1 Introduction:

Cosmology deals with structure and the evolution of the cosmos as a whole. We aim to understand how the Universe has evolved into its present status and how it might develop in the future. These questions interested mankind since centuries. Greek philosophers

- Geocentric world model: earth in center, planets and sun circle around → Ptolemäus (≈ 100 – 160)
  → dominated a long time our thinking
- Heliocentric world view: sun is in the center Universe Aristoteles (≈ 310 BC – 230 BC), rediscovered by Kepler based on his own astronomical observations.

1.1 Overview:

Beginning of 20th Century Cosmology became part of natural sciences: technical improvement due to upcoming telescopes and general relativity came up in 1915. New results from Hubble

(1889 – 1953) were quite influential:
- proved existence of other galaxies
- other galaxies move away from us, even the faster the larger their distance

4 fundamental forces:
- strong / weak force: atomic or sub-atomic world
- electromagnetic force: screened by matter due to polarisation / magnetisation effects
- gravity remains to be dominant for structure / evolution of Universe

1917: A. Einstein applied his generality relativity to the Universe. Einstein field equations describe metric of space-time under the assumption that energy / matter distribution is known.

Symmetry assumptions:

(A1) Averaged over sufficiently large scales the observable properties of the Universe are isotropic, i.e. independent of the direction. This is not valid in der immediate cosmological neighborhood. But this assumption is supported by measuring the Cosmic Microwave Background (CMB) (ν = 1 – 300 GHz, λ = 30 cm – 1 mm), stems from about 300.000 years after Big Bang, perfectly isotropic, follows Planck radiation formula with a temperature of about 3 K.

(A2) cosmological principle: Our position in the Universe is by no means preferred to any other. This reflects to Copernican revolution of the word model of that time that the Earth is not in centre of the Universe.

(A1)+(A2): Universe is both homogeneous and isotropic

Applying these symmetries to Einstein field equations leads to different possible space-time structures. Comparison with experimental data then allows to discard some of these possible structures.

The last 2 decades led to many new astronomical observations which led to new insights:

- detecting supernovae, i.e. explosions of stars, with Hubble Space Telescope indicated that the expansion of Universe is accelerated
- More recent analysis of CMB and its polarization by satellites COBE, WMAP, Planck → led to a lot of information about early Universe.

1.2 Olbers' Paradoxon:

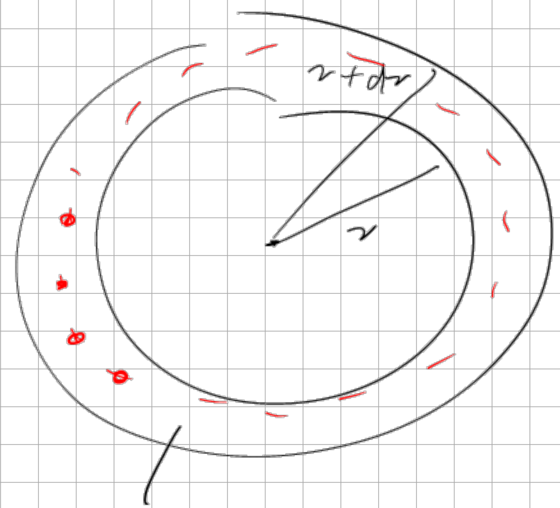
Centuries-old problem, goes back to Kepler in 16th century, formulated by Olbers (1758-1840): Why is it dark at night?

Seems to have straight-forward answer: sun at back of earth, other stars far away so their light does not reach.

Quantative consideration based on assumptions:

- Universe is infinitely large.
- Density of stars is constant on average in Universe.
- Only one star-type with one and the same luminosity (power in Watt radiated by star): radiation current

$$S(r) = \frac{L}{4\pi r^2}$$



$$dV = 4\pi r^2 dr$$

$$dN = n\,dV = 4\pi r^2 n\,dr$$

$$dS_{tot} = S(r)\,dN = \frac{L}{\cancel{4\pi r^2}} \cancel{4\pi r^2} n\,dr = \underbrace{Ln}_{const.}\,dr$$

$$S_{tot} = \int dS_{tot} = \int_0^\infty L n\,dr = \text{"}\infty\text{"}$$

How to explain this obvious disagreement with observation?

Assumption of point-like stars not correct.

Similar to forest: you do not see trees behind a tree

But still a finite brightness is expected.

Other assumptions can not be true:

- $S(r)$ drops off faster with r due to deformed spacetime
- Universe is finite
- Universe is infinite, but due to finite light propagation we can see the whole Universe.

E. R. Harrison:

- The dark night sky paradox: Am. J. Phys. 45, 119–124 (1977)
- Darkness at night – A riddle of the Universe (Harvard Press, 1987)

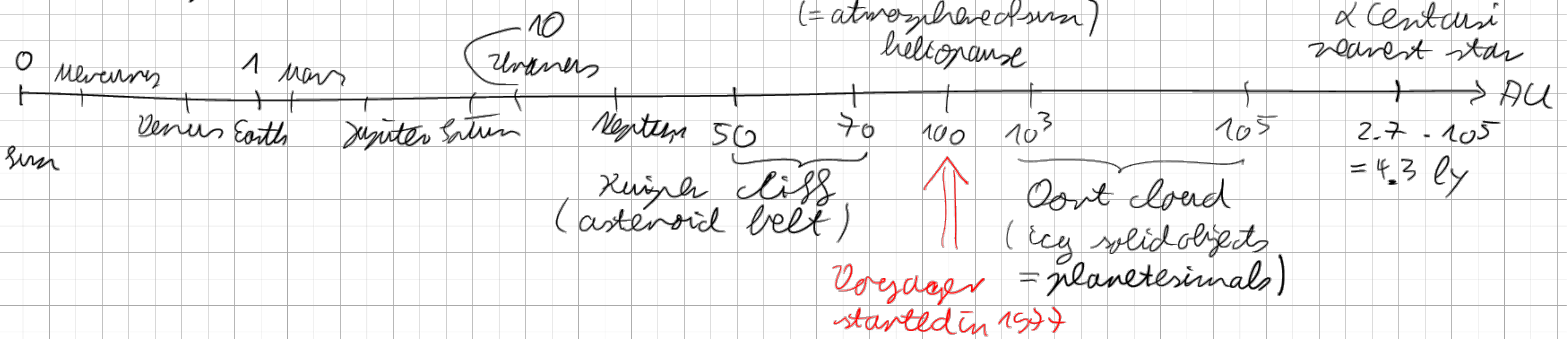
1.3 Structure of the Universe:

Solar-system, Milky Way, Clusters, Superclusters

1.3.1 Solar System:

length scale: astronomical unit AU $= 1.496 \cdot 10^8$ km $= 8.3$ light minutes

$\hat{=}$ average distance between earth and sun



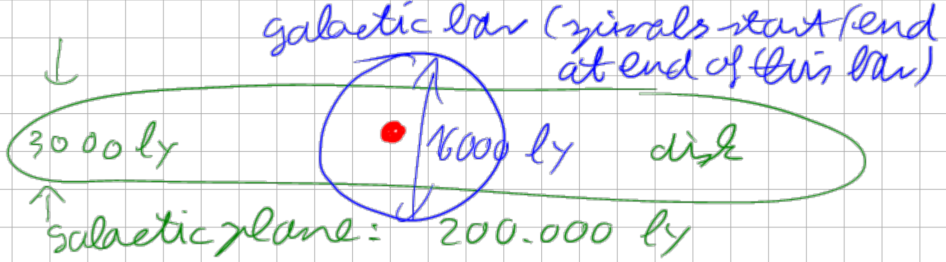
1.3.2 Milky way:

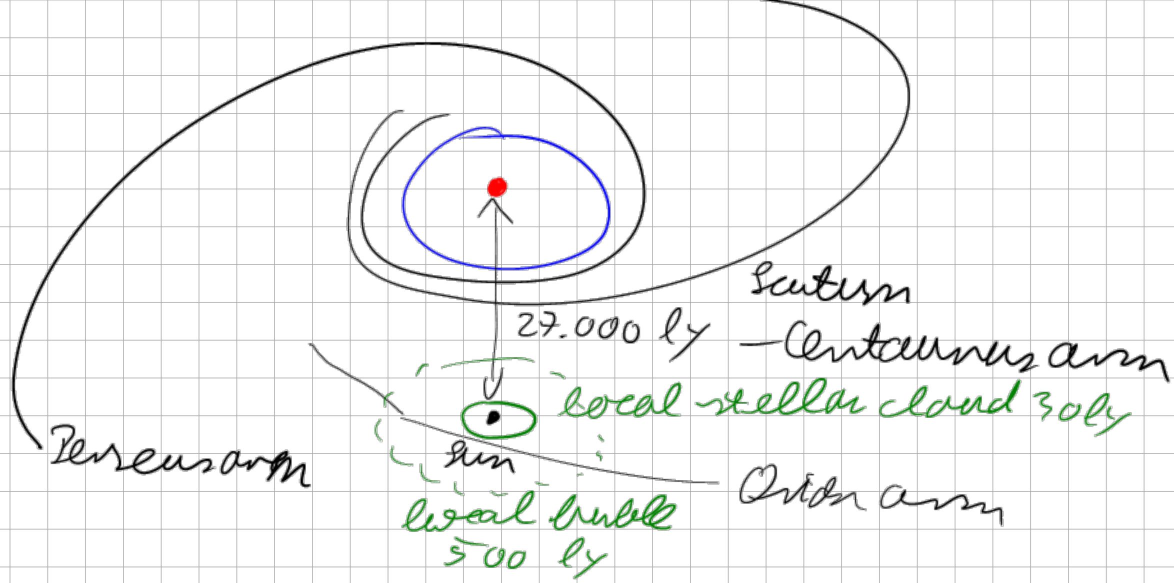
1 light year = 1 ly $= 9.4 \cdot 10^{12}$ km $= 6.3 \cdot 10^4$ AU

spiral galaxy consisting of 10^{11} stars

side view

top view





supermassive black hole

Sagittarius A*: $4.1 \cdot 10^6 M_\odot$

YouTube: The best Milky Way animation by Gaia (2 min)

1.3.3 Local Group of Galaxies:

YouTube video: "A 20 minute tour"