ASTR 511

Galactic Astronomy

Lecture 10

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?

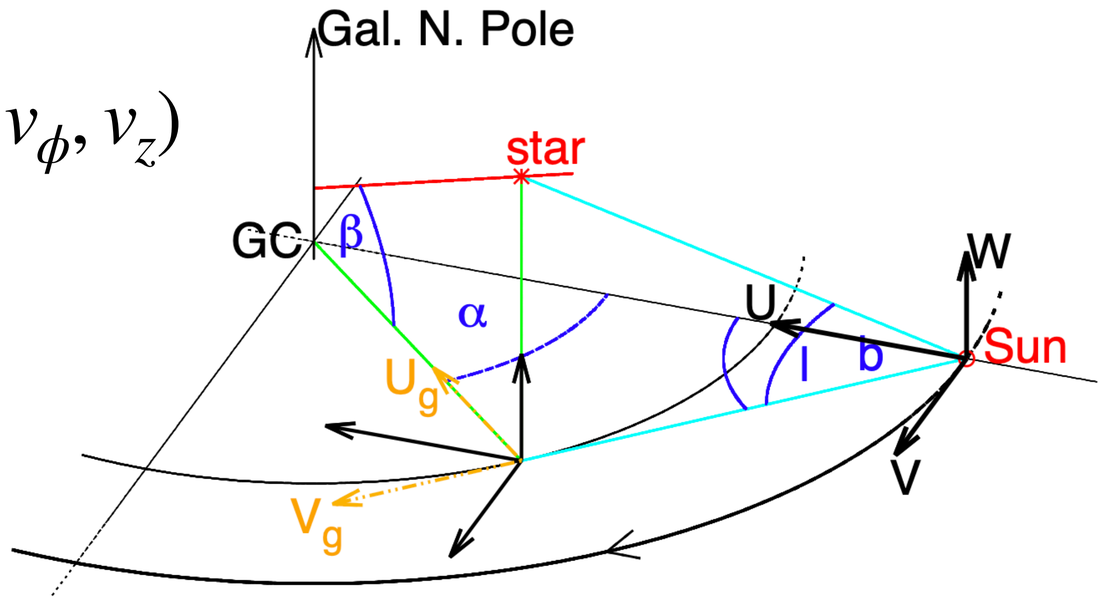
Questions about Homework(s)?

- 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!

https://galaxiesbook.org/chapters/A.-Coordinate-systems.html

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…



Ramírez-Preciado+2018

“6-D Phase Space”

- 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

~~"6-D Phase Space"~~

"7-D Phase Space"

Including metallicity!

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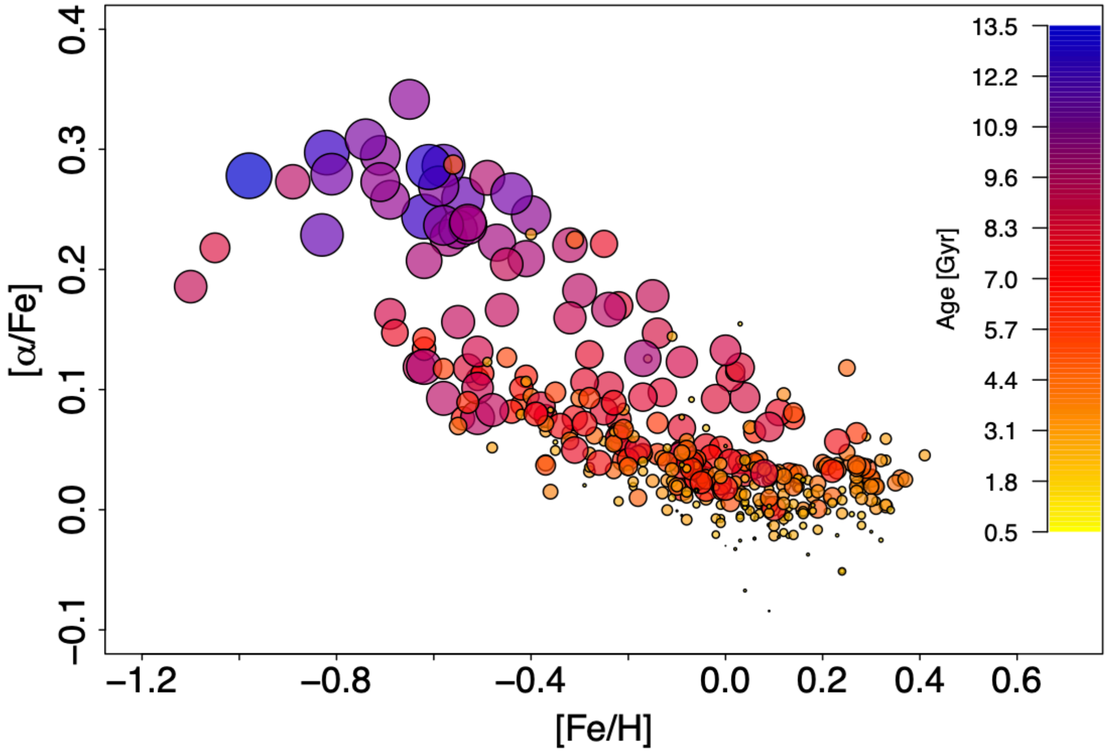
Ages from Velocities

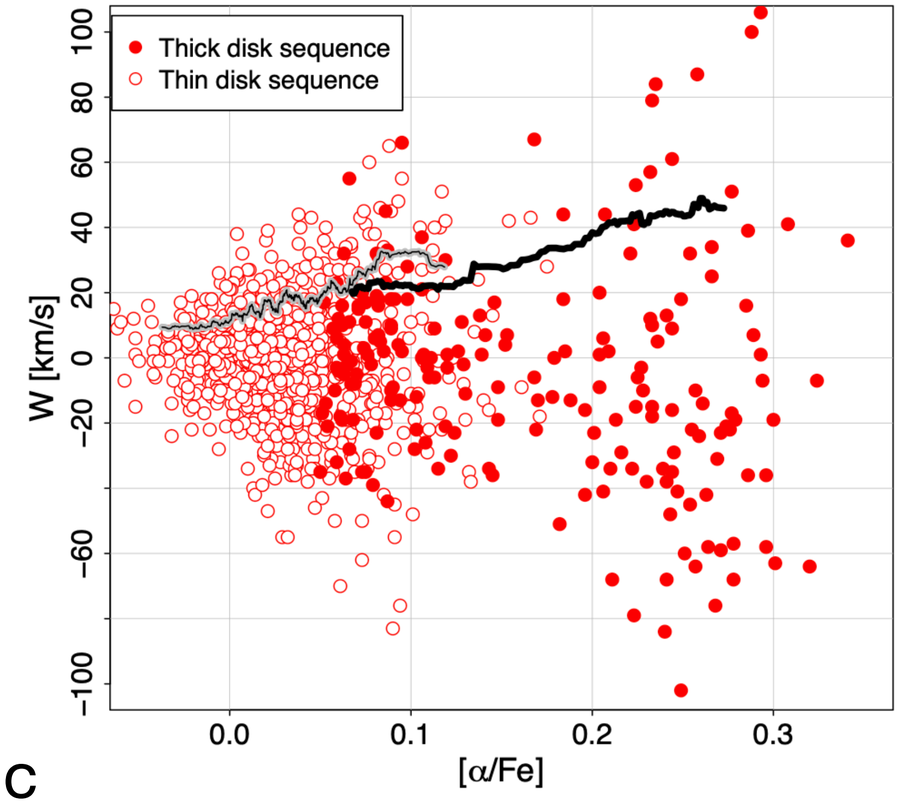
- We mentioned this last week, but let's show a good example!
- Previously: discussed some ways to get ages into a "Wallerstein-Tinsley" diagram like this (e.g. isochrone & chemical model fits)
- Also said scale-height is related to stellar age
- Velocities: stars get knocked around over time! (Stellar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

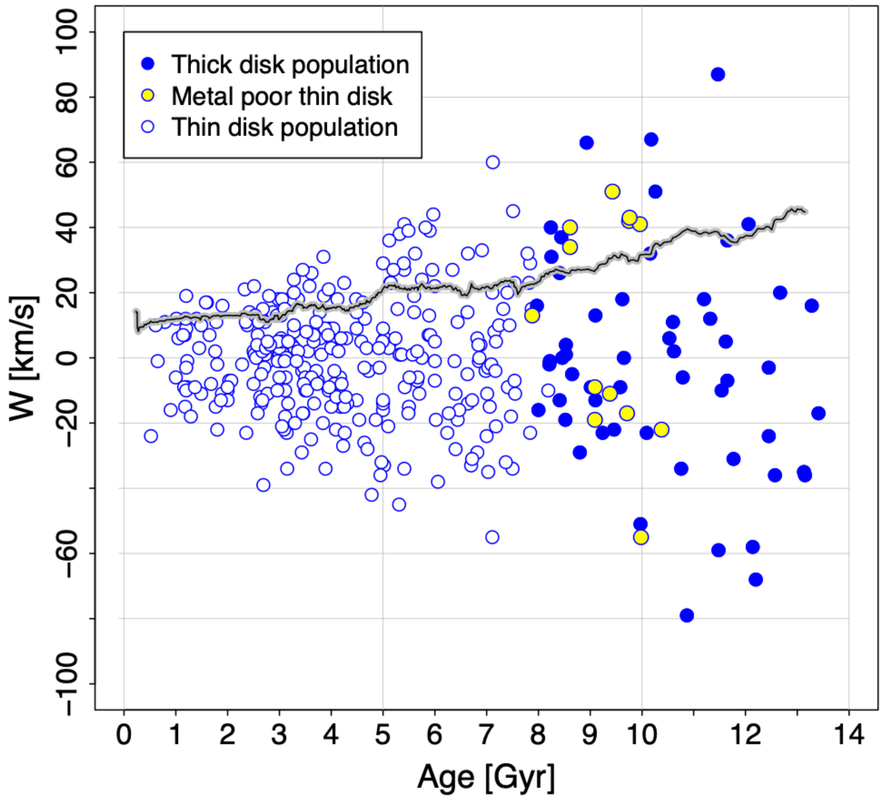


Haywood+2013

Ages from Velocities

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





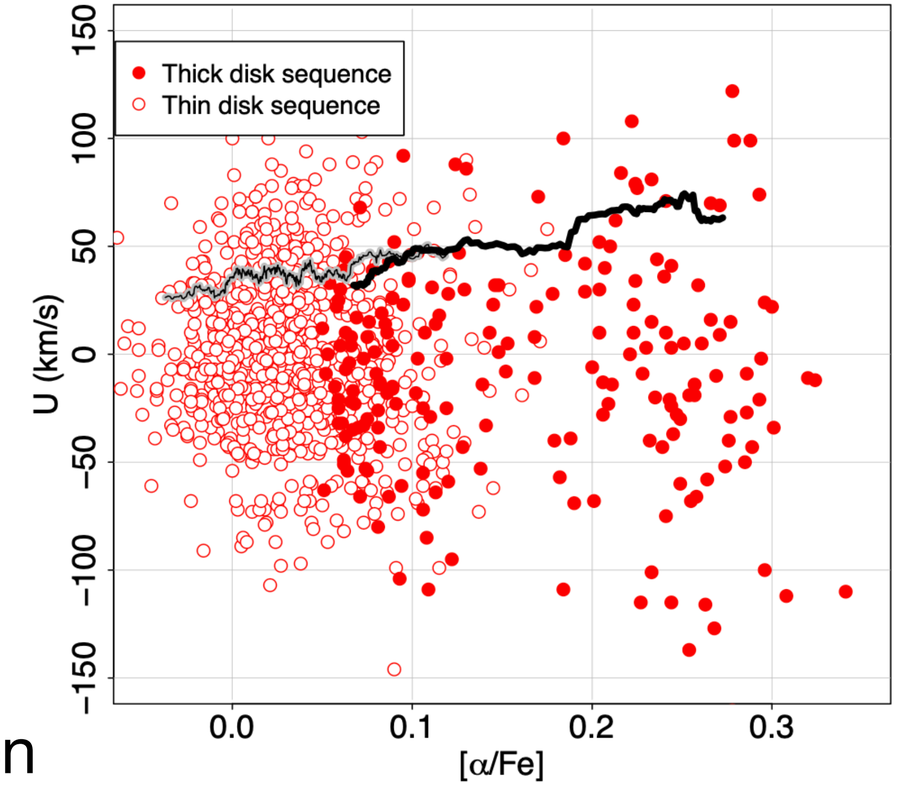
- σ_W is the age metric
- This typically used to infer age for a *population*, though large (outlier) values are clearly suggestive of old ages!

Haywood+2013

Ages from Velocities

- See some of the same trends seen in U (or radial velocity, v_R)

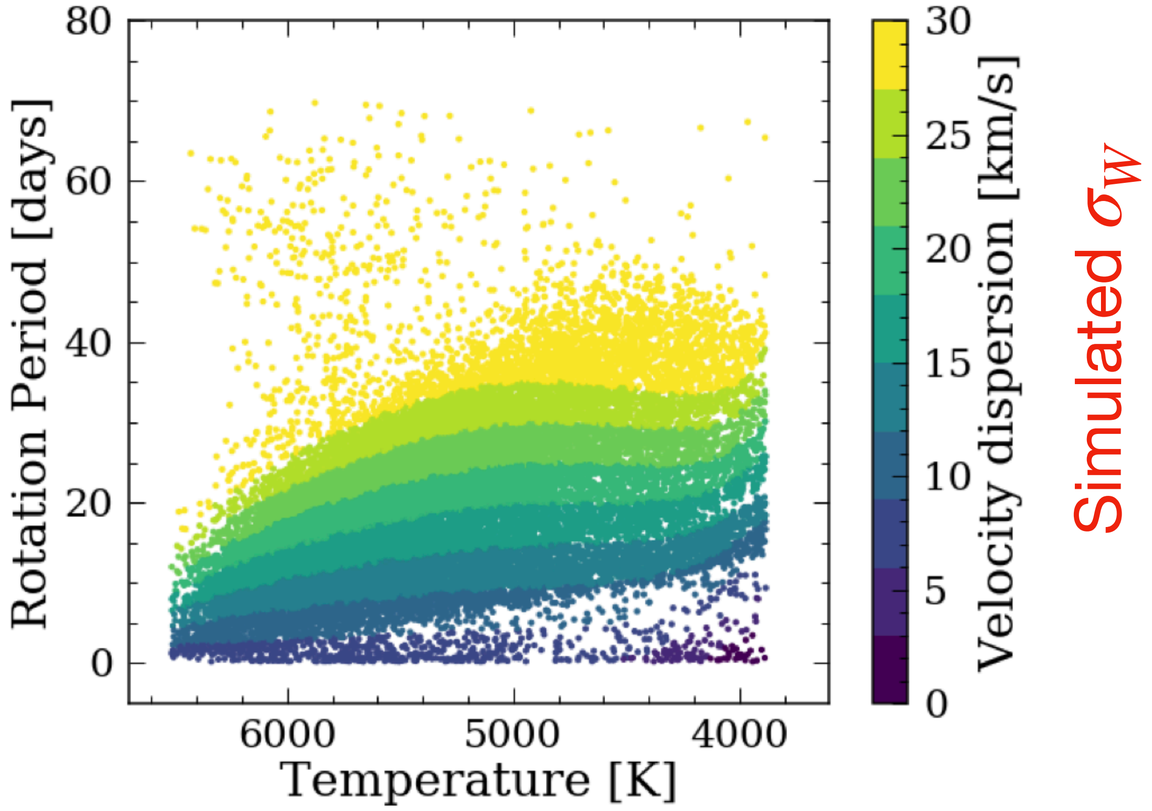
- Vertical signal is *stronger*:
  less radial migration
  more vertical scattering the disk



Haywood+2013

Ages from Velocities

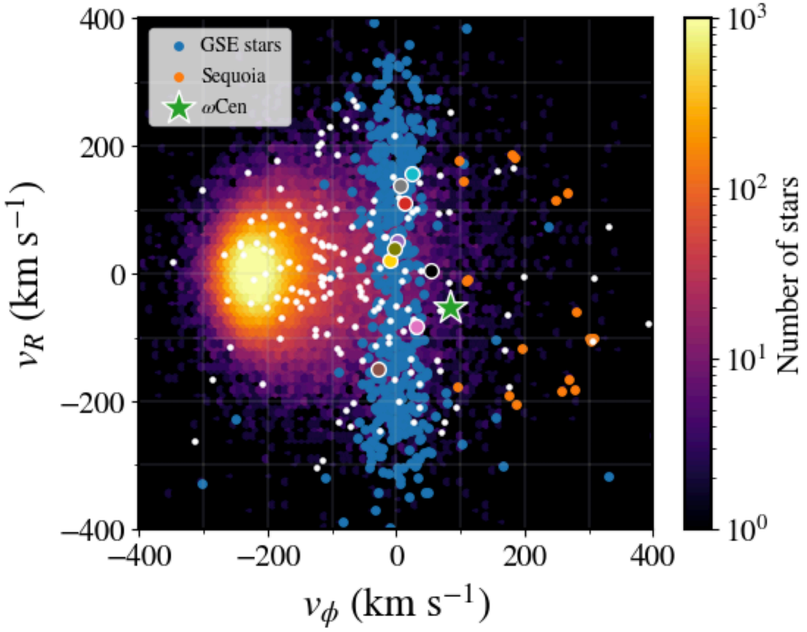
- **Vertical velocity dispersion**: Long history of use, but currently being compared directly to many other age metrics for cross-calibration



Lu+2021

Gaia-Enceladus/Sausage Velocities

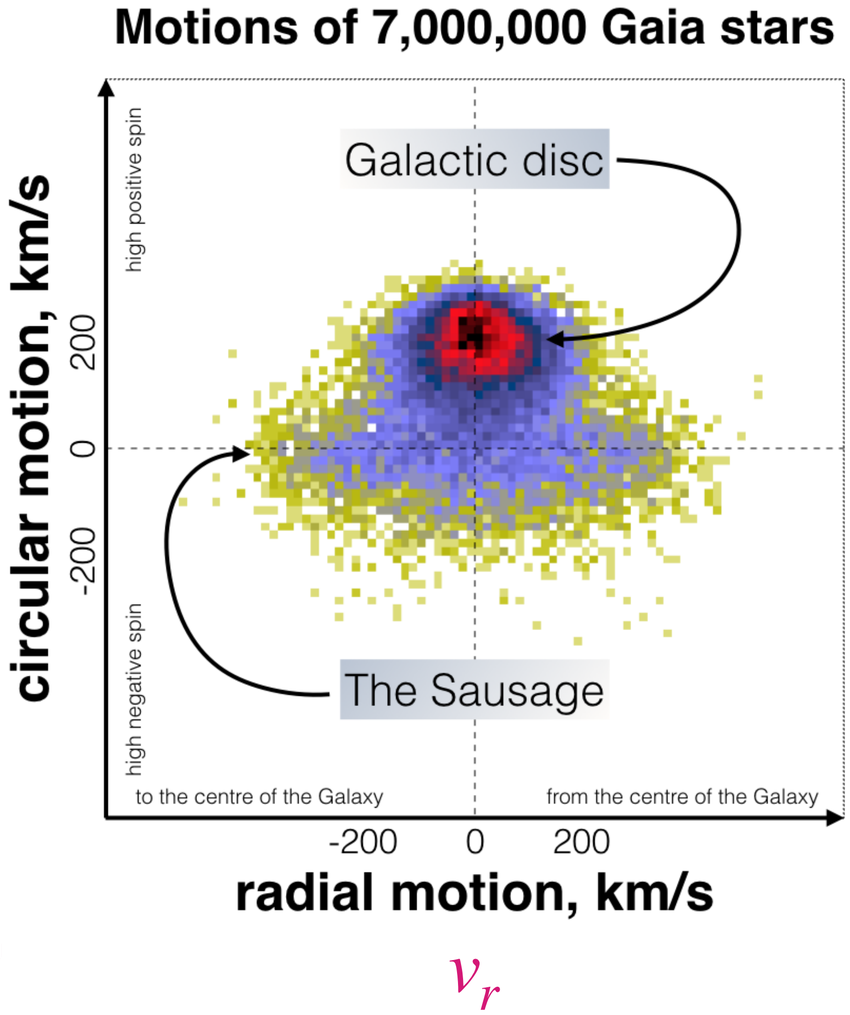
- As published in e.g. Belokurov+2018 uses galactic spherical velocities
  - NOTE: they use v_θ for rotation, disagrees with coords written out by e.g. Bovy Galaxies book: (r,ϕ,θ)



Limberg+2022

v_θ

- v_ϕ sign flipped
- **Define your coords, esp. the azimuthal direction!**

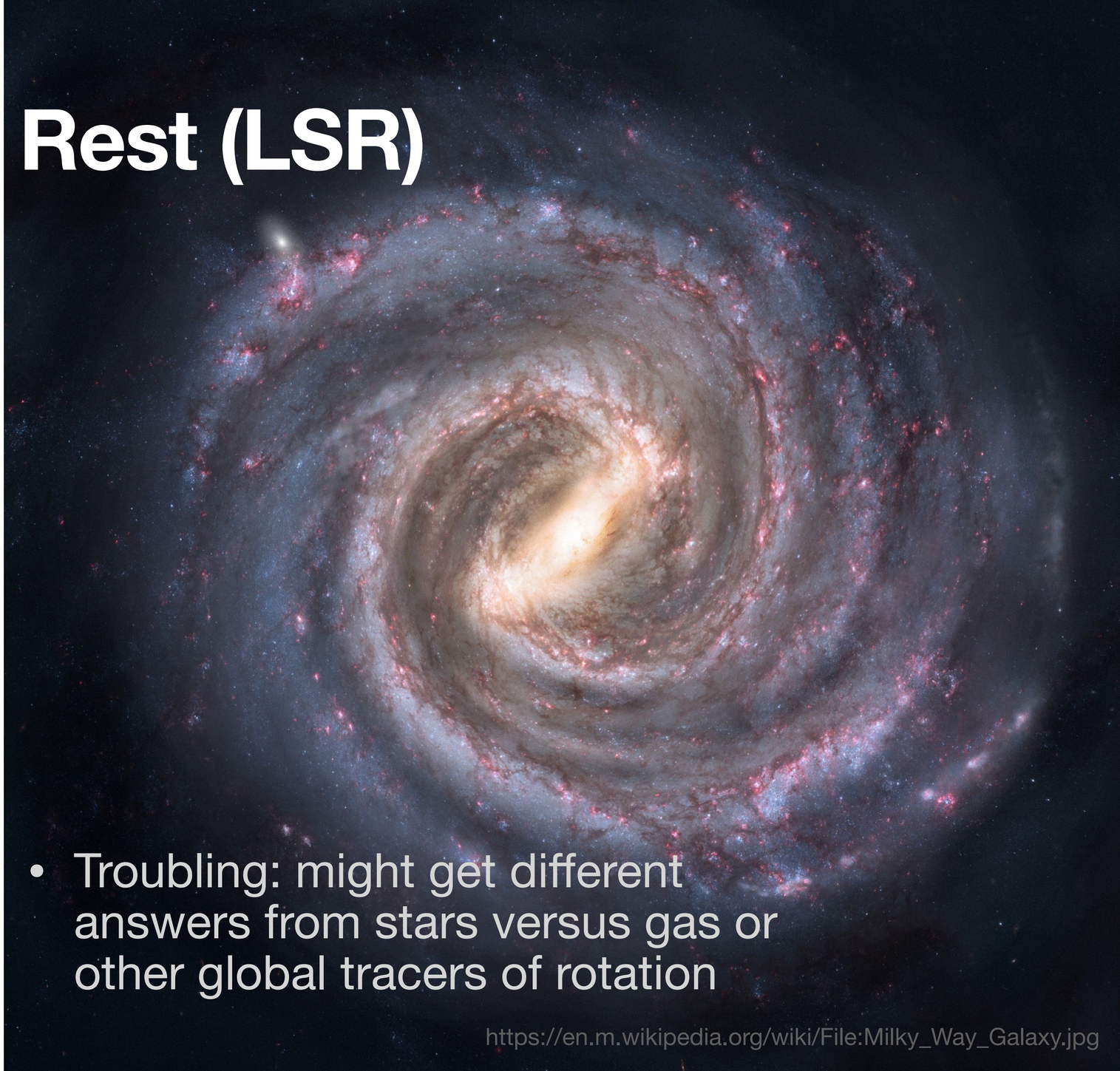


v_r

https://people.ast.cam.ac.uk/~vasily/gaia_sausage/info.html

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

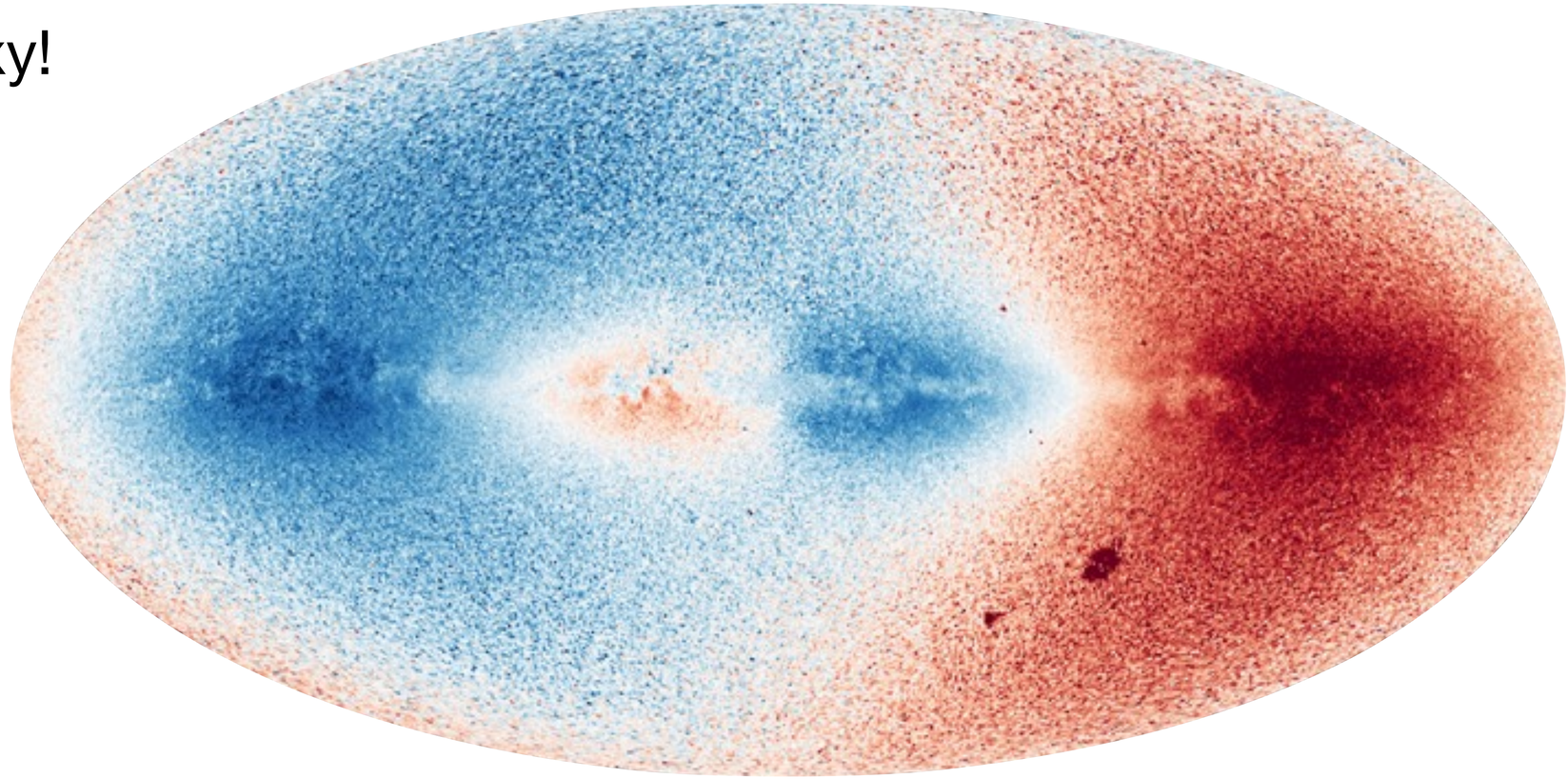
https://en.m.wikipedia.org/wiki/File:Milky_Way_Galaxy.jpg

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!

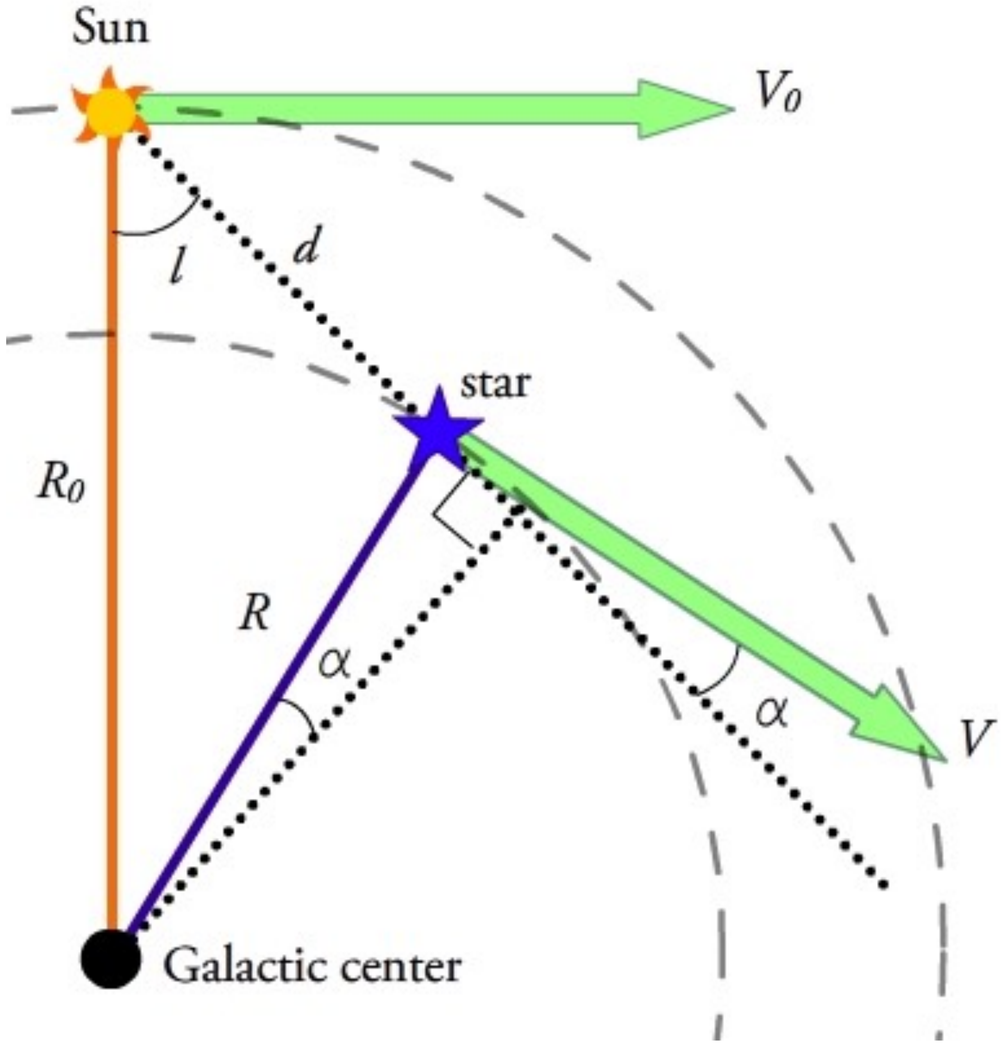
- IAU standard values: A=15 km/s/kpc, B=-10 km/s/kpc

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!

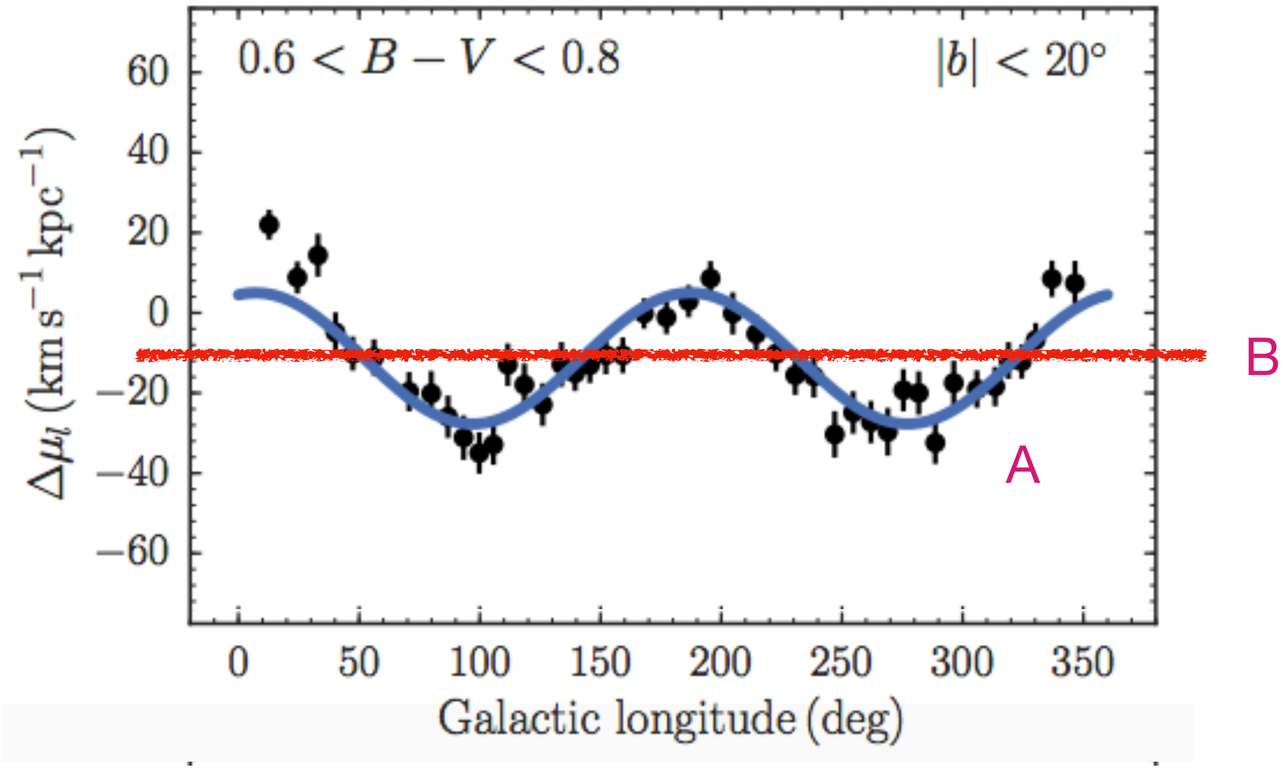


https://commons.wikimedia.org/wiki/File:Oort_constants_derivation_diagram.jpg

Oort Constants

- IAU standard values:
  A=15 km/s/kpc, B=-10 km/s/kpc
- Gaia DR1: A=15.3, B=-11.9

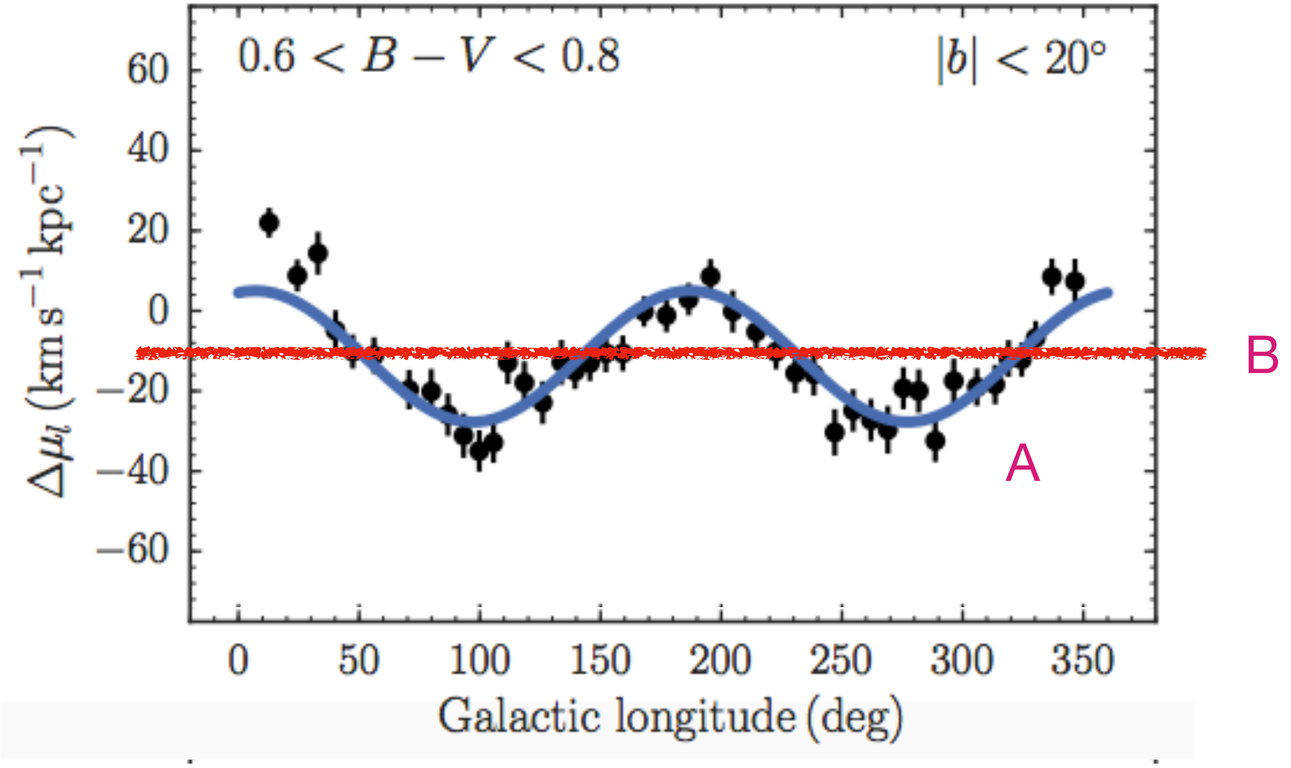
$$V_{\mathrm{obs,\,r}} = Ad\sin(2l)$$
$$V_{\mathrm{obs,\,t}} = Ad\cos(2l) + Bd$$



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”~~

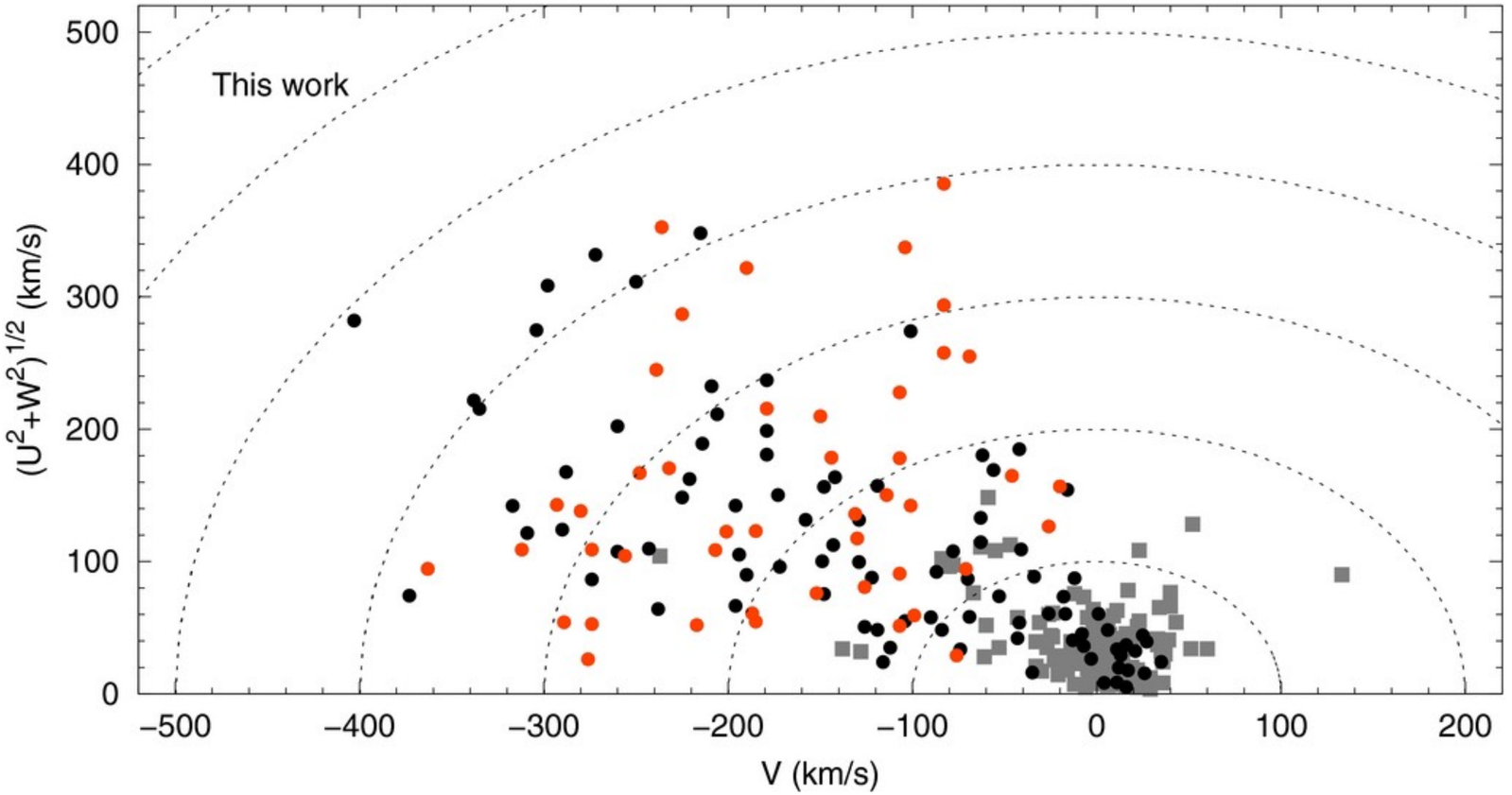
“7-D Phase Space”

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

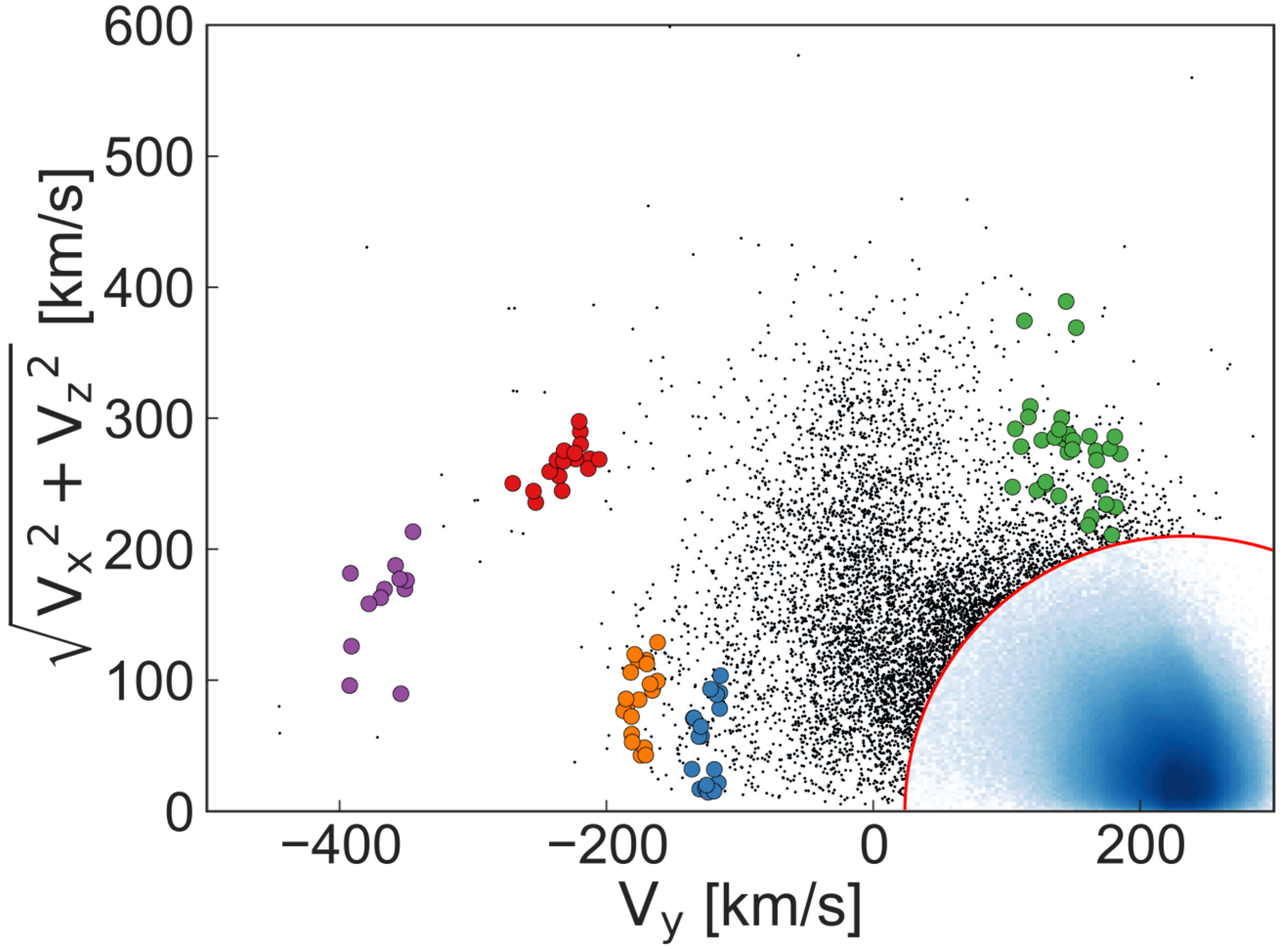
Toomre Diagram

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



Toomre Diagram

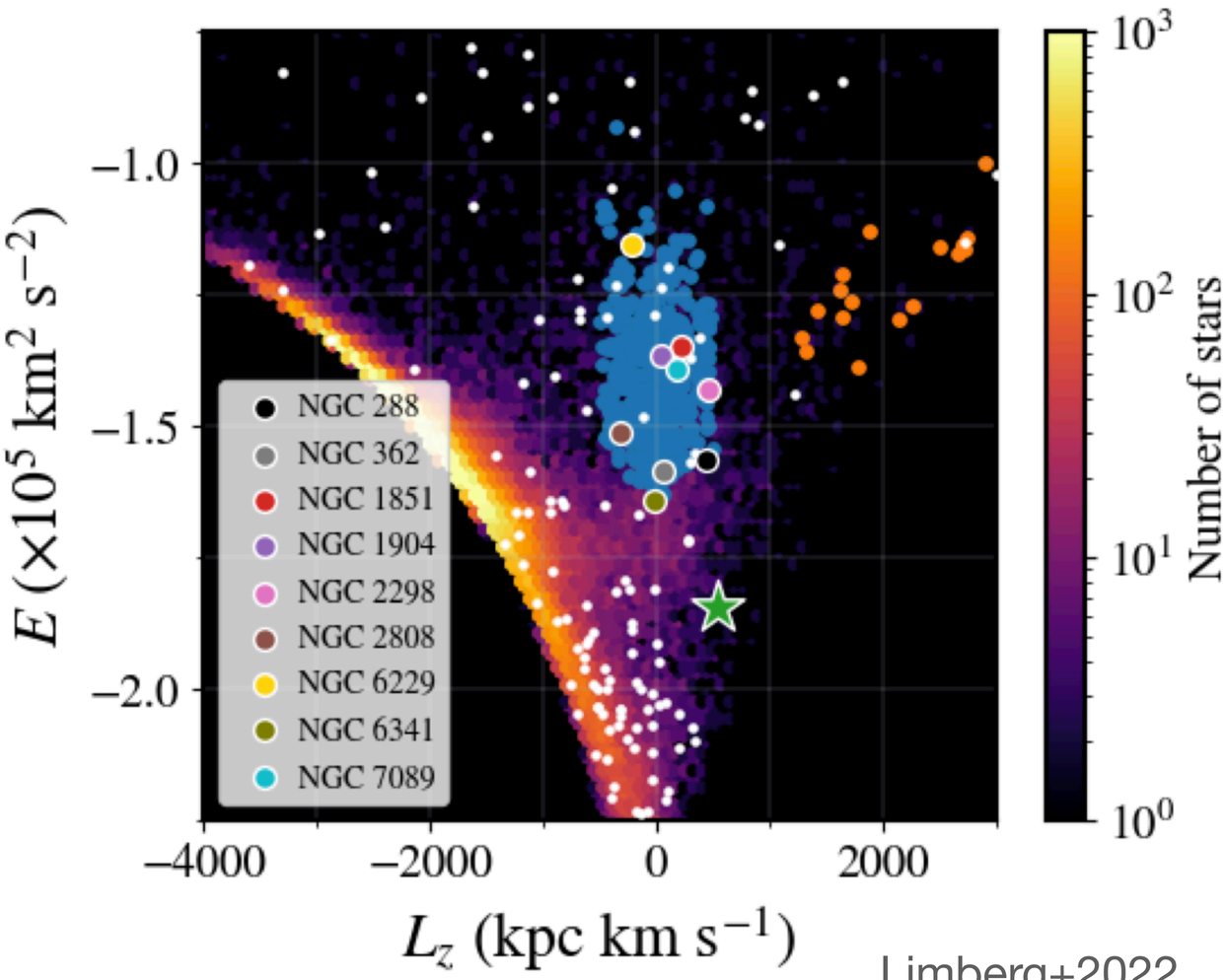
- Can also see features in galactocentric velocities!
- This diagram explores an "integral of motion" i.e. reducing dimensionality of 6-D phase space
- Here you can pick out disk vs. groups in the halo



Koppleman+2018

Lindblad Diagram

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

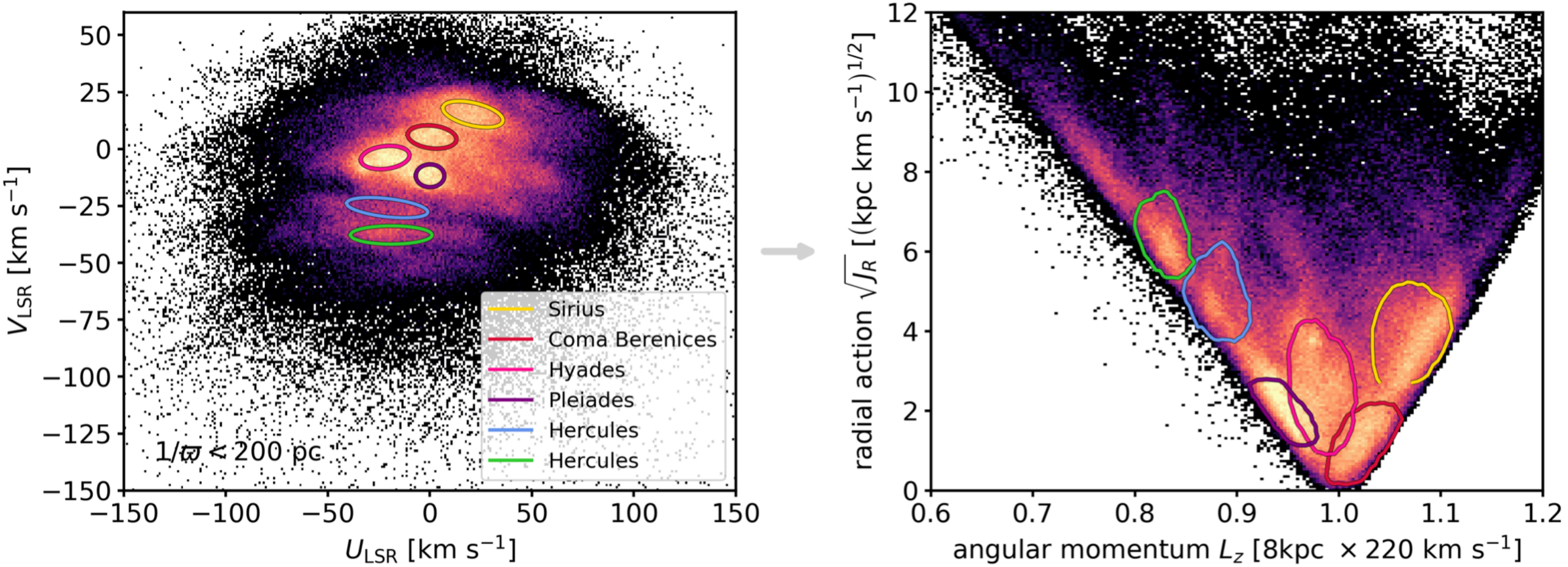


Limberg+2022

Action Angles & Coordinates

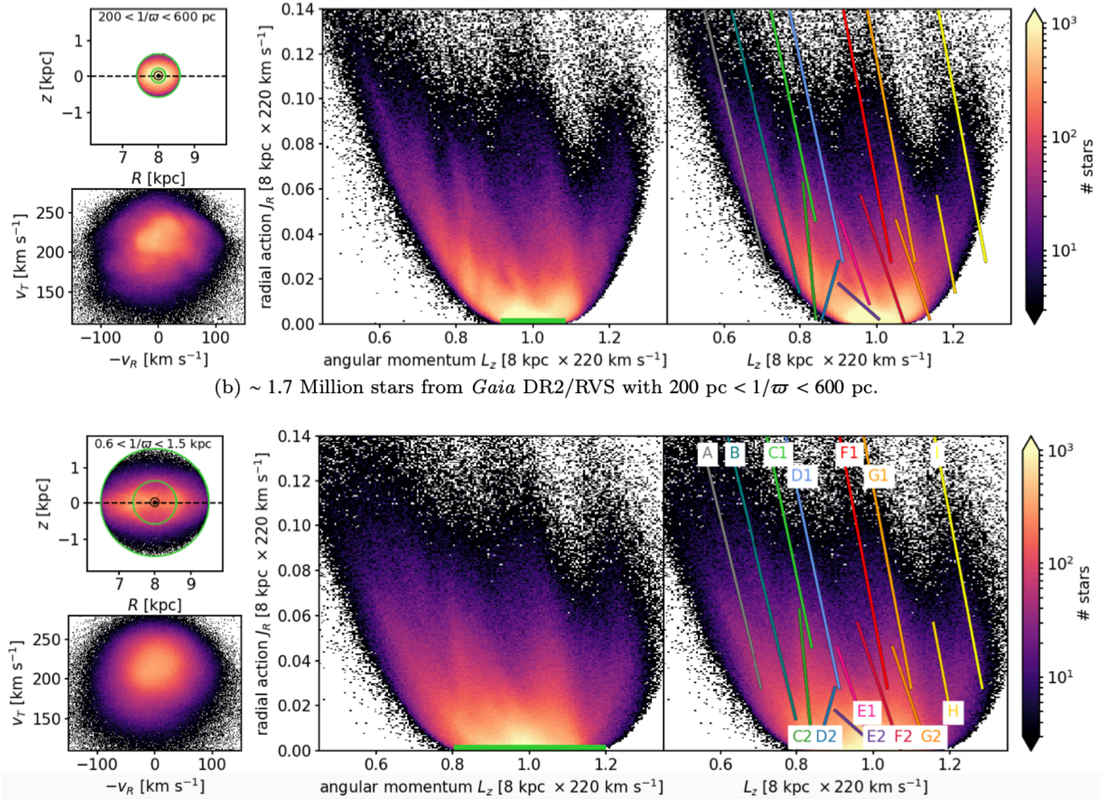
- Foundation laid out by Binney & Tremaine 2008 (famous textbook)
  - Need a proper dynamics course… to fully grok this
    (i.e. I'm about to do a *bad* job explaining this today!)
- A review by McMillan & Binney (2008)
- A practical view from Trick+2019 in Gaia DR2
  - Compute momentum vectors, e.g.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

Action Angles & Coordinates

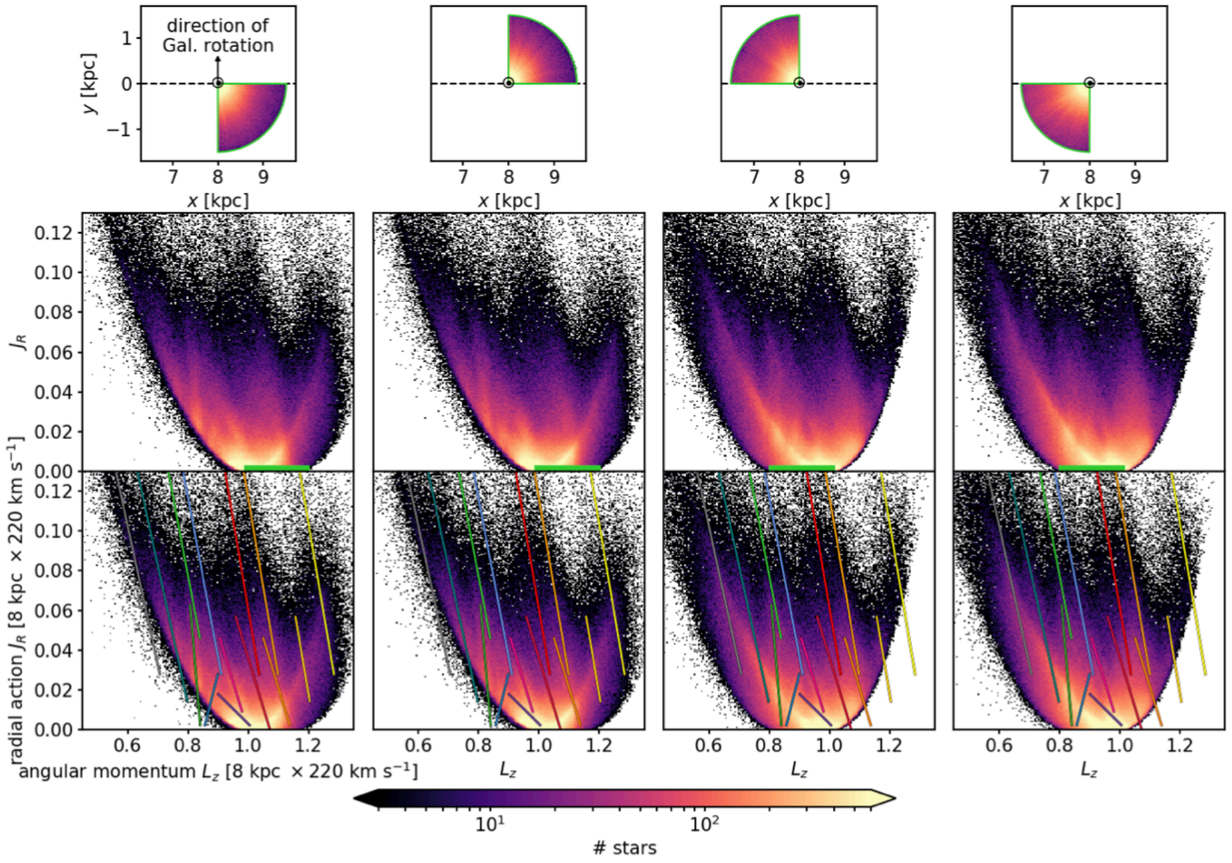


- Trick+2019

Action Angles & Coordinates

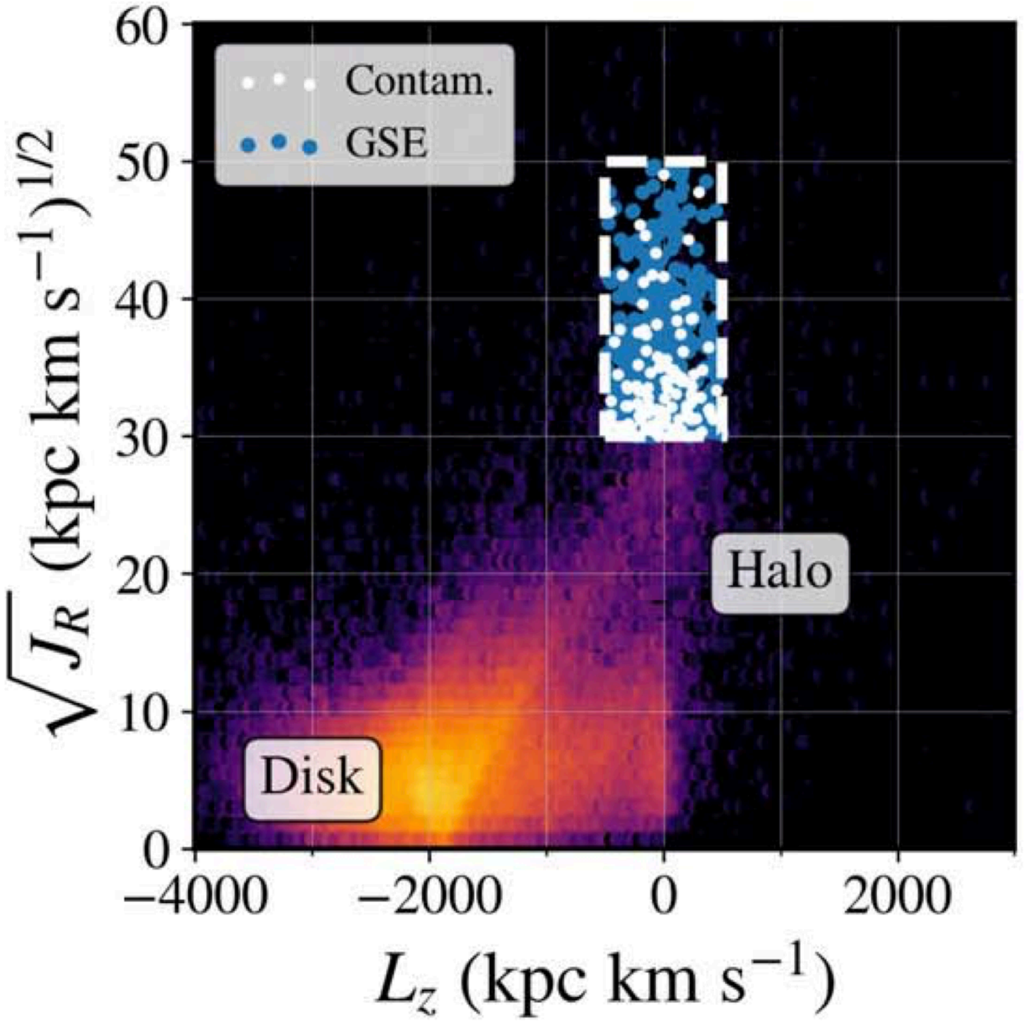


(b) ~ 1.7 Million stars from *Gaia* DR2/RVS with 200 pc < $1/\varpi$ < 600 pc.

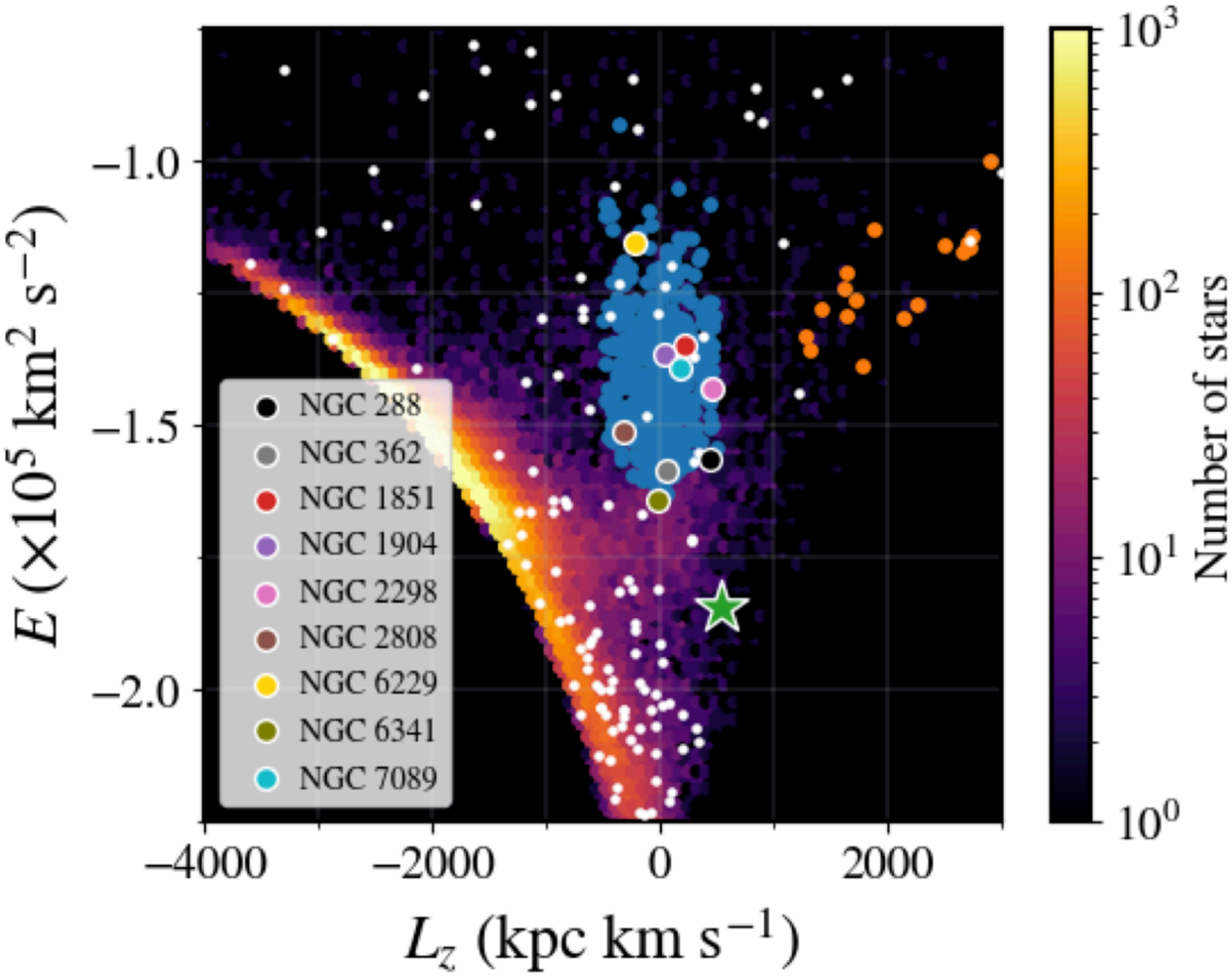


- [Trick+2019]

Action Angles & Coordinates



versus



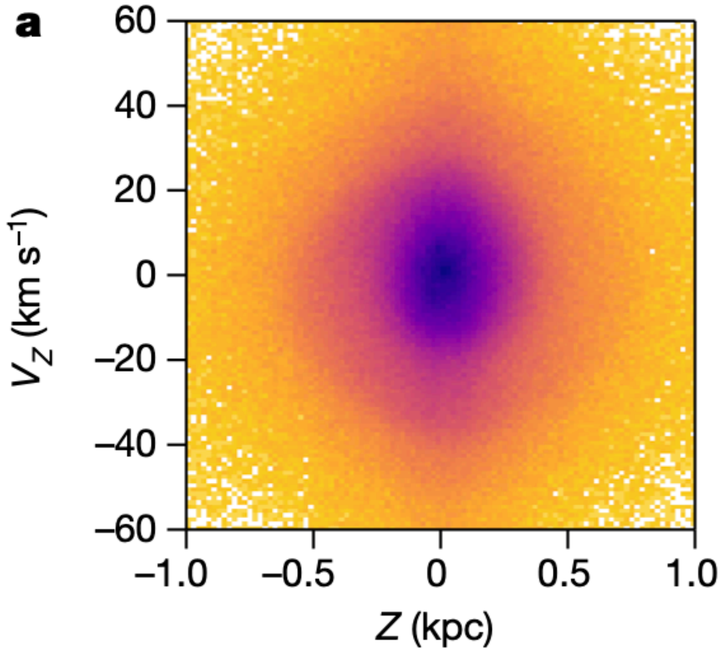
Limberg+2022

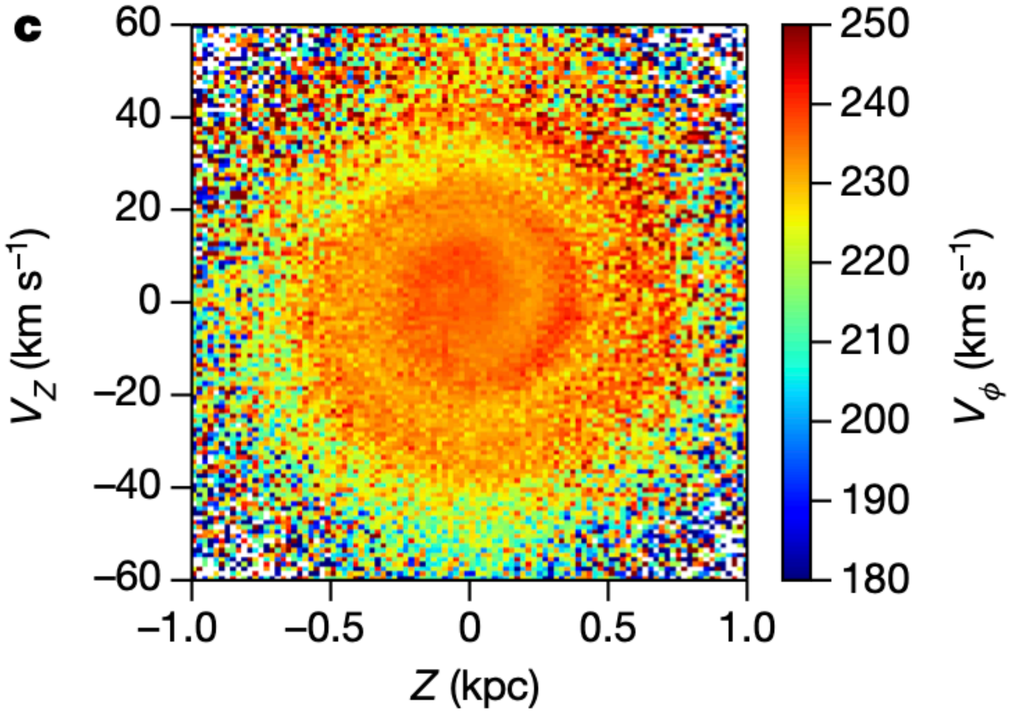
Phase Space Spiral

- An intriguing feature discovered in Gaia DR2 (Antoja+2018)
  Mentioning this also because it's recent and neat!

- Tracing the (Z, v_Z) plane for nearby stars

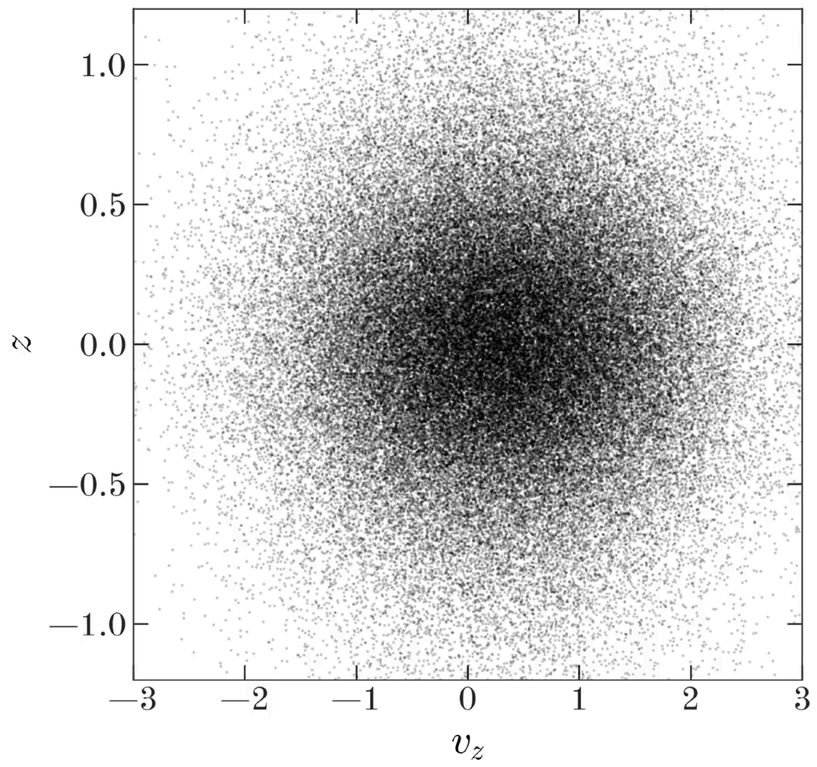
- Disk is "perturbed"

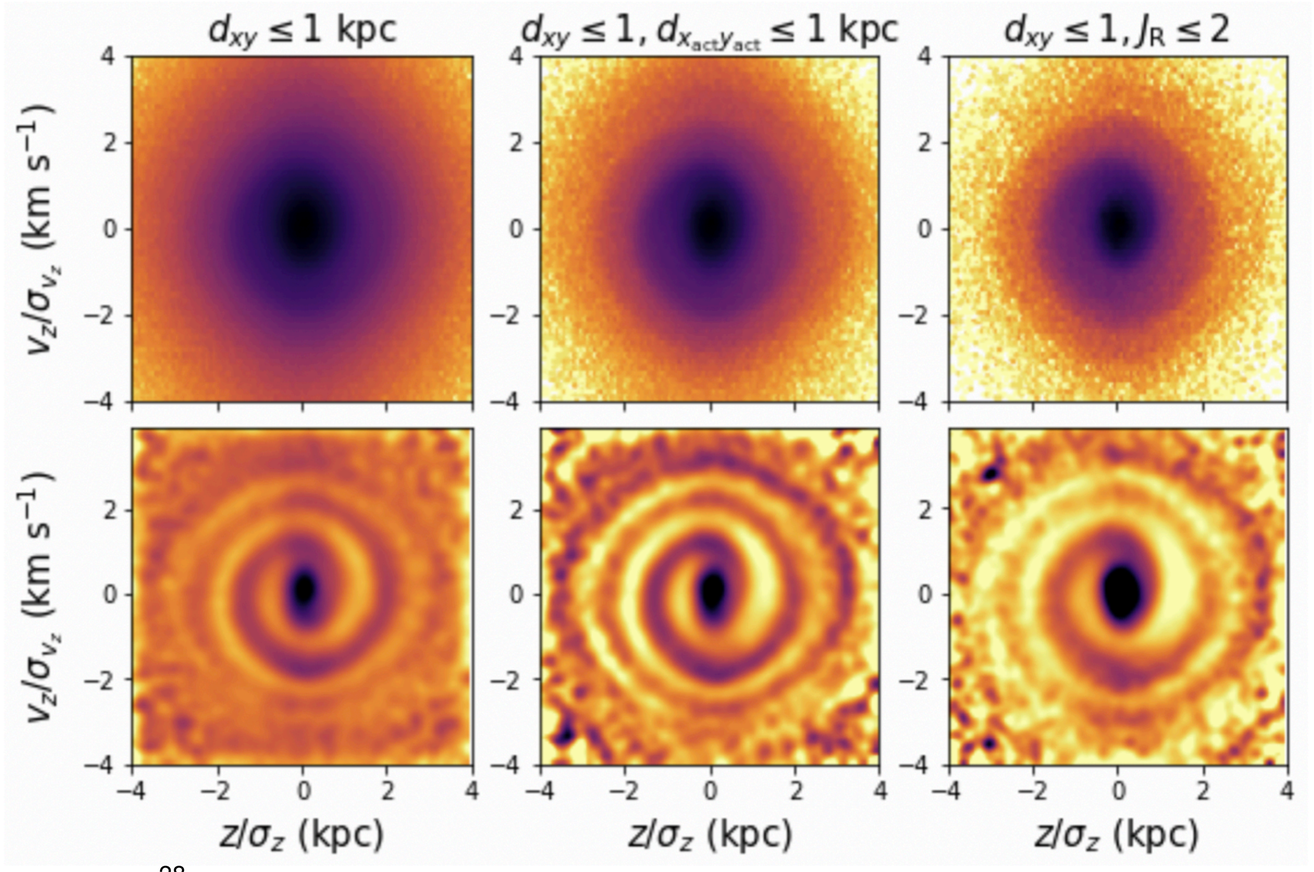




Phase Space Spiral

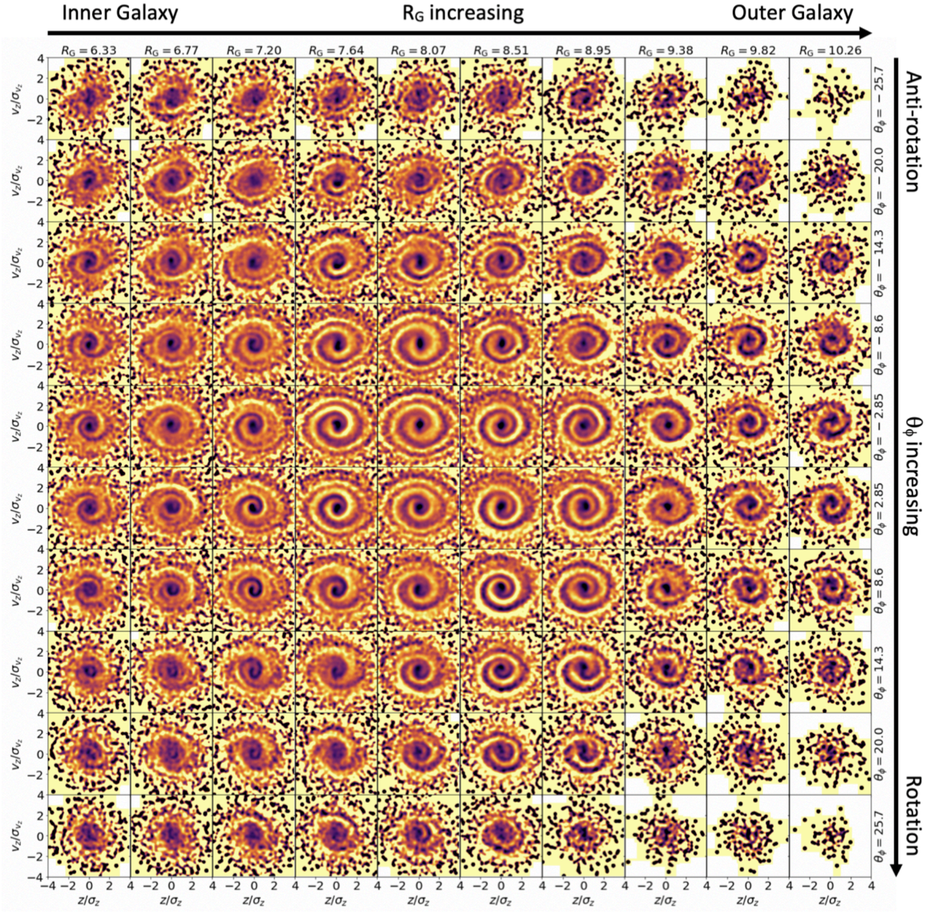
- Spiral structure changes as function of phase-space (or action-space)
- e.g. see Hunt+2022 with Gaia DR3



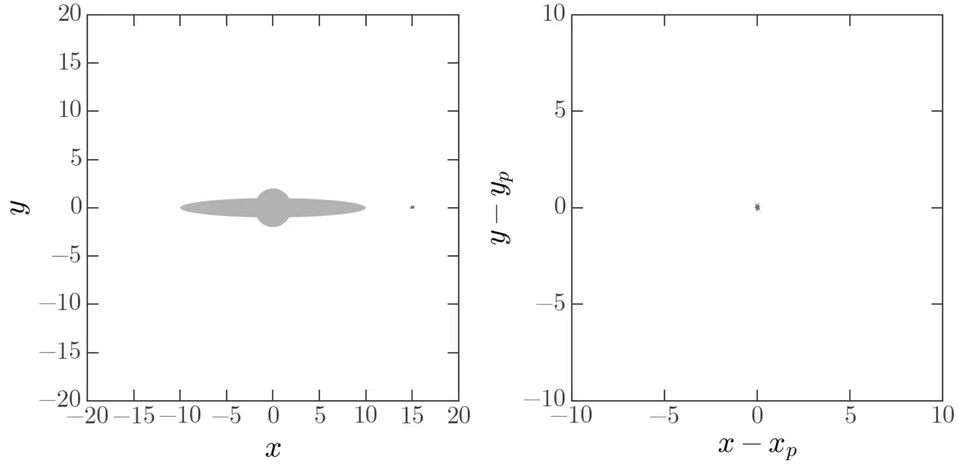


Phase Space Spiral(s)

- 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!**