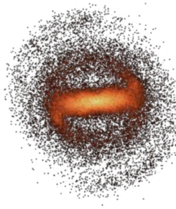
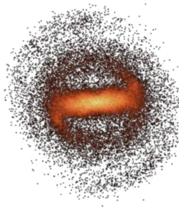


The buildup and dynamical evolution of galaxies

E. Athanassoula

Observatoire de Marseille

Outline



– Halo formation in the hierarchical scenario

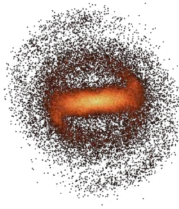
– Dynamical evolution of galaxies

– Formation of the bulge component

– Dark matter haloes in elliptical galaxies

– Bars as drivers of dynamical evolution

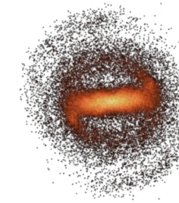
CDM



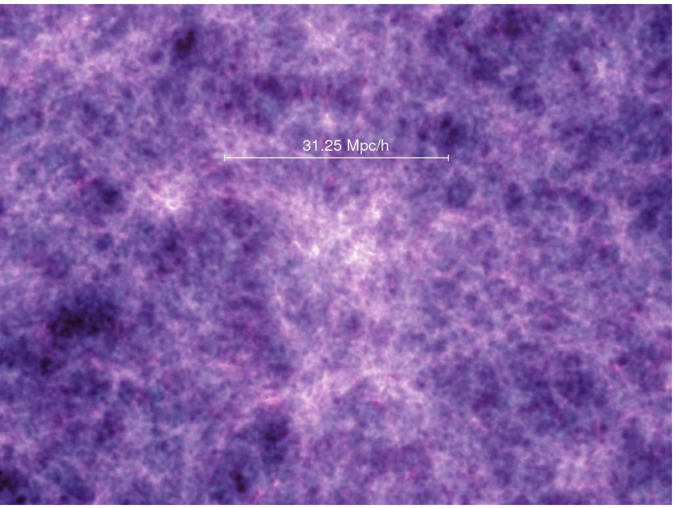
–LCDM has become the leading theoretical picture for the formation of structure in the Universe. It predicts that such structures grow hierarchically through gravitational instability. Structures grow as objects of progressively larger mass merge and collapse to form newly virialised systems.

Millennium simulation

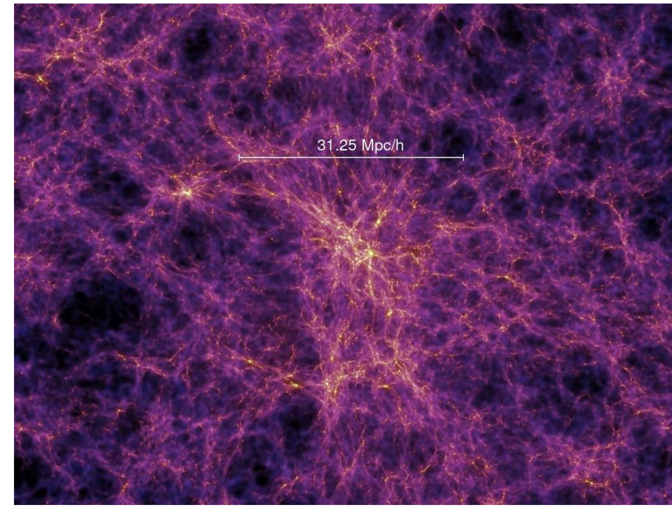
(Springel et al 2005)



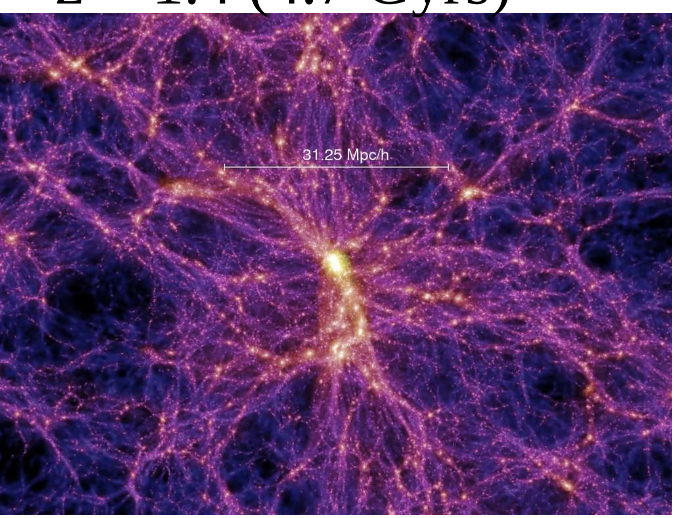
Z = 18.3 (0.21 Gyrs)



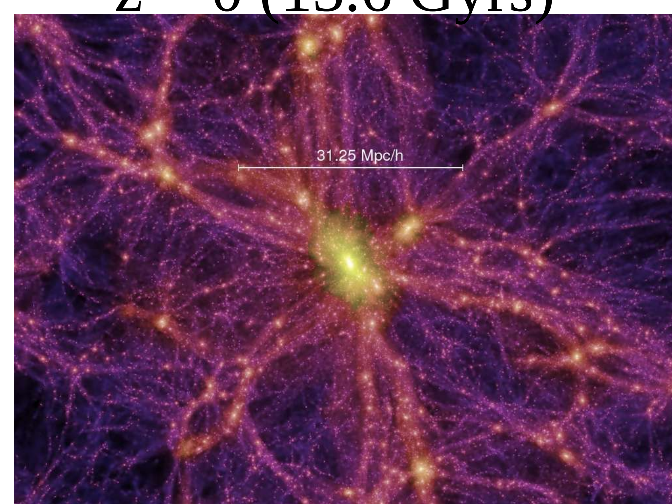
z = 5.7 (1 Gyrs)



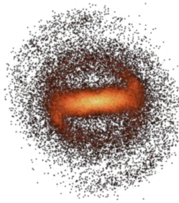
z = 1.4 (4.7 Gyrs)



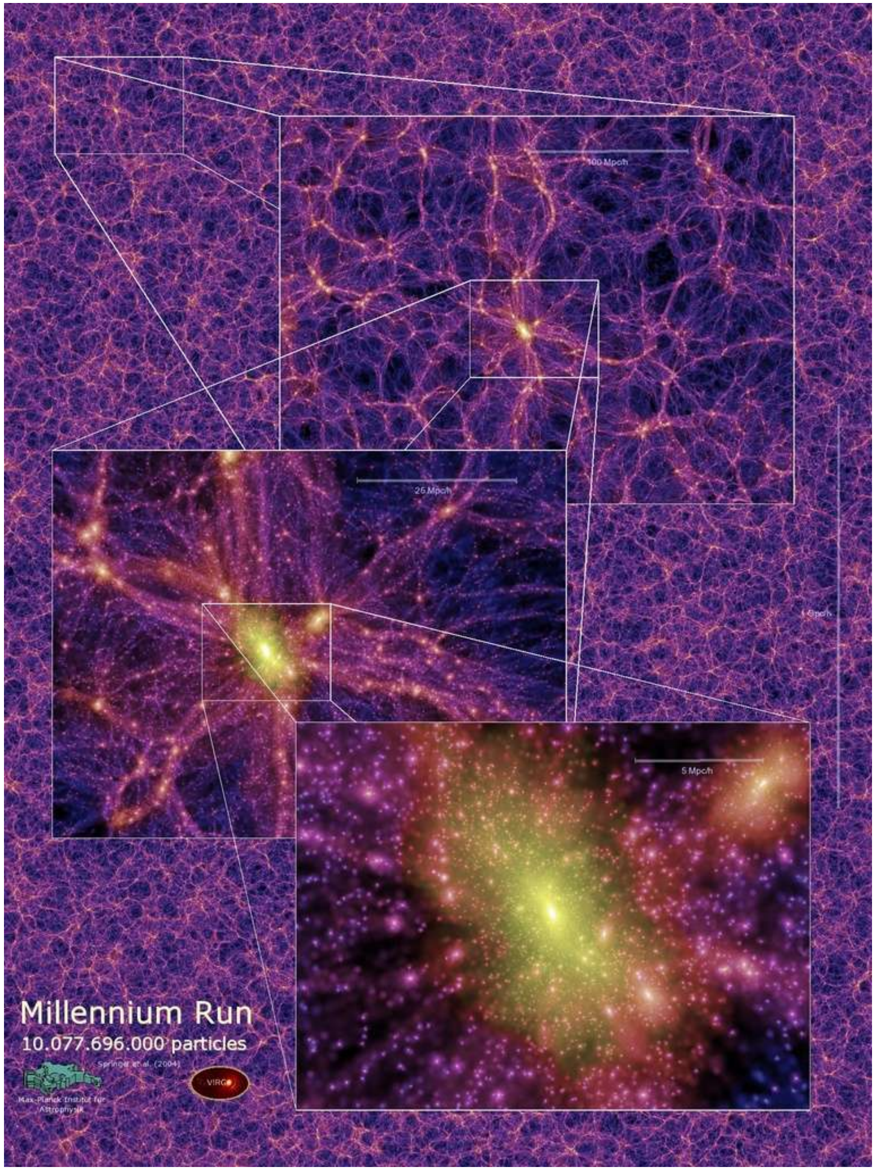
z = 0 (13.6 Gyrs)



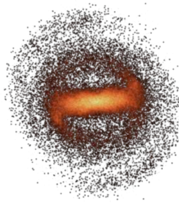
Millennium simulation

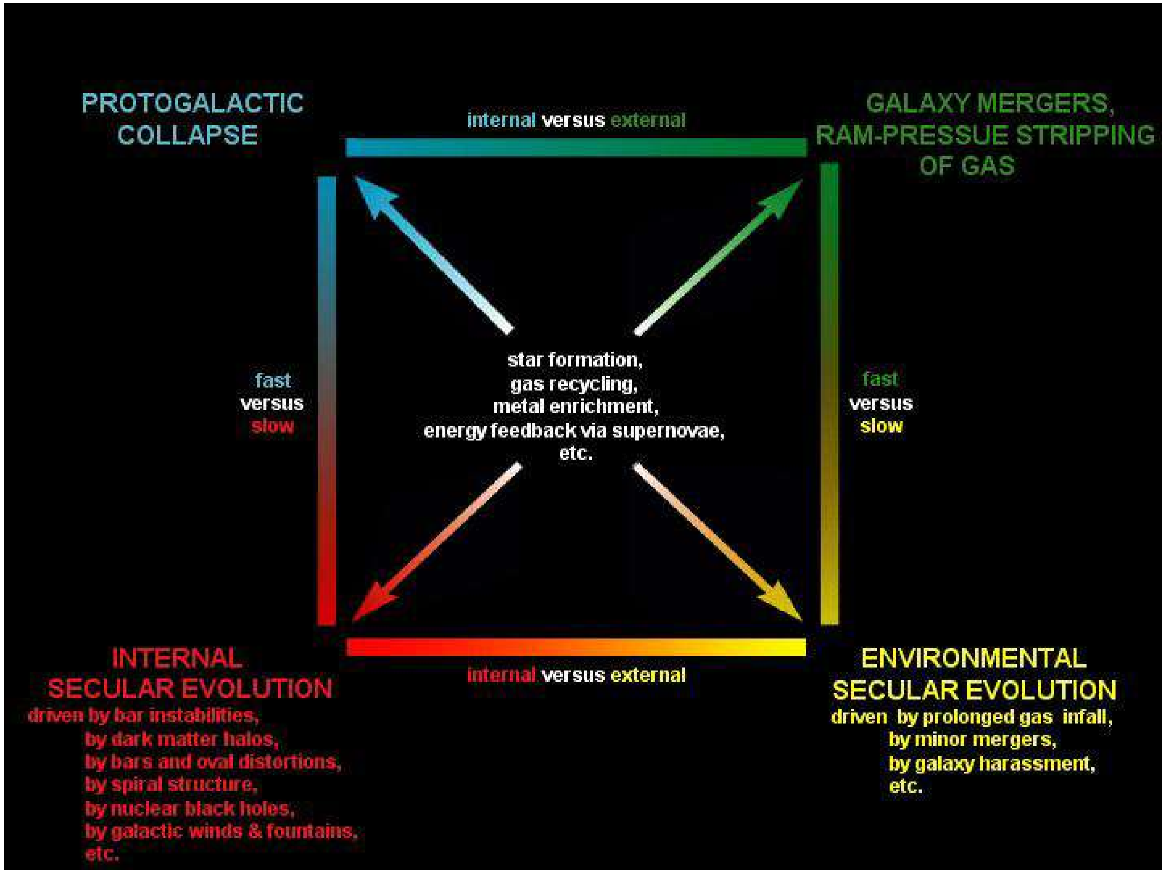


(Springel et al 2005)



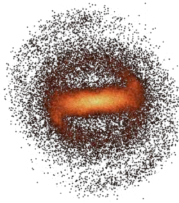
Galaxy Evolution





Zwicky (1957)
Kormendy (1982)
Kormendy & Kennicutt (2004)

Bulge definitions



Definition 1 :

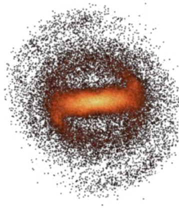
A smooth light distribution that swells out of the central part of a disc viewed edge-on

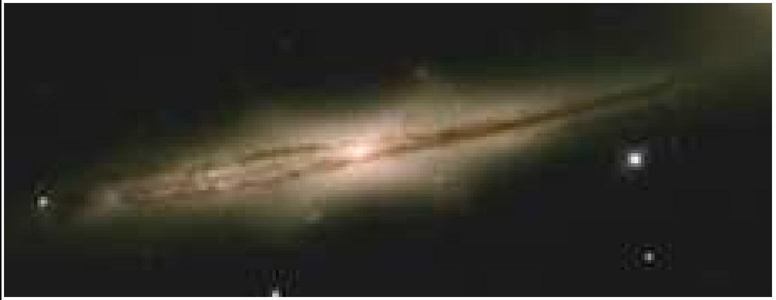
Definition 2 :

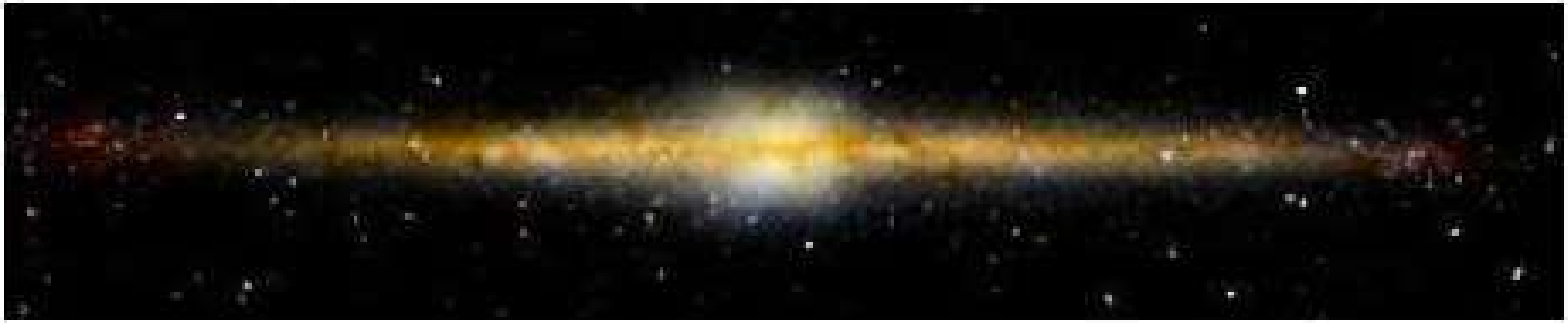
From photometric profiles

The bulge is identified as the extra light in the central part of the disc, above the extrapolated exponential fitting the remaining (non-central) part.

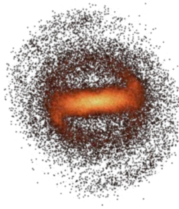
Bulges







Bulge definitions



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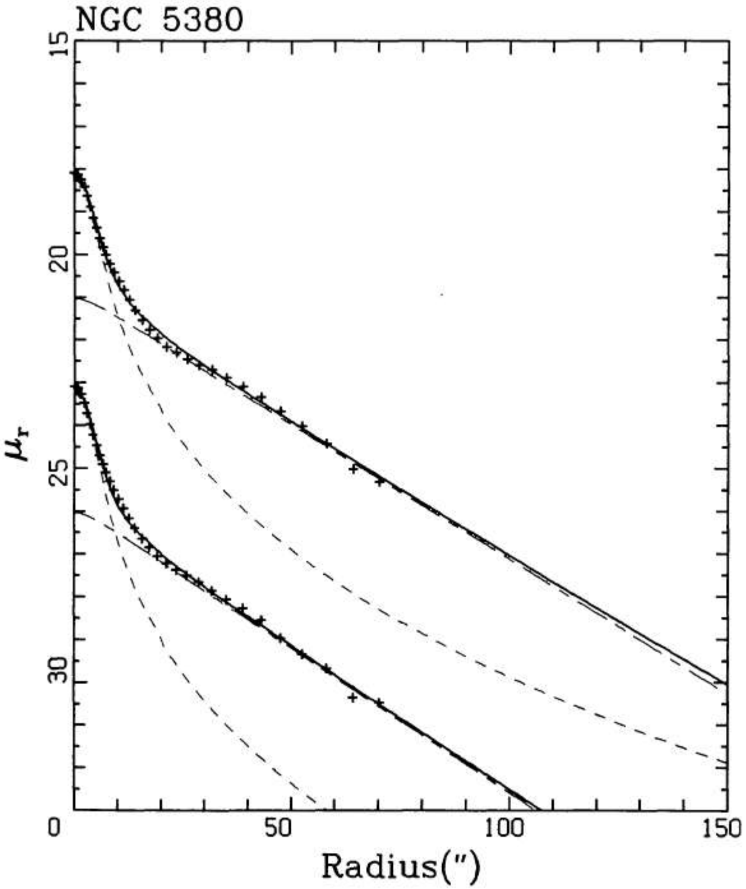
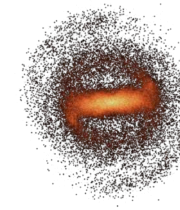


Types of bulges (1)



Three different types of bulges - distinguished via their formation histories (Athanassoula 2005)

1) Classical Bulges
Formed by gravitational collapse, or hierarchical merging and corresponding dissipative processes. Fast process and sometimes externally driven.

Examples : Steinmetz & Muller (1995), Steinmetz & Navarro (2002), Samland & Gerhard (2003), Sommer-Larsen et al (2003, 2004, 2005)

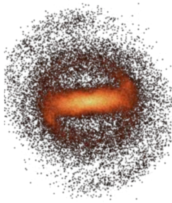
Variants : Noguchi (1998, 1999), Immeli et al (2004a, b), Pfenniger (1993), Athanassoula (1999), Aguerri, Balcells & Peletier (2001), Fu, Huand & Deng (2003)

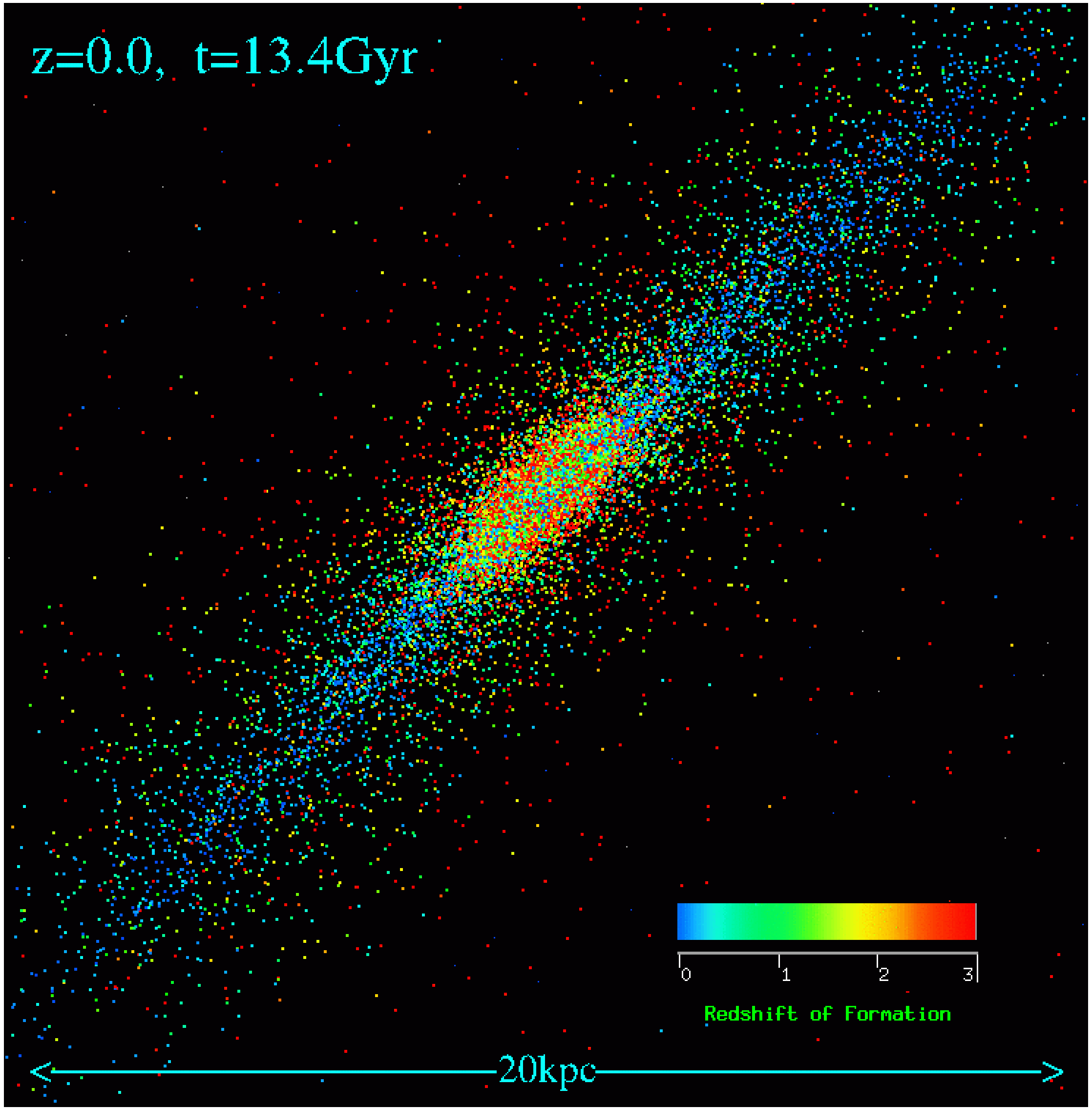
Similarities to elliptical galaxies : photometrical radial profiles, kinematics, stellar populations

2) Box/peanut bulges
They are parts of bars seen edge-on

3) Discy-bulges
Inflow of gas to the central regions and subsequent star formation

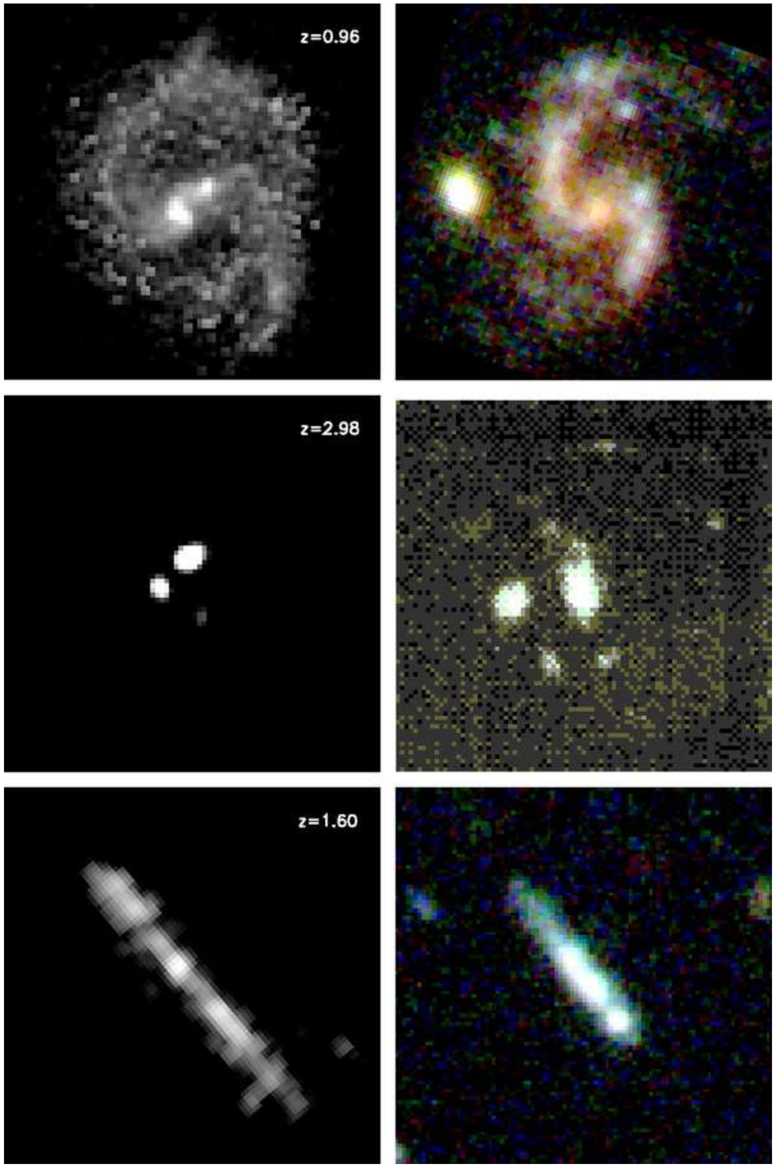
Formation of classical bulges : collapse and merging

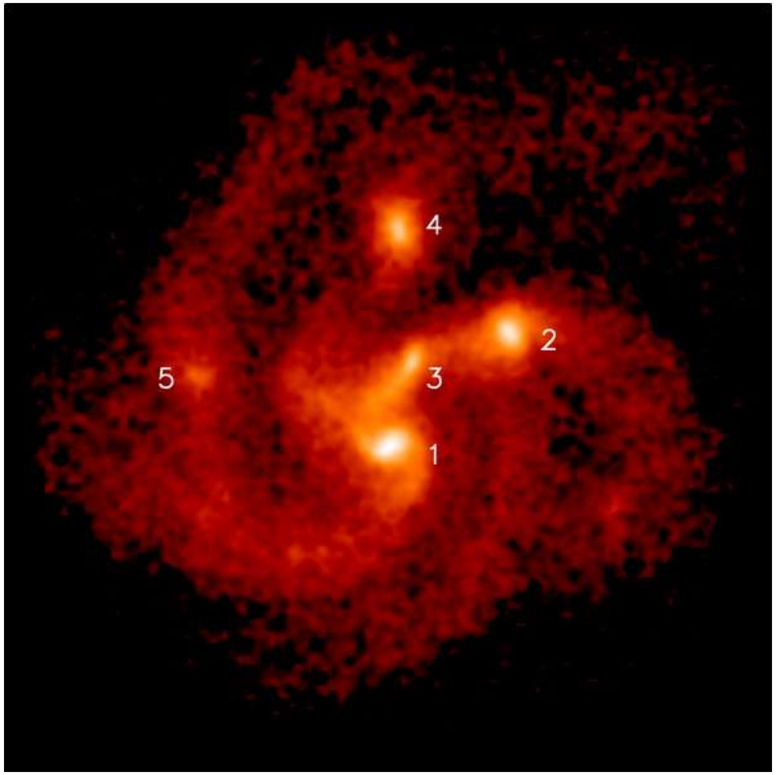




Sommer-Larsen et al (2005)

Classical bulge formation from clumps in the proto-disc

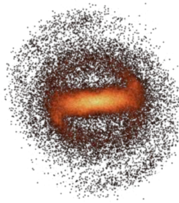


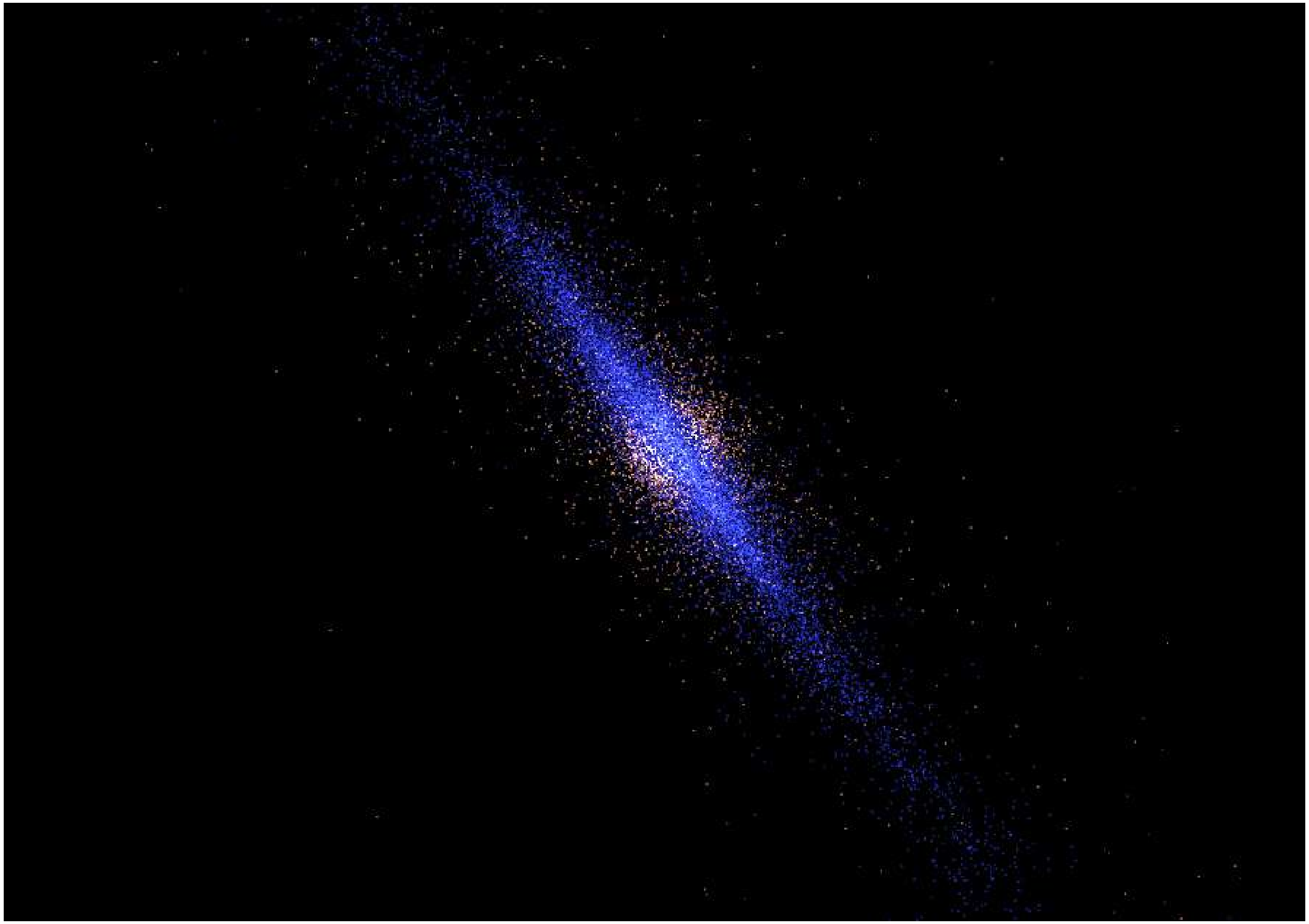


Noguchi (1998, 1999)

Immeli et al (2004a,b)

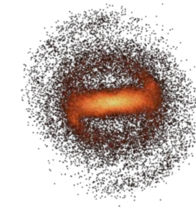
Classical bulge formation : companion infall





Athanassoula (1999)

Types of bulges (2)



Three different types of bulges - distinguished via their formation histories (Athanassoula 2005)

1) Classical Bulges

2) Box/peanut bulges
They are parts of bars seen edge-on. Relativelly slow formation process and slow evolution. Internal process.

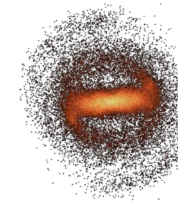
N-body simulations : Combes & Sanders 1981; Combes et al 1990; Raha et al 1991; Athanassoula & Misiriotis 2002; Athanassoula 2003; O'Neil & Dubinski 2003; Athanassoula 2005

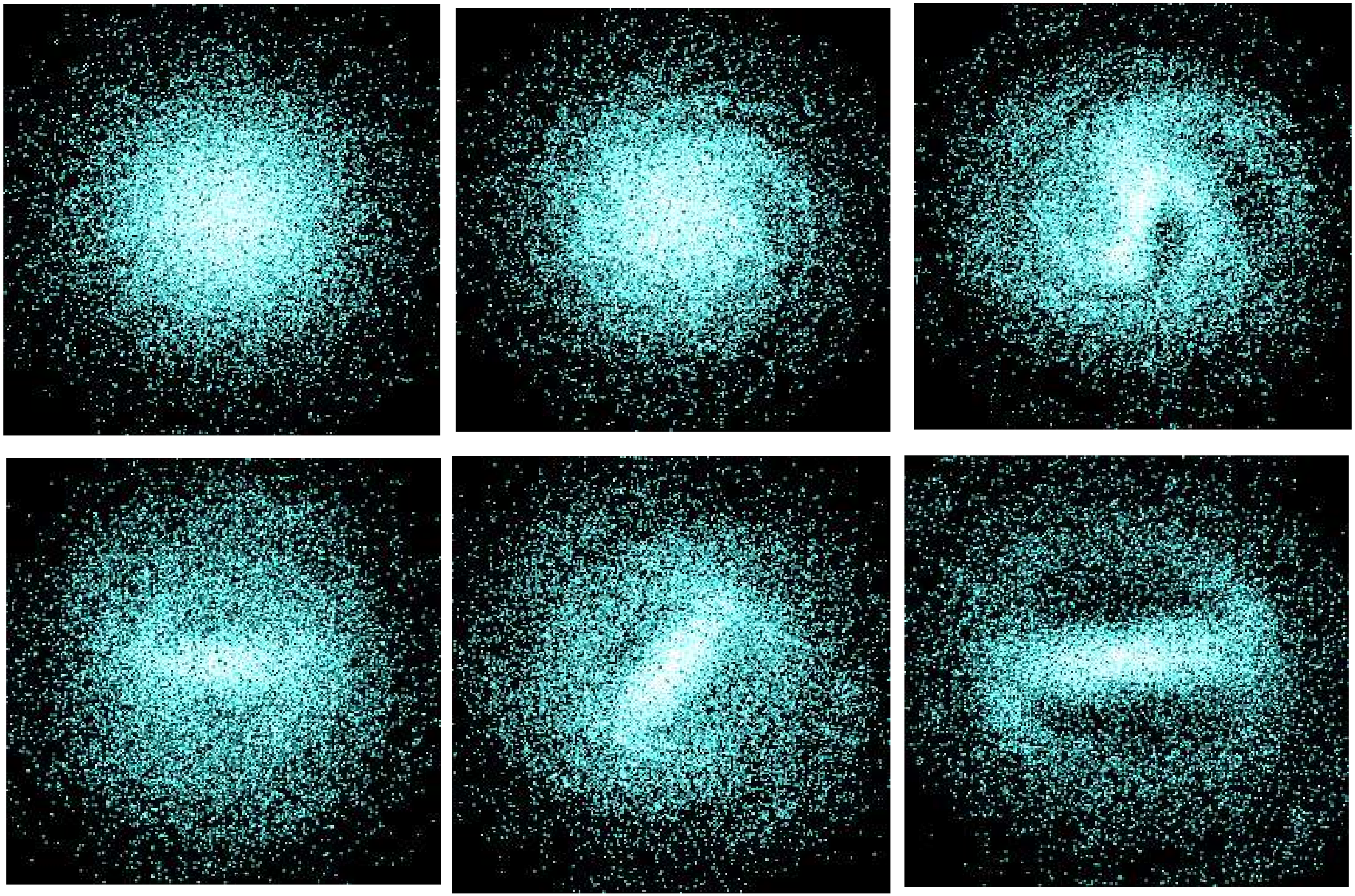
Orbital structure : Pfenniger 1984; Skokos, Patsis & Athanassoula 2002a,b; Patsis, Skokos & Athanassoula 2002, 2003

Observations and comparison with simulations : Bureau & Freeman 1999; Bureau & Athanassoula 1999, 2005; Athanassoula & Bureau 1999; Chung & Bureau 2004

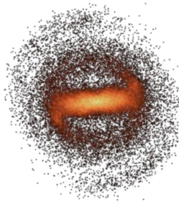
3) Discy-bulges
Inflow of gas to the central regions and subsequent star formation

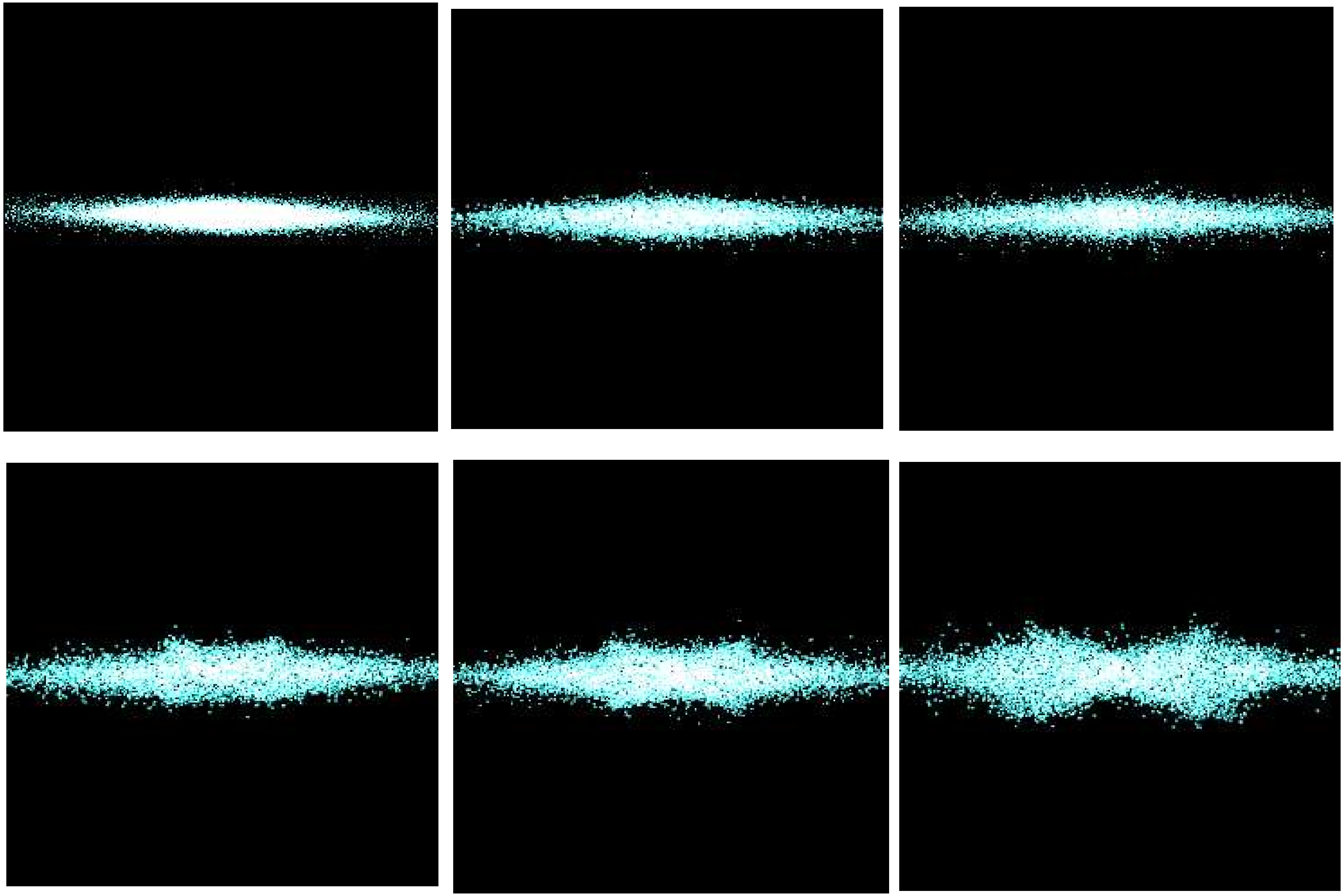
Time evolution
Face-on view



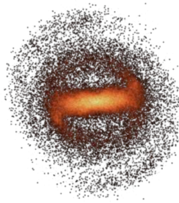


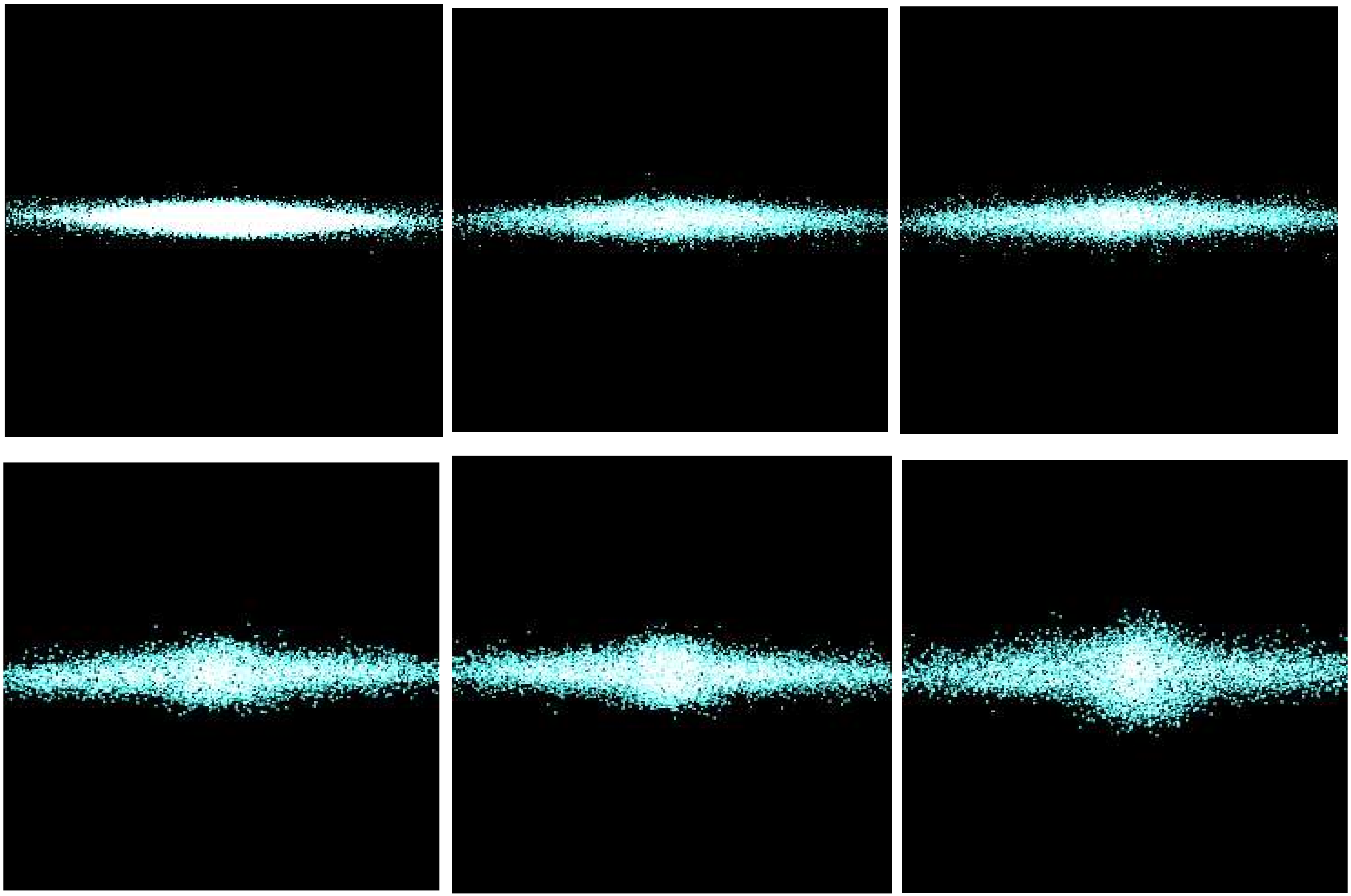
Time evolution
Side-on view



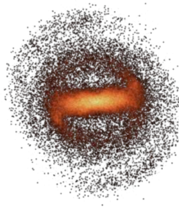


Time evolution
End-on view

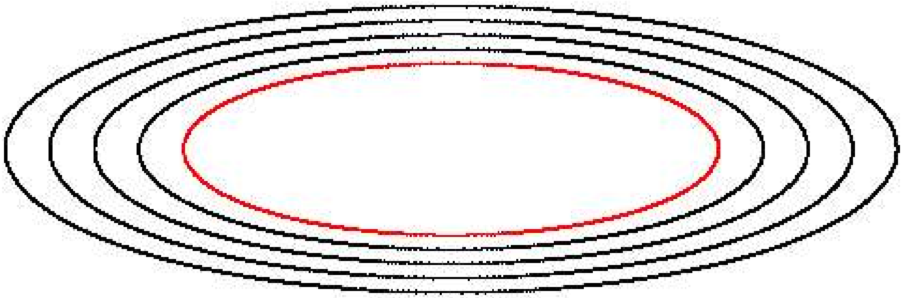




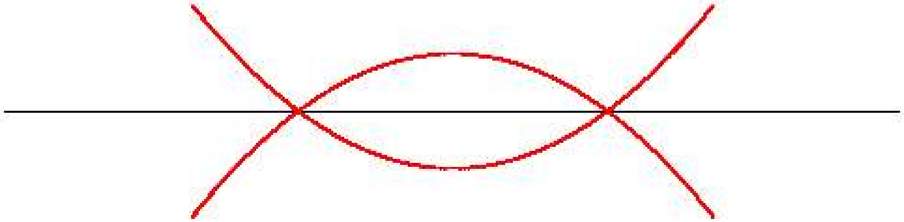
Orbits (schematic)

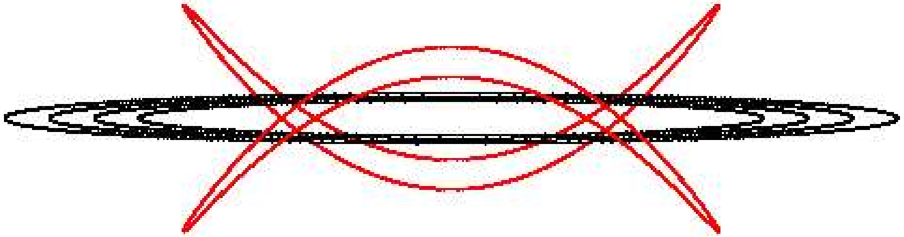


Face-on



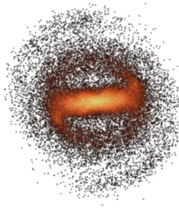
Edge-on

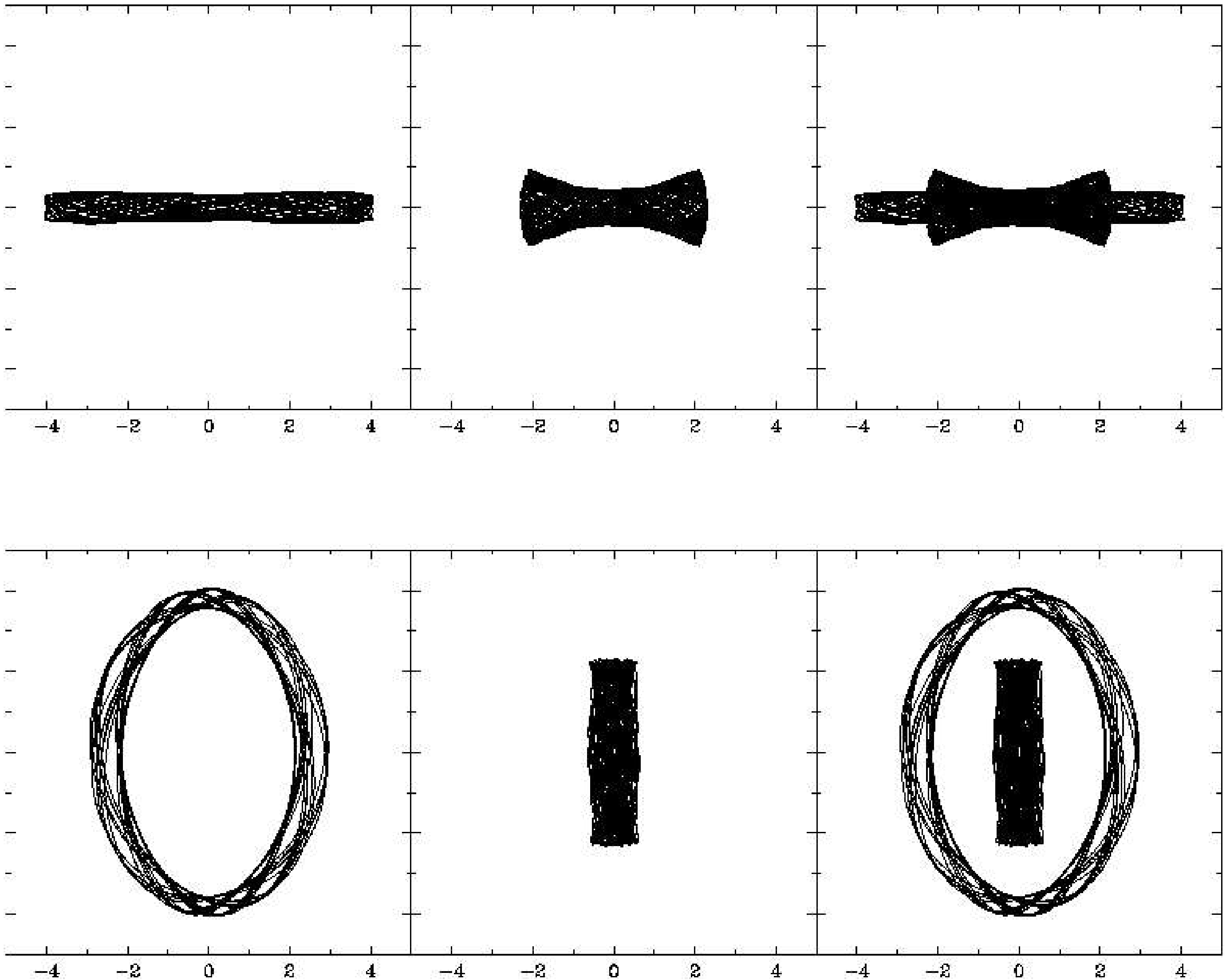




At an angle

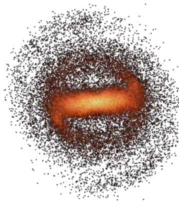
Orbits (cont.)



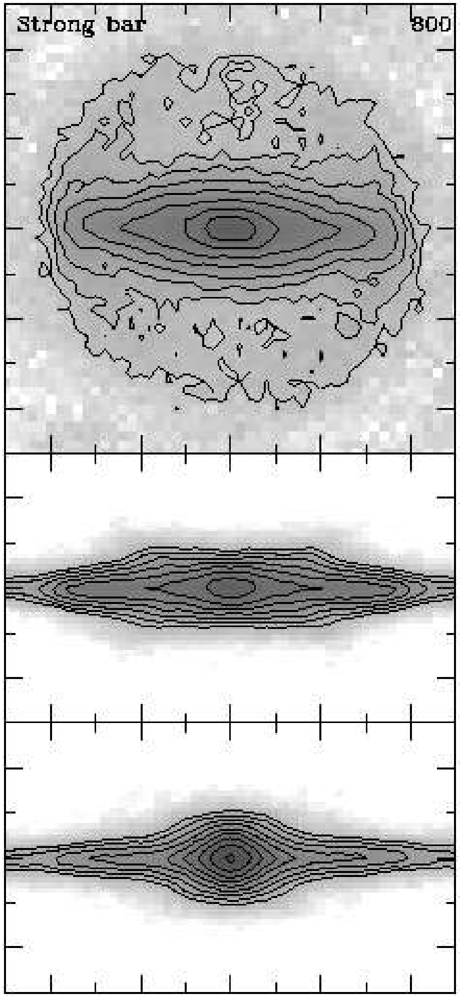


Athanassoula 2005

N-body simulations



A bar seen :



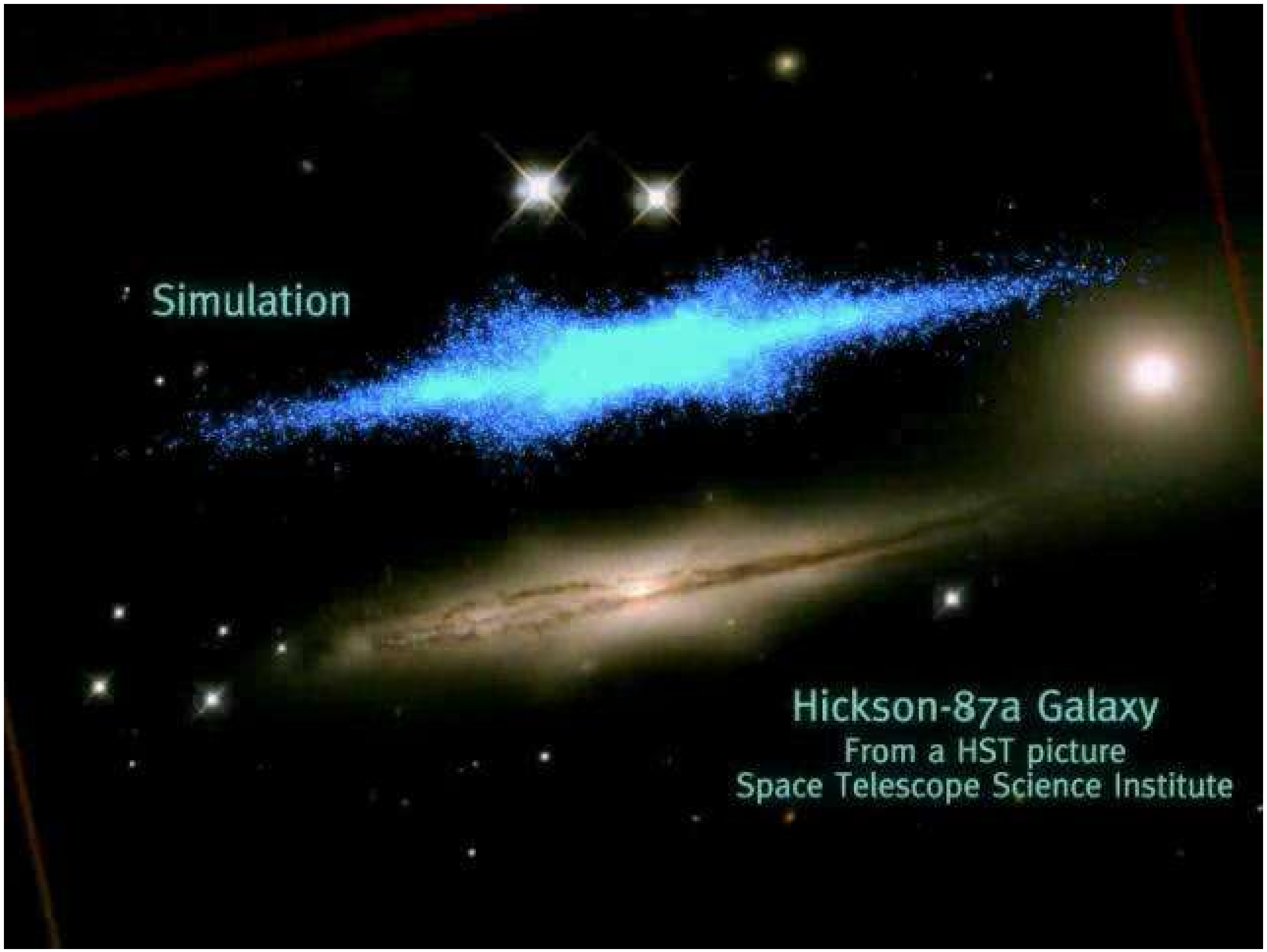
Face-on

Edge-on and side-on

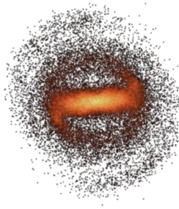
Edge-on and end-on

Athanassoula 2005

N-body simulations



Box/peanut bulges are just parts of bars seen edge-on



Comparing simulations viewed edge-on with observations :

Morphology

Photometry

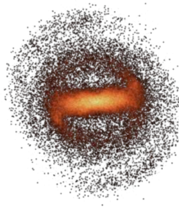
- Radial profiles (Athanassoula and Misiriotis 2004)
- Unsharp masking (Aronica, Athanassoula, Bureau, Bosma et al 2003, Athanassoula 2004)

Kinematics

- 'Cylindrical rotation' (Athanassoula and Misiriotis 2002)
- PVDs (Bureau and Athanassoula 2004, Athanassoula 2004)
- V/ sigma (Debattista, Carollo, Mayer and Moore 2004)

see Kormendy and Kennicutt 2004 for other references

Types of bulges (3)



Three different types of bulges - distinguished via their formation histories (Athanassoula 2005)

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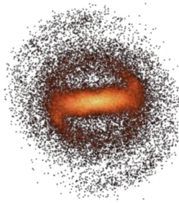
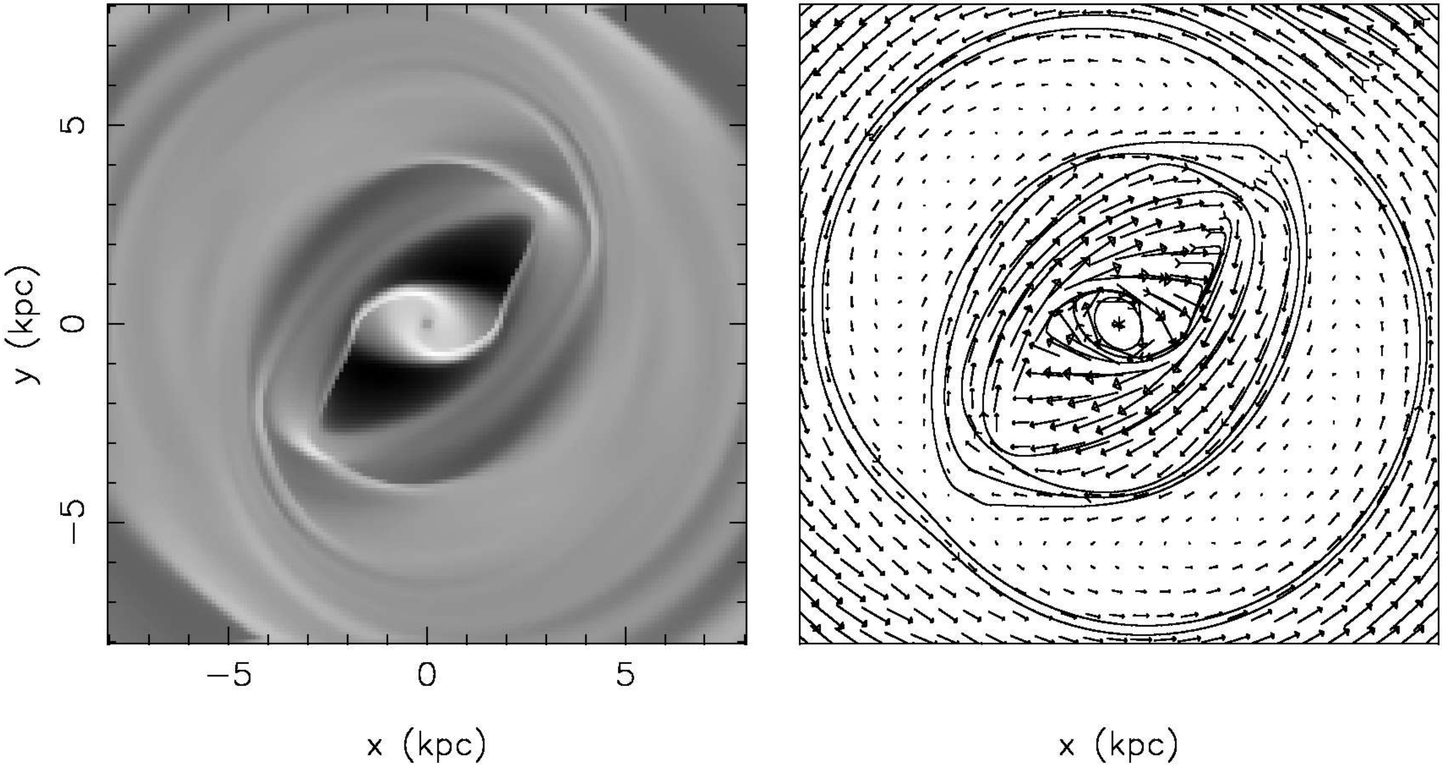
3) Discy-bulges
Inflow of gas to the central regions and subsequent star formation

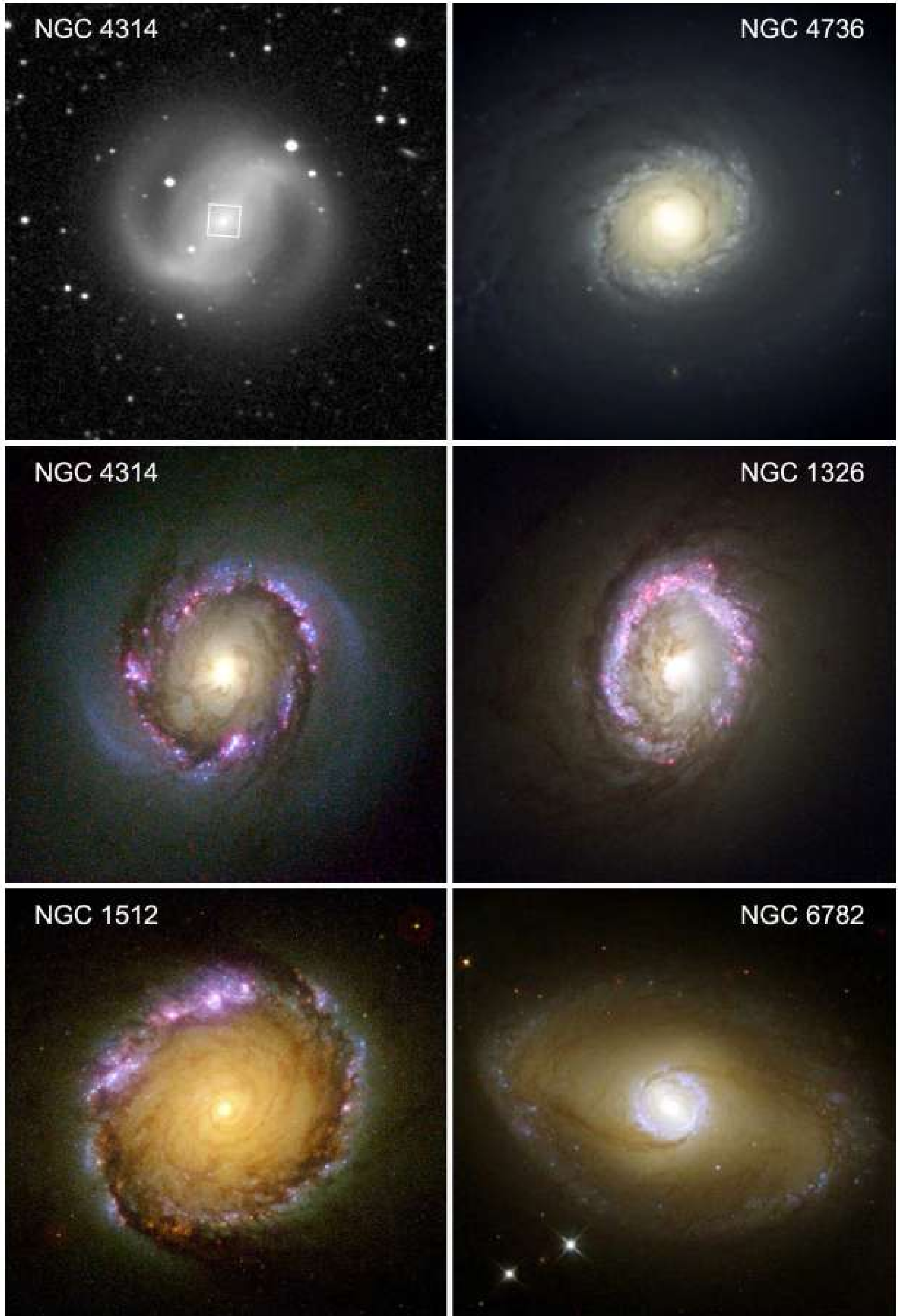
Observations : Carollo, Stiavelli & Mack 1998; Carollo & Stiavelli 1998; Kormeny 1993; Kormendy & Kennicutt 2004

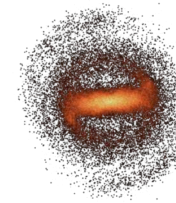
Simulations : Athanassoula 1992; Friedli & Benz 1993; Heller & Shlosman 1994; Regan & Teuben 2004

Gas inflow

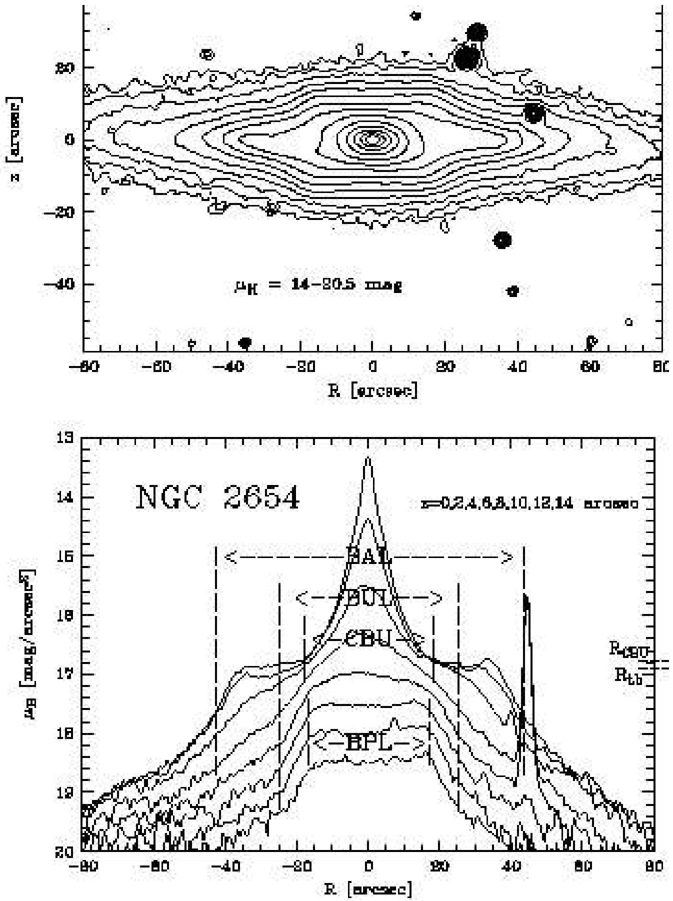




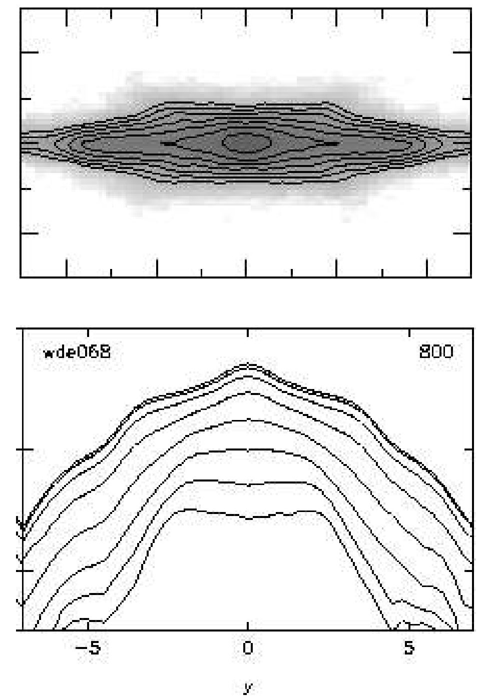

NGC 4314
NGC 4736
NGC 4314
NGC 1326
NGC 1512
NGC 6782



Horizontal cuts

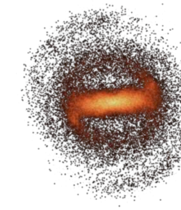


Lutticke, Dettmar and Pohlen, 2000



Athanassoula 2005 (also Athanassoula and Misiriotis 2002)

Summary (bulge types)



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They are parts of bars seen edge-on

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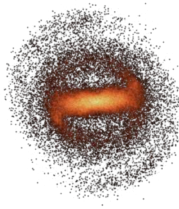
Inflow of gas to the central regions and subsequent star formation

In many cases their observational properties should allow us to distinguish them

But beware : More than one type of bulge can co-exist in the galaxy

Dark matter haloes in elliptical galaxies



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

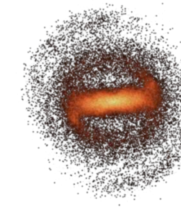
Many observations (X-ray, gravitational lensing, etc etc) argue that ellipticals are also embedded in dark matter haloes

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 :

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

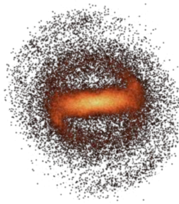
$$\alpha \equiv -dln\rho/dlnr$$

$$\gamma \equiv -dln\sigma_r^2/dlnr$$

$$\beta = \begin{cases} -\infty & : \ circular \\ 0 & : \ isotropic \\ +1 & : \ radial \end{cases}$$

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

Merging in S-S pairs



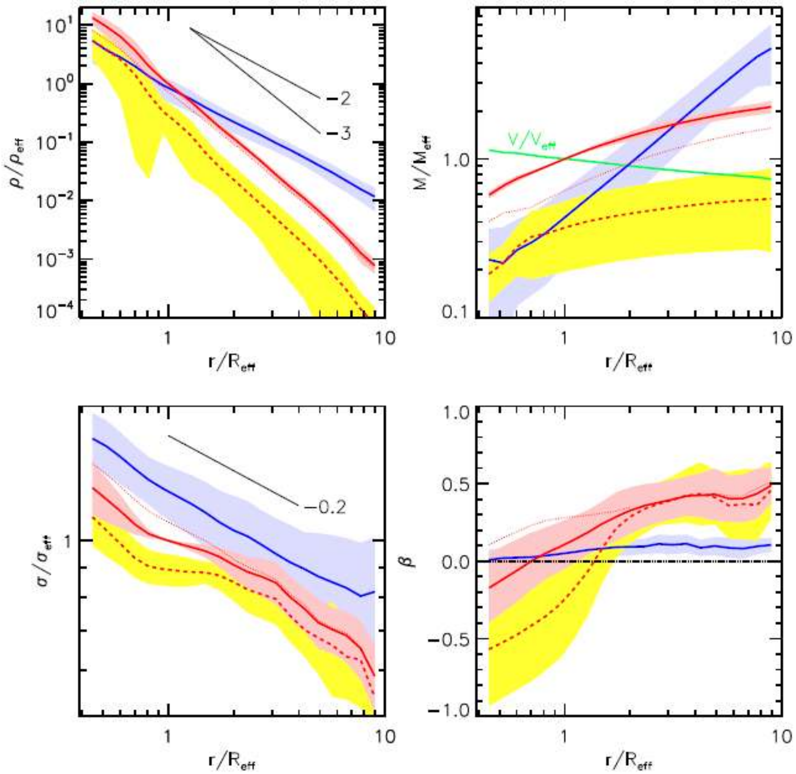
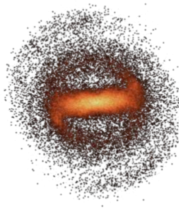


Figure 1. Three-dimensional profiles of the simulated merger remnants. Ten galaxies at two different times after the merger (typically 0.8 and 1.3 Gyr) are stacked together. Dark matter (blue) versus stars (red), divided into the old ones from the progenitors (dotted) and those newly formed during the merger (dashed). The scaling is such that the curves for the stars (all, solid red) are matched at $R_{\rm eff}$. The shaded areas mark 1σ scatter. The panels refer to density ρ, mass M and circular velocity V, velocity dispersion σ and anisotropy β, with "eff" referring to the quantities at $R_{\rm eff}$.

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)

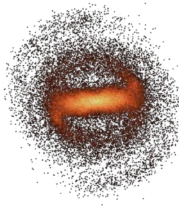
5 E : spherical; all galaxies identical; with (or without) a common halo

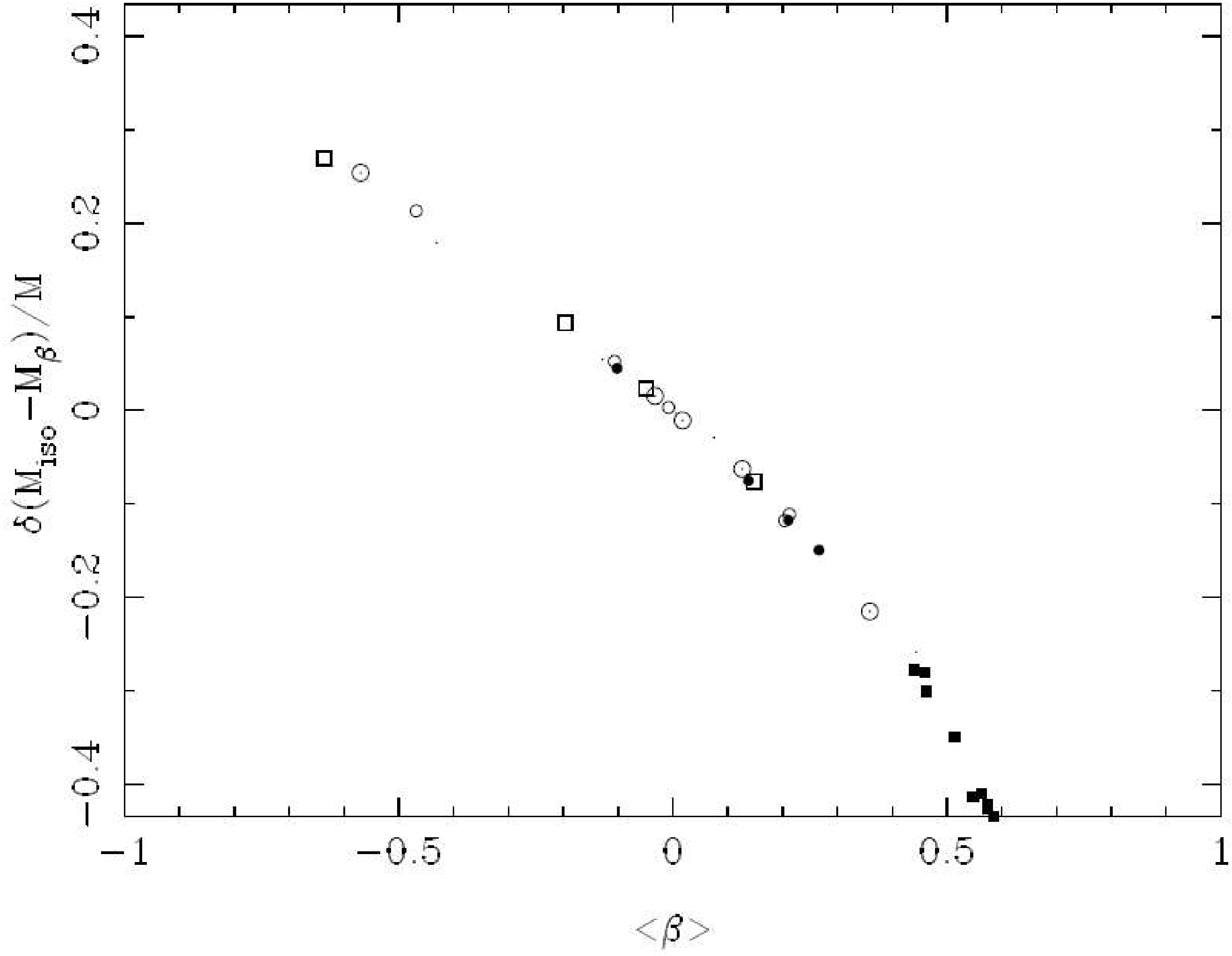
~ 35 simulations

~ 1 to 2 million particles per simulation

Athanassoula 2005

Anisotropic ellipticals

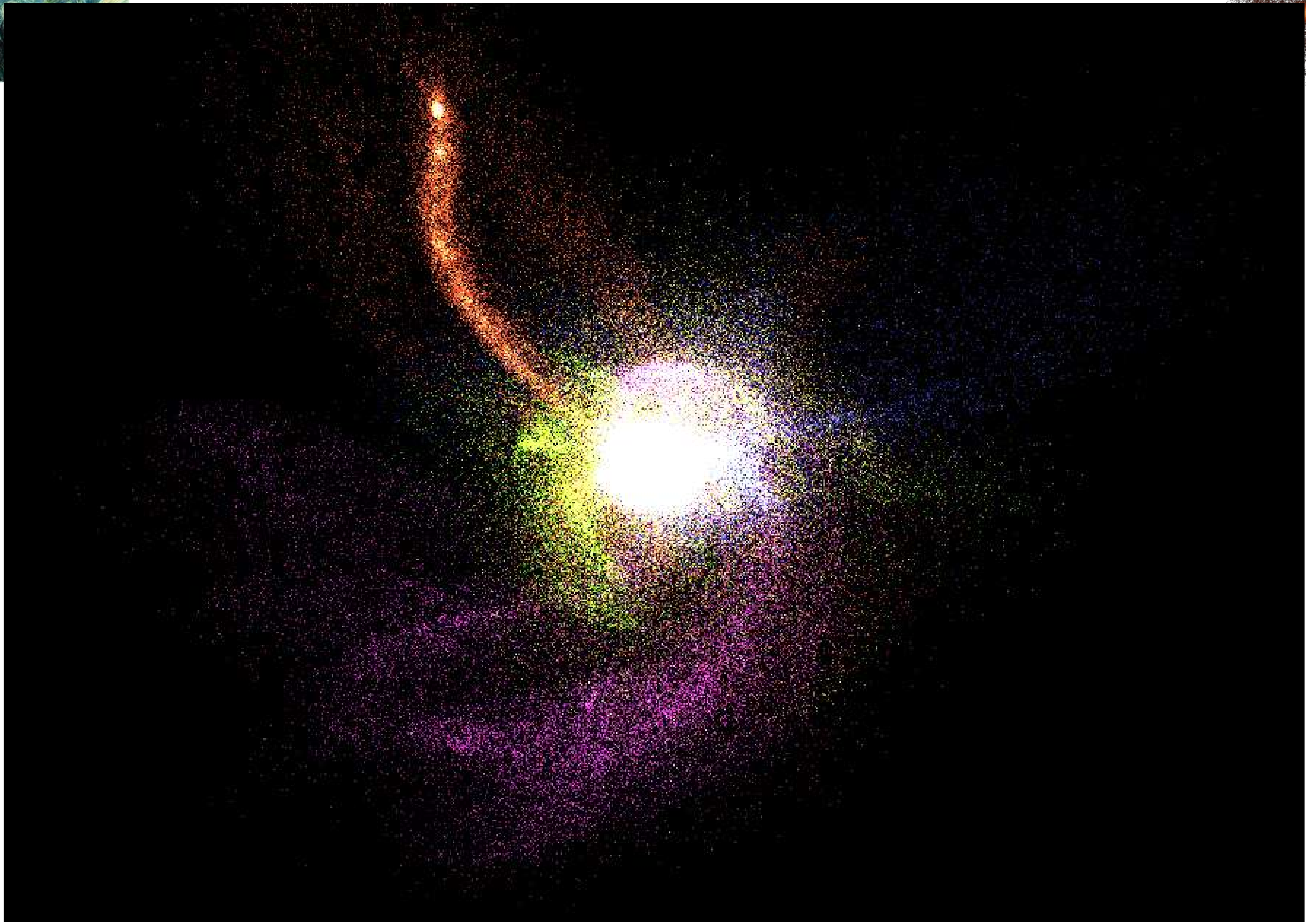


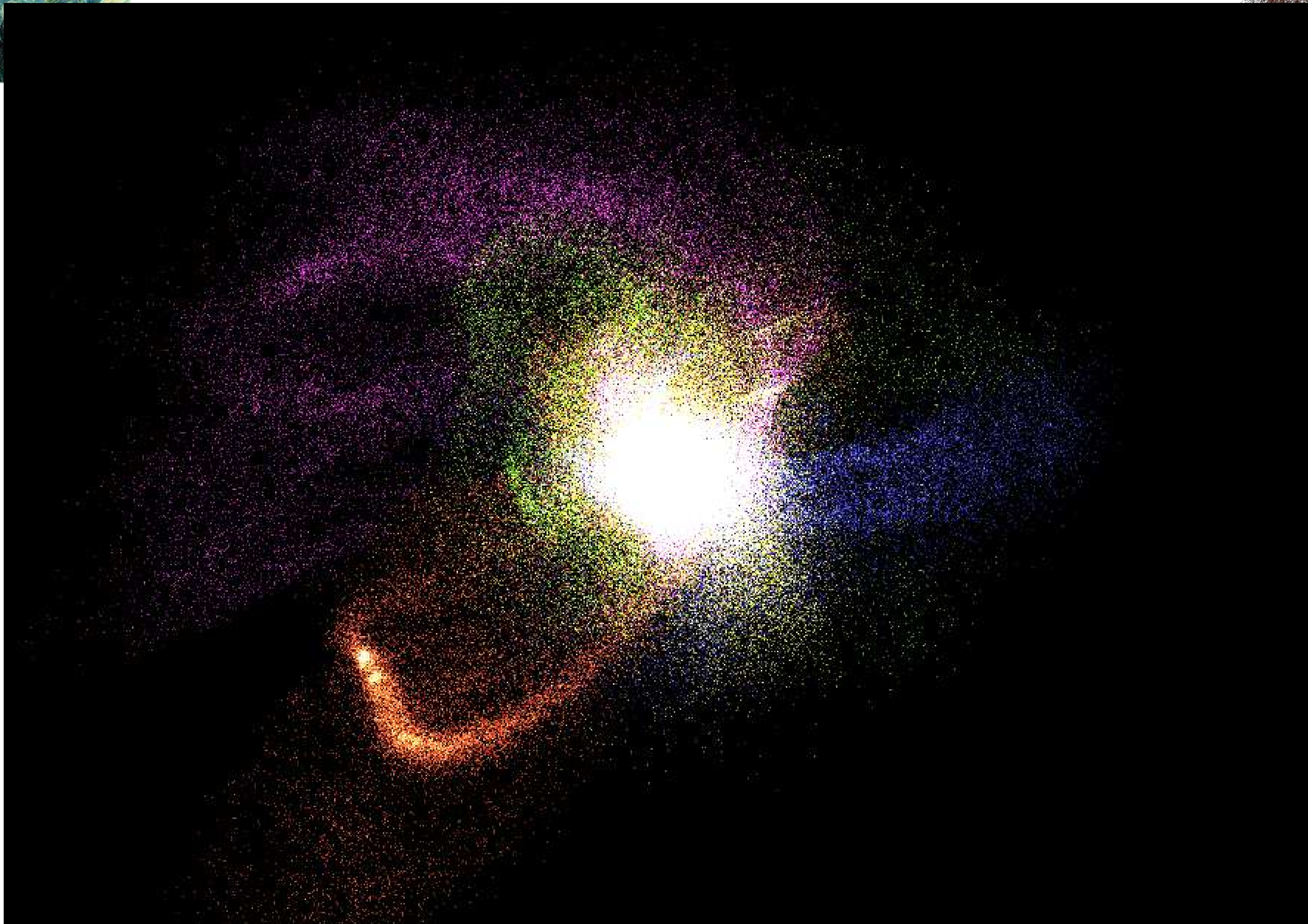


< Circular

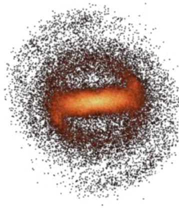
Radial >





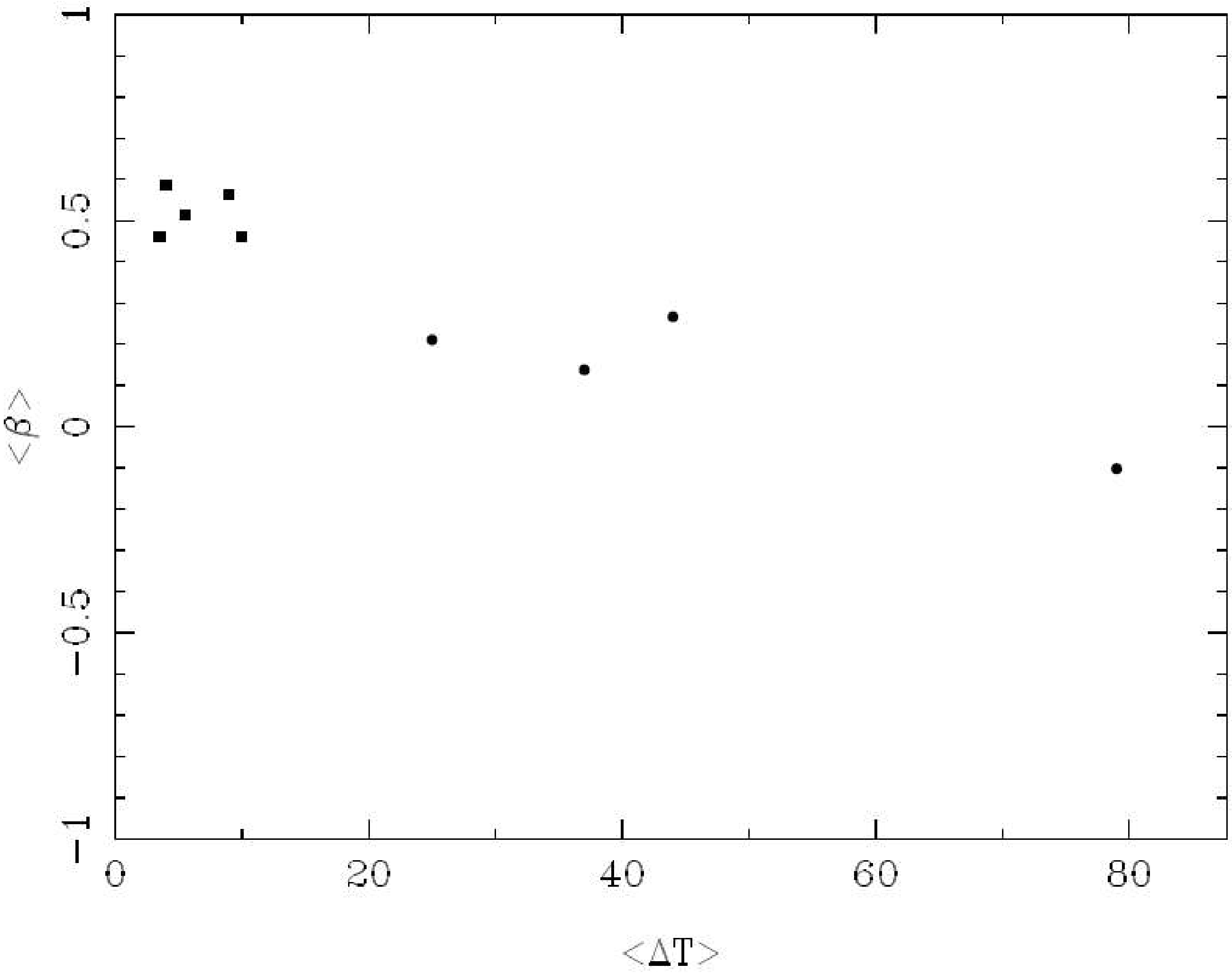


Anisotropic ellipticals

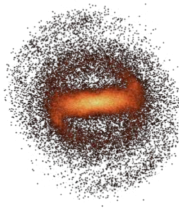


Radial

Circular



Anisotropic ellipticals



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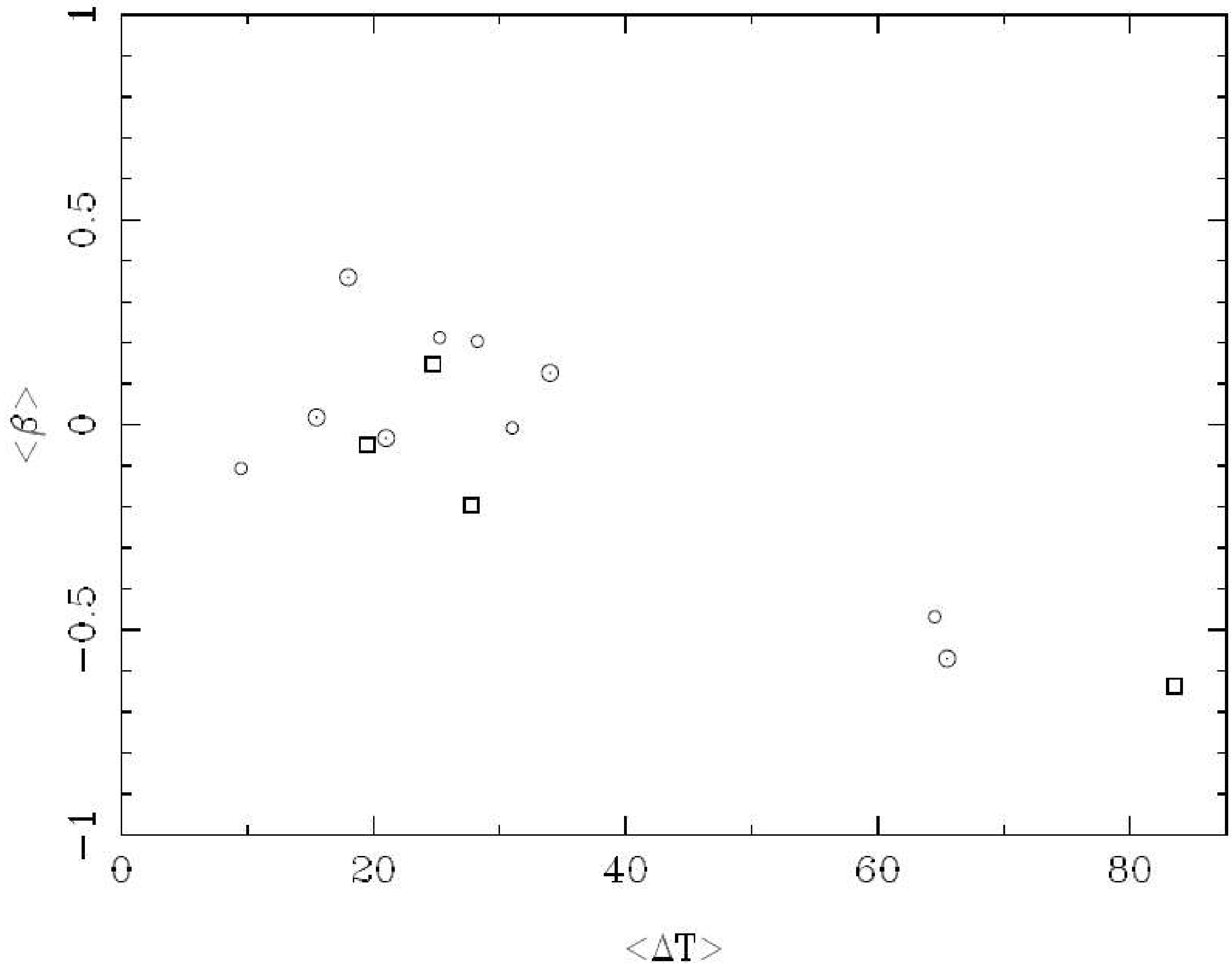
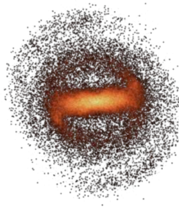
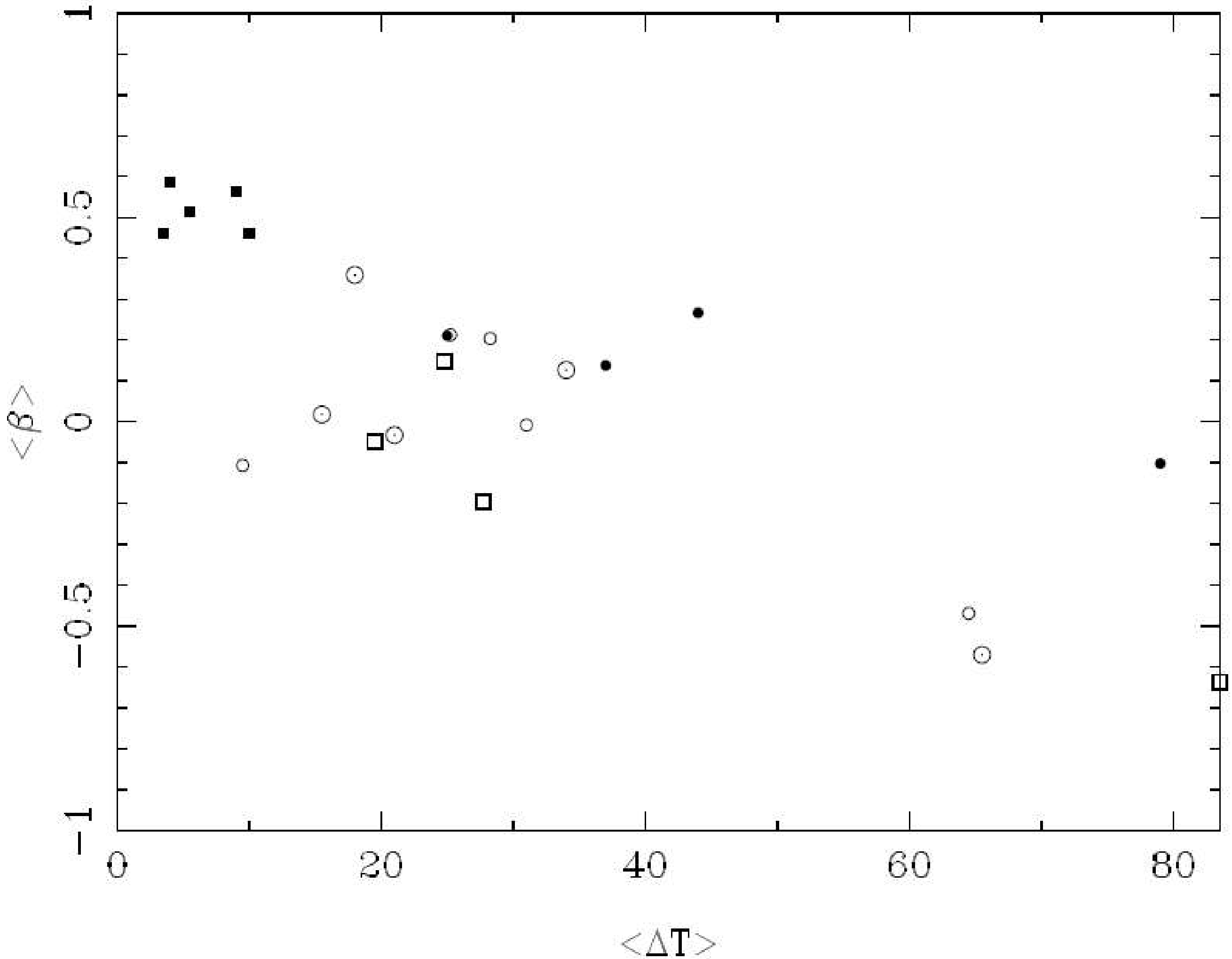


Circular

Anisotropic ellipticals

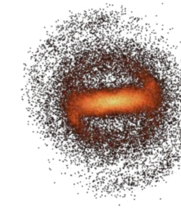


Radial



Circular

Bars

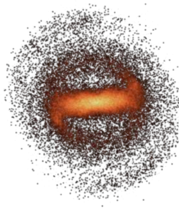


Dynamical systems evolve in the direction of increasing entropy.
Disc galaxies achieve this by transferring their angular momentum outwards.
This can be done by non-axially-symmetric perturbations, as e.g. bars.

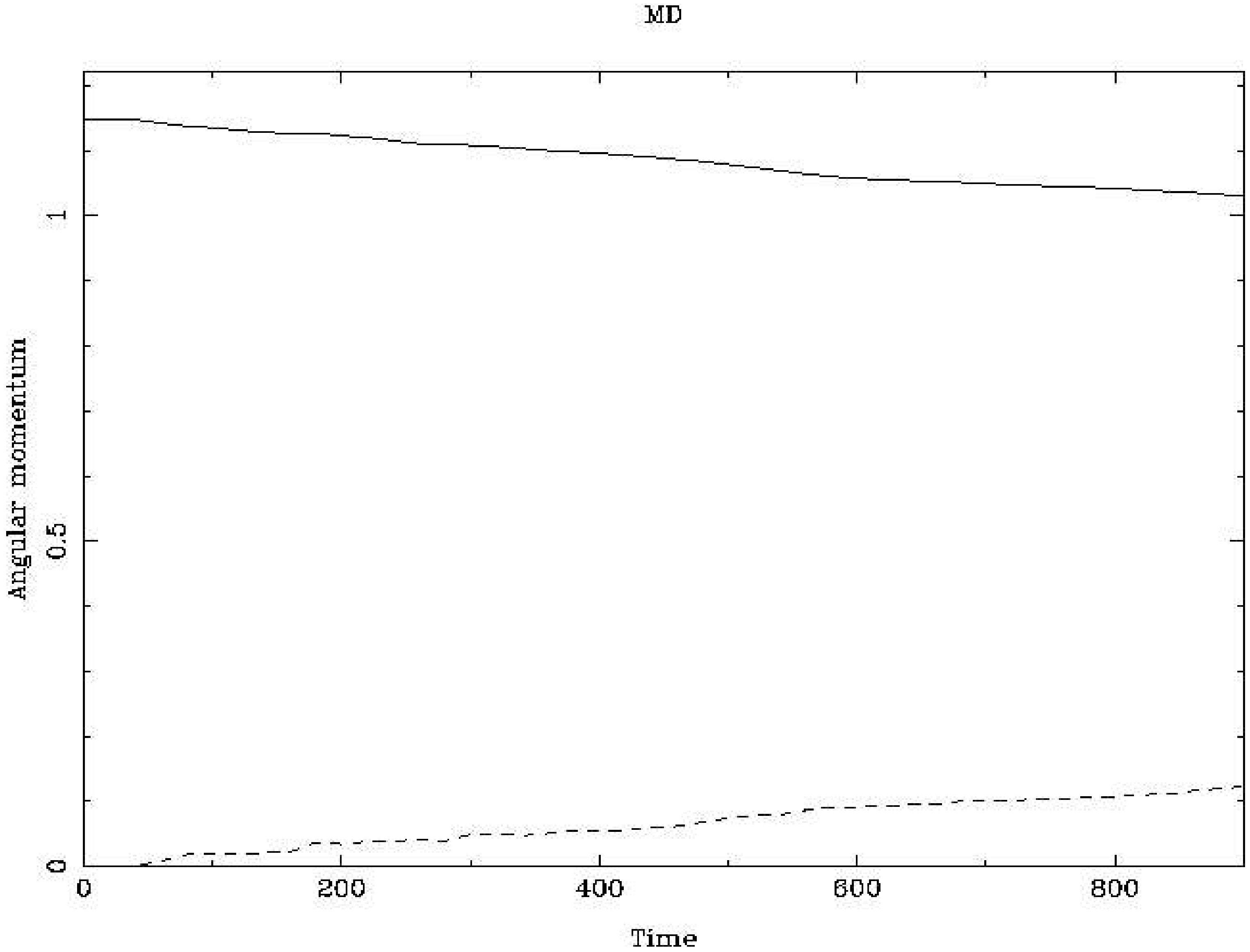
Bars, by transferring angular momentum outwards, will increase their strength.

Angular momentum exchange drives the dynamical evolution of barred galaxies.

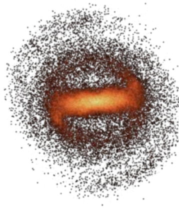
Angular momentum transfer

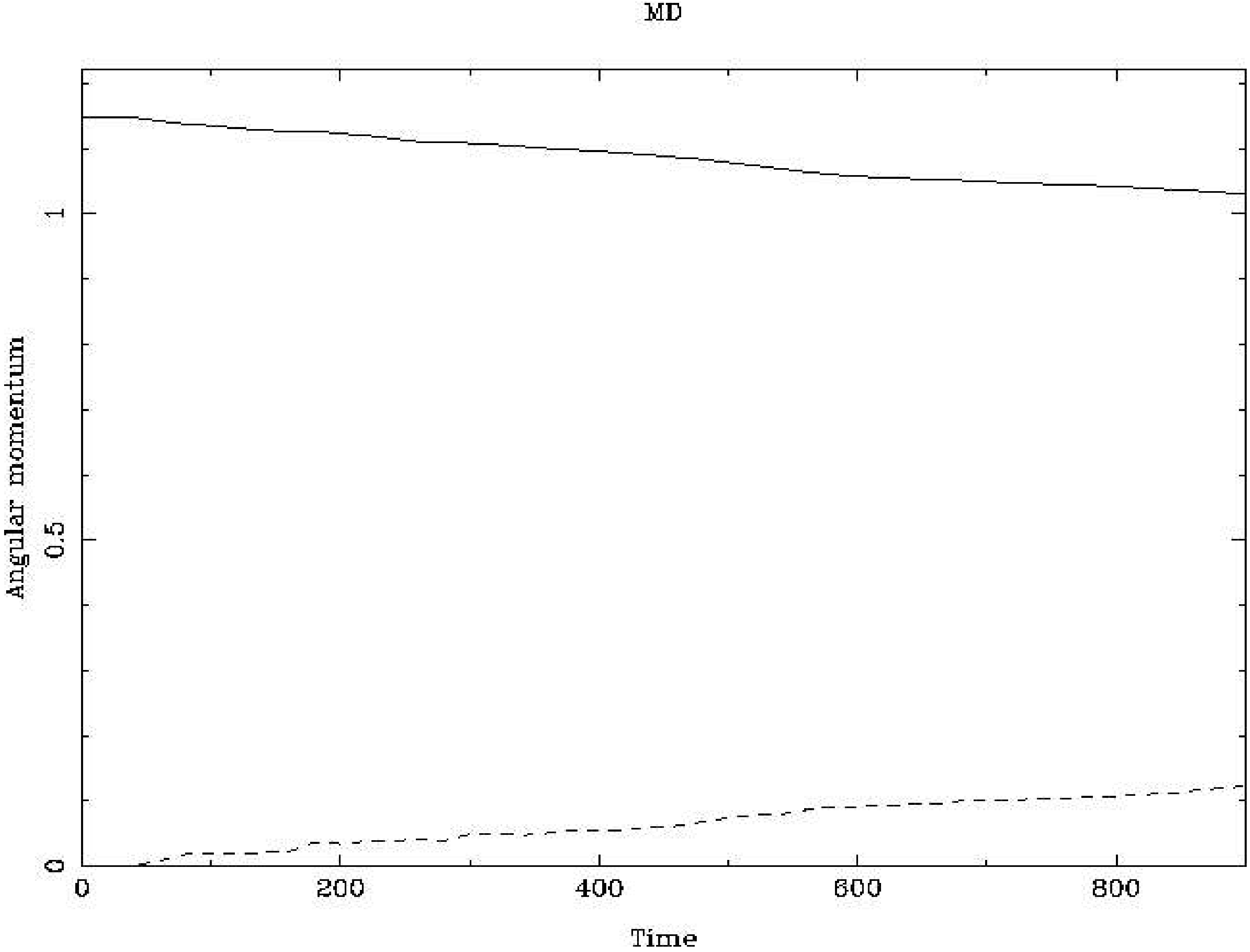


in disc



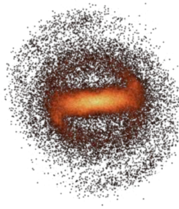
Angular momentum transfer

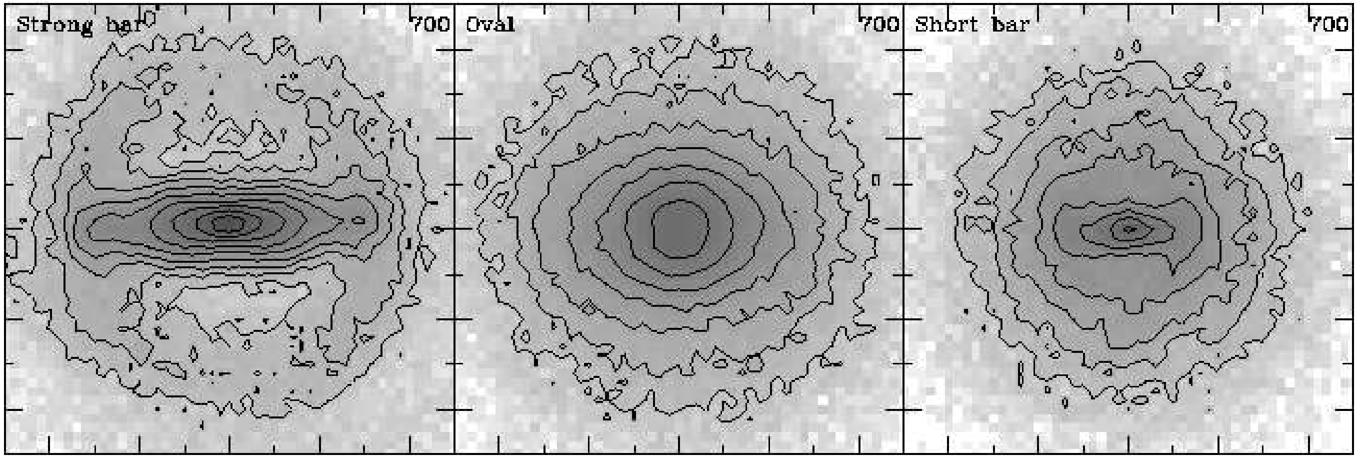




in halo

Bar morphology





Considerable amount of angular momentum is exchanged

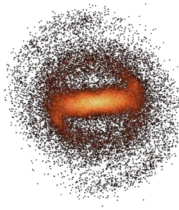
Little angular momentum exchanged

Responsive halo

Hot halo

Hot outer disc

Bar driven secular evolution



Bar driven secular evolution :

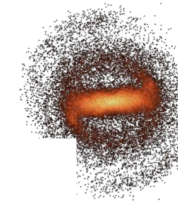
Bars grow longer, thinner and more massive with time; i.e. stronger

Their pattern speed decreases

They drive angular momentum outwards. In particular this will give some net rotation to haloes, in the same sense as the bar rotation

They drive material within corotation inwards, thus resulting to an enhanced central concentration of the disc, both for the stellar and gaseous component. This extra gas can, at least in some cases, 'feed the monster'

They drive spirals and heat the disc



The End