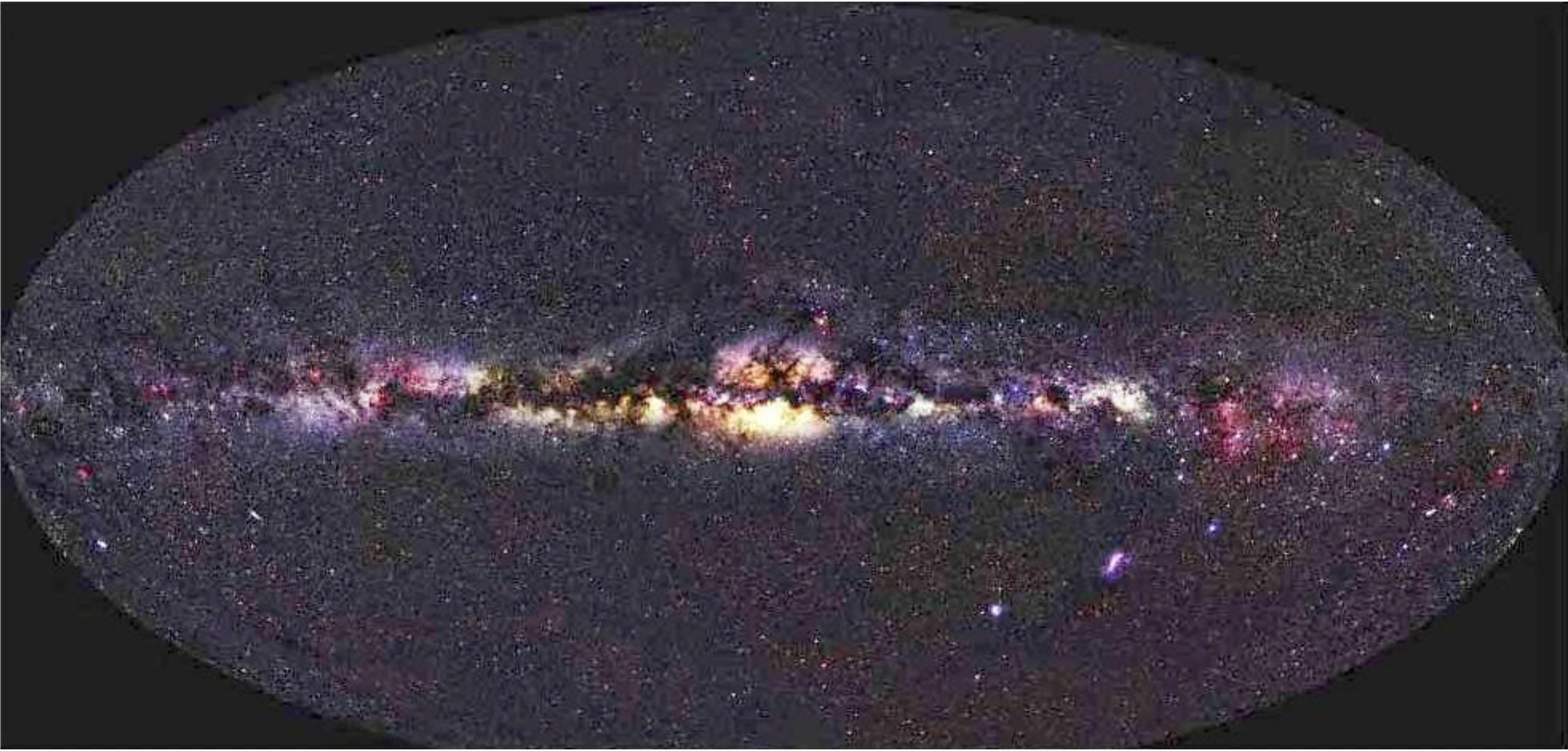
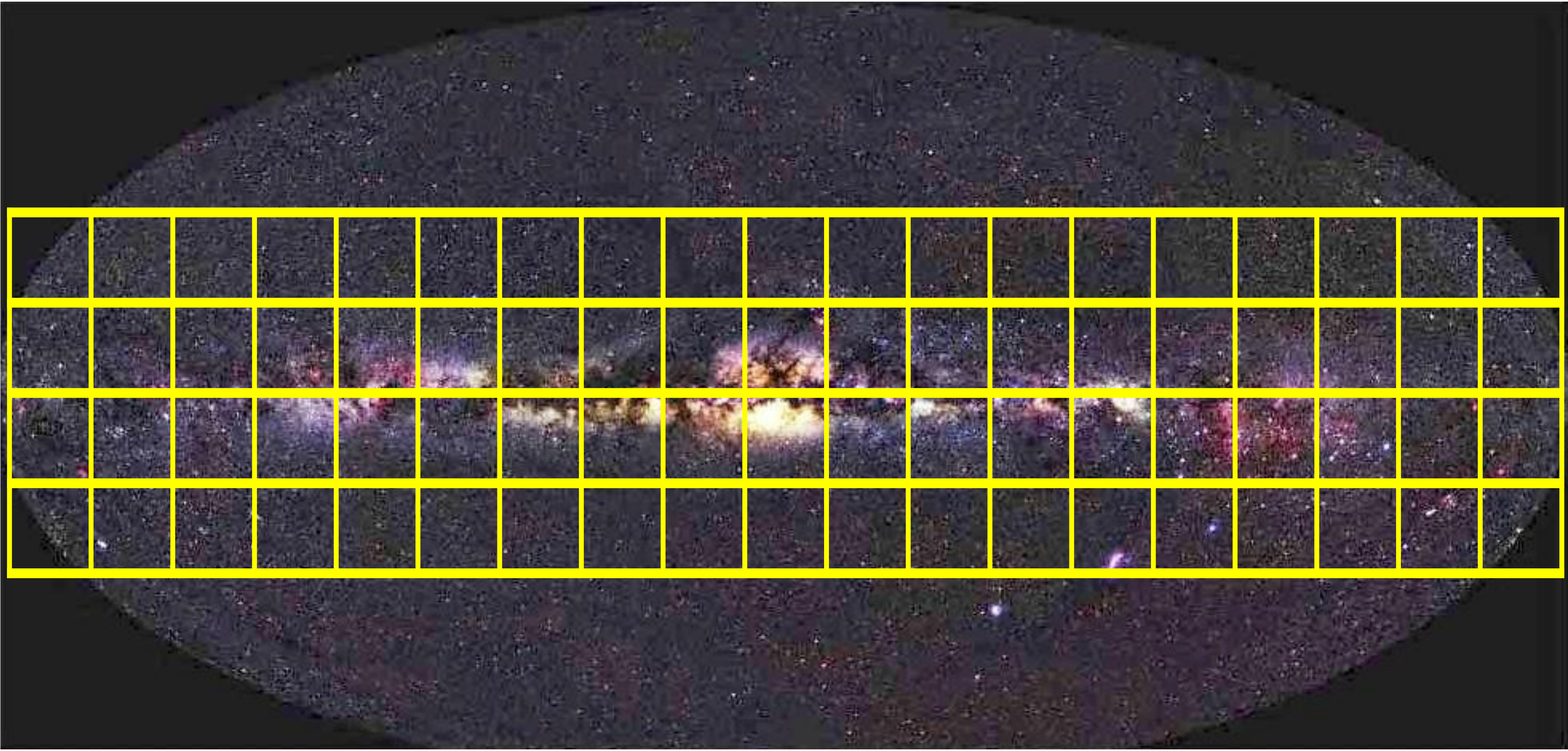
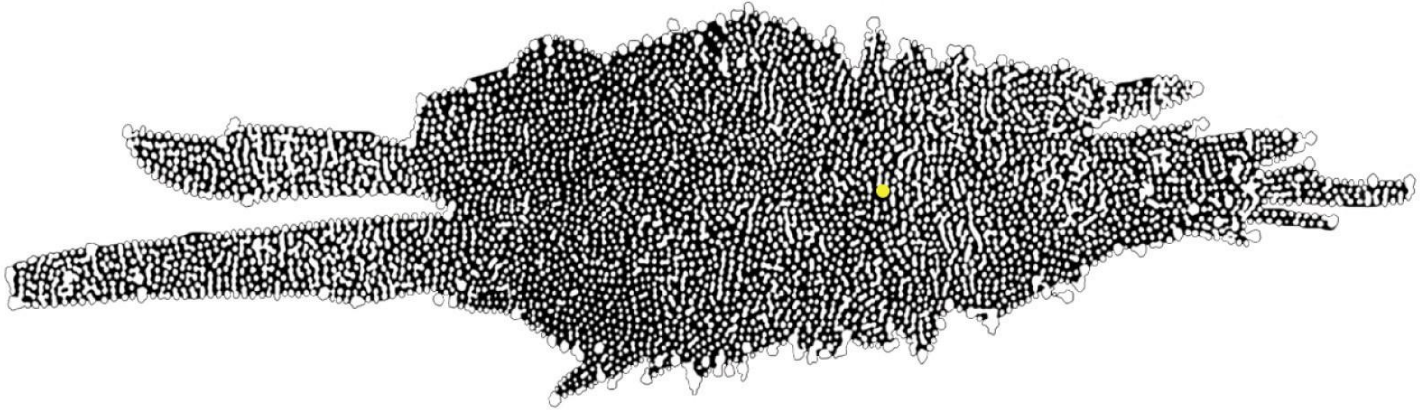
ASTR368

The Milky Way



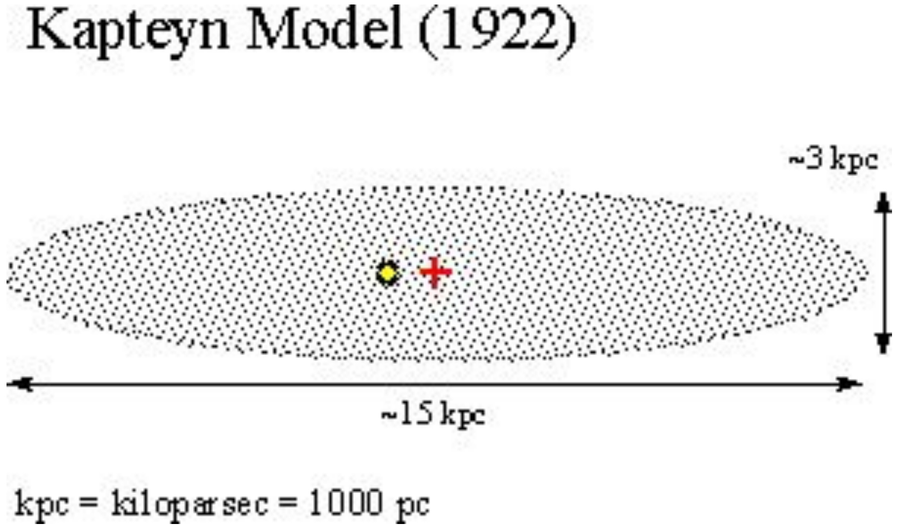




Herschel (1738-1822) found that the Milky Way was shaped something like an amoeba/frisbee 5,000 pc across with the Sun nearly in the center.

Did correctly figure out that it was a disk!

Kapteyn Universe

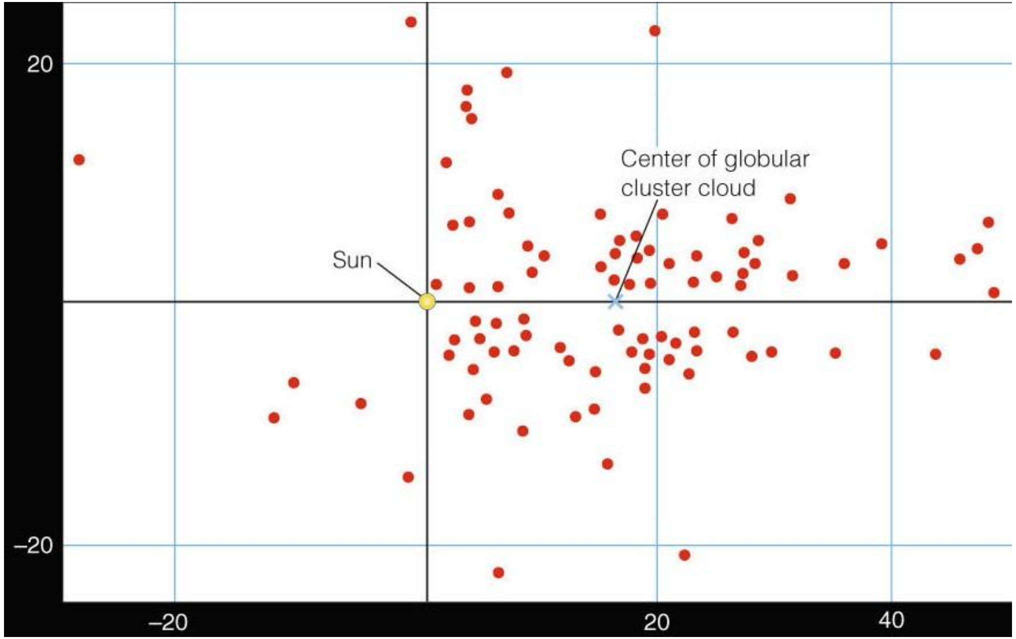


- Galaxy ~15kpc in diameter
- Sun 650pc from center
- Density decreases from center

Why doesn’t this method work???

Hint:

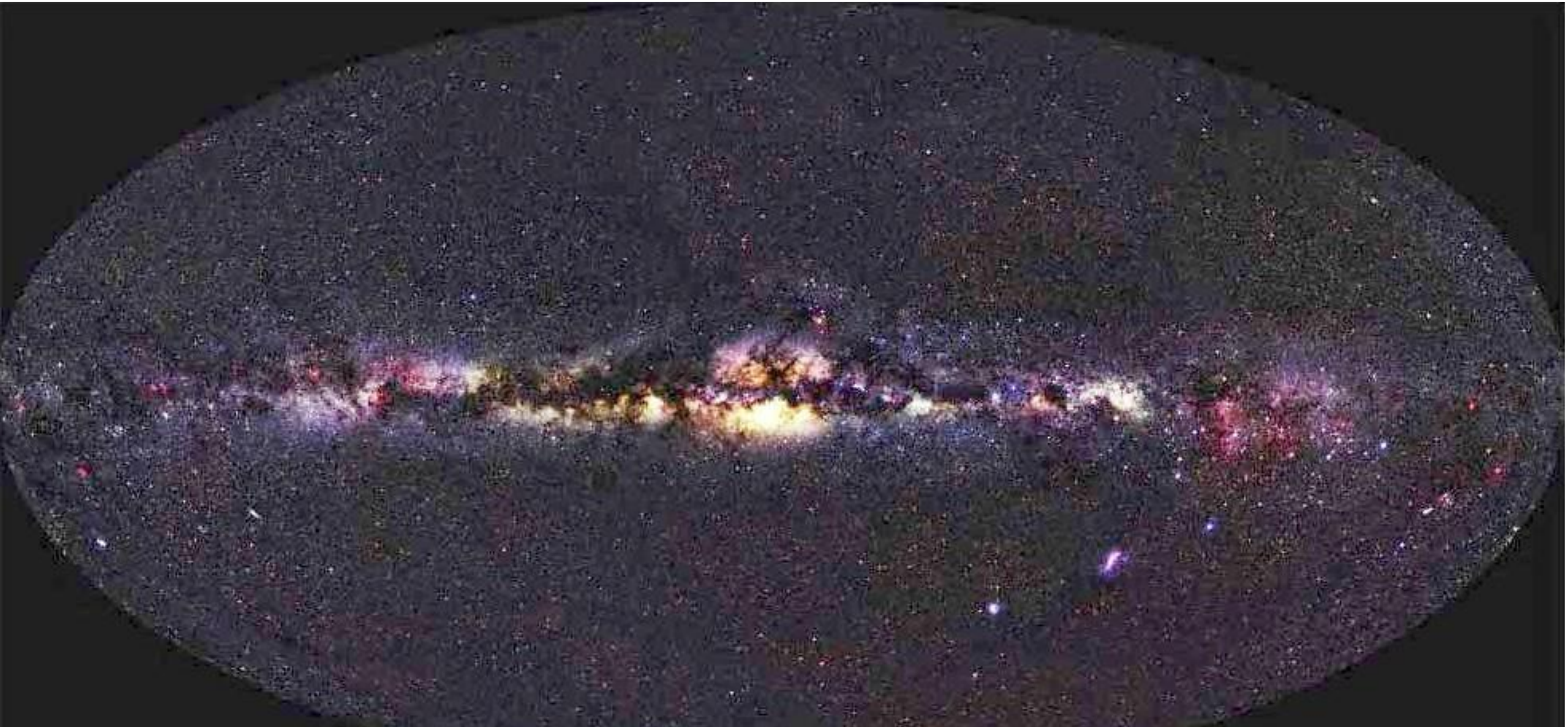
Shapley's Milky Way



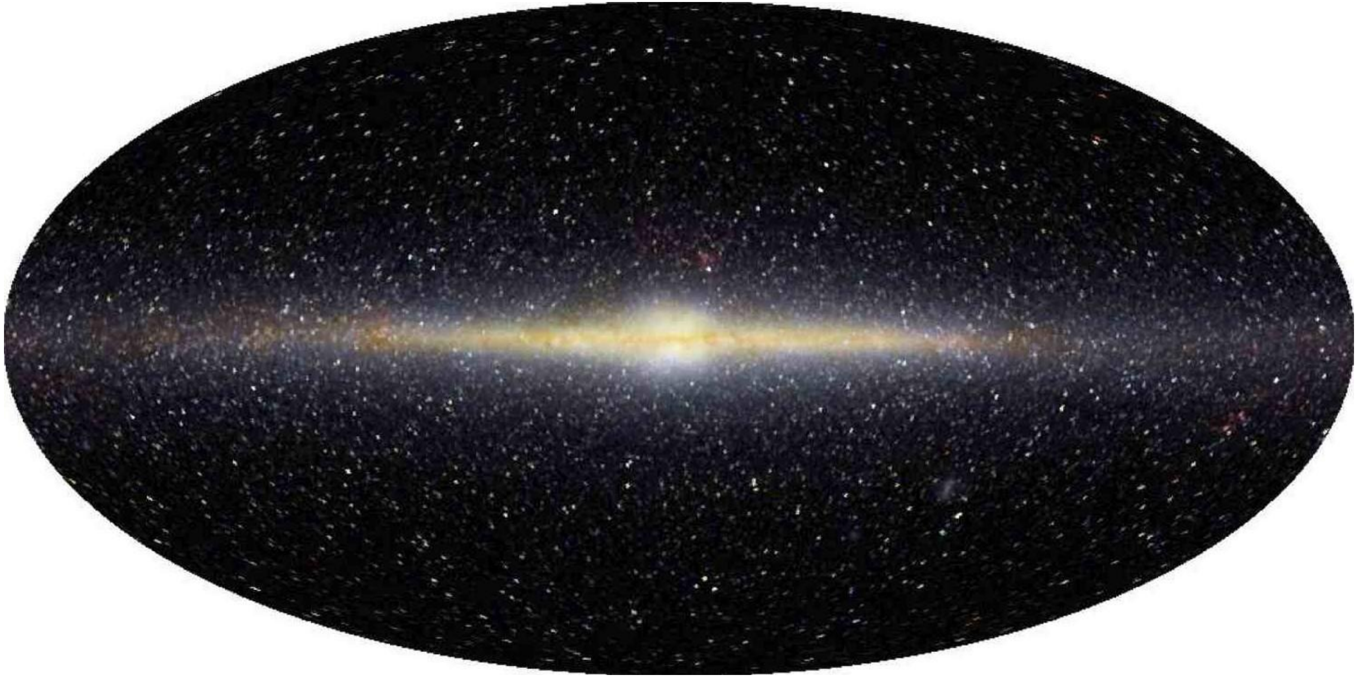
kpc

kpc

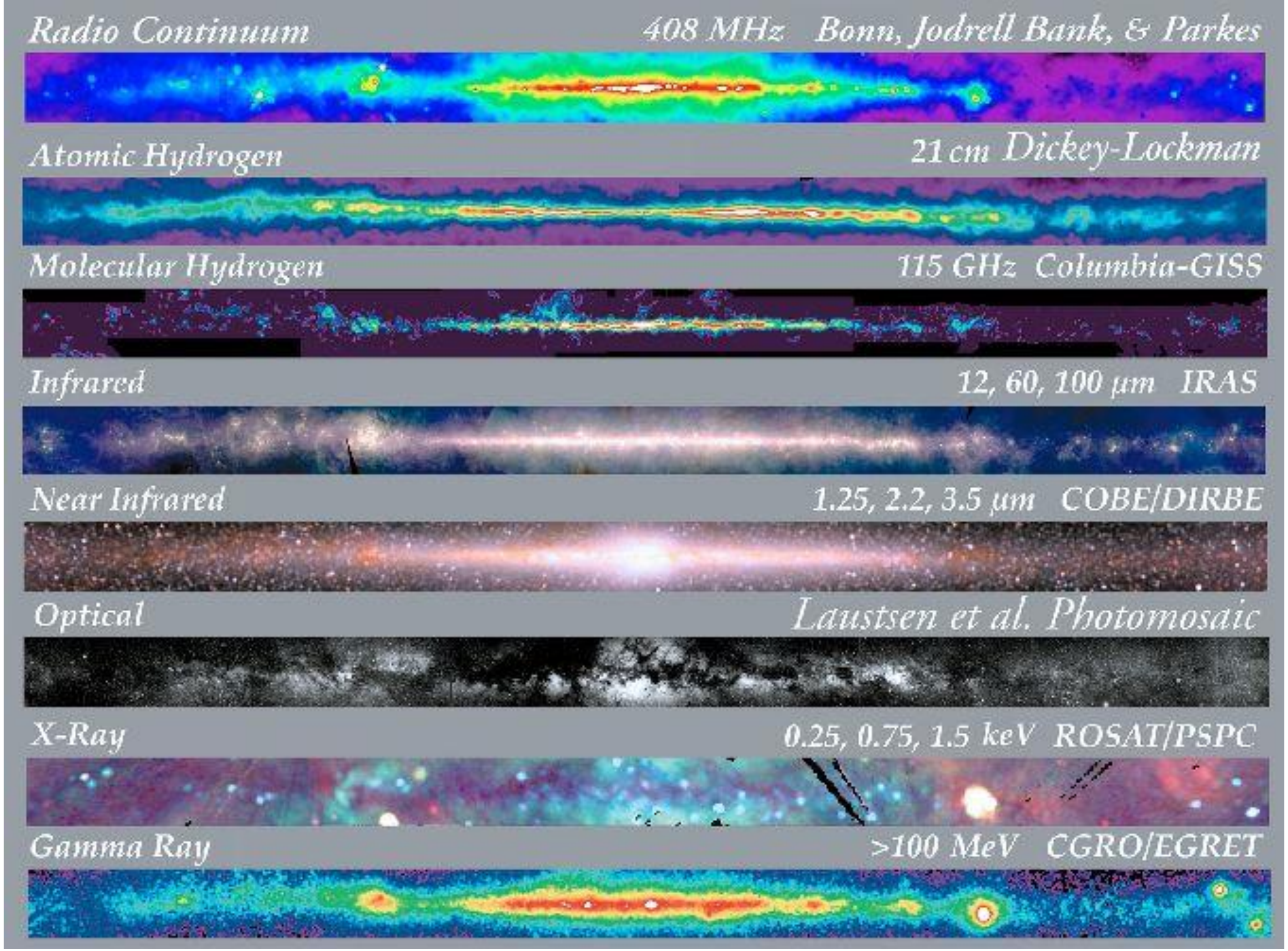
The Milky Way in Visible Light



The Milky Way in Infrared Light



There is less absorption by dust in the infrared.


Radio Continuum
408 MHz Bonn, Jodrell Bank, & Parkes
Atomic Hydrogen
21 cm Dickey-Lockman
Molecular Hydrogen
115 GHz Columbia-GISS
Infrared
12, 60, 100 μm IRAS
Near Infrared
1.25, 2.2, 3.5 μm COBE/DIRBE
Optical
Laustsen et al. Photomosaic
X-Ray
0.25, 0.75, 1.5 keV ROSAT/PSPC
Gamma Ray
>100 MeV CGRO/EGRET

Disks			
	Neutral Gas	Thin Disk	Thick Disk
M (10^{10} $M_\odot$)	0.5^a	6	0.2 to 0.4
L_B (10^{10} $L_\odot$)^b	—	1.8	0.02
M/L_B ($M_\odot/L_\odot$)	—	3	—
Radius (kpc)	25	25	25
Form	e^{-z/h_z}	e^{-z/h_z}	e^{-z/h_z}
Scale height (kpc)	< 0.1	0.35	1
σ_w (km s^{-1})	5	16	35
[Fe/H]	$> +0.1$	-0.5 to $+0.3$	-2.2 to -0.5
Age (Gyr)	$\lesssim 10$	8^c	10^d

Spheroids			
	Central Bulge^e	Stellar Halo	Dark-Matter Halo
M (10^{10} $M_\odot$)	1	0.3	190^{+360}_{-170} ^{f}
L_B (10^{10} $L_\odot$)^b	0.3	0.1	0
M/L_B ($M_\odot/L_\odot$)	3	~ 1	—
Radius (kpc)	4	> 100	> 230
Form	boxy with bar	$r^{-3.5}$	$(r/a)^{-1}\,(1 + r/a)^{-2}$
Scale height (kpc)	0.1 to 0.5^g	3	170
σ_w (km s^{-1})	55 to 130^h	95	—
[Fe/H]	-2 to 0.5	< -5.4 to -0.5	—
Age (Gyr)	< 0.2 to 10	11 to 13	~ 13.5

[a] $M_{\rm dust}/M_{\rm gas} \simeq 0.007$.

[b] The total luminosity of the Galaxy is $L_{B,\rm tot} = 2.3 \pm 0.6 \times 10^{10}$ $L_\odot$, $L_{\rm bol,tot} = 3.6 \times 10^{10}$ $L_\odot$ ($\sim 30\%$ in IR).

[c] Some open clusters associated with the thin disk may exceed 10 Gyr.

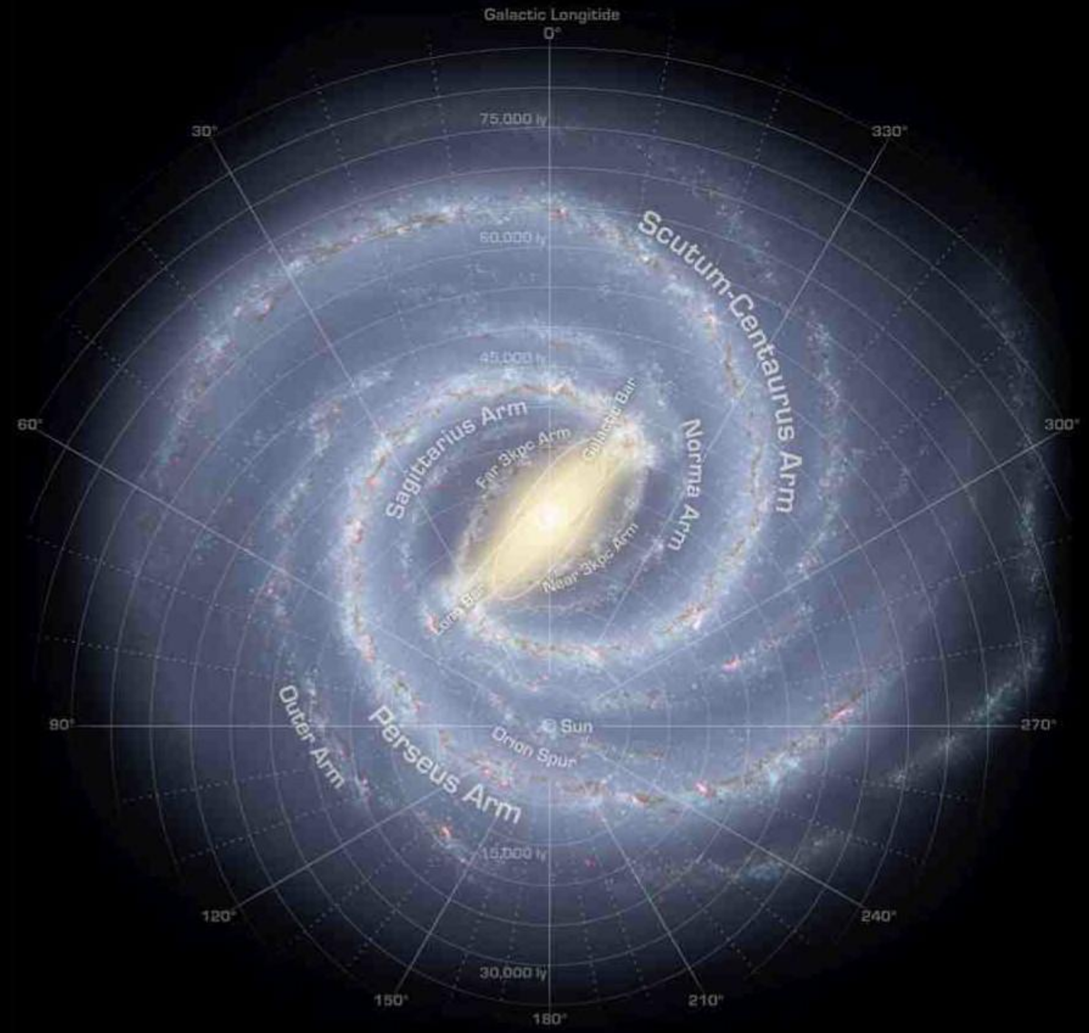
[d] Major star formation in the thick disk may have occurred 7–8 Gyr ago.

[e] The mass of the black hole in Sgr A* is $M_{\rm bh} = 3.7 \pm 0.2 \times 10^6$ $M_\odot$.

[f] $M = 5.4^{+0.2}_{-3.6} \times 10^{11}$ $M_\odot$ within 50 kpc of the center.

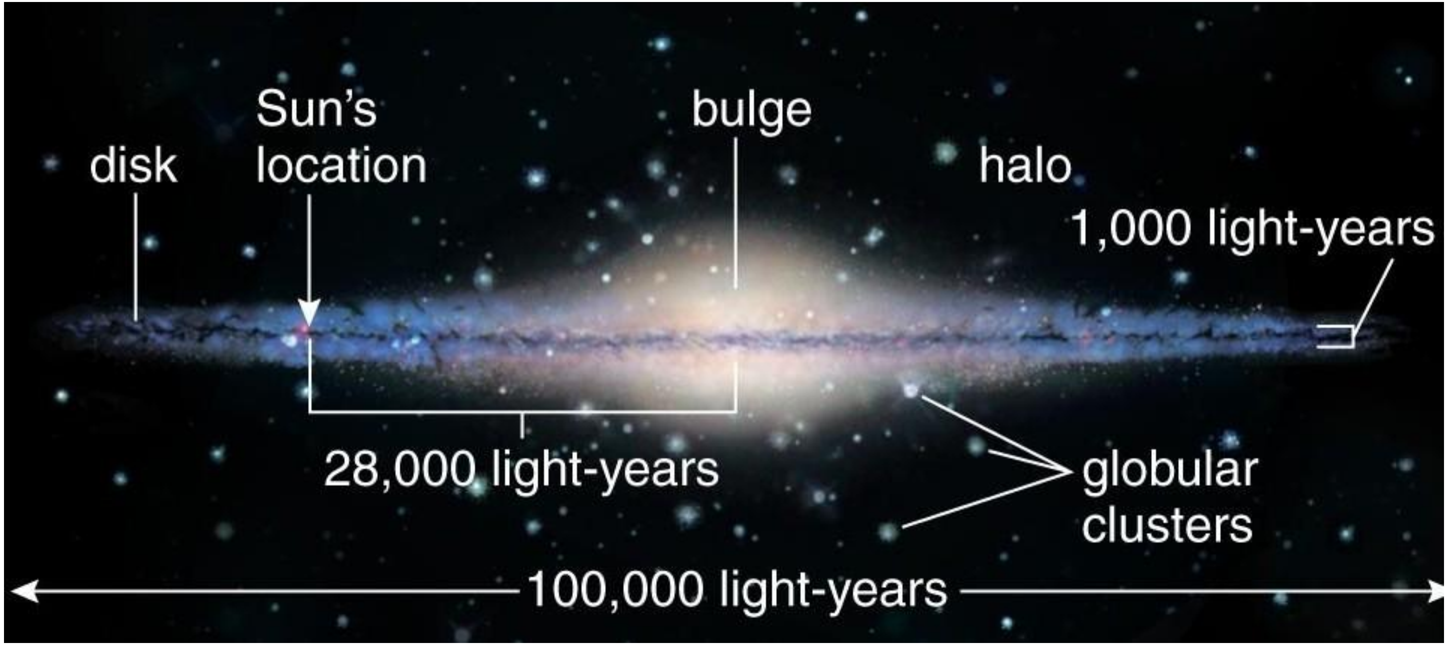
[g] Bulge scale heights depend on age of stars: 100 pc for young stars, 500 pc for old stars.

[h] Dispersions increase from 55 km s^{-1} at 5 pc to 130 km s^{-1} at 200 pc.



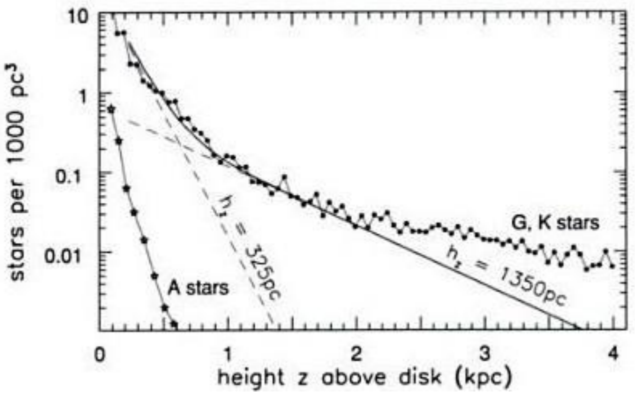
Galactic Longitide
0°
75,000 ly
30°
330°
60,000 ly
Scutum-Centaurus Arm
45,000 ly
Sagittarius Arm
Galactic Bar
Far 3kpc Arm
Norma Arm
60°
300°
Near 3kpc Arm
Long Bar
Outer Arm
Perseus Arm
Sun
Orion Spur
90°
270°
15,000 ly
120°
240°
30,000 ly
150°
210°
180°

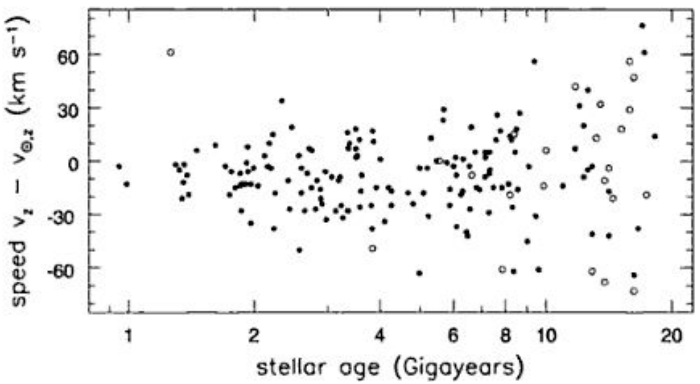
Edge-on Representation of the Milky Way



1pc ~ 3ly

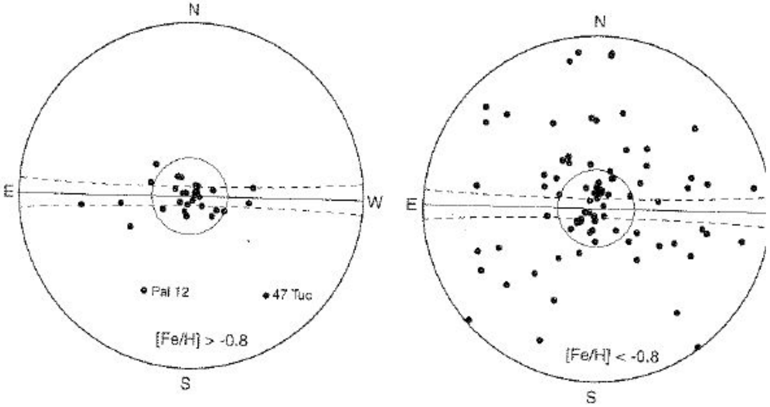
Thin and Thick Disks



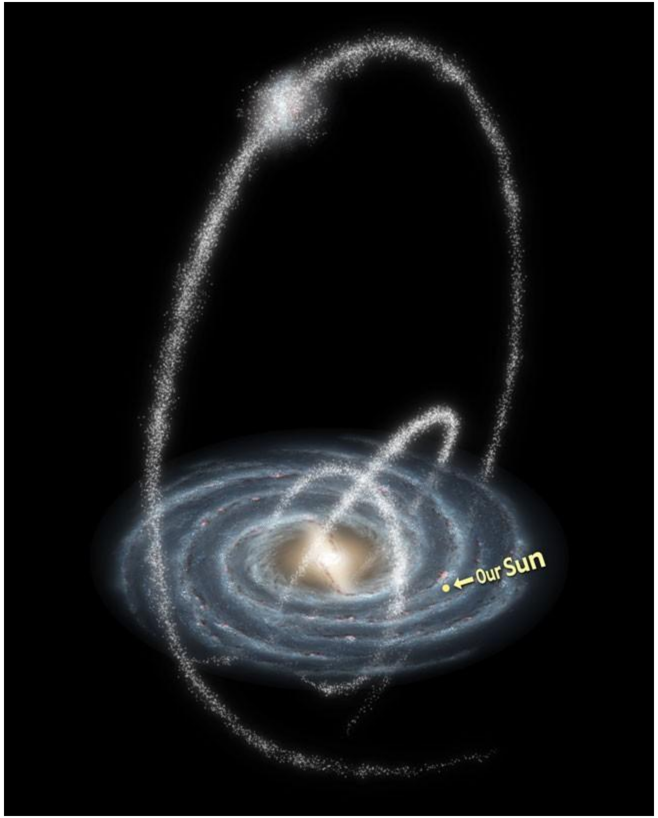


Thick disk number density is lower than that of thin disk

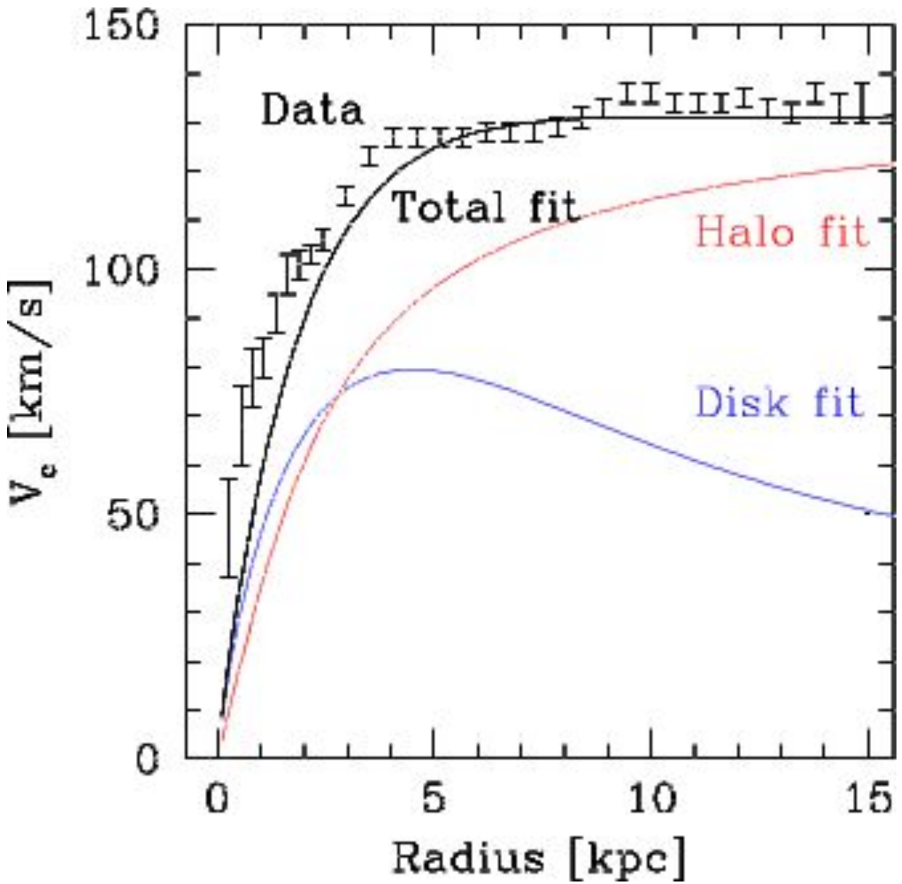
Thick disk has older stars, because only the older stars have had time to migrate from their birth sites in the thin disk.


N
E
W
S
Pal 12
47 Tuc
[Fe/H] > -0.8
N
E
S
[Fe/H] < -0.8

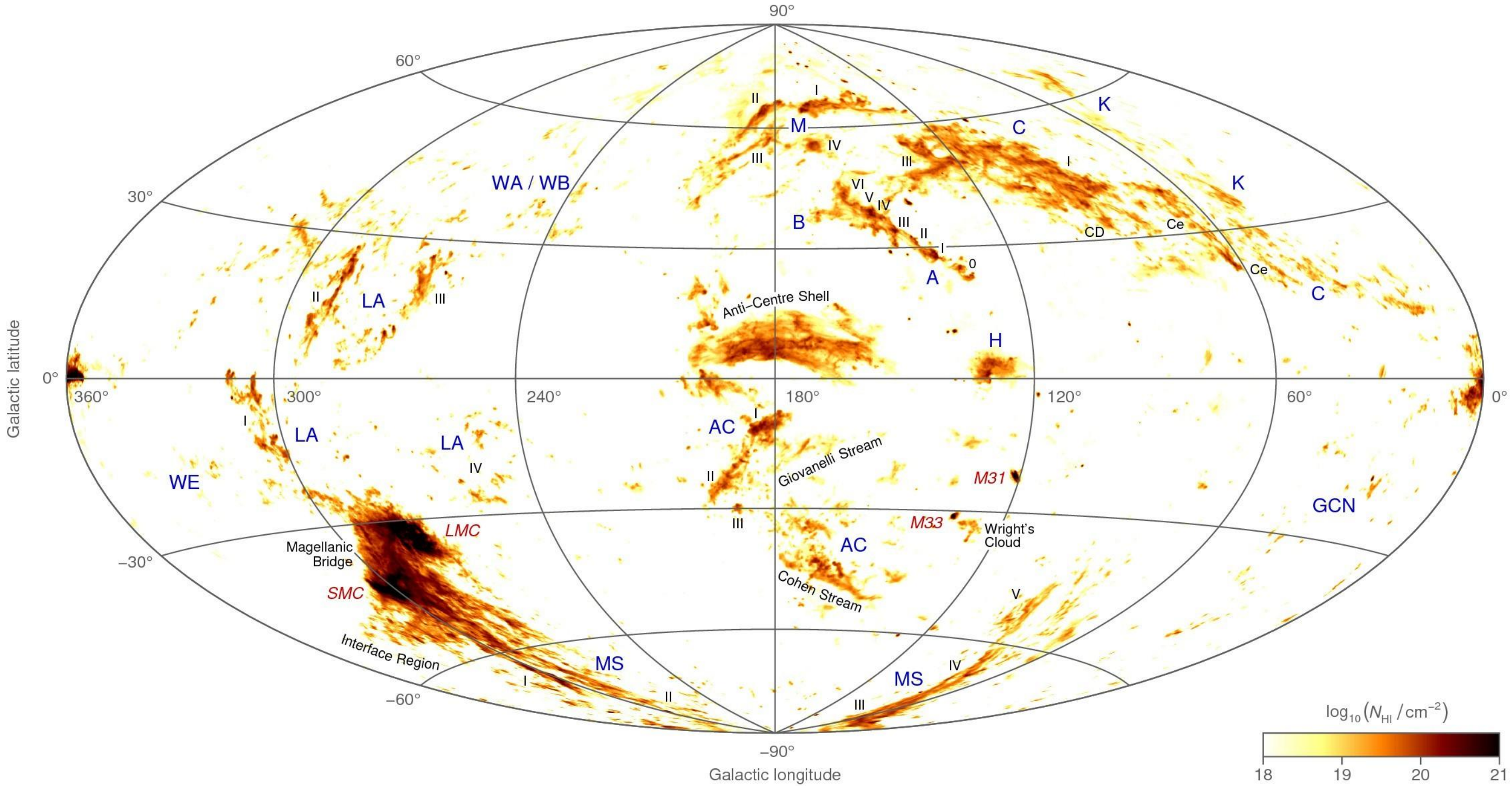
Stellar Streams in the Halo/Disk



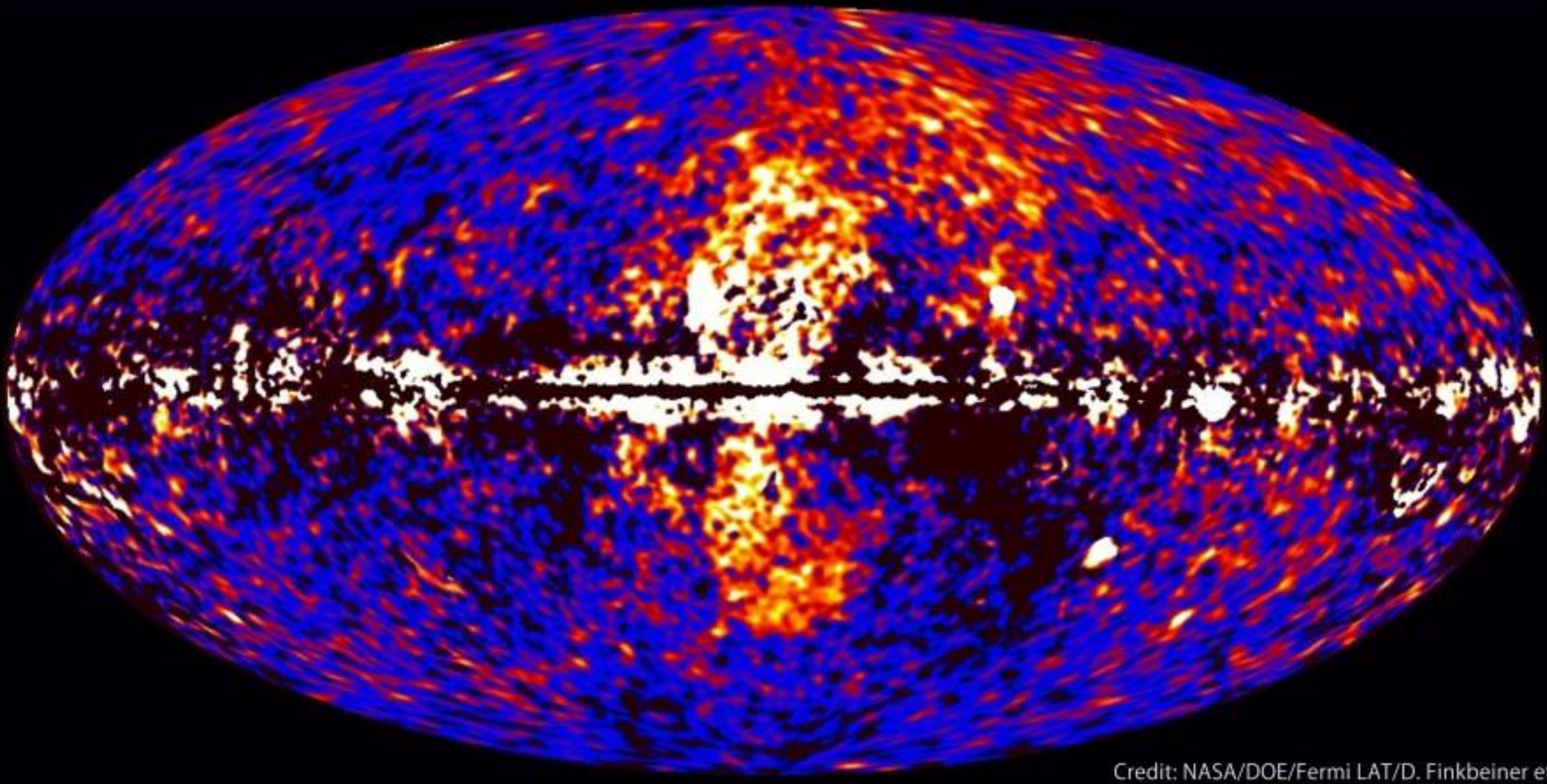
At large distances, halo (dark matter) dominates



Cool Halo – High Velocity Clouds

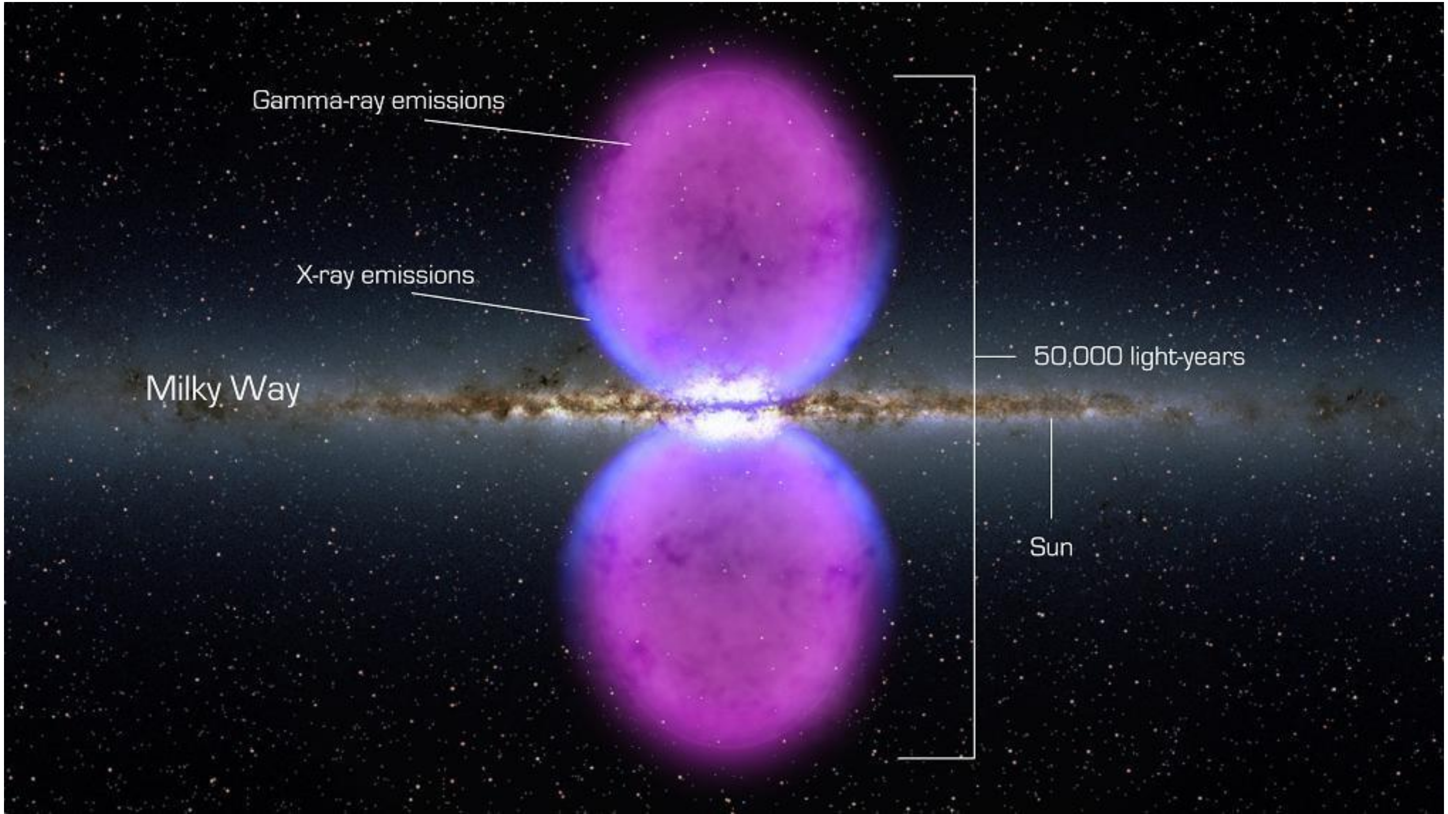


Fermi data reveal giant gamma-ray bubbles

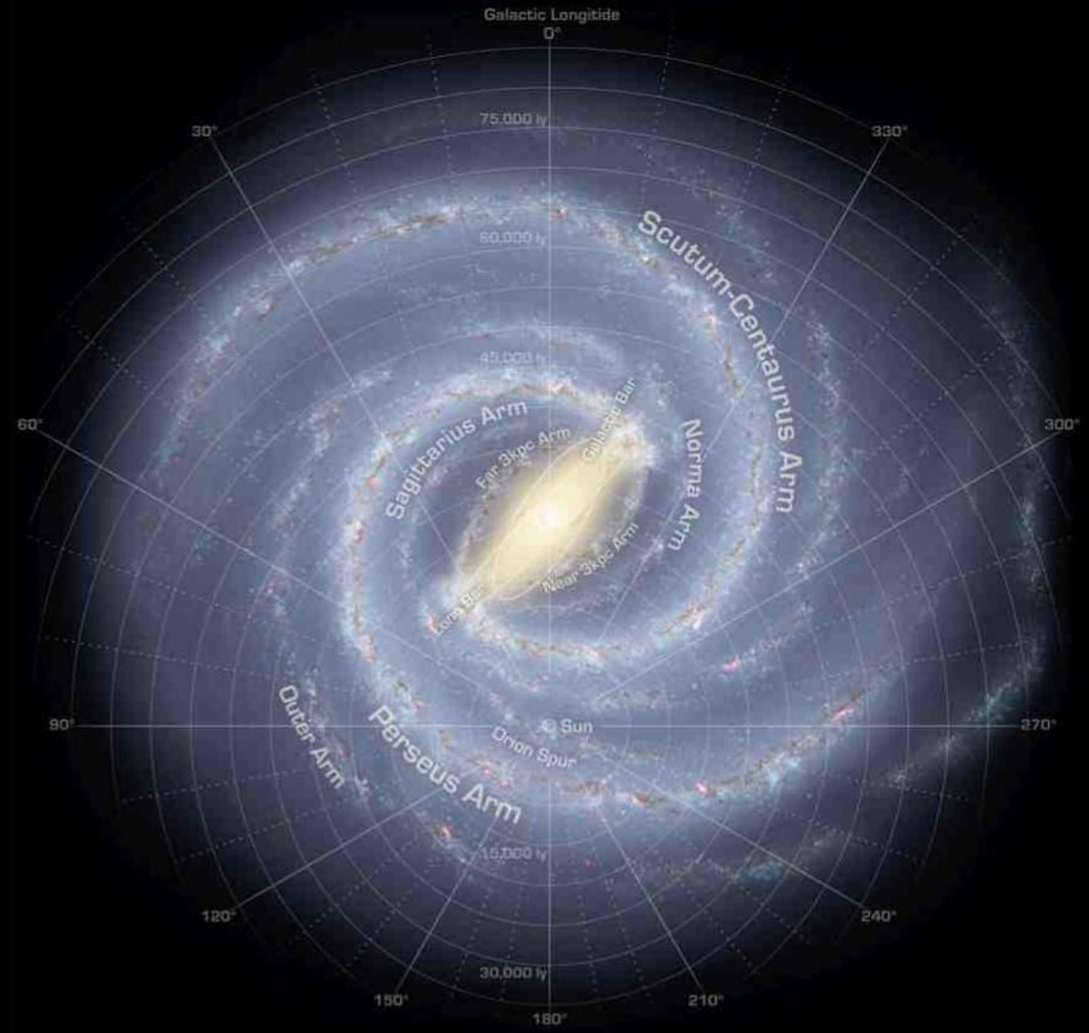


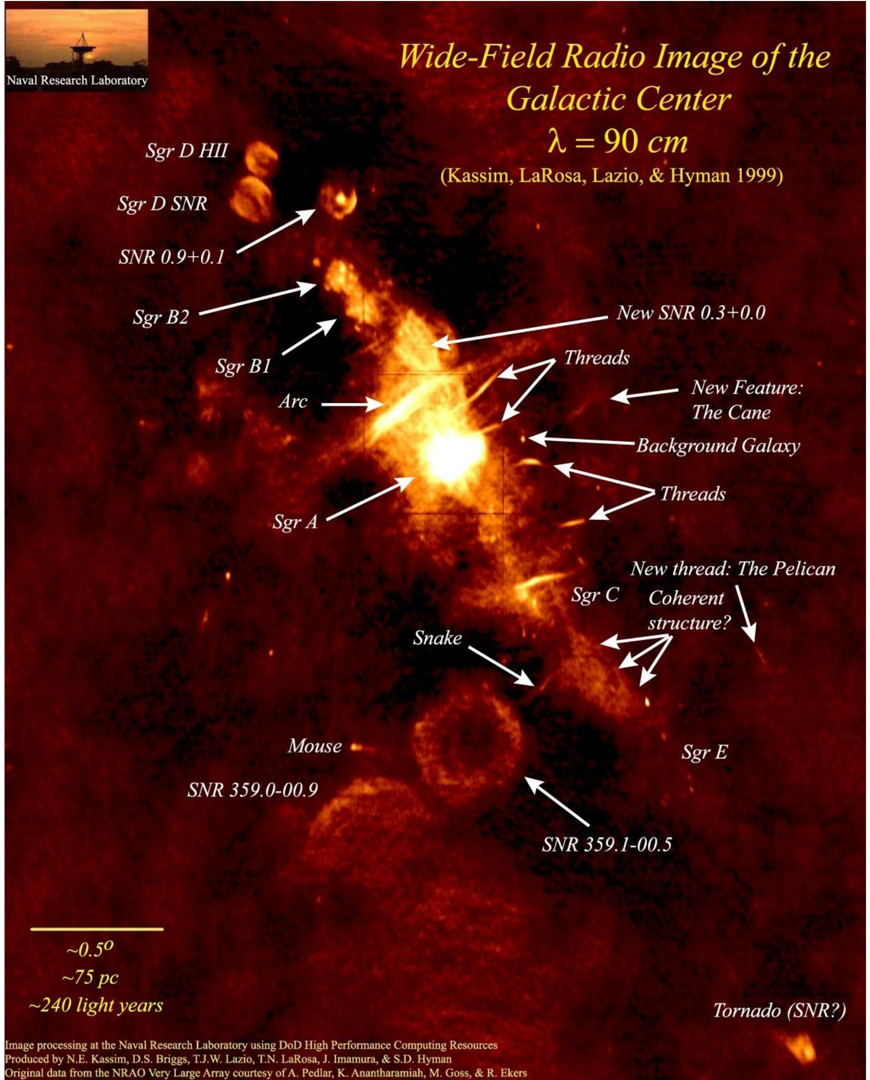
Credit: NASA/DOE/Fermi LAT/D. Finkbeiner et al.

Fermi (Gamma Ray) Bubbles

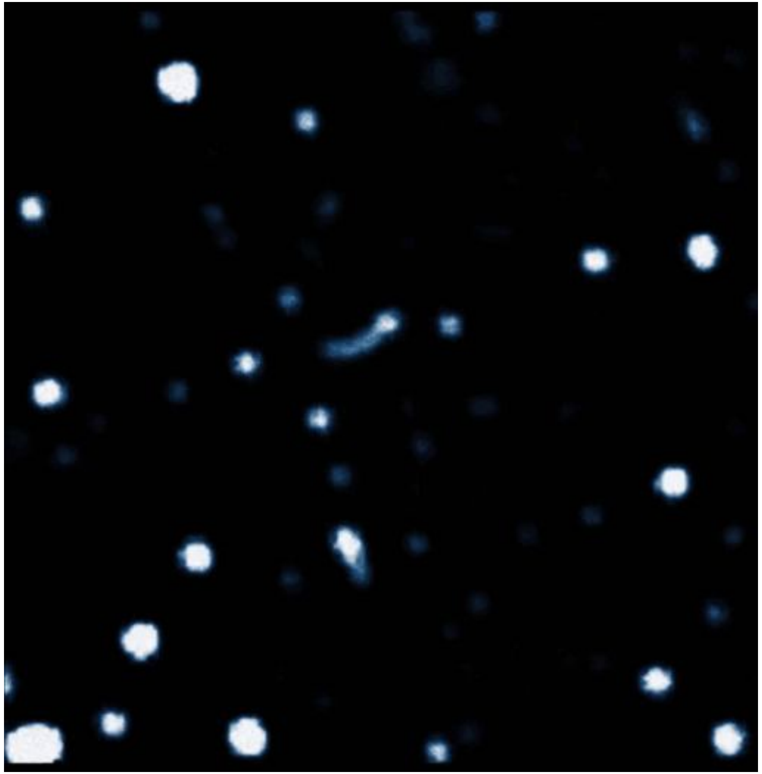


Milky Way Bar shown in Bulge

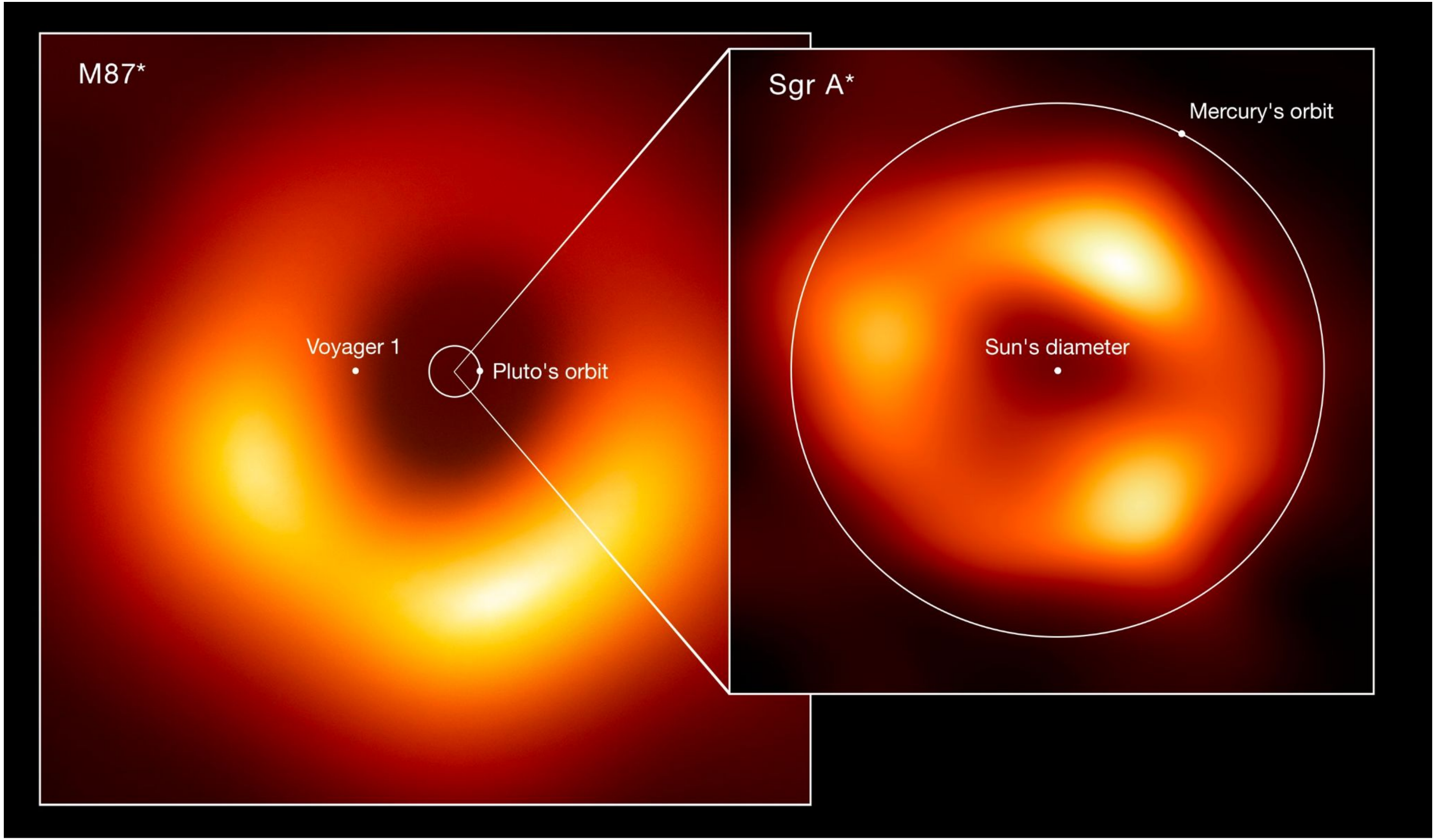

Galactic Longitide
0°
30°
330°
60°
300°
90°
270°
120°
240°
150°
210°
180°
75,000 ly
60,000 ly
45,000 ly
15,000 ly
30,000 ly
Scutum-Centaurus Arm
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Norma Arm
Near 3kpc Arm
Long Bar
Outer Arm
Perseus Arm
Sun
Orion Spur


Naval Research Laboratory
Wide-Field Radio Image of the Galactic Center
λ = 90 cm
(Kassim, LaRosa, Lazio, & Hyman 1999)
Sgr D HII
Sgr D SNR
SNR 0.9+0.1
Sgr B2
Sgr B1
New SNR 0.3+0.0
Threads
New Feature: The Cane
Arc
Background Galaxy
Threads
Sgr A
New thread: The Pelican
Sgr C
Coherent structure?
Snake
Mouse
Sgr E
SNR 359.0-00.9
SNR 359.1-00.5
~0.5°
~75 pc
~240 light years
Tornado (SNR?)
Image processing at the Naval Research Laboratory using DoD High Performance Computing Resources
Produced by N.E. Kassim, D.S. Briggs, T.J.W. Lazio, T.N. LaRosa, J. Imamura, & S.D. Hyman
Original data from the NRAO Very Large Array courtesy of A. Pedlar, K. Anantharamiah, M. Goss, & R. Ekers

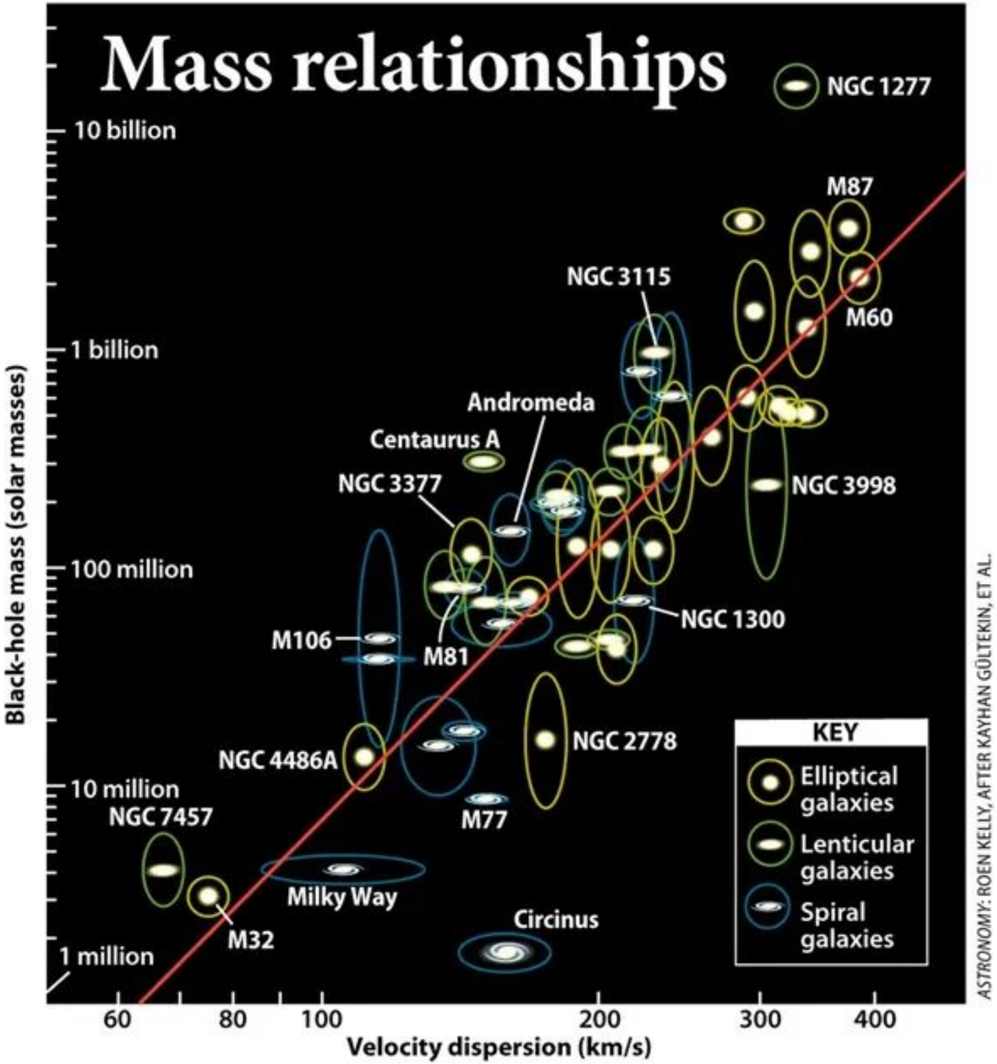
Galactic Center Black Hole



Sgr A* Imaged!

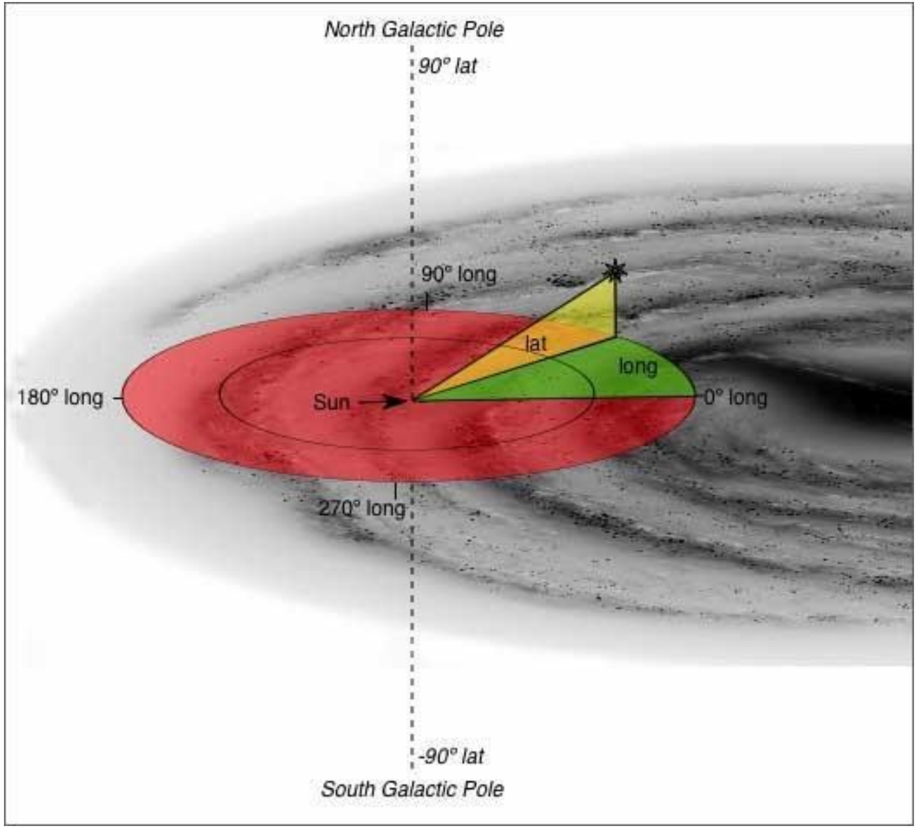


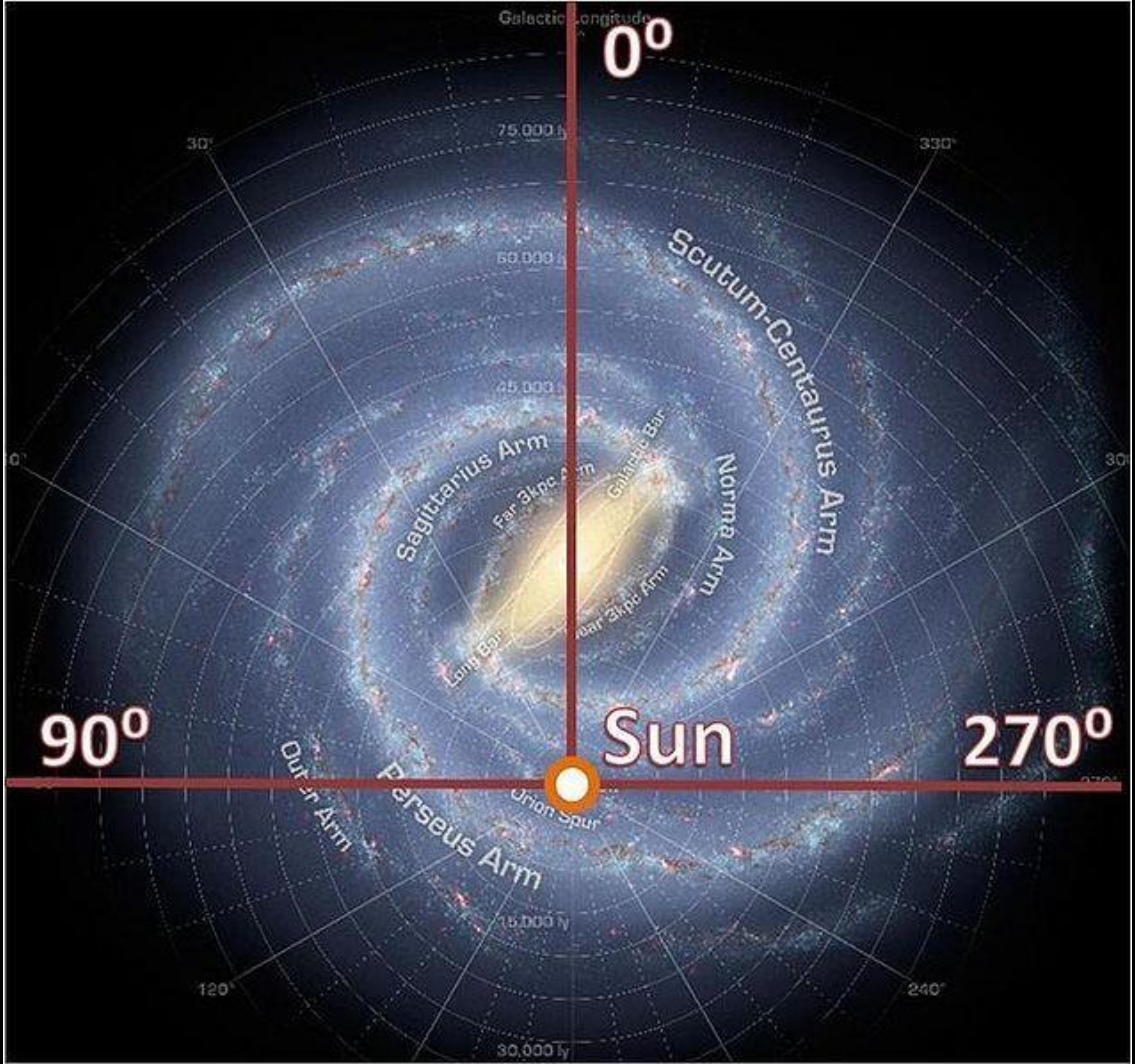
M87*
Voyager 1
Pluto's orbit
Sgr A*
Mercury's orbit
Sun's diameter



Mass relationships
NGC 1277
10 billion
M87
NGC 3115
M60
1 billion
Andromeda
Centaurus A
NGC 3377
NGC 3998
100 million
M106
M81
NGC 1300
NGC 2778
NGC 4486A
10 million
NGC 7457
M77
Milky Way
M32
Circinus
1 million
KEY
Elliptical galaxies
Lenticular galaxies
Spiral galaxies
Black-hole mass (solar masses)
60
80
100
200
300
400
Velocity dispersion (km/s)
ASTRONOMY: ROEN KELLY, AFTER KAYHAN GÜLTEKIN, ET AL.

Galactic Coordinates





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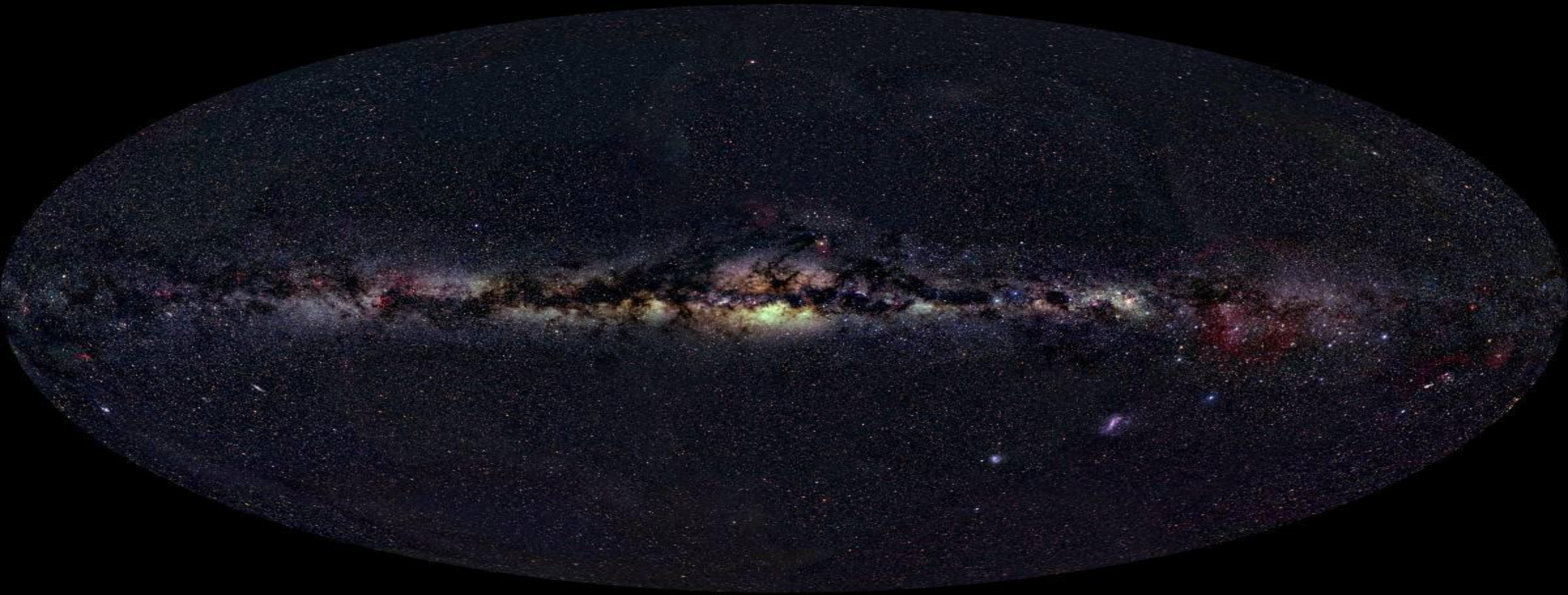
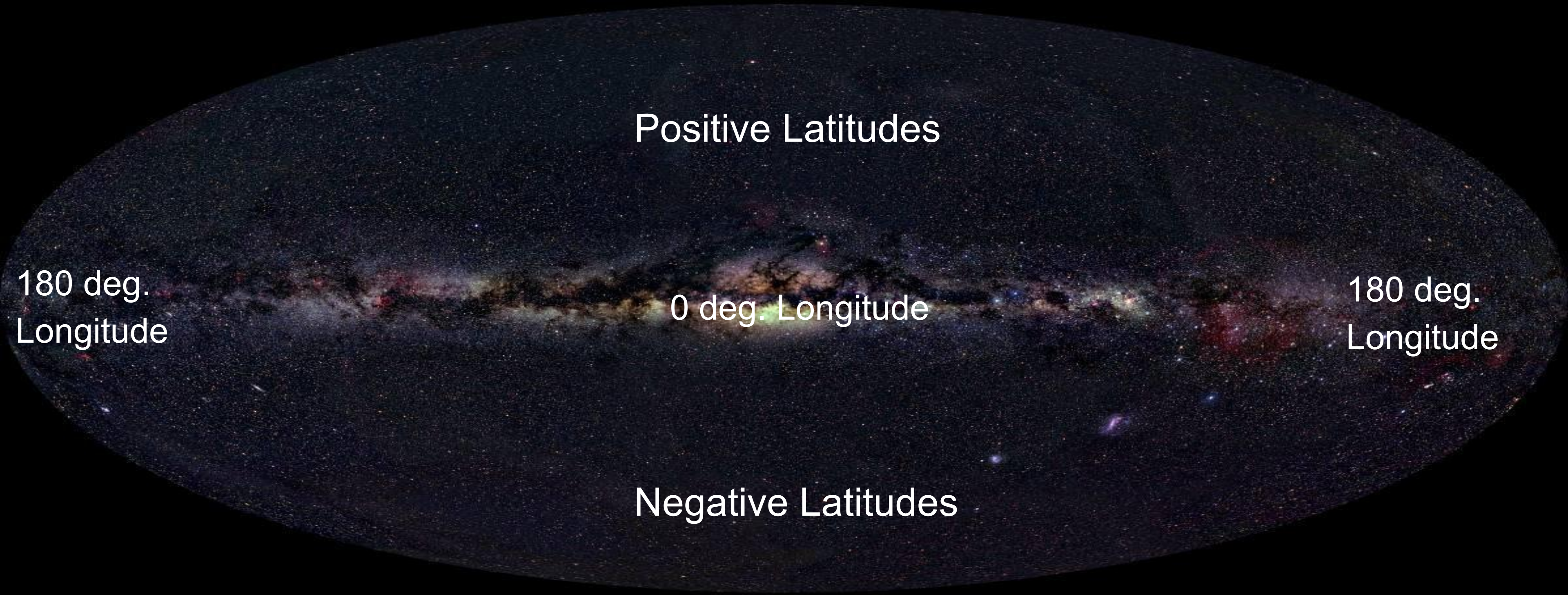
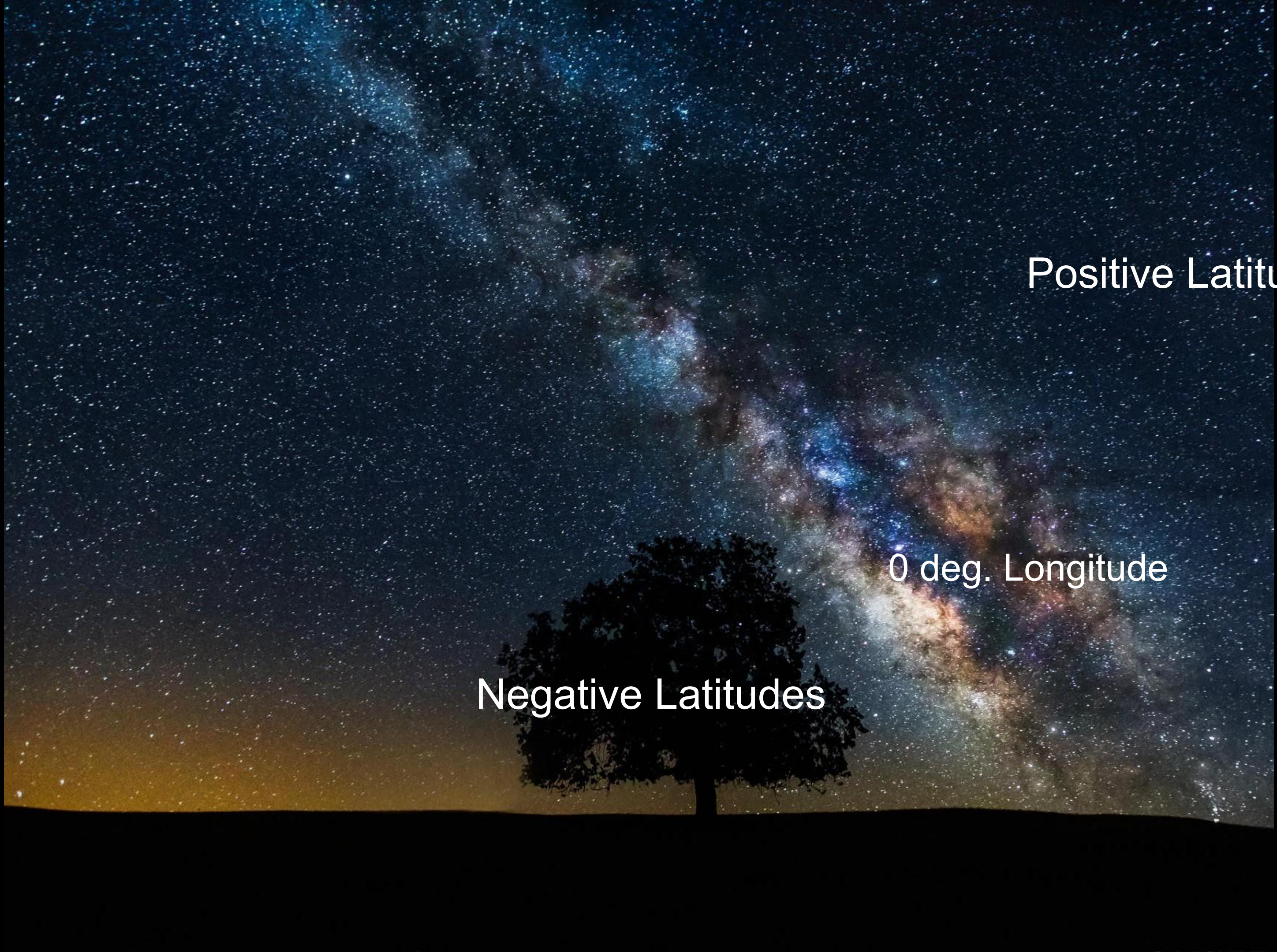
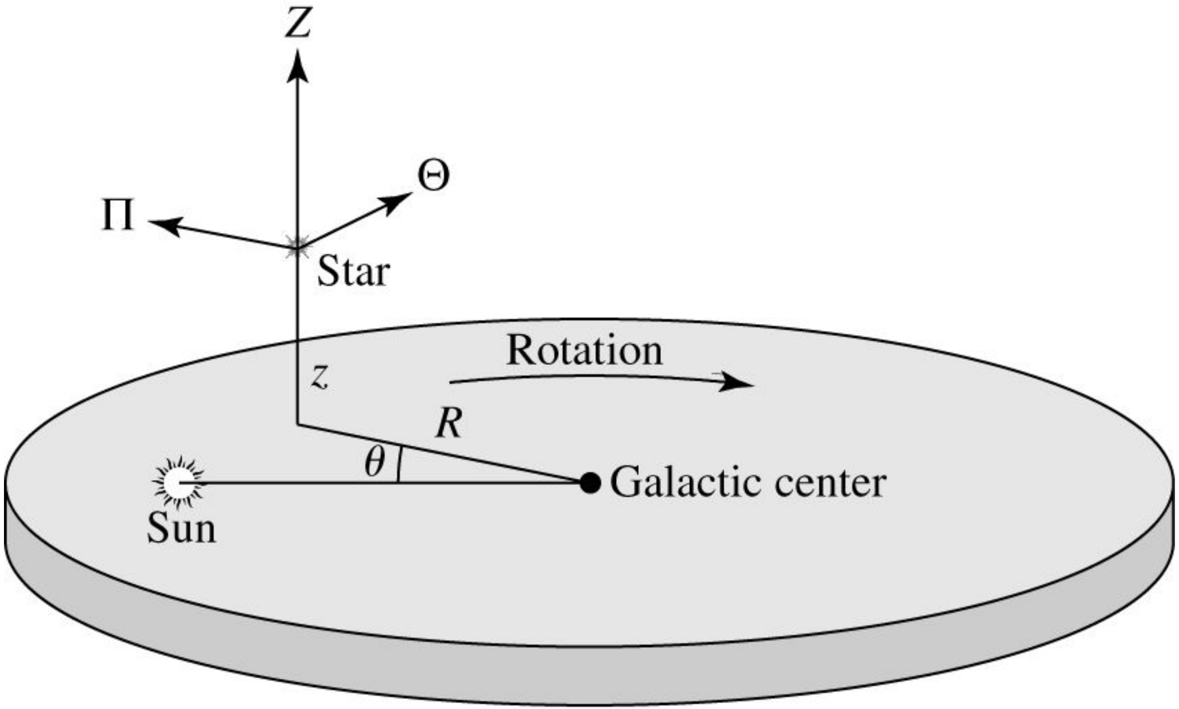
90°
Sun
270°
Outer Arm
Perseus Arm
Orion Spur
15,000 ly
120°
240°
30,000 ly



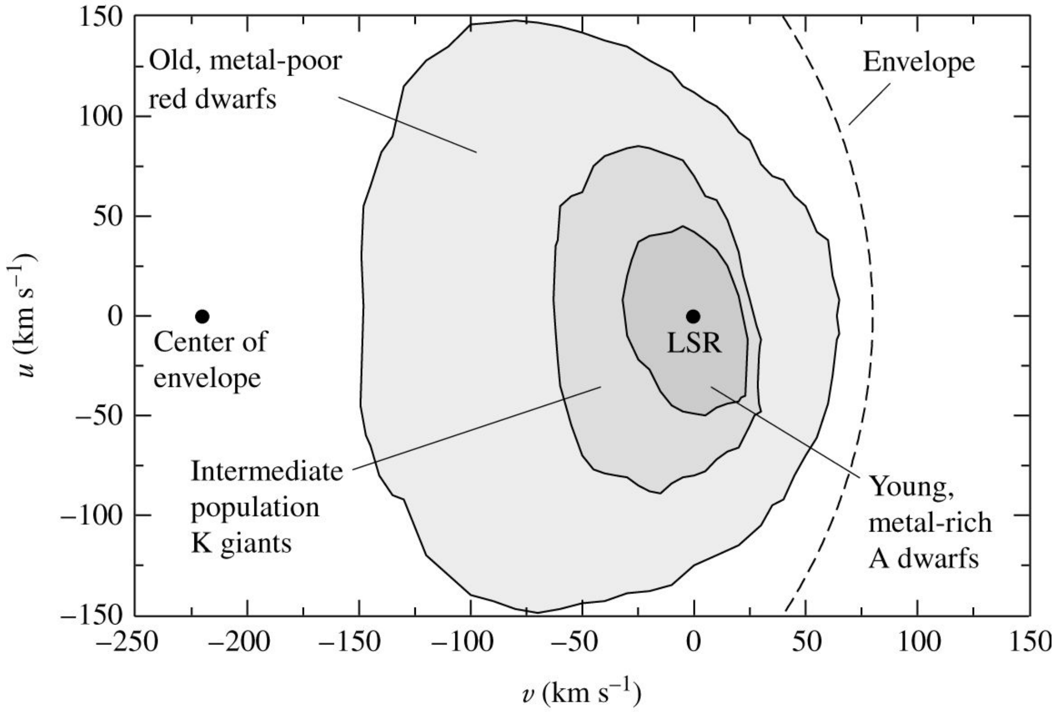

Positive Latitudes
180 deg. Longitude
0 deg. Longitude
180 deg. Longitude
Negative Latitudes

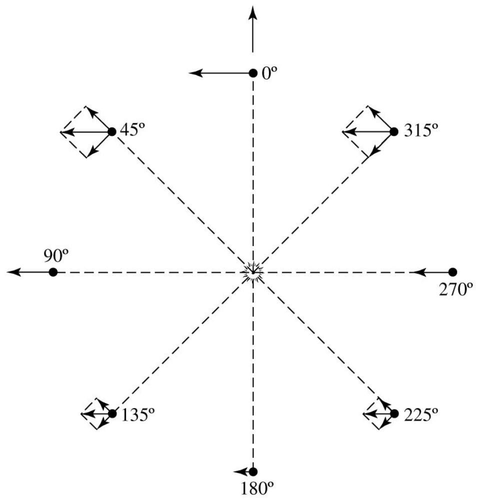

Positive Latitudes
0 deg. Longitude
Negative Latitudes

Galactic Center Cylindrical Coordinates

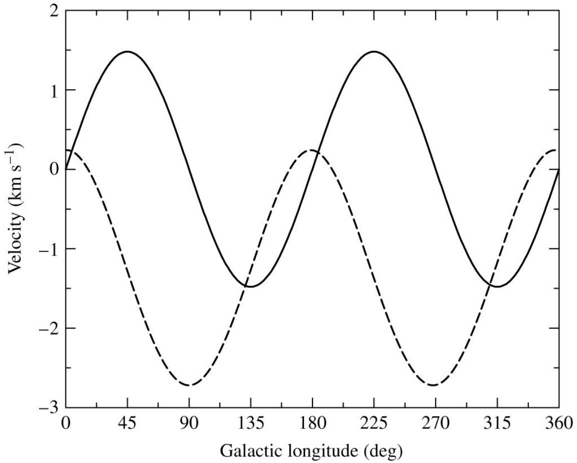


Observations of Stars Show





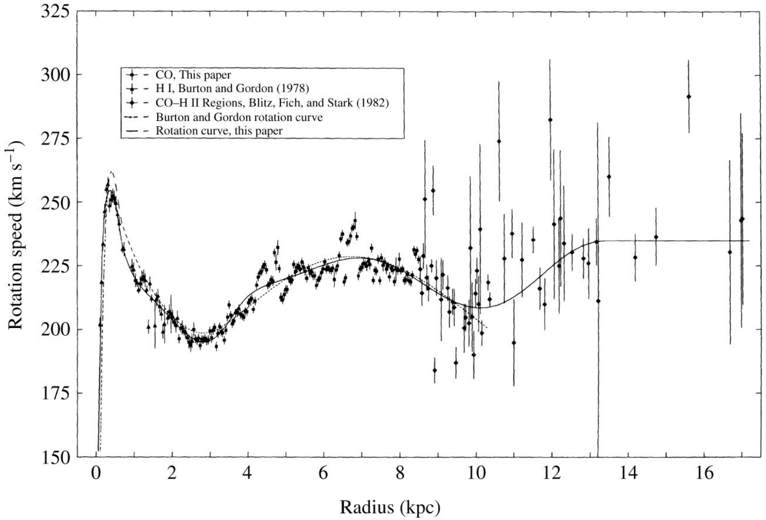
(a)



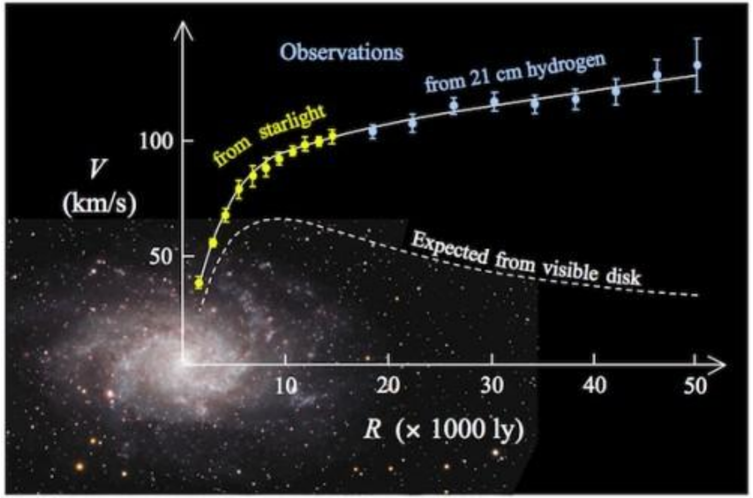
(b)

Radial (solid) and transverse (dashed) velocities as a function of *l*. Dependence is sin (2*l*)

Milky Way



Other galaxy



THE ASTROPHYSICAL JOURNAL, 885:131 (18pp), 2019 November 10
https://doi.org/10.3847/1538-4357/ab4a11

Trigonometric Parallaxes of High-mass Star-forming Regions: Our View of the Milky Way

M. J. Reid[1], K. M. Menten[2], A. Brunthaler[2], X. W. Zheng[3], T. M. Dame[1], Y. Xu[4], J. Li[4], N. Sakai[5], Y. Wu[6,7], K. Immer[8], B. Zhang[9], A. Sanna[2], L. Moscadelli[10], K. L. J. Rygl[11], A. Bartkiewicz[12], B. Hu[4], L. H. Quiroga-Nuñez[8,13], and H. J. van Langevelde[8,13]

Θ = 237km/s-1.4km/s*R (for R>3.7 kpc)

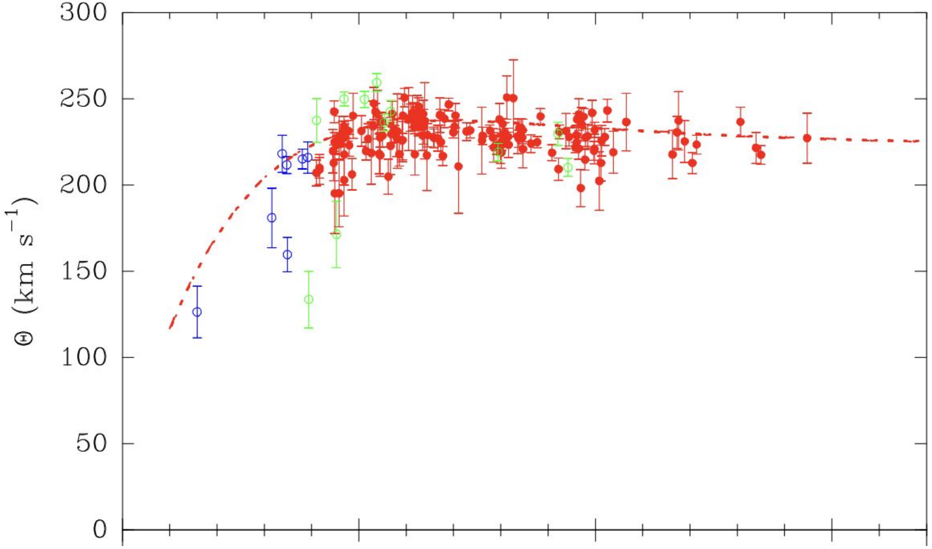
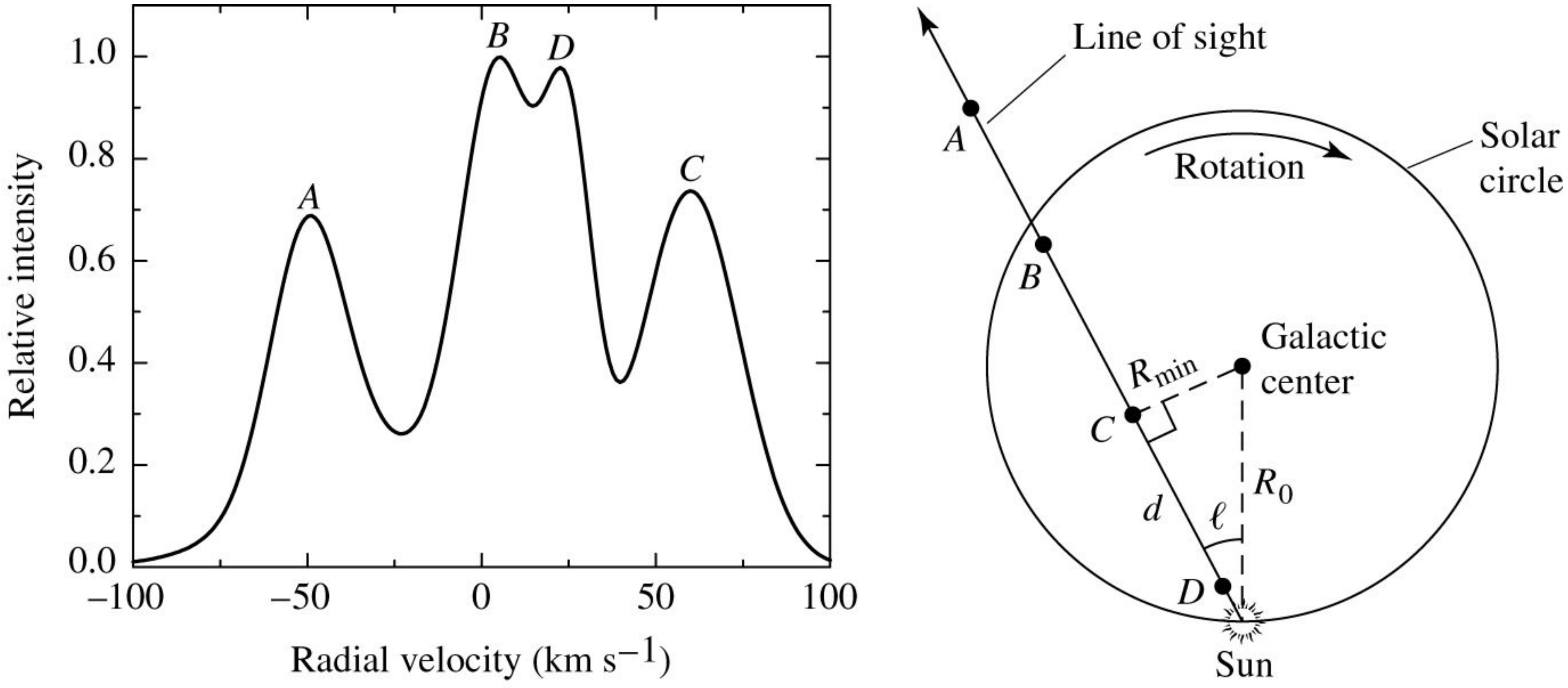


Table 3
Bayesian Fitting Results

	A1	A5
	Fitted Parameters	
R_0 (kpc)	8.22 ± 0.22	8.15 ± 0.15
$U_\odot$ (km s^{-1})	10.8 ± 1.2	10.6 ± 1.2
$V_\odot$ (km s^{-1})	13.6 ± 6.7	10.7 ± 6.0
$W_\odot$ (km s^{-1})	7.6 ± 0.9	7.6 ± 0.7
$\overline{U_s}$ (km s^{-1})	6.1 ± 1.9	6.0 ± 1.4
$\overline{V_s}$ (km s^{-1})	−2.1 ± 6.5	−4.3 ± 5.6
a_2	0.96 ± 0.08	0.96 ± 0.05
a_3	1.62 ± 0.03	1.62 ± 0.02
	Calculated Values	
Θ_0 (km s^{-1})	237 ± 8	236 ± 7
$(\Theta_0 + V_\odot)$ (km s^{-1})	249 ± 7	247 ± 4
$(\Theta_0 + V_\odot)/R_0$(km s^{-1} kpc^{-1})	30.46 ± 0.43	30.32 ± 0.27



1.0
0.8
0.6
0.4
0.2
0.0
Relative intensity
A
B
D
C
−100
−50
0
50
100
Radial velocity (km s−1)
Line of sight
A
B
Rotation
Solar circle
Galactic center
R_min
C
R_0
d
ℓ
D
Sun

(a) (b)

A&A 625, L10 (2019)
https://doi.org/10.1051/0004-6361/201935656

Astronomy & Astrophysics

LETTER TO THE EDITOR

A geometric distance measurement to the Galactic center black hole with 0.3% uncertainty★

The GRAVITY Collaboration: R. Abuter[8], A. Amorim[6], M. Bauböck[1], J. P. Berger[5], H. Bonnet[8], W. Brandner[3], Y. Clénet[2], V. Coudé du Foresto[2], P. T. de Zeeuw[10,1], J. Dexter[1], G. Duvert[5], A. Eckart[4,13], F. Eisenhauer[1], N. M. Förster Schreiber[1], P. Garcia[7], F. Gao[1], E. Gendron[2], R. Genzel[1,11], O. Gerhard[1], S. Gillessen[1], M. Habibi[1], X. Haubois[9], T. Henning[3], S. Hippler[3], M. Horrobin[4], A. Jiménez-Rosales[1], L. Jocou[5], P. Kervella[2], S. Lacour[2,1], V. Lapeyrère[2], J.-B. Le Bouquin[5], P. Léna[2], T. Ott[1], T. Paumard[2], K. Perraut[5], G. Perrin[2], O. Pfuhl[1], S. Rabien[1], G. Rodriguez Coira[2], G. Rousset[2], S. Scheithauer[3], A. Sternberg[12,14], O. Straub[1], C. Straubmeier[4], E. Sturm[1], L. J. Tacconi[1], F. Vincent[2], S. von Fellenberg[1], I. Waisberg[1], F. Widmann[1], E. Wieprecht[1], E. Wiezorrek[1], J. Woillez[8], and S. Yazici[1,4]

(Affiliations can be found after the references)

Received 10 April 2019 / Accepted 25 April 2019

ABSTRACT

We present a 0.16% precise and 0.27% accurate determination of R_0, the distance to the Galactic center. Our measurement uses the star S2 on its 16-year orbit around the massive black hole Sgr A* that we followed astrometrically and spectroscopically for 27 years. Since 2017, we added near-infrared interferometry with the VLTI beam combiner GRAVITY, yielding a direct measurement of the separation vector between S2 and Sgr A* with an accuracy as good as 20 μas in the best cases. S2 passed the pericenter of its highly eccentric orbit in May 2018, and we followed the passage with dense sampling throughout the year. Together with our spectroscopy, in the best cases with an error of 7 km s^{-1}, this yields a geometric distance estimate of $R_0 = 8178 \pm 13_{\rm stat.} \pm 22_{\rm sys.}$ pc. This work updates our previous publication, in which we reported the first detection of the gravitational redshift in the S2 data. The redshift term is now detected with a significance level of 20σ with $f_{\rm redshift} = 1.04 \pm 0.05$.

Key words. black hole physics – astrometry – Galaxy: nucleus