Introduction to Cosmology
II. Modeling the Universe

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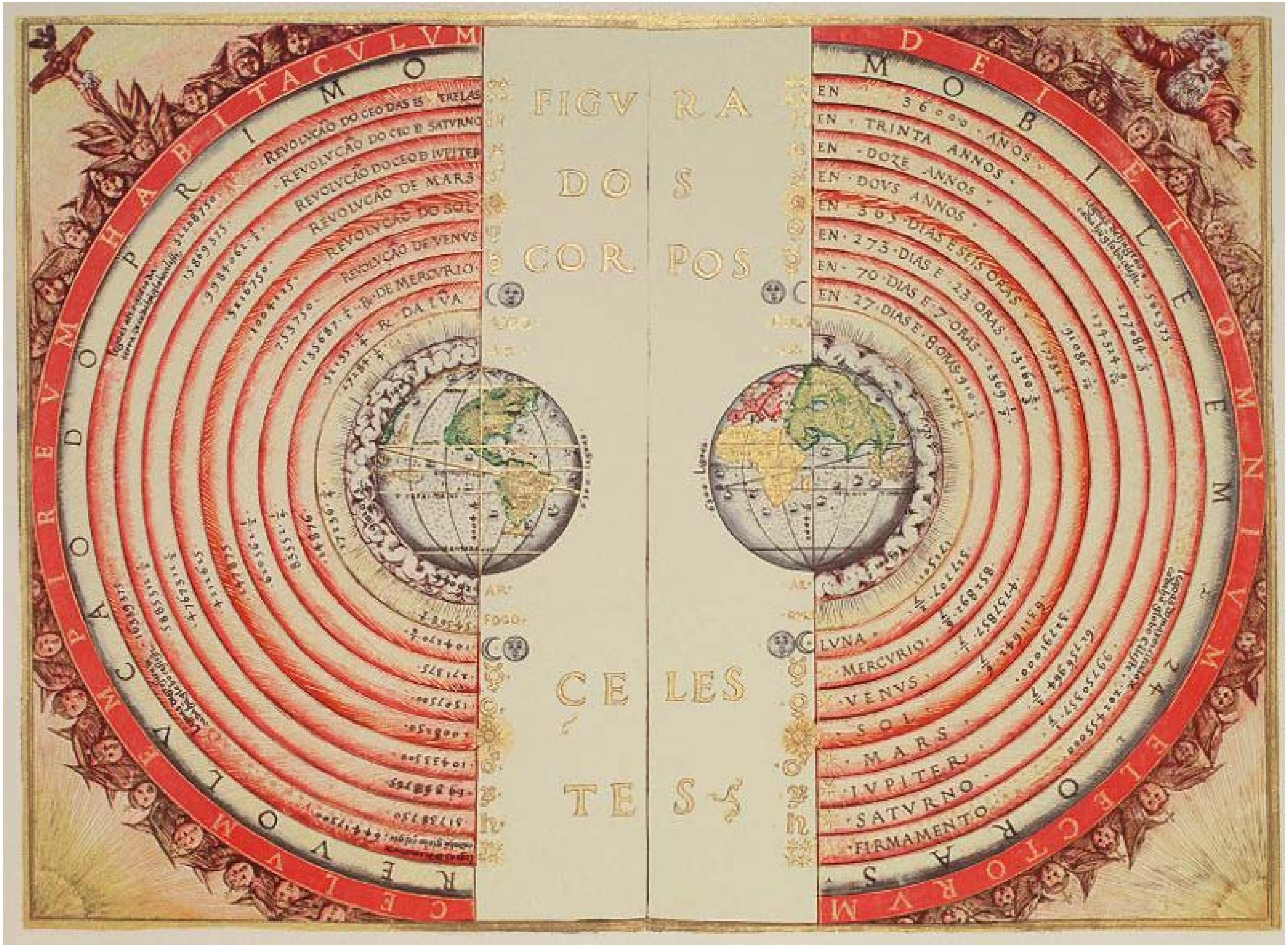
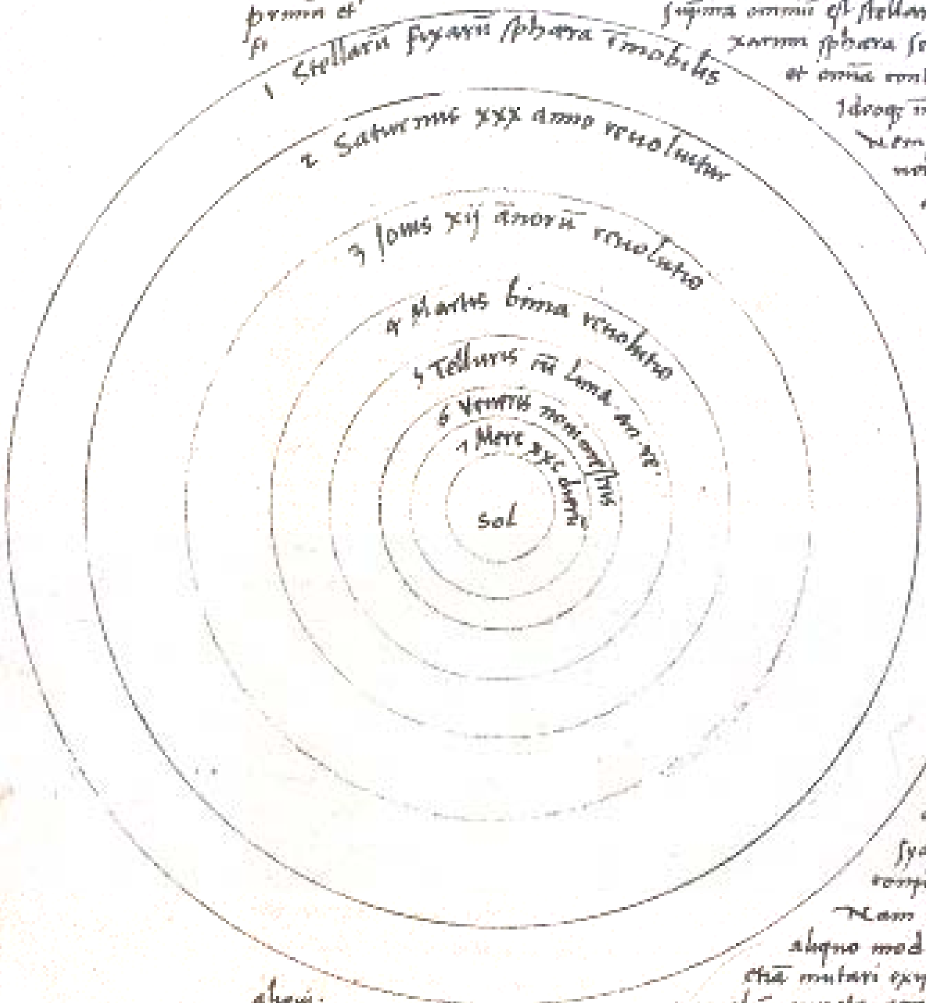
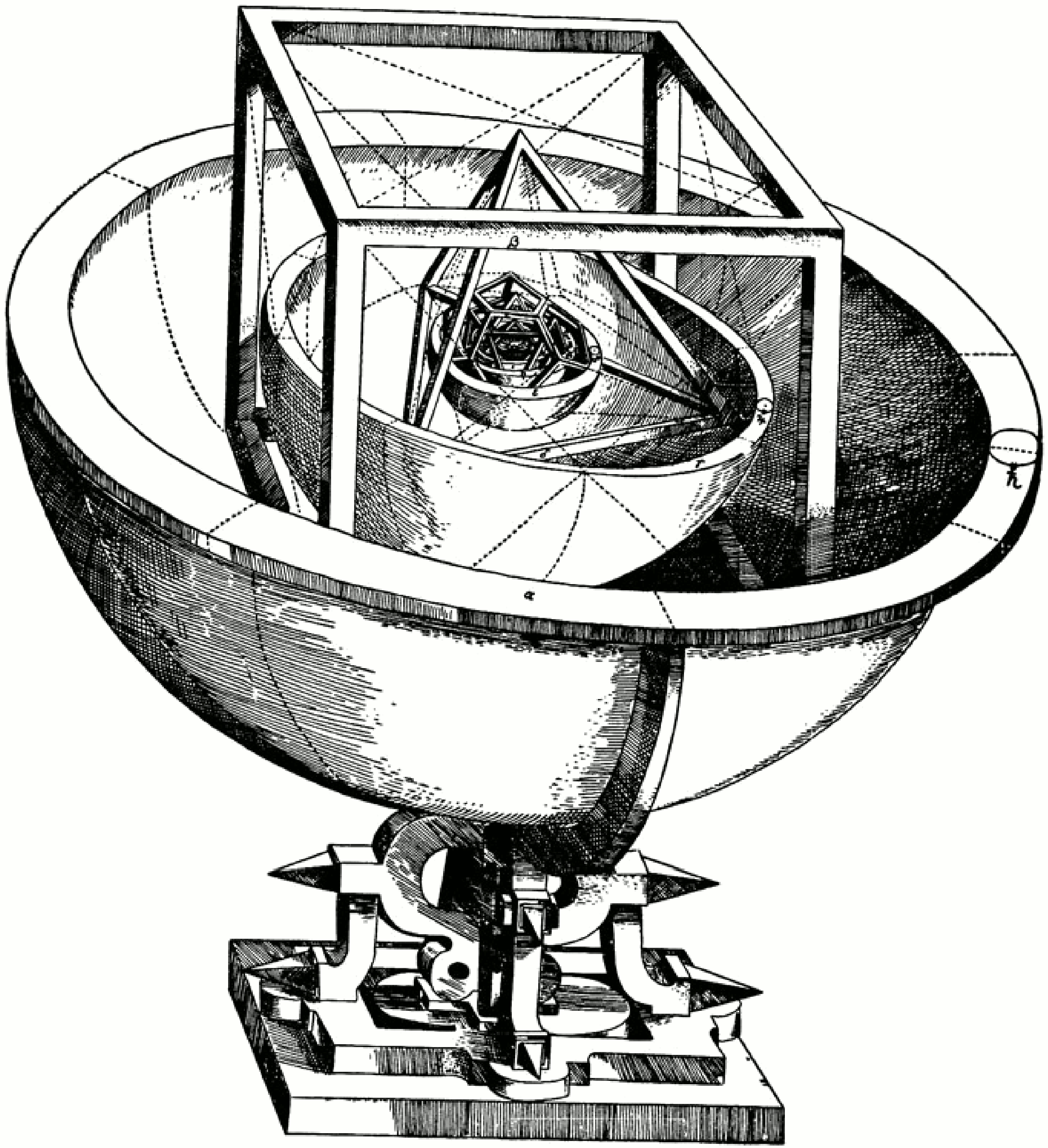

FIGVRA DOS CORPOS ÇELESTES
CELVM EMPIREVM HABITACVLVM DEI ET OMNIVM ELECTORVM
REVOLVÇAO DO PRIMO MOBILE EM 24 ORAS
REVOLVÇÃO DO CEO DAS ESTRELAS EN 36000 AÑOS
REVOLVÇÃO DO CEO E SATVRNO EN TRINTA ANNOS
REVOLVÇÃO DO CEO D IVPITER EN DOZE ANNOS
REVOLVÇÃO DE MARS EN DOVS ANNOS
REVOLVÇÃO DO SOL EN 365 DIAS
REVOLVÇÃO DE VENVS EN 273 DIAS E SEIS ORAS
R. DE MERCVRIO EN 70 DIAS E 23 ORAS
R. DA LVA EN 27 DIAS E 7 ORAS
AR
FOGO
LVNA
MERCVRIO
VENVS
SOL
MARS
IVPITER
SATVRNO
FIRMAMENTO

ratione salva manente; nemo enim convenientiorem allegabit
quam ut magnitudinem orbium multitudo temporis metiatur; ordo sphae-
rarum sequitur in hunc modum: a summo capientes initium.
Prima et suprema omnium est stellarum fixarum sphaera seipsam
et omnia continens
ideoque immobilis
nempe uni-
versi locus
ad quem
motus
et po-
si-
tio
ce-
terorum
omnium
syderum
conferatur.
Nam quod
aliquo modo illam
etiam mutari existimant
aliqui:
nos aliam, cur ita appareat
in deductione motus terrestris assignabimus causam. Sequitur
errantium primus Saturnus: qui XXX anno suum complet circu-
itum. Post hunc Jupiter duodecennali revolutione mobilis. Deinde
Mars, qui biennio circuit. Quartum in ordine annua revolu-
tio locum obtinet: in quo terram cum orbe Lunari tanquam epicyclo
contineri diximus. Quinto loco Venus nono mense reducitur





$$\Delta\varphi - \Lambda\varphi = 4\pi G\varrho$$

when $\varrho = \varrho_0 = \text{const}$

$$\varphi = -\frac{4\pi G}{\Lambda}\varrho_0$$

$$ds^2 = c^2dt^2 - \left[\delta_{ab} + \frac{x_a x_b}{R^2 - (x_1^2 + x_2^2 + x_3^2)}\right] dx^a dx^b$$

where $a, b = 1, 2, 3$.

$$G_{\mu\nu} = \kappa T_{\mu\nu} + \Lambda g_{\mu\nu},$$

where $\kappa = \dfrac{8\pi G}{c^2}$.

$$-\frac{2}{R^2} + \Lambda = -\frac{\kappa \varrho}{2}, \quad \Lambda = \frac{\kappa \varrho}{2}$$

$$\Lambda = \frac{\kappa \varrho}{2} = \frac{1}{R^2}$$

$$M = 2\pi^2 R^3 \varrho = 4\pi^2 \frac{R}{\kappa} = \frac{32\pi^2}{\sqrt{\kappa^3 \varrho}}$$

Let us calculate Λ and R assuming that

$\varrho = \varrho_{crit} = 0.946 \cdot 10^{-29} \mathrm{g/cm}^3$

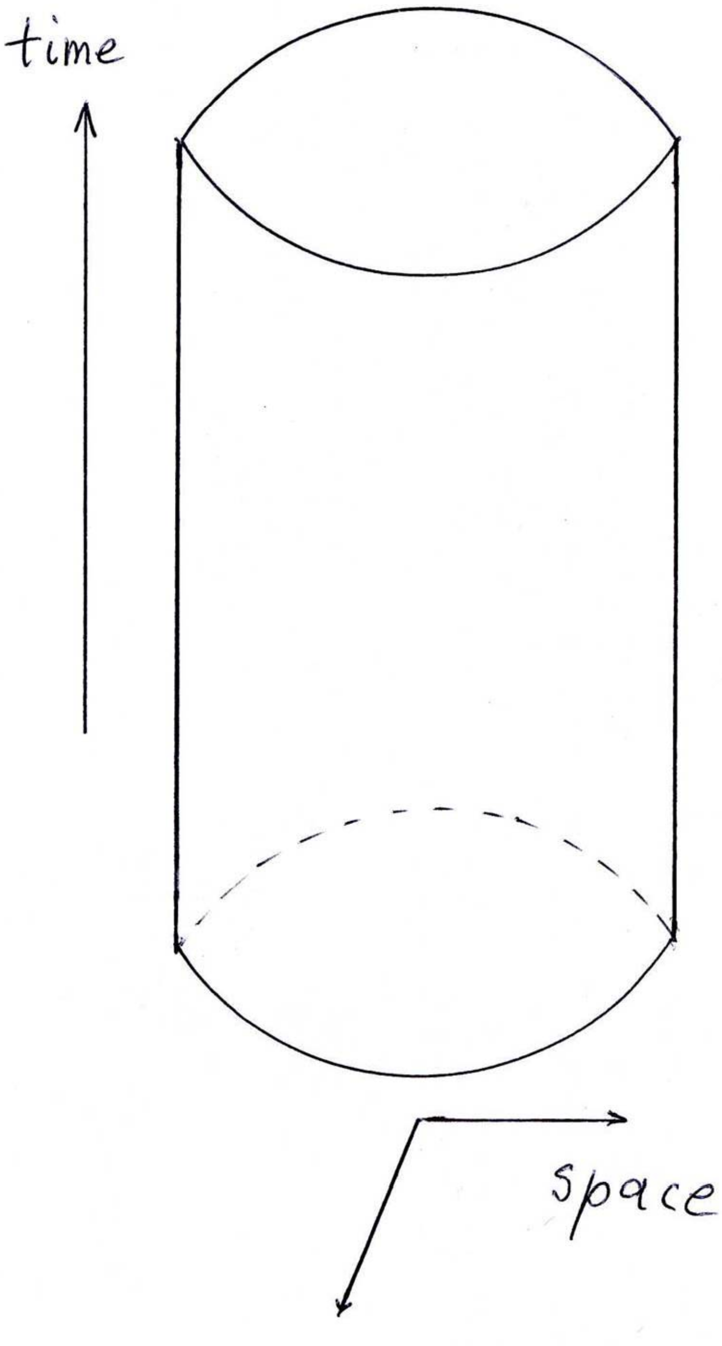
$$\Lambda = 8.87 \cdot 10^{-57} \mathrm{cm}^{-2}$$

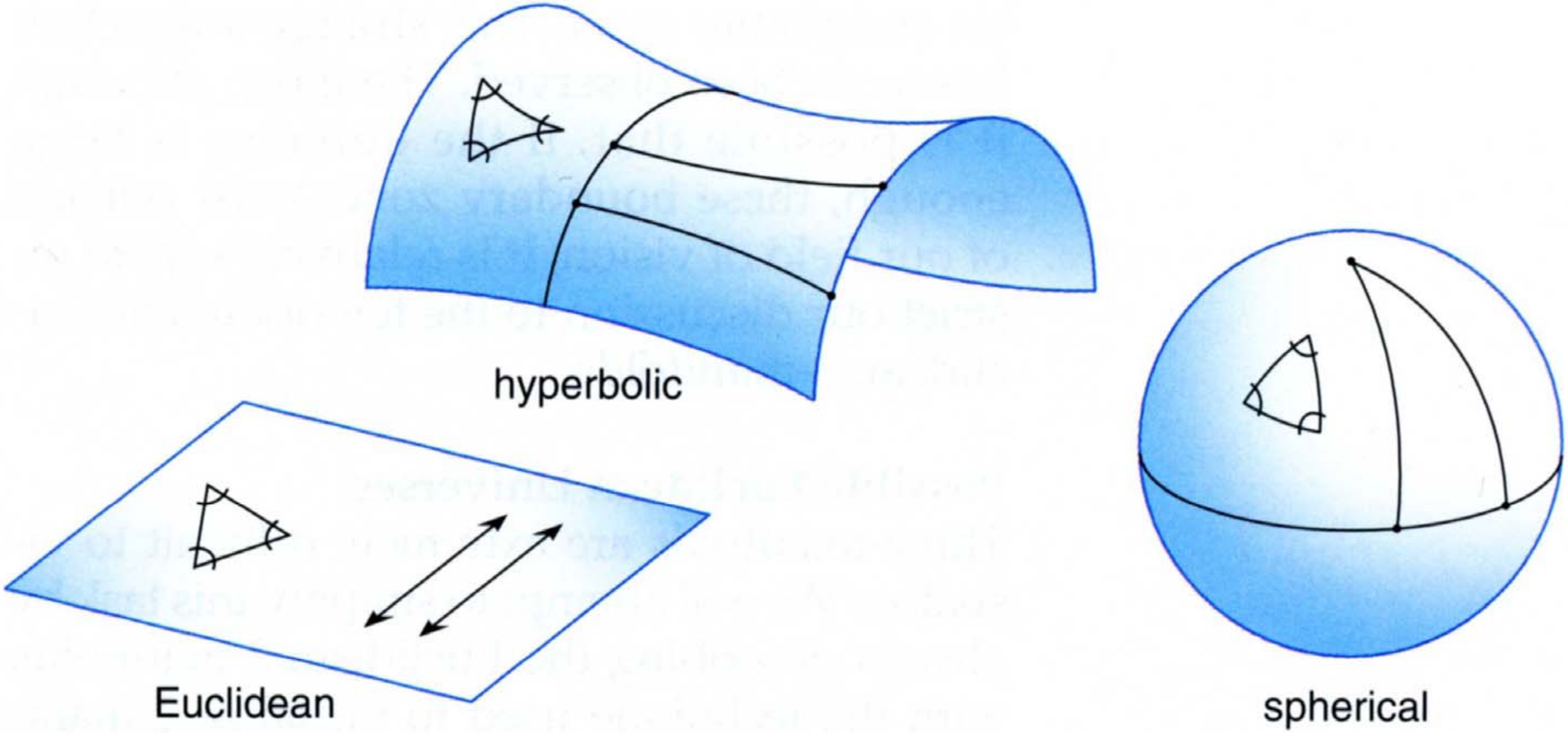
$$R = \frac{1}{\sqrt{\Lambda}} = 1.06 \cdot 10^{28} \mathrm{cm} = 3440 \mathrm{Mpc}$$

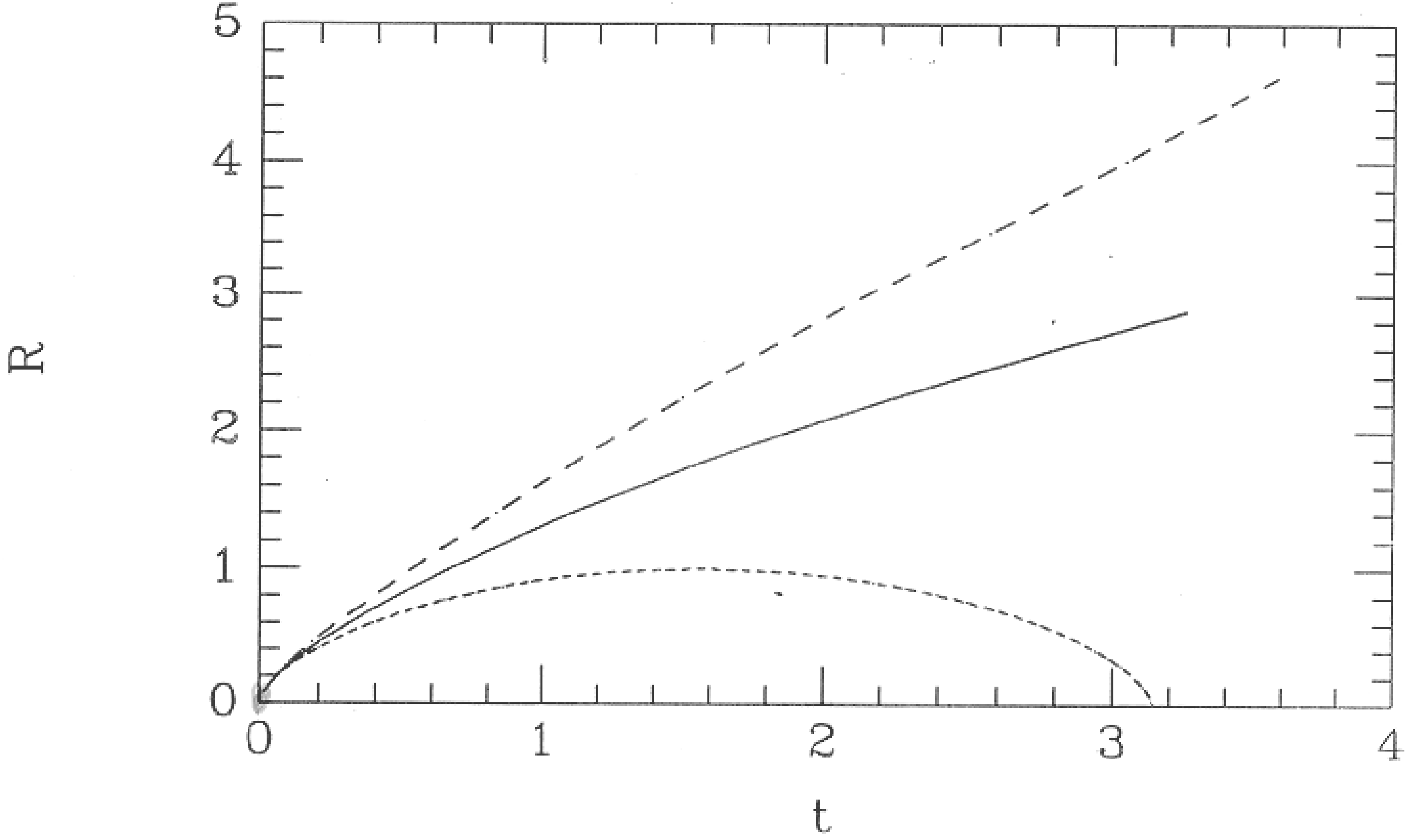
Present data

$$R = R_H = 1.2 \cdot 10^{28} \mathrm{cm} = 3896 \mathrm{Mpc}$$

$$\Lambda = 1.46 \cdot 10^{-56} \mathrm{cm}^{-2}$$


time
space


hyperbolic
Euclidean
spherical



R
t
0
1
2
3
4
5

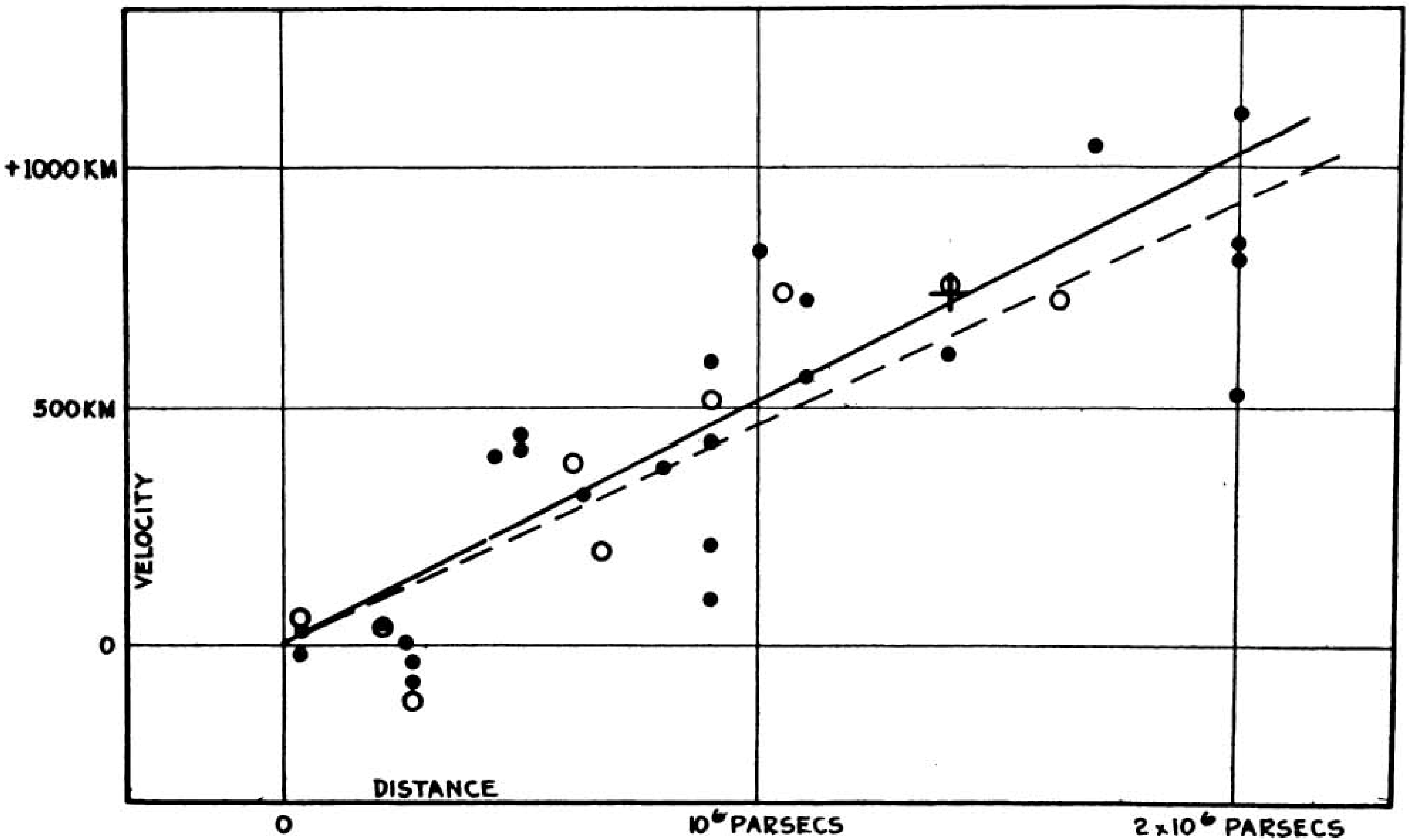
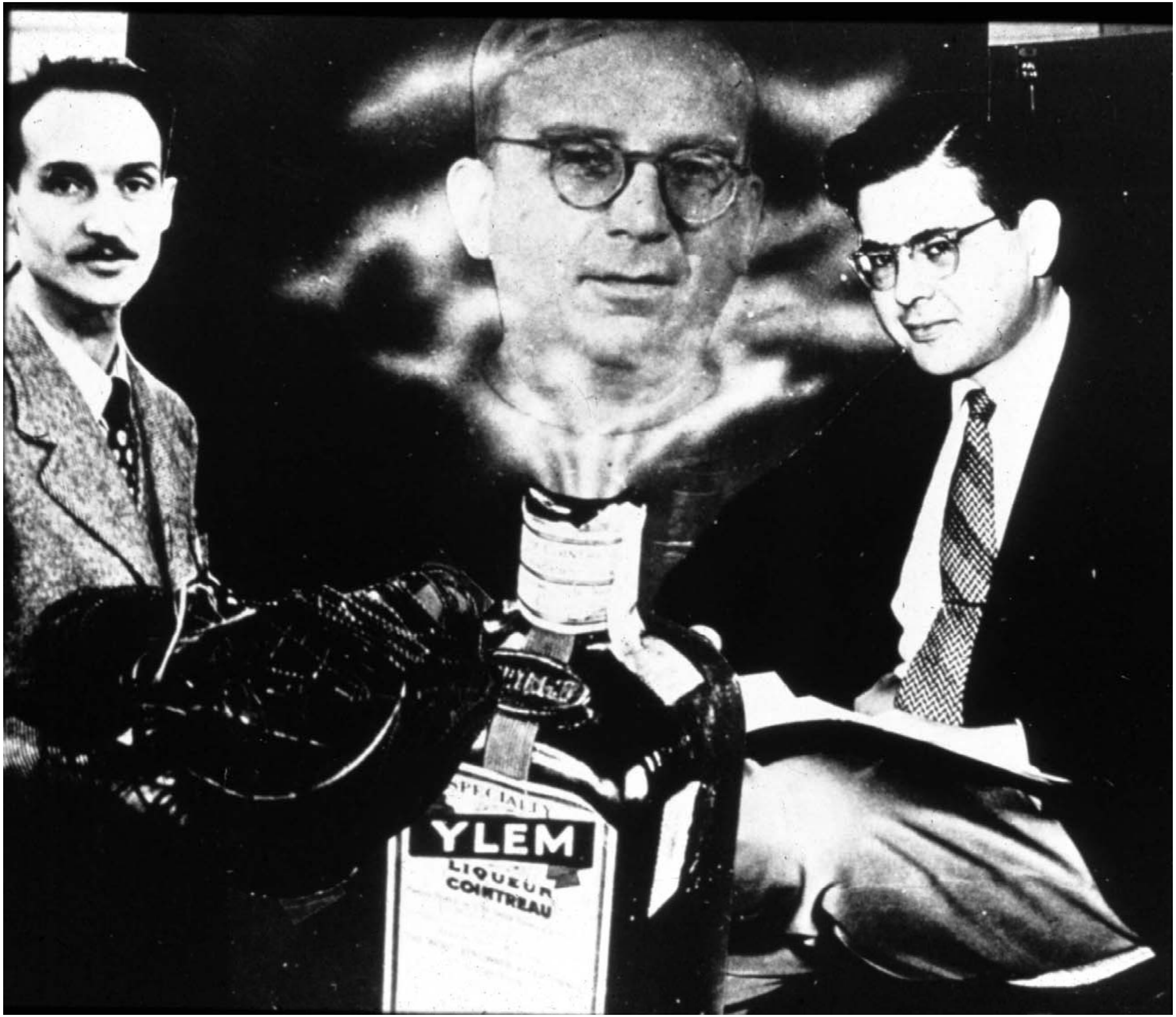
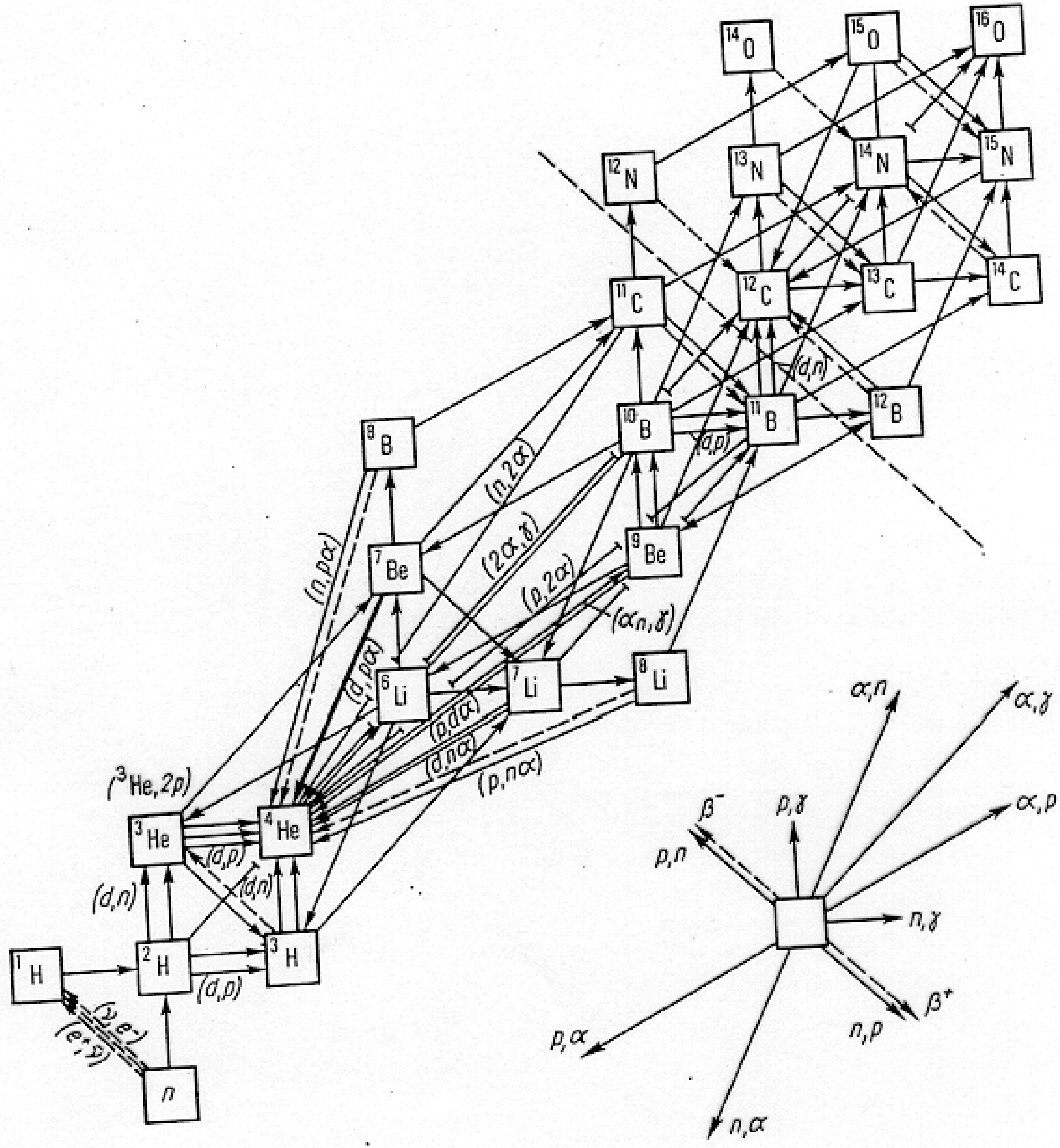
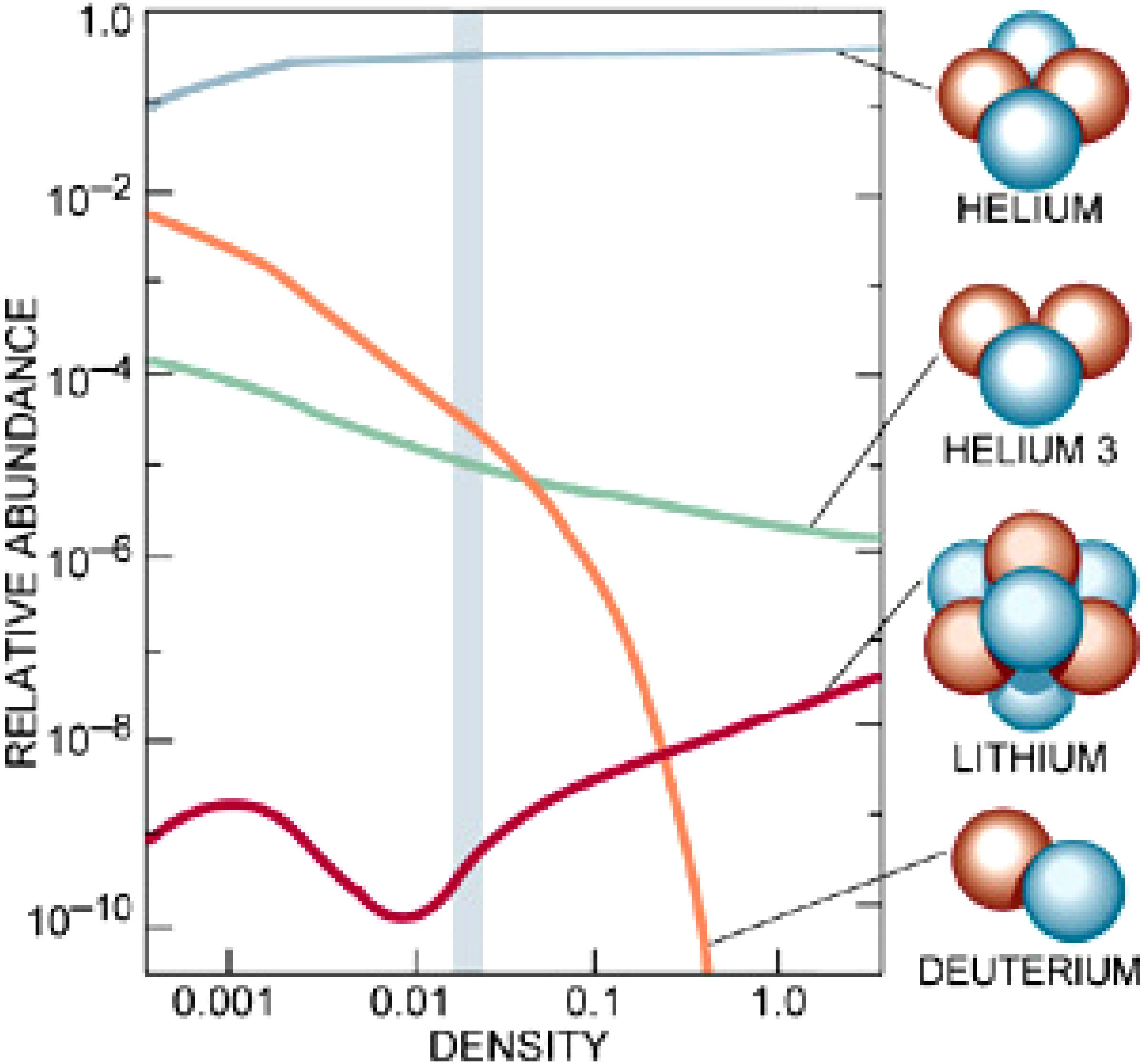


Fig. 16-27a, p.331


YLEM
COINTREAU



14O
15O
16O
12N
13N
14N
15N
11C
12C
13C
14C
9B
10B
11B
12B
(d,n)
(d,p)
7Be
9Be
6Li
7Li
8Li
(n,2α)
(2α,γ)
(p,2α)
(αn,γ)
(n,pα)
(d,nα)
(p,dα)
(d,nα)
(p,nα)
(3He,2p)
3He
4He
(d,p)
(d,n)
(d,n)
1H
2H
3H
(d,p)
(ν,e−)
(e+ν)
n
α,n
α,γ
β−
p,γ
α,p
p,n
n,γ
β+
n,p
p,α
n,α



1.0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
RELATIVE ABUNDANCE
0.001
0.01
0.1
1.0
DENSITY
HELIUM
HELIUM 3
LITHIUM
DEUTERIUM

Similarly, noticing that, in the present era, the radiation-density must vary in inverse proportion to the fourth power of the time (because $\rho \approx T^4$, $T \sim l^{-1}$, and $l \sim t$), we find,

$$\rho_{\text{rad.}} \text{ (present)} = \frac{3 \cdot 1 \times 10^{37}}{t^4} \text{ gm per cm}^3. \qquad \dots .(10)$$

For the present density of residual radiation we obtain 6×10^{-32}, corresponding to about 6°K. Thus we may conclude that the residual heat found at present in the Universe is comparable with the heat provided by nuclear transformations in stars.

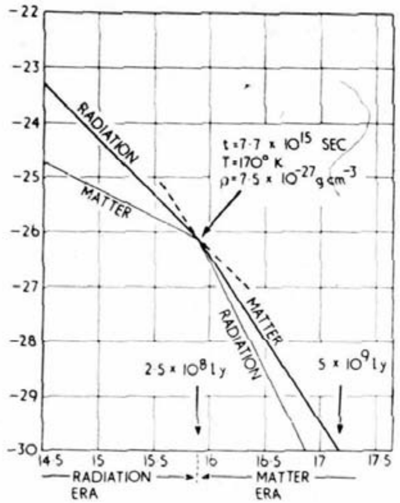
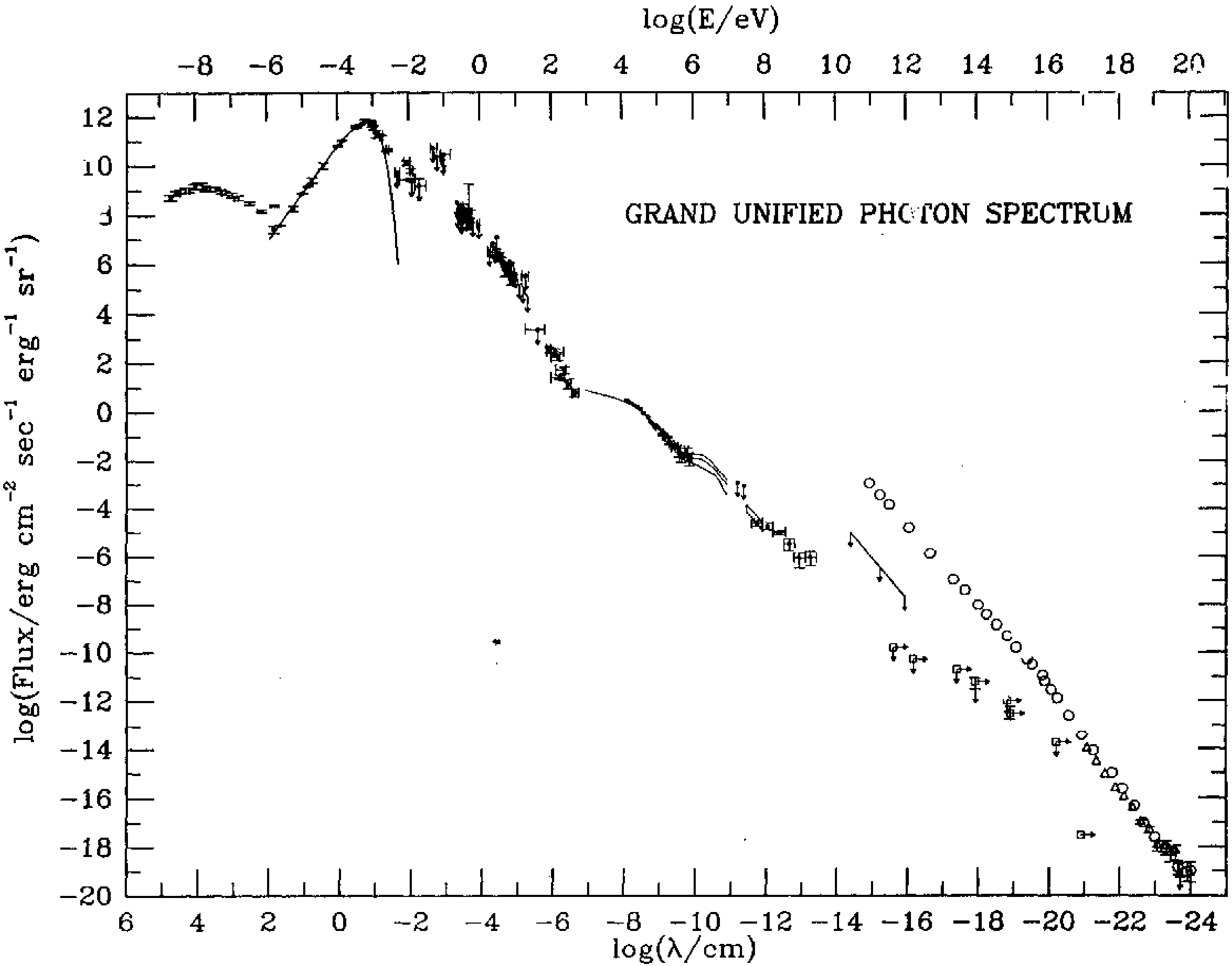


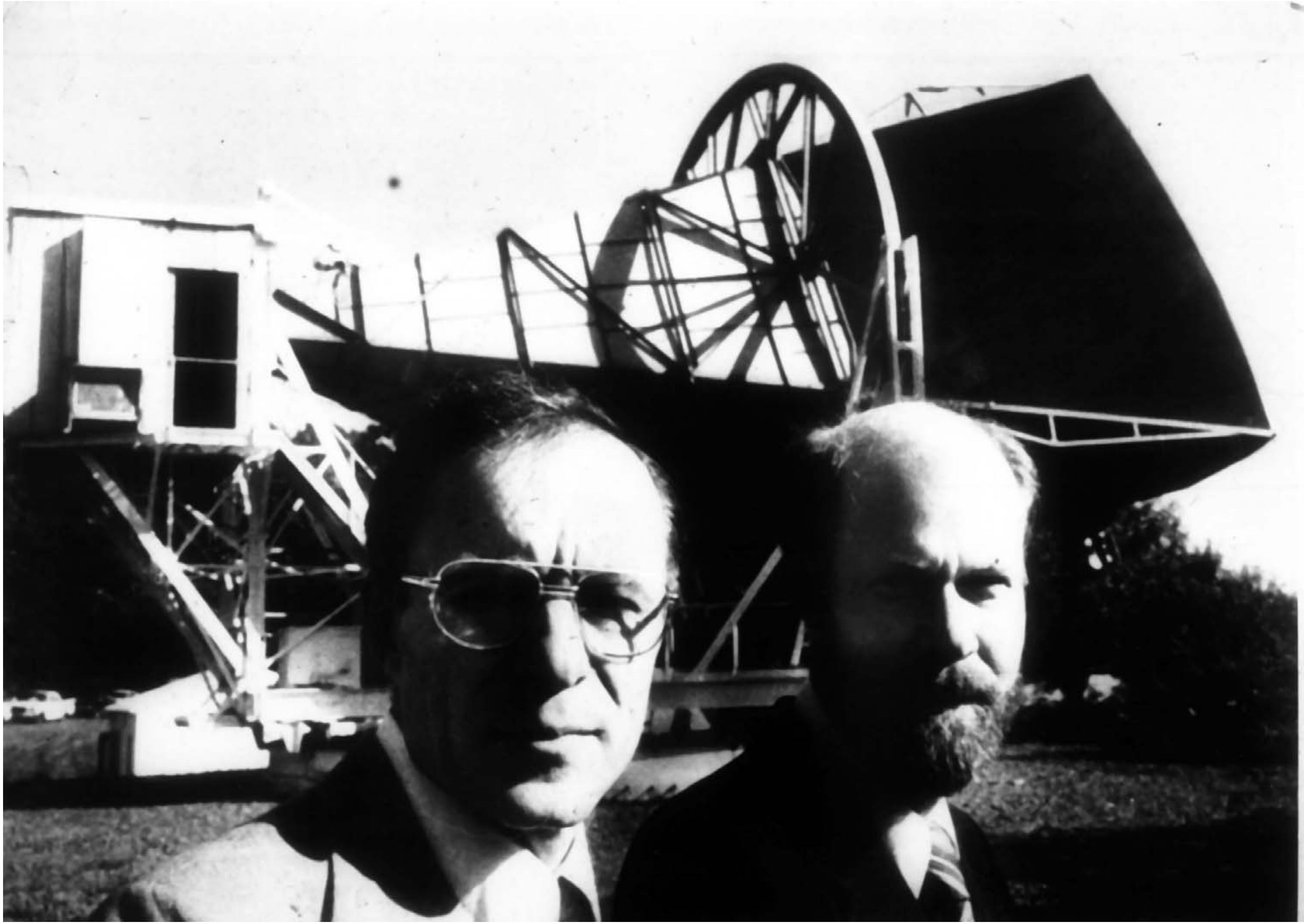
Fig. 1. The densities, in gm per cm³, of matter and radiation (ordinates) plotted against time in seconds (abscissae); logarithmic scale

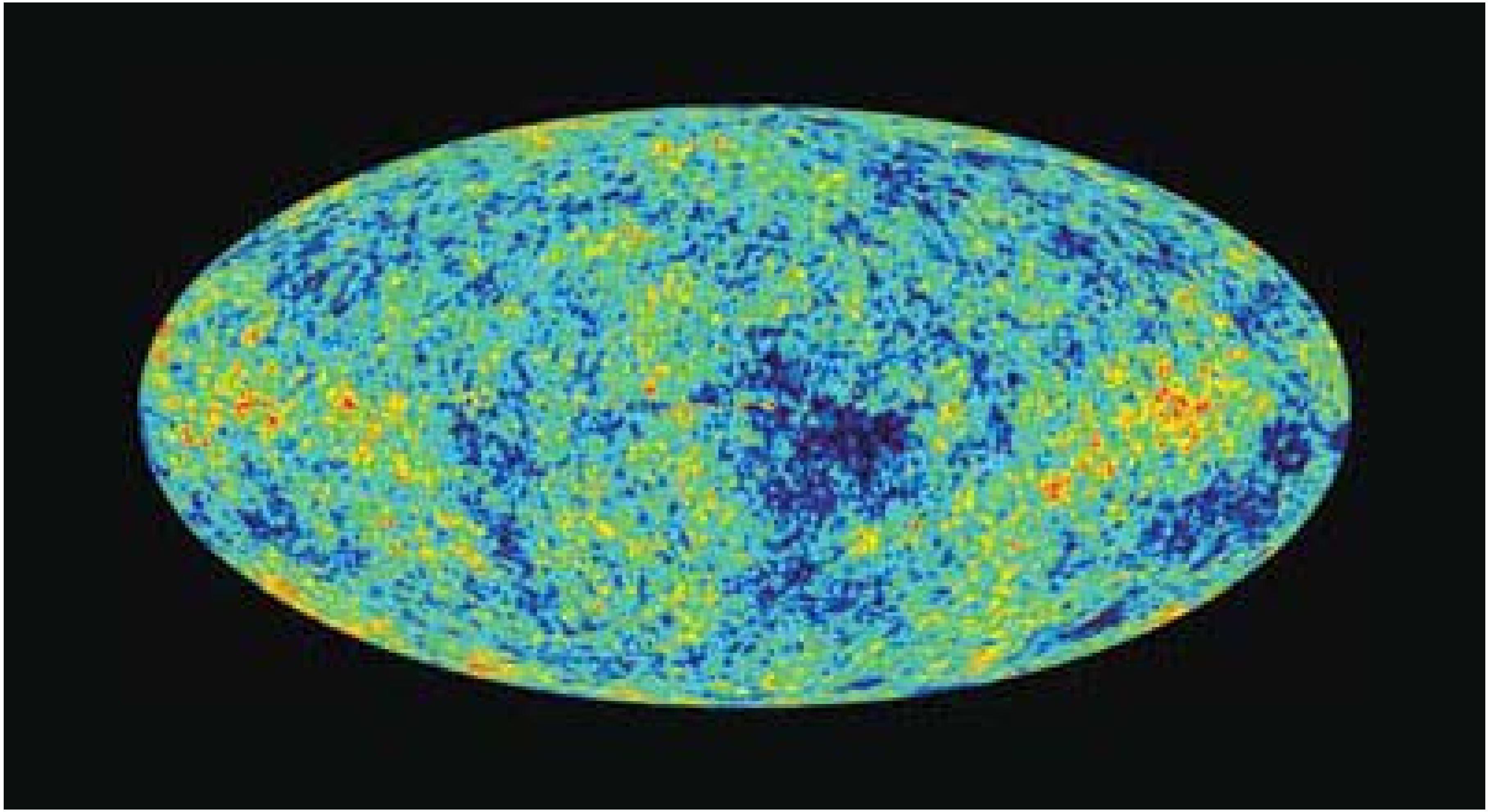
4. Formation of Chemical Elements and Origin of Galaxies

The above considerations give us a general picture of changing physical conditions characteristic of the evolutionary history of our Universe. We will indicate here only quite briefly how this information can be used for the explanation of various characteristic properties of the Universe as we know it to-day. First of all, it may be suggested that, at least partially, the relative abundances of the atoms of various chemical elements were conditioned by thermonuclear reactions which took place at high speed during the very early stages of expansion while the temperature of the Universe was exceedingly high. And, in fact, the calculations in that direction, carried out by the present writer*, and later in some more detail by Fermi and Turkevich,† lead to a value of the H/He ratio which is in good agreement with observational data. However, there are still some difficulties to be overcome in understanding the abundances of heavier elements, and there is a possibility that the original distribution was partially modified by various processes during the later stages of the evolution.



log(E/eV)
−8 −6 −4 −2 0 2 4 6 8 10 12 14 16 18 20
GRAND UNIFIED PHOTON SPECTRUM
log(Flux/erg cm^{-2} sec^{-1} erg^{-1} sr^{-1})
12 10 8 6 4 2 0 −2 −4 −6 −8 −10 −12 −14 −16 −18 −20
6 4 2 0 −2 −4 −6 −8 −10 −12 −14 −16 −18 −20 −22 −24
log(λ/cm)





Old Universe – *New* Numbers

$\Omega_{tot} = 1.02^{+0.02}_{-0.02}$

$w < -0.78$ (95% CL)

$\Omega_\Lambda = 0.73^{+0.04}_{-0.04}$

$\Omega_b h^2 = 0.0224^{+0.0009}_{-0.0009}$

$\Omega_b = 0.044^{+0.004}_{-0.004}$

$n_b = 2.5 \times 10^{-7}{}^{+0.1\times10^{-7}}_{-0.1\times10^{-7}}$ cm^{-3}

$\Omega_m h^2 = 0.135^{+0.008}_{-0.009}$

$\Omega_m = 0.27^{+0.04}_{-0.04}$

$\Omega_\nu h^2 < 0.0076$ (95%CL)

$m_\nu < 0.23$ eV (95% CL)

$T_{cmb} = 2.725^{+0.002}_{-0.002}$ K

$n_\gamma = 410.4^{+0.9}_{-0.9}$ cm^{-3}

$\eta = 6.1 \times 10^{-10}{}^{+0.3\times10^{-10}}_{-0.2\times10^{-10}}$

$\Omega_b \Omega_m^{-1} = 0.17^{+0.01}_{-0.01}$

$\sigma_8 = 0.84^{+0.04}_{-0.04}$ Mpc

$\sigma_8 \Omega_m^{0.5} = 0.44^{+0.04}_{-0.05}$

$A = 0.833^{+0.086}_{-0.083}$

$n_s = 0.93^{+0.03}_{-0.03}$

$dn_s/d \ln k = -0.031^{+0.016}_{-0.018}$

$r < 0.71$ (95% CL)

$z_{dec} = 1089^{+1}_{-1}$

$\Delta z_{dec} = 195^{+2}_{-2}$

$h = 0.71^{+0.04}_{-0.03}$

$t_0 = 13.7^{+0.2}_{-0.2}$ Gyr

$t_{dec} = 379^{+8}_{-7}$ kyr

$t_r = 180^{+220}_{-80}$ Myr (95% CL)

$\Delta t_{dec} = 118^{+3}_{-2}$ kyr

$z_{eq} = 3233^{+194}_{-210}$

$\tau = 0.17^{+0.04}_{-0.04}$

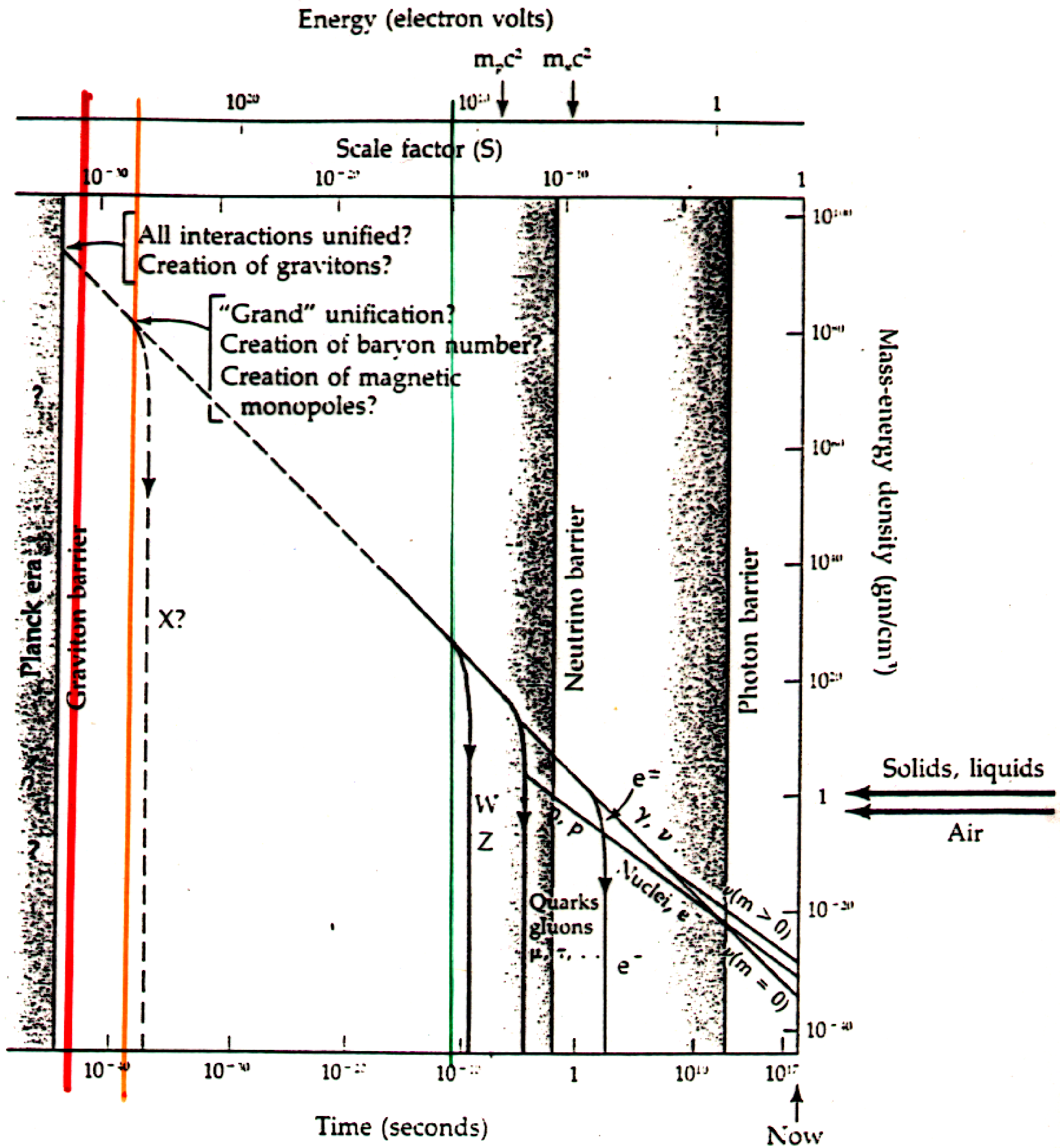
$z_r = 20^{+10}_{-9}$ (95% CL)

$\theta_A = 0.^\circ598^{+0.002}_{-0.002}$

$d_A = 14.0^{+0.2}_{-0.3}$ Gpc

$l_A = 301^{+1}_{-1}$

$r_s = 147^{+2}_{-2}$ Mpc

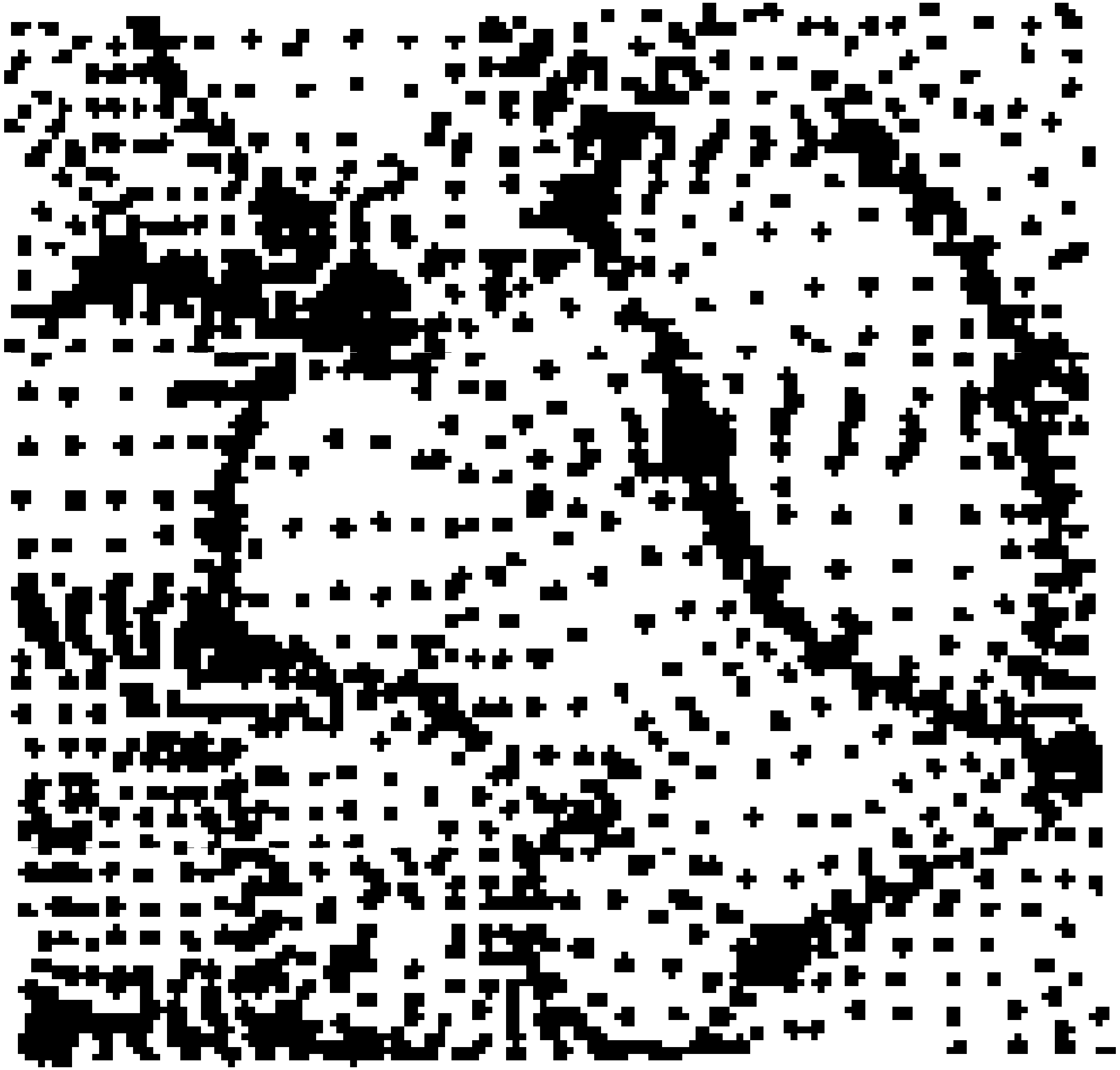


Energy (electron volts)
m_pc^2
m_ec^2
1
Scale factor (S)
1
All interactions unified?
Creation of gravitons?
"Grand" unification?
Creation of baryon number?
Creation of magnetic
monopoles?
X?
Planck era
Graviton barrier
Neutrino barrier
Photon barrier
W
Z
Quarks
gluons
e⁻
Nuclei, e⁻
e±
γ, ν
ν(m > 0)
ν(m = 0)
n, p
Mass-energy density (gm/cm³)
1
Solids, liquids
Air
1
Time (seconds)
Now

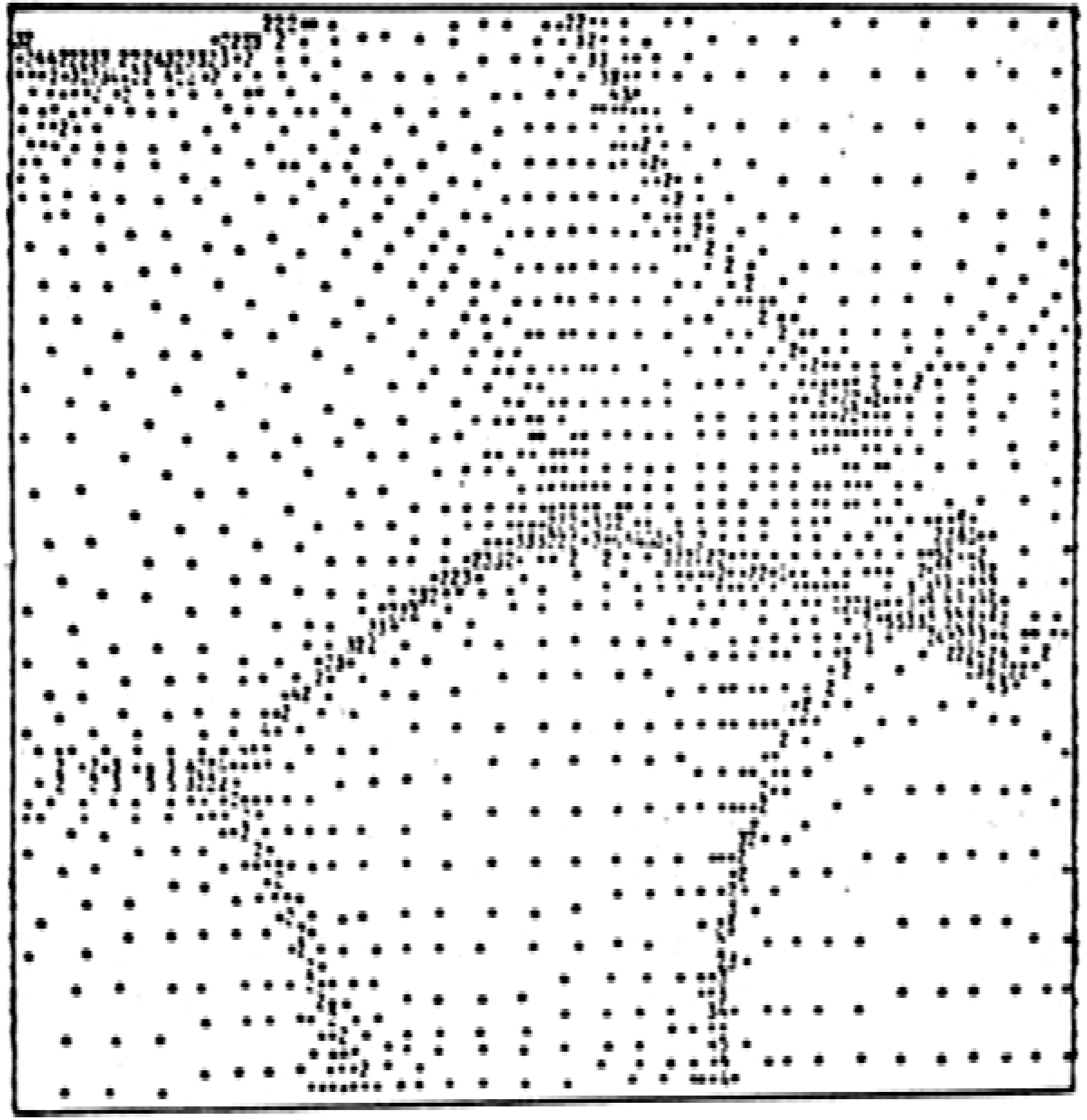
Temperature anisotropy (adiabatic mode)

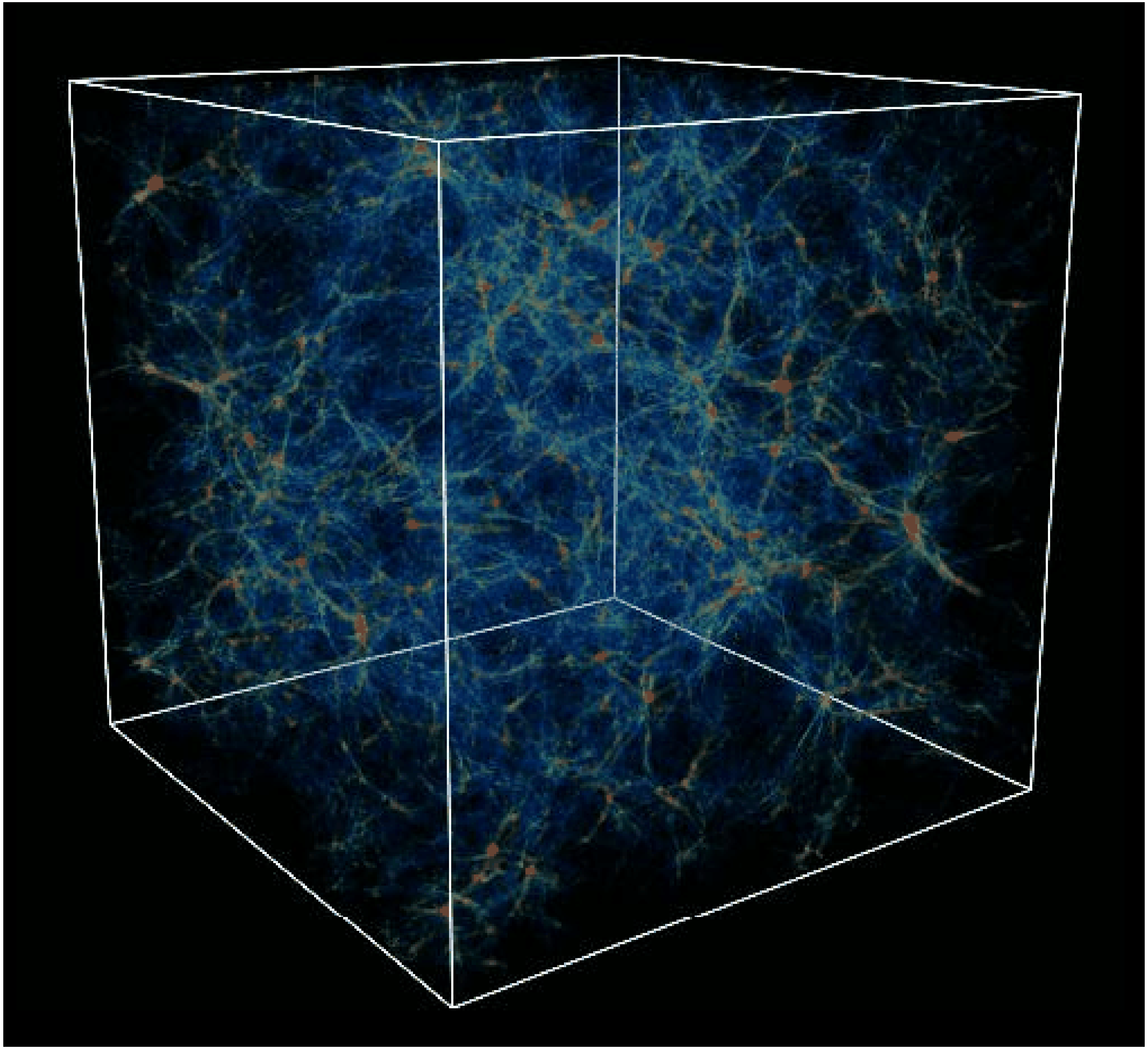
$$(\frac{\delta T}{T})_{obs} \sim 10^{-5}$$

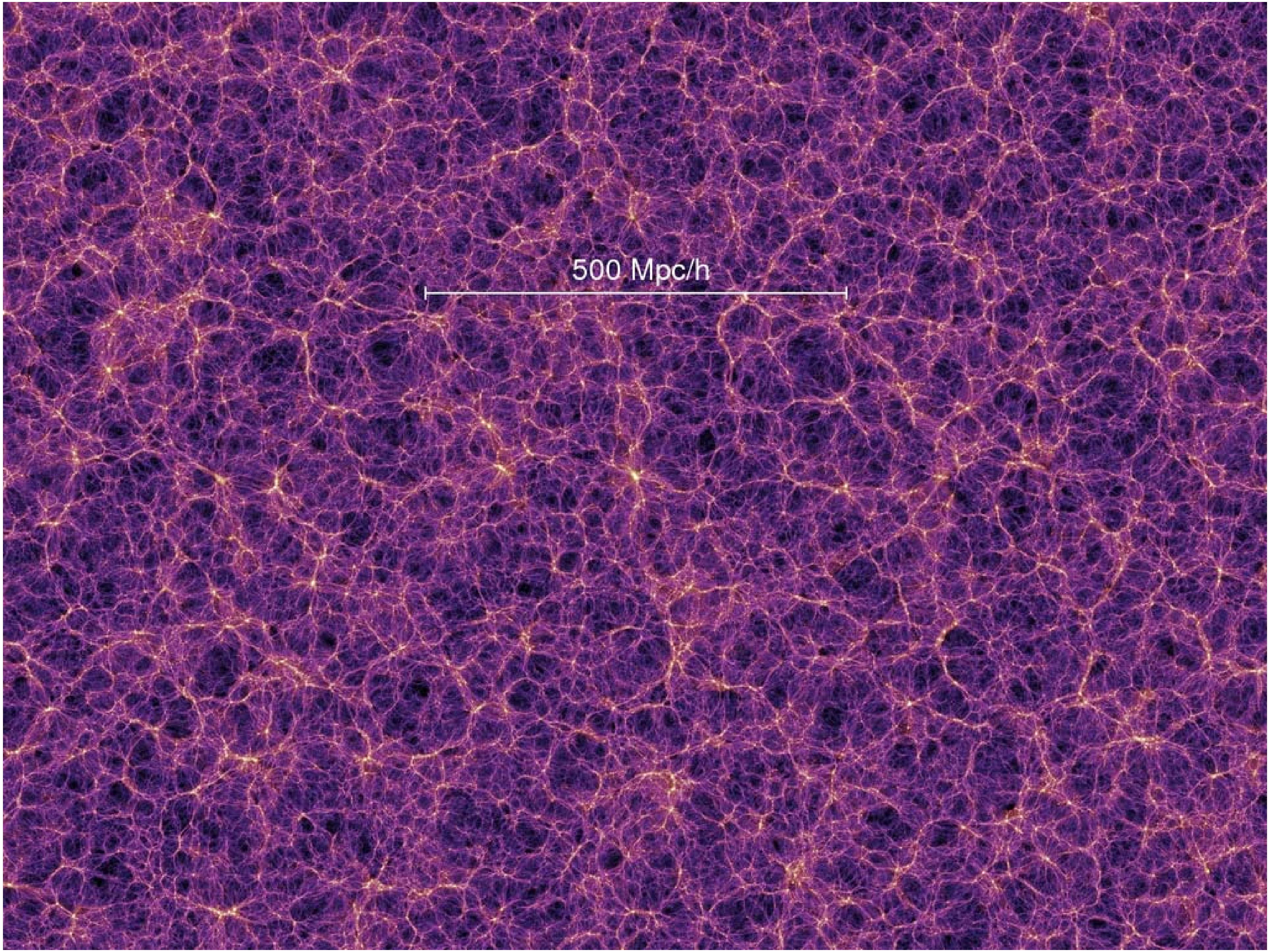
$$\frac{\delta \varrho}{\varrho} \sim 3 \frac{\delta T}{T}$$

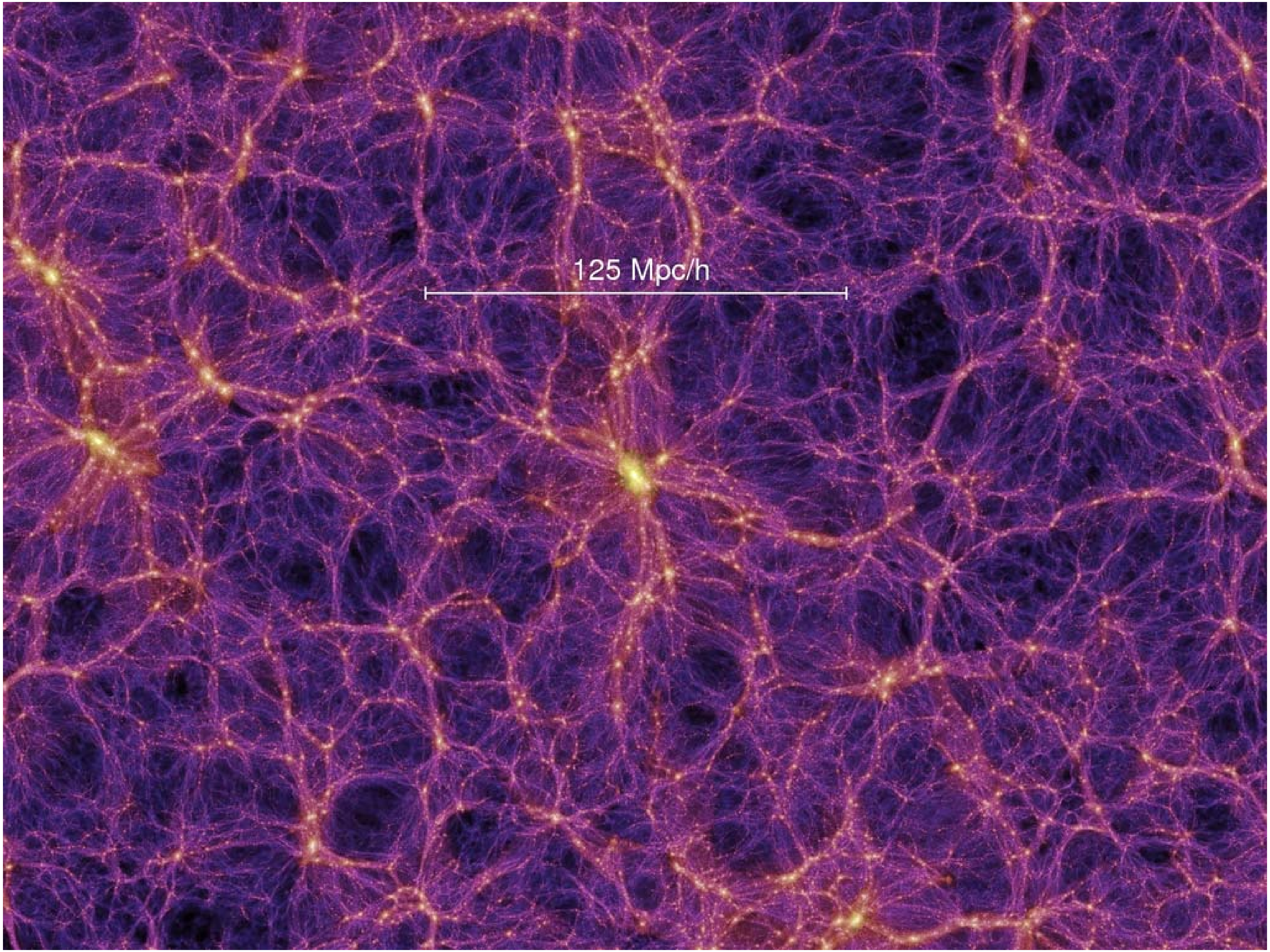


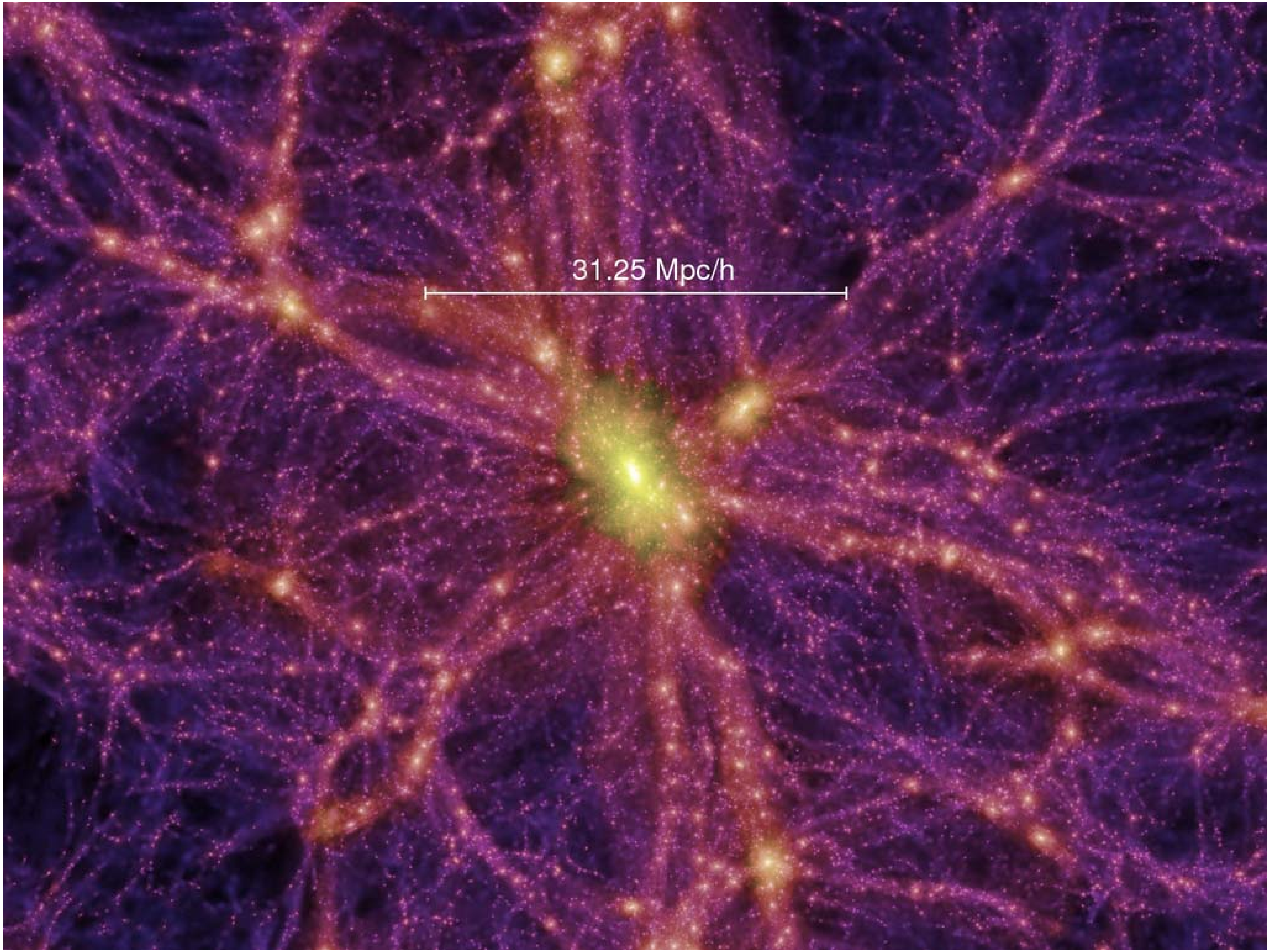
(a)

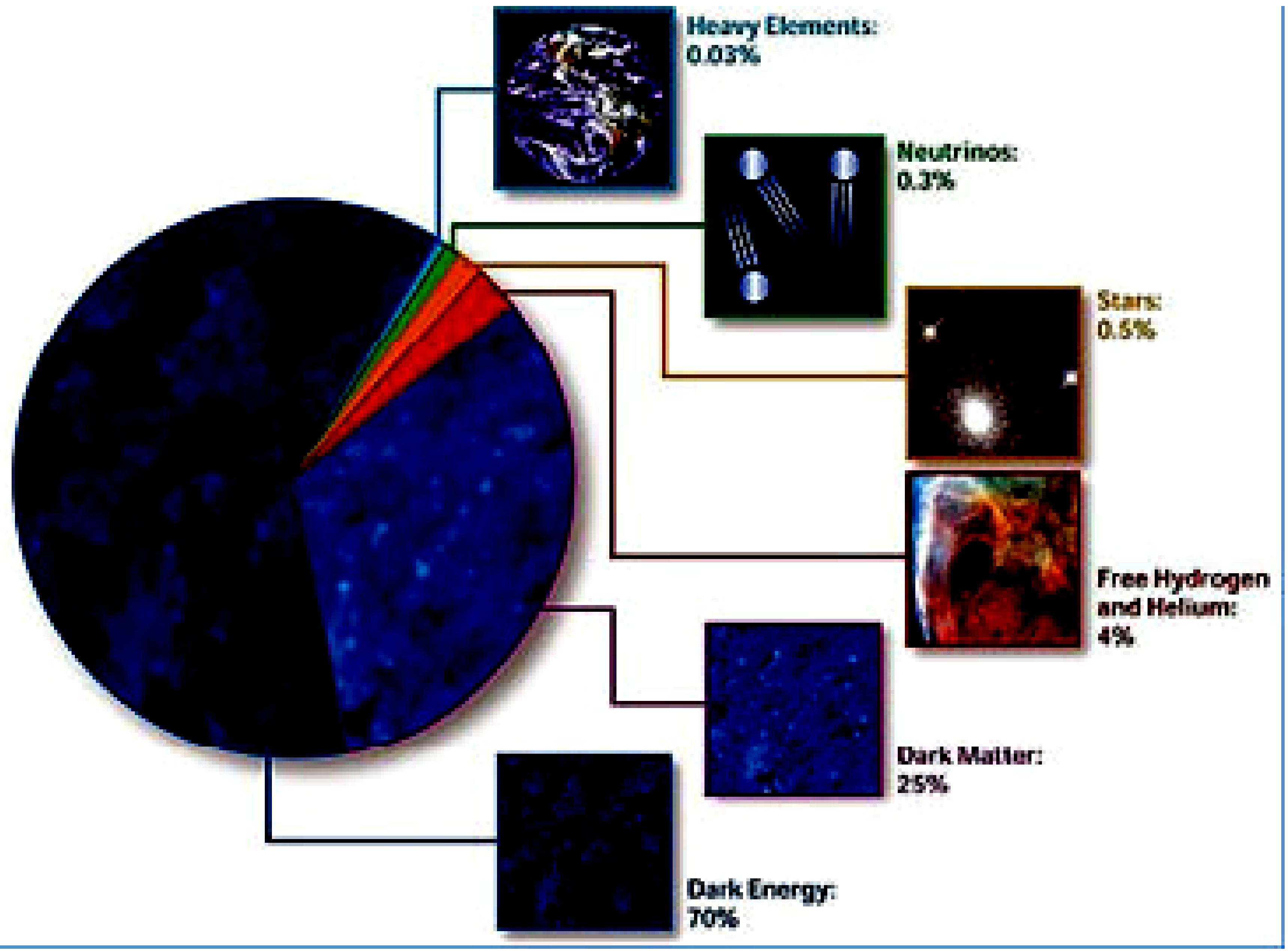




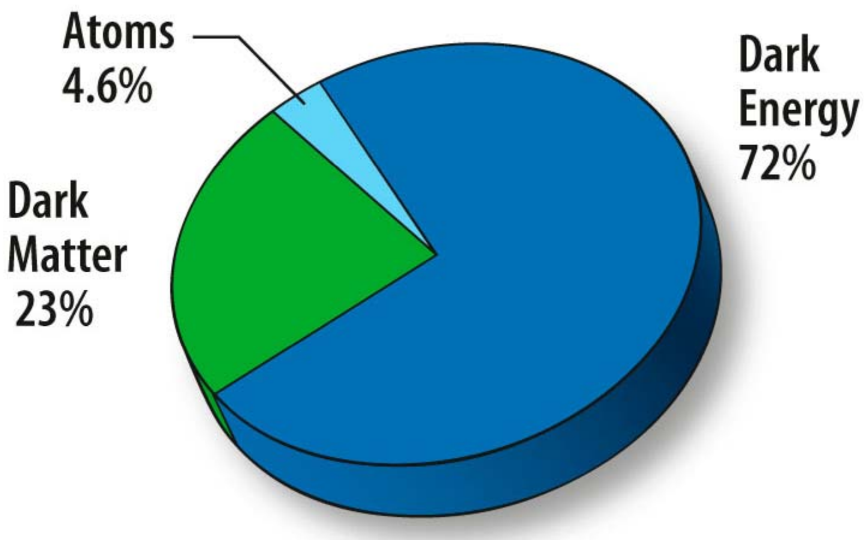

500 Mpc/h


125 Mpc/h

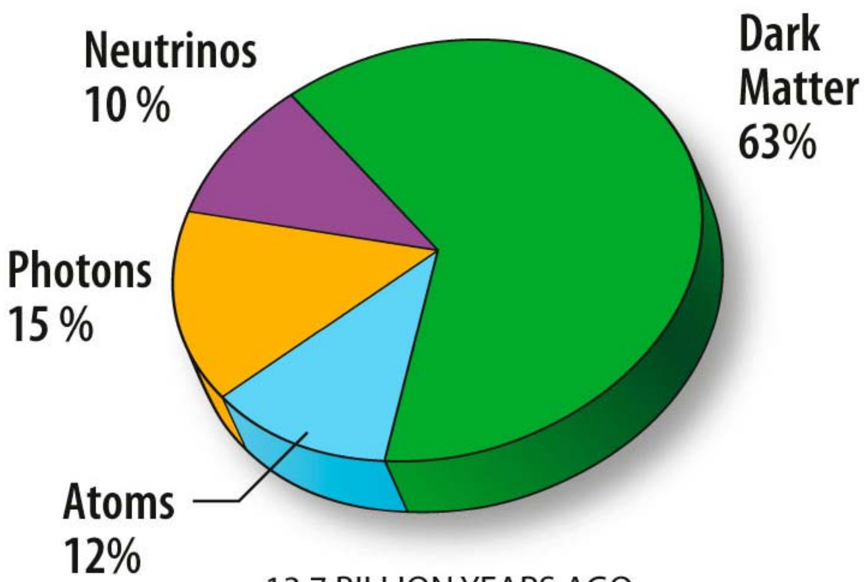

31.25 Mpc/h



Heavy Elements: 0.03%
Neutrinos: 0.3%
Stars: 0.5%
Free Hydrogen and Helium: 4%
Dark Matter: 25%
Dark Energy: 70%



TODAY



13.7 BILLION YEARS AGO
(Universe 380,000 years old)

Possible dark matter particles

neutralino, $m_N \sim 50$ GeV,

gravitino,

axions,

other WIMPs

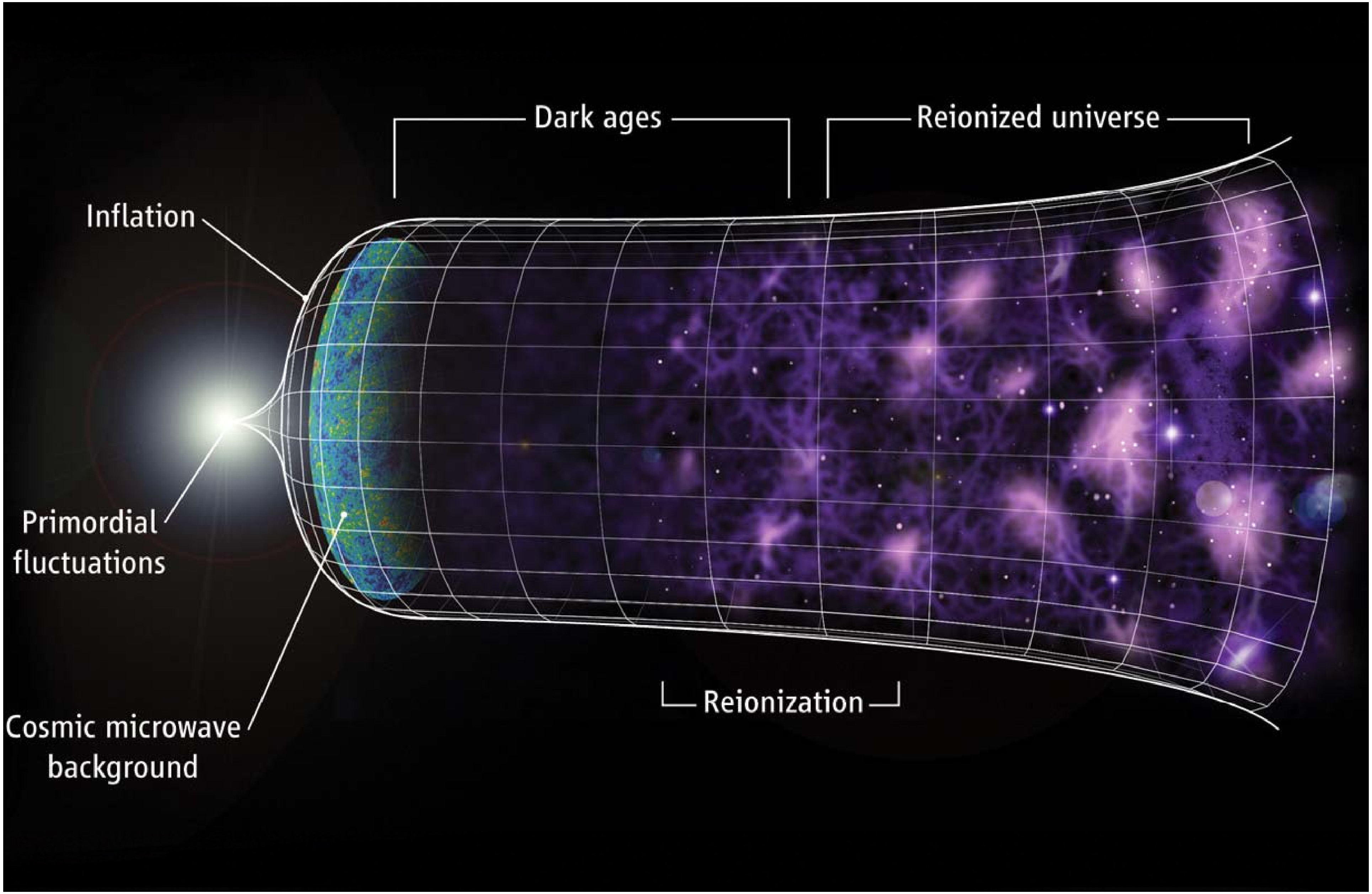
Dark energy

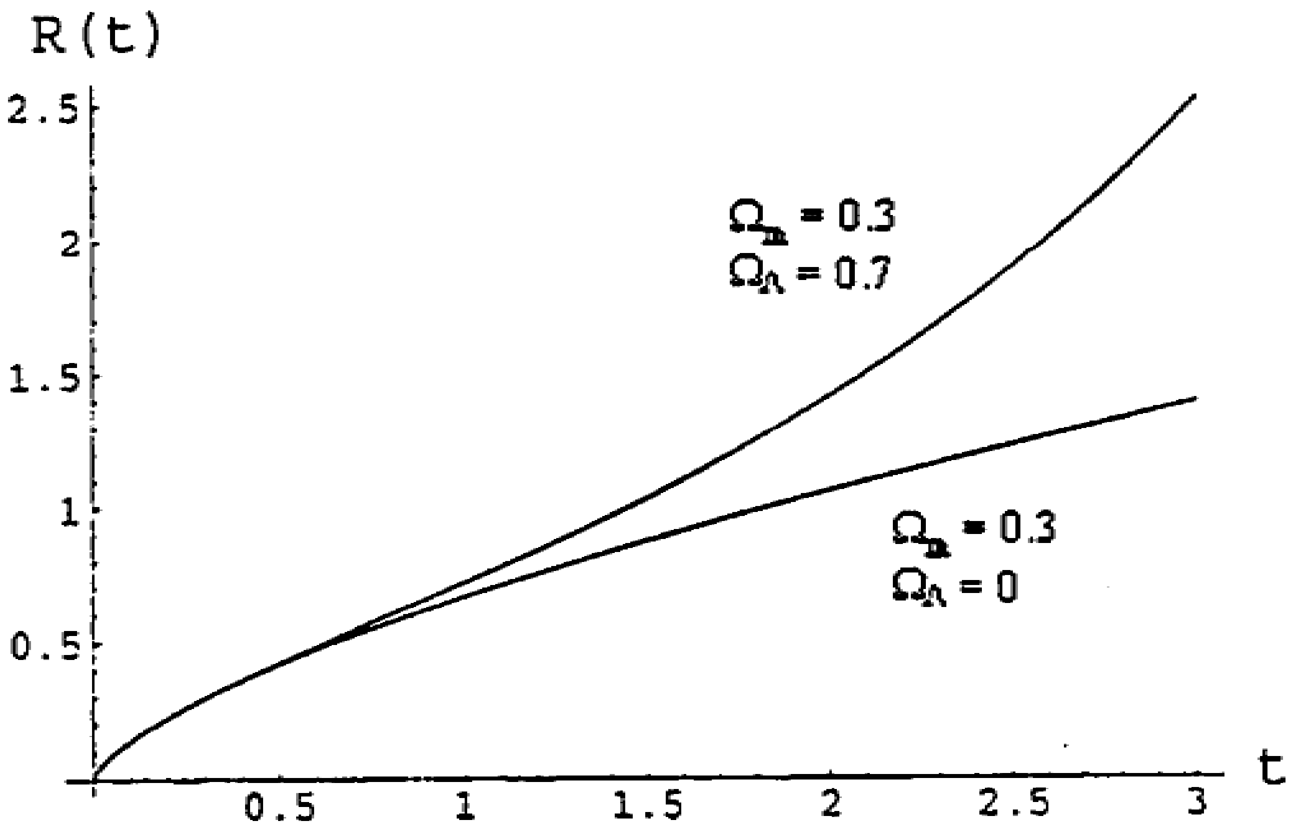
cosmological constant,

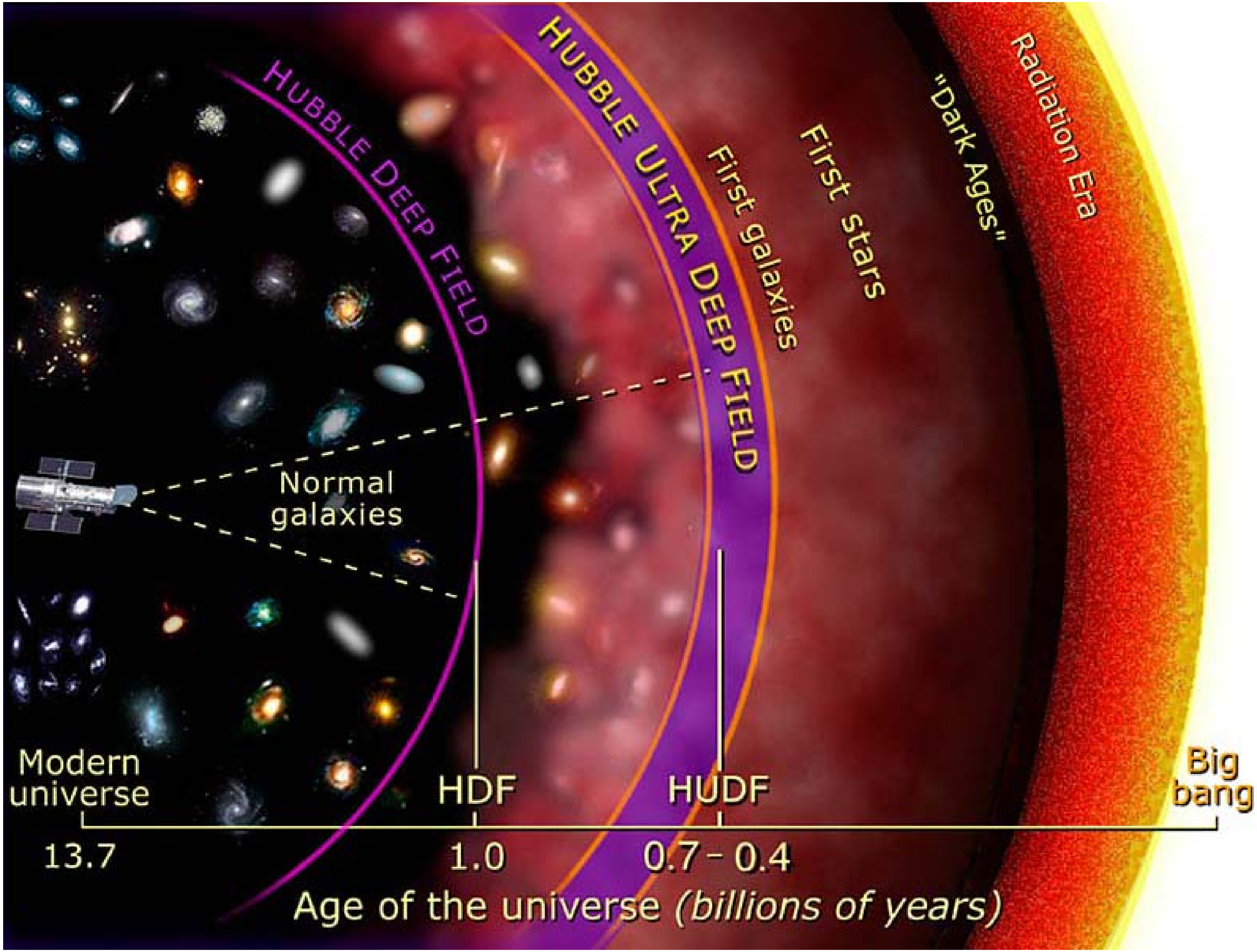
vacuum energy,

quintessence (potential energy of some scalar field)

????


Dark ages
Reionized universe
Inflation
Primordial
fluctuations
Cosmic microwave
background
Reionization


R(t)
2.5
2
1.5
1
0.5
t
0.5
1
1.5
2
2.5
3
$\Omega_m = 0.3$
$\Omega_\Lambda = 0.7$
$\Omega_m = 0.3$
$\Omega_\Lambda = 0$


HUBBLE DEEP FIELD
HUBBLE ULTRA DEEP FIELD
First galaxies
First stars
"Dark Ages"
Radiation Era
Normal galaxies
Modern universe
HDF
HUDF
Big bang
13.7
1.0
0.7 – 0.4
Age of the universe *(billions of years)*