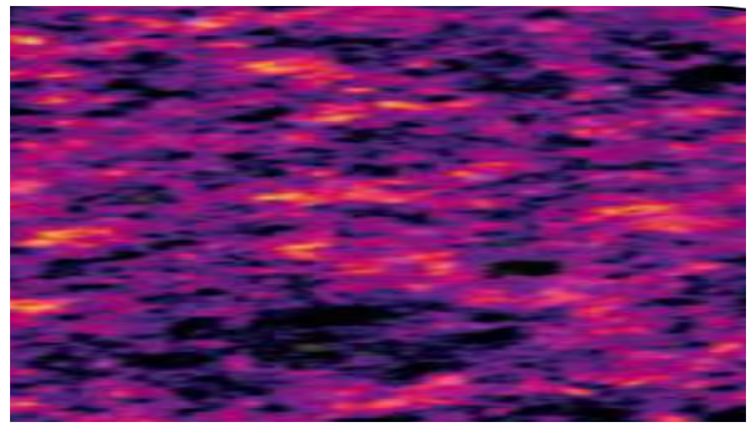
After inflation - (p)reheating

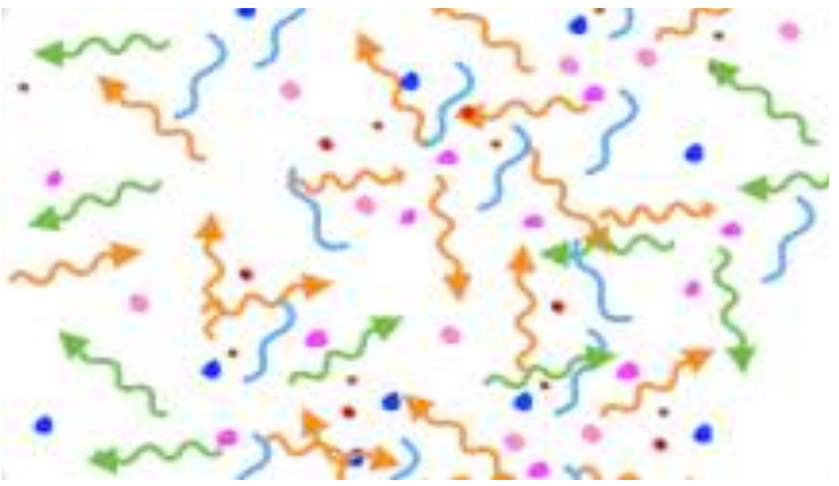


Causes the accelerated expansion - quasi-exponential

Leaves the universe empty!!

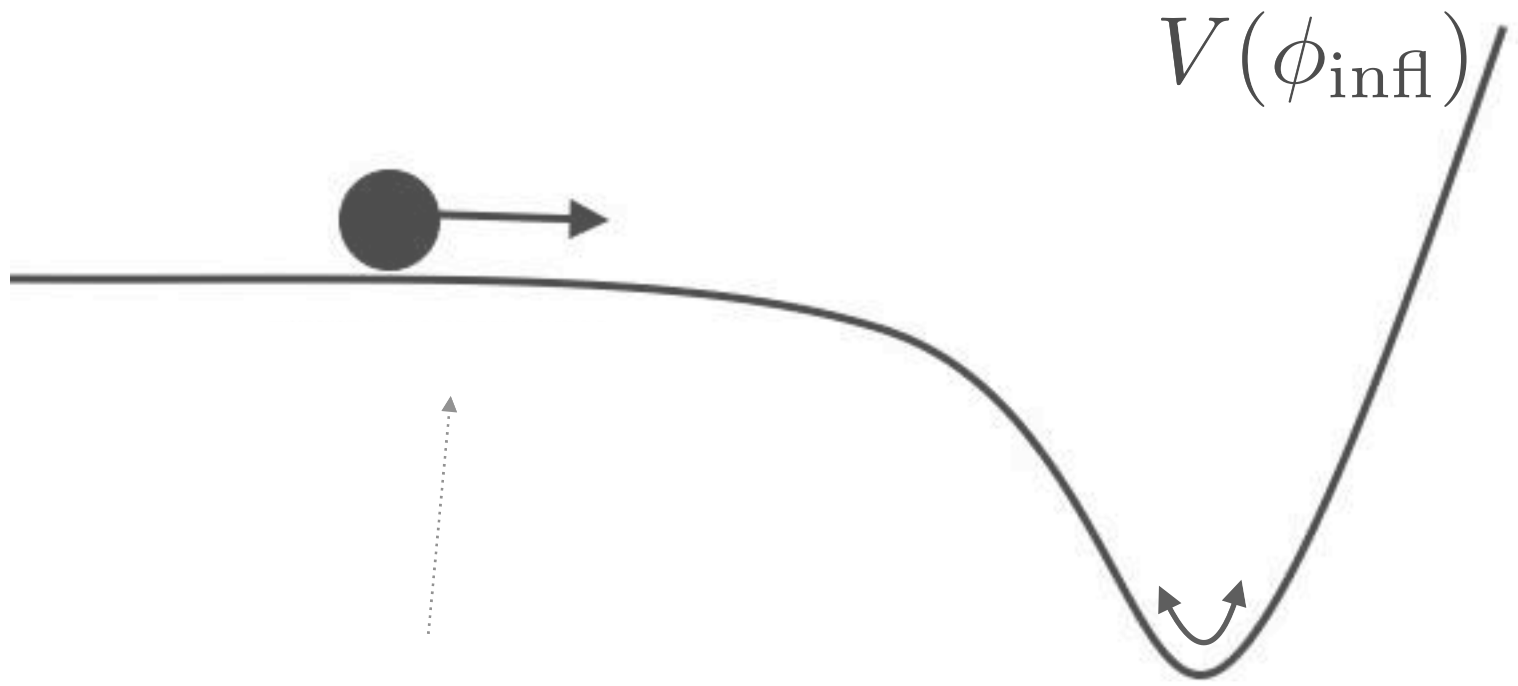
By the end of inflation, the *inflaton* decays, and the product of this decay are the particles of the standard model → starts the SCM





(P)reheating: populates the universe with particles. Creates all the elementary particles (or its precursors) that we have today.

After inflation - (p)reheating



Causes the accelerated expansion - quasi-exponential

PREHEATING

Non-perturbative

$$\ddot{\chi}_k + \left(k^2 + g^2\sigma^2 + 2g^2\sigma\Phi\ \sin mt\right)\chi_k = 0$$

Parametric resonance!!

REHEATING

Perturbative

To avoid that the universe ends up empty, the inflaton has to couple to Standard Model field

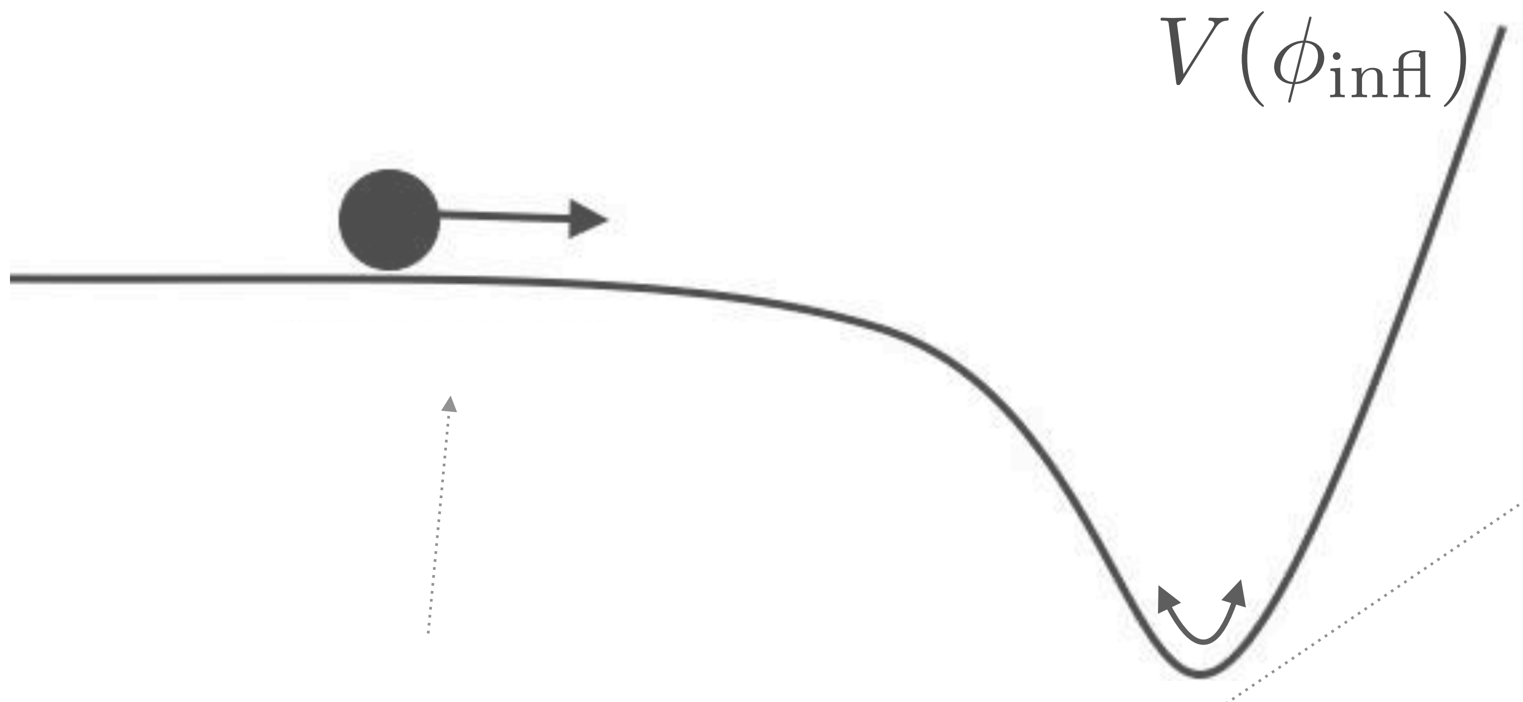
$$\dot{\rho}_\phi + 3H\rho_\phi = -\Gamma_\phi\rho_\phi$$

THERMALIZATION

Needs to lead into the SCM universe - in thermal equilibrium

HOW?

After inflation - (p)reheating



Causes the accelerated expansion - quasi-exponential

PREHEATING

Non-perturbative

Initial stage of reheating

After inflation, the scalar field starts to oscillate on the bottom of the potential

(frequency m)

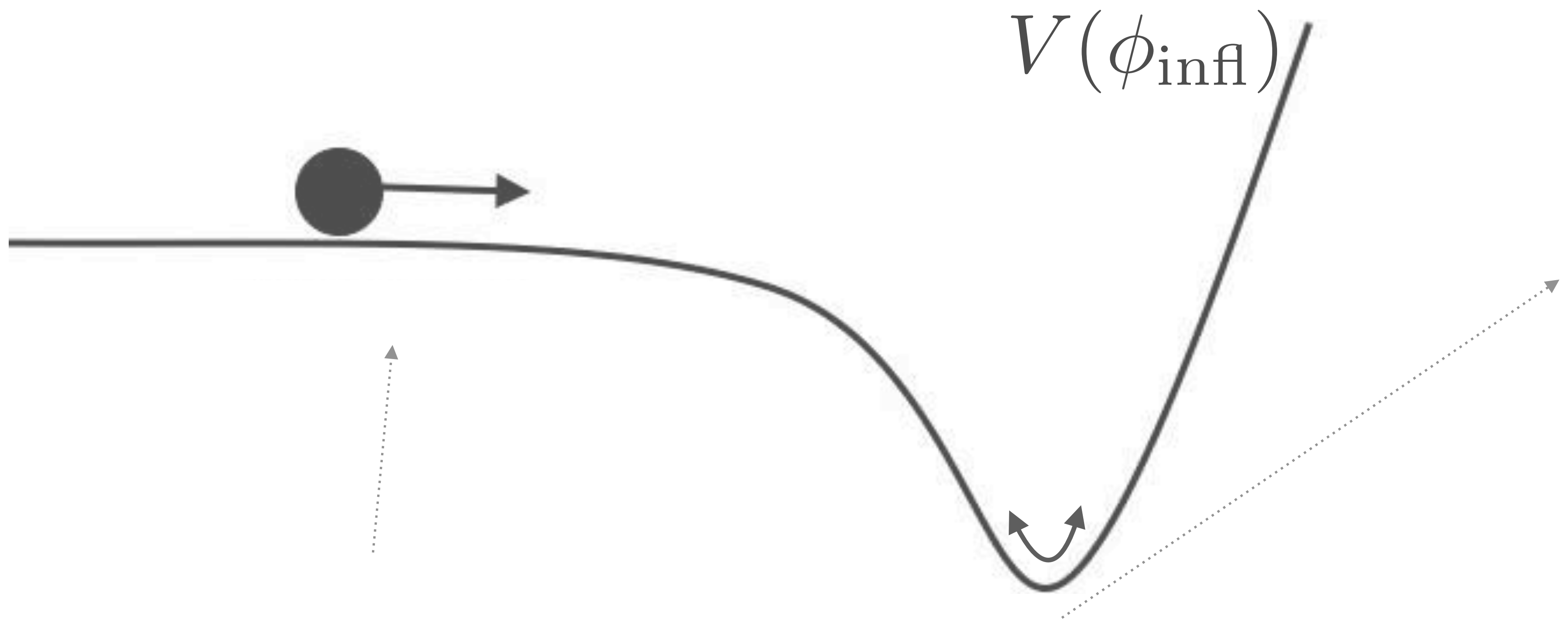
$$\ddot{\phi} + 3H\dot{\phi} = -m^2\phi$$

$$H^{-1} \gg m^{-1}$$

Efficient transfer of energy from the inflaton to scalar fields

Not fermions!
Pauli exclusion principle

After inflation - (p)reheating



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Non-perturbative

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After inflation, the scalar field starts to oscillate on the bottom of the potential

(frequency m)

$$\ddot{\phi} + 3\cancel{H}\dot{\phi} = -m^2\phi$$

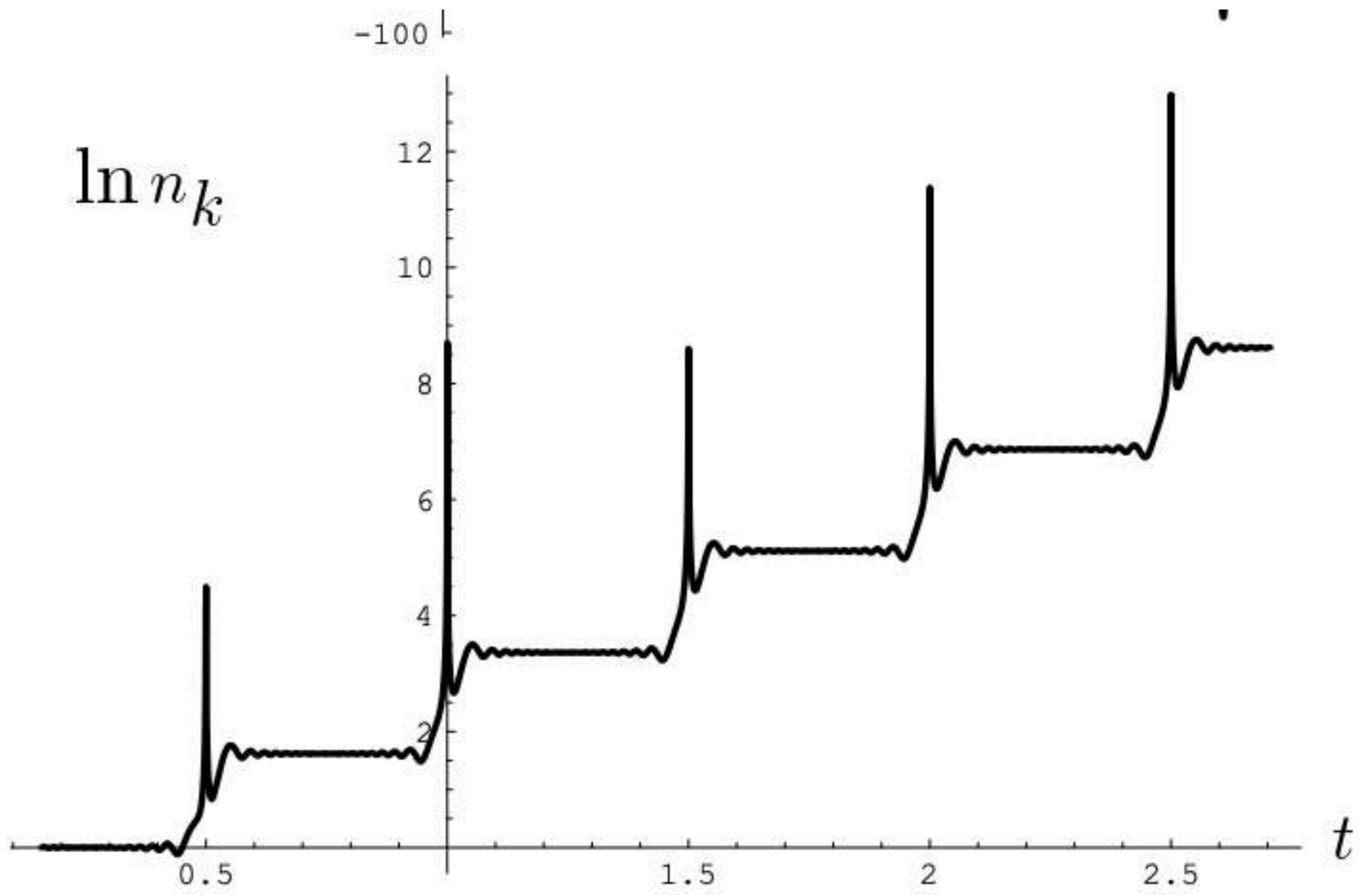
$$H^{-1} \gg m^{-1}$$

Oscillating inflation coupled to a quantum scalar field:

$$\phi(t)$$

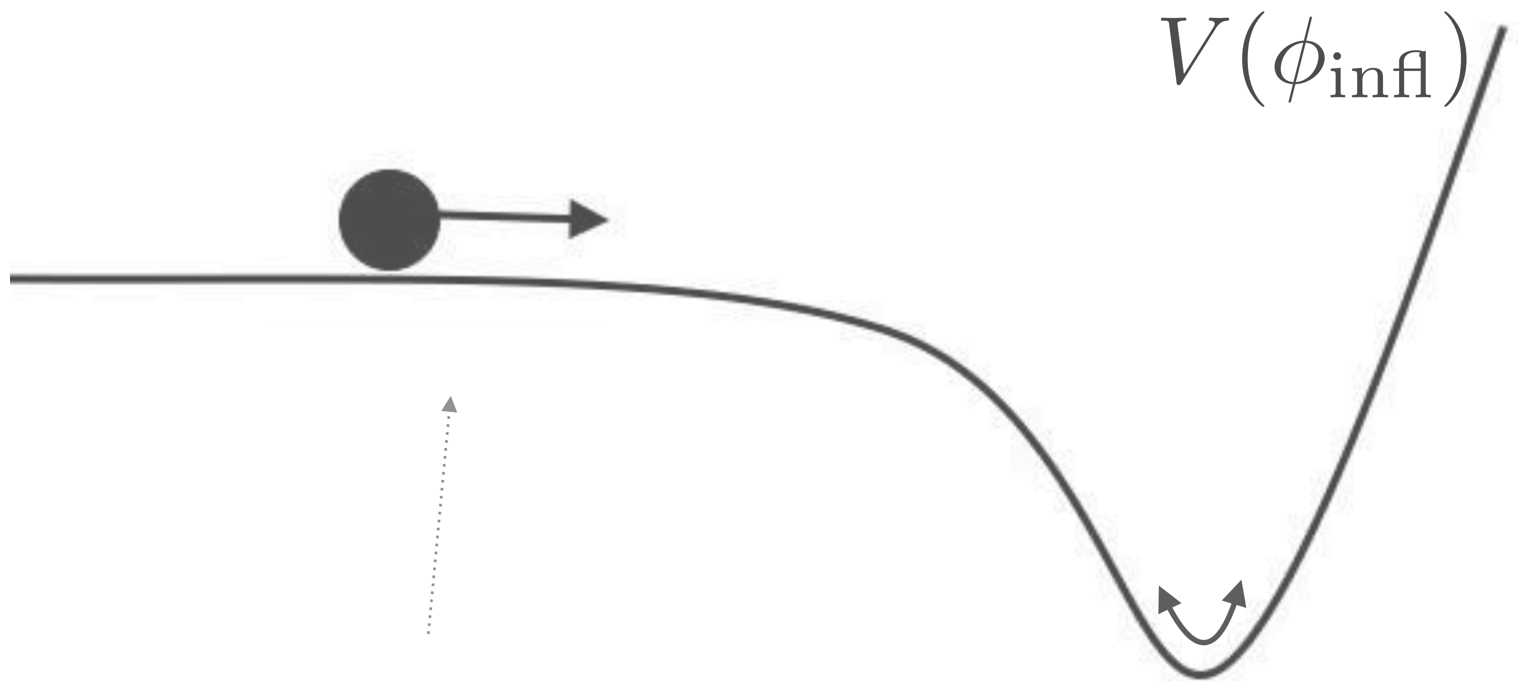
$$\ddot{\chi}_k + \left(k^2 + g^2\sigma^2 + 2g^2\sigma\Phi\ \sin mt\right)\chi_k = 0$$

Parametric resonance!!



Copious production of particles

After inflation - (p)reheating



Causes the accelerated expansion - quasi-exponential

REHEATING

Perturbative

To avoid that the universe ends up empty, the inflaton has to couple to Standard Model field

parametrizes the inflaton decay rate

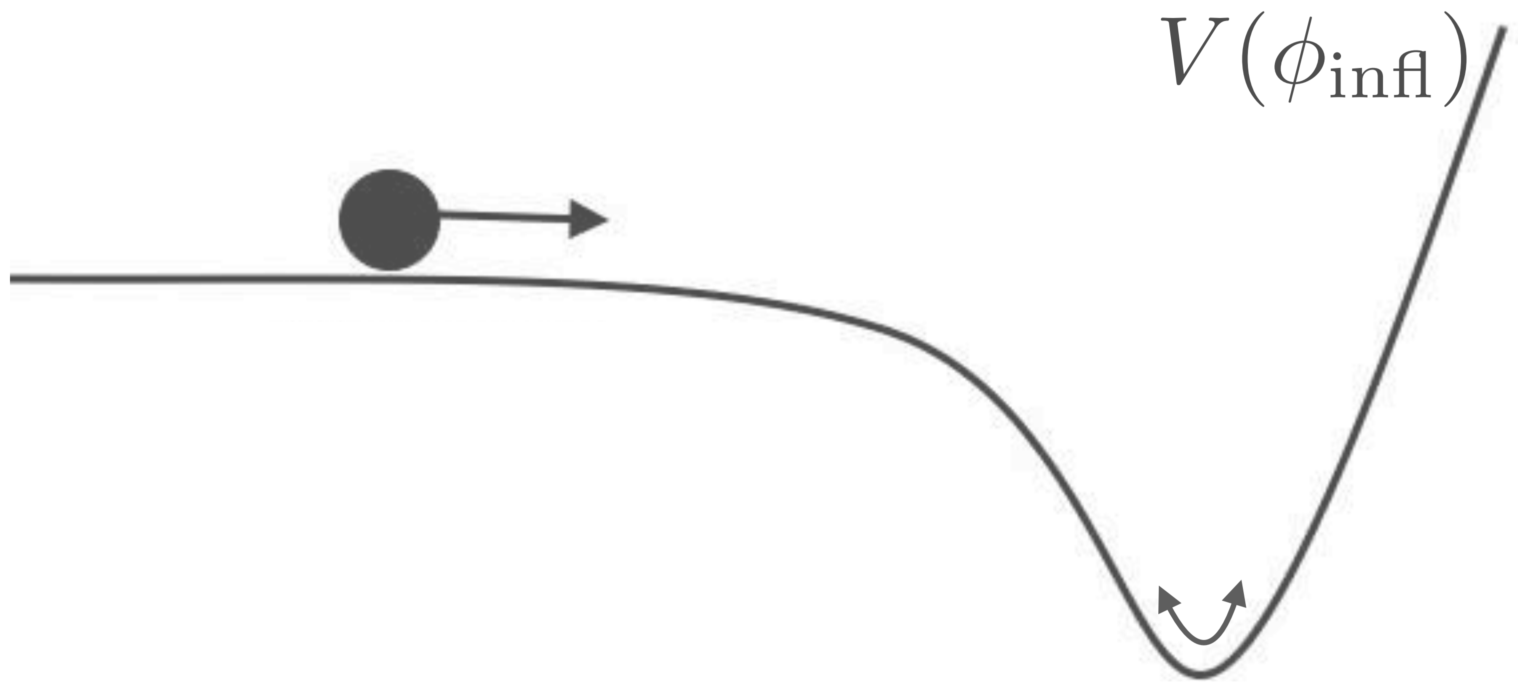
$$\dot{\rho}_\phi + 3H\rho_\phi = -\Gamma_\phi \rho_\phi$$

The energy stored in the inflaton field will then be transferred into ordinary particles

Slow-decay - like the case where the ase if the *inflaton* can only decay into fermions

Γ_ϕ??

After inflation - (p)reheating



REHEATING

Perturbative

To avoid that the universe ends up empty, the inflaton has to couple to Standard Model fields

$$\mathcal{L} = \frac{1}{2}(\partial_\mu\varphi)^2 - V(\varphi) + \frac{1}{2}\sum_i \left[(\partial_\mu\chi_i)^2 - \underbrace{\left(m^2_{\chi_i}(0) + g_i^2\varphi^2\right)}_{m^2_{\chi_i}} \chi_i^2 \right] - \sum_i g_i^2 \sigma\varphi\chi_i^2 \,.$$

Decaying rate:

$$\Gamma_{\varphi\to\chi\chi} = \frac{g_\chi^2\sigma^2}{8\pi m}\,,$$

$$\Gamma_{\varphi\to\psi\bar{\psi}} = \frac{g_\psi^2 m}{8\pi}\,. \qquad \text{(fermions)}$$

End of reheating: $\Gamma_{total} \sim H$

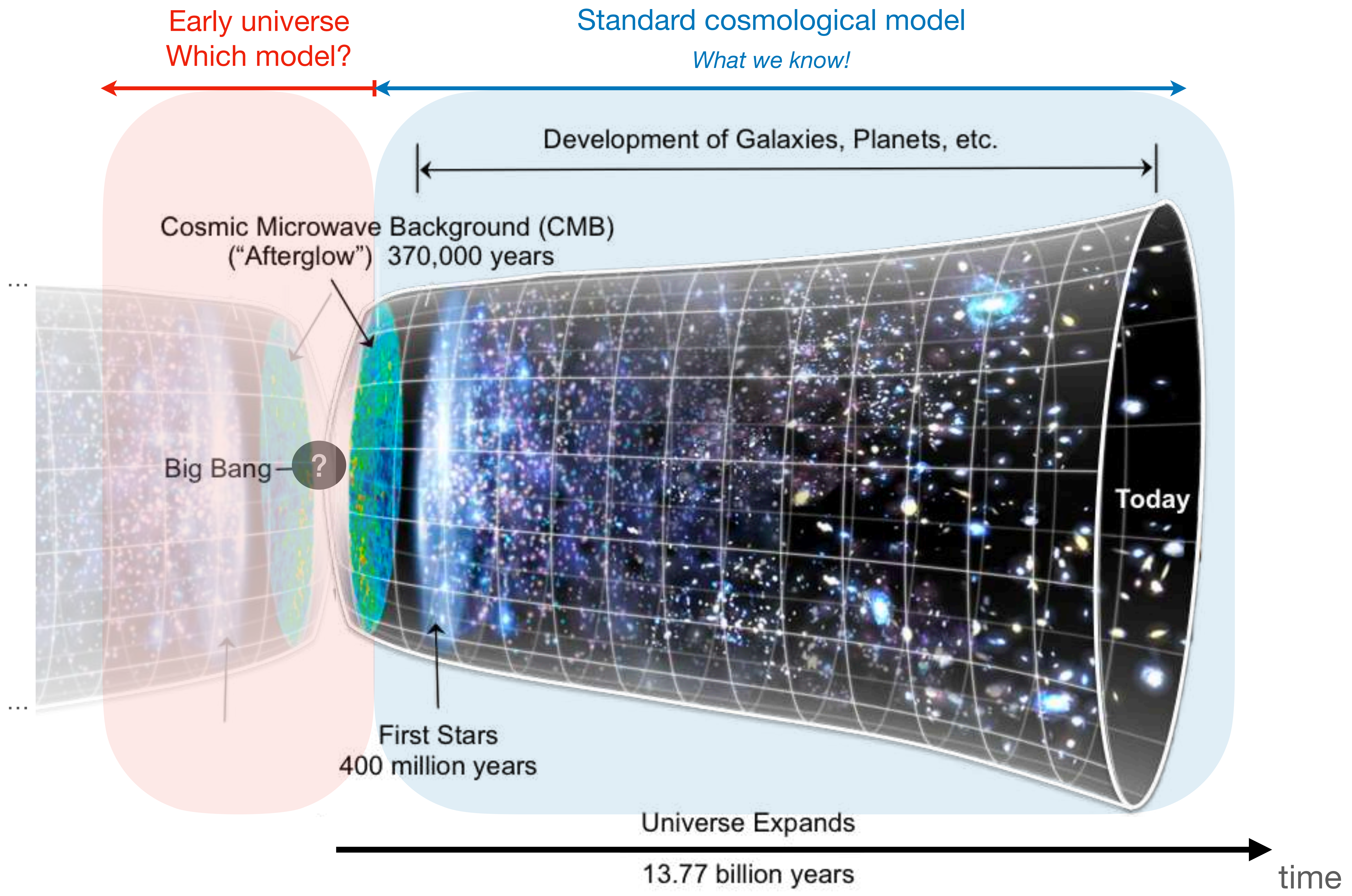
Assuming thermal equilibrium happens right after reheating

$$T_{reaq} \simeq 0,2 \left(\frac{100}{g^*}\right)^{1/4} \sqrt{\Gamma_{total} m_{pl}}$$

Particle number density: $n_\varphi = \frac{\rho}{m} \propto \mathrm{e}^{-(3H+\Gamma_{total})t}$

Observations, CMB, put a limit - $T_{\text{reheat}} < 10^6$ GeV

Summary


Early universe
Which model?
Standard cosmological model
What we know!
Development of Galaxies, Planets, etc.
Cosmic Microwave Background (CMB)
("Afterglow") 370,000 years
...
Big Bang
?
Today
...
First Stars
400 million years
Universe Expands
13.77 billion years
time