

# **ASTR 511**

## **Galactic Astronomy**

### **Lecture 06, Part II**

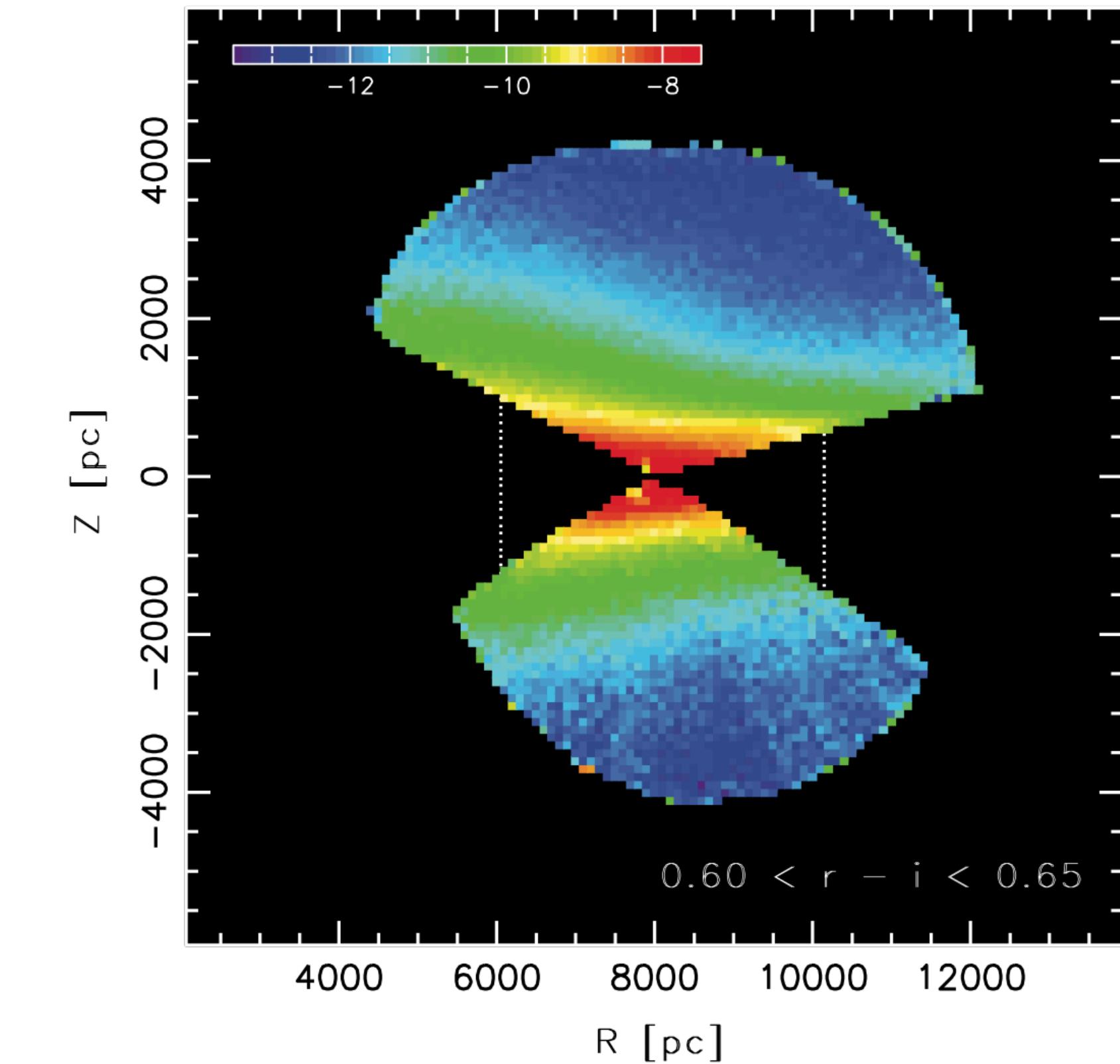
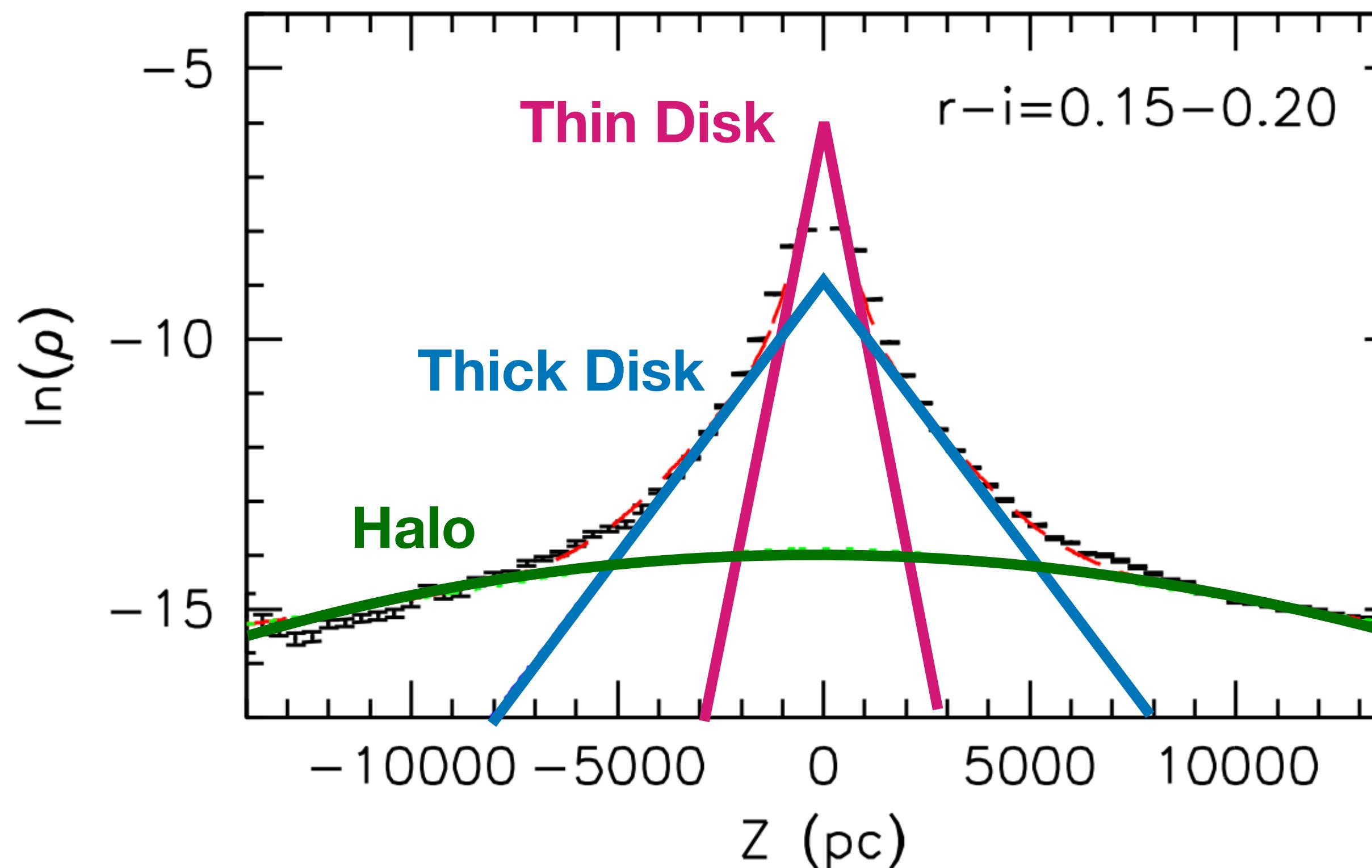
#### **Structure & Properties of the Milky Way**

Prof. James Davenport (UW)

Winter 2023

# The Milky Way's Disk

- in  $(R, Z)$  space:  
An “exponential disk”, e.g. Jurić+2008



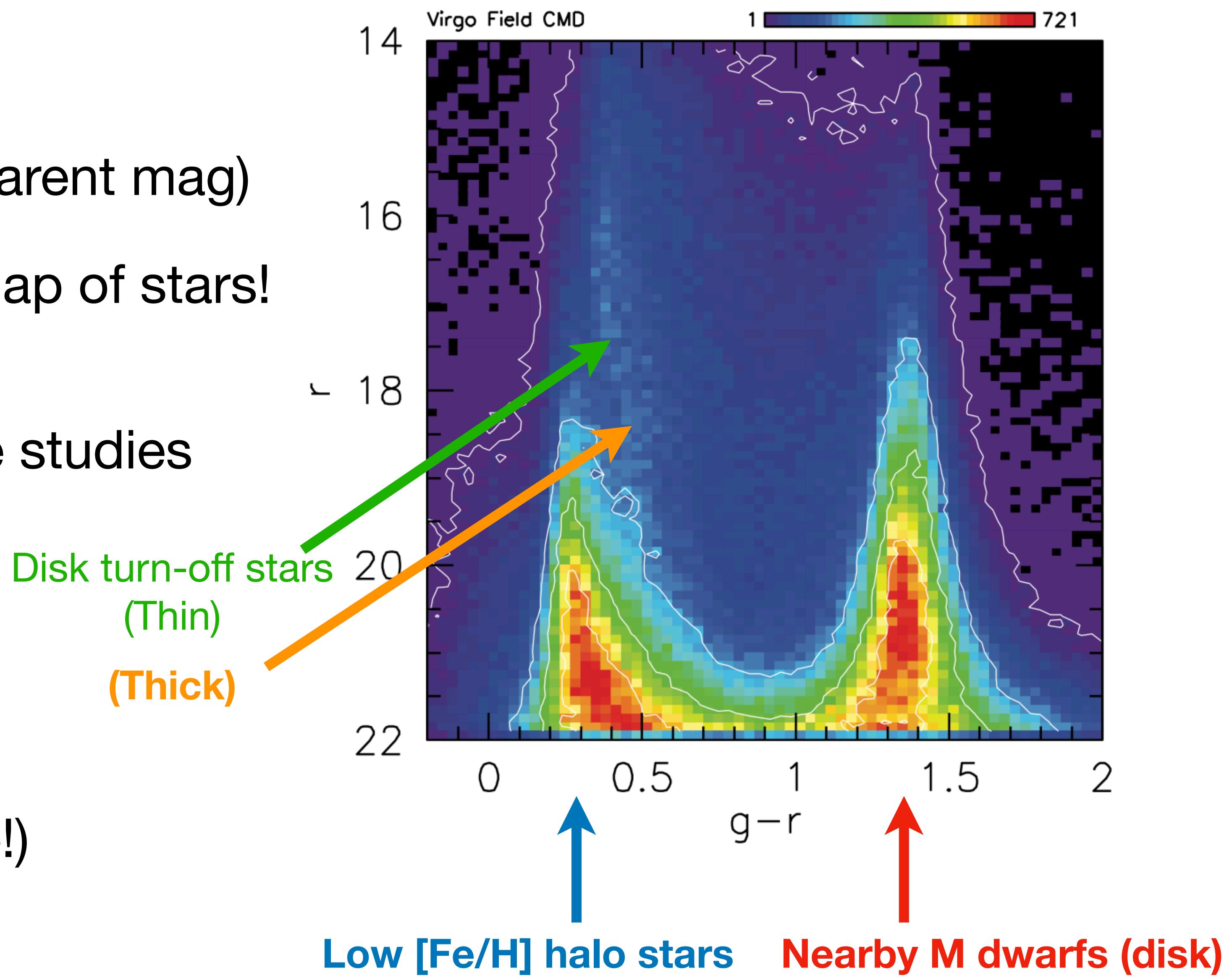
neighborhood within  $\sim 2$  kpc. They show a striking simplicity in good agreement with a double exponential disk model,

$$\rho(R, Z) = \rho(R_\odot, 0) e^{R_\odot/L} \exp\left(-\frac{R}{L} - \frac{Z + Z_\odot}{H}\right), \quad (19)$$

where  $\rho$  is the number density of disk stars,  $R_\odot$  and  $Z_\odot$  are the cylindrical coordinates of the Sun, and  $L$  and  $H$  are the exponential scale length and scale height, respectively. This model pre-

# Hess Diagram

- A CMD *without* distances (apparent mag)
  - NOT just a heat or density map of stars!  
e.g. wrong here
- Important for galactic structure studies  
e.g. Jurić+2008
- A few key features...  
(e.g. Gao+2012)
- You see this in your HW2, w/  
cluster distinctly on top (I hope!)



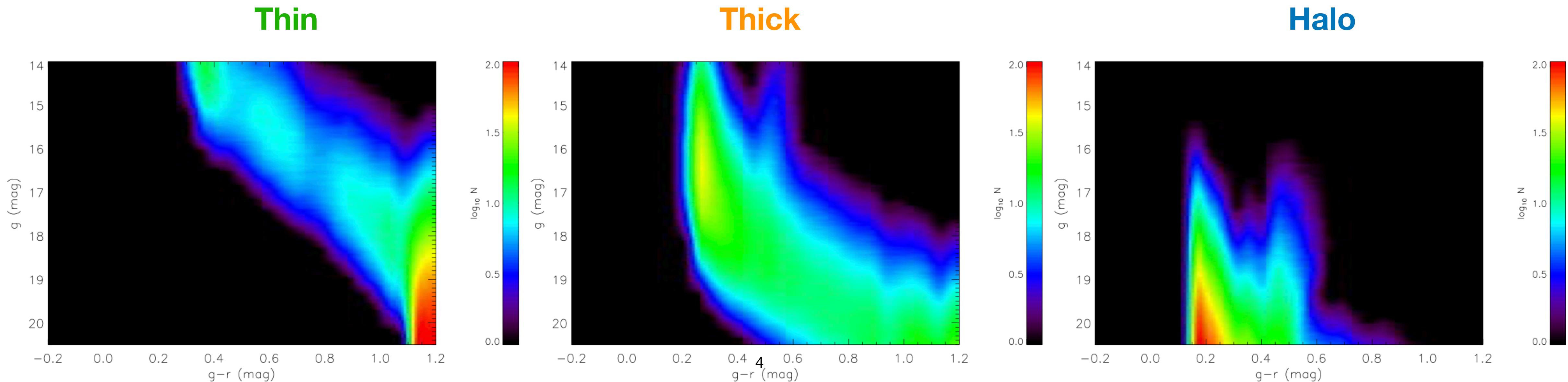
# Hess Diagram

- Use stellar models (isochrone + IMF, binary frac), star formation history assumptions, gal structure model (e.g. Besançon, galfast) to forward-model Hess Diagram

(Gao+2012)

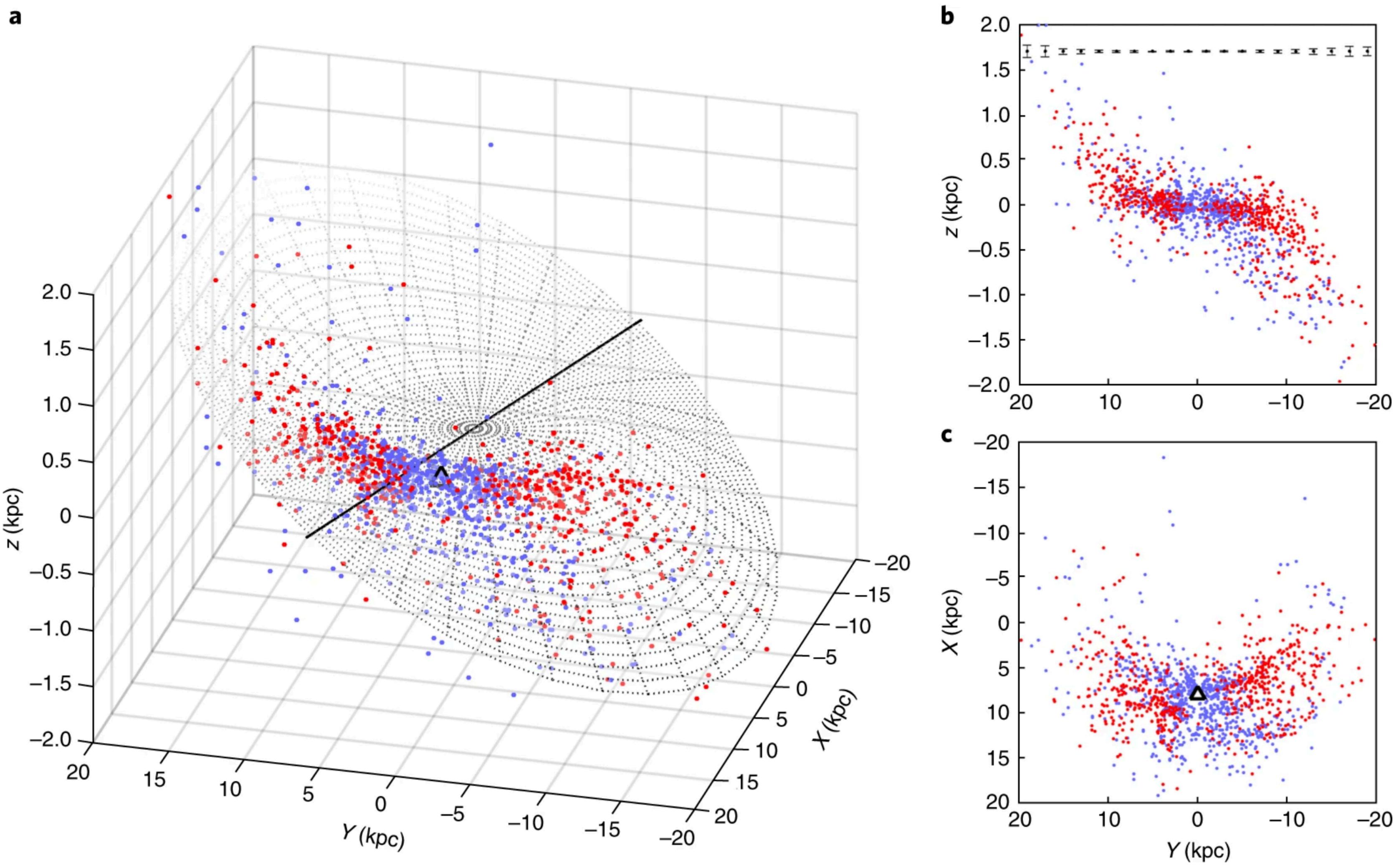
- Hess Diagram not very popular right now b/c of Gaia...

- Prediction:  
As we reach limits of Gaia distances, & especially when LSST comes online, Astronomers will rediscover this handy framework!



# Warped Disk

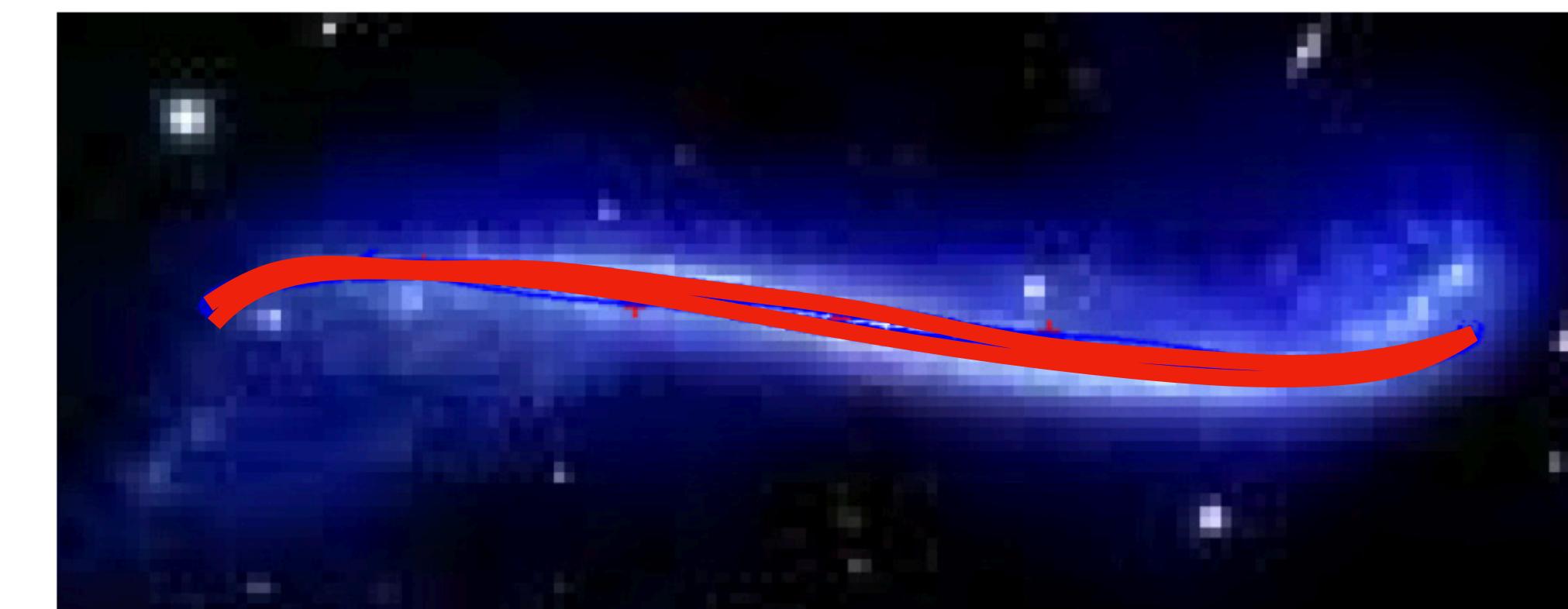
- Long seen in gas (HI)
- Now traced w/ stars
- Here: Cepheids from WISE + Gaia DR2
- Likely caused by merger from dwarf galaxy... but which?!
  - Sagittarius ?



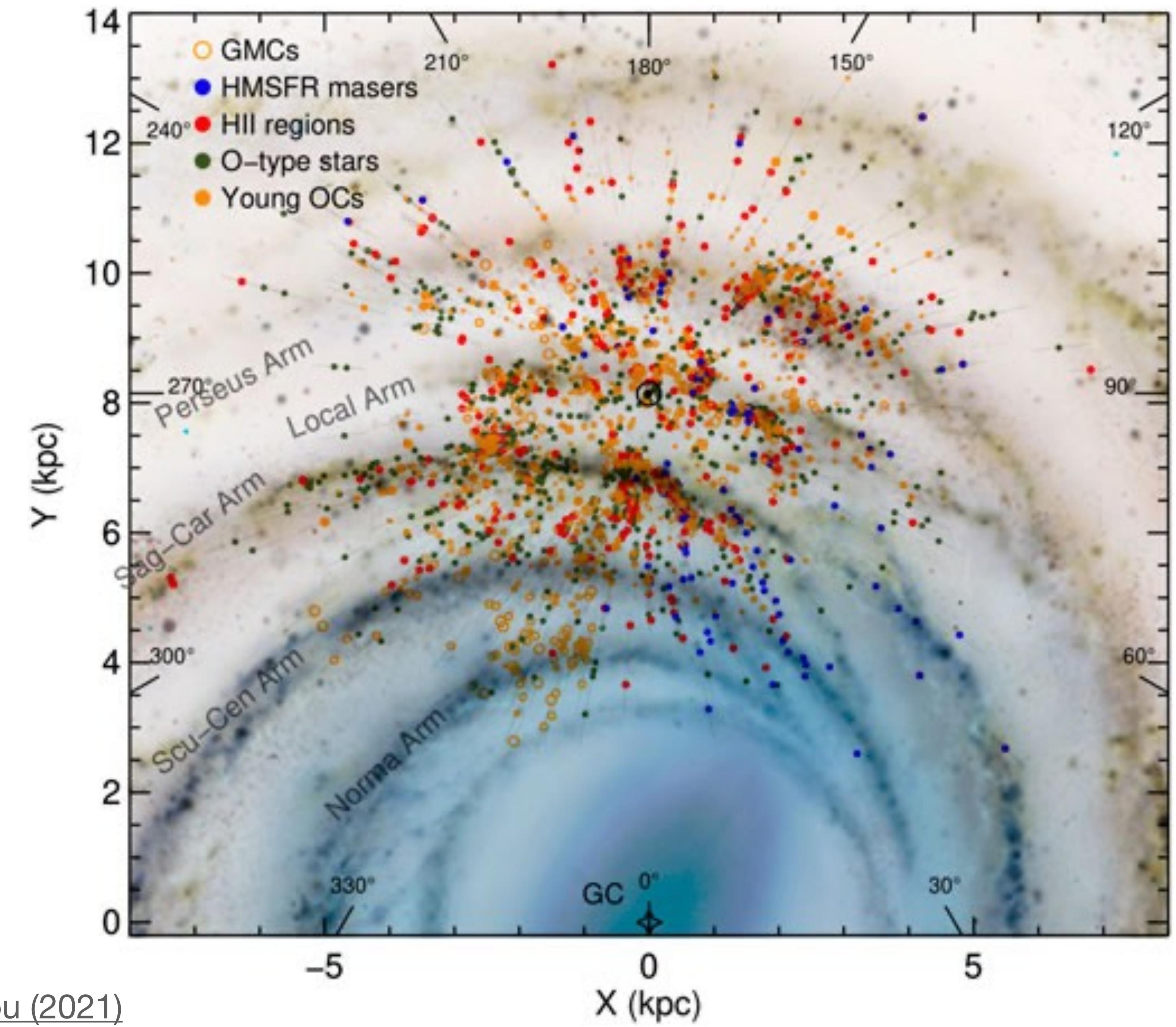
Chen+2019

# Warped Disk

- Warped disks are very common!
- ~50% of edge-on spirals show evidence for a warp (Sánchez-Saavedra+2003)
- Warps may be caused by merger events, OR could be long-lived features... e.g. a generic outcome of disk+bar orbital dynamics (Sánchez-Martín+2016)



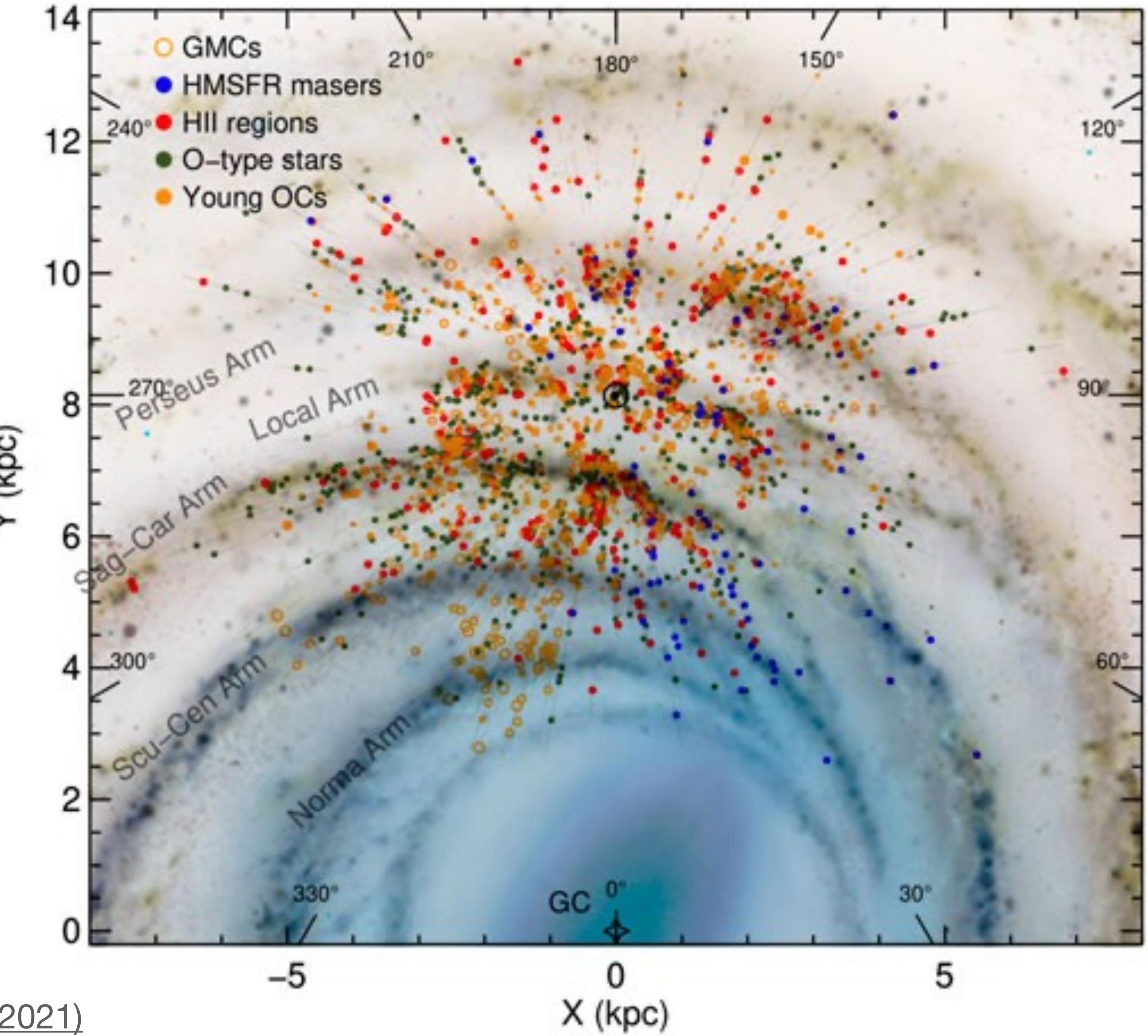
From Lecture 2  
 $d > 500\text{pc}$



Hou (2021)

# Spiral Arms

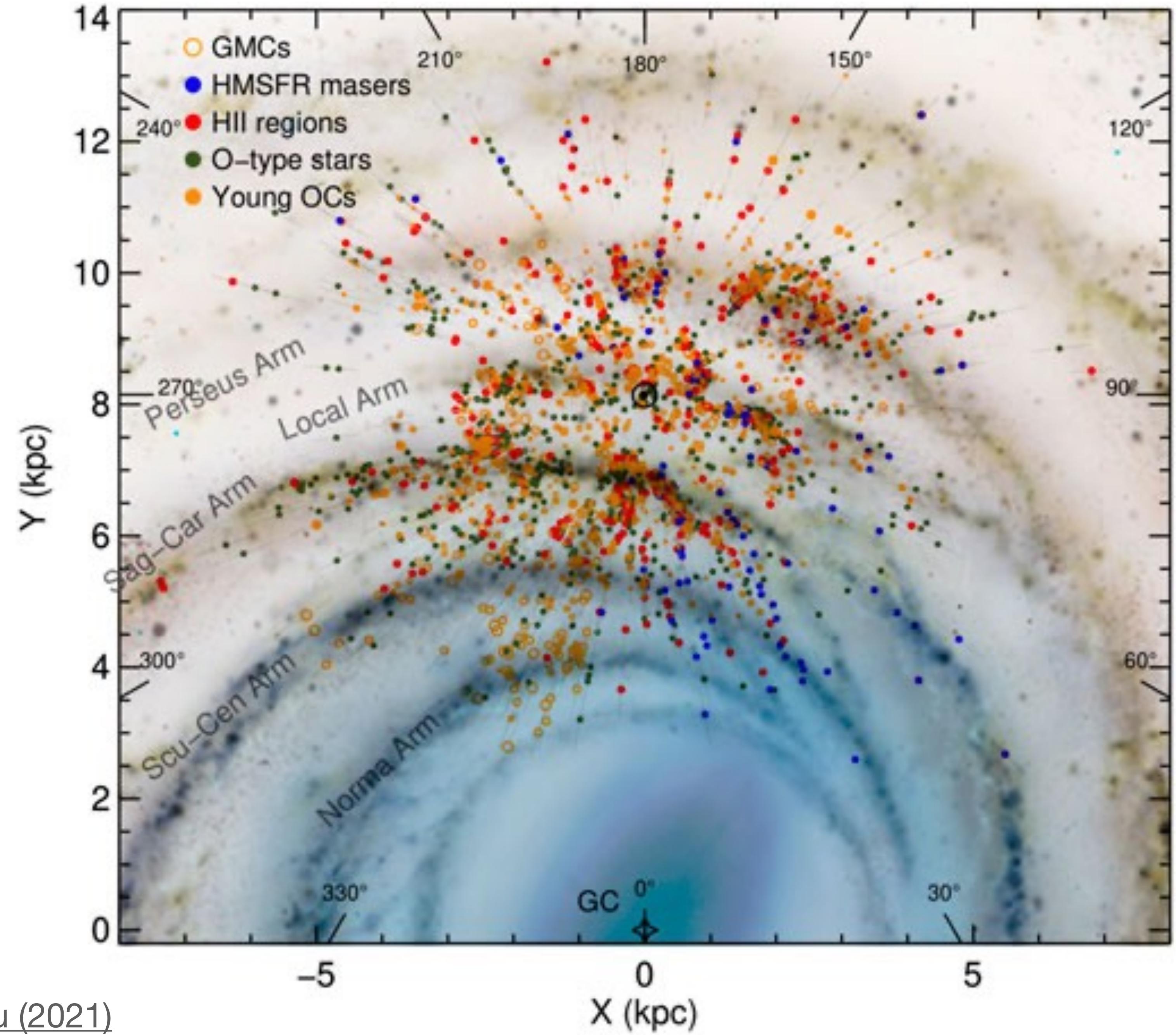
- Arm-like features seen with *many* tracers: gas, GMC's, clusters, cepheids, stars, masers...
- Shape is usually described as a **logarithmic spiral**



Hou (2021)

# Spiral Arms

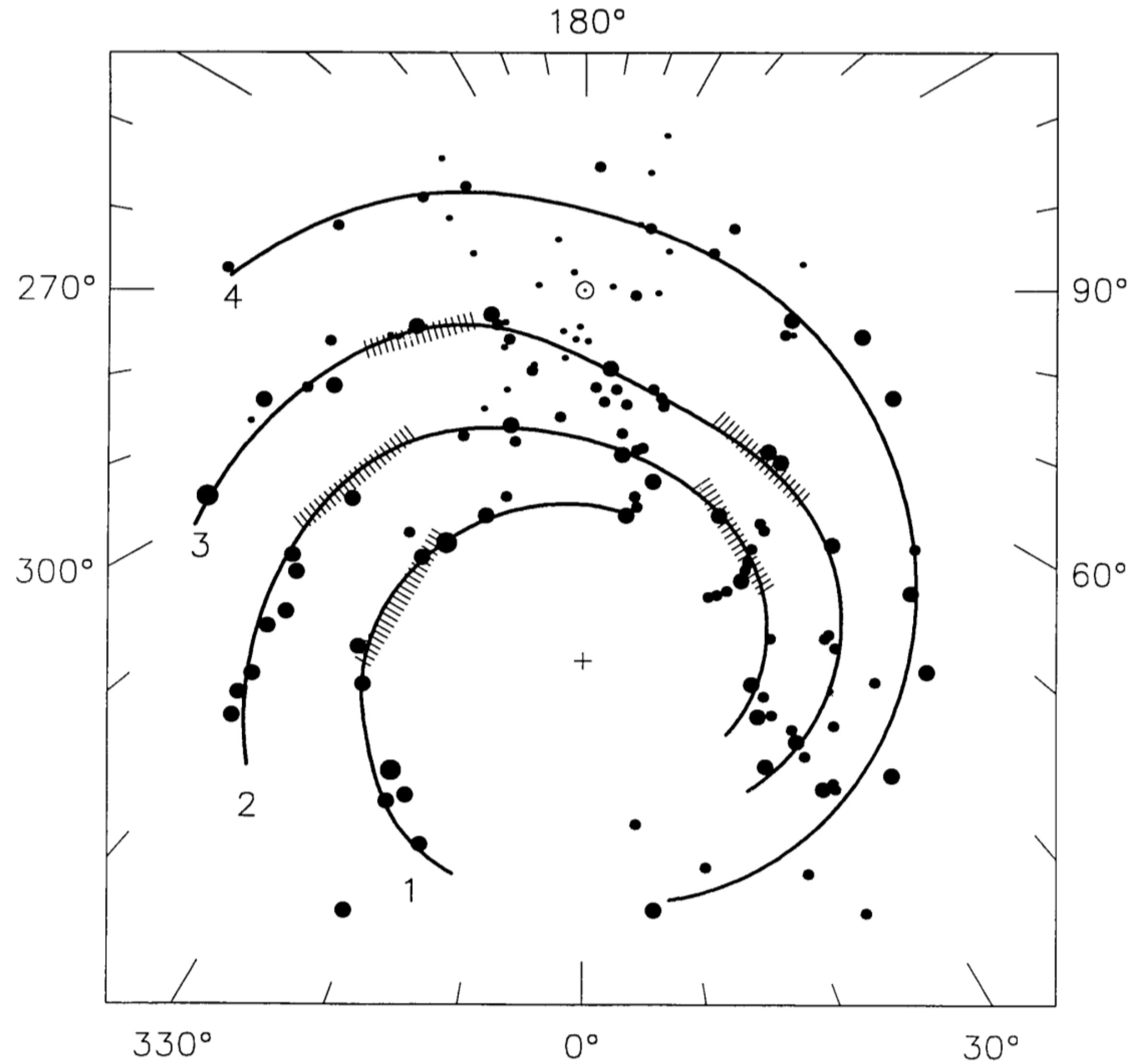
- Typical Description:  
MWY has **4 spiral arms** in solar neighborhood
- Or maybe 2? Long debated, esp. for a Spiral+Bar galaxy...
- Or maybe (probably) has a bunch of “spurs” between strong spiral features
- We maybe live on the edge of a spur



Hou (2021)

# Spiral Arms

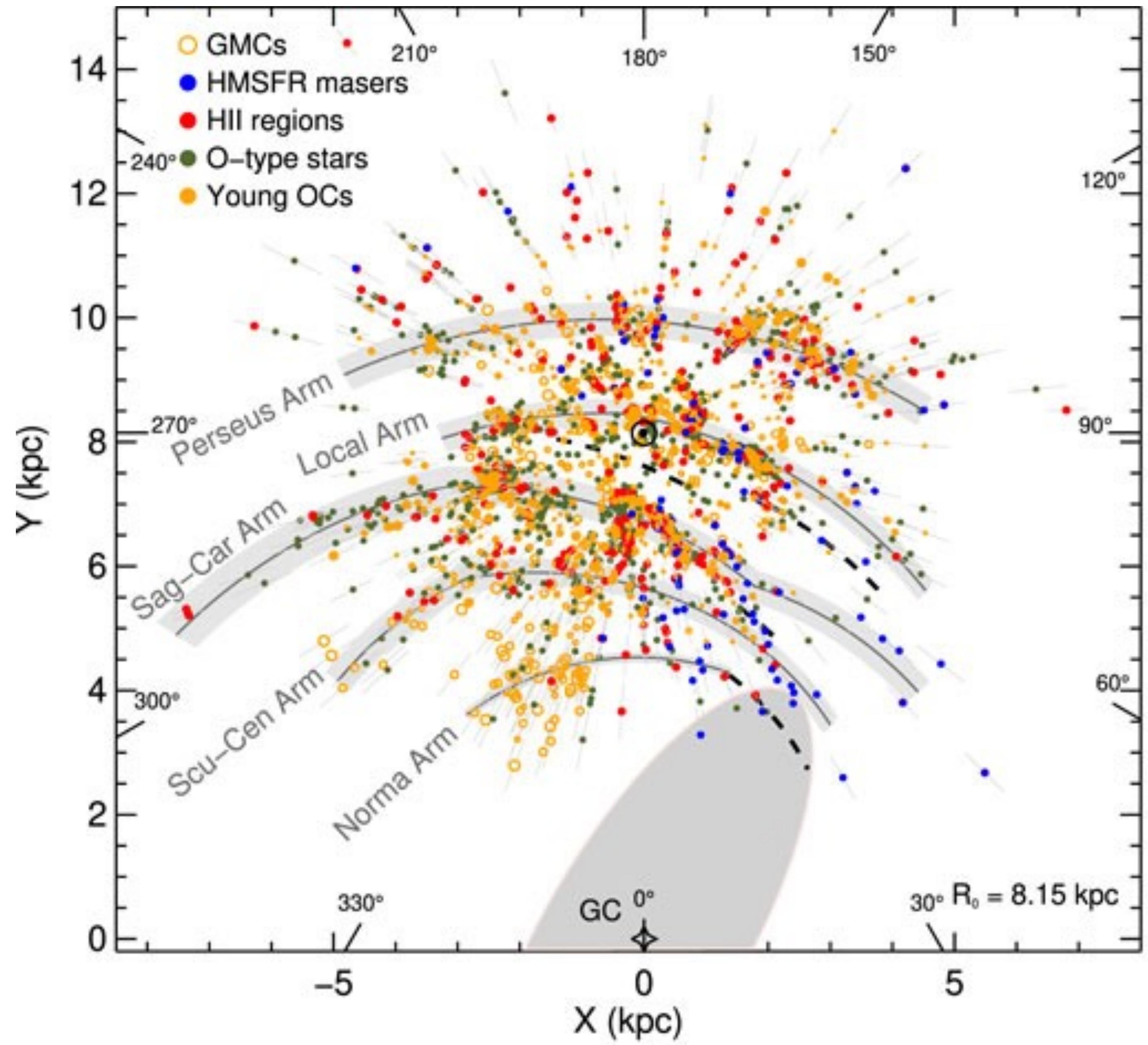
- Basic 4-arm model,  
very popular for ~30yrs



Pulsar distances: Taylor & Cordes (1993)

# Spiral Arms

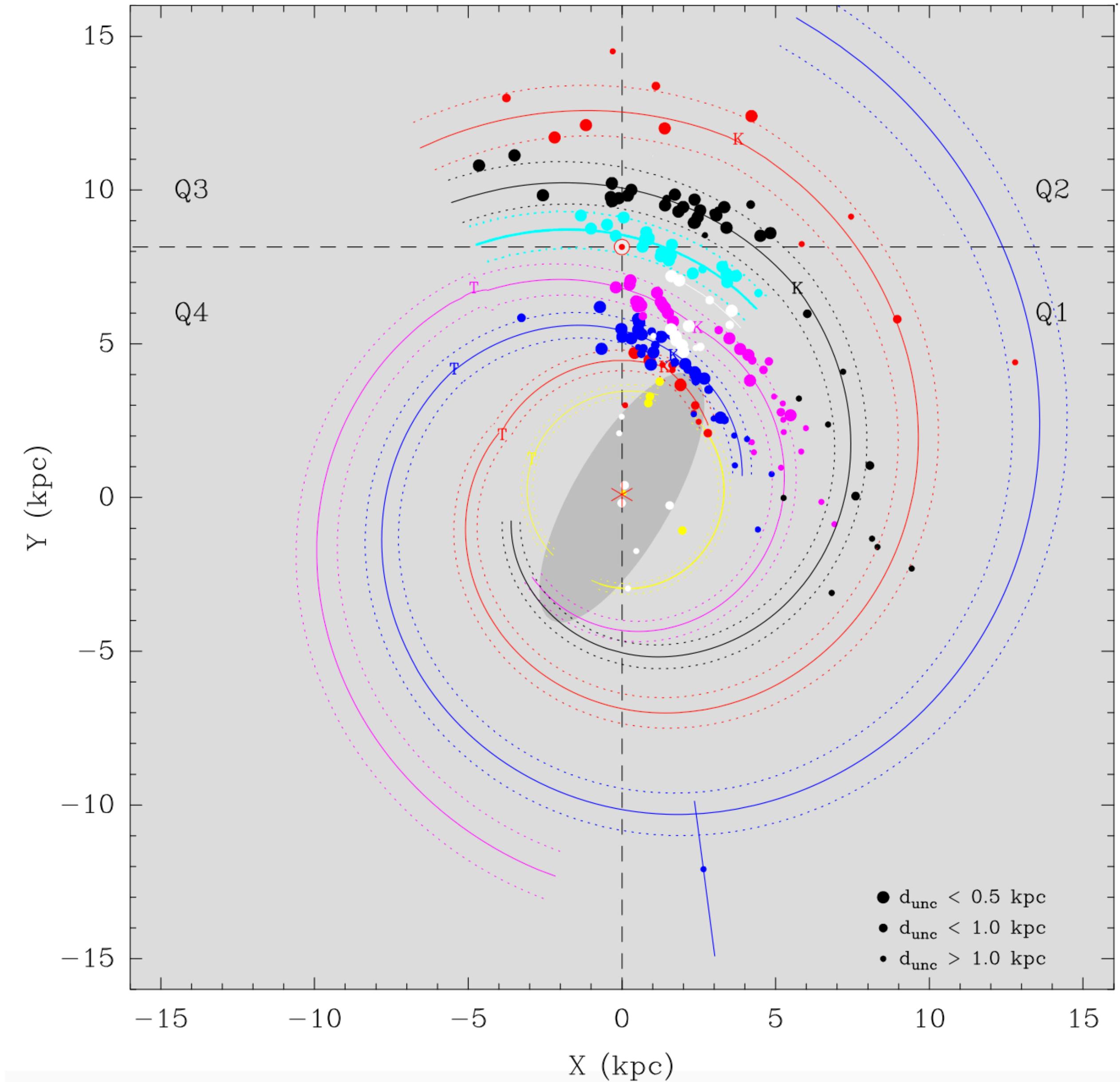
- Scu-Cen Arm
- Sag-Car Arm
- Local Arm (“Orion”)
  - Is it really an Arm, or a spur?
- Perseus Arm
- Norma-Outer Arm



Hou (2021)

# Spiral Arms

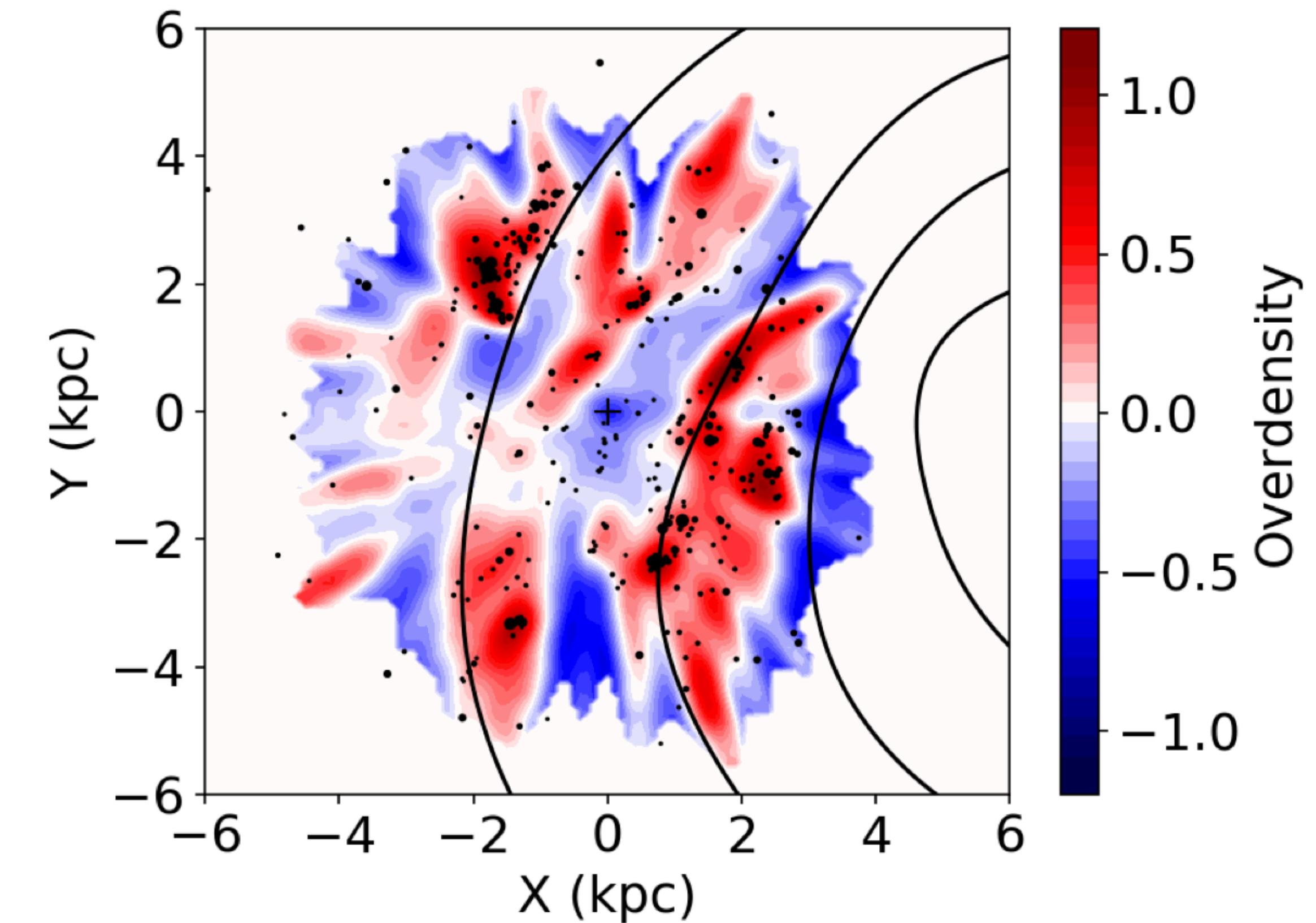
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Star forming regions: [Reid+2019](#)

# Spiral Arms

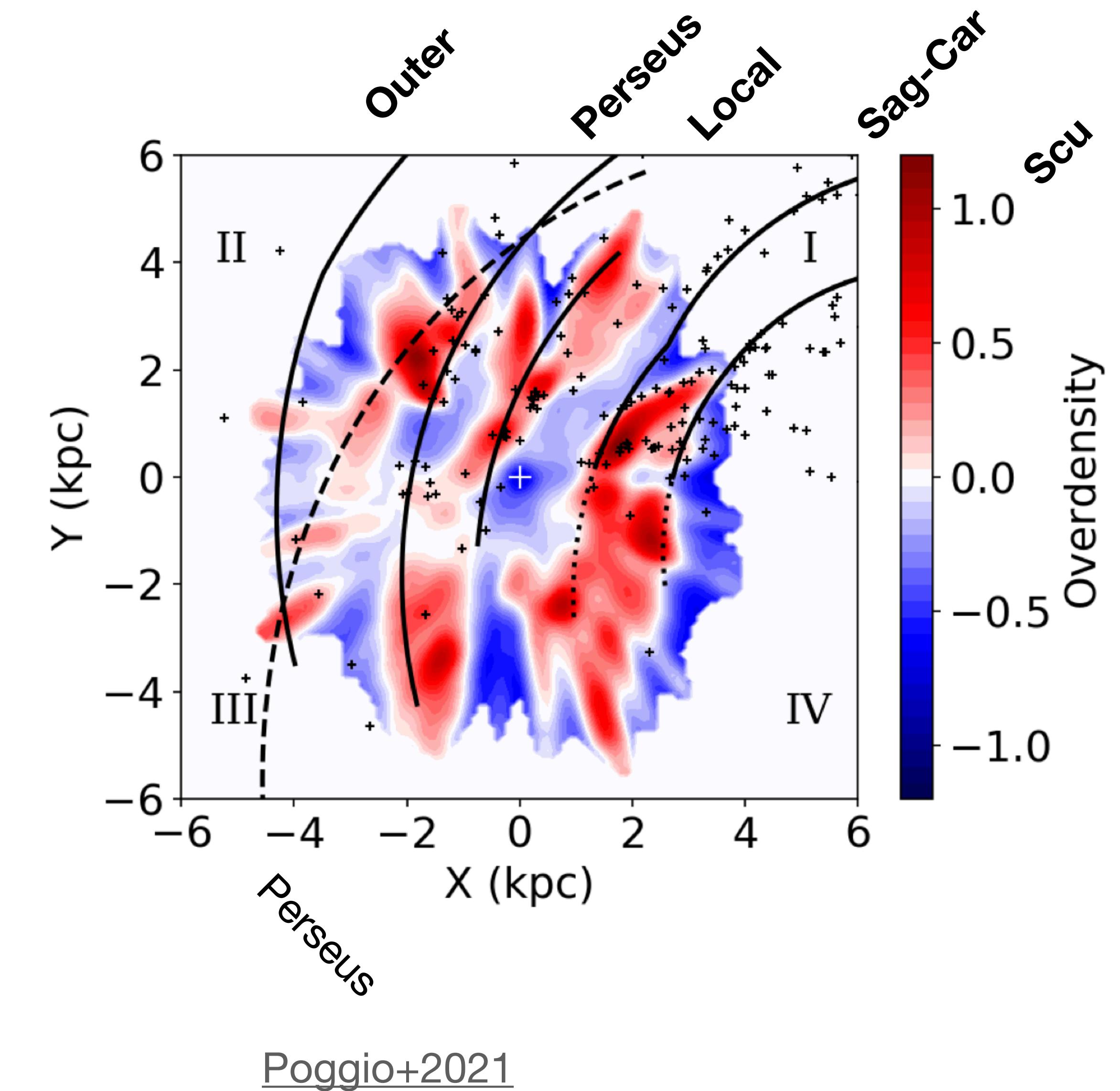
- Gaia traces out structure with young field stars!
- Not a *great* fit to some standard arm models (e.g. Taylor & Cordes 1993)



Poggio+2021

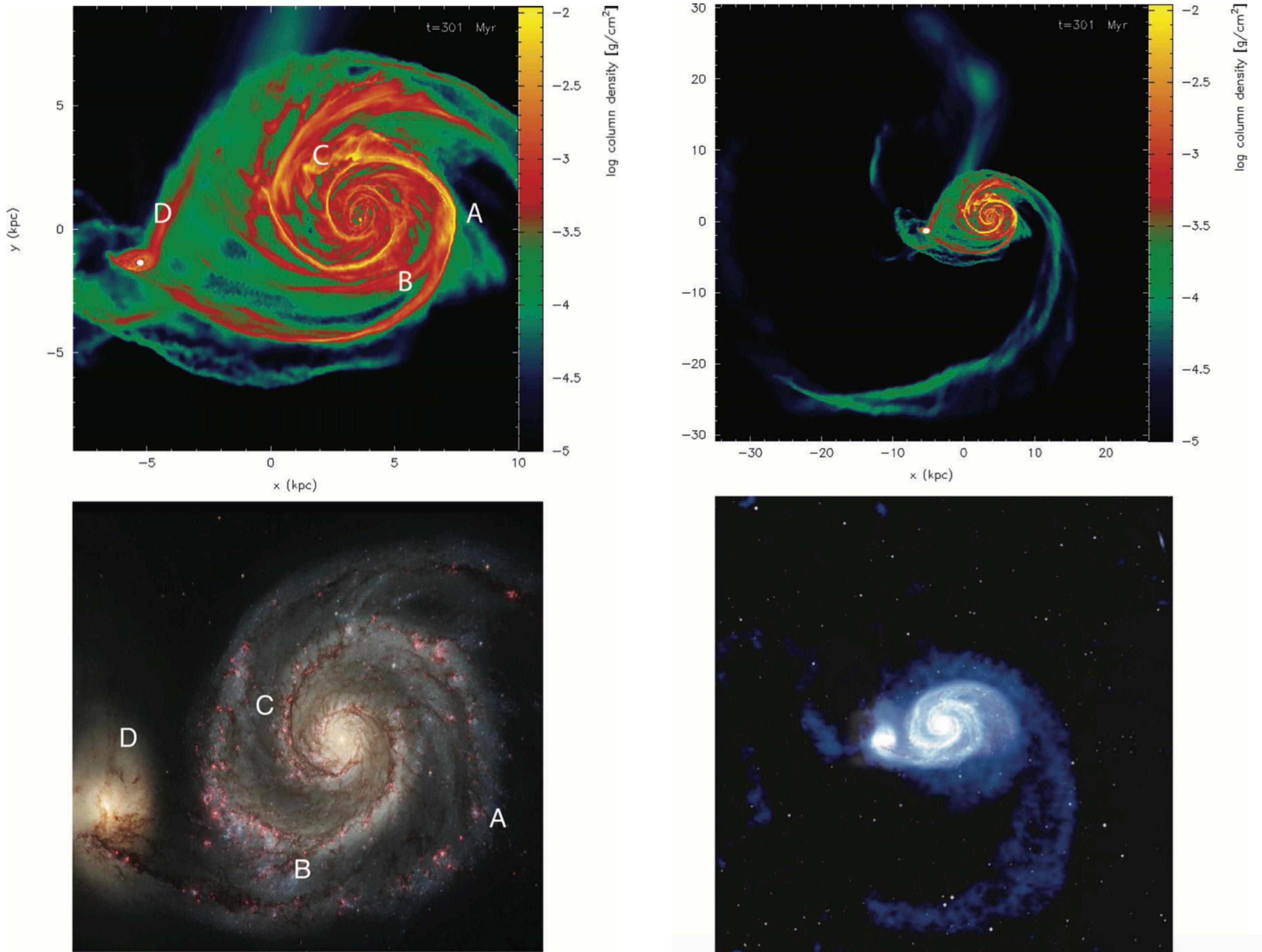
# Spiral Arms

- Some better alignment with Reid+2019 model (black lines)
- Except Perseus arm looks more like Levine+2006
- Lots of pure cartographic exploration to still be done here!



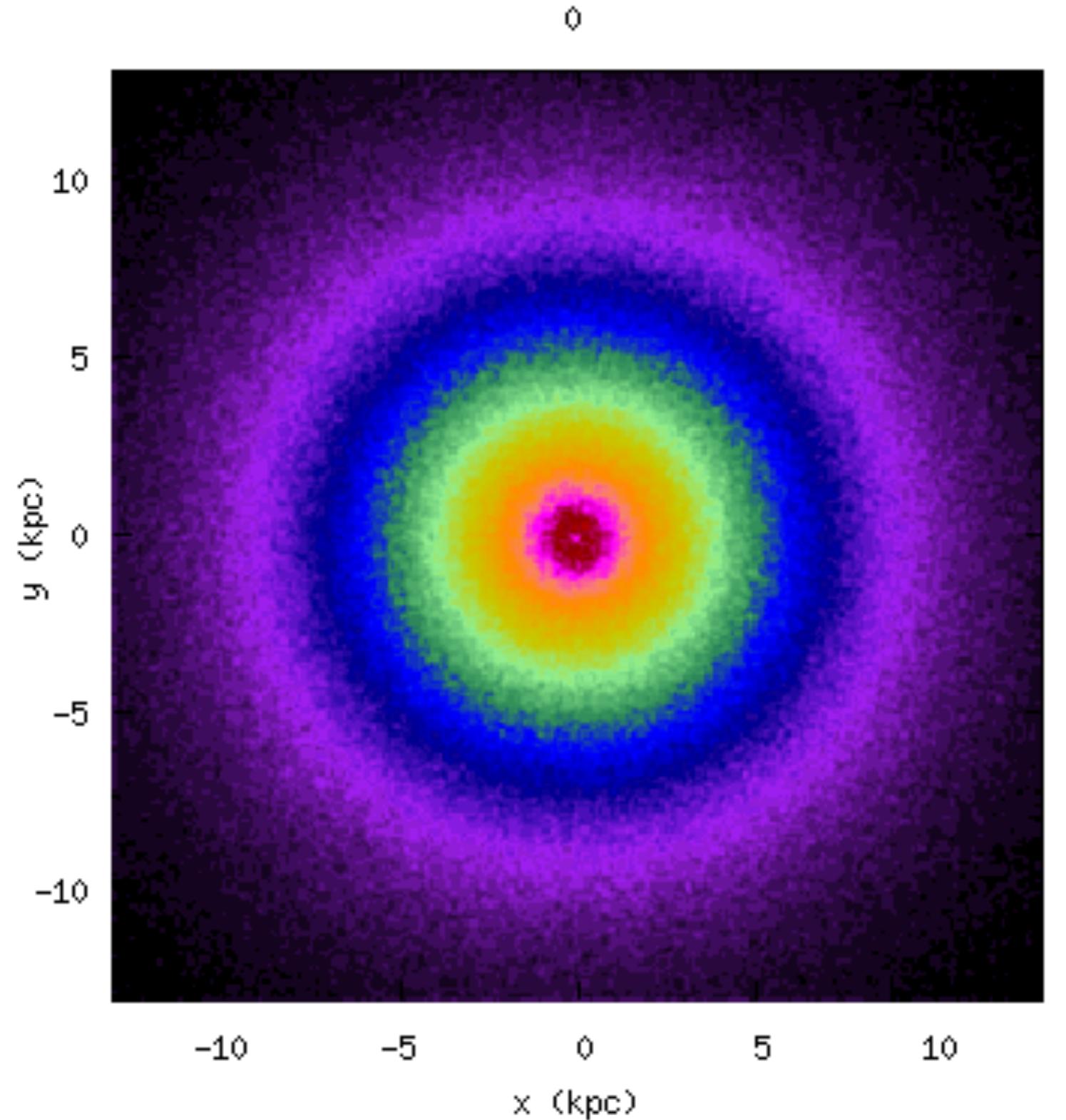
# Spiral Arms

- M51 grand spiral structure, with lots of spur-like features reproduced well with Galaxy+merger model
- No strong bar though



# Spiral Arms

- Lots of simulation work in this space
- Exploring bar, resonances, mergers...



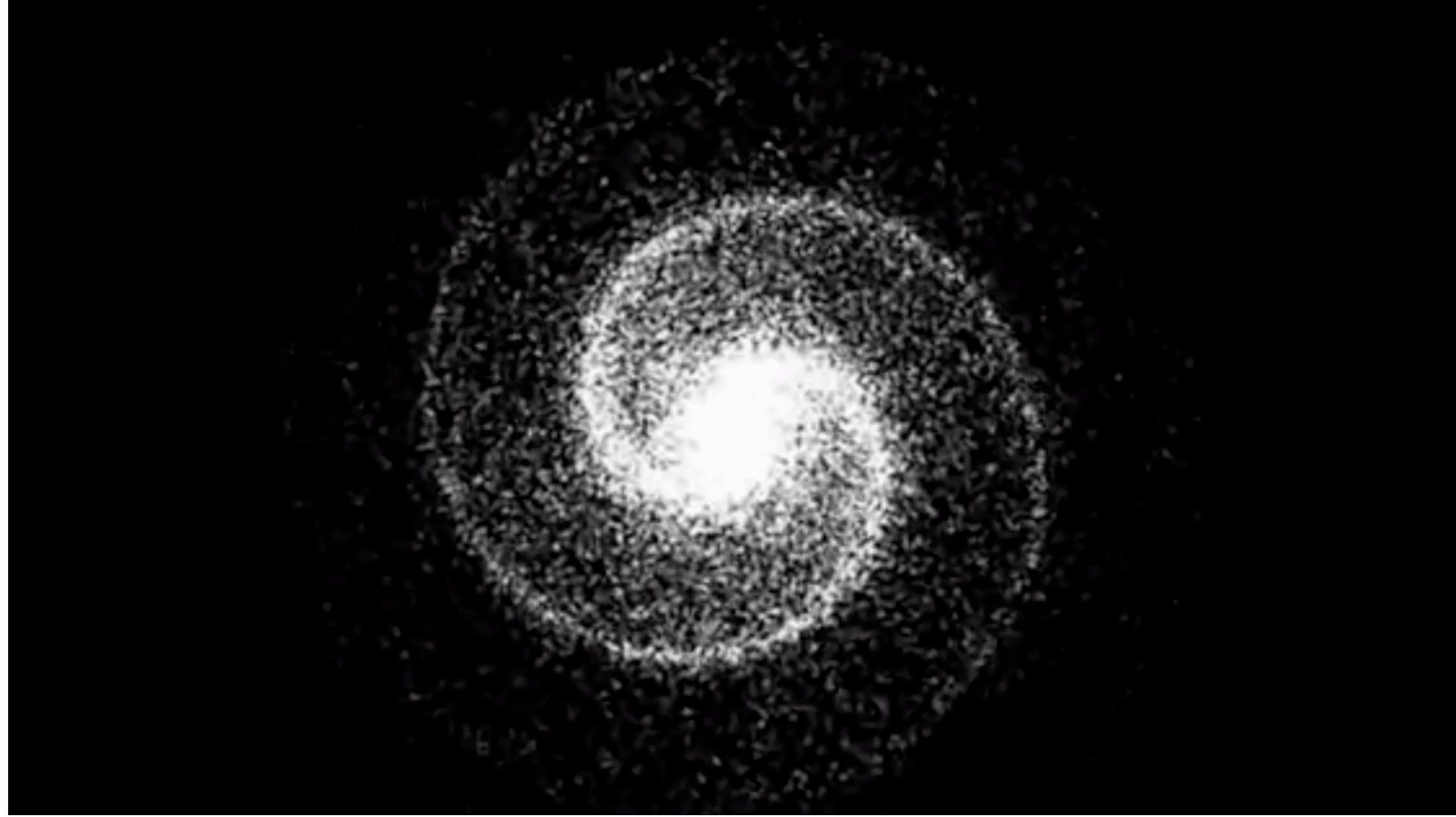
Quillen+2011

# Spiral Arms

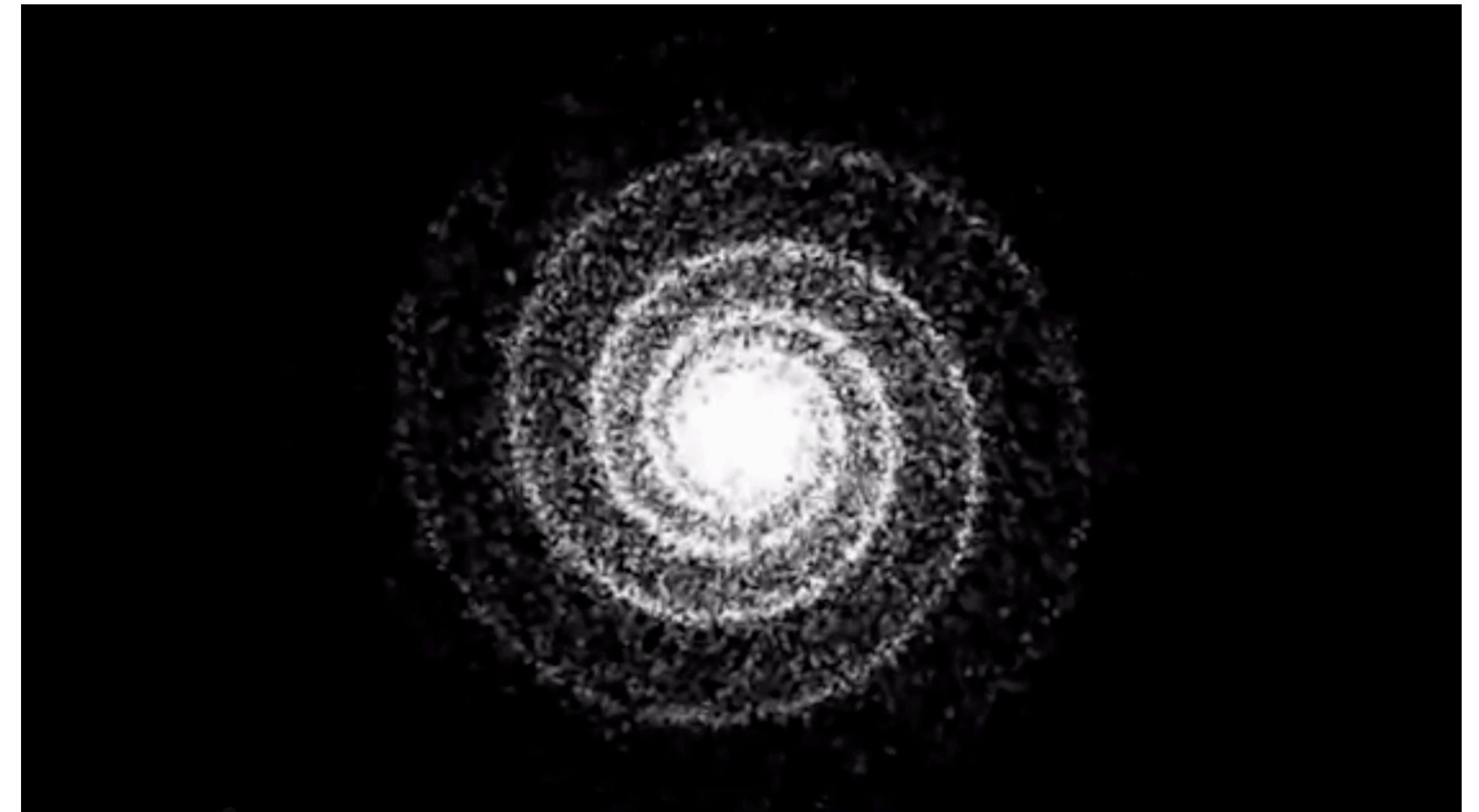
- Density Wave Theory: Lin & Shu (1964)
- Spiral structure long lived, due to a propagating density wave, NOT a fixed structure
- Critically: NOT due to shear or differential rotation of the disk (which IS there)
- Reminds me of: traffic jam propagation

# Spiral Arms

Fixed Pattern

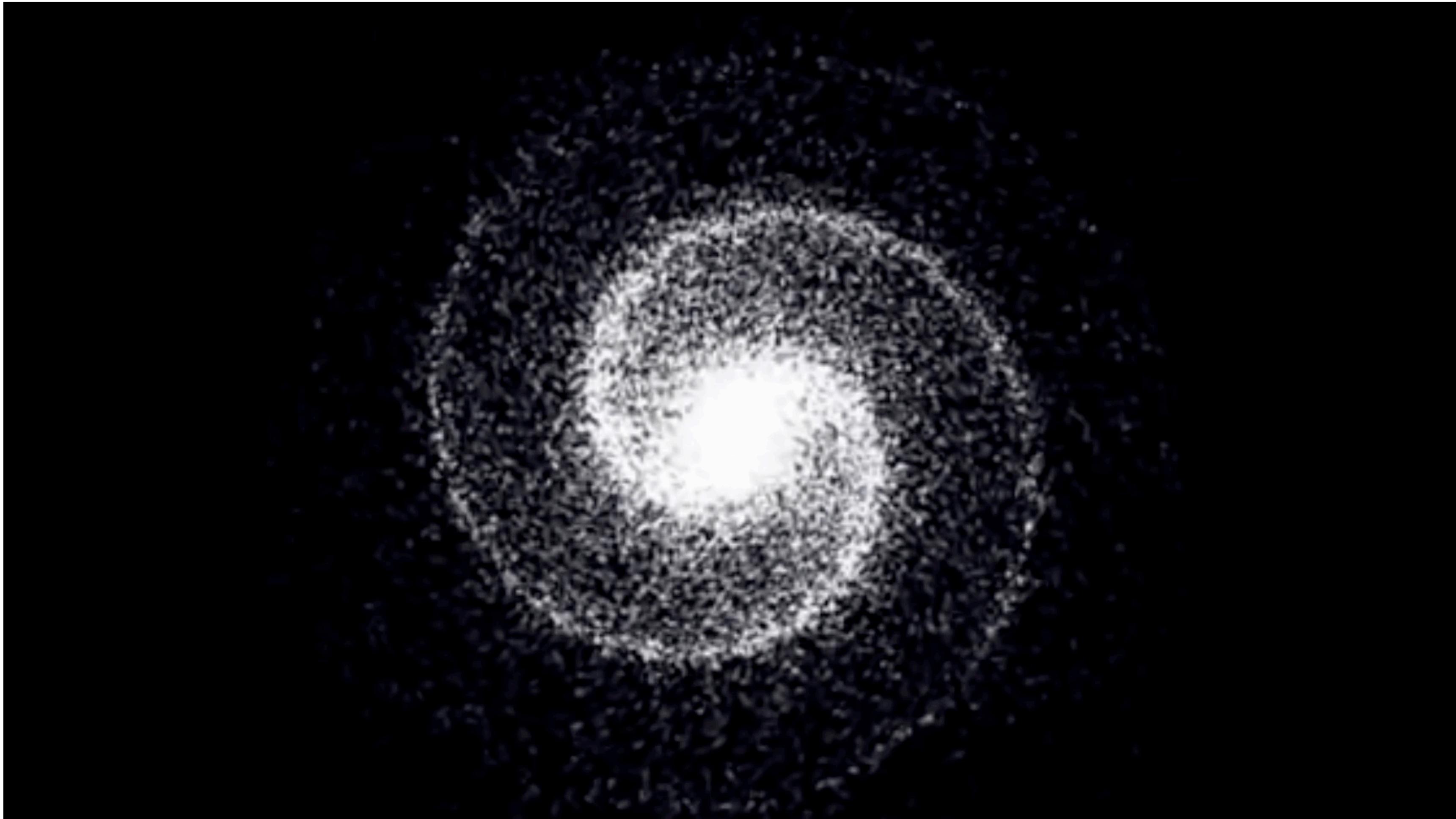


Diff. Rot.



# Spiral Arms

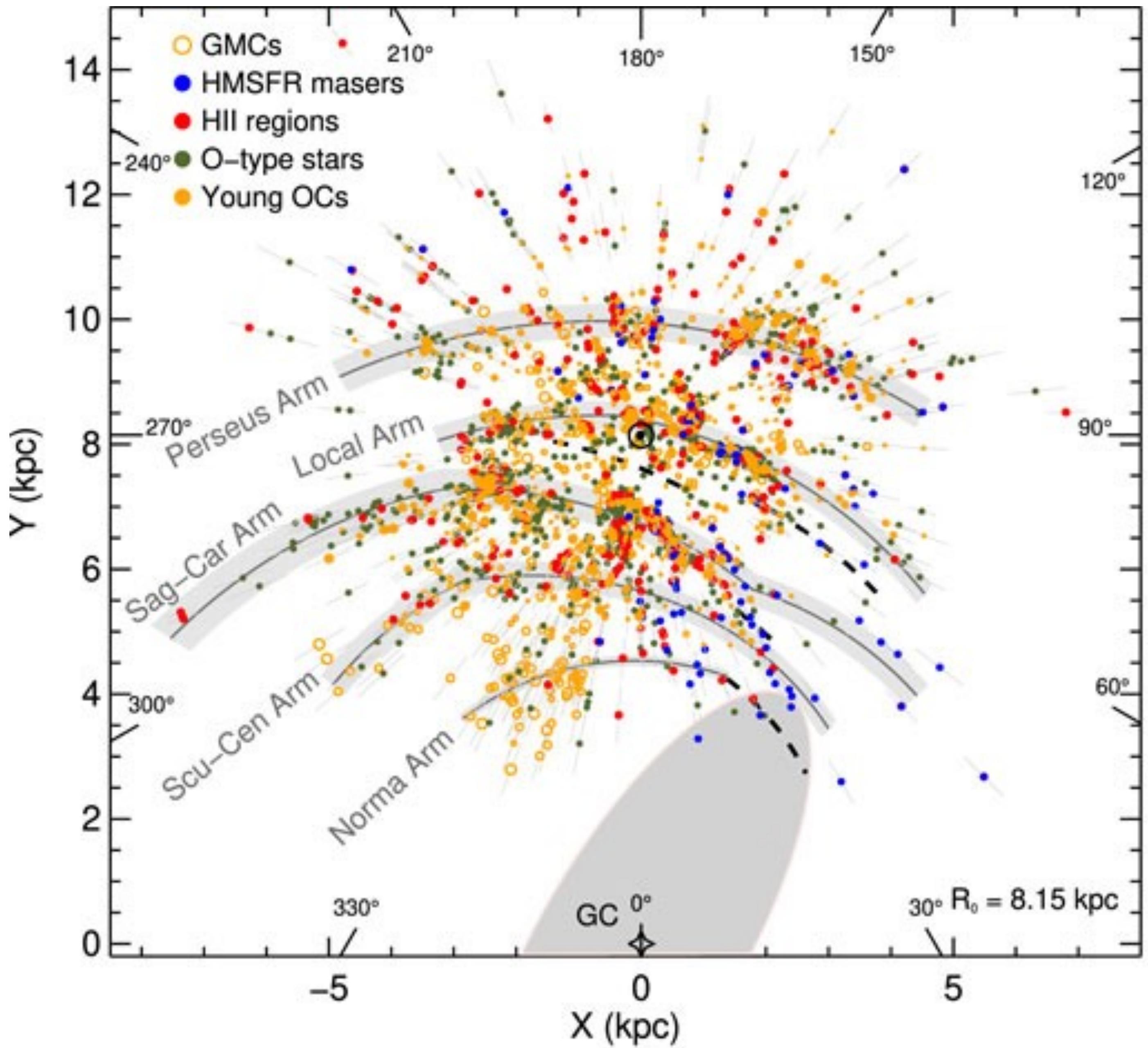
Density Wave



Kinda freaks me out  
see also: [Shepard tones](#)

# Bulge + Bar

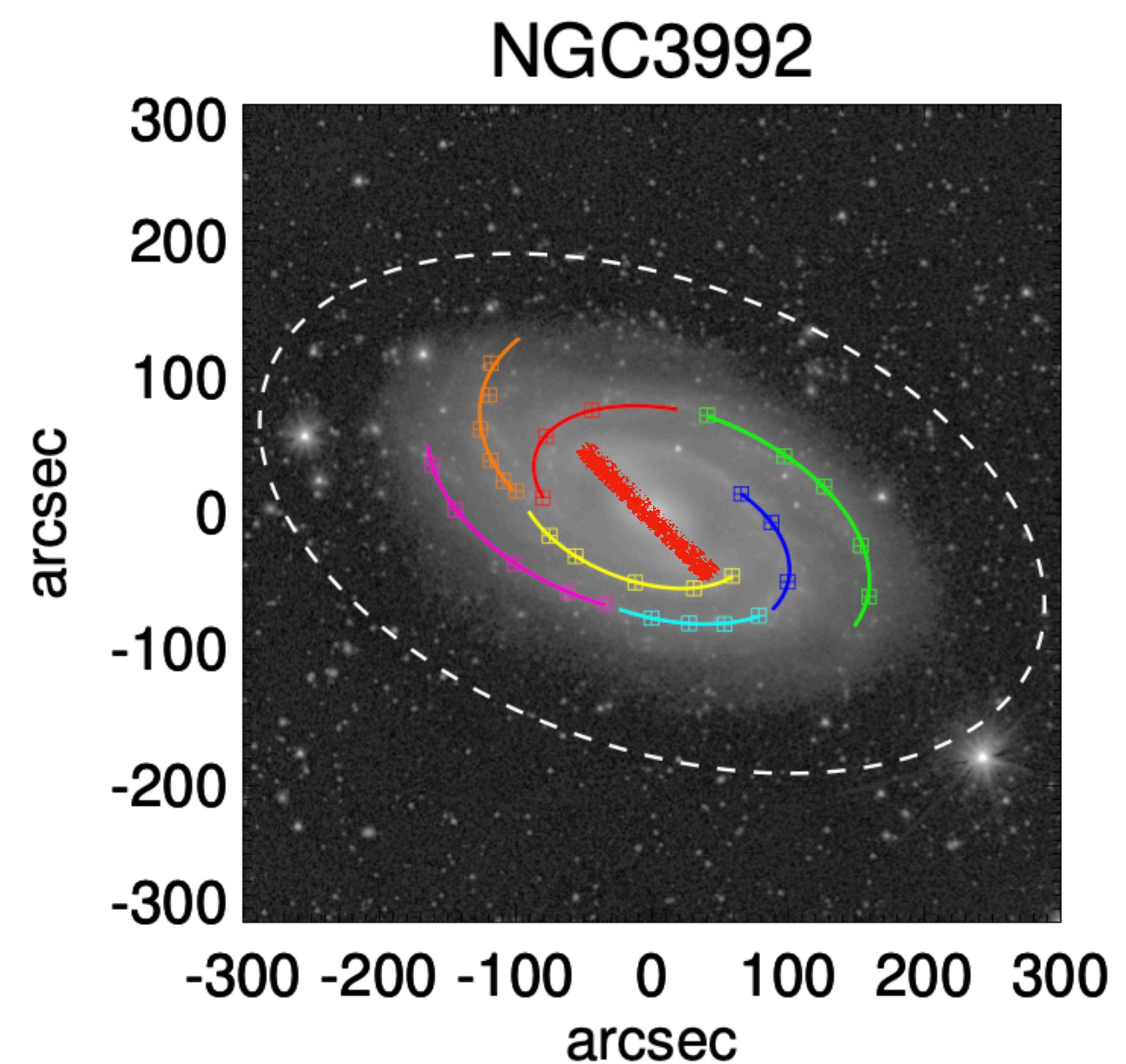
- MWY seems to have a fairly large bar, 4-5kpc half-length
- See how far the bar extends, way into the disk!
- Norma Arm might be connected to the bar



Hou (2021)

# Bulge + Bar

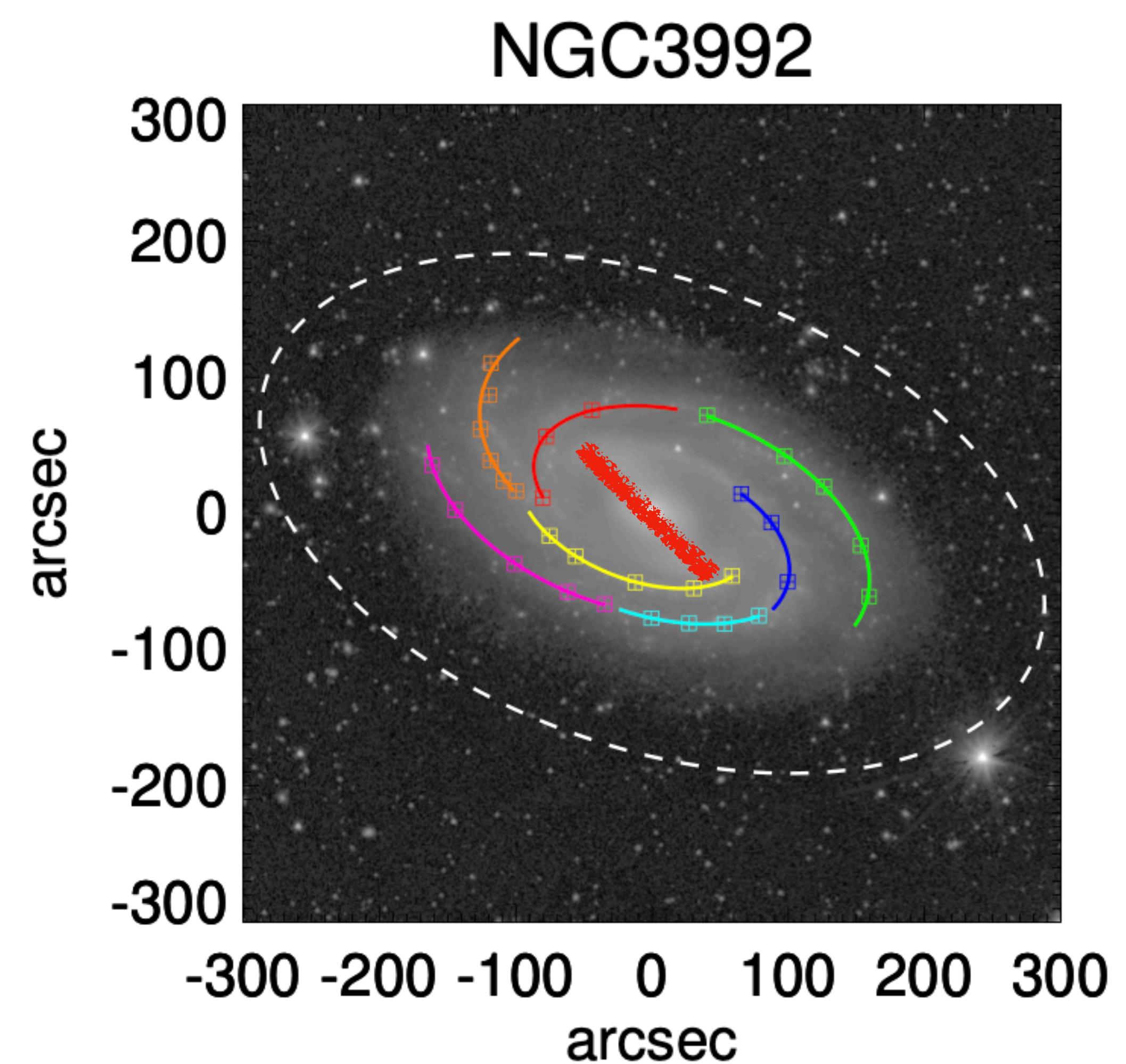
- Resonance w/ bar invoked to be driver of “grand spiral” structure and spiral strength
- Bars could drive density waves that form spirals  
(Normandy & Norman 1979)
- Bars might govern orbital “manifolds” that dictate spiral structure (e.g. Athanassoula+2009)



Díaz-García+2019

# Bulge + Bar

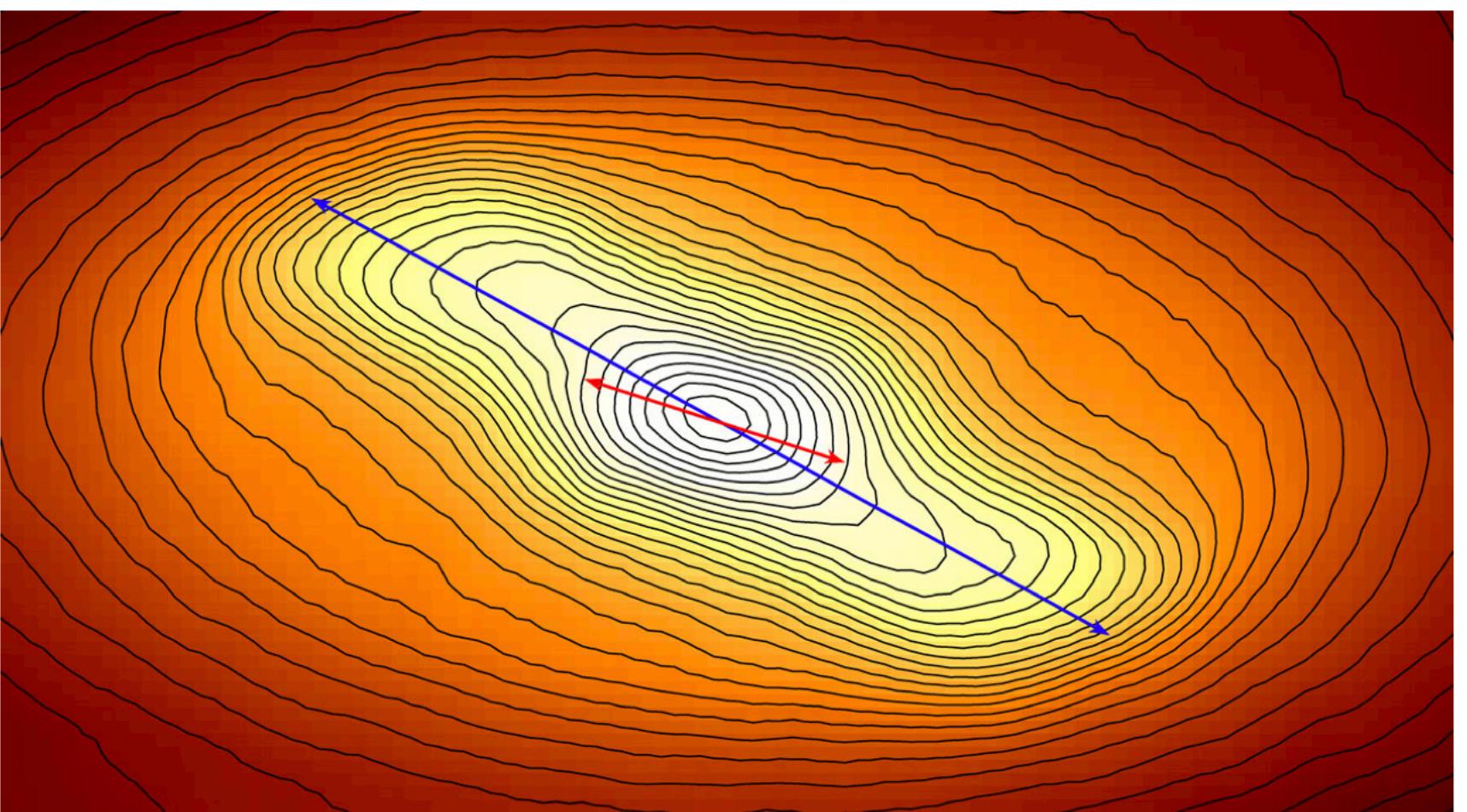
- New surveys of galaxy properties find weak/no evidence that spiral arms are driven by bars, but bar & spiral strength may correlate (e.g. Díaz-García+2019)
  - “Most likely, discs that are prone to the development of strong bars are also reactive to the formation of prominent spirals, explaining the observed coupling between bar and spiral amplitudes.”
- Bars relatively common for all kinds of spiral galaxies. (e.g. Sarkar+2023)



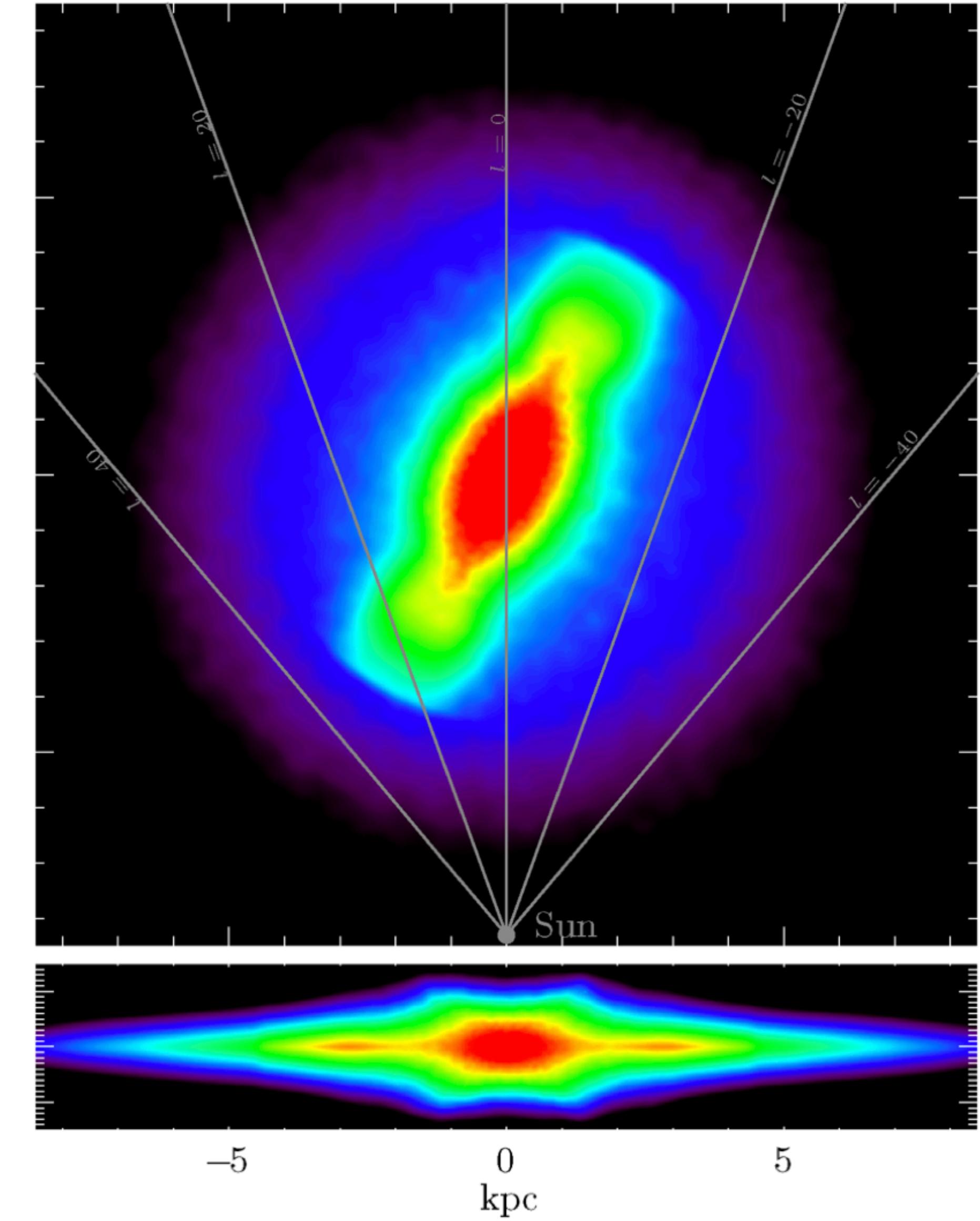
Díaz-García+2019

# Bulge + Bar

- Bulge & Bar may be the same thing
- Some evidence of a two-component bar?!  
(Wegg+2015)
- Maybe even NO bulge, just disk + bar  
(Di Matteo+2015)

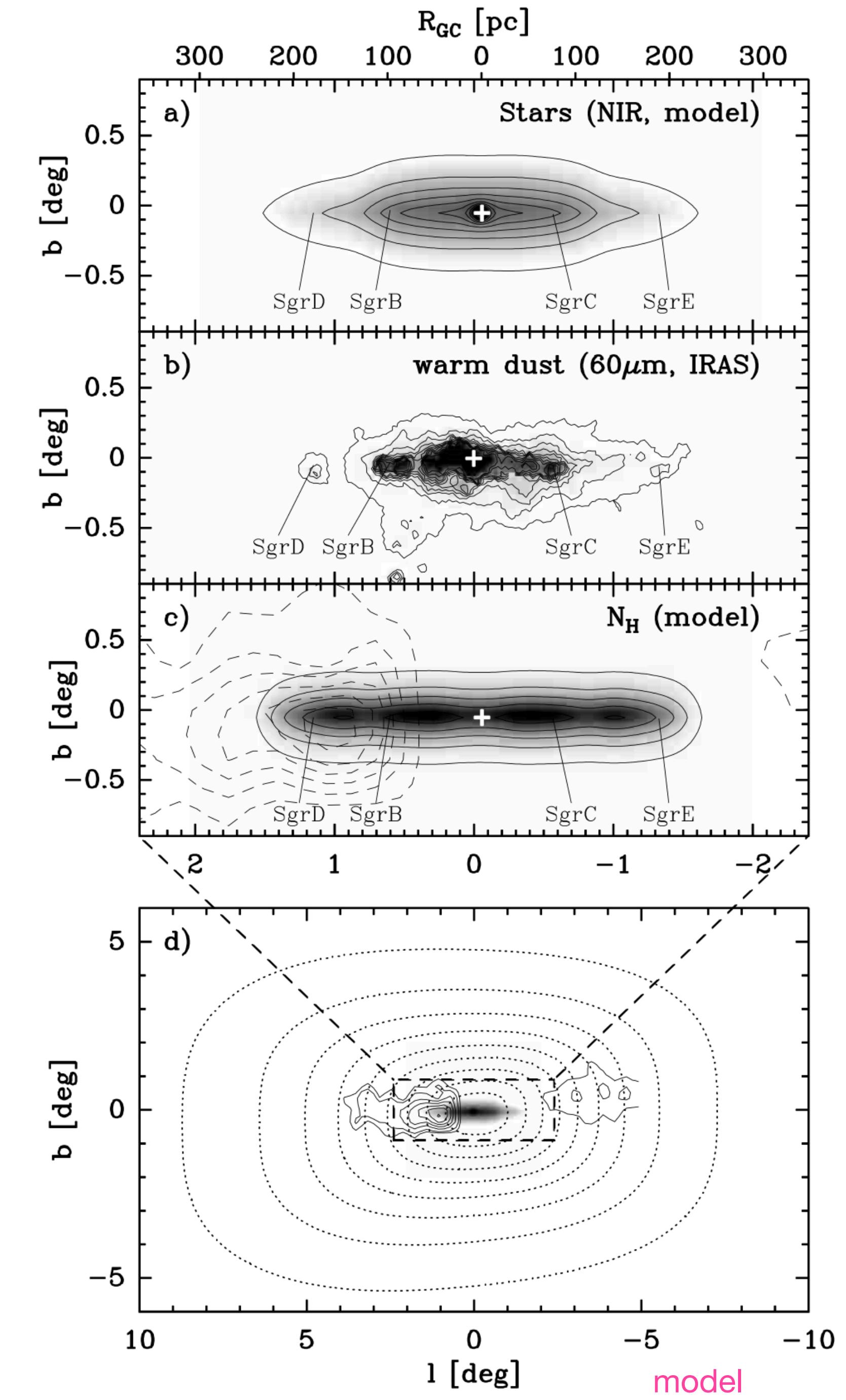
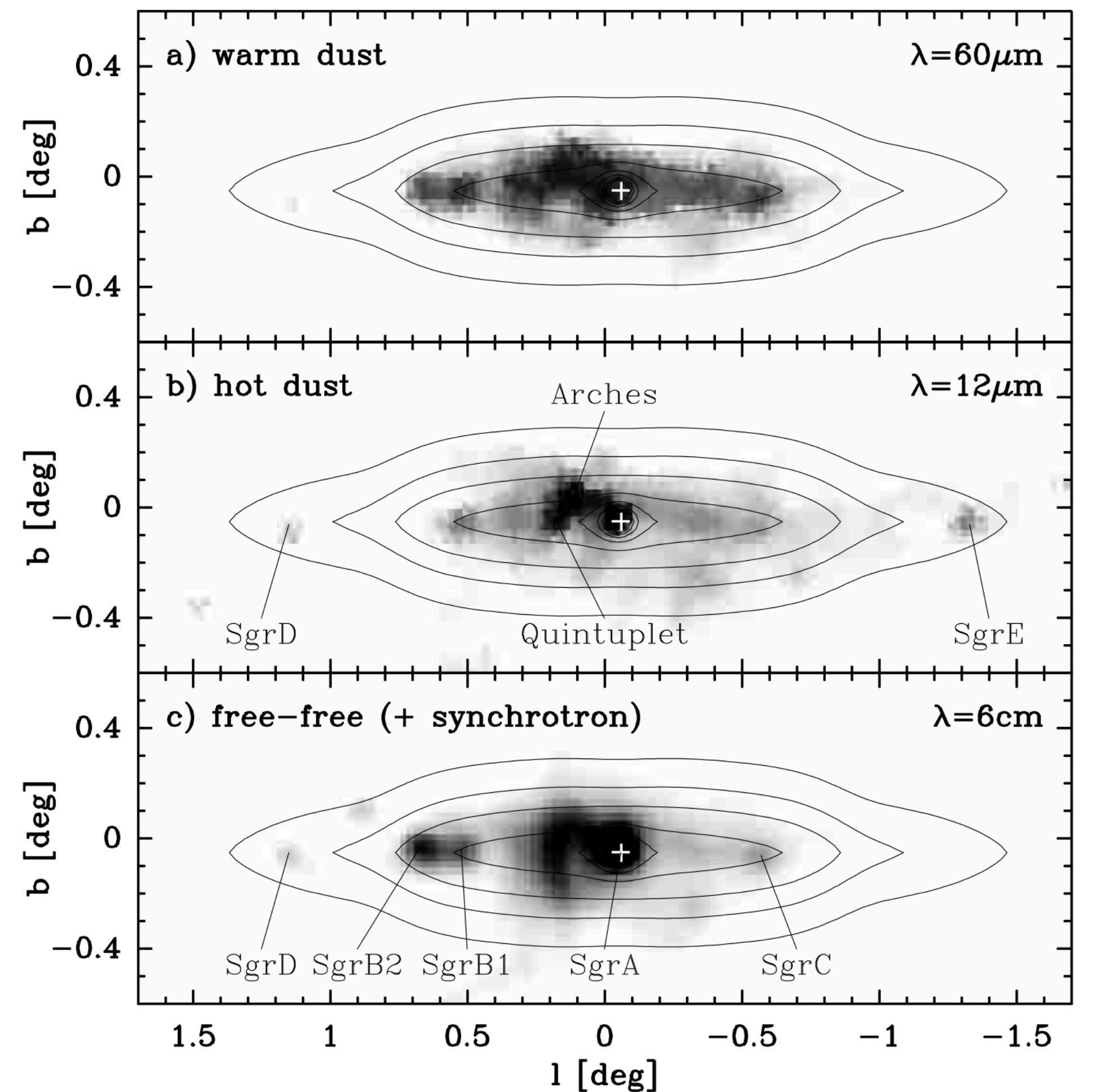


model



# Nuclear Cluster

- In the *very* center is the Nuclear Cluster, with a disk-like structure around it (Launhardt+2001)

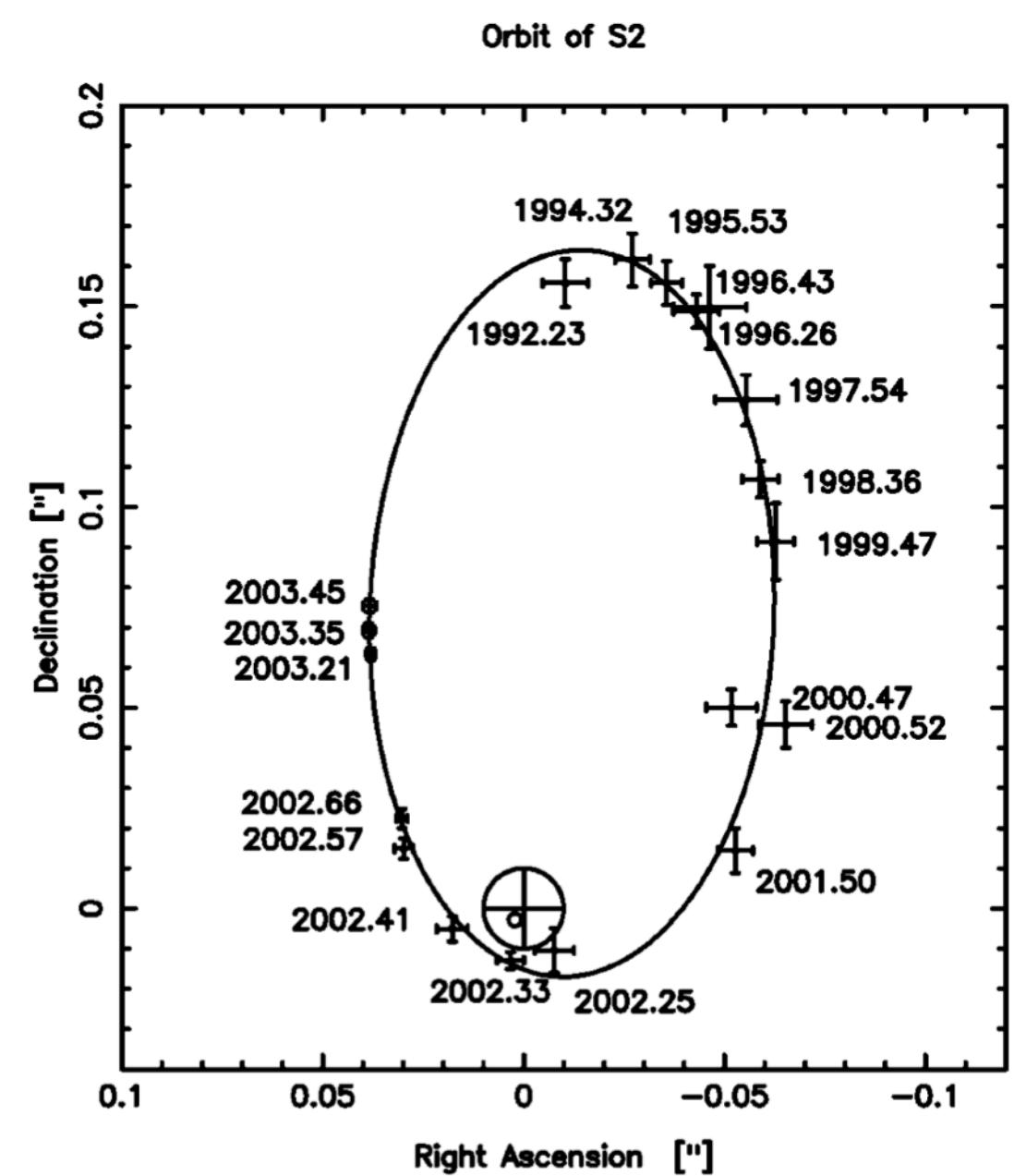
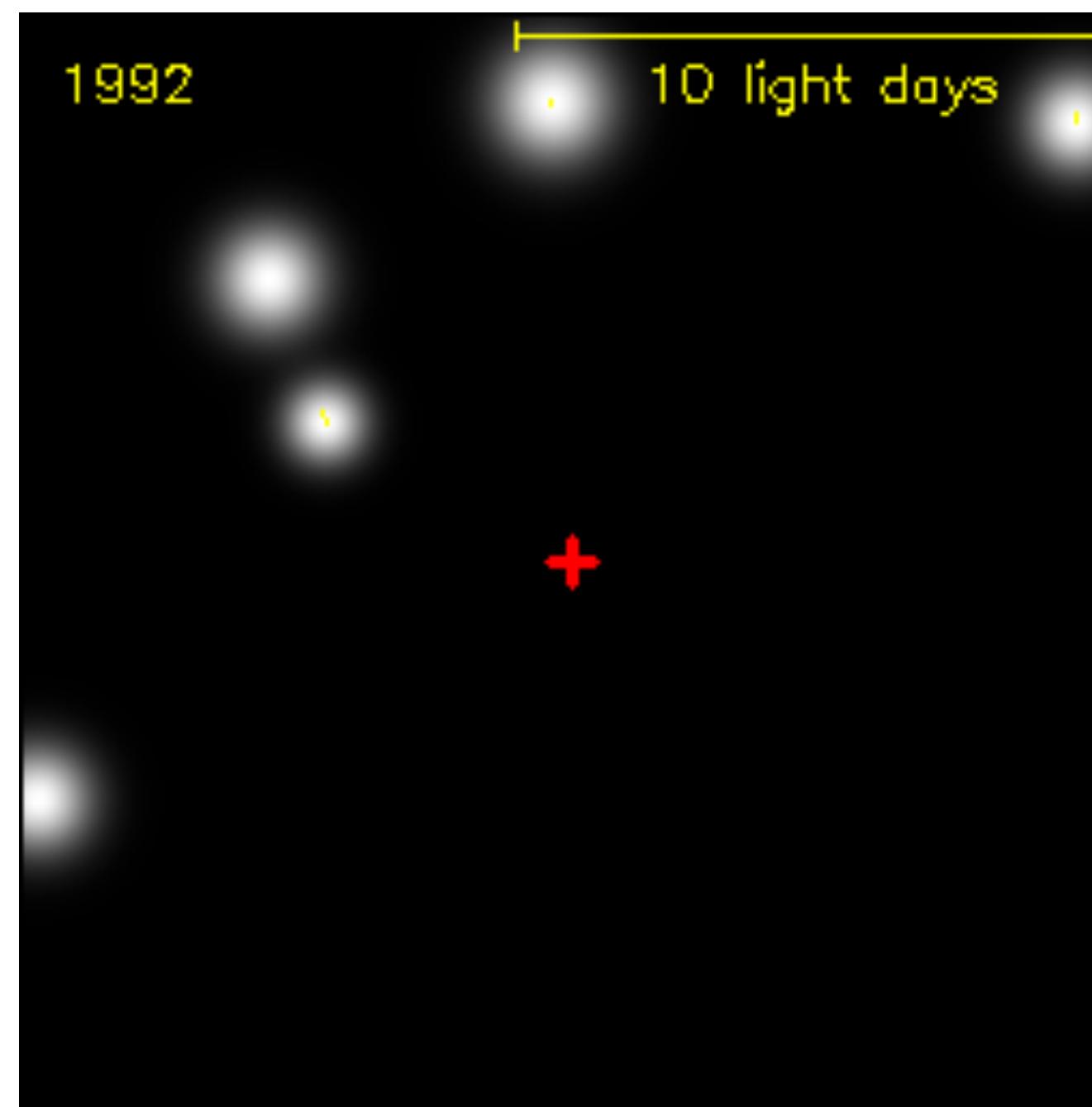


# Distance to Galactic Center: $R_0$

- This number critical to SO MUCH of our geometry... Historically wide range of values considered (though 8kpc favored by some 100yrs ago!)
- IAU standard value has long been  $R_0 = 8.5$  kpc, still see this used a LOT (e.g. in the Gaia Catalog of Nearby Stars, using the “Besançon” MWY model)
- People even recently claim much smaller values
  - e.g.  $R_0 = 7.5$  kpc by modeling globular cluster distribution: Francis & Anderson (2014)
  - **Best estimate currently seems to be: 8.122 kpc**, measured by modeling orbit of star “S2” at the Galactic Center (GRAVITY collab. 2018)

# Distance to Galactic Center: $R_0$

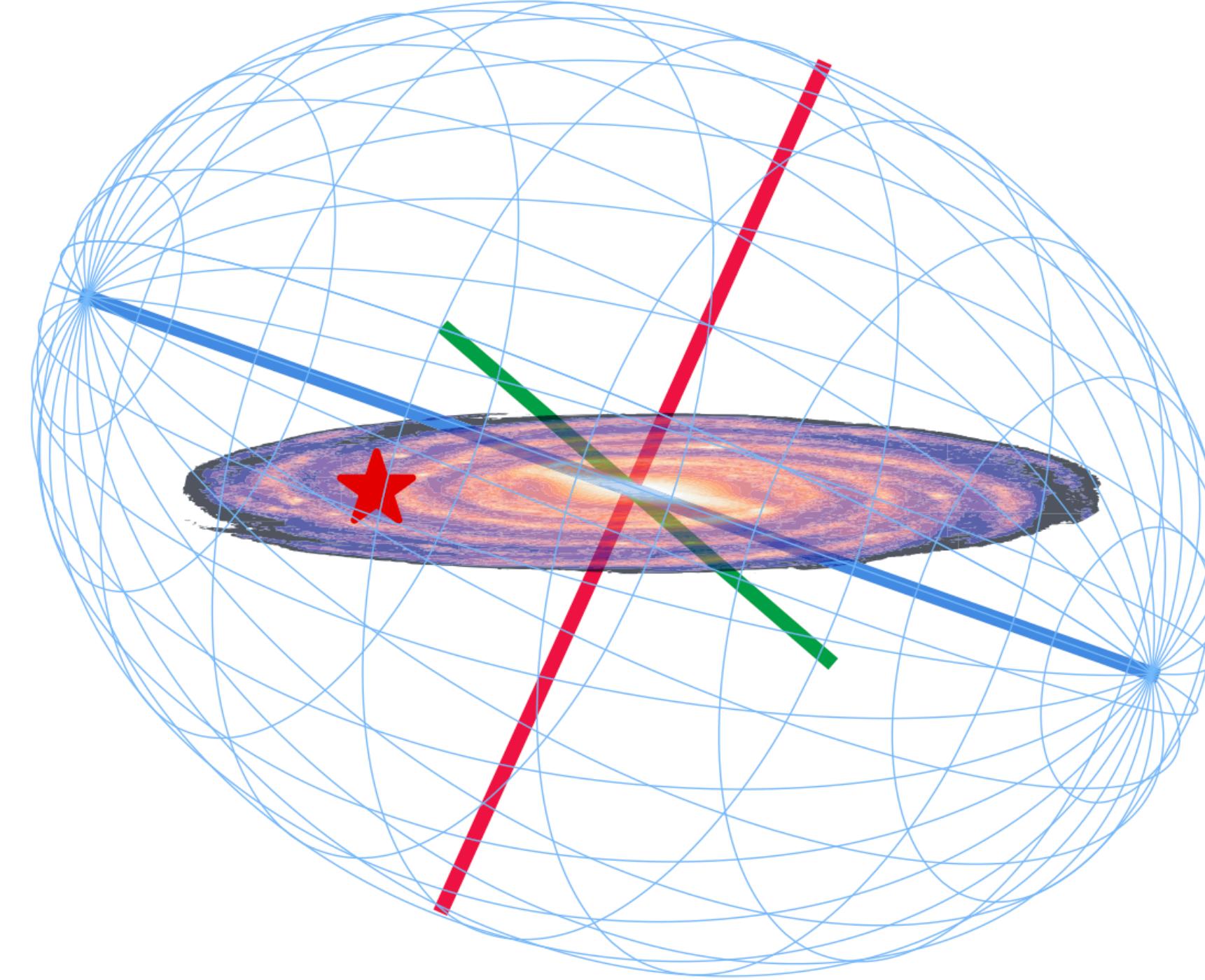
- Best distance comes from fitting the orbit of star S2 around Sag A\* (e.g. [Eisenhauer+2003](#))
- This is a classic technique developed for binary stars ([See 1895](#)), if you can measure RV's & astrometric shifts, then solve for binary mass, orbital separation, and distance (Kepler's 3rd Law + geometry!)



# Halo (Stellar)

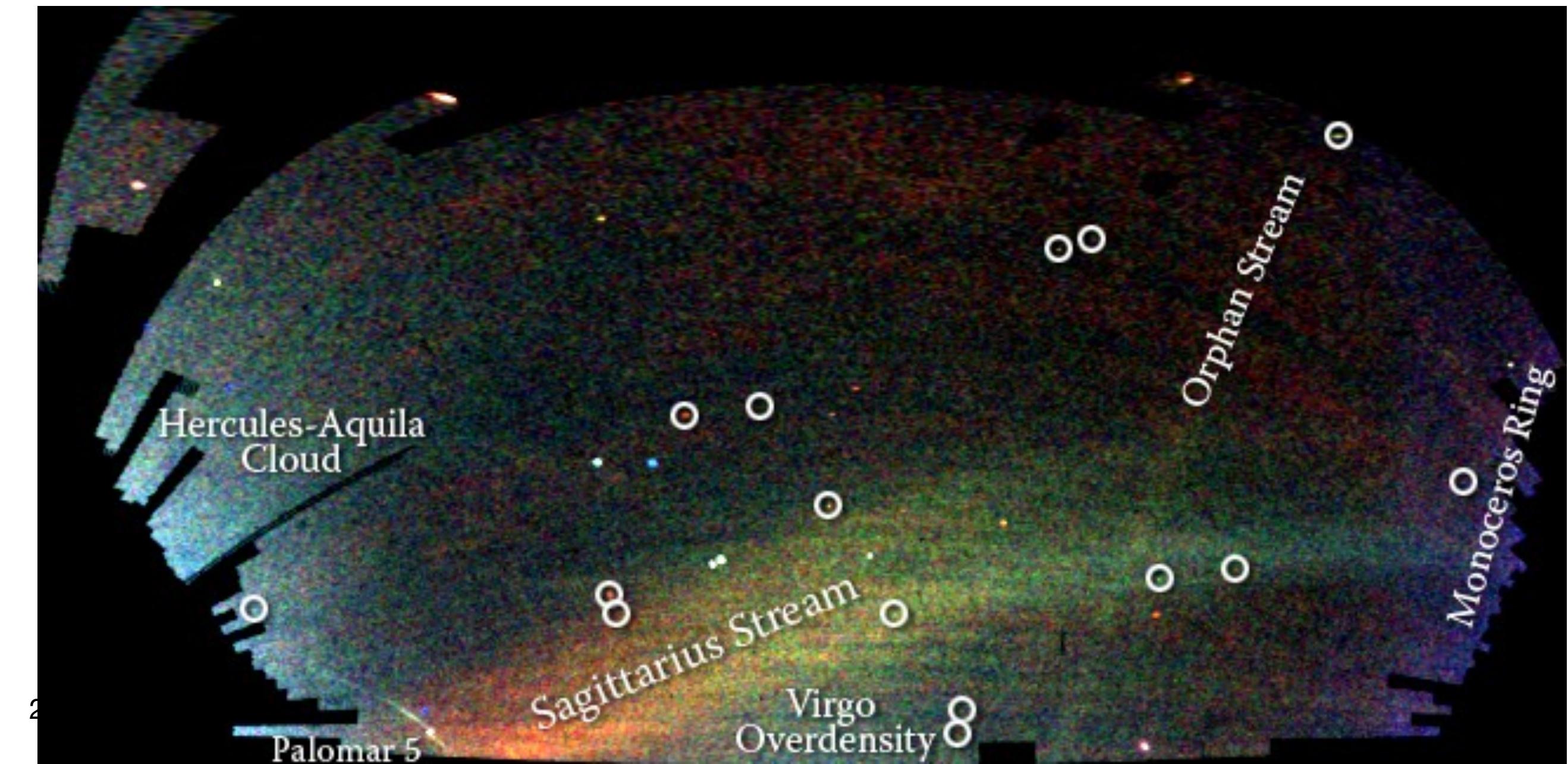
- Triaxial (not spherical!)
- Old, metal poor
- Substructure, hints at origin
  - Globular Clusters
  - Streams
  - (Dwarf) galaxy mergers
  - **Gaia Sausage**

“Field of Streams”  
Belokurov+2006



Axis Ratios  
10 : 8 : 7

Han+2022



# Mass of Components

- Bulge + Bar:  $9.1 \times 10^9 M_\odot$
- Disk:  $5.2 \times 10^{10} M_\odot$  e.g. from Licquia & Newman (2015)
- Stellar Halo:  $\sim 10^9 M_\odot$
- Nuclear cluster region:  $3.3 \times 10^6 M_\odot$  e.g. from Genzel+1997
- Dark Matter Halo:  $1.4 \times 10^{11} M_\odot$  (within 20 kpc) e.g. from Posti & Helmi (2019)

# Next Week:

- Halo substructure, tidal tails, and mergers
- Chemical Cartography
- Star Formation History of the MWY