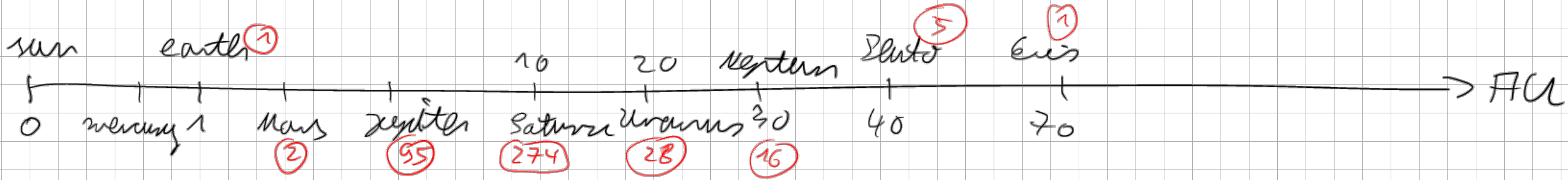
1.3 Structure of the Universe – Where are we in the Universe?

1.3.1 Our Solar System:



—: moons, satellites

Pluto discovered in 1930, in 1990's other objects of similar mass were discovered, e.g. Eris in 2005 is more massive Pluto

$\Rightarrow$ definition of dwarf planets: orbit the sun, due to gravity rounded, but gravitational field insufficient to affect other planet $\rightarrow$ "moons of sun"

1.3.2 Milky Way:

1.3.3 Local Group of Galaxies:

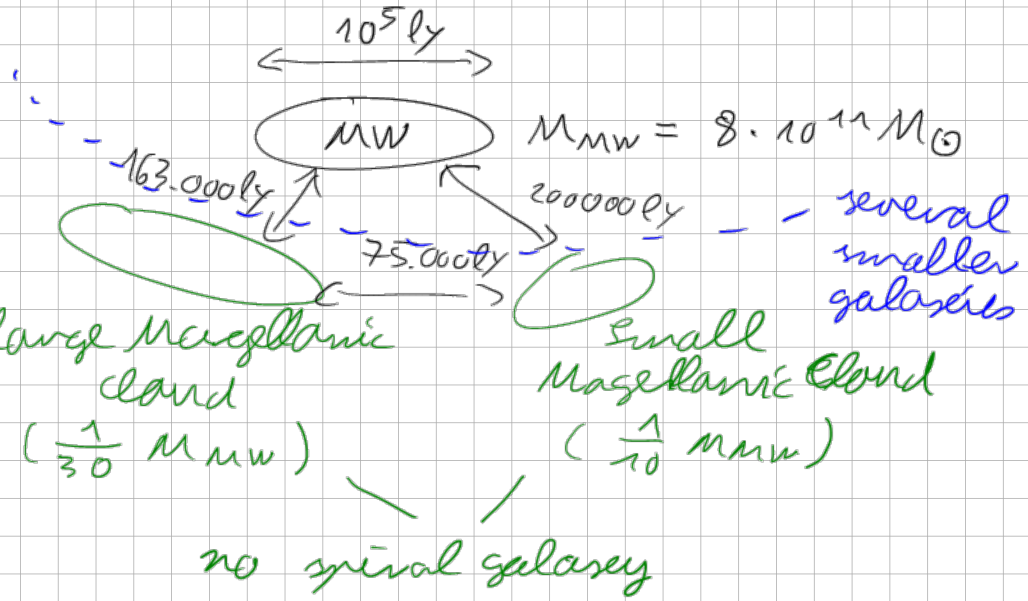
- Galaxies cluster due to gravity.

  poor cluster $\approx$ up to 50 galaxies

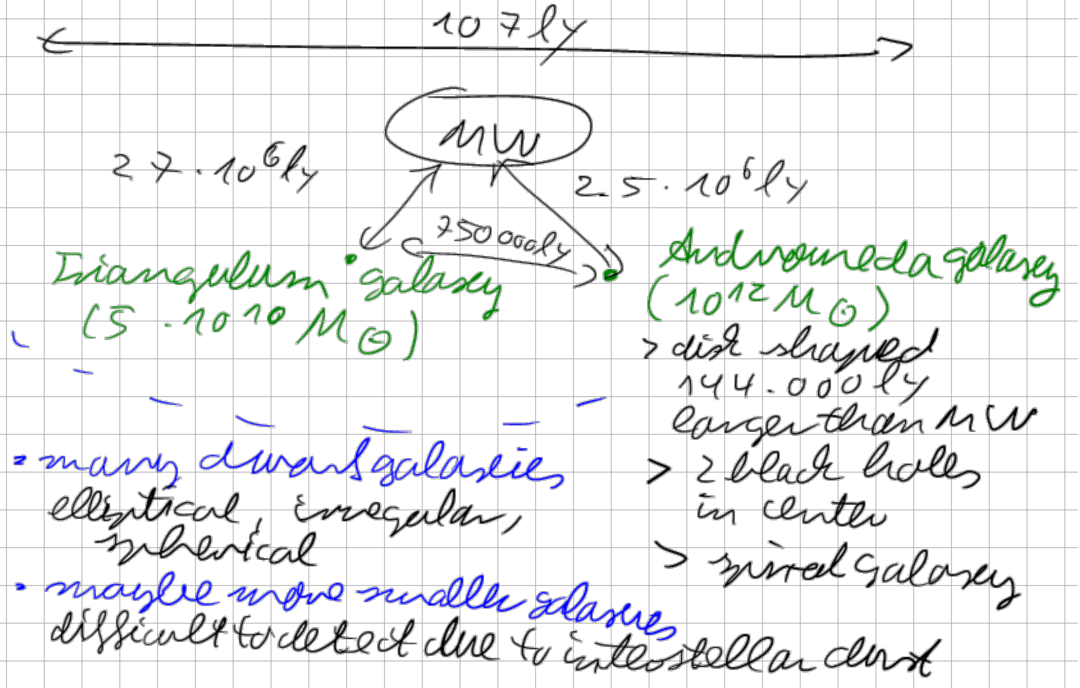
  rich cluster $\gg$ 50 galaxies

- $\dfrac{\text{distance between galaxies}}{\text{galaxy size}} \ll \dfrac{\text{distance between stars}}{\text{average star size}}$

galaxies near Milky Way are gravitationally affected

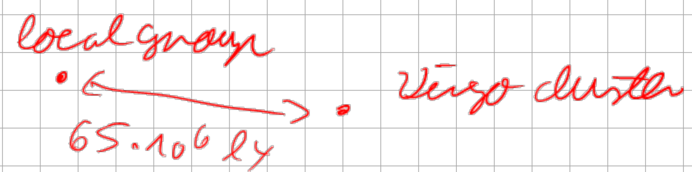


Global view of Local Group



1.3.4 Virgo supercluster:

- Clusters of galaxies do not exist alone, due to gravity they form super-clusters
- Virgo supercluster is one of 10^7 superclusters in observable universe
- It contains 100 galaxy groups and clusters, which located within a diameter of 10^8 ly



- Fornax cluster
- Eridanus cluster

- Virgo supercluster is part of an even greater supercluster

$\Rightarrow$ Laniakea with a diameter of $5.2 \cdot 10^{8}$ ly (discovered 2014)

$M_{Laniakea} \approx 10^{17} M_\odot$

- compare this with the whole Universe (visible)

diameter: $1.4 \cdot 10^{10}$ ly $\rightarrow$ Laniakea $\approx \frac{1}{100}$ of this

mass: $10^{24} M_\odot$ $\rightarrow$ Laniakea $\approx 10^{-7}$ of this

1.4 Hubble's Discoveries:

Hubble (1889 – 1953) made in 1920's and 1930's two major contributions which have until now a strong impact on our understanding of Universe:

- To prove that the Milky Way is not the only galaxy in the Universe
- to put forward the notion of an expanding Universe

already in 1927 Lemaître (1894 – 1966) formulated the idea

Hubble worked at the Mt. Wilson Observatory → Hooker telescope located northeast of Los Angeles, was put in operation in 1917, 2.5 m telescope largest telescope until 1948.

1.4.1 Other Galaxies:

Observed special class of stars: Cepheids

big stars which periodically vary their brightness (1 – 100 days)

law: $\underbrace{L}_{\text{luminosity (radiation power in Watt)}} = L_0 - \delta \cdot \ln \frac{P}{P_0}$ ← pulsation period

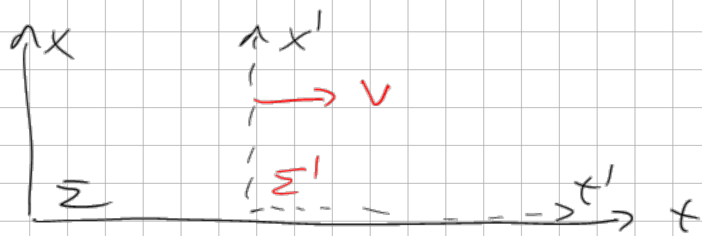
• Used for measuring distances

• Shapley (1885 – 1972) in 1918: cepheids in globular star cluster in Milky Way
→ standard candle

• Hubble measured cepheids in Andromeda nebula, had larger distances than the extension of Milky Way → other galaxies than Milky Way
→ 1925: Astronomical Society

1.4.2 Distance Dependent Redshift:

1912 Slipher (1875 – 1969) spectral shifts of distant galaxies
1913 Andromeda nebula → blue shift (moves to us)
⇒ Doppler effect



Lorentz transformation:

$$x = \frac{x' + vt'}{\sqrt{1-\frac{v^2}{c^2}}} \xrightarrow{v/c \ll 1} x' + vt'$$

$$t = \frac{t' + \frac{v}{c^2}x'}{\sqrt{1-\frac{v^2}{c^2}}} \xrightarrow{v/c \ll 1} \underbrace{t'}_{\text{Galilei transformation}}$$

wave in Σ: $\psi(x,t) = A\, e^{i(\omega t - kx)}$ $\qquad \omega = 2\pi f \qquad c = \frac{\omega}{k}$

$k = \frac{2\pi}{\lambda} \qquad = \lambda f$

wave in Σ':

$$\psi(x',t') = A\, e^{i\left[\omega \frac{t' + \frac{v}{c^2}x'}{\sqrt{1-\frac{v^2}{c^2}}} - k \frac{x' + vt'}{\sqrt{1-\frac{v^2}{c^2}}}\right]} = A\, e^{i(\omega' t' - k' x')}$$

$$\omega' = \frac{\omega - kv}{\sqrt{1-\frac{v^2}{c^2}}} = \frac{2\pi f}{\sqrt{1-\frac{v^2}{c^2}}}\left(1-\frac{v}{c}\right) \stackrel{!}{=} 2\pi f', \quad f' = f\sqrt{\frac{1-\frac{v}{c}}{1+\frac{v}{c}}} \quad \Bigg\} \; c' = f'\lambda'$$

$$k' = \frac{k - \frac{\omega v}{c^2}}{\sqrt{1-\frac{v^2}{c^2}}} = \frac{2\pi}{\lambda}\frac{1}{\sqrt{1-\frac{v^2}{c^2}}}\left(1-\frac{v}{c}\right) \overset{!}{=} \frac{2\pi}{\lambda'}, \quad \left.\lambda' = \lambda\sqrt{\frac{1+\frac{v}{c}}{1-\frac{v}{c}}}\;\right| \quad = f\lambda = c$$

characterize Doppler effect by dimensionless quantity
= red shift parameter

$$z = \frac{\lambda'}{\lambda} - 1 = \frac{f}{f'} - 1 = \sqrt{\frac{1+\frac{v}{c}}{1-\frac{v}{c}}} - 1 \approx \frac{v}{c} + \dots \Rightarrow z > 0 \,\hat{=}\, v > 0$$

Note: frequency shifts can also have different reasons

- gravitational redshift
- cosmological redshift due to expansion of Universe. (i.e. from a time dependent metric)

Hubble: 1929 ⇒ possible relation between magnitude of red shift and distance of galaxies from us, use Cepheides for distance measurements
⇒ red shift turned out to be larger, the farther away the galaxies are

escape velocity: $\quad v = c\,z \quad \Rightarrow \quad v = \underbrace{H_0}_{\text{Hubble constant}} d$ value today

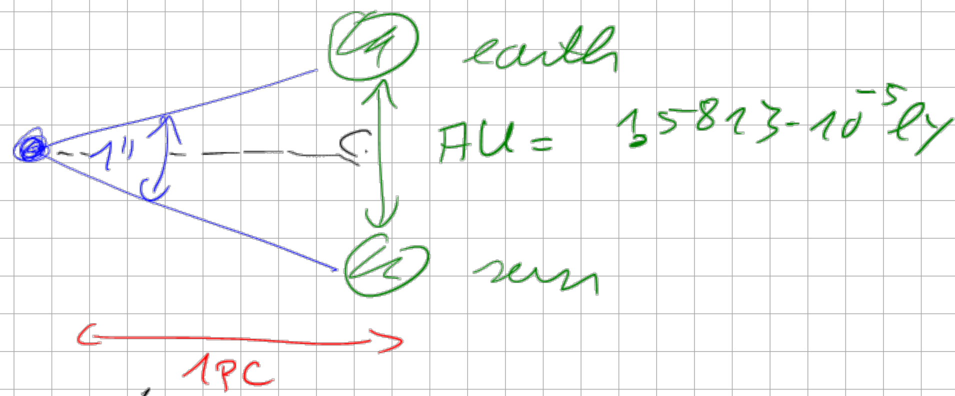
$$[H_0] = \frac{1}{s}$$

Astrophysics one uses instead: $\frac{km}{s}\,\frac{1}{Mpc}$

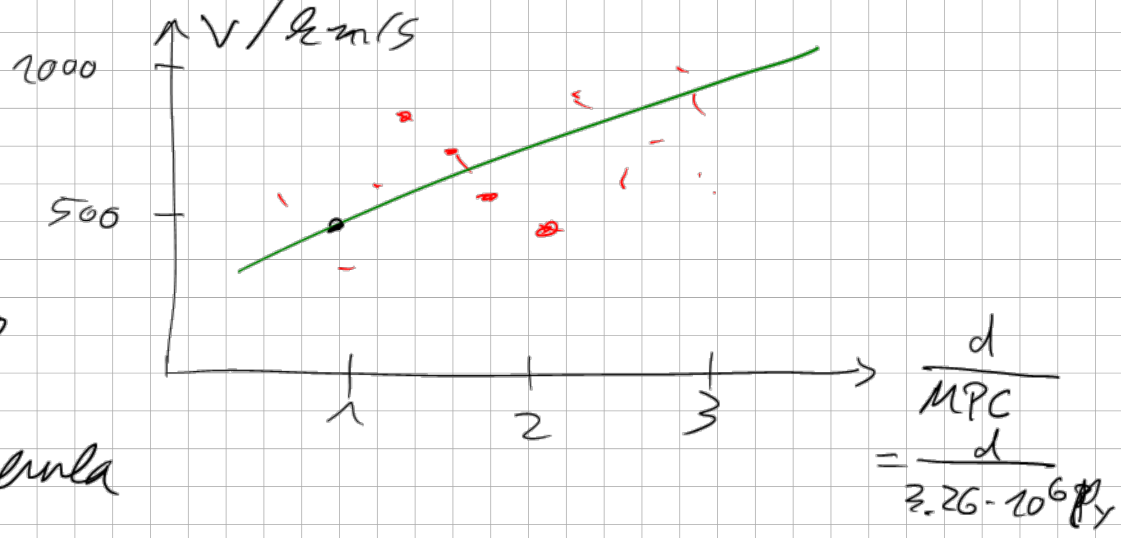
10^6 (M), pc: parsecond = parallactical second

$$\tan\left(\frac{1''}{2}\right) \approx \frac{1''}{2} = \frac{AU/2}{1\,pc} \Rightarrow$$

$$\Rightarrow 1\,pc = \frac{AU}{1''} = 1.5813\cdot 10^{-5}\,ly \cdot \frac{360\cdot 3600}{2\pi} = 3{,}26\,ly$$



The data scatter a lot, but this is not a measurement error but has physical origin:
There are two contributions to take into account



- Each galaxy has a peculiar velocity which is independent of the dynamics of the Universe. E.g. Andromeda nebula with a blue shift.

Physical definition of Laniakea, i.e. our immediate neighborhood in Universe
→ measure a peculiar velocity (2014) => diameter Laniakea 160 MPC

- Objects with negligible peculiar velocity: comoving objects

Historical value of Hubble: $H_0 = 500\,\frac{km}{s}\,\frac{1}{MPC}$

This is much too large in comparison to todays values:

> Hubble Space Telescope: $H_0 = 72 \pm 8\,\frac{km}{s}\,\frac{1}{MPC}$

> observe microwave background radiation

- WMAP mission: $H_0 = 69.32 \pm 0.8 \frac{km}{s} \frac{1}{Mpc}$ (*)
- Planck satellite: $H_0 = 67.66 \pm 0.042 \frac{km}{s} \frac{1}{Mpc}$

} early universe

→ In our local group: $H_0 = 74.22 \pm 1.82 \frac{km}{s} \frac{1}{Mpc}$

⇒ Ongoing controversy about the precise value of Hubble constant

All escaping galaxies must have been together at some time in the past

$$\cancel{d} = v\,t = (H_0\,\cancel{d})\,t \Rightarrow t = \frac{1}{H_0} \overset{(*)}{=} \underline{14.02 \cdot 10^9 a}$$