# Modeling rings annd spirals in barred galaxies using manifolds: morphology and kinematics

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Dynamics and evolution in disc galaxies
Puschino-Moscow

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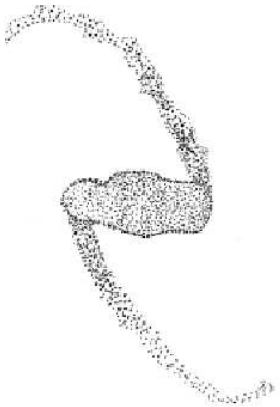
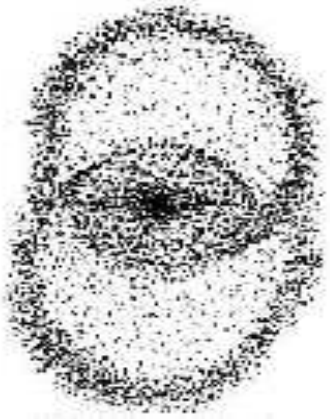
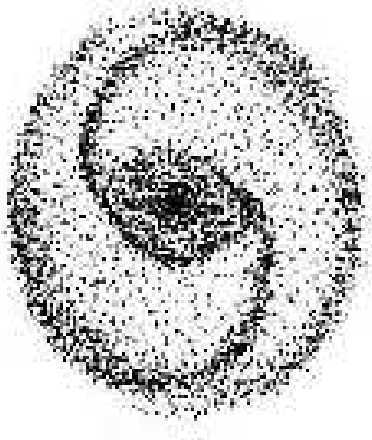
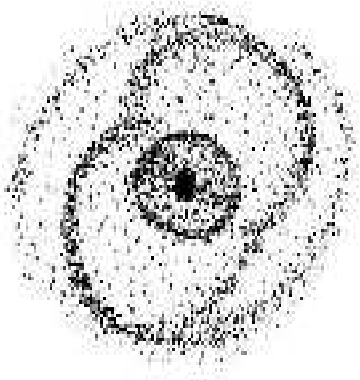
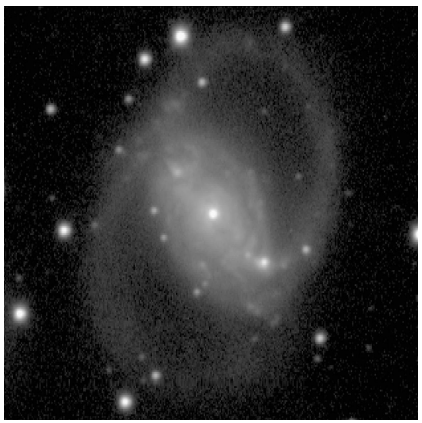
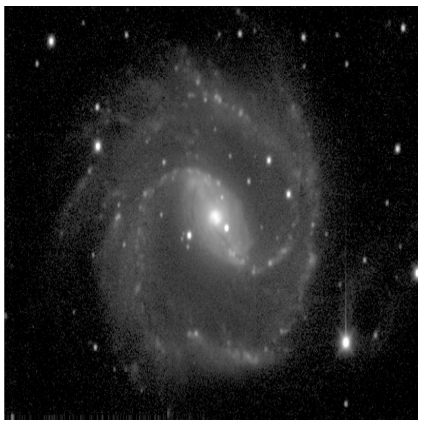
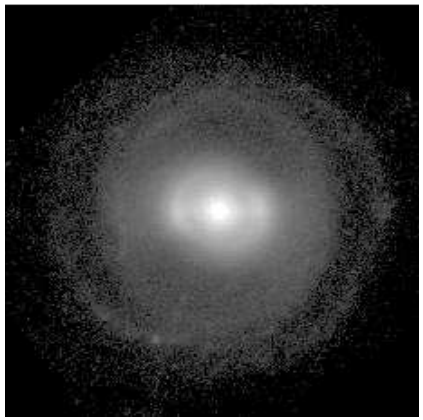
# Motivation

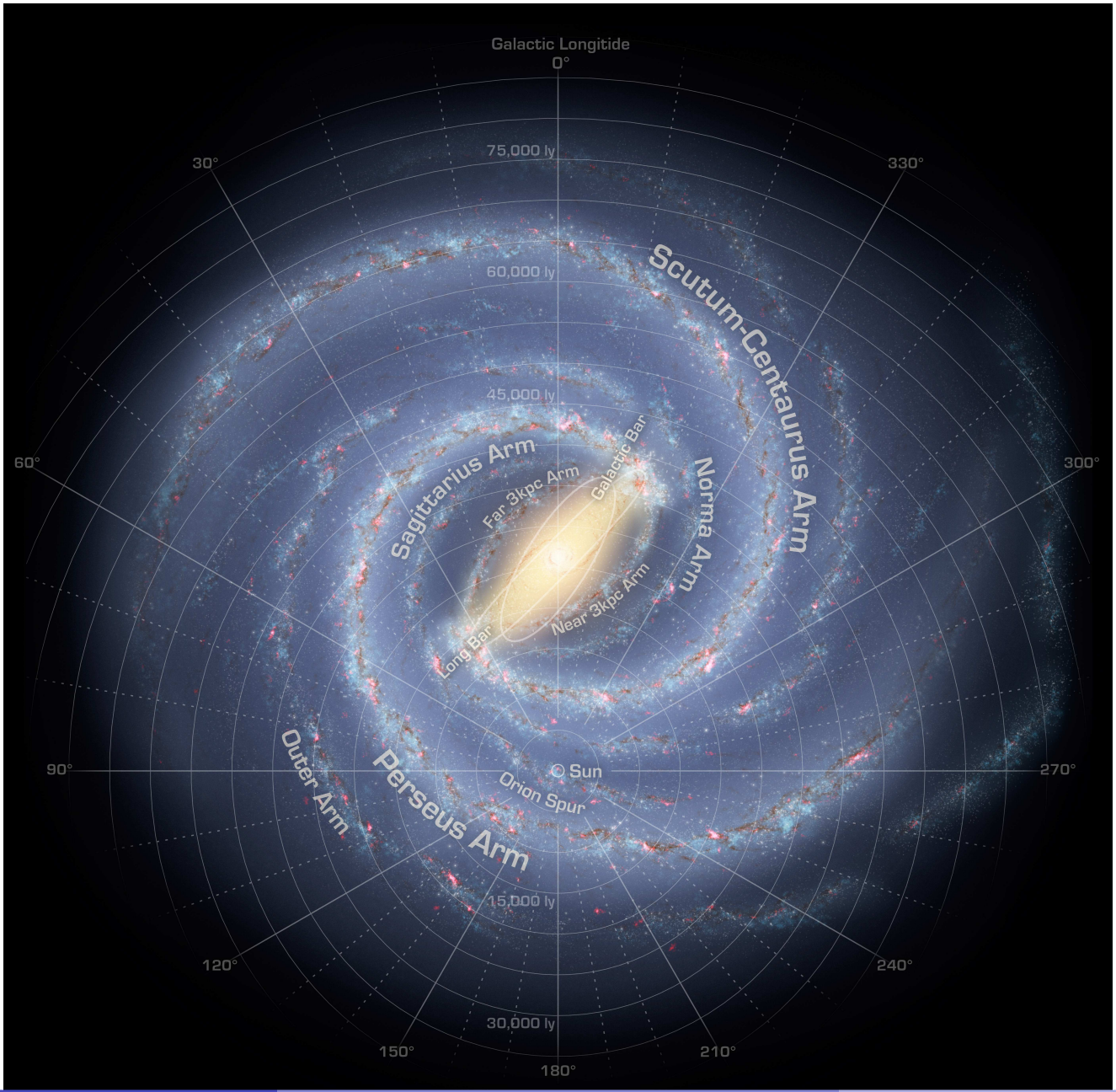
NGC 1365
Spiral arms

NGC 2665
$R_1$

NGC 2935
$R_2$

NGC 1079
$R_1R_2$

# New motivation



# Equations of motion

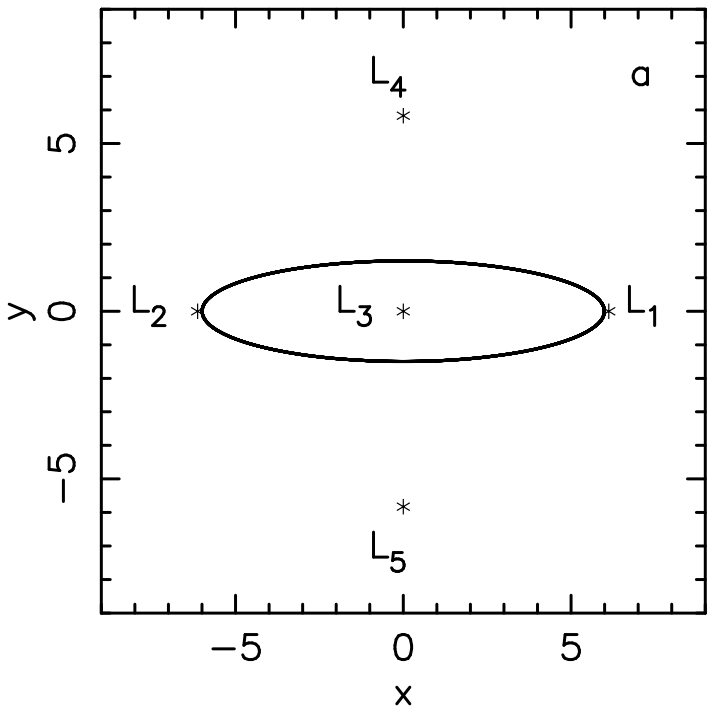
- The equations of motion of a system that rotates counter-clockwise are described in vectorial form by:

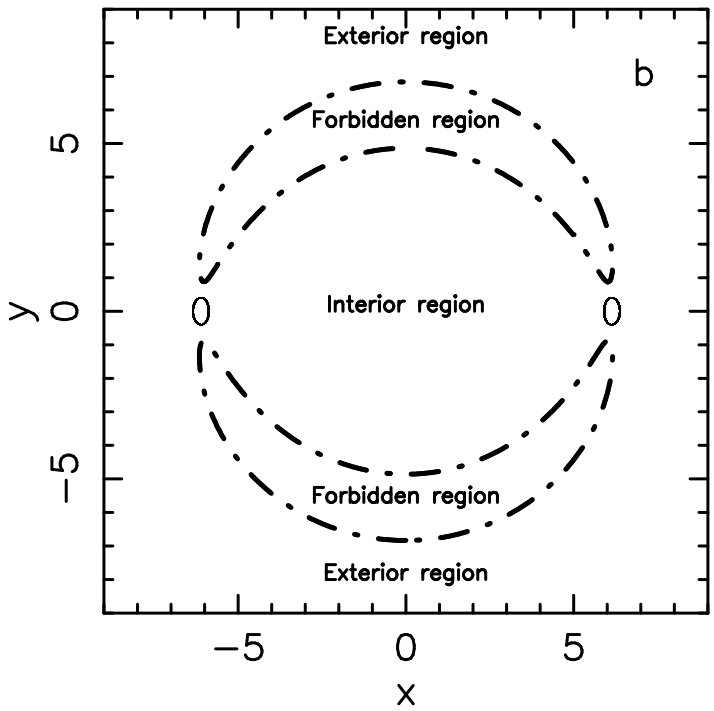
$$\ddot{\mathbf{r}} = -\nabla \mathbf{\Phi}_{\rm eff} - 2(\mathbf{\Omega} \times \dot{\mathbf{r}}),$$

  where
  - $\mathbf{r} = (x, y, z)$ is the position vector,
  - $\mathbf{\Omega} = (0, 0, \Omega)$ is the rotation velocity vector around the z-axis clockwise,
  - $\Phi_{\rm eff} = \Phi - \frac{1}{2}\Omega^2 (x^2 + y^2)$ is the effective potential.
- The potential: $\Phi = \Phi_b + \Phi_{axi}$. Different models for $\Phi_b$.
- We define the Jacobi constant or Jacobi energy as $E_J = \frac{1}{2}|\dot{\mathbf{r}}|^2 + \Phi_{\rm eff}$.
- The zero velocity surface of a given energy level is the surface obtaine when: $\Phi_{\rm eff}(x, y, z) = E_J$. We define the zero velocity curve, its cut with the $z = 0$ plane.

# Quick review of the dynamics in the rotating reference frame

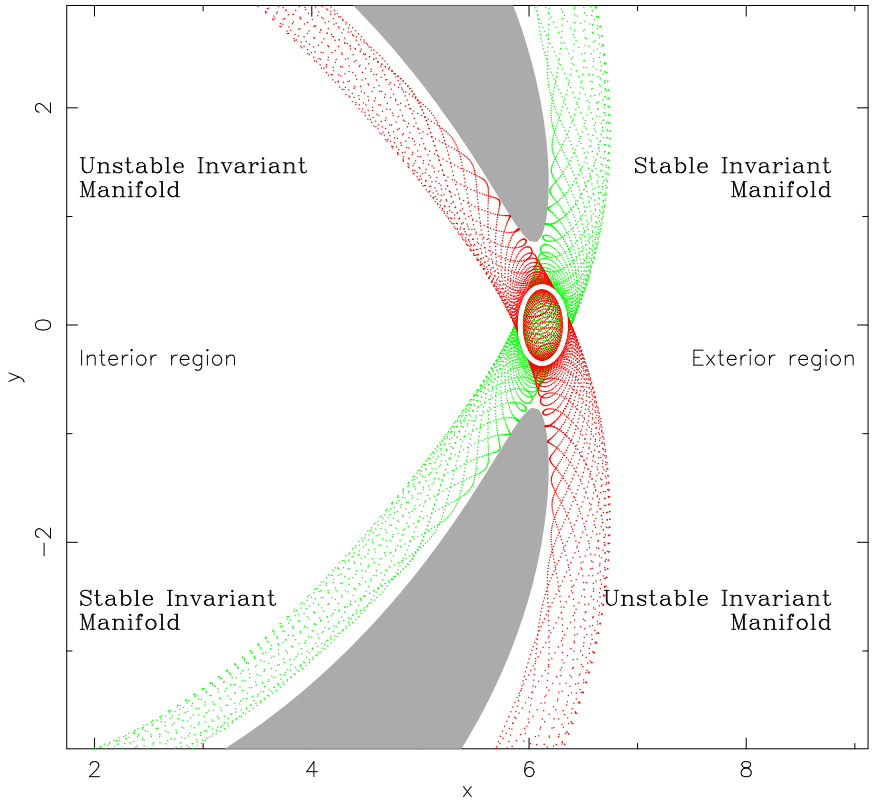
- 5 equilibrium points: $L_1$ and $L_2$ are saddle points
- Family of unstable planar Lyapunov orbits around $L_1$ and $L_2$, for a wide range of energies.



# Nonlinear stable and unstable invariant manifolds

- Using NF - reduction to the centre manifold: only Lyapunov orbits and invariant tori (Romero-Gómez et al. 2009)
- "Directly", integrating i.c. taken in the direction given by the most unstable eigenvalue of the monodromy matrix.

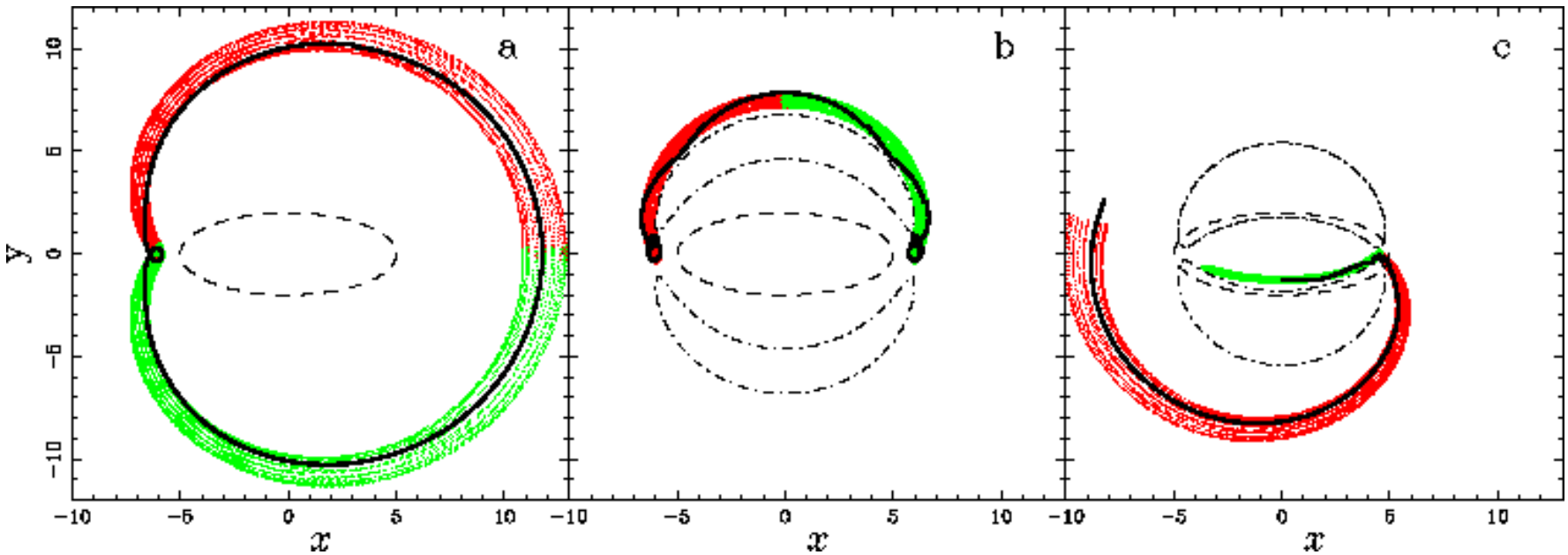



Romero-Gómez et al. (2006)

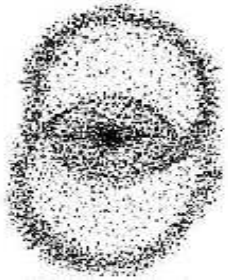
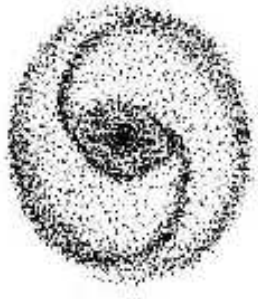
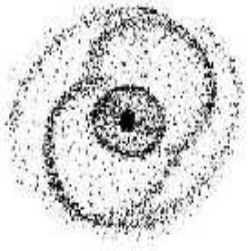
# Transfer of matter: Homoclinic and heteroclinic orbits

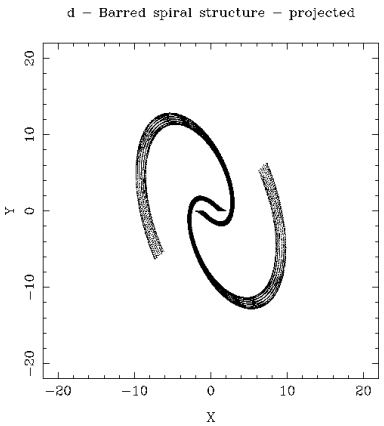
- Homoclinic orbits, $\psi$, s.t. $\psi \in W^u_{\gamma_i} \cap W^s_{\gamma_i}$, $i = 1, 2$
- Heteroclinic orbits, $\psi'$, s.t. $\psi' \in W^u_{\gamma_i} \cap W^s_{\gamma_j}$, $i \neq j$, $i, j = 1, 2$

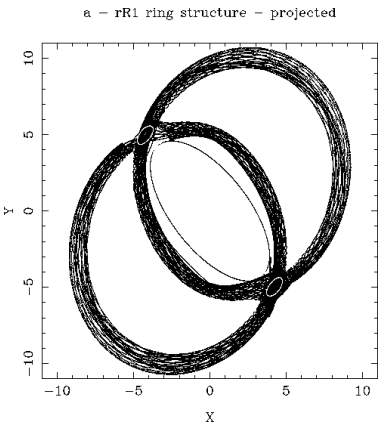
Romero-Gómez et al. (2007)

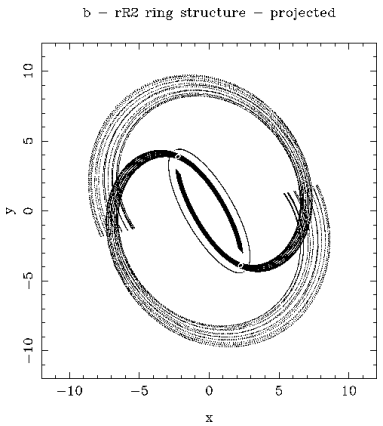


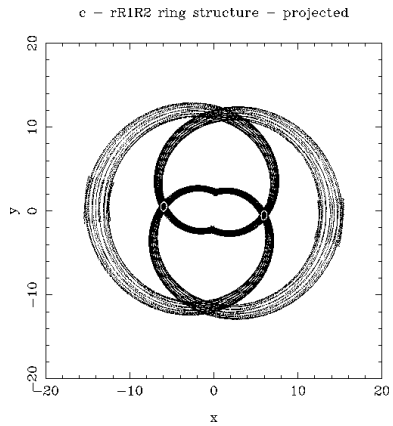

Homoclinic Heteroclinic Transit

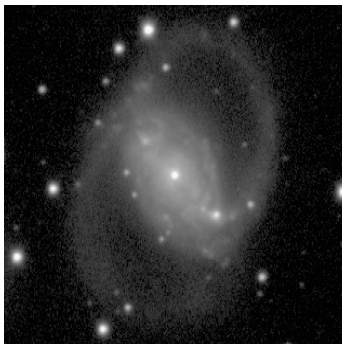
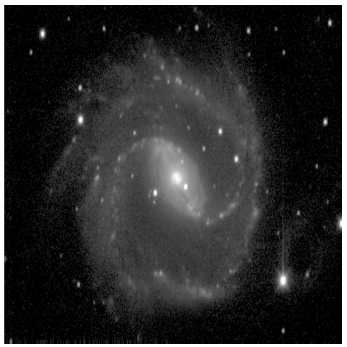
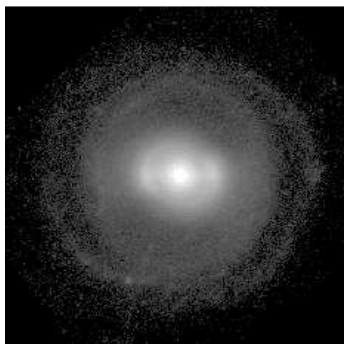










NGC 1365 Spiral arms

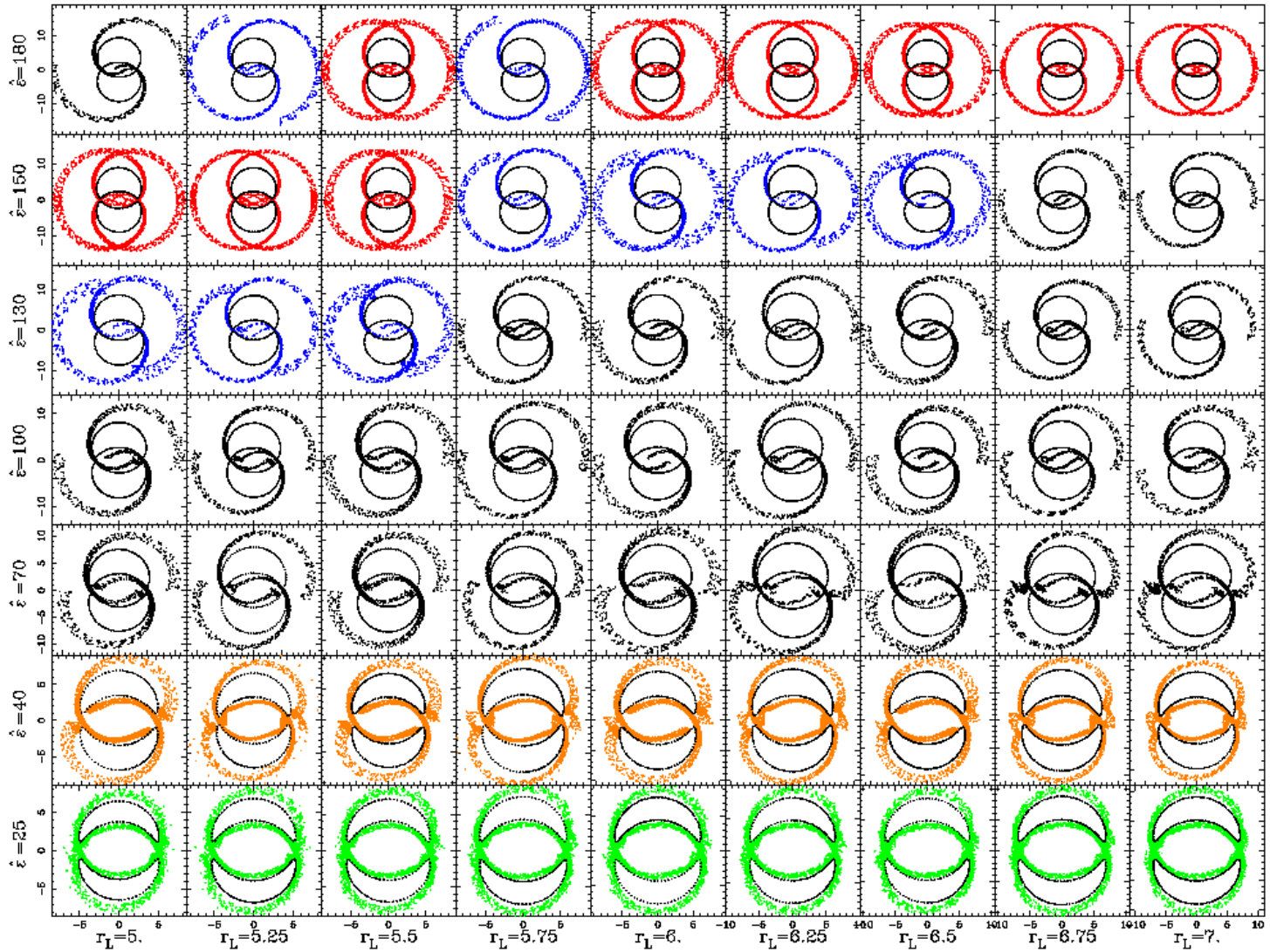
NGC 2665 $R_1$

NGC 2935 $R_2$

NGC 1079 $R_1R_2$

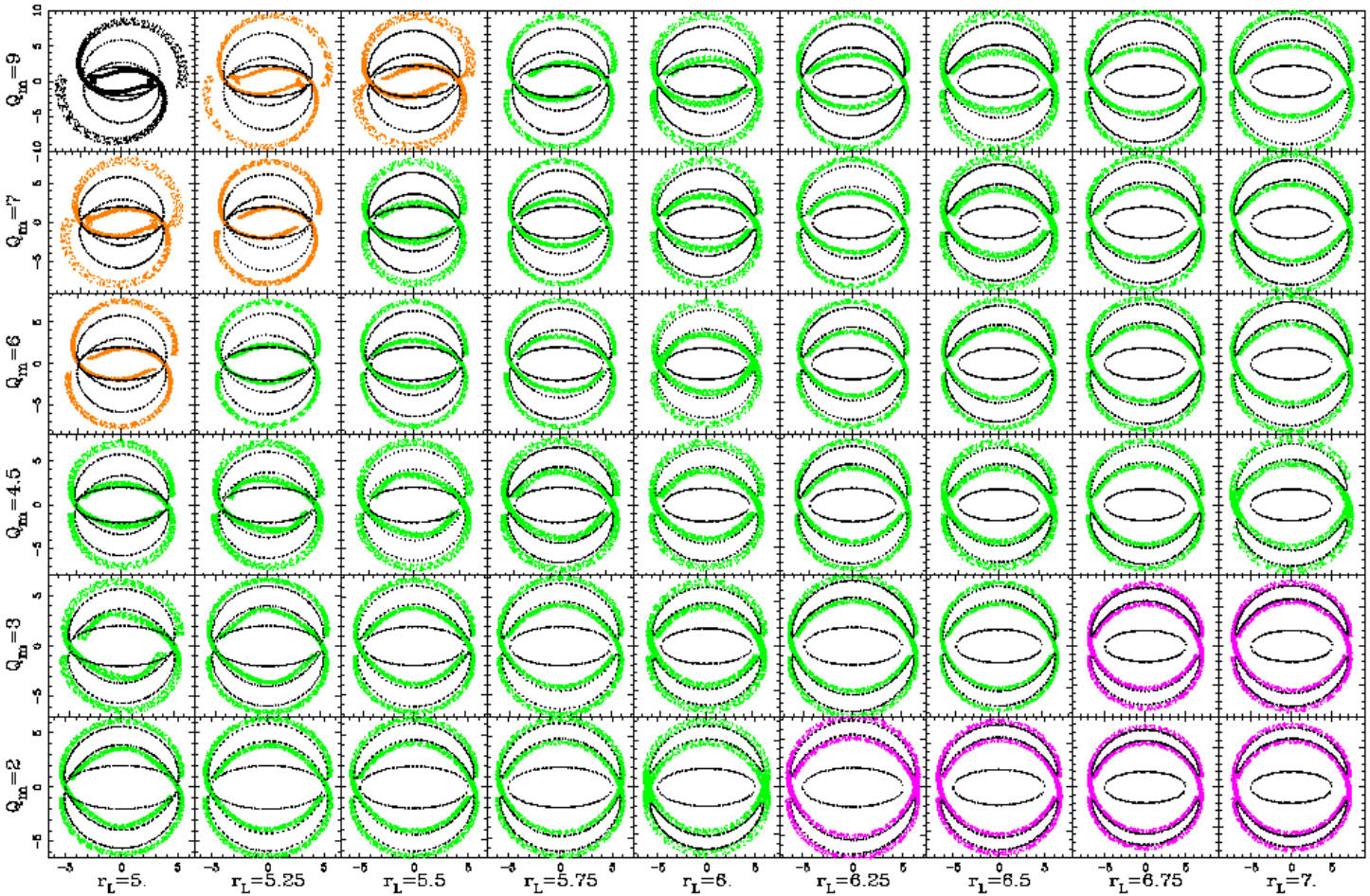
# 2D parameter study - BW type of bar - Flat rotation curve

Athanassoula, Romero-Gómez & Masdemont (2009)



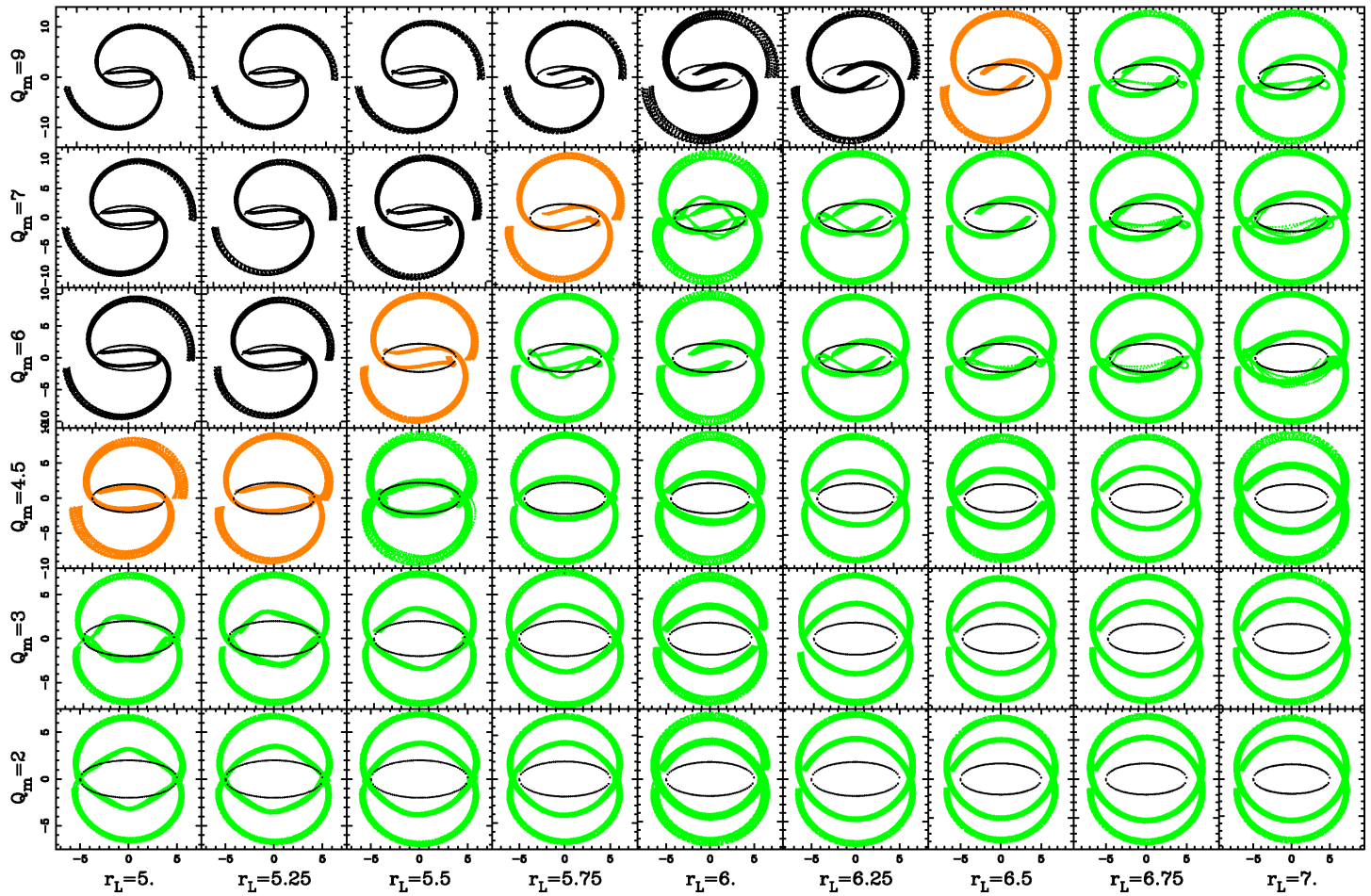
# 2D parameter study - Ferrers type of bar - Flat rotation curve

Athanassoula, Romero-Gómez & Masdemont (2009)



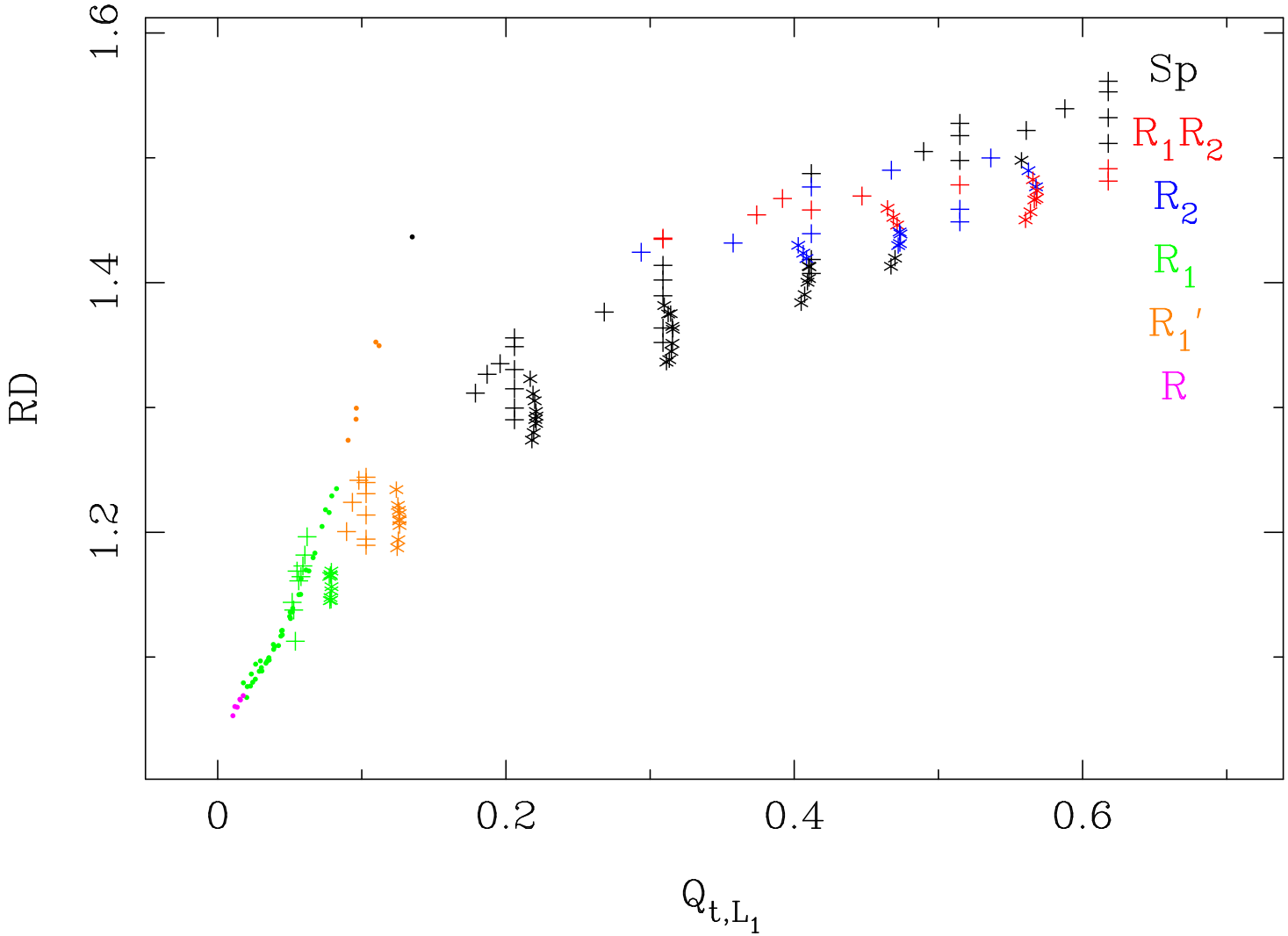
# 2D parameter study - Ferrers type of bar - Decreasing rotation curve

Athanassoula, Romero-Gómez, Bosma & Masdemont (2009)



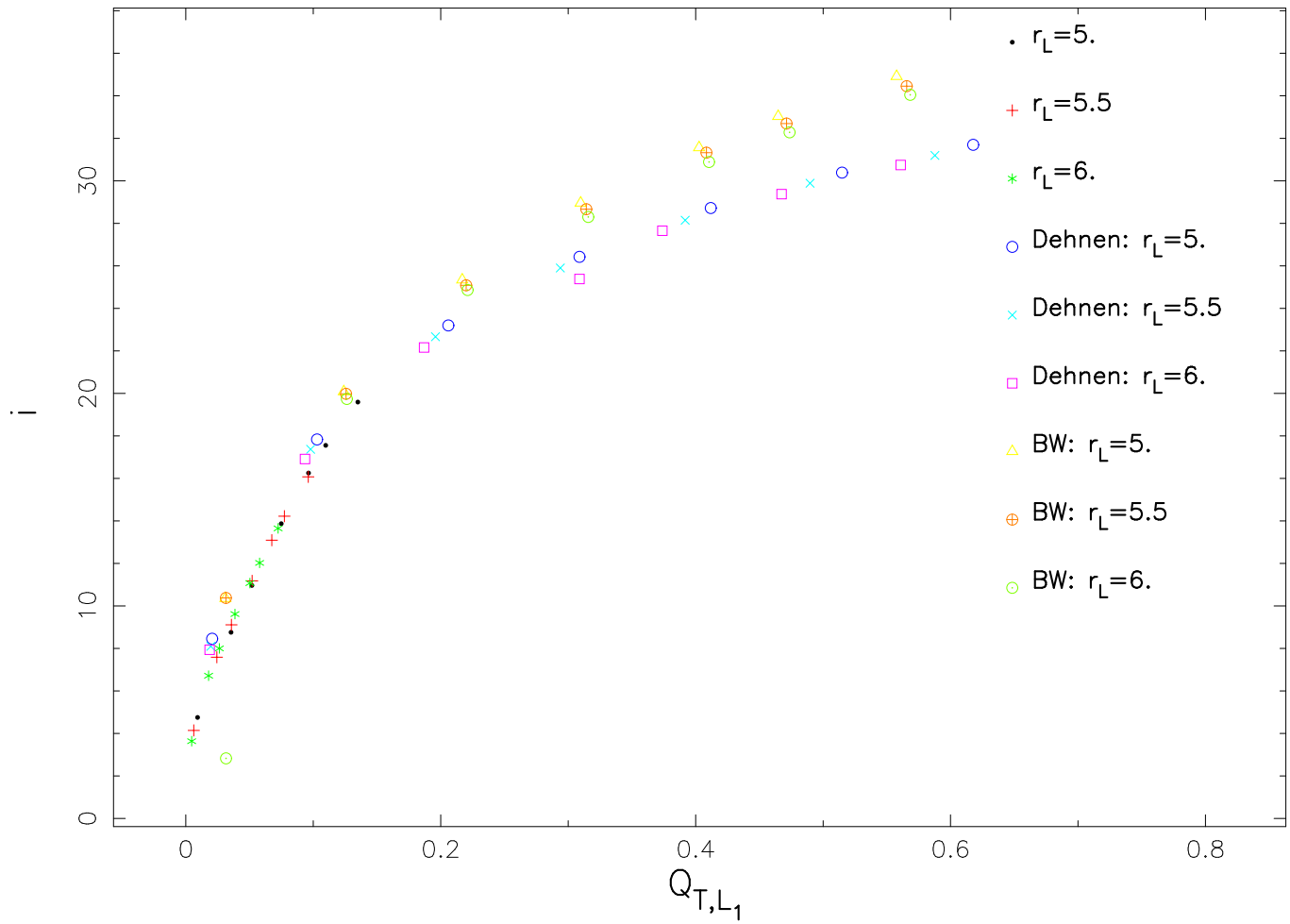
# 2D parameter study - prediction tool

Athanassoula, Romero-Gómez & Masdemont (2009)

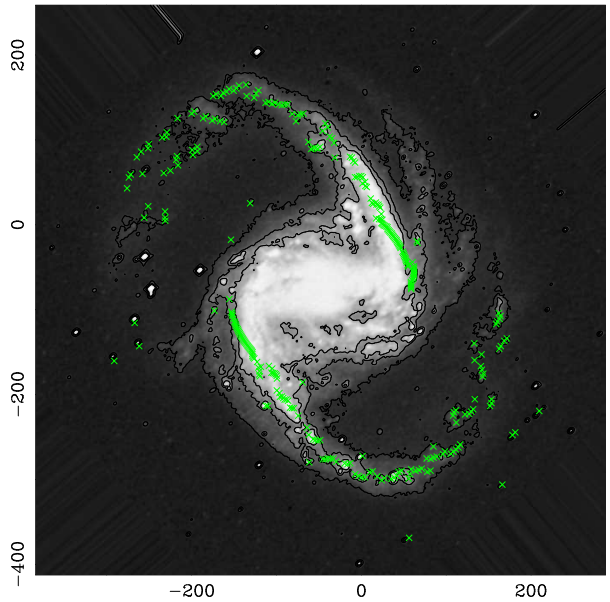


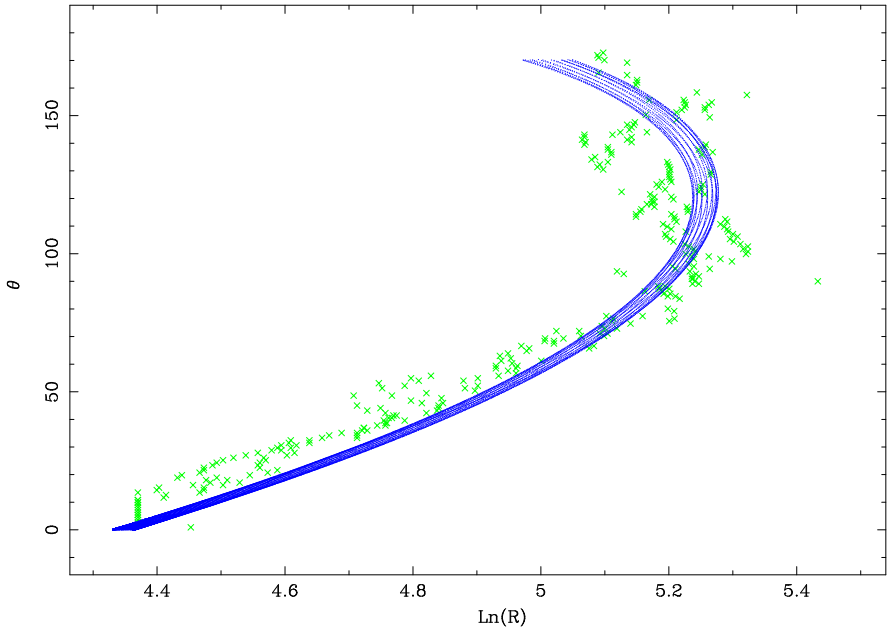
# Pitch angle vs strength parameter

According to observations, the pitch angle of the spiral arm increases in galaxies with a strong bar.



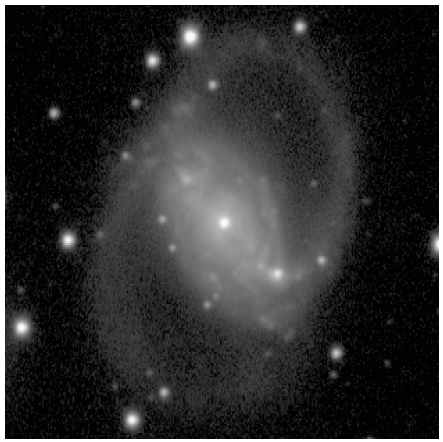
# Photometrics: Pitch angle

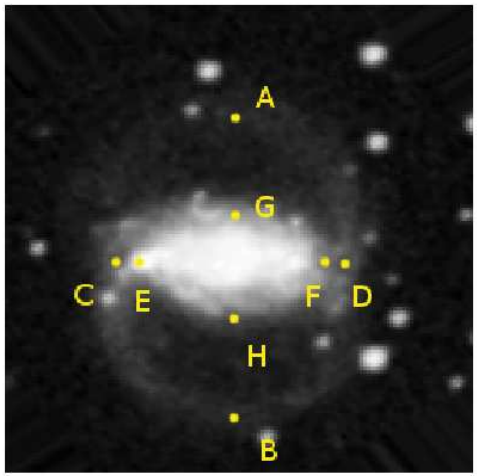


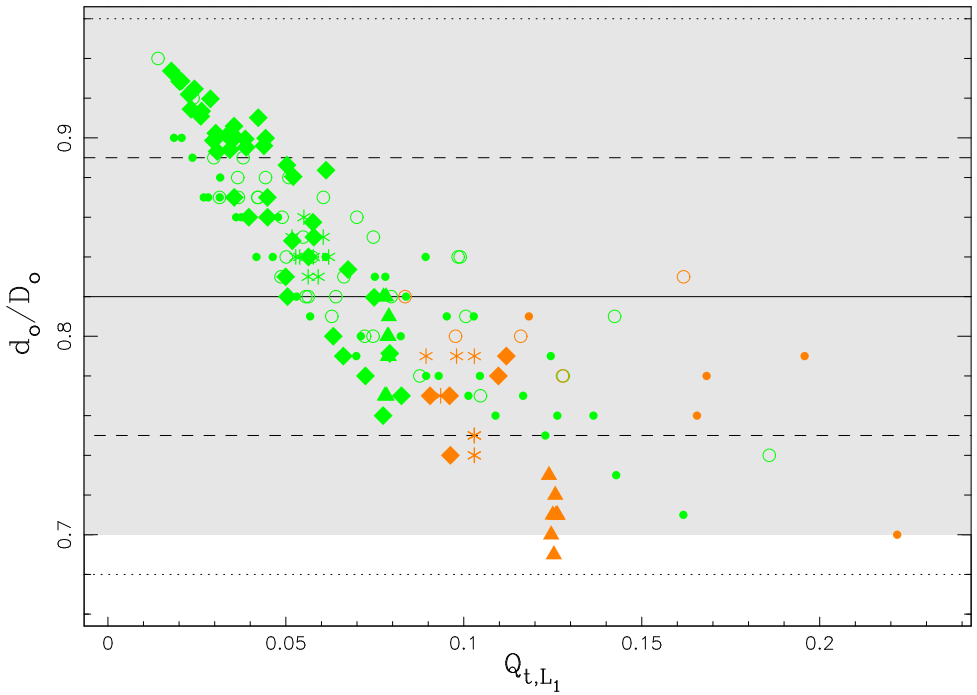



# Ratio of the outer ring diameters vs strength parameter

We find a good correlation between the ratio of the outer ring diameters with the strength of the bar. (Athanassoula, Romero-Gomez, Bosma & Masdemont 2009)



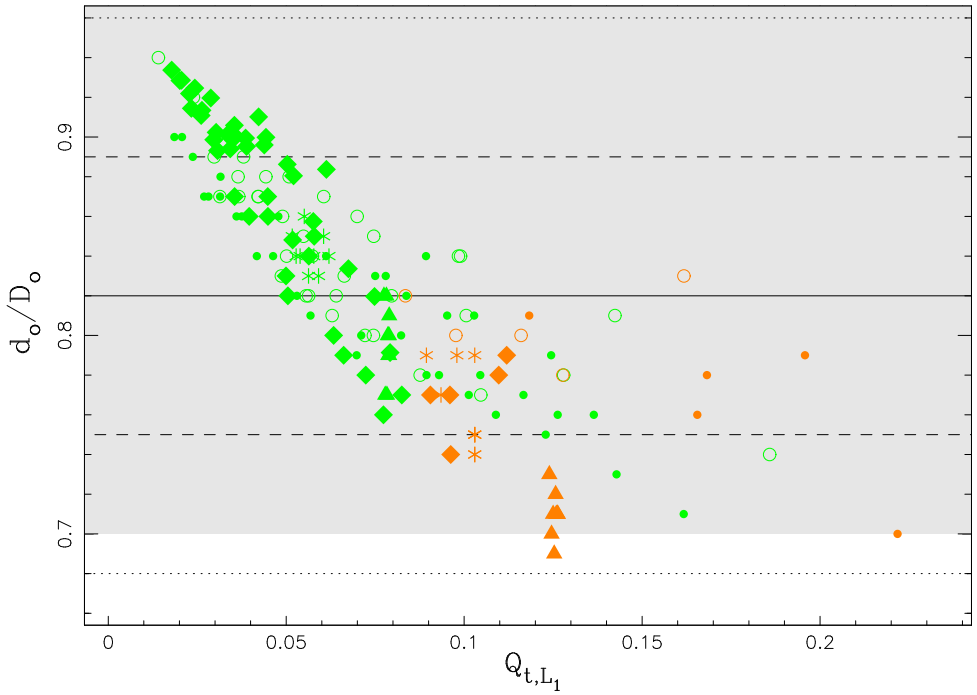


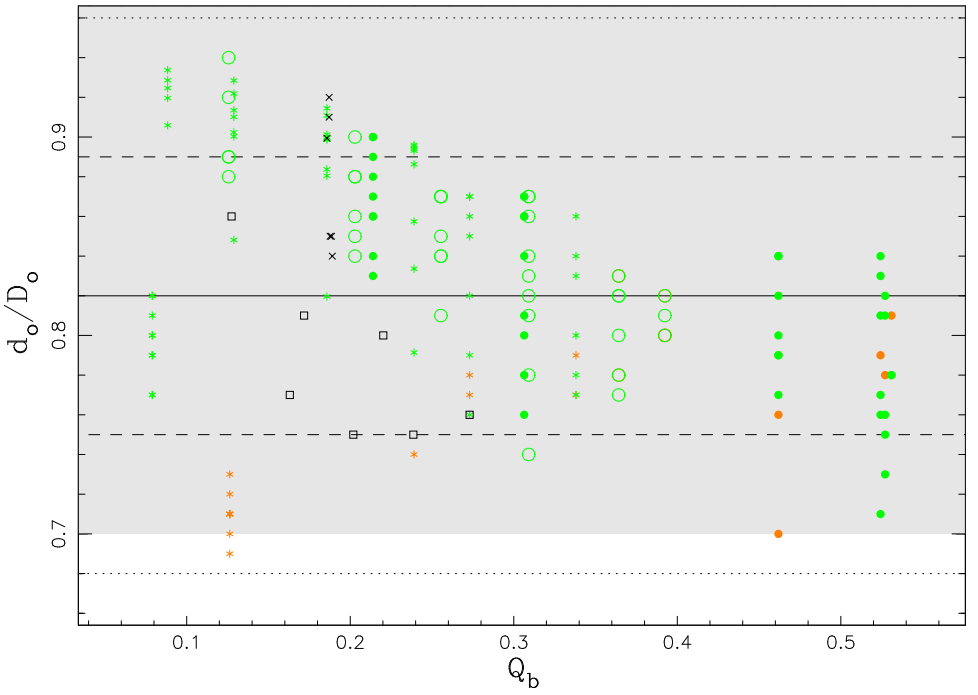

$$d_o/D_o = CD/AB$$

# Ratio of the outer ring diameters vs strength parameter: $Q_{t,L_1}$ or $Q_b$?

(Athanassoula, Romero-Gomez, Bosma & Masdemont 2009)



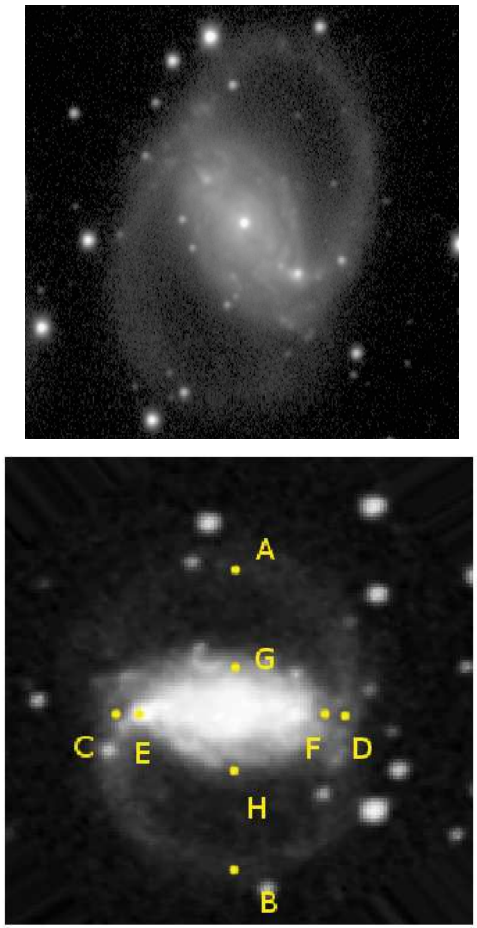

Rank correlation=-0.95

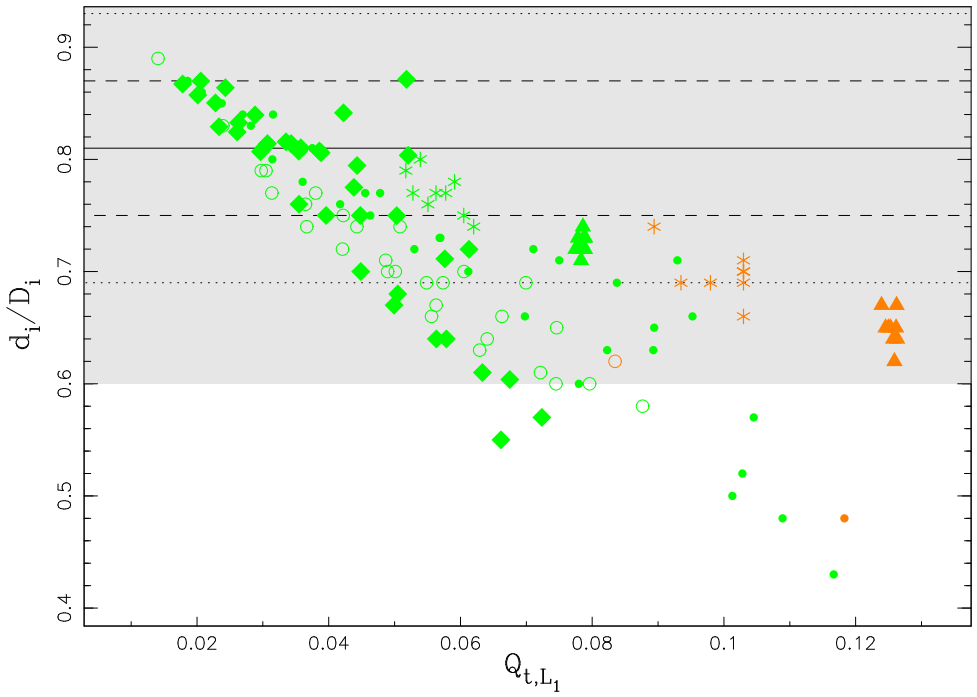



Rank correlation=-0.001

# Ratio of the inner ring diameters vs strength parameter

We find a good correlation between the ratio of the inner ring diameters with the strength of the bar. (Athanassoula, Romero-Gomez, Bosma & Masdemont 2009)

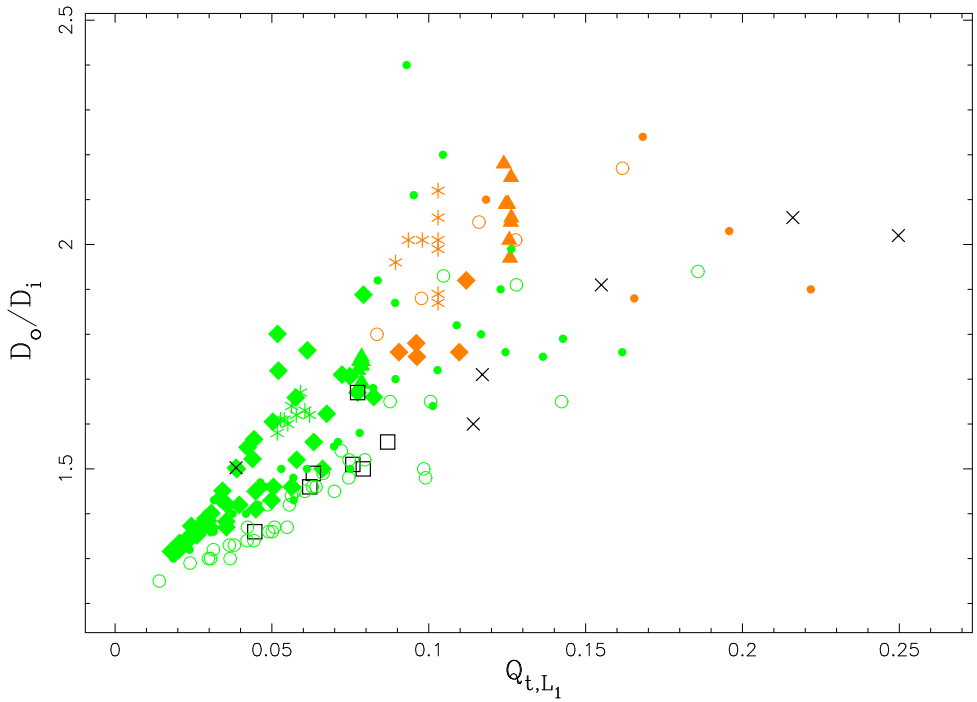



$$d_i/D_i = GH/EF$$

# Ratio of the major axis of the outer ring to the major axis of the inner ring vs strength parameter

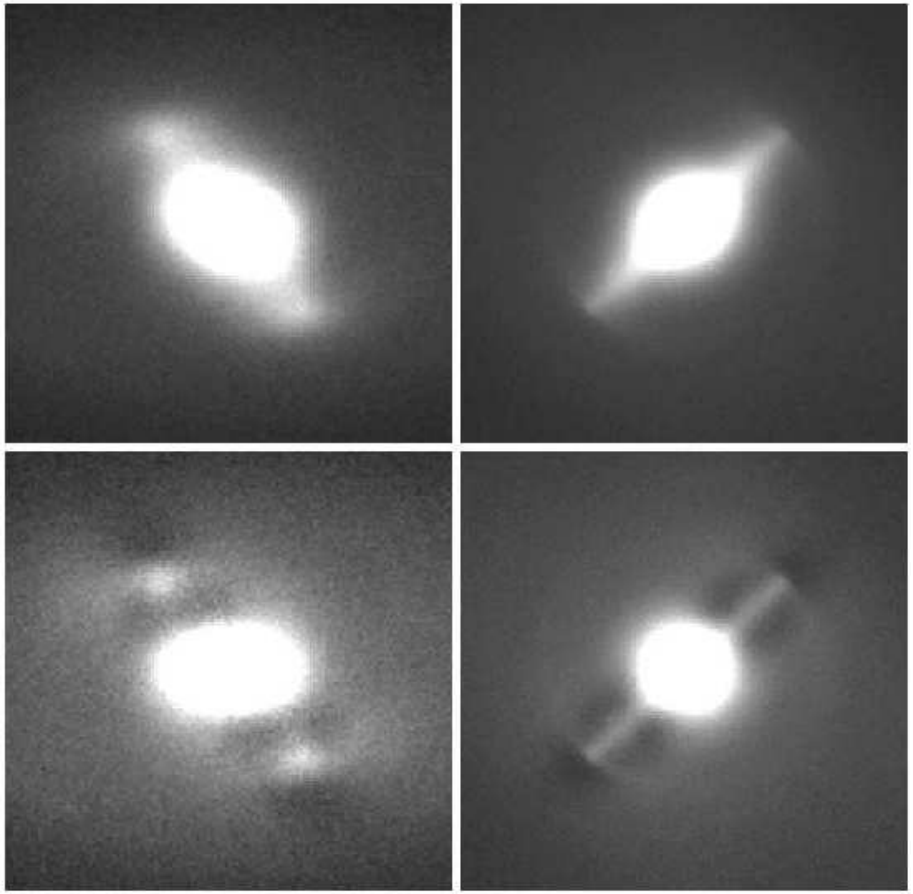
(Athanassoula, Romero-Gomez, Bosma & Masdemont 2009)




Note that models with decreasing rotation curve or with an early-type models have larger $D_o/D_i$.

# Stabilisation of $L_1$ and $L_2$ - ansae formation? -I

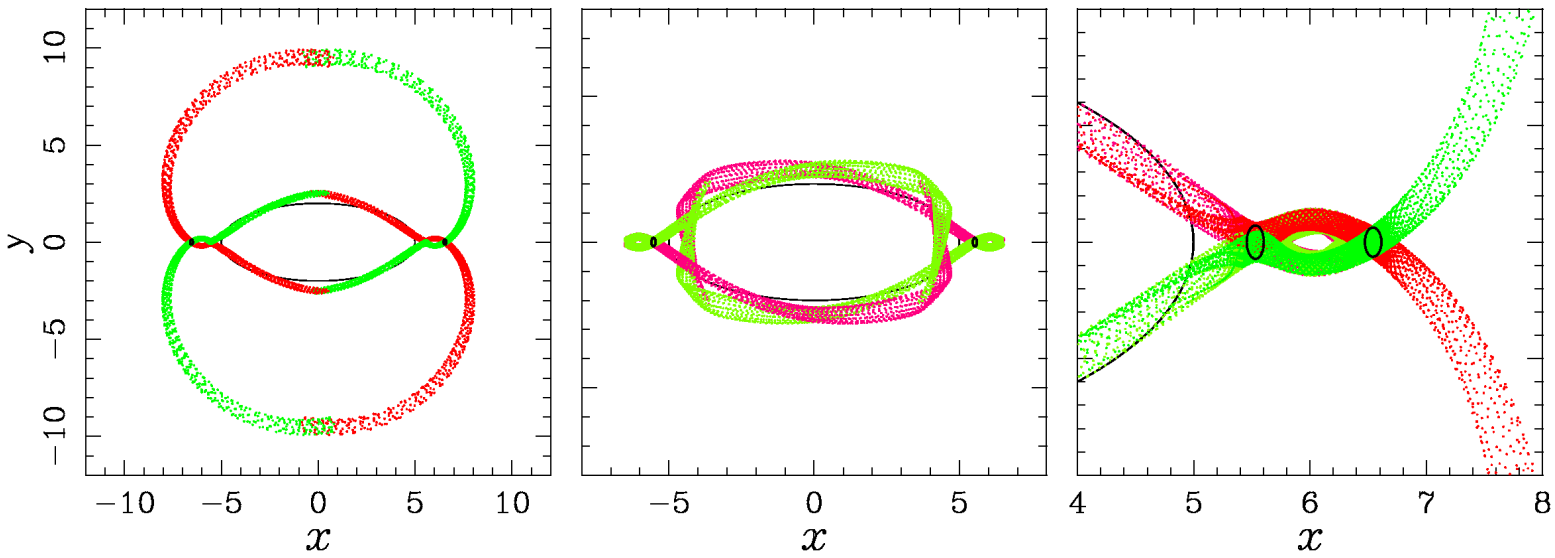
What if material gets concentrated at the ends of the bar?



ansae bars "normal" bars

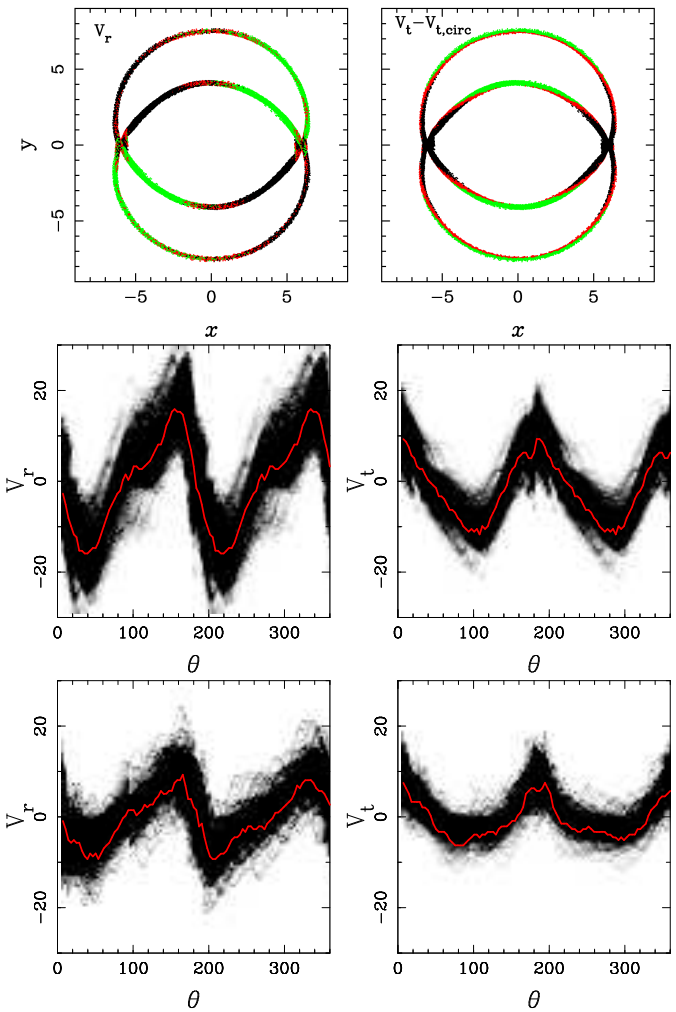
# Stabilisation of $L_1$ and $L_2$ - ansae formation? -II

Athanassoula, Romero-Gomez & Masdemont 2009



# Kinematics along the ring - I: Radial and tangential velocities

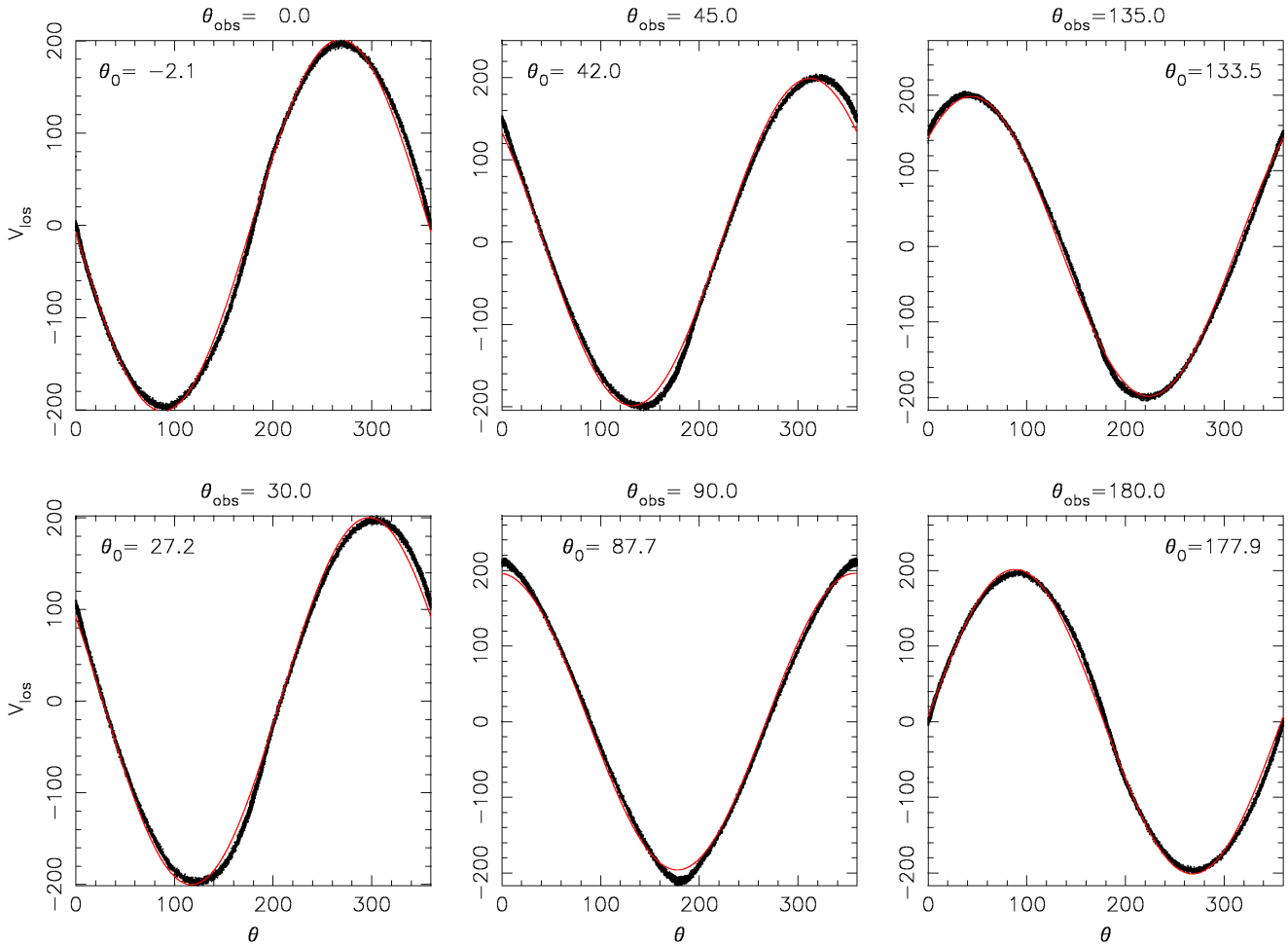
(Athanassoula, Romero-Gomez, Bosma & Masdemont 2010)




- Galactocentric Radial and tangential velocities in the inertial frame of reference. Black: positive values; Green: negative values; Red: values around zero (-2.5,2.5).
- Radial and tangential velocities along the inner ring.
- Radial and tangential velocities along the outer ring.

# Kinematics along the ring - II: Line-of-sight radial velocities

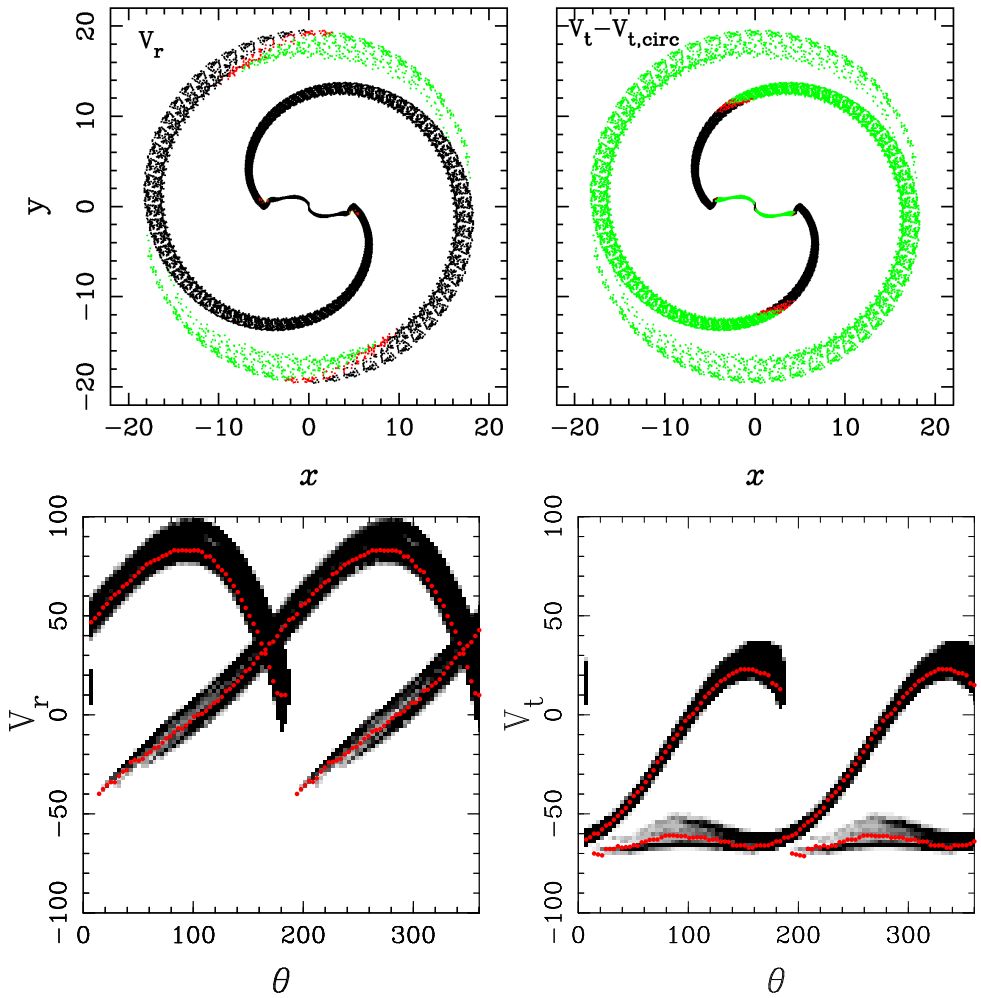
(Athanassoula, Romero-Gomez, Bosma & Masdemont 2010)




Red curve: $A\,sin(\theta - \theta_o)$

# Kinematics along the spiral - I: Radial and tangential velocities

(Athanassoula, Romero-Gomez, Bosma & Masdemont 2010)



# Kinematics along the spiral - II: Line-of-sight radial velocities

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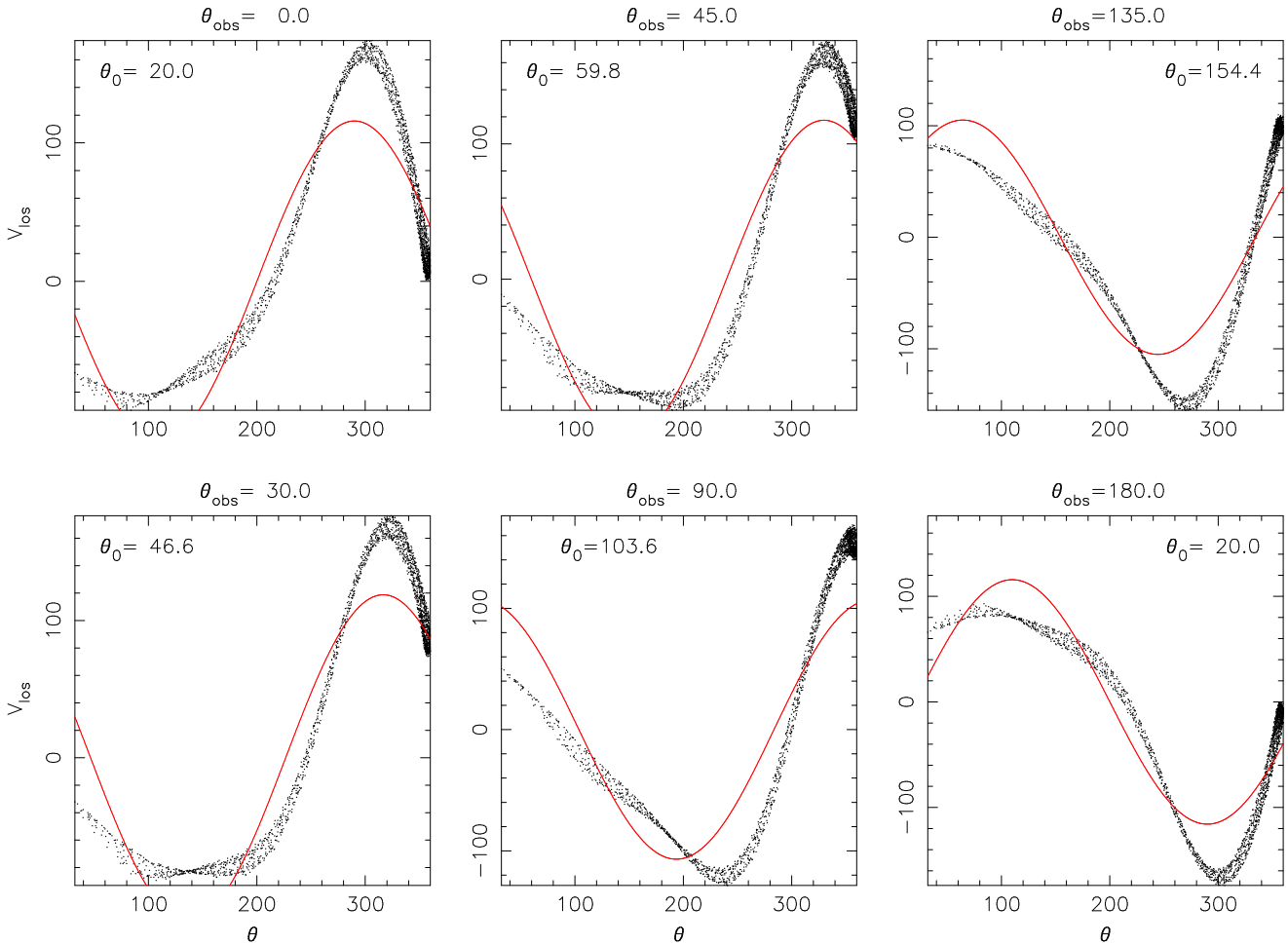
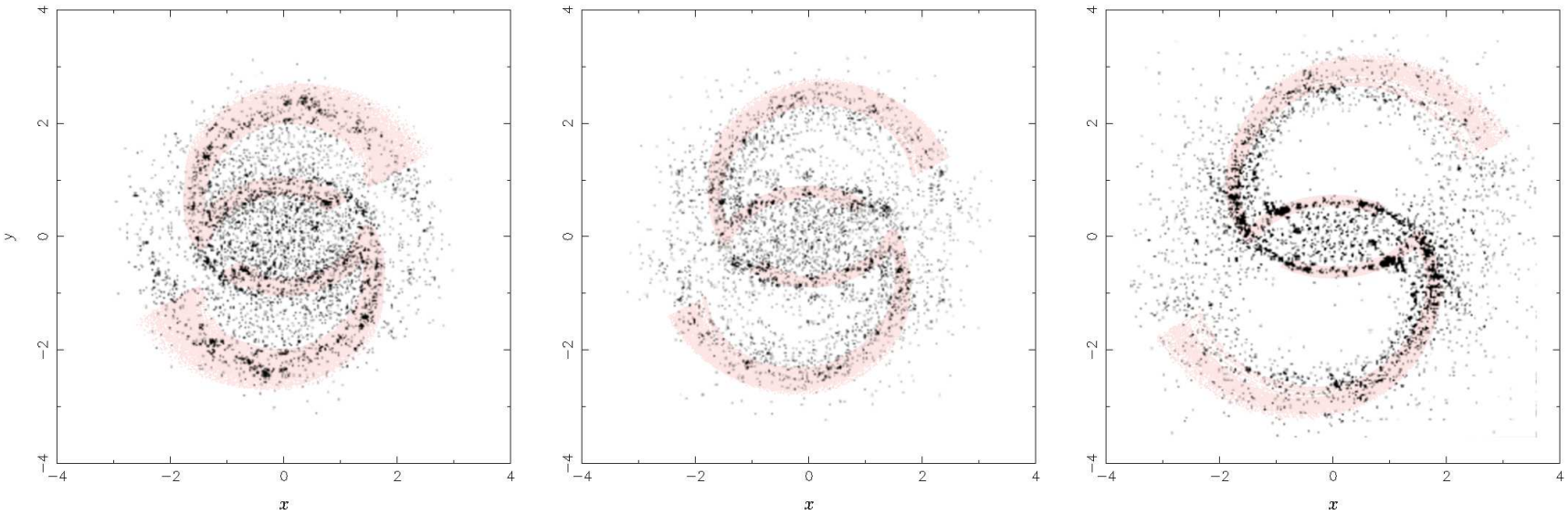



Red curve: $A\,sin(\theta - \theta_o)$

# Comparison to gas response

Schwarz 1984; Athanassoula, Romero-Gomez, Bosma & Masdemont 2010

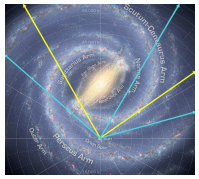


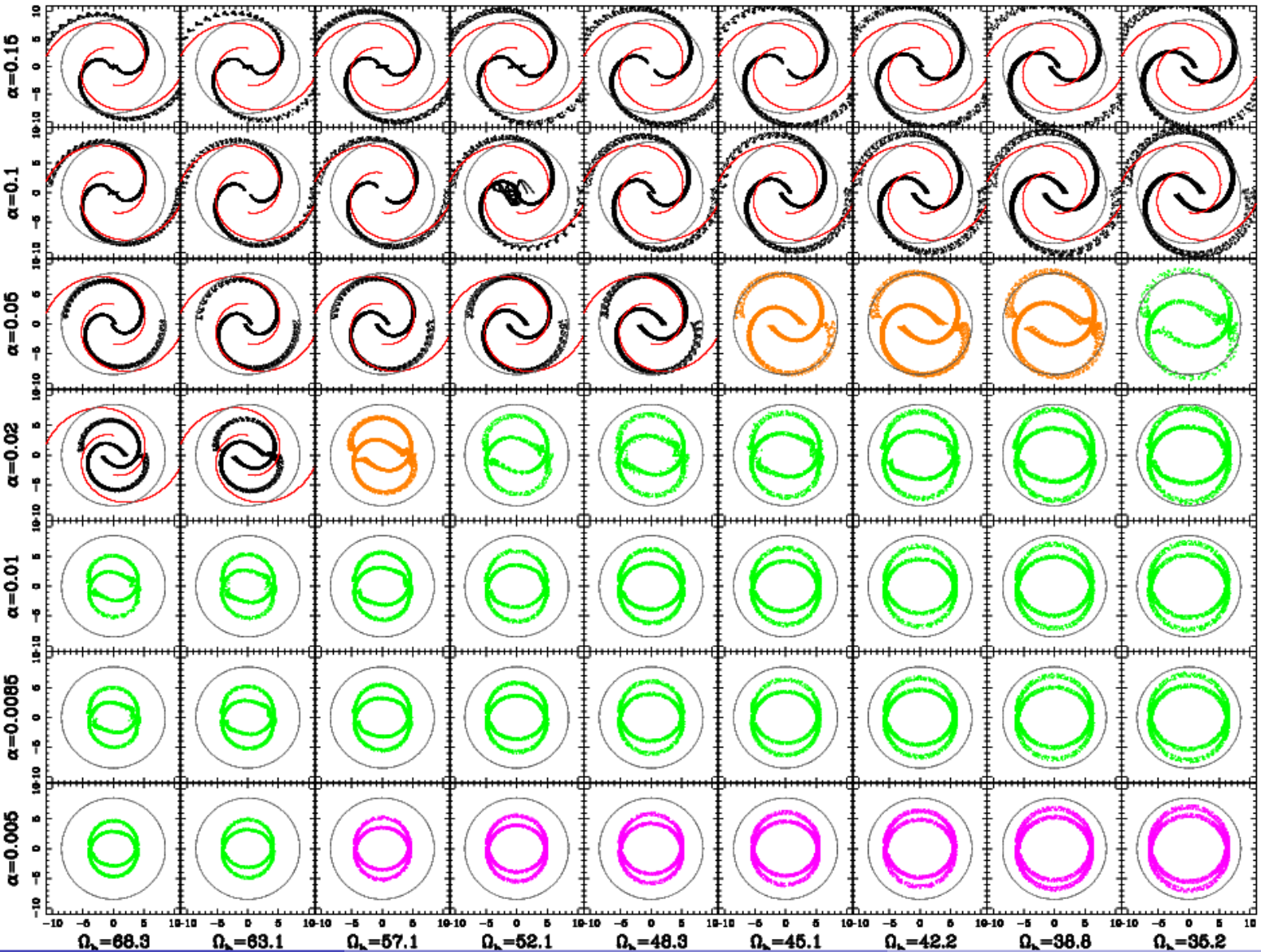
# A possible model for the Milky Way?

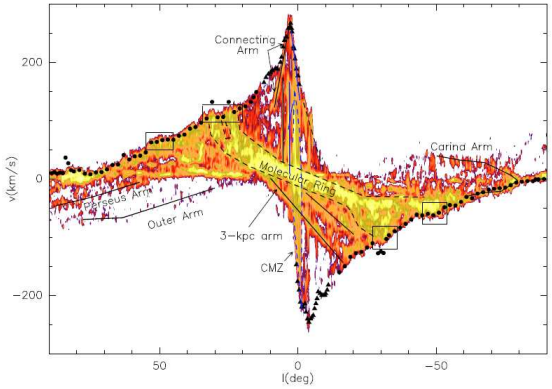
Romero-Gomez et al. (2010), in preparation

- Constraints: morphological (shape, number of arms,...), kinematical (bar pattern speed, arms pattern speed, l-v diagrams, presence of moving groups, rotation curve, sense of rotation (clockwise!)...)
- **Morphology**: To obtain two open spiral arms we need a strong bar with forces extending to the outer parts (i.e. a large value of $Q_{t,L_1}$).
- **Kinematics**: Spirals are present in the l-v diagrams.

# Morphology of the Milky Way



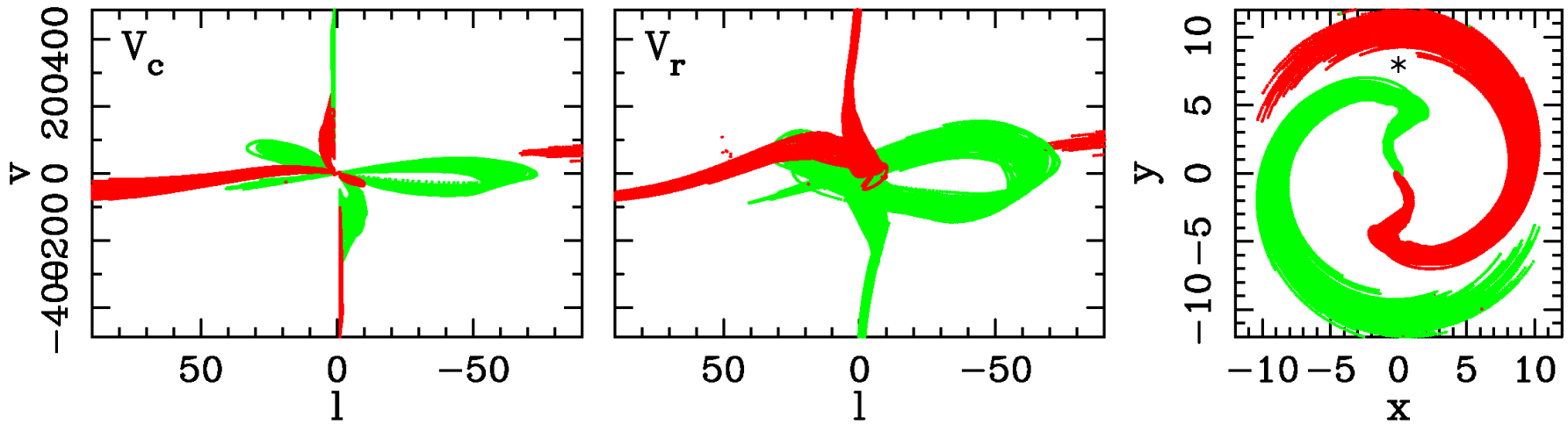





# Kinematics of the Milky Way

(Heliocentric) Line-of-sight radial velocity as a function of the longitude.

$\Omega = 63.2,\ \alpha = 0.100$



# 2 bars?

Parameters: Galactic bar at 20° from the Sun-GC direction, $a_G = 3.13$ kpc, $M_G = 10^{10}\, M_\odot$, Long bar at 40°, $a_L = 4.5$ kpc.

# Thanks!

The Starry night (Vincent van Gogh)