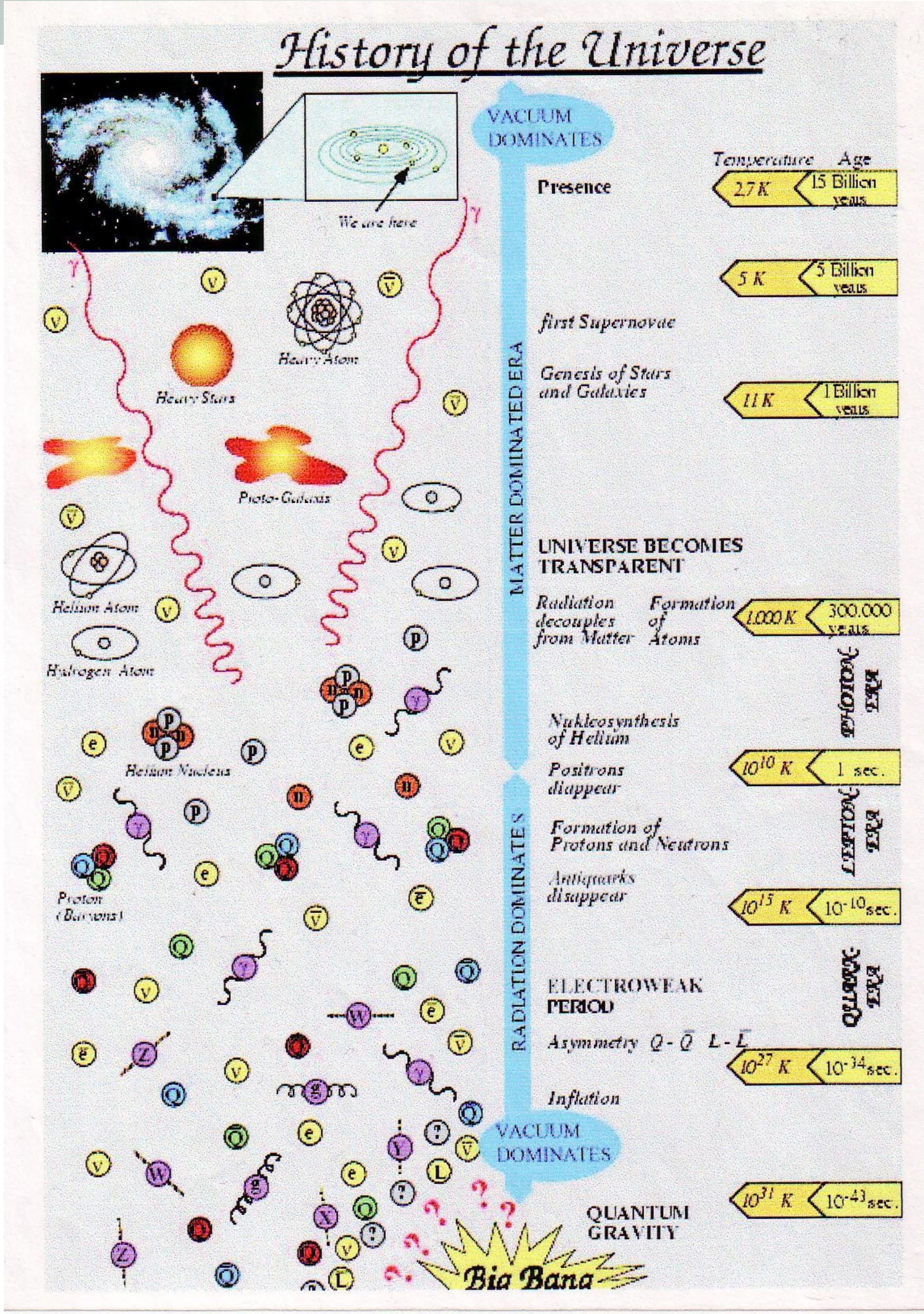
FIZIKALNA

KOZMOLOGIJA

X. OD PRVOTNIH FLUKTUACIJA DO STRUKTURA NA VELIKIM SKALAMA



VEZA FIZIKE ČESTICA I KOZMOLOGIJE

- **"Glashowljeva zmija":**

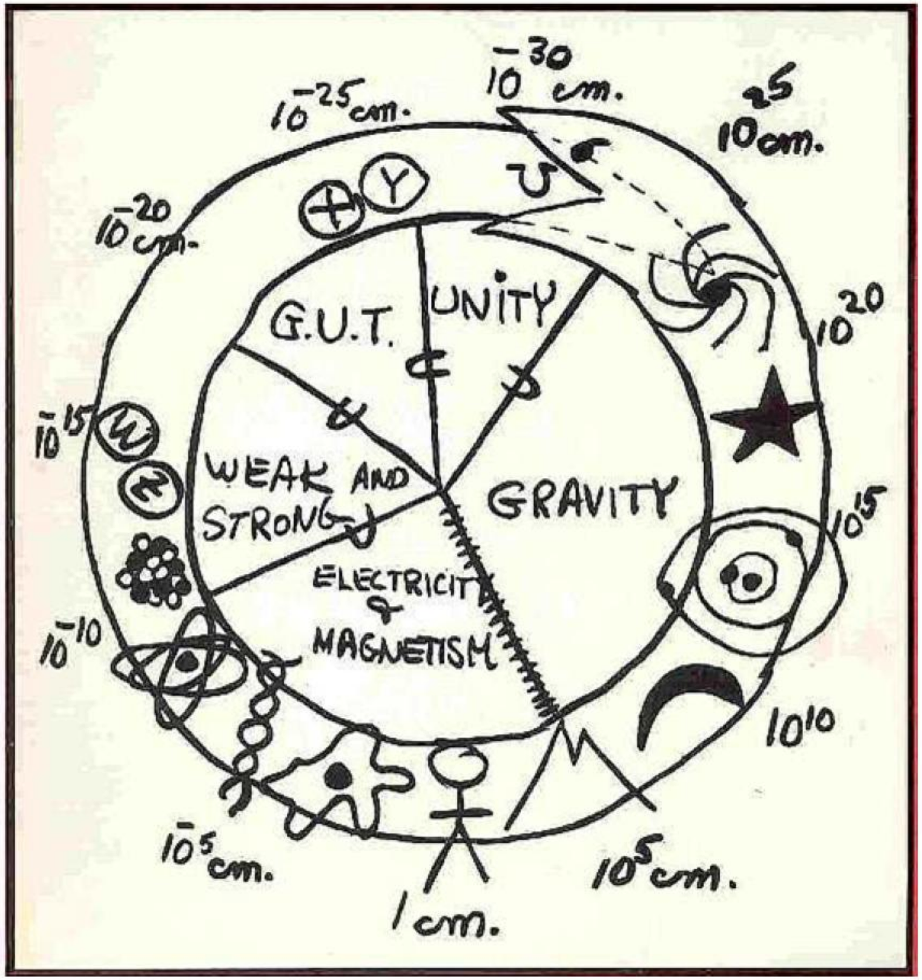


Fig. 1 S. Glashow serpent swallowing its tail, illustrating the interconnection between particle physics and cosmology [1].

1. S. L. Glashow and H. Georgi. New York Times Magazine (26-09-1982), 1982.

DANAŠNJE RAZUMIJEVANJE POVIJESTI SVEMIRA

(de Vega, astro-ph/0307477)

Od rane inflatorne ere

Time	Energy Scale 1 GeV $= 1.16\,10^{13}$ K	Physical Phenomena	Era $1+z = a(\text{today})/a(t)$ Scale Factor $a(t)$
$\sim 10^{-44}$ sec.	$\sim 10^{19}$GeV	Quantum Gravity String Theory Inflation starts	$z > 10^{26+20} = 10^{46}$ $a(t) \sim e^{Ht}$ Inflationary Era
$\sim 10^{-30}$sec.	$\sim 10^{12}$GeV	Inflation Ends and	$z \sim 10^{20}$

preko stvaranja čestica i lakih elemenata

		Particle Creation Starts	
		Reheating Transition	
		GUT Phase Transition	$a(t) \sim \sqrt{t}$
		Hot Big Bang: Thermalization	
$\sim 10^{-10}$sec.	$\sim 10^{3}$GeV	Electro-Weak Phase Transition	
		Baryon Asymmetry Originates?	Radiation
	$\sim 10^{2}$GeV	Baryogenesis	Dominated
$\sim 10^{-4}$sec.	~ 1GeV	Quark-hadron and Chiral	Era
$\sim 10^{-2}$sec.	~ 0.1GeV	Phase Transitions	
		$\gamma,\ \nu,\ ,e,\ \bar{e}, n, p$ in thermal equilibrium	
	~ 1MeV	Neutrinos decouple	
1sec.			
		Nucleosynthesis	
100sec.	~ 0.1MeV	Creation of Light Elements	$z \sim 10^{4}$

do stvaranja opaženih struktura

20000 years		Structure Formation Begins Onset of Gravitational Unstability	$a(t) \sim t^{2/3}$
10^5 years		Atoms Form	$z \sim 10^3$
		Photon Decoupling The Universe Becomes Transparent	Matter Dominated Era
10^9 years	first bound structures	Galaxy Formation	
		Solar system formation	Cold matter dominates but dark energy...
$1.4\,10^{10}$ years	$\sim 10^{-4}$eV	Today	$z = 1$

PITANJA VEZANA UZ RANU INFLATORNU ERU:

- **Što je pogonilo inflaciju i kako je ona završila?**
- **Priroda tamne energije i kako se mijenja u prostoru i vremenu?**
- **Priroda tamne tvari i njen utjecaj na evoluciju struktura u svemiru?**

Ispitni seminari

“FOSILI” KOJI NAM MOGU NEŠTO REĆI O INFLACIJI:

- **Perturbacija gustoća**

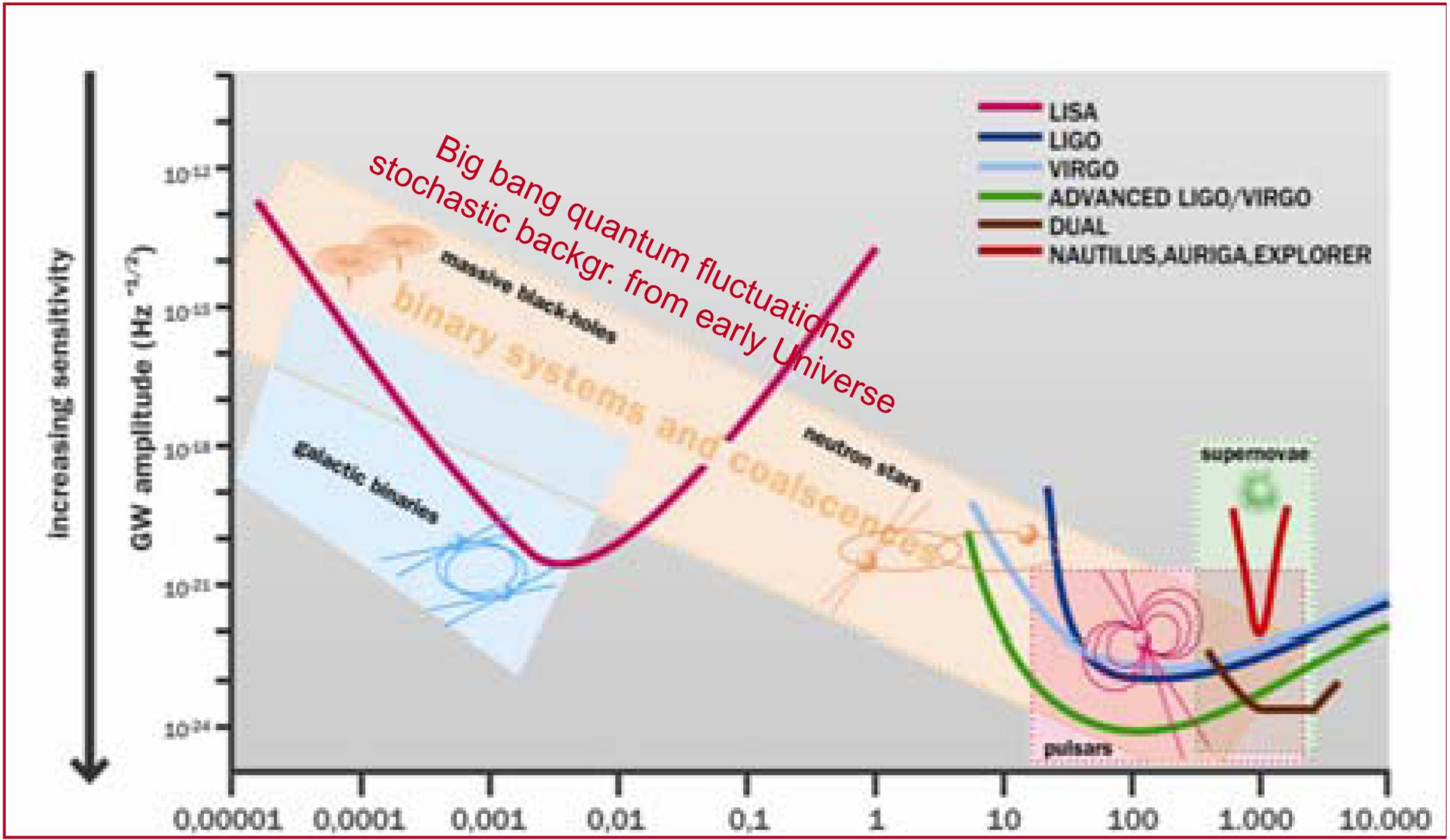
- generira anizotropije CMBa putem Sachs-Wolfe efekta

- ravni spektar fluktuacija potreban za formiranje galaktika (Harrison-Zeldovich)

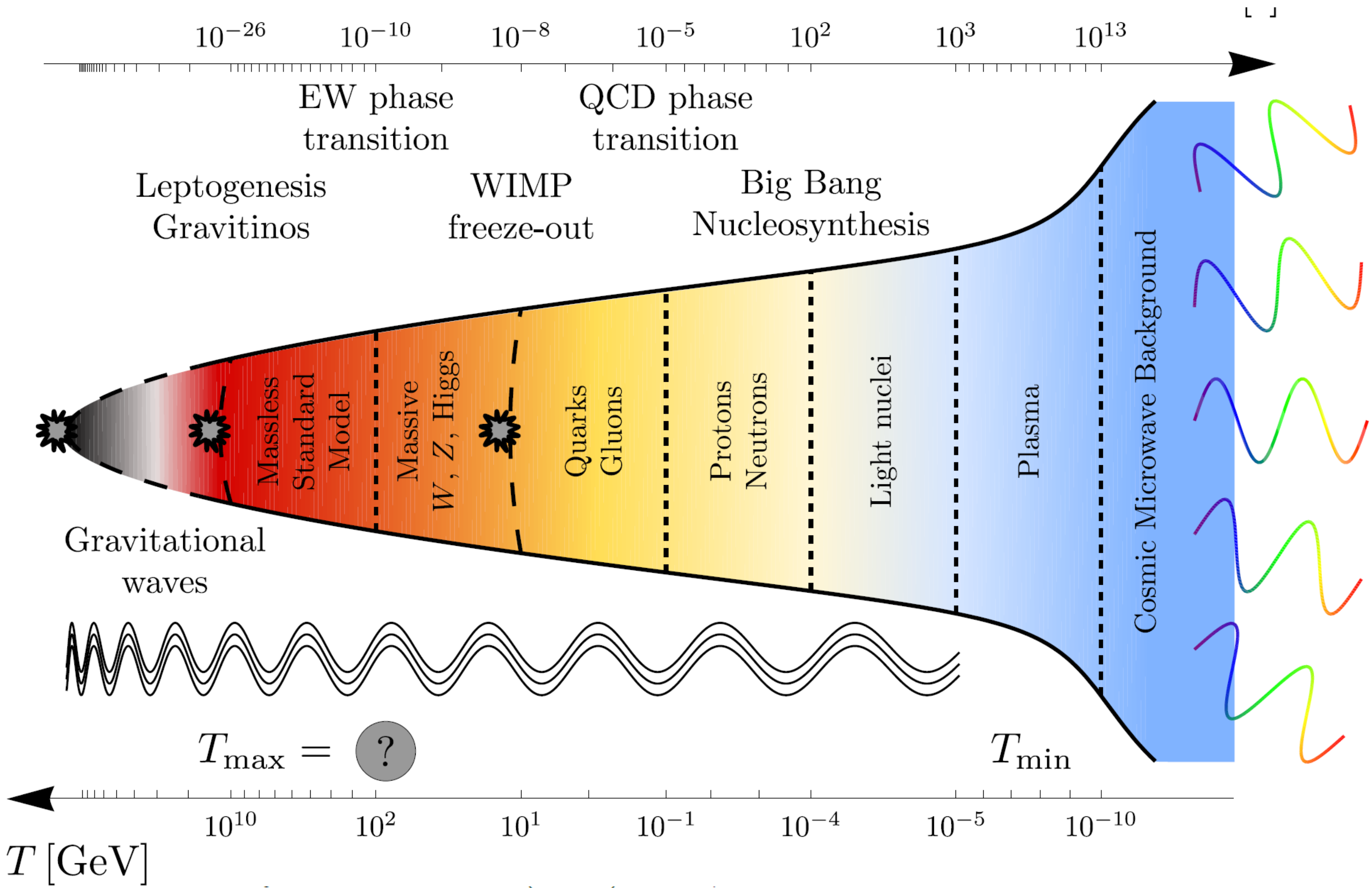
- **Gravitacijski valovi**

Seminari?

Gravitacijski valovi



VRUĆA TERMIČKA FAZA SVEMIRA

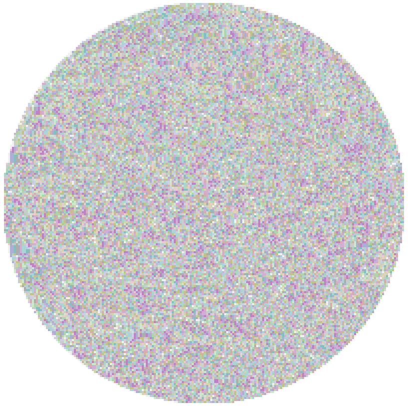


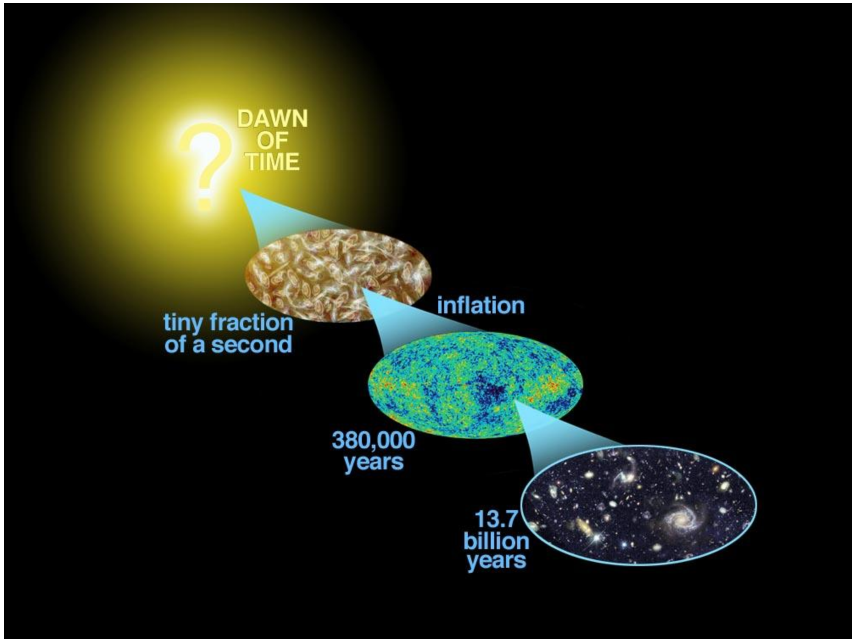
K. Schmitz, *The B-L Phase Transition: Implications for Cosmology and Neutrinos.* PhD thesis, 2012. arXiv:1307.3887. DESY-THESIS-2012-039.

Fig. 2 Chronology of the hot thermal phase of the early universe. The top scale shows the time after the Big Bang and the bottom scale the corresponding post-inflationary reheating temperature [3].

Figure 2.1: Timeline of the hot thermal phase of the early universe illustrating (i) the relation between the temperature of the thermal bath T and the cosmic time t (cf. Eq. (2.23)), (ii) the chronology of several important, partly hypothetical nonequilibrium processes, (iii) a representative selection of those forms of matter or energy that are respectively involved in these processes, and (iv) several possibilities for the reheating temperature after inflation (cf. Sec. 3.1).

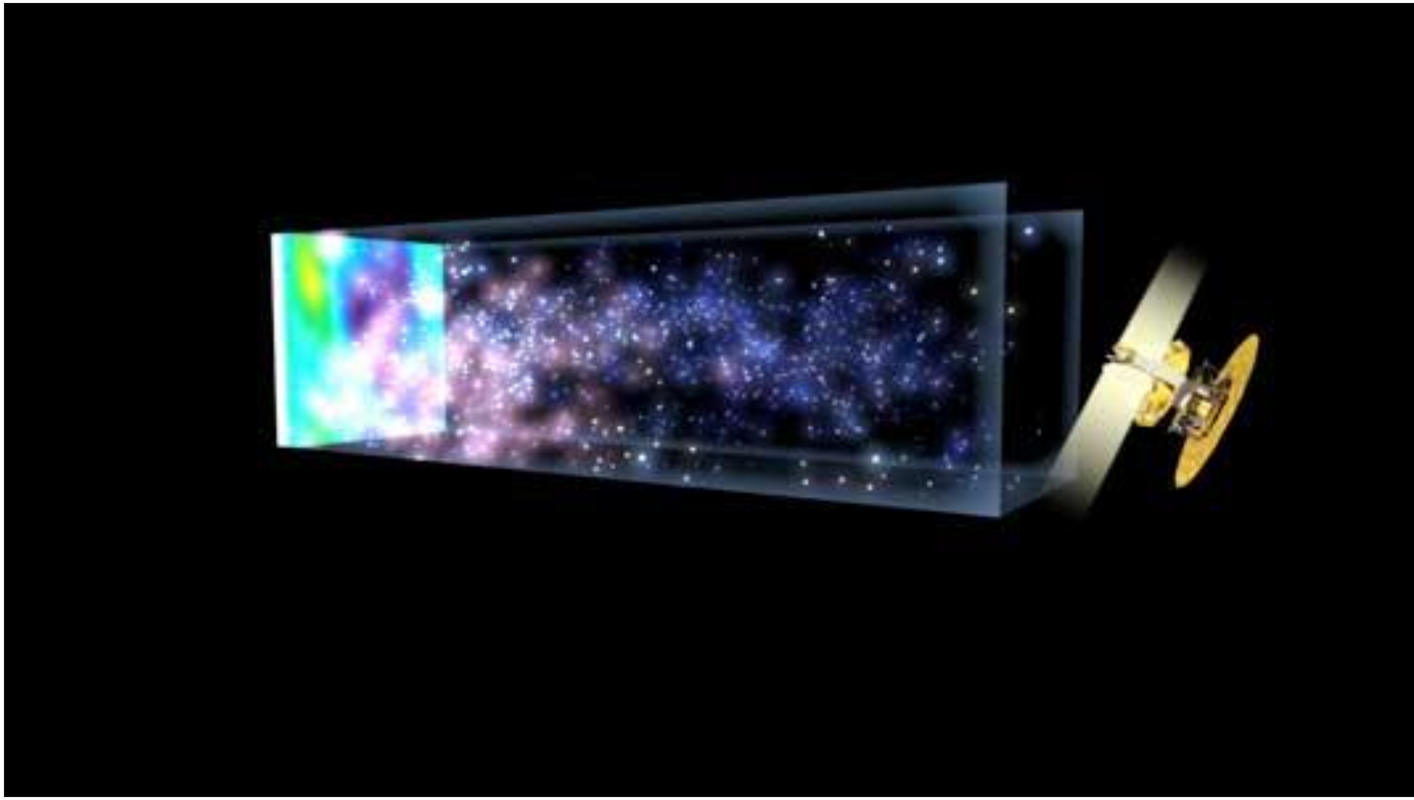
Da bismo razumjeli “najveće”, moramo poznavati “najmanje”

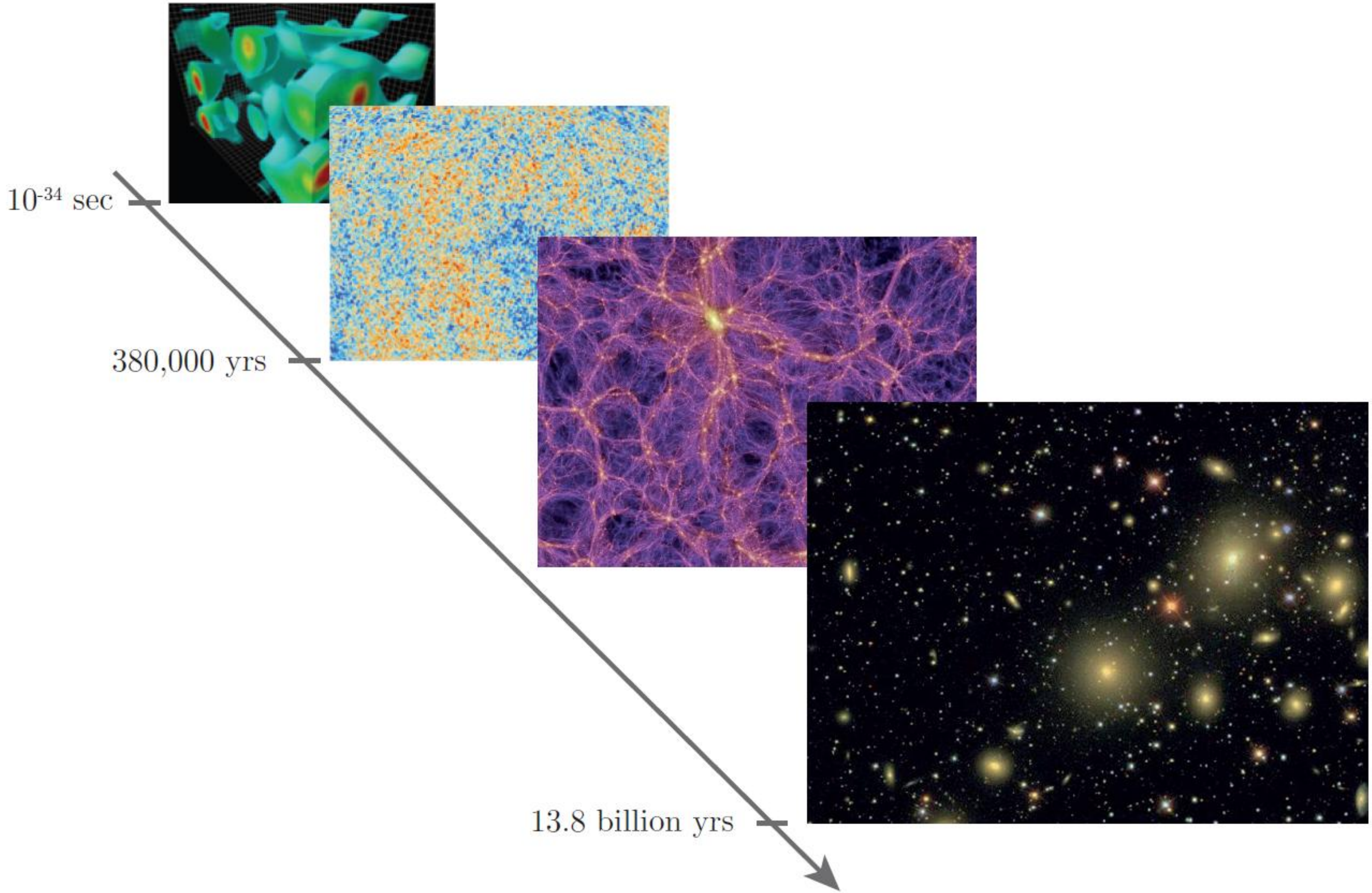




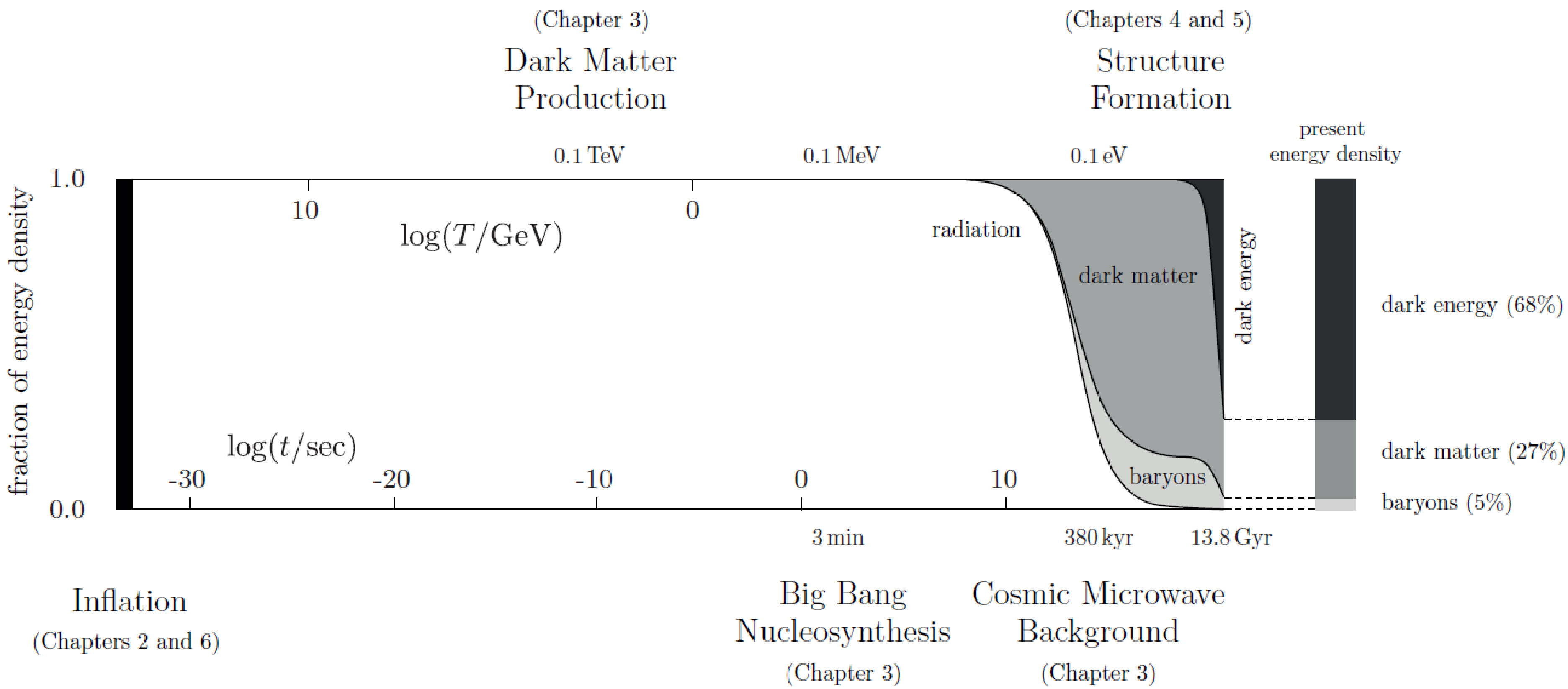
ASTRONOMSKI SVIJET KAO PRESLIKA KVANTNOG SVIJETA RANOG SVEMIRA

PORIJEKLO STRUKTURA NA NAJVEĆOJ SKALI – u kvantnim fluktuacijama sa samog početka svemira





10^{-34} sec
380,000 yrs
13.8 billion yrs


(Chapter 3)
Dark Matter Production
(Chapters 4 and 5)
Structure Formation
0.1 TeV
0.1 MeV
0.1 eV
present energy density
1.0
0.0
fraction of energy density
10
0
log(T/GeV)
radiation
dark matter
dark energy
baryons
log(t/sec)
-30
-20
-10
0
10
3 min
380 kyr
13.8 Gyr
dark energy (68%)
dark matter (27%)
baryons (5%)
Inflation
(Chapters 2 and 6)
Big Bang Nucleosynthesis
(Chapter 3)
Cosmic Microwave Background
(Chapter 3)

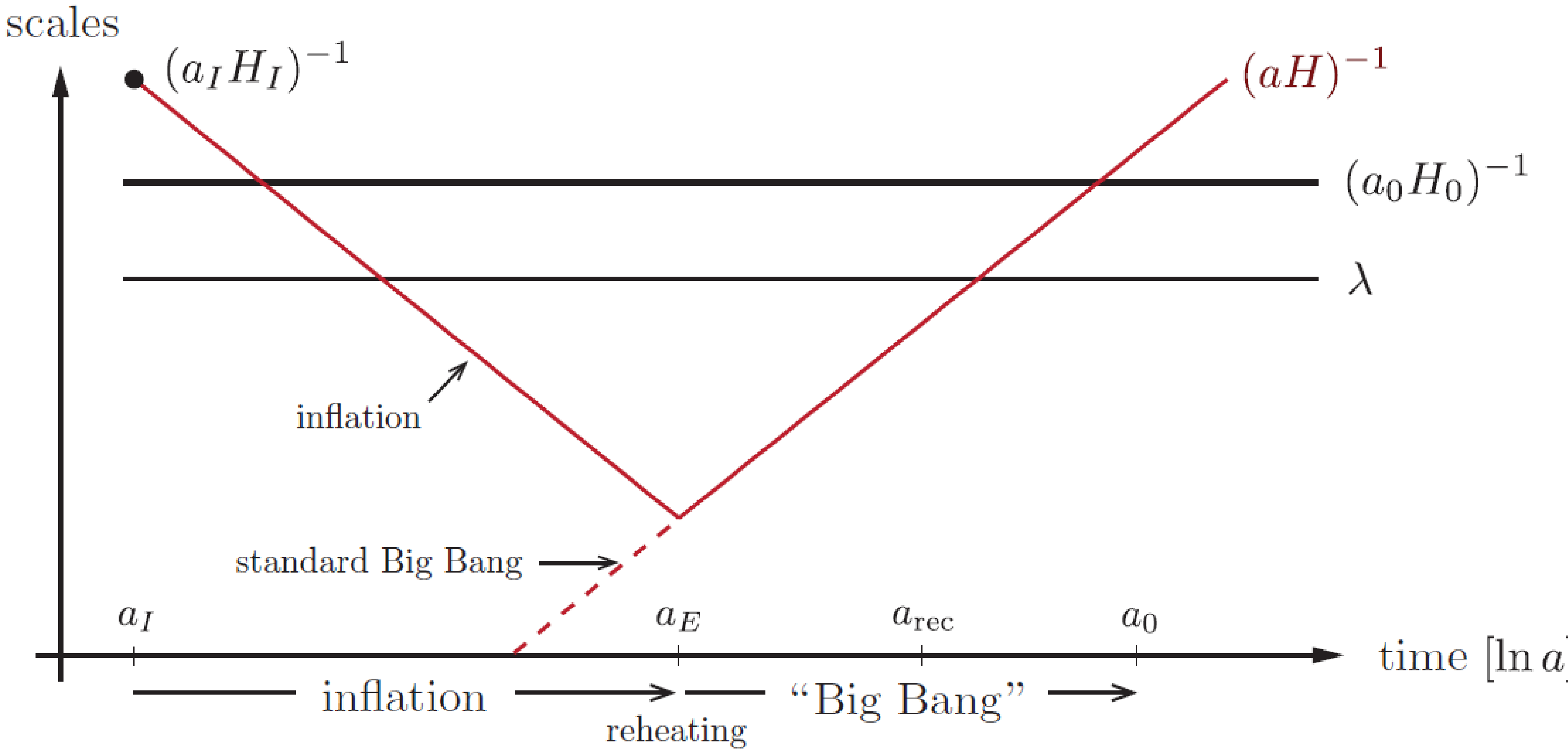
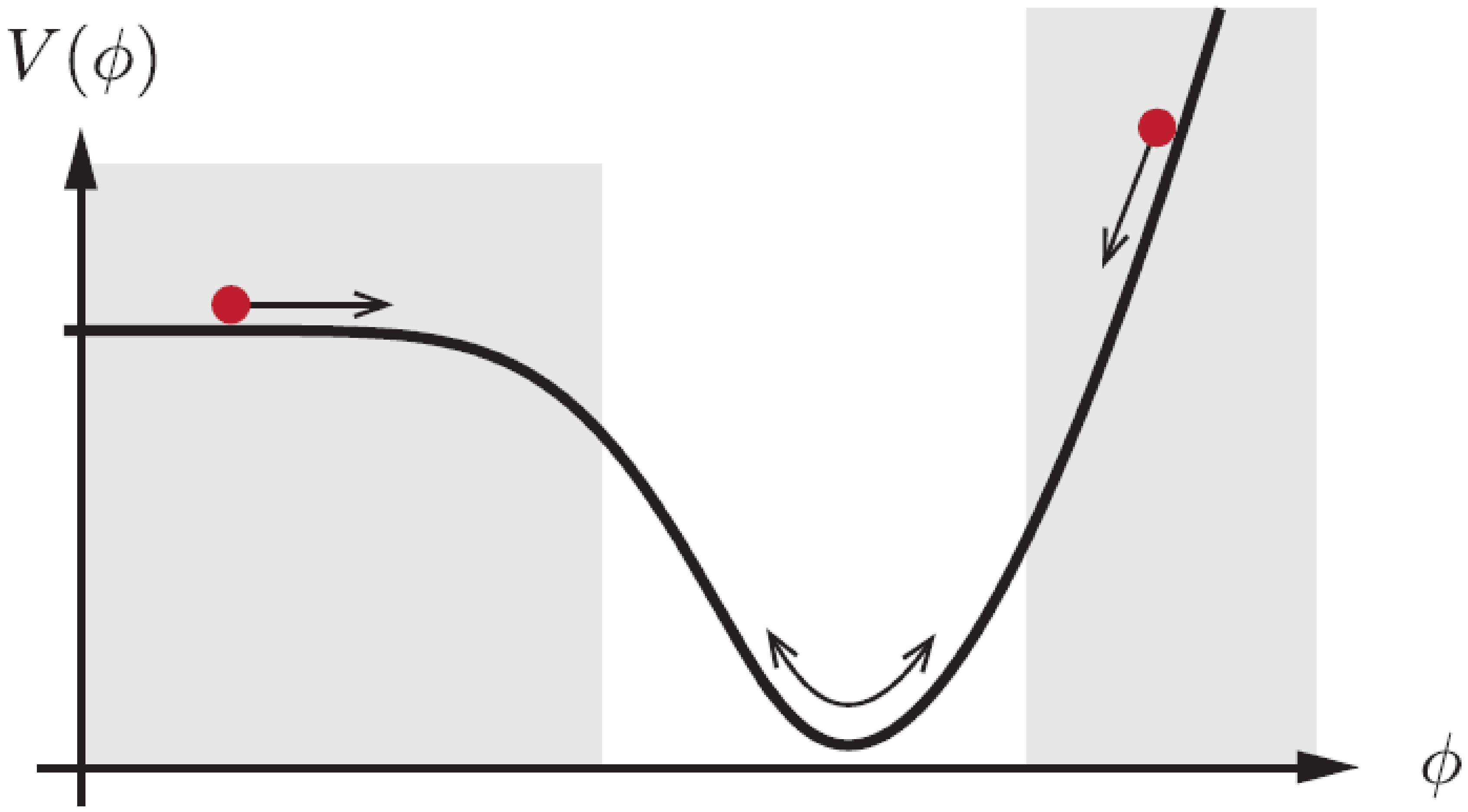
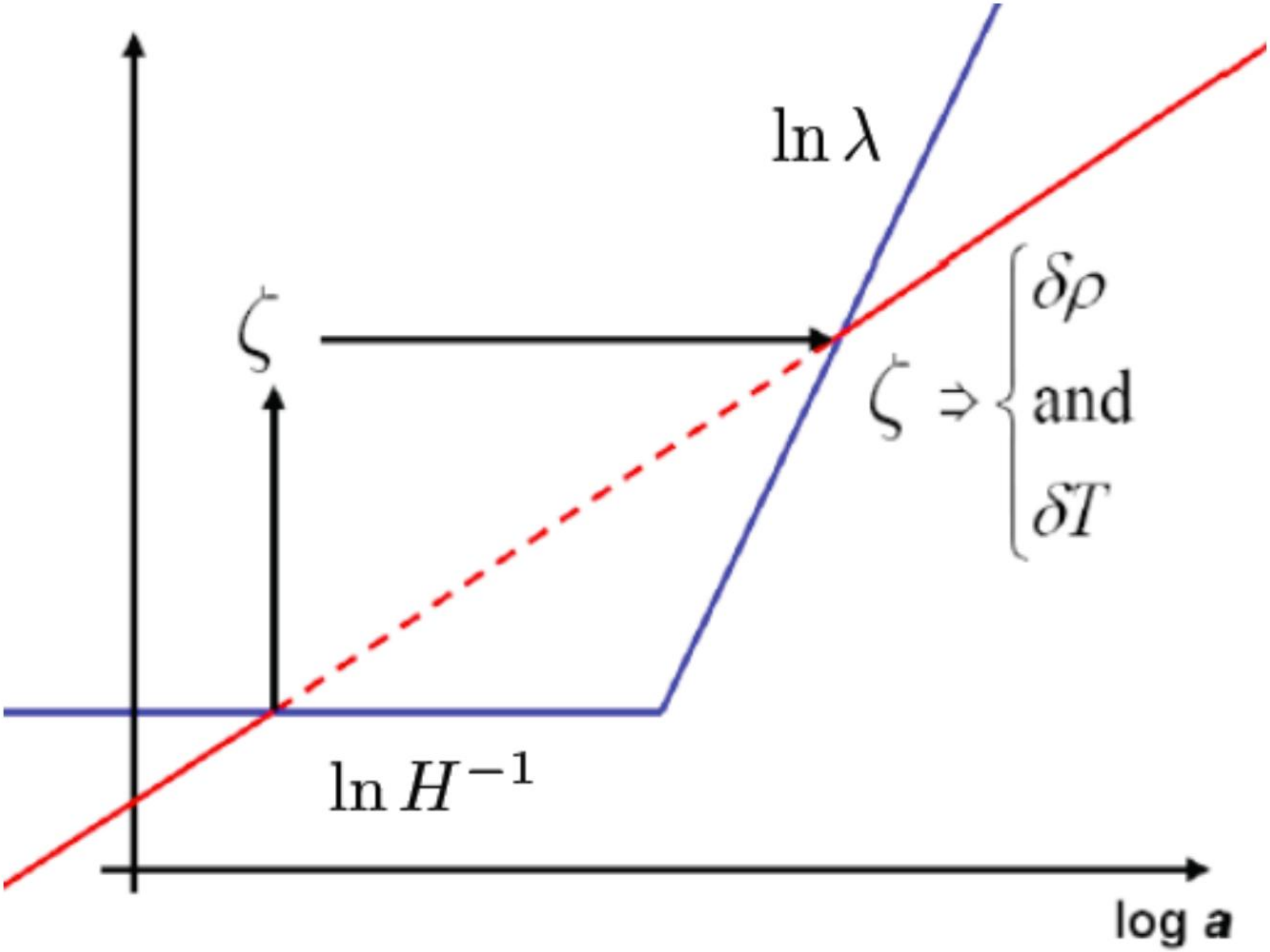


Figure 2.4: *Scales of cosmological interest were larger than the Hubble radius until* $a \approx 10^{-5}$ *(where today is at* $a(t_0) \equiv 1$*). However, at very early times, before inflation operated, all scales of interest were smaller than the Hubble radius and therefore susceptible to microphysical processing. Similarly, at very late times, the scales of cosmological interest are back within the Hubble radius. Notice the symmetry of the inflationary solution. Scales just entering the horizon today, 60 e-folds after the end of inflation, left the horizon 60 e-folds before the end of inflation.*



Example of a slow-roll potential. Inflation occurs in the shaded parts

GENERIRANJE QM FLUKTUACIJA TIJEKOM INFLACIJE



“ORIJENTIRI” KROZ KOJE PROLAZI SVEMIR NAKON PERIODA INFLACIJE:

- **Bariogeneza;**
- **Elektroslabi fazni prijelaz;**
- **QCD fazni prijelaz;**
- **Epoha zamrzavanja tamne tvari (odvezivanje tamne tvari od plazme)**
- **Odvezivanje neutrina... nukleosinteza**

Seminari:

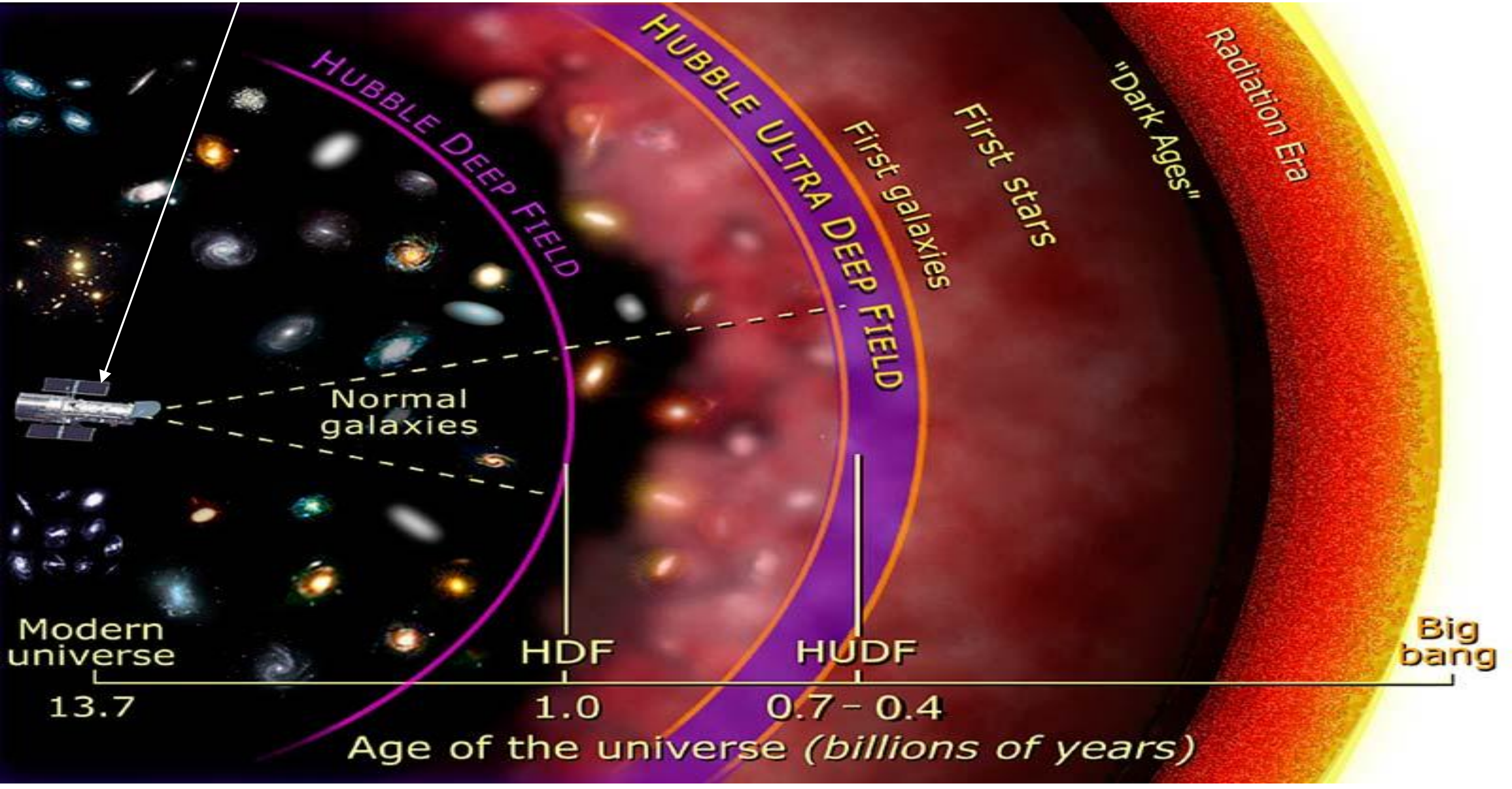
VIDLJIVI SVEMIR NAKON REKOMBINACIJE (predmet opažačke kozmologije) :

- Dostupna nam je “fotografija” iz ere rekombinacije (CMB),:
- “Siva zona” između miliona i milijarde godina – izučavanje neutralnog vodika (relikta rekombinacije) putem 21 cm linije

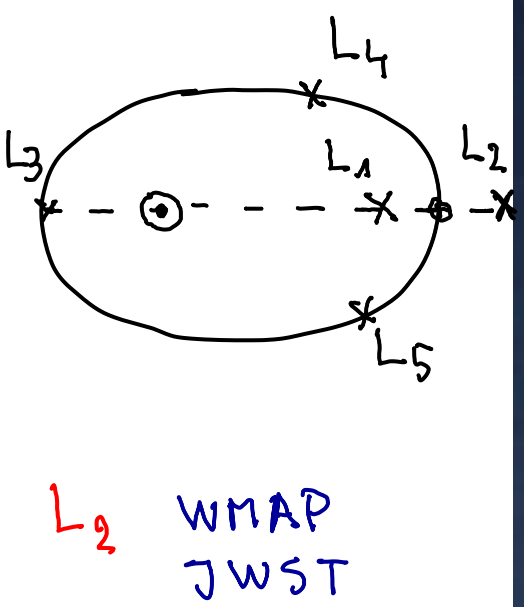
JWST & GMT teleskopi (Loeb, astro-ph/0603360)

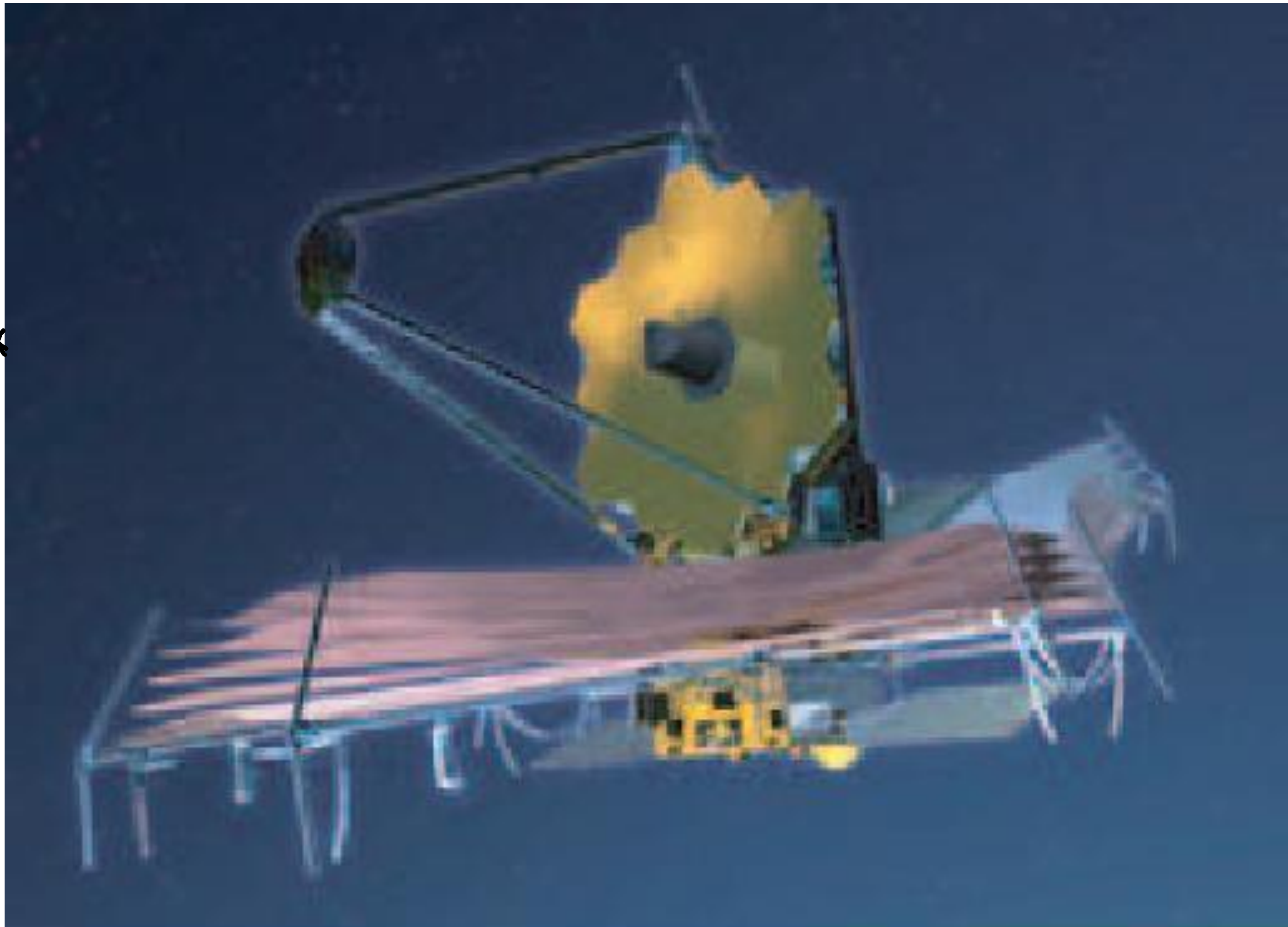
Seminari:

Prva svjetlost svemira



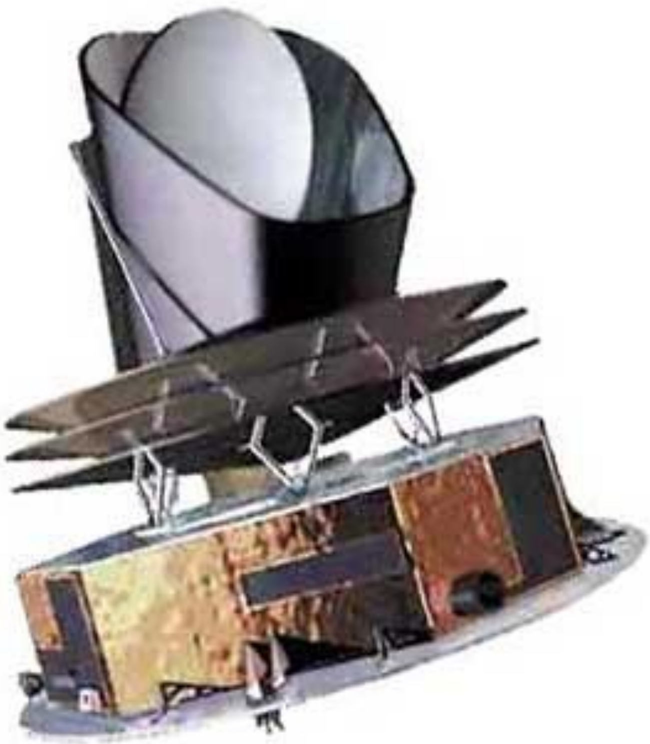
JWST (James Webb Space Telescope) na 0.6-28 μm, NASA 2011 (www.jwst.nasa.gov) u 1.5 Mkm L2 točki





GMT (Giant Magellan Telescope) promjera 8.4 m (www.gmto.org) za opažanje 1. generacije galaktika

ESA lansirala Herschel Space Laboratory i PLANCK Satelite



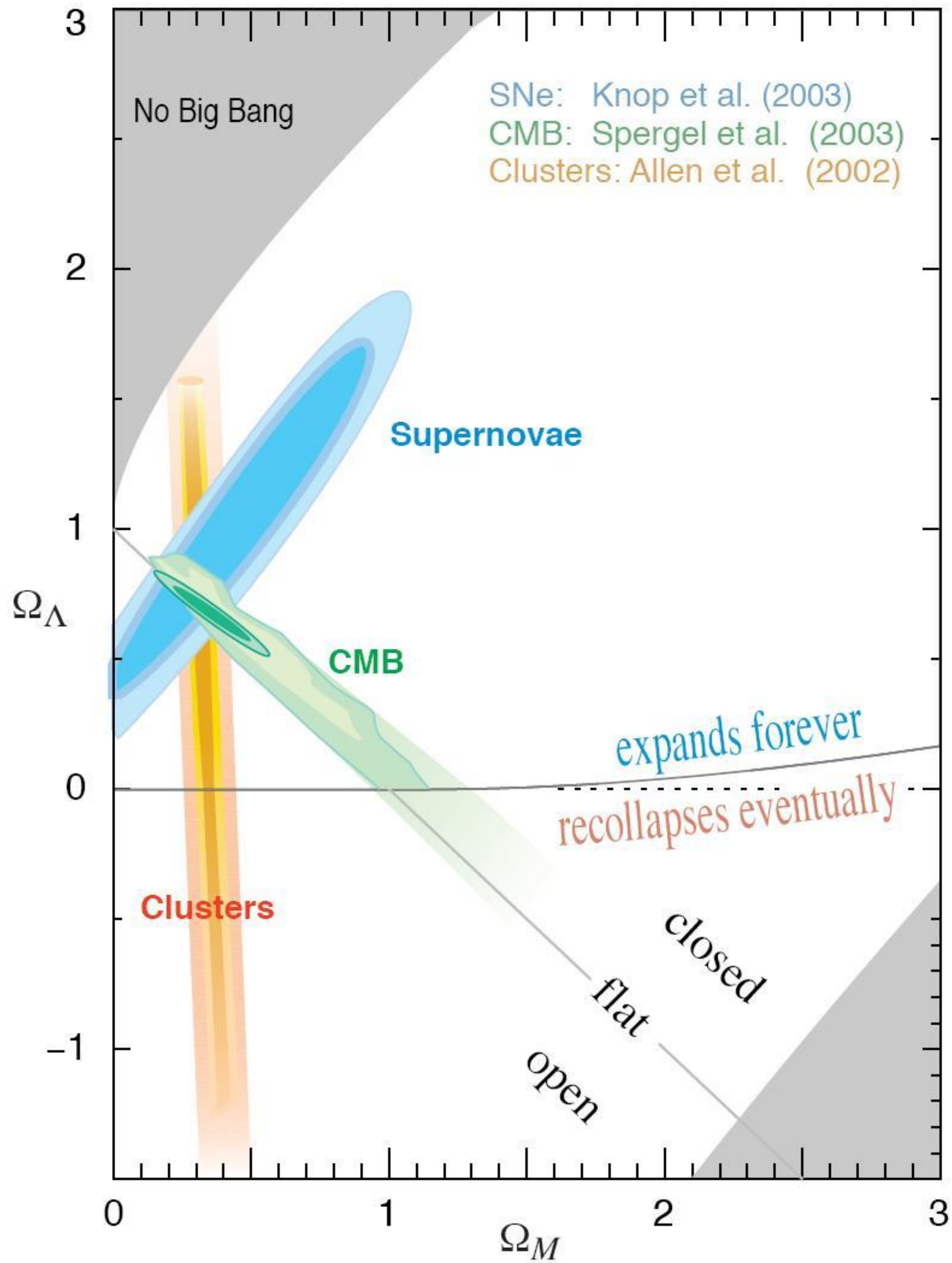
TAMNI SASTOJCI SVEMIRA (mogu se pratiti indirektno, putem vidljivih sastojaka, “tracers”) :

- DM opažanjima u rendgenskom i vidljivom spektru
- Evolucija DE praćenjem SN Ia

  & “X-ray clustera” do z=2

SPEKTAR PRVOTNIH FLUKTUACIJA U GUSTOĆI (na velikim skalama, preko 10 Mpc) :

- DM Poznat iz anizotropija CMBa, slabog fokusiranja i “Lyα šume”



No Big Bang
SNe: Knop et al. (2003)
CMB: Spergel et al. (2003)
Clusters: Allen et al. (2002)
Supernovae
CMB
Clusters
expands forever
recollapses eventually
closed
flat
open
Ω_Λ
Ω_M
3
2
1
0
–1
0
1
2
3

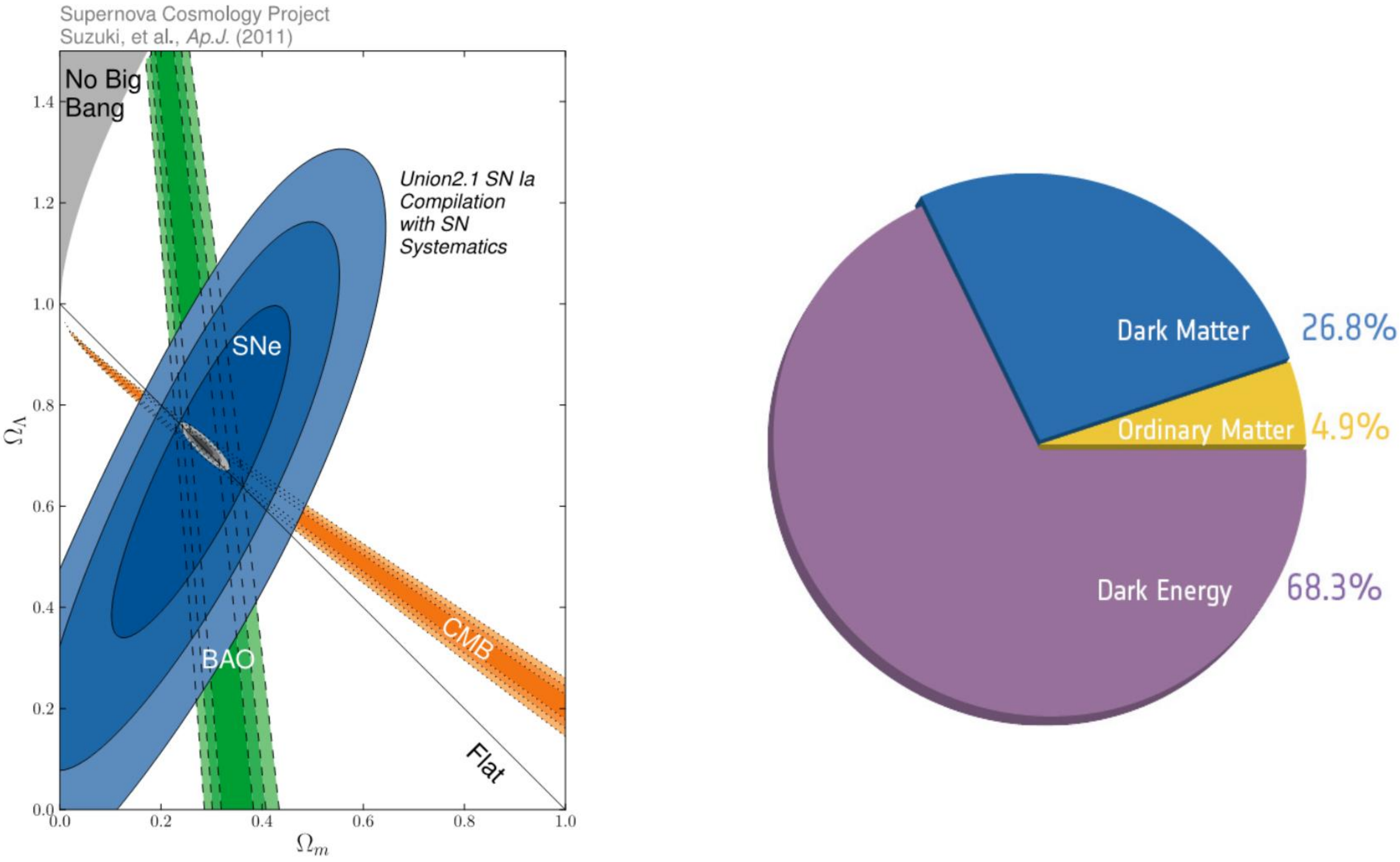
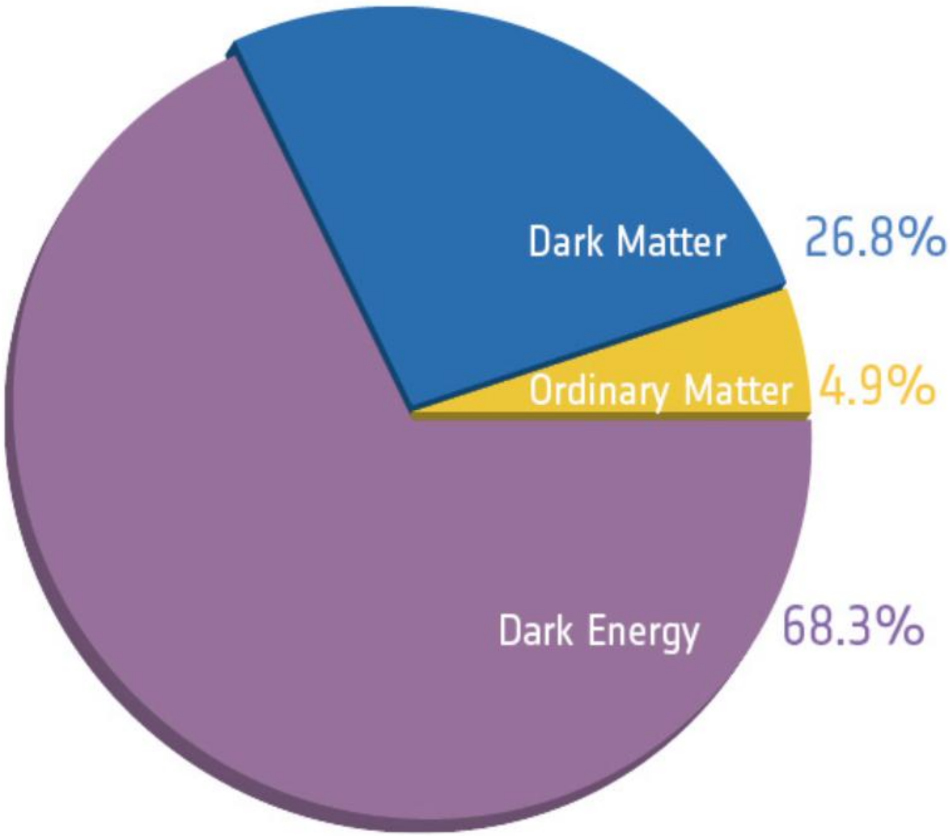


Figure 1. Left: Constraints on Ω_λ and Ω_m from Supernovae (SNe), Cosmic Microwave Background (CMB) and Baryon Acoustic Oscillations (BAO) [16]. From [17]. Right: The relative amounts of the different constituents of the Universe [18]. From [19].



[16] N. Suzuki, D. Rubin, C. Lidman, G. Aldering, R. Amanullah, et al. The Hubble Space Telescope Cluster Supernova Survey: V. Improving the Dark Energy Constraints Above z¿1 and Building an Early-Type-Hosted Supernova Sample. *Astrophys.J.*, 746:85, 2012.

[17] Supernova Cosmology Project. http://supernova.lbl.gov/.

[18] P.A.R. Ade et al. Planck 2013 results. XVI. Cosmological parameters. *Astron.Astrophys.*, 571:A16, 2014.

[19] Planck. http://sci.esa.int/planck/.

Content of the Universe:

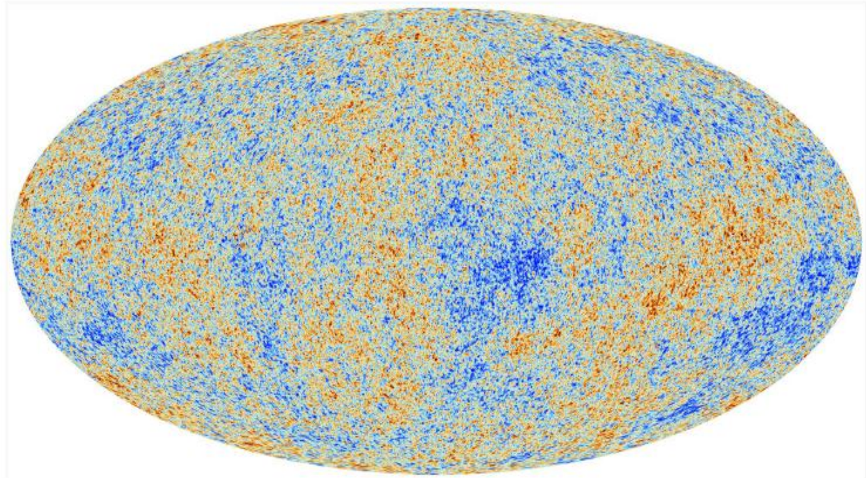
Dark Energy $\propto$ 70%

Dark Matter $\propto$ 25%

Baryonic matter $\propto$ 5%

Matter $\Omega_m - 0.3$

- dark matter $\Omega_{dm} - 0.25$
- baryons $\Omega_b - 0.05$
- neutrinos $\Omega_\nu - 10^{-3}$
- photons $\Omega_r - 10^{-4}$



Standard spatially-flat six-parameter CDM cosmology well describes observations.
Some parameter estimations (1σ):
baryons $\Omega_b h^2 = 0.02205 \pm 0.00028$
dark matter $\Omega_c h^2 = 0.1199 \pm 0.0027$
spectral index $n_s = 0.9603 \pm 0.0073$
Hubble const. $\mathrm{H}_0 = 67.3 \pm 1.2 \mathrm{km\ s}^{-1}\ \mathrm{Mpc}^{-1}$
total mater $\Omega_m = 0.315 \pm 0.017$
non-Gaussianity $f_{local} = 2.7 \pm 5.8$
No evidence for additional neutrino-like relativistic particles: $N_{eff} = 3.30 \pm 0.27$

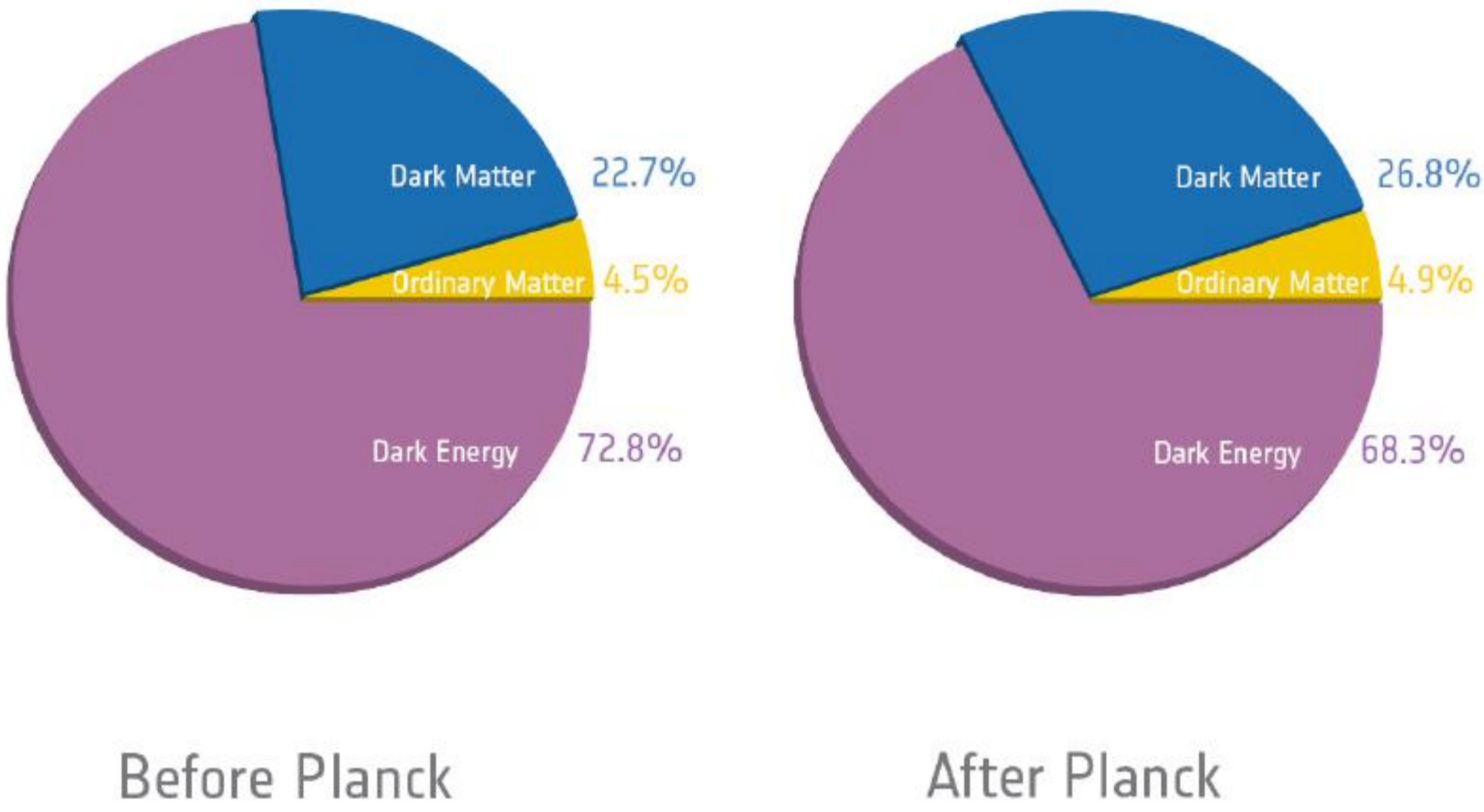
12 PARAMETARA STANDARDNOG KOZMOLOŠKOG MODELA

1 temperature:	T_0			
1 timescale:	H_0			
4 densities:	Ω_Λ	$\Omega_{\rm CDM}$	$\Omega_{\rm B}$	Ω_ν
1 pressure:	$w \equiv p/\rho$			
1 mean free path:	$\tau_{\rm reion}$			
4 fluctuation descriptors:	A	n	$n' \equiv dn/d\ln k$	$r \equiv T/S$
12 total parameters				

INVENTAR KOZMIČKIH PARAMETARA – nakon WMAPa

Hubble parameter	$h = 0.71\ ^{+0.04}_{-0.03}$
Baryon density	$\Omega_B = 0.044 \pm 0.004$
Matter density	$\Omega_M = 0.27 \pm 0.04$
Dark energy density	$\Omega_\Lambda = 0.73 \pm 0.04$
Total energy density	$\Omega_{tot} = 1.02 \pm 0.02$
Neutrino density	$\Omega_\nu h^2 \leq 0.0076$ (95 % C.L.)
Dark energy equation of state	$w < -0.78$ (95 % C.L.)

KOZMIČKI PARAMETRI NAKON PLANCKA



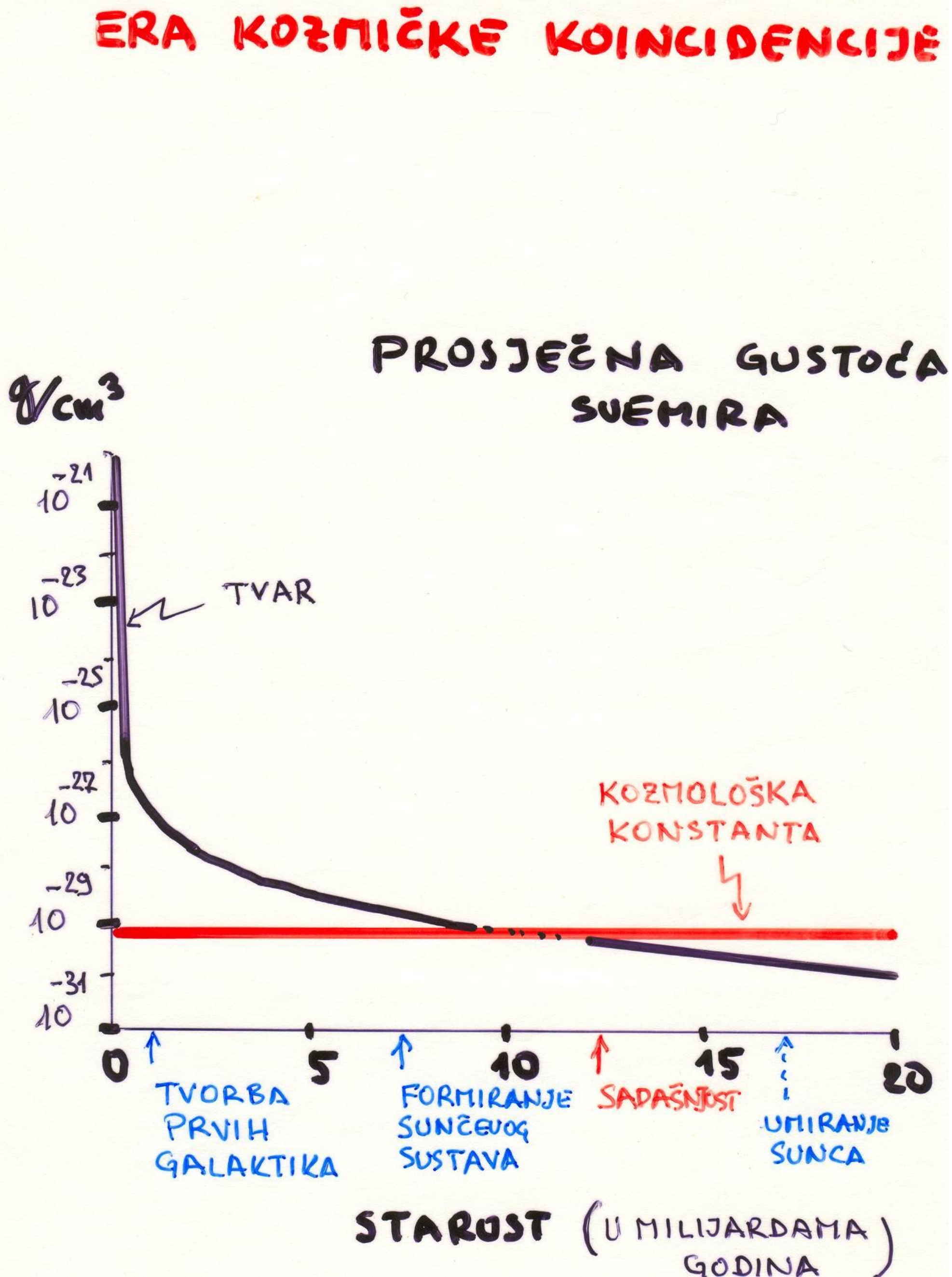
http://pdg.lbl.gov/2014/astrophysics- cosmology/astro-cosmo.html

	Planck+WP +highL	*Planck*+WP +highL+BAO	*WMAP9*+eCMB +BAO
$\Omega_b h^2$	0.02207 ± 0.00027	0.02214 ± 0.00024	0.02211 ± 0.00034
$\Omega_c h^2$	0.1198 ± 0.0026	0.1187 ± 0.0017	0.1162 ± 0.0020
$100\,\theta_{MC}$	1.0413 ± 0.0006	1.0415 ± 0.0006	–
n_s	0.958 ± 0.007	0.961 ± 0.005	0.958 ± 0.008
τ	$0.091^{+0.013}_{-0.014}$	0.092 ± 0.013	$0.079^{+0.011}_{-0.012}$
$\ln(10^{10}\Delta^2_{\mathcal{R}})$	3.090 ± 0.025	3.091 ± 0.025	3.212 ± 0.029
h	0.673 ± 0.012	0.678 ± 0.008	0.688 ± 0.008
σ_8	0.828 ± 0.012	0.826 ± 0.012	$0.822^{+0.013}_{-0.014}$
Ω_m	$0.315^{+0.016}_{-0.017}$	0.308 ± 0.010	0.293 ± 0.010
Ω_Λ	$0.685^{+0.017}_{-0.016}$	0.692 ± 0.010	0.707 ± 0.010

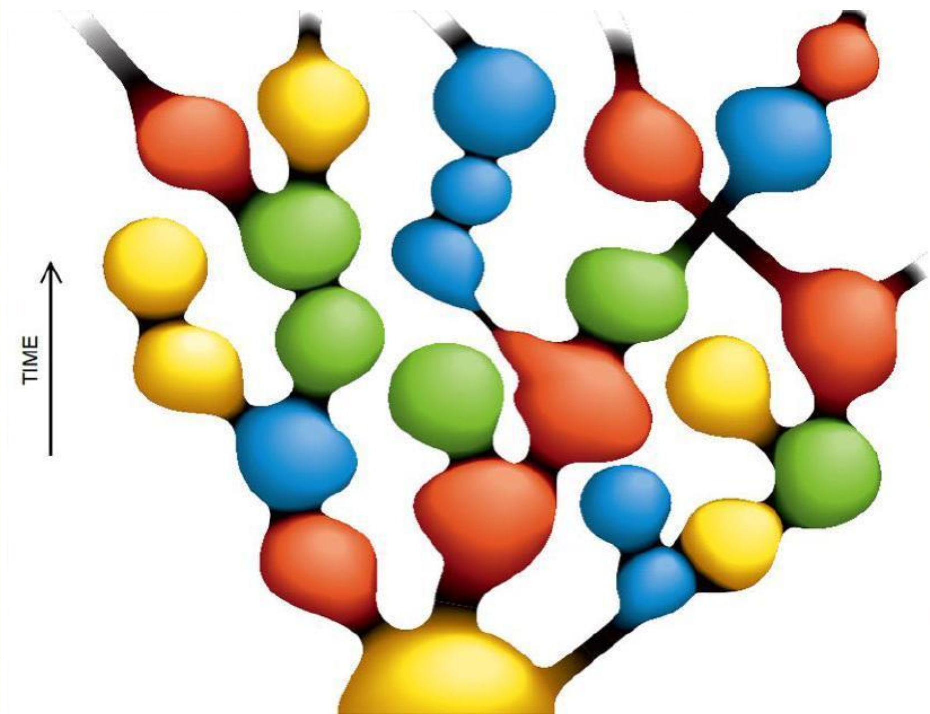
PITANJA S KOJIMA SMO POČELI OVAJ KOLEGIJ:

- Starost, veličina i geometrija svemira?
- Kakav je početak i kraj svemira?
- Kakav je sastav svemira?
- Nastanak tvari i opaženih struktura?

MULTIVERSE?



ERA KOZMIČKE KOINCIDENCIJE
PROSJEČNA GUSTOĆA SVEMIRA
g/cm³
10⁻²¹
10⁻²³
10⁻²⁵
10⁻²⁷
10⁻²⁹
10⁻³¹
TVAR
KOZMOLOŠKA KONSTANTA
0
5
10
15
20
TVORBA PRVIH GALAKTIKA
FORMIRANJE SUNČEVOG SUSTAVA
SADAŠNJOST
UMIRANJE SUNCA
STAROST (U MILIJARDAMA GODINA)



TIME