STELLAR DISTANCES AND MOTIONS

Lezione IV- Fisica delle Galassie
Cap. 25 'The Milky Way galaxy' and Cap. 24 'The Nature of galaxies'
Carrol & Ostlie

For the spiral arms and corotation
http://cosmo.nyu.edu/~jb2777/resonance.html

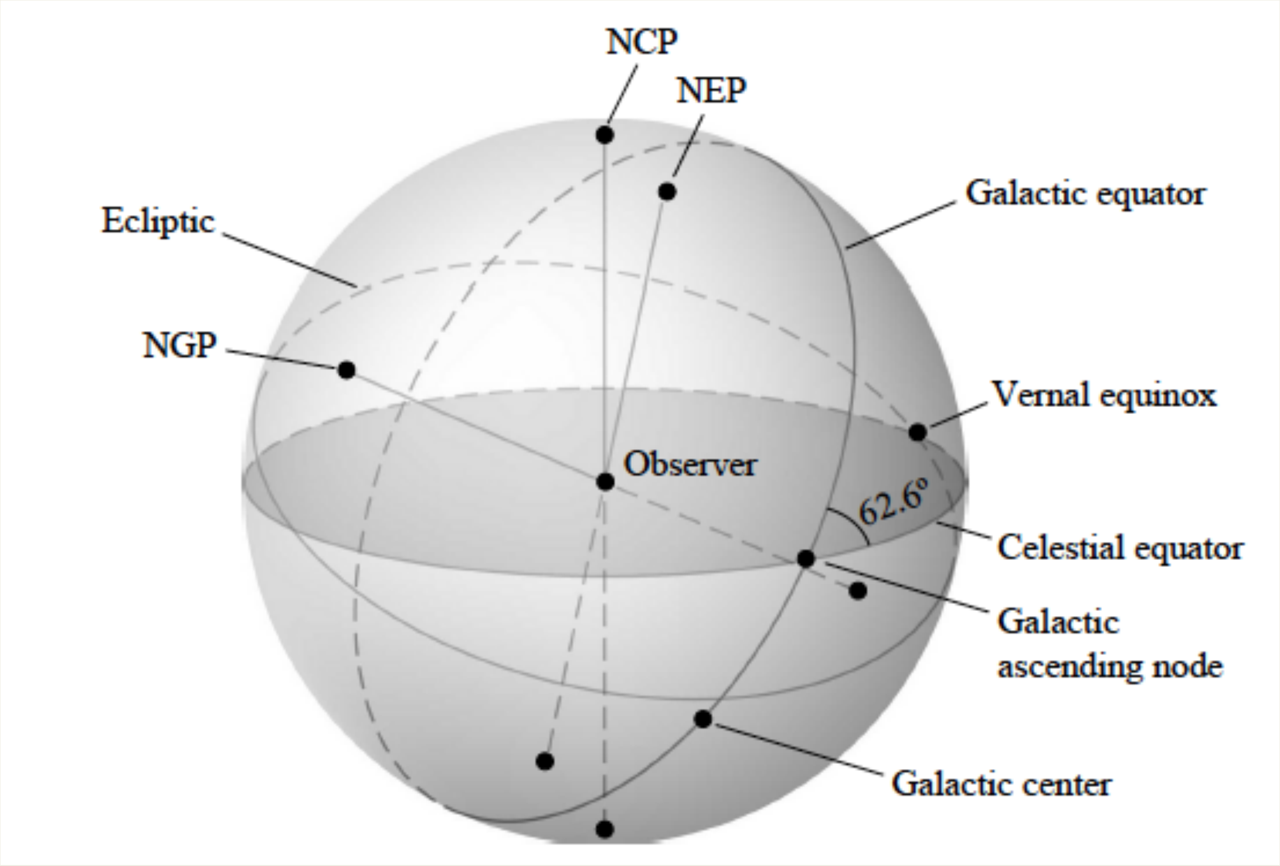
Laura Magrini

Aim of this lecture

- Define the Galactic coordinates and the cylindrical coordinate systems
- Study the motions inside the MW
- Define the rotation curve and its implications
  - Spiral pattern
  - Resonant radii
  - Implication for stellar migration
- Define some methods to measure distances:
  - Trigonometric Parallax
  - Main sequence fitting
  - Spectroscopic parallaxes
  - Period-luminosity relationship for Cepheids

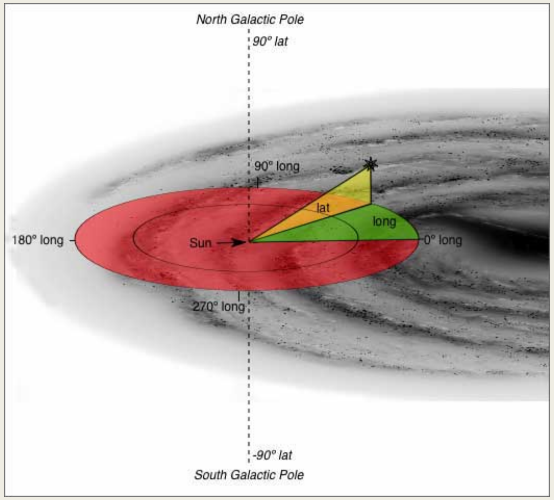
The Galactic coordinate system

North celestial pole (NCP), the north ecliptic pole (NEP), and north Galactic pole (NGP) are all on the front of the celestial sphere.



The intersection of the mid-plane of the Galaxy with the celestial sphere forms the Galactic equator (angle between celestial equator and the Galactic Plane → 62.6^0)

The Galactic coordinate system: to describe the position within the Galaxy



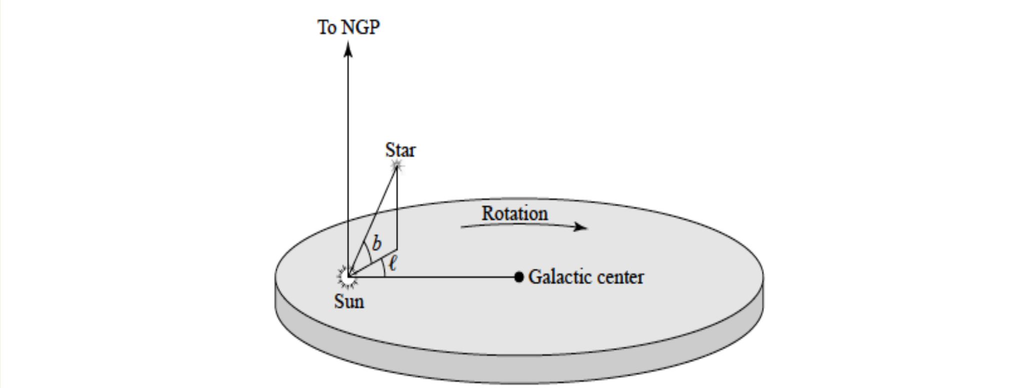


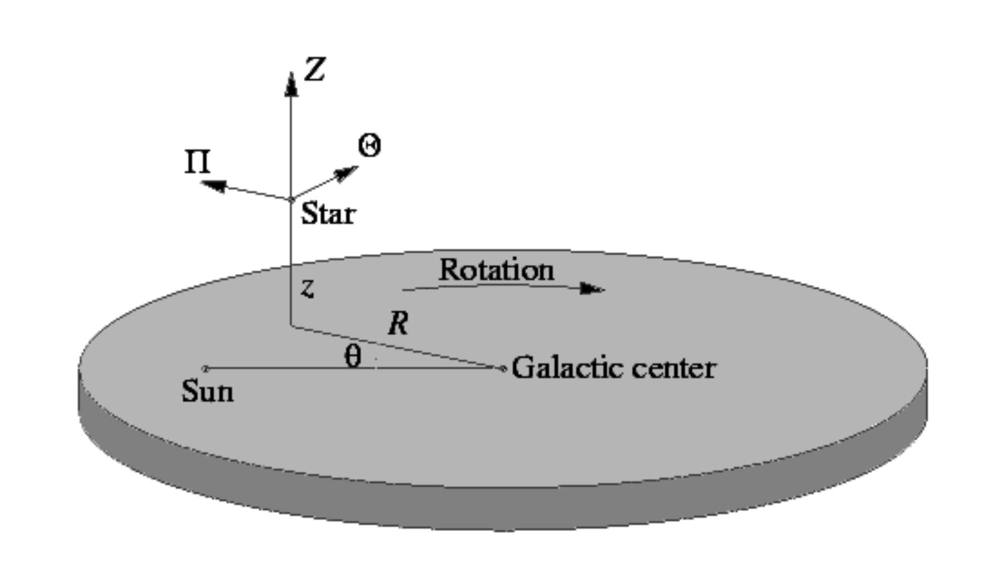
FIGURE 17 The definition of the Galactic coordinates ℓ and b. The direction of rotation of the Galaxy is also labeled.

- **Galactic latitude (b)** and **Galactic longitude (l)** are defined from the location of the Sun
- *b* is measured in degree along a great circle that passes through the north Galactic pole
- *l* is measured in degree, along the Galactic equator, counterclockwise, from the Galactic North Pole
- l=0° and b=0° corresponds ~ to the location of Sgr A, the Galactic Centre

→ Good to represent objects as seen from the Earth

The cylindrical coordinate system: to describe the motions in the Galaxy

- To complement the Galactic coordinate system, **a cylindrical coordinate system** is used. It places the **center of the Galaxy** at the **origin** for studying kinematics and dynamics



Why the cylindrical system for kinematics:

- the Sun is moving about the Galactic Centre
- A system centred on the Sun is a non-inertial reference frame

R increases outward

Θ increases in the direction of the Galactic rotation

Z increases toward the North

The cylindrical coordinate system

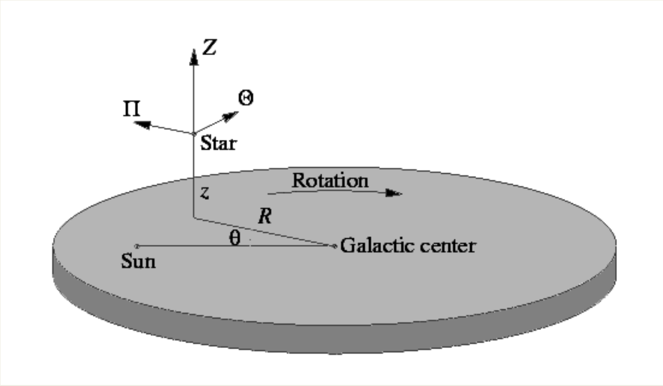
- The corresponding velocity components are labelled:

$$\Pi \equiv \frac{dR}{dt}, \qquad \Theta \equiv R\frac{d\theta}{dt}, \qquad Z \equiv \frac{dz}{dt}.$$

π radial velocity

Θ angular velocity

Z vertical velocity



The dynamical local standard rest

- We consider the Sun as the site of all observations of the Galaxy
- Definition of the Local standard rest (LSR):

A point that is instantaneously centered on the Sun and moving in a perfectly circular orbit along the solar circle about the Galactic center.

$$\Pi_{LSR} \equiv 0, \qquad \Theta_{LSR} \equiv \Theta_0, \qquad Z_{LSR} \equiv 0,$$

- The Sun does not follow a simple planer orbit: it moves slowly inward and farther North
- Its orbital period of the Sun is 230 Myr → very long compared to observation time-scales → the drift of the Sun with respect to the definition of the dynamical local standard rest is negligible

The peculiar velocity

- The velocity of a star relative to the LSR is known as the peculiar velocity

$$\mathbf{V} = (V_R, V_\theta, V_z) \equiv (u, v, w)$$

$$u = \Pi - \Pi_{LSR} = \Pi,$$
$$v = \Theta - \Theta_{LSR} = \Theta - \Theta_0,$$
$$w = Z - Z_{LSR} = Z.$$

→ *U* radial

→ *V* rotation

→ *W* vertical

The Sun has its own peculiar velocity (the LRS is defined with perfectly circular orbit along the Solar circle):

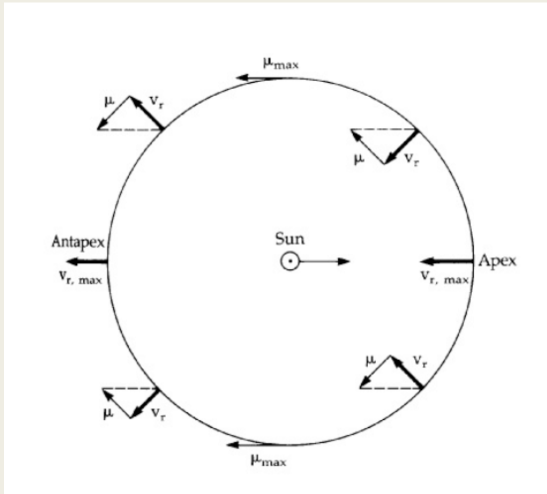
$$u_\odot = -10.0 \pm 0.4 \text{ km s}^{-1},$$
$$v_\odot = 5.2 \pm 0.6 \text{ km s}^{-1},$$
$$w_\odot = 7.2 \pm 0.4 \text{ km s}^{-1},$$

→ Towards the Galactic centre

→ More rapidly than the LRS, in the direction of Galactic rotation

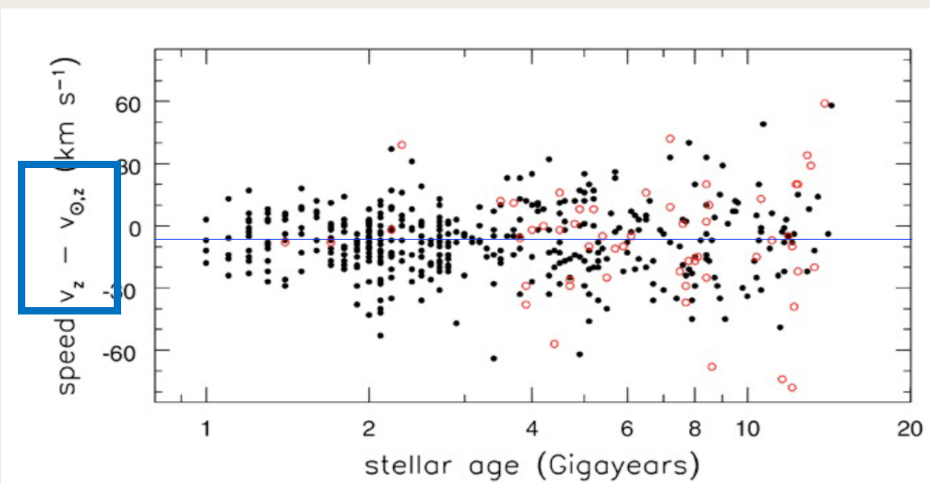
→ Toward the North, out of the Plane

The peculiar velocity of the Sun



Measuring average proper motions and radial velocities of stars distributed around the Sun allows us to derive the peculiar velocity of the Sun

For the vertical component:



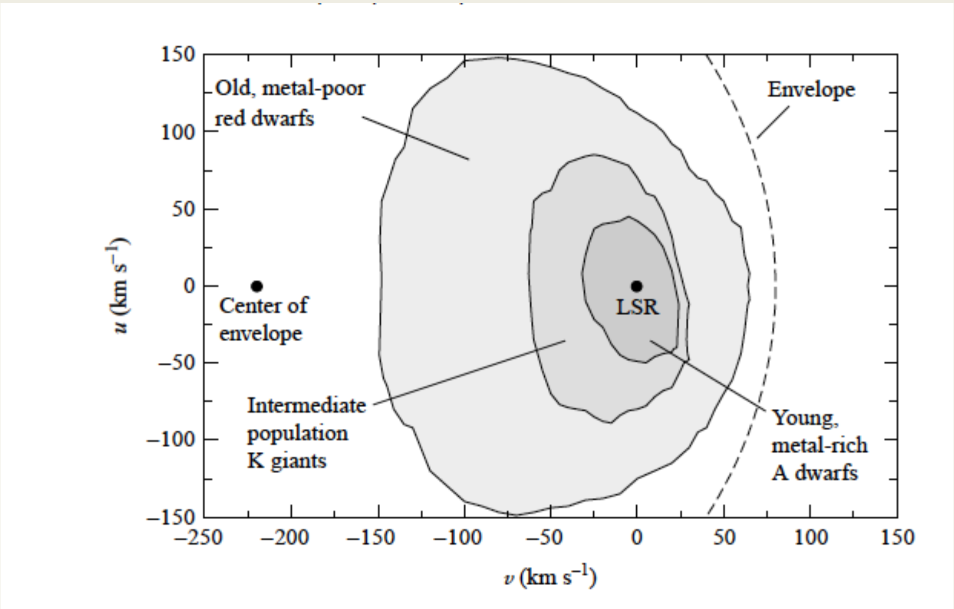
$$u_\odot = -10.0 \pm 0.4 \text{ km s}^{-1},$$

$$v_\odot = 5.2 \pm 0.6 \text{ km s}^{-1},$$

$$w_\odot = 7.2 \pm 0.4 \text{ km s}^{-1},$$

The peculiar velocities in the LSR

- Now that the Solar motion is known, the velocities of stars relative to the Sun can be transformed into **peculiar motions relative to the LSR**.
- Plotting one component of peculiar motion against another for a specific sample of stars in the Solar neighborhood → we obtain **the velocity ellipsoids**



→ *U* radial

→ *V* rotation

Velocity–metallicity relation:

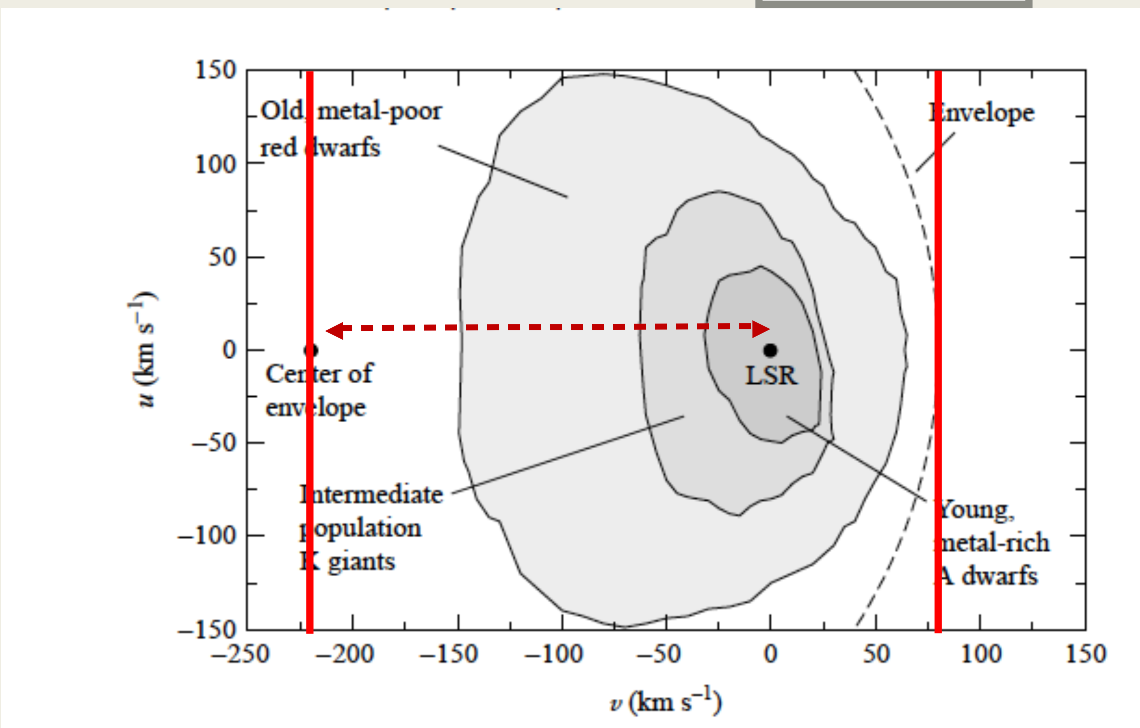
- The oldest stars have larger peculiar velocities (in u and v)
- Young stars have orbits close to the LSR (they belong to the thin disc)

The peculiar velocities in the LSR

- **Asymmetric drift**

→ *U* radial

→ *V* rotation



→ Velocities of halo stars allow to estimate the zero point of the LSR → Θ_0=220 km s^{-1}

Velocity–metallicity relation:

- Few stars with v > +65 km/s
- There are stars with very negative velocities v ~ -200 km/s (metal poor RR Lyrae)

→ We can draw an envelope with radius ~ -300 km/s, centered at -220 km/s

- **Halo stars without rotational velocity** should exhibit peculiar v velocities that simply **reflect the motion of the LSR** (i.e., v ≃ $-\Theta_0$)

The mass within the Solar circle: using the 3rd Kepler low and the Solar period

→ Period corresponding to R_0=8 kpc and Θ_0=220 km/s

considering :

- pc=3.08 x 10^{13} km
- yr=3.15 x 10^{7} s
- G=6.67 x 10^{-11} $m^3/kg\ s^2$
- $M_\odot$=2 x 10^{33} kg

- $P=2\pi R_\odot/\Theta_\odot$=230 Myr

→ Mass within the Solar circle, from the third Kepler law

$$M=4\pi^2 R_\odot^3 / G P_\odot^2 = 8.8 \times 10^{10} M_\odot$$

- It agrees with other estimates of luminous matter, but it is less than the total mass (the dark matter halo is not included)

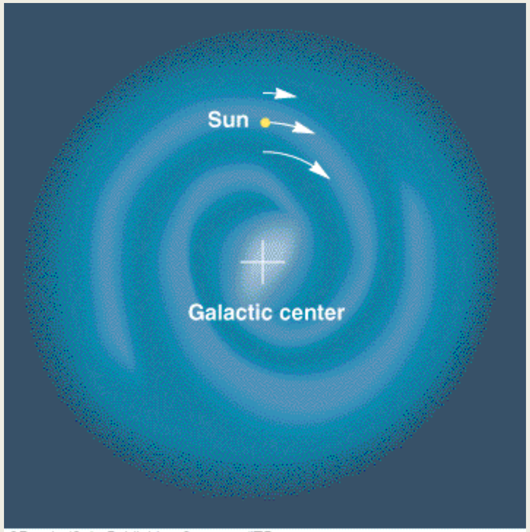
Differential Galactic Rotation & Oort's Constants

For external disc galaxies, the rotation velocity can be measured by observing the Doppler-shift of spectral lines at different distances from the centres of galaxies

→ For the Milky Way, our position within the Galactic midplane prevent to measure the rotation curve in an easy way

→ To confirm the rotation of our Galaxy prior to the discovery of the HI line, in 1927 **Oort derived a way to measure the Galactic rotation from just a small fraction of stars in the local neighborhood**

→ Proving that **the Galaxy is rotating in a differential way**



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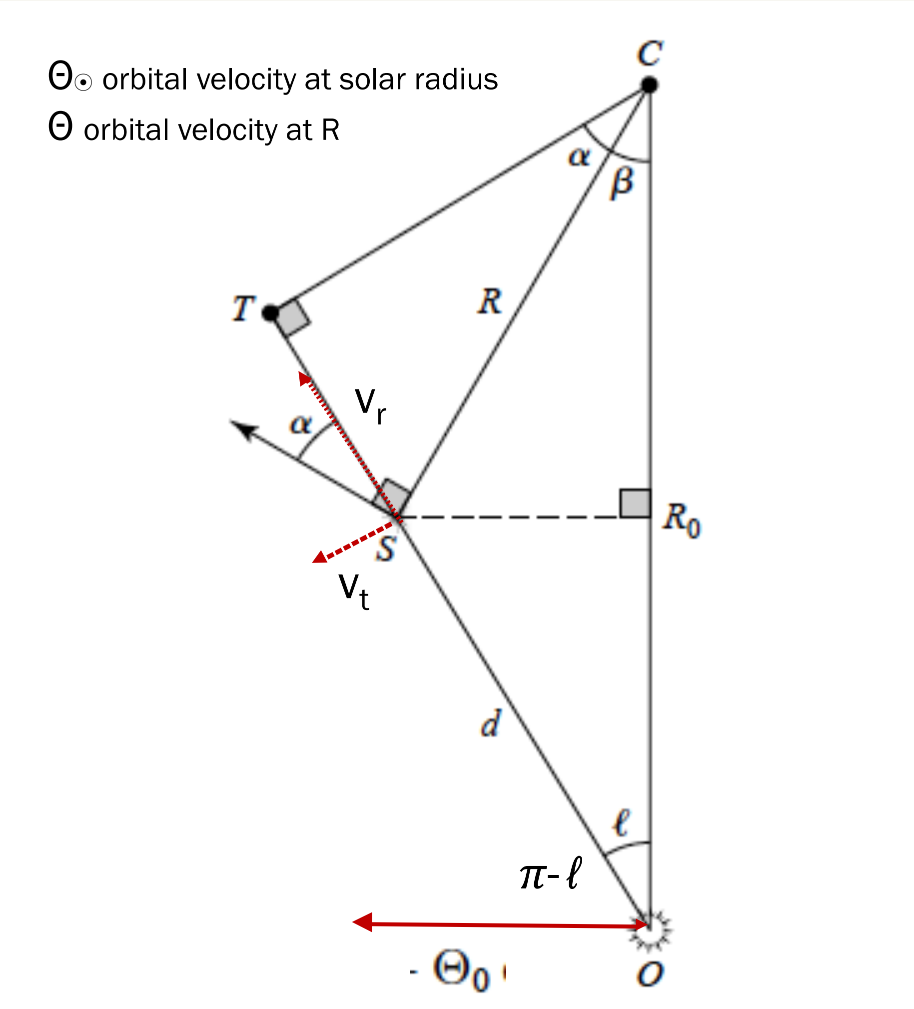
Differential Galactic Rotation & Oort's Constants

To determine the differential rotation curve of the Galactic disc, we follow the formalism of Oort



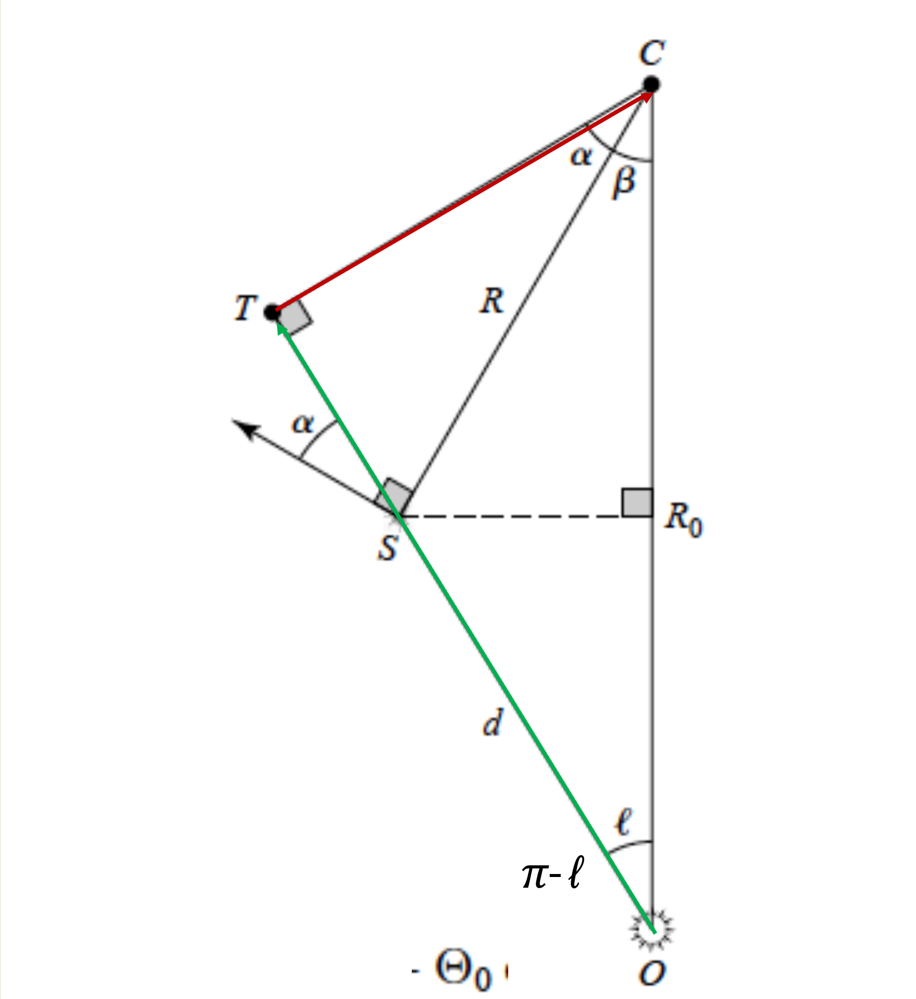
- C position of the Galactic Centre
- O position of the Sun
- S position of a star, with longitude ℓ and distance d from the Sun
- The arrow in S indicates the relative velocity between the Sun and the star

The **observed** radial and transversal velocities of the star S are:

$$v_r = \Theta \cos \alpha - \Theta_0 \sin \ell,$$

$$v_t = \Theta \sin \alpha - \Theta_0 \cos \ell,$$

Angular velocity curve



- Valid for circular orbits
- Measurements of *Vr*, *Vt*, and *d* allow to estimate Ω

Definition of angular-velocity curve:

$$\Omega(R) \equiv \frac{\Theta(R)}{R},$$

The radial and transversal velocities of the star S are:

$$v_r = \Omega R \cos\alpha - \Omega_0 R_0 \sin\ell,$$

$$v_t = \Omega R \sin\alpha - \Omega_0 R_0 \cos\ell.$$

Considering that:

$$R\cos\alpha = R_0 \sin\ell,$$

$$R\sin\alpha = R_0\cos\ell - d.$$

We can express as:

$$v_r = (\Omega - \Omega_0)\, R_0 \sin\ell,$$

$$v_t = (\Omega - \Omega_0)\, R_0 \cos\ell - \Omega d.$$

Solar neighborhood approximation

In the make the assumption that Ω(R) is a smoothly varying function of R, we can expand it with the Taylor formula (for small distances):

$$\Omega(R) = \Omega_0(R_0) + \left.\frac{d\Omega}{dR}\right|_{R_0}(R - R_0) + \cdots .$$

$$\Omega - \Omega_0 \simeq \left.\frac{d\Omega}{dR}\right|_{R_0}(R - R_0),$$

$$\Omega = \Theta/R,$$

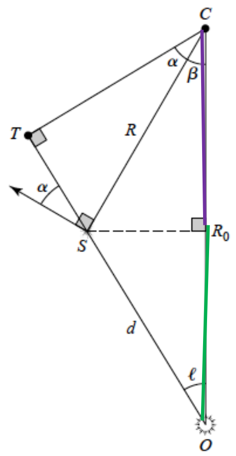
$$v_r \simeq \left[\left.\frac{d\Theta}{dR}\right|_{R_0} - \frac{\Theta_0}{R_0}\right](R - R_0)\sin\ell,$$

$$v_t \simeq \left[\left.\frac{d\Theta}{dR}\right|_{R_0} - \frac{\Theta_0}{R_0}\right](R - R_0)\cos\ell - \Omega_0 d.$$

The Oort constants

For d << R_0 (Solar Neighborhood)→ cos β~1

$$R_0 = d\cos\ell + R\cos\beta \simeq d\cos\ell + R,$$



And defining the Oort's constants as (they are computed for the Solar distance, so they are constants):

$$A \equiv -\frac{1}{2}\left[\left.\frac{d\Theta}{dR}\right|_{R_0} - \frac{\Theta_0}{R_0}\right],$$

$$B \equiv -\frac{1}{2}\left[\left.\frac{d\Theta}{dR}\right|_{R_0} + \frac{\Theta_0}{R_0}\right],$$

The Oort constants

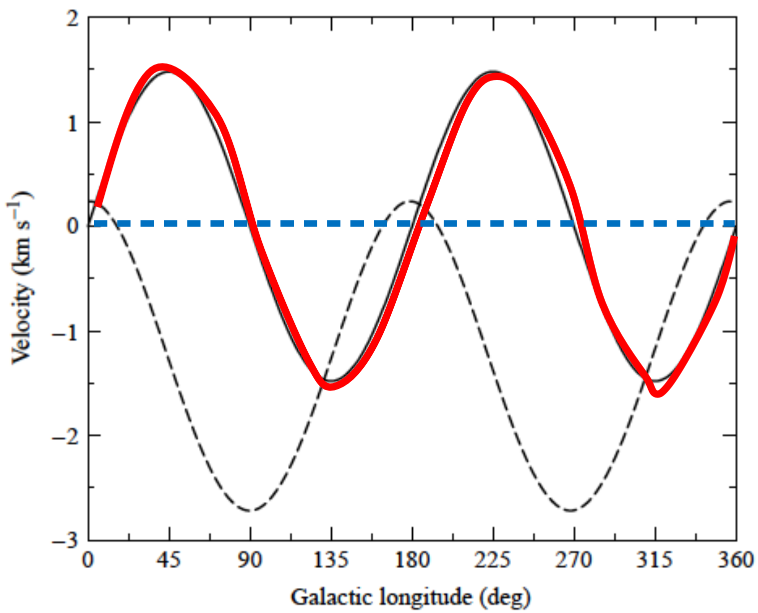
For d << R_0 (Solar Neighborhood)

The differential rotation is revealed by the dependence of radial and transverse velocities from longitude

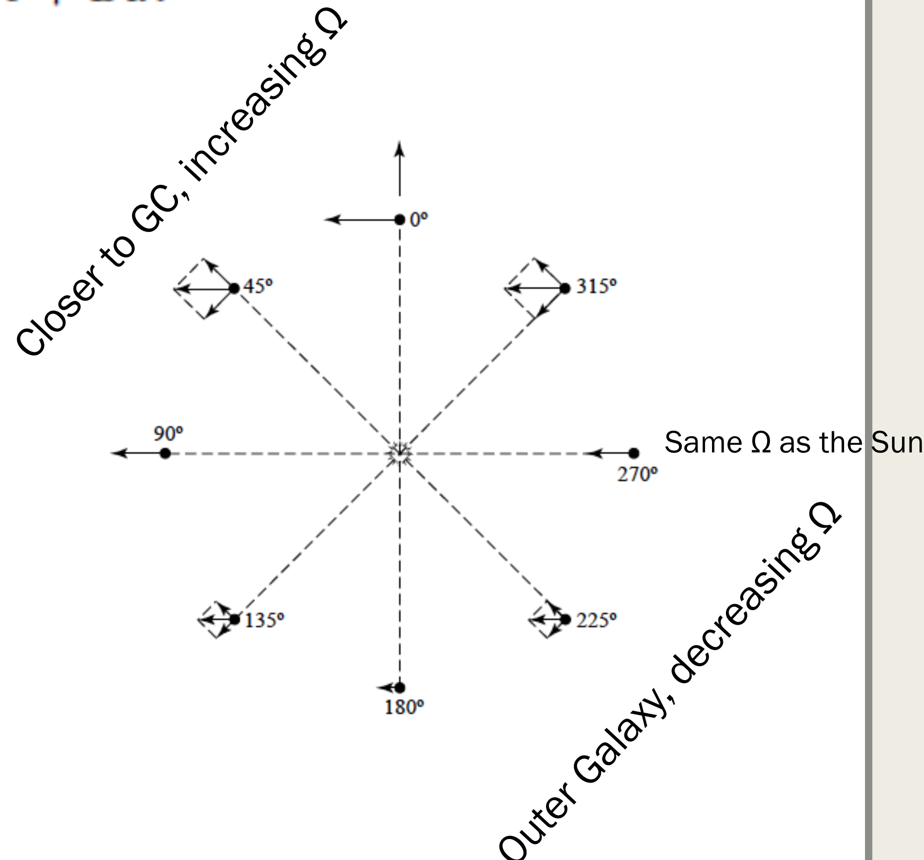
$$v_r \simeq Ad \sin 2\ell,$$

$$v_t \simeq Ad \cos 2\ell + Bd.$$

(a)



(b)



The Oort constants

For d << R_0 (Solar Neighborhood)

For the radial velocities:

- For l=270° and l=90° stars are moving at the same Ω as the Sun → v_r=0 km s $^{-1}$
- For l=0° and l=180° stars have no radial velocity components → v_r=0 km s $^{-1}$
- For intermediate angles l=45° assuming an increasing Ω(R), stars are closer to the GC and thus they are outrunning the Sun
- For l=225° they are overtaking the Sun

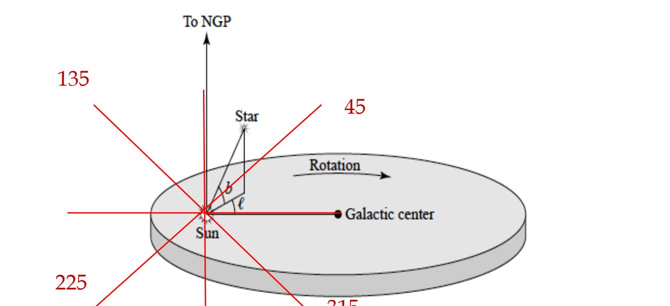
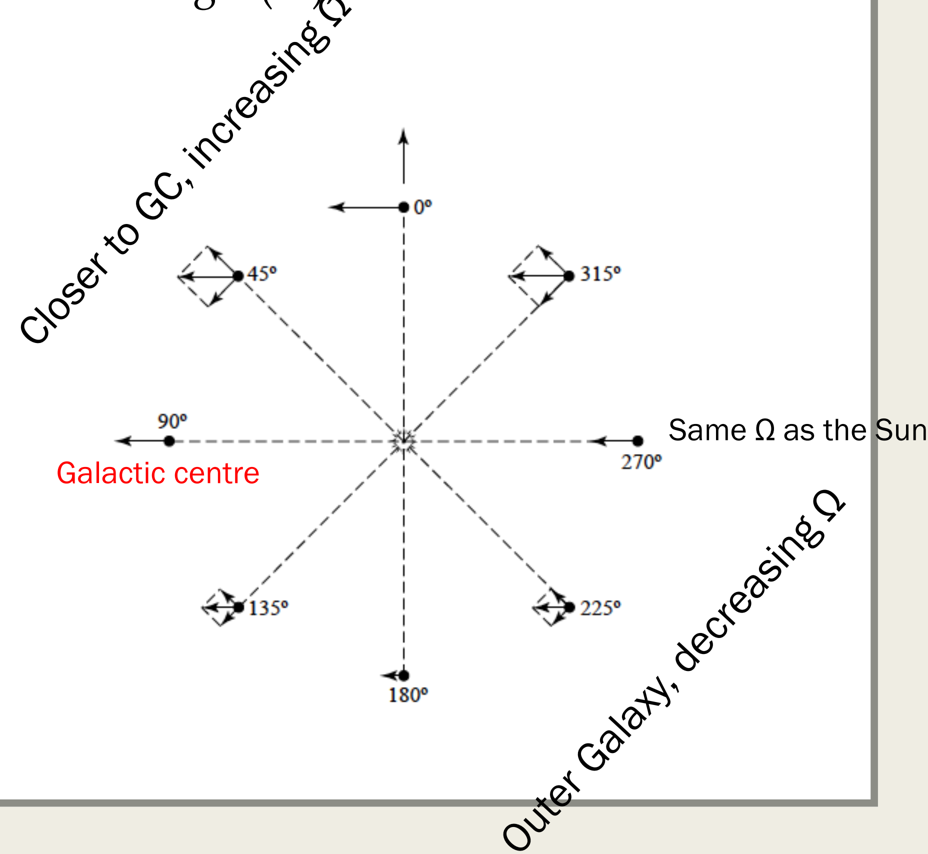


FIGURE 17 The definition of the Galactic coordinates ℓ and b. The direction of rotation of the Galaxy is also labeled.

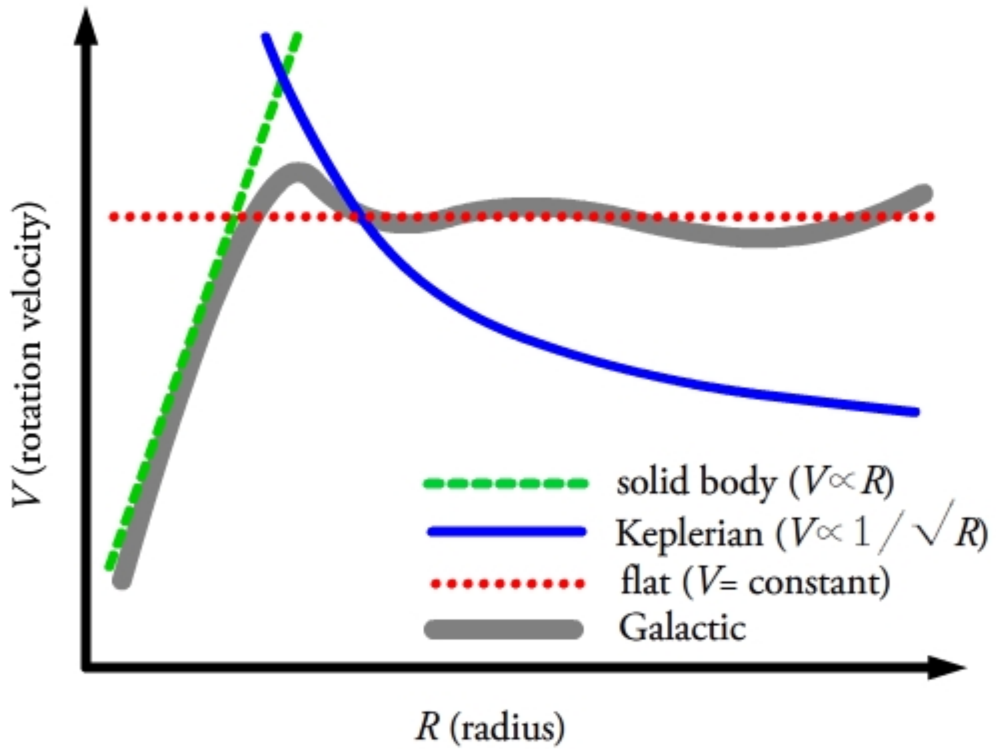


The Oort constants

Meaning of the Oort's constants (A=14 km s^{-1} kpc^{-1} and B=-12 km s^{-1} kpc^{-1}):

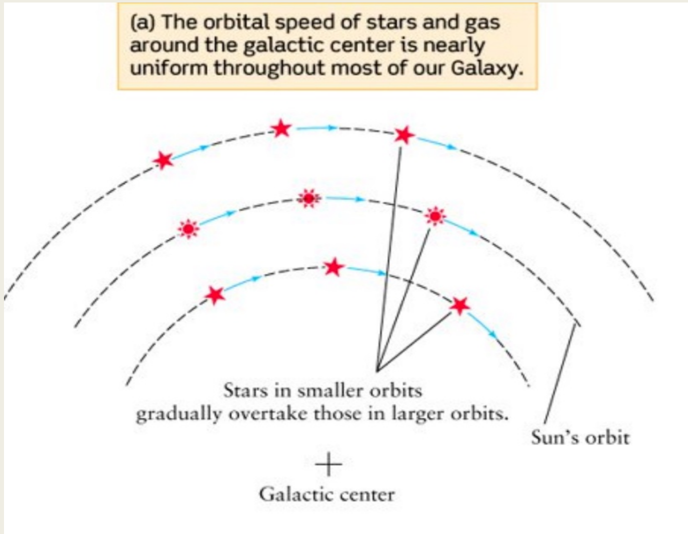
We can compare the measured values of A and B, with those derived for three simple models of rotation curves: solid body, Keplerian, and flat

- In the solid body rotation A=0 and B=-Ω
- In the Keplerian rotation A=20 km s^{-1} kpc^{-1} and B=-7 km s^{-1} kpc^{-1}
- In the flat rotation curve A=13.6 km s^{-1} kpc^{-1} and B=-13.6 km s^{-1} kpc^{-1}

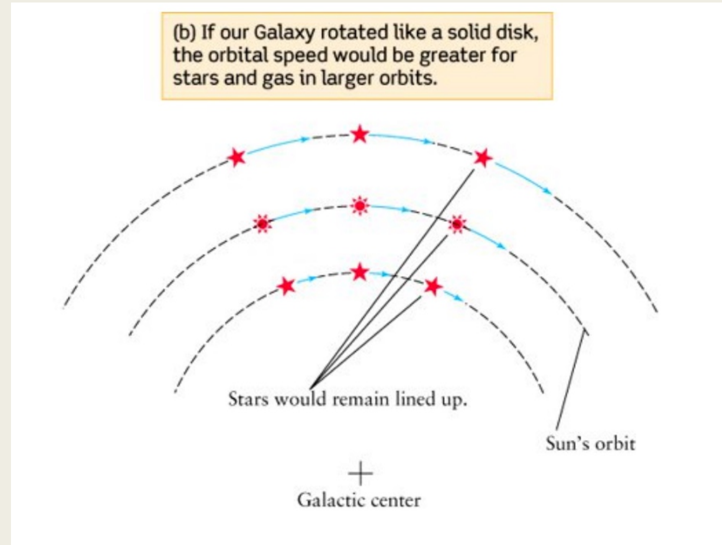


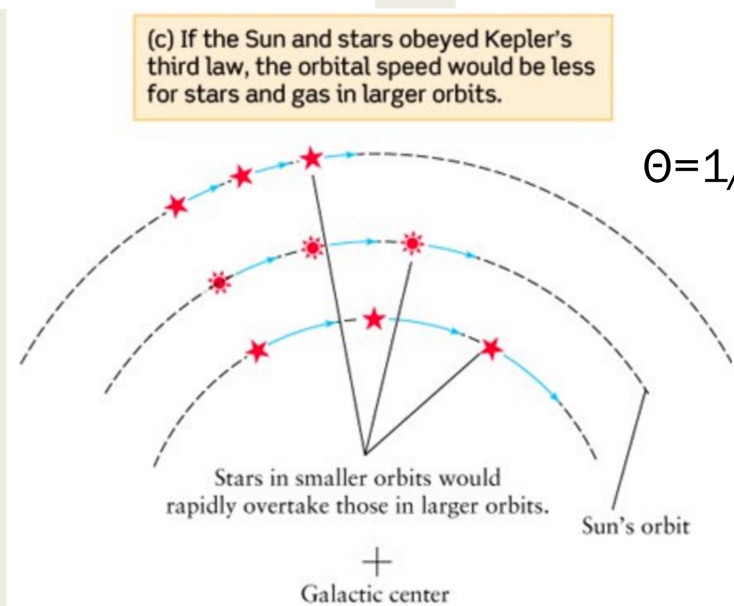
The Oort constants and different kinds of rotation

$\Theta=\text{cost} \rightarrow \Omega=1/R$



$\Theta=1/R \rightarrow \Omega=\text{cost}$





$\Theta=1/\sqrt{R} \rightarrow \Omega=1/\sqrt{R^3}$

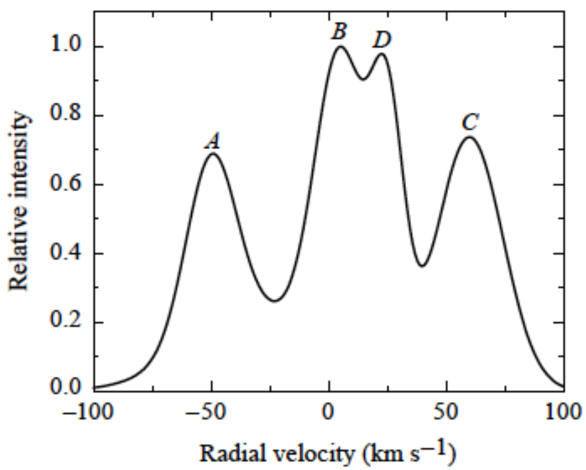
Galactic rotation and the HI 21-cm line

The 21-cm emission from H I is able to **penetrate virtually** the entire Galaxy, making it an indispensable tool in probing the structure of the Milky Way.

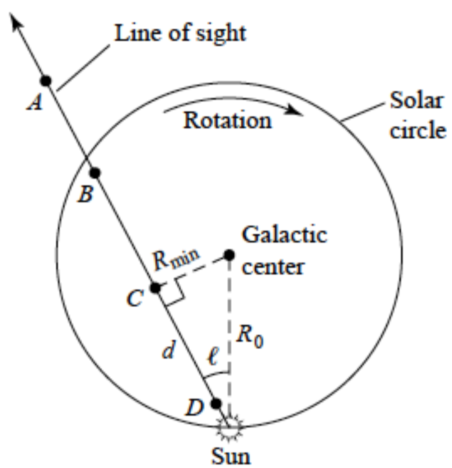
$$v_r = (\Omega - \Omega_0)\, R_0 \sin \ell,$$

$$v_t = (\Omega - \Omega_0)\, R_0 \cos \ell - \Omega d.$$

Considering the relation without the Taylor approximation, we can investigate the Galactic rotation curve, by measuring v_r as a function of ℓ, together with the distance of the emitting region from the Sun.

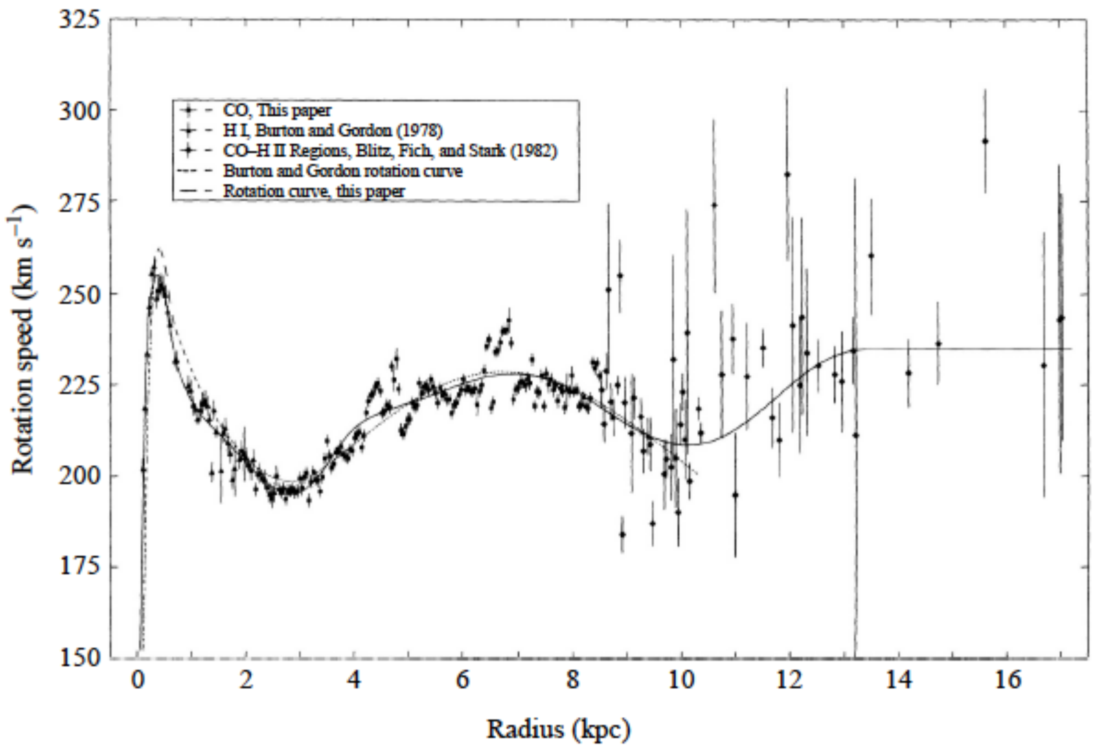


(a)



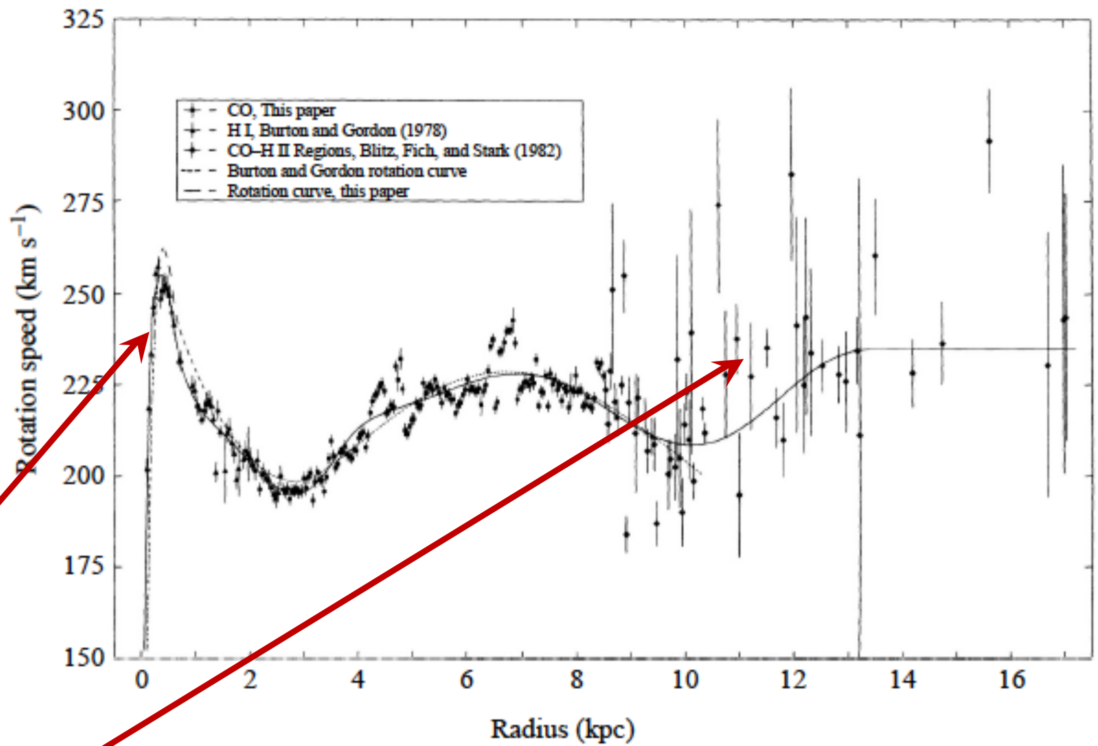
(b)

Galactic rotation curve



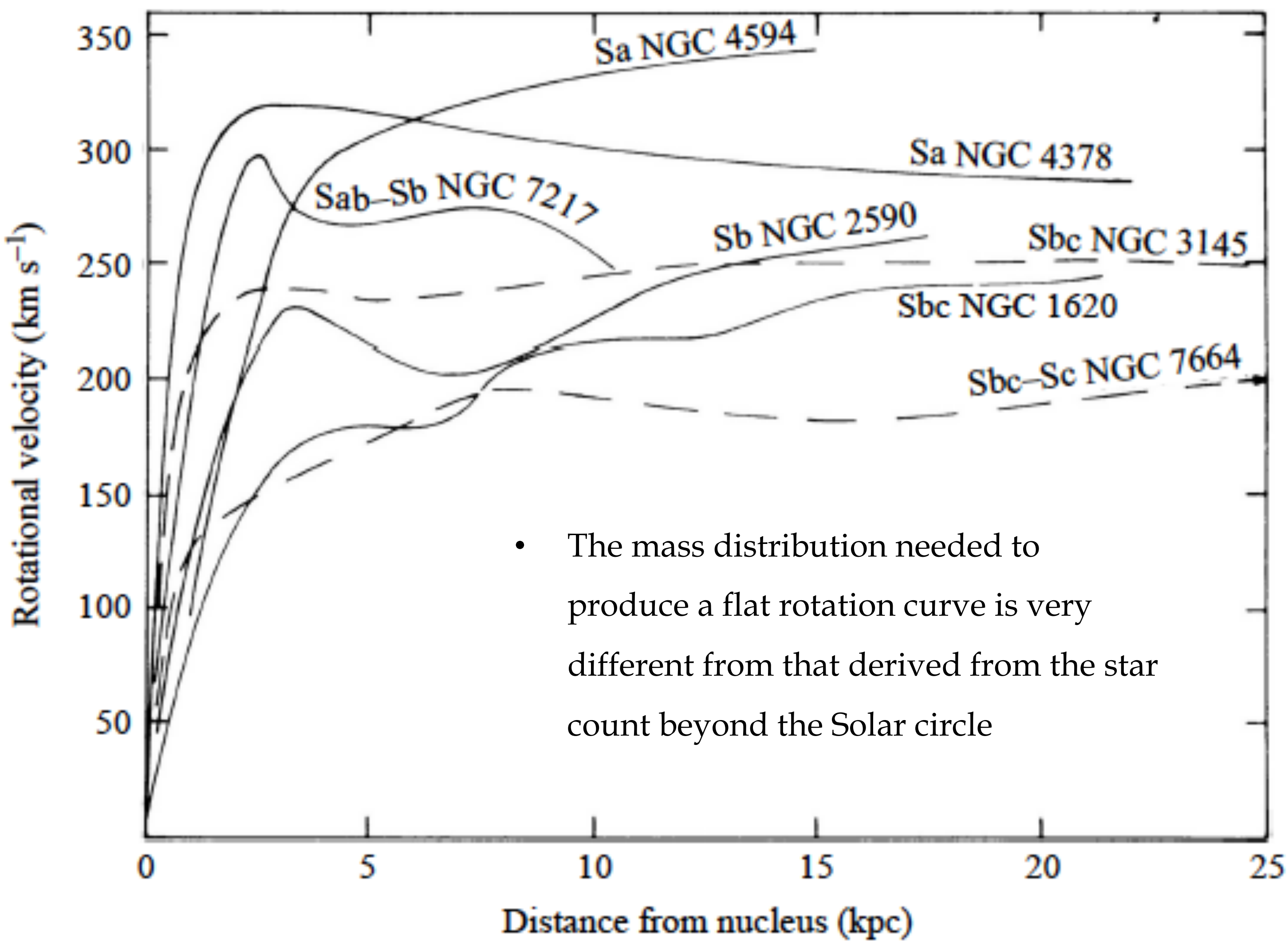
- The rotation curve of the Galaxy **does not decrease significantly with distance**
- According to Newtonian mechanics, if most of the mass is located within the solar circle, the rotation curve should decrease as $\propto R^{-1/2}$ (Keplerian motion)

Galactic rotation curve



- Rigid-body rotation in the inner disc → mass spherically distributed with constant density
- Flat rotation curves suggest that the bulk of the mass in the outer portions of the Galaxy are spherically distributed with a density law that is proportional to r $^{-2}$

Rotation curves in other galaxies



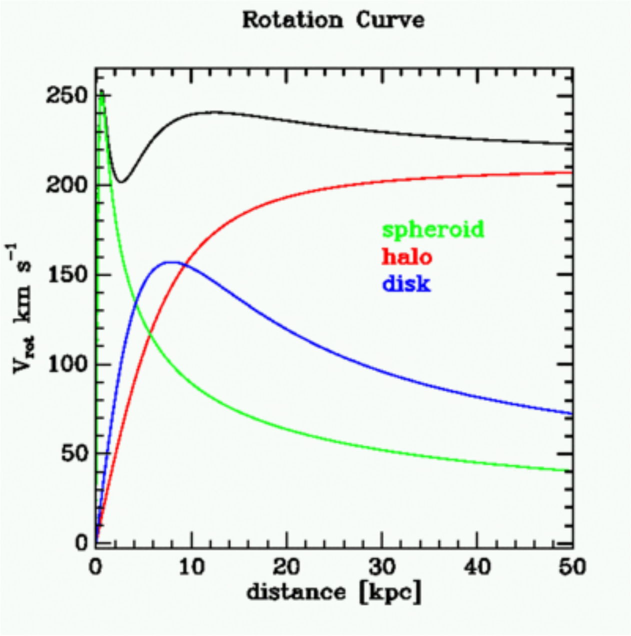
- The mass distribution needed to produce a flat rotation curve is very different from that derived from the star count beyond the Solar circle

Dark matter density profile

$$\rho(r) = \frac{\rho_0}{1 + (r/a)^2},$$

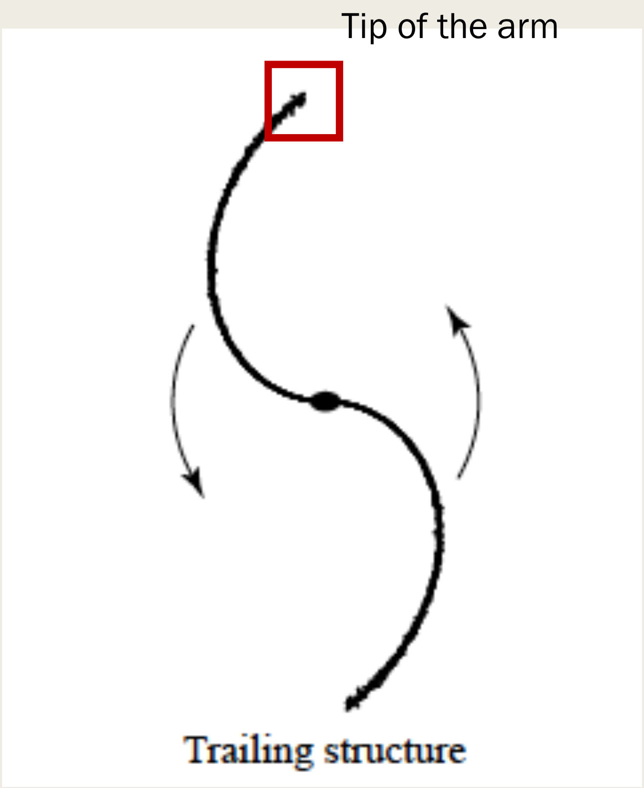
where ρ_0 and a are chosen as parametric fits to the overall rotation curve. Note that for $r \gg a$, the **r^{-2} dependence** is obtained, and **$\rho \sim$ constant** when $r \ll a$.

A similar profile is often used for modeling other galaxies as well, with different choices for ρ_0 and a .



The link between rotation and spiral arms

The spiral arms as quasi-stationary density waves

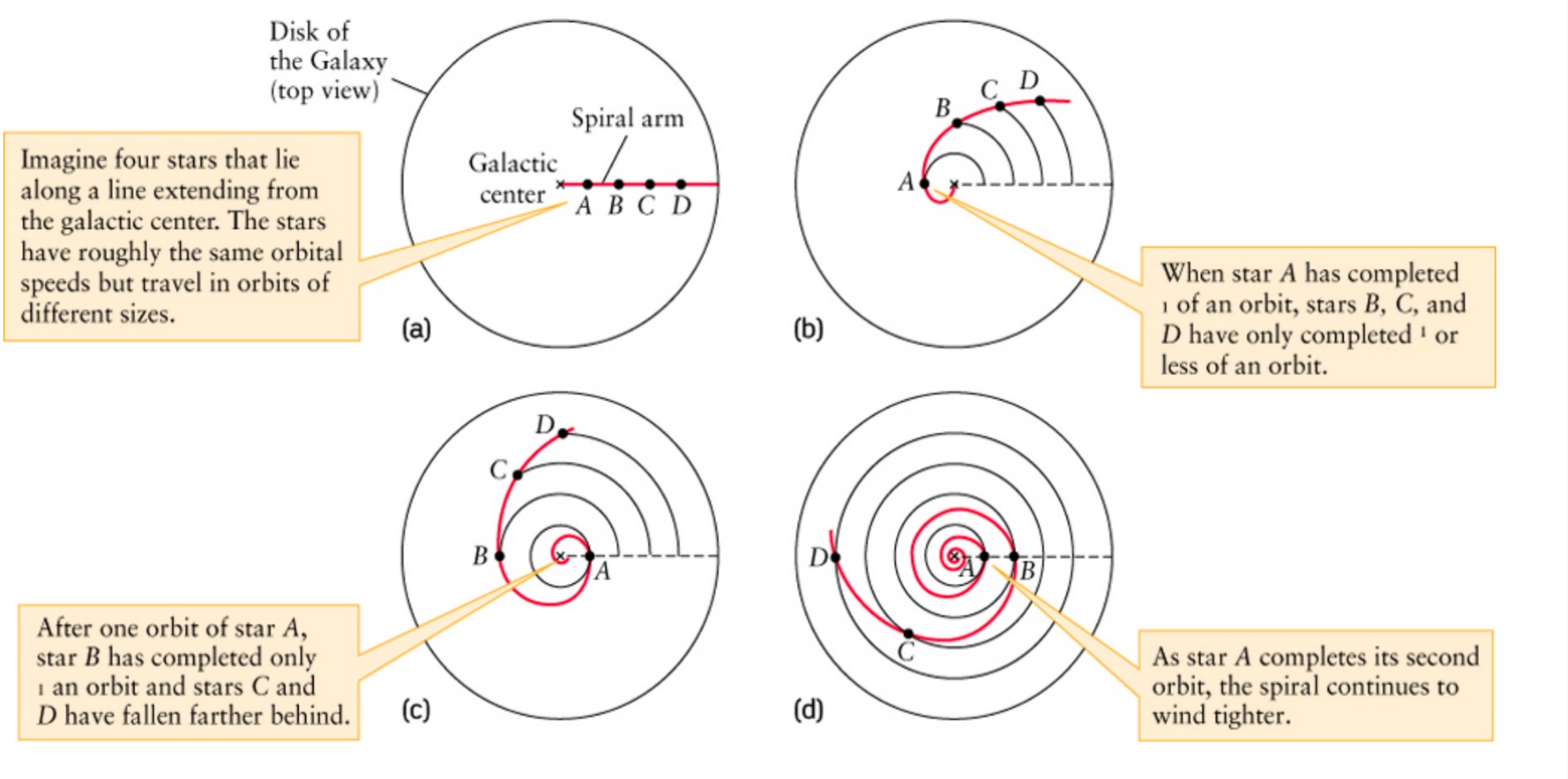


The general appearance of spiral galaxies suggests that in most cases their arms are trailing, meaning that the tips of the arms point in the opposite direction from the direction of rotation

Rotation curve and spiral arms

The effect of differential rotation (v (R)= constant→ Ω (R) =R^{-1}) will lead to a natural generation of trailing spiral arms

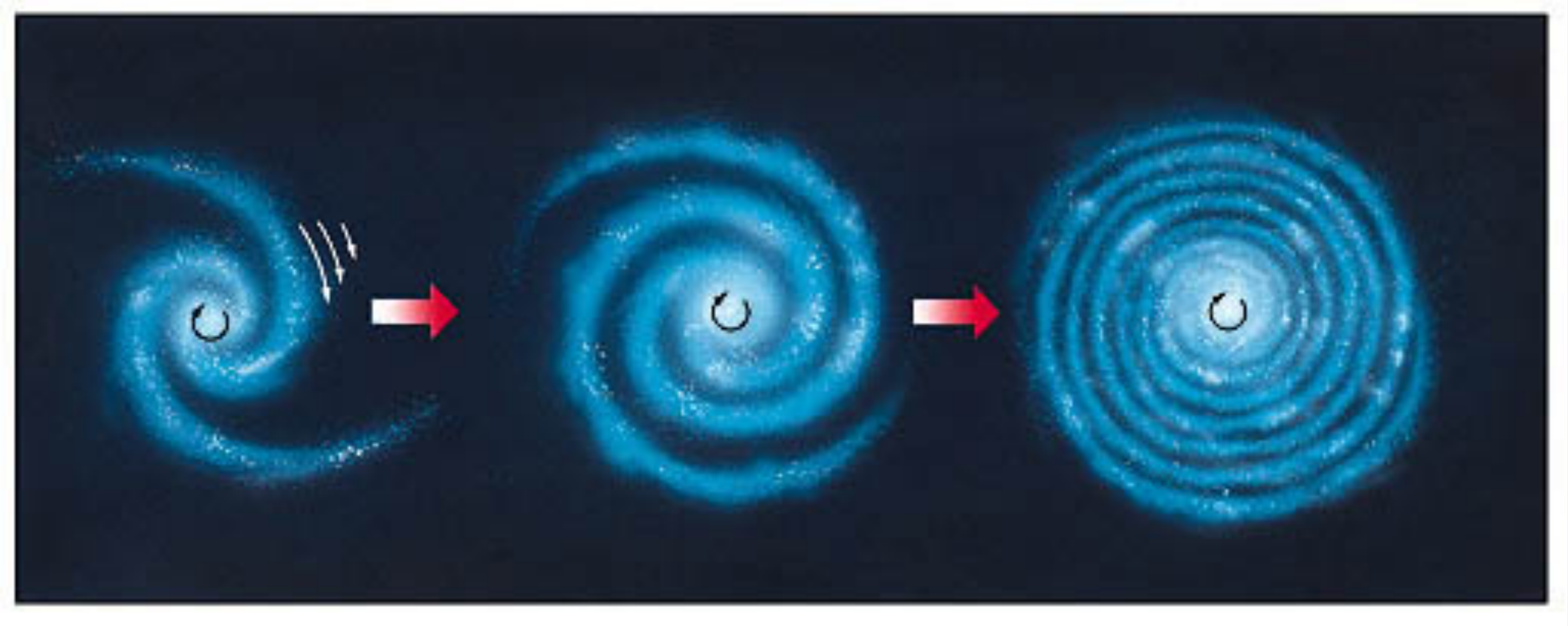
→ After only a few orbits, the spiral arms will become too tightly wound to be observed



Winding problems → rotation cannot explain alone the spiral arms

→ **spiral arms cannot be *material* (arms composed of a fixed set of stars)**

Winding problem



Since we are not observing galaxies like that, the origin of the spiral arms should be different

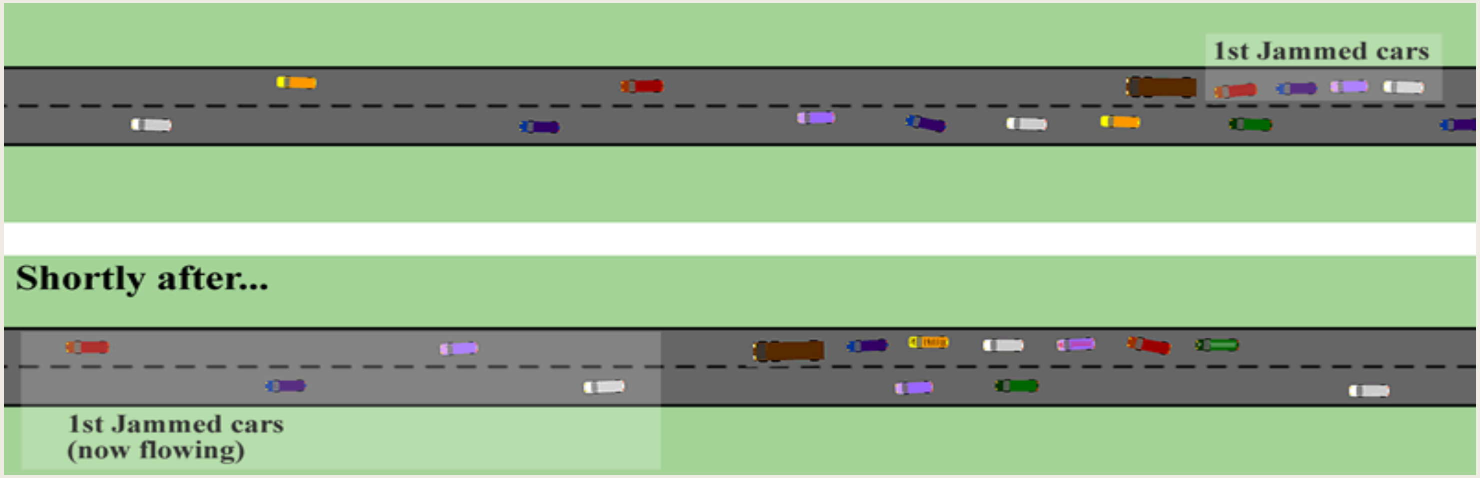
The spiral arms as quasi-stationary density waves

Following the theory of **Shu and Lin, spiral arms are regions of the disc with greater density** (produced by self-gravity of the disc → due to asymmetry in the halo, perturbation by neighbor galaxies. …..).

→ Stars, but also gas and dust, move across the spiral arms

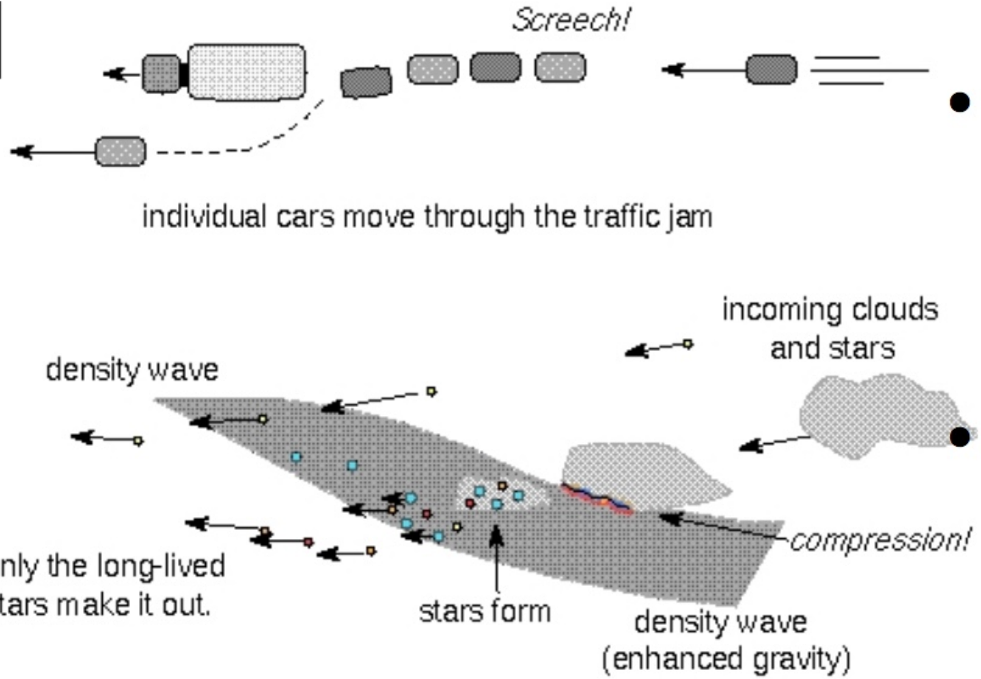
→ When gas and dust reach the spiral arm, they are compressed and star formation is activated

A visual way to understand spiral arms → **spiral arms can be thought as peak a the traffic jam, due to an accident or to a slow truck**



The spiral arms as quasi-stationary density waves

A Similar Schematic:



Spiral density waves are like traffic jams. Clouds and stars speed up to the density wave (are accelerated toward it) and are tugged backward as they leave, so they accumulate in the density wave (like cars bunching up behind a slower-moving vehicle). Clouds compress and form stars in the density wave, but only the fainter stars live long enough to make it out of the wave.

Credit: Ivezic

The spiral arms as quasi-stationary density waves

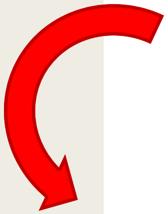
Ω_{gp} is the global pattern speed od the spiral system: in the reference frame rotating at Ω_{gp} the spiral arms are quasi-stationary

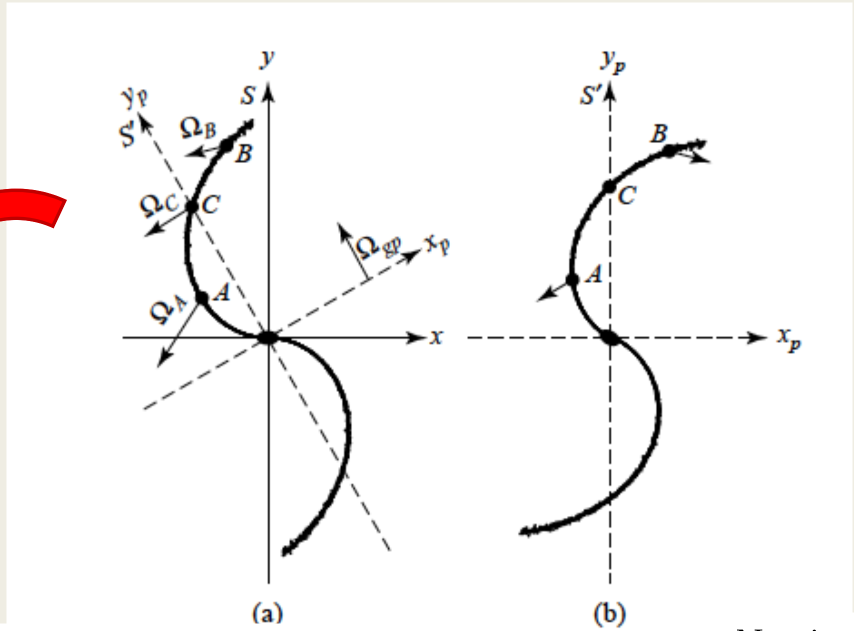
What about stars?

- Stars near the **center of the Galaxy** can have orbital periods that are shorter than the density wave pattern ($\Omega > \Omega_{gp}$) → they will overtake a spiral arm, move through it, and continue on until they encounter the next arm.

- Stars sufficiently **far from the center** will be moving more slowly → the density wave pattern and will be overtaken by it ($\Omega < \Omega_{gp}$)

- At a specific distance from the center, called the **corotation radius** (Rc), the stars and density waves will move together.





inertial reference frame

Non-inertial reference frame, rotating at Ω_{gp}

How spiral arms are maintained?

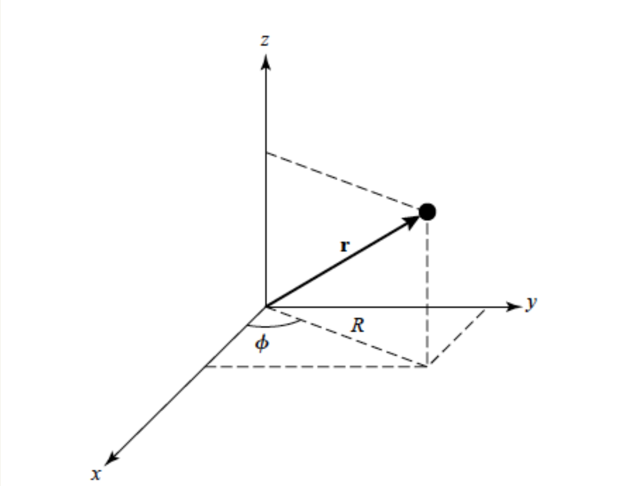
- Spiral arms are not composed by fixed group of stars
- Stars are allowed to pass through a quasi-static density wave
- **How the wave of enhanced density has been established and maintained?**

Small-Amplitude Orbital Perturbations:

→ Motion in an axially symmetric gravitational field that is also symmetric about the Galactic midplane

→ harmonic oscillation around the equilibrium position

Position of a star above the Galactic Plane



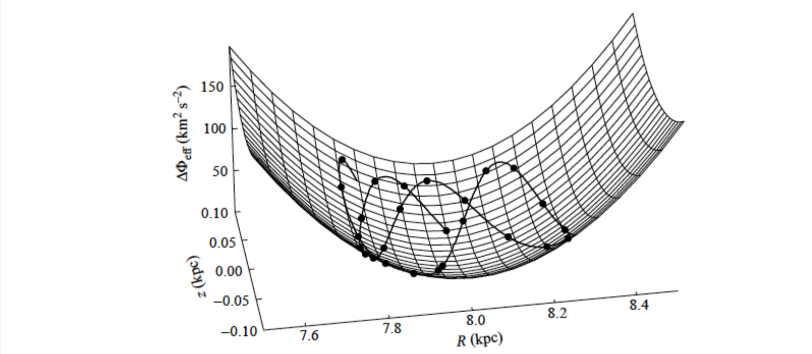


FIGURE 24 The effective gravitational potential well for a star that is executing a general first-order simple harmonic oscillation about a perfectly circular orbit near the midplane of a disk galaxy. In this case, the star is assumed to be oscillating about the equilibrium position ($R_m = 8$ kpc, $z = 0$). $\Delta\Phi_{\rm eff} = \Phi_{\rm eff} - \Phi_{{\rm eff},m}$.

Epicyclic motions

For the Sun,

The period of the epicycle is 170 Myr

The rotational period is 230 Myr

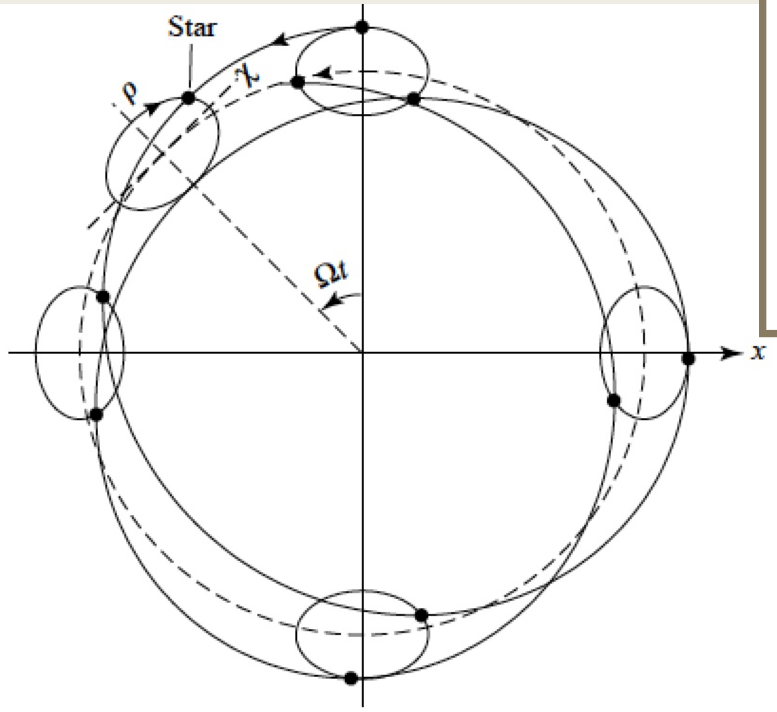


FIGURE 25 In an inertial reference frame a star's orbital motion in the galactic midplane (solid line) forms a nonclosing rosette pattern. In the first-order approximation, the motion can be imagined as being the combination of a retrograde orbit about an epicycle and the prograde orbit of the center of the epicycle about a perfect circle (dashed line). The dimensions of the epicycle have been exaggerated by a factor of five to illustrate the effect.

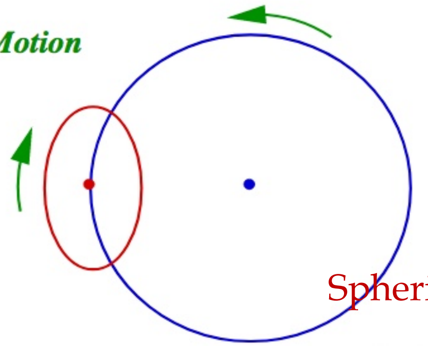
Epicyclic motions: nearly circular orbits

$r = R + \varepsilon(t)$ with $\varepsilon << R$

The motion can be approximately described as the combination of orbital motion around a disk galaxy and an epicyclic motion in radius:

Epicyclic Motion

Frequency of epicyclic motion = 2π/κ



Orbital Frequency around Disk Galaxy = 2π/Ω

Spherical potential $\Phi(r) = \frac{1}{2}\Omega^2 r^2 + \text{constant}$

The orbital frequency of a star Ω(R) can be written as follows

$$\Omega^2(R) = \frac{1}{R}\left(\frac{\partial \Phi}{\partial R}\right)_{(R,0)}$$

Meanwhile, the frequency of epicyclic motion κ(R) can be written as follows:

$$\kappa^2(R_g) = \left(R\frac{d\Omega^2}{dR} + 4\Omega^2\right)_{R_g}.$$

The frequency of epicycle motion is very similar to the orbital frequency:

In general, Ω < κ < 2 Ω

Near the solar system, the epicycle frequency κ ~ 1.3 Ω

Epicyclic motions

→ a visual way to represent stellar orbits

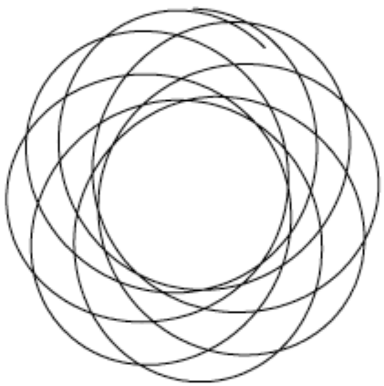


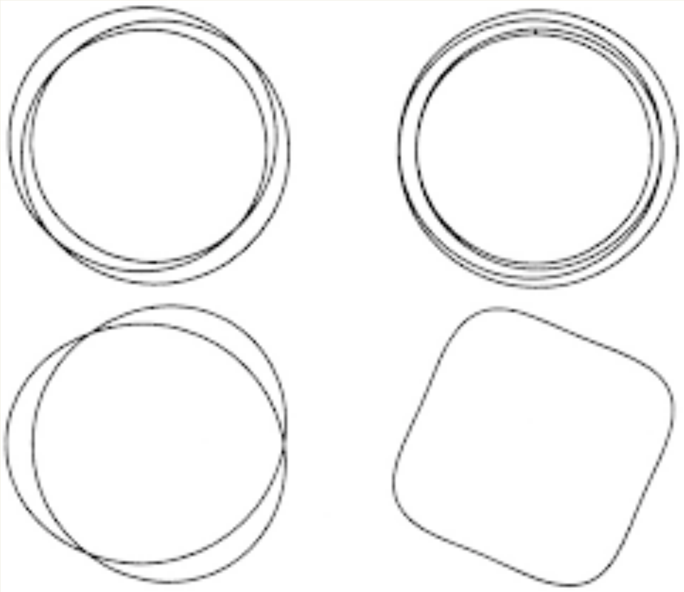
Figure 3.1 A typical orbit in a spherical potential (the isochrone, eq. 2.47) forms a rosette.

Stellar orbits can be characterized by two different periods:

Period for orbit around galaxy = **2π/Ω**

Period for epicyclic orbit = **2π/κ**

→ The orbits are closed if the ratios of the two periods is an integer



Orbits in the Ω_{gp} system:

Bar Two spiral arms

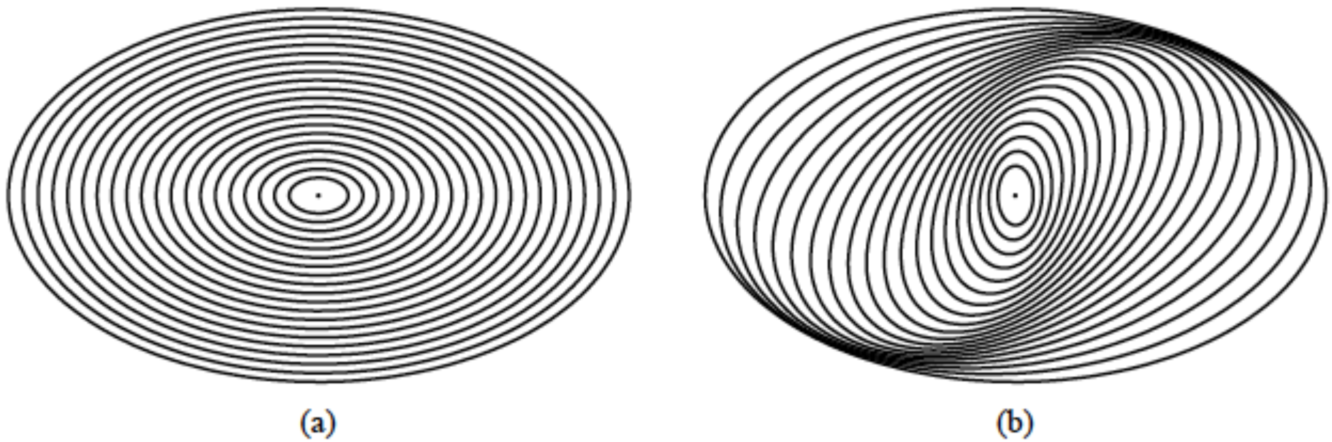


FIGURE 28 (a) Nested oval orbits with aligned major axes, as seen in a reference frame rotating with the global angular pattern speed ($n = 1, m = 2$), or $\Omega_{gp} = \Omega - \kappa/2$. The result is a bar-like structure. (b) Each oval is rotated relative to the orbit immediately interior to it. The result is a two-armed grand-design spiral density wave.

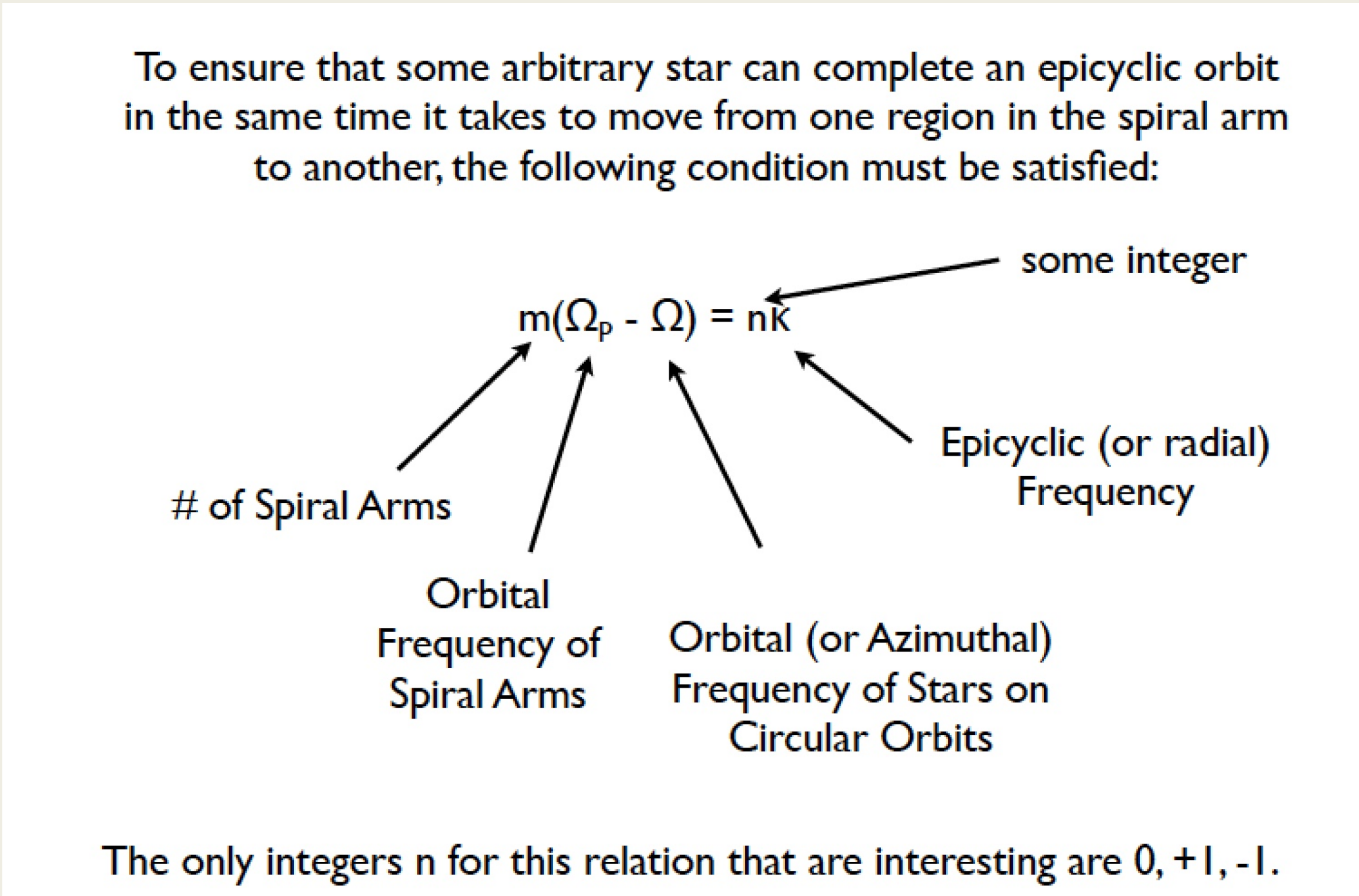
Seen from the non-inertial frame (rotating at Ω_{gp}), the resulting orbital patterns (due to epicyclic orbits) could be nested with their major axes aligned (a –appearance of a bar).

A small rotation in the orbits can produce the spiral arm pattern (b).

Which resonances drive spiral density wave growth?

→ The epicyclic frequencies **have resonances with the rotational velocity of the spiral patter**

→ Within the radii corresponding to resonances the spiral density waves are supported and incremented



Which resonances drive spiral density wave growth?

This results in a number of well known resonances:

Inner Lindblad resonance:

$$\Omega_p = \Omega - \kappa/m$$

Outer Lindblad resonance:

$$\Omega_p = \Omega + \kappa/m$$

Corotational radius:

$$\Omega_p = \Omega$$

Most relevant cases:

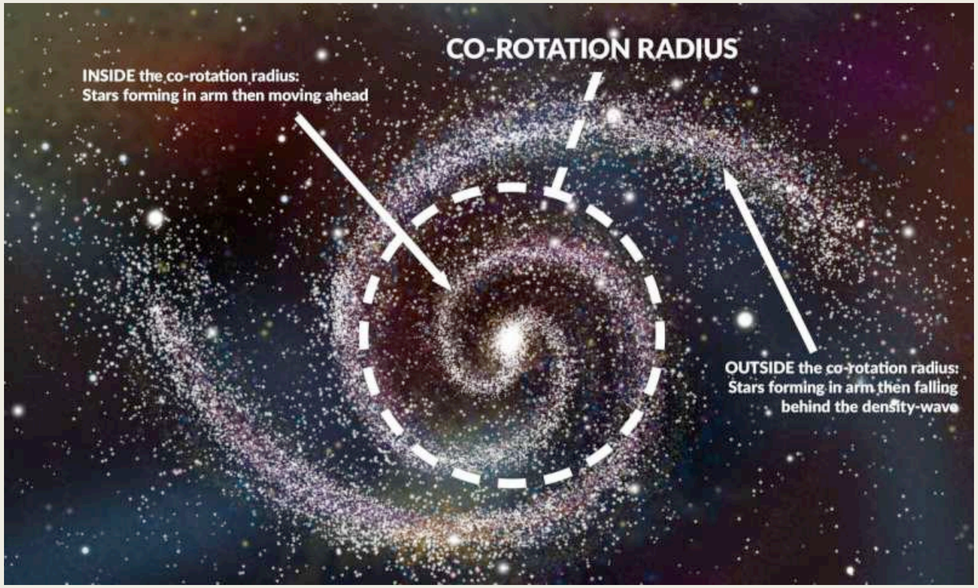
$$\Omega_p = \Omega - \kappa/2$$

$$\Omega_p = \Omega + \kappa/2$$

$$\Omega_p = \Omega$$

In most cases, the only relevant case is that of two spiral arms, i.e., $m = 2$

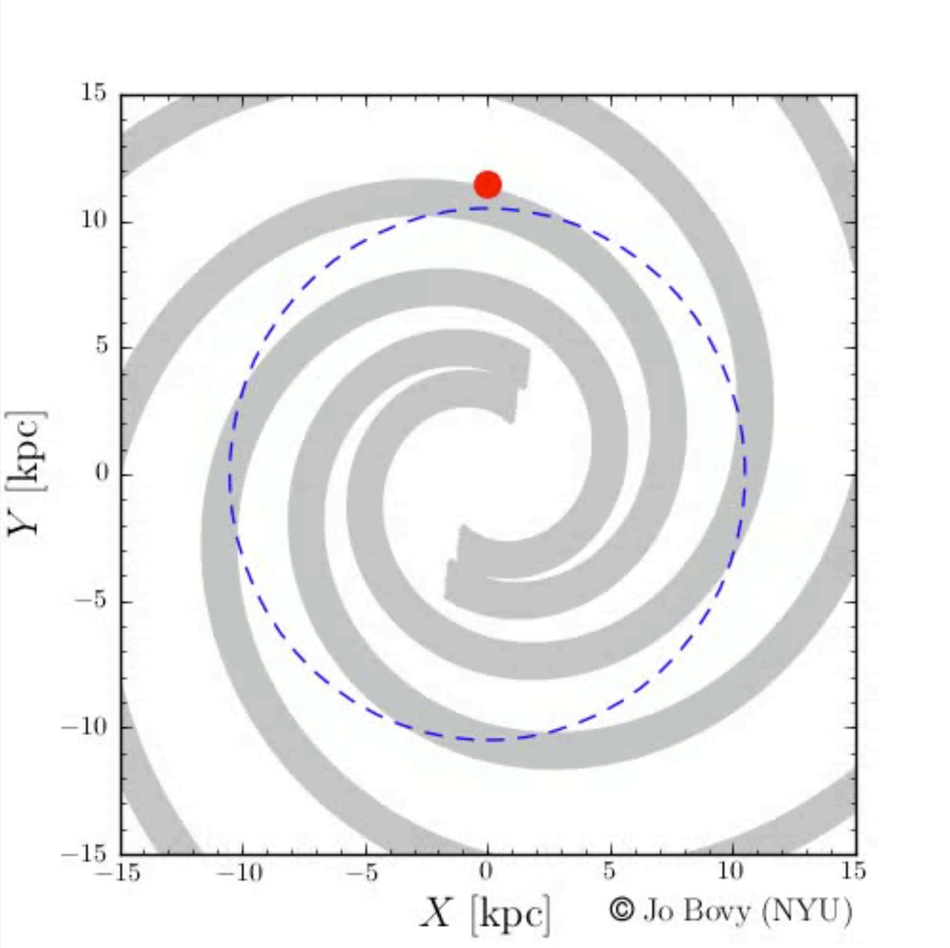
The corotation radius



Stars within the arms are not necessarily stationary, though at a certain distance from the center, R_c, **the corotation radius**, the stars and the density waves move together.

Inside that radius, stars move more quickly ($\Omega > \Omega_{gp}$) than the spiral arms, and outside, stars move more slowly ($\Omega < \Omega_{gp}$)

Corotational radius

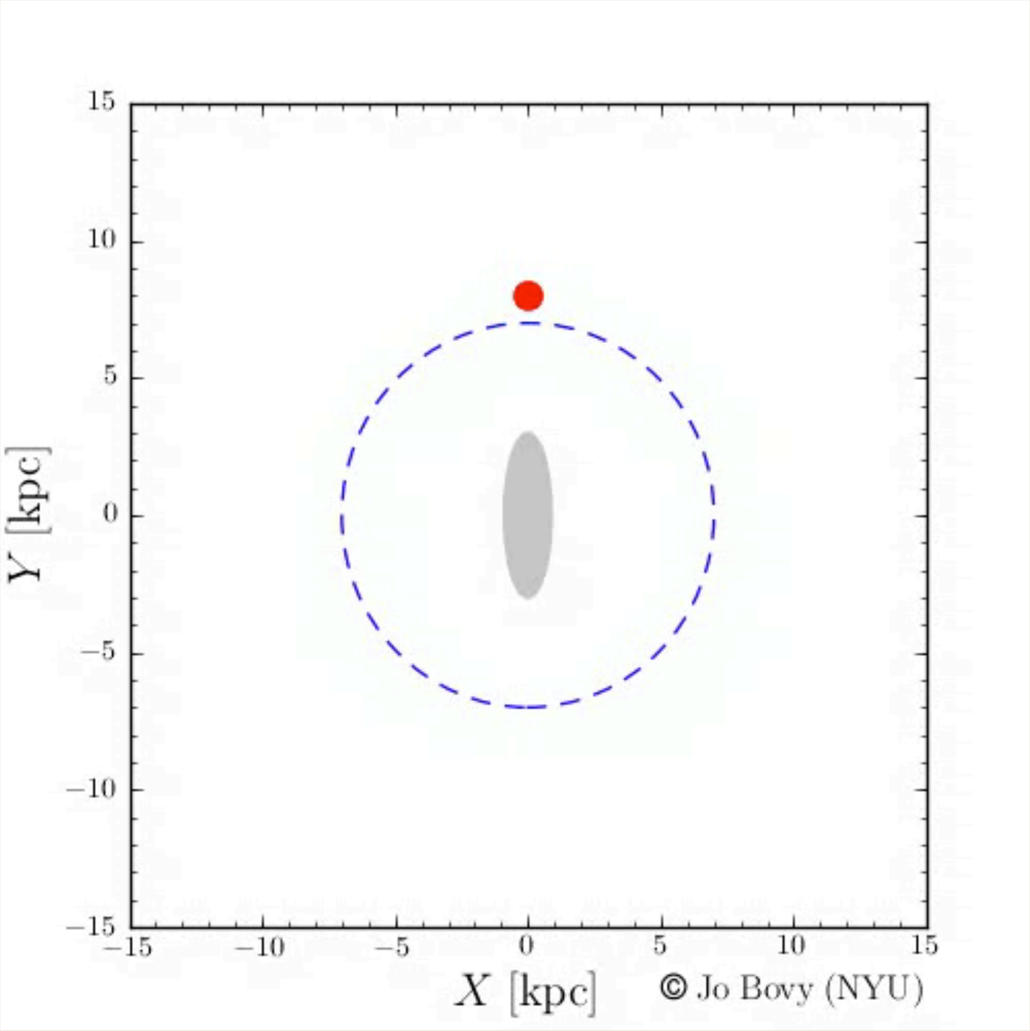


m=4

Four spiral arms

Videos produced by J. Bovy
http://cosmo.nyu.edu/~jb2777/resonance.html

Outer Lindblad radius



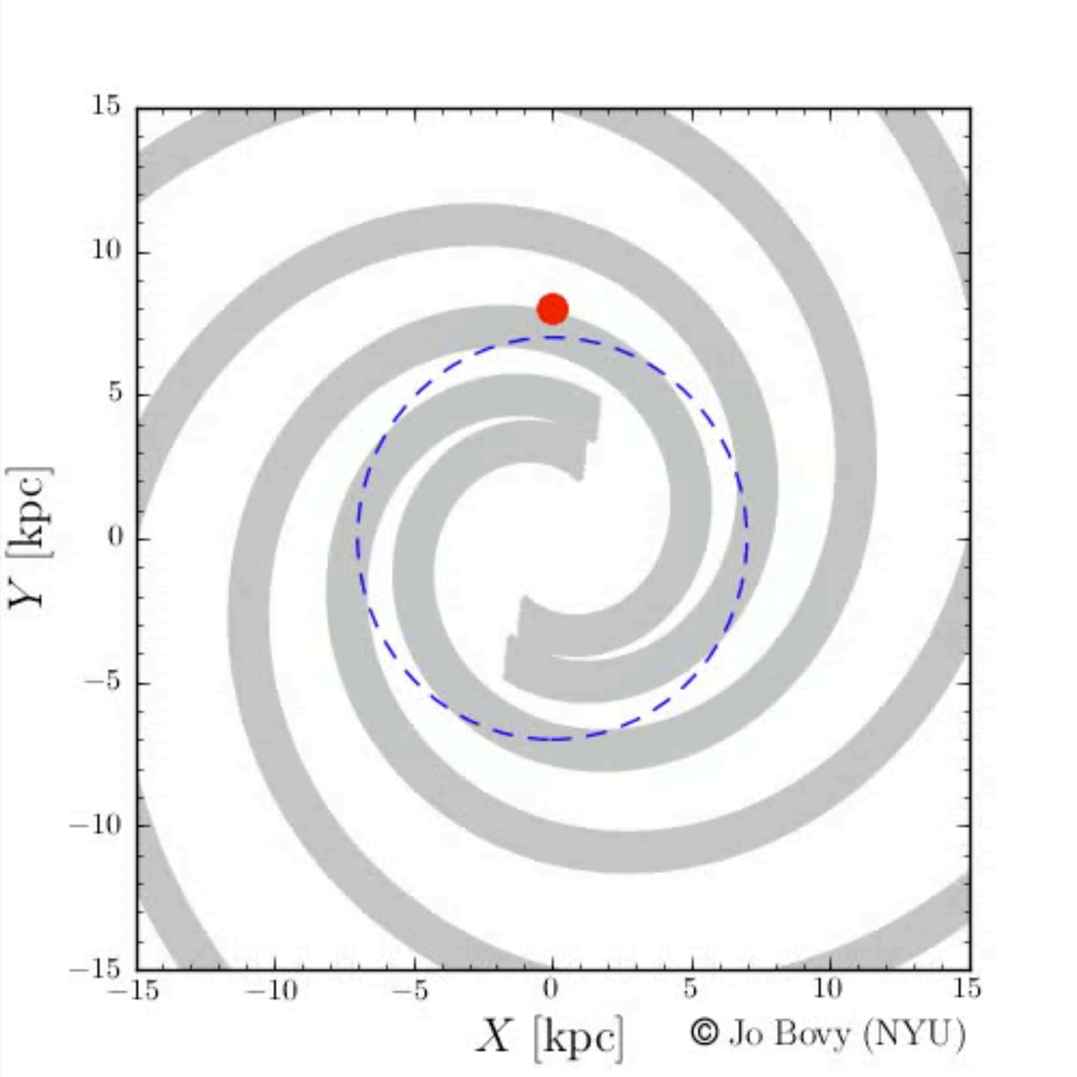
m=2

Two spiral arms → same dynamics of a Barred galaxy

$\Omega = \Omega_{gp} + k/2$

Videos produced by J. Bovy
http://cosmo.nyu.edu/~jb2777/resonance.html

Inner Lindblad radius



m=4

Four spiral arms

$\Omega = \Omega_{gp} - k/2$

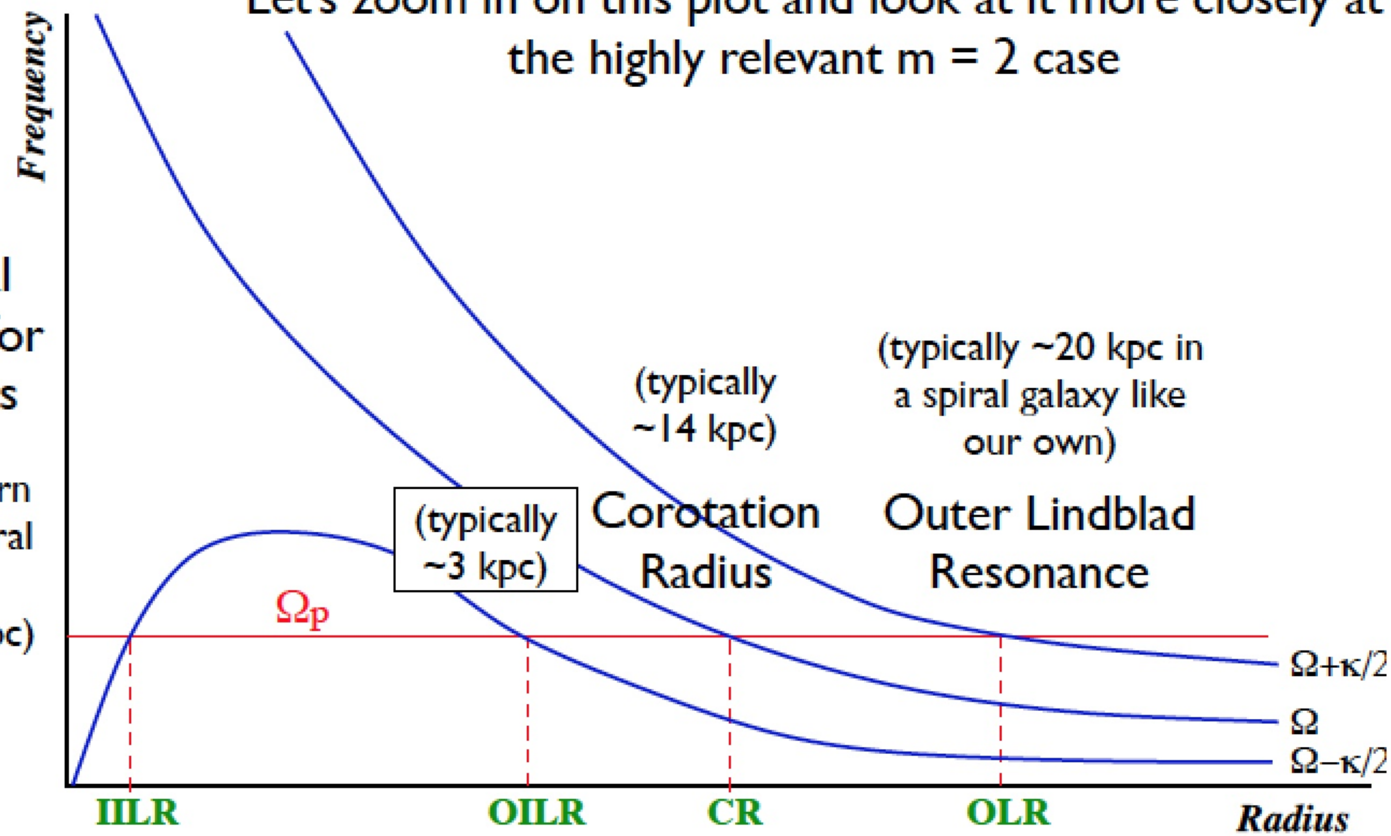
Videos produced by J. Bovy
http://cosmo.nyu.edu/~jb2777/resonance.html

What are the typical physical radii where these resonances apply?

Let's zoom in on this plot and look at it more closely at the highly relevant m = 2 case

Rotational frequency for spiral arms

(typical pattern speed for spiral arms Ω_p ~15 km/s / kpc)



Inner Lindblad Resonances (Can be more than one)

Different rotation curves:

→ mass distribution in galactic component

→ resonances

→ spiral pattern

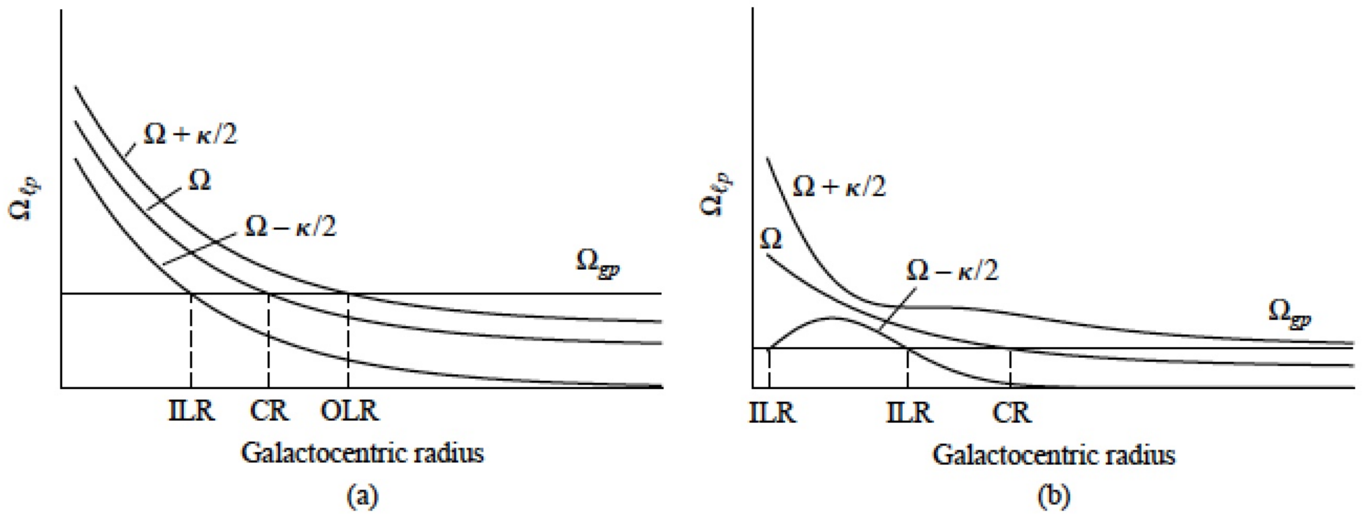
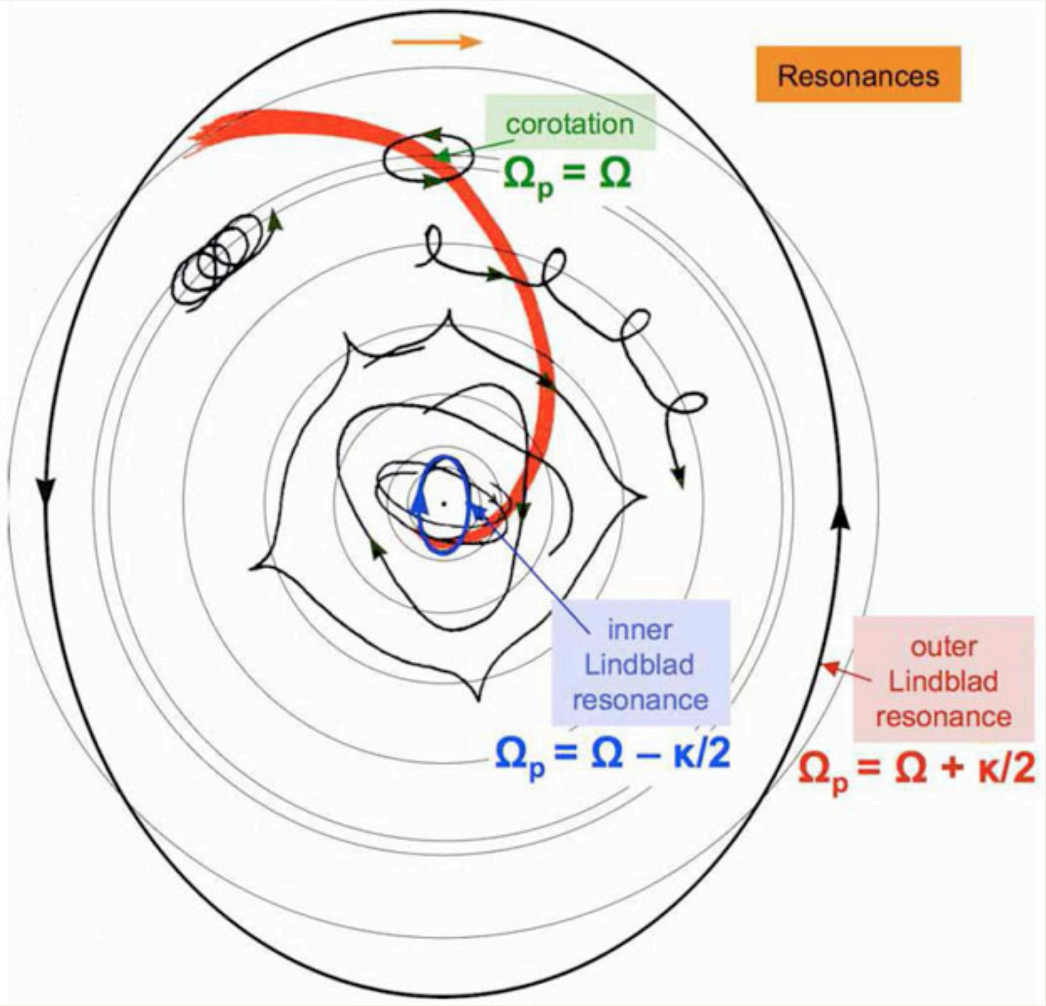


FIGURE 30 The existence of resonance radii depends on the global angular pattern speed of the arms and the shape of the galaxy's rotation curve. (a) A galaxy with a single inner Lindblad resonance (ILR), a corotation resonance (CR), and an outer Lindblad resonance (OLR). (b) A galaxy with two ILRs, a CR, and no OLR. Note that for sufficiently large values of Ω_{gp}, there may not be any ILRs.

Properties of resonances

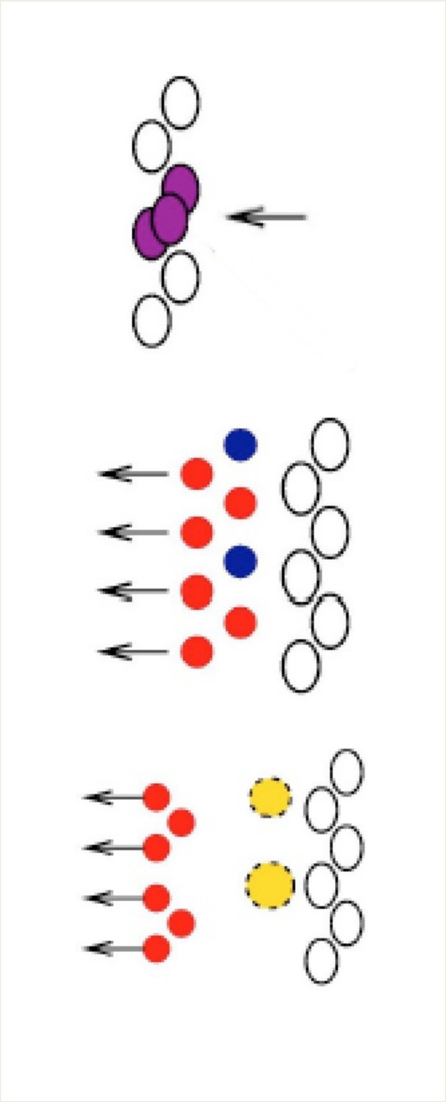


Spiral density waves can only survive and grow between the inner Lindblad resonance and outer Lindblad resonance.

These waves cannot pass through the inner Lindblad resonance (they are damped inside this radius)

Properties of spiral density wave

When the gas in the spiral density wave is compressed, it results in the formation of stars (due to the high gas densities induced by these compression waves) → **O-B stars, young star forming regions are located in the spiral arms**



After the stars form, they will approximately move at the circular velocity of the spiral galaxy -- which is often faster than the pattern speed of the spiral arm

The high mass stars formed in the spiral density compression waves die (SNe explosions or otherwise) shortly after leaving the spiral arm compression wave, but the lower mass (redder) stars continue to rotate around the disk.

The effect of resonances on stellar migration

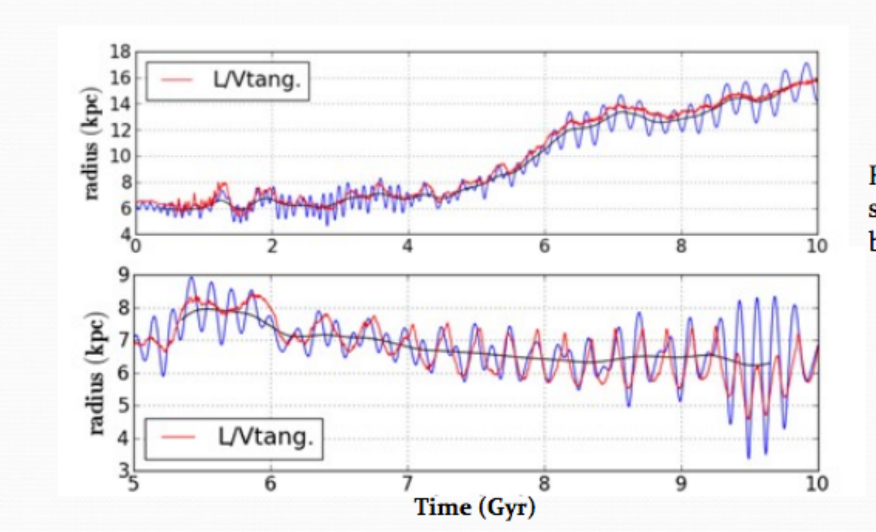
- Resonance locations can actually lead to damping of spiral waves
- Collisions of gas clouds should also increase significantly at resonance positions → energy will be dissipate
- Change in angular moments → in stellar orbits

Churring:

change in angular momentum→ change in radius

Blurring:

Increase in the epicycle amplitude of stars



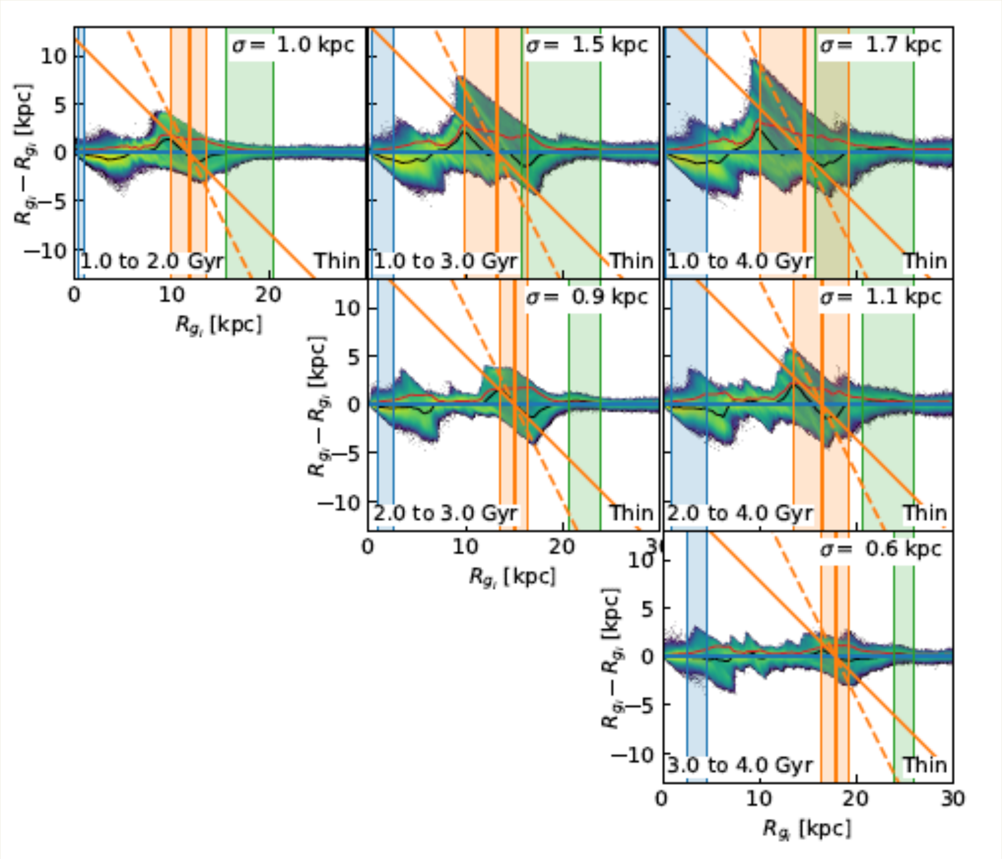
Radius evolution of two star particles in an N-body/SPH simulation.

The effect of resonances on stellar migration

Halle et al. 2008

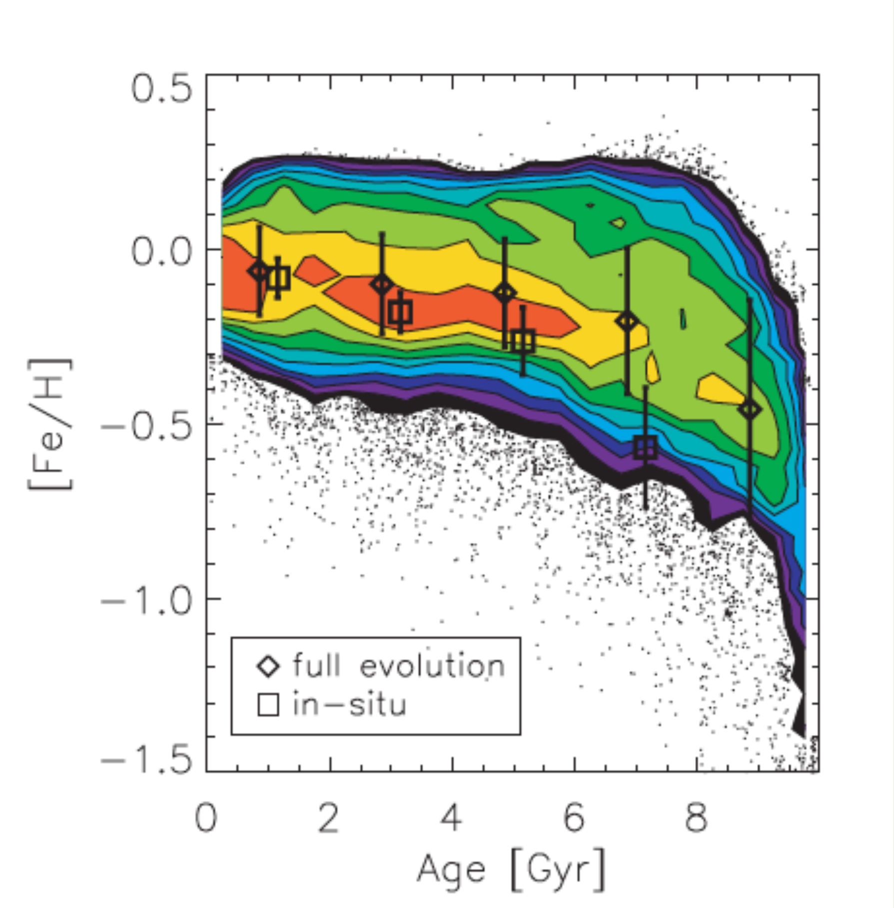
Change in the orbital radius of stars in different epochs of Galaxy evolution

→ The orange band indicates the location of the corotation radius where there is the **maximum variation**



The effect of resonances on stellar migration

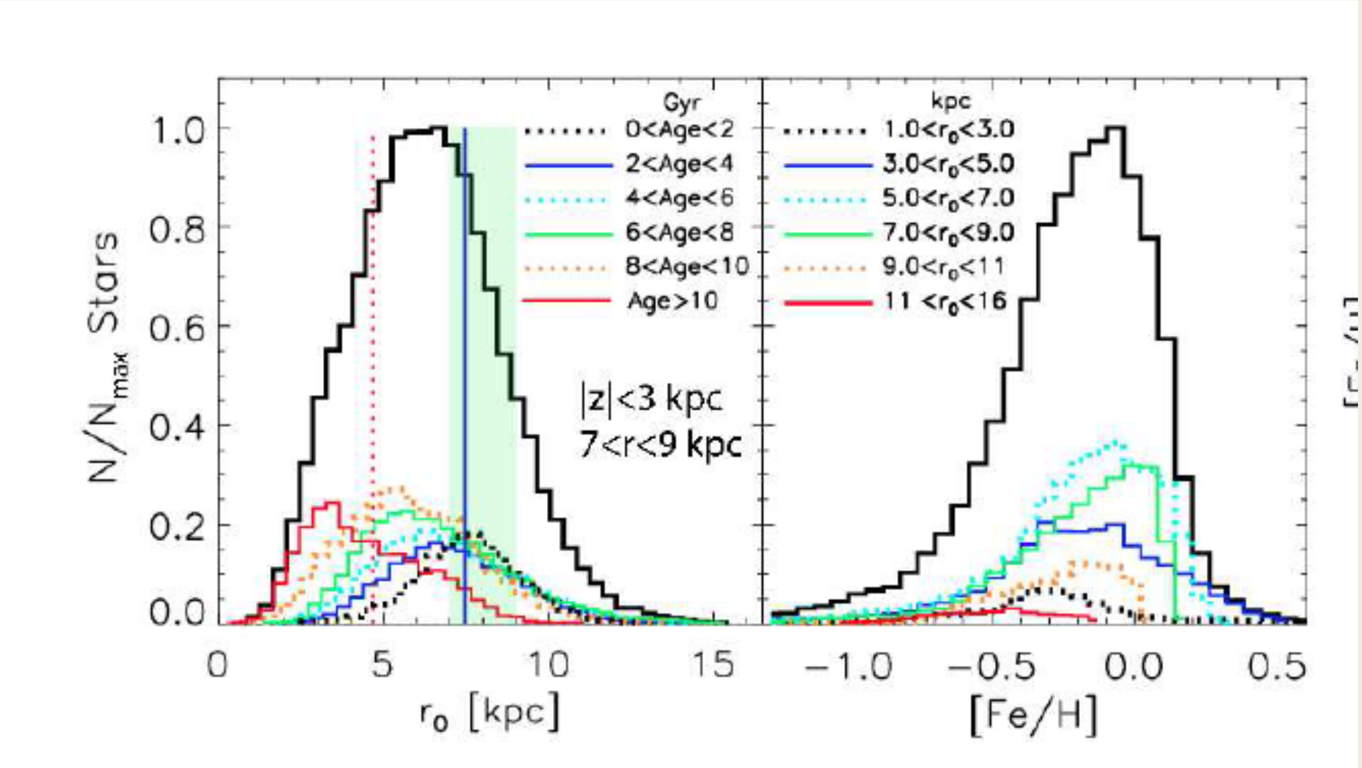
Roskar et al. (2008)



Age-metallicity relationship in the Solar neighbourhood

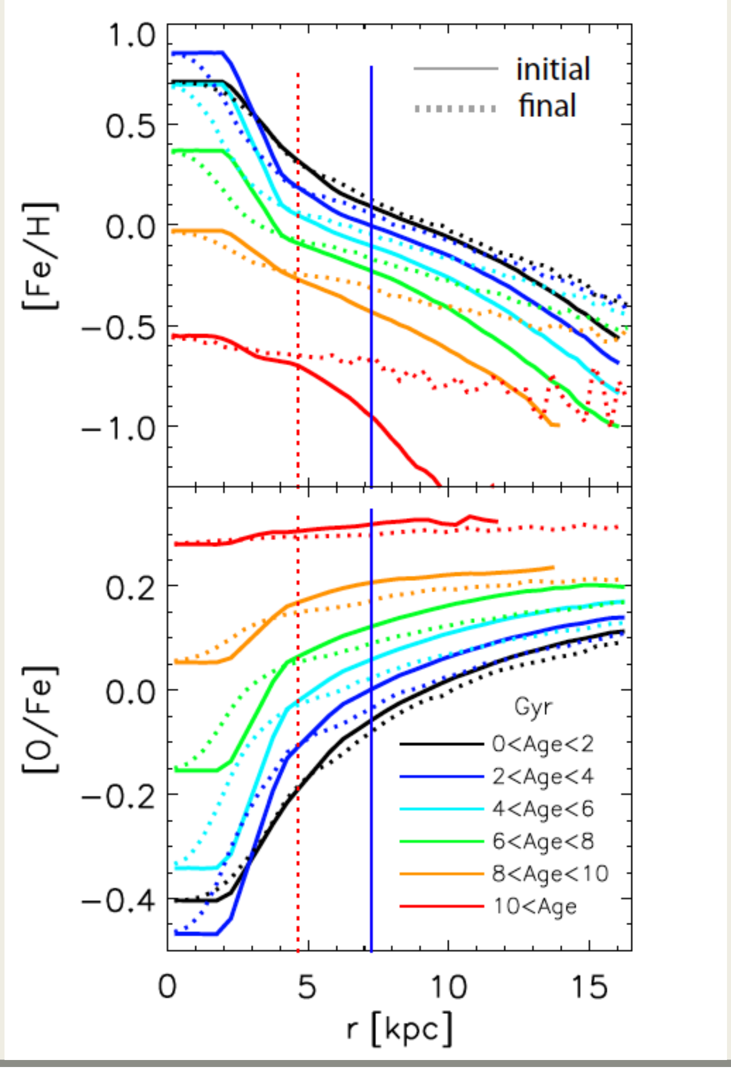
The effect of resonances on stellar migration

Minchev et al. (2013)



Metallicity distribution function in the Solar neighbourhood: only 20% of the stars in the solar neighbourhood were born there!

The effect of resonances on stellar migration



Minchev et al. (2013)

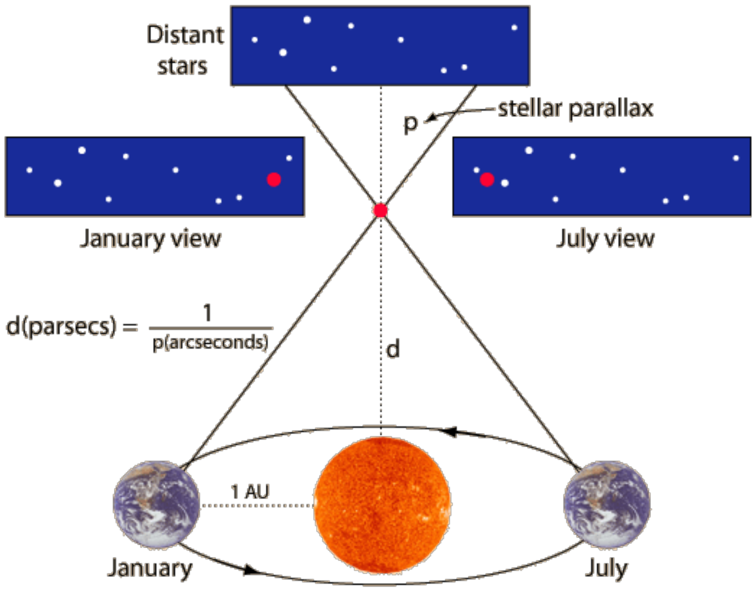
Radial metallicity gradients: the effect of radial migration

DISTANCE MEASUREMENTS

Stellar parallax:

Apparent motion of distant stars caused by orbital motion of Earth

As the Earth orbits the Sun, our viewing position changes, and closer stars appear to move relative to more distant objects. In the course of a year, a nearby star traces out an elliptical path against the background of distant stars. The angle ϖ on the sky is the parallax.



$$\frac{r}{d} = \tan \varpi \approx \varpi \, \mathrm{rad}$$

Where r is (=1 AU) the mean radius of the Earth's orbit and ω is expressed in radians

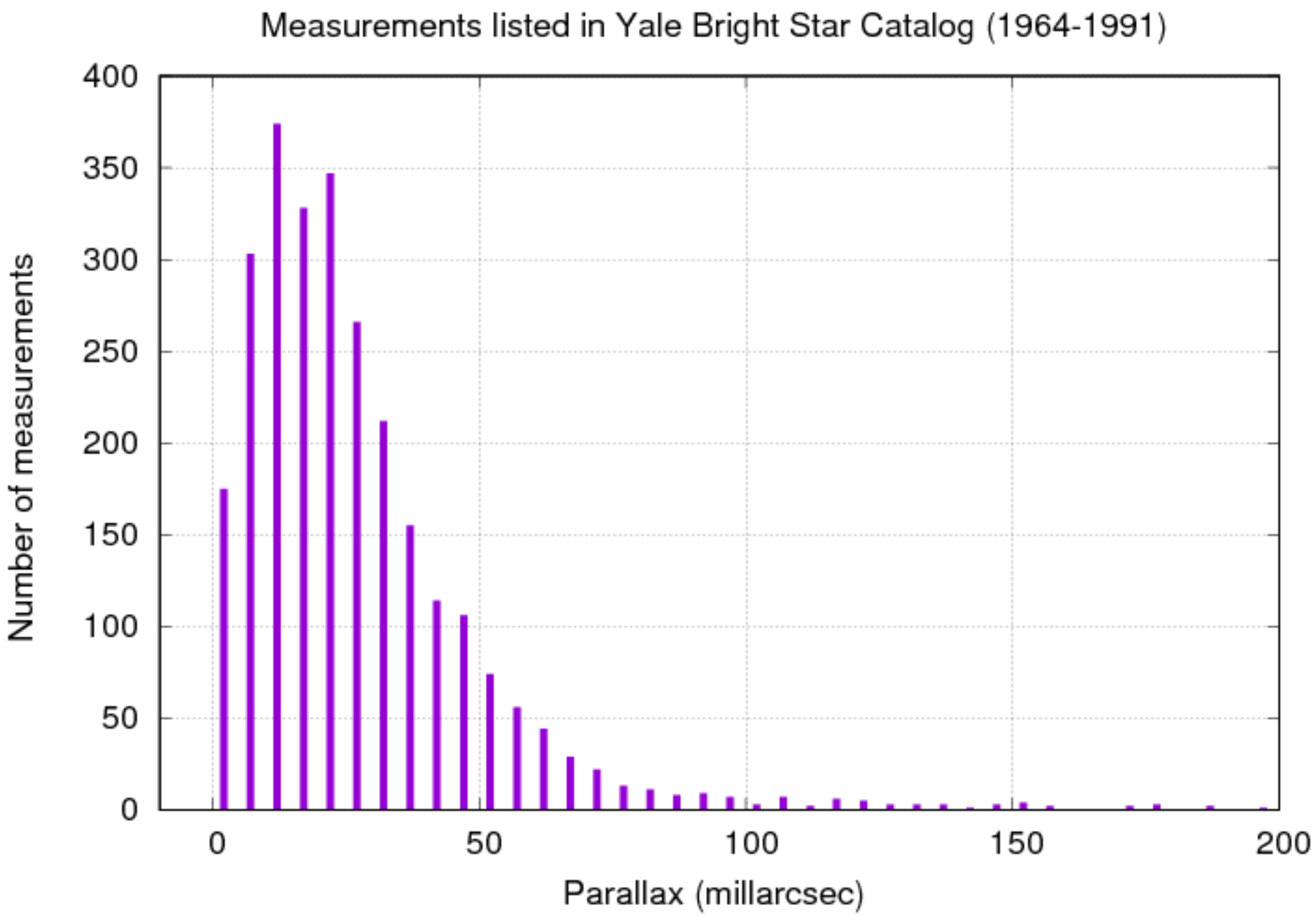
1 parsec is the distance at which a star would have a parallax of 1″

$$d = \frac{1}{\varpi''} \, \mathrm{pc}$$

DISTANCE MEASUREMENTS

Stellar parallax:

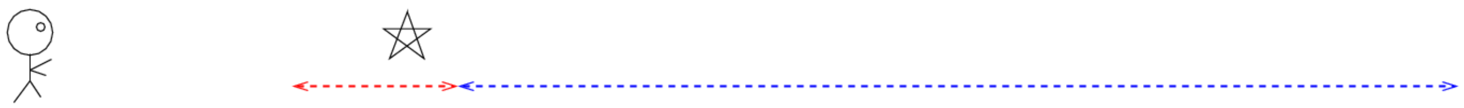
Available parallaxes of nearby bright stars (pre-Hipparcos and pre-Gaia satellites)



DISTANCE MEASUREMENTS

Errors on distances from parallax:

symmetric errors in angle lead to asymmetric errors in distance



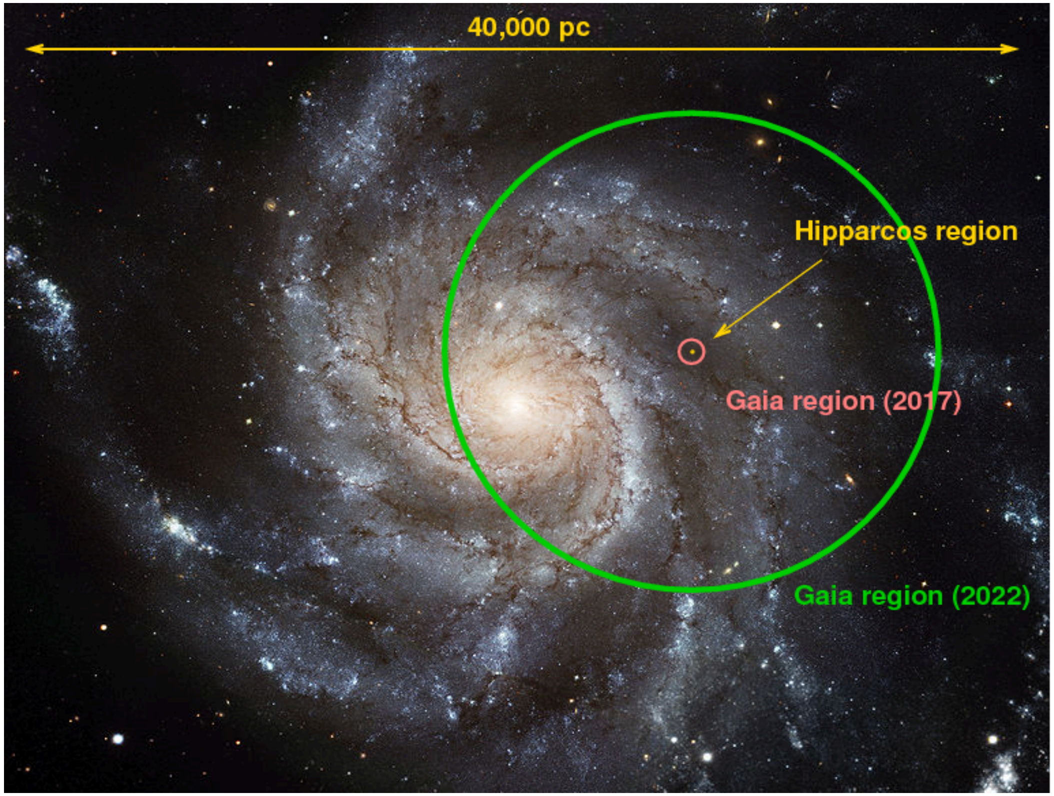
π = 10 +/- 7 mas (milli arcsec)

$d=1/\pi$

From the positive error we obtain: π_p = 17 mas → $d_p=1/17\text{x}10^{-3}=59$ pc

From the negative error we obtain: π_n = 3 mas → $d_p=1/17\text{x}10^{-3}=333$ pc

DISTANCE MEASUREMENTS



Gaia is greatly increasing our knowledge of the stellar neighborhood. It is producing a catalog of roughly 100 million stars with distances good to about 10 percent.

The Hipparcos catalog contains only 120000 entries, of which only about 40000 accurate distances.

DISTANCE MEASUREMENTS

Trigonometric parallaxes of a large database of stars is allowing to **calibrate other methods**, which, in turn, can be applied to stars at larger distances:

→ Features of the CMD diagram

  → Main sequence

  → Absolute magnitude of the Turn-Off and/or Red clump and/or horizontal branch

→ Spectroscopic distances

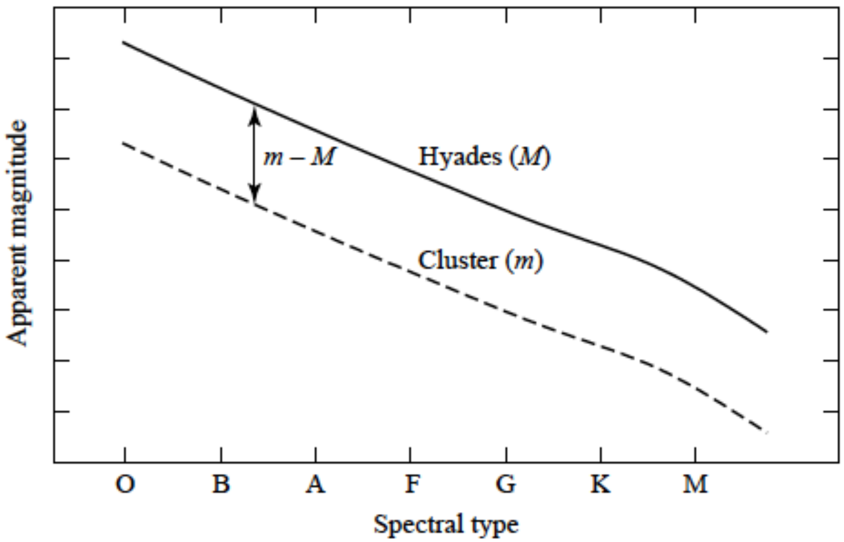
→ Pulsating stars

DISTANCE MEASUREMENTS

Main sequence fitting:

By comparing the apparent magnitudes of other cluster H–R diagram main sequences to the Hyades, it is possible to find the distance moduli of those clusters

Assuming that the reddening is known, the distances to those clusters can be determined. This distance technique is known as **main-sequence fitting** and it is a more precise procedure than spectroscopic parallax (based on single stars) because it relies on a large number of stars significantly reducing statistical errors



DISTANCE MEASUREMENTS

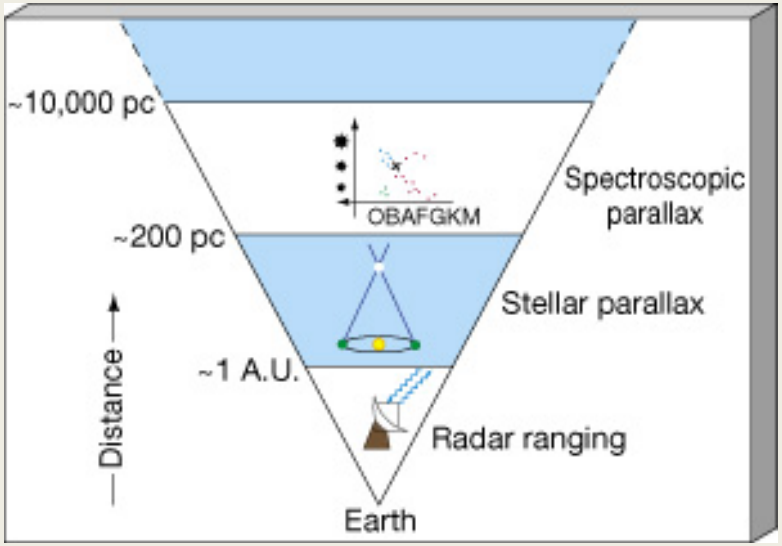
Spectroscopic distances:

→ Measure the apparent magnitude of a star

→ Classify its spectral type, through spectroscopy

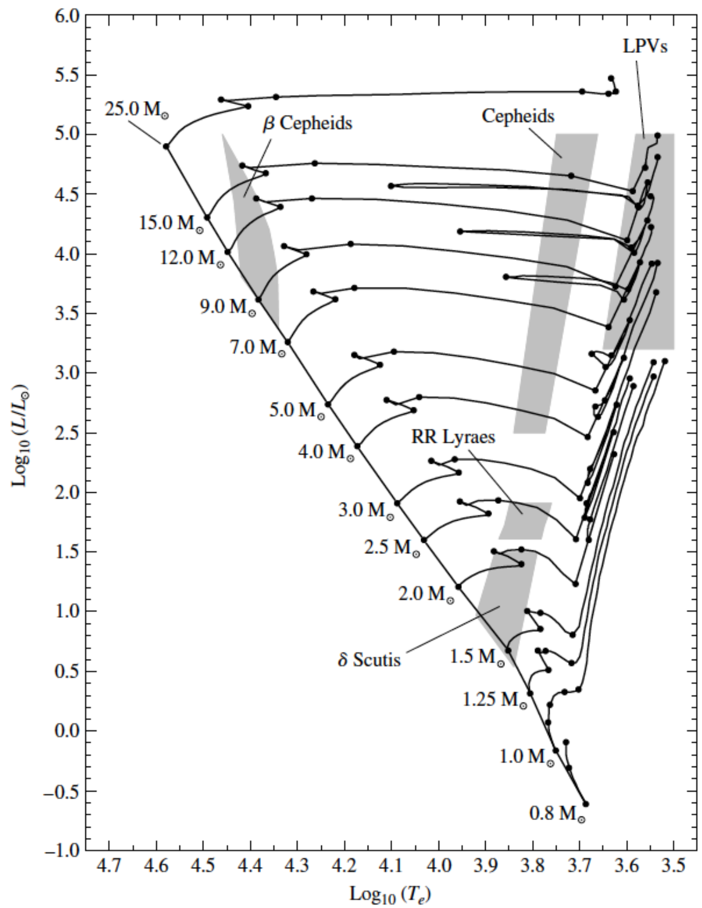
→ For main sequence, from the spectrum we can derive the luminosity class → related to the absolute magnitude

→ From the apparent magnitude (m) and absolute magnitude (M) of the star, we can calculate the distance



DISTANCE MEASUREMENTS

The Cepheid Distance Scale



- The majority of pulsating stars occupy a narrow strip on the right side of the HR diagram

- As stars evolve, they enter the **instability strip** and start pulsating

Type	Range of Periods	Population Type	Radial or Nonradial
Long-Period Variables	100–700 days	I,II	R
Classical Cepheids	1–50 days	I	R
W Virginis stars	2–45 days	II	R
RR Lyrae stars	1.5–24 hours	II	R
δ Scuti stars	1–3 hours	I	R,NR
β Cephei stars	3–7 hours	I	R,NR
ZZ Ceti stars	100–1000 seconds	I	NR

DISTANCE MEASUREMENTS

The Cepheid Distance Scale

- All of the types of stars falling in the instability strip share a common mechanism that drives the oscillations

- The radial oscillations of a pulsating star are the results of **sound waves resonating in the stellar interior**. Estimating the time-scale for the sound wave to cross the diameter of a star of radius R and computing the pressure from hydrostatic equilibrium:

$$v_s = \sqrt{\frac{\gamma P}{\rho}}.$$

Adiabatic sound speed,
as function of P, pressure
and density ρ

DISTANCE MEASUREMENTS

The Cepheid Distance Scale

$$P(r) = \frac{2}{3}\pi G\rho^2 \left(R^2 - r^2\right).$$

Pressure, in the assumption of hydrostatic equilibrium and constant density

$$\Pi \approx 2\int_0^R \frac{dr}{v_s} \approx 2\int_0^R \frac{dr}{\sqrt{\frac{2}{3}\gamma\pi G\rho\left(R^2 - r^2\right)}},$$

$$\boxed{\Pi \approx \sqrt{\frac{3\pi}{2\gamma G\rho}}.}$$

Longer periods for less dense -more massive → more luminous stars

DISTANCE MEASUREMENTS

The Cepheid Distance Scale

Period-luminosity-color relation that provide the absolute magnitute of the star:

$$M_{\langle V\rangle} = -3.53 \log_{10} P_d - 2.13 + 2.13(B - V),$$

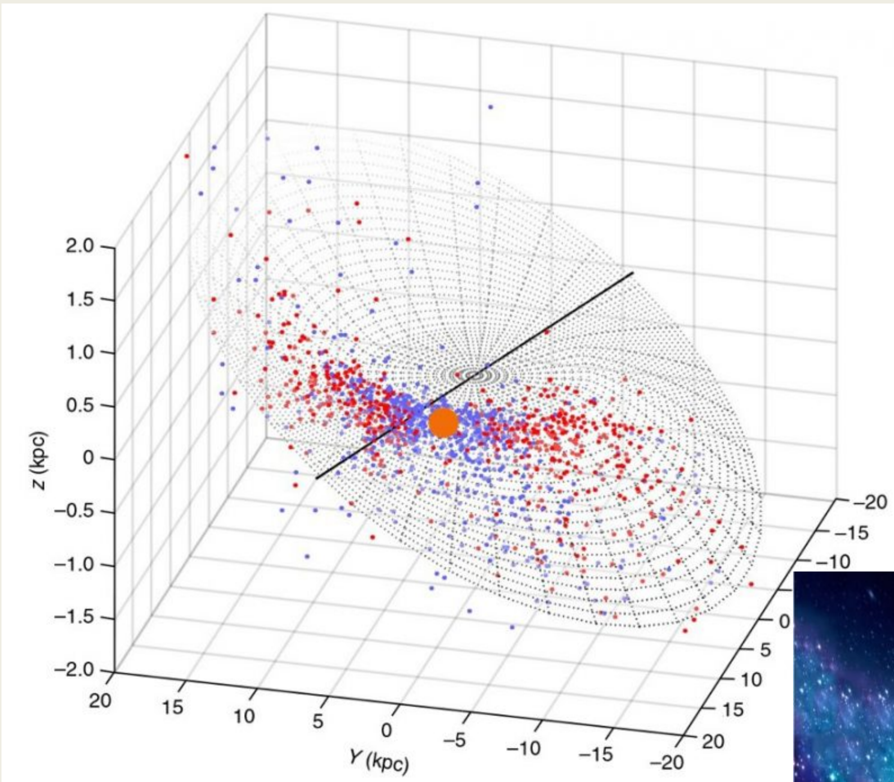
P_d is the period in day, (B-V) is the color index, usually ranging from 0.4 to 1.1, and M_v is the absolute magnitude.

→ Shapley measured the distances to Pop II Cepheids in Globular clusters, determining the diameter of the Galaxy

→ Hubble discovered Cepheids in M31, establishing that it was located outside the Milky Way.

→ The relation was finally calibrated around ~1990 with trigonometric parallaxes from Hipparcos

DISTANCE MEASUREMENTS



Direct measurement of distances between the Sun and a large sample of stars to help construct a 3D map of the galaxy using Cepheids
(Skowron et al. 2019)

Summary

- In our Galaxy, we can measured proper motions and radial velocities of individual stars
  - Define a proper system to study motion within the Galaxy
  - Estimate the rotation curve with the Oort method
  - Compare it with the rotation curve from HI lines
  - Mass distribution in the Milky Way
- Spiral arms: a quasi-stationary density wave
  - The connection between stellar orbits and spiral arms
  - The effect of resonances
  - Stellar migration
- Stellar distances:
  - Trigonometric distances
  - Calibrating other methods (CMD features, pulsating stars, etc)