Manifolds and orbits in a warped bar potential

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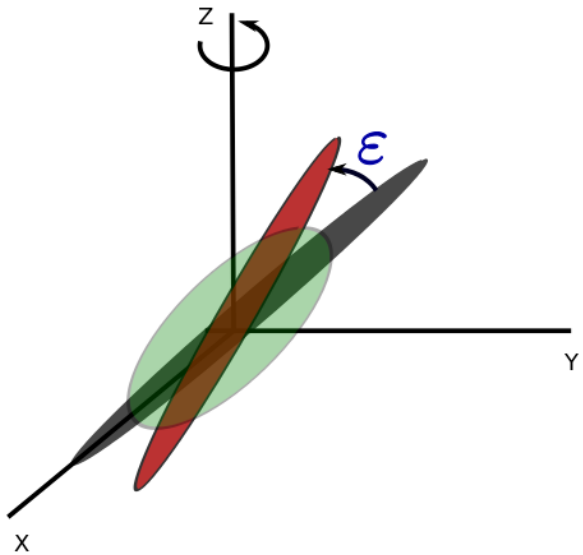
Model and Potentials

- What is the goal?

Galaxy ESO 510-G13 photographed by Hubble telescope.



Equations of motion

- The Precessing Miyamoto-Nagai Ferrers galactic model:

$$\begin{cases} \dot{x_1} = x_4 \\ \dot{x_2} = x_5 \\ \dot{x_3} = x_6 \\ \dot{x_4} = 2\Omega\cos(\varepsilon)x_5 + \Omega^2\cos(\varepsilon)^2 x_1 + \Omega^2\sin(\varepsilon)\cos(\varepsilon)x_3 + \phi_{x_1} \\ \dot{x_5} = -2\Omega\cos(\varepsilon)x_4 - 2\Omega\sin(\varepsilon)x_6 + \Omega^2 x_2 + \phi_{x_2} \\ \dot{x_6} = 2\Omega\sin(\varepsilon)x_5 + \Omega^2\sin(\varepsilon)\cos(\varepsilon)x_1 + \Omega^2\sin(\varepsilon)^2 x_3 + \phi_{x_3} \end{cases}$$

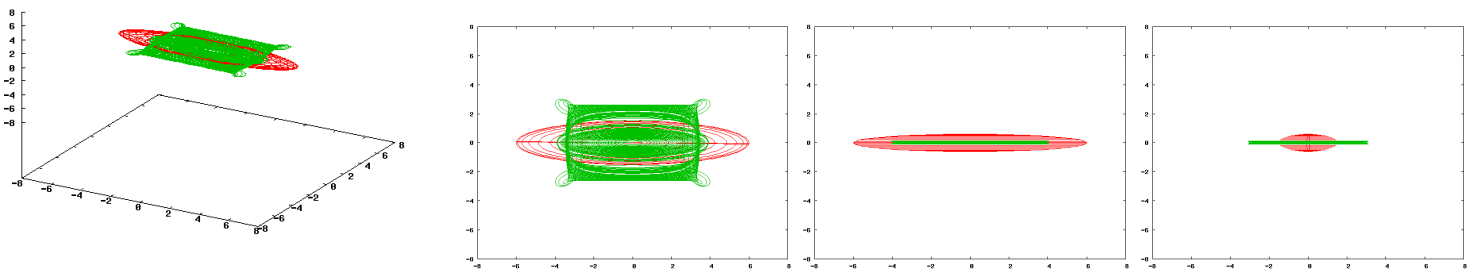
  ε the tilt angle, Ω the angular velocity of the bar and ϕ the potential ($\phi = \phi_{bar} + \phi_{disc}$).

- Model as in **Pfenniger (1984)**:
  Ferrers bar + Miyamoto-Nagai disc

- with **parameters**:
  - $A = 3$, $B = 1$, $a = 6$, $b = 1.5$, $c = 0.6$ (kpc), $n = 2$.
  - $GM_d \in [0.5, 0.9]$, $GM_b \in [0.1, 0.4]$ ($G(M_d + M_b) = 1$).
  - $\Omega \in [0.05, 0.06]$ rad/[u$_t$] $= [24.44, 29.33]$ km/s/kpc.
  - $\varepsilon \in [0, 0.2]$ rad $= [0, 5.73]^\circ$ (ε *tilt angle*).

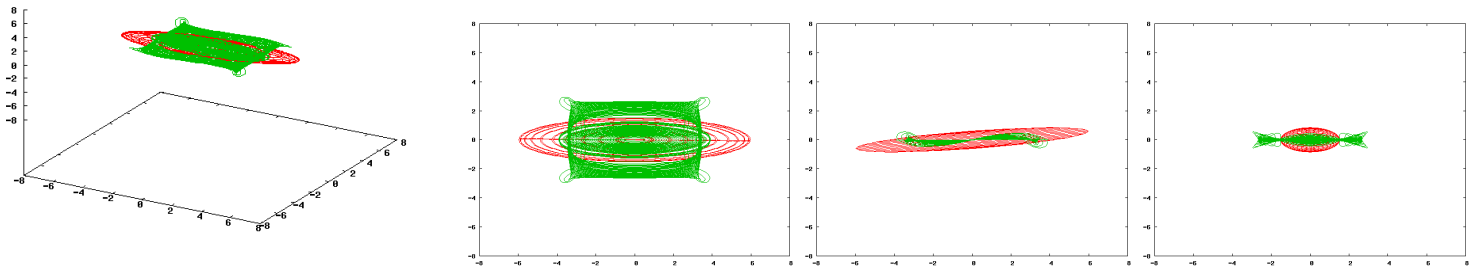
Periodic orbits, L_3

- Periodic orbits in central equilibrium point, L_3.
  - Stable periodic orbits give structure to the bar.
  - Parameters: $GM_b = 0.1$, $\Omega = 0.05471$.
    - Tilt angle $\underline{\varepsilon = 0}$:

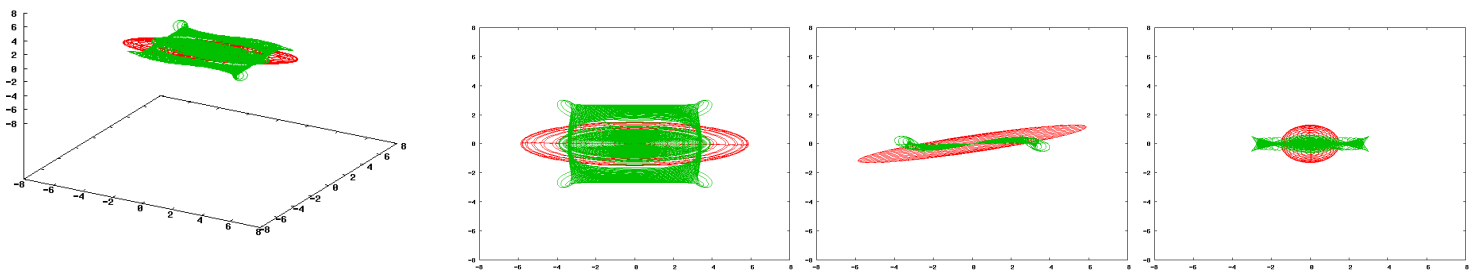


Modify the tilt angle

- Tilt angle $\varepsilon = 0.1$:

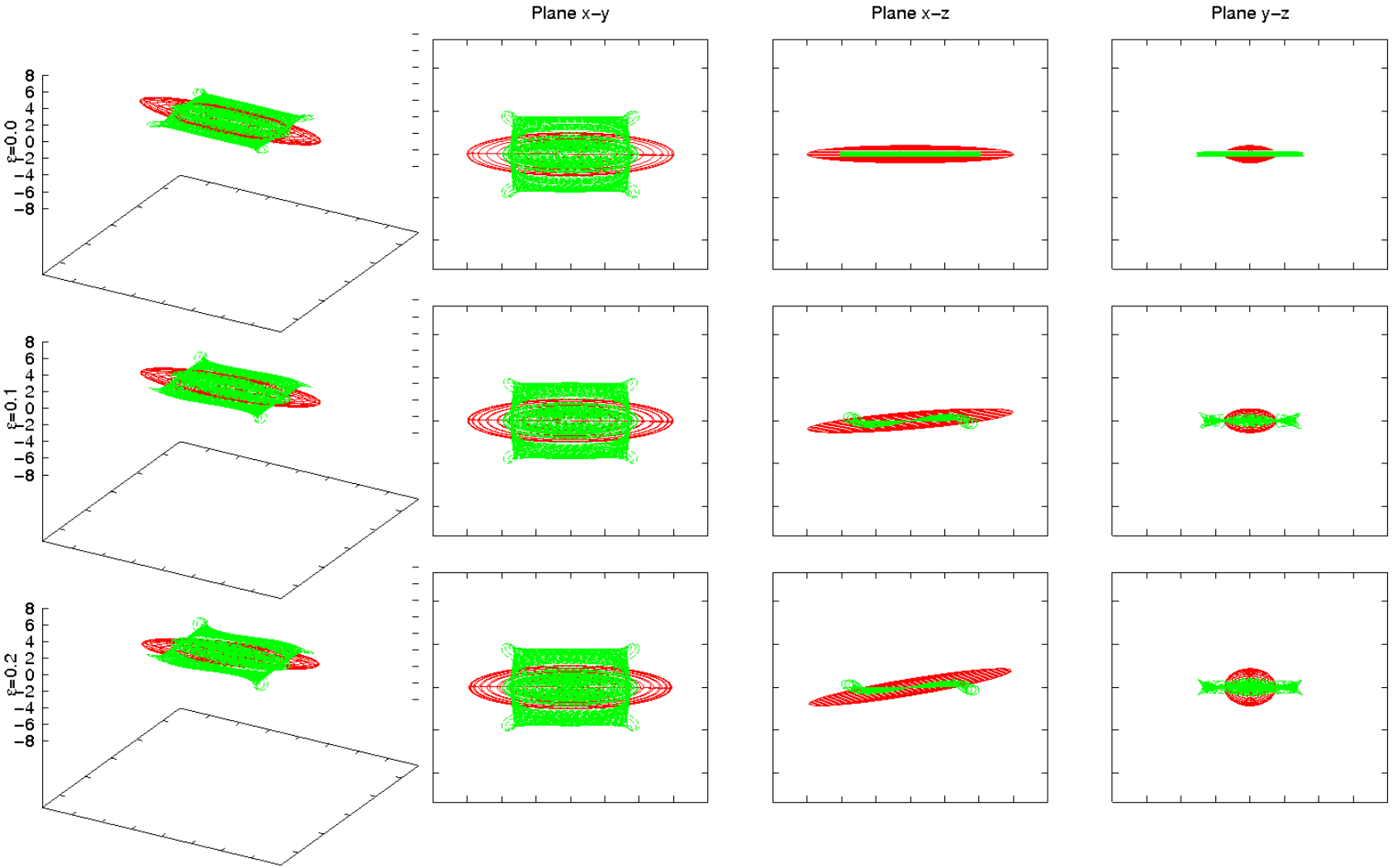


- Tilt angle $\varepsilon = 0.2$:

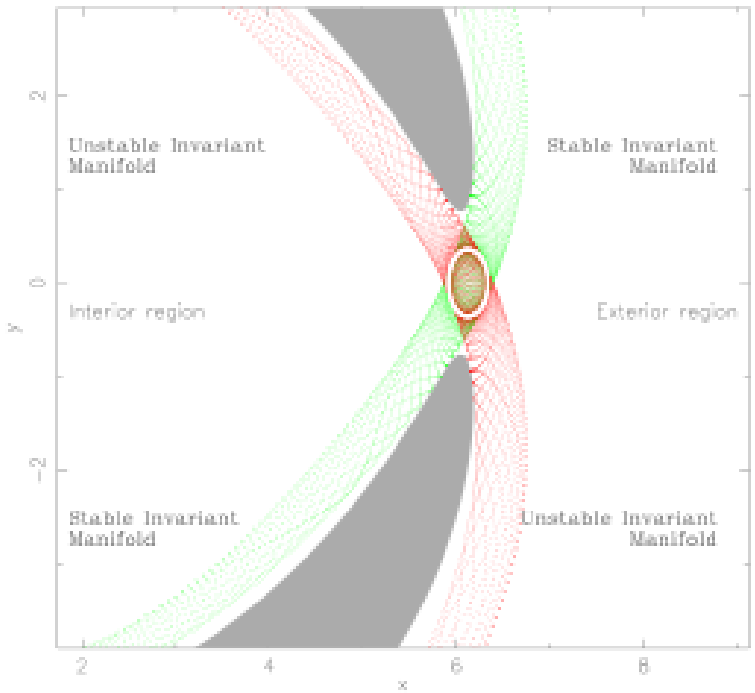


$\varepsilon = 0, 0.1, 0.2$

Comparison between $\varepsilon's$



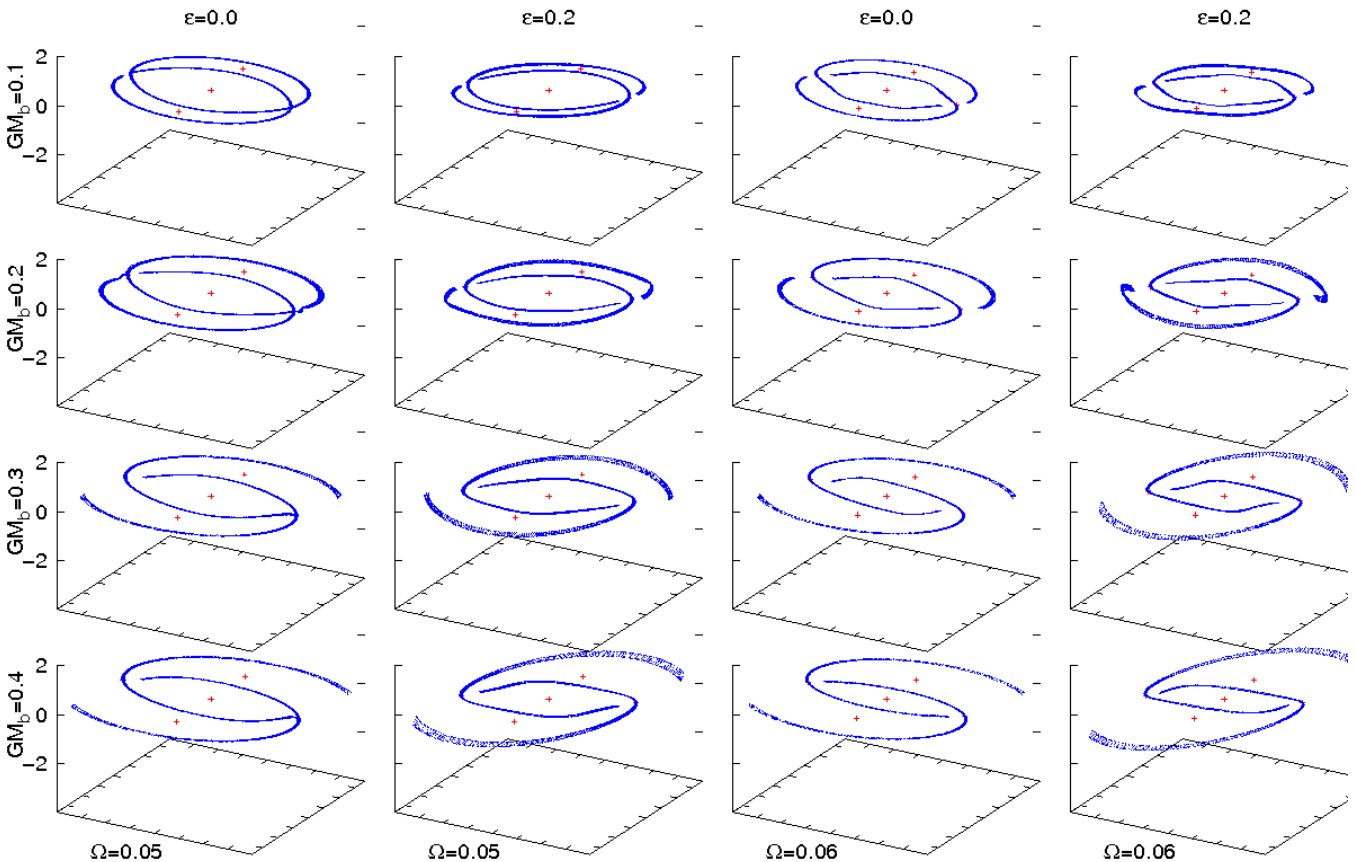
Invariant manifolds



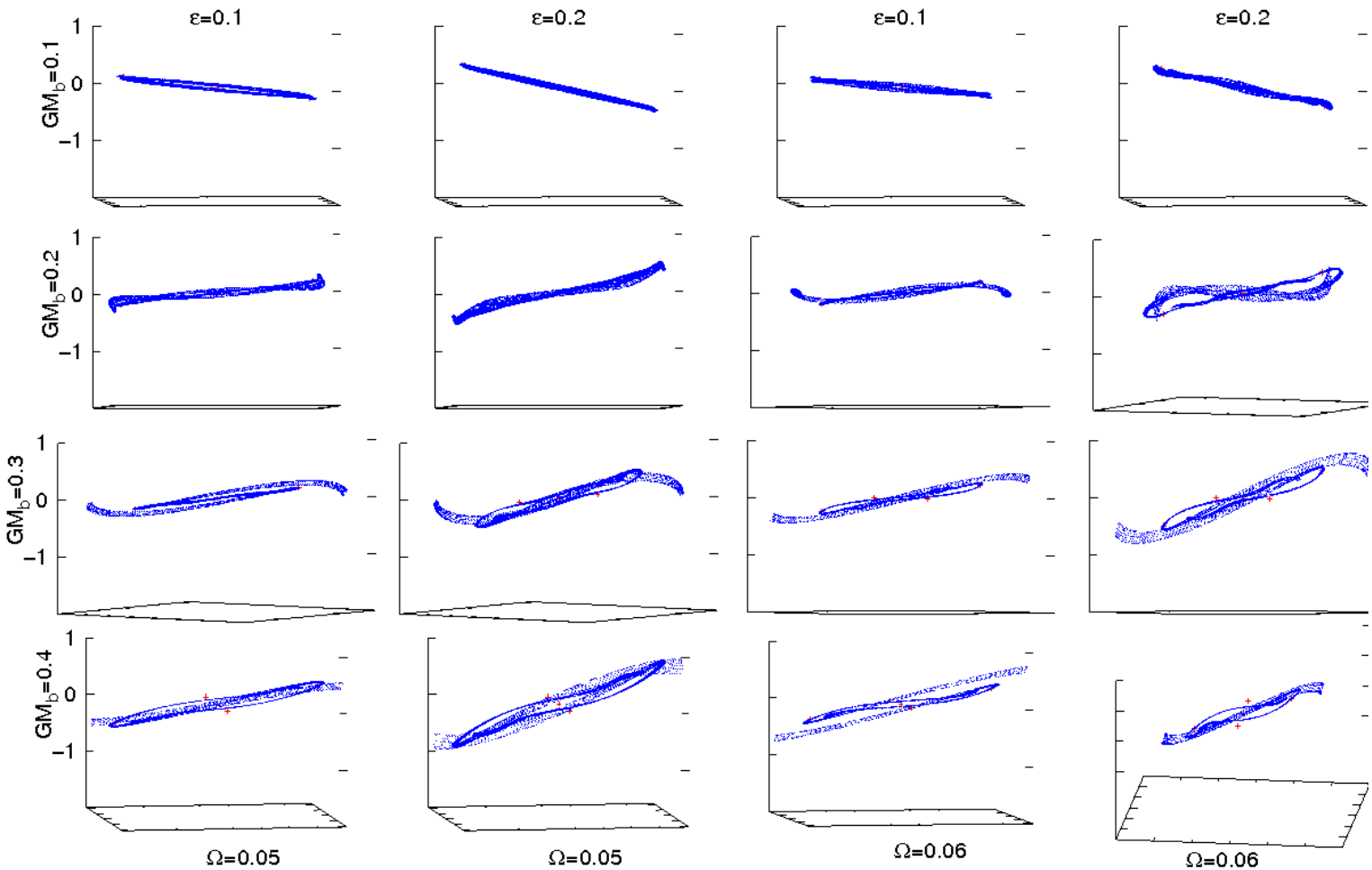
Invariant manifolds. In the centre of the plot, a white solid line shows the Lyapunov orbit around L_1. The two branches of the unstable invariant manifold are indicated by red lines, the two branches of the stable invariant manifold by green lines, and grey by the forbidden region surrounded by the zero velocity curves.

Morphology of a galaxy

- Morphology given by the invariant manifolds when varying Ω, the bar mass, GM_b, and the inclination ε:



Galaxy warps

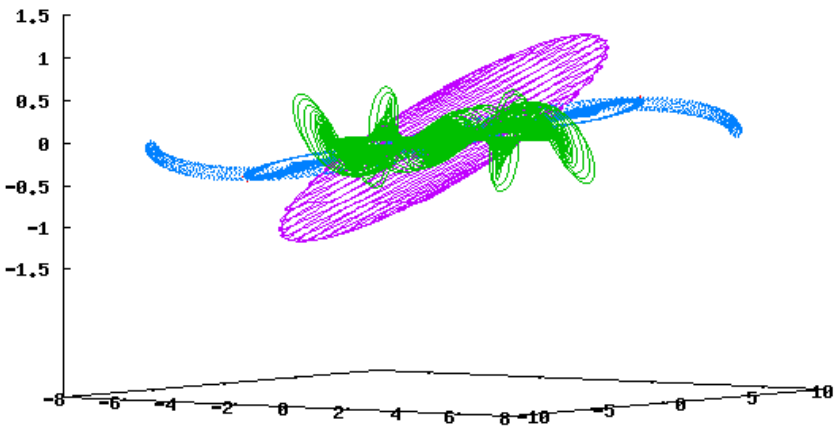


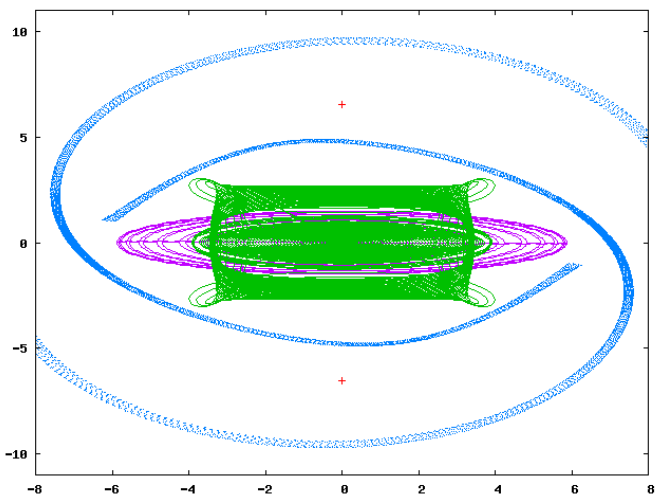
How stars feel this precession?

- Test-particle simulations:
  - Hot initial conditions simulating old disc population (K-giants).
  - Integrating i.c. in the precessing galactic model introducing the bar adiabatically.

Por si acaso...

Untsable invariant manifolds and periodic orbits for $\varepsilon = 0.2$





Model and Potentials

- Model: Ferrers bar + Miyamoto-Nagai disc.
- Potential: $\phi = \phi_{bar} + \phi_{disc}$.

$$\phi_{bar} = \pi\, G\, abc \frac{\rho_0}{n+1} \int_\lambda^\infty \frac{du}{\Delta(u)} (1 - m^2(u))^{(n_h+1)}$$

$$\phi_{disc} = -\frac{GM_d}{\sqrt{R^2 + (A + \sqrt{B^2 + z^2})^2}}$$

  - *Parameters*:
    - $A = 3,\ B = 1,\ n = 2,\ a = 6,\ b = 1.5,\ c = 0.6.$
    - $GM_d \in [0.5, 0.9],\ GM_b \in [0.1, 0.4]$ $(G(M_d + M_b) = 1).$
    - $\Omega \in [0.05, 0.06],\ \varepsilon \in [0, 0.2].$