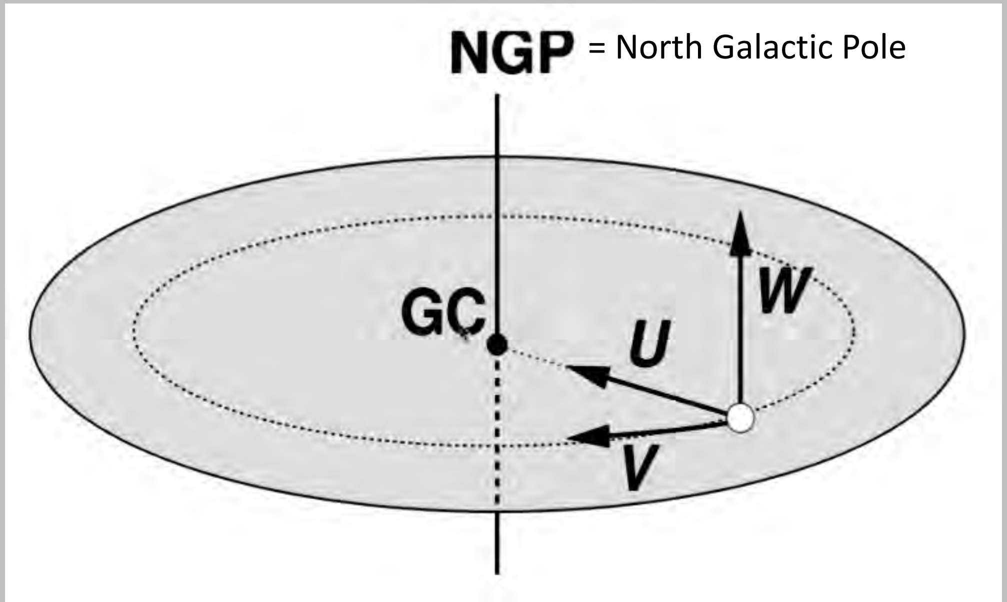
Solar Motion

How do we define the motion of the Sun? How do we even know the Sun is moving? Look at the velocities of nearby stars:

- Most stars have small velocities relative to the Sun: $\lesssim 30$ km/s.
- Metal-poor halo stars have a high relative velocity: $V_{rel} \approx 200 - 250$ km/s.

Define velocities relative the **Local Standard of Rest** (LSR), which is a point in space which is:

- located at the Sun's position (R=8.2 kpc from center);
- moving on a perfectly circular orbit around the Galaxy;
- staying exactly in the disk plane



Stars (including the Sun) will have a motion ***with respect to this LSR*** of (U, V, W) where

U	Towards/Away from GC	$+U$ is inward
V	Along the direction of rotation	$+V$ is forward
W	Up/Down out of disk plane	$+W$ is northward

So in these coordinates, a star moving on a perfectly circular orbit has $(U, V, W) = (0,0,0)$ km/s.

Solar Motion

How do we measure the Sun's motion relative to the Local Standard of Rest?

Imagine looking at the radial velocities (v_r) and proper motions (μ) of stars in all directions around us. Stars around us, on average, should be moving with the LSR (even though any individual star may not be!).

If the Sun was moving with the LSR, then the average velocities of stars in all directions around us should be zero. But if the Sun is moving in a particular direction, then stars in that direction should on average be moving towards us.

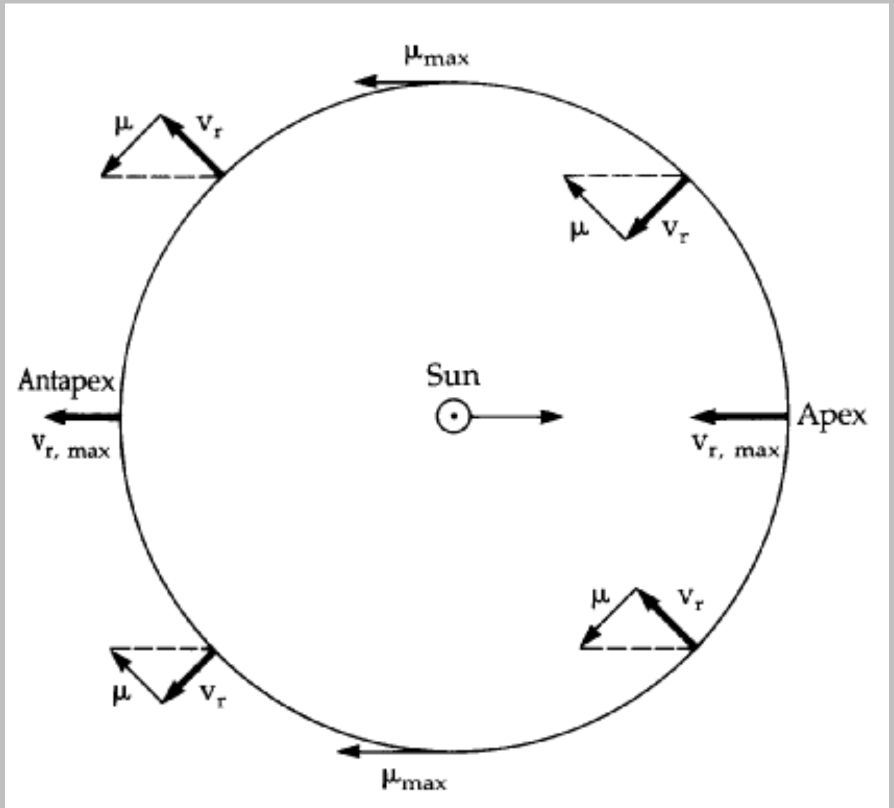
By measuring the average motions of stars in all directions, we derive the Sun's peculiar motion with respect to the LSR:

$(U_\odot, V_\odot, W_\odot) = (+11, +12, +7)$ km/s (Schoenrich+10)

So the Sun is moving:

- a bit towards the Galactic Center ($U_\odot = +11$ km/s)
- a bit faster than the LSR ($V_\odot = +12$ km/s)
- a bit northward out of the Galactic Plane ($W_\odot = +7$ km/s)

Remember: this is doesn't include the rotation speed ($V_{circ} \approx 220$ km/s).



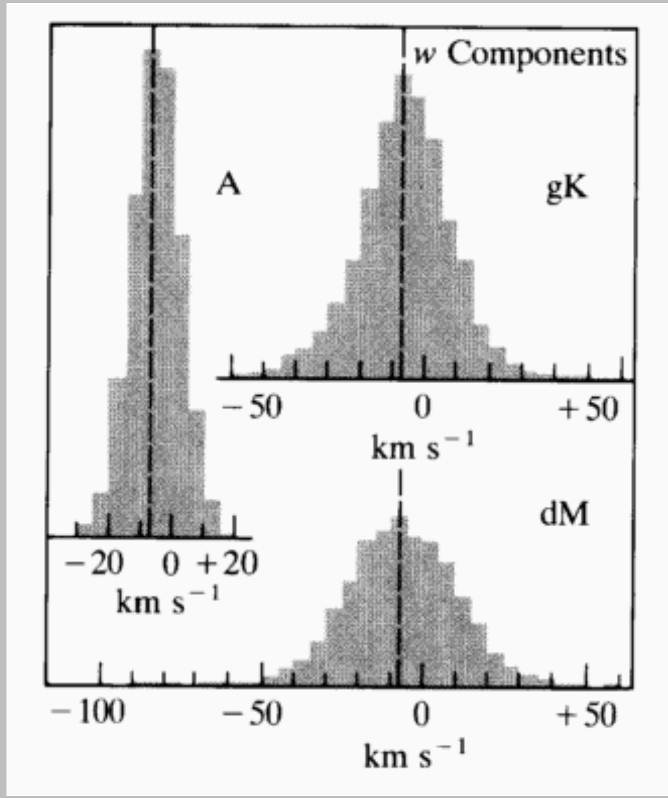
The Velocities of stars

Look at a histogram of W (vertical) velocities of samples of stars with different spectral types:

- A stars: fairly massive main sequence stars
- gK: evolved red giant stars
- dM: low mass main sequence stars

Notice:

- The average velocity of each sample is ≈ -7 km/s. *Why?*
- The spread in velocity is smaller for A stars than for gK and dM stars. *Why?*



Add in B stars and white dwarfs (WD), and compare velocity dispersion and scale height (thickness) of the different populations

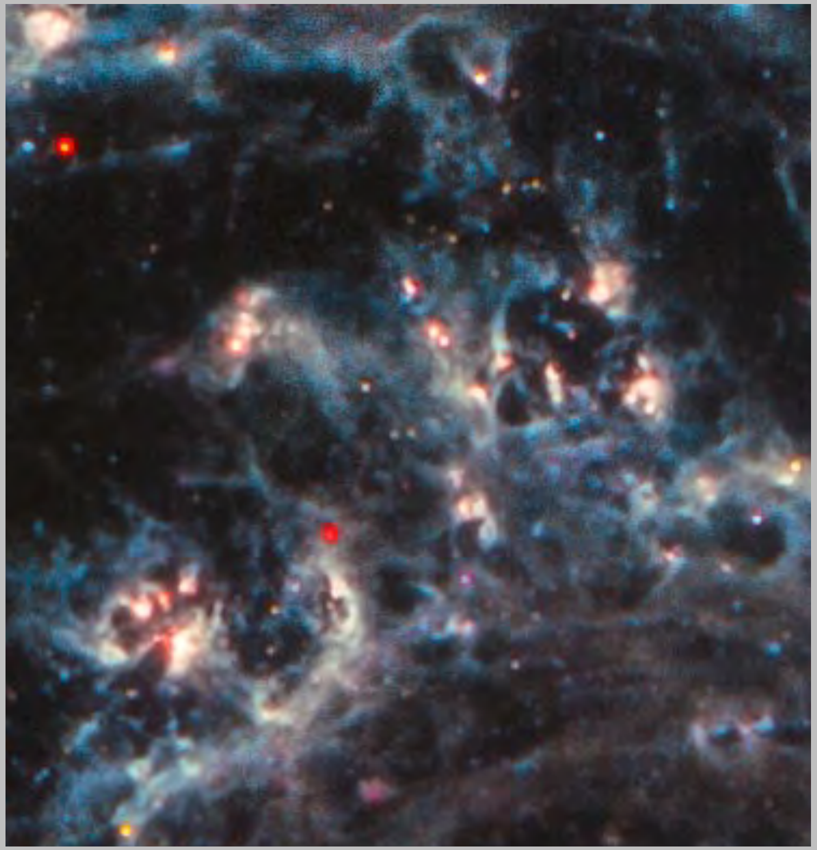
Increasing Mean Age ↓

Stars	Velocity Dispersion	Scale height
B	6 km/s	60 pc
A	9 km/s	120 pc
gK	17 km/s	270 pc
dM	18 km/s	350 pc
WDs	25 km/s	500 pc

Questions:

- Why does velocity dispersion increase with age?
- Why does velocity dispersion correlate with scale height?

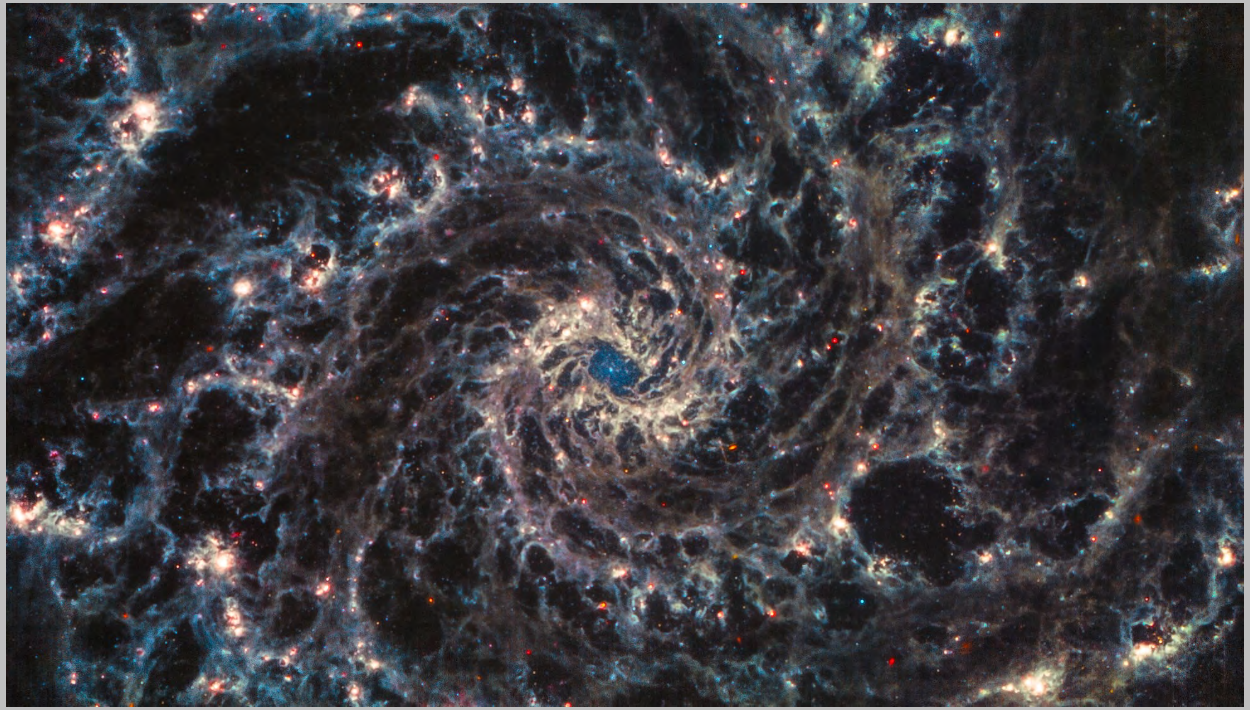
Disk Heating



The Galaxy's disk is not perfect smooth: there are lumps of material on large scales (spiral arms, the bar) and small scales (giant molecular clouds).

Stars are born from interstellar gas which moves on nearly circular orbits, and so newly formed stars also move on nearly circular orbits.

But over time, gravitational encounters with spiral arms and giant molecular clouds can scatter stars, increasing their random motions. As a group, their velocity dispersion increases with time. This process is called "disk heating."



Vertical velocity dispersion and the Oort Limit

Why would velocity dispersion and scale height correlate? Because of gravitational balance.

Think of a star oscillating up and down in the disk, held by the gravitation force of some mass *M*. We can balance kinetic and potential energy: $\frac{1}{2}m_* v_z^2 \cong \frac{GMm_*}{z}$ or, more simply: $v_z^2 \cong \frac{2GM}{z}$.

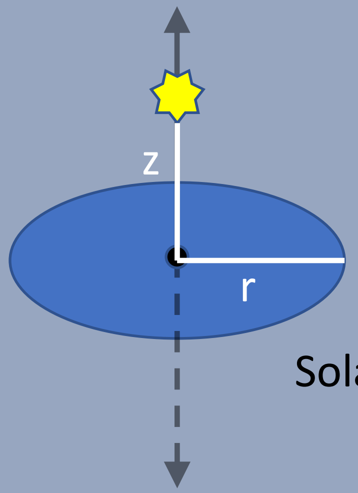
What is M? think of a patch of the disk with radius r and surface density Σ_0 (in $M_\odot/pc^2$). It will have a mass of $M = \Sigma_0 \pi r^2$.

If $r \approx z$, we can put that in for M and get $v^2 \cong 2\pi G \Sigma_0 z$

Now consider of a group of stars. Replace individual values (v^2, z) with group values (σ_W^2, h_z) to get: $\sigma_W^2 \sim 2\pi G \Sigma_0 h_z$

This is known as the **Oort Limit**, and can be used to estimate the total mass density of the Galactic disk in the solar neighborhood.

Current estimates come in around $\Sigma_0 \approx 70\ M_\odot/pc^2$ or so.



Solar neighborhood

Galactic disk

Compare

Inventory of Stars and Gas	
Stars	$\Sigma_{stars} \approx 37\ M_\odot/pc^2$
Gas (HI+H_2)	$\Sigma_{gas} \approx 13\ M_\odot/pc^2$
Total	$\Sigma_{tot} \approx 50\ M_\odot/pc^2$

The Rotation of the Milky Way

The circular velocity of the disk at the Sun's distance from the Galactic center ($R_0 = 8.2$ kpc) is $V_c \approx 230$ km/s.

From this we can derive:

- The orbital period of the Sun:

$$T = \frac{2\pi R_0}{V_c} = \frac{2\pi(8200)}{230} \approx 225 \text{ Myr.}$$

because 1 km/s ≈ 1 pc/Myr!

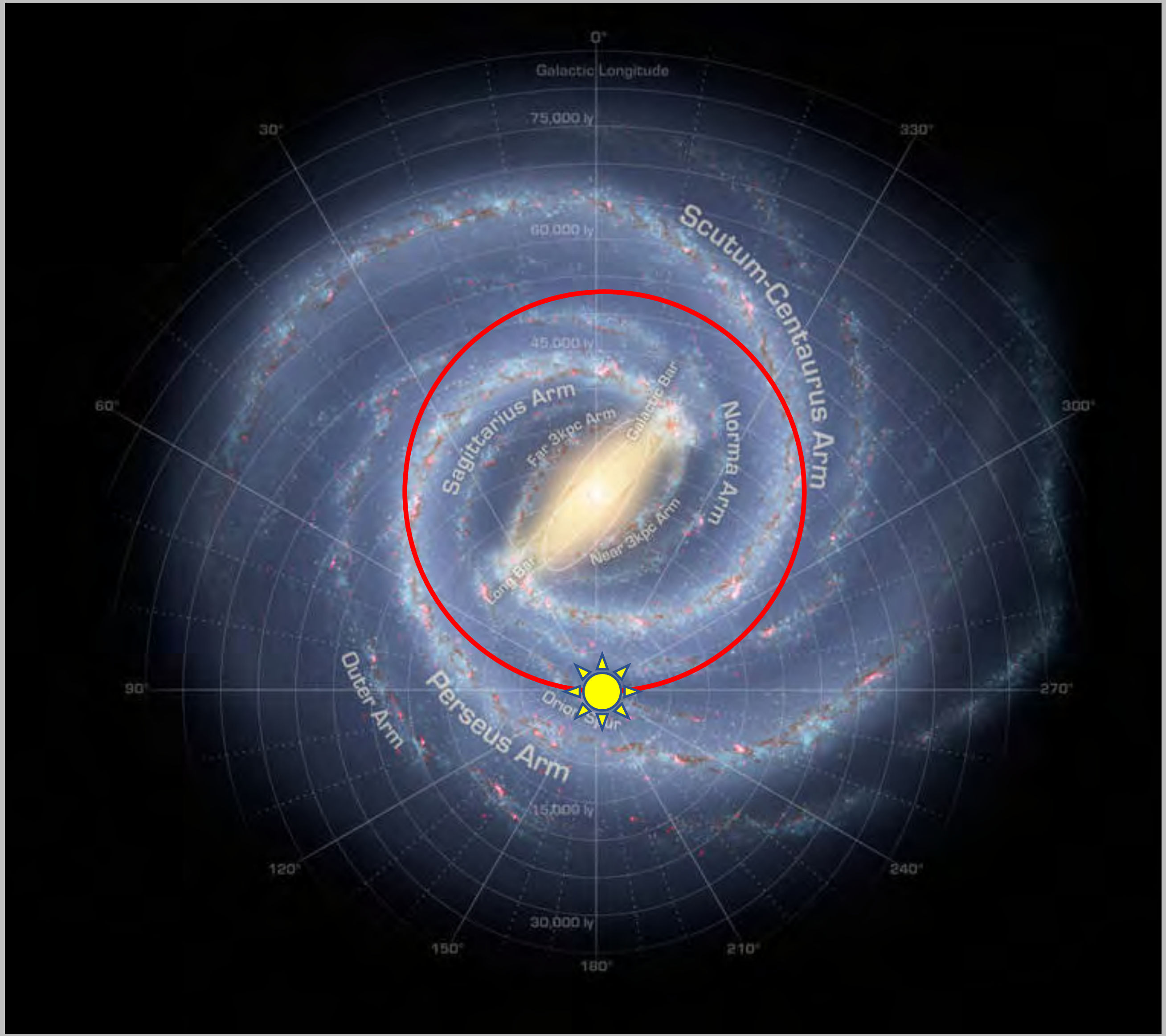
- The Galaxy's mass inside R_0:

$$M(< R_0) = \frac{V_c^2 R_0}{G} = \frac{(230^2)(8200)}{4.43\times10^{-3}} \approx 10^{11}\ M_\odot$$

using [pc,km/s,$M_\odot$] version of G!

But what about the rotation speed at other radii?

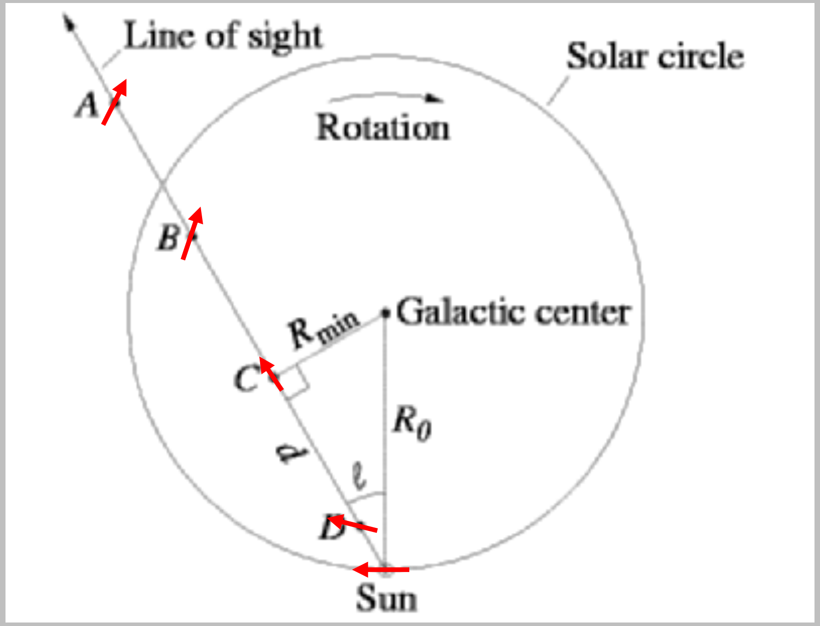
- *What does the rotation curve $V_c(R)$ look like?*
- *What would we **expect** it to look like?*

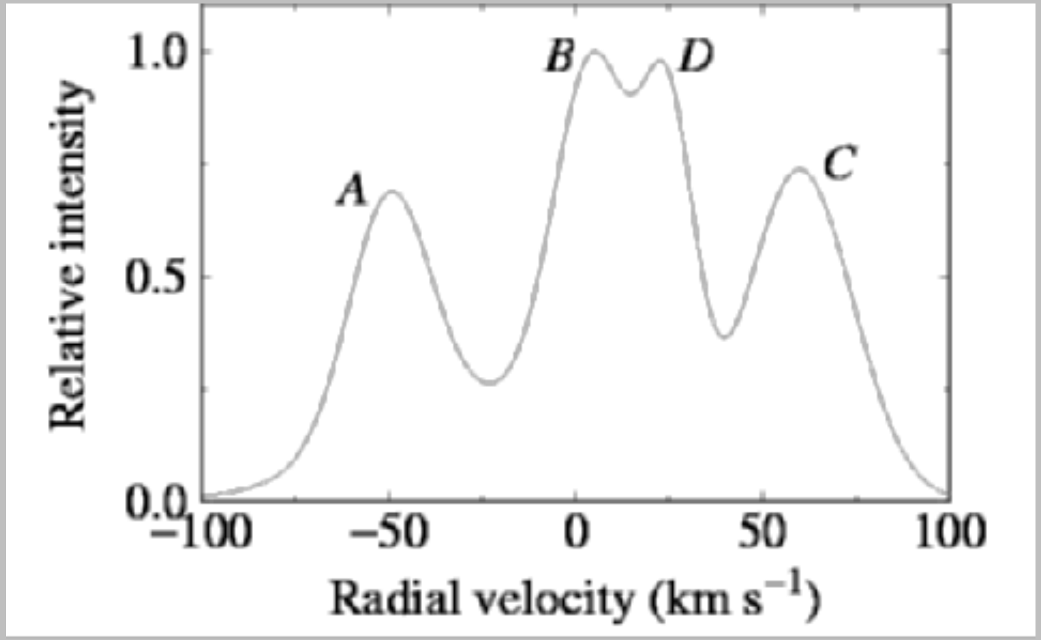


Measuring the Milky Way Rotation Curve

Want to map velocities of objects in the disk moving on ***circular*** orbits. What kinds of objects are these? *gas clouds!*

21-cm HI emission: no extinction at radio wavelengths. Map the HI velocities as a function of Galactic longitude, look for maximum velocity. Imagine gas clouds strung out along some line of sight, and the velocities you measure:





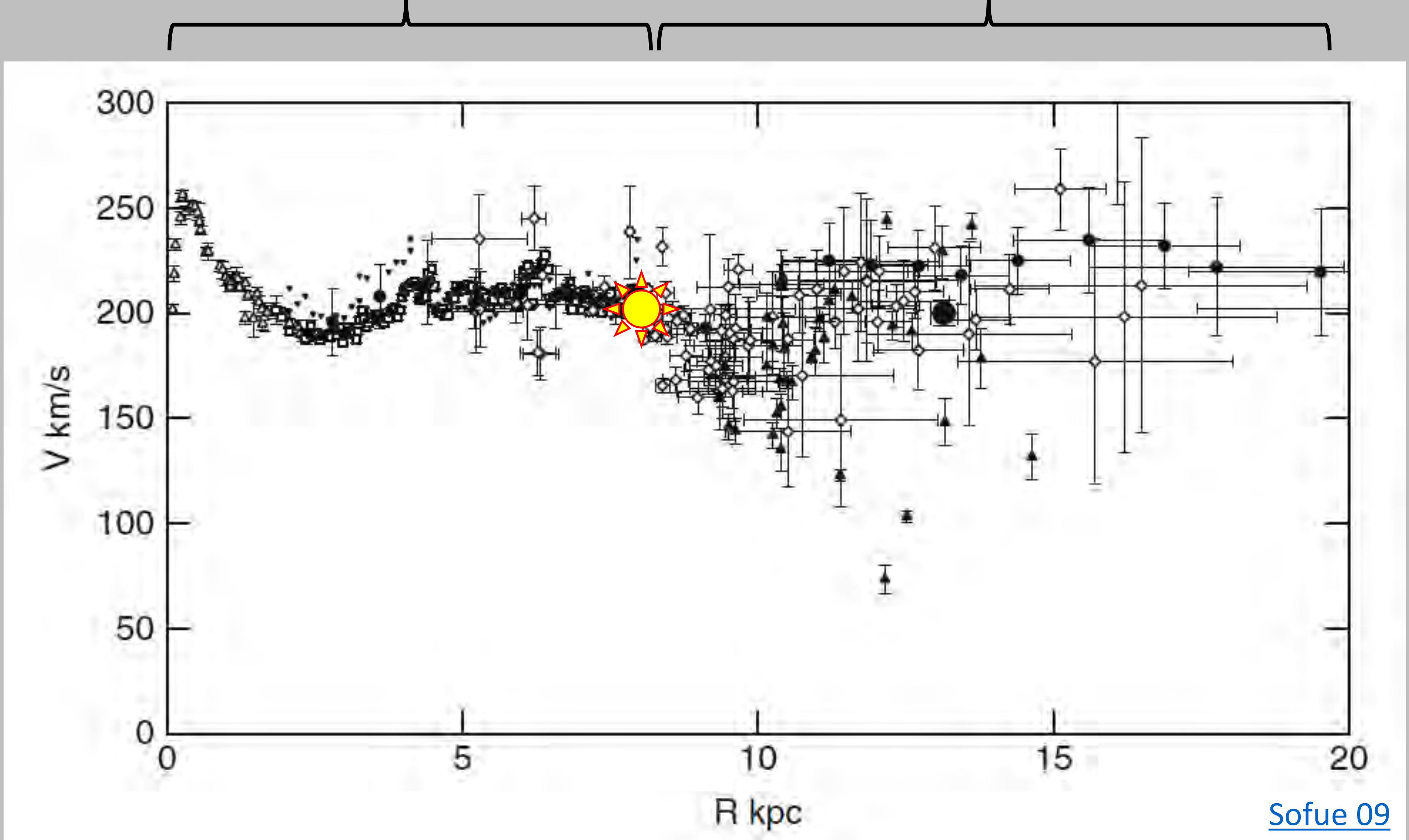
After taking out the Sun's motion, the line of sight velocity of cloud C should be the circular speed at $R_{min} = R_0 \sin \ell$.

Works well inside the solar circle: $R < R_0$. Beyond that, there is no tangent point and actual distances are needed. Use other tracers of young stars: Cepheids, HII regions, etc.

Milky Way Rotation Curve

Inside R_0 the tangent point method works well.

Outside R_0 we need distances to objects, which increases uncertainties.



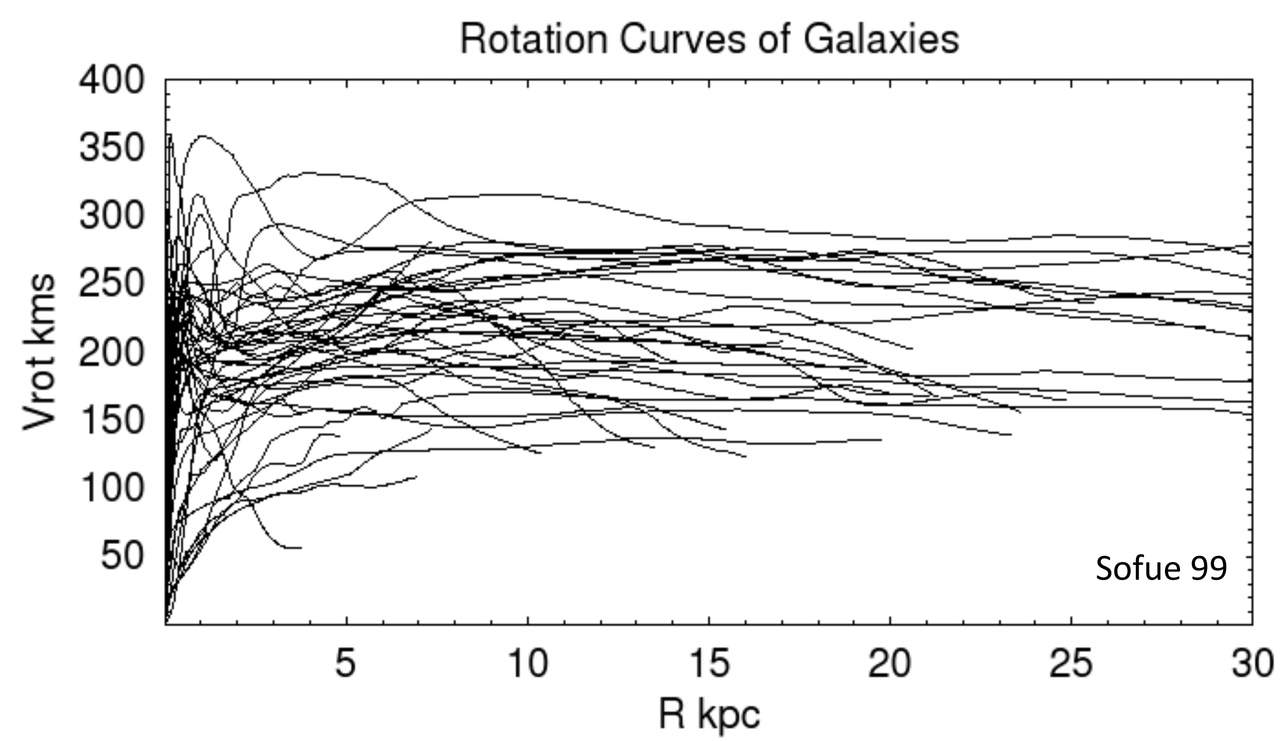
Flat Rotation Curves

The rotation curve of the Milky Way (*and nearly all other spiral galaxies!*) is essentially **flat:** $V_c(R) \approx$ constant.

What does this mean? Think about dynamical mass:

$$V_c{}^2(R) = \frac{GM(<R)}{R} \quad \longrightarrow \quad M(<R) = \frac{RV_c{}^2(R)}{G}$$

If $V_c(R) =$ constant, then M grows as R: there is more and more mass at larger and larger distances from the center! This is most definitely ***not*** how the stars are distributed!



Evidence for a lot of mass as far out as 100 kpc or more!

Total dynamical mass $\approx 10^{12}\ M_\odot$
Total star + gas mass $\approx 10^{11}\ M_\odot$

So roughly 90% of the mass in galaxies like the Milky Way is unseen "dark matter."

The Dark Matter Halo

Doesn’t emit light (at any wavelength)
Doesn’t absorb light (at any wavelength)

The only way to detect (so far) it is through gravitational motions.

What could it be?

- low mass stars (brown dwarfs)?
- dark interstellar gas clouds?
- free floating space donkeys?

No! Anything made of normal matter (a.k.a. “baryonic matter”) is ruled out by cosmological considerations.

Two classes of solutions:

- **Particle physics:** hypothetical new class of particles, never observed or detected.
- **Gravity:** The law of gravity changes in ways we dont understand, so motion does not imply large unseen mass.