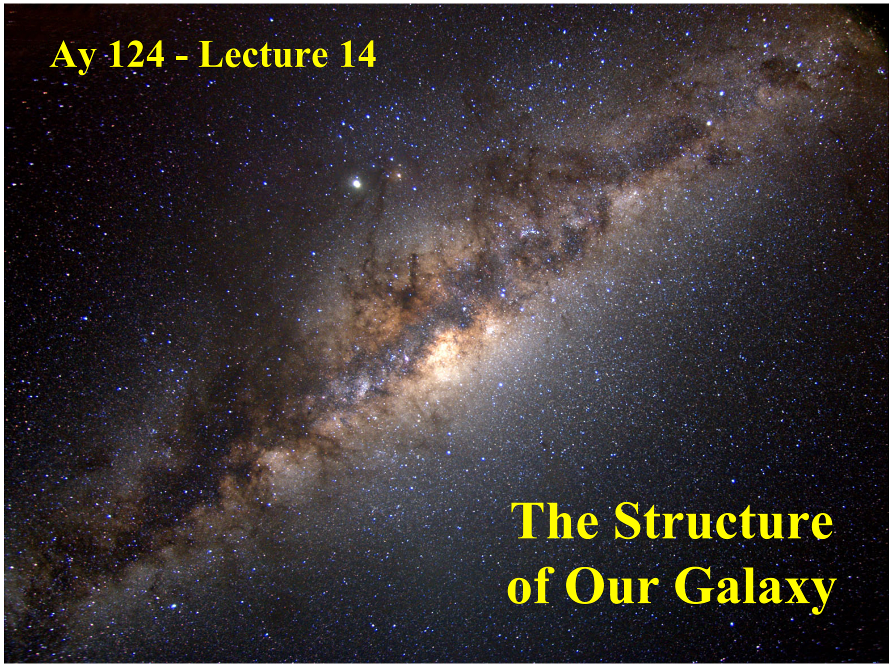
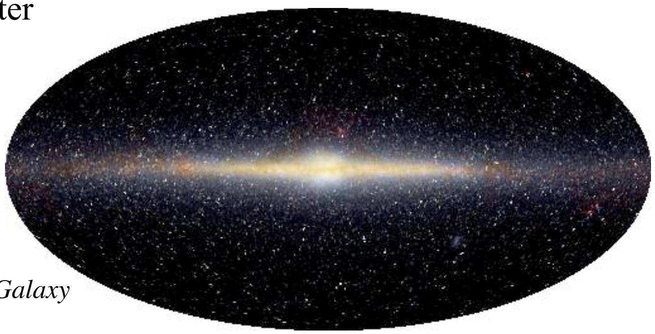
Ay 124 - Lecture 14



The Structure of Our Galaxy

Our Galaxy - The Milky Way

- Overall structure and major components
- The concept of stellar populations
- Stellar kinematics: basics
- Galactic rotation and the evidence for a dark halo
- Galactic bar
- Galactic center



COBE/DIRBE
IR image of our Galaxy

A Modern View of the Galaxy

Actually, there is the thin disk, and the thick disk

Actually, there is the stellar halo, the gaseous corona, and the dark halo

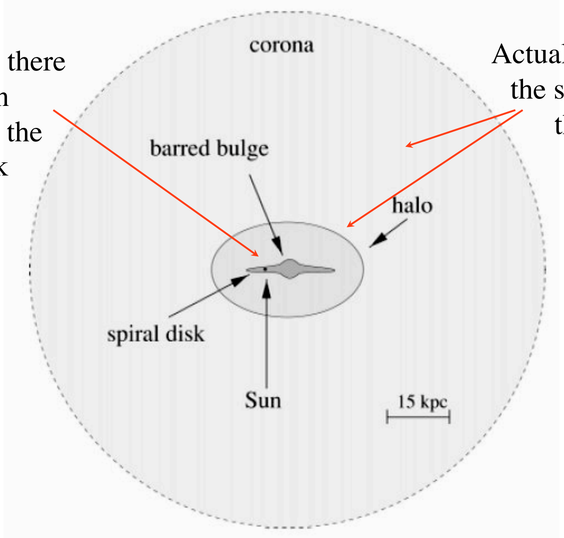
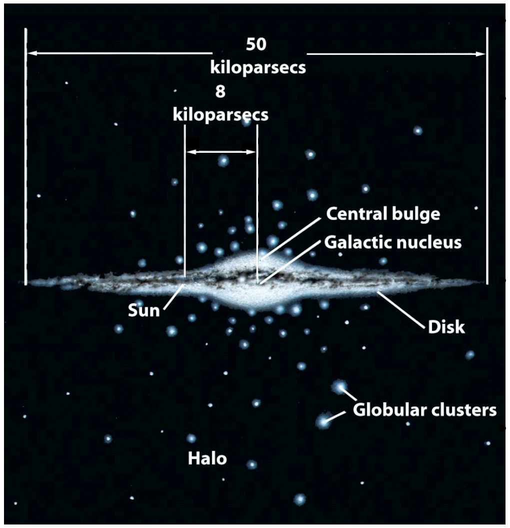


Figure 1. Main structural components of the Milky Way

Another Schematic View



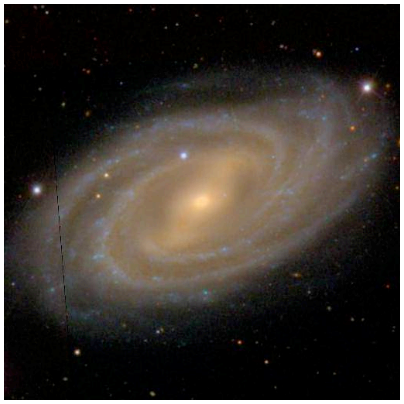
There are ~ 2×10^{11} stars in the Galaxy

An exponential disk ~ 50 kpc in diameter and ~ 0.3 - 1 kpc thick; contains young to intermediate age stars and ISM

Nested "spheroids" of bulge and halo, containing old stars, hot gas, and dark matter

The Sun orbits around the center with V ~ 220 km/s, and a period of ~ 2×10^8 yr

Other Spiral Galaxies Indicate How The Milky Way Might Look



NGC 3992

Nearly Face-On Sb

NGC 891

Edge-On Sb

Principal Parameters of the MW

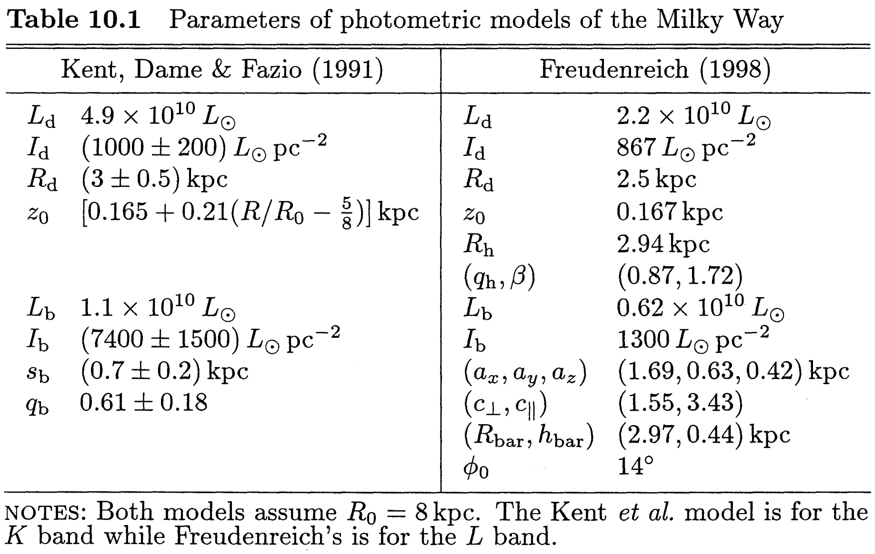


Table 10.1 Parameters of photometric models of the Milky Way

Kent, Dame & Fazio (1991)		Freudenreich (1998)	
L_d	$4.9 \times 10^{10}\,L_\odot$	L_d	$2.2 \times 10^{10}\,L_\odot$
I_d	$(1000 \pm 200)\,L_\odot\,\mathrm{pc}^{-2}$	I_d	$867\,L_\odot\,\mathrm{pc}^{-2}$
R_d	$(3 \pm 0.5)\,\mathrm{kpc}$	R_d	$2.5\,\mathrm{kpc}$
z_0	$[0.165 + 0.21(R/R_0 - \frac{5}{8})]\,\mathrm{kpc}$	z_0	$0.167\,\mathrm{kpc}$
		R_h	$2.94\,\mathrm{kpc}$
		(q_h, β)	$(0.87, 1.72)$
L_b	$1.1 \times 10^{10}\,L_\odot$	L_b	$0.62 \times 10^{10}\,L_\odot$
I_b	$(7400 \pm 1500)\,L_\odot\,\mathrm{pc}^{-2}$	I_b	$1300\,L_\odot\,\mathrm{pc}^{-2}$
s_b	$(0.7 \pm 0.2)\,\mathrm{kpc}$	(a_x, a_y, a_z)	$(1.69, 0.63, 0.42)\,\mathrm{kpc}$
q_b	0.61 ± 0.18	$(c_\perp, c_\parallel)$	$(1.55, 3.43)$
		$(R_\mathrm{bar}, h_\mathrm{bar})$	$(2.97, 0.44)\,\mathrm{kpc}$
		ϕ_0	$14°$

NOTES: Both models assume $R_0 = 8\,\mathrm{kpc}$. The Kent *et al.* model is for the K band while Freudenreich's is for the L band.

Major Components of the Galaxy

The disk: thin, roughly circular disk of stars with coherent rotation about the Galactic center.

$$L_{disk} \approx 15 - 20 \times 10^9 L_{sun}$$

$$M_{disk} \approx 6 \times 10^{10} M_{sun}$$

Disk extends to at least 15 kpc from the Galactic center. Density of stars in the disk falls off exponentially, both radially and vertically:

$$n(R) \propto e^{-R/h_R}$$

disk scale length $h_R \sim 3$ kpc

Most of the stars (95%) lie in a **thin disk,** with a vertical scale height ~ 300 pc. Rest form a **thick disk** with a vertical scale height ~ 1 kpc. Thin disk stars are younger.

Also a gas disk, thinner than either of the stellar disks.

Major Components of the Galaxy

- **The bulge**: central, mostly old spheroidal stellar component:

$$L_{bulge} \approx 5 \times 10^9 L_{sun}$$

$$M_{bulge} \approx 2 \times 10^{10} M_{sun}$$

Galactic center is about 8 kpc from the Sun, the bulge is a few kpc in radius

- **The halo**, contains:

(i) Field stars - total mass in visible stars ~10^9 M_{sun}. All are old, metal-poor, have random motions. Very low density.

(ii) Globular clusters. A few % of the total halo stellar content.

(iii) Gas with T ~ 10^5 - 10^6 K. Total mass unknown.

(iii) Dark matter. Physical nature unknown. About 90% of the total mass.

Principal Components of the Galaxy

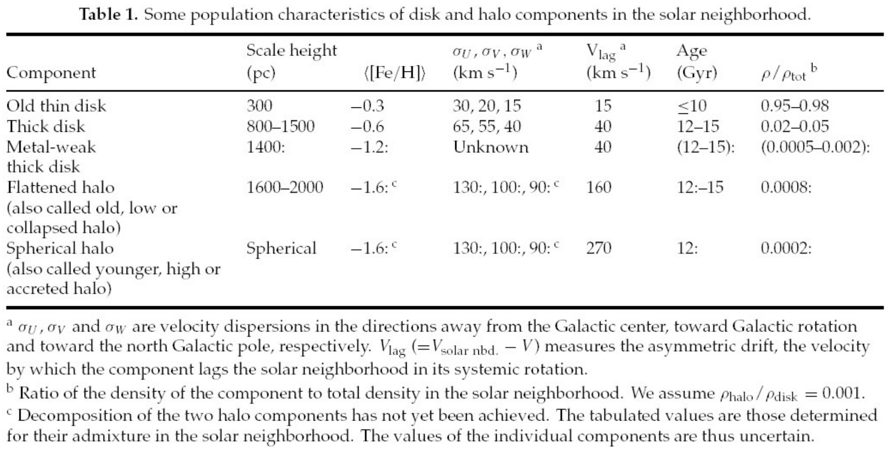


Table 1. Some population characteristics of disk and halo components in the solar neighborhood.

Component	Scale height (pc)	⟨[Fe/H]⟩	$\sigma_U, \sigma_V, \sigma_W$ [a] (km s^{-1})	V_{lag} [a] (km s^{-1})	Age (Gyr)	ρ/ρ_{tot} [b]
Old thin disk	300	–0.3	30, 20, 15	15	≤10	0.95–0.98
Thick disk	800–1500	–0.6	65, 55, 40	40	12–15	0.02–0.05
Metal-weak thick disk	1400:	–1.2:	Unknown	40	(12–15):	(0.0005–0.002):
Flattened halo (also called old, low or collapsed halo)	1600–2000	–1.6: [c]	130:, 100:, 90: [c]	160	12:–15	0.0008:
Spherical halo (also called younger, high or accreted halo)	Spherical	–1.6: [c]	130:, 100:, 90: [c]	270	12:	0.0002:

[a] σ_U, σ_V and σ_W are velocity dispersions in the directions away from the Galactic center, toward Galactic rotation and toward the north Galactic pole, respectively. V_{lag} $(=V_{\mathrm{solar\ nbd.}} - V)$ measures the asymmetric drift, the velocity by which the component lags the solar neighborhood in its systemic rotation.

[b] Ratio of the density of the component to total density in the solar neighborhood. We assume $\rho_{halo}/\rho_{disk} = 0.001$.

[c] Decomposition of the two halo components has not yet been achieved. The tabulated values are those determined for their admixture in the solar neighborhood. The values of the individual components are thus uncertain.

The Concept of Stellar Populations

- Originally discovered by Baade, who came up with 2 populations:

  Pop. I: young stars in the (thin) disk, open clusters

  Pop. II: old stars in the bulge, halo, and globular clusters

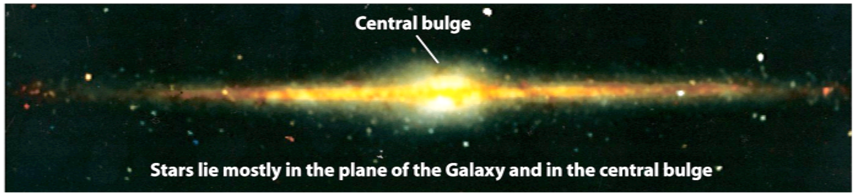
  – Today, we distinguish between the old, metal-rich stars in the bulge, and old, metal-poor stars in the halo

  – Not clear whether the Pop. I is homogeneous: young thin disk, vs. intermediate-age thick disk
- A good modern definition of stellar populations:

  Stellar sub-systems within the Galaxy, distinguished by density distributions, kinematics, chemical abundances, and presumably formation histories. Could be co-spatial.

Due to the dust obscuration, the best ways to probe the Galactic structure are in infrared, and H I 21 cm line, which also provides the kinematics.

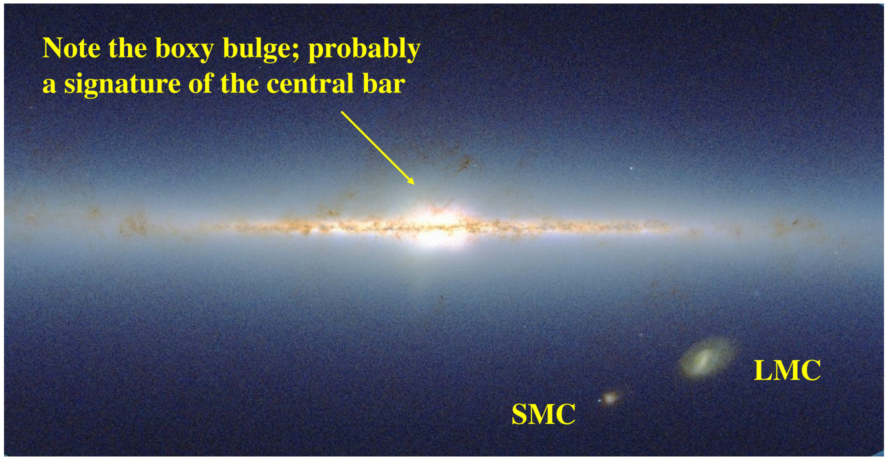
(a) Infrared emission from dust at wavelengths of 25, 60, and 100 μm



(b) Infrared emission from dust at wavelengths of 1.2, 2.2, and 3.4 μm

An IR View of the Galaxy:

(2MASS JHK composite, clipped a bit in longitude)



Note the boxy bulge; probably a signature of the central bar

An IR View From COBE

The observed structure is well reproduced by modern theoretical models

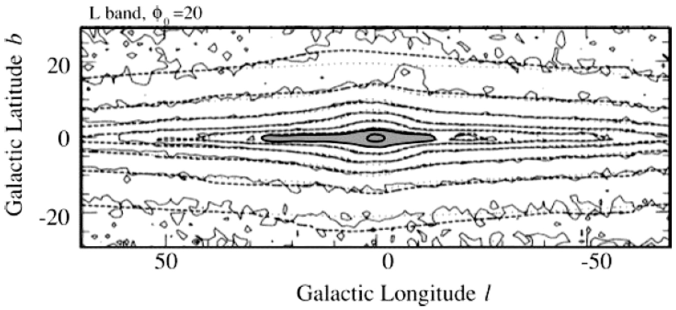
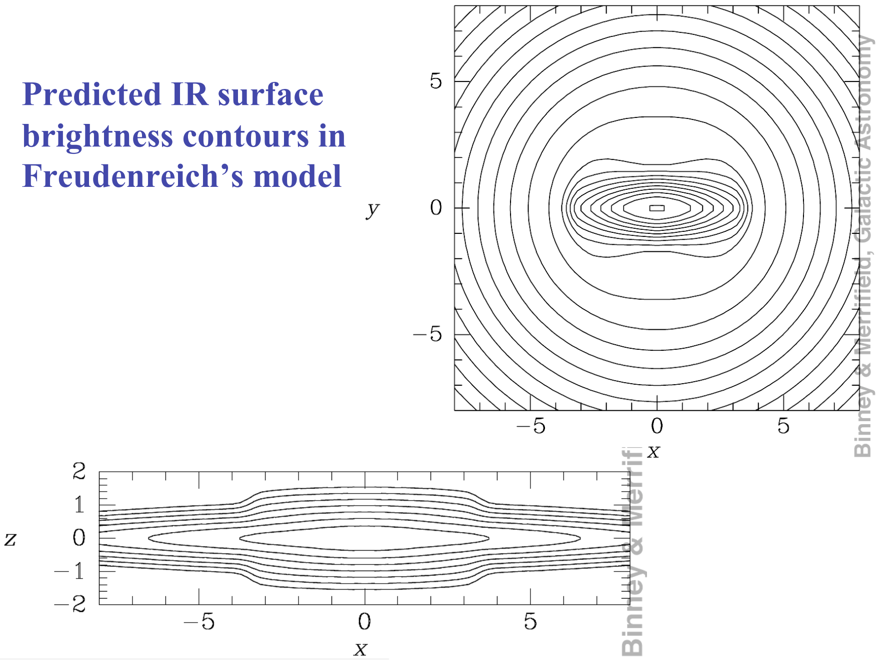


Figure 3. A comparison between the dust-corrected 3.4 μm flux density distribution as obtained by the COBE satellite (full contours, see also Arendt *et al* 1994) and a model (dashed contours; Binney *et al* 1997). In order to demonstrate that the Galaxy is not axisymmetric we filled in the top two contour lines.

Predicted IR surface brightness contours in Freudenreich's model

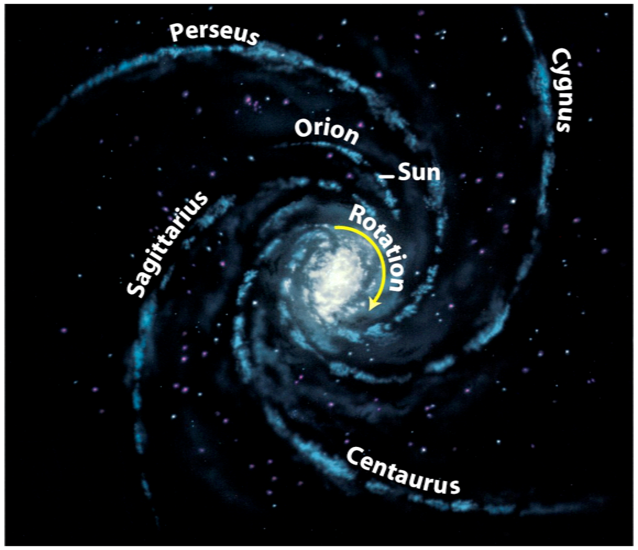


Binney & Merrifield, Galactic Astronomy

Binney & Merrifield

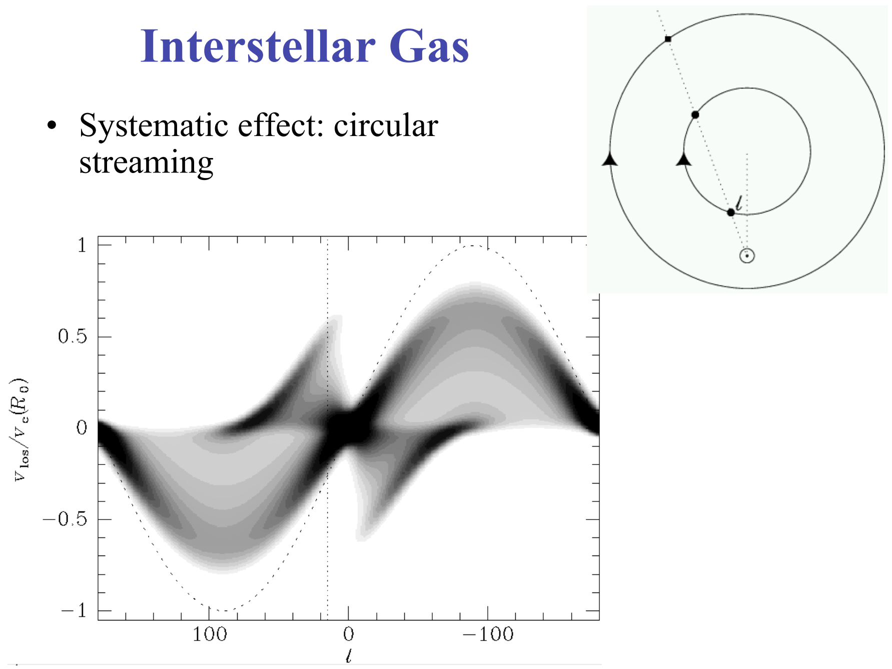
Probing the Galactic Structure Using H I 21 cm Line

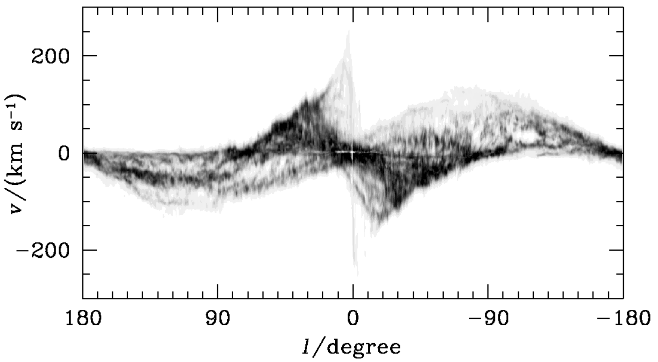
OB associations, H II regions, and molecular clouds in the galactic disk outline the spiral arms



Interstellar Gas

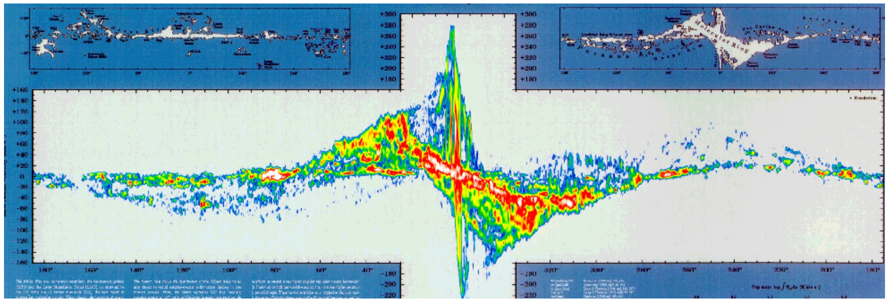
- Systematic effect: circular streaming

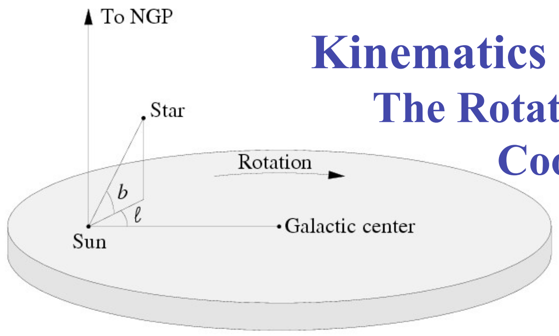




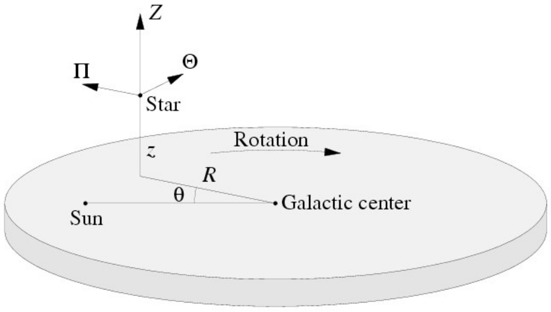
H I

CO





Kinematics of the Galaxy:
The Rotating, Cylindrical Coordinate System



$\Pi \equiv dR/dt$

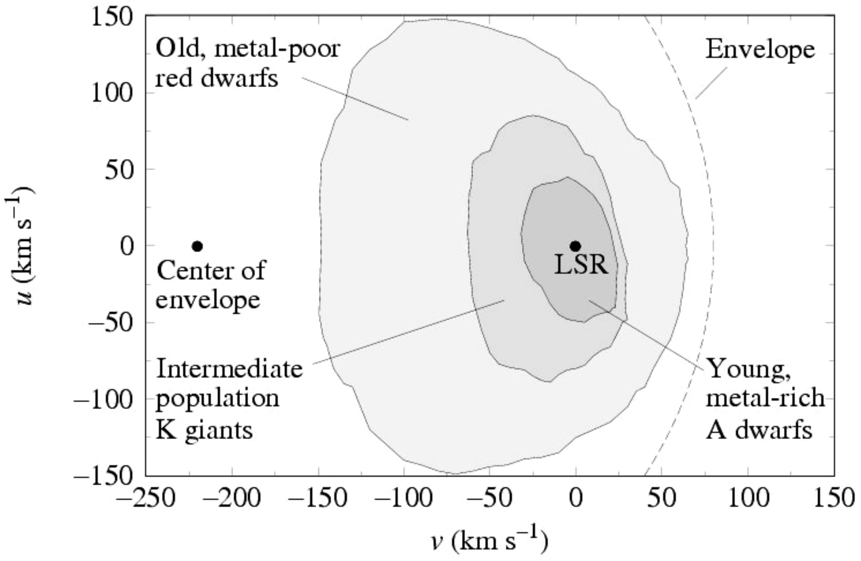
$\Theta \equiv R\, d\theta/dt$

$Z \equiv dz/dt$

The Local Standard of Rest

- Defined as the point which co-rotates with the Galaxy at the solar Galactocentric radius
- Orbital speed of the LSR: $\Theta_{LSR} = \Theta_0 = 220$ km/s
- Define the peculiar velocity relative to the LSR as:
  - $u = \Pi - \Pi_{LSR} = \Pi$
  - $v = \Theta - \Theta_{LSR} = \Theta - \Theta_0$
  - $w = Z - Z_{LSR} = Z$
- The Sun's peculiar motion relative to the LSR:
  - $u_\odot = -9$ km/s
  - $v_\odot = +12$ km/s
  - $w_\odot = +7$ km/s

Stellar Kinematics Near the Sun

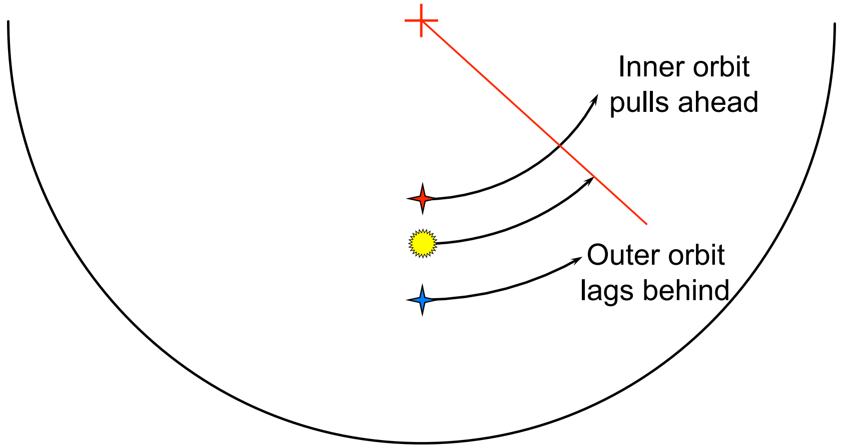


Stellar Kinematics Near the Sun

- Velocity dispersion of stars increases with their mean age: the evidence for a stochastic acceleration due to GMC and spiral arm encounters in a differentially rotating Galaxy
- The shape of the velocity ellipsoid also changes: older stars rotate more slowly; the thick disk rotates with a speed of about a half of that of the thin disk; and the halo does not seem to have a detectable rotation

---

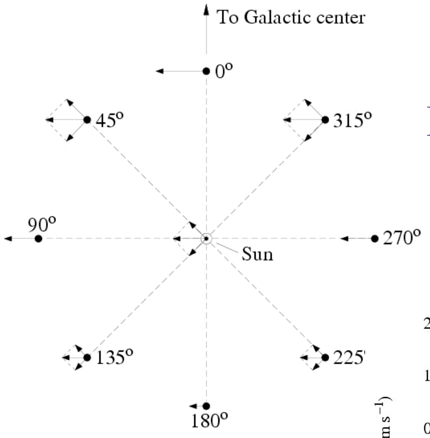
Differential Rotation

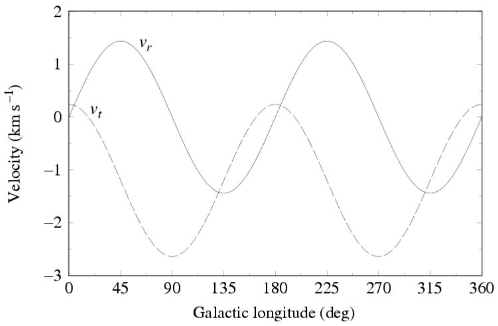


Inner orbit pulls ahead

Outer orbit lags behind

The Appearance of Differential Rotation





Quantifying the Differential Rotation

The mean radial velocity v_r and proper motion μ of a group of stars at Galactic longitude ℓ and distance d from the sun is then

$$v_r = Ad\sin 2\ell, \quad \mu = A\cos 2\ell + B,$$

where the Oort constants A and B are given by

$$A \equiv \frac{1}{2}\left(\frac{\Theta}{R} - \frac{d\Theta}{dR}\right)_{R_o}, \quad B \equiv -\frac{1}{2}\left(\frac{\Theta}{R} + \frac{d\Theta}{dR}\right)_{R_o}.$$

The values of the A and B constants, which measure the local shear and vorticity respectively, can be derived from local measurements of radial velocity and proper motion, and constrain the values of Θ_o, R_o, and $(d\Theta/dR)_{R_o}$.

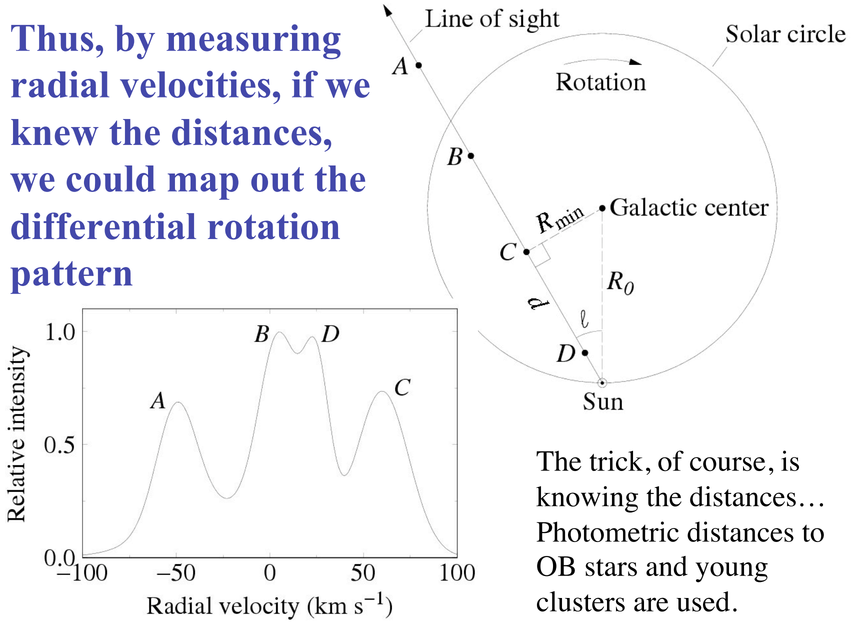
in a differentially rotating disk the radial velocity of an object relative to the LSR is given by

$$v_r = \left[\frac{\Theta(R)}{R} - \frac{\Theta_o}{R_o}\right] R_o \sin\ell, \qquad 3.$$

where $\Theta(R)$ is the circular velocity at the Galactocentric distance R of the object and ℓ is its Galactic longitude. Camm analyzed a sample of planetary

---

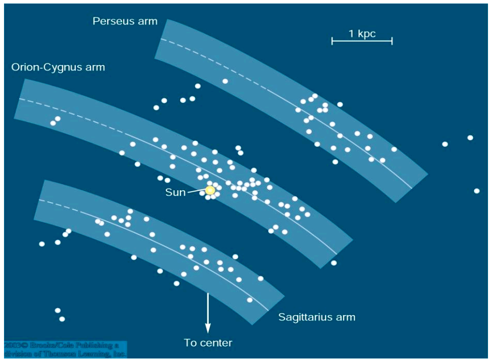
Thus, by measuring radial velocities, if we knew the distances, we could map out the differential rotation pattern



The trick, of course, is knowing the distances… Photometric distances to OB stars and young clusters are used.

Combining Distances and Velocities

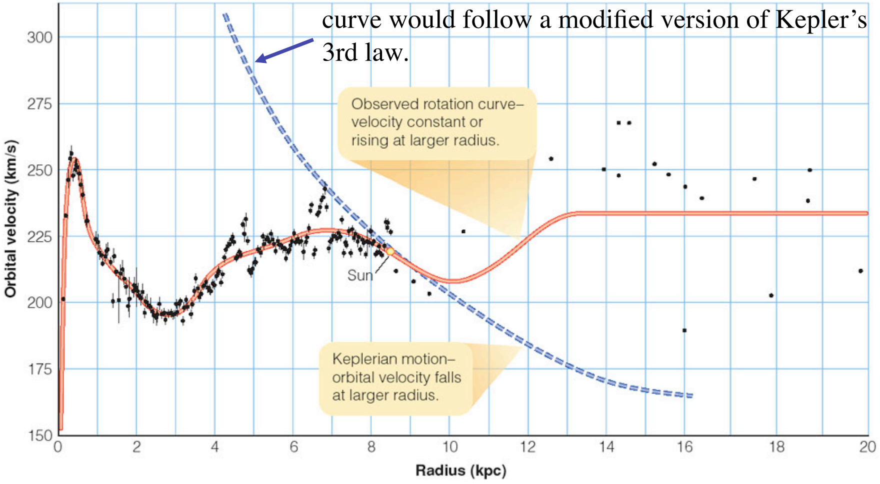
- Since the spiral density waves concentrate the H I, and also may trigger star formation, we can associate young stars, OB associations and clusters with ISM peaks



- Since these stars must be young, they could not have moved very far relative to the gas
- Fortunately, they are also very bright and can be seen far away
- Of course, the extinction must be also understood very well

---

The Observed Rotation Curve of the Milky Way



If all mass was concentrated in the center, rotation curve would follow a modified version of Kepler's 3rd law.

Observed rotation curve–velocity constant or rising at larger radius.

Keplerian motion–orbital velocity falls at larger radius.

Interpreting the Rotation Curve

Motions of the stars and gas in the disk of a spiral galaxy are approximately circular (v_R and $v_z << v_\phi$).

Define the circular velocity at radius r in the galaxy as V(r). Acceleration of the star moving in a circular orbit must be provided by a net inward gravitational force:

$$\frac{V^2(r)}{r} = -F_r(r)$$

To calculate $F_r(r)$, must in principle sum up gravitational force from bulge, disk and halo.

If the mass enclosed within radius r is M(r), gravitational force is:

$$F_r = -\frac{GM(r)}{r^2}$$

Simple model predicts the rotation curve of the Milky Way ought to look like:

$$v \approx \sqrt{\frac{GM_{galaxy}}{R}} = 210 \left(\frac{M_{galaxy}}{8 \times 10^{10} M_{sun}} \right)^{1/2} \left(\frac{R}{8 \text{ kpc}} \right)^{-1/2} \text{ km s}^{-1}$$

This number is about right - Sun's rotation velocity is around 200 km s^{-1}.

Scaling of velocity with $R^{-1/2}$ is not right - actual rotation velocity is roughly constant with radius.

Implies:

- gravity of visible stars and gas largely explains the rotation velocity of the Sun about the Galactic center.
- Flat rotation curve requires extra matter at larger radii, over and above visible components.

Dark matter…

(From P. Armitage)

Mass Distribution in a Uniform Sphere:

If the density ρ is constant, then:

$$M(r) = \frac{4}{3}\pi r^3 \rho$$

$$V(r) = \sqrt{\frac{4\pi G\rho}{3}} r$$

Rotation curve rises linearly with radius, period of the orbit $2\pi r$ / V(r) is a constant independent of radius.

Roughly appropriate for central regions of spiral galaxies.

(From P. Armitage)

Power law density profile:

If the density falls off as a power law:

$$\rho(r) = \rho_0 \left(\frac{r}{r_0} \right)^{-\alpha}$$

…with $\alpha < 3$ a constant, then:

$$V(r) = \sqrt{\frac{4\pi G \rho_0 r_0^\alpha}{3 - \alpha}} r^{1-\alpha/2}$$

For many galaxies, circular speed curves are approximately flat (V(r) = constant). Suggests that mass density in these galaxies may be proportional to r^{-2}.

(From P. Armitage)

Simple model for a galaxy with a core:

Spherical density distribution:

$$4\pi G\rho(r) = \frac{V_H^2}{r^2 + a_H^2}$$

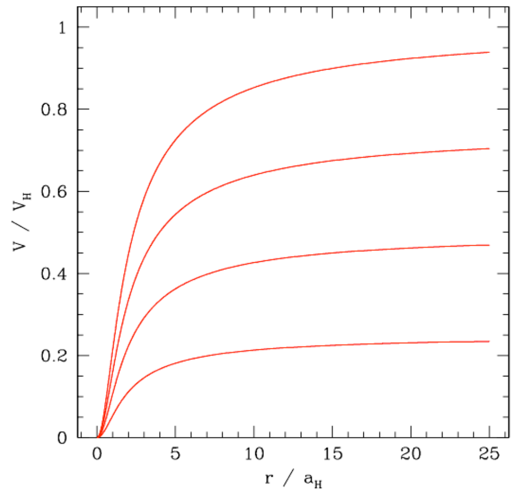
- Density tends to constant at small r
- Density tends to r^{-2} at large r

Corresponding circular velocity curve is:

$$V(r) = V_H\sqrt{1 - \frac{a_H}{r}\arctan\left(\frac{r}{a_H}\right)}$$

(From P. Armitage)

Resulting rotation curves:



Not a bad representation of the observed rotation curves …

(From P. Armitage)

Galactic Bar: Timeline

•1950s: Oort and others posit an “explosive event” at Galactic Ctr. to explain expanding spiraal features, but energy budget exorbitant (van der Kruit 1971)

Short bar/triaxial bulge

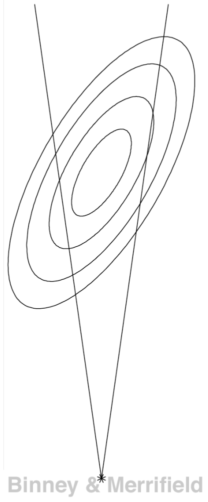
- 1964: de Vaucouleurs first suggests central bar
- 1991: Blitz & Spergel suggest rotating triaxial spheroid to explain large-scale *l*-*v* asymmetries in HI; Binney et al. model HI, CO & CS i.t.o. central bar
- 1995: *COBE*/DIRBE detects IR diffuse emission asymmetries in gal. long. (Dwek et al.); Unavane & Gilmore (NIR point sources)
- 1998: Freudenreich (model of *COBE*/ DIRBE diffuse NIR maps)
- 2005: Babusiaux & Gilmore (NIR point sources)

Long bar

- 1975: Peters (modelling HI flow)
- 1992: Weinberg (AGB stars)
- 2000: Hammersley et al. (NIR point sources)
- 2005: Benjamin et al. (GLIMPSE)
- 2006: Cabrera-Lavers et al. (red clump sources)

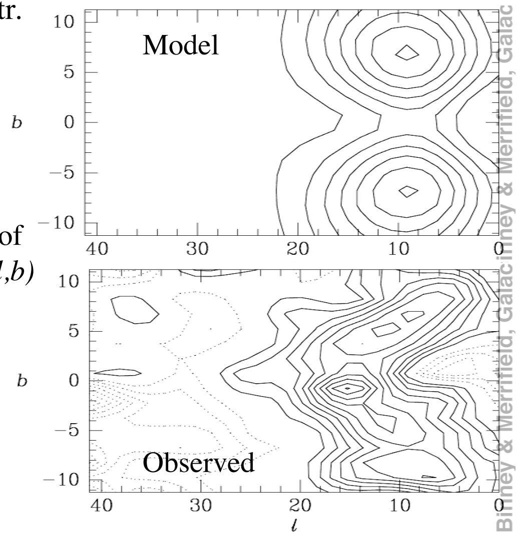
Looking for a Bar

Expect asymmetry of surface brightness or source counts on the opposite sides of the Gal. ctr.



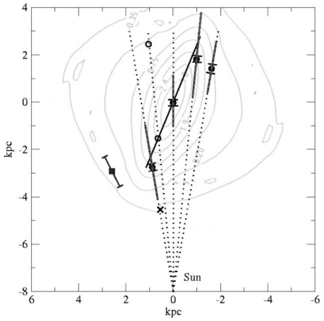
Binney & Merrifield

Contours of *I(l,b) / I(-l,b)*



Inner Bar

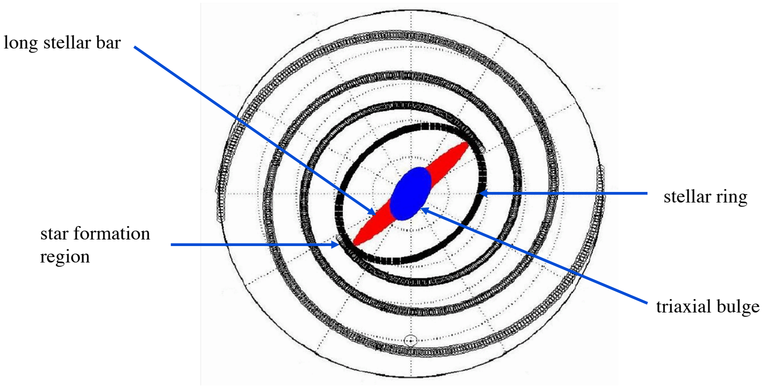
- Deep NIR photometry of RC stars in five l.o.s. very close to GP
- Fat bar (*b*/*a* = (3-4/10))
- φ = 22 +/- 5 deg
- At *l* = -9.8 deg a pseudo-ring defining end of bar (Hammersley et al. 2000 point interpreted as lying on pseudo-ring)



Babusiaux & Gilmore (2005), fig. 7: Overlaid is Bissantz & Gerhard (2002) model of the bar

---

Tenerife model


long stellar bar

stellar ring

star formation region

triaxial bulge

Cabrera-Lavers (2004), PhD thesis

Gas Responds to the Spiral Density Wave Pattern, and the Rotating Bar

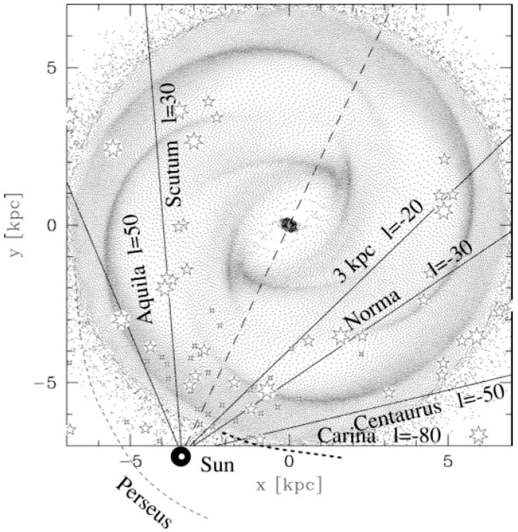
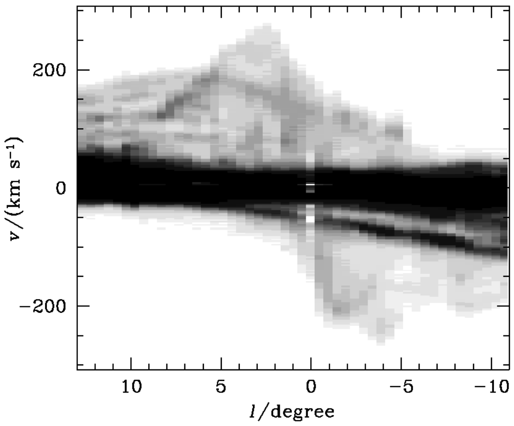


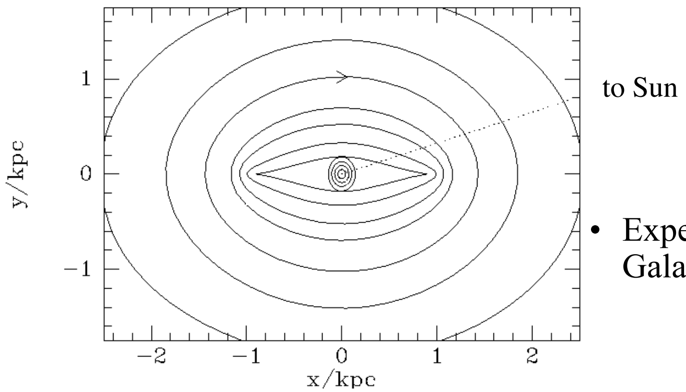
Figure 5. The gas flow in the Galactic disk under the influence of the barred bulge with a bar angle ϕ = 20°, corotation radius at ~3.1 kpc as well as a dark halo component (Englmaier and

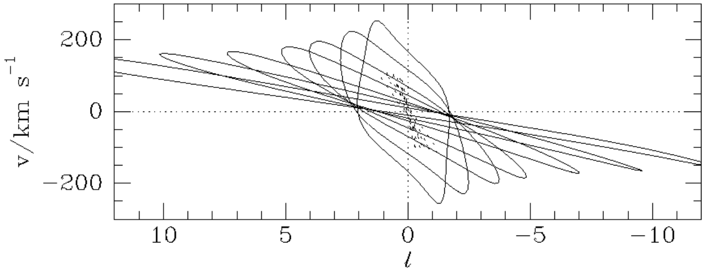
---

The Galactic Bar

- Gas towards the GC moving away at ~150km/s



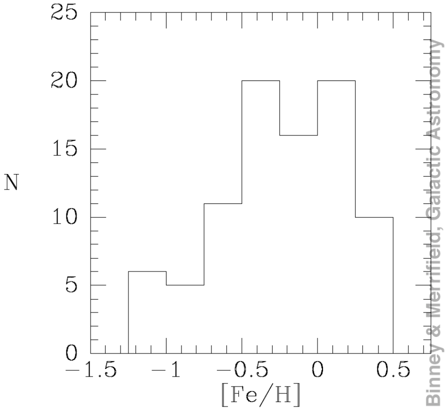


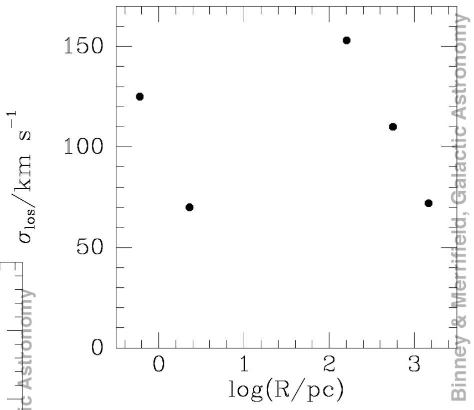


- Expected if Galaxy barred

Galactic Bulge

- Old, metal-rich stellar pop. (self-enrichment)



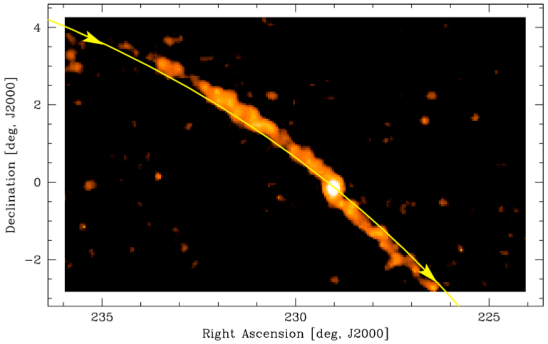


- Roughly flat velocity dispersion ~ 110 km/s

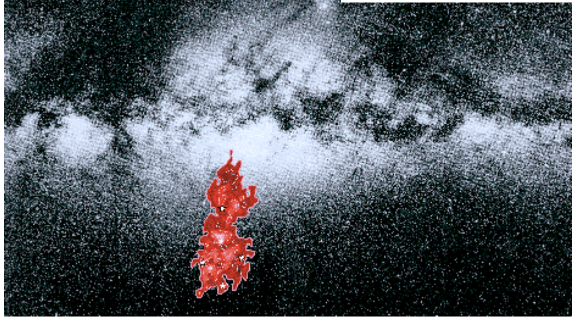
Formation of the Milky Way Galaxy: The Early Models

- **The Monolithic Collapse** (Eggen, Lynden-Bell, & Sandage)
  - Galaxy bulge and halo form within a single free-fall time
  - Stars on more eccentric (~ radial) orbits most metal-poor
  - Disk forms later
  - No longer believed, but some aspects may be right
- **Hierarchical Merging** (Searle & Zinn)
  - Old stars form in small systems (~ dwarf galaxies), and get merged into the Galactic halo
  - Disk forms later
  - Now believed to be basically correct, but does not treat formation of the metal-rich bulge very well

Hierarchical Formation of the Galaxy's Halo Continues Today



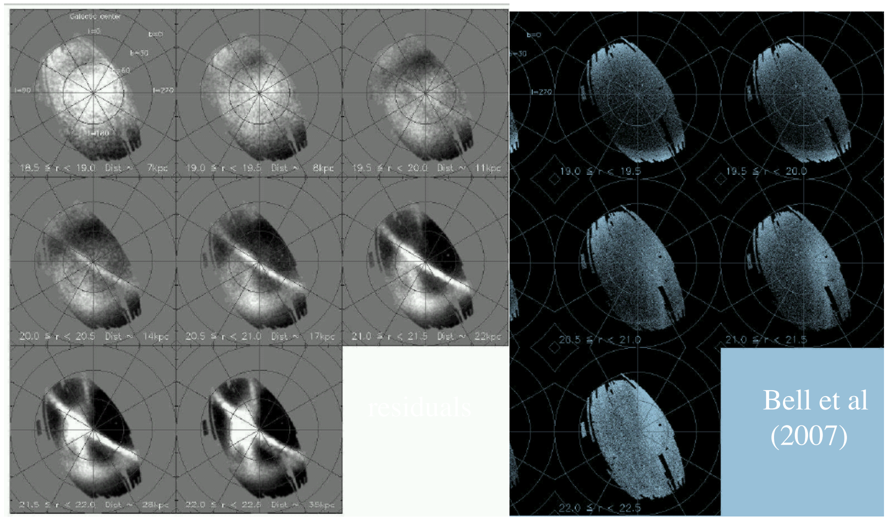
↑ Palomar 5 globular cluster tidal tail



↩ Sagittarius dwarf galaxy

Stellar Halo: Star Count Residuals

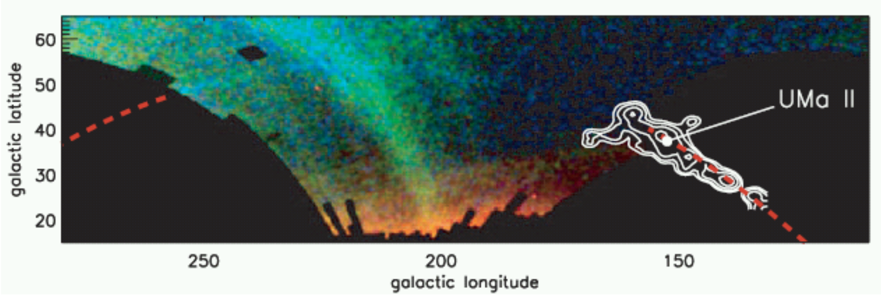
(Observed – Model, from SDSS)



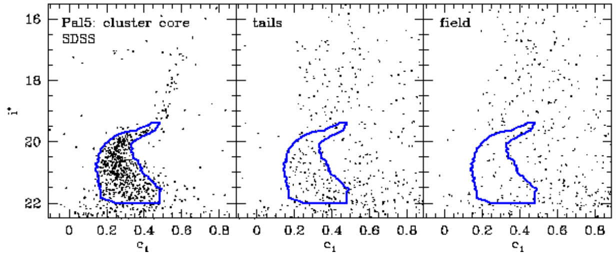
residuals

Bell et al (2007)

Stellar Streams in the Galactic Halo

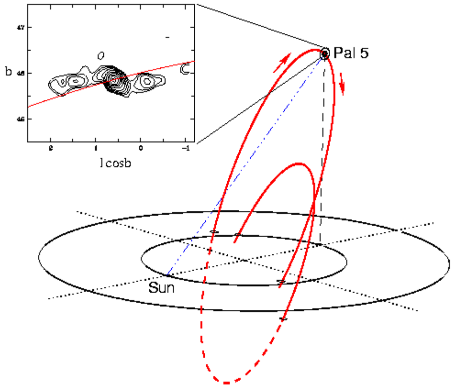


Belokurov et al (2007)



Sloan digital sky survey (SDSS)

Tidal streams (Pal 5)



Formation of Our Galaxy: A Summary

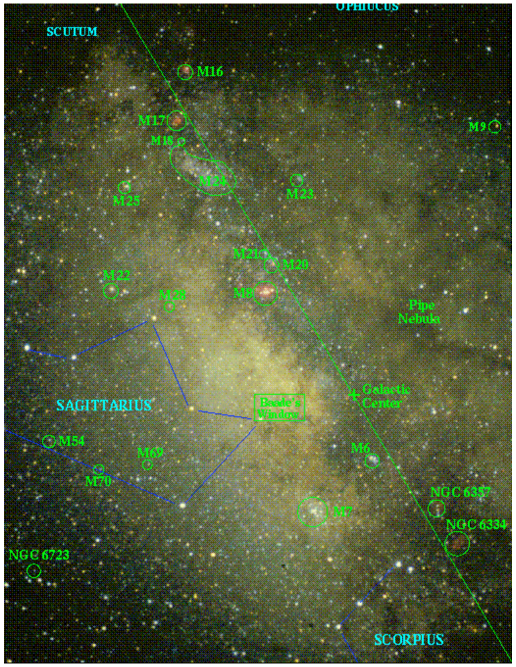
- Dark halo assembly by infall and merging of DM density fluctuations, with one dominant potential well
- Star formation ignites in densest fragments ~ 13 Gyr ago
- In the proto-Bulge, SN ejecta are recycled, leading to an old, metal-rich stellar population
- In smaller fragments, most of which get tidally disrupted to make the stellar halo and globular clusters, and only the low, primordial abundances are retained
- These first star forming systems produce the pressure-supported stellar components of the Galaxy (bulge, halo)

Formation of Our Galaxy: A Summary

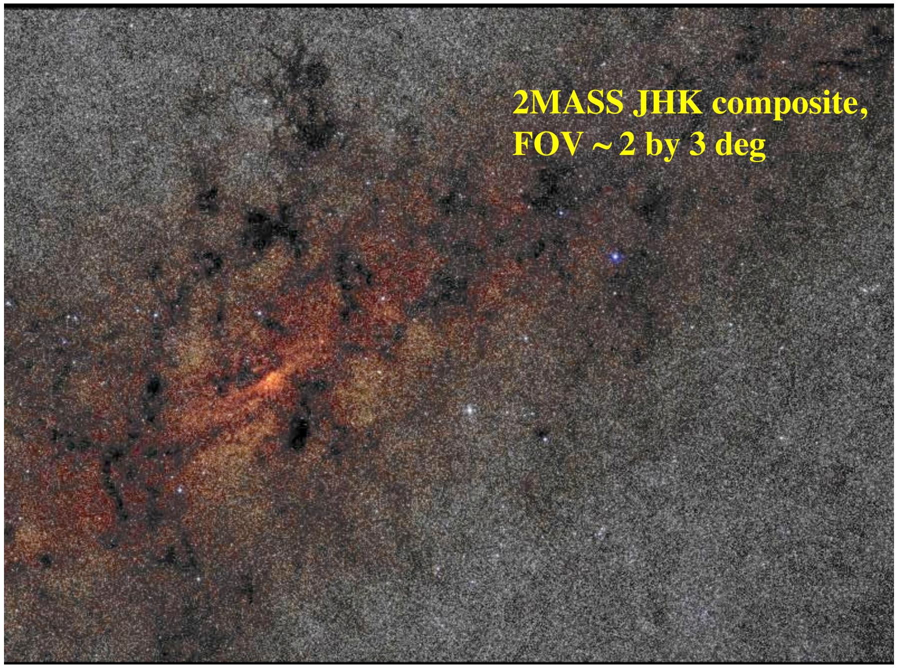
- Subsequent dissipative accretion of gas forms the proto-disk of the Milky Way
- Star formation in the disk stars from the densest regions near the center and expands outward (~ 9 Gyr ago in the Solar neighborhood?)
- Enriched gas is recycled within the disk, leading to ever higher abundances
- No major mergers happened - otherwise the cold, thin disk would not have survived
- The origins of the thick disk are murky: an intermediate system between the bulge and the thin disk

---

Now Let's Go To The Galactic Center …

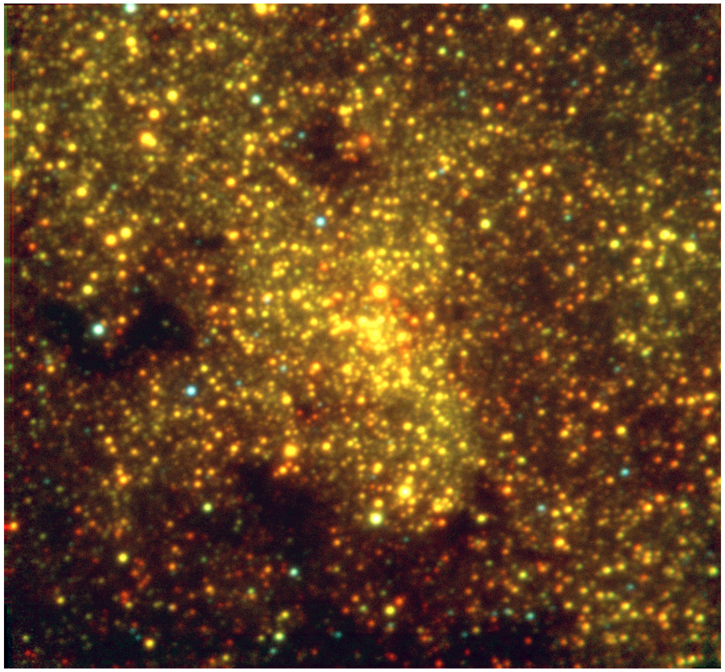


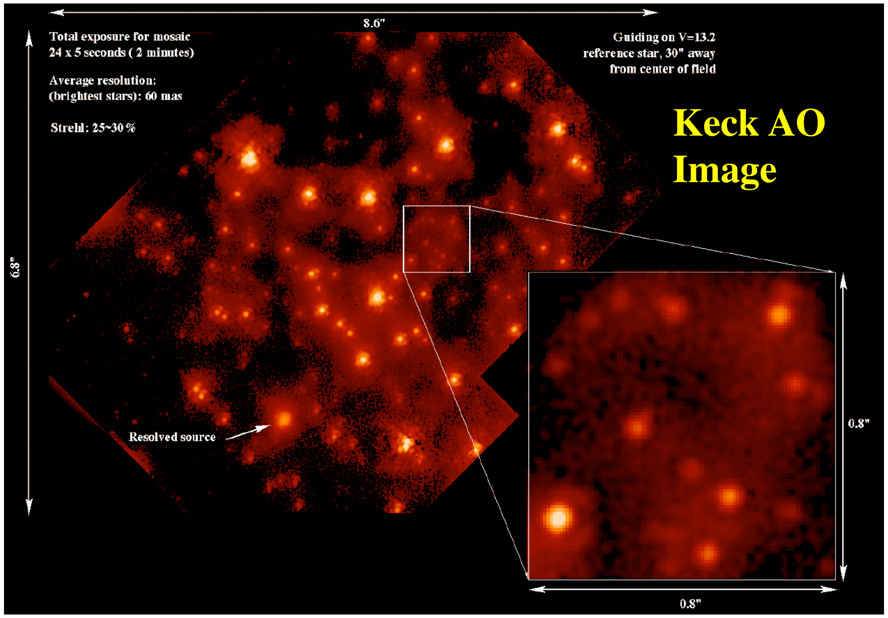
Visible light image,
~ 10 by 15 deg



2MASS JHK composite, FOV ~ 2 by 3 deg

K-band image, FOV = 1.7 arcmin

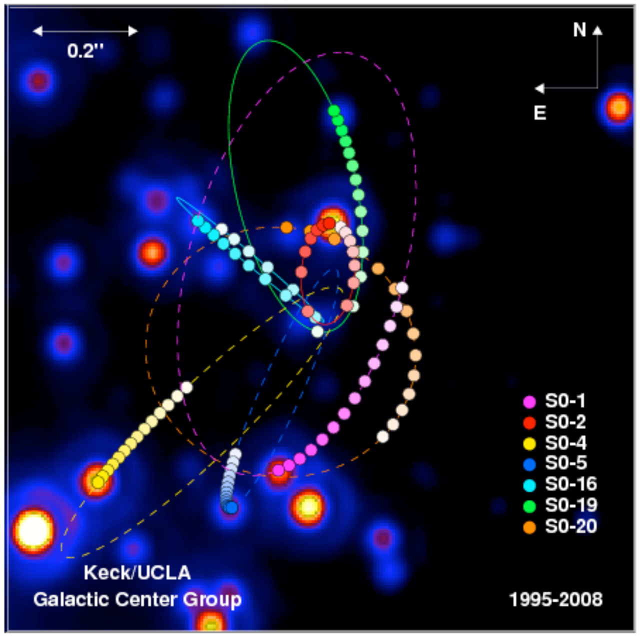




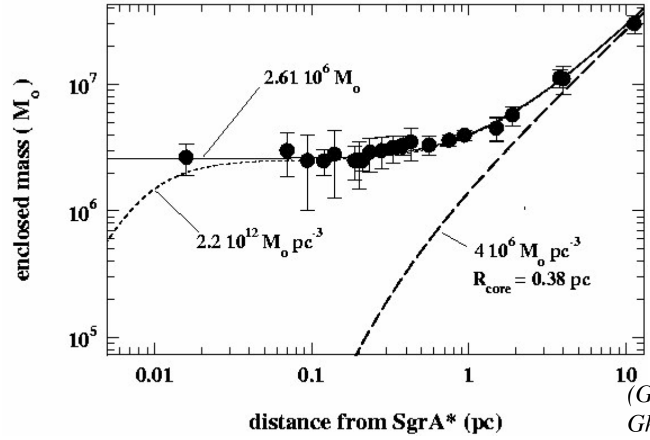
Note: at D = 8 kpc, 1 arcsec = 8000 au = 1.2×10^{16} cm

Proper Motions of Stars Near the Galactic Center

From Keck IR speckle imaging *(A. Ghez et al.)*



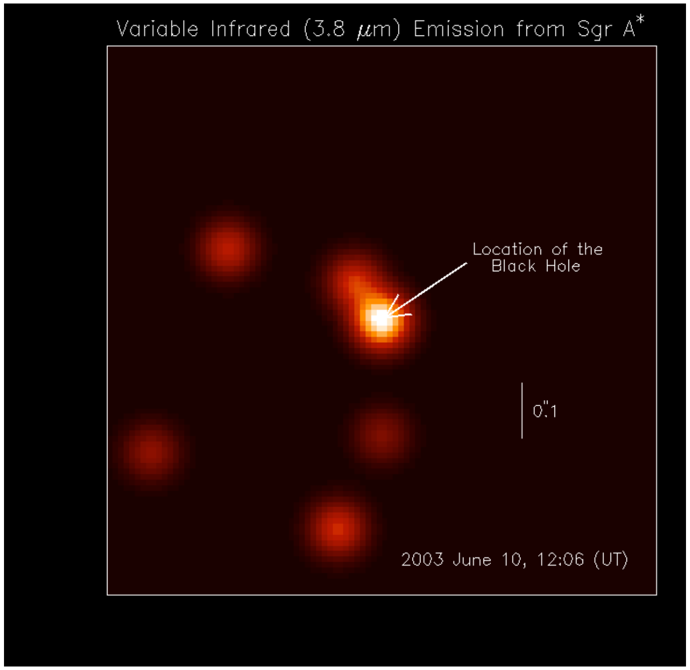
Dynamical Evidence for a Supermassive Black Hole at the Galactic Center



(Genzel et al., Ghez et al.)

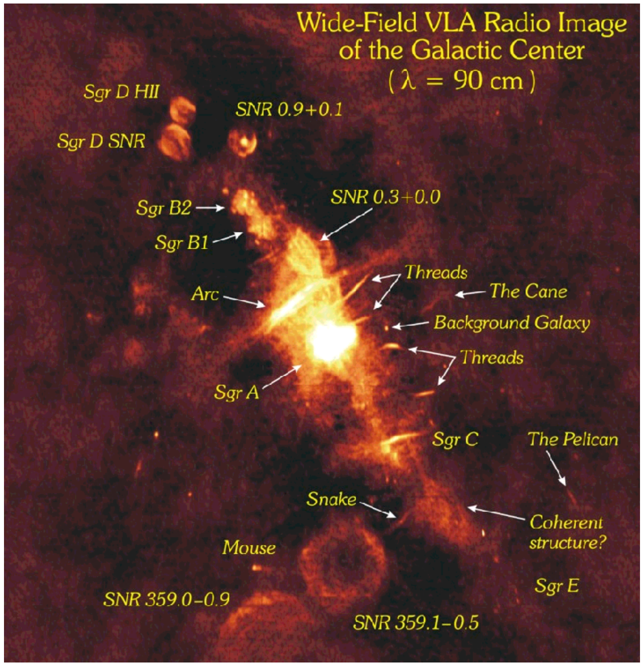
Note: $R_S\ (M_\bullet = 2.6 \times 10^6\ M_\odot) = 7.8 \times 10^8$ cm $= 6.5 \times 10^{-8}$ arcsec

Variable IR Emission From the Galactic Center Source

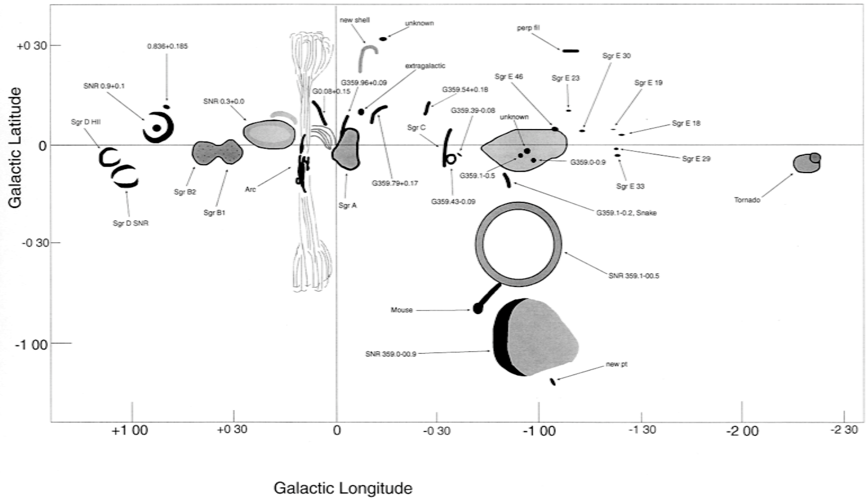


From Keck IR AO imaging *(A. Ghez et al.)*

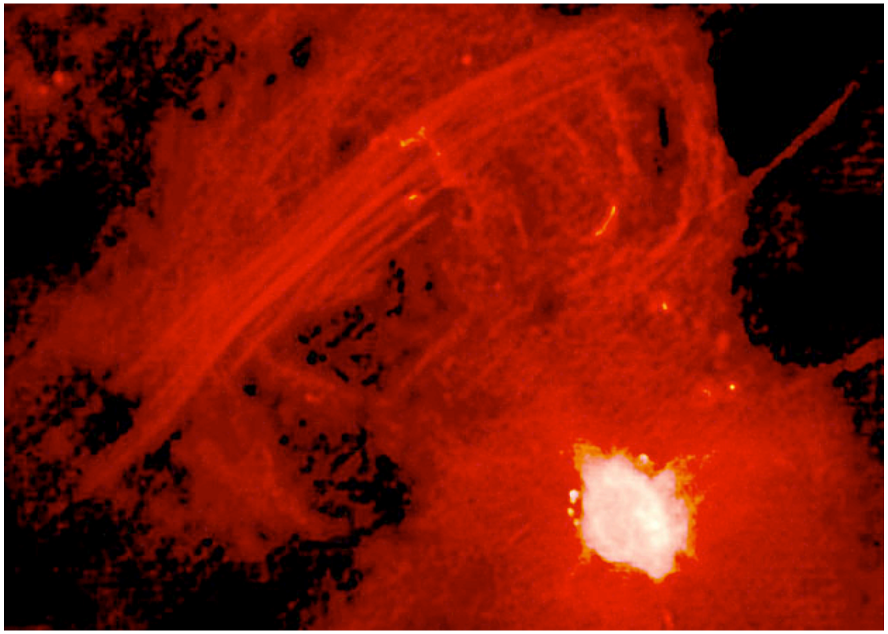
The Galactic Center Region in Radio: Evidence for Lots of Star Formation



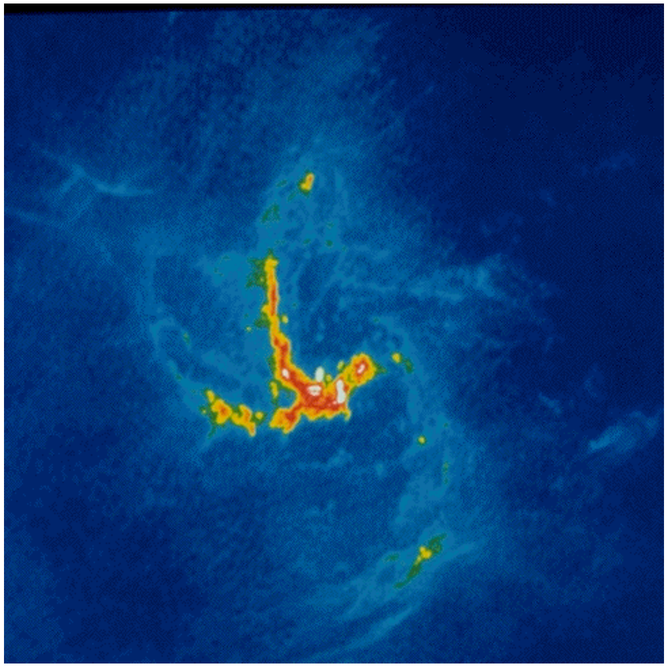
The Galactic Center Region in Radio: A Schematic View



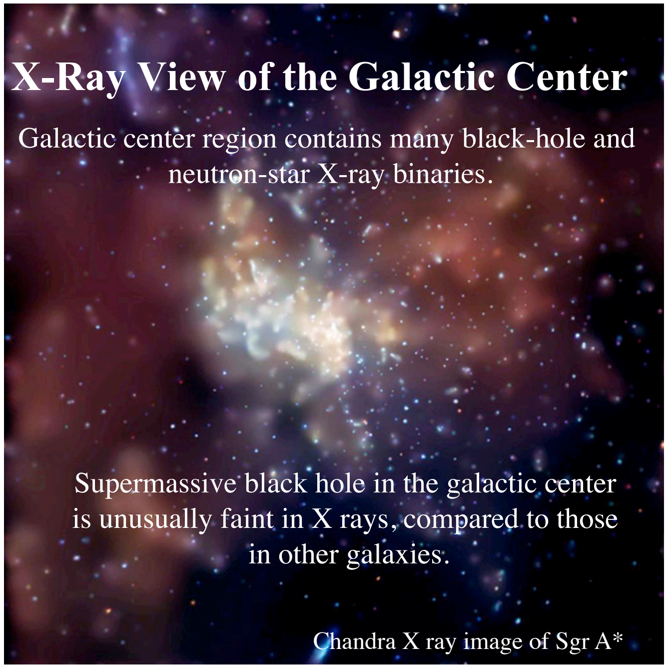
Radio Filaments and Arches



Mini-Spiral of Ionized Gas



Feeding
the black
hole?



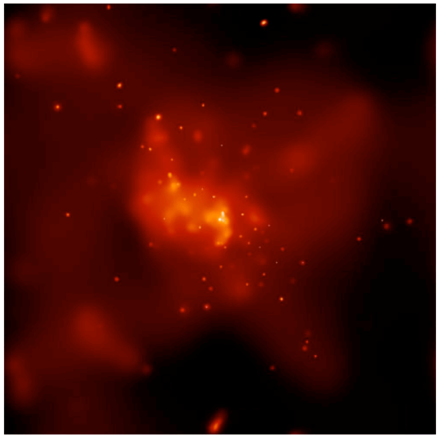
X-Ray View of the Galactic Center

Galactic center region contains many black-hole and neutron-star X-ray binaries.

Supermassive black hole in the galactic center is unusually faint in X rays, compared to those in other galaxies.

Chandra X ray image of Sgr A*

X-ray Flare from Sgr A*



*Chandra image of Sgr A**

- The rapid flare rise/drop time (< 10 min) implied that the emission region is only 20 times the size of the event horizon of the 2.6 million $M_\odot$ black hole.
- Observations are consistent with the existence of a supermassive black hole at the center of our Galaxy.
- Energy from flare probably came from a comet-sized lump of matter…torn apart before falling beneath the event horizon!