Chapter VI: Cosmology
1. The cosmological principle
based on slides of P.C. Aichelburg

The cosmological principle

- A manifold is homogeneous if it looks the same at every point
- A manifold is isotropic at a point p if it looks the same in all directions at p
- Thus a manifold which is homogeneous and isotropic looks the same at all points in all directions

The cosmological principle

- There exists a cosmological time function t
- The surfaces {t=const} (“the level sets of t”) are homogeneous and isotropic
- Is it ???? on which scales ????

LOOKING INTO THE DISTANT PAST

Sun	8 Lmin
Sun - Pluto	5,5Lh
alpha centauri	4,3 Lj
center of galaxy	30.000 Lj
LMC & SMC	200.000 Lj
Andromeda	2.000.000 Lj
Virgo cluster	20.000.000 Lj
Coma cluster	100.000.000 Lj
farthest supernovae	10.000.000.000 Lj

1 Lj = 9.460.800.000.000 km

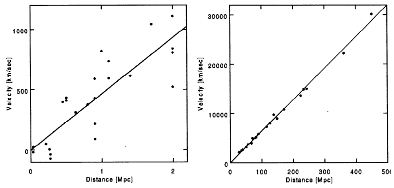
STRUCTURES

Earth	
Sun (stars)	330.000 Earth
galaxy	100.000.000.000 stars
cluster	10-1000 galaxies
supercluster	10 -100 clusters
universe	100.000.000.000 galaxies

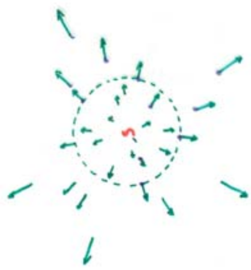
basic observations

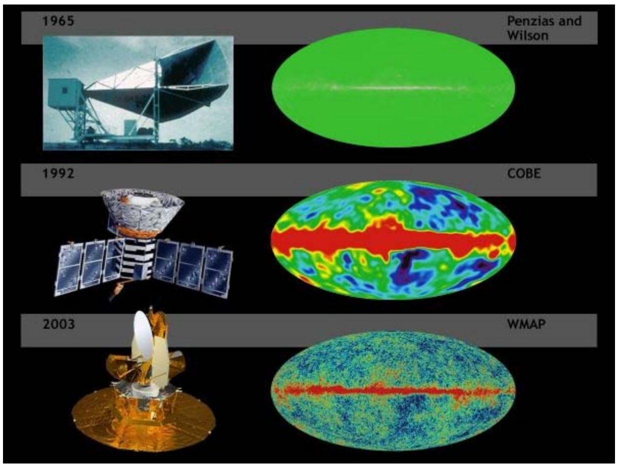
- matter distribution: homogeneous, isotropic ?
- Hubble law: v = H . D
- cosmic microwave background (CMB)

RECESSION OF GALAXIES

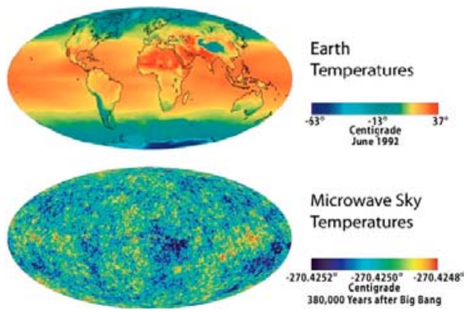


Expansion of the universe

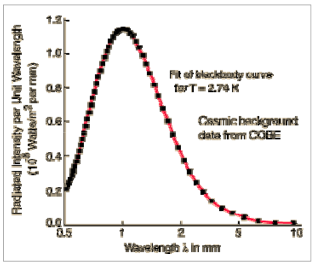




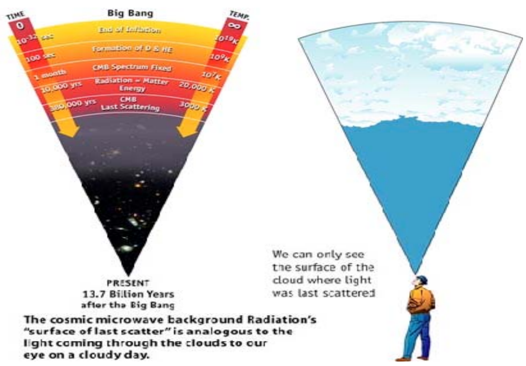
CMB

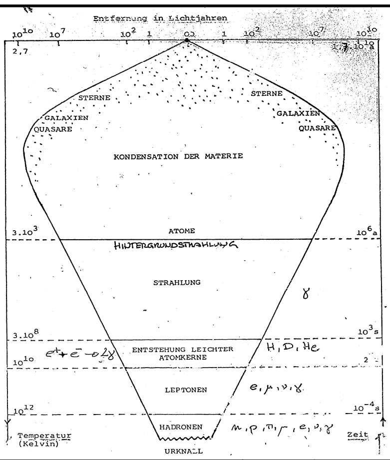


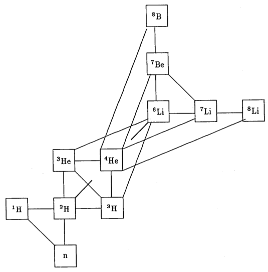
cosmic background radiation



what we see



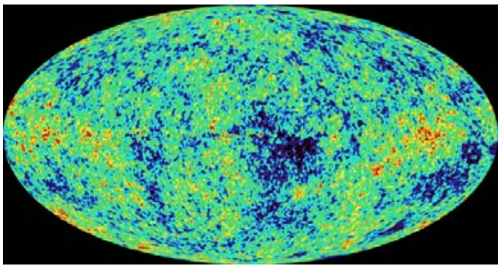




$n + e^+ = p + \nu$	$p + e^- = n + \tilde{\nu}$	$n + p = d + \gamma$
$d + p = {}^3\mathrm{He} + \gamma$	$d + n = {}^3\mathrm{H} + \gamma$	$d + d = {}^3\mathrm{He} + n$
$d + d = {}^3\mathrm{H} + p$	$d + \alpha = {}^6\mathrm{Li} + \gamma$	${}^3\mathrm{H} = {}^3\mathrm{He} + e^- + \nu$
${}^3\mathrm{H} + p = {}^3\mathrm{He} + n$	${}^3\mathrm{H} + p = {}^4\mathrm{He} + \gamma$	${}^3\mathrm{H} + d = {}^4\mathrm{He} + n$
${}^3\mathrm{H} + \alpha = {}^7\mathrm{Li} + \gamma$	${}^3\mathrm{He} + n = {}^4\mathrm{He} + \gamma$	${}^3\mathrm{He} + d = {}^4\mathrm{He} + p$
${}^3\mathrm{He} + {}^3\mathrm{He} = {}^4\mathrm{He} + 2p$	${}^3\mathrm{He} + \alpha = {}^7\mathrm{Be} + \gamma$	${}^6\mathrm{Li} + n = {}^7\mathrm{Li} + \gamma$
${}^6\mathrm{Li} + p = {}^7\mathrm{Be} + \gamma$	${}^7\mathrm{Li} + n = {}^8\mathrm{Li} + \gamma$	${}^7\mathrm{Li} + d = 2\alpha + n$
${}^7\mathrm{Li} + p = 2\alpha$	${}^7\mathrm{Be} + p = {}^8\mathrm{B} + \gamma$	${}^7\mathrm{Be} + d = 2\alpha + p$
${}^7\mathrm{Be} + n = 2\alpha$	${}^6\mathrm{Li} + n = {}^3\mathrm{H} + \alpha$	${}^6\mathrm{Li} + p = {}^3\mathrm{He} + \alpha$
	${}^7\mathrm{Li} + p = {}^7\mathrm{Be} + n$	

Abbildung 6.3: Kernreaktionen bis $A = 8$

WMAP



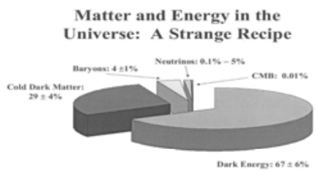


FIG. 10 The composition of the Universe today. Because the different components of the mass/energy budget evolve differently, the composition changes with time. For example, at very early times, photons and other relativitic particles were the dominant component; from 10,000 years until a few billion years ago, matter was the dominant component, and in the future dark energy will be the dominant component.

TABLE I OUR 16 COSMOLOGICAL PARAMETERS

Parameter	Value[a]	Description	WMAP[b]
		Ten Global Parameters	
h	0.72 ± 0.07	Present expansion rate[c]	$0.71^{+0.04}_{-0.03}$
q_0	-0.67 ± 0.25	Deceleration parameter[d]	-0.66 ± 0.10[e]
t_0	13 ± 1.5 Gyr	Age of the Universe[f]	13.7 ± 0.2 Gyr
T_0	2.725 ± 0.001 K	CMB temperature[g]	
Ω_0	1.03 ± 0.03	Density parameter[h]	1.02 ± 0.02
Ω_B	0.039 ± 0.008	Baryon Density[i]	0.044 ± 0.004
Ω_{CDM}	0.29 ± 0.04	Cold Dark Matter Density[i]	0.23 ± 0.04
Ω_ν	$0.001 - 0.05$	Massive Neutrino Density[j]	
Ω_X	0.67 ± 0.06	Dark Energy Density[i]	0.73 ± 0.04
w	-1 ± 0.2	Dark Energy Equation of State[k]	< -0.8 (95% cl)

A short history of space and time

time = 10^{-43} sec size = 10^{-30} today temp = 10^{32} Kelvin
The Planck era. Quantum gravity is important; current theories are inadequate. We can't get any closer to the Big Bang at t=0 and say anything with confidence (or even with informed speculation).

time = 10^{-35} sec size = 10^{-26} today temp = 10^{28} Kelvin
Inflation. A temporary period of domination by a form of dark energy at an ultra-high energy scale. A speculative theory, but one that has so far been consistent with observations.

time = 10^{-12} sec size = 10^{-15} today temp = 10^{15} Kelvin
Electroweak phase transition. At high temperatures, electromagnetism is unified with the weak interactions. This is the temperature at which they become distinct.

time = 10^{-6} sec size = 10^{-12} today temp = 10^{12} Kelvin
Quark-gluon phase transition. Quarks and gluons become bound into the protons and neutrons we see today.

time = 10 sec size = 10^{-9} today temp = 10^{9} Kelvin
Primordial nucleosynthesis. The universe cools to a point where protons and neutrons can combine to form light atomic nuclei, primarily Helium, Deuterium, and Lithium.

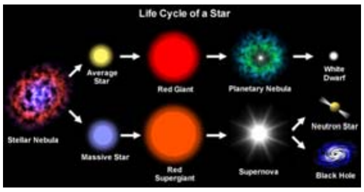
time = 3.7×10^{5} years size = 10^{-3} today temp = 3×10^{3} Kelvin
Recombination. The universe cools to a point where electrons can combine with nuclei to form atoms, and becomes transparent. Radiation in the Cosmic Microwave Background is a snapshot of this era.

time = 10^{8} years size = 10^{-1} today temp = 30 Kelvin
The dark ages. Small ripples in the density of matter gradually assemble into stars and galaxies.

time = 9×10^{9} yearssize = 5×10^{-1} today temp = 6 Kelvin
Sun and Earth form. From the existence of heavy elements in the Solar System, we know that the Sun is a second-generation star, formed about five billion years ago.

time = 13.7×10^{9} yearssize = 10^{0} todaytemp = 2.74 Kelvin
Today.

Leben der Sterne



THE COSMOLOGICAL CONSTANT