

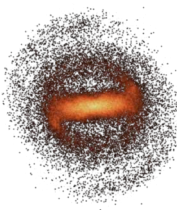
# Existence and properties of a bar in the inner halo of barred galaxies

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# Angular momentum exchange



Angular momentum exchange drives the dynamical evolution of barred galaxies

Emission/Absorption occurs principally at the resonances.

Emitters : principally material at near-resonance in the inner disc

Absorbers : principally material at near-resonance in the outer disc **and in the halo**

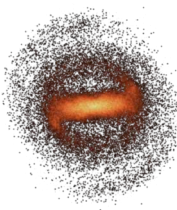
Inner disc (bar) -----> Outer disc + halo

The bar is a negative angular momentum feature. As it loses angular momentum

- it will grow stronger
- it will slow down (i.e. its pattern speed decreases)



# Role of the halo



Both for the disc and the halo, there is more angular momentum gained/lost at a given resonance if :

- the density is higher there
- the resonant material is colder

So, **for equal amounts of mass**, the outer disc will take more angular momentum than the halo, because it is colder.

But there is considerably less mass in the outer disc than in the halo, so the role of the halo can be very important, or even predominant.

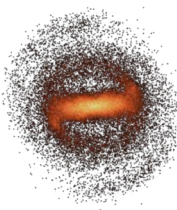
Bars immersed in massive responsive haloes can grow stronger than bars immersed in weaker haloes and very much stronger than bars immersed in rigid haloes

It is thus reasonable to expect that, while the bar evolves, the halo properties will also evolve

- The change in the halo radial profile
- The formation of an oval in the inner halo



# Outline



The role of the halo in the evolution of barred galaxies

Formation of an oval/bar in the inner parts of the halo ('the halo bar')

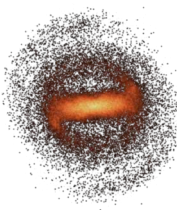
Orbital structure in haloes : Near-resonant orbits, regular orbits and chaos

WIMPS, halo geometry and dark matter annihilation signal

Haloes to the rescue when BHs or central mass concentrations (CMCs) threaten bars



# Resonances

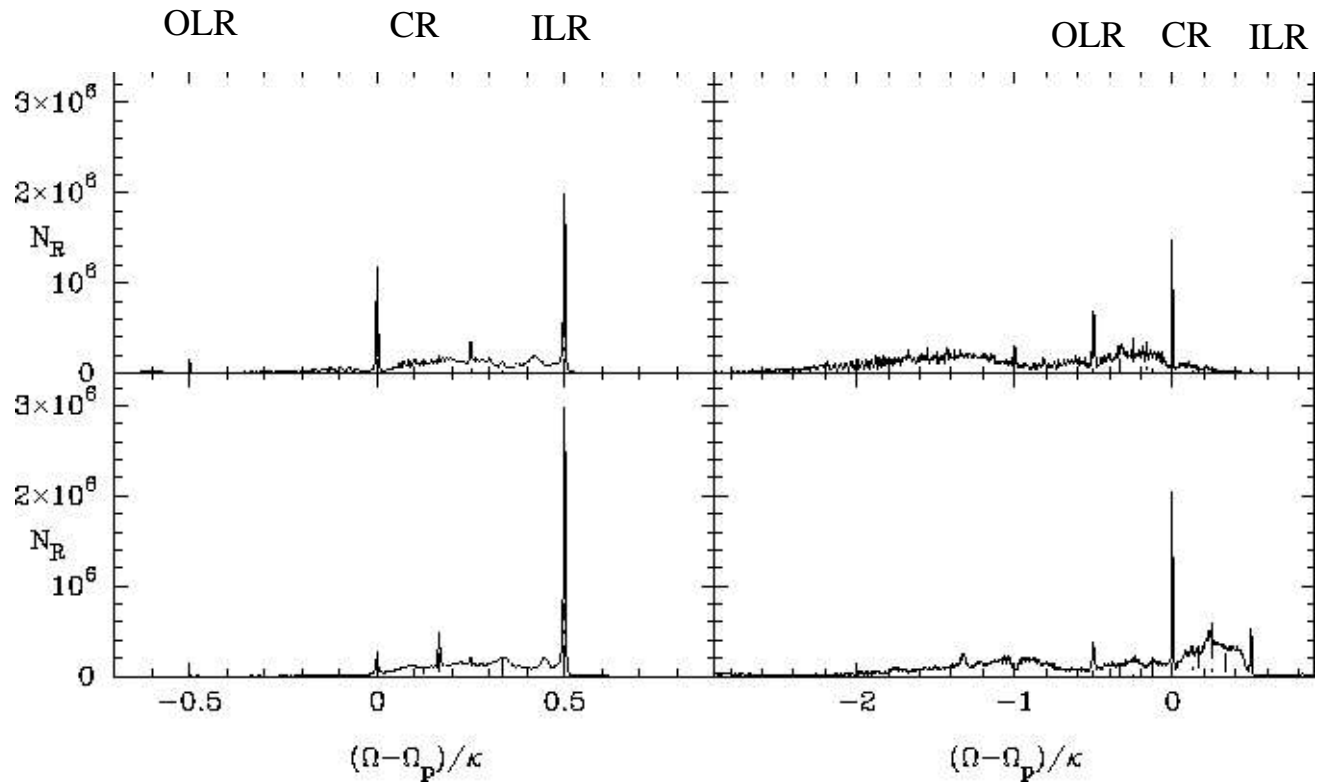


disc

halo

Simulation 1

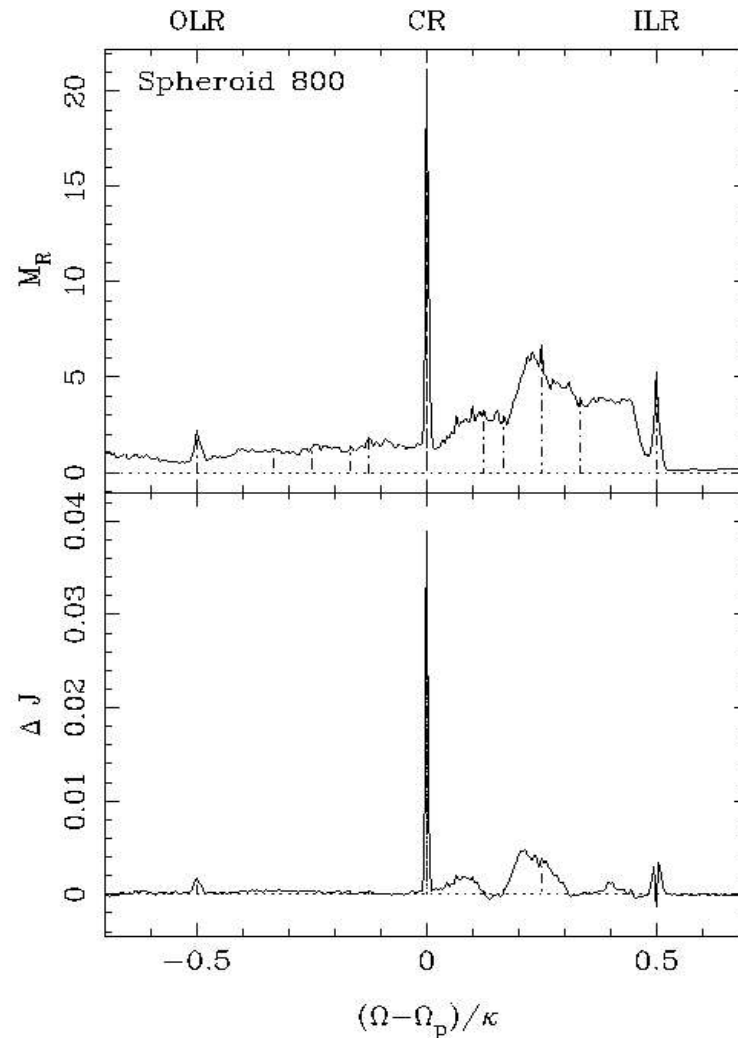
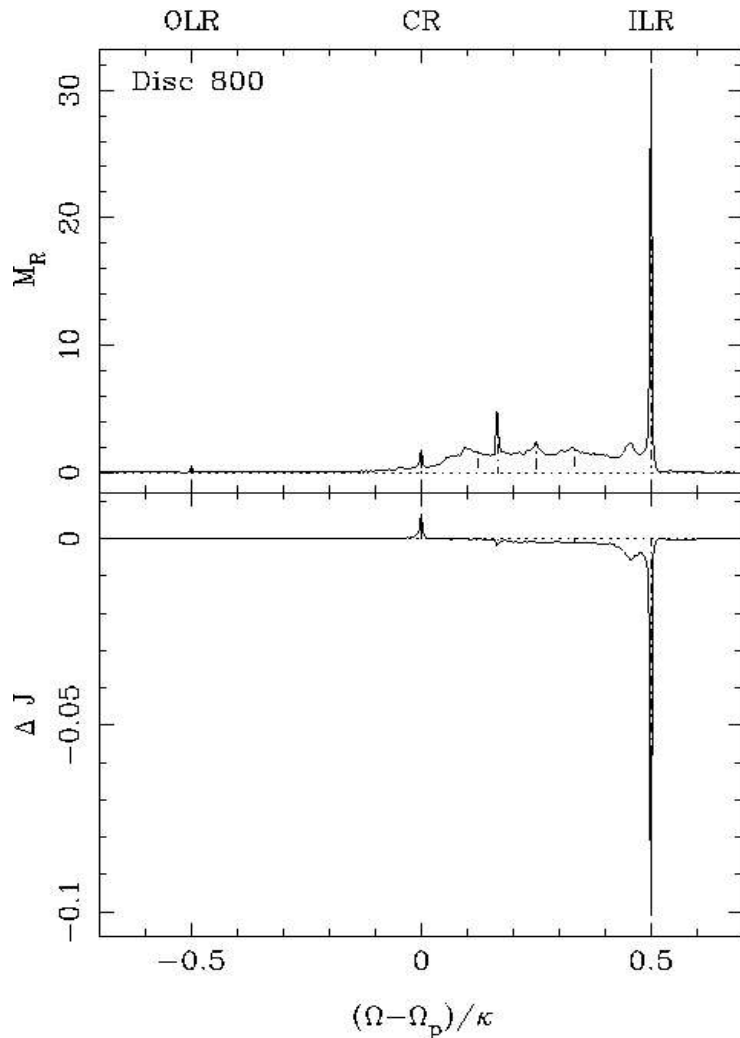
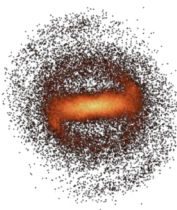
Simulation 2





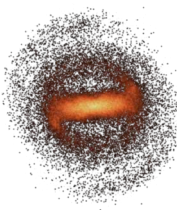
# Emitters and absorbers

Example from a strong bar case Athanassoula 2003



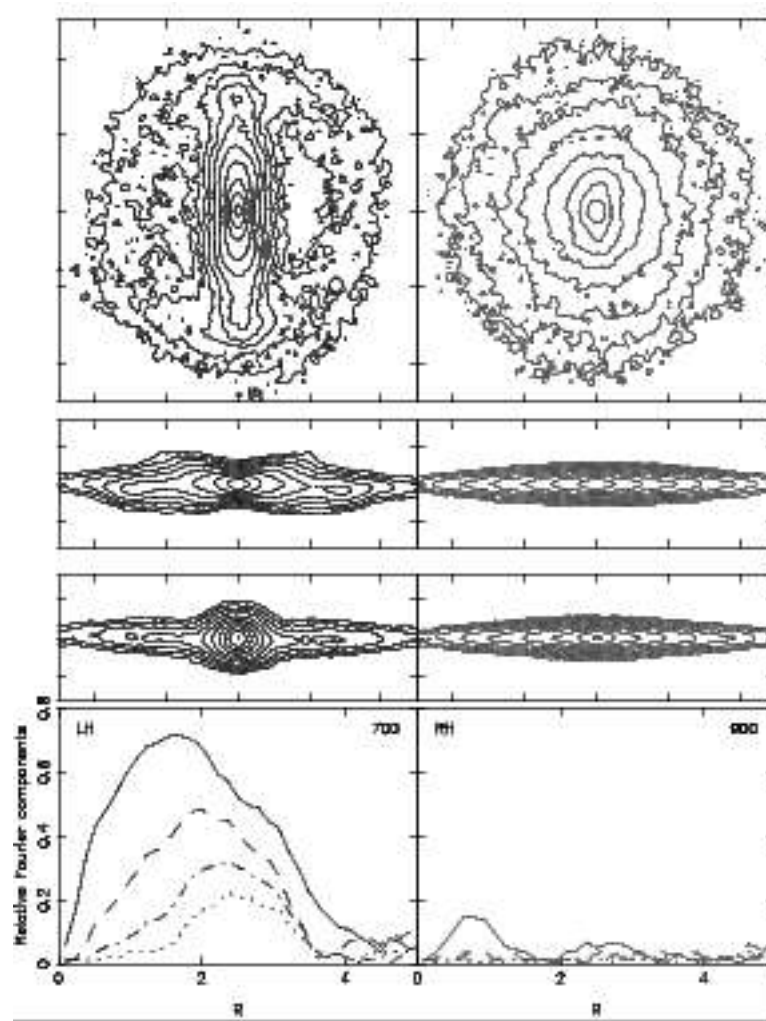


# Live versus rigid halo



Live halo

Halo can  
receive  
angular  
momentum



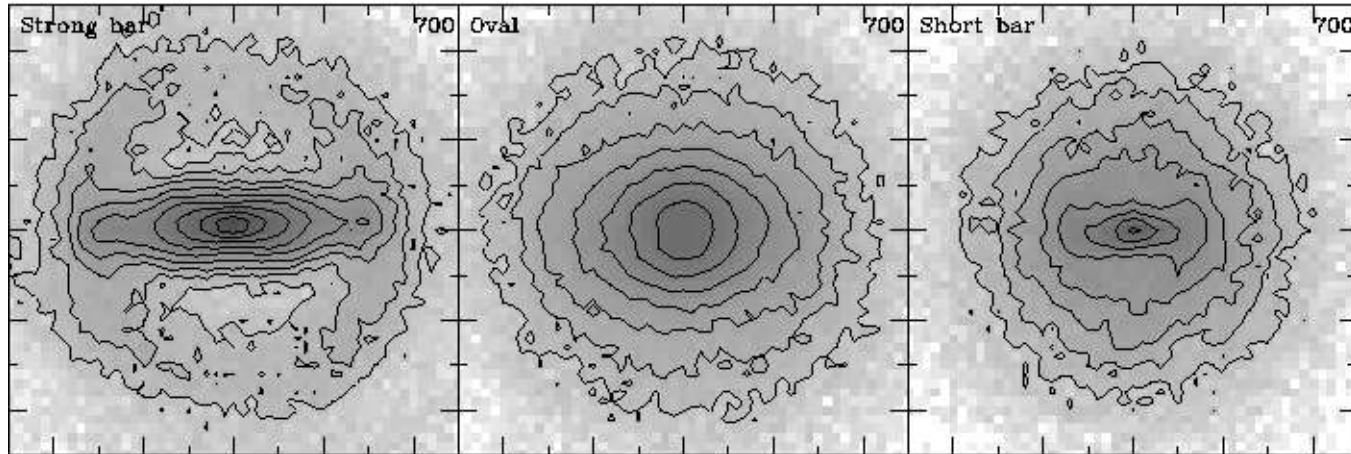
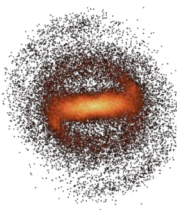
Rigid halo

Halo can not  
receive  
angular  
momentum

Athanassoula 2002



# Bar morphology



Considerable amount of angular momentum is exchanged

Little angular momentum exchanged

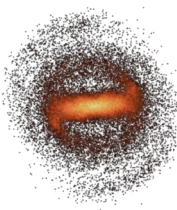
Responsive halo

Hot halo

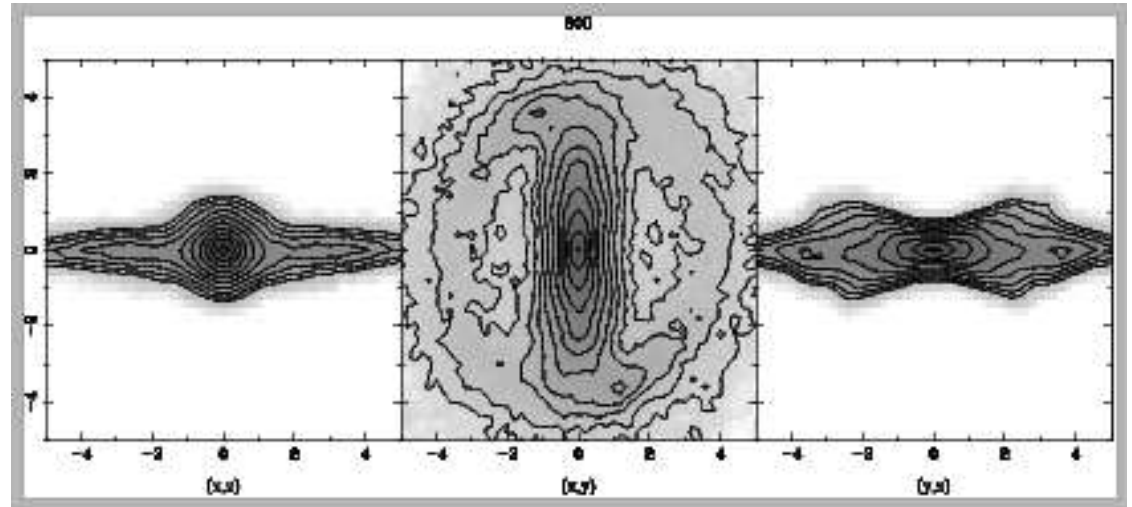
Hot outer disc



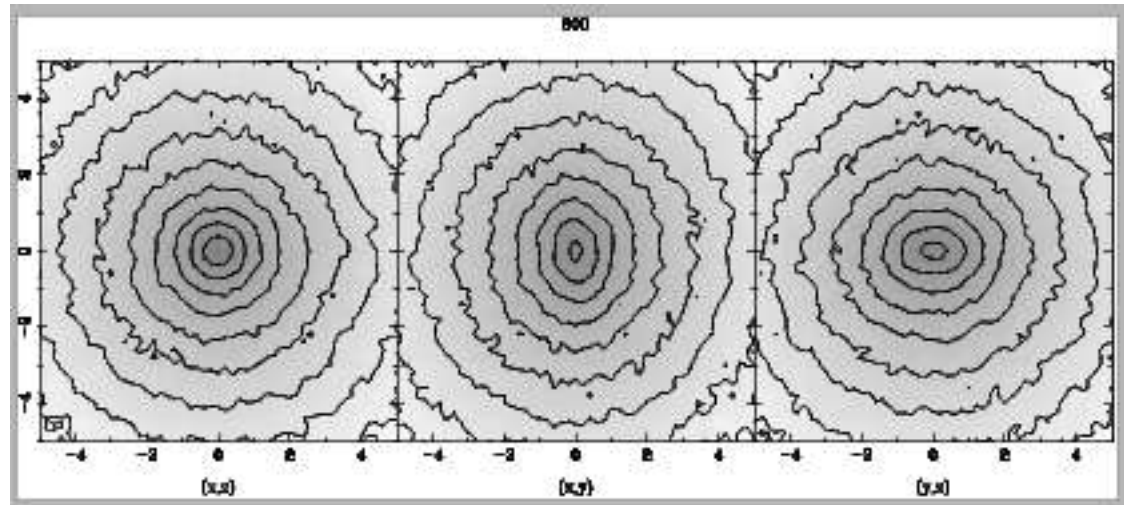
# A bar in the halo



disc

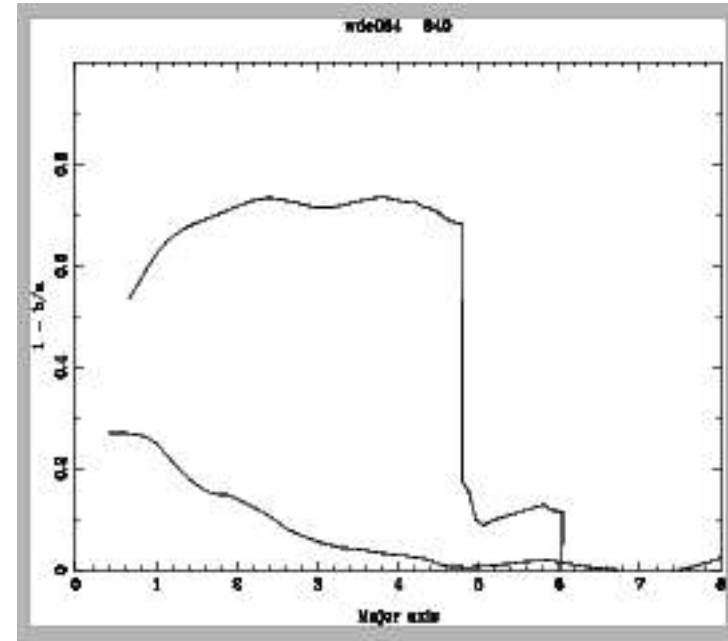
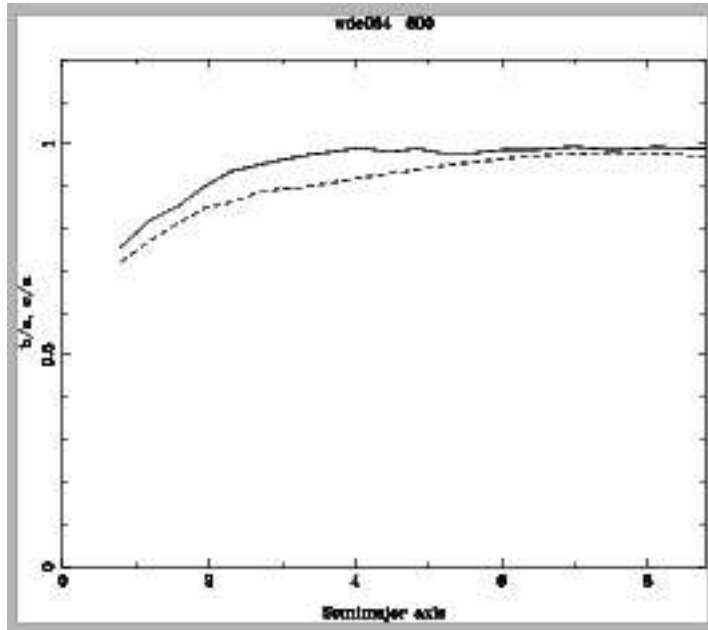
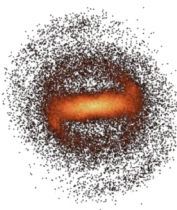


halo



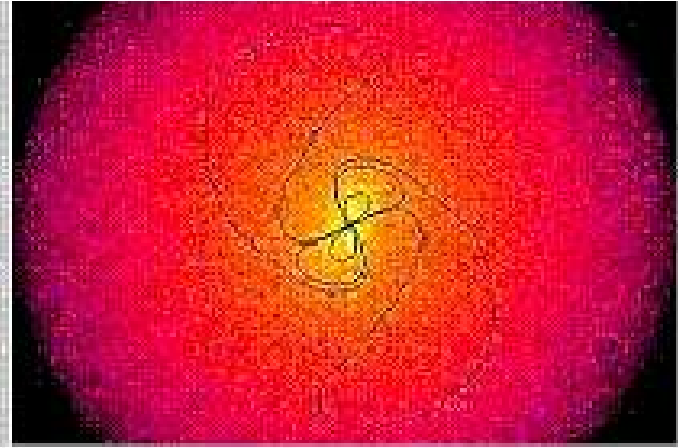
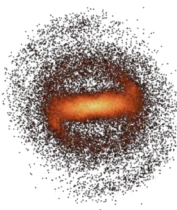


# Halo bar axial ratio

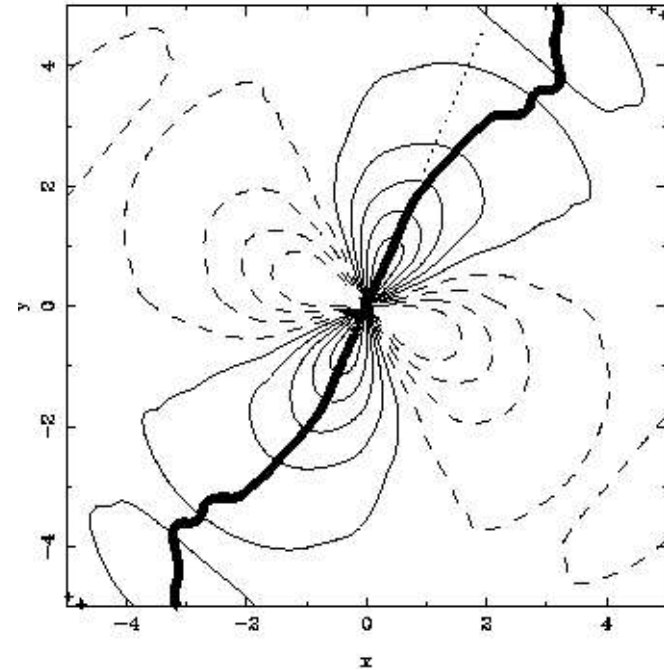




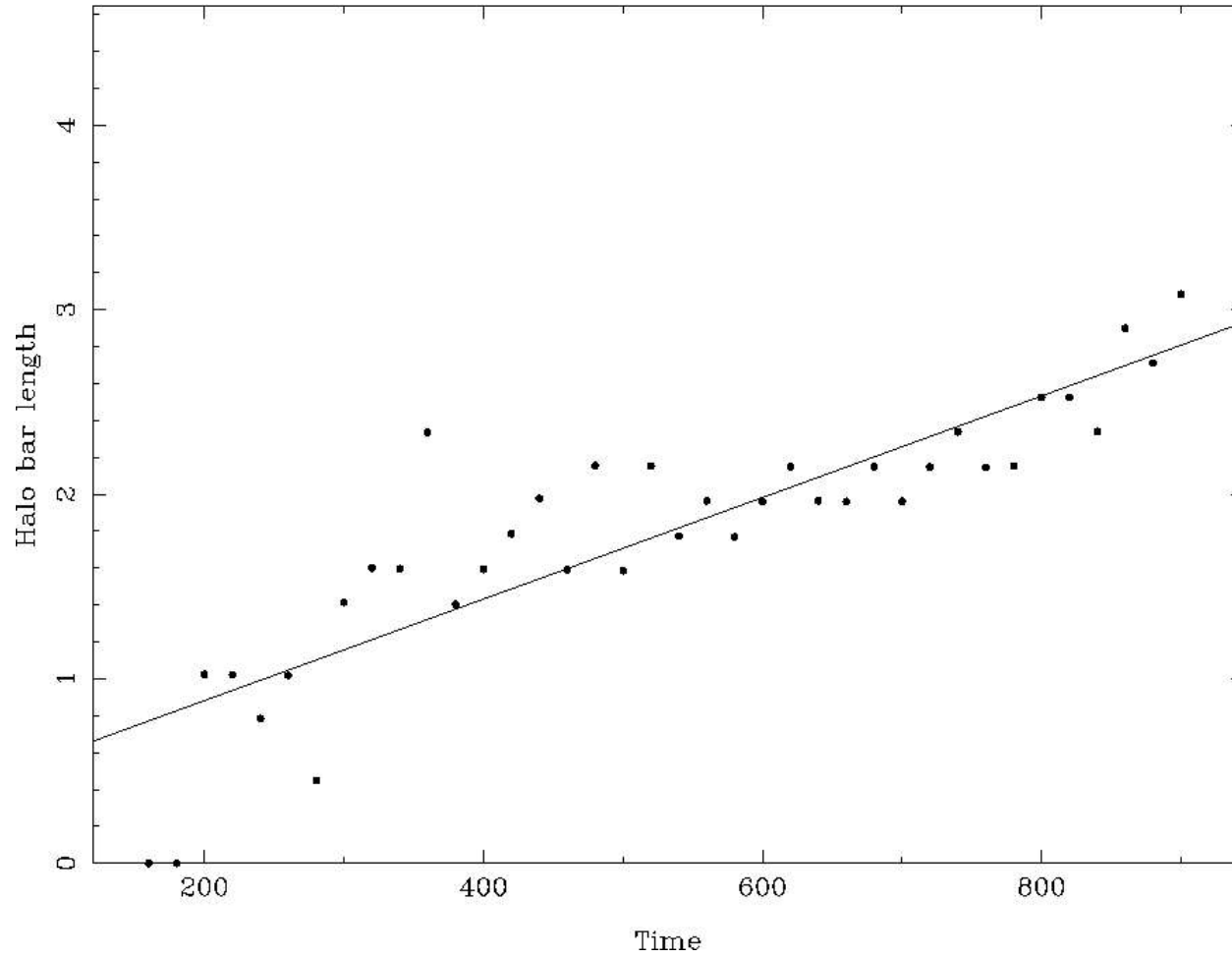
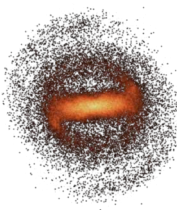
# Halo bar ( $l=2, m=2$ )



Holley-Bockelmann, Weinberg & Katz 2003

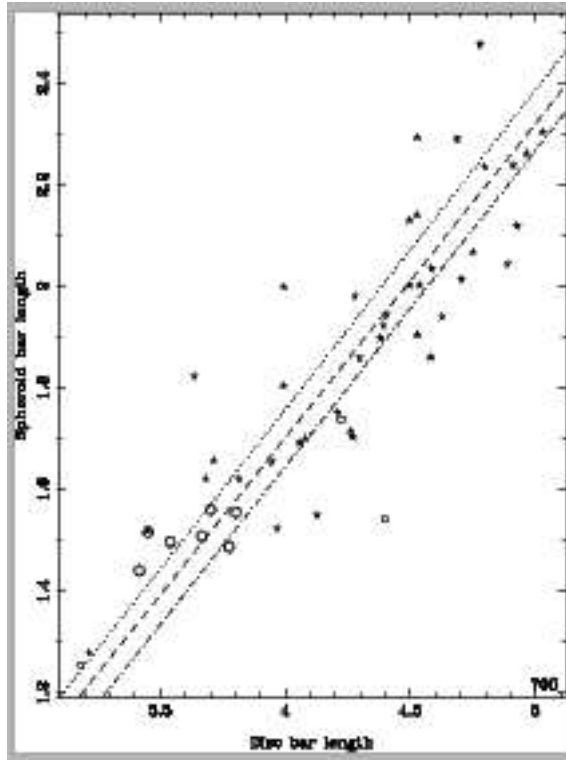
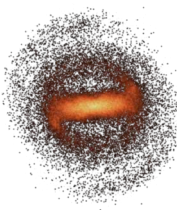


# Halo bar length

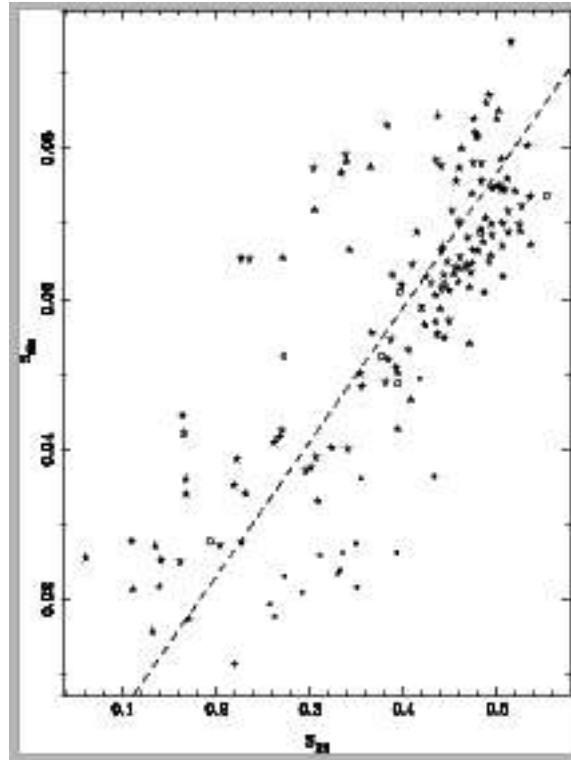




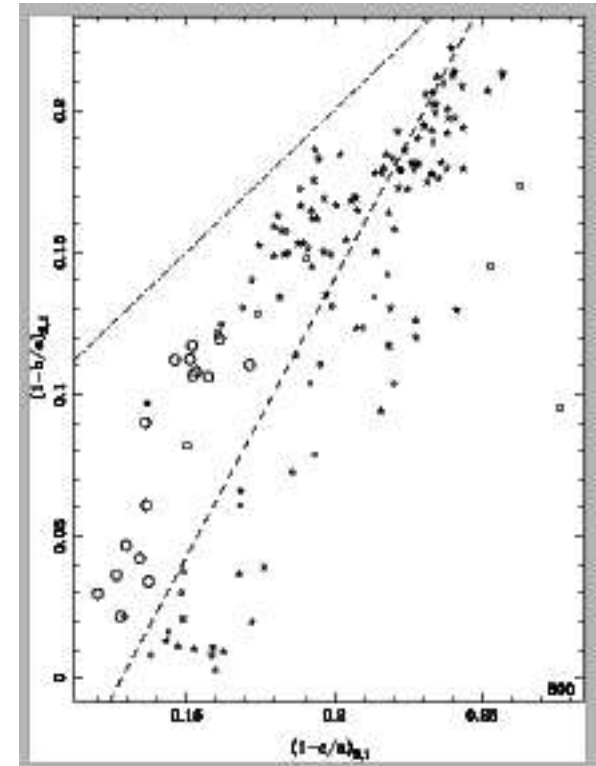
# Correlations between disc bar and halo bar properties



Disc and halo  
bar lengths



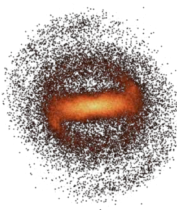
Disc and halo  
bar strengths



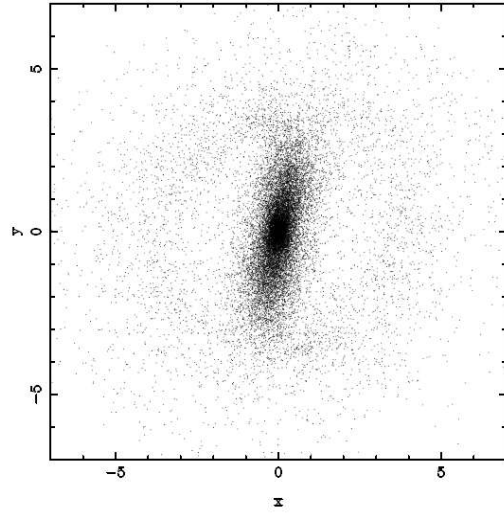
Halo shape



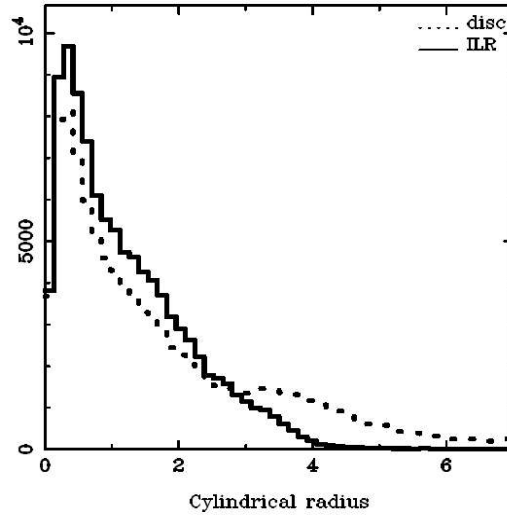
# Where are the near-ILR disc particles ?



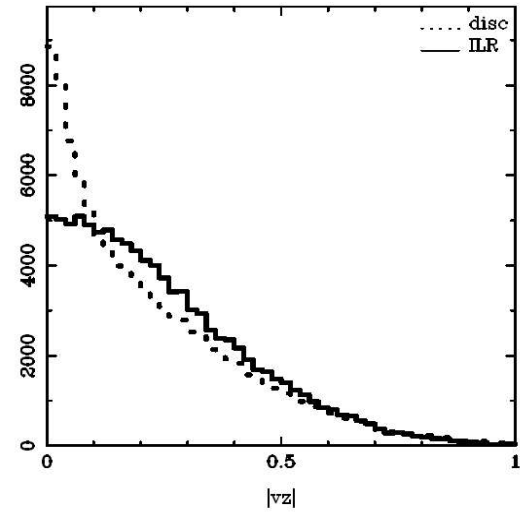
wde397 disc t = 800



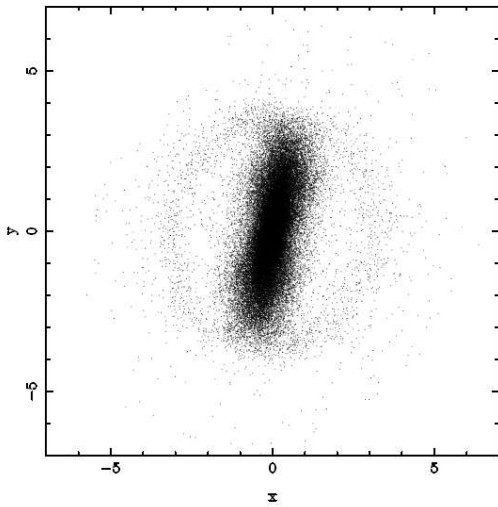
wde397 ILR at t = 800 disc t = 800



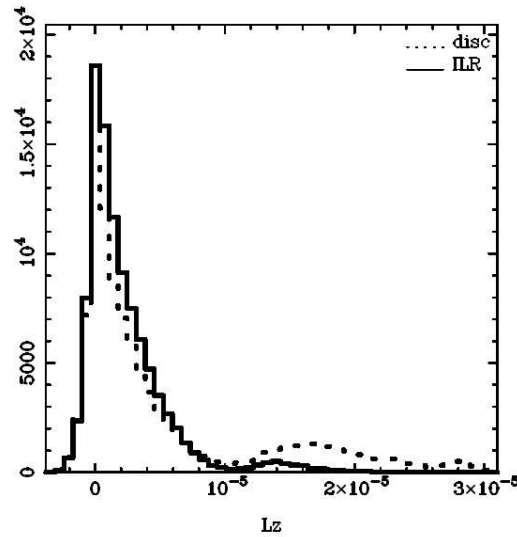
wde397 ILR at t = 800 disc t = 800



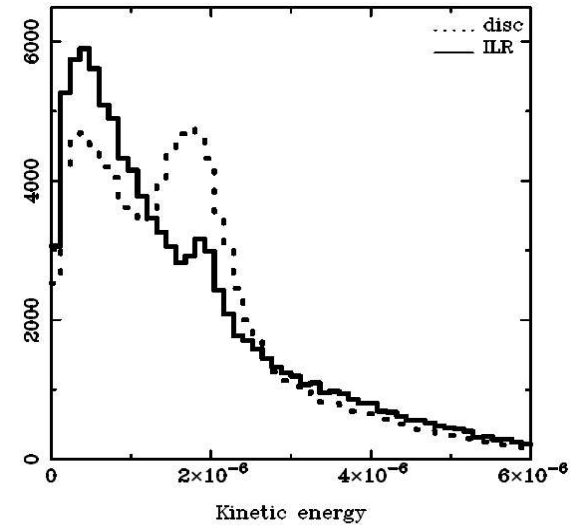
time = 800; particles at ILR at t = 800



wde397 ILR at t = 800 disc t = 800

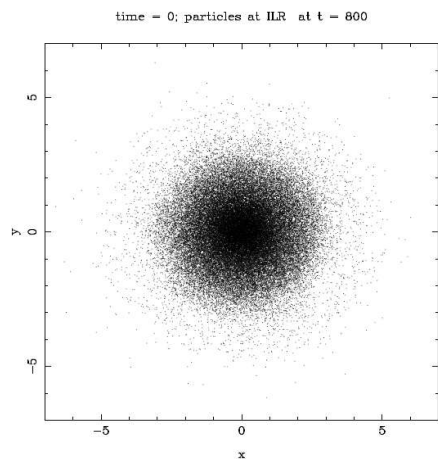
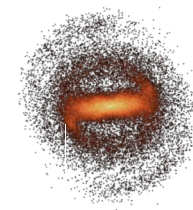


wde397 ILR at t = 800 disc t = 800

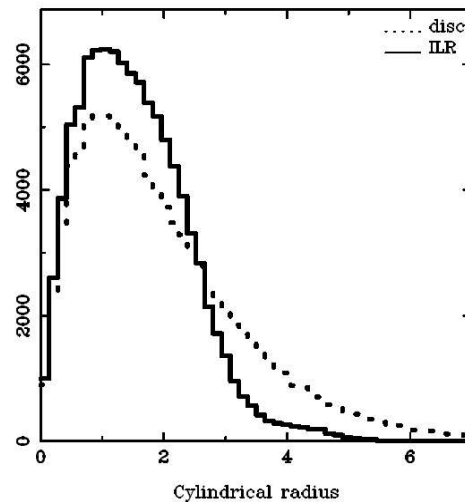




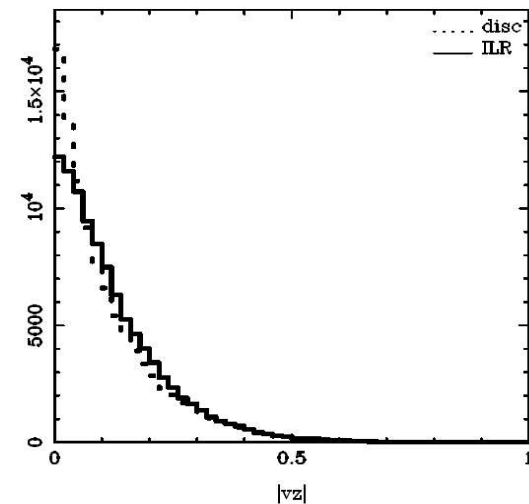
# Where were initially the near-ILR disc particles ?



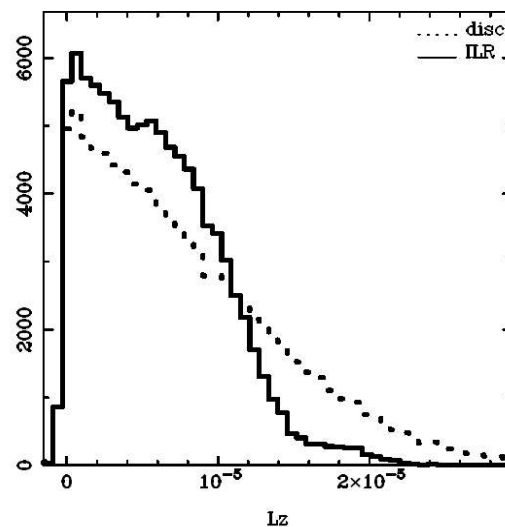
wde397 ILR at t = 800 disc t = 0



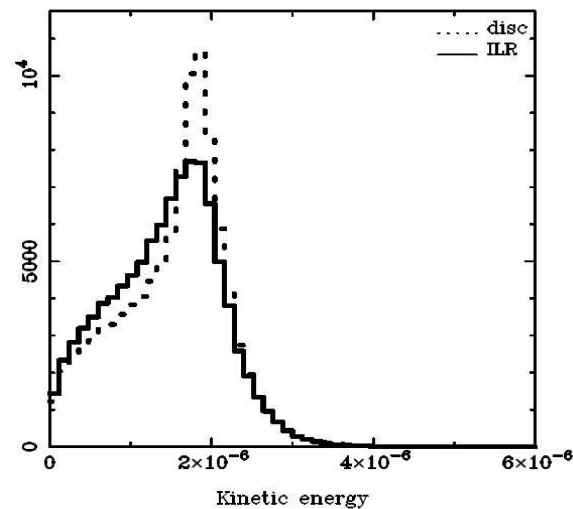
wde397 ILR at t = 800 disc t = 0



wde397 ILR at t = 800 disc t = 0

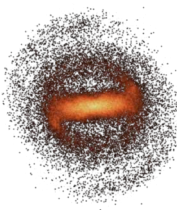


wde397 ILR at t = 800 disc t = 0

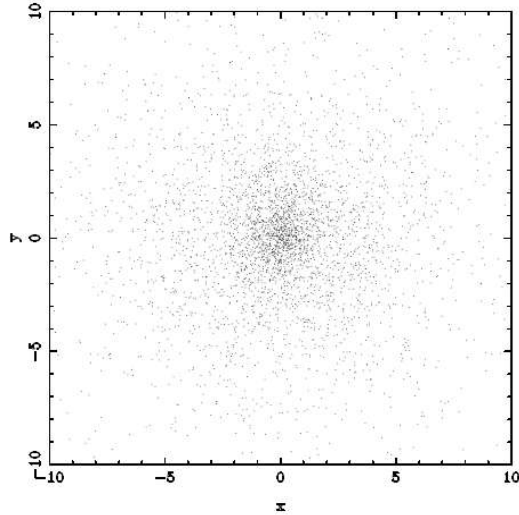




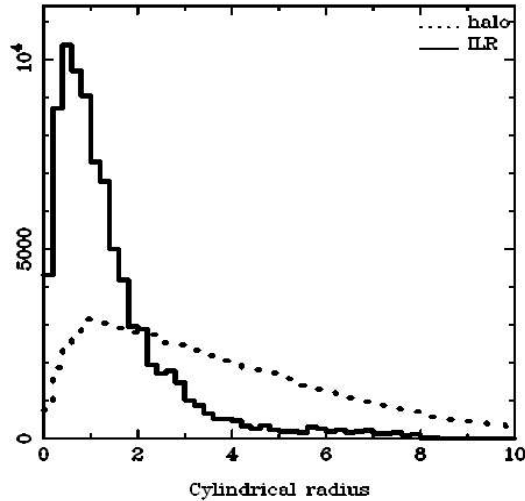
# Where are the halo near-ILR particles ?



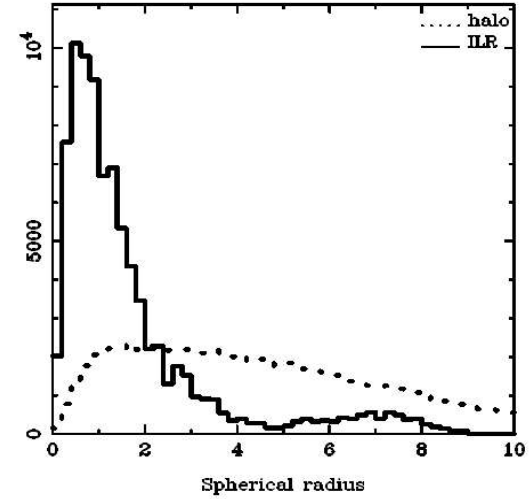
wde397 halo t = 800



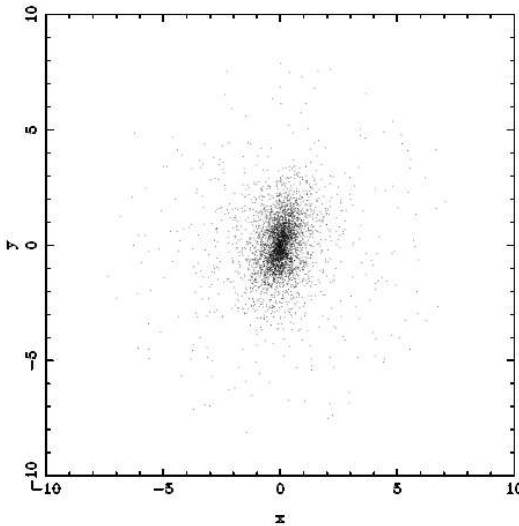
wde397 ILR at t = 800 halo t = 800



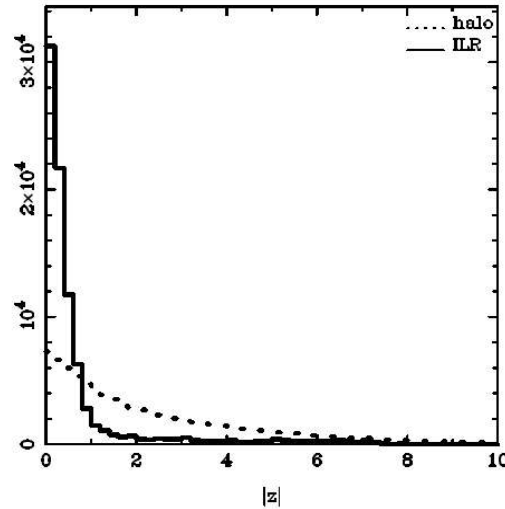
wde397 ILR at t = 800 halo t = 800



time = 800; particles at ILR at t = 800

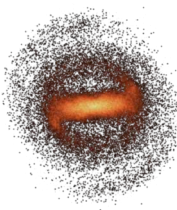


wde397 ILR at t = 800 halo t = 800

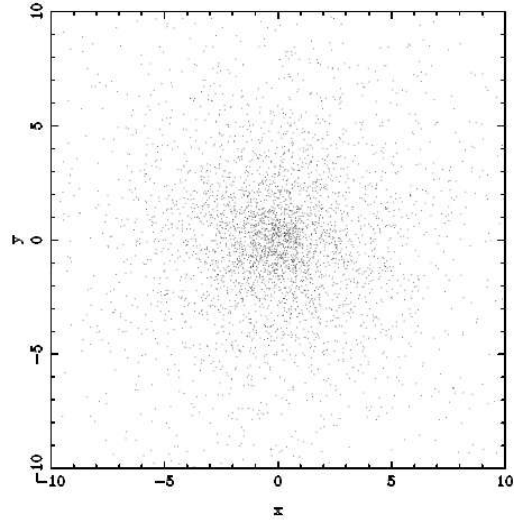




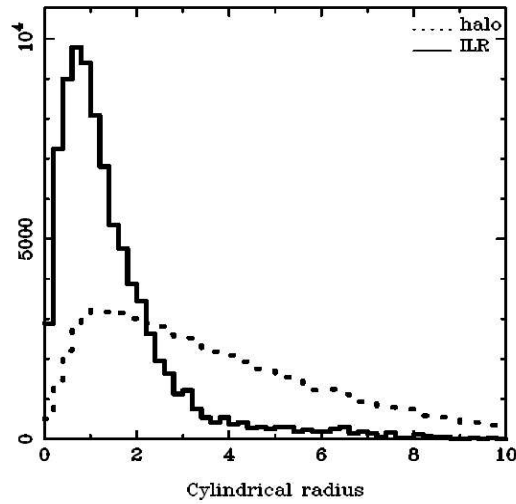
# Where were initially the halo near-ILR particles ?



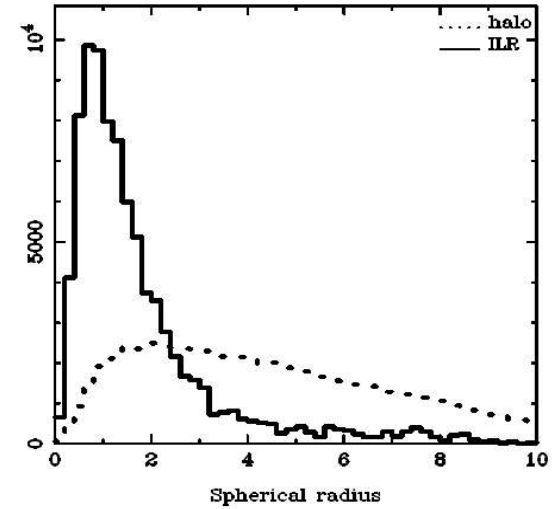
wde397 halo t = 0



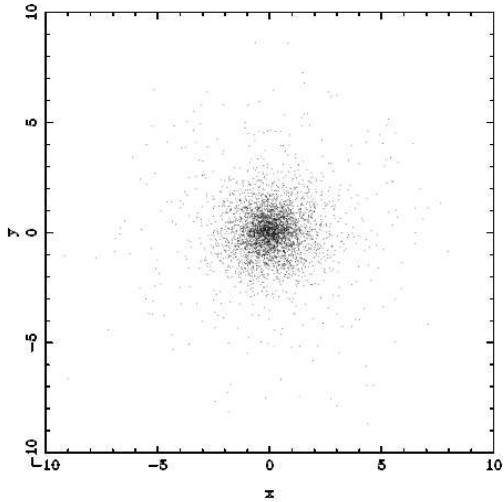
wde397 ILR at t = 800 halo t = 0



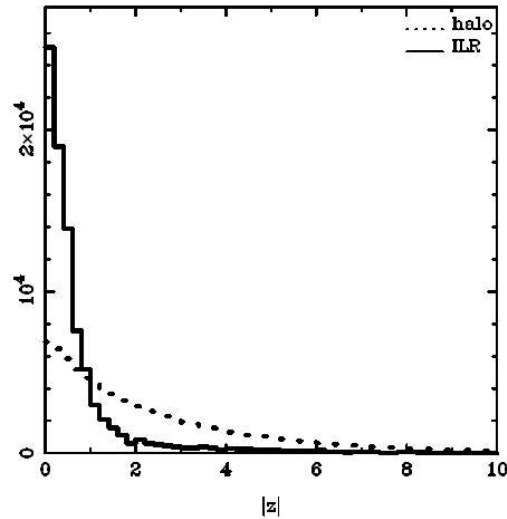
wde397 ILR at t = 800 halo t = 0



time = 0; particles at ILR at t = 800

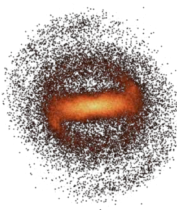


wde397 ILR at t = 800 halo t = 0





# Resonant particles



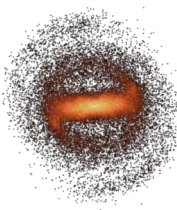
Particles which are near-resonant at a given time are not randomly chosen from the initial distribution function.

Particles at near-ILR have preferentially initially smaller cylindrical and spherical radii. They have initially preferentially smaller values of  $L_z$ , the  $z$  component of the angular momentum.

Particles at near-CR have preferentially initially intermediate cylindrical and spherical radii (not in the innermost or outermost regions). They have initially preferentially smaller values of  $|u_z|$  and larger values of  $L_z$  than average.



# Halo orbital structure

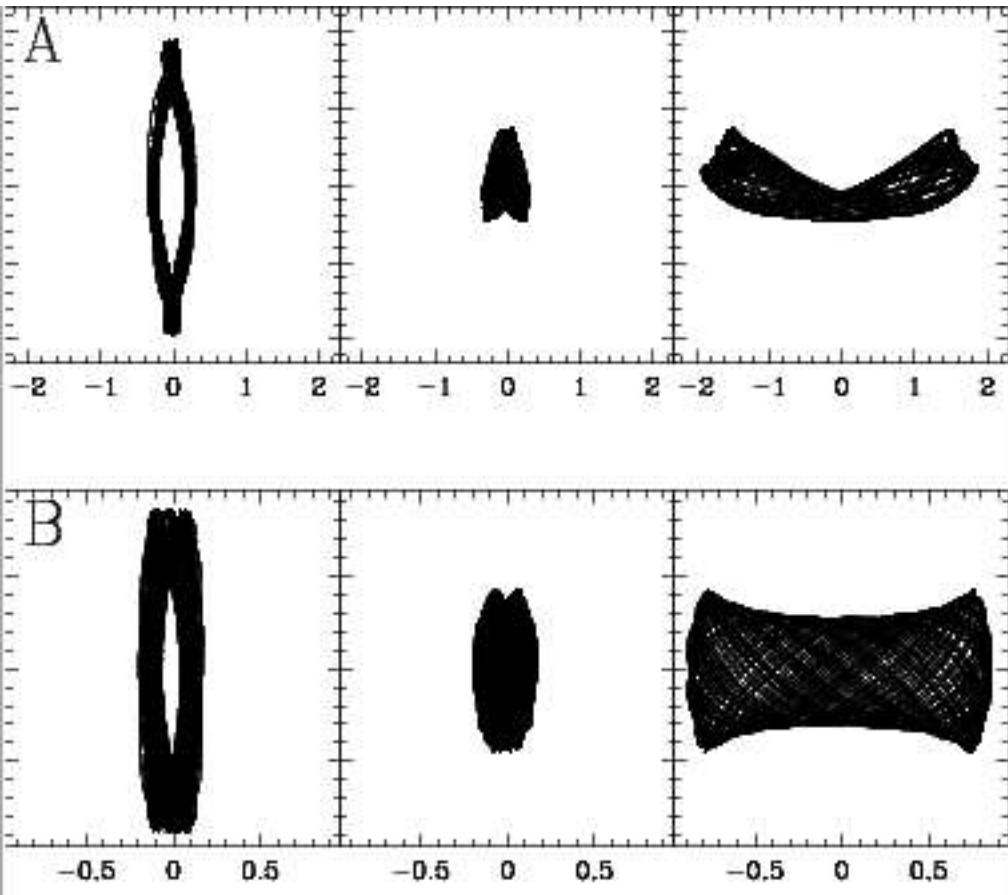
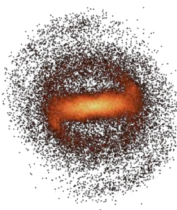


Halo near-resonant orbits are mainly trapped around Lagrangian periodic orbits and around x1-tree periodic orbits

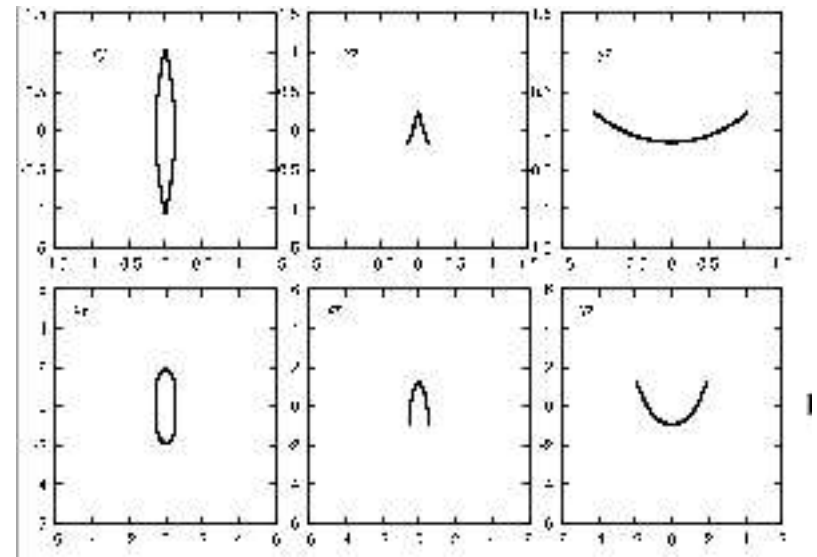
(x1-tree is the 3D extension of the x1 family)



# Halo x1-tree orbits



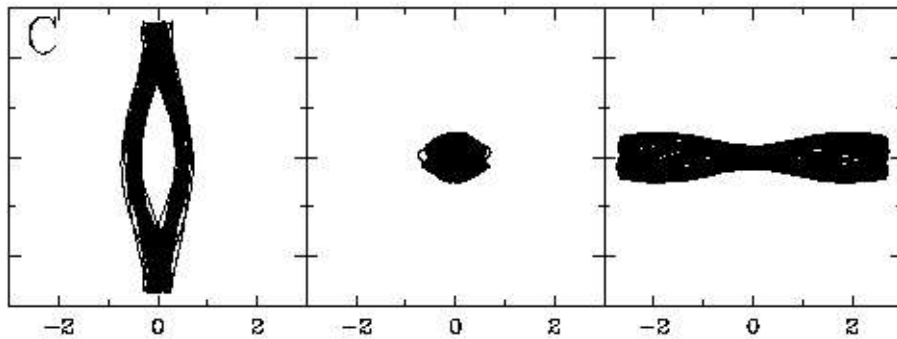
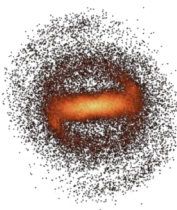
x1v1



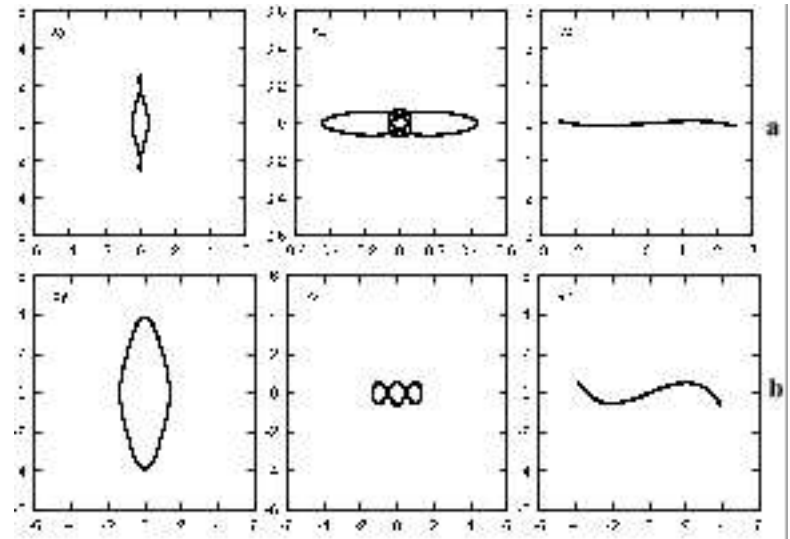
Skokos, Patsis and Athanassoula (2002)



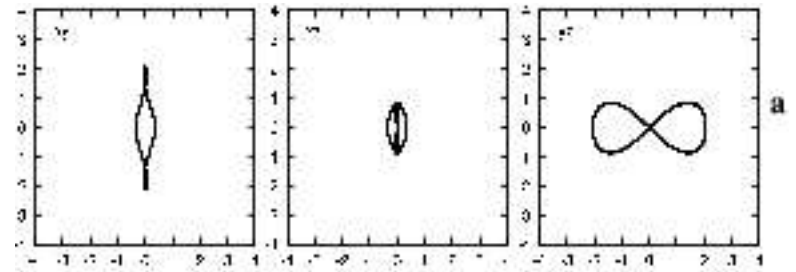
# Halo x1-tree orbits



x1v4 - stable

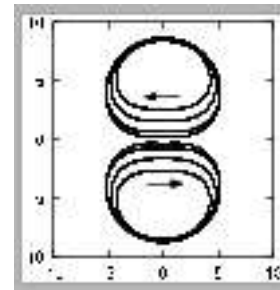
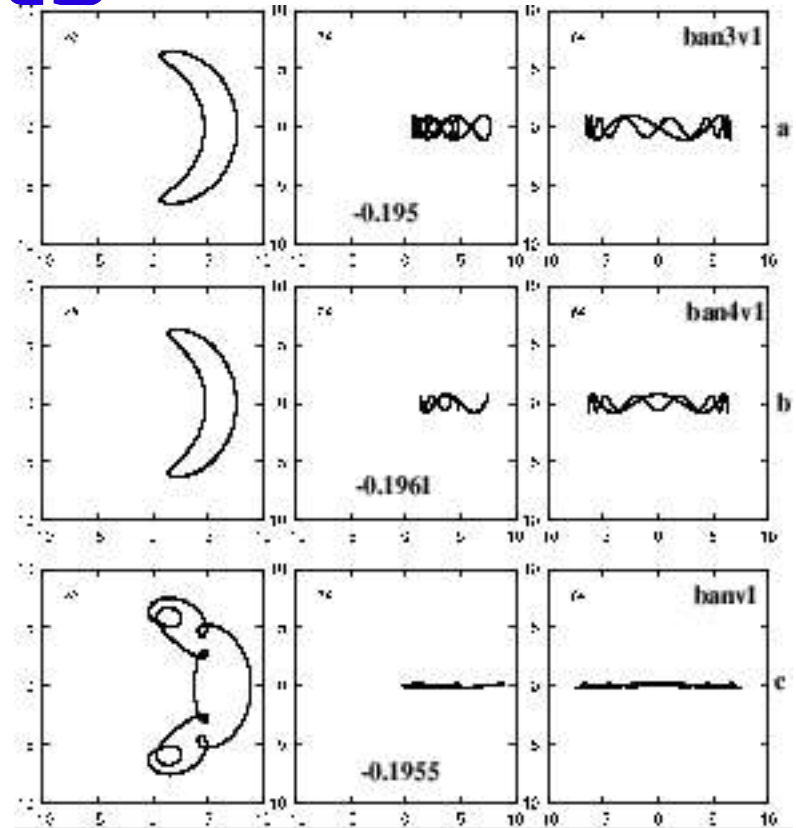
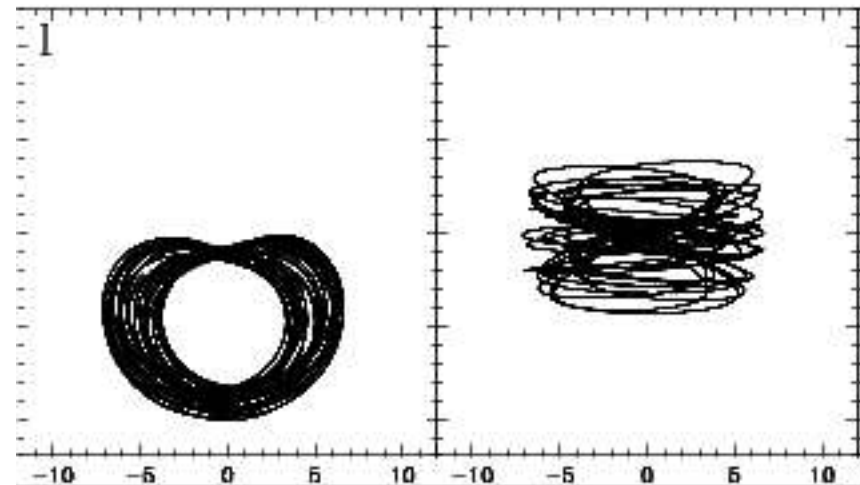
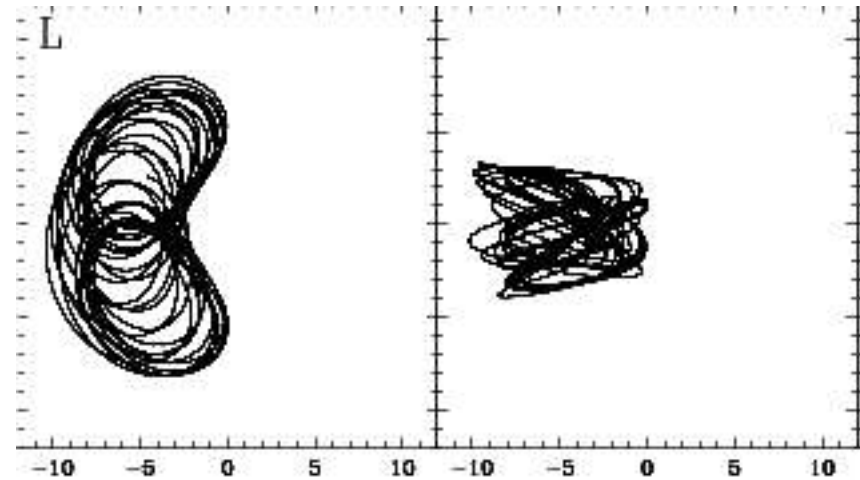
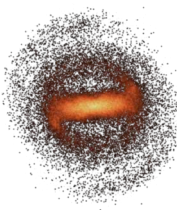


x1v2 - unstable



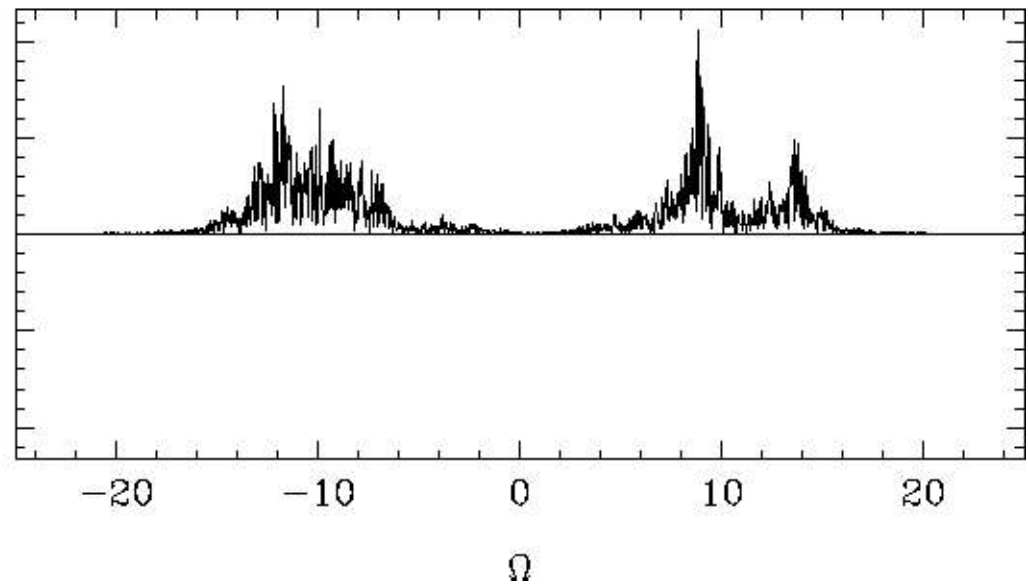
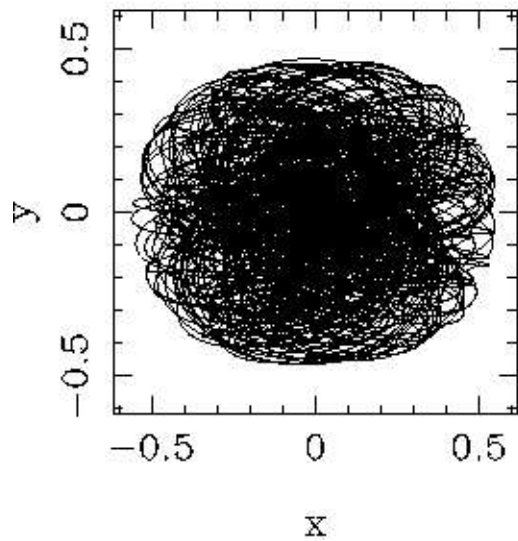
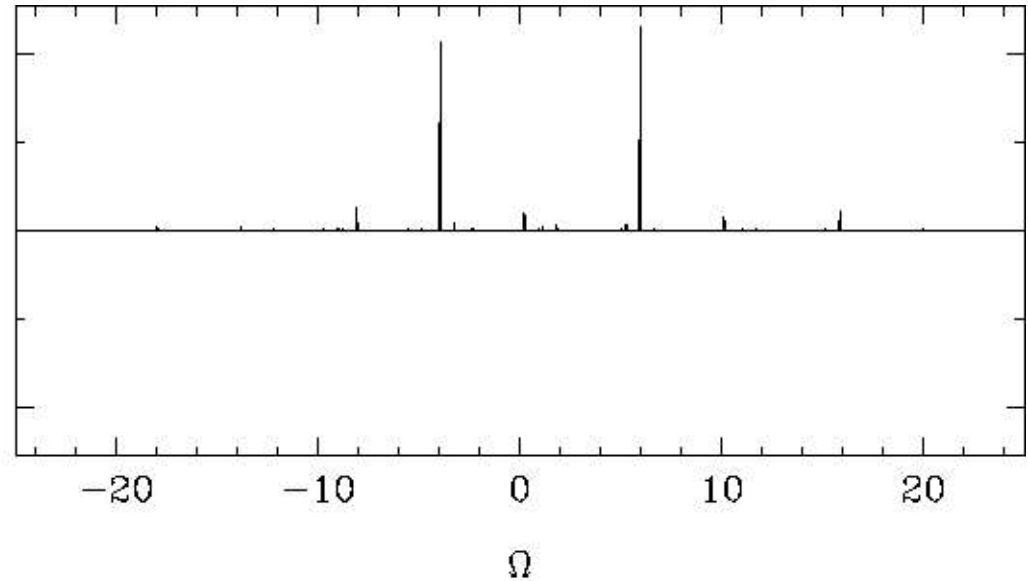
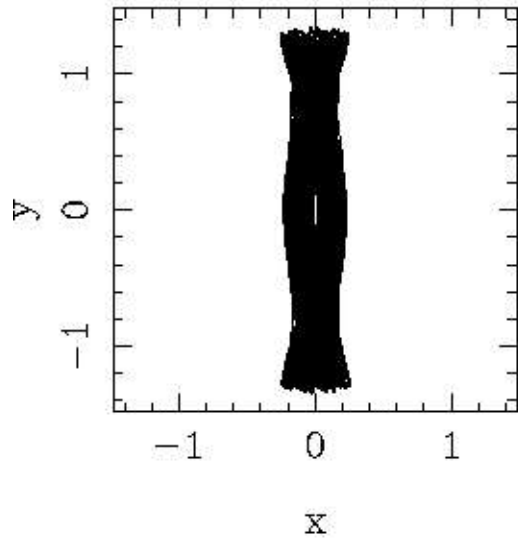
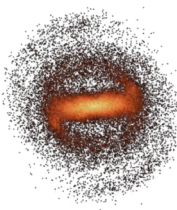


# Halo Lagrangian orbits



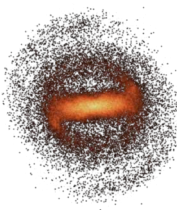
Skokos, Patsis and Athanassoula 2002

# Measuring chaos

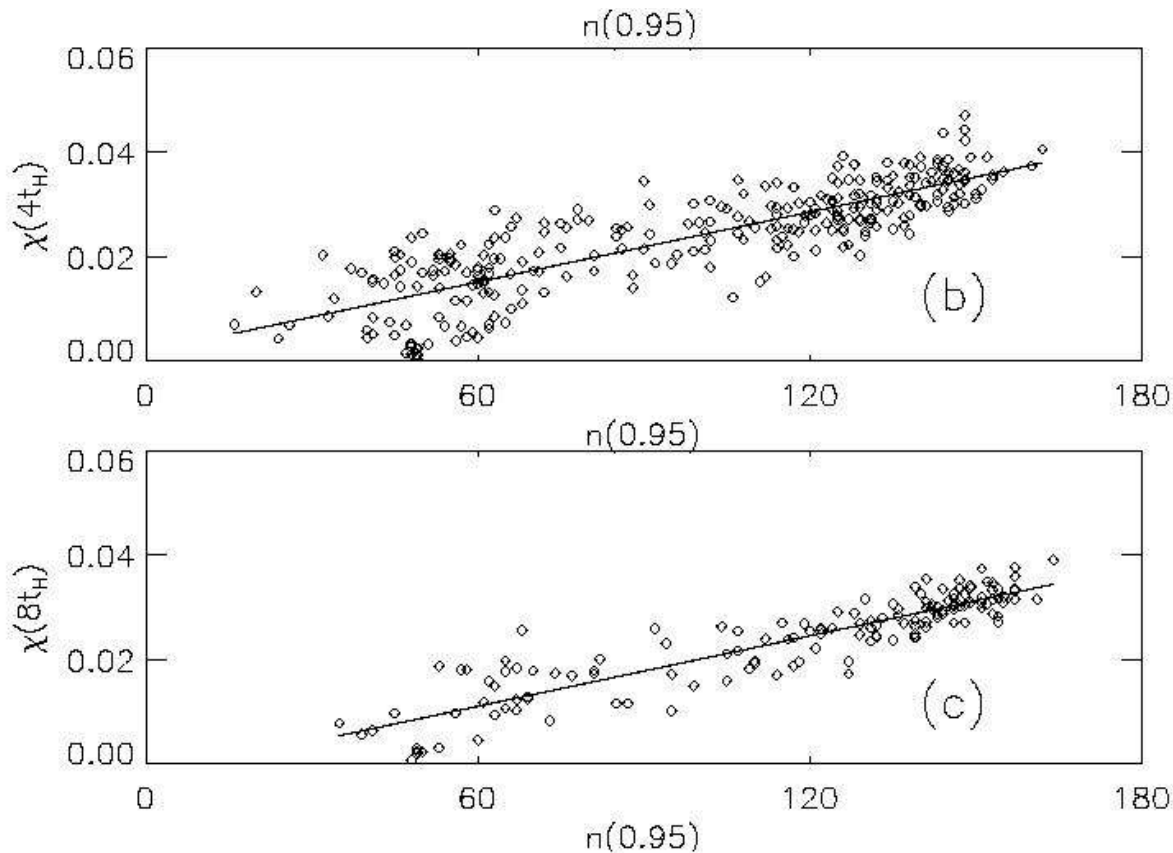




# Complexity and Lyapounov exponents



This measure of chaos performs as well as Lyapunov coefficients

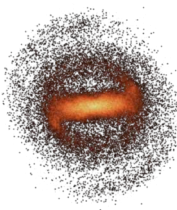


Kandrup, Eckstein & Bradley (1997)

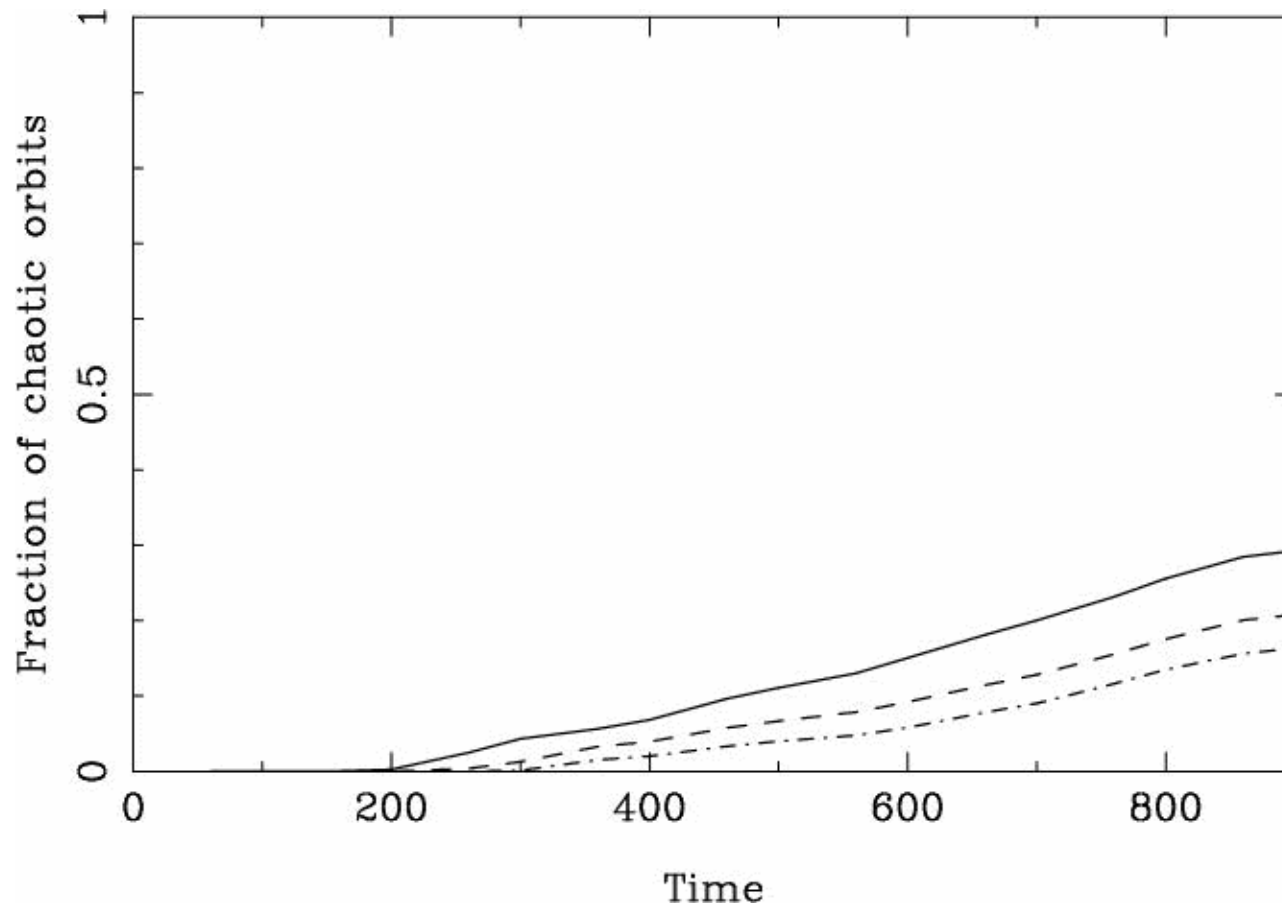
**Fig. 8.** **a** A scatter plot of  $\chi$  vs.  $n(0.95)$  for the segments shown in Fig. 5d, now sampled at an interval  $\Delta t = 2t_H$ . **b** The same for  $\Delta t = 4t_H$ . **c** The same for  $\Delta t = 8t_H$ . **d** The same for  $\Delta t = 16t_H$ .



# Halo orbital structure

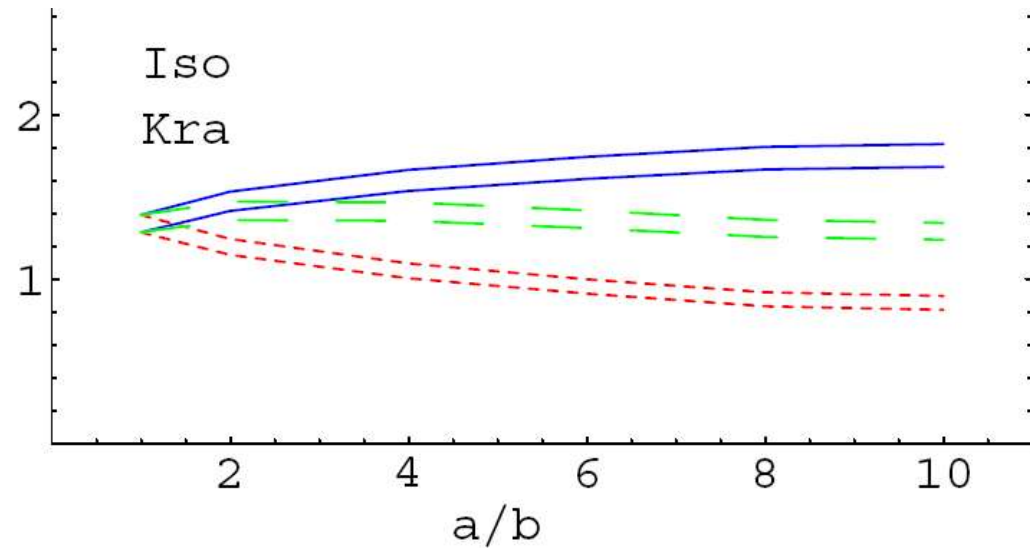
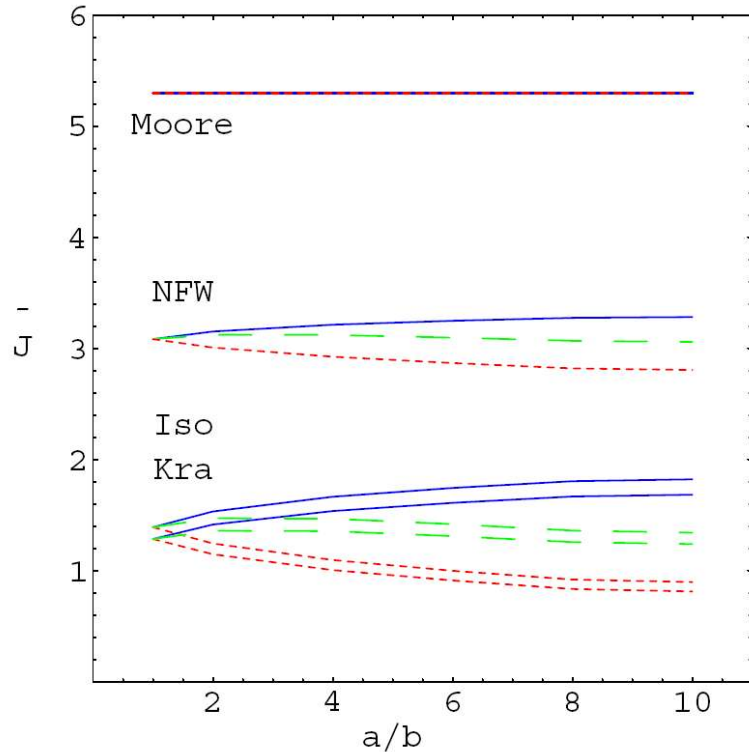
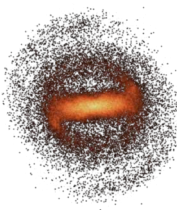


Chaos (more precisely complexity) can be found amongst halo orbits. The fraction depends on the strength of the disc bar.



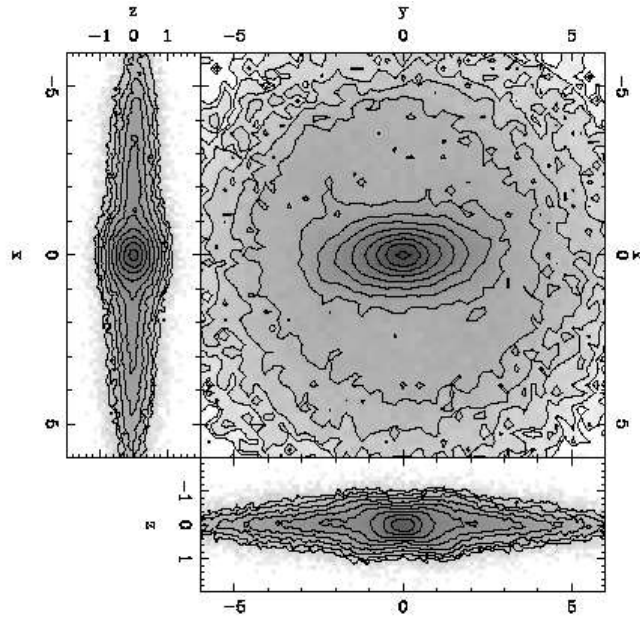
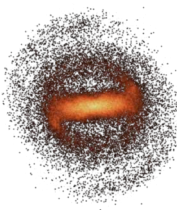


# Halo Geometry and Dark Matter Annihilation Signal

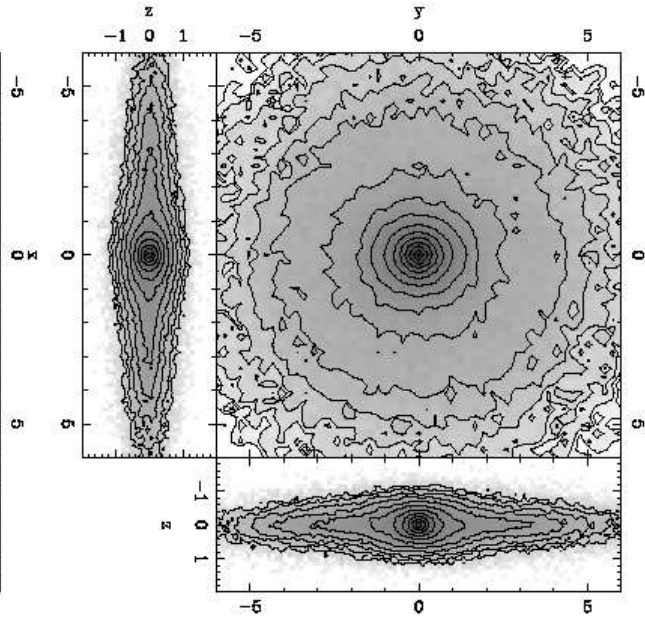




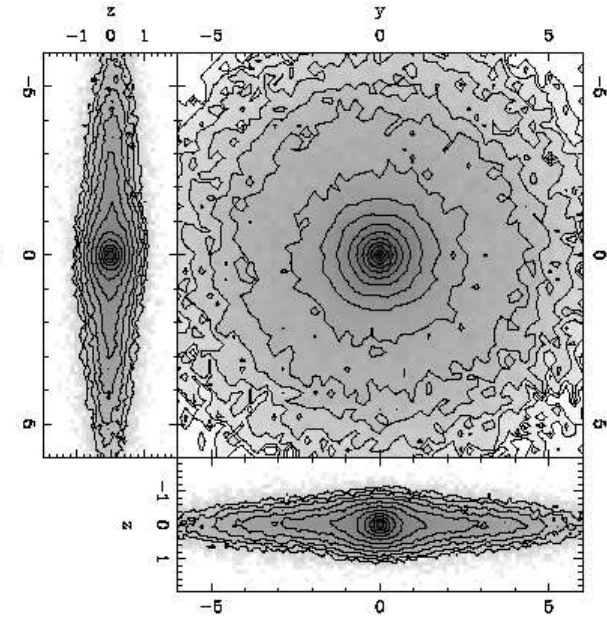
# CMC in MD-type models



No CMC



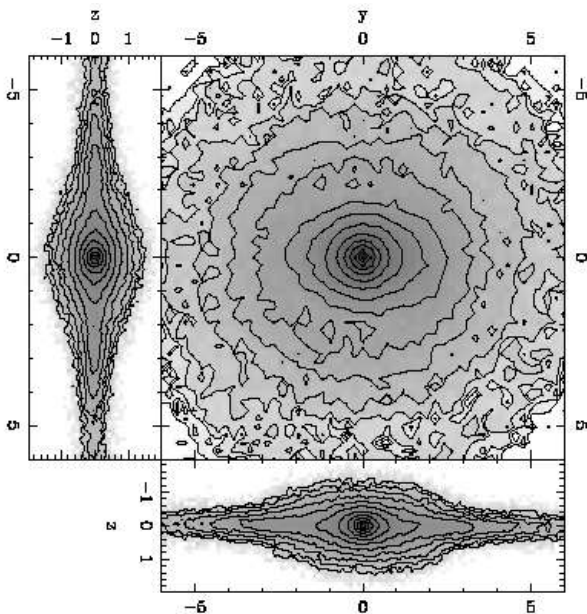
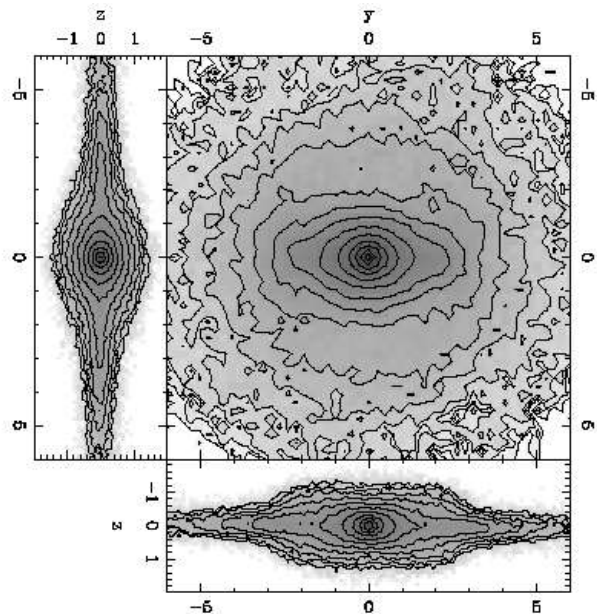
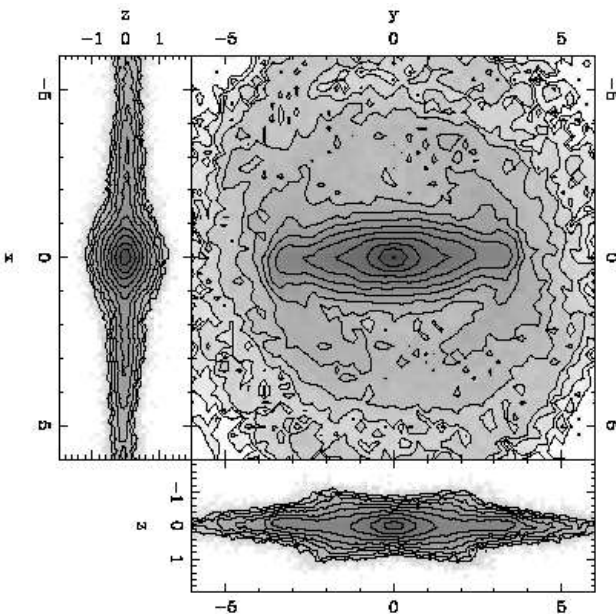
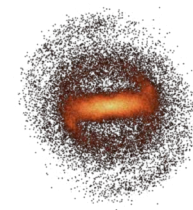
CMC = 5%



CMC = 10%



# CMC in MH-type models



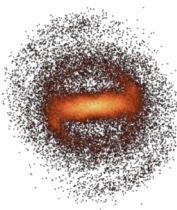
No CMC

CMC = 5%

CMC = 10%



# Summary (1)



The halo plays a crucial part in the evolution of barred galaxies. Its near-resonant particles absorb angular momentum emitted from the disc particles and thus help the bar become stronger.

A bar (oval) forms in the inner parts of the halo

Its departure from sphericity is strongest near the center and decreases outwards. It is always fatter than the disc bar.

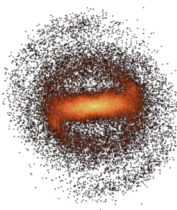
Its length increases with time, but it always stays shorter than the disc bar.

It is roughly aligned with the disc bar (but trails it slightly) and turns with the same pattern speed. The  $m=2$  component continues outside the halo bar, trailing behind the disc bar

The lengths and strengths of the disc and halo bar correlate.



# Summary (2)



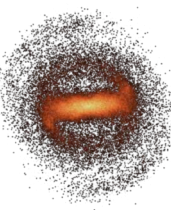
Halo near-resonant orbits are similar to disc near-resonant orbits (same families)

After the bar forms, a considerable fraction of the halo orbits becomes chaotic

Particles that become near-resonant are not randomly chosen from the initial halo distribution function. Depending on the resonance (ILR, CR or OLR) they have preferentially smaller/bigger values of radii, angular momentum and velocities.

The halo geometry can influence the amplitude of the dark matter annihilation signal if the halo is not too cuspy ( $< 1$ )

A massive and responsive halo makes it harder for a BH or a central mass concentration to destroy a bar



The End