Milky Way II

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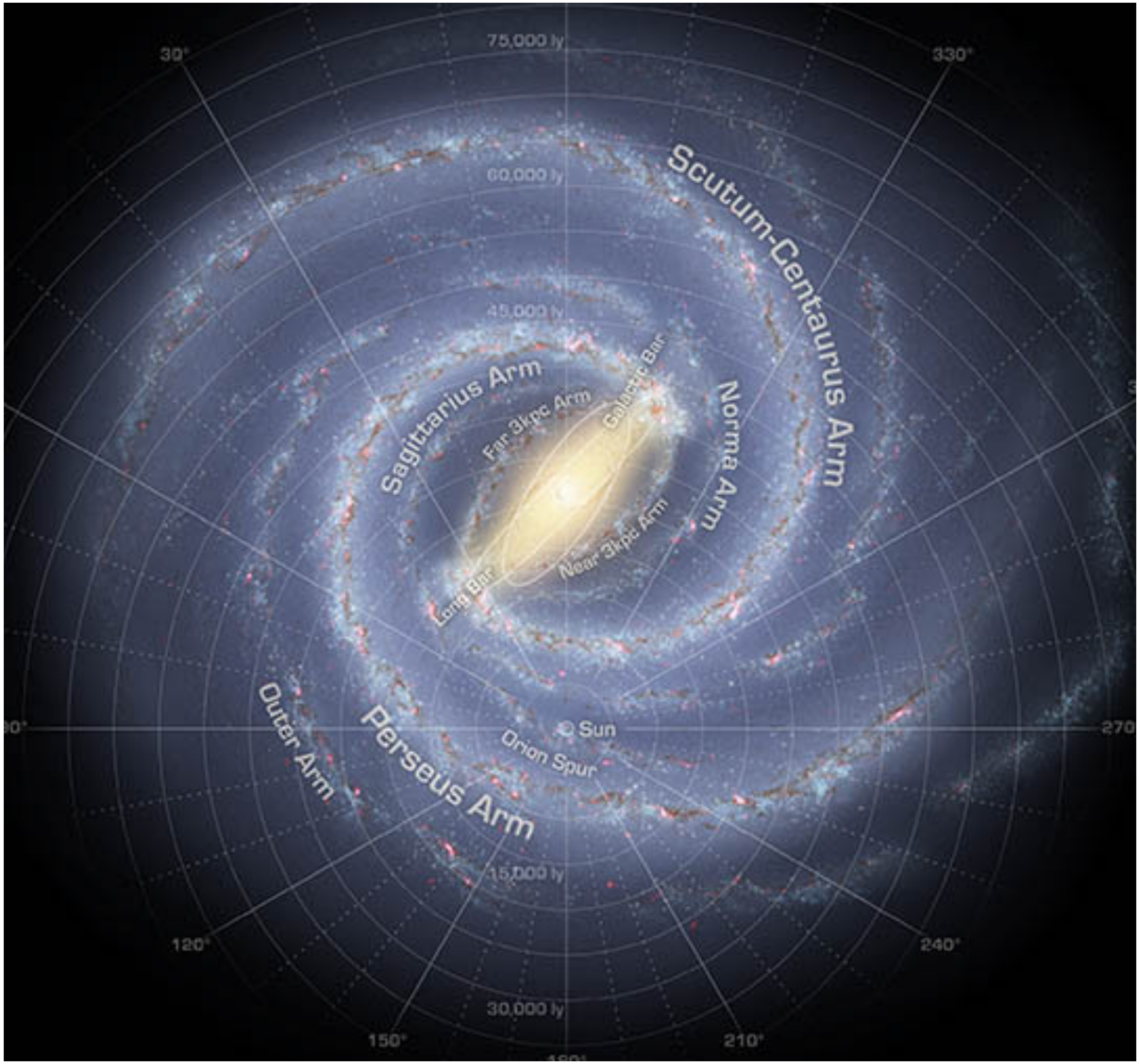
MW Kinematics

MW's Disc

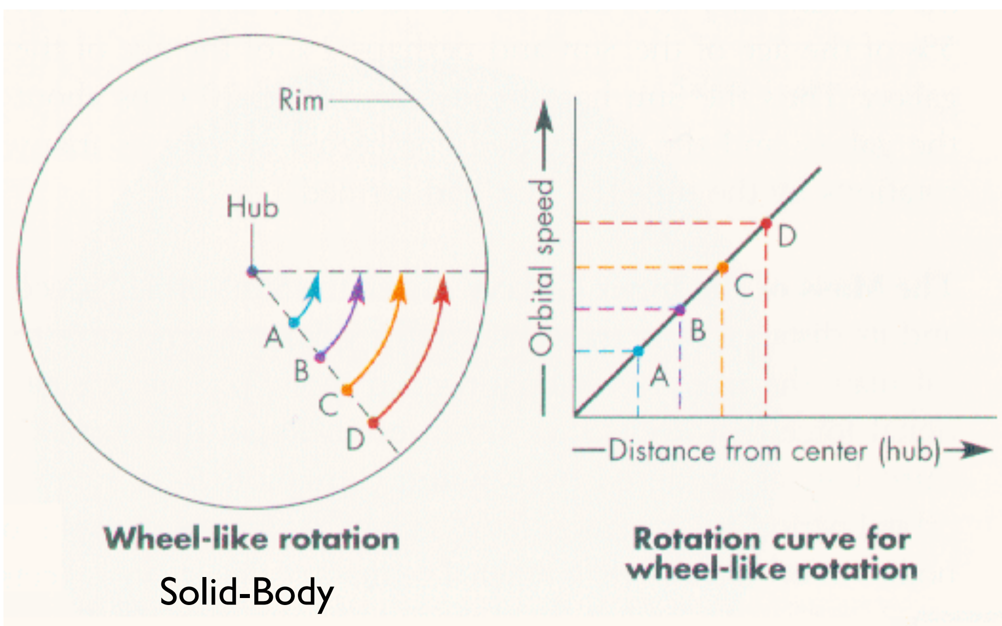


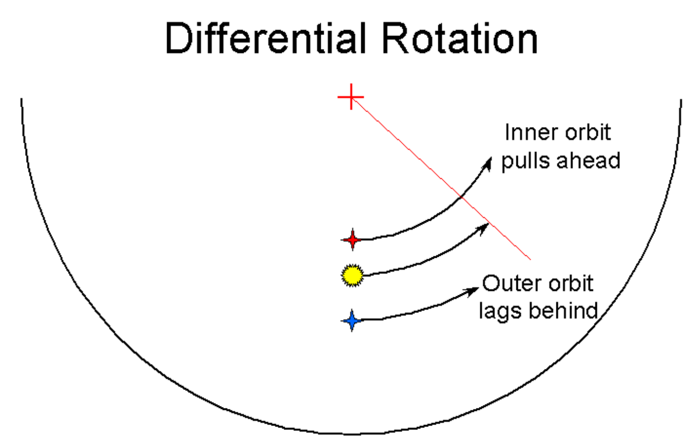
75,000 ly
30°
330°
60,000 ly
Scutum-Centaurus Arm
45,000 ly
Sagittarius Arm
Galactic Bar
Far 3kpc Arm
Norma Arm
Near 3kpc Arm
Long Bar
Outer Arm
Perseus Arm
Sun
Orion Spur
15,000 ly
120°
240°
30,000 ly
150°
210°

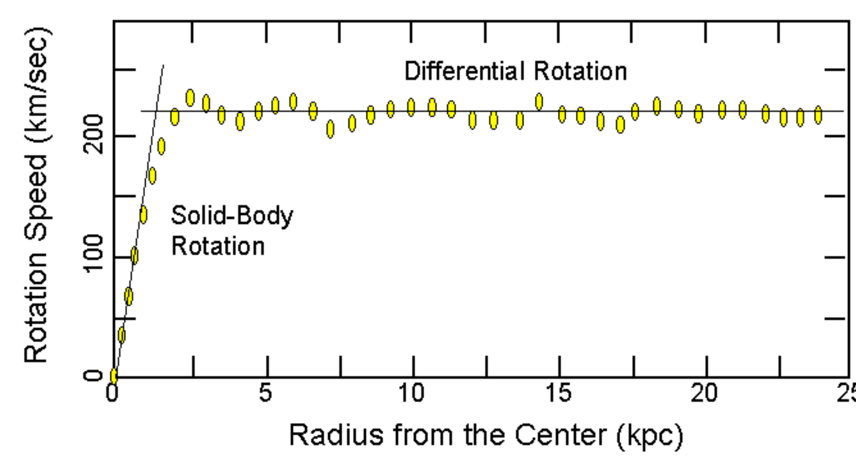
Differential Rotation

The Galaxy rotates differentially, which means that stars closer to the center take less time to complete their orbits around the Galaxy than those farther out

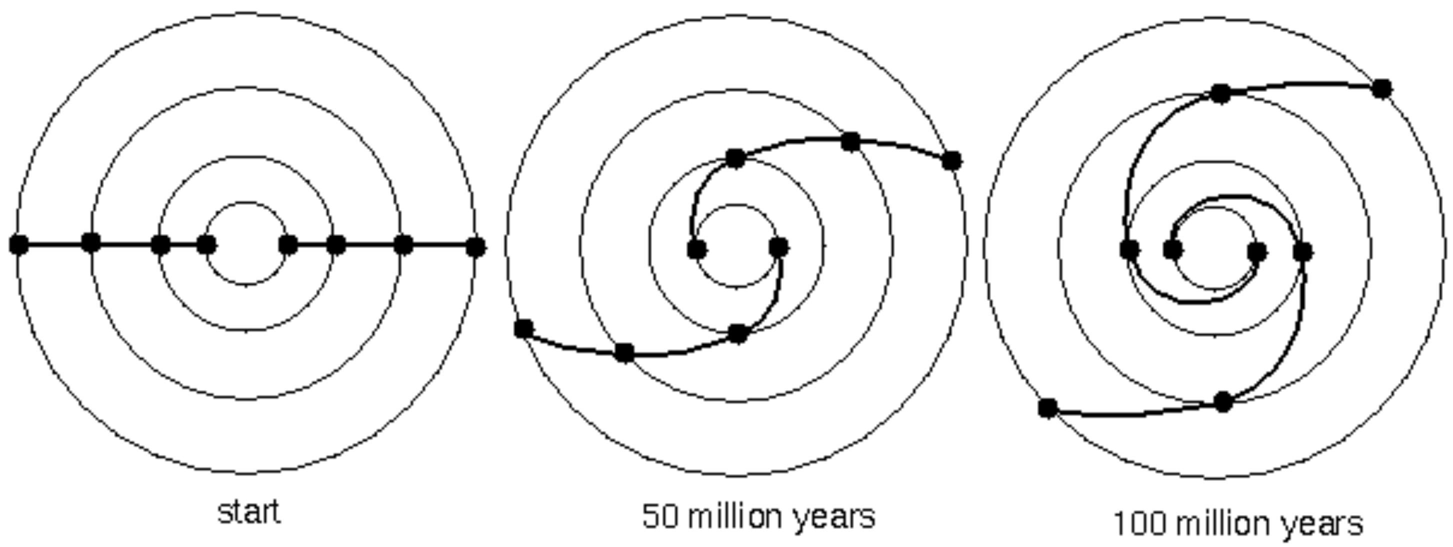
If the Galaxy rotated as a solid (or rigid) body, then all stars in circular motion would take the same time to complete their orbits around the Galaxy







Consequences of differential rotation



Differential rotation: stars near the center take less time to orbit the center than those farther from the center. Differential rotation can create a spiral pattern in the disk in a short time.

Differential rotation implies that stars exhibit both radial, tangential and vertical motions.

By studying these motions, we can infer the rotation curve of the Galaxy.

Stellar motions in MW disc: galactic rotation

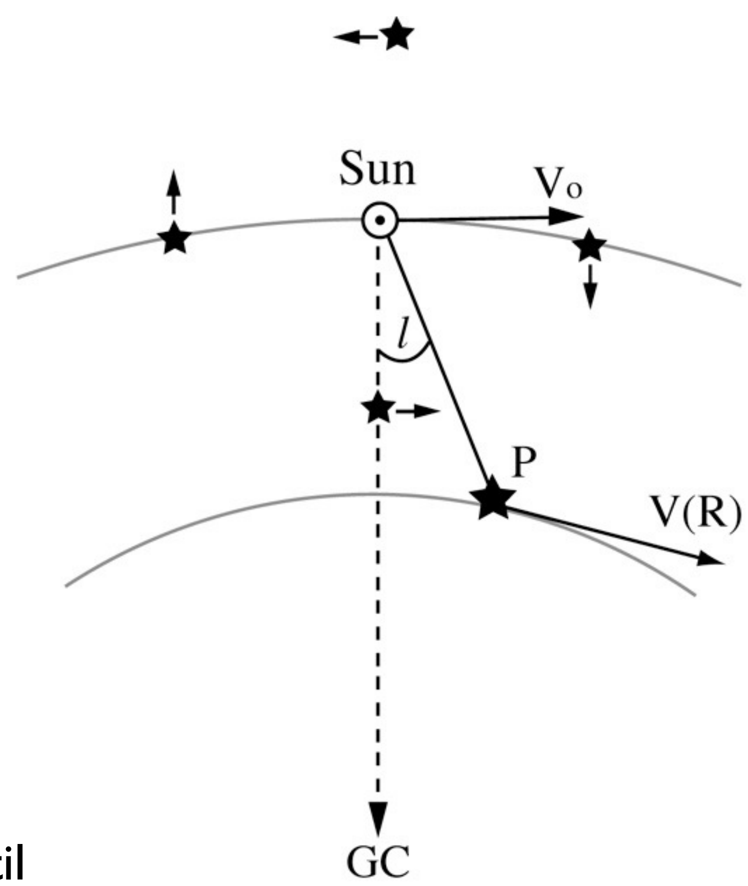
To a good approximation stars and gas in the disc of the Milky Way move in nearly circular paths about the Galactic centre.

Stars closer to the Galactic centre complete their orbits in less time than than those further out

DIFFERENTIAL ROTATION

This was first discovered from the proper motions of nearby stars: we typically see stars orbiting in the same direction but those closer to the Galactic centre pass us in their orbits; those further away fall behind.

This effect was already noticed in around 1900, but it wasn't until 1927 that Jan Oort explained this as an effect of Galactic rotation.

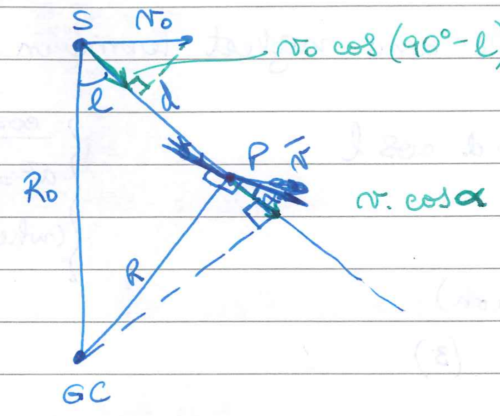


Sparke & Gallagher, Fig 2.18

We can take advantage of this orderly motion to map out the distribution from measured velocities.

Stellar motions in MW - radial velocities

Stellar motions in MW disc — radial velocities.



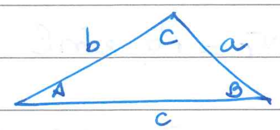
(Note: transversal distance between S and P should be small for this construction).

The star (or gas cloud) P recedes from us at a radial velocity

$$v_r = v \cos\alpha - v_0 \sin l \quad (1)$$

Now we use the sine rule which says:

$$\frac{a}{\sin A} = \frac{b}{\sin B} = \frac{c}{\sin C}$$



where "a" is the side opp. to the angle A.

therefore we have

$$\frac{\sin l}{R} = \frac{\sin(90° + \alpha)}{R_0}$$

and $\sin(90° + \alpha) = \cos\alpha$

$$\therefore \frac{\sin l}{R} = \frac{\cos\alpha}{R_0} \Rightarrow \cos\alpha = (\sin l)\frac{R_0}{R}$$

Replacing in (1):

$$v_r = v\frac{R_0}{R}\sin l - v_0 \sin l = R_0 \sin l \left(\frac{v}{R} - \frac{v_0}{R_0}\right) \quad (2)$$

Stellar motions in MW disc: radial velocities

We can calculate the radial velocity of a star (or a gas cloud), assuming that it follows a circular orbit.

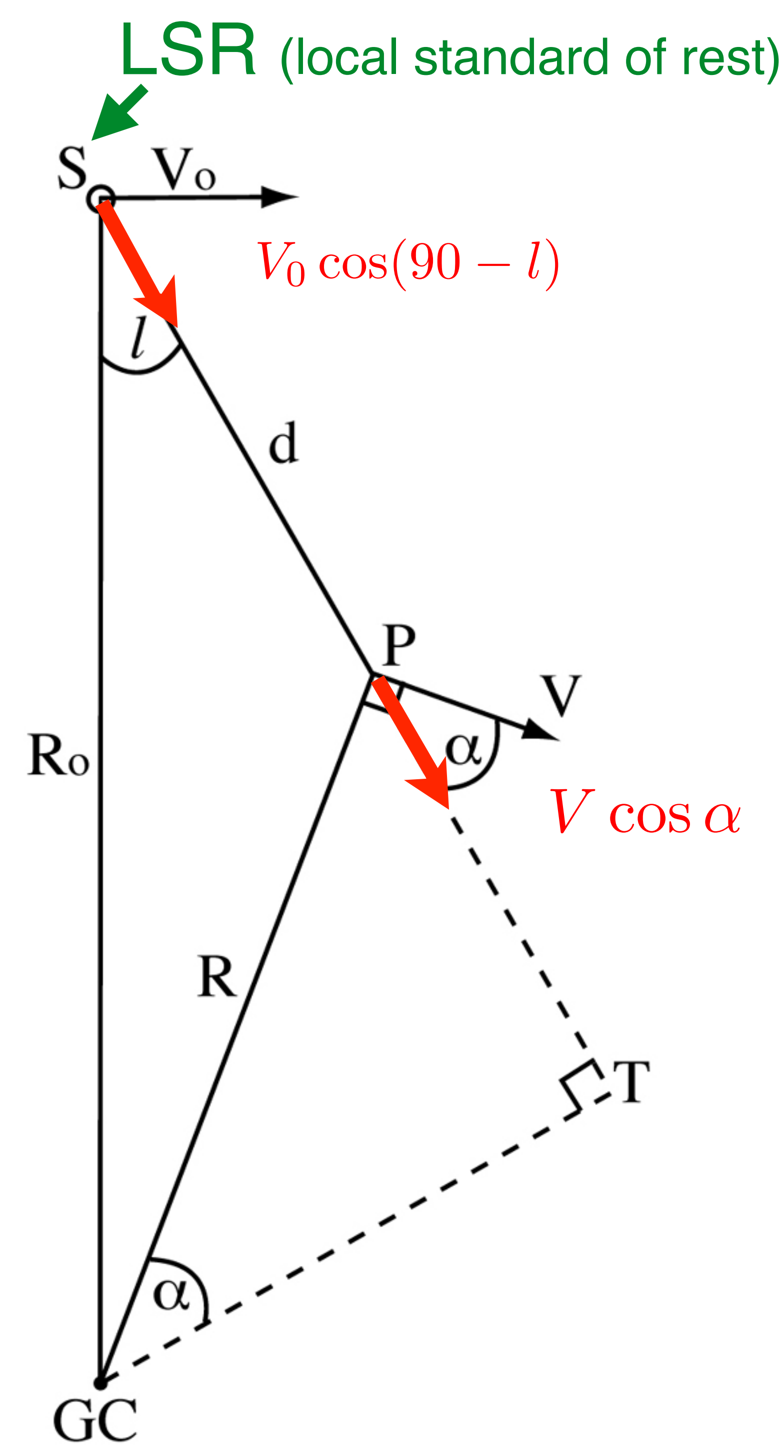
At radius R_0 the Sun orbits with speed V_0, while a star at P at radius R has orbital speed V(R). The star moves away from us at speed

$$V_r = V\cos\alpha - V_0 \sin l$$

using the sine rule, we have $\sin l / R = \sin(90+\alpha)/R_0$

and so $$V_r = R_0 \sin l \left(\frac{V}{R} - \frac{V_0}{R_0} \right)$$

If the Milky Way rotated rigidly, the distance between stars would not change, and V_r would always be 0. In fact stars further from the centre take longer to complete their orbits; the angular speed V/R drops with radius R.



Sparke & Gallagher, Fig 2.19

Oort's constants

When the star or gas cloud P is very close to the Sun S, then $d \ll R$ and $R \approx R_0$ and we can neglect terms in d^2, using the cosine rule.

$$R^2 = R_0^2 - 2R_0 d \cos l$$

gives $$R \approx R_0 - d\cos l$$

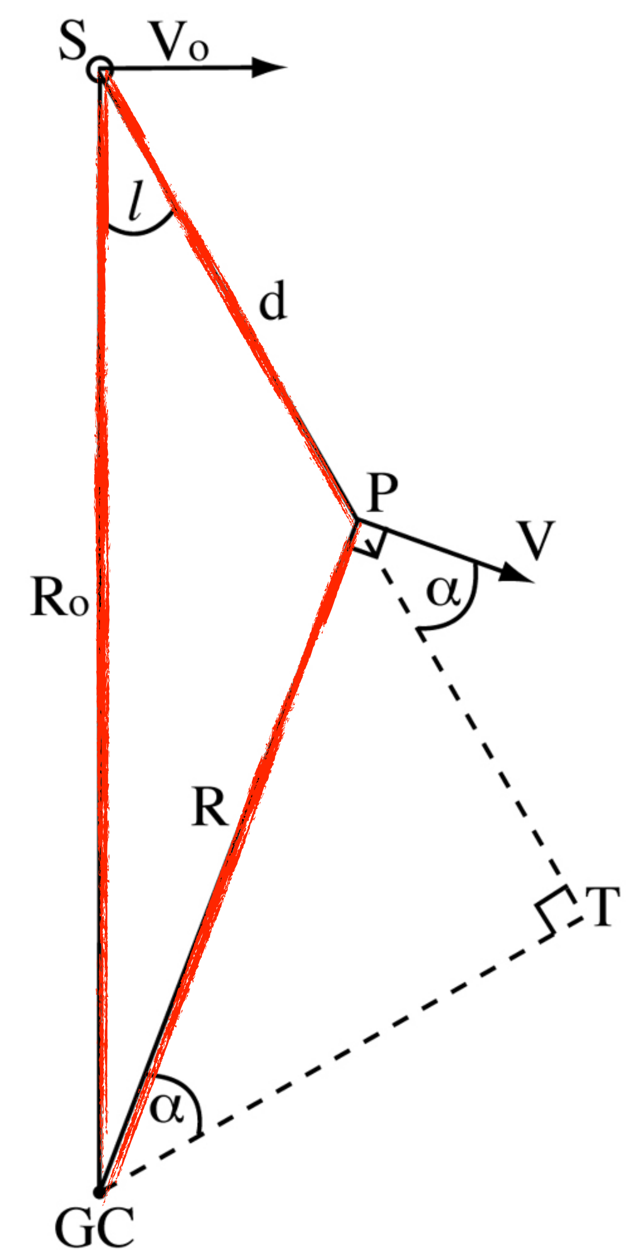
$$V_r = R_0 \sin l \left(\frac{V}{R} - \frac{V_0}{R_0}\right)$$ then becomes, for small difference in V/R

$$= R_0 \sin l \;\delta(V/R) \qquad \frac{d(V/R)}{dR} = \frac{\delta(V/R)}{\delta R} = \frac{\delta(V/R)}{R - R_0}$$

$$\approx R_0 \sin l \frac{d(V/R)}{dR}(R - R_0)$$

$$\approx d\sin(2l)\left[-\frac{R}{2}\left(\frac{d(V/R)}{dR}\right)\right]_{R_0} \qquad \equiv d\; A\sin(2l)$$

A is one of Oort's constants, and is measured to be 14.8±0.8 km/s/kpc
it measures local shear, or deviation from rigid rotation



Sparke & Gallagher, Fig 2.19

Oort's constants (cont.)

The proper motion of a star at P relative to the Sun, S can be calculated in a similar way. The tangential velocity is:

$$V_t = V \sin\alpha - V_0 \cos l$$

$$R_0 \cos l = R \sin\alpha + d$$

$$V_t = R_0 \cos l \left(\frac{V}{R} - \frac{V_0}{R_0} \right) - V \frac{d}{R}$$

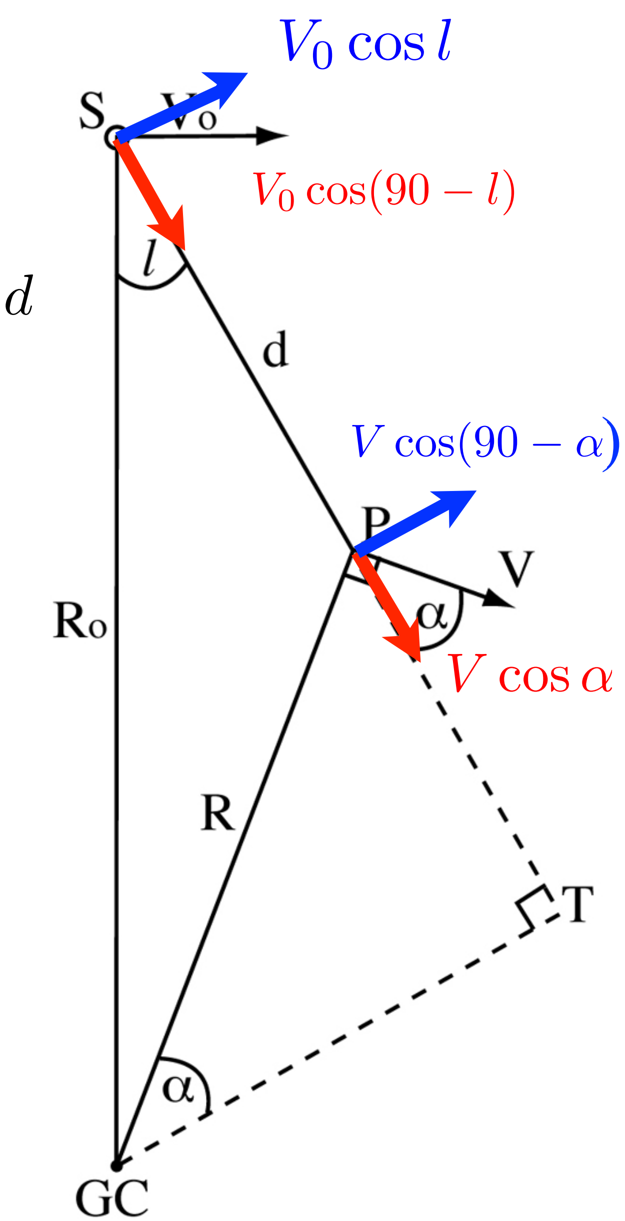
Close to the Sun, $R_0 - R \approx d \cos l$, and so V_t varies almost linearly with distance, d.

$$V_t \approx d \cos(2l) \left[-\frac{R}{2} \left(\frac{d(V/R)}{dR} \right) \right] - \frac{d}{2} \left[\frac{1}{R} \frac{d(RV)}{dR} \right]_{R_0}$$

$$\equiv d \, [A \cos(2l) + B]$$

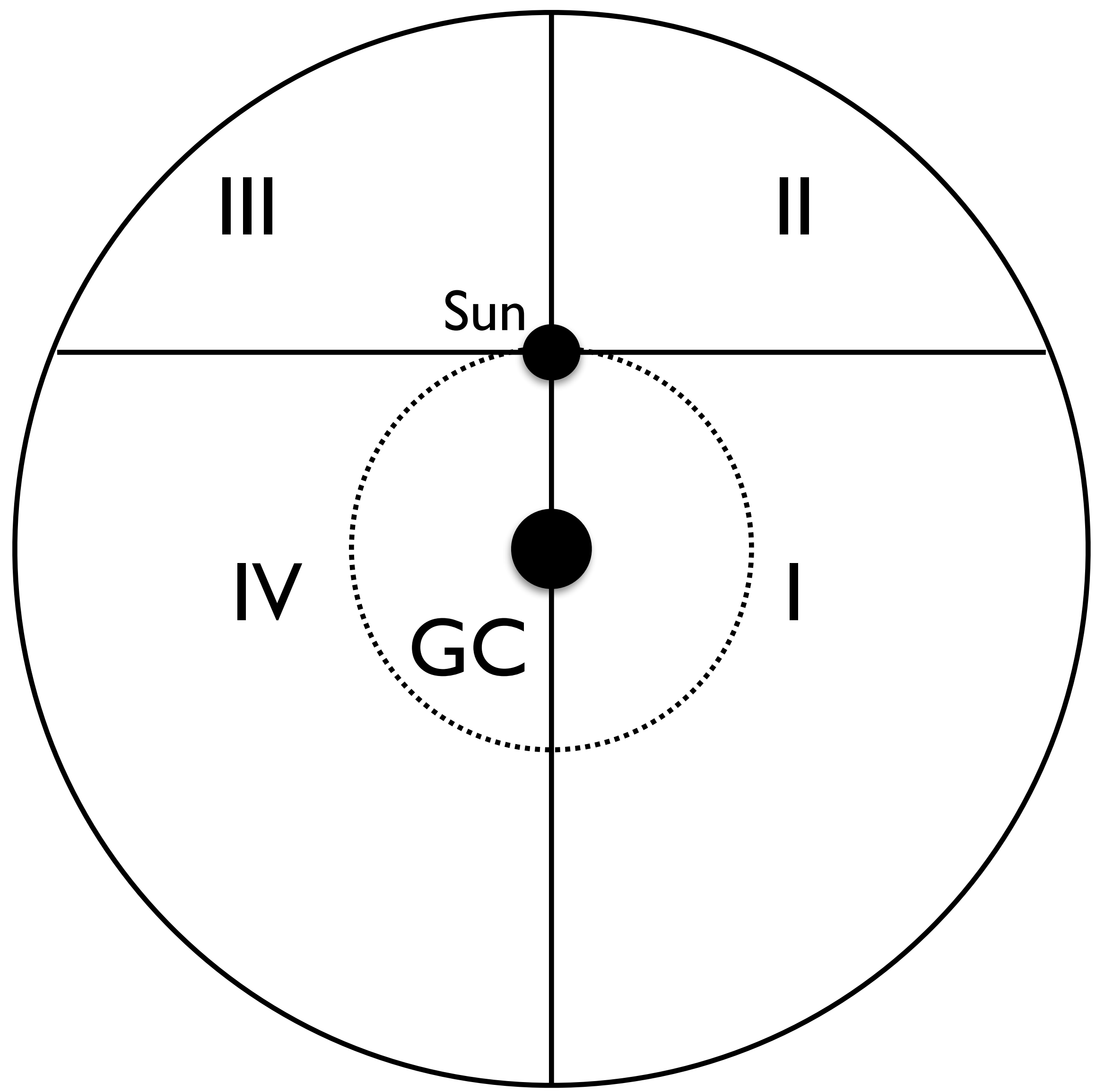
→ B is the second of Oort's constants, and is measured to be -12.4±0.6 km/s/kpc

it measures the local vorticity, or angular momentum gradient in the disc.



Sparke & Gallagher, Fig 2.19

Gas motion pattern



QI : v_r= (v(R) - v_0) >0

if we are within Sun's orbit, and is <0 otherwise

QII : v_r= (v(R) - v_0)<0

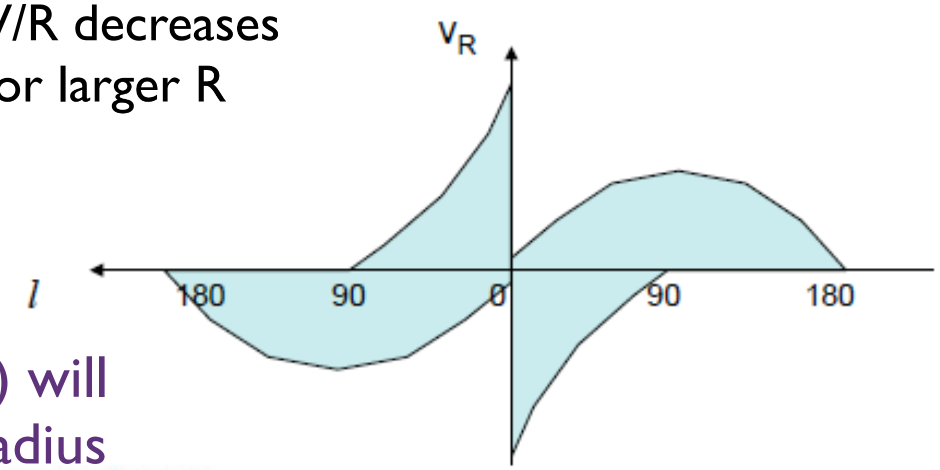
(always)

QIII, QIV — repeat QII, QI with opposite sign

Any point between the GC and us (Solar System) will move faster than us, while any point which is at larger radius from the GC will move more slowly.

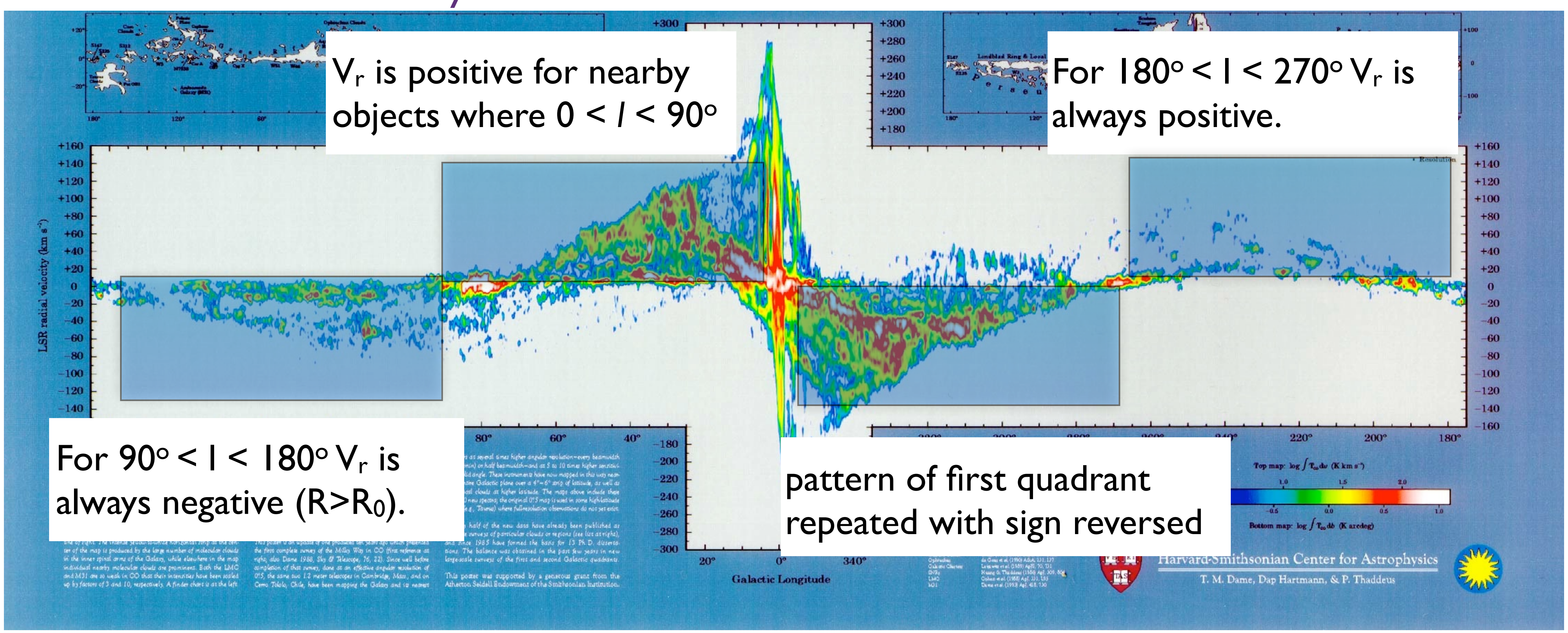
Gas motion pattern (cont.)

V/R decreases
for larger R



$$V_r = R_0 \sin l \left(\frac{V}{R} - \frac{V_0}{R_0} \right)$$ tells us

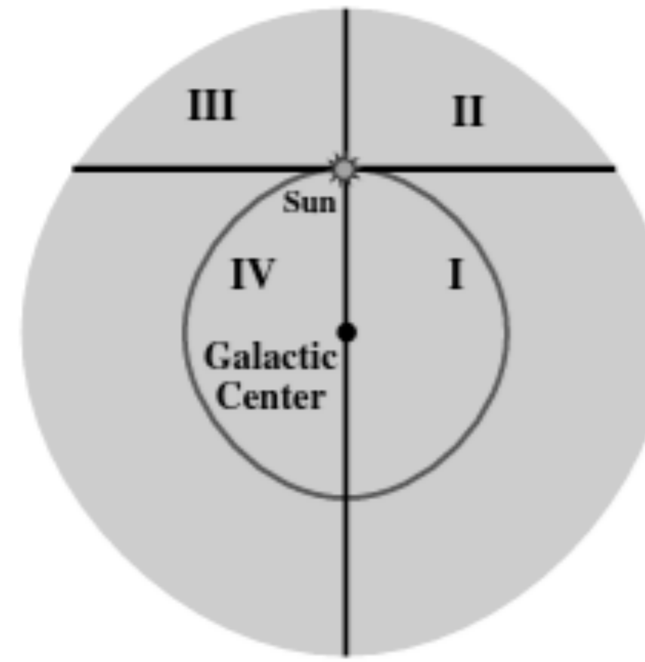
Any point that is between the GC and us (Solar System) will move faster than us, while any point which is at larger radius from the GC will move more slowly.



these HI observations of the Milky Way are reproduced in Sparke & Gallagher, Fig 2.20

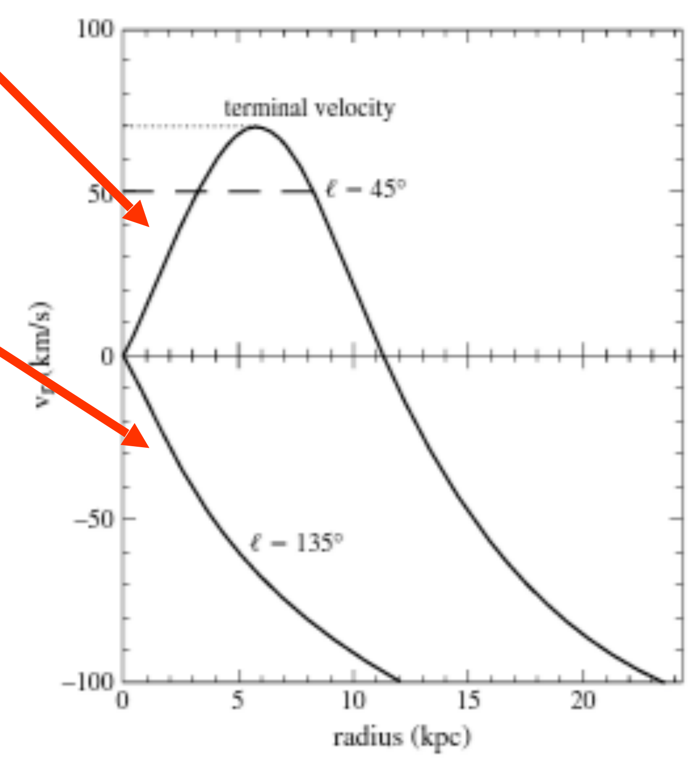
Stellar motions (cont.)

To map out v_r throughout Galaxy, divide the Galaxy into 4 quadrants based on value of galactic longitude.



Quad I (l<90) - looking at material closest to GC, [V(R) - V_0] gets larger and v_r increases. At point of closest approach (subcentral point) v_r is at maximum for that los and then continues to decrease to Sun's orbit. Beyond Sun's orbit, v_r becomes negative and increases in absolute value.

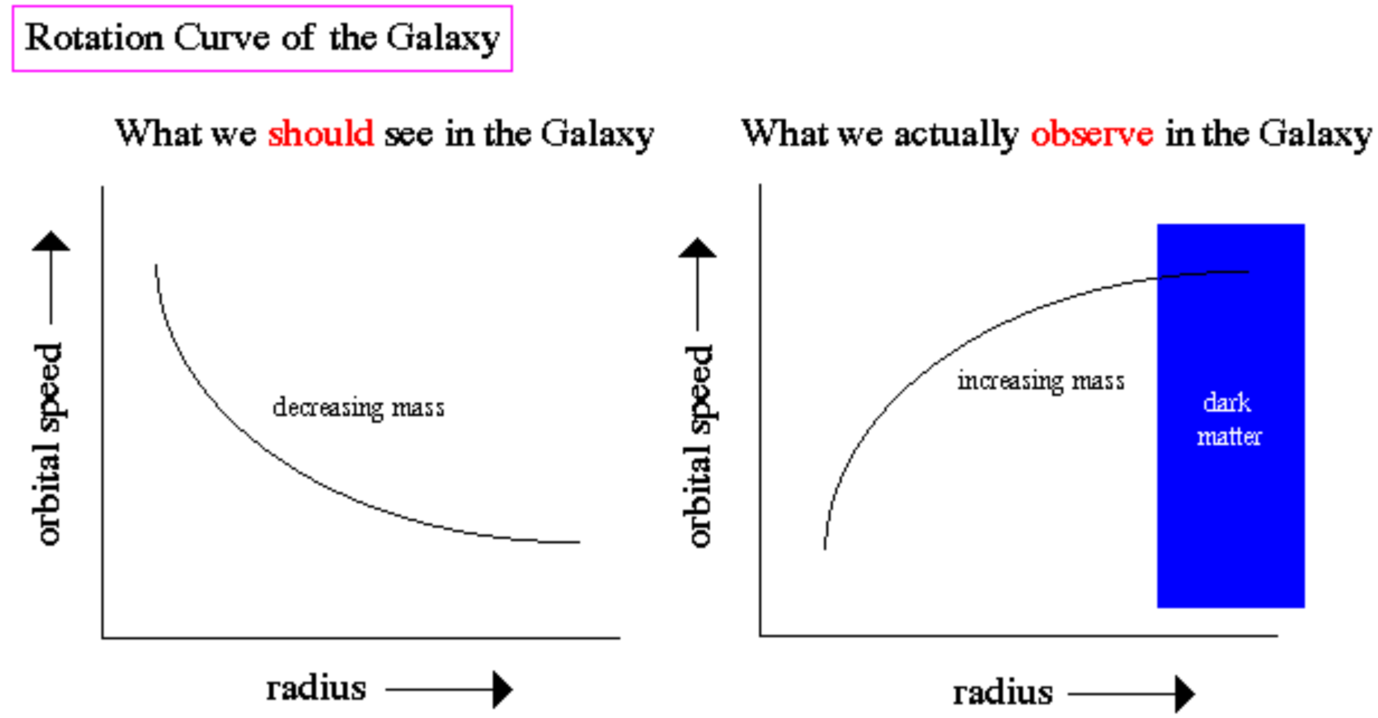
Quad II (90<l<180) - all lines of sight pass through orbits beyond the Sun No maximum v_r but absolute values increase with d.

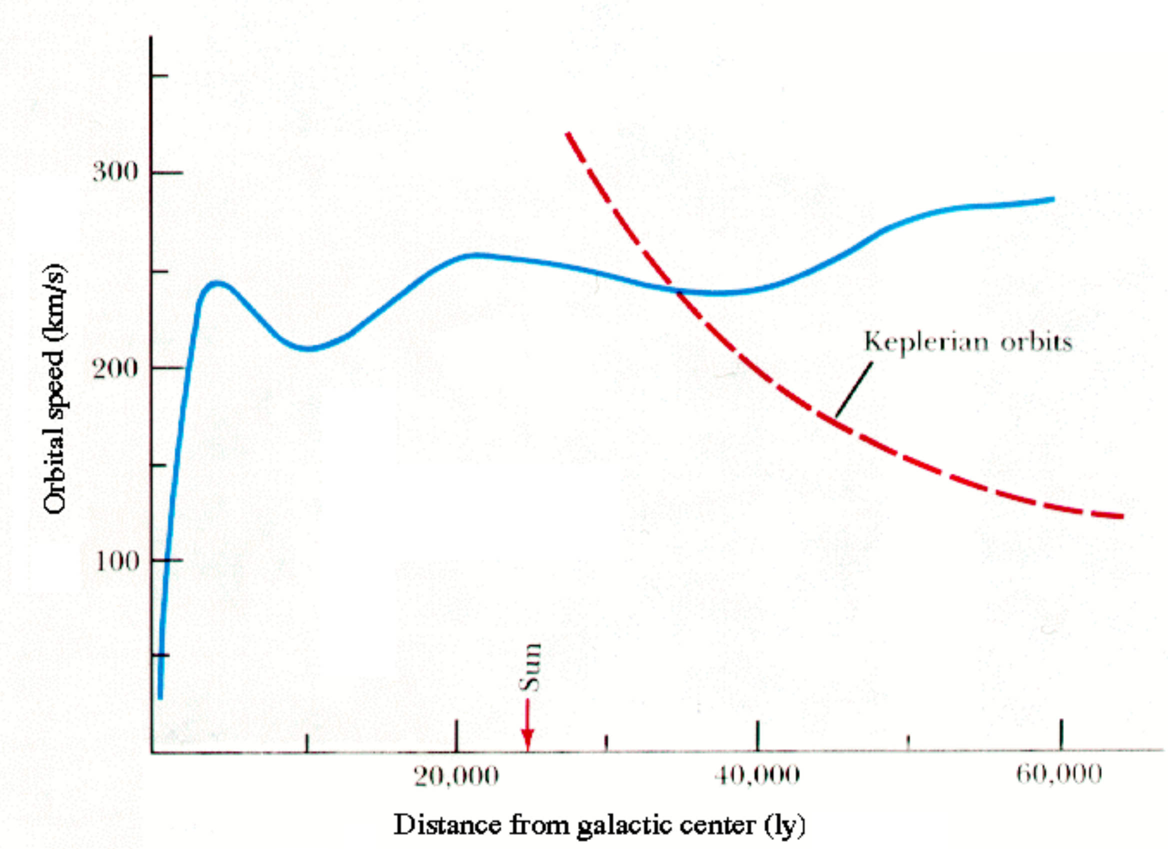


Quad III (180<l<270) - similar to Quad II but opposite signs.

Quad IV (l>270) - similar to Quad I except reverse signs.

MW Rotation


Rotation Curve of the Galaxy
What we should see in the Galaxy
What we actually observe in the Galaxy
orbital speed
decreasing mass
radius
orbital speed
increasing mass
dark matter
radius

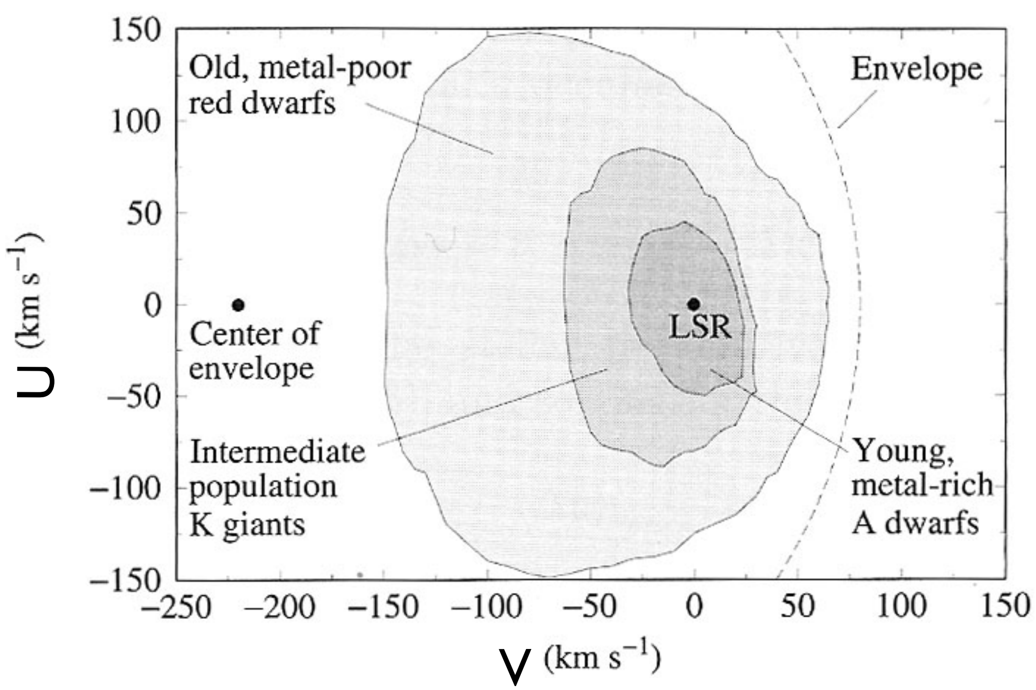

300
200
100
Orbital speed (km/s)
Keplerian orbits
Sun
20,000
40,000
60,000
Distance from galactic center (ly)

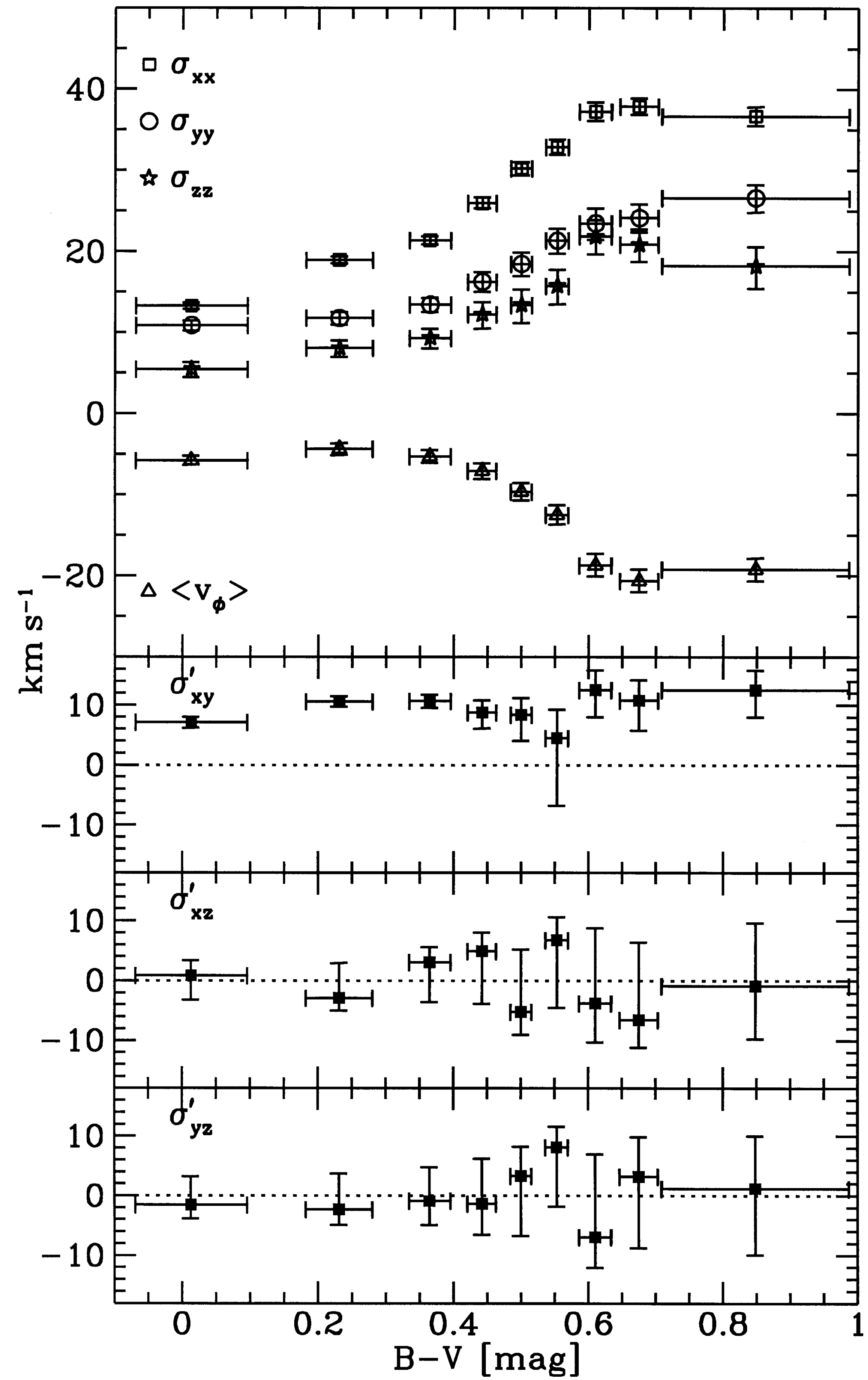
The MW disc in 3D

All velocity dispersions of MW disk stars in the Solar Neighborhood increase with color until B–V~0.6, and all stars with B–V<0.6 have ages<10 Gyr.

Random motions are clearly driven by processes that take time.

e.g., scattering by GMCs, spiral arms, graininess in MW potential, etc.



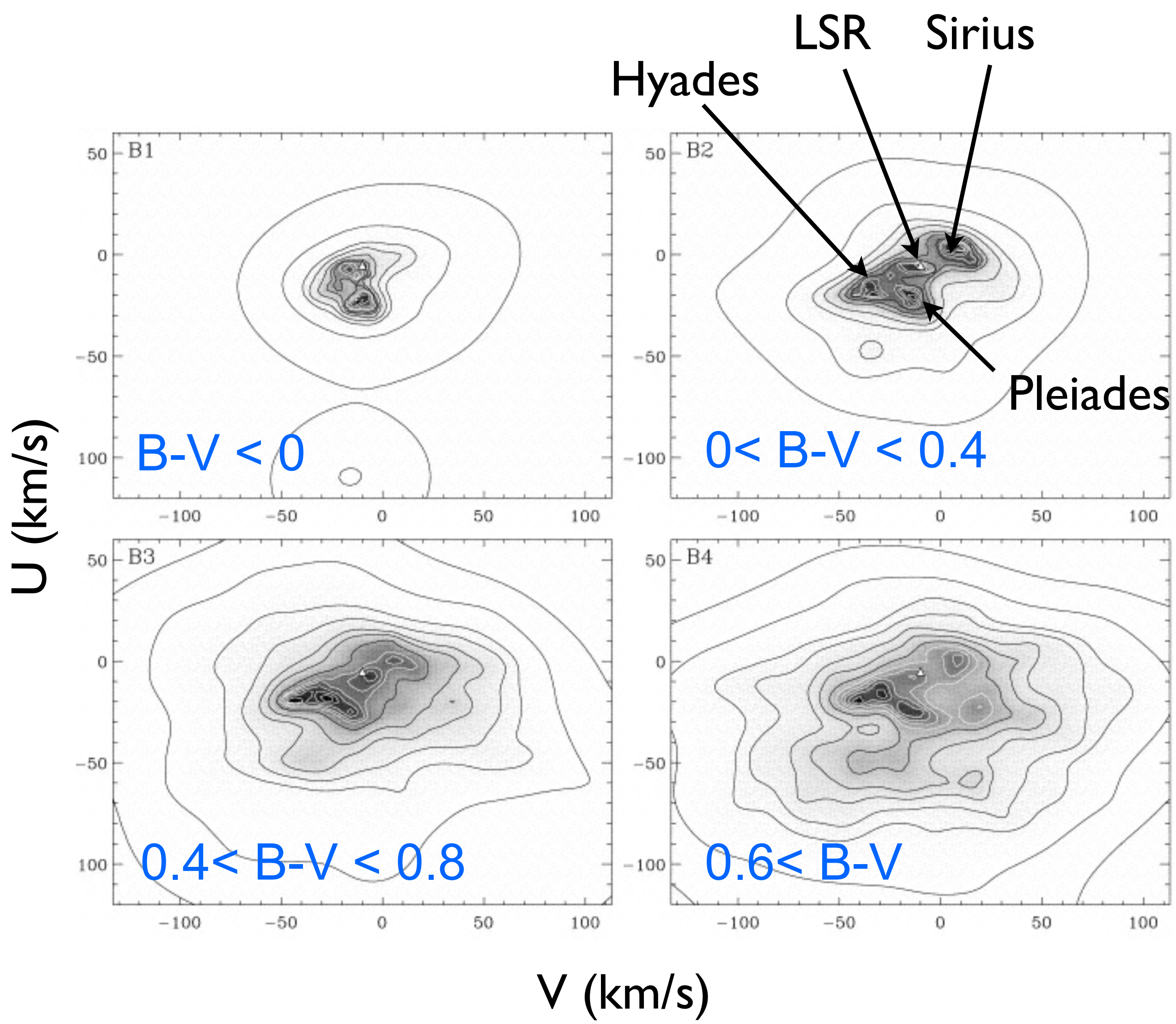


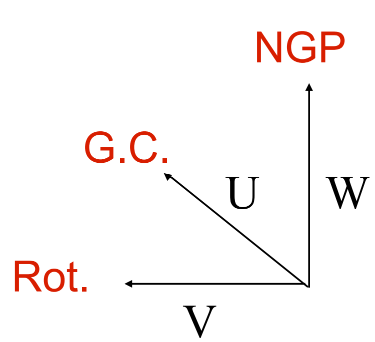
Stellar streams

The distribution of stars in velocity space is not smooth. Projections in U and V space show a lot of structure including moving groups/streams.

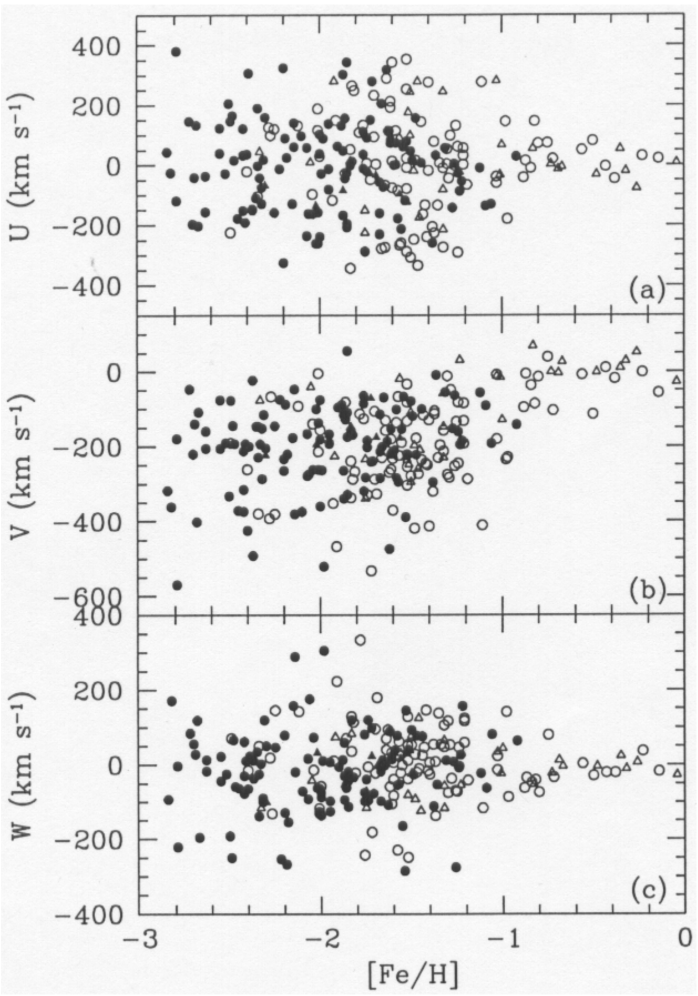
These are

Groups of stars born together and/or dynamical perturbations (due to a bar or spiral structure)





MW kinematics: bulge versus halo



The halo stars (selected by abundance) show a very-nearly Schwarzschild distribution in velocities.

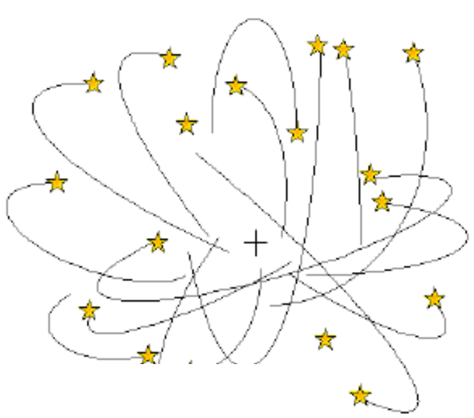
principal axes closely aligned to (R, Θ, Z) directions.

The halo does not appear to rotate and has velocity dispersions (140, 105, 95) km s^{-1}

Halo stars move on very eccentric orbits.

Large speeds means they must travel very far away from the Galactic Center.

Can be used to estimate escape velocity and thus mass of Milky Way

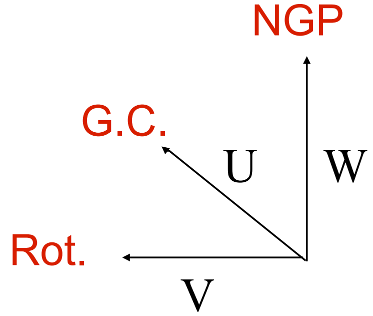


Kinematically, the bulge is not an extension of the halo

Bulge stars also have higher metallicities, closer to the disk.

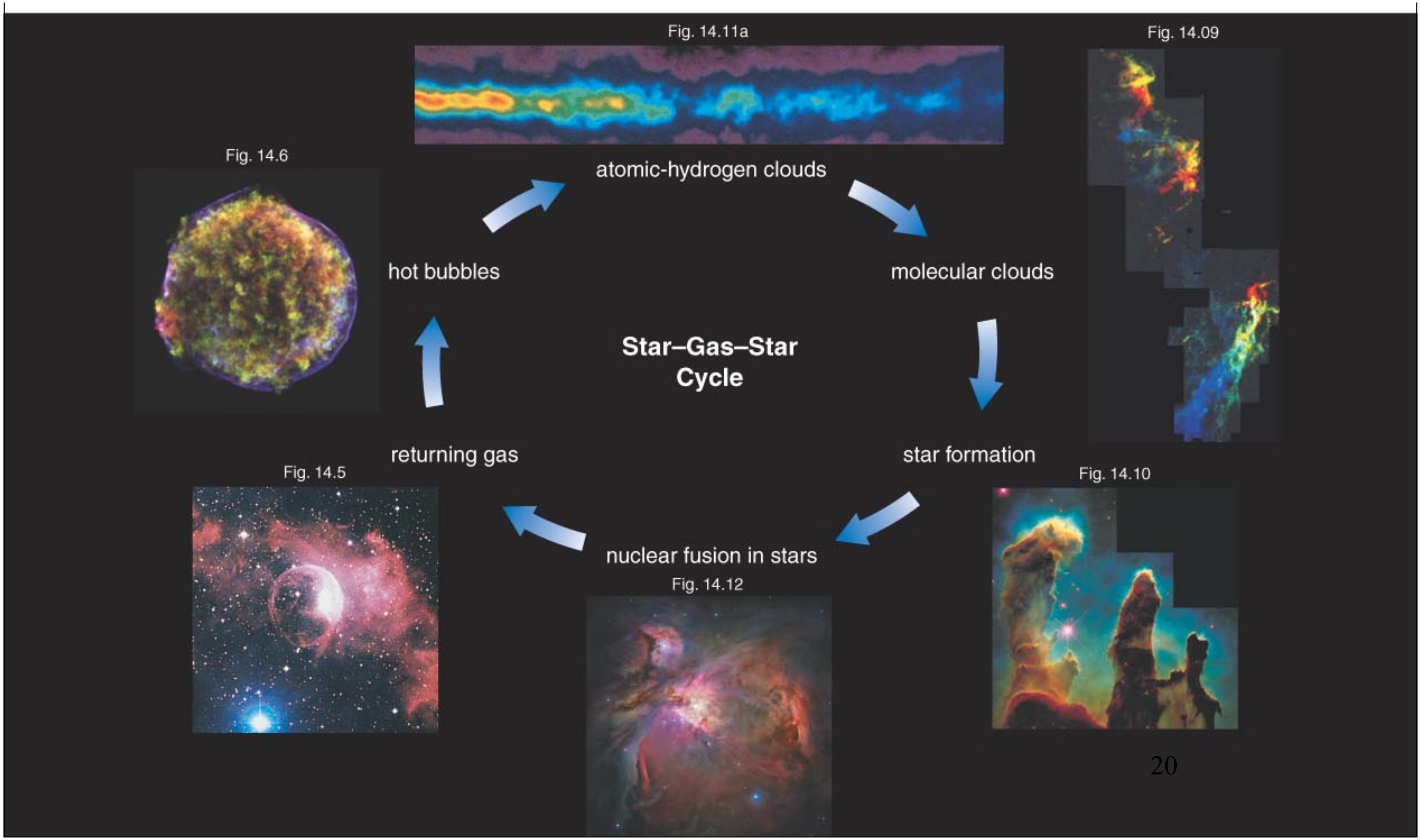
The bulge rotates at ~100 km s^{-1}

Velocity dispersion is lower than the halo but higher than the disk: $\sigma_{\rm los} \sim 60 - 110 \ {\rm km\, s^{-1}}$

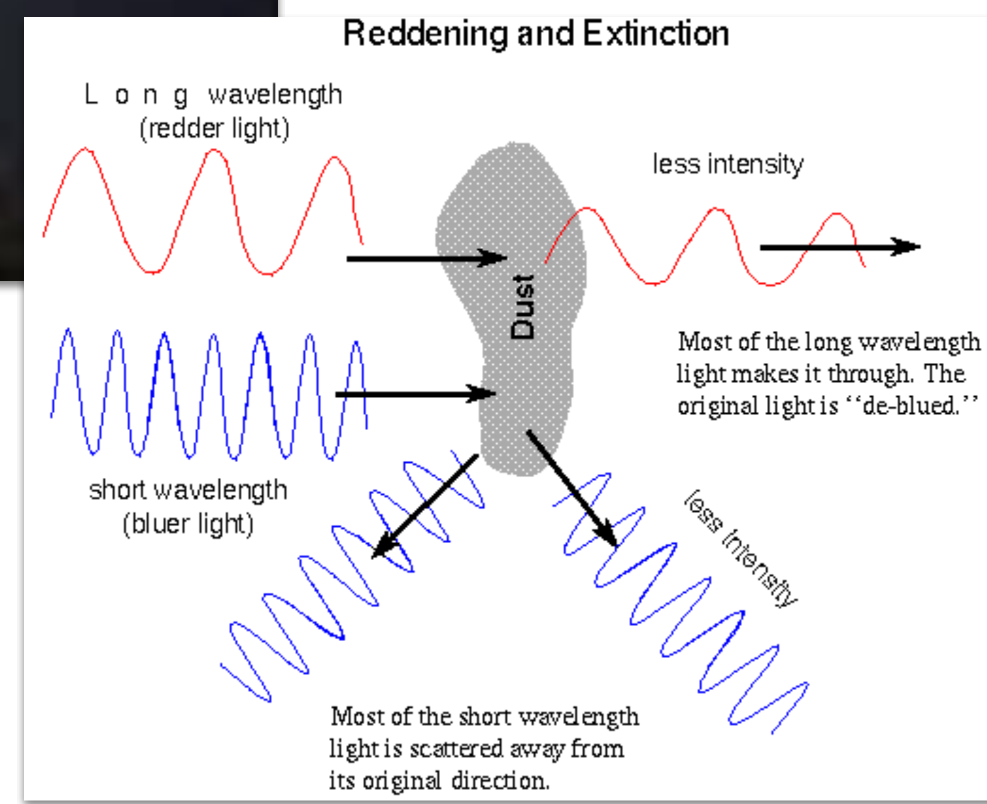


The MW’s ISM

Gas recycling

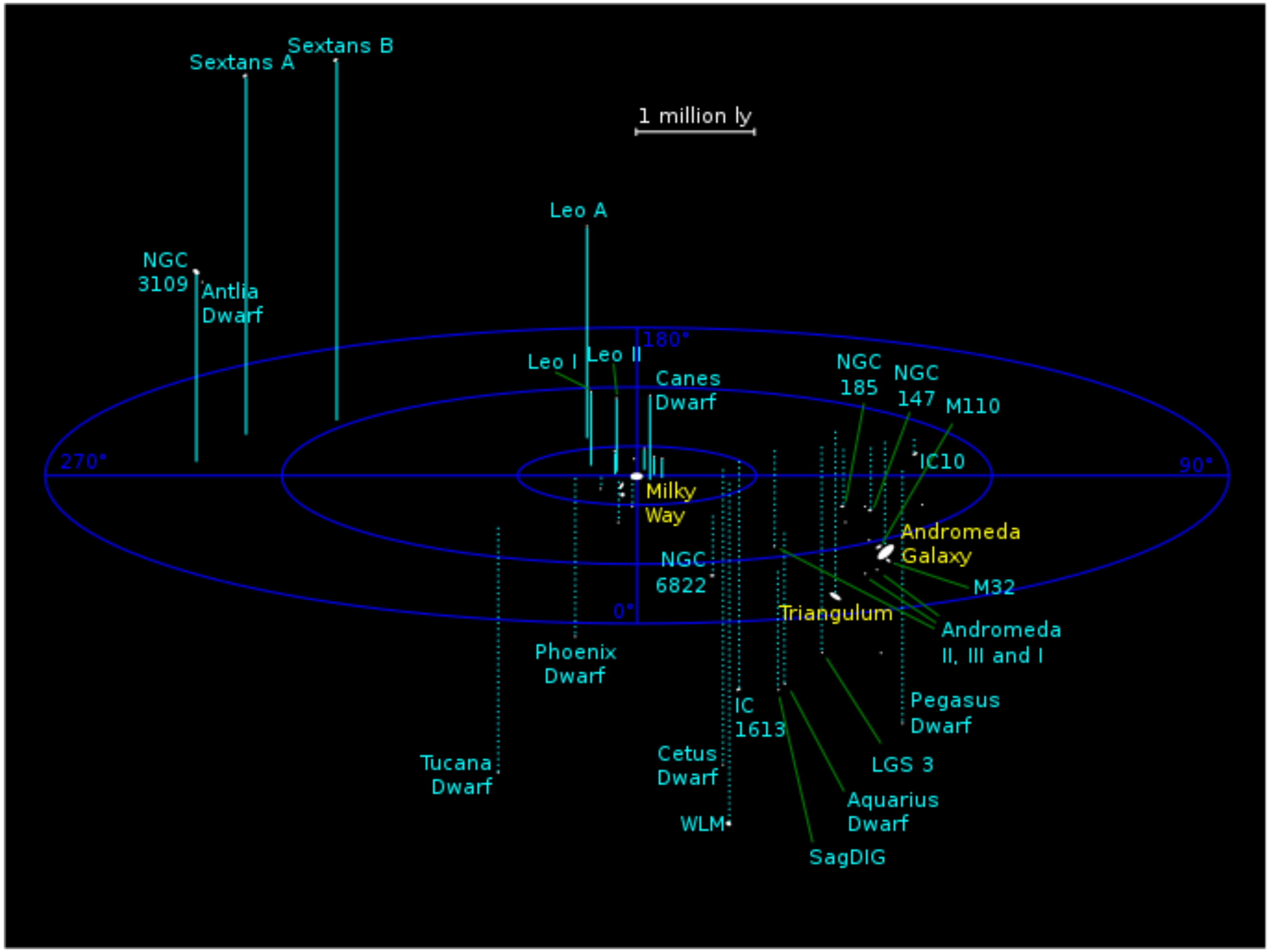


Dust in the ISM

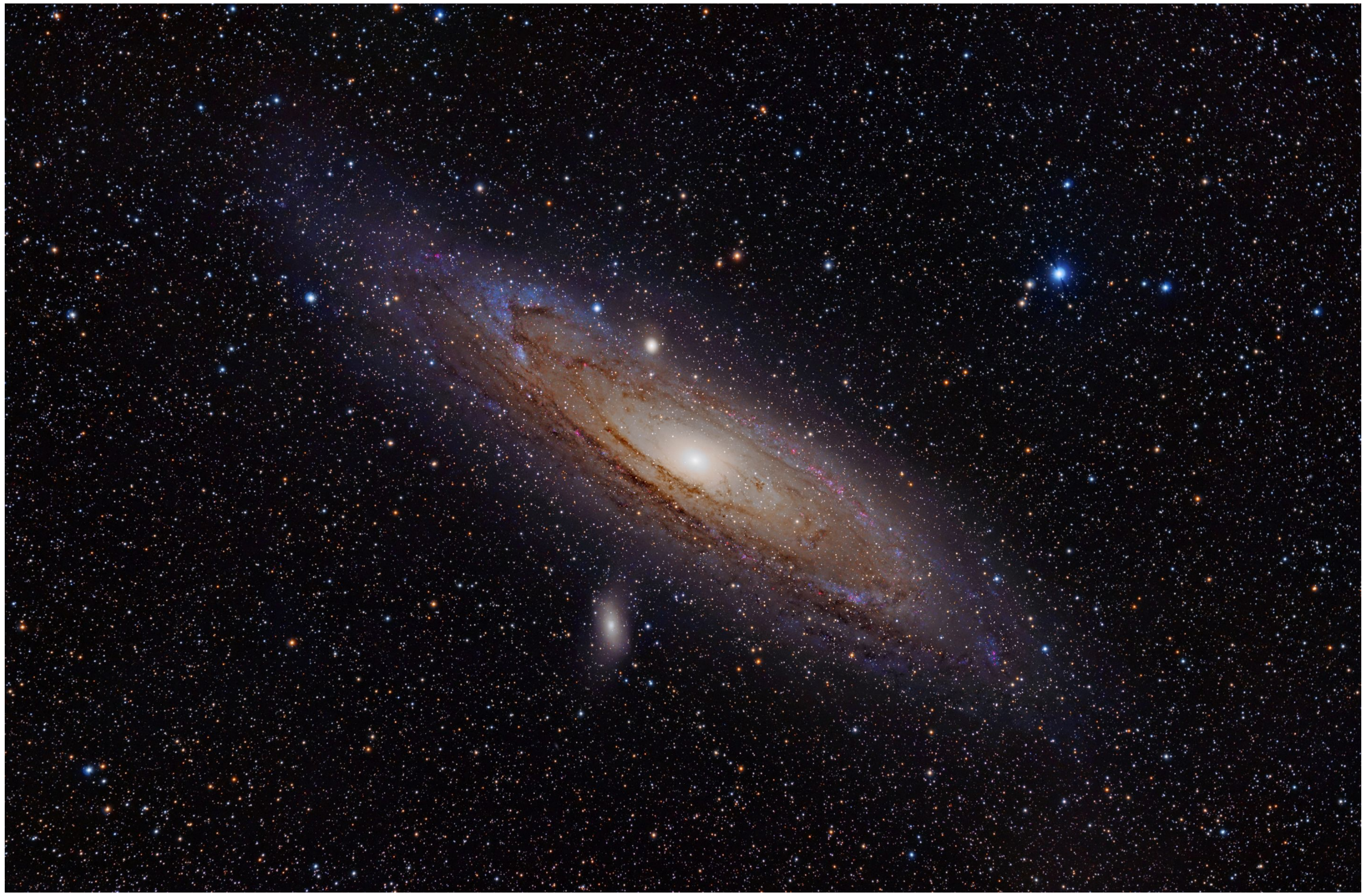


The Local Group

Components of the Local Group



Andromeda (M31)



Picture credit: A. Evans

3 x 1 sq. deg on sky

halo with metal-rich stars

1.5 x MW luminosity

1.5 x MW amount of HI

MW Satellites - the Large Magellanic Cloud

15 x 13 sq. deg on sky

~ 14 kpc

L ~ 2×10^9 Lsun

(10% MW luminosity)

barred galaxy

rich in HI

Picture credit: R. Gendler; ESO

MW Satellites - the Small Magellanic Cloud

Picture credit: S. Guisard

7 x 4 sq. deg on sky

~ 14 kpc

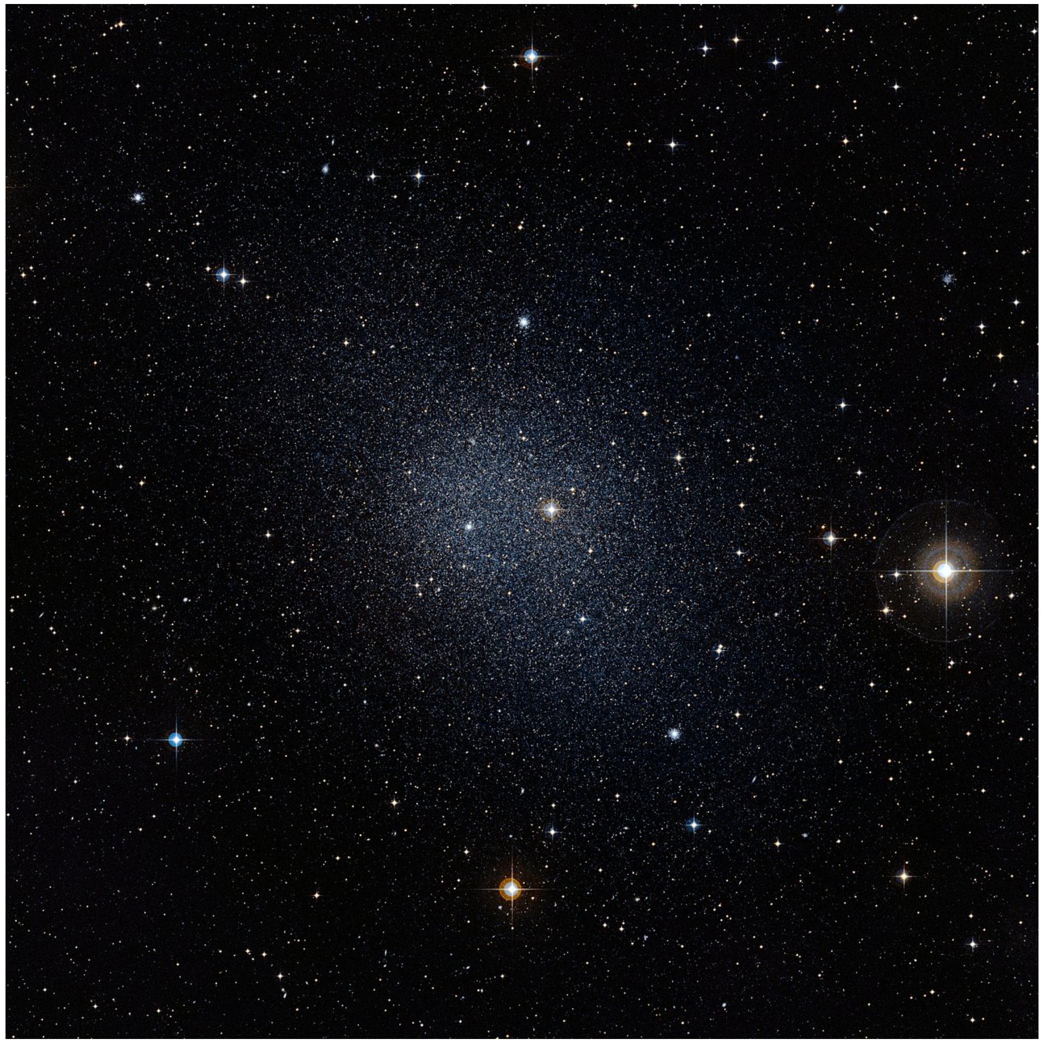
Irr galaxy

rich in HI

Dwarf spheroidal galaxies

There are at least 10 DS satellites to the MW

Fornax



Picture credit: ESO/Digitised Sky Survey 2

~ x100 fainter than LMC and SMC

rich in very old stars

similar to GC, but stars spread over distances that are x10-100

HI free