NPAC course on Astroparticles

I - ASTRONOMY: the Milky Way

Electromagnetic waves (photons)

Most of the information we have on celestial objects comes from the study of the electromagnetic radiation (photons) they emit

photons move at the speed of light: $c = 3 \times 10^{10} \mathrm{cm/s}$ *

are characterised by a wavelength: λ

a frequency: ν

$\nu\lambda = c$

and an energy: $\epsilon = h\nu$ **

Planck's constant: $h = 6.6 \times 10^{-27} \mathrm{cm^2 g\ s^{-1}}$

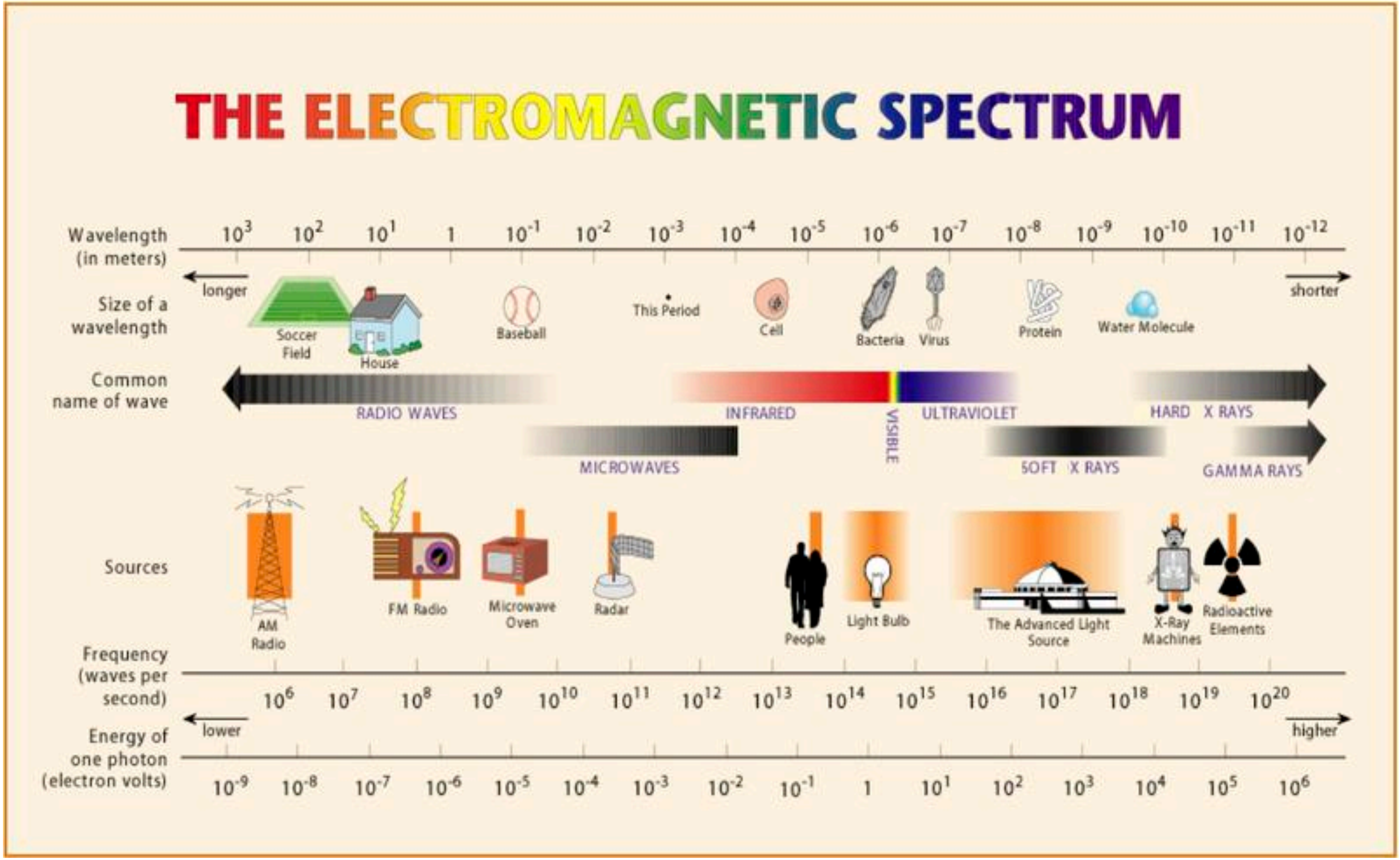
a body at temperature T emits a thermal radiation @characteristic energy: $\epsilon = k\,T$

Boltzmann's constant: $k = 1.4 \times 10^{-16} \mathrm{erg/K}$

* astronomers use mostly Gauss units

** very often expressed in eV (1 eV = 1.6 x 10^{-12} erg)

The electromagnetic spectrum



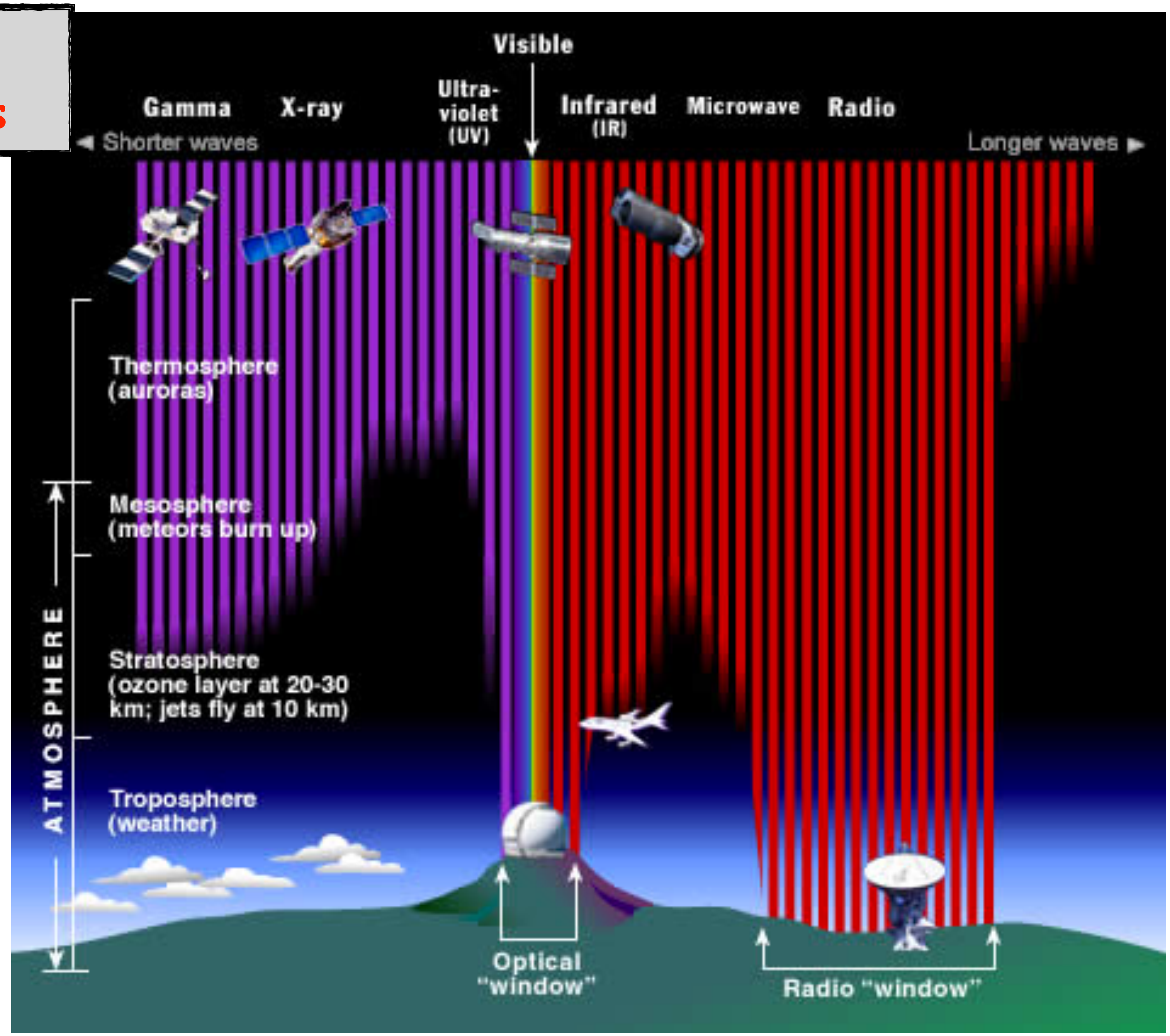
The electromagnetic spectrum

The Earth's atmosphere is opaque to most frequencies

light (visible by human eye)

$$3800 - 7600 \text{ Å}$$

$$400 - 790 \text{ THz}$$

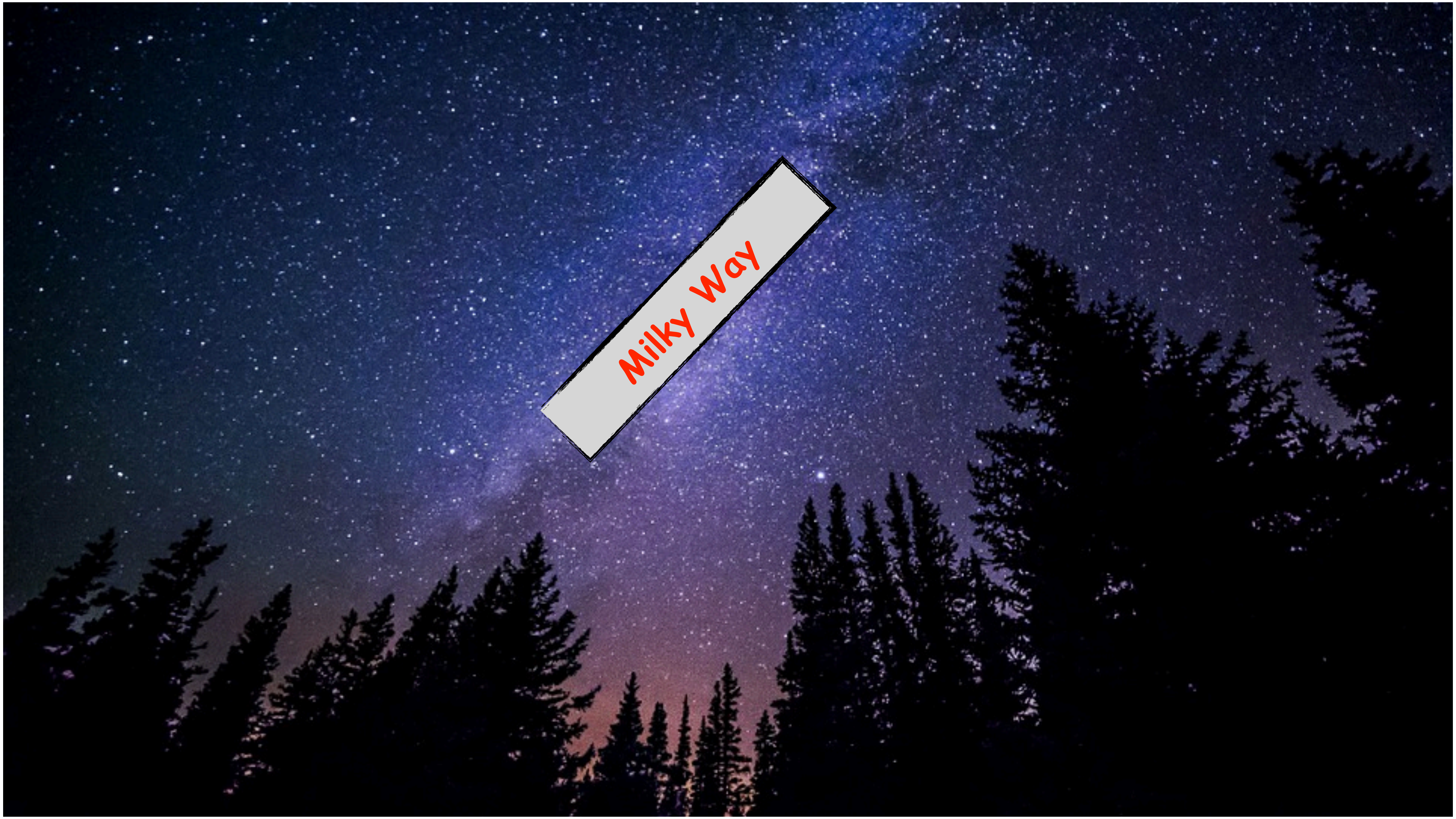


Optical

Radio

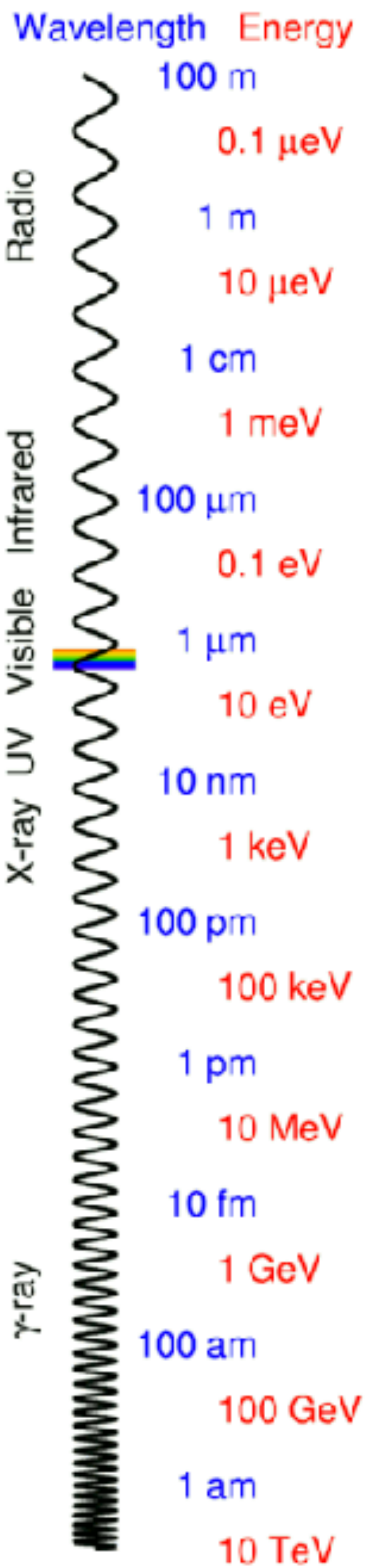
credits: NASA

The Milky Way in the night sky



Visible -> stars

The electromagnetic spectrum

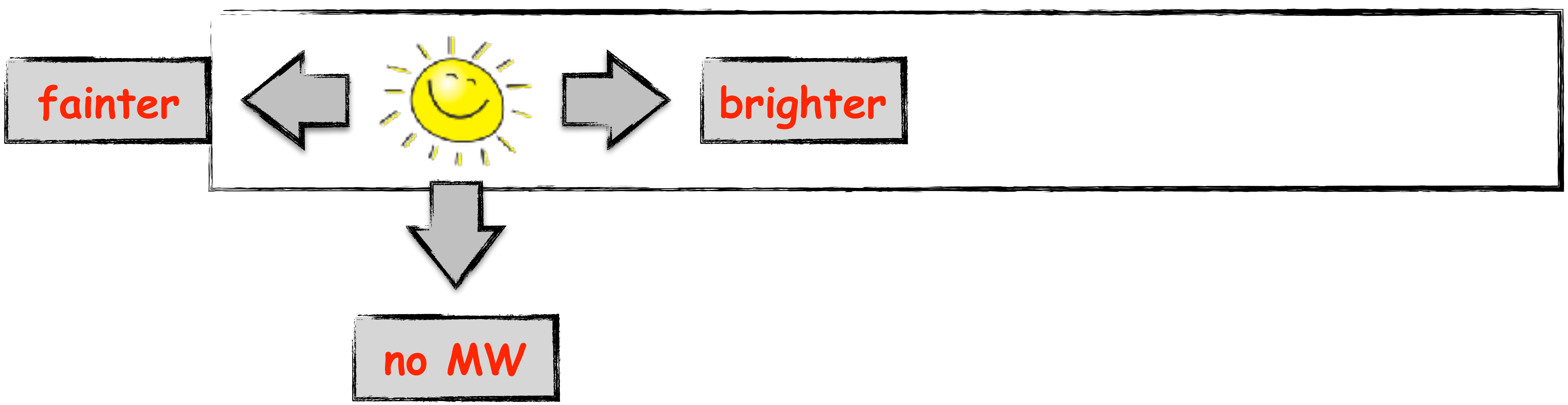


visible light -> stars

The Milky Way

The Milky Way is brighter when observed from the southern hemisphere

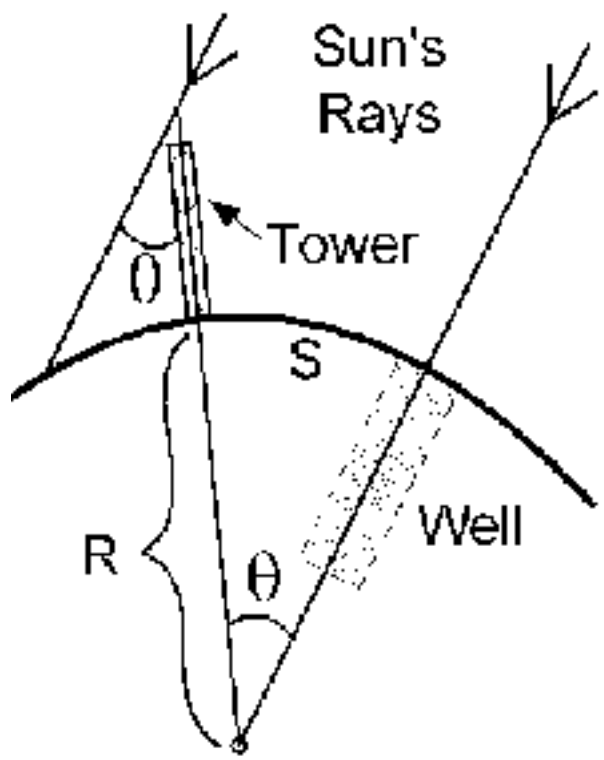
how big (and massive, and bright, ...) is the MW?



Our galaxy is a disk system and we are located away from the centre...

The Earth radius

First measured by Eratosthenes in Alexandria in ~200 BC !!!



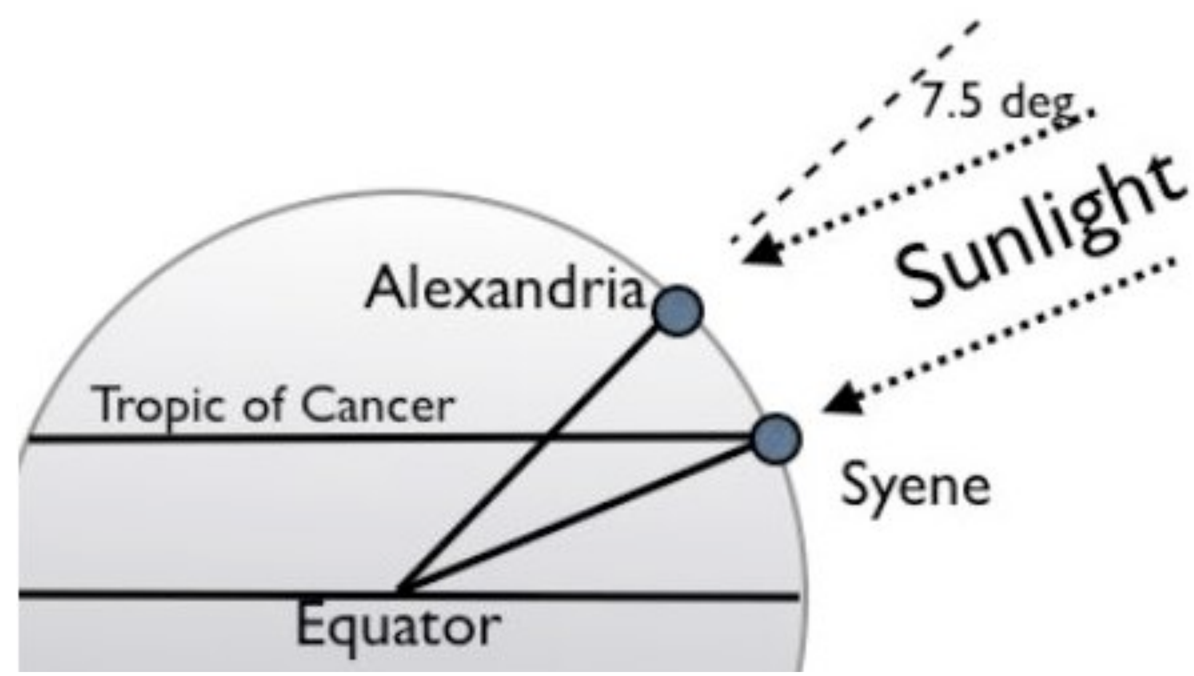
- Eratosthenes knew that in Syene at noon of the summer solstice the sun was at the zenith
- On the same day at noon the sun was ~7° away from zenith
- He also knew that the distance between Syene and Alexandria is ~800 km
- Luckily, Syene and Alexandria are roughly at the same longitude

in radians

$$S \approx R\ \theta \quad \Rightarrow \quad R \approx 6500\ \text{km}$$

Earth's radius

(the real answer is ~6400 km !!!)



The Earth mass and density

Gravitational acceleration on Earth surface -> $g \sim 9.8 \ \mathrm{m/s^2}$

1687: Newton's law of universal gravity -> $F = \frac{GMm}{R^2}$

1798: Henry Cavendish measures Newton's constant -> $G = 6.7 \times 10^{-8} \mathrm{cm^3/g/s^2}$

$$g = \frac{GM}{R^2} \quad \longrightarrow M \sim 6 \times 10^{27} \mathrm{g}$$

Earth's mass

$$M = \frac{4\pi}{3} R^3 \varrho \quad \longrightarrow \varrho \sim 5 \ \mathrm{g/cm^3}$$

Earth's density

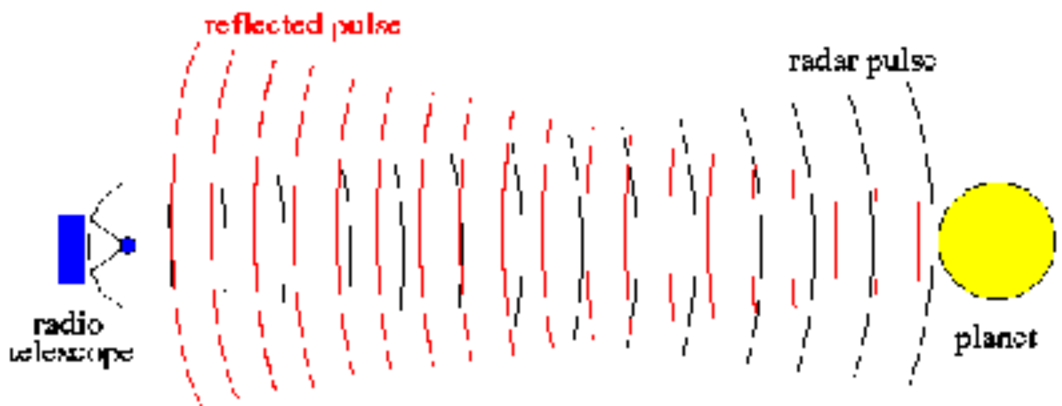
Astronomical quantities

Earth	radius ~ 6400 km	mass ~ 6 x 10^{27} g	density ~ 5 g/cm^3

How distant is the sun?

A long history of attempts...

in modern times, the distance to planets can be measured with radars

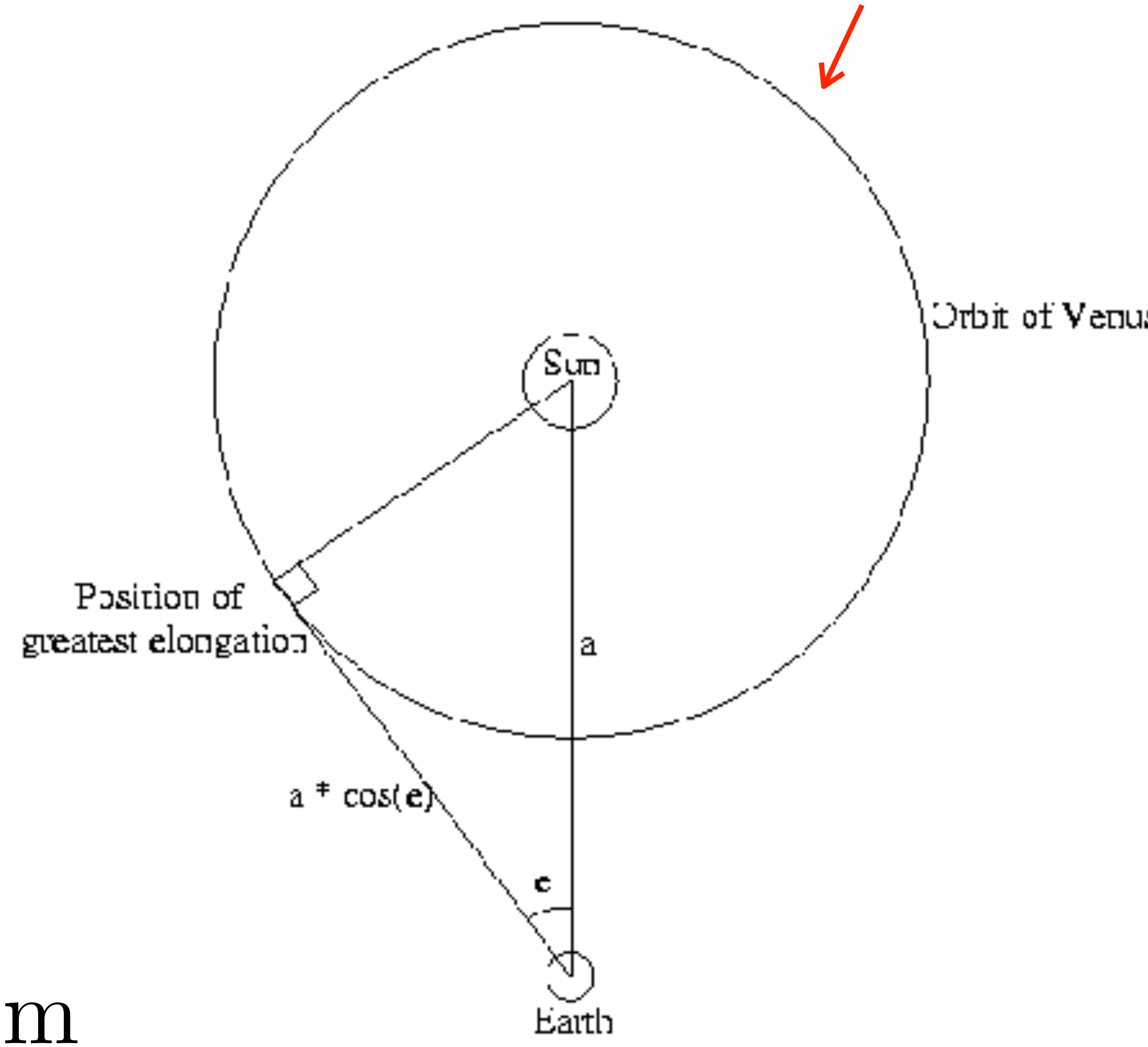


a radio pulse is beamed to the planet in question, and reflected pulse is detected and timed, the time of reflect times the speed of light equals the distance to the planet

$$a = 1.5 \times 10^8 \mathrm{km} = 1.5 \times 10^{13} \mathrm{cm}$$

Astronomical Unit

~spherical orbit



then one can measure the maximum elongation of a planet

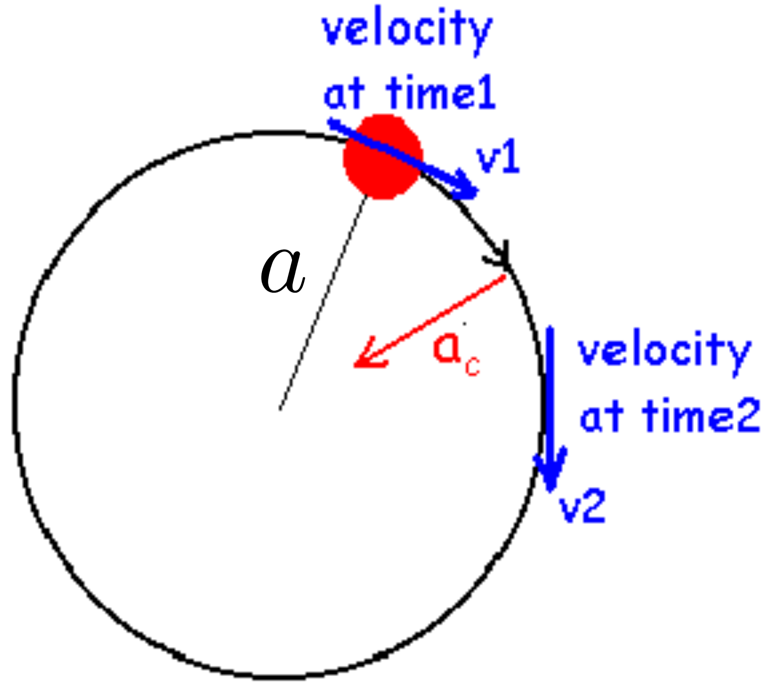
The sun's radius and mass

The sun's apparent size is θ~0.5° in diameter -> $R_\odot \sim a\,\frac{\theta}{2} \sim 7 \times 10^{10}\mathrm{cm}$

The Earth rotates around the sun on an almost spherical orbit at almost constant speed

Earth's velocity -> $$v = \frac{2\pi a}{3.15 \times 10^7\ \mathrm{s}} \approx 30\ \mathrm{km/s}$$

1 yr



Centripetal acceleration -> $$\frac{v^2}{a} = \frac{GM_\odot}{a^2}$$

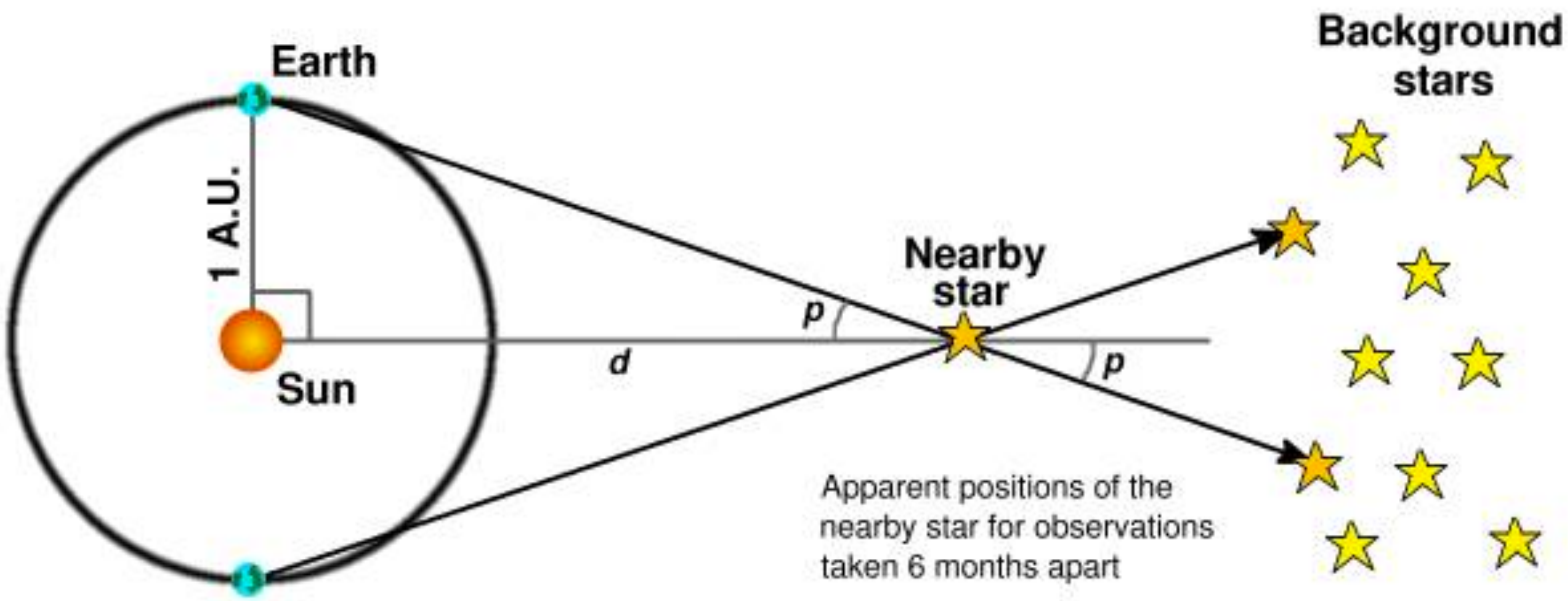
$$M_\odot = 2 \times 10^{33}\mathrm{g}$$

$$\varrho_\odot = 1.4\ \mathrm{g/cm^3}$$

Astronomical quantities

Earth	radius ~ 6400 km	mass ~ 6×10^{27} g	density ~ 5 g/cm^3
1.5×10^{13} cm			
Sun	radius ~ 7×10^{10} cm	mass ~ 2×10^{33} g	density ~ 1.4 g/cm^3

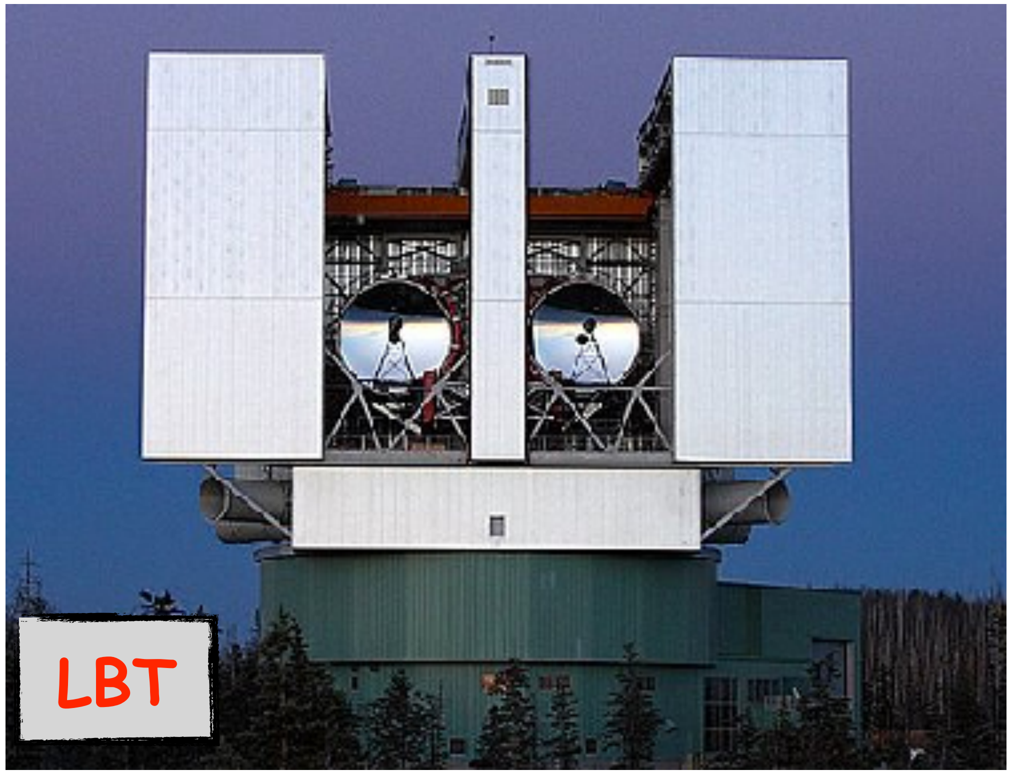
Parallaxes



$$d \sim \frac{a}{p}$$

$$1 \text{ rad} = 206265 \text{ arcsec}$$

$$p = 1 \text{ arcsec} \longrightarrow 1 \text{ pc} = 3 \times 10^{18} \text{cm}$$



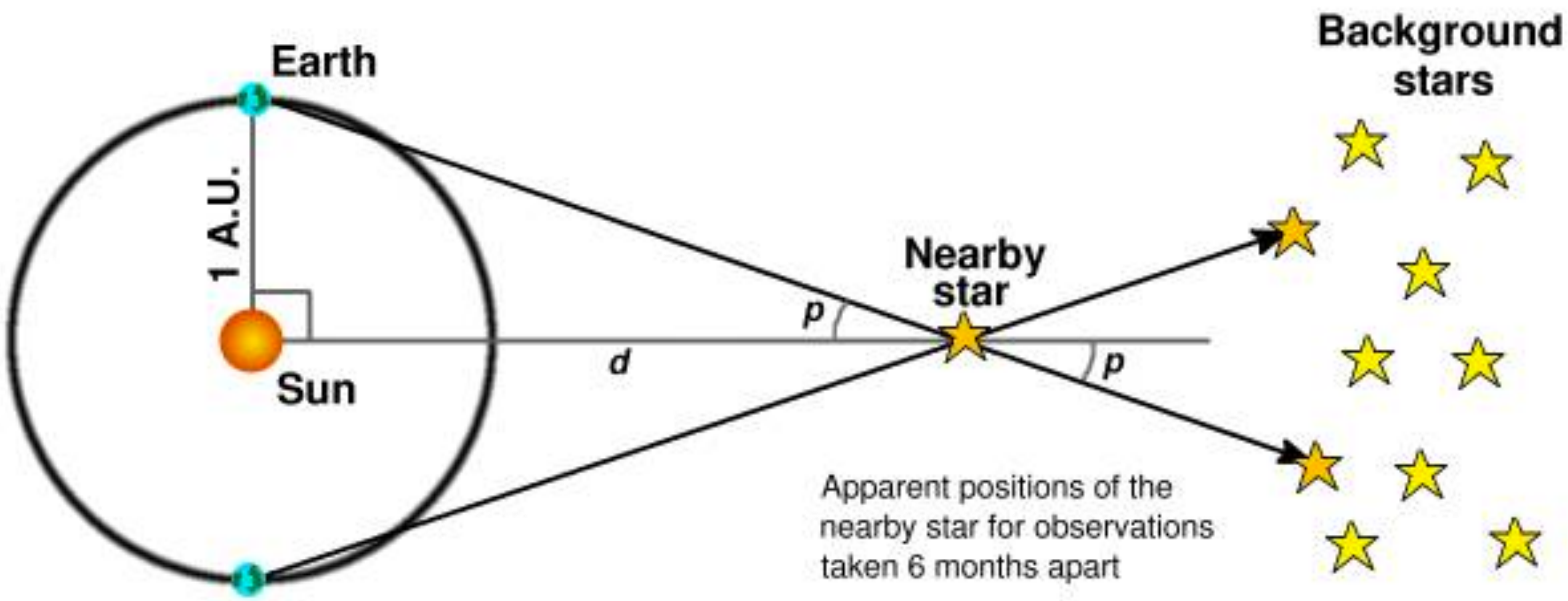
angular resolution

$$\delta\theta \sim \frac{\lambda}{D} \approx 0.02 \text{ arcsec}$$

wavelength (λ)

mirror diameter (D)

Parallaxes



$$d \sim \frac{a}{p}$$

$$1 \text{ rad} = 206265 \text{ arcsec}$$

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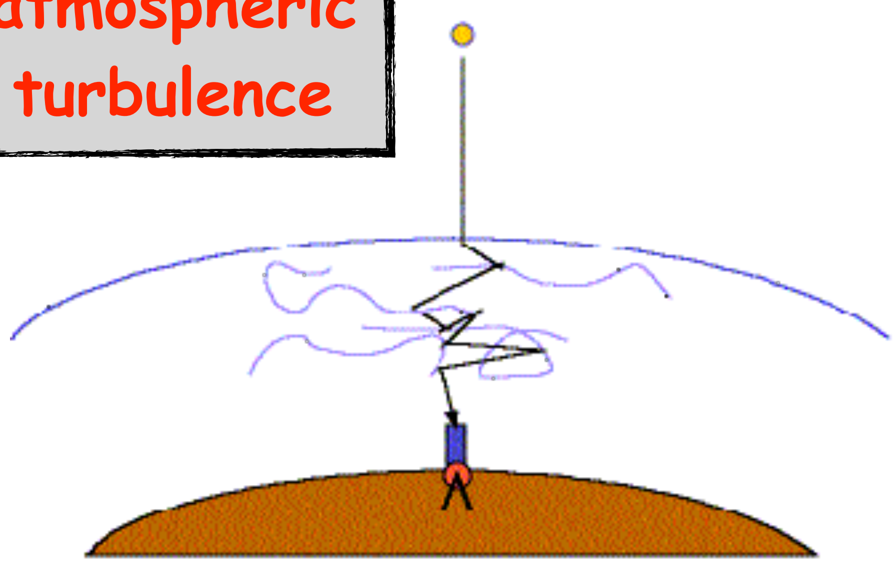
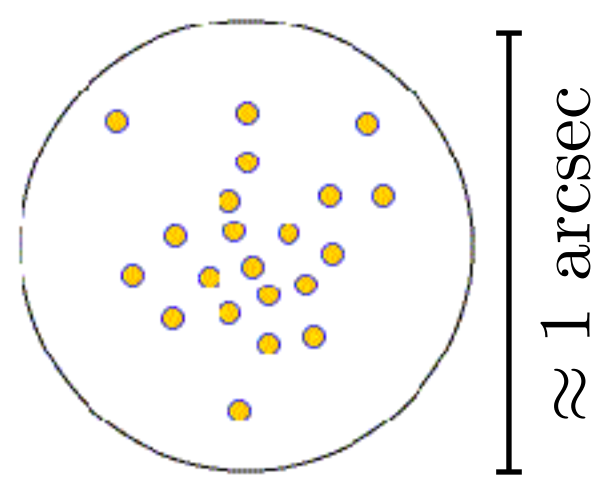
atmospheric turbulence



atmosphere refracts starlight in random directions very quickly—stars "twinkle".

telescope view (high magnification)



multiple images created

$$\delta\theta \sim \frac{\lambda}{D} \approx 0.02 \text{ arcsec}$$

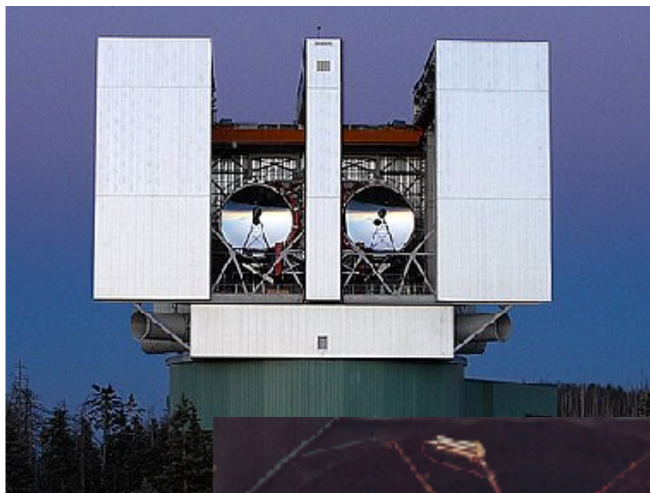
wavelength (λ)

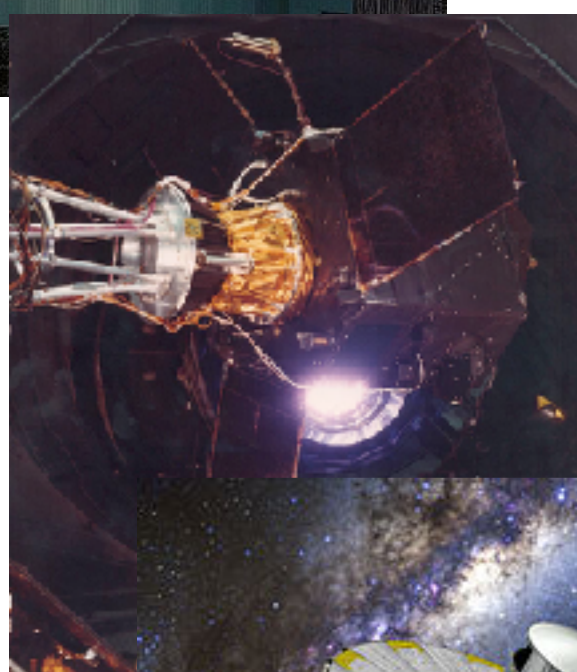
mirror diameter (D)

seeing

Limitations of parallaxes

The blurring on the image of a star (seeing) limits the accuracy in determining the position of a star





ground based telescopes

$$p_{min} \approx 0.01 \text{ arcsec} \longrightarrow d_{max} \approx 100 \text{ pc}$$

Hypparcos (satellite, 1989-1993)

$$p_{min} \approx 0.001 \text{ arcsec} \longrightarrow d_{max} \approx 1 \text{ kpc}$$

Gaia (satellite, taking data)

$$\longrightarrow d_{max} \approx 10 \text{ kpc}$$

Astronomical quantities

Earth radius ~ 6400 km mass ~ 6×10^{27} g density ~ 5 g/cm^3

1.5×10^{13} cm

Sun radius ~ 7×10^{10} cm mass ~ 2×10^{33} g density ~ 1.4 g/cm^3

1.3 pc

Alpha Centauri

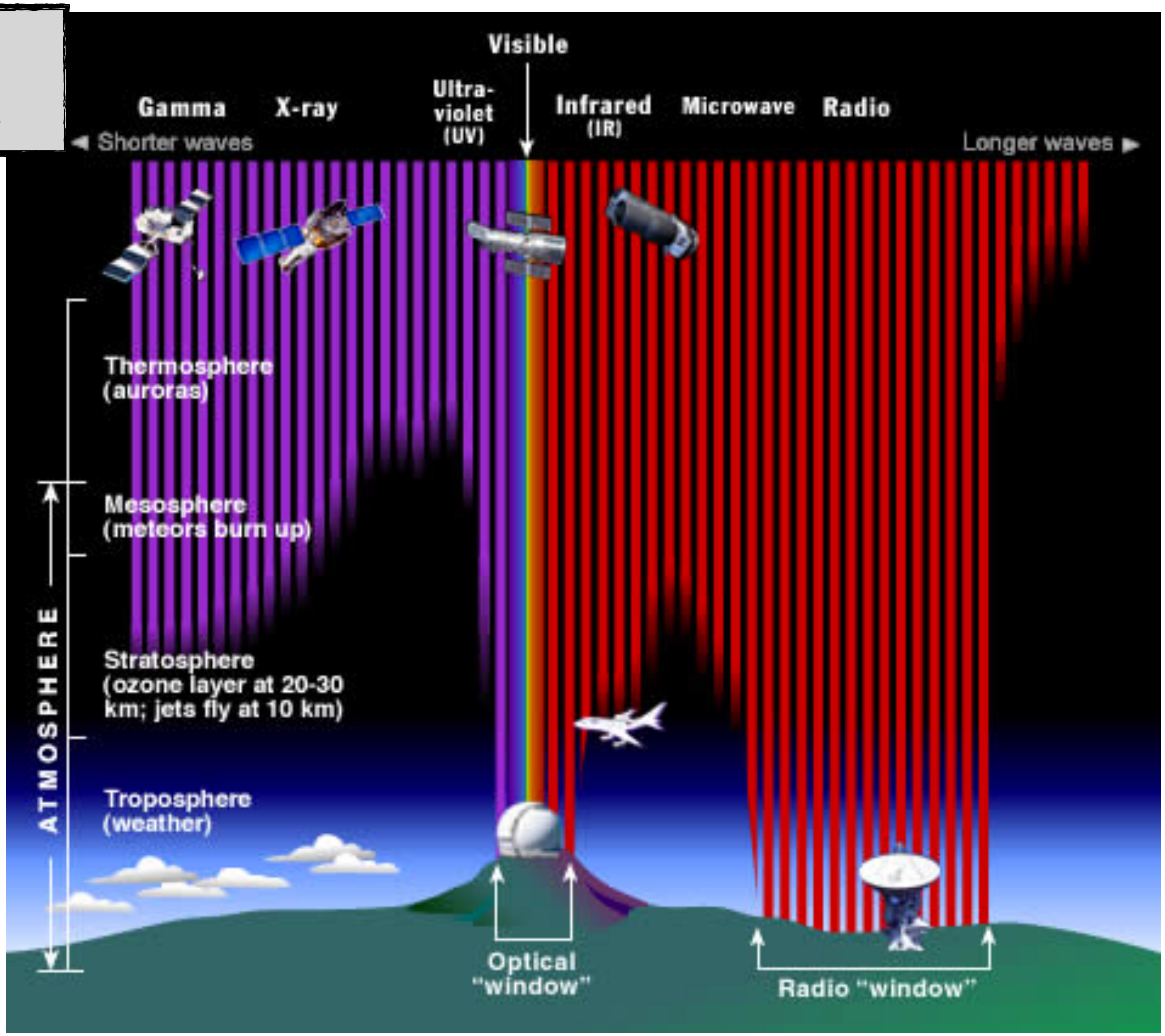
The radio window

The Earth's atmosphere is opaque to most frequencies

radio window

$$\lambda > 1 \text{ cm}$$

$$\nu < 30 \text{ GHz}$$



Optical

Radio

Radio telescopes and interferometry

Very Long Baseline Interferometry

Distance to the centre of the Milky Way

At radio frequencies the effect of atmospheric seeing is negligible

>1 cm

$$\delta\theta \sim \frac{\lambda}{D} \longrightarrow \delta\theta \approx \text{milliarcsec}$$

size of the Earth!!!

positions of radio sources can be determined with great accuracy

parallaxes from radio observations allowed to measure the distance of the supermassive black hole located at the galactic centre -> ~8 kpc

other (more indirect) methods gave consistent results

Astronomical quantities

Earth radius ~ 6400 km mass ~ 6 x 10^{27} g density ~ 5 g/cm^3

1.5 x 10^{13} cm

Sun radius ~ 7 x 10^{10} cm mass ~ 2 x 10^{33} g density ~ 1.4 g/cm^3

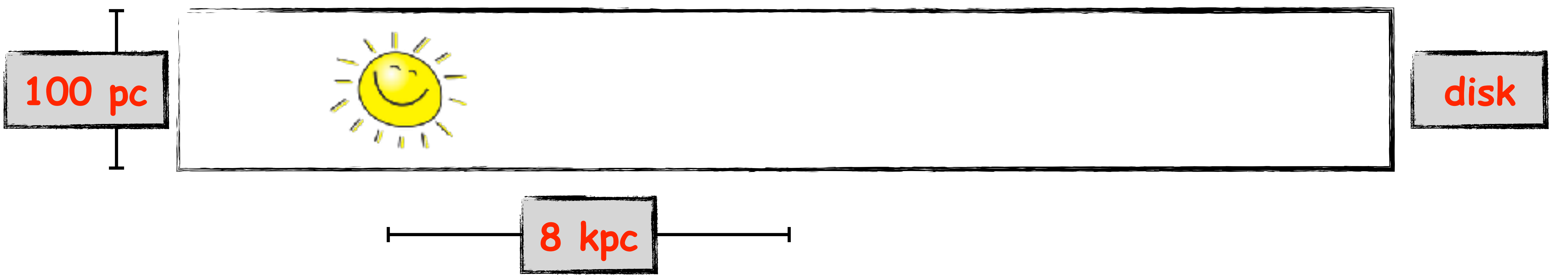
1.3 pc

Alpha Centauri

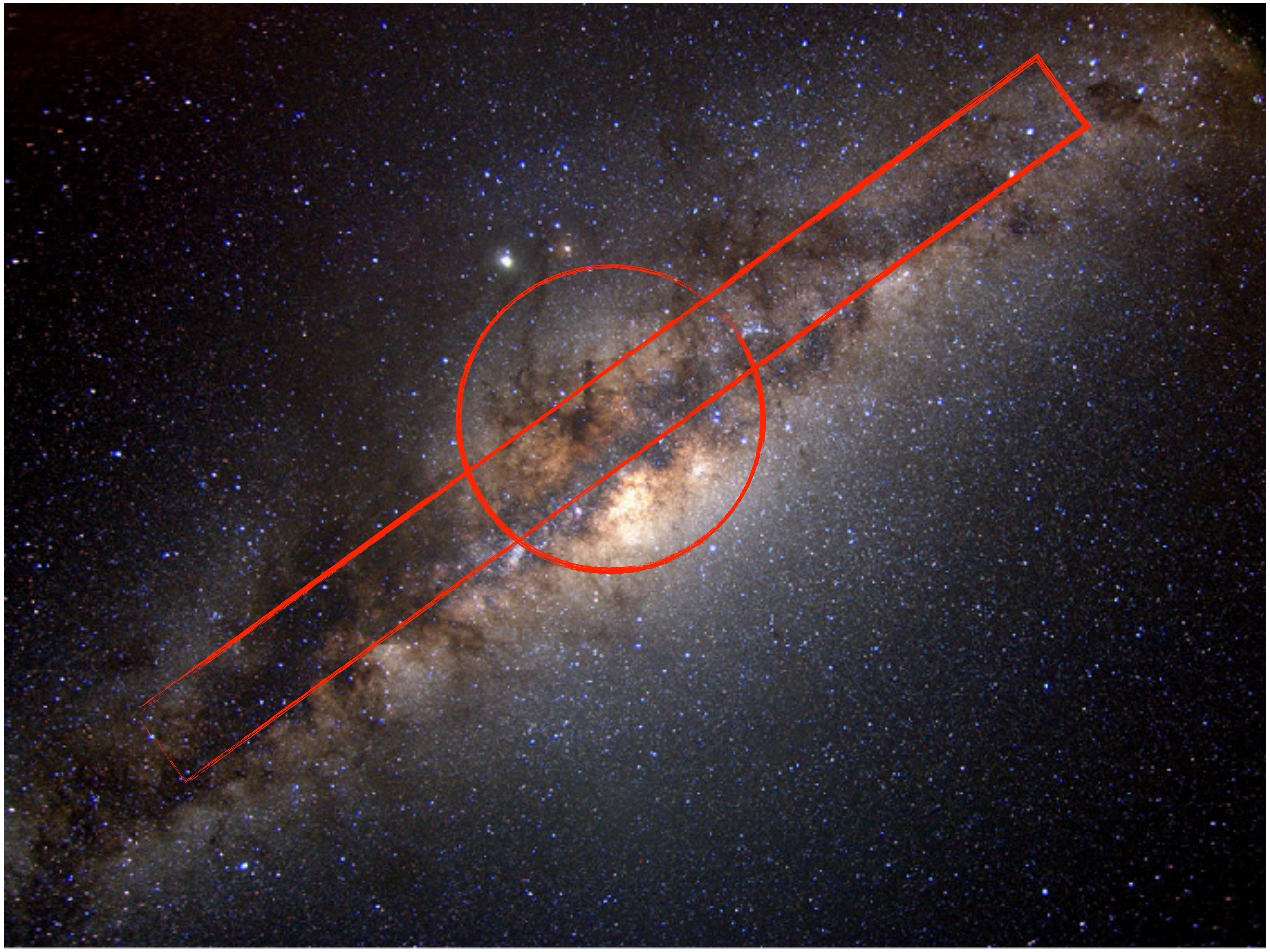
8 kpc

Galactic Centre

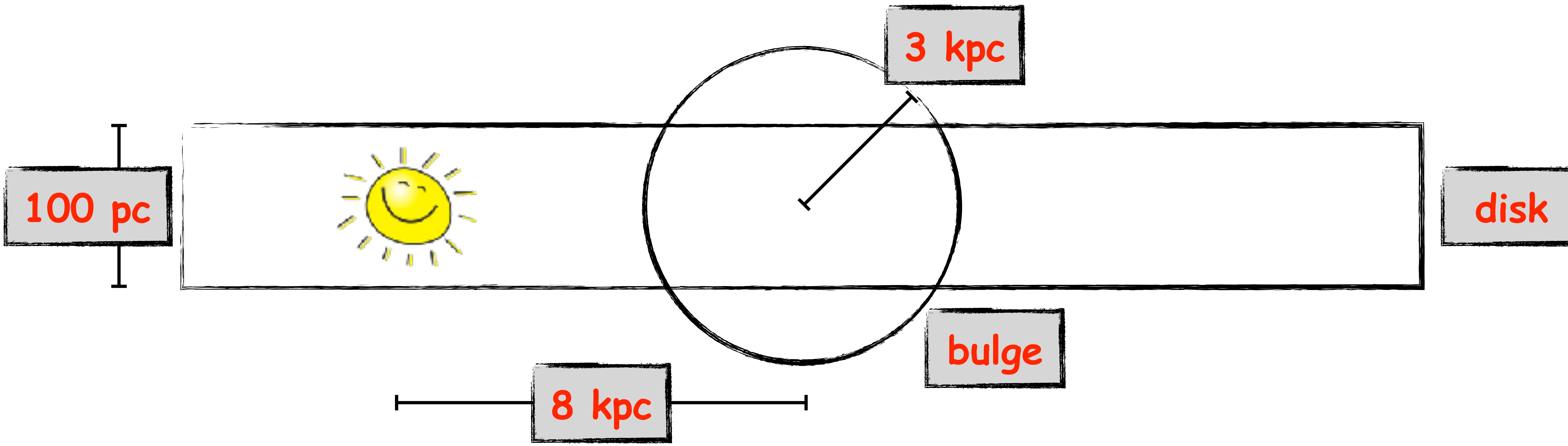
The Milky Way



The galactic bulge

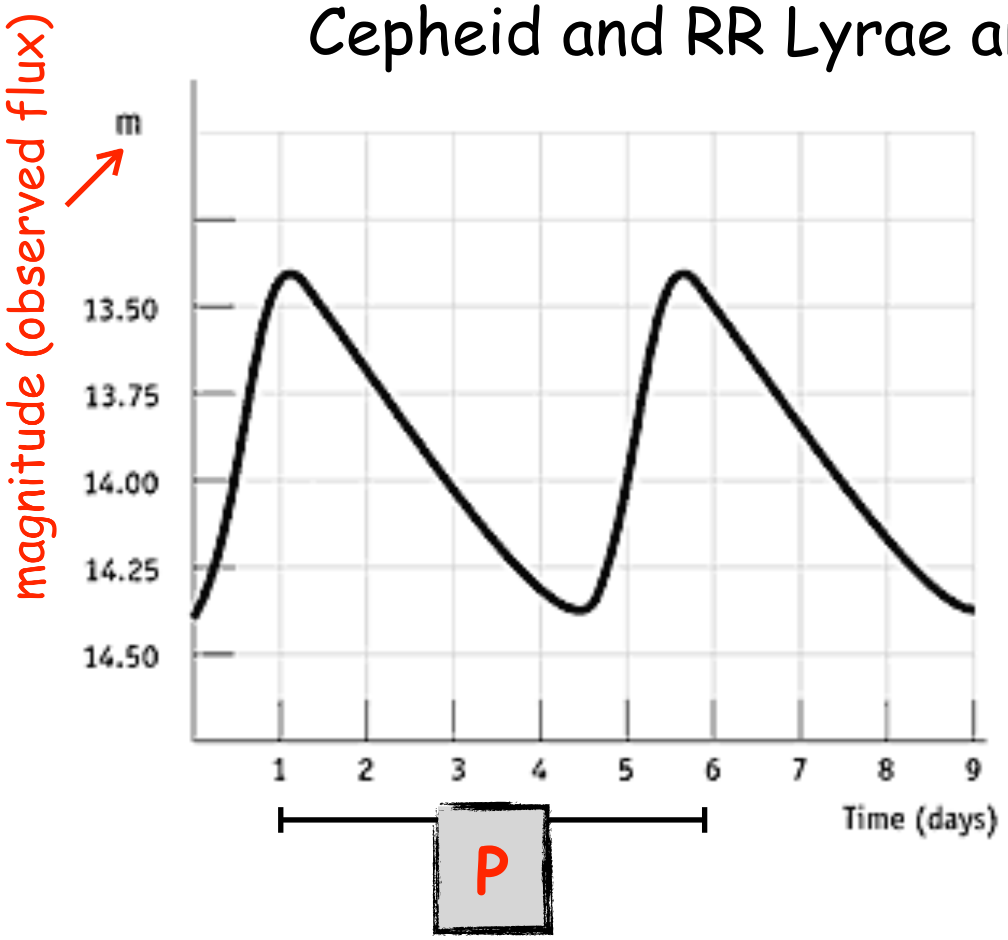


The Milky Way

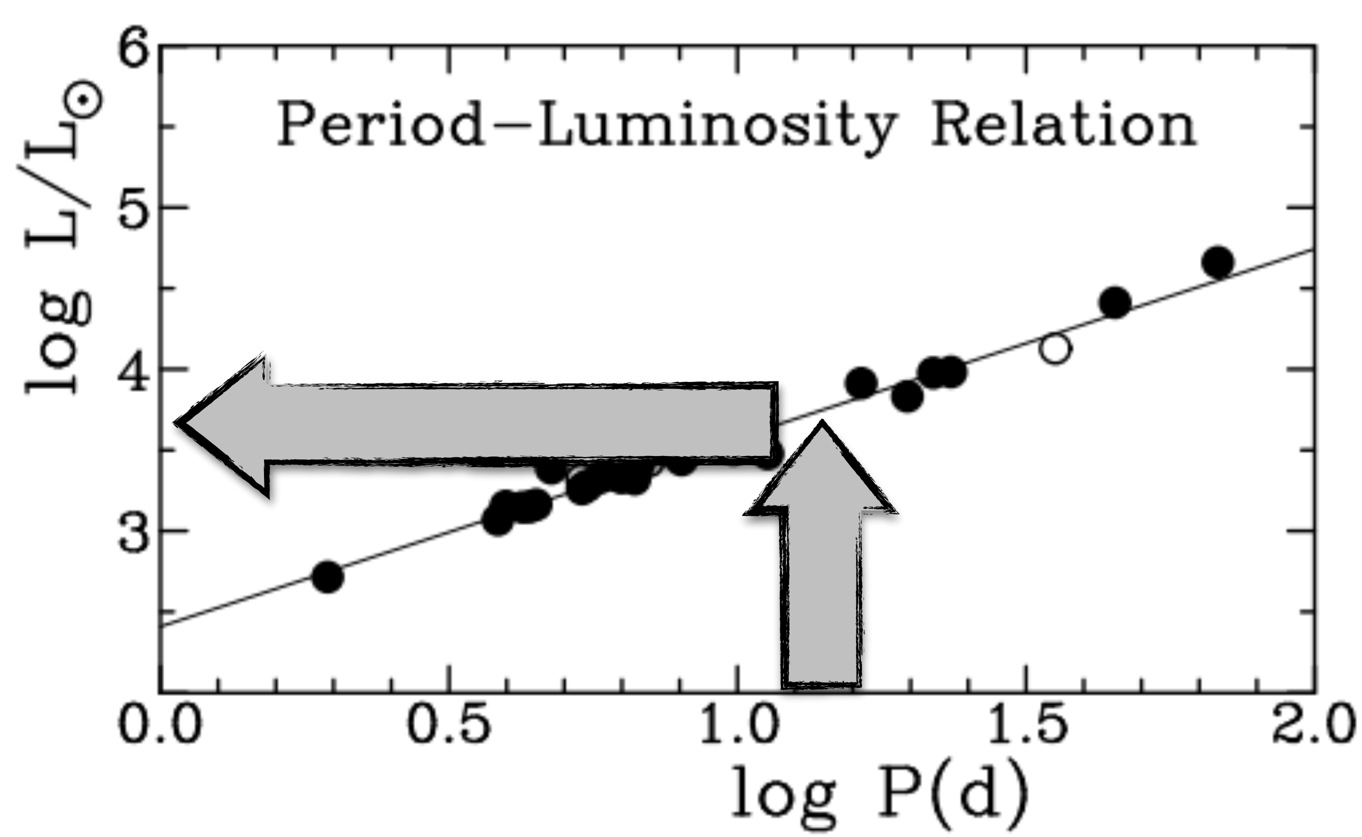


Larger distances: Cepheids and RR Lyrae

Cepheid and RR Lyrae are variable stars characterised by a period P

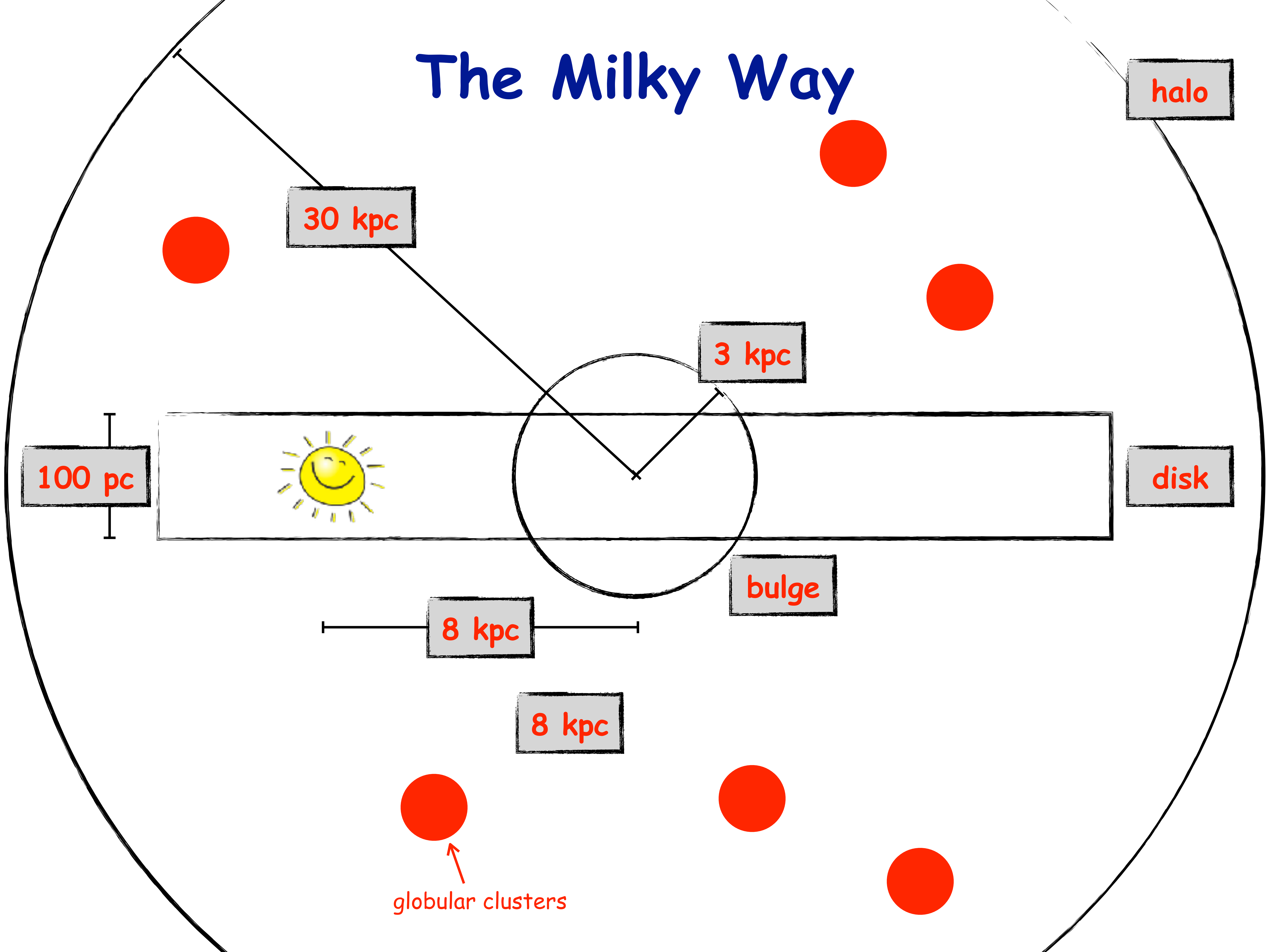


- Take some Cepheids of known distance D (for example, measured from parallaxes)
- from their observed flux, measure the luminosity $L = F \times (4\pi D^2)$
- build a period-luminosity diagram



- now take a Cepheid of unknown distance, and from its period derive the luminosity L
- the distance can be derived as $D = (F/4\pi L)^{1/2}$
- Cepheids are STANDARD CANDLES

The Milky Way



The mass of the Milky Way: stars

total photon energy output

Solar luminosity $L_\odot \sim 4 \times 10^{33}$ erg/s

Solar mass $M_\odot \sim 2 \times 10^{33}$ g

MW luminosity $L_{MW} \rightarrow$ can be measured

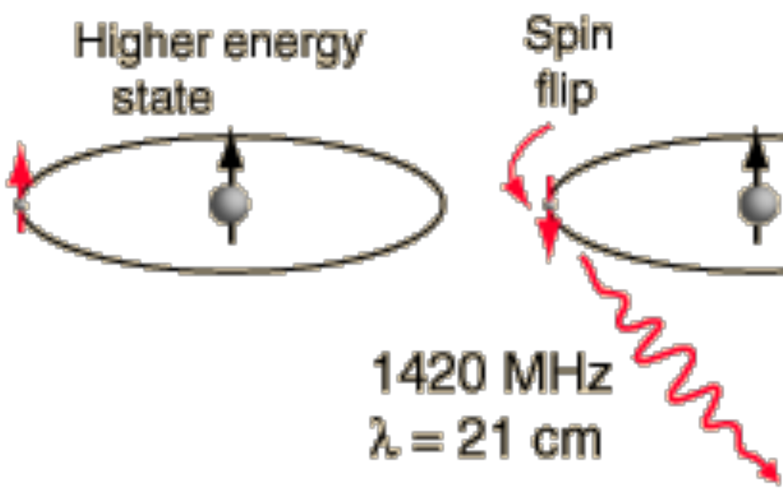
MW stellar mass $M_{MW} \rightarrow ?$

very very rough

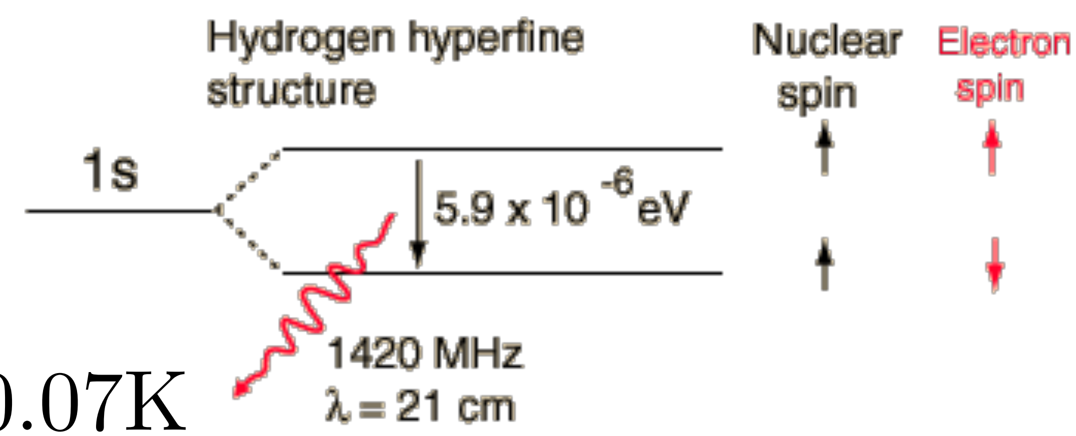
Assumption $\frac{M_\odot}{L_\odot} \approx \frac{M_{MW}}{L_{MW}} \longrightarrow M_{MW} \approx 10^{11} M_\odot$

Atomic H in the Milky Way

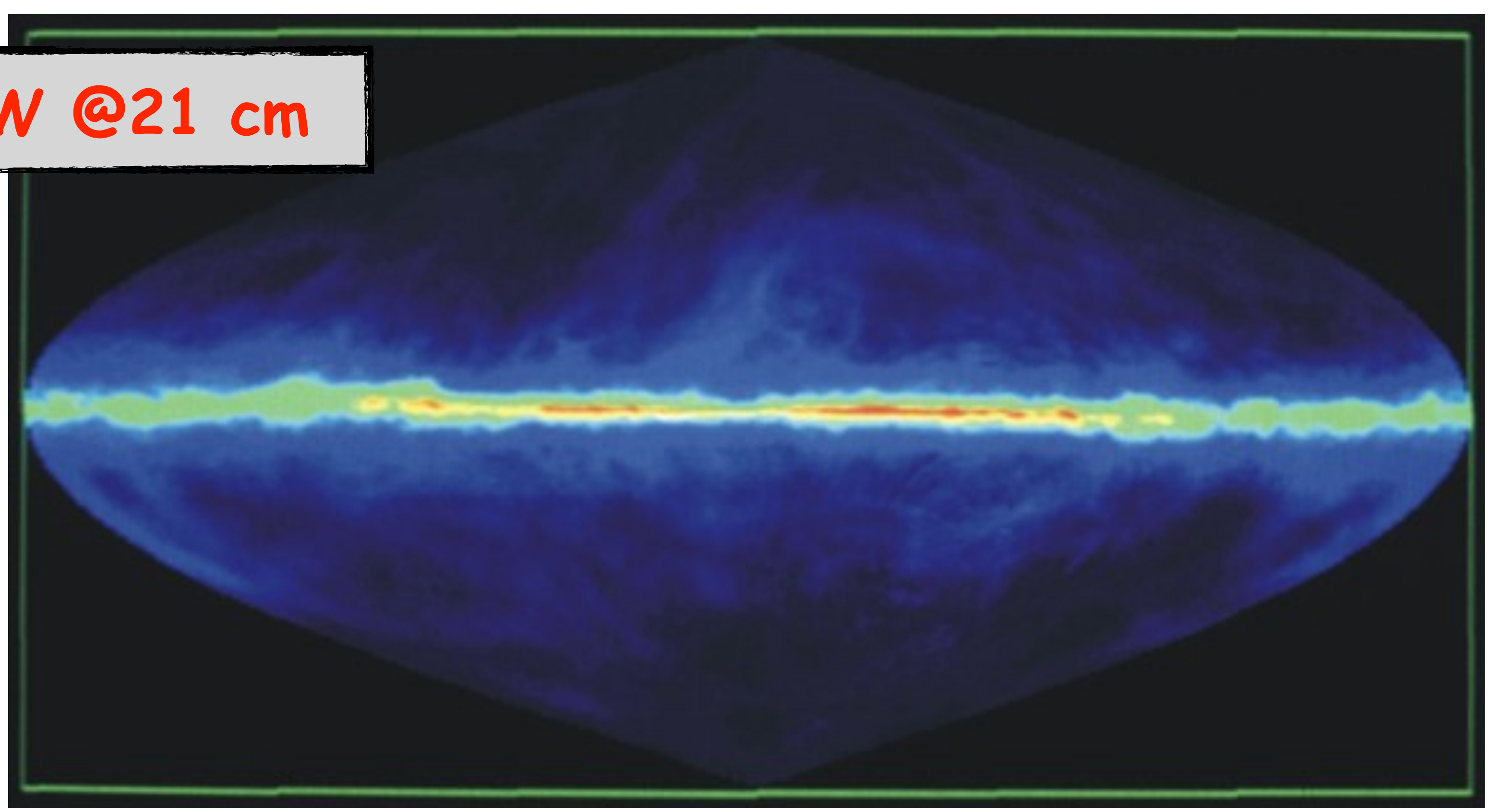
Hydrogen hyperfine structure



$$T = \frac{\epsilon}{k} \sim 0.07\text{K}$$

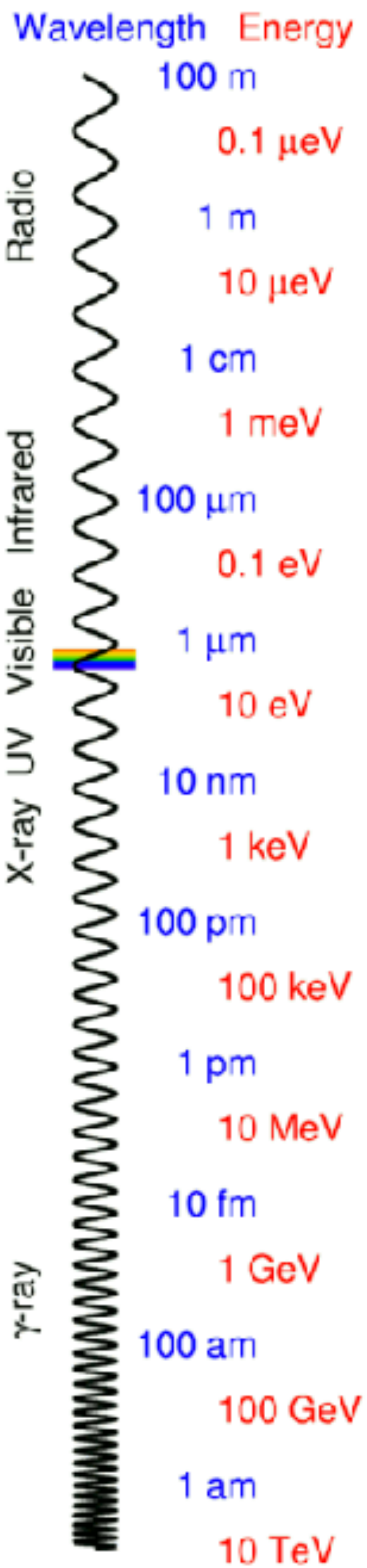


MW @21 cm



The disk of the Milky Way is filled with a diffuse gas of neutral H

The electromagnetic spectrum



21 cm line -> atomic neutral Hydrogen (HI)

visible light -> stars

The interstellar medium (ISM)

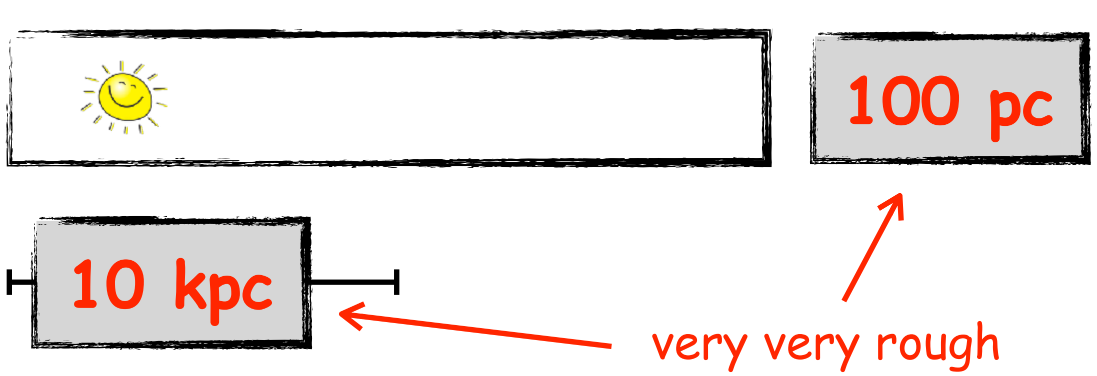
Is the diffuse matter that exists in the space between stars

Observations of the MW in the 21 cm and in other lines (especially CO) revealed that:

- more than 90% (in number) of the ISM particles are Hydrogen
- 80% of which are atomic Hydrogen, either neutral (HI) or ionised (HII)
- the remaining 20% is molecular Hydrogen (H_2)

$$M_{ISM} \approx 10^{10} M_{\odot}$$

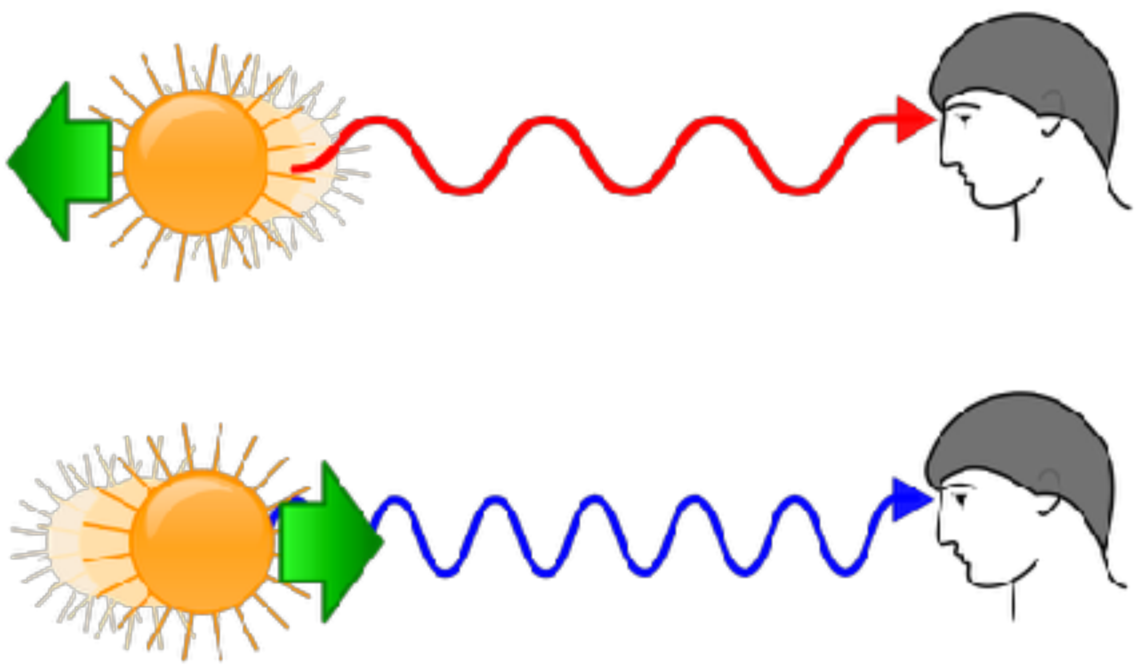
~10% of the stellar mass



$$n_{ISM} \approx 1 \text{ cm}^{-3}$$

The MW rotation curve

Doppler effect

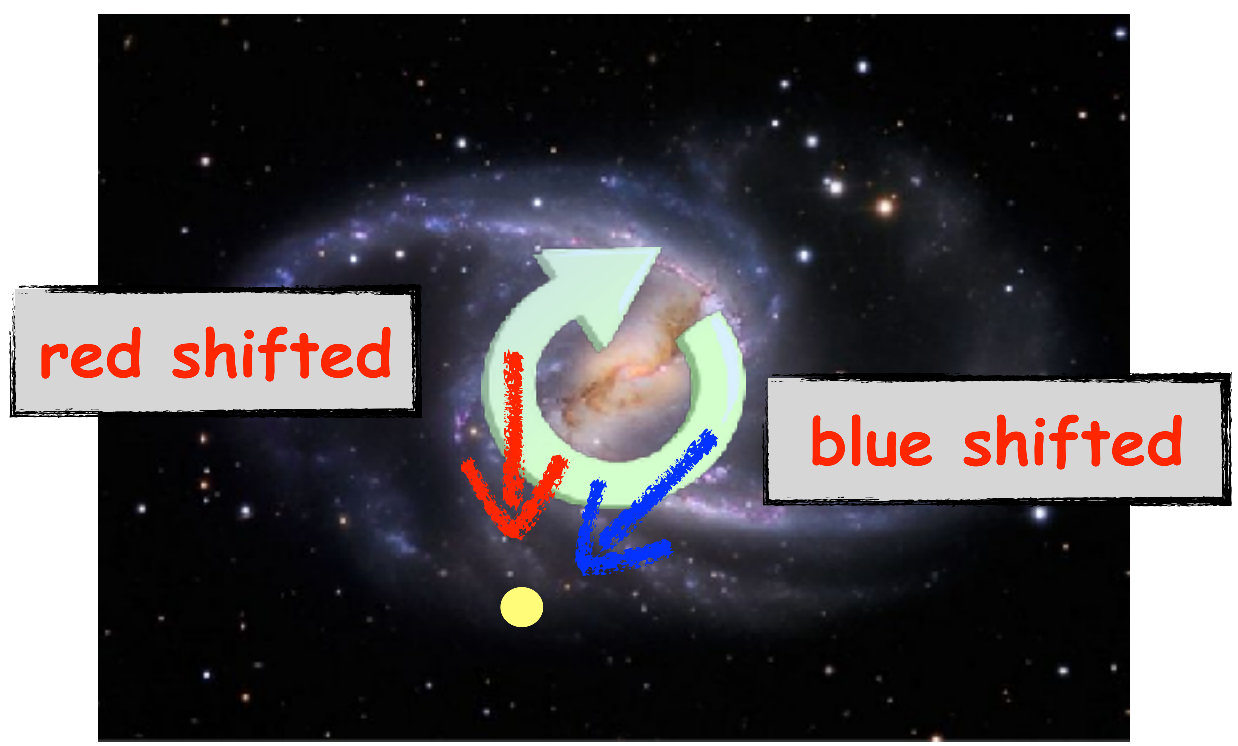


wavelength shift

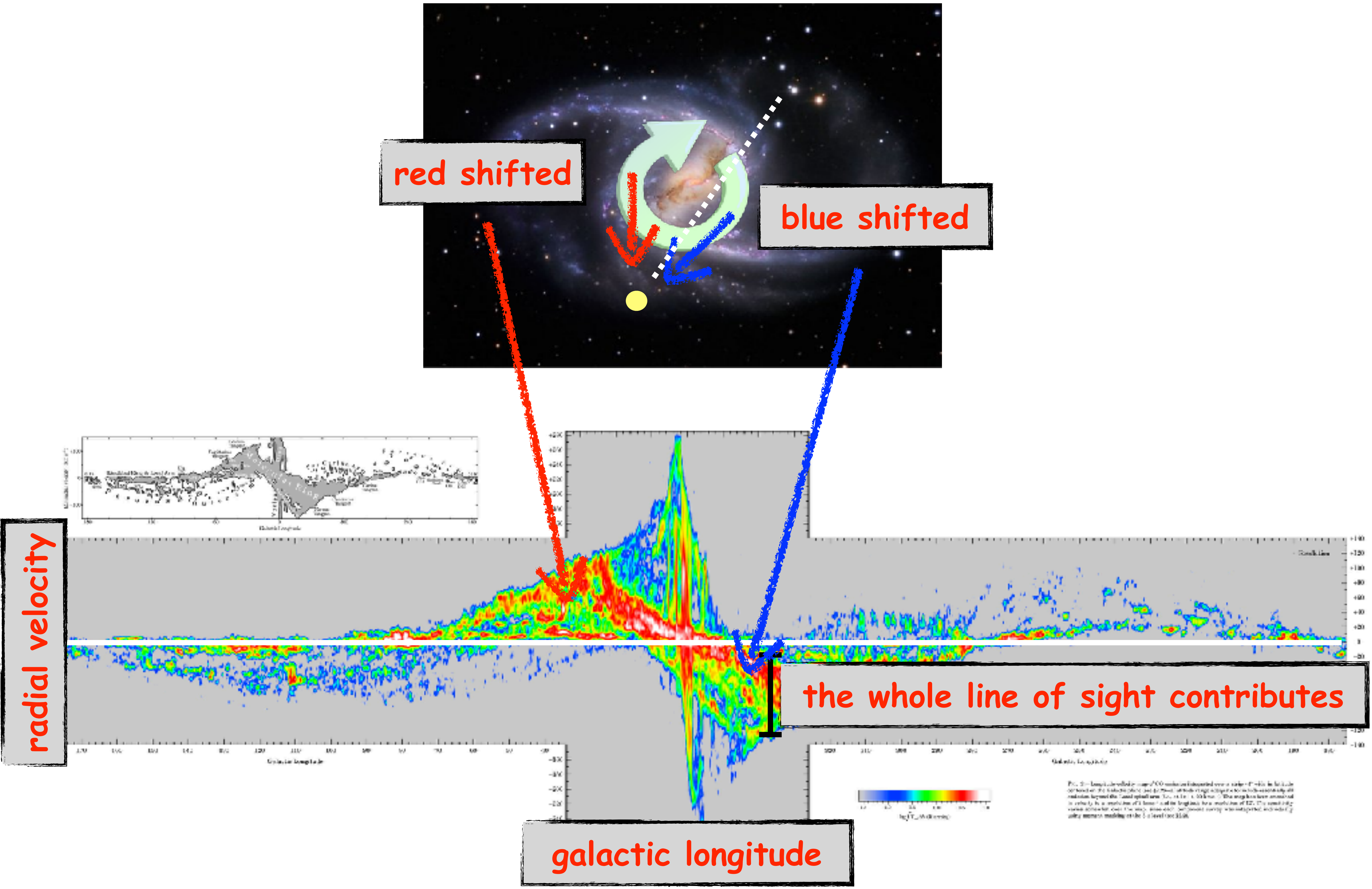
velocity along the line of sight

$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$

wavelength in the rest frame of the source

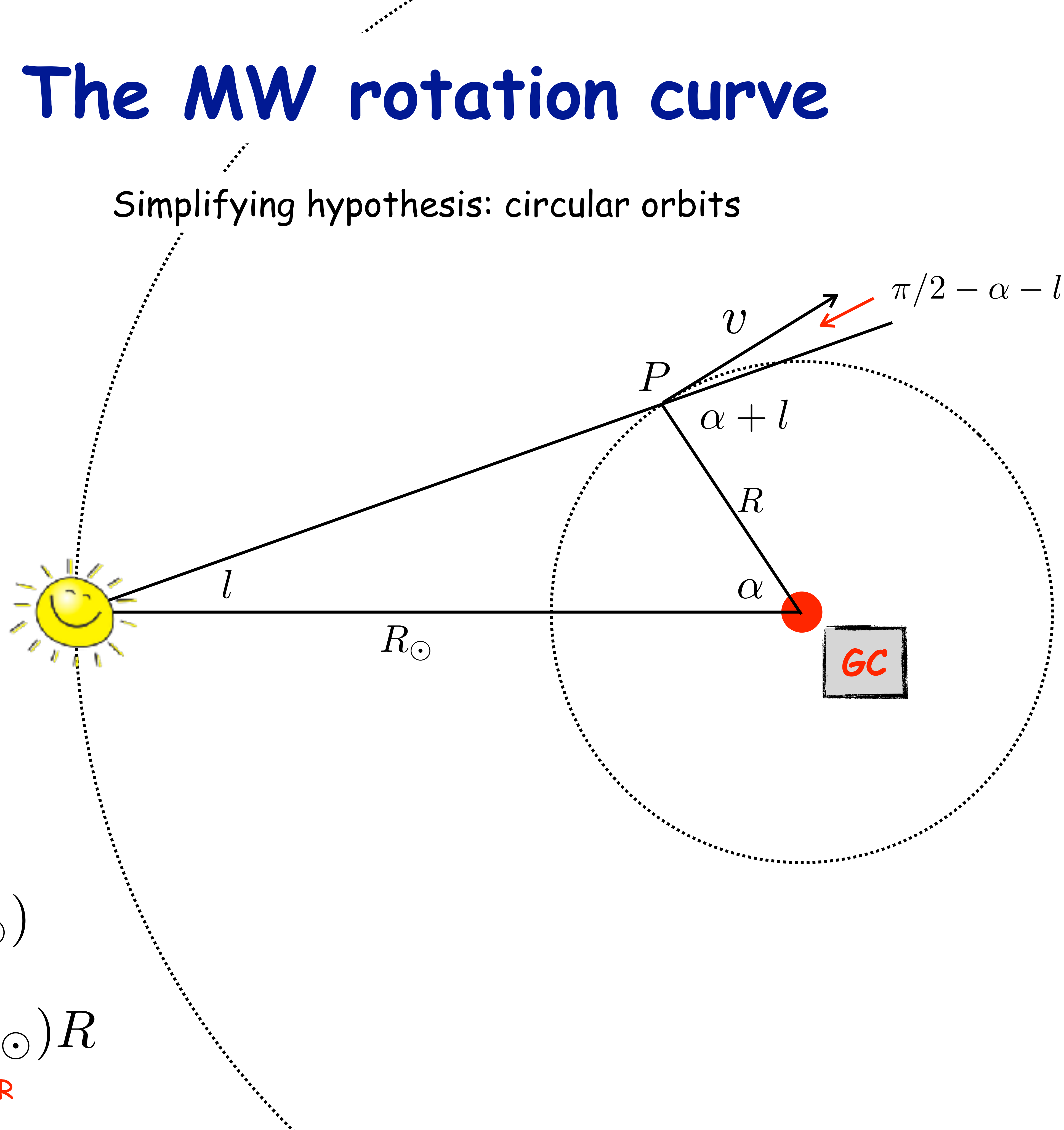


The MW rotation curve



The MW rotation curve

Simplifying hypothesis: circular orbits



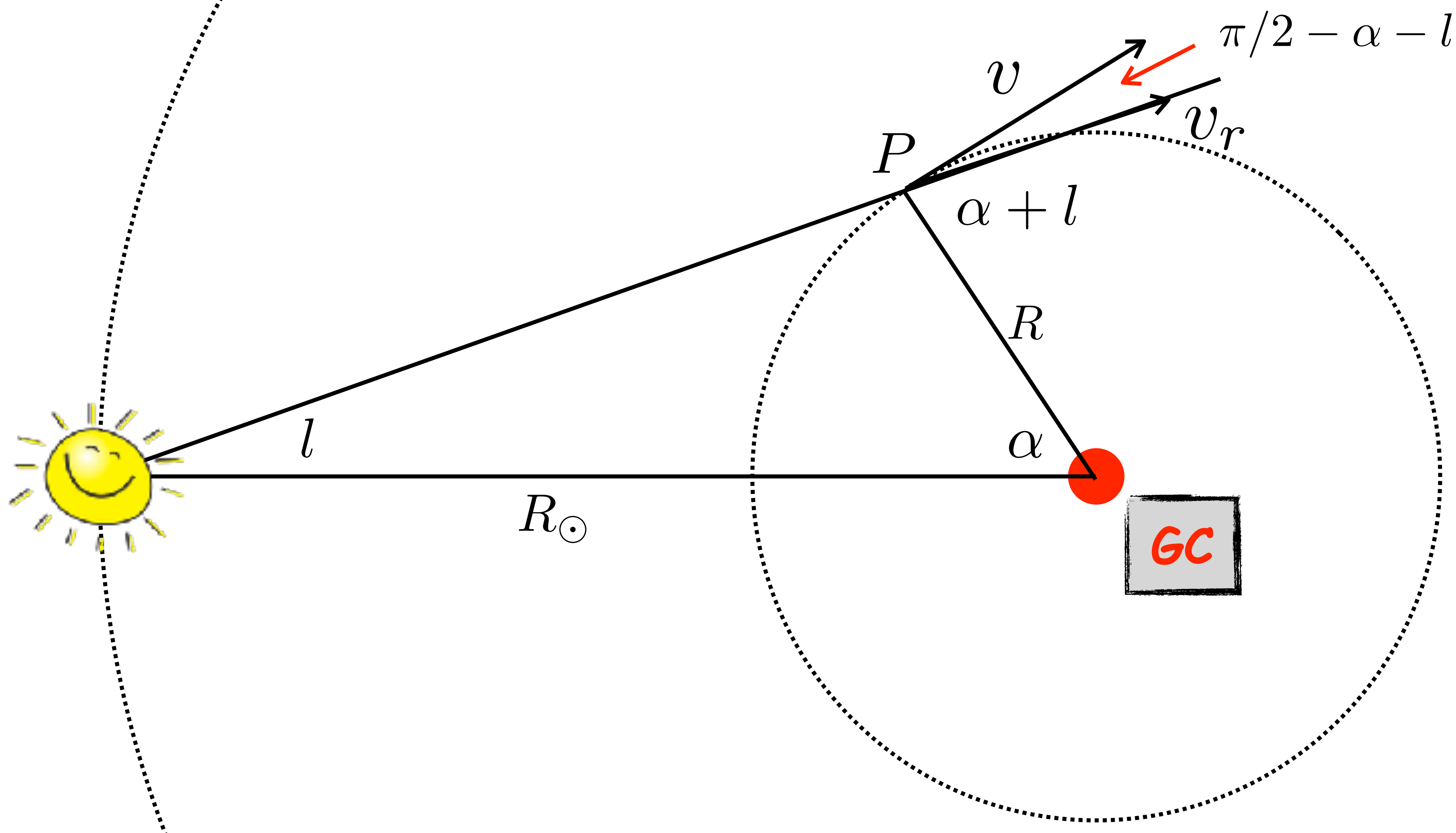
$$\omega_\odot = \omega(R_\odot)$$

$$v = (\omega - \omega_\odot)R$$

this depends on R

The MW rotation curve

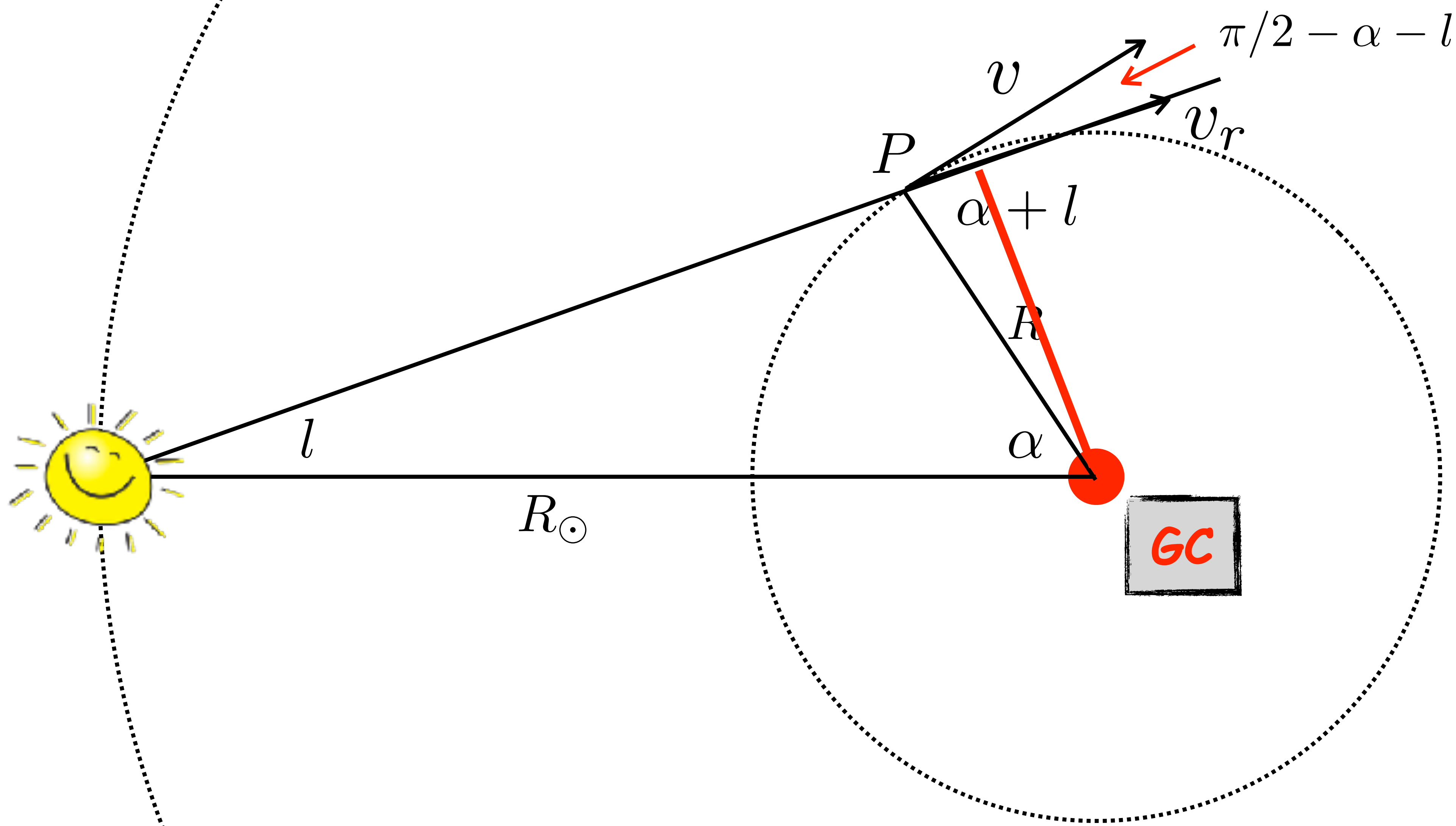
What we measure are RADIAL velocities



$$v_r = (\omega - \omega_\odot) R \cos(90 - l - \alpha) = (\omega - \omega_\odot) R \sin(l + \alpha)$$

The MW rotation curve

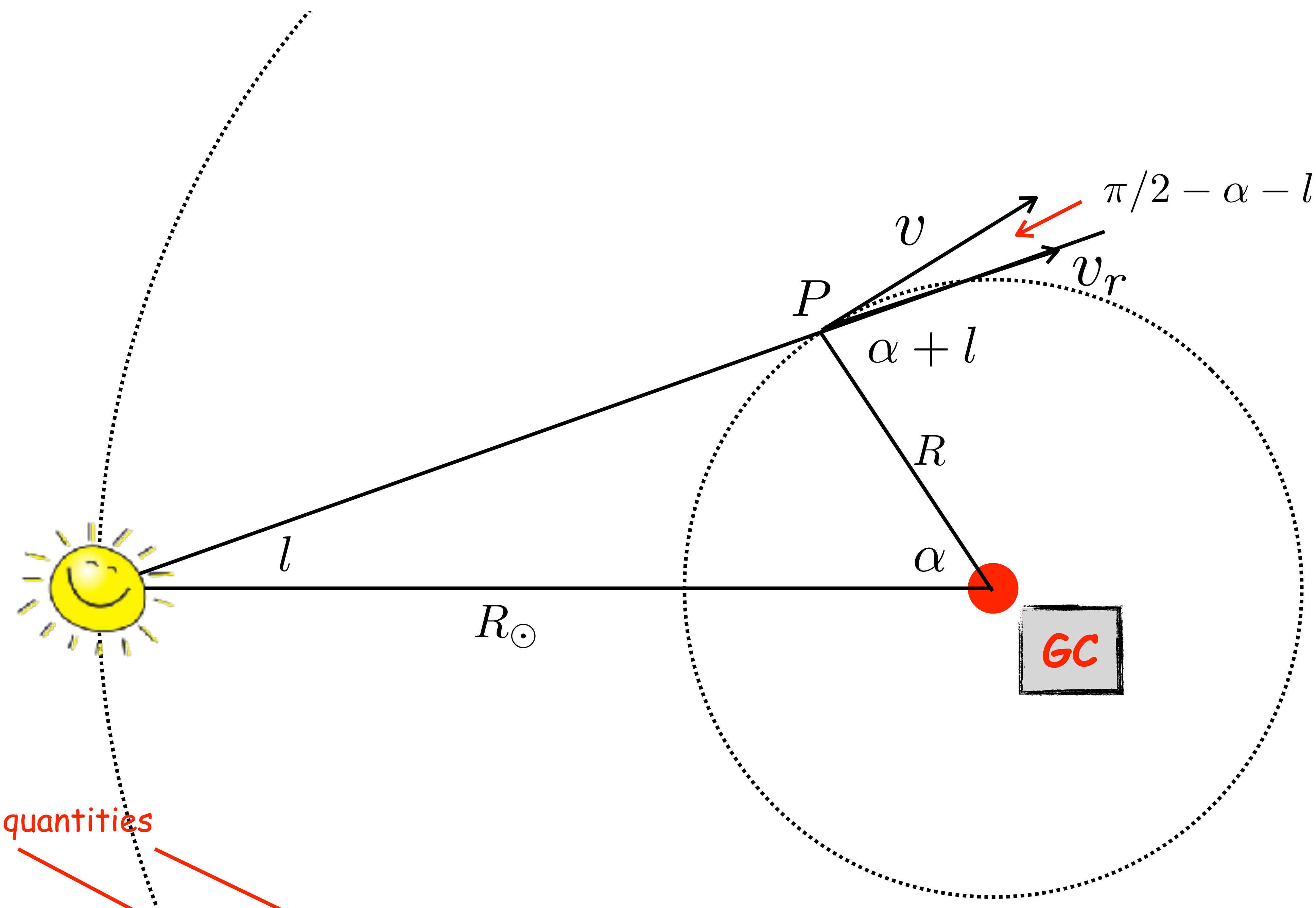
What we measure are RADIAL velocities



$$v_r = (\omega - \omega_\odot) R \cos(90 - l - \alpha) = (\omega - \omega_\odot) R \sin(l + \alpha)$$

$$= R_\odot \sin(l)$$

The MW rotation curve



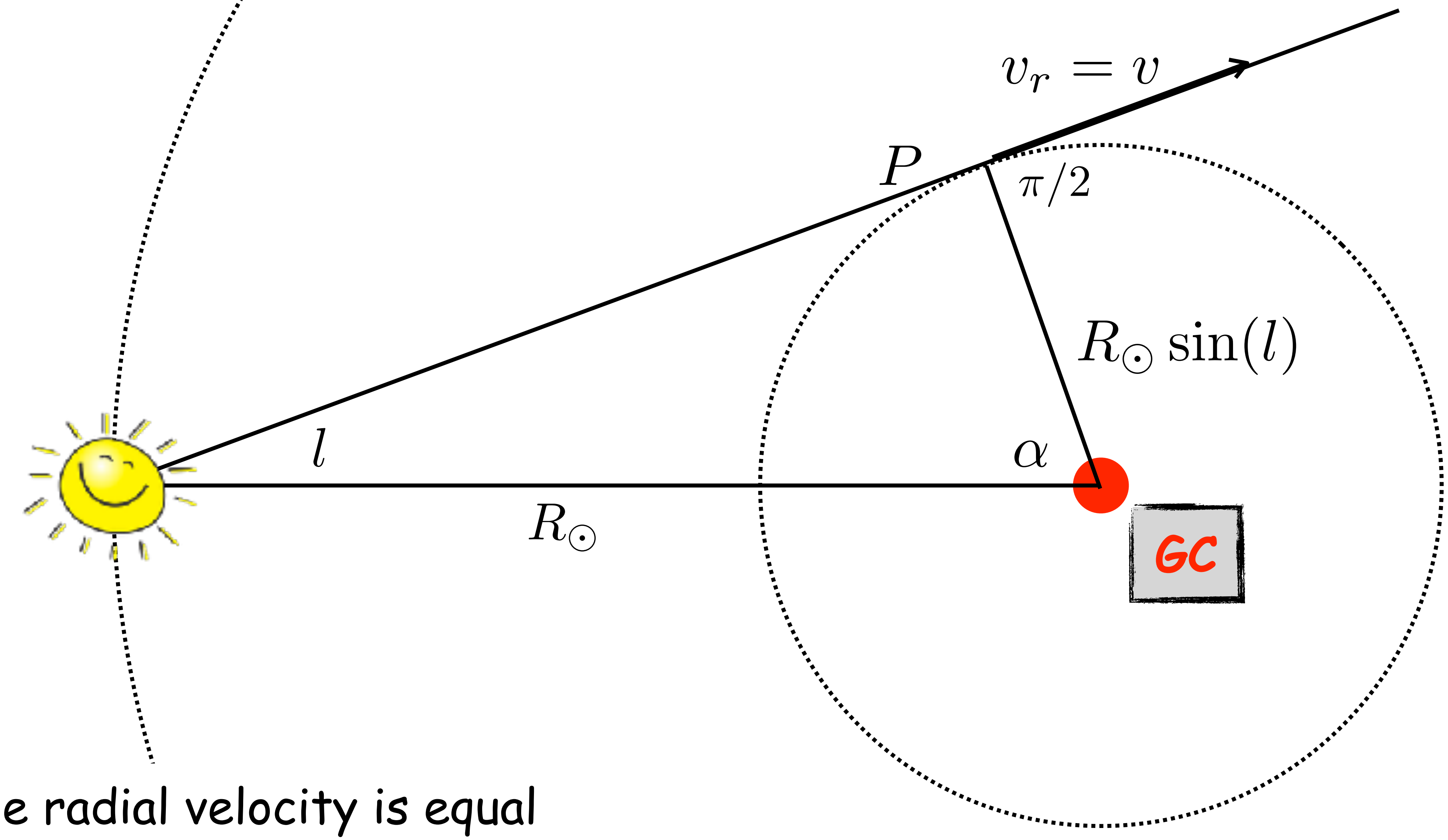
measured quantities

$$v_r = (\omega - \omega_\odot) R_\odot \sin(l)$$

this depends on R

The MW rotation curve

Consider now the particular case $\alpha + l = \pi/2$



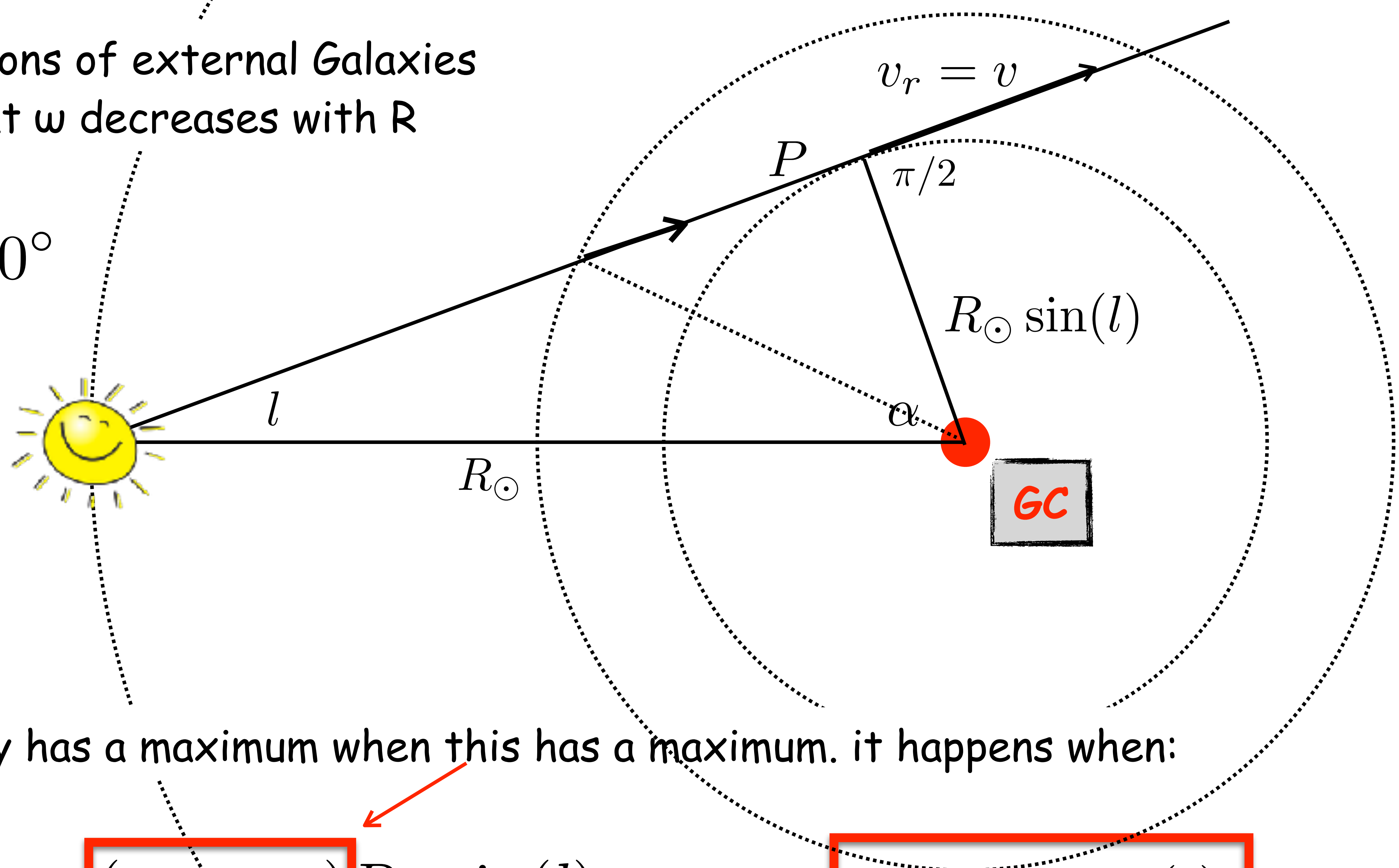
in this case the radial velocity is equal to the orbital velocity around the galactic cetre

The MW rotation curve

WARNING! We measure a range of radial velocities all along a given line of sight

from observations of external Galaxies
we know that ω decreases with R

$0^\circ < l < 90^\circ$



the radial velocity has a maximum when this has a maximum. it happens when:

$$v_r = (\omega - \omega_\odot) R_\odot \sin(l) \qquad R = R_\odot \sin(l)$$

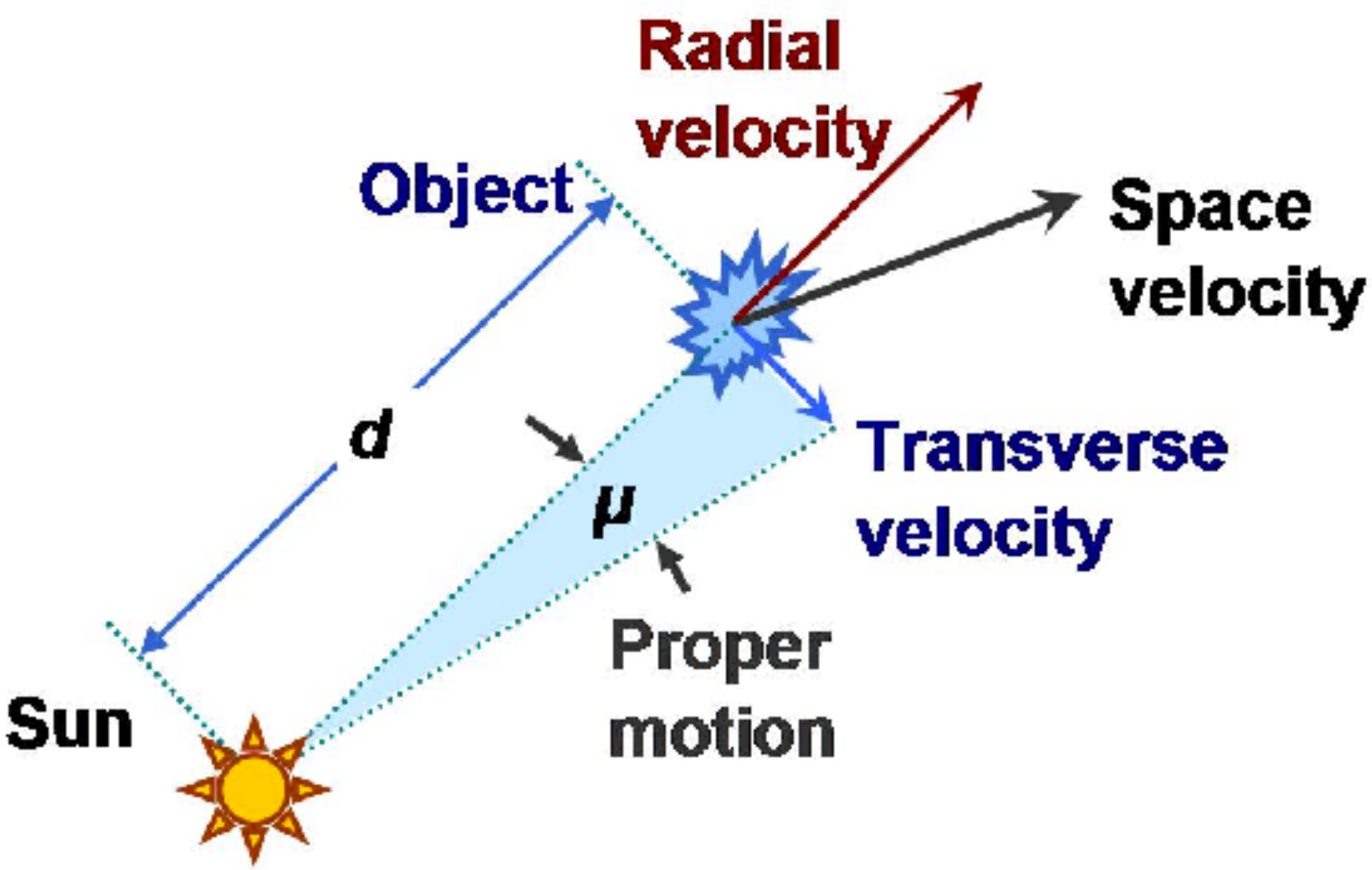
in this way we can measure the rotation curve for $0 < R < R_\odot$

Proper motions of stars

apparent motion of the star -> μ
doppler effect -> radial velocity
parallax -> distance

transverse velocity $v_t = \mu\ d$

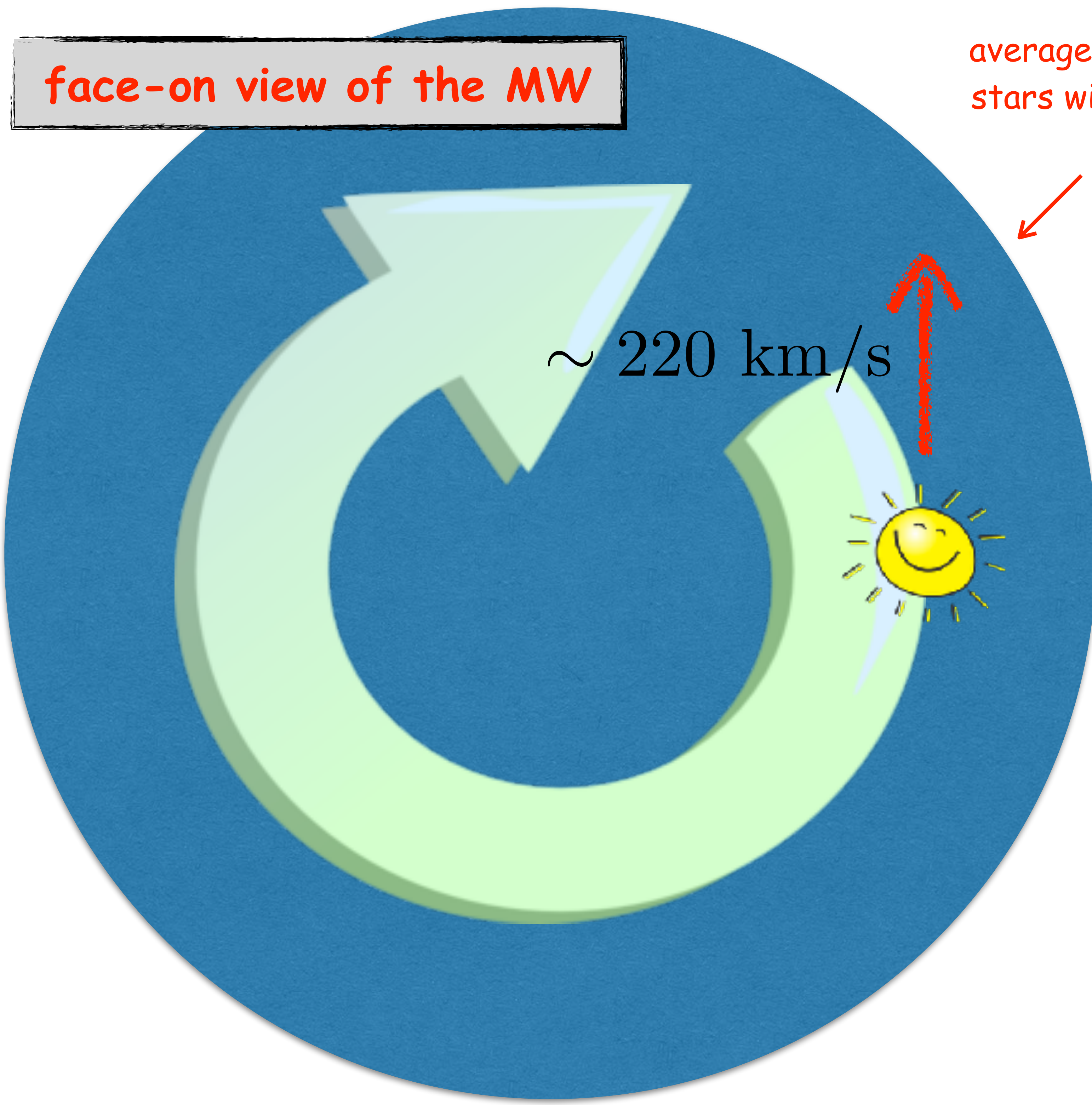
total velocity $v^2 = v_t^2 + v_r^2$



- Stars in the vicinity of the sun have typical random velocities ~10 km/s
- the average of these velocities is different from zero
- this is due to the fact that the sun has a proper motion with respect to the population of neighbouring stars (~10-15 km/s)
- Local Standard of Rest -> the rest frame where the average of star's random velocities is zero

The velocity of the sun

very few stars in the vicinity of the sun are characterised by very large proper motions



average speed of high velocity
stars with respect to the LSR

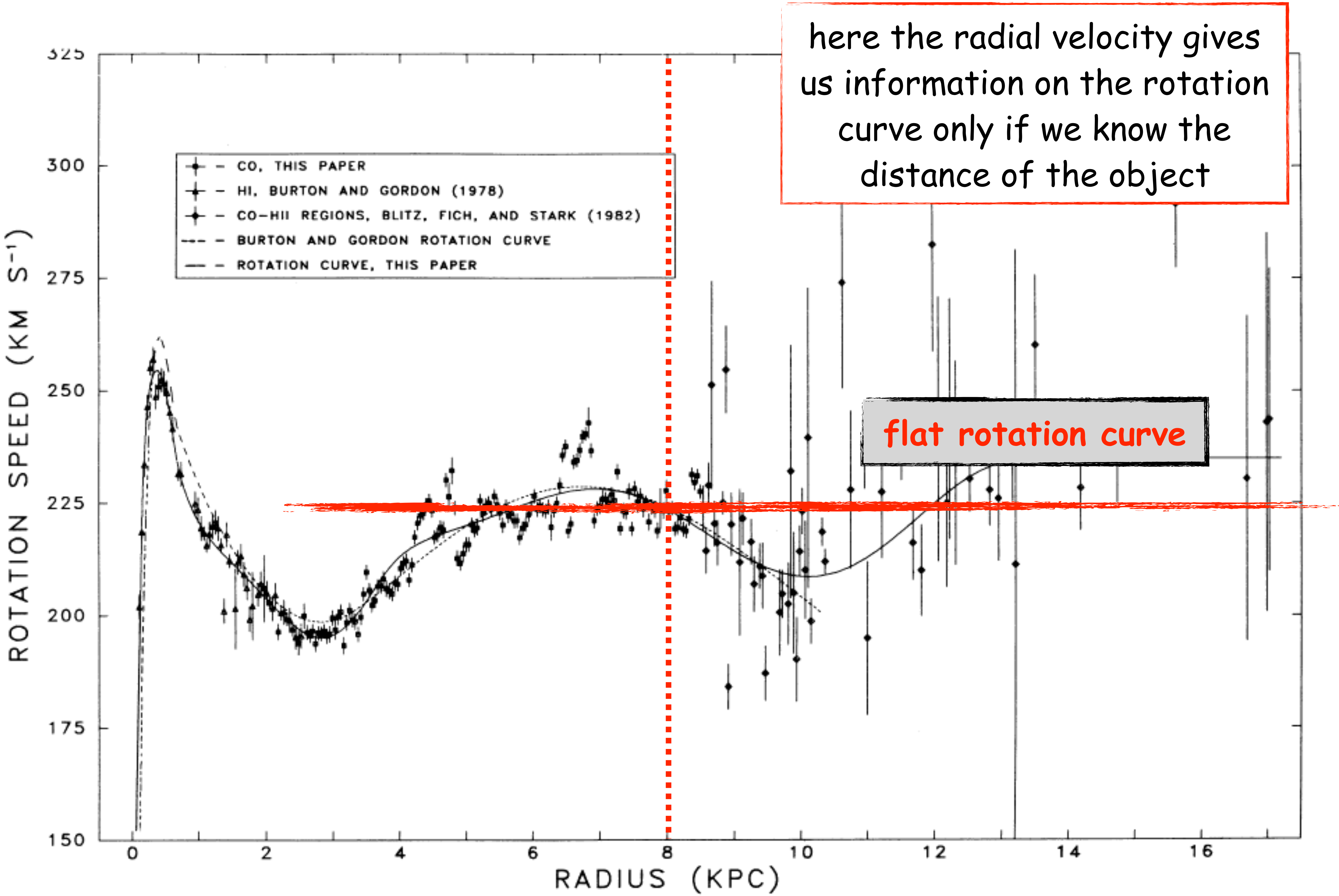
interpretation

- cold stellar component -> disk
- hot stellar component -> halo
- the galactic disk is supported by rotation
- the halo is supported by velocity dispersion (no rotation)
- the LSR (i.e. all the stars close to the sun) rotates around the GC at a speed of ~220 km/s

$$v_\odot \sim 220 \text{ km/s}$$

$$t_\odot = \frac{2\pi R_\odot}{v_\odot} \sim 220 \text{ Myr}$$

The rotation curve of the MW



Galactic dynamics

assumption: the surface density of the disk follows the distribution of light

$$\Sigma = \Sigma_0 e^{-R/R_d}$$

the mass is concentrated towards the centre

far away from the centre...

$$\frac{v^2}{R} = \frac{GM}{R^2} \longrightarrow v = \left(\frac{GM}{R}\right)^{1/2}$$

this is not flat! -> evidence for the existence of matter which is not traced by light (dark matter)

Dark matter

simplest assumption: spherical distribution of dark matter M(R)

$$\frac{v^2}{R} = \frac{GM(R)}{R^2}$$

$$M(R) = 4\pi \int_0^R \mathrm{d}R R^2 \varrho(R) = \frac{v^2}{G} R$$

d/dR -> $\varrho(R) = \frac{v^2}{4\pi G} R^{-2}$

$$M(R) = 10^{12} \left(\frac{R}{100 \text{ kpc}} \right) M_\odot$$

mass of the MW

Astronomical quantities

Earth radius ~ 6400 km mass ~ 6×10^{27} g density ~ 5 g/cm^3

1.5×10^{13} cm

Sun radius ~ 7×10^{10} cm mass ~ 2×10^{33} g density ~ 1.4 g/cm^3

1.3 pc

Alpha Centauri

8 kpc

Galactic Centre

MW radius ~ 30 kpc

mass ~ 10^{12} M_{sun} **DM** ρ ~ 6×10^{-25} g/cm^3 (@ the sun)

mass ~ 10^{11} M_{sun} **stars** ρ ~ 1 star/pc^3 (@ the sun)

mass ~ 10^{10} M_{sun} **gas** ρ ~ 1/cm^3

~1 Mpc

Andromeda galaxy