Orbital classification in a barred galactic model

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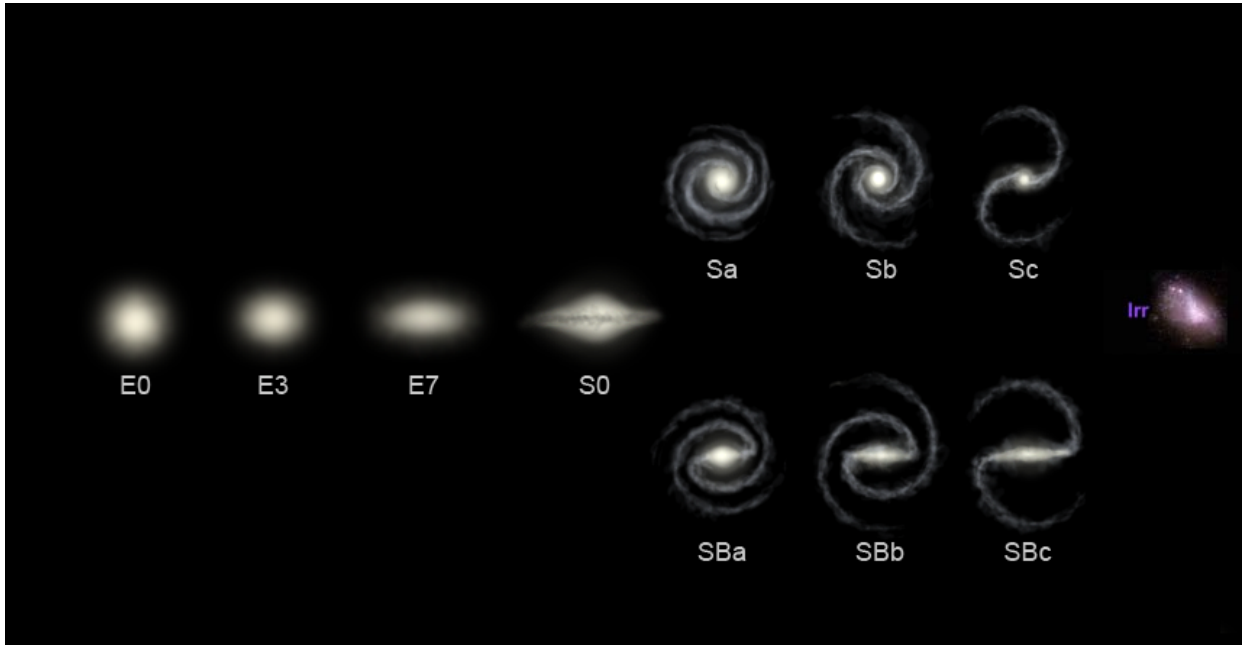
- Statistical morphological analysis for the orbits of barred models?
- Conclusions

Introduction: classification of galaxies

Morphological classification of galaxies



1/3 are elliptical

2/3 are spirals

A small percentage are irregular or are merging (Lintott et al 2011; Willet et al 2013)

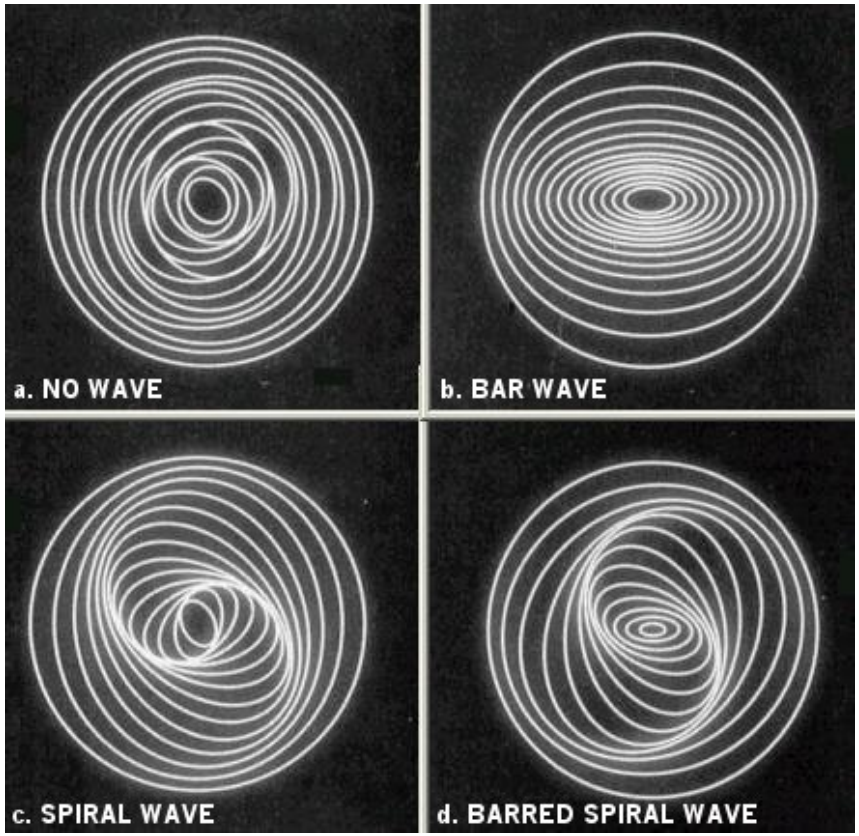
(Lintott et al 2011; Willet et al 2013)

Galaxia barrada NGC 1300

Introduction: growth of structures, density waves

Density Waves: Lin & Shu (1964) and Bertin & Lin (1996).

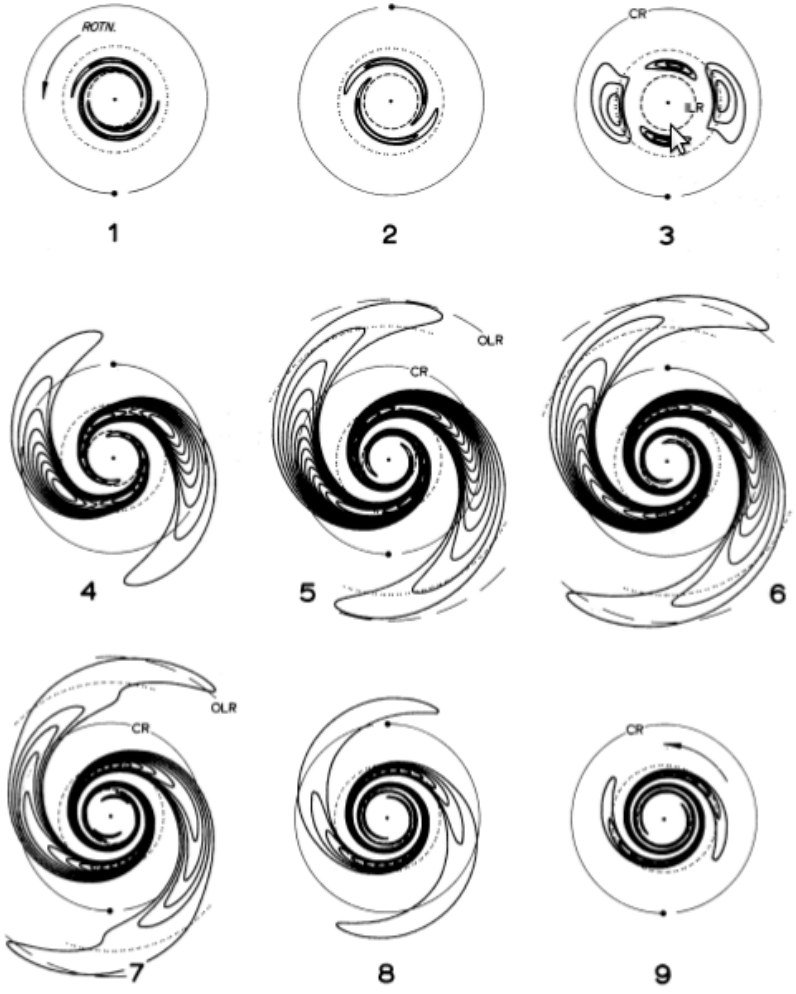
In this theory, the spiral arms are explained as long-lived quasi-stationary density waves with a constant pattern speed.



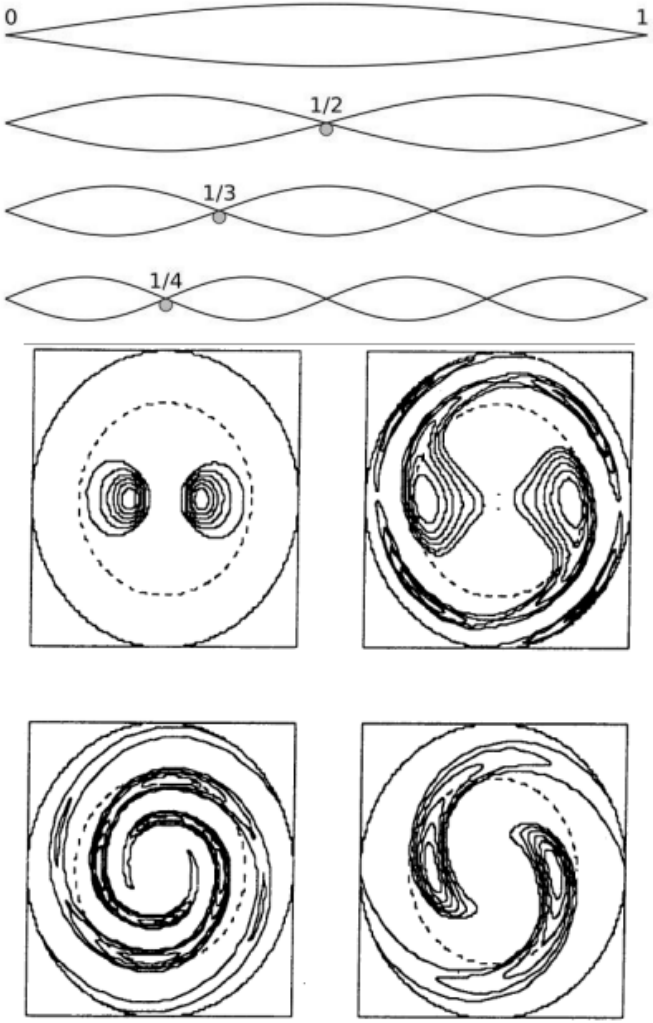
- The waves are the result of global modes (Bertin & Lin 1996) or couple modes (Masset & Tagger 1997).
- Swing-amplification (Toomre 1981).
- N-body simulations show that the spiral arms fade out after some galactic rotations (Sellwood & Carlberg 1984).
- The spiral arms are considered to be corotating with the rest of the disc at every radius; they are material spiral arms (Roca-Fàbrega et al. 2013)

Introduction: growth of structures, density waves

Swing Amplification Toomre (1972)



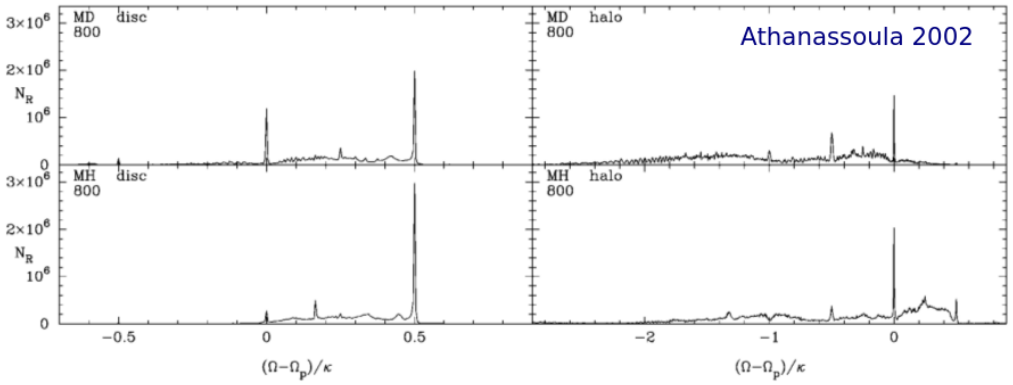
Teoría Modal (Bertin et al 1989)

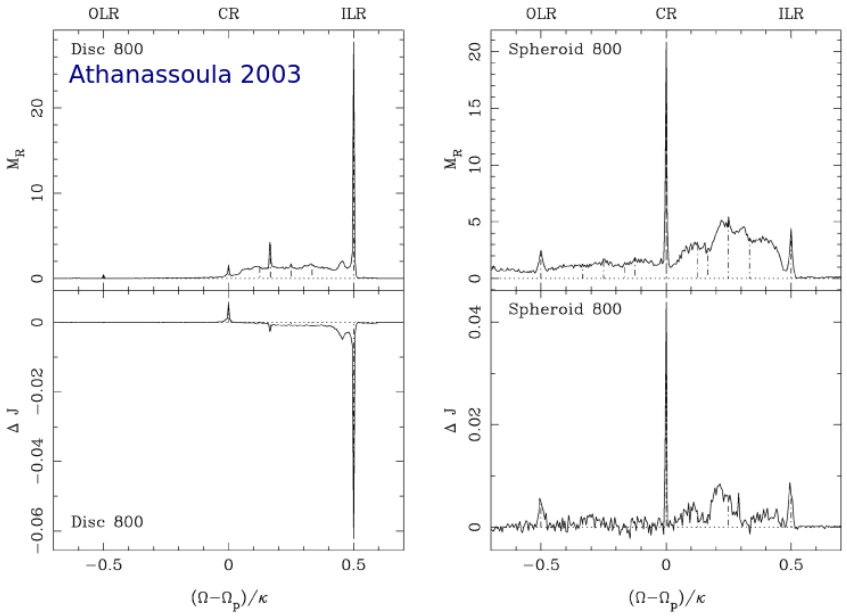


Introduction: exchange of angular momentum

Bar formation and evolution are very complex phenomena and depend on the exchange of angular momentum between the various resonances in the various components in the galaxy.

- the corresponding distribution functions (halo, disc and bulge) near the resonance.
- velocity dispersion.
- disc-halo mass ratios.





However, what are the critical limits of such parameters? or what are the critical parameter that assesses the stability of a disc galaxy?

Global stabilities: are there stability limits to generate a bar?

Valencia-Enríquez et al. 2019 shows

$$\epsilon_m = \frac{V_{max}}{\sqrt{GM_d/r_d}} \quad \Longrightarrow \quad 0.7 \leq \epsilon_m \leq 1.2 \;\; \text{unstable to bar formation}$$

Taking $\epsilon_{m,crit} \approx 1$

$$\lambda_{crit} = \left(\frac{\epsilon_{m,crit}}{V_{max}}\right)^2 GM_d \frac{\sqrt{2f_c}}{r_{200} f_r} = \frac{GM_d}{V_{max}^2} \frac{\sqrt{2f_c}}{r_{200} f_r},$$

where

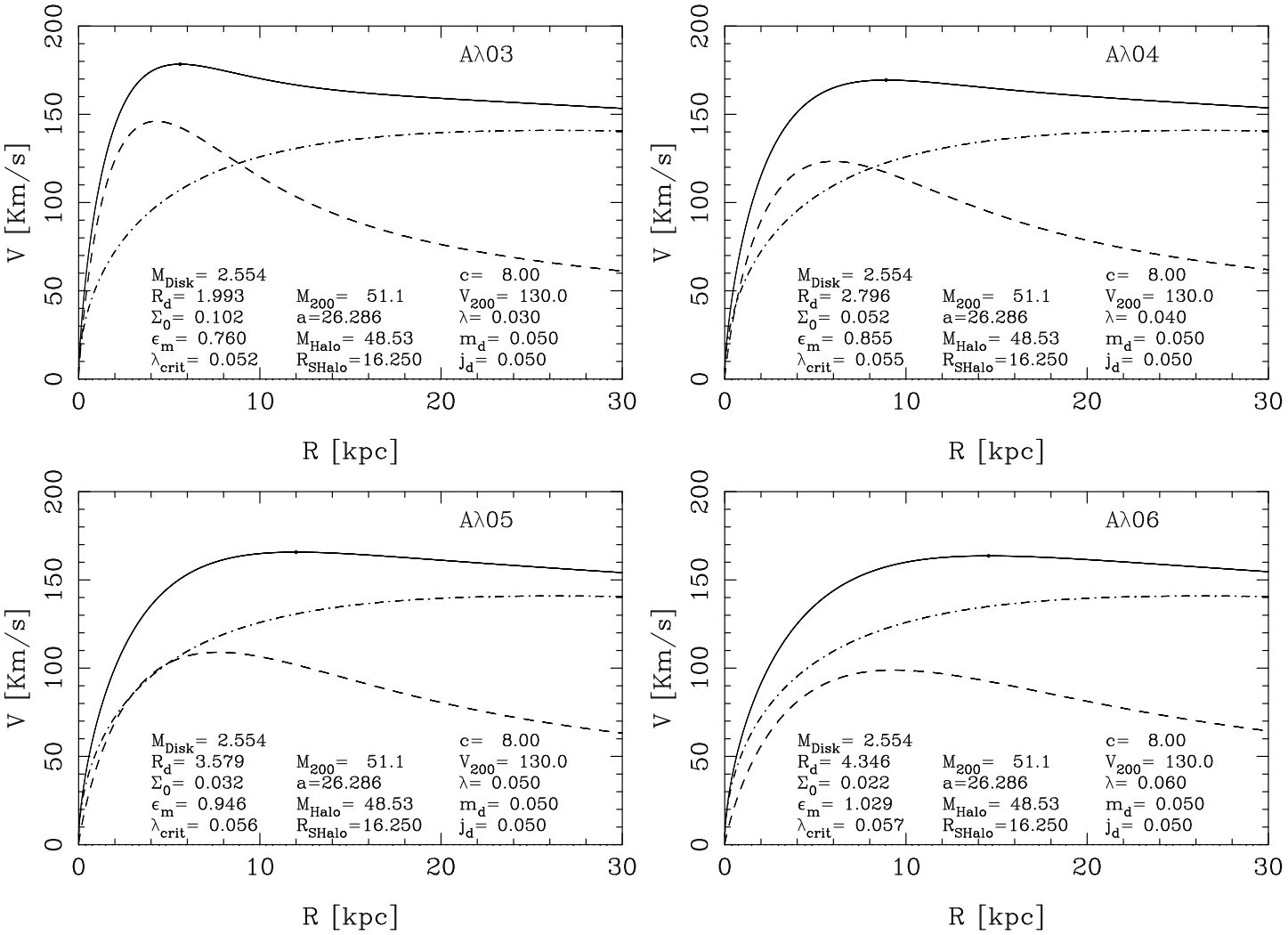
$$f_c = \frac{c\left[1 - 1/(1+c)^2 - 2ln(1+c)/(1+c)\right]}{2\left[ln(1+c) - c/(1+c)\right]^2}, \quad \text{and} \quad f_r = 2\left[\int_0^{r_{200}} e^{-r/r_d} \frac{r^2}{r_d^3} \frac{v_c(r)}{V_{200}} dr\right]^{-1}.$$

so

$$\begin{cases} \lambda_d > \lambda_{crit}, & \text{stable against bar formation} \\ \lambda_d \leqslant \lambda_{crit}, & \text{unstable to bar formation} \end{cases}$$

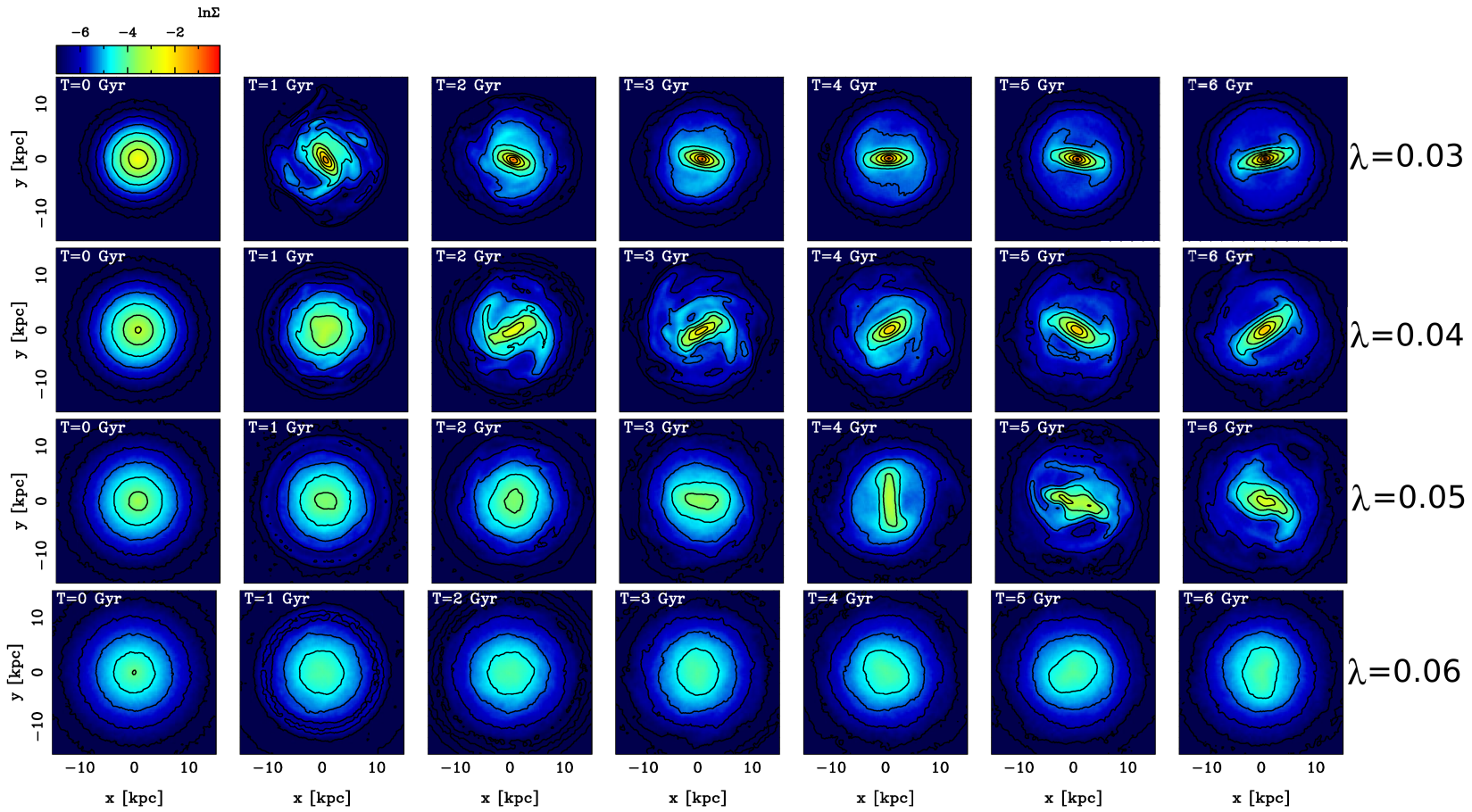
Global stabilities: the models

Initial rotation curves for our models. Their structural parameters are shown in each plot.



Global stabilities: temporal evolution

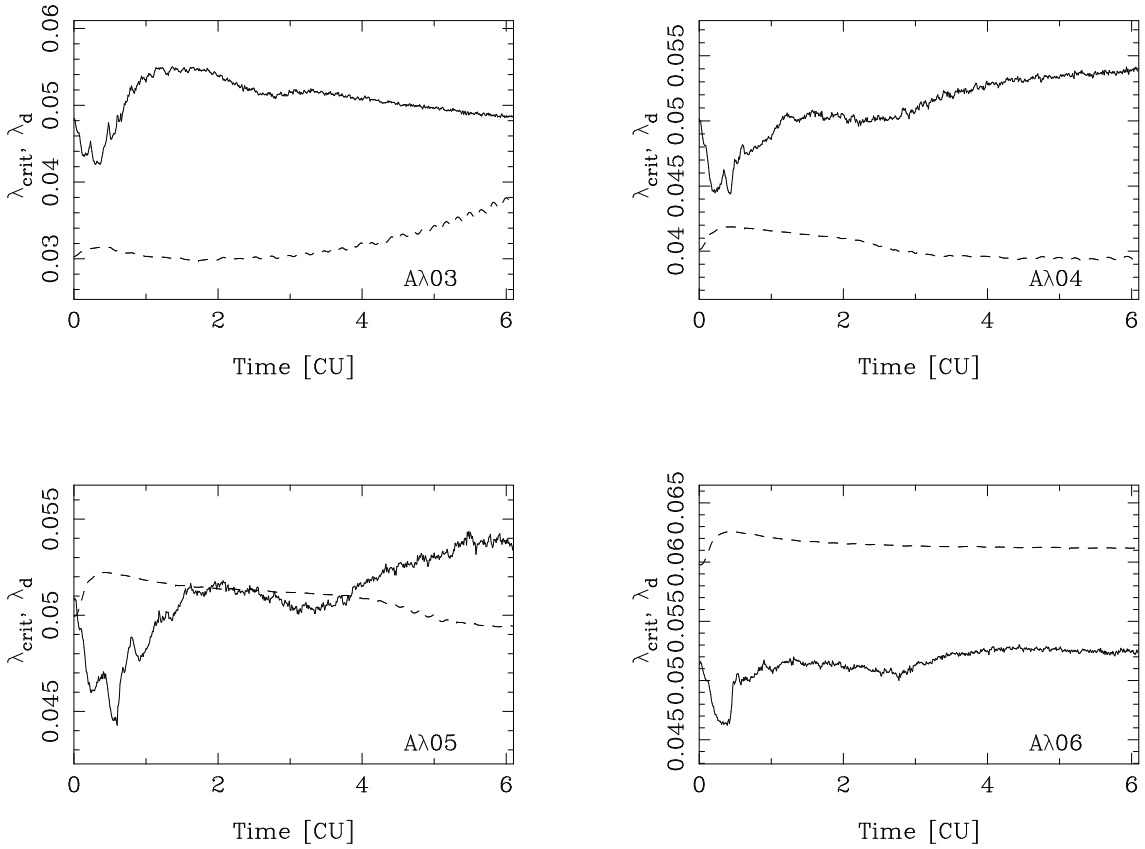
We employ the N-body code Gadget2, based on Springel (2005). Tolerance parameter $\theta_{tol} = 0.5$. The softening length for the disc particles is $\varepsilon = 0.01$ and for the halo ones is $\varepsilon = 0.1$.



Face-on surface logarithm density maps for our models and their evolution. From top to bottom, we present the evolution of models $A\lambda03$, $A\lambda04$, $A\lambda05$, and $A\lambda06$, respectively.

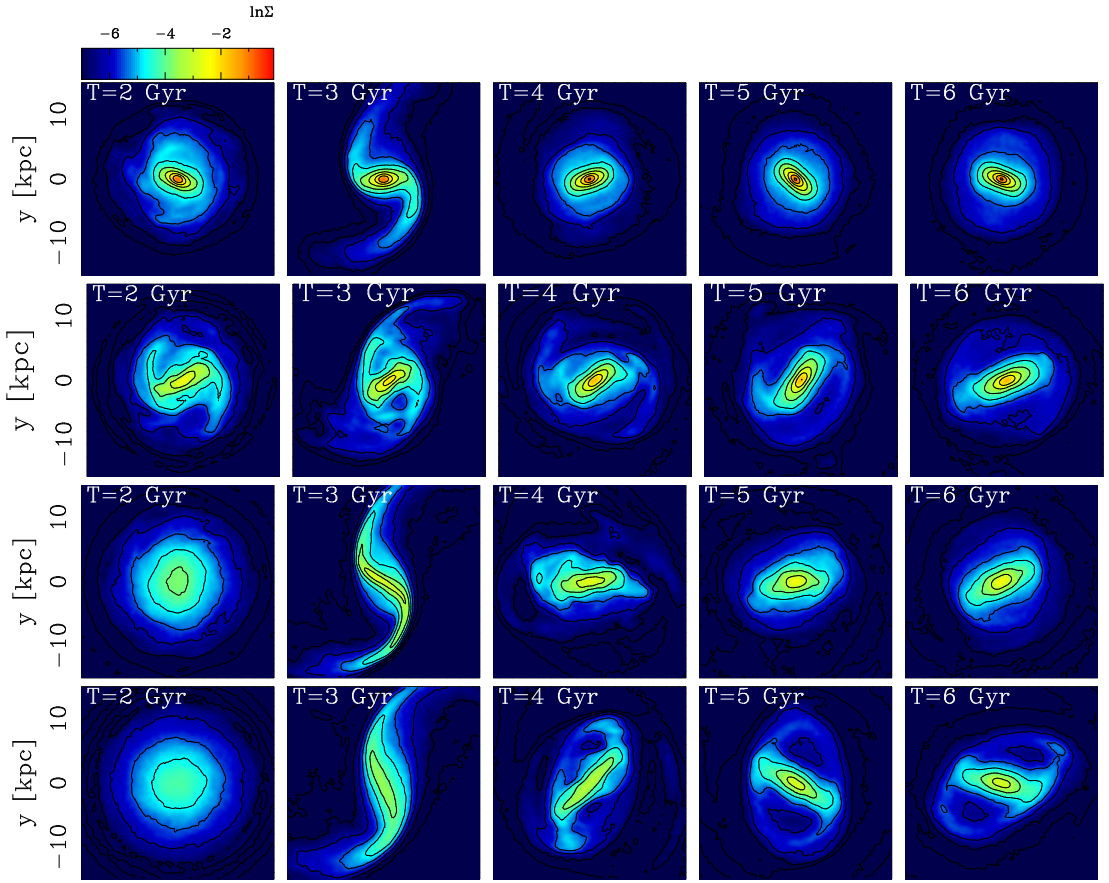
Global Stabilitie: Results of GSP (λ_d, λ_{crit}), and ϵ_m

- λ_d is depicted with a dashed line.
- λ_{crit} is depicted with a continuous line.
- We show $\begin{cases} \lambda_d > \lambda_{crit}, & \text{stable against bar formation} \\ \lambda_d \leqslant \lambda_{crit}, & \text{unstable to bar formation} \end{cases}$



Global stabilities: interactions

Face-on surface logarithm density maps for interactions of group Pm

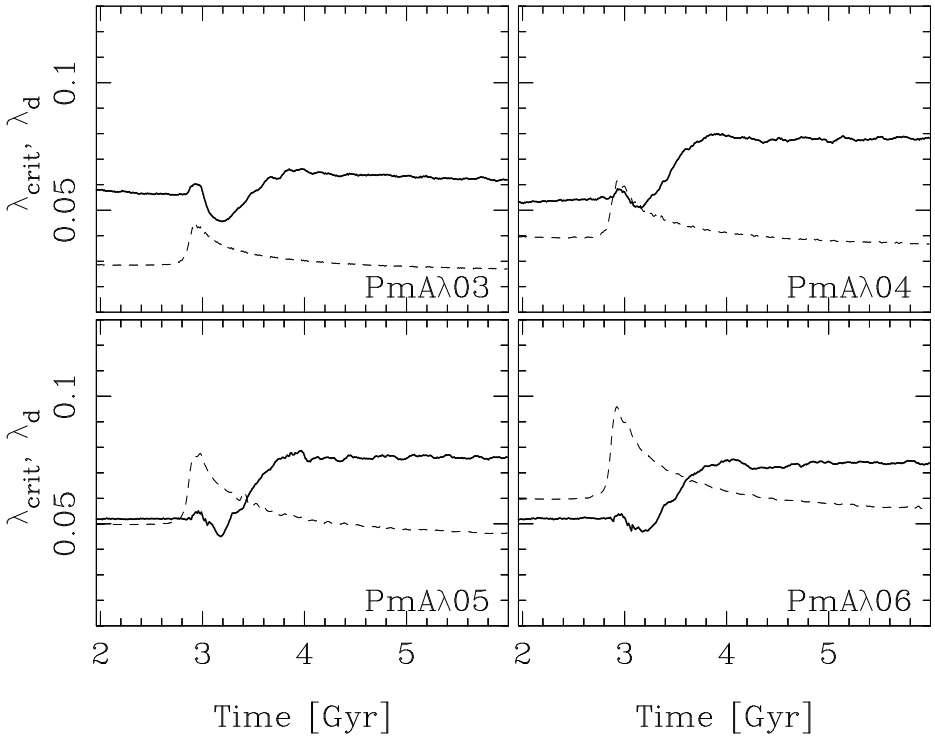


Movie play

Global stabilities: interactions - GSP

Global Stability Parameters for perturbed models.

- λ_{crit} is depicted by solid line.
- λ_d is depicted by dashed line.

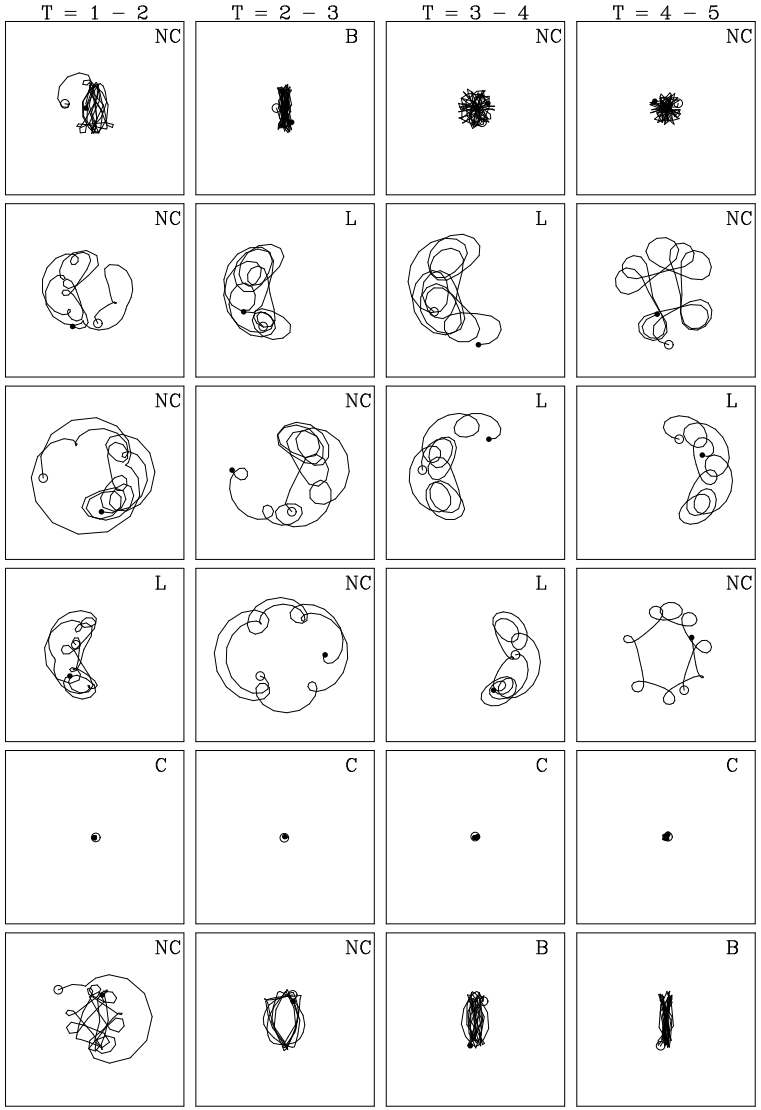


The bar in our disc galaxies models are formed below the stability limits in both isolated and perturbed discs, and this depends on how close are the parameters from their critical values.

Statistical morphological analyzes for the orbits of barred models

Valencia-Enríquez et al. (2017)

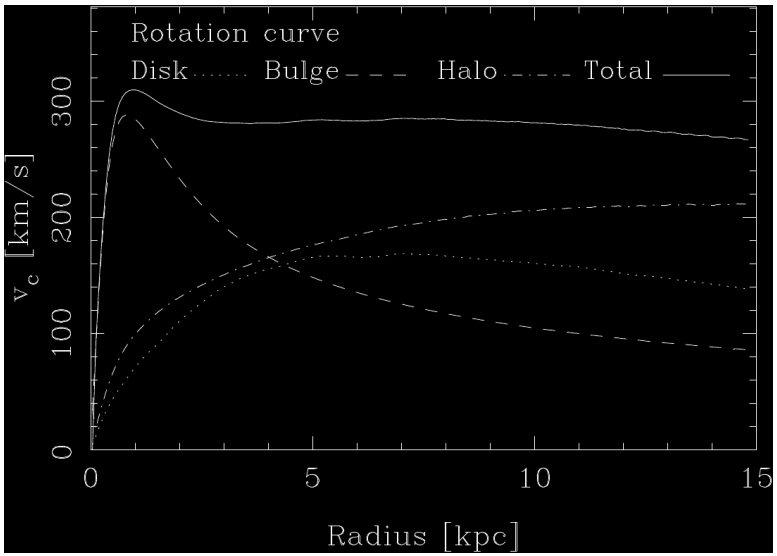
Morphological analyzes for the orbits



Morphological analyzes for the orbits

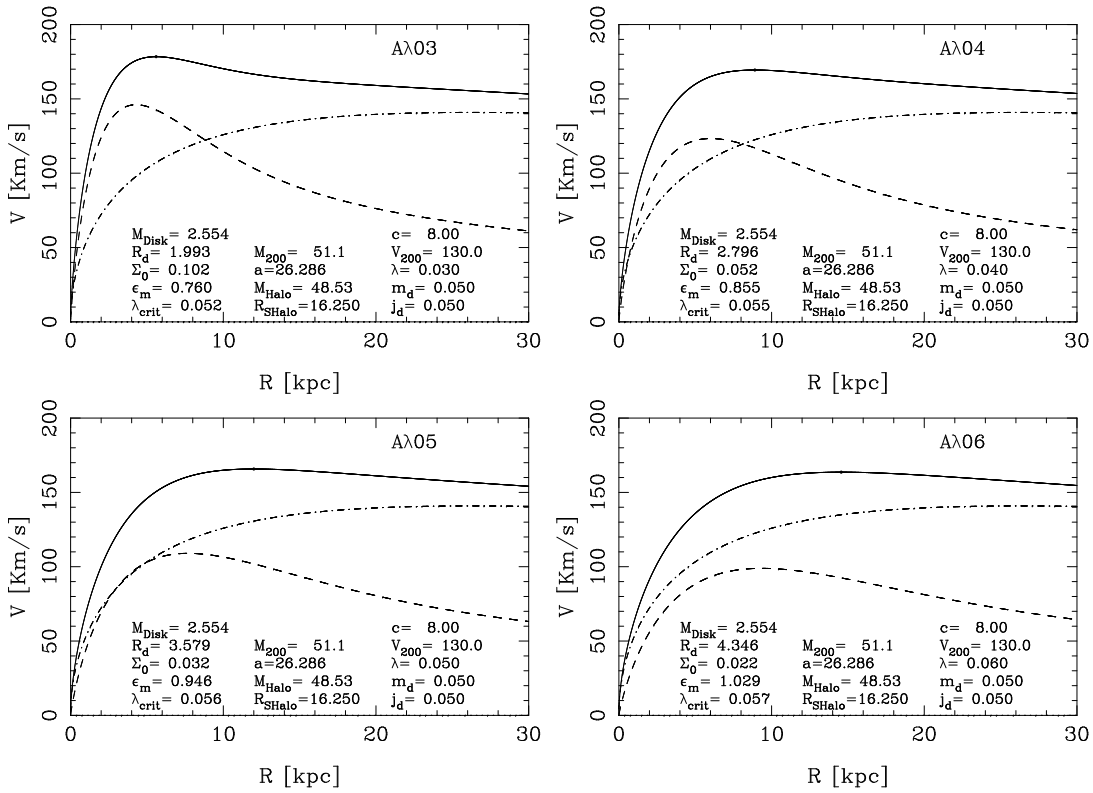
With Bulge

s37_z10M
s37_z10MS
s37_z10MX
s37_z10MXS



Without Bulge

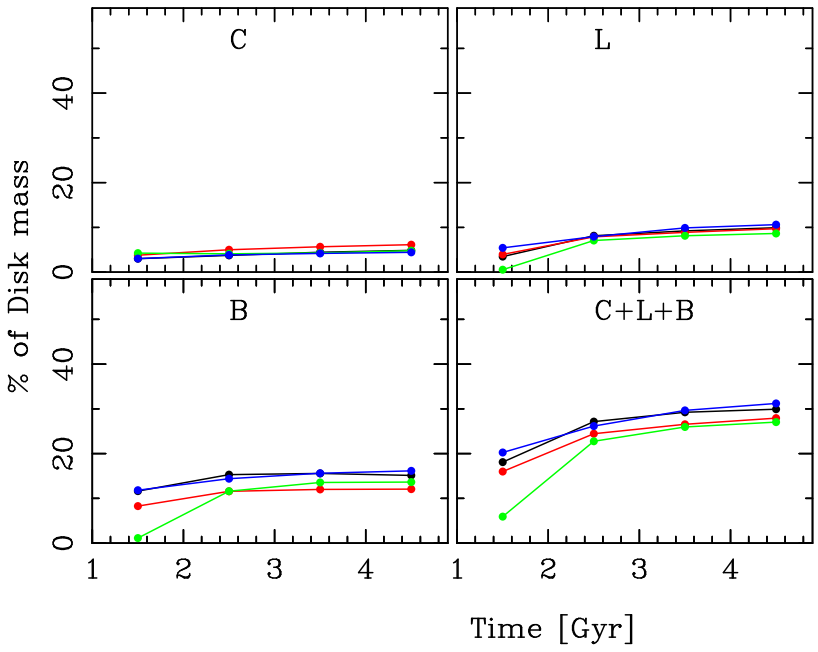
Aλ03
Aλ04
Aλ05
Aλ06



Morphological analyzes for the orbits

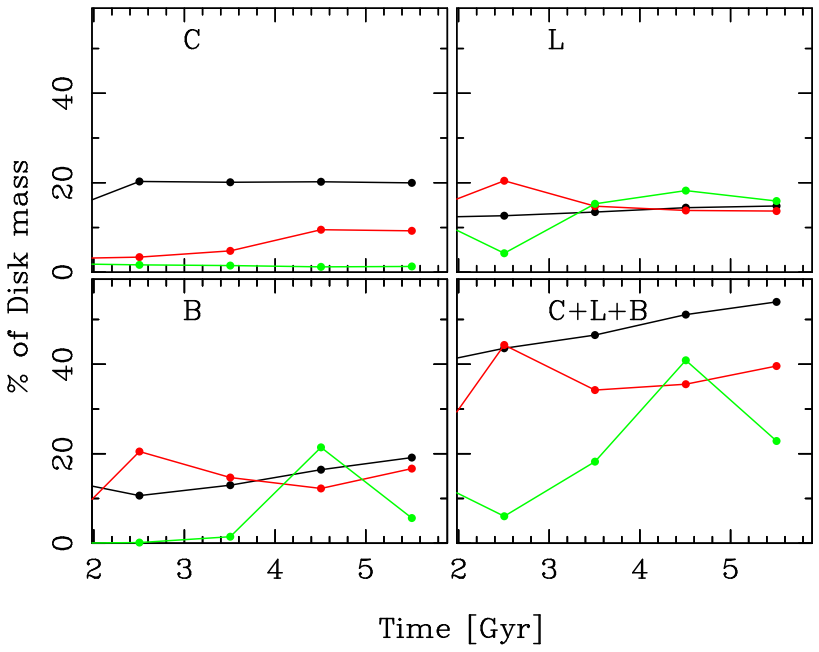
With Bulge

s37_z10M
s37_z10MS
s37_z10MX
s37_z10MXS



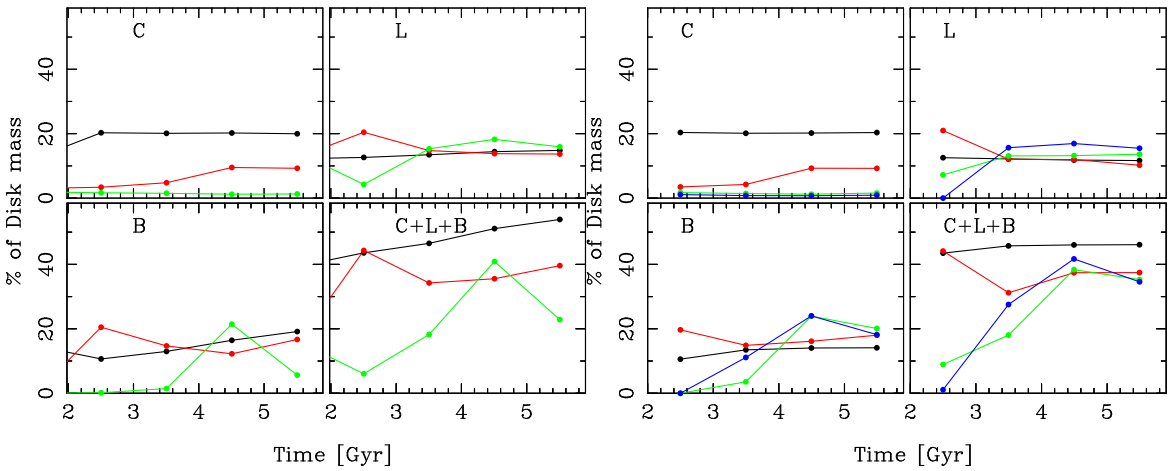
Without Bulge

Aλ03
Aλ04
Aλ05
Aλ06

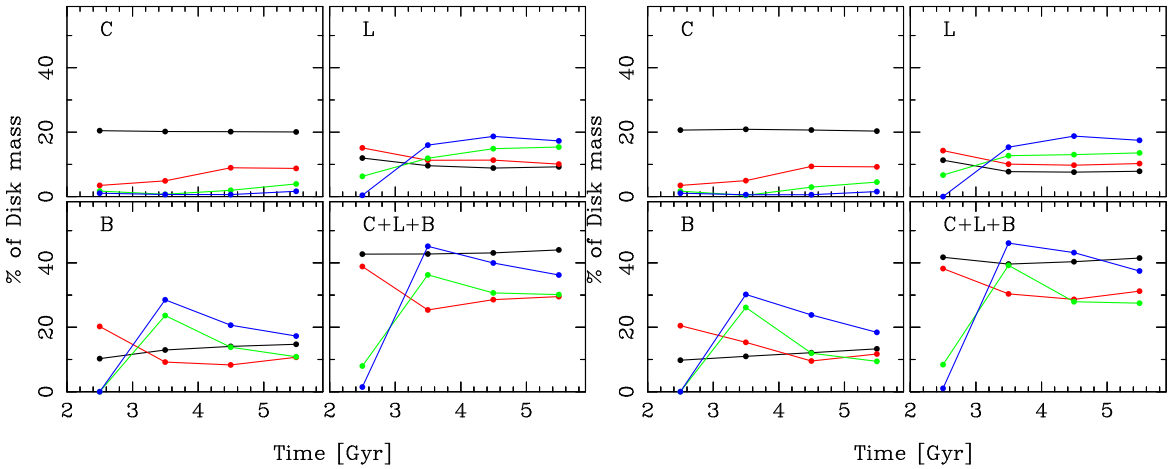


Morphological analyzes for the orbits

Statistical orbital analyzes in the bar frame for all simulations



(a) Isolated models. (b) Pw models.



(c) Pm models. (d) Ps models.

Fourier Transform (Laskar 1990, Šidlichovský & Nesvorný (1996))

To study the orbits, we have to find the peaks of the Fourier transform (FT) of a time series of the radius, r(t).

The FT $H_r(\omega)$ has the following form:

$$H_r(\omega) = \left| \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} R(t) \exp\left(-i\omega(t - t_1)\right) dt \right|$$

where $R(t)$ is the radius $r(t)$ * the Hanning Window. $R(t) = r(t) * (1 - \cos(\pi t/\tau))/2$, and $\tau = (t_2 - t_1)/2$

$r(t)$ originates from a simulation, we have it in a sampled form as $r_n = r(t_1 + \delta_t)$

where $n = 0,\ 1, ..., N - 1$ and $\delta_t = (t_2 - t_1)/N$.

In our case $N \approx 5000$ and $\delta_t = 0.001$ Gyr.

Hence, we have to approximate the integral as the sum:

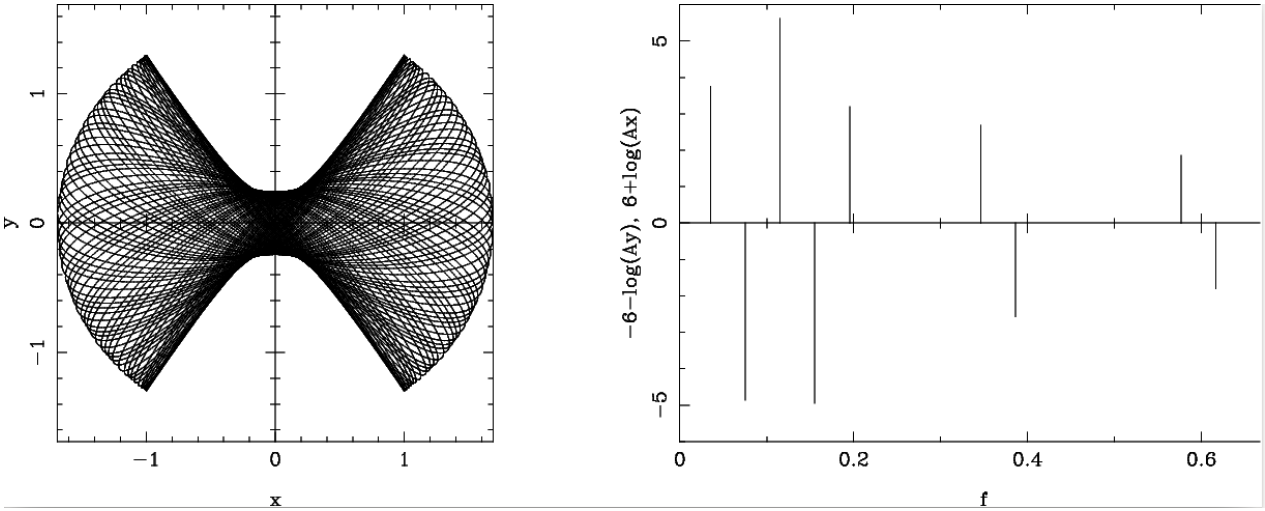
$$H_r(\omega) = \left| \frac{1}{N} \sum_{n=1}^{N} R_n \exp\left(-i\omega n \delta_t\right) \right|$$

To find the maximum, we search for a maximal value of $H_r(\omega_k)$ and we denote its location by w_k . The frequency w_K is only an approximate location of the peak and We denote the obtained maximum of P_r by ω_{max}

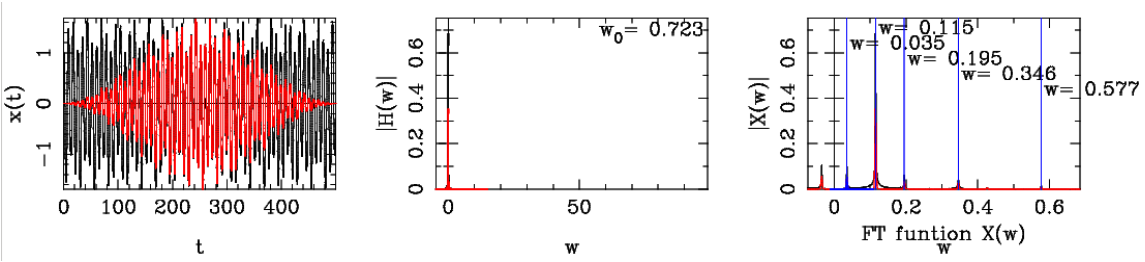
Fourier Transform (Laskar 1990, Šidlichovský & Nesvorný (1996))

Orbit in a Logarithmic potential $\Phi_L = \frac{v_0^2}{2} ln \left[R_c + x^2 + \frac{y^2}{q^2} \right]$. (Carpintero & Aguilar (1998))

An orbit from the Logarithmic potential

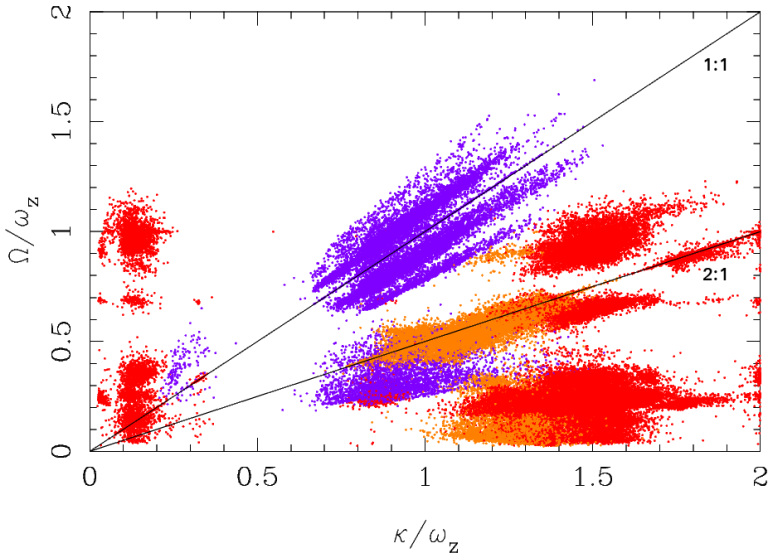


Getting the frequency



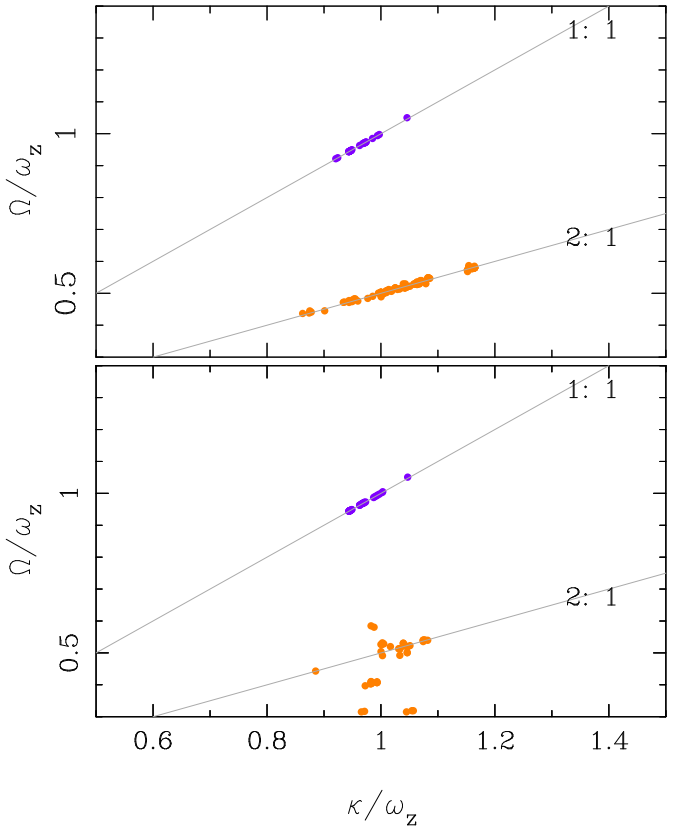
Morphological analyzes for the orbits

The frequency map for the orbits of model $A\lambda03$ N-body simulation



The disc resonances of the form $m_1 \frac{\Omega}{\omega_z} + m_2 \frac{\kappa}{\omega_z} = 0$ are shown by black lines. Orange points represent Bar orbits, and purple ones depict Loop orbits.

Frequency map for integrated orbits in a fixed potential



200 orbits in 3D potential integrated with a **Dehen halo, a Miyamoto-Nagai disc and a Ferrers bar**. Similar to the rotation curve of model $A\lambda03$.

Conclusions

- The bar in our disc galaxies models are formed below the stability limits in both isolated and perturbed discs, and this depends on how close are the parameters from their critical values.
- We show that a lot of orbits supporting the bar in the morphological classification are around of the 2:1 resonance, while the orbits around of the Lagrangian points are in 1:1 resonance.

THANKS

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