A dynamically young and perturbed Milky Way disk

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Context

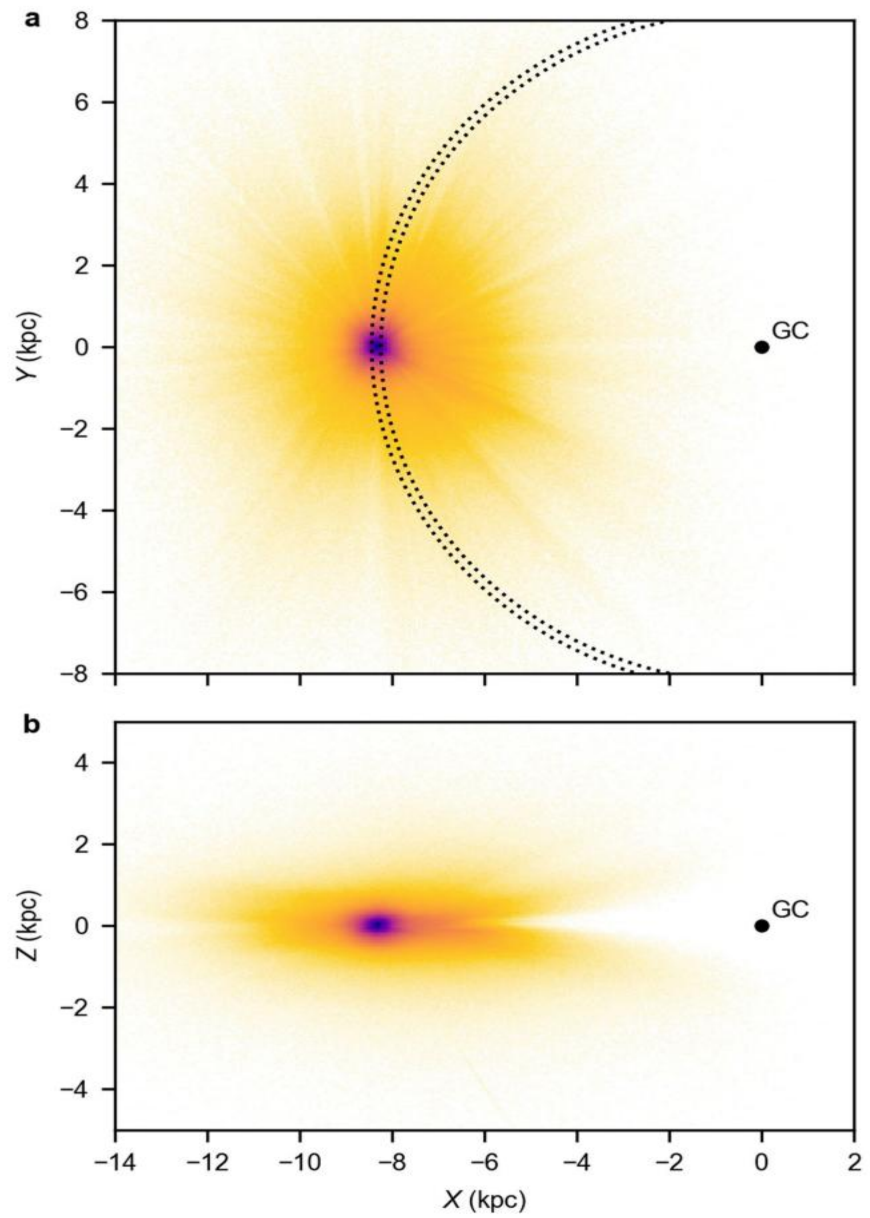
- Evolution of the Milky Way disk affected by several phenomena:
- Bar and the spiral arms induce radial migration of stars and can trap or scatter stars close to orbital resonances.
- External perturbations from satellite galaxies cause:
  - Dynamical heating of the Galaxy.
  - Ring-like structures in the disk.
  - Correlations between different components of the stellar velocity.
  - Phase wrapping' signatures in the disk, such as arched velocity structures in the motions of stars in the Galactic plane.

- Some manifestations of these dynamical processes have already been detected:
- Kinematic substructure in samples of nearby stars.
- Density asymmetries and velocities across the Galactic disk that differ from the axisymmetric and equilibrium expectations.
- Signatures of incomplete phase mixing in the disk.

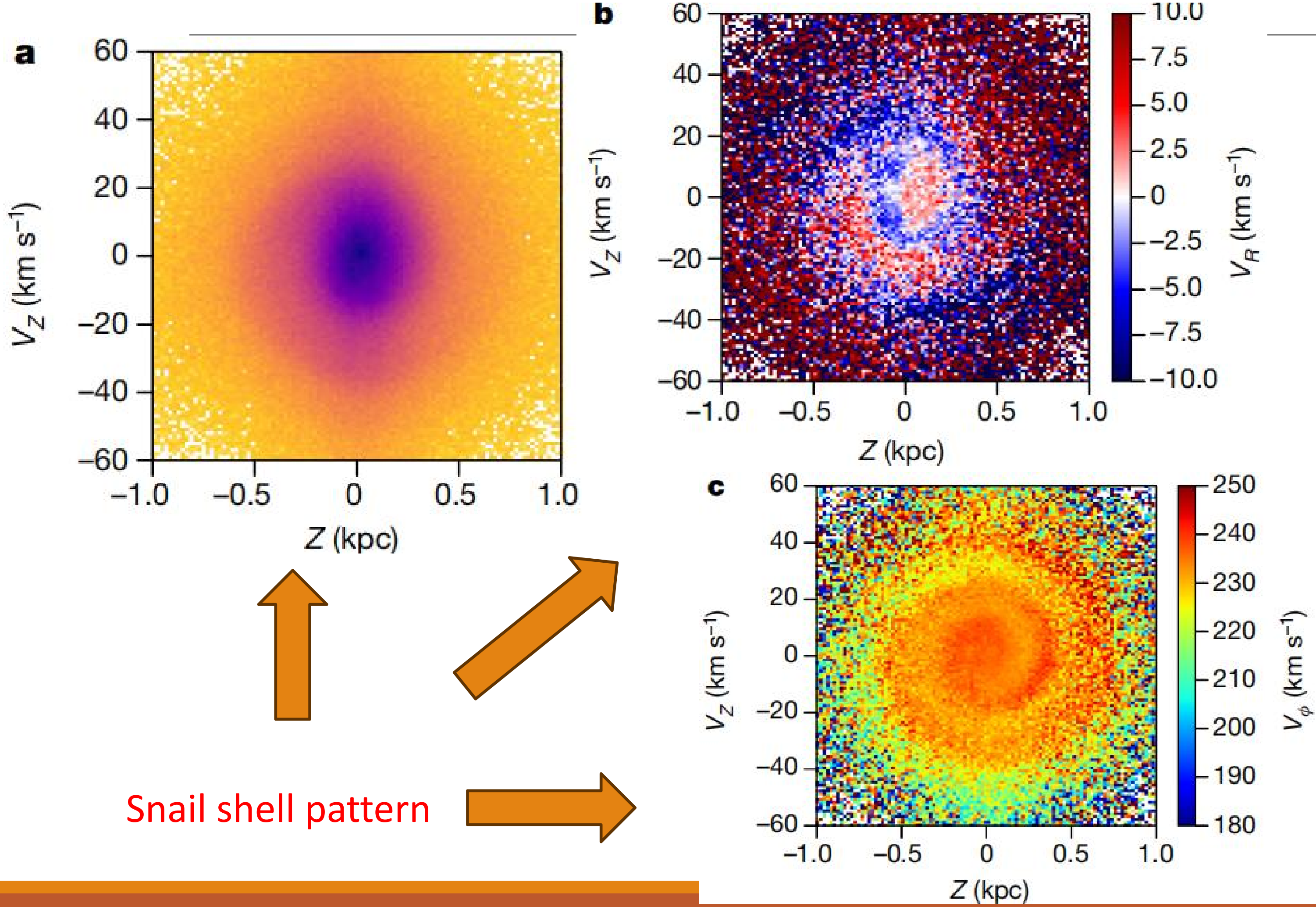
Sample

- 6,376,803 stars.
  - Gaia DR2 sources having five parameter astrometric solution (positions, parallax and proper motion) and radial velocity.
  - Filter: Positive parallax, relative uncertainty < 20 % .
- **Coordinate transformation:** Heliocentric position and velocity components transformed into cylindrical Galactic reference frame (R, ϕ, Z, V_R, V_ϕ, V_Z) .

where R is positive towards Galactic anticenter, ϕ is positive in the direction of Galactic rotation and Z is positive towards Galactic north pole.

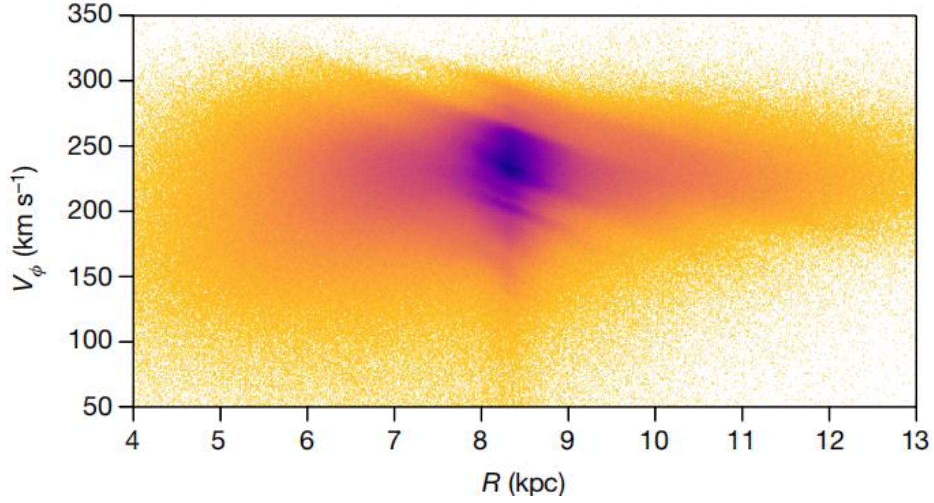


Substructures in phase space projections (not predicted by existing models)



- ❑The pattern is particularly pronounced in the case of Vϕ, even up to $V_Z \approx 40$ km/s.
- ❑ There is a gradient of different values of Vϕ across the spiral shape, which follows the density variations.

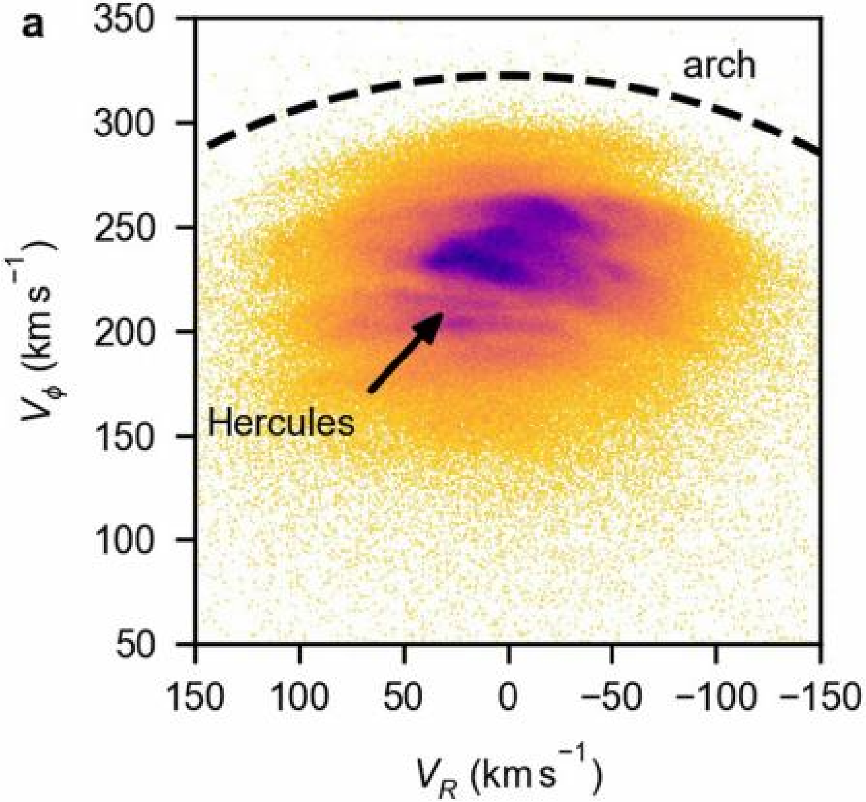
Ridges

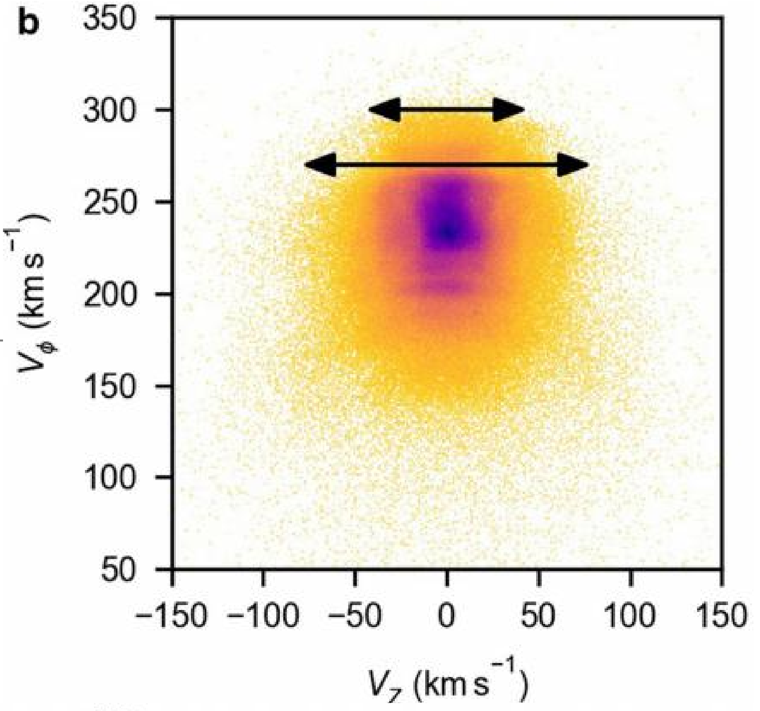


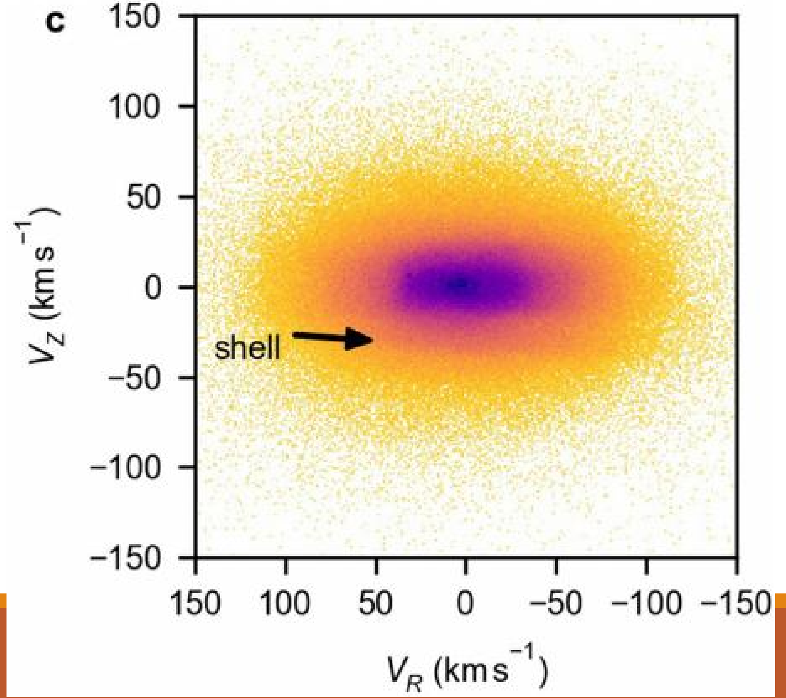
Co-relation between velocity components

❑2D histograms in velocity space for stars located at 8.24 < R < 8.44 kpc, in bins of 1 km/s .

- (a) Different streams, thin arches. Dotted line is constant KE in the plane predicted for substructure generated in horizontal phase mixing.
- (b) Box like structure, extent varies with Vϕ.
- (c) Galactic warp is not visible, shells represents different projection of snail shell pattern .







Models for vertical phase mixing

- ❑ Snail shell is a effects of phase mixing in 2 dimensions.
- ❑ Toy model for Z-Vz plane of Galaxy: to include the phase mixing.

Anharmonic oscillator with vertical potential:

$$\Phi(Z) \propto -\alpha_0 + \frac{1}{2}\alpha_1 Z^2 - \frac{1}{4}\alpha_2 Z^4$$

With oscillation frequency:

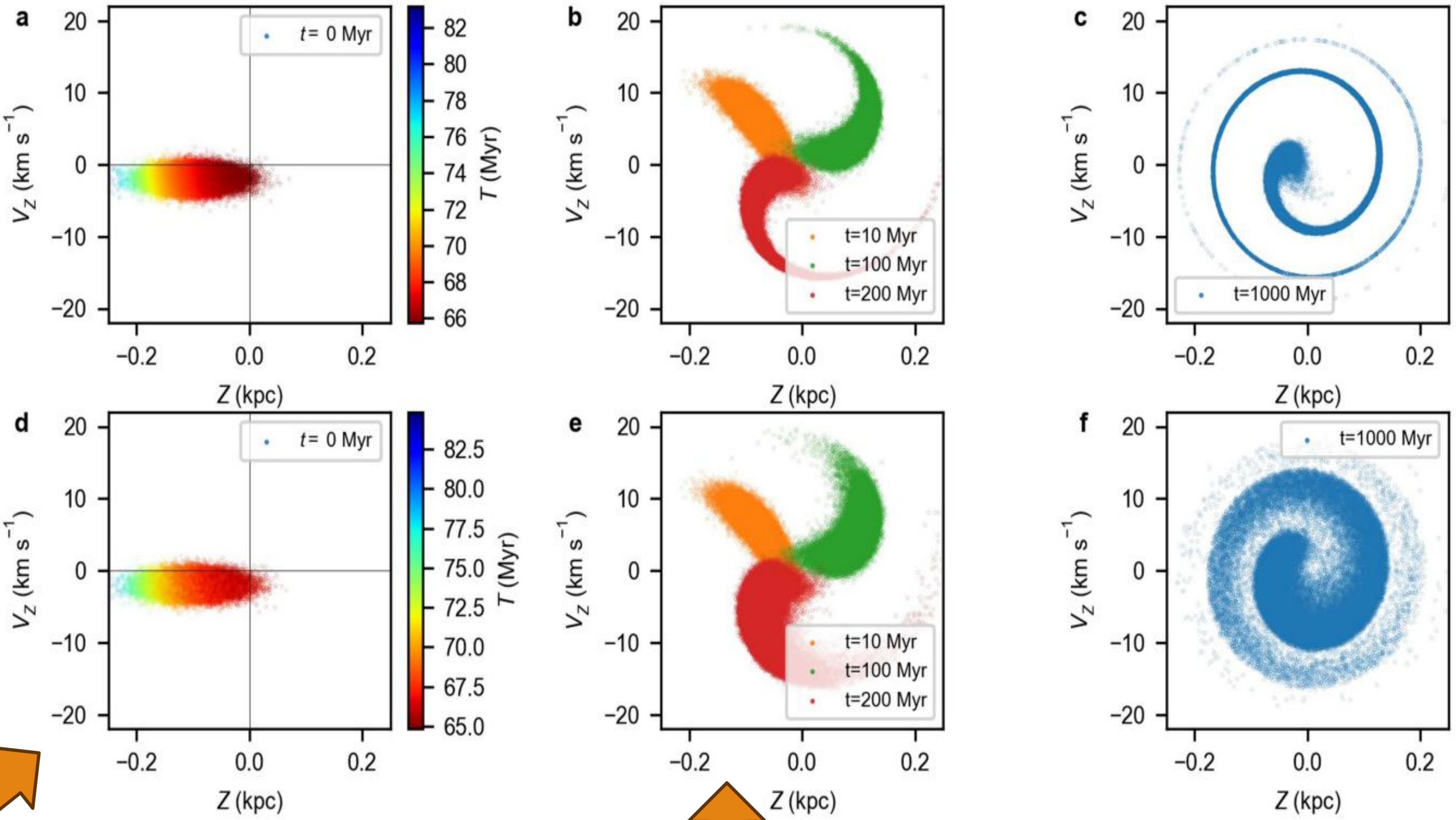
$$\nu(A,R) = \alpha_1(R)^{1/2}\left[1 - \frac{3\alpha_2(R)A^2}{8\alpha_1(R)}\right]$$

- ❑ Stellar motion is simple harmonic oscillator with different frequencies:

$$Z = A\cos[\nu(A,R)t + \phi_0]$$
$$V_Z = -A\nu(A,R)\sin[\nu(A,R)t + \phi_0]$$

Initial Gaussian distribution with fixed R= 8.5 kpc

- This motion will trace an oval shape in clockwise direction the Z-Vz projection.
- Since, stars revolve at different angular speeds depending on their frequency. Thus, an ensemble of stars will stretch out in phase space, with the range of frequencies causing a spiral shape.
- Time evolution of stars using toy model.
- As time goes by, the spiral gets more tightly wound and eventually so tightly wound that the distribution appears to be smooth.
- The observed shape implies that this time has not yet been reached in the Milky Way, hence phase mixing is currently taking place in the Galactic disk.



More closer to the observed distribution

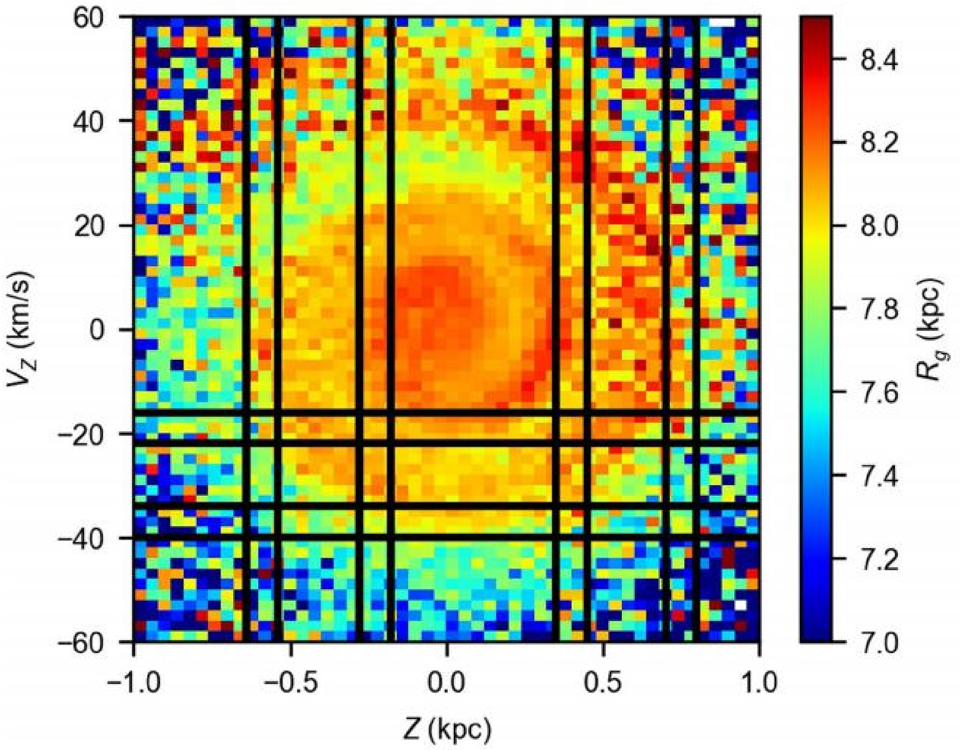
Skewed normal distribution having different R, skewness = 10, initial R = 8.4 kpc, scale parameter 0.2 kpc.

- Shape of the spiral can be used to obtain information about:

  (i) Shape of the potential, which determines the vertical frequencies.

  (ii) Starting time of phase mixing.

  (iii) Type of perturbation that brought the disk into a non-equilibrium state, which sets the initial conditions for the phase-mixing event that we are witnessing.



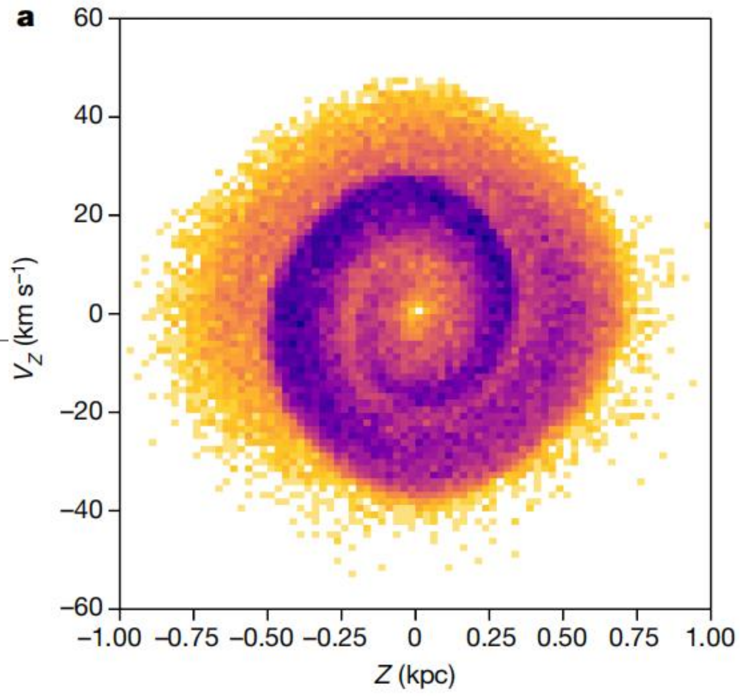
- Time of phase mixing is determined from two consecutive spiral turns.

$$t = \frac{2\pi}{\nu_2 - \nu_1}$$

$$R_g \approx V_\phi R_\odot / [V_c(R_\odot)],$$

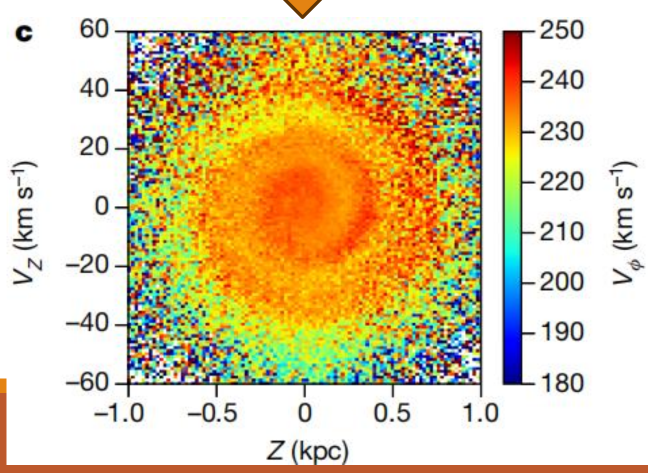
- Using several consecutive turns as well as potentials for the Milky Way, the estimated time of vertical phase-mixing is between 300 Myr and 900 Myr ago.

Simulated results

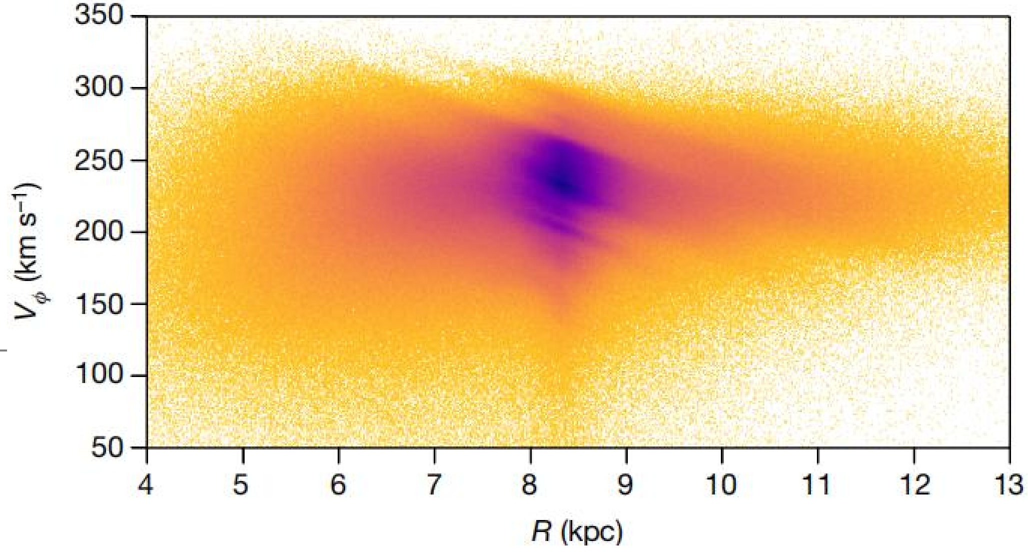


- ❑ Performed simulation by integrating the orbits of 100,000 test particles for 500 Myr in Galactic potential starting from ta distribution which is not in equilibrium.
- ❑ Similar to observed pattern.
- ❑ A possible perturbation that might have initiated this vertical phase mixing is the influence of a satellite galaxy. Particularly, the pericentric passage of Sagittarius dwarf galaxy. Most models claim this passage between 200 - 1,000 Myr ago, which is consistent with these findings.
- ❑ Other processes that may induce snail shell patterns:
  - ➢ Formation of the central bar and of the transient spiral structure provided that these processes can induce vertical asymmetries
  - ➢ Other global changes in the potential.
  - ➢ Dissolution of a massive stellar system such as a cluster or accreted satellite.

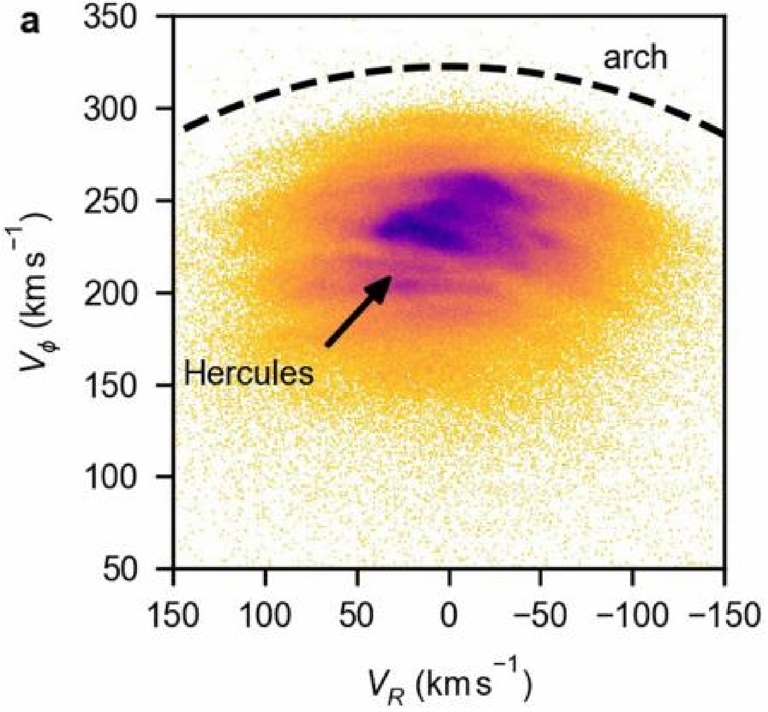
Observed



Ridges



- This study showed various thin diagonal ridges which were not shown earlier.
- Arches are projections of ridges in solar neighborhood.
- Their characteristics vary with distance from the Galactic center, diminishing their velocity towards the outskirts of the Galaxy in a continuous way.
- These diagonal ridges could be signatures of phase mixing in the horizontal direction.
- The bar and the spiral arms could induce diagonal ridges through their resonant orbital structure, creating regions in phase space of stable and unstable orbits, and hence with over densities and gaps.



Model for horizontal phase mixing and resonance

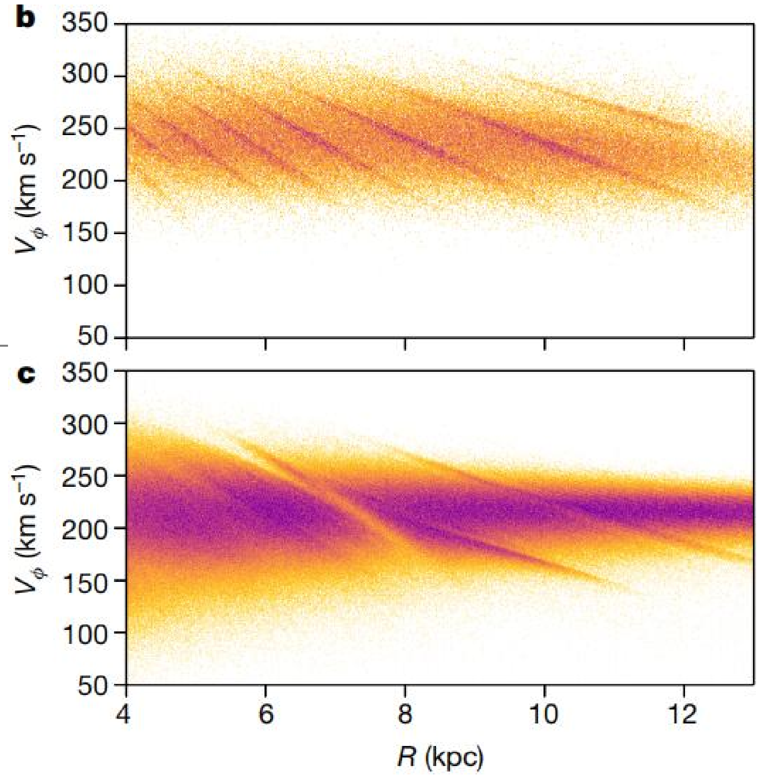
- **Horizontal phase mixing:**

- The model was constructed by integrating orbits in Galactic potential given by Allen & Santiallan (1991).
- Initial distribution of test particles follows skewed normal distribution.
- Particles were integrated for 1 Gyr . Added particles in the disk which were integrated for longer timescale.

- **Horizontal resonances :**

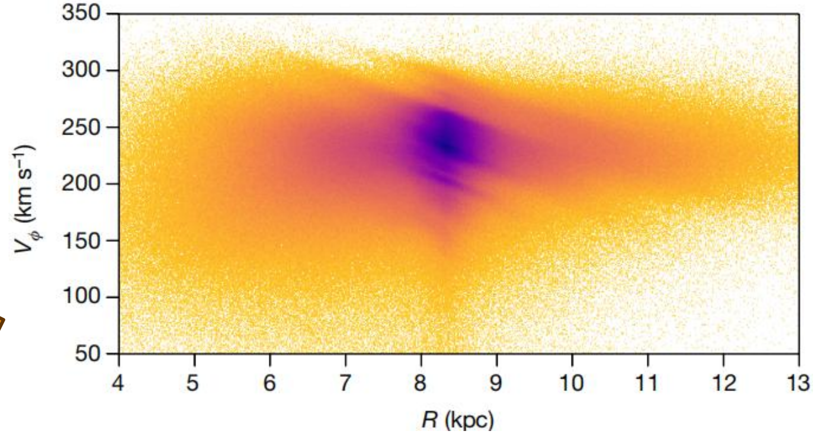
- The toy model was constructed by including Galactic bar in above model.
- Used total 68 million particles to integrate.

Simulated results



- The toy model of phase mixing (b) and a disk simulation with a Galactic potential that contains a bar (c) both show several diagonal ridges.
- The Vϕ separation of consecutive ridges in the data is about 10 km/s. Comparing this to toy model indicates that, if these ridges are caused by phase mixing from a single perturbation, it should have taken place longer ago than the perturbation that gave rise to the vertical mixing.
- This is consistent with the timing derived using the separation between arches in the local velocity plane and with the existence of a group of co-moving stars that appear not to be fully phase mixed vertically and suggests that another perturbation occurred about 2 Gyr ago.
- The relationship between the various features is not clear, and it is not unlikely that there are or were several perturbations creating superposed features.

observed



Summary

- Performed analysis of the motions of six million stars in the Milky Way disk and found that phase space distribution contains different substructures with various morphologies, such as snail shells and ridges, when spatial and velocity coordinates are combined.

- Concluded that the disk must have been perturbed between 300 million and 900 million years ago, consistent with estimates of the previous pericentric passage of the Sagittarius dwarf galaxy. Their findings show that the Galactic disk is dynamically young and that modelling it as time-independent and axisymmetric is incorrect.

- Their interpretation of the features found in this analysis is based on toy models, the main limitations of which are:

- [ ] their lack of self-consistency.
- [ ] The choice of initial conditions not necessarily reflecting those stemming from the impact of a satellite galaxy,
- [ ] The fact that they studied separately both the effects of resonances and phase mixing.

- A challenging task for the future will be to model these findings taking into account collective effects, such as in the perturbative regime, and with self-consistent *N*-body models.