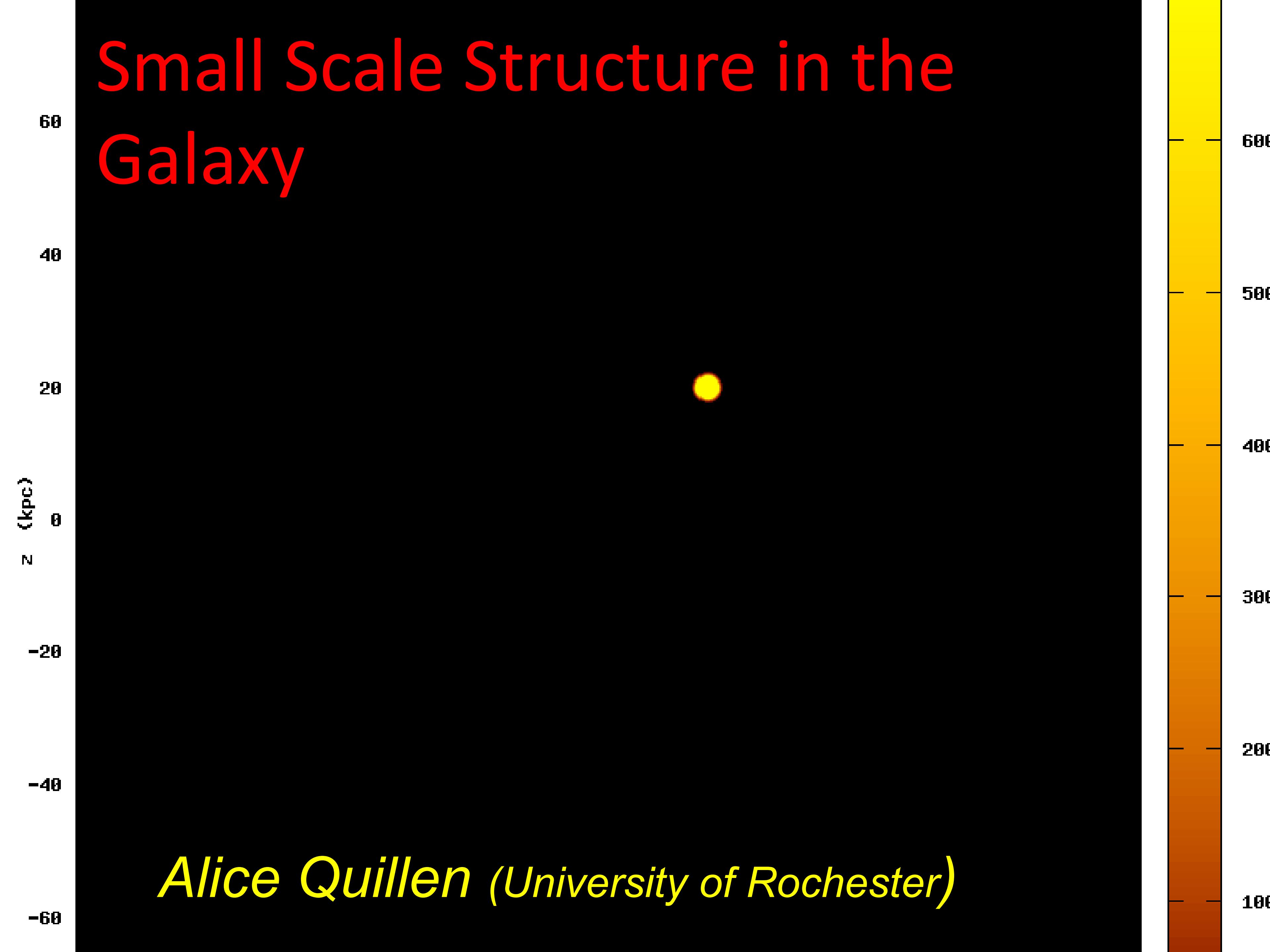
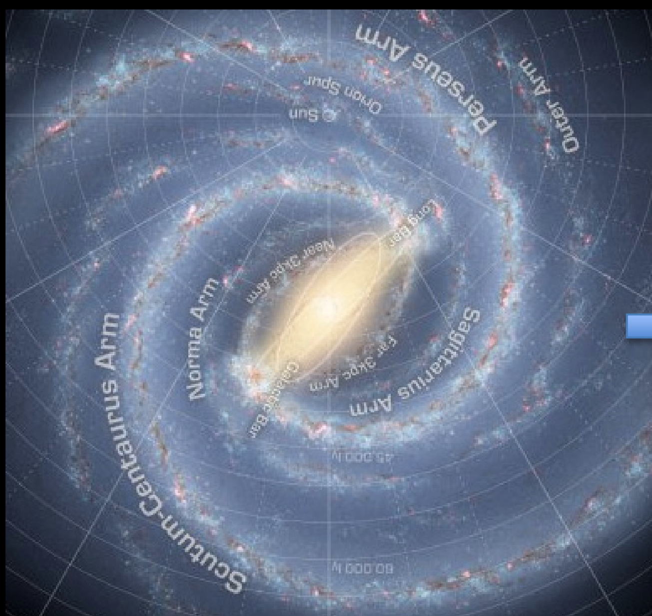
Small Scale Structure in the Galaxy



Alice Quillen (University of Rochester)

Morphology of the Milky Way

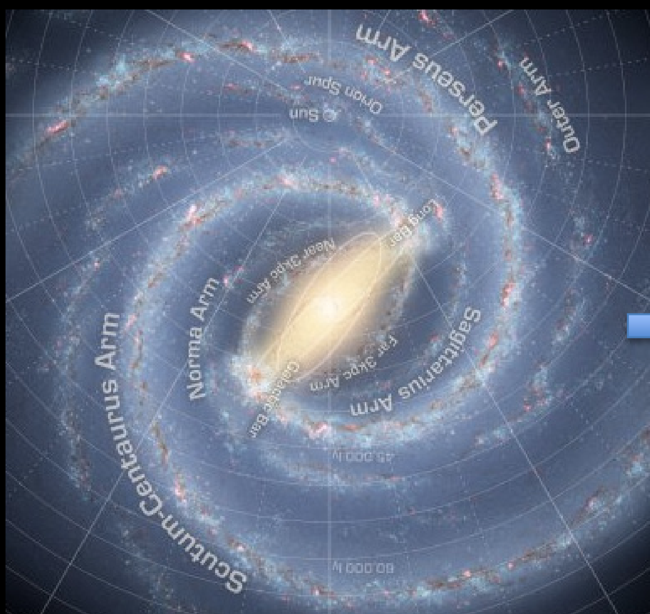
Distances uncertain.
Projection is difficult.



Cartoons favor 2 or 4 armed symmetrical structures because they are assumed.
Dominant constrains are the tangents

Burkhard Fuchs

test particle simulations have primarily explored steady state spiral models. What is the signature of a transient or varying spiral wave?

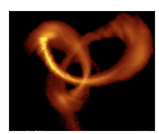


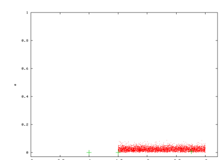
Integrating many particles on a GPU

- Test particle simulations
- Direct N-body simulations with tracers
- QYMSYM

Collaborators :

Justin Comparetta

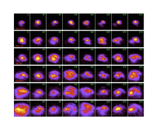




Alex Moore (QYMSYM)

Ivan Minchev (migration, resonant heating)

Michaela Bagley, Jamie Dougherty



Richard Edgar (sneth.pas.rochester.edu)

Challenges

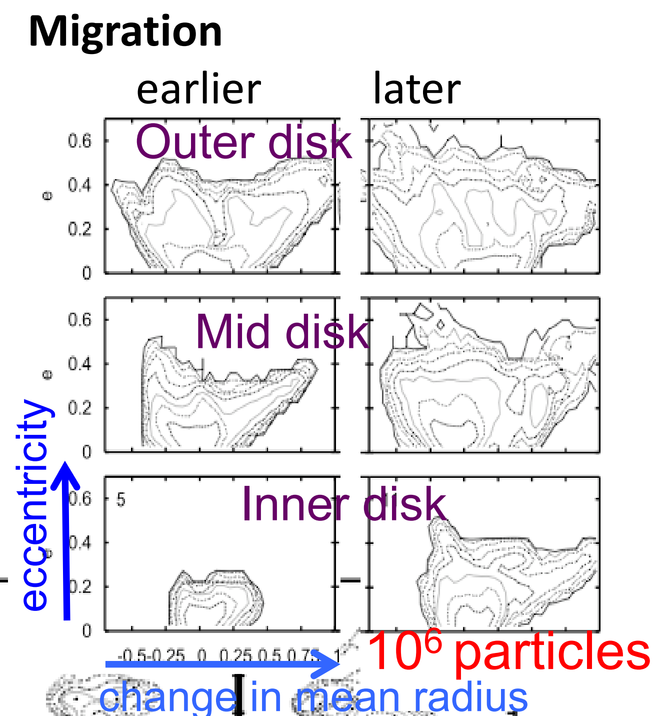
Uncertainty in mechanisms

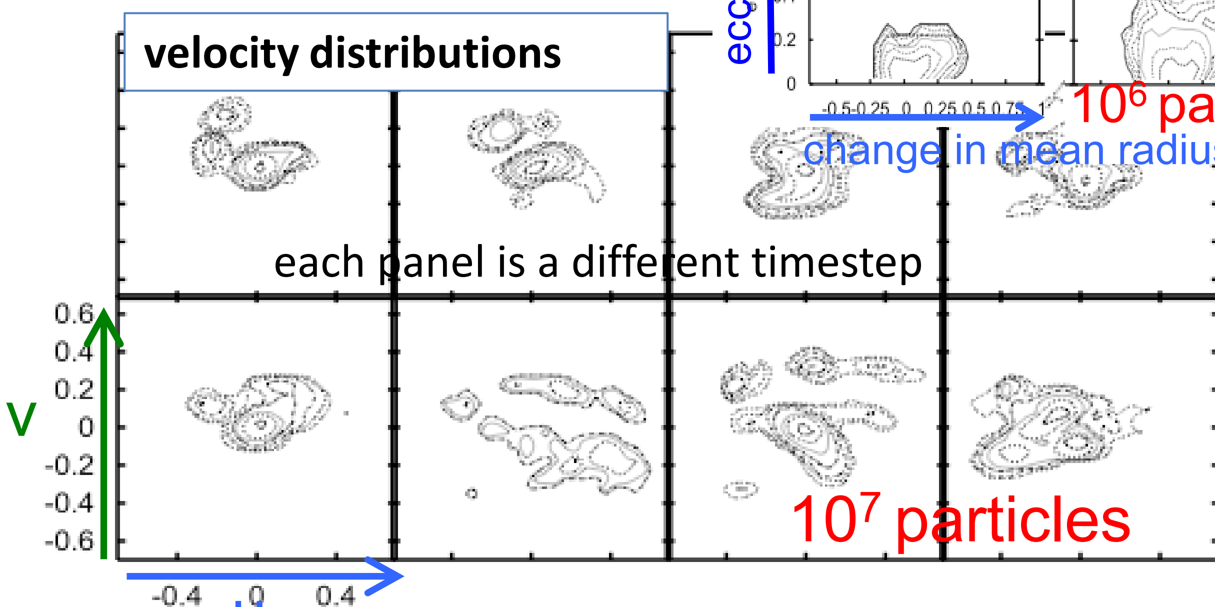
- Spiral structures: modal or transient or coupled?
- Migration, mixing and heating, dependence on time and position, how much due to mergers vs spiral/bar
- Star formation: wave driven vs localized bursts
- Lopsided and warped outer Galaxy (common but possibly important), role of mergers in triggering spiral structure and affective heating and mixing

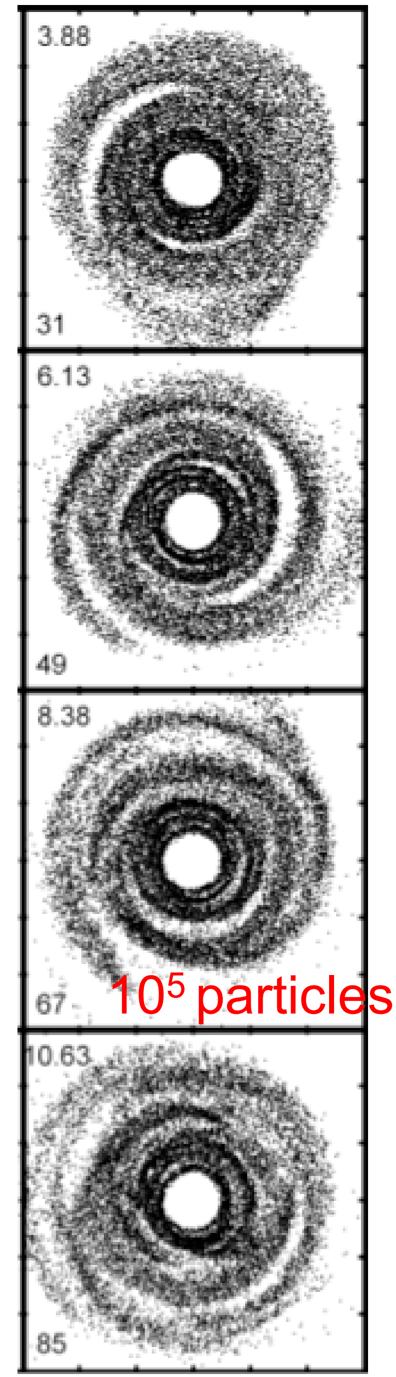
To explain and understand

- Lack of strong correlation between metallicity and kinematics in disk-- Large metallicity scatter in disk
- Structure in velocity fields
- Nature of spiral structure in our Galaxy (patterns, number of arms, lifetimes) -- lack of consensus

Disk perturbed by a low mass satellite passing through the disk







Induced over short timescales: heating, migration, extended disk, warping, lopsidedness, streams

Two topics

1) Galactic disk, Milky Way model

Goal: understand Milky Way disk structure from local velocity distributions observed in forthcoming large surveys. Interpret abundances in terms of formation and evolution (chemical tagging)

2) Tidal tails, e.g., disruption of Sagittarius dwarf

Goal: Constraints on CDM, dark matter sub-halo distribution from tidal tail substructure

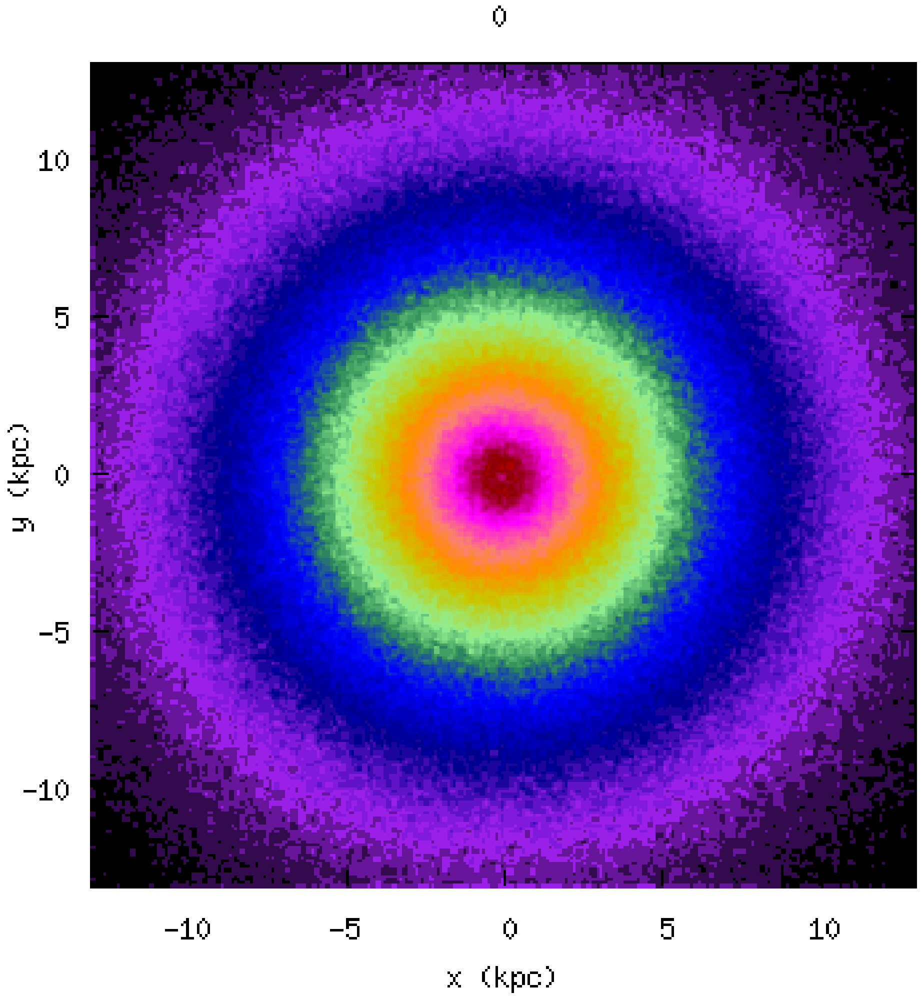
Most previous work on disk velocity distributions done with test particle simulations

Most previous work on tidal tails from disrupted dwarf galaxies use limited numbers of particles in the tail

Numerical details

- Hybrid N-body, massive + tracer particles. For disk: running 1 million massive particle + 3 million tracer. Self-consistent N-body with extra particles to resolve substructure. Smoothing length 10pc, force resolution not quite good enough.
- Modified Phi-grape (Harfst et al. 09) with Sapporo GPU replacement for Grape (Gaburov et al. 09).
- using GalacticICS for initial conditions (Widrow and Dubinski 05) Milky Way model satisfies a suite of observational constraints to match current Milky Way
- Halo is live but under-resolved.

Michaela's simulations



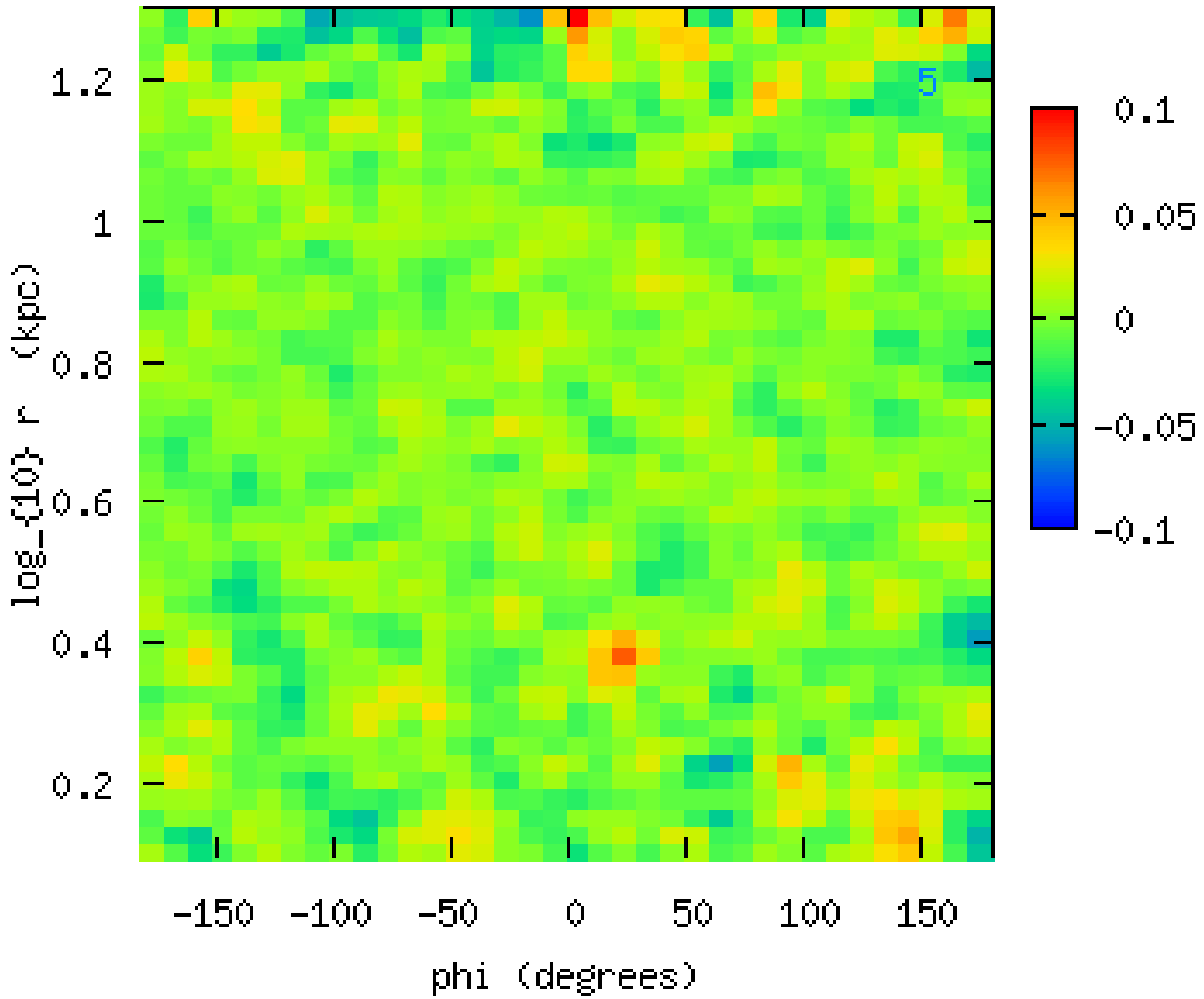
Only disk particles are shown.
Halo is live, center of bulge moves

Center of mass remains within a smoothing length throughout simulation

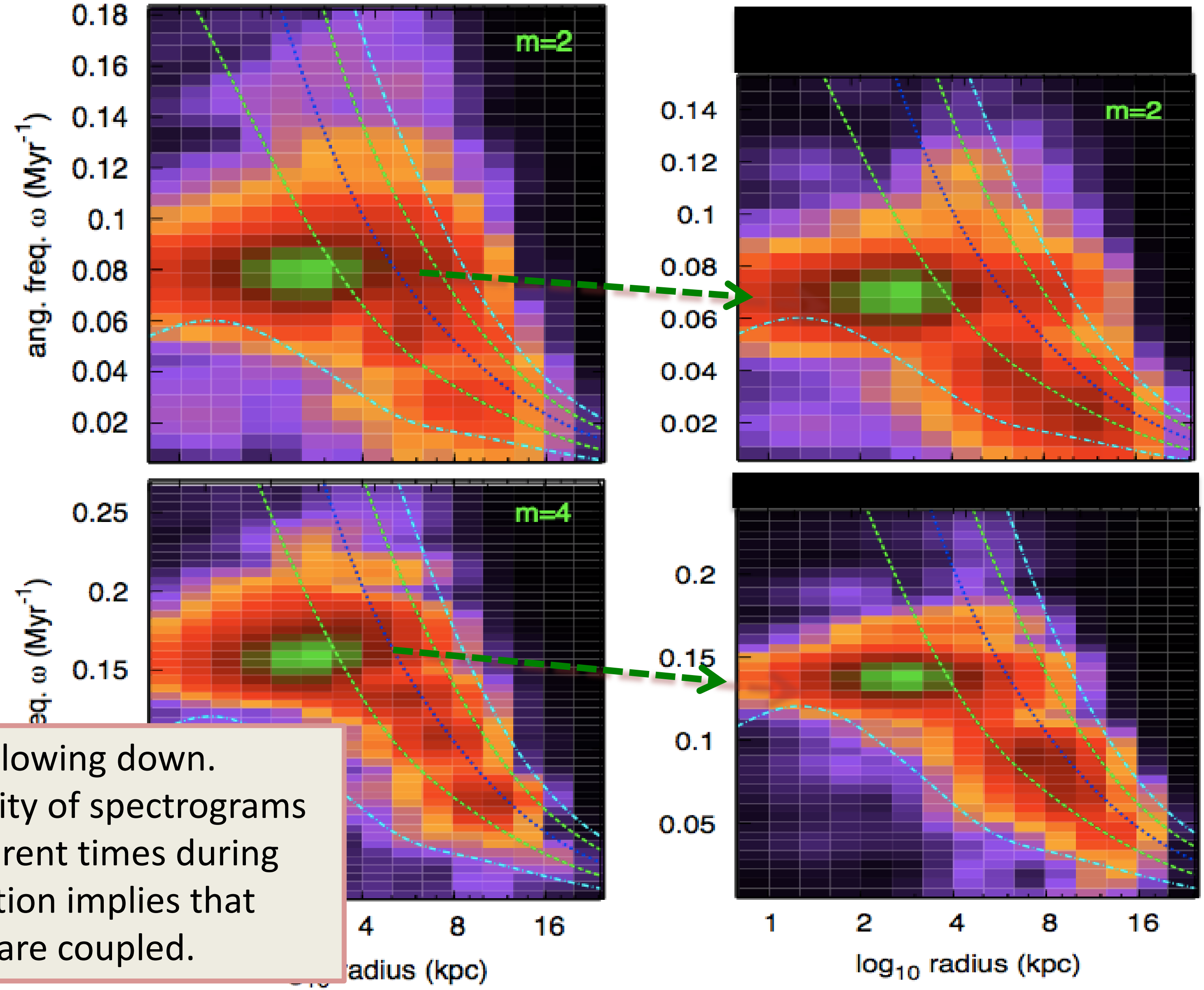
In polar coordinates

logarithmic spirals on top are slower than bar on the bottom

Constructive and destructive interference between patterns

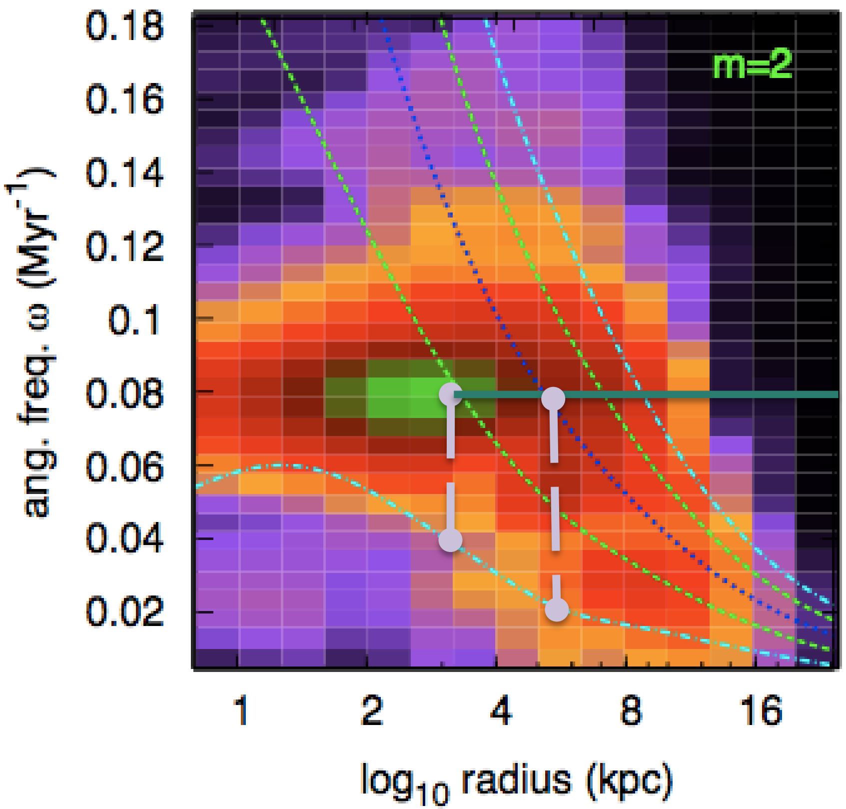


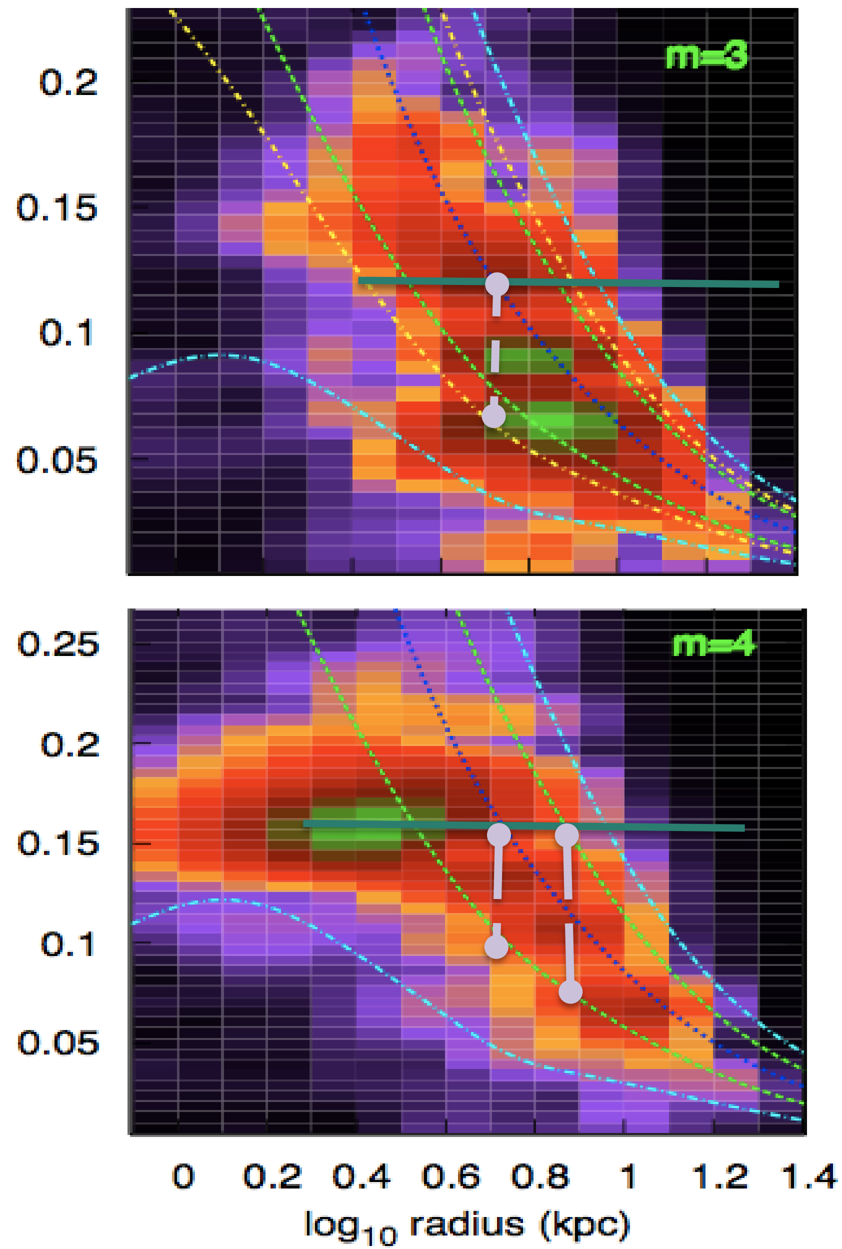
Spectrograms mid and late simulation



Bar is slowing down. Similarity of spectrograms at different times during simulation implies that waves are coupled.

Wave coupling





A resonance of one wave may be coincident with a resonance of another wave

Three-armed wave

Non-linear Wave coupling

$$
\begin{aligned}
m_s &= m_l + m_b \\
\omega_s &= \omega_l + \omega_b \\
3\Omega_s &= \Omega_l + 2\Omega_b
\end{aligned}
$$

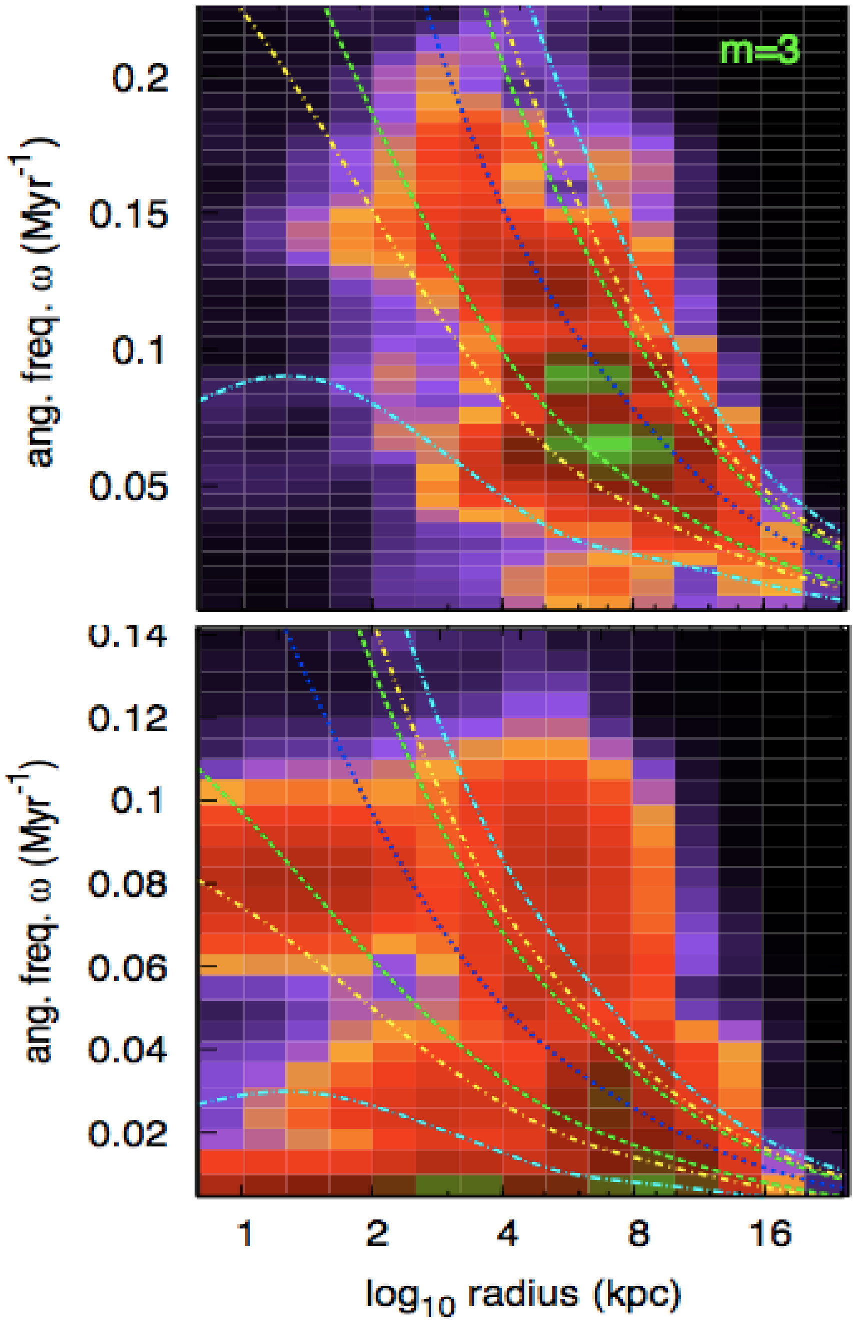
Bar and slow lopsided structure, likely coupled to three-armed waves

Sygnet et al. 88

Tagger et al. 97

Masset & Tagget 87

Rautiainen et al. 99



Models for spiral structure

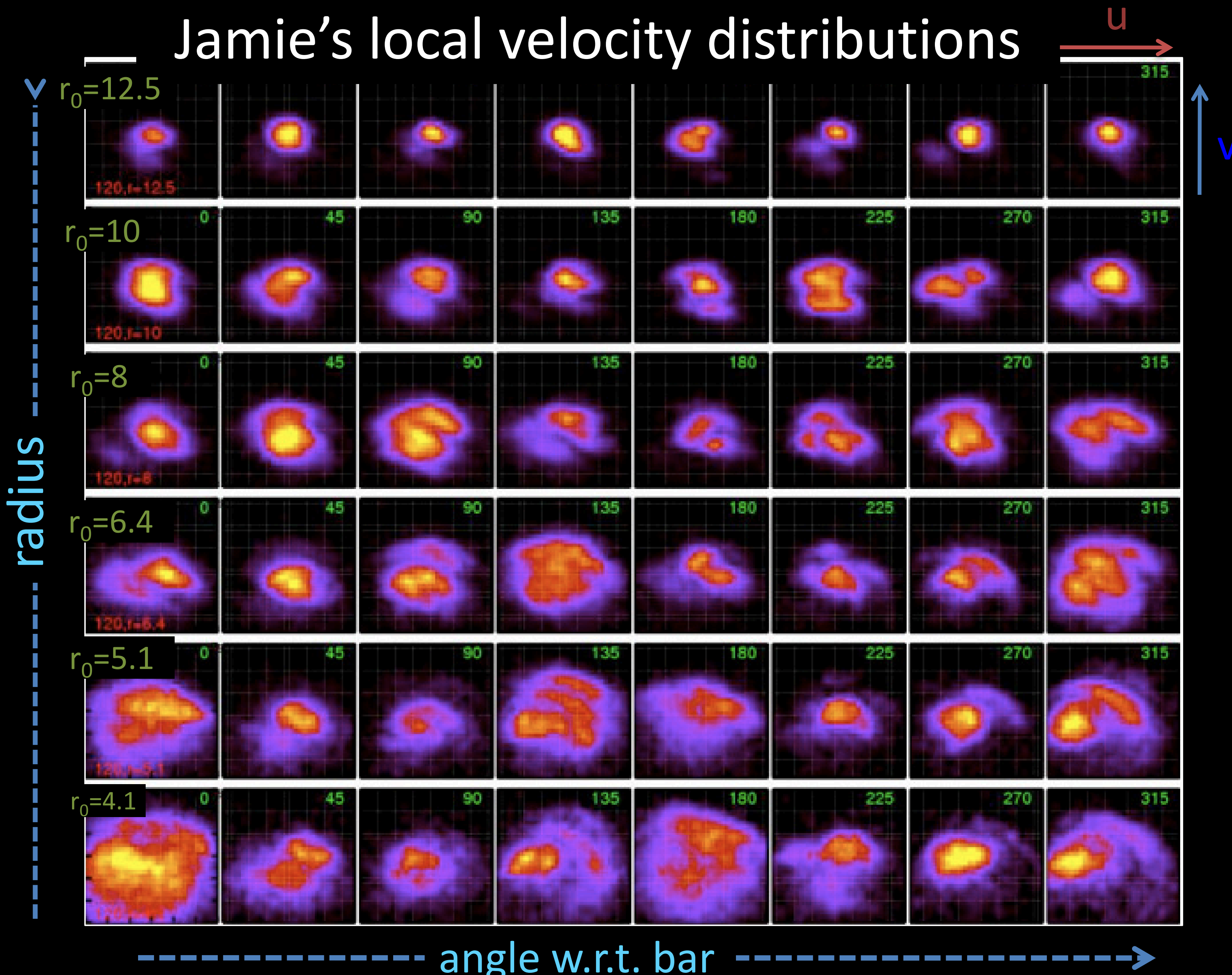
We had been expecting:

- modes, long lived (Lin-Shu)
- transient, stochastic waves (Toomre, Elmegreen, Sellwood)

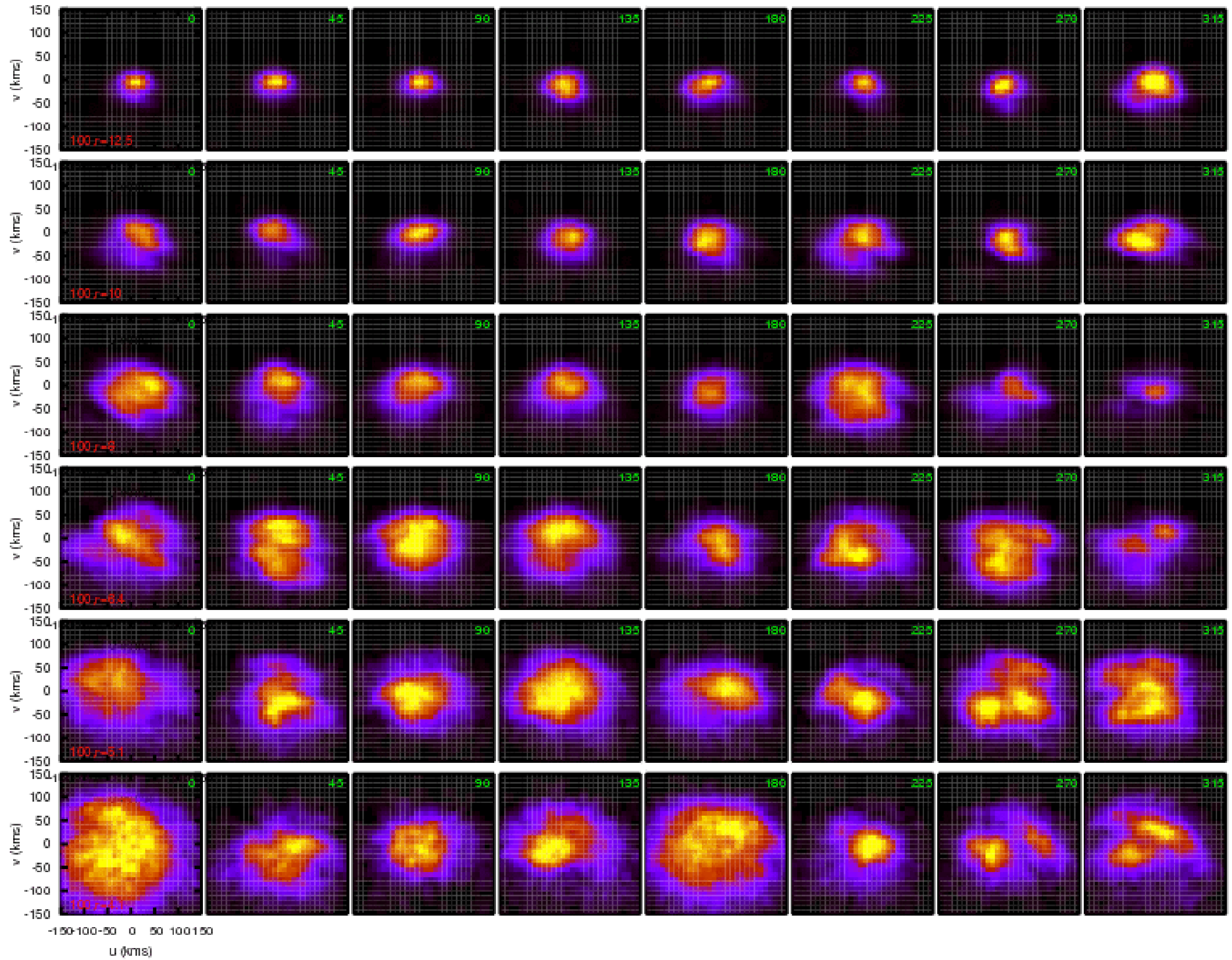
What we might be seeing:

- coupled (via non-linear terms) waves (Tagger, Masset)

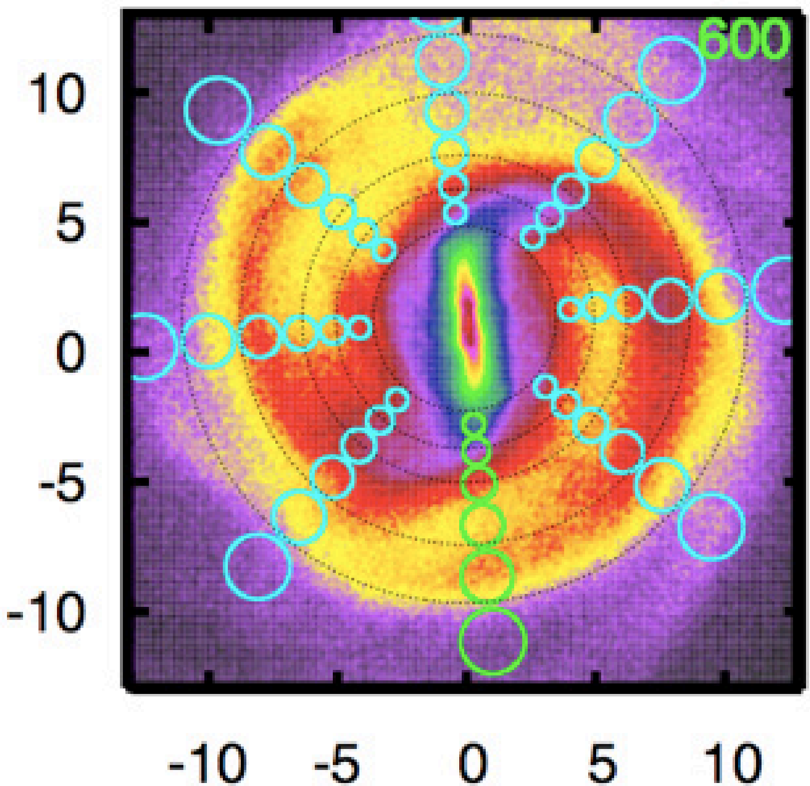
Jamie's local velocity distributions

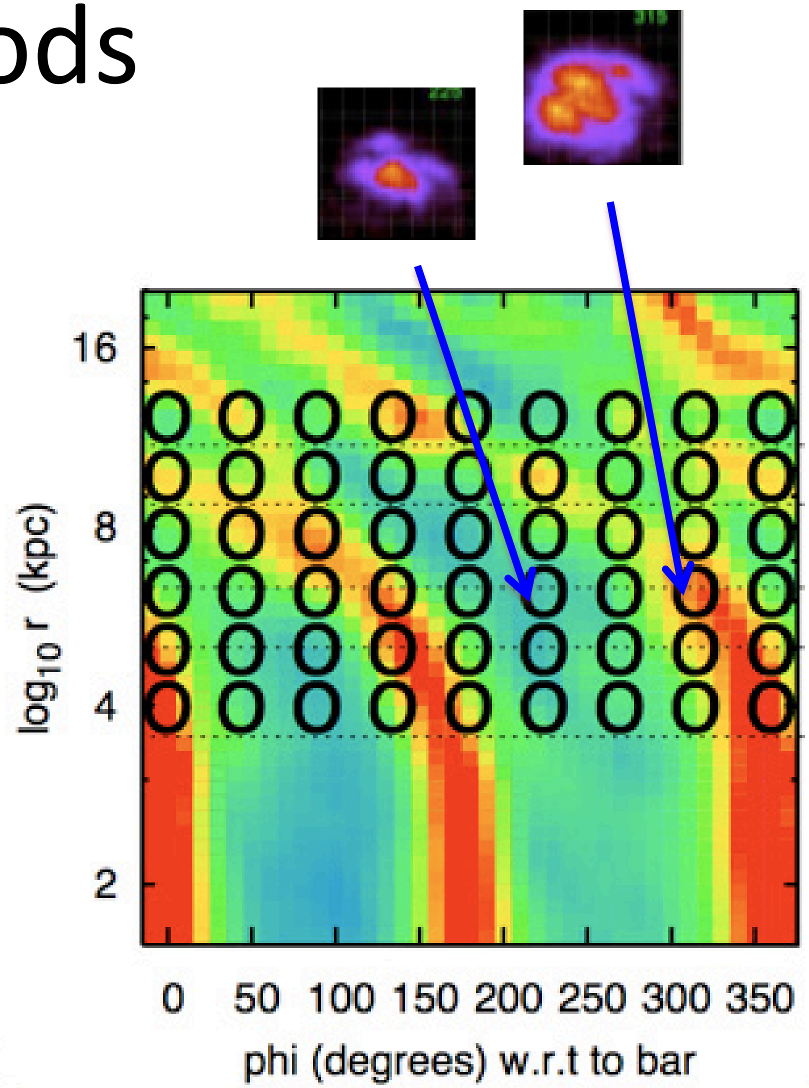


As a function of time



Local neighborhoods



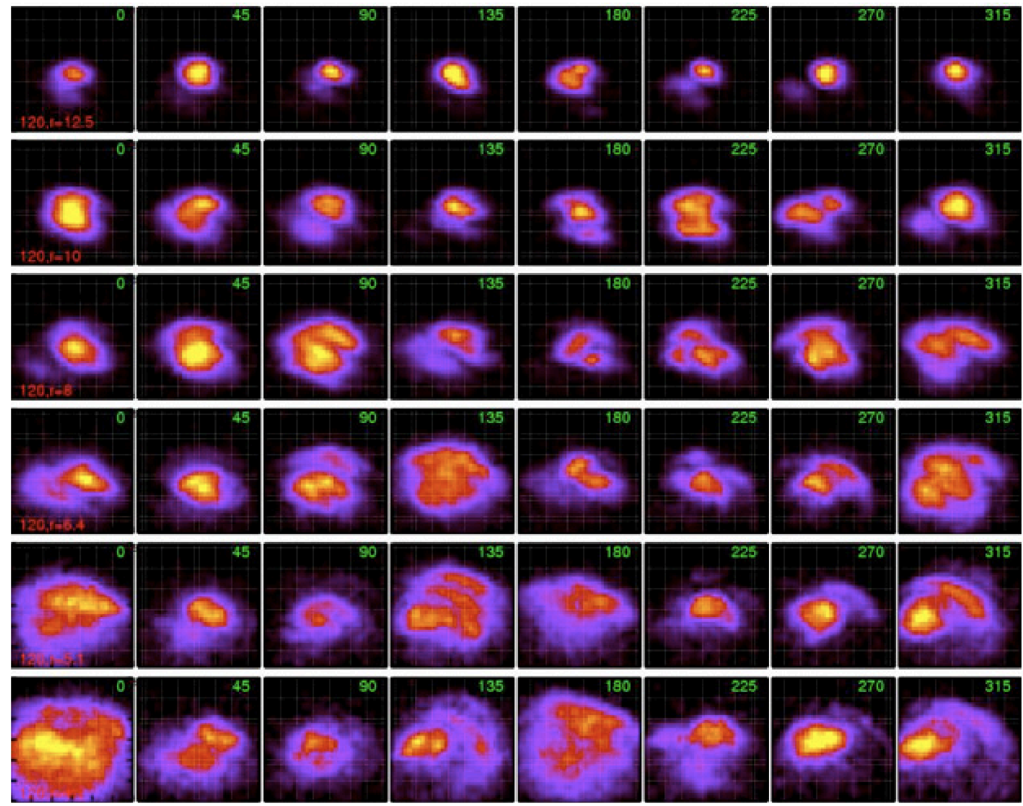


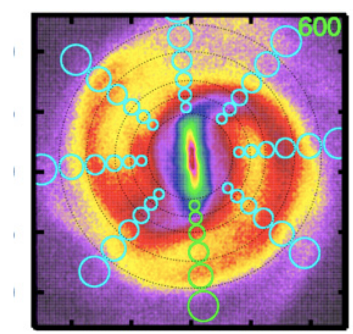
Comments on the local velocity distributions

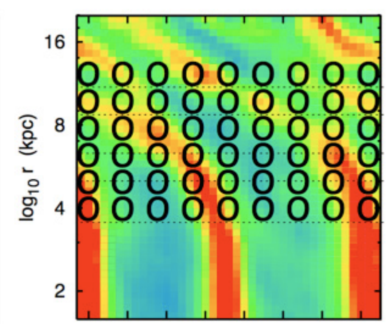
- Low dispersion interarm
- Higher dispersions and arcs on arm peaks
- Gaps, arcs and clumps everywhere in the galaxy

- Gaps from bordering neighborhoods tend to be at shifted v velocities.

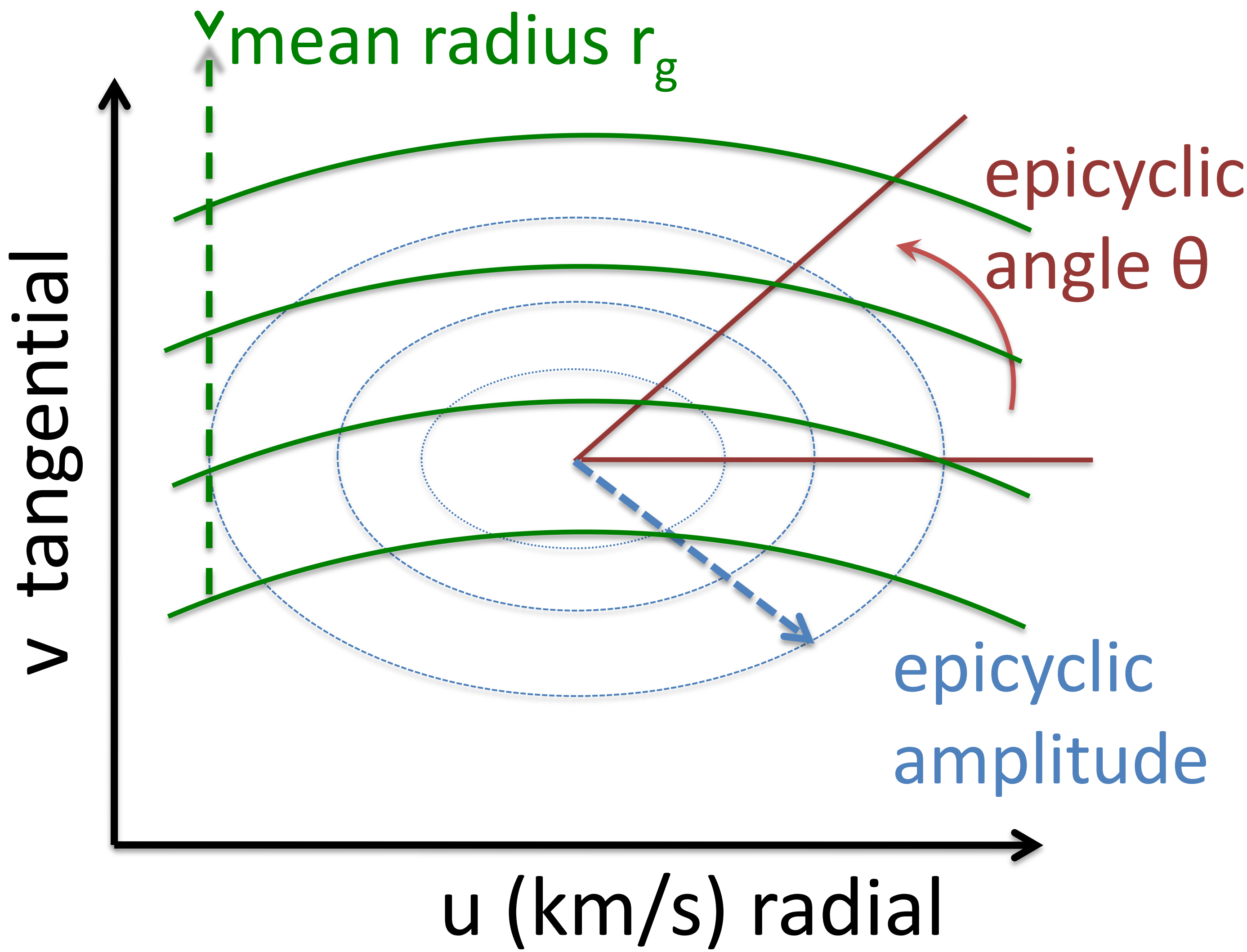
v *sets angular momentum so mean orbital radius*



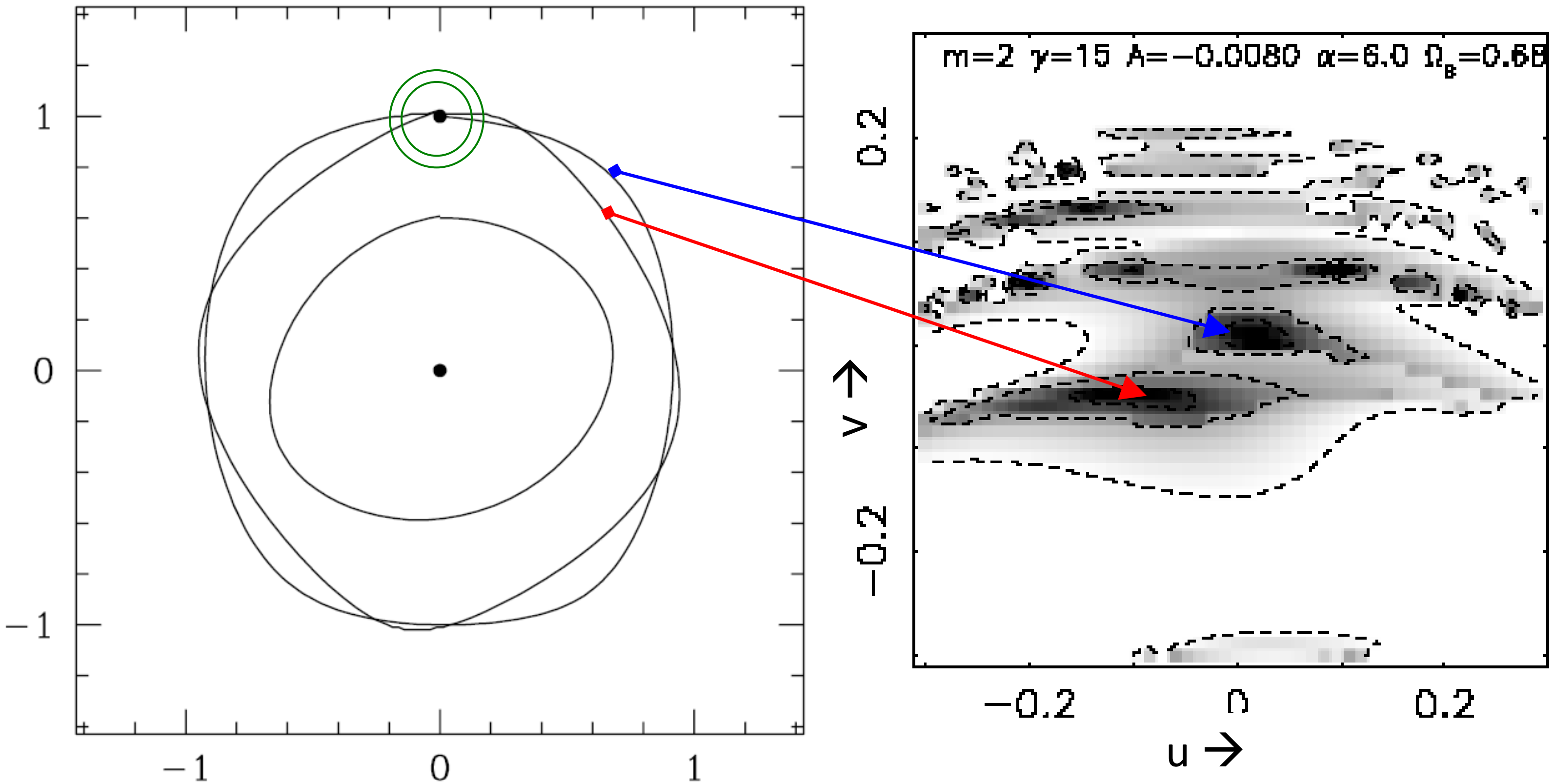




uv plane vs orbital elements



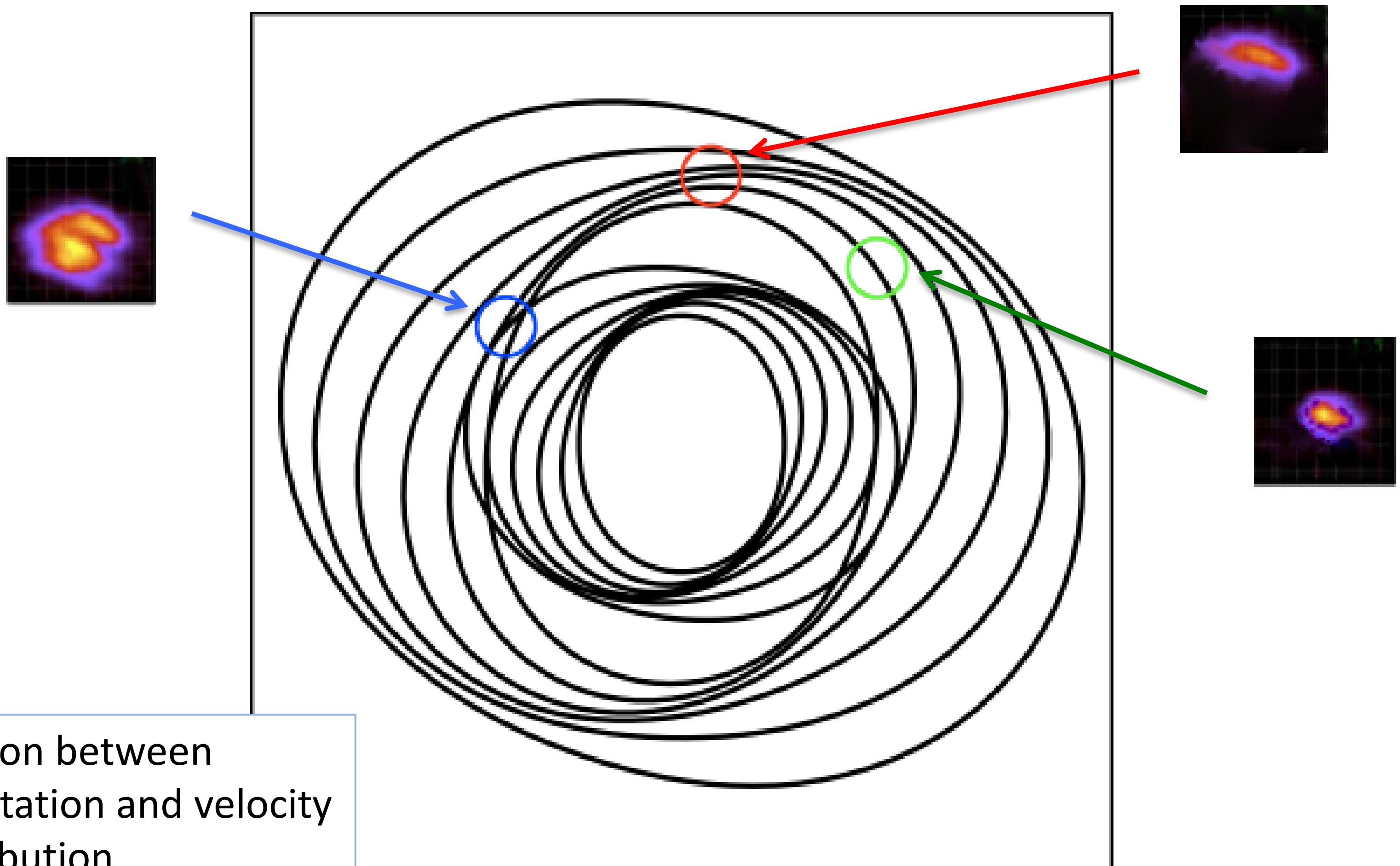
We *had expected* resonances to account for gaps in velocity distribution



Near the 4:1 Lindblad resonance. Each region on the *u,v* plane corresponds to a different family of closed/periodic orbits

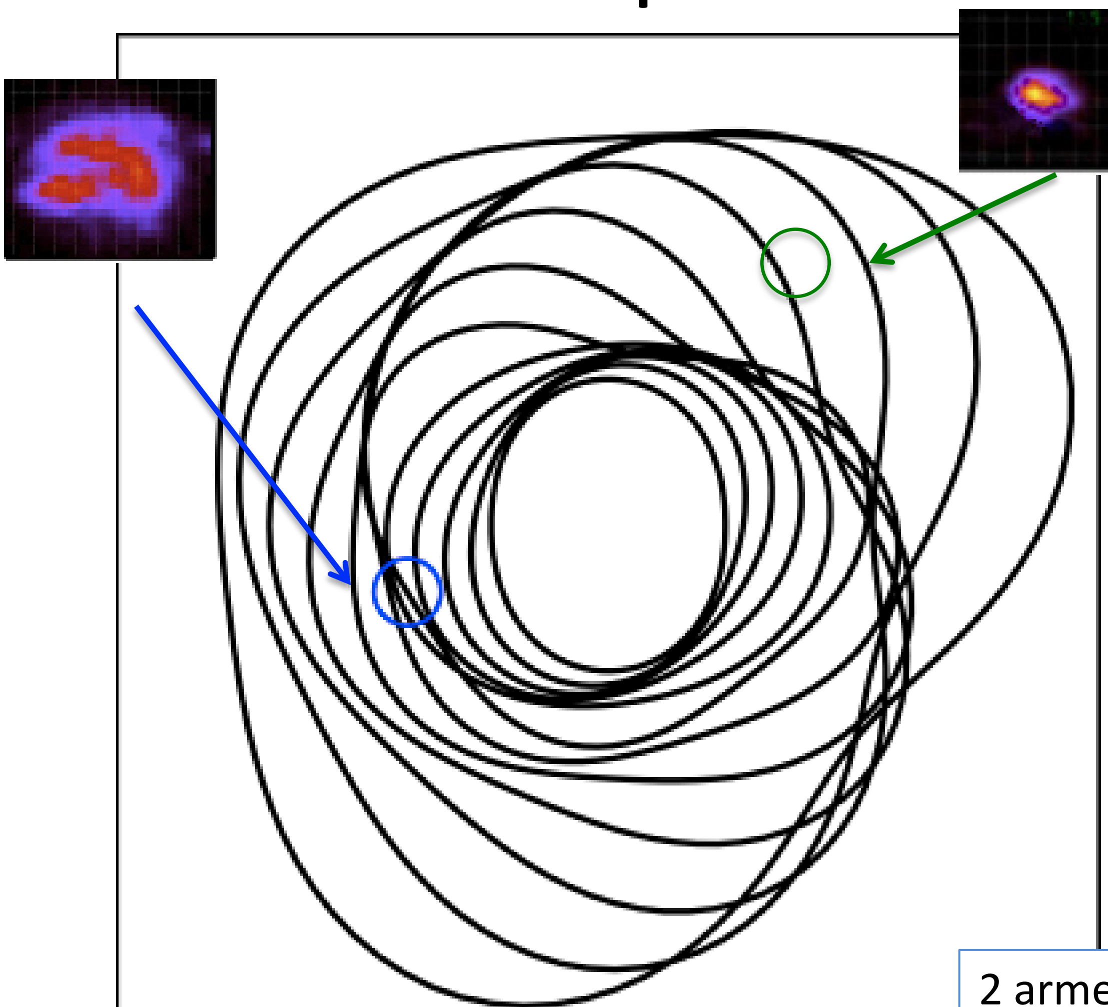
No nearly circular orbits exist near resonance so there is a gap in velocity distribution

Discontinuities in spiral structure



relation between orientation and velocity distribution

Discontinuities in spiral structure when multiple waves are present



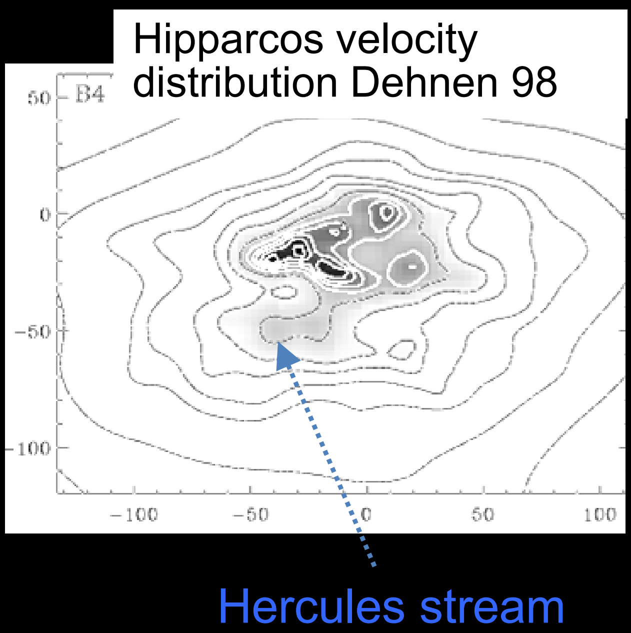
2 armed inner + 3 armed outer pattern

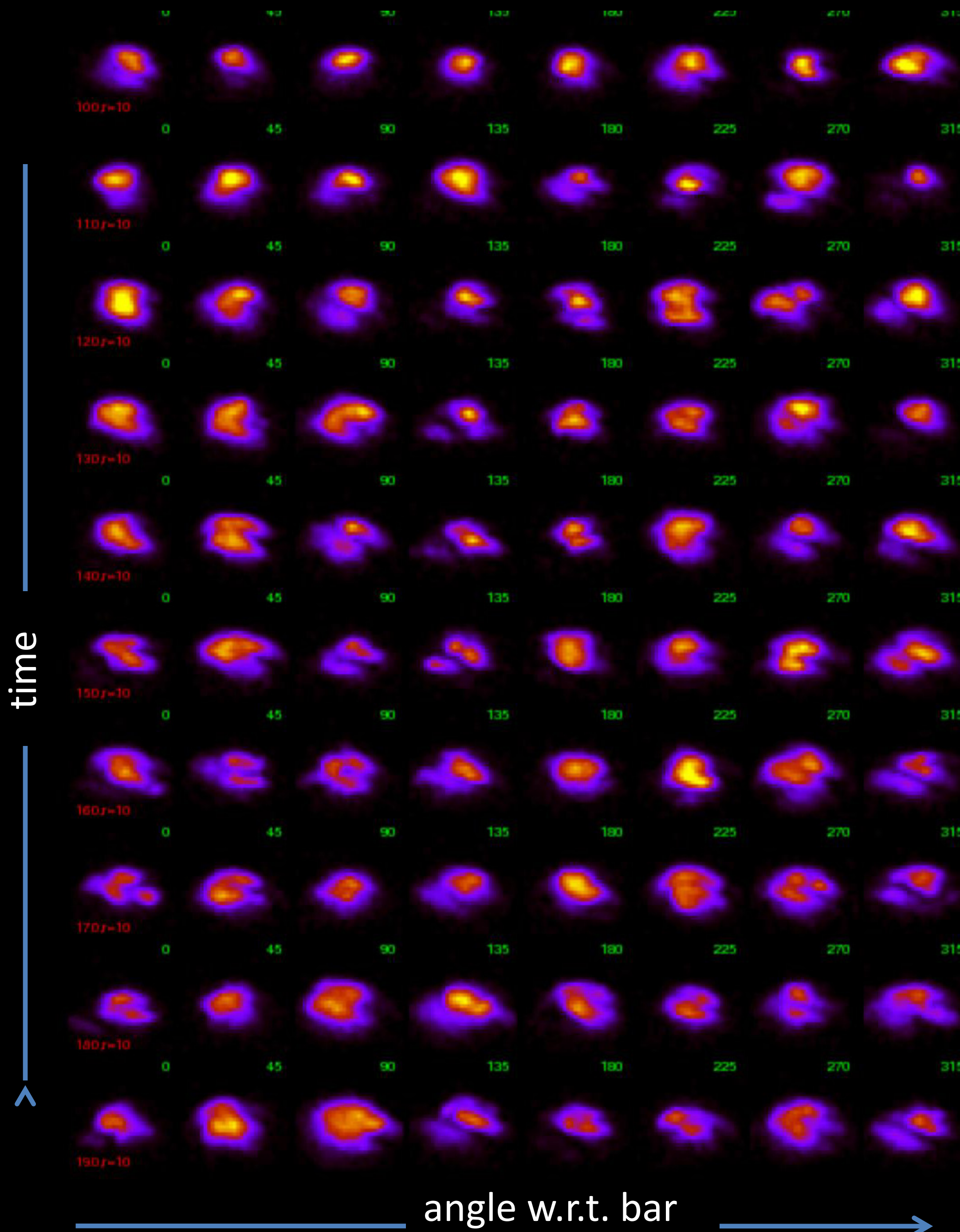
Armlets
Kinks or bends in spiral arms

Manifest in velocity distributions as gaps

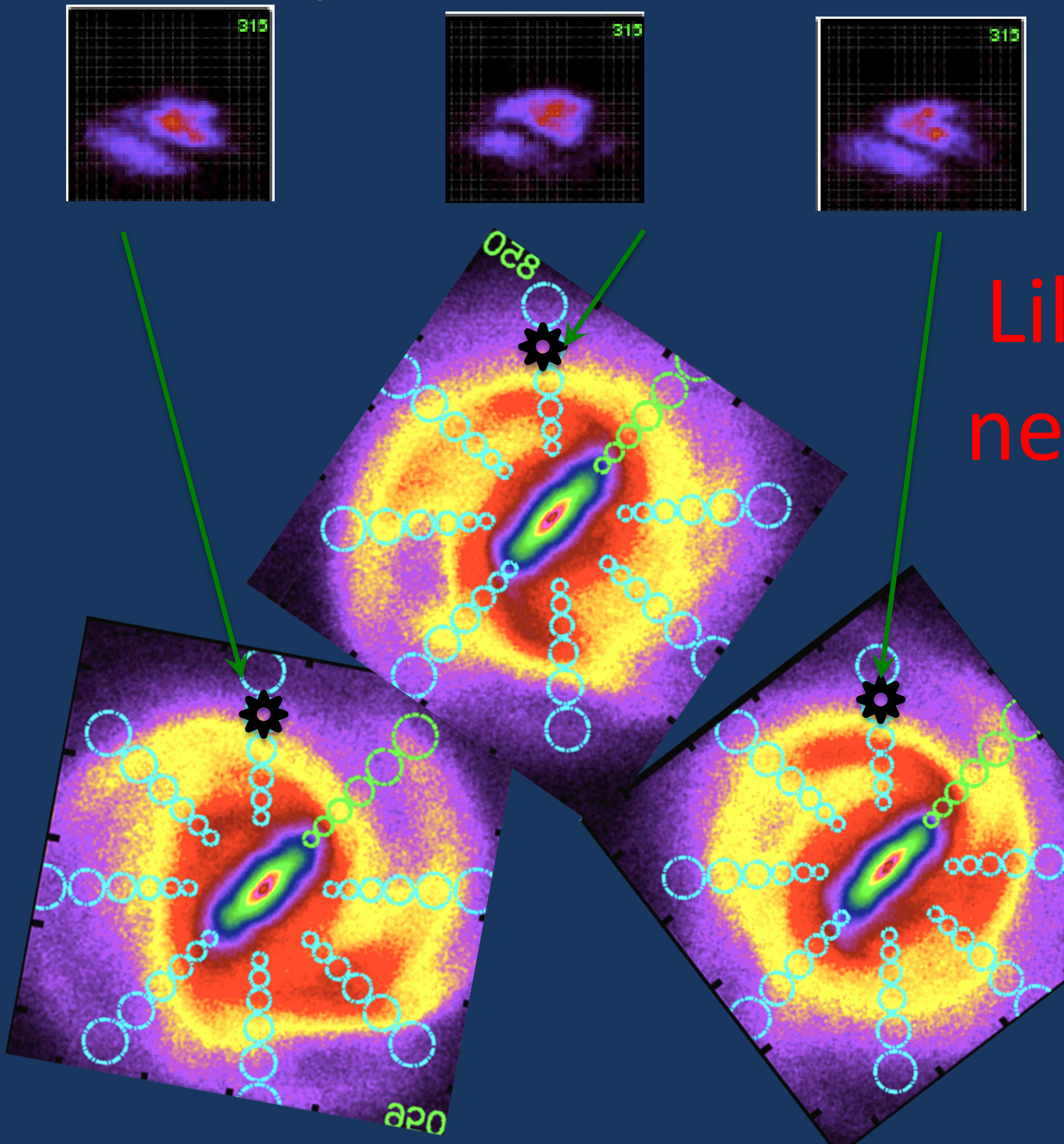
Deviations from symmetry in two armed structure can be predicted with addition of an additional 3 armed structure, that at different times gives armlets

Hercules stream-like structure near bar’s Outer Lindblad Resonance

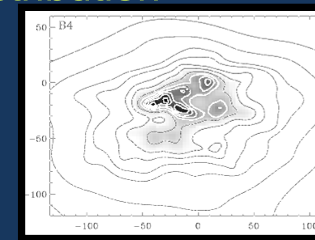




velocity distributions at different times



Hipparcos velocity distribution



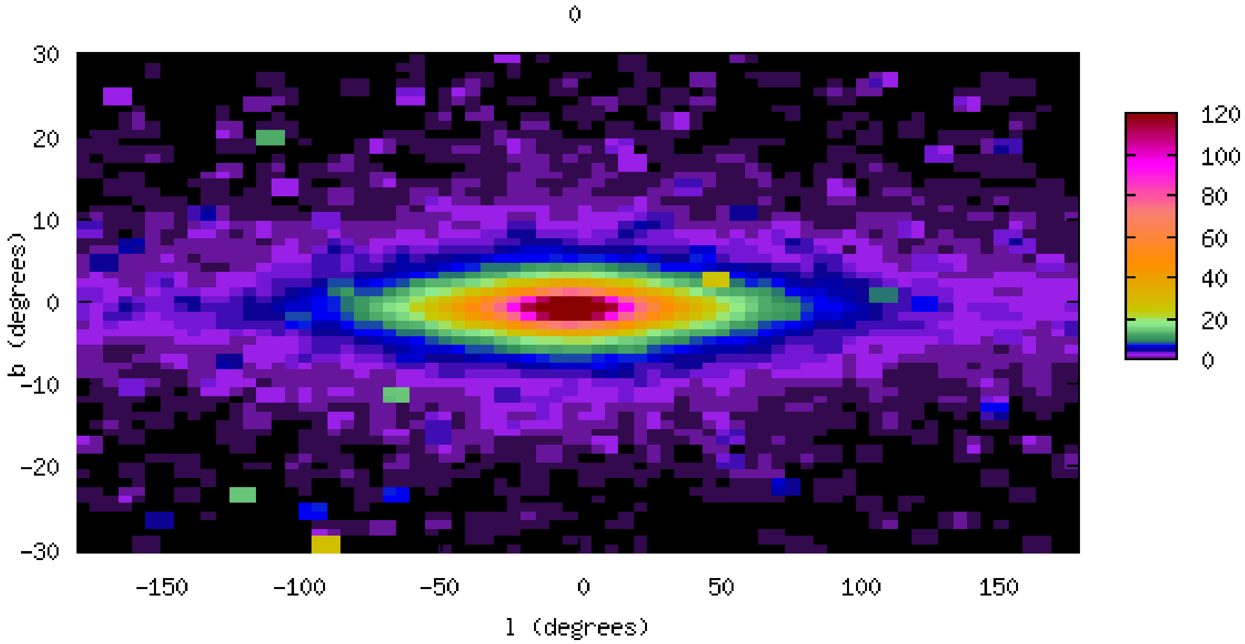
Like the solar neighborhood

Bob Hurt's cartoon

Interpretation of our Galaxy

- Biased view of the disk velocity distribution due to our inter-arm location in Galaxy (on arm peaks the velocity dispersion higher and there are gaps)
- Lack of consensus of local spiral pattern: Models with more than one pattern are needed to understand the morphology
- Lopsided motion in the Galaxy is present based on HI lopsidedness, -- the bar and lopsided motion to couple to a three-armed pattern – We should consider other than 2 or 4 armed cartoon models (and fitting parameters). Likely a 3 armed wave is present in the solar neighborhood.
- Models with velocity distributions similar to our Galaxy have bar in correct orientation, tend to have a large spiral arm just interior to solar circle, consistent with tangent seen in GLIMPSE stellar (not dust) tangents, the Crux/Scutum/Centaurus arm. Little constraint on the location of other arms from solar neighborhood velocity distribution alone. Only 2 tangent arms would be consistent with GLIMPSE survey (as our simulations lack gas)

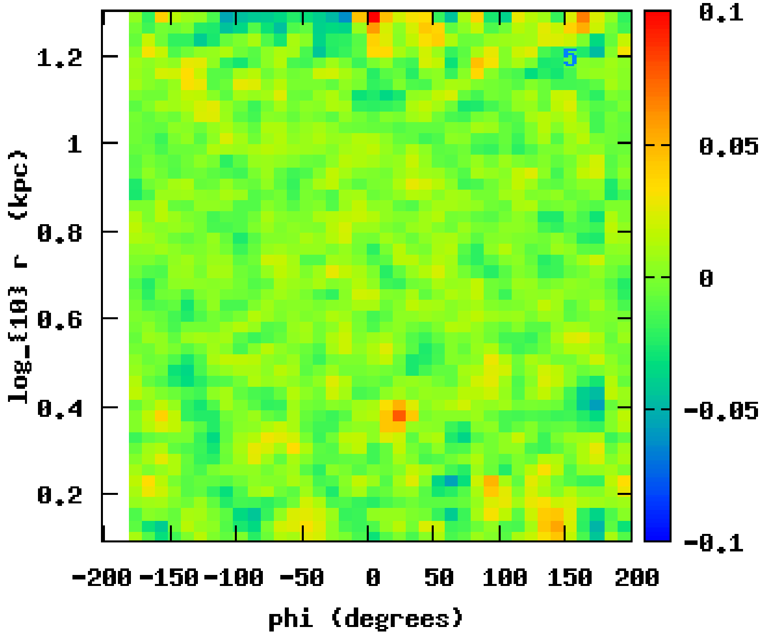
Our view in the galaxy



warping as well as sloshing

Star formation with multiple patterns

In a frame corotating with a position outside the bar



Star formation is not continuous

Armlets appear and disappear causing localized bursts of star formation

Most bursts move from inner to outer radius, opposite to what may is seen in the solar neighborhood cluster distribution within 200 pc of the Sun (Mamajec)

Despite localized density peaks the galaxy still looks like a spiral galaxy

	Coupled and multiple density waves	Transient spirals
Heating and radial migration	Chaotic diffusion. Wave coupling implies resonance overlap (e.g., Shevchenko, Minchev). Heating/Migration rate strongly is dependent on position in galaxy and likely to be maximum when and where both bar and spirals are present. As a bar slows down, resonances can be swept through the disk.	Heating via appearance and disappearance of spiral arms. Migration associated with corotation resonance. No prescription for prediction differences in migration/heating rates with position or time.
Star formation	Short local bursts can occur where there is constructive interference between waves	Continuous star formation predicted as single waves pass through the disk.
Implication: It should be possible to differentiate between these scenarios		

Caveats

- One simulation – based on GALACTICS initial conditions for Milky Way model, but lacking gas
- Undersampled halo, heating of disk by halo but at level expected from molecular clouds
- Poor force resolution, this is a noisy but rich simulation
- Growth of lopsided mode could be due to poor energy conservation
- Increasing numbers of particles and using smaller timesteps may give an unrealistic galaxy --- if a quieter and more accurate simulation fails to grow a lopsided mode and our galaxy has one (it is lopsided) then outside perturbations are needed to seed it. Particularly important if three armed waves are due to bar/lopsided coupling

Final Comments on galactic disk

- Structure in velocity distribution expected all over the galaxy
- Gaps in velocity distribution related to
  - changes in dominant wave
  - Lindblad resonances as spiral waves beginning and end at them and are coupled
  - discontinuities in arms

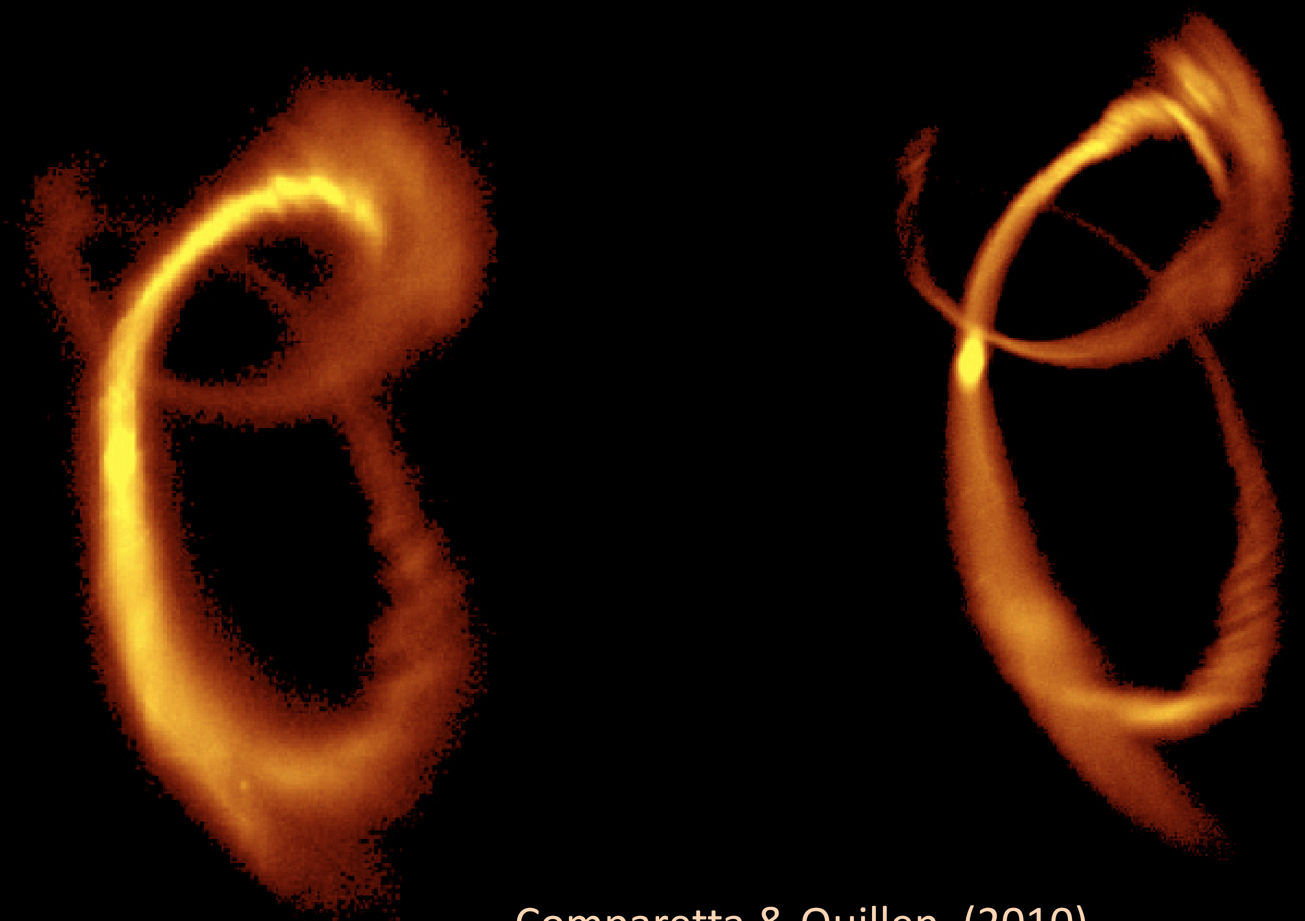
- More work needed to
  - figure out patterns speeds, strengths and offsets from velocity distributions
  - Match up structure in galaxy to models (including armlets) – possibly waves at all radii are coupled
  - Relate radial migration and heating to waves present in simulation
  - look at better and more simulations (shorter bar, more particles yet want spiral structure)
  - understand the non-linear mode coupling

Structure of Self-Gravitating Stellar Tidal tails

Substructure in tails is resolved with a few million particles in disrupting dwarf

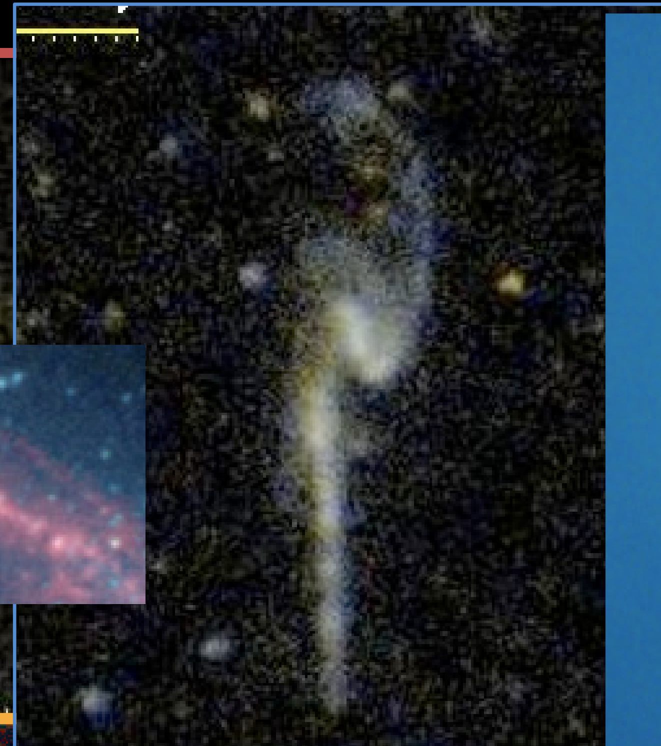
Substructure depends on number of dark matter halo particles?

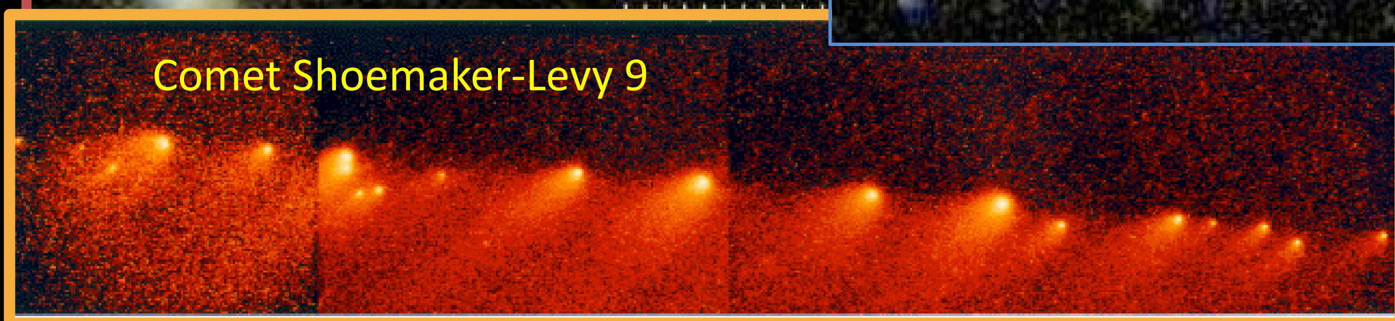
10^4 halo particles 10^5 halo particles

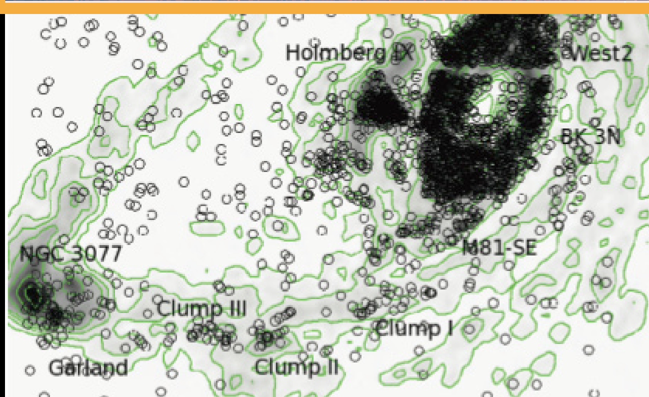


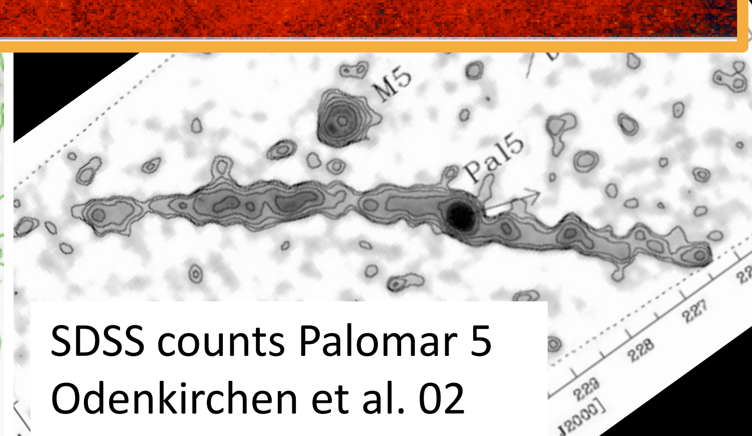
Comparetta & Quillen (2010)

Smith et al. 2010



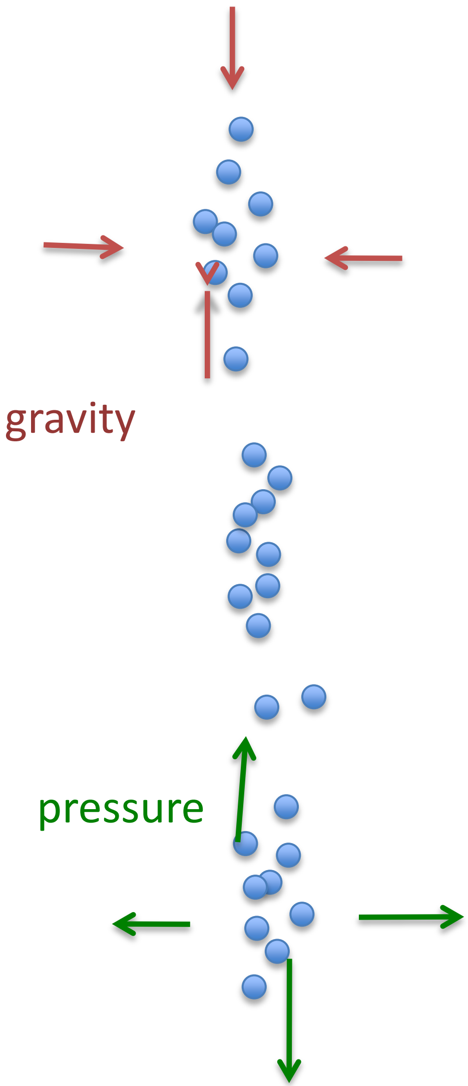






SDSS counts Palomar 5
Odenkirchen et al. 02

Jeans Instability



- For gas:
  - Gravity pulls clumps together
  - Pressure prevents collapse
  - Magnetic pressure prevents varicose collapse of a gas cylinder (Chandrasekhar & Fermi 1953) Longitudinal collapse still possible (e.g., Ostriker ‘64)
- For stars:
  - Gravity pulls together
  - Random motions prevent collapse at small wavelengths -- Landau damping in a plasma (Fridman & Polyachenko)

Jeans Instability of a stellar Cylinder

- Growth rate depends on the wavelength,
  - for plane waves larger wavelength perturbations grow more quickly
- Wavelengths larger than the cylinder diameter don’t feel gravity as strongly

→ There is a fastest growing wavelength – as there was for the Plateau-Rayleigh instability

Longitudinal Perturbations of a Stellar Cylinder

σ_* velocity dispersion or sound speed
μ linear mass density
G gravitational constant
r_0 cylinder radius
f(z,v) = $f_0 + f_1$ distribution function (see Fridman and Polyachenko)
Linearized version of the collisionless Boltzmann equation

$$\left[\frac{\partial}{\partial t} + v\frac{\partial}{\partial z}\right] f_1 - \frac{\partial \Phi_1}{\partial z}\frac{\partial f_0}{\partial v} = 0$$

Perturbations on a cylinder proportional to cos *kz* produce gravitational perturbations of the form

$$\Phi_1(z) \approx -2G\mu_0 a|1 - \ln kr_0|\cos kz$$

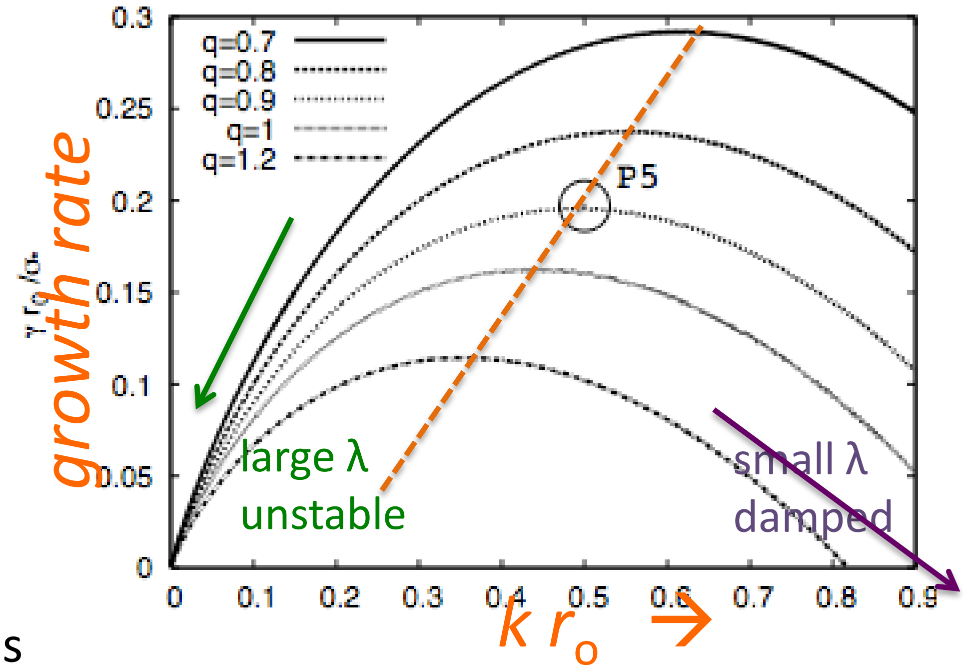
and a very approximate dispersion relation

$$1 - q^{-1}|1 - \ln kr_0|\left[\sqrt{\pi}e^{\gamma'^2}\gamma'\left(\mathrm{erf}\gamma' - 1\right) + 1\right] = 0$$

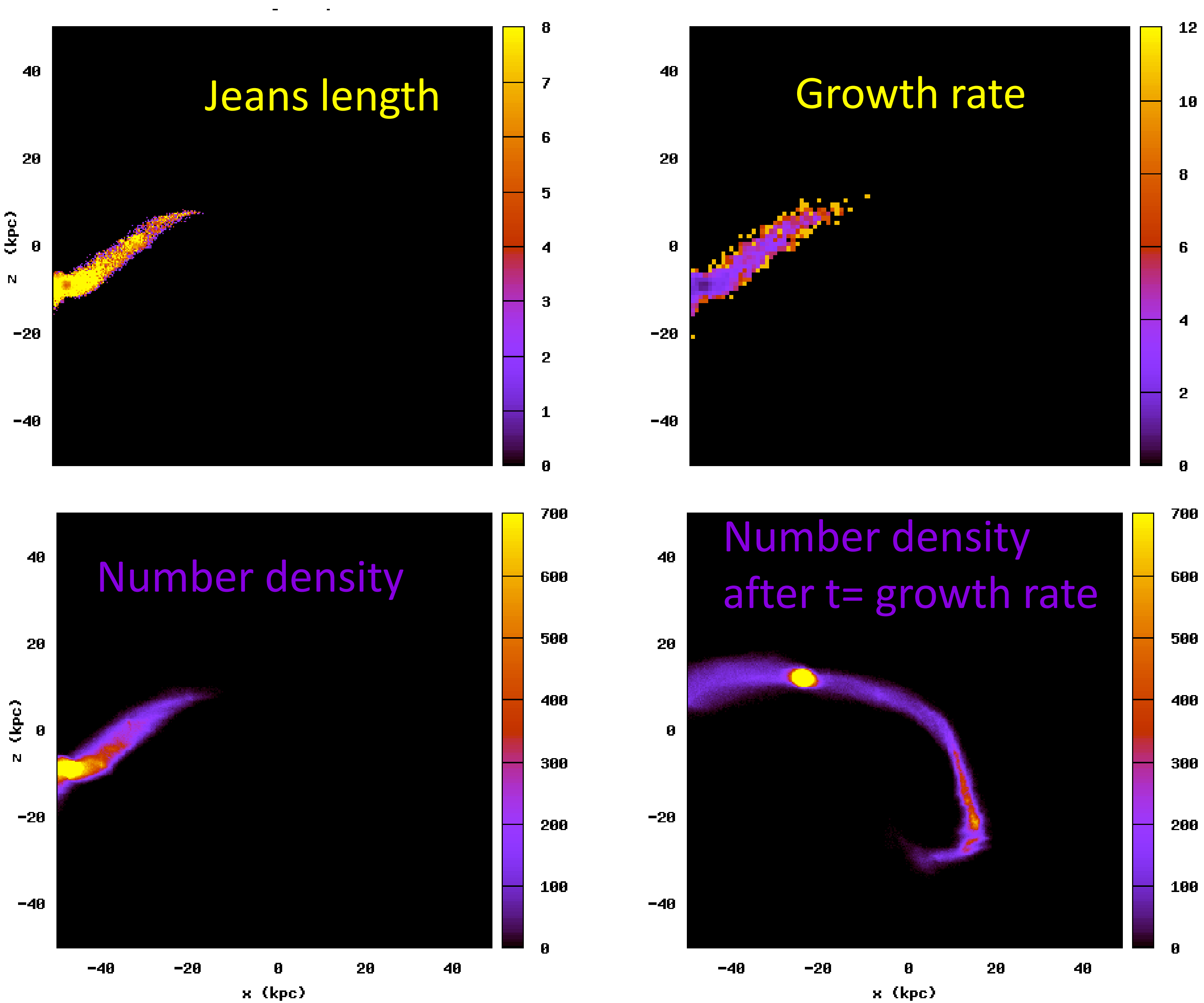
Wavelengths and Growth rates of the fastest growing wavelength

$$q \equiv \frac{\sigma_*^2}{2G\mu} = \frac{2}{(k_J r_0)^2}$$

- For wavelengths sufficiently long there is instability
- Instability cuts off at short wavelengths due to Landau damping
- With motions restricted to along tail, only one parameter determines fastest growing wavelength



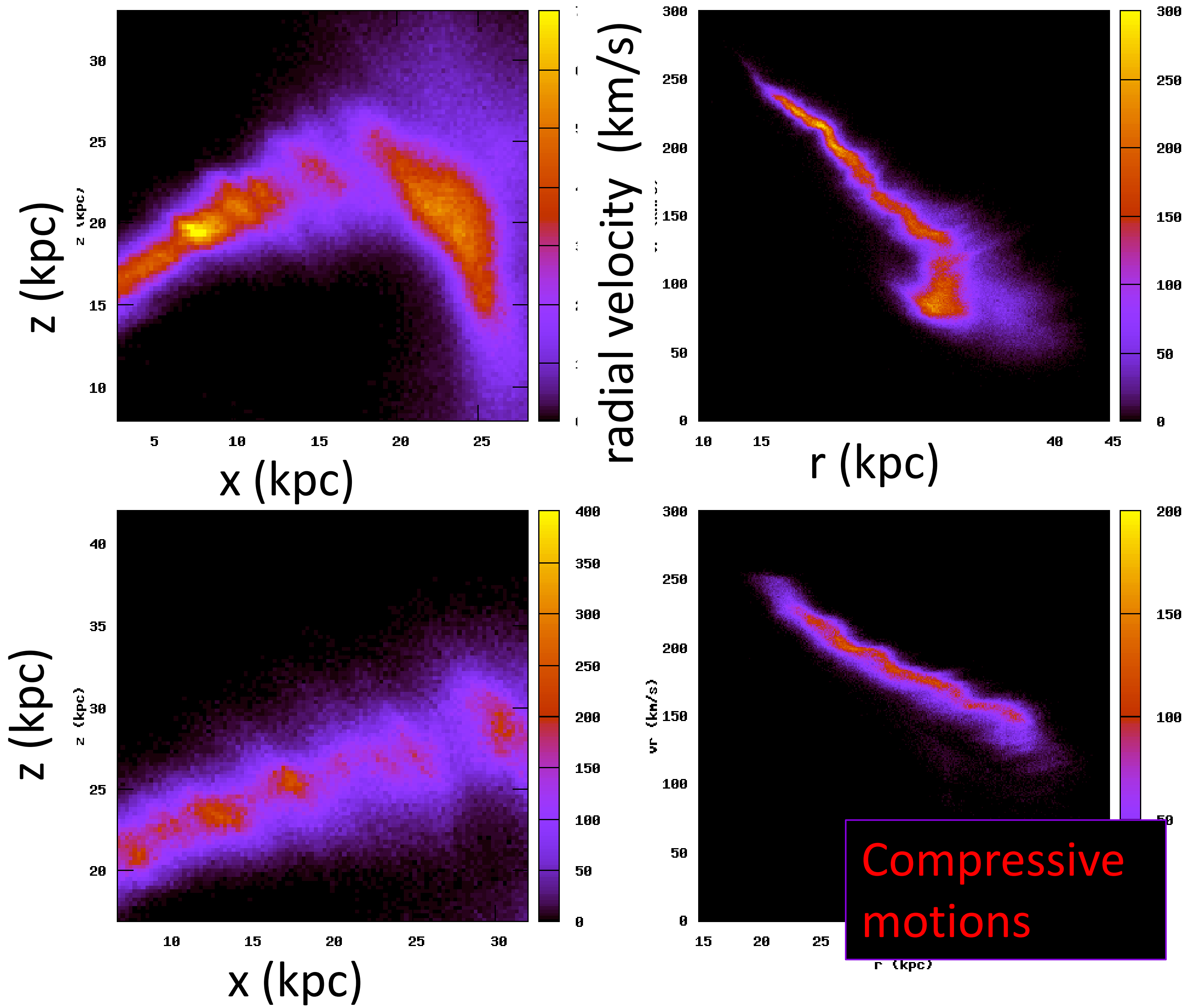
- For q~1 fastest growing wavelength has λ~few times r_0 and growth rate ~ σ/r_0
- Estimate is not accurate as it is difficult to calculate for kr_0~1 near the fastest growing wavelength
- To first order, sausage and longitudinal variations have same dispersion relation



Jeans length
Growth rate
Number density
Number density
after t= growth rate
z (kpc)
x (kpc)

Real space

Velocity space



Comments on Jeans Instability

- All tidal tails and filaments are unstable to clumping via Jeans Instability. However the growth timescale and wavelength could be long enough that for all practical purposes clumps will not form
- There is a fastest growing wavelength. Calculating its properties is non-trivial as it lies in the regime $k\, r_0 \sim 1$
- Instability itself may have heated the tail. At first we thought this would allow better estimates of tail density and dispersion but now think that constraints on past properties of the tail are more likely.
- Clumping has not been found in some systems (e.g., Sag dwarf tidal tails). Does that mean not there or just not found?

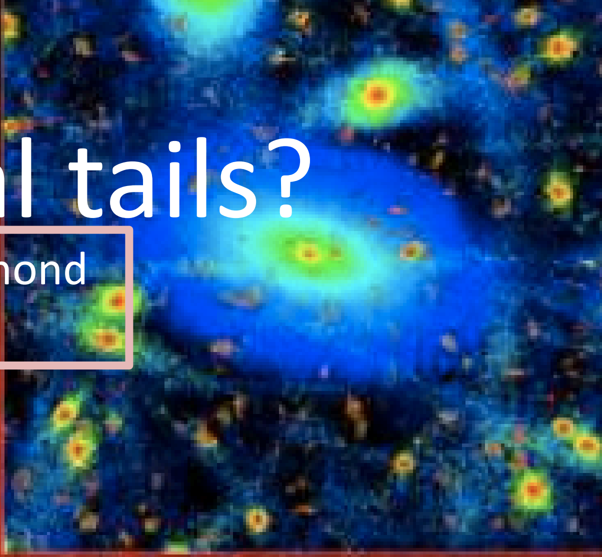
Tests of CDM

- CMD predicts many subhalos; over production of Dwarf galaxies problem.
- Observational Constraints on subhalos:
  – lensing of distant objects -- so far no strong constraints; (Zackrisson & Riehm 2010) but perhaps promising future
  – gamma rays from dark matter (enhanced by large phase space density in subhalos)
  – tidal tails?

Dark matter Sub-halos causing structure in tidal tails

- Heating of Palomar 5 tail: (Johnston, Spergel, Haydn 2002, Ibata et al. 2002)
- Clumping in dwarf tails: (Siegal-Gaskins and Valluri 2008)
- Kinks or folding of Palomar 5 like tail (Carlberg 2009)
- Seeding of Jeans instability, followed by heating which changes the wavelength of maximum growth rate? (us)

Testing CDM with tidal tails?



via Lactae II, Diemond et al 2008

- ~10% of halo is in subhalos
- ~ 10^9 $M_\odot$/ kpc in subhalos
- $dN/dM \sim M^{-2}$ for subhalos
- a few subhalos of 10^7 $M_\odot$ with v_{max} ~3 km/s will lie within Sagittarius dwarf stream or with 1 kpc of Pal 5's stream.
- a halo of 10^8 $M_\odot$ will pass through a Sag tail or within 1 kpc of a Pal 5 tail in one orbital period (order Gyr) with v_{max} ~10 km/s
- our halo particles are too many and too big (a challenge for better simulations)
- Perturbations of order a km/s expected from sub-halos

Summary

- Approach: simulated as many particles as we could in tidal tails and galactic disk. Tracer particles used to show structure without sacrificing self-consistency
- Interesting sub-structure predicted: could be revealed by future surveys of ~ a billion stars.
- Potential CDM test possible with tidal tails?
- Coupled wave view of spiral structure may have interesting consequences for mapping the Milky Way and understanding migration and heating of disk