Stellar Streams and Phase Space distributions

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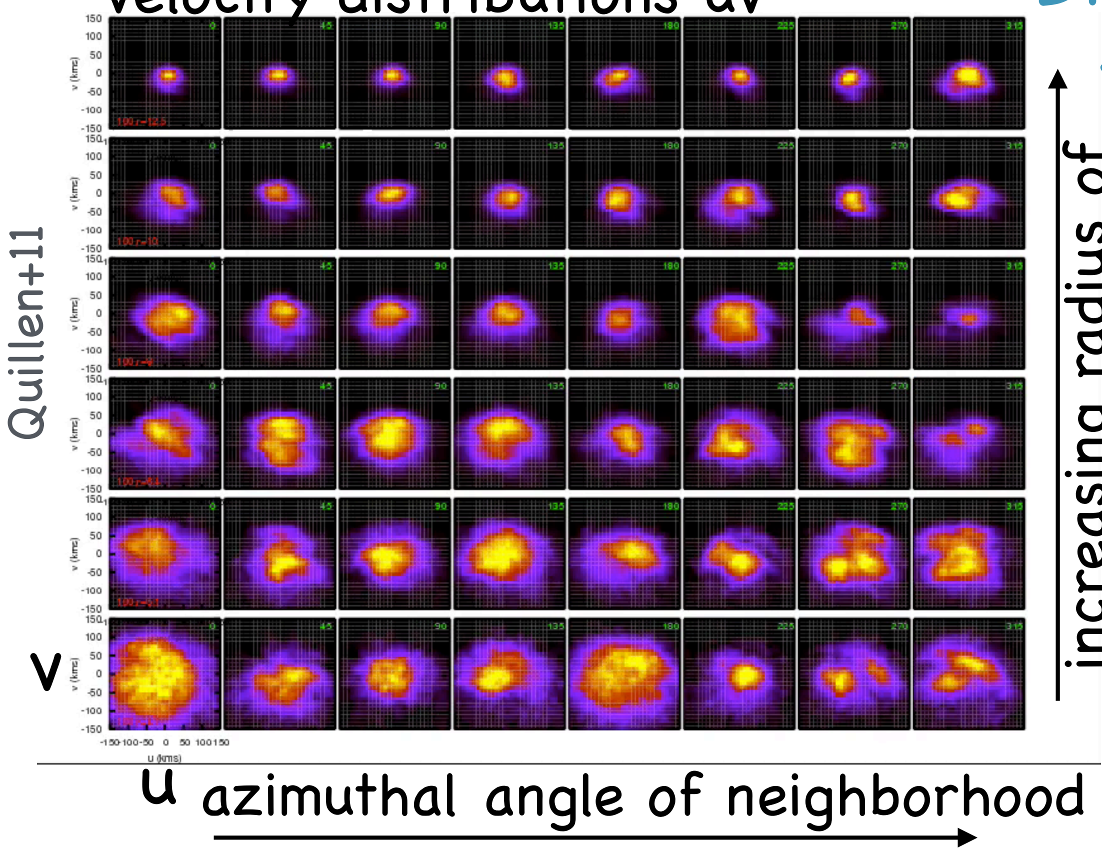
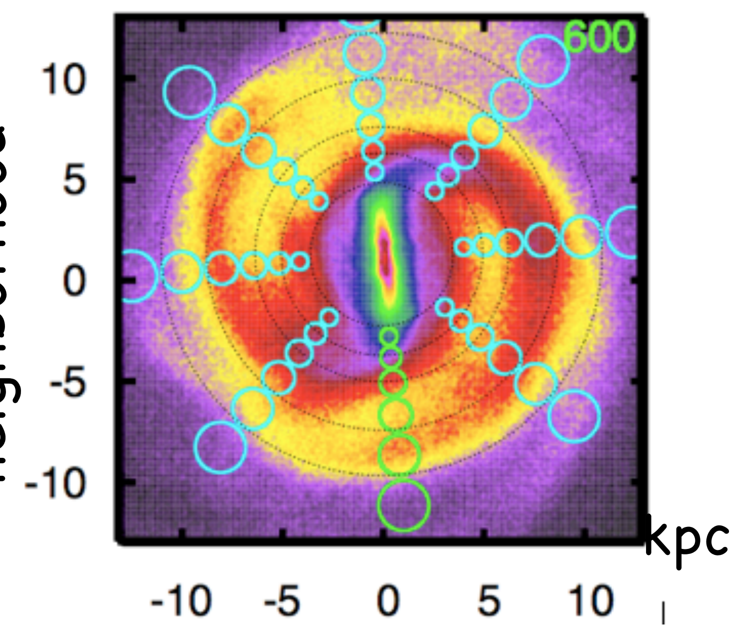
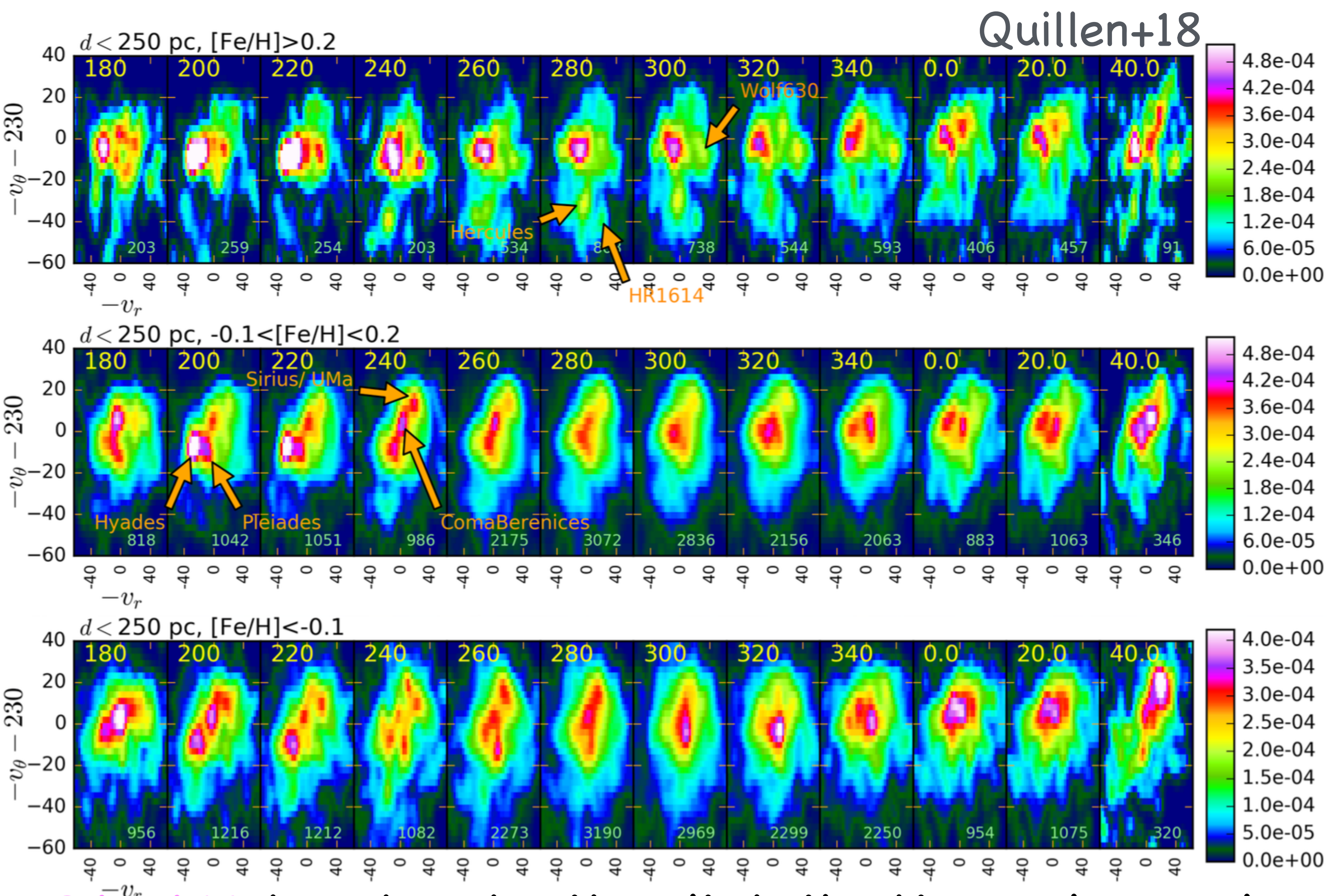
velocity distributions uv



Dissection of an N-Body simulation containing tracer particles





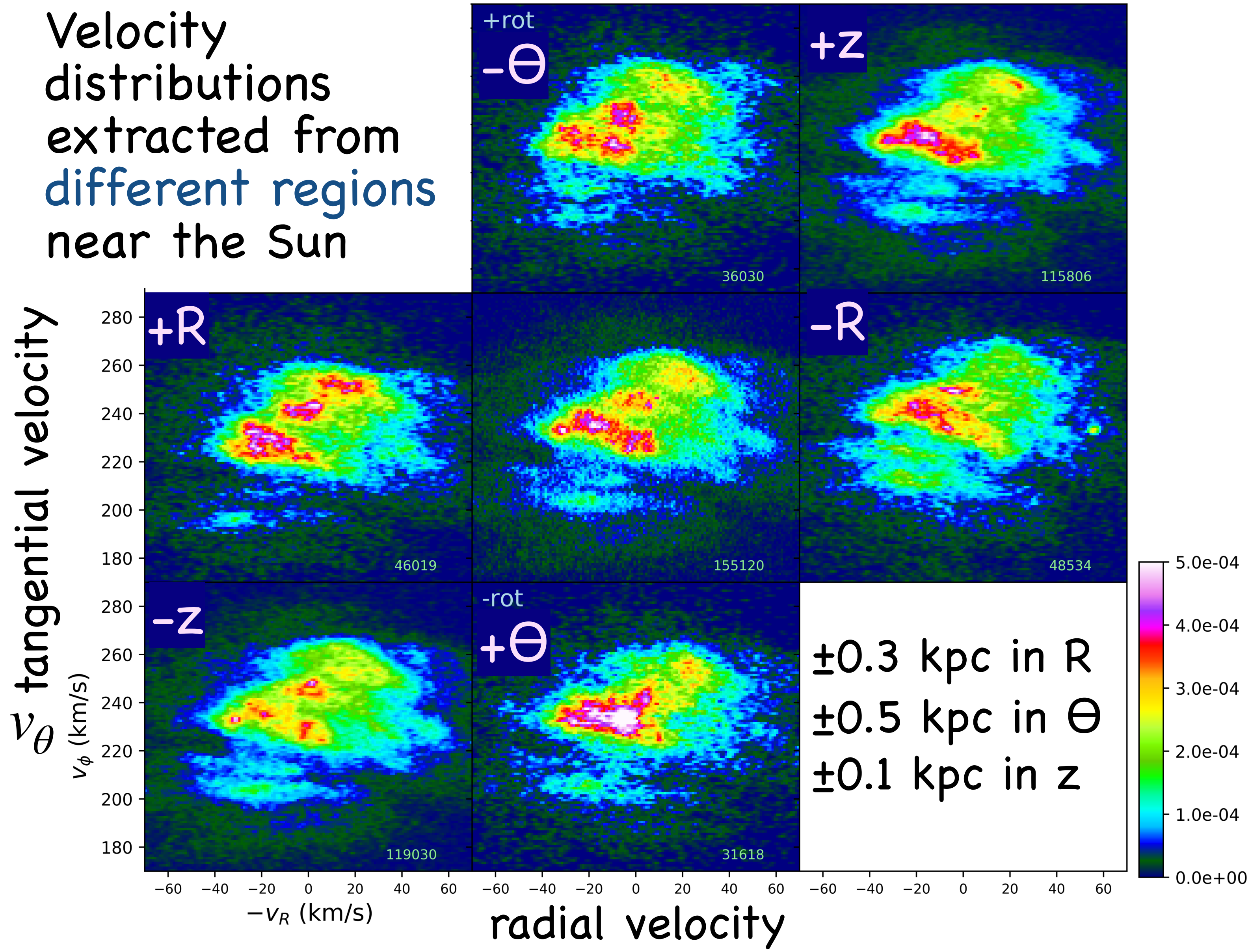
GALAH local velocity distributions depend on:

direction, **hemisphere**, distance, metallicity

Gradients of peaks of order 10 km/s over a few hundred pc

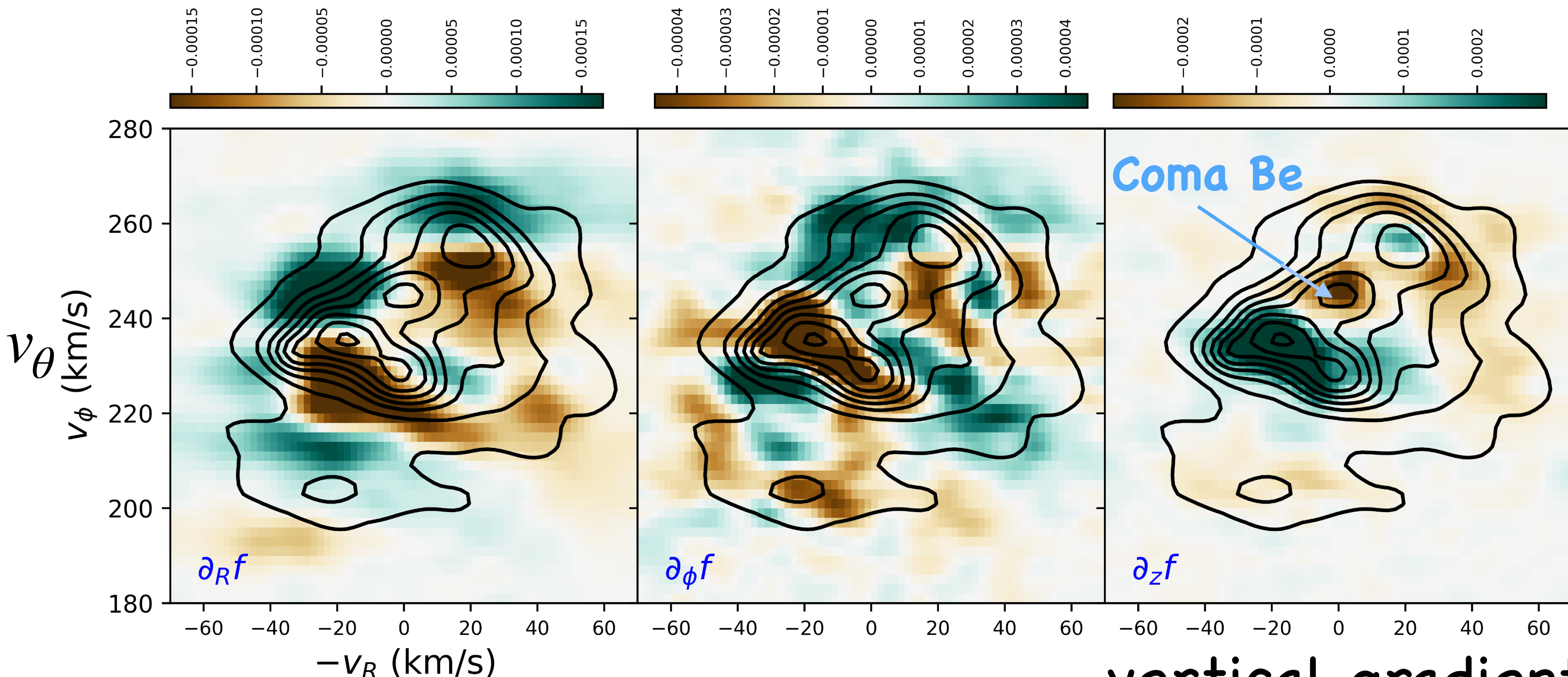
GAIA DR2 stars with radial velocities

Velocity distributions extracted from different regions near the Sun



Gradients of local velocity distribution

GAIA DR2 stars with radial velocities



radial gradient

$$\frac{1}{2dR}\left[f\left(R+dR,\theta,z\right)-f\left(R-dR,\theta,z\right)\right]$$

$$\frac{1}{2Rd\theta}\left[f\left(\theta+d\theta\right)-f\left(\theta-d\theta\right)\right]$$

vertical gradient!

$$\frac{1}{2dz}\left[f\left(z+dz\right)-f\left(z-dz\right)\right]$$

Approximations for the Stellar Phase Space Distribution Function

Assumption	$f(\mathbf{x}, \mathbf{v}, t)$	Examples
Constant in a rotating frame	$\boxed{f(R, \theta - \Omega_p t, z, \mathbf{v})}$ cylindrical coordinates	Weinberg-Tremaine method for measuring bar pattern speeds
Evolved from an initial non-uniform action angle distribution	$\boxed{f(\mathbf{I}, \boldsymbol{\theta} - \boldsymbol{\Omega}(\mathbf{I})t)}$ action/angle coordinates	Phase wrapping for the Arcturus Stream Minchev+09, but also Quillen+09, delaVega+15, Antoja+18, Khanna+19
Recent local perturbations	$\boxed{\frac{\partial f}{\partial t} \propto f(\theta - \Omega_p t - \alpha \ln R)}$	Apo+pericenter crossing of spiral arms Quillen+19
Relaxed Near Resonance	$\boxed{f(J_R, J_s)}$ Depend on an action variable conjugate to a resonant angle	Ridges in velocity distribution from bar resonances Monari+18 (also see Hunt+19,Michtchenko)

In search of pattern speeds

Phase space distribution $f(\mathbf{x}, \mathbf{v}, t)$

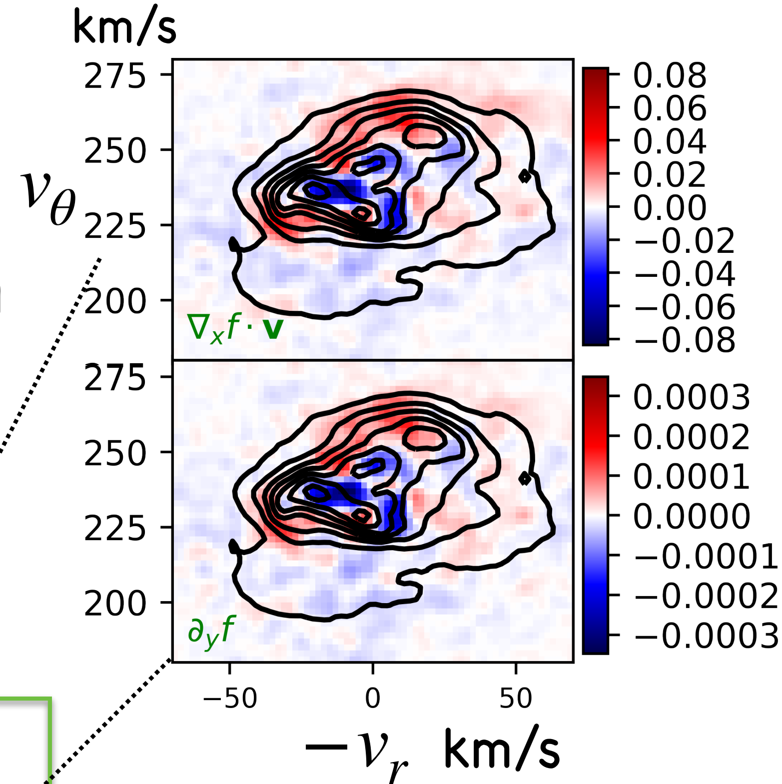
Collisionless Boltzmann equation

$$\frac{df}{dt} = \frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla_{\mathbf{x}} f + \frac{d\mathbf{v}}{dt} \cdot \nabla_{\mathbf{v}} f = 0$$

Assume that distribution function depends on pattern speed Ω_p

$$\boxed{f(r, \theta - \Omega_p t, z, \mathbf{v})}$$

$$-\Omega_p \nabla_\theta f + \mathbf{v} \cdot \nabla_{\mathbf{x}} f - \nabla \Phi \cdot \nabla_{\mathbf{v}} f = 0$$



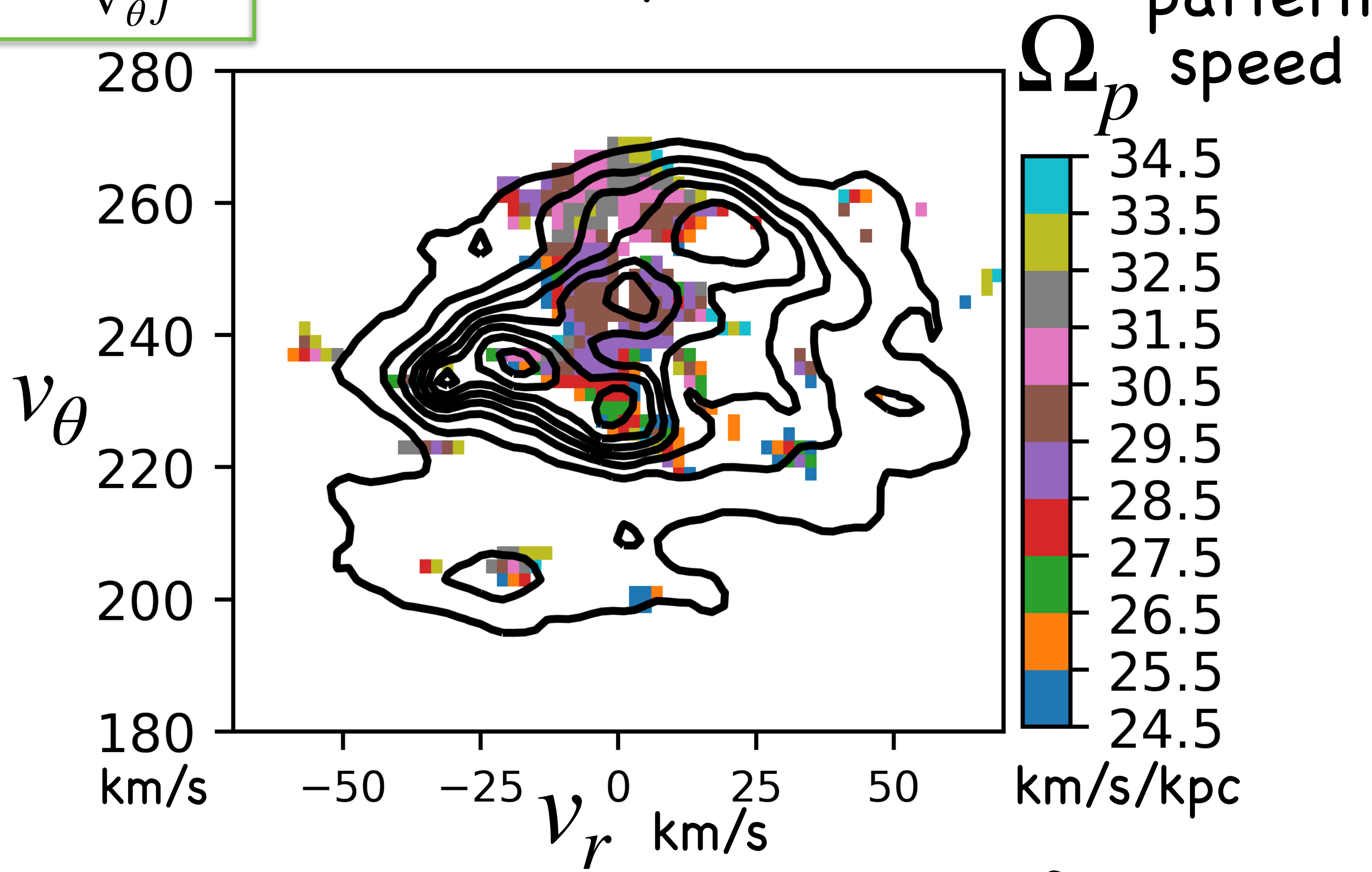
At a velocity peak the pattern speed

$$\boxed{\Omega_p = \frac{\mathbf{v} \cdot \nabla_{\mathbf{x}} f}{\nabla_\theta f}}$$

Non-integrated version of Weinberg Tremaine method

In search of pattern speeds

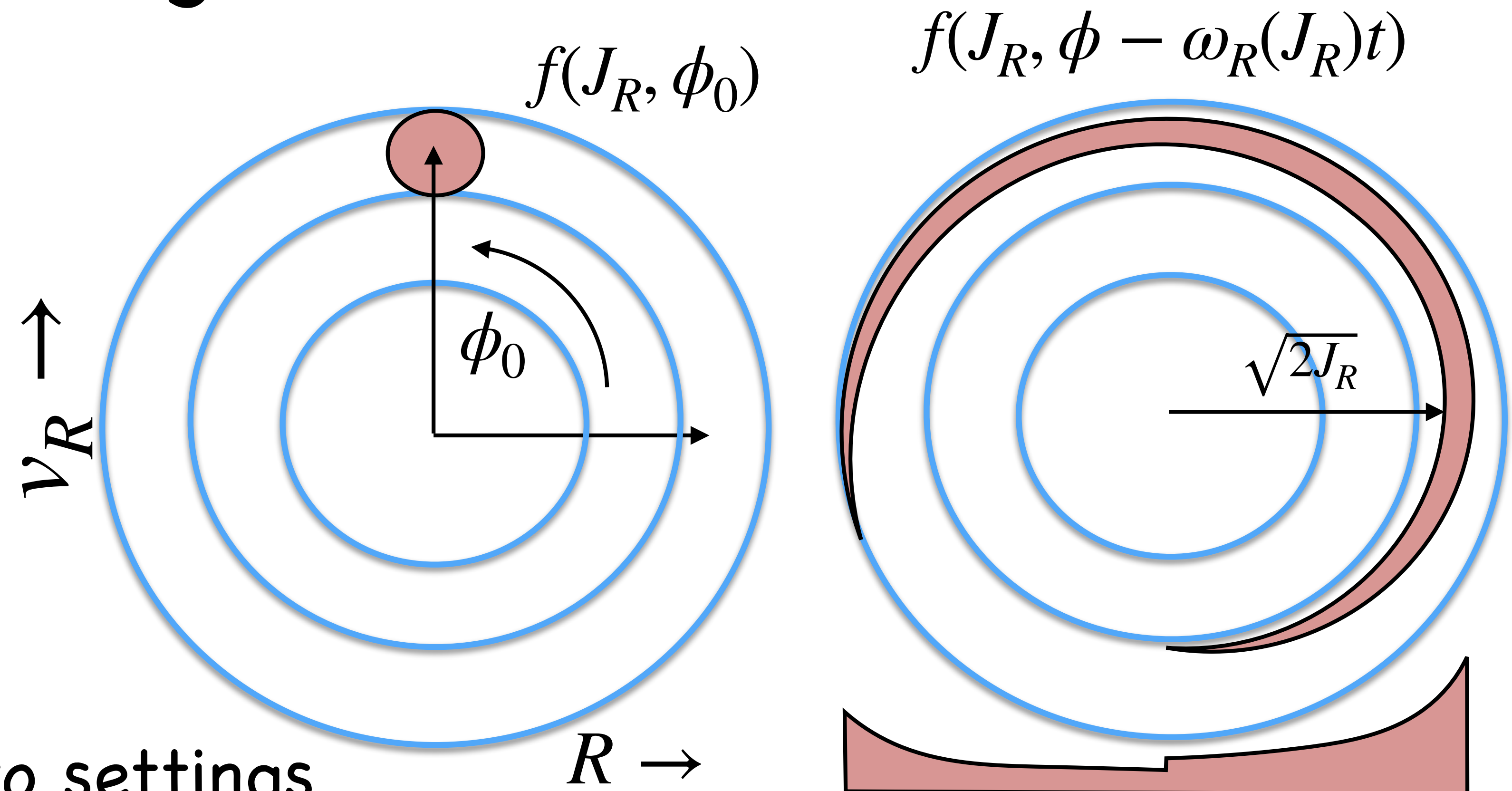
$$\boxed{\Omega_p = \frac{\mathbf{v} \cdot \nabla_{\mathbf{x}} f}{\nabla_\theta f}}$$ at velocity peaks



→ Bad assumption on distribution function!

Phase wrapping
(1 deg freedom)

$$\phi = \phi_0 + \omega_R(J_R)t$$



Two settings

1. Minor merger debris originates at a particular velocity and position (e.g. elliptical galaxies with shells)
2. Galaxy disk is perturbed resulting in an uneven distribution in phase space (Minchev+09)

Phase wrapping

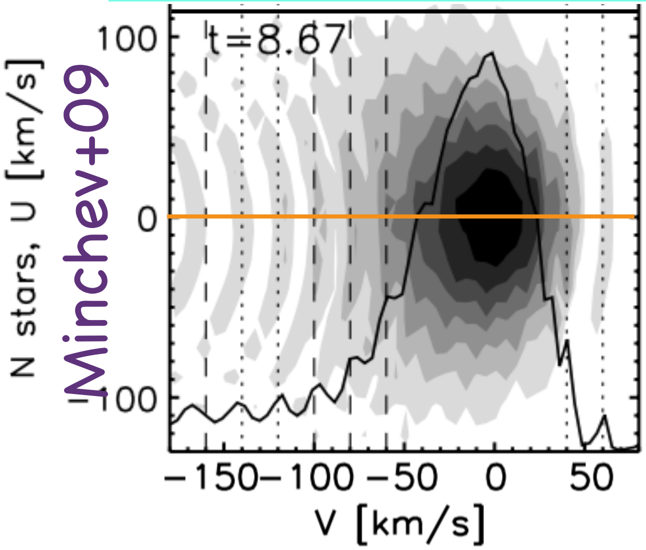
$$\boxed{f(\mathbf{I}, \boldsymbol{\theta} - \boldsymbol{\Omega}(\mathbf{I})t)}$$

time since perturbation

Satisfies Collisionless Boltzmann eqn if Hamiltonian is independent of time and angles

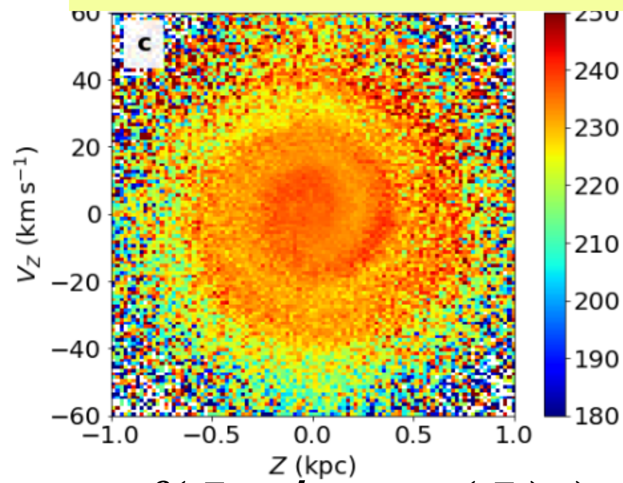
Epicyclic freedom

Minchev+09



No dependence on azimuthal angle, arcs are symmetrical about the u=0 line

Vertical freedom



Antoja+18

$$f(L, J_r, \phi - \kappa(L, J_R)t)$$

$$\phi(L, E) = \phi_0 + \kappa(L, E)t$$ Epicyclic angle

$$f(J_z, \phi_z - \nu(J_z)t)$$

Also see Monari+18

Weight assumes an initial skewed distribution

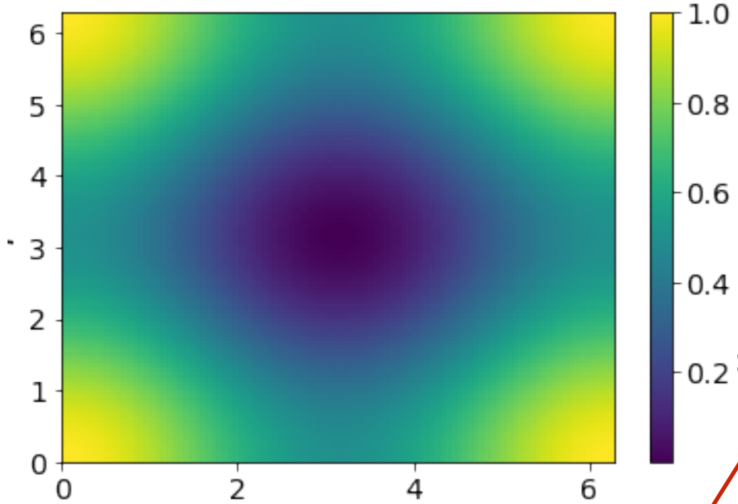
$$w(L, E) = \exp(-e/e_0)[\underbrace{1 + e^2\cos(\kappa t)}_{\text{Initial epicyclic distribution is lopsided}}]$$

eccentricity e(L,E)

Phase wrapping azimuthal+epicycle

Number density at the time of perturbation

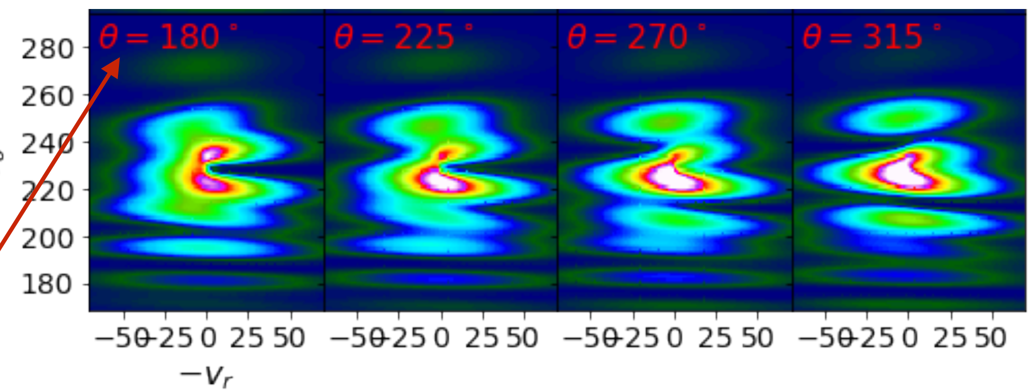
epicyclic angle φ



azimuthal angle Θ

$$\boxed{f(\mathbf{I}, \boldsymbol{\theta} - \boldsymbol{\Omega}(\mathbf{I})t)}$$

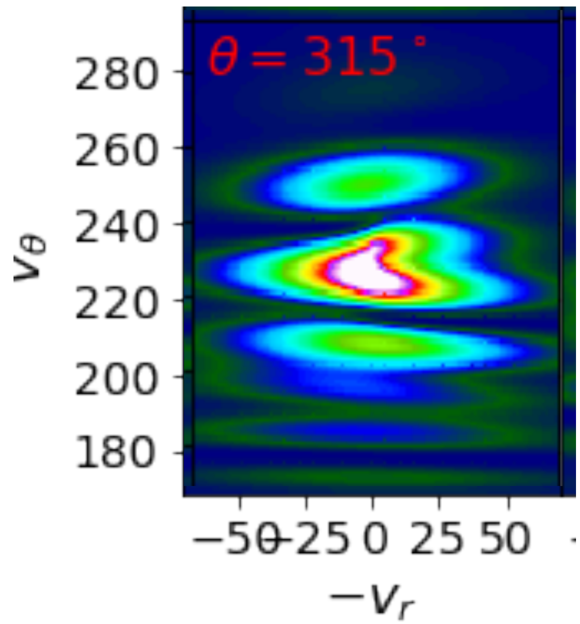
Number density in velocity distributions 2 Gyr later

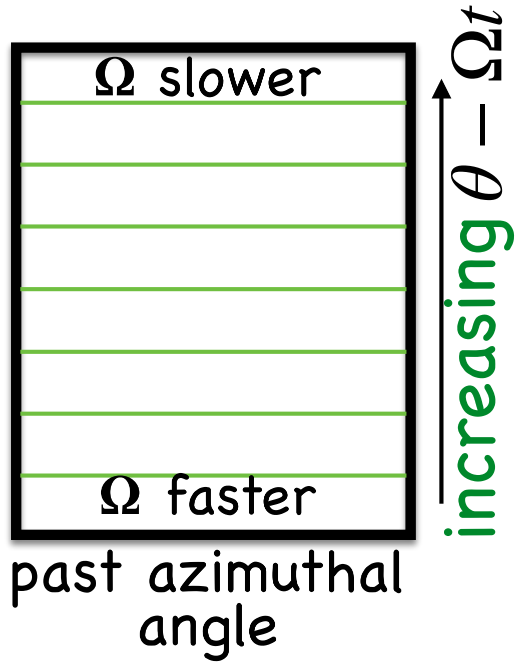


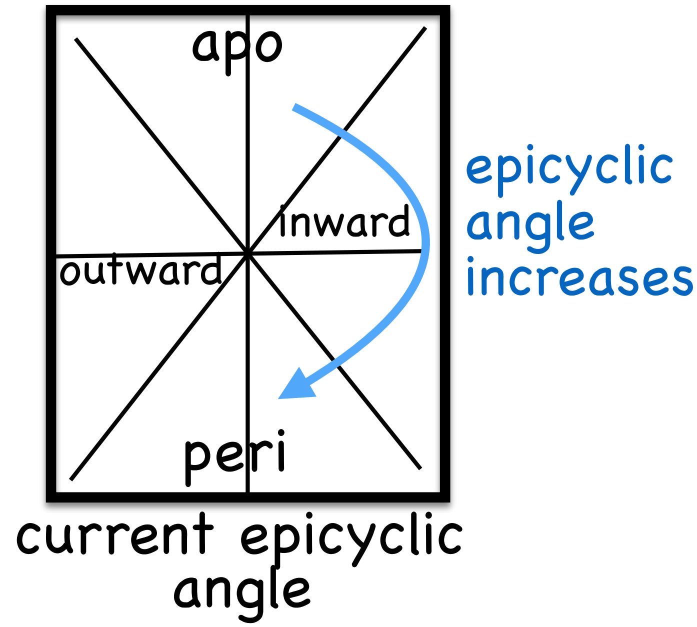
galactocentric angle of Sun's current position w.r.t to perturbation

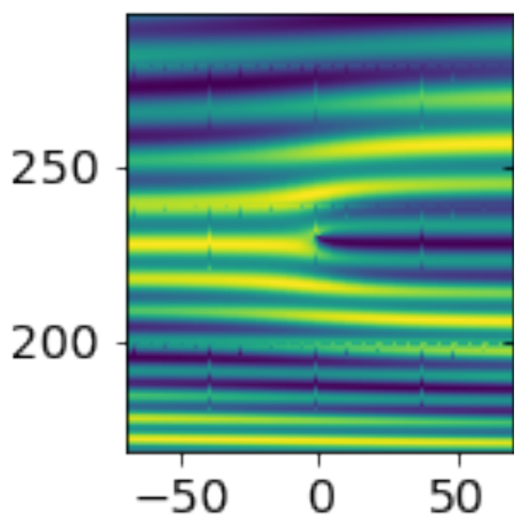
Gaps in velocity distribution in phase wrapping modes
Horizontal features nearly aligned with angular momentum

Phase wrapping azimuthal+epicycle









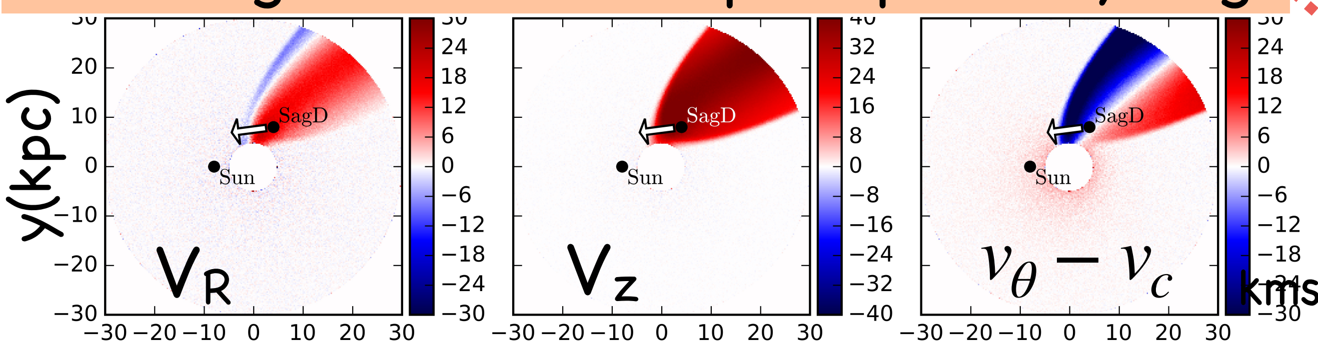
$$\cos(\theta - \Omega t)\cos(\phi - \kappa t)$$ t=2 Gyr

Gives a tilt to streams
Tilts could also come from the initial perturbation

Impulse Perturbations to Milky Way disk

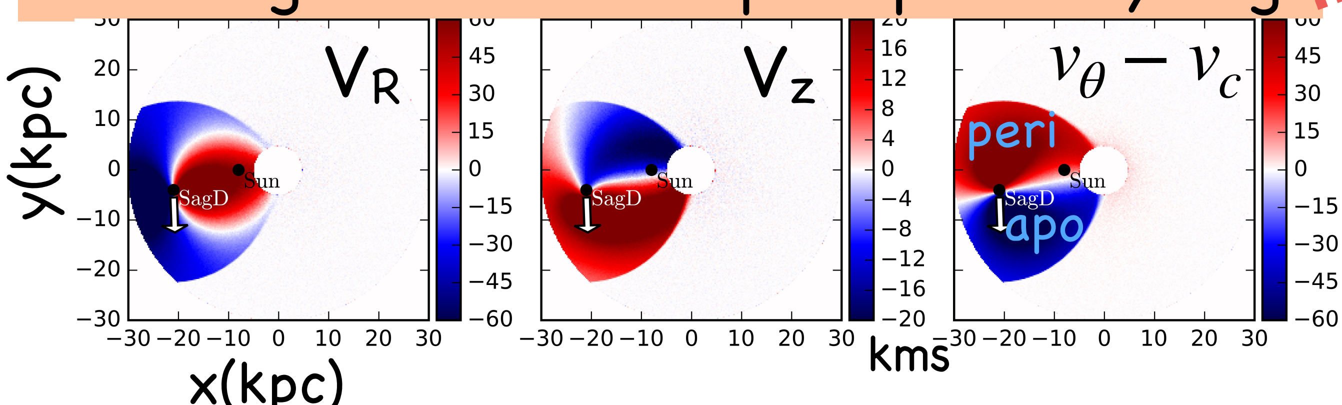
Epicyclic/ Azimuthal/ Vertical

From Sagittarius dwarf periapse 1 Gyr ago



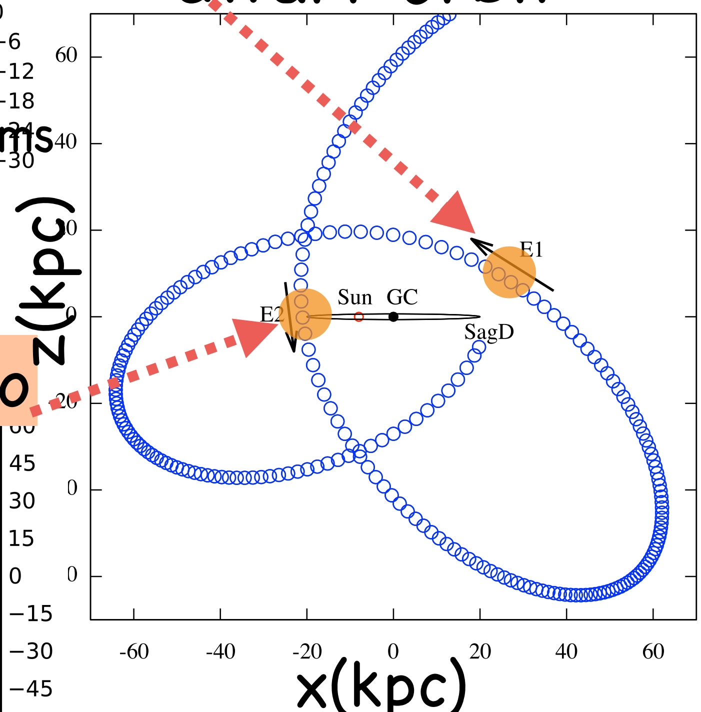
One vertical epicycle peak, two radial in a localized region in azimuth

From Sagittarius dwarf periapse 2 Gyr ago



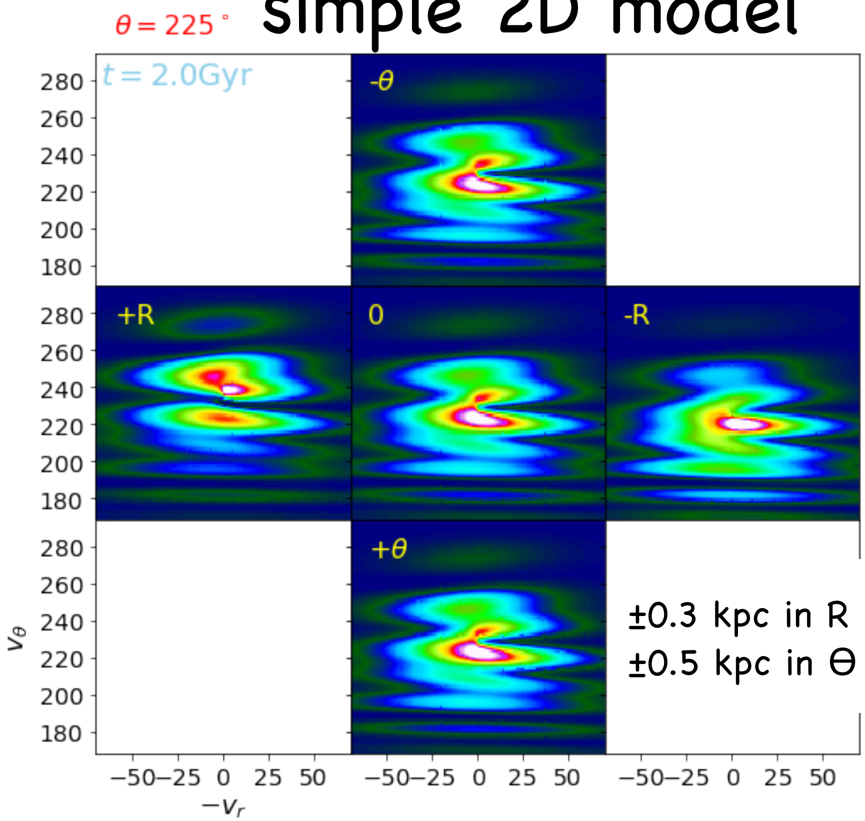
Two vertical epicycle peaks, two/four radial

Sagitarius dwarf orbit

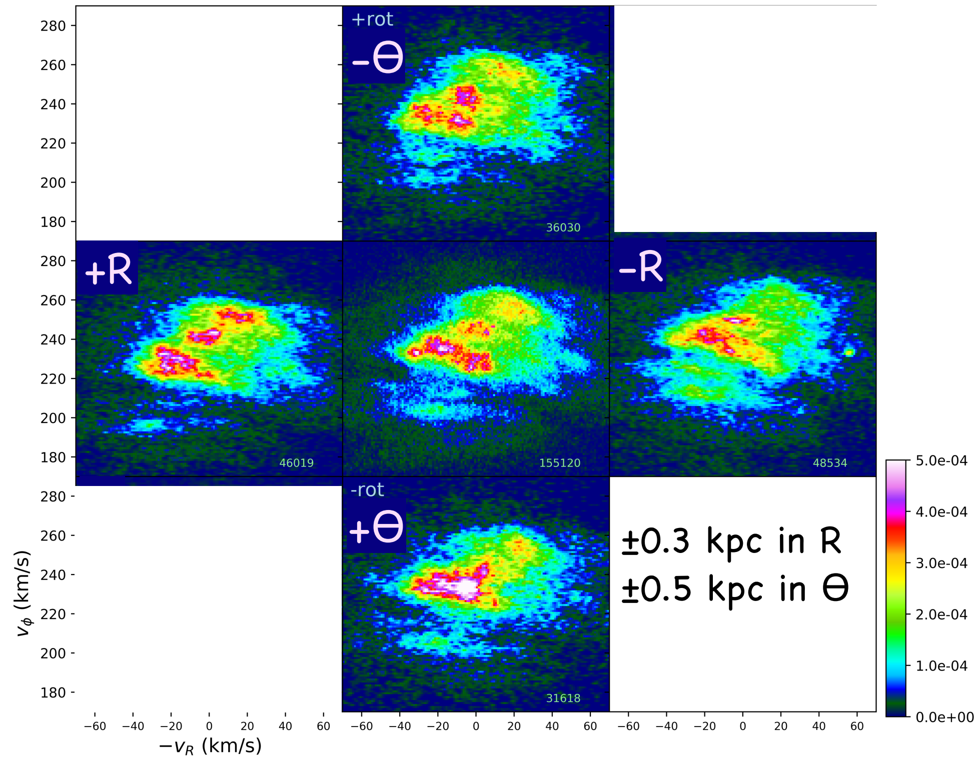


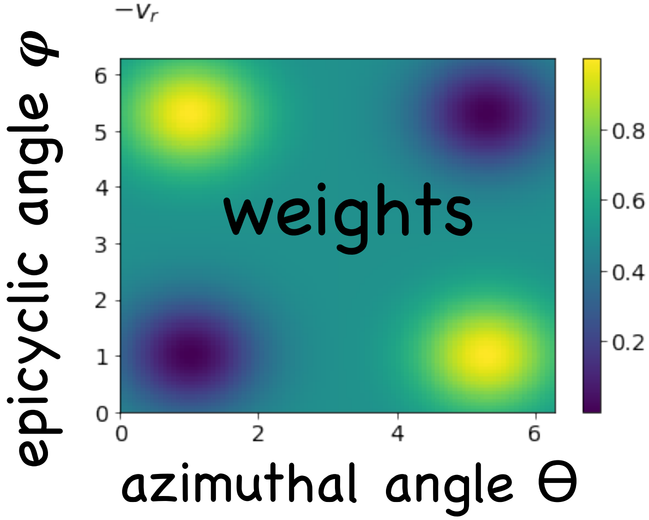
delaVega+15 vertical gradients seen -no self gravity

simple 2D model



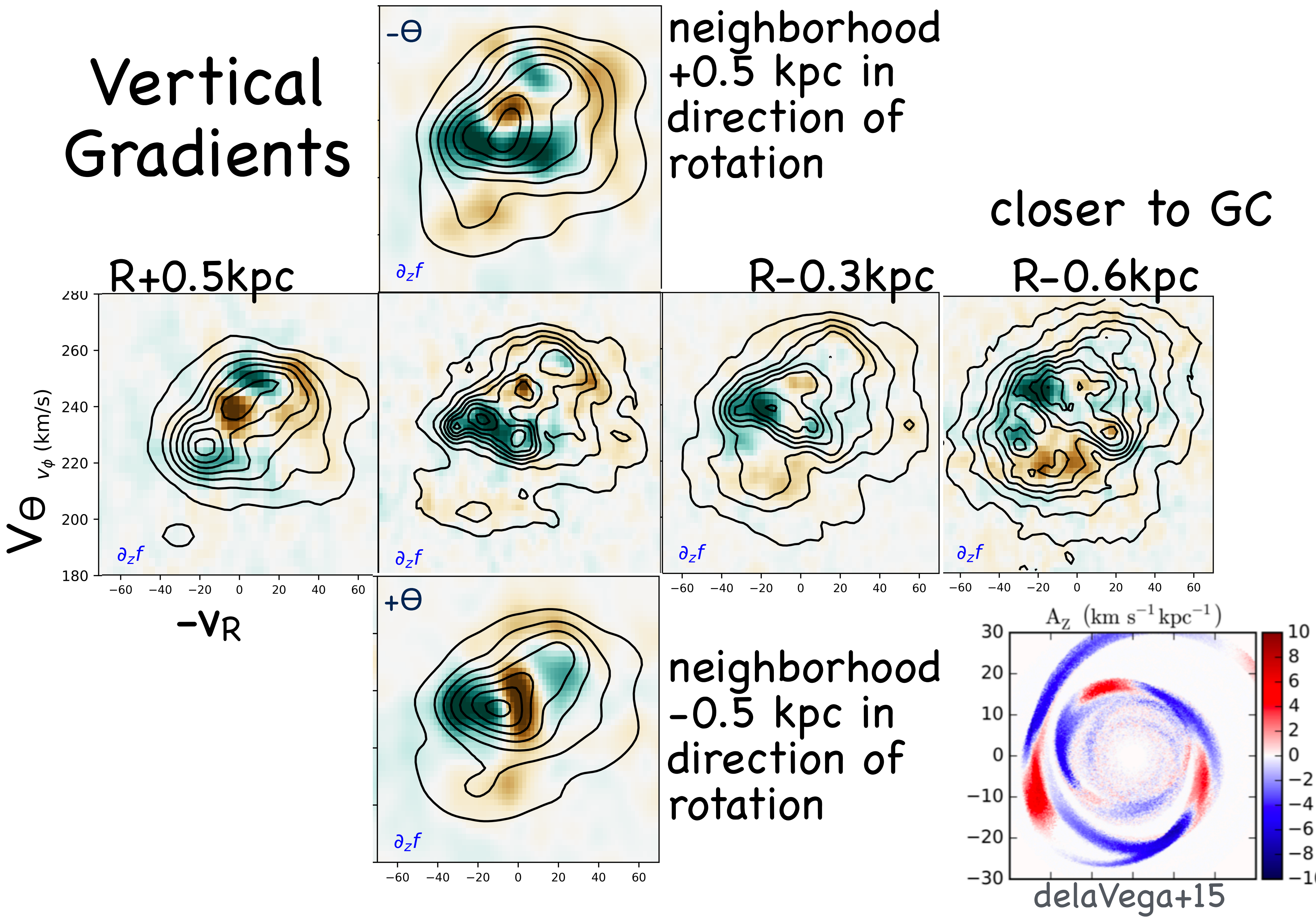
GAIA DR2 data





High eccentricity feathers seen in velocity distributions might be due to phase wrapping of perturbations from a dwarf galaxy, however inversion problem is hard ...

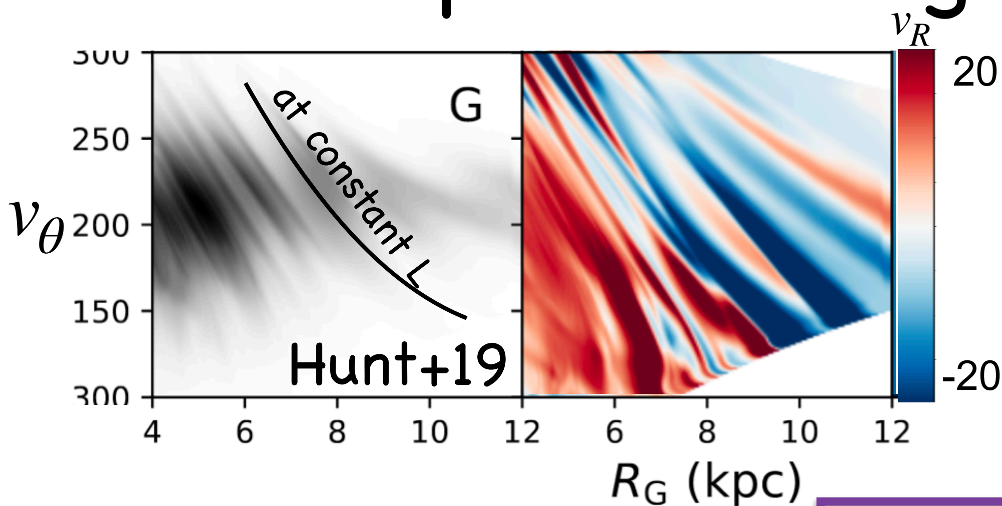
Vertical Gradients



Epicyclic phases and Vertical Phases

- Vertical degree of freedom may help to devise a strategy for inverting to describe past perturbations on the Galactic disk
- Self gravity is important (Larry Widrow's bending and breathing waves) — though bending/breathing and vertical gradients do not require self-gravity within a phase wrapping picture
- Following perturbation, background potential is adiabatically varying?

Features depend on angular momentum L_z



frequencies:
angle rotation rate,
epicyclic, vertical

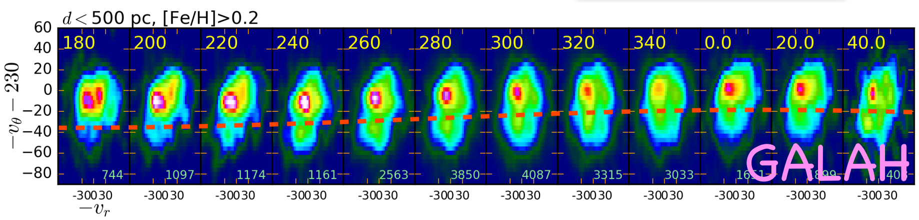
Phase wrapping view

$$\boxed{f(\mathbf{I}, \boldsymbol{\theta} - \boldsymbol{\Omega}(\mathbf{I})t)}$$

- Gradient in f() dominated by variations in frequencies and these depend on L_z
- Large time t since perturbation means tightly wrapped features, nearly parallel to L_z
- Time since perturbation 1-2 Gyr (e.g. Monari+18) the range is wide because there could be substructure in the initial perturbations
- Phase wrapping should decrease in amplitude in inner Galaxy

Features depend on angular momentum L_z

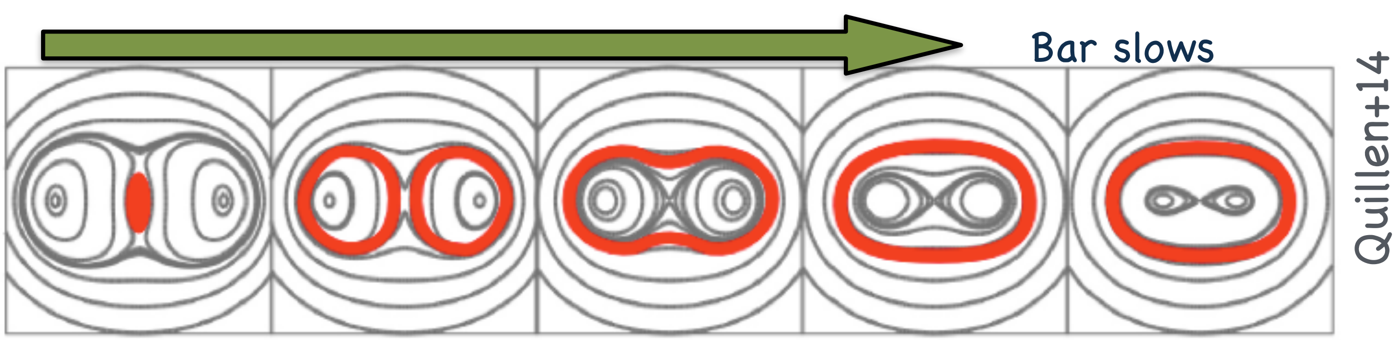
Resonant view $f(J_R, J_s)$



- L sets the rotation period so the location of orbital resonances
- Gradient in f() strong near narrow resonances
- Dependence of Hercules stream on L (GALAH)

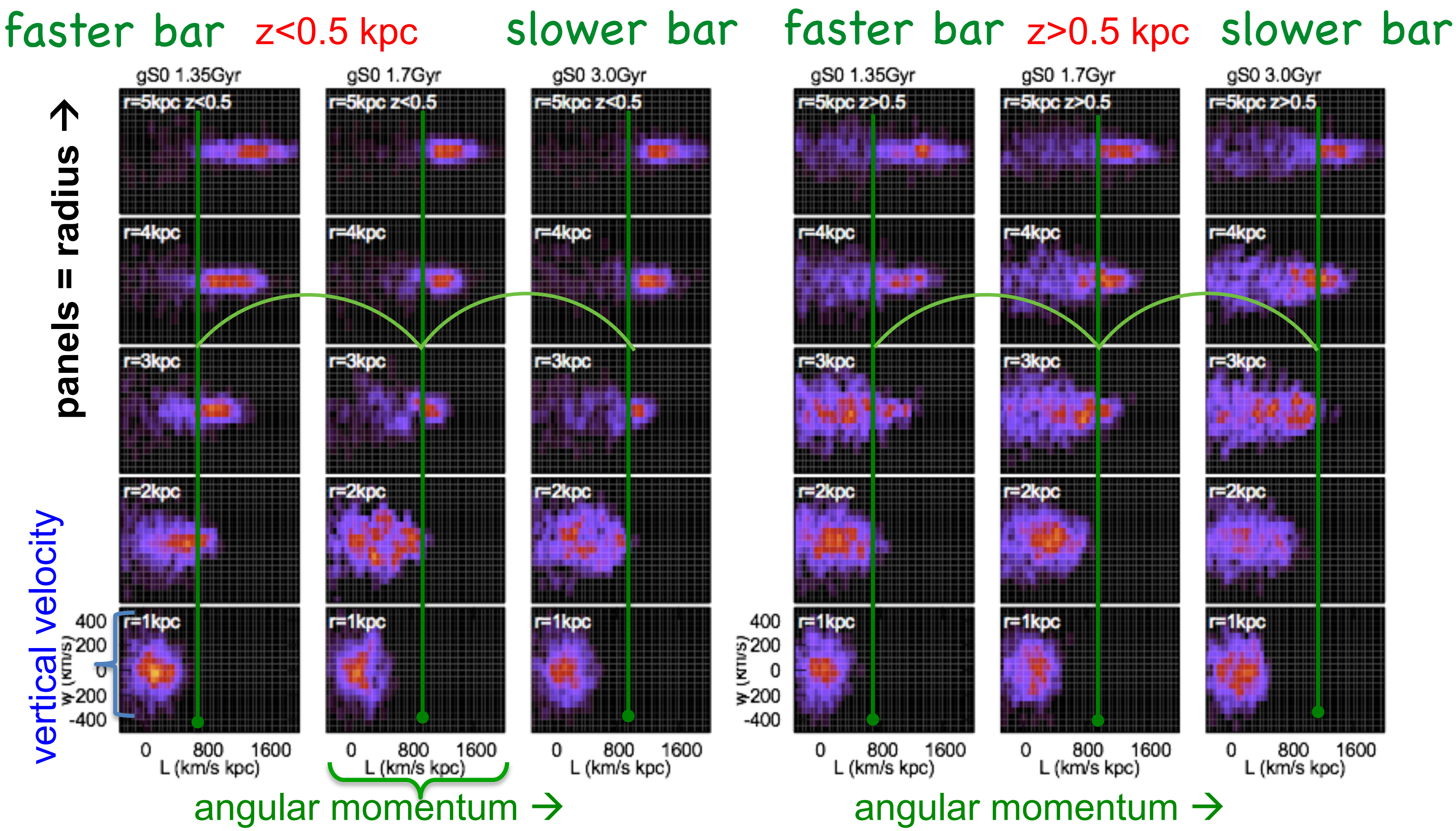
- Many features means many resonances (e.g. Monari+18, Michtchenko+18) — but are high order resonances strong enough?

Time dependent behavior? Resonant heating/capture?
In the X-shape bulge, the 2:1 vertical resonance is the only bar resonance strong enough to lift stars out of the plane



v_z vs L_z distributions in a simulated bulge

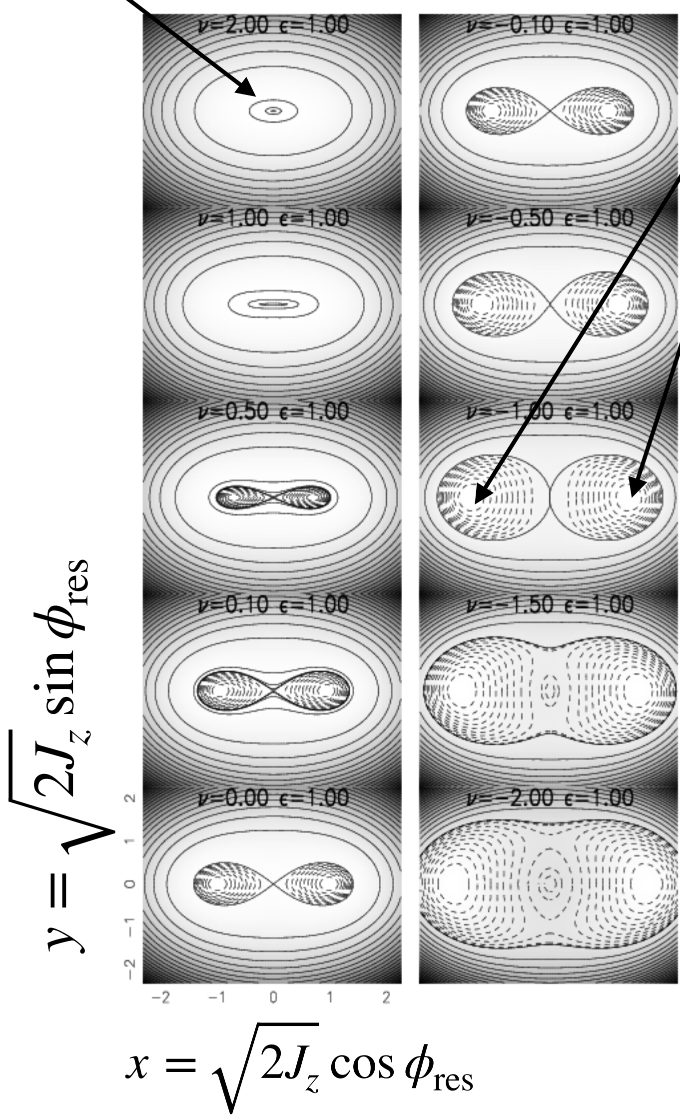
panels = time→ measured in N-body simulation



in plane stars are rare below a particular angular momentum value set by the 2:1 vertical resonance

Hamiltonian model for the bulge's X/peanut

orbits in the plane



Banana orbits

$$H = H_0 + H_1$$

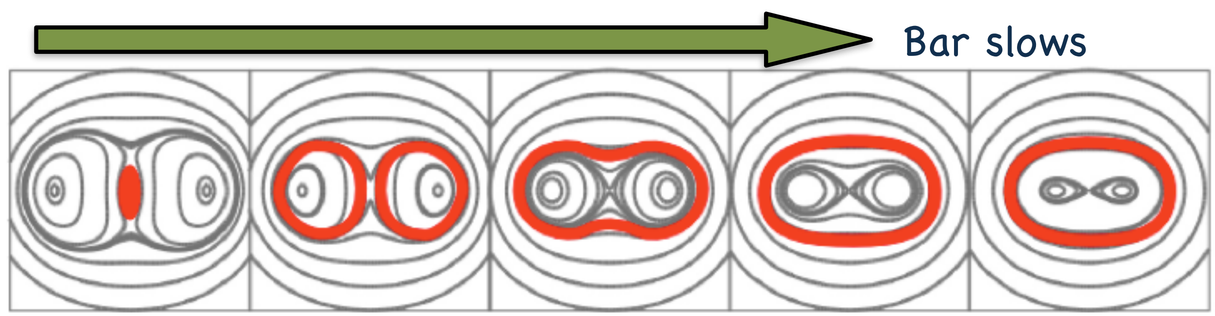
$$H_0 = J_\theta \Omega + J_R \kappa + J_z \nu$$

unperturbed motion

$$\phi_{\rm res} = \phi_z - 2(\theta - \Omega_p t)$$ resonant angle

$$H(J_3, \phi_{\rm res}) = aJ_3^2 + \delta J_3 + \epsilon J_3 \cos 2\phi_{\rm res}$$

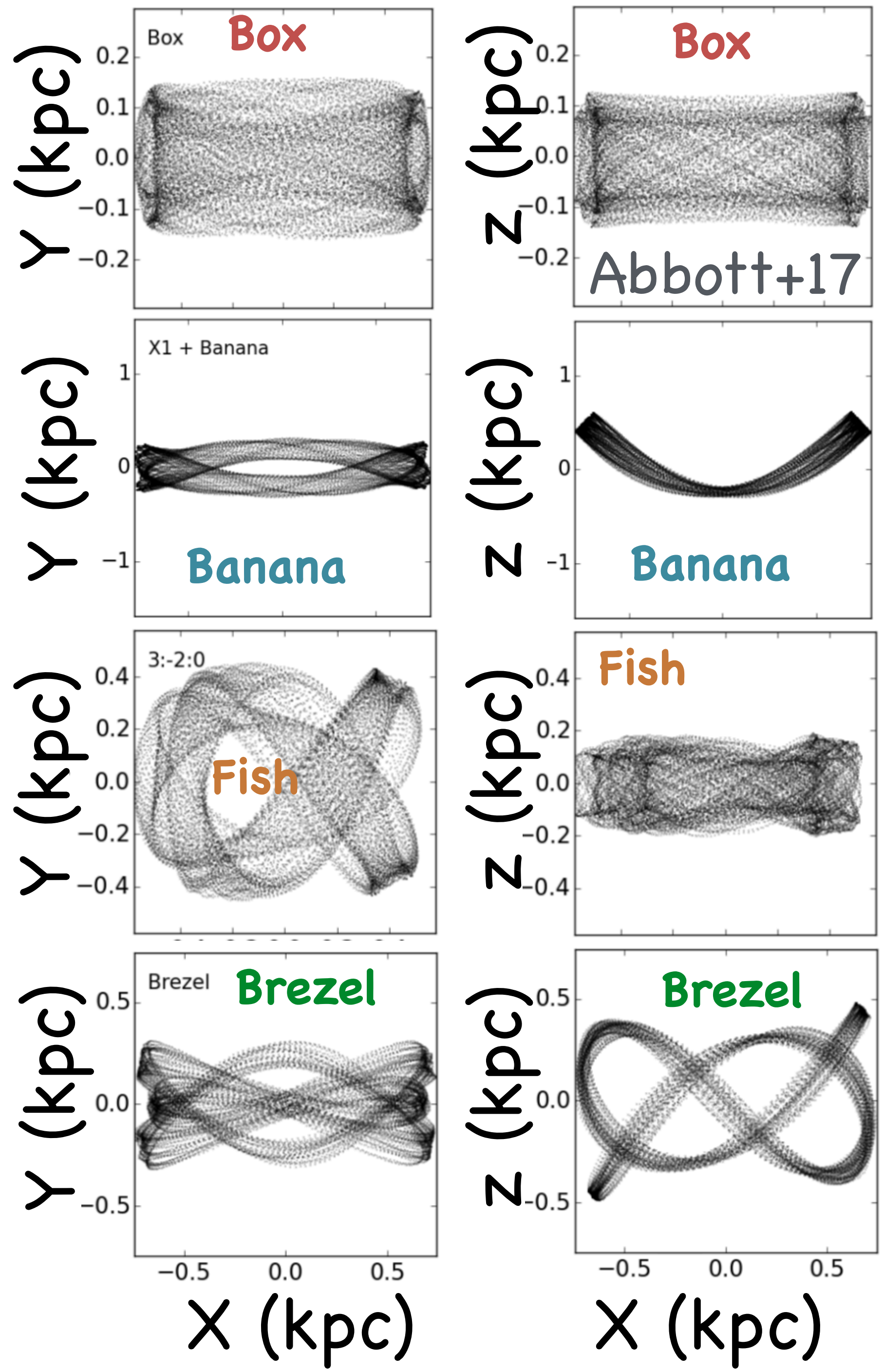
bar perturbation



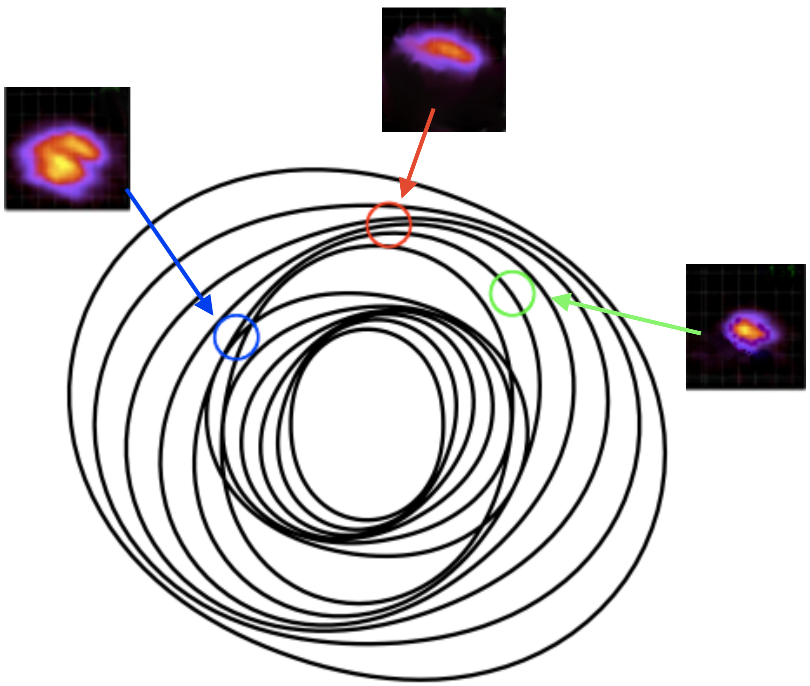
Quillen+14

Orbit Shapes In the Bar's X

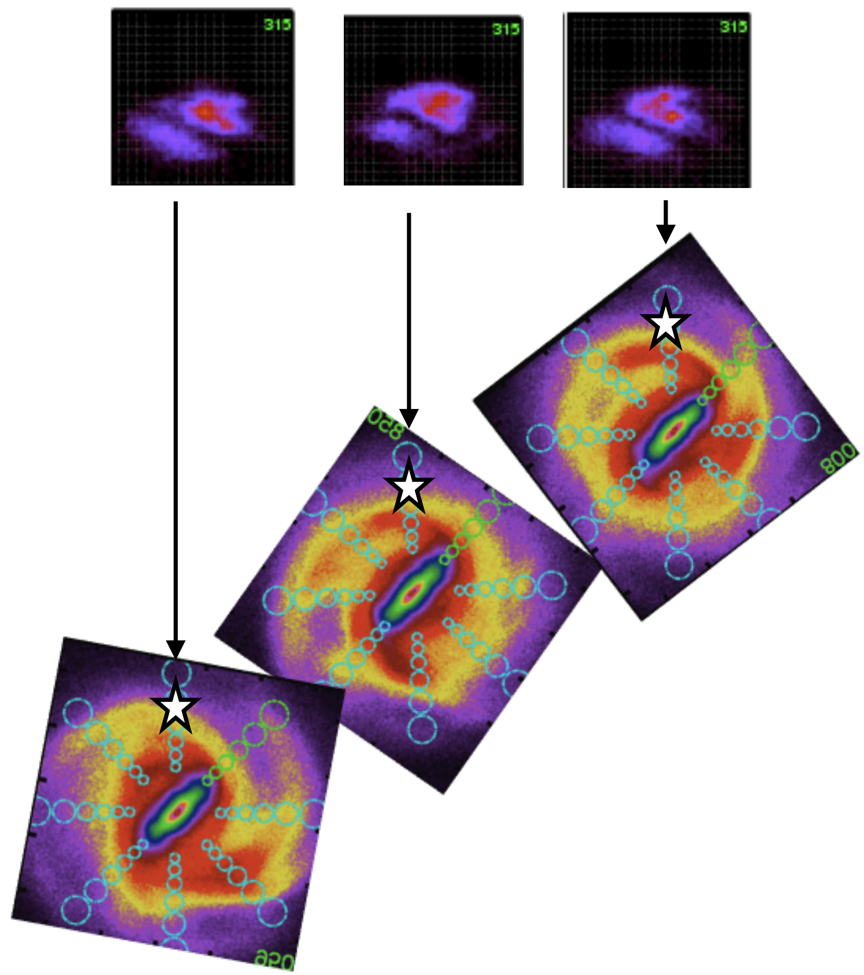
- Abbott+17 classifying orbits in a N-body finding only a small fraction in bananas.
- Does this mean a resonant heating model is wrong?
- No: The resonance is thin and leaves stars distant from periodic orbits.
- The resonance provides a lifting mechanism, needed to explain a growing X as the bar continues to slow down after buckling
- As the resonance moves outward, the lifted orbits can become brezels, fish and boxes



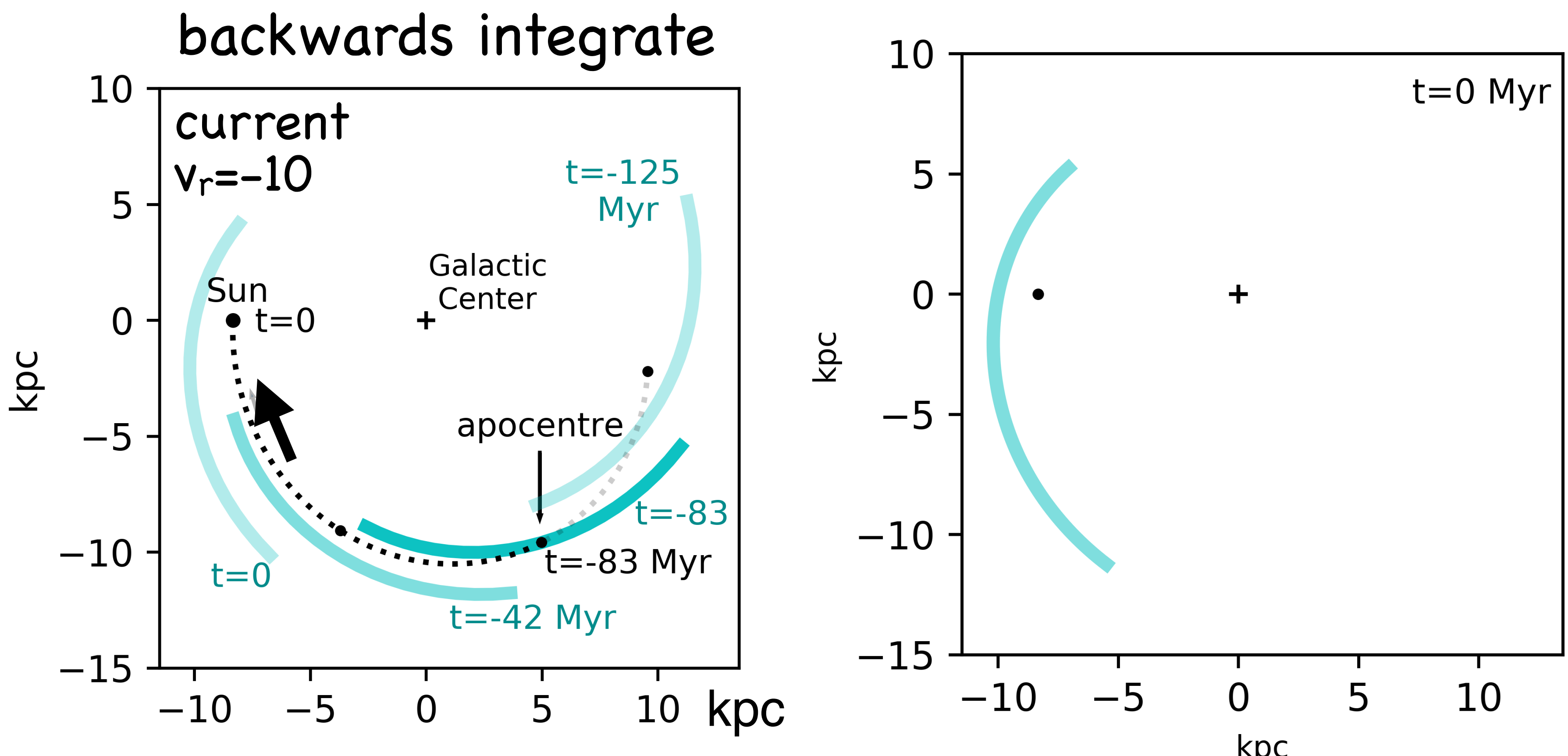
Discontinuities in velocity distributions and spiral structure



relation between orientation vectors and velocity distribution



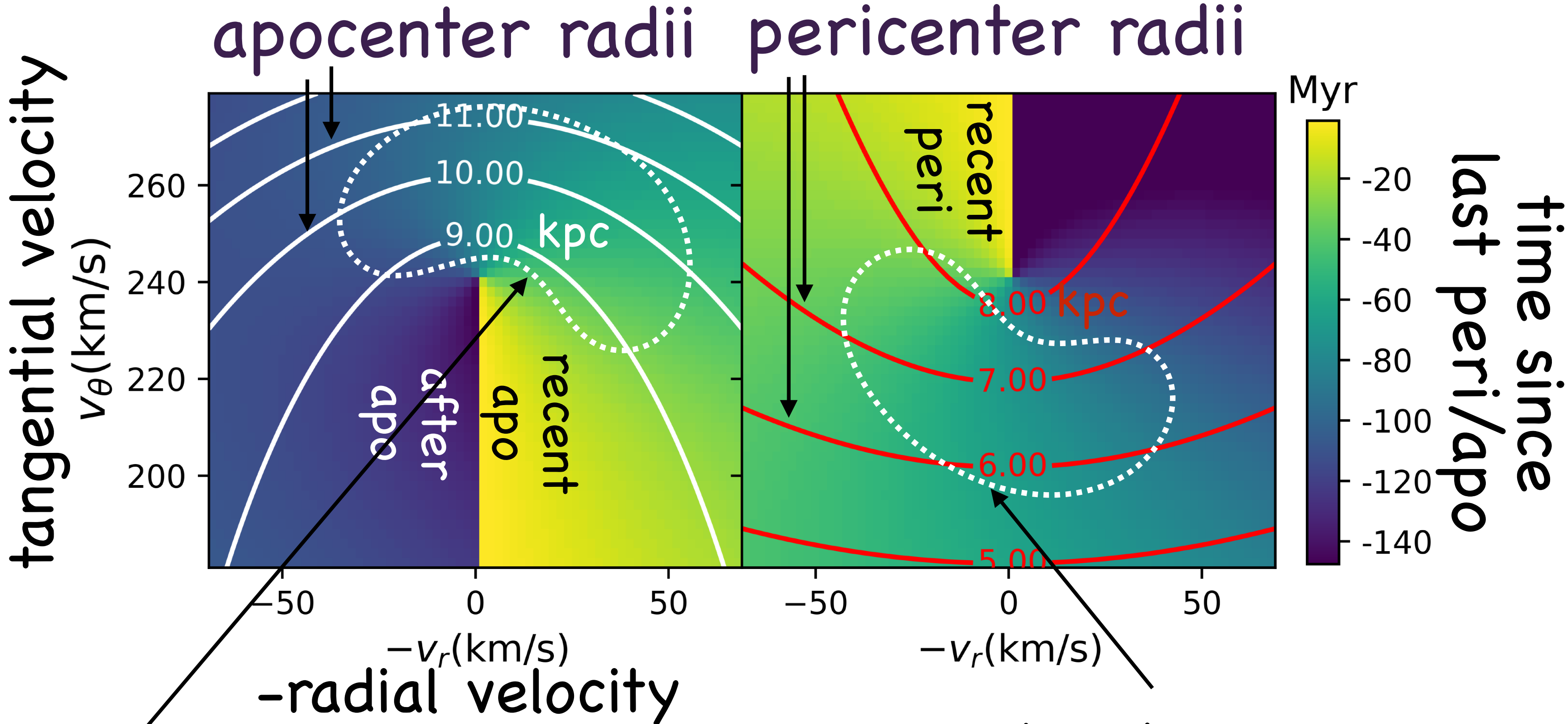
An orbit that grazers the Perseus arm 83 Myr ago



Bumps and wiggles seen in rotation curves imply that spiral arms are strong enough to perturb stars by 10-30 km/s

-Also see Martinez-Medina+19

Backwards orbit integration



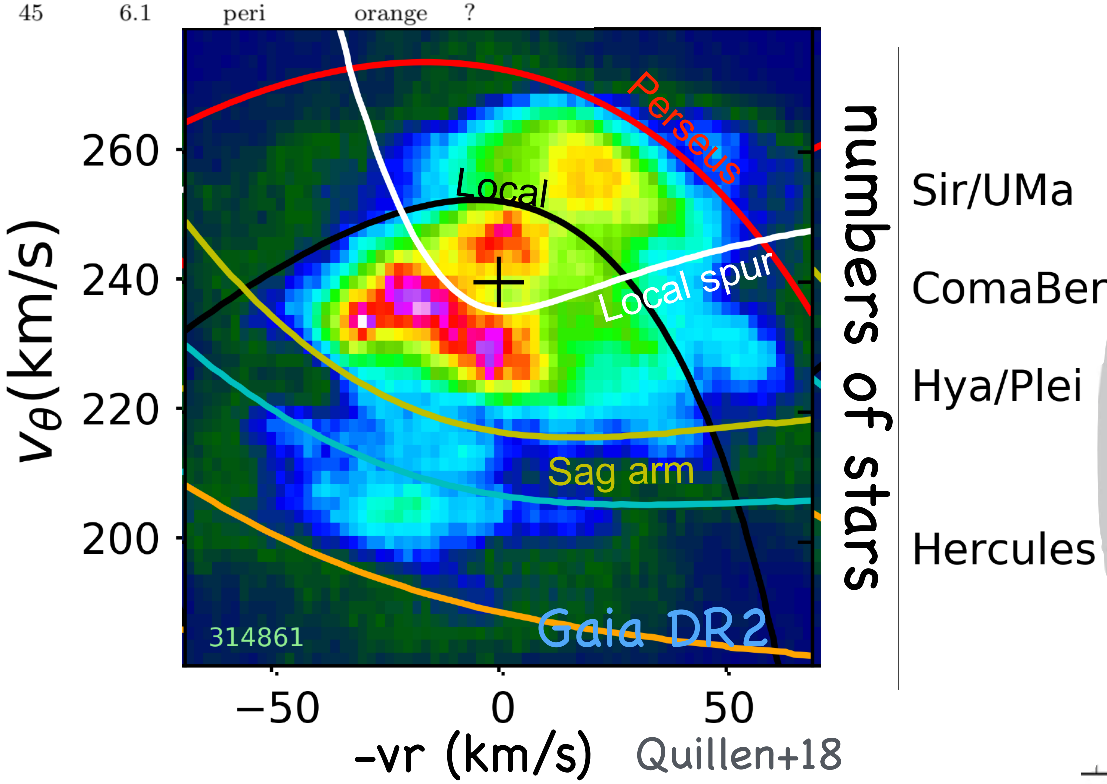
Stars recently at apocenter moving inward into the solar neighborhood

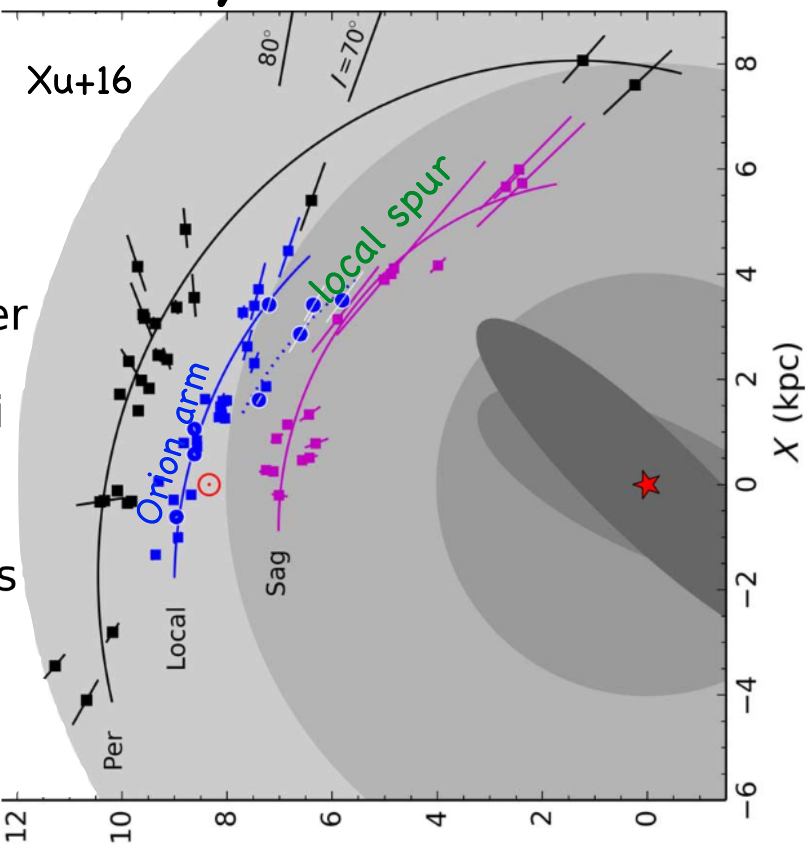
Stars born near pericenter, move outward into solar neighborhood

Table 1. Spiral arm boundaries

Speed Ω_s	radius R_{s0}	peri/apo	color	arm
20	10.0	apo	red	Perseus
27	9.2	apo	black	Local Arm
29	8.0	peri	white	Local Spur
33	7.0	peri	yellow	Sag, BR
35	6.5	peri	cyan	Sagittarius
45	6.1	peri	orange	?

Apo/Pericenter spiral arm grazing model for divisions in GAIA DR2 velocity distributions





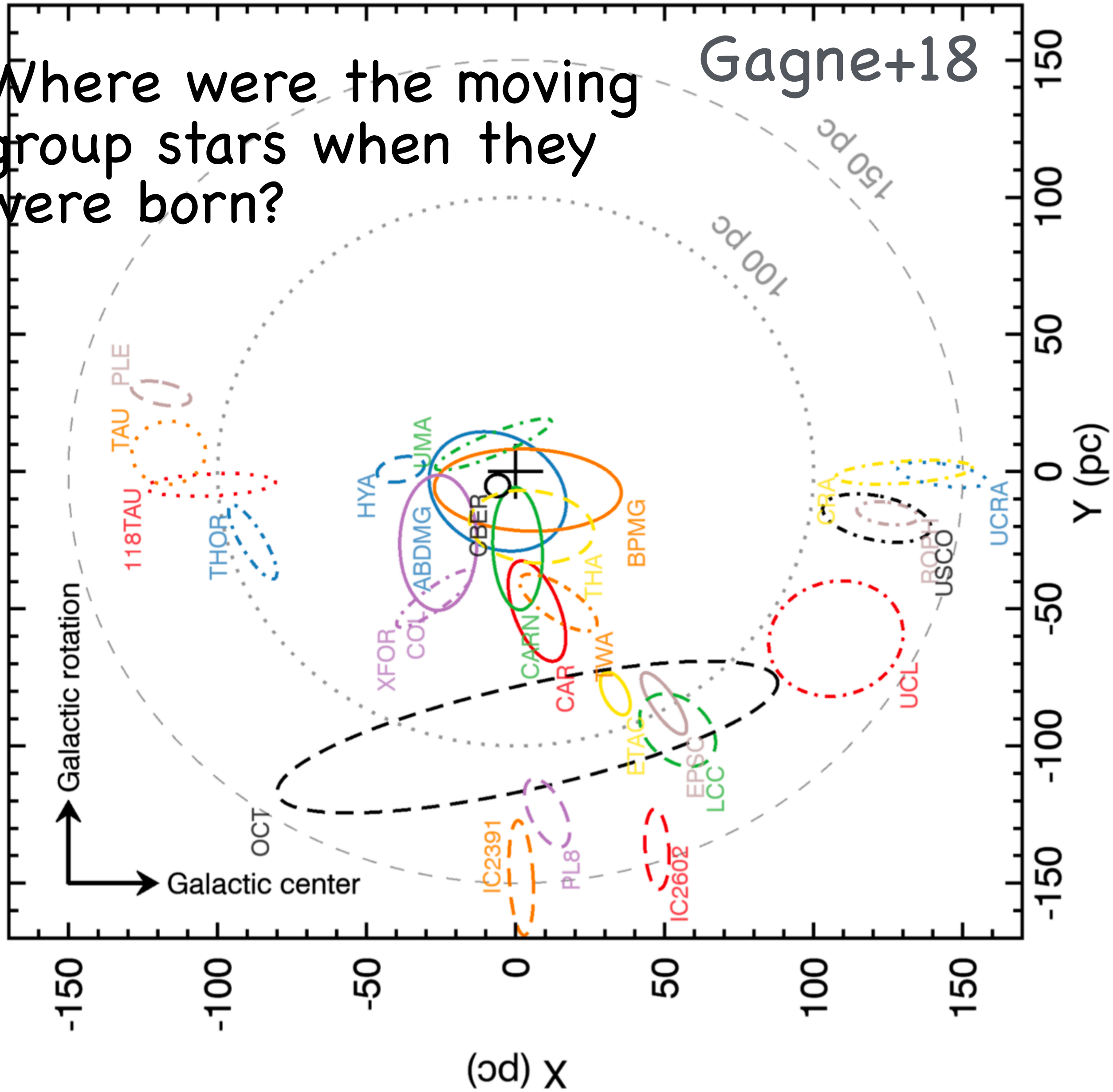
Nice curves on the uv plane!

Dependent on pattern speeds, winding angle and offsets

Not great for high eccentricity feathers

Moving groups in the Galactic plane

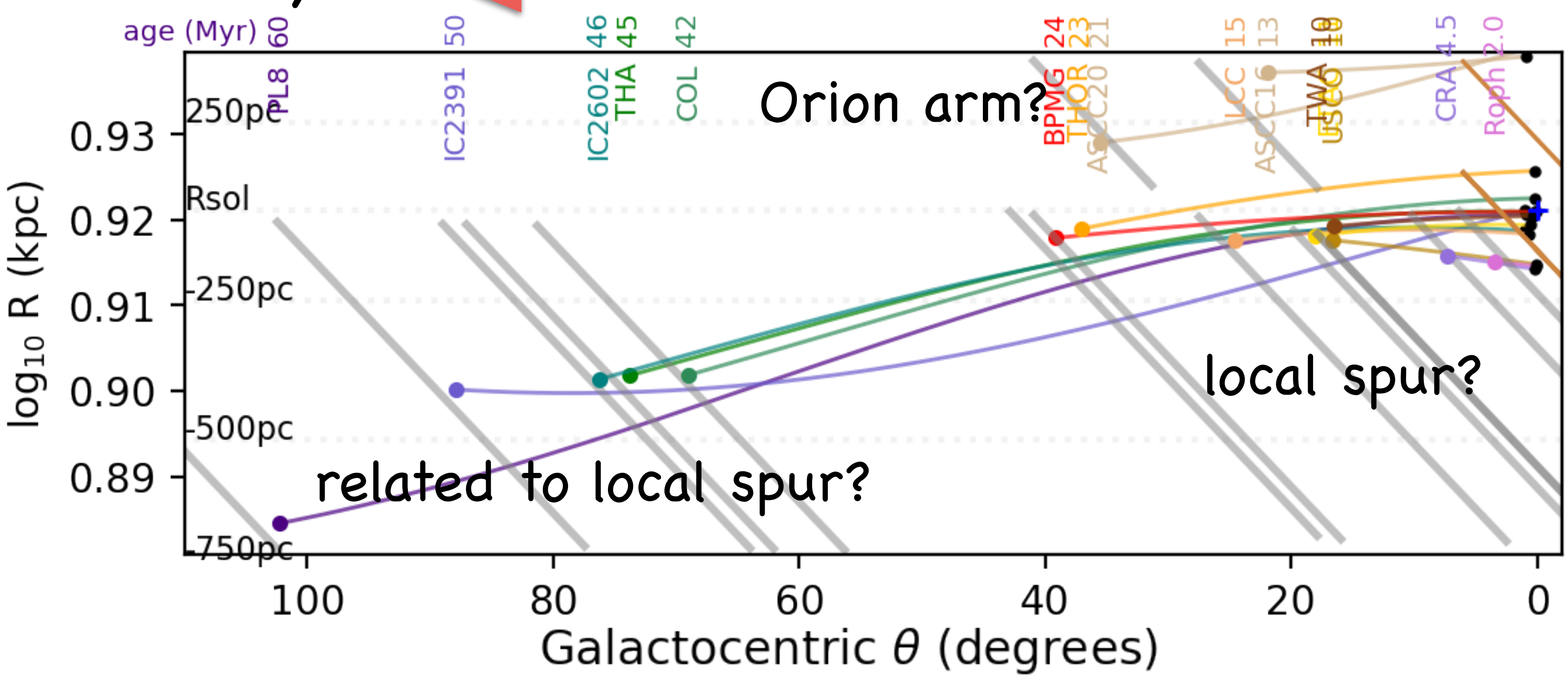
Where were the moving group stars when they were born?



Orion

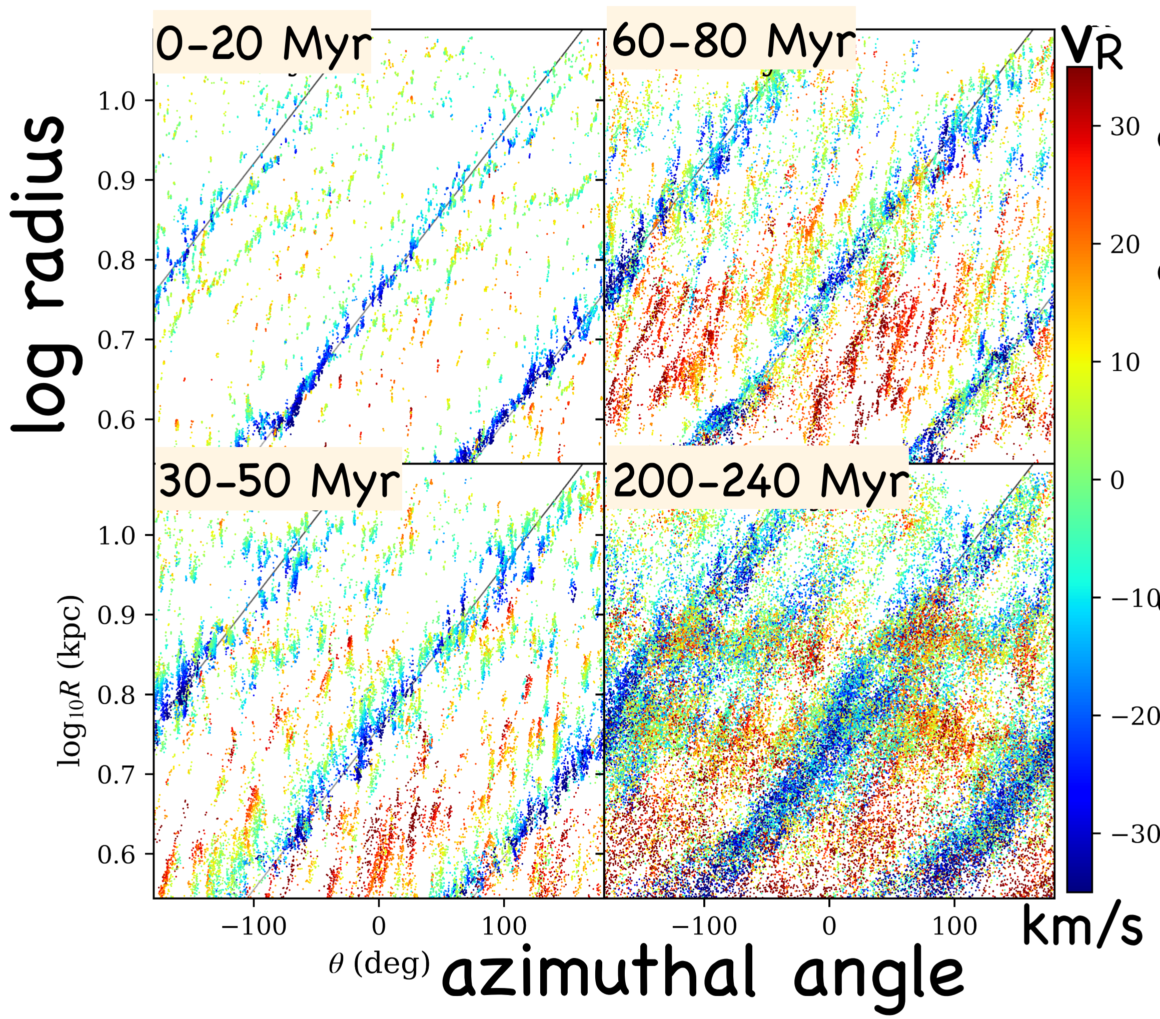
Where were the moving group stars when they were born?

60Myr Now



- Many of these are moving out to their current position
- All near ones are maybe from Local spur, near corotation
- Orion star formation seems associated with a different feature!

Forced 2-arm spiral GASOLINE2 simulation with star formation by Alex Pettitt



- Colors show radial velocity
- Stars are born moving inward but soon afterward some move outward and away from the birth arm
- Velocities are dependent on spiral potential but azimuthal distribution depends on age

Summary

- Numbers of stars + accuracy of GAIA positions and velocities make it possible to directly work with the stellar phase space distribution function f(x,v,t)
- Abundance of nice dynamical models that give approximations to f(x,v,t) and predict substructure (streaks/gaps) in velocity or action distributions! 🙂
- Time dependent models seem necessary …
- Phase wrapping models are difficult to invert 🤔
- Bar/spiral resonance models perhaps should not depend on weak resonances or should be modified to be time dependent
- Recent locations of spiral arms might be revealed via recently formed stars
- For the future: hybrid models (spiral + perturbations + resonant) and improved approximations …