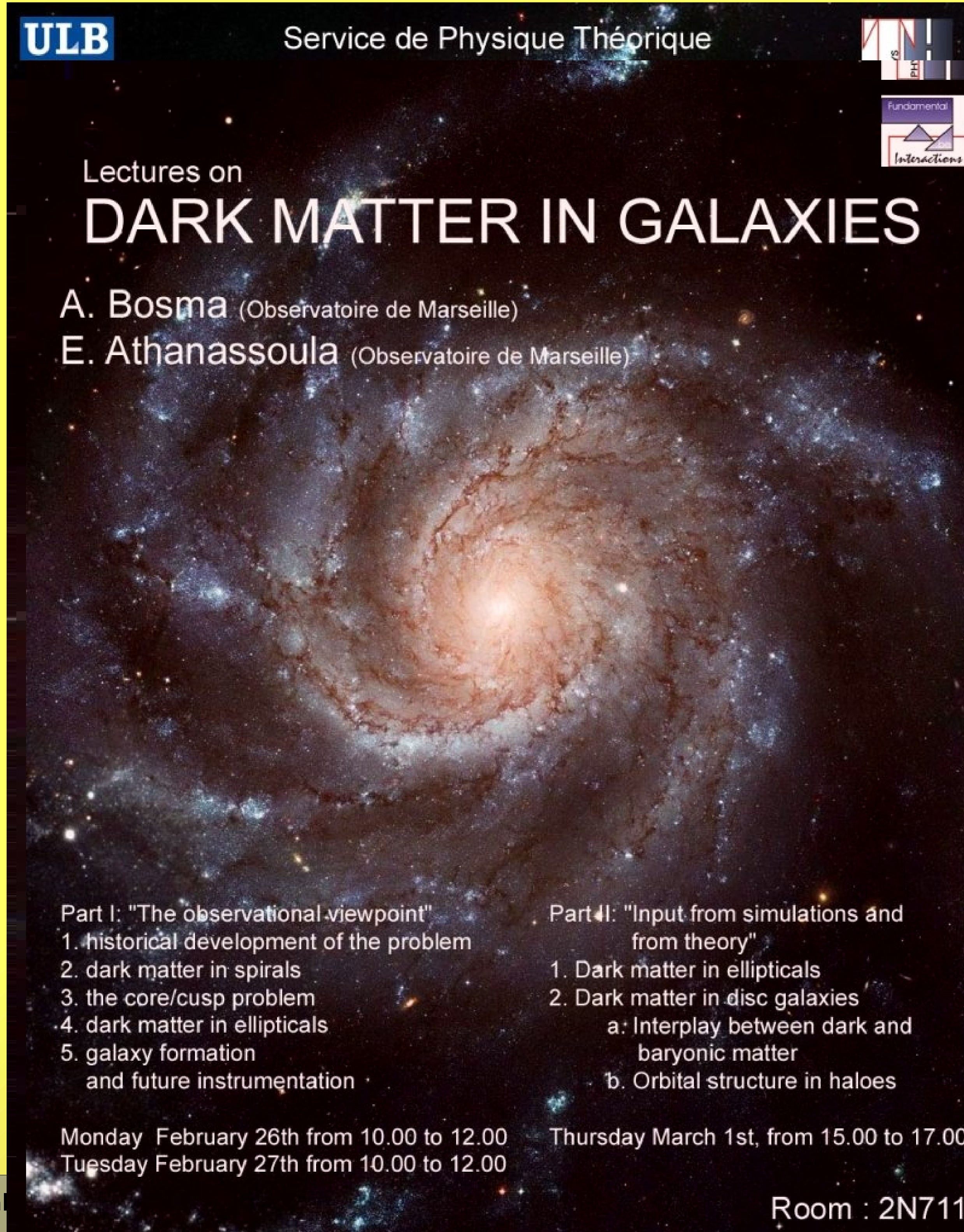

ULB
Service de Physique Théorique
Fundamental Interactions
Lectures on
DARK MATTER IN GALAXIES
A. Bosma (Observatoire de Marseille)
E. Athanassoula (Observatoire de Marseille)
Part I: "The observational viewpoint"
1. historical development of the problem
2. dark matter in spirals
3. the core/cusp problem
4. dark matter in ellipticals
5. galaxy formation
and future instrumentation
Part II: "Input from simulations and
from theory"
1. Dark matter in ellipticals
2. Dark matter in disc galaxies
a. Interplay between dark and
baryonic matter
b. Orbital structure in haloes
Monday February 26th from 10.00 to 12.00
Tuesday February 27th from 10.00 to 12.00
Thursday March 1st, from 15.00 to 17.00
Room : 2N711

Dark matter :

Theoretical input

E. Athanassoula

Observatoire de Marseille

Layout

- The importance of dynamics for Dark Matter studies
- N-bodies
- Dark matter in disc galaxies
- Dark matter in ellipticals
- Dark matter in groups and clusters
- Conclusions

Disc Galaxies

Some material, e.g. gas, or young stars, is on near-circular orbits

$$F = \frac{GM(r)}{R^2}$$

$$V_{circ}^2 = \frac{GM(r)}{R}$$

Elliptical galaxies

Hardly any material on circular orbits, so use the virial theorem

Schematically :

$$2K + W = 0$$

$$K = 0.5M < v^2 >$$

K is the kinetic energy

$$W$$

W is the potential energy

$$< v^2 > = |W|/M = GM/r_g \simeq 0.4GM/r_h$$

rh is the median radius

In practice : Use a model and constraints from both photometry and kinematics
Also use radial profile information

Galactic dynamics

Equation de Boltzmann $\qquad f(x, v, t)$

$$d_t f = \partial_t f + v\partial_x f - \partial_x \Phi \cdot \partial_v f = 0$$

Equation de Poisson

$$\partial_x^2 \Phi(x,t) = 4\pi G \int f(x,v) d^3 v$$

$$\rho(x) \longleftrightarrow \sum_i m_i$$

N corps

Boucle sur le temps

N-bodies

Boucle sur le temps

Calcul du potential et de la force

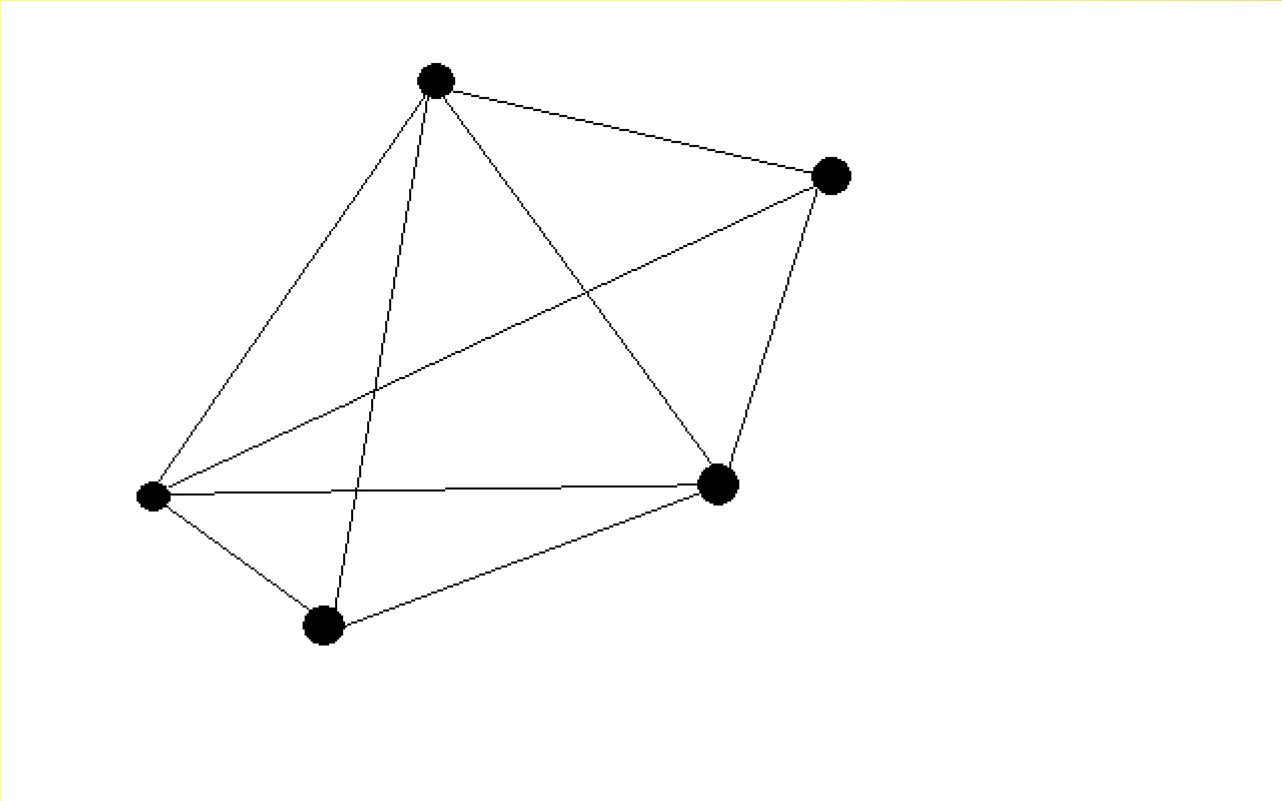
$$\mathbf{F}_i = G m_i \sum_{j \neq i}^{N} \frac{m_j(\mathbf{x}_j - \mathbf{x}_i)}{(|\mathbf{x}_i - \mathbf{x}_j|^2 + \epsilon^2)^{1.5}}$$

$$\Phi_i = G m_i \sum_{j \neq i}^{N} \frac{m_j}{(|\mathbf{x}_i - \mathbf{x}_j|^2 + \epsilon^2)^{0.5}}$$

Resoudre les equations du mouvement

$$d_t^2 x_i = -\partial_x \Phi(x_i, t)$$

Direct summation



N (N - 1)

O(N2)

Why use N-body simulations ?

Complementary to analytical approach (Analytical work is only possible in oversimplified cases, but provides good insight)

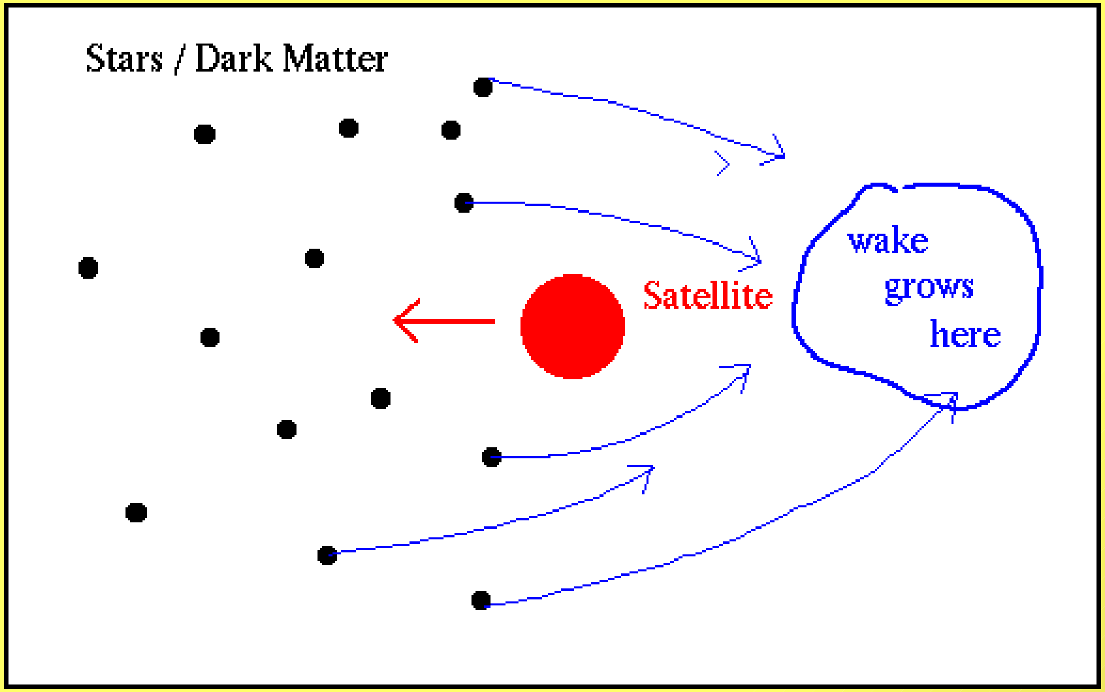
Allows to follow evolution with time

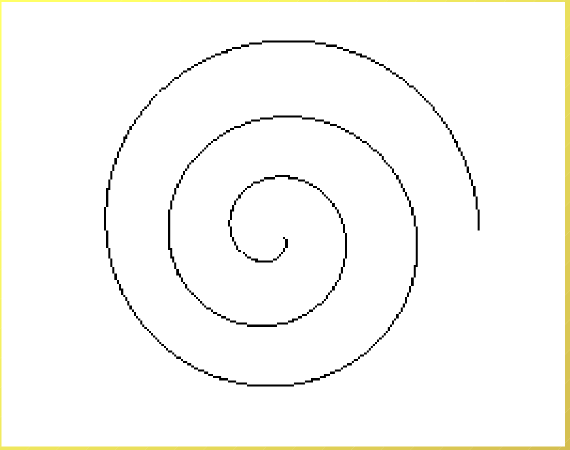
Allows to see interactions between stars, gas and dark matter. Also interactions between different components, or between components and substrucure

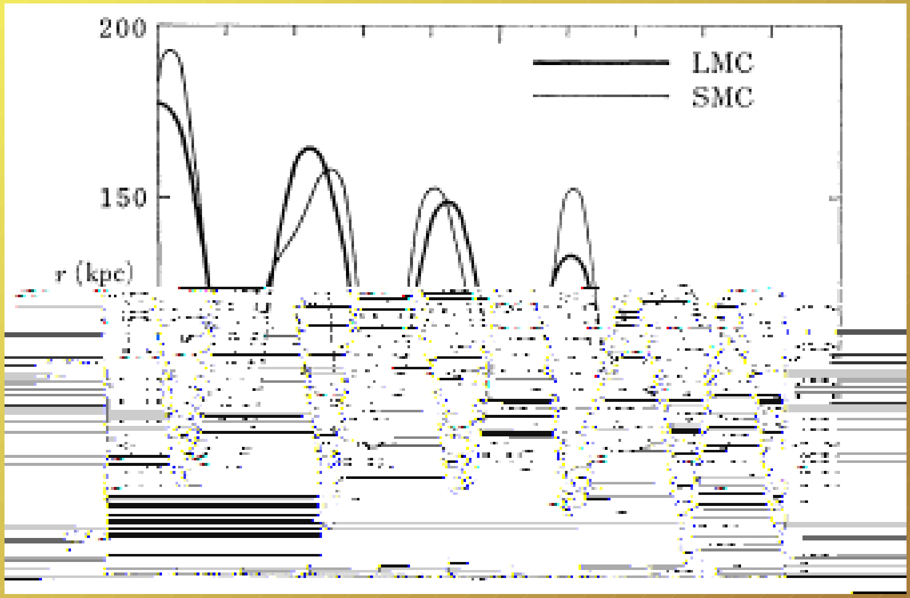
Progress in both computer hardware and in software allow now models which are sufficiently realistic :

to set constraints on the halo

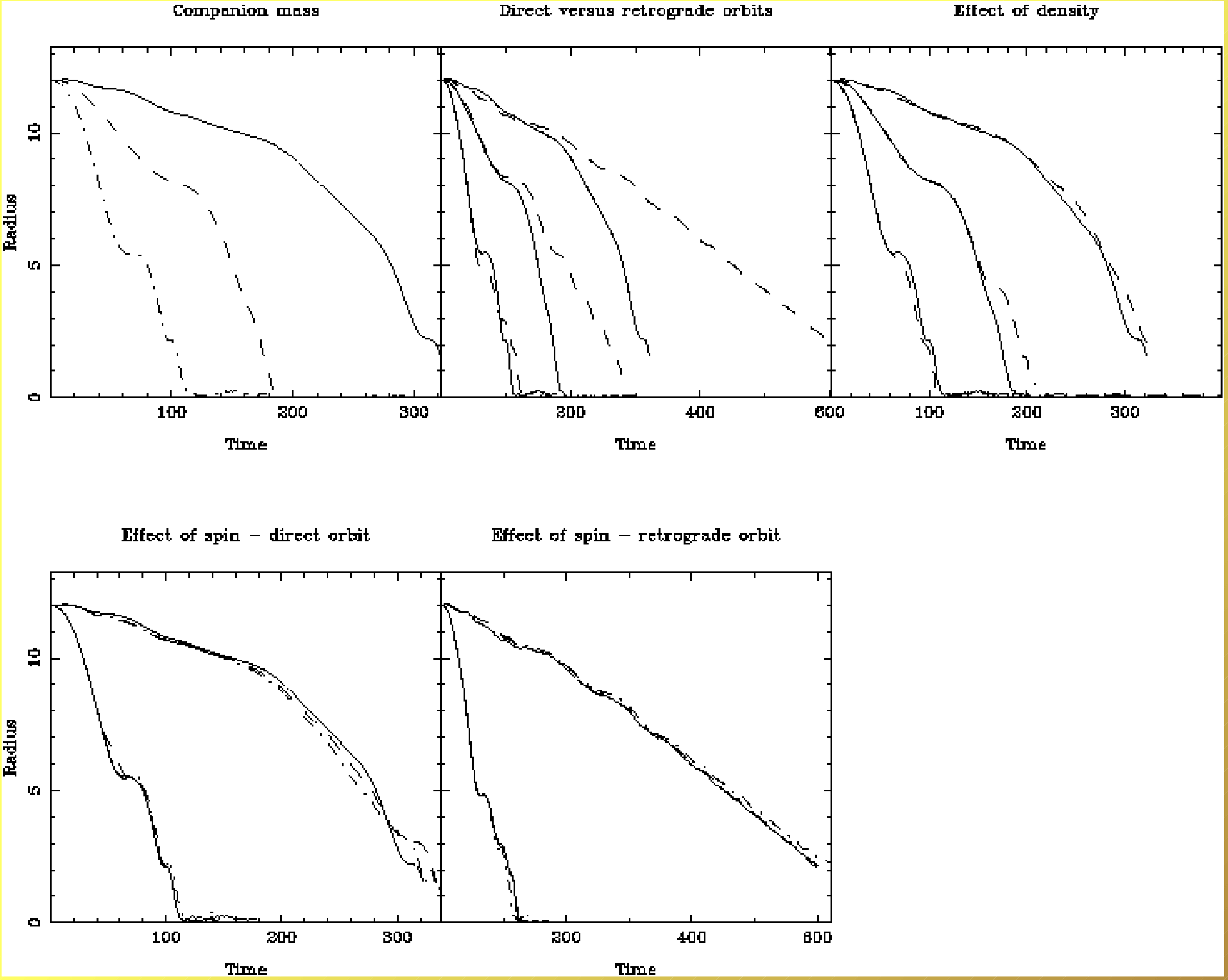
to be compared with observations (observations give only 2D spatial information, only 1D in velocity, and , for an individual object, no information on the time evolution)







Murai & Fujimoto (1980)



Companion mass
Direct versus retrograde orbits
Effect of density
Effect of spin – direct orbit
Effect of spin – retrograde orbit
Radius
Time

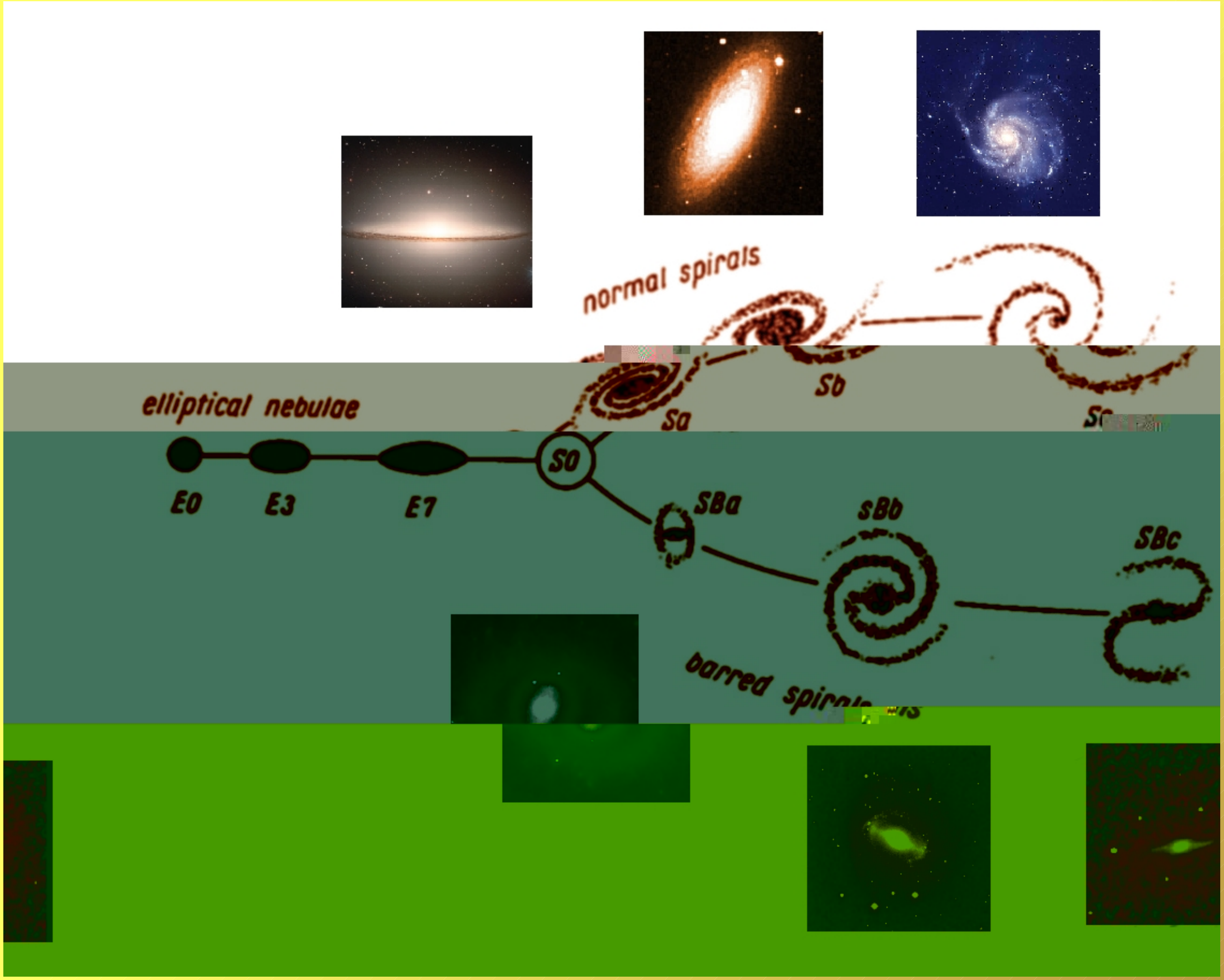
Depends on :

Halo density
Mass of the satellite
Relative velocity

Constraints from :

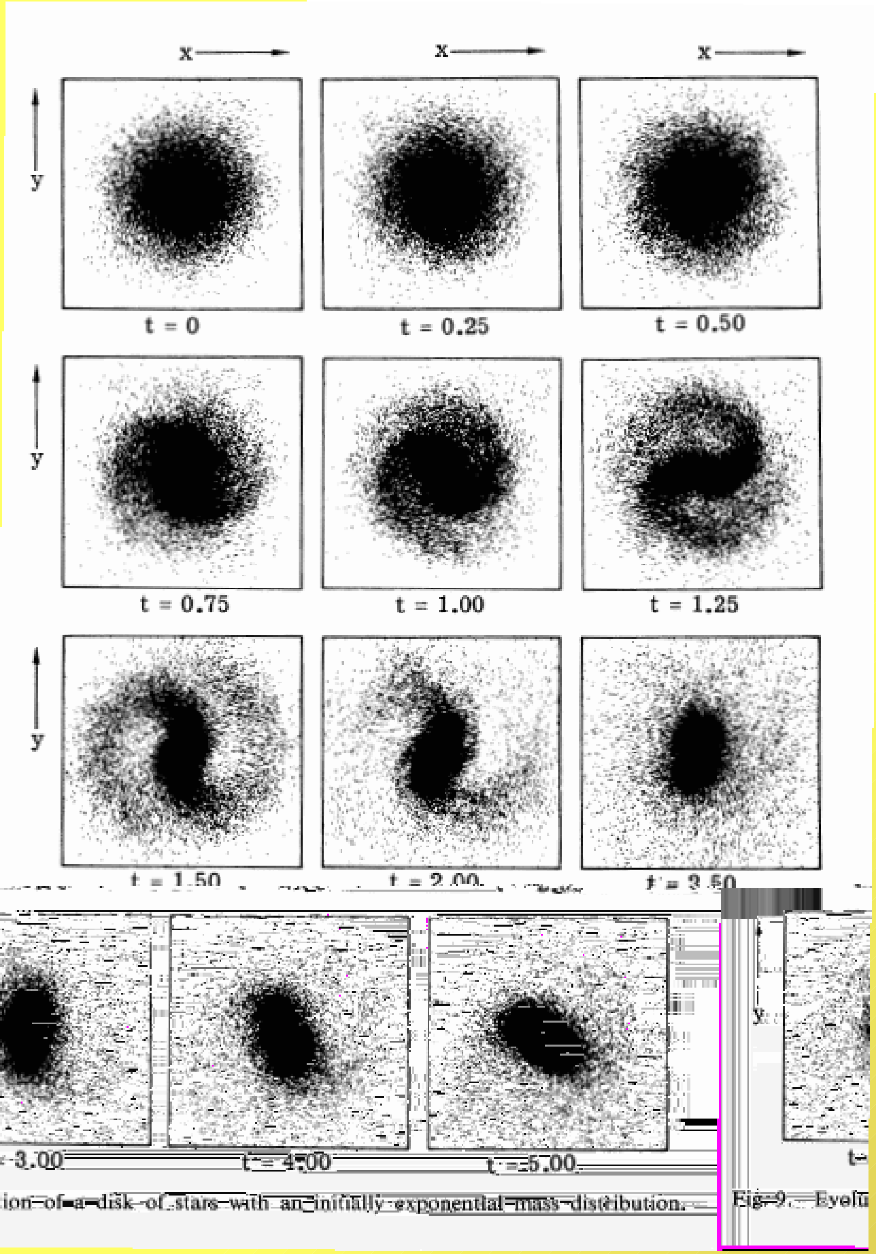
Satellite luminosity
Satellite velocity (LOS)
Past trajectory (movie)

Hubble classification



Bar galaxies

The first N-body simulations



A self-gravitating disc is bar unstable, and the bar is very robust

Miller, Prendergast and Quirk (1970)

Hohl (1971)

Dark halo : needed ?

Ostriker & Peebles (1973)

A NUMERICAL STUDY OF THE STABILITY OF FLATTENED GALAXIES: OR, CAN COLD GALAXIES SURVIVE?*

J. P. OSTRIKER
Princeton University Observatory

AND

P. J. E. PEEBLES
Joseph Henry Laboratories, Princeton University
Received 1973 May 29

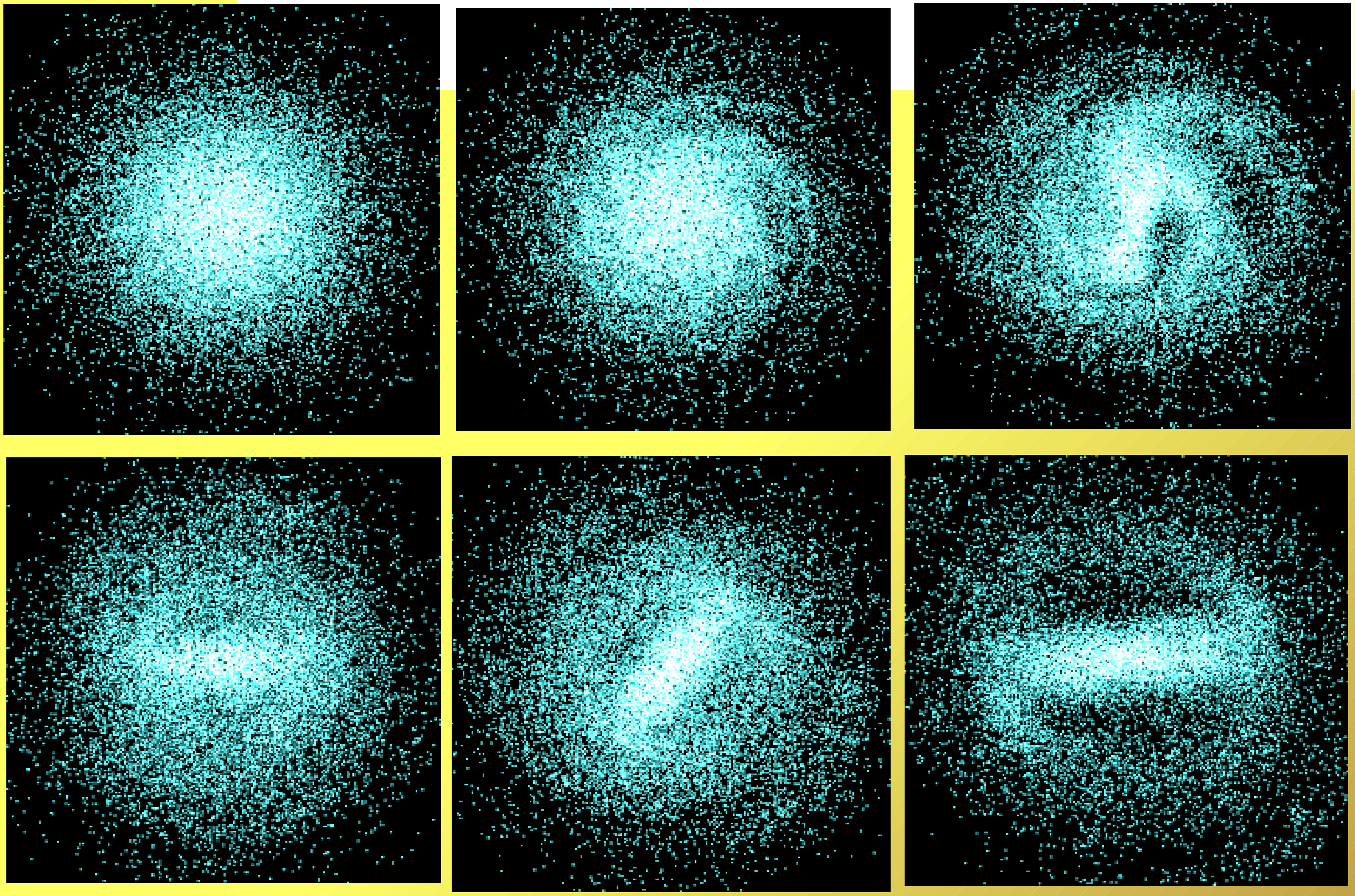
ABSTRACT

To study the stability of flattened galaxies, we have followed the evolution of simulated galaxies containing 150 to 500 mass points. Models which begin with characteristics similar to the disk of our Galaxy (except for increased velocity dispersion and thickness to assure local stability) were found to be rapidly and grossly unstable to barlike modes. These modes cause an increase in random kinetic energy, with approximate stability being reached when the ratio of kinetic energy of rotation to total gravitational energy, designated t, is reduced to the value of 0.14 ± 0.02. Parameter studies indicate that the result probably is not due to inadequacies of the numerical N-body simulation method. A survey of the literature shows that a critical value for limiting stability $t \simeq 0.14$ has been found by a variety of methods.

Models with added spherical (halo) component are more stable. It appears that halo-to-disk mass ratios of 1 to $2\frac{1}{2}$, and an initial value of $t \simeq 0.14 \pm 0.03$, are required for stability. If our Galaxy (and other spirals) do not have a substantial unobserved mass in a hot disk component, then apparently the halo (spherical) mass *interior* to the disk must be comparable to the disk mass. Thus normalized, the halo masses of our Galaxy and of other spiral galaxies *exterior* to the observed disks may be extremely large.

* Supported in part by the National Science Foundation.

Time evolution
Face-on view



Resonances and angular momentum exchange

Angular momentum exchange drives the dynamical evolution of barred galaxies

Absorption/Emission occurs principally at resonances

inner disc (bar) -------------------> outer disc

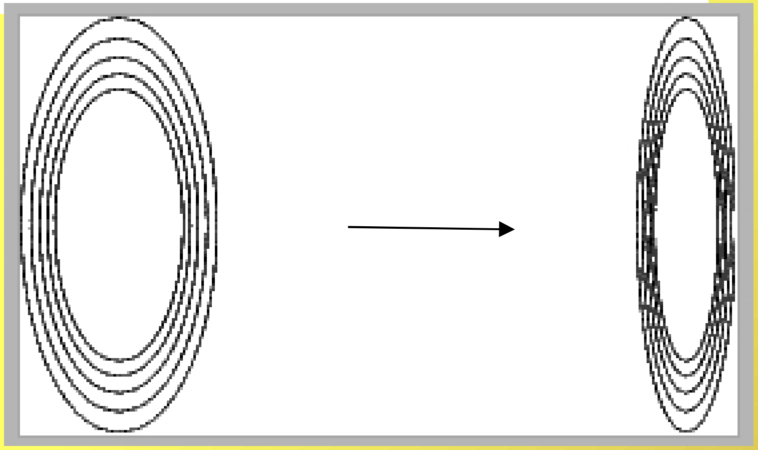
Lynden-Bell and Kalnajs 1972

inner disc (bar) -------------------> outer disc + halo

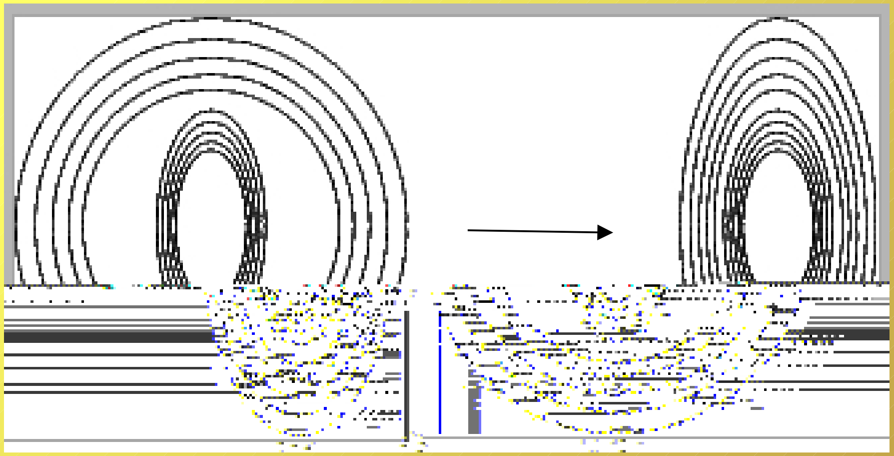
Athanassoula 2002, 2003, 2004

Angular momentum lost by the bar : how ?

- orbits become thinner



- bar traps stars which where on near-circular orbits around it, into its outer parts



- bar rotates slower

Resonances and angular momentum exchange

Angular momentum exchange drives the dynamical evolution of barred galaxies

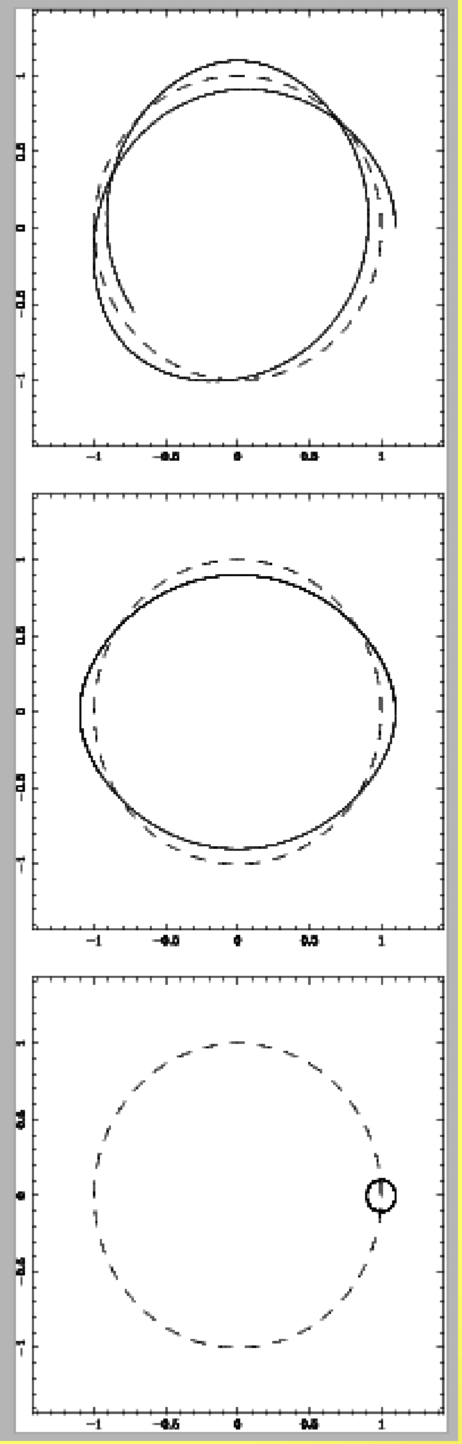
Absorption/Emission occurs principally at resonances

inner disc (bar) -------------------> outer disc

Lynden-Bell and Kalnajs 1972

inner disc (bar) -------------------> outer disc + halo

Athanassoula 2002, 2003, 2004



$\Omega - \Omega_p$ Angular frequency

κ Epicyclic frequency

$\frac{(\Omega - \Omega_p)}{\kappa}$ = ½ Inner Lindblad resonance

$\Omega = \Omega_p$ Corotation resonance

Analytical predictions

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

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

The bar is a negative angular momentum feature (Kalnajs 1970, Lynden-Bell & Kalnajs 1972). As it loses angular momentum

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

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

Analytical work :
Athanassoula (2002, 2003, 2005), Fuchs (2004), Fuchs & Athanassoula (2005), Kalnajs (1970), Lynden-Bell & Kalnajs (1972), Tremaine & Weinberg (1985), Weinberg (1985, 2004).

N-body simulations

± High resolution simulations

± 1 to 10 million particles

± ~500 simulations

Analytical predictions

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

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

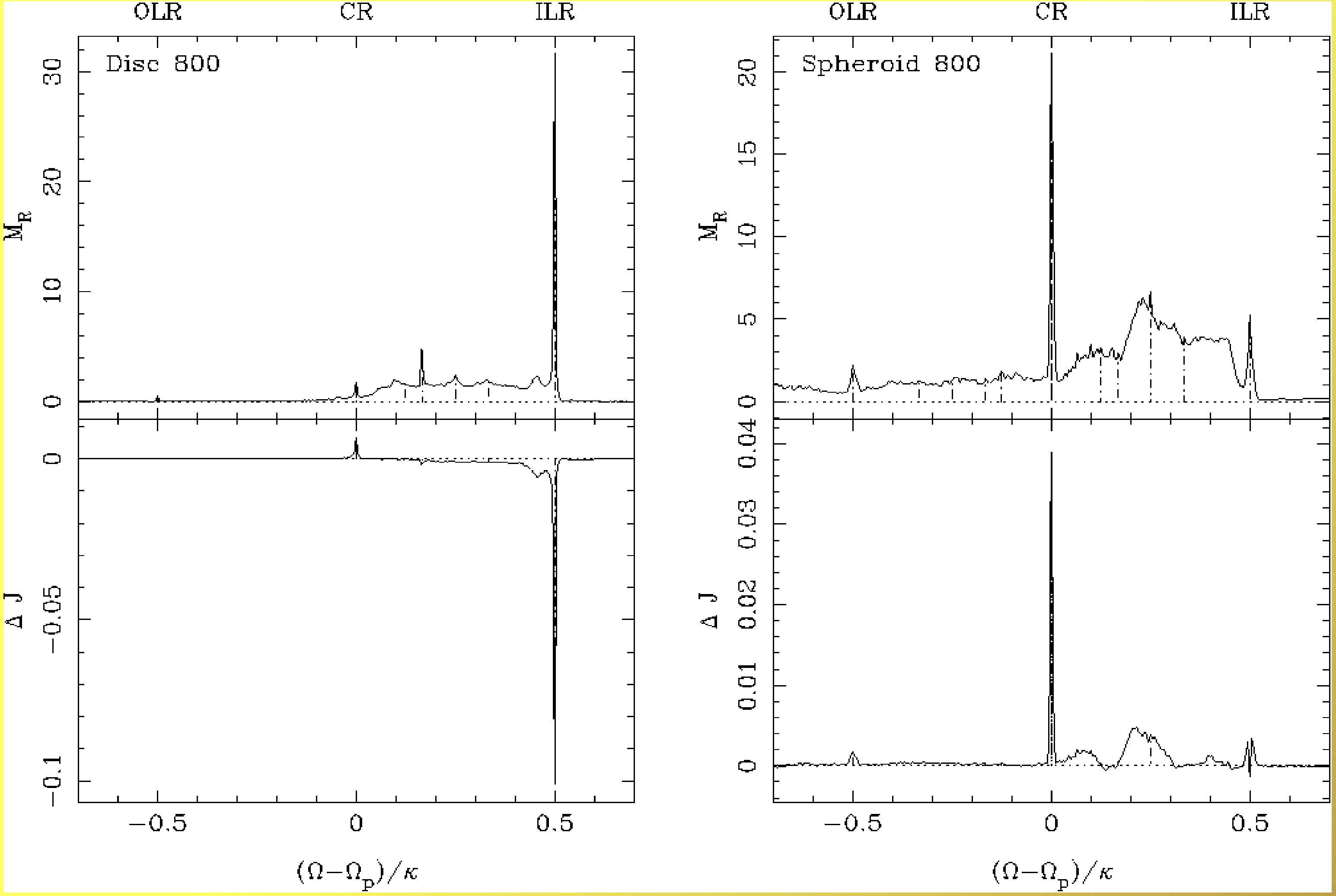
The bar is a negative angular momentum feature (Kalnajs 1970, Lynden-Bell & Kalnajs 1972). As it loses angular momentum
- it will grow stronger
- it will slow down (i.e. its pattern speed decreases)

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

Analytical work :
Athanassoula (2002, 2003, 2005), Fuchs (2004), Fuchs & Athanassoula (2005), Kalnajs (1970), Lynden-Bell & Kalnajs (1972), Tremaine & Weinberg (1985), Weinberg (1985, 2004).

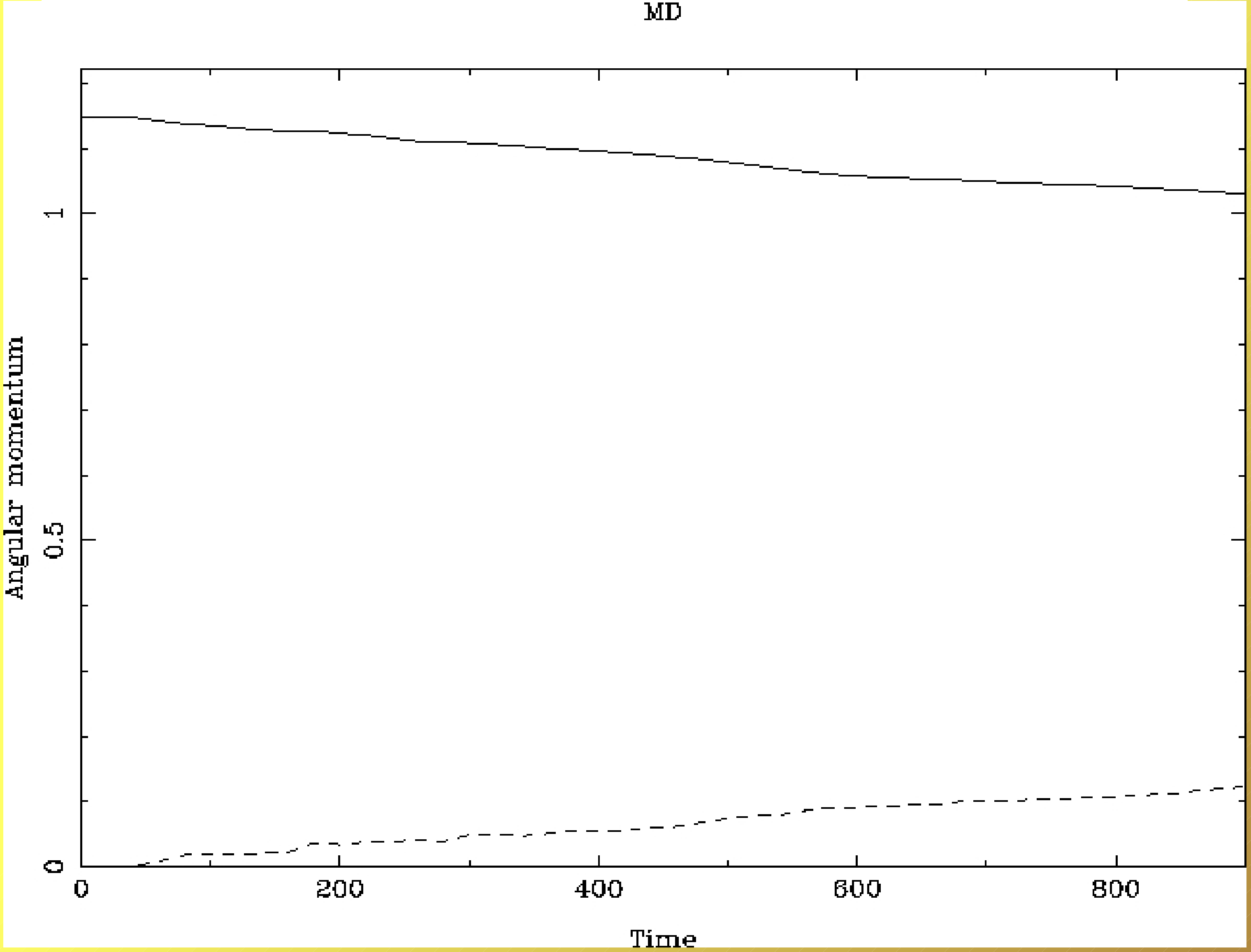
Emitters and absorbers

Example from a strong bar case Athanassoula 2003



Angular momentum transfer

in disc



in halo

Analytical predictions

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

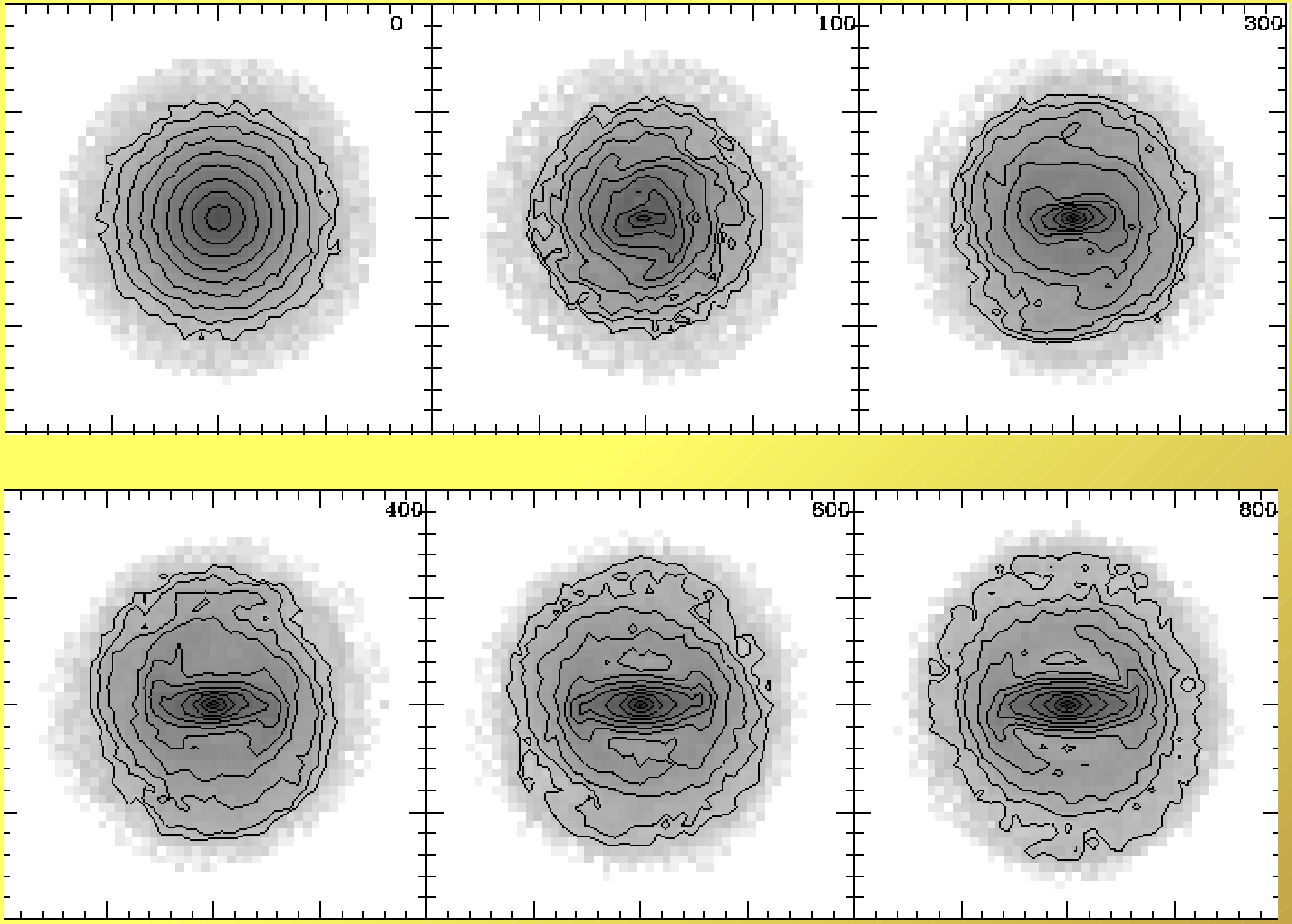
Absorbers : (principally material at near-resonance in the) outer disc and in the halo

The bar is a negative angular momentum feature (Kalnajs 1970, Lynden-Bell & Kalnajs 1972). As it loses angular momentum
- it will grow stronger
- it will slow down (i.e. its pattern speed decreases)

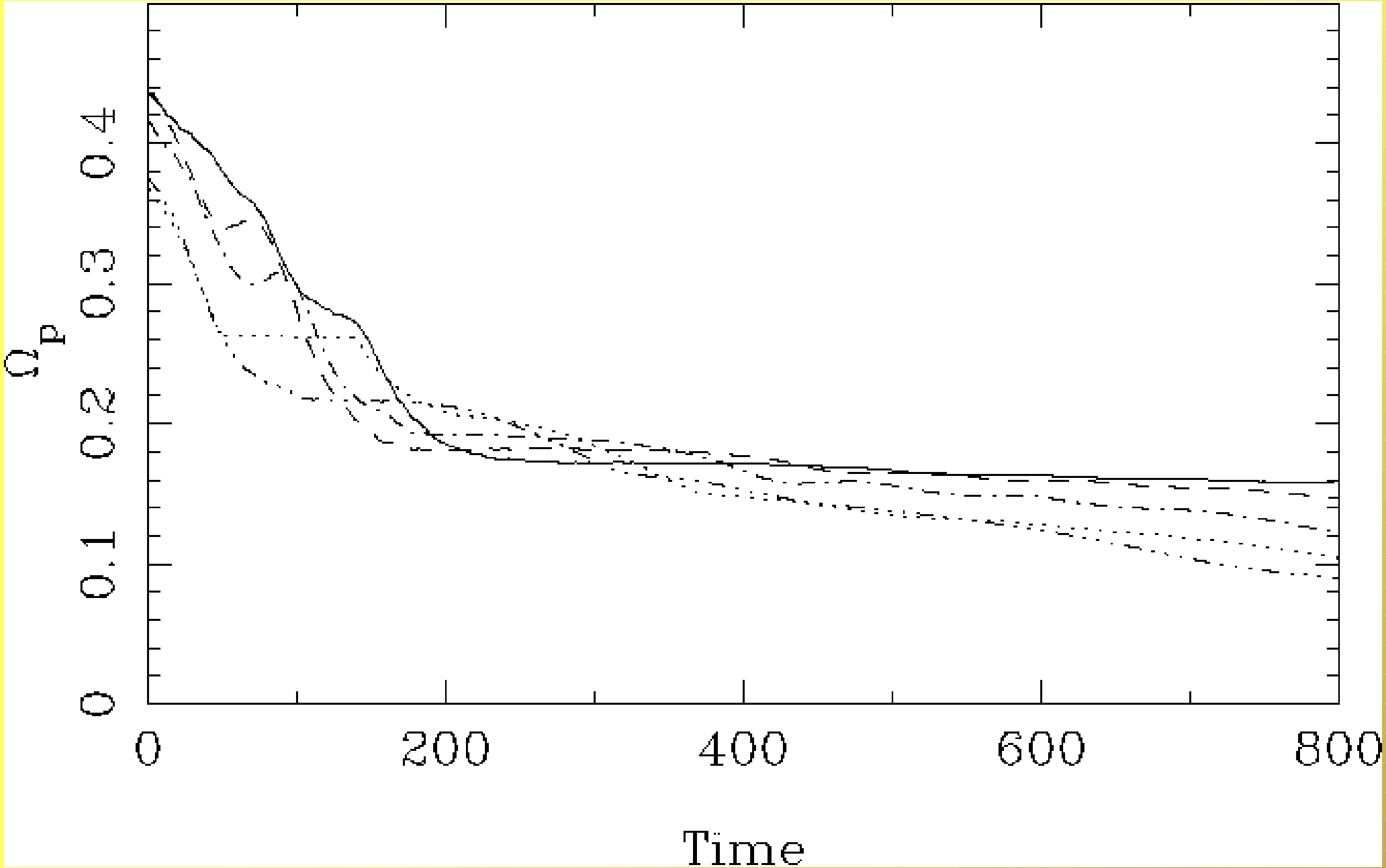
Both for the disc and the halo, there is more angular momentum gained/lost at a given resonance if :
- the density is higher there
- the resonant material is colder

Analytical work :
Athanassoula (2002, 2003, 2005), Fuchs (2004), Fuchs & Athanassoula (2005), Kalnajs (1970), Lynden-Bell & Kalnajs (1972), Tremaine & Weinberg (1985), Weinberg (1985, 2004).

Bar strength increases with time



Pattern speed decreases with time



Analytical predictions

Emitters : (principally material at near-resonance in the) inner disc
Absorbers : (principally material at near-resonance in the) outer disc and in the halo

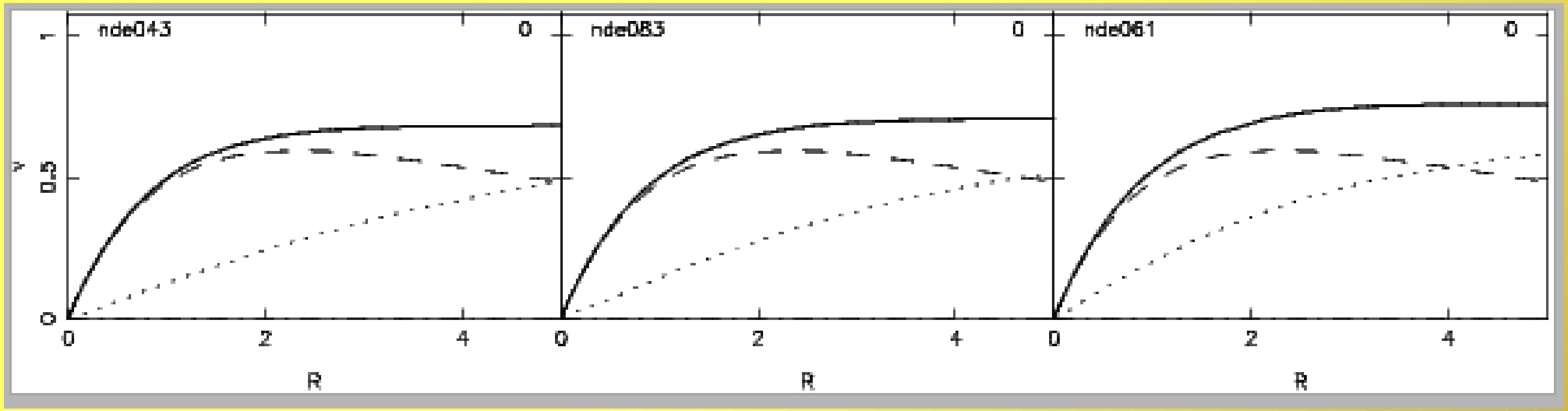
The bar is a negative angular momentum feature (Kalnajs 1970, Lynden-Bell & Kalnajs 1972). As it loses angular momentum
- it will grow stronger
- it will slow down (i.e. its pattern speed decreases)

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

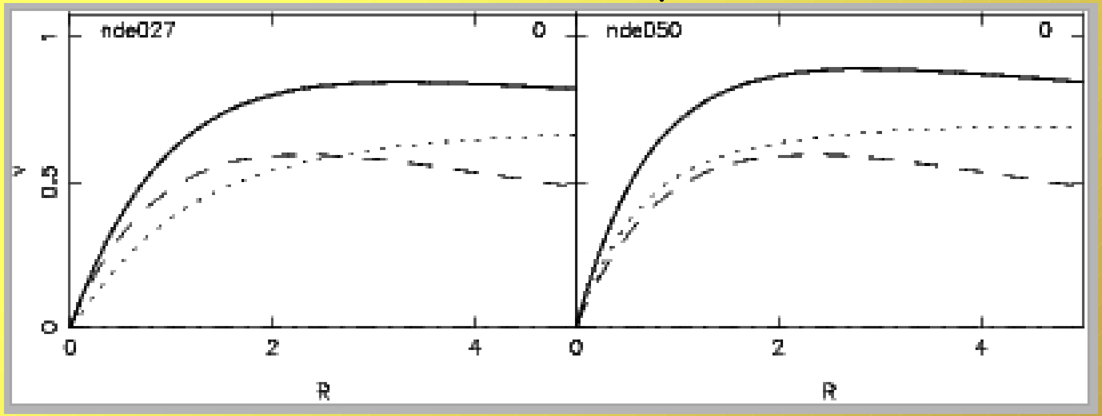
Analytical work :
Athanassoula (2002, 2003, 2005), Fuchs (2004), Fuchs & Athanassoula (2005), Kalnajs (1970), Lynden-Bell & Kalnajs (1972), Tremaine & Weinberg (1985), Weinberg (1985, 2004).

A series of haloes with different central concentrations

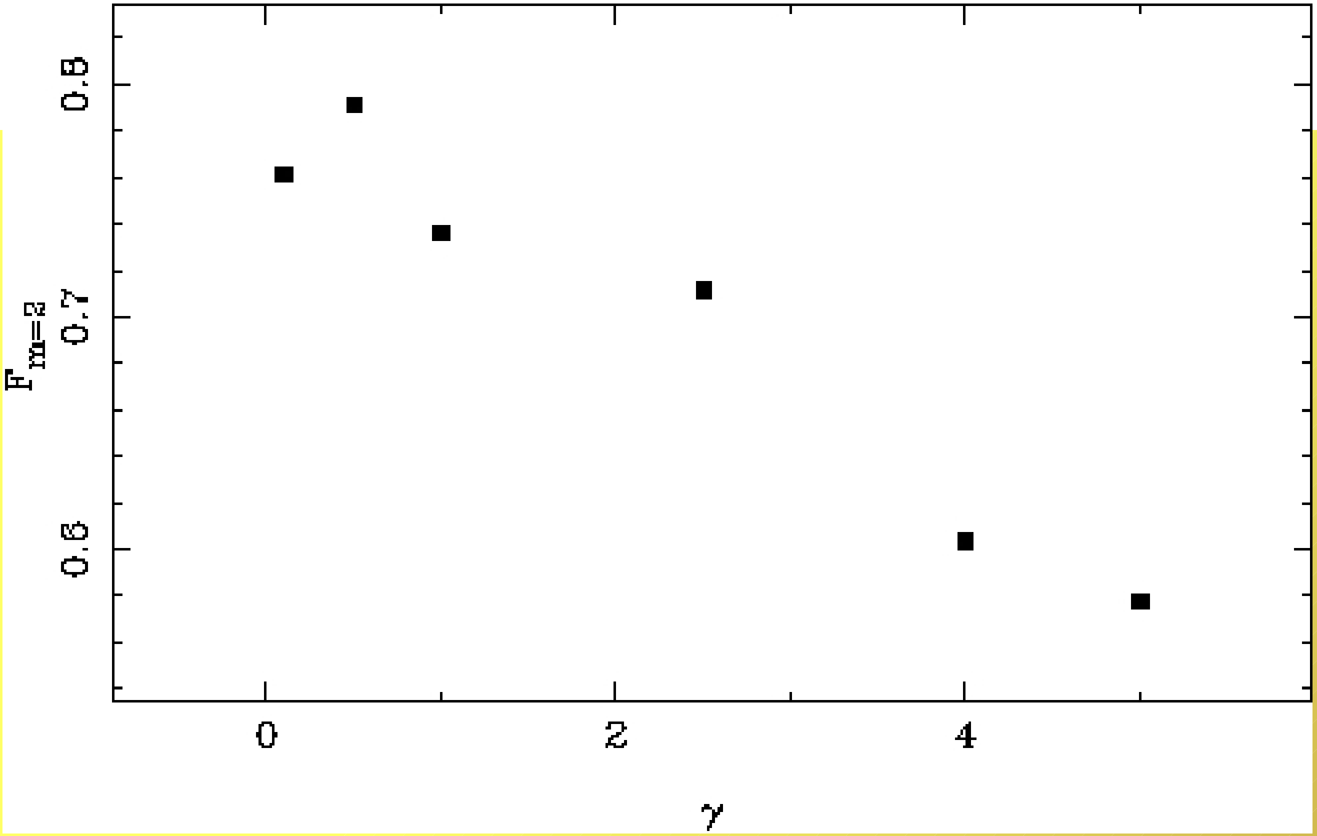
$\gamma = 5.$ $\gamma = 4.$ $\gamma = 2.5$



$\gamma = 1.$ $\gamma = 0.5$

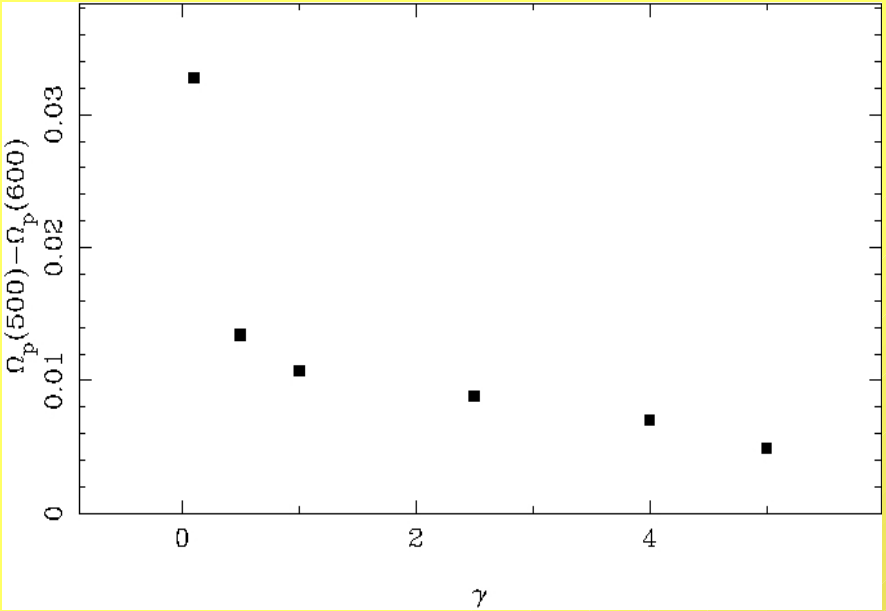


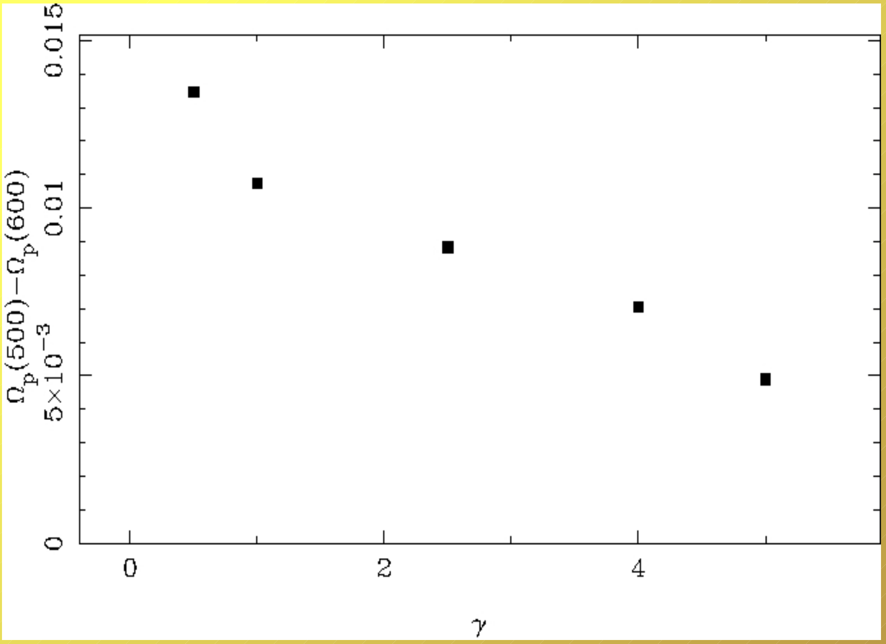
Bar strength



The stronger the halo, the more angular momentum it can absorb, i.e. take away from the bar, the stronger the bar will grow.

Bar slow down





Also : Little and Carlberg 1991, Hernquist and Weinberg 1992, Athanassoula 1966, Debattista and Sellwood 2000, Athanassoula 2003, O'Neill and Dubinski 2003, Valenzuela and Klypin 2003, Holley-Bochelmann and Katz 2004

Analytical predictions

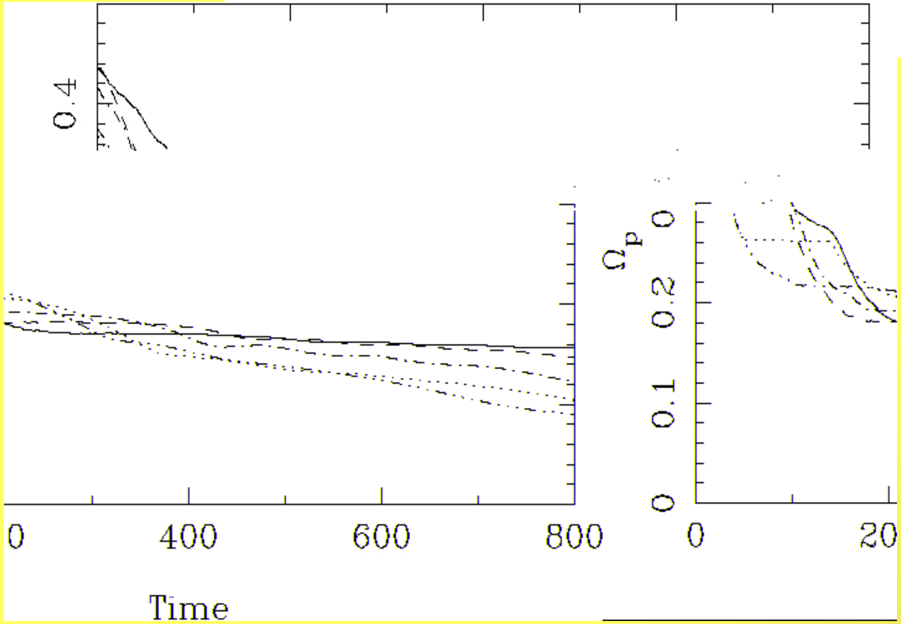
Emitters : (principally material at near-resonance in the) inner disc
Absorbers : (principally material at near-resonance in the) outer disc and in the halo

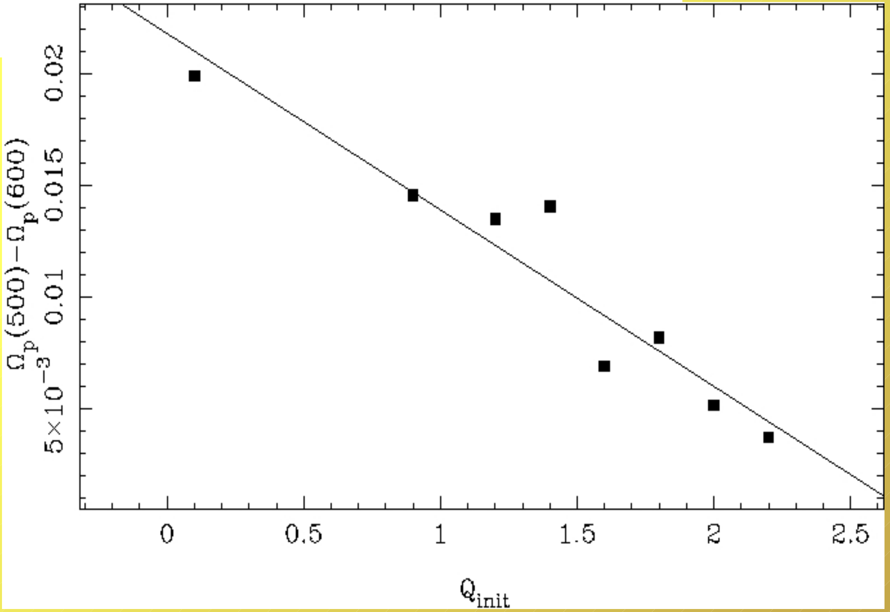
The bar is a negative angular momentum feature (Kalnajs 1970, Lynden-Bell & Kalnajs 1972). As it loses angular momentum
- it will grow stronger
- it will slow down (i.e. its pattern speed decreases)

Both for the disc and the halo, there is more angular momrntum gained/lost at a given resonance if :
- the density is higher there
- the resonant material is colder

Analytical work :
Athanassoula (2002, 2003, 2005), Fuchs (2004), Fuchs & Athanassoula (2005), Kalnajs (1970), Lynden-Bell & Kalnajs (1972), Tremaine & Weinberg (1985), Weinberg (1985, 2004).

Velocity dispersion of the disc component

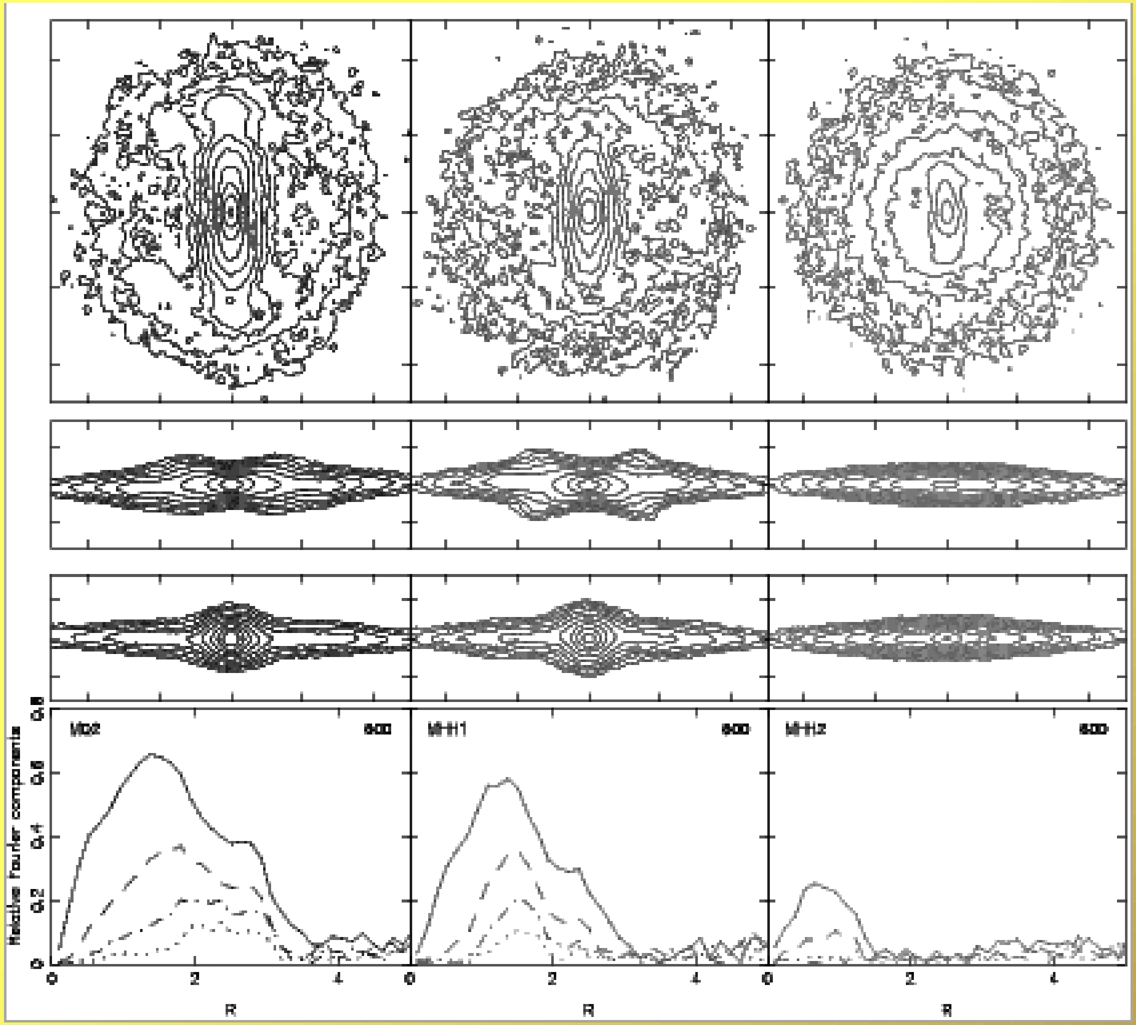




Bars formed in discs which were initially colder are slowing down more

Velocity dispersion of the halo component

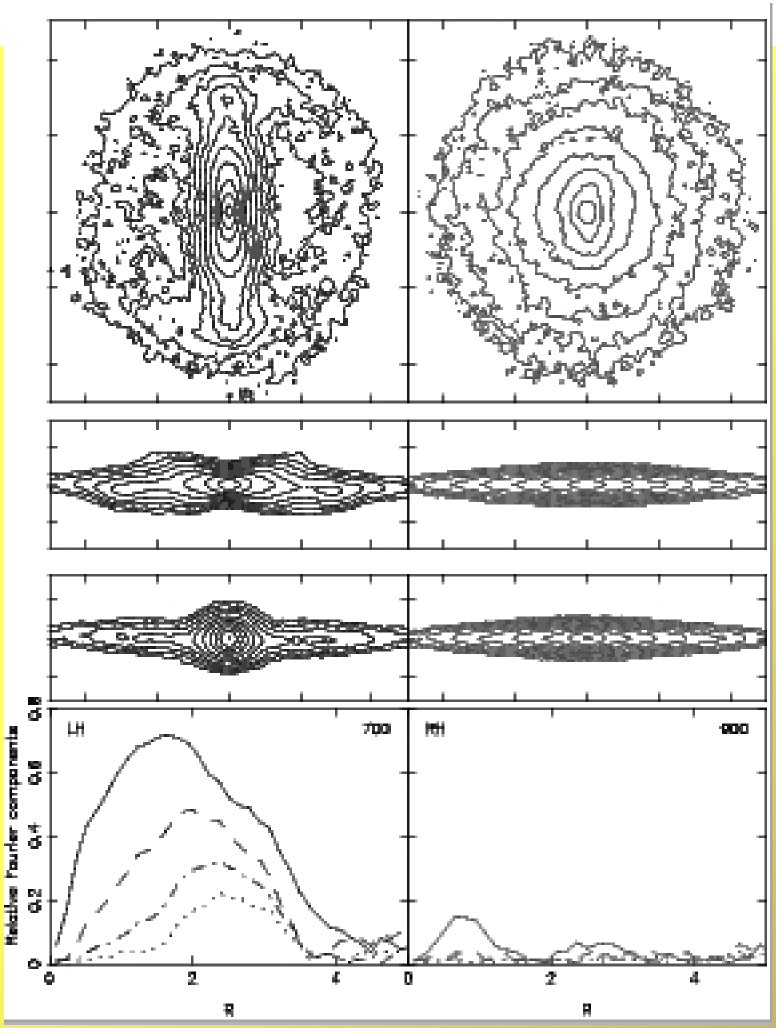
cool hot



Live versus rigid halo

Live halo

Halo can receive angular momentum



Rigid halo

Halo can not receive angular momentum

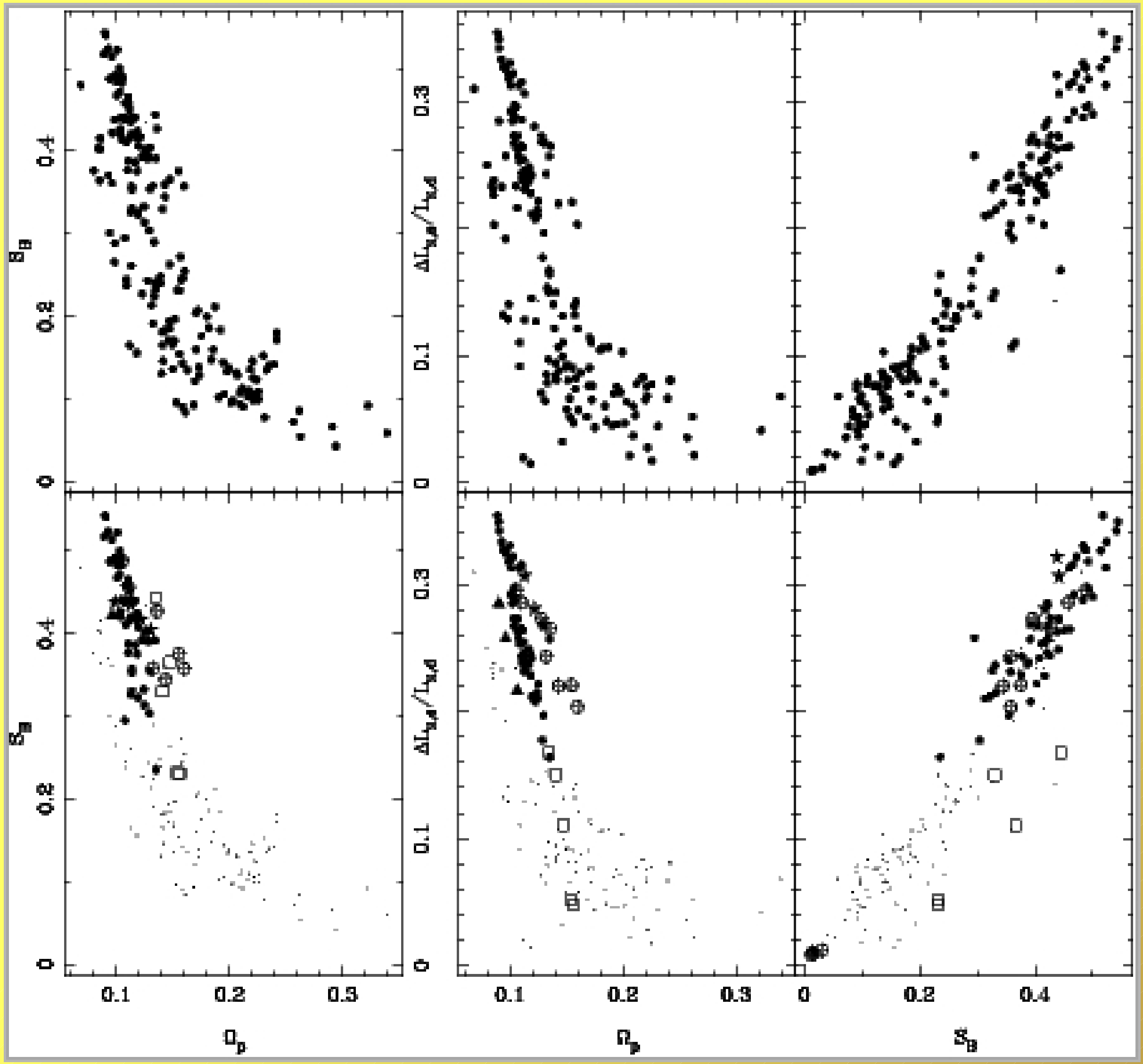
Evolution

The evolution rate (rate at which the bar strength increases and at which the pattern speed decreases) depends on :

- the amount of material ready to emit/absorb angular momentum.
- how hot the disc is
- how hot the halo is

In isolated galaxies, there should be as much material absorbed as emitted. So the halo should be strong, but not beyond a limit.
In interacting systems, angular momentum can be given to the companion. So bars can grow stronger in such systems.

Basic correlations



MD & MH-type models

Stronger bars

Longer, thinner and more massive

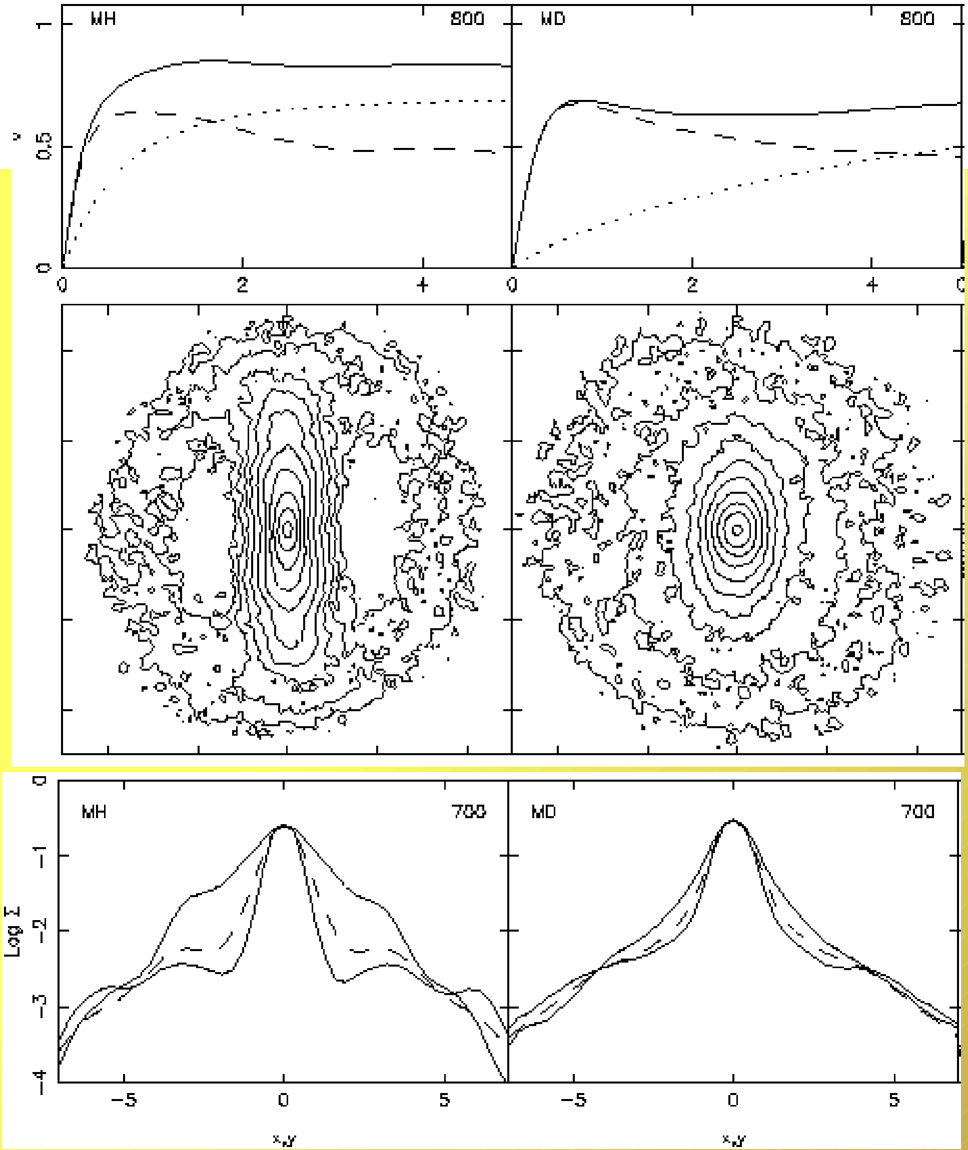
Often ansae

Flat radial density profiles (Elmegreen & Elmegreen 1985)

Rectangular-like isodensity contours

Strong m = 2 and strong relative m = 4, 6, 8 Fourier components

Peanuts when seen edge-on



Athanassoula & Misiriotis 2002

Less strong bars

Fatter

Never ansae

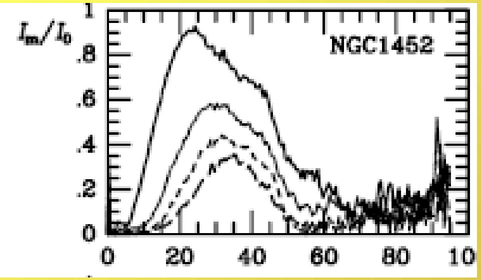
Exponential-like radial density profiles (E&E 85)

Elliptical-like isodensity contours

m = 6 and 8 Fourier components in the noise

Boxy edge-on shape

2D Fourier analysis

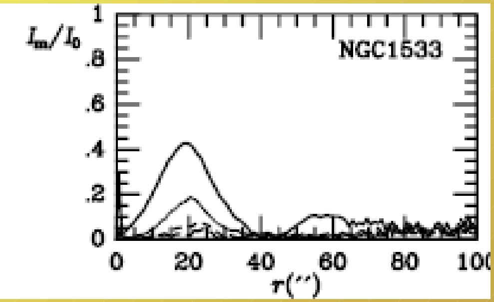


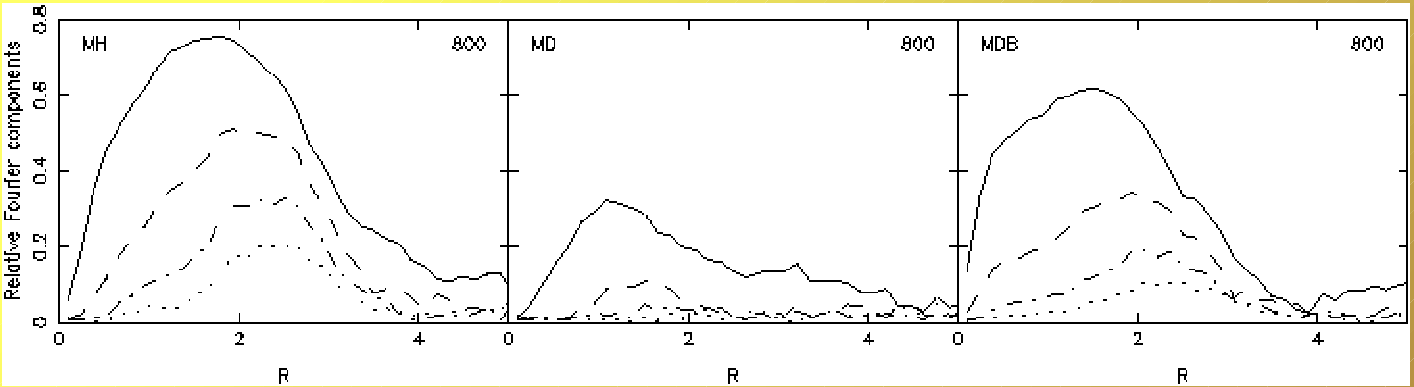
$$A_m(r) = \frac{1}{\pi}\int_0^{2\pi} \Sigma(r,\theta) cos(m\theta) d\theta, \qquad m = 0, 1, 2, ... \qquad (1)$$

and

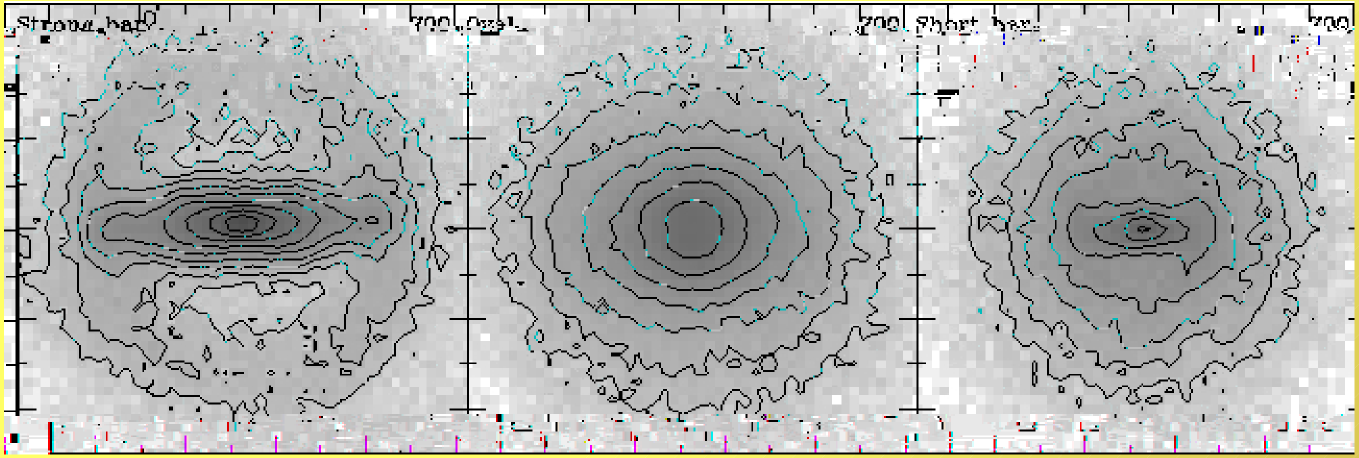
$$B_m(r) = \frac{1}{\pi}\int_0^{2\pi} \Sigma(r,\theta) sin(m\theta) d\theta, \qquad m = 1, 2, ... \qquad (2)$$

$$\sqrt{A_m^2 + B_m^2}/A_0 \qquad (3)$$





Bar morphology



Considerable amount of angular momentum is exchanged

Little angular momentum exchanged

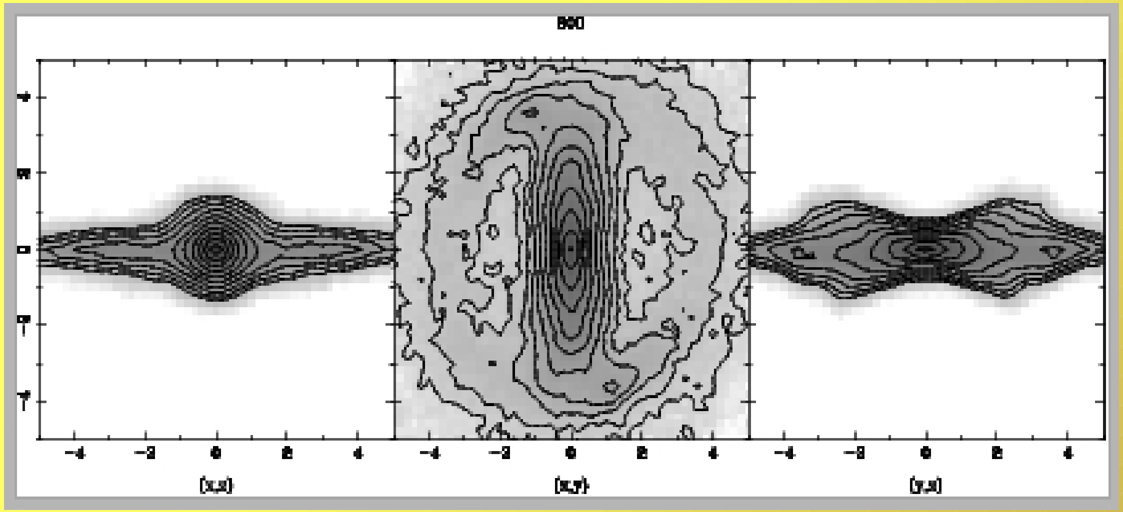
Responsive halo

Hot halo

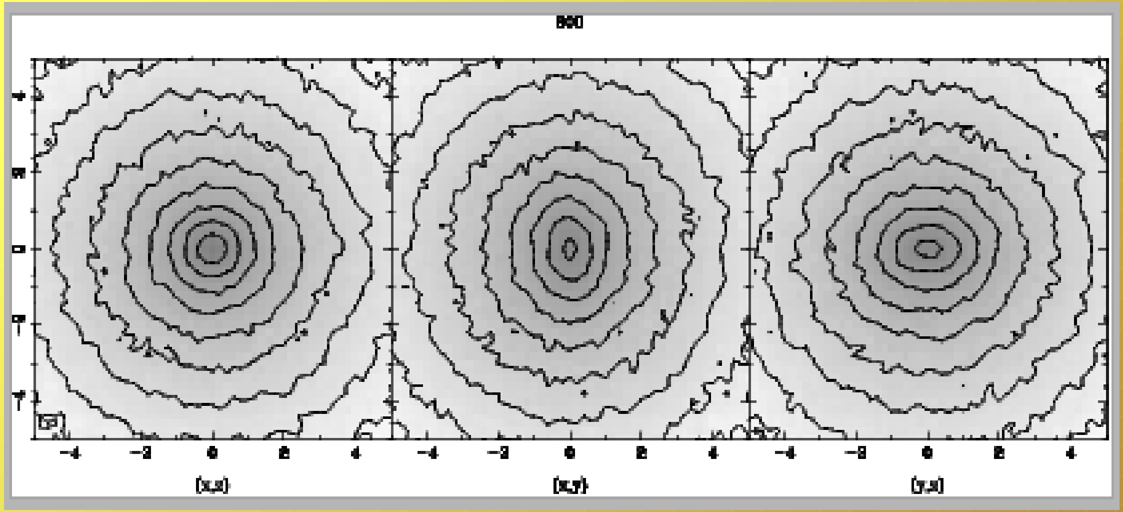
Hot outer disc

A bar in the halo

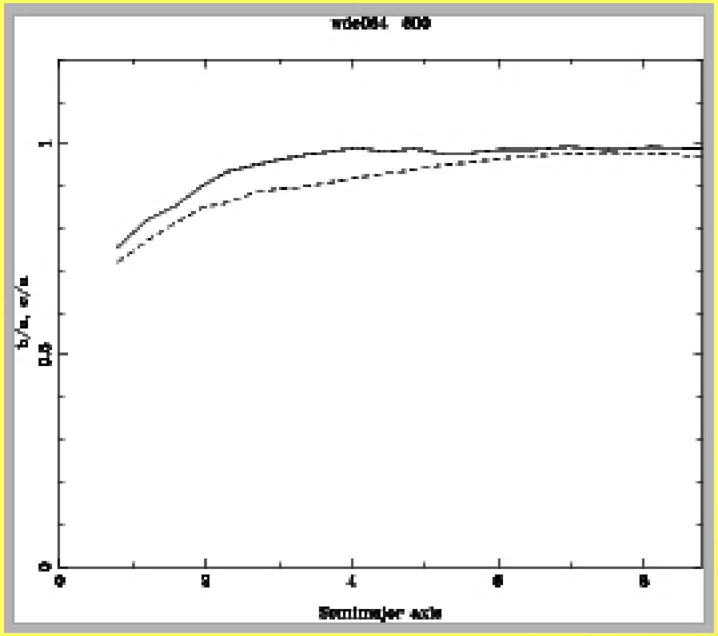
disc

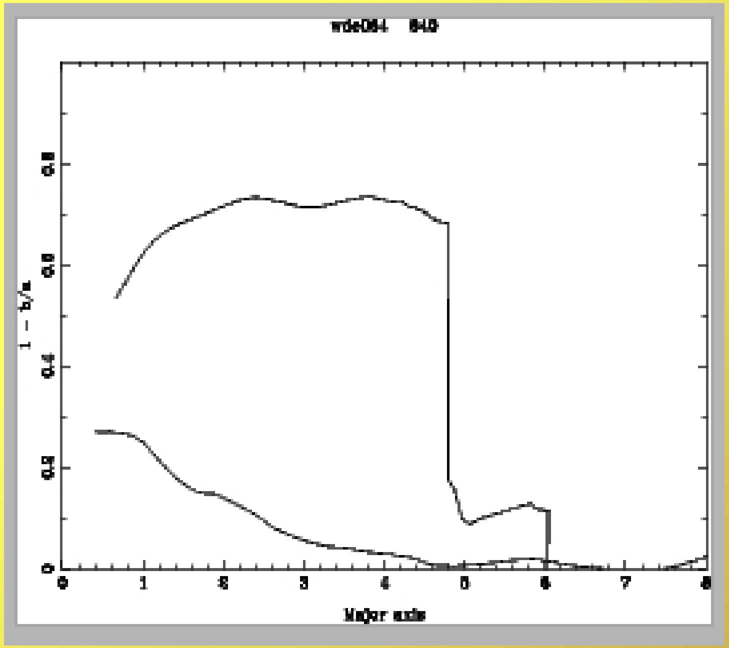


halo

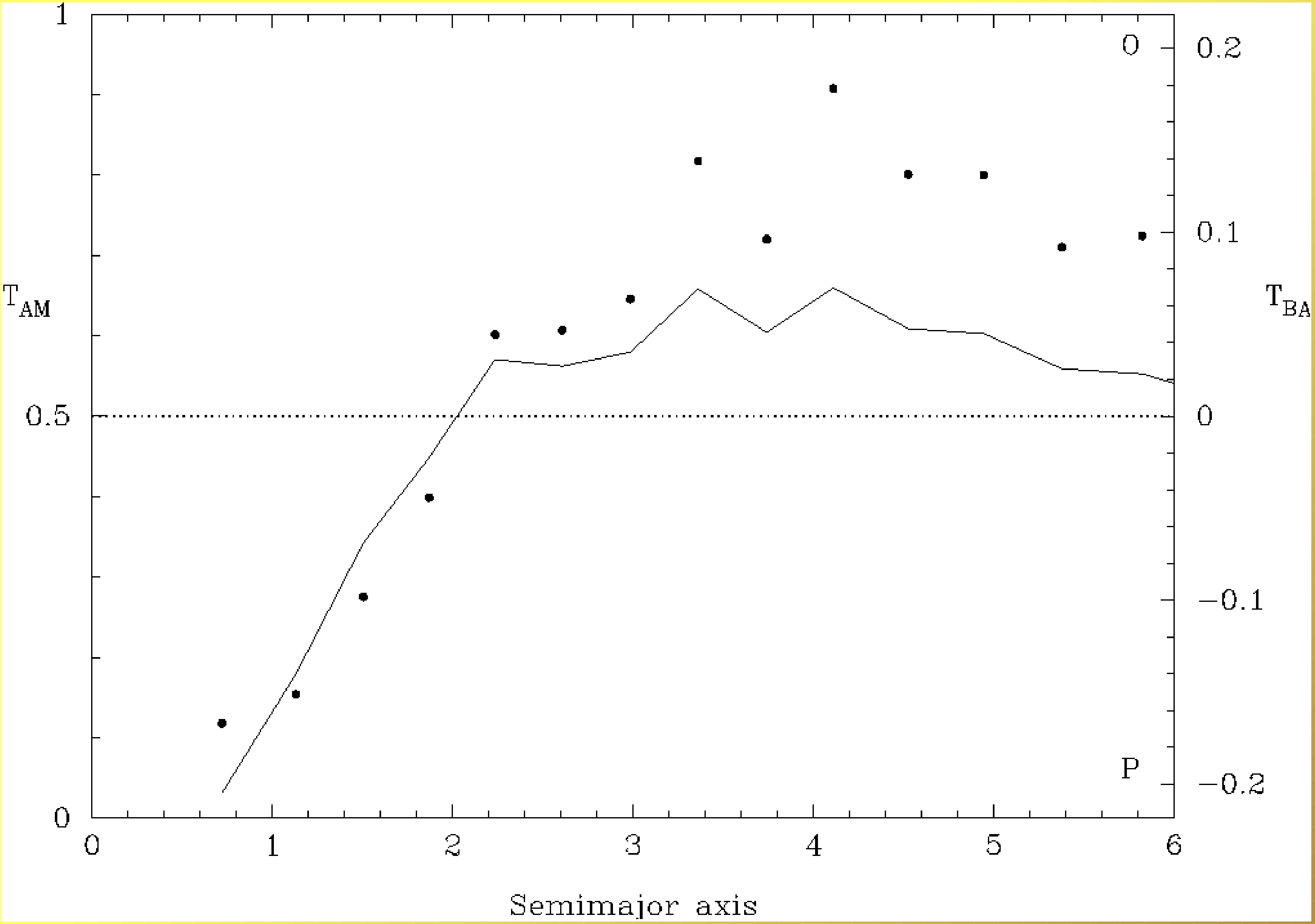


Halo bar axial ratio





T=(b-c)/(a-b)



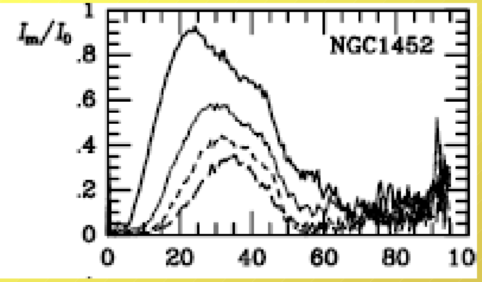
2D Fourier analysis

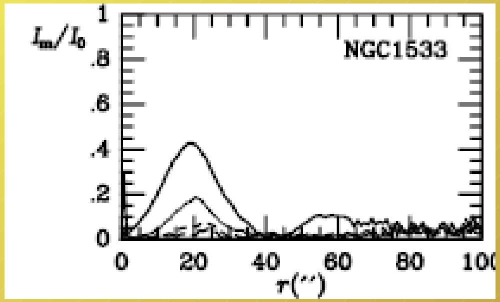
$$A_m(r) = \frac{1}{\pi}\int_0^{2\pi} \Sigma(r,\theta)cos(m\theta)d\theta, \qquad m = 0,1,2,..... \quad (1)$$

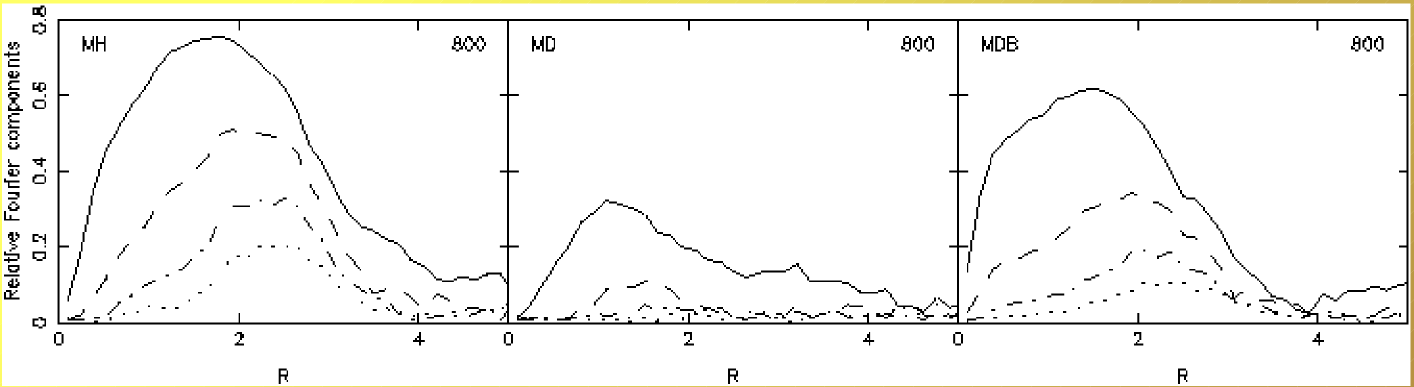
and

$$B_m(r) = \frac{1}{\pi}\int_0^{2\pi} \Sigma(r,\theta)sin(m\theta)d\theta, \qquad m = 1,2,..... \quad (2)$$

$$\sqrt{A_m^2 + B_m^2}/A_0 \qquad (3)$$







Spherical Harmonics

$$\rho(r,\theta,\phi) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} \rho_{lm} Y_l^m(\theta,\phi)$$

$$Y_l^m(\theta,\phi) = \sqrt{\frac{2l+1}{4\pi}\frac{(l-|m|)!}{(l+|m|)!}}\, P_l^{|m|}(cos\theta)\, e^{im\phi} \begin{cases} (-1)^m & \text{if } m \geq 0 \\ 1 & \text{if } m < 0 \end{cases}$$

$$Y_l^{-m}(\theta,\phi) = (-1)^m Y_l^{-m*}(\theta,\phi)$$

$$\rho_{lm}(r) = \int_0^{\pi} \int_0^{2\pi} d\phi\, Y_l^{-m*}(\theta,\phi)\ \rho(r,\theta,\phi)$$

$$\rho(r,\theta,\phi) = \sum_k \frac{m_k}{r_k^2}\delta(r-r_k)\delta(\phi-\phi_k)\delta(cos\theta - cos\theta_k)$$

$$M_{lm}(r) = \sum_i m_i Y_l^{-m*}(\theta_i,\phi_i)$$

$$\rho(r,\theta,\phi) = \sum_{l=0}^{\infty} \sum_{m=0}^{l} P_l^m(cos\theta)\,[\overline{A_{lm}}(r)\, cos(m\phi) + \overline{B_{lm}}(r)\, sin(m\phi)]$$

$$\overline{A_{lm}}(r) = N_{lm} \sum_k \frac{m_k}{r_k^2}\delta(r-r_k)P_l^m(cos\theta_k)cos(m$$

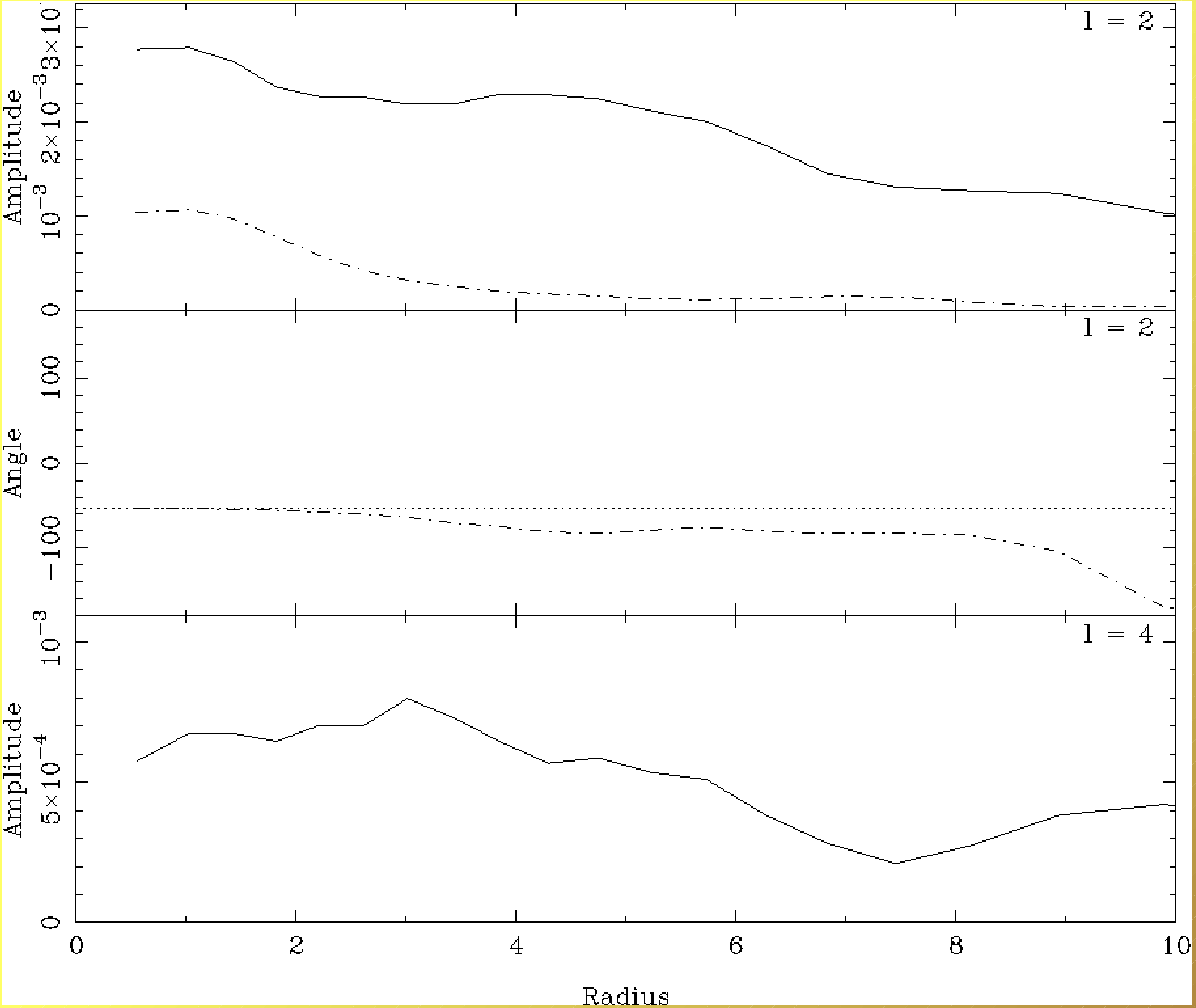
$$\overline{B_{lm}}(r) = N_{lm} \sum_k \frac{m_k}{r_k^2}\delta(r-r_k)P_l^m(cos\theta_k)sin(m$$

$$N_{lm} = \frac{2l+1}{4\pi}(2-\delta_{m0})\frac{(l-m)!}{(l+n}$$

$$A_{lm}(r) = N_{lm} \sum_k\ m_k\ P_l^m(cos\theta_k)\ c$$

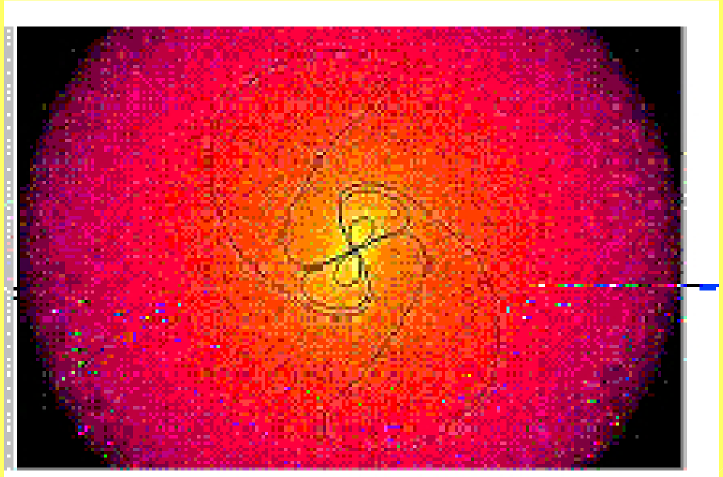
$$B_{lm}(r) = N_{lm} \sum_k\ m_k\ P_l^m(cos\theta_k)\ sin(m\phi_k)$$

$$H_{lm}(r) = \sqrt{A_{lm}^2(r) + B_{lm}^2(r)}$$

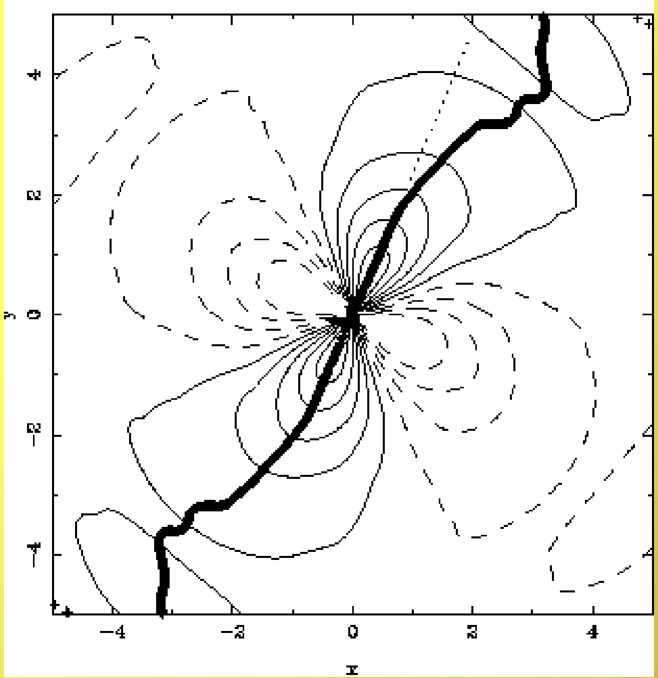


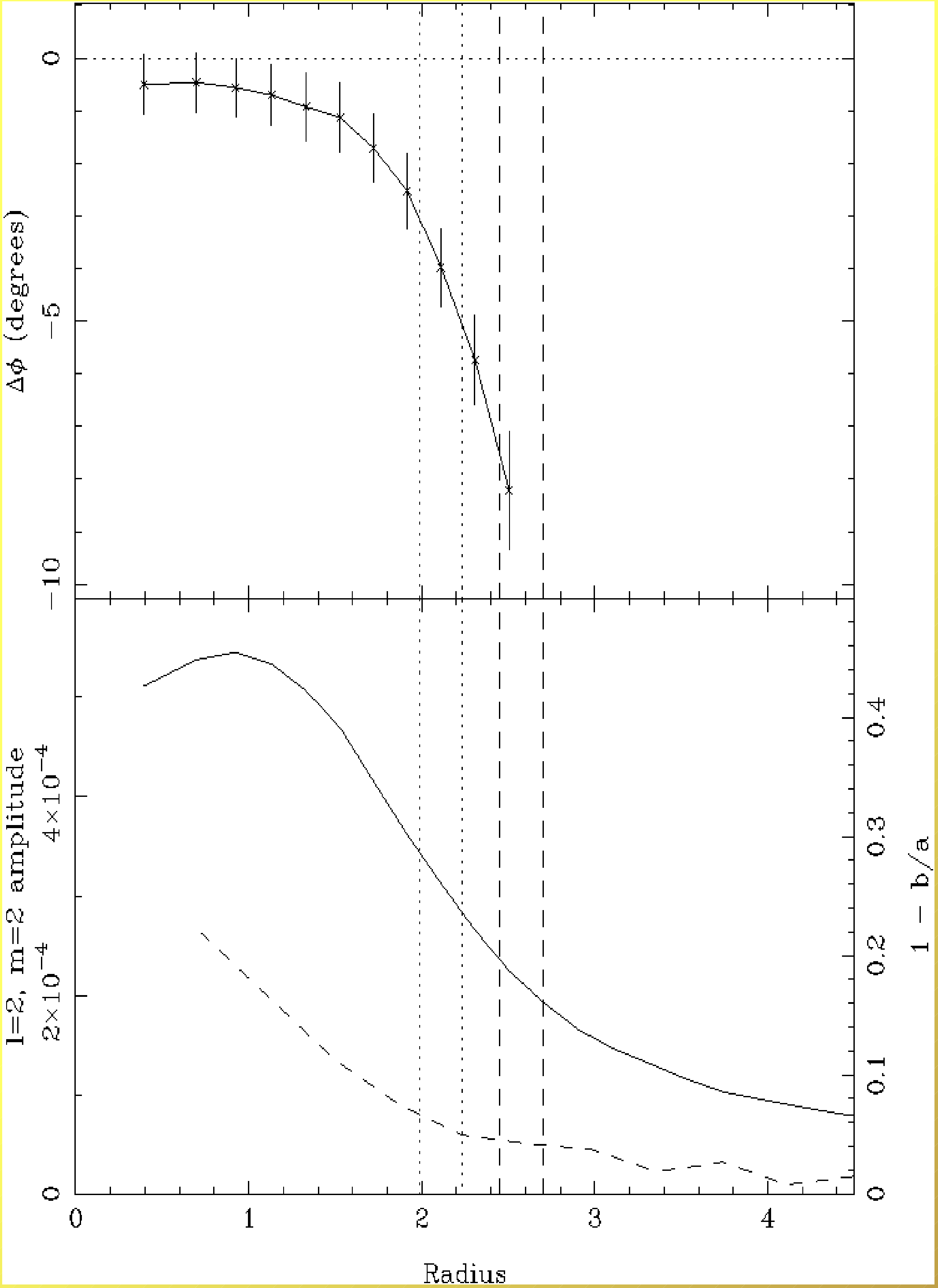
l = 2
Amplitude
0
10^{-3}
2×10^{-3}
3×10^{-3}
l = 2
Angle
100
0
−100
l = 4
Amplitude
0
5×10^{-4}
10^{-3}
0
2
4
6
8
10
Radius

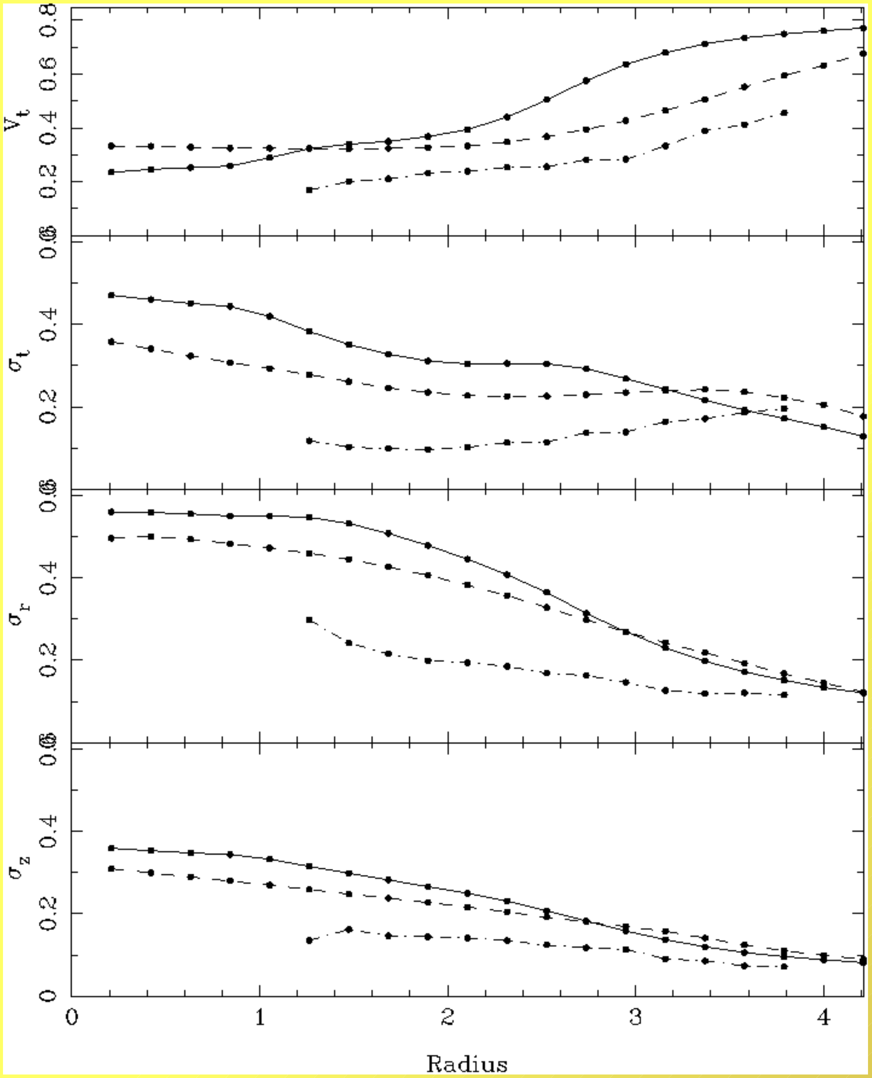
Halo bar (l=2, m=2)

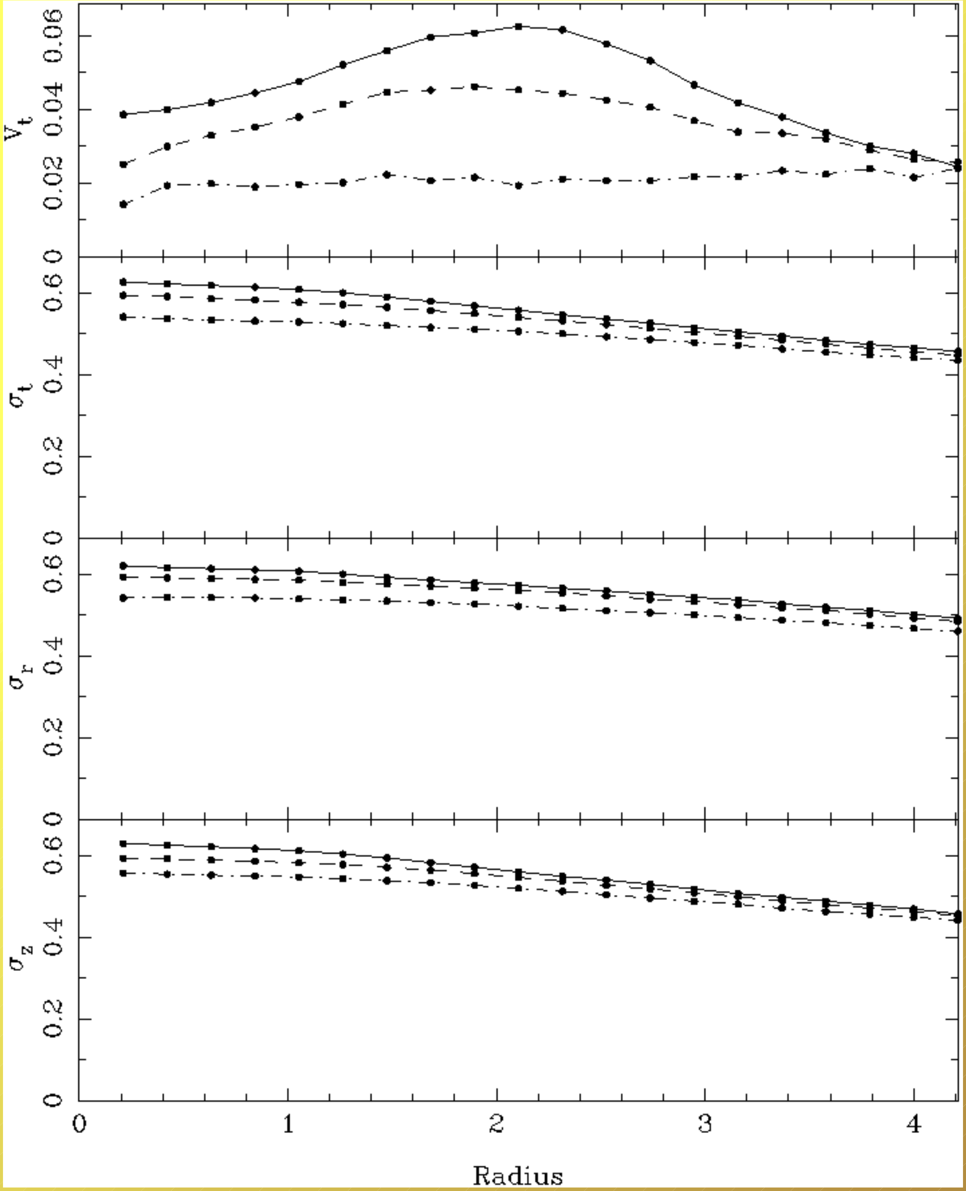


olley-Bockelmann, Weinberg & Katz 2003



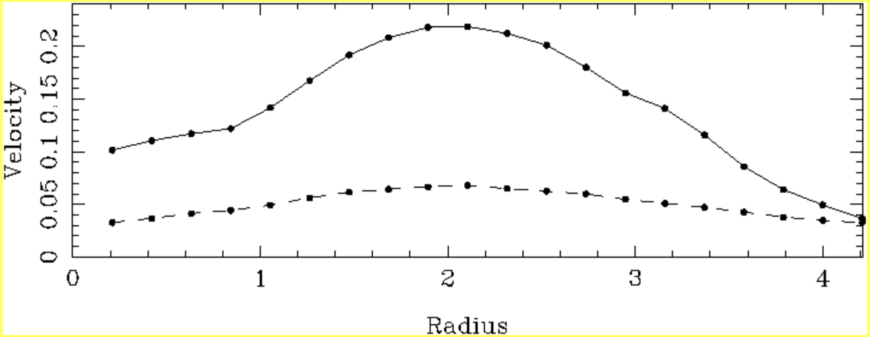

Δφ (degrees)
0
−5
−10
l=2, m=2 amplitude
4×10^{-4}
2×10^{-4}
0
1 − b/a
0.4
0.3
0.2
0.1
0
0
1
2
3
4
Radius

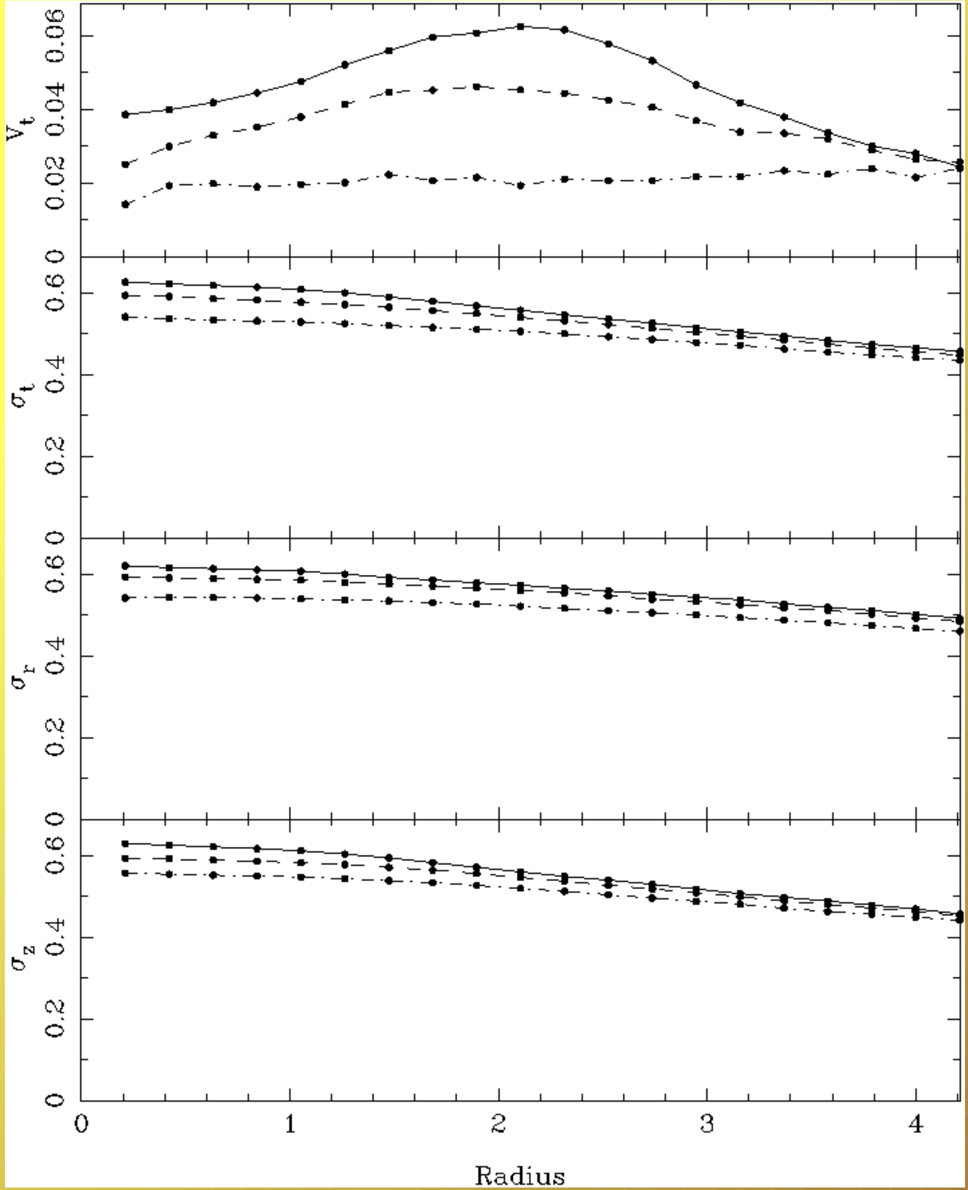




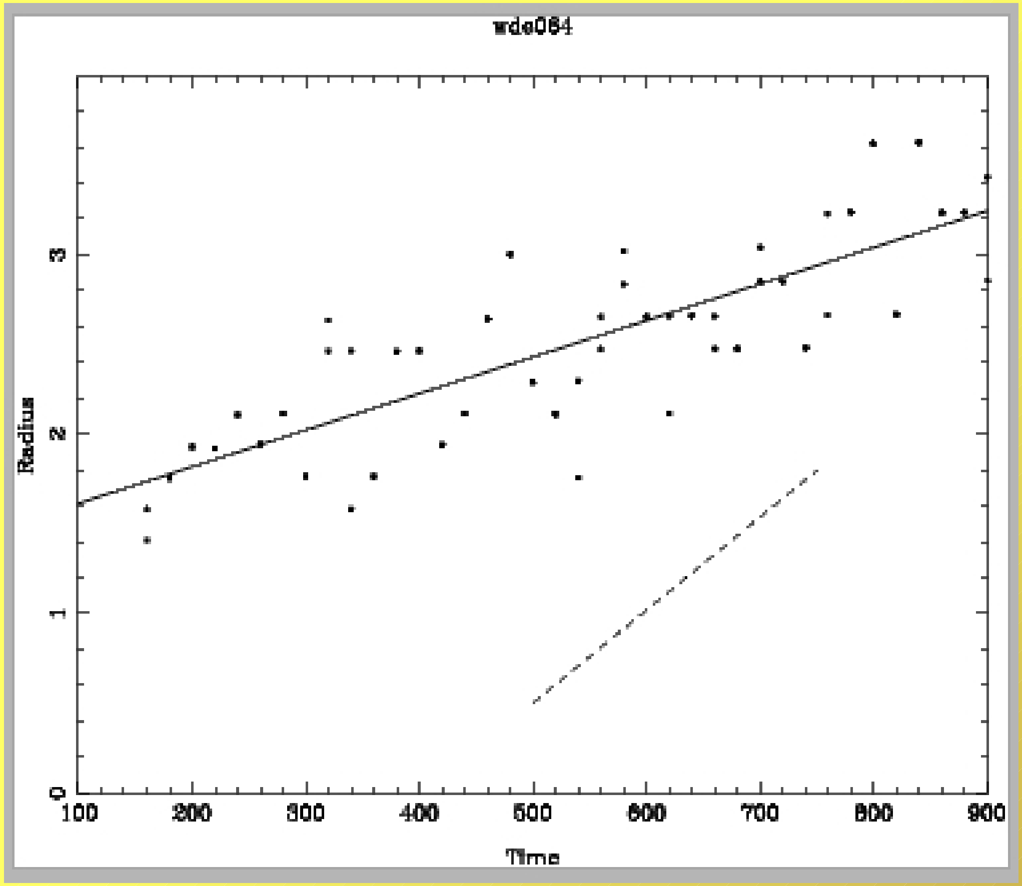
PNe ???

GAIA vv


Velocity
0
0.05
0.1
0.15
0.2
0
1
2
3
4
Radius

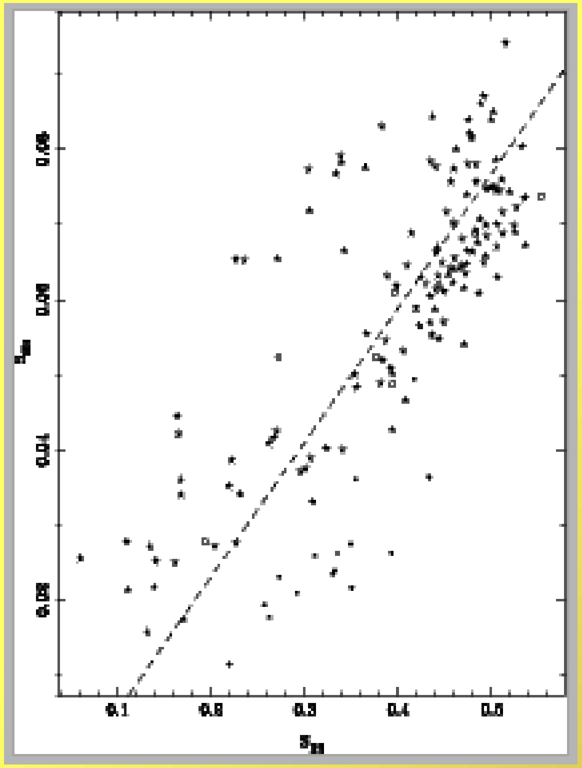

V_t
0
0.02
0.04
0.06
σ_t
0.2
0.4
0.6
σ_r
σ_z
0
1
2
3
4
Radius

Halo bar length

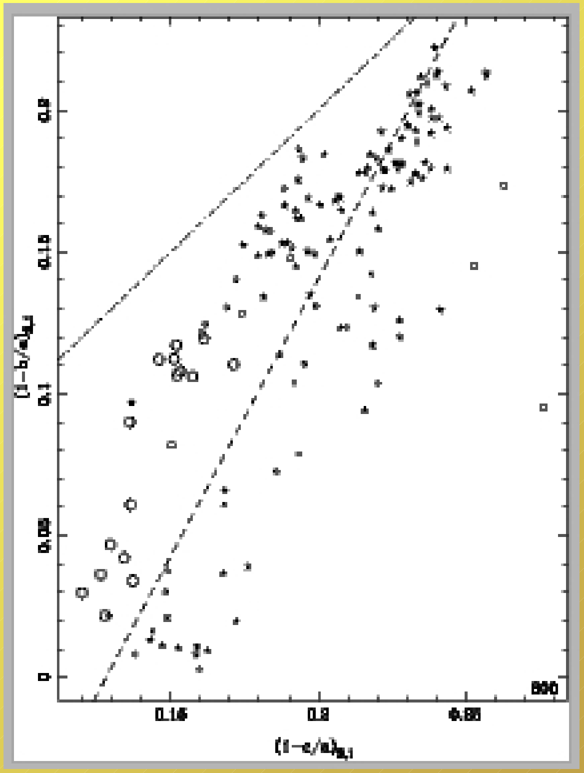


Correlations between disc and halo bar properties

Disc and halo bar lengths



Disc and halo bar strengths



Halo shape

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.

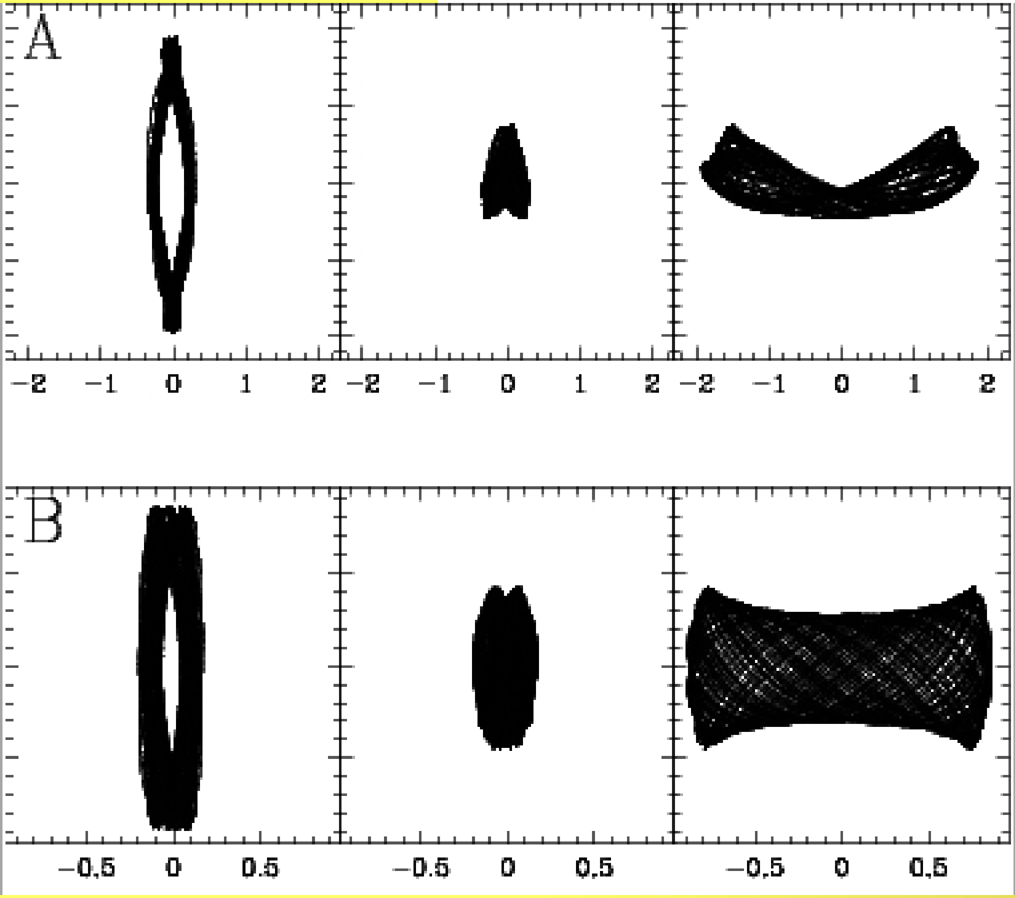
Particles at near-CR have preferentially initially intermediate cylindrical and spherical radii (not in the innermost or outermost regions). They have initially preferentially smaller values of $|u_z|$ and larger values of L_z than average.

Halo orbital structure

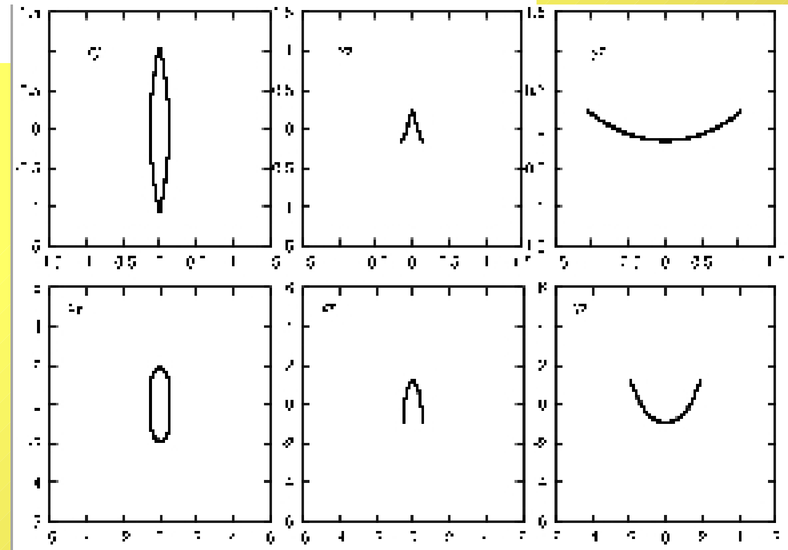
Halo near-resonant orbits are mainly trapped around Lagrangian periodic orbits and around x1-tree periodic orbits

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

Halo x1-tree orbits

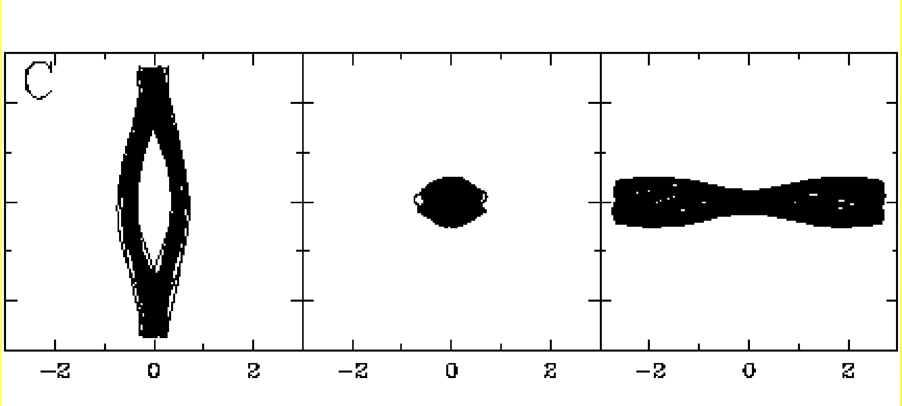


x1v1

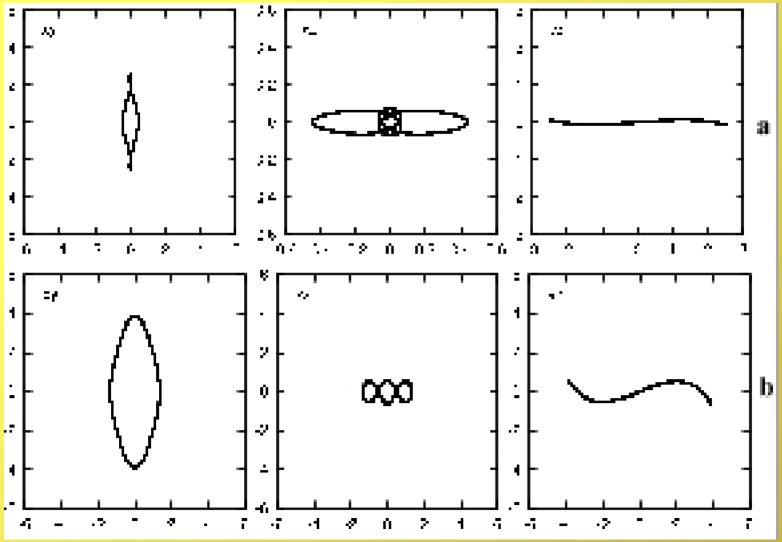


Skokos, Patsis and Athanassoula (2002)

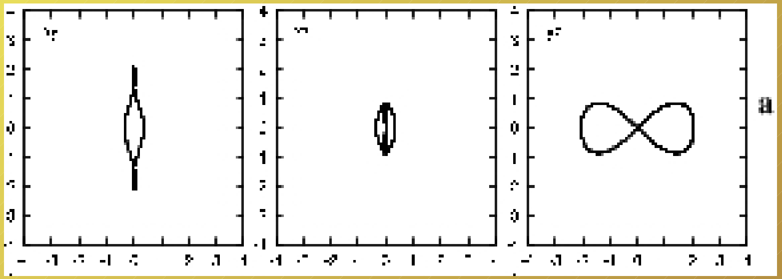
Halo x1-tree orbits



x1v4 - stable

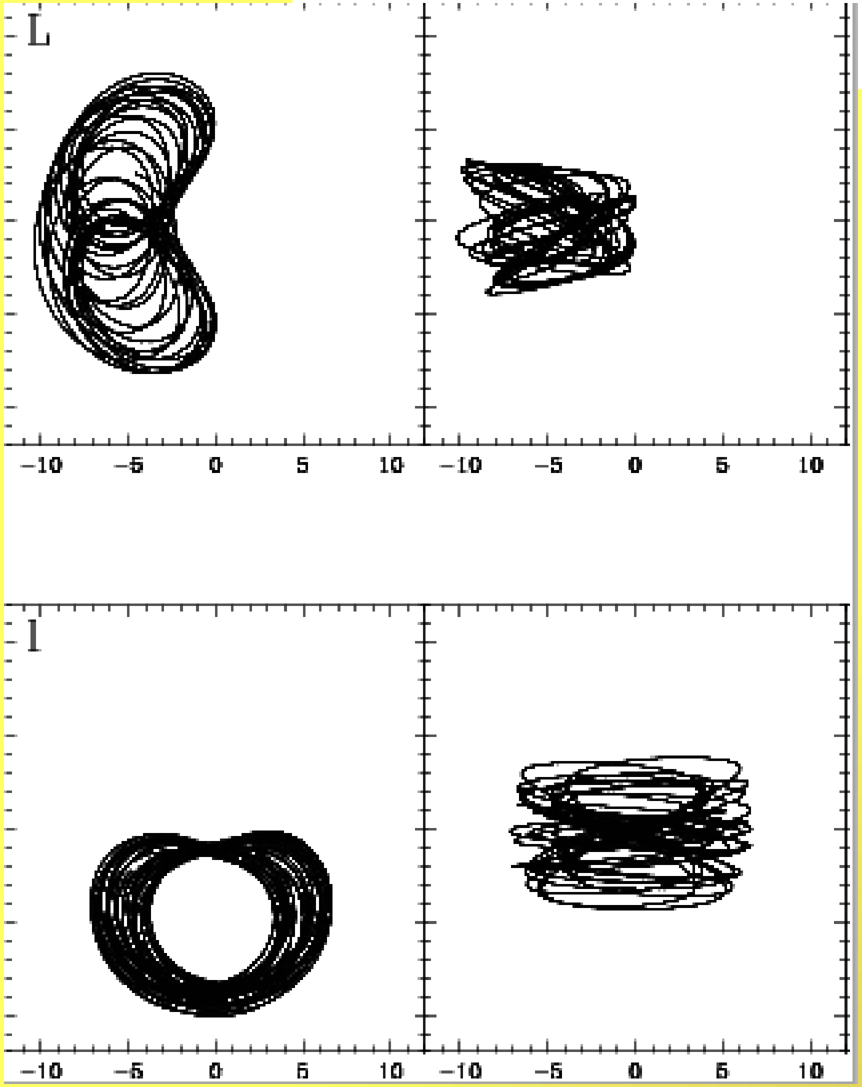


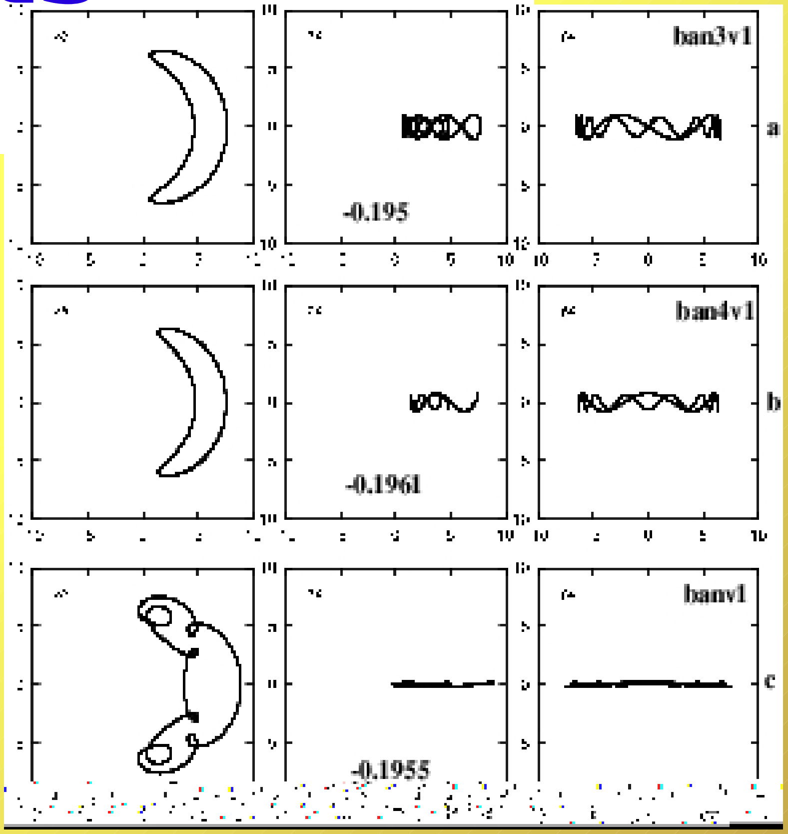
x1v2 - unstable

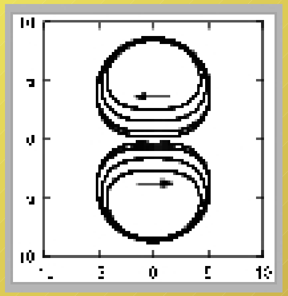


Skokos, Patsis and Athanassoula 2002

Halo lagrangian orbits

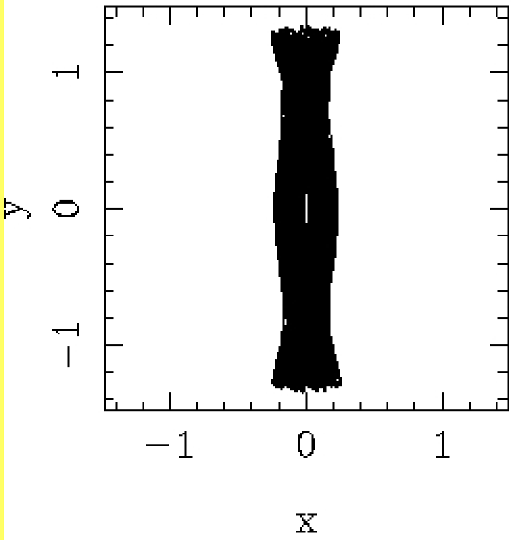


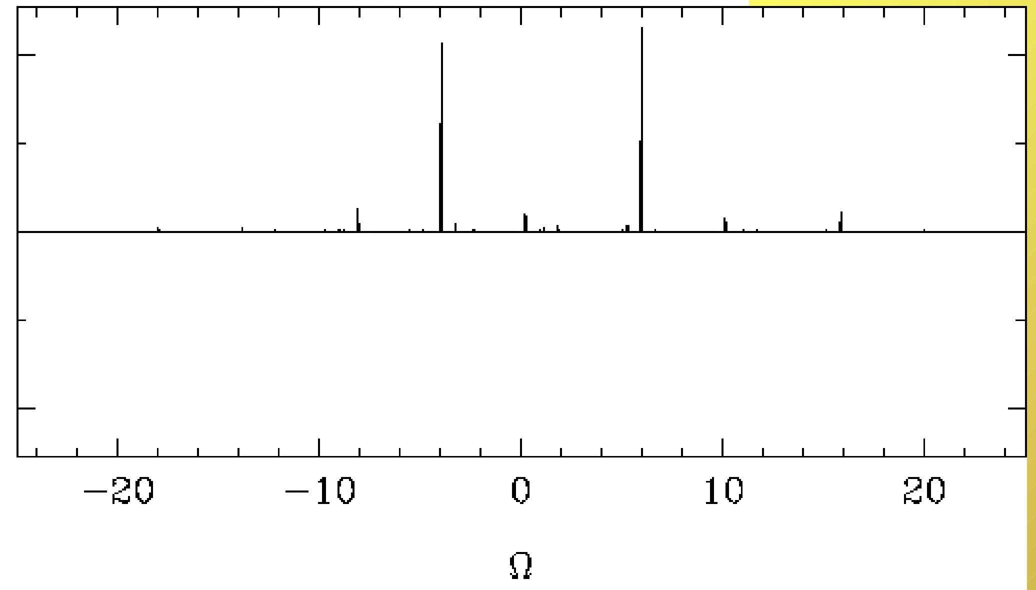


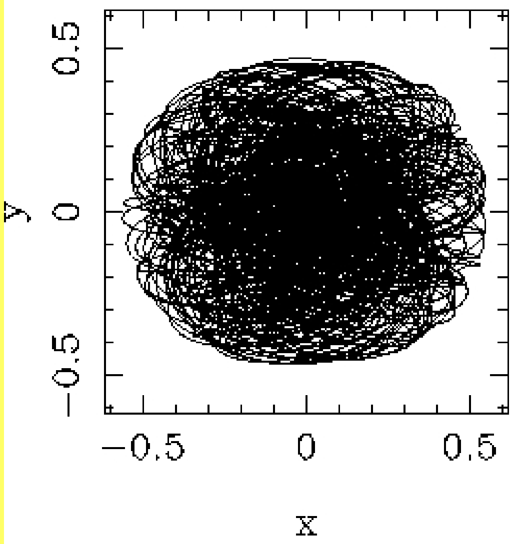


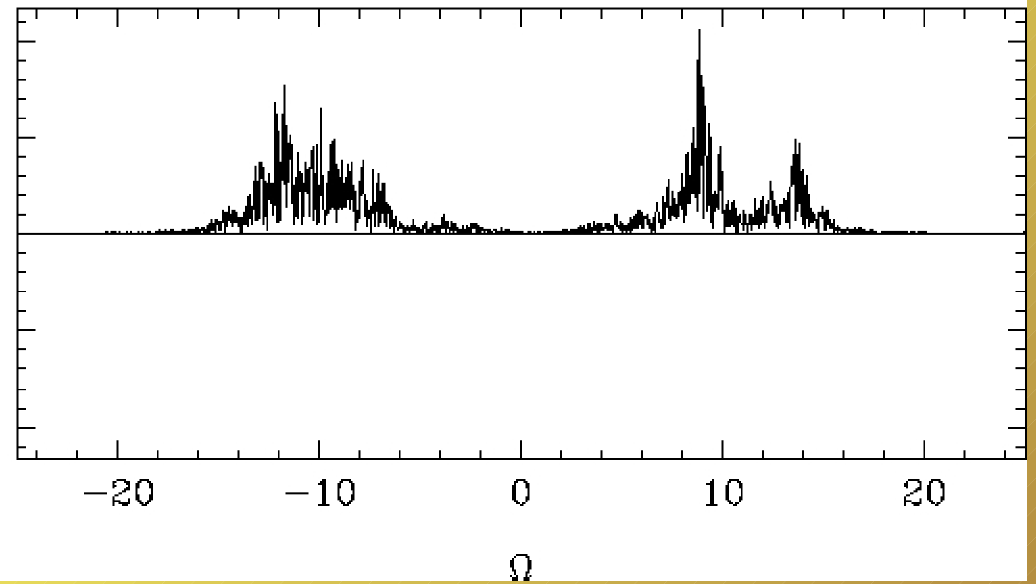
Skokos, Patsis and Athanassoula 2002

Measuring chaos



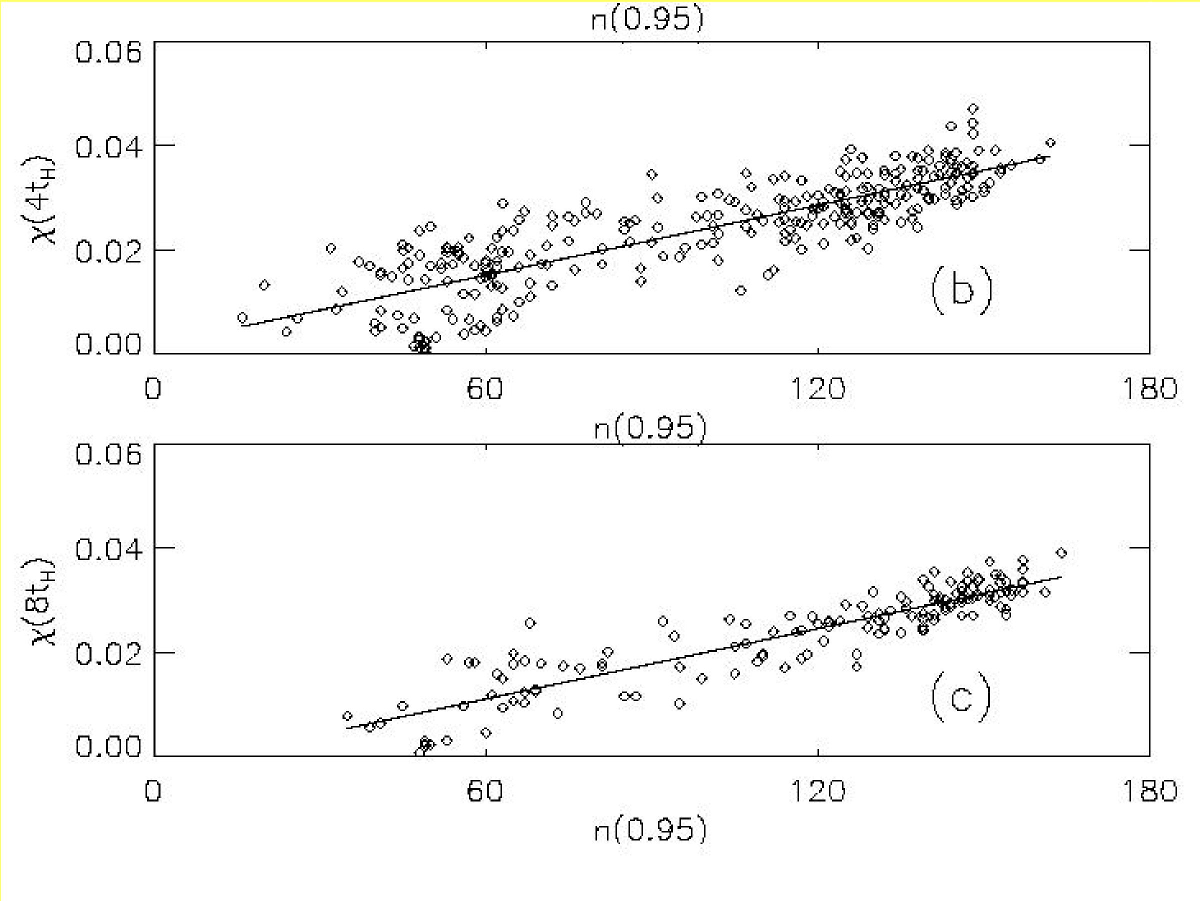






Complexity and Lyapounov exponents

This measure of chaos performs as well as Lyapunov coefficients

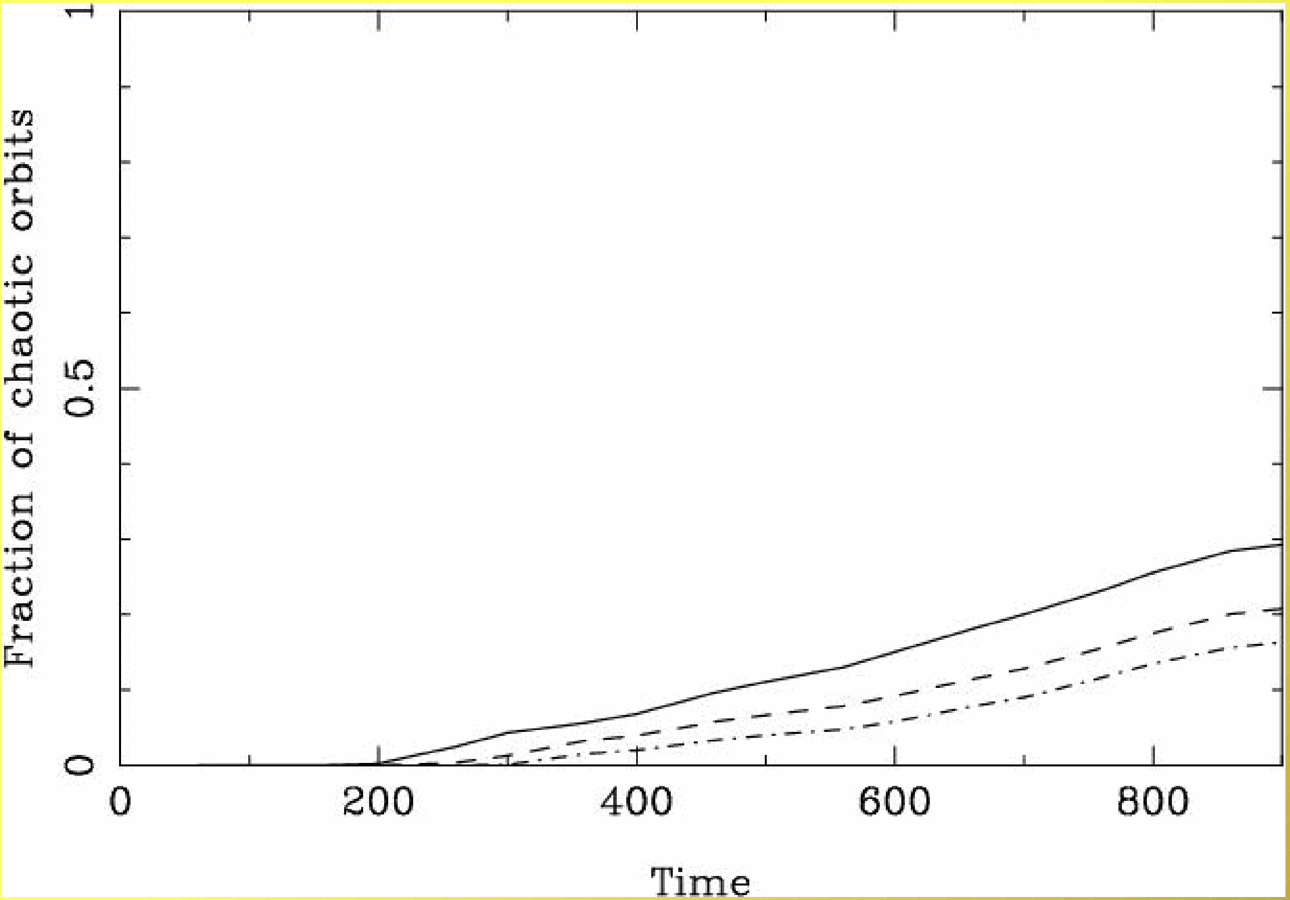


Kandrup, Eckstein & Bradley (1997)

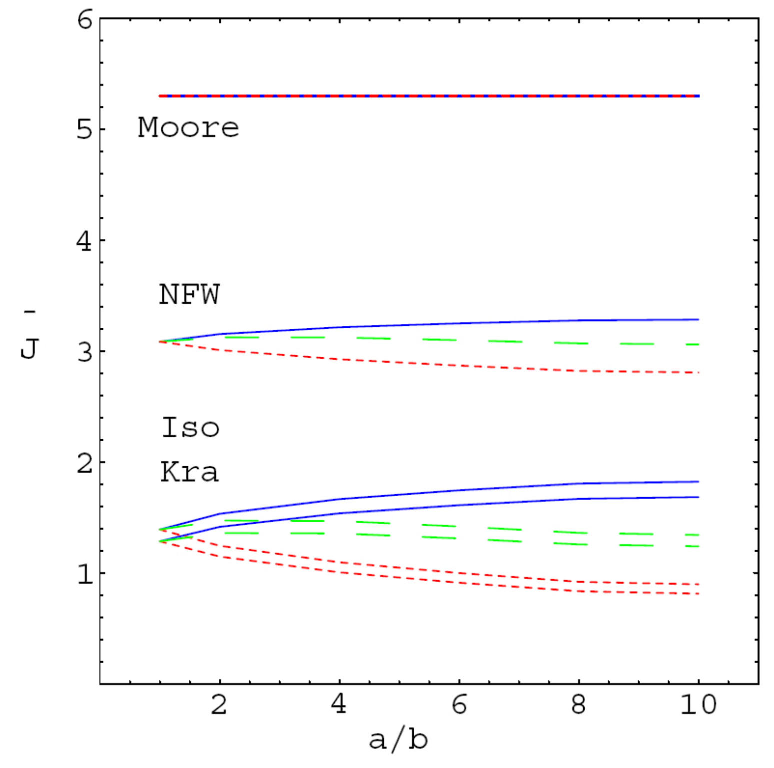
Fig. 8. a A scatter plot of χ vs. $n(0.95)$ for the segments shown in Fig. 5d, now sampled at an interval $\Delta t = 2t_H$. **b** The same for $\Delta t = 4t_H$. **c** The same for $\Delta t = 8t_H$. **d** The same for $\Delta t = 16t_H$.

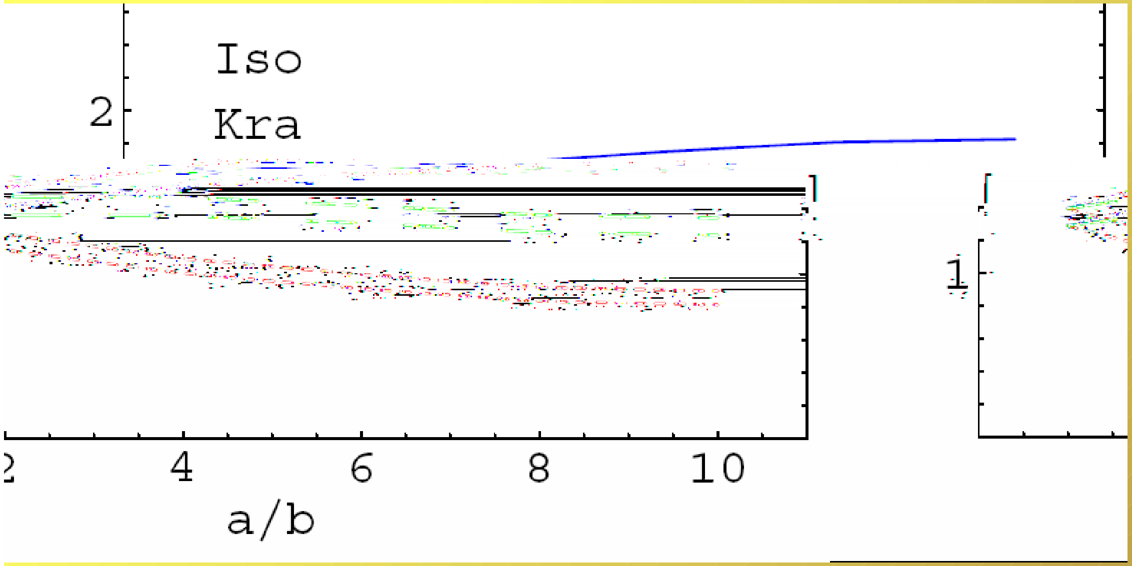
Halo orbital structure

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



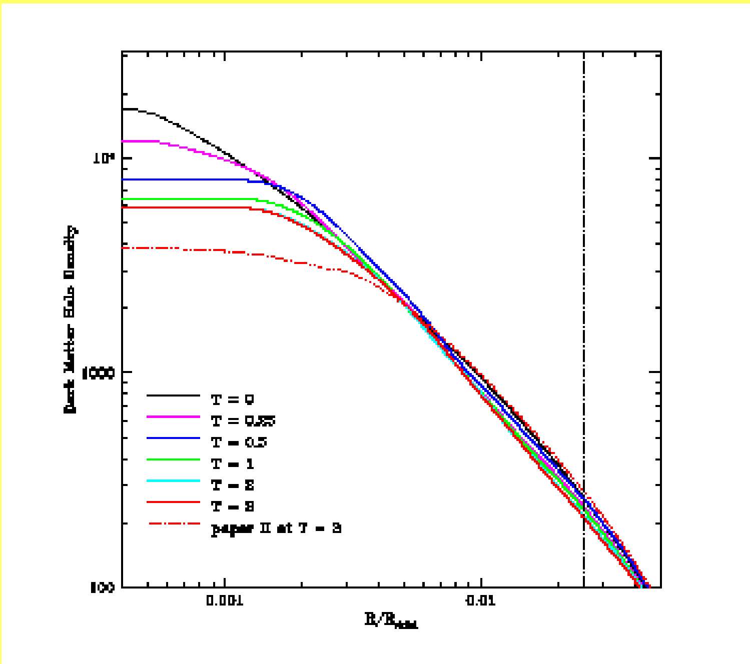
Halo Geometry and Dark Matter Annihilation Signal





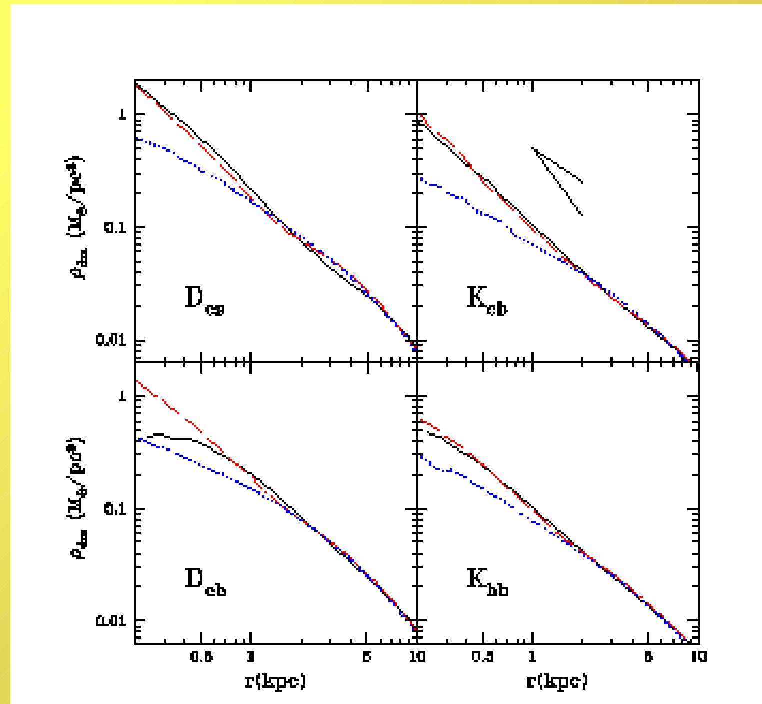
Athanassoula, Ling & Nezri 2005

Cusp vs core controversy



Holley-Bockelmann, Weinberg, Katz 2003

T=0 blue dotted
T=6 Gyr black solid



Colin, Valenzuela, Klypin 2006
Sellwood 2003, 2006a,b

Competing effects :

Particles at ILR gain angular momentum and move outwards

The radial density profile of the disc becomes more centrally concentrated with time due to the bar. This pulls the halo inwards

Halo gains angular momentum and becomes more flat. This means that z of halo particles may decrease. Then spherical radius may decrease though the cylindrical radius increases

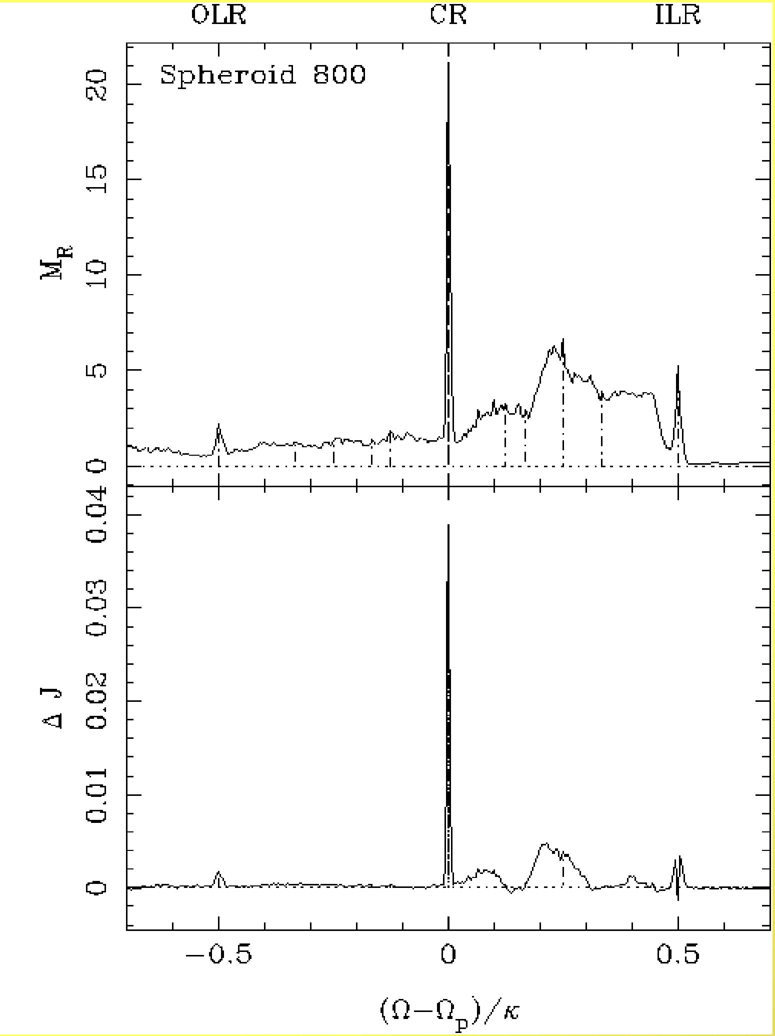
Halo particle orbits will become more elongated. Then they contribute more to the central density even though their mean cylindrical radius increases

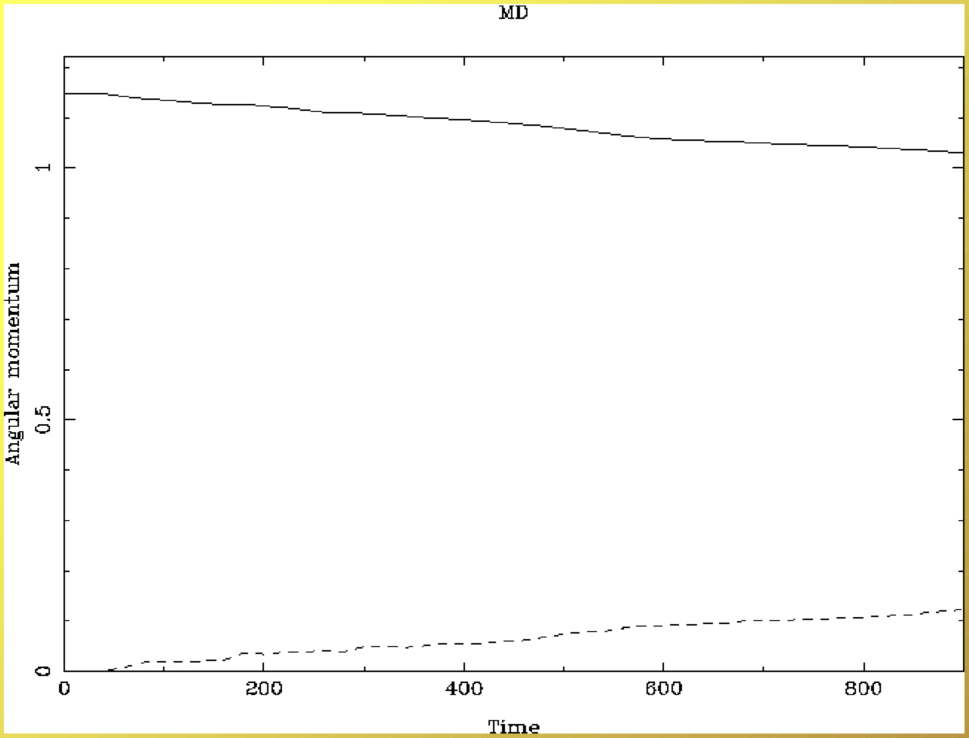
===> result will depend on properties of the distribution functions

In real galaxies there is gas that will fall to the center due to the bar and so will pull the halo further inwards

Competing effects :

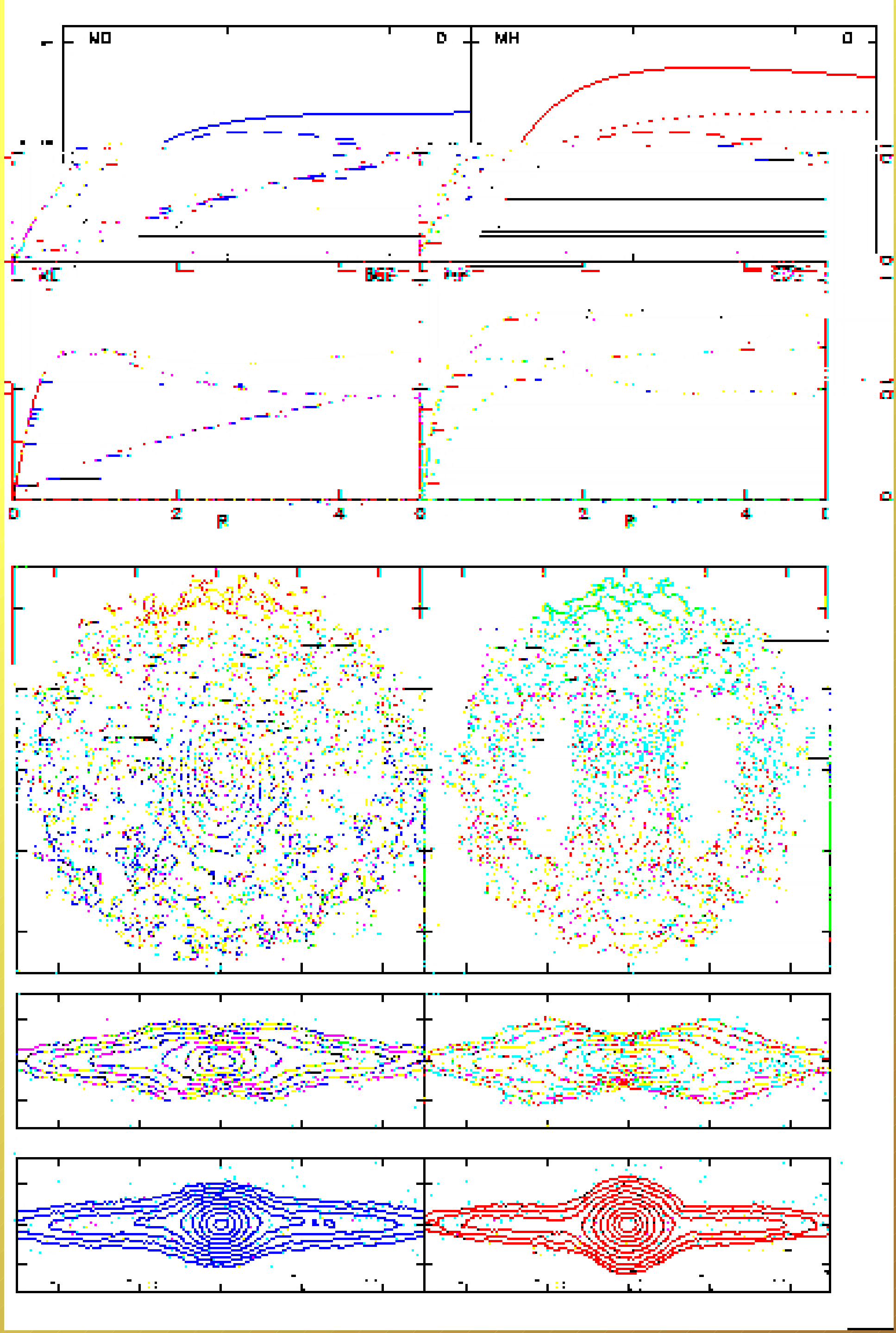
Particles at ILR gain angular momentum and move outwards





Competing effects :

The radial density profile of the disc becomes more centrally concentrated with time due to the bar. This pulls the halo inwards



Competing effects :

Particles at ILR gain angular momentum and move outwards

The radial density profile of the disc becomes more centrally concentrated with time due to the bar. This pulls the halo inwards

Halo gains angular momentum and becomes more flat. This means that z of halo particles may decrease. Then spherical radius may decrease though the cylindrical radius increases

Halo particle orbits will become more elongated. Then they contribute more to the central density even though their mean cylindrical radius increases

===> result will depend on properties of the distribution functions

In real galaxies there is gas that will fall to the center due to the bar and so will pull the halo further inwards

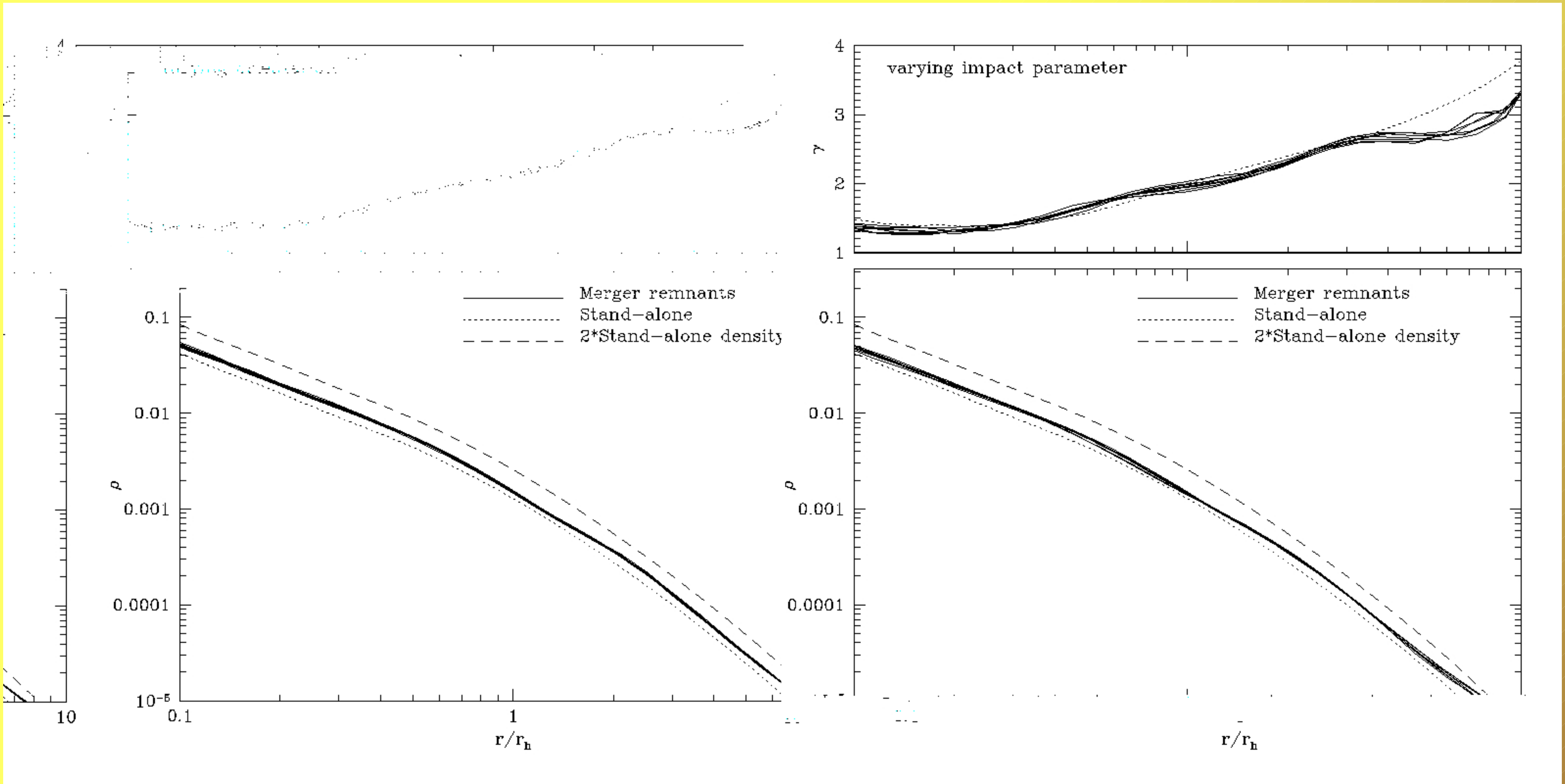
(see discussion by Athanassoula 2004- IAU 220)

Dark Matter in elliptical galaxies

Ellipticals are believed to form from mergings.

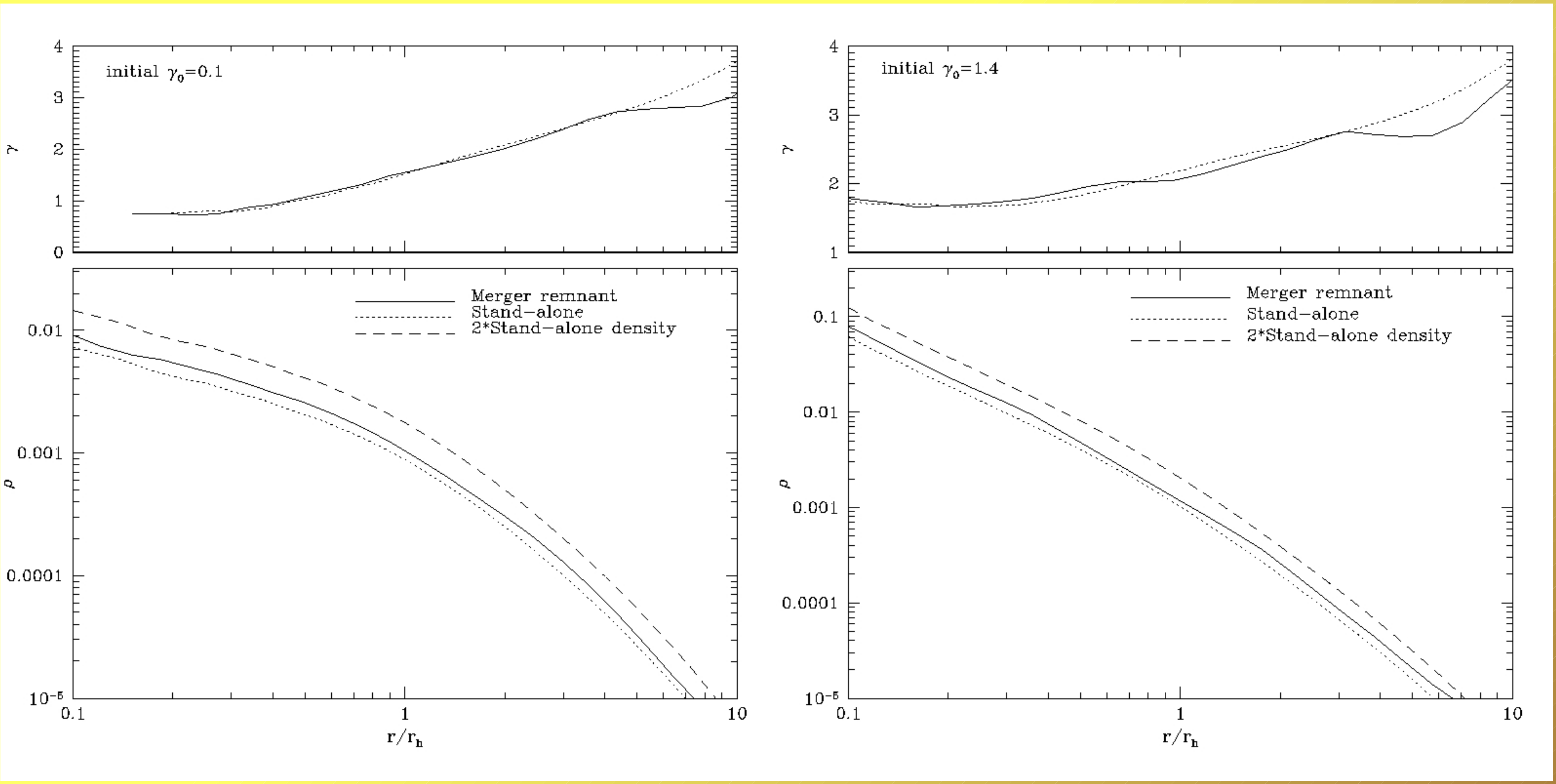
Simulations of mergings

Density radial profile in the merger remnant

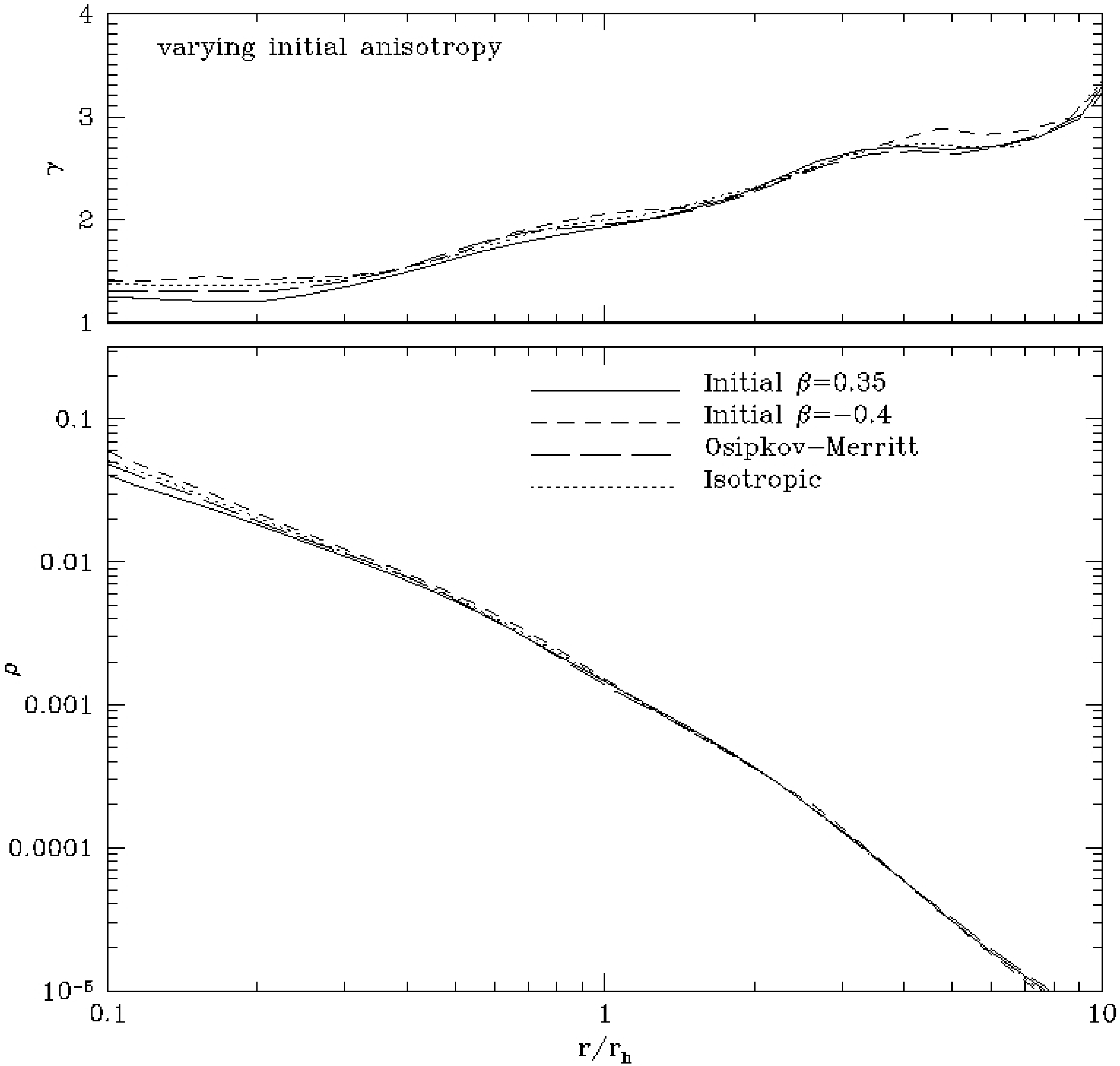


McMillan, Athanassoula & Dehnen 2007

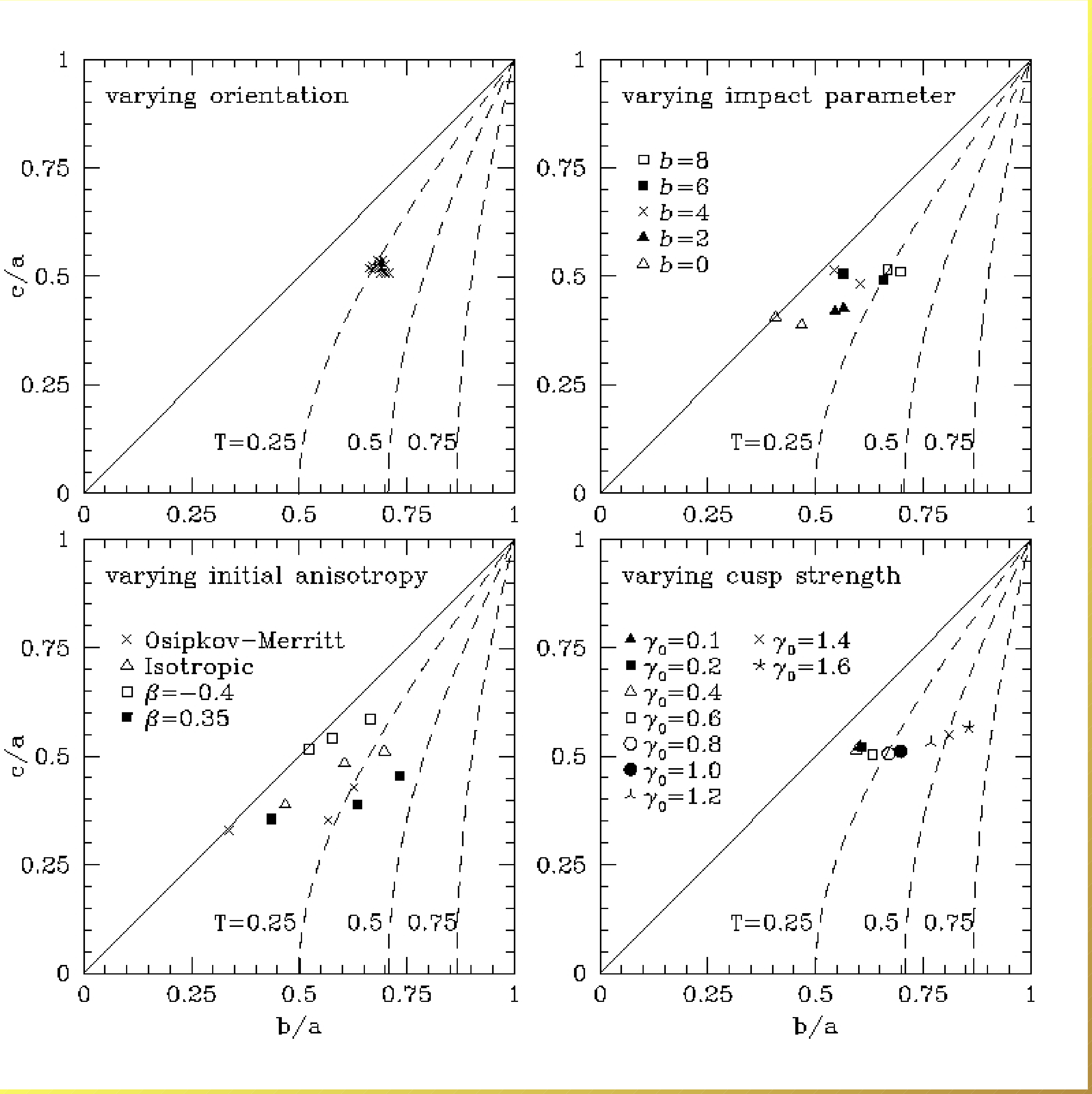
Density radial profile in the merger remnant



McMillan, Athanassoula & Dehnen 2007



varying initial anisotropy
γ
4
3
2
1
ρ
0.1
0.01
0.001
0.0001
10^{-5}
0.1
1
10
r/r_h
Initial β=0.35
Initial β=−0.4
Osipkov−Merritt
Isotropic


varying orientation
varying impact parameter
b=8
b=6
b=4
b=2
b=0
varying initial anisotropy
Osipkov−Merritt
Isotropic
β=−0.4
β=0.35
varying cusp strength
γ0=0.1
γ0=0.2
γ0=0.4
γ0=0.6
γ0=0.8
γ0=1.0
γ0=1.2
γ0=1.4
γ0=1.6
T=0.25
0.5
0.75
c/a
b/a
0
0.25
0.5
0.75
1

Dark matter haloes in elliptical galaxies

HI-rotation curves have shown that spiral discs reside in extended massive dark matter haloes

Many observations (X-ray, gravitational lensing, etc etc) argue that ellipticals are also embedded in dark matter haloes

Dark matter is also a basic ingredient in LCDM cosmology

Yet : PNe measurements by Romanowsky et al (2003) for the normal ellipticals NGC 821, 3379 and 4494 and by Mendez et al (2001) for NGC 4697 argue for “little if any dark matter”

So how can that be ?

Some basics

From the spherical Jeans equation :

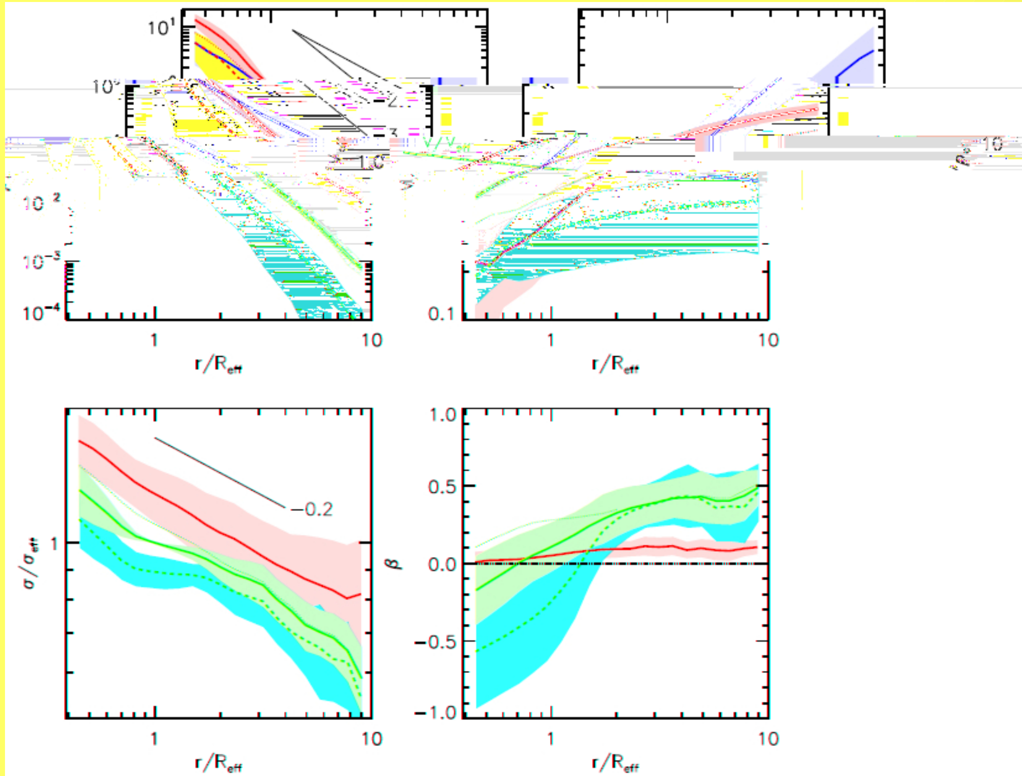
$$M(r) = [\alpha(r) + \gamma(r) - 2\ \beta(r)]\ \sigma_r^2(r)\ r$$

$$\alpha \equiv -dln\rho/dlnr$$

$$\gamma \equiv -dln\sigma_r^2/dlnr \qquad \beta = \begin{cases} -\infty & : \quad circular \\ 0 & : \quad isotropic \\ +1 & : \quad radial \end{cases}$$

$$\beta \equiv 1. - \sigma_\theta^2/\sigma_r^2$$

Merging in S-S pairs



. Three-dimensional profiles of the simulated merger remnants. Ten galaxies at ent times after the merger (typically 0.8 and 1.3 Gyr) are stacked together. Dark lue) versus stars (red), divided into the old ones from the progenitors (dotted)

Figure 1 two differ matter (b

Dekel, Stoehr, Mamon, Cox, Primack 2005

Merging in groups

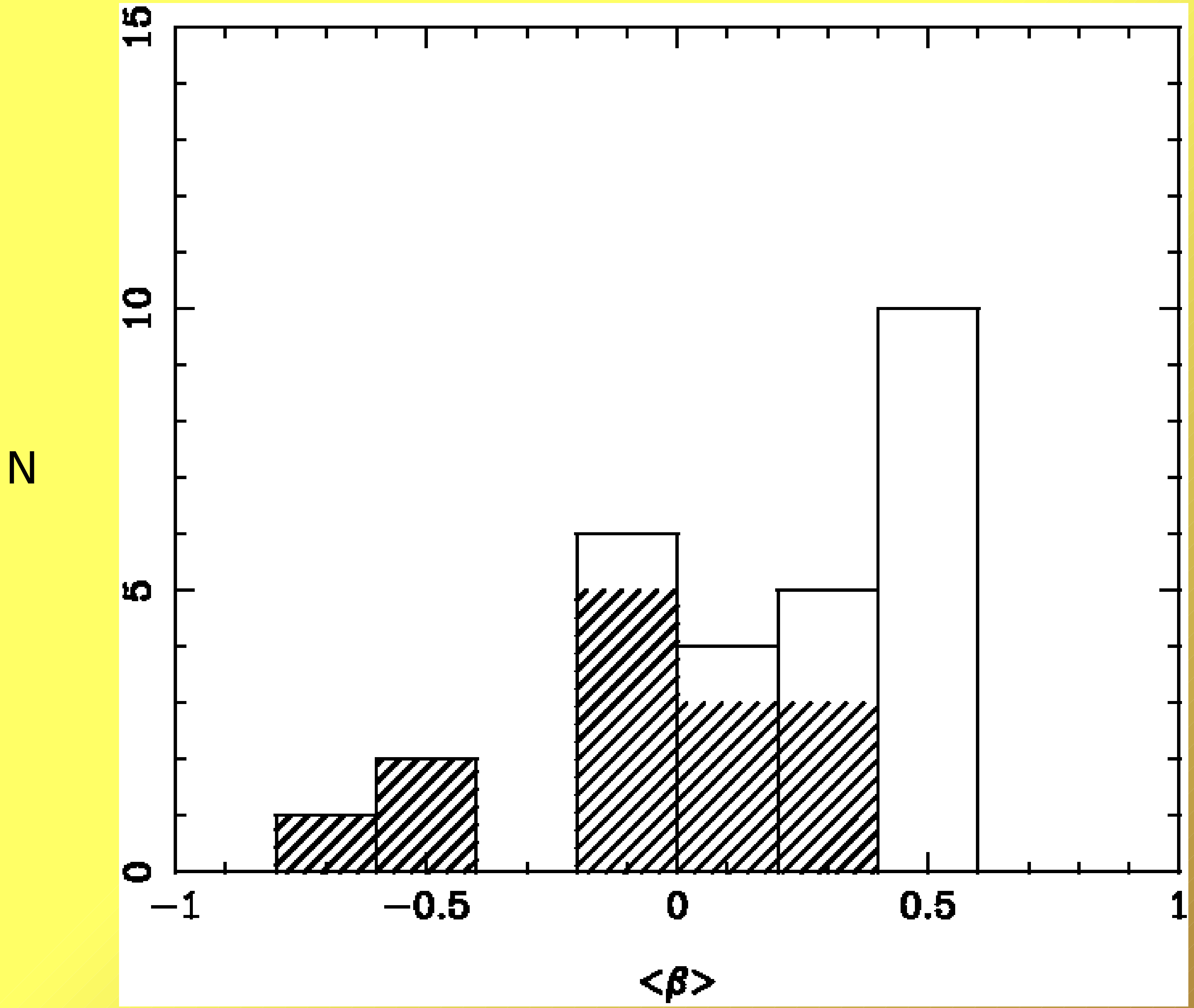
Groups of 4 or 5 identical galaxies

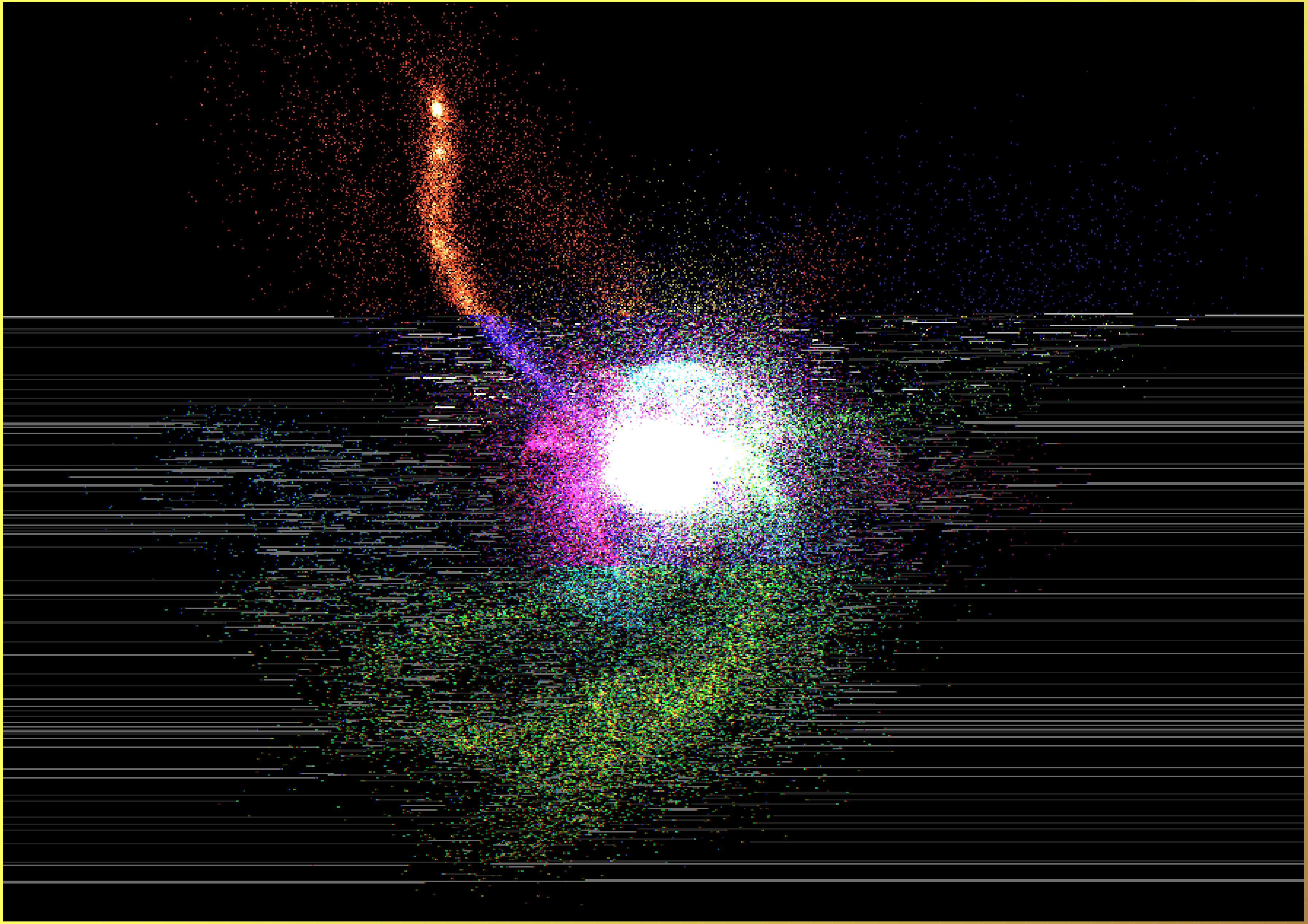
4 or 5 S : (S = disc + halo ; all galaxies identical; random orientations of the discs)

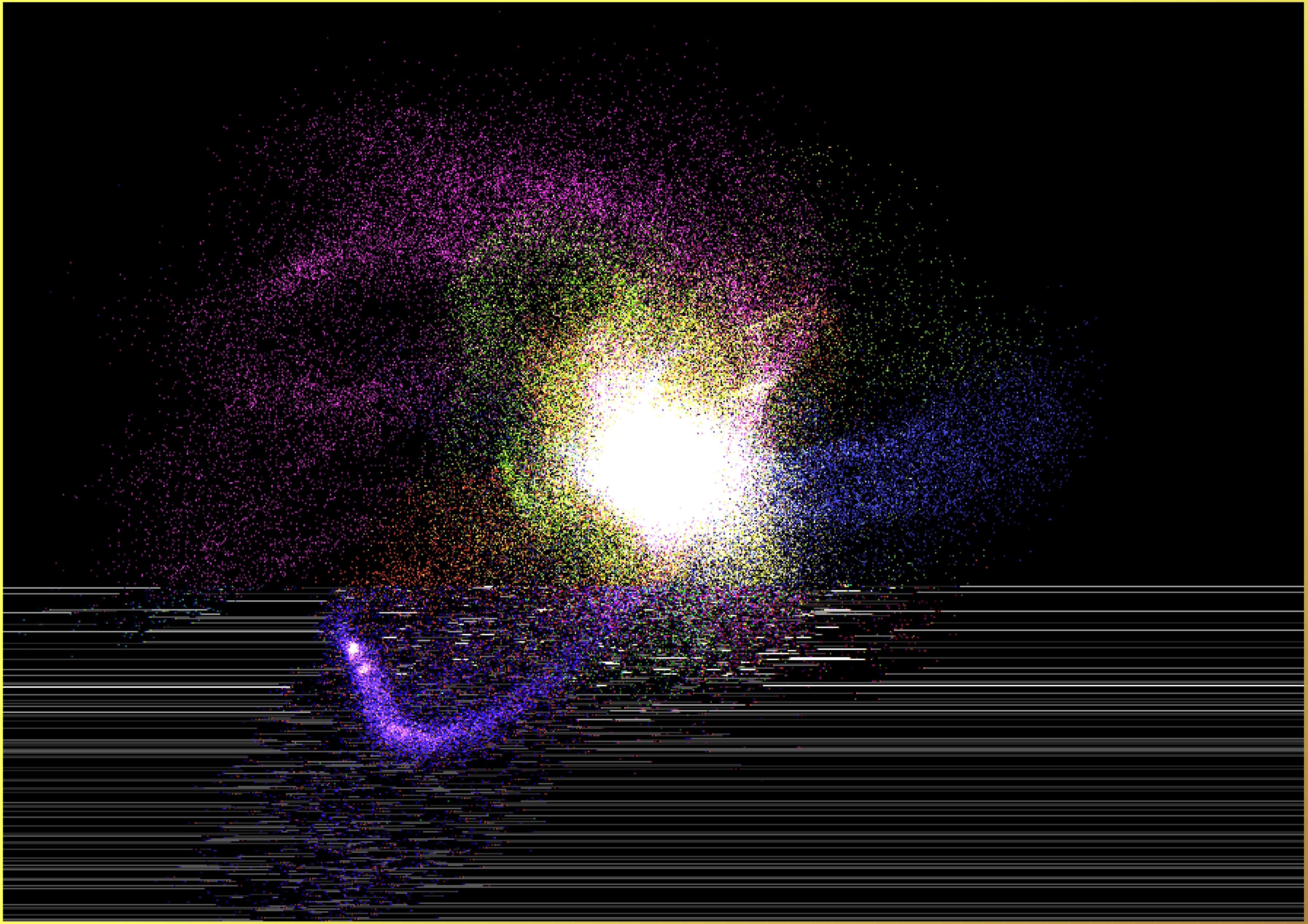
5 E : spherical; all galaxies identical; with (or without) a common halo

~ 35 simulations
~ 1 to 2 million particles per simulation

Athanassoula 2005


N
0
5
10
15
−1
−0.5
0
0.5
1
<β>

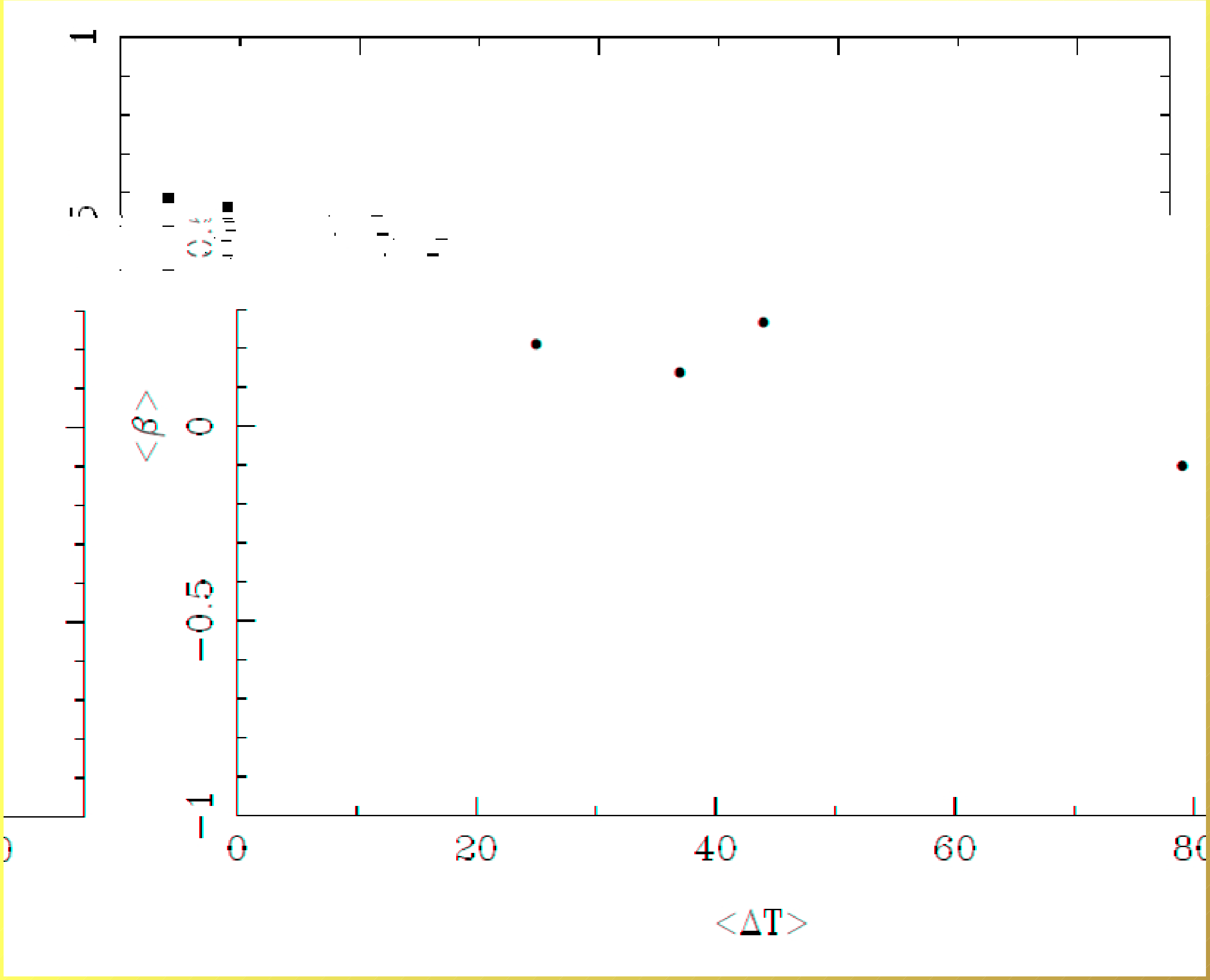




Groups of disc galaxies

Radial

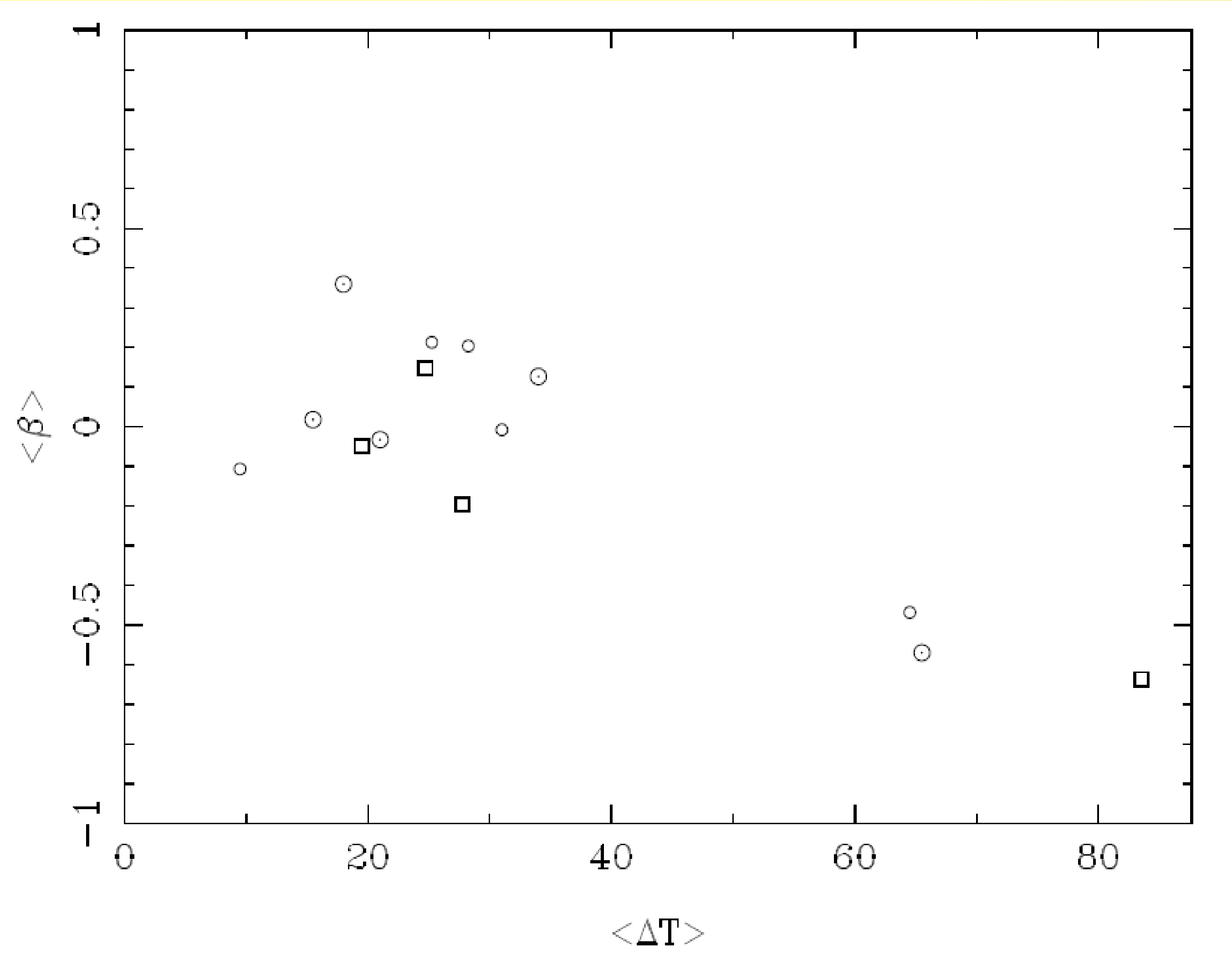
Circular



Groups of elliptical galaxies

Radial

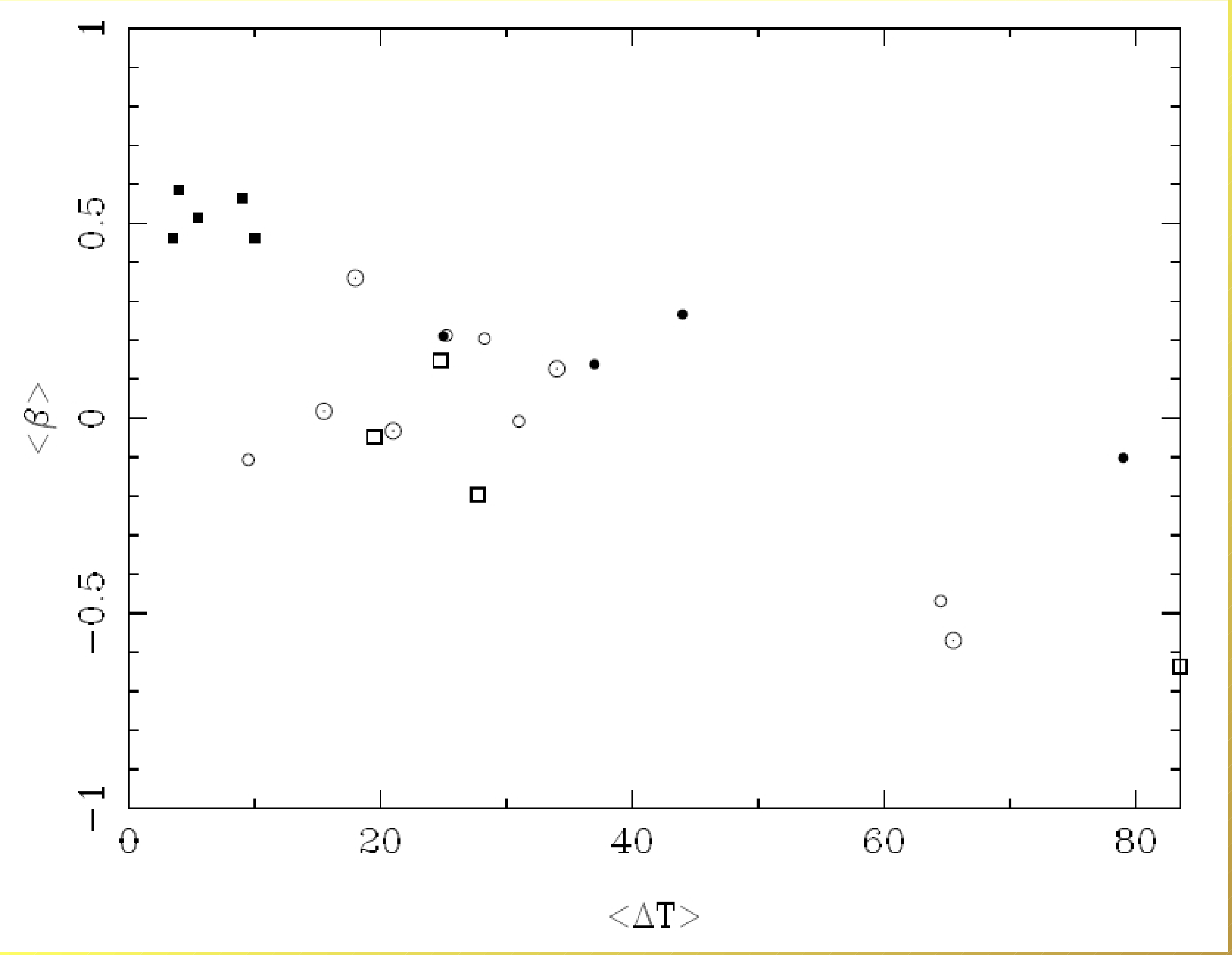
Circular



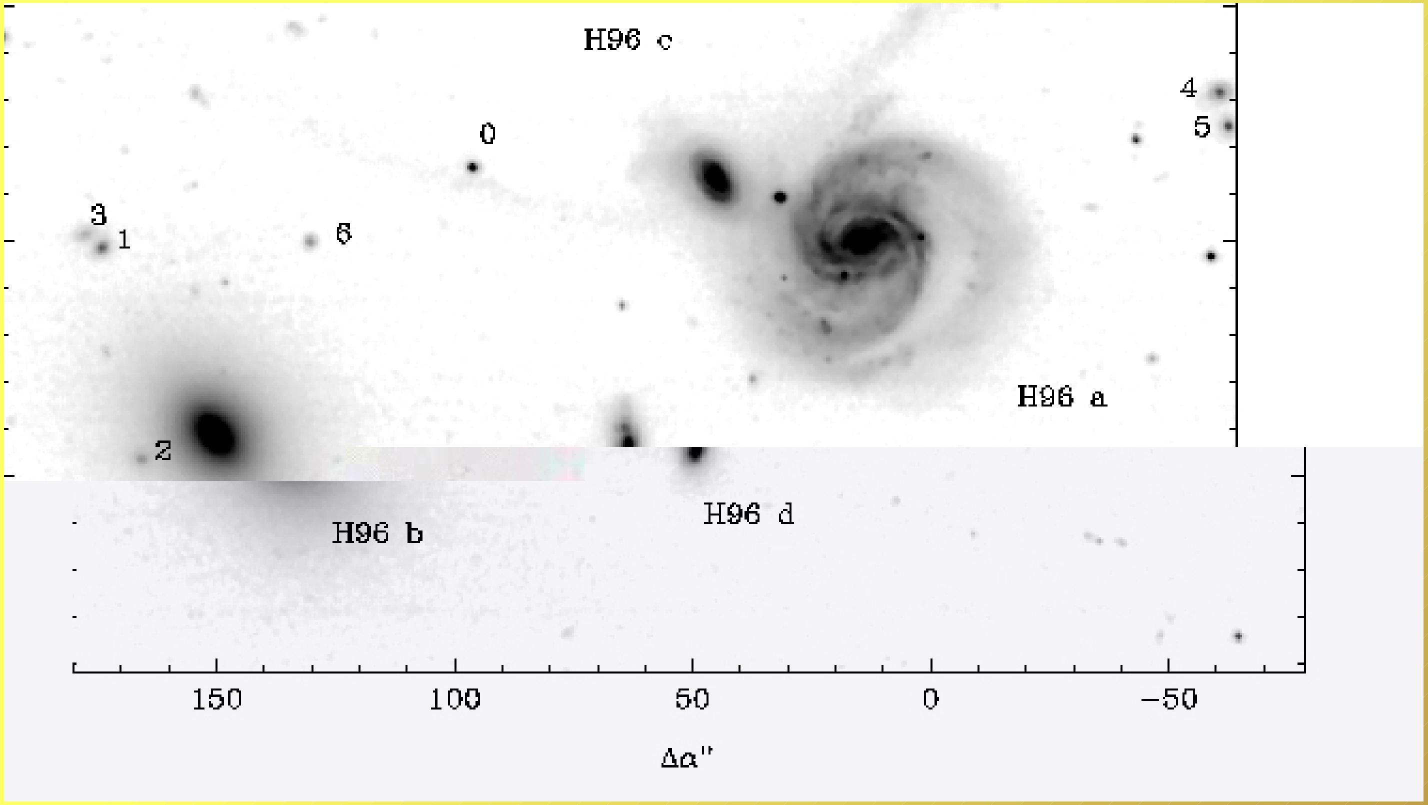
All groups

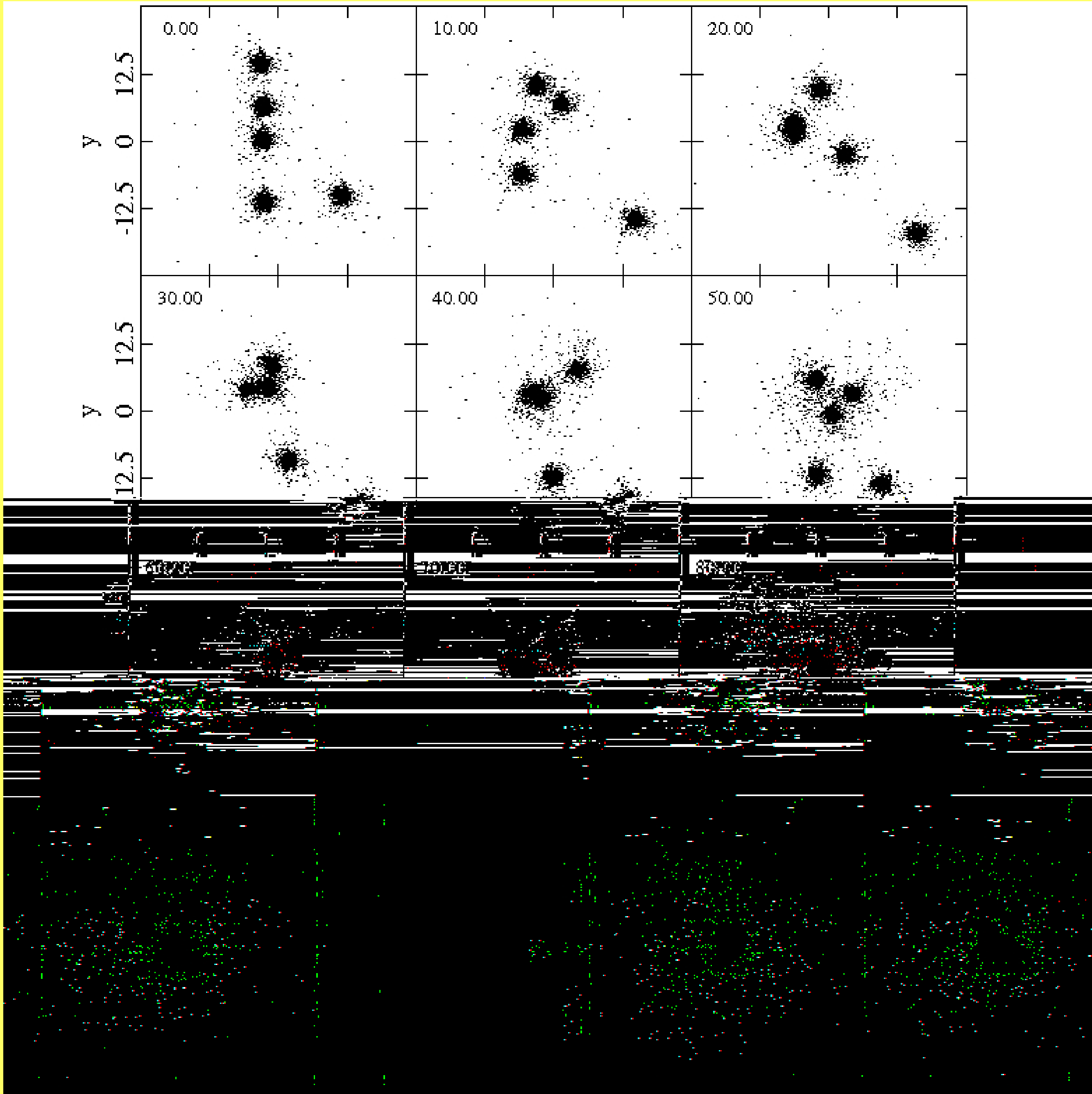
Radial

Circular



Hickson Compact Groups





Athanassoula, Makino, Bosma 1997

Athanassoula, Makino, Bosma (1997)

Groups of 5 identical elliptical galaxies
Common halo (CH) Individual halo (IH)

In general, groups with IH merge faster than groups with CH

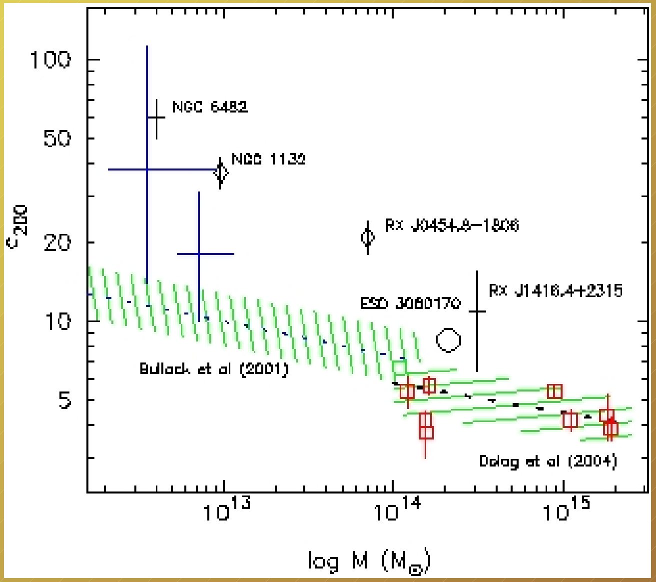
CH : If not centrally concentrated ==> merge slower
if also high M(CH) / M(tot) ==> merge yet slower

Group with a high halo-to total mass ratio and a density with very little central concentration ===> Survives without merging for more than a Hubble time

Khosroshahi, Ponman, Jones (2007, astro-ph/0702095)

Scaling relations in fossil galaxy groups

Chandra X-ray observations



The End

Fin

Einde

Ende

Telos