Dynamics of Barred Galaxies in Triaxial Dark Matter Haloes

Rubens Eduardo Garcia Machado

advisors: Evangelie Athanassoula (LAM)
& Ronaldo Eustáquio de Souza (IAG)

Universidade de São Paulo
USP
LAM
LABORATOIRE D'ASTROPHYSIQUE DE MARSEILLE
UNIVERSITÉ DE PROVENCE
Aix - Marseille 1

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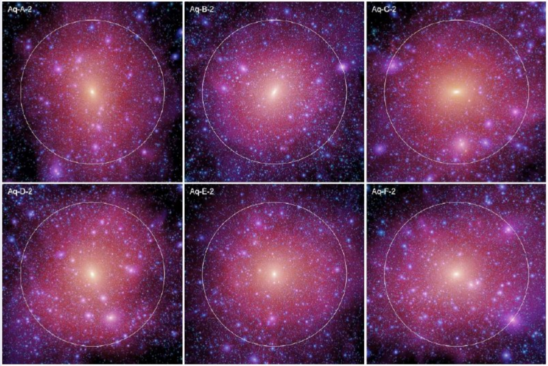
Outline of the presentation

Part I
Introduction

Dark matter haloes: shapes

Cosmological simulations

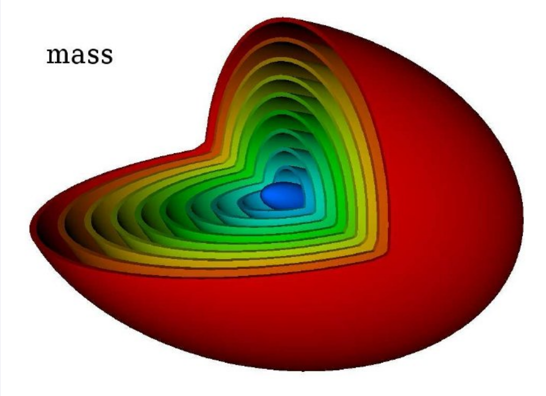


Springel et al. (2008)

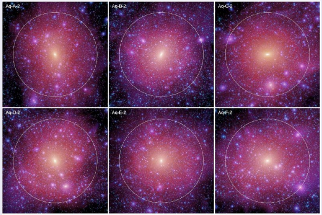
- from the cosmological simulations of structure formation:
- dark matter haloes are generally triaxial
- major-to-minor axis ratio of as much as 2 is not uncommon

Dark matter haloes: shapes

Triaxial shape



Kuhlen, Diemand & Madau (2007)

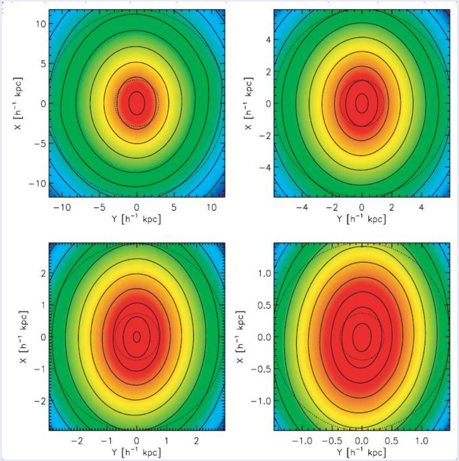


Springel et al. (2008)

- from the cosmological simulations of structure formation:
- dark matter haloes are generally triaxial
- major-to-minor axis ratio of as much as 2 is not uncommon

Haloes and barred galaxies

Elliptical halo potentials

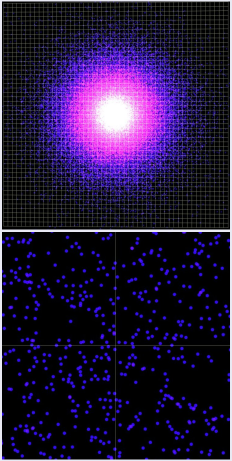


Hayashi et al. (2007)

Barred galaxy

- What about bar formation within an elongated potential?

Numerical simulations

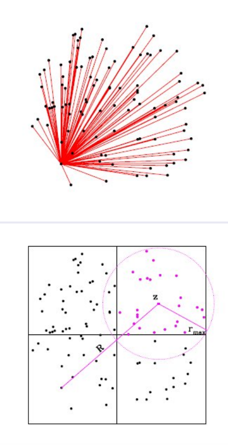


N-body problem

- calculate force on each particle due to $N-1$ other particles
- $F_i = \sum_{i \neq j} \frac{G\ m_i\ m_j}{|r_i - r_j|^2}$

Numerical simulations

Tree algorithm



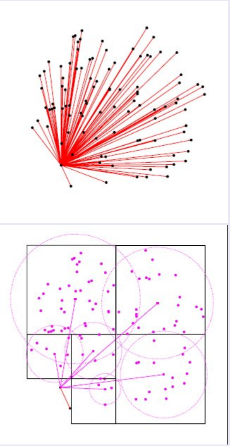
Dehnen (2006)

N-body problem

- calculate force on each particle due to $N-1$ other particles
- $F_i = \sum_{i \neq j} \frac{G\ m_i\ m_j}{|r_i - r_j|^2}$
- instead, approximate far-away particles by the centre-of-mass of that cell

Numerical simulations

Tree algorithm



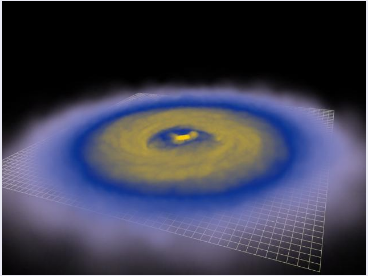
Dehnen (2006)

colisionless simulations

- **gyrfalcON** code (Dehnen 2000)
- $N \sim 10^6$ particles
- mass resolution $\sim 10^5 M_\odot$

Numerical simulations

gas



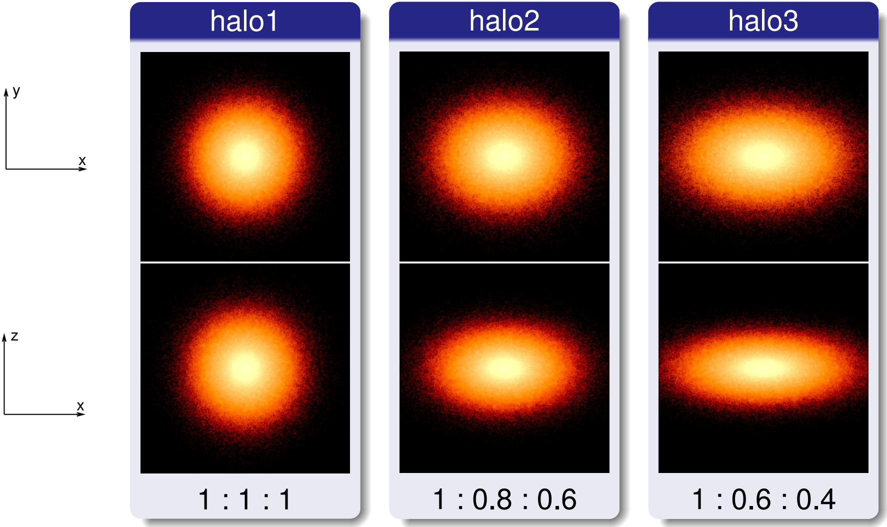
GADGET2 (Springel 2005)

- TreePM: Tree and particle-mesh
- SPH: smoothed particle hydrodynamics

Part II

Collisionless simulations

Initial conditions: haloes



halo IC: iterative method (Rodionov et al. 2010)

Initial conditions: density profiles

DISC (exponential)

$$\rho_d(R,z) = \frac{M_d}{4\pi z_0 R_d^2} \exp\left(-\frac{R}{R_d}\right) \mathrm{sech}^2\left(\frac{z}{z_0}\right)$$

HALO (Hernquist)

$$\rho_h(r) = \frac{M_h}{2\pi^{3/2}} \frac{\alpha}{r_c} \frac{\exp\left(-r^2/r_c^2\right)}{r^2+\gamma^2}$$

$R_d = 1$ is the unit of length (say, 3.5 kpc)

Epycicle approximation

Measure from the triaxial haloes:

- $\epsilon_{pot}(R)$: ellipticity of halo potential (as a function of radius)
- $v_c(R)$: circular velocity (as a function of radius)

ellipticity of the orbits and ellipticity of the potential

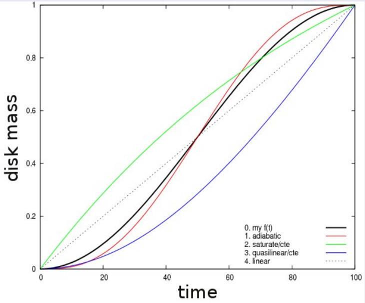
$$\epsilon_R = \left[\frac{\frac{2v_c^2}{R} + \frac{dv_c^2}{dR}}{\frac{2v_c^2}{R} - \frac{dv_c^2}{dR}} \right]_{R_0} \epsilon_{pot}$$

reassignment of disc orbit coordinates:

$$\begin{cases} R = R_0 \left[1 - \frac{\epsilon_R}{2} \cos(2\Omega_0 t) \right] \\ \varphi = \Omega_0 t + \frac{\epsilon_R + \epsilon_v}{4} \sin(2\Omega_0 t) \end{cases}$$

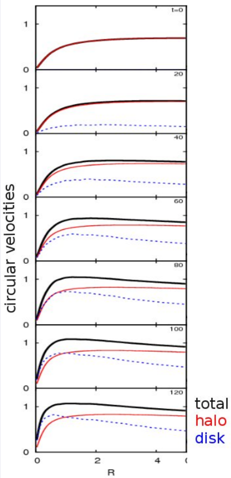
Disc growth

growth of disc mass

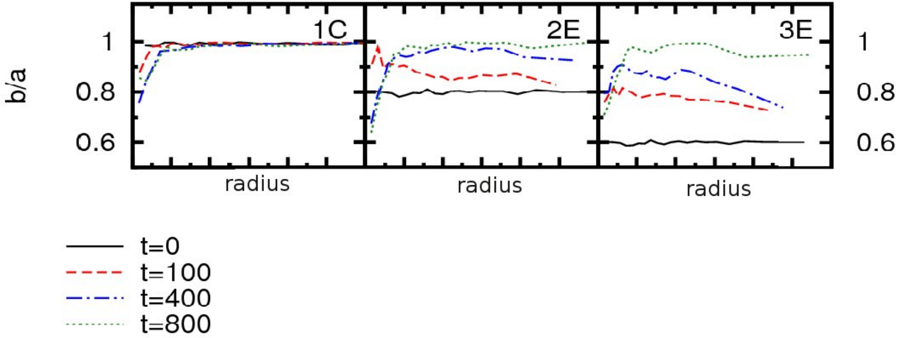


- disc mass is grown "adiabatically"
- timescale of $\sim$ 1 Gyr

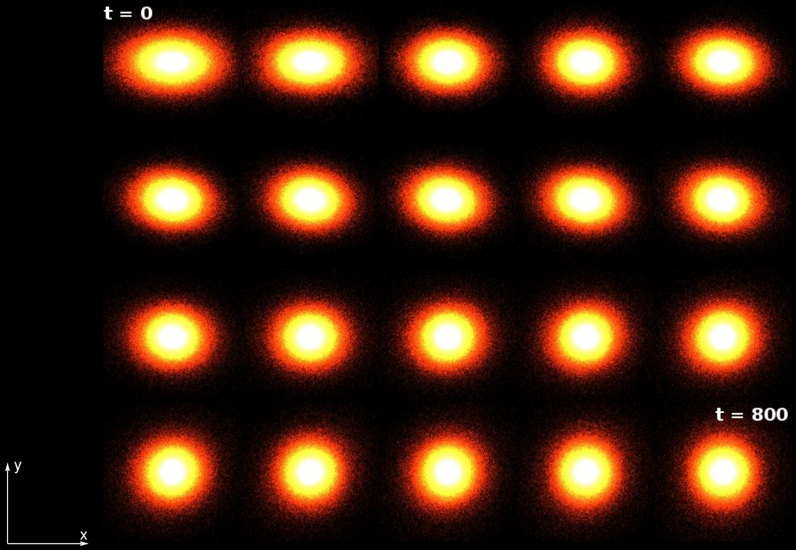
circular velocities



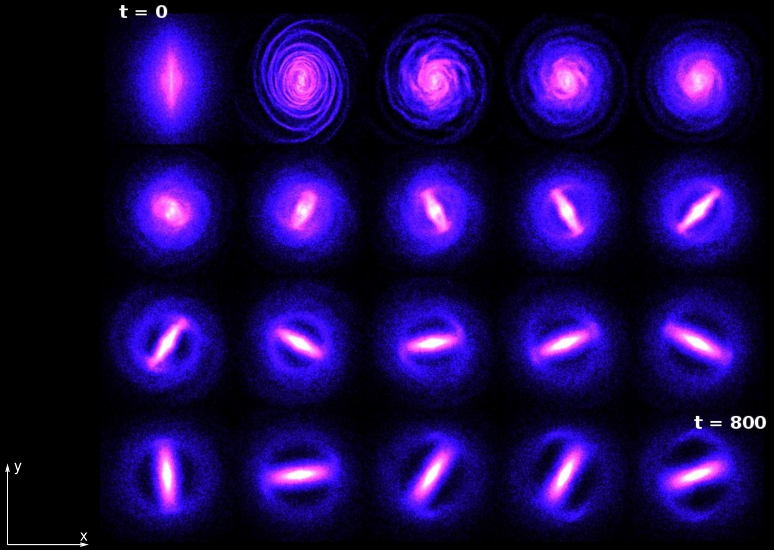
Circularisation of the haloes



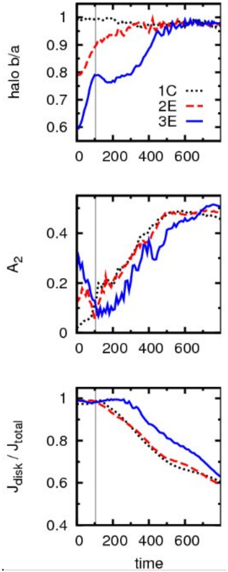
Haloes: initially triaxial



Discs: initially elliptical



Circularisation of the haloes



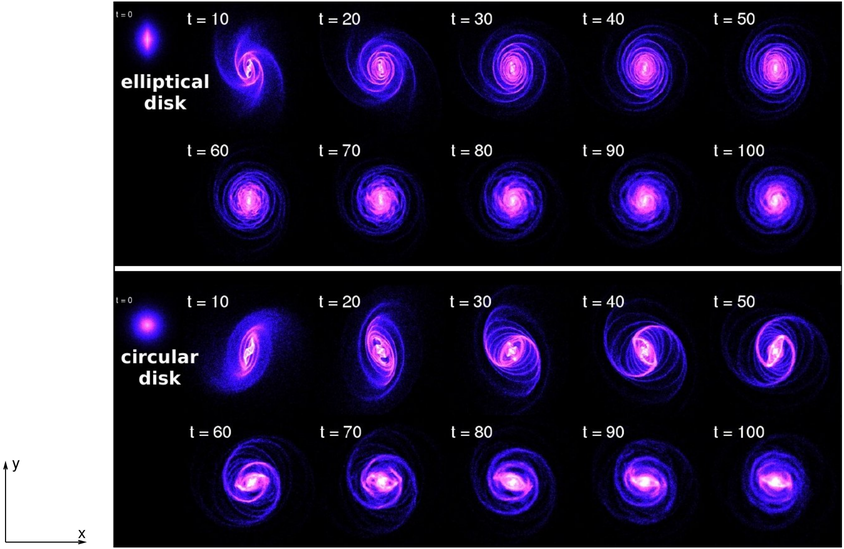
halo 1

halo 2

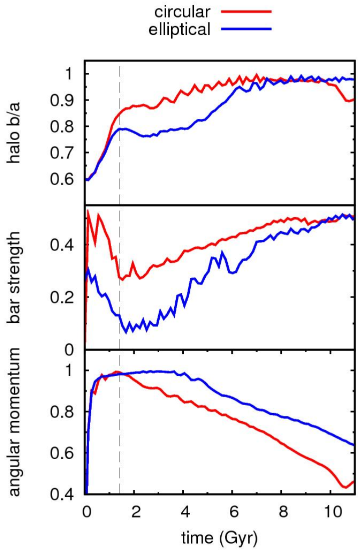
halo 3

- two phases of circularisation
- circularisation linked to bar strength

Elliptical versus circular discs



Elliptical versus circular discs



initially circular disc
x
initially elliptical disc

Bar formation causes further halo circularisation

how to check this?

compare halo shapes in the absence of bars:

1. large halo core
2. less massive disc
3. hot disc
4. rigid disc
5. artificially axisymmetric disc

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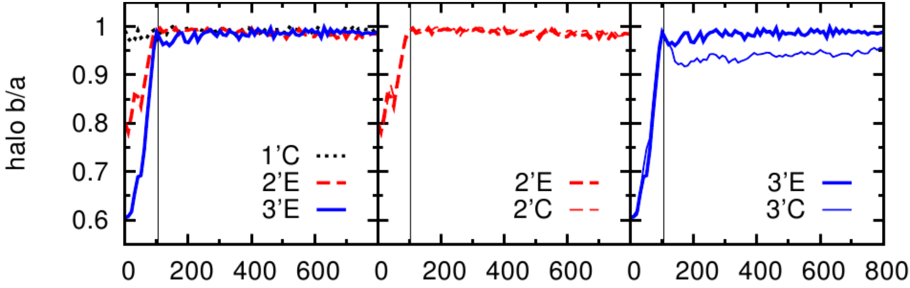
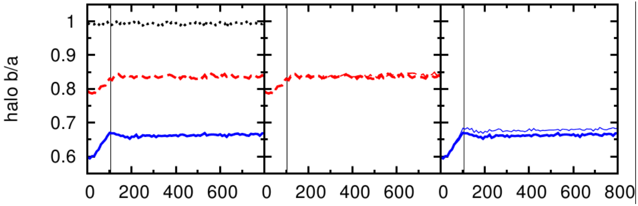
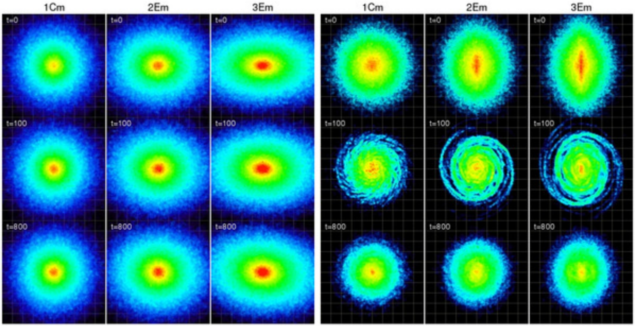
1. Large halo core



- halo too susceptible to circularisation
- halo completely circularised by disc growth alone

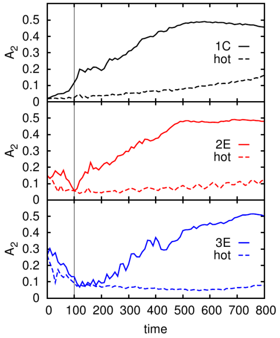
2. Less masive discs

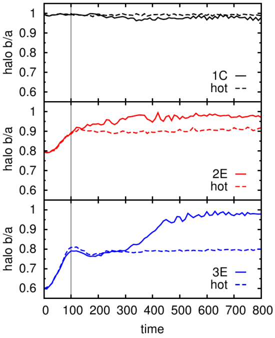


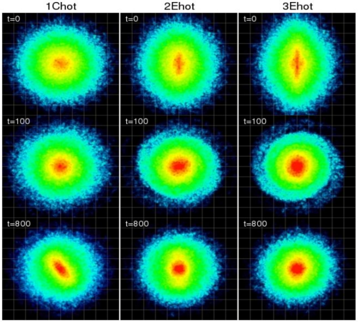


- almost no bars
- haloes remain triaxial

3. Hot discs

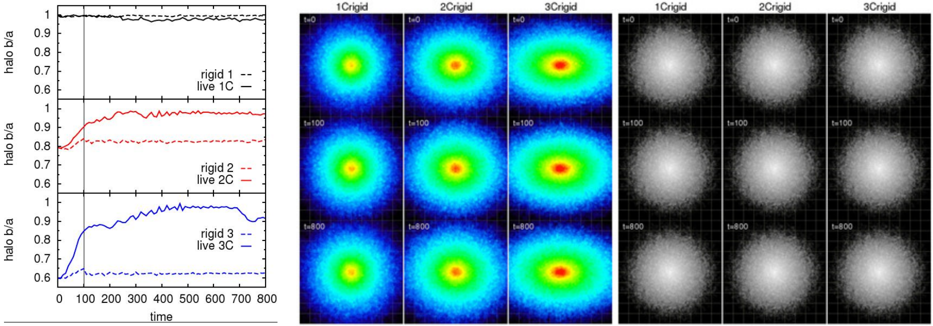






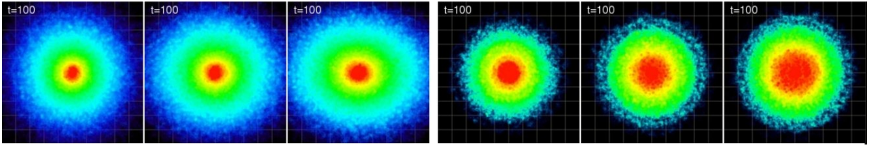
- very weak bars
- haloes remain triaxial

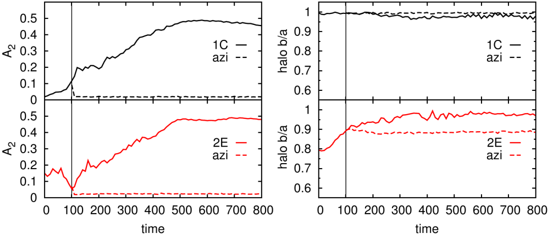
4. Rigid discs



- no bars at all (analytic disc potential)
- haloes remain triaxial

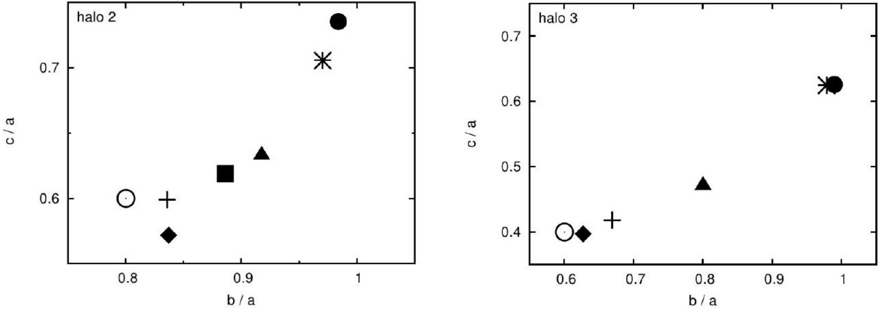
5. Artificially axisymmetric discs





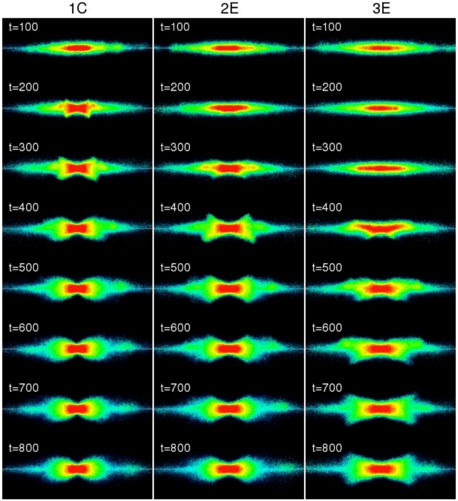
- no bars
  (no non-axisymmetry)
- haloes remain triaxial

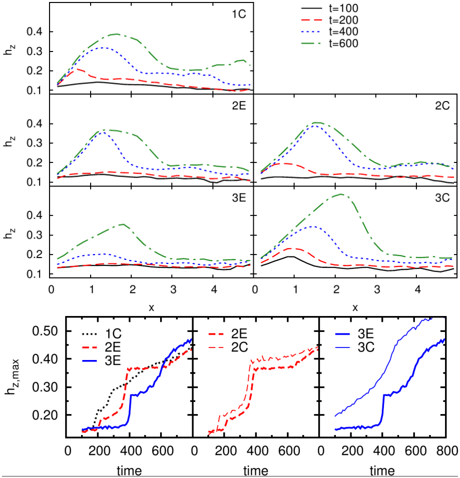
Vertical flattening



$\mathbf{c/a}$ also increases, but to a lesser degree

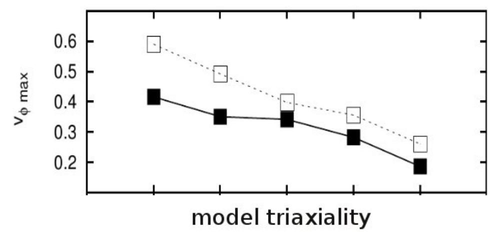
Peanut-shaped bulges





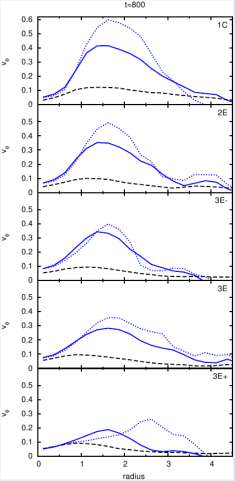
Halo kinematics: disc-like halo particles

peak tangential velocities



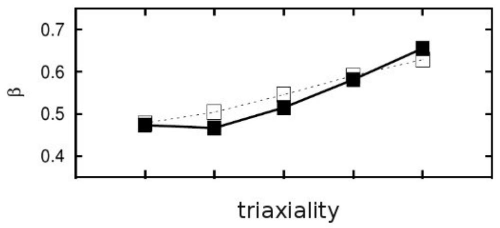
- some halo particles rotate (in a layer within **|z| < 2 kpc**)
- rotation is less important in triaxial models

tangential velocities



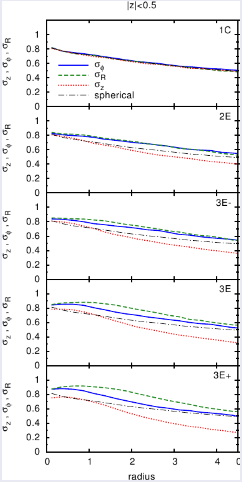
Halo kinematics: velocity anisotropy

velocity anisotropy



- haloes remain anisotropic (even after circularisation)

velocity dispersions

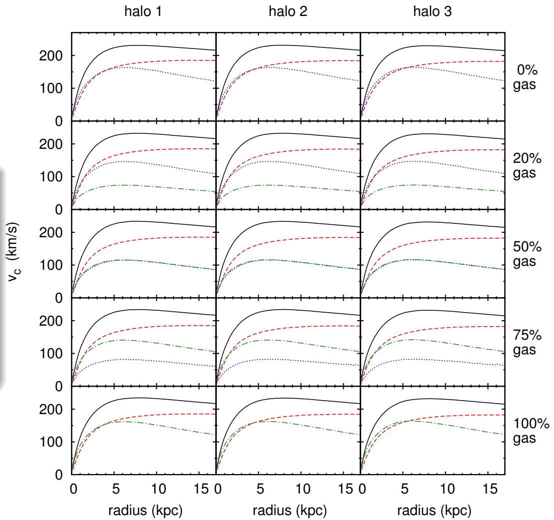


Part III

Simulations including gas

Simulations including gas

- a fraction of the disc mass is in the form of gas
- 15 models: 3 halo shapes $\times$ 5 gas fractions

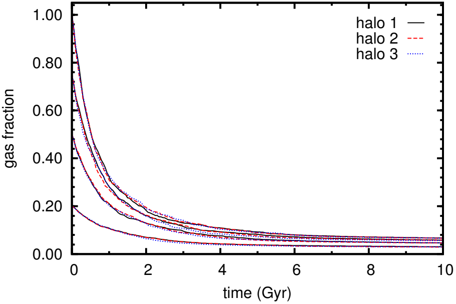


Gas fraction

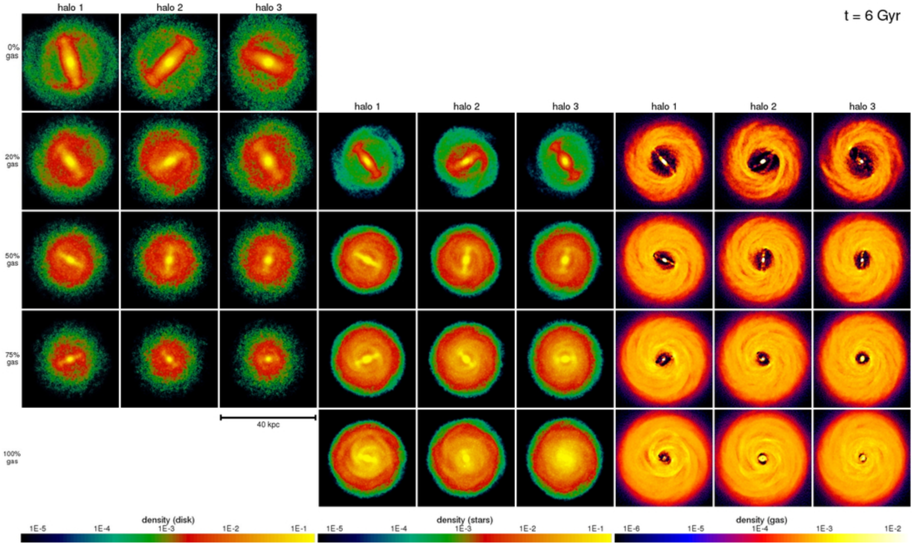
- due to star formation, gas fraction decreases over time

gas fraction in the disc

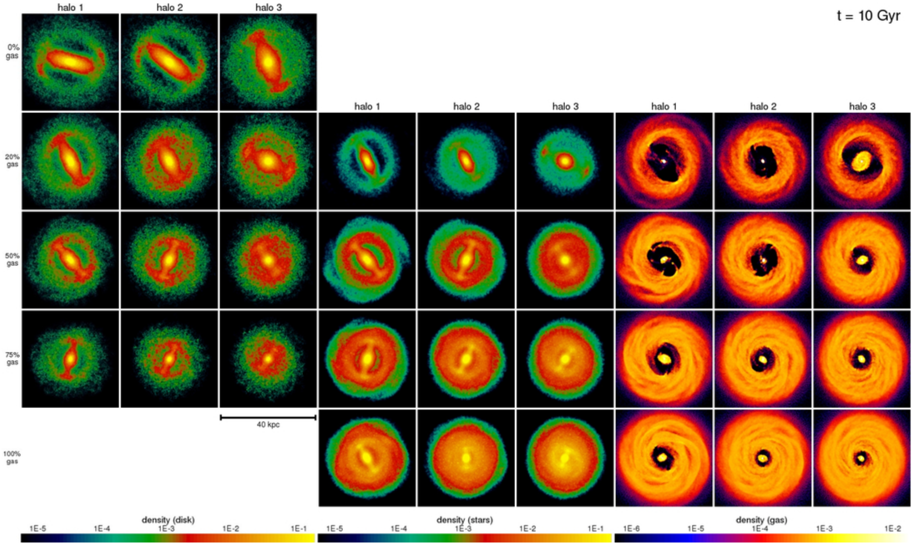
time (Gyr)	gas fraction			
0	20%	50%	75%	100%
2	7%	13%	16%	19%
5	4%	6%	8%	9%
10	3%	5%	6%	7%



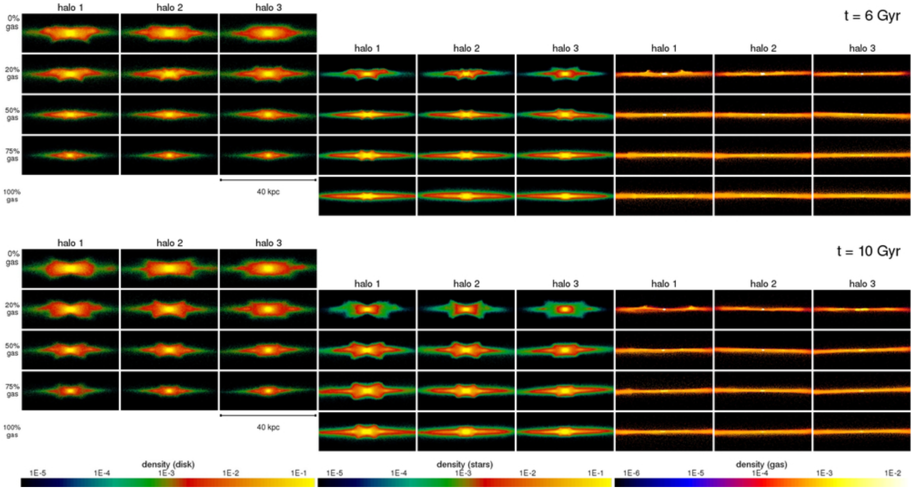
Disk, stars, gas: face-on (t=6 Gyr)



Disk, stars, gas: face-on (t=10 Gyr)

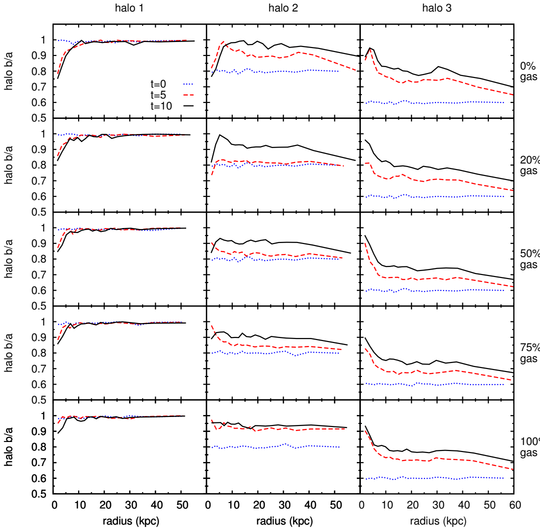


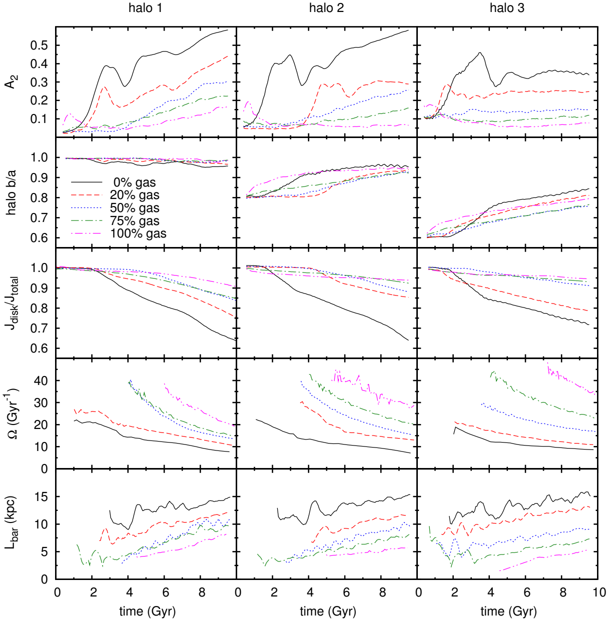
Disk, stars, gas: edge-on



Halo circularisation

- haloes become more circular at all radii
- halo bar in the inner region if stellar bar is strong



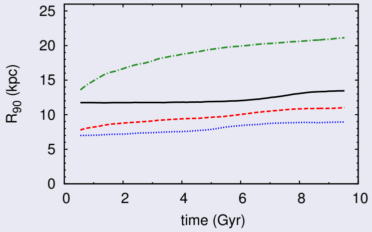

halo 1
halo 2
halo 3
A_2
halo b/a
J_{disk}/J_{total}
Ω (Gyr^{-1})
L_{bar} (kpc)
0% gas
20% gas
50% gas
75% gas
100% gas
time (Gyr)

Different stellar ages: bar strength

disc components:

- **stars**, young stars, youngest stars and gas

R_{90}



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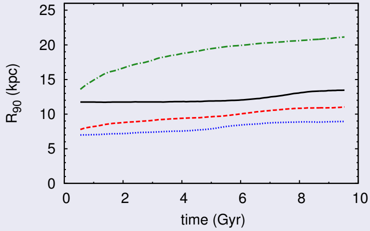
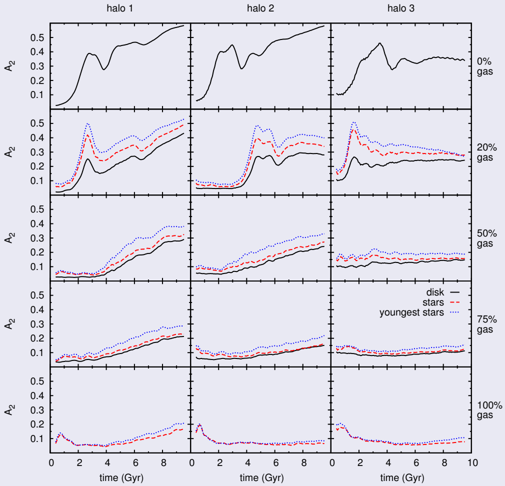


bar strength

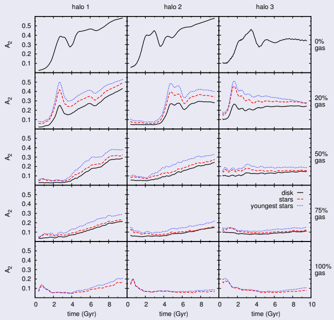


Different stellar ages: angular momentum

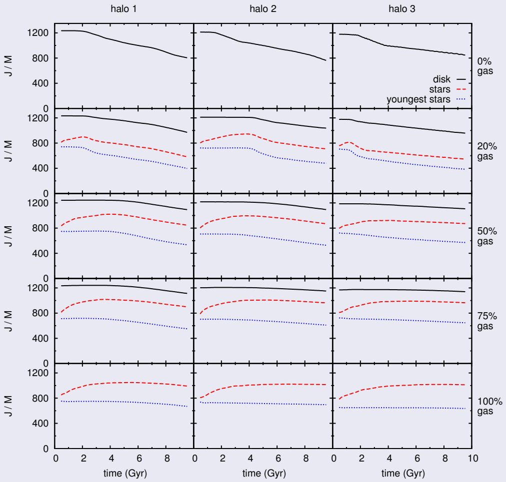
disc components:

- **stars**, young stars,
  youngest stars

bar strength

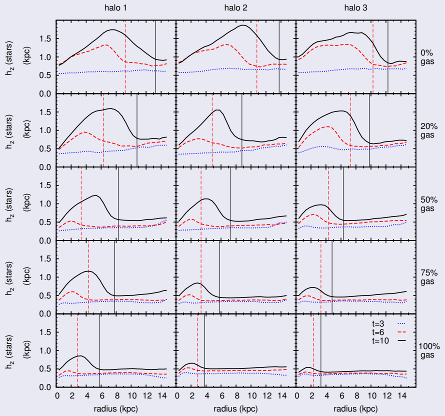


angular momentum

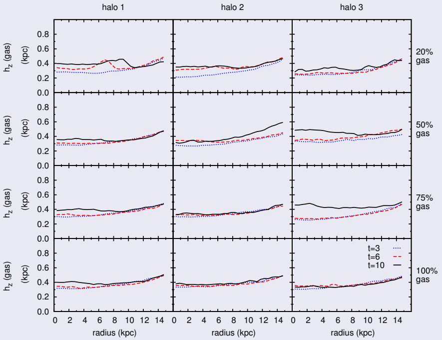


Disc vertical structure

stars

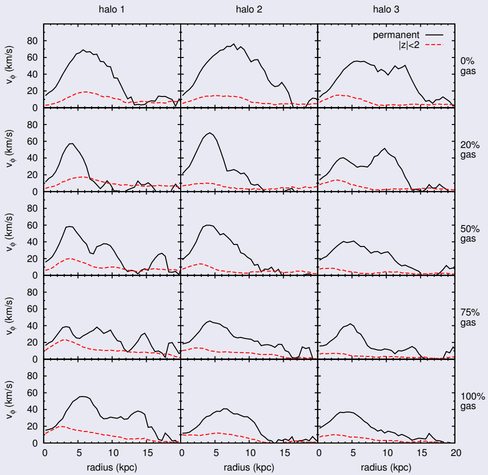


gas



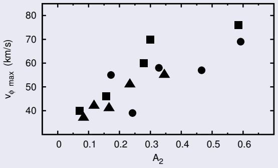
Halo kinematics: disc-like halo particles

tangential velocities



- peak tangential velocities correlated to bar strength

$v_\phi \times A_2$



Part IV

Summary and perspectives

Summary

1. circular discs are not adequate IC for triaxial haloes
2. halo is circularised in two phases:
   - during disc growth
   - during bar formation
3. in the absence of a bar the halo may remain triaxial

1. presence of gas inhibts strong bars more importantly than halo triaxiality
2. rotation of disc-like halo particles is more important in the spherical case and is correlated do bar strength
3. triaxial haloes retaint the anisotropy of their velocity dispersions even after being circularised

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Perspectives

1. Use models for statistical study of the orbits.
2. How do gas properties (SF, feedback, etc) affect the evolution?
3. So far we have only considered isolated galaxies. It would be interesting to study interactions with such models.
4. Similar work, but in a cosmologically-motivated setting.

the end