Gravitational waves from the early Universe

Part 1

Sachiko Kuroyanagi

(Nagoya University)

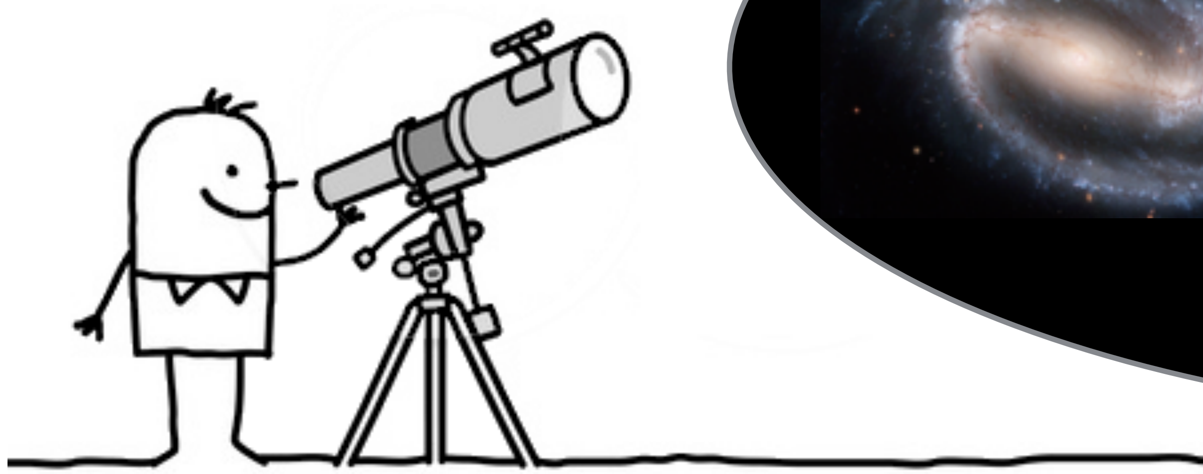
13 July 2017

GW mini-school@NTNU


New window of observation
has just opened
We expect new insights to astrophysics
and also on cosmology?

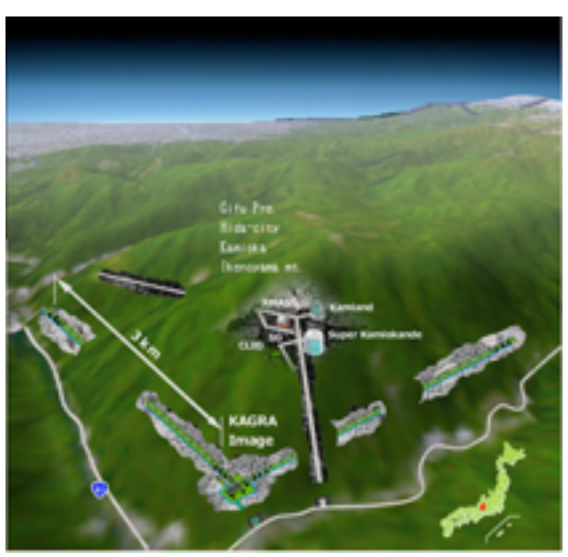
Advantages of gravitational wave observation I

Telescope



objects with light

GW detector



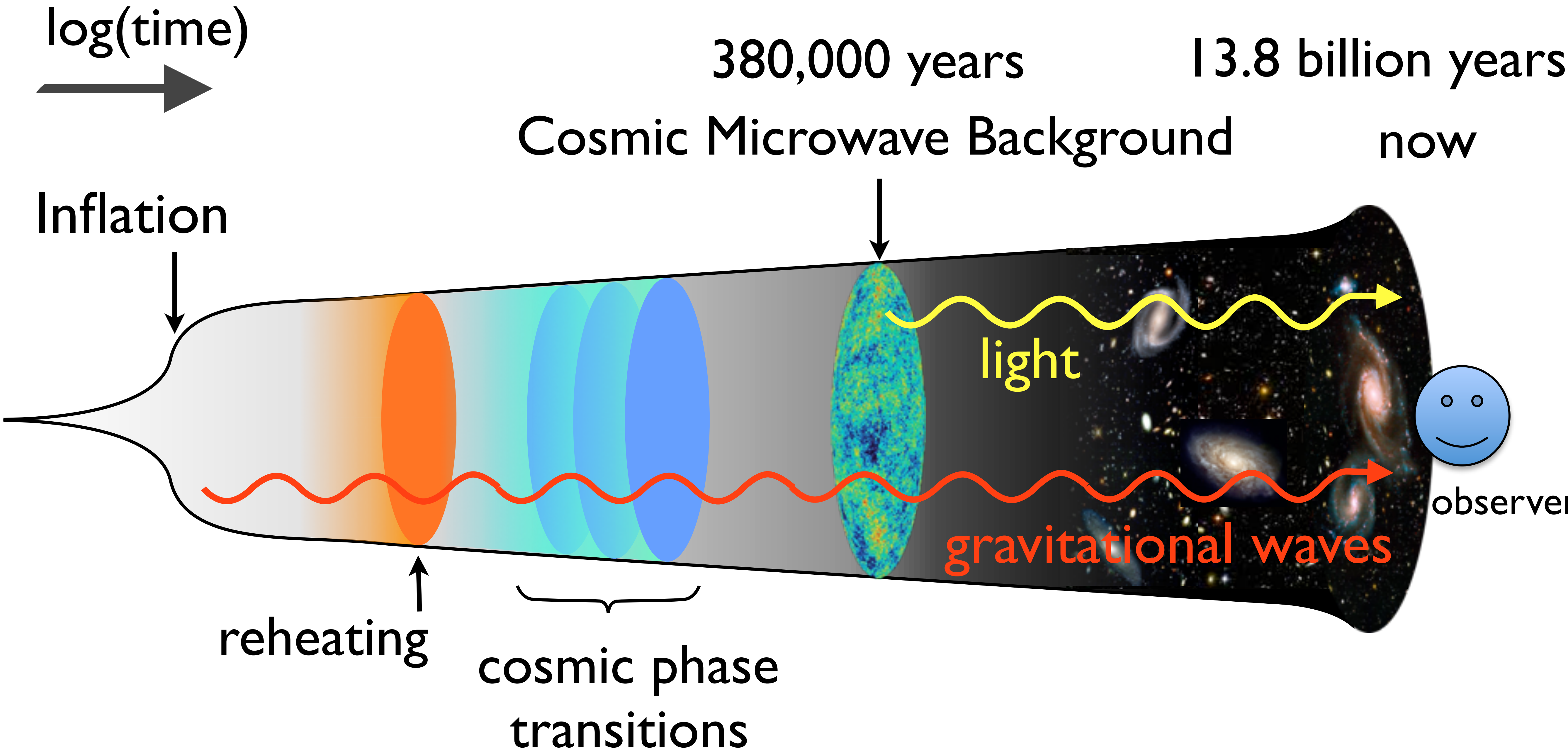
?

Black holes, Neutron stars, etc
→ do not emit light

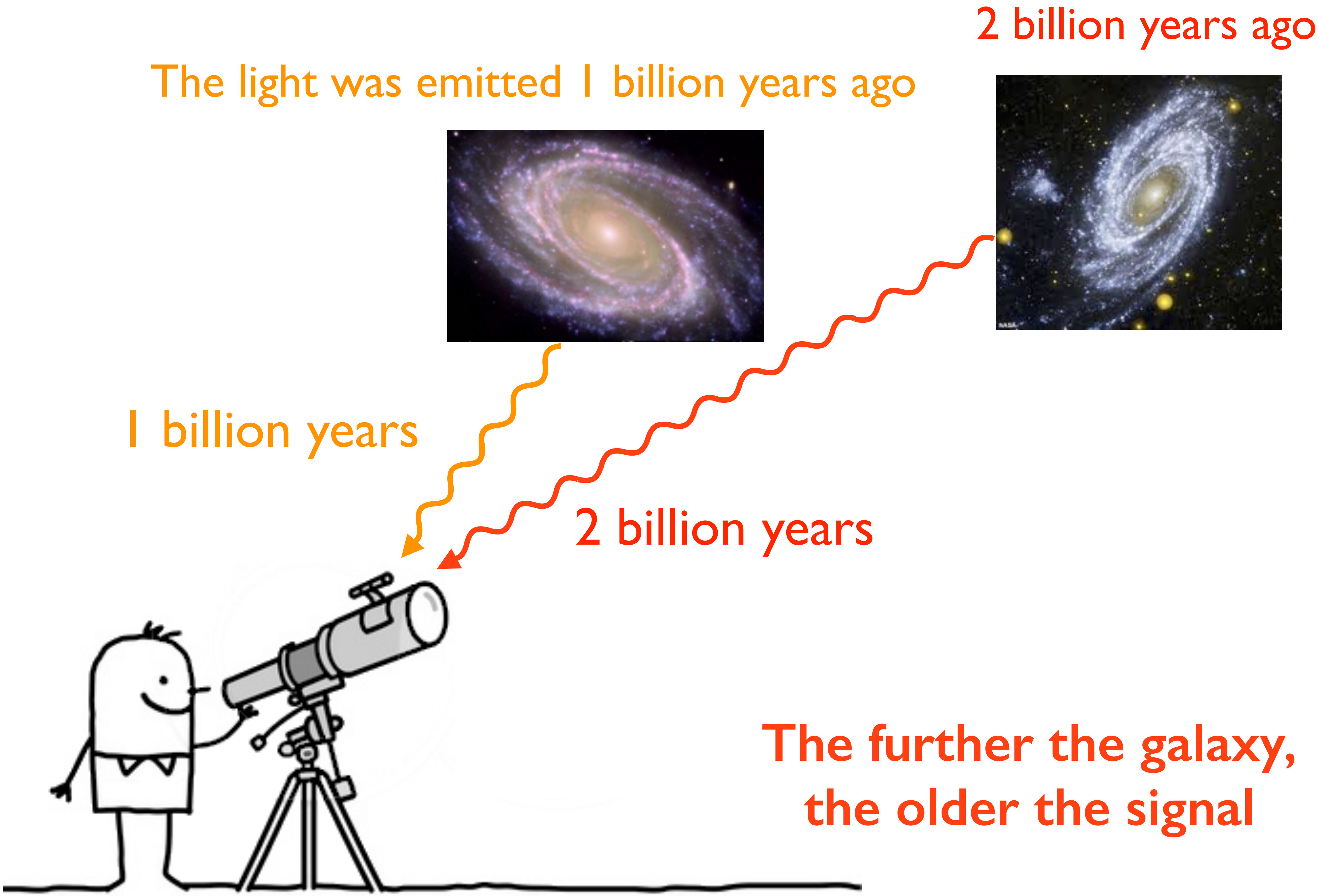
shows completely different aspects of the Universe!

Advantages of gravitational wave observation 2

We may be able to observe the very early universe!



Basics 1. The speed of light is finite: $c = 3\times10^8$ m/s



Basics 2. The Universe is expanding

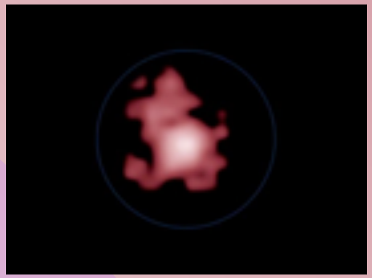
discovered by
Edwin Hubble
in 1929

Galaxies are moving away from us!

The most distant galaxy (March 2016): GN-z11

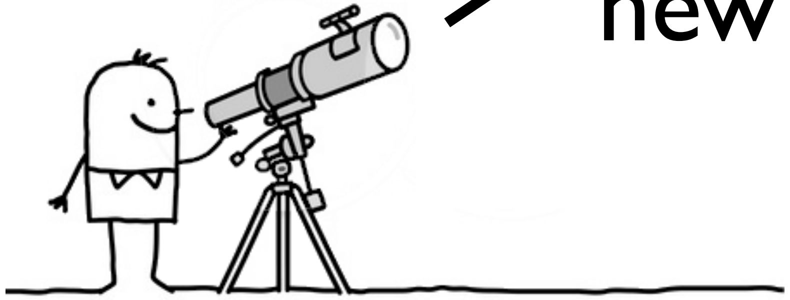
light was emitted 13.4 billion years ago
31.9 billion light-year away now

→0.4 billion years after the birth



old galaxies

new galaxies



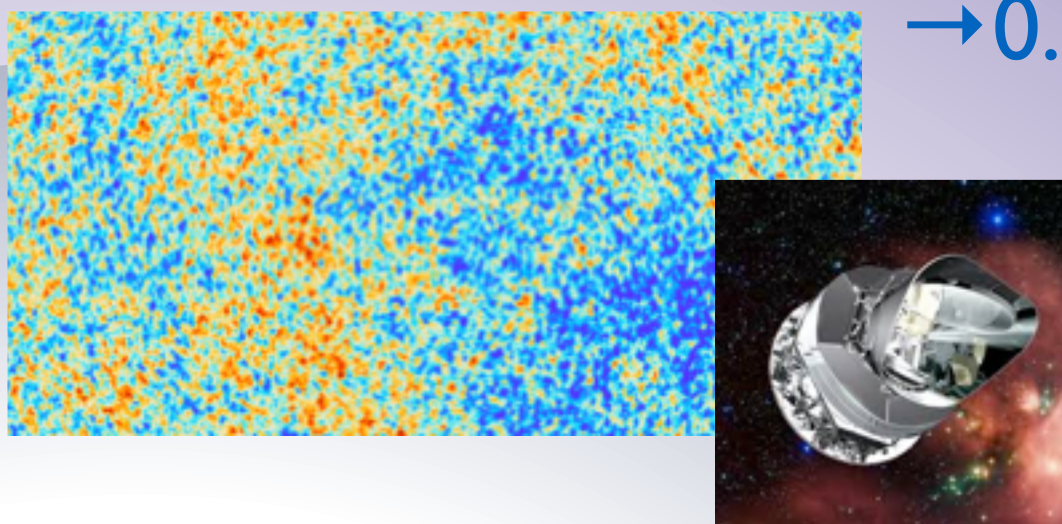
**The further the galaxy,
the older the signal**

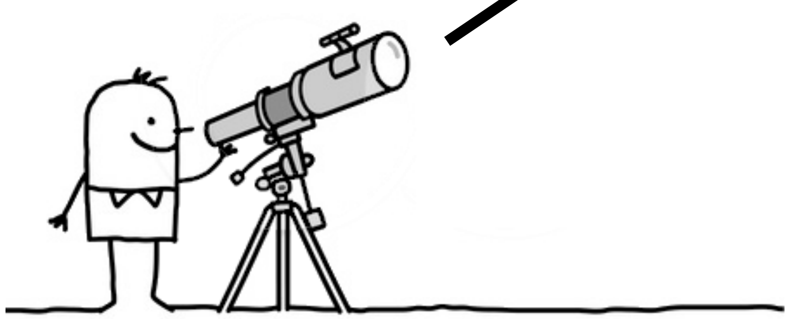
The oldest signal:

Cosmic Microwave background (CMB)

lights from 13.8 billion years ago

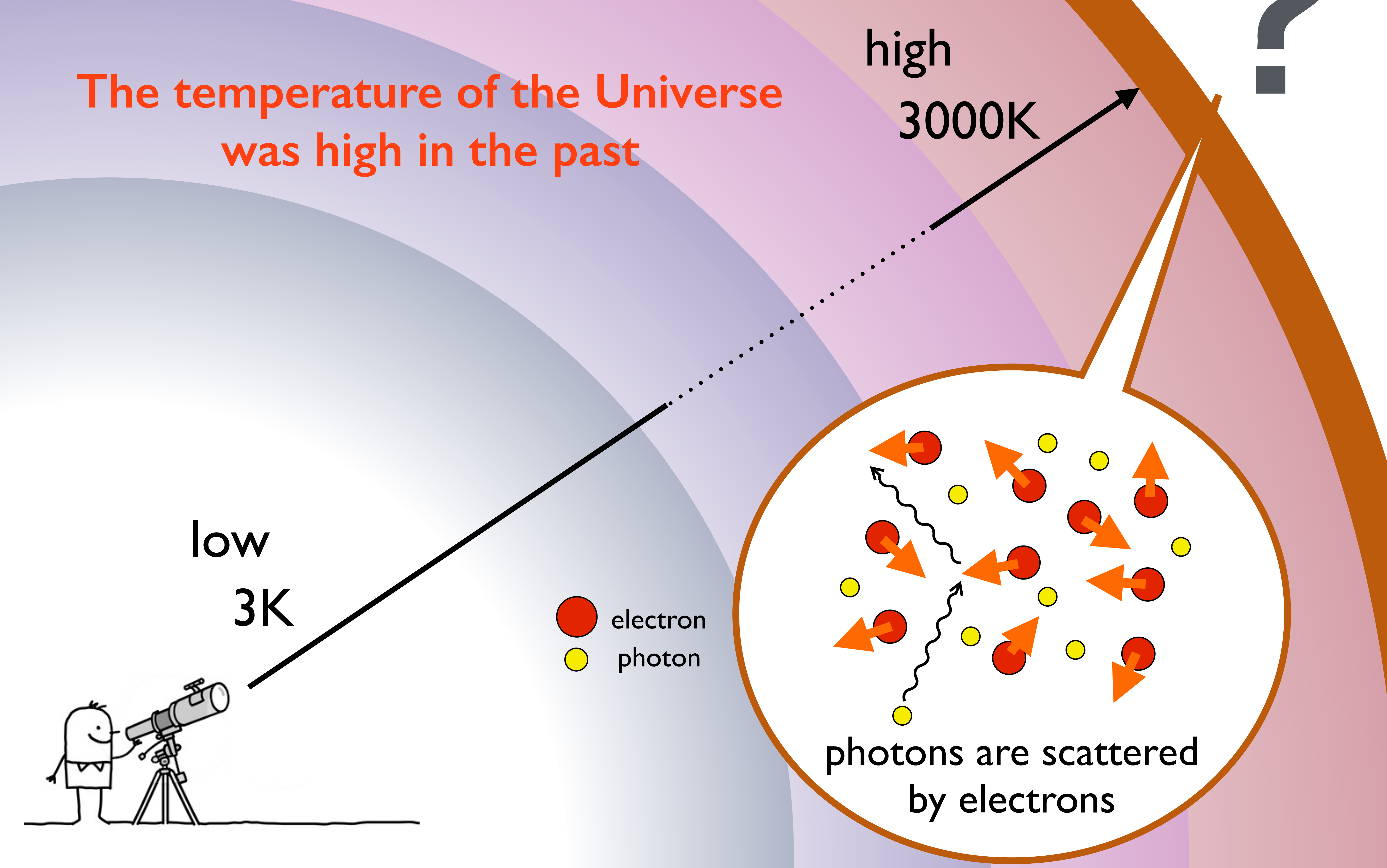
→0.38 million years after the birth

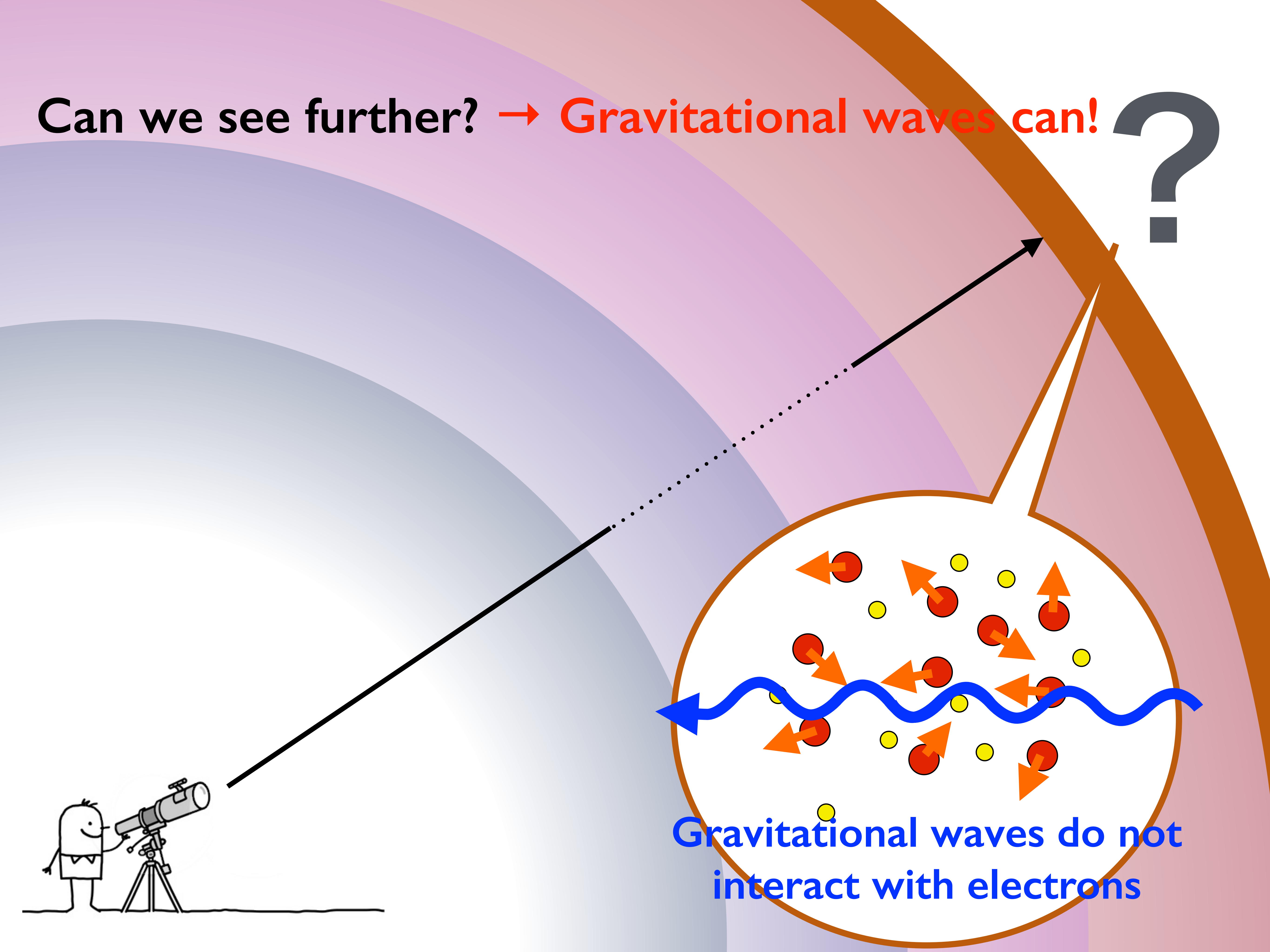




Can we see further? → No (currently)

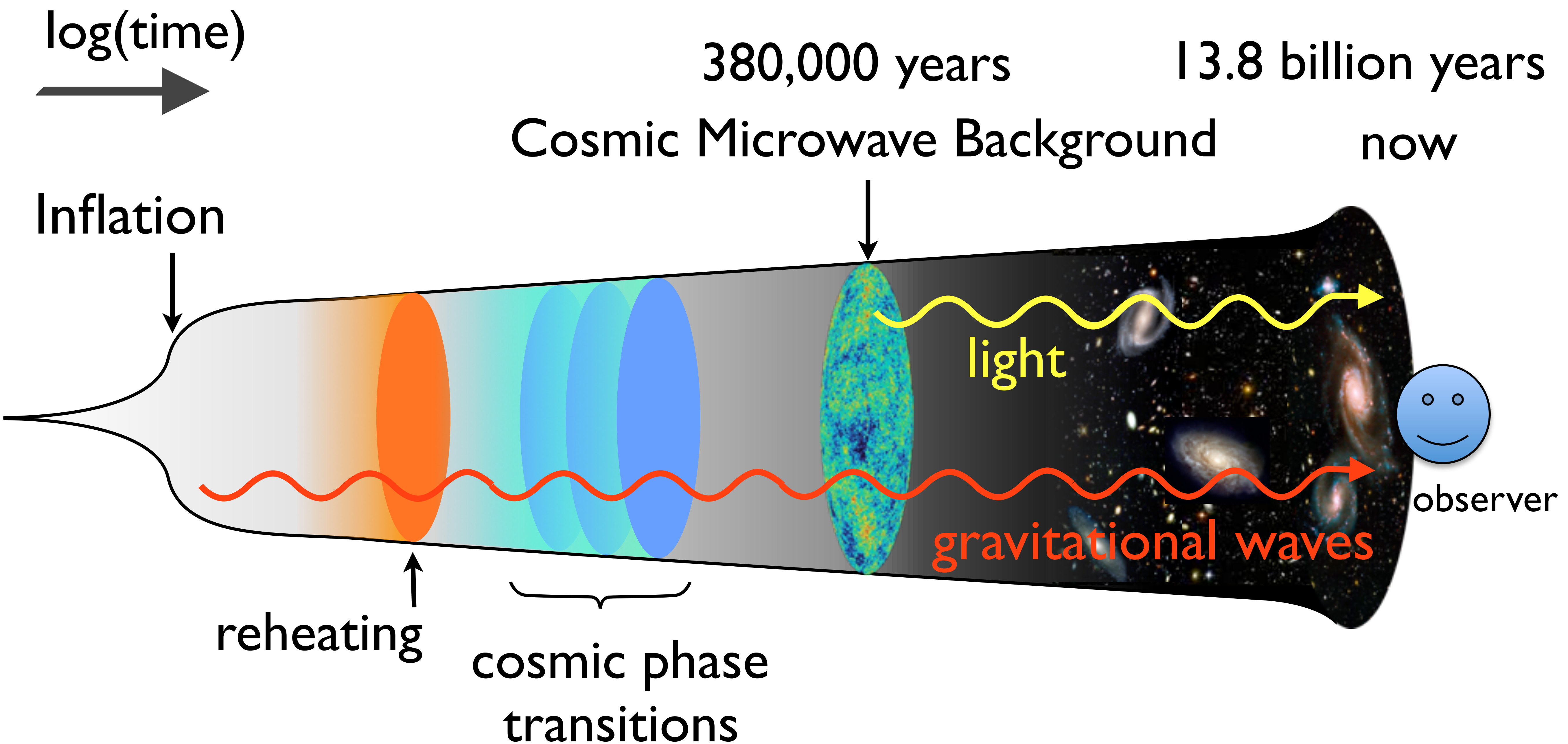
The temperature of the Universe was high in the past




Can we see further? → Gravitational waves can!
?
Gravitational waves do not interact with electrons

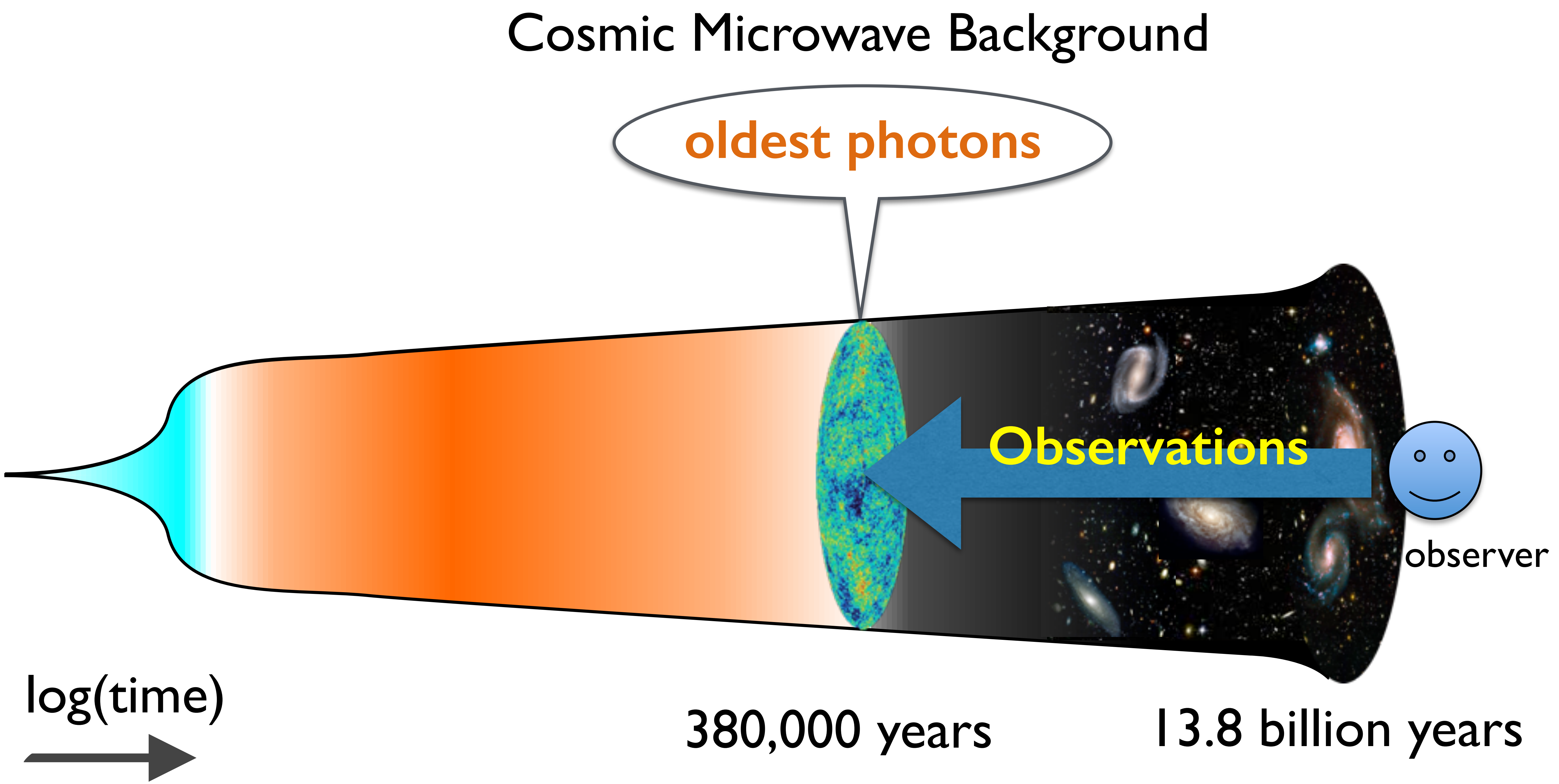
Advantages of gravitational wave observation 2

Only gravitational waves can directly bring us the information of the early Universe!



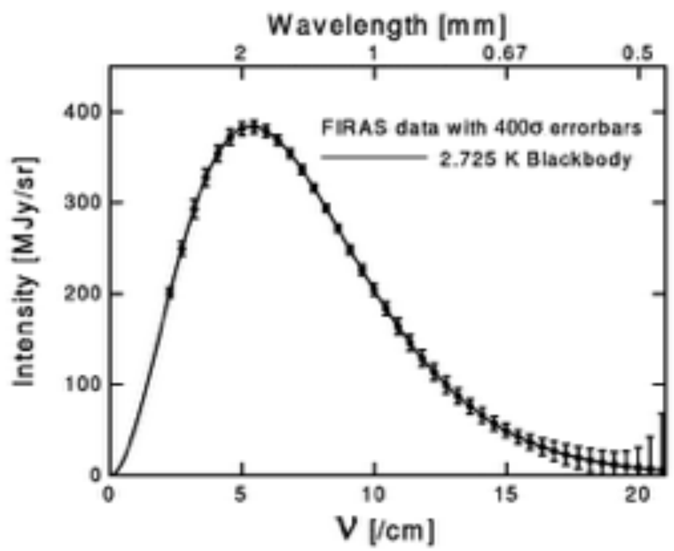
Basics of cosmology

What do we know from observations?

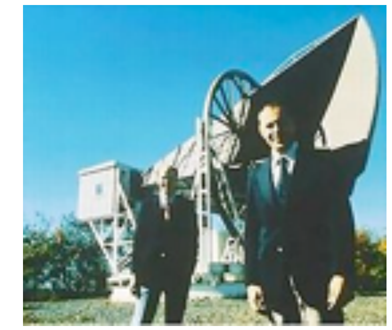


What do we know from observations?

Cosmic Microwave Background



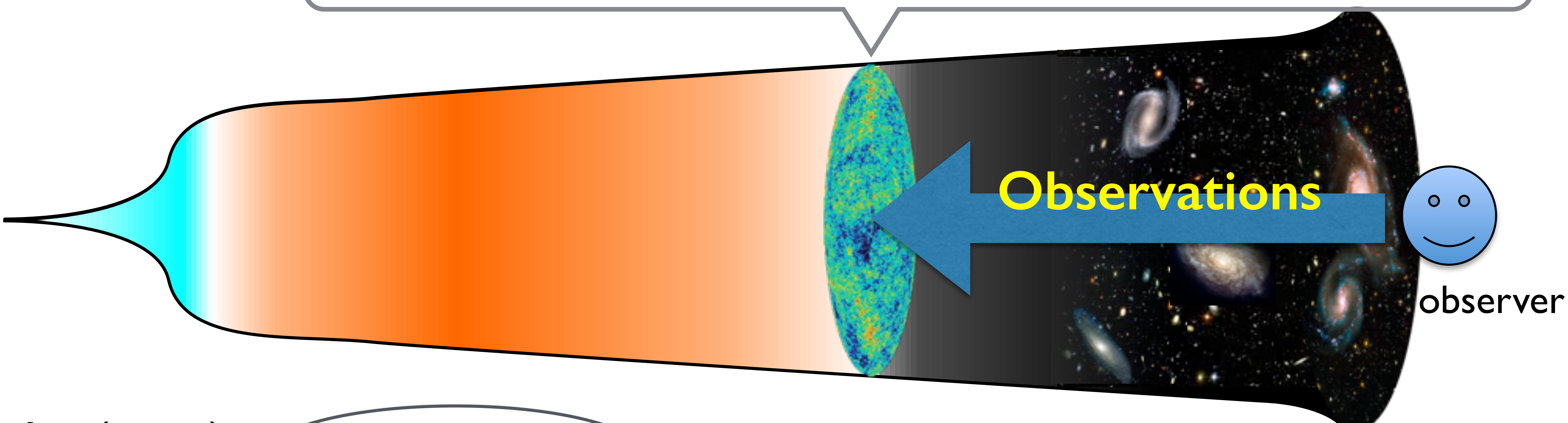
discovered by
Penzias and R. Wilson
in 1964



Perfect black body spectrum

→ Photons were in thermal equilibrium

→ The Universe was dense and hot



log(time) →

recombination

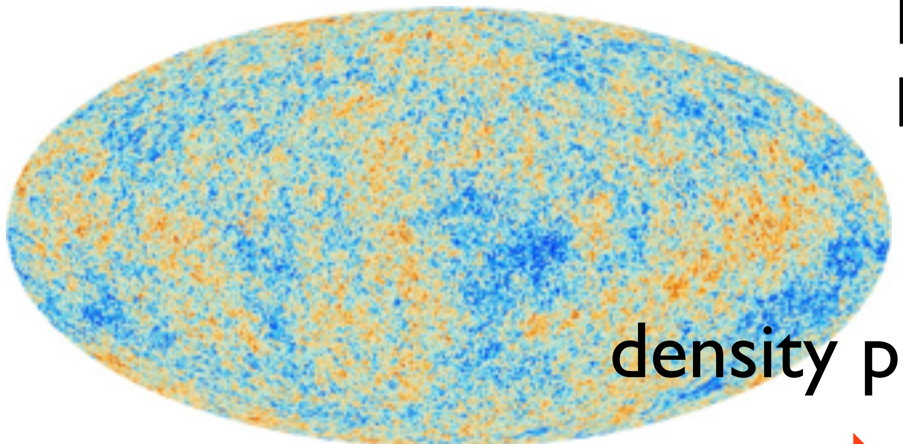
380,000 years

13.8 billion years

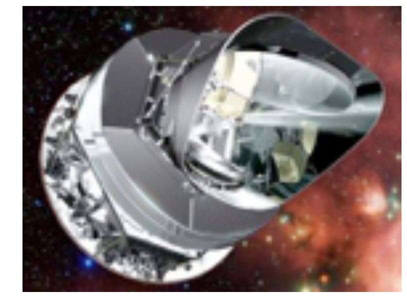
T~3000K: electrons + protons → hydrogen atoms

What do we know from observations?

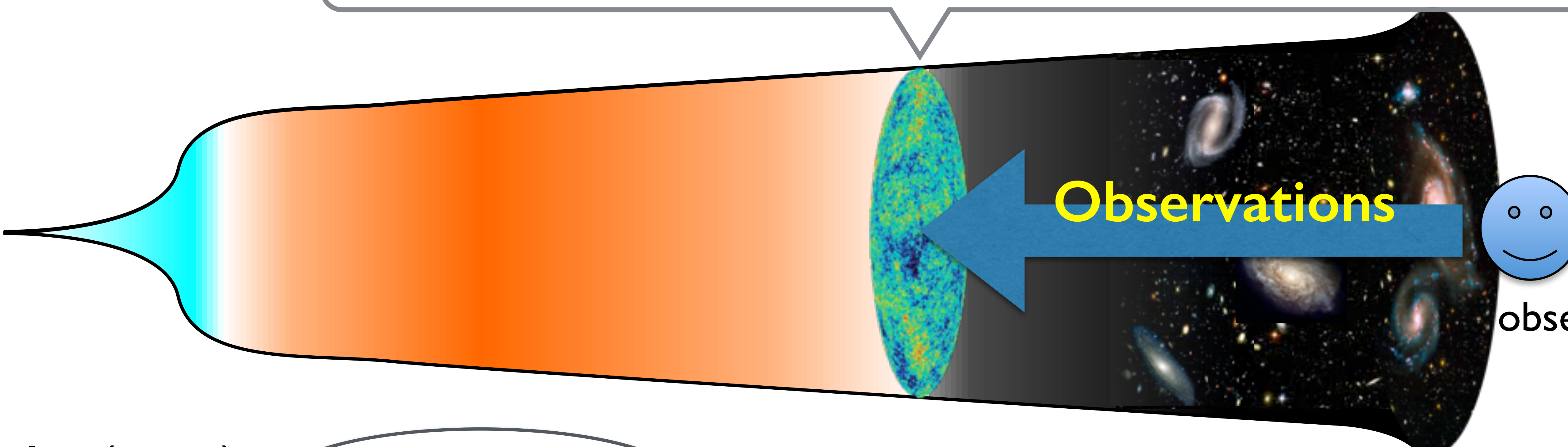
Cosmic Microwave Background



Full sky map from
Planck satellite



density perturbations in the early Universe
→ Origin of the large scale structure



log(time)

recombination

380,000 years

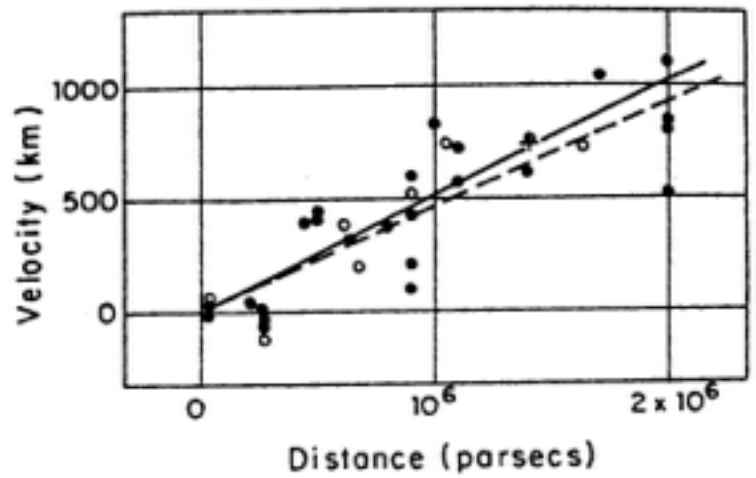
13.8 billion years

T~3000K: electrons + protons → hydrogen atoms

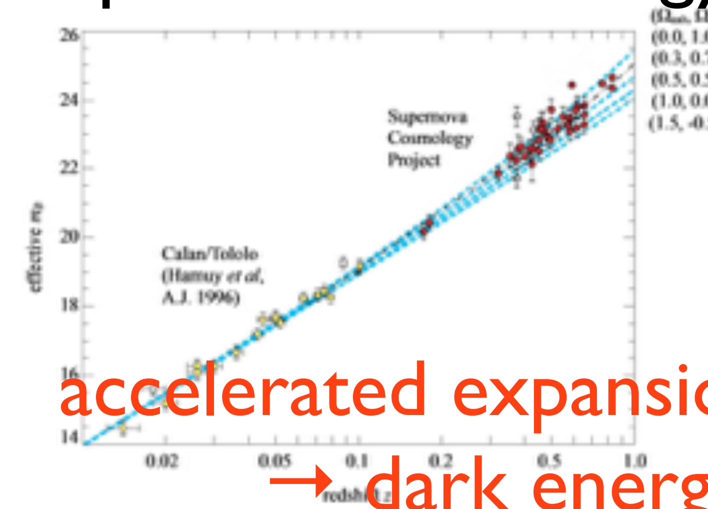
What do we know from observations?

Expansion of the Universe

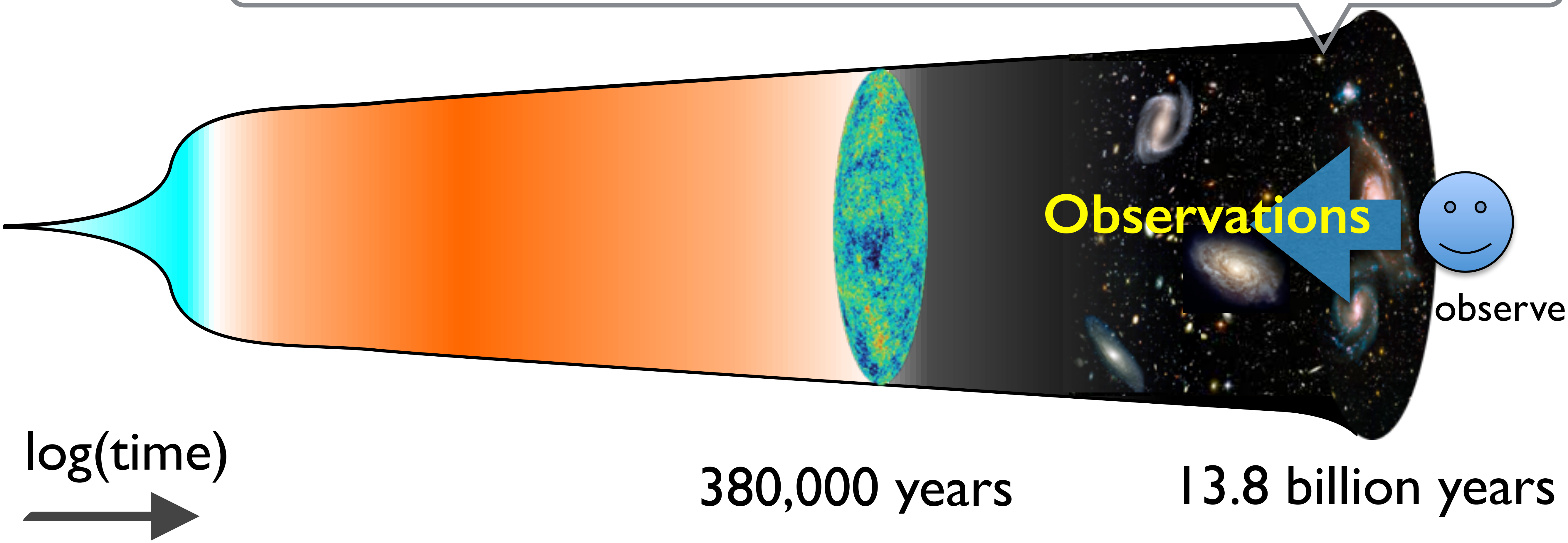
discovered by
Edwin Hubble
in 1929



supernova cosmology



accelerated expansion
→ dark energy?



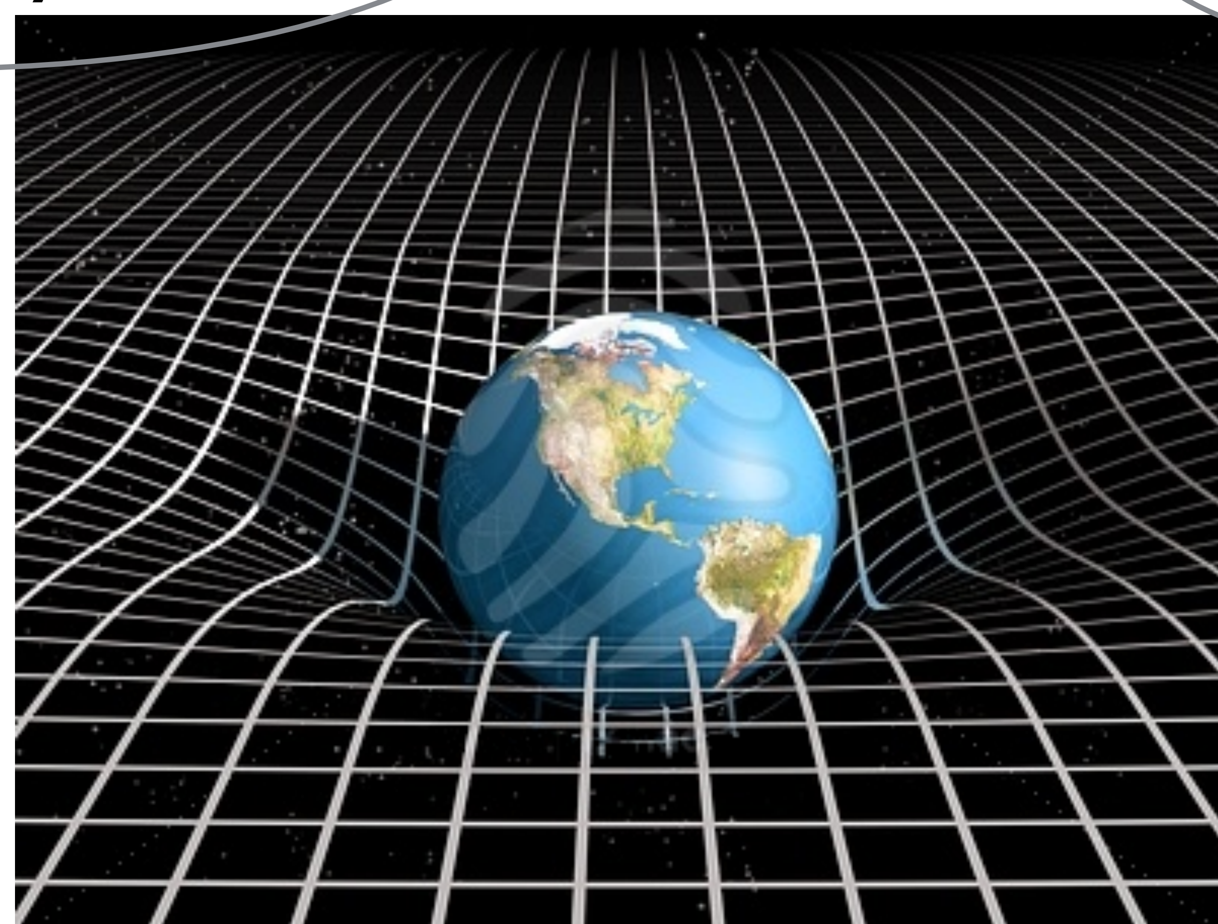
Equation for the expanding Universe

Einstein equation

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Curvature of the space-time
= Gravity

Matter



Equation for the expanding Universe

Einstein equation

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

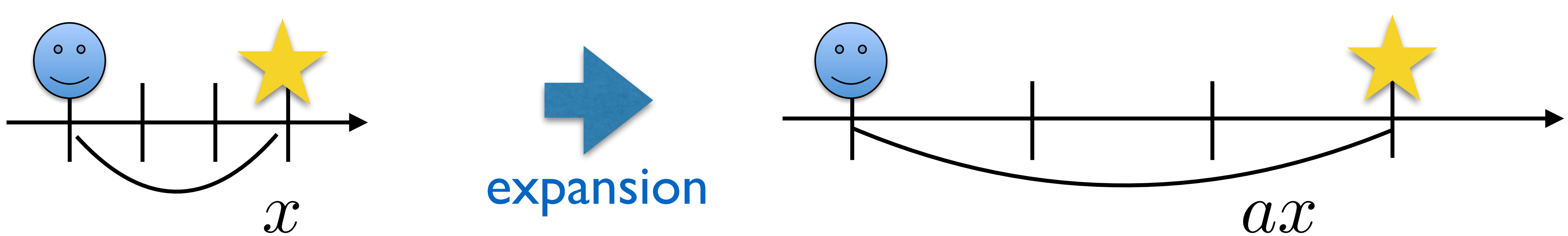
Geometry
of the Universe

Robertson-Walker metric (homogeneous and isotropic)

$$ds^2 = -dt^2 + a^2(t)\left[\frac{dr^2}{1-Kr^2} + r^2(d\theta^2 + \sin^2\theta d\phi^2)\right]$$

$a(t)$: scale factor K : curvature (<10^{-2} from CMB observation)

Scale factor characterizes the expansion of the Universe



Equation for the expanding Universe

Einstein equation

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Matter components of the Universe

$$T_{\mu\nu} = \begin{pmatrix} -\rho & 0 & 0 & 0 \\ 0 & p & 0 & 0 \\ 0 & 0 & p & 0 \\ 0 & 0 & 0 & p \end{pmatrix}$$

ρ : density p : pressure

Geometry of the Universe

Robertson-Walker metric

$$ds^2 = -dt^2 + a^2(t)\left[\frac{dr^2}{1-Kr^2} + r^2(d\theta^2 + \sin^2\theta d\phi^2)\right]$$

$a(t)$: scale factor K : curvature (<10^{-2} from CMB observation)

Friedmann equation: $$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2}$$

Equation for the expanding Universe

Friedmann equation: $$H^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2}$$

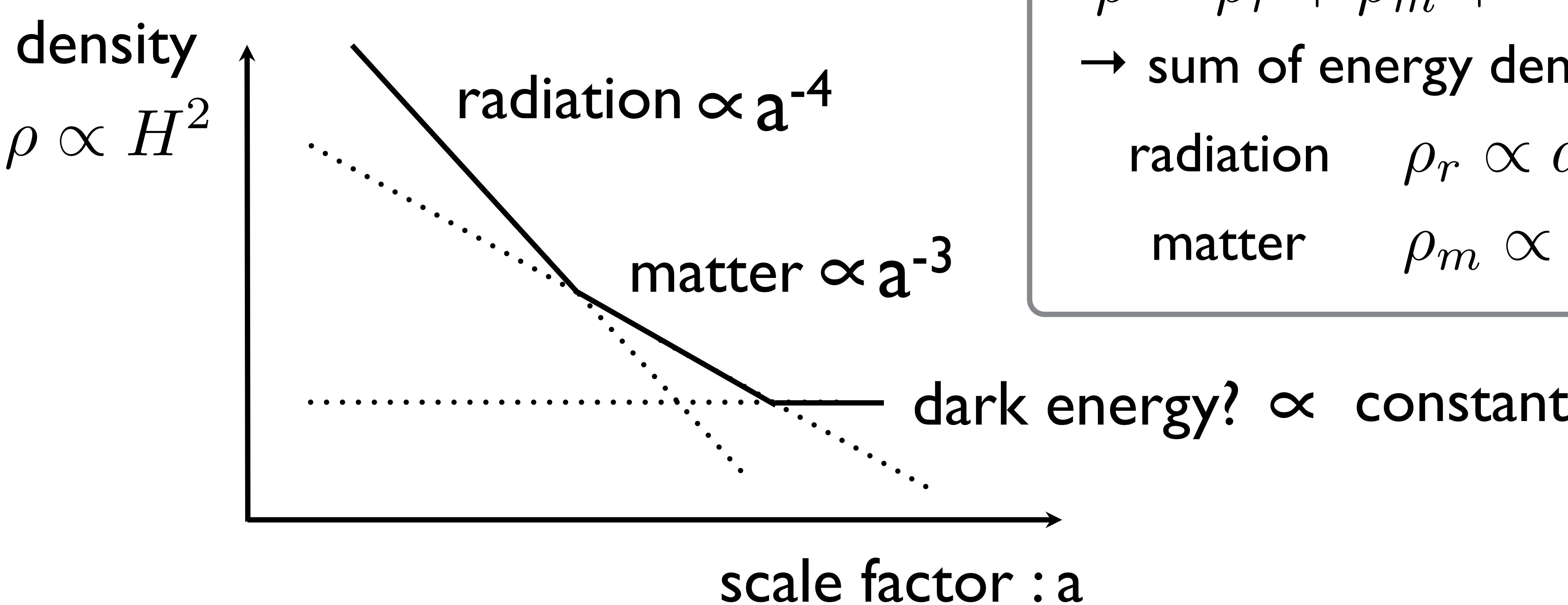
$$H \equiv \frac{\dot{a}}{a}$$: Hubble parameter

$$\rho = \rho_r + \rho_m + \cdots$$

→ sum of energy densities

radiation $\rho_r \propto a^{-4}$

matter $\rho_m \propto a^{-3}$



Equation for GWs in the expanding Universe

Einstein equation

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Geometry

Flat Universe + tensor perturbations (=GWs)

$$ds^2 = -dt^2 + a^2(t)(\delta_{ij} + h_{ij})dx^i dx^j$$

$a(t)$: scale factor

$$\ddot{h}_{ij} + 3H\dot{h}_{ij} - \frac{1}{a^2}\nabla^2 h_{ij} = 16\pi G \Pi_{ij}$$

H affects GW evolution

anisotropic stress : transverse-traceless part of $T_{\mu\nu}$

Meaning of H

$$H \equiv \frac{\dot{a}}{a}$$

speed of expansion

$$d_H \equiv cH^{-1}$$: Hubble horizon

$\sim$ region of causality

x

$$v = Hx$$

$v < c$

we have information of the object

$v > c$

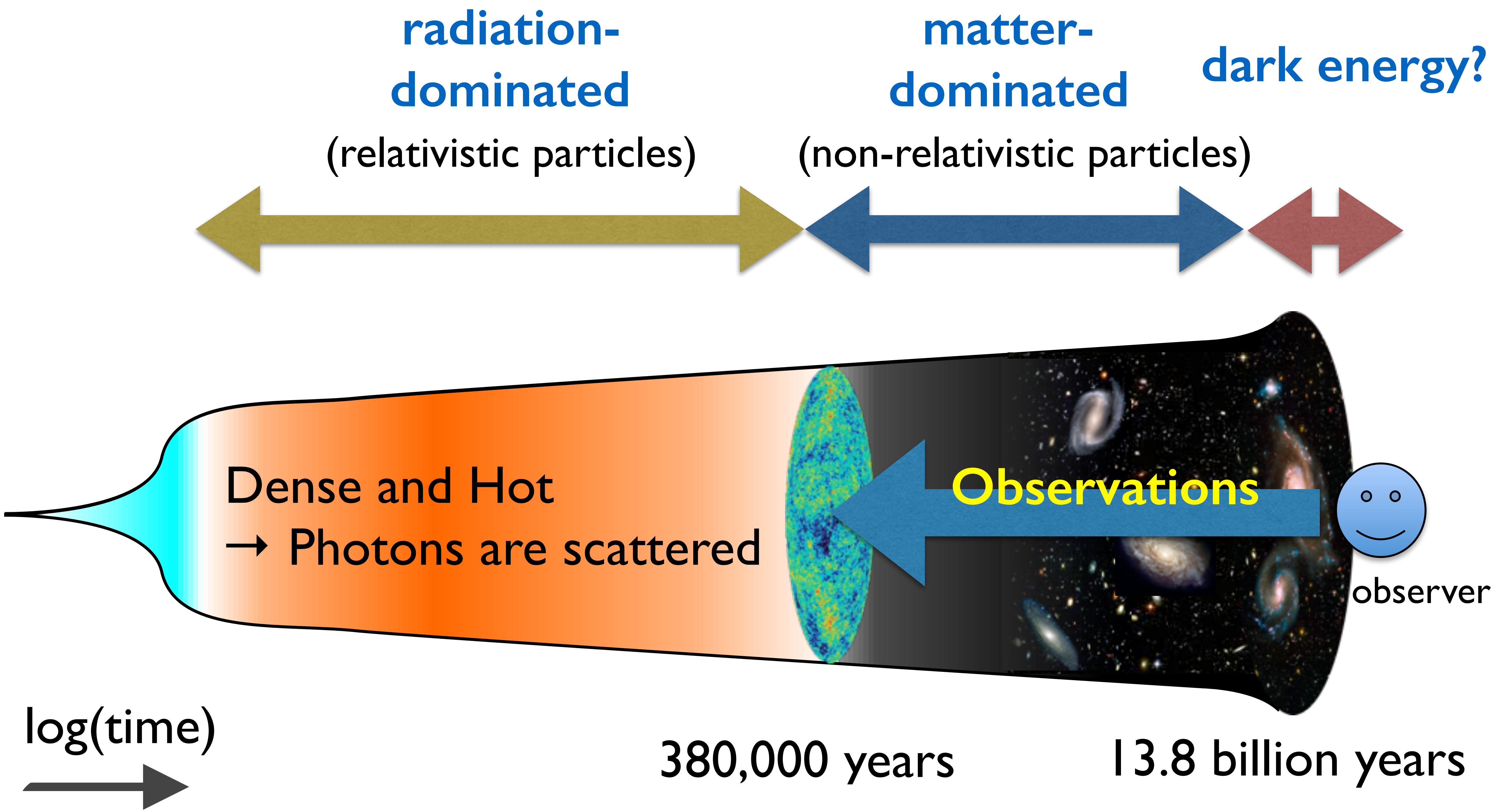
no information

To be precise… $L_H = \int_0^t \frac{cdt}{a(t)} \propto d_H$

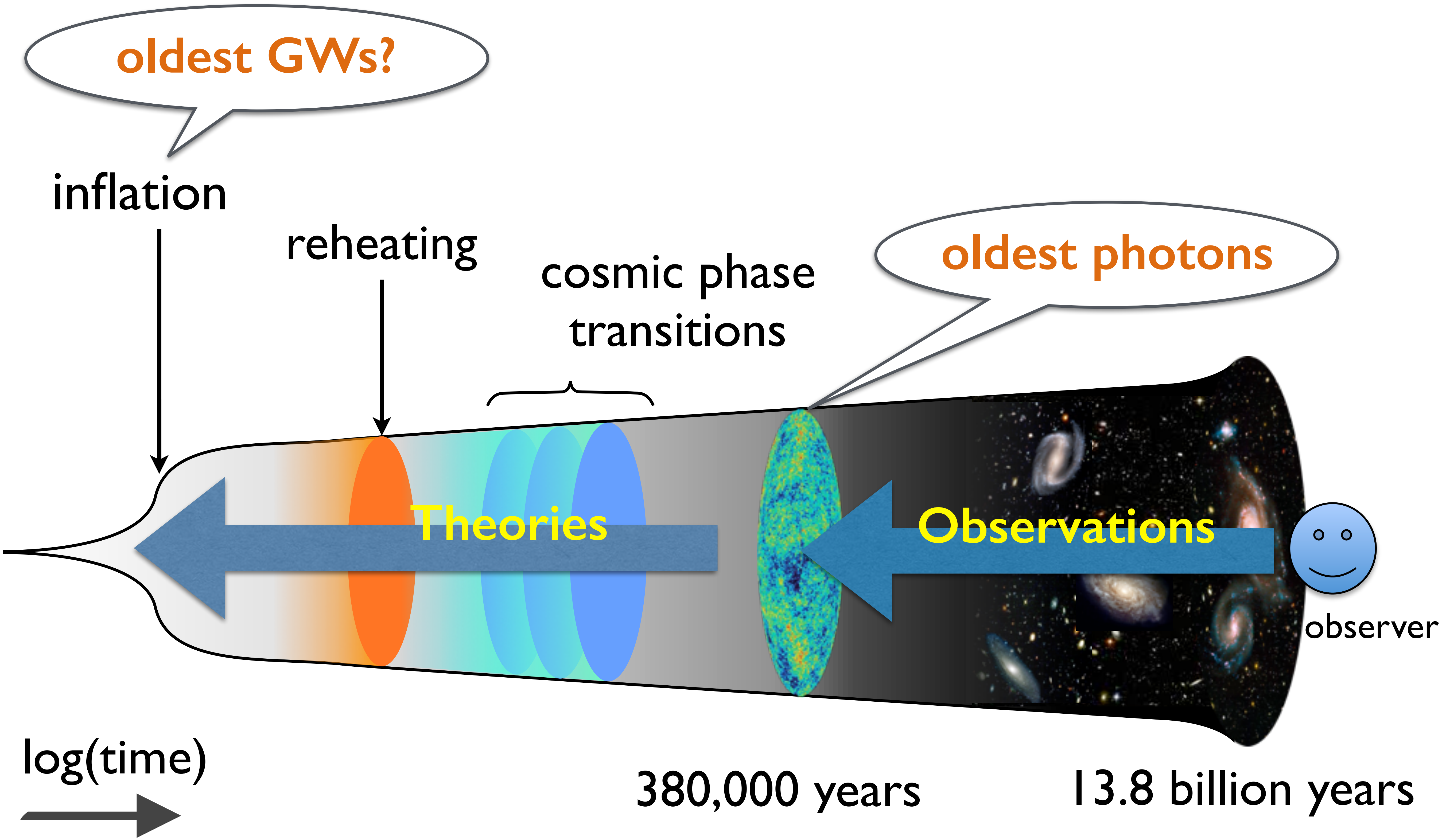
for radiation- and matter-dominated Universe

Summary of observational facts

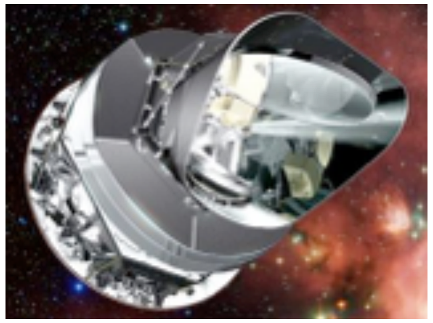
Expansion rate → density components of the Universe



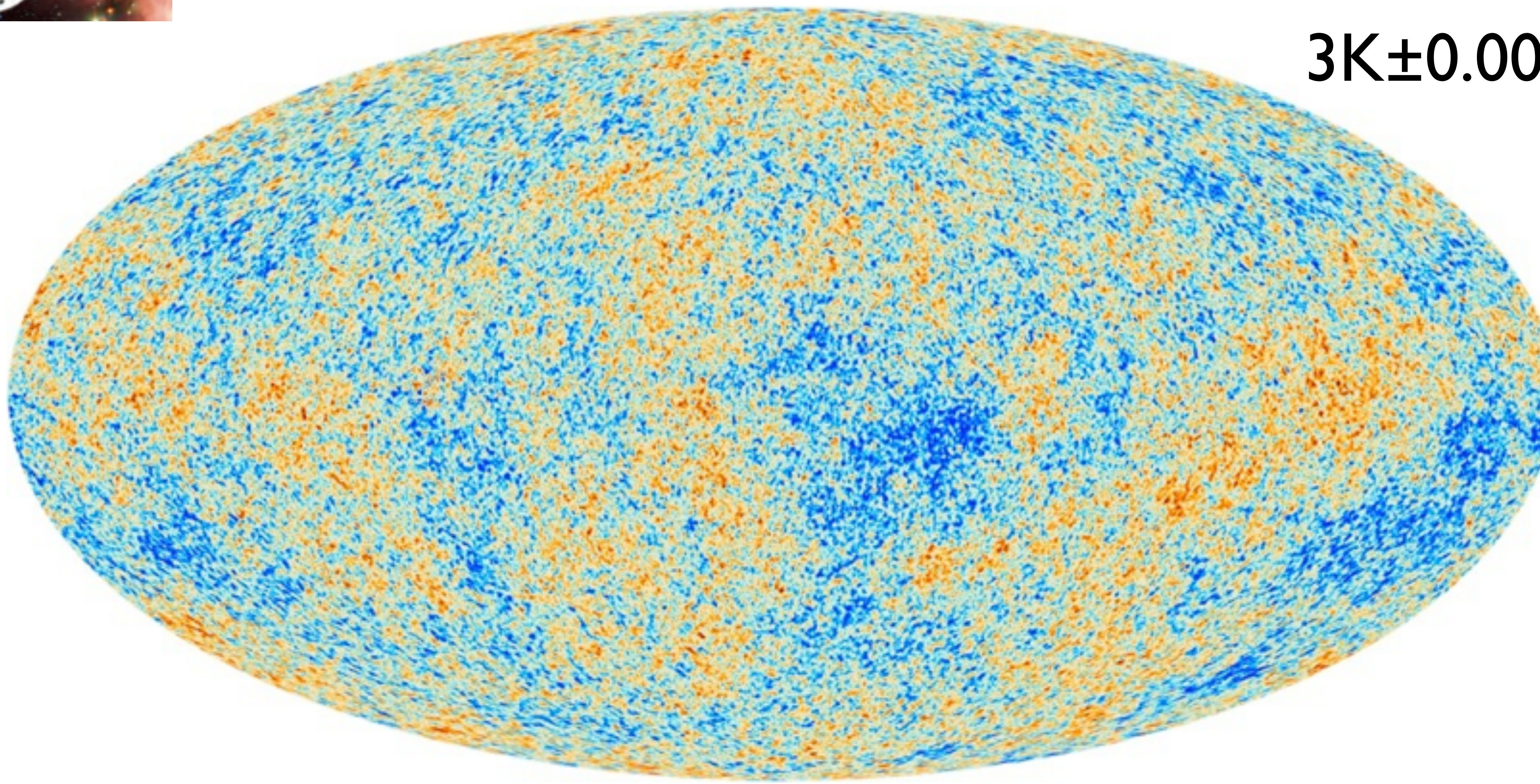
What happened in the early Universe?



Theories of the early Universe



Full sky map of CMB by Planck satellite



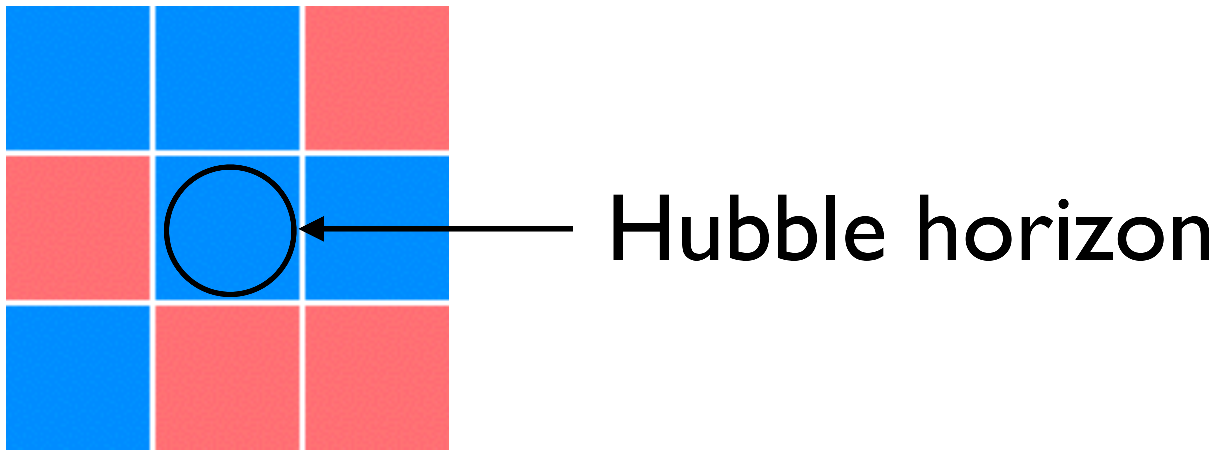
3K±0.00001K

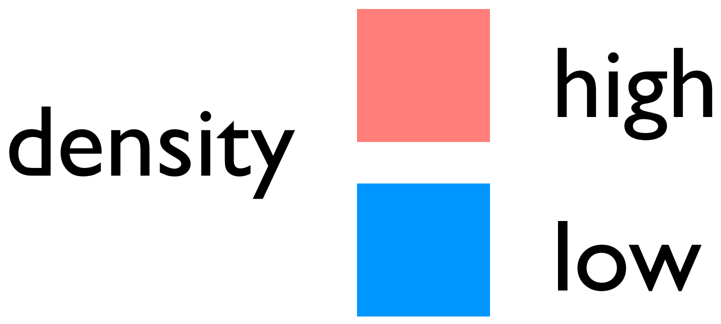
Why the Universe is so uniform?
What's the origin of ±0.00001K?

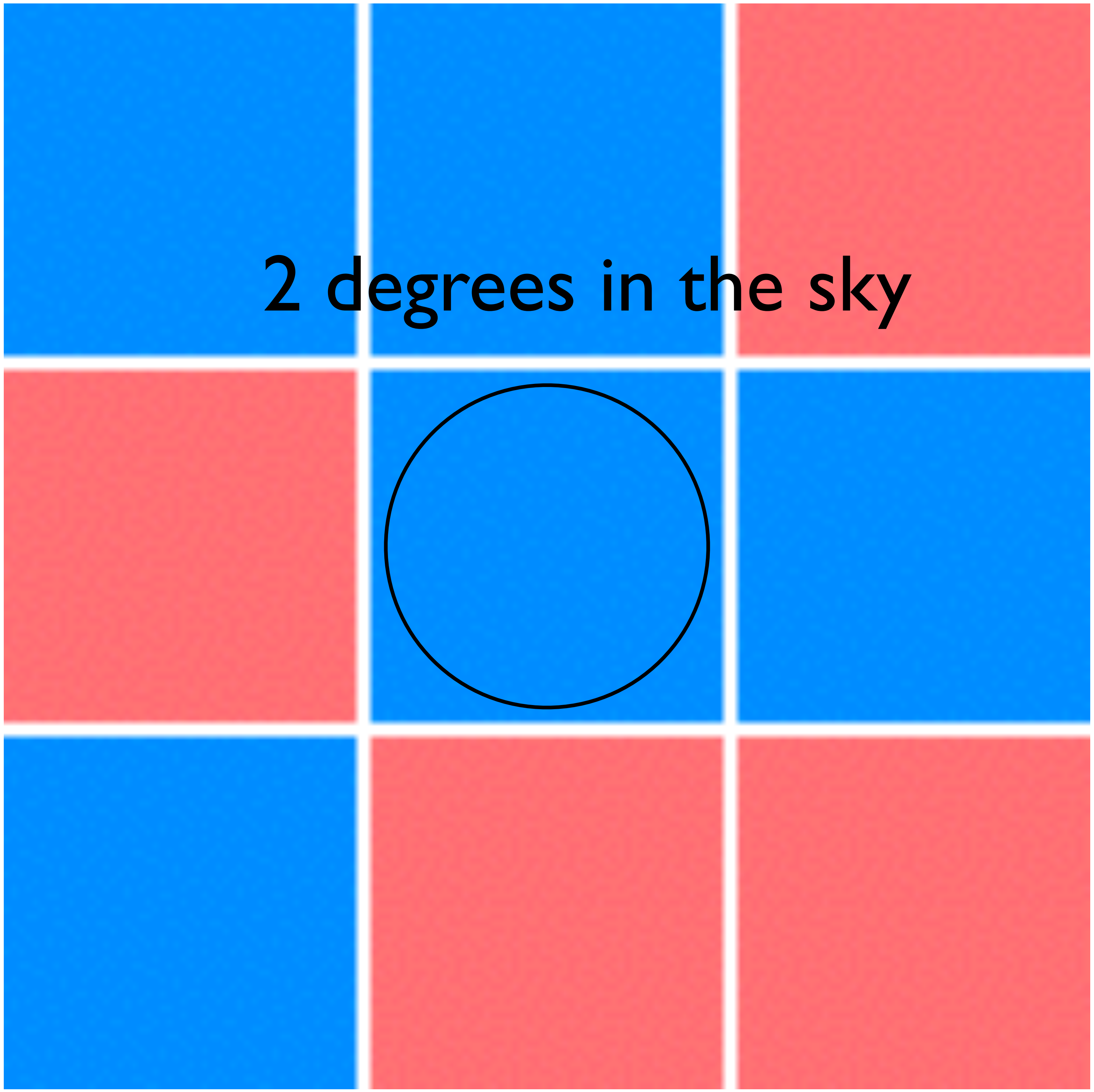
→ **Inflation solves the questions**

At the recombination…

Arbitral initial condition

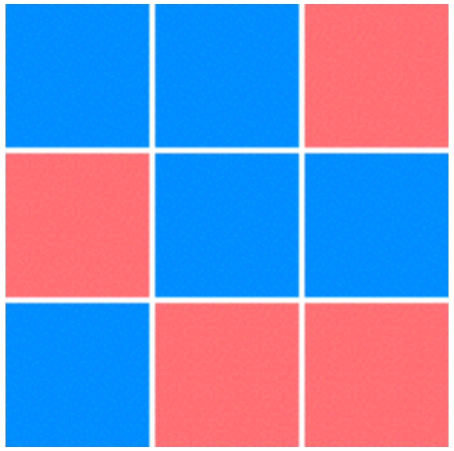





2 degrees in the sky

Idea of inflation

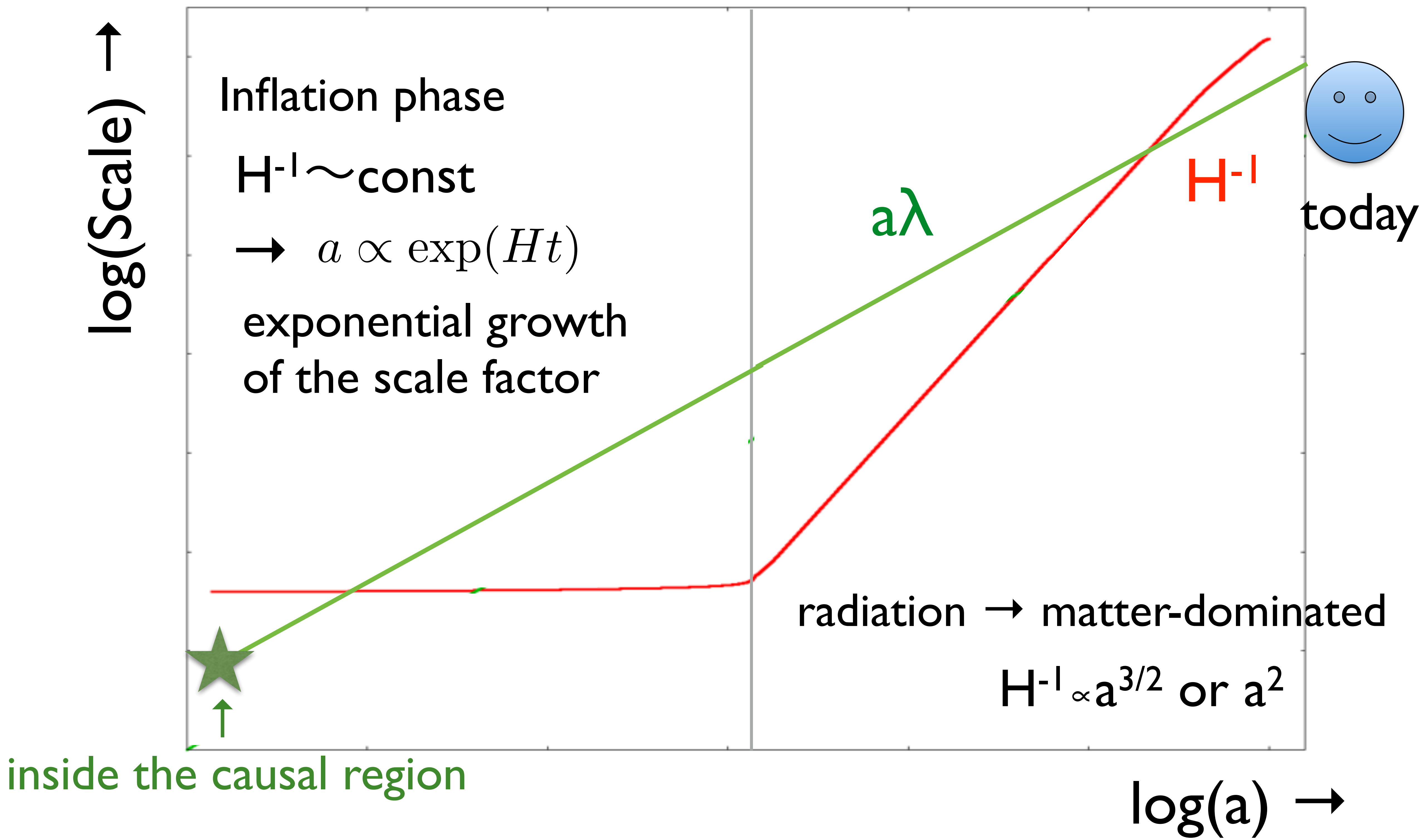
in the very early time of the Universe…



Uniform Universe

H^{-1}: Hubble horizon

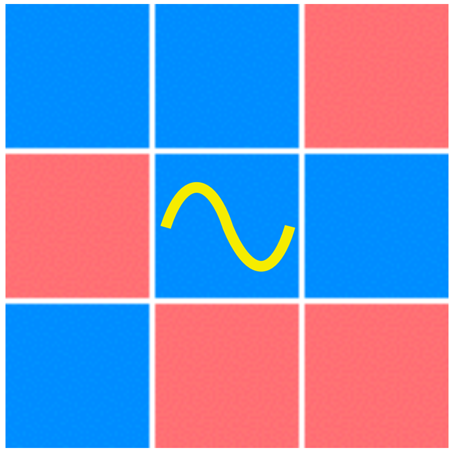
$a\lambda$: physical scale



GWs from the early Universe

Generation of GWs in inflation

quantum fluctuation in space-time



becomes classical

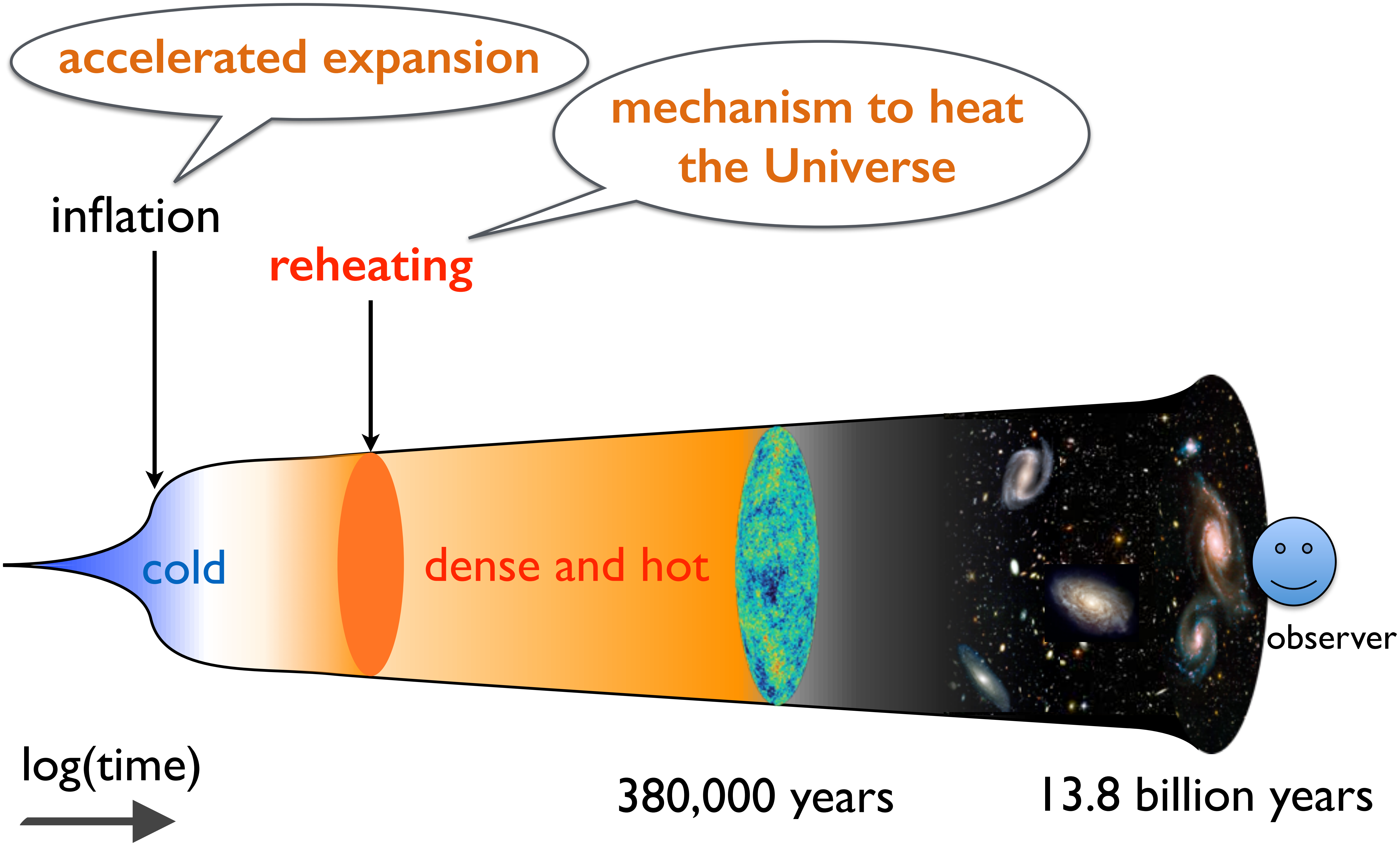
→ gravitational wave

density perturbations are also generated in similar way

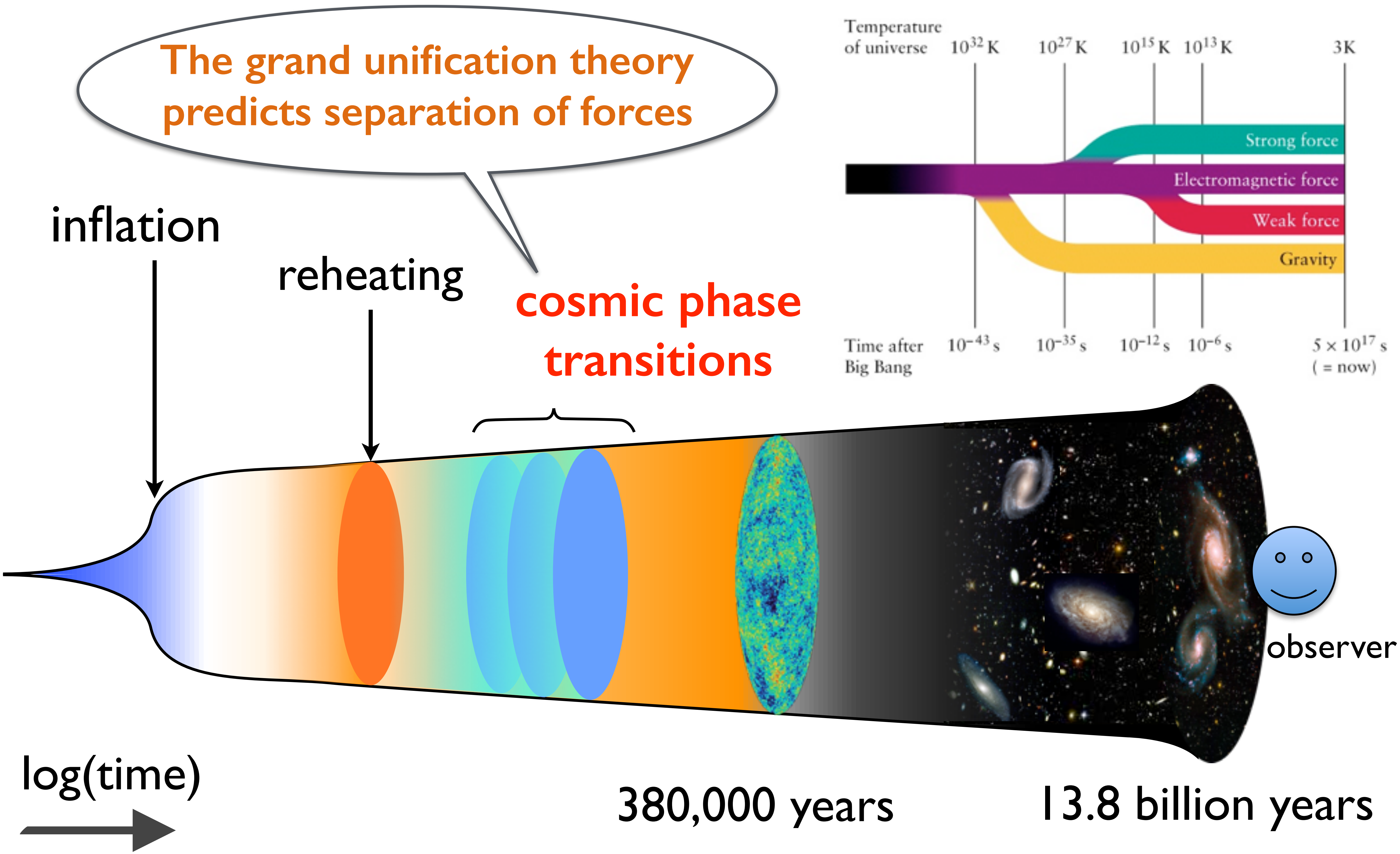
→ origin of 3K±0.00001K

good match with observations

What happened in the early Universe?



What happened in the early Universe?



GW generation

Equation for GWs

$$\ddot{h}_{ij} + 3H\dot{h}_{ij} - \frac{1}{a^2}\nabla^2 h_{ij} = 16\pi G \Pi_{ij}$$

1. Non-negligible initial condition

- **Inflation**

  → quantum fluctuations

2. Sourced by matter component of the Universe

- **Preheating**

  → rapid particle productions

- **Phase transition**

  → bubble collisions

- **Cosmic strings**

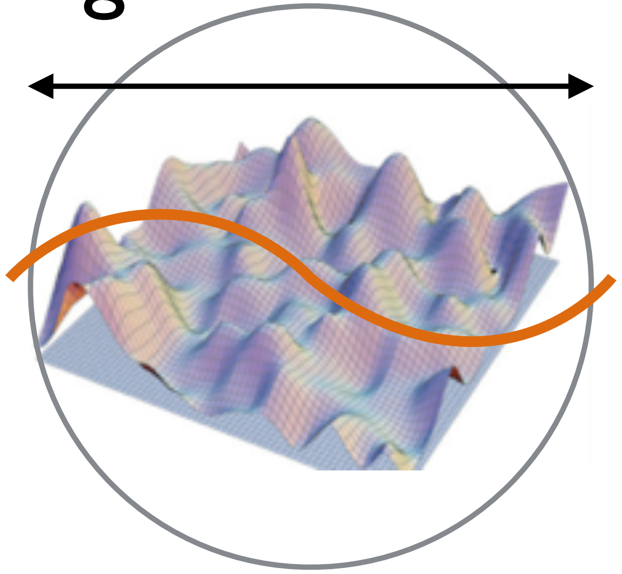
  → heavy string objects generated in phase transition

GW generation

Equation for GWs

$$\ddot{h}_{ij} + 3H\dot{h}_{ij} - \frac{1}{a^2}\nabla^2 h_{ij} = 16\pi G \Pi_{ij}$$

Hubble horizon
= region of causality



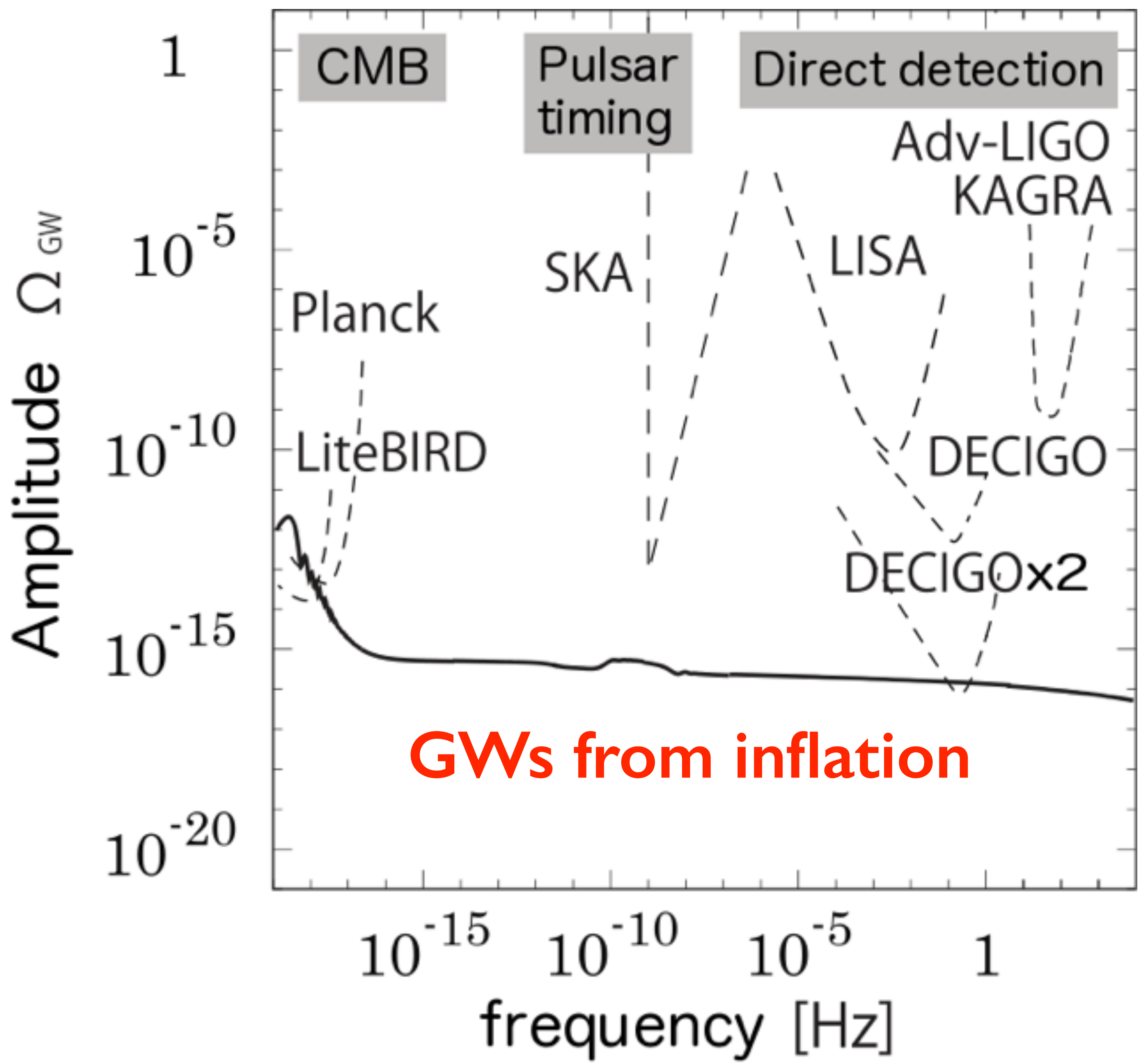
wavelength of GWs at generation
< Hubble horizon size

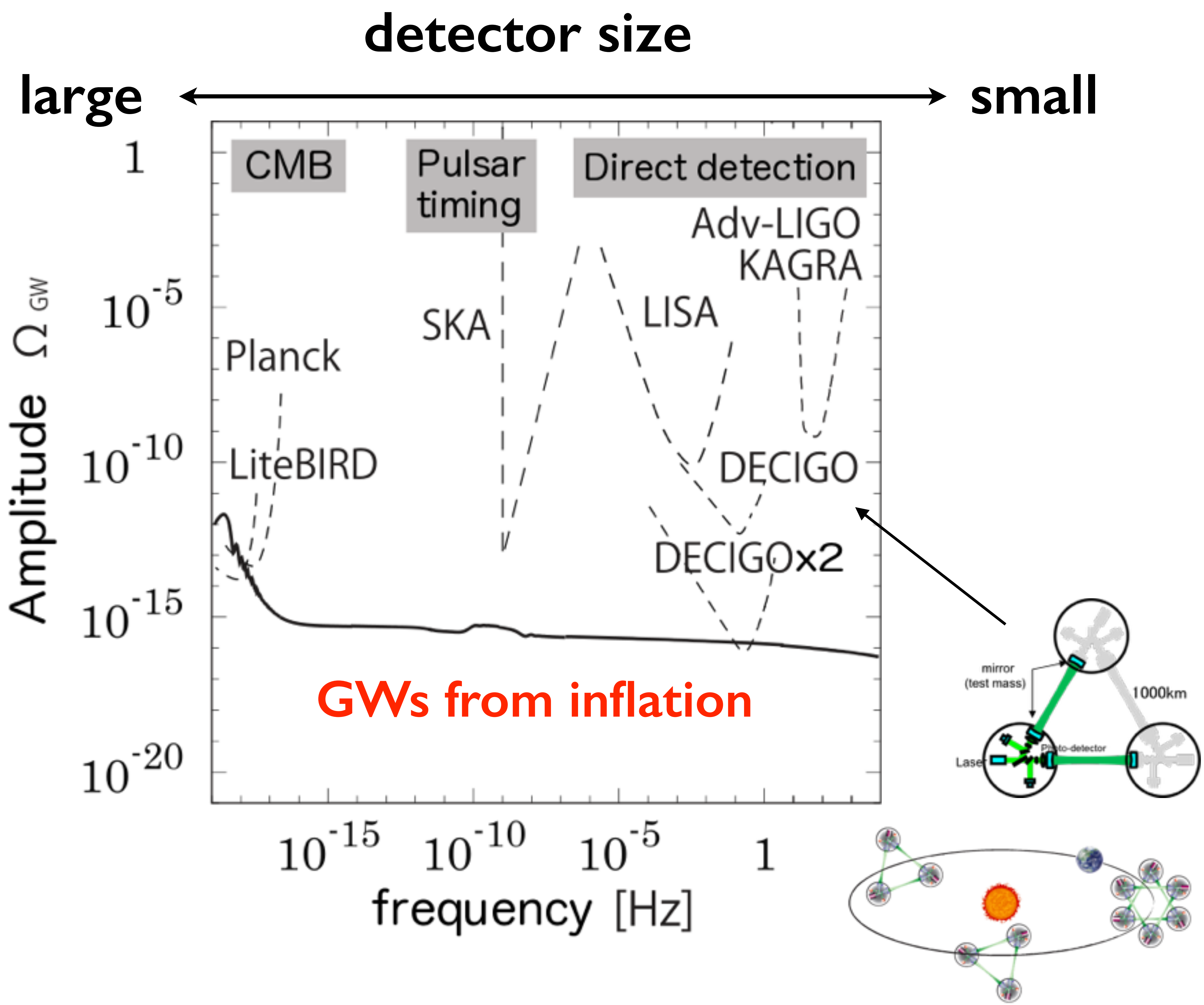
→ $f/a < H$

2. Sourced by matter component of the Universe

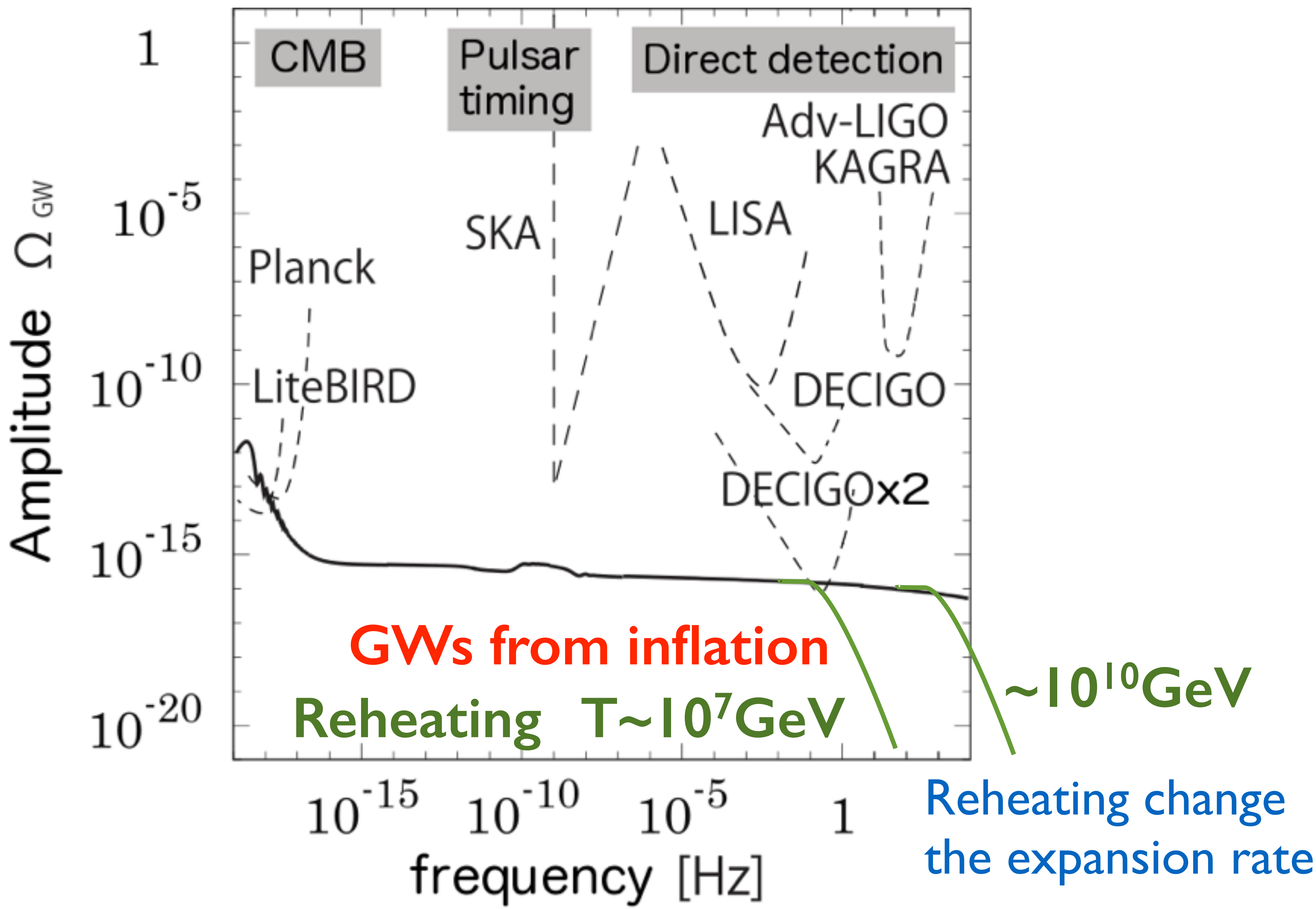
- **Preheating**
→ rapid particle productions
- **Phase transition**
→ bubble collisions
- **Cosmic strings**
→ heavy string objects generated in phase transition

Sensitivities of gravitational wave experiments

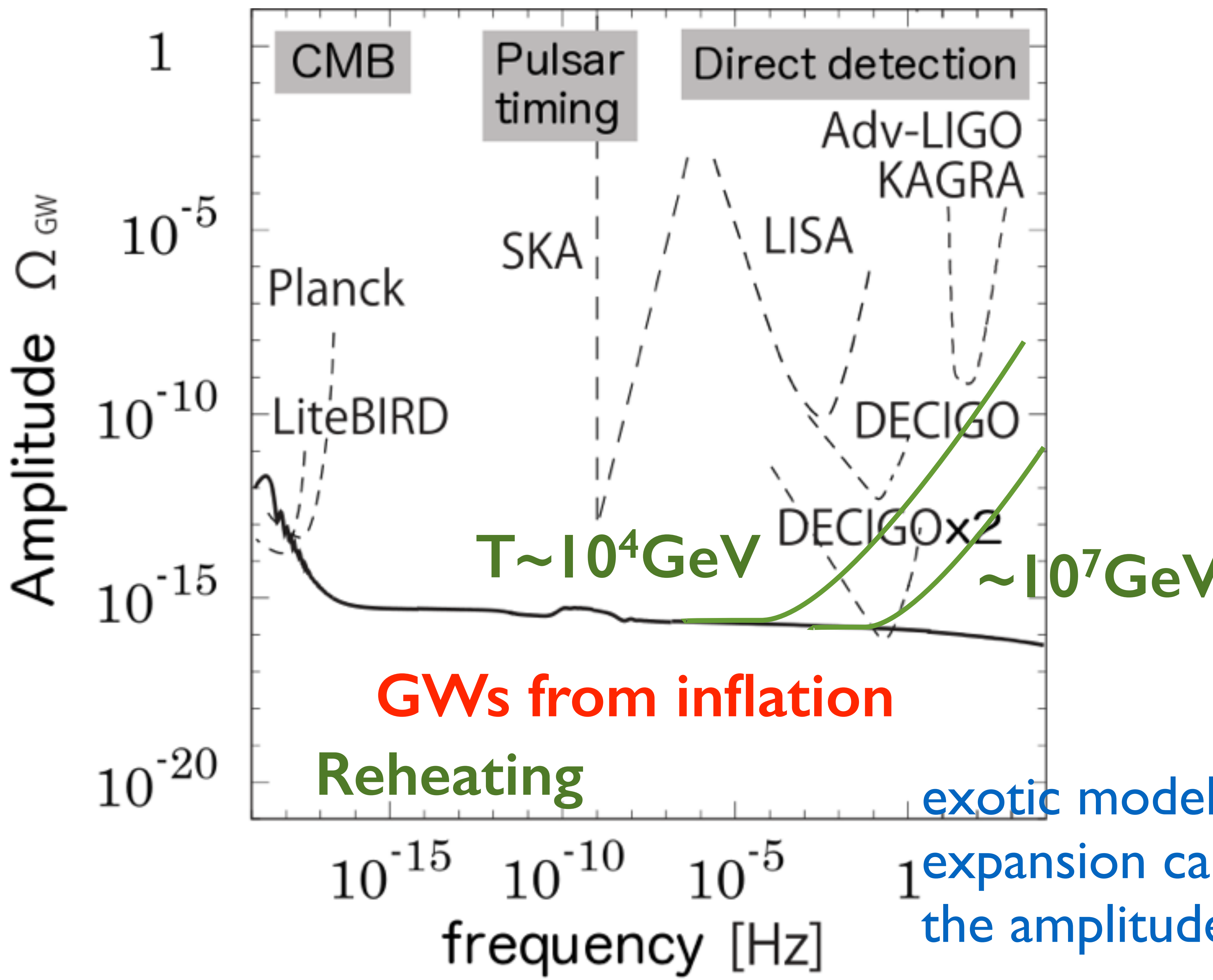



detector size
large
small
CMB
Pulsar timing
Direct detection
Adv-LIGO
KAGRA
SKA
LISA
Planck
LiteBIRD
DECIGO
DECIGOx2
GWs from inflation
Amplitude Ω_{GW}
1
10^{-5}
10^{-10}
10^{-15}
10^{-20}
10^{-15}
10^{-10}
10^{-5}
1
frequency [Hz]
mirror
(test mass)
1000km
Laser

Sensitivities of gravitational wave experiments

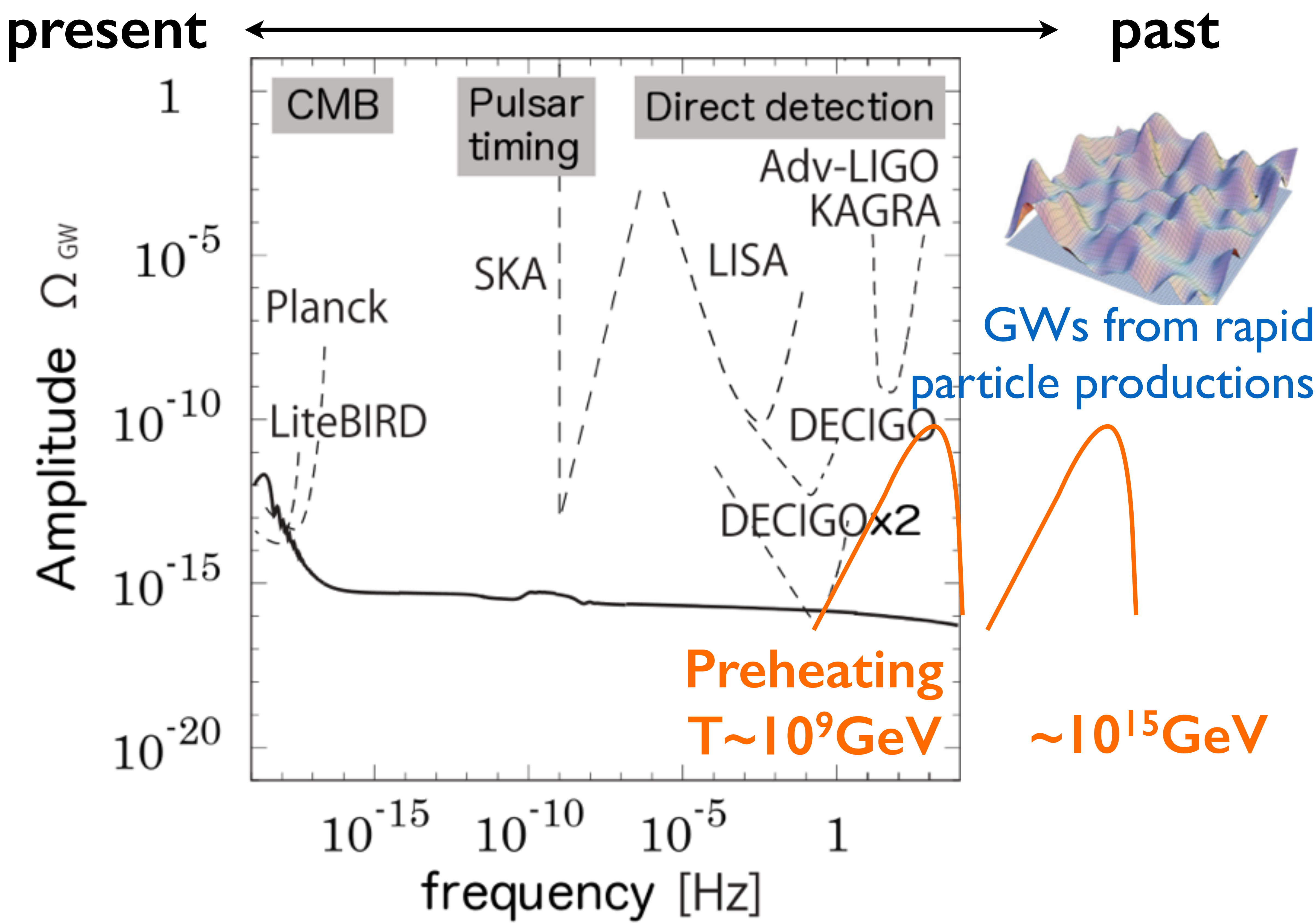


Sensitivities of gravitational wave experiments



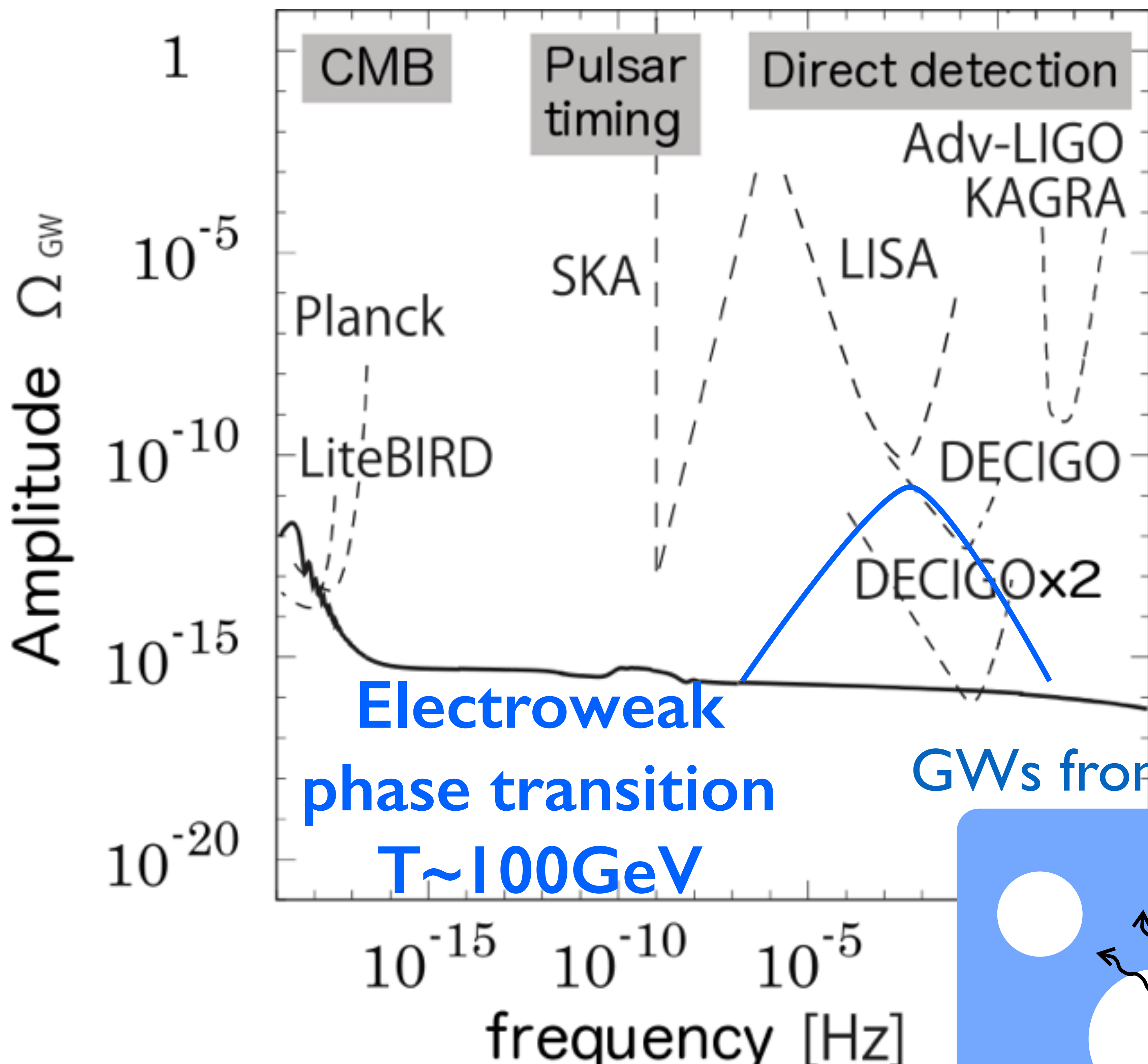
exotic model of the expansion can enhance the amplitude

frequency at the generation ~ (Hubble horizon)$^{-1}$

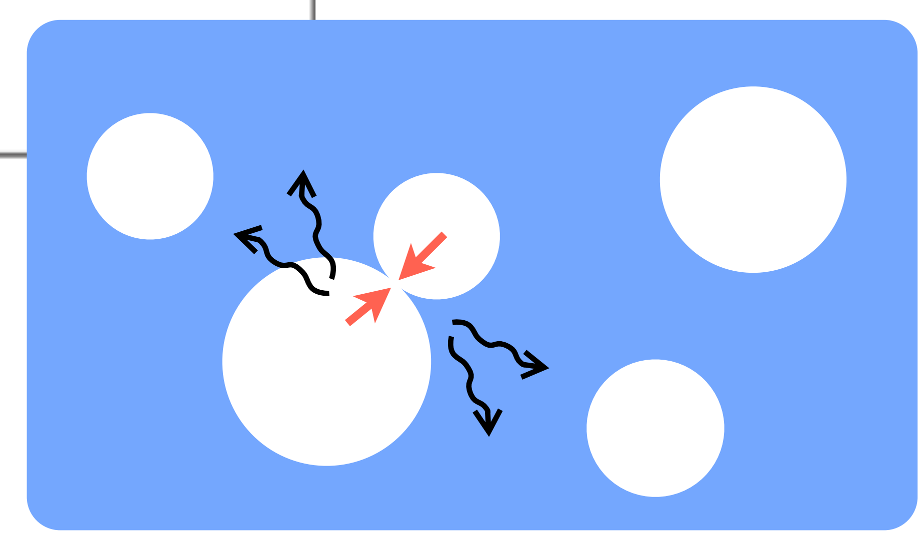


frequency at the generation ~ (Hubble horizon)$^{-1}$

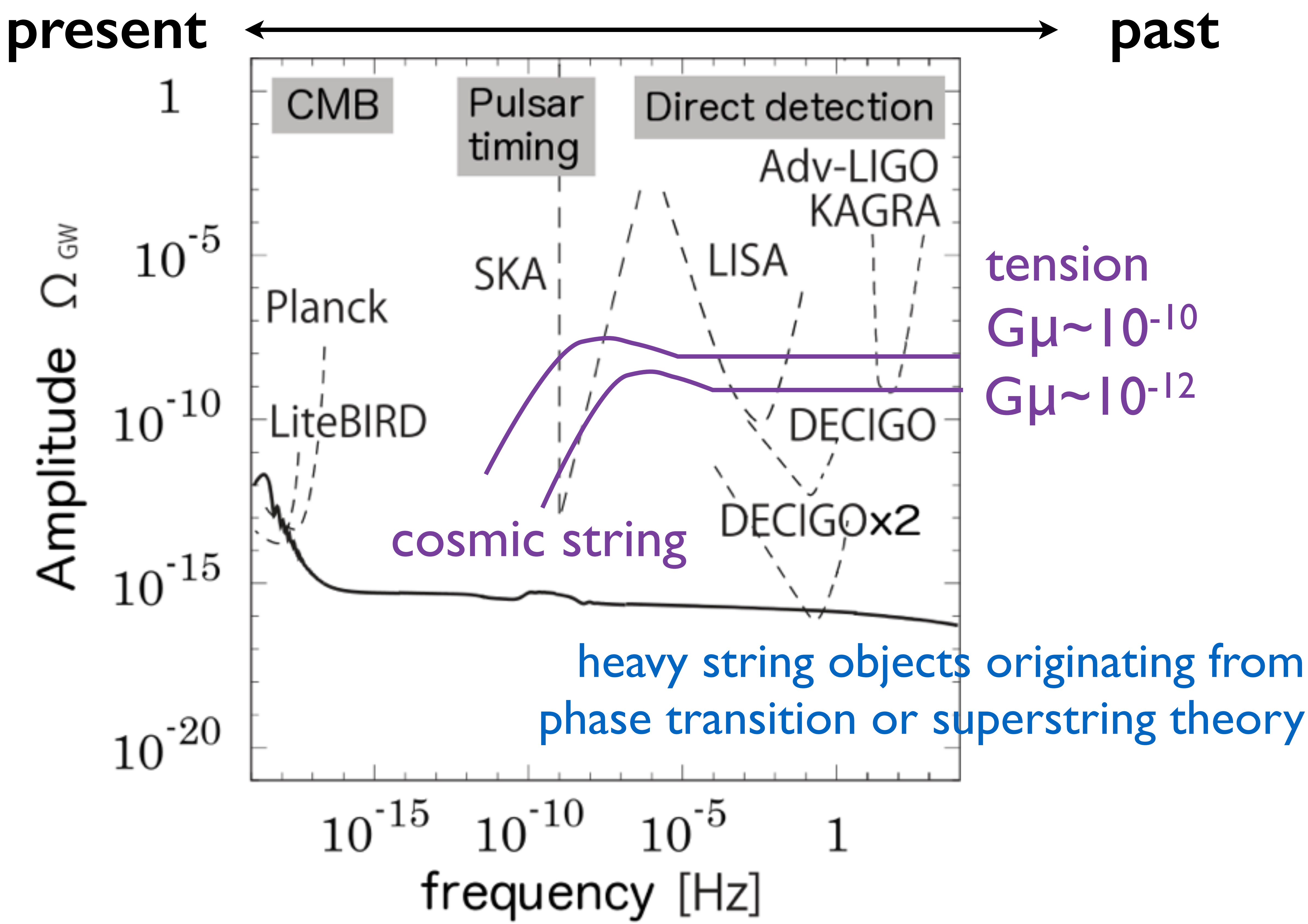
present ⟷ past



GWs from bubble collisions



frequency at the generation ~ (Hubble horizon)$^{-1}$



Summary

GWs can become a powerful probe of the very early Universe

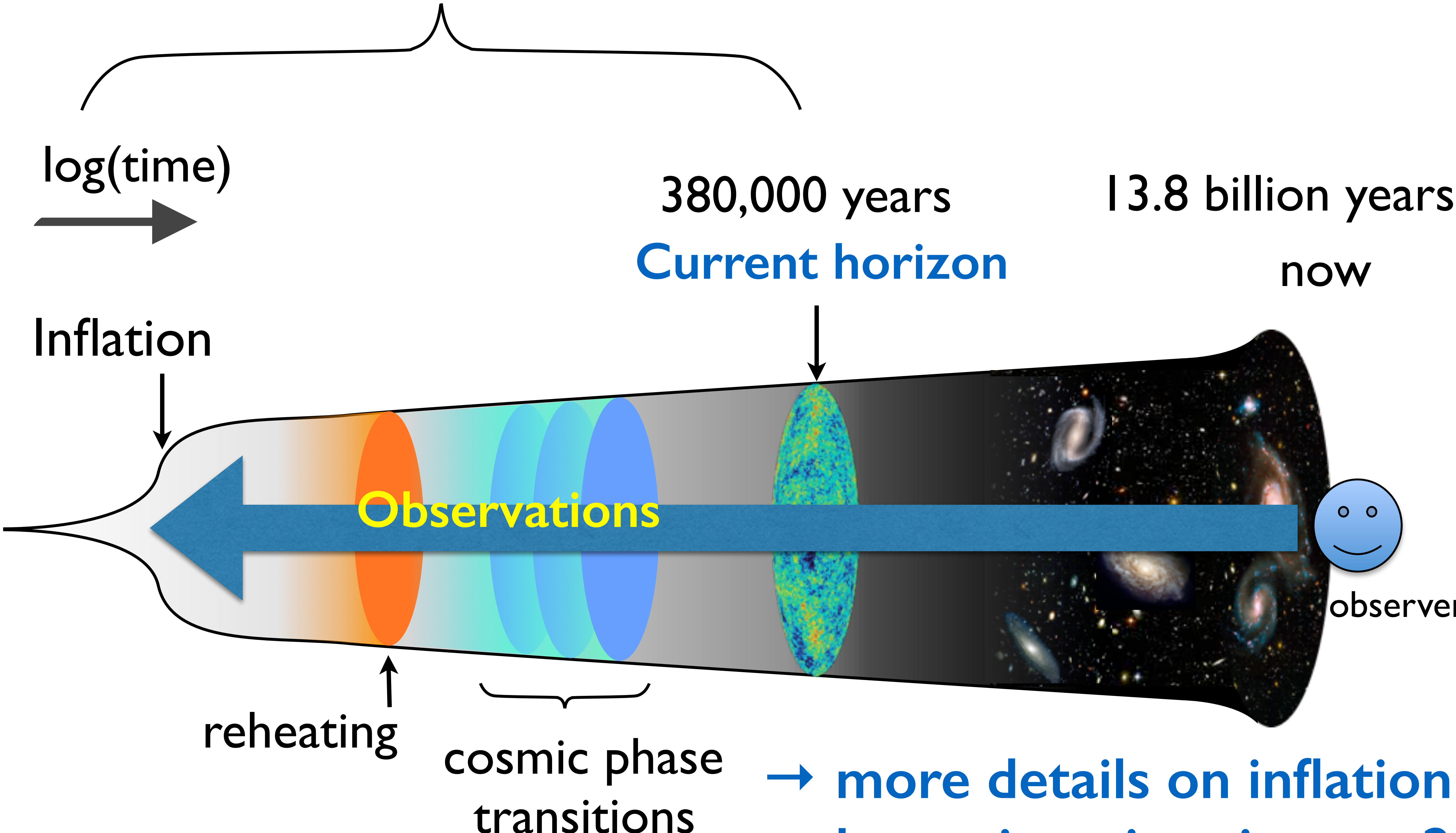
Takaaki Kajita
(PI of KAGRA)

In the interview of the Nobel prize in 2015…

> It was something to extend
> the horizon of knowledge
> for human beings

GWs extend the actual horizon of the Universe!

Events beyond the horizon contains
full of information about high-energy physics



→ more details on inflation
and cosmic strings in part 2