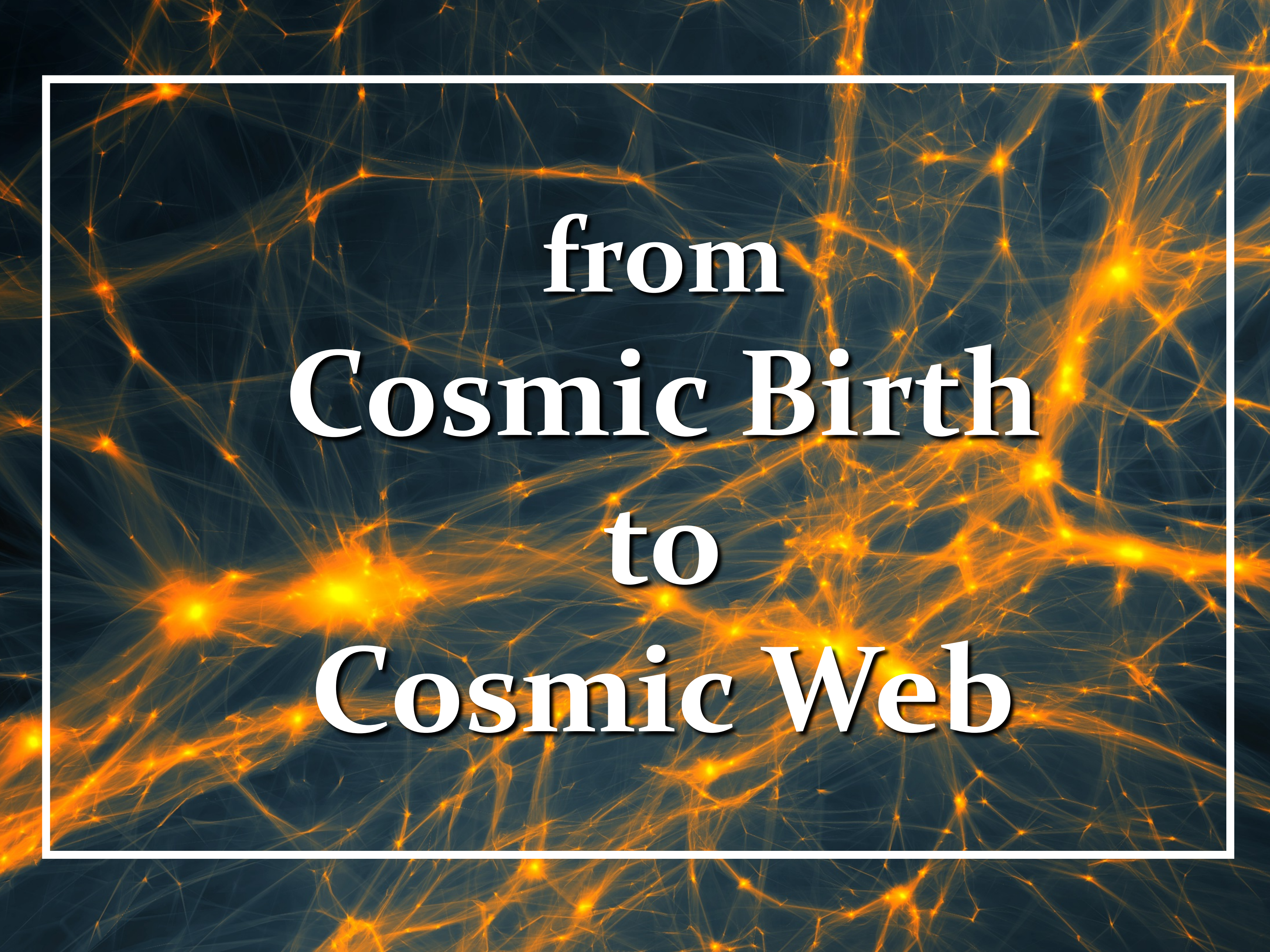


from Cosmic Birth to Cosmic Web

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

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

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

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 !!!

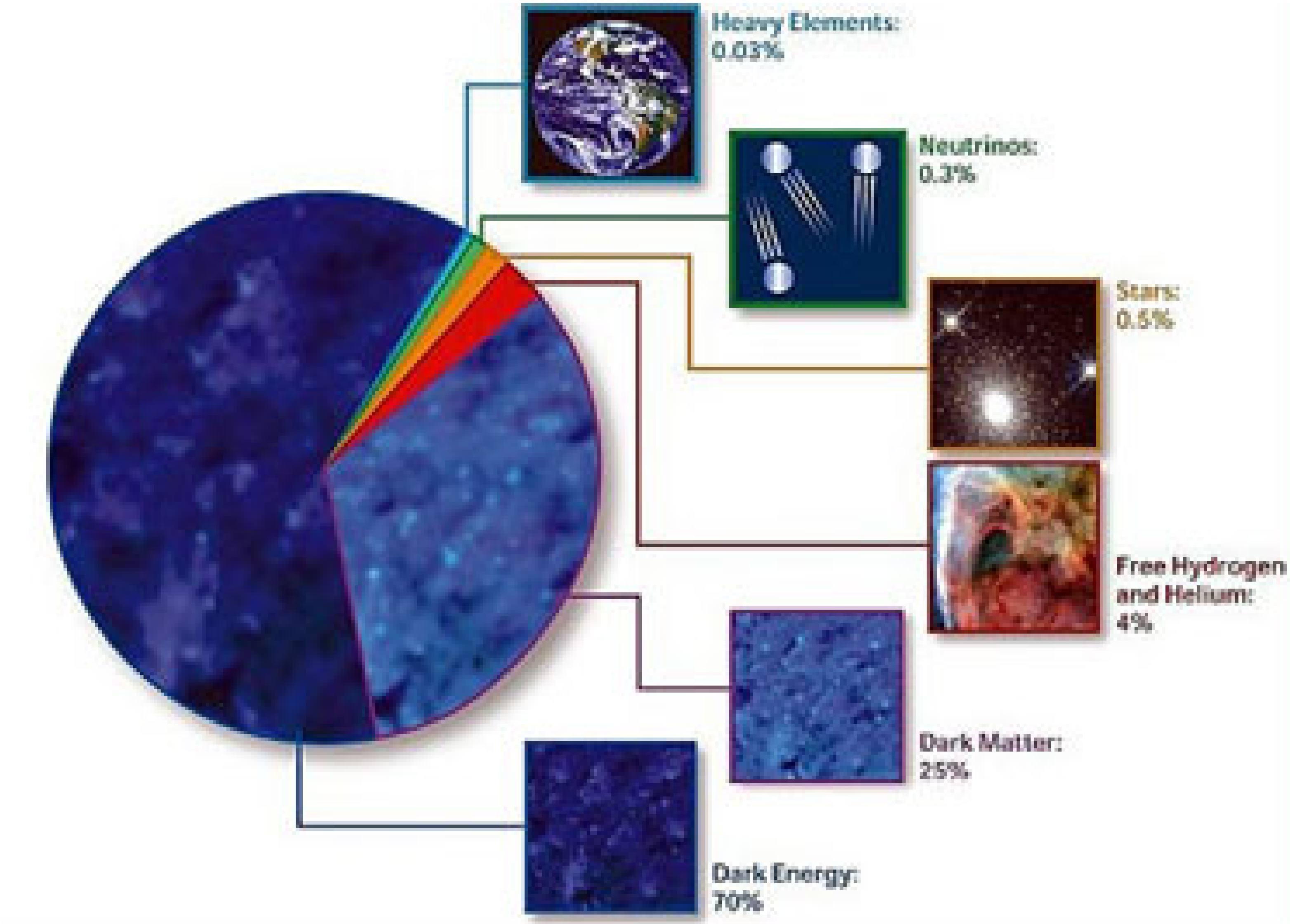
Present-day Cosmic Density:

$$\rho_0 = 1.8791 \times 10^{-29}\, \Omega h^2 \; g\, cm^{-3}$$
$$= 2.78 \times 10^{11}\, \Omega h^2 \quad M_{\odot} Mpc^{-3}$$

what the Universe exists of:

Cosmic Constituents

Cosmic Components



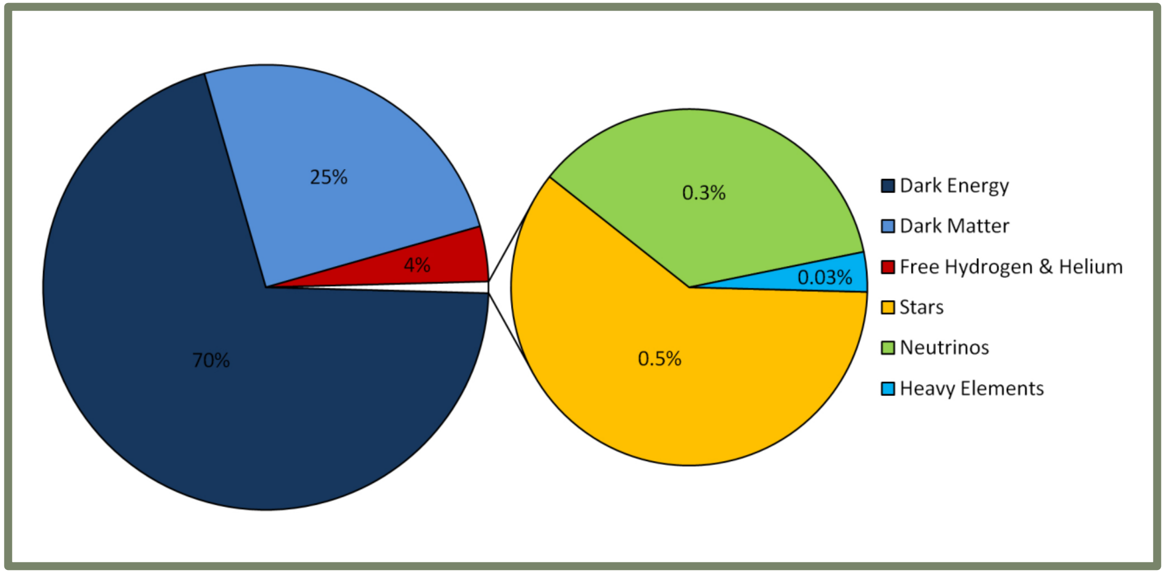
Cosmic Energy Inventarisation

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			$10^{-4.3\pm0.0}$	
2.2	neutrinos			$10^{-2.9\pm0.1}$	
2.3	prestellar nuclear binding energy			$-10^{-4.1\pm0.0}$	
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			0.00036 ± 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			$10^{-5.6\pm0.3}$	
3.13	sequestered in massive black holes			$10^{-5.4}(1+\epsilon_n)$	
4	primeval gravitational binding energy				$-10^{-6.1\pm0.1}$
4.1	virialized halos of galaxies			$-10^{-7.2}$	
4.2	clusters			$-10^{-6.9}$	
4.3	large-scale structure			$-10^{-6.2}$	

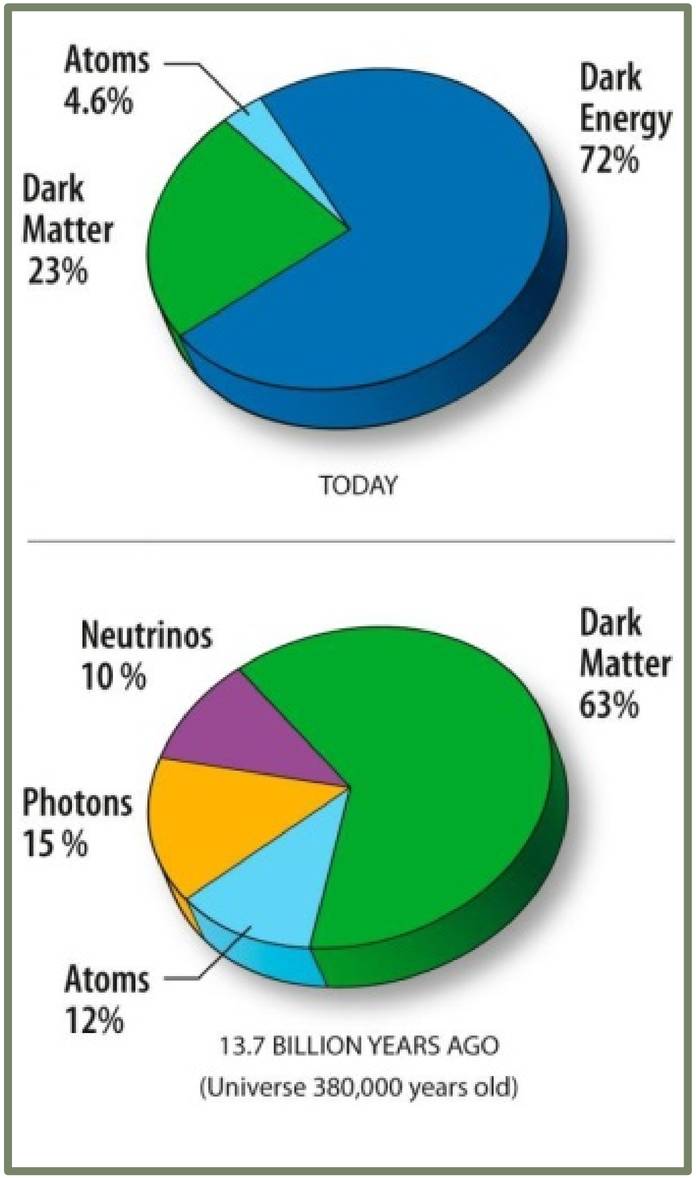
sterren slechts ~0.1% energie Heelal

Fukugita & Peebles 2004

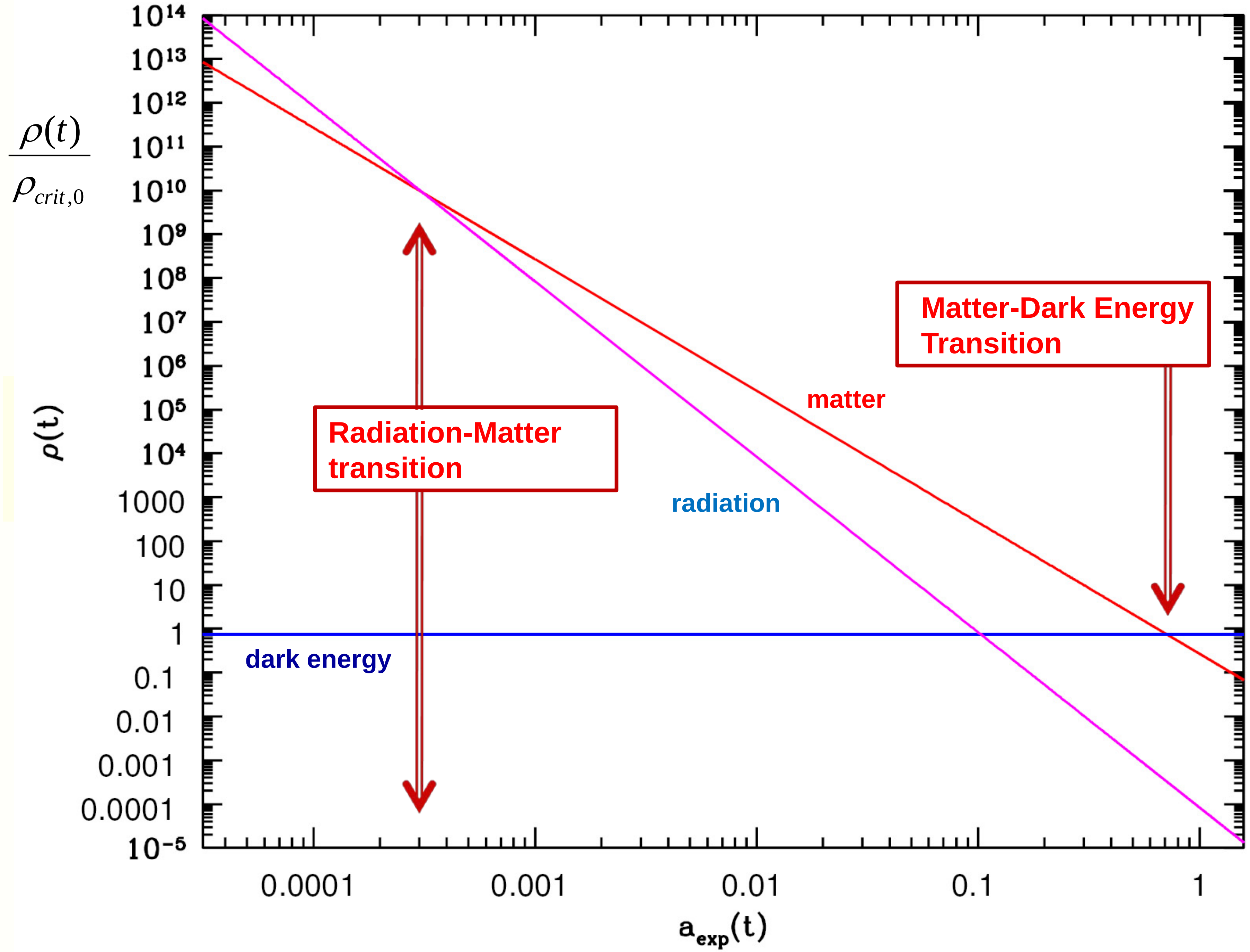
Cosmic Constitution



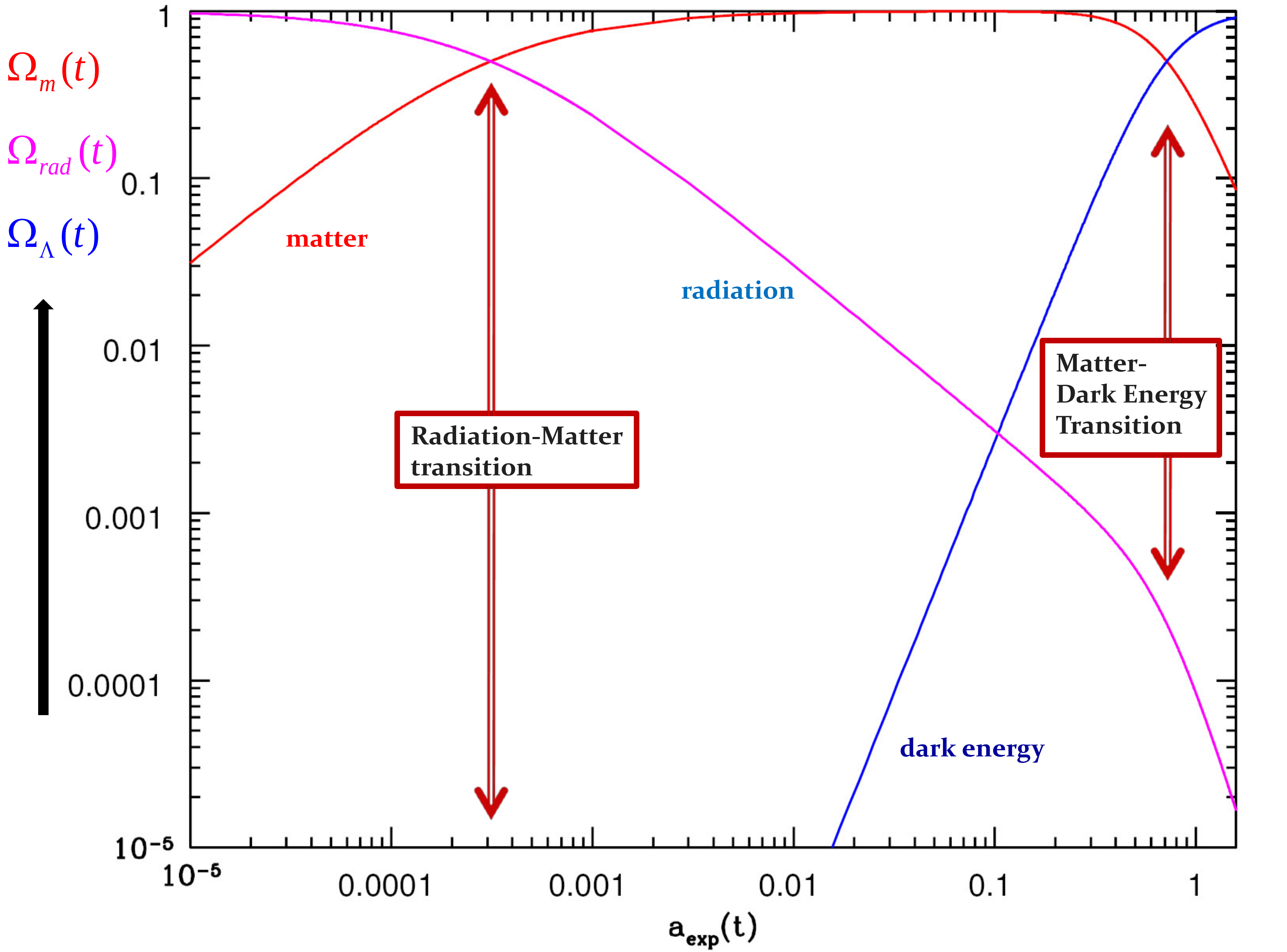
Cosmic Pie Diagram



Changes in Time:



$\frac{\rho(t)}{\rho_{crit,0}}$
ρ(t)
10¹⁴
10¹³
10¹²
10¹¹
10¹⁰
10⁹
10⁸
10⁷
10⁶
10⁵
10⁴
1000
100
10
1
0.1
0.01
0.001
0.0001
10⁻⁵
0.0001
0.001
0.01
0.1
1
$a_{exp}(t)$
Radiation-Matter transition
Matter-Dark Energy Transition
matter
radiation
dark energy


$\Omega_m(t)$
$\Omega_{rad}(t)$
$\Omega_\Lambda(t)$
1
0.1
0.01
0.001
0.0001
10^{-5}
matter
radiation
dark energy
Radiation-Matter transition
Matter-Dark Energy Transition
10^{-5}
0.0001
0.001
0.01
0.1
1
$a_{exp}(t)$

Dark Matter

Matter

- Baryonic Matter
- Nonbaryonic Dark Matter

Baryonic Matter

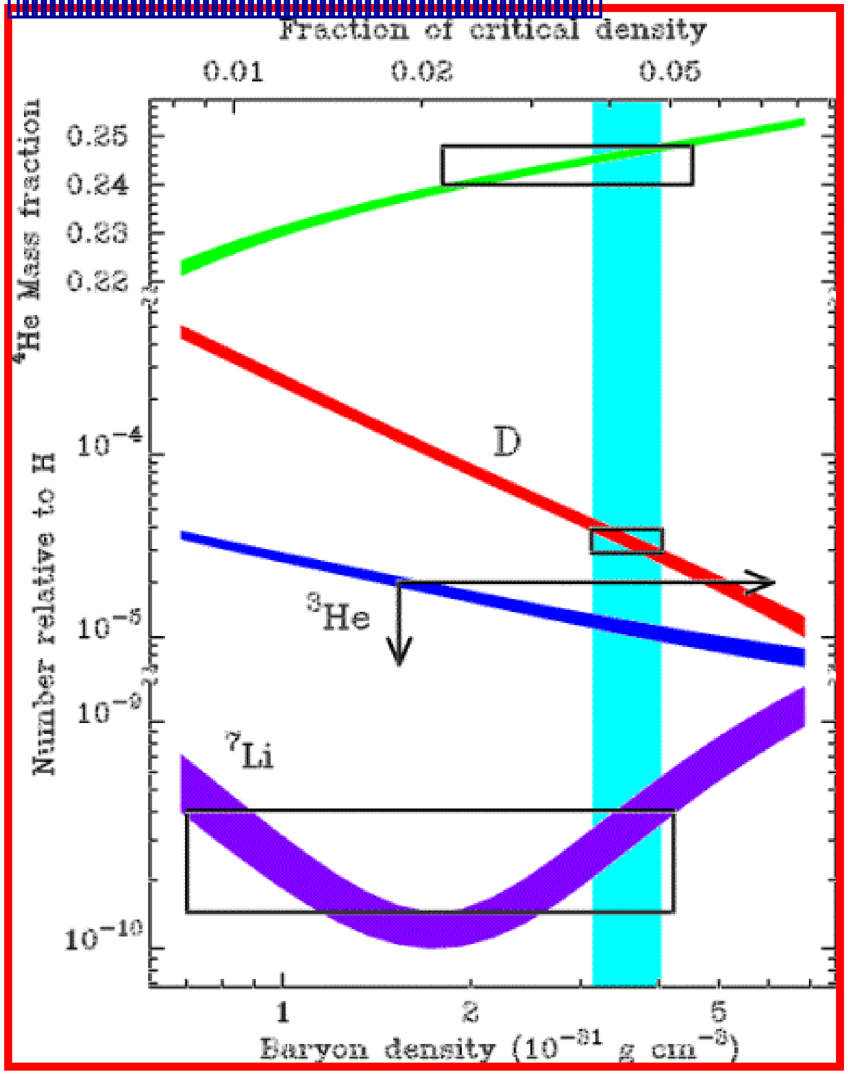
The amount of baryonic matter in the Universe is (by now) very well determined, by two independent determinations:

1) Primordial Nucleosynthesis

2) Acoustic Oscillations in CMB power spectrum,

2^{nd} peak (CMB)

Baryonic Matter: primordial nucleosynthesis

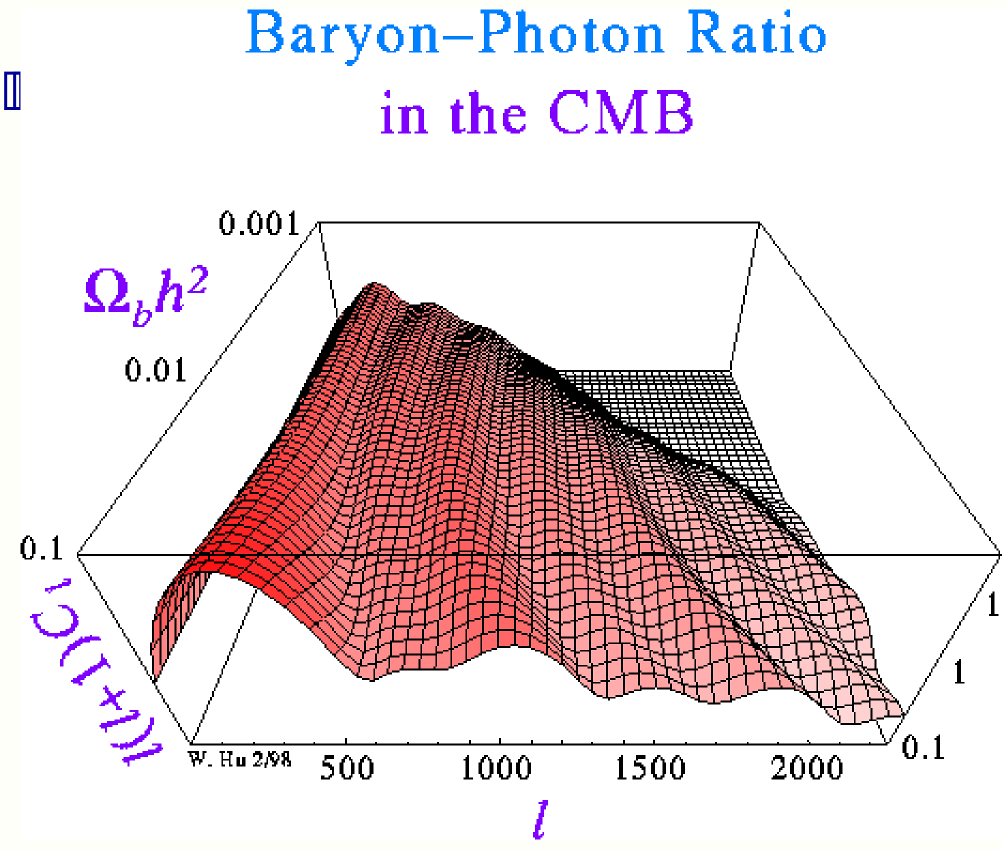


From measured light element abundances:

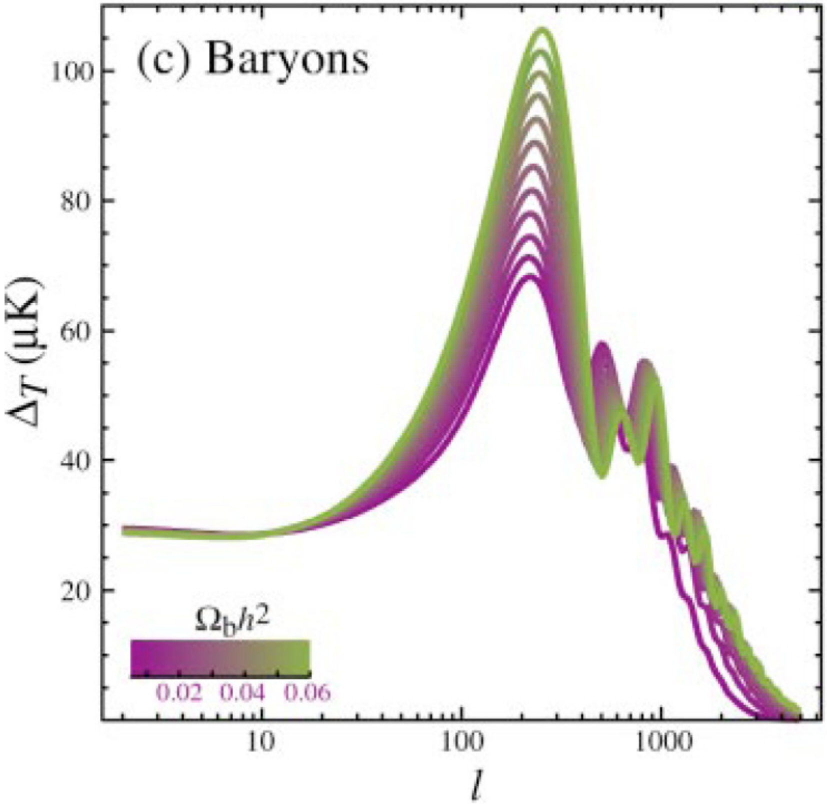
$$\eta \equiv \frac{n_B}{n_\gamma}$$

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

Baryonic Matter: CMB



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		
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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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3.13	sequestered in massive black holes			$10^{-5.4}(1 + \epsilon_n)$	

Non-baryonic DM: candidates

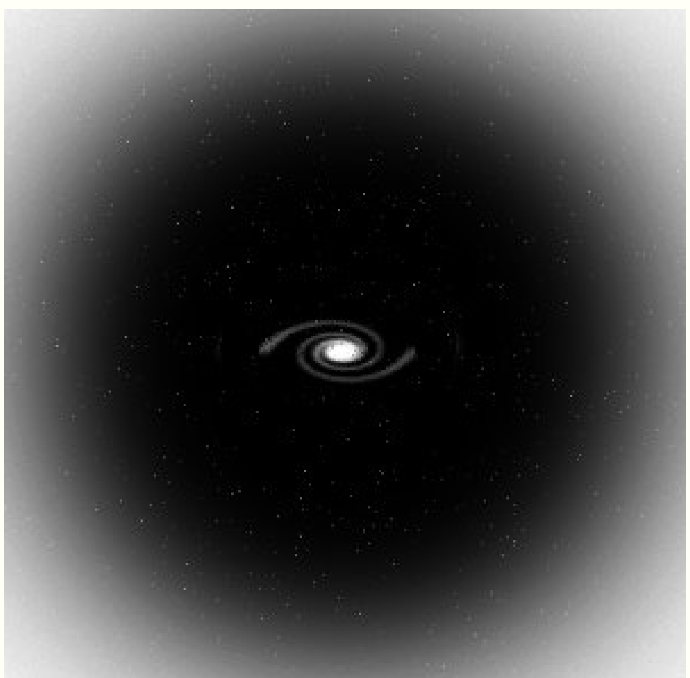
WIMPs:	Weakly Interacting Massive Particles
	- neutrinos - sterile neutrinos - neutralinos - ....
MACHOs:	Massive astrophysical compact halo object
Modified Gravity:	modification of General Relativity
SIMPs ...	Strongly Interacting Massive Particles

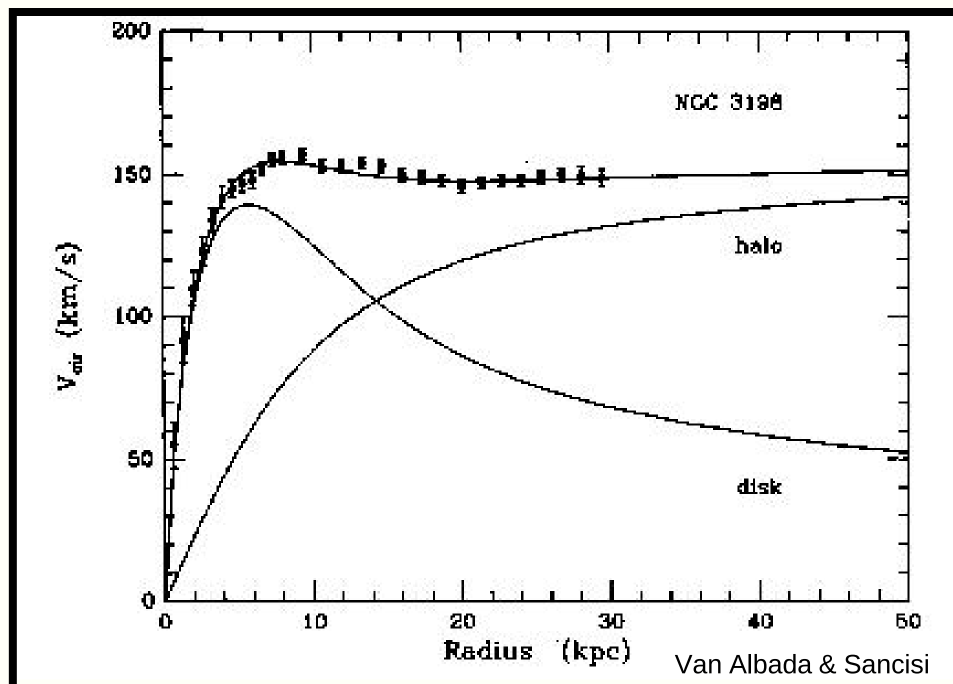
Dark Matter: disk galaxies

- 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".





Van Albada & Sancisi

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

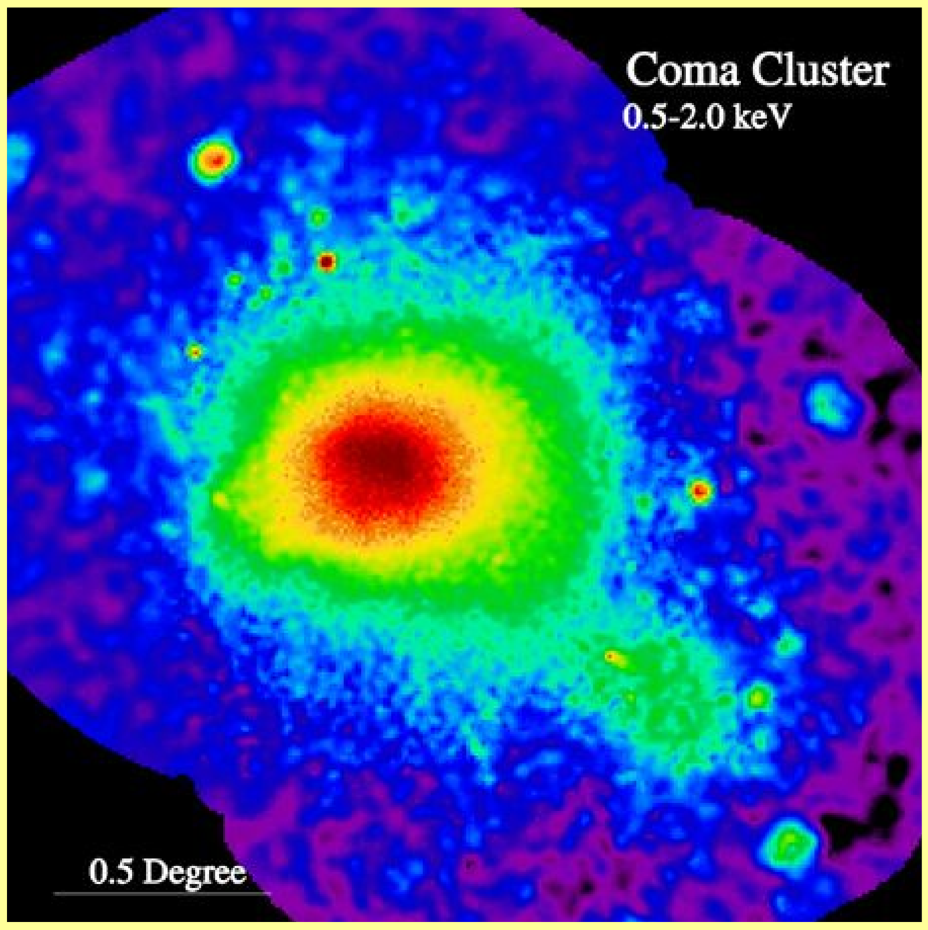
Intracluster Gas,

trapped and heated to a temperature of the order of

$T \sim 10^8$ 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

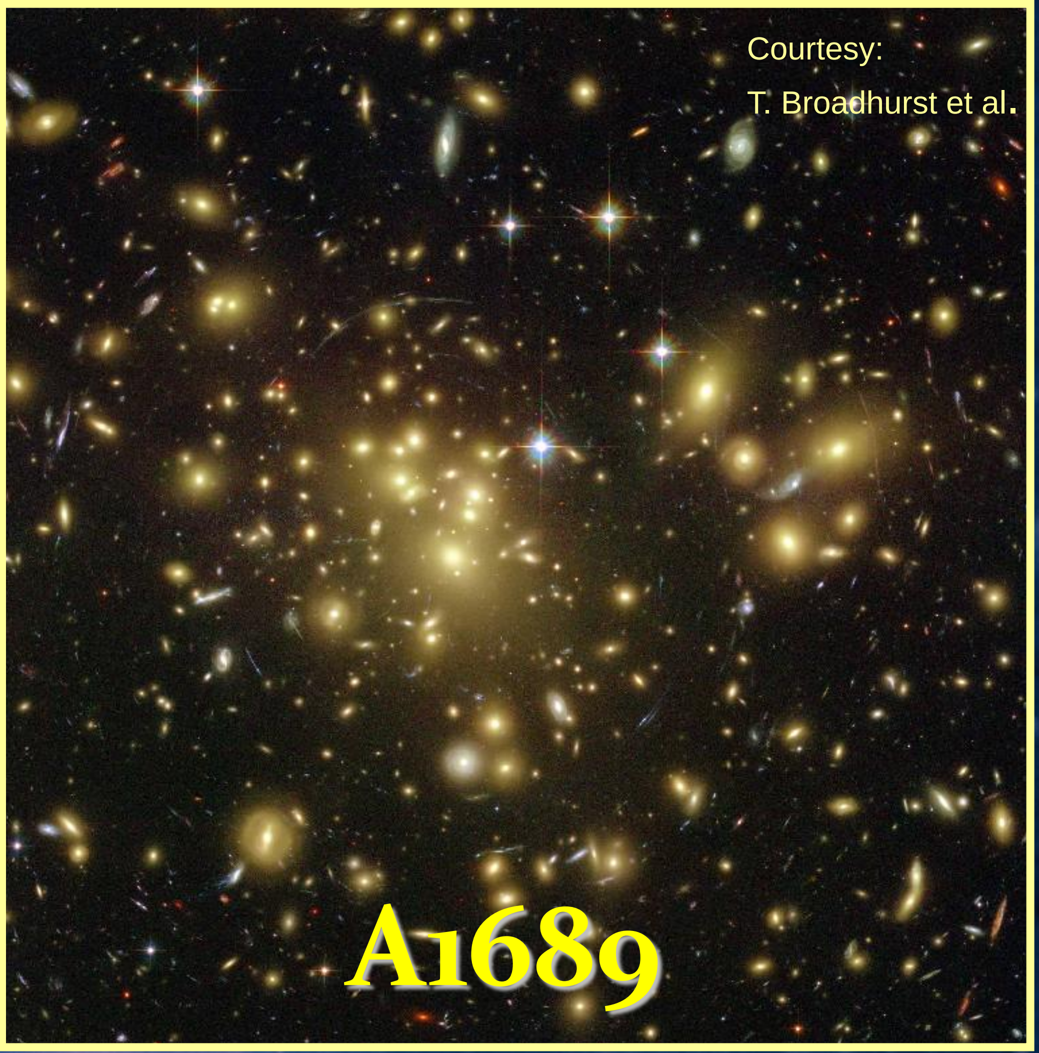
According to

Einstein's theory of

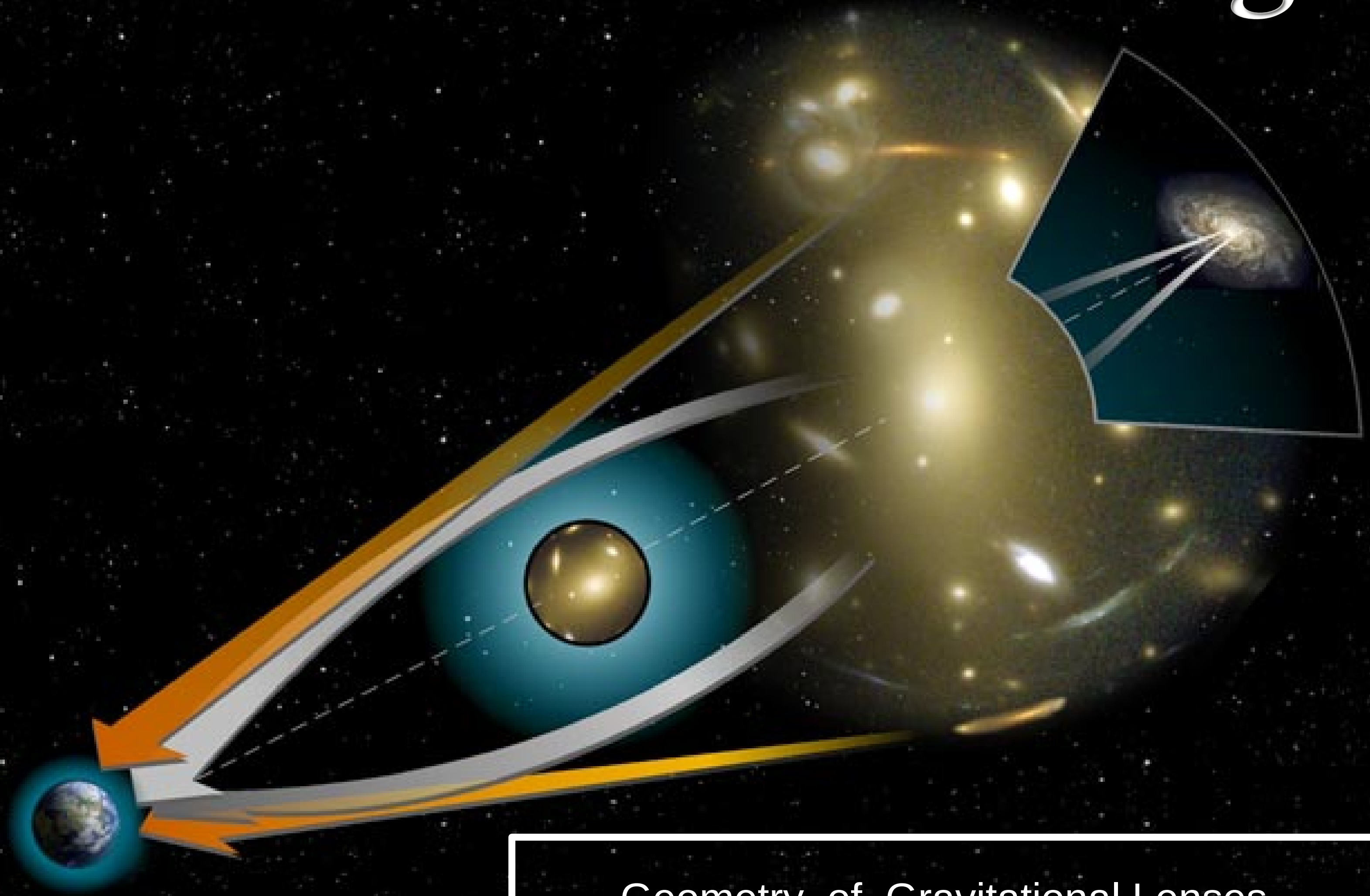
General Relativity,

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

Gravitational Lens



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

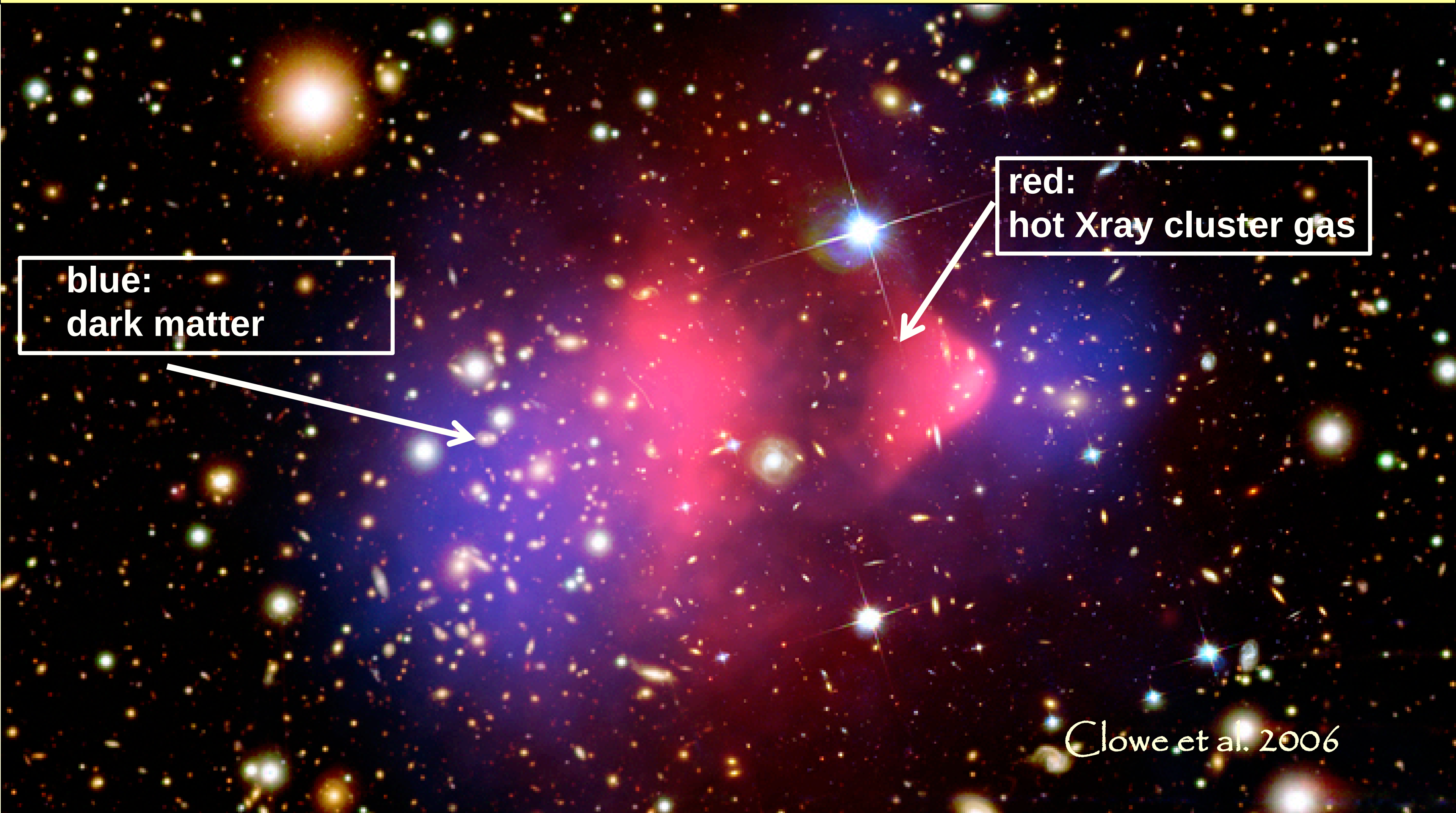
Einstein's theory of

General Relativity,

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

Gravitational Lens.

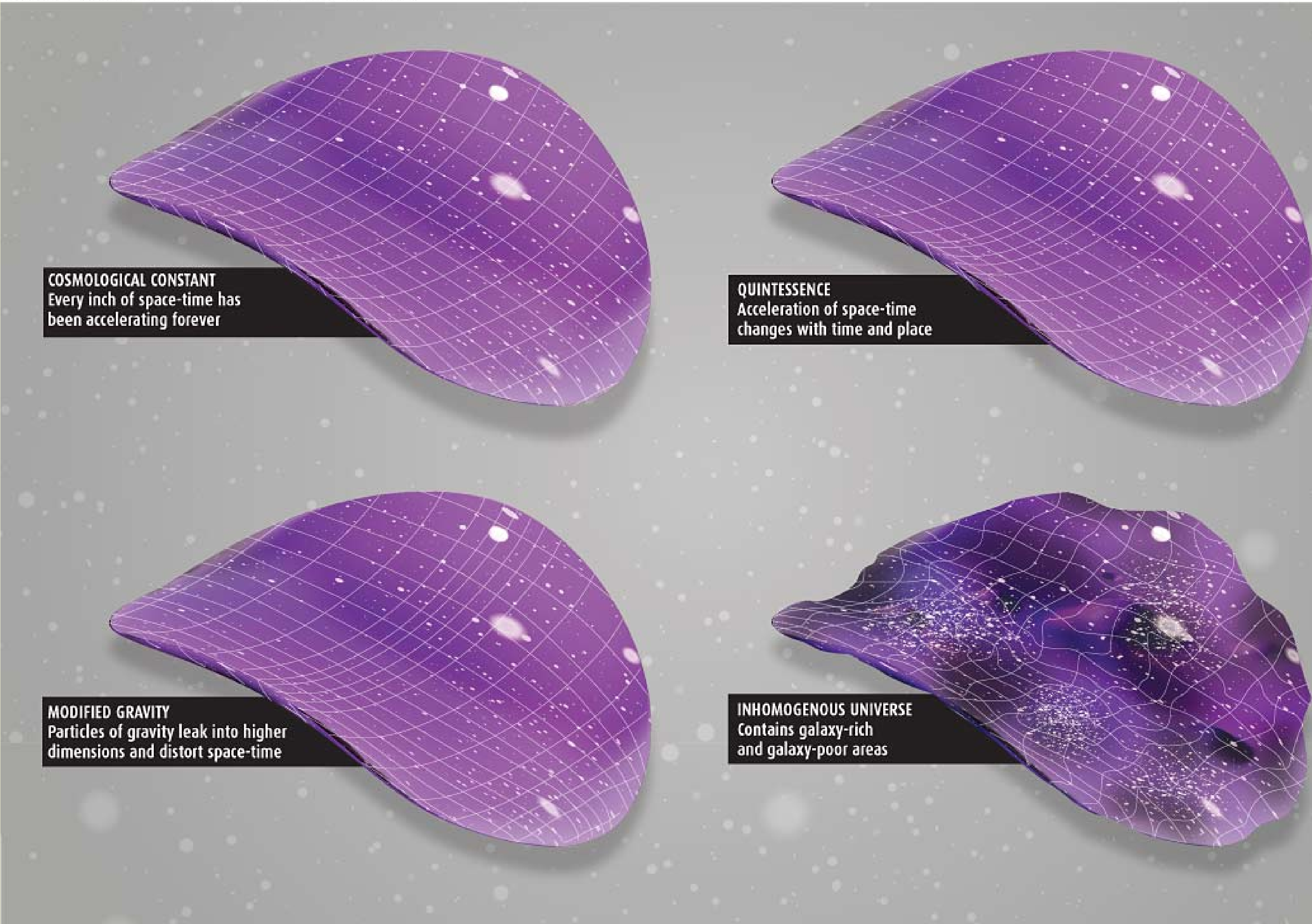
Bullet Cluster colliding …



Dark Energy

FOUR WAYS TO EXPAND THE UNIVERSE

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



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 ?

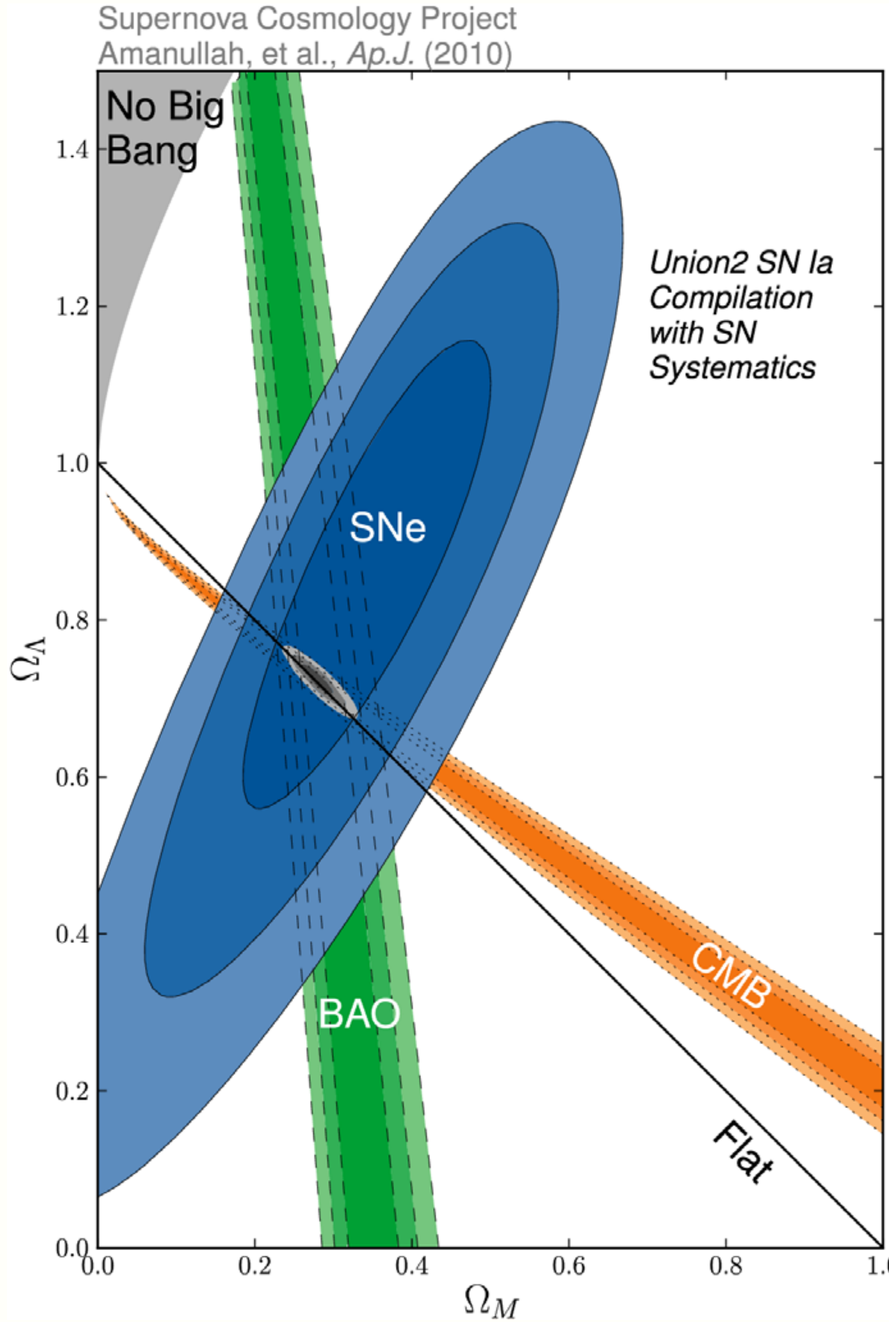
Ω_m vs. Ω_Λ

$$q \approx \frac{\Omega_m}{2} - \Omega_\Lambda$$

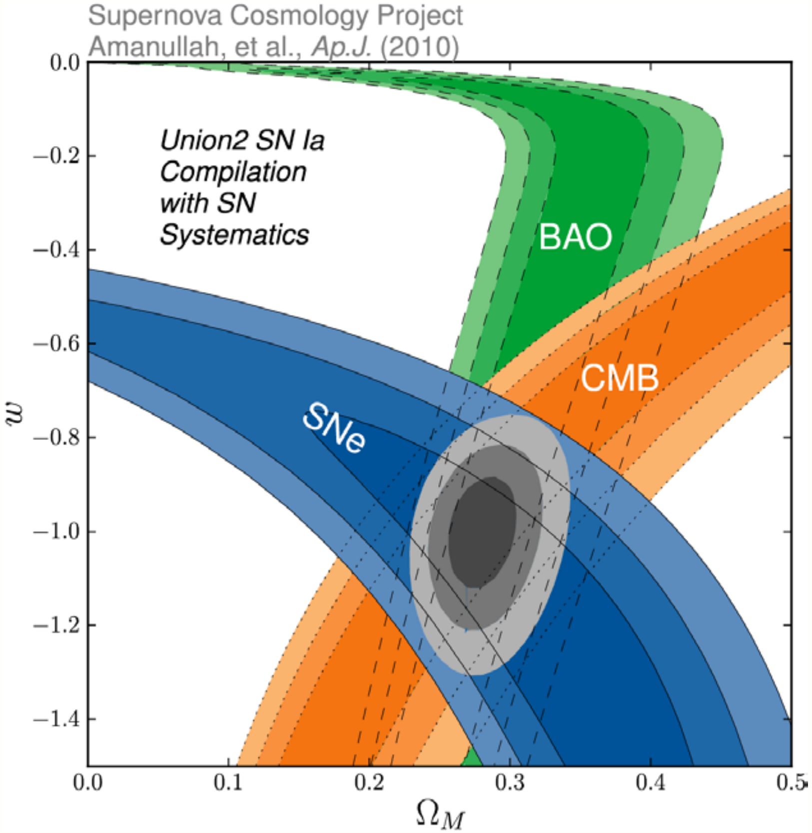
$$k = \frac{H^2 R^2}{c^2}(\Omega_m + \Omega_\Lambda - 1)$$

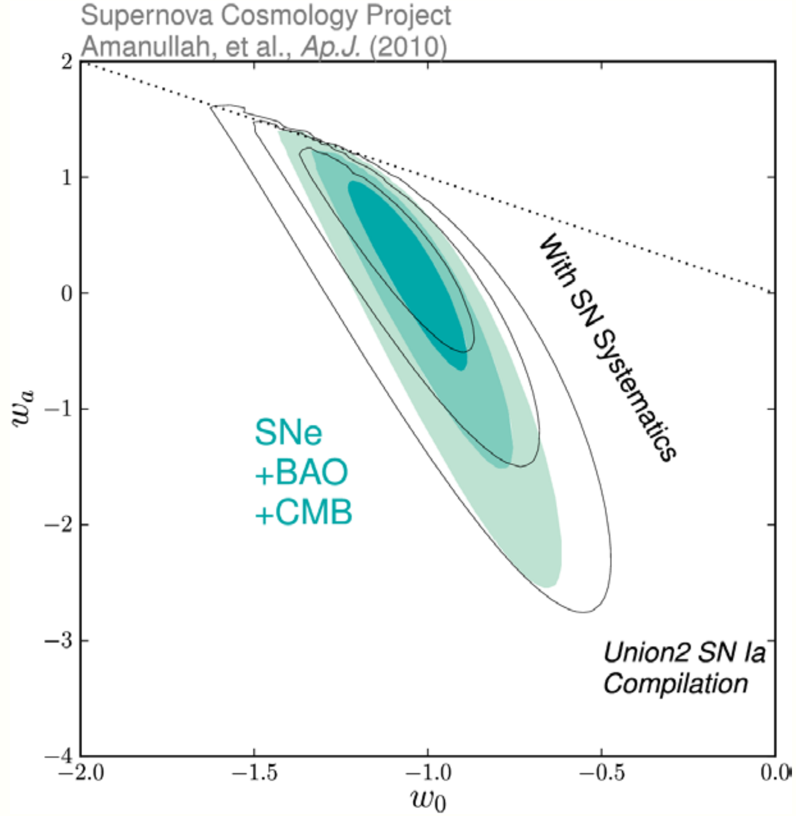
SCP Union2 constraints (2010)

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

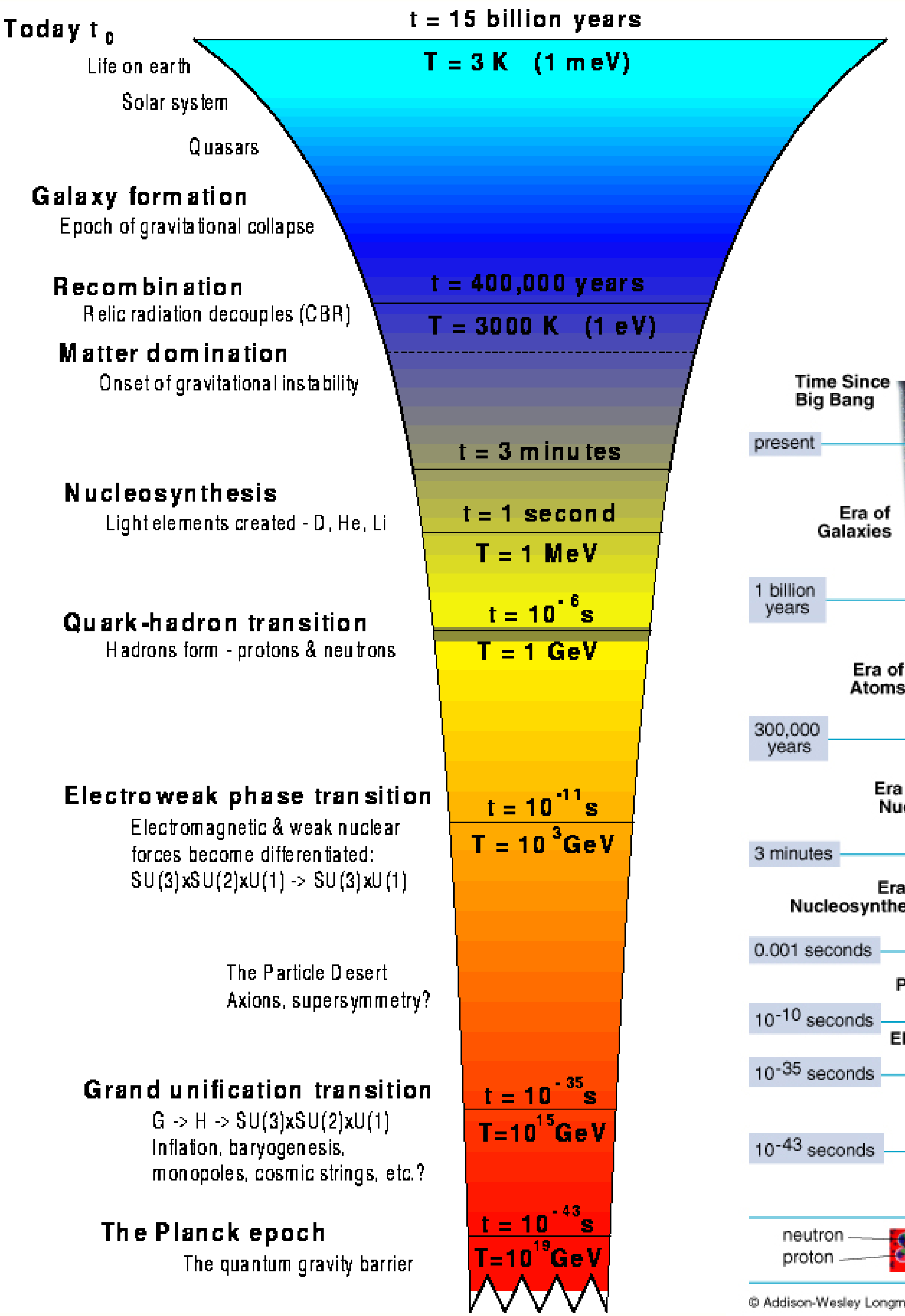
Adiabatic Expansion

- The Universe of Einstein, Friedmann & Lemaitre expands *adiabacally*

- Energy of the expansion of the Universe corresponds to the decrease in the energy of its constituents

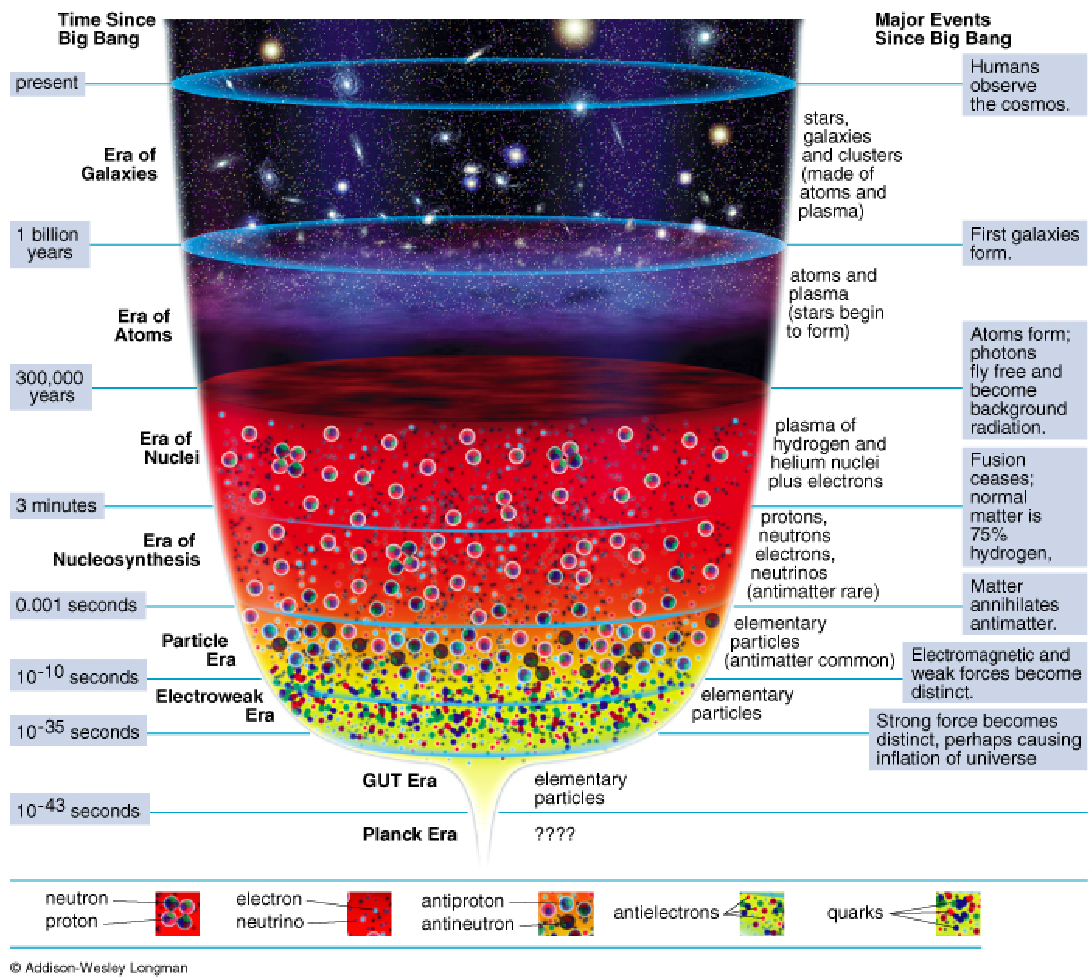
- *The Universe COOLS as a result of its expansion !*

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



Adiabatic Expansion

reconstruction Thermal History of the Universe



Cosmic Epochs

Planck Epoch		$t < 10^{-43}$ sec
Phase Transition Era	GUT transition electroweak transition quark-hadron transition	10^{-43} sec $< t < 10^{5}$sec
Hadron Era		$t \sim 10^{-5}$ sec
Lepton Era	muon annihilation neutrino decoupling electron-positron annihilation primordial nucleosynthesis	10^{-5} sec $< t <$ 1 min
Radiation Era	radiation-matter equivalence recombination & decoupling	1 min $< t <$ 379,000 yrs
Post-Recombination Era	Structure & Galaxy formation Dark Ages Reionization Matter-Dark Energy transition	$t >$ 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)

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

fundamental physics:
- poorly known
- speculative

VERY early universe

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

History of the Universe in Four Episodes: III

(III)

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

Standard

Hot Big Bang

Fireball

fundamental microphysics:

known very well

- primordial nucleo-synthesis
- blackbody radiation: CMB

History of the Universe in Four Episodes: IV

(IV)

complex macrophysics:

-Fundamentals known

- complex interplay

t > 10^{13} sec

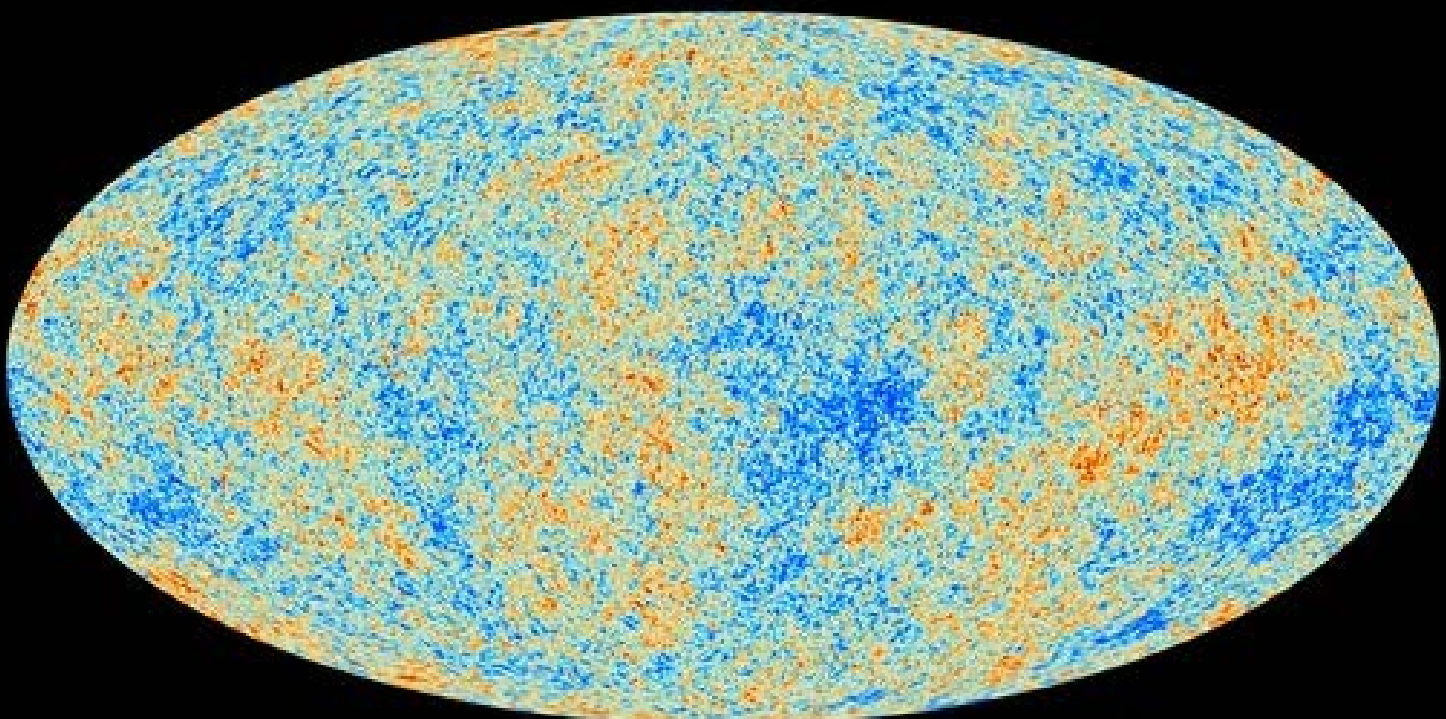
Post (Re)Combination universe

- structure formation:

  stars,
  galaxies
  clusters
  …

Cosmic Curvature

Cosmic Microwave Background



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

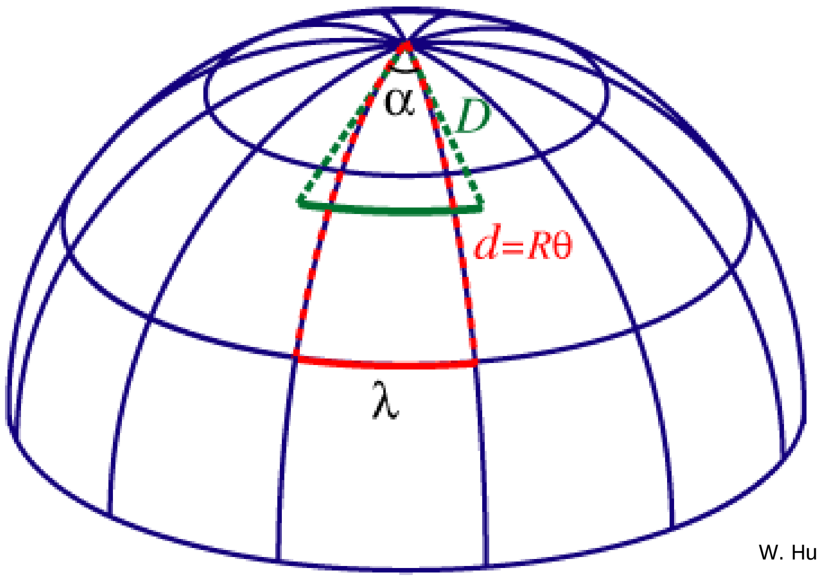
- **379,000 years after Big Bang**
- **Subhorizon perturbations: primordial sound waves**
- **ΔT/T < 10-5**

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**

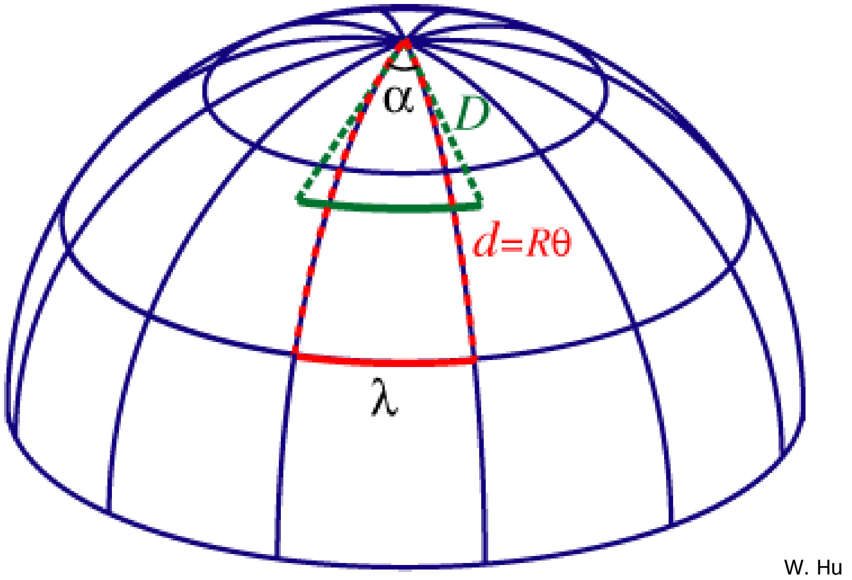
Geometry of Space



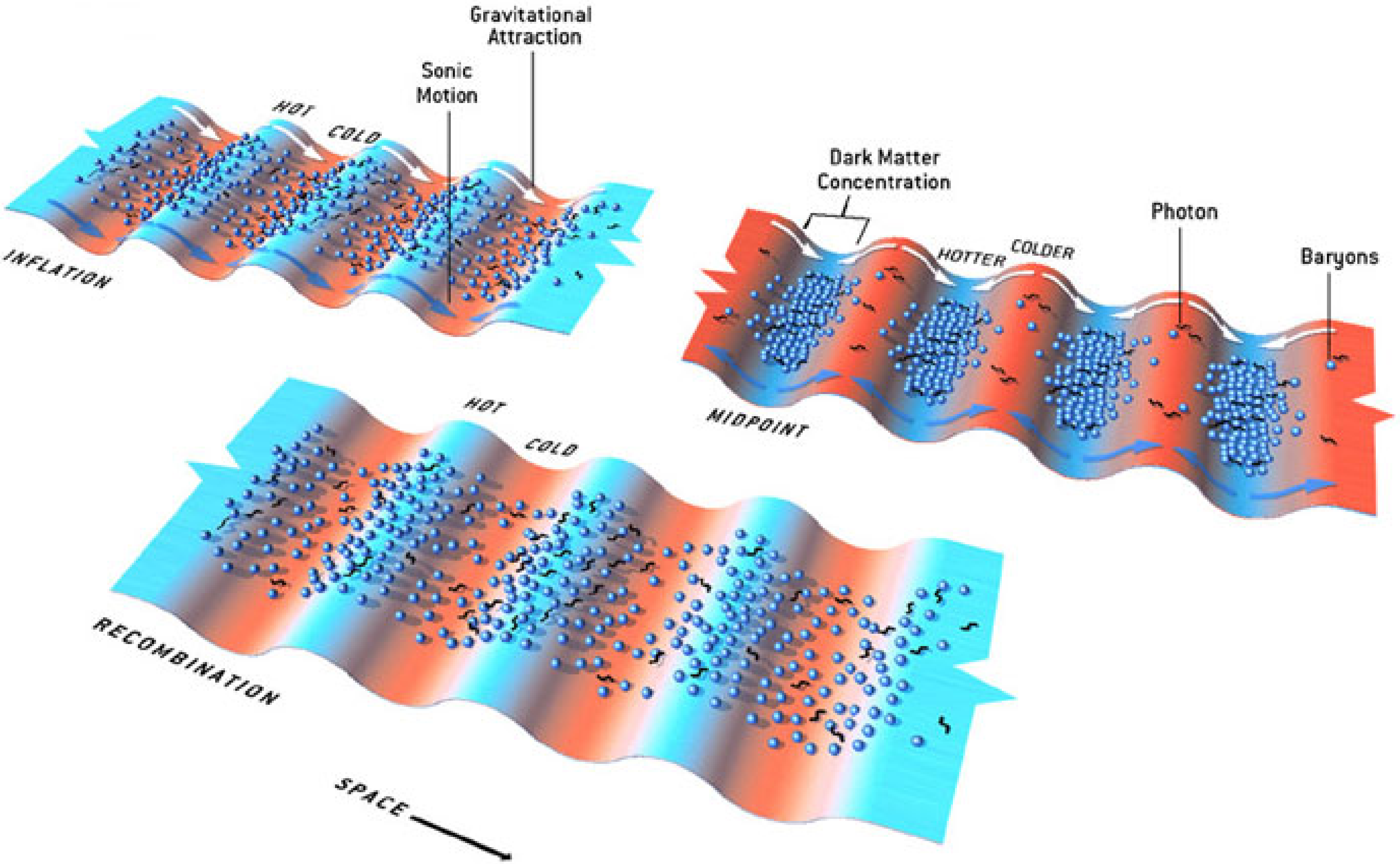
Measuring Curvature

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

Temperature Fluctuations
CMB



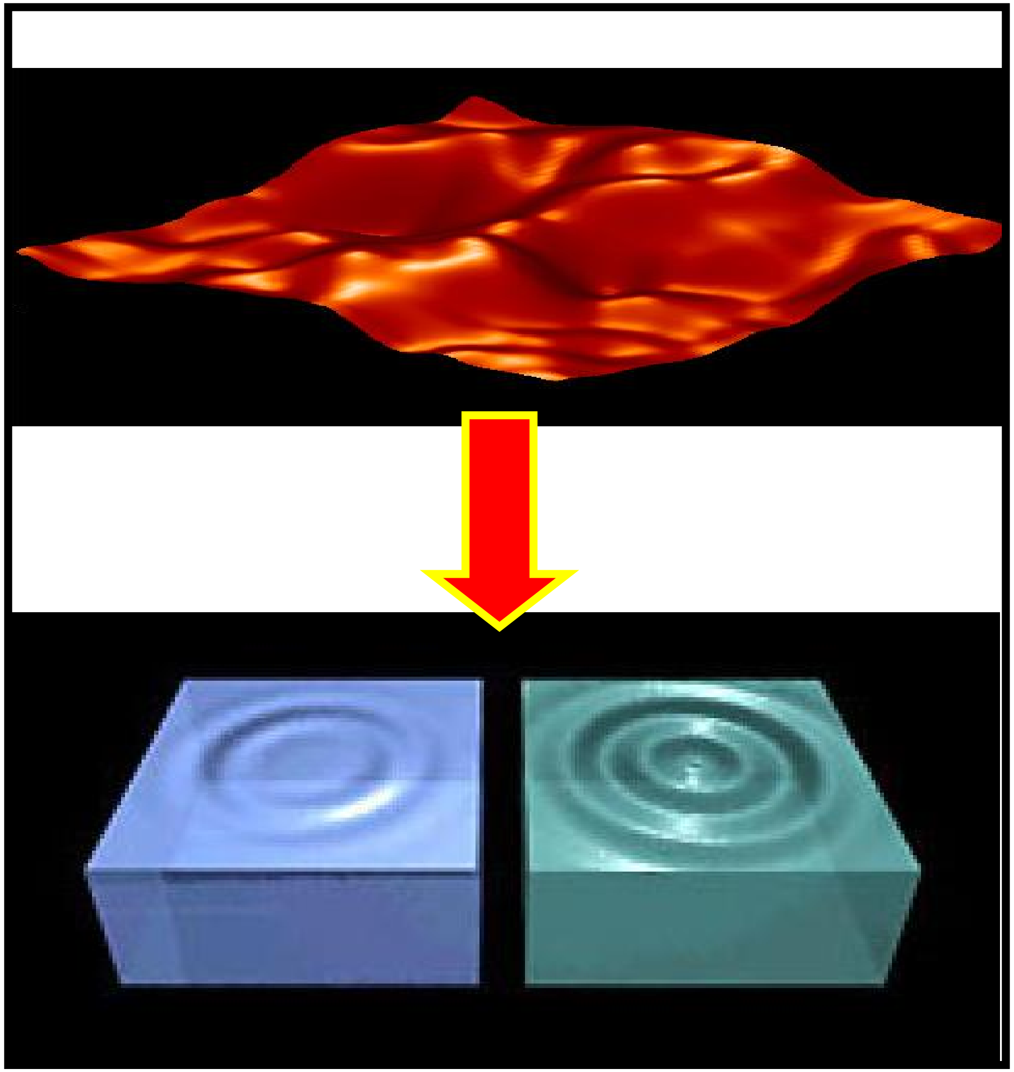
Fluctuations-Origin



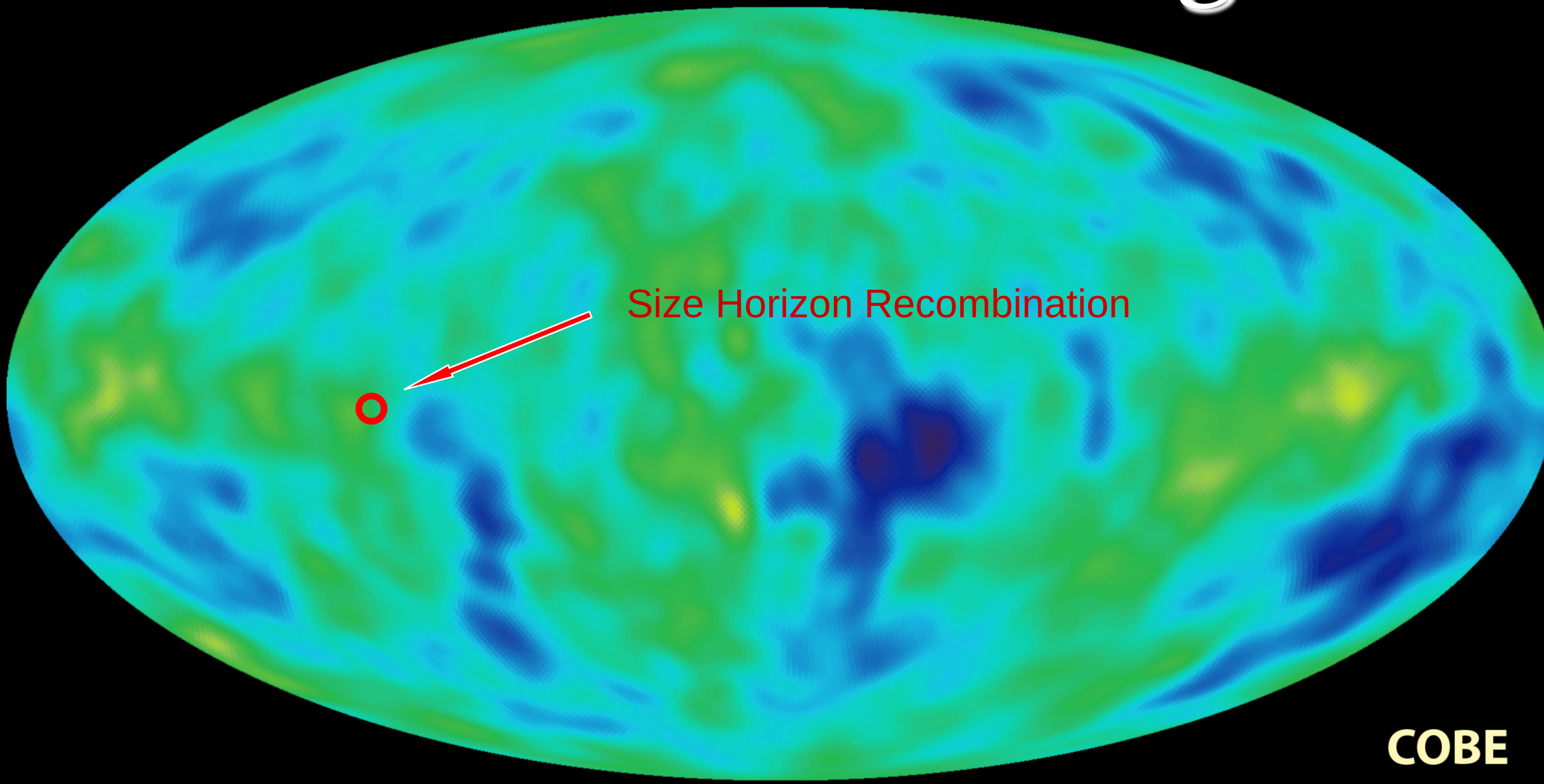
Music of the Spheres

- 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: θ~1º
  - exact scale maximum compression, the “cosmic fundamental mode of music”

W. Hu



Cosmic Microwave Background

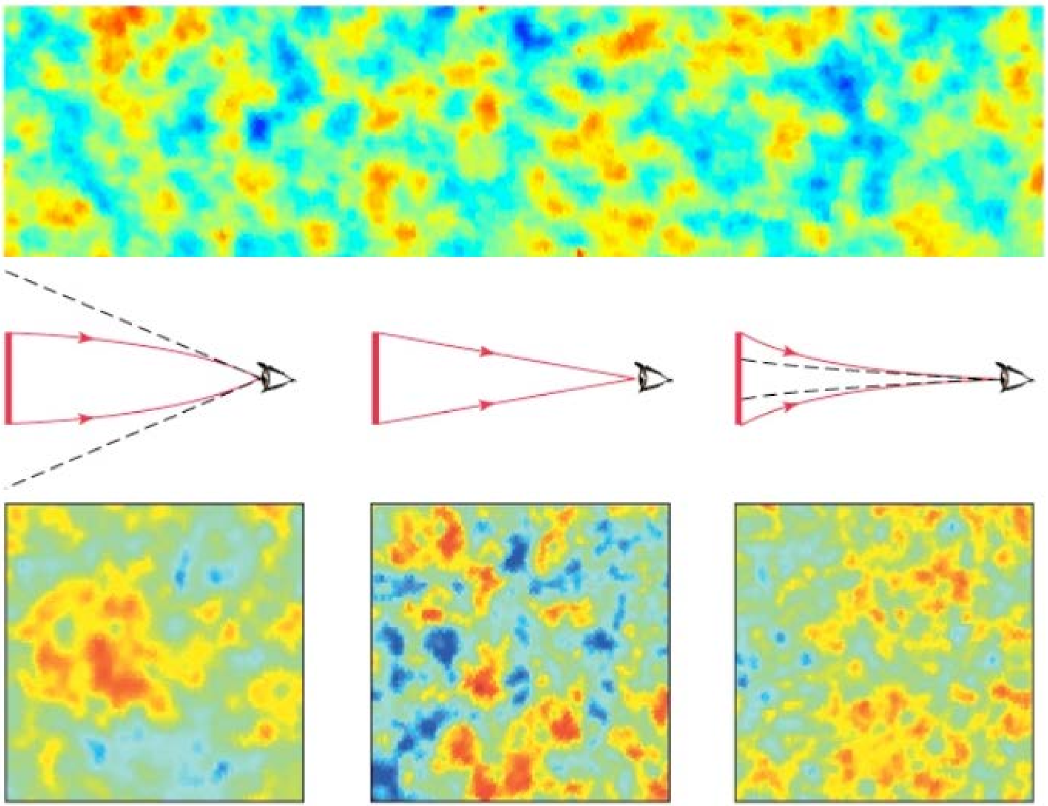


COBE measured fluctuations: > 7°

Size Horizon at Recombination spans angle ~ 1°

Flat universe from CMB

- **First peak: flat universe**



Closed:
hot spots
appear larger

Flat:
appear as big
as they are

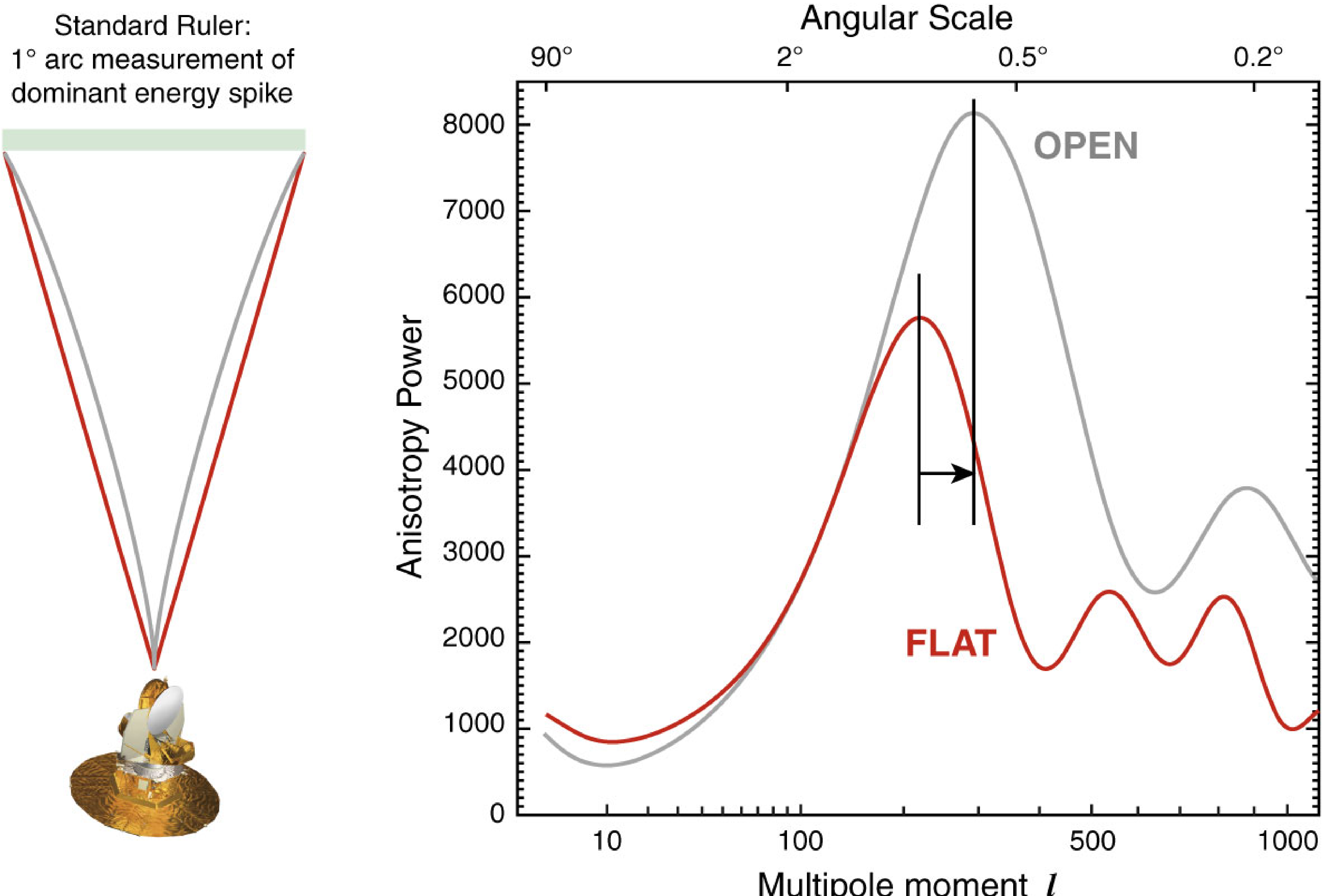
Open:
spots appear
smaller

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

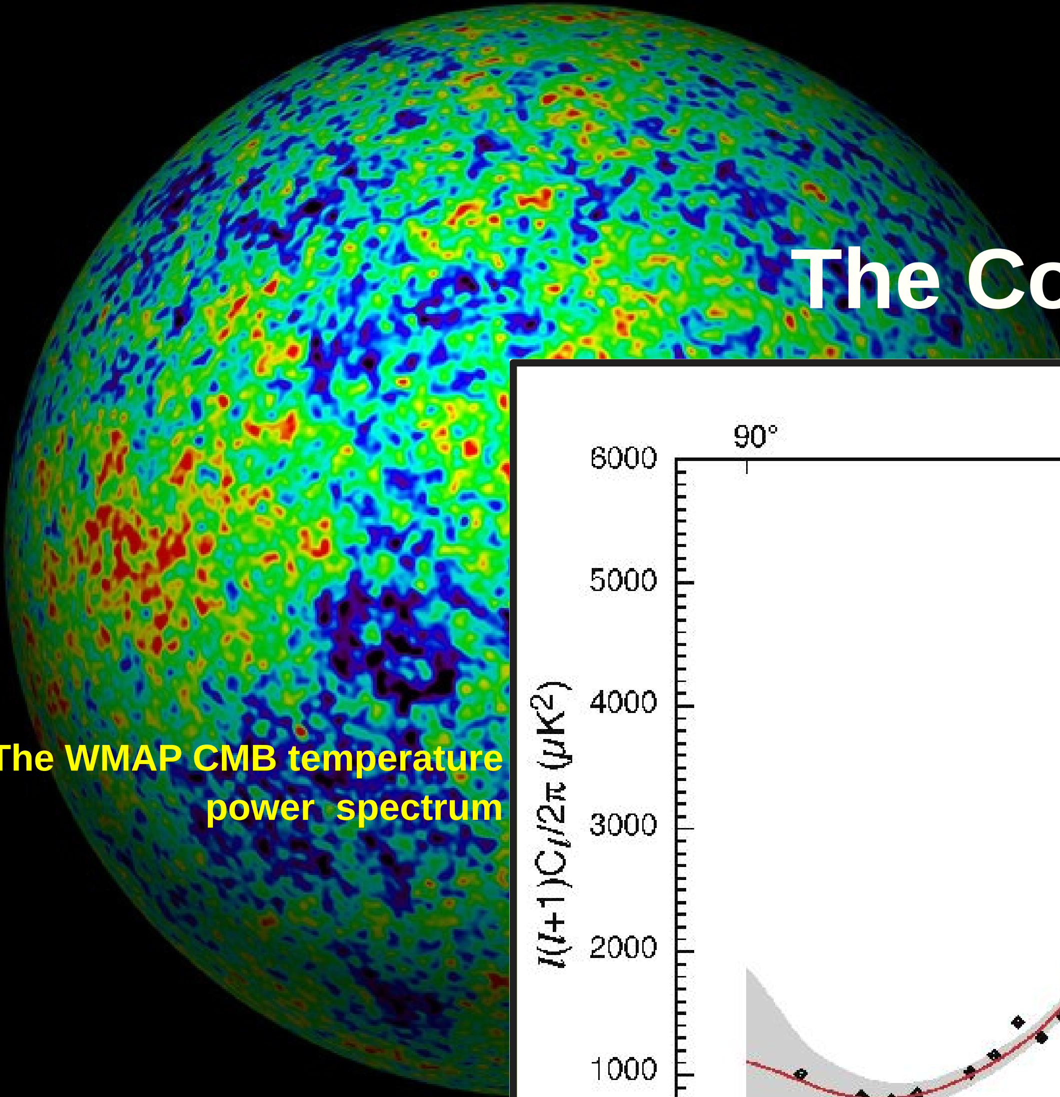
from this we know the
- length of the legs of the triangle
- the angle at which we are measuring the sound horizon.

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

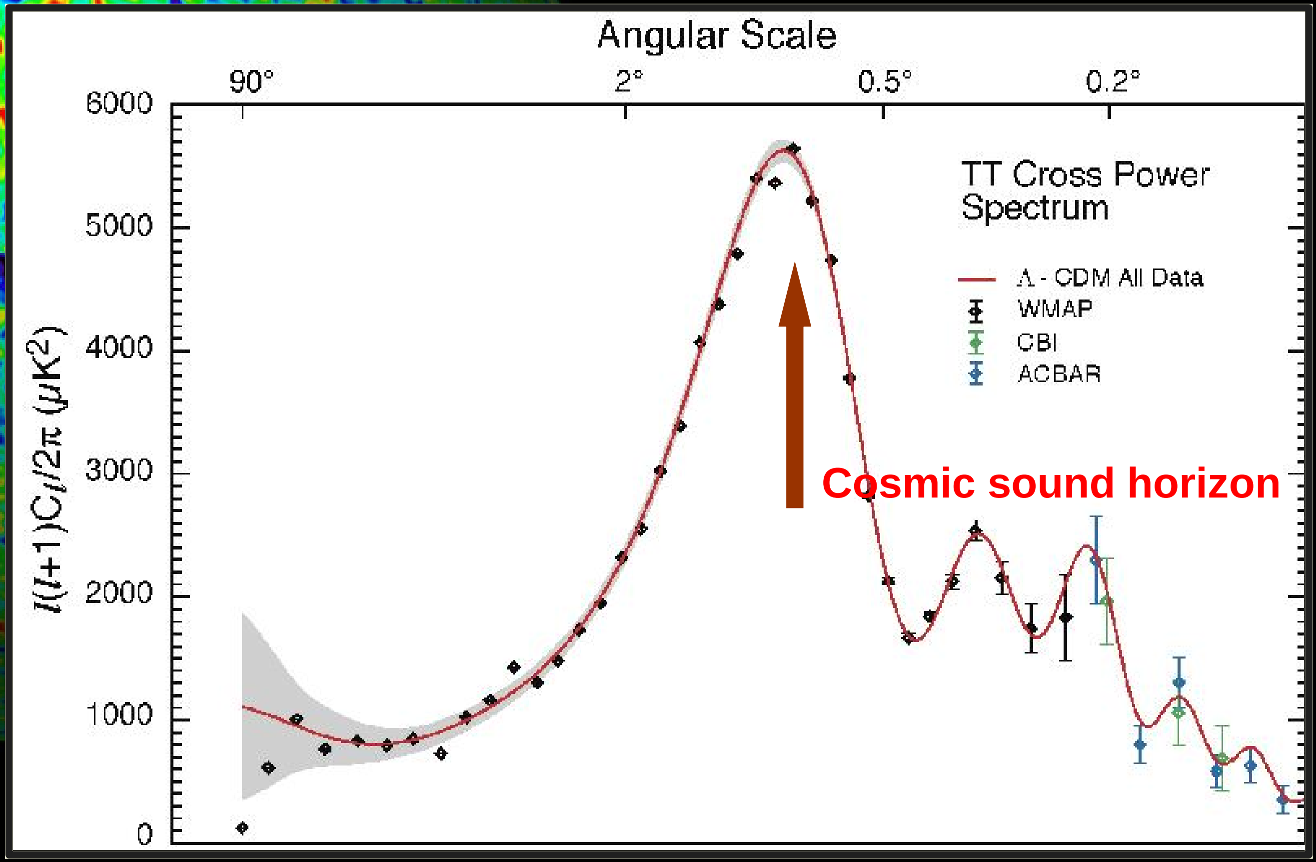
$$\ell \approx 200/\sqrt{1-\Omega_k}$$


Standard Ruler:
1° arc measurement of
dominant energy spike
Angular Scale
90°
2°
0.5°
0.2°
Anisotropy Power
8000
7000
6000
5000
4000
3000
2000
1000
0
OPEN
FLAT
10
100
500
1000
Multipole moment l

The Cosmic Tonal Ladder

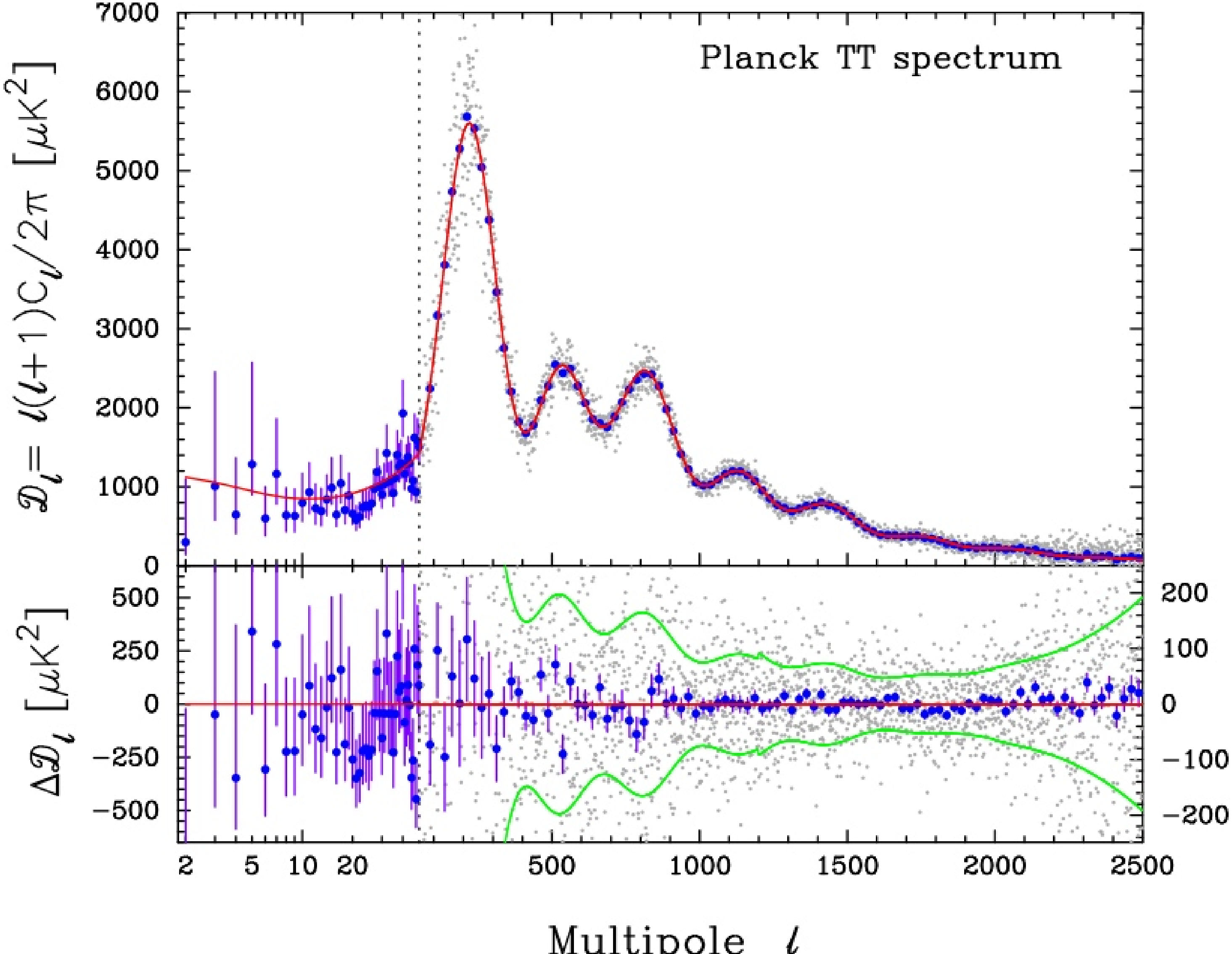


The WMAP CMB temperature power spectrum



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.

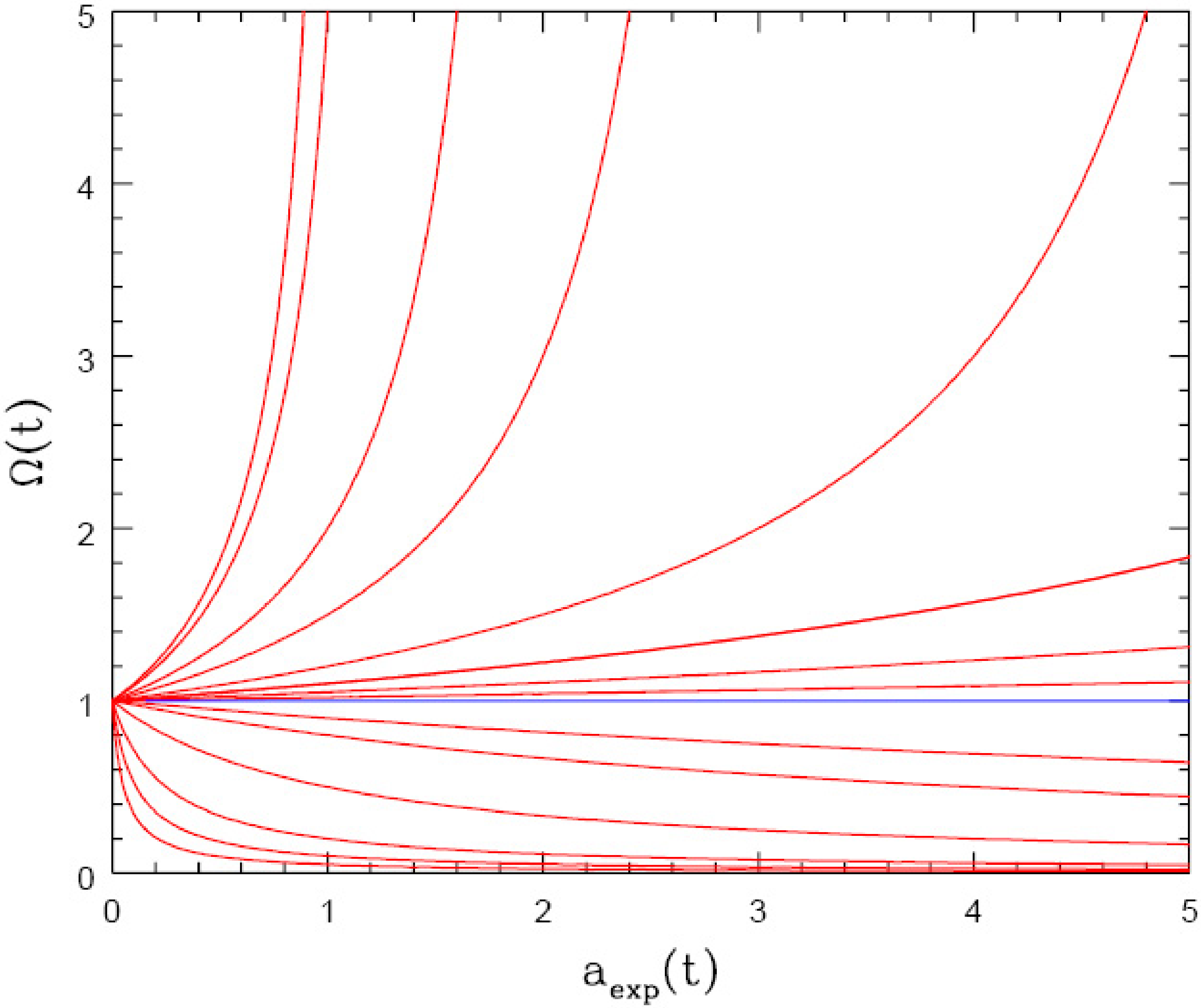
Reversely, that means that any small deviation from flatness in the early Universe would have been strongly amplified nowadays …

We would therefore expect to live in a Universe that would either be almost
□ =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.

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

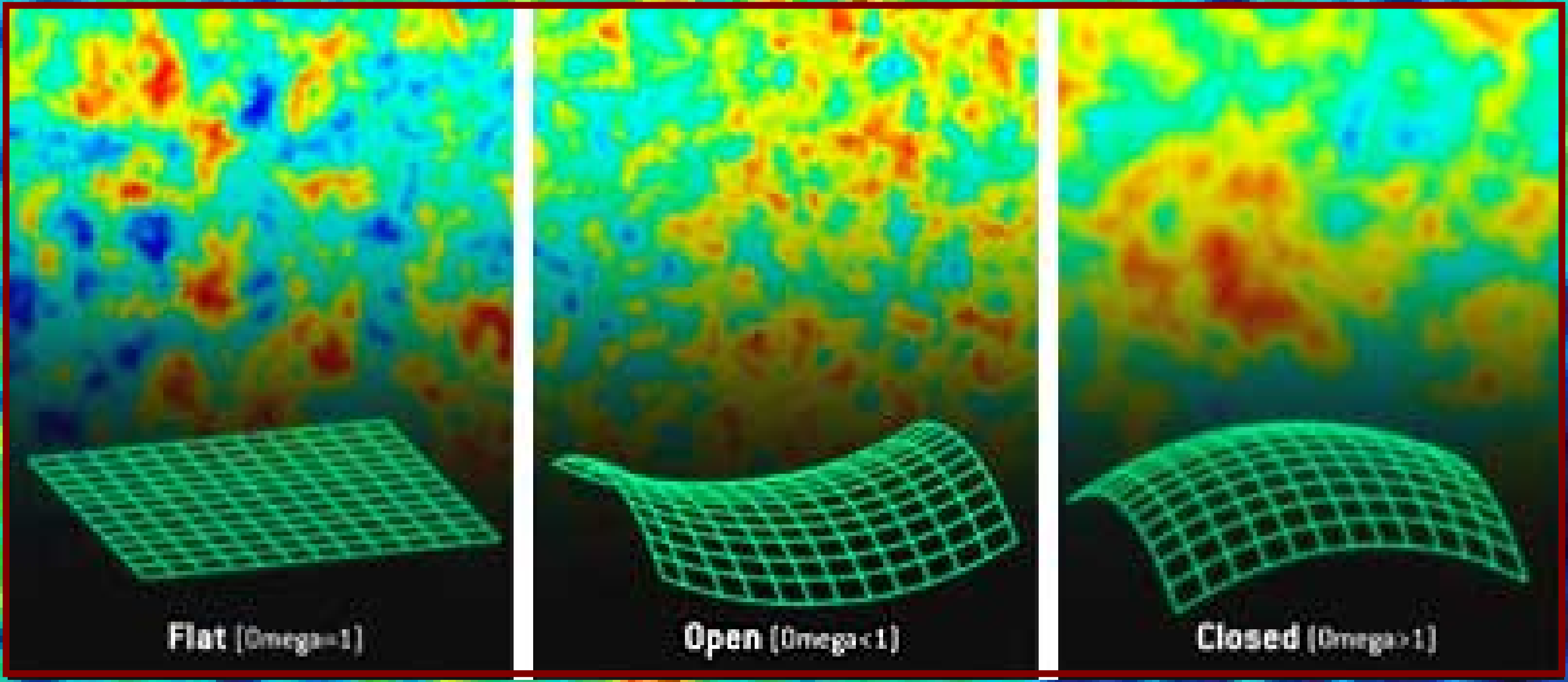
- Big Bang nucleosynthesis
  a_{nuc}3.610^{-8}

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

- Planck time

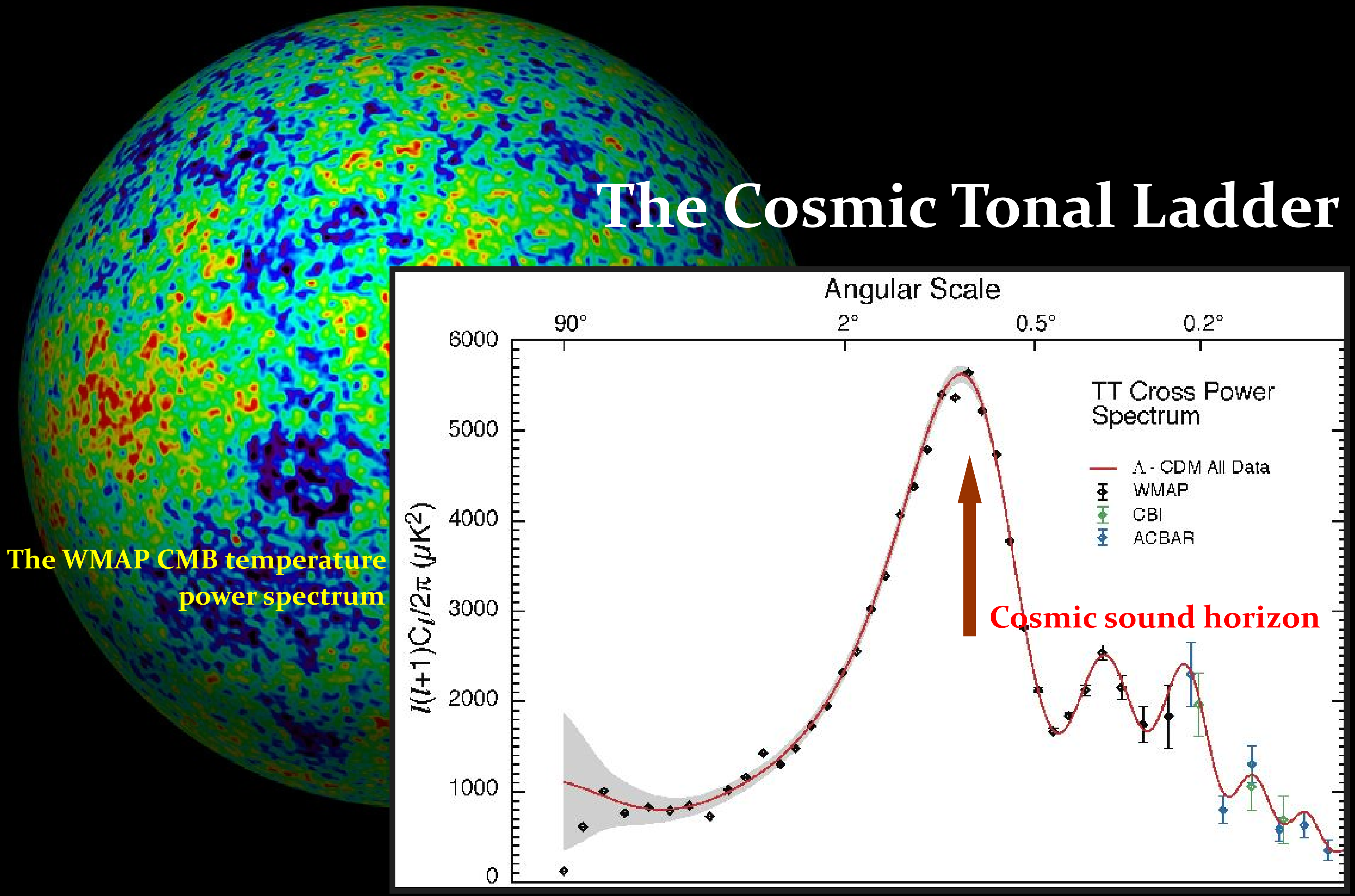
$$\left|1-\Omega_{P}\right|\leq 1\times 10^{-60}$$

Angular CMB temperature fluctuations



CMB: Universe almost perfectly Flat !

The Cosmic Tonal Ladder



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:

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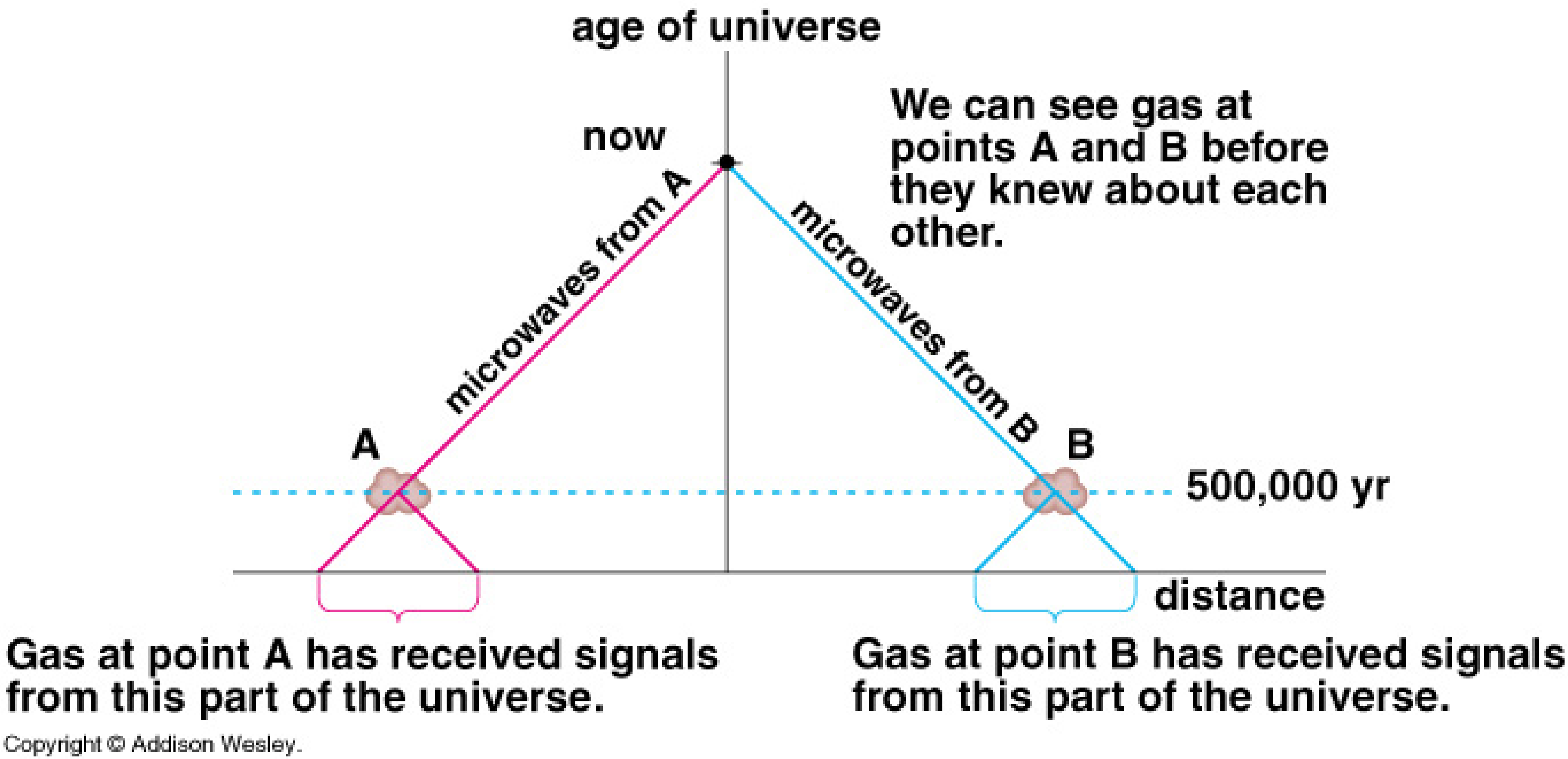
- What is the region of space with which we are in contact ?
  Region with whom we have been able to exchange photons
  (photons: fastest moving particles)
- From which distance have we received light.
- Complication: - light is moving in an expanding and curved space
  - fighting its way against an 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:

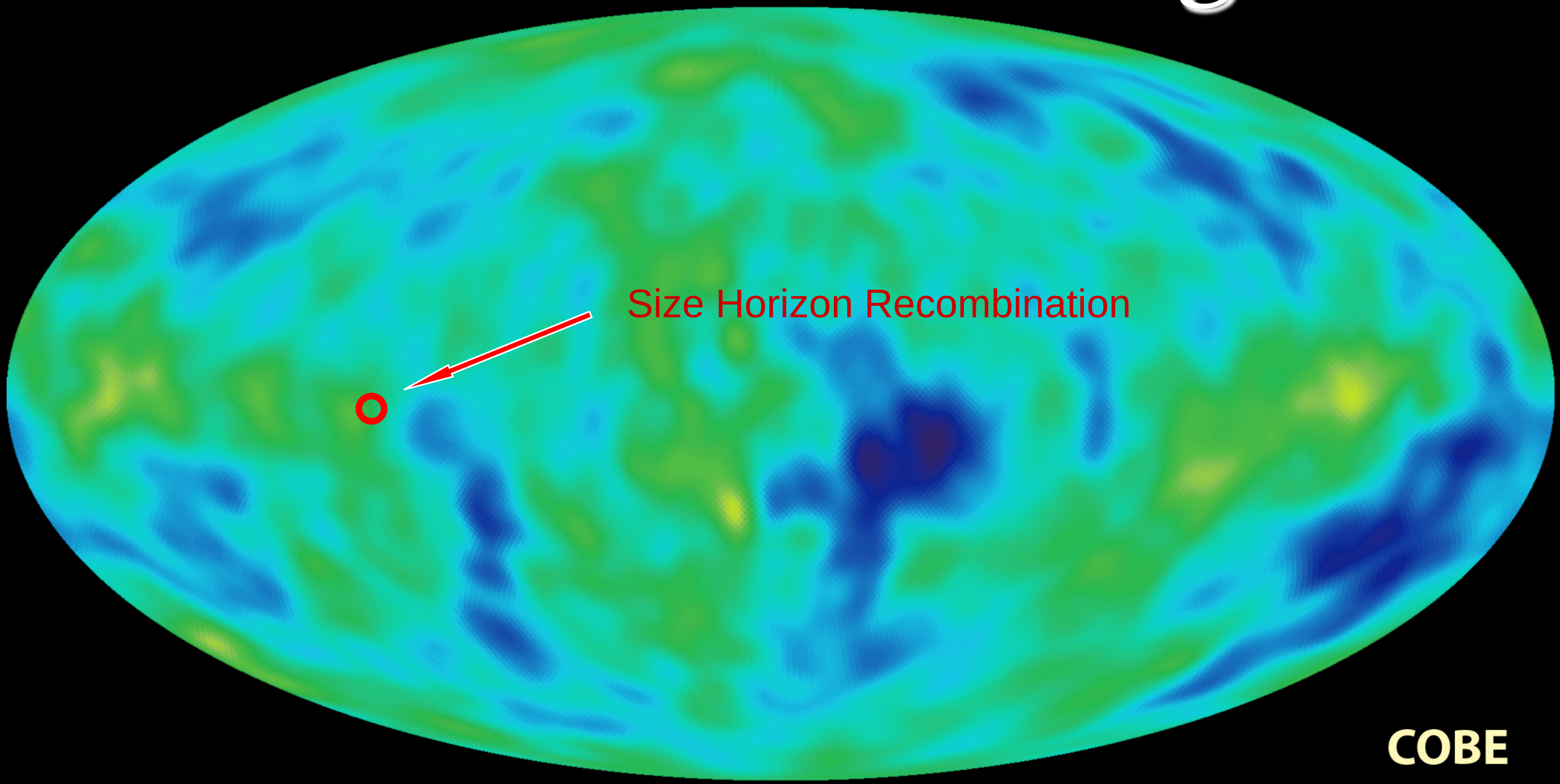
$$R_{Hor} = 3ct$$

$\theta \gg 1^\circ$ 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

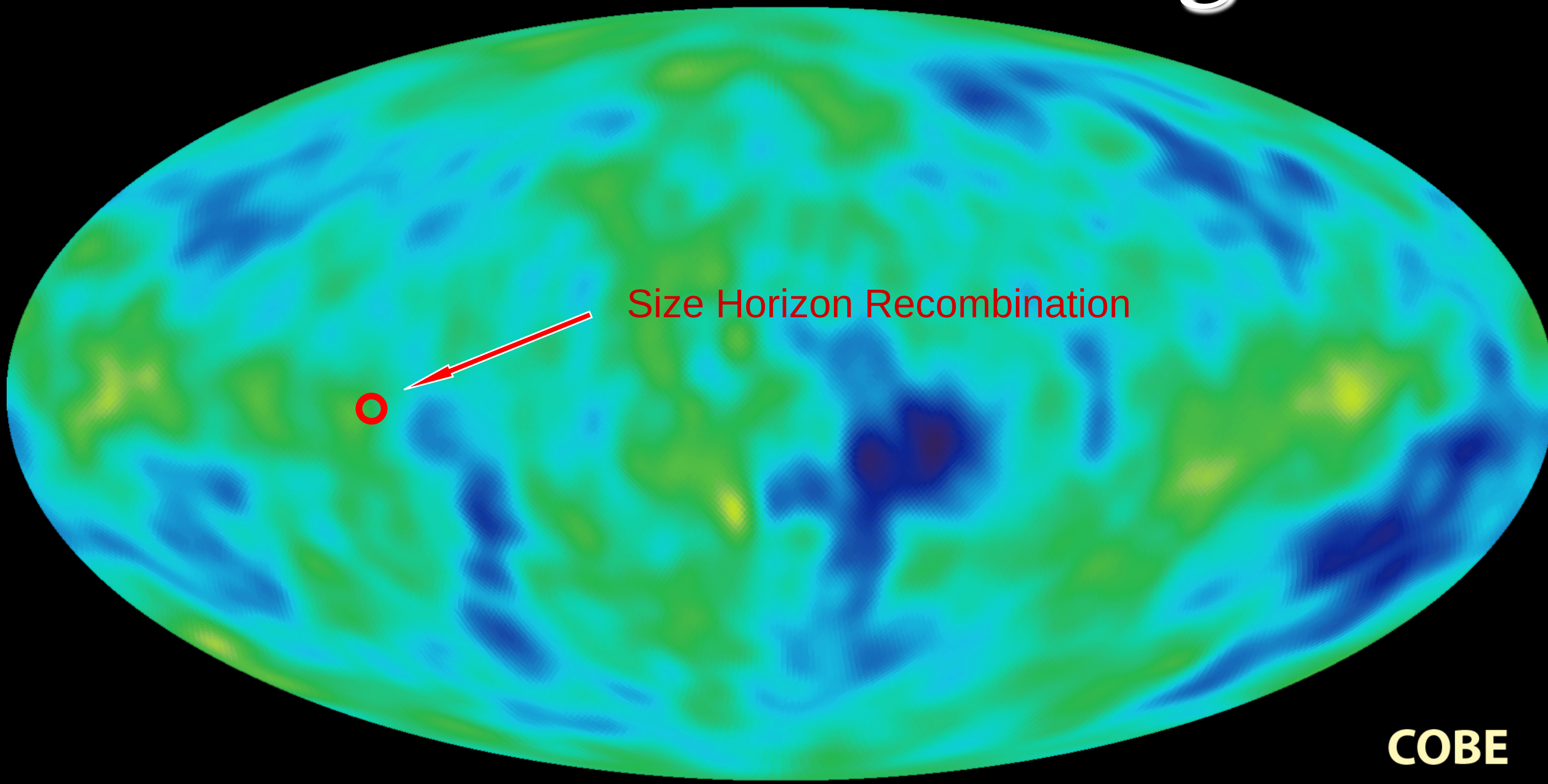


COBE measured fluctuations: > 7°

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: $> 7^{o}$
Size Horizon at Recombination spans angle $\sim 1^{o}$

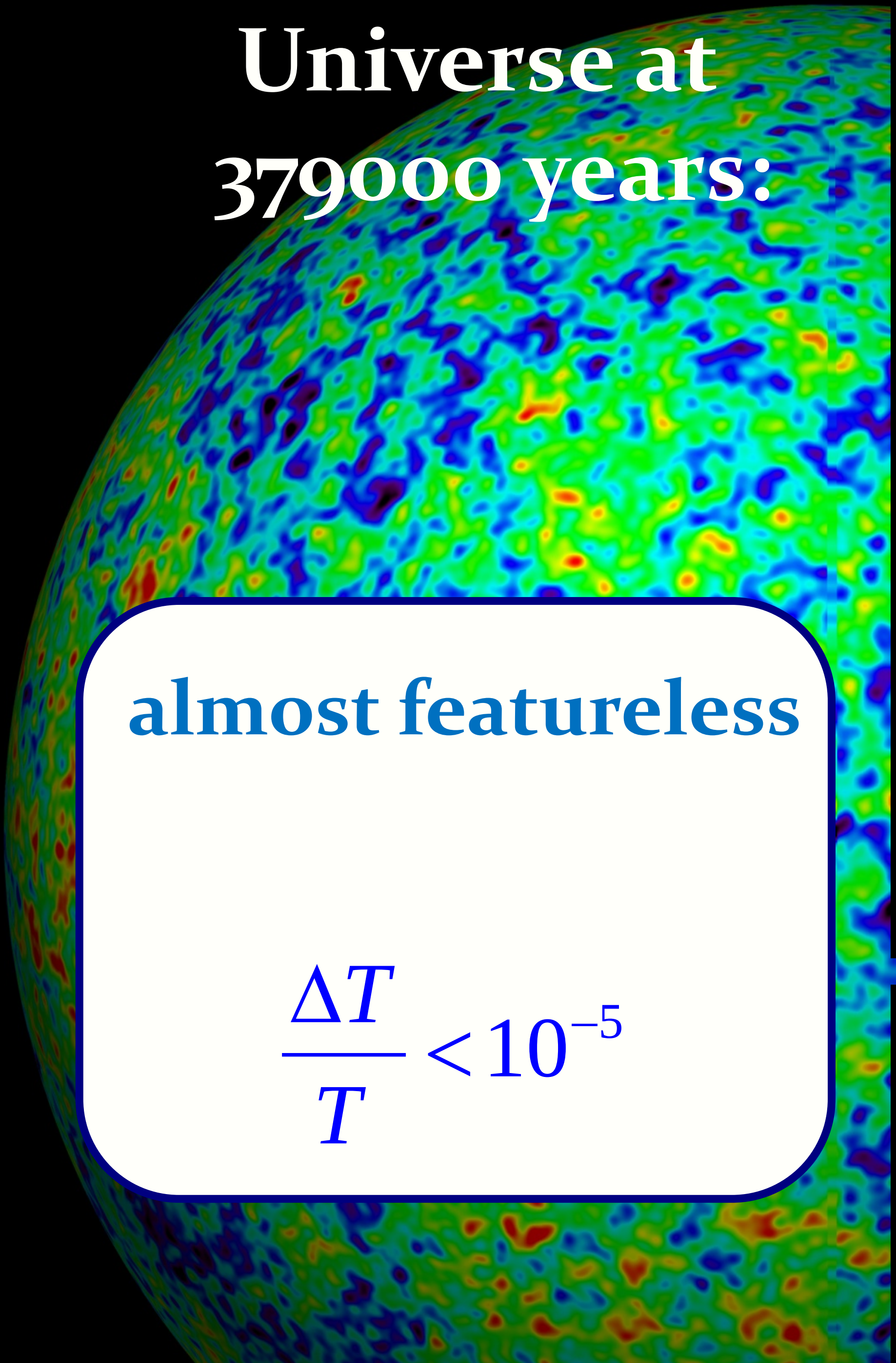
COBE proved that superhorizon fluctuations do exist: prediction Inflation !!!!!

Structure Problem

Primordial Noise:

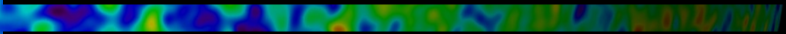
Seeds of Cosmic Structure

Universe at 379000 years:



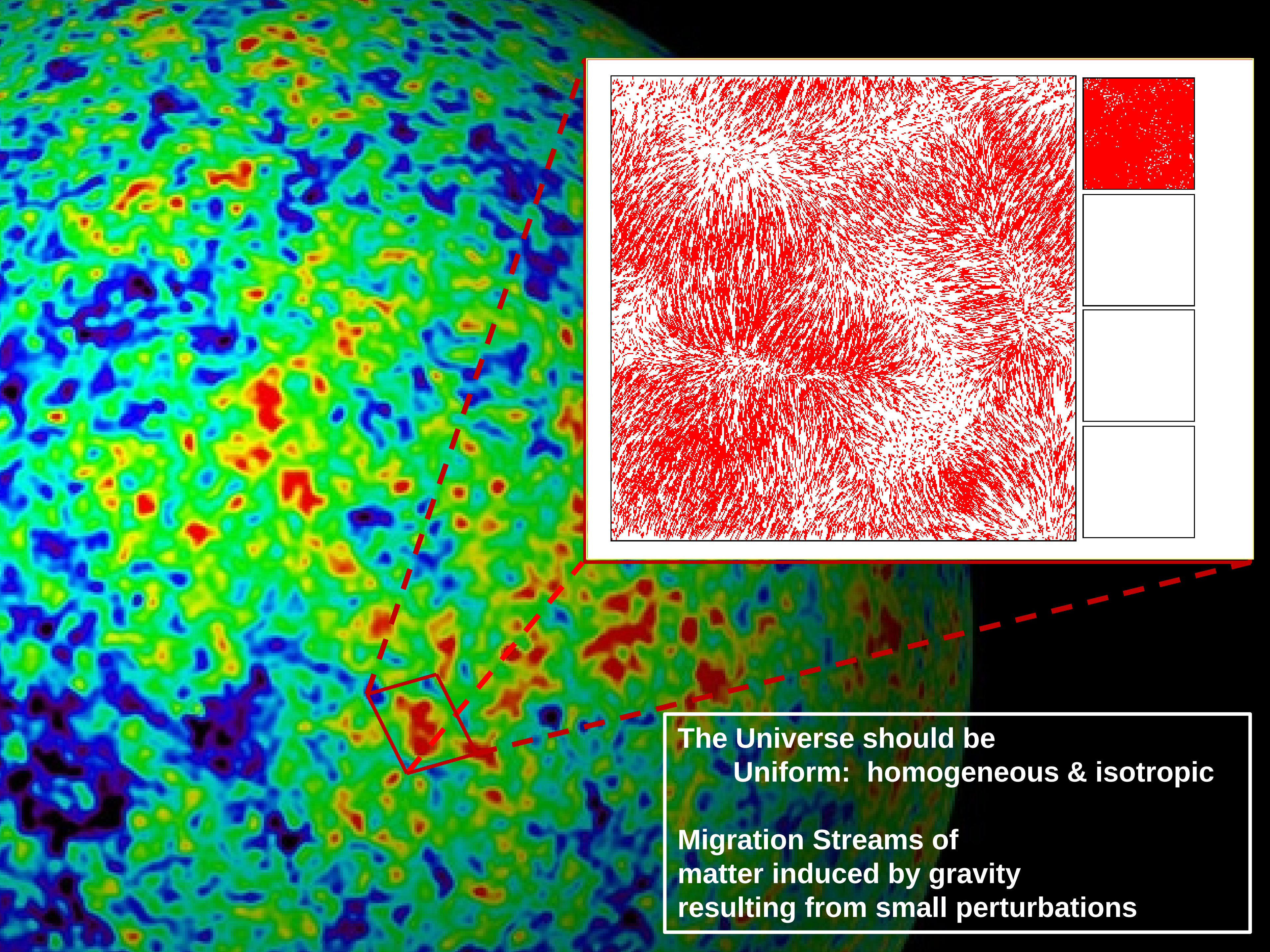
almost featureless

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



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

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


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

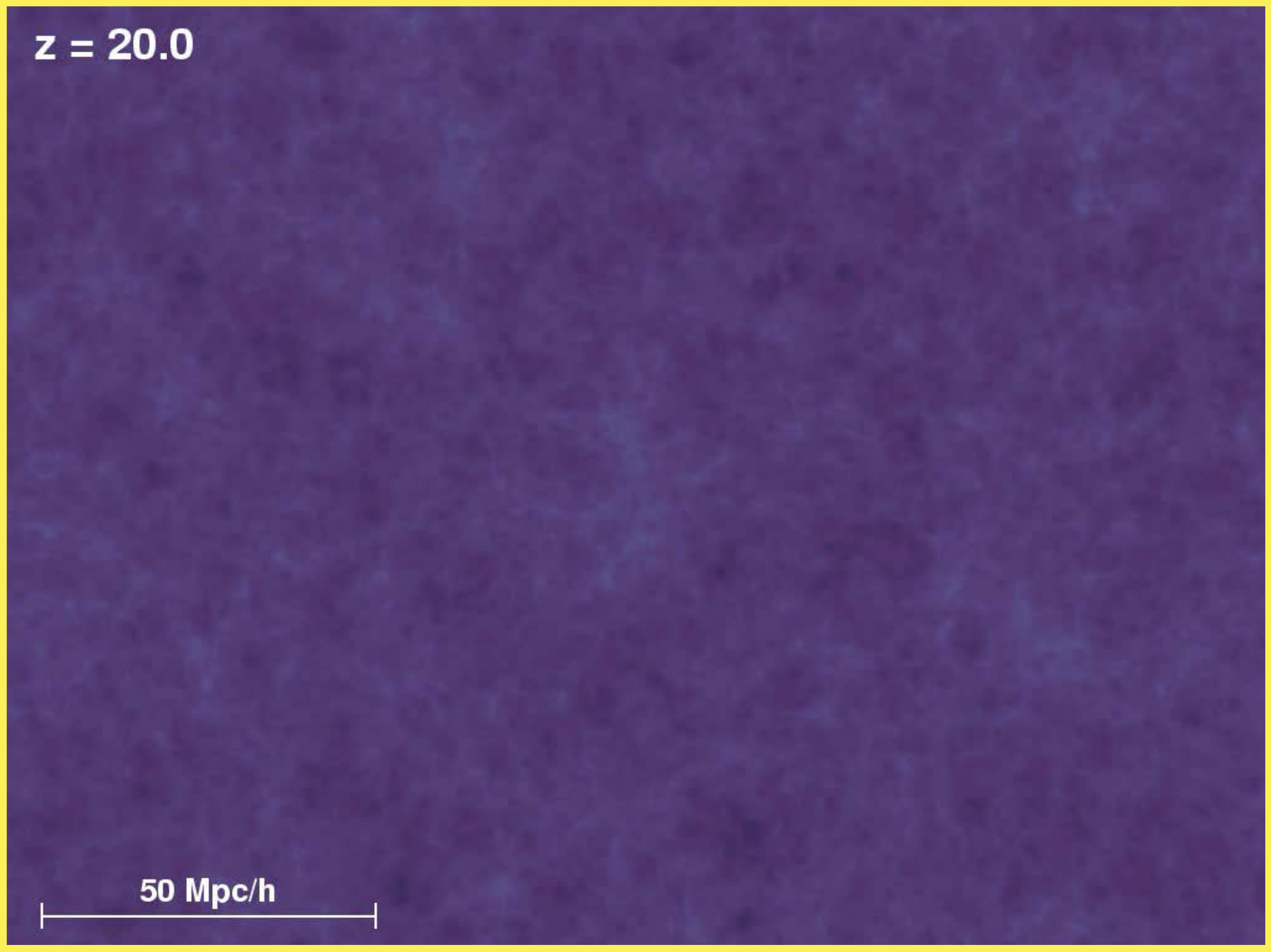
Cosmic Structure Formation

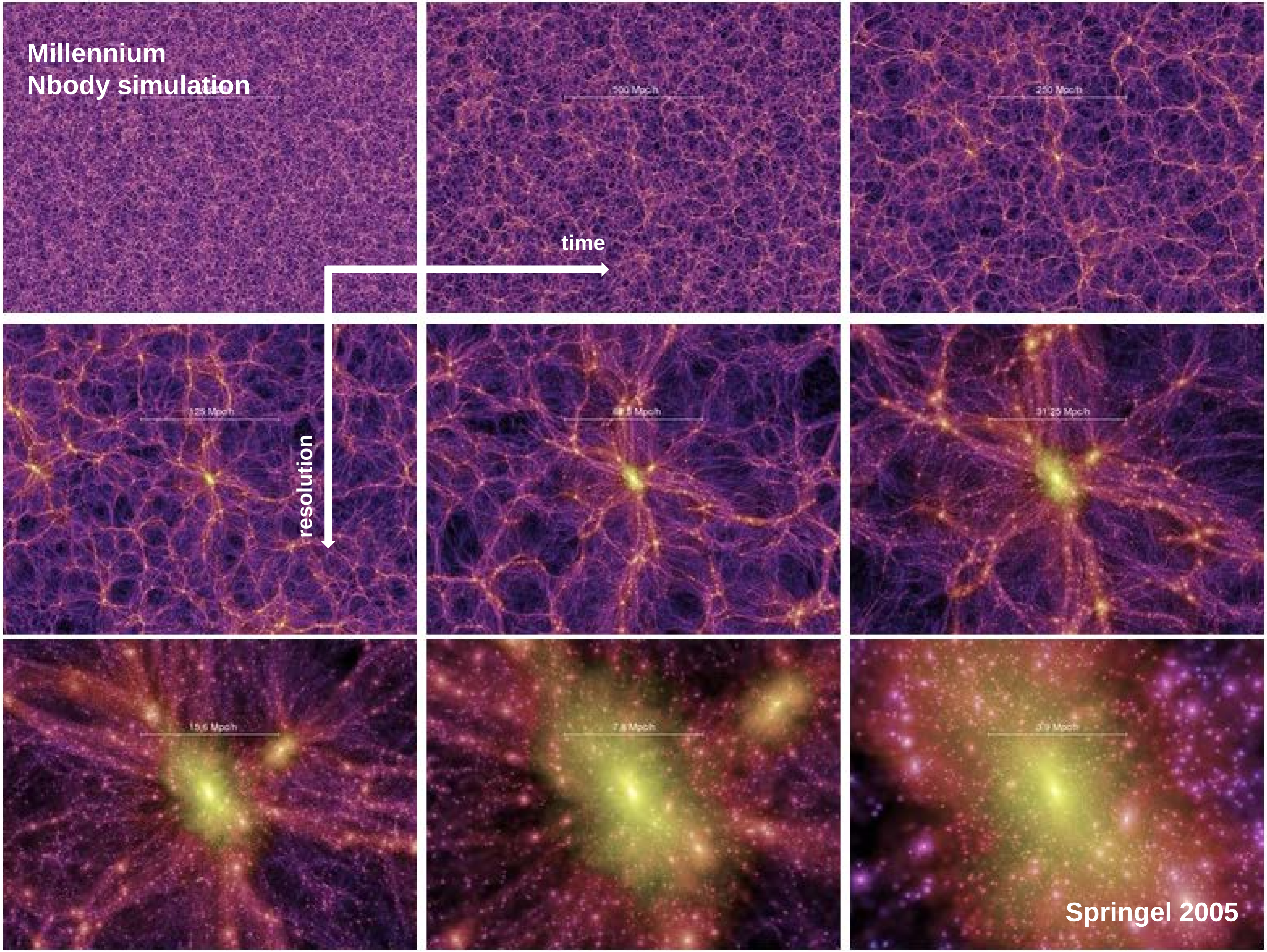
Formation
Cosmic Web:

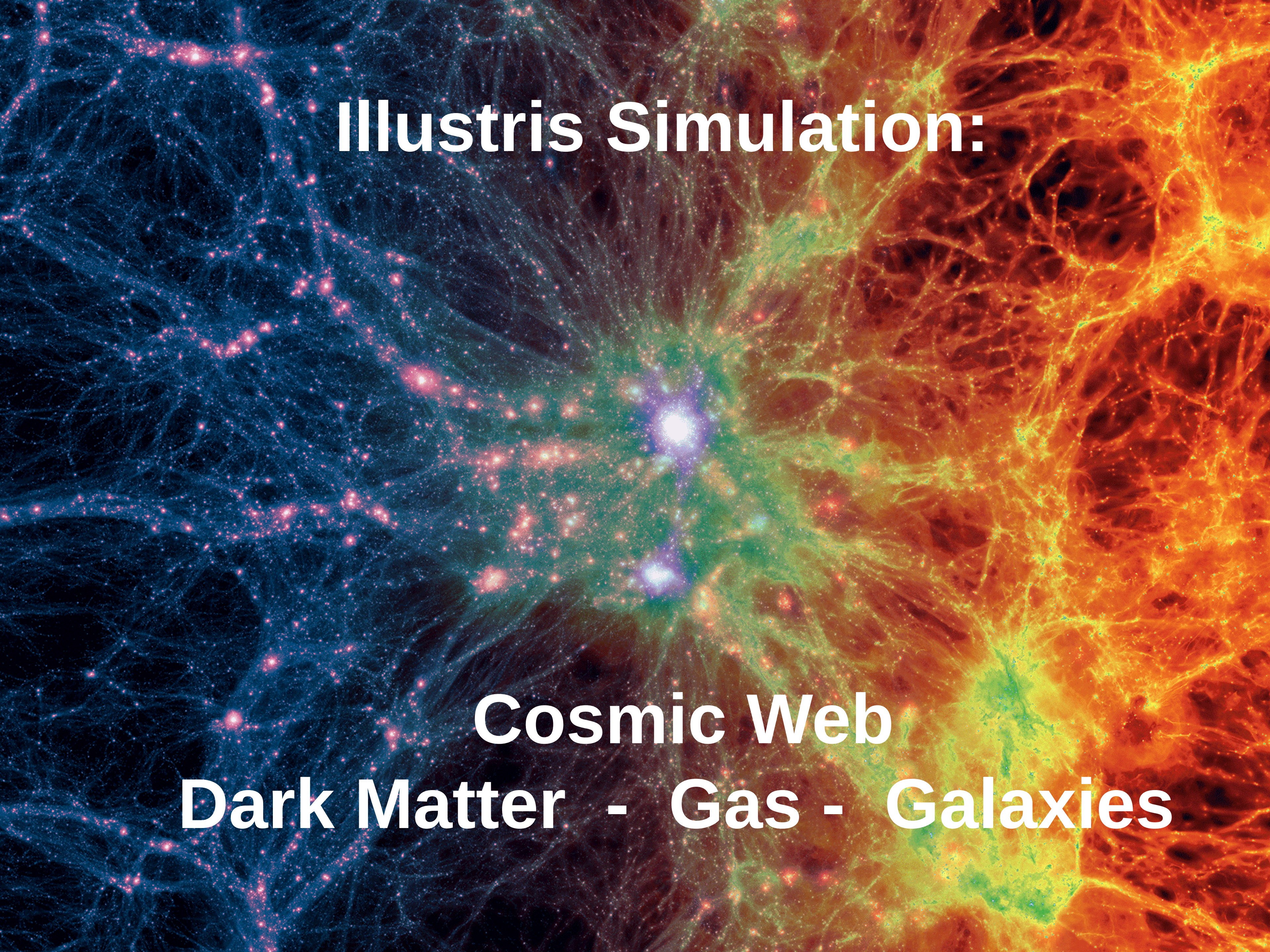
simulation
sequence

(cold)
dark matter

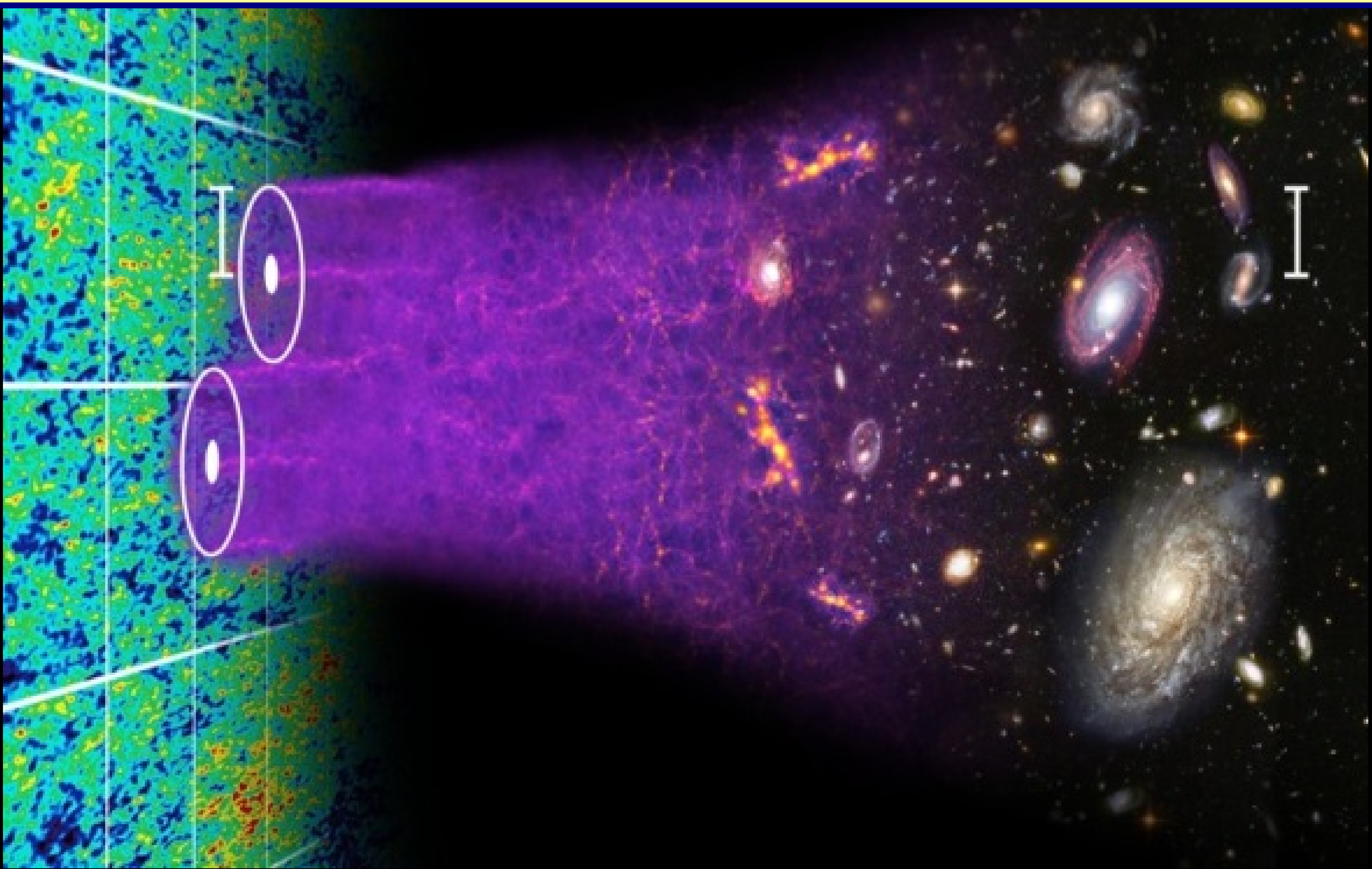
(courtesy:
Virgo/V. Springel).



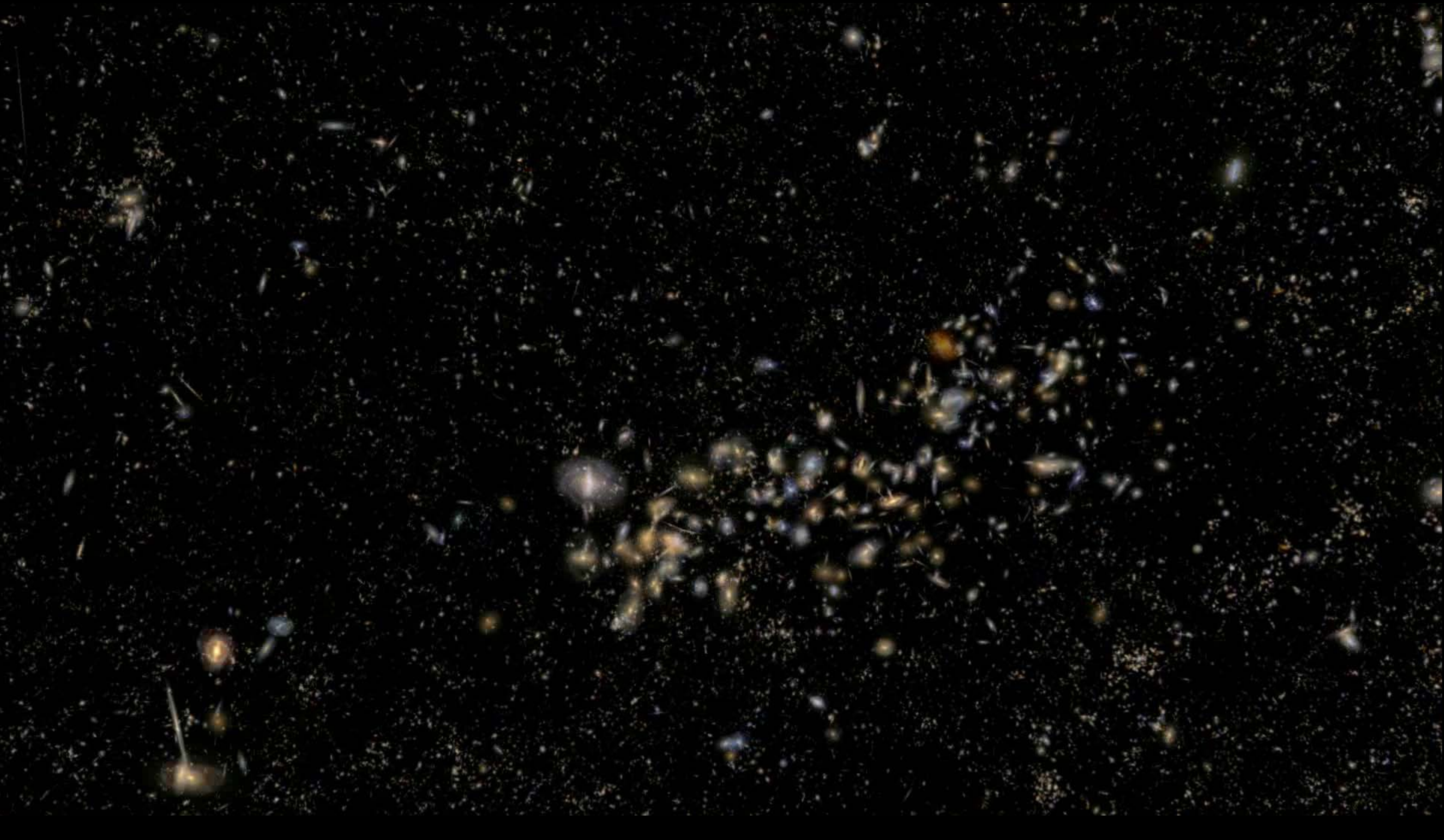

Millennium
Nbody simulation
time
resolution
Springel 2005


Illustris Simulation:
Cosmic Web
Dark Matter - Gas - Galaxies

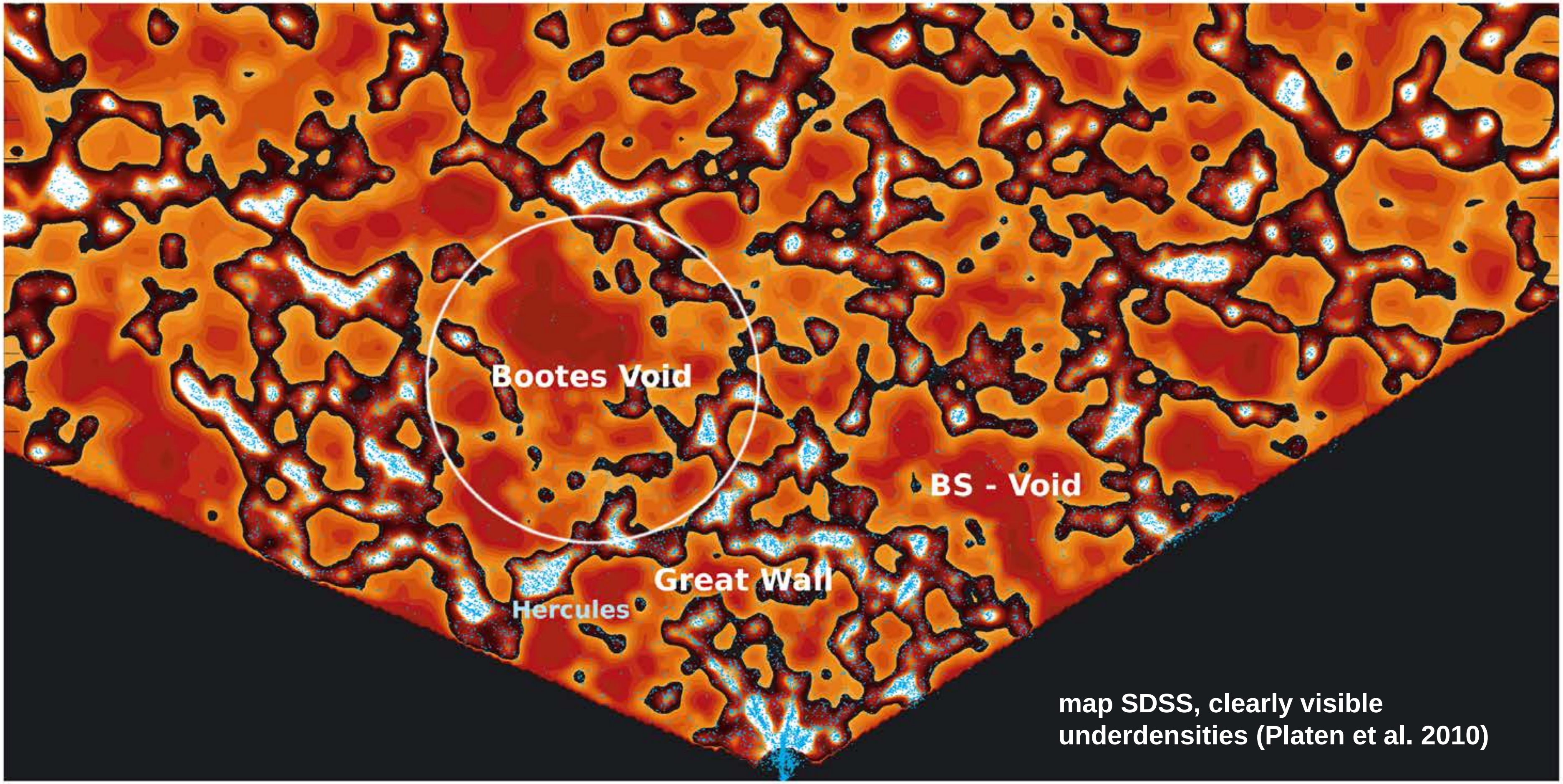
Formation Cosmic Structures



Universe at 13.8 Gyrs: rich & complex structure

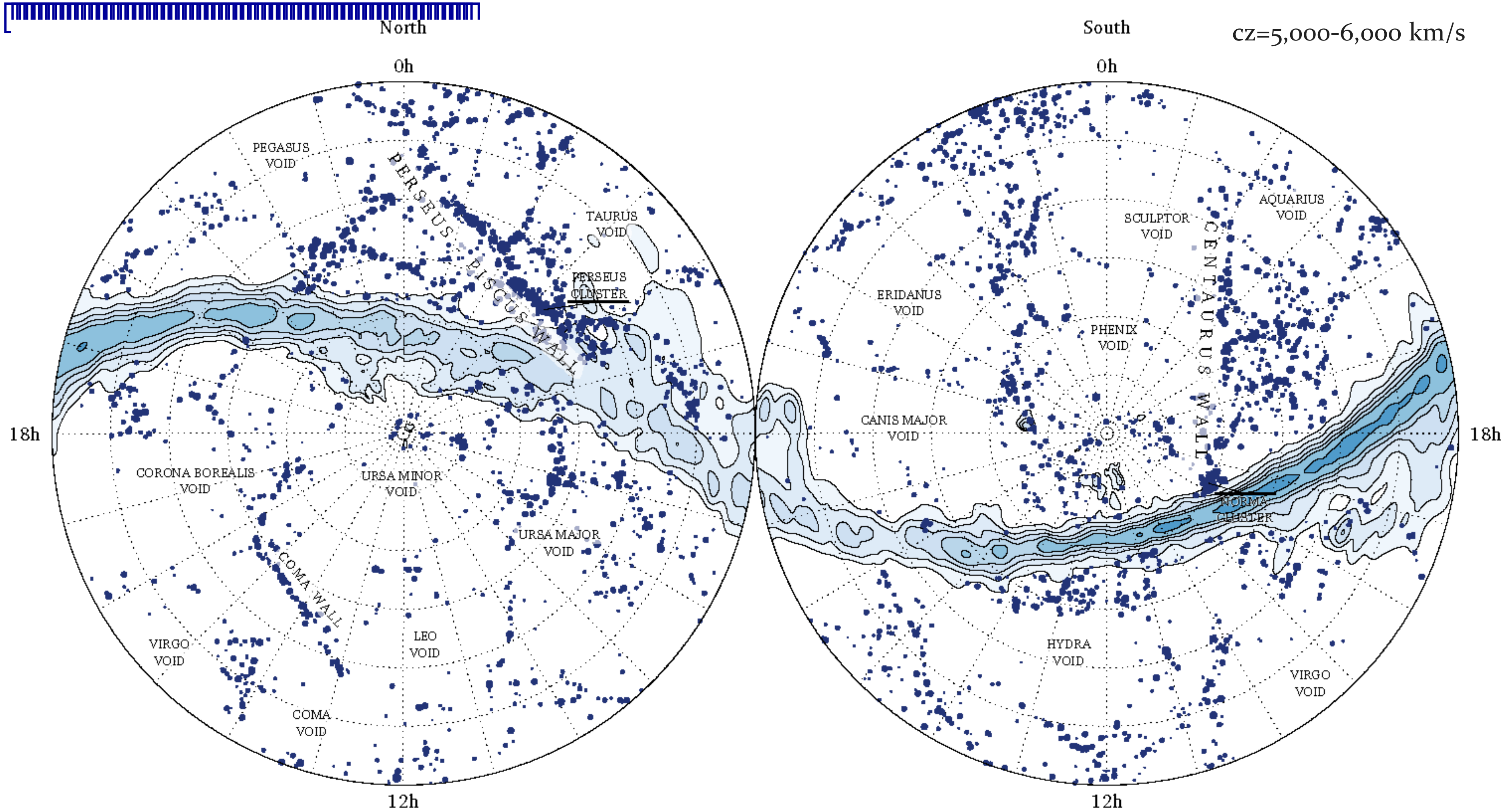


SDSS Galaxy Survey



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

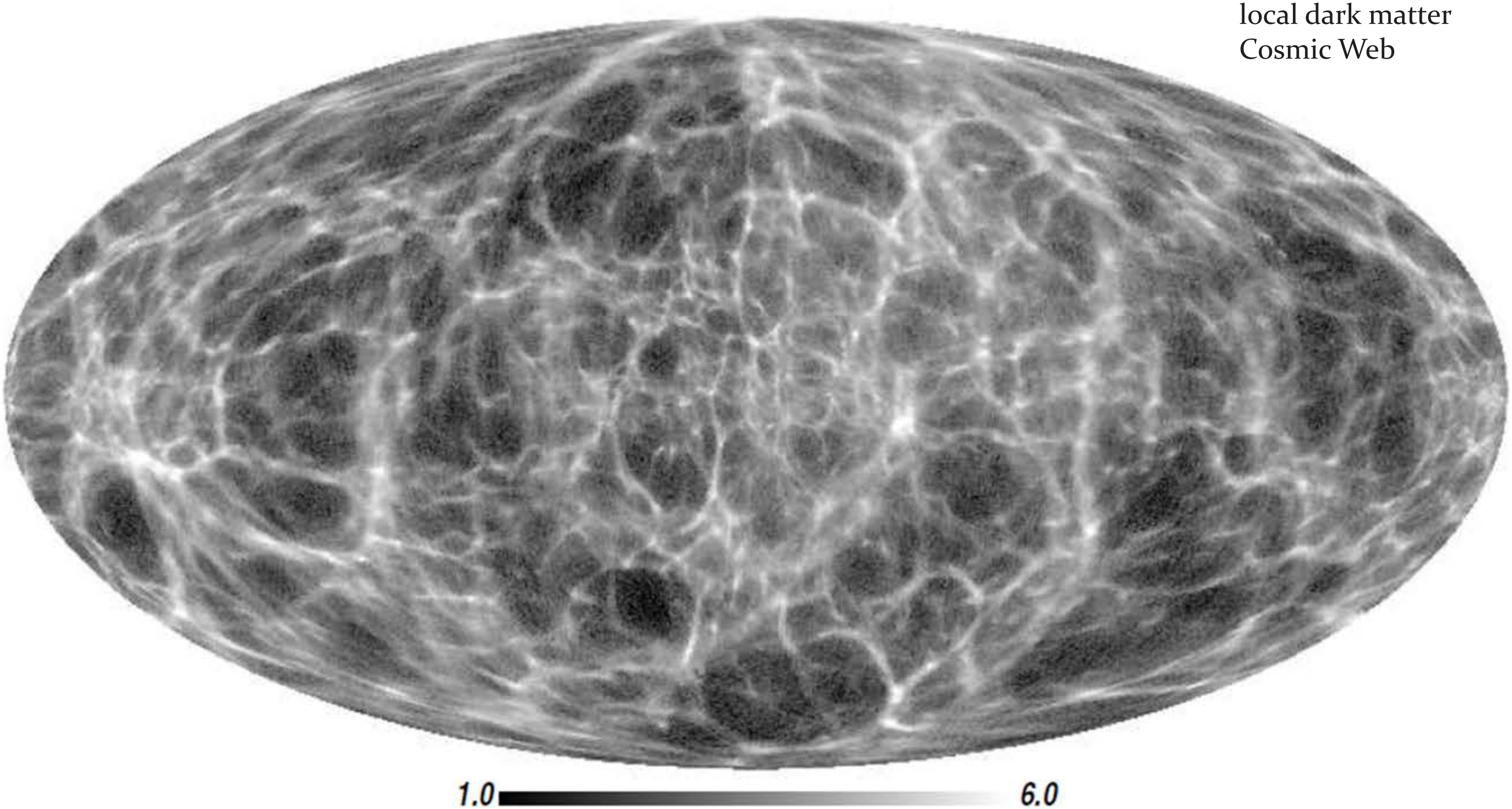


Courtesy: Johan Hidding

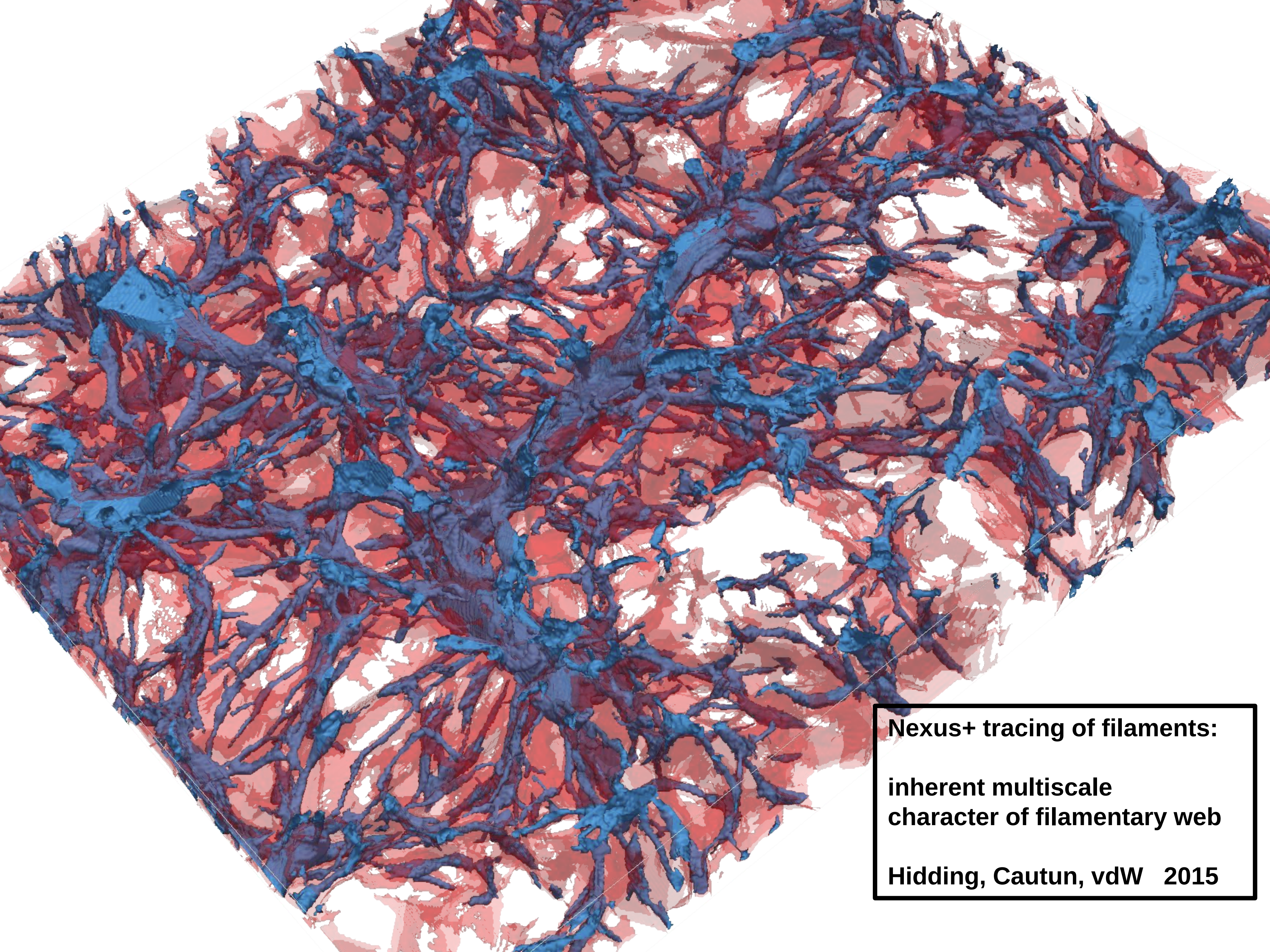
local Cosmic Web: 2MRS

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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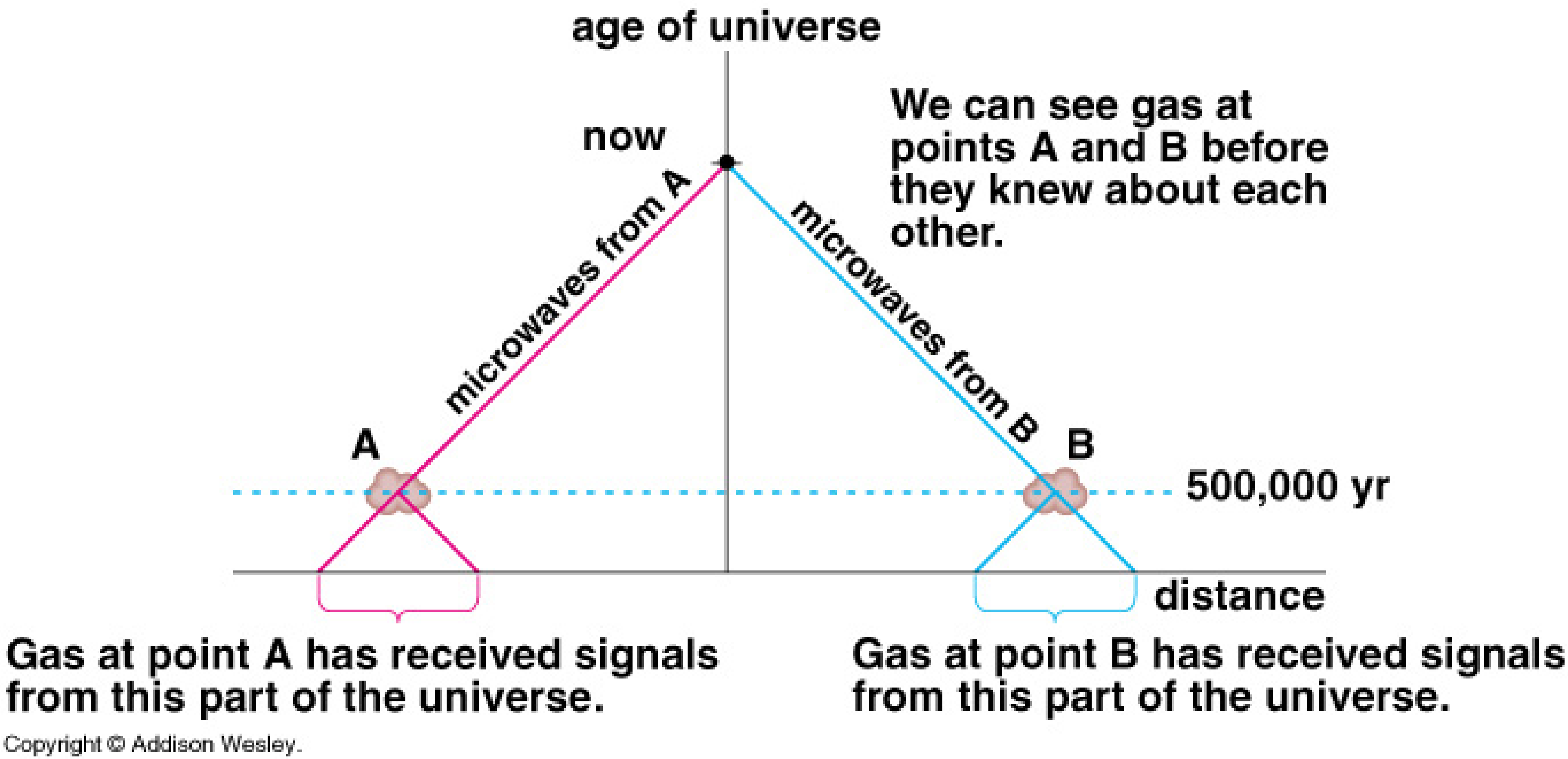
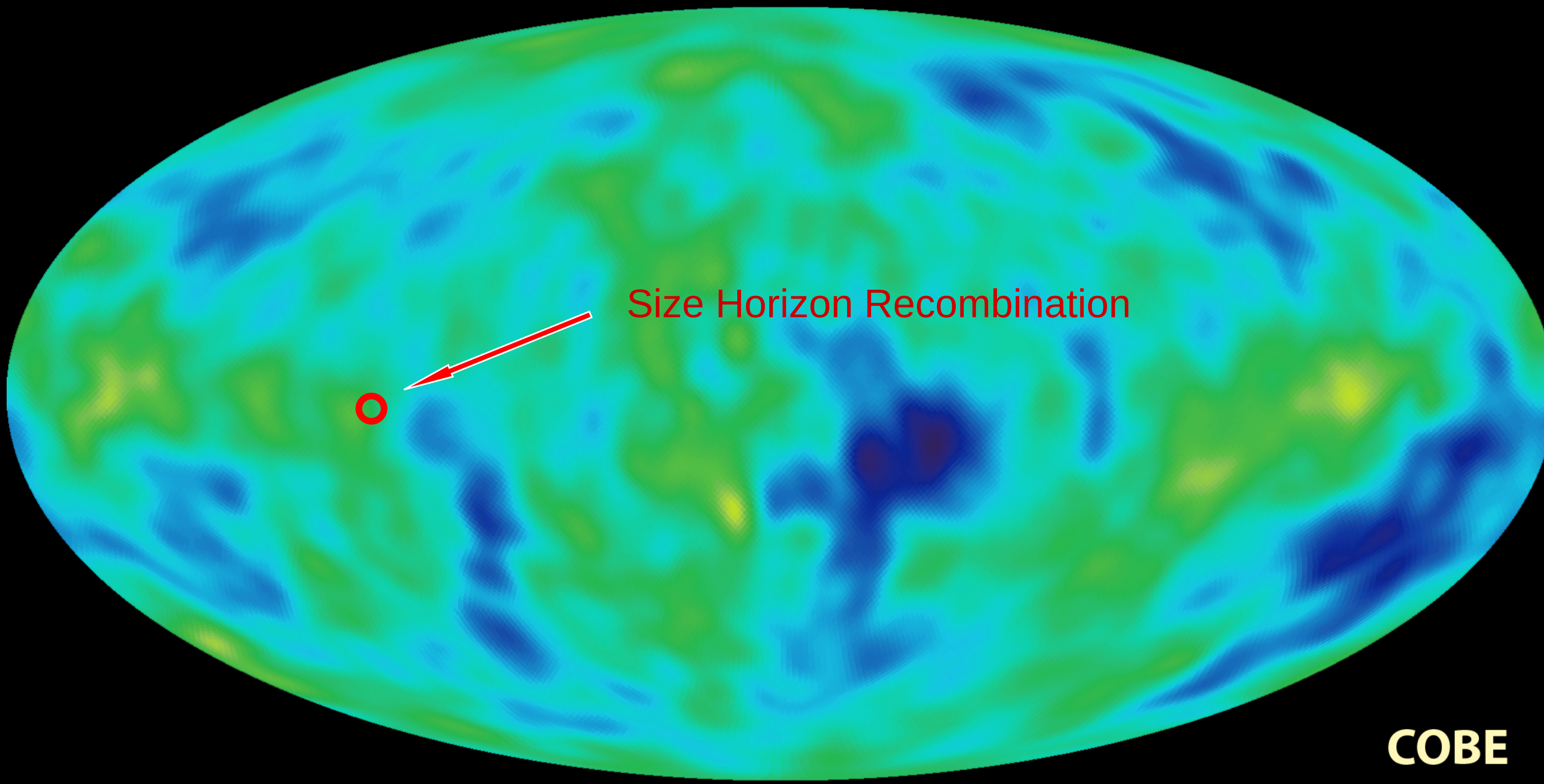
Horizon of the Universe

Cosmic Horizon



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

Probleem van Kosmische Horizon



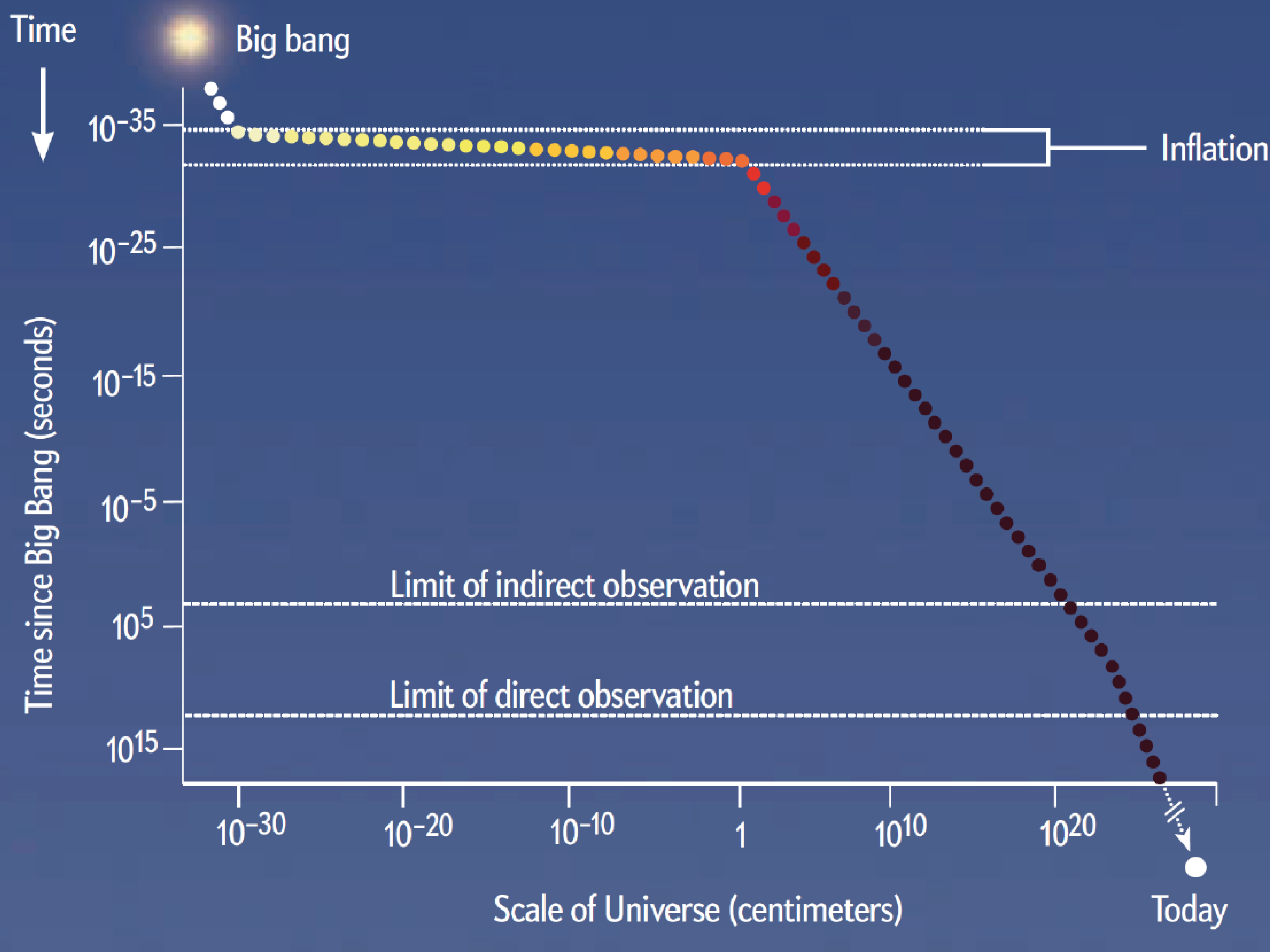
COBE metingen CMB temperatuur fluctuaties: > 7°

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?

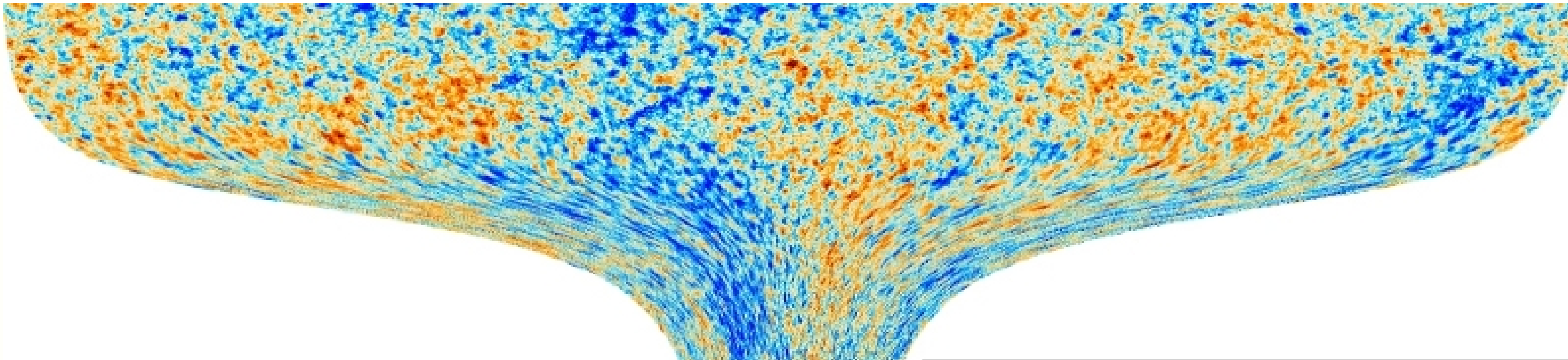
INFLATION


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
105
1015
Limit of indirect observation
Limit of direct observation
10−30
10−20
10−10
1
1010
1020
Scale of Universe (centimeters)
Today

Kosmische Inflatie

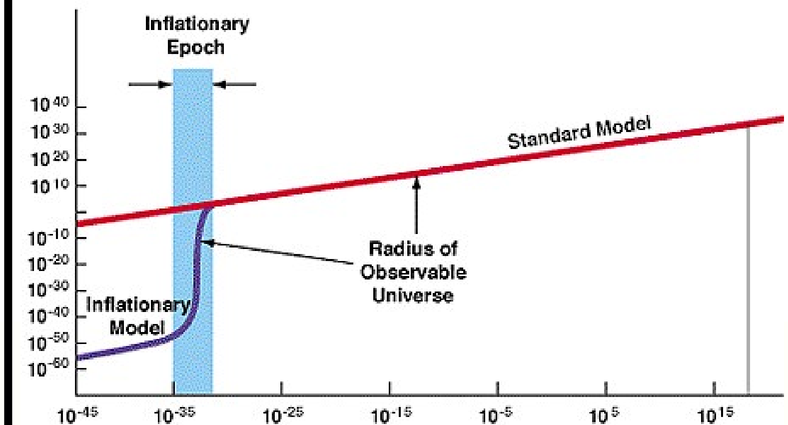


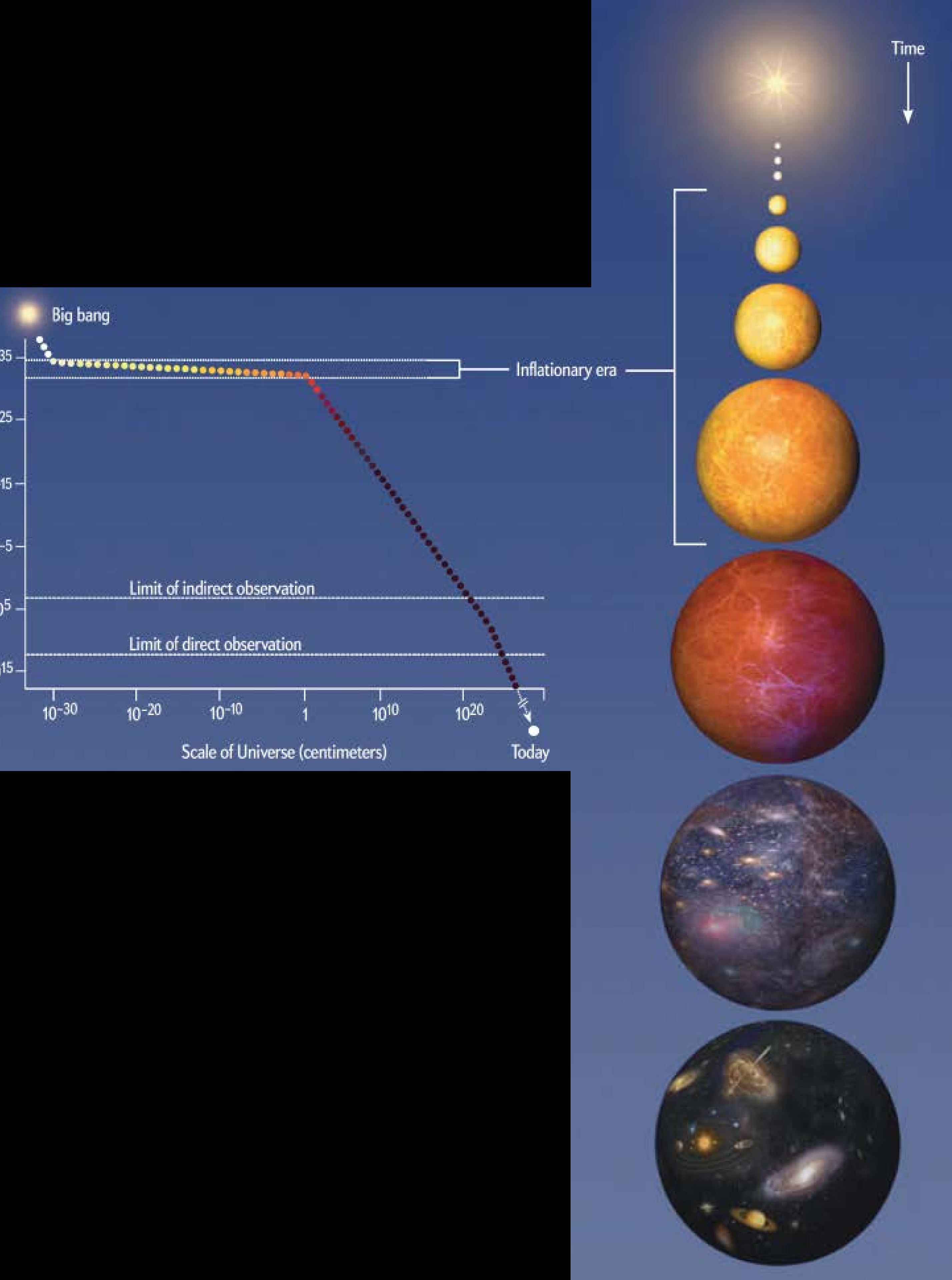
~ 10^{-36} sec. na Big Bang:

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

Afmeting huidige zichtbare Heelal:

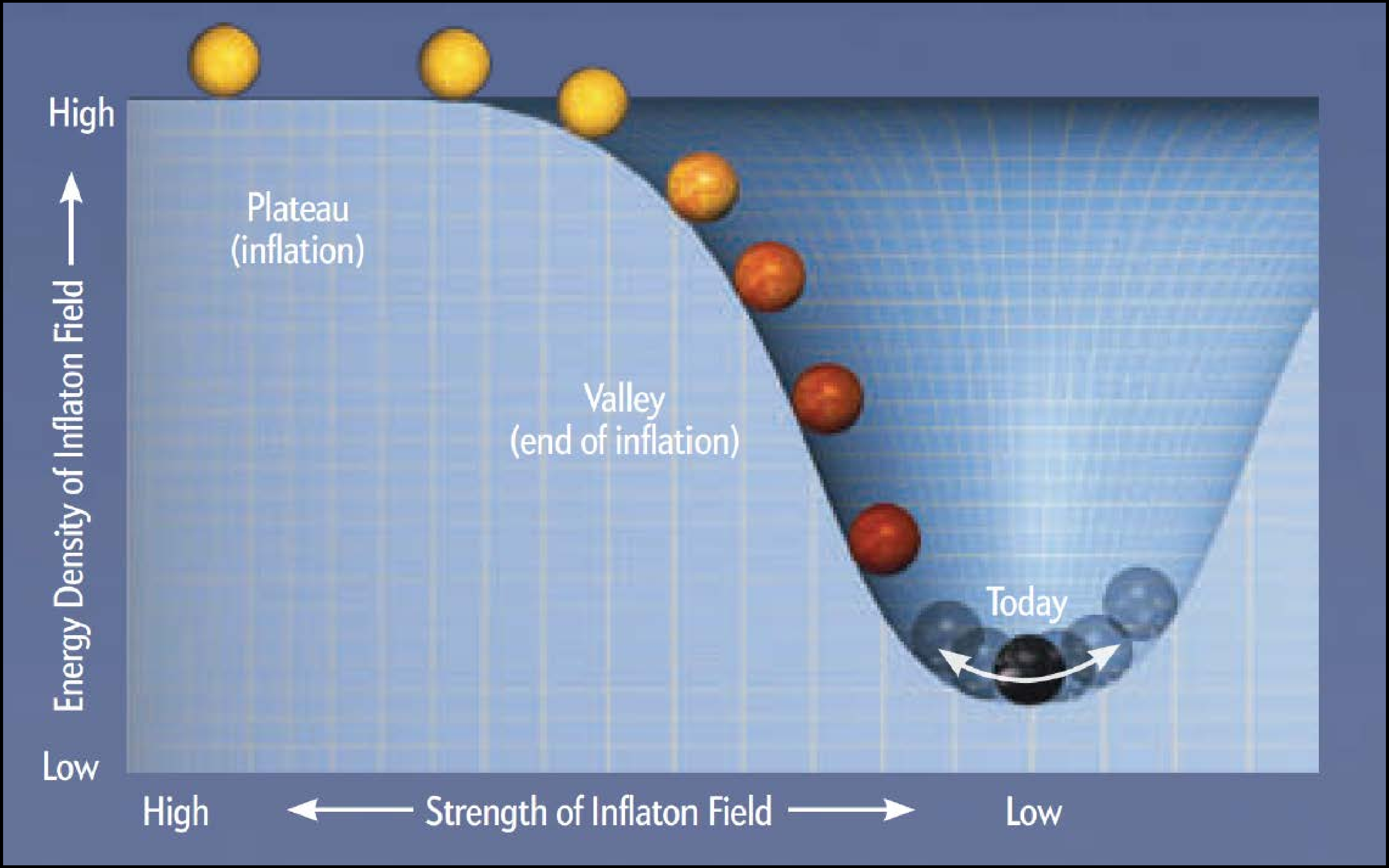
begin inflatie: 10^{-15} afmeting atoom
eind inflatie: diameter van stuiver



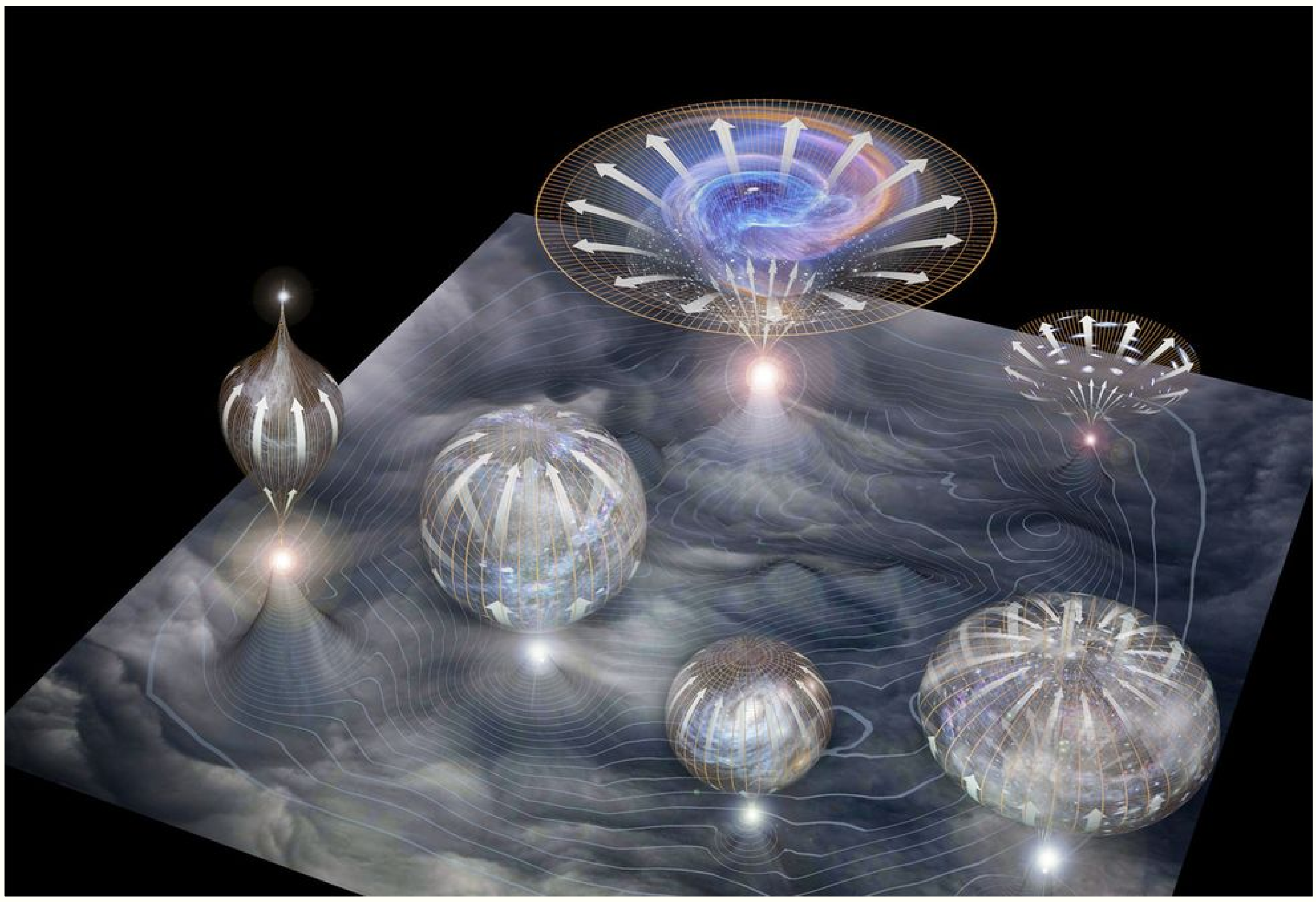


Time
Inflationary era
Big bang
Limit of indirect observation
Limit of direct observation
10^{-30}
10^{-20}
10^{-10}
1
10^{10}
10^{20}
Scale of Universe (centimeters)
Today

Propelling Inflation: Inflaton



Inflatie & Multiverse



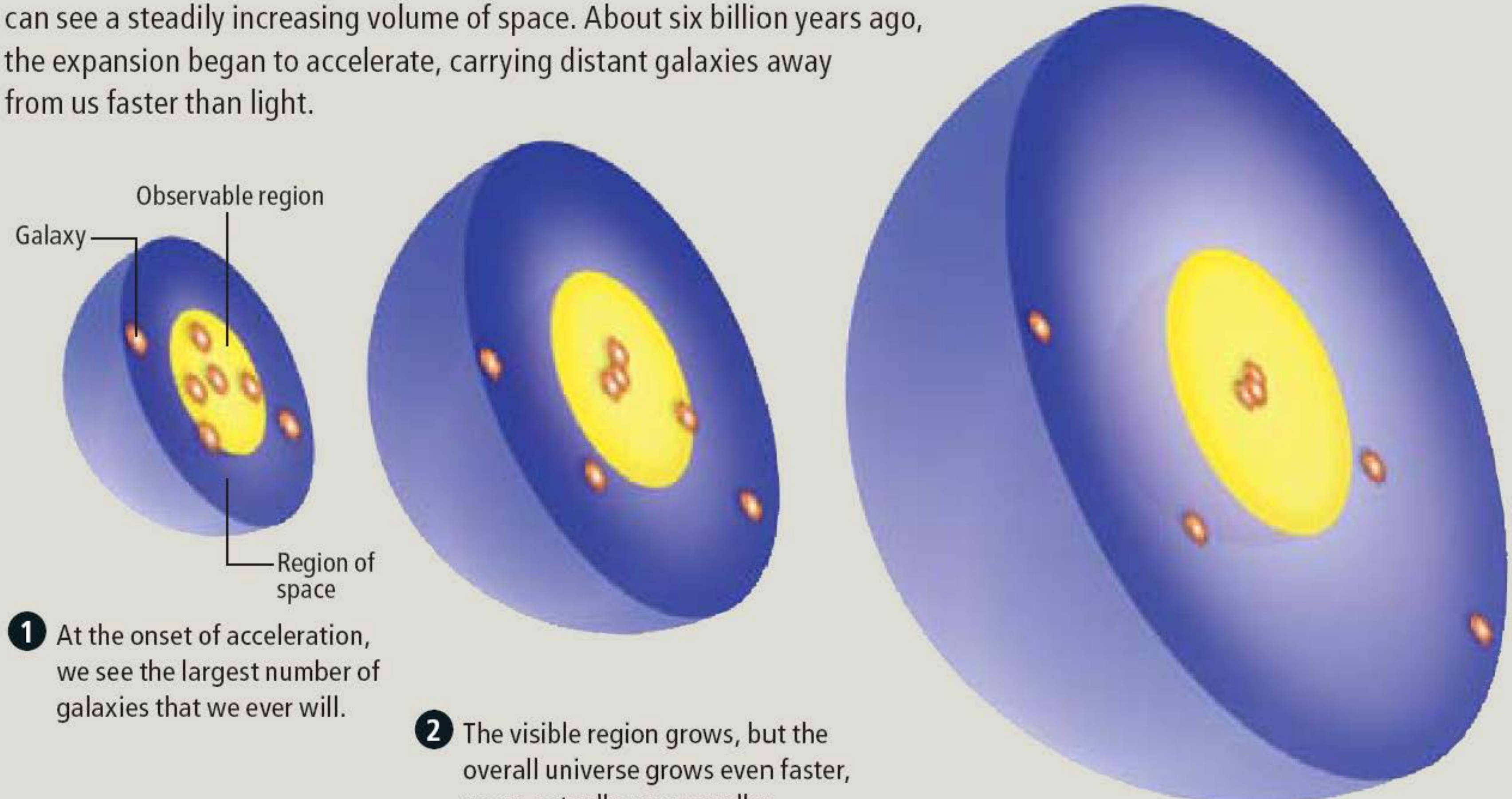
Cosmic Future

Cosmic Fate

100 Gigayears:
the end of Cosmology

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.