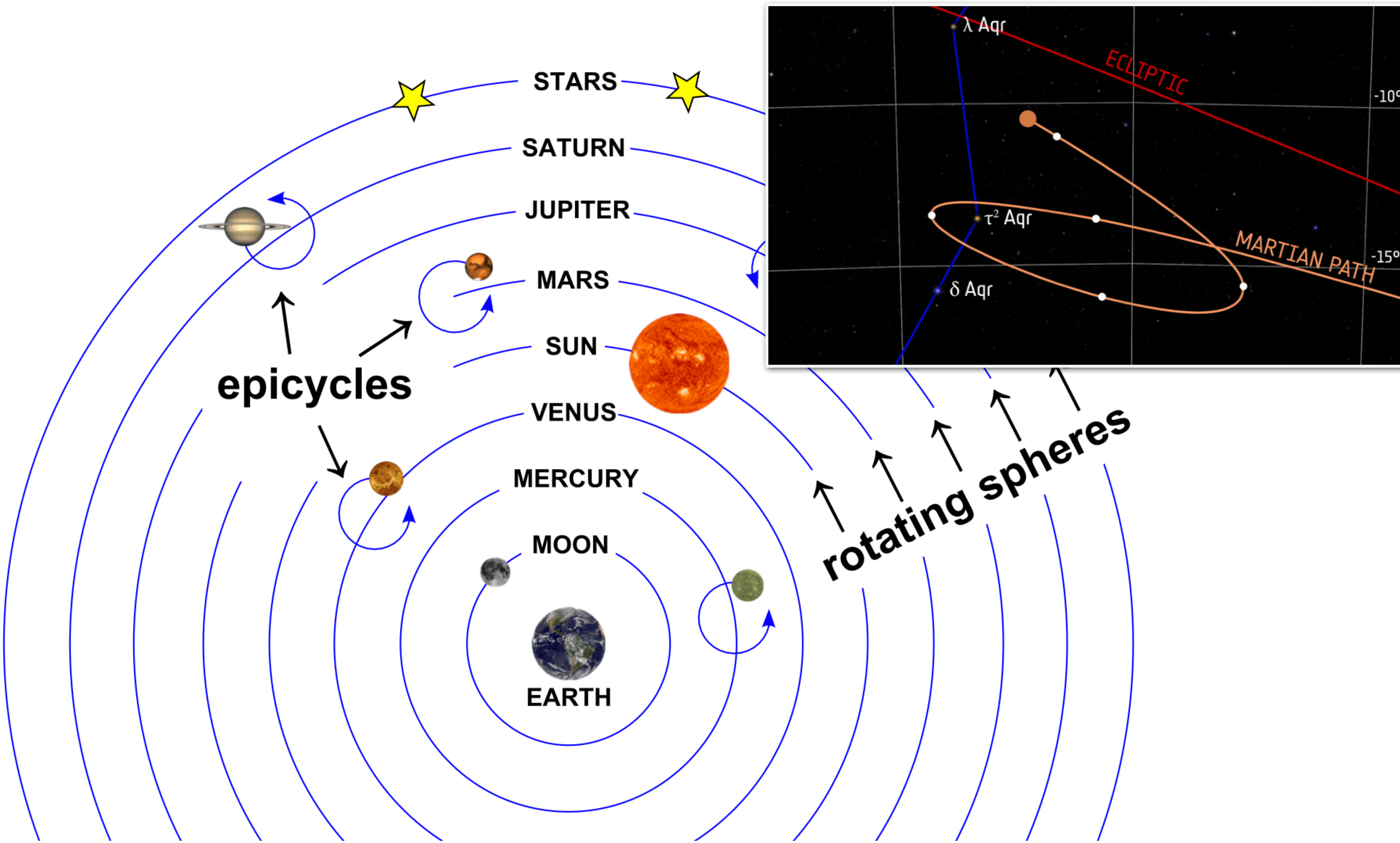
Chap 20: The Milky Way Galaxy
(inside views of a normal spiral galaxy)

Devils Tower, Wyoming

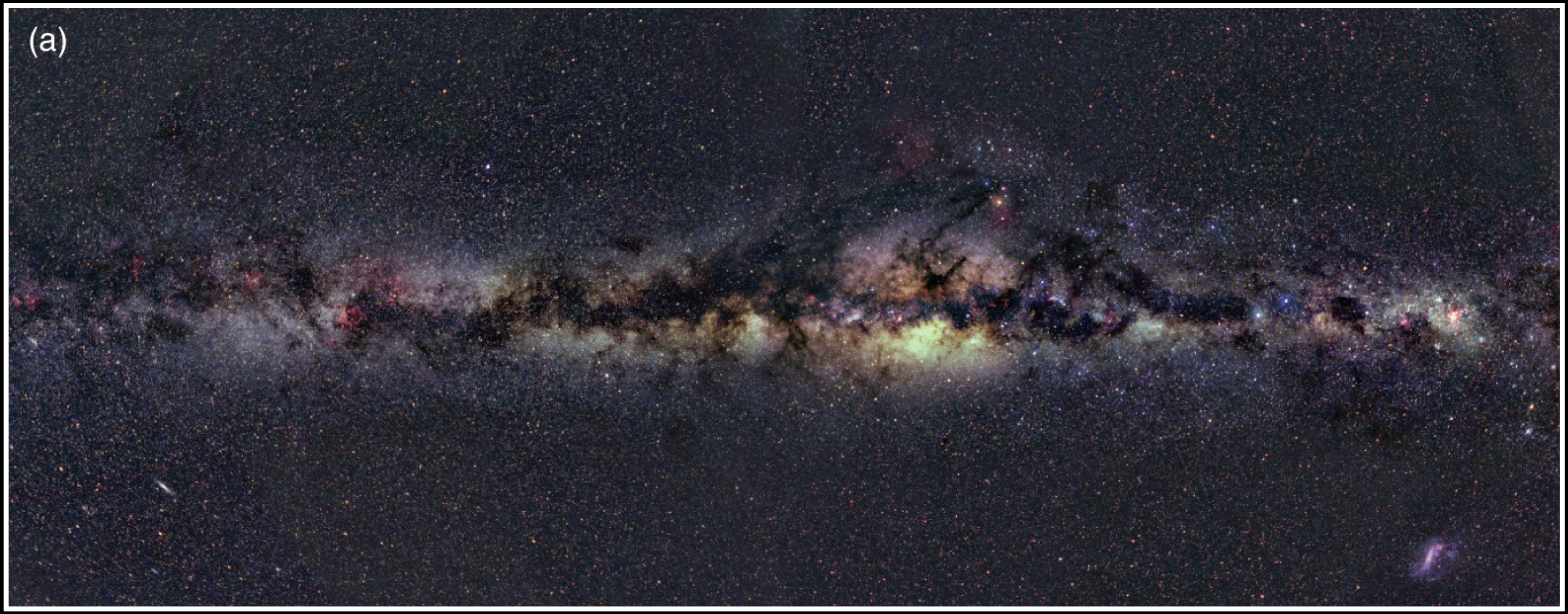
Astronomers had faced a similar challenge in the solar system



Ptolemy’s modified geocentric model (with epicycles and deferents)

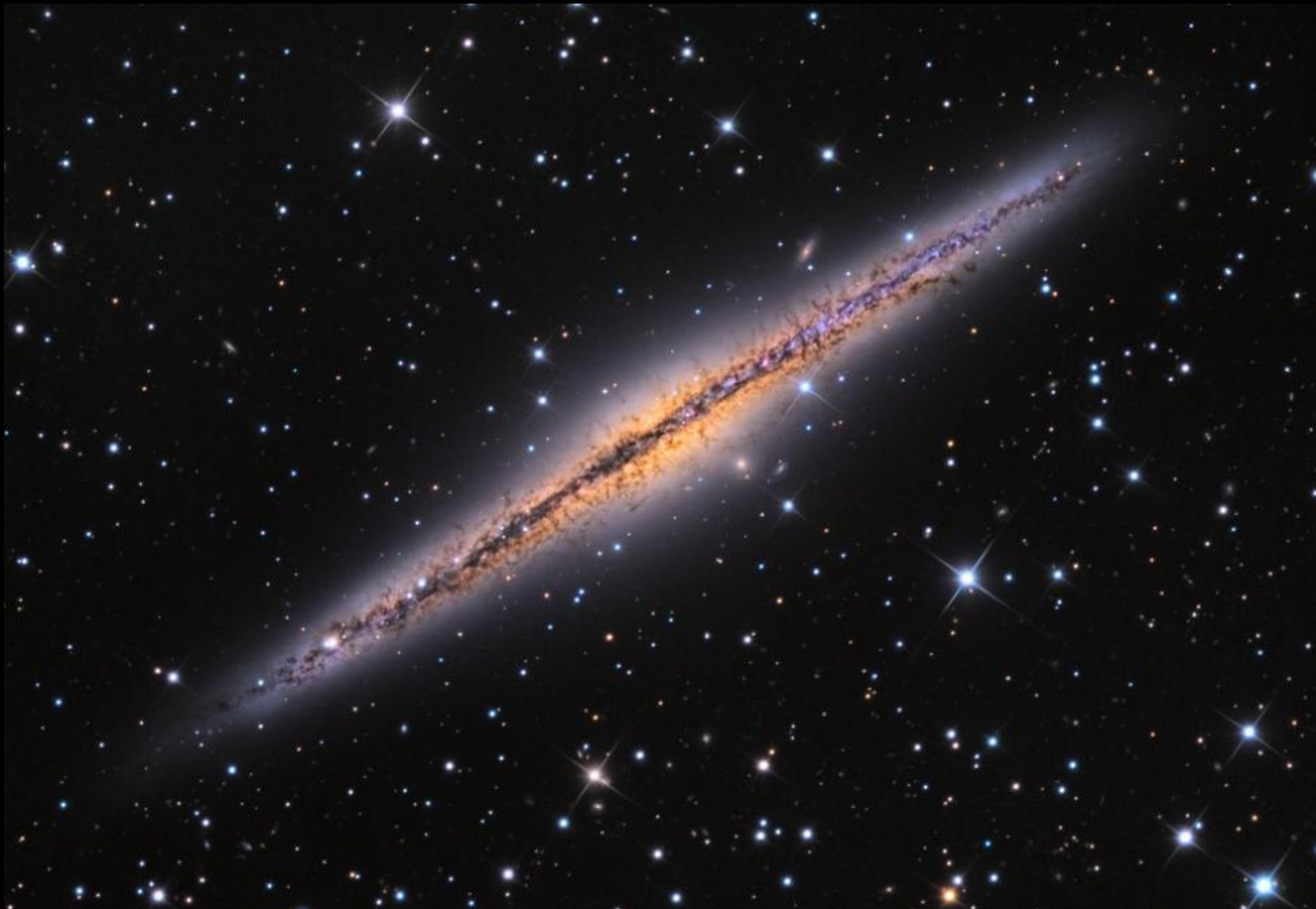
Chap 20: The Milky Way Galaxy

- What does a spiral galaxy look like from inside?
- How to map the spiral arms?
- How fast are we moving?
- How to measure the rotation curve of the Milky Way disk?
- Galactocentric distance (§19)
- The stellar populations and the chemical enrichment history of the Galaxy
- Who are our closest neighbors? The local group and the local super cluster



Viewing the Galaxy from inside at multiple wavelengths

NGC 891 - an edge-on spiral galaxy

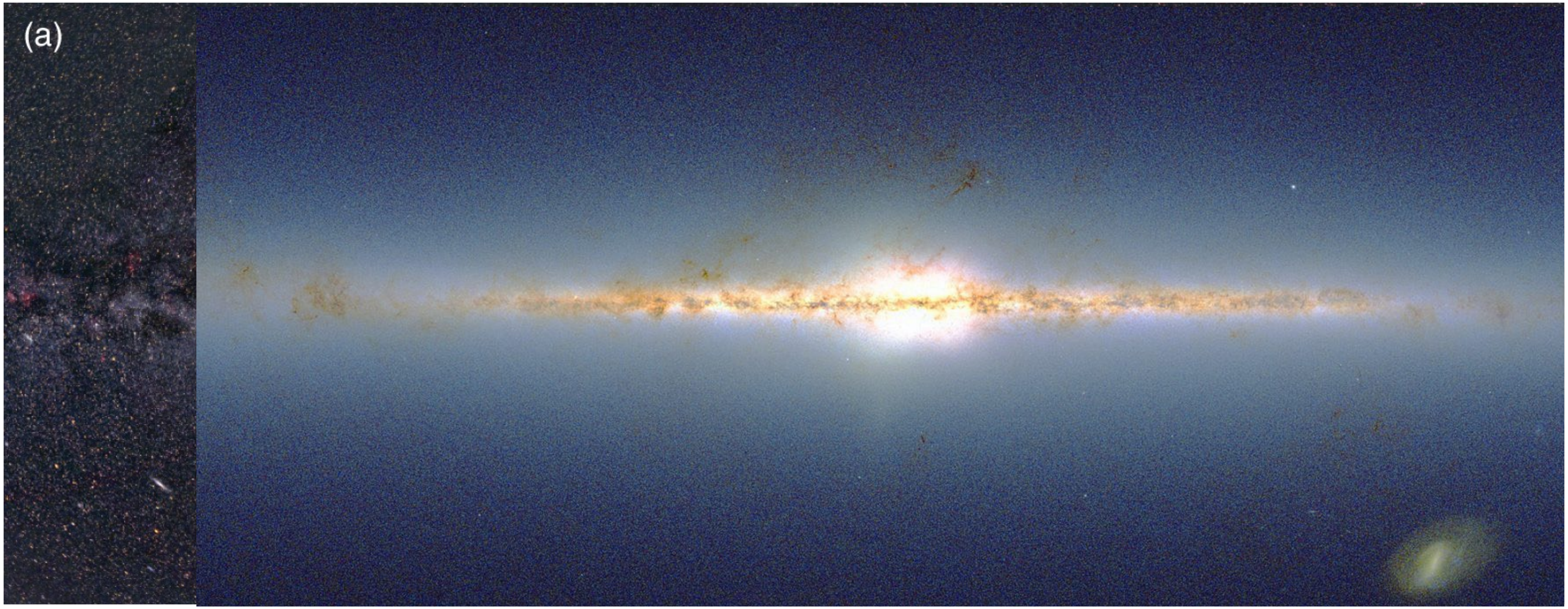


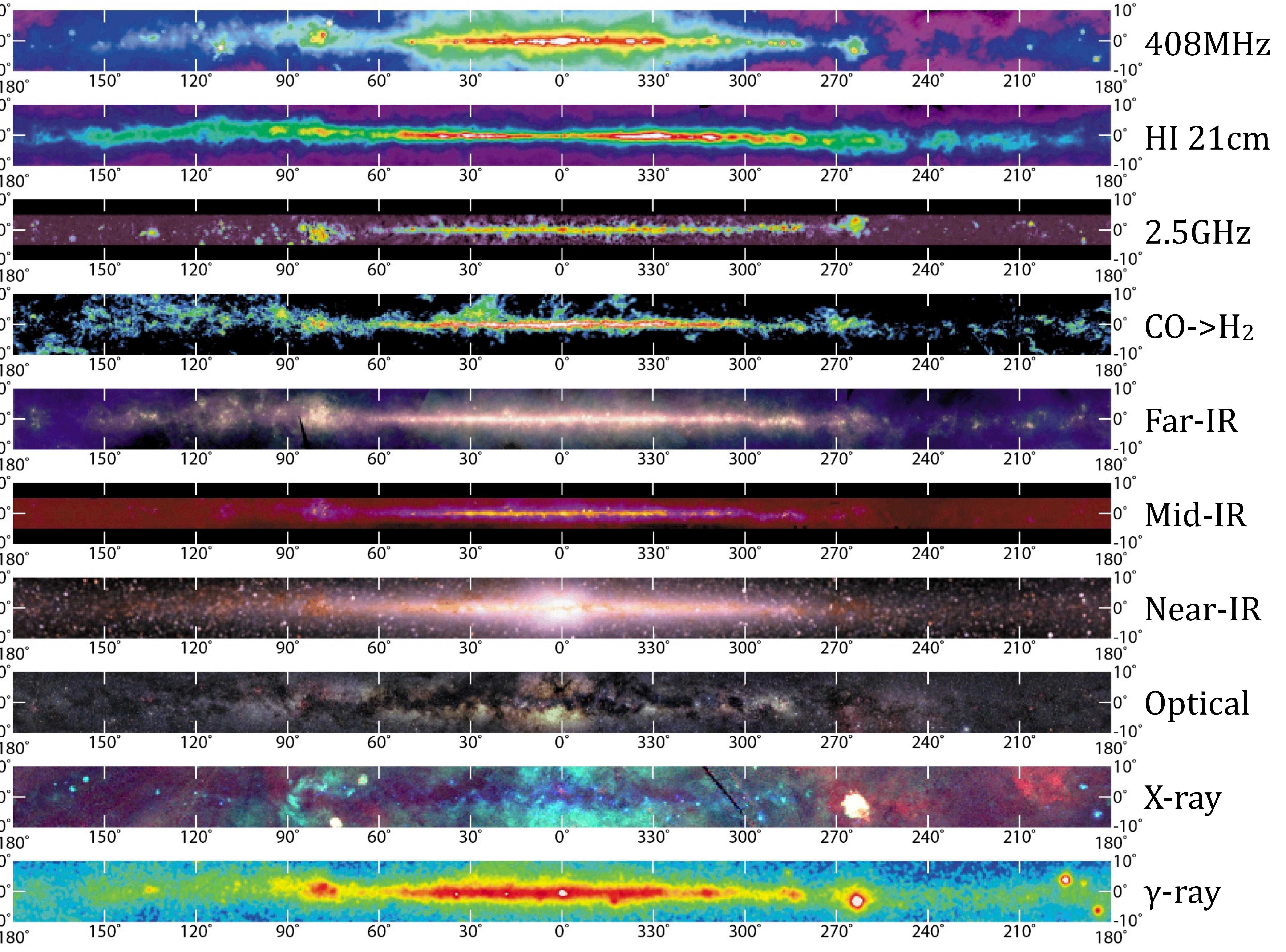
Milky Way compared to NGC 891 (an edge-on Spiral galaxy)

a.

MW galaxy in optical vs. infrared wavelengths

- The IR light is less attenuated by dust, revealing the central stellar bulge of the galaxy.




408MHz
HI 21cm
2.5GHz
CO->H2
Far-IR
Mid-IR
Near-IR
Optical
X-ray
γ-ray
180° 150° 120° 90° 60° 30° 0° 330° 300° 270° 240° 210° 180°
10° 0° -10°

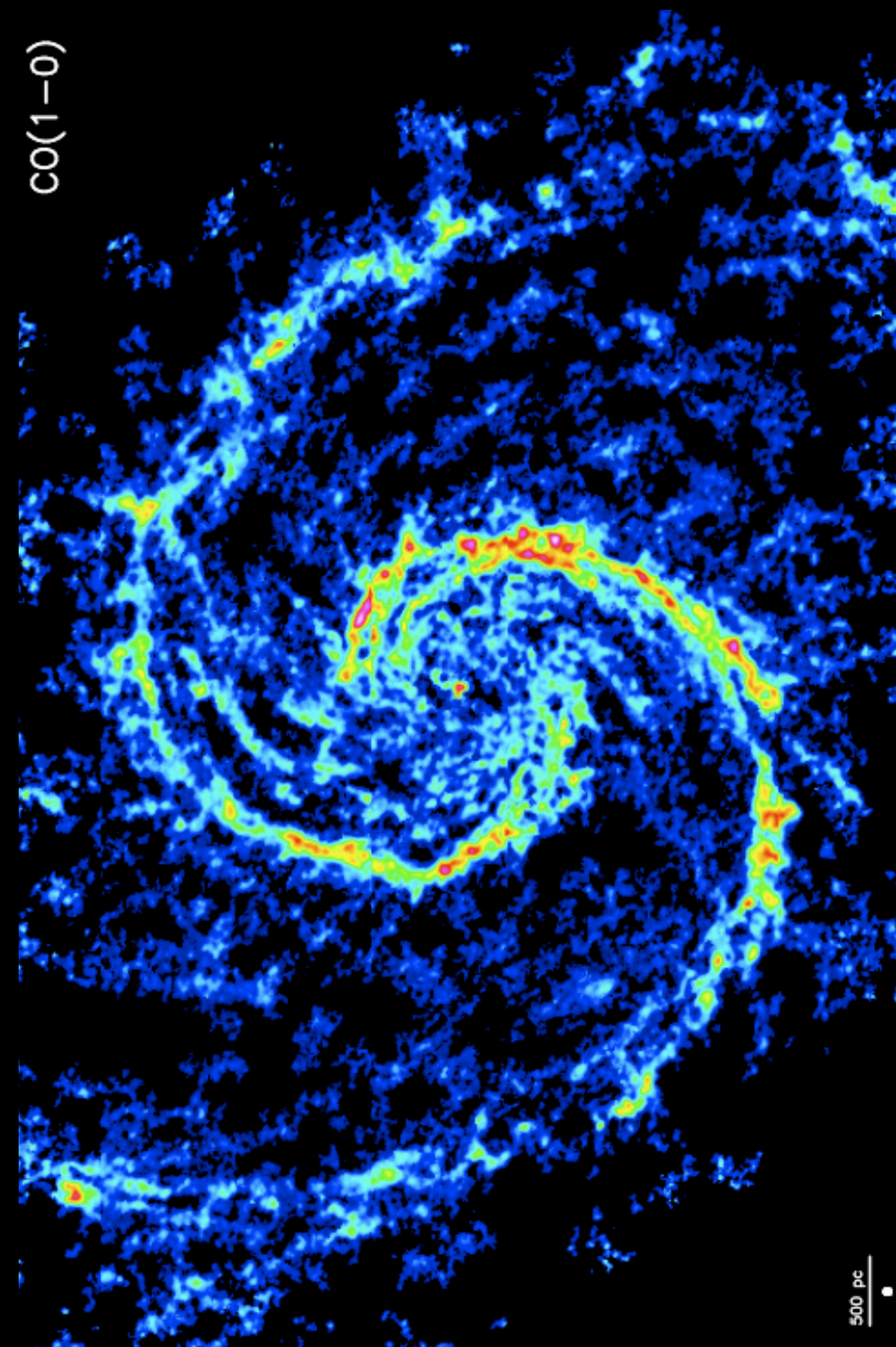
The Multi-phase Interstellar Medium of the Milky Way Galaxy

COMPONENT OF OF INTERSTELLAR MEDIUM	TEMPERATURE	DENSITY	STATE OF HYDROGEN
Hot intercloud gas	~1,000,000 K	~0.005 atoms/cm^3	Ionized
Warm intercloud gas	~8000 K	0.01–1 atom/cm^3	Ionized or neutral
Cold intercloud gas	~100 K	1–100 atoms/cm^3	Neutral
Interstellar clouds	~10 K	100–1,000 atoms/cm^3	Molecular or neutral

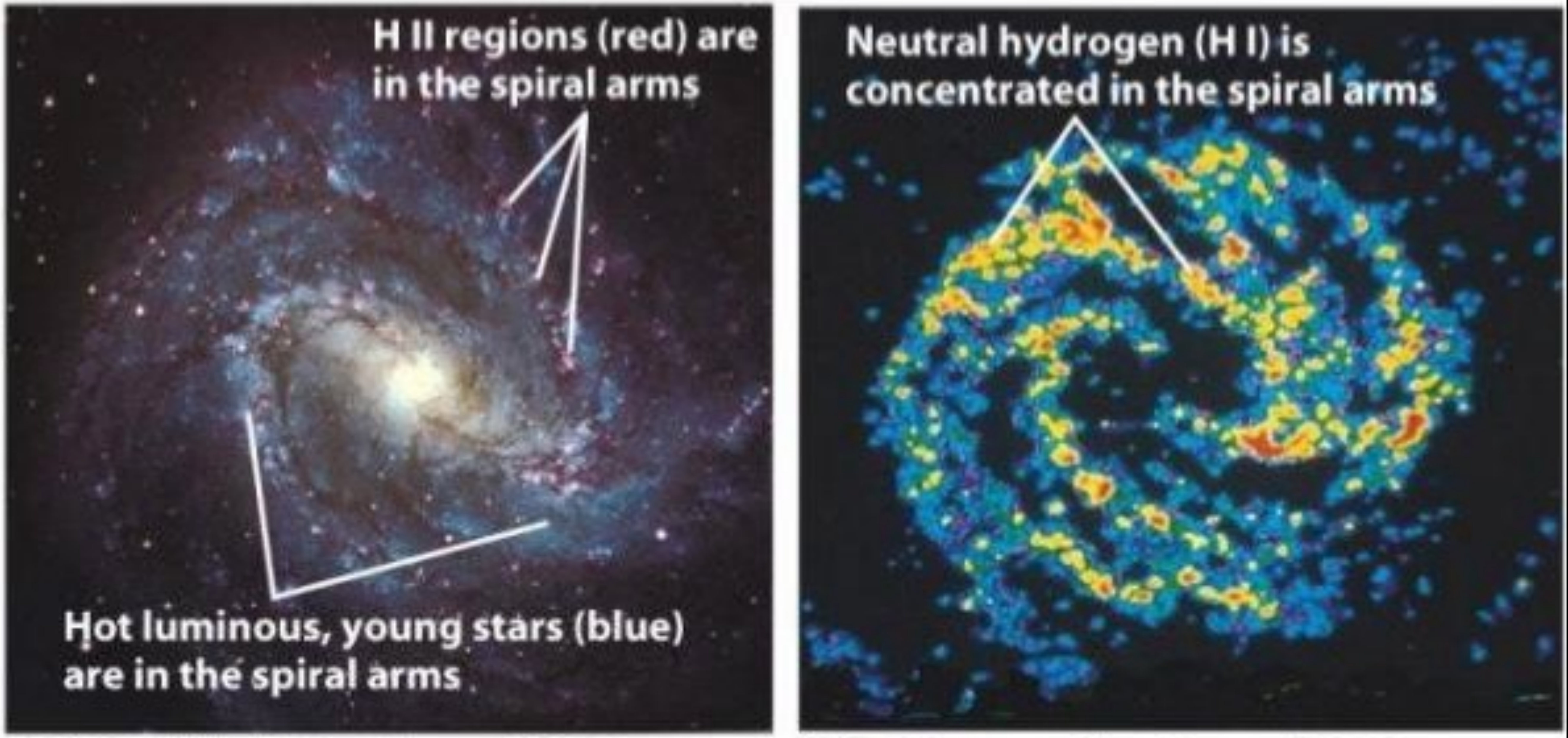
How the spiral arms were identified?

From outside, the Milky Way would look much like M109
But, *how did we know? What trace spiral arms?*

What trace spiral arms in other spiral galaxies?



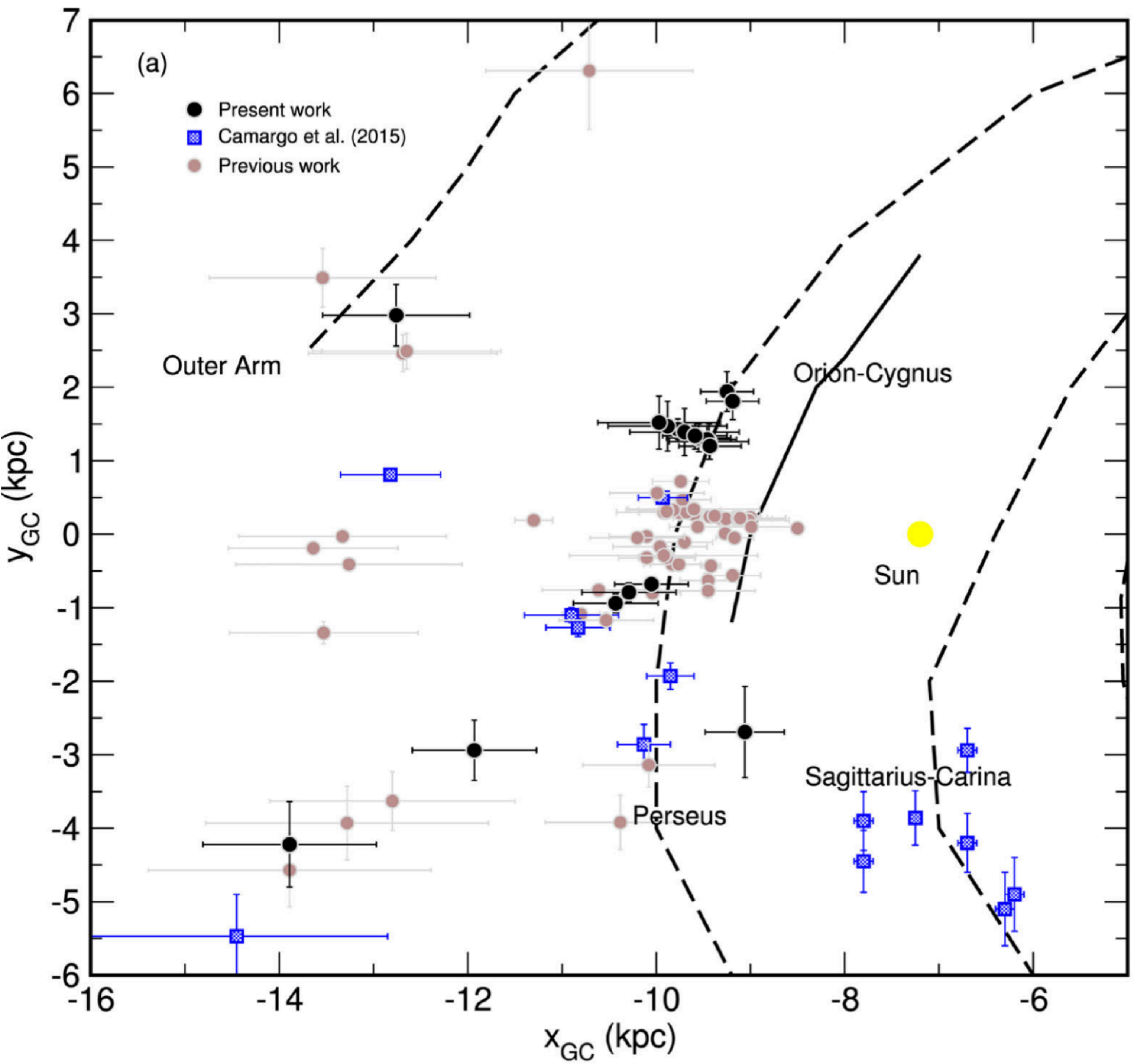
What trace spiral arms in other spiral galaxies?



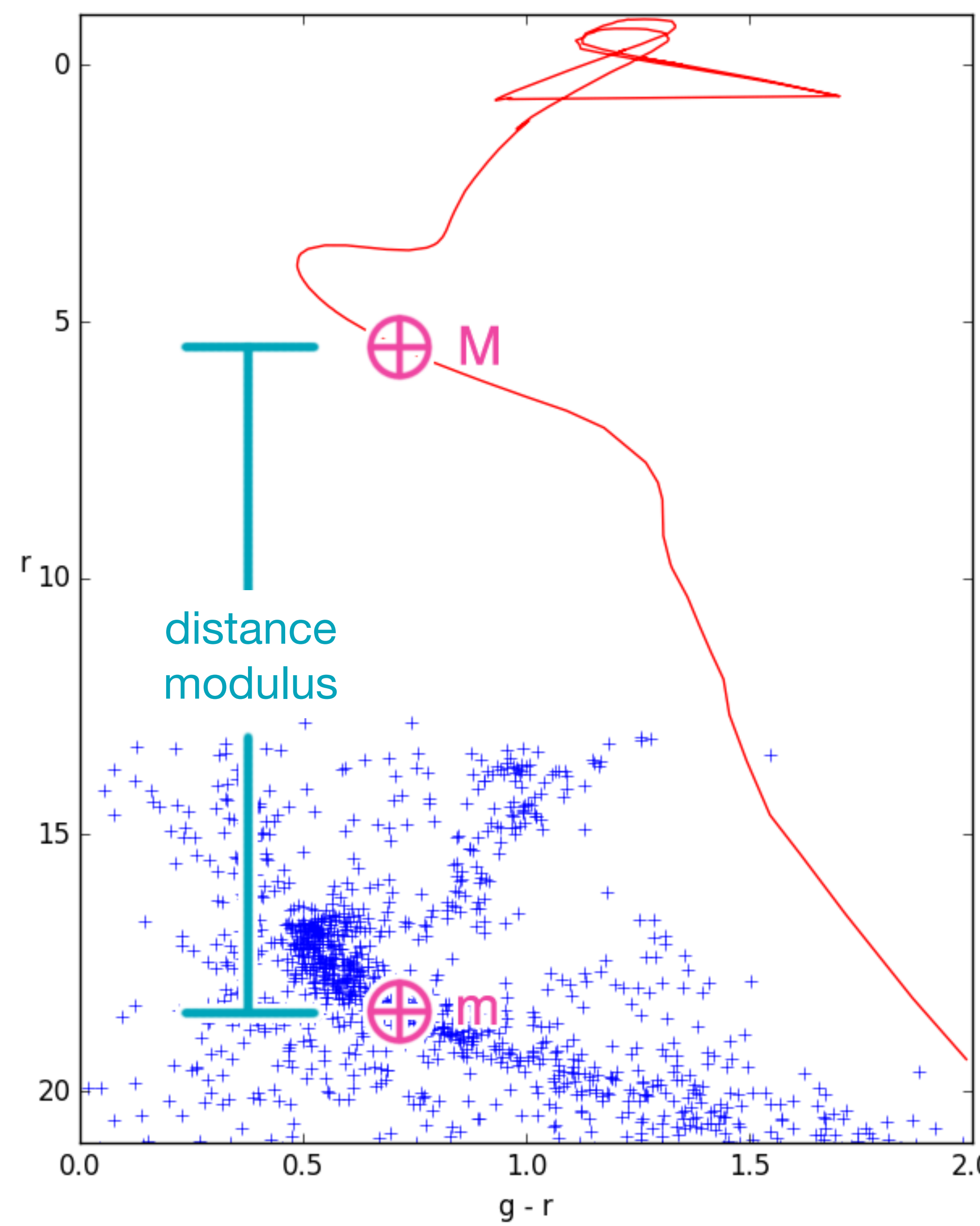
(a) Visible-light view of M83 (b) 21-cm radio view of M83

Tracing the spiral arms with young star clusters

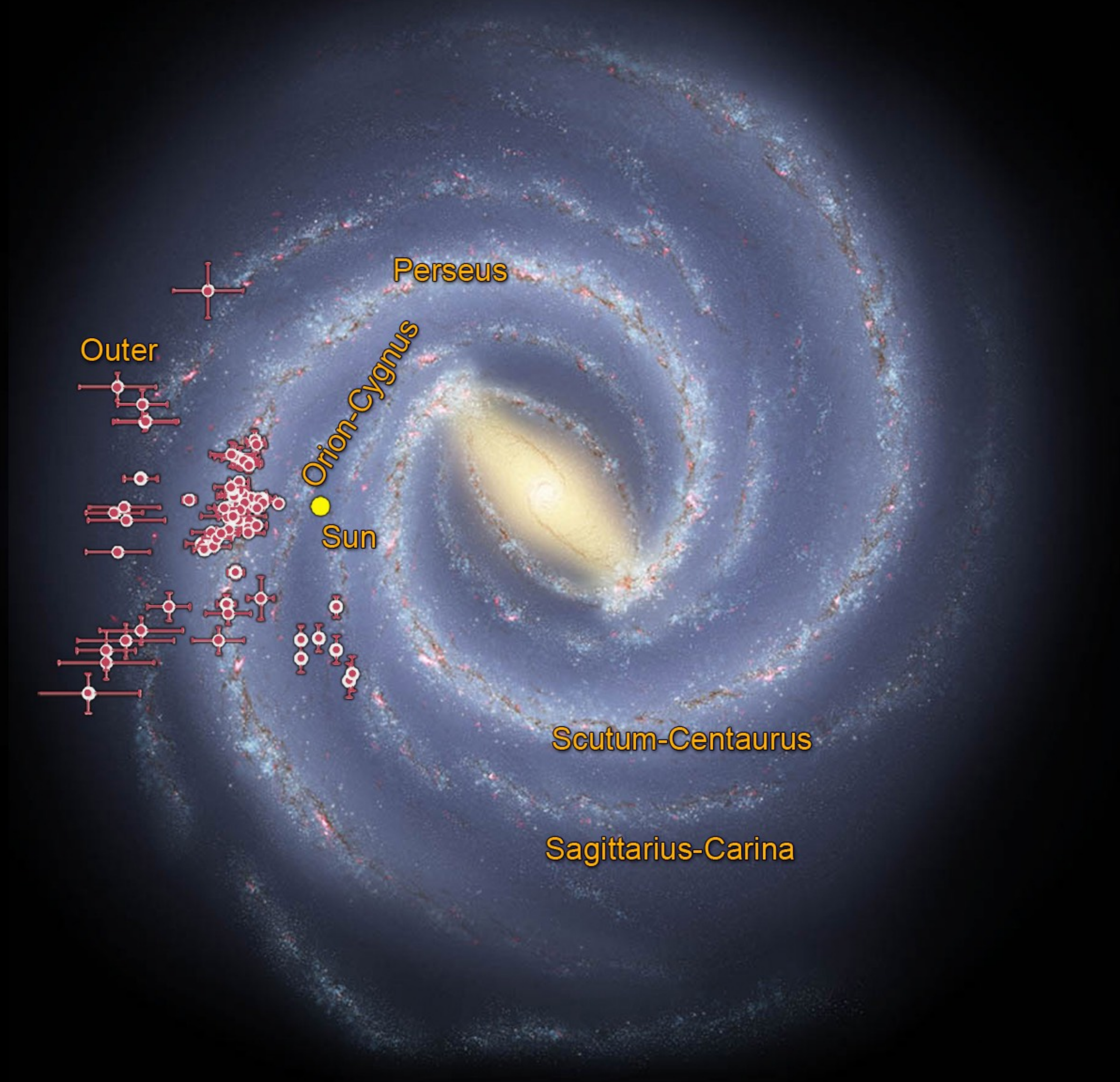
We know the directions to the star clusters, but how do we measure their distances to us? Which distance method would you use?



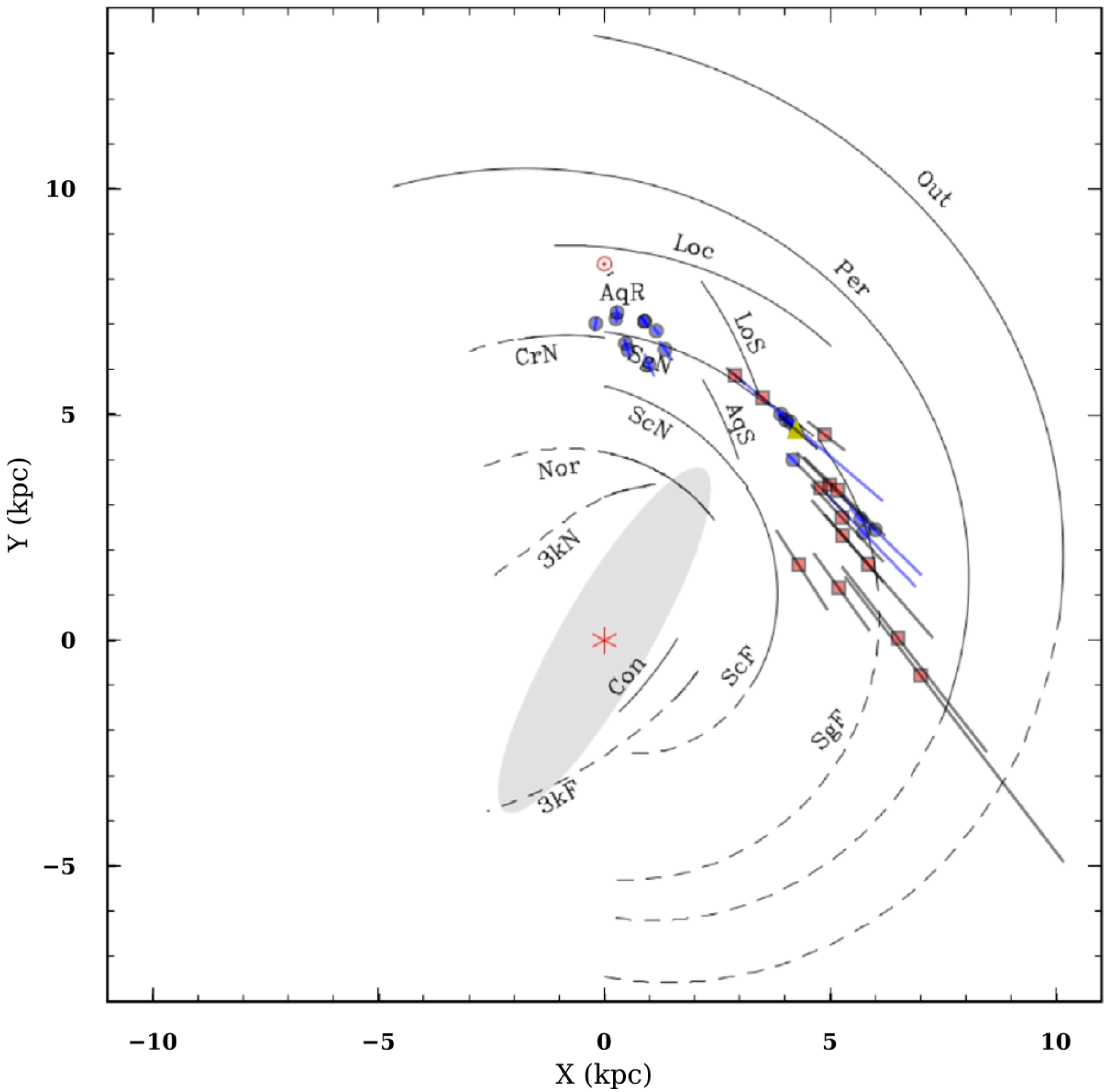
Camargo, Bonatto, and Bica 2015



Tracing the spiral arms with young star clusters



Tracing the spiral arms with astrophysical masers in star-forming regions

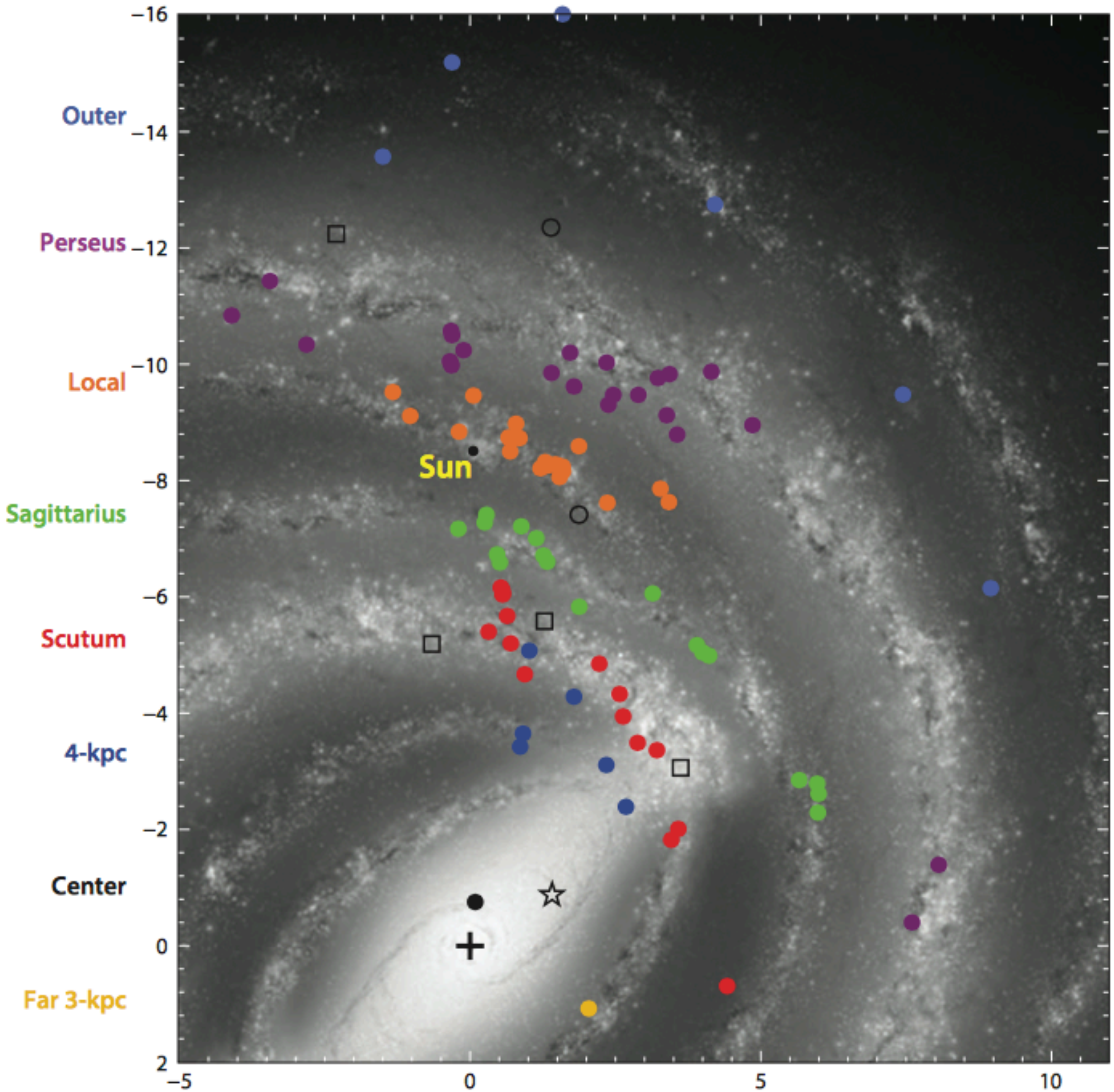


Colored dots are the locations of newly formed OB-type stars determined from **trigonometric parallaxes** using associated **methanal** and **water masers:** CH_3OH at 6.7 GHz & H_2O at 22 GHz.

Parallaxes were determined with the VLBA & VLBI networks of radio interferometers

Wu, Reid, Sakai et al 2019

Tracing the spiral arms with molecular masers in star-forming regions



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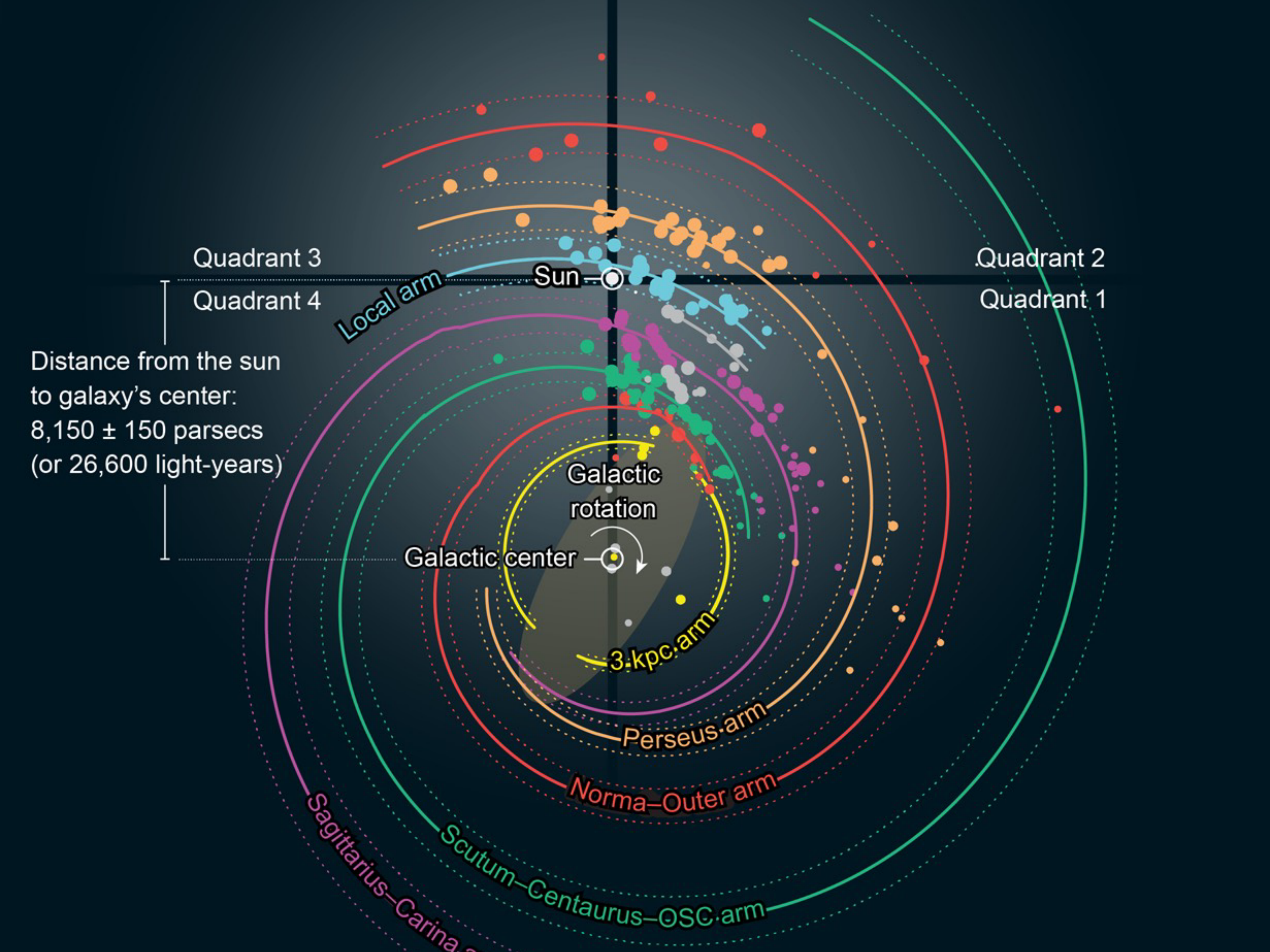
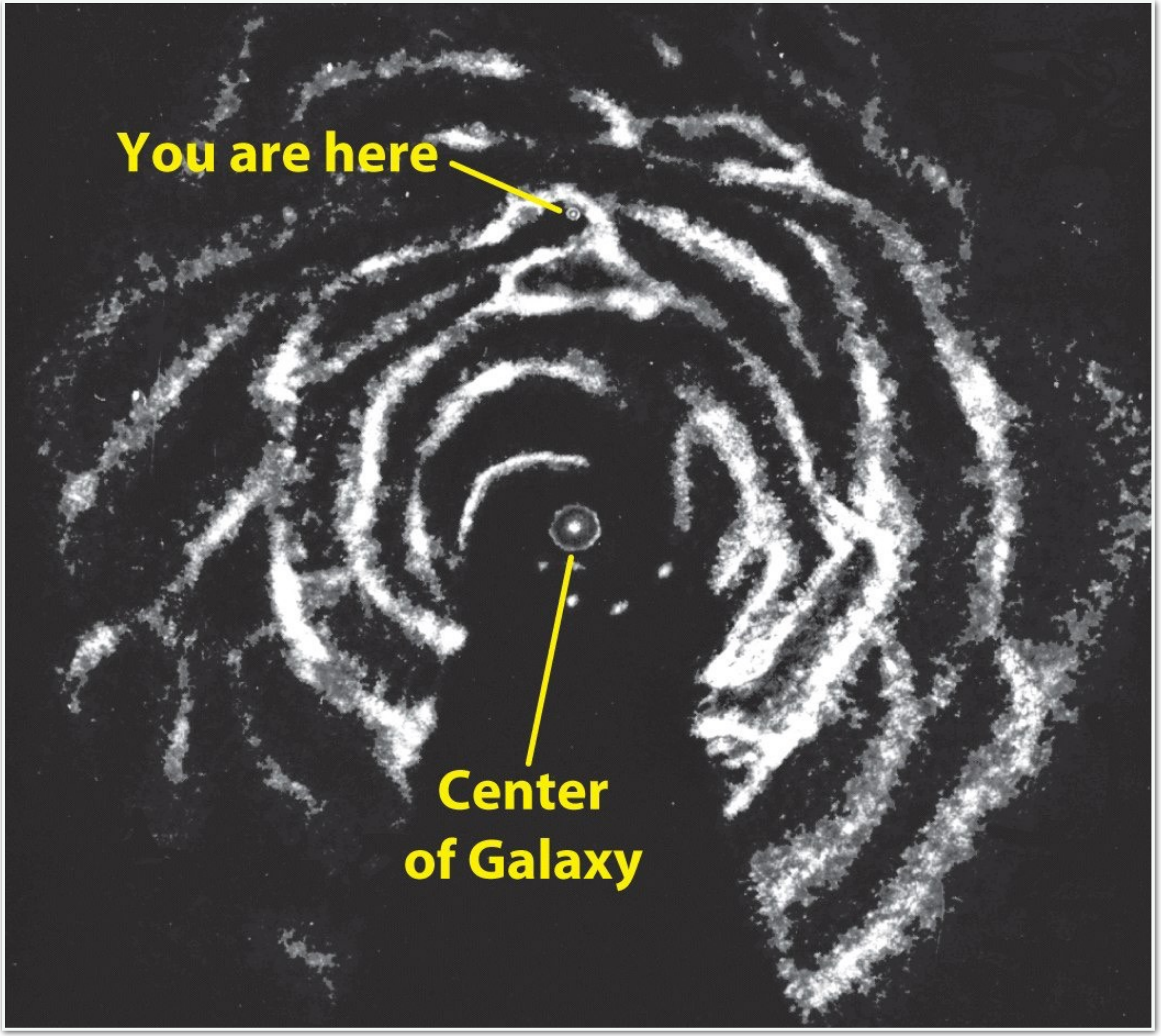
Parallaxes were determined with the VLBA & VLBI networks of radio interferometers

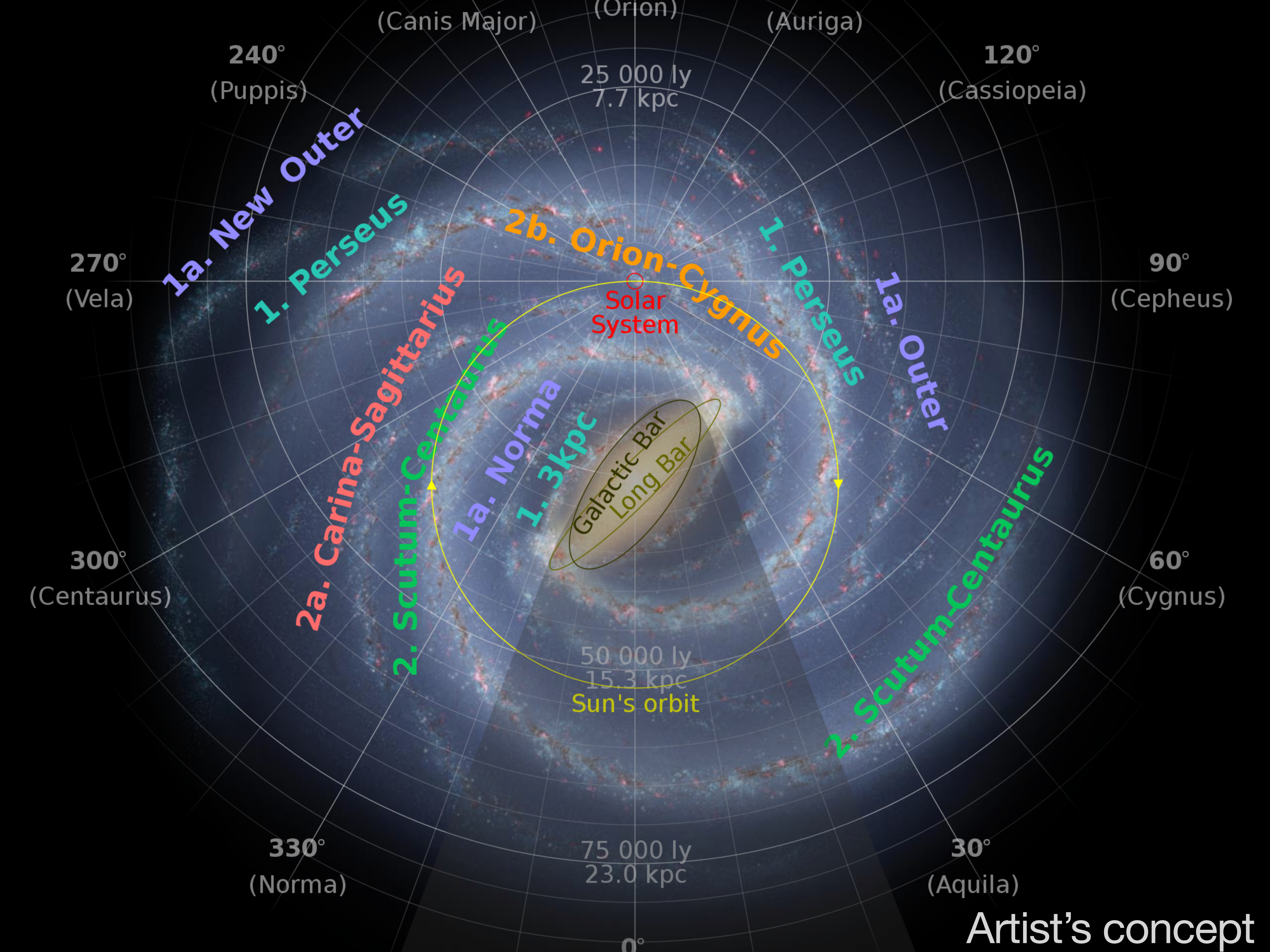
Reid & Honma 2014



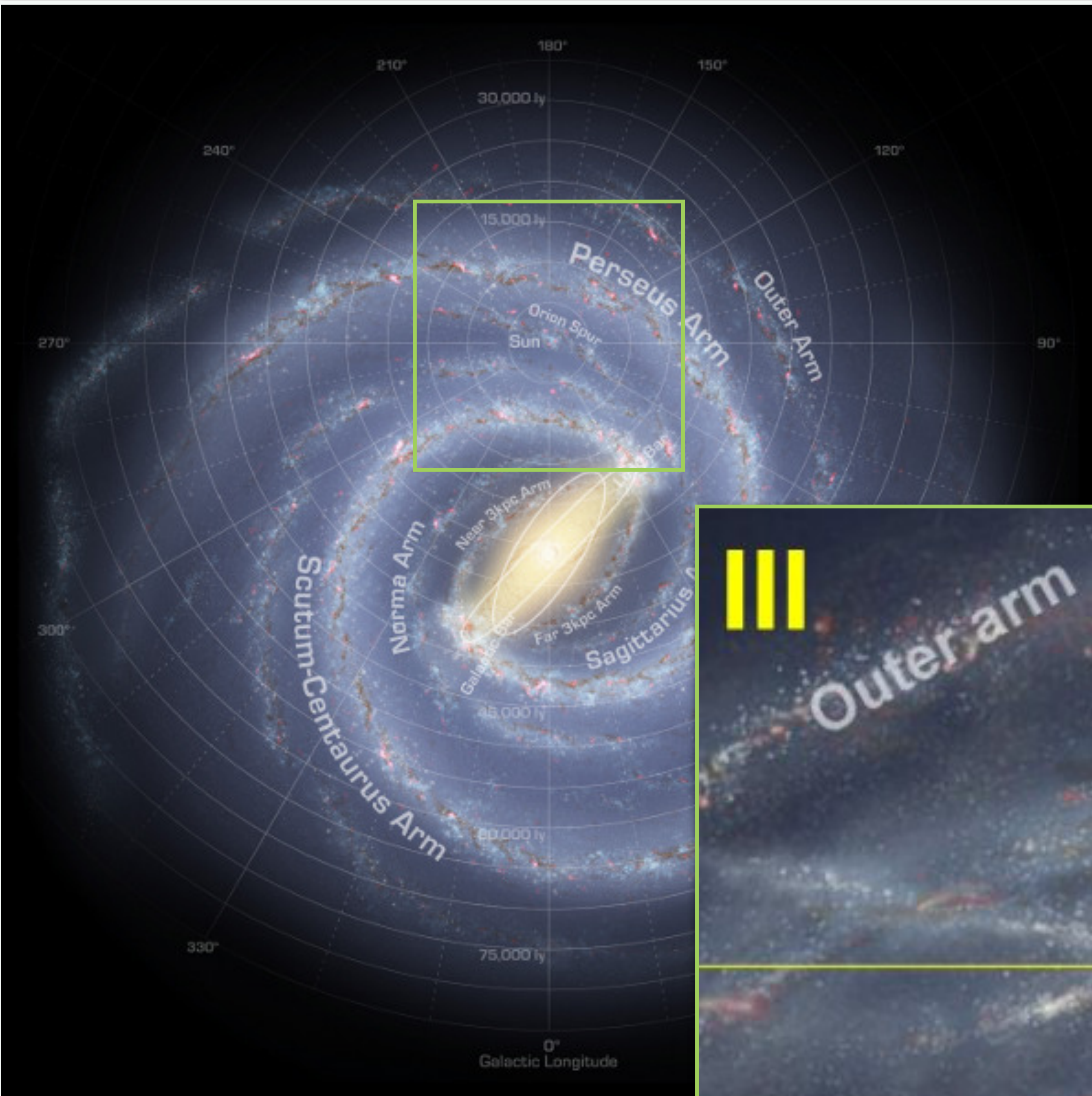
Quadrant 3
Quadrant 2
Quadrant 4
Quadrant 1
Sun
Local arm
Distance from the sun to galaxy's center: 8,150 ± 150 parsecs (or 26,600 light-years)
Galactic rotation
Galactic center
3 kpc arm
Perseus arm
Norma–Outer arm
Scutum–Centaurus–OSC arm

Tracing the Spiral arms in HI 21cm emission (to be discussed later)

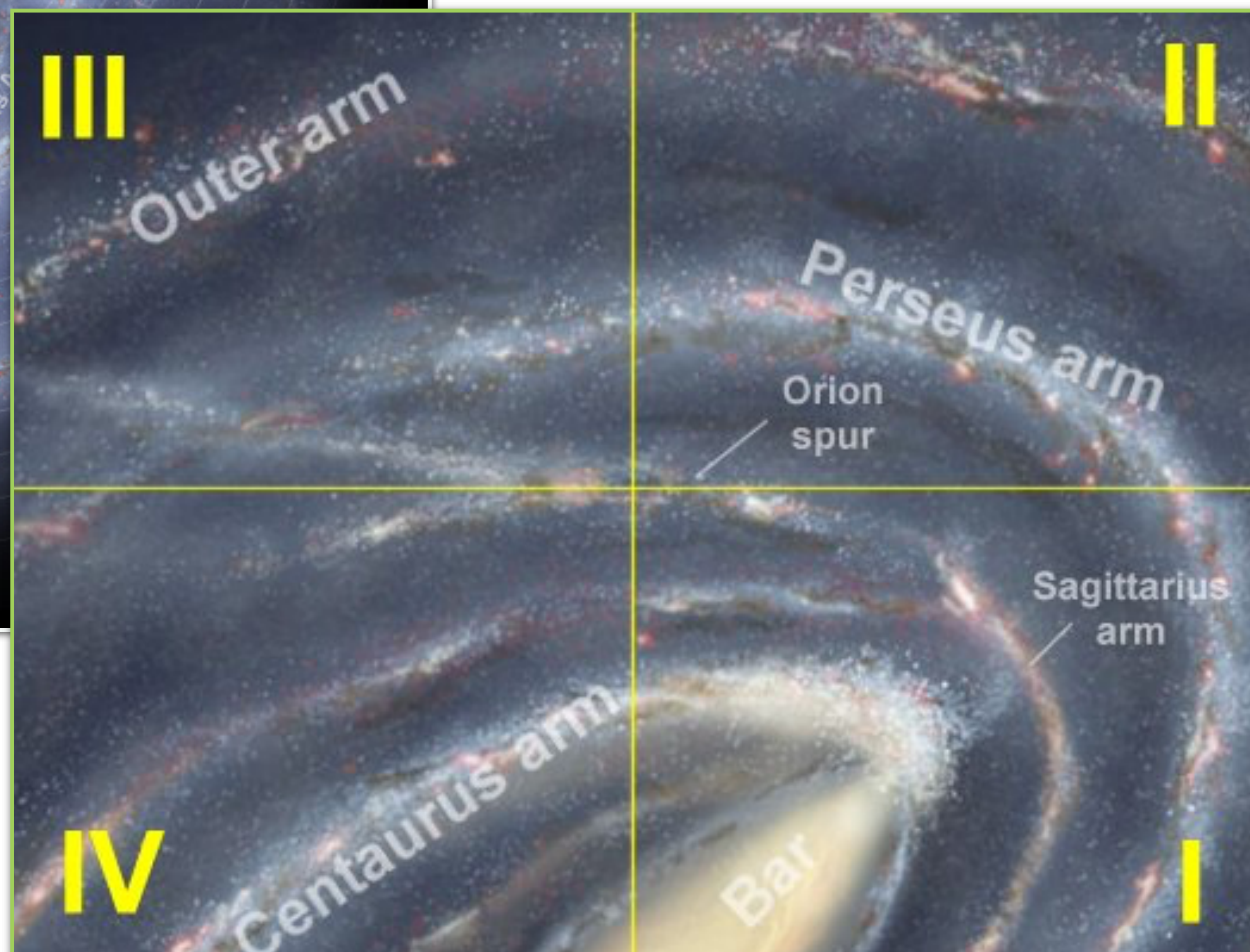




Artist's concept



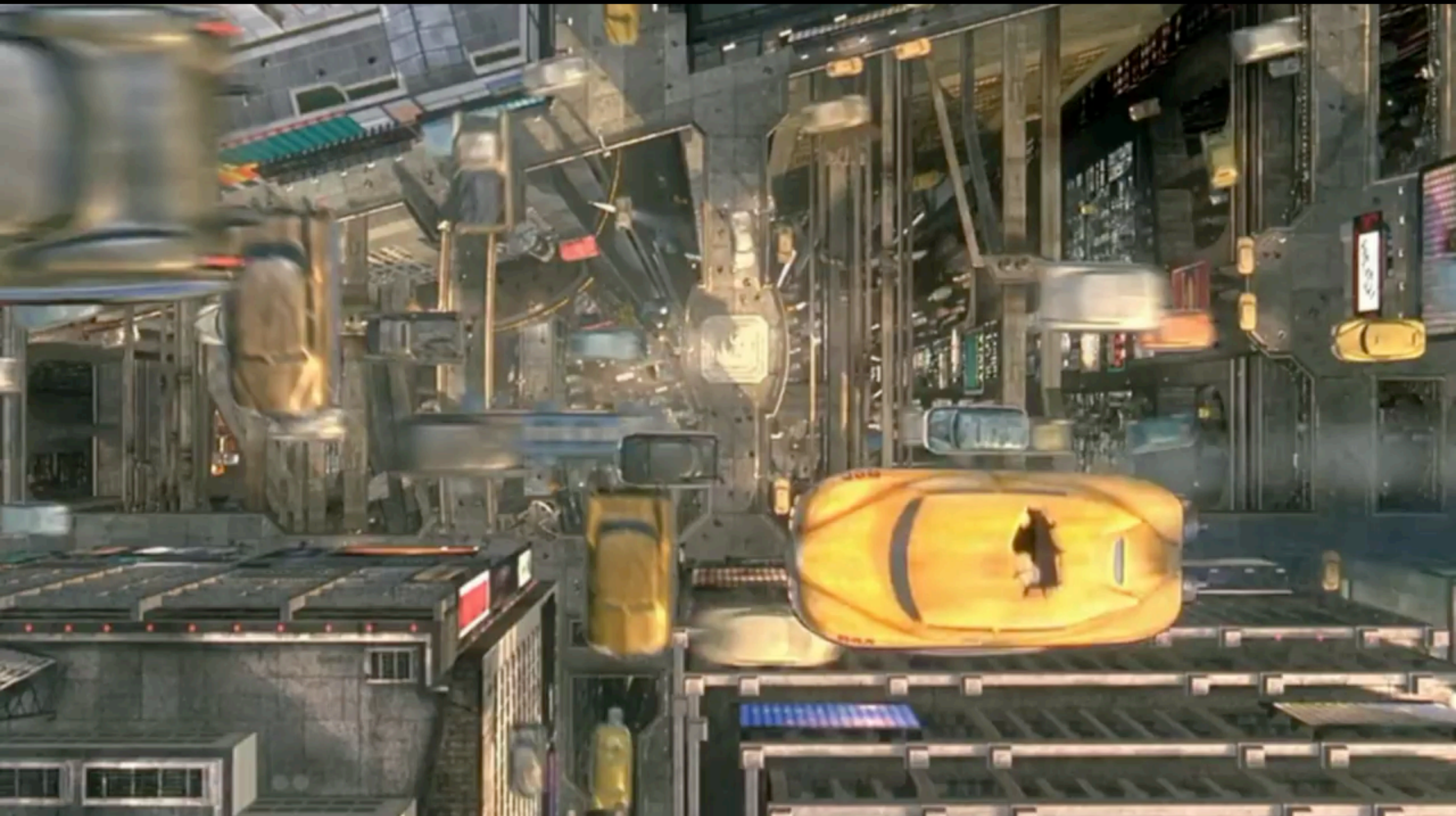
The Milky Way is
an SBc type galaxy w/
two major spiral arms
and 3 smaller arms



Our location in the MW disk

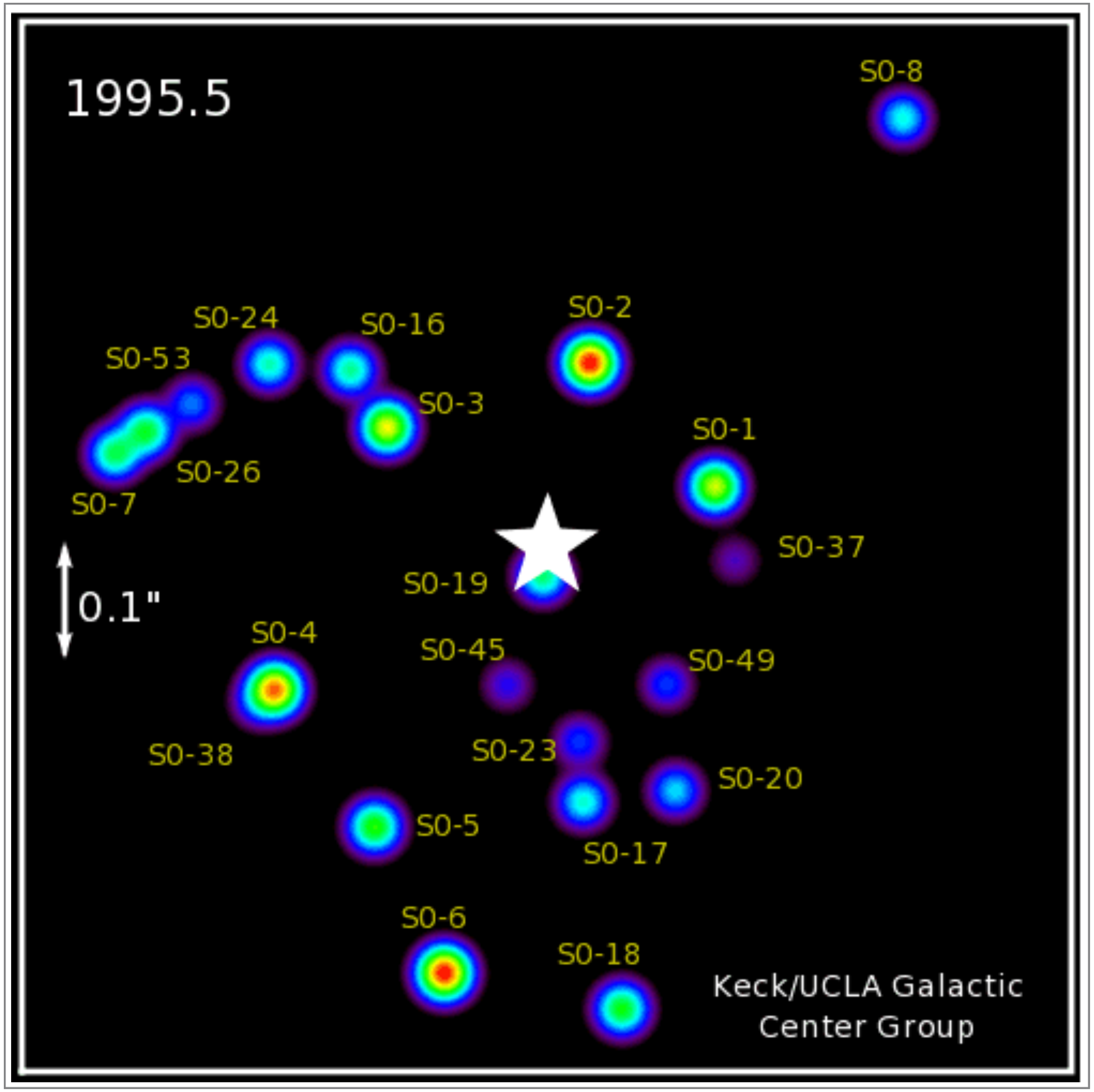
How fast are we moving in the Galaxy?

The Fifth Element (1997): Taxi Scene



How fast are we moving in the galaxy?

Mass and distance of the SMBH in the Milky Way Galaxy



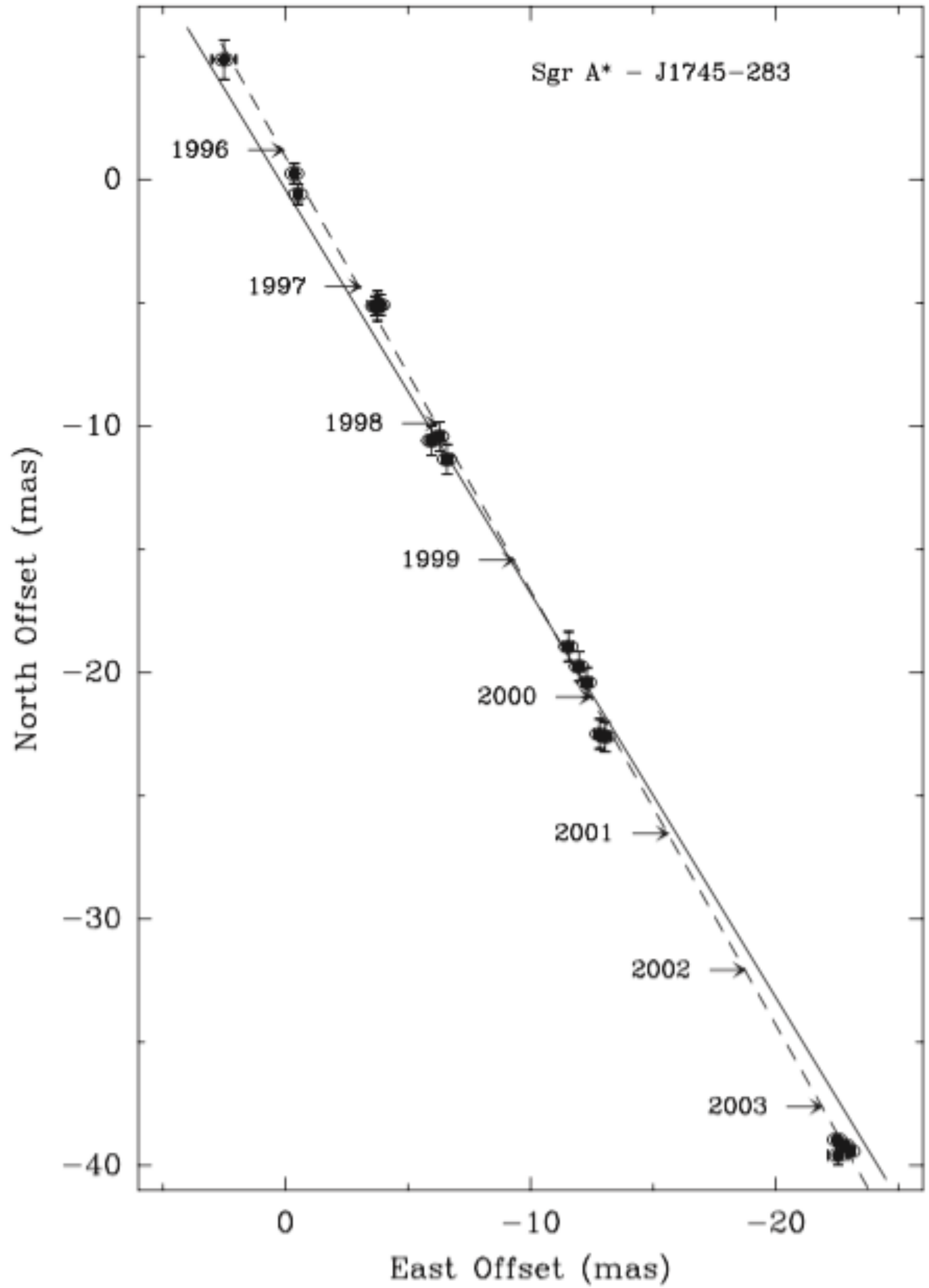
By monitoring **individual star's orbits and their velocities,** we can measure both the mass and the distance of the SMBH:

Mass: 4 million M_{sun}
Distance: 8.3 kpc

As we move, stationary objects appear to move in the opposite direction

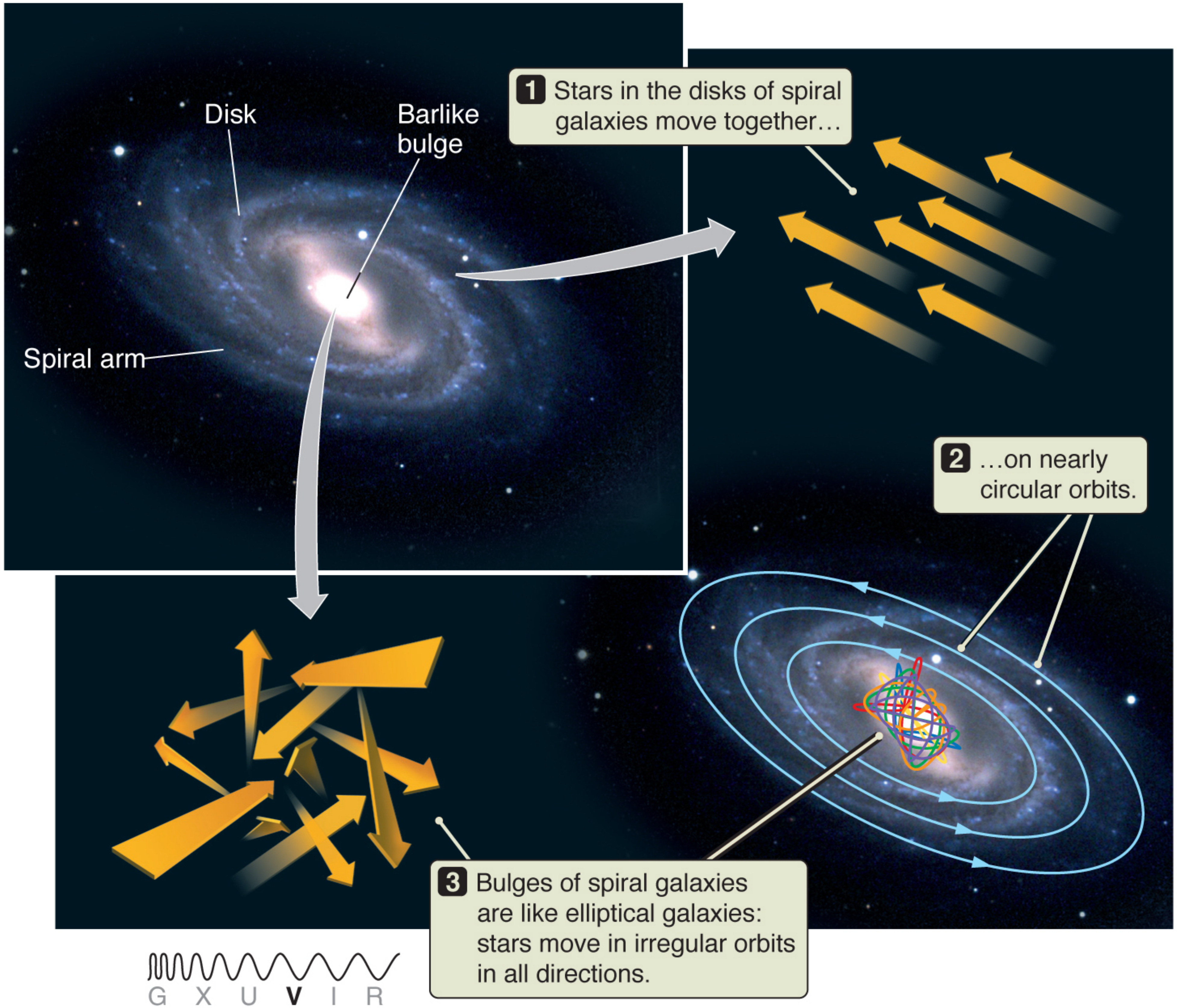
The Galactic Center Approach: Distance + Proper Motion of Sgr A*

- First determine the geometric distance (*d* in kpc) to Sgr A* based on the orbit of star **S0-2** and its radial velocity curve.
- Then measure the proper motion (μ in mas/yr) of Sgr A* against distant quasars.
- Multiplying the proper motion by the distance gives our velocity: $V(\text{km/s}) = 4.74 \cdot \mu(\text{mas/yr}) \cdot d(\text{kpc})$
  - The mean proper motion is about 6.4 mas/yr (Reid & Brunthaler 2004; right figure)
  - The distance is 8.3 kpc (Genzel+2010)
  - $V = 4.74 * 6.4 * 8.3 =$ **250 km/s**




How fast are we moving in the galaxy?

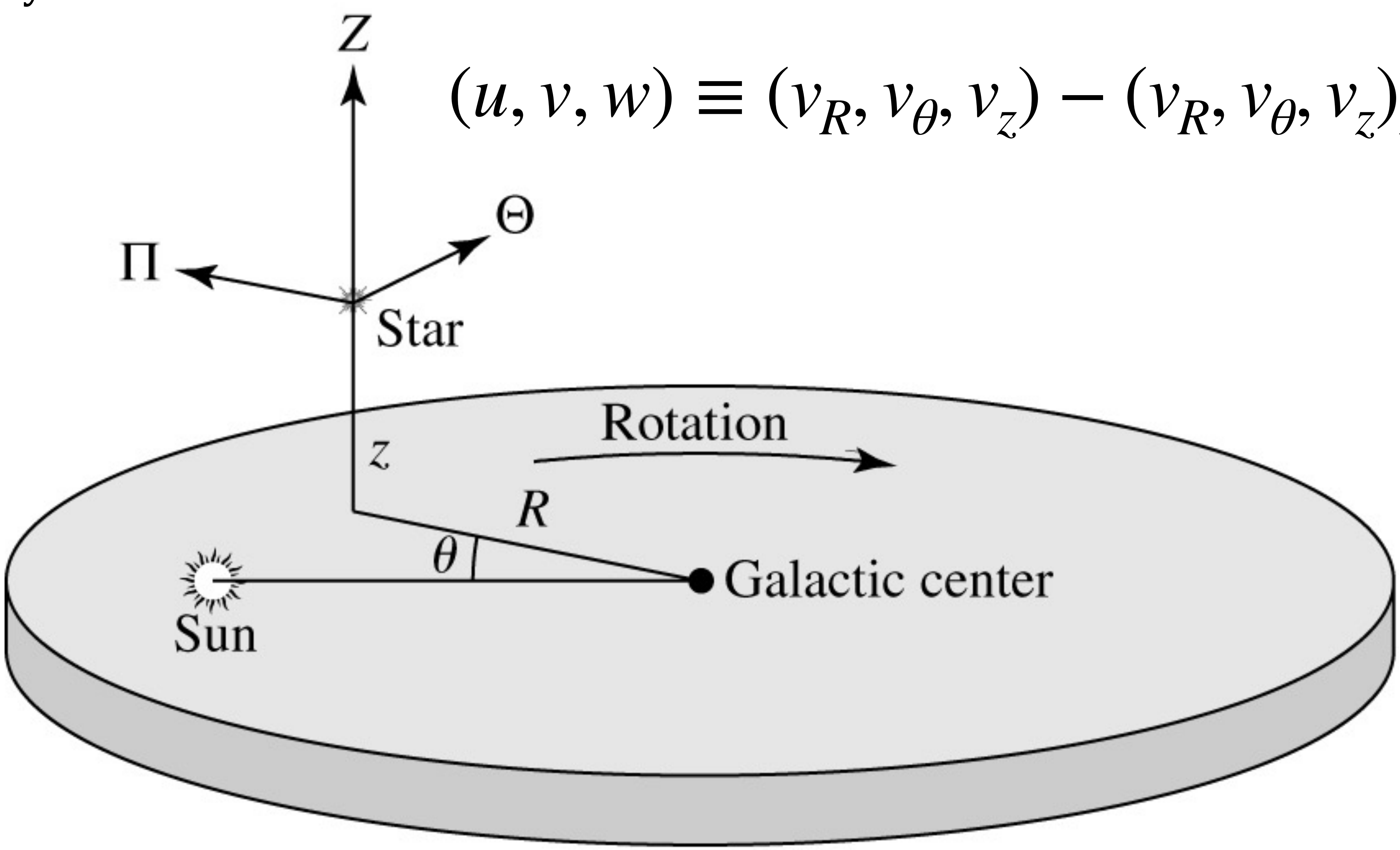
Spiral Galaxies:
Circular Orbits of Disk Stars + Irregular Orbits of Bulge stars & Halo stars



The peculiar velocity approach: Solar neighborhood stars

- The **peculiar velocities** of nearby stars relative to the Sun can be measured with Doppler shift combined with proper motion
- The **distribution of the peculiar velocities of a group of stars** whose mean velocity to the galaxy is expected to be zero can in turn tell us our velocity in the Galaxy

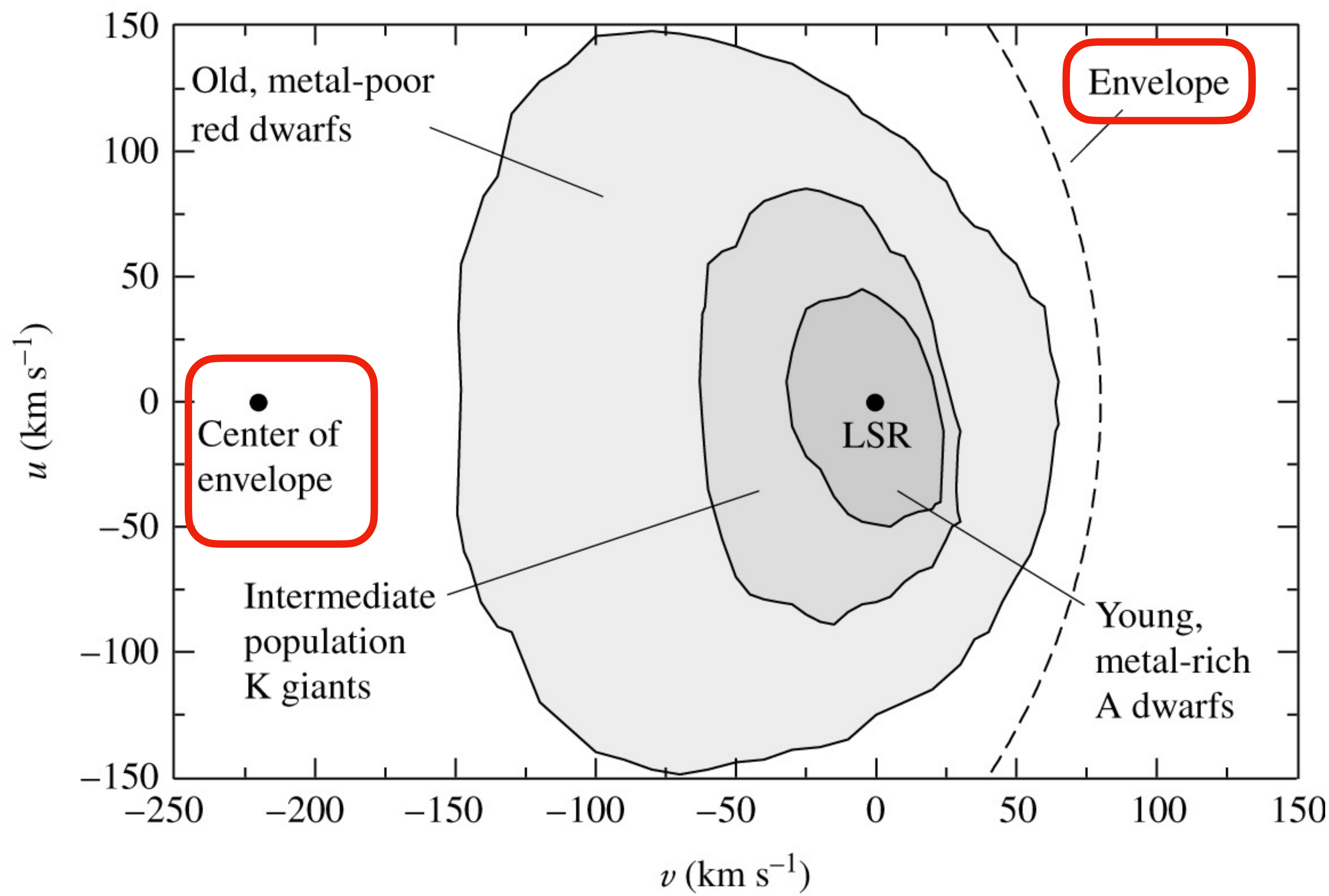
$$(u, v, w) \equiv (v_R, v_\theta, v_z) - (v_R, v_\theta, v_z)_{LSR}$$



Cylindrical coordinates and velocities

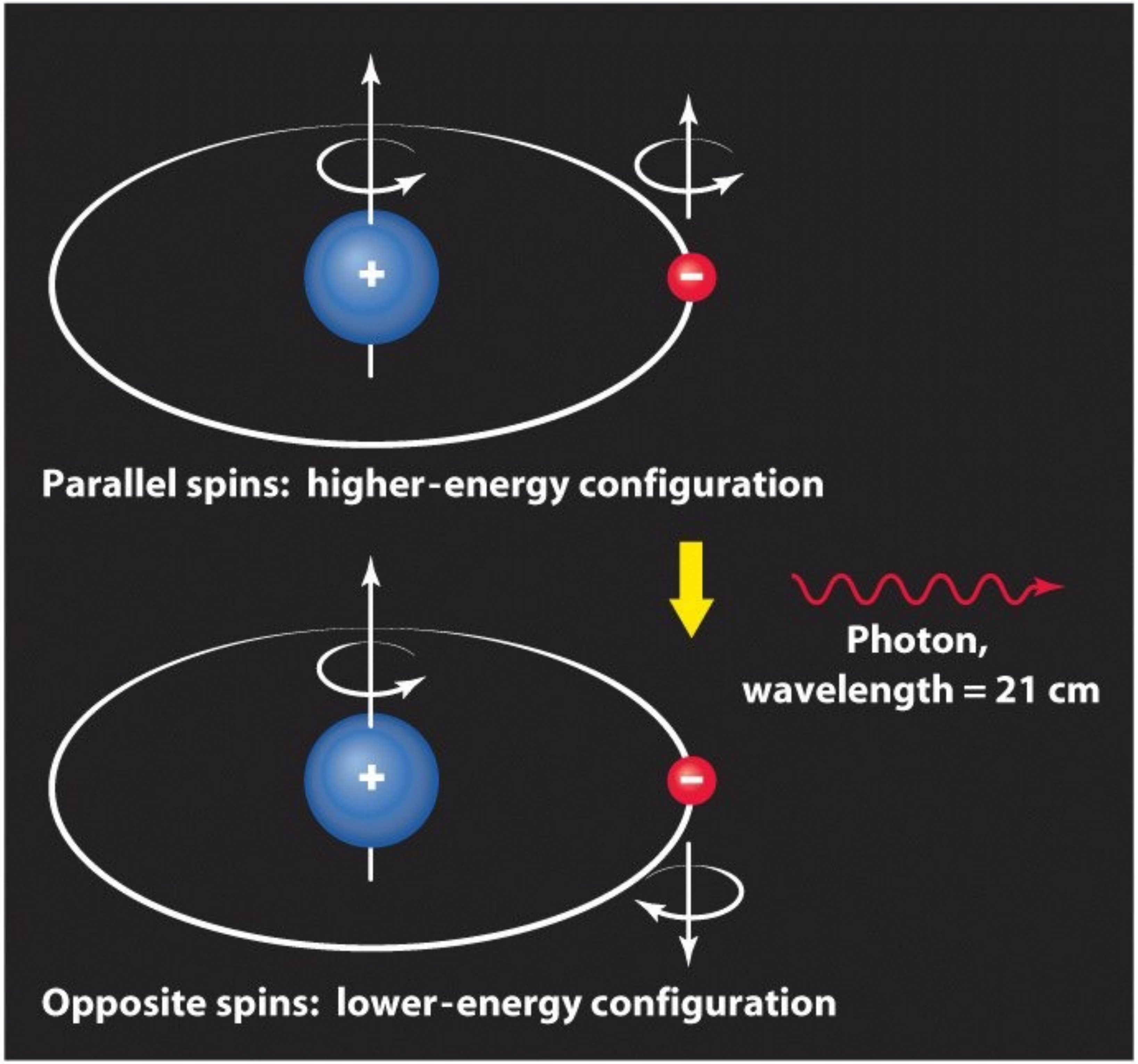
The peculiar velocity approach: Solar neighborhood stars

- **Young metal-rich stars in the disk** move at the same velocity as the solar system, so collectively they define the **local standard of rest (LSR)**
- **Older and more metal-poor stars** develop wider distributions which terminate on a circle with a radius of ~300 km/s and a center at ***v* = -220 km/s** and ***u* = 0 km/s**.
- This **circular envelope** marks the boundary of random motions of **halo stars** and **300 km/s** is the apparent **escape velocity** and the offset of **-220 km/s** in azimuth direction is **the velocity of the LSR** relative to the halo stars.



How the rotation curve was measured?

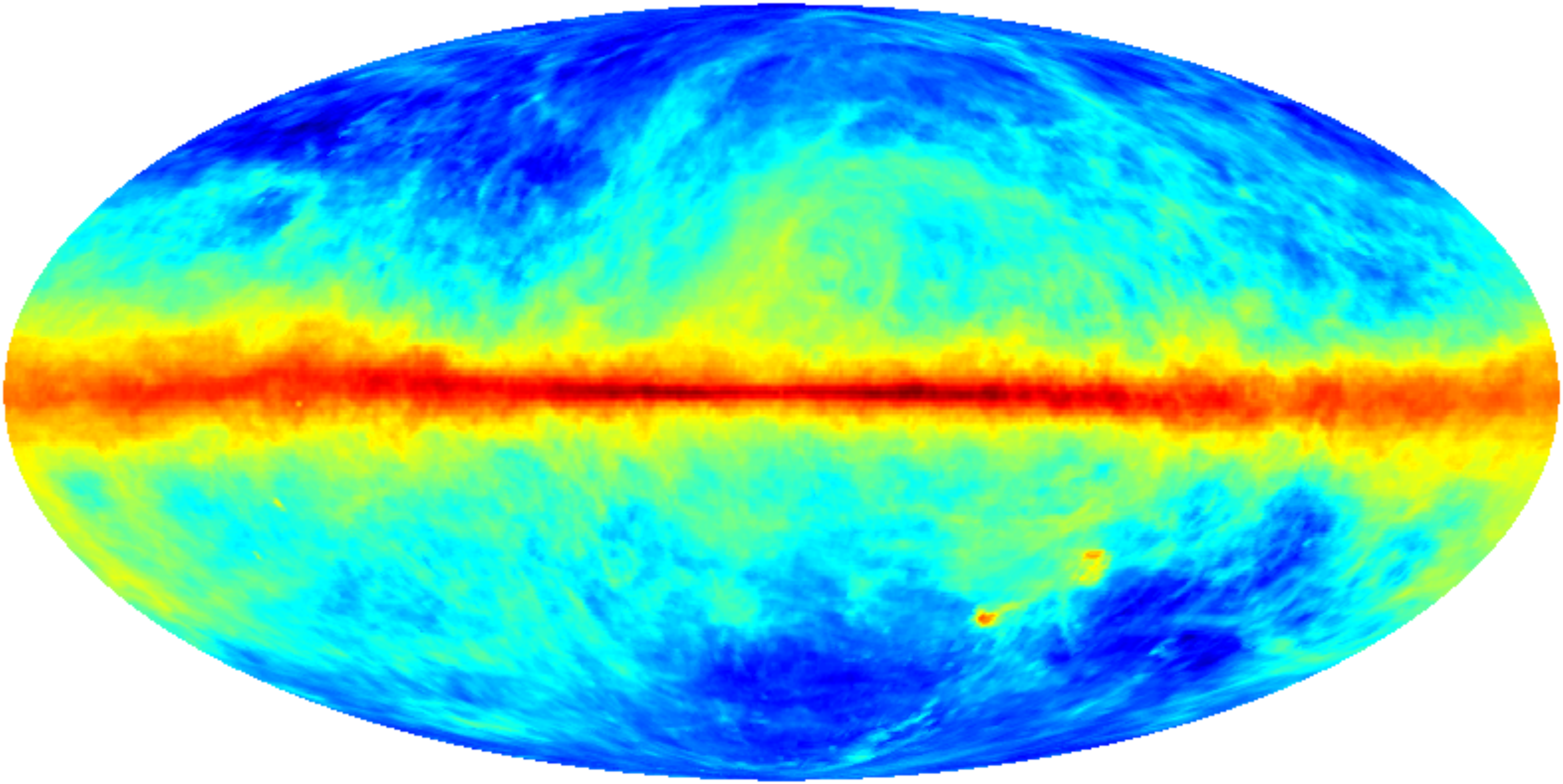
Neutral atomic hydrogen (HI) emits photons at a wavelength of 21 cm



(b) The magnetic energy of a proton and electron depends on their relative spin orientation

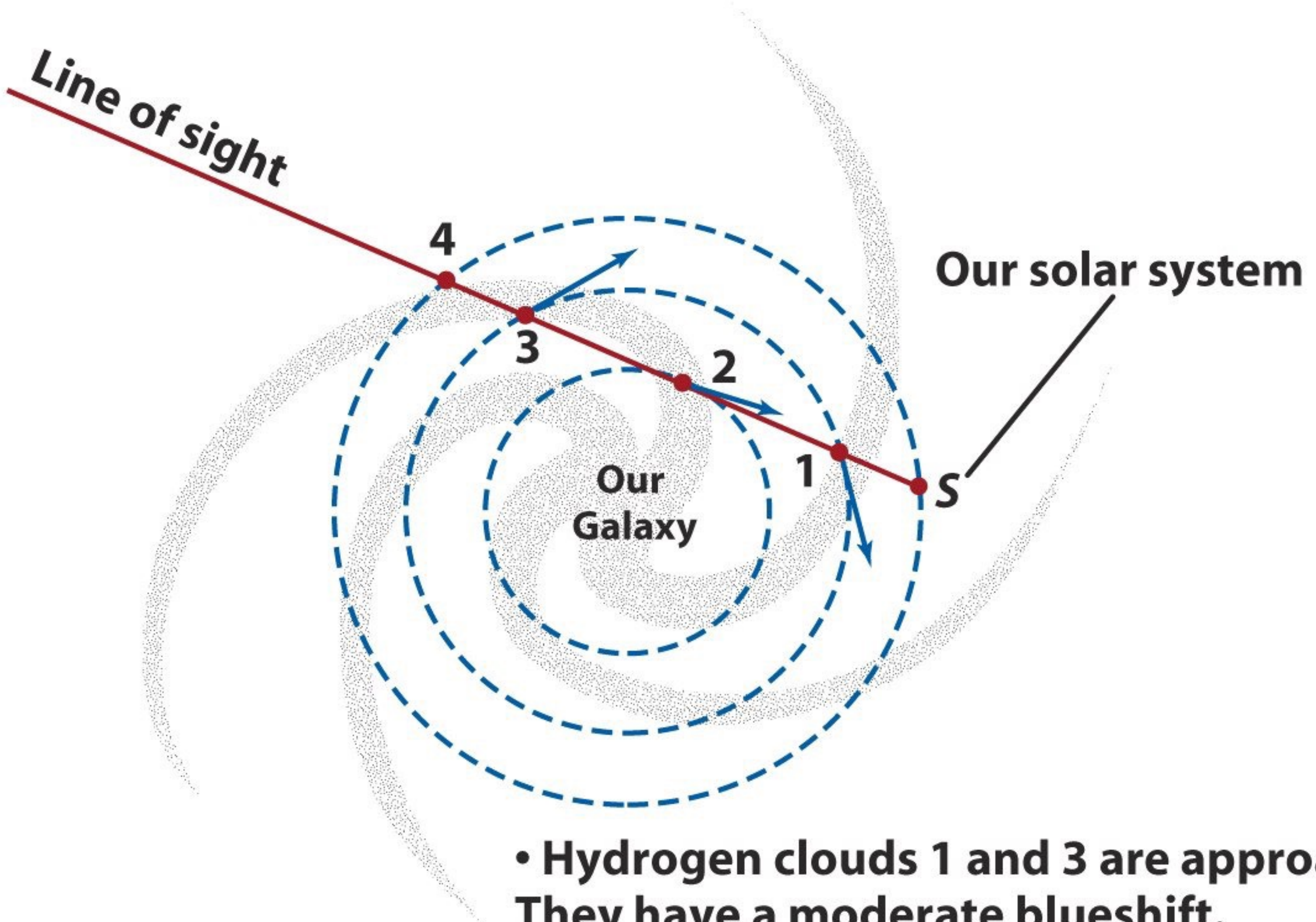
- The photon has quite a low energy (5.9e-6 eV) so it's easy to be excited to the upper level
- At such a long wavelength, the emission signal is not affected by dust along the line of sight

HI 21 cm emission from the Leiden/Dwingeloo HI survey



Kalbera+2005

Pointing a radio telescope towards one direction in the plane of the MW disk, multiple clouds at different locations are observed all at once, but we don't know their distances



• Hydrogen clouds 1 and 3 are approaching us: They have a moderate blueshift.

• Hydrogen cloud 2 is approaching us at a faster speed: It has a larger blueshift.

• Hydrogen cloud 4 is neither approaching nor receding: It has no redshift or blueshift.

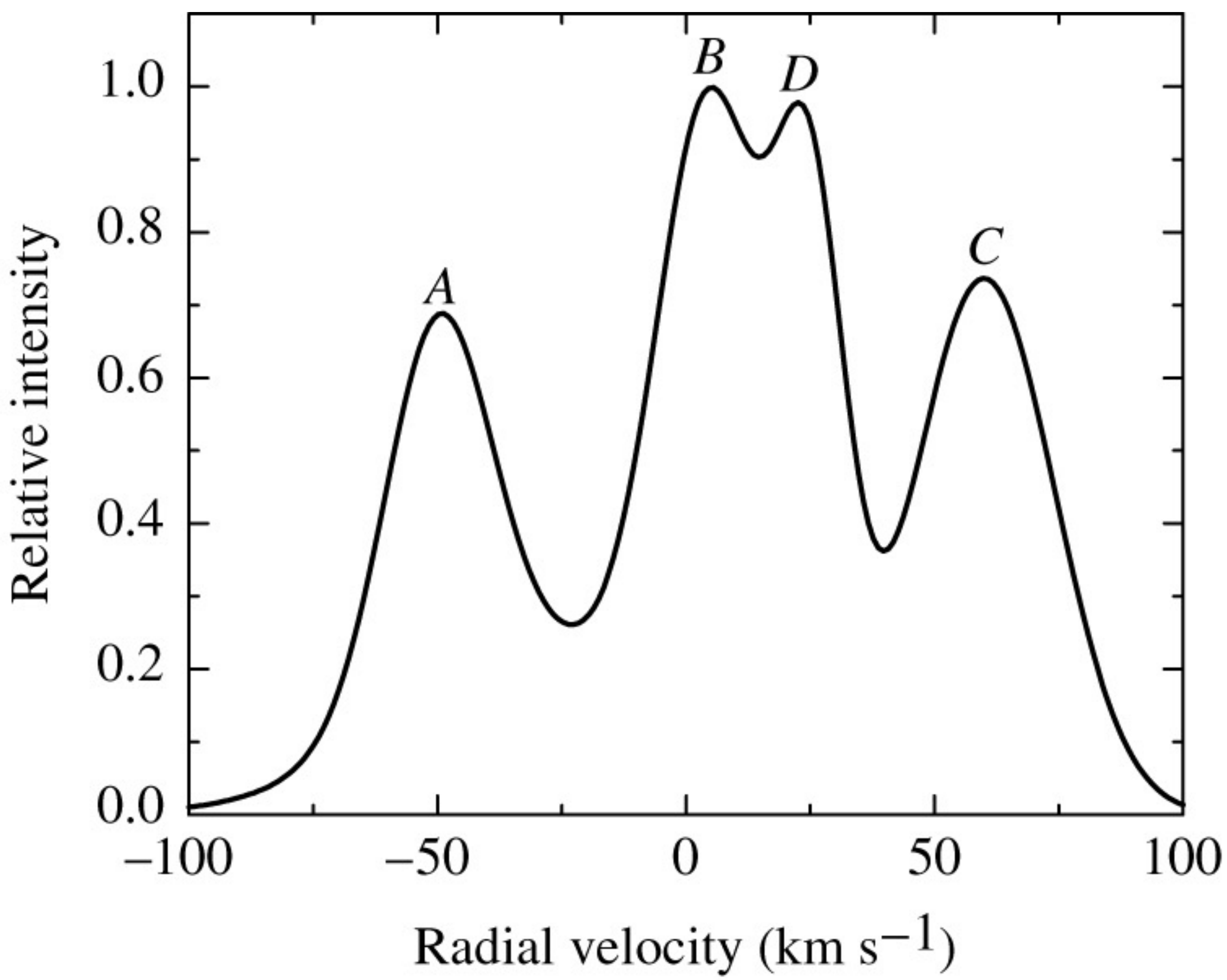
How to interpret 21cm observation along a given galactic latitude

- Assuming pure circular motions around the Galactic Center, it's easy to obtain the following geometric relations, when -90 < l < +90 deg:

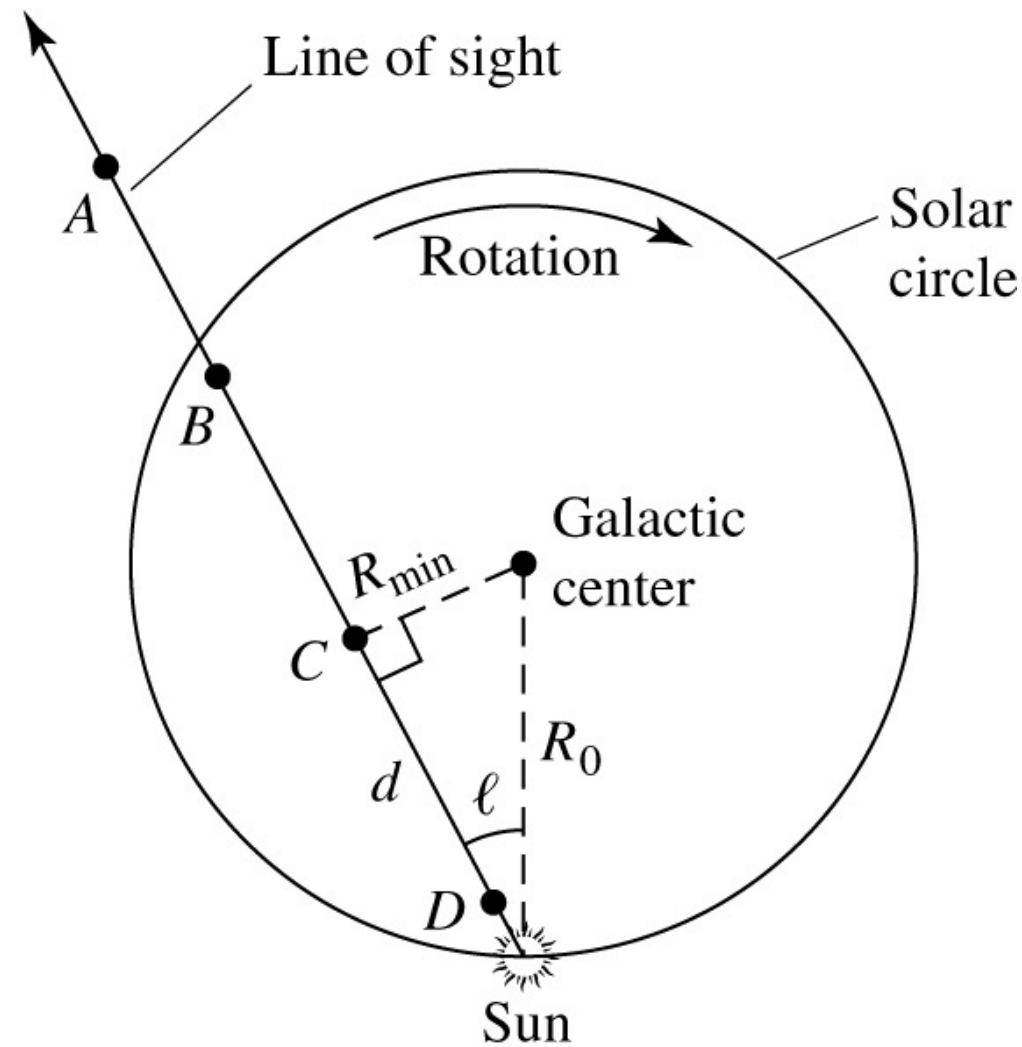
$$R_{\min} = R_0 \sin(l)$$

$$\max(V_r) = \Theta(R_{\min}) - \Theta(R_0)\ \sin(l)$$

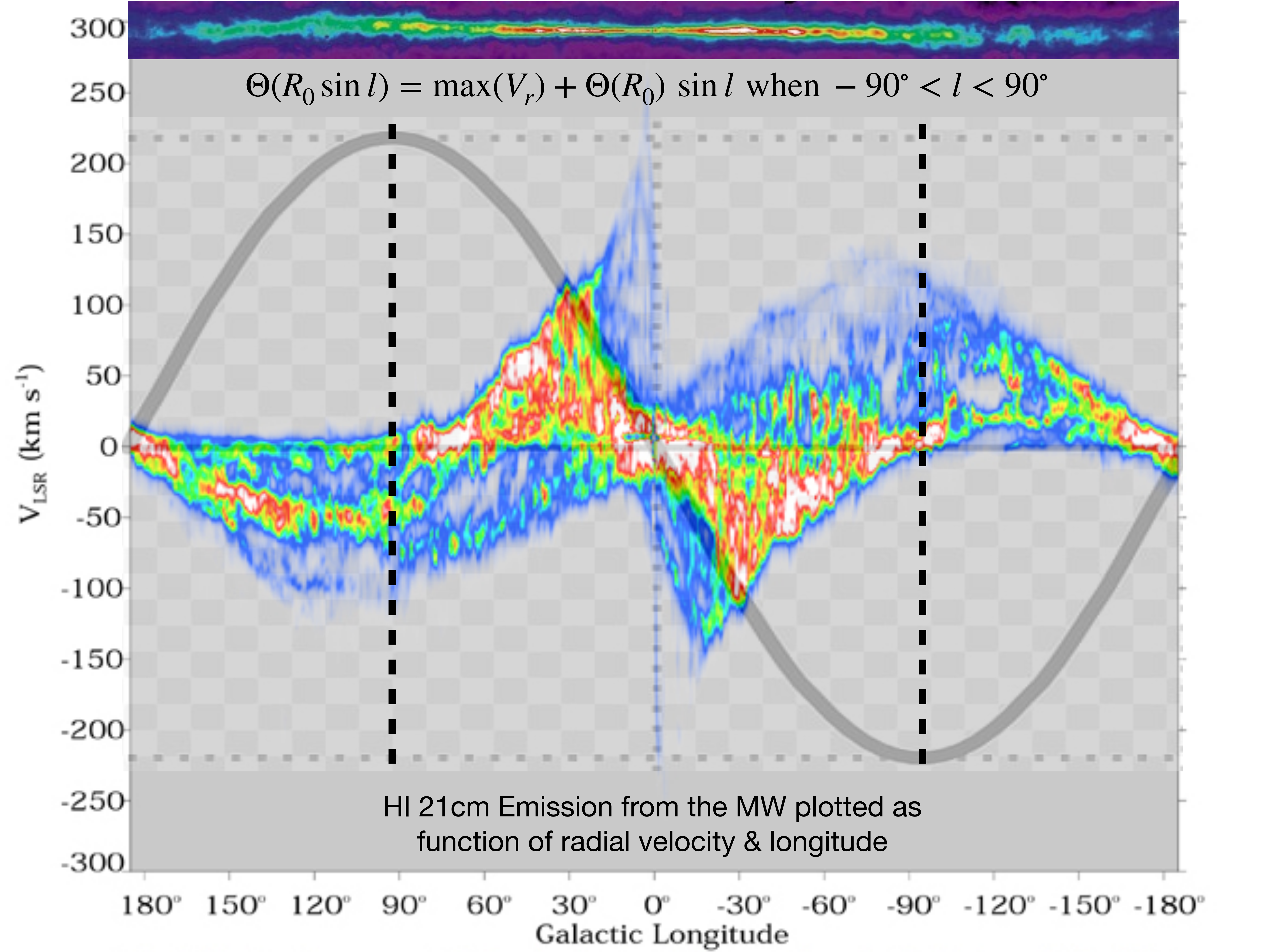
$$\Rightarrow \Theta(R_0 \sin l) = \max(V_r) + \Theta(R_0)\ \sin l$$



(a)

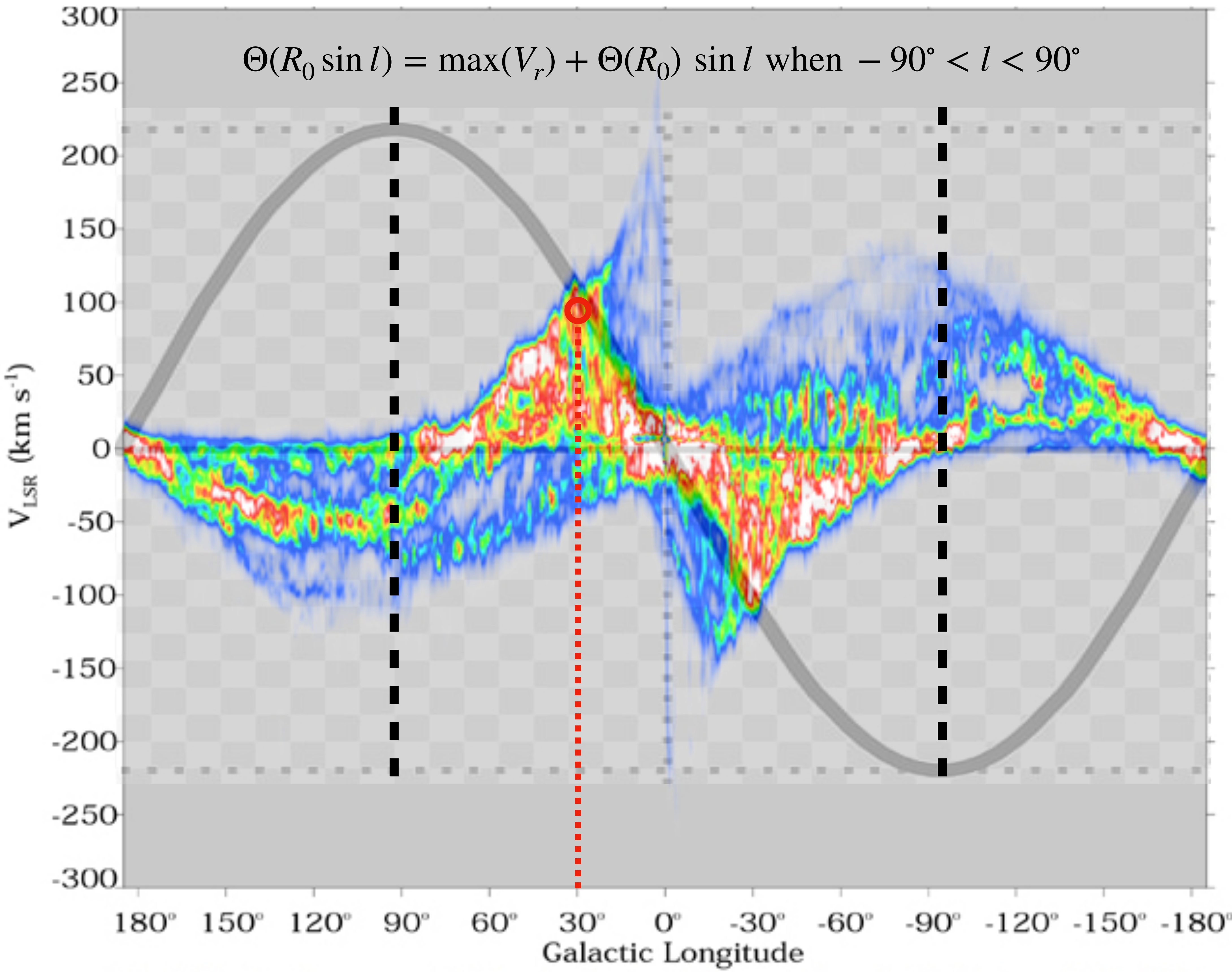


(b)

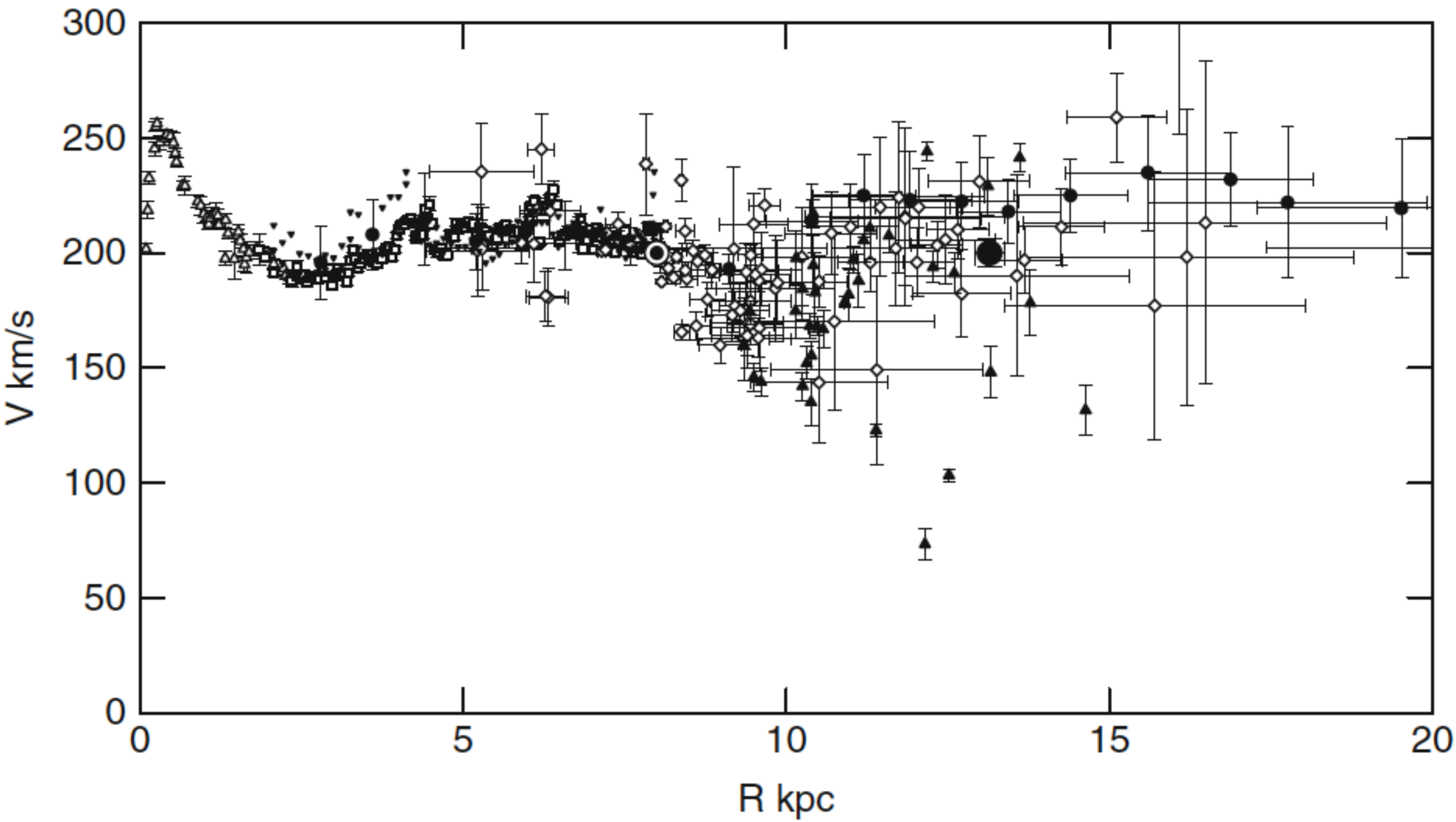


$\Theta(R_0 \sin l) = \max(V_r) + \Theta(R_0)\ \sin l$ when $-90^\circ < l < 90^\circ$
HI 21cm Emission from the MW plotted as function of radial velocity & longitude
V_{LSR} (km s^{-1})
300
250
200
150
100
50
0
-50
-100
-150
-200
-250
-300
180°
150°
120°
90°
60°
30°
0°
-30°
-60°
-90°
-120°
-150°
-180°
Galactic Longitude

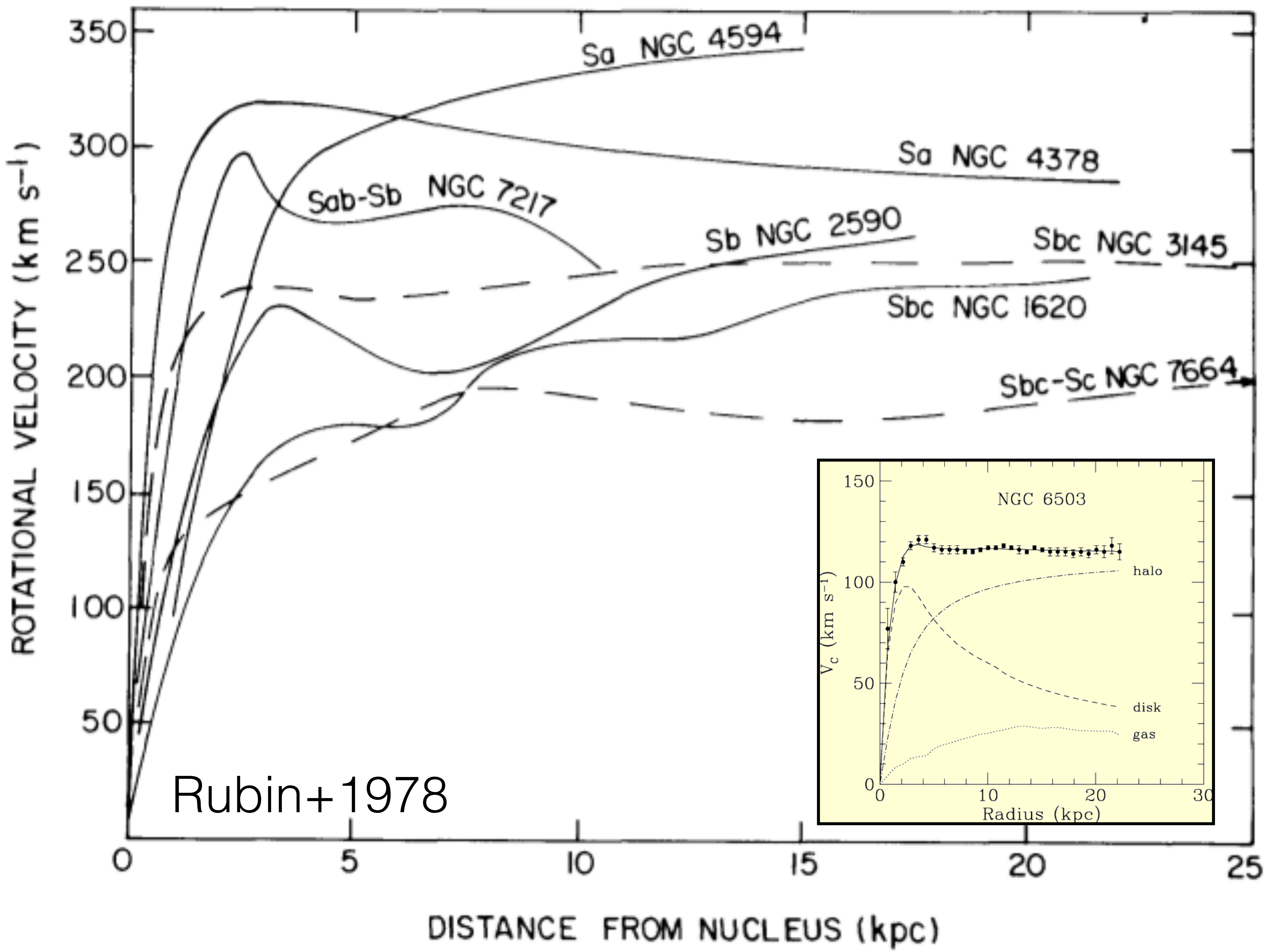
Practice: Based on data in this plot, calculate the rotation velocity at Galactocentric distance of 4 kpc



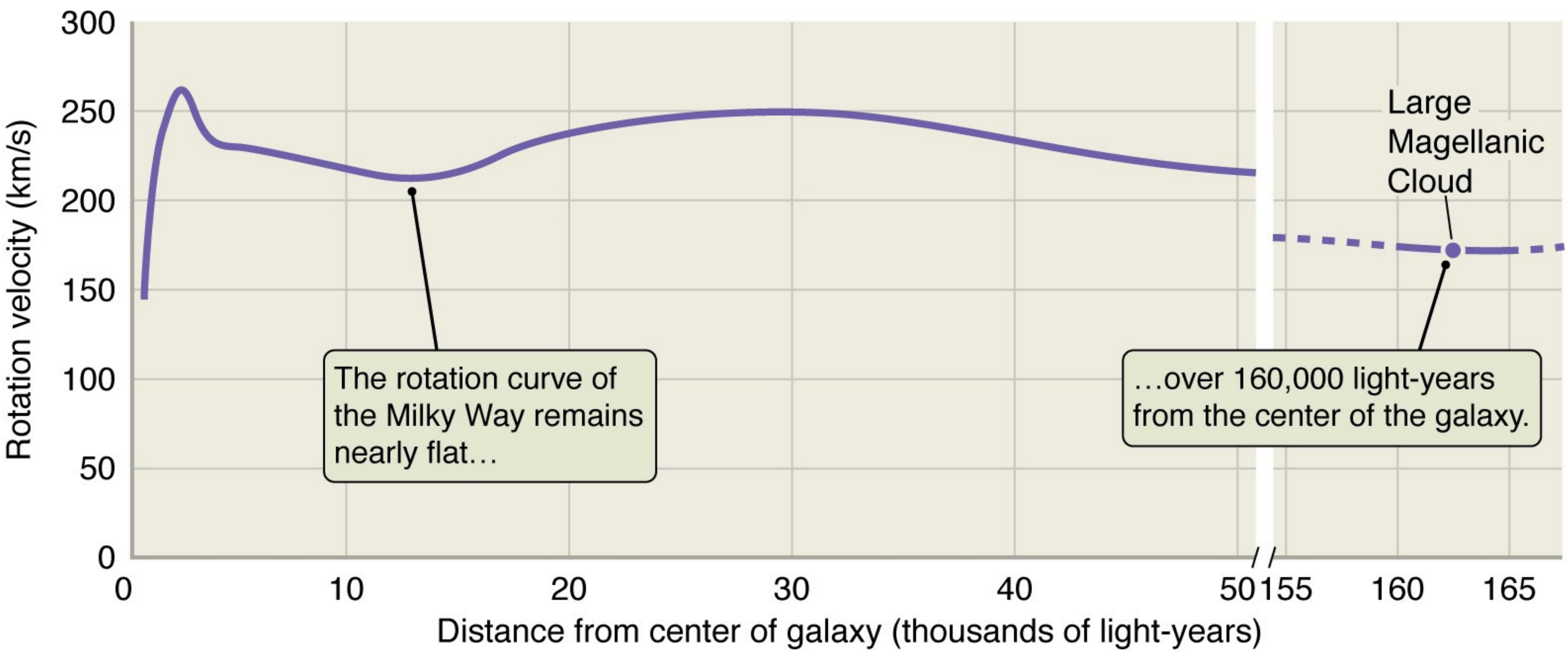
Inferred rotation curve of the MW Galaxy from 21cm and others



Flat Rotation Curves of Local Spirals



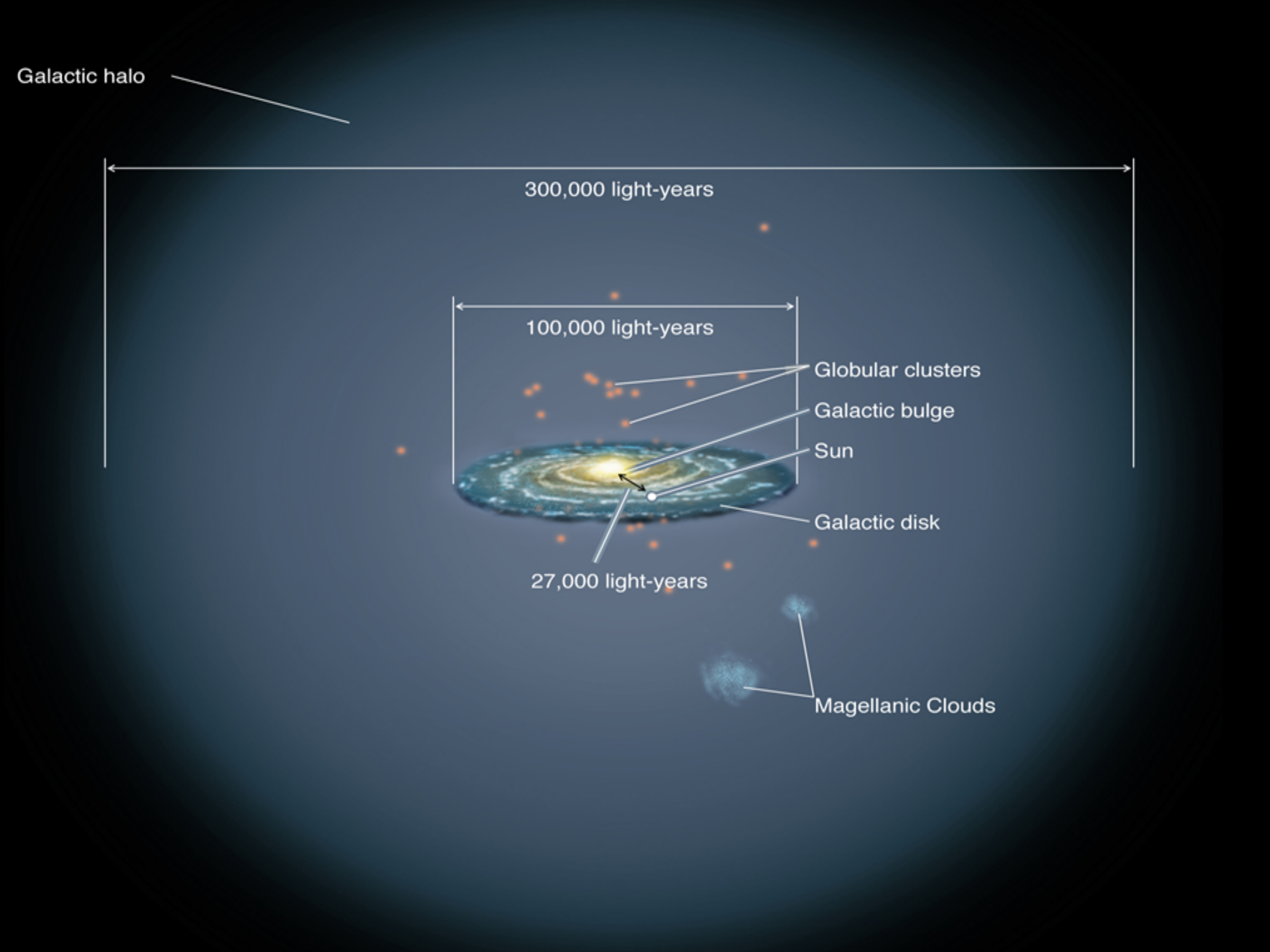
Similar to other spirals, our Galaxy is mostly dark matter



- Rotation curve yields **total enclosed mass** of the Milky Way at a range of galactocentric distances *r*:

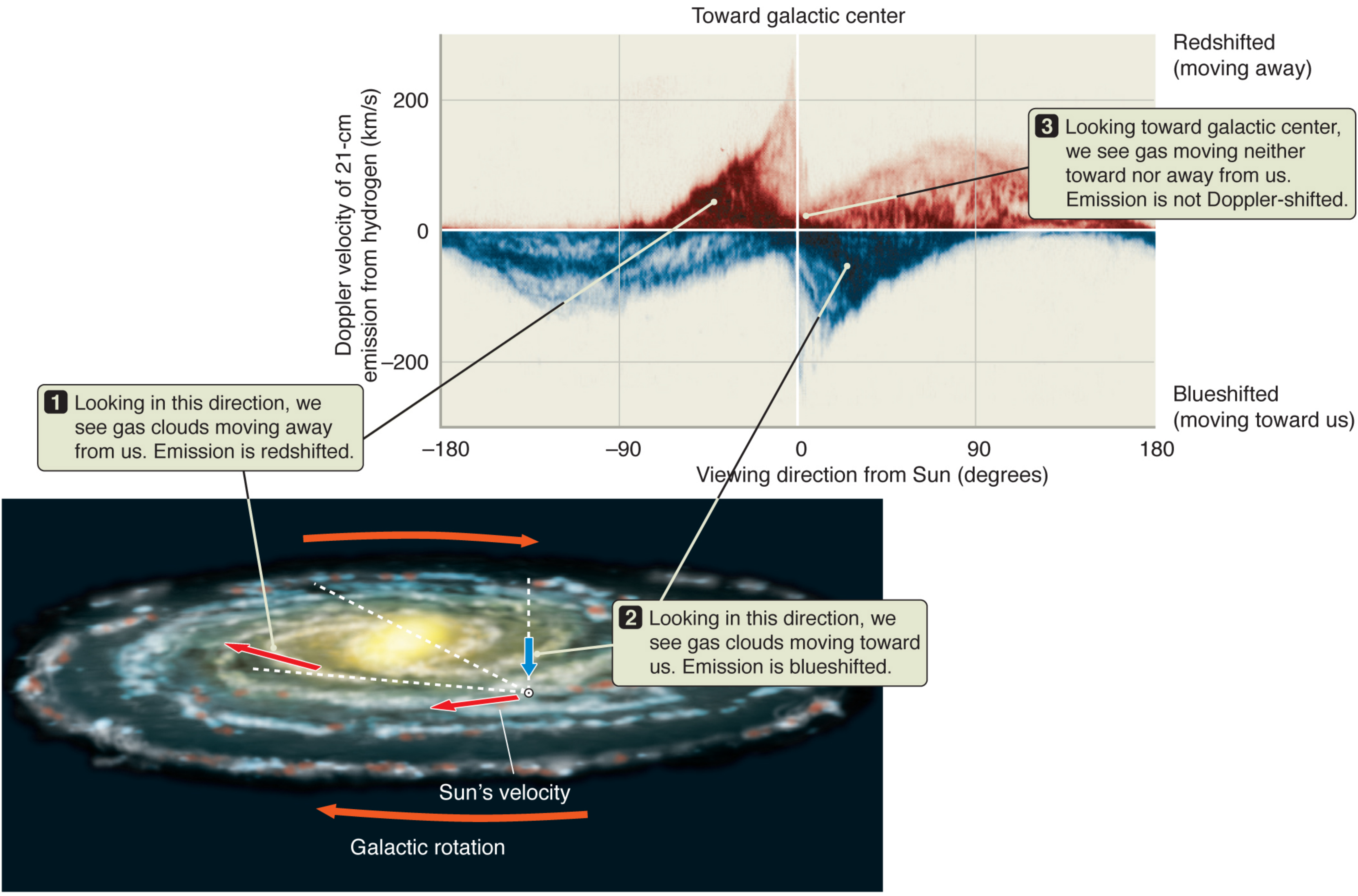
$$V_{\rm circ} = \sqrt{GM(r)/r} \Rightarrow M(r) = V_{\rm circ}^2 r/G$$

- Compare this to the mass in stars and gas ($\sim 10^{11}\ M_{\rm sun}$), it is concluded that there is much more mass than what is visible.

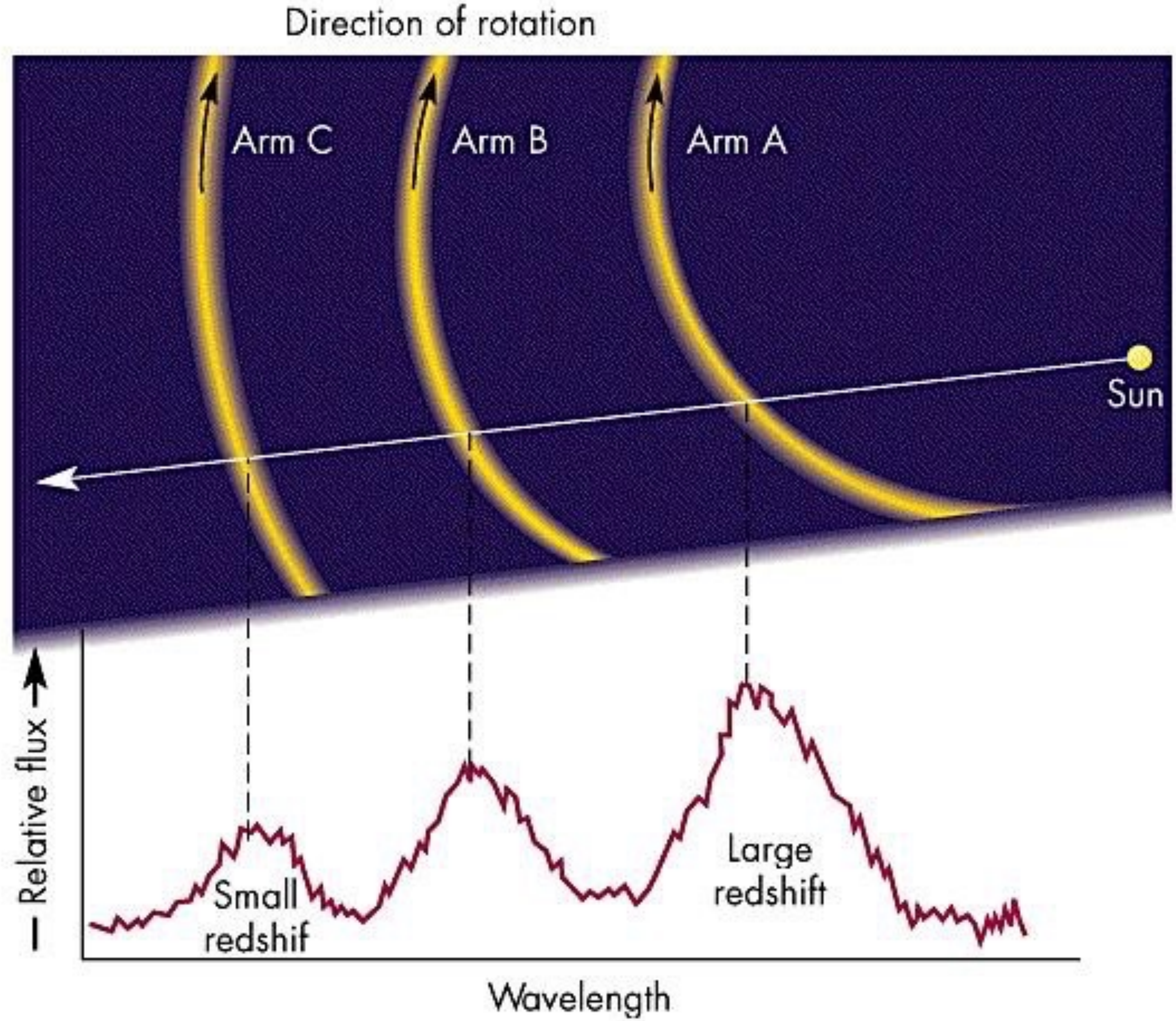

Galactic halo
300,000 light-years
100,000 light-years
Globular clusters
Galactic bulge
Sun
Galactic disk
27,000 light-years
Magellanic Clouds

How the spiral arms were mapped out in HI 21cm?

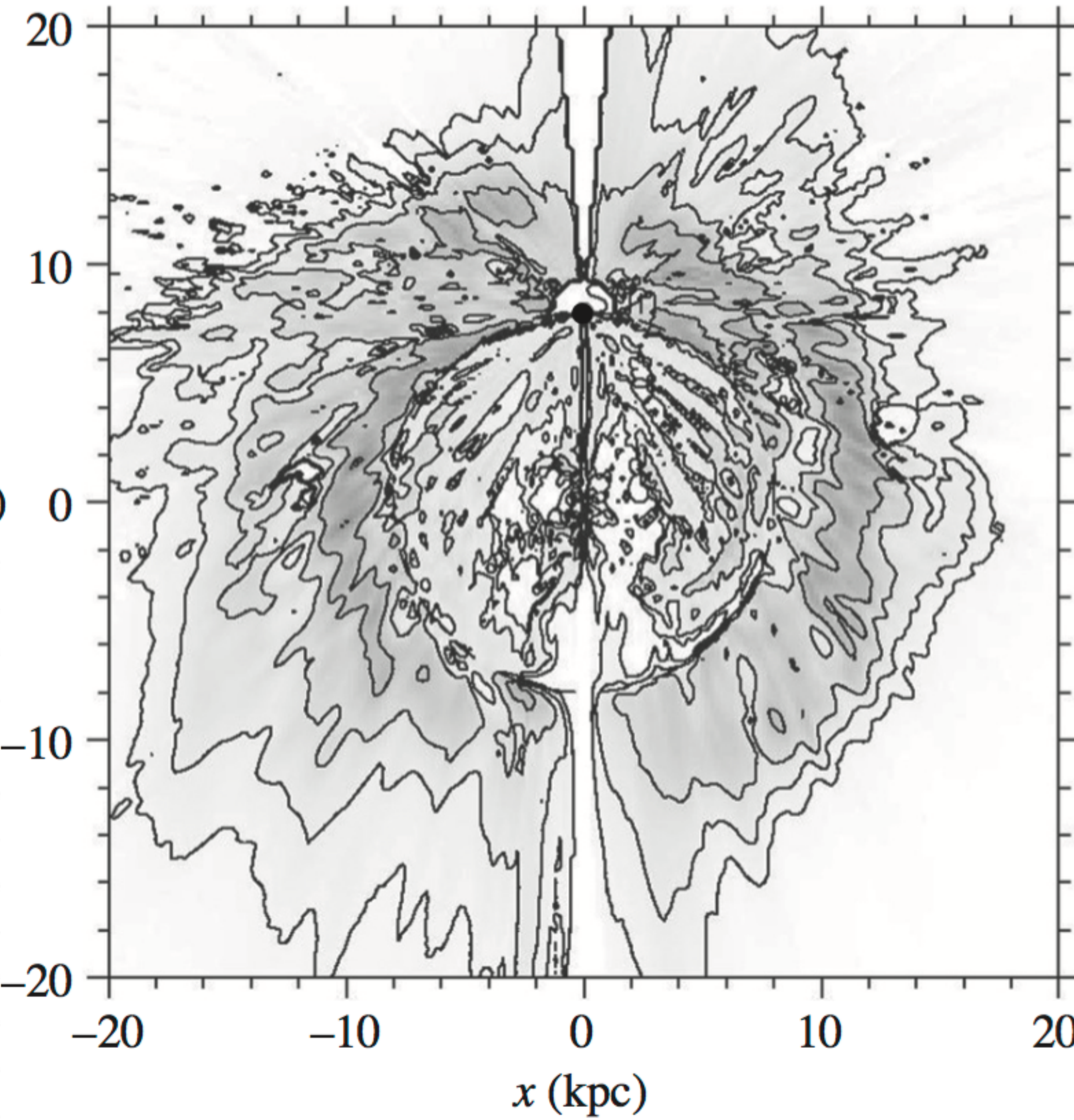
Rotation of the disk as seen from inside

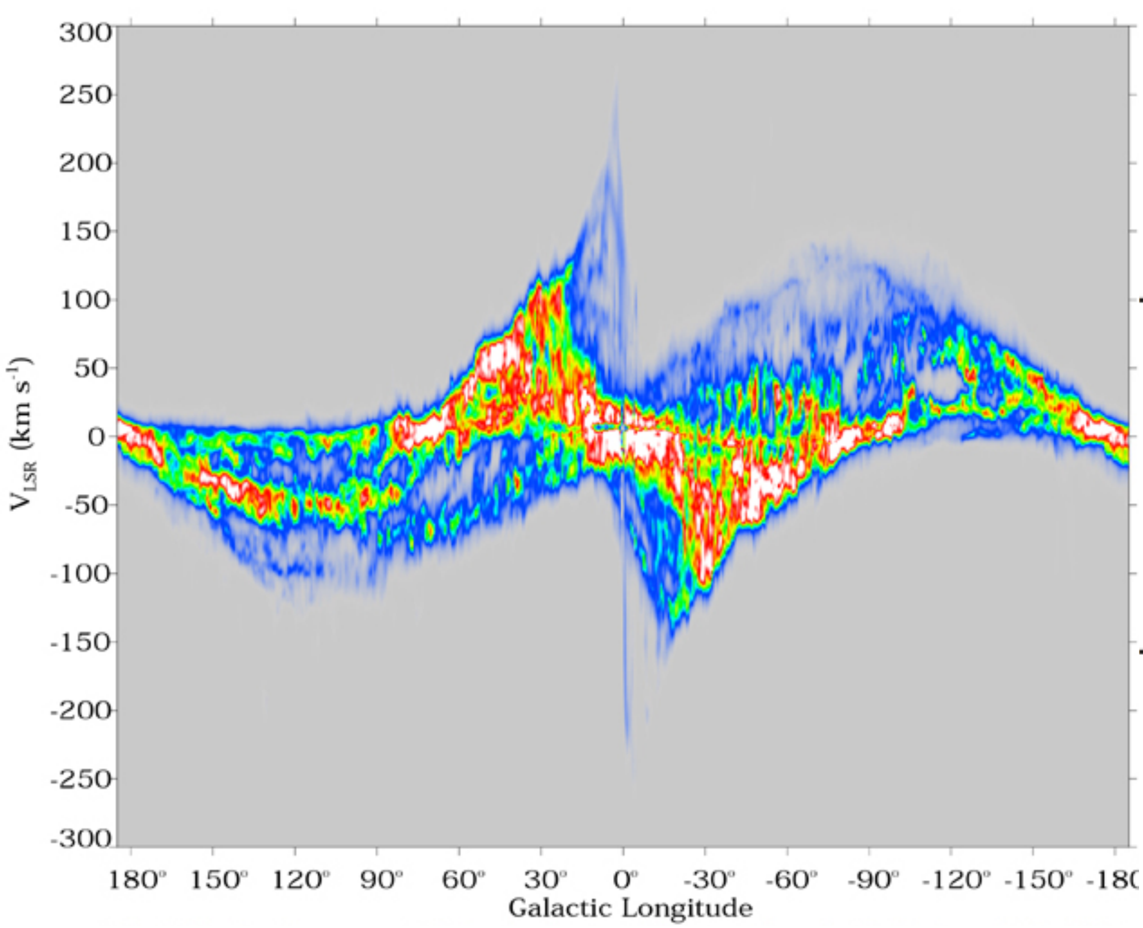


Separating HI clouds at different distances

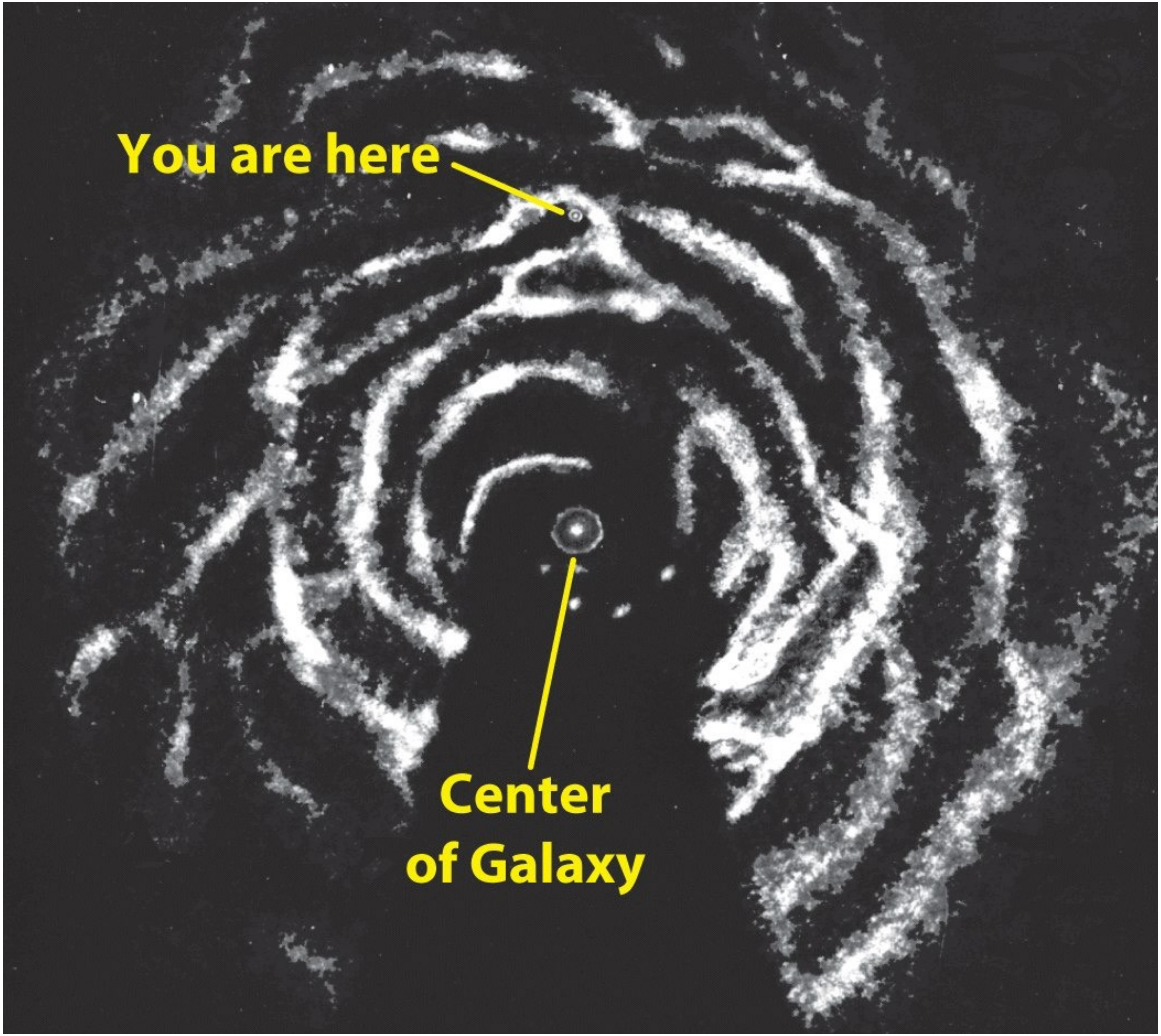


Assuming pure circular motion and the rotation curve allows the HI 21cm emission to be mapped as surface density





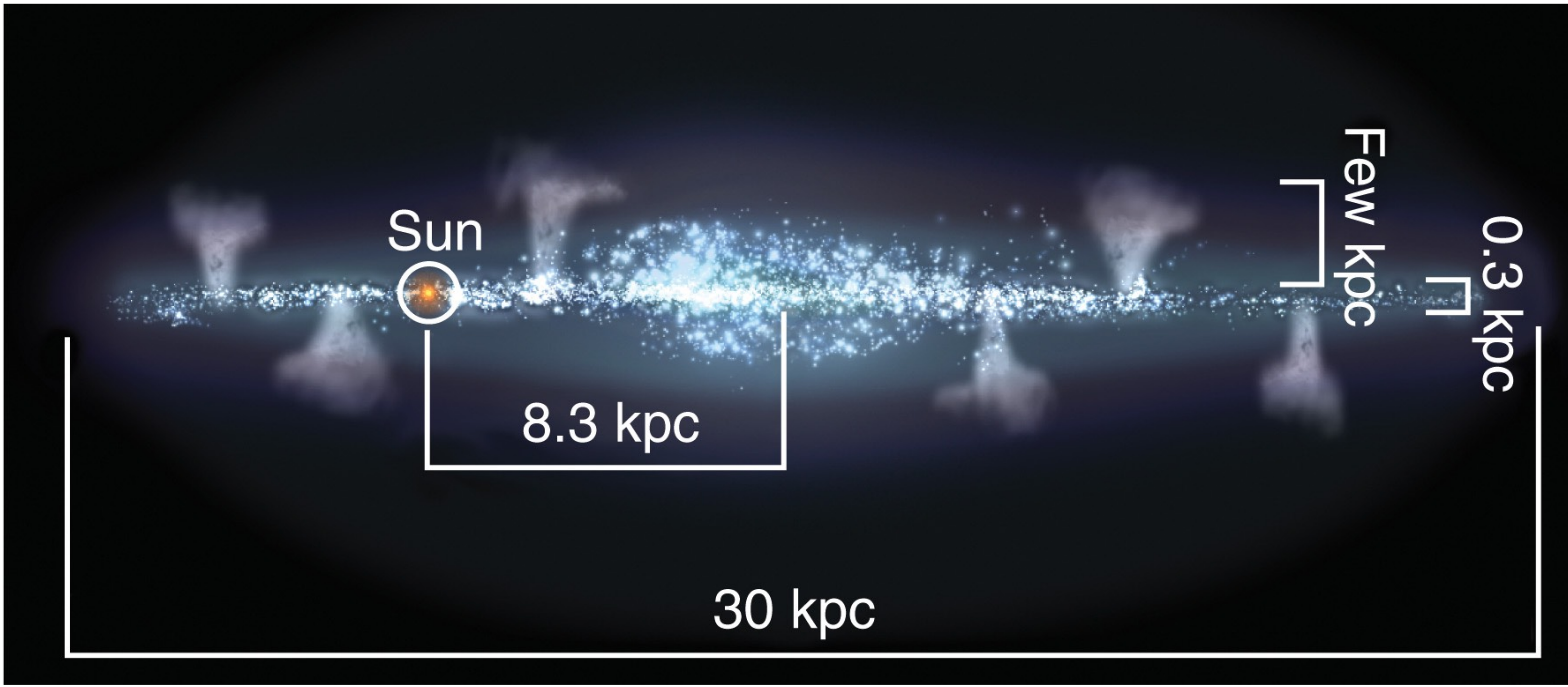
HI 21 cm emission rendered in (x,y) face-on view



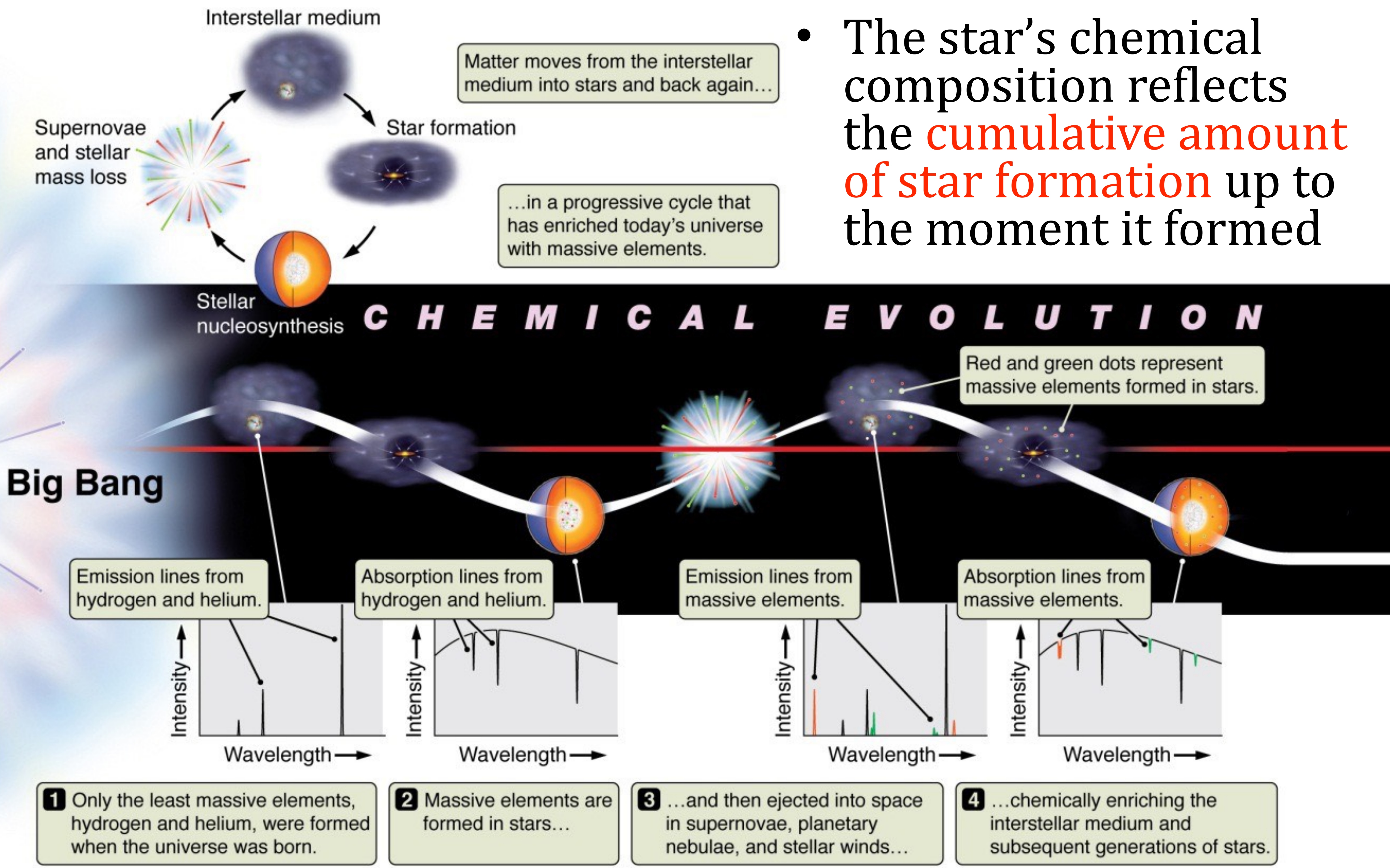
Stellar populations and chemical evolution

Galactic Fountains

In this artist's concept of galactic fountains, metal-enriched gas is first pushed away from the disk by **stellar winds** from young stars and **supernova** explosions, and it later falls back onto the disk to form new generations of stars (that are more metal-rich).

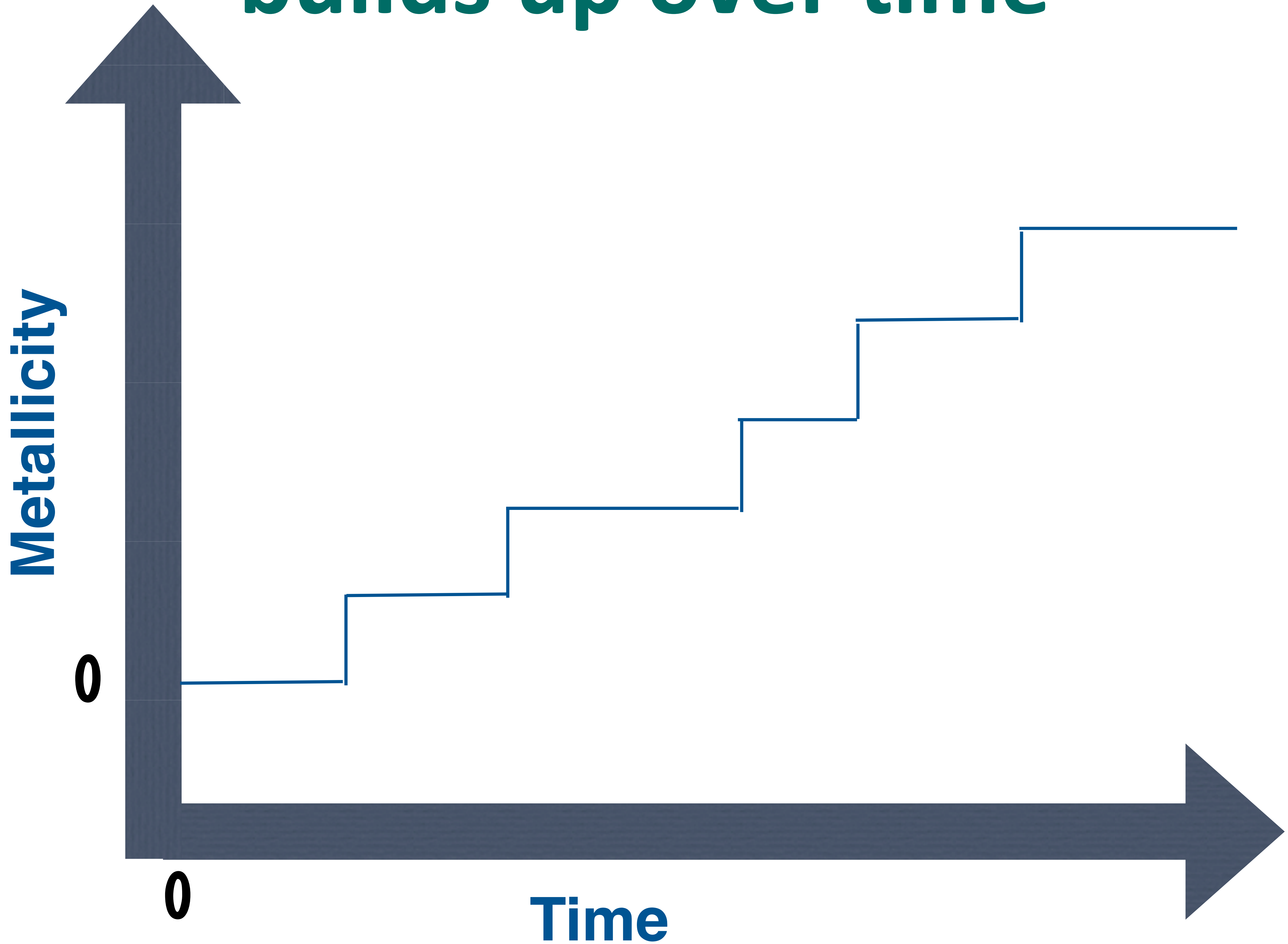


- The chemical composition of a star's atmosphere is the same as that of the ISM out of which it was formed

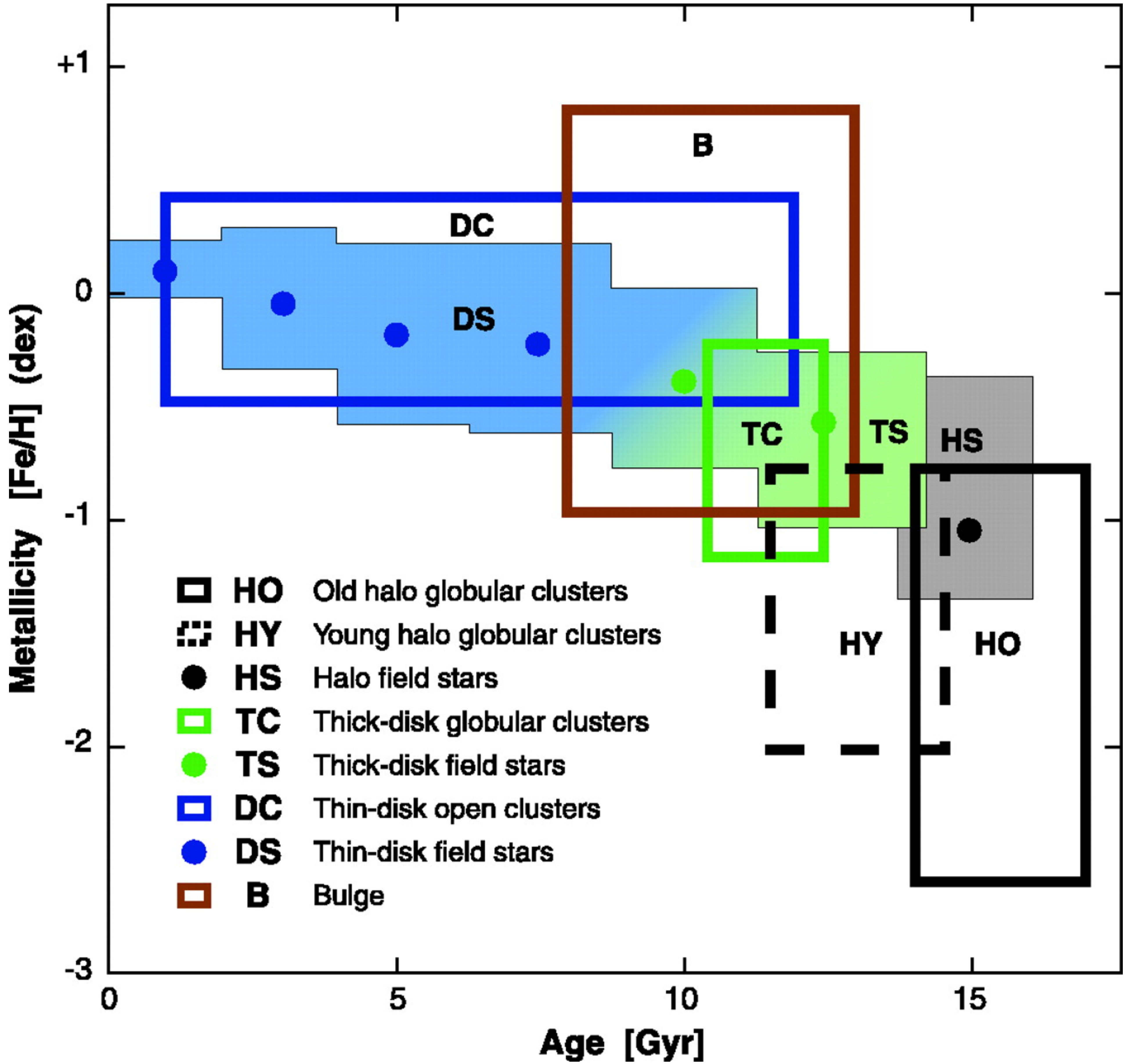


- The star's chemical composition reflects the cumulative amount of star formation up to the moment it formed

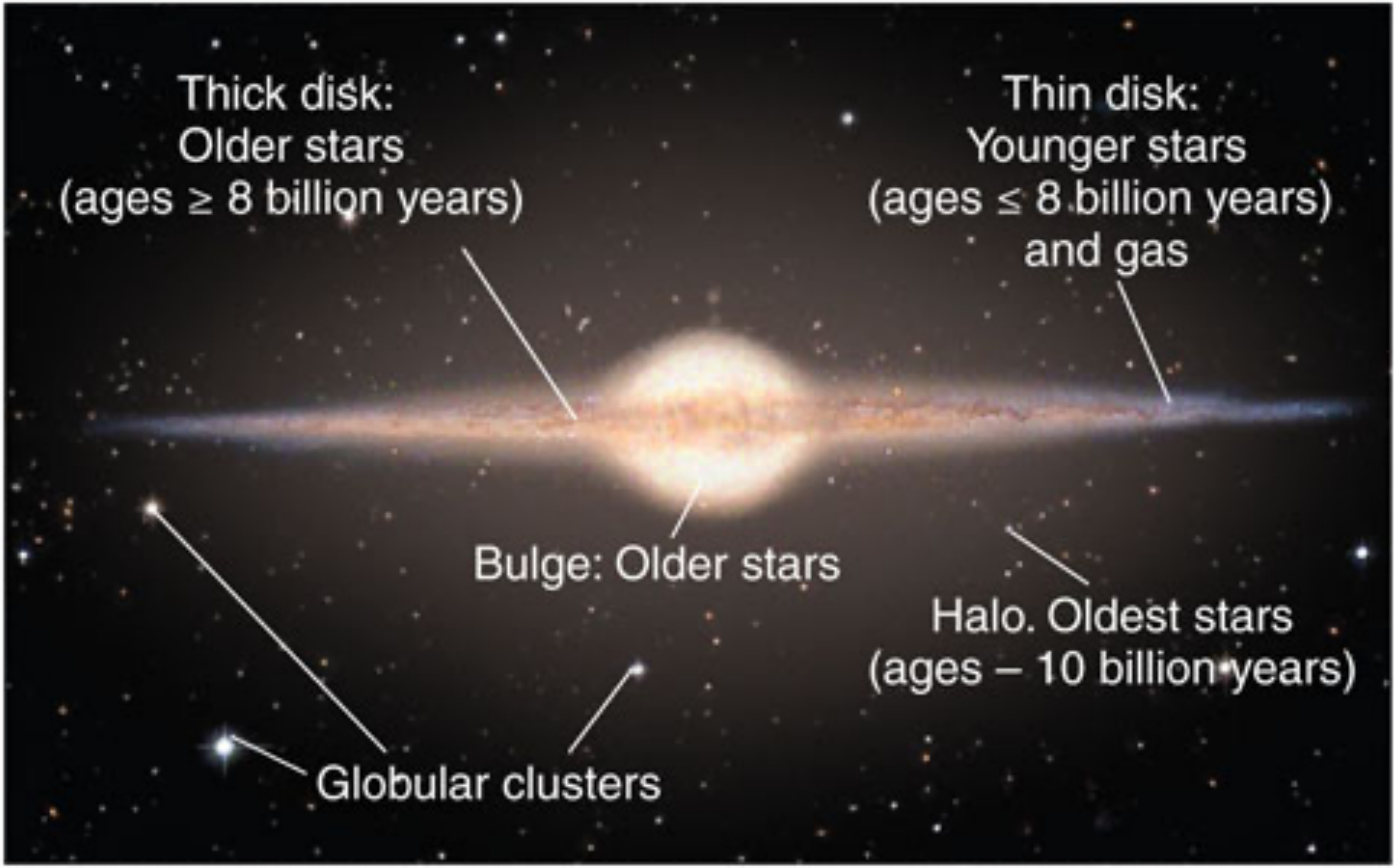
Metallicity of the ISM builds up over time



Metallicity vs. Age for various stellar populations

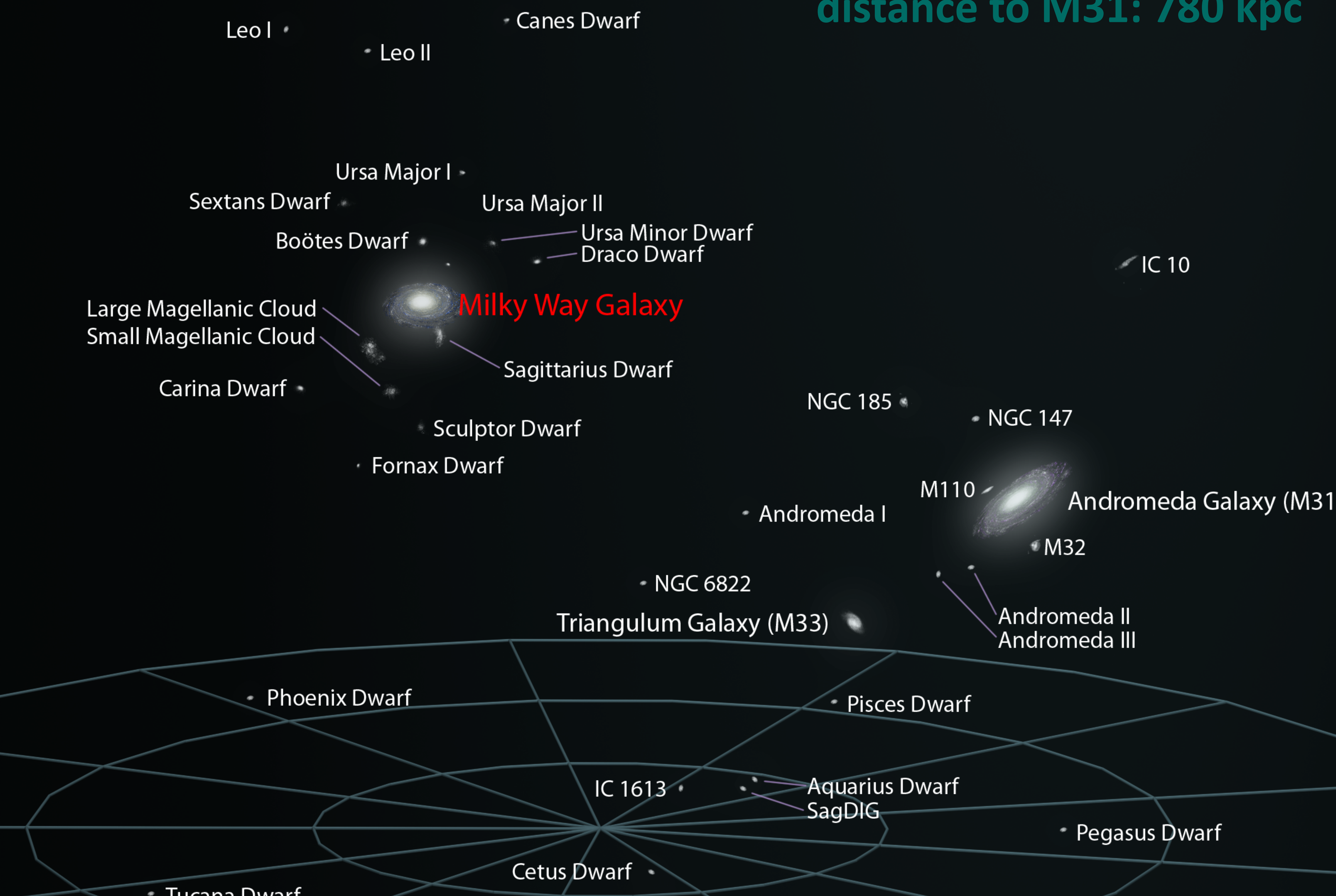


Ages of the stars in the MW

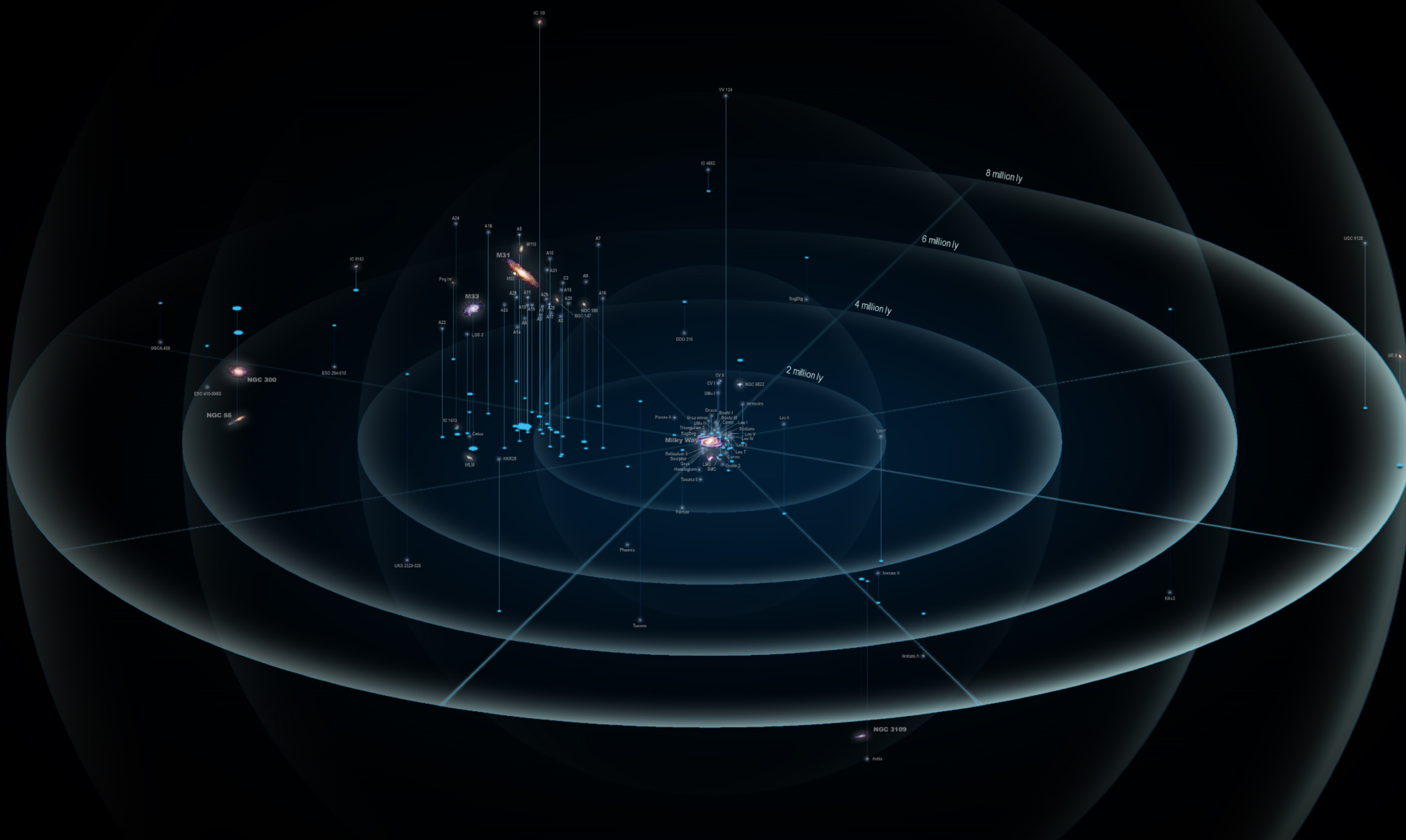


Our closest neighbors and the future of the Milky Way

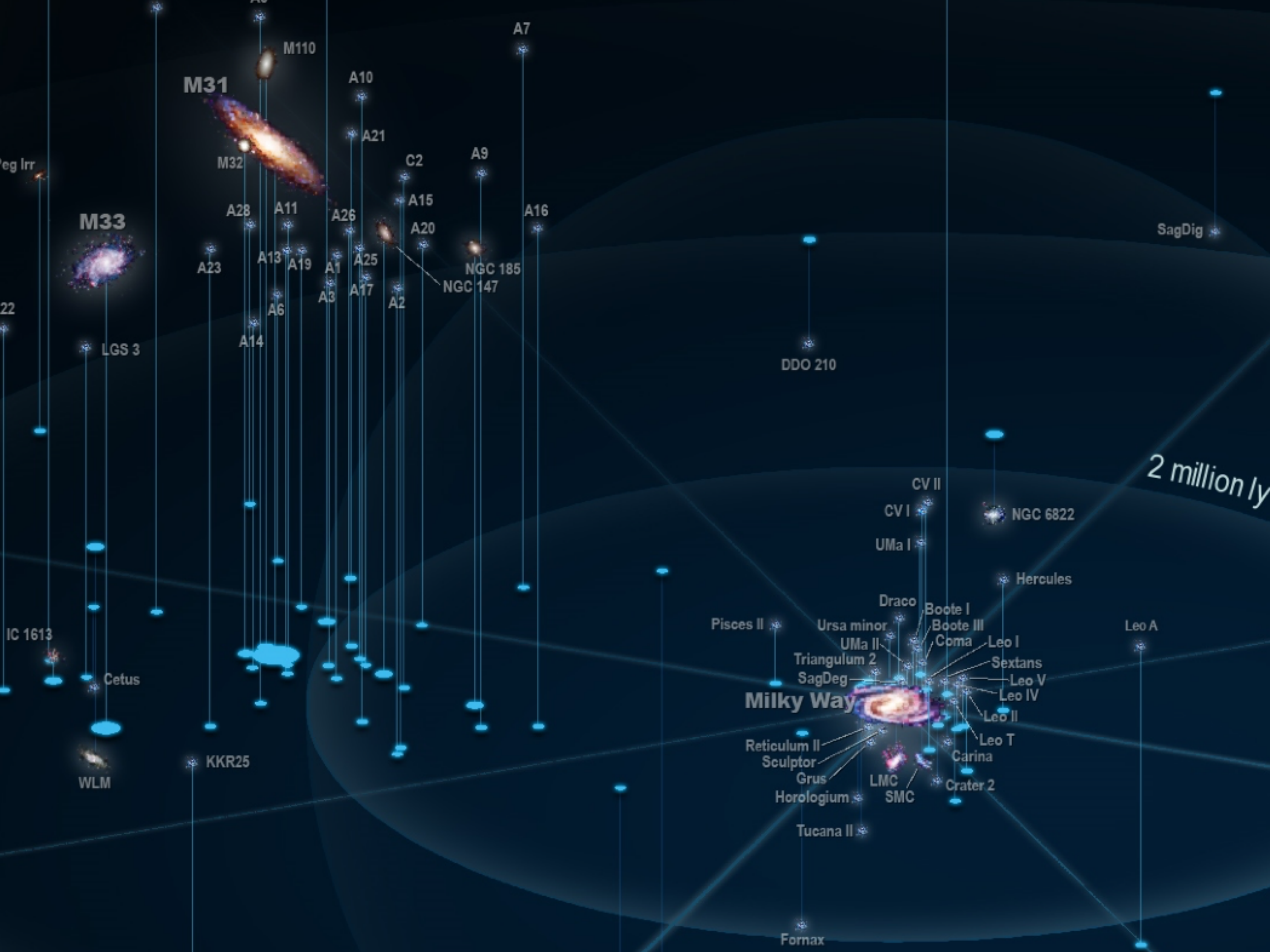
The Local Group
distance to M31: 780 kpc



Local Group and nearest galaxies



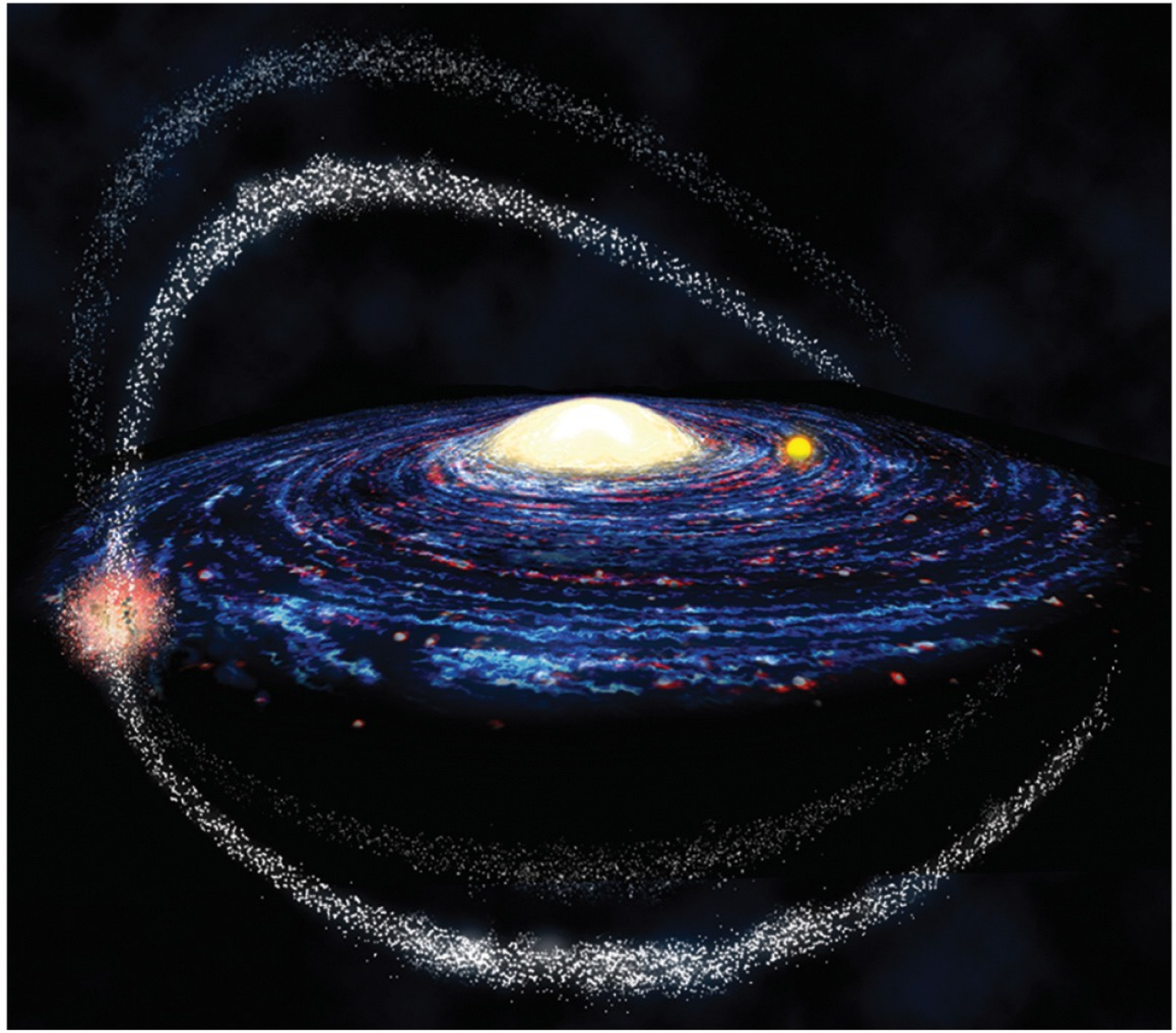
More than 54 galaxies in 2 Mpc



M110
A7
M31
A10
A21
M32
C2
A9
M33
A28
A11
A26
A15
A20
A16
SagDig
A23
A13
A19
A1
A25
NGC 185
A3
A17
A2
NGC 147
A6
A14
LGS 3
DDO 210
2 million ly
CV II
CV I
NGC 6822
UMa I
Hercules
Draco
Boote I
Pisces II
Ursa minor
Boote III
IC 1613
UMa II
Coma
Leo I
Leo A
Triangulum 2
Sextans
SagDeg
Leo V
Cetus
Milky Way
Leo IV
Leo II
Leo T
Reticulum II
Carina
KKR25
Sculptor
WLM
Grus
LMC
Crater 2
SMC
Horologium
Tucana II
Fornax

The Future of the Milky Way

- Mergers and collisions continue in the Local Group.
- The Milky Way is currently colliding with the Sagittarius Dwarf Galaxy, creating streams of stars.
- The Milky Way is on a head-on collision course with Andromeda.
  - The galaxies will make contact in 4 billion years, but the merger will take another 2 billion years.
  - A giant elliptical galaxy will be the result.

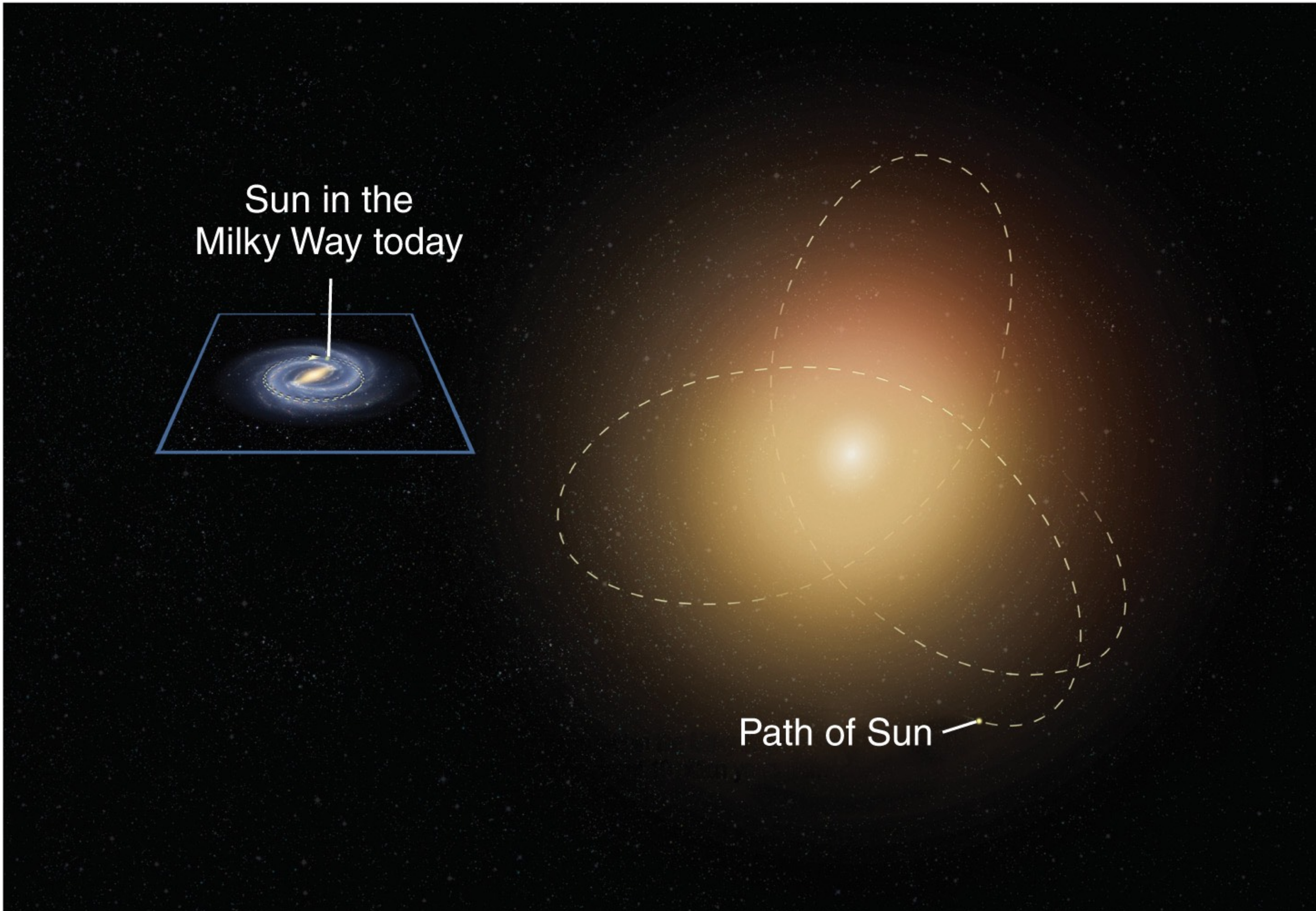


Amanda Smith/University of Cambridge

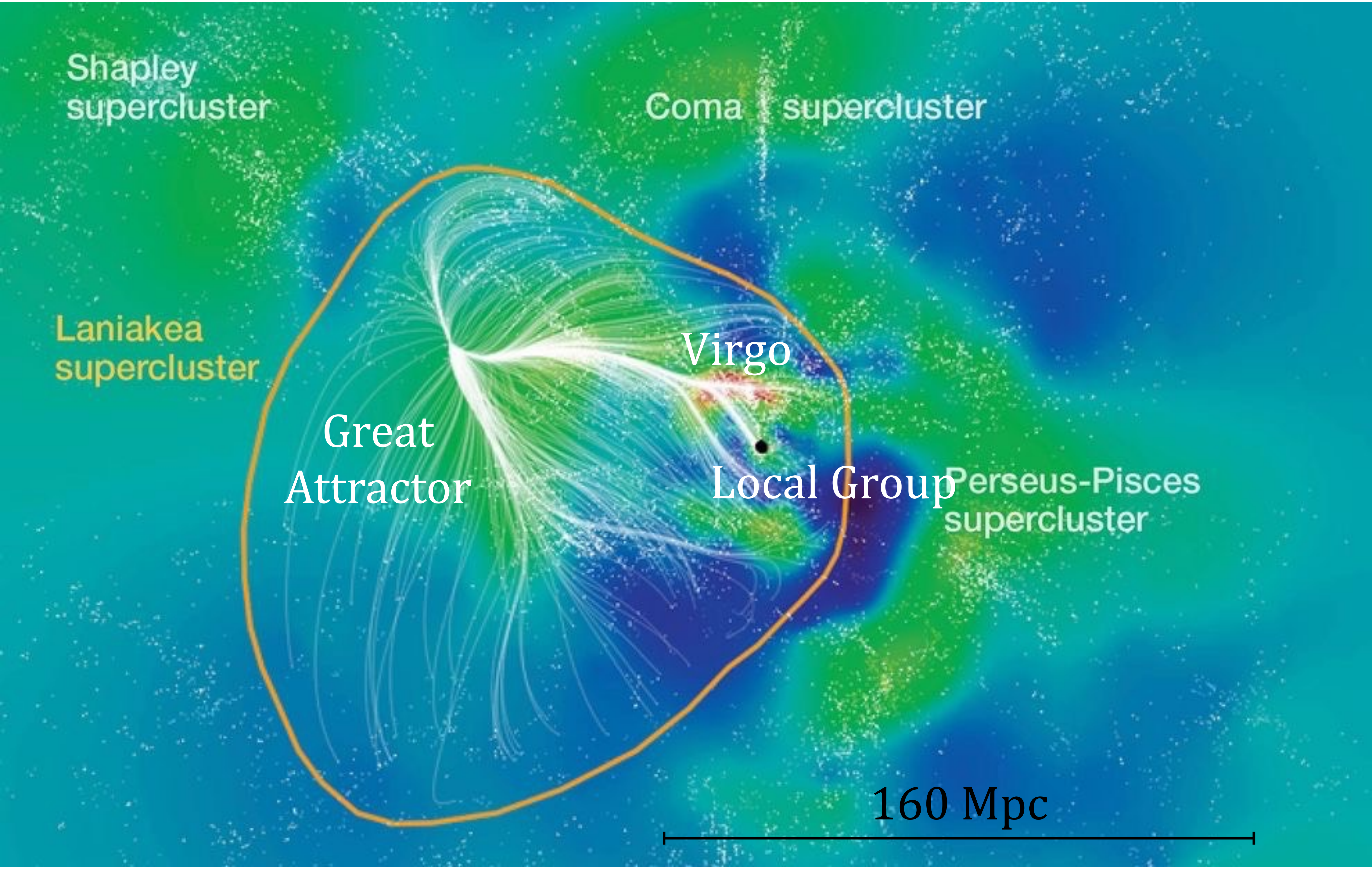
A Collision with Andromeda

- This computer simulation shows what the night sky might look like as the Milky Way collides with Andromeda in 4 billion years.

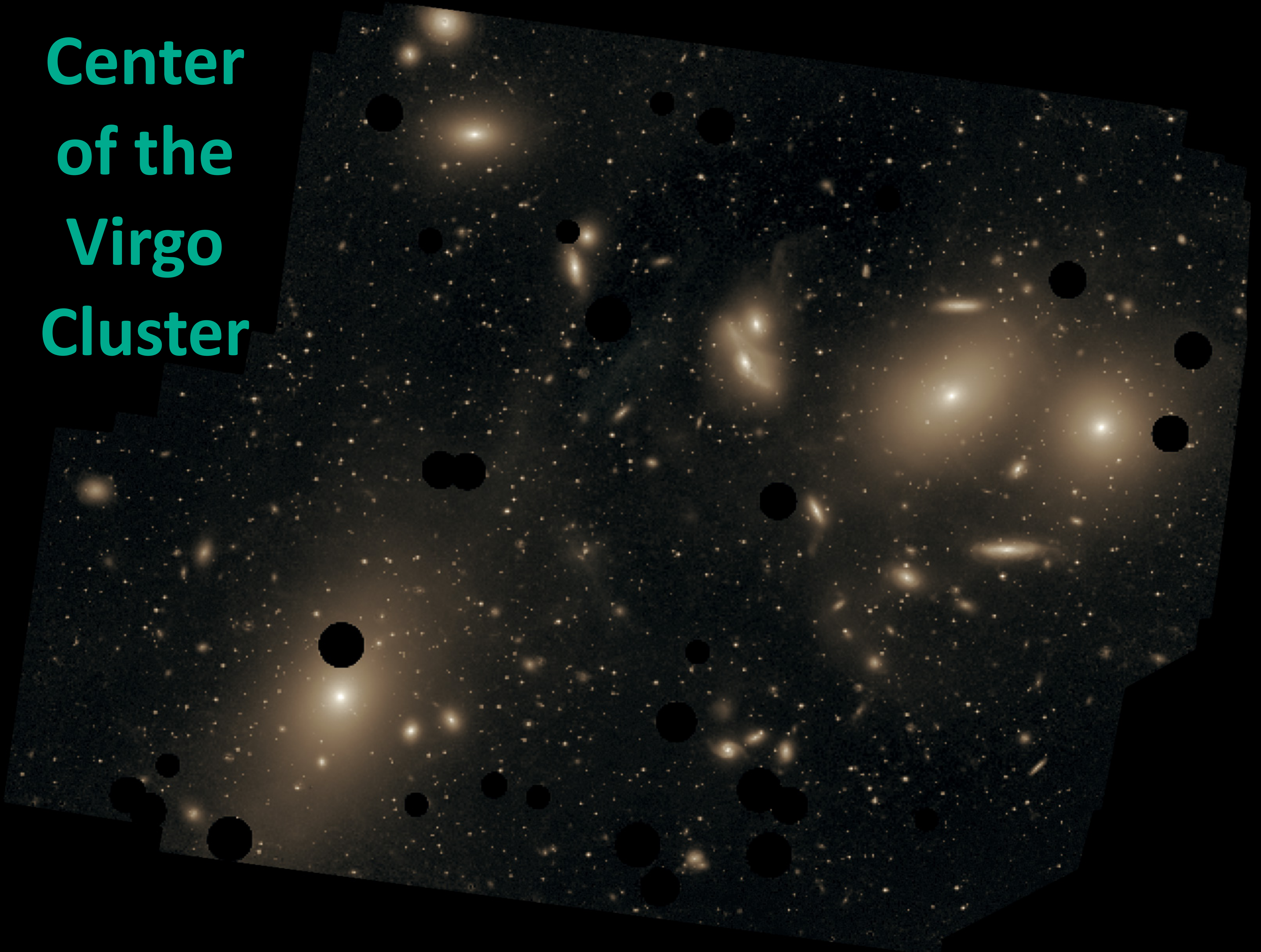
The Orbit of the Solar System after the merger of Milky Way and Andromeda Galaxy



Laniakea: The Local Supercluster



Center of the Virgo Cluster



The Scales and Masses of Various Galactic Structures

- Groups (1 Mpc, 1e13 Msun)
- Clusters (2 - 10 Mpc, 1e14 Msun)
- Superclusters (100 Mpc, 1e15 Msun)
- Large-Scale Filaments (100 Mpc - 1 Gpc)

Chap 20: The Milky Way Galaxy

- What does a spiral galaxy look like from inside?
- How to map the spiral arms?
- How fast are we moving?
- How to measure the rotation curve of the Milky Way disk?
- Galactocentric distance (§19)
- The stellar populations and the chemical enrichment history of the Galaxy
- Who are our closest neighbors? The local group and the local super cluster