

ASTR 511

Galactic Astronomy

Lecture 09

Kinematics, Rotation, Oort Constants

Prof. James Davenport (UW)

Winter 2023

A note about scheduling

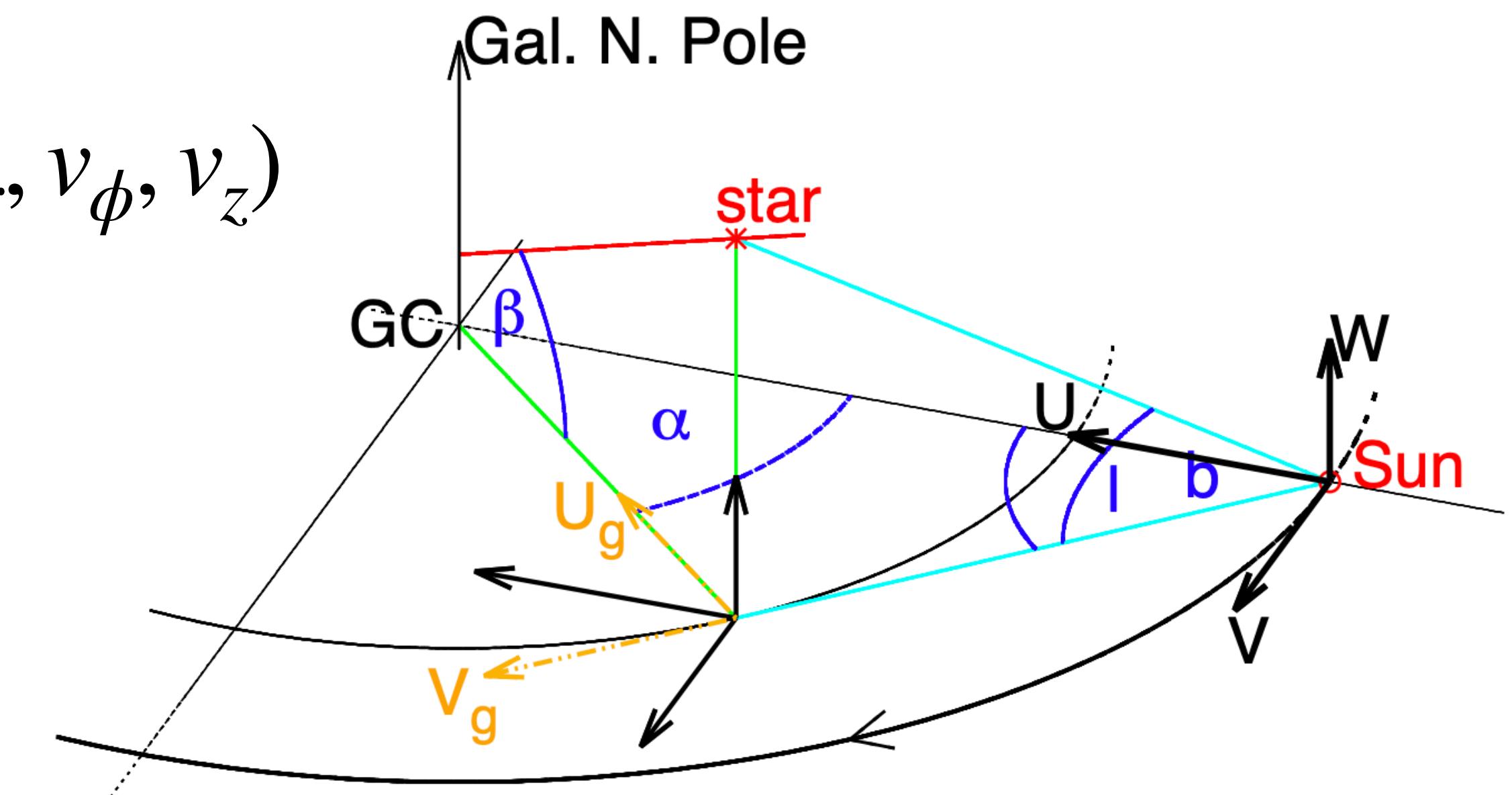
- Slated to have final lecture on Thursday, March 2 (prospective grad visit)
- But it turns out I can't be here March 2 :(
- Would folks be available instead on Friday, March 3?

Questions about Homework(s)?

- A few still working on HW2 (that's AOK!)
- HW3 nominally due this week
- **Final Project: Part 1 due this week**
 - This one *does* need to be turned in, so I can make sure you have some topic ideas!

More Fun with Coordinate Systems

- We've seen galactocentric (X, Y, Z)
 - There's of course (v_X, v_Y, v_Z)
- Now behold: (u, v, w) : galactic cylindrical coordinates, centered on us, and associated velocities: (U, V, W)
- Galactocentric *cylindrical* coordinates: (v_r, v_ϕ, v_z)
- Galactocentric *spherical* coordinates: (r, ϕ, θ) and (v_r, v_ϕ, v_θ)
 - NOTE: v_ϕ sign flipped between cylindrical and spherical systems...



“7-D Phase Space”

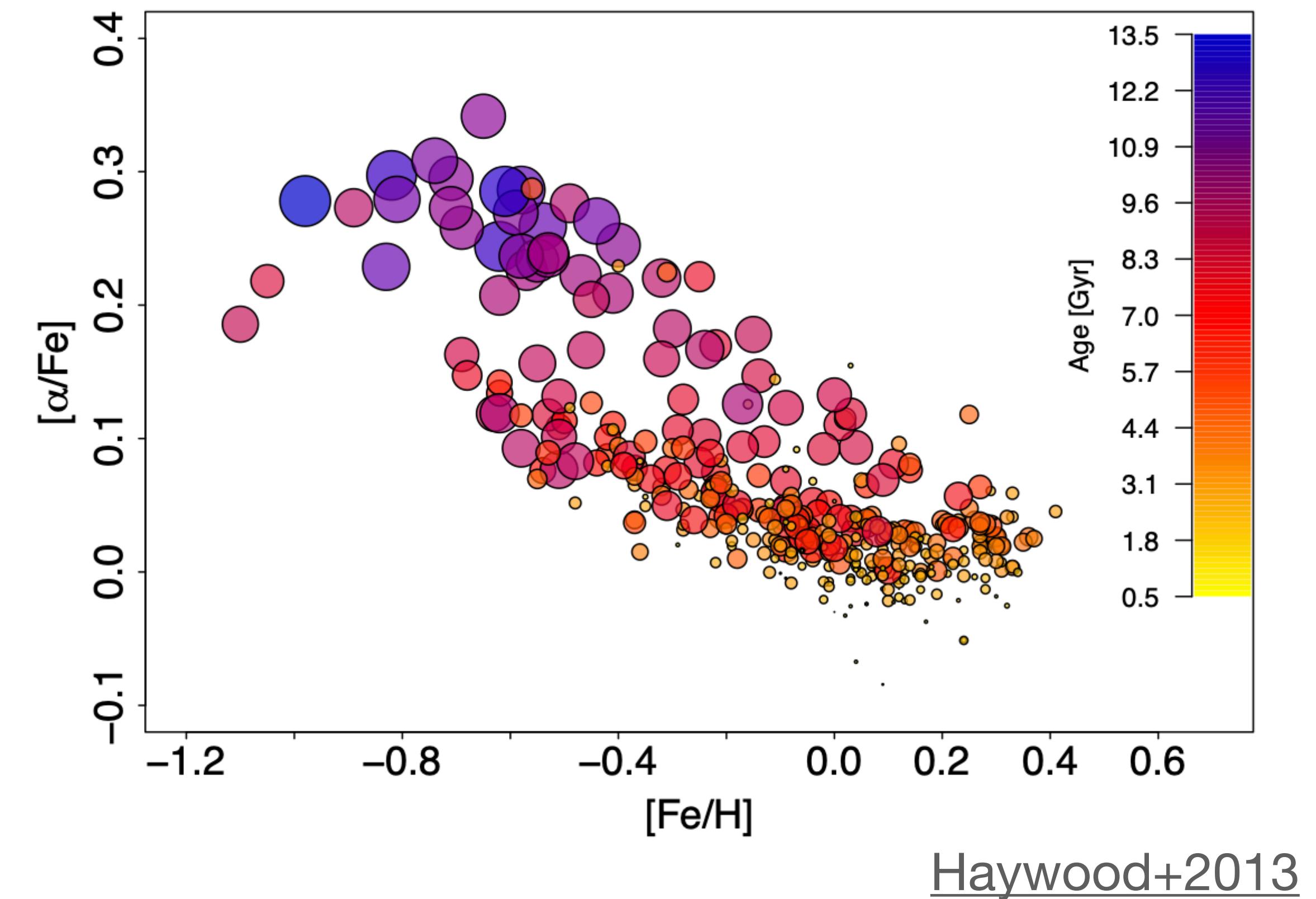
“6-D Phase Space”

Including metallicity!

- This is ~all you can know about an objects instantaneous dynamics:
 - 3-D positions (u, v, w)
 - 3-D velocities (U, V, W)
 - Measured as: (RA, Dec, parallax, pm_RA, pm_Dec, RV)
 - Gaia DR3 can do them all!
 - Positions, parallax, PM for 1.4 Billion stars
 - RVs for 33 Million stars
 - All other surveys combined: a few million stars

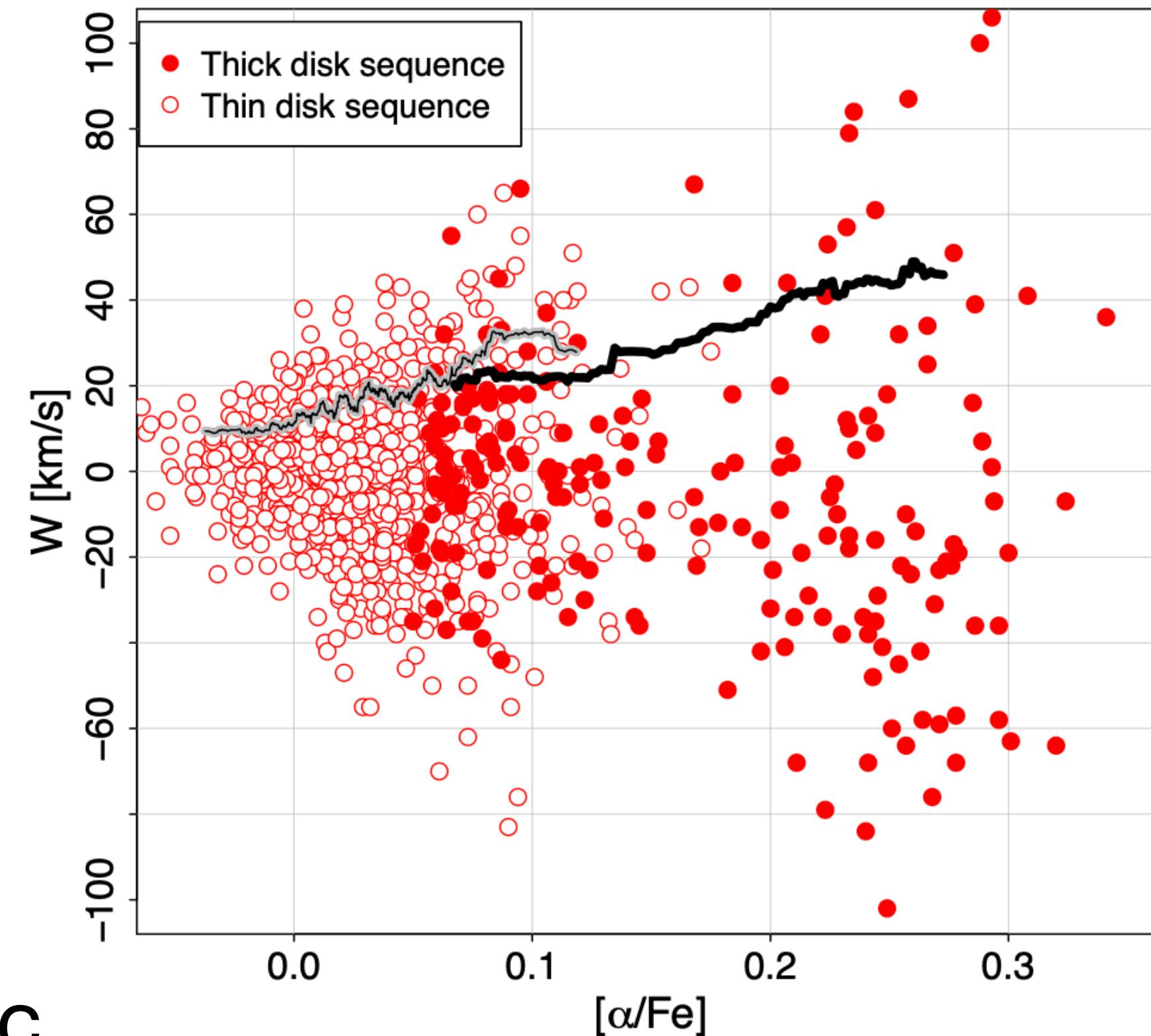
Ages from Velocities

- We mentioned this last week, but let's show a good example!
- Previously: discussed some ways to get ages into a “Wallerstein-Tinsley” diagram like this (e.g. isochrone & chemical model fits)
- Also said scale-height is related to stellar age
- Velocities: stars get knocked around over time! (Stellar migration) Signatures in the velocity distribution(s)

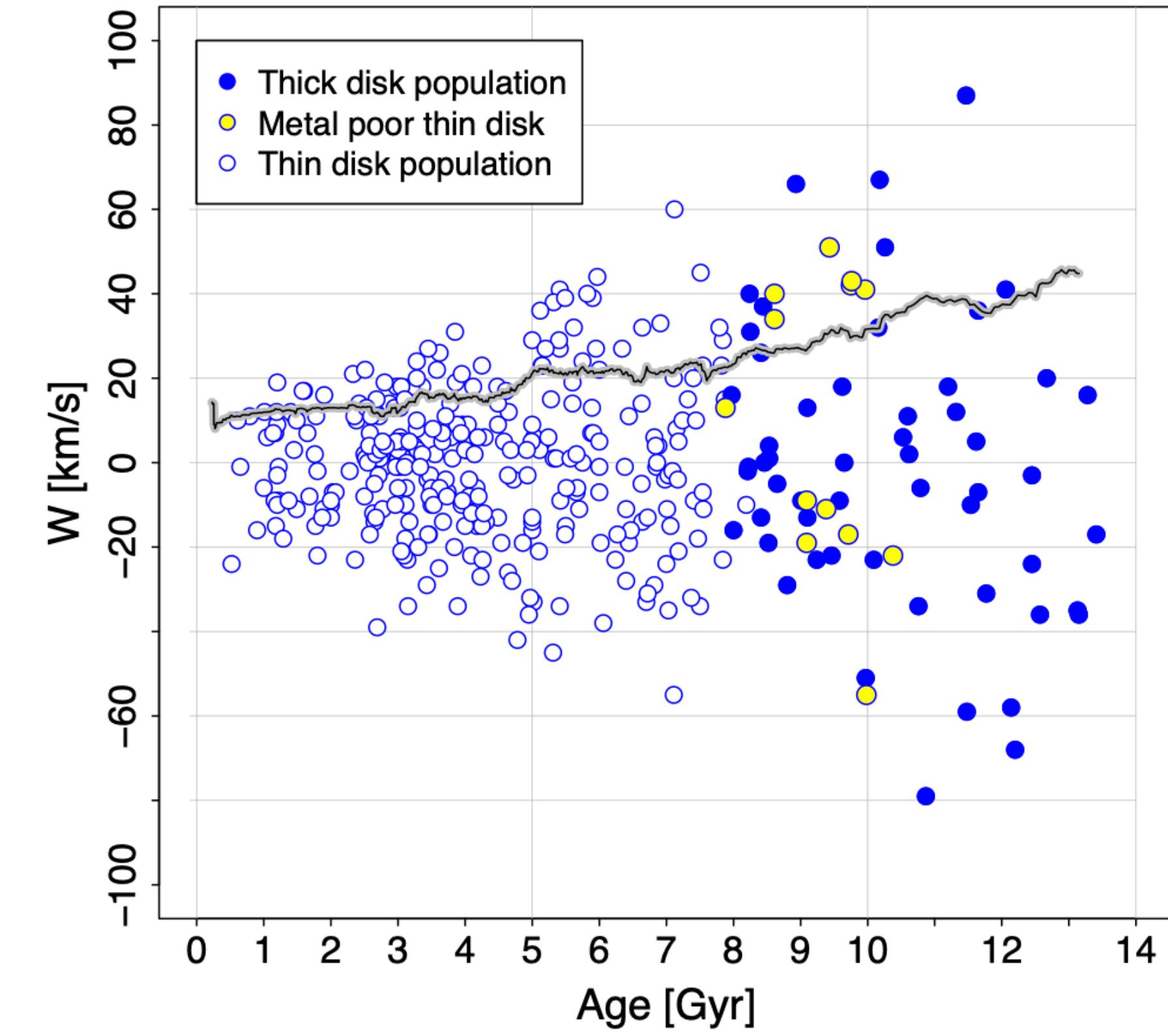


Ages from Velocities

- W , same as v_z
- Max vertical velocity shows **trend in age** (**& strong trend in chemistry!**)



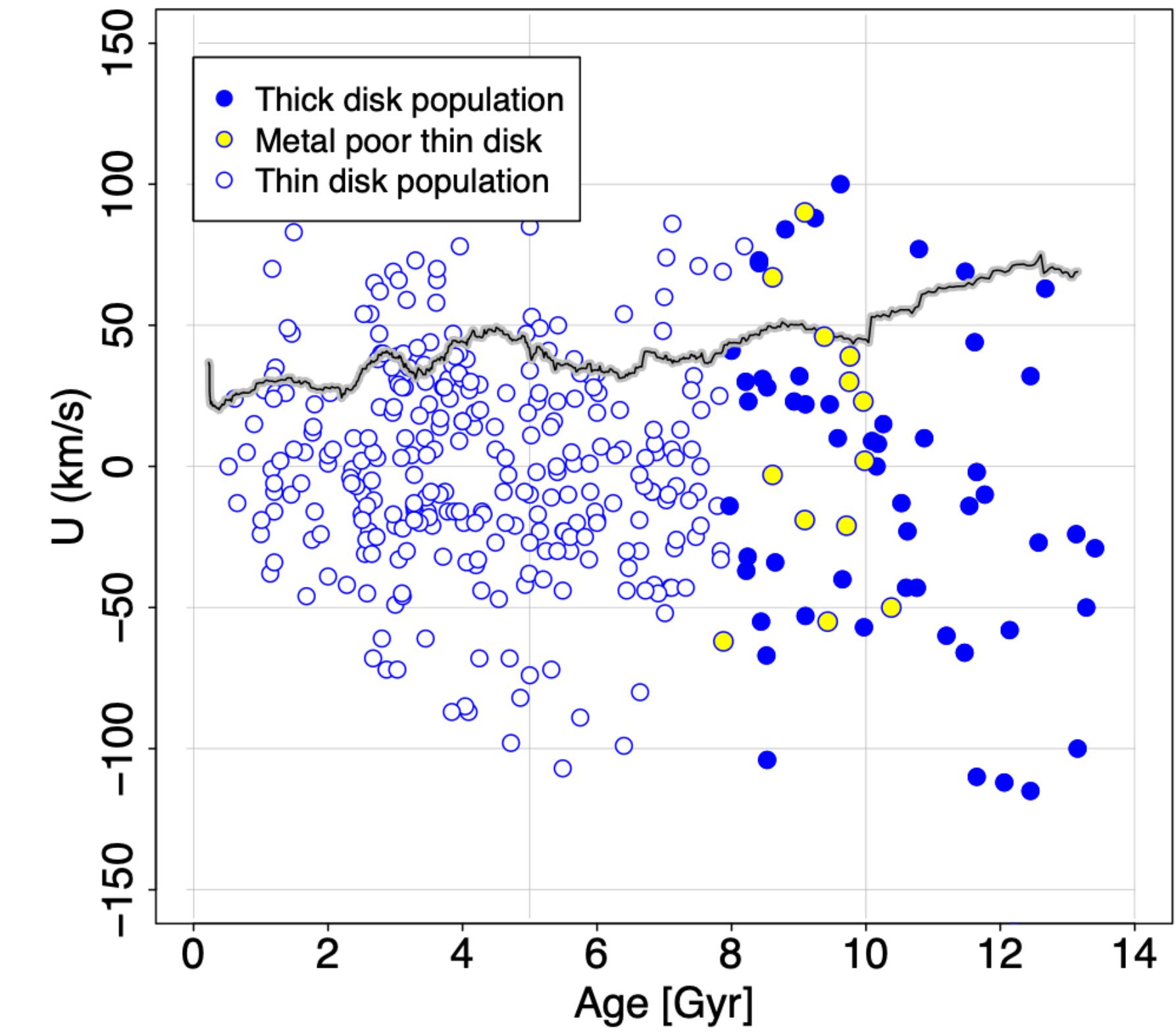
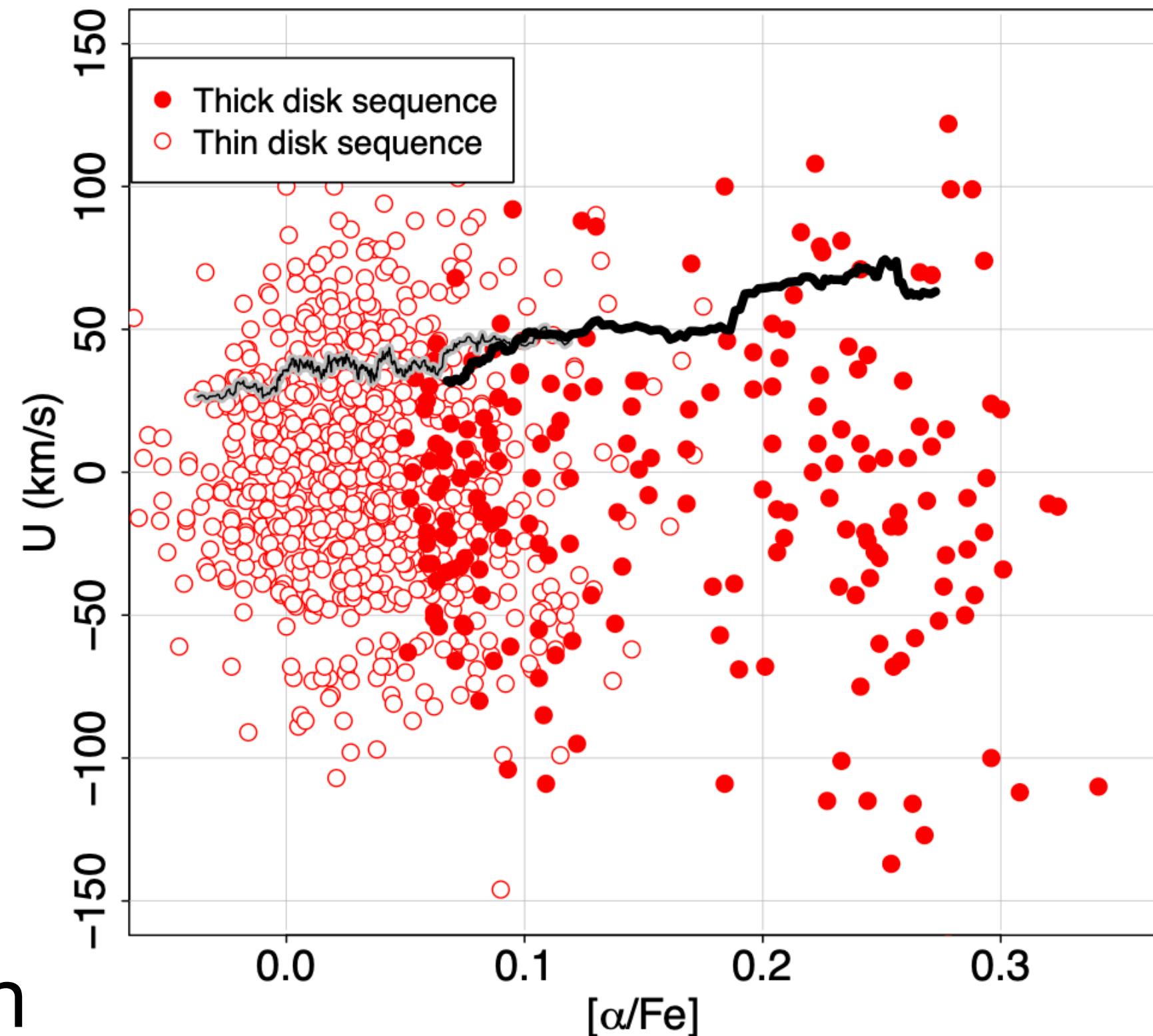
- σ_W is the age metric
- This typically used to infer age for a *population*, though large (outlier) values are clearly suggestive of old ages!



[Haywood+2013](#)

Ages from Velocities

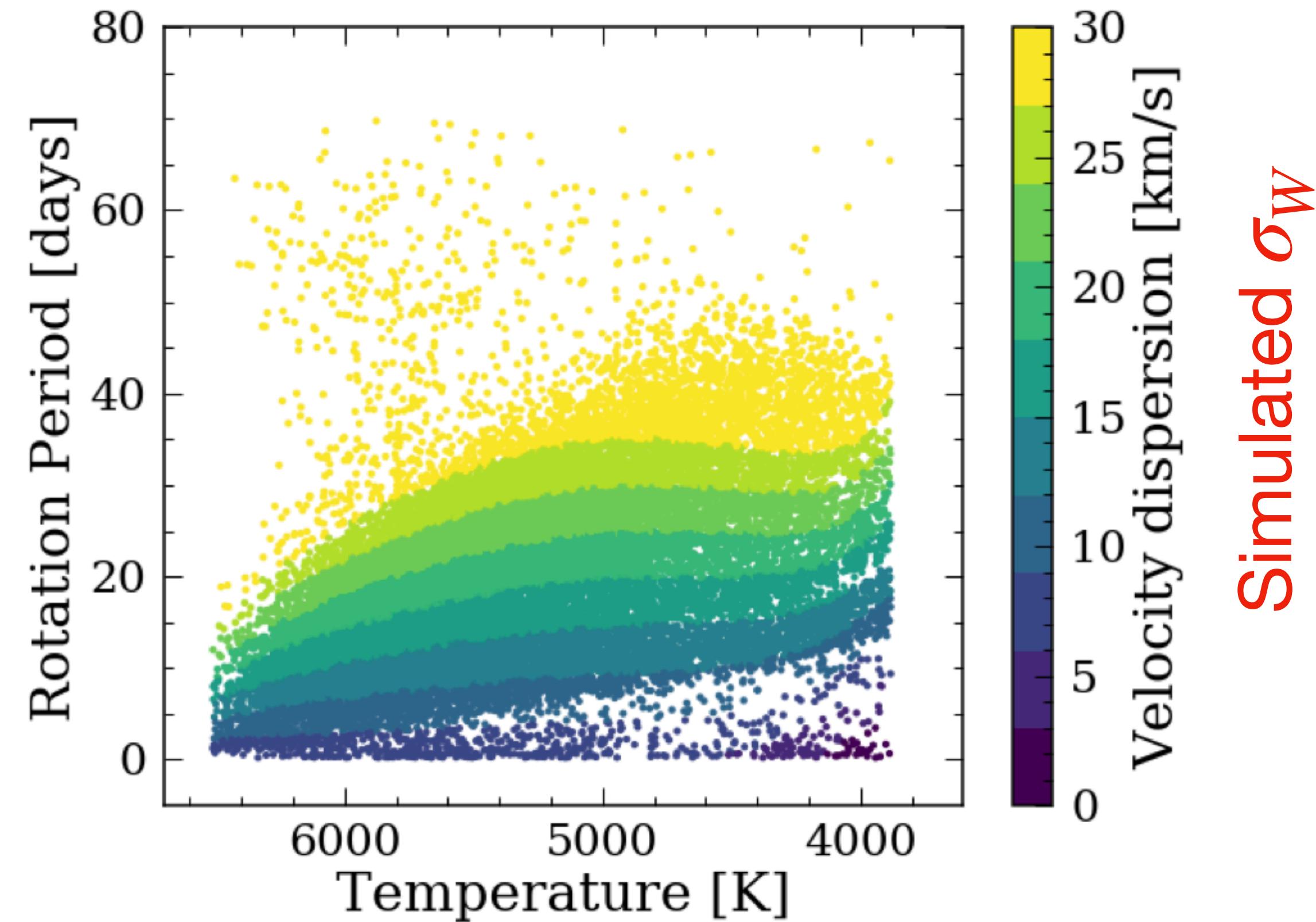
- See some of the same trends seen in U (or radial velocity, v_R)
- Vertical signal is *stronger*: less radial migration more vertical scattering the disk



Haywood+2013

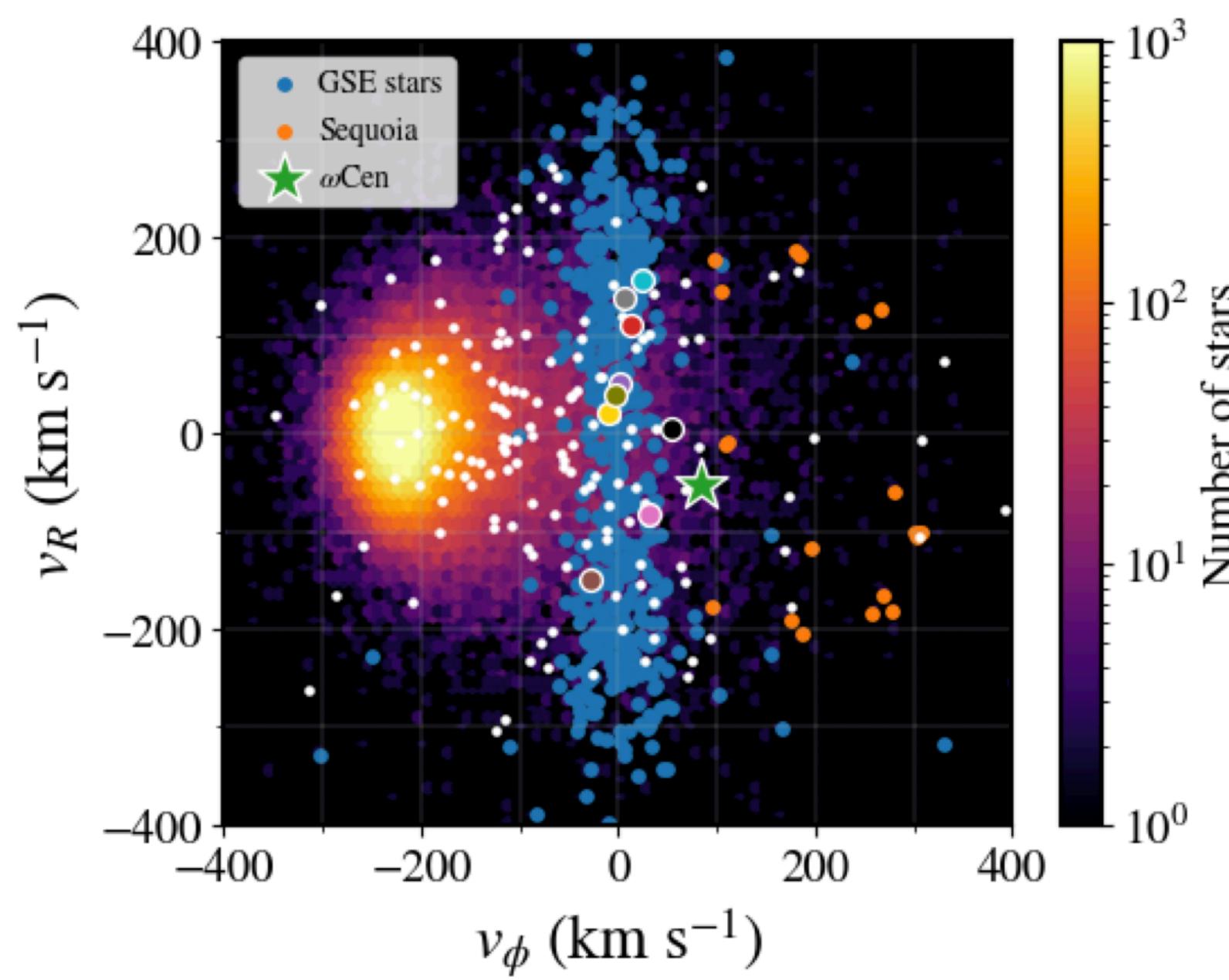
Ages from Velocities

- **Vertical velocity dispersion:** Long history of use, but currently being compared directly to many other age metrics for cross-calibration



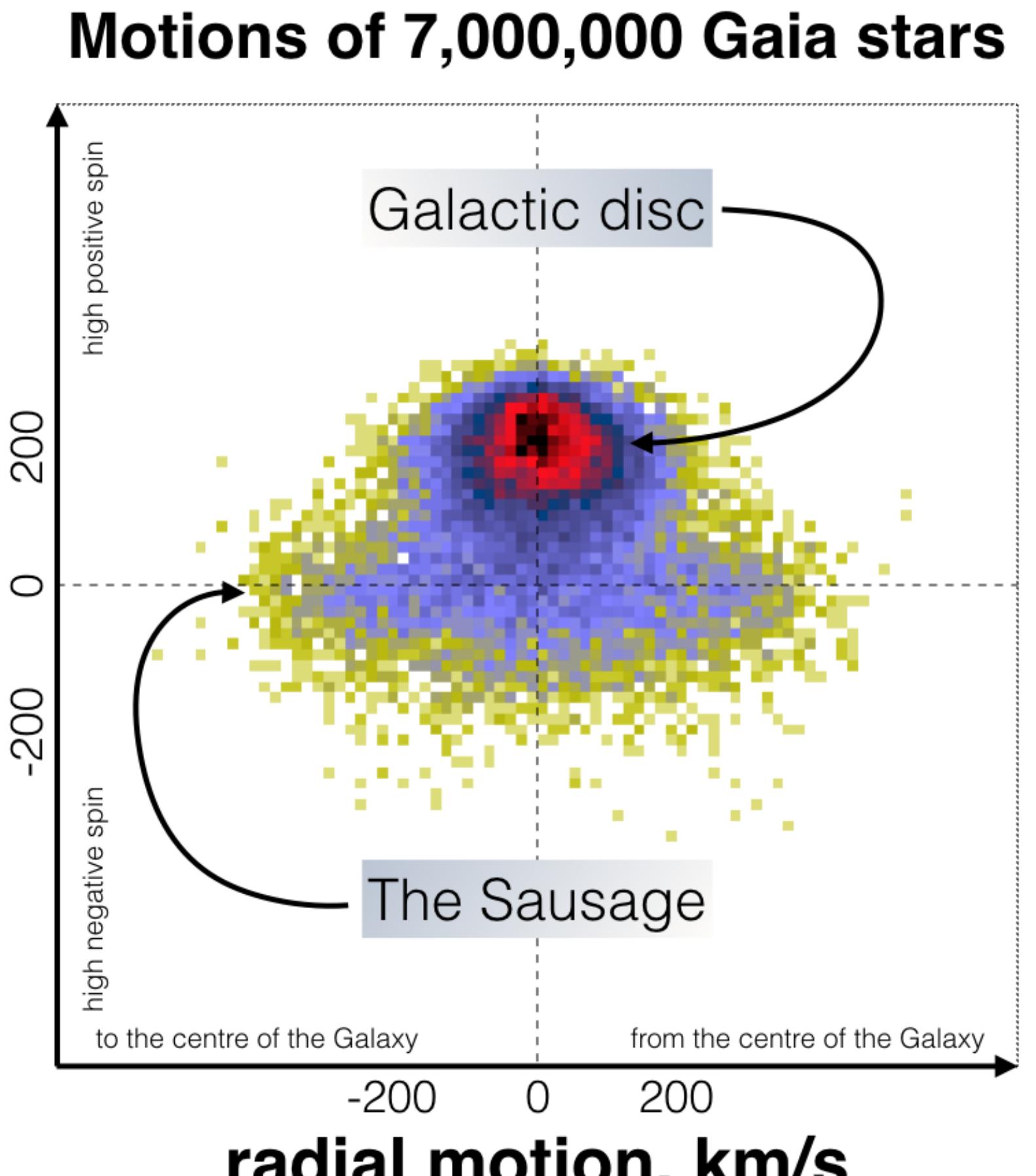
Gaia-Enceladus/Sausage Velocities

- As published in e.g. [Belokurov+2018](#) uses galactic spherical velocities
 - NOTE: they use v_θ for rotation, disagrees with coords written out by e.g. [Bovy Galaxies book](#): (r, ϕ, θ)



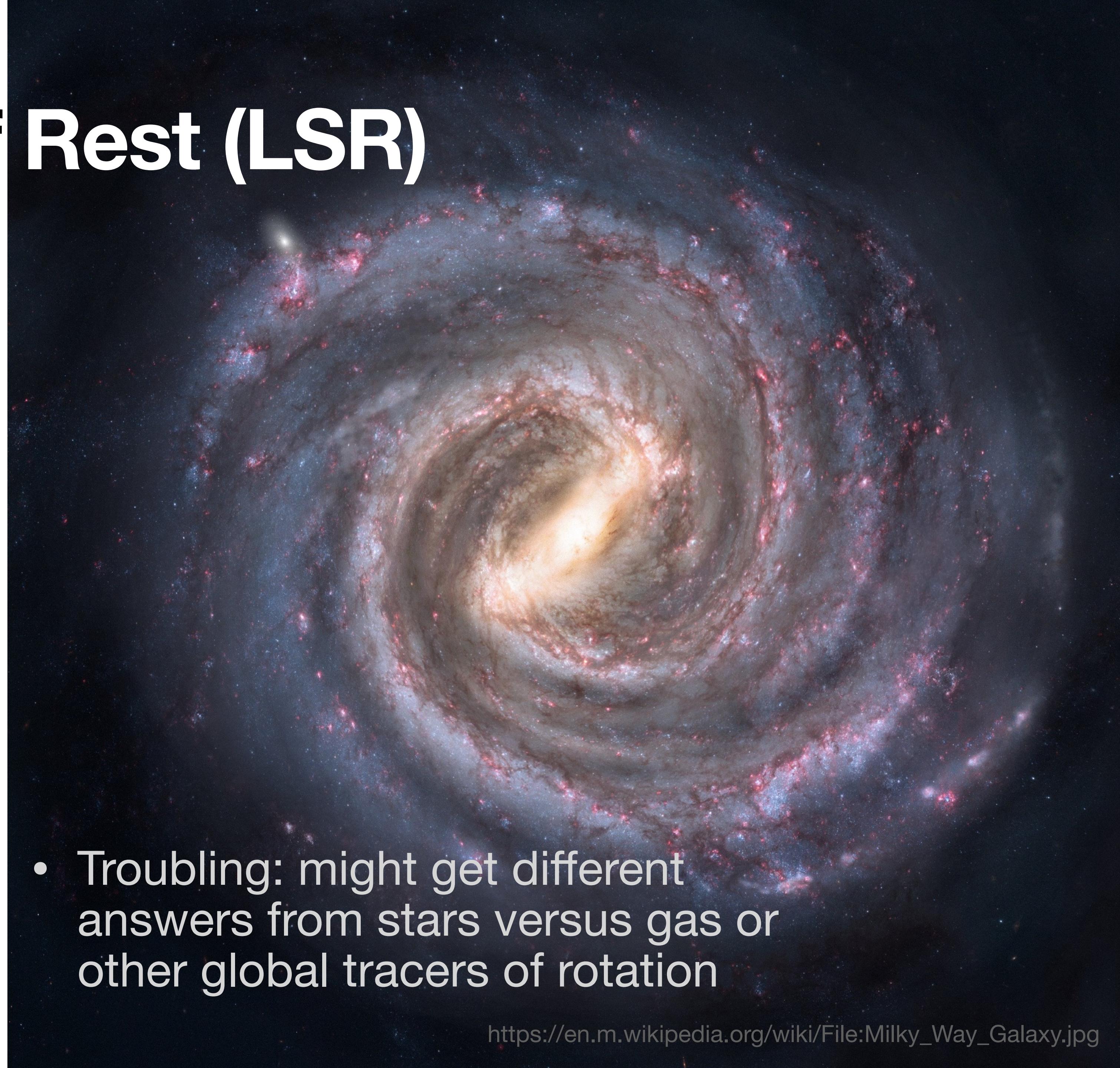
• v_ϕ sign flipped

• Define your coords,
esp. the azimuthal
direction!



Local Standard of Rest (LSR)

- How fast is the *normal* velocity at our location in the disk?
- Classic values:
 $(v_r, v_\phi, v_z) = (0, 220, 0)$ km/s
- Sometimes see $v_\phi = 240$ km/s
(assumed w/ Gaia DR2),
also written V_{LSR}
- Good:
 $v_{LSR} = 232.8$ km/s
(Schönrich+2010)
- Troubling: might get different answers from stars versus gas or other global tracers of rotation

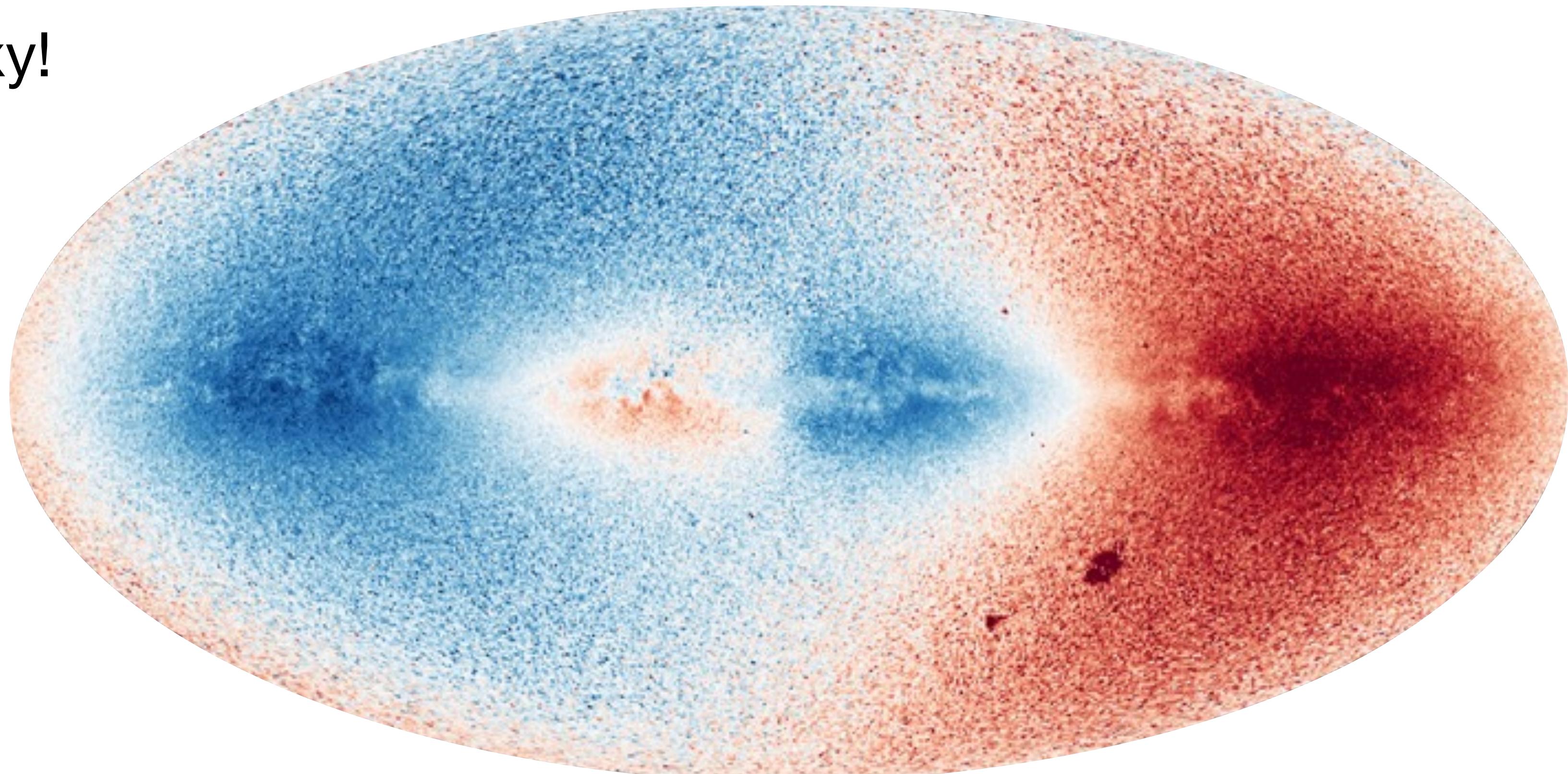


Solar Peculiar Motion

- How much are we moving relative to the LSR?
- Again: [\(Schönrich+2010\)](#)
 - $(U, V, W) = (11.1, 12.24, 7.25)$ km/s
 - We're *not* moving very fast relative to the LSR!

Galactic Rotation

- We live in a rotating galaxy!
- I love this example from Gaia DR2 using radial velocities
- Here's an example of remaking this figure by Bovy w/ galpy



Gaia+2018

Oort Constants

- MWY isn't rotating like solid body, there's differential rotation!
- Oort (1927) the classic reference
 - Fairly readable derivation on Wikipedia for classic constants A and B
 - Bovy book very good here!
- IAU standard values: A=15 km/s/kpc, B=-10 km/s/kpc

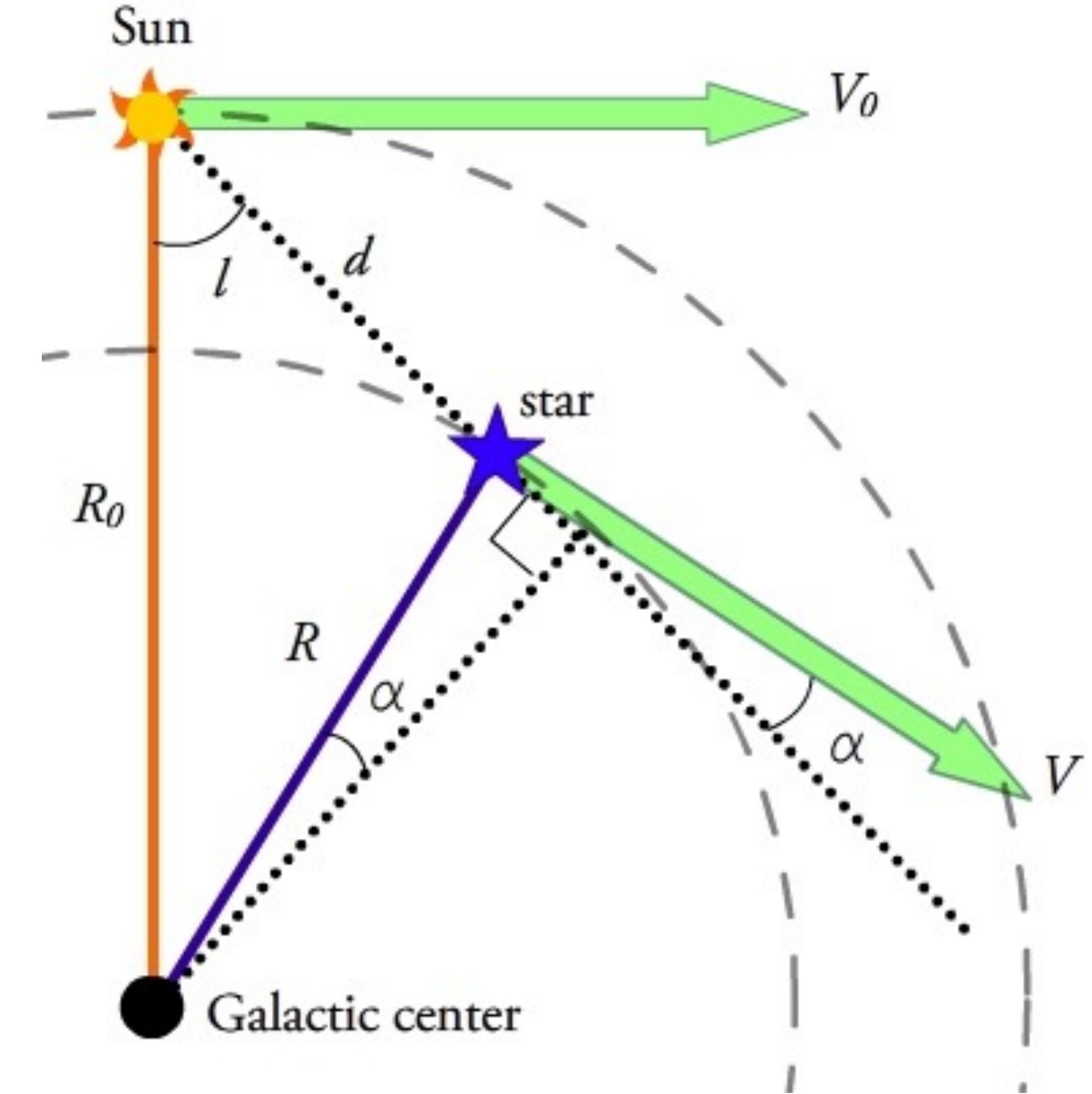
Oort Constants

- Assuming circular rotation for everything, and azimuthal symmetry of MWY
- A is the azimuthal shear (diff rot)
- B is the rotation at the solar radius

$$V_{\text{obs}, r} = Ad \sin(2l)$$

$$V_{\text{obs}, t} = Ad \cos(2l) + Bd$$

- Note funny units for A & B: km/s/kpc
- So if you know PM (tangential velocity) and parallax (distance), you can solve for A, B!

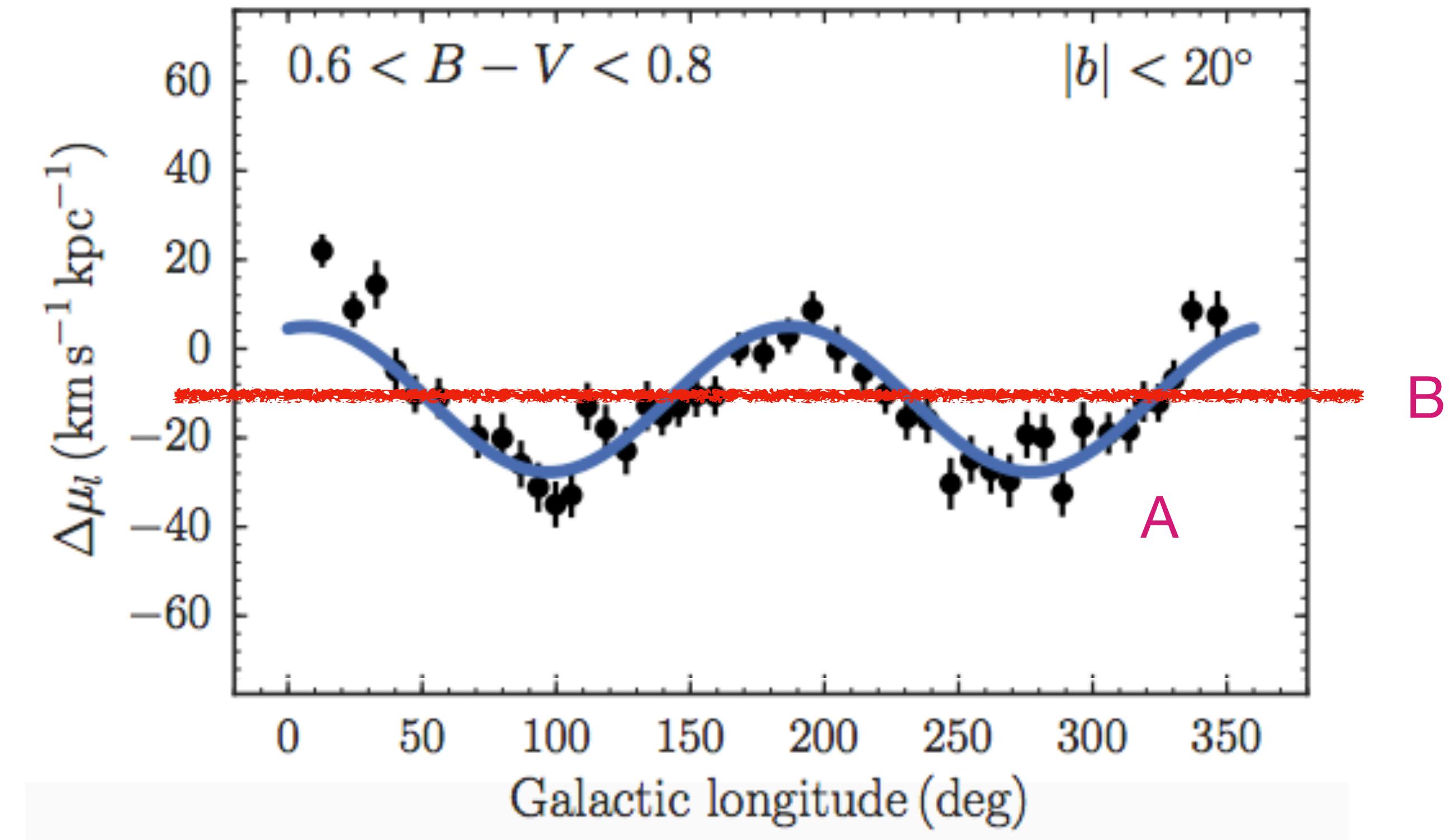


Oort Constants

- IAU standard values:
 $A=15 \text{ km/s/kpc}$, $B=-10 \text{ km/s/kpc}$
- Gaia DR1: $A=15.3$, $B=-11.9$

$$V_{\text{obs, r}} = Ad \sin(2l)$$

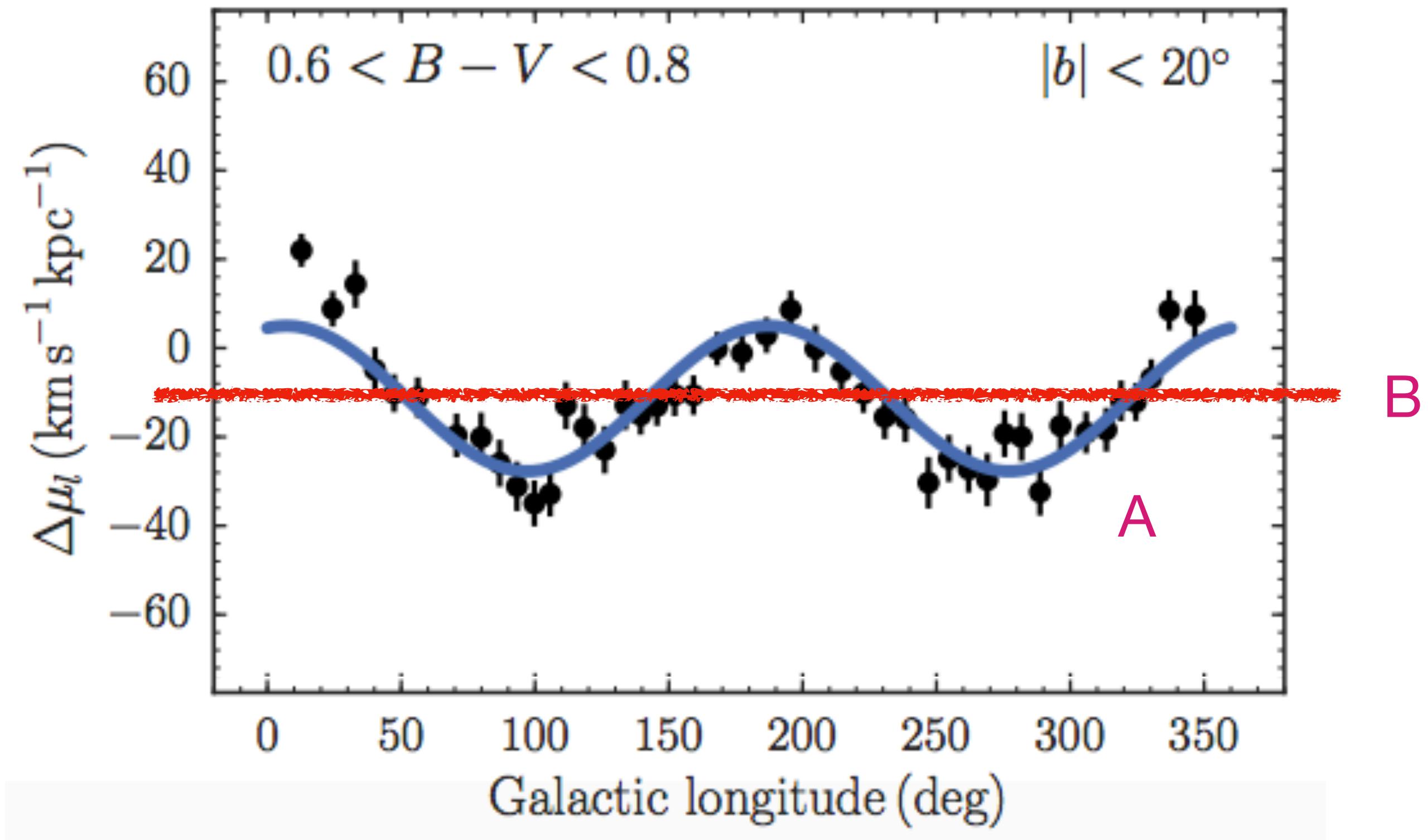
$$V_{\text{obs, t}} = Ad \cos(2l) + Bd$$



Bovy (2017)

Oort Constants

- But wait, **our galaxy *isn't* perfectly axisymmetric...**
- There are higher-order terms in the derivation of Oort Constants via Taylor series expansion
- Next Constants called: C and K
- Can include dependents on galactic longitude (l) and latitude (b)
- Bovy (2017) showed w/ Gaia DR1 C&K are small but ***non-zero!***
 - Others finding same thing w/ Gaia DR2, e.g. Li+2019



Bovy (2017)

“6-D Phase Space”

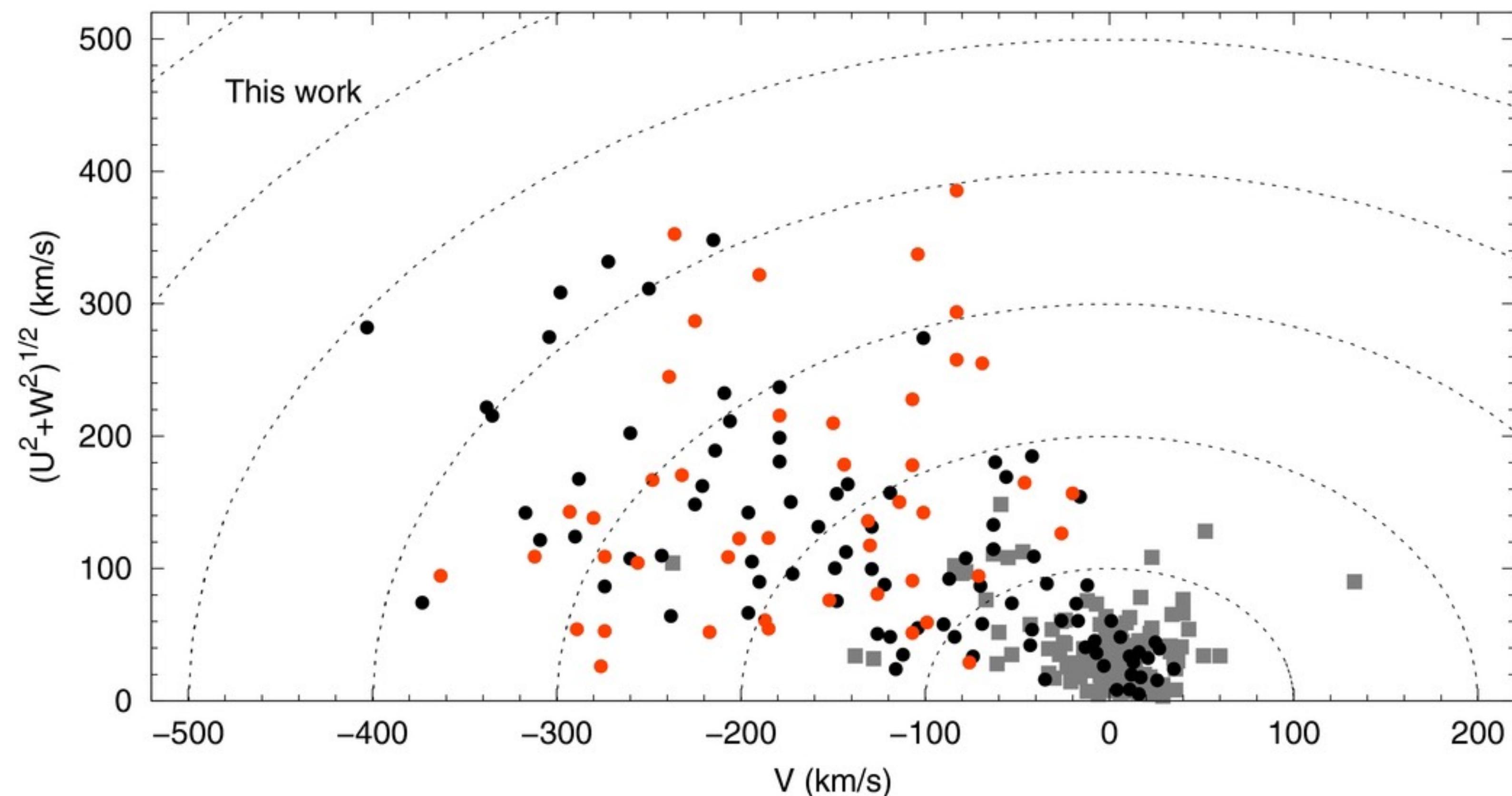
“7-D Phase Space”

Including metallicity!

- Why do we work in these high-D spaces?
- Group of stars (streams, remnants, disks, etc) may have very different appearing orbits, but share underlying *orbital properties*
 - Stars from a merger probably have similar momentum
 - Stars born in the disk experience similar scattering histories
- Can we reduce dimensionality? (YES!)
 - Combine dimensions (e.g. velocity vectors)
 - Remnants have same “Integrals of motion”, even after phase mixing

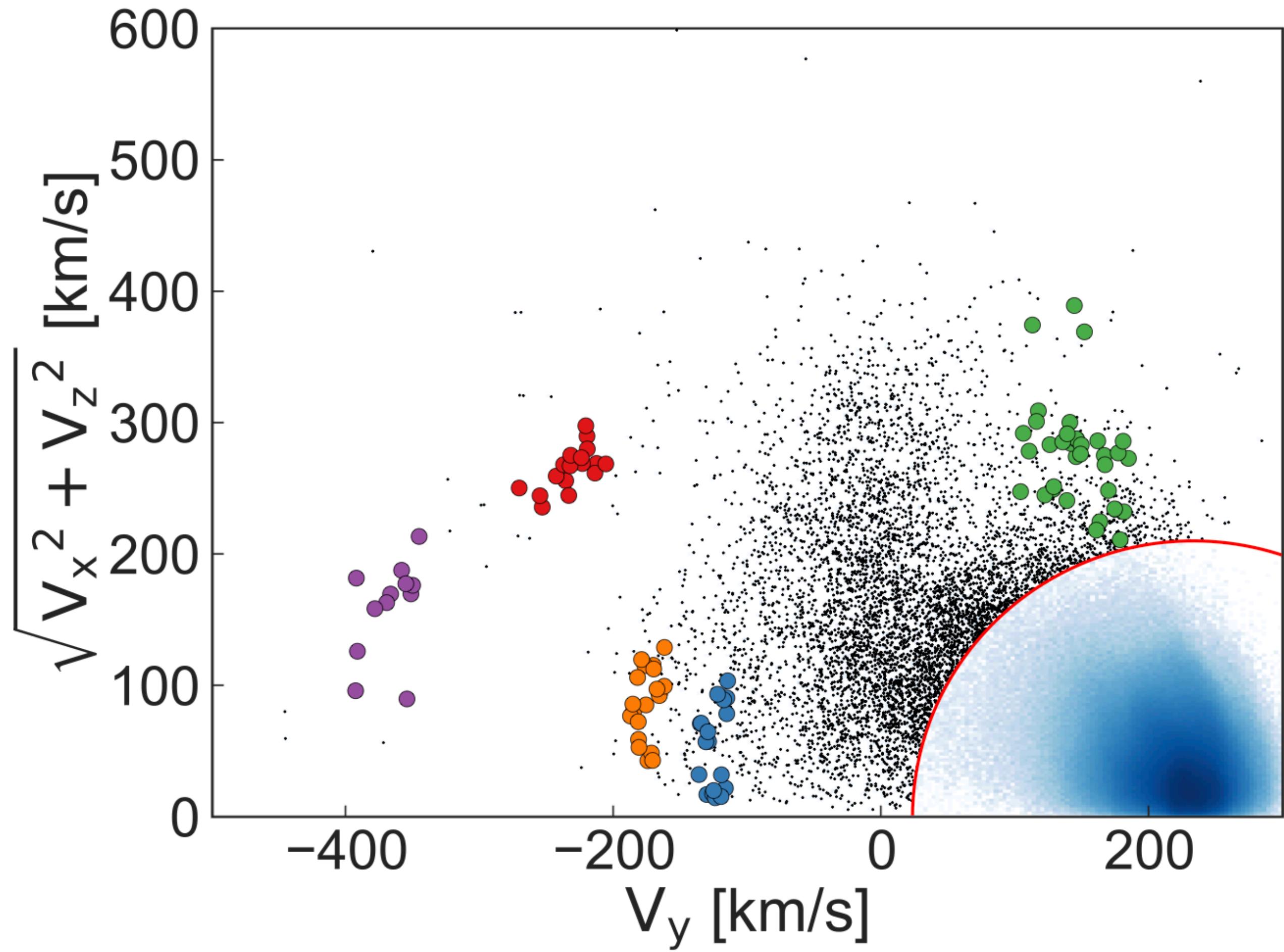
Toomre Diagram

- **U+W** (Radial + Vertical velocity) as a function of **V** (rotational velocity)
- V in LSR frame!
- One potential space to pull out kinematic populations



Toomre Diagram

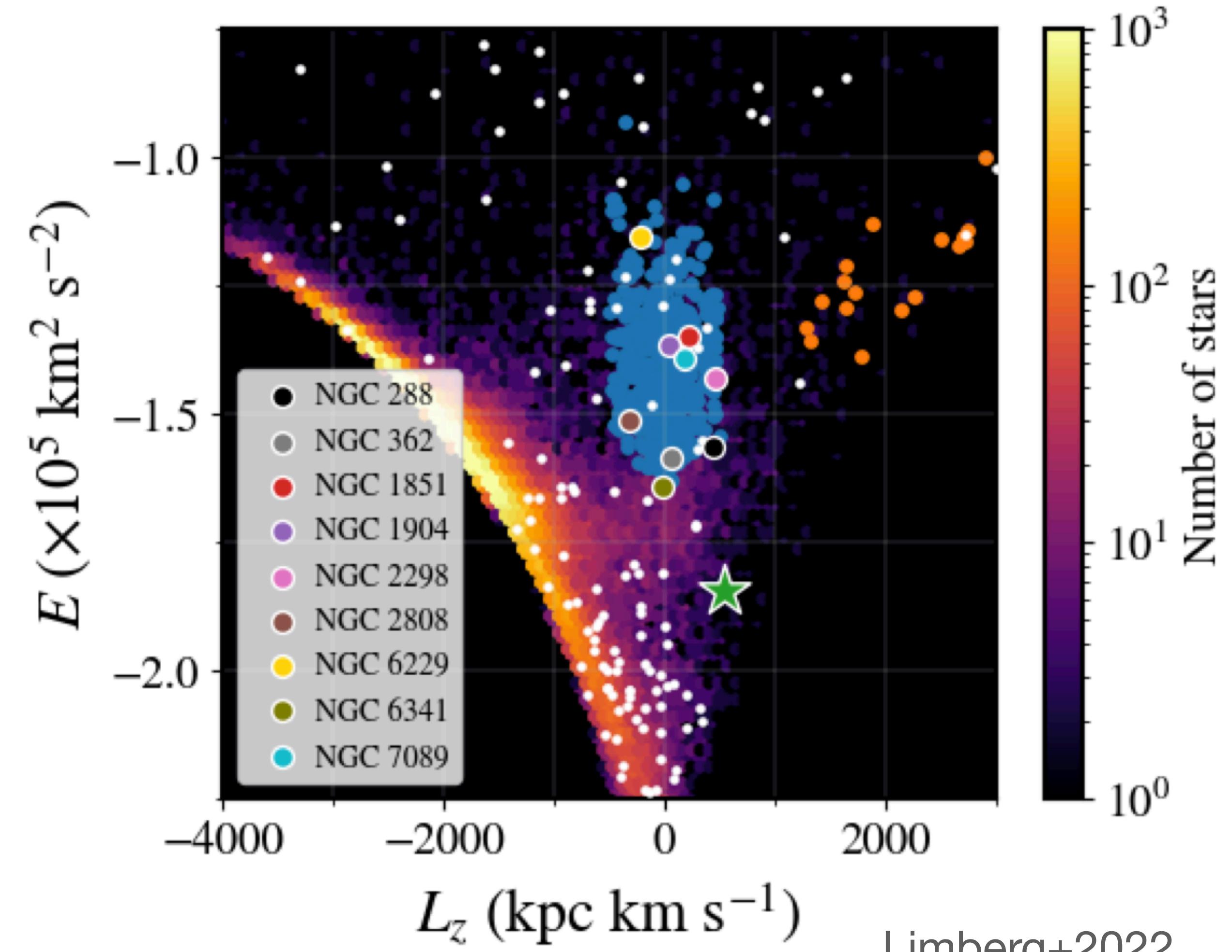
- Can also see features in galactocentric velocities!
- This diagram explores an “integral of motion” i.e. reducing dimensionality of 6-D phase space
- (More on this in discussion of orbits & dynamics.)



Koppleman+2018

Lindblad Diagram

- Two “integrals of motion”:
 - Total energy versus vertical angular momentum
- e.g. a good explanation of quantities by Carollo+2014
 - $L_Z = R_{XY} \times v_\phi$
 - $E = L_Z^2/2r^2 + \Phi(r, Z)$

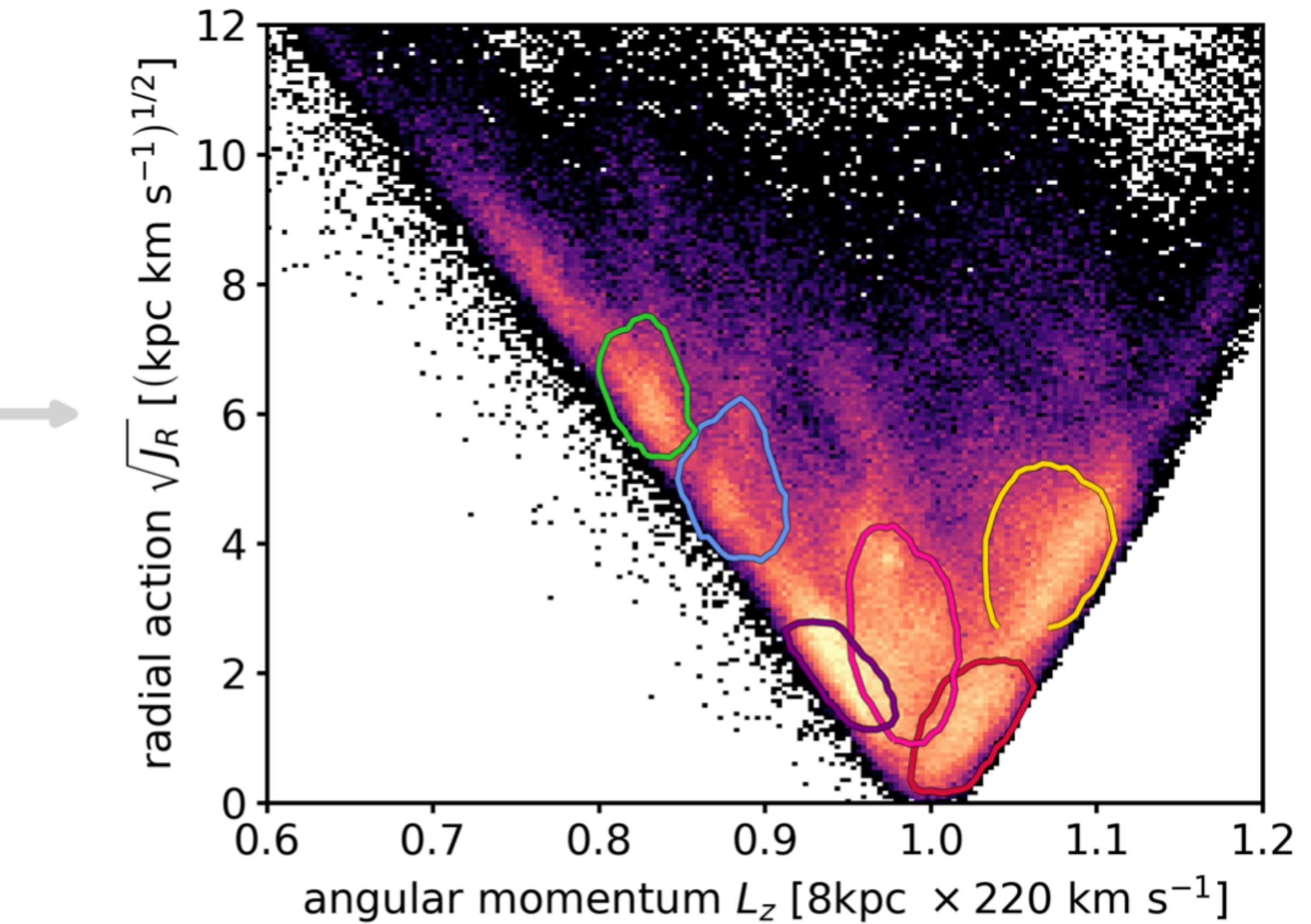
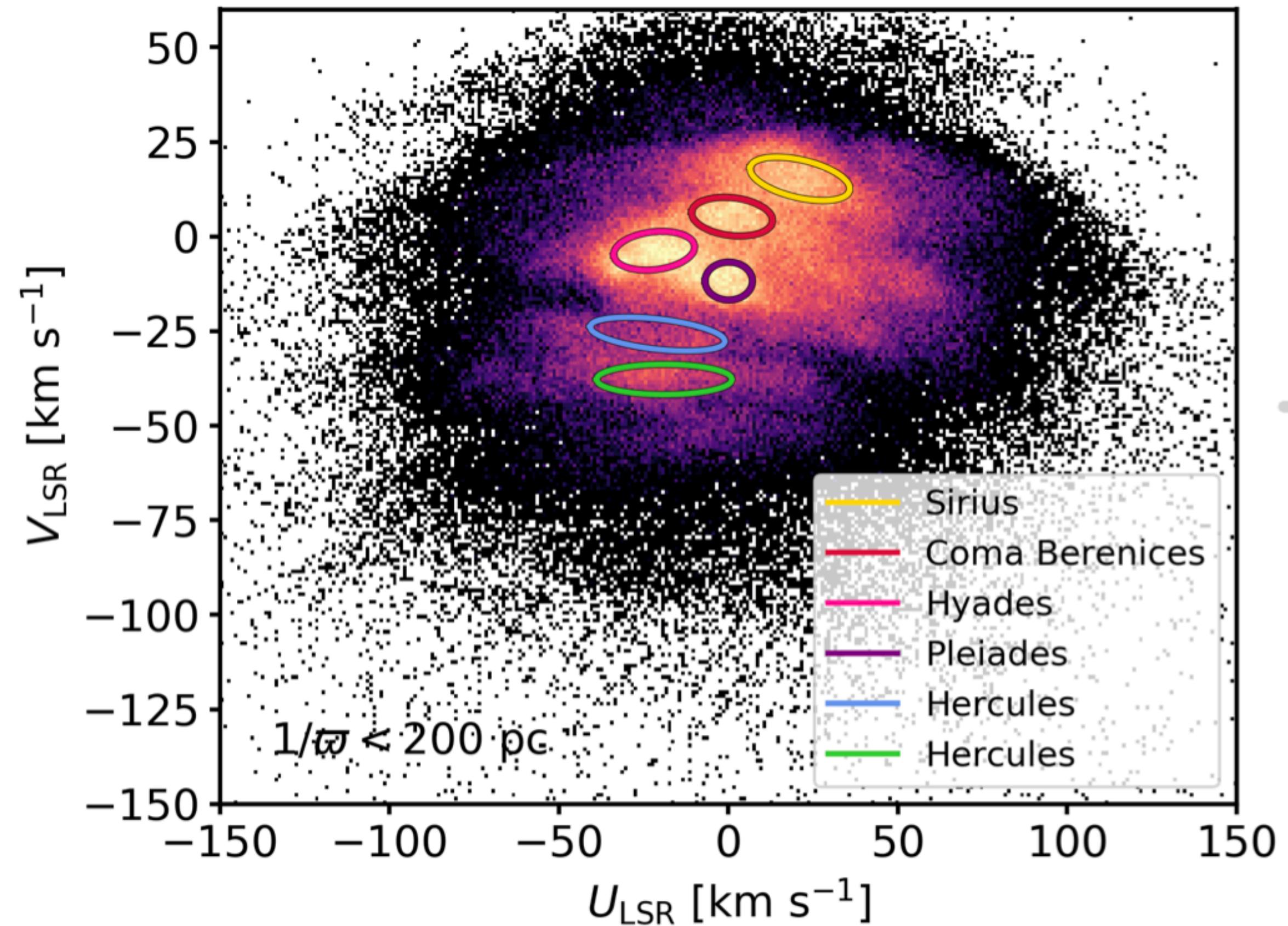


Limberg+2022

Action Angles & Coordinates

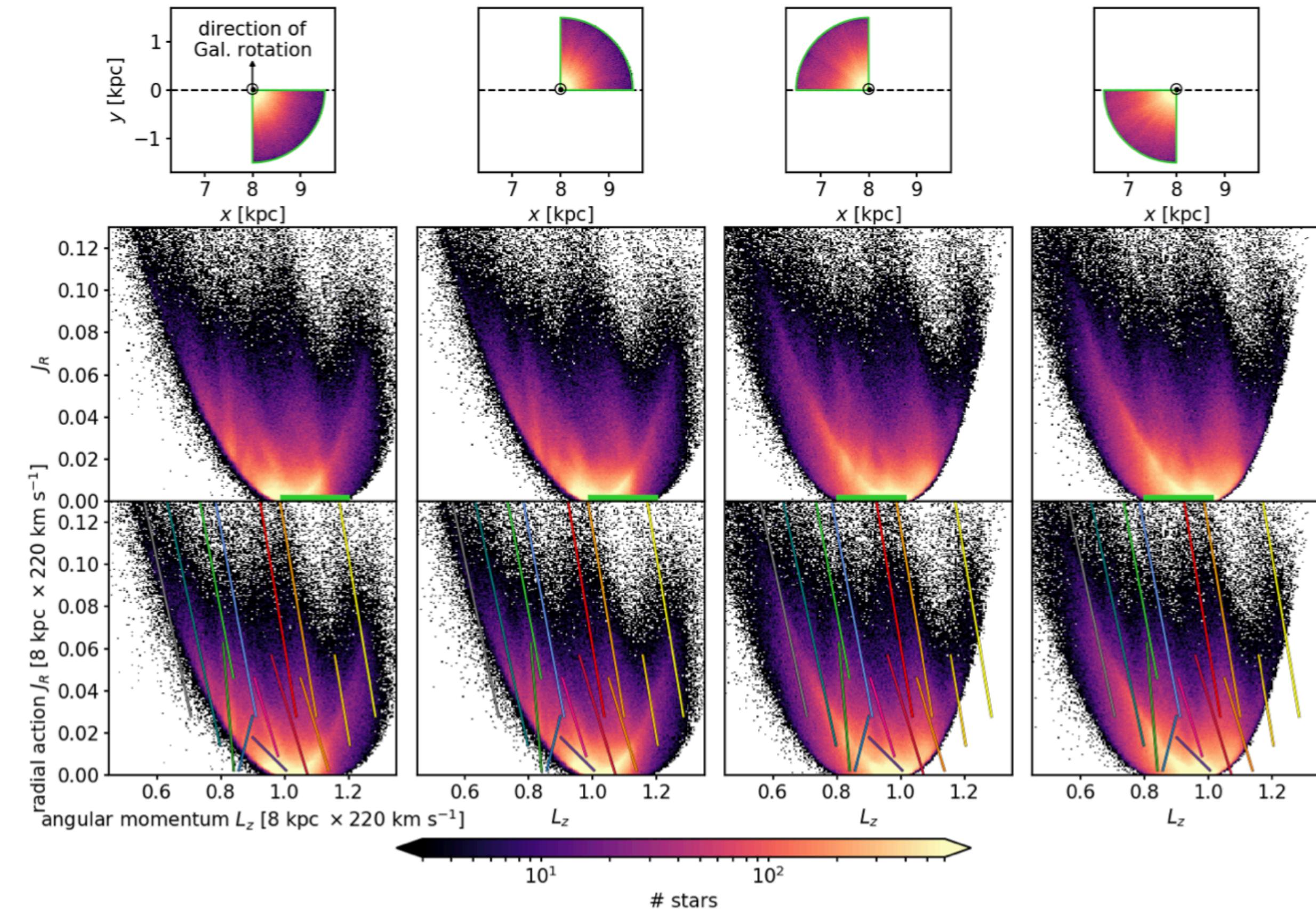
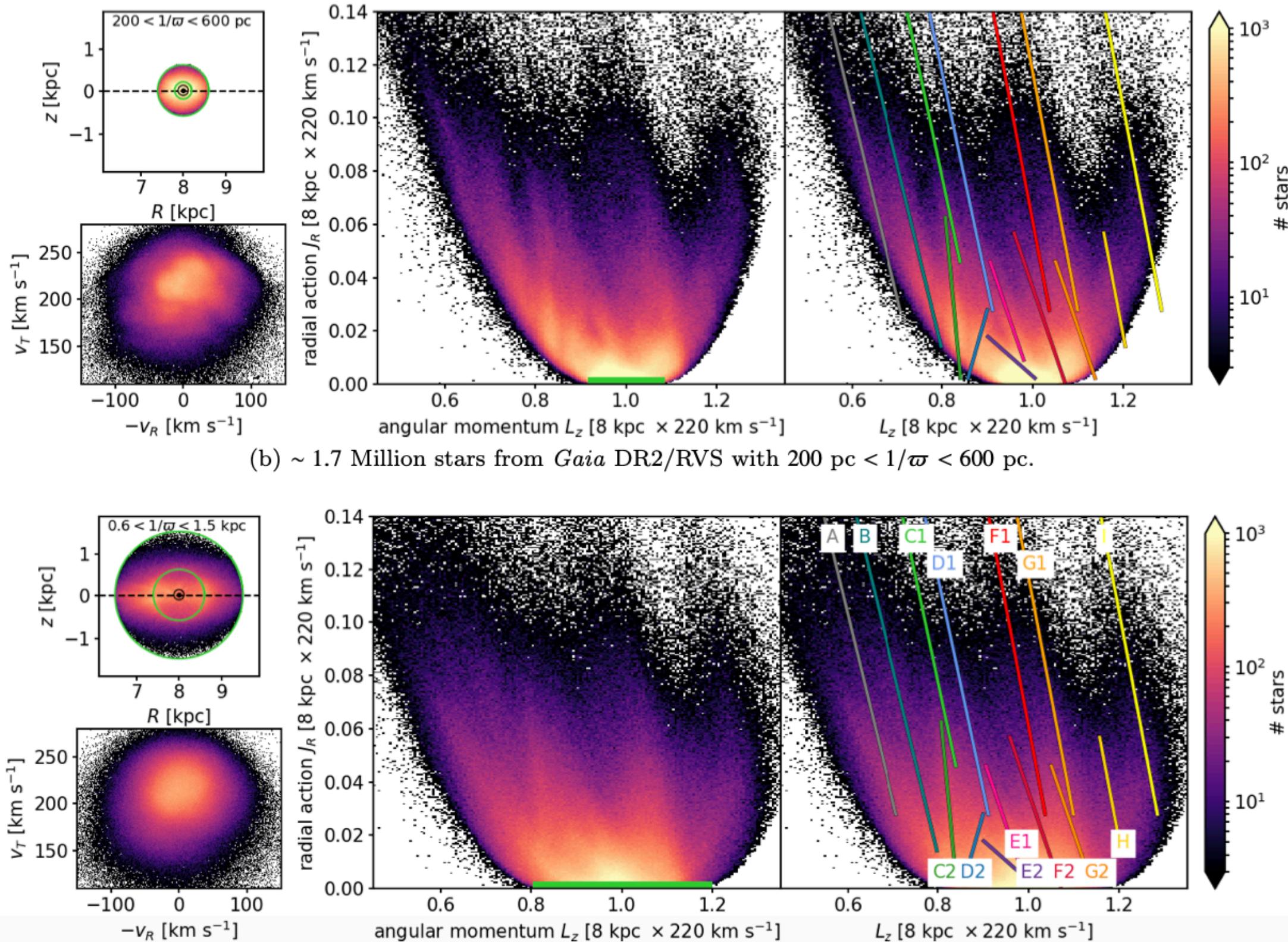
- Foundation laid out by Binney & Tremaine 2008 (famous textbook)
 - Need a proper dynamics course... to fully grok this (i.e. I'm about to do a *bad* job explaining this today!)
- A review by [McMillan & Binney \(2008\)](#)
- A practical view from [Trick+2019](#) in Gaia DR2
 - Compute momentum vectors, e.g. J_R, J_Z or J_ϕ
 - L_Z is also an action (in an axisymmetric potential)

Action Angles & Coordinates



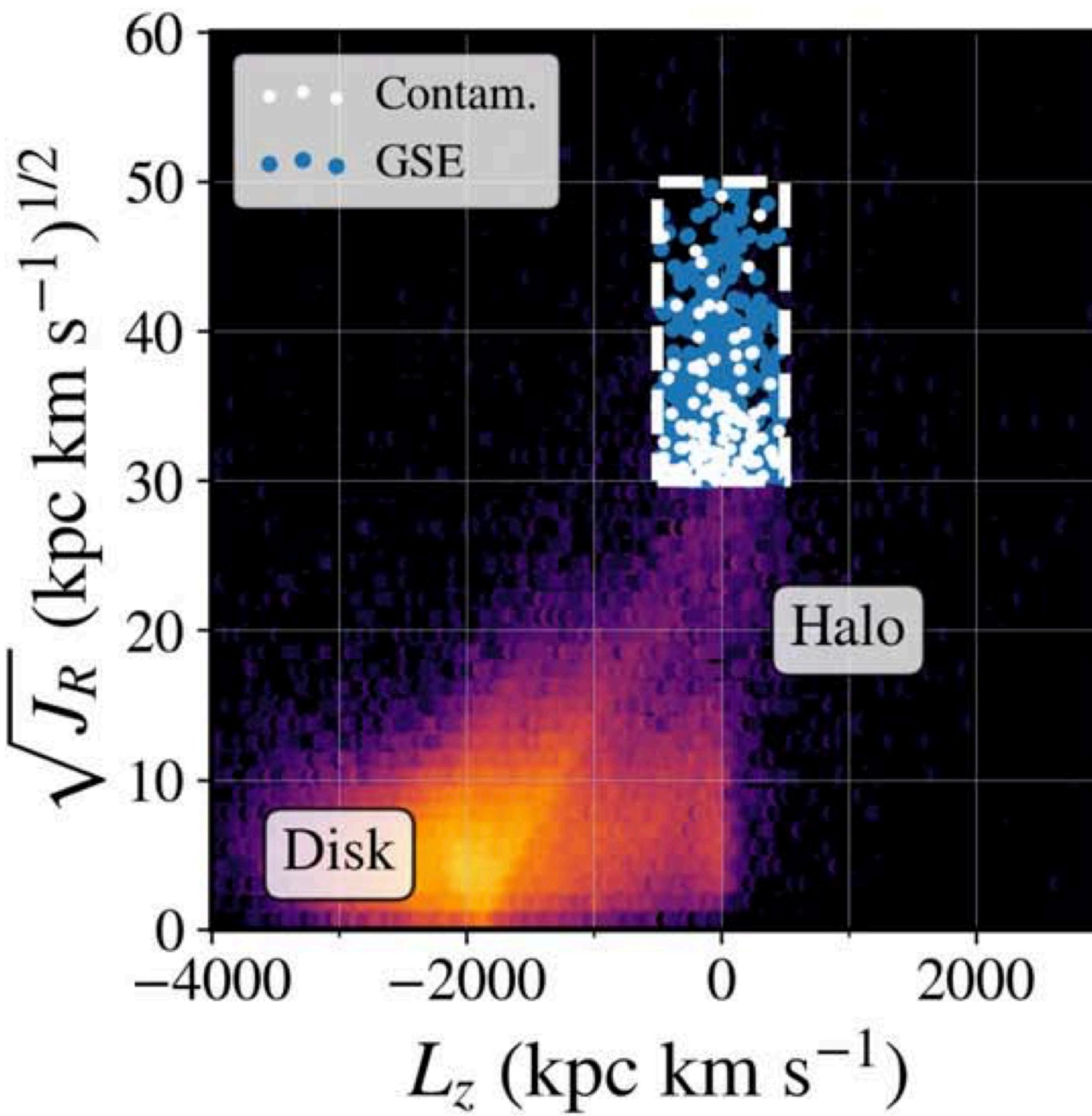
- Trick+2019

Action Angles & Coordinates

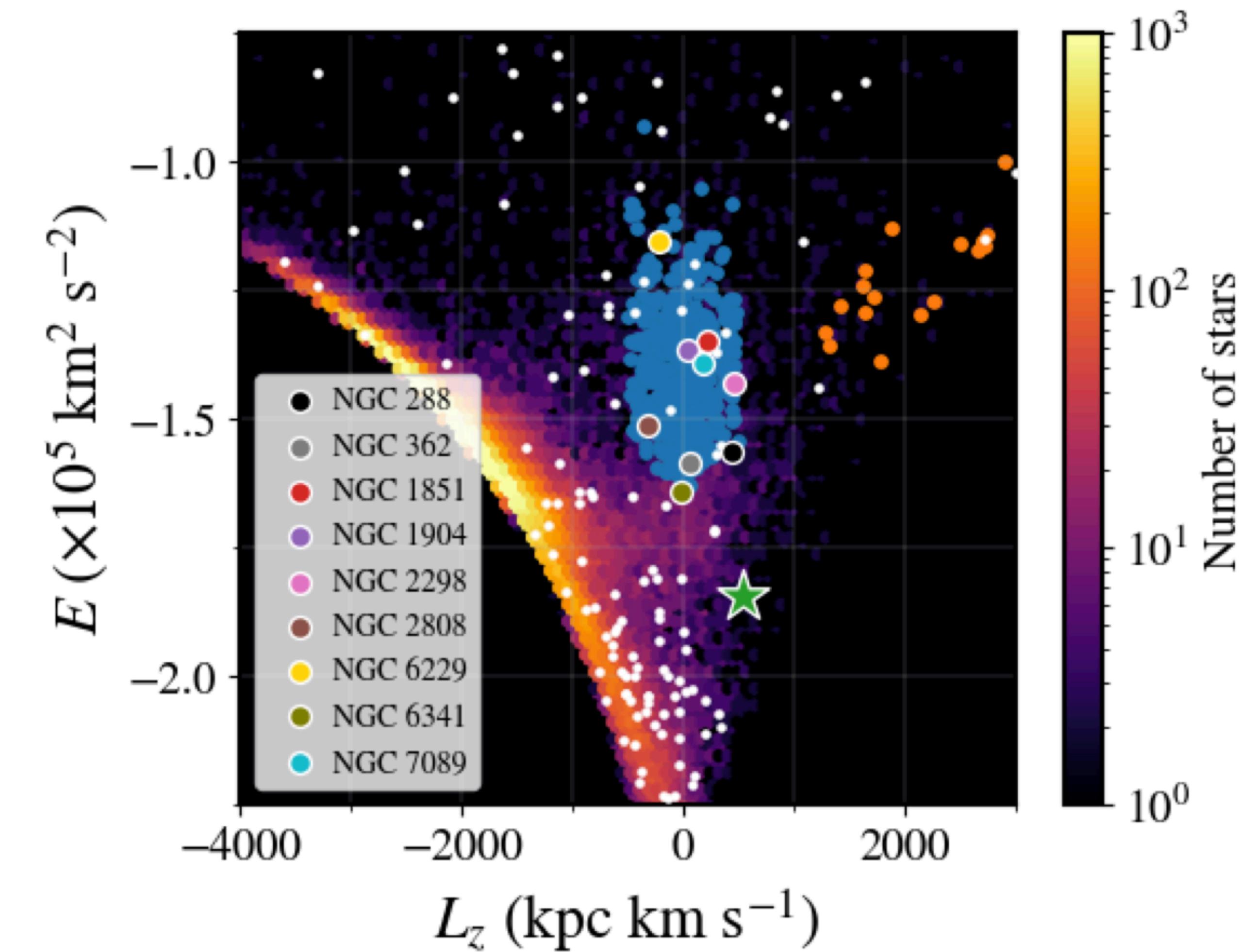


- Trick+2019

Action Angles & Coordinates

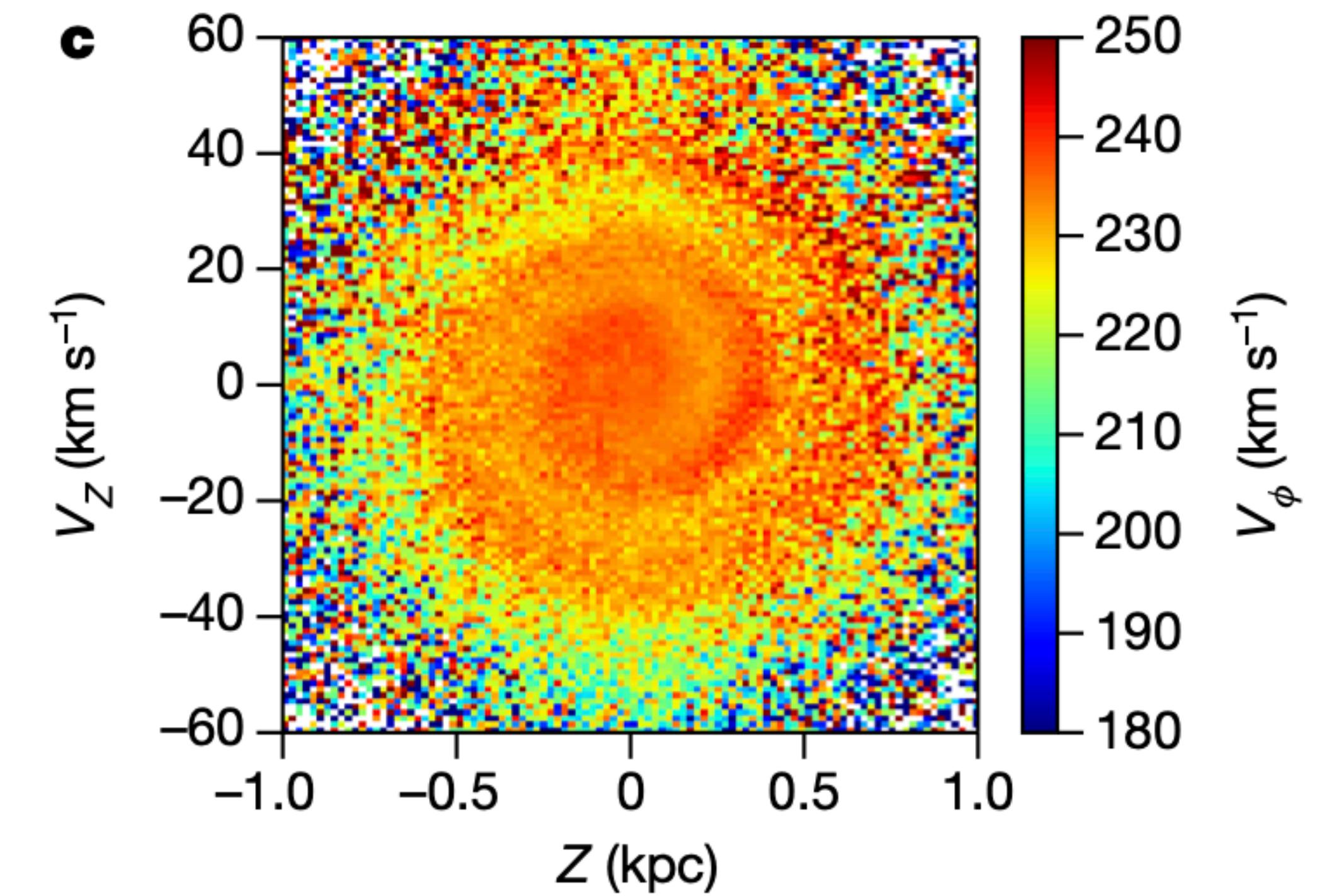
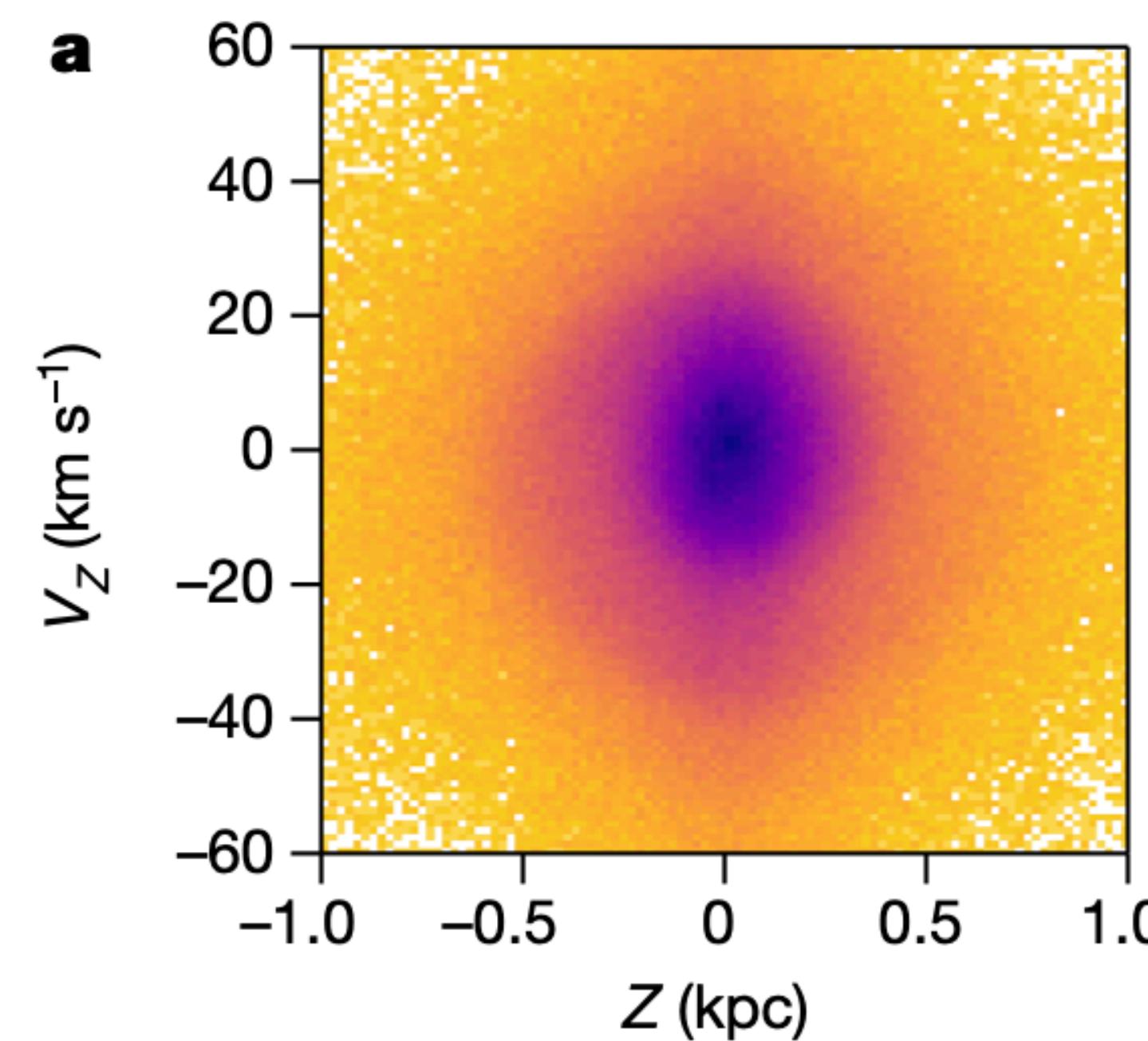


versus



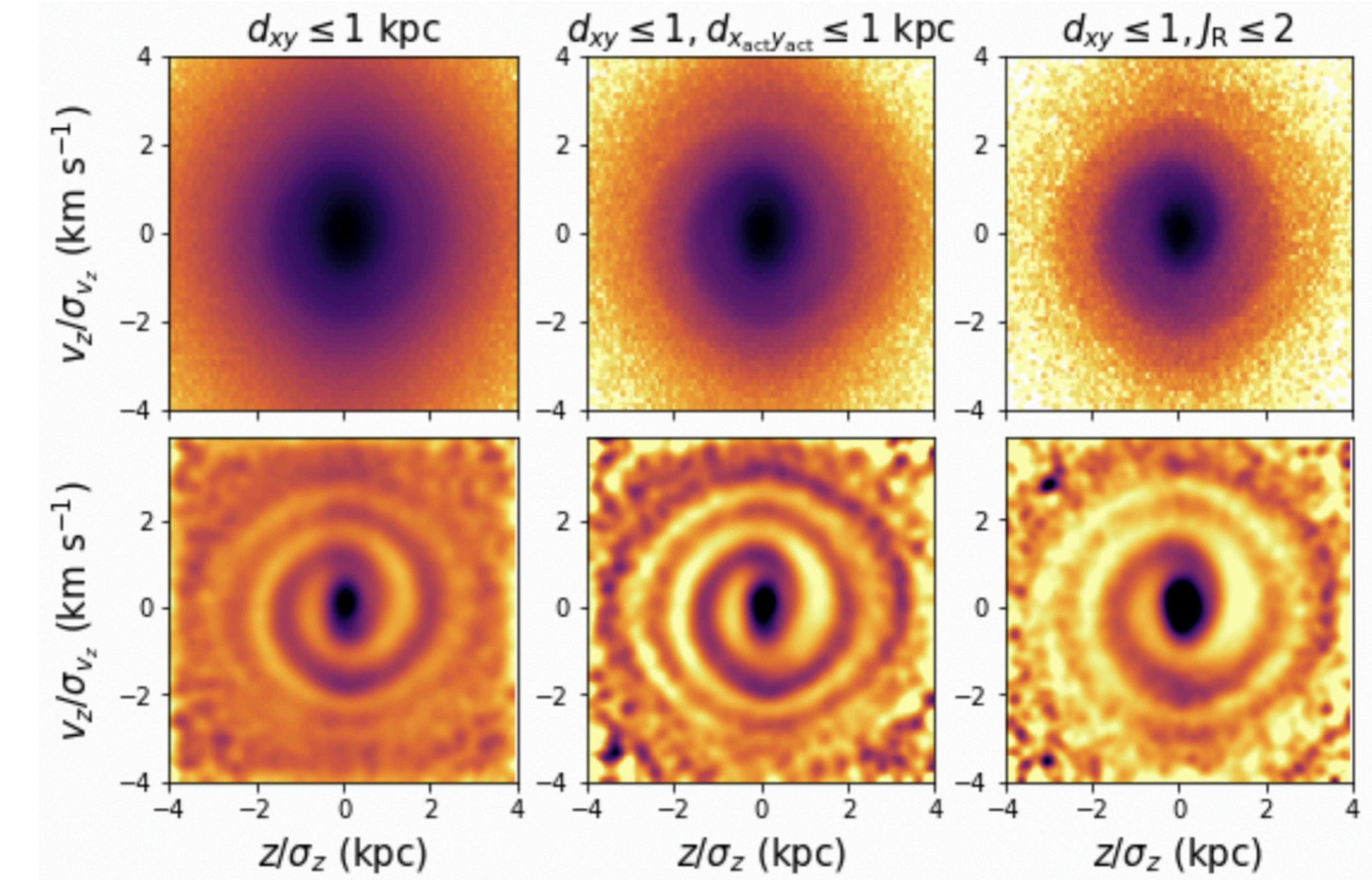
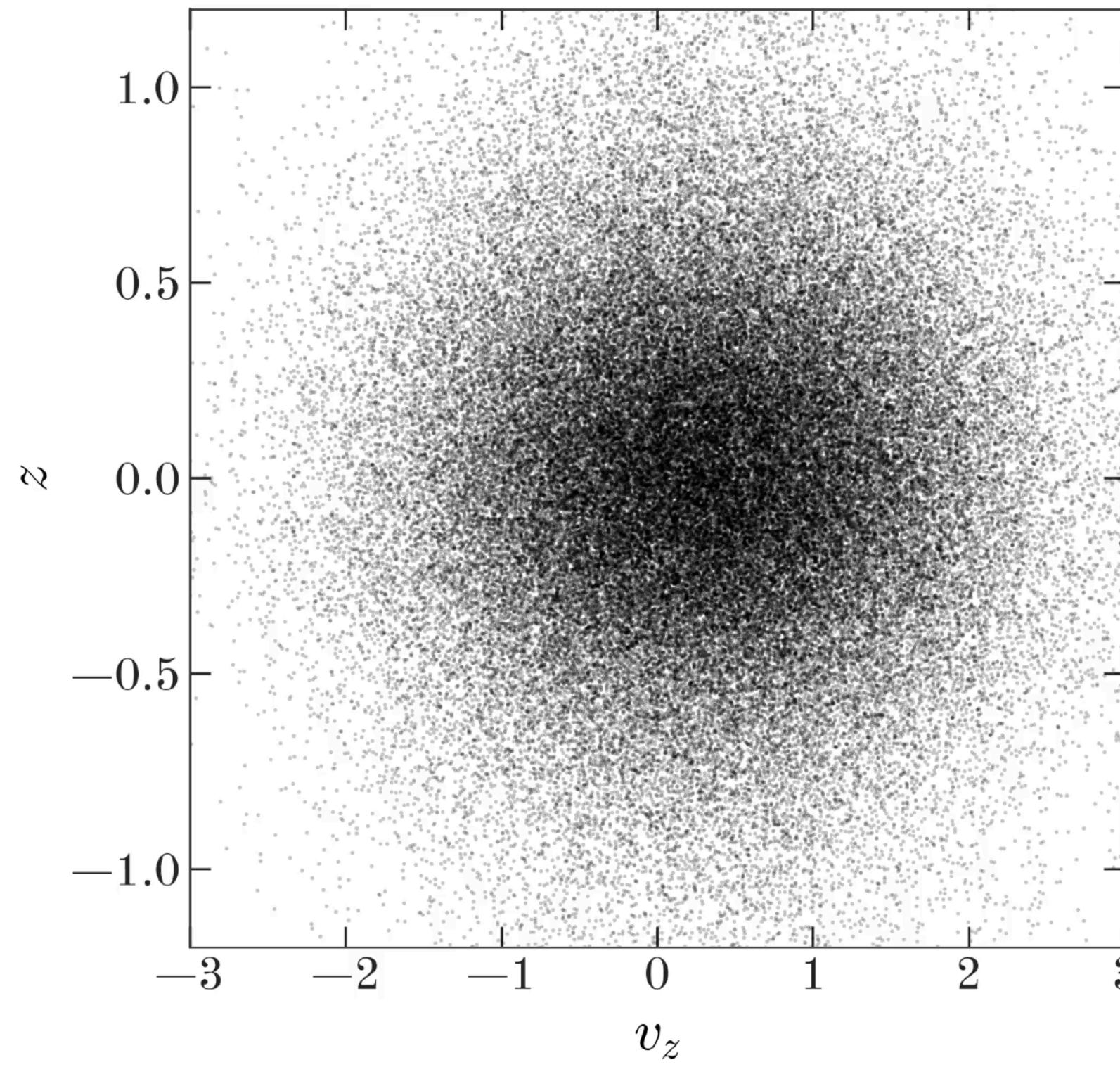
Phase Space Spiral

- An intriguing feature discovered in Gaia DR2 ([Antoja+2018](#))
- Tracing the (Z, v_Z) plane for nearby stars
- Disk is “perturbed”



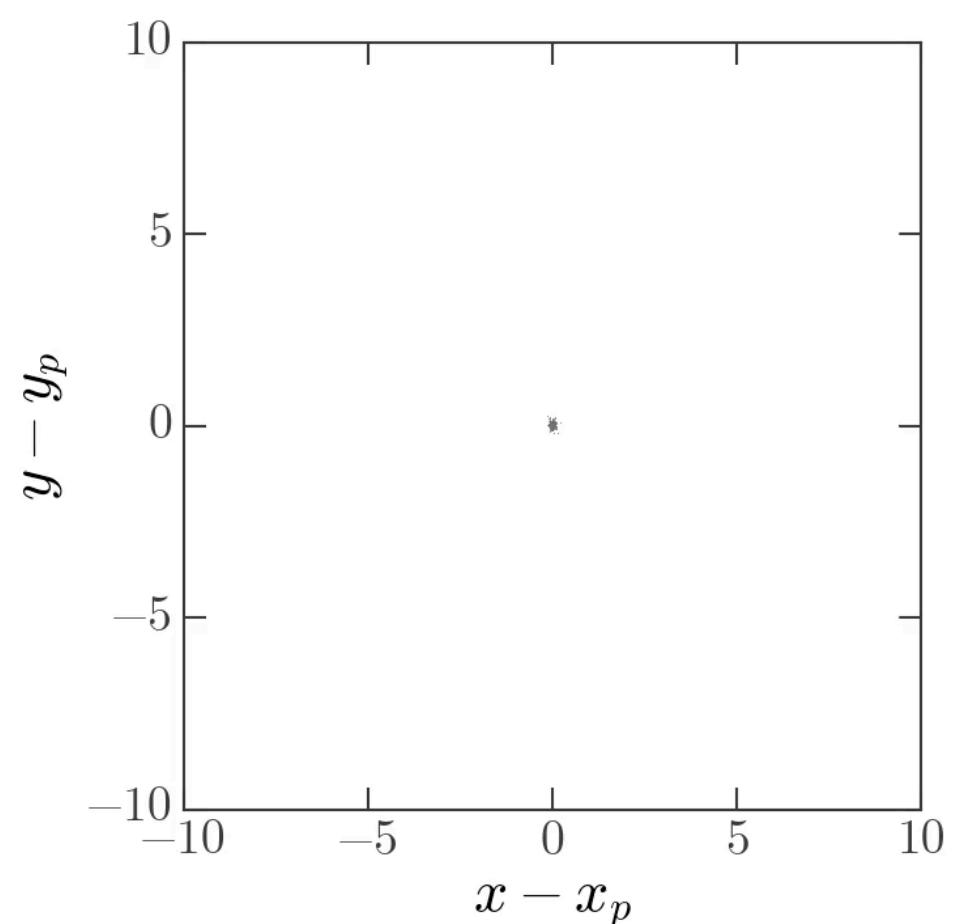
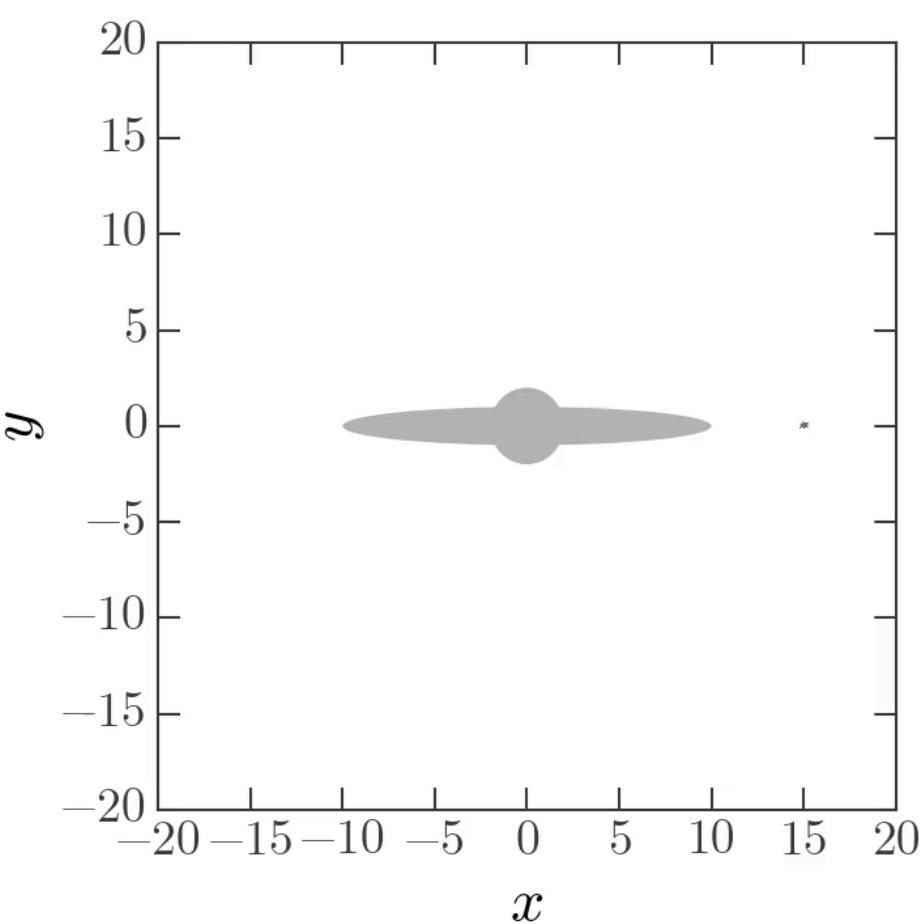
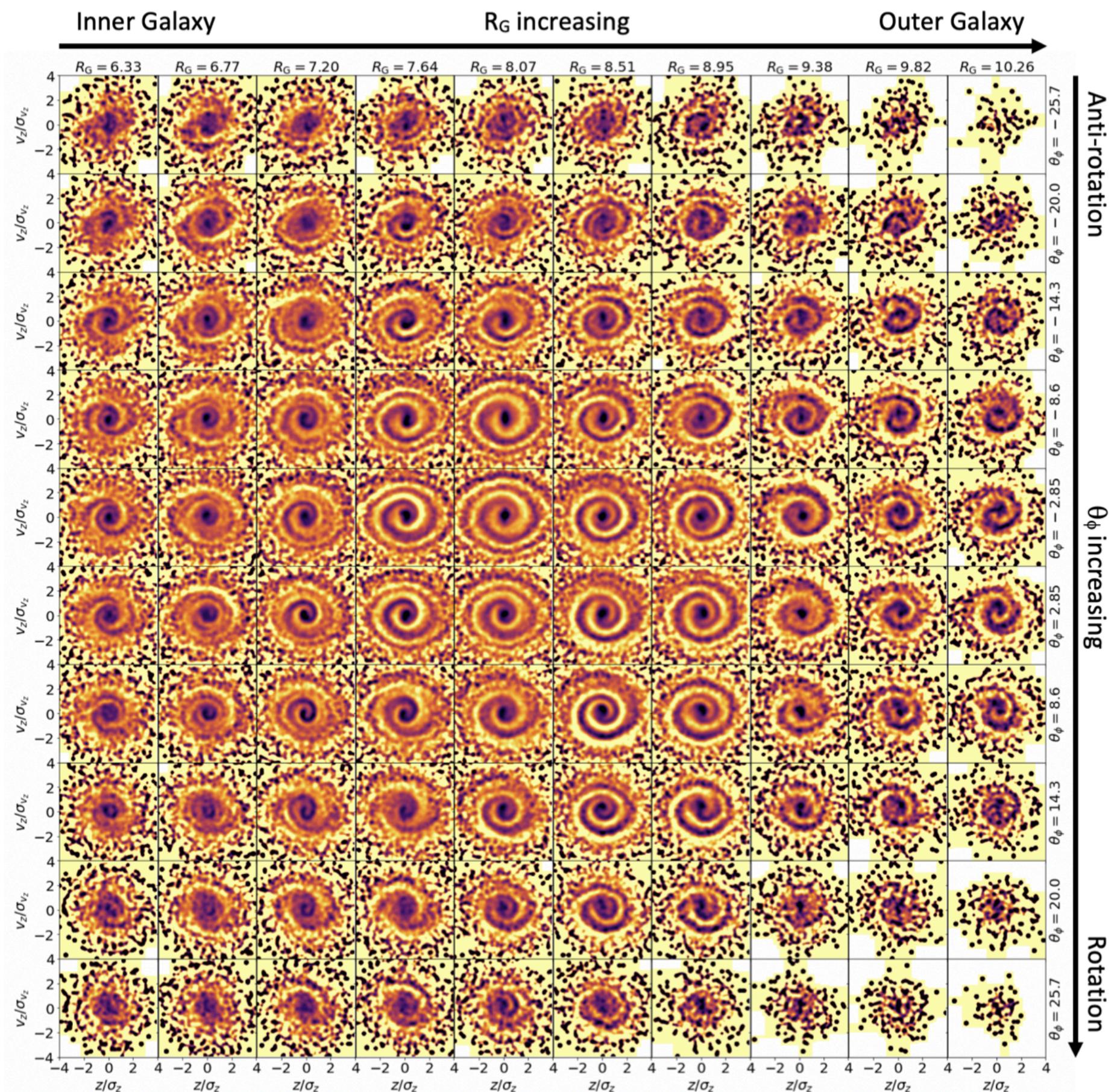
Phase Space Spiral

- Spiral structure changes as function of phase-space (or action-space)
- e.g. see [Hunt+2022](#) with Gaia DR3



Phase Space Spiral(s)

- Could be caused by the bar ([Khoperskov+2019](#))
- Or a merger ([Binney & Schönrich 2018](#))
- Or a few mergers... ([Hunt+2022](#))
- If you like this stuff, check out
[Adrian Price-Whelan's](#)
AAS 237 page & work!



6-D Takeaways

- Complicated Elegant spaces or projections of 6-D position-velocity to view dynamics and orbital motion in
 - Buy donuts for dynamicists!
- Compelling for picking out substructure and understanding its origin
- Several spaces are highly model dependent (i.e. shape gravitational potential)
- **Once again: the MWY looks like a mess of mergers!**