ASTR 511

Galactic Astronomy

Lecture 06

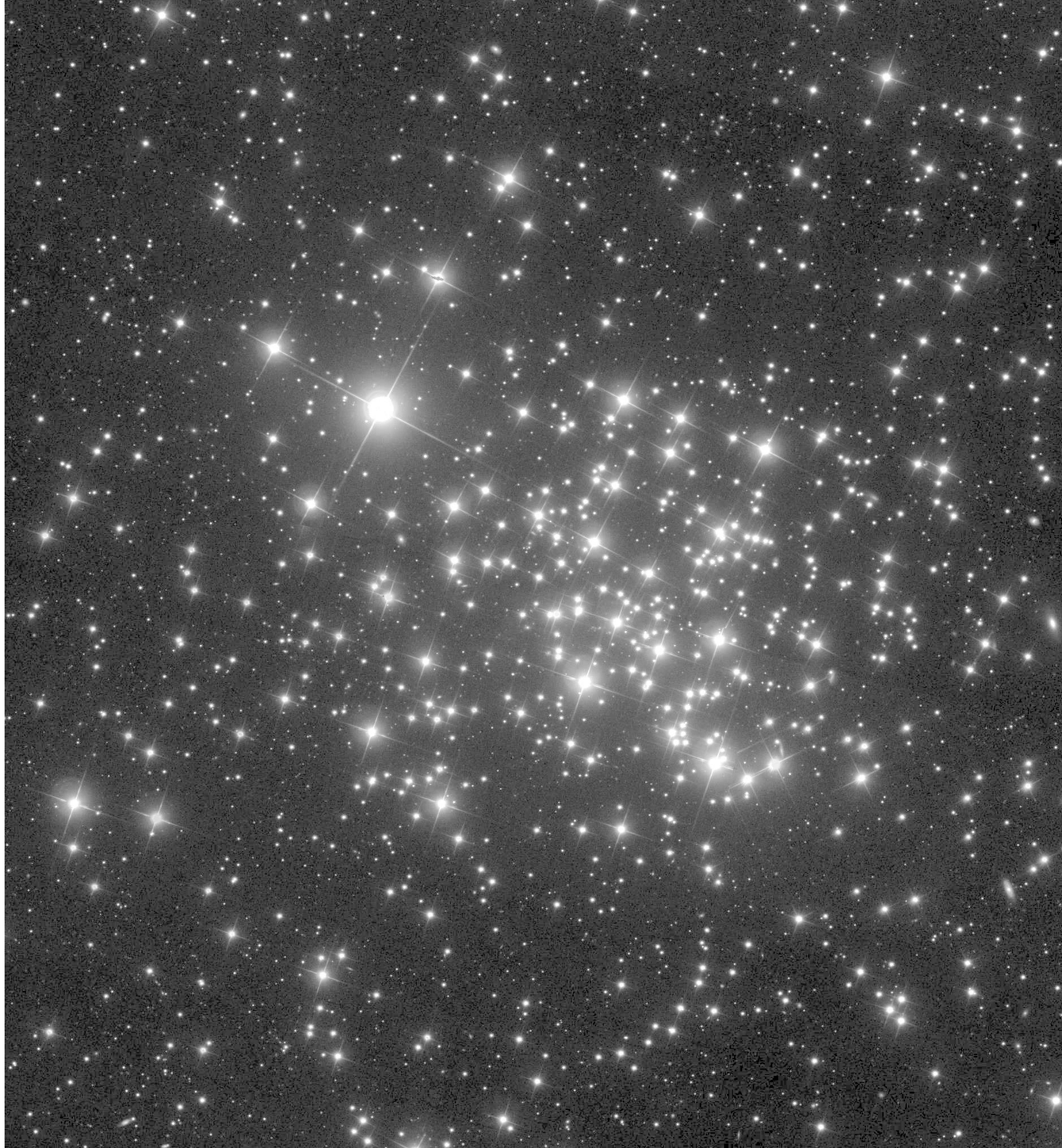
Structure & Properties of the Milky Way

Prof. James Davenport (UW)

Winter 2023

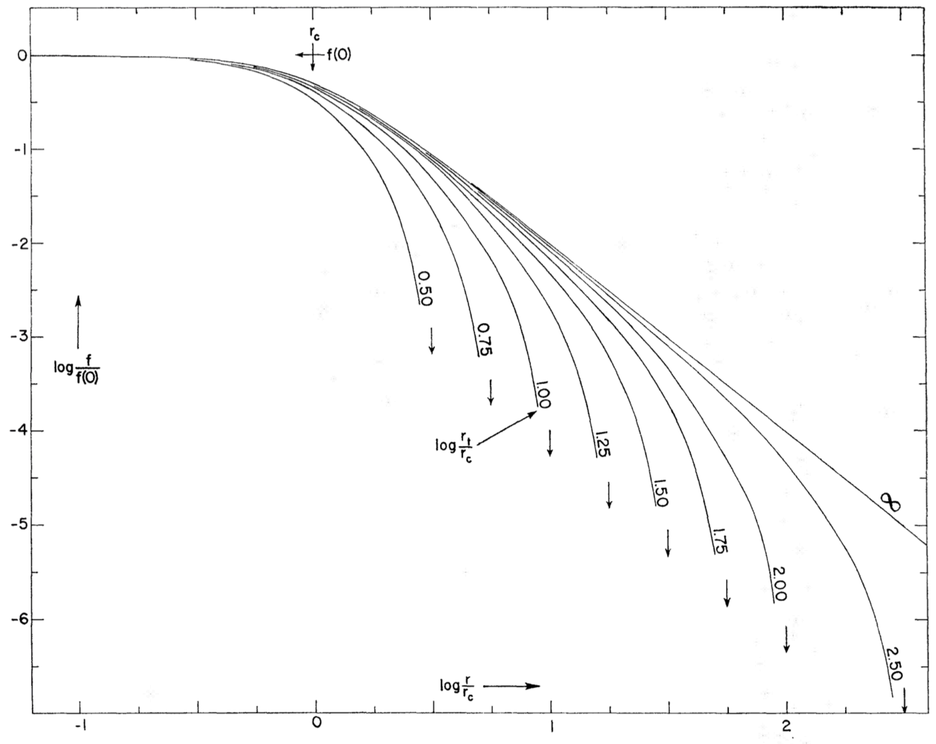
Homework 2

- Any Questions?
- People getting bottlenecked by `n=2000` limit for “basic queries”?
  - Any good workarounds (folks using ADQL? GCNS?)



King Profiles

- Cluster density profiles developed by Ivan King (1962)



$$f = k\left\{\frac{1}{[1+(r/r_c)^2]^{\frac{1}{2}}} - \frac{1}{[1+(r_t/r_c)^2]^{\frac{1}{2}}}\right\}^2. \qquad (14)$$

In a typical globular cluster r_t/r_c is of the order of 30, so that for small to moderate values of r/r_c Eq. (14) differs only slightly from Eq. (13) with

Through the kind cooperation of the Editor, Figs. 5–8 have been printed on such a scale that they can be used directly with inch-scale graph paper. The horizontal and vertical units are 1.25 inches and 0.5 inch, respectively.

Final Project

- Part 1: Pick your topic,
  due in a couple weeks (Feb 17)
  - LMK if you're stuck!
- This will be the subject of both your Final Presentation and your Term Paper

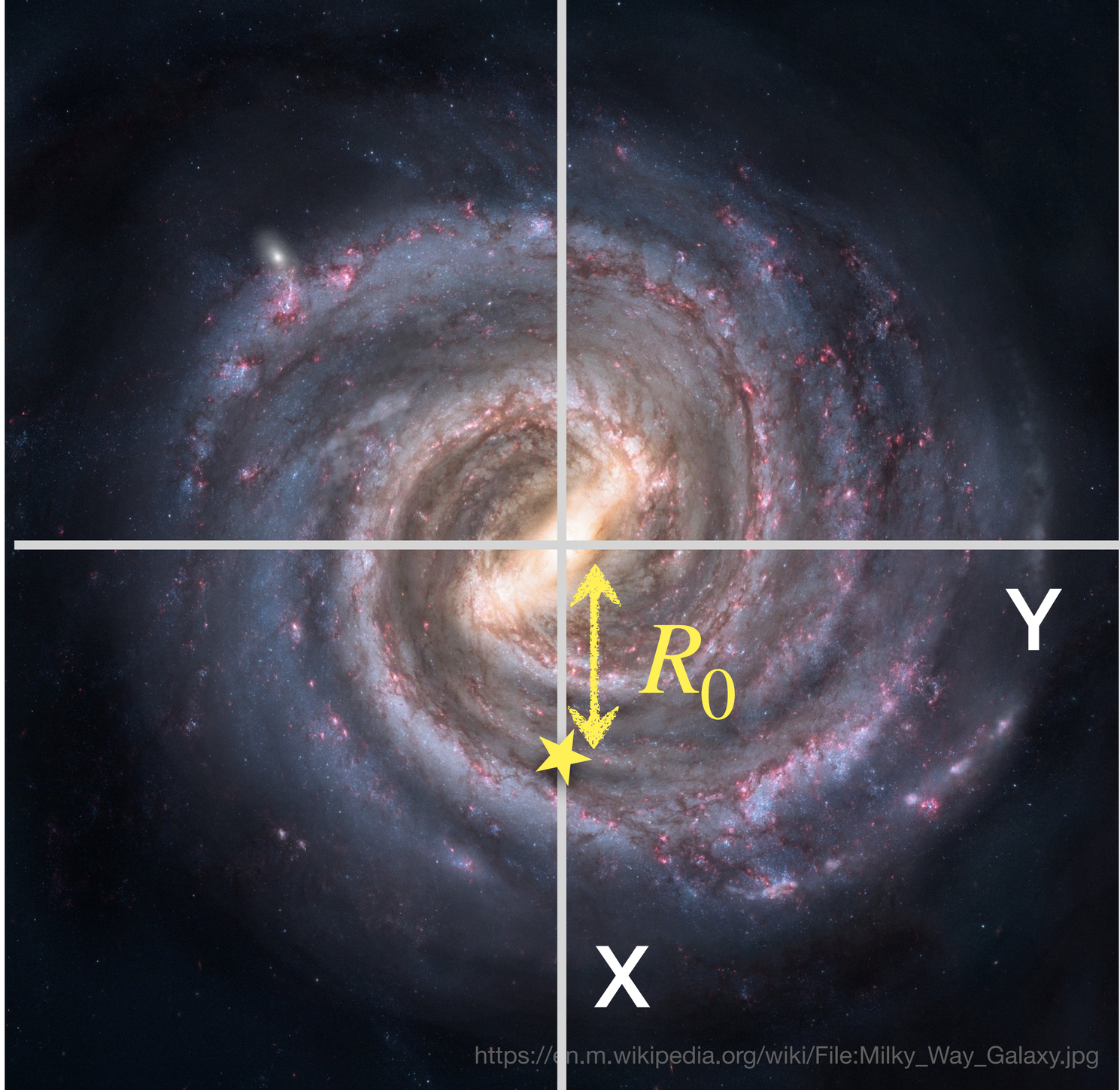
Today

- We've already toured the "Solar Neighborhood" (Lecture 2)
- and reviewed many of the observable features of the Milky Way (Lectures 3 & 4)
- **Today let's tour the Galaxy more broadly, especially focused on this beautiful disk!**

https://en.m.wikipedia.org/wiki/File:Milky_Way_Galaxy.jpg

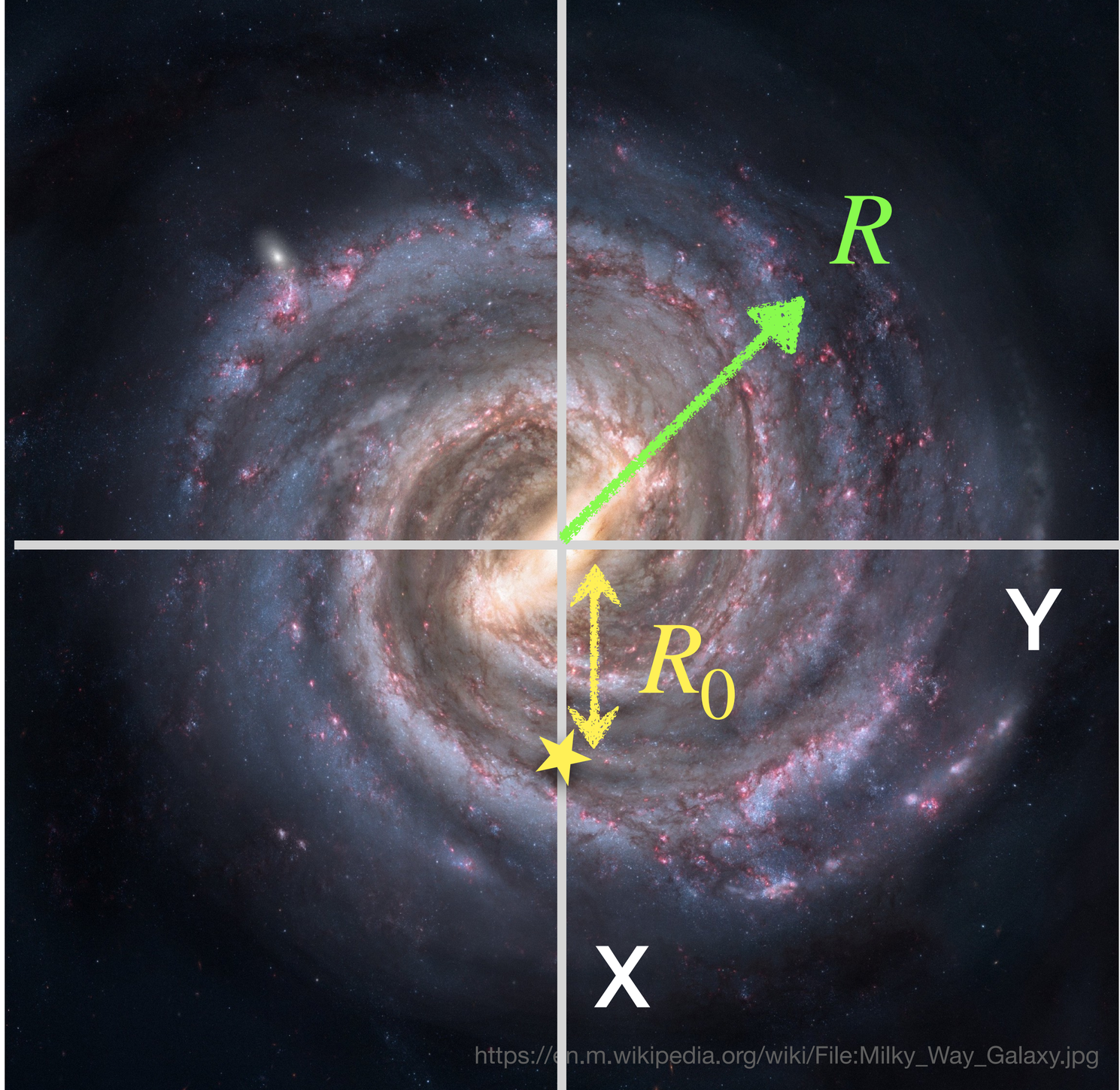
Coordinates

- Galactocentric XYZ Coordinate Frame
- (X,Y) are the top-down view of the Galaxy
  - Sun is at $(X = R_0, Y = 0)$
- Z is the vertical direction, very important for dynamics & star counts!
  - Sun is at $Z = 27\text{pc}$ (Chen+2001)



Coordinates

- Ignore spiral structure… assume galaxy is azimuthally symmetric
- Common to see things plotted in (R, Z) where $R = \sqrt{X^2 + Y^2}$
- Sometimes written as R_{XY}, as distinct from R_{XYZ} used in studying e.g. dark matter halo



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)

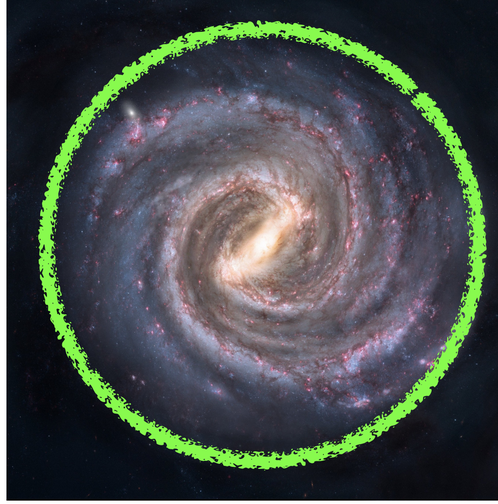
Distance to Galactic Center: R_0

- *A word on astropy…*

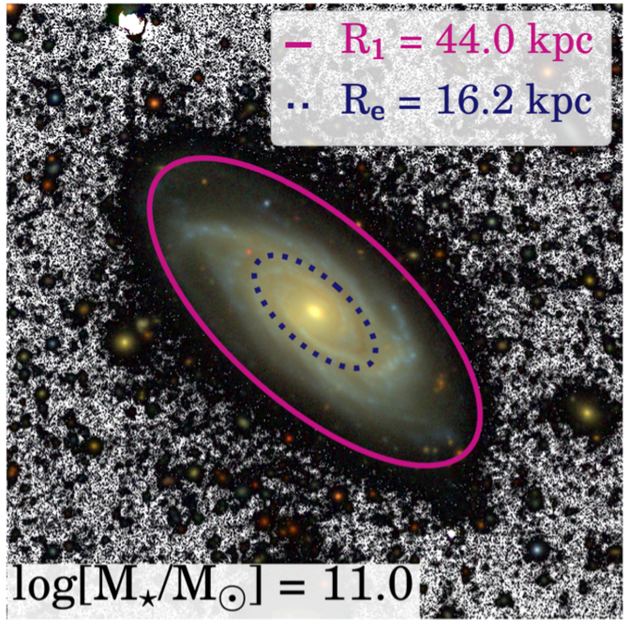
- The default value for R_0 changes between Astropy versions! This is good, but be aware of it!

- You can get in major yet subtle trouble when switching coordinate frames,
  e.g. (RA, Dec, dist) -> (X,Y,Z)
  and trying to match to existing catalogs or models.

The Milky Way's Disk



- **The disk is ~26kpc in diameter…** how do you draw that radius?
- "Isophotal", i.e. pick a surface brightness cutoff? (Goodwin+1998)
- Half-light size? (e.g. de Vaucouleurs 1948)
- These are all effective sizes, based on survey depth… something maybe more physical?
  - A threshold in stellar mass density? $1 M_{\odot}/\mathrm{pc}^2$ (Trujillo+2020)
- Neutral H traced out to at least 25kpc (Levine+2006)



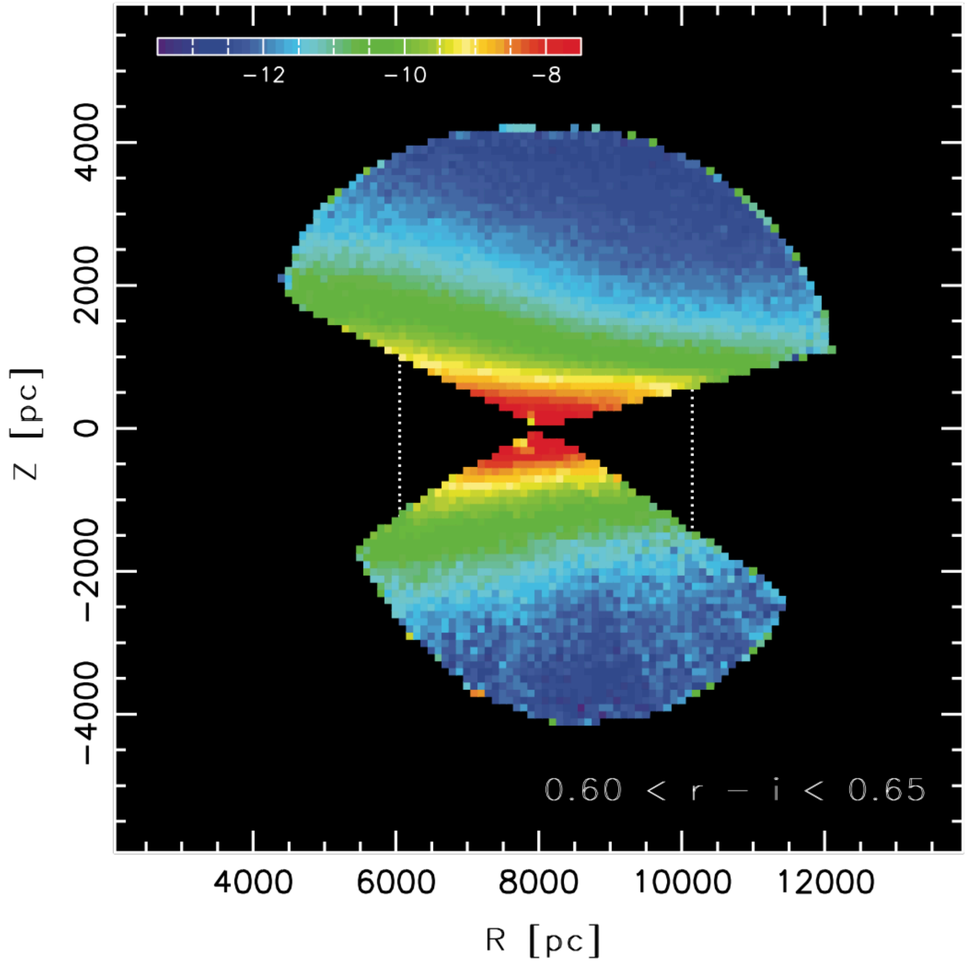
The Milky Way's Disk

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

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

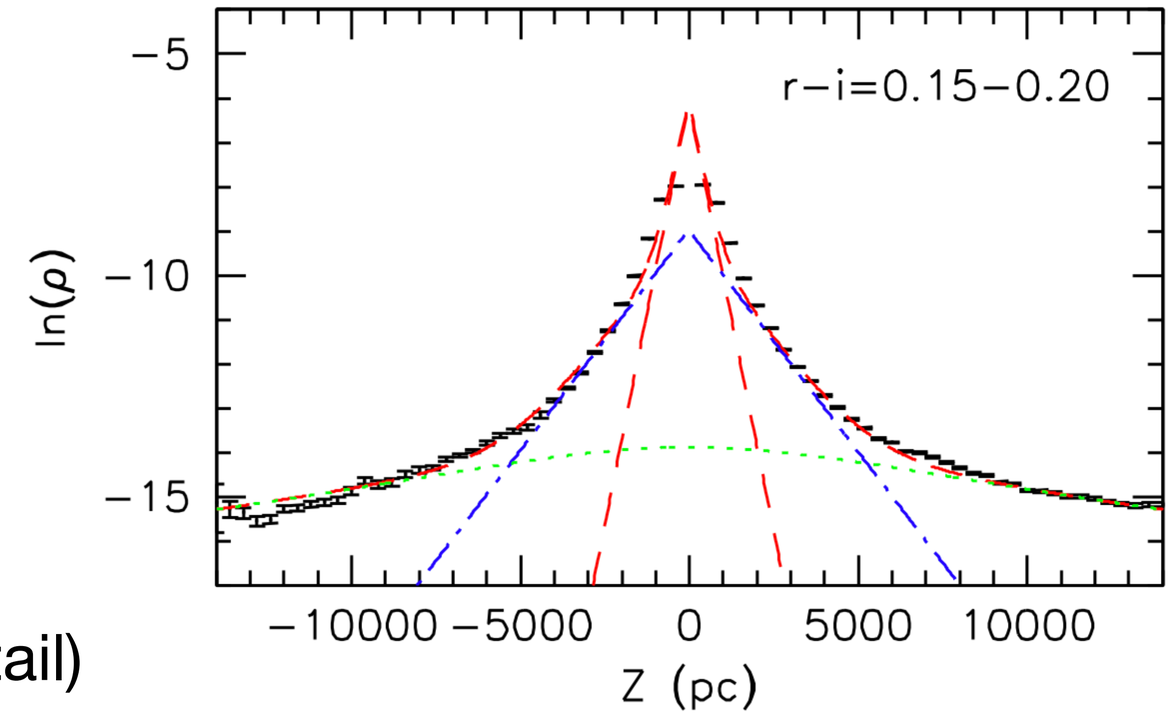
$$\rho(R,Z) = \rho(R_\odot, 0) e^{R_\odot/L} \exp\left(-\frac{R}{L} - \frac{Z+Z_\odot}{H}\right), \quad (19)$$

where ρ 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-



The Milky Way's Disk

- Jurić+2008
- Vertical density profile seems to support 2 disks:
  - H~300pc, L~2500pc
  - H~900pc, L~3500pc
- Good **1st-order** description of the disk
- Does it work for all stars? All ages?
  All galactocentric radii? (Obv. not in detail)



The Milky Way's Disk

- Many other disk profiles (parameterizations) explored…

1-) Simple double exponential disk (Fig. 12):

$$\rho(R,Z,l) = \exp\left(-\frac{R-R_0}{R_H} - \frac{|Z-Z_0(R)|}{Z_H}\right)$$

$$Z_0(R) = \begin{cases} (R-R_0)\times A_W & \mathrm{R} > R_0 \\ 0 & \mathrm{R} < R_0 \end{cases}$$

2-) Double exponential disk + thick disk (Fig. 13):

$$\rho(R,Z,l) = \exp\left(-\frac{R-R_0}{R_H} - \frac{|Z-Z_0(R)|}{Z_H}\right)\ (1-R_{Sol})$$

$$+\exp\left(-\frac{R-R_0}{R_{HT}} - \frac{|Z|}{Z_{HT}}\right)\ R_{Sol}$$

3-) Isothermal disk:

$$\rho(R,Z,l) = \exp\left(-\frac{R-R_0}{R_H}\right)\ \mathrm{sech}^2\left(-\frac{|Z-Z_0(R)|}{Z_H}\right)$$

4-) Isothermal disk + thick disk (Fig. 14):

$$\rho(R,Z,l) = \exp\left(-\frac{R-R_0}{R_H}\right)\ \mathrm{sech}^2\left(-\frac{|Z-Z_0(R)|}{Z_H}\right)\ (1-R_{Sol}$$

$$+\exp\left(-\frac{R-R_0}{R_{HT}} - \frac{|Z|}{Z_{HT}}\right)\ R_{Sol}$$

5-) Disk with variable scale height (Fig. 15, l=180, Fig. 18, l=240):

$$\rho(R,Z,l) = \exp\left(-\frac{R-R_0}{R_H} - \frac{|Z-Z_0(R)|}{Z_H(R)}\right)\times(1+A_T)^{-1}$$

$$Z_H(R) = \begin{cases} (1+(R-R_0)\ A_T)\times H_Z & \mathrm{R} > R_0 \\ 1 & \mathrm{R} < R_0 \end{cases}$$

6-) Disk with variable scale height and flattening (Fig. 17 l=180, Fig. 19, l=240): Let's define:

$$F(x,\beta) = 1 - \exp\left(-\beta\ \exp(-x)\right)$$

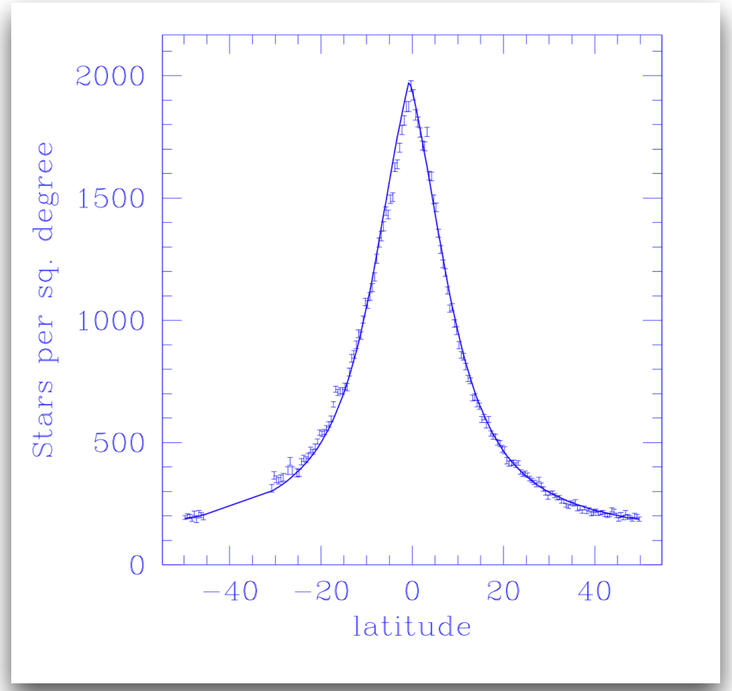
Then:

$$\rho(R,Z,l) = \exp\left(-\frac{R-R_0}{R_H}\right)\times F\left(\frac{|Z-Z_0(R)|}{Z_{HT}},\beta(R)\right)$$

$$\times\left((1+A_T)\int_0^{+\alpha} F(x,\beta)dx\right)^{-1}$$

With the same definition of $Z_H(R)$ as for the previous model, and:

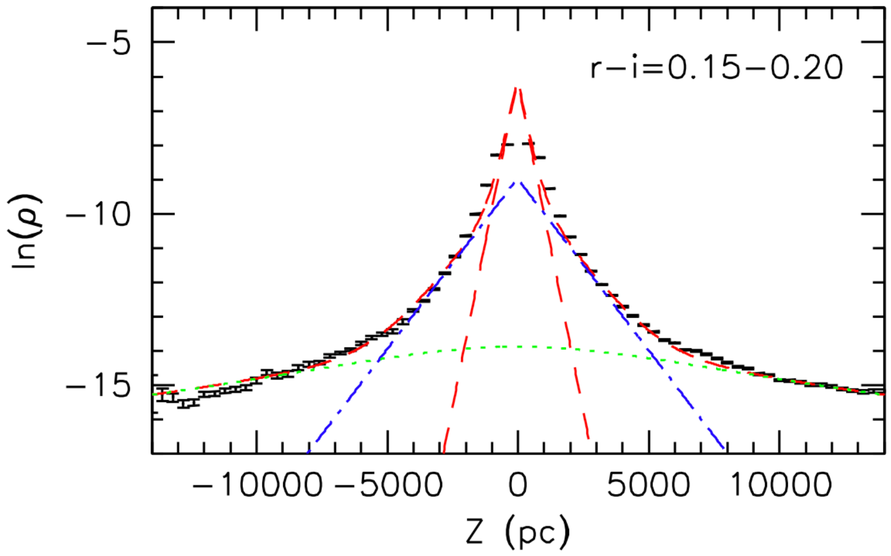
$$\beta(R) = \begin{cases} 1+(R-R_0)\ A_F & \mathrm{R} > R_0 \\ 1 & \mathrm{R} < R_0 \end{cases}$$



Alard (2000)

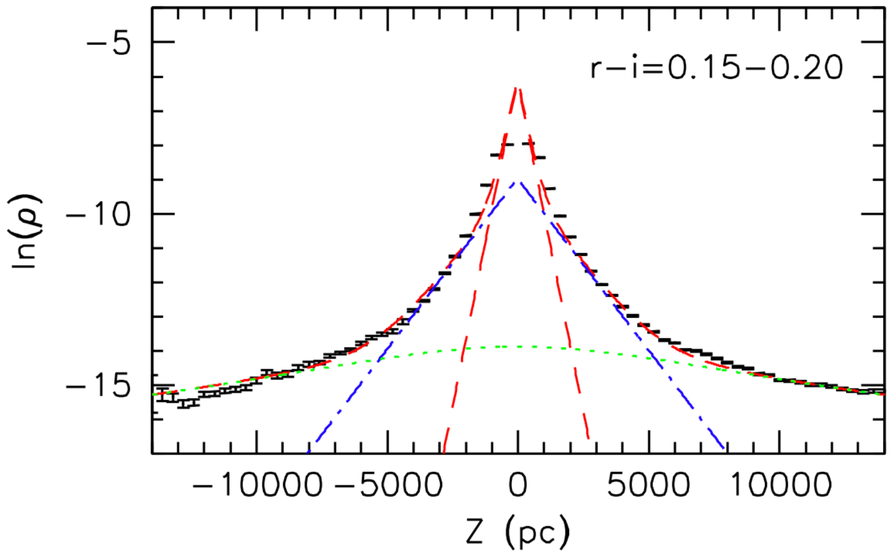
A Second “Thick” Disk?

- The “thick disk” first discovered in 1980’s as an excess component in stellar density profile as a function of height (Z), when trying to study Disk+Halo
- Usually attributed to Gilmore & Reid (1983), but early hints in e.g. Yoshii (1982)
- Seem to have distinct kinematic, chemical, & age distribution of stars… how?!
- Debate reignited in 2000’s with e.g. SDSS.
  - Is it even a distinct component, or is the disk just have continuous heating?



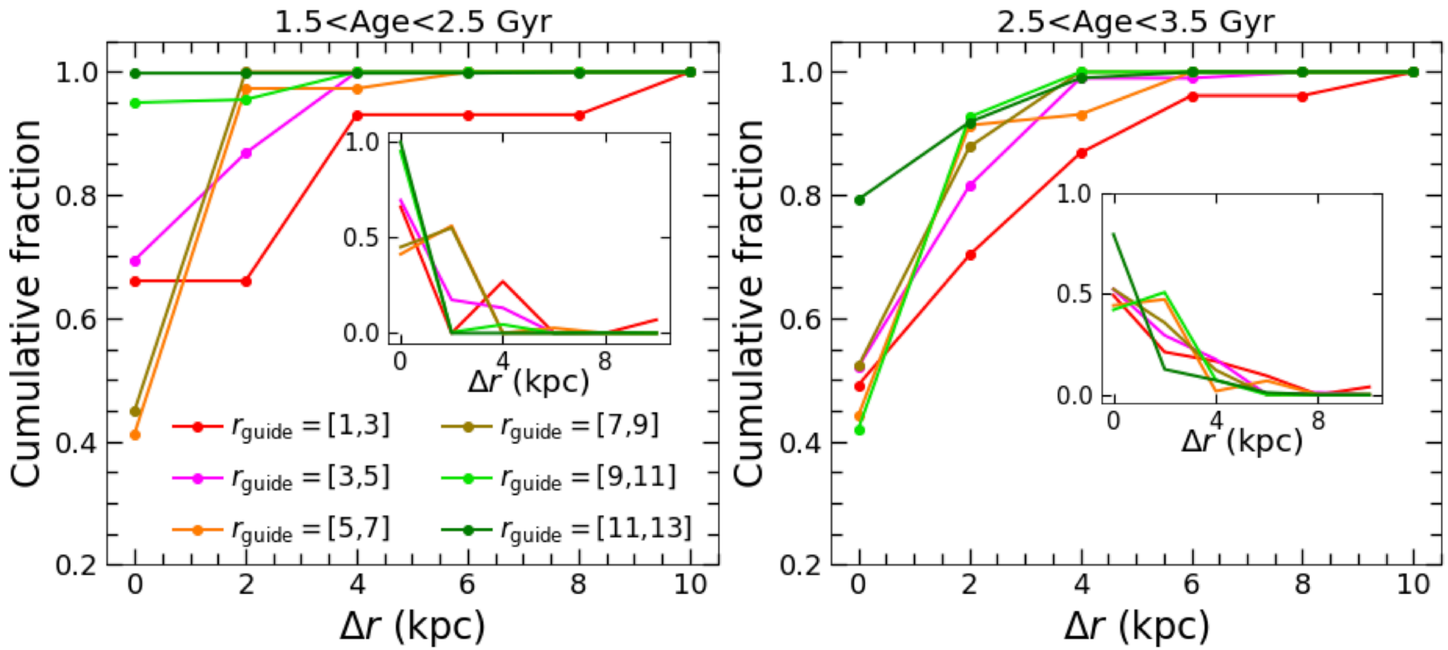
A Second “Thick” Disk?

- General wisdom: stars are “heated” (i.e. given higher vertical velocities) over time due to scattering from arms/GMC/etc
- Stars born near midplane. Older stars found higher up
- Vertical density AND vertical velocities therefore very useful for statistically describing stellar populations
- Early suggestions: thick disk must be older
- Backed up by *chemical cartography* (we’ll discuss that later!)



Other stellar migration?

- Stars also undergo “radial migration”, again due to dynamical interactions within the disk.
- This mostly a random scattering of 1-2 kpc, net radial migration weak (none?)
- e.g. Lian+2022



A Second “Thick” Disk?

- Debate sort of ongoing… Some claim no distinct population, especially in abundance distributions

THE MILKY WAY HAS NO DISTINCT THICK DISK

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- Yet many still use concept to describe the vertical density and kinematic profiles of the disk

Milky Way Thin and Thick Disk Kinematics with Gaia EDR3 and RAVE DR5

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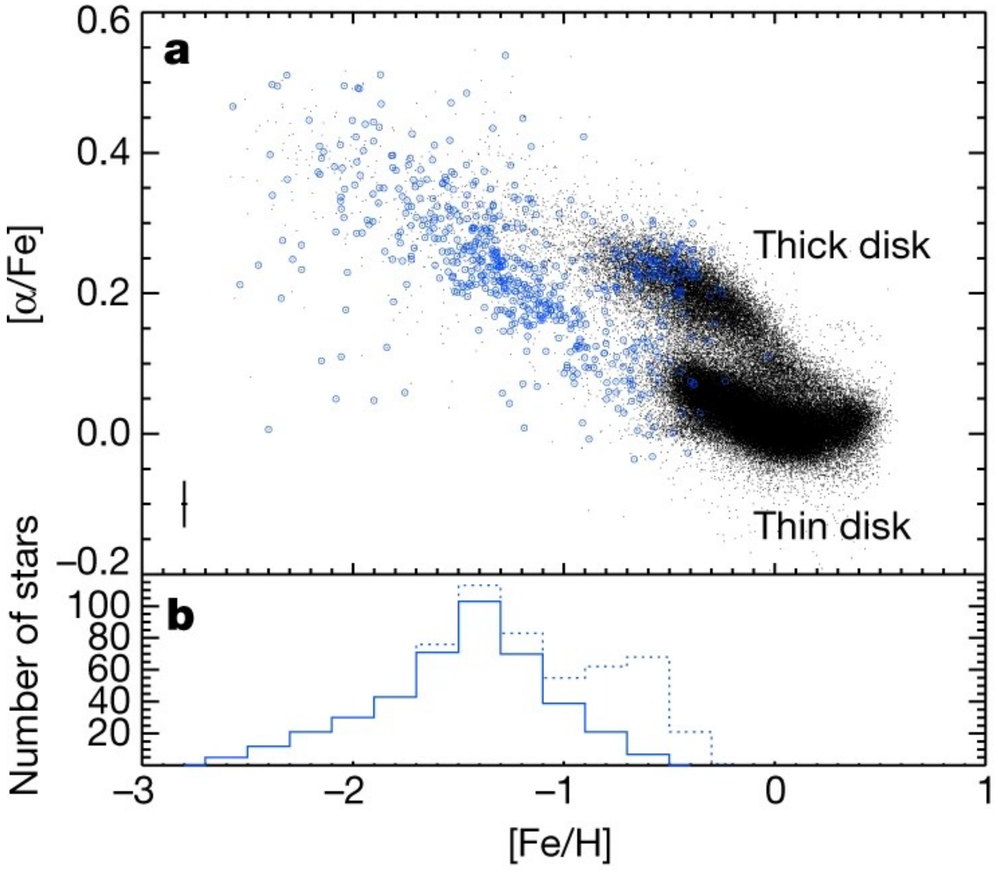
A Second “Thick” Disk?

- Seems like there *probably* is a distinct 2nd component
- May be at least partially due to the Gaia-Enceladus merger (Helmi+2018)
- Also explains much of the inner halo density & kinematic
- And *maybe another* weird feature of the disk…



THE MILKY WAY'S WARP

Warp

Sun

Bulge

Disk

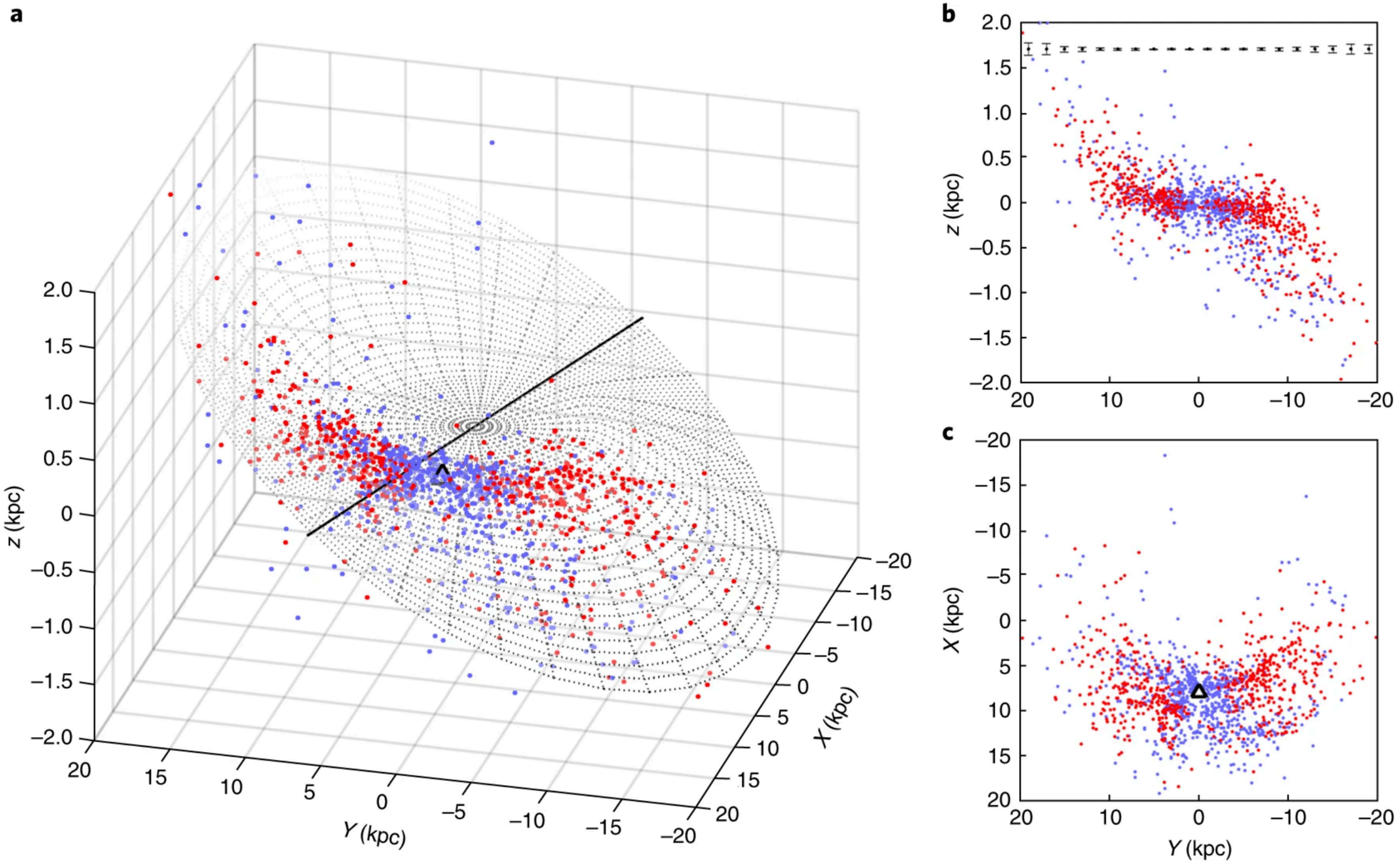
26 000
light years

52 000
light years

https://sci.esa.int/web/gaia/-/the-milky-way-s-warp

Warped Disk

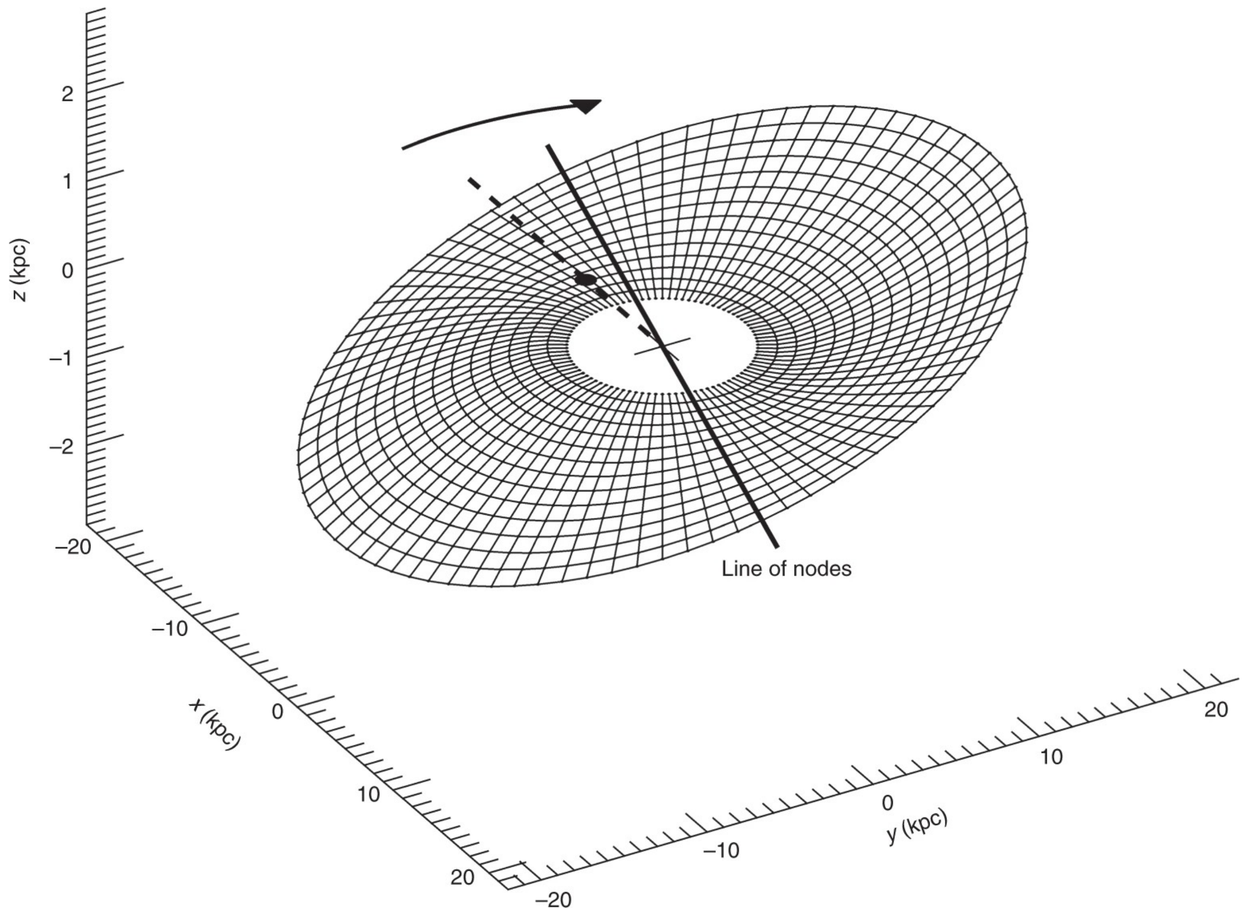
- Long seen in gas (HI)
- Now traced w/ stars
- Here: Cepheids from WISE + Gaia DR2
- Likely caused by merger from dwarf galaxy… but which?!
  - Sagittarius ?



Chen+2019

Warped Disk

- Warp shape seems to precess
- Moves with Galactic rotation (but slower)
- Favors a single dynamical interaction origin, rather than “the relic of the ancient assembly history…”



Poggio+2020

Warped Disk

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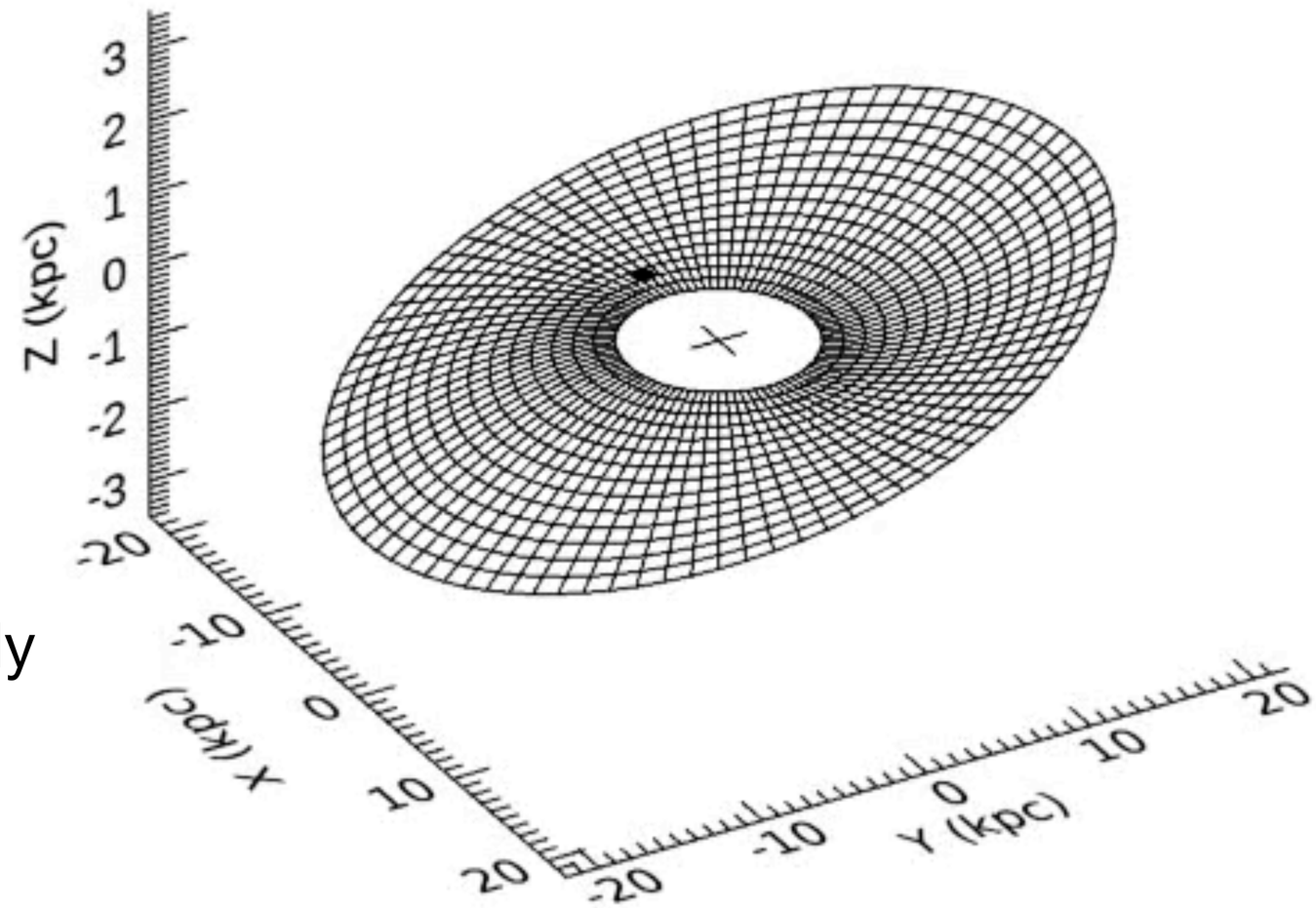
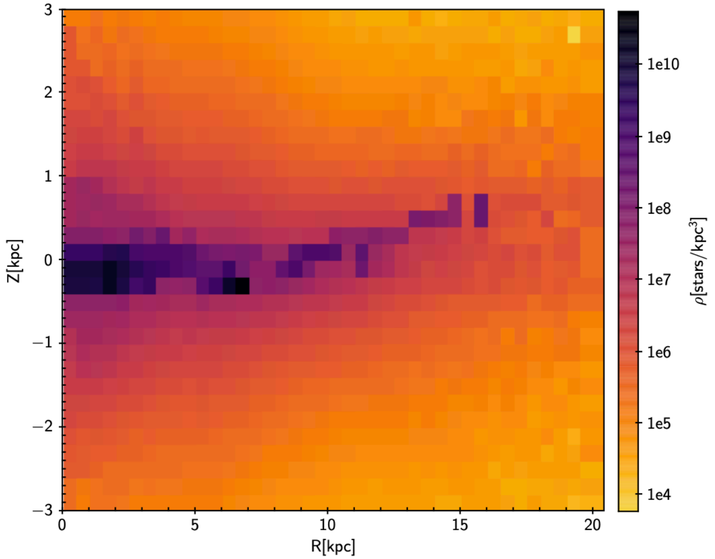


Poggio+2020

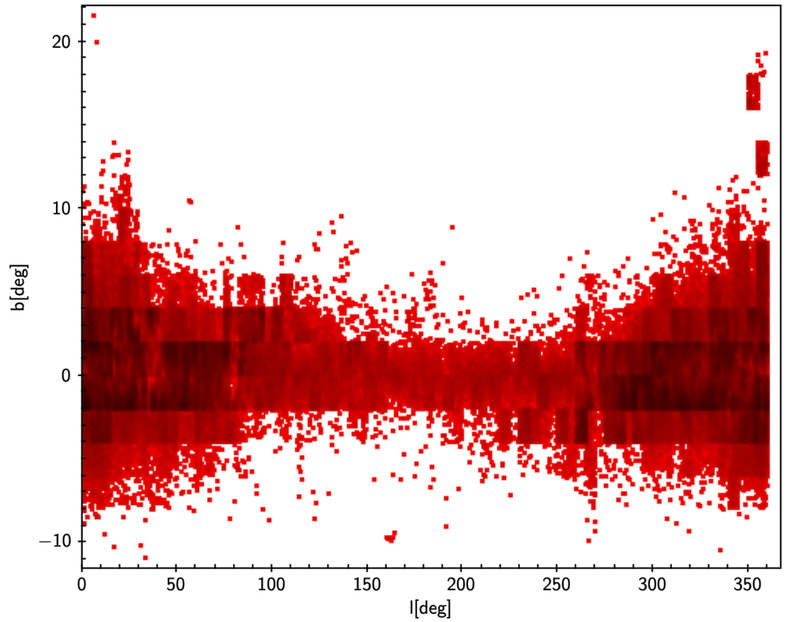
Flared Disk

- Scale-height increases at large galactocentric radius (R)
- Seen in both stars and gas
- Usually ascribed to property of the thick disk at large radius
- e.g. see Chrobáková+2022 with Gaia
- Probably another byproduct of merger-driven thick disk



(a) $0° < \phi < 30°$

Warp

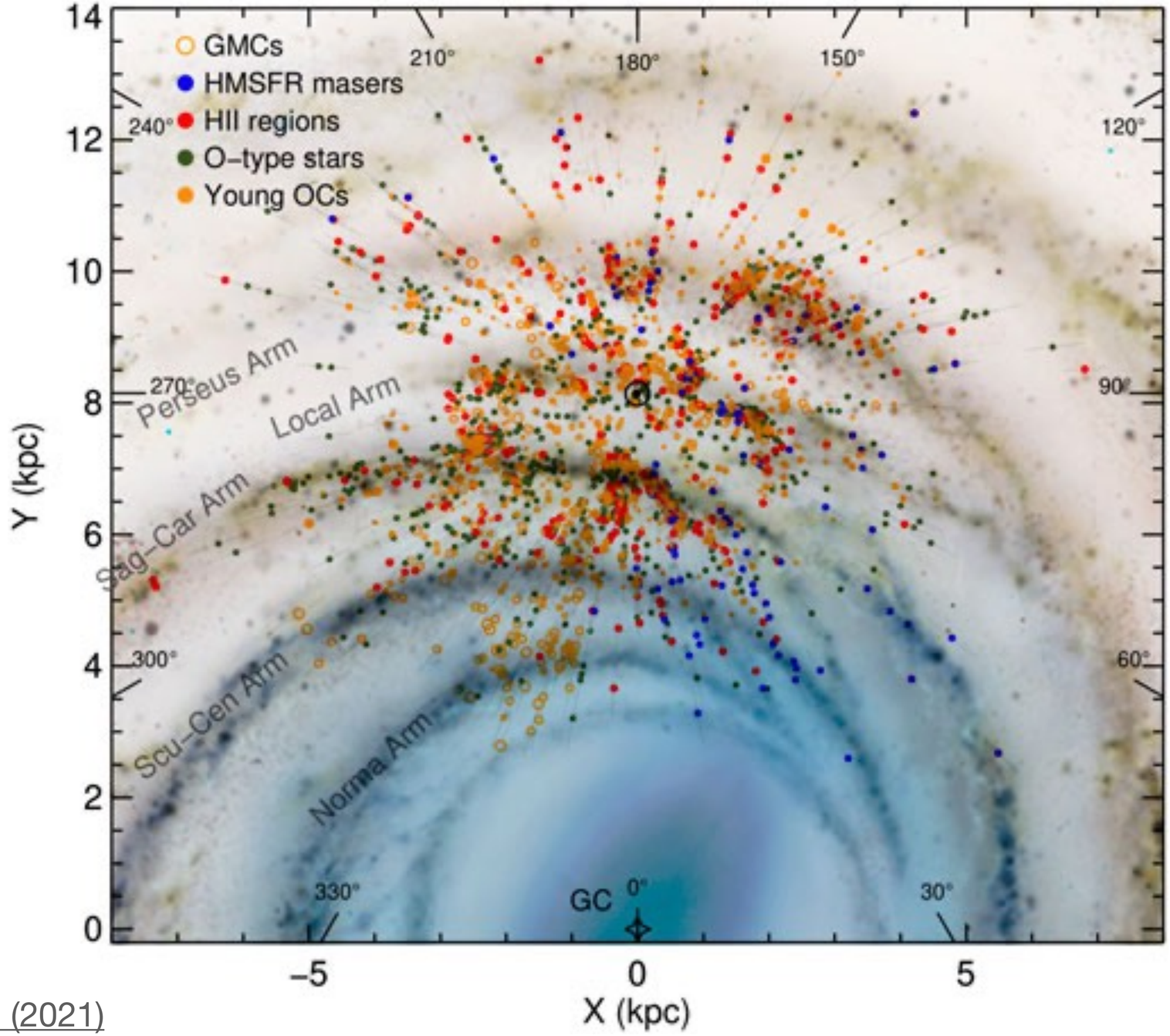


Flare


Break: 5 min, or 2 day?

From Lecture 2

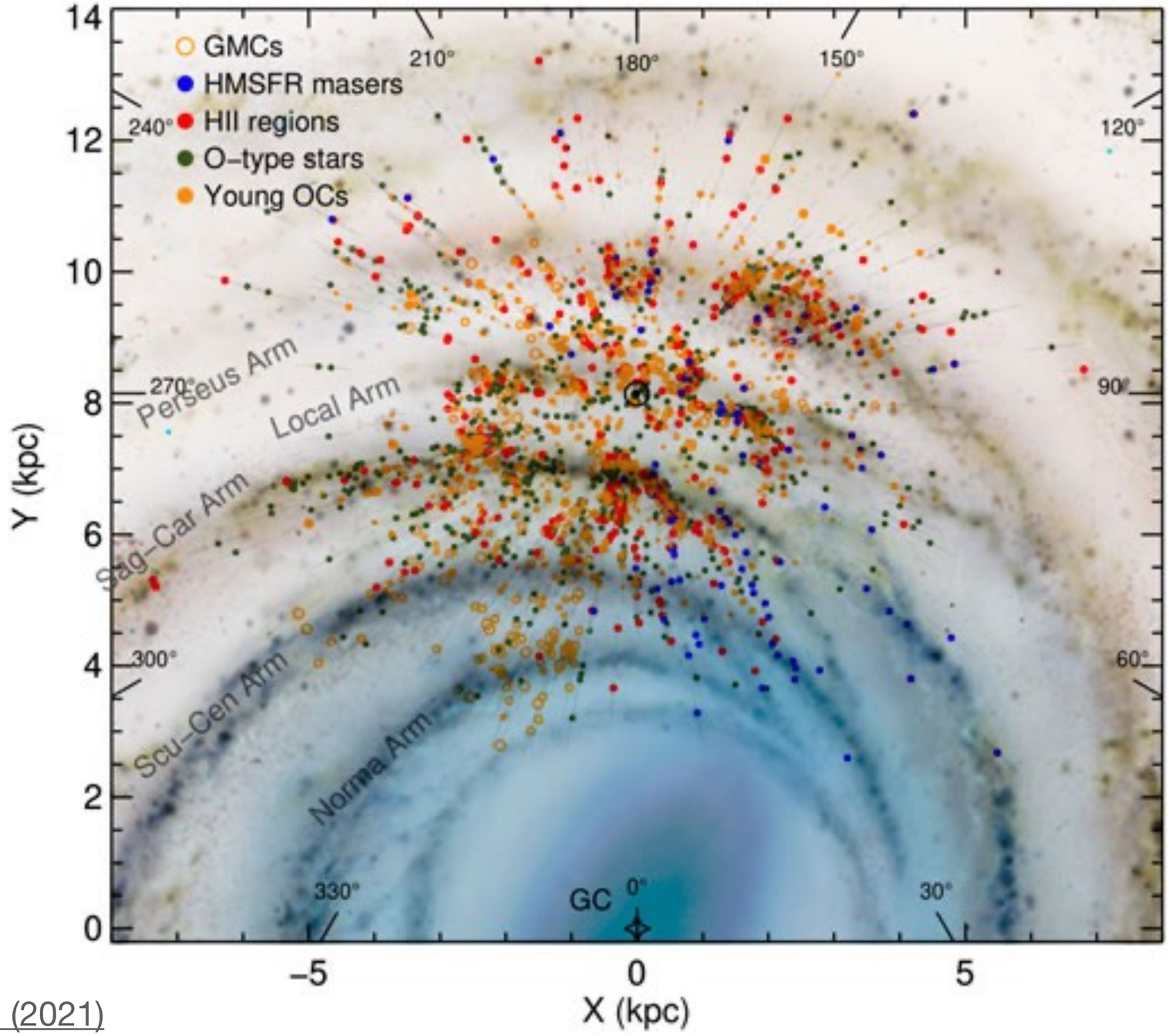
$d > 500\text{pc}$



Hou (2021)

Spiral Arms

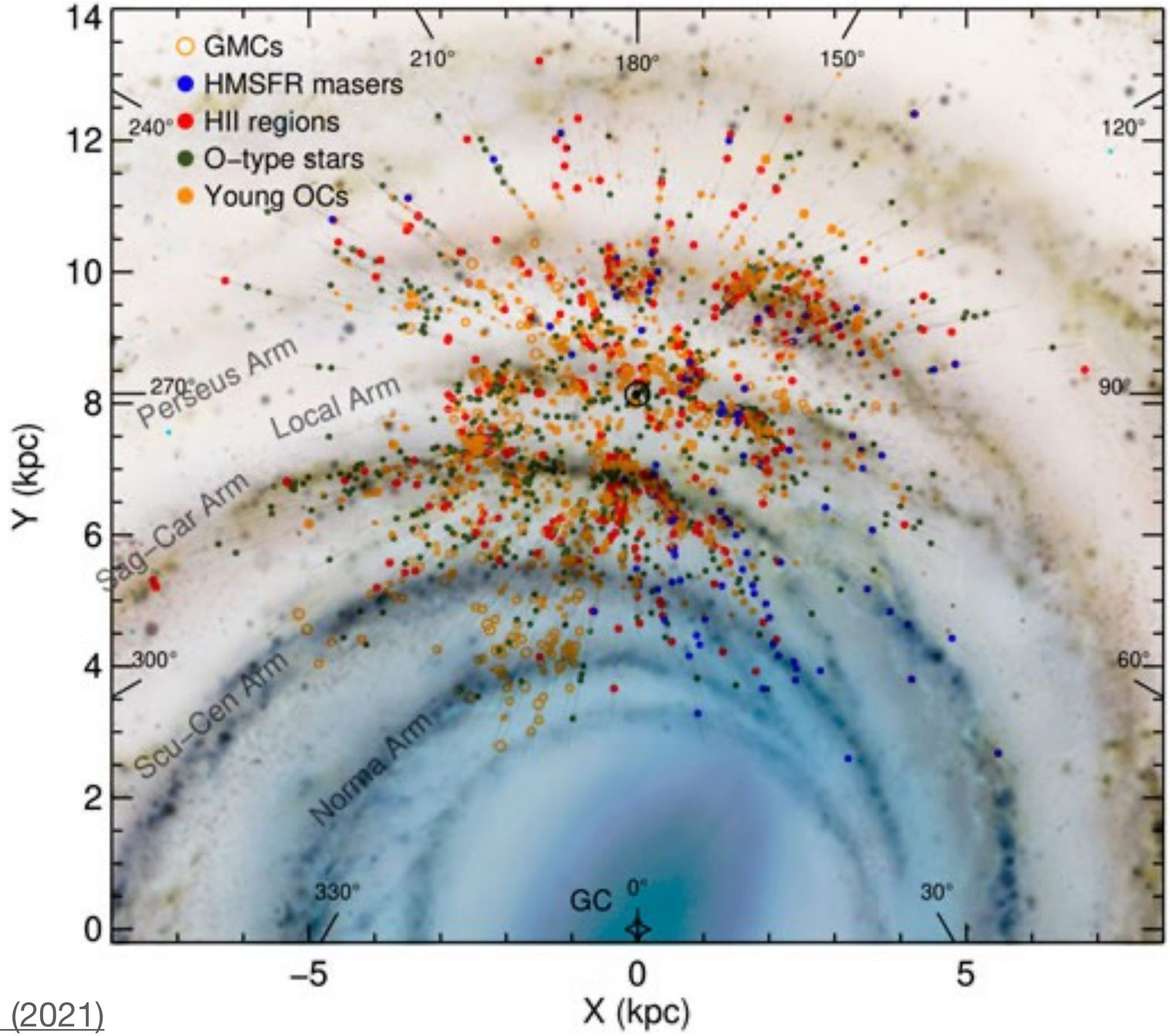
- Arm-like features seen with *many* tracers: gas, GMC's, clusters, cepheids, stars, masers…
- Shape is usually described as a **logarithmic spiral**



Hou (2021)

Spiral Arms

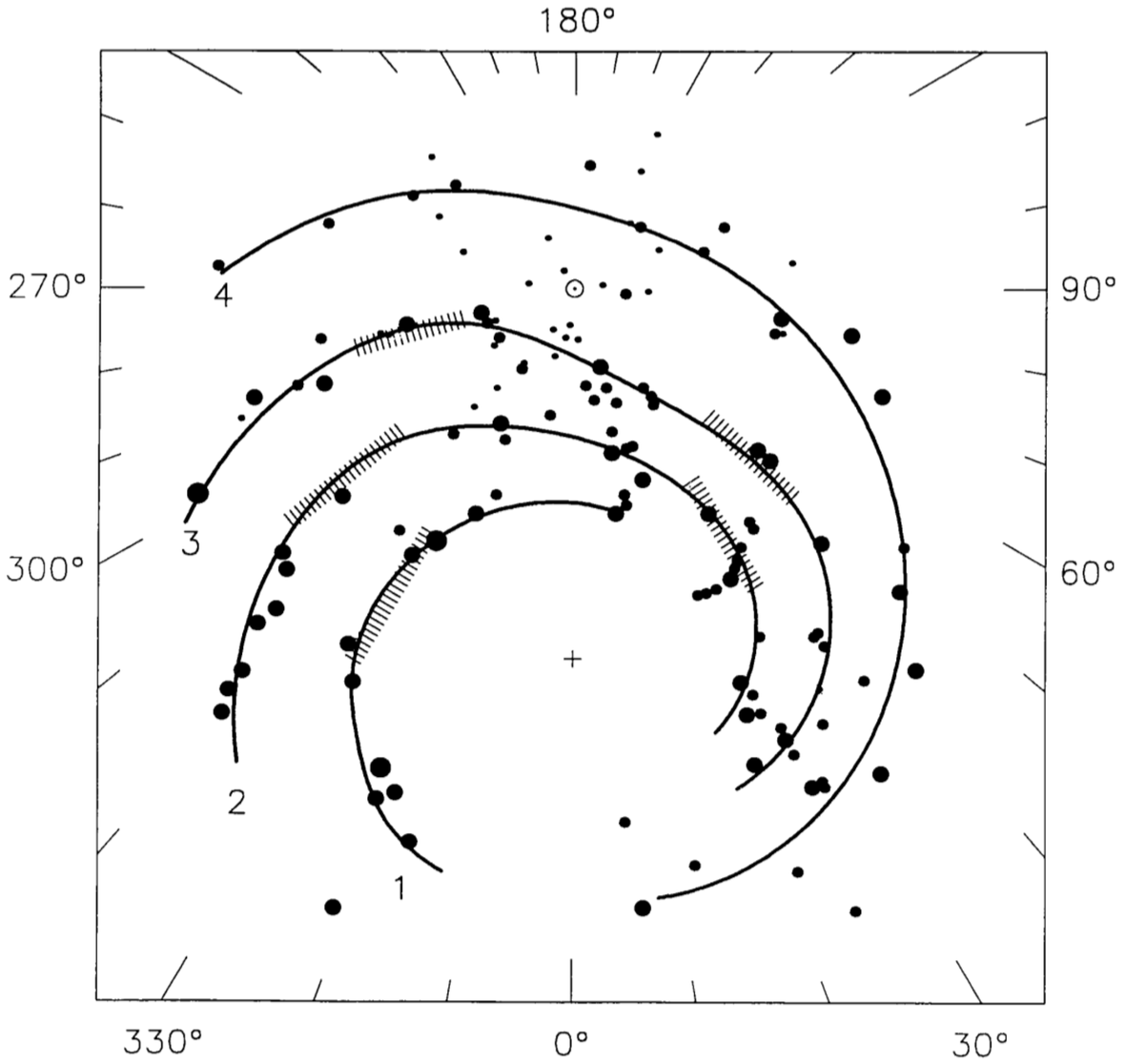
- Typical Description: MWY has **4 spiral arms** in solar neighborhood
- Or maybe 2? Long debated, esp. for a Spiral+Bar galaxy…
- Or maybe (probably) has a bunch of “spurs” between strong spiral features
- We maybe live on the edge of a spur



Hou (2021)

Spiral Arms

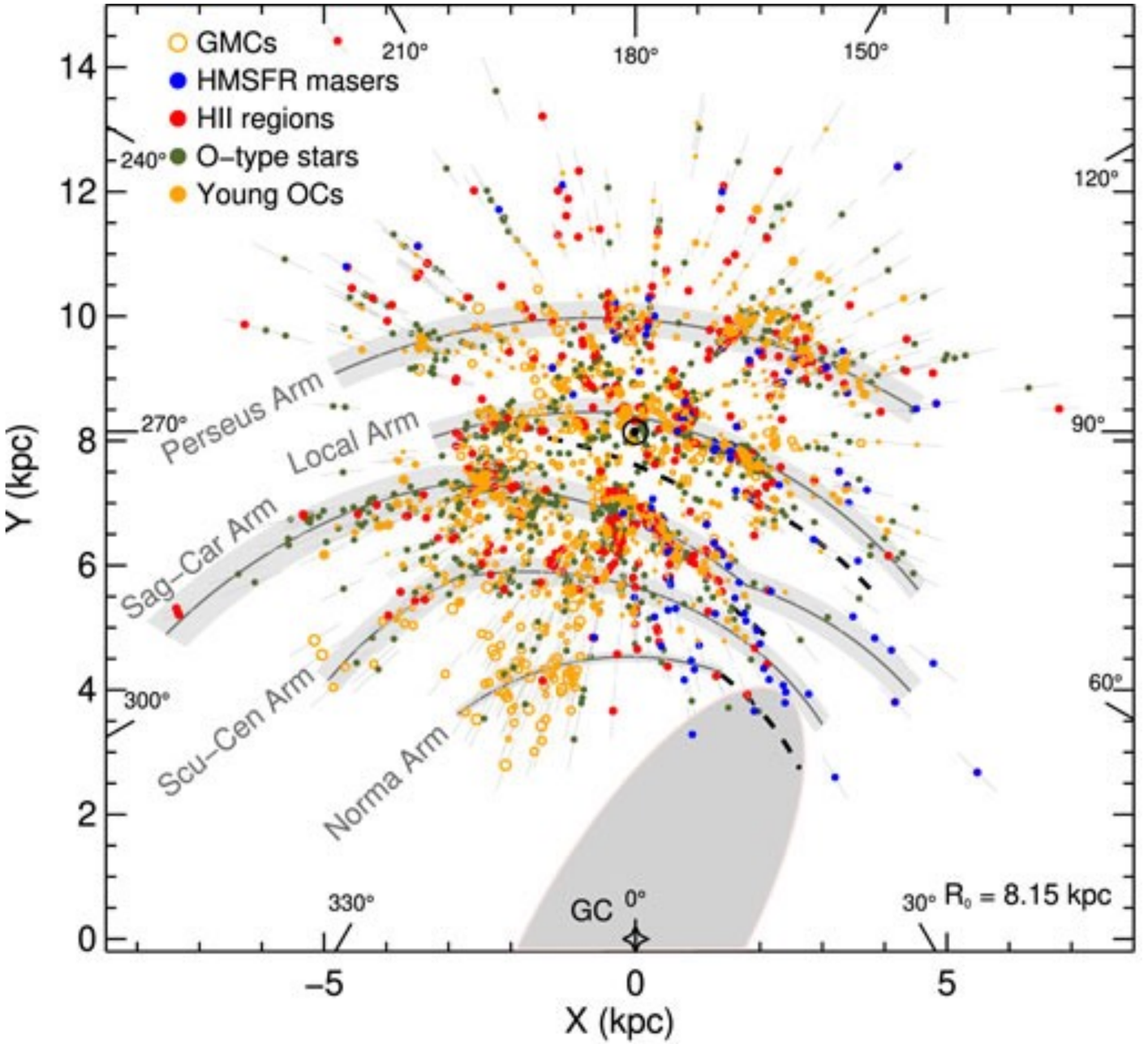
- Basic 4-arm model, very popular for ~30yrs



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



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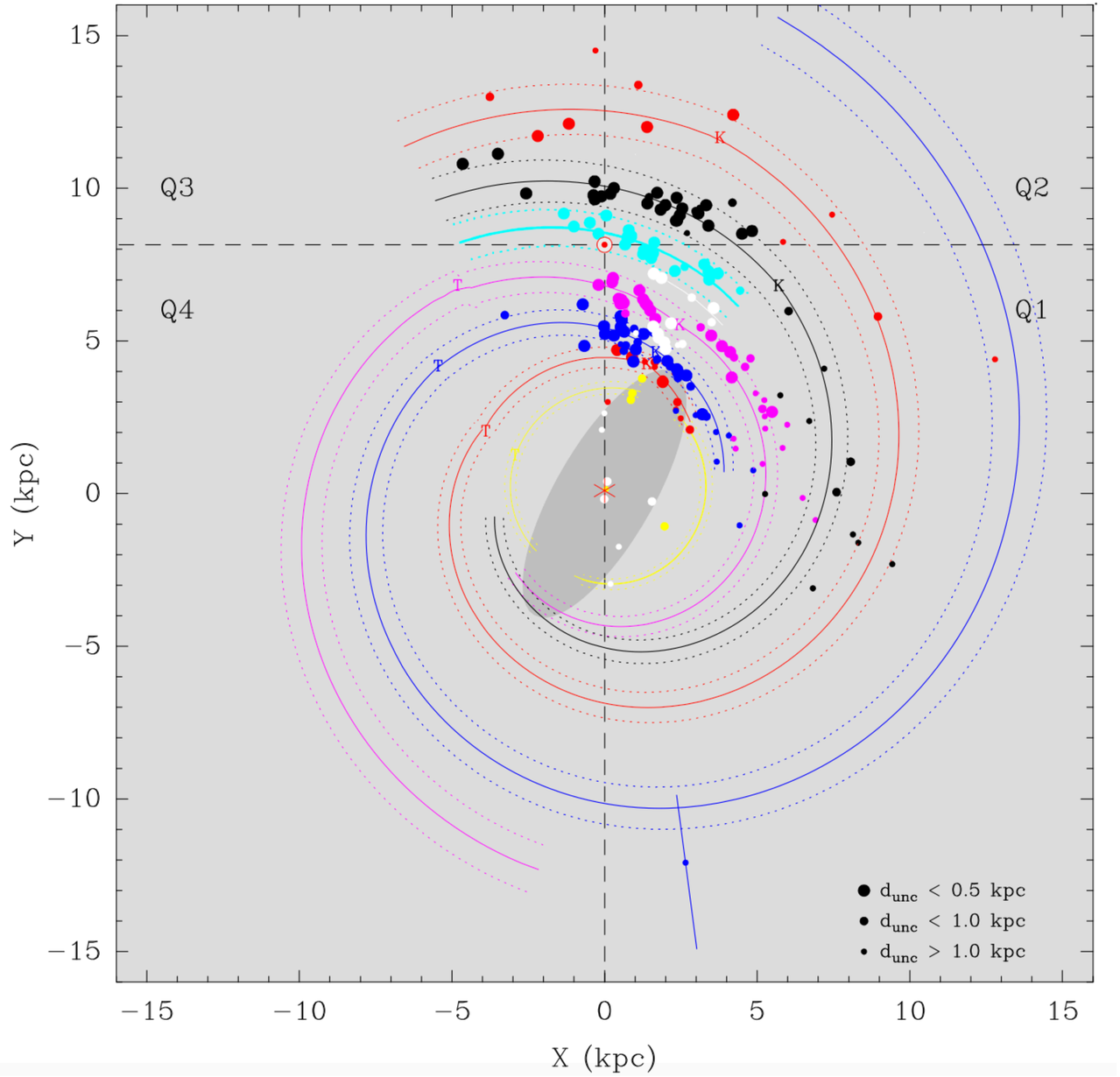
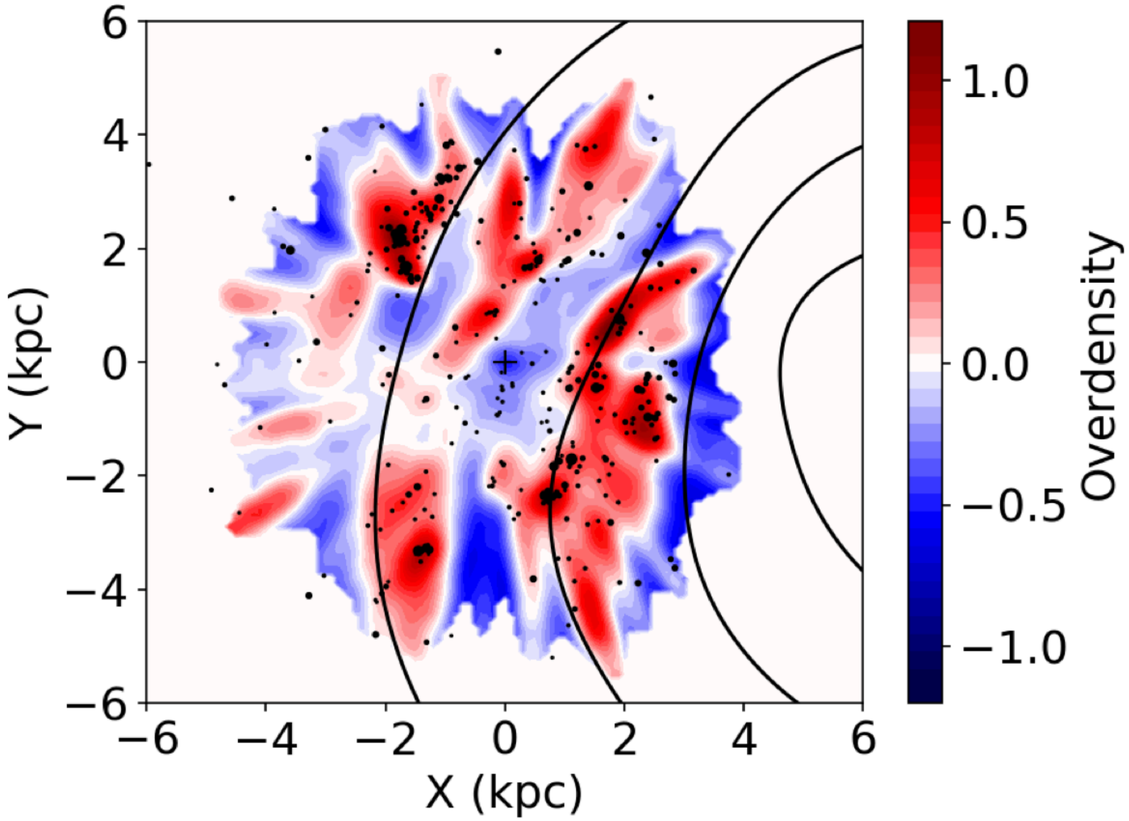


Star forming regions: Reid+2019

Spiral Arms

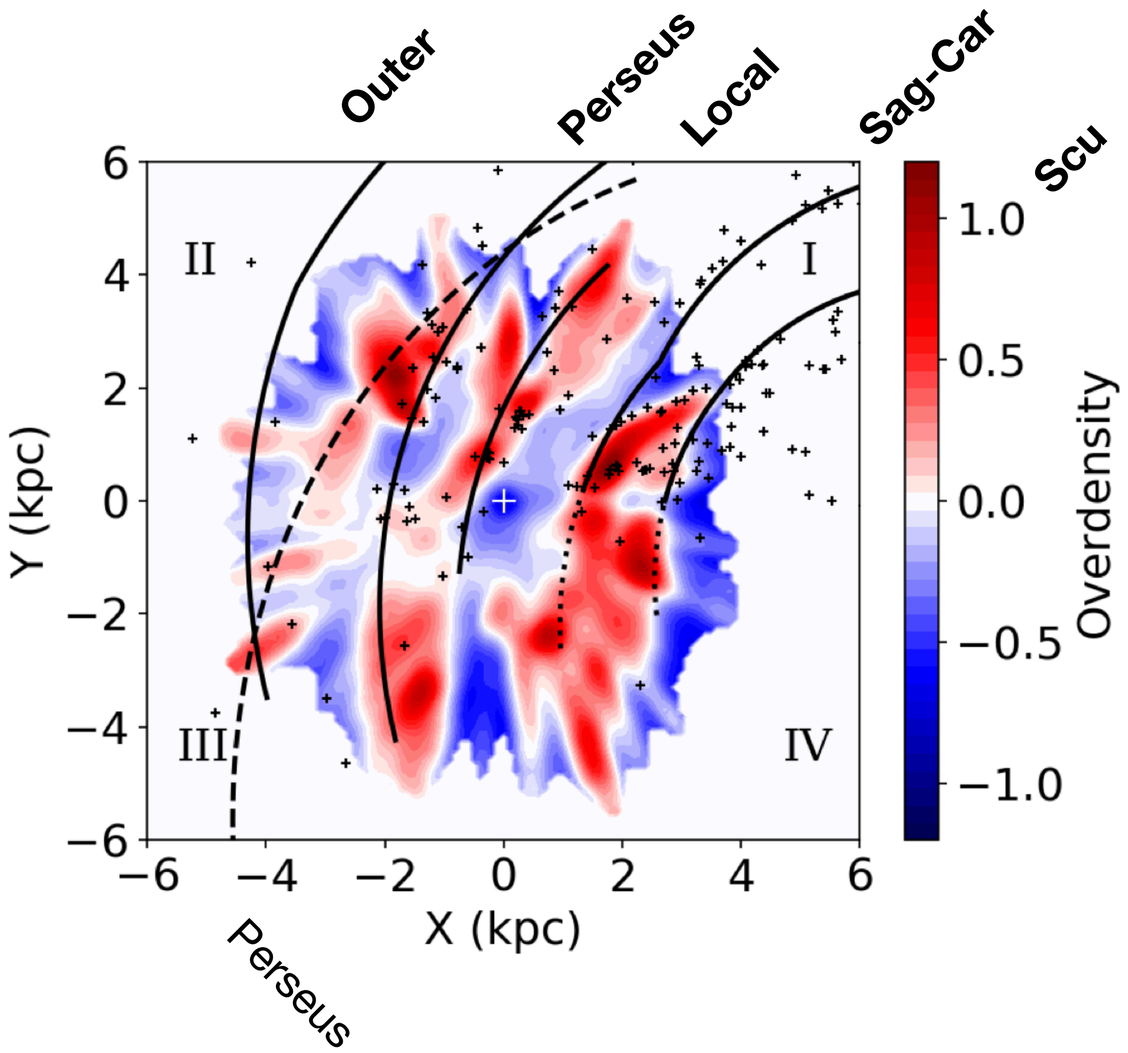
- Gaia traces out structure with young field stars!
- Not a *great* fit to some standard arm models (e.g. Taylor & Cordes 1993)



Poggio+2021

Spiral Arms

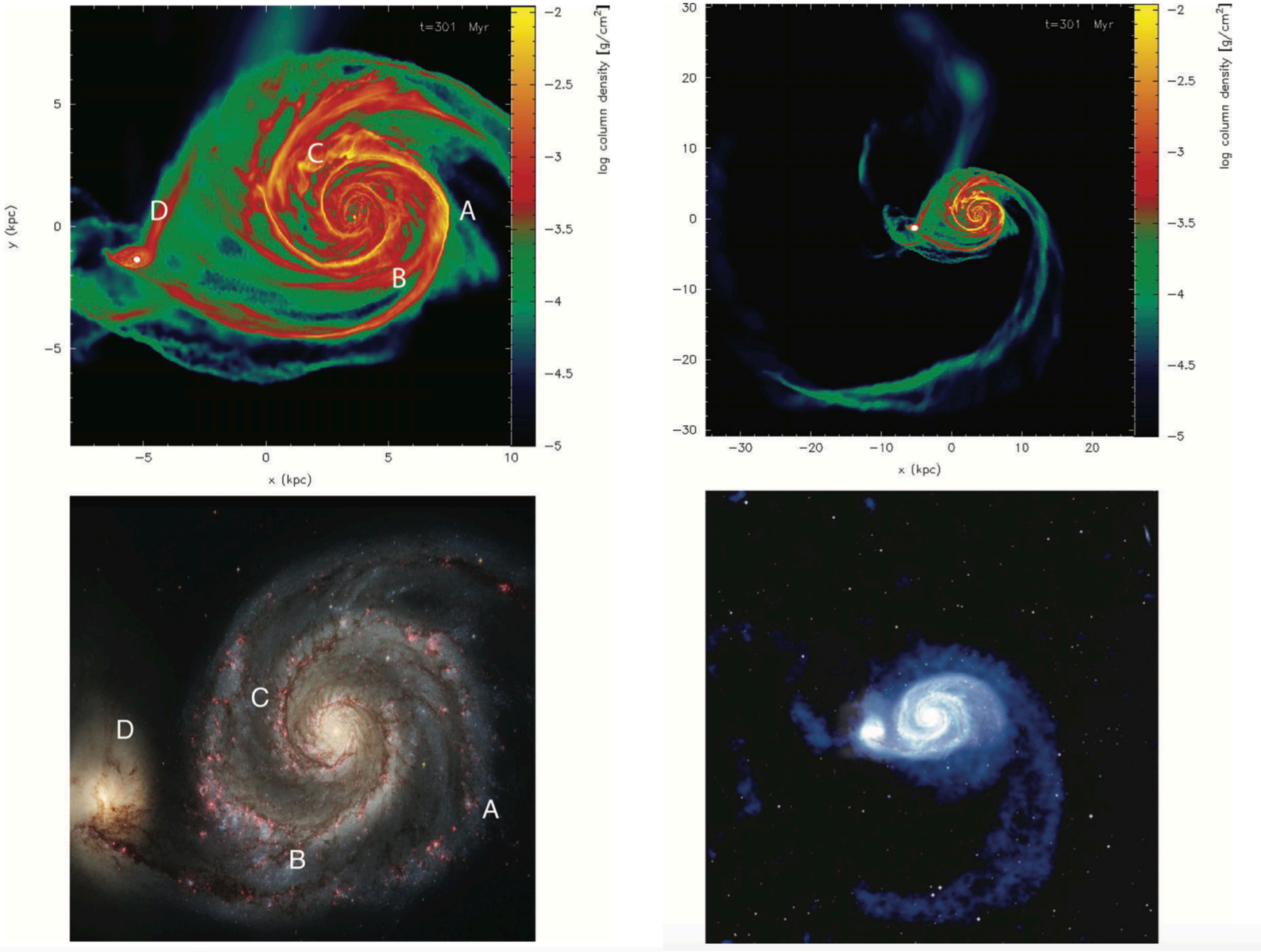
- Some better alignment with Reid+2019 model (black lines)
- Except Perseus arm looks morel like Levine+2006
- Lots of pure cartographic exploration to still be done here!



Poggio+2021

Spiral Arms

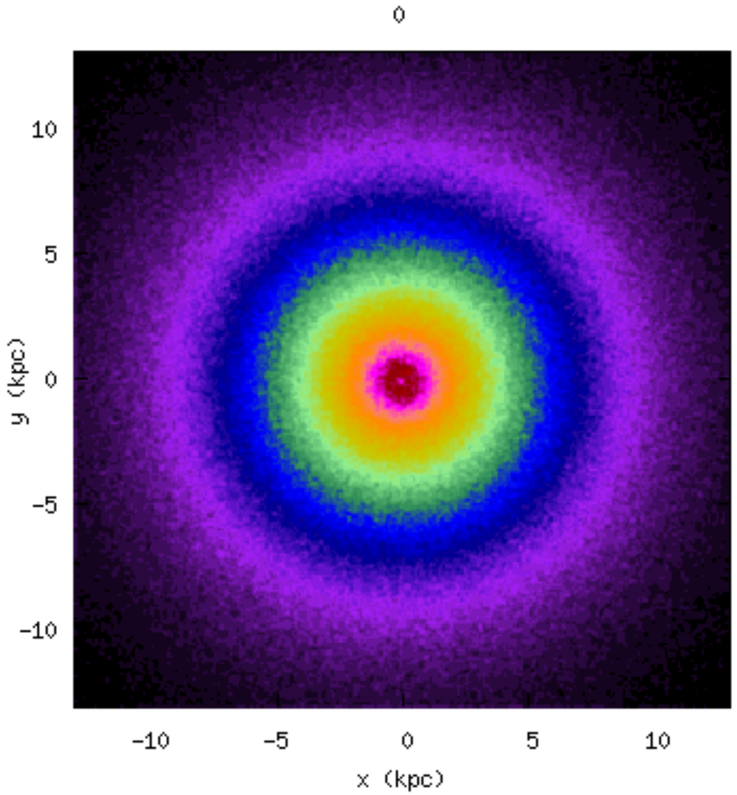
- M51 grand spiral structure, with lots of spur-like features reproduced well with Galaxy+merger model
- No strong bar though



Dobbs+2010

Spiral Arms

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



Quillen+2011

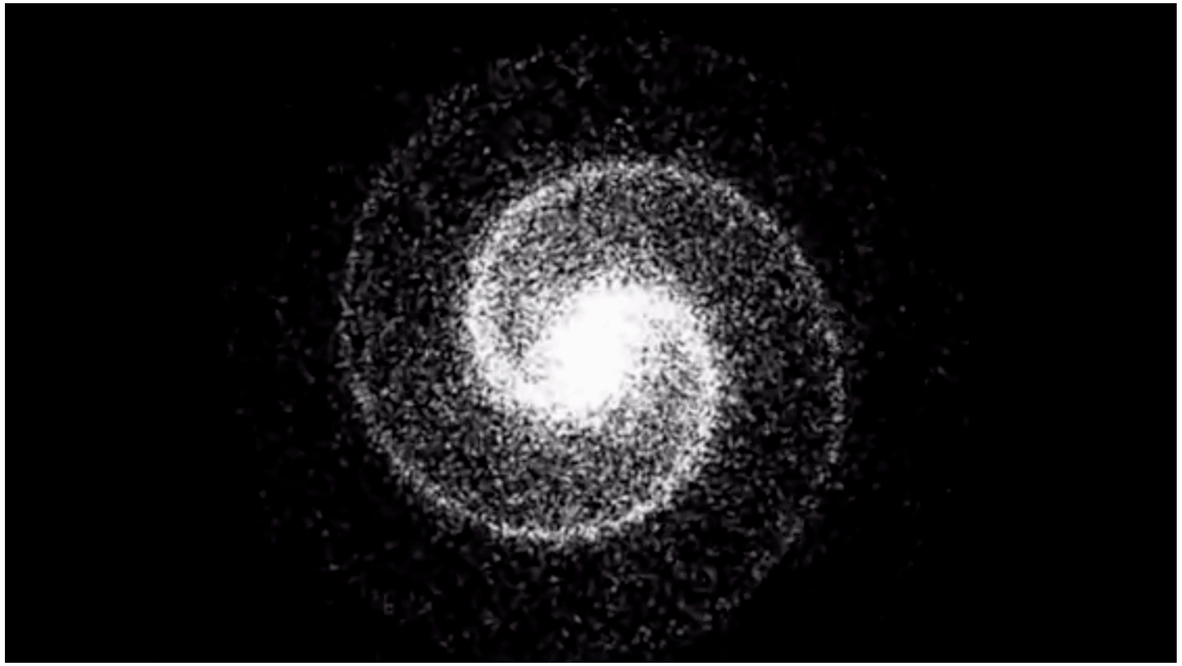
Spiral Arms

- 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)

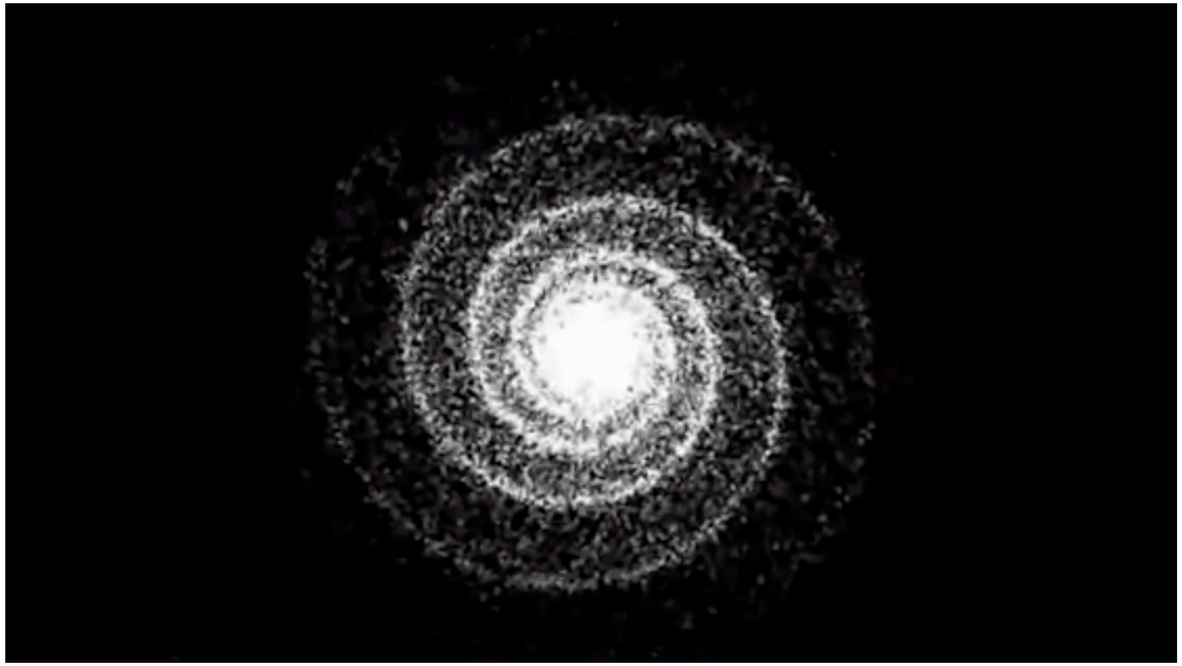
- Reminds me of: traffic jam propagation

Spiral Arms

Fixed Pattern



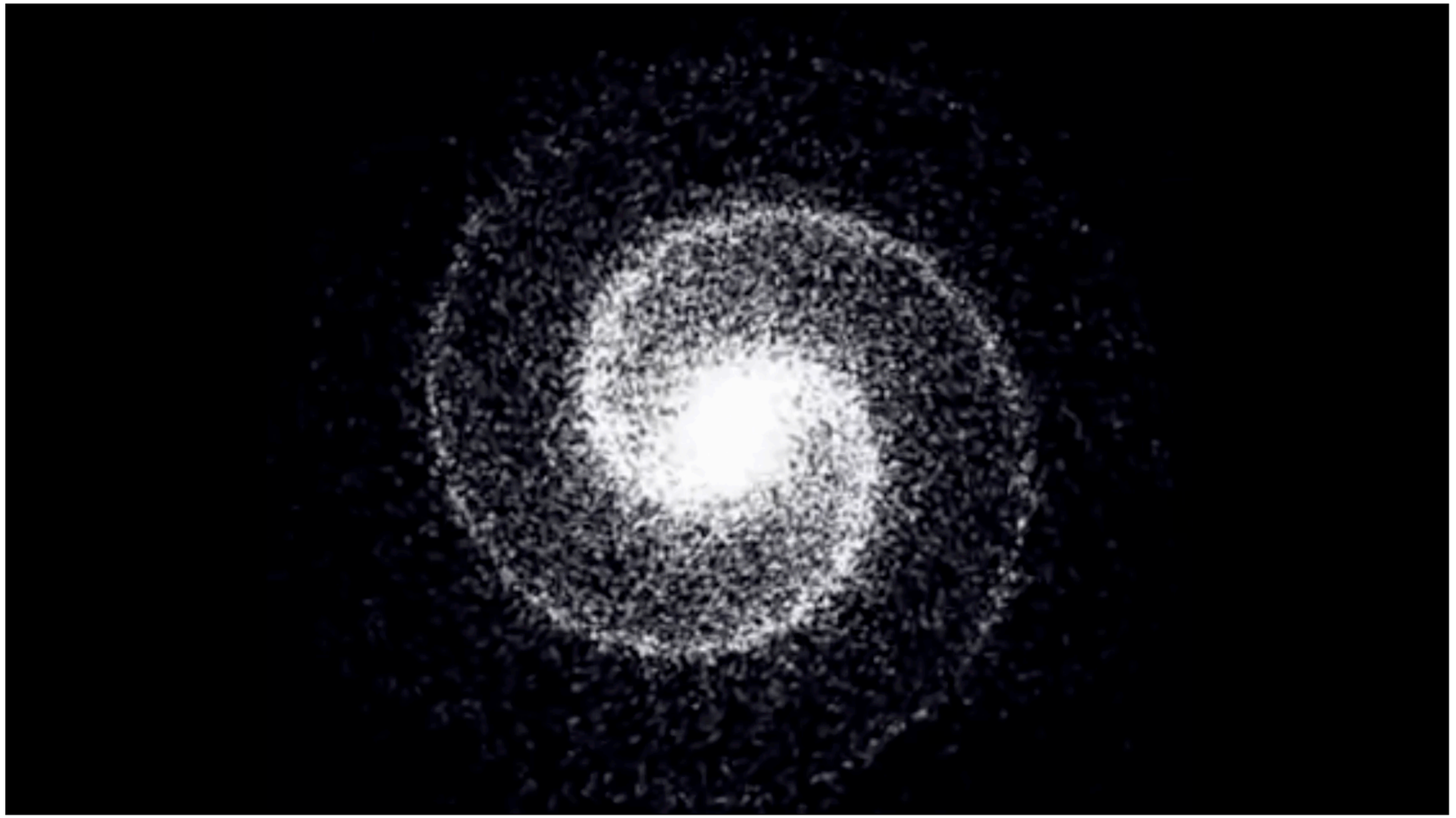
Diff. Rot.



https://en.wikipedia.org/wiki/File:Galaxy_rotation_rigid.ogv

Spiral Arms

Density Wave

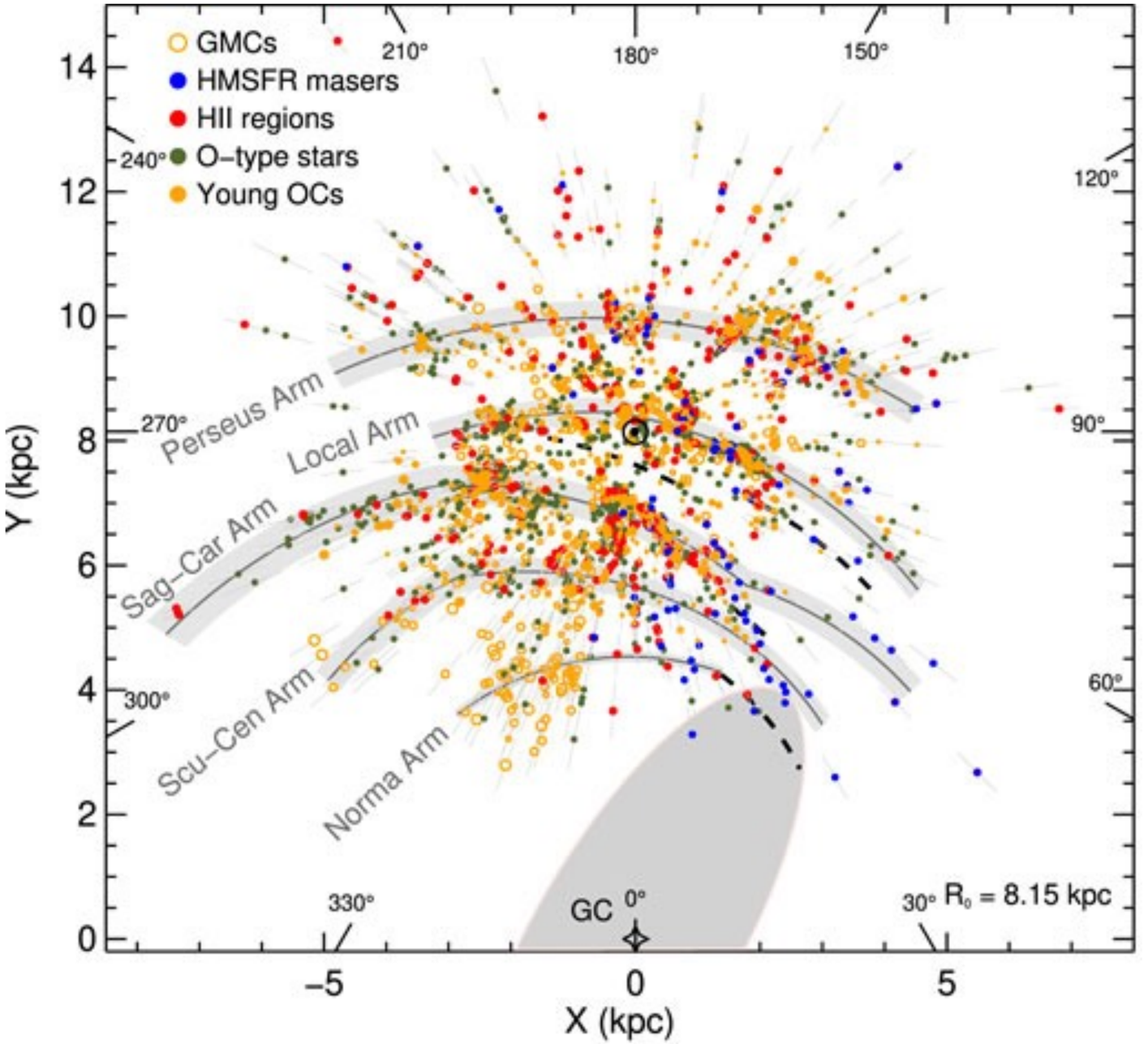


Kinda freaks me out
see also: Shepard tones

https://en.wikipedia.org/wiki/File:Galaxy_rotation_rigid.ogv

Bulge + Bar

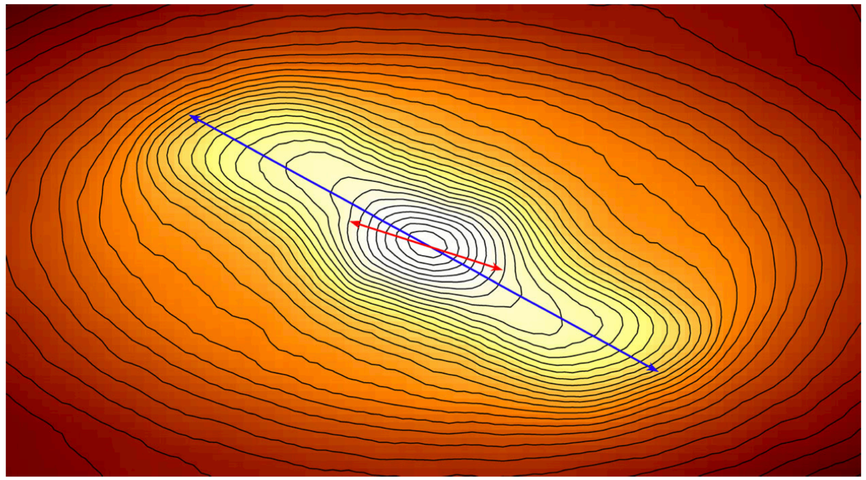
- MWY seems to have a fairly large bar, 4-5kpc half-length
- See how far the bar extends, way into the disk!
- Resonance w/ bar may drive much of “grand spiral” structure



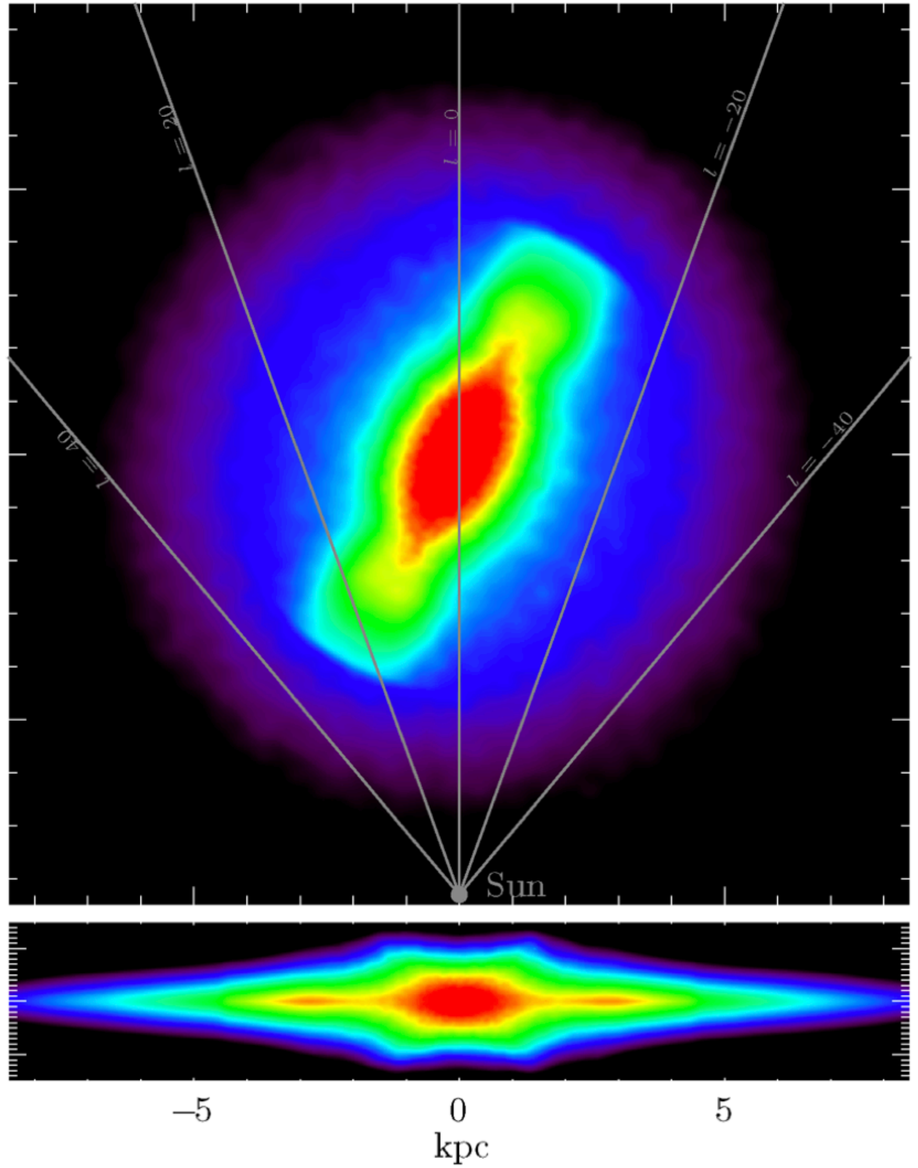
Hou (2021)

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)

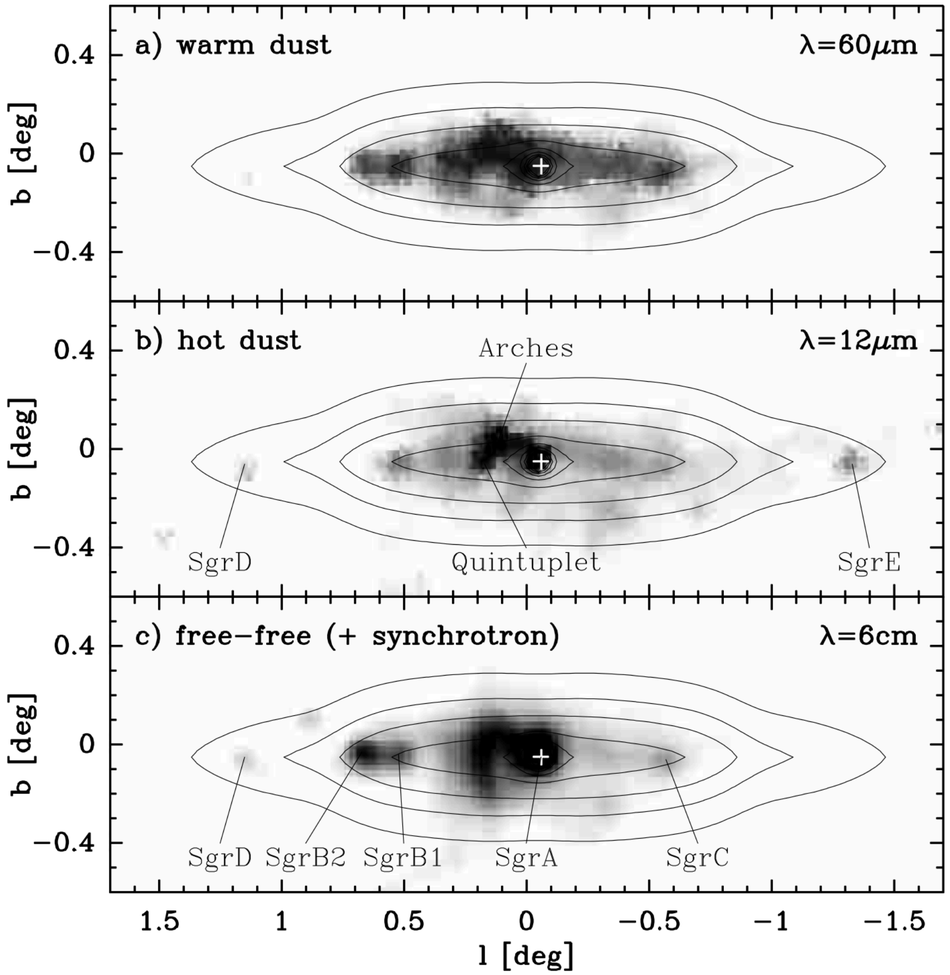


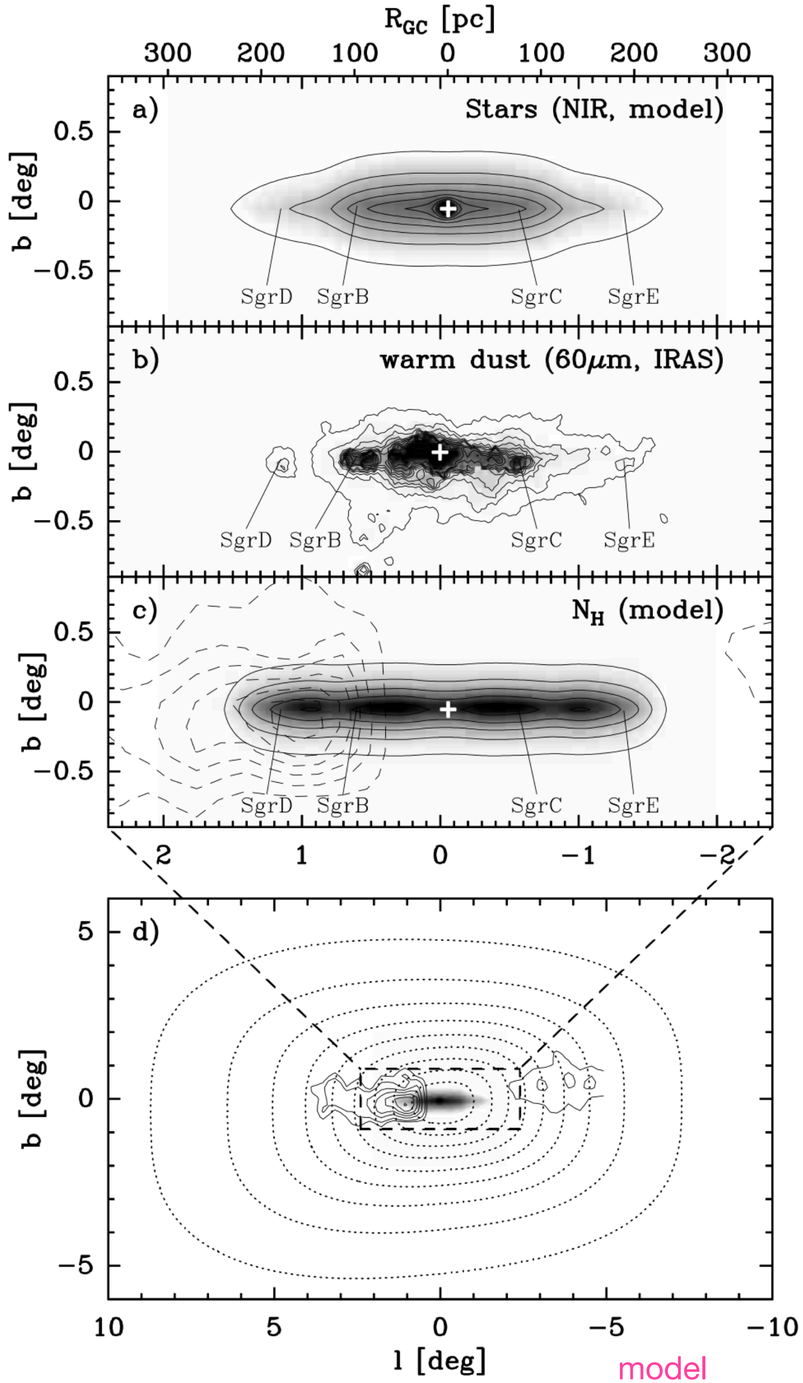
model



Nuclear Cluster

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

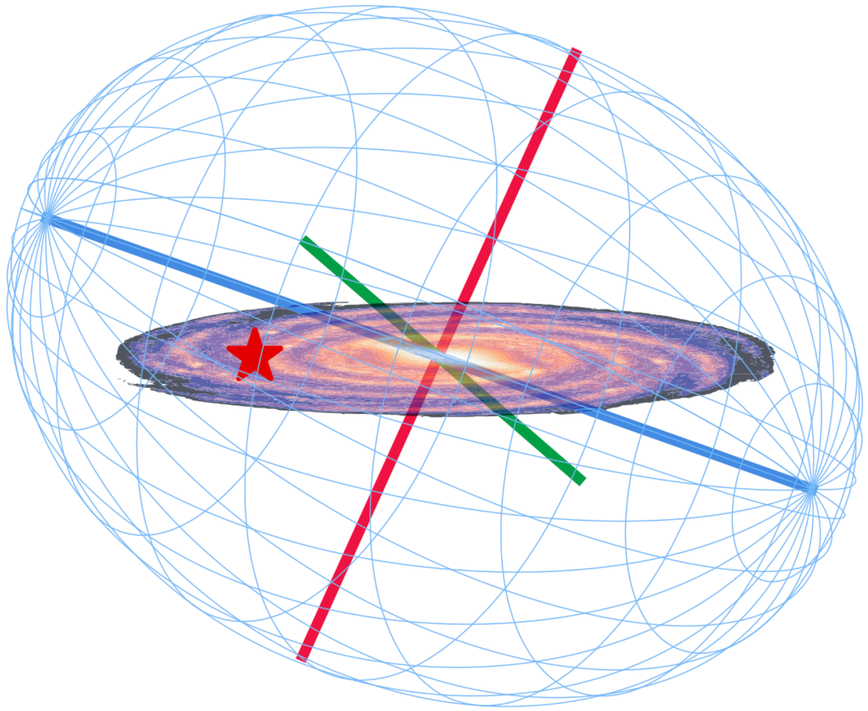




model

Halo (Stellar)

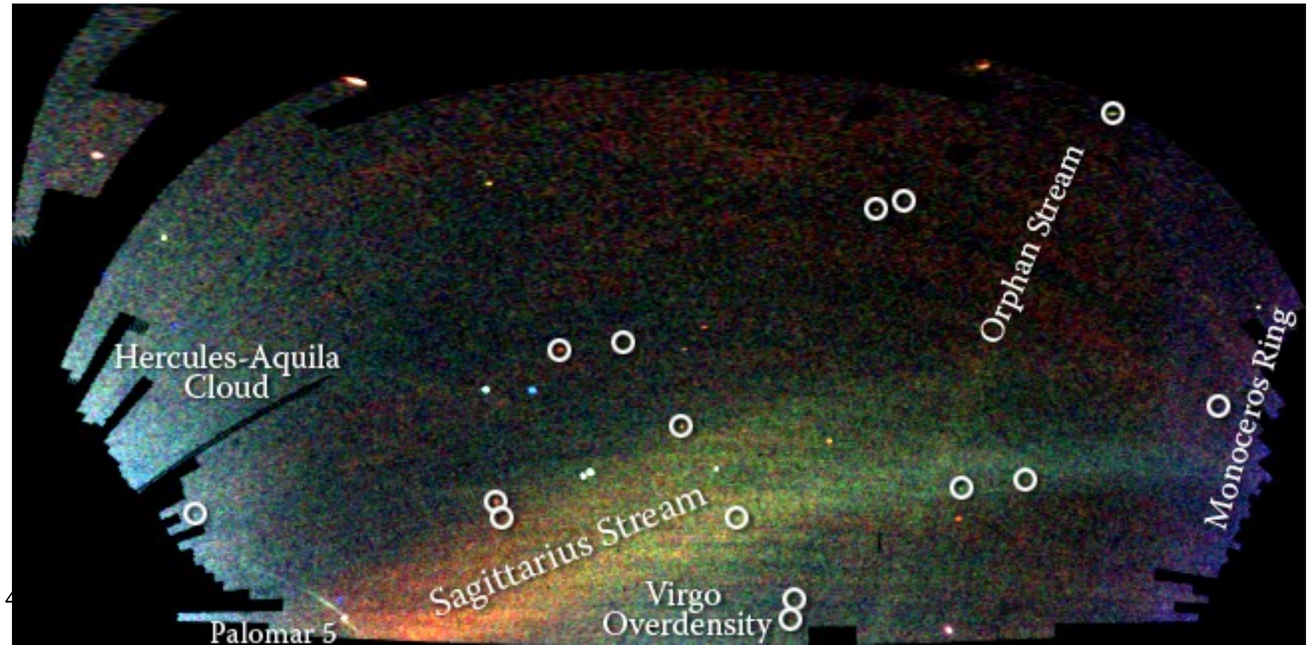
- **Triaxial (not spherical!)**
- Old, metal poor
- **Substructure**, hints at origin
  - Globular Clusters
  - Streams
  - (Dwarf) galaxy mergers
  - Gaia Sausage



Axis Ratios

10 : 8 : 7

Han+2022



"Field of Streams"
Belokkurov+2006

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: ~$10^9 M_\odot$
- 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 time:

- Star Counts in the Milky Way