ASTR 511

Galactic Astronomy

Lecture 06

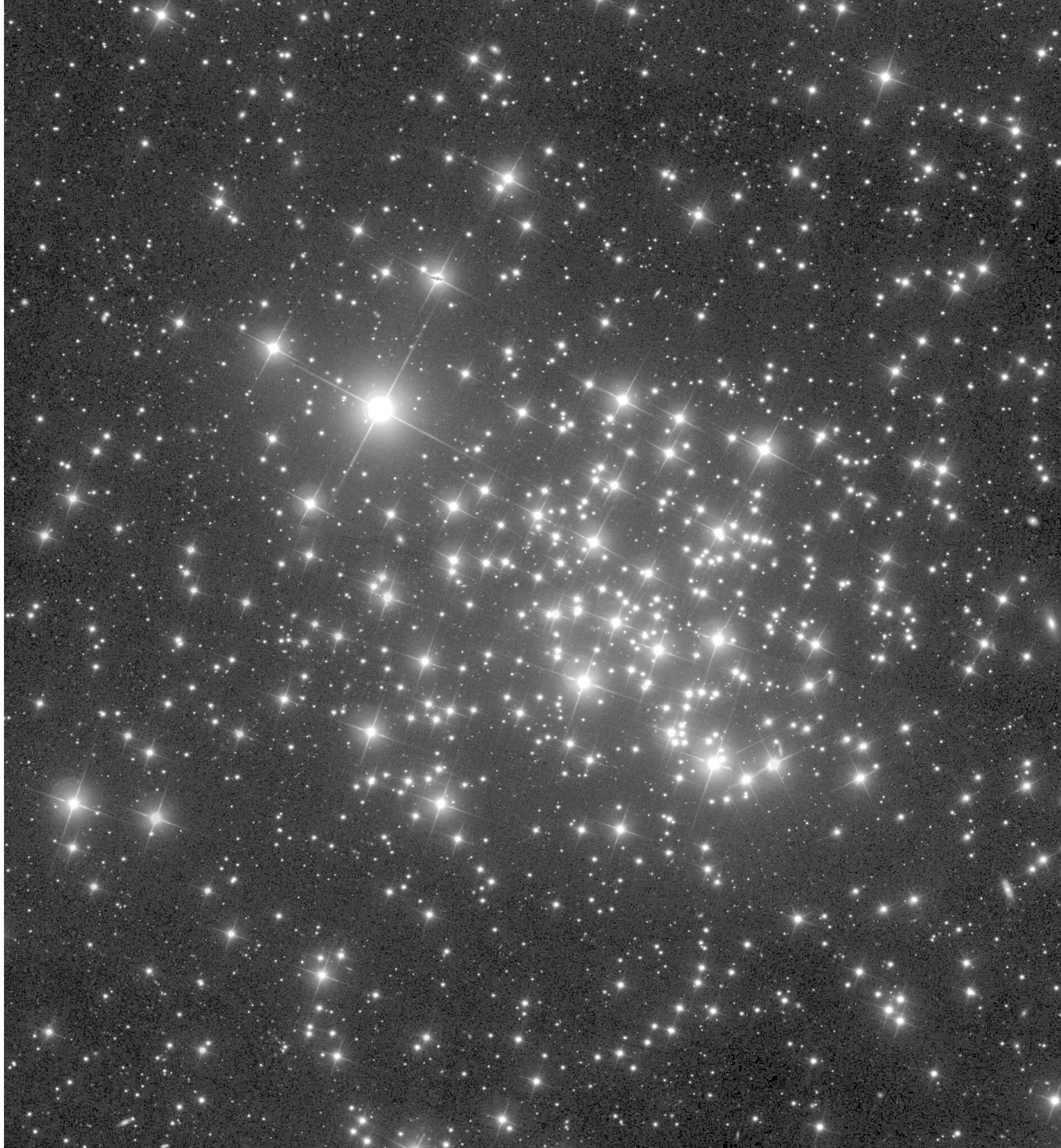
Structure & Properties of the Milky Way

Prof. James Davenport (UW)

Winter 2023

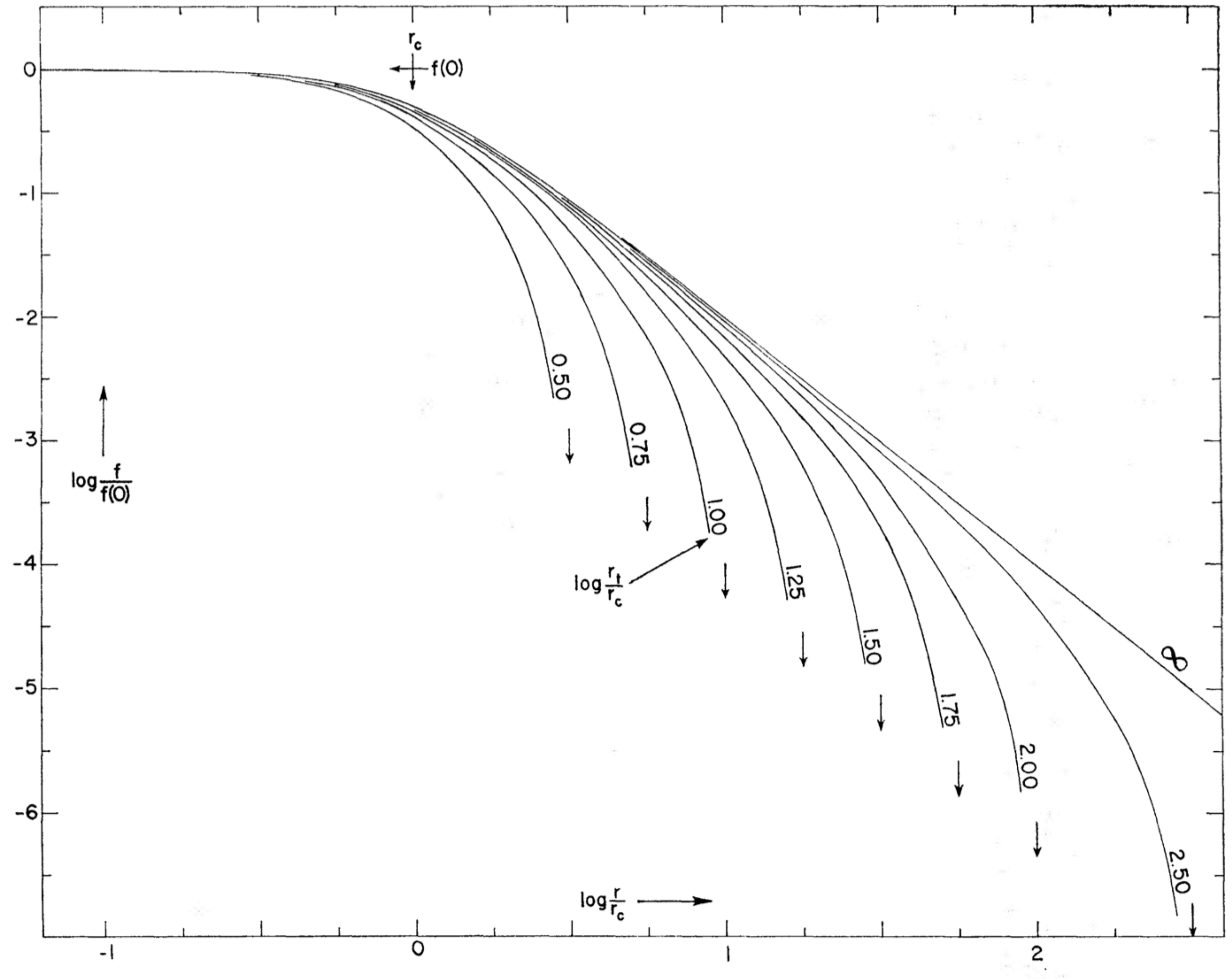
Homework 2

- 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

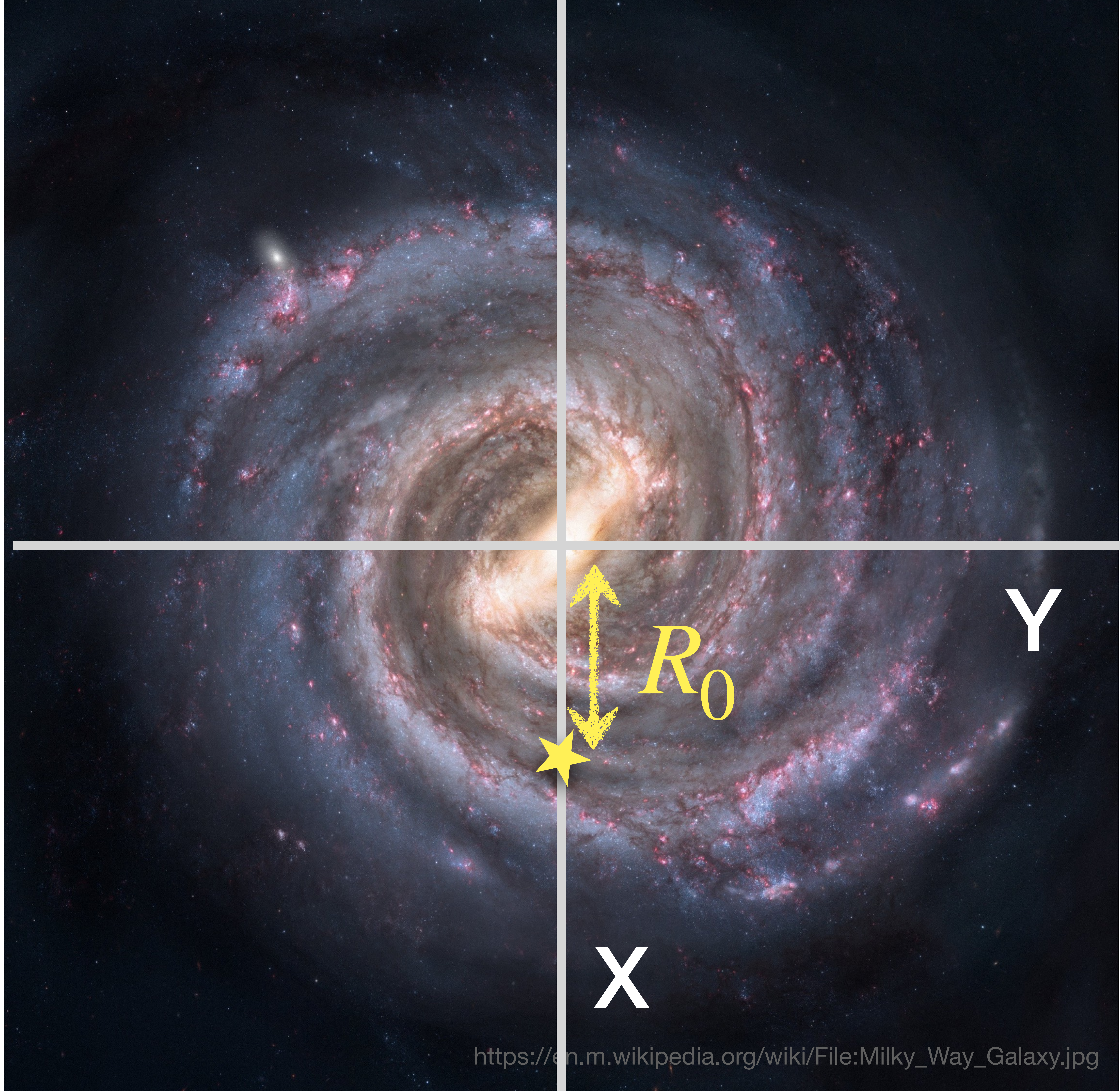
Today

- 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

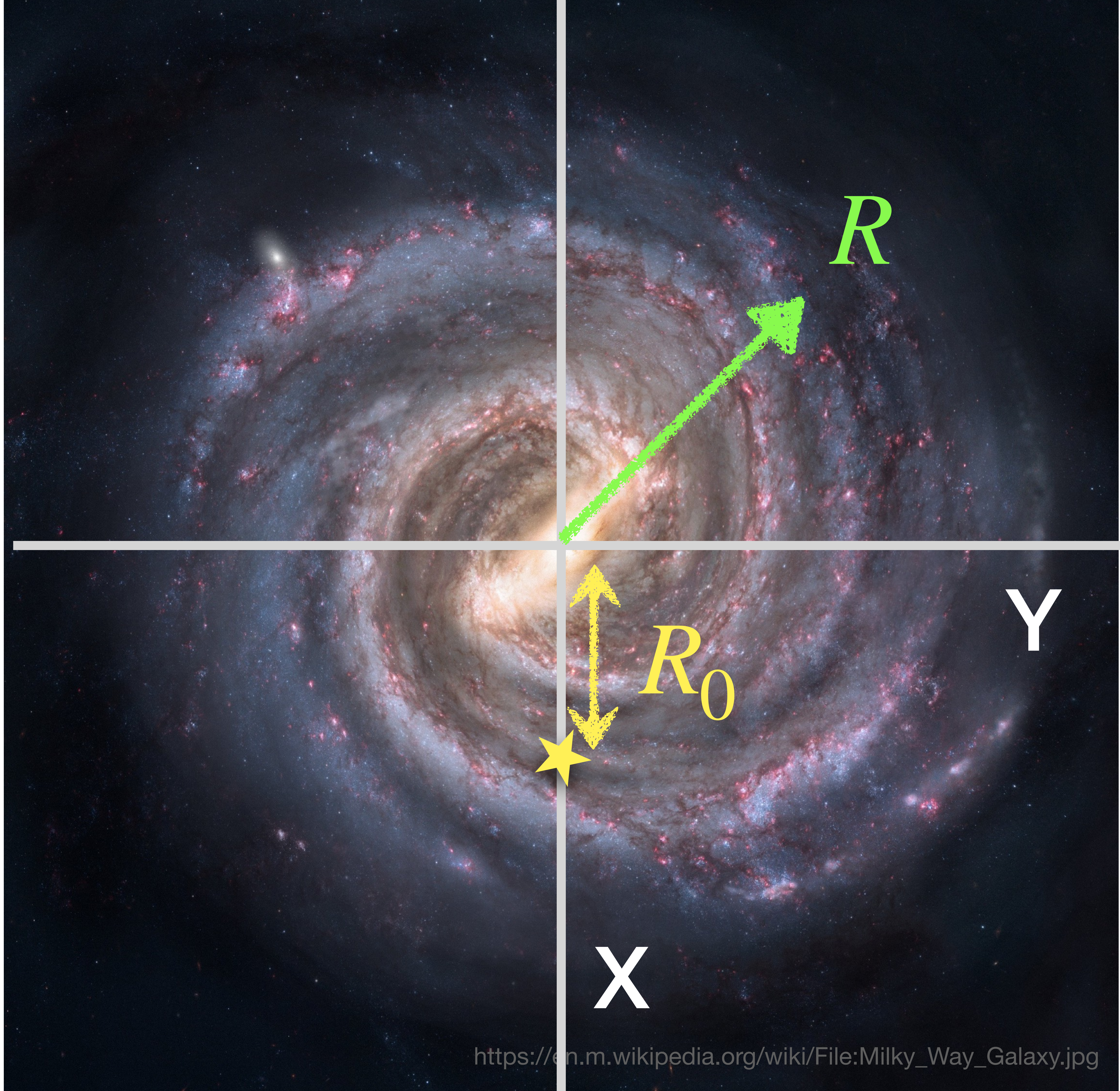
Coordinates

- 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



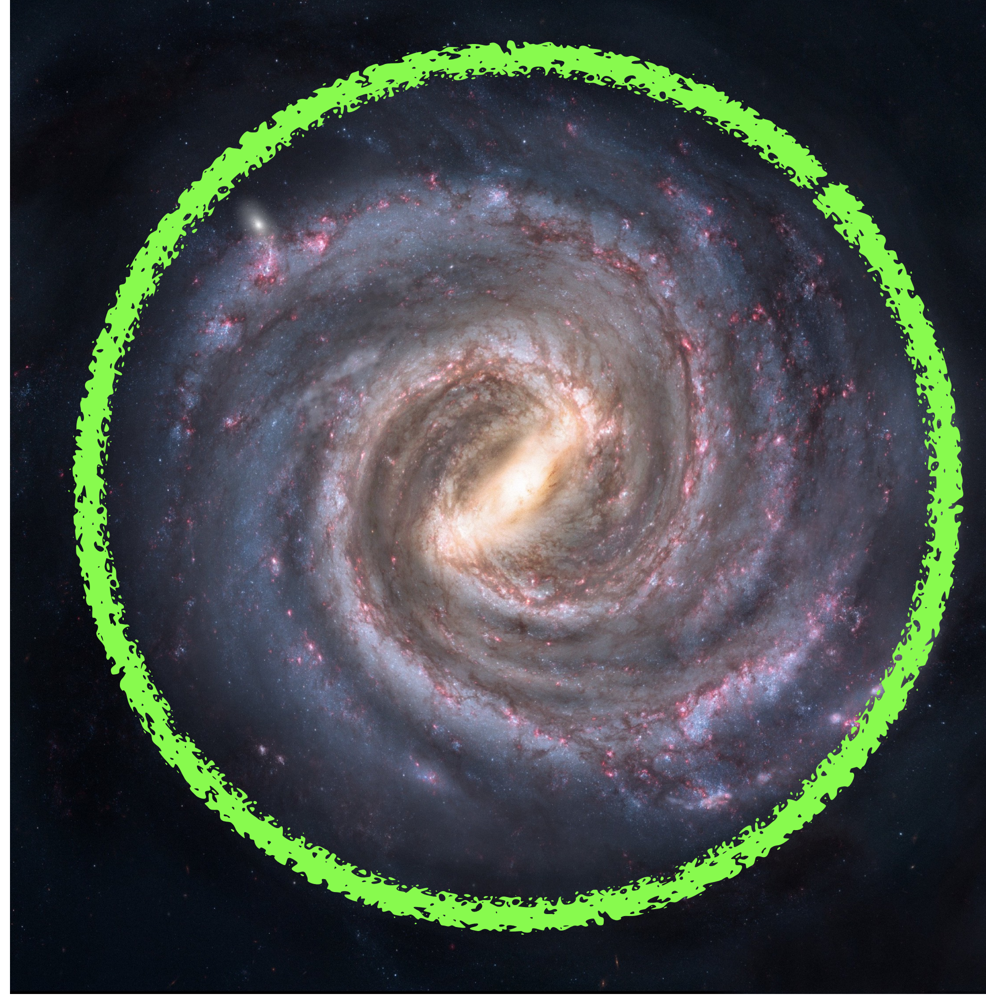
Distance to Galactic Center: R_0

- 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)

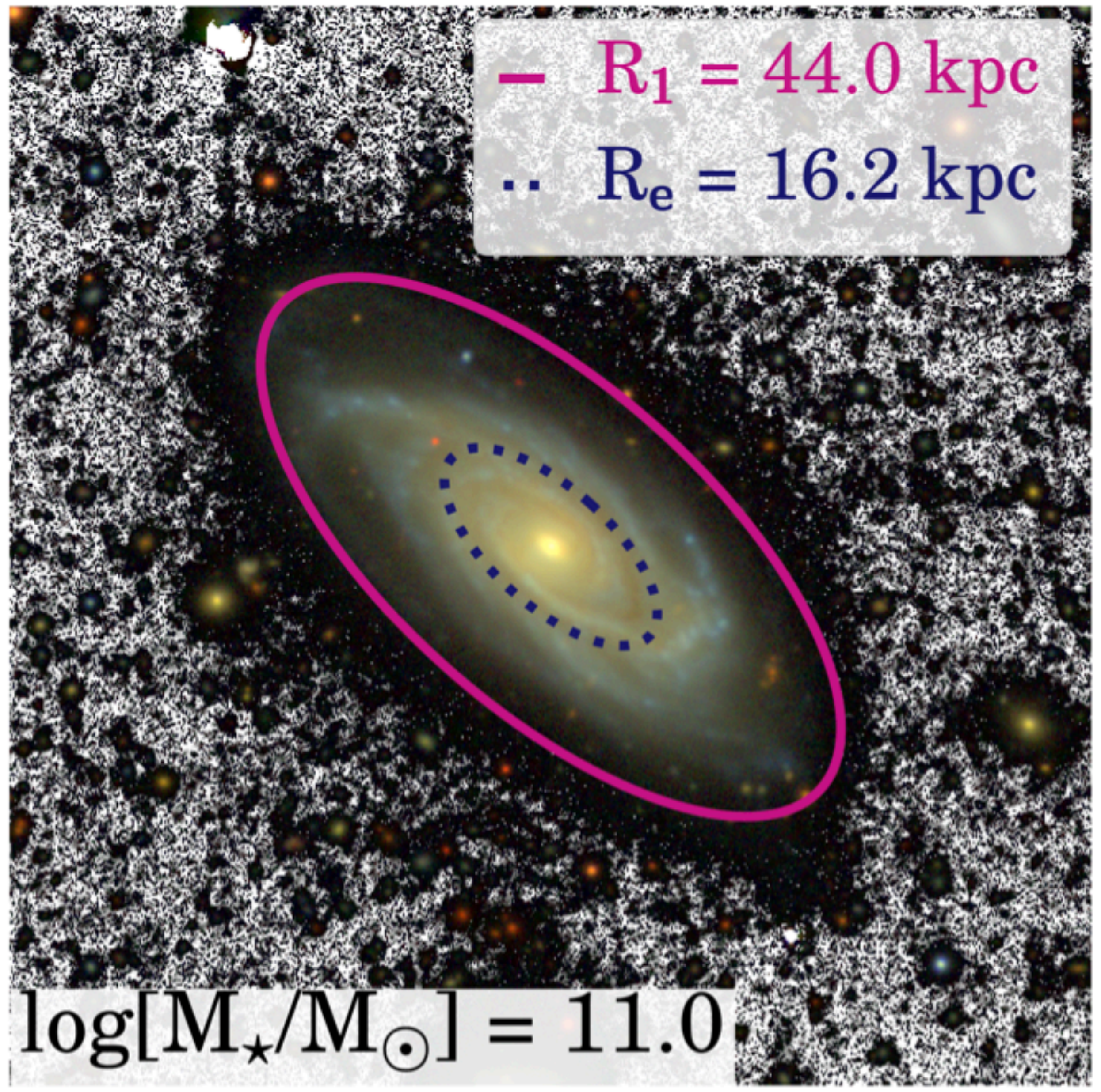
Distance to Galactic Center: R_0

- *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)



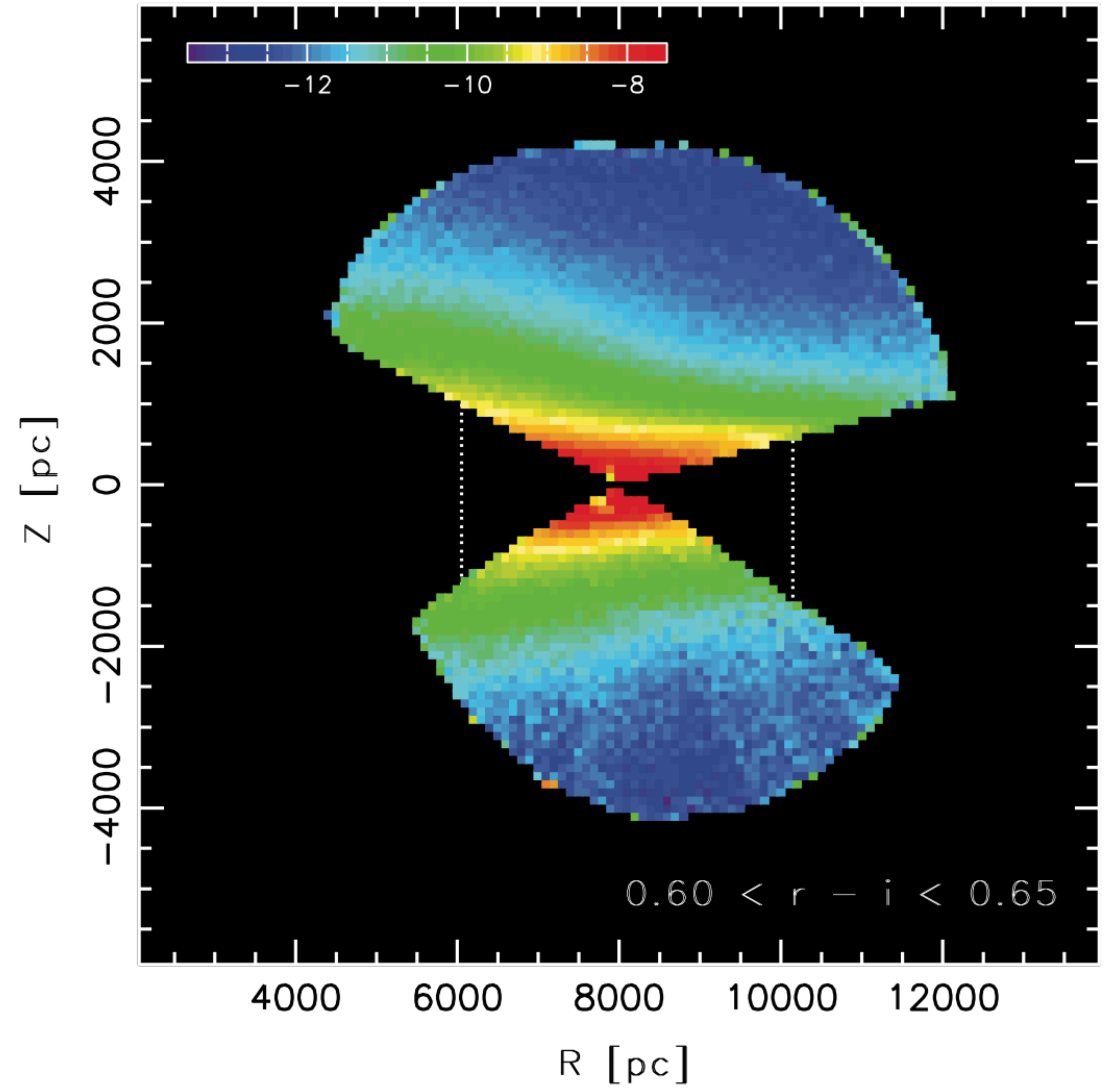
The Milky Way’s Disk

- 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,

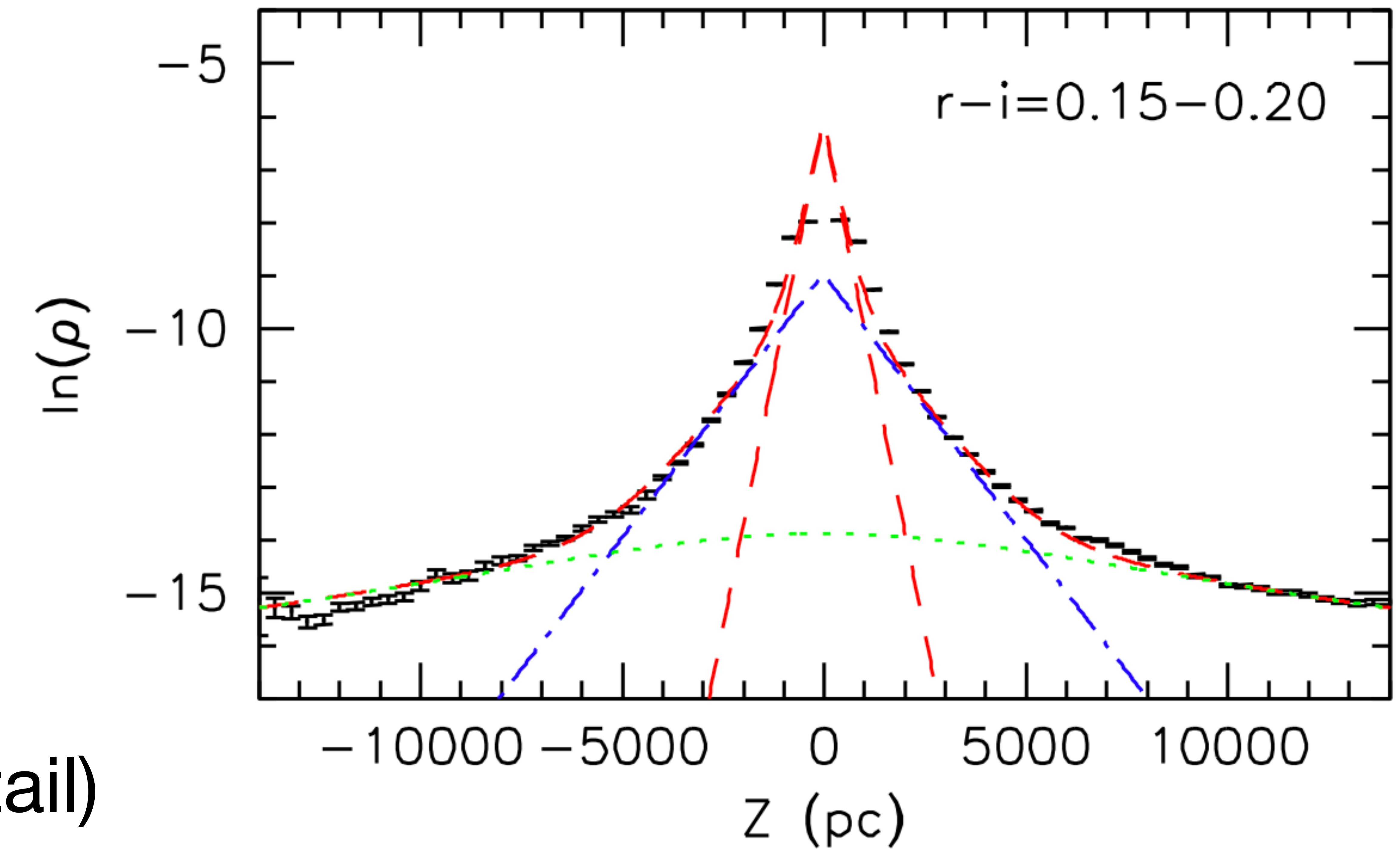
$$\rho(R,Z) = \rho(R_\odot, 0)e^{R_\odot/L} \exp\left(-\frac{R}{L} - \frac{Z + Z_\odot}{H}\right), \quad (19)$$

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):

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

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

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:

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

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

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

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

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

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

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

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

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

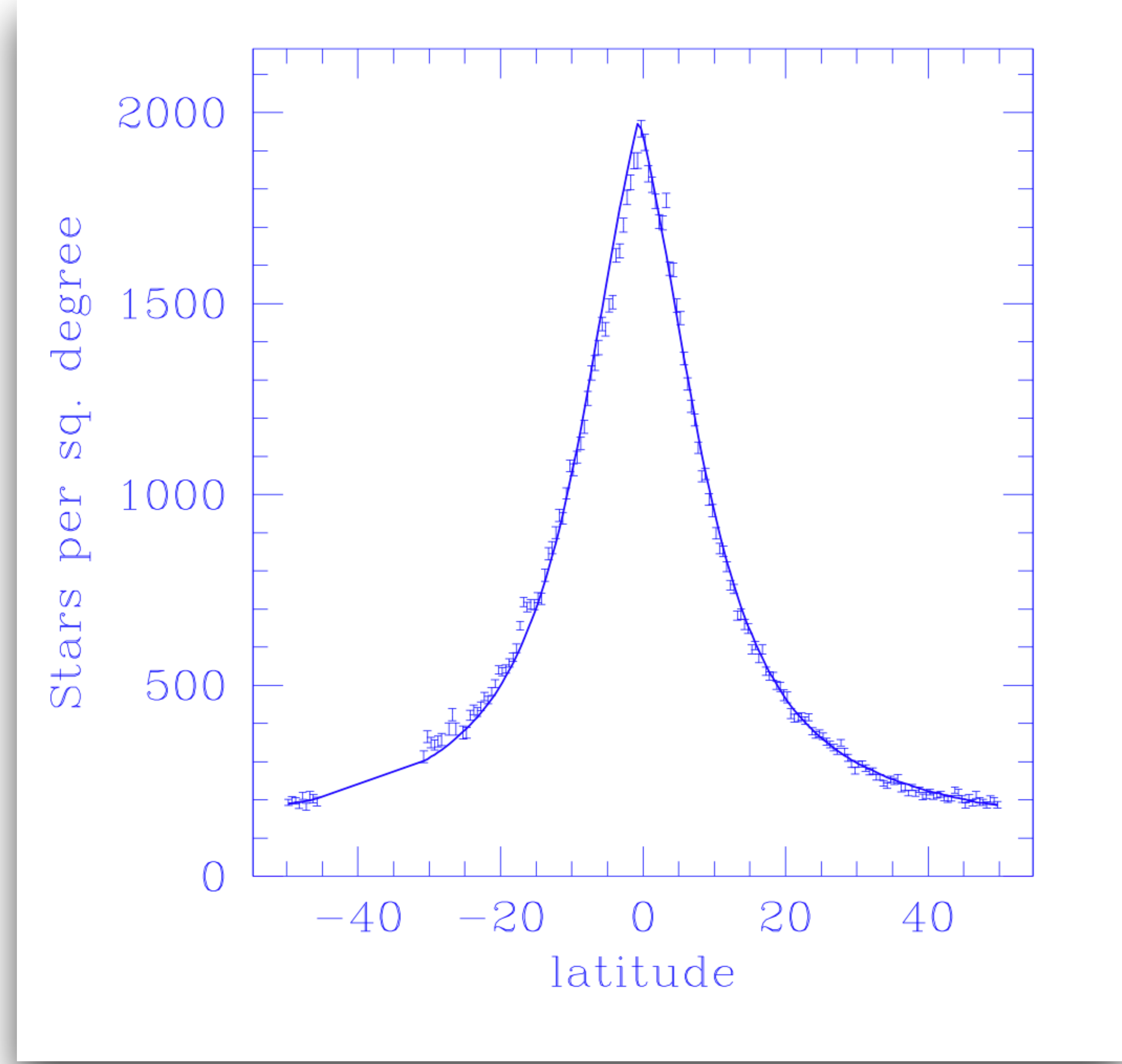
Then:

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

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

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

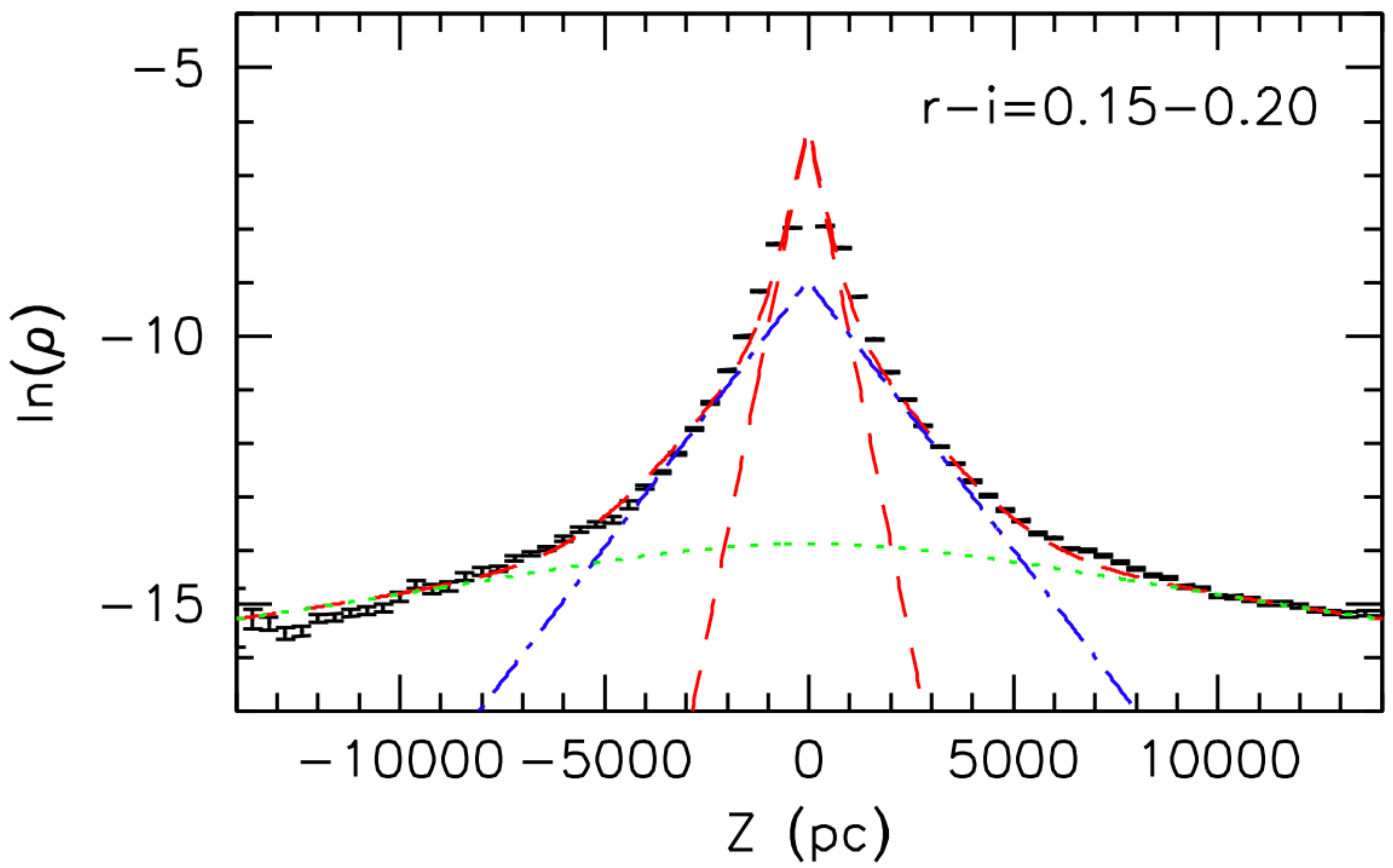
$$\beta(R) = \begin{cases} 1+(R-R_0)\ A_F & \text{R} > R_0 \\ 1 & \text{R} < R_0 \end{cases}$$



Alard (2000)

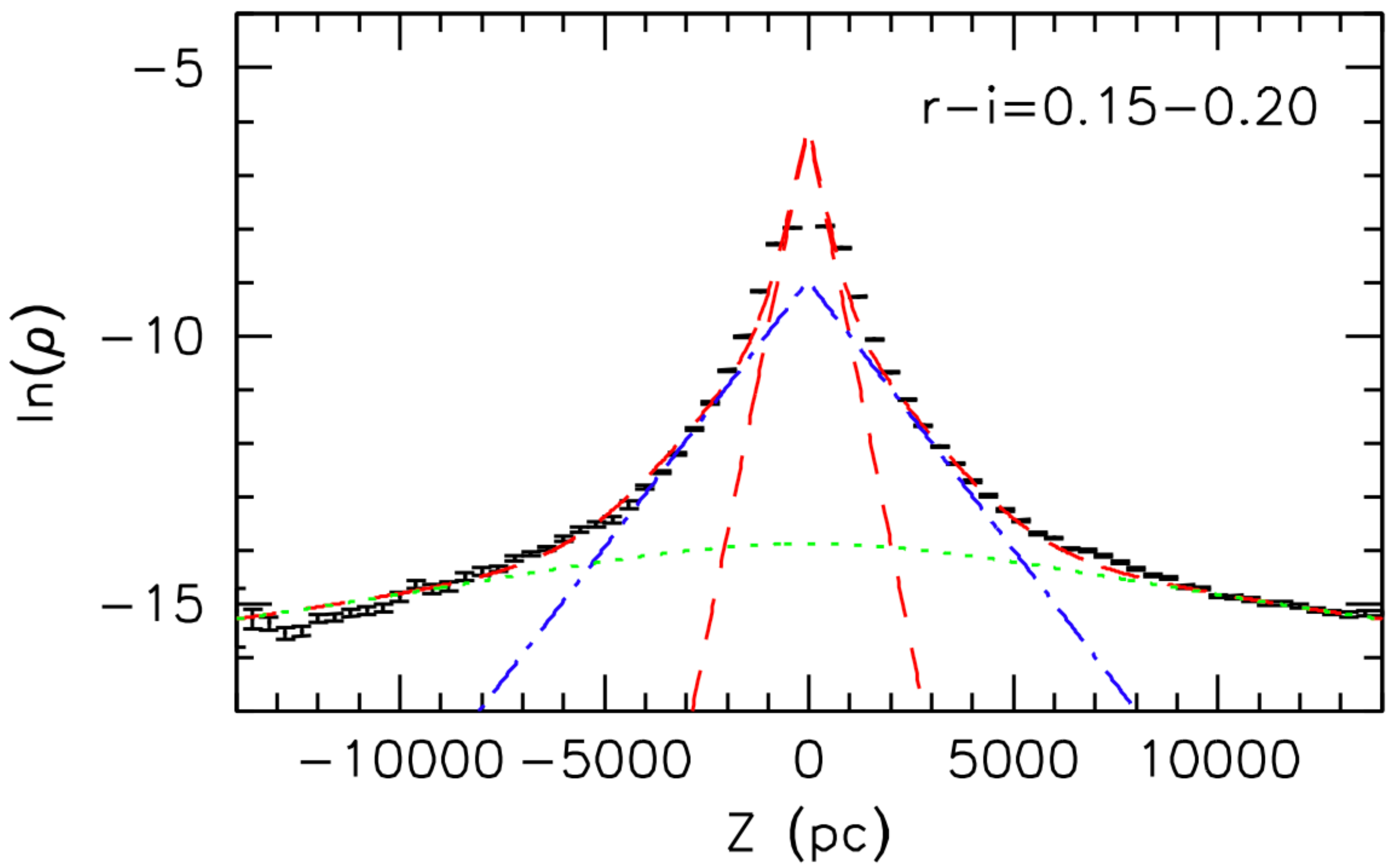
A Second “Thick” Disk?

- 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?



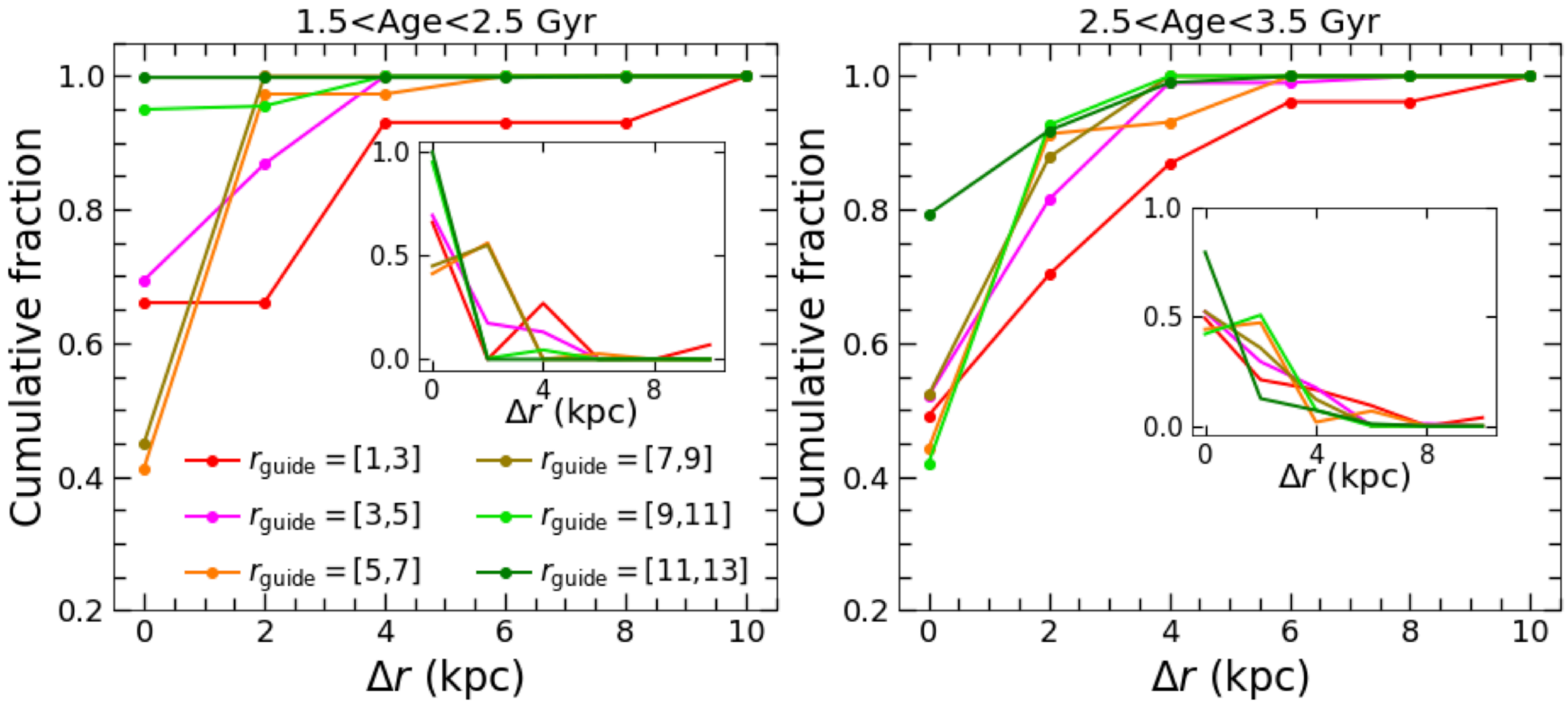
A Second “Thick” Disk?

- 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

Jo Bovy[1,4], Hans-Walter Rix[2], and David W. Hogg[2,3]
[1] Institute for Advanced Study, Einstein Drive, Princeton, NJ 08540, USA; bovy@ias.edu
[2] Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany
[3] Center for Cosmology and Particle Physics, Department of Physics, New York University, 4 Washington Place, New York, NY 10003, USA
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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

Katherine Vieira[1], Giovanni Carraro[2], Vladimir Korchagin[3], Artem Lutsenko[2], Terrence M. Girard[4], and William van Altena[5]
[1] Instituto de Astronomía y Ciencias Planetarias, Universidad de Atacama, Copayapu 485, Copiapó 1531772, Chile
[2] Dipartimento di Fisica e Astronomia, Universitá di Padova, Vicolo Osservatorio 3, I-35122 Padova, Italy; giovanni.carraro@aas.org
[3] Southern Federal University, Stachki 194, Rostov-on-Don 344090, Russia
[4] Department of Physics, Southern Connecticut State University, 501 Crescent Street, New Haven, CT 06515, USA
[5] Department of Astronomy, Yale University, 52 Hillhouse Avenue, New Haven, CT 06511, USA
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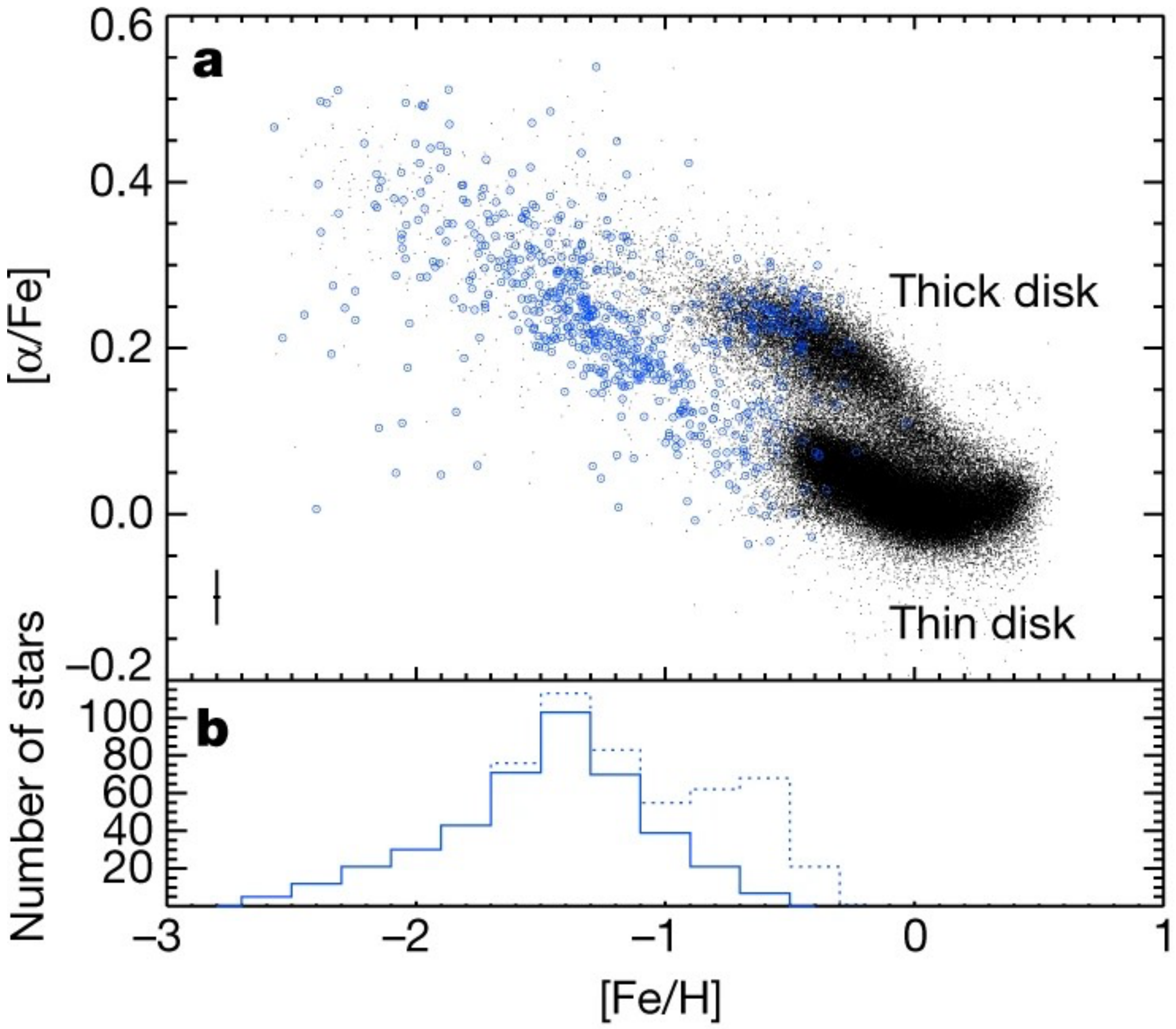
A Second "Thick" Disk?

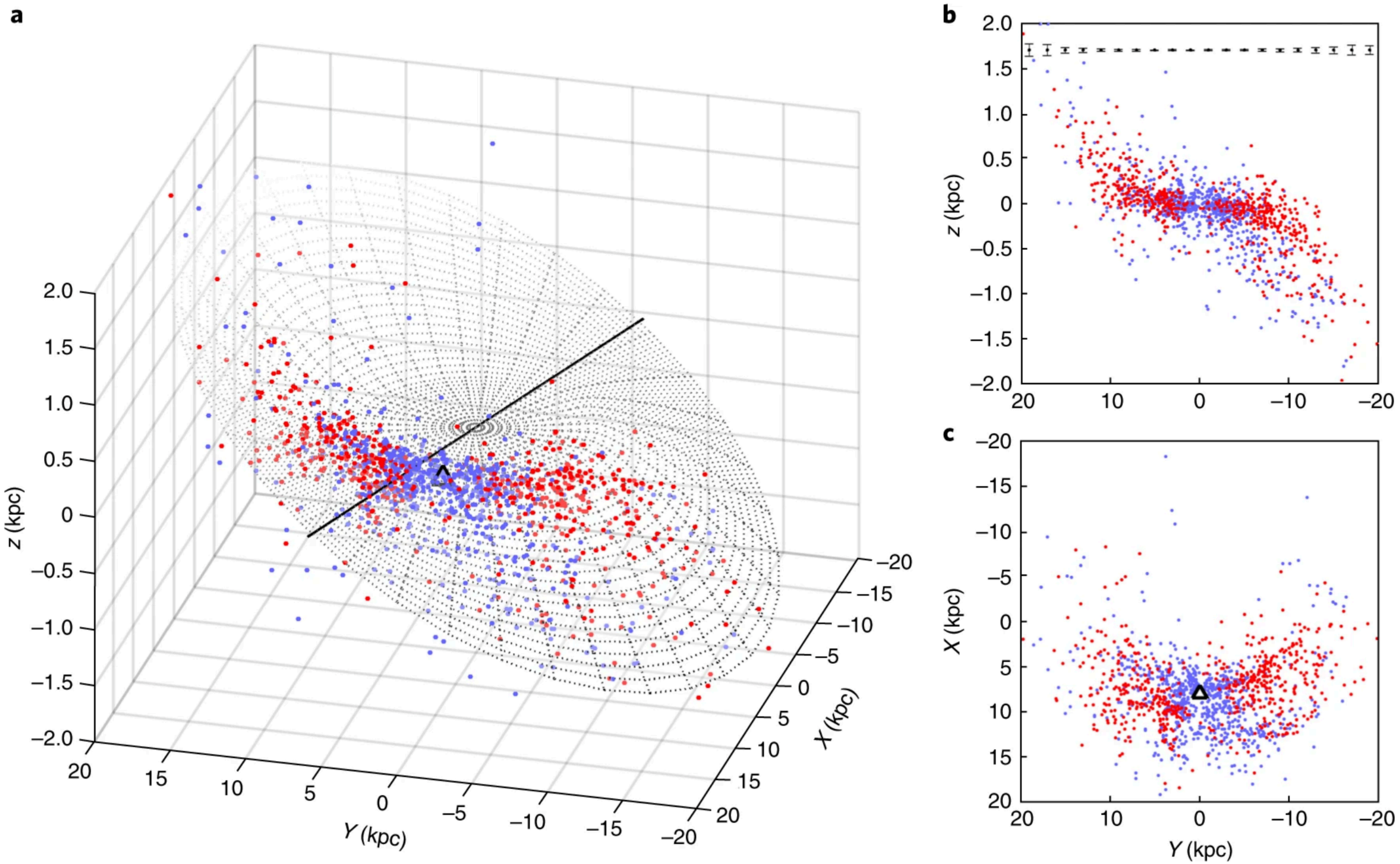
- Seems like there *probably* is a distinct 2nd component
- May be at least partially due to the Gaia-Enceladus merger (Helmi+2018)
- Also explains much of the inner halo density & kinematic
- And *maybe another* weird feature of the disk…



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

Warped Disk

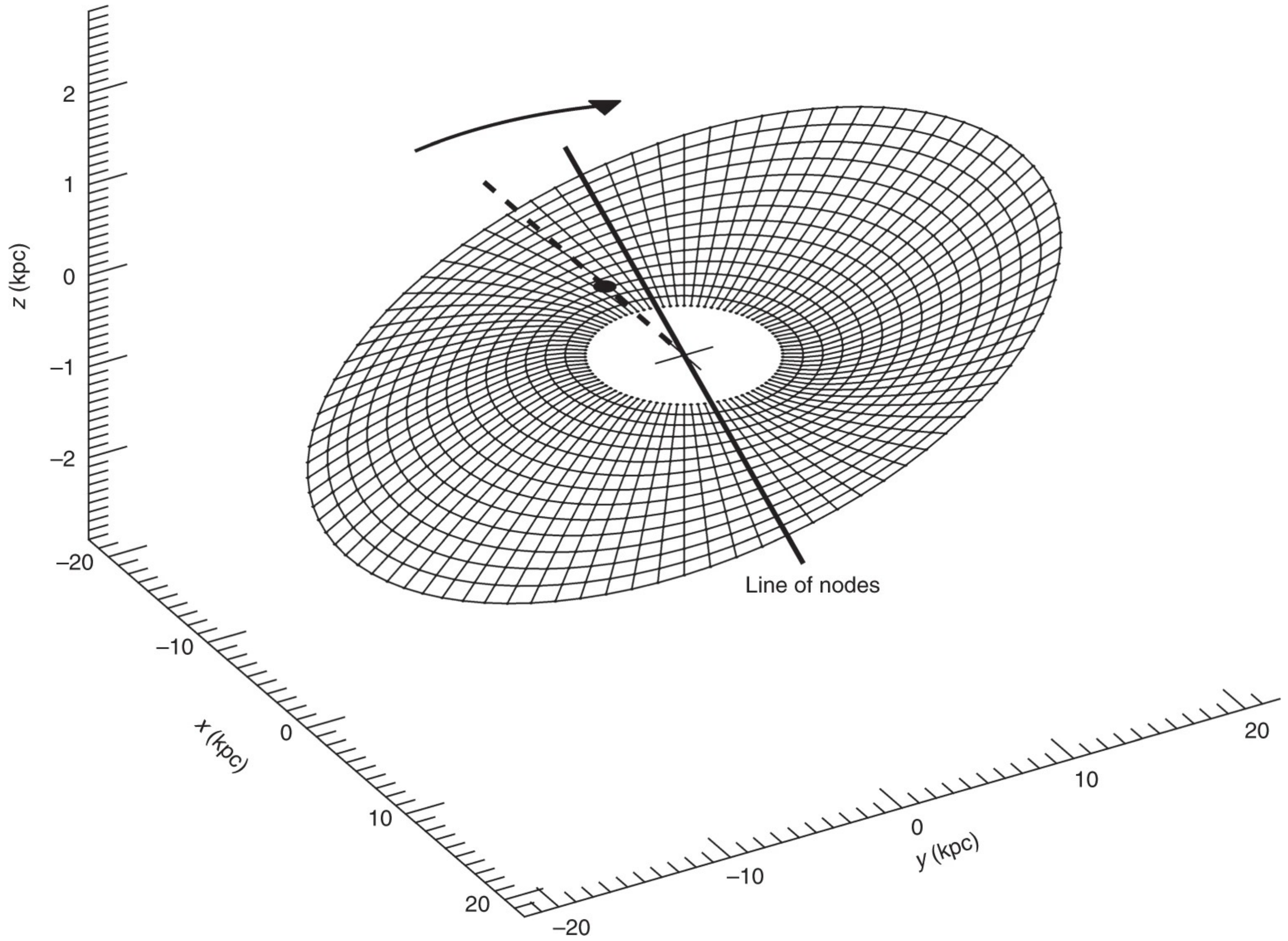
- Long seen in gas (HI)
- Now traced w/ stars
- Here: Cepheids from WISE + Gaia DR2
- Likely caused by merger from dwarf galaxy… but which?!
  - Sagittarius ?



Chen+2019

Warped Disk

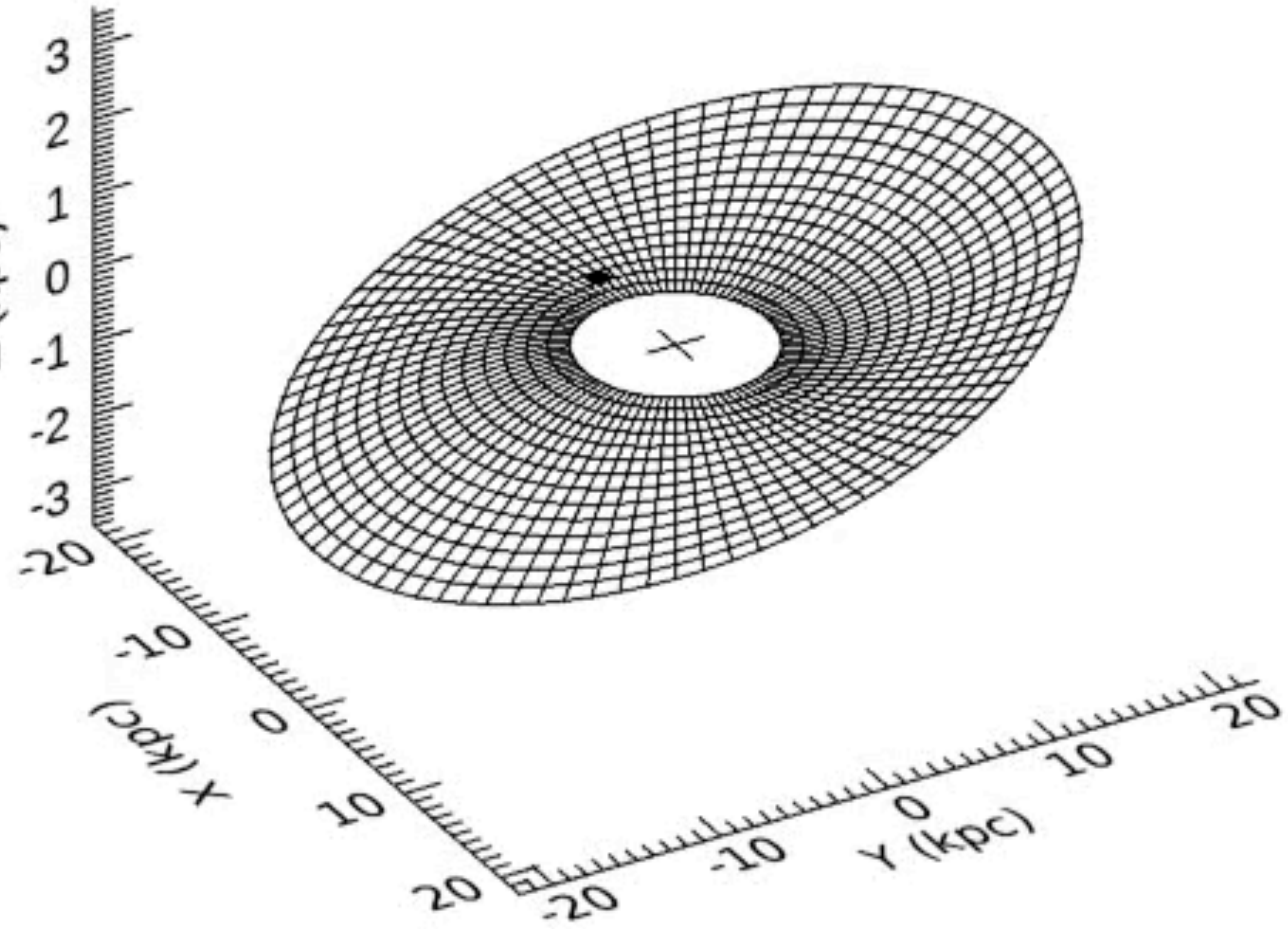
- Warp shape seems to precess
- Moves with Galactic rotation (but slower)
- Favors a single dynamical interaction origin, rather than “the relic of the ancient assembly history…”



Poggio+2020

Warped Disk

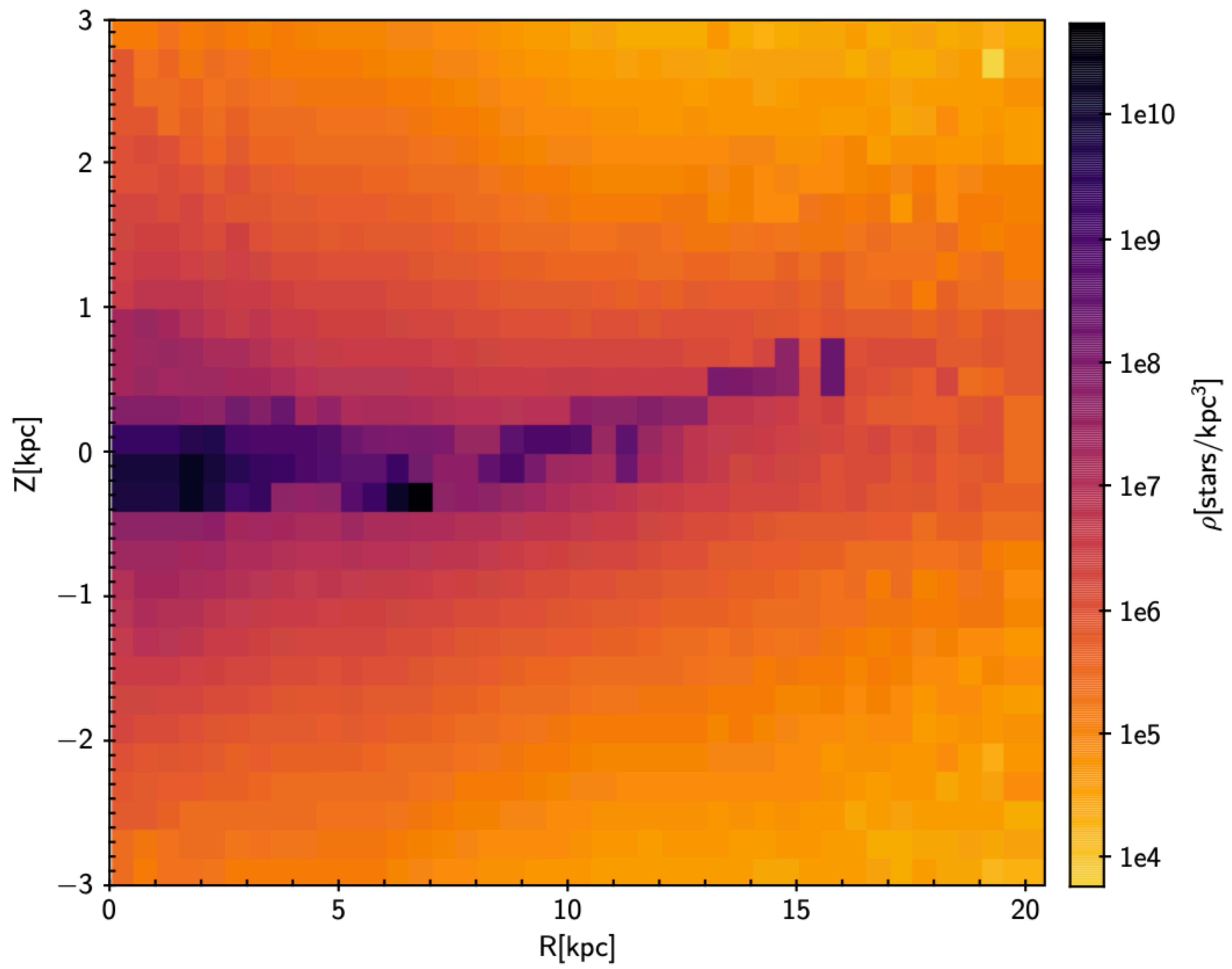
- Warp shape seems to precess
- Moves with Galactic rotation (but slower)
- Favors a single dynamical interaction origin, rather than “the relic of the ancient assembly history…”



Poggio+2020

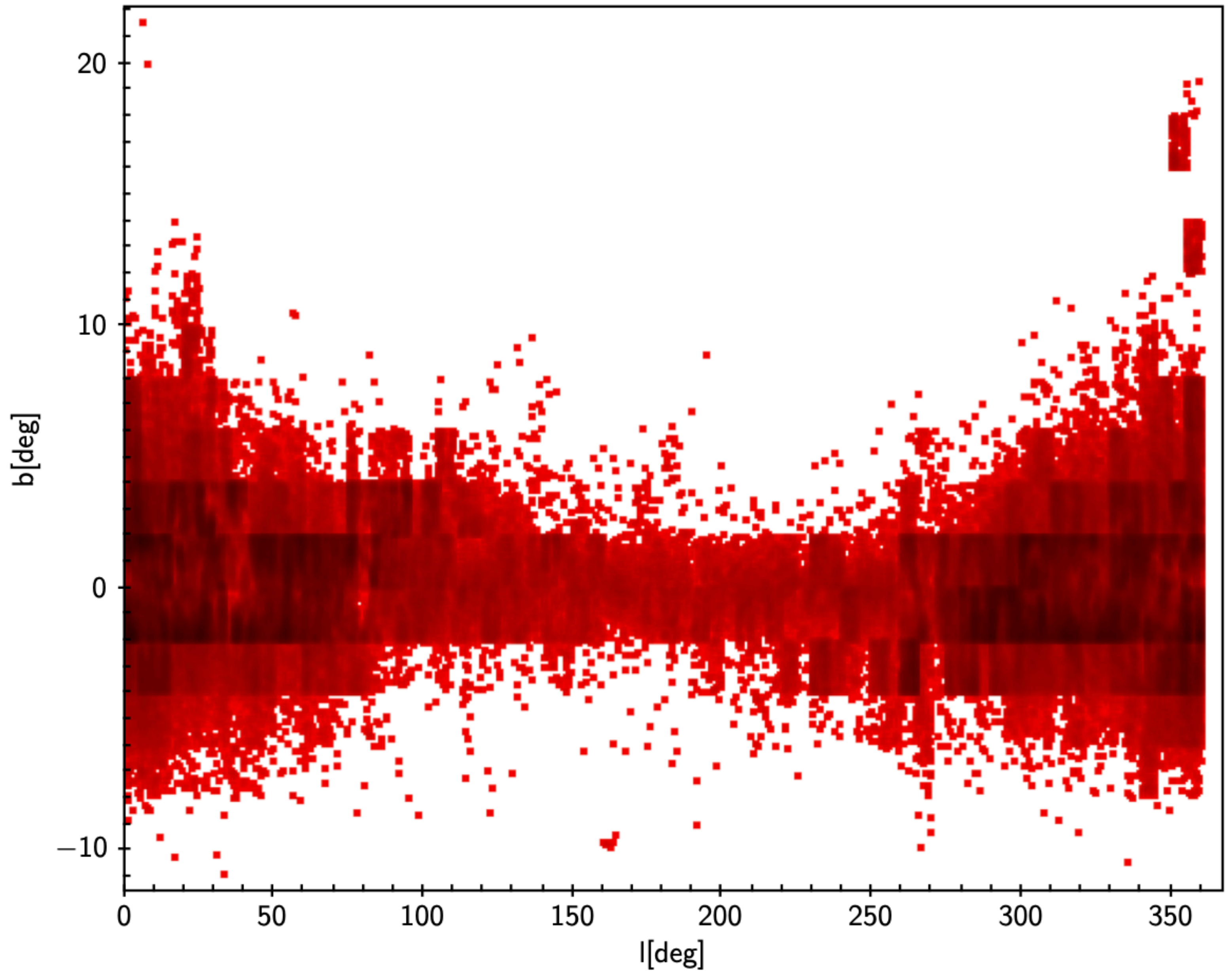
Flared Disk

- 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?