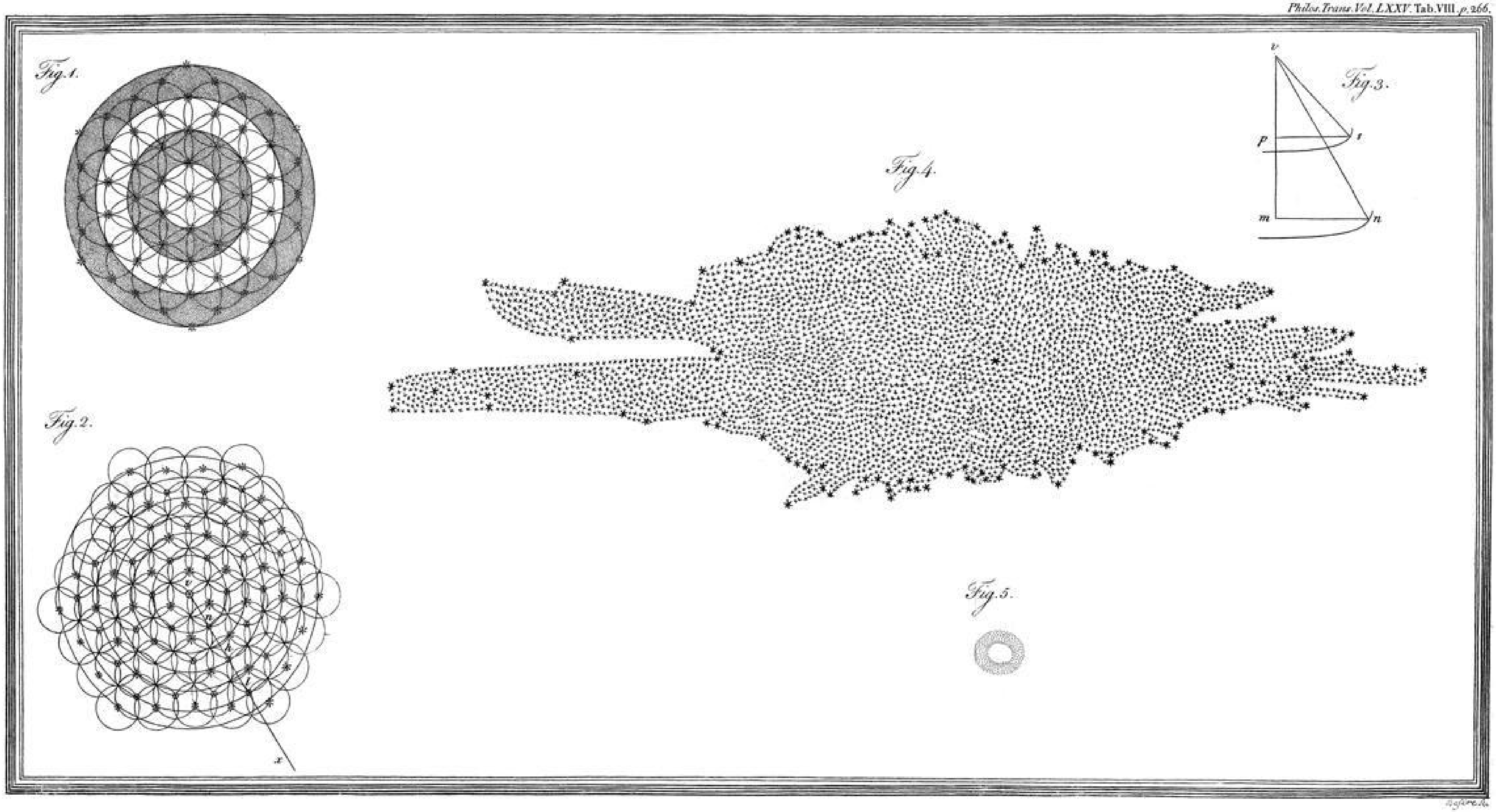
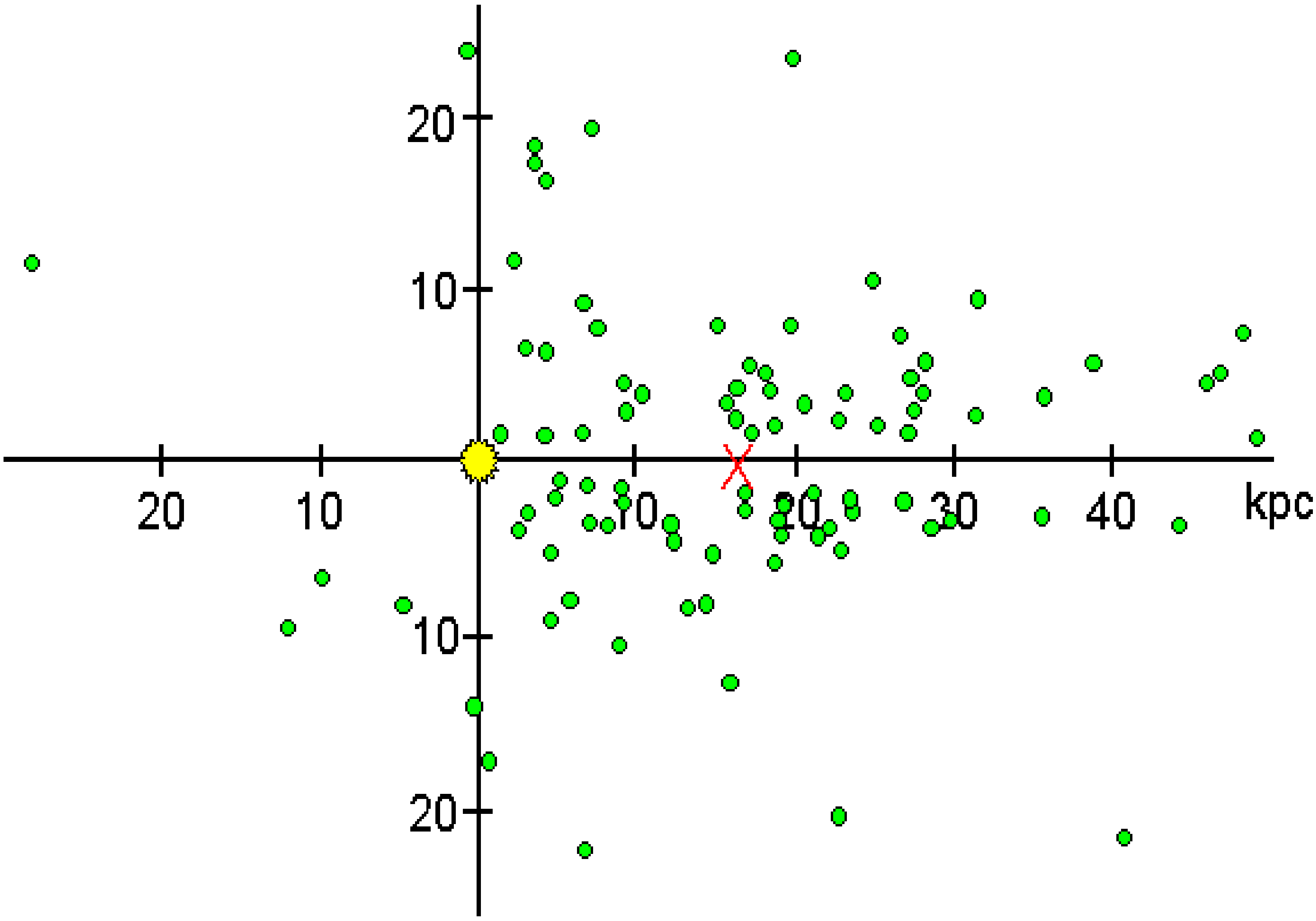
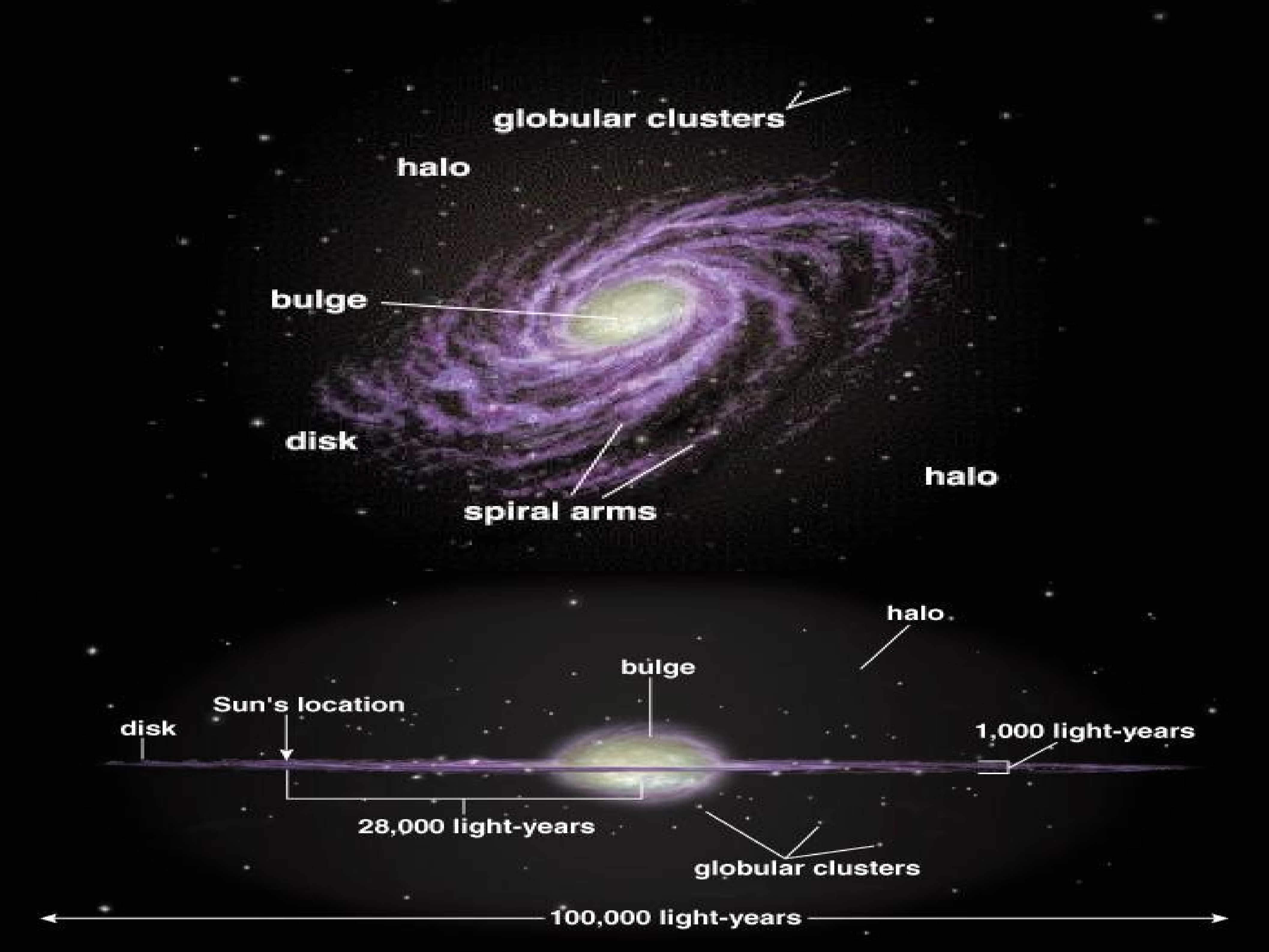
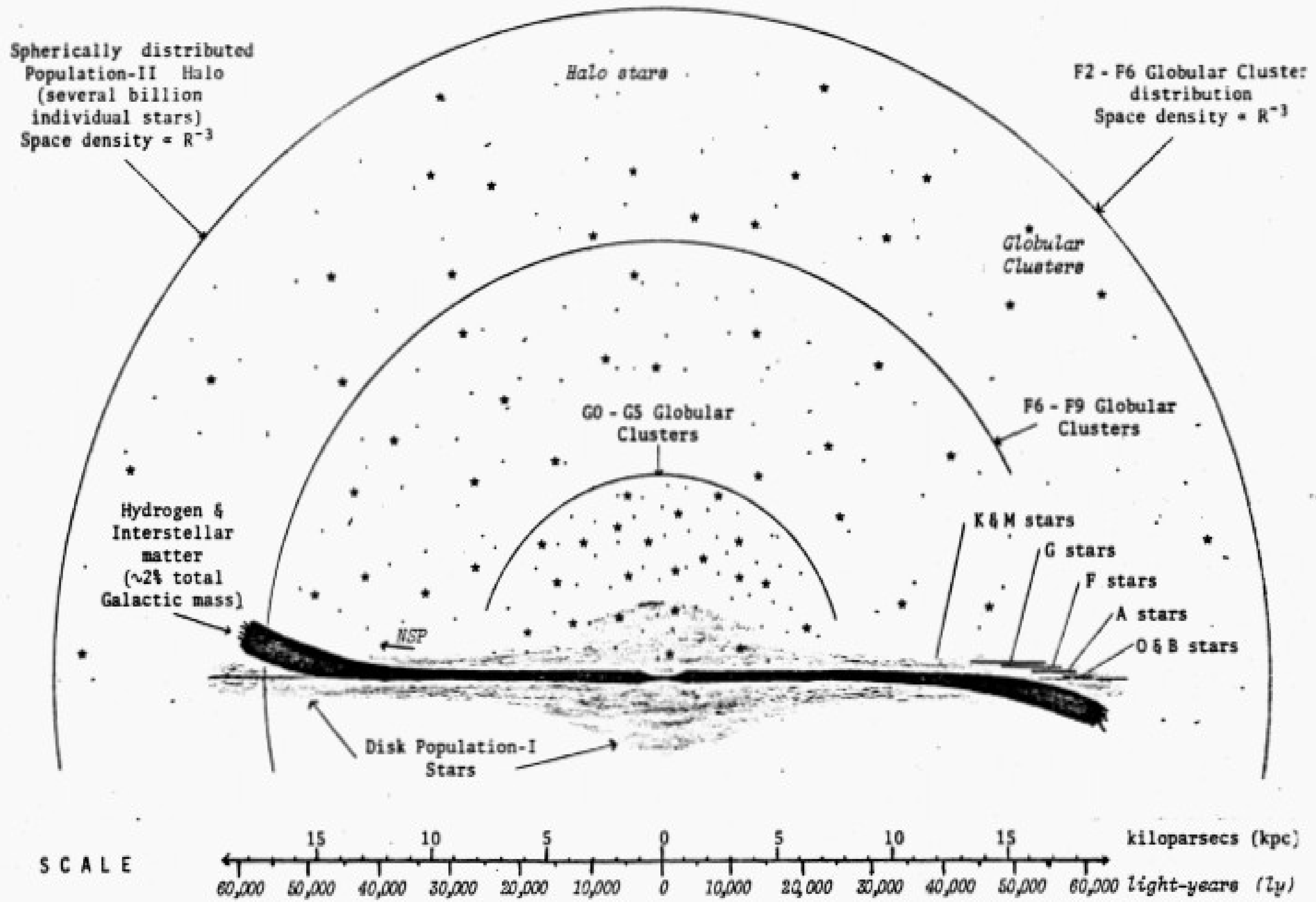
Herschel's Galaxy



Shapley's Globular Cluster Distribution



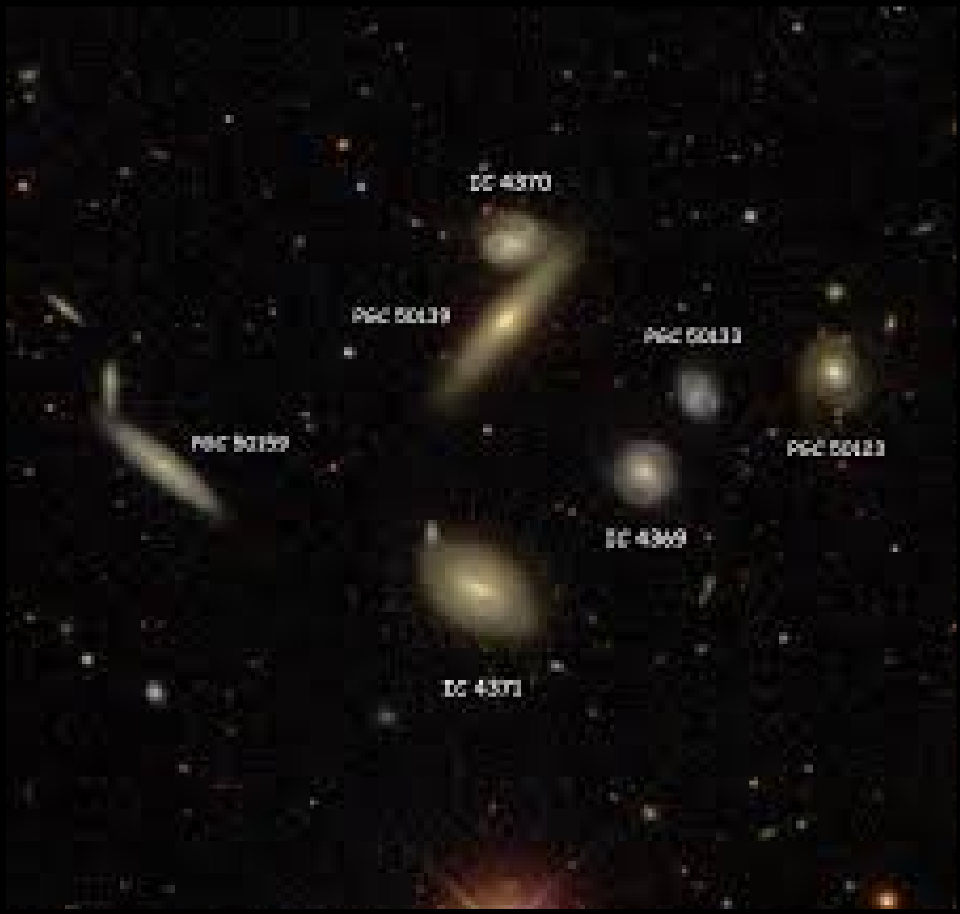

globular clusters
halo
bulge
disk
halo
spiral arms
halo
bulge
Sun's location
disk
1,000 light-years
28,000 light-years
globular clusters
100,000 light-years


Spherically distributed Population-II Halo (several billion individual stars) Space density ∝ R^-3
Halo stars
F2 - F6 Globular Cluster distribution Space density ∝ R^-3
Globular Clusters
F6 - F9 Globular Clusters
G0 - G5 Globular Clusters
Hydrogen & Interstellar matter (~2% total Galactic mass)
NSP
K & M stars
G stars
F stars
A stars
O & B stars
Disk Population-I Stars
SCALE
15
10
5
0
5
10
15
kiloparsecs (kpc)
60,000
50,000
40,000
30,000
20,000
10,000
0
10,000
20,000
30,000
40,000
50,000
60,000
light-years (ly)

Spiral Galaxies

Galaxy Groups

Local Group

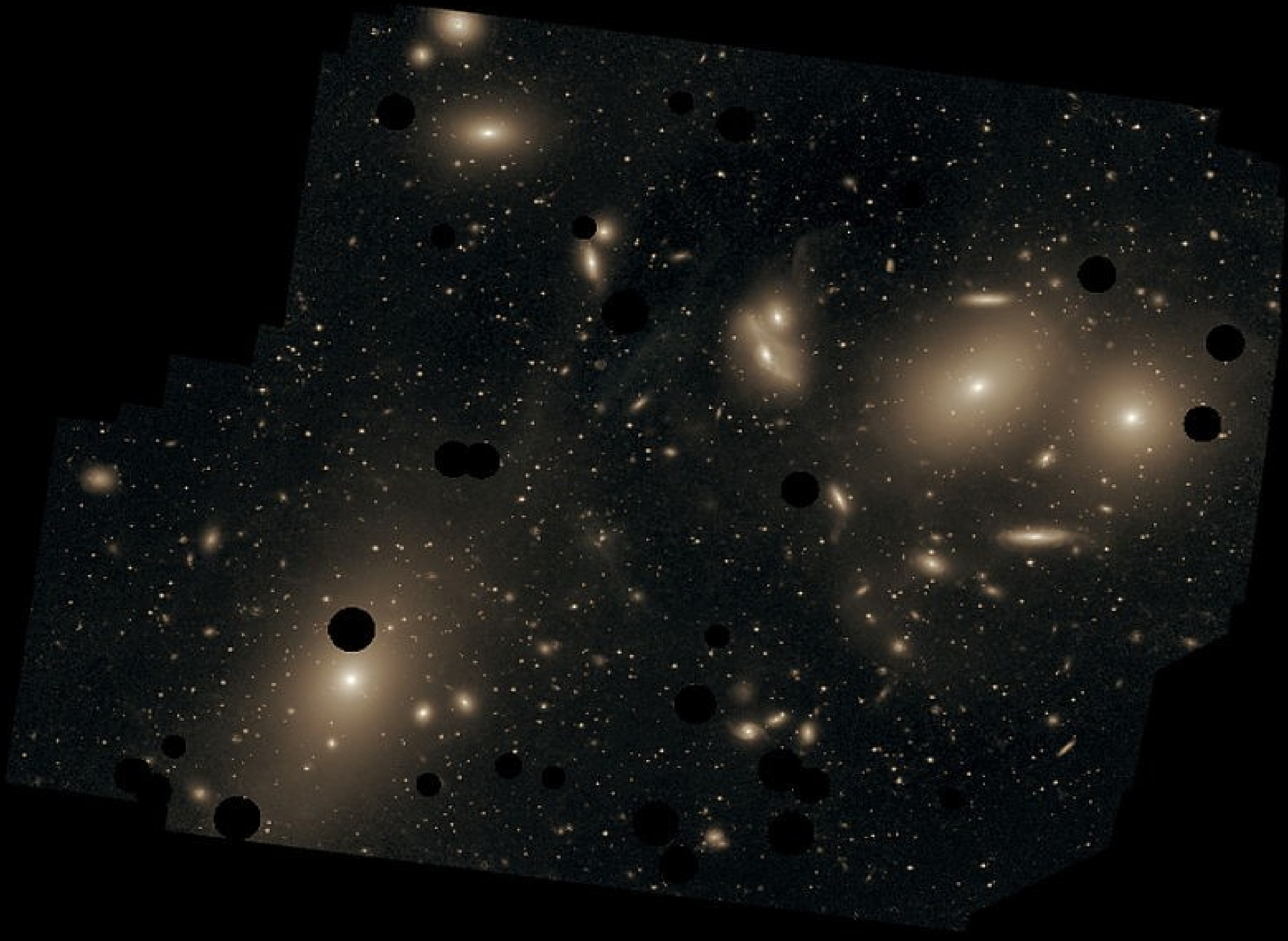


Hickson Compact Group 70

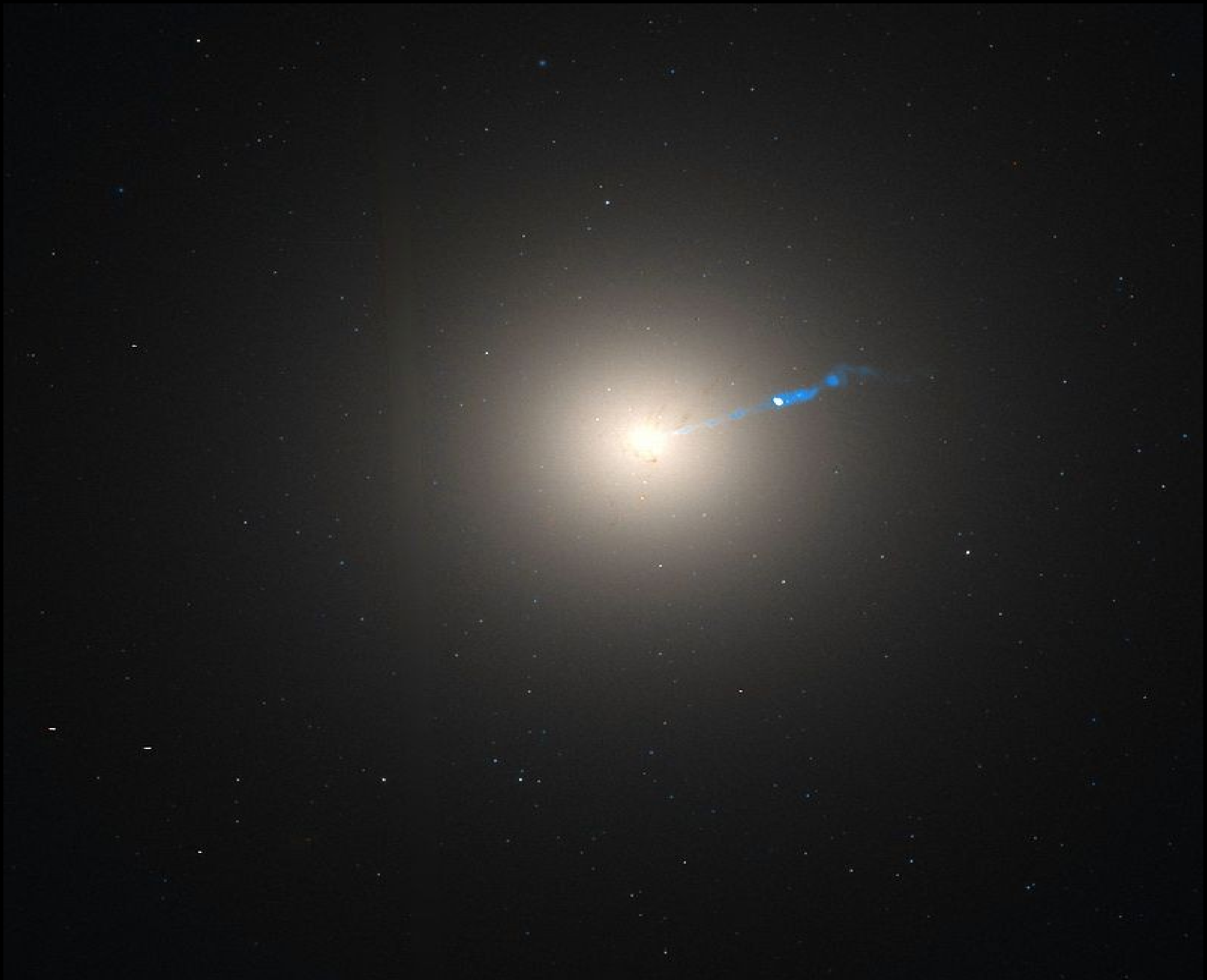
Irregular Galaxies

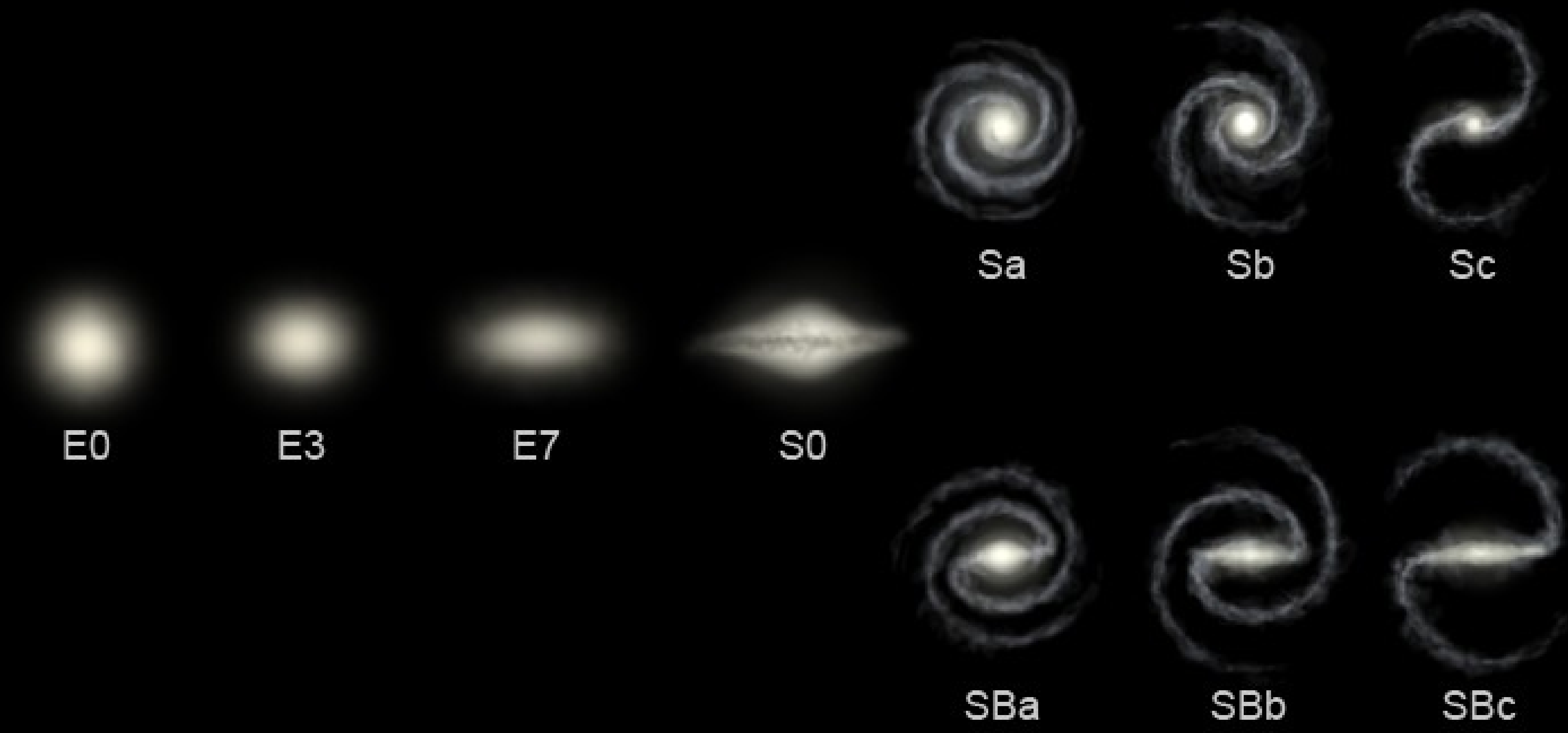
Elliptical Galaxies

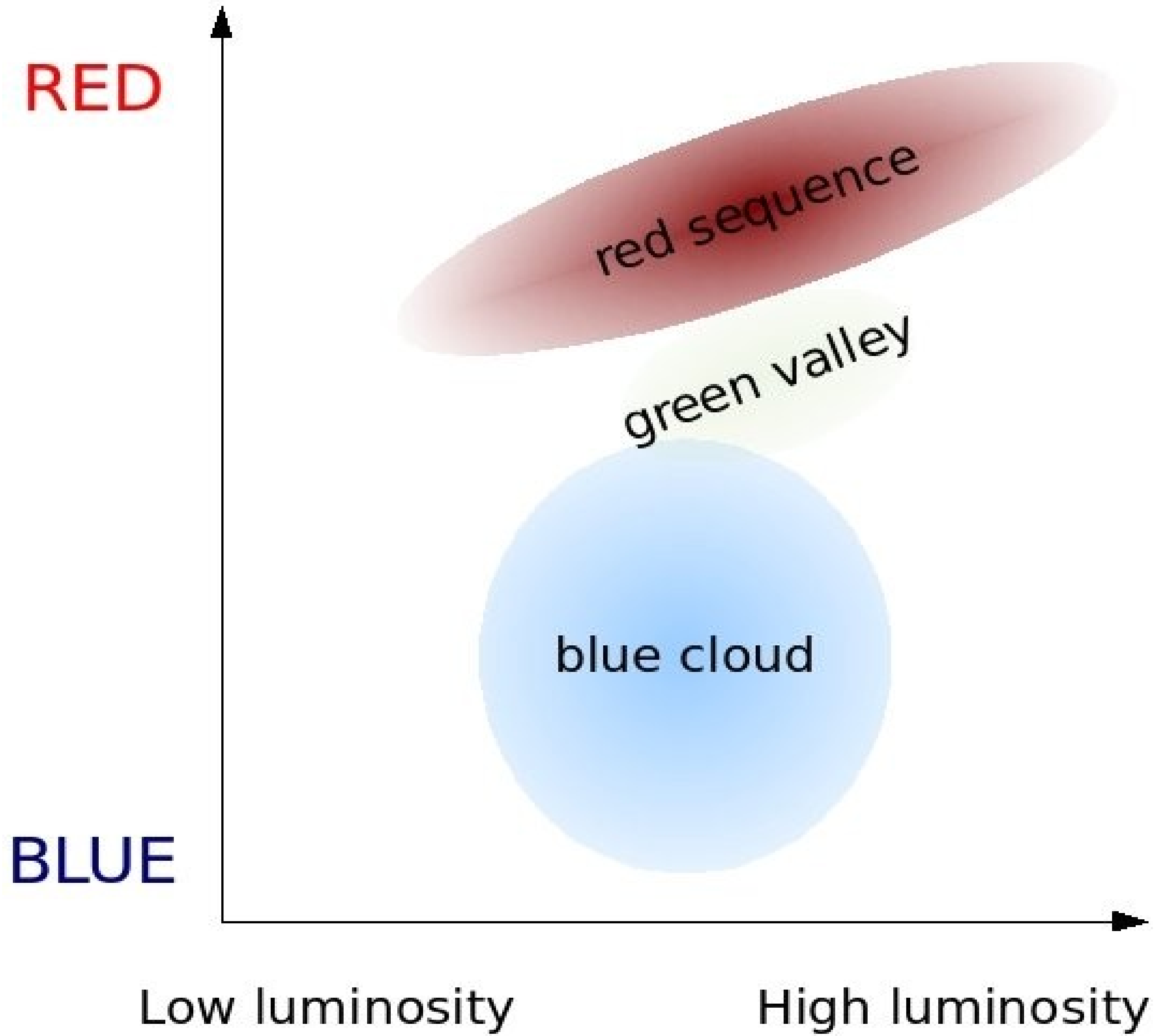
Virgo Cluster



M 87 - Virgo Cluster cD



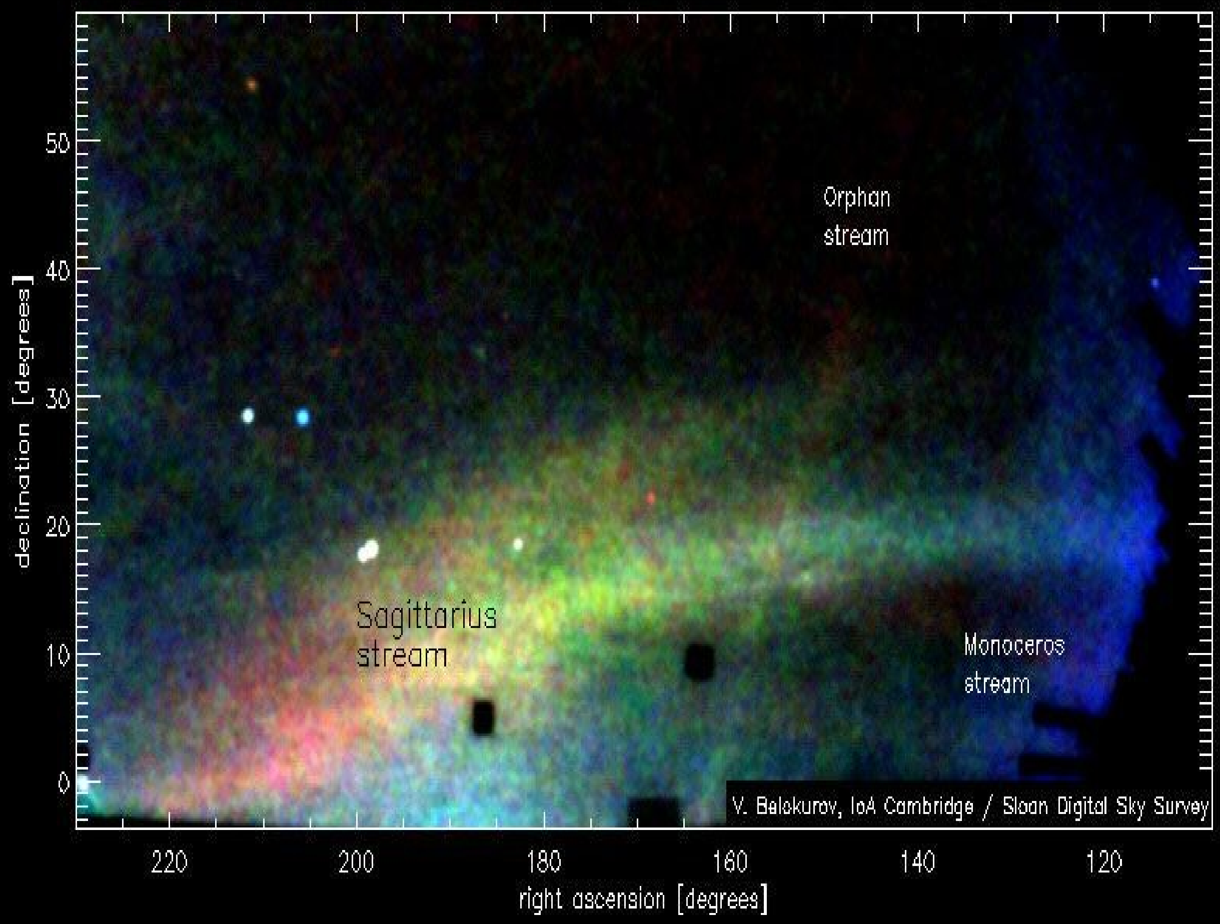

Sa
Sb
Sc
E0
E3
E7
S0
SBa
SBb
SBc

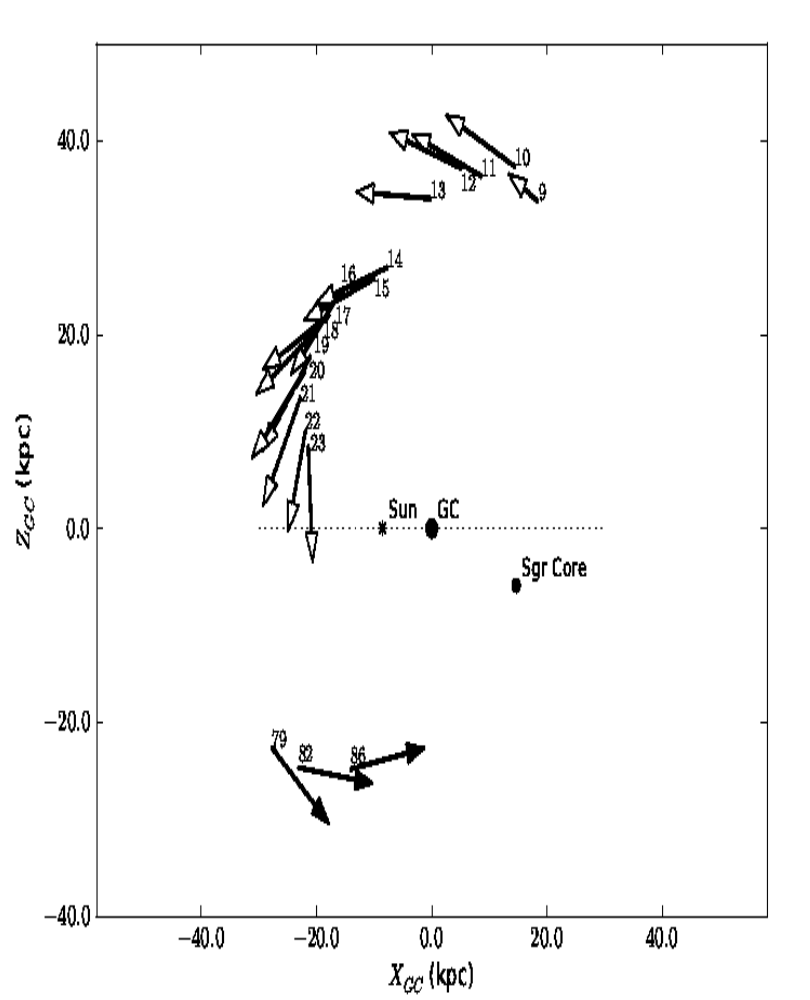

RED
red sequence
green valley
blue cloud
BLUE
Low luminosity
High luminosity

The MilkyWay galaxy

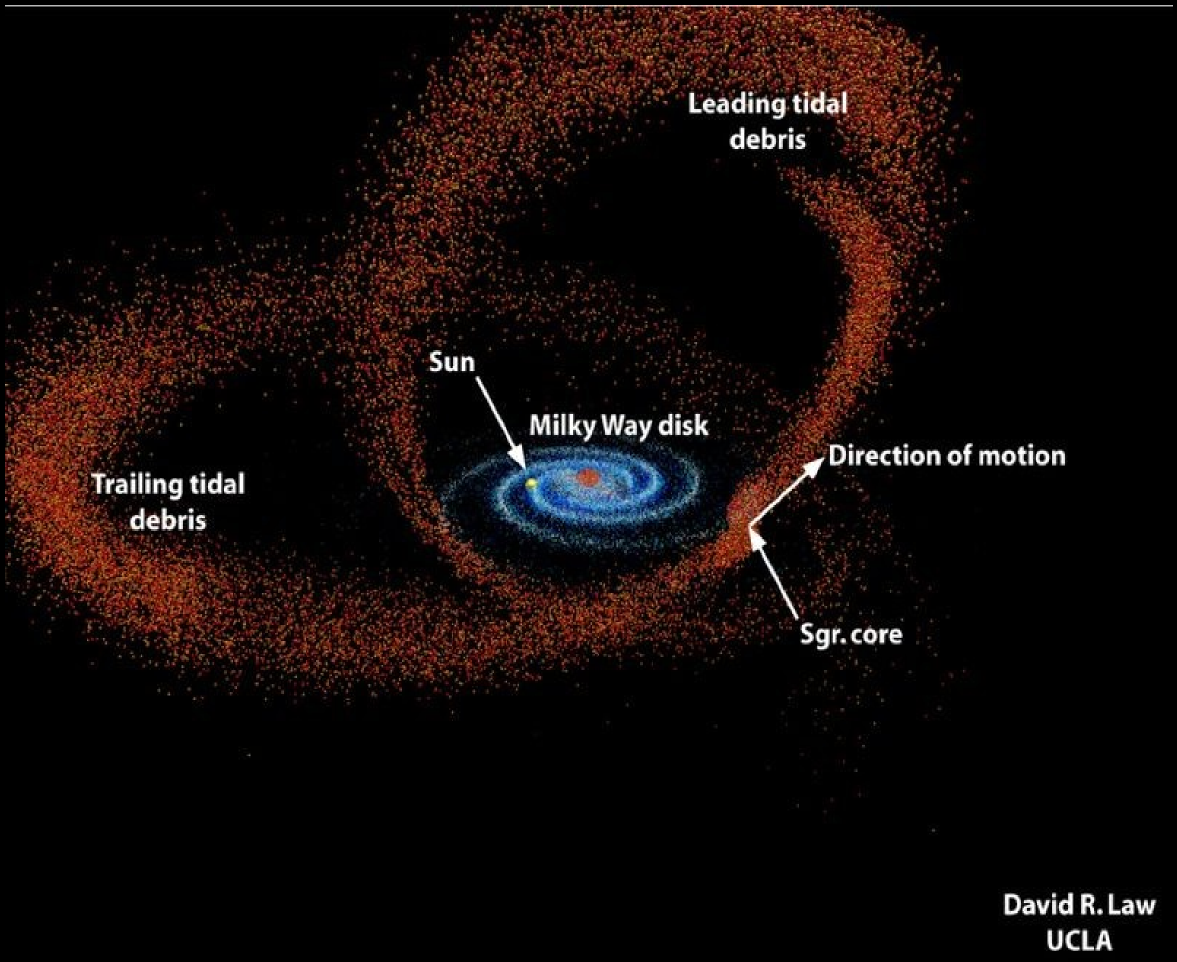
A large SBb (or SBc) spiral galaxy with ongoing star formation (Pop II)

Sag. Stream

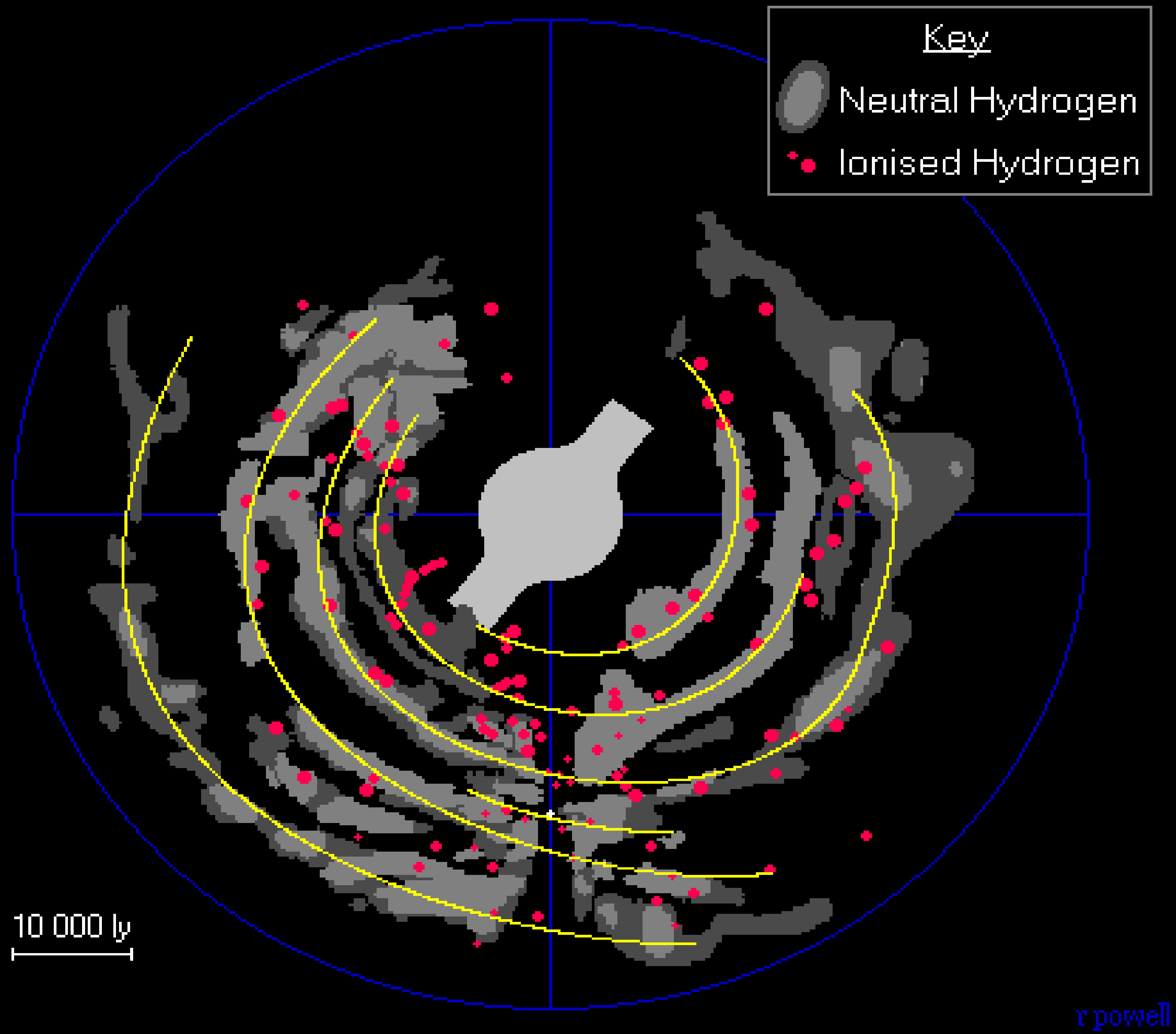

Orphan stream
Sagittarius stream
Monoceros stream
V. Belokurov, IoA Cambridge / Sloan Digital Sky Survey
declination [degrees]
right ascension [degrees]
220
200
180
160
140
120
0
10
20
30
40
50


Sun
GC
Sgr Core
Z_{GC} (kpc)
X_{GC} (kpc)
40.0
20.0
0.0
−20.0
−40.0

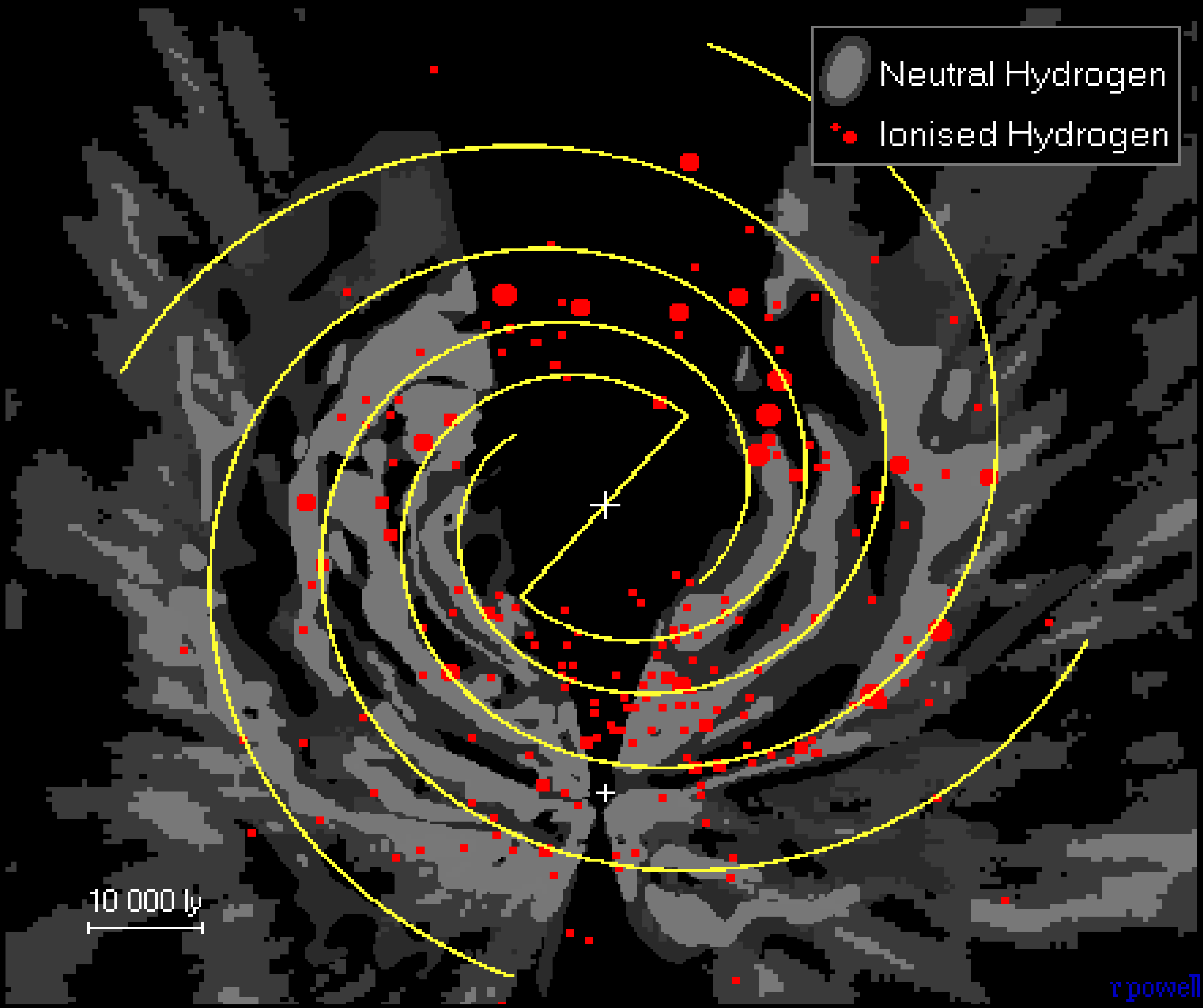
Sag. Stream


Leading tidal debris
Sun
Milky Way disk
Direction of motion
Trailing tidal debris
Sgr. core
David R. Law
UCLA

Sag. Stream



Key
Neutral Hydrogen
Ionised Hydrogen
10 000 ly
r powell



Neutral Hydrogen
Ionised Hydrogen
10 000 ly
r powell

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October 9, 2014

The observed spiral structure of the Milky Way★ ★★

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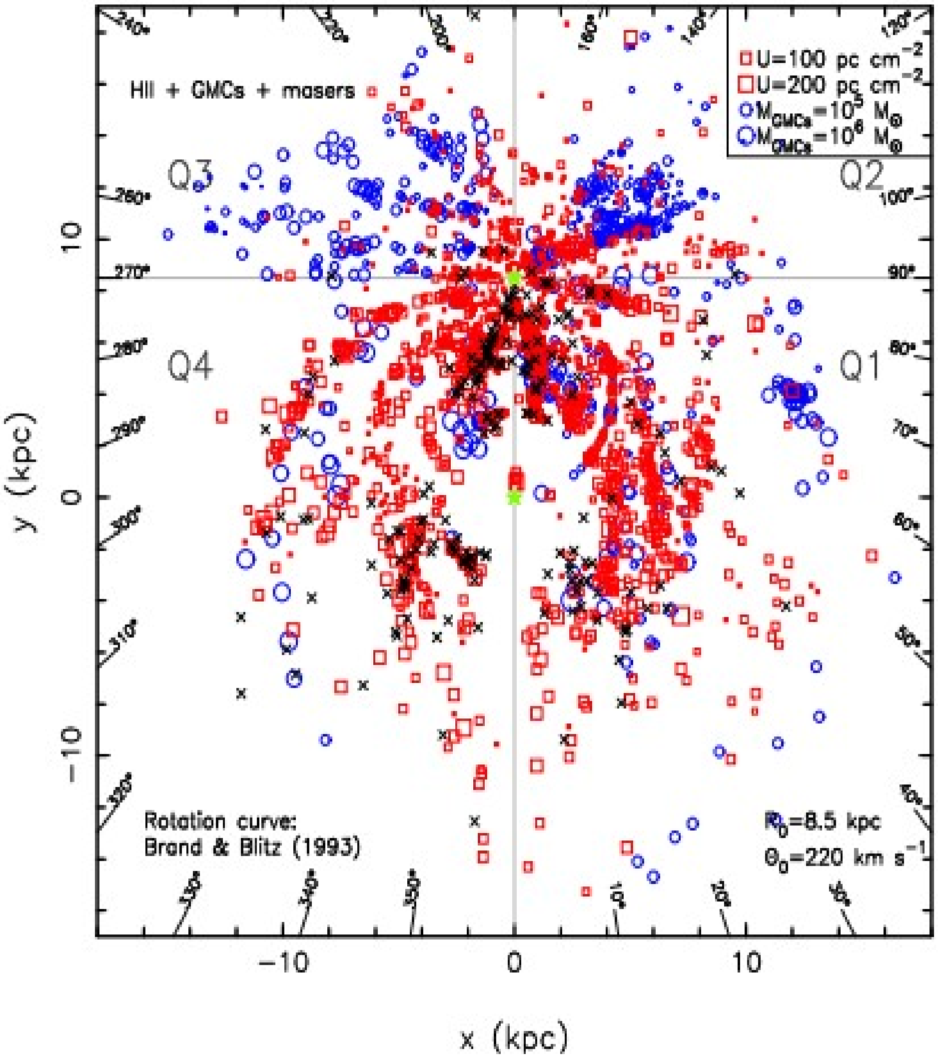
ABSTRACT

Context. The spiral structure of the Milky Way is not yet well determined. The keys to understanding this structure are to increase the number of reliable spiral tracers and to determine their distances as accurately as possible. HII regions, giant molecular clouds (GMCs), and 6.7 GHz methanol masers are closely related to high mass star formation, and hence they are excellent spiral tracers. The distances for many of them have been determined in the literature with trigonometric, photometric and/or kinematic methods.
Aims. We update the catalogs of Galactic HII regions, GMCs, and 6.7 GHz methanol masers, and then outline the spiral structure of the Milky Way.
Methods. We collected data for more than 2500 known HII regions, 1300 GMCs, and 900 6.7 GHz methanol masers. If the photometric or trigonometric distance was not yet available, we determined the kinematic distance using a Galaxy rotation curve with the current IAU standard, $R_0 = 8.5$ kpc and $\Theta_0 = 220$ km s^{-1}, and the most recent updated values of $R_0 = 8.3$ kpc and $\Theta_0 = 239$ km s^{-1}, after velocities of tracers are modified with the adopted solar motions. With the weight factors based on the excitation parameters of HII regions or the masses of GMCs, we get the distributions of these spiral tracers.
Results. The distribution of tracers shows at least four segments of arms in the first Galactic quadrant, and three segments in the fourth quadrant. The Perseus Arm and the Local Arm are also delineated by many bright HII regions. The arm segments traced by massive star forming regions and GMCs are able to match the HI arms in the outer Galaxy. We found that the models of three-arm and four-arm logarithmic spirals are able to connect most spiral tracers. A model of polynomial-logarithmic spirals is also proposed, which not only delineates the tracer distribution, but also matches the observed tangential directions.

Key words. Galaxy: disk – Galaxy: structure – Galaxy: kinematics and dynamics – HII regions – ISM: clouds



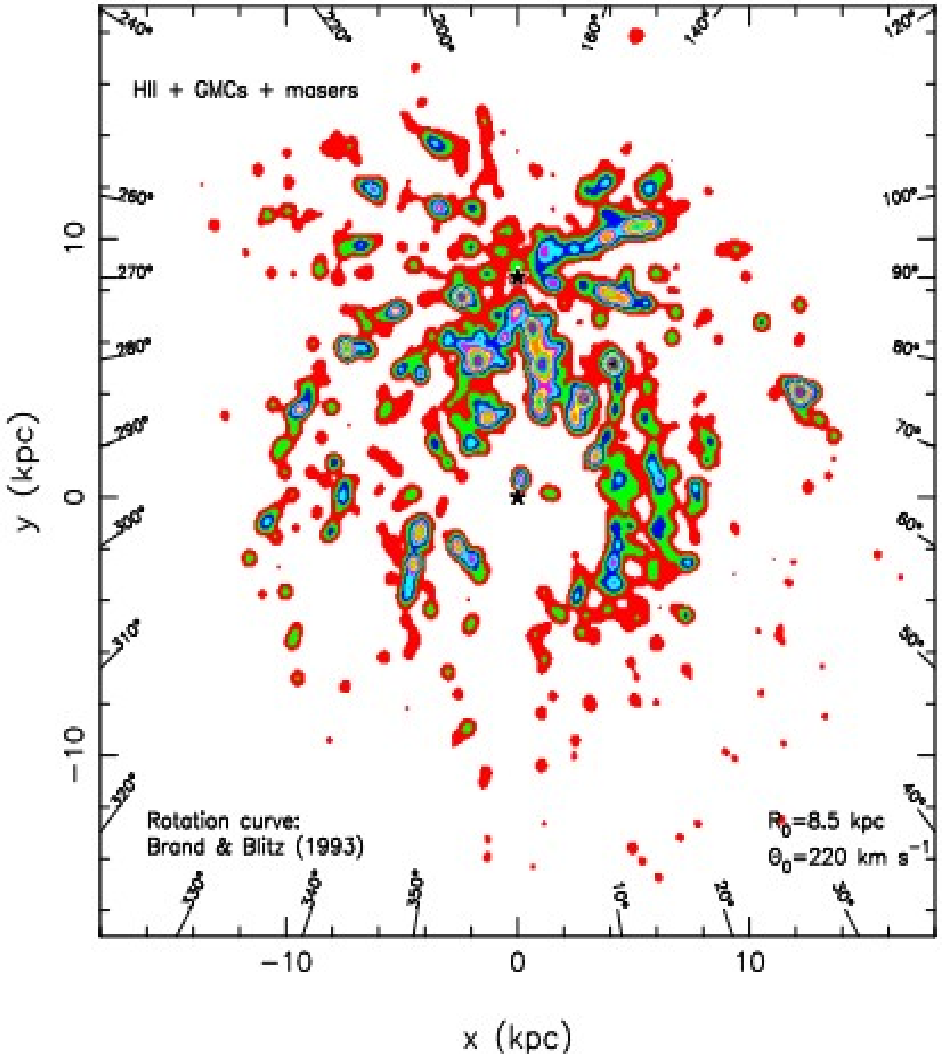
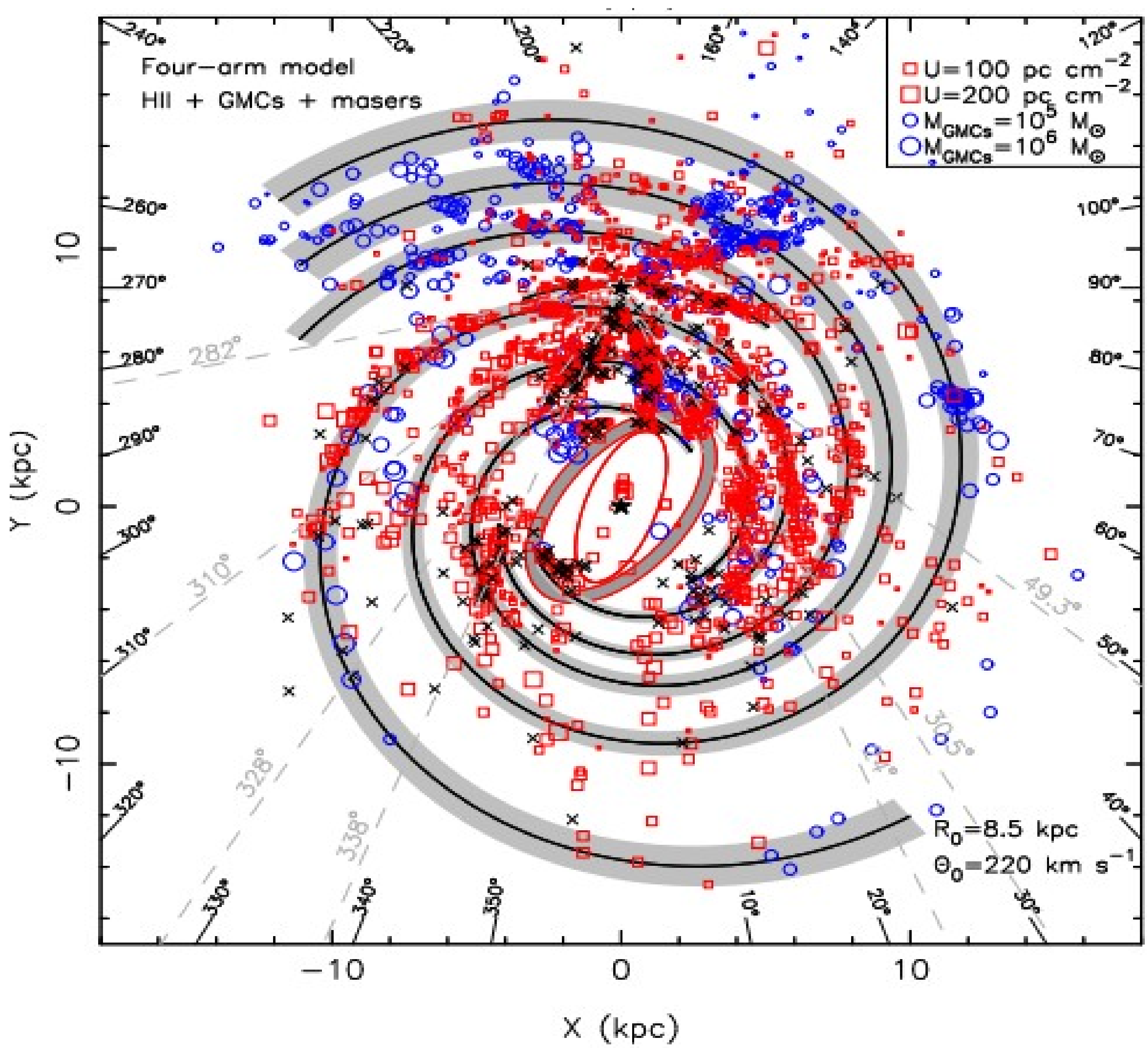


Fig. 15. *Left*: distributions of HII regions, GMCs, and 6.7 GHz methanol masers projected into the Galactic plane. The symbols are the same as those in Fig. 2. The kinematic distances are estimated using the rotation curve of BB93. *Right*: color intensity map of spiral tracers. The IAU standard R_0 = 8.5 kpc and Θ_0 = 220 km s^{-1} and standard solar motions are adopted in deriving the kinematic distances if no photometric or trigonometric distance is available.



In polar coordinates (r, θ), the ith arm can be given as logarithmic form:

$$\ln \frac{r}{R_i} = (\theta - \theta_i) \tan \psi_i, \tag{3}$$

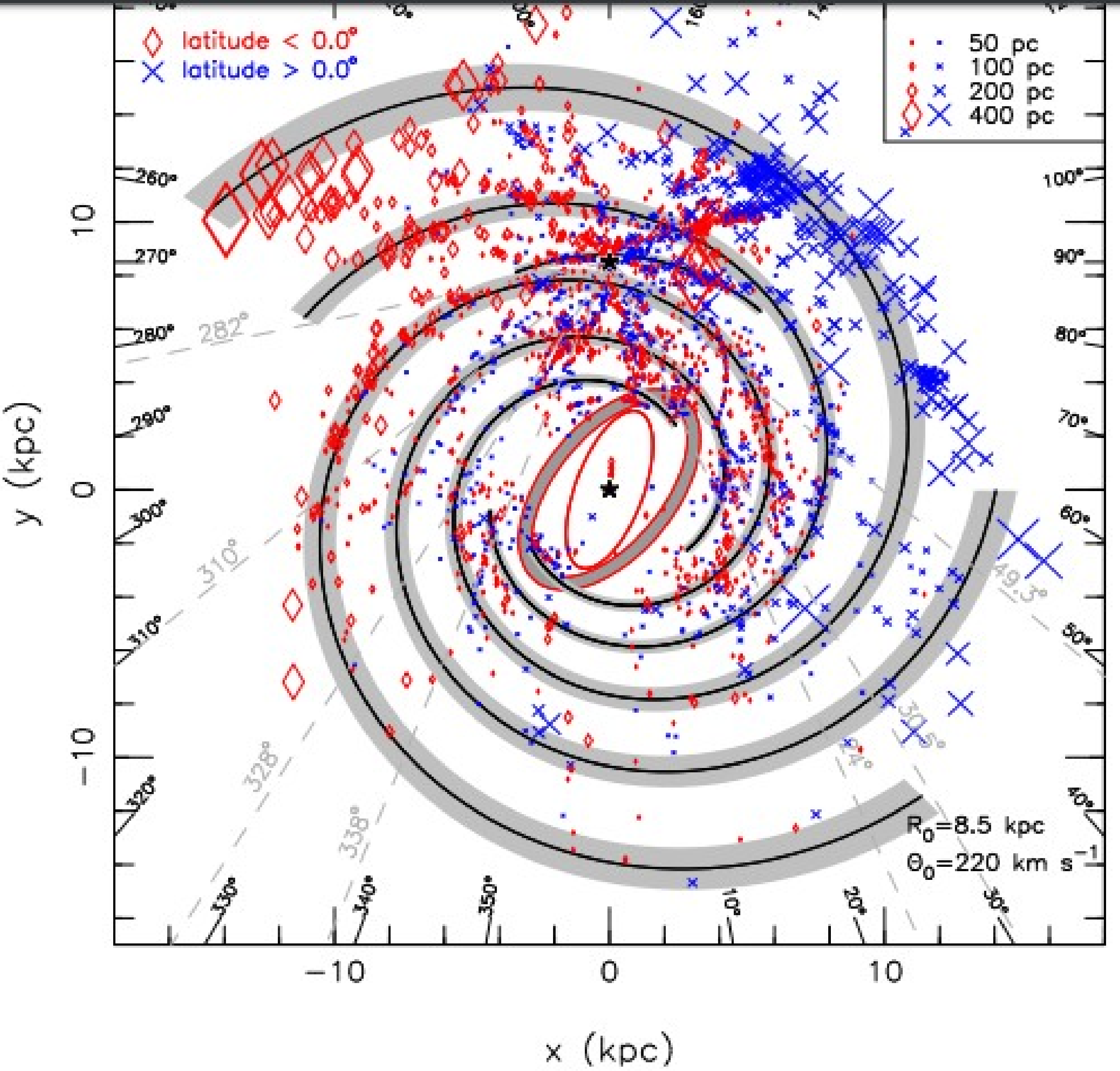
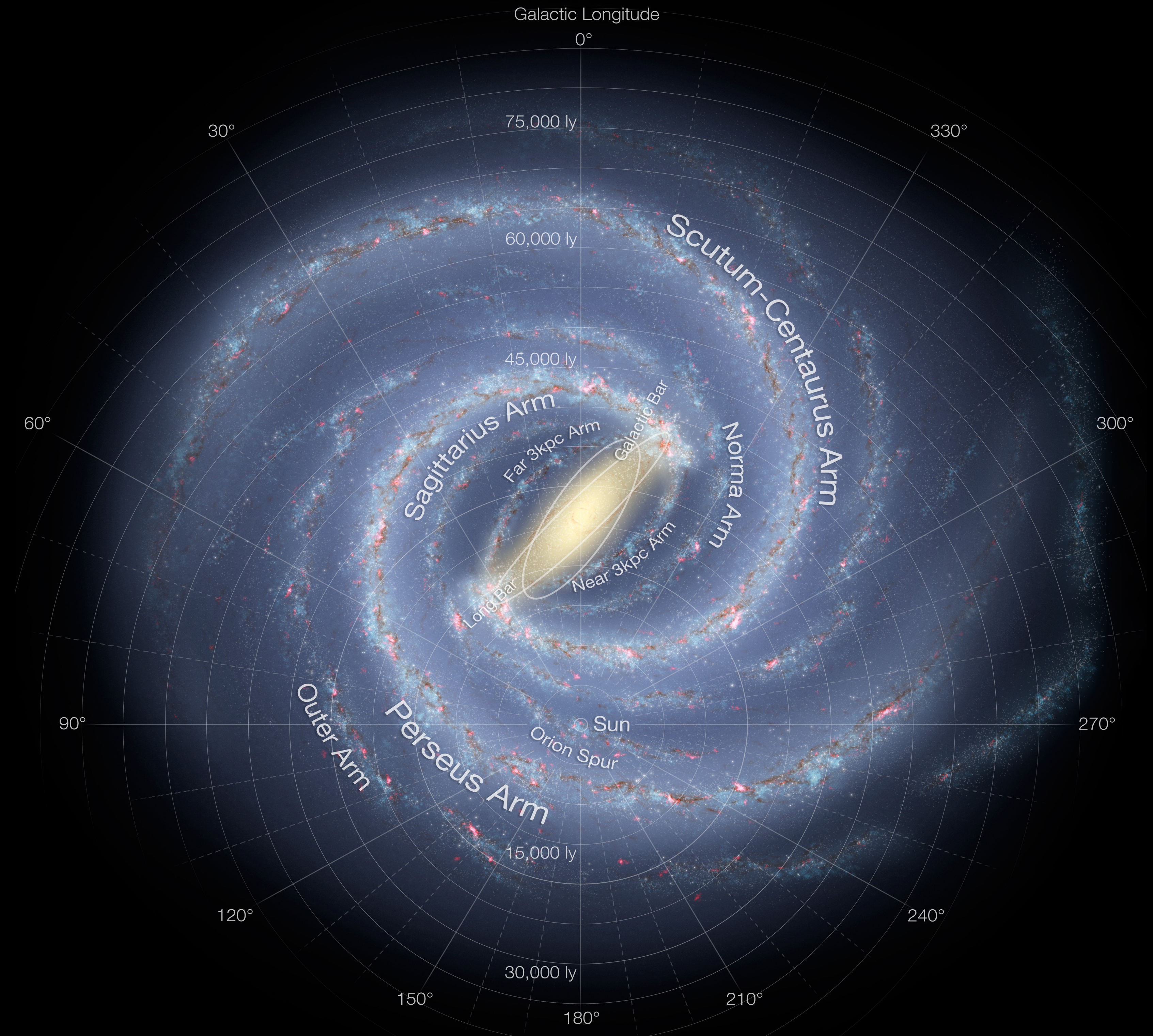
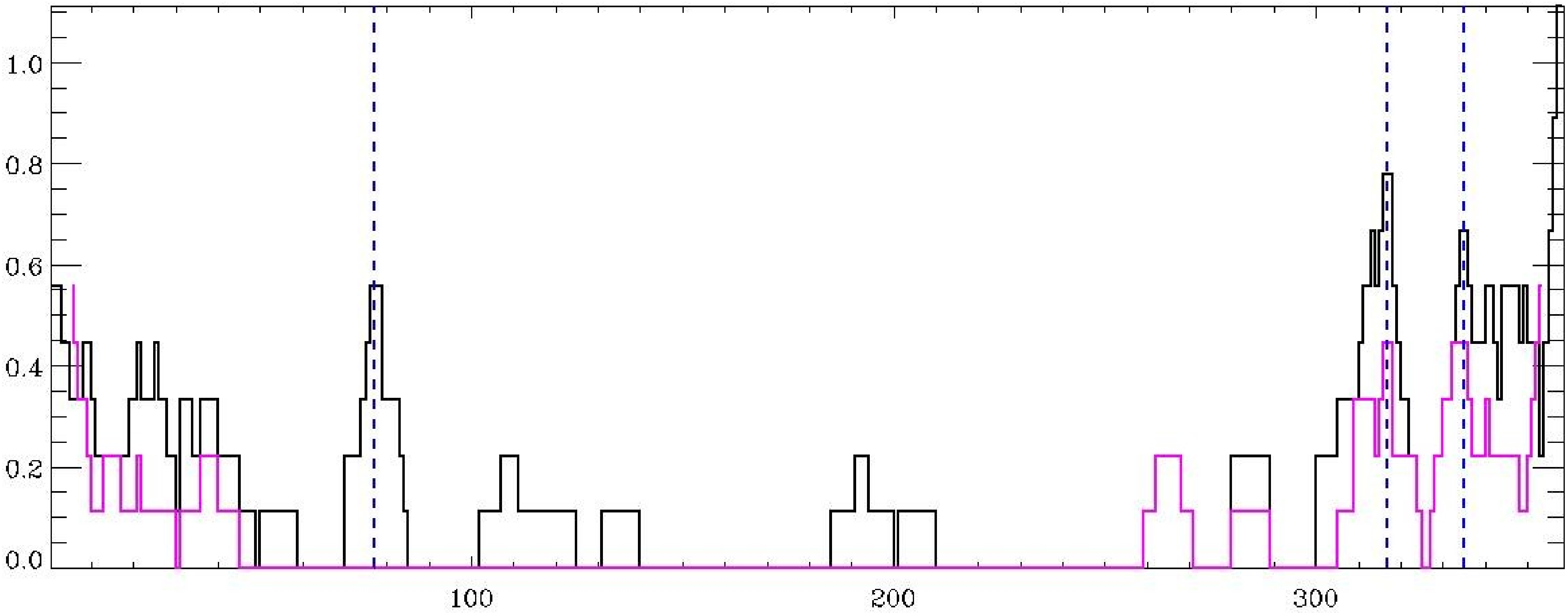
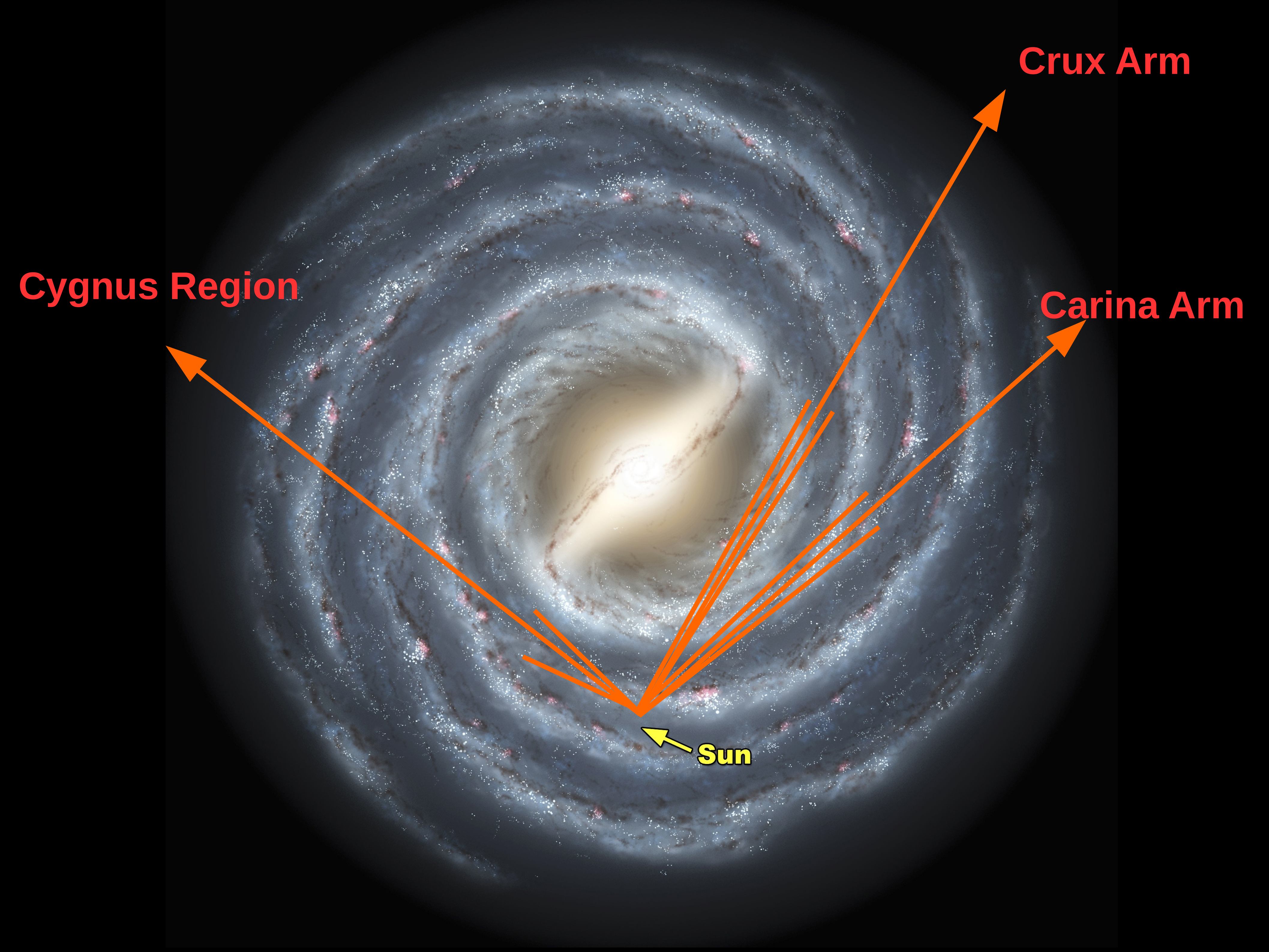


Fig. 16. Evidence of Galactic warp as shown by the distributions of HII regions, GMCs, and 6.7 GHz methanol masers. Note that the diamonds here indicate the tracers of $b < 0.0°$, and the blue crosses indicate the tracers of $b > 0.0°$. The symbol size is proportional to the offset from the Galactic plane. The outlines are the best-fitted four-arm model (see the *upper right panel* of Fig. 10).

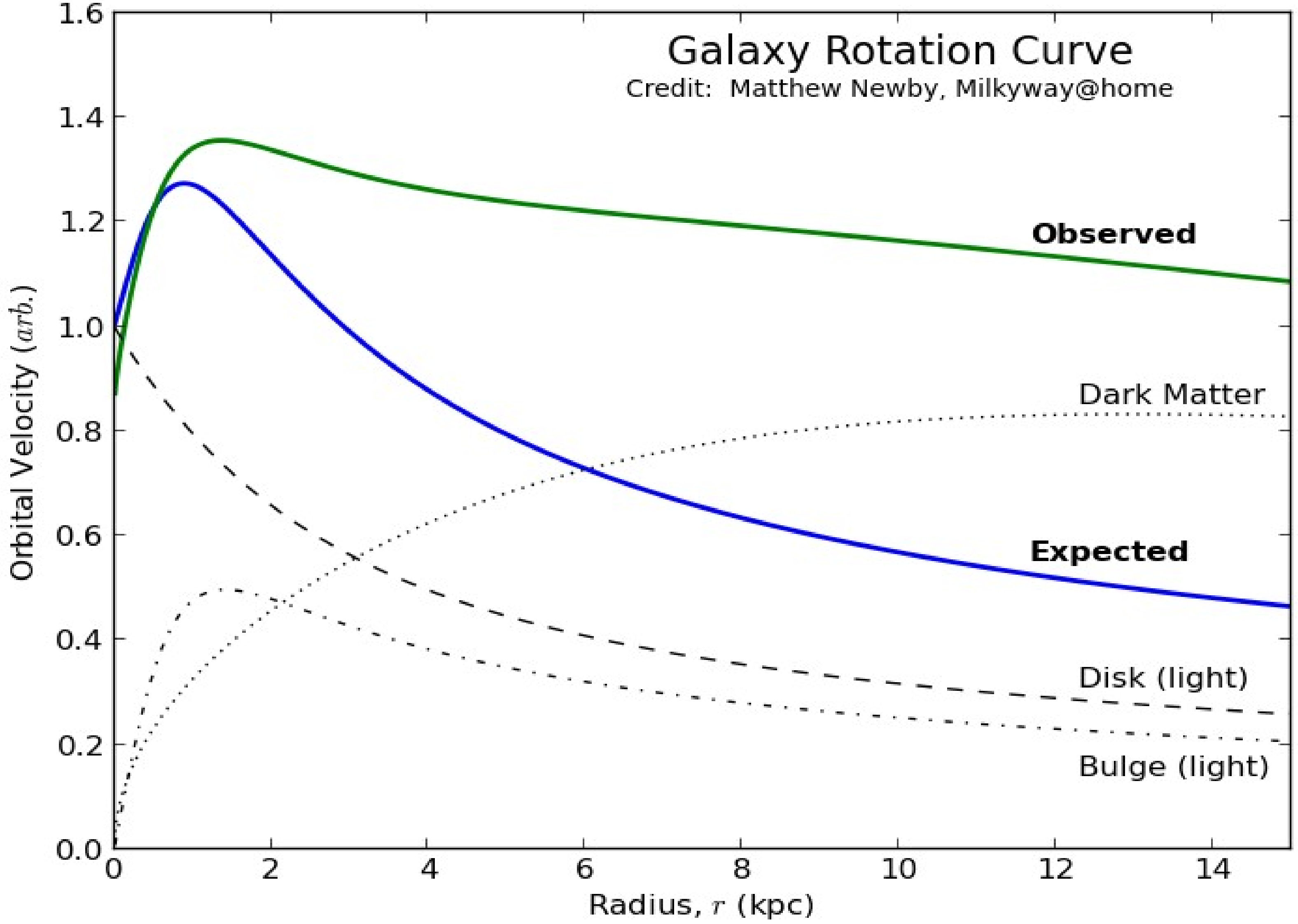

Galactic Longitude
0°
30°
330°
75,000 ly
60,000 ly
45,000 ly
Scutum-Centaurus Arm
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Norma Arm
60°
300°
Near 3kpc Arm
Long Bar
Outer Arm
Perseus Arm
Sun
Orion Spur
90°
270°
15,000 ly
120°
240°
30,000 ly
150°
210°
180°

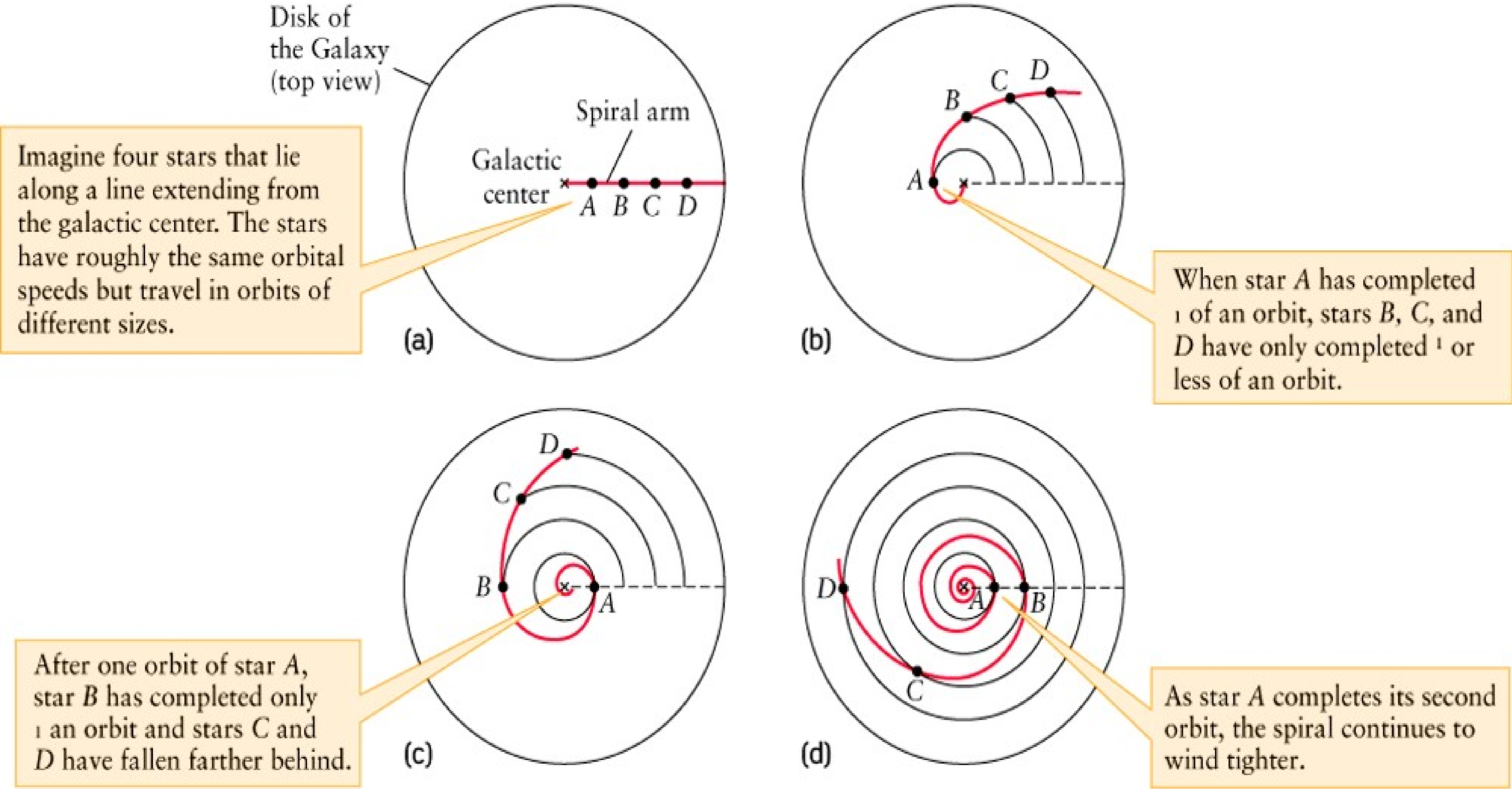
TeV sources along the Galactic Plane



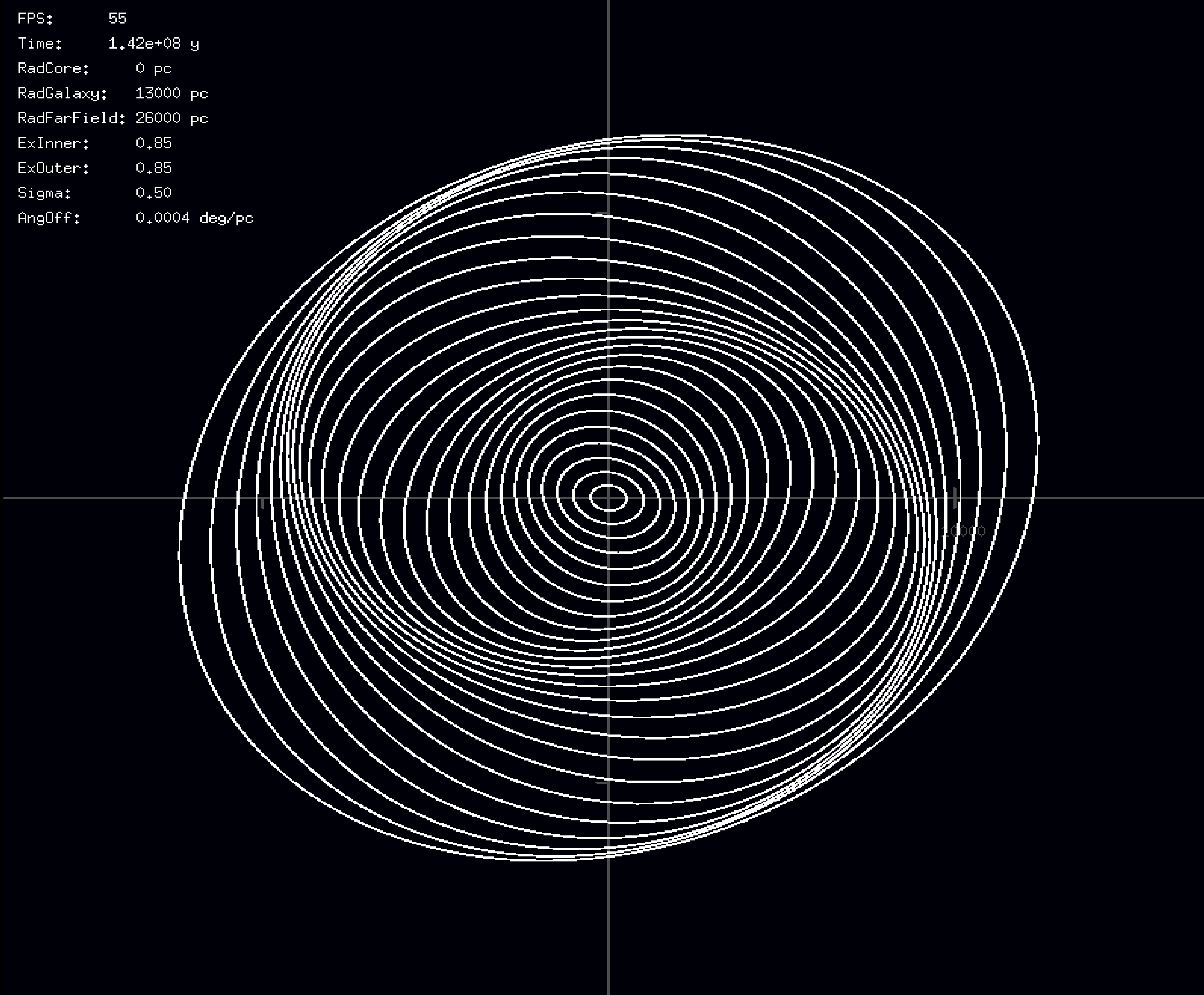

Crux Arm
Cygnus Region
Carina Arm
Sun

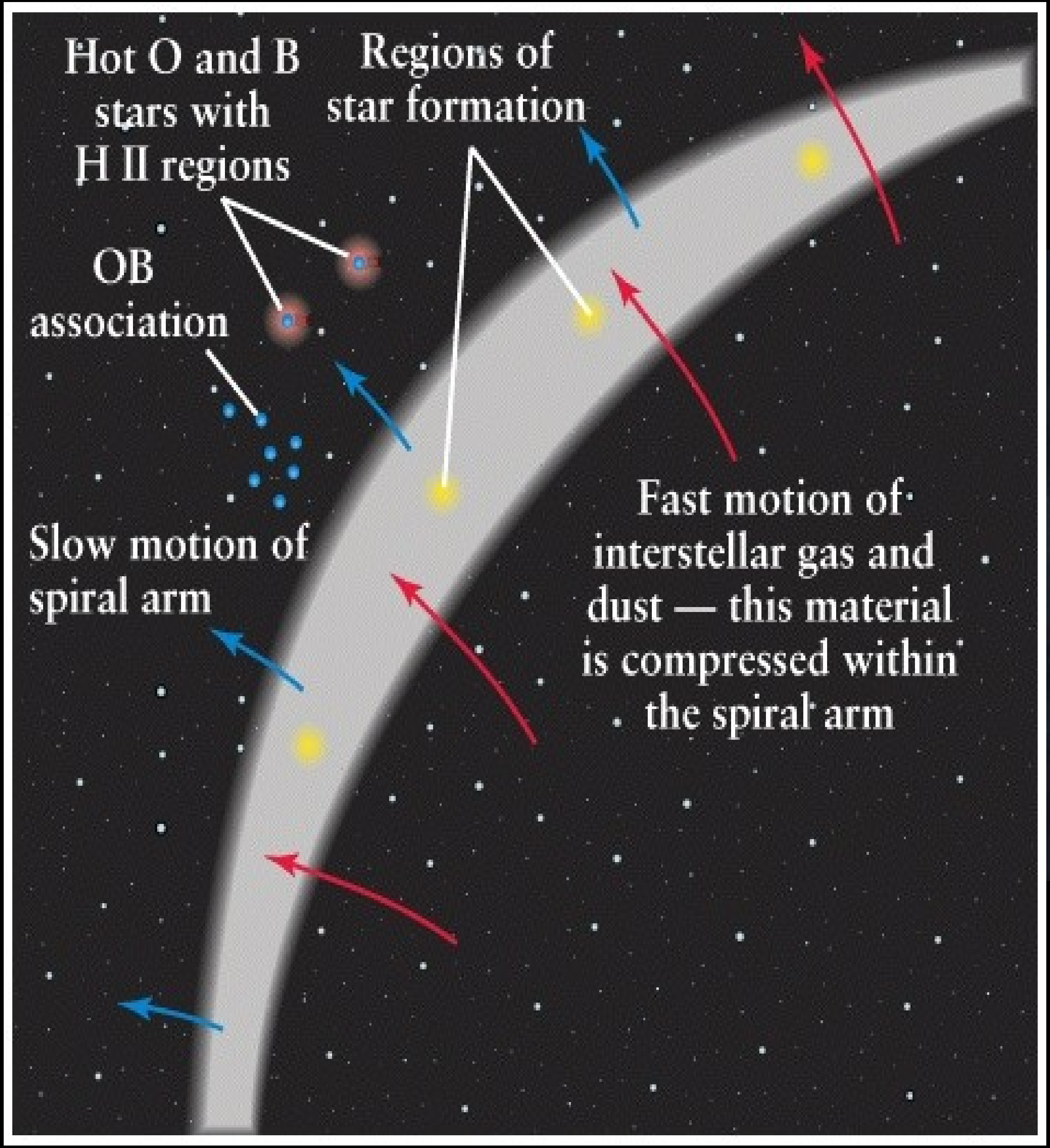
Galactic Rotation Curve





Disk of the Galaxy (top view)
Spiral arm
Galactic center
A B C D
Imagine four stars that lie along a line extending from the galactic center. The stars have roughly the same orbital speeds but travel in orbits of different sizes.
(a)
B C D
A
(b)
When star A has completed 1 of an orbit, stars B, C, and D have only completed 1 or less of an orbit.
D
C
B
A
After one orbit of star A, star B has completed only 1 an orbit and stars C and D have fallen farther behind.
(c)
D A B
C
(d)
As star A completes its second orbit, the spiral continues to wind tighter.


FPS: 55
Time: 1.42e+08 y
RadCore: 0 pc
RadGalaxy: 13000 pc
RadFarField: 26000 pc
ExInner: 0.85
ExOuter: 0.85
Sigma: 0.50
AngOff: 0.0004 deg/pc


Hot O and B stars with H II regions
Regions of star formation
OB association
Slow motion of spiral arm
Fast motion of interstellar gas and dust — this material is compressed within the spiral arm

The Interstellar Medium

Interstellar Matter

Molecular Clouds

Neutral Hydrogen

H II regions

Dust

InterStellar Radiation Field

(stars, dust, CBM)

Magnetic Field

Cosmic Rays

The Interstellar Medium

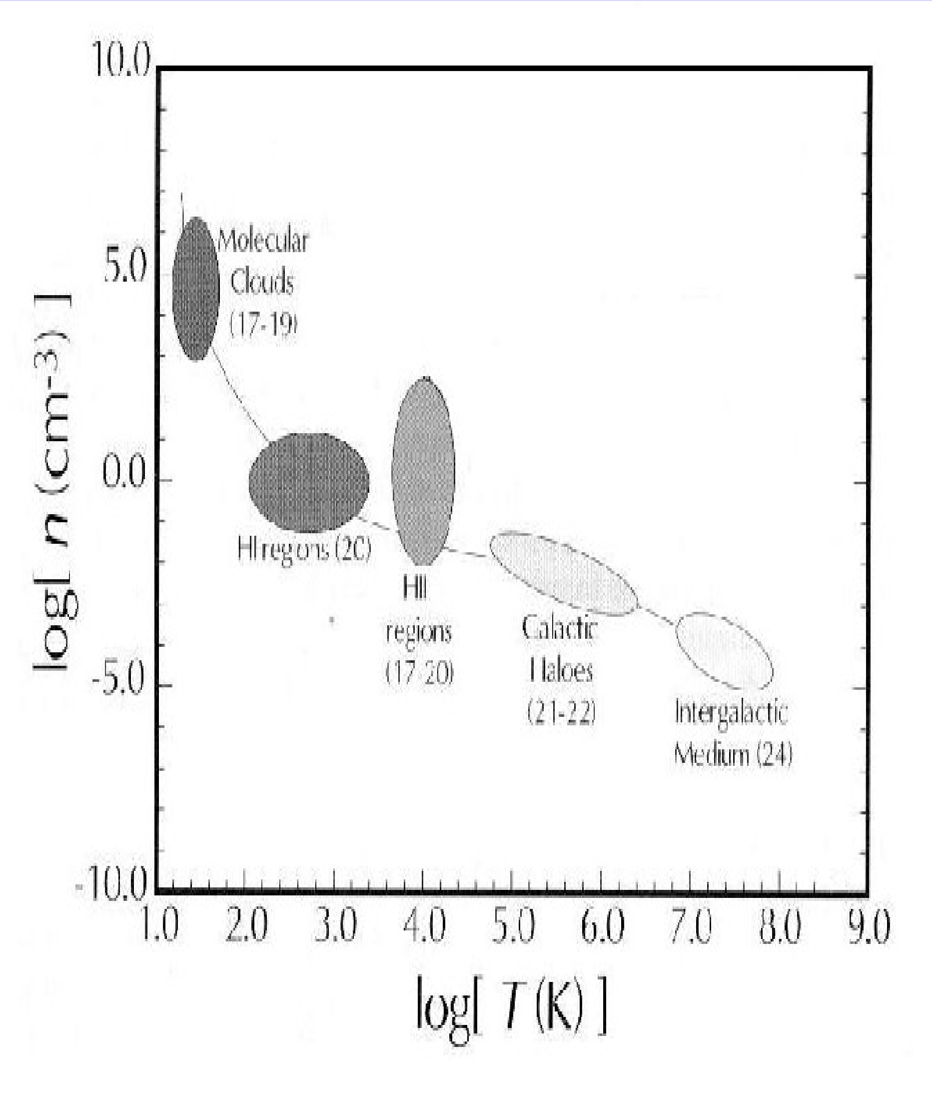
$$E_{gas} \sim 1 \text{ eV} / \text{cm}^3$$

$$U_{ISRF} \sim 1 \text{ eV} / \text{cm}^3$$

$$U_B \sim 1 \text{ eV} / \text{cm}^3$$

$$E_{CR} \sim 1 \text{ eV} / \text{cm}^3$$

The 5 phases of IS-matter



Regions	Density (cm^{-3})	T (K)	ISM Mass Fraction
Molecular clouds	10^3	10 – 30	40-50%
HI cold	1-100	80	40-50%
warm	0.3-1	6000	4-6%
HII warm	0.1 – 1	6000-12000	0.1%
hot	10-2	10^6	

Ionized Hydrogen (HII)

Two phase medium in pressure balance

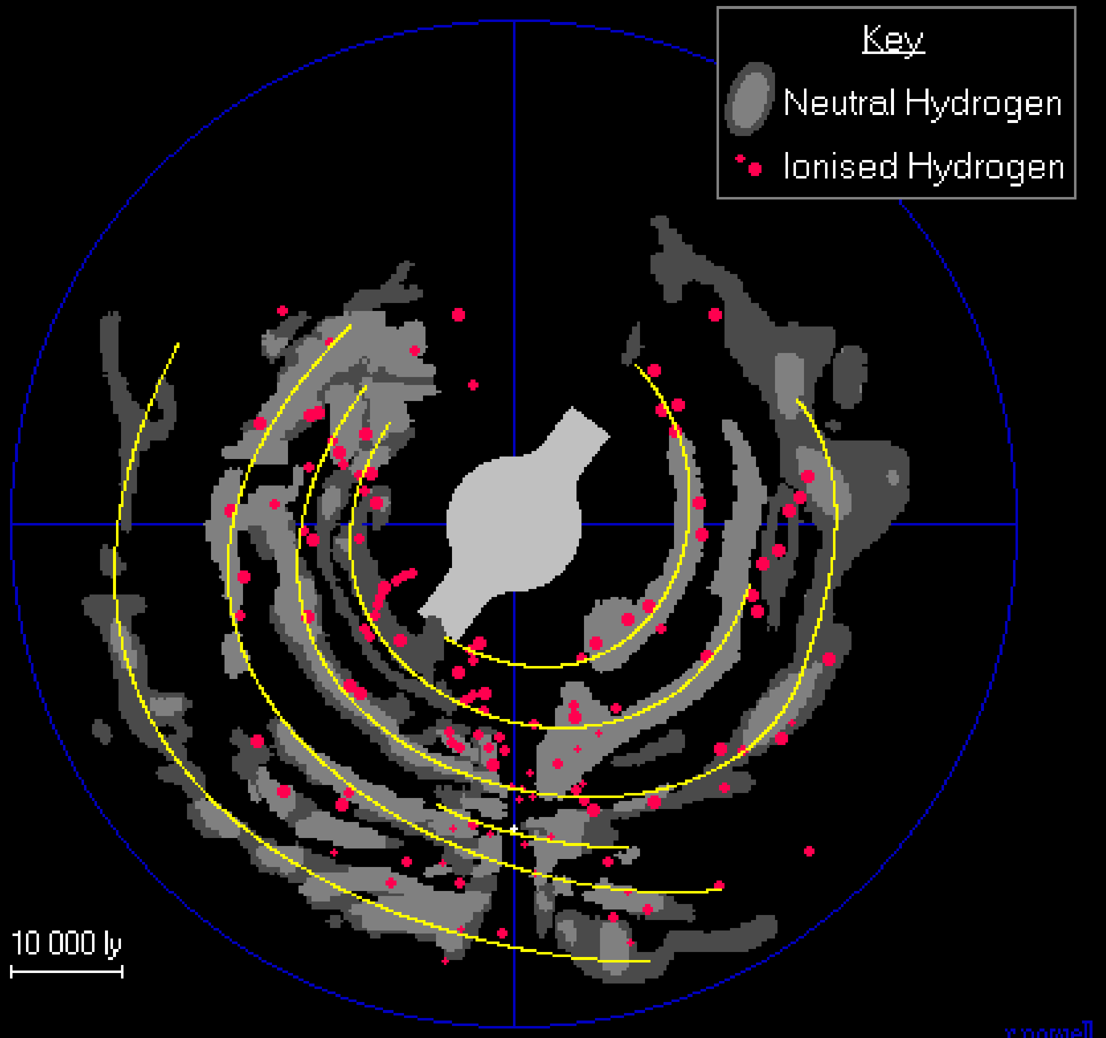
Warm (6000-12000 K)

- Photoionized by hot young stars
- $n = 1\ cm^{-3}$

Hot (10^6 K)

- $n = 10^{-2}\ cm^{-3}$
- Buoyancy
- Local bubble

Neutral Hydrogen (HI)



Two phase medium in pressure balance

Cold (100 K)

Mass

Dense sheet

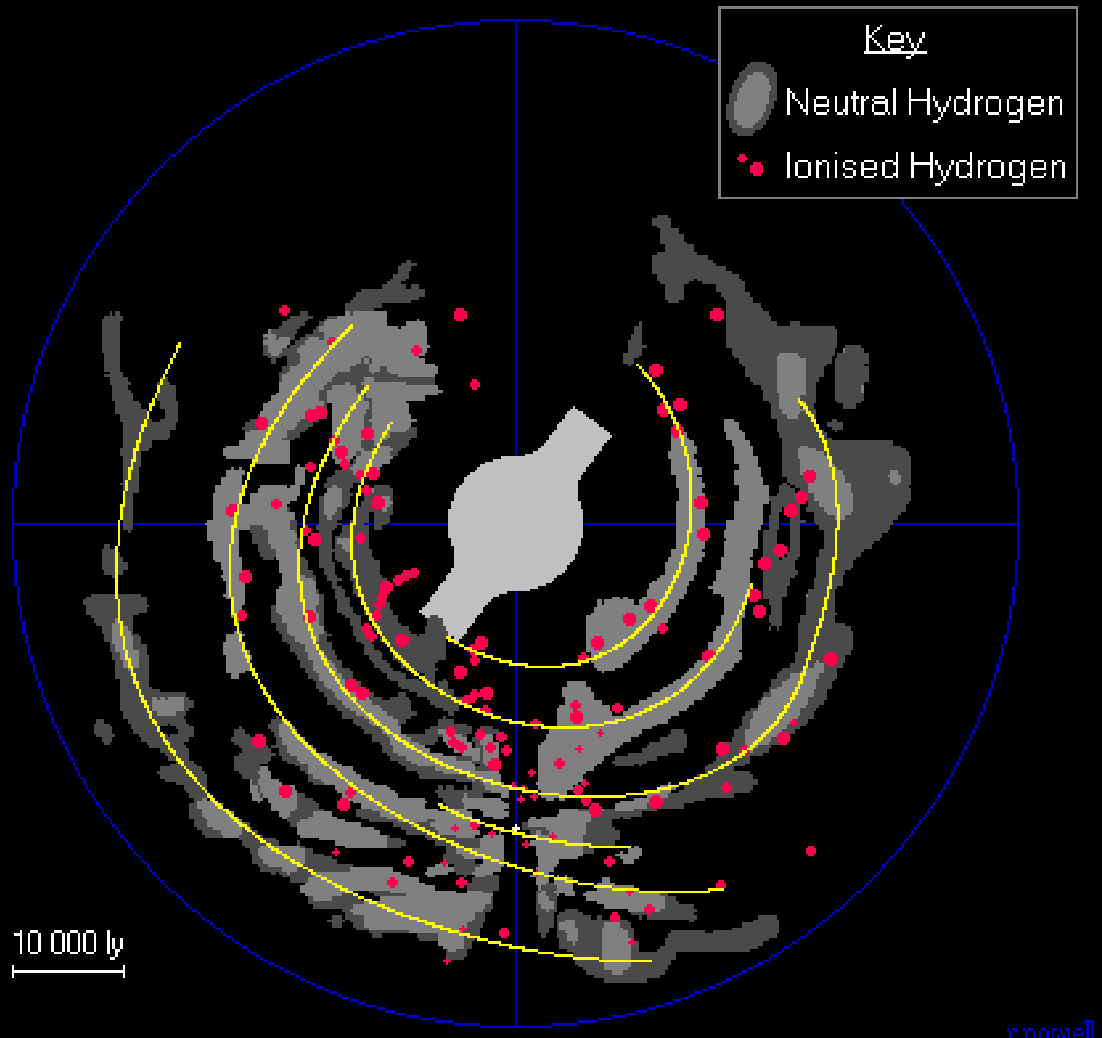
No grav. Bound

$n = 20–60\ cm^{-3}$

Warm (6000 K)

30–60 % volume

Neutral Hydrogen (HI)



Ground level of neutral hydrogen ($1^2S_{1/2}$) is split into two sublevels

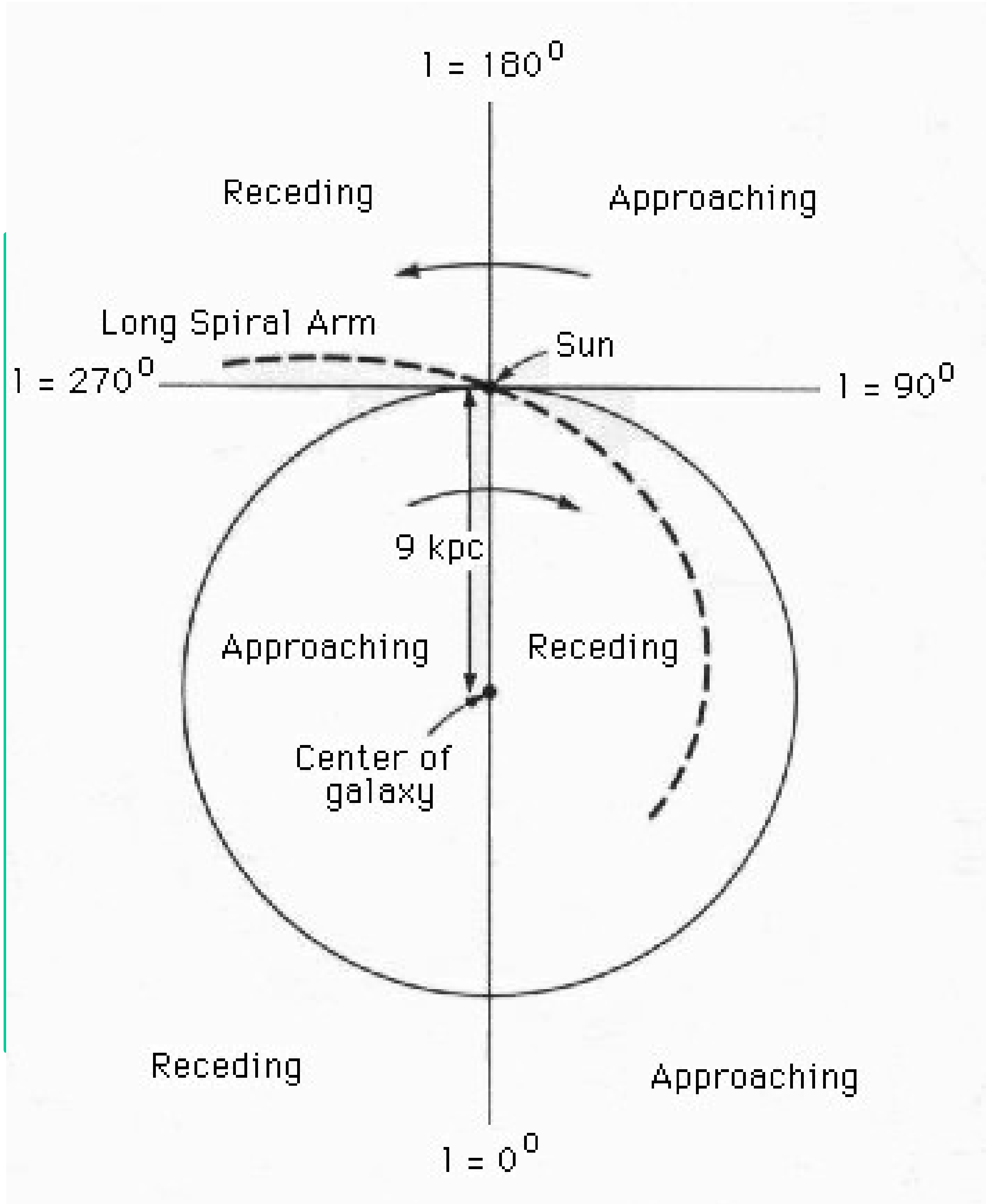
F = J + I = 0,1

Tiny energy separation ($t = 1.1\ 10^7$ years)

Radio emission at 1420.4 MHz or 21 cm

Spin temperature T_S

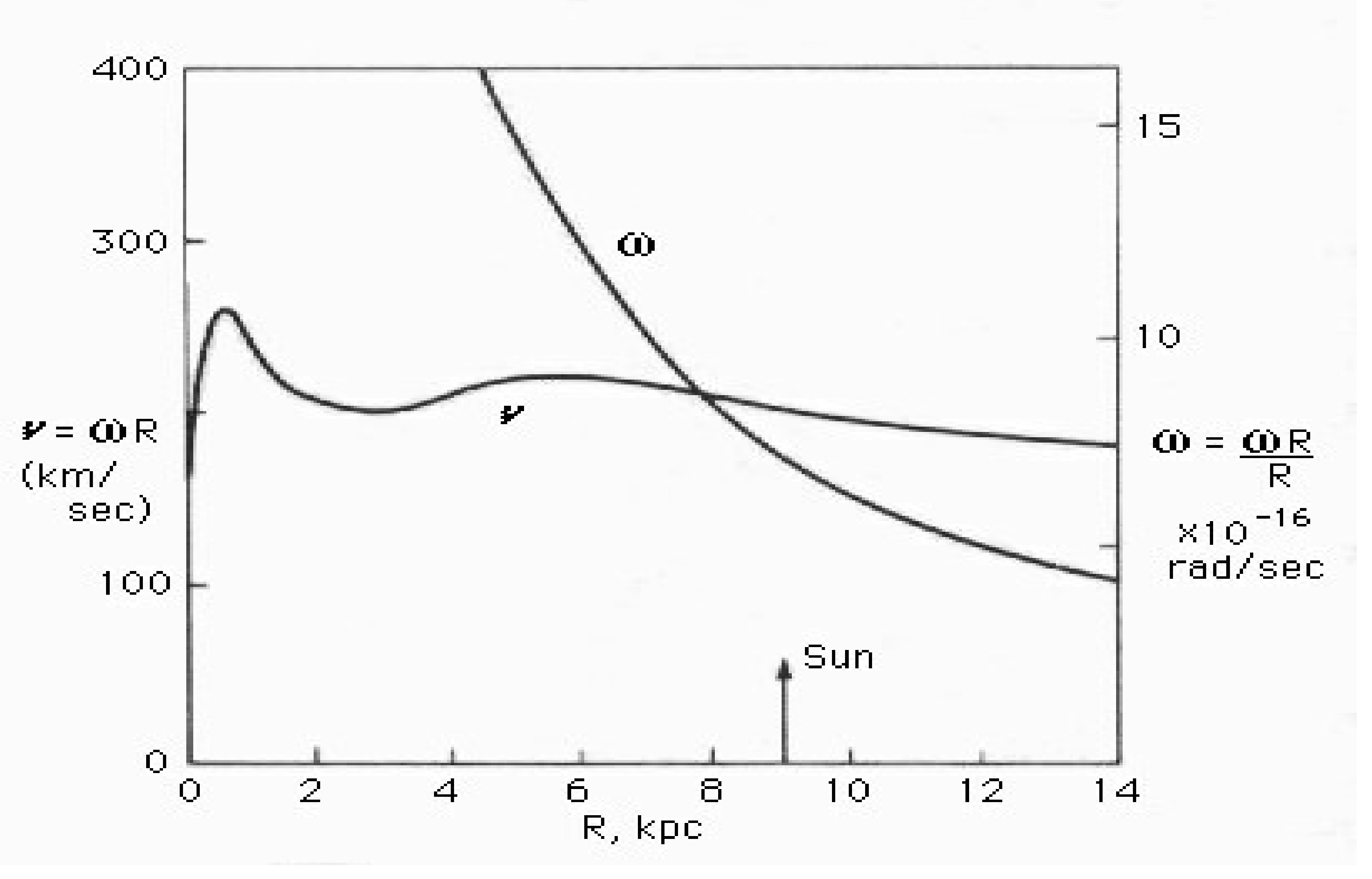
Radio Data deprojection



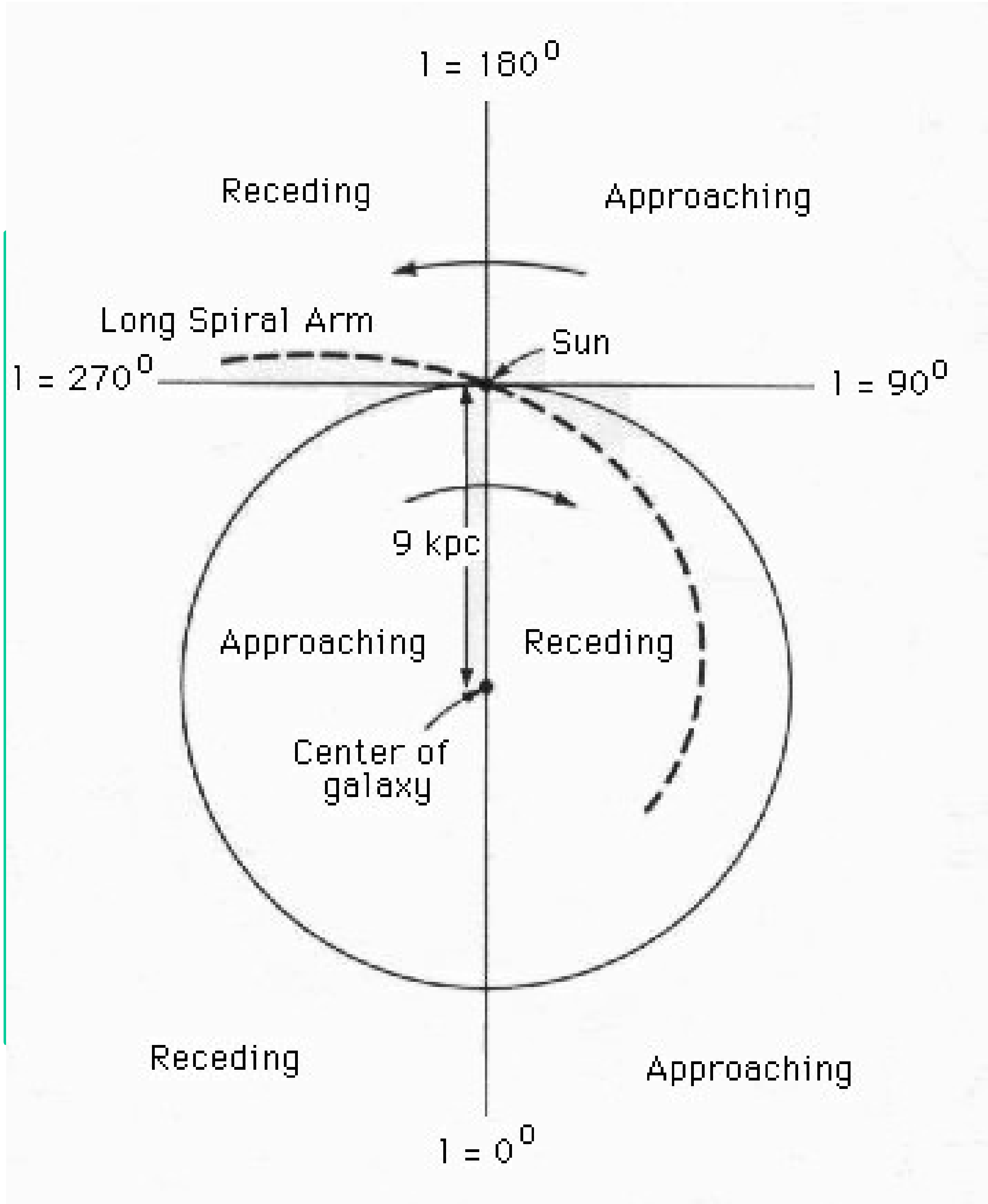
Radio Data deprojection

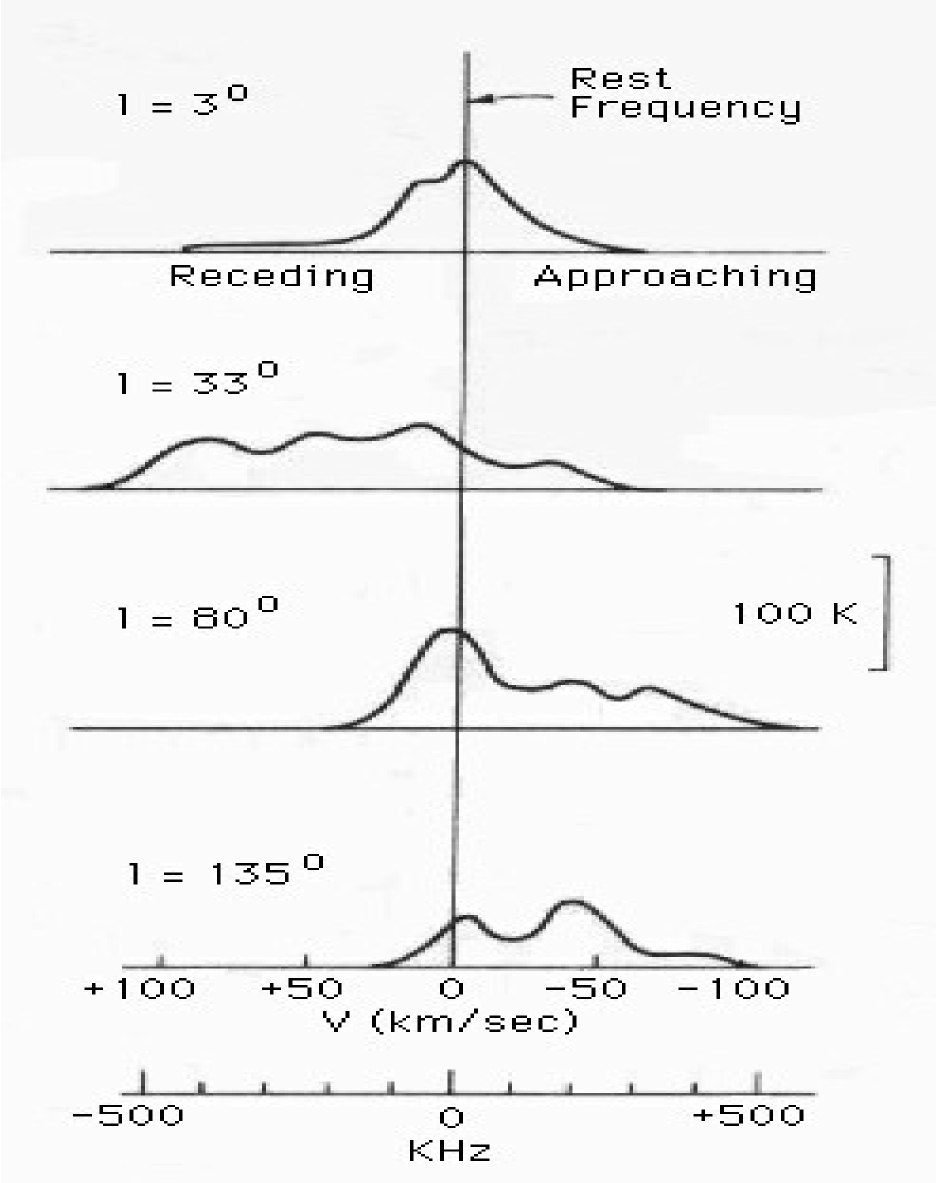
Galactic rotation curve

Clemens 1985

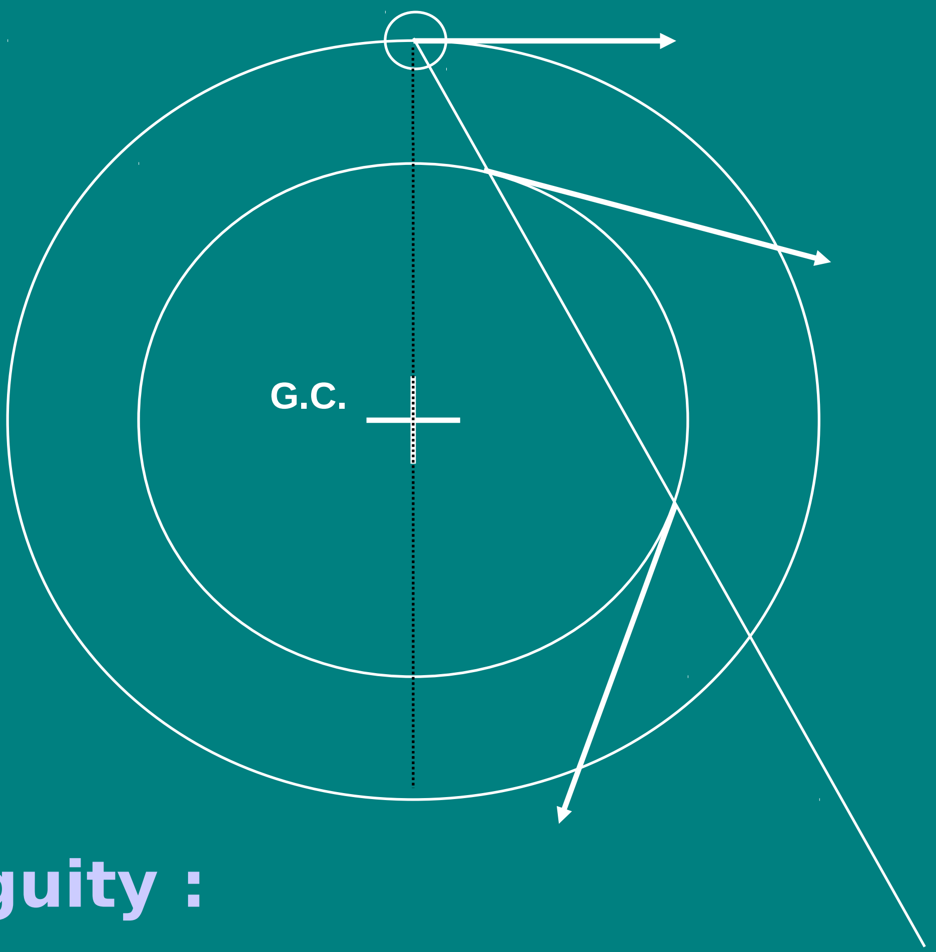


Radio Data deprojection





Near-Far distance ambiguity:



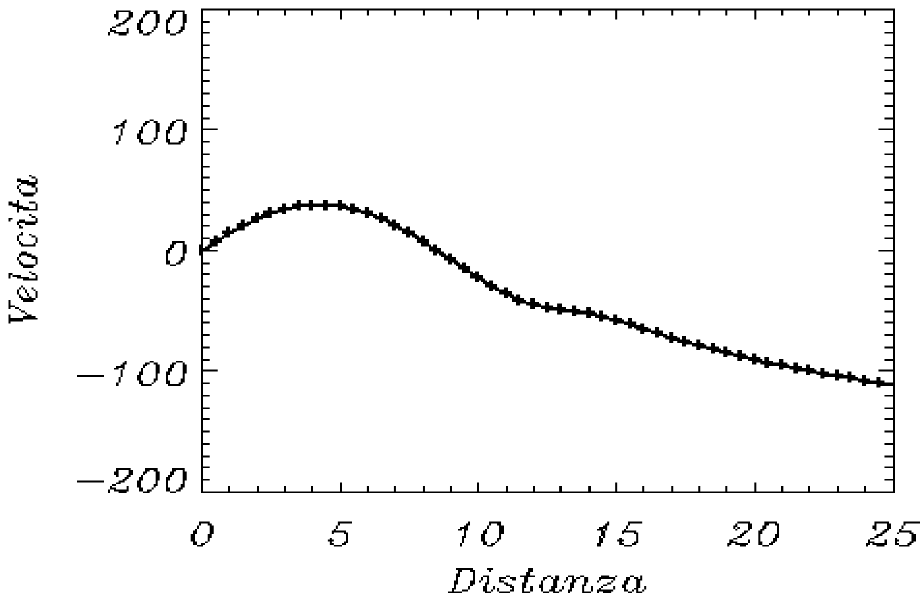
Dinamical ambiguity :

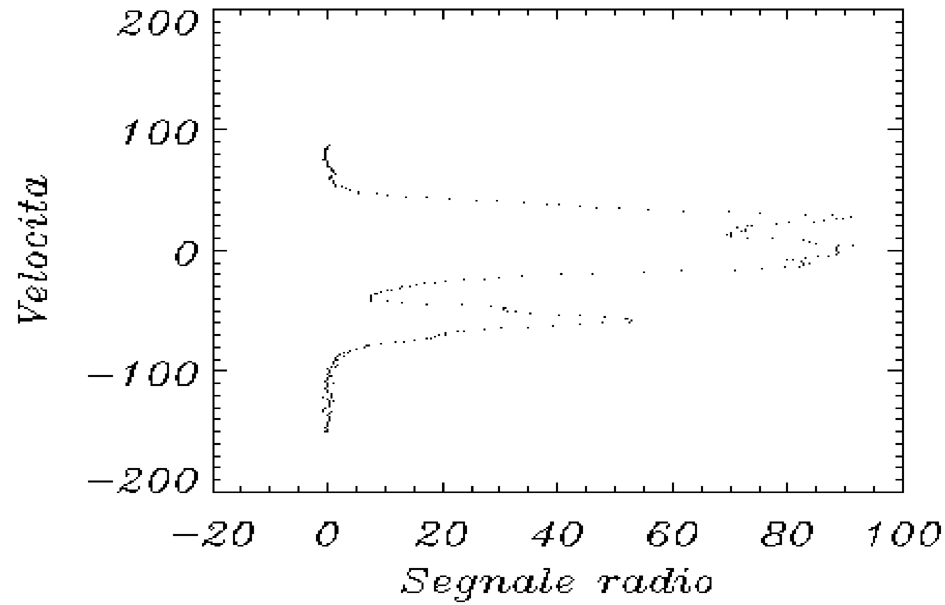
$$w.f. \propto e^{-\frac{1}{2}\frac{z}{Z_{gas}}}$$

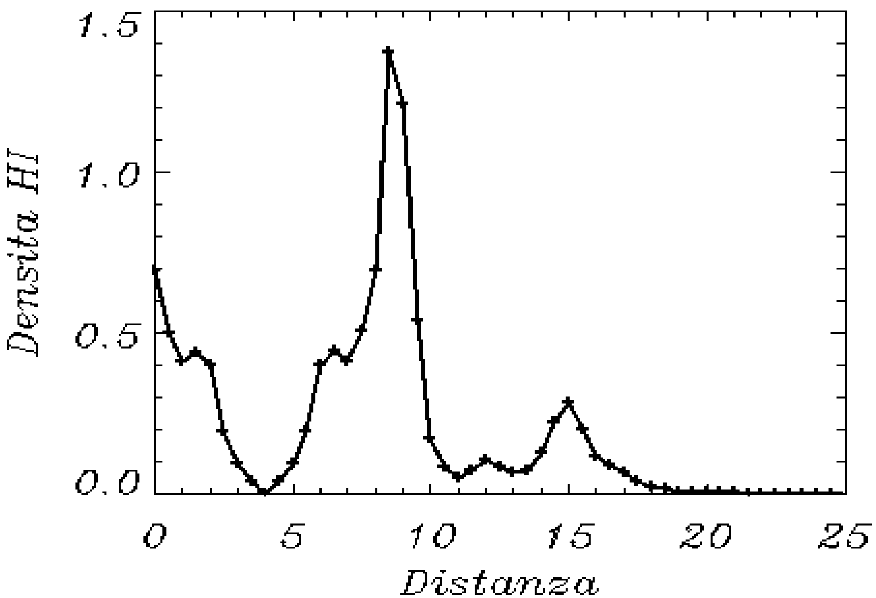
$Z_{gas} = 100\ pc$ for HI

$Z_{gas} = 60\ pc$ for H_2

Radio Data deprojection







Lat. 0.00000

Long. 60.0000

Neutral Hydrogen Survey

Leiden-Dwingeloo survey at 21 cm

(Hartmann et al 1997)

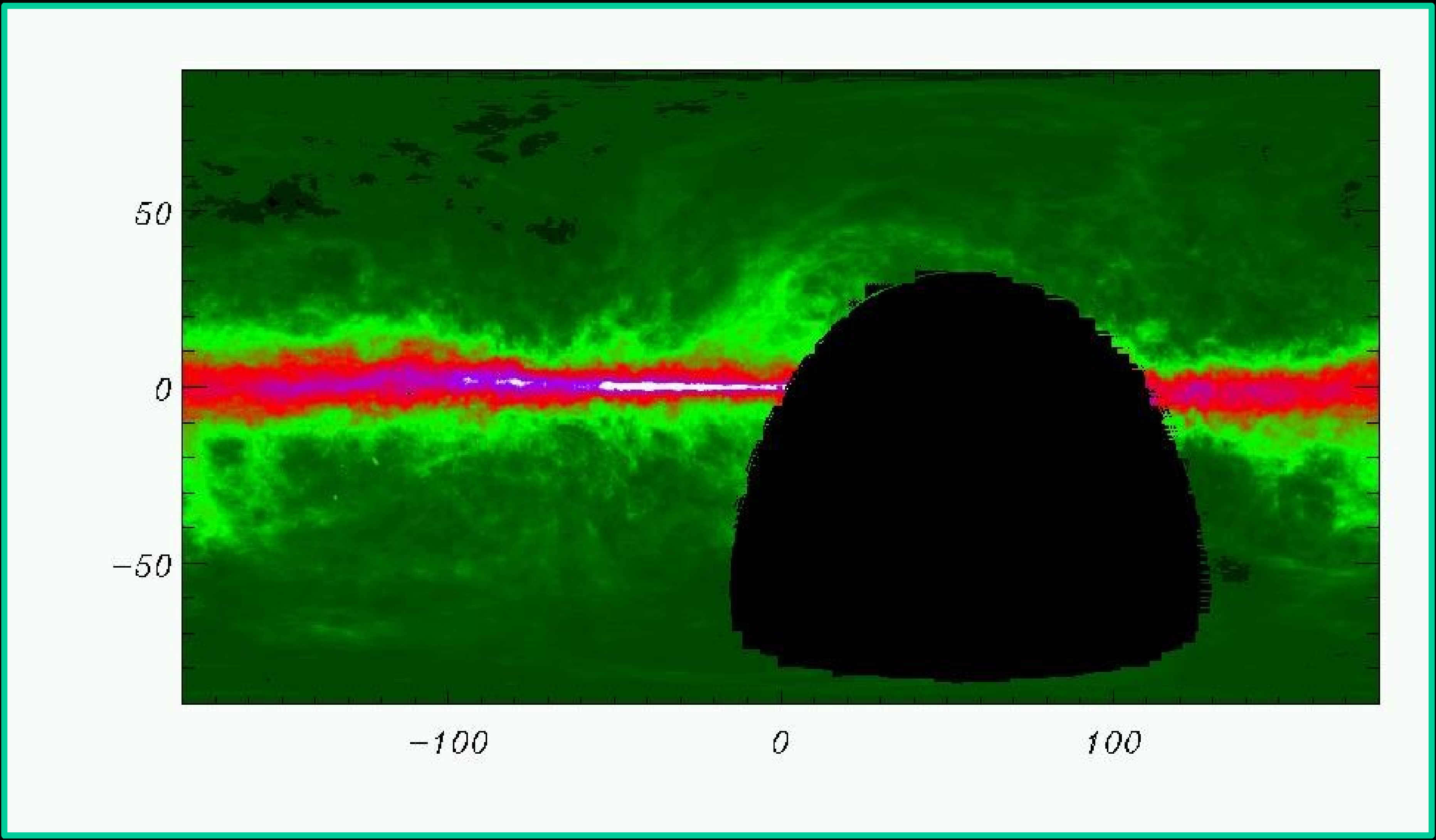
Spatial resolution: 30’

Velocity resolution: 1.03 km/s

Velocity range: -450,400 km/s

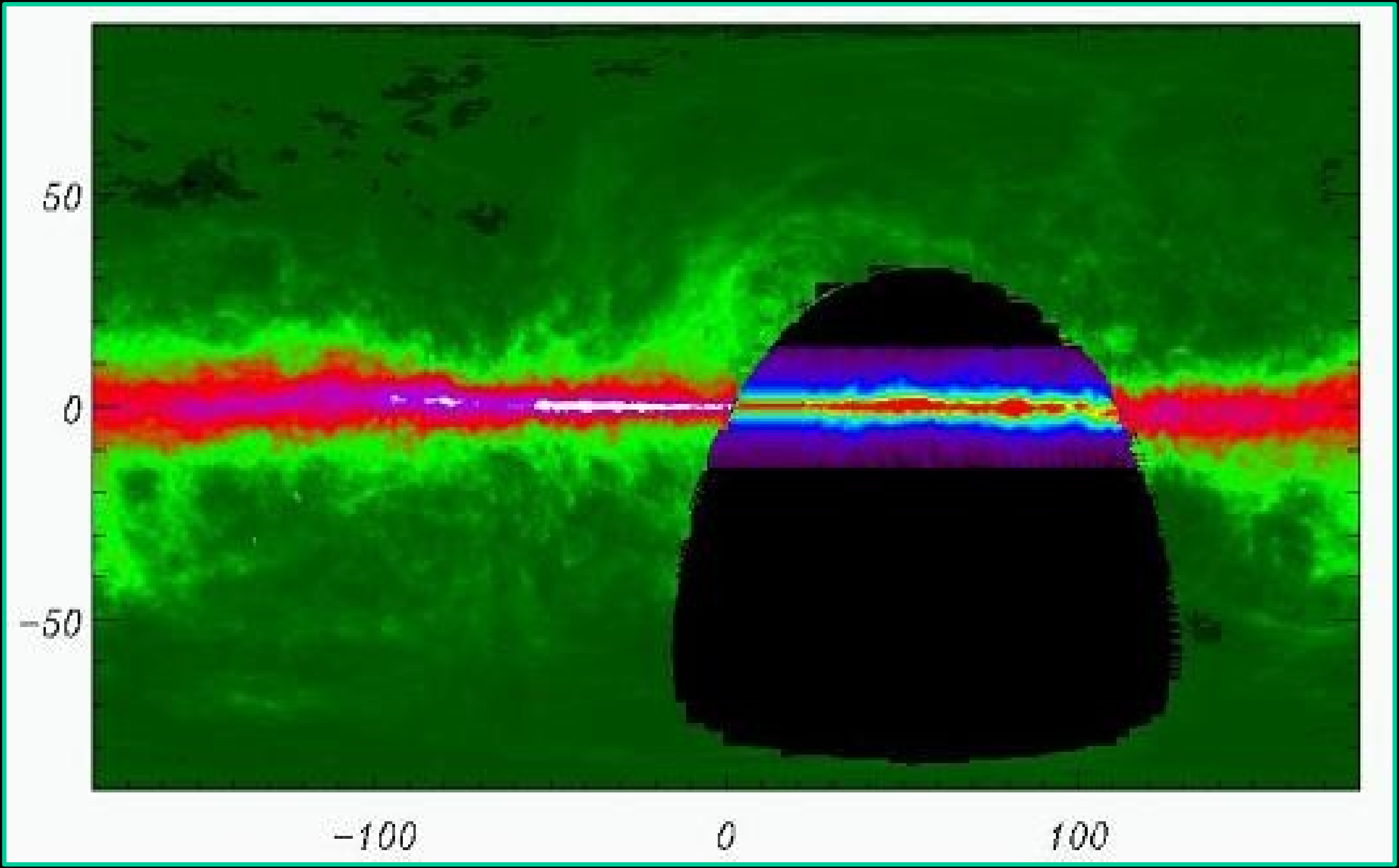
Sensitivity: 0.07° K

Neutral Hydrogen



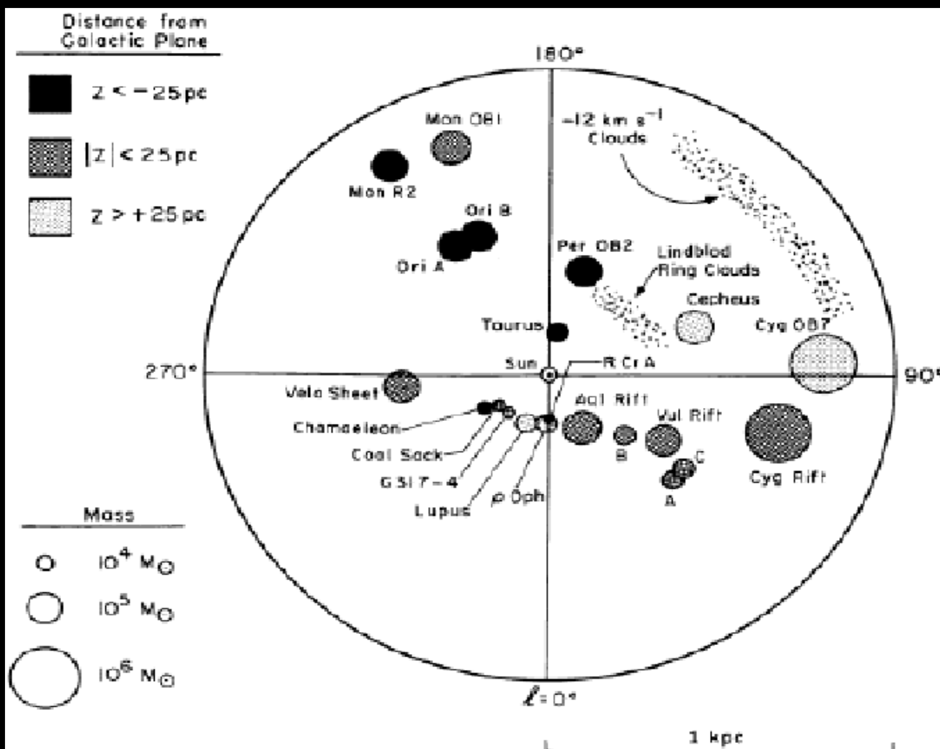
Leiden-Dwingeloo survey at 21 cm (Hartmann et al 1997)

Neutral Hydrogen



Leiden-Dwingeloo survey + Parkes (Kerr et al 1986)

The molecular clouds



Concentrated in *Giant Clouds* (10^4 10^8 Msol) self graviting

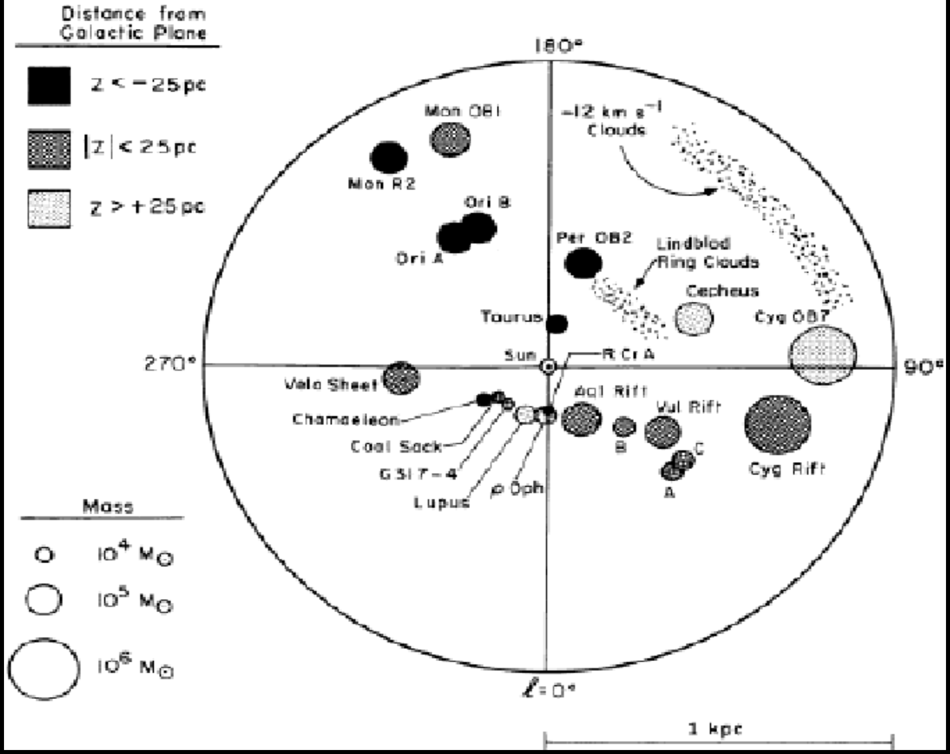
with n > 10^3 cm^{-3}

Optically thick (dust, H_2)

Along spirala arms

Small scale thickness (120 pc)

The molecular clouds



H_2 is homopolar → No vibrational or rotational emission

CO is the abundant molecule after H_2

CO emits strong line radiation at 2.6 mm (J 1→0)

CO tracer of H_2

n_{H2} proportional to L_{CO}

CO Survey

(Dame et al. 2001)

CO observation

J 1→0 115 GHz

31 survey combined

Spatial resolution: 12’ or more
Velocity resolution: 0.65 km/s

Sensitivity: 0.62° K

$X = n_{HI}/n_{CO} = 1.8\ 10^{20}\ cm^{-2}\ K^{-1}\ km^{-1}\ s$

CO Survey →Molecular Clouds

Hydrogen distribution

HI density :

$$n_{HI} = -\frac{1.83}{\Delta r} \int_{\Delta v} T_S \ln\left[1 - \frac{T_b(v)}{T_S}\right] dv \qquad atom\ cm^{-3} \qquad T_S = 125\ K$$

Molecular Clouds density :

$$n_{H_2} = \frac{2X}{\Delta r} \int_{\Delta v} T_b(v)\, dv \qquad atom\ cm^{-3} \qquad X = 1.8\ 10^{20}\ H_2\, cm^{-2}\, (K\ km\ s^{-1})^{-1}$$

DUST

Cold Dust (15-25 K) associated to the HI regions and molecular clouds. Heated by both old and young stellar population

Warm dust (30-40 K) associated to HII regions. Heated by OB stars

Hot dust (250-500 K)

very small grains (5 A) heated by ISRF

normal grains (1 micron) heated by M giants

Interstellar Radiation Field

Cosmic Background Radiation

Model of the Interstellar Radiation Field

Far Infrared (dust)

Near Infrared (late stars)

Optical/UV (OB stars)

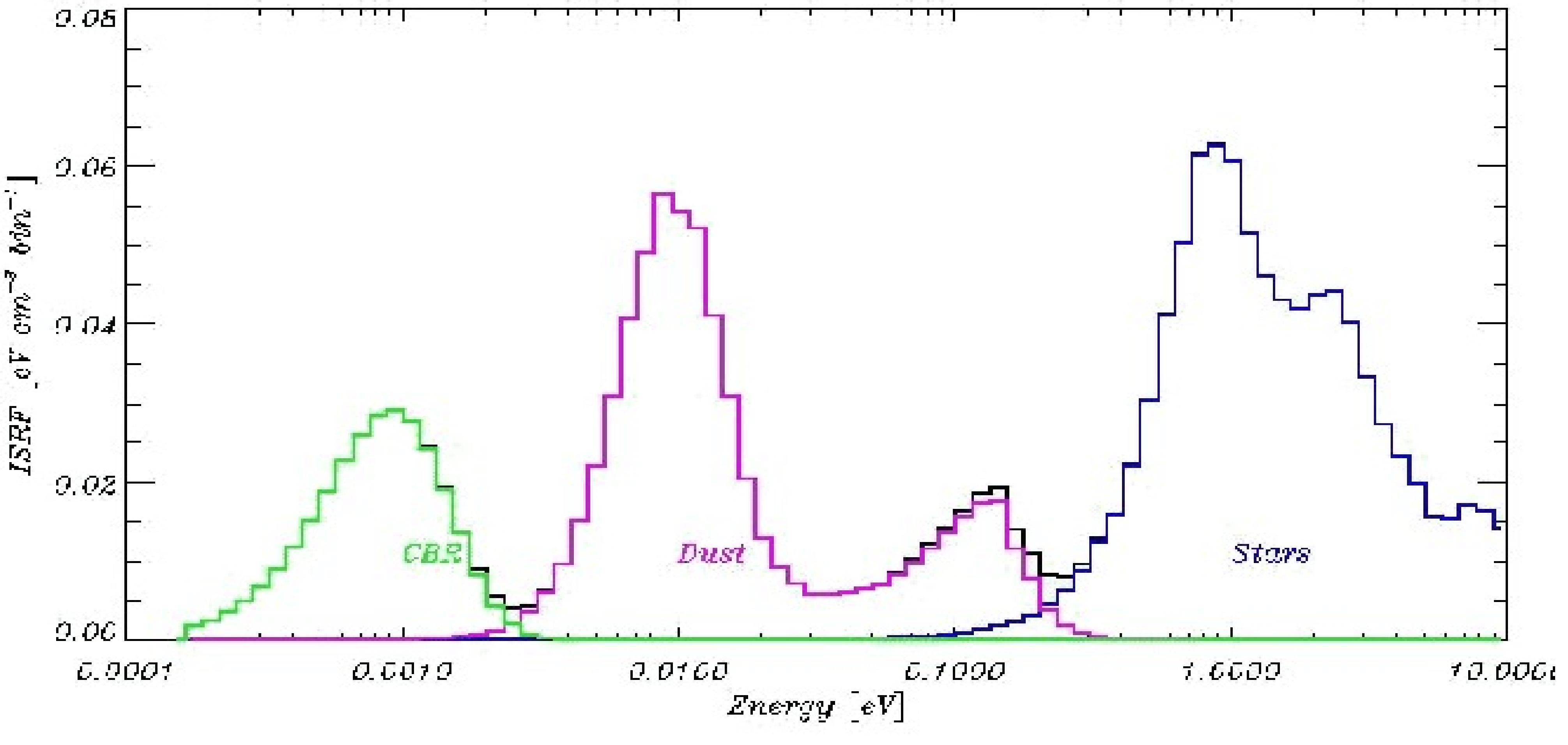
$$ISRF(\vec{r},\nu) = \int_{MW} \frac{\varepsilon(\vec{r}',\nu)}{|\vec{r}-\vec{r}'|^2} e^{-\int k(\vec{r}',\nu)\,ds}\, dV'$$

ISRF model :

$\boldsymbol{\varepsilon}$ from COBE/DIRBE emissivities + detailed stellar model

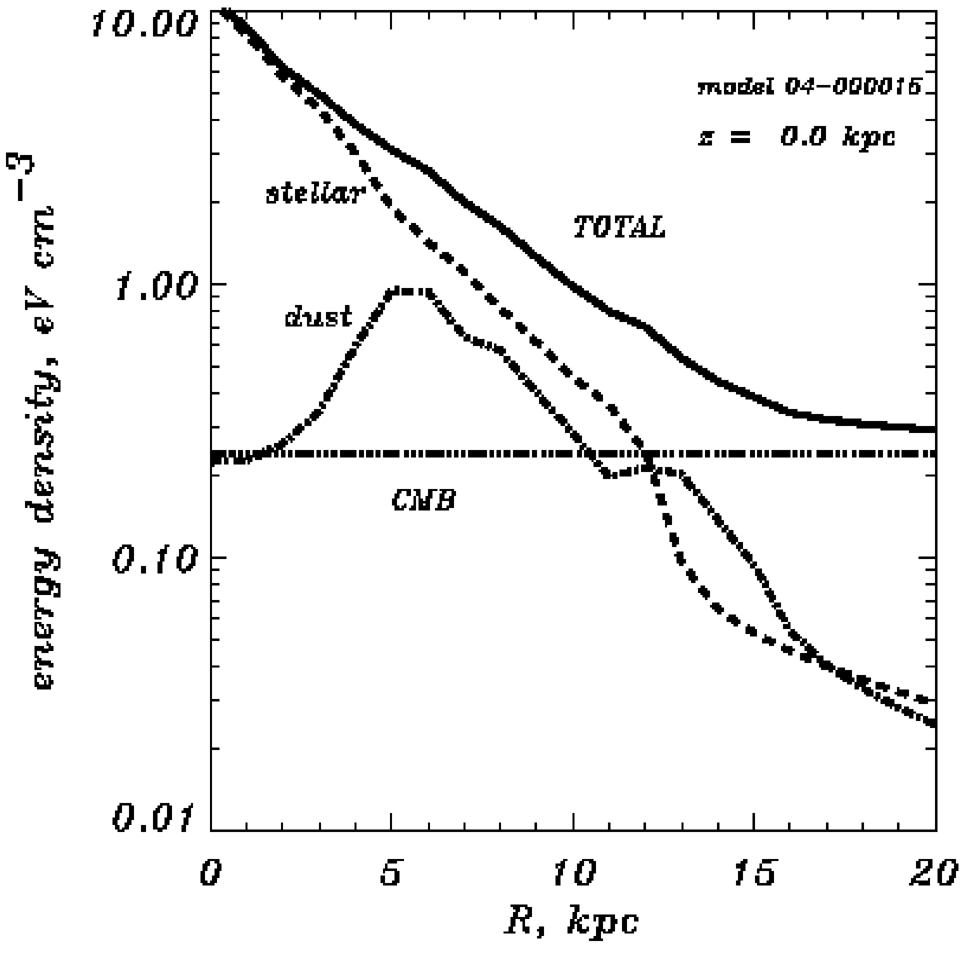
k from extinction curves, grain albedo

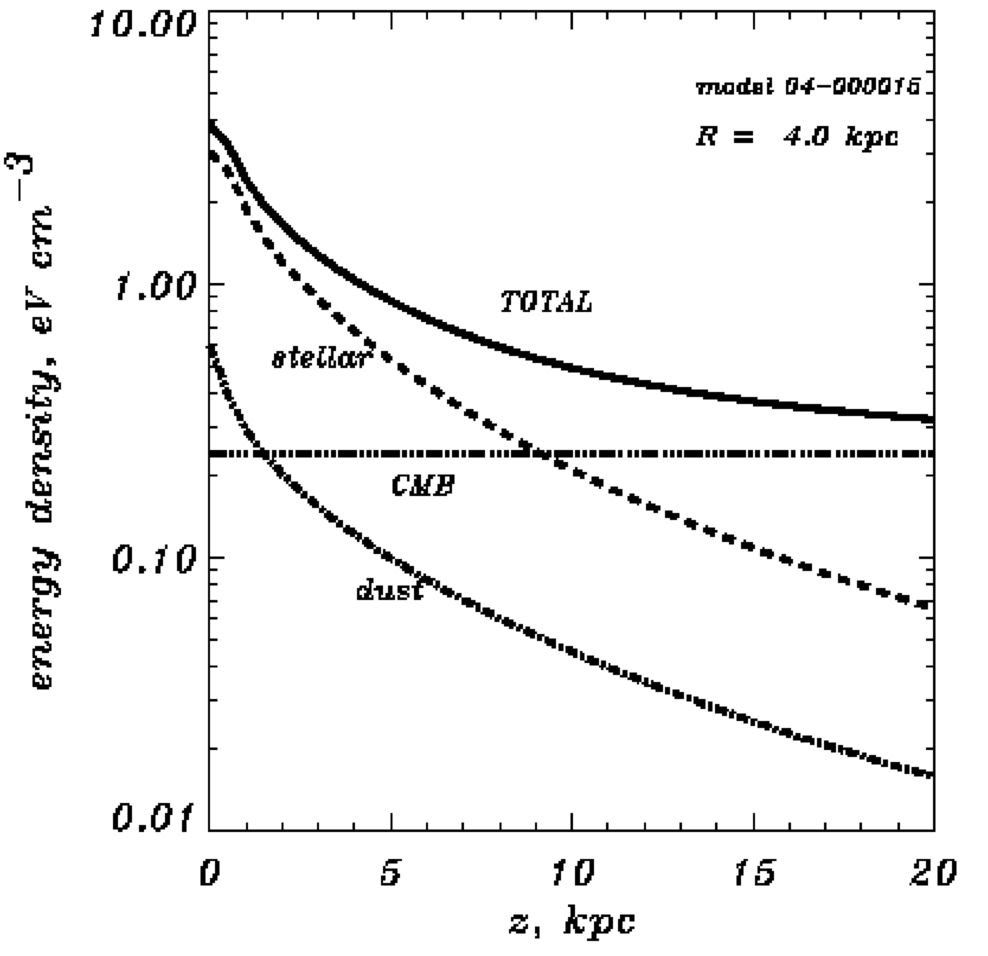
The Interstellar Radiation Field



Strong, Moskalenko, & Reimer (2000)

The Interstellar Radiation Field





Strong, Moskalenko, & Reimer (2000)

The magnetic field

Ordered, large-scale magnetic field
(2 - 6 microGauss)

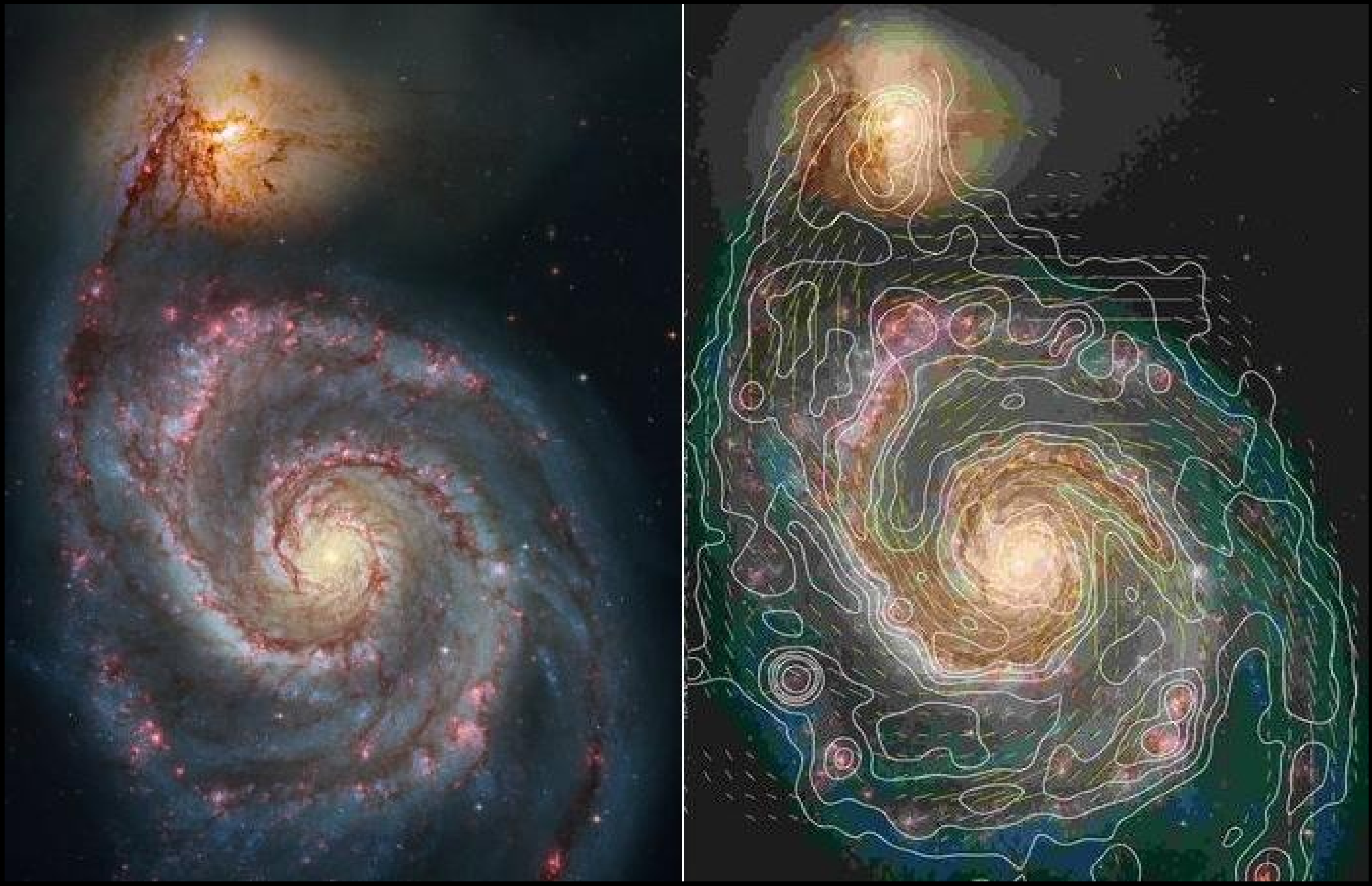
Explored with:

Starlight polarization

Faraday Rotation

Zeeman splitting

The magnetic field



The magnetic field