A visualization of the cosmic web, showing a complex network of glowing orange and yellow filaments and nodes against a dark blue background. The nodes represent galaxy clusters, and the filaments represent the large-scale structure of the universe.

from
Cosmic Birth
to
Cosmic Web

FRW Dynamics

In a FRW Universe,
densities are in the order of the critical density,
the density at which the Universe has a flat curvature

$$\rho_{crit} = \frac{3H_0^2}{8\pi G} = 1.8791h^2 \times 10^{-29} \text{ g cm}^{-3}$$

$$\begin{aligned}\rho_0 &= 1.8791 \times 10^{-29} \Omega h^2 \text{ g cm}^{-3} \\ &= 2.78 \times 10^{11} \Omega h^2 M_\odot \text{ Mpc}^{-3}\end{aligned}$$

FRW Dynamics

In a matter-dominated Universe,
the evolution and fate of the Universe entirely determined
by the (energy) density in units of critical density:

$$\Omega \equiv \frac{\rho}{\rho_{crit}}$$

Arguably, Ω is the most important parameter of cosmology !!!

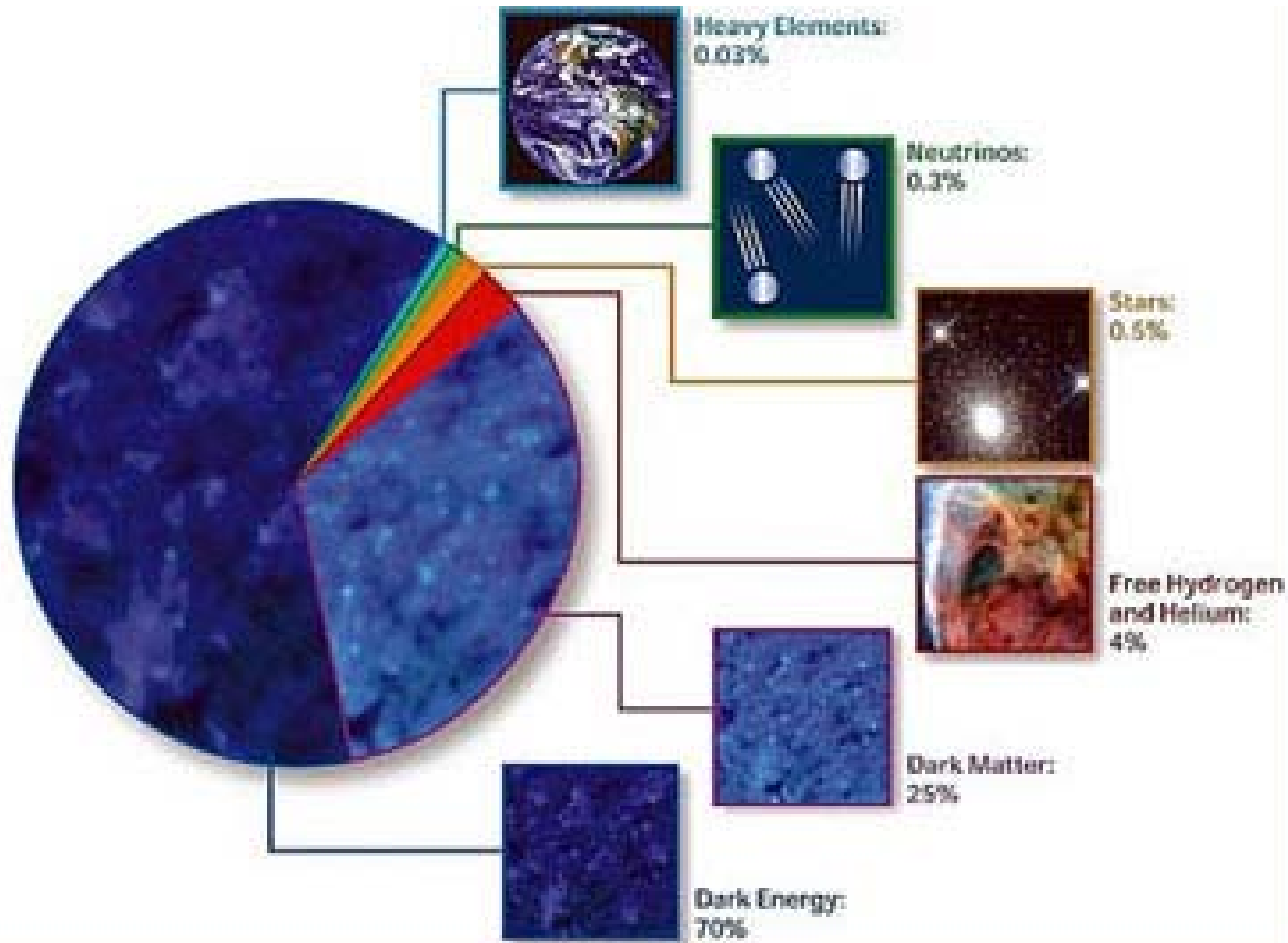
Present-day
Cosmic Density:

$$\begin{aligned}\rho_0 &= 1.8791 \times 10^{-29} \Omega h^2 \text{ g cm}^{-3} \\ &= 2.78 \times 10^{11} \Omega h^2 M_{\odot} \text{ Mpc}^{-3}\end{aligned}$$

what the Universe exists of:

Cosmic Constituents

Cosmic Components



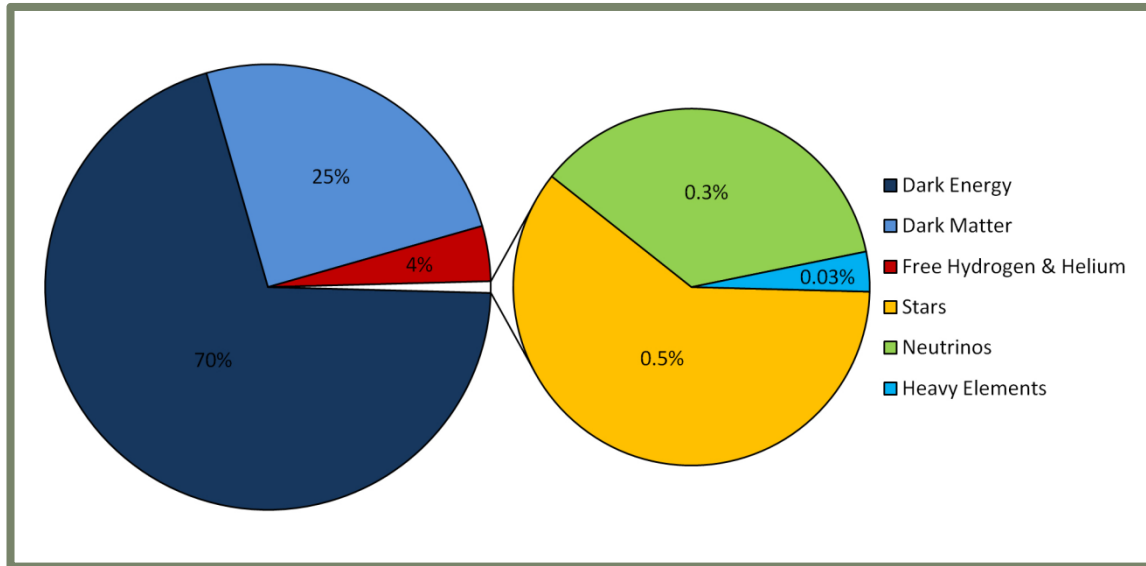
Cosmic Energy Inventarisatie

1	dark sector			0.954 ± 0.003
1.1	dark energy		0.72 ± 0.03	
1.2	dark matter		0.23 ± 0.03	
1.3	primeval gravitational waves		$\lesssim 10^{-10}$	
2	primeval thermal remnants			0.0010 ± 0.0005
2.1	electromagnetic radiation		$10^{-4.3 \pm 0.0}$	
2.2	neutrinos		$10^{-2.9 \pm 0.1}$	
2.3	prestellar nuclear binding energy		$-10^{-4.1 \pm 0.0}$	
3	baryon rest mass			0.045 ± 0.003
3.1	warm intergalactic plasma		0.040 ± 0.003	
3.1a	virialized regions of galaxies	0.024 ± 0.005		
3.1b	intergalactic	0.016 ± 0.005		
3.2	intracluster plasma		0.0018 ± 0.0007	
3.3	main sequence stars	spheroids and bulges	0.0015 ± 0.0004	
3.4		disks and irregulars	0.00055 ± 0.00014	
3.5	white dwarfs		0.00038 ± 0.00008	
3.6	neutron stars		0.00005 ± 0.00002	
3.7	black holes		0.00007 ± 0.00002	
3.8	substellar objects		0.00014 ± 0.00007	
3.9	HI + HeI		0.00062 ± 0.00010	
3.10	molecular gas		0.00016 ± 0.00006	
3.11	planets		10^{-6}	
3.12	condensed matter		$10^{-5.6 \pm 0.3}$	
3.13	sequestered in massive black holes		$10^{-5.4}(1 + \epsilon_n)$	
4	primeval gravitational binding energy			$-10^{-6.1 \pm 0.1}$
4.1	virialized halos of galaxies		$-10^{-7.2}$	
4.2	clusters		$-10^{-6.9}$	
4.3	large-scale structure		$-10^{-6.2}$	



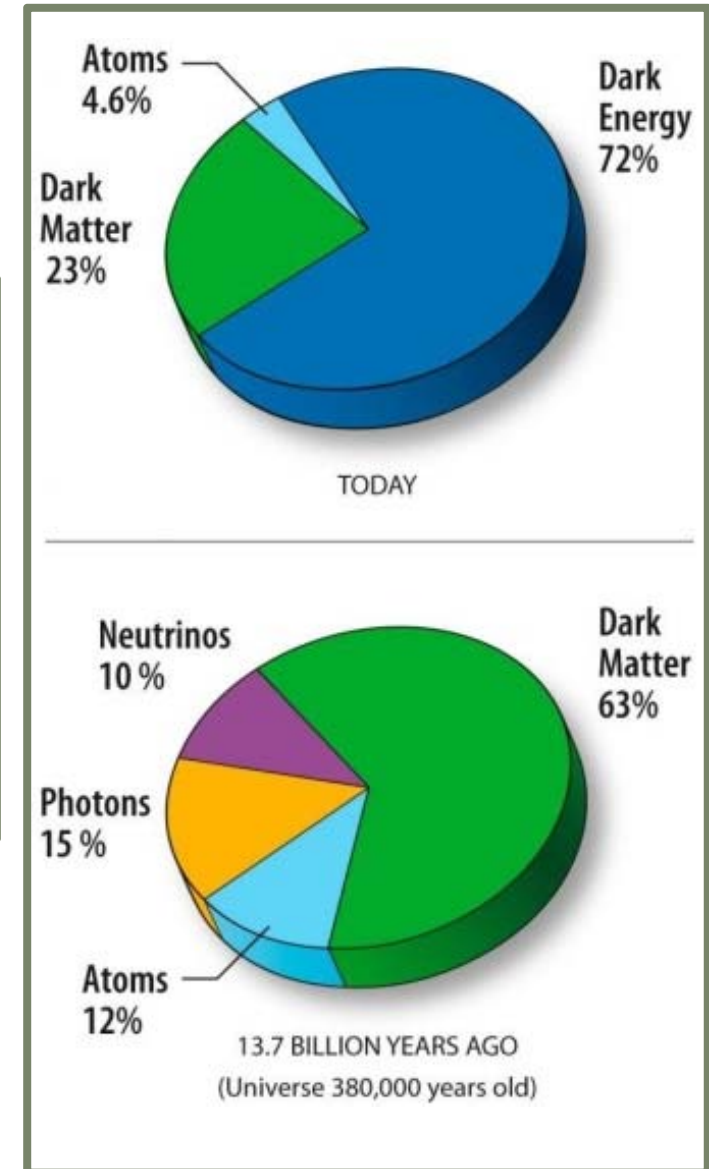
sterren slechts
~0.1% energie
Heelal

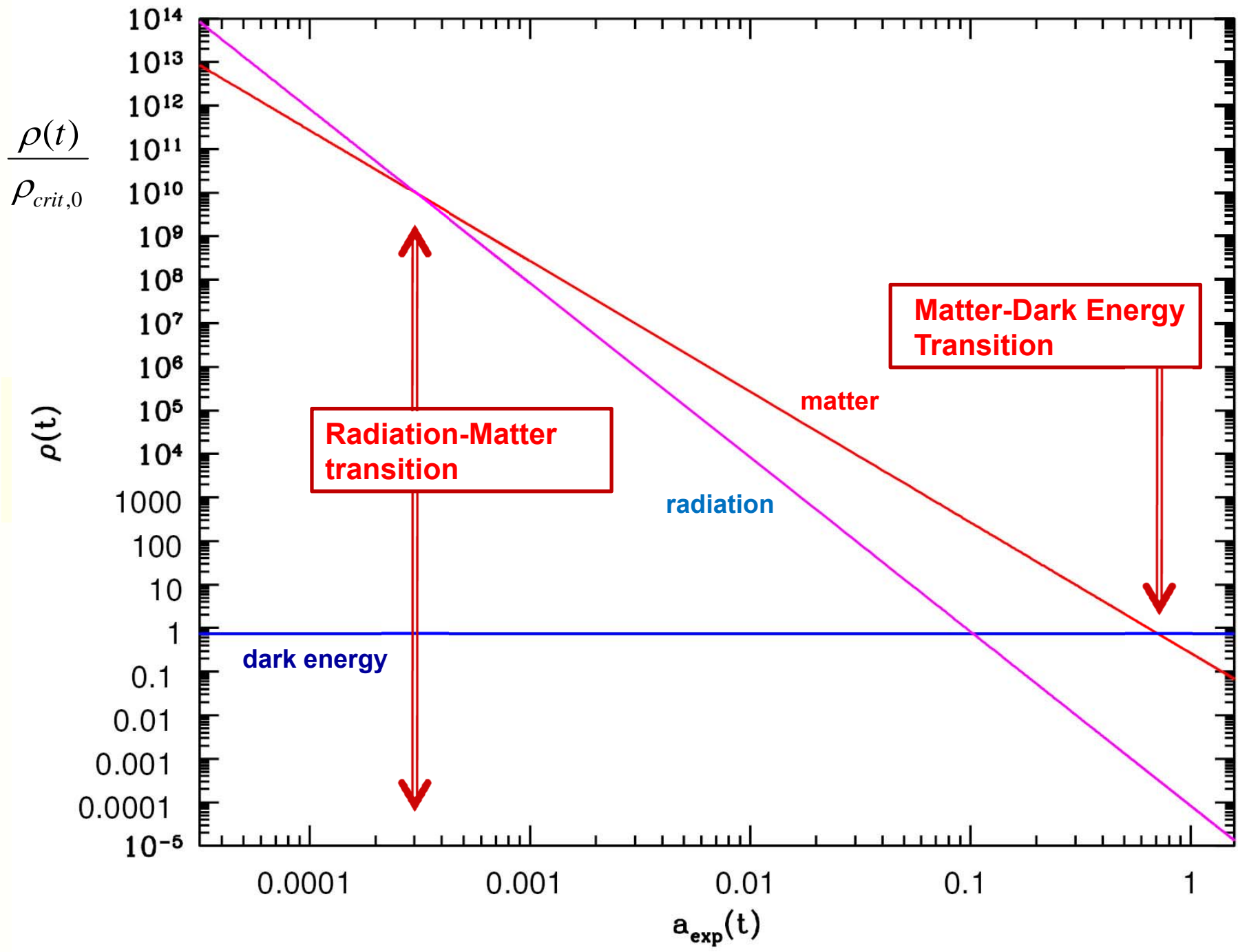
Cosmic Constitution

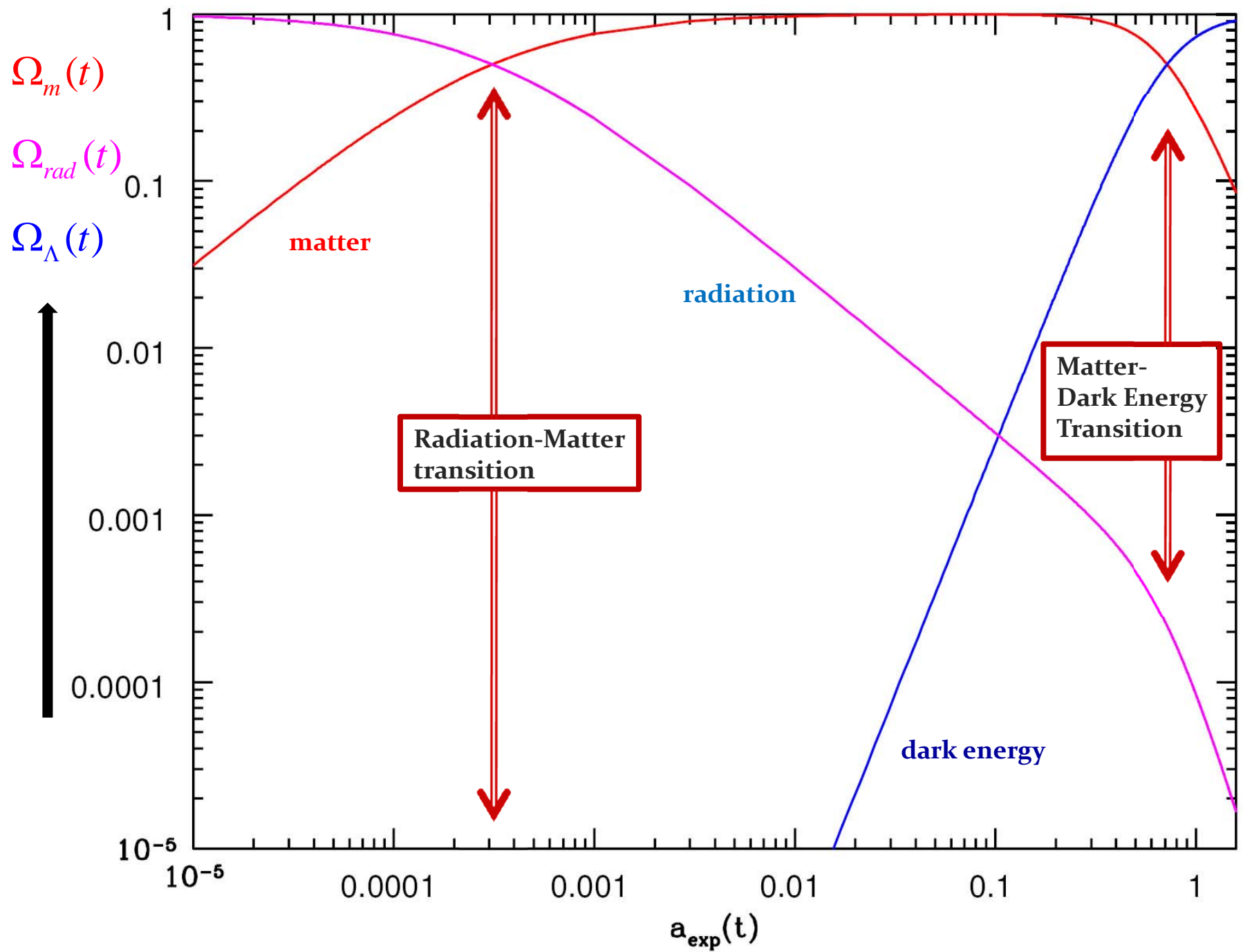


Cosmic Pie Diagram

Changes in Time:







Dark Matter

Matter

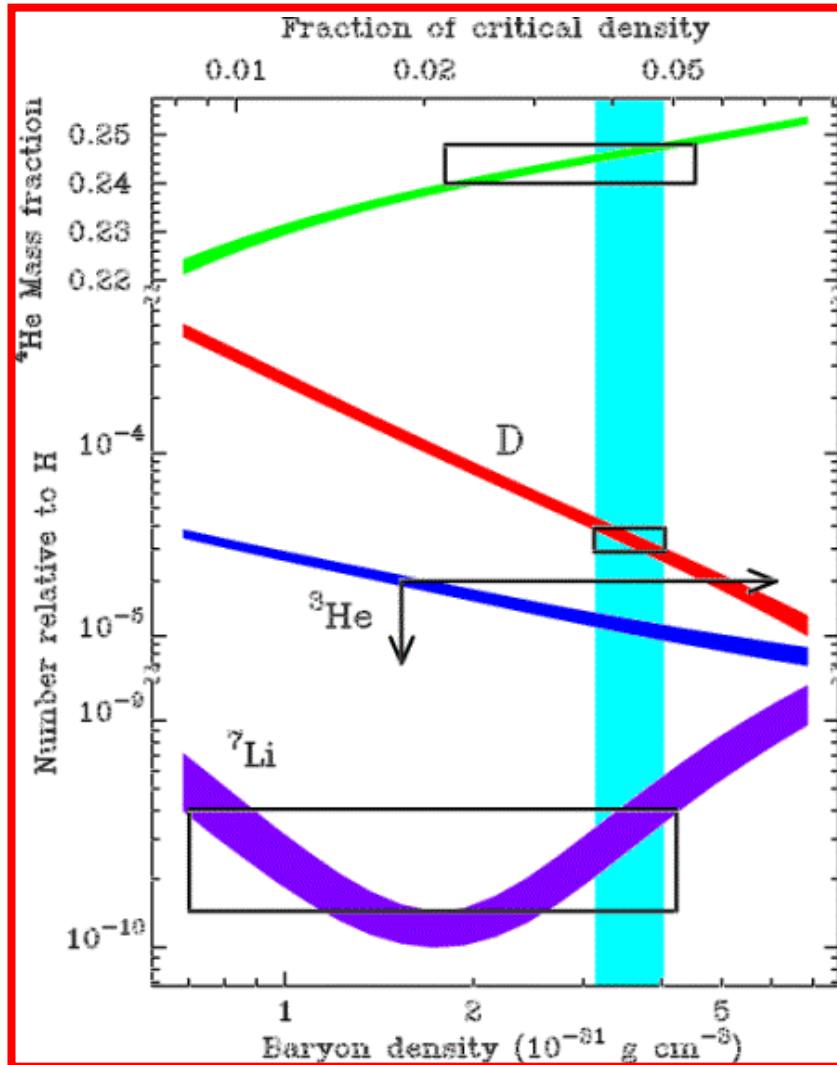
- **Baryonic Matter**
- **Nonbaryonic Dark Matter**

Baryonic Matter

The amount of baryonic matter in the Universe is (by now) very well determined, by two independent determinations:

- 1) Primordial Nucleosynthesis
- 2) Acoustic Oscillations in CMB power spectrum,
2nd peak (CMB)

Baryonic Matter: primordial nucleosynthesis



From measured light element abundances:

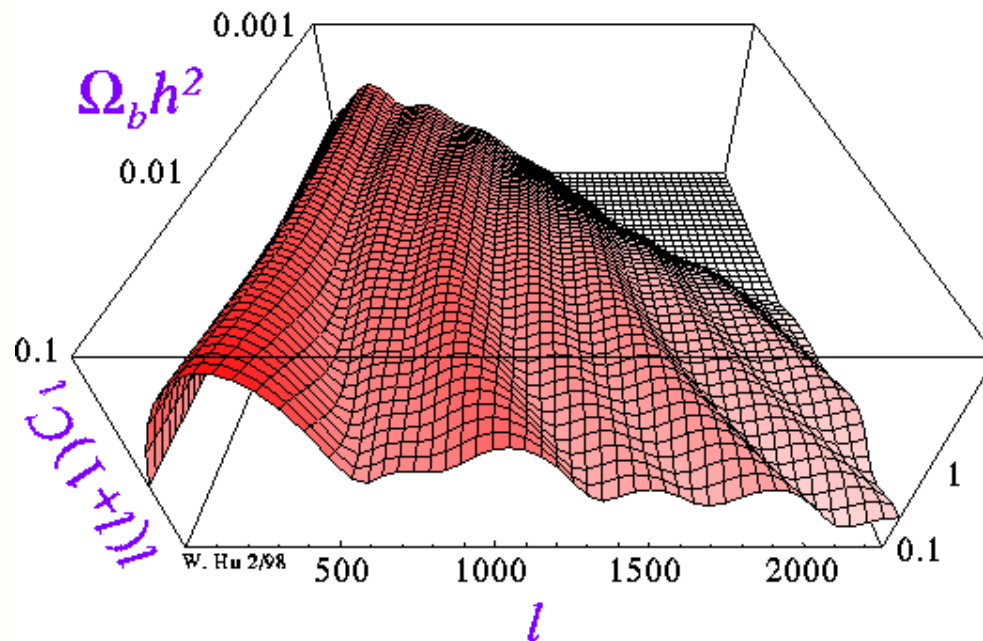
$$\eta \equiv \frac{n_B}{n_\gamma}$$



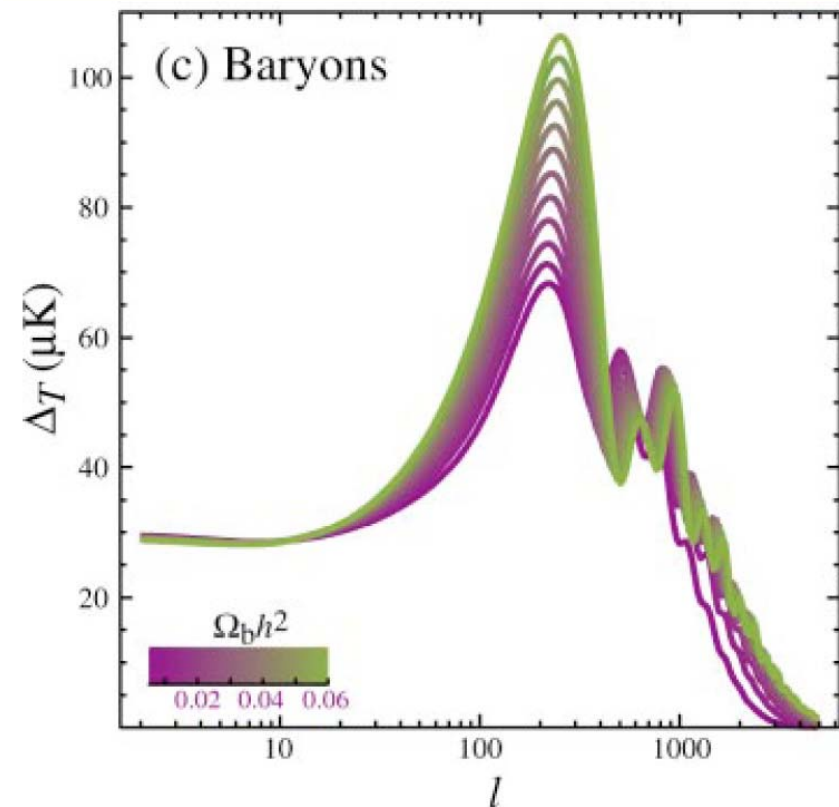
$$0.005 \lesssim \Omega_b h^2 \lesssim 0.026$$

Baryonic Matter: CMB

Baryon-Photon Ratio in the CMB



Due to baryon drag in the primordial baryon-photon gas, 2nd peak in CMB spectrum is suppressed:



$$\Omega_b h^2 \approx 0.0224 \pm 0.0009$$

$$\Omega_b \approx 0.044 \pm 0.004$$

Baryonic Matter

Cosmic Baryons

3	baryon rest mass			0.045 ± 0.003
3.1	warm intergalactic plasma			0.040 ± 0.003
3.1a	virialized regions of galaxies	0.024 ± 0.005		
3.1b	intergalactic	0.016 ± 0.005		
3.2	intracluster plasma			0.0018 ± 0.0007
3.3	main sequence stars		spheroids and bulges	0.0015 ± 0.0004
3.4			disks and irregulars	0.00055 ± 0.00014
3.5	white dwarfs			0.00036 ± 0.00008
3.6	neutron stars			0.00005 ± 0.00002
3.7	black holes			0.00007 ± 0.00002
3.8	substellar objects			0.00014 ± 0.00007
3.9	HI + HeI			0.00062 ± 0.00010
3.10	molecular gas			0.00016 ± 0.00006
3.11	planets			10^{-6}
3.12	condensed matter			$10^{-5.6 \pm 0.3}$
3.13	sequestered in massive black holes			$10^{-5.4}(1 + \epsilon_n)$

Fukugita & Peebles 2004

Baryonic Matter

Note:

- **STARS** are but a fraction of the total amount of baryonic matter
- There is still a large amount of undetected baryonic matter:
 - hiding as warm Intergalactic Gas (WHIM) ?

3	baryon rest mass			0.045 ± 0.003
3.1	warm intergalactic plasma			0.040 ± 0.003
3.1a	virialized regions of galaxies	0.024 ± 0.005		
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3.12	condensed matter			$10^{-5.6 \pm 0.3}$
3.13	sequestered in massive black holes			$10^{-5.4}(1 + \epsilon_n)$

Non-baryonic DM: candidates

WIMPs: Weakly Interacting Massive Particles

- neutrinos
- sterile neutrinos
- neutralinos
-

MACHOs: Massive astrophysical compact halo object

Modified Gravity: modification of General Relativity

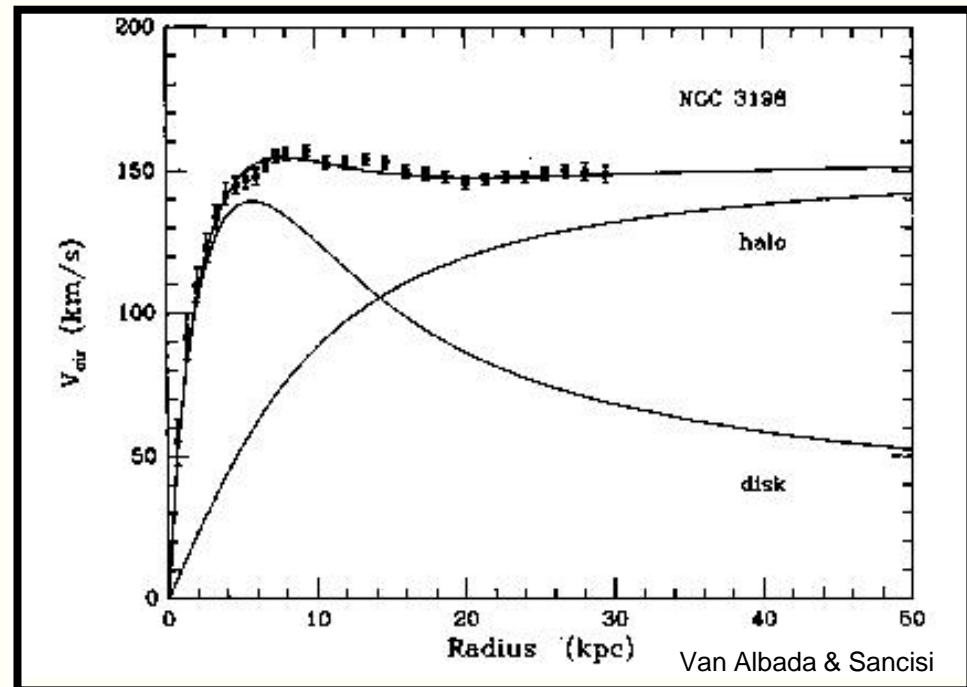
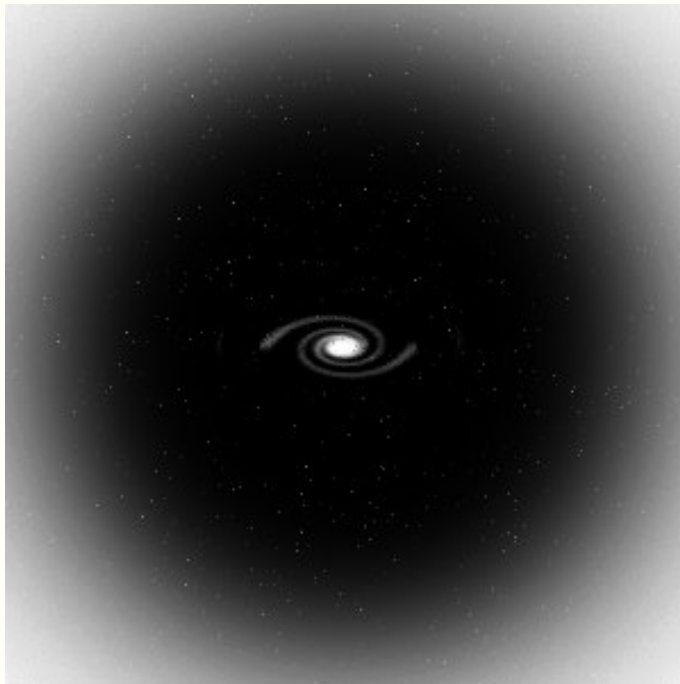
SIMPs ... Strongly Interacting Massive Particles

Dark Matter: disk galaxies

- The dark matter in these galactic dark halos will keep the stars and gas clouds in the outer reaches of the spiral galaxies swirling around the galaxy with such high velocities.

$$GM(r)/r = v_c^2$$

- Moreover, the dark matter halos would provide a natural stabilization of the thin and fragile rotating spiral discs, which otherwise are rather unstable structures which would easily be disrupted by “perturbative vibrations”.



Clusters of Galaxies: X-ray intracluster gas

Baryonic matter in clusters is not only confined to galaxies:

~ 2 to 5 times more baryonic mass in the form of a **diffuse hot X-ray emitting**

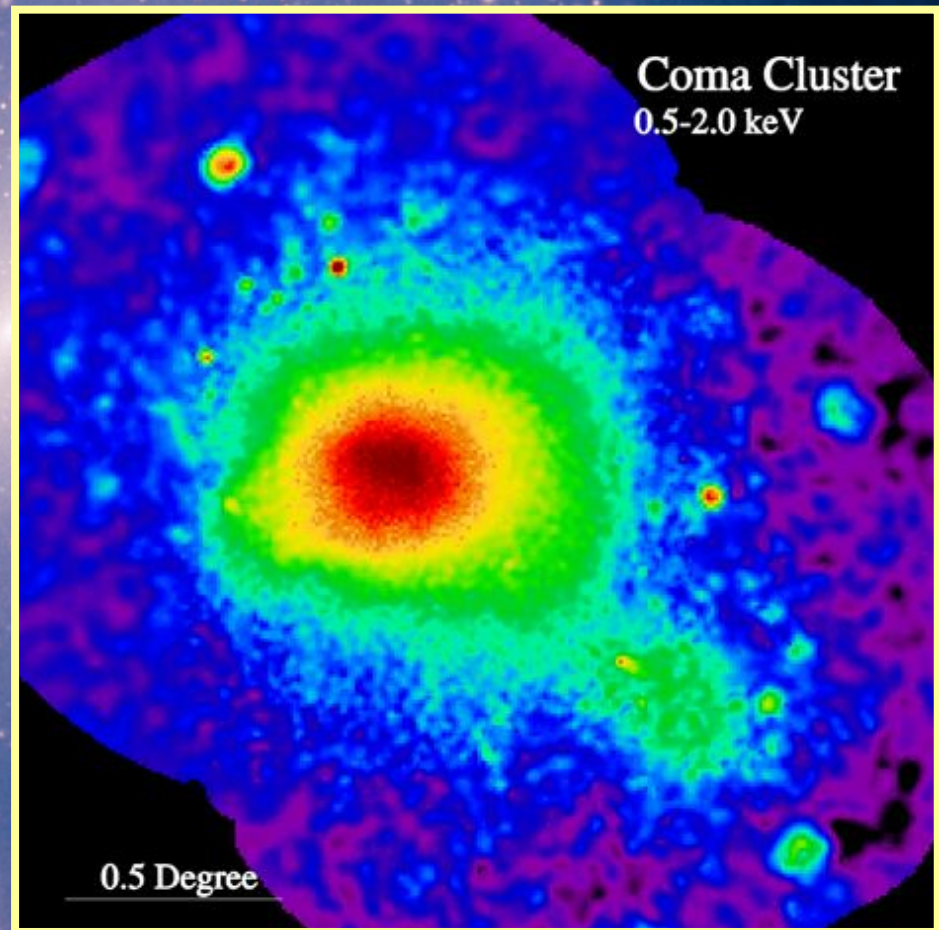
Intracluster Gas,

trapped and heated to a temperature of the order of

$$T \sim 10^8 \text{ K}$$

by the gravitational potential of the cluster.

At such high temperatures, this gas is a fully ionized plasma, producing powerful X-ray emission, bremsstrahlung radiation induced by the electron-ion interactions.



ROSAT X-ray image Coma Cluster

Clusters of Galaxies: Gravitational Lenses

A highly promising method to determine the amount and distribution of

matter in the Universe

looks at the way it affects

the trajectories of photons

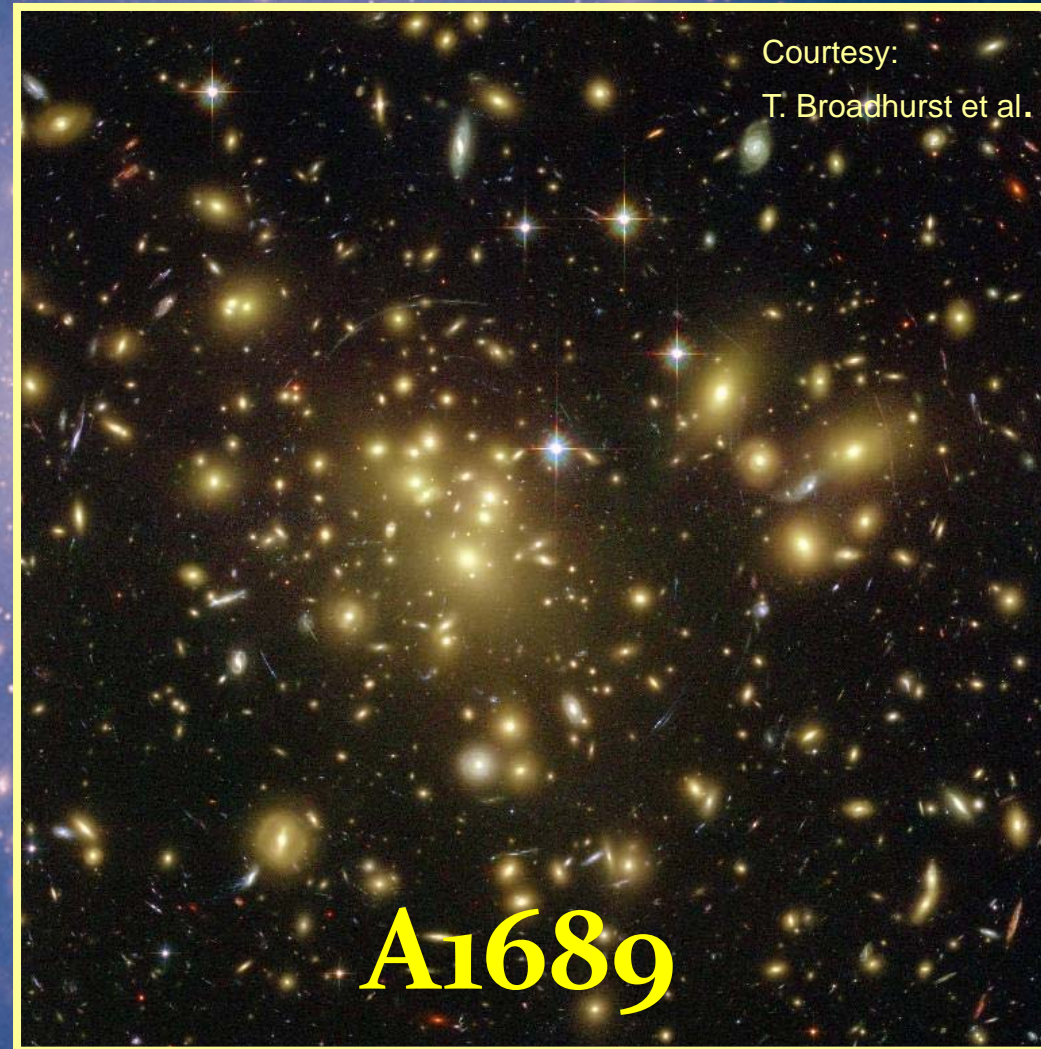
According to

Einstein's theory of

General Relativity,

gravitational potential wells will bend and focus light. Dark matter concentrations act as a

Gravitational Lens

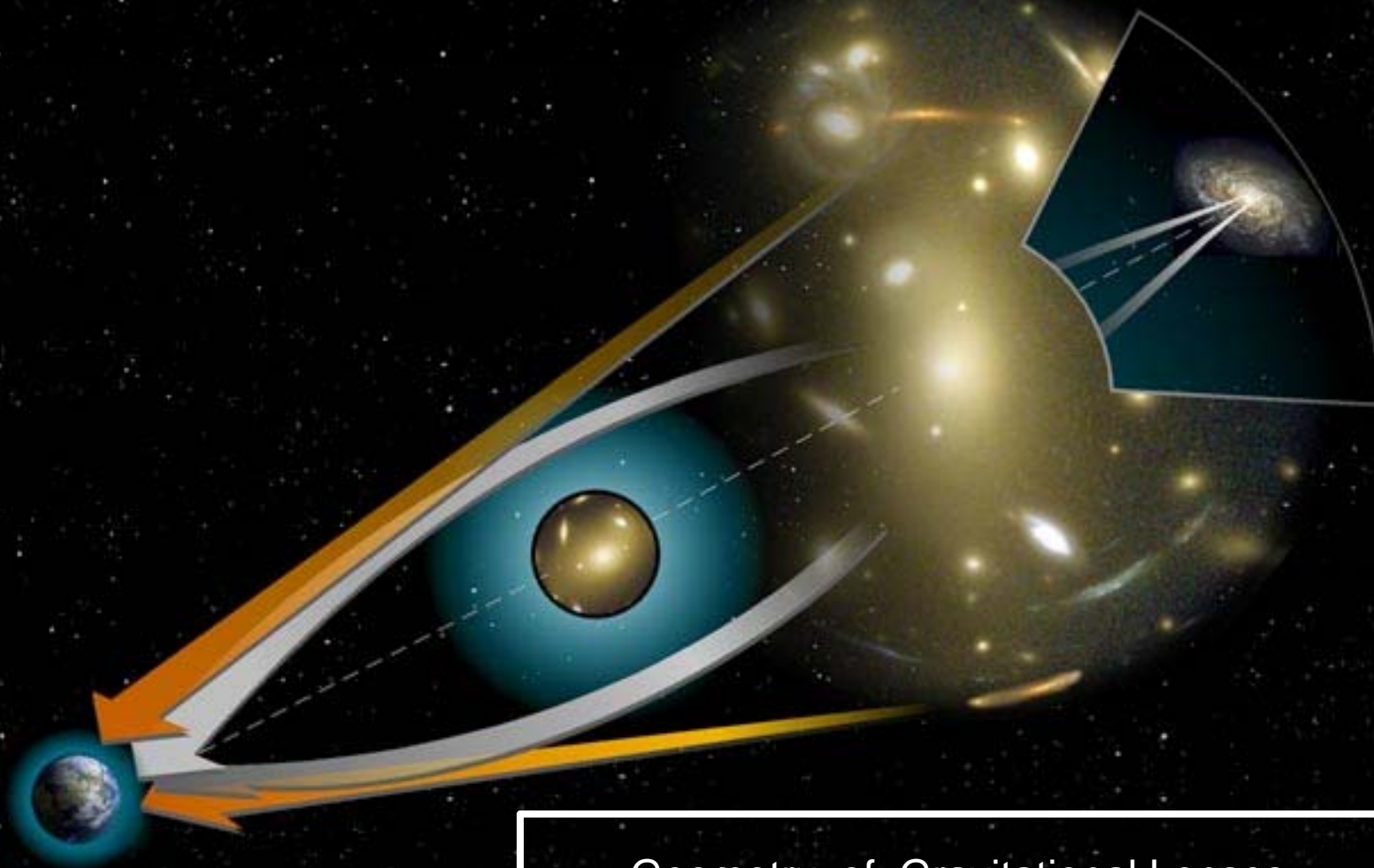


Courtesy:

T. Broadhurst et al.

A1689

Clusters: Gravitational Lensing



Geometry of Gravitational Lenses

Clusters of Galaxies: Dark Matter Map

A highly promising method to determine the amount and distribution of

matter in the Universe

looks at the way it affects

the trajectories of photons.

According to

Einstein's theory of

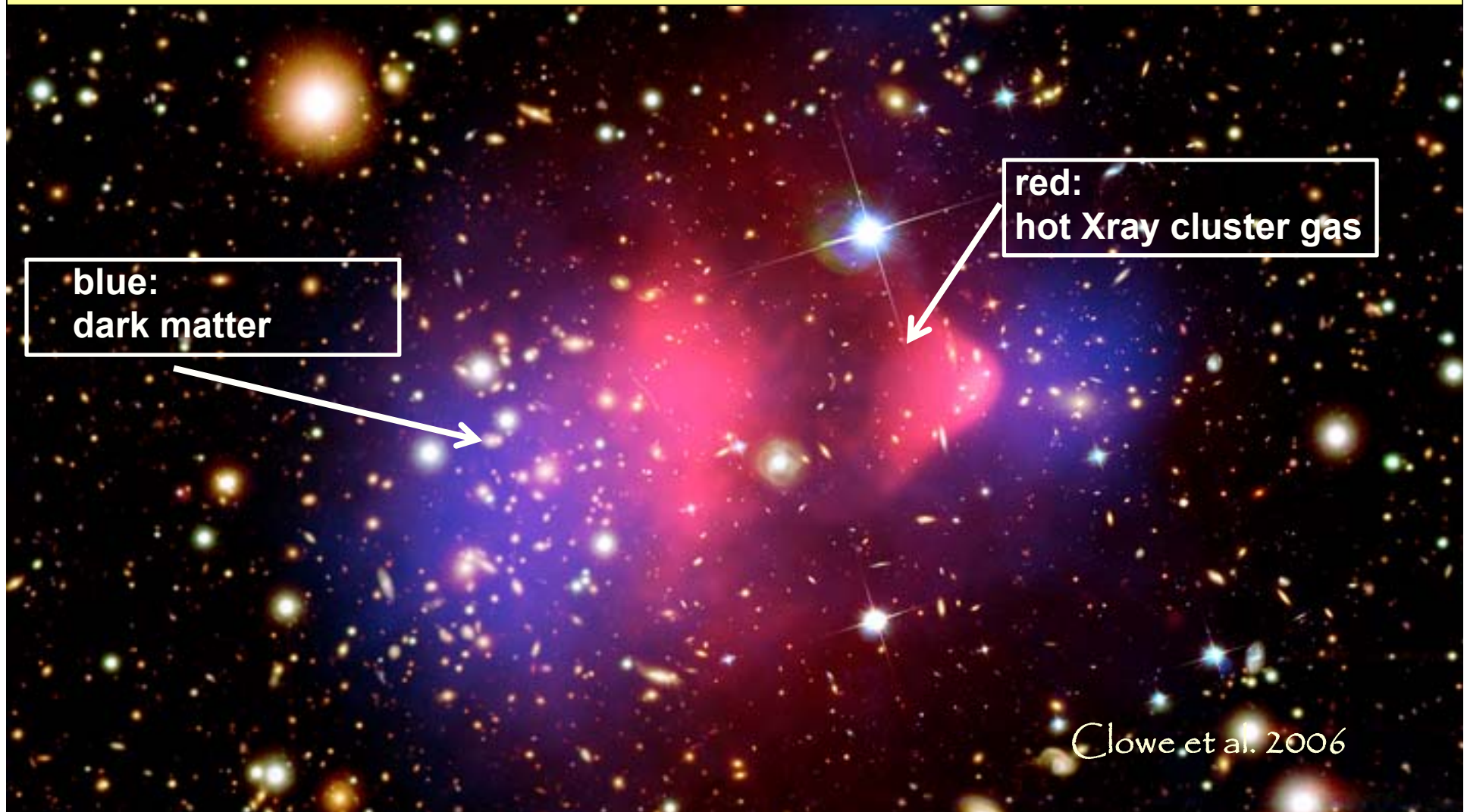
General Relativity,

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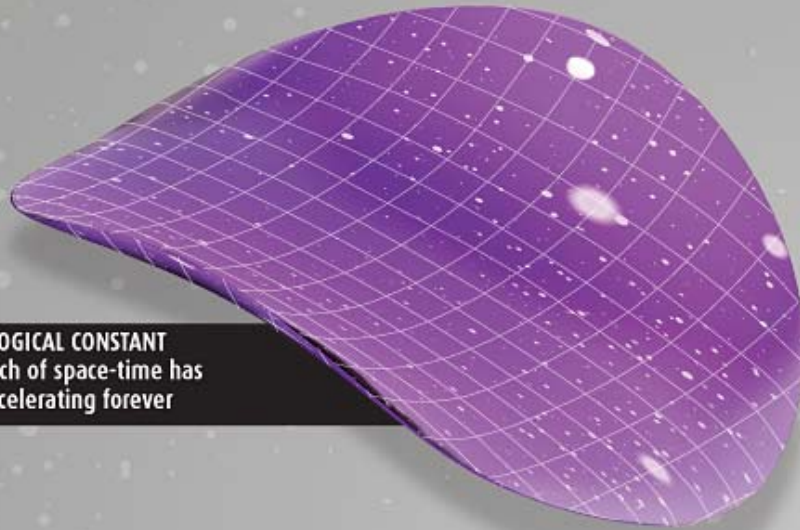
Bullet Cluster colliding ...



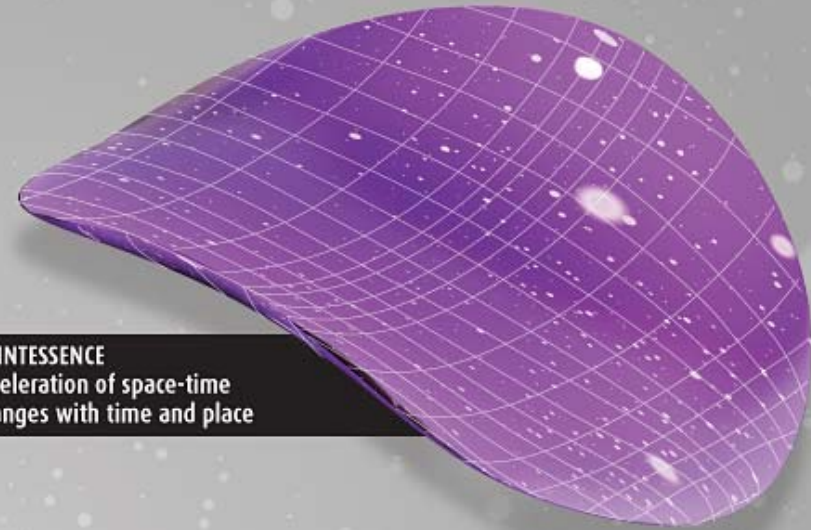
Dark Energy

FOUR WAYS TO EXPAND THE UNIVERSE

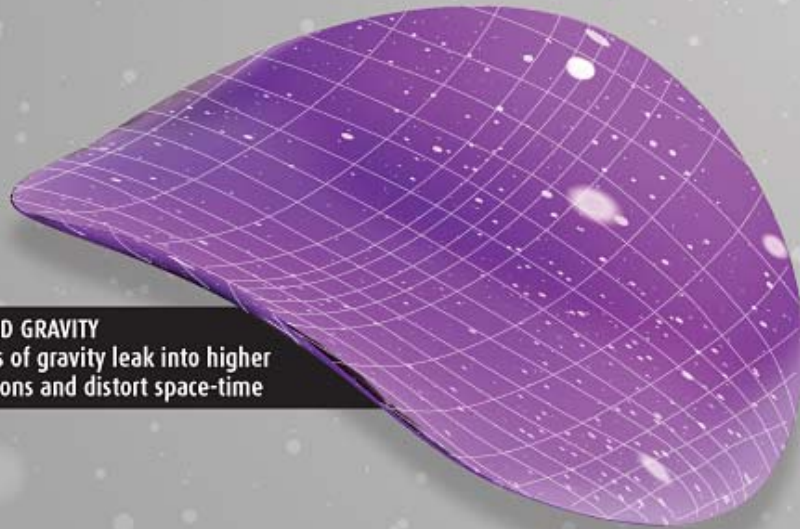
How space-time looks depends on the nature of dark energy



COSMOLOGICAL CONSTANT
Every inch of space-time has been accelerating forever



QUINTESSENCE
Acceleration of space-time changes with time and place



MODIFIED GRAVITY
Particles of gravity leak into higher dimensions and distort space-time



INHOMOGENOUS UNIVERSE
Contains galaxy-rich and galaxy-poor areas

Dark Energy: Identity & Nature

**Huge and ever growing
list of suggestions on**

identity & nature of Dark Energy:

- **Cosmological Constant**
- **Cosmic Backreaction**
(inhomogeneities)
- **Modified Gravity**
- **Quintessence,**
in a variety of flavours
- **Phantom Energy**
- **Chameleon Energy**
- **Chaplygin gas**
- **Agegraphic DE**
-

Dark Energy = Vacuum Energy

Ya. Zel'dovich - 1960s

S. Weinberg - 1989

**Cosmological Constant to be
identified with zero-point
vacuum energy ?**

minor problem:

1st order estimate

off by 120 orders magnitude:

$\sim 10^{120}$

Phantom Energy:



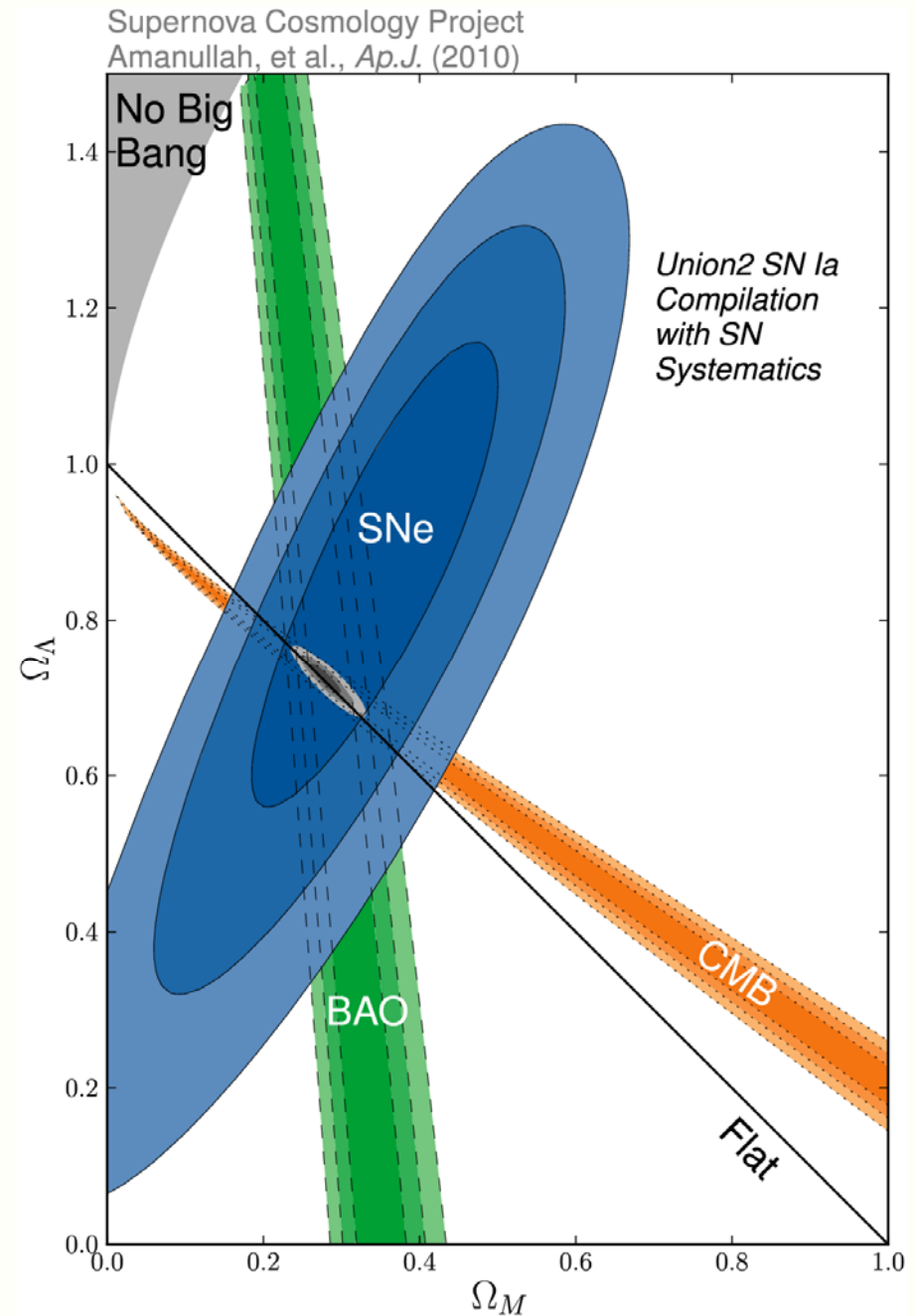
De Big Rip ?

Ω_m vs. Ω_Λ

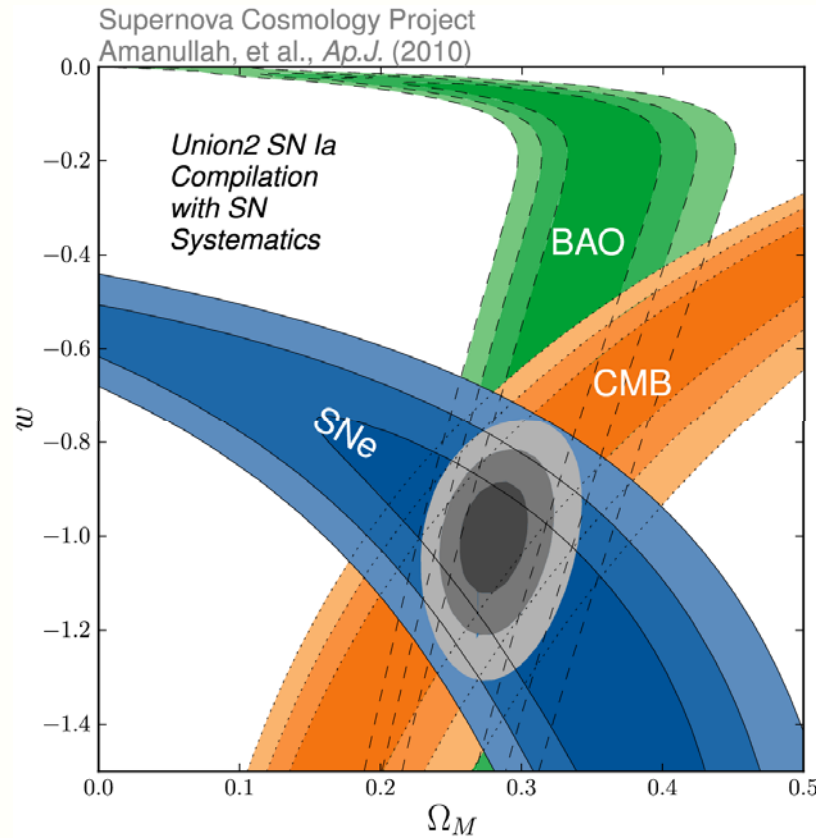
$$q \approx \frac{\Omega_m}{2} - \Omega_\Lambda$$
$$k = \frac{H^2 R^2}{c^2} (\Omega_m + \Omega_\Lambda - 1)$$

SCP Union2 constraints (2010)

on values of matter density Ω_m
dark energy density Ω_Λ

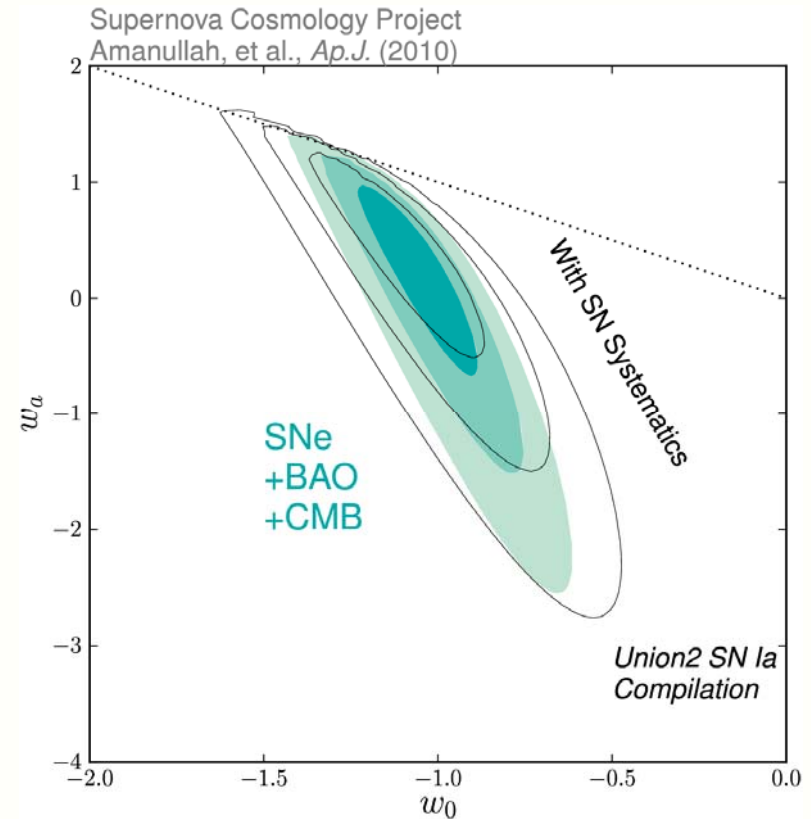


Dark Energy Eqn.State



SCP Union2 constraints (2010)

**on values of matter density Ω_m
dark energy eqn. state w**



on dynamical evolution dark energy:

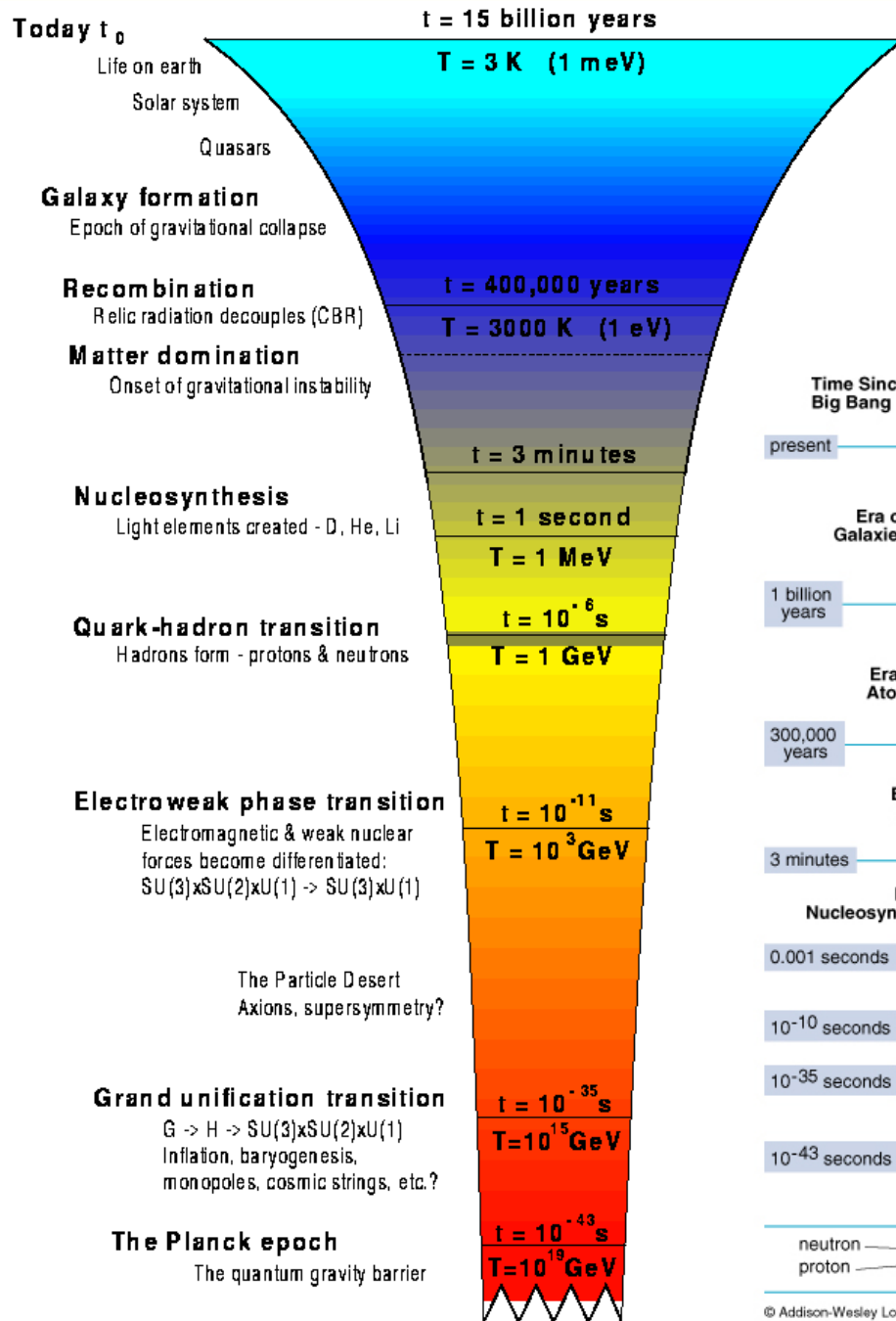
**eqn. state parameters w_0
 w_a**

Adiabatic Expansion

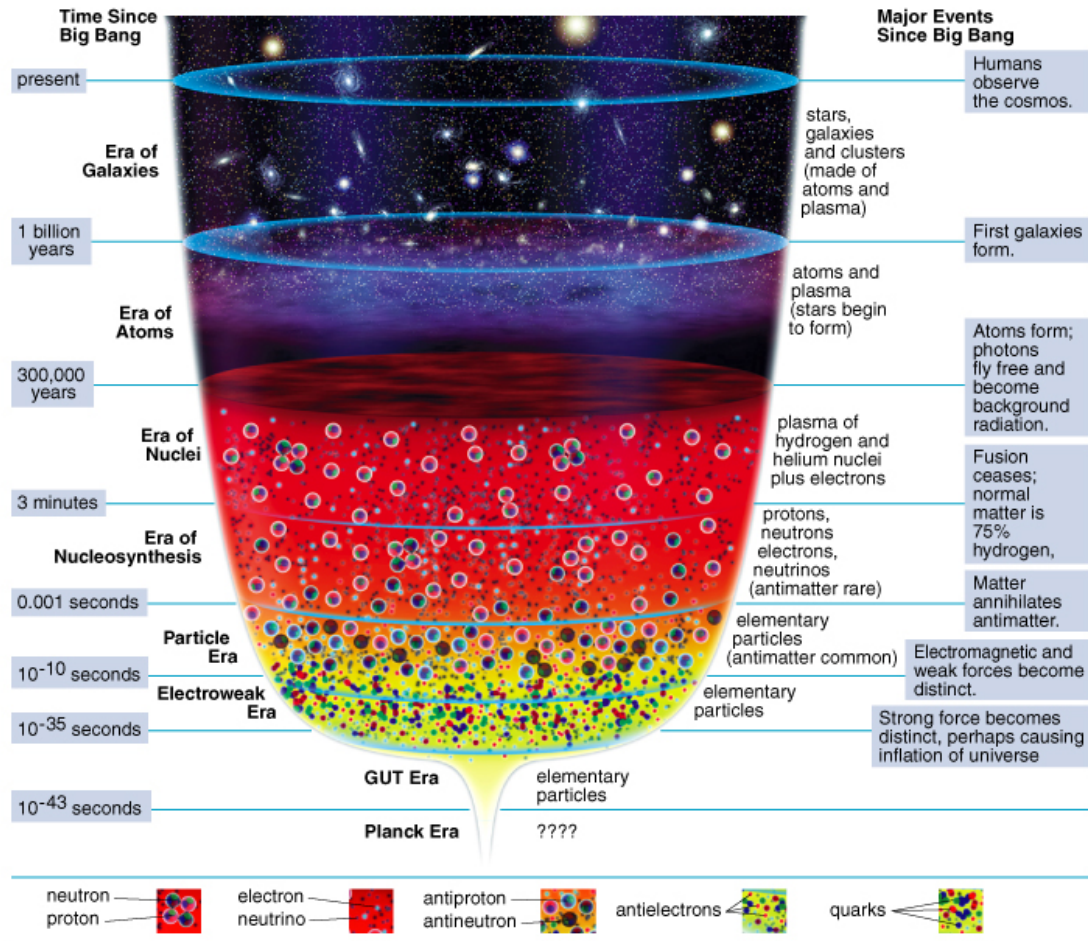
Adiabatic Expansion

- The Universe of Einstein, Friedmann & Lemaitre expands *adiabatically*
- Energy of the expansion of the Universe corresponds to the decrease in the energy of its constituents
- *The Universe COOLS as a result of its expansion !*

$$T(t) \propto 1 / a(t)$$



Adiabatic Expansion reconstruction Thermal History of the Universe



Cosmic Epochs

Planck Epoch

Phase Transition Era

Hadron Era

Lepton Era

Radiation Era

Post-Recombination Era

GUT transition
electroweak transition
quark-hadron transition

muon annihilation
neutrino decoupling
electron-positron annihilation
primordial nucleosynthesis

radiation-matter equivalence
recombination & decoupling

Structure & Galaxy formation
Dark Ages
Reionization
Matter-Dark Energy transition

$t < 10^{-43}$ sec

10^{-43} sec $< t < 10^5$ sec

$t \sim 10^{-5}$ sec

10^{-5} sec $< t < 1$ min

1 min $< t < 379,000$ yrs

$t > 379,000$ yrs

History of the Universe in Four Episodes: I

On the basis of the

- 1) complexity of the involved physics
 - 2) our knowledge of the physical processes
- we may broadly distinguish four cosmic episodes:

(I)

Origin universe

???

$t < 10^{-43}$ sec

fundamental physics:

- totally unknown

Planck Era

History of the Universe in Four Episodes: II

(II)

$10^{-43} < t < 10^{-3} \text{ sec}$

**VERY early
universe**

fundamental physics:
- poorly known
- speculative

- Ω_{tot} :
curvature/
flatness
- Ω_b (n_b/n_γ)
- 'exotic'
dark matter
- primordial
fluctuations

History of the Universe in Four Episodes: III

(III)

$$10^{-3} < t < 10^{13} \text{ sec}$$

**Standard
Hot Big Bang
Fireball**

fundamental
microphysics:
known very well

- primordial nucleosynthesis
- blackbody radiation: CMB

History of the Universe in Four Episodes: IV

(IV)

$t > 10^{13}$ sec

Post

(Re)Combination

universe

- structure formation:

stars,
galaxies
clusters

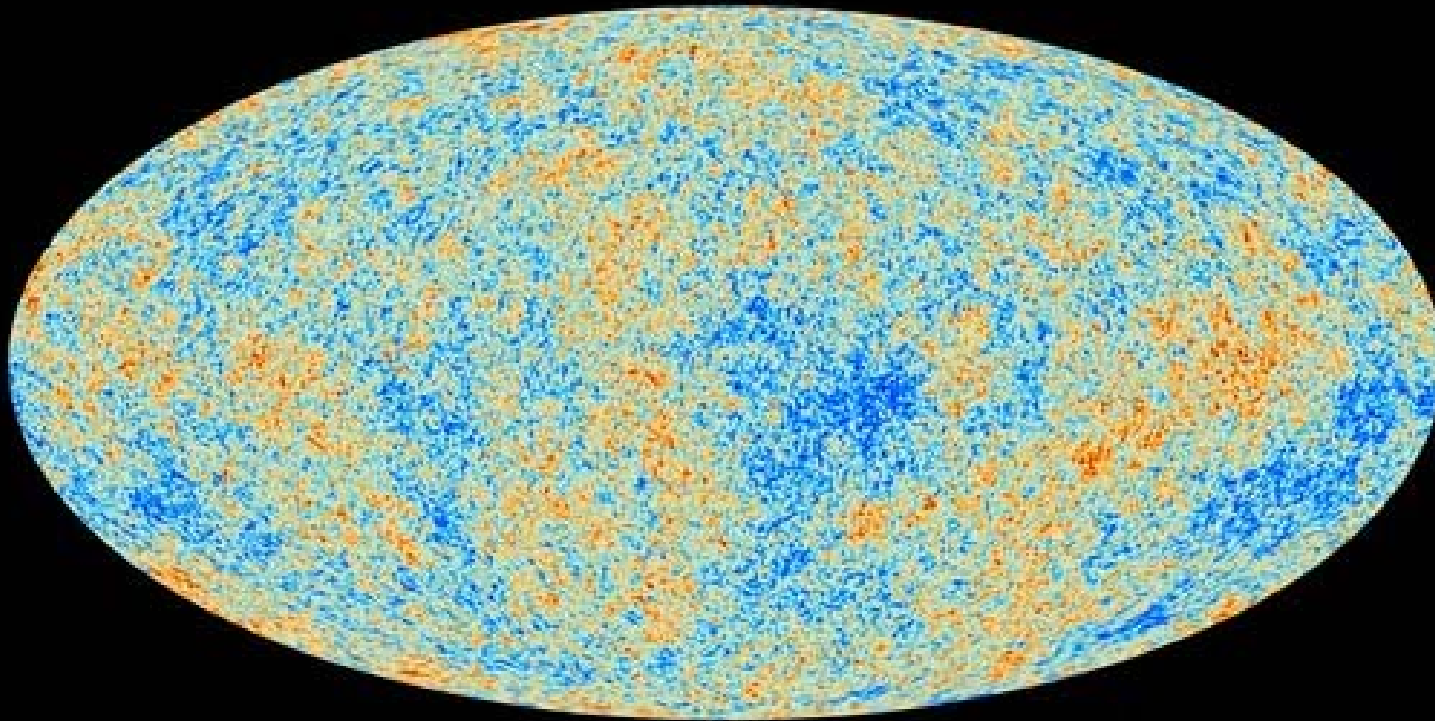
...

complex macrophysics:

- Fundamentals known
- complex interplay

Cosmic Curvature

Cosmic Microwave Background



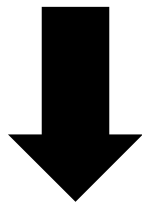
Map of the Universe at Recombination Epoch (Planck, 2013):

- 379,000 years after Big Bang
- Subhorizon perturbations: primordial sound waves
- $\Delta T/T < 10^{-5}$

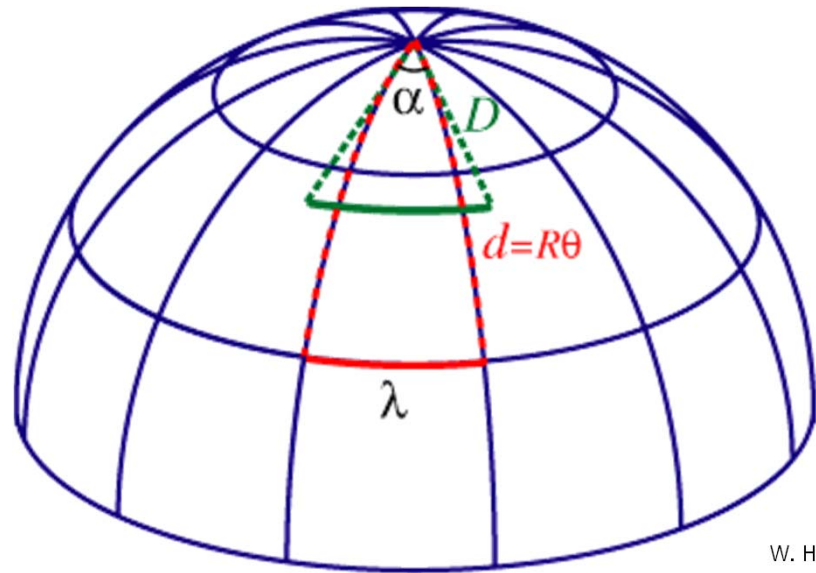
Measuring Curvature

Measuring the Geometry of the Universe:

- Object with known physical size, at large cosmological distance
- Measure angular extent on sky
- Comparison yields light path, and from this the curvature of space

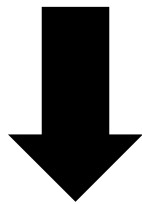


Geometry of Space

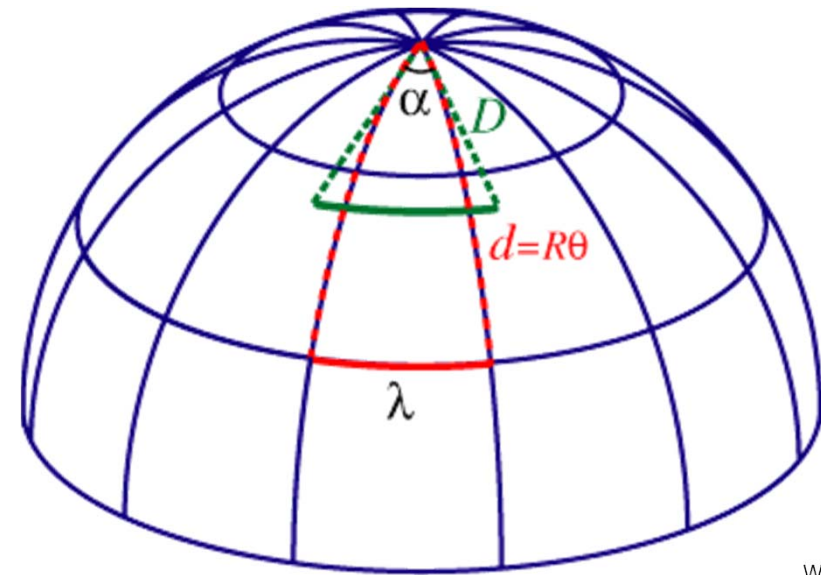


Measuring Curvature

- Object with known physical size, at large cosmological distance:
- Sound Waves in the Early Universe !!!!

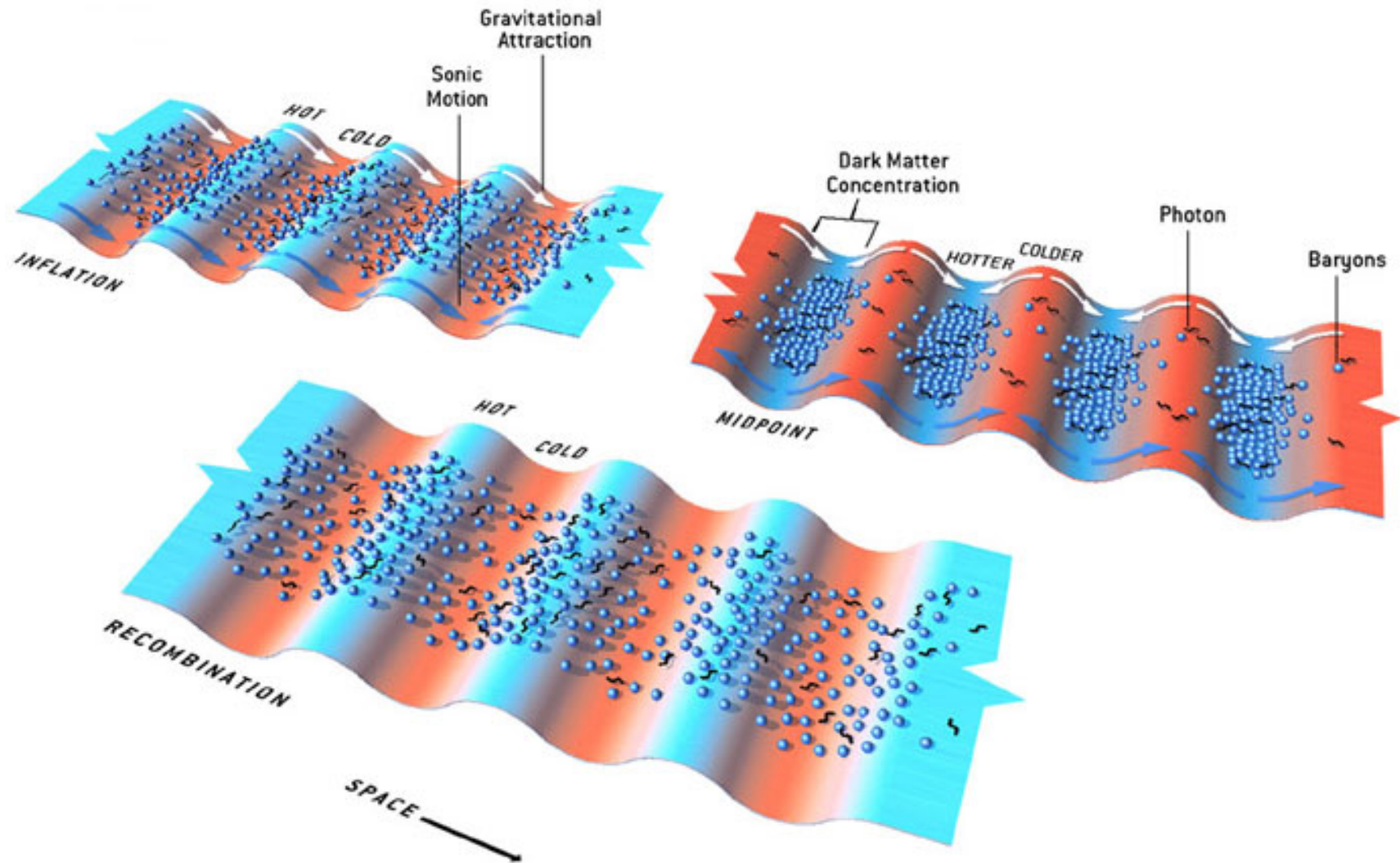


**Temperature Fluctuations
CMB**



W. Hu

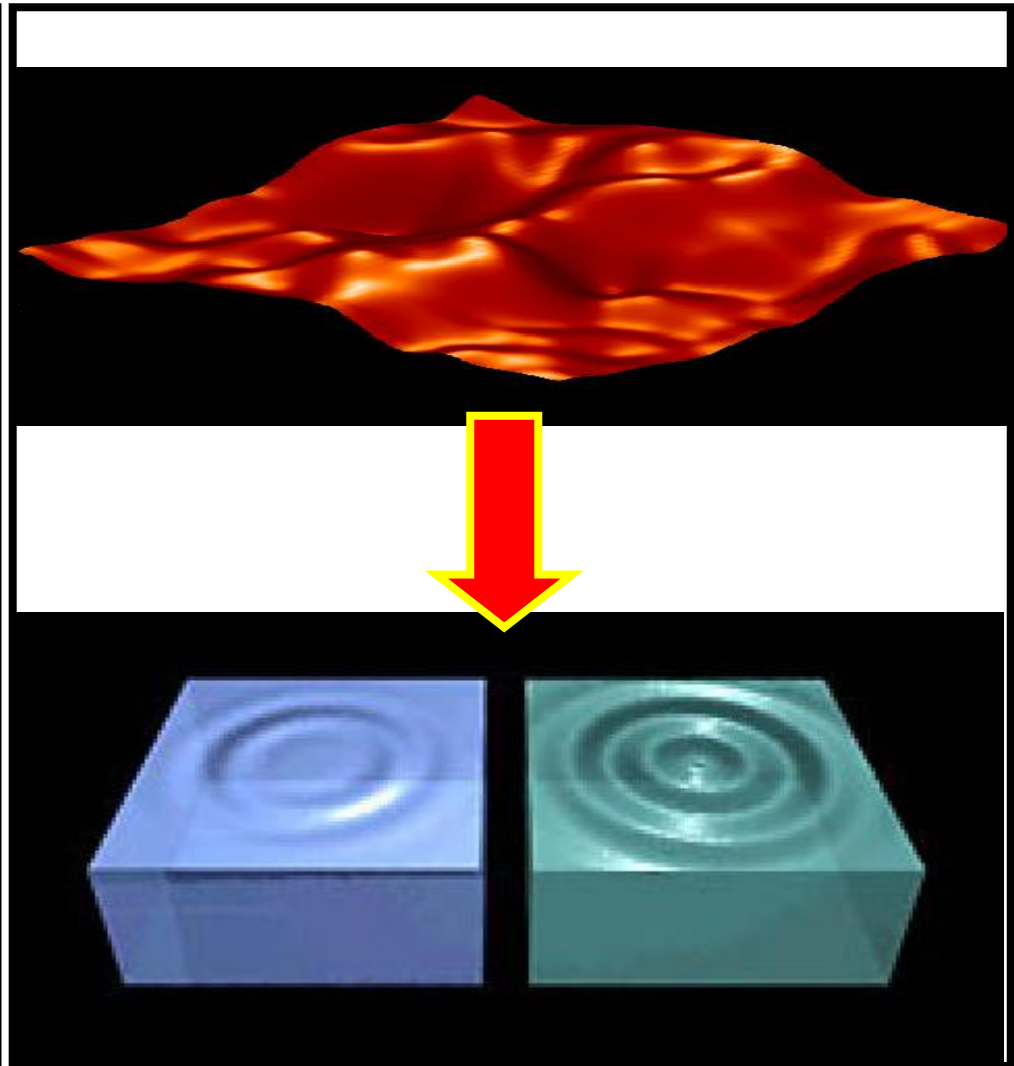
Fluctuations-Origin



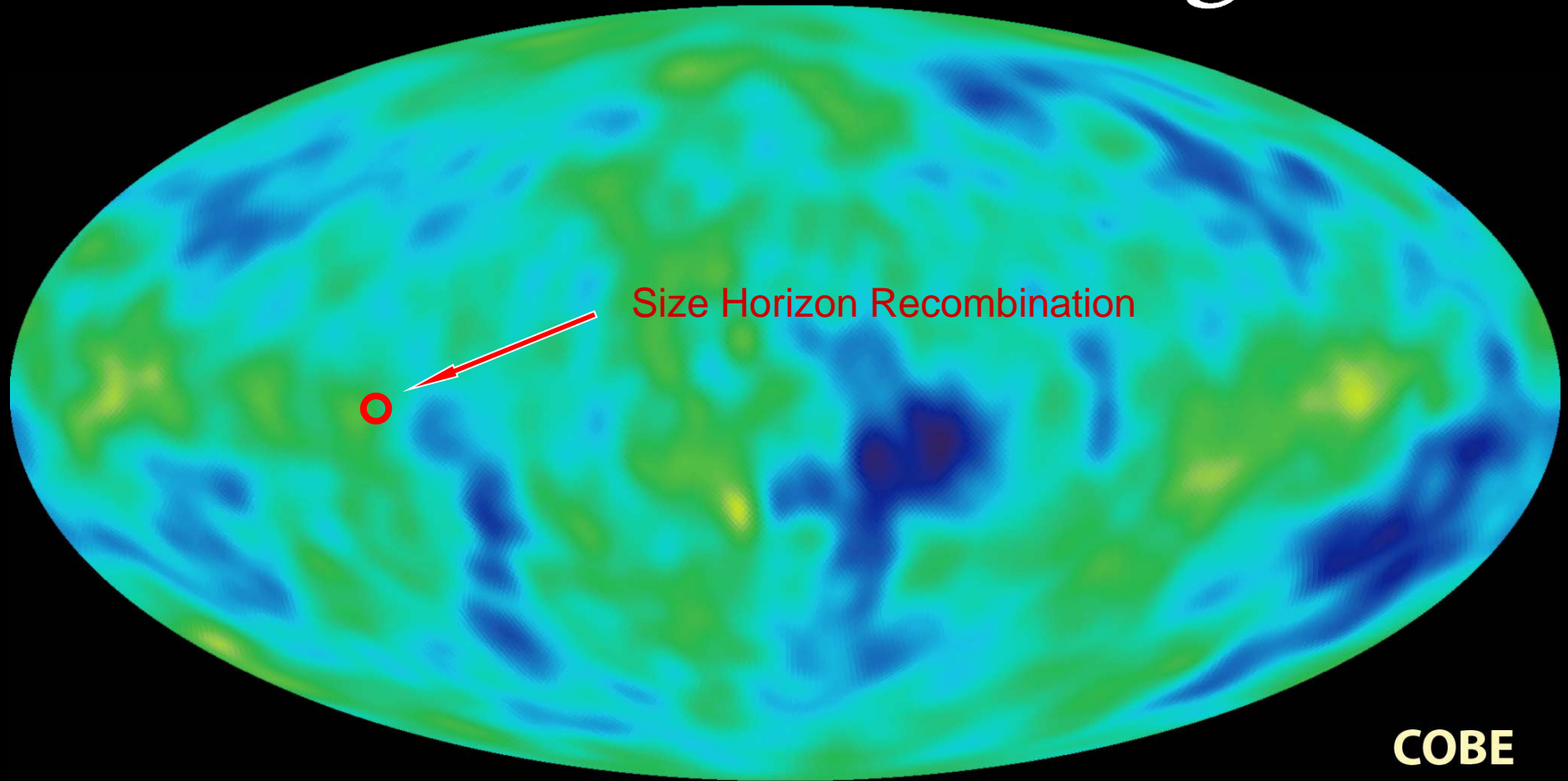
Music of the Spheres

- small ripples in primordial matter & photon distribution
- gravity:
 - compression primordial photon gas
 - photon pressure resists
- compressions and rarefactions in photon gas: sound waves
- sound waves not heard, but seen:
 - compressions: (photon) T higher
 - rarefactions: lower
- fundamental mode sound spectrum
 - size of “instrument”:
 - (sound) horizon size last scattering
- Observed, angular size: $\theta \sim 1^\circ$
 - exact scale maximum compression, the “cosmic fundamental mode of music”

W. Hu



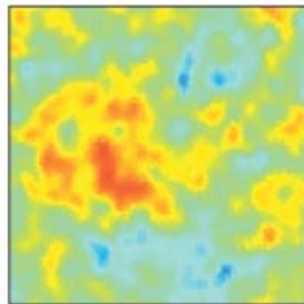
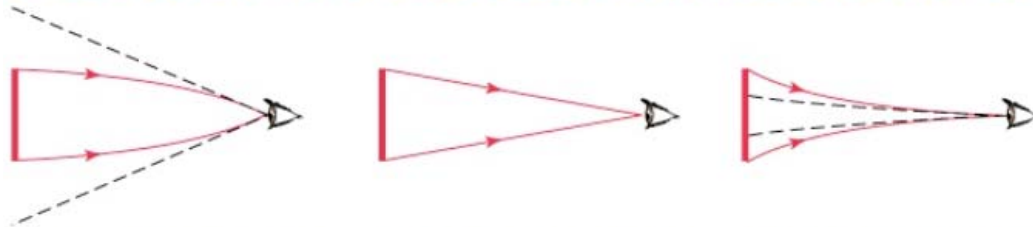
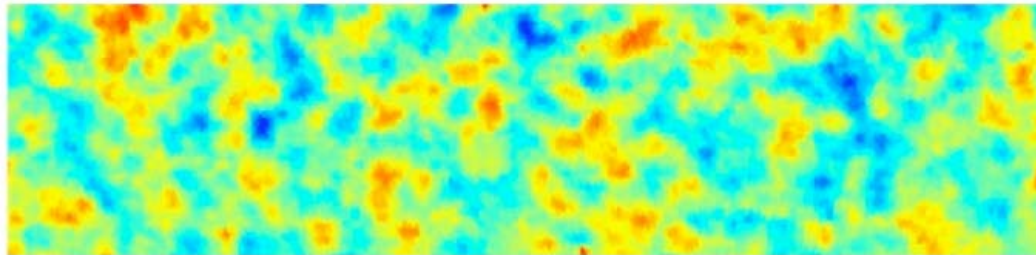
Cosmic Microwave Background



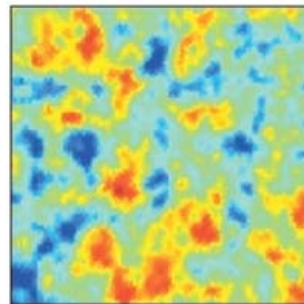
COBE measured fluctuations: $> 7^\circ$
Size Horizon at Recombination spans angle $\sim 1^\circ$

Flat universe from CMB

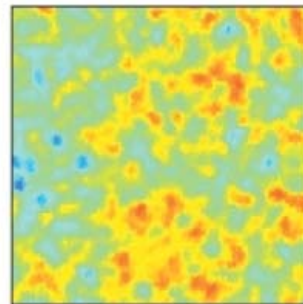
- **First peak: flat universe**



Closed:
hot spots
appear larger



Flat:
appear as big
as they are



Open:
spots appear
smaller

We know the redshift and the time it took for the light to reach us:

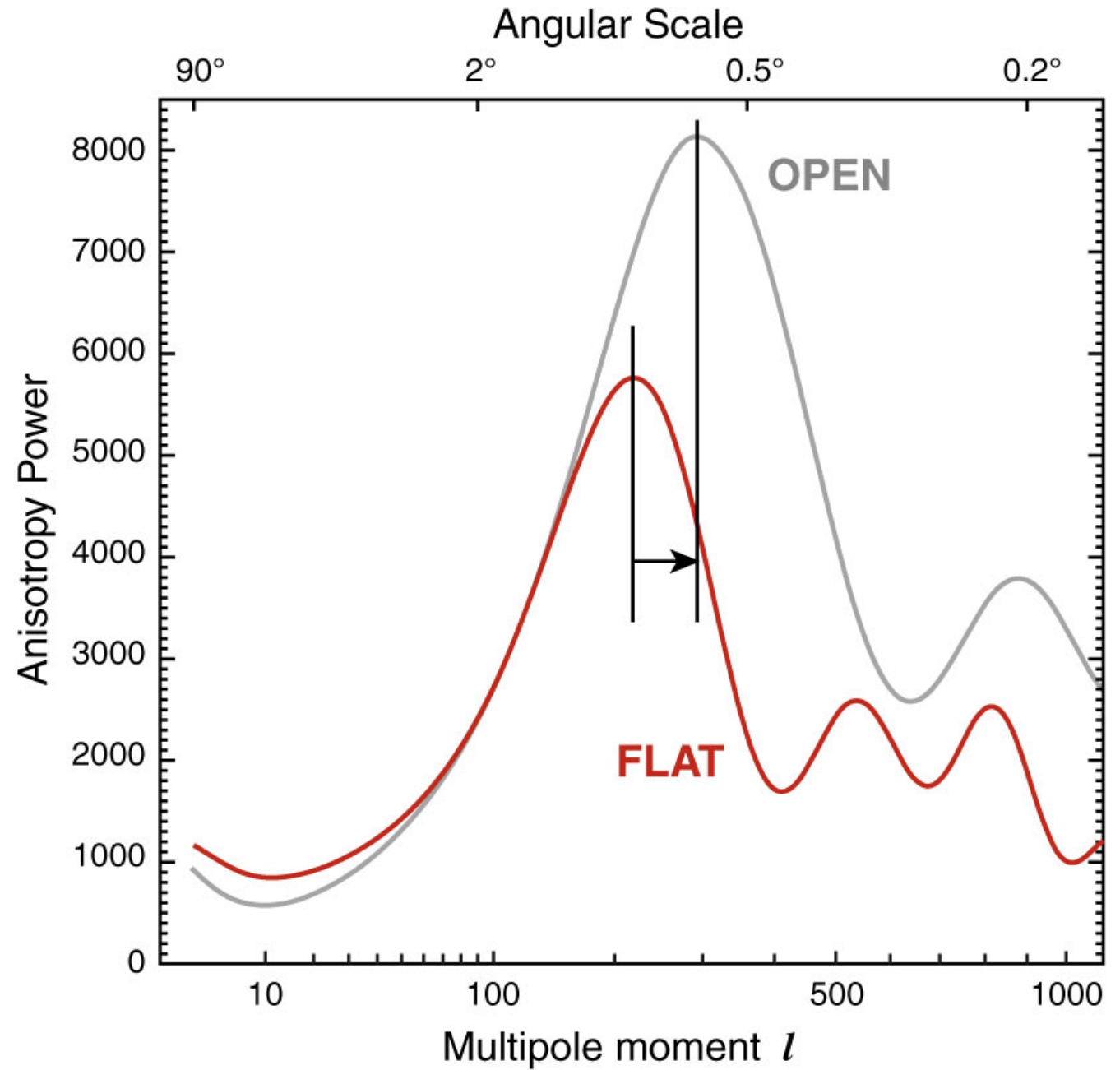
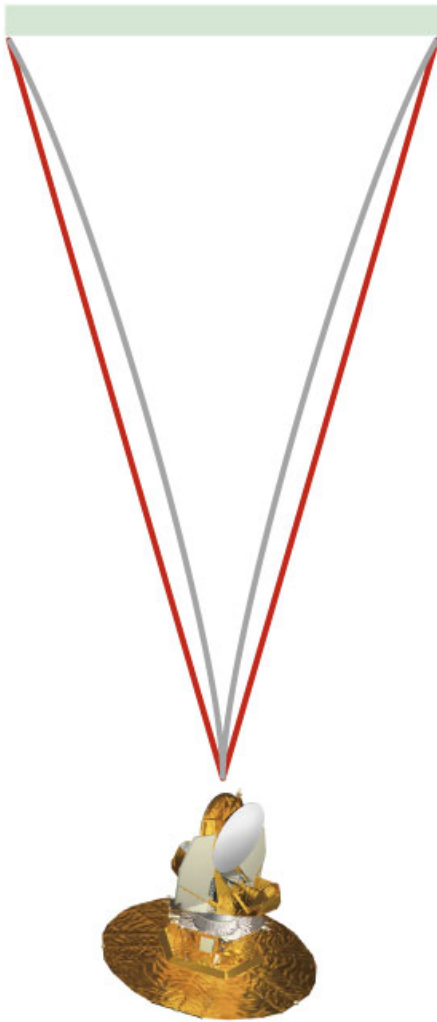
from this we know the

- length of the legs of the triangle
- the angle at which we are measuring the sound horizon.

$$v \approx \frac{c}{\sqrt{3}}$$

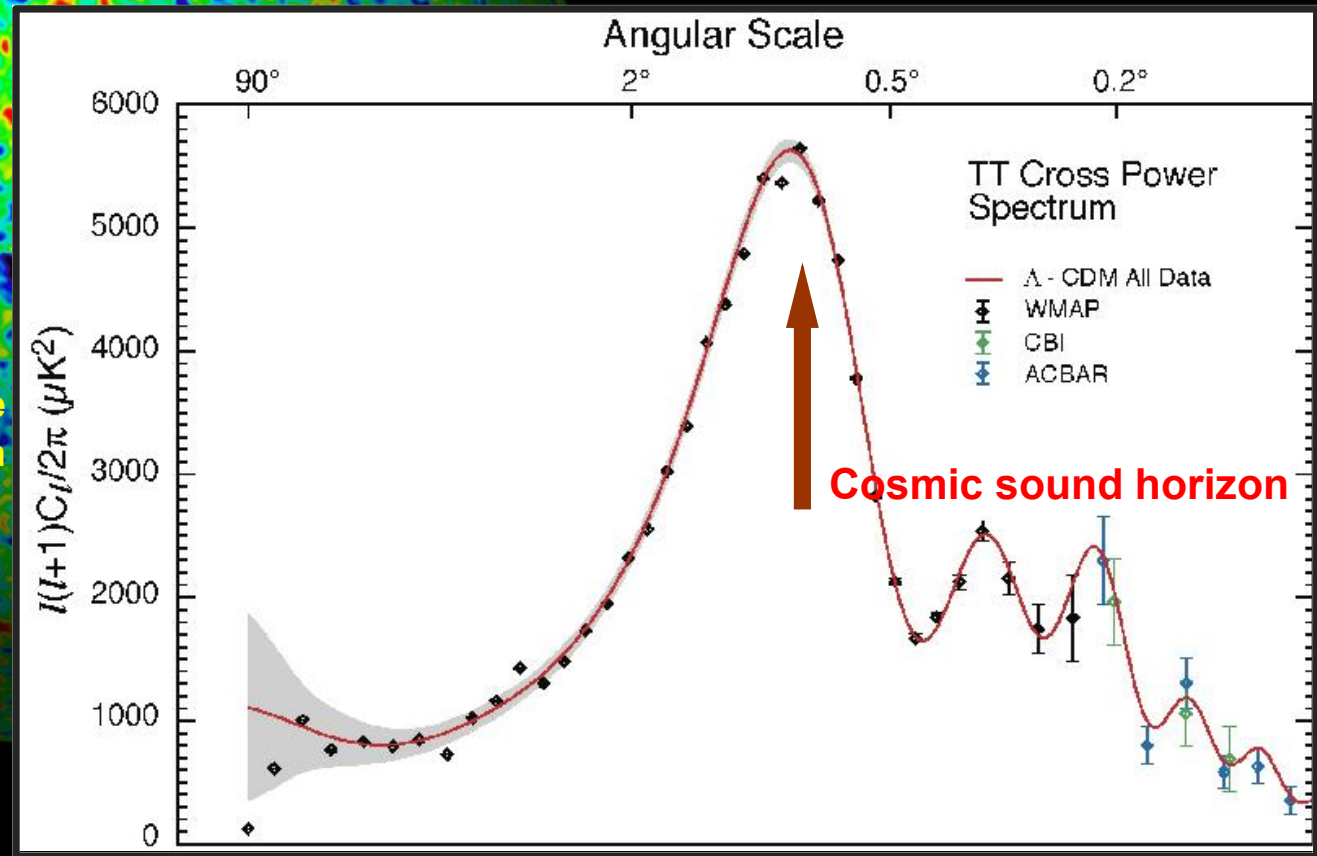
$$\ell \approx 200 / \sqrt{1 - \Omega_k}$$

Standard Ruler:
1° arc measurement of
dominant energy spike



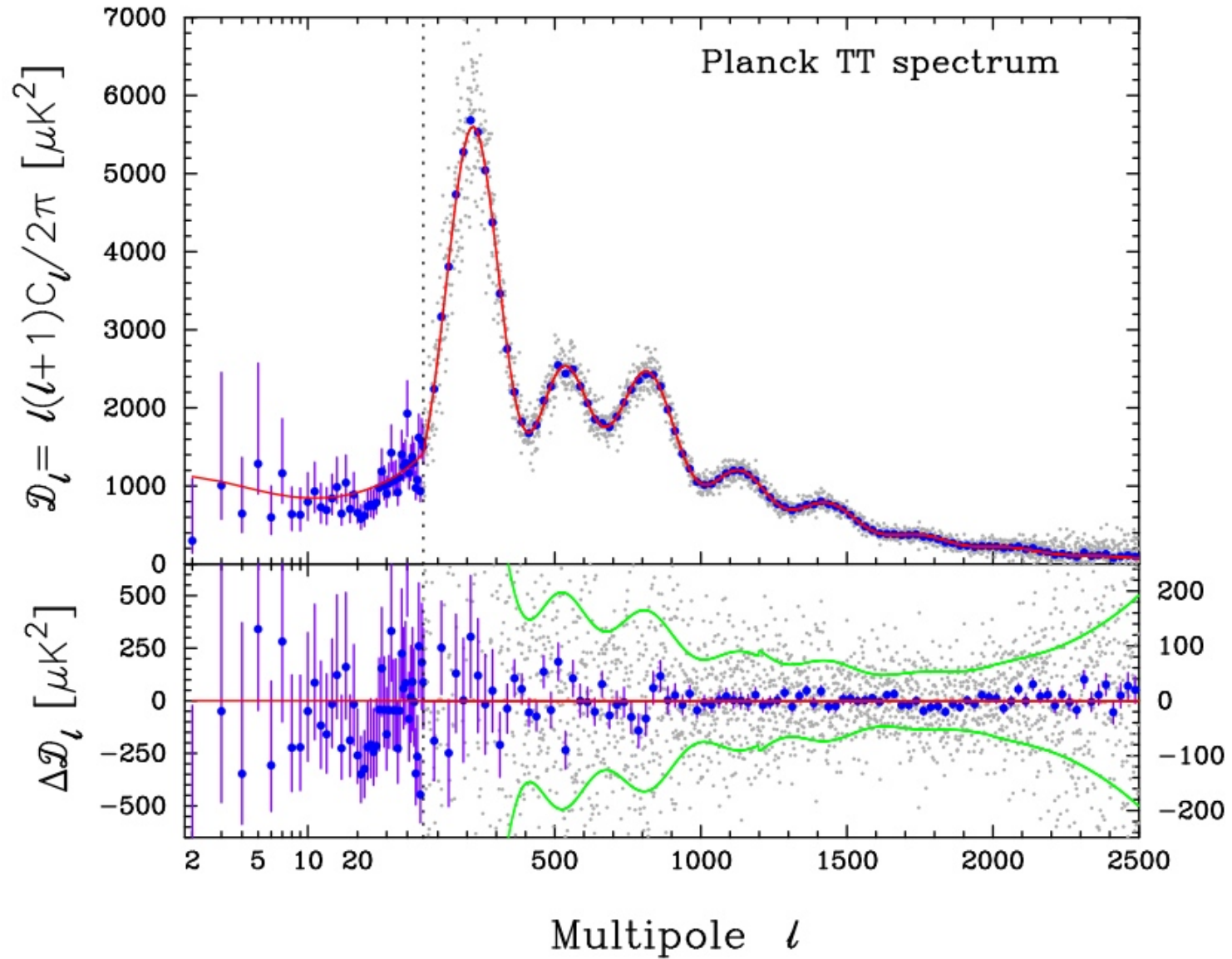
The Cosmic Tonal Ladder

The WMAP CMB temperature power spectrum



The Cosmic Microwave Background Temperature Anisotropies:
Universe is almost perfectly FLAT !!!!

CMB - Fluctuations



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.

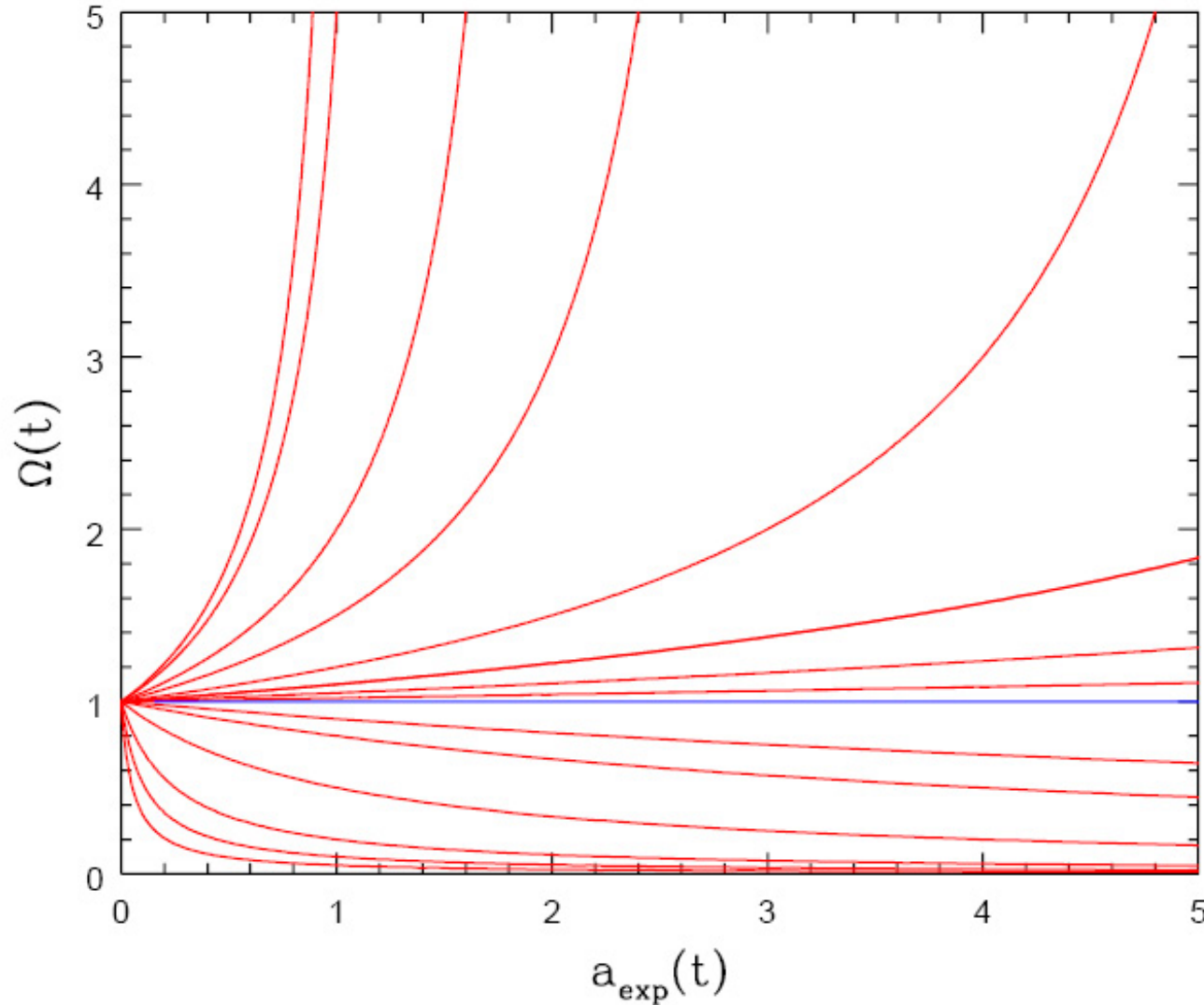
Reversely, that means that any small deviation from flatness in the early Universe would have been strongly amplified nowadays ...

We would therefore expect to live in a Universe that would either be almost $\Omega=0$ or $\Omega\sim\infty$;

Yet, we find ourselves to live in a Universe that is almost perfectly flat ... $\Omega_{\text{tot}}\sim 1$

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

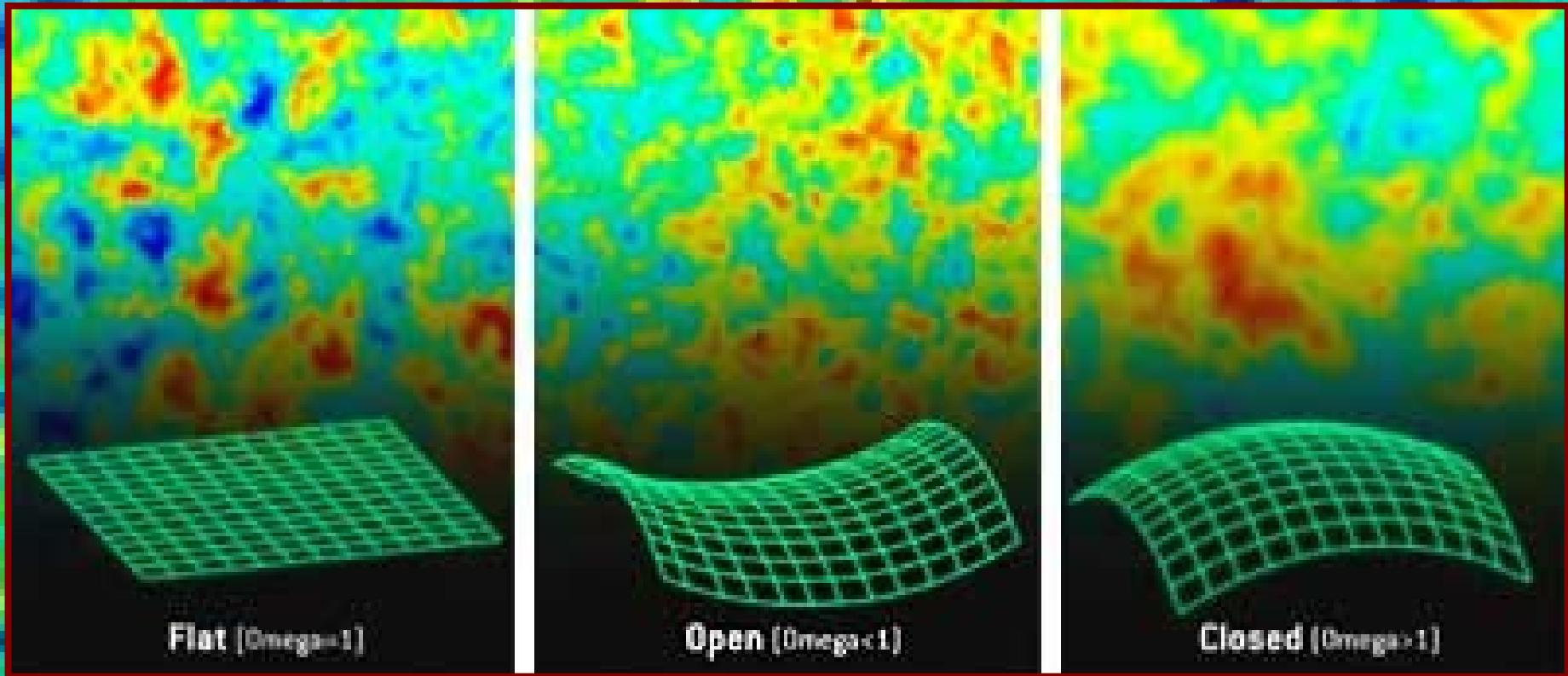
$$a_{nuc} \sim 3.6 \times 10^{-8}$$

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

- Planck time

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

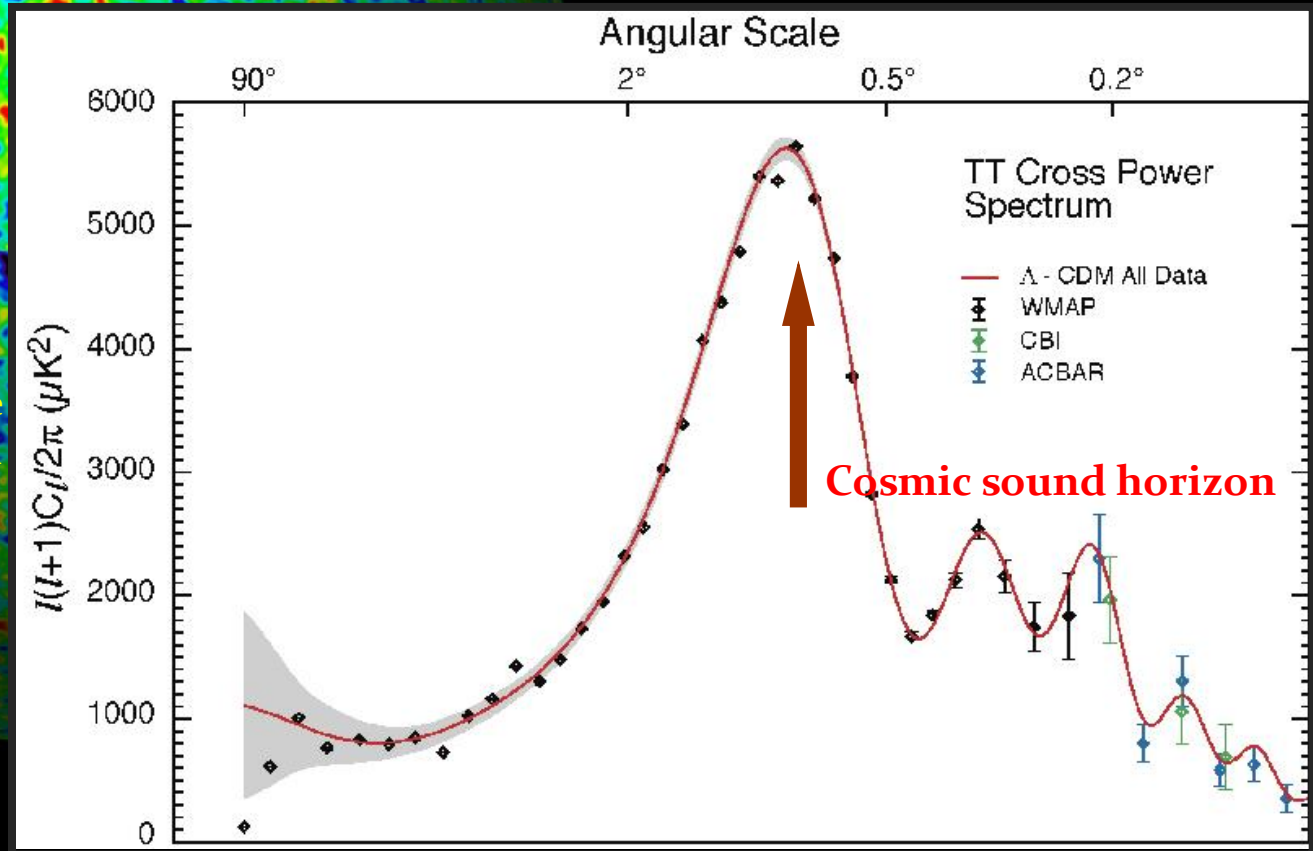
Angular CMB temperature fluctuations



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

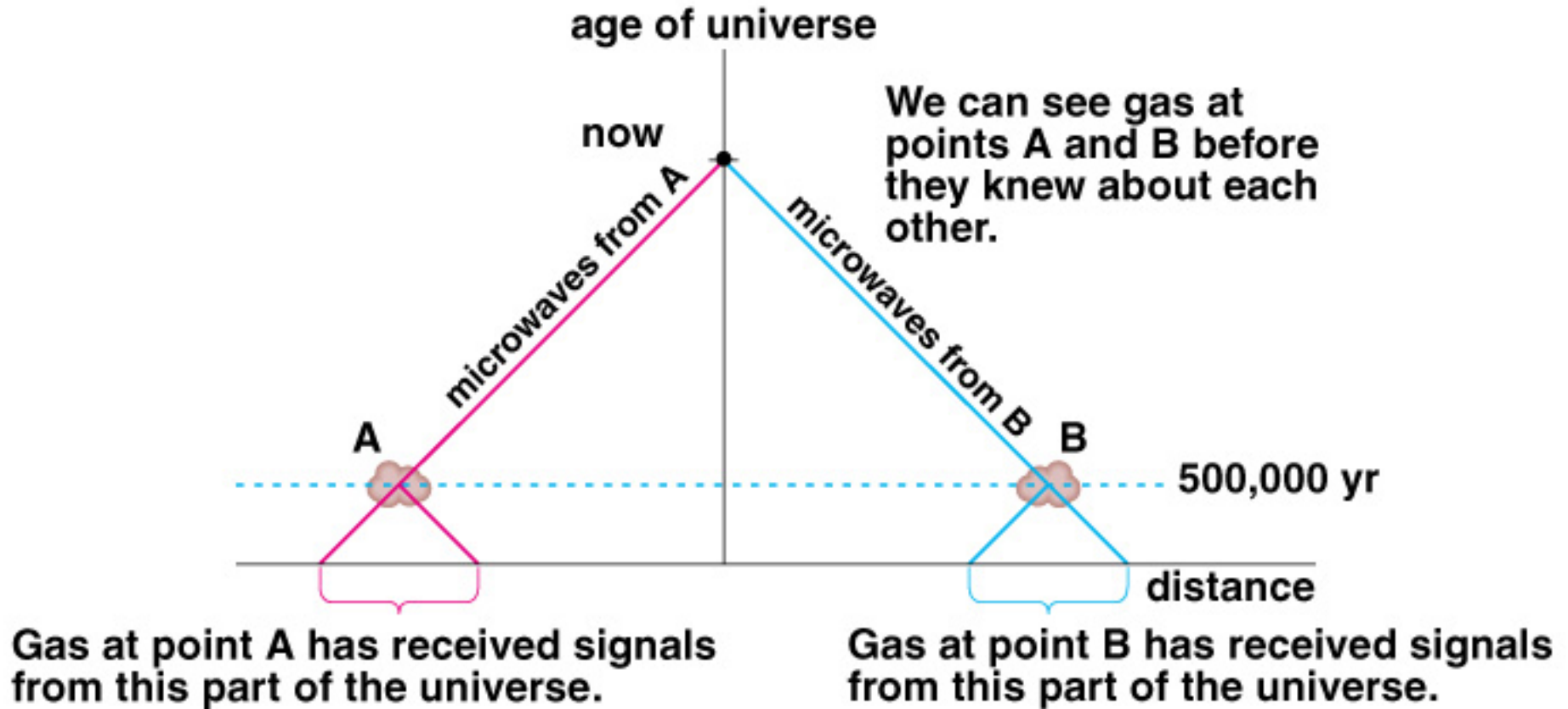
Cosmic Horizons

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



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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:

$$R_{Hor} = 3ct$$



$$\theta \gg 1^\circ$$

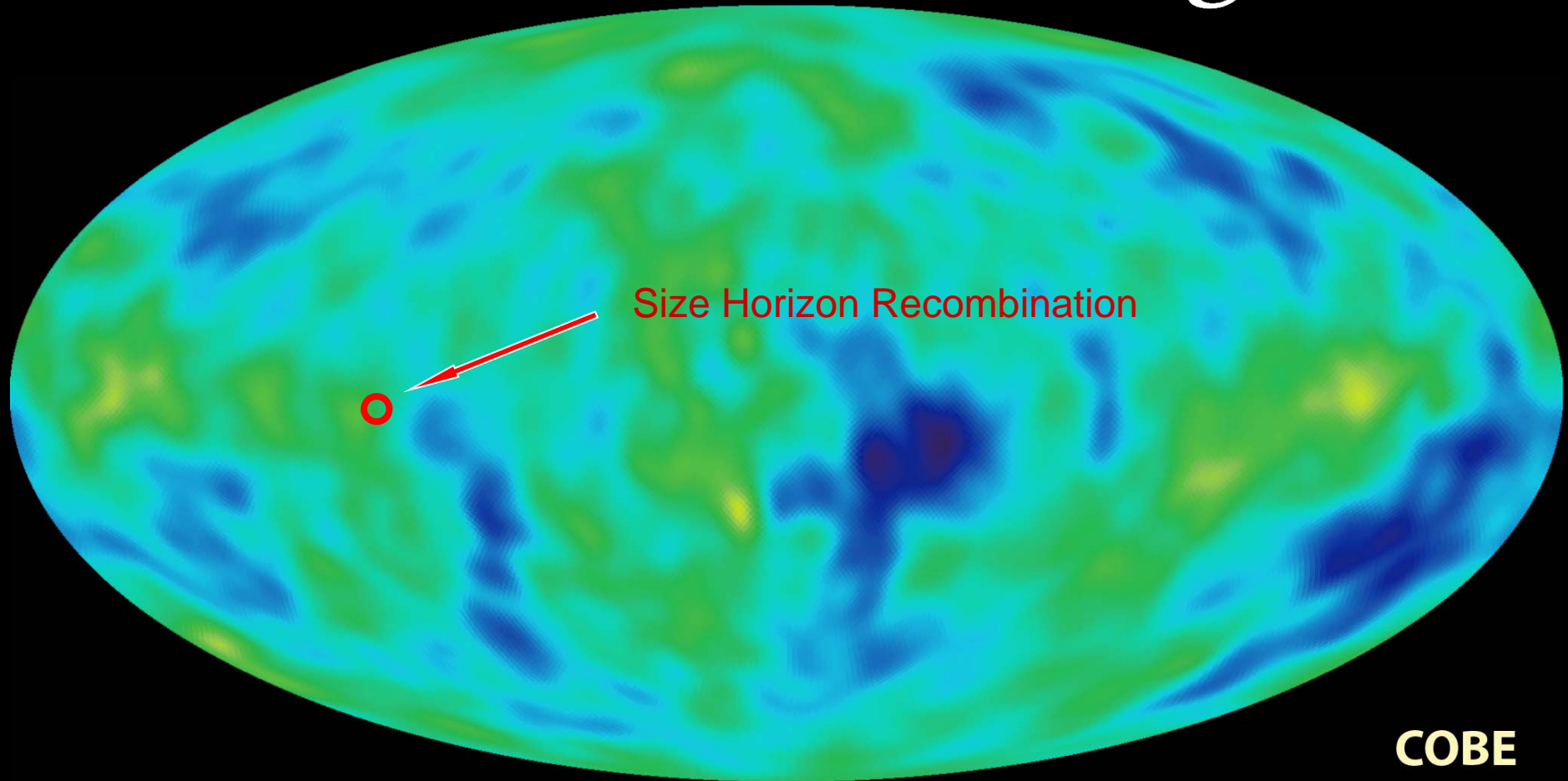
Large angular scales:
NOT in physical contact

$$\theta \ll 1^\circ$$

Small angular scales:
In physical (thus, also thermal) contact

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

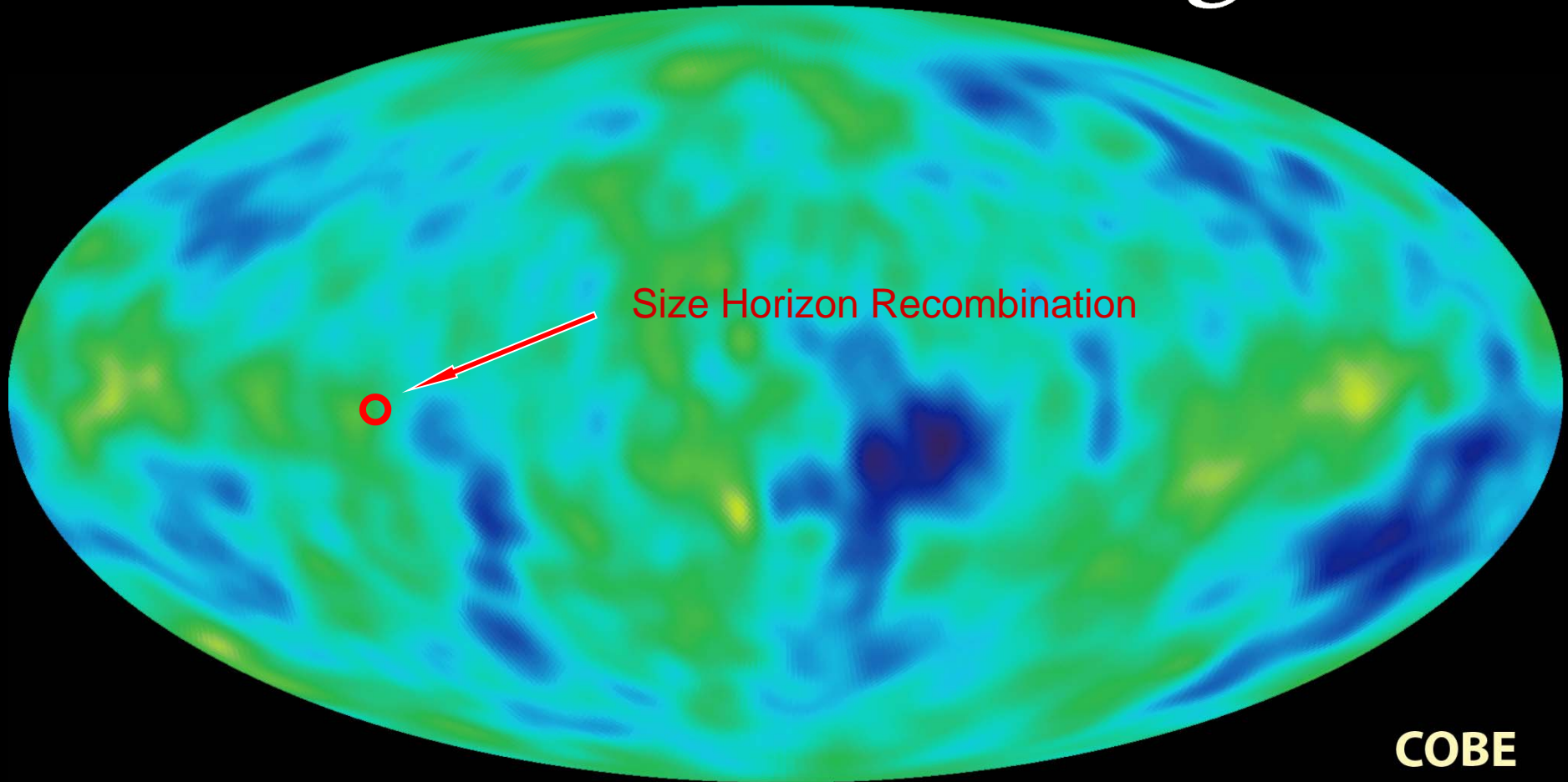
Cosmic Microwave Background



COBE measured fluctuations: $> 7^\circ$
Size Horizon at Recombination spans angle $\sim 1^\circ$

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

Cosmic Microwave Background



COBE measured fluctuations: $> 7^\circ$
Size Horizon at Recombination spans angle $\sim 1^\circ$

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

Structure Problem



Primordial Noise:
Seeds of
Cosmic Structure

Universe at
379000 years:

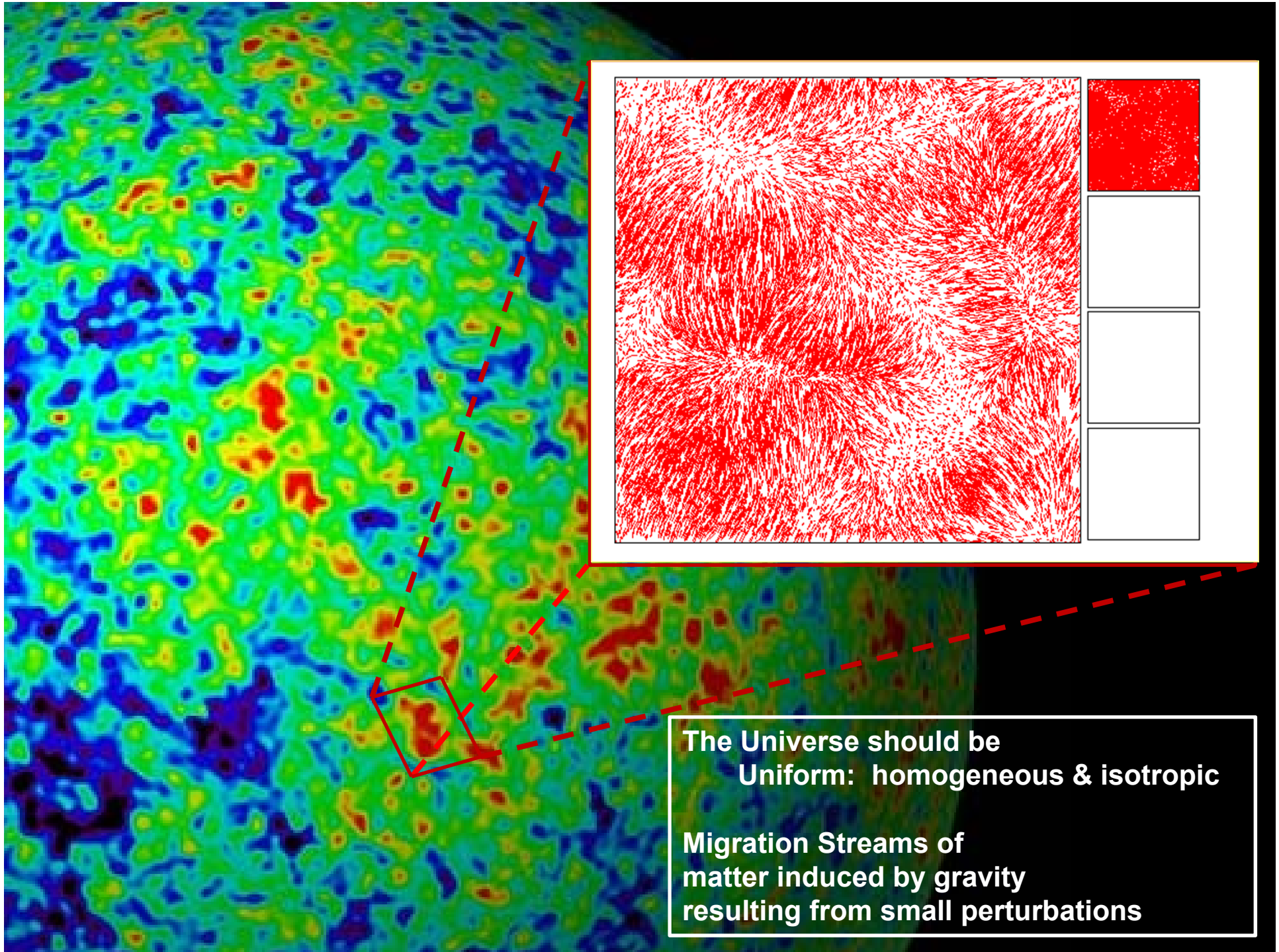
almost featureless

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



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

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



**The Universe should be
Uniform: homogeneous & isotropic**

**Migration Streams of
matter induced by gravity
resulting from small perturbations**

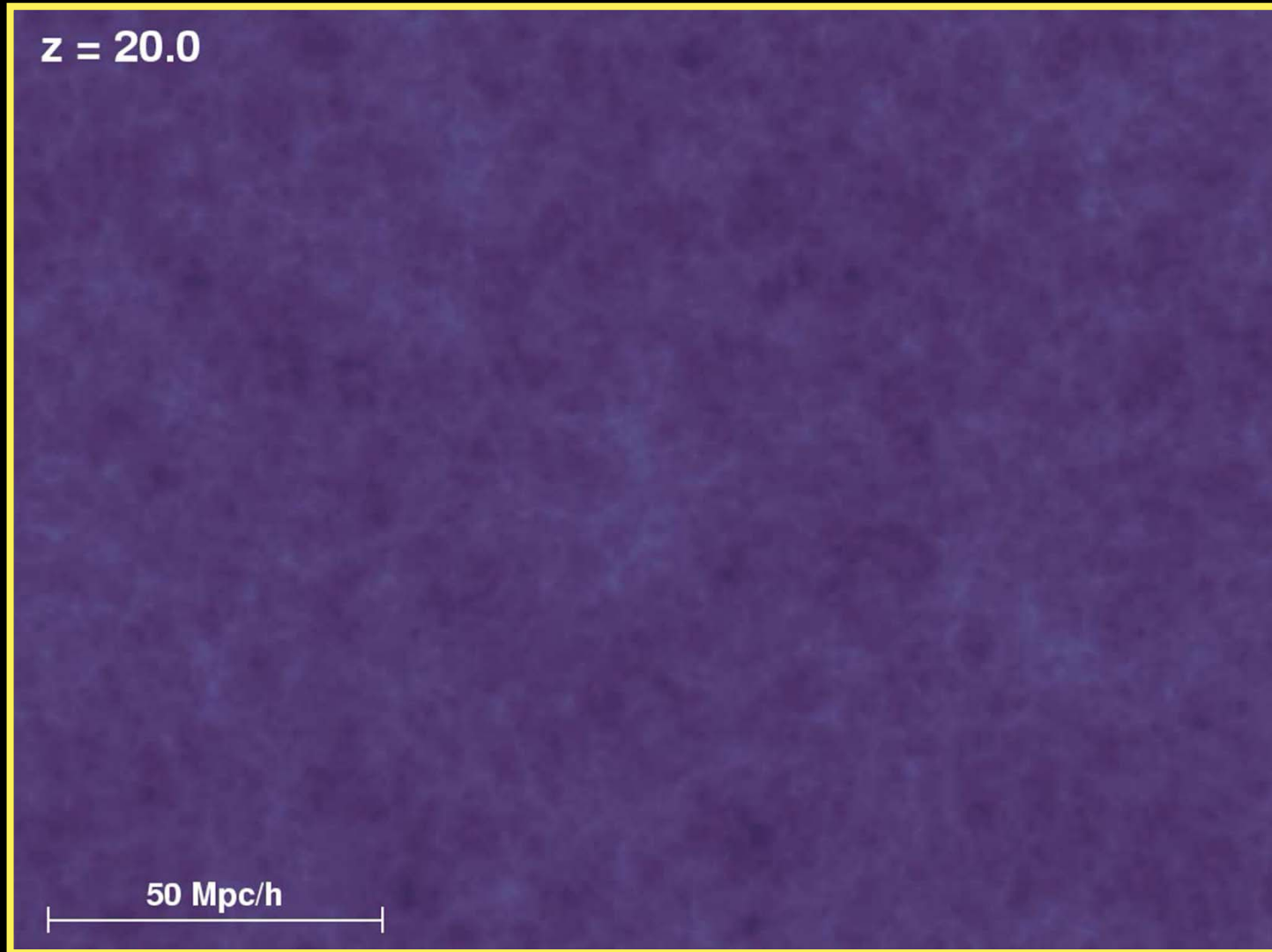
Cosmic Structure Formation

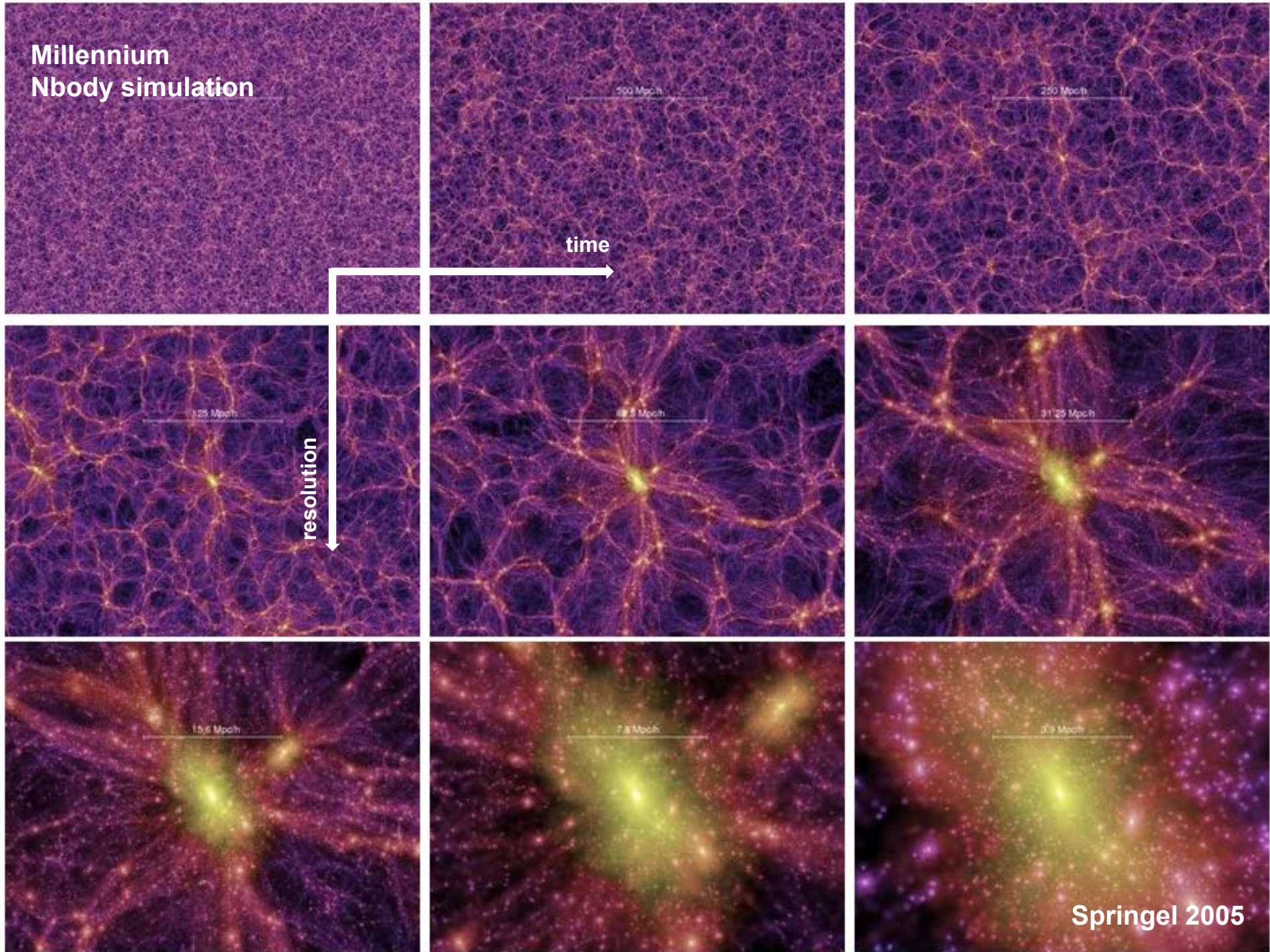
**Formation
Cosmic Web:

simulation
sequence

(cold)
dark matter**

(courtesy:
Virgo/V. Springel).





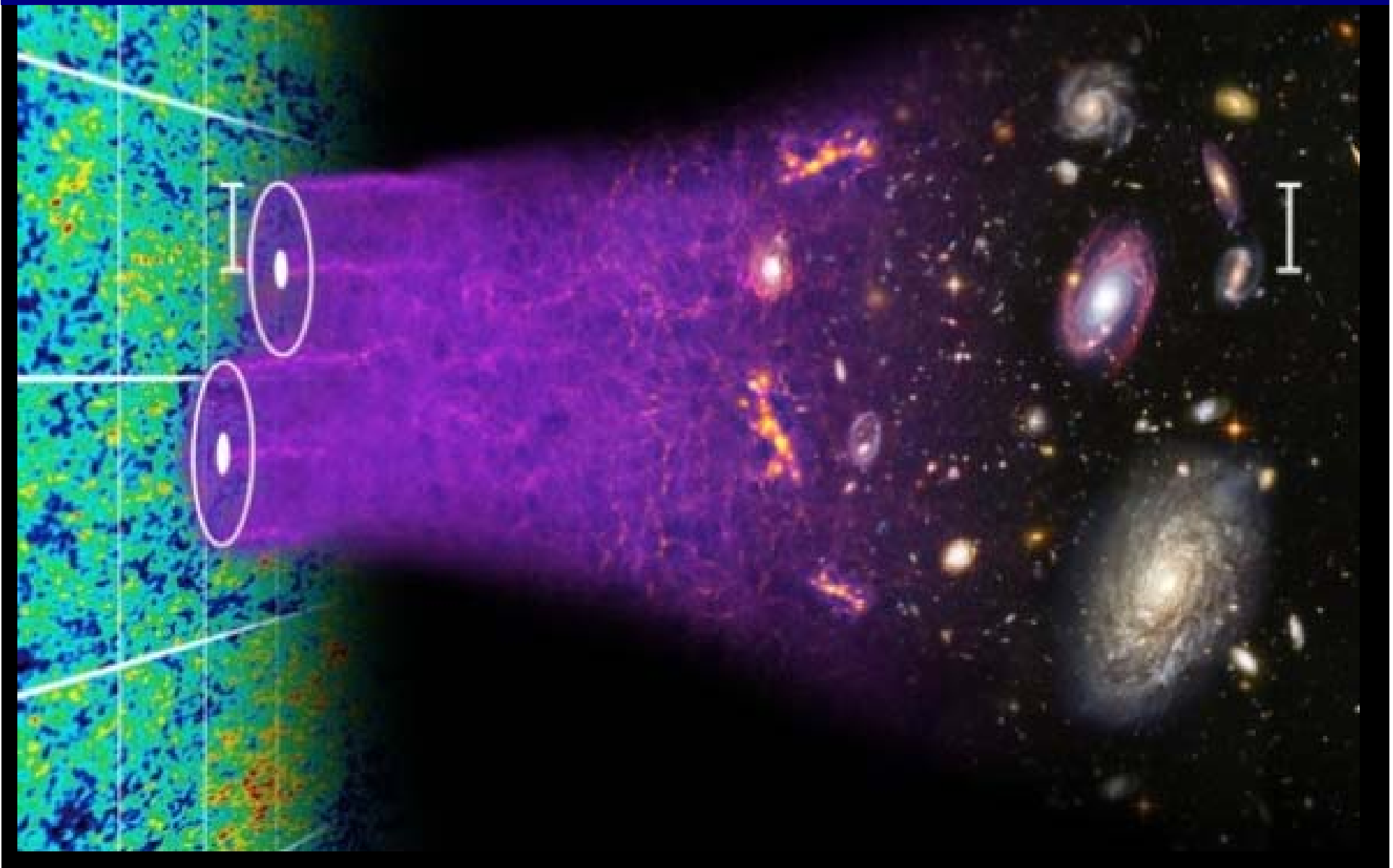
A visualization of the Cosmic Web from the Illustris simulation. The image shows a complex network of filaments and nodes. The filaments are colored in a gradient from blue on the left to orange and red on the right. The nodes, where filaments intersect, are highlighted with bright, multi-colored spots (purple, green, yellow, and orange). The overall structure is dense and interconnected, representing the large-scale structure of the universe.

Illustris Simulation:

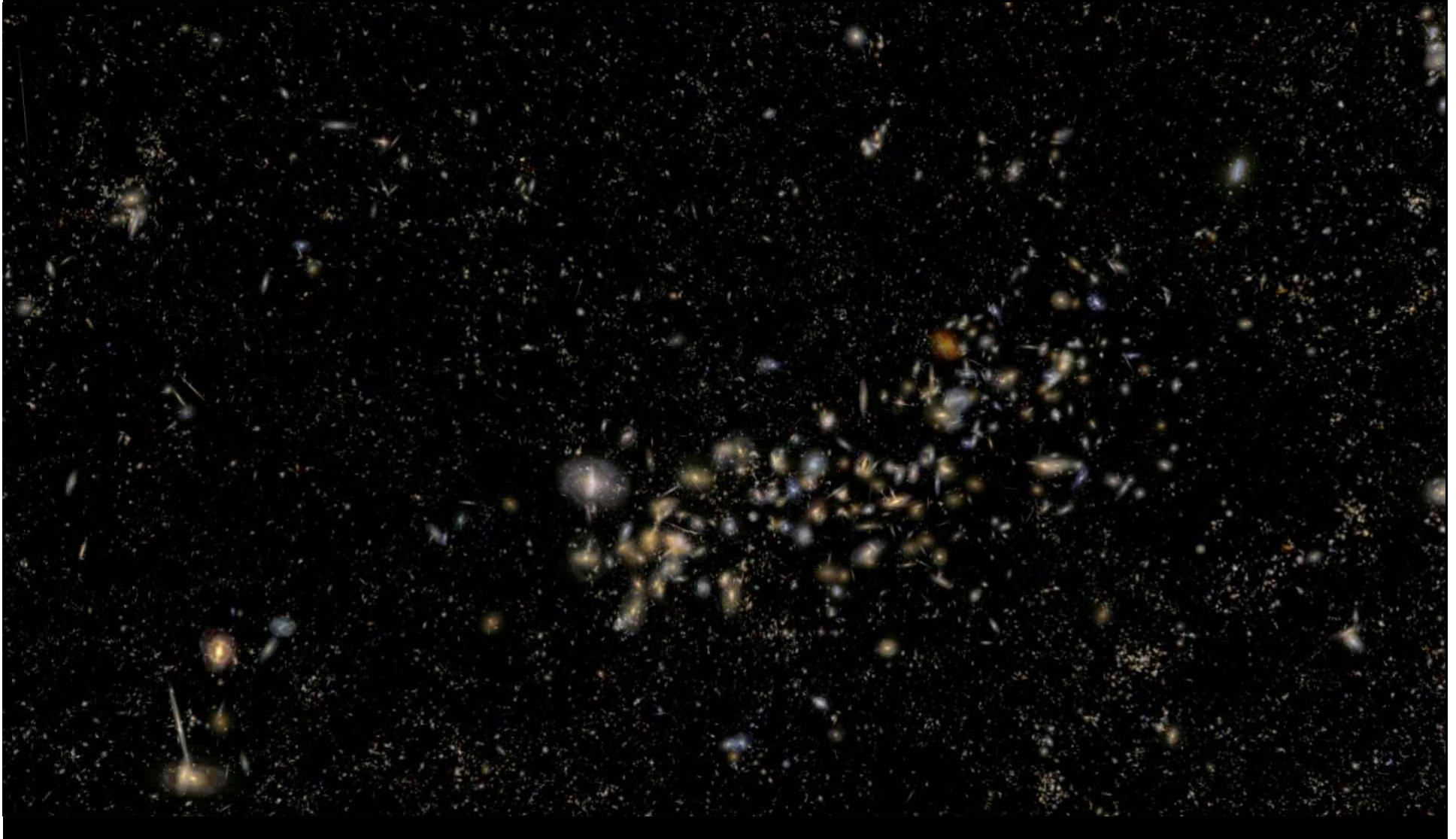
Cosmic Web

Dark Matter - Gas - Galaxies

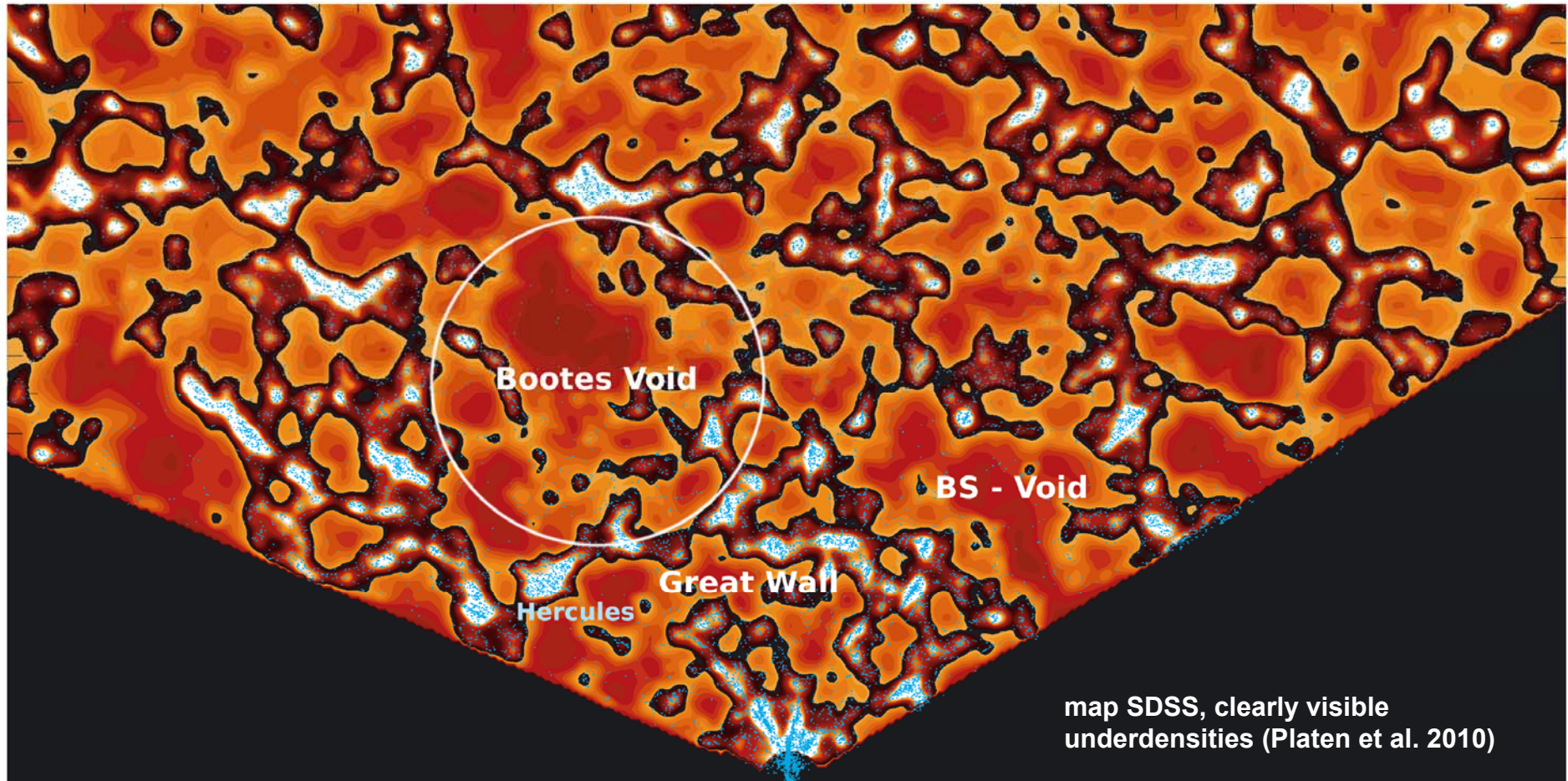
Formation Cosmic Structures



Universe at 13.8 Gyrs: rich & complex structure

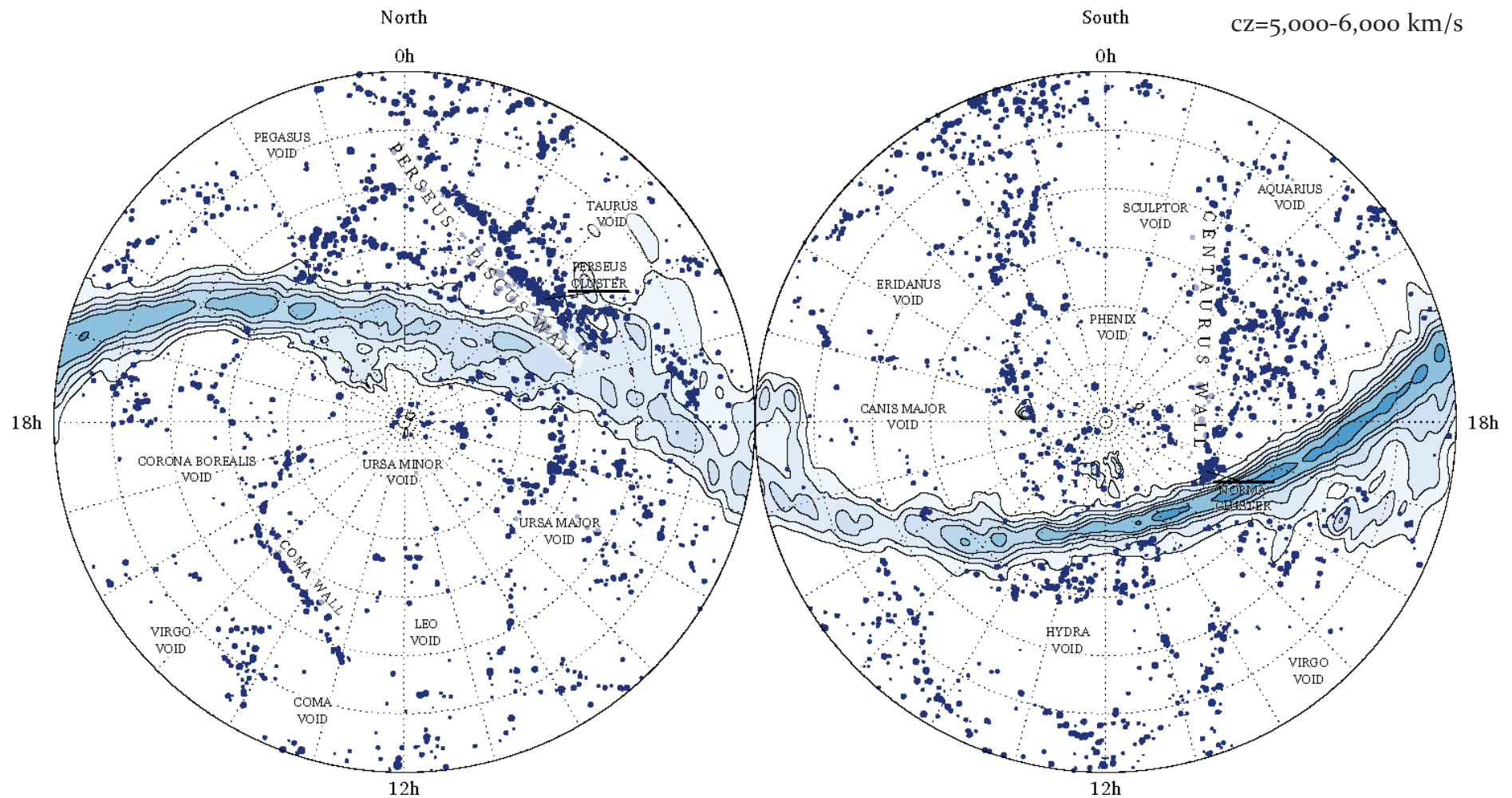


SDSS Galaxy Survey



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

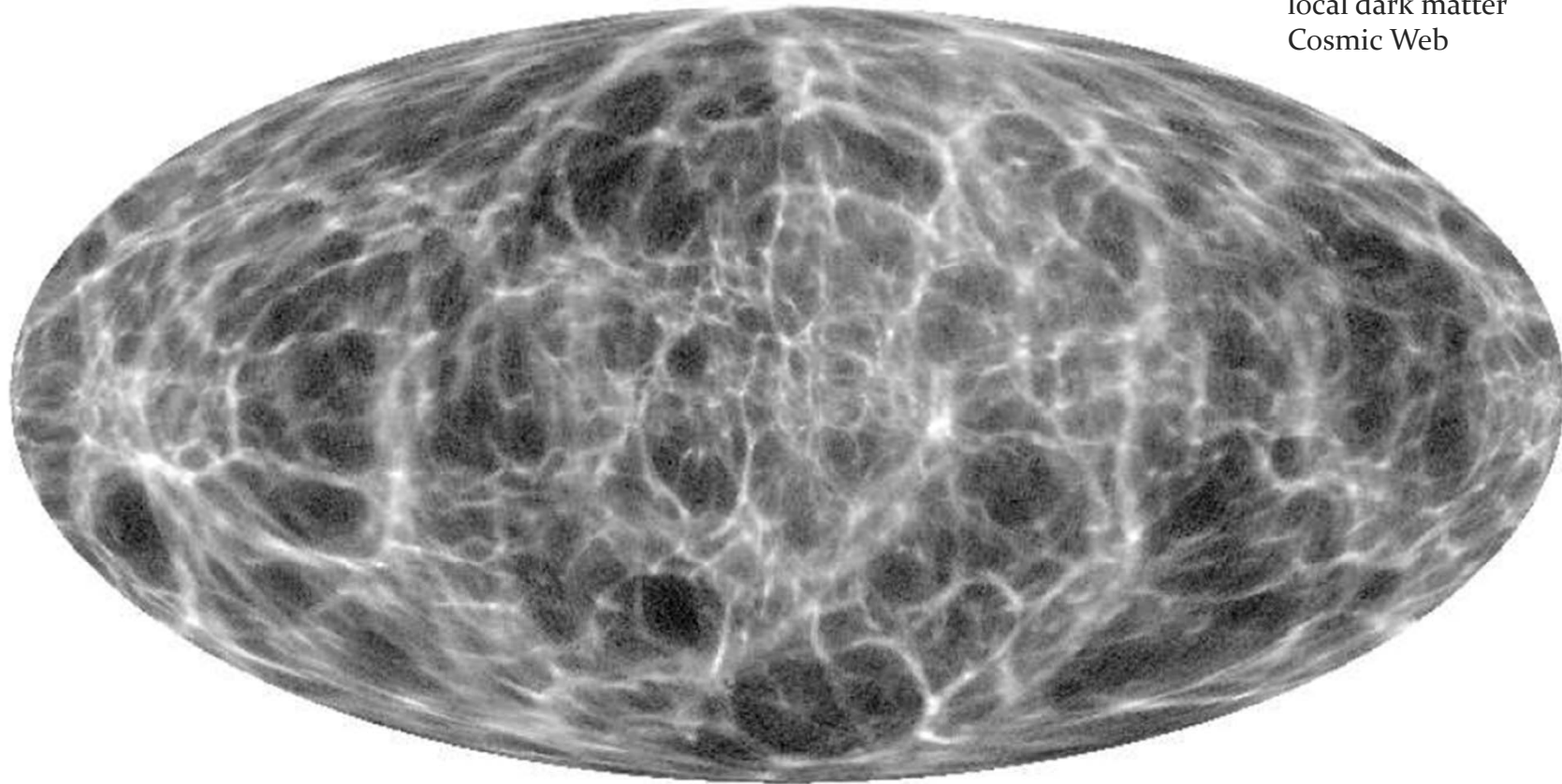


Courtesy: Johan Hidding

local Cosmic Web: z MRS

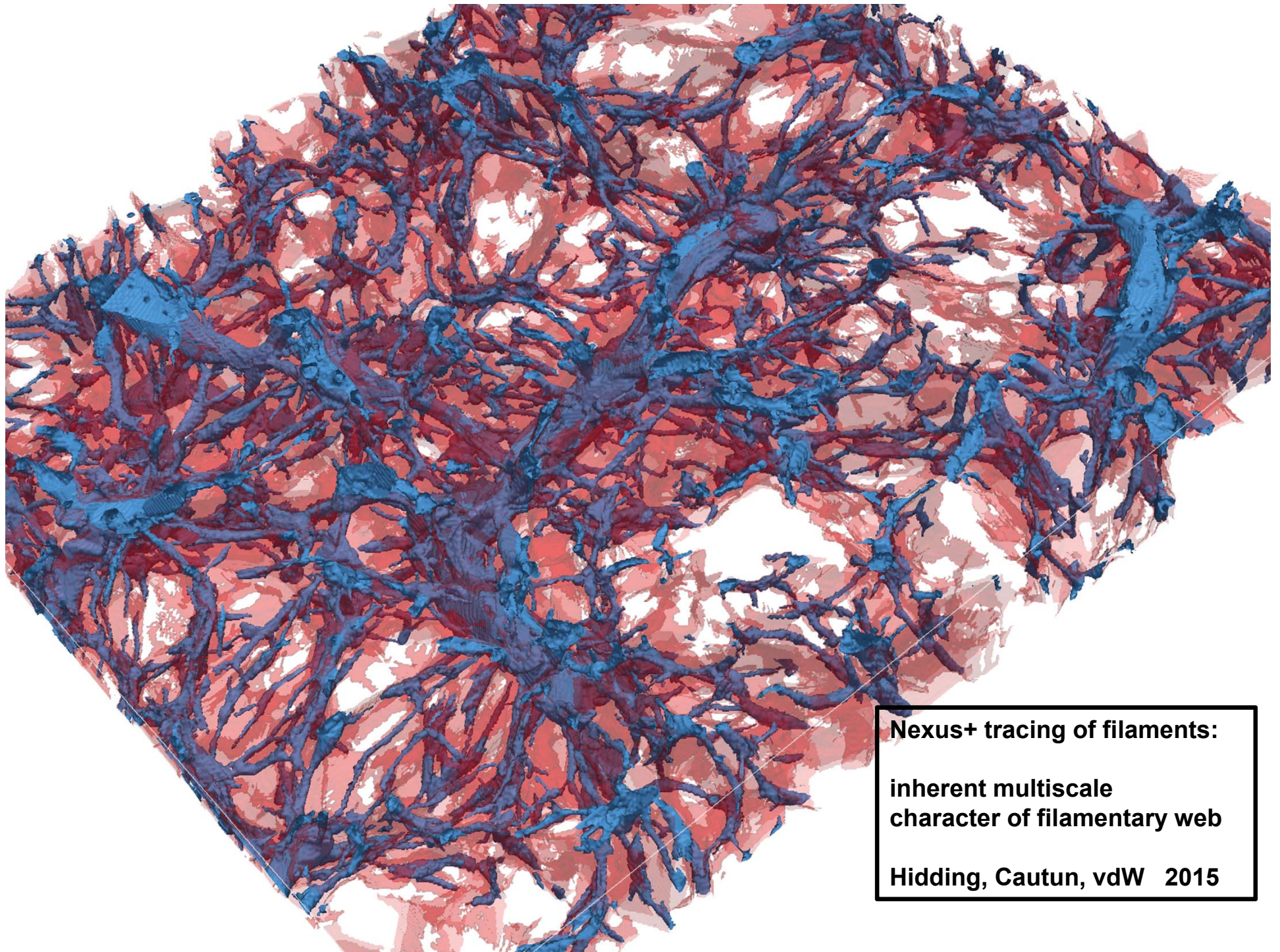
most detailed reconstruction
of the

local dark matter
Cosmic Web



1.0  6.0

Courtesy: Francisco Kitaura



Nexus+ tracing of filaments:

**inherent multiscale
character of filamentary web**

Hidding, Cautun, vdW 2015

Horizon Problem

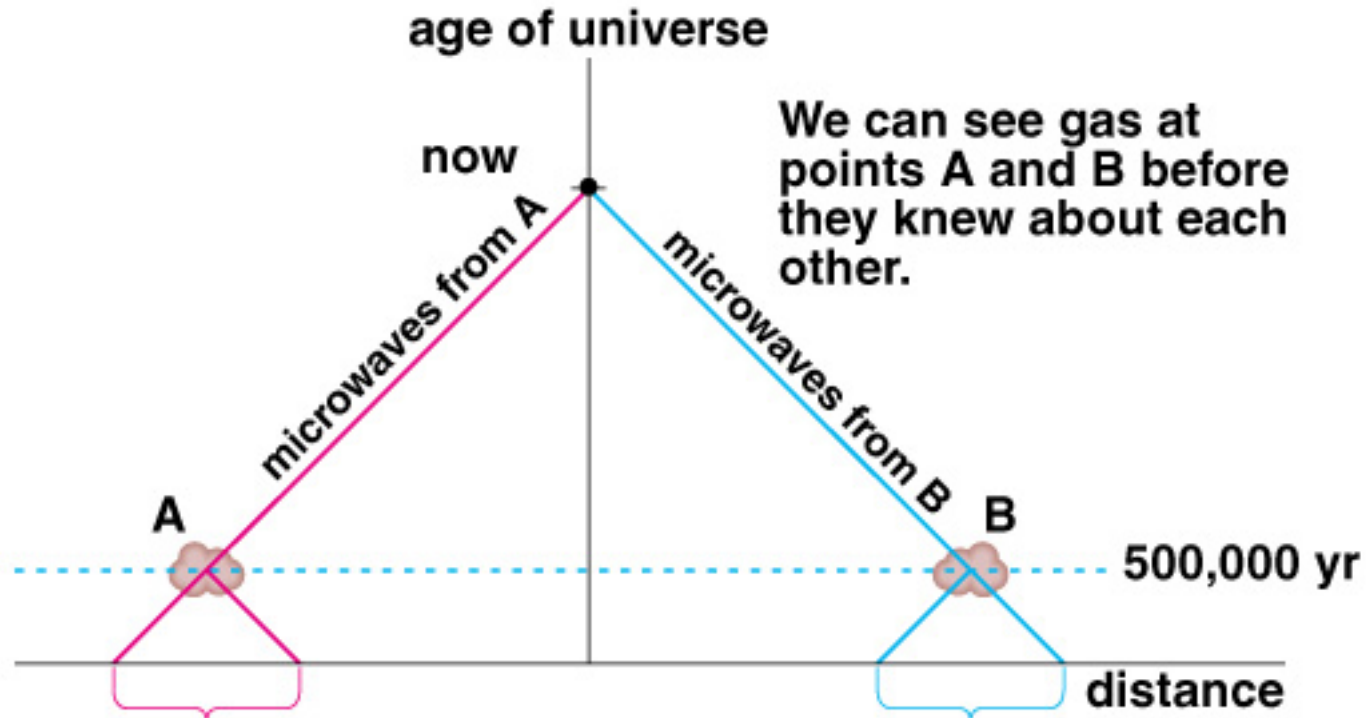
Cosmic Horizons

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Horizon of the Universe

Cosmic Horizon



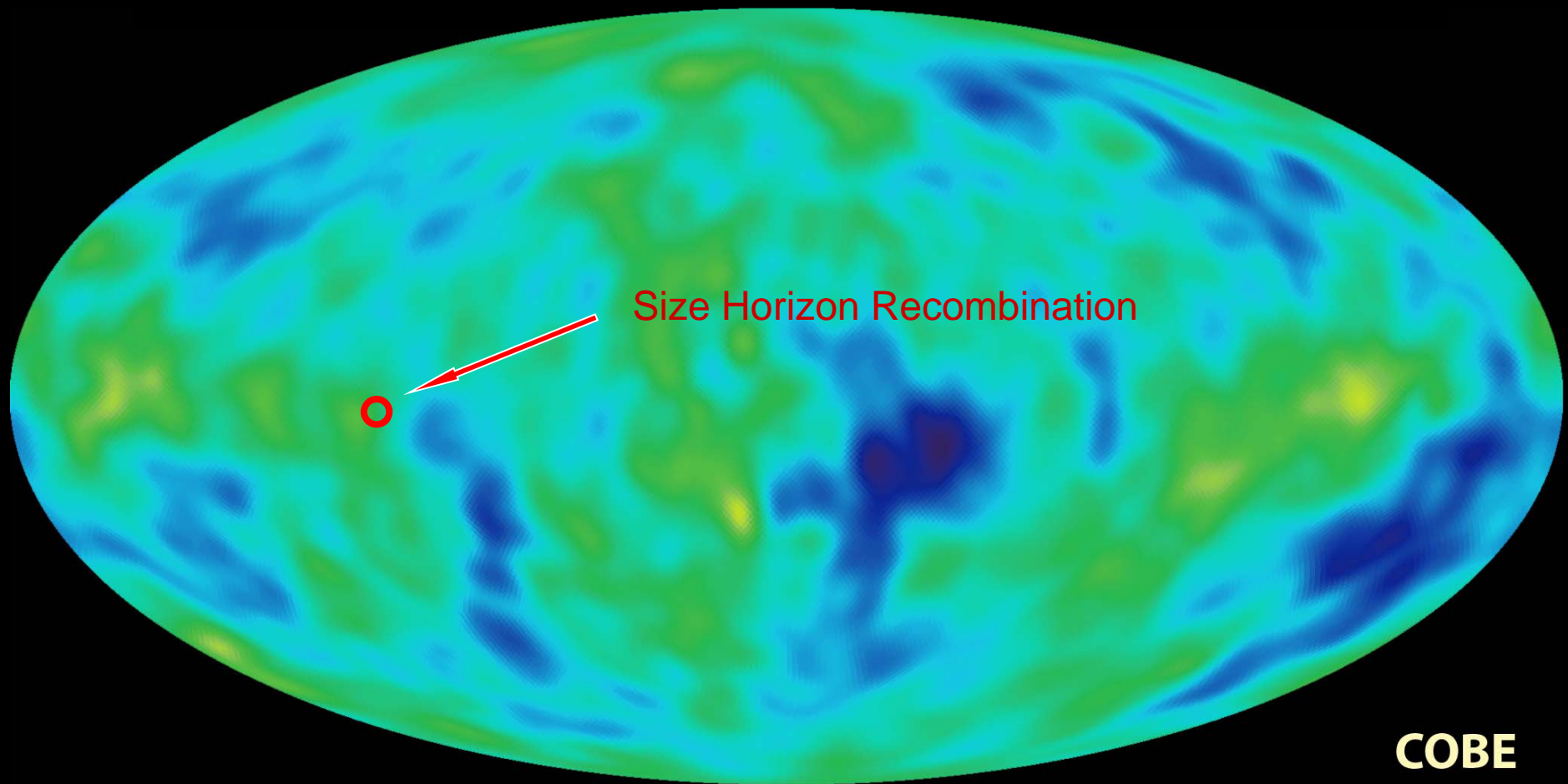
Gas at point A has received signals from this part of the universe.

Gas at point B has received signals from this part of the universe.

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

Probleem van Kosmische Horizon



COBE metingen CMB temperatuur fluctuaties: $> 7^\circ$
Schaal Horizon Zichtbare Heelal 379000 jr. na Big Bang: $\sim 1^\circ$

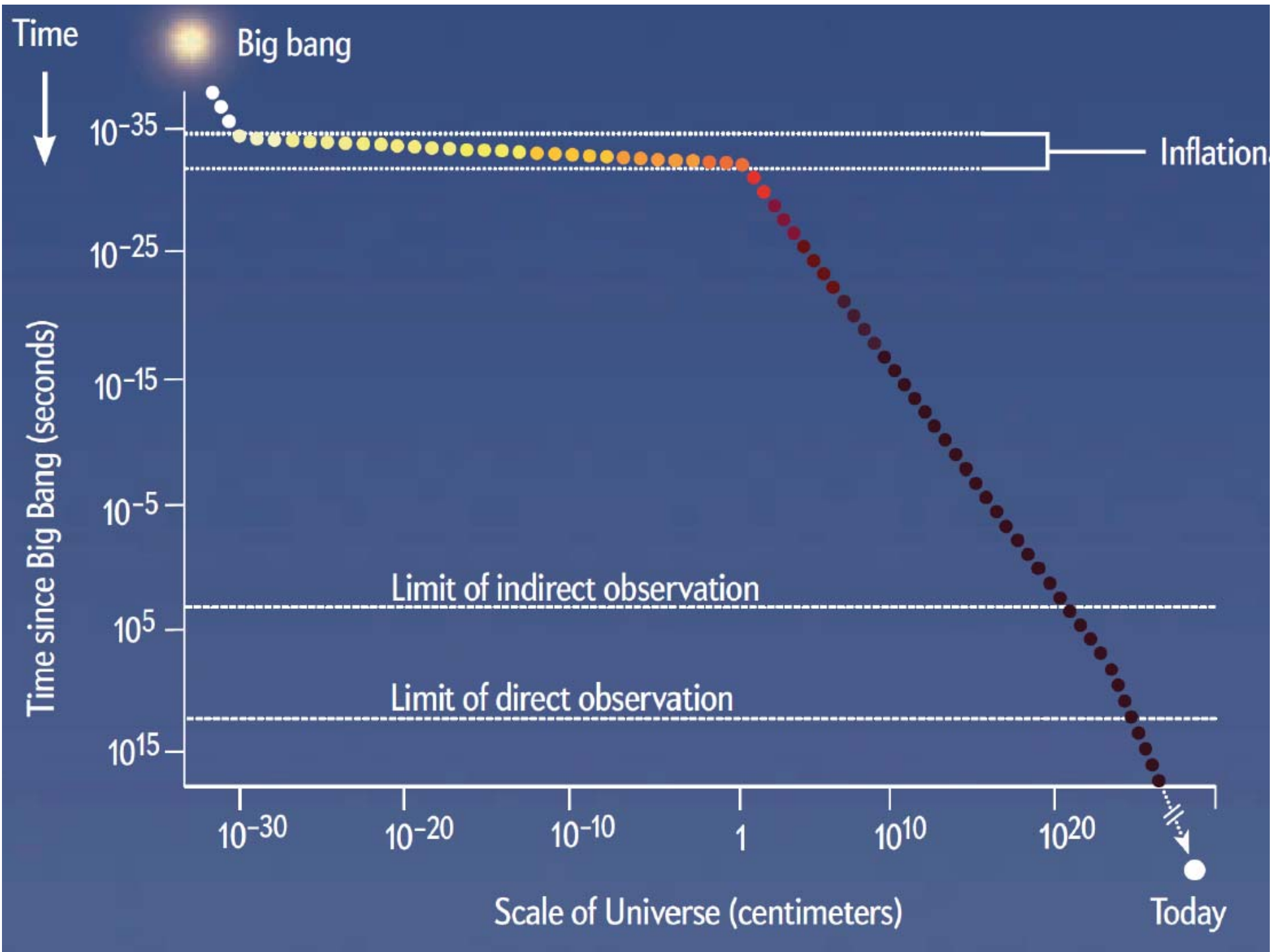
Temperatuur hetzelfde over gehele hemel,
maar hoe kan dat zonder ooit in thermisch contact te zijn geweest?

INFLATION

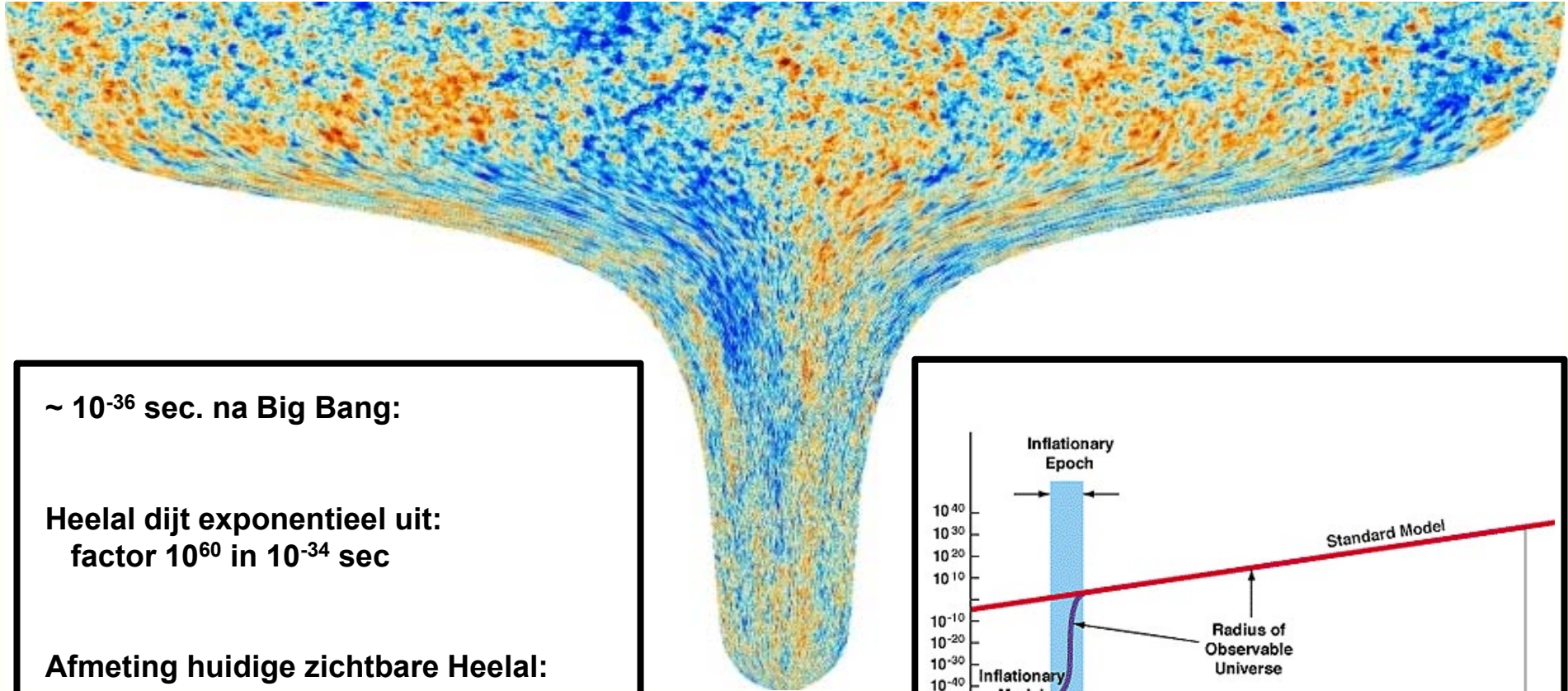


10^{-36} sec
after Big Bang:

Inflation of the Universe



Kosmische Inflatie

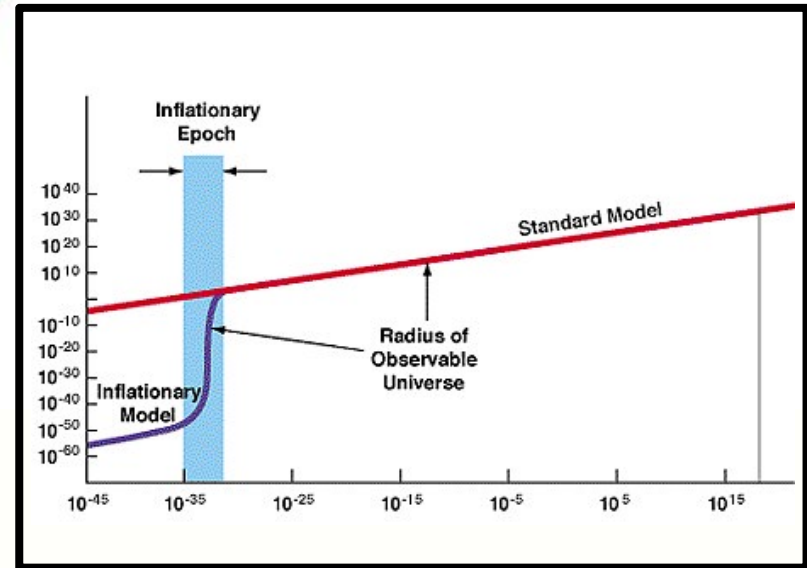


~ 10^{-36} sec. na Big Bang:

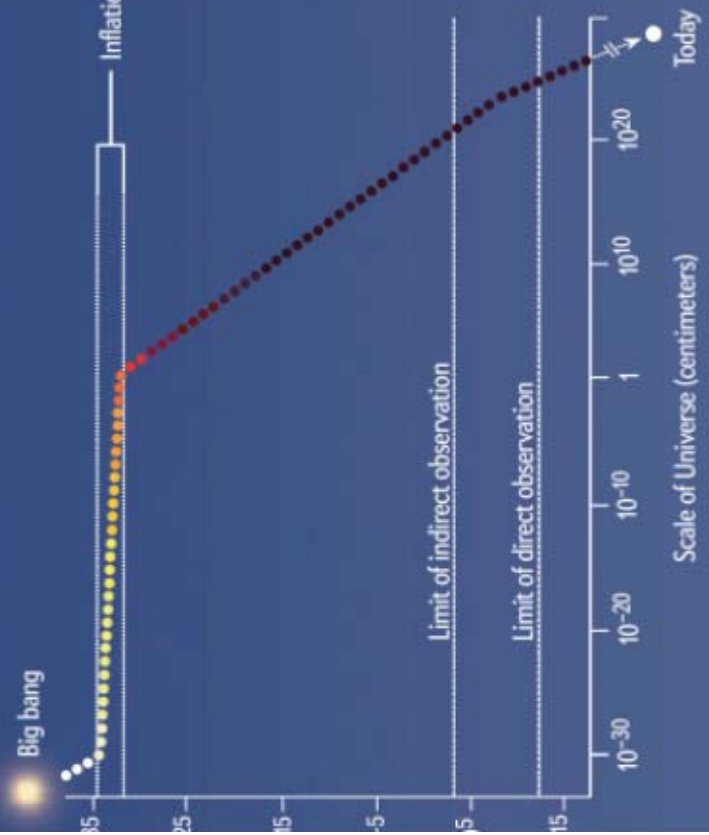
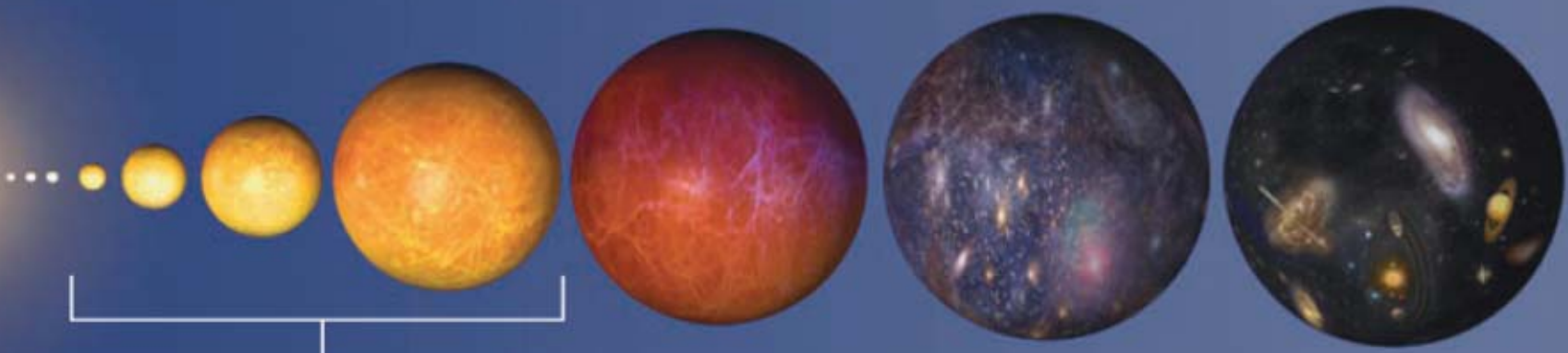
Heelal dijt exponentieel uit:
factor 10^{60} in 10^{-34} sec

Afmeting huidige zichtbare Heelal:

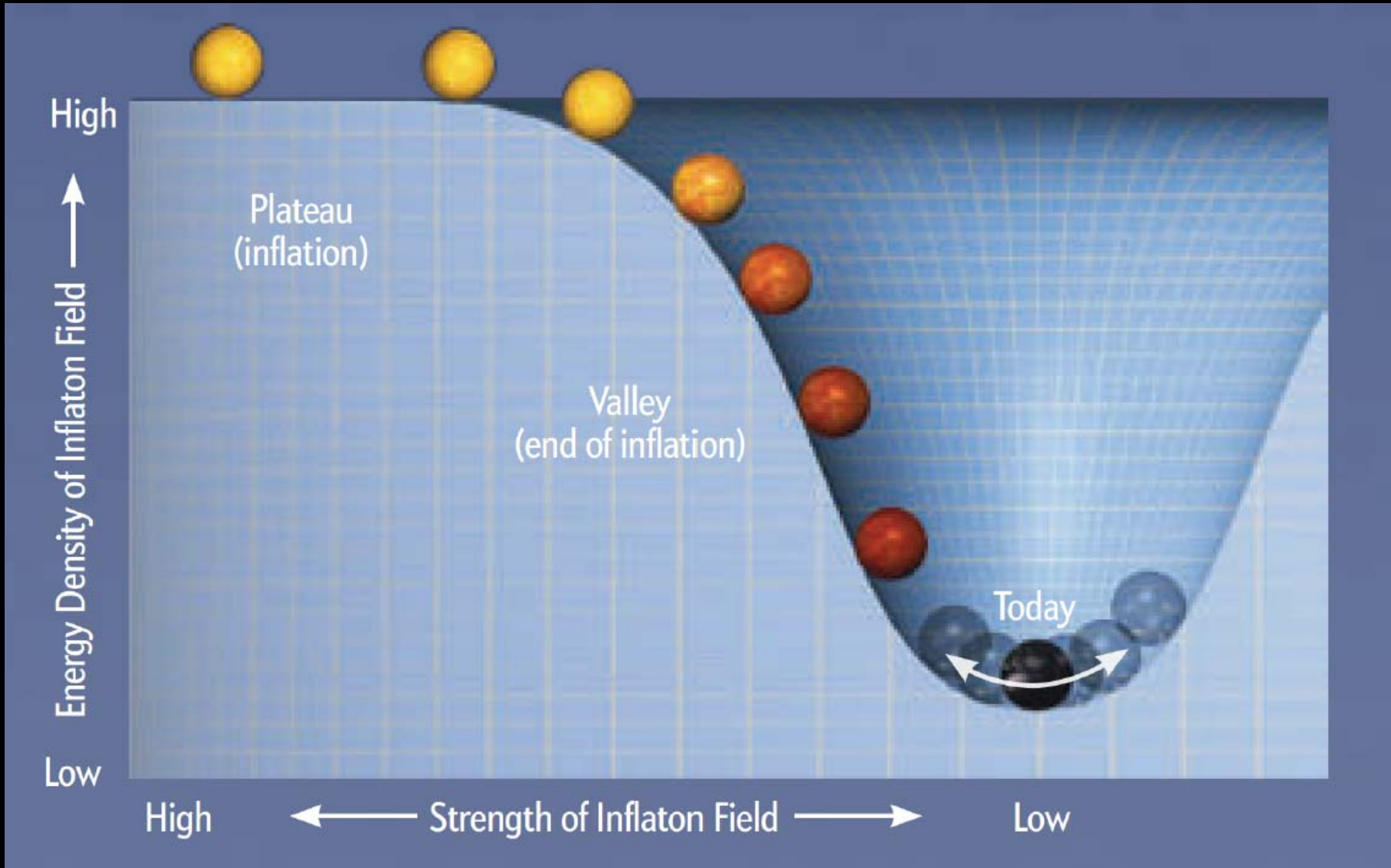
begin inflatie: 10^{-15} afmeting atoom
eind inflatie: diameter van stuiver



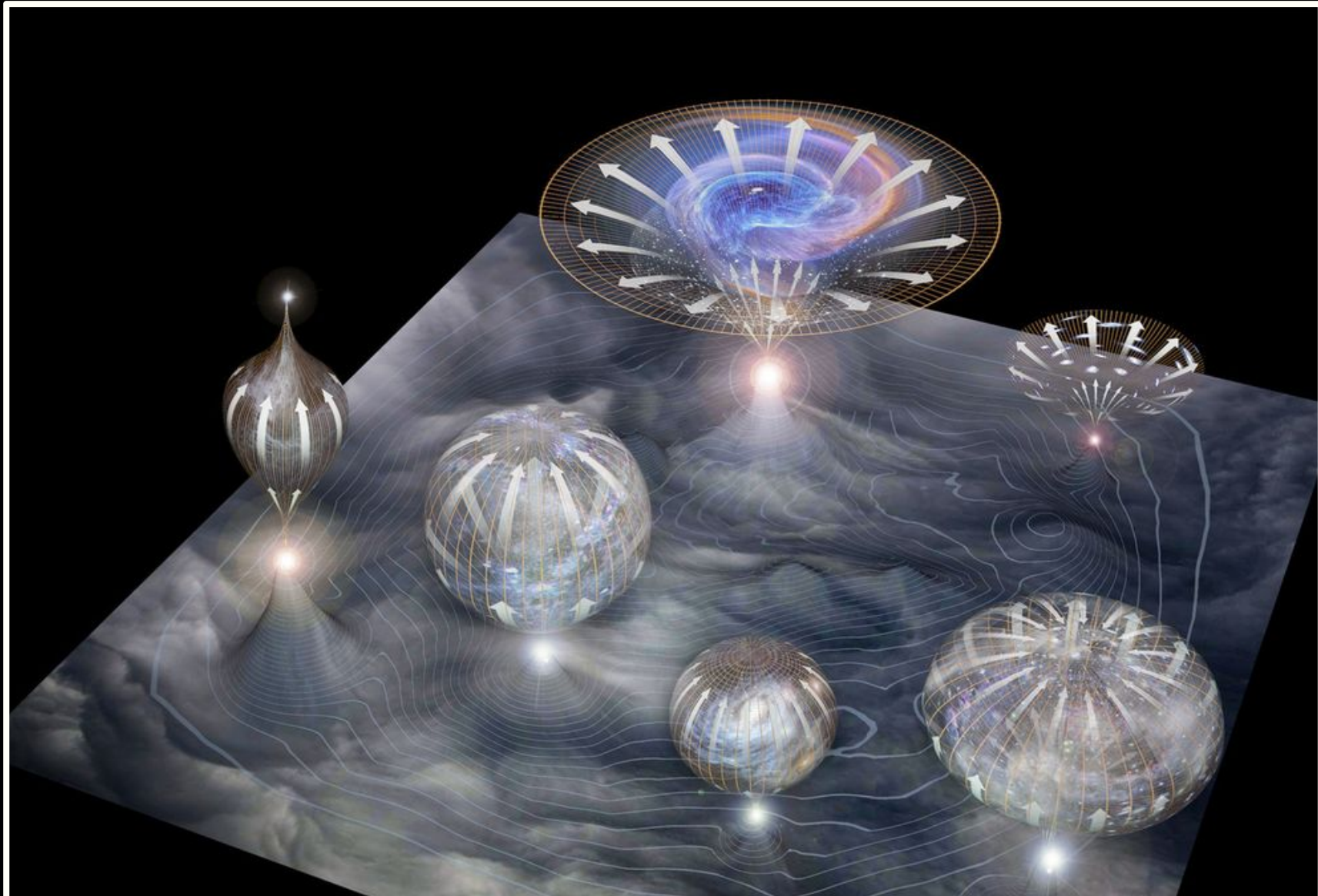
Time →



Propelling Inflation: Inflaton



Inflatie & Multiverse



Cosmic Future

Cosmic Fate

100 Gigayears: the end of Cosmology

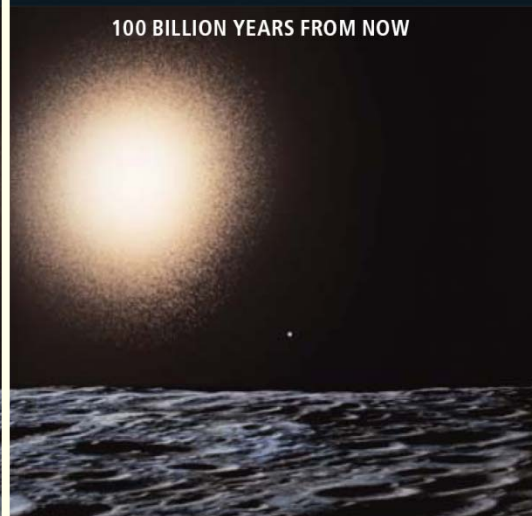
The night sky on Earth (assuming it survives) will change dramatically as our Milky Way galaxy merges with its neighbors and distant galaxies recede beyond view.



DIFFUSE BAND stretching across the sky is the disk of the Milky Way. A few nearby galaxies, such as Andromeda and the Magellanic Clouds, are visible to the naked eye. Telescopes reveal billions more.



ANDROMEDA has been moving toward us and now nearly fills the sky. The sun swells to red giant size and subsequently burns out, consigning Earth to a bleak existence.



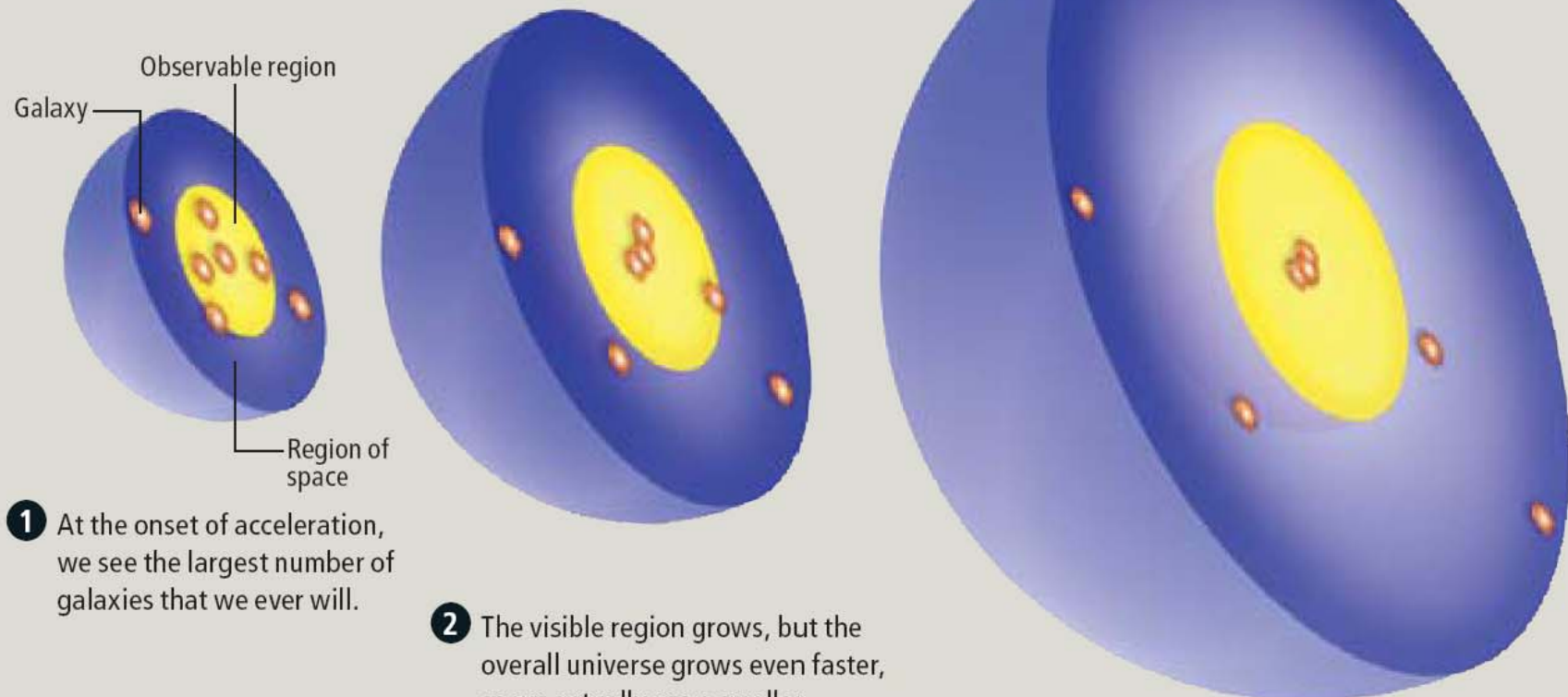
SUCCESSOR to the Milky Way is a ball-like supergalaxy, and Earth may float forlornly through its distant outskirts. Other galaxies have disappeared from view.



LIGHTS OUT: The last stars burn out. Apart from dimly glowing black holes and any artificial lighting that civilizations have rigged up, the universe goes black. The galaxy later collapses into a black hole.

EXPANDING UNIVERSE, SHRINKING VIEW

The universe may be infinite, but consider what happens to the patch of space around us (*purple sphere*), of which we see only a part (*yellow inner sphere*). As space expands, galaxies (*orange spots*) spread out. As light has time to propagate, we observers on Earth (or our predecessors or descendants) can see a steadily increasing volume of space. About six billion years ago, the expansion began to accelerate, carrying distant galaxies away from us faster than light.



1 At the onset of acceleration, we see the largest number of galaxies that we ever will.

2 The visible region grows, but the overall universe grows even faster, so we actually see a smaller fraction of what is out there.

3 Distant galaxies (those not bound to us by gravity) move out of our range of view. Meanwhile, gravity pulls nearby galaxies together.

NOTE:

Because space is expanding uniformly, alien beings in other galaxies see this same pattern.