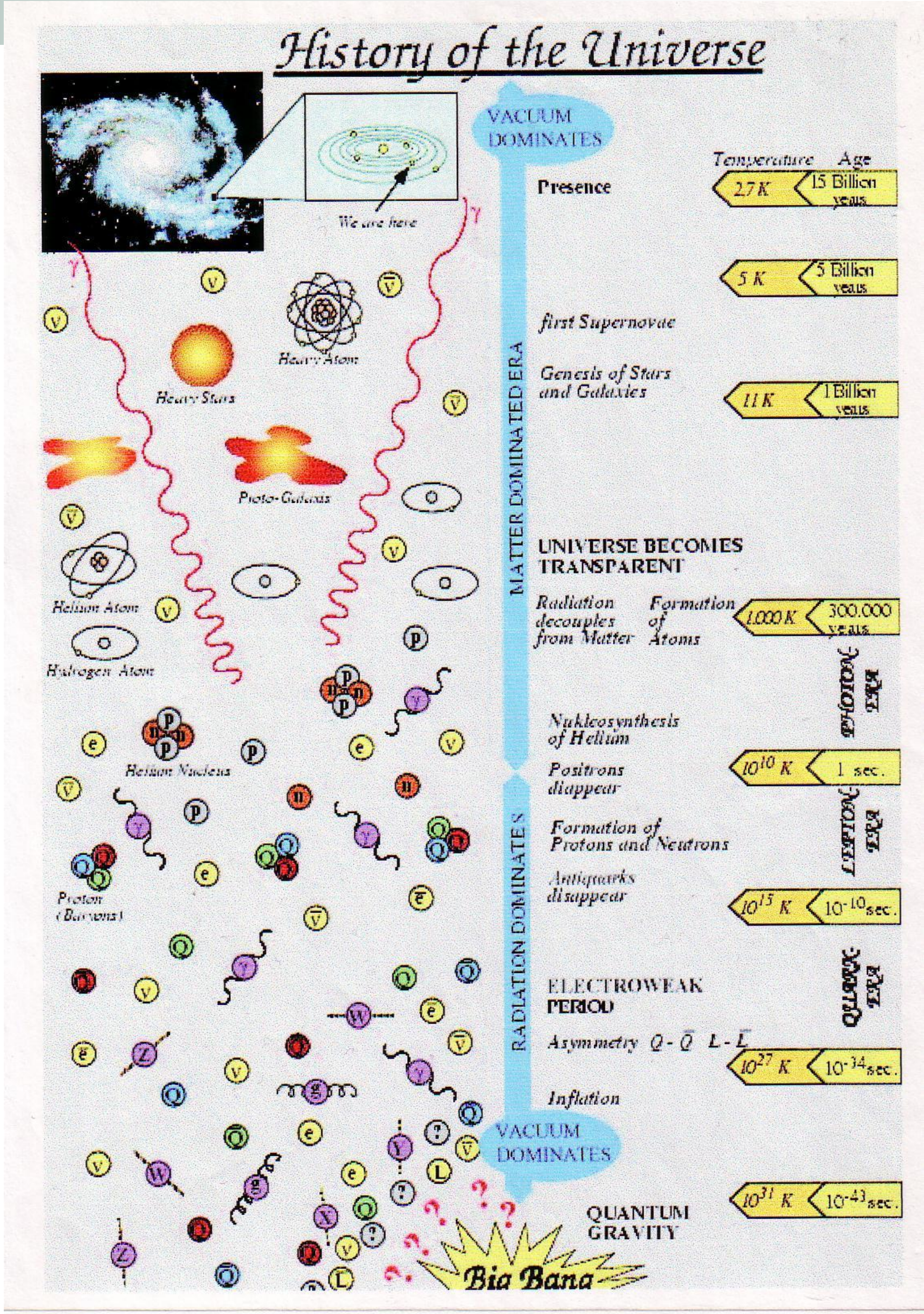
FIZIKALNA KOZMOLOGIJA

Galaktički svemir u širenju

Nalazimo sebe u slijedu civilizacija koje pokušavaju razumjeti svoje mjesto u svemiru (pritom je svaka umišljala da, ako ništa drugo, ono razumije prirodu svemira).

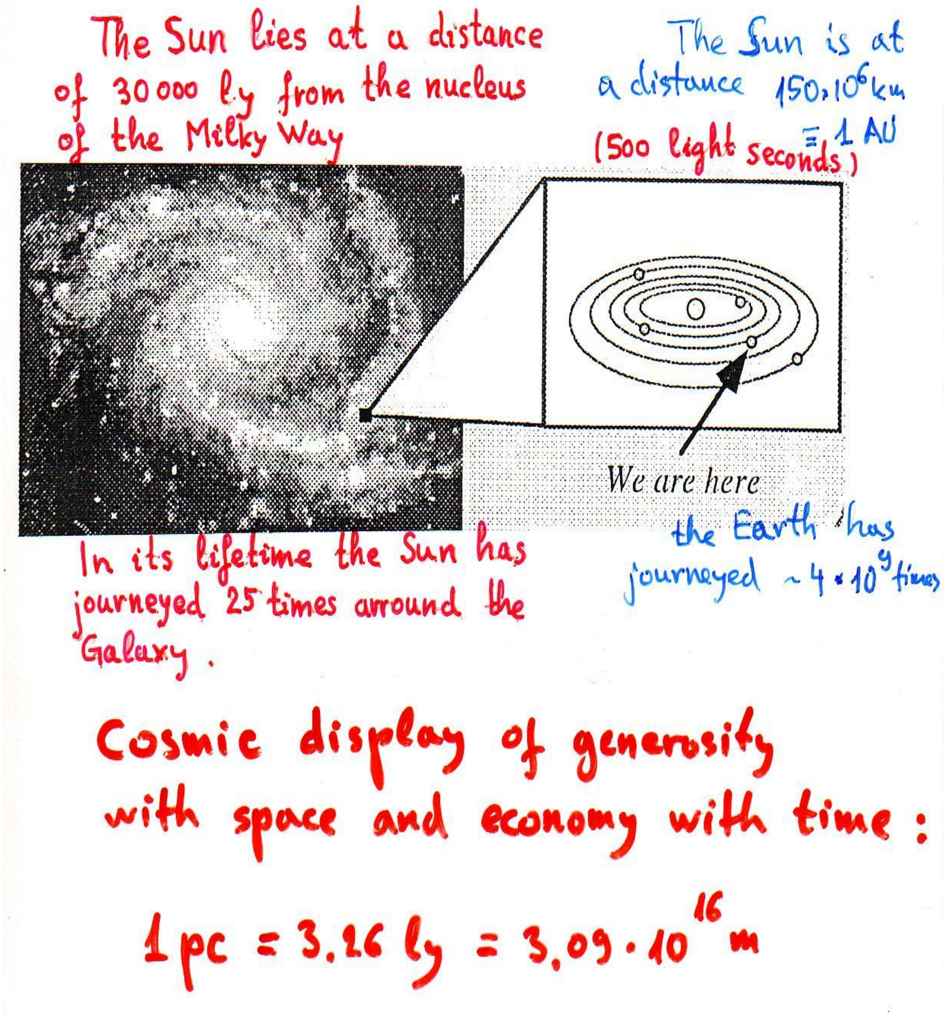


Što je to kozmologija?

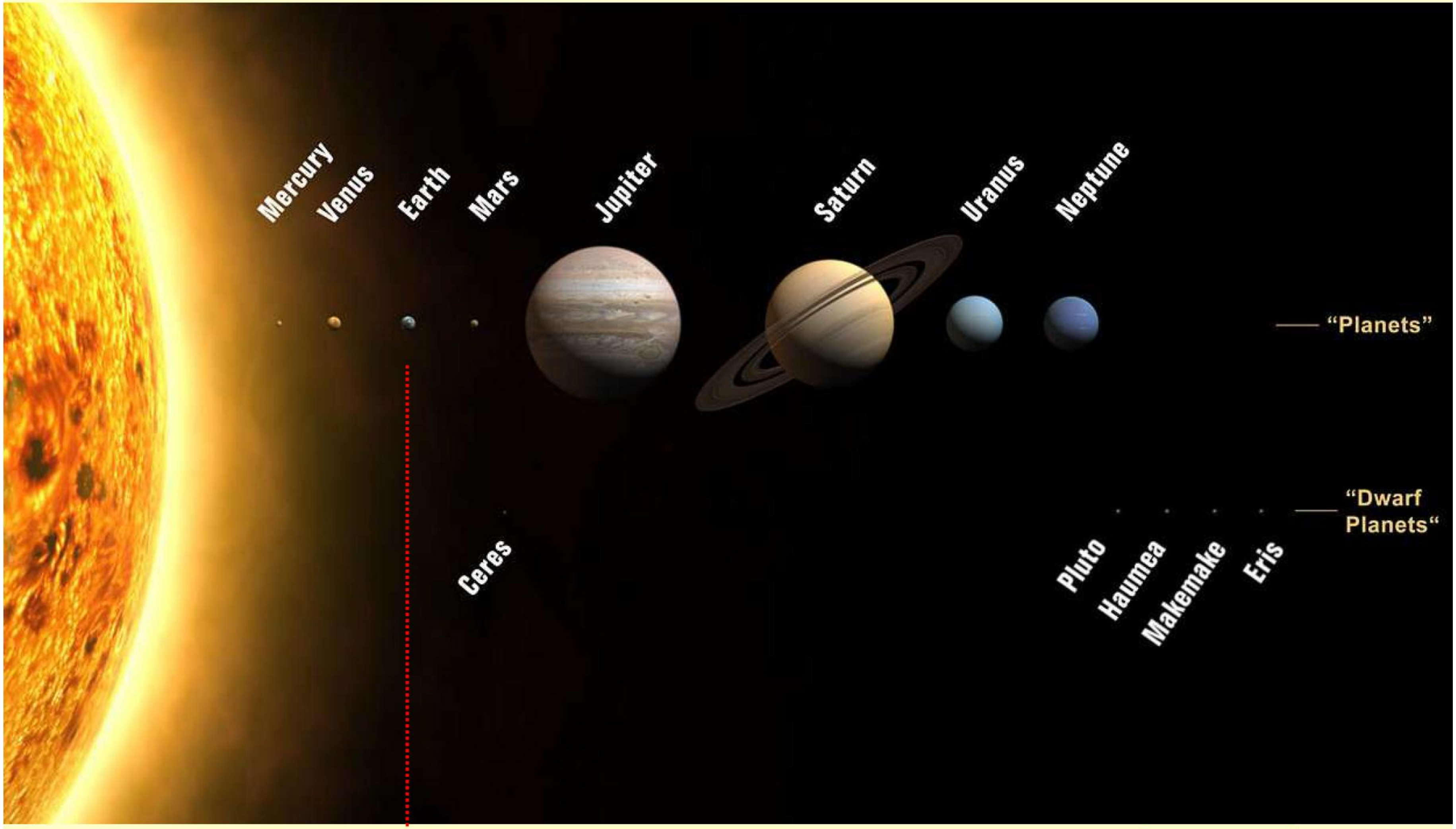
- Studij svemira u najširem smislu;
- Kozmologija kao znanost, **fizikalna kozmologija**, posvećena svemiru na najvećoj ljestvici (do nedavno suprotstavljena FEČ kao ispitivanju subatomskog), danas doživljava susret s fizikom čestica pri izučavanju ranog svemira

Svemir doživljavamo kao **TVAR** u prostoru i vremenu

- Svemir = **model svemira** (koji je jedan kao što je jedna Zemlja): Aristotelov, Kopernikov, Newtonov, ...
- razbacivanje prostorom
- škrtost vremenom



The known universe: the solar system



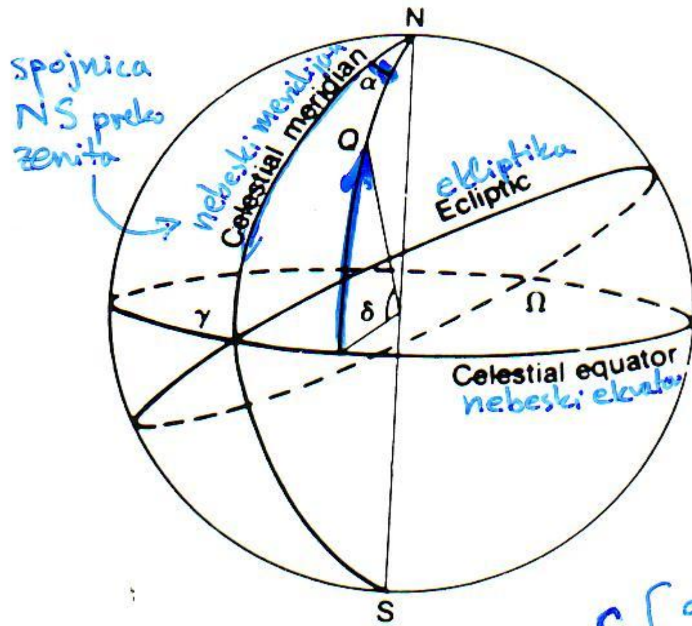
Earth-Sun distance ~ 150. 10^6 km ~ 1 AU

The known universe: the Milky Way

- Barred spiral galaxy (200-400 billion stars)
- distances:
  ∅ ~100,000 ly ~ 30kpc
  Sun-Gal. center ~ 10kpc

note:
1ly=63,240 AU   1pc=3.26 ly

EKVATORSKE KOORDINATE

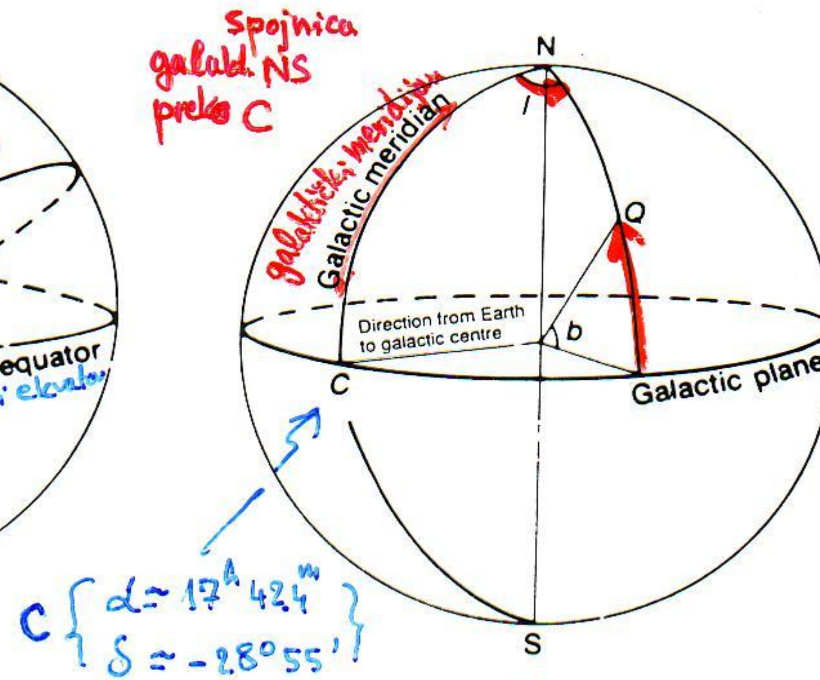


(a)

"astronomske"

δ (deklinacija)
kutna udaljenost od nebeskog ekvatora ;

GALAKTIČKE KOORDINATE



(b)

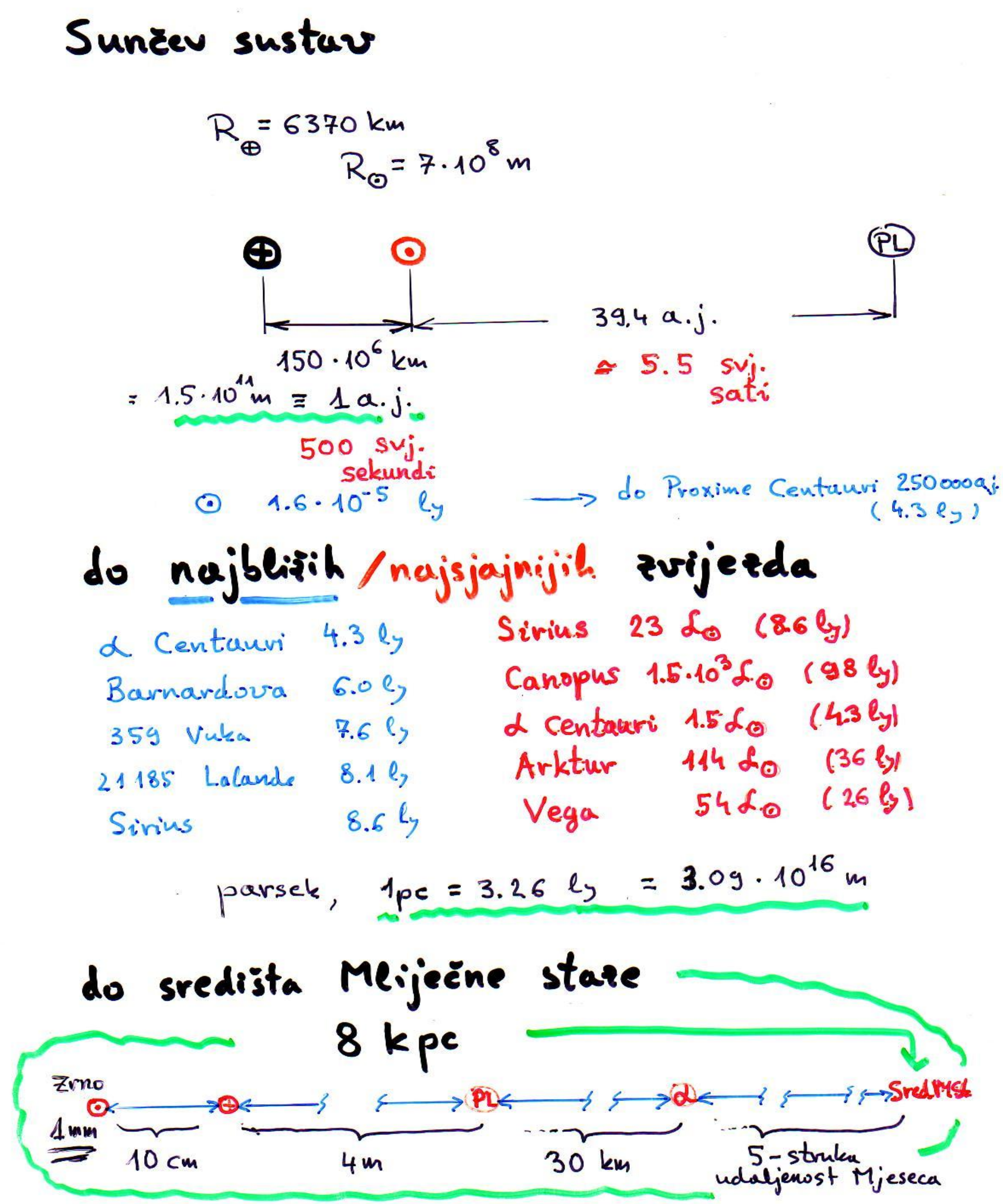
"kozmološke"

l (galaktička duljina)

b (gal. širina)

Prostorna praznina

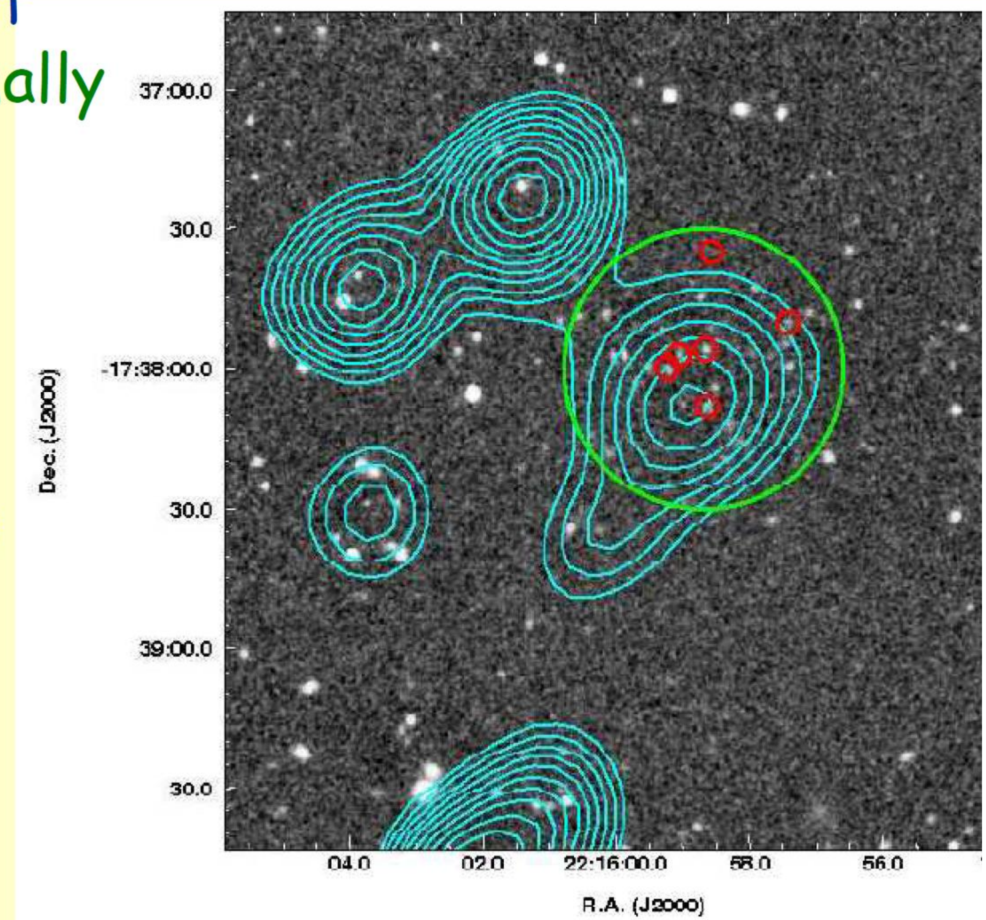
- neznatno kontaminirana materijom unutar galaktika
- *Vježba 1.1*: usporedba veličina i masa u svemiru
- *Vježba 1.2*: procjena količine helija stvorene zvijezdama naše galaktike



Clusters of galaxies

XMMXCS J2215.9-1738 (2006)

clusters : largest and most massive known gravitationally bound structures



Typical features:

- 50 to 1,000's of galaxies
- hot X-ray emitting gas

- $\varnothing \sim$ 2 to 10 Mpc
- 10^{14} to 10^{15} M_{solar}

distance from Earth: 3 Gpc

The large scale structures

Large scale structures: galaxies → clusters → superclusters, making a network of voids and filaments

Superclusters: chains of 10's-100's clusters, 10^{16} M_{solar}

size: 15 – 100Mpc

Voids: 90% of space

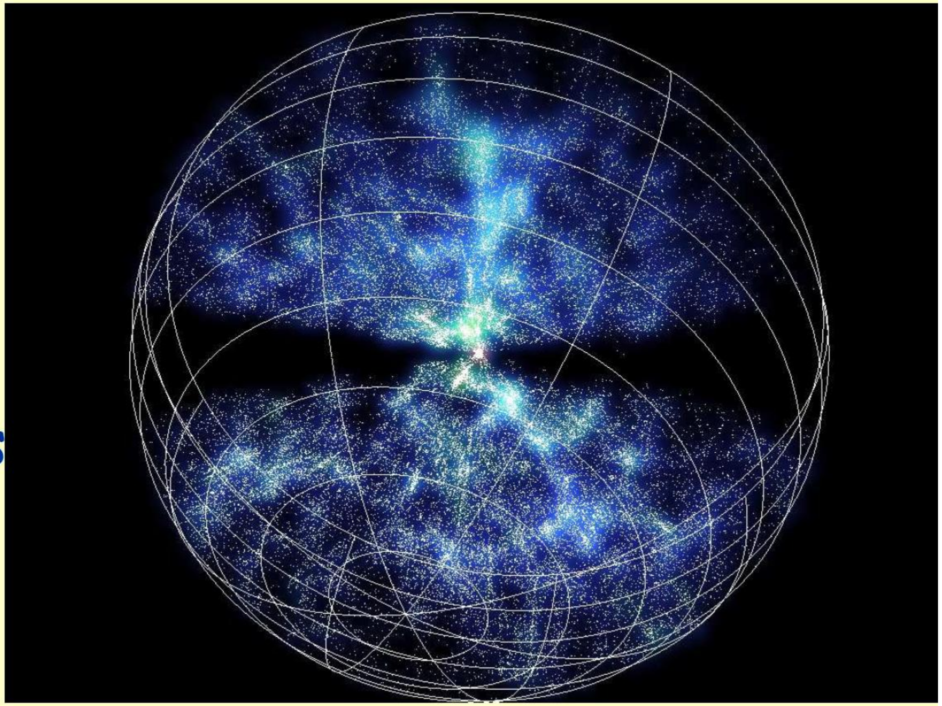
∅ 25 – 125Mpc

Filaments: 90% of galaxies

length 90 – 300 Mpc

width 45 – 90 Mpc

thickness 5 – 9 Mpc



6dF Galaxy Redshift Survey, (2009)

Vježba 1.3: Olbersov paradoks

Basic observation: the sky is dark at night.

Let f be the flux of a star with luminosity L, at a distance r from us:

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

For an infinite, homogenous, static Universe, assuming n stars per unit volume, neglecting absorption, the total flux arriving from the whole Universe is:

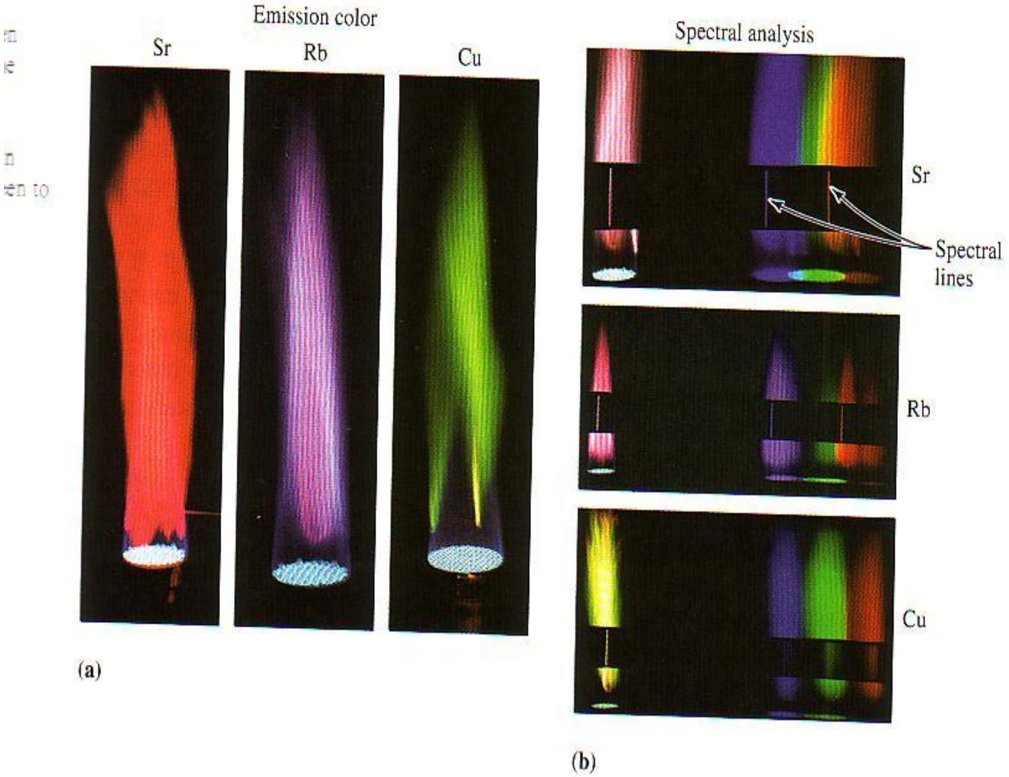
(2) $$f_{\mathrm{Total}} = \int_0^\infty \frac{L}{4\pi r^2} n 4\pi r^2 \, \mathrm{d}r = nL \int_0^\infty \mathrm{d}r = \infty. \quad \text{Oops.}$$

Why is the night sky not uniformly, infinitely bright?

Spektralna analiza
G. Kirchoff (1860)

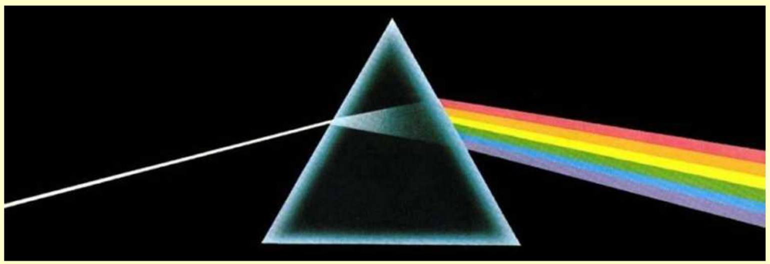
Isti kemijski elementi

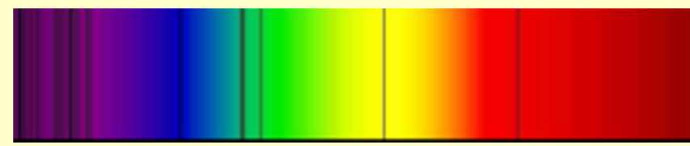
na nebu i na Zemlji



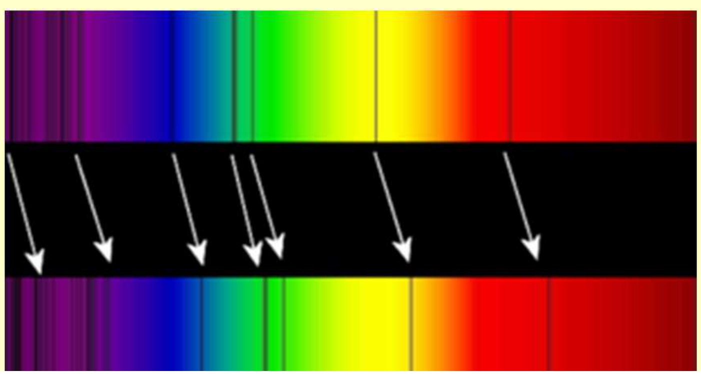
Spectroscopy

- Emitted light spectrum ⇒ spectral lines ⇒ astro. object composition, environment … and motion relative to Earth.





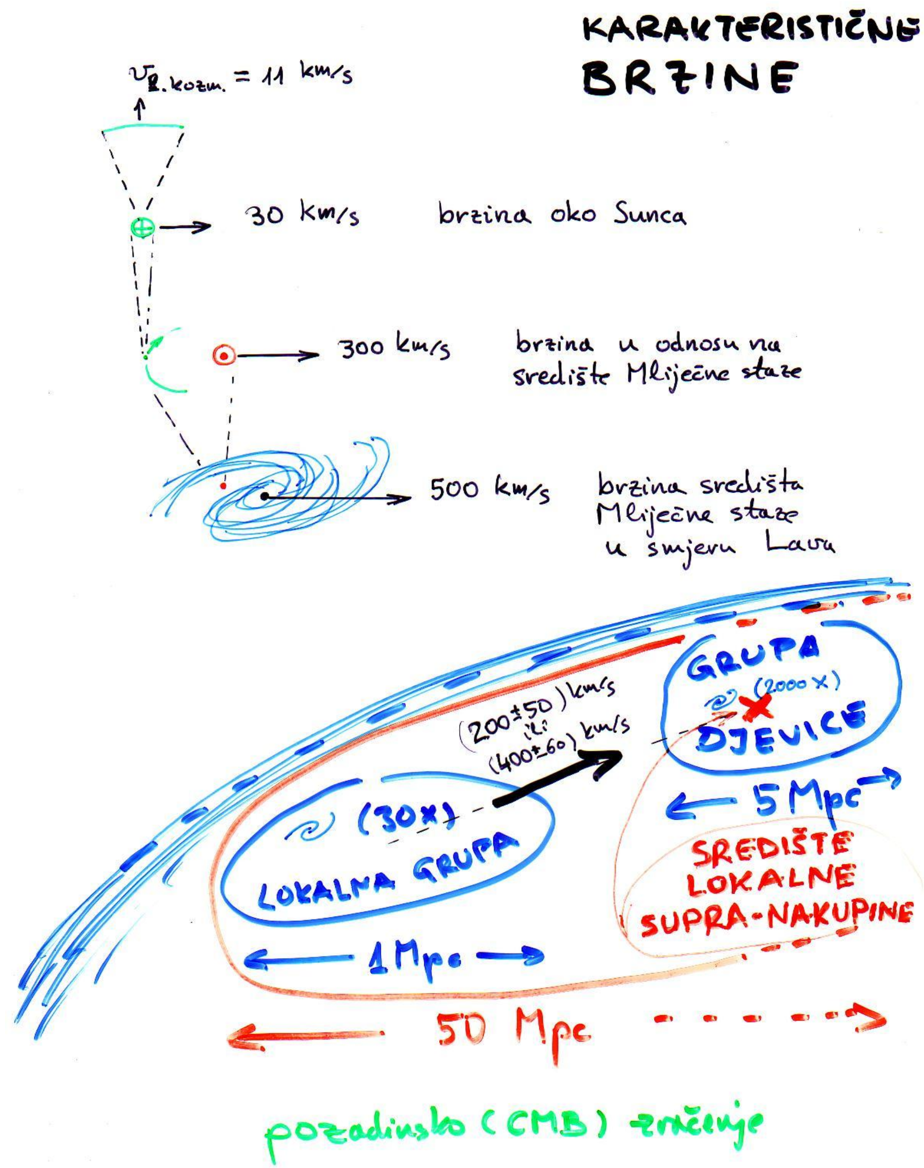
- Redshift : the object moves away from us ⇒ λ_γ increases



$$z \equiv \frac{\lambda_{observed} - \lambda_{emitted}}{\lambda_{emitted}}$$

Relativna gibanja

- mala Zemaljska jedinica udaljenosti (1m)
- velika Zemaljska jedinica vremena (sekunda = 300 000 km)
- **Dz. 1.1: Kozmičke brzine**



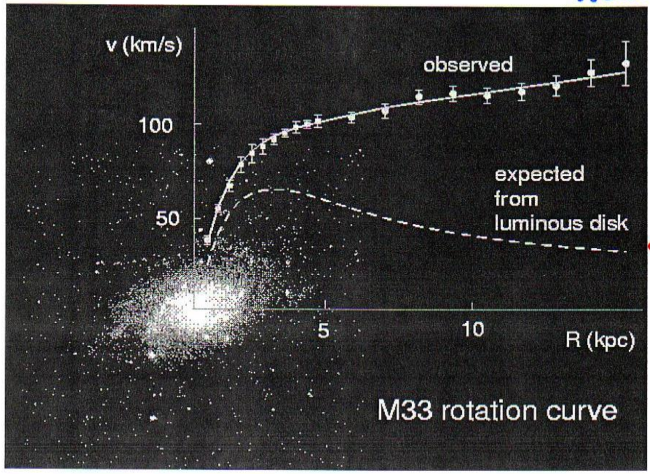
Karakteristične brzine osobnih gibanja

- **Tamna tvar galaktičkih haloa na temelju Dopplerovih pomaka linija neutralnog vodika u haloima**

-TAMNE SPEKTRALNE LINIJE MIKROVALNE ASTRONOMIJE
(FEČ, STR. 115)

TAMNA TVAR

BARIONSKA (machoi u galaktičkim haloima)



← (*)

Newtonova gravitacija (masa m u kruženju na udaljenosti r)

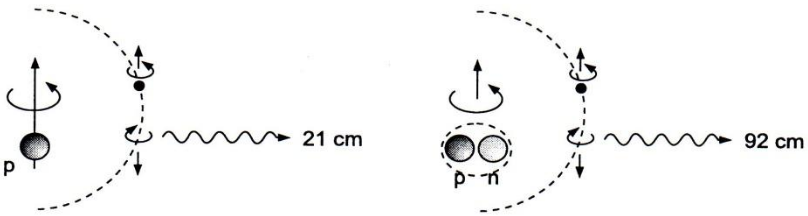
$$\frac{m v^2}{r} = G_N \frac{m M(r)}{r^2}$$

– za masu koncentriranu u središtu galaktike očekujemo $v \propto r^{-1/2}$ (*)

– opaženo $v \simeq$ konst. daje $M(r) = \frac{v^2}{G_N} r$ => gustoća mase $\rho(r) \propto r^{-2}$

dok bi opadanje svjetline (luminoziteta) tražilo eksponencijalni pad!

Vježba 1.4: Procjena gustoće "vidljivog" u odnosu na "nevidljivo"

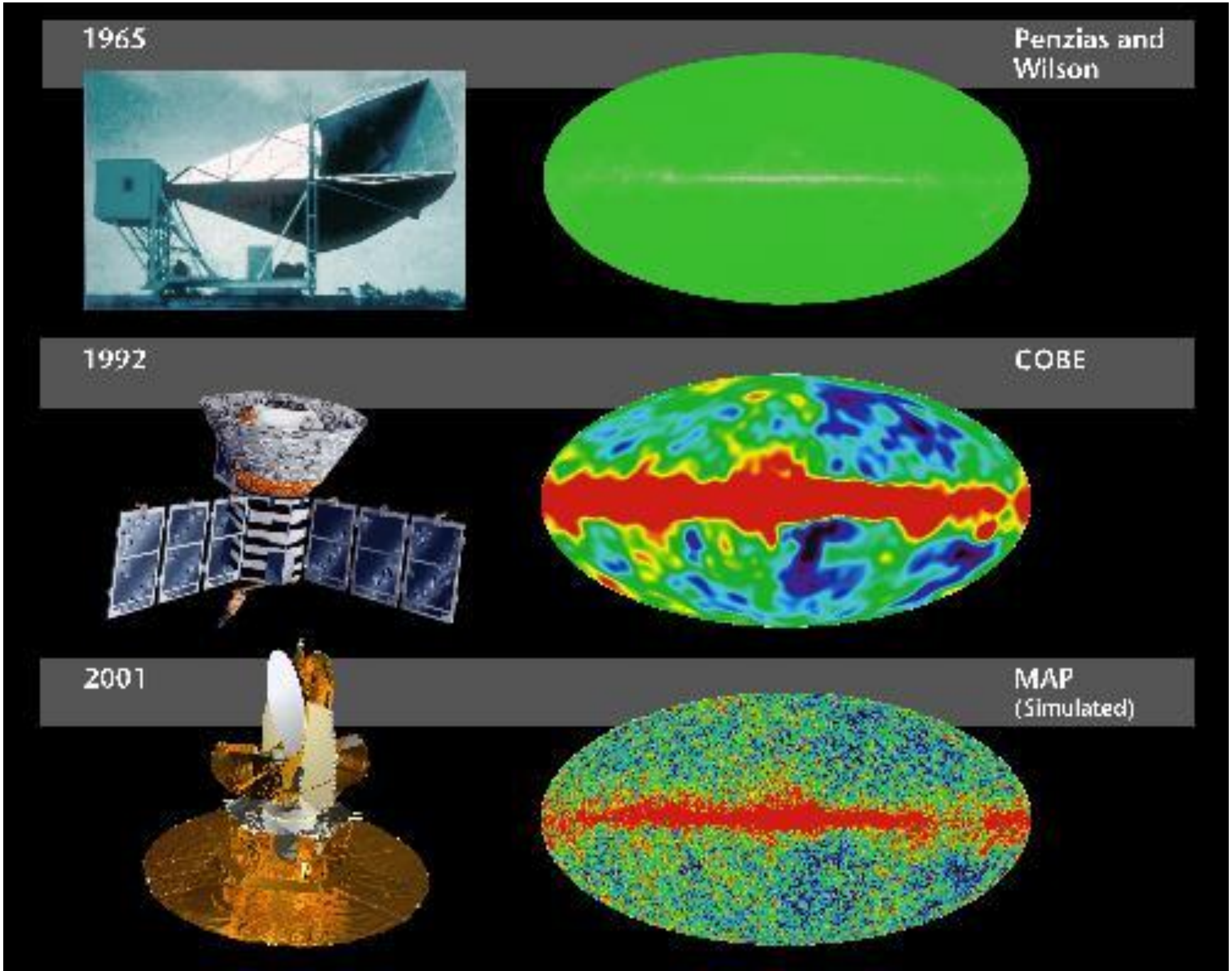


A. Penzias i R. Wilson (1965)

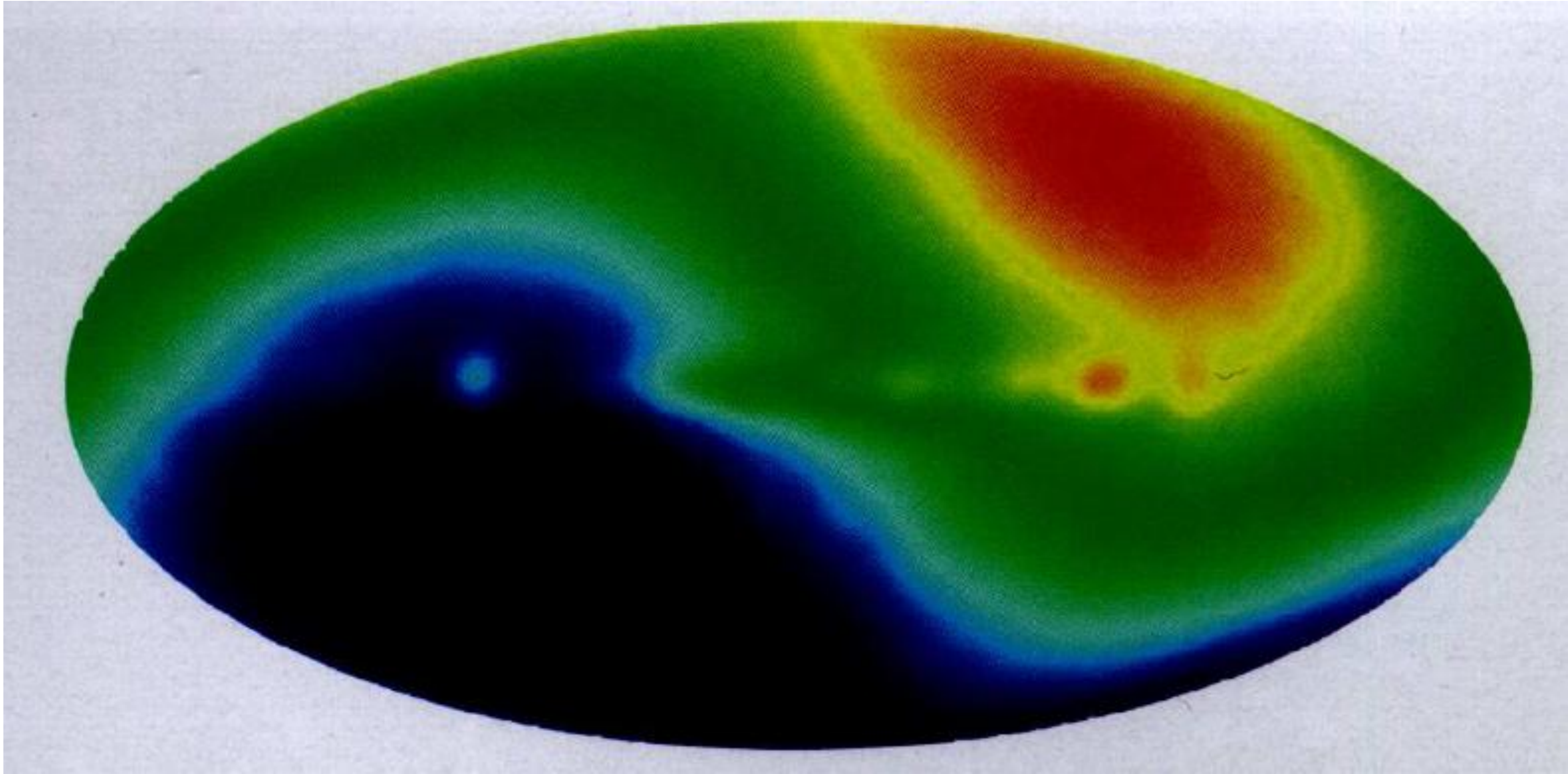
signal u mirkovalnom području iz svih smjerova neba

Potvrda predviđanja Georga Gamowa (1948)
-pozadinskog zračenja od 5K
-prvotne nukleosinteze (25% He)

POZADINSKO MIKROVALNO ZRAČENJE

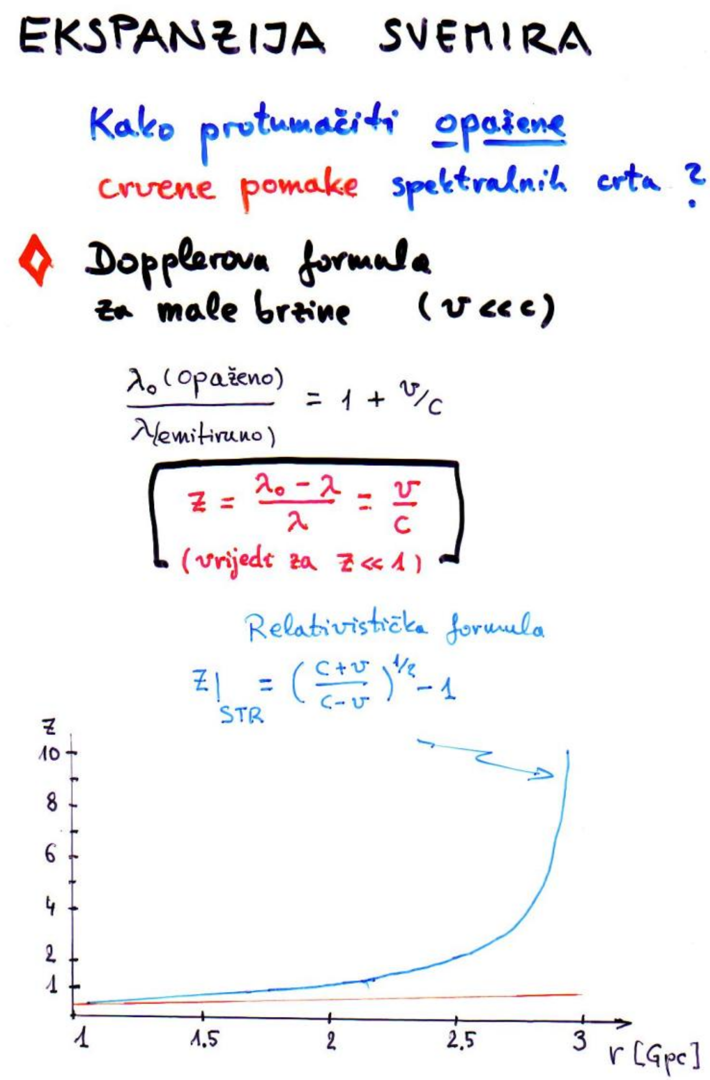


DIPOLNA ANIZOTROPIJA CMB-a
(COBEovo mjerenje v=371(1)km/s odgovara razlici 3 mK)



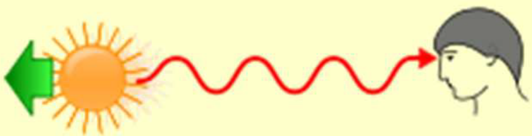
2. Porijeklo svemirskih crvenih pomaka

- Dz. 1.2: Dopplerovi pomaci (STR/NR)
- Dz. 1.3: Gravitacijski crveni pomaci
- Izvangalaktički crveni pomaci

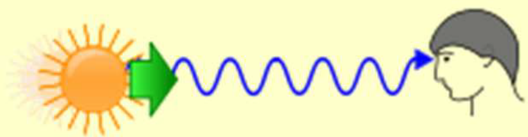


Different origins of redshifts/blueshifts

Doppler effect : redshift/blueshift due to relative motion



$$1+z=\gamma\left(1+\frac{v_{//}}{c}\right) \qquad z\approx\frac{v_{//}}{c} \quad \textit{for small } v_{//}$$



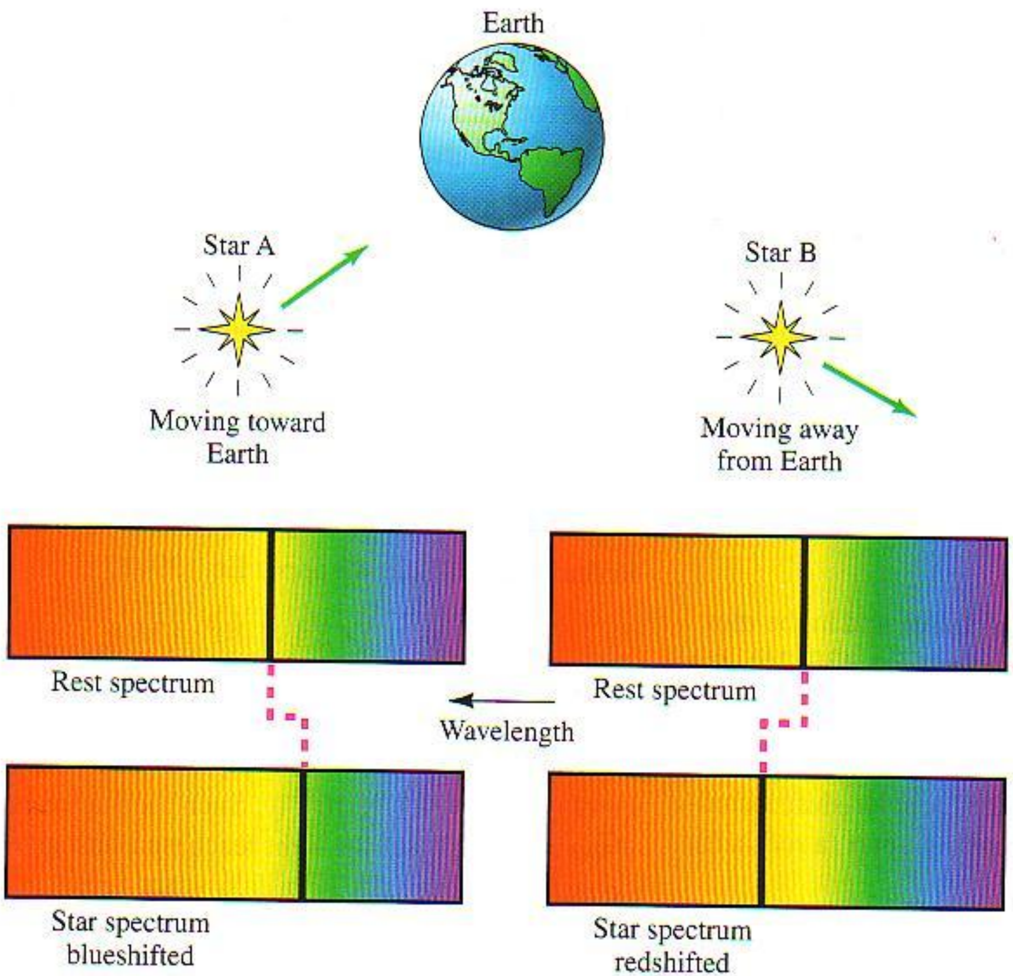
(in Minkowski space i.e. flat spacetime)

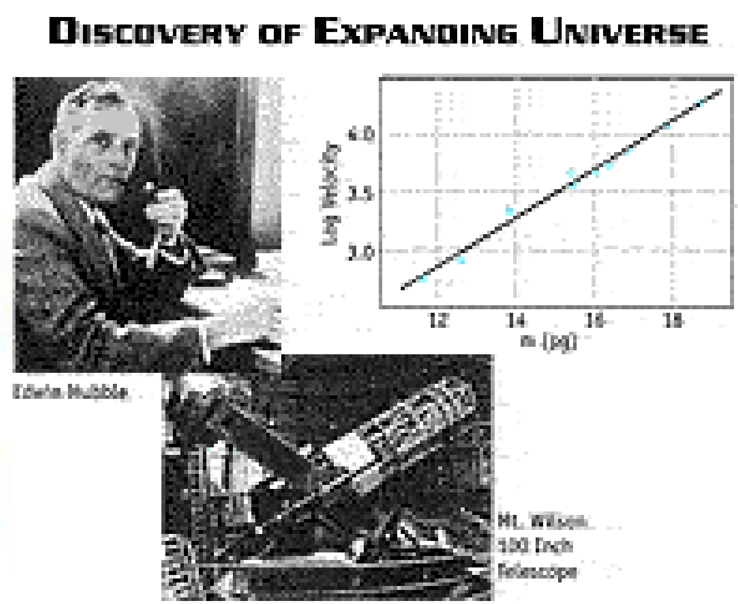
Gravitational red/blue shift : radiation moving out of/into a gravitational field.

e.g. grav. redshift $1+z=\dfrac{1}{\sqrt{1-2GM/rc^2}}$

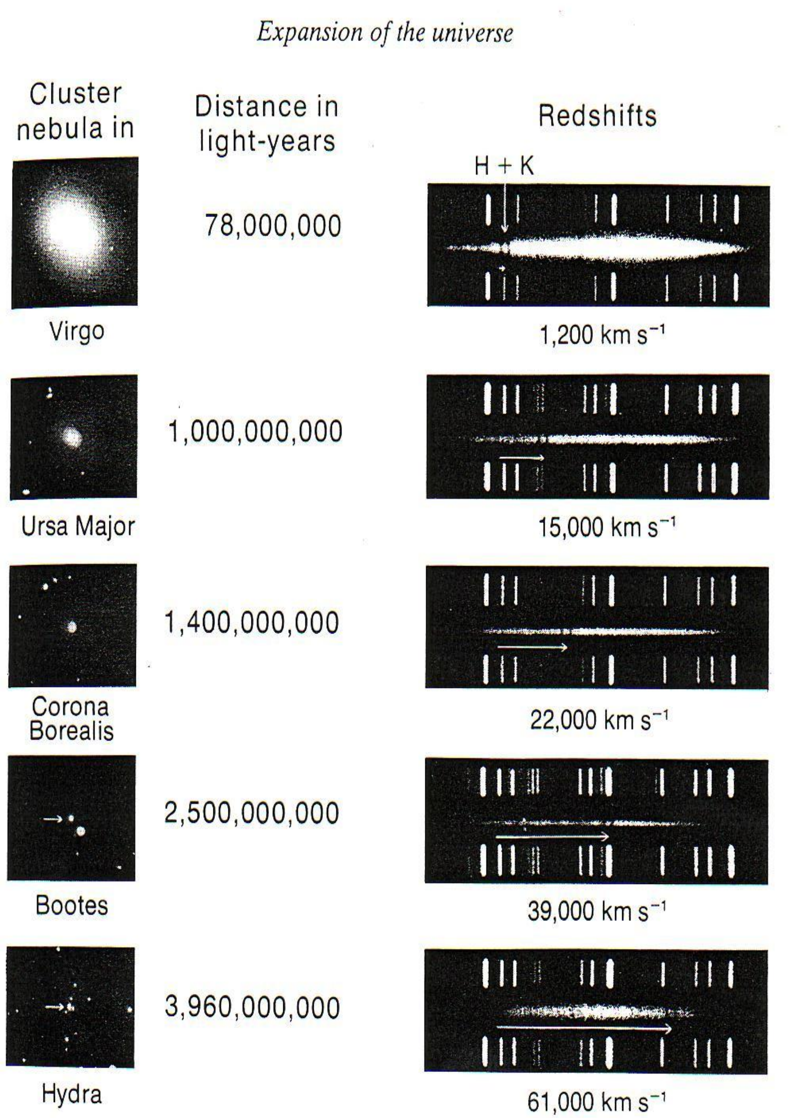
Cosmological redshift : dominant for distant sources (above 1Mpc or z>0.01). See next slides.

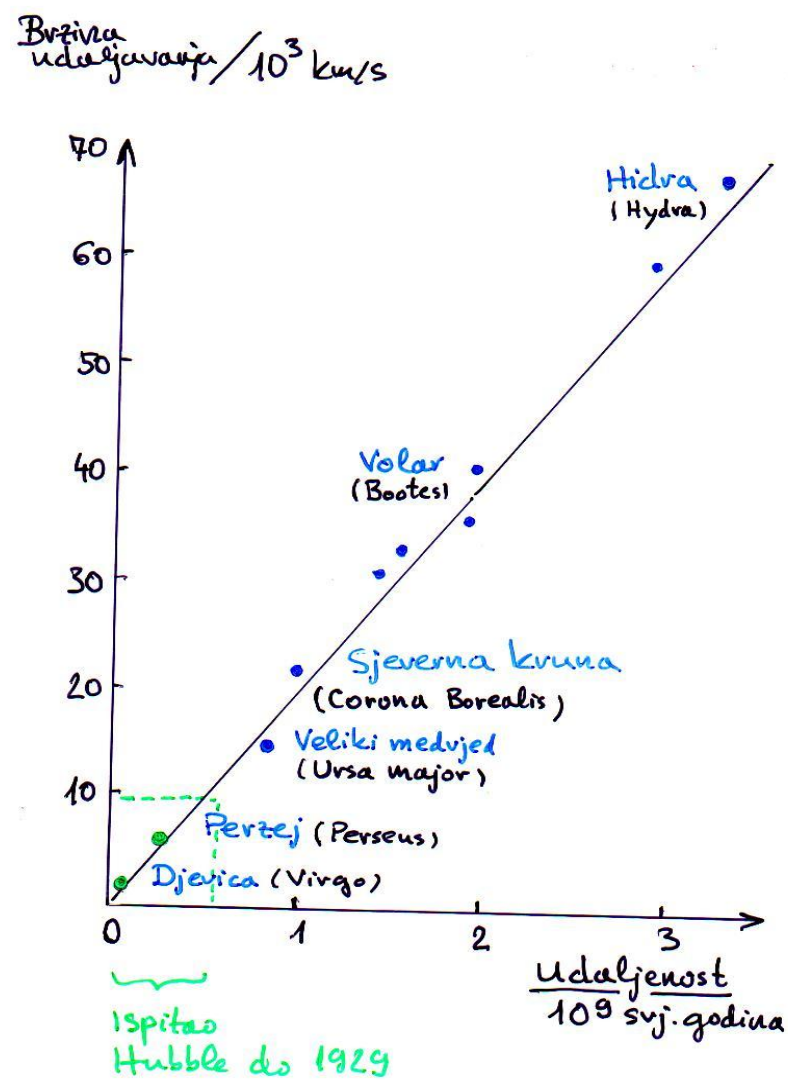
Edvin Hubble ustanovljava svemir u *širenju*





Zakon: z/udalj.(expt) & v/udalj.(teor)





Hubble's Law

Hubble observed a displacement of known spectral lines to longer wavelengths.

The displacement was larger for fainter (and thus approximately more distant) galaxies.

This displacement, known as redshift, is defined by

$$z = \frac{\lambda_{\rm obs} - \lambda_{\rm em}}{\lambda_{\rm em}}$$

For nearby galaxies $(z << 1)$, $z \sim \frac{v}{c}$

Hence the more distant a galaxy is, the faster it is receding from Earth.

Hubble's Law

$H_0 = v/d$ — finding d is the difficult bit; needs calibrating (still!); Hubble himself was out by a factor of 10 originally!

The most recent measurement (from the Hubble Space Telescope) is $H_0 \sim 70\ \mathrm{kms^{-1}Mpc^{-1}}$ (10 per cent accuracy).

Note the funny units (H_0 has dimensions of 1/time); it is convenient to measure d in Mpc and v in $\mathrm{kms^{-1}}$.

The Hubble expansion must mean the expansion of space-time itself (worked out by Lemaître).

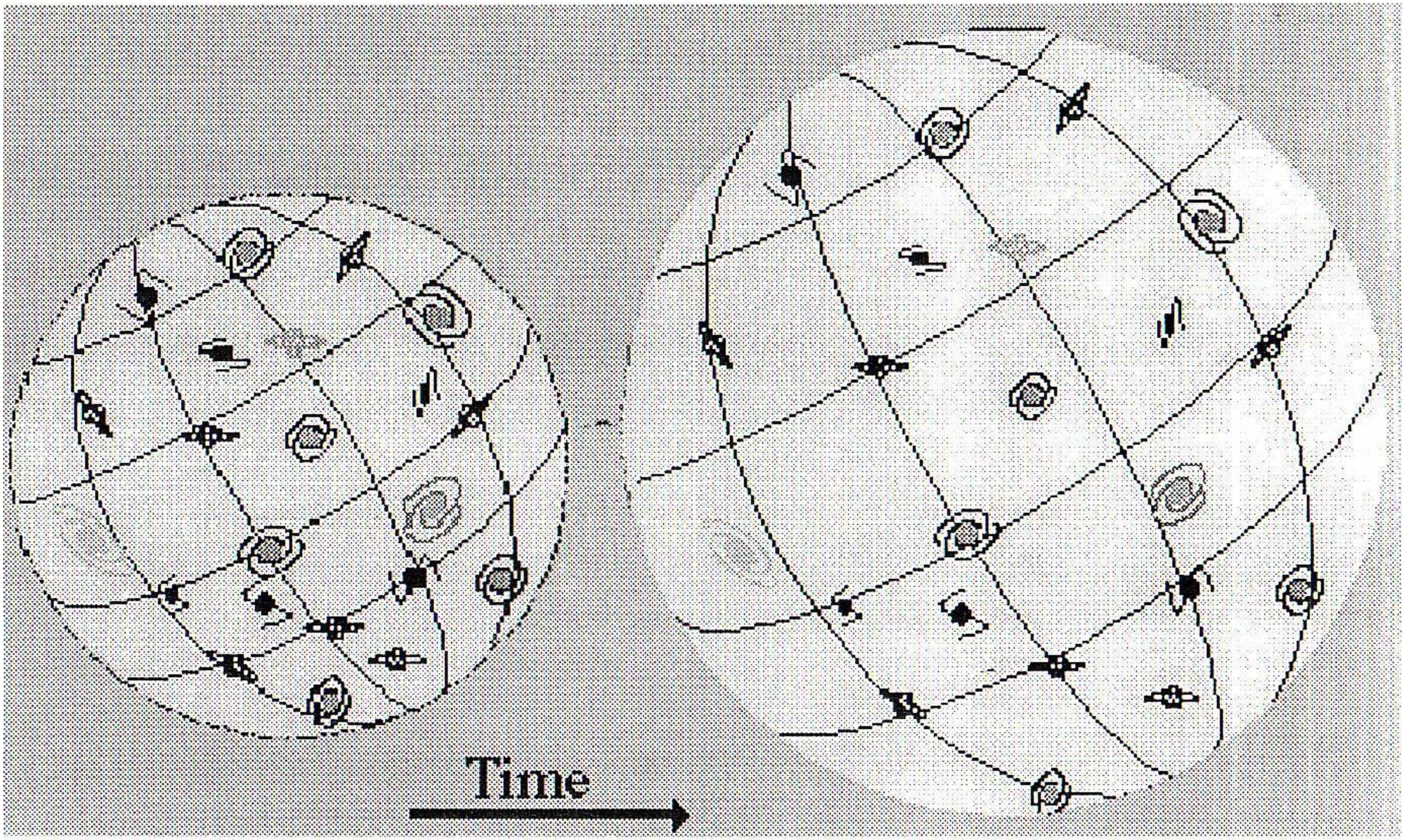
Hubble's Law & Olbers' Paradox

The Hubble expansion helps solve Olber's paradox: the farthest galaxies recede too quickly for light to ever reach us. (But no violation of SR as space-time itself is expanding!)

Furthermore, the Universe is too young: not enough time for light to have reached us from distant galaxies. The maximum distance is known as the particle horizon.

The Universe could also be spatially finite (although observations now suggest otherwise).

Sugibajuće koordinate (comoving co-ordinates)



Comoving co-ordinates

As the Universe expands at the same rate everywhere, the physical distance r and co-moving distance x are simply related by

(3) $$r = a(t)x$$

$a(t)$ is the scale factor of the universe, which can be viewed as a time-dependent magnification factor.

Today, it is convenient to set $a = 1$, i.e. $r = x$. But in the past, $a < 1$, so $r < x$, for the same comoving separation, x, as today.

Note that a given volume of co-moving co-ordinate space always contains the same number of galaxies, assuming $\dot{x} = 0$.

The Hubble Parameter

Why recession velocity (v) is proportional to distance (r)... since $v = \mathrm{d}r/\mathrm{d}t$ we can write

(4) $$v = \frac{|\dot{r}|}{|r|} r.$$

Since $r = ax$ and x is time-independent, we may write:

(5) $$v = \frac{\dot{a}}{a} r.$$

We can then identify the Hubble parameter as

(6) $$H = \frac{\dot{a}}{a}.$$

The Scale Factor & Redshift

Consider two nearby points, separated by distance $\mathrm{d}r$. The relative velocity due to the Hubble expansion is

(7) $$\mathrm{d}v = H\mathrm{d}r = \frac{\dot{a}}{a}\mathrm{d}r.$$

For a photon travelling between the two points, Doppler says the change in wavelength is

(8) $$\frac{\mathrm{d}\lambda}{\lambda_{\mathrm{em}}} = \frac{\mathrm{d}v}{c}.$$

The photon takes a time $\mathrm{d}t = \mathrm{d}r/c$ to travel between the two points, thus

(9) $$\frac{\mathrm{d}\lambda}{\lambda_{\mathrm{em}}} = \frac{\dot{a}}{a}\frac{\mathrm{d}r}{c} = \frac{\dot{a}}{a}\mathrm{d}t = \frac{\mathrm{d}a}{a}.$$

The Scale Factor & Redshift

Integrating gives $\ln\lambda = \ln a +$constant, hence a light wave expands as $\lambda \propto a$.

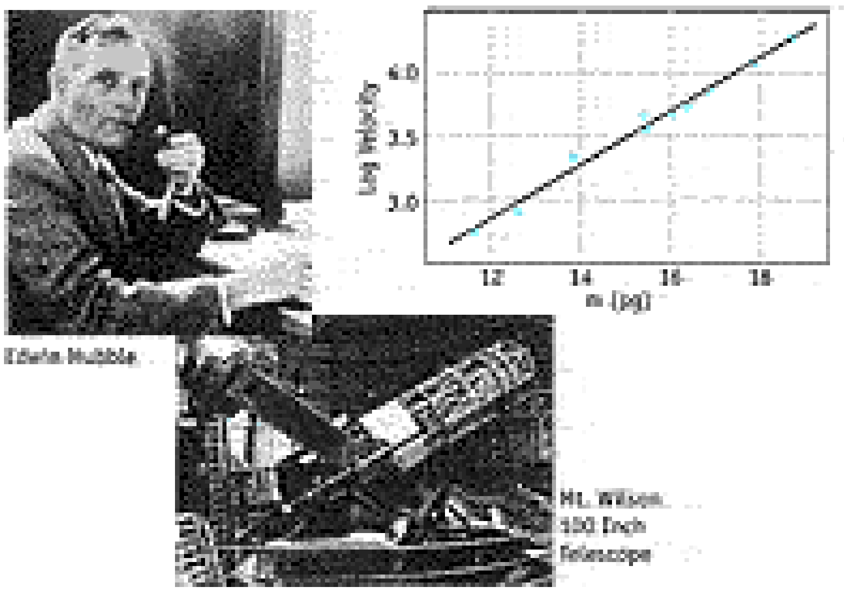
Using the earlier definition of redshift we get

$$1 + z = \frac{\lambda_{\rm obs}}{\lambda_{\rm em}} = \frac{a_{\rm obs}}{a_{\rm em}}. \qquad (10)$$

If we set $a_{\rm obs} = 1$ (ie we observe the light today) then $a = 1/(1+z)$. E.g. light observed with twice its emitted wavelength (e.g. the Ly-α line, emitted at $121.6\rm nm$ but observed at $243.2\rm nm$) was emitted when the Universe was half its present size!

Ekspanzija samog prostora

DISCOVERY OF EXPANDING UNIVERSE



Opaženi zakon "crveni pomak – udaljenost"

$$z = \text{konst.} \times \text{udaljenost}$$

uz pretpostavku da su crveni pomaci uzrokovani Dopplerovim (nerelativističkim) učinkom ($v = z \cdot c$)

$$v = z \cdot c = H_0 \cdot D$$

Hubble-ova konstanta (opisuje ŠIRENJE)

$$H_0 = \begin{cases} 530 \text{ km s}^{-1} \text{ Mpc}^{-1} & \text{(originalno)} \\ (50-100) \text{ km s}^{-1} \text{ Mpc}^{-1} & \text{(danas)} \end{cases}$$

$$H_0 = 100\, h_0 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

($h_0 = 0.5 - 0.8$) → [0.72 ± 0.07 Turner, Feb. 2002]

Cefeide, SNe: $h_0 = 0.72(8)$ (WMAP: $h_0 = 0.71$)

◆ Izvangalaktički crveni pomaci nisu rezultat Dopplerovog učinka

(Spoznaja Howard-a Robertson-a i Georges-a Lemaitre-a krajem 20-tih → otkriće svemirske EKSPANZIJE !)

Video lecture

Rocky (Kolb)

CERN 2002

***Vježba 1.5*: Hubbleovo vrijeme**