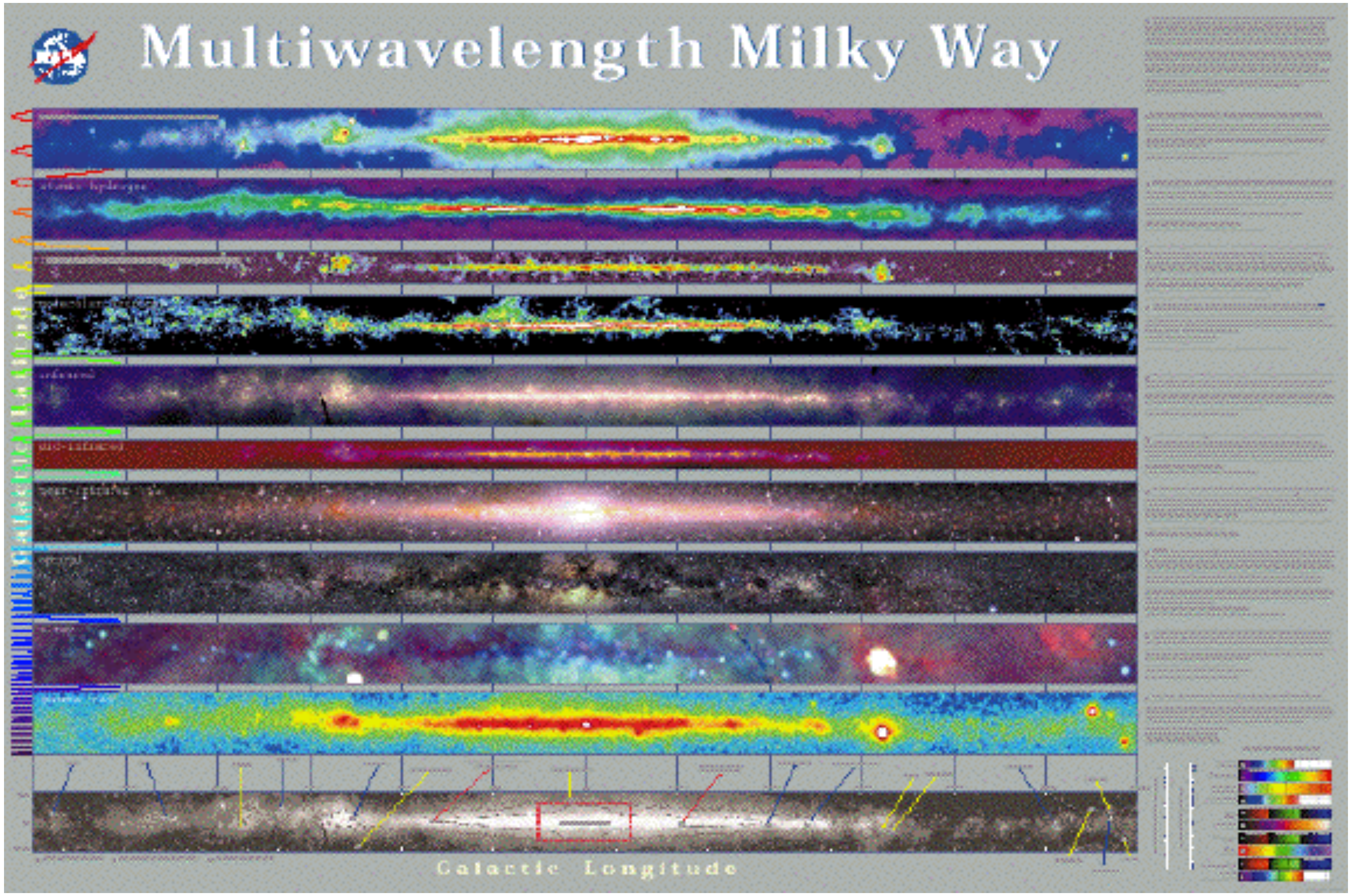
Our Milky Way (MW) Galaxy

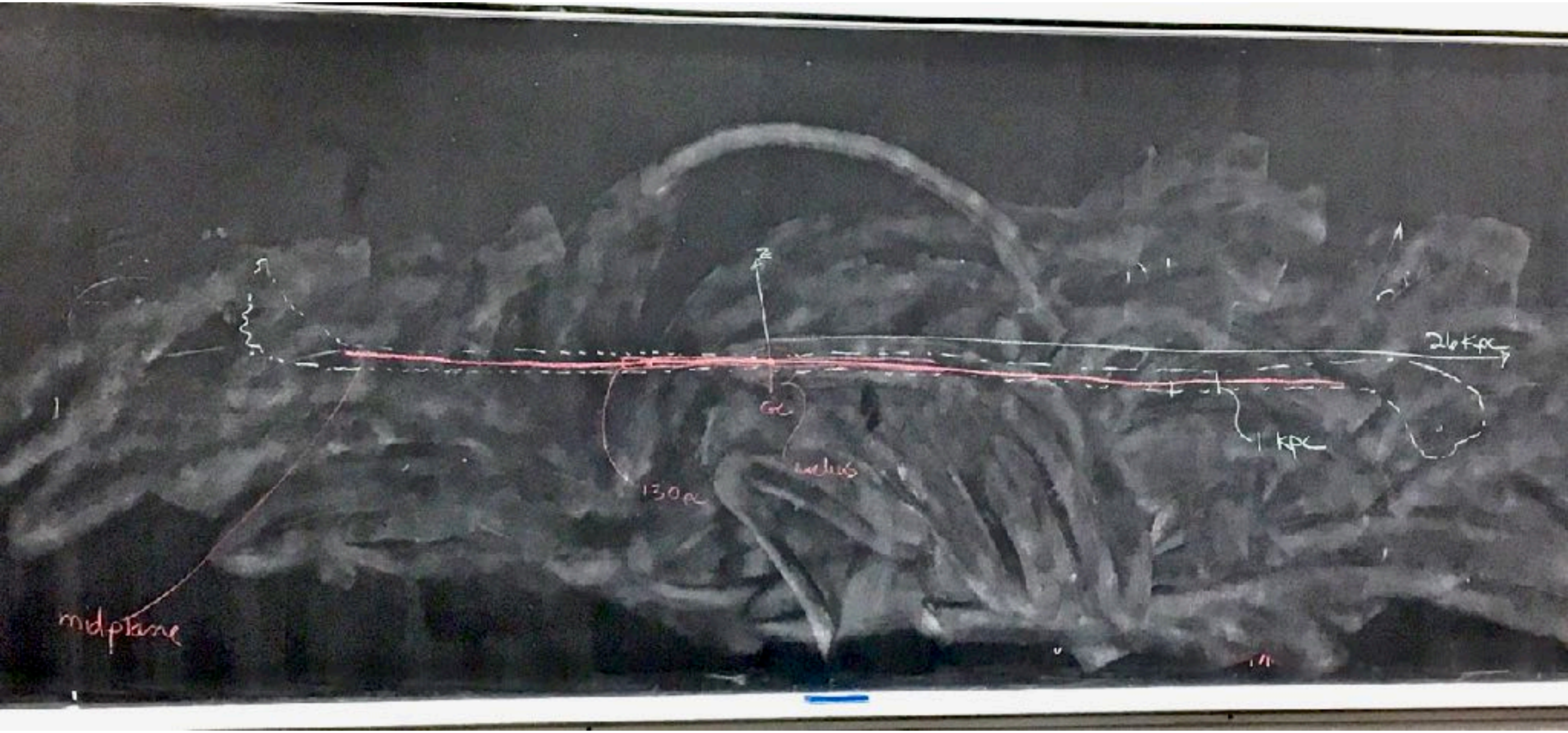
L*, M* but not SFR*



(SFR is less than 5 solar mass per year)

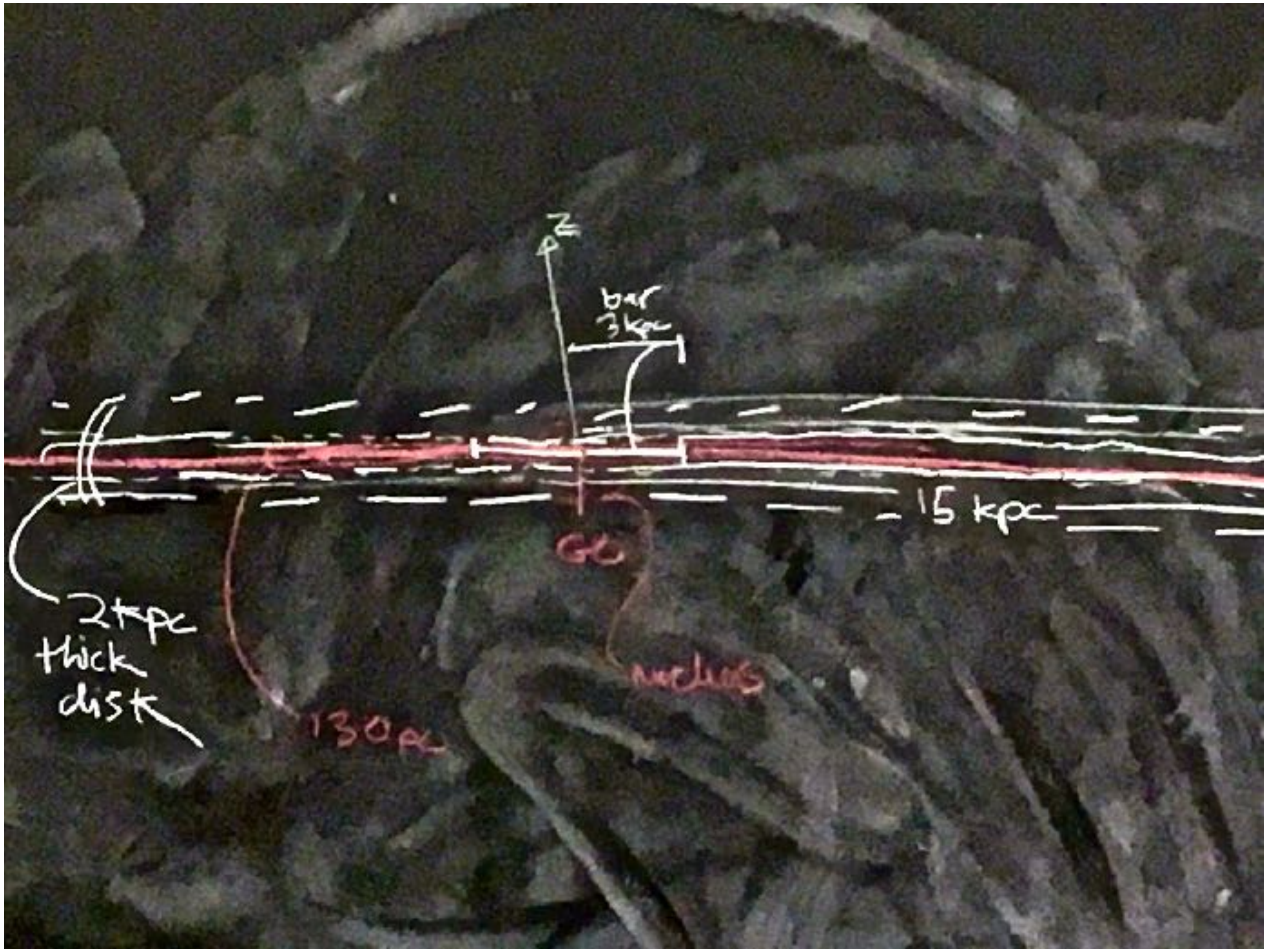
(Our galaxy is revered as “**G**alaxy” and others are merely “**g**alaxy” ;-) .)

MW Structure Diagram



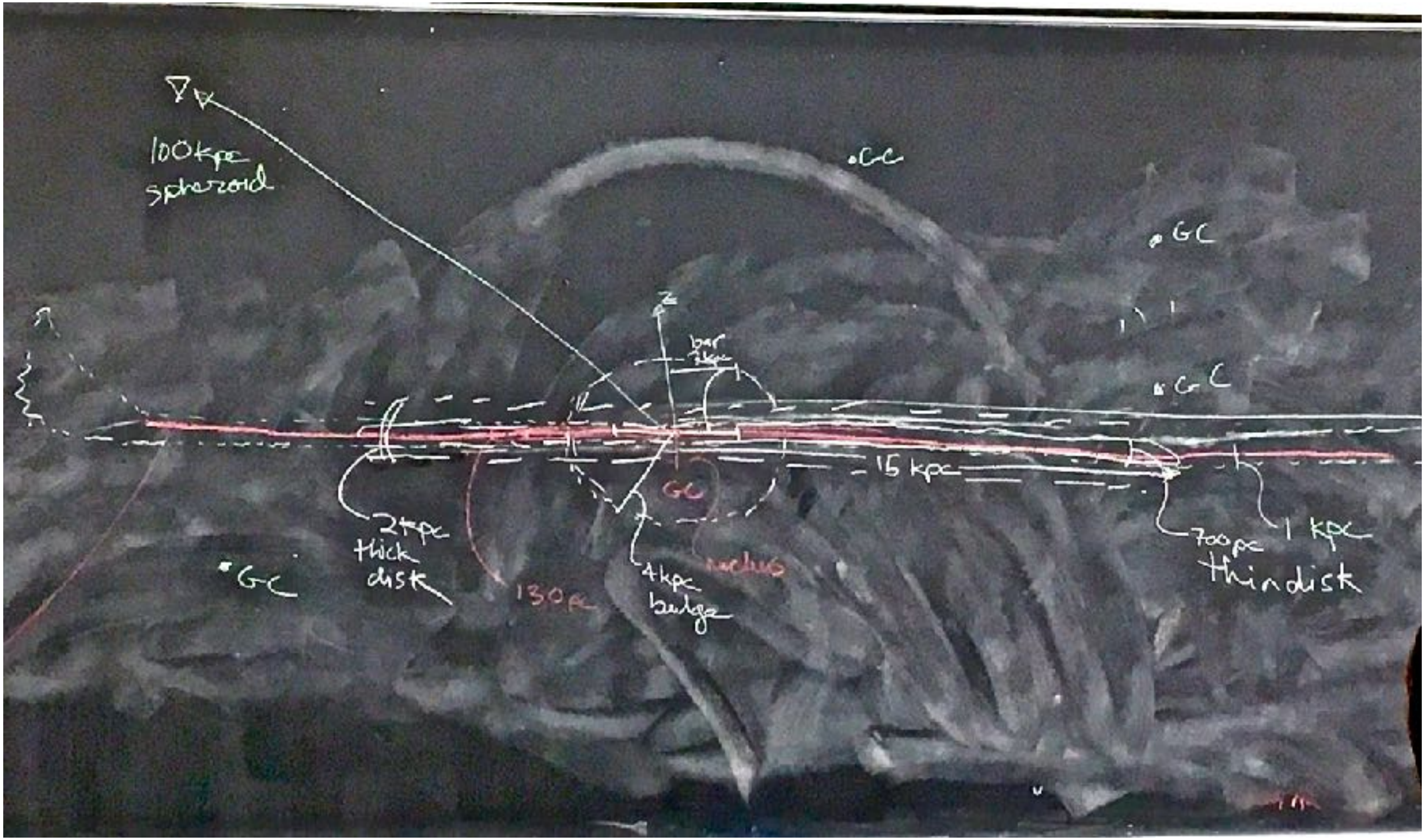
- Midplane
- molecular layer
- HI layer

MW Structure Diagram



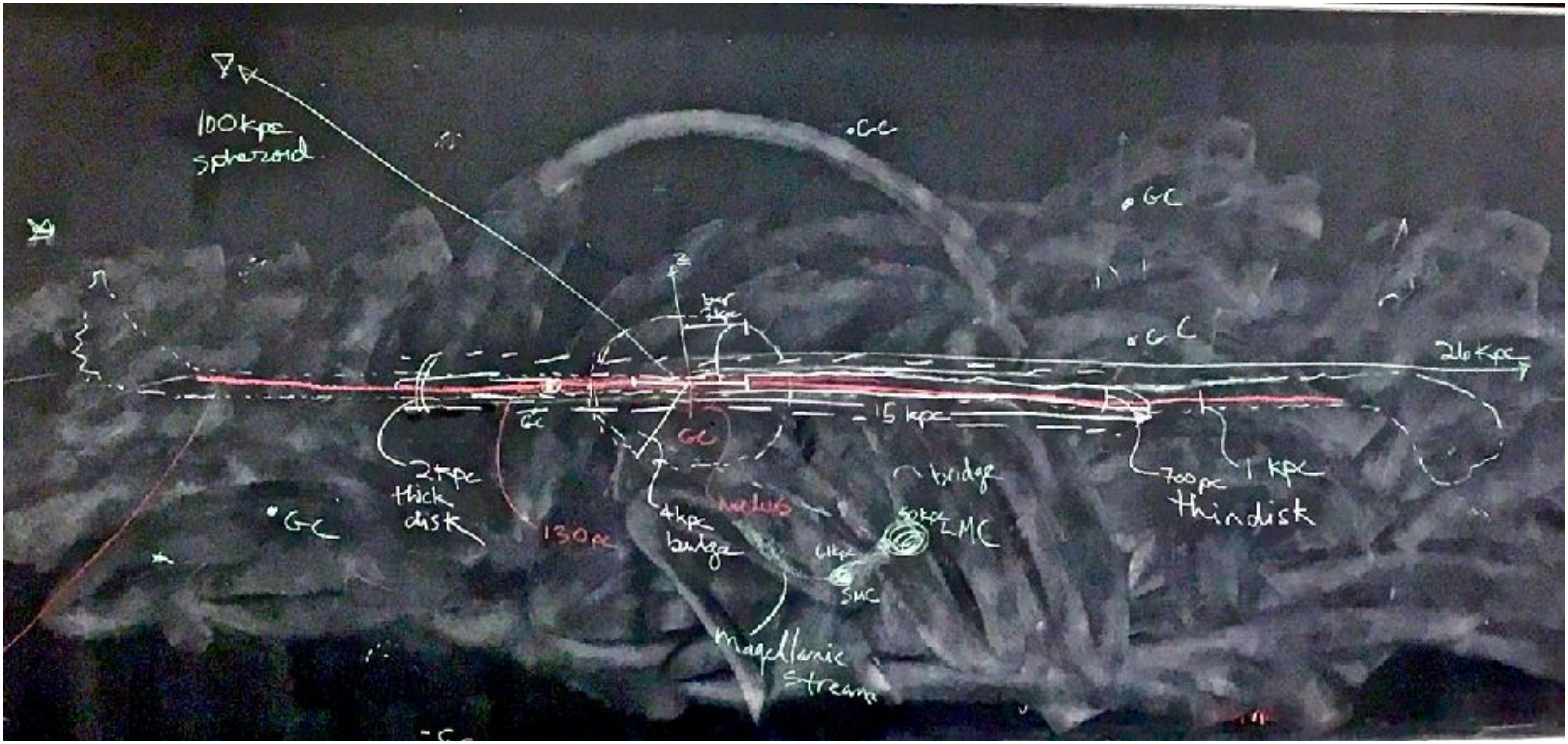
- GC == galactic centre
- Bar
- thin and thick stellar disks

MW Structure Diagram



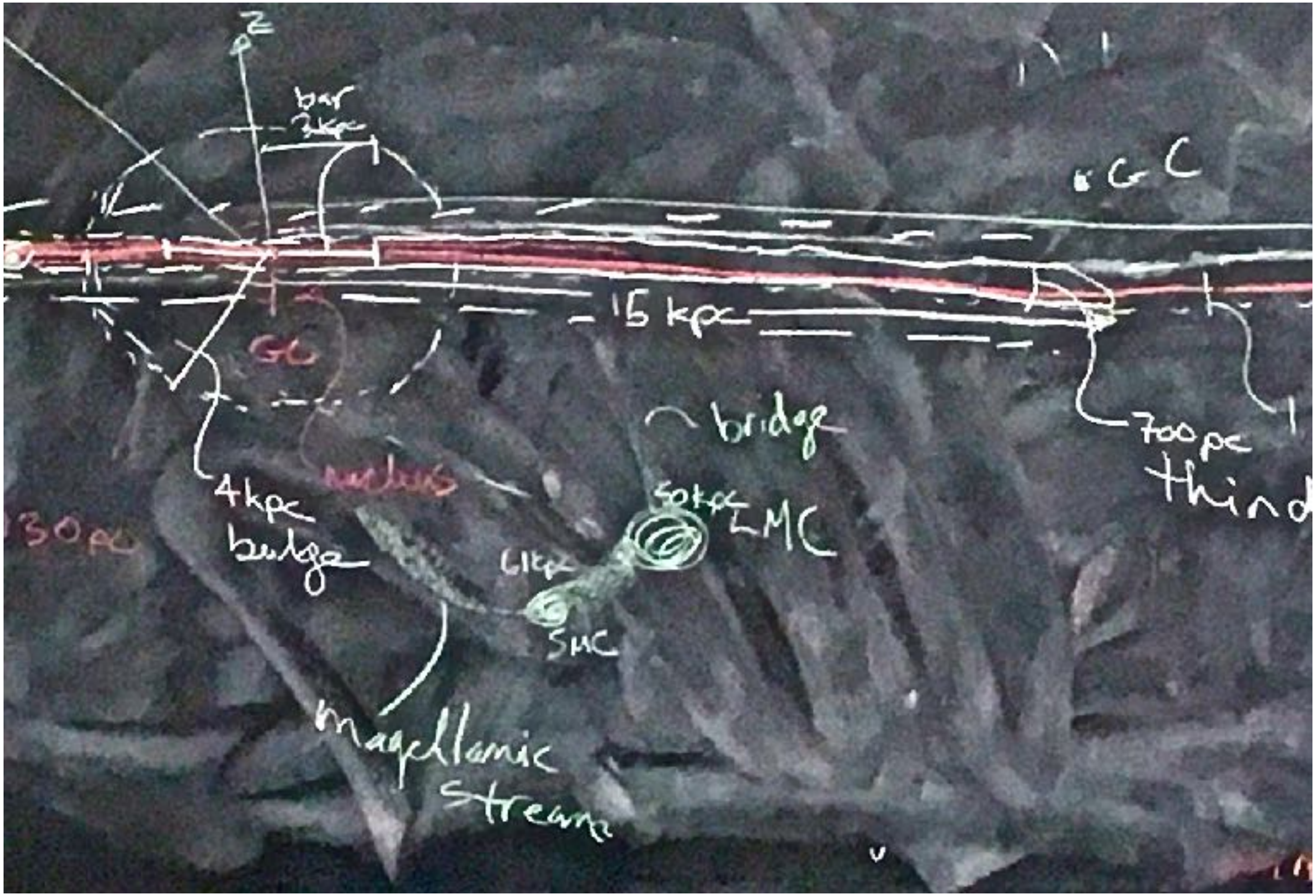
- Bulge
- Spheroid
- GC == globular clusters

MW Structure Diagram



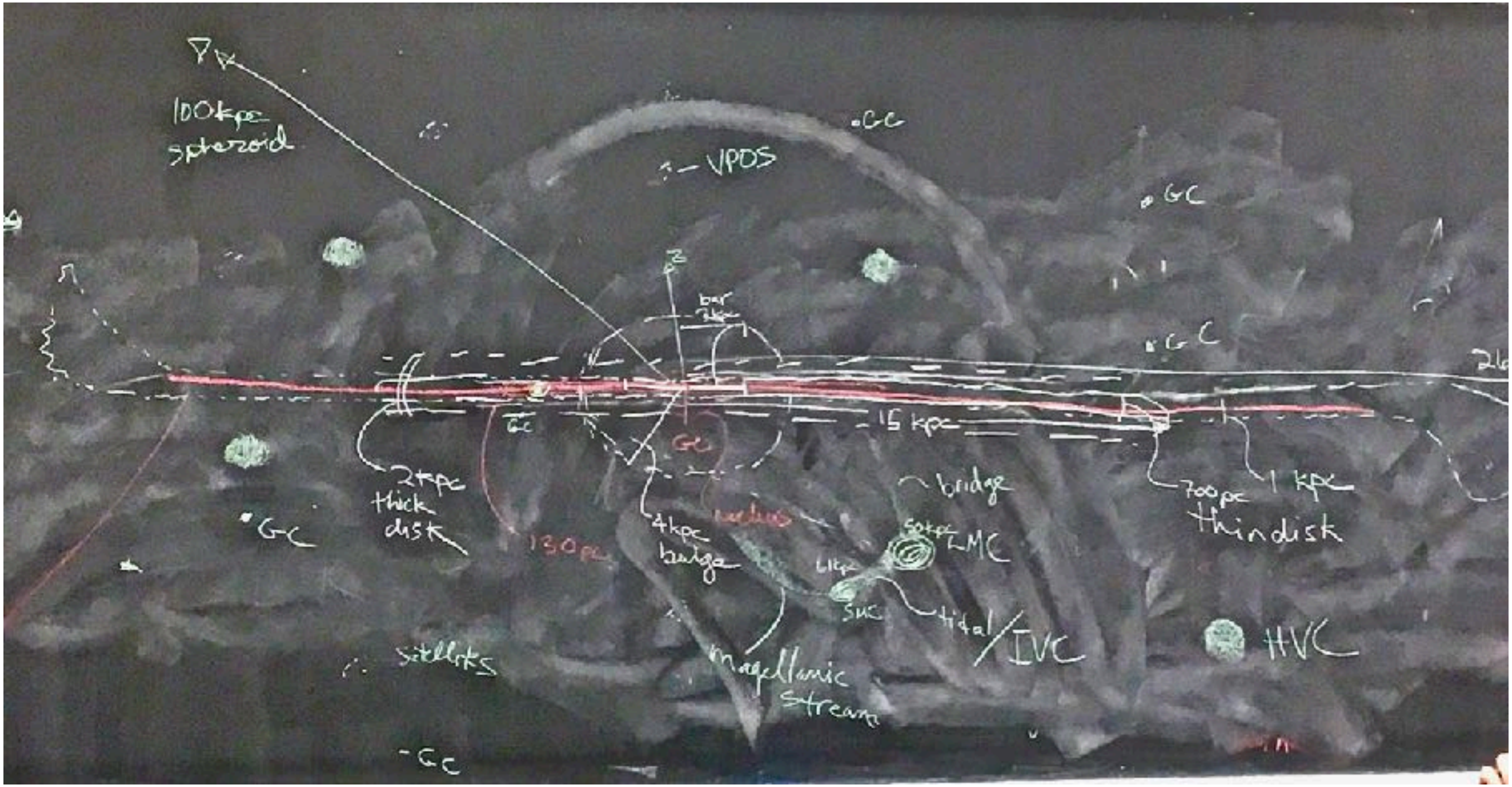
- Satellite galaxies
- Large and Small Magellanic Clouds (LMC, SMC)

MW Structure Diagram



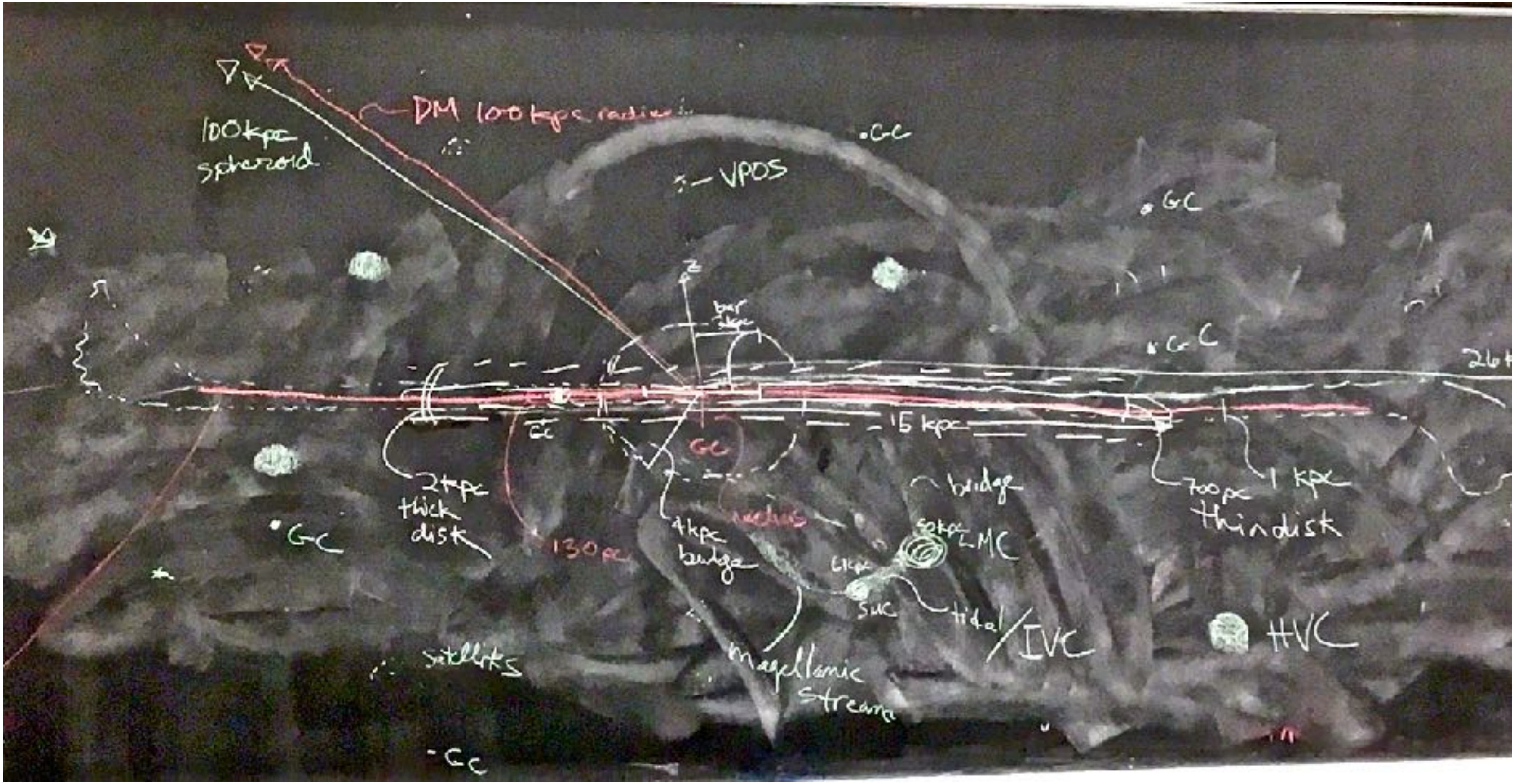
- Tidal material between Magellanic Clouds (MC) and between MW

MW Structure Diagram



- HVC == High Velocity Clouds
- VPOS == Vast Polar Structure of dwarf satellites

MW Structure Diagram



- DM == Dark Matter Halo

Light versus Mass contribution to Observations of MW

P. 63 S+G

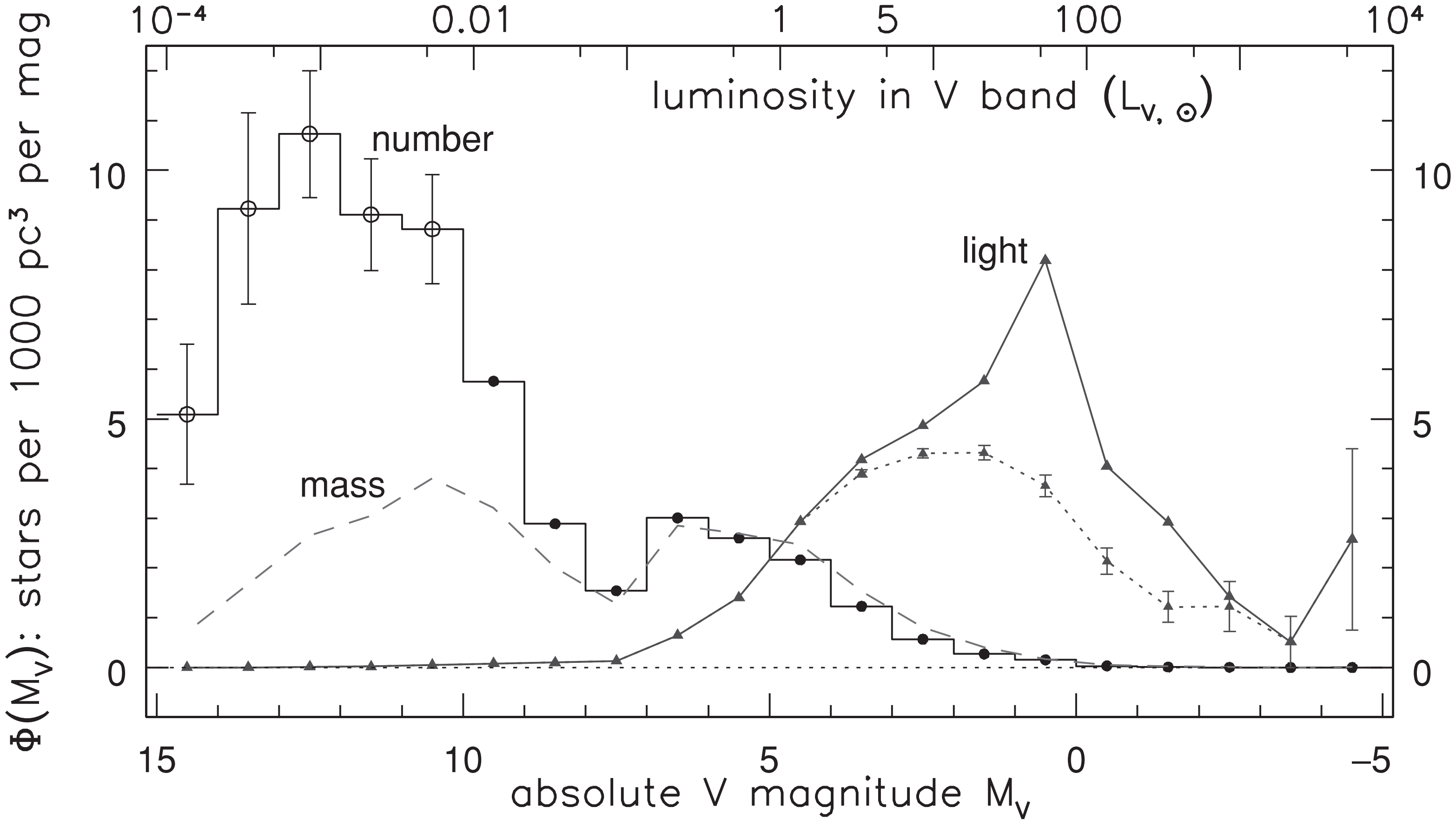


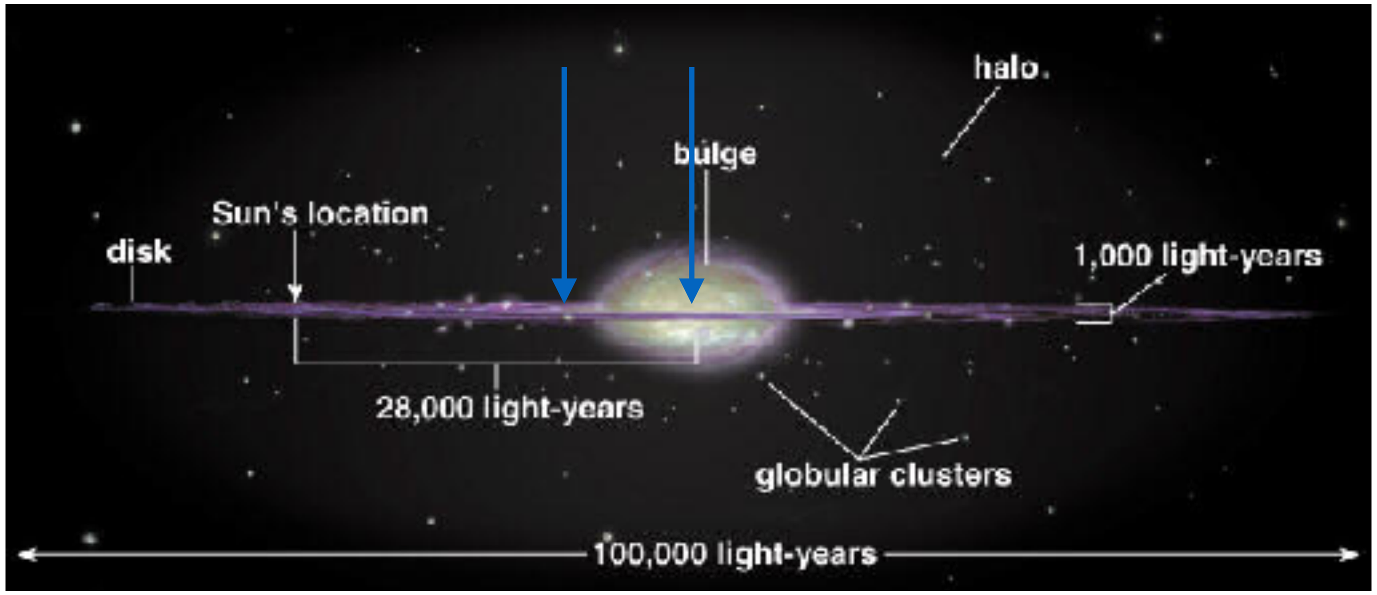
Fig. 2.3. The histogram shows the luminosity function $\Phi(M_V)$ for nearby stars: solid dots from stars of Figure 2.2, open circles from Reid *et al.* 2002 *AJ* **124**, 2721. Lines with triangles show $L_V \Phi(M_V)$, light from stars in each magnitude bin; the dotted curve is for main-sequence stars alone, the solid curve for the total. The dashed curve gives $\mathcal{M}\Phi_{\rm MS}(M_V)$, the mass in main-sequence stars. Units are $L_\odot$ or $\mathcal{M}_\odot$ per 10 pc cube; vertical bars show uncertainty, based on numbers of stars in each bin.

S+G P70-72

Scale Length

The distance required while moving parallel to the galactic plane within the disk for the density of stars to fall by a factor of e.

The sun lies about 8kpc from the center of the Milky Way. The scale length of the Milky Way is about 3kpc.



An approximation of the density of stars, n, of a given type, S, at a location R, z, defined by galactic co-ordinates.

$$n(R,z,S) = n(0,0,S)\exp[-R/h_R(S)]\exp[-|z|/h_z(S)]$$

(h_R == scale length; h_z == scale height)

Scale Height

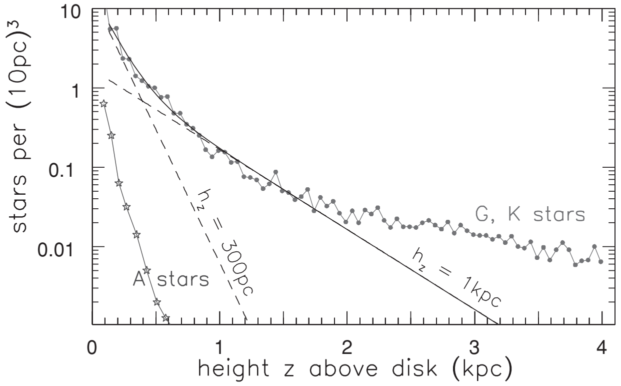


Fig. 2.8. Looking toward the south Galactic pole, filled circles show the density of stars with $5 < M_V < 6$; these are late G and early K dwarfs. Sloping dashed lines show $n(z) \propto \exp(-z/300\,\mathrm{pc})$ (thin disk) and $n(z) \propto \exp(-z/1\,\mathrm{kpc})$ (thick disk); the solid curve is their sum. At $z \gtrsim 2\,\mathrm{kpc}$, most stars belong to the metal-poor halo. A dwarfs (star symbols) lie in a very thin layer – N. Reid and J. Knude.

The distance required while moving perpendicular to the galactic plane for the density of stars to fall by a factor of e.

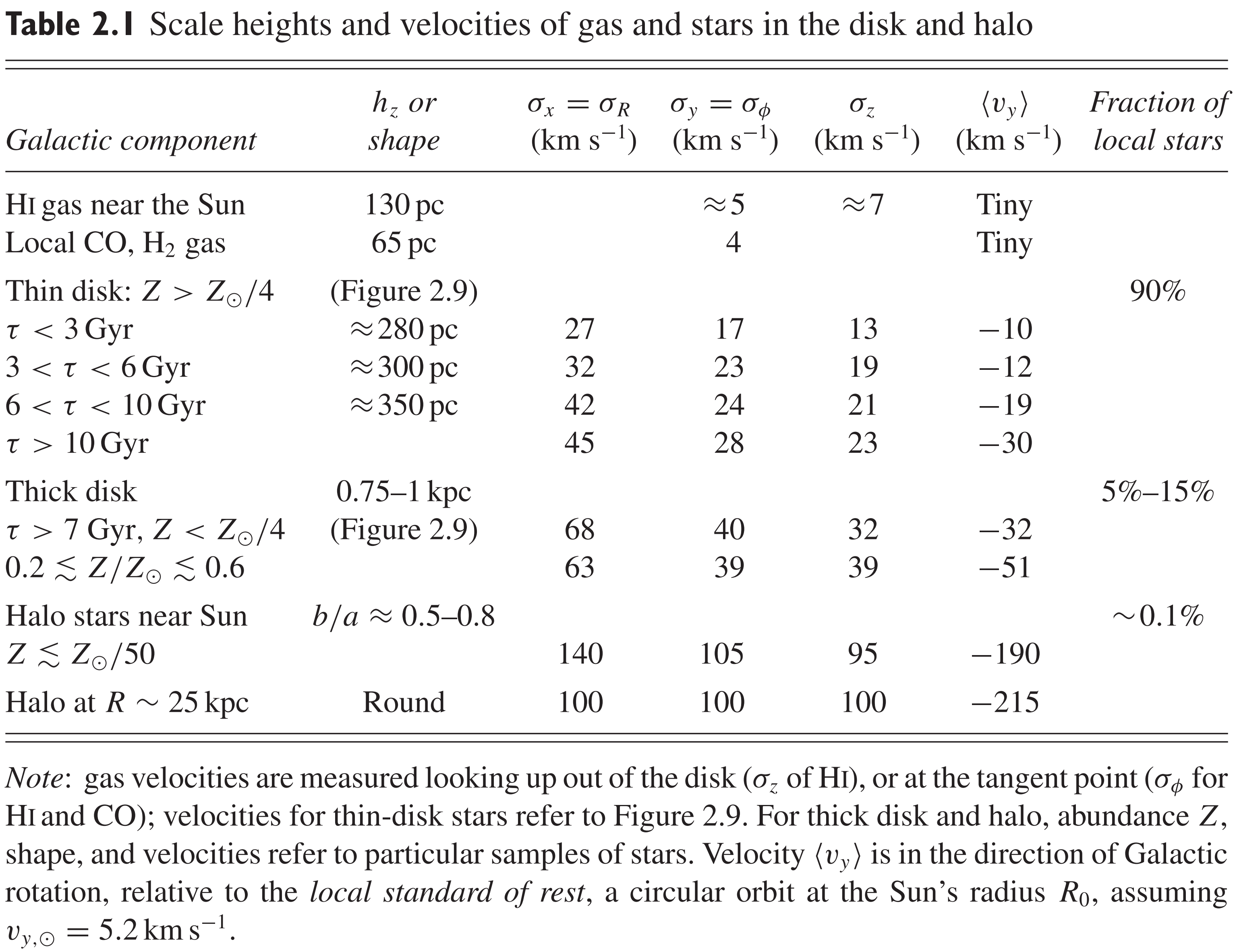


Table 2.1 Scale heights and velocities of gas and stars in the disk and halo

Galactic component	h_z *or shape*	$\sigma_x = \sigma_R$ (km s^{-1})	$\sigma_y = \sigma_\phi$ (km s^{-1})	σ_z (km s^{-1})	$\langle v_y \rangle$ (km s^{-1})	*Fraction of local stars*
HI gas near the Sun	130 pc		≈5	≈7	Tiny	
Local CO, H_2 gas	65 pc		4		Tiny	
Thin disk: $Z > Z_\odot/4$	(Figure 2.9)					90%
$\tau < 3$ Gyr	≈280 pc	27	17	13	−10	
$3 < \tau < 6$ Gyr	≈300 pc	32	23	19	−12	
$6 < \tau < 10$ Gyr	≈350 pc	42	24	21	−19	
$\tau > 10$ Gyr		45	28	23	−30	
Thick disk	0.75–1 kpc					5%–15%
$\tau > 7$ Gyr, $Z < Z_\odot/4$	(Figure 2.9)	68	40	32	−32	
$0.2 \lesssim Z/Z_\odot \lesssim 0.6$		63	39	39	−51	
Halo stars near Sun	$b/a \approx 0.5$–0.8					∼0.1%
$Z \lesssim Z_\odot/50$		140	105	95	−190	
Halo at $R \sim 25$ kpc	Round	100	100	100	−215	

Note: gas velocities are measured looking up out of the disk (σ_z of HI), or at the tangent point (σ_ϕ for HI and CO); velocities for thin-disk stars refer to Figure 2.9. For thick disk and halo, abundance Z, shape, and velocities refer to particular samples of stars. Velocity $\langle v_y \rangle$ is in the direction of Galactic rotation, relative to the *local standard of rest*, a circular orbit at the Sun's radius R_0, assuming $v_{y,\odot} = 5.2\,\mathrm{km\,s^{-1}}$.

S+G Sec. 2.4.2
A physical picture

Components

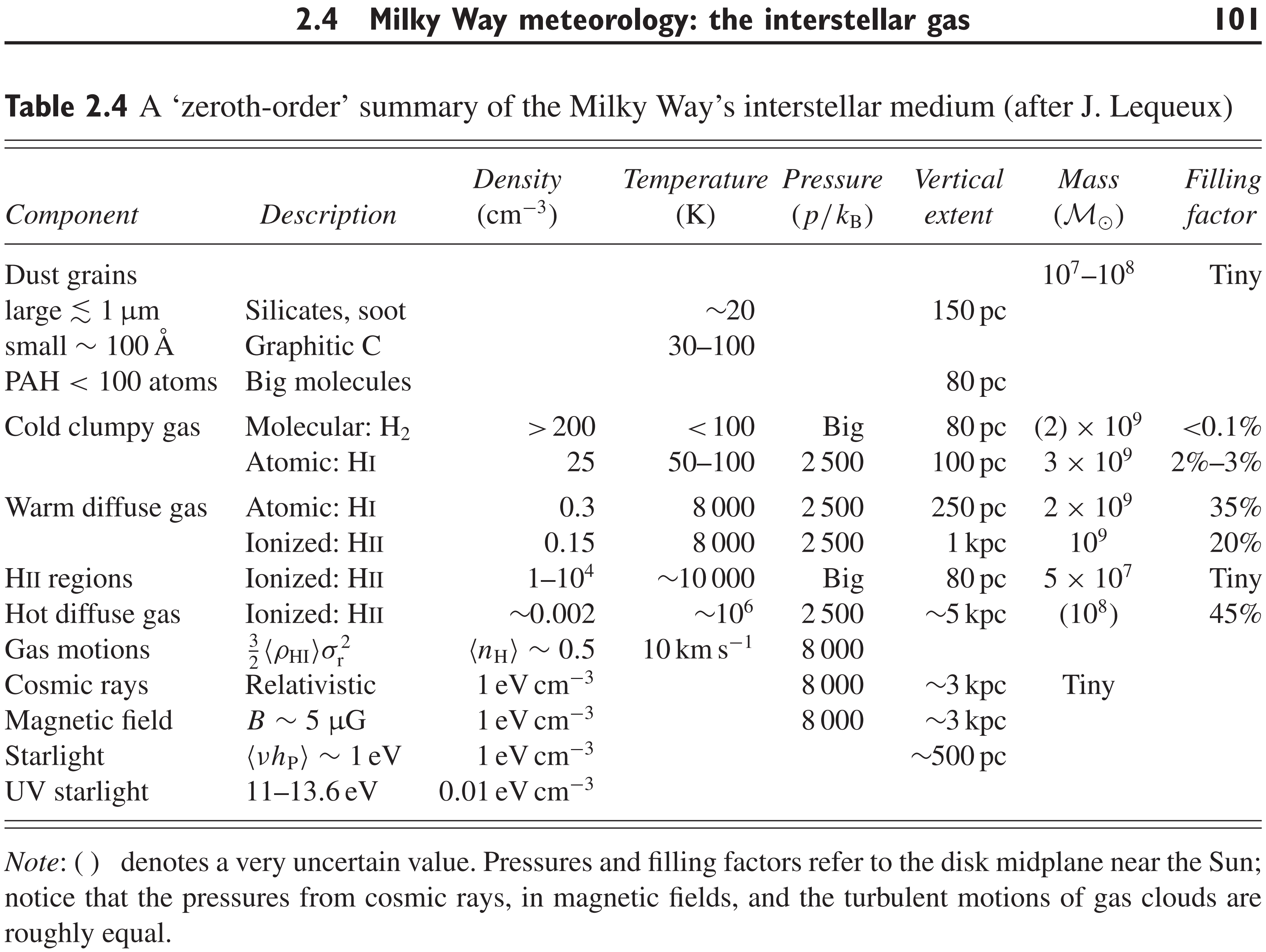


Table 2.4 A 'zeroth-order' summary of the Milky Way's interstellar medium (after J. Lequeux)

Component	*Description*	*Density* (cm^{-3})	*Temperature* (K)	*Pressure* (p/k_B)	*Vertical extent*	*Mass* ($\mathcal{M}_\odot$)	*Filling factor*
Dust grains						10^7–10^8	Tiny
large $\lesssim 1\ \mu$m	Silicates, soot		~20		150 pc		
small ~ 100 Å	Graphitic C		30–100				
PAH < 100 atoms	Big molecules				80 pc		
Cold clumpy gas	Molecular: H_2	> 200	< 100	Big	80 pc	(2) × 10^9	<0.1%
	Atomic: HI	25	50–100	2 500	100 pc	3 × 10^9	2%–3%
Warm diffuse gas	Atomic: HI	0.3	8 000	2 500	250 pc	2 × 10^9	35%
	Ionized: HII	0.15	8 000	2 500	1 kpc	10^9	20%
HII regions	Ionized: HII	1–10^4	~10 000	Big	80 pc	5 × 10^7	Tiny
Hot diffuse gas	Ionized: HII	~0.002	~10^6	2 500	~5 kpc	(10^8)	45%
Gas motions	$\frac{3}{2}\langle\rho_{\mathrm{HI}}\rangle\sigma_r^2$	$\langle n_H\rangle \sim 0.5$	10 km s^{-1}	8 000			
Cosmic rays	Relativistic	1 eV cm^{-3}		8 000	~3 kpc	Tiny	
Magnetic field	$B \sim 5\ \mu$G	1 eV cm^{-3}		8 000	~3 kpc		
Starlight	$\langle \nu h_P\rangle \sim 1$ eV	1 eV cm^{-3}			~500 pc		
UV starlight	11–13.6 eV	0.01 eV cm^{-3}					

Note: ( ) denotes a very uncertain value. Pressures and filling factors refer to the disk midplane near the Sun; notice that the pressures from cosmic rays, in magnetic fields, and the turbulent motions of gas clouds are roughly equal.

S+G: Sec. 2.3

Kinematics:

- rotation
- features

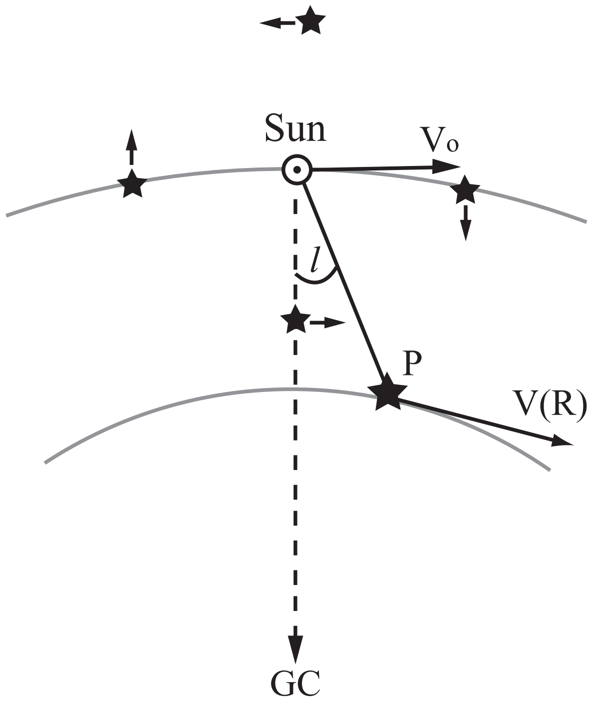
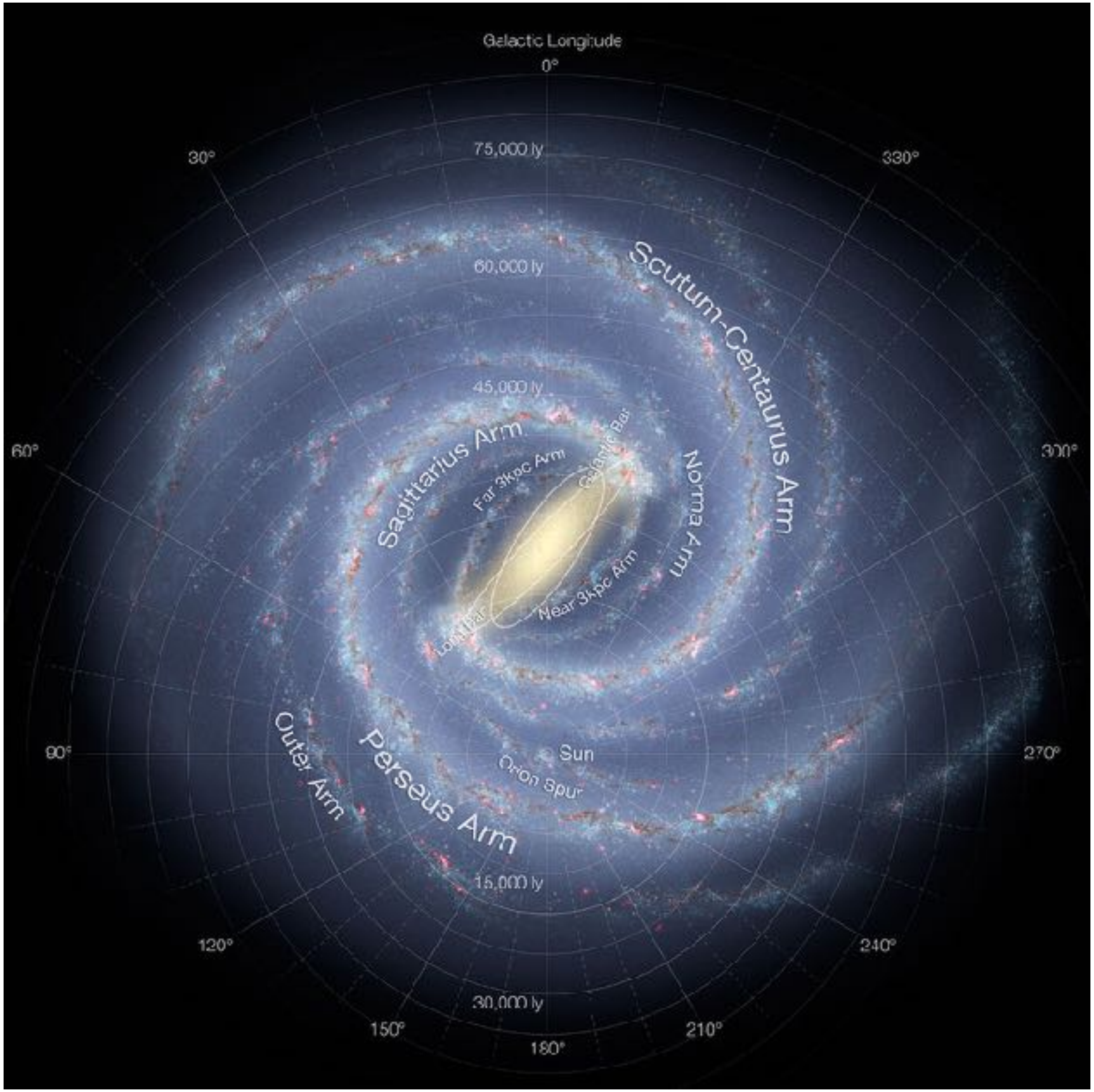


Fig. 2.18. Galactic rotation: stars closer to the Galactic center (GC) pull ahead of us in their orbits, while those further out are left behind. A star at the same Galactocentric radius moves sideways relative to us.

Differential Rotation

Galactic Coordinates:
ℓ == longitude
b == latitude

Degrees on image are "ℓ".



NASA/JPL-Caltech/ESO/R. Hurt

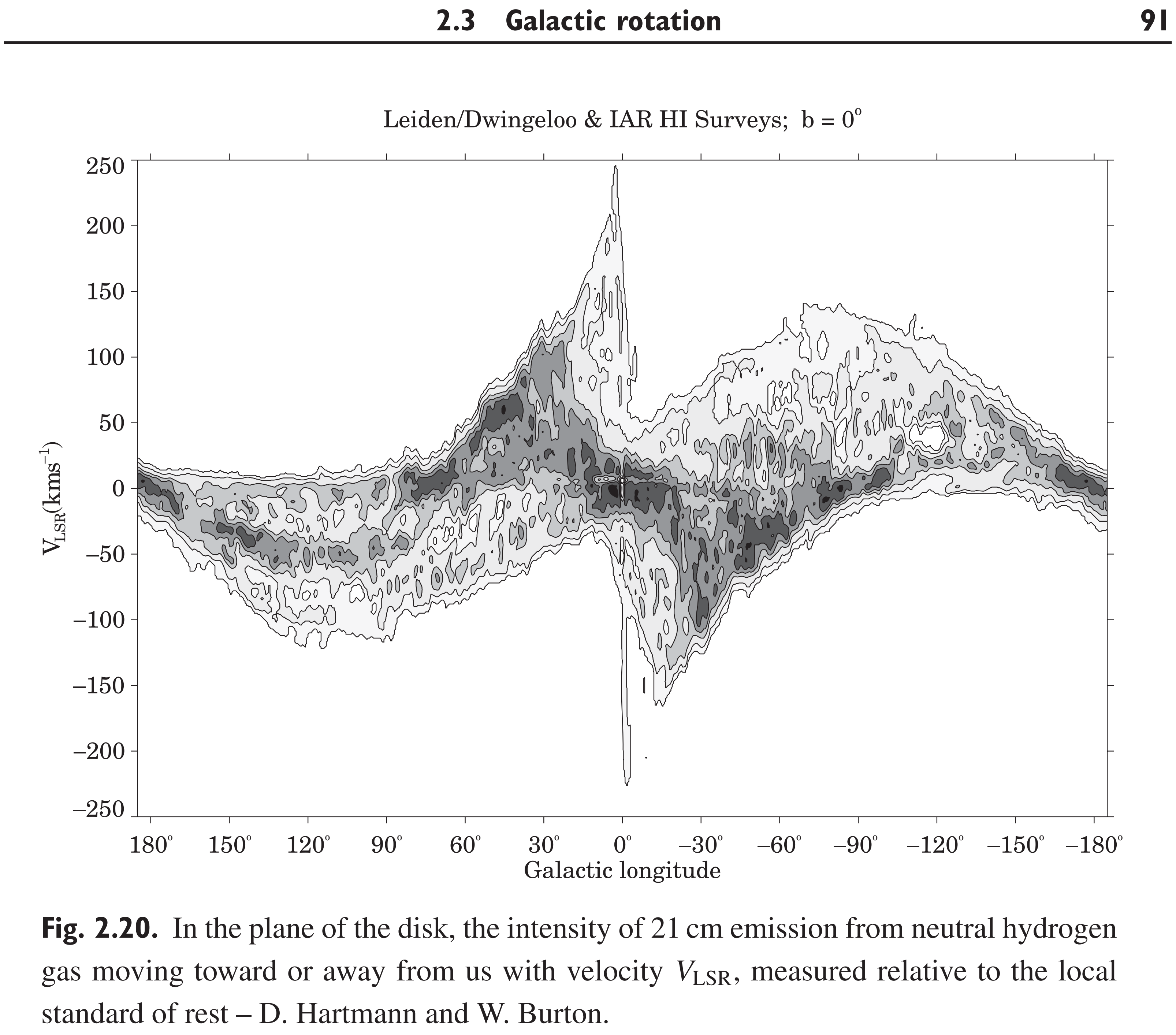
Canadian Galactic Plane Survey (CGPS)

Data cubes available at the
Canadian Astronomy Data Centre

http://www.cadc-ccda.hia-iha.nrc-cnrc.gc.ca/en/search/?collection=CGPS&noexec=true#resultTableTab

Show stepping through cube.

(Outreach example at http://www.ucalgary.ca/ras/CGPSpress/shell)



2.3 Galactic rotation 91

Fig. 2.20. In the plane of the disk, the intensity of 21 cm emission from neutral hydrogen gas moving toward or away from us with velocity V_{LSR}, measured relative to the local standard of rest – D. Hartmann and W. Burton.

Transpose the cube and do a moment 0 along “b”.

Why does it look like this?

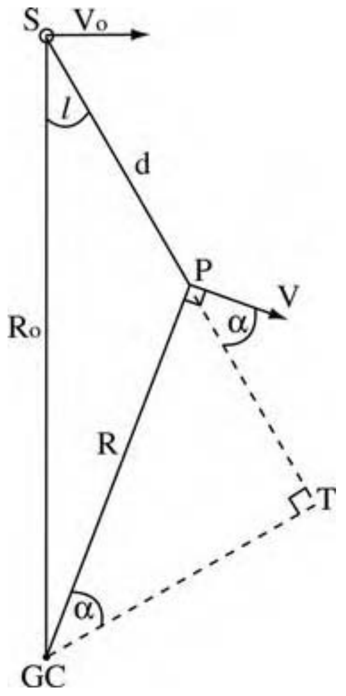


Fig. 2.19. Galactic rotation: a star or gas cloud at P with longitude l and Galactocentric radius R, at distance d from the Sun, orbits with speed $V(R)$. The line of sight to P is closest to the Galactic center at the *tangent point* T.

The Sun does not lie exactly in the Galactic midplane, but about 15 pc above it, and its path around the Galactic center is not precisely circular. The *local standard of rest* is defined as the average motion of stars near the Sun, after correcting for

Usually (but not always; see Problem 2.16 below), we assume that the local standard of rest follows a circular orbit around the Galactic center. In 1985 the International Astronomical Union (IAU) recommended the values $R_0 = 8.5\,\text{kpc}$, for the Sun's distance from the Galactic center, and $V_0 = 220\,\text{km}\,\text{s}^{-1}$, for its speed in that circular orbit. To allow workers to compare their measurements, astronomers often compute the distances and speeds of stars by using the IAU values, although current estimates are closer to $R_0 \approx 8\,\text{kpc}$ and $V_0 \approx 200\,\text{km}\,\text{s}^{-1}$.

Observed velocity along line of sight

Project circular velocities onto the LOS for radial velocities.

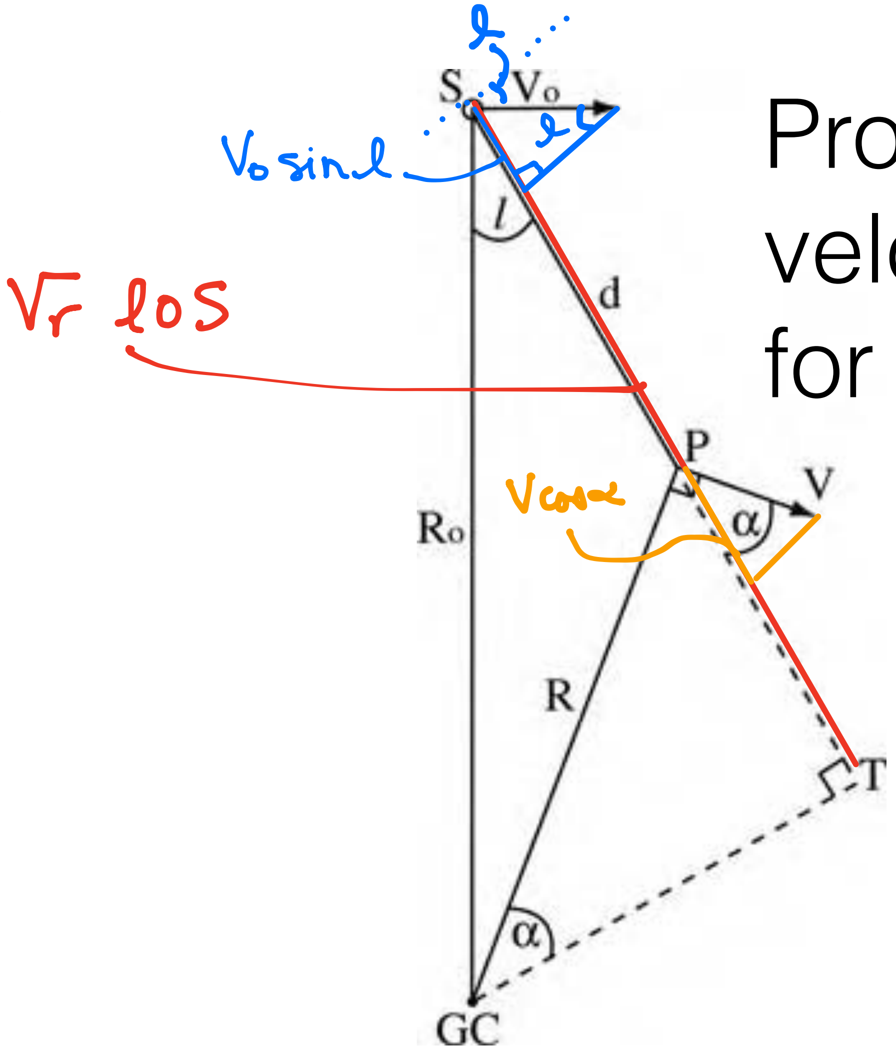


Fig. 2.19. Galactic rotation: a star or gas cloud at P with longitude l and Galactocentric radius R, at distance d from the Sun, orbits with speed $V(R)$. The line of sight to P is closest to the Galactic center at the *tangent point* T.

We can calculate the radial velocity V_r of a star or gas cloud, assuming that it follows an exactly circular orbit; see Figure 2.19. At radius R_0 the Sun (or more precisely, the local standard of rest) orbits with speed V_0, while a star P at radius R has orbital speed $V(R)$. The star moves away from us at speed

$$V_r = V \cos\alpha - V_0 \sin l. \tag{2.10}$$

Using the sine rule, we have $\sin l / R = \sin(90^\circ + \alpha)/R_0$, and so

$$V_r = R_0 \sin l \left(\frac{V}{R} - \frac{V_0}{R_0} \right). \tag{2.11}$$

Via some algebra.

sine rule:

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

$\because \sin(90+\alpha) = \cos\alpha$

$$\frac{\sin l}{R} = \frac{\cos\alpha}{R_0}$$

$$\rightarrow \cos\alpha = \frac{R_0}{R}\sin l$$

$$\therefore v_r = V\cos\alpha - V_0 \sin l$$

$$= V\frac{R_0}{R}\sin l - V_0\frac{R_0}{R_0}\sin l$$

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

We can calculate the radial velocity V_r of a star or gas cloud, assuming that it follows an exactly circular orbit; see Figure 2.19. At radius R_0 the Sun (or more precisely, the local standard of rest) orbits with speed V_0, while a star P at radius R has orbital speed $V(R)$. The star moves away from us at speed

$$\underline{V_r =} V \underline{\cos\alpha -} V_0 \underline{\sin l.} \tag{2.10}$$

Using the sine rule, we have $\sin l/R = \sin(90^\circ + \alpha)/R_0$, and so

$$V_r = R_0 \sin l \left(\frac{V}{R} - \frac{V_0}{R_0} \right). \tag{2.11}$$

Problem 2.15 For a simple model of the Galaxy with $R_0 = 8$ kpc and $V(R) = 220\,\text{km s}^{-1}$ everywhere, find $V_r(l)$ for gas in circular orbit at $R = 4, 6, 10,$ and 12 kpc. Do this by varying the Galactocentric azimuth ϕ around each ring; find d for each (ϕ, R), and hence the longitude l and V_r. Make a plot similar to Figure 2.20 showing the gas on these rings. In Figure 2.20 itself, explain

Appendix C **415**

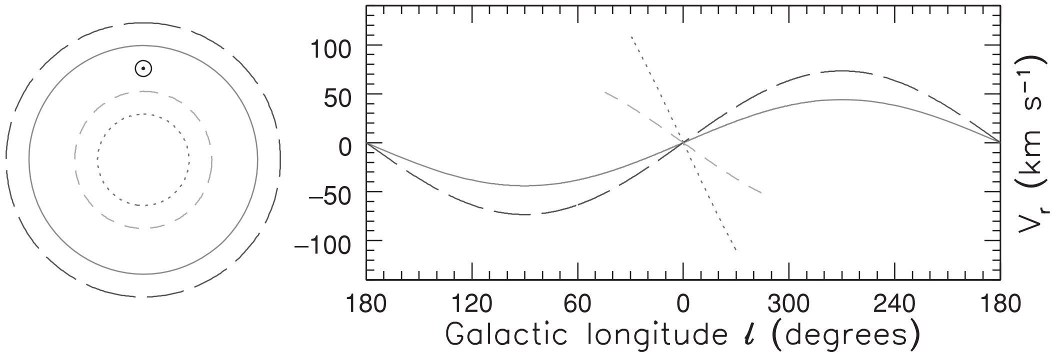


Fig. C.1. Radial velocity V_r of gas on four rings, at radii $R = 4, 6, 10,$ and 12 kpc, with circular speed $V(R) = 220\,\text{km s}^{-1}$. The Sun ⊙ is at $R_0 = 8$ kpc.

B+M
Numerical Model of a gravitational potential with Bar

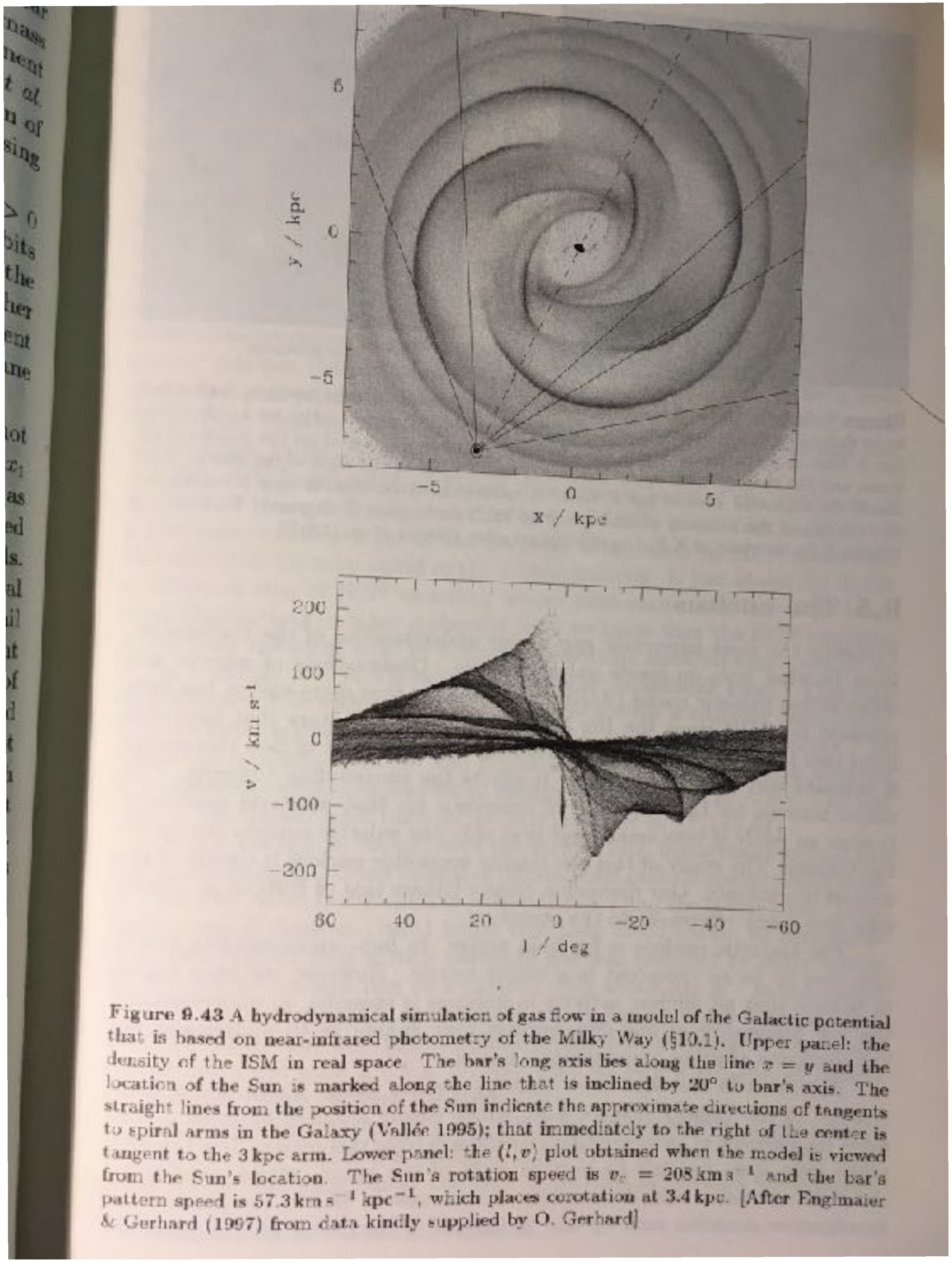


Figure 9.43 A hydrodynamical simulation of gas flow in a model of the Galactic potential that is based on near-infrared photometry of the Milky Way (§10.1). Upper panel: the density of the ISM in real space. The bar's long axis lies along the line $x = y$ and the location of the Sun is marked along the line that is inclined by 20° to bar's axis. The straight lines from the position of the Sun indicate the approximate directions of tangents to spiral arms in the Galaxy (Vallée 1995); that immediately to the right of the center is tangent to the 3 kpc arm. Lower panel: the (l, v) plot obtained when the model is viewed from the Sun's location. The Sun's rotation speed is $v_0 = 208\,\mathrm{km\,s^{-1}}$ and the bar's pattern speed is $57.3\,\mathrm{km\,s^{-1}\,kpc^{-1}}$, which places corotation at 3.4 kpc. [After Englmaier & Gerhard (1997) from data kindly supplied by O. Gerhard]

Notice how it replicates the structure in the observed PV plot (next page).

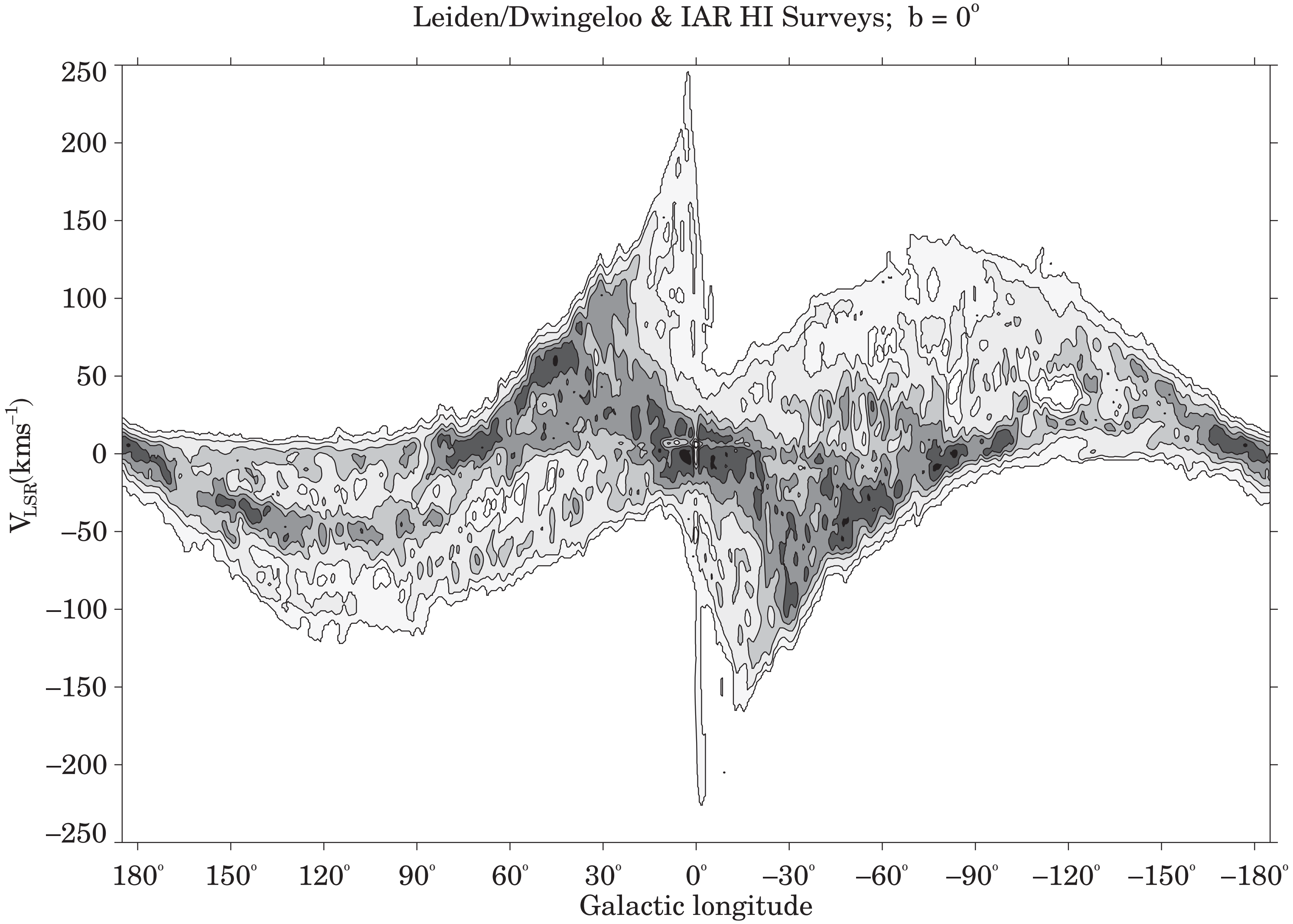
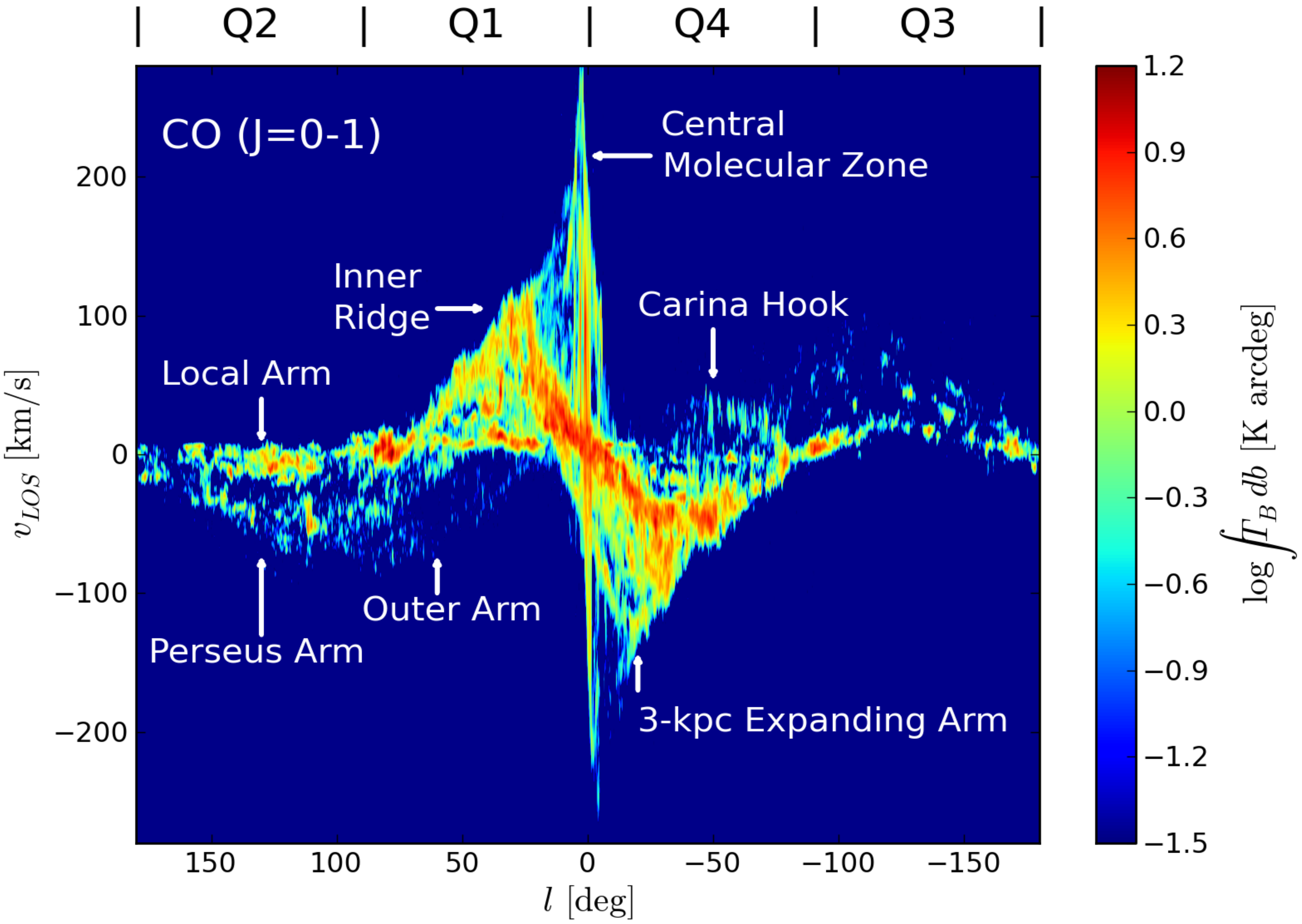


Fig. 2.20. In the plane of the disk, the intensity of 21 cm emission from neutral hydrogen gas moving toward or away from us with velocity $V_{\rm LSR}$, measured relative to the local standard of rest – D. Hartmann and W. Burton.


| Q2 | Q1 | Q4 | Q3 |
CO (J=0-1)
Central Molecular Zone
Inner Ridge
Carina Hook
Local Arm
Perseus Arm
Outer Arm
3-kpc Expanding Arm
v_{LOS} [km/s]
200
100
0
−100
−200
150
100
50
0
−50
−100
−150
l [deg]
1.2
0.9
0.6
0.3
0.0
−0.3
−0.6
−0.9
−1.2
−1.5
$\log \int T_B \, db$ [K arcdeg]

ROTATION CURVE

To form the rotation curve we need R which in general is hard to know.

Tangent point method can be used in inner region.

To get R, one needs d between sun and cloud at p.

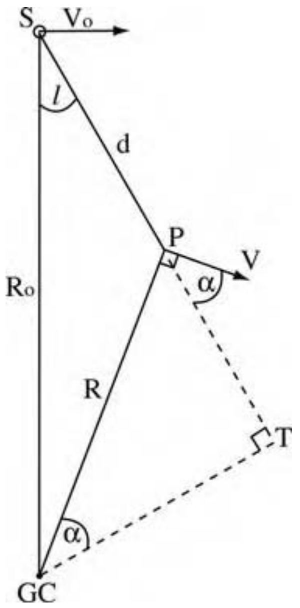


Fig. 2.19. Galactic rotation: a star or gas cloud at P with longitude *l* and Galactocentric radius *R*, at distance *d* from the Sun, orbits with speed *V*(*R*). The line of sight to P is closest to the Galactic center at the *tangent point* T.

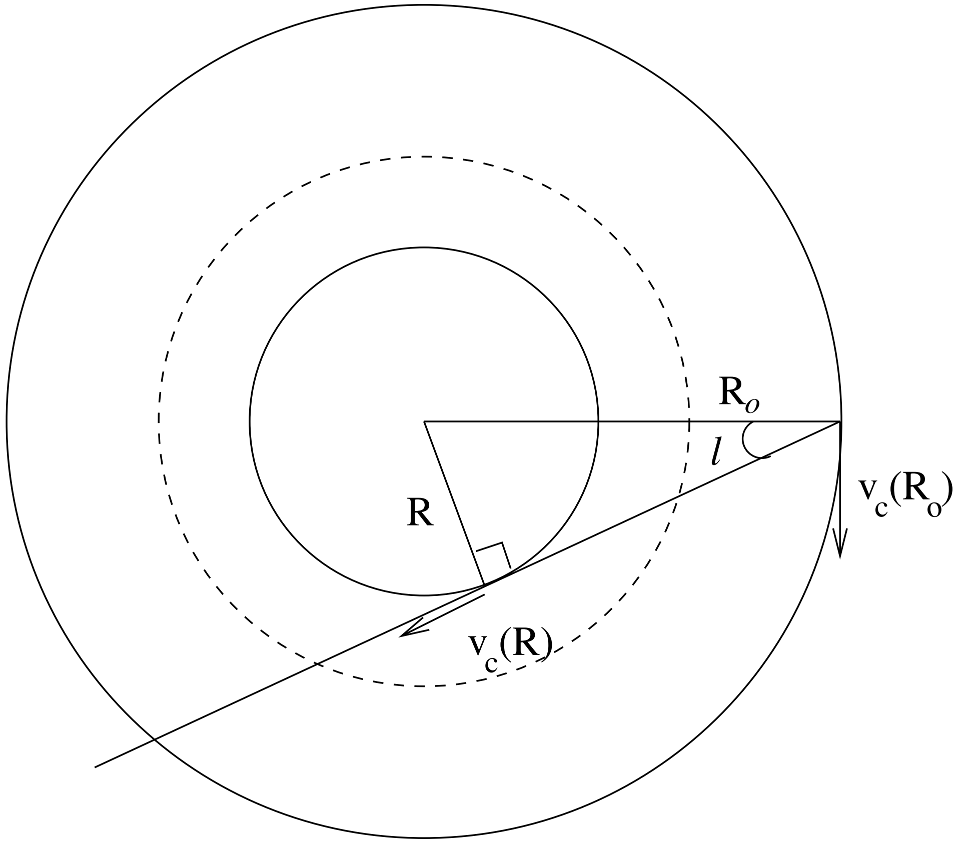


Figure 1: The tangent point method

AST1420 Galactic Rotation
John Dubinski (Lecture 6)

ROTATION CURVE

Tangent point method can be used in inner region.

- Pick an ℓ.
- v_r will be max at tangent to an orbit.
- v_r will be zero on sun’s orbit

(v/r== angular speed and is same on same orbit).

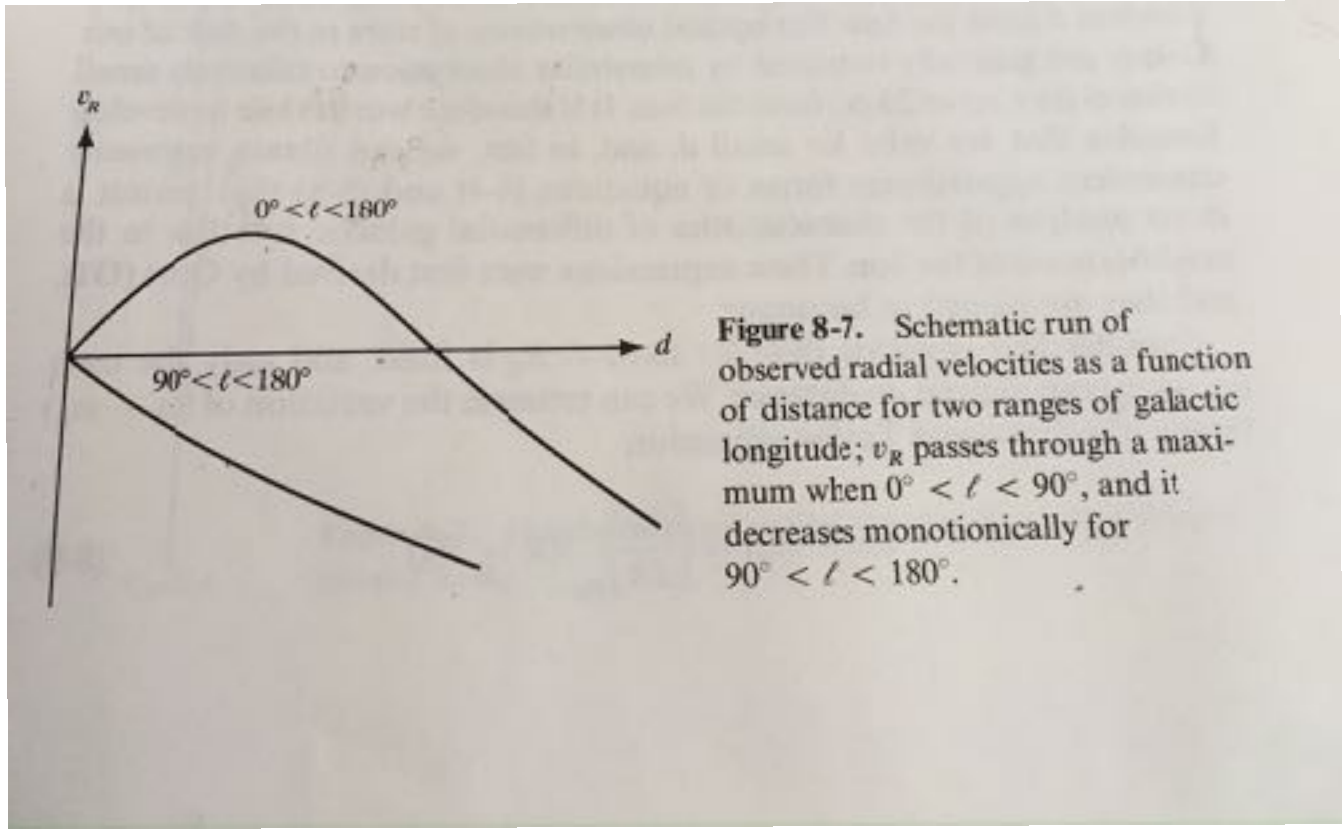


Figure 8-7. Schematic run of observed radial velocities as a function of distance for two ranges of galactic longitude; v_R passes through a maximum when 0° < ℓ < 90°, and it decreases monotionically for 90° < ℓ < 180°.

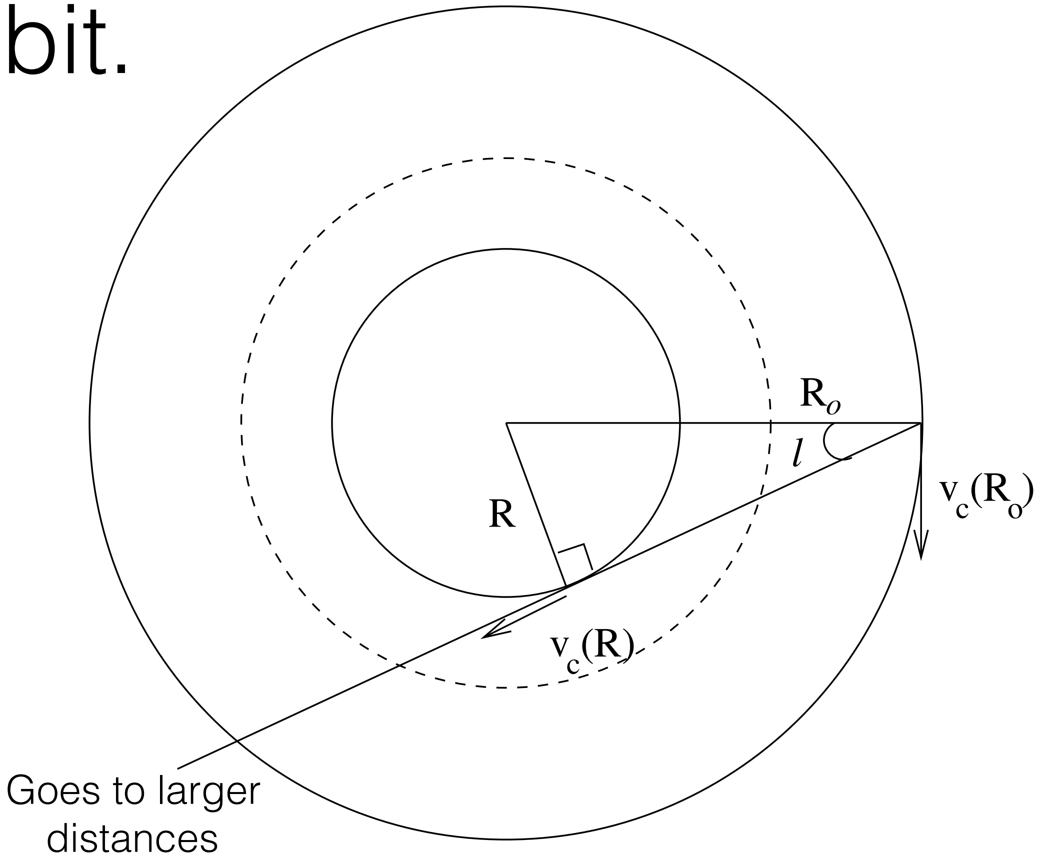


Figure 1: The tangent point method

AST1420 Galactic Rotation

John Dubinski (Lecture 6)

M+B P. 471

In outer region R keeps increasing and V/R smaller than V_0/R_0 —> negative slope.

Distance d —> R from GC —> rotation curve.

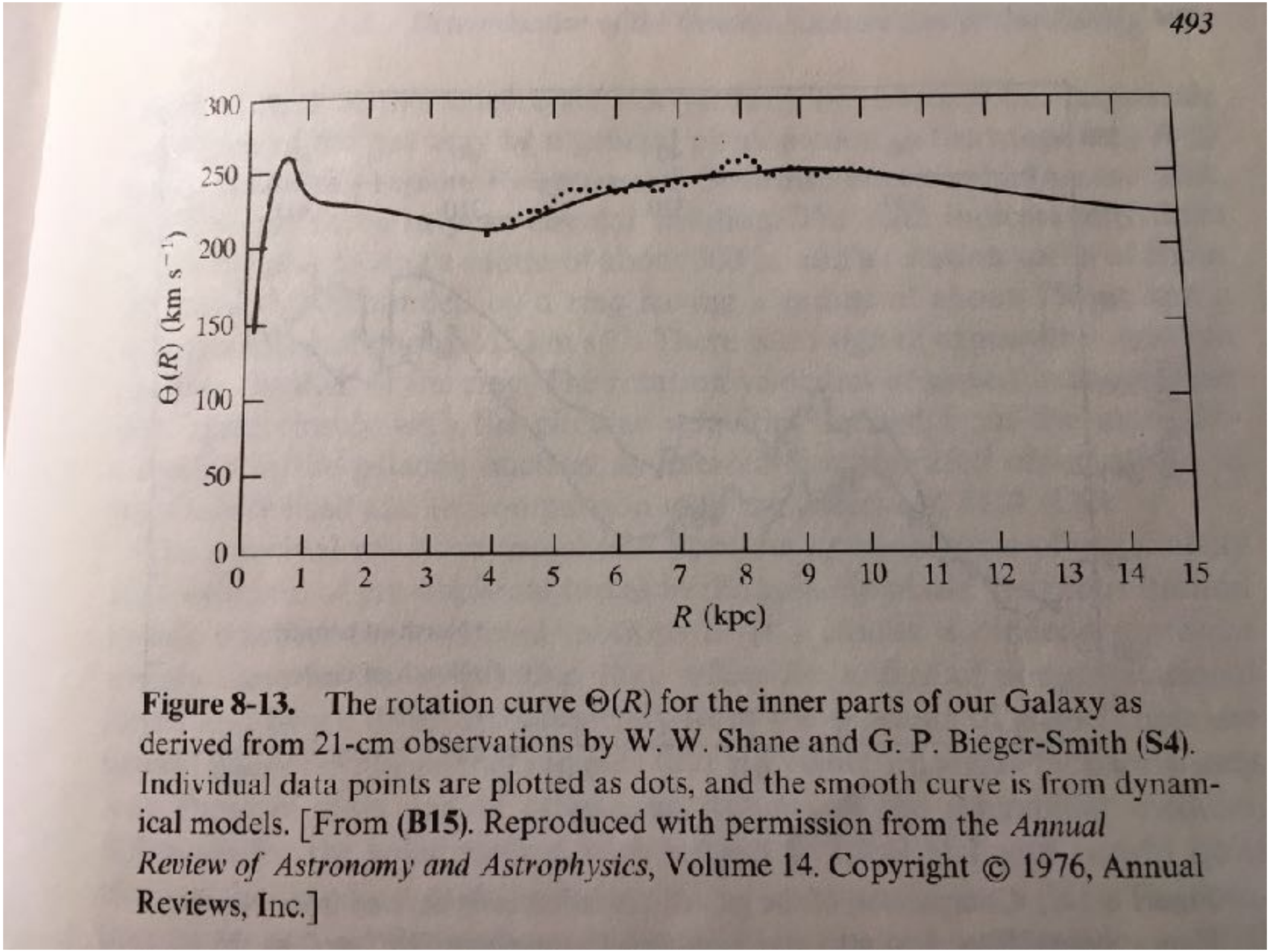
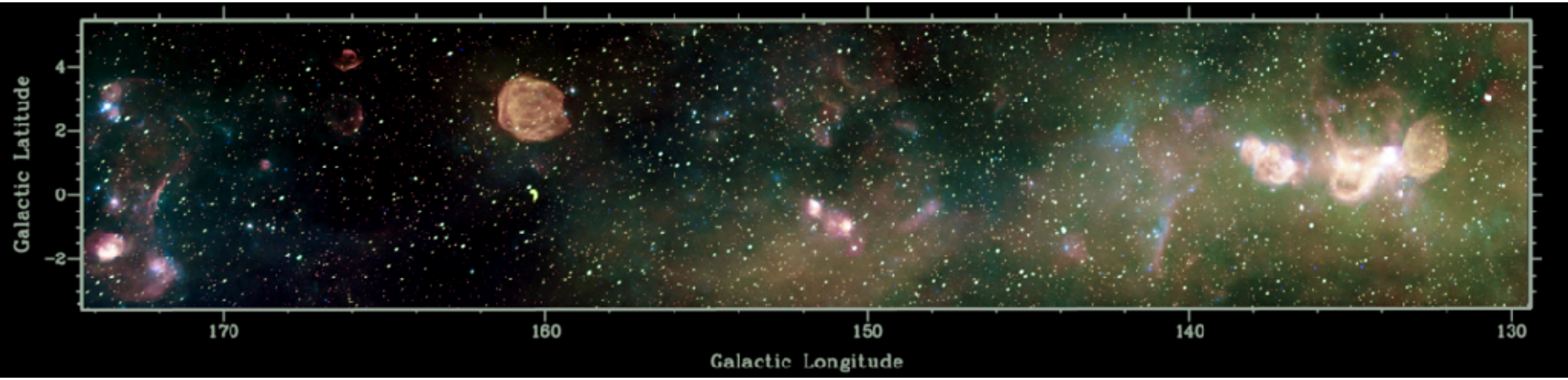


Figure 8-13. The rotation curve $\Theta(R)$ for the inner parts of our Galaxy as derived from 21-cm observations by W. W. Shane and G. P. Bieger-Smith (**S4**). Individual data points are plotted as dots, and the smooth curve is from dynamical models. [From (**B15**). Reproduced with permission from the *Annual Review of Astronomy and Astrophysics*, Volume 14. Copyright © 1976, Annual Reviews, Inc.]

Features of the MW.

Mid-plane (b=-3.6 to +5.6)

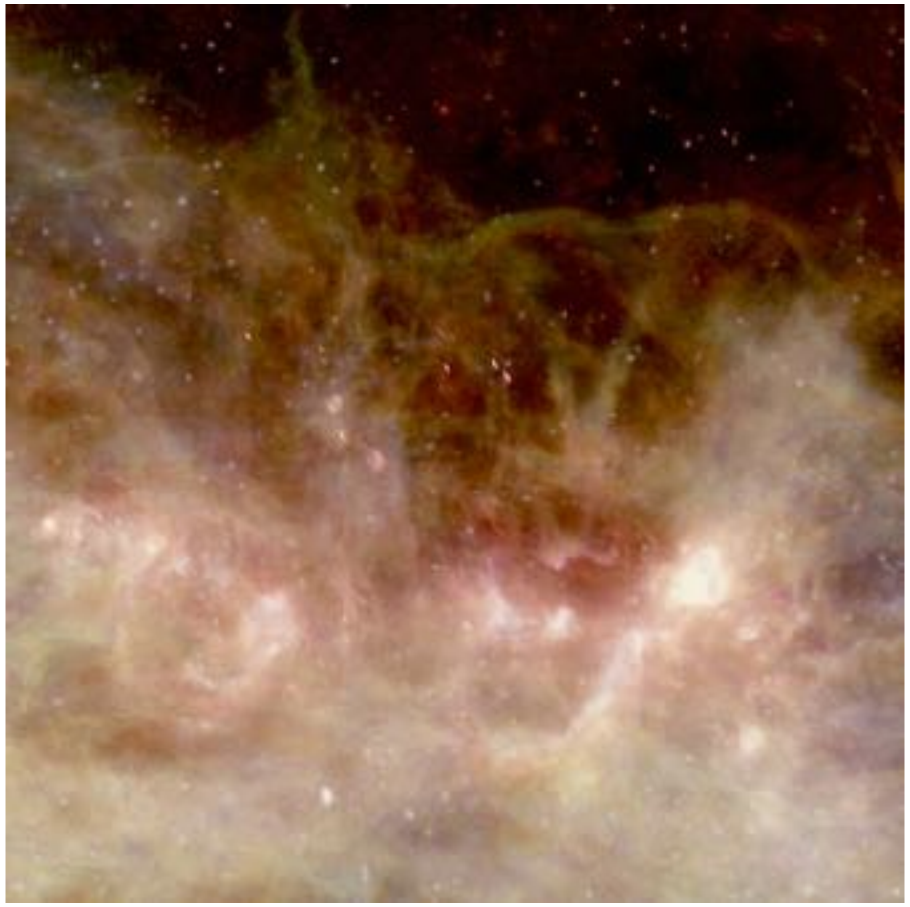
Canadian Galactic Plane Survey



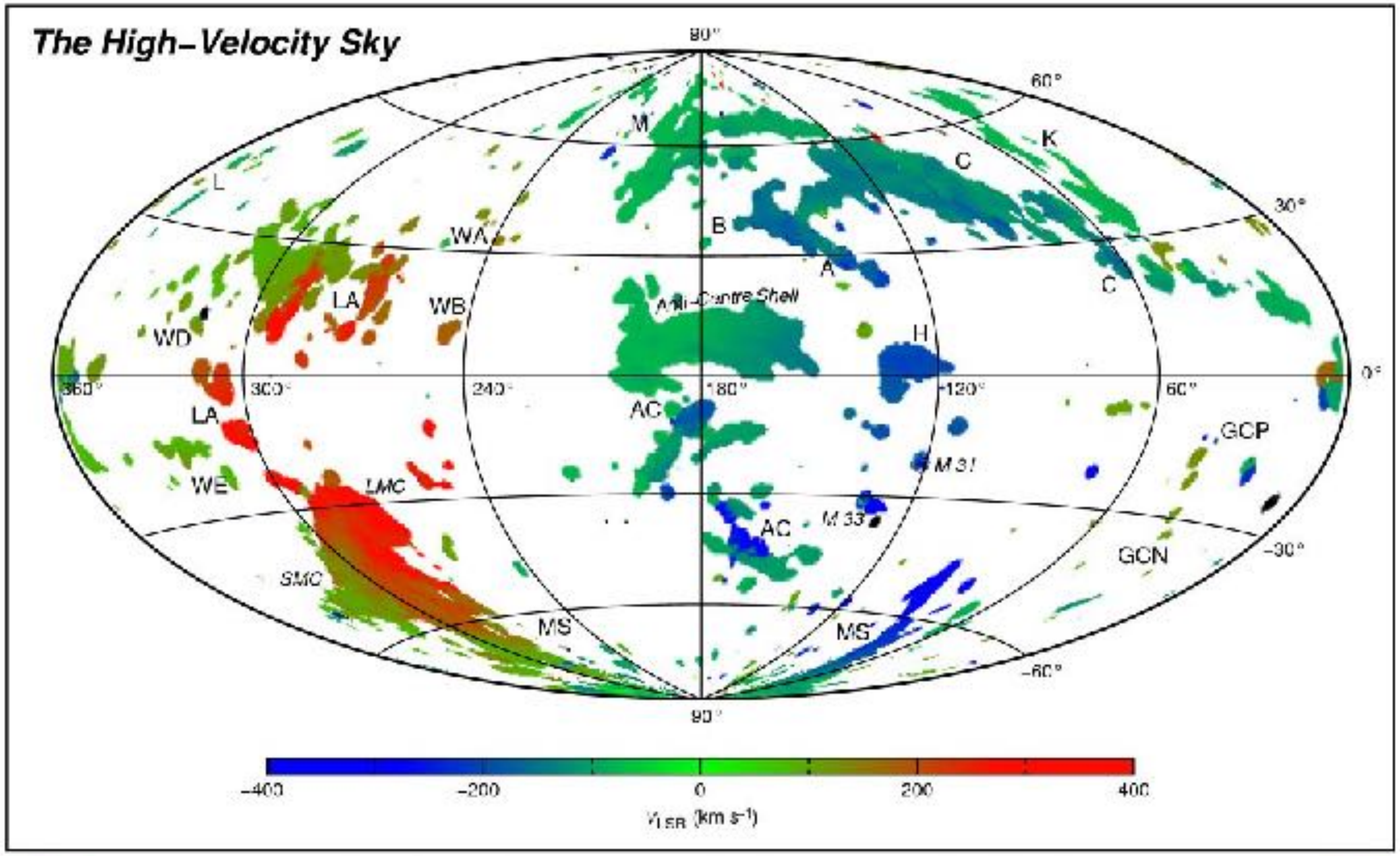
Anticentre

W4 “Chimney”

—> Material and energy into Halo



High Velocity Clouds



Tobias Westmeier, CSIRO Australia Telescope National Facility

Based on the Leiden/Argentine/Bonn Survey (Kalberla et al. 2005, A&A 440, 775)
and the Milky Way model of P. Kalberla (Kalberla et al. 2007, A&A, in press).

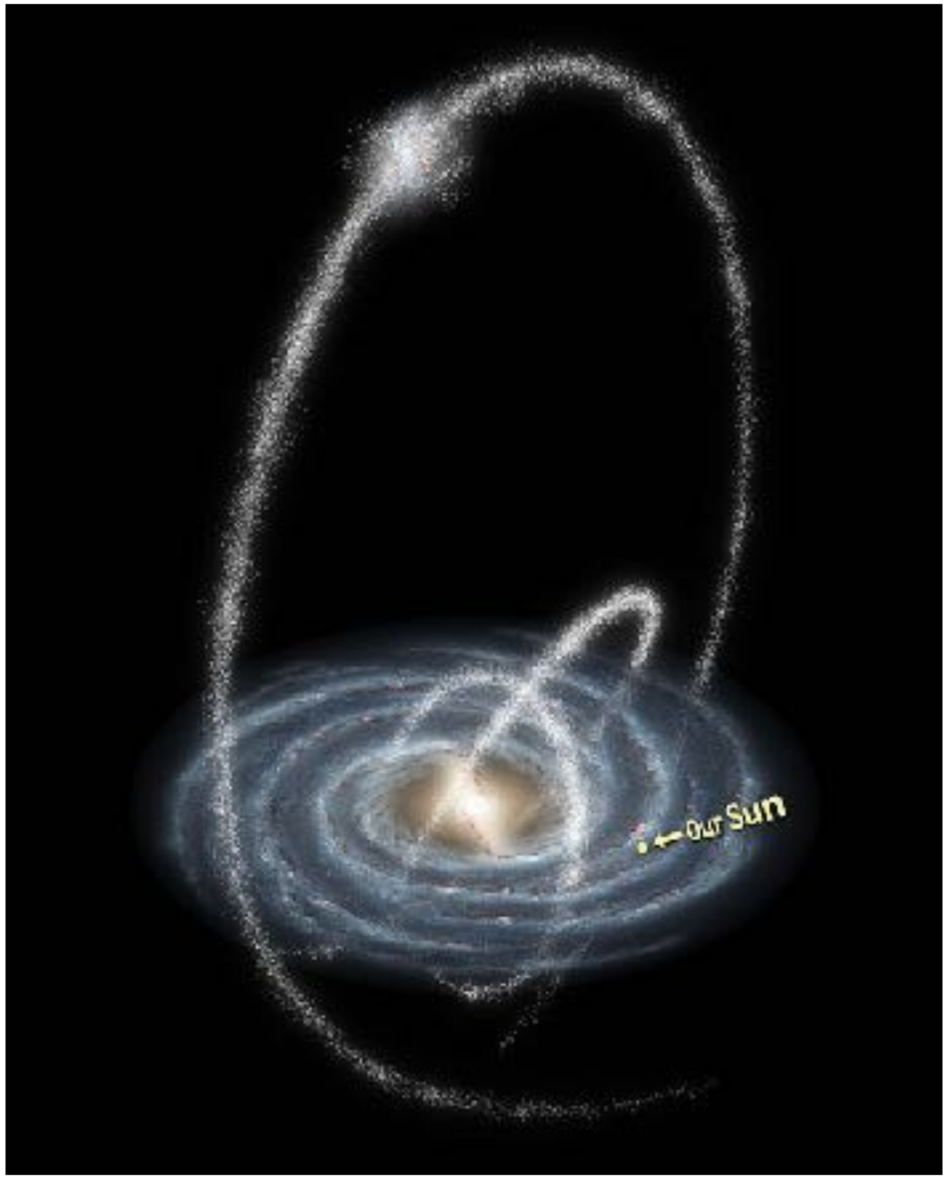
- Velocity differs from rotation curve velocity.
- LMC, SMC bridge — tidal.
- Others origin: outflow and subsequent inflow?

“Fossils”

The goals of Galactic Archaeology are to find signatures or fossils from the epoch of Galaxy assembly.

- identify observationally how important mergers and accretion events were in building up the Galactic disk, bulge and halo of the Milky Way.
- reconstruct the star-forming aggregates (clouds that formed stars; globular clusters) and accreted galaxies that built up the the Galaxy.
- recognize aggregates:
  - kinematically as stellar moving groups.
  - by their chemical signatures (chemical tagging)

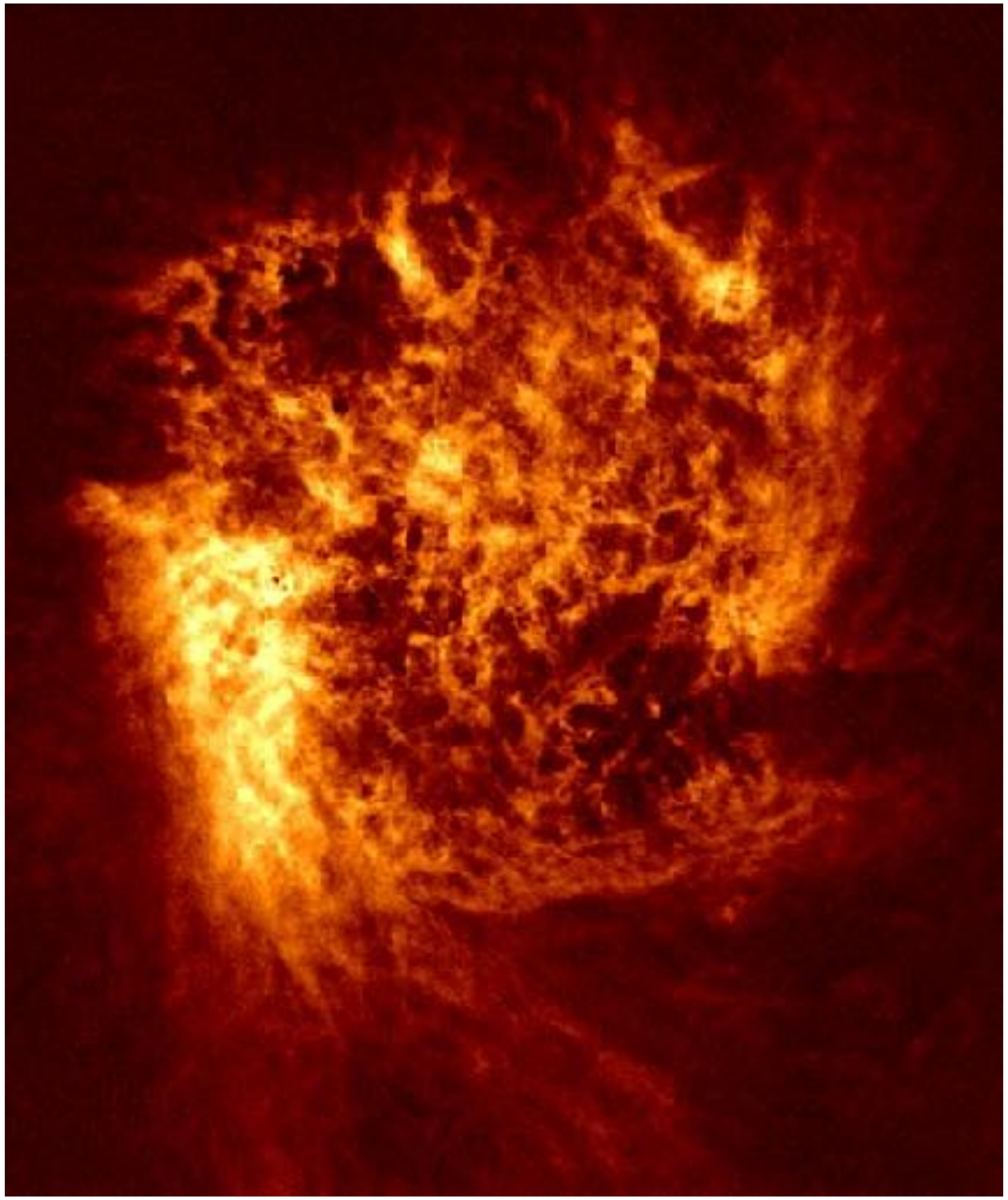
https://ned.ipac.caltech.edu/level5/Sept15/Freeman/Freeman5.html



NASA

Satellite Galaxies

- about 2 dozen



Large Magellanic Cloud
(face-on disk)

ATCA plus Parkes image in HI by S. Kim, L. Staveley-Smith, M. Dopita, K. Freeman, R. Sault, M. Kesteven, D. McConnell, M. Calabretta and R

Satellite Galaxies

News this week!

Vast Polar Structure (VPOS)

"… bolsters the standard cosmological model, or the Cold Dark Matter paradigm, by showing that the vast polar structure formed well after the Milky Way and is an unstable structure."

If the VPOS instead lasted a dynamical time it could be a problem for Lambda CDM cosmology (Lambda == Dark Energy; Cold Dark Matter). However using HST proper motion measurements and simulations indicates that

- planar structures in Lambda CDM are not that rare (e.g. 1 in 10 probability)
- the VPOS is transient, having existed for less than a Gyr (e.g. timescale of mergers).

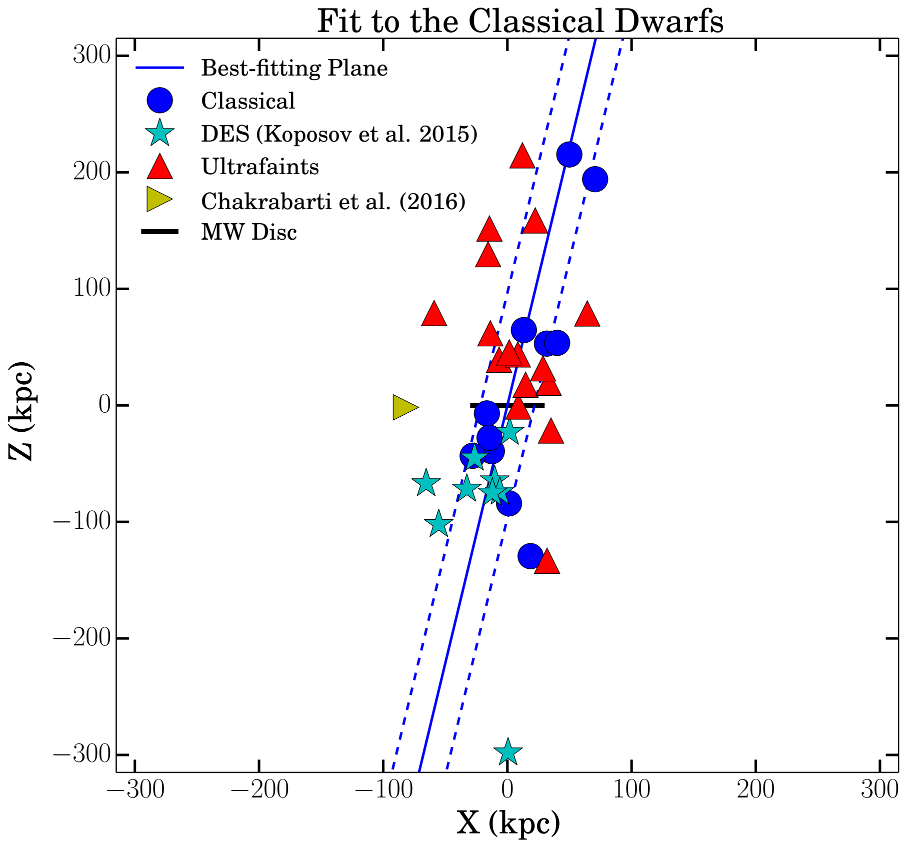


Figure 1. All known dwarf galaxies surrounding the Milky Way are displayed (including those that are not spectroscopically confirmed) and the VPOS is shown via the solid blue line. The solid horizontal line in the centre represents the Milky Way galactic disc, and the dotted lines bordering the VPOS represent the rms distance, $D_{\rm rms} = 21.3$ kpc, of the dwarfs from the fitted plane. The system is viewed from infinity and rotated by angle $\phi = 158.0°$ so that the VPOS is viewed edge on.

Andrew Lipnicky and Sukanya Chakrabarti

http://www.rit.edu/news/story.php?id=60486

Segue into Galaxies and Observational Cosmology

Includes Large Scale Structure

1st reader: Ben
2nd readers: Cole and Kate