Cosmology,

lect. 8

Inflationary Universe

Standard Big Bang:

what it cannot explain …

- **Flatness Problem**

  the Universe is remarkably flat, and was even (much) flatter in the past

- **Horizon Problem**

  the Universe is nearly perfectly isotropic and homogeneous, much more so in the past

- **Monopole Problem:**

  There are hardly any magnetic monopoles in our Universe

- **Fluctuations, seeds of structure**

  Structure in the Universe: origin

Flatness Problem

Flatness Problem

FRW Dynamical Evolution:

Going back in time, we find that the Universe was much flatter than it is at the present.

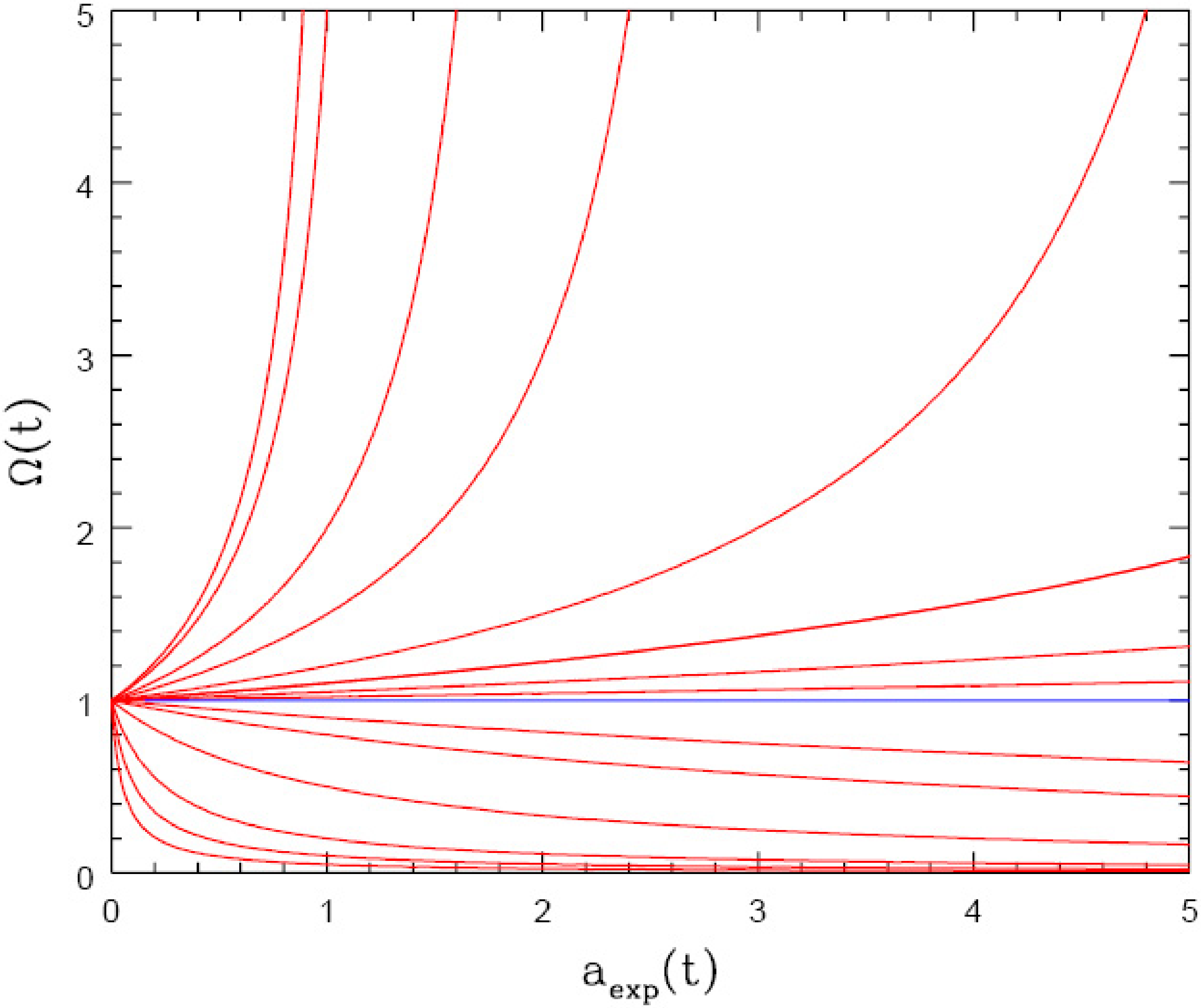
Reversely, that means that any small deviation from flatness in the early Universe would have been strongly amplified nowadays ...

We would therefore expect to live in a Universe that would either be almost
□=0 or □□□;

Yet, we find ourselves to live in a Universe that is almost perfectly flat ... $□_{tot}$□1

How can this be ?

Flatness Evolution



$$\left(\frac{1}{\Omega}-1\right)=a(t)\left(\frac{1}{\Omega_0}-1\right)$$

- At radiation-matter equiv.

$$|1-\Omega_{rm}|\leq 2\times 10^{-4}$$

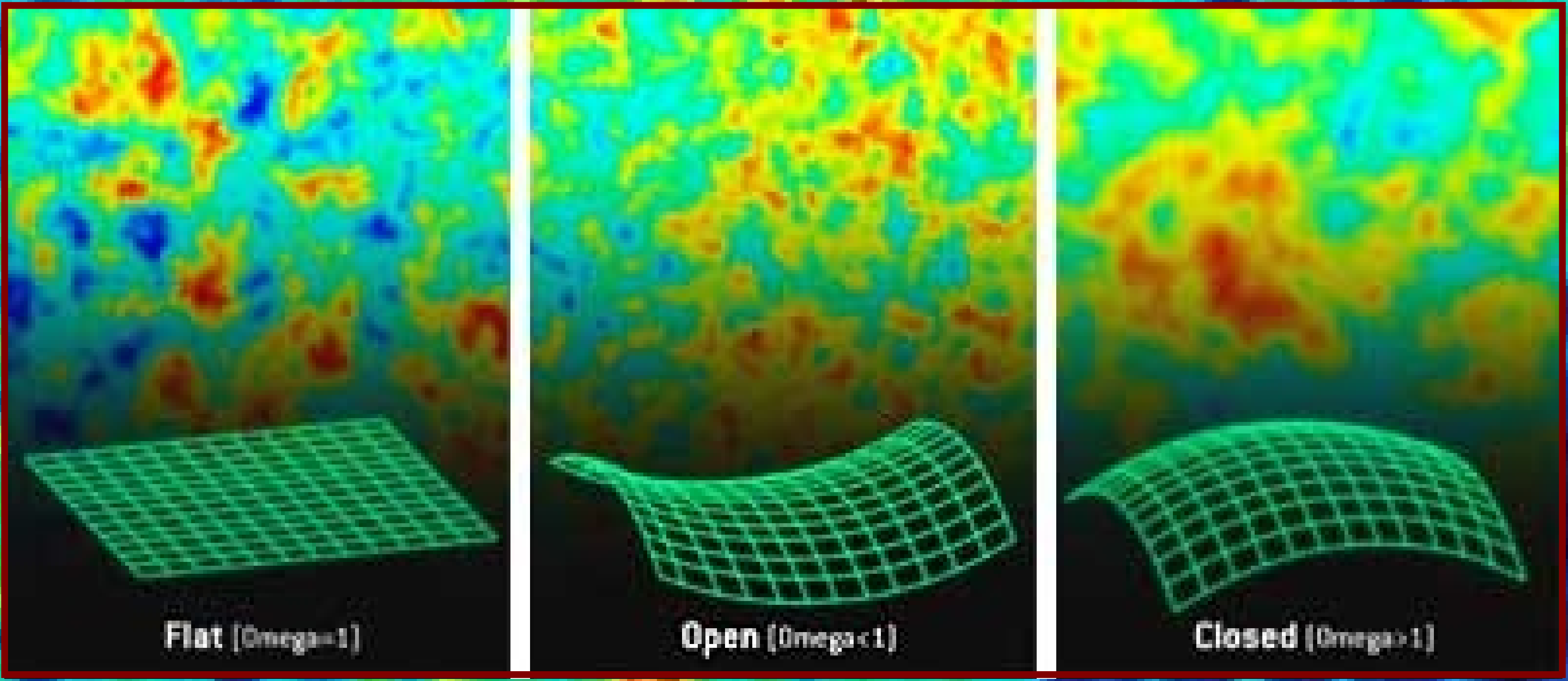
- Big Bang nucleosynthesis
  $a_{nuc} \approx 3.6 \times 10^{-8}$

$$|1-\Omega_{nucl}|\leq 3\times 10^{-14}$$

- Planck time

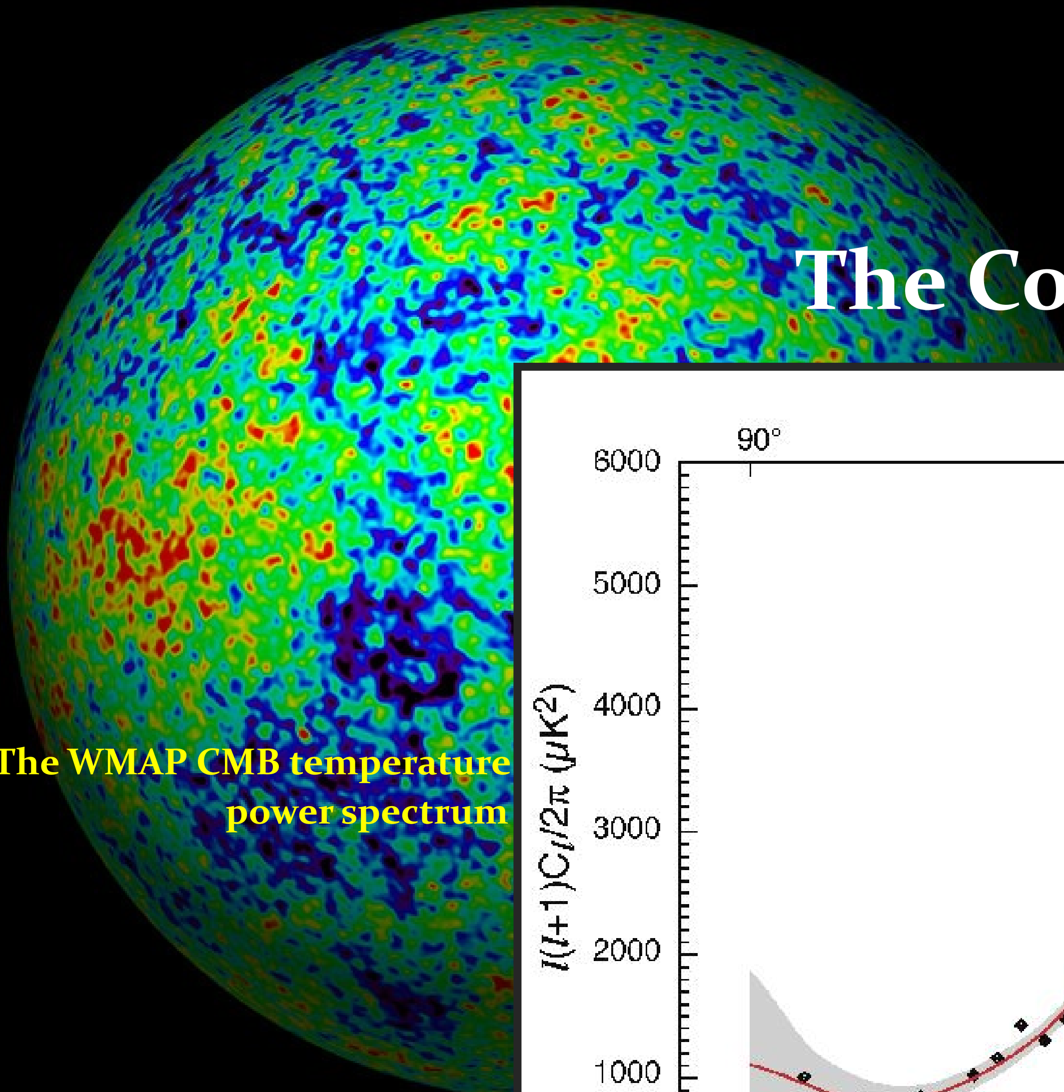
$$|1-\Omega_{P}|\leq 1\times 10^{-60}$$

Angular CMB temperature fluctuations

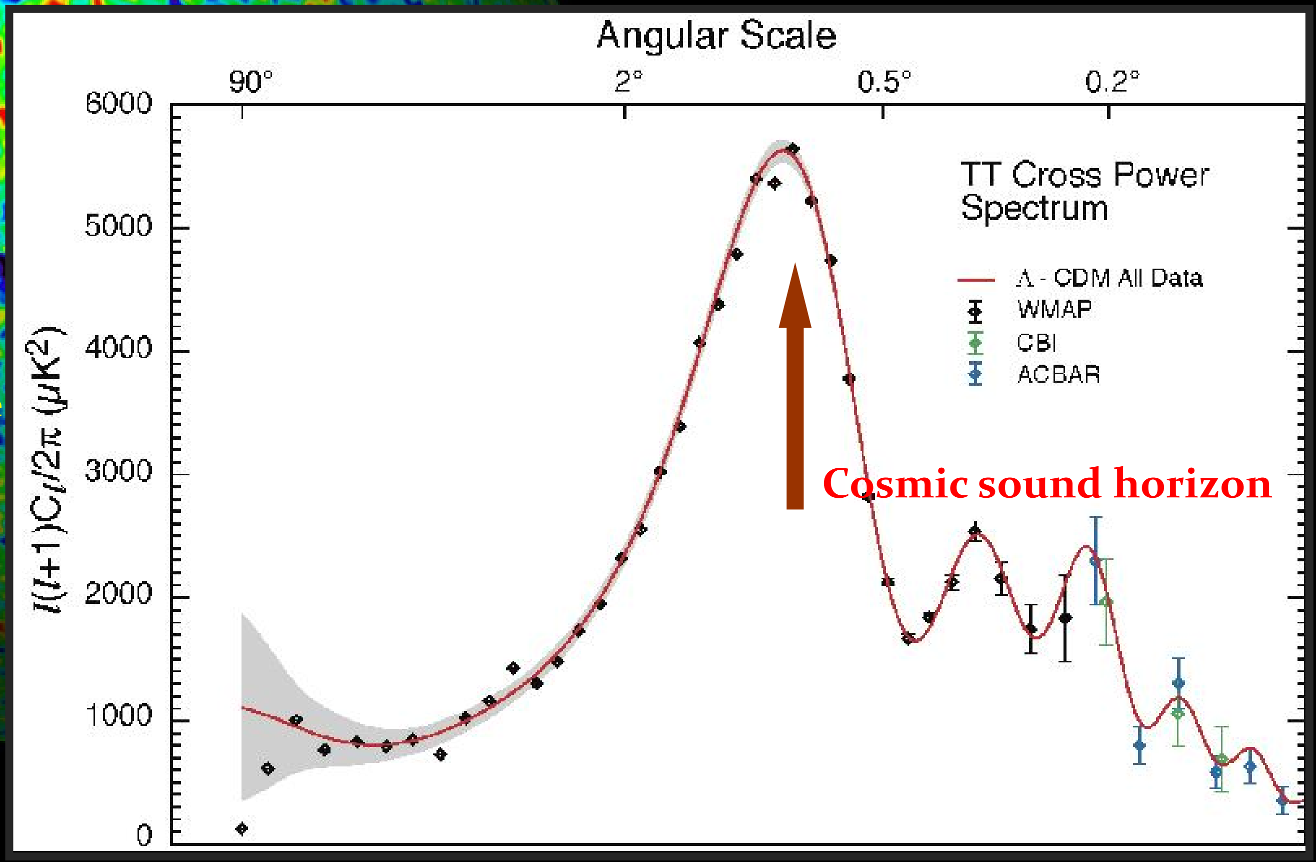


CMB: Universe almost perfectly Flat !

The Cosmic Tonal Ladder



The WMAP CMB temperature power spectrum



The Cosmic Microwave Background Temperature Anisotropies:

Universe is almost perfectly flat

Horizon Problem

Cosmic Horizons

Fundamental Concept for our understanding of the physics of the Universe:

- Physical processes are limited to the region of space with which we are or have ever been in physical contact.

- What is the region of space with which we are in contact ?
  Region with whom we have been able to exchange photons
  (photons: fastest moving particles)

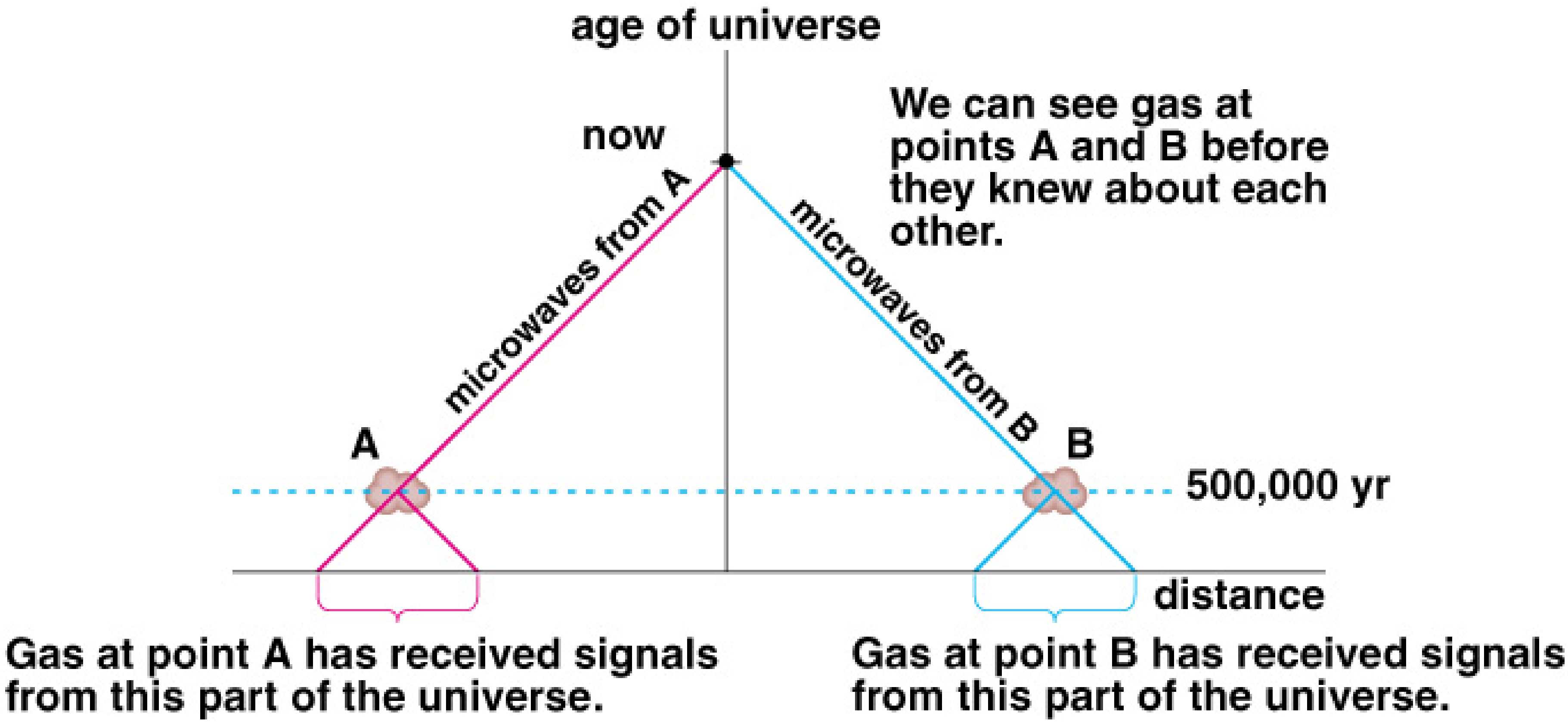
- From which distance have we received light.

- Complication: - light is moving in an expanding and curved space
  - fighting its way against an expanding background

- This is called the

Horizon of the Universe

Cosmic Horizons



Horizon of the Universe:
distance that light travelled since the Big Bang

Cosmic Horizons

In an Einstein-de Sitter Universe

$$R_{Hor} = 3ct$$

Horizon distance in physical space

Horizon of the Universe:
distance that light travelled since the Big Bang

Cosmic Horizons

The horizon distance at recombination/decoupling
(ie. time at which Cosmic Microwave Background is coming from)

angular size on the sky:

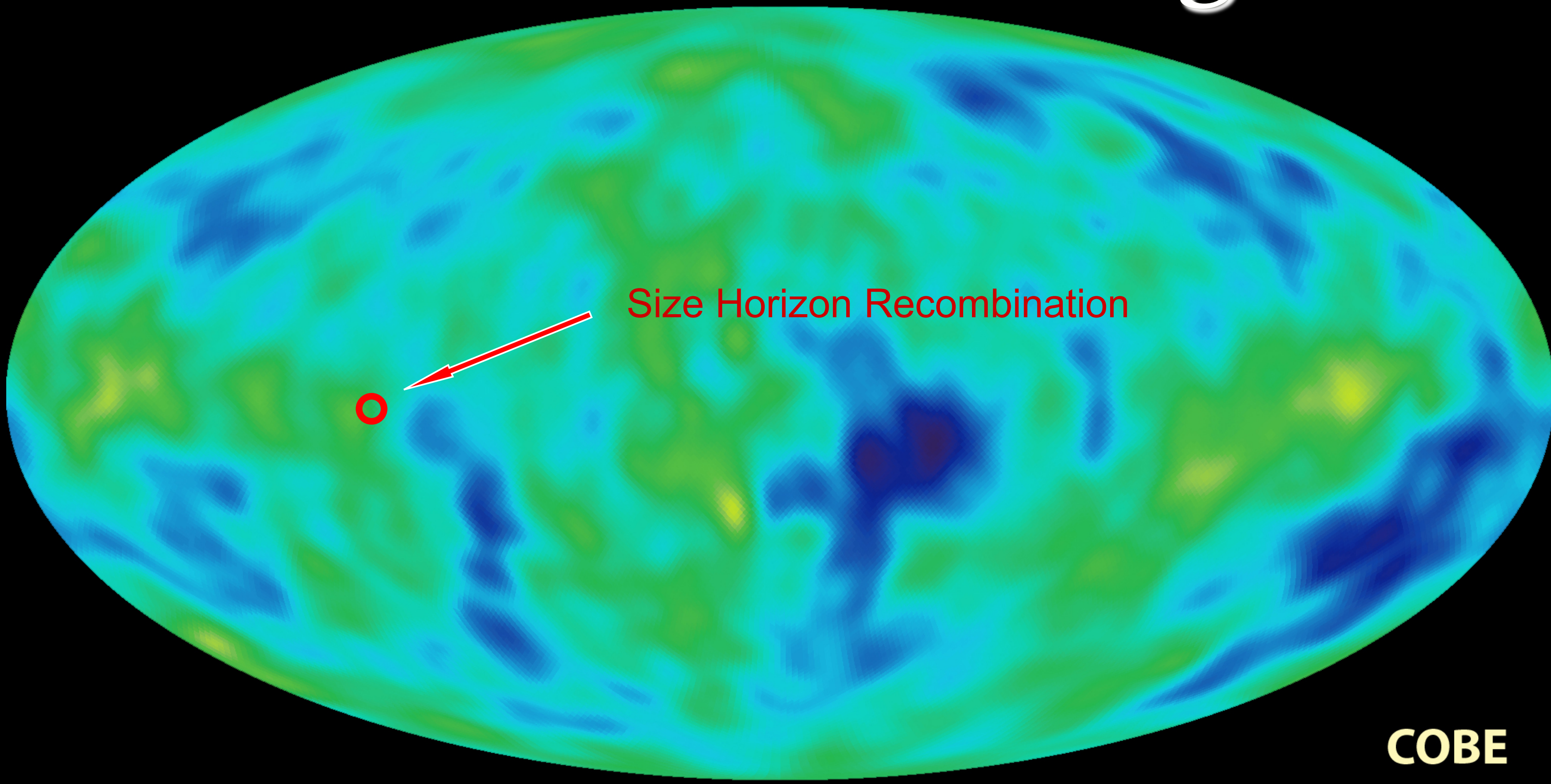
$$R_{Hor} = 3ct$$

$\theta \gg 1^\circ$ Large angular scales:
NOT in physical contact

$\theta \ll 1^\circ$ Small angular scales:
In physical (thus, also thermal) contact

Horizon of the Universe:
distance that light travelled since the Big Bang

Cosmic Microwave Background

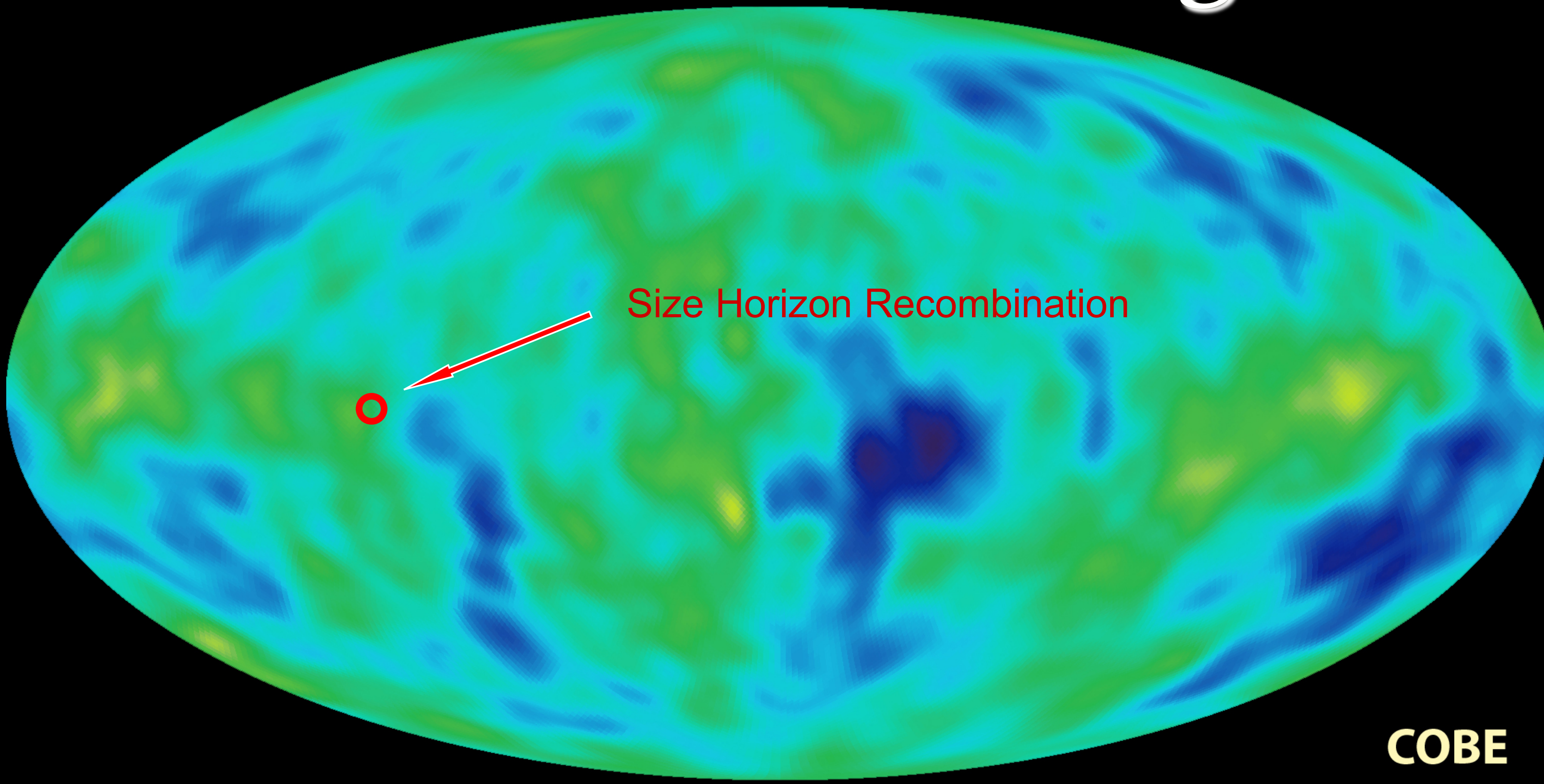


COBE measured fluctuations: > 7°

Size Horizon at Recombination spans angle ~ 1°

How can it be that regions totally out of thermal contact have the same temperature ?

Cosmic Microwave Background



COBE measured fluctuations: > 7°

Size Horizon at Recombination spans angle ~ 1°

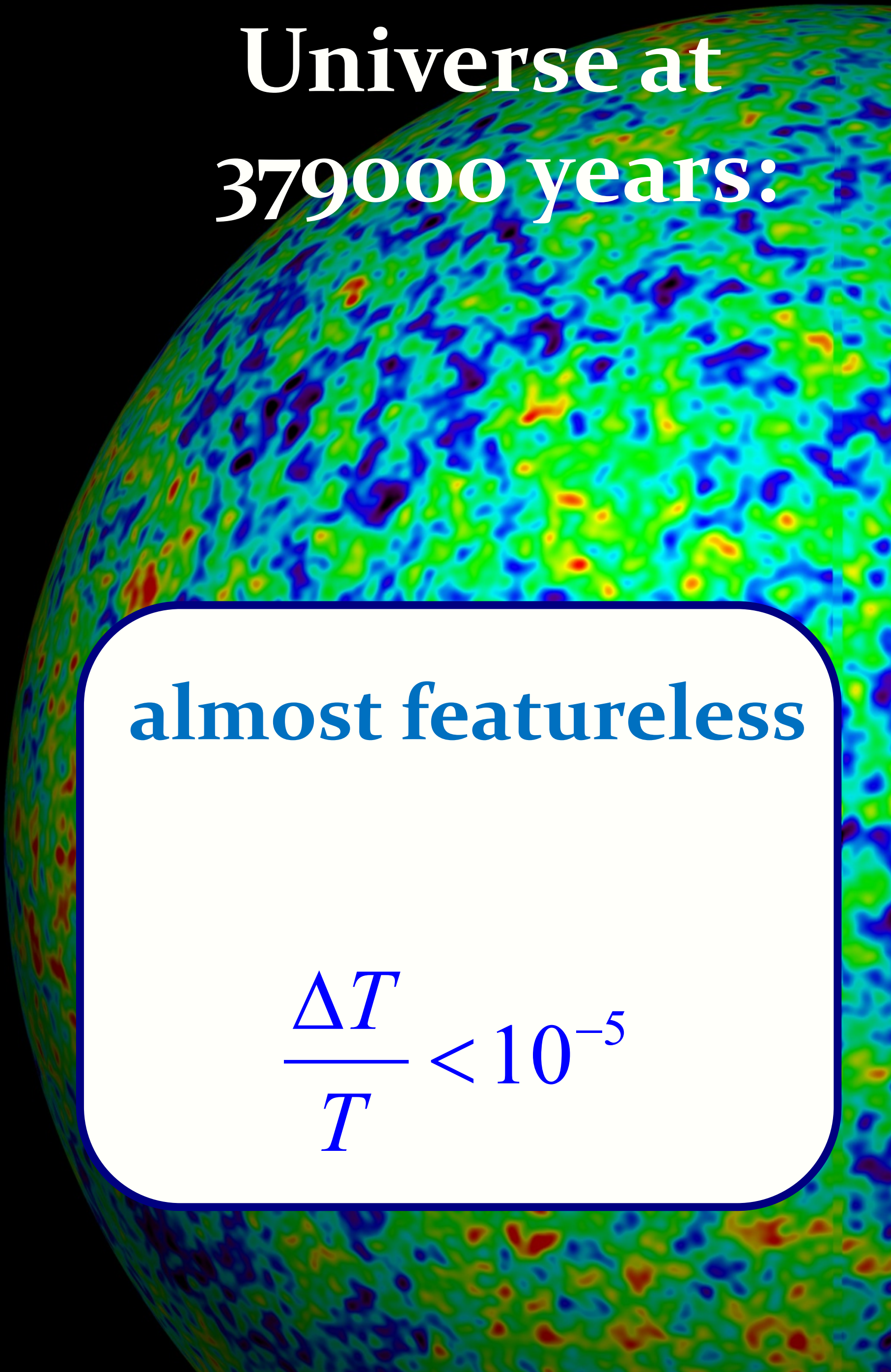
COBE proved that superhorizon fluctuations do exist: prediction Inflation !!!!!

Structure Problem

Primordial Noise:

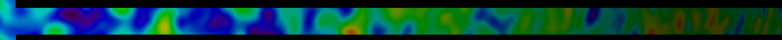
Seeds of Cosmic Structure

Universe at 379000 years:



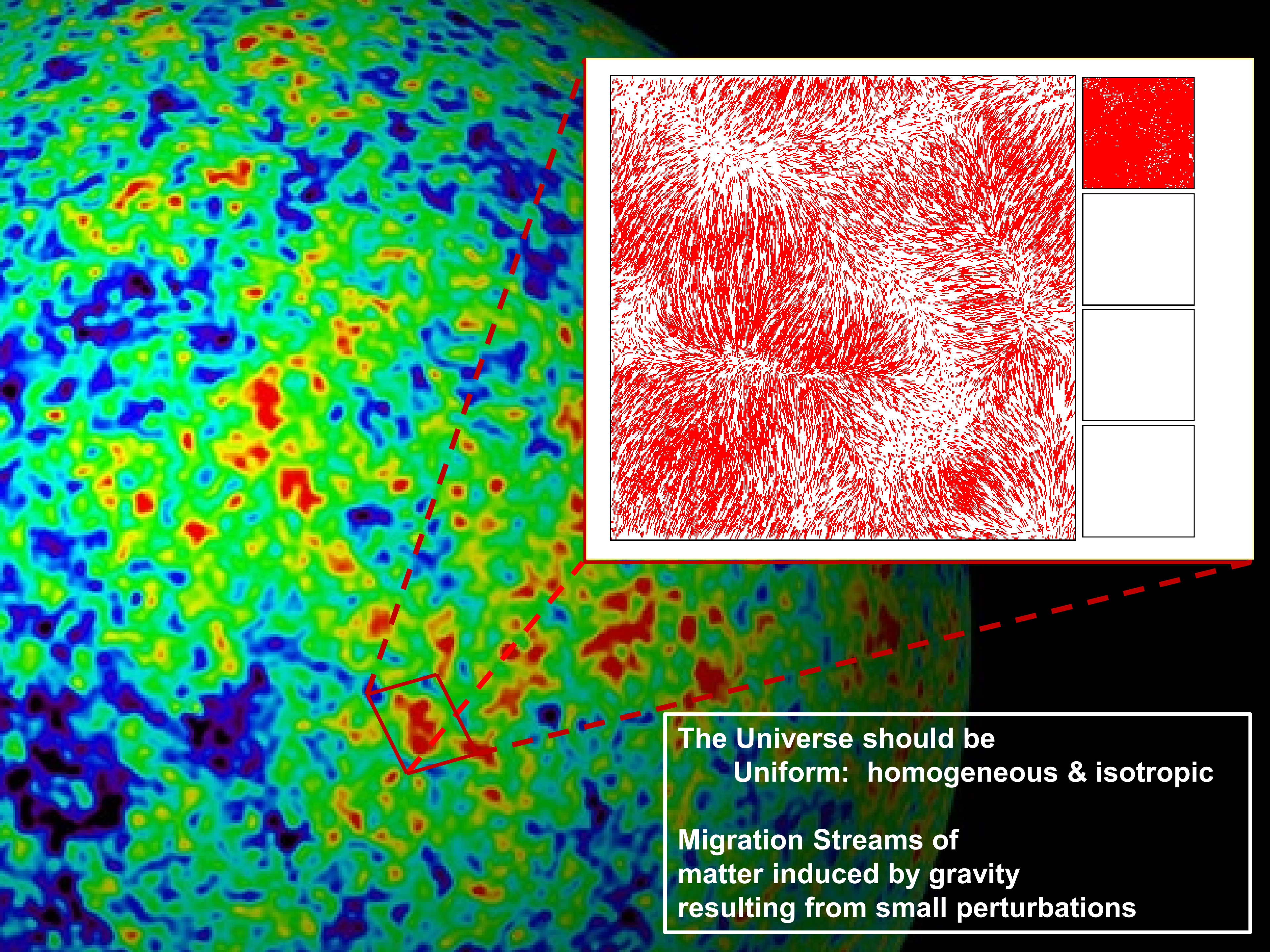
almost featureless

$$\frac{\Delta T}{T} < 10^{-5}$$

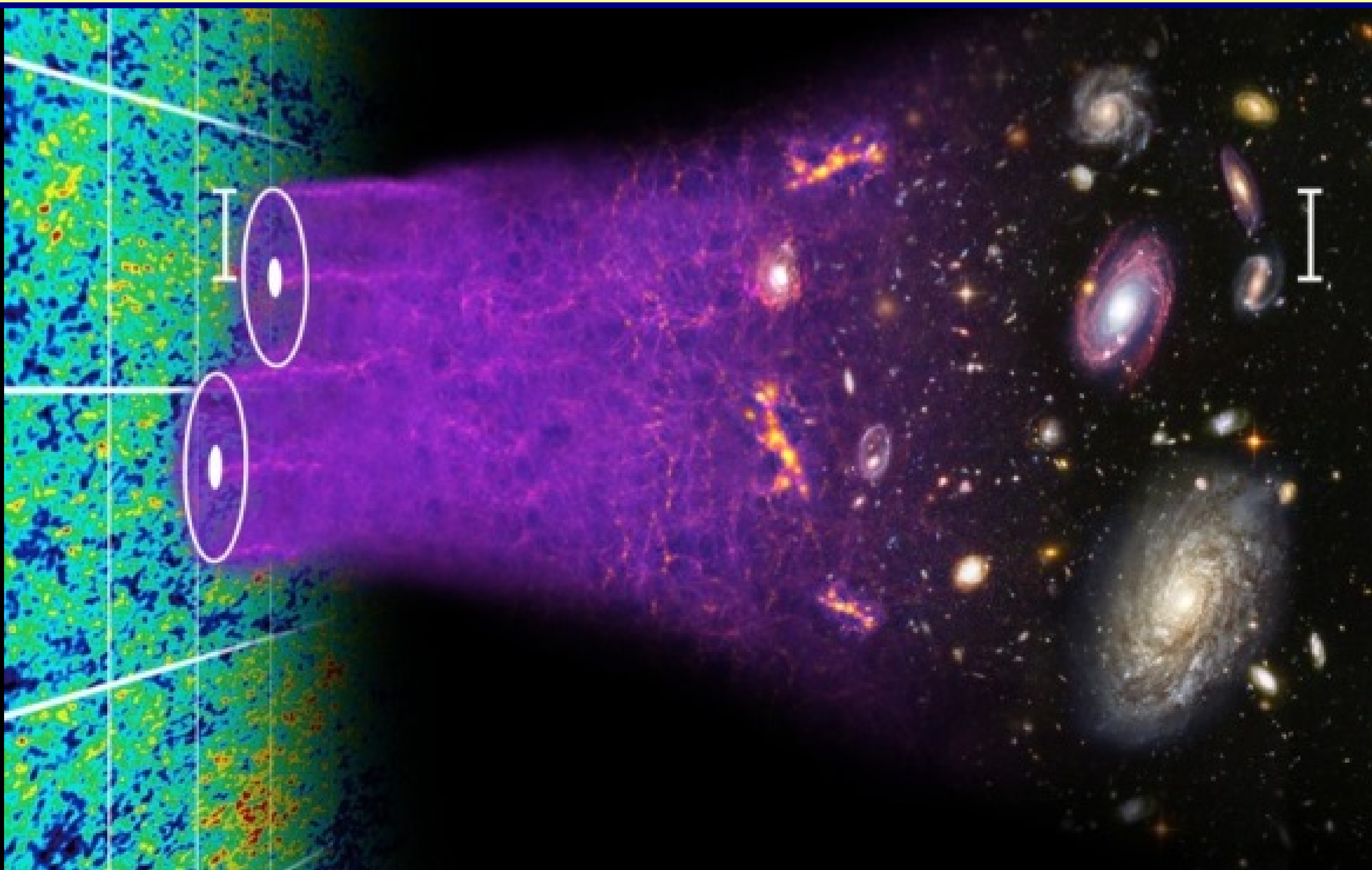


$$\frac{\Delta r}{r} \leq 1.4 \times 10^{-3}$$

$$\frac{\Delta r}{r} \sim 10^{-5} : \; r \sim 60.4\, m$$


The Universe should be
Uniform: homogeneous & isotropic
Migration Streams of
matter induced by gravity
resulting from small perturbations

Formation Cosmic Structures



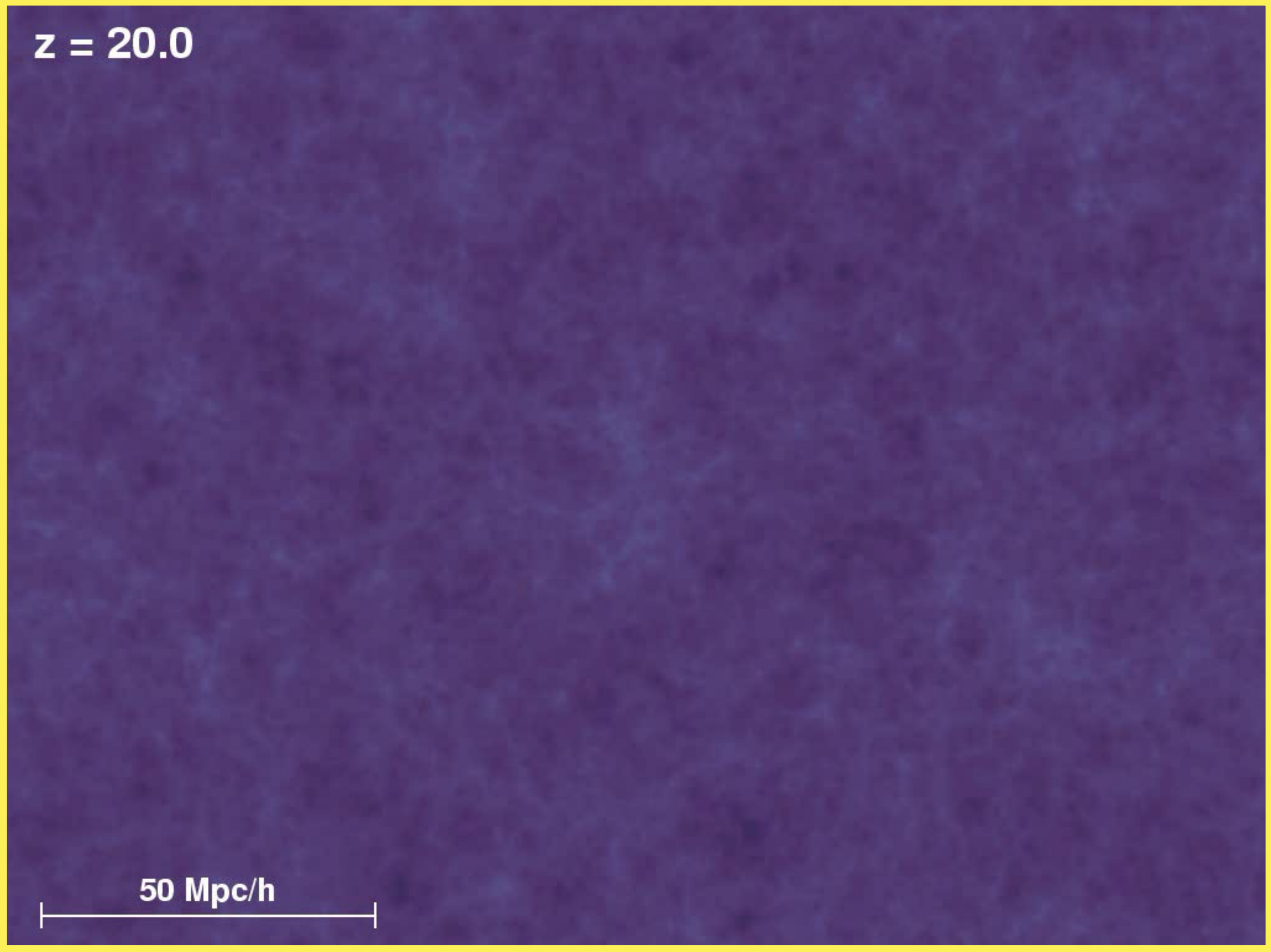
Cosmic Structure Formation

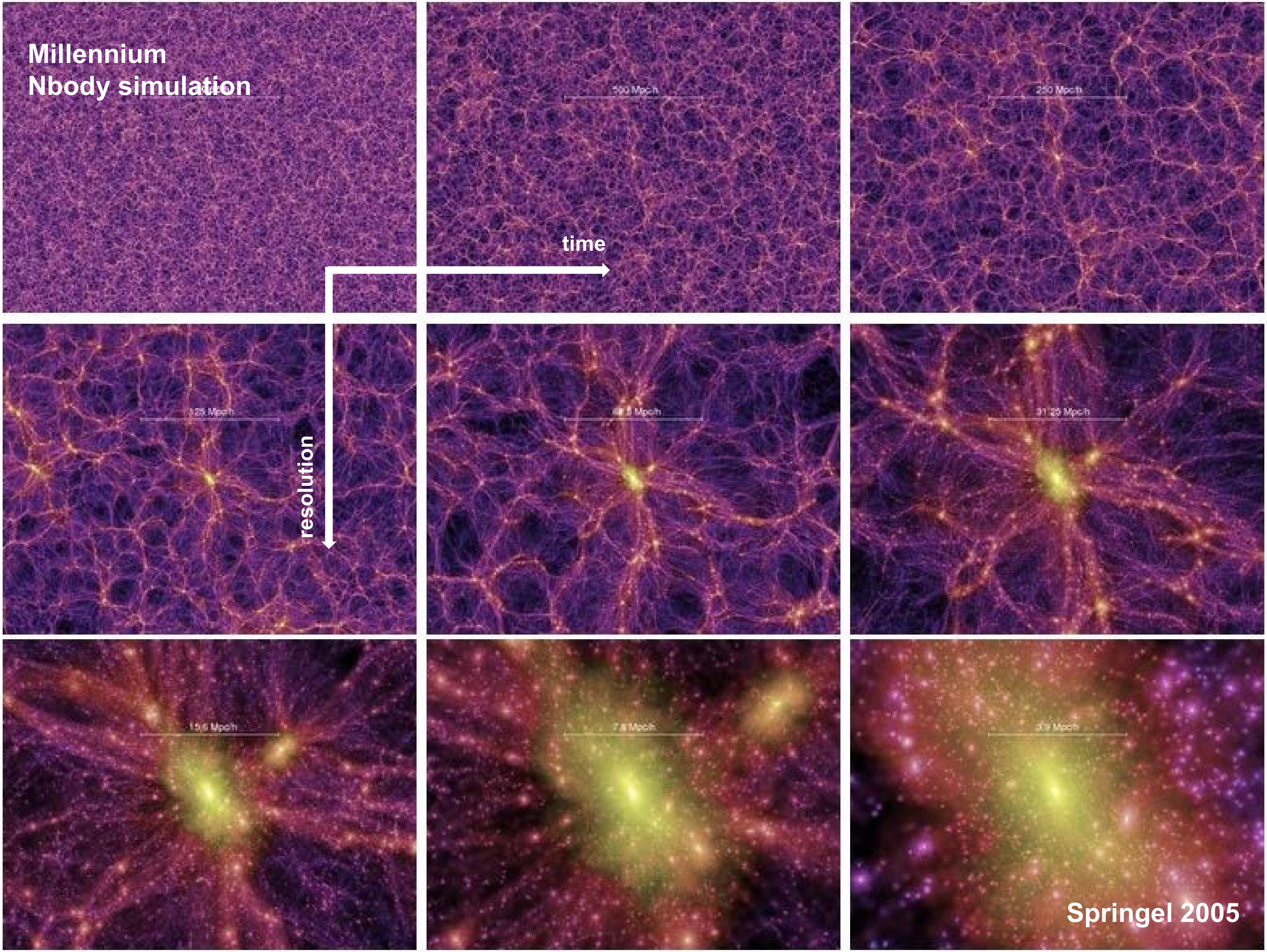
Formation
Cosmic Web:

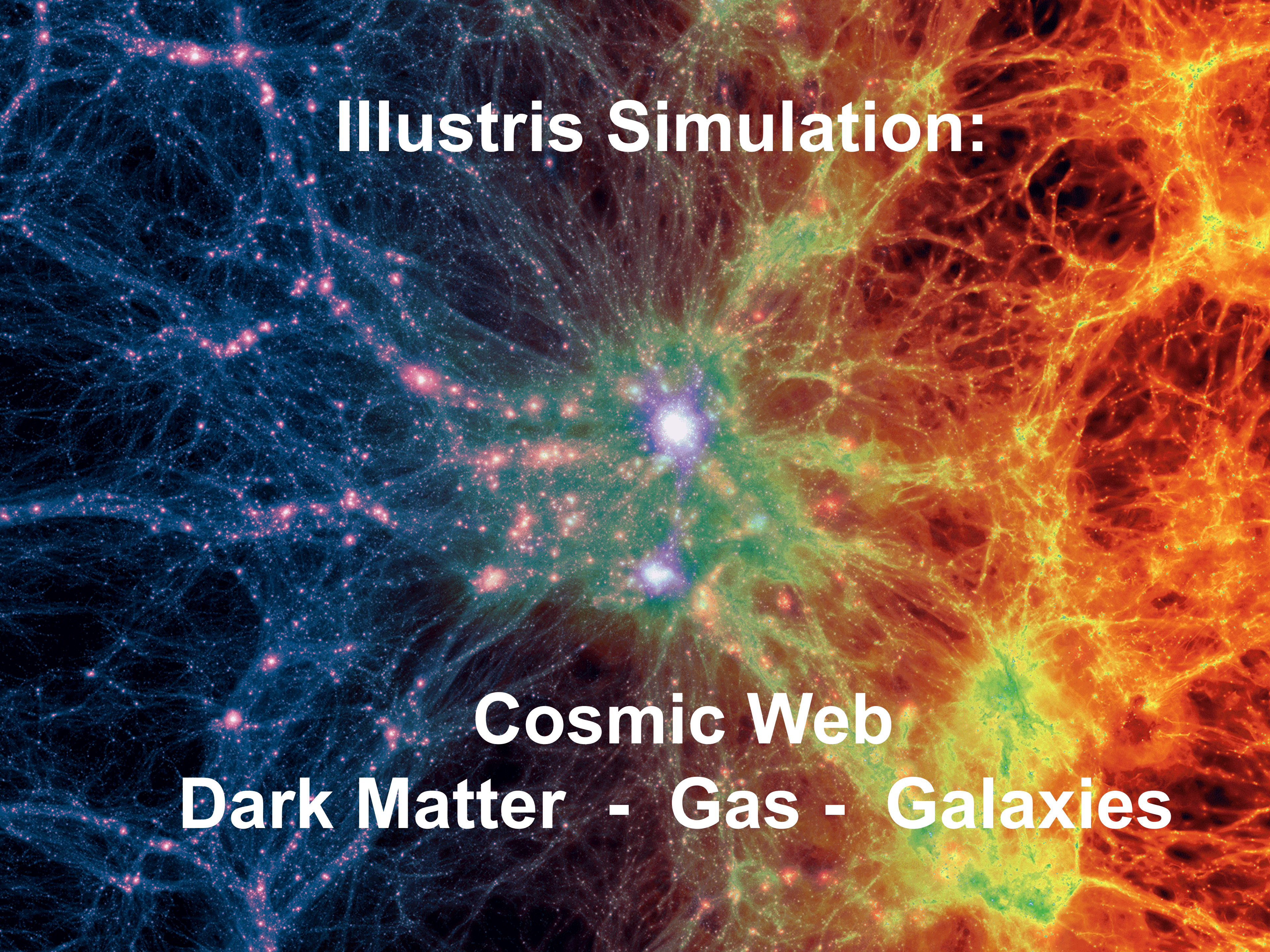
simulation
sequence

(cold)
dark matter

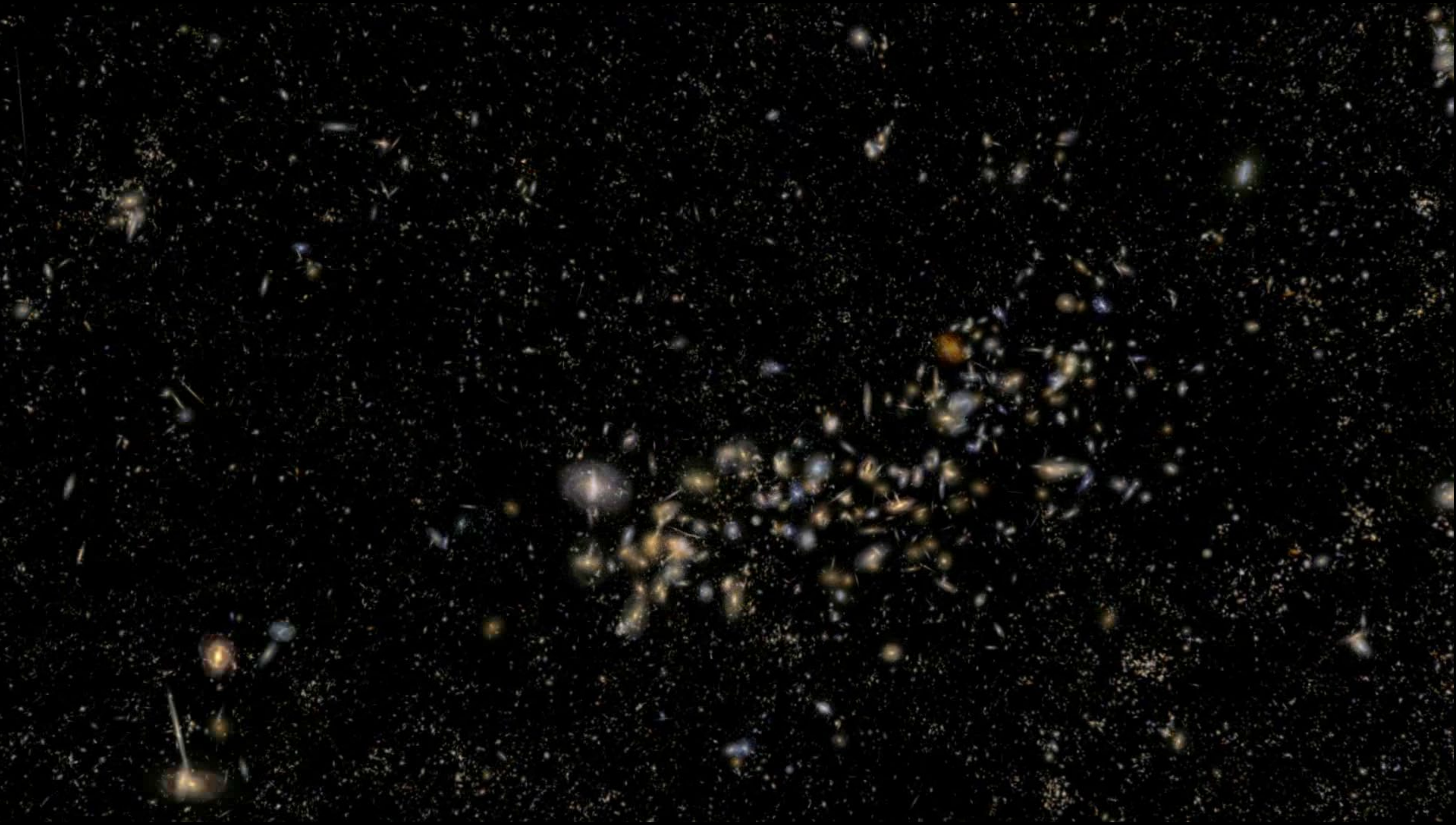
(courtesy:
Virgo/V. Springel).



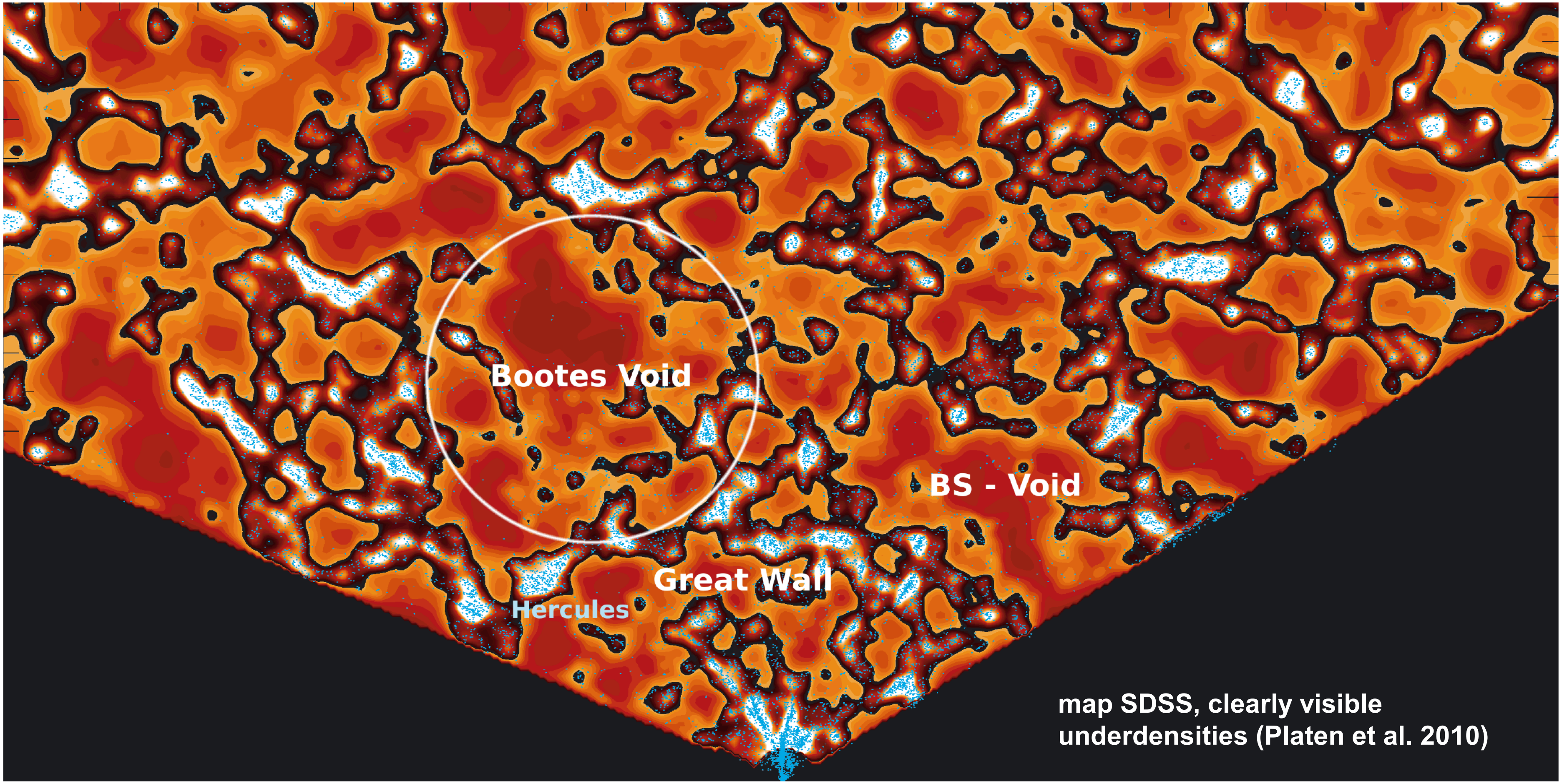

Millennium
Nbody simulation
time
resolution
Springel 2005


Illustris Simulation:
Cosmic Web
Dark Matter - Gas - Galaxies

Universe at 13.8 Gyrs: rich & complex structure

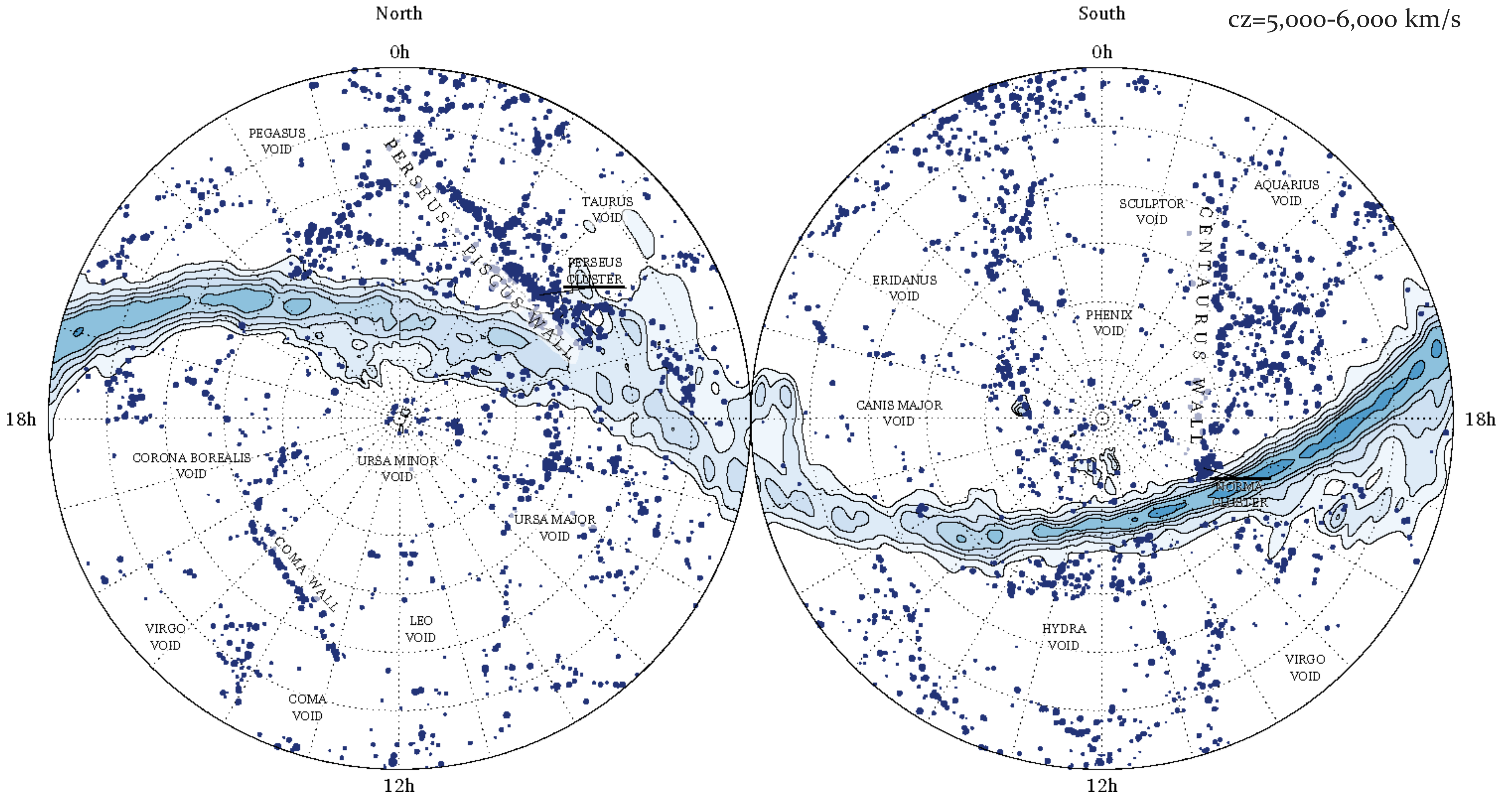


SDSS Galaxy Survey



with the advent of large galaxy redshift surveys
– LCRS, 2dFGRS, SDSS, 2MRS –
voids have been recognized as one of the quintessential components of the Cosmic Web

local Cosmic Web: 2MRS

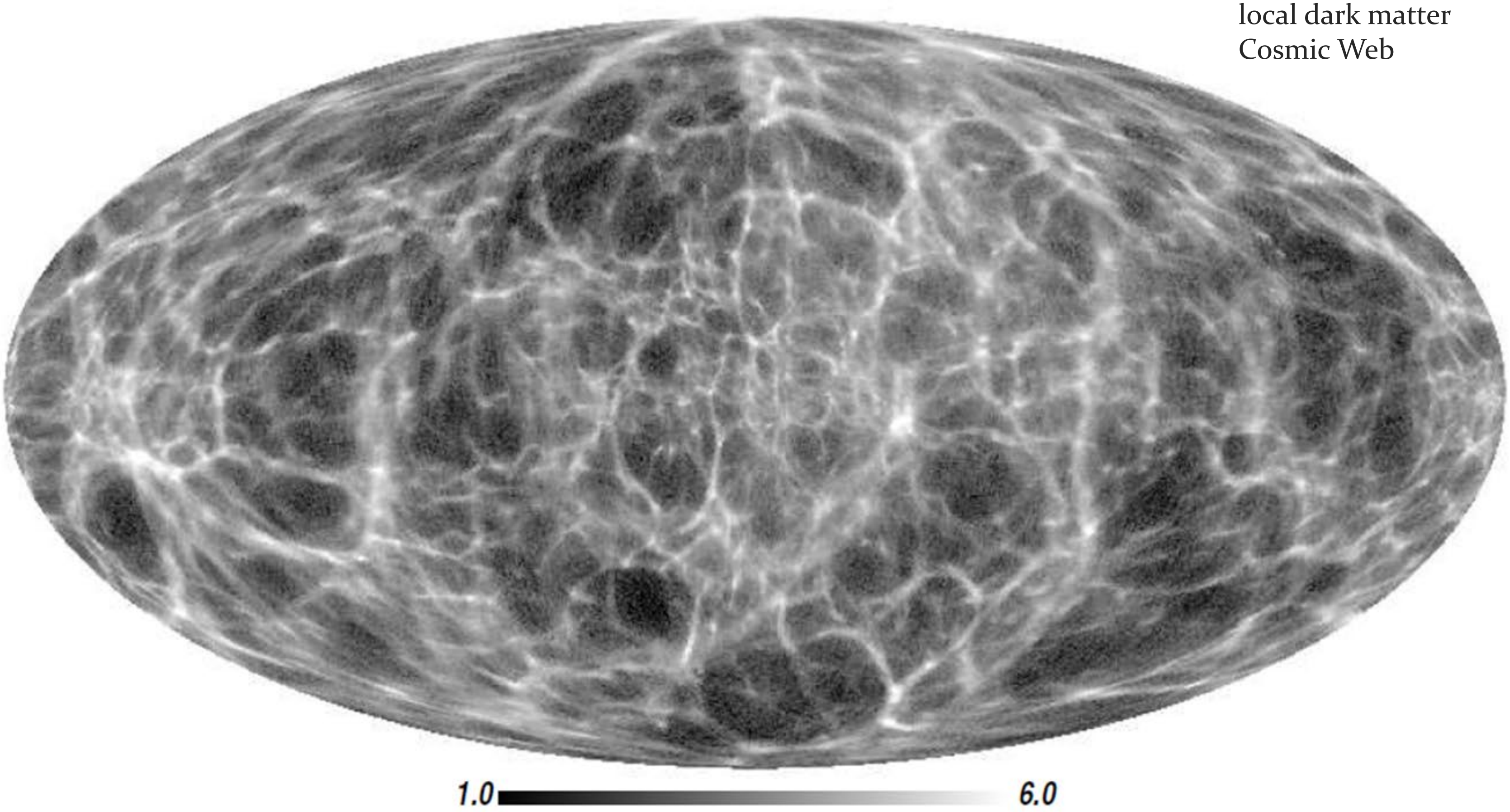


Courtesy: Johan Hidding

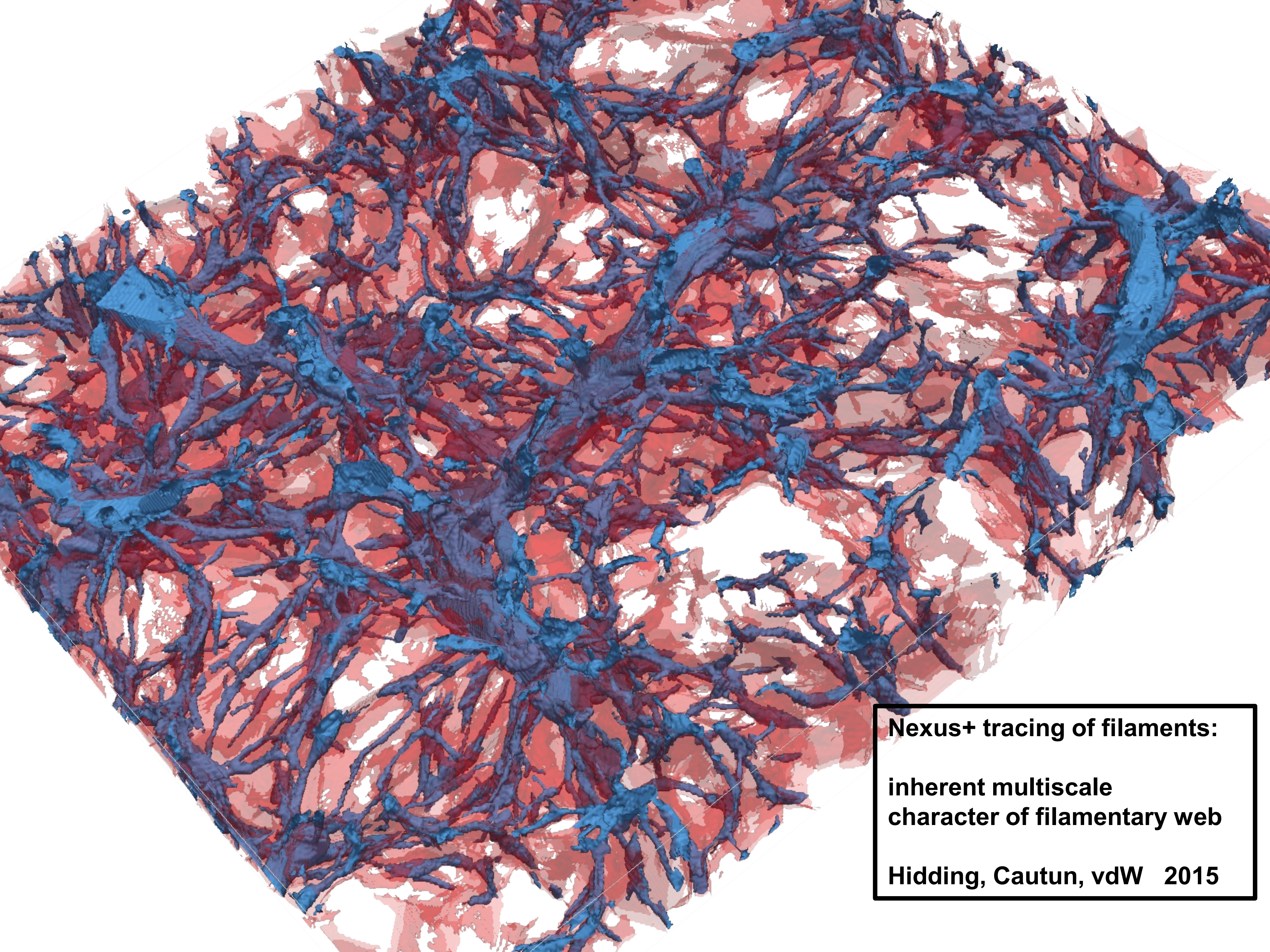
local Cosmic Web: 2MRS

most detailed reconstruction
of the

local dark matter
Cosmic Web



Courtesy: Francisco Kitaura


Nexus+ tracing of filaments:
inherent multiscale
character of filamentary web
Hidding, Cautun, vdW 2015

Horizon Problem

Cosmic Horizons

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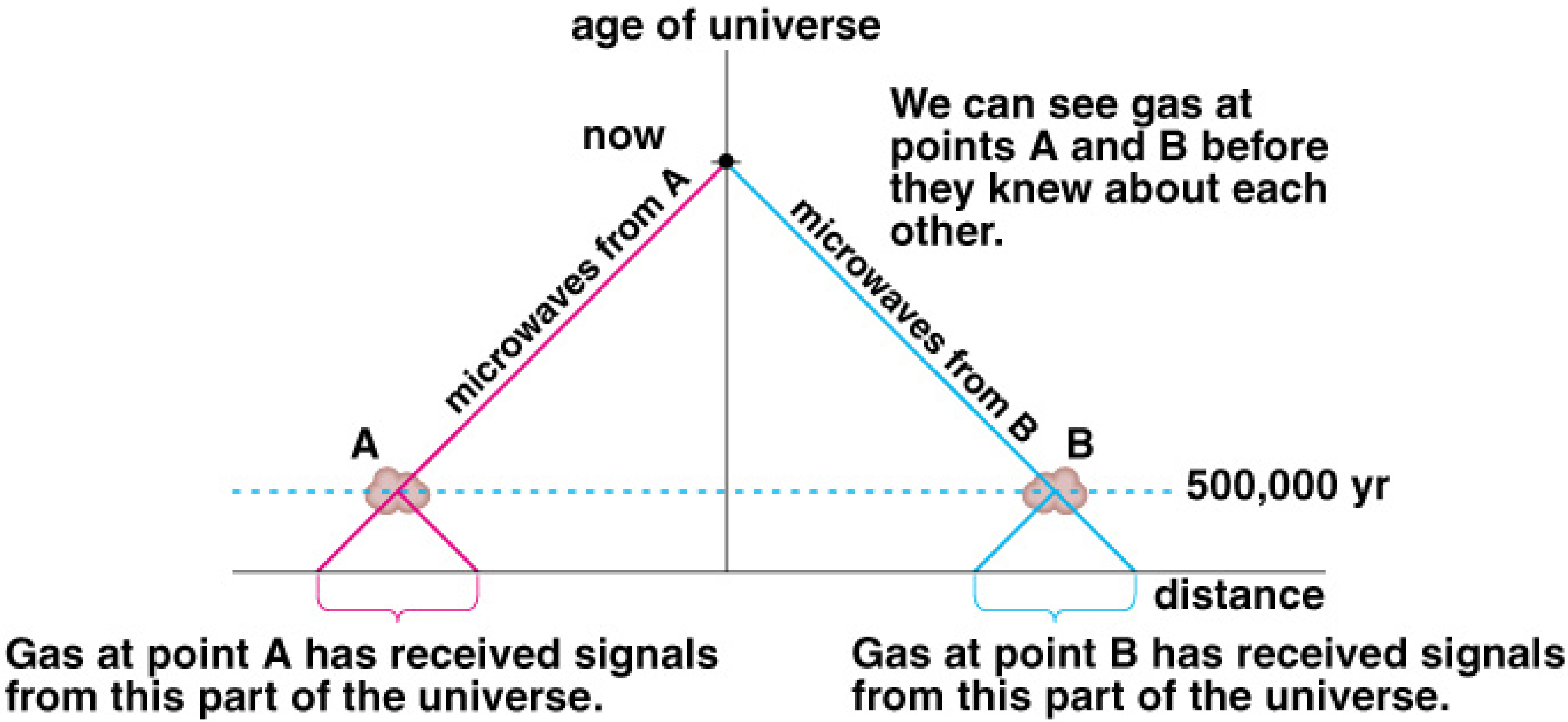
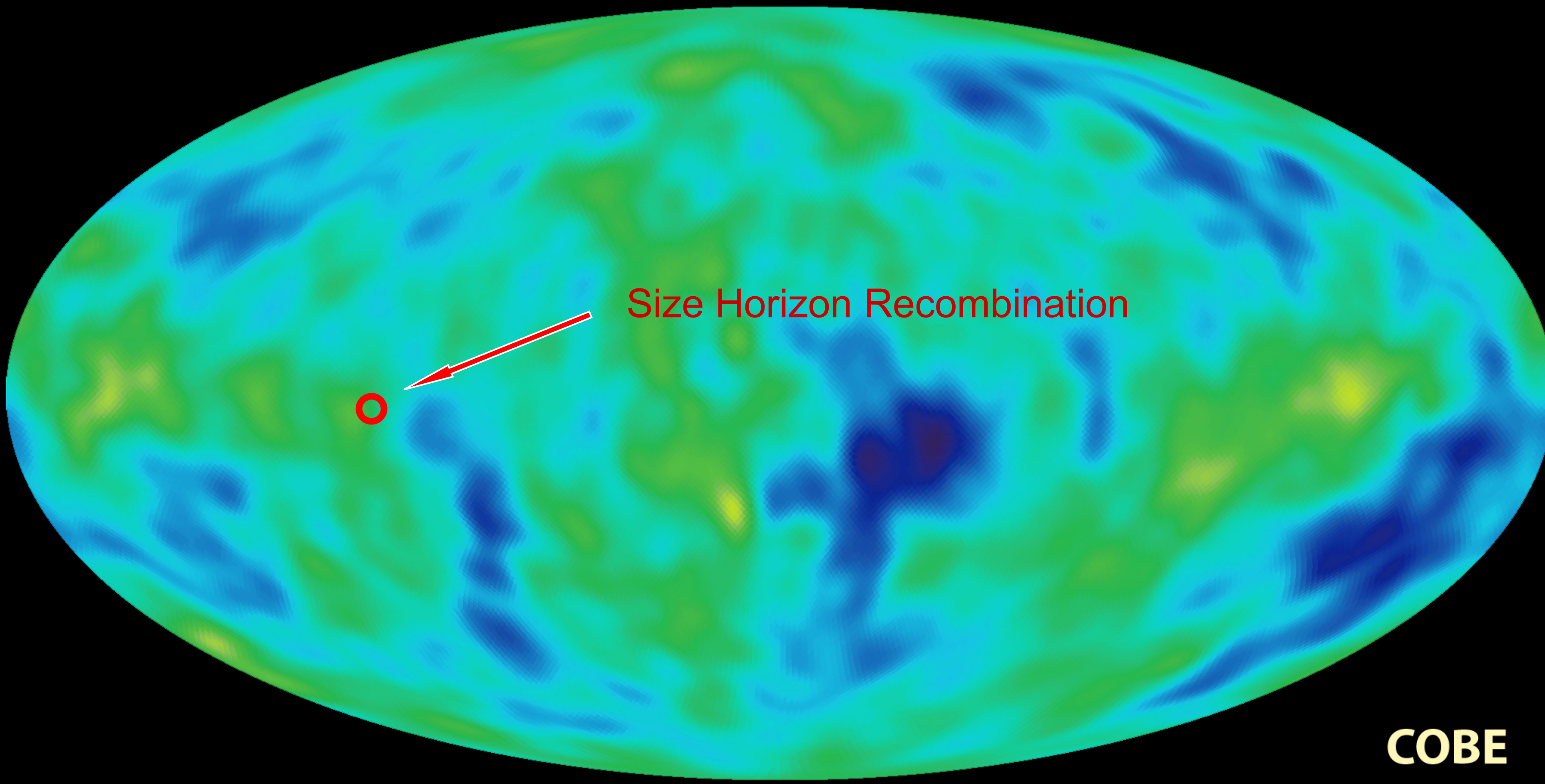
Cosmic Horizon



(Particle) Horizon of the Universe:
distance that light travelled since Big Bang

Probleem van Kosmische Horizon

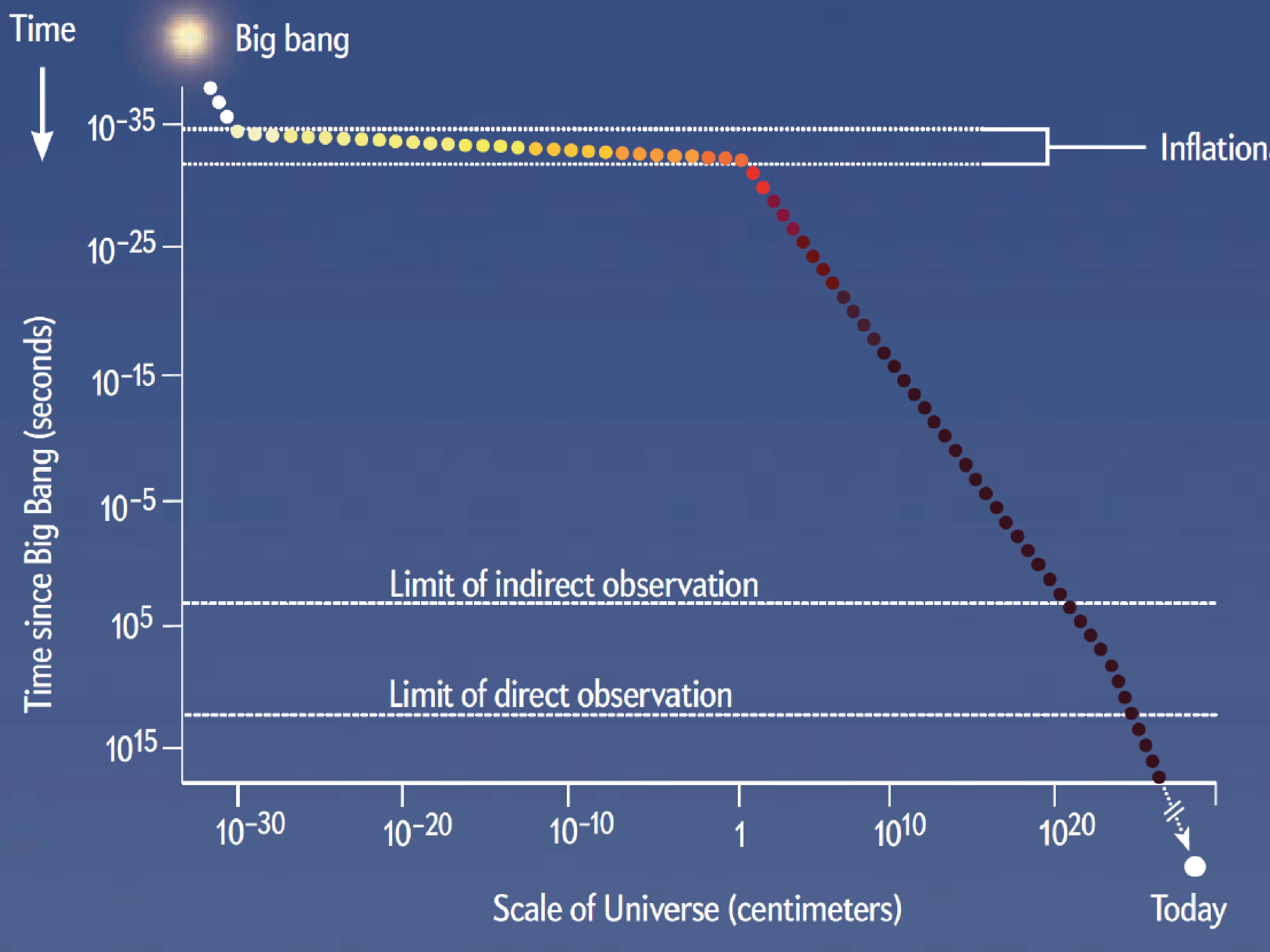


COBE metingen CMB temperatuur fluctuaties: > 7°
Schaal Horizon Zichtbare Heelal 379000 jr. na Big Bang: ~ 1°

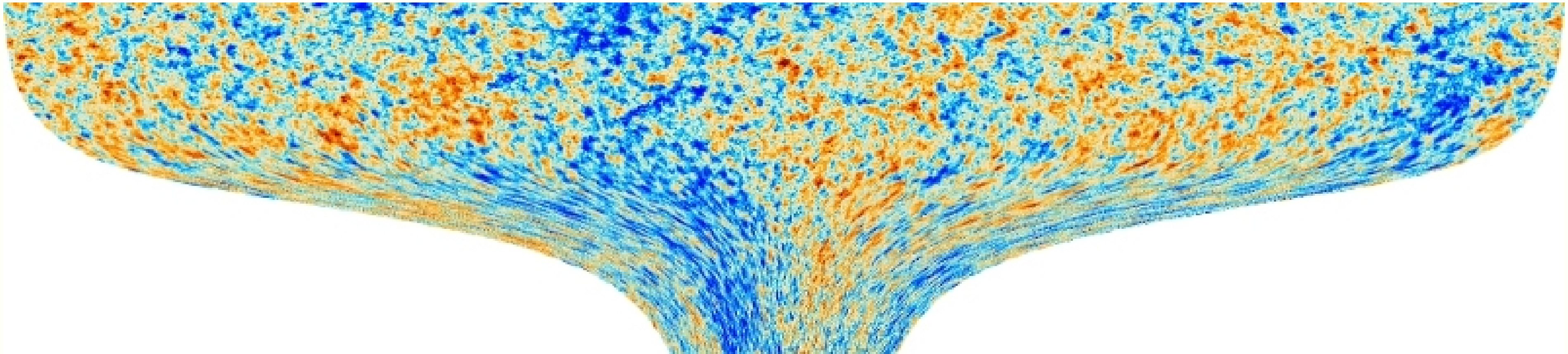
Temperatuur hetzelfde over gehele hemel,
maar hoe kan dat zonder ooit in thermisch contact te zijn geweest?

INFLATION


10^{-36} sec
after Big Bang:
Inflation of the Universe


Time
Big bang
Inflation
Time since Big Bang (seconds)
10−35
10−25
10−15
10−5
10^5
10^15
Limit of indirect observation
Limit of direct observation
10−30
10−20
10−10
1
10^10
10^20
Scale of Universe (centimeters)
Today

Kosmische Inflatie

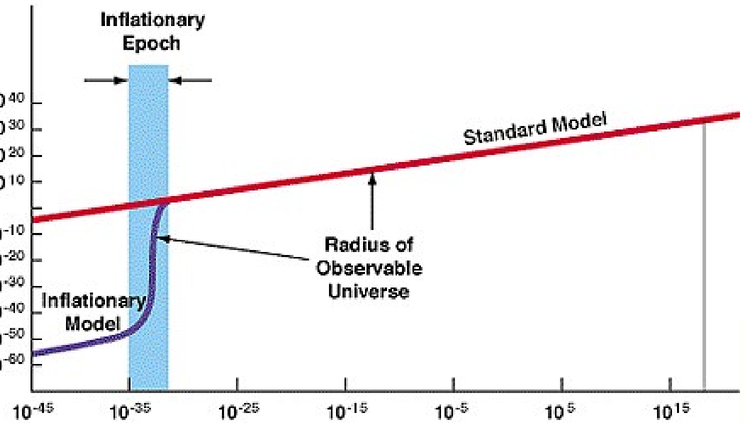


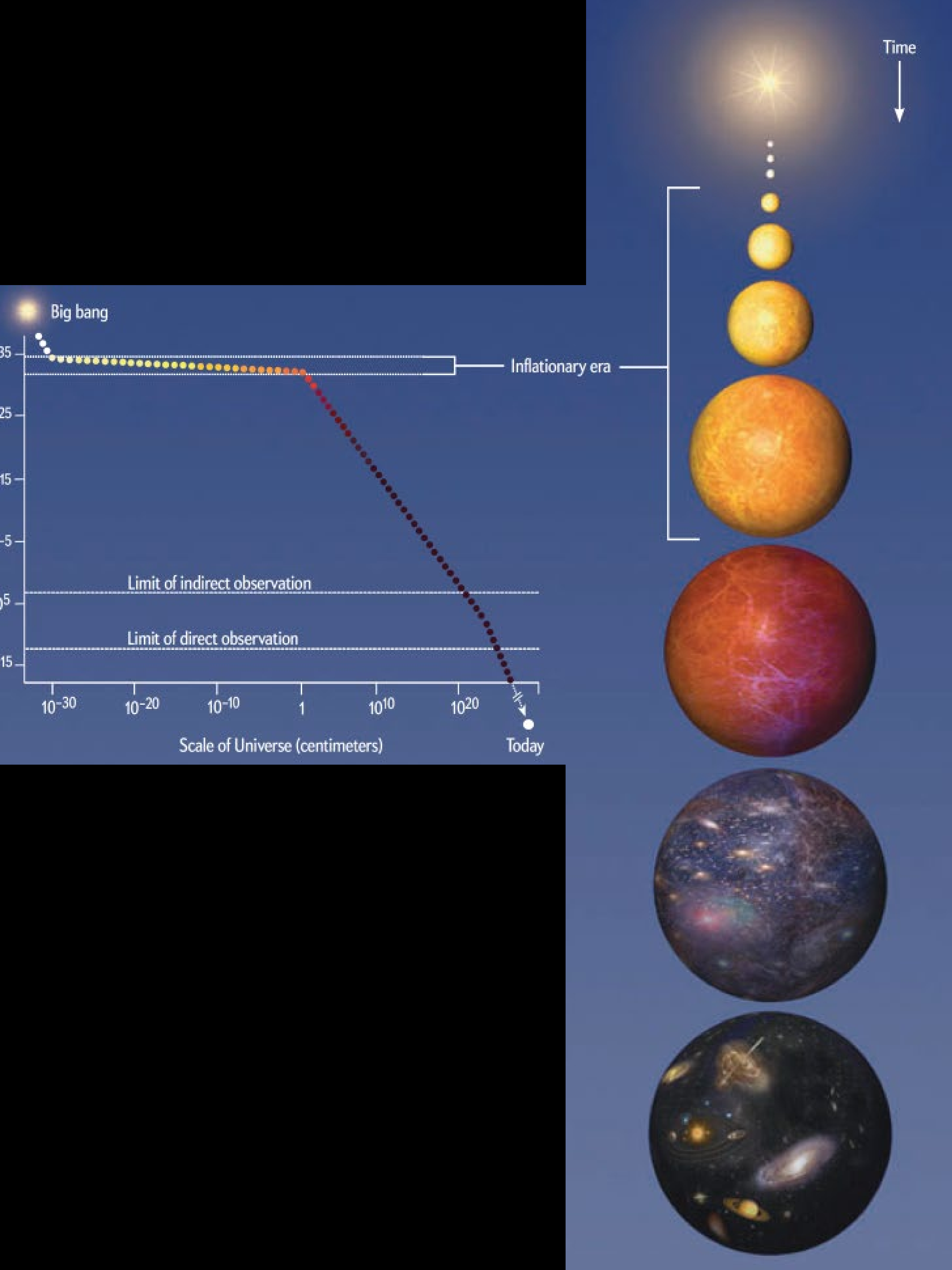
~ 10^{-36} sec. na Big Bang:

Heelal dijt exponentieel uit:
factor 10^{60} in 10^{-34} sec

Afmeting huidige zichtbare Heelal:

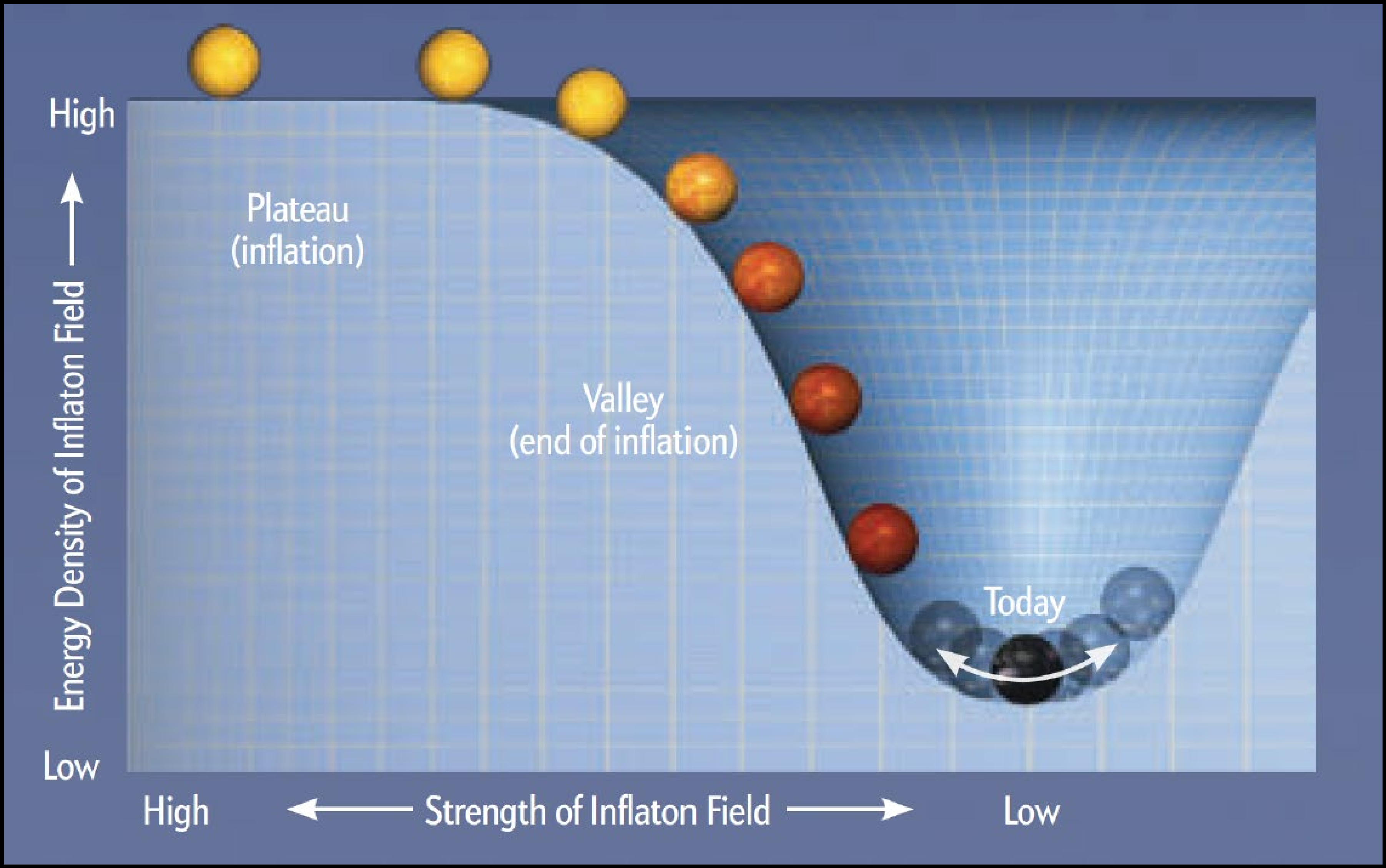
begin inflatie: 10^{-15} afmeting atoom
eind inflatie: diameter van stuiver





Time
Inflationary era
Big bang
Limit of indirect observation
Limit of direct observation
10^{-30}
10^{-20}
10^{-10}
1
10^{10}
10^{20}
Scale of Universe (centimeters)
Today

Propelling Inflation: Inflaton



Inflatie & Multiverse