Dissecting the Phase Space Snail

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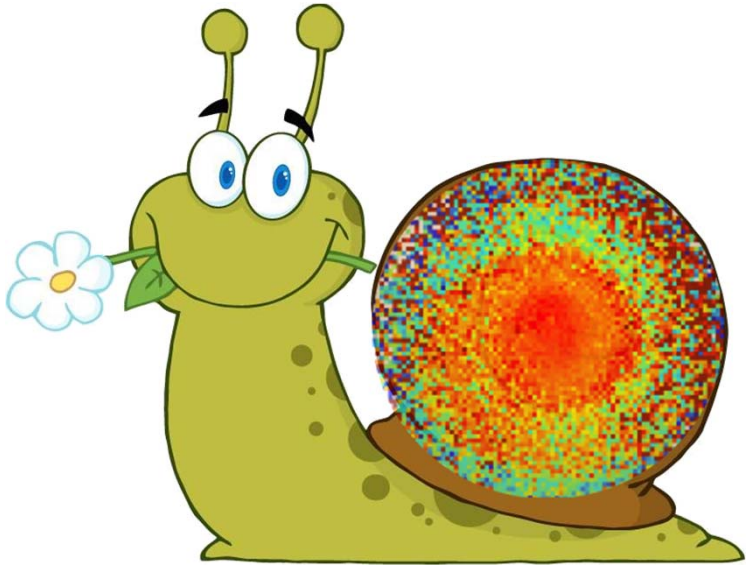
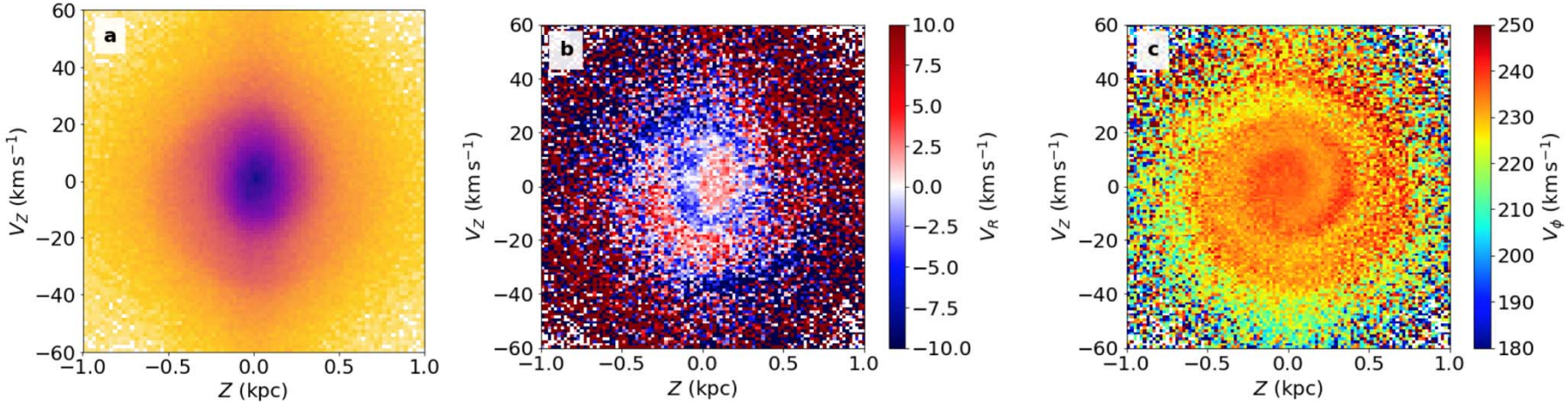


Li & Shen (2019), submitted, coming soon on Astro-ph

Vertical phase-mixing

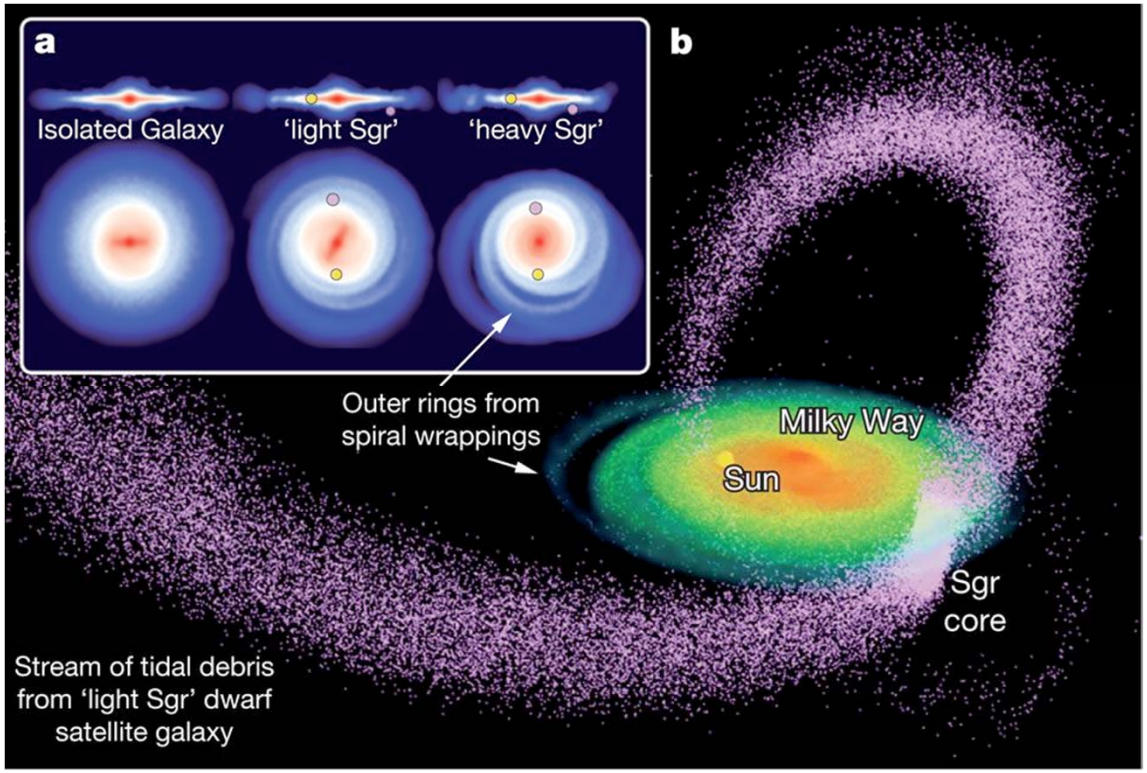
- A snail shell/spiral feature in the (z-V_Z) phase space (PS)
  - phase mixing of stars
- The V_ϕ color-coded PS shows more prominent snail shell (up to V_Z ~ 40km/s)
  - suggesting tight correlation between the in-plane and vertical motions?



Antoja et al. (2018) Nature

Origins of vertical phase-mixing

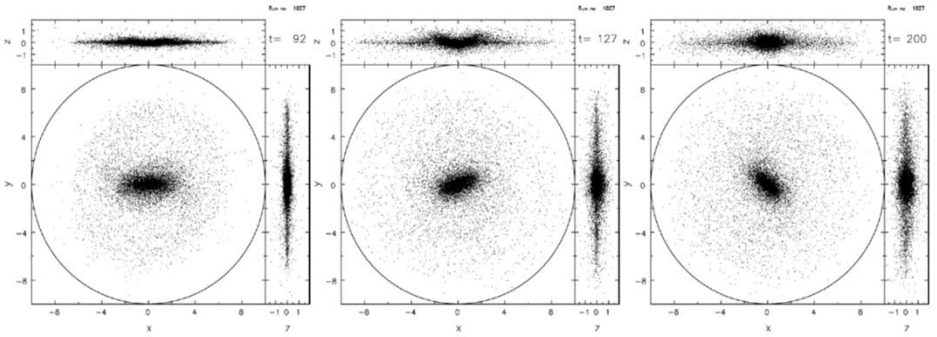
- **Scenario I:** Induced by merging Sgr dwarf?
  - Antoja+18, Binney & Schonrich 18; Tian et al. 2018; Bland-hawthorn+19; Darling & Widrow 2019; Laporte+2019
  - Vertical Perturbation event on the Milky Way disk at ~300 – 900 Myr ago

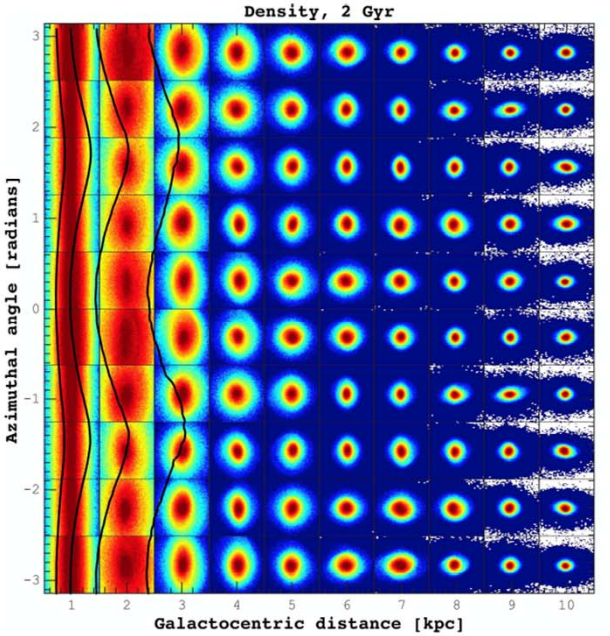


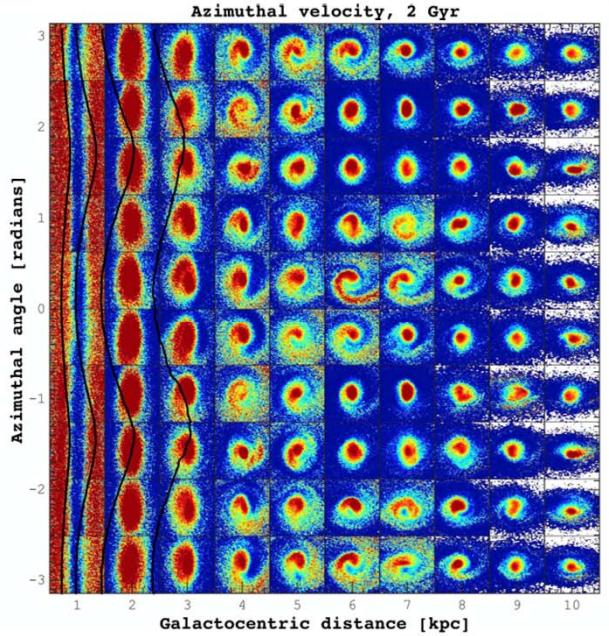
Purcell et al. (2011)

Origins of vertical phase-mixing

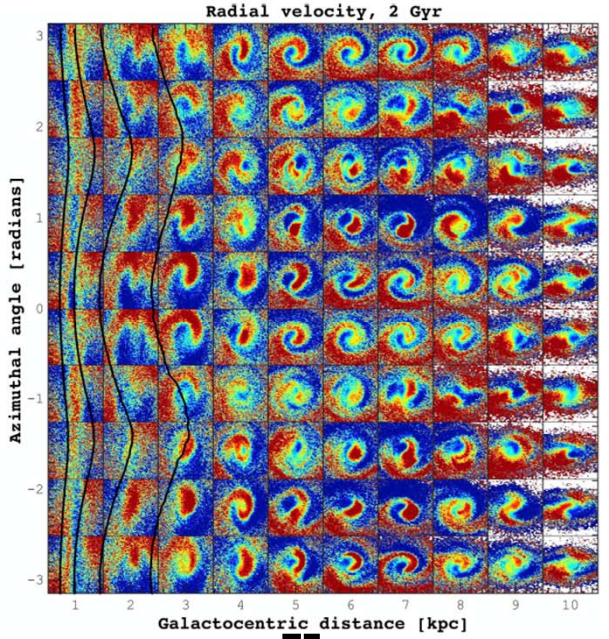
- **Scenario II**: Induced by a bar buckling event
  - Can persist for up to 4 Gyrs
  - V_R PS is most clear







V_ϕ



V_R

Khoperskov et al. (2018)

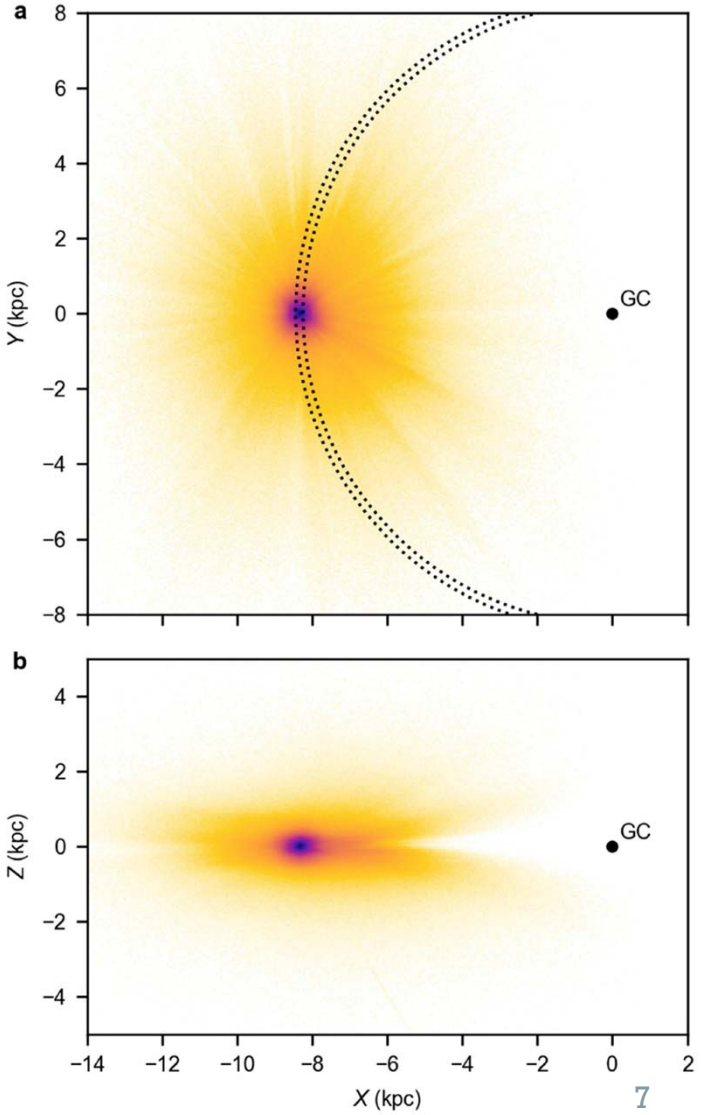
Motivations

- What is the connection between the in-plane streams and the vertical mixing?
- Origin of the snail shell: internal vs. external
- Coupling between the in-plane and vertical motions
- Vertical perturbation event time scale

Sample selection

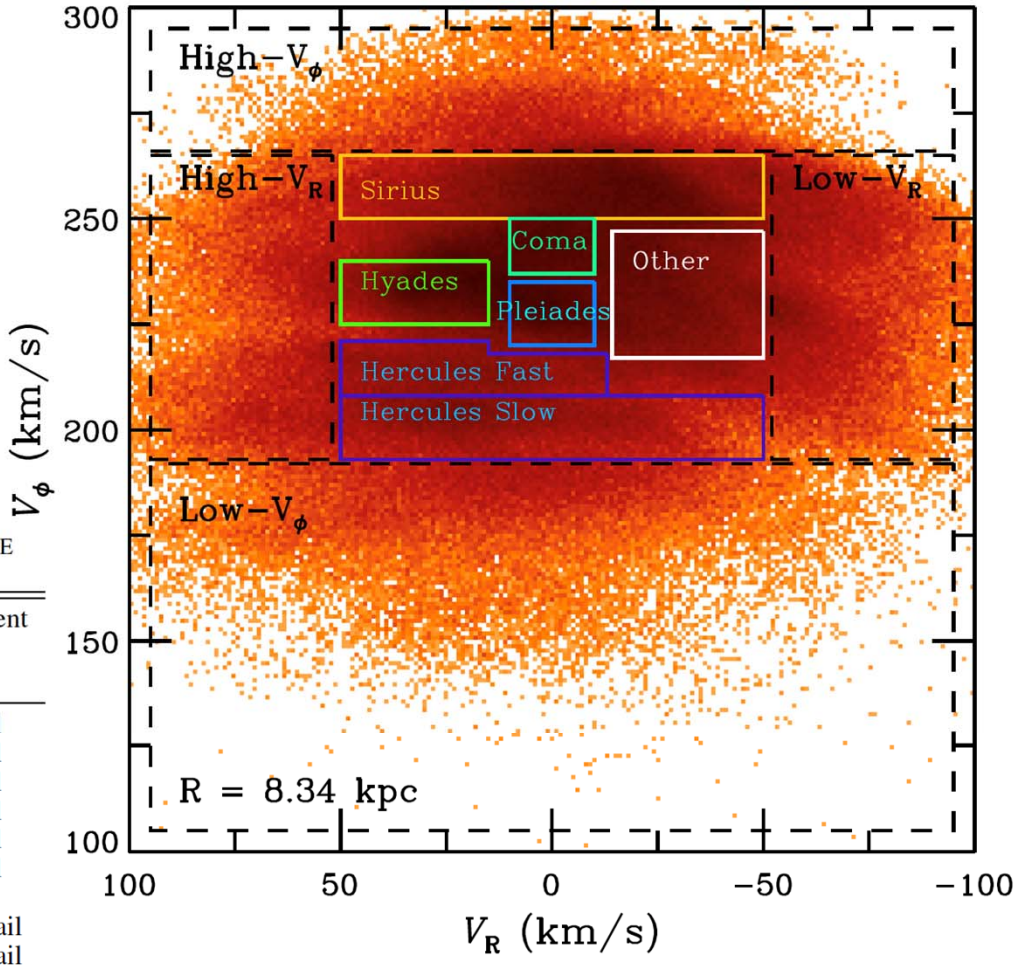
Antoja et al. (2018)

- Sample selection
  - Similar to Antoja+18
  - stars with parallax with relative uncertainties < 20%
  - 6D phase space coordinates
  - 6.3 million stars, 4 < R < 13 kpc
  - Snd.: 8.34 ± 0.1kpc
  - |z|<1.0 kpc
  - → 0.93m stars



Kinematic streams

- At R_0, we select 6 streams (Sirius, Hyades, Coma, Pleiades, Hercules Fast & Slow) and "Other", Low/High-V_ϕ, Low/High-V_R regions



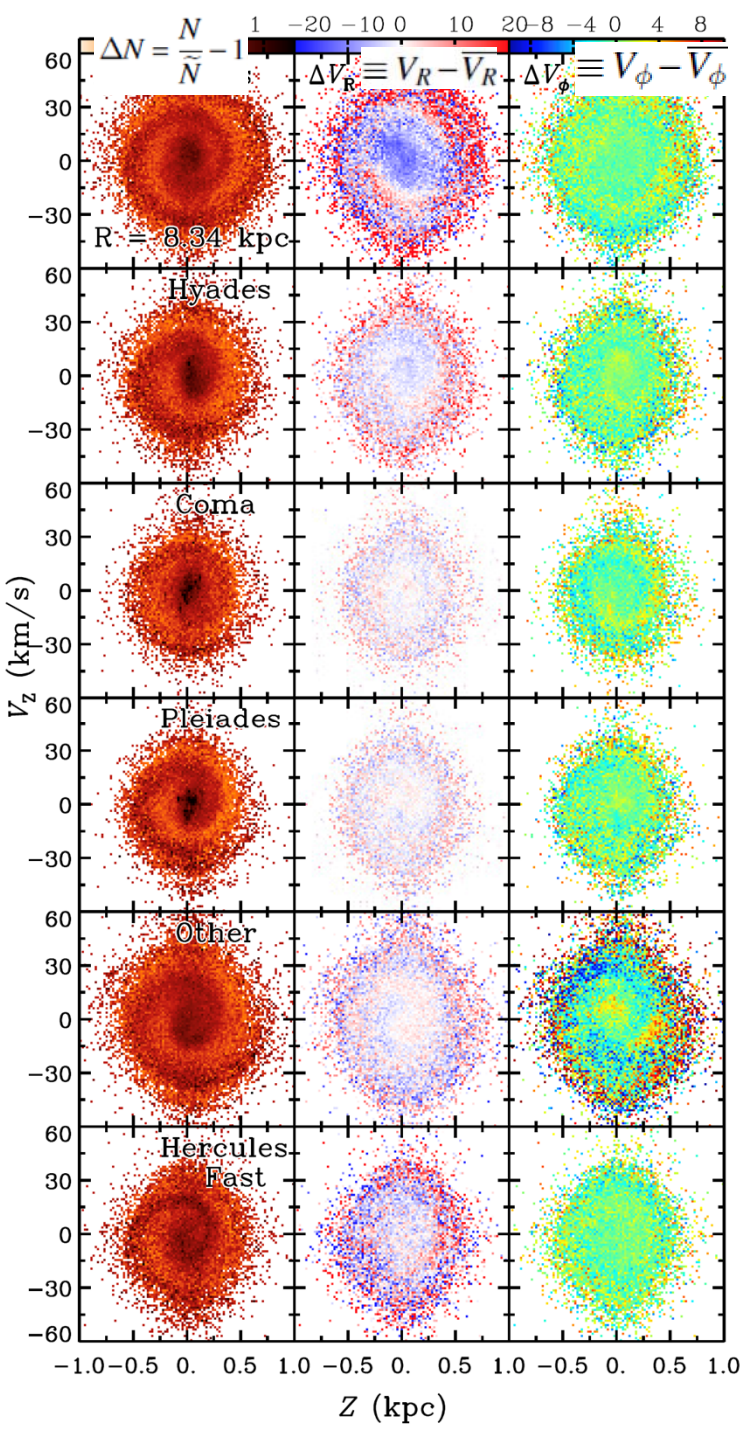
PROPERTIES OF THE STREAMS/REGIONS IN THE $V_R - V_\phi$ PHASE SPACE

Name	V_ϕ (km/s)	V_R (km/s)	Number of Stars	Comment
(1)	(2)	(3)	(4)	(5)
Sirius	[250, 265]	[-50, 50]	136,133	Snail
Hyades	[225, 240]	[15, 50]	77,267	Snail
Coma Berenices	[237, 250]	[-10, 10]	51,139	Snail
Pleiades	[220, 235]	[-10, 10]	57,574	Snail
"Other"	[217, 247]	[-50, -15]	110,570	Snail
Hercules Fast	[208, 221]	[15, 50]	46,042	Snail
	[208, 218]	[-13, 15]		
Hercules Slow	[193, 208]	[-50, 50]	64,947	No Snail
Low–V_ϕ	[100, 192]	[-100, 100]	68,749	No Snail
High–V_ϕ	[265, 300]	[-100, 100]	41,899	No Snail
Low–V_R	[193, 265]	[-100, -50]	71,654	No Snail
High–V_R	[193, 265]	[50, 100]	47,886	No Snail

Li & Shen (2019), submitted

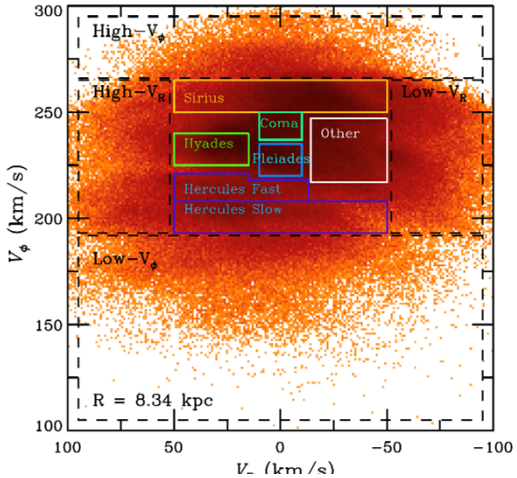
Kinematic streams in z-V_z

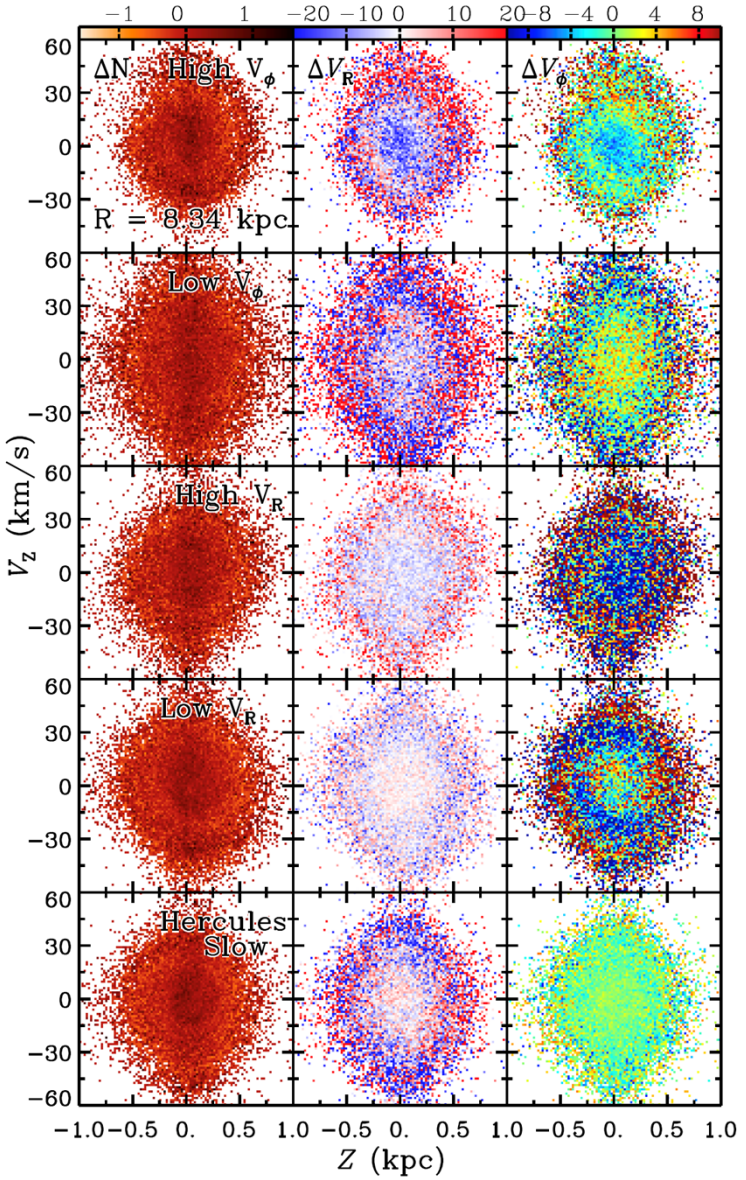
- Many streams show a snail shell
  - Unsharp masking (Laporte+19)
- Nearly similar snail shells among different streams
  - Clear snail shell in the number density (n) PS
  - Relatively weaker snail shell in V_R and V_ϕ color-coded PS



Kinematic streams in z-V_Z

- Many streams/regions do NOT show a snail shell
  - Hercules slow
  - Low/High-V_ϕ, Low/High-V_R
- For each individual stream or region, the snail shell is not clear in the V_R or V_ϕ color-coded PS





Li & Shen (2019), submitted

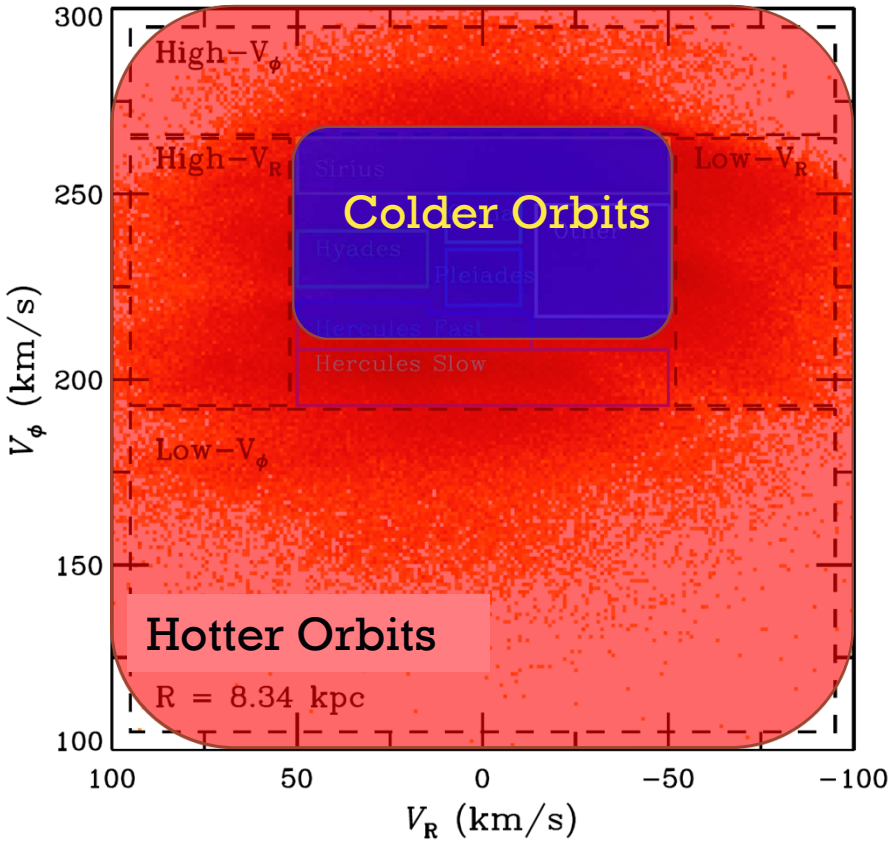
What do we conclude?

- Are the phase mixing only happening in the moving groups?
  - Michtchenko+19: "the vertical phase space spiral $Z–V_Z$ is produced by the well-known moving groups (MGs)"
  - "mainly due to internal origin rather than external origin… supports the hypothesis of a long formation time scale (several Gyr ago)

We strongly disagree!

Colder vs. hotter dichotomy

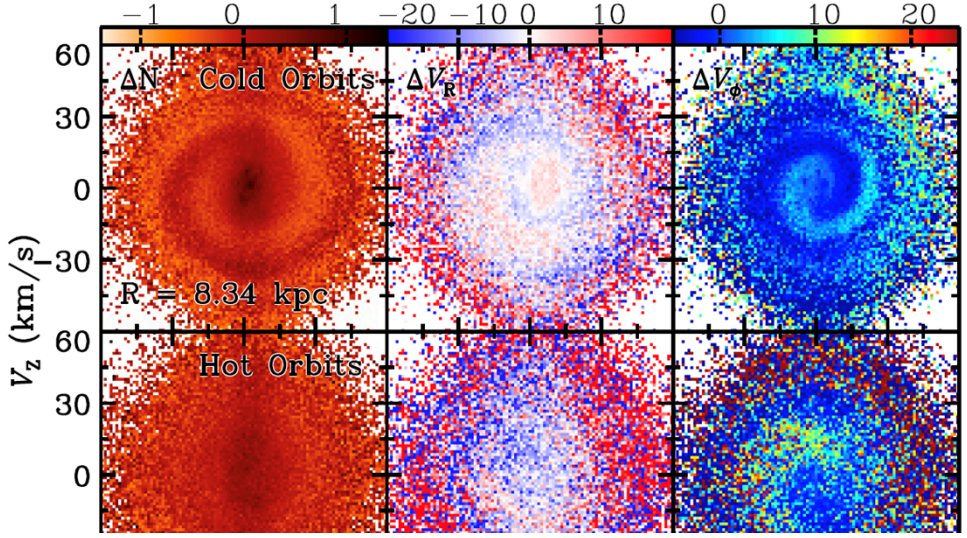
- Only "colder" orbits show a snail shell only in number density of z-V_Z
  - Include Sirius, Coma, Hyades, Pleiades, and Hercules Fast streams, and "Other" region
- "Hotter" orbits do NOT show a snail in *n*, V_Φ, V_R color-coded PS
- Should focus on colder orbits (α_0/younger disk)
- V_ϕ - V_R space good to tell "hotter" from "colder"



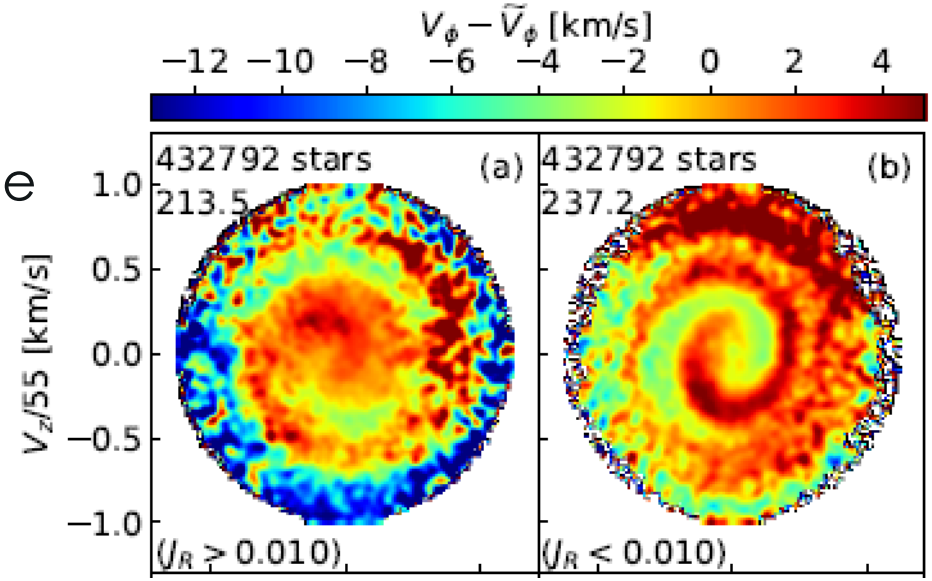
"Colder" ≡ $|V_R| < 50$ km/s
& $|V_\phi - V_{LSR}| < 30$ km/s

Colder vs. hotter orbits

- All the stars on colder orbits
  - Clear snail shell in the number density PS
  - Relatively weaker snail shell in V_R and V_ϕ color-coded PS
- All the stars on hotter orbits
  - No clear snail shell

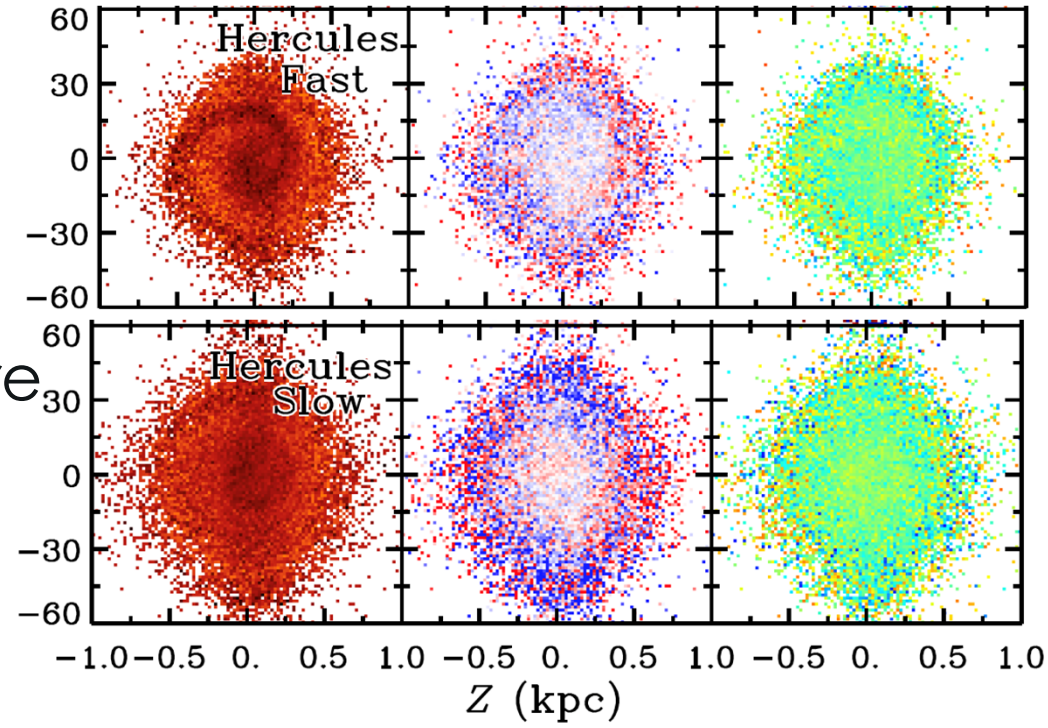


- Bland-Hawthorn+19's "hotter" (large J_R) may contain some of "colder" orbits defined by us
  - Easy to understand the difference



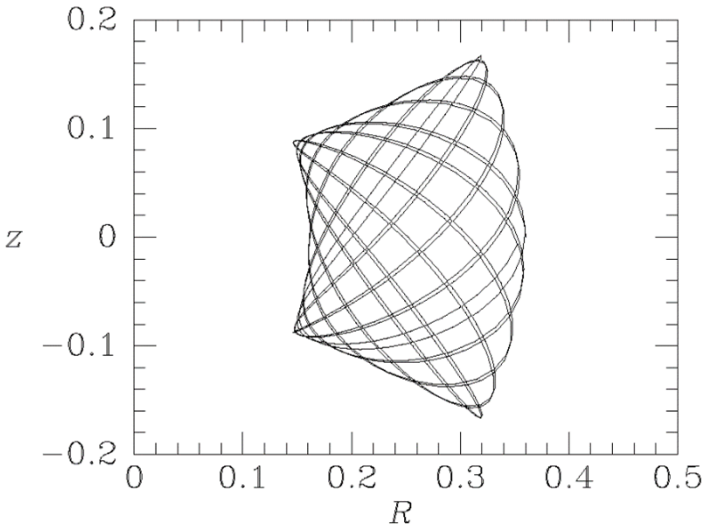
Hercules "Fast" vs. "Slow"

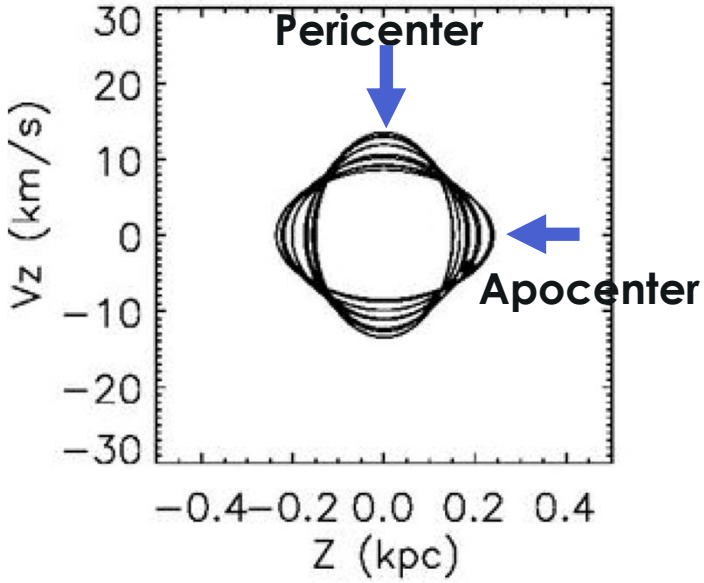
- "Fast" shows snail shell
- "Slow" does not
- Not small number statistics
  - The Hercules Slow stream has 40% more stars than the Fast stream!
- Hercules stream(s) cannot form by a single physical mechanism?



Hotter orbits

- Hotter = Large radial range
- peri. to apo., J_Z conserved but Ω_Z decreases (smaller vertical restoring force)
- Elongation of a PS ellipse changes during one P. while area fixed (Also see Joss's talk)
- → Easier to get blurred in phase space with time
- Snail shell may have phase wrapped away in z-V_z PS

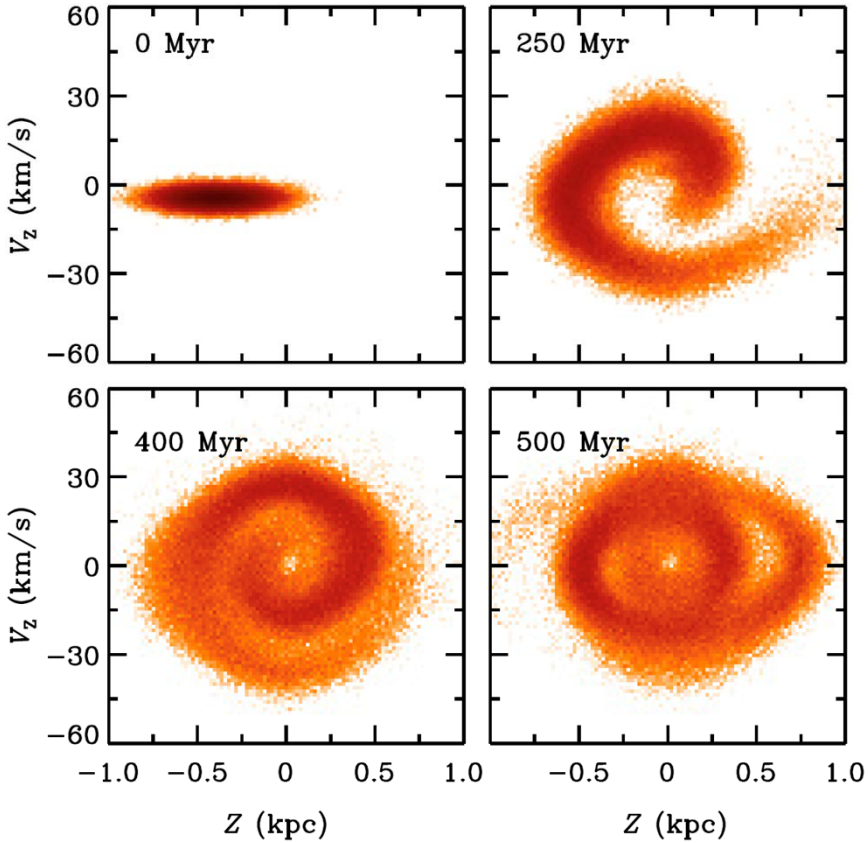




$$\omega_z \sim V_{Z,\max} / Z_{\max}$$

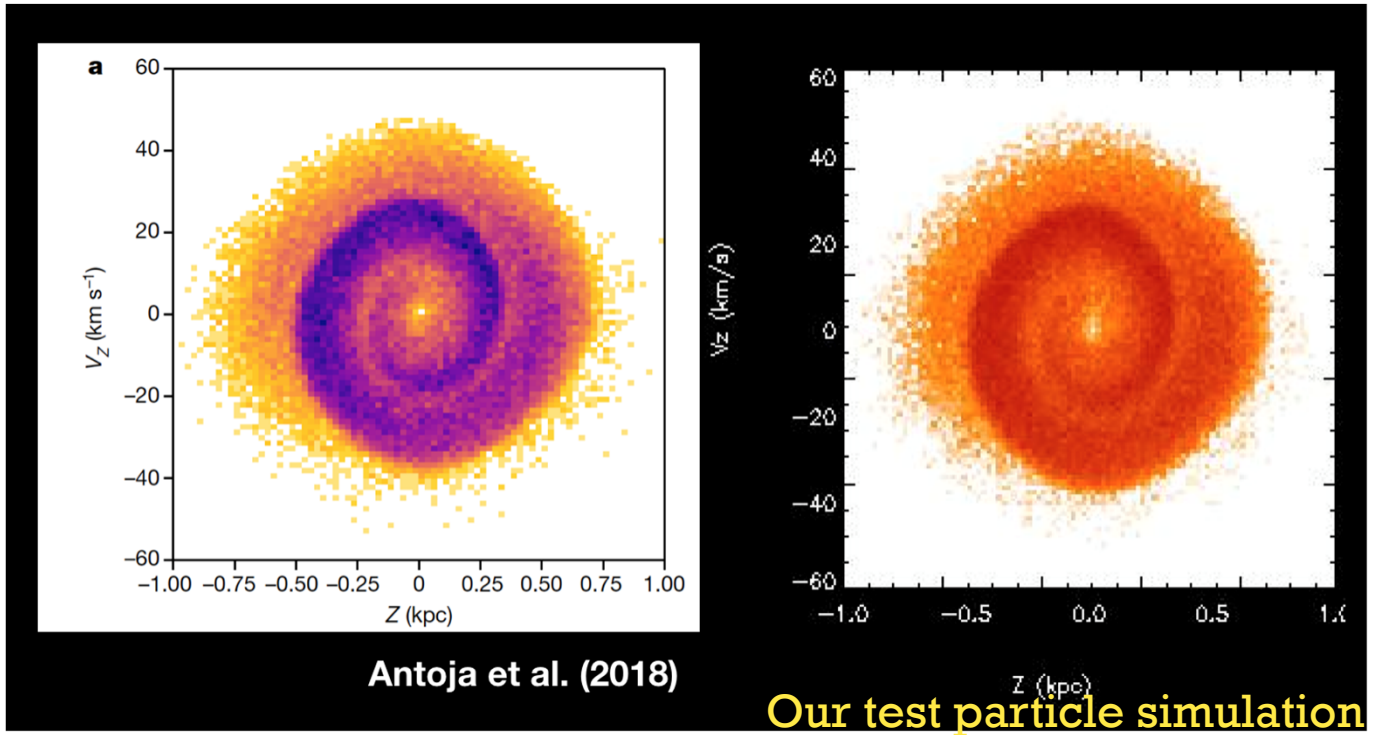
Hotter orbits show no snail

- Lack of snail shell in hotter orbits may help put tighter constraints on the phase-mixing event
- Test particle simulation shows that the event should have happened at least 400~500 Myr ago



Test particle simulations (I)

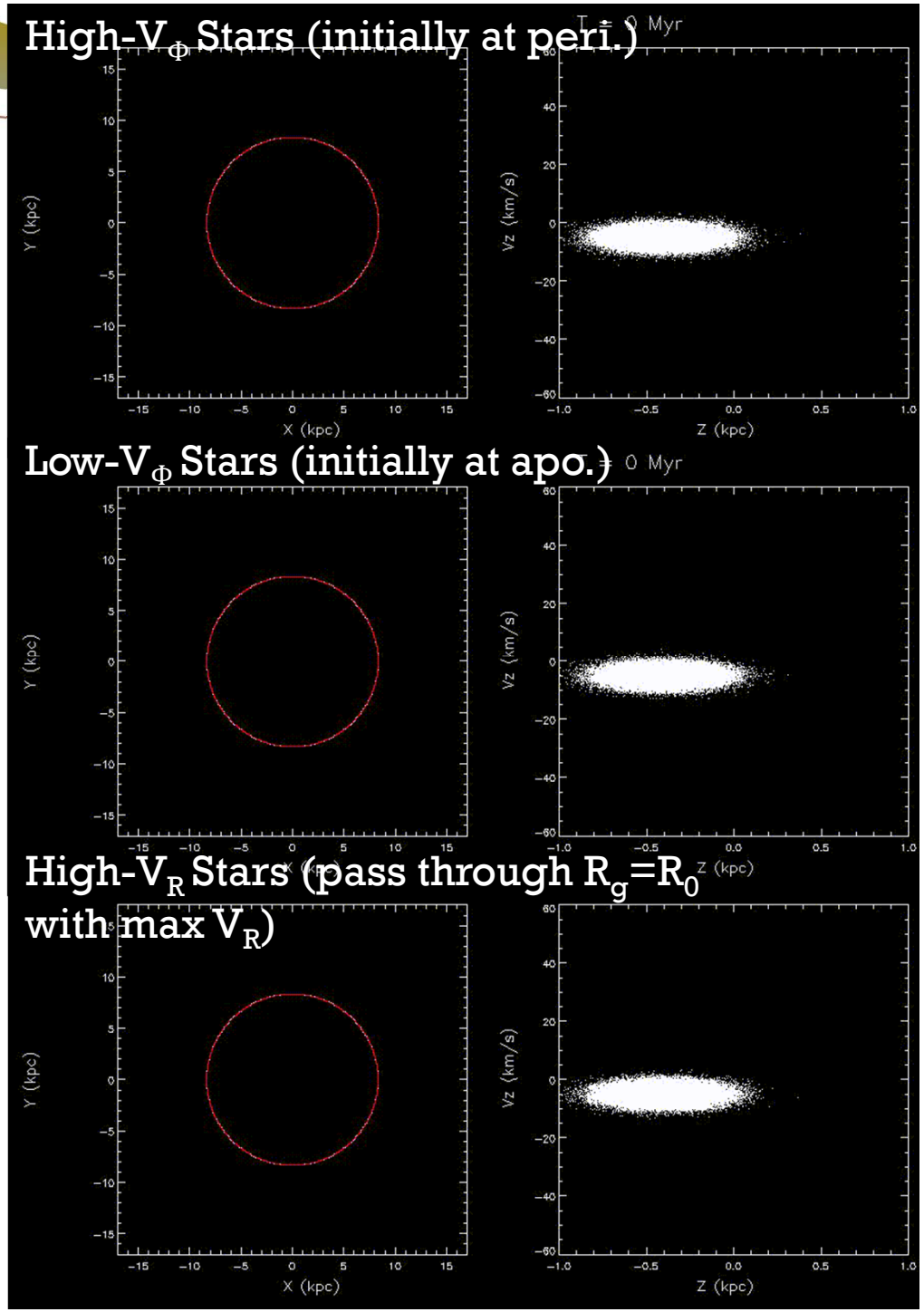
- Realistic Milky Way potential (Irrgang et al. 2013)
- Well reproduce the simulations in Antoja et al. (2018) where they did not allow R to change
- Our simulations do treat R variation properly.



Test particle simulations (I)

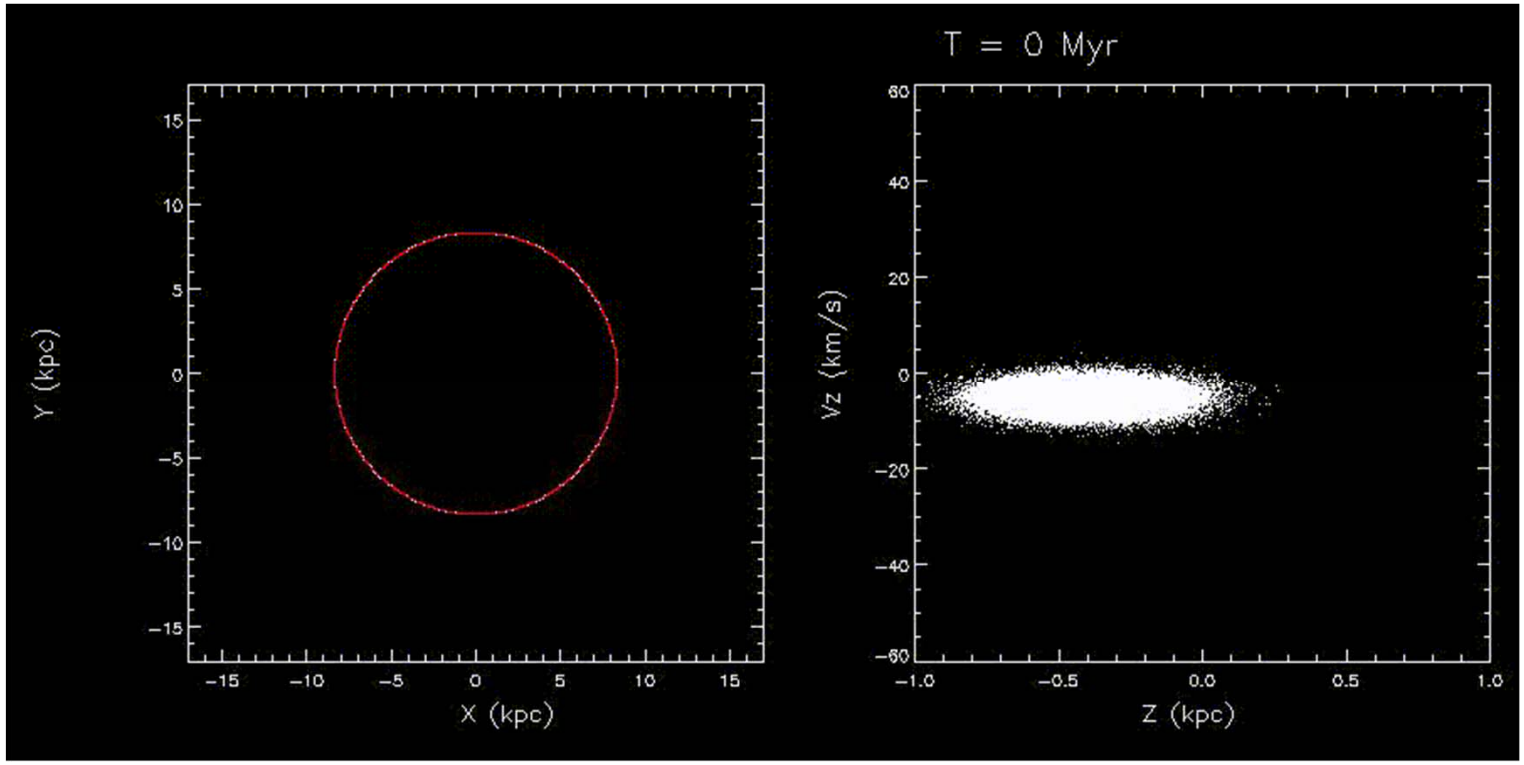
- Initial conditions
  - R (=R_0), homogeneous Φ ,
  - z, V_Z perturbed
  - V_R, V_Φ follows a Gaussian of some dispersion
- Evolution of 3 typical hotter orbits

Red circle = R_0



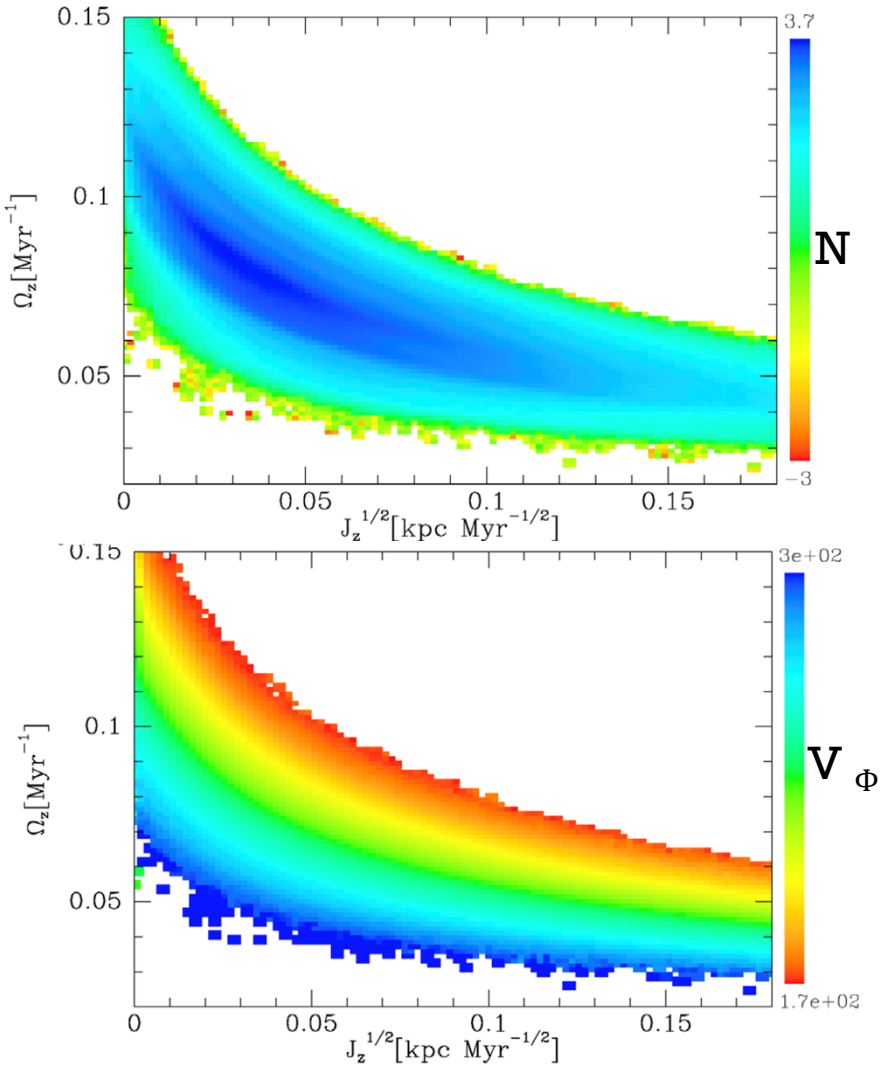
Test particle simulations (II)

- Evolution of colder orbits (Coma)
- Snail shell can sustain for a much longer time
- Consistent with other studies



Ω_z - $\sqrt{J_z}$ plane

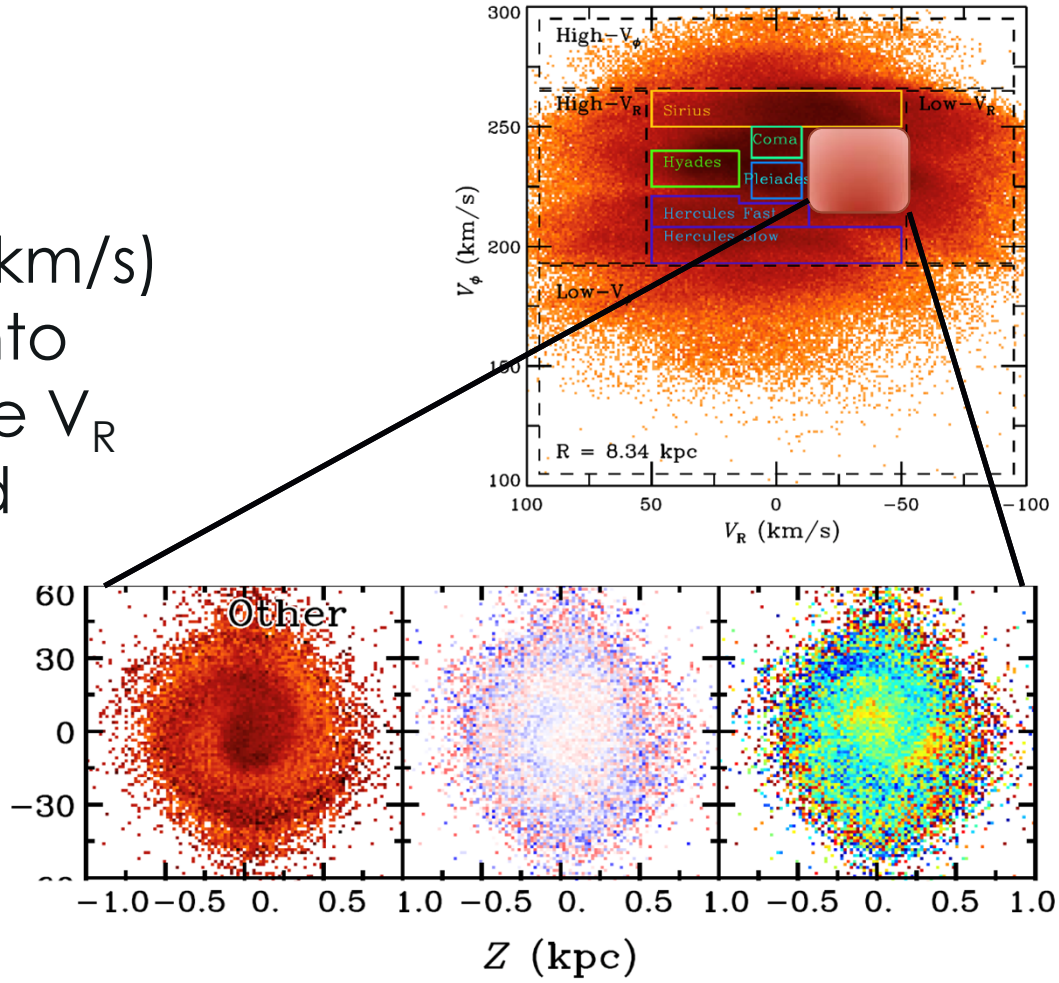
- Very helpful
- Anti-correlation
  - Create aharmonic oscillations to make snail shell
- "Broad swath"
- Streams tends to have different V_Φ → sliced it up in Ω_Z - $\sqrt{J_z}$ plane
  - Nice snail shell
- But # density plots do show clear snails → stars in Ω_Z - $\sqrt{J_z}$ plane is narrower than a "broad swath"



Binney & Schonrich 2018

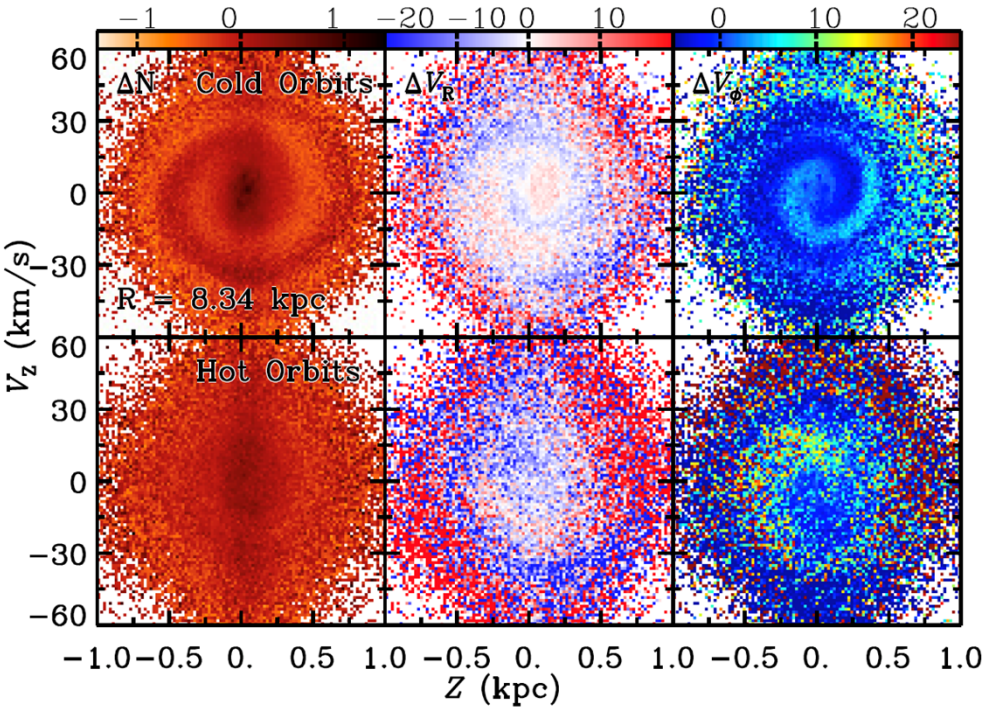
V_Φ color-coded phase space

- "Other" region
  - The large V_R and V_ϕ ranges (40 km/s, 30 km/s) should transferred into clear snail shell in the V_R and V_ϕ color-coded phase spaces.
  - Not seen in data



V_ϕ color-coded phase space

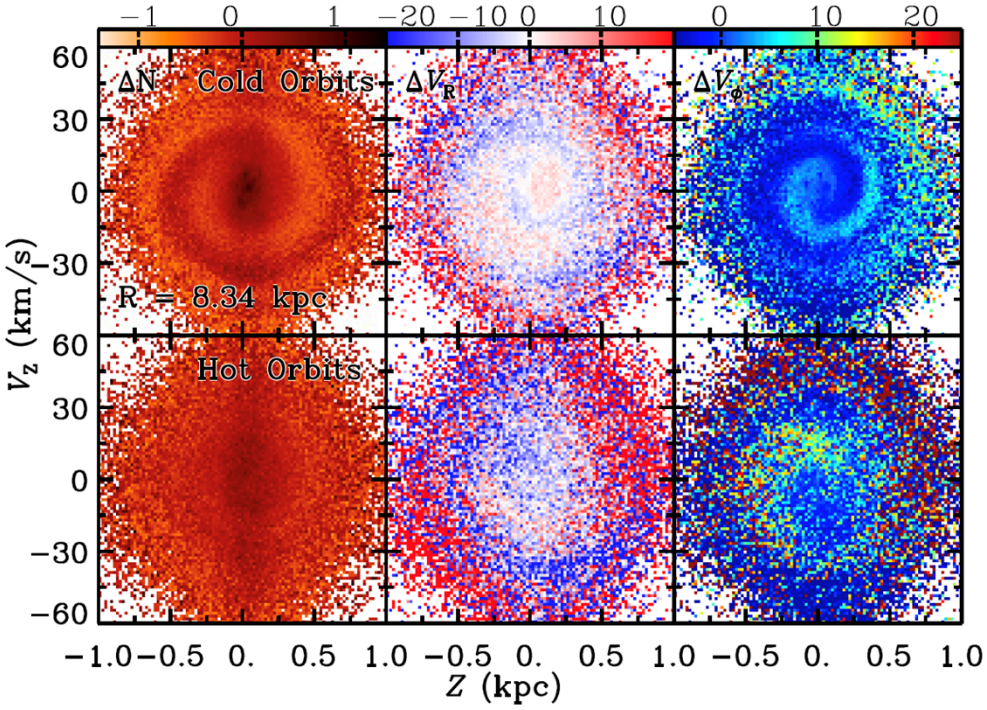
- Weaker snail shell in V_R and V_ϕ color-coded phase space
- → weaker coupling of in-plane and vertical motion?
  - Due to small R_g difference?



Combined plot for all colder/hotter orbits

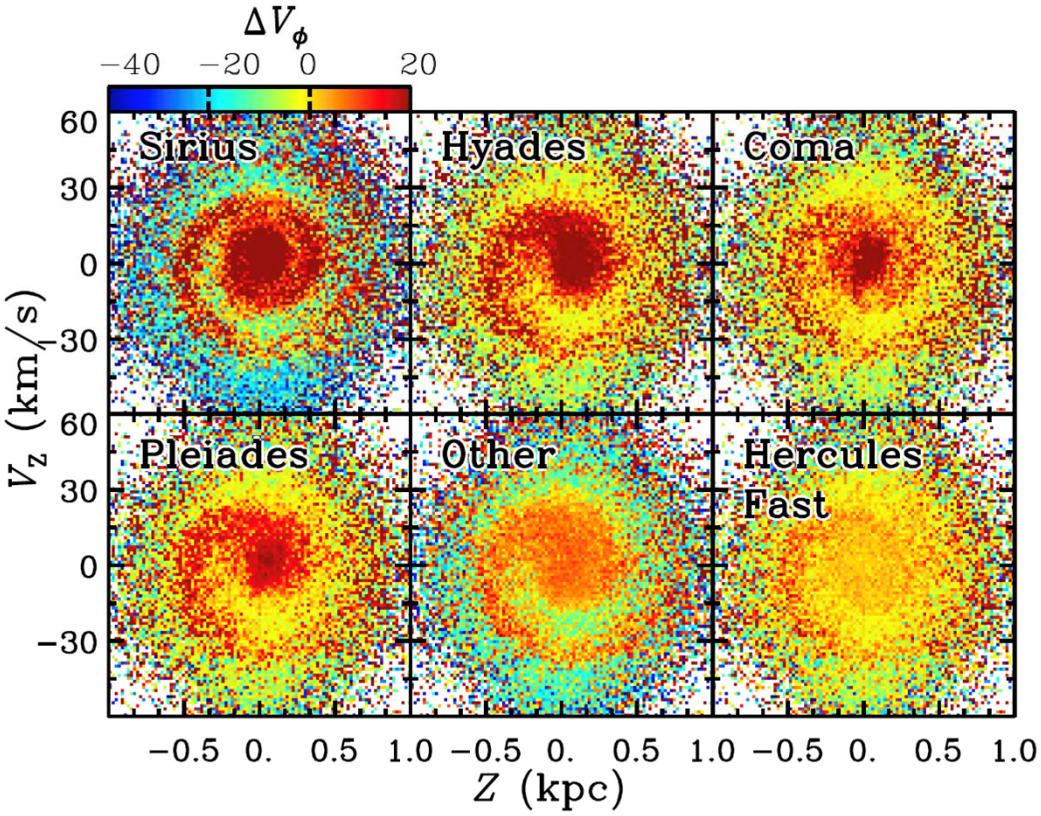
V_R color-coded phase space

- Much weaker than predicted by current models
- Especially the bar buckling model?
  - Khoperskov+19: "The spiral structure is **more clearly seen in the distribution of radial velocity (z, V_z) space**; this structure is less evident in azimuthal velocity, but still distinguishable in density distribution."



Enhanced V_Φ c-c phase space

- V_Φ c-c is enhanced due to "colder" orbits snail shell is contrasted on a smooth background which has a different V_Φ
  - Combine individual stream with the hotter orbits (as a smooth background) to highlight the snail shell
  - Reflecting the number density distribution of the phase space snail shell



Can we tell which event perturbed the MW disk?

- Two scenarios
- 1. merging Sgr dwarf
  - Happened at least ~400-500 Myr ago
  - If too late, then no time for hotter orbits to phase wrap away
- 2. bar buckling event
  - Data shows weaker snail shells in the V_R c-c PS than the # density or V_Φ c-c
  - No clear snail for hotter orbits —- to be shown by the model
  - Bending waves due to the bar buckling are too weak compared to those excited by Sgr dwarf? (Laporte et al. 2019)

Summary

- Explore connection of in-plane streams and the vertical phase mixing
- **Hercules stream has two branches, which may not be explained by a single mechanism**
- **PS snail shell exists only in the main kinematic streams, i.e., the dynamically "colder" orbits (α_0/younger disk)**
- The hotter orbits may have phase wrapped away already due to the much larger dynamical range to facilitate faster phase mixing.
- To explain the lack of a well-defined snail shell in the hotter orbits, the disk should be perturbed **at least ~ 400-500 Myr ago**
- Only the colder orbits exhibit the ongoing vertical phase mixing, with the featureless hotter orbits providing a background to highlight the snail shell of the colder orbits in the V_ϕ color-coded PS
- The bar buckling perturbation scenario is less favored