



Formation and evolution of galactic
structures:
Nature versus nurture

Input from theory and simulations

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LAM/OAMP
Marseille



- Incomplete
- Reflect the opinion of the reviewer.
- Only few cases are clear-cut. $P_{\text{nature}}/P_{\text{nurture}}$
- $P = P(z)$
- Destruction of structures



Disc Galaxies

Disc

Bulge

Bar

Spiral

Warps

Bridges and tails

Thick discs

Rings

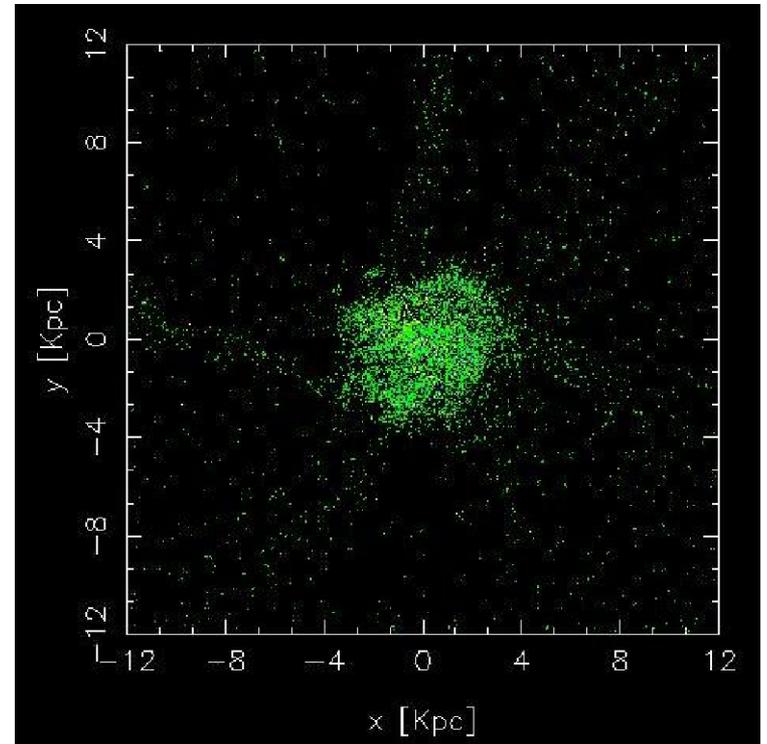
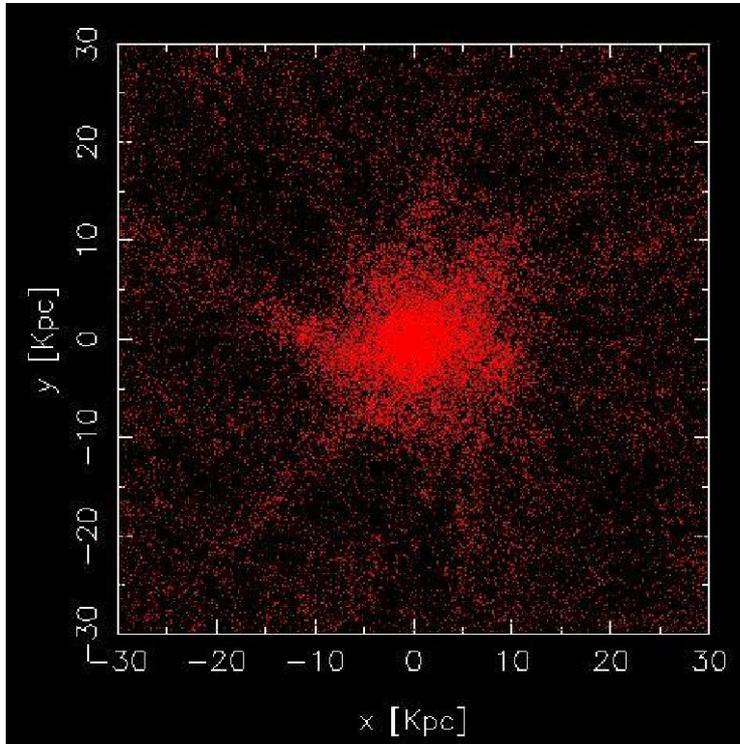
Ellipticals

Shells and ripples

Dust lanes with
peculiar kinematics



Disc : Nature

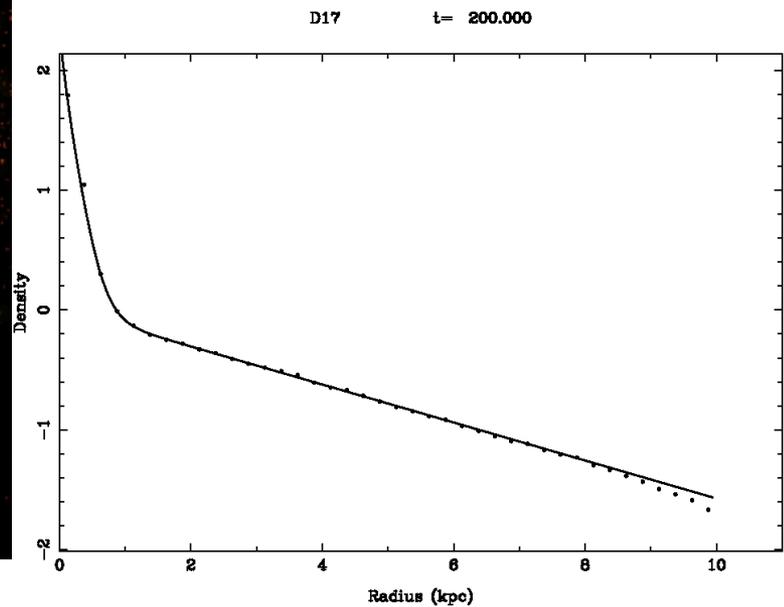
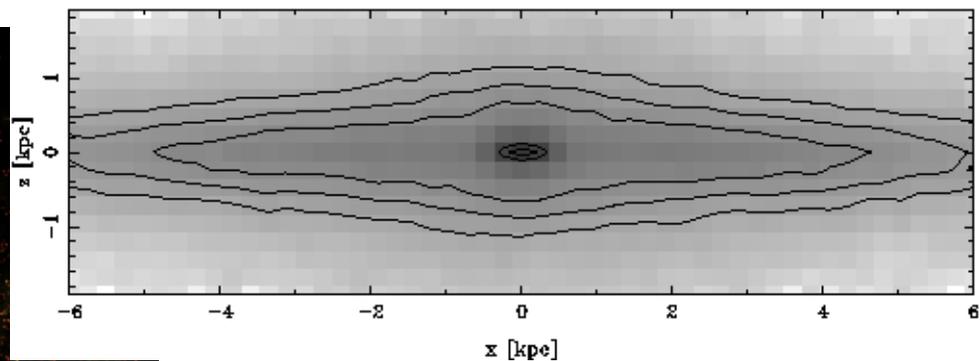
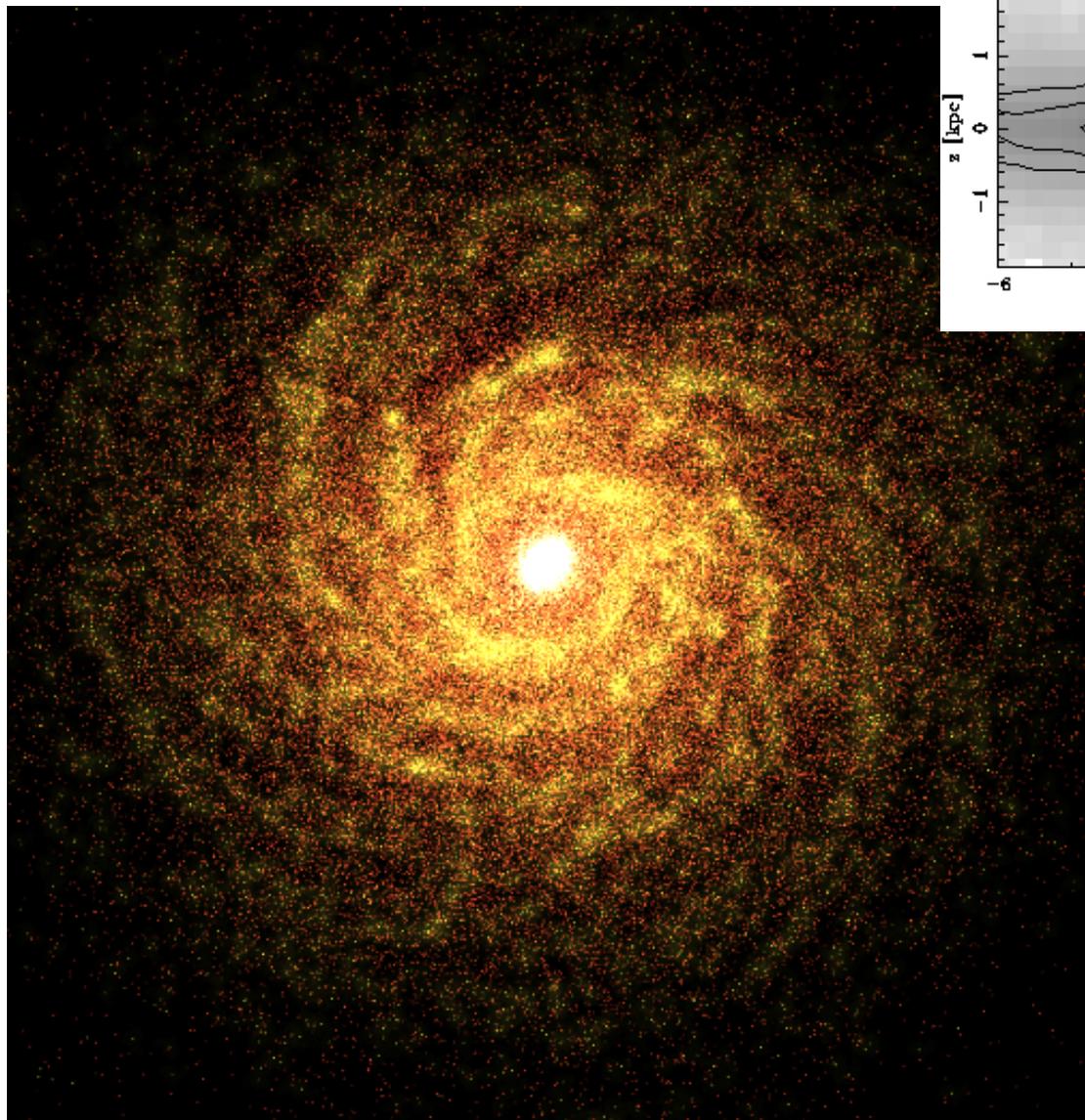


Heller, Shlosman and Athanassoula 2007

Fall & Efstathiou 80; Gunn 82, Dekel et al 03, 06, 08; Keres 05, 2008; Brooks 08; Agertz 09



Disc: Nature





Disc: Nurture

Disc + Disc = Elliptical

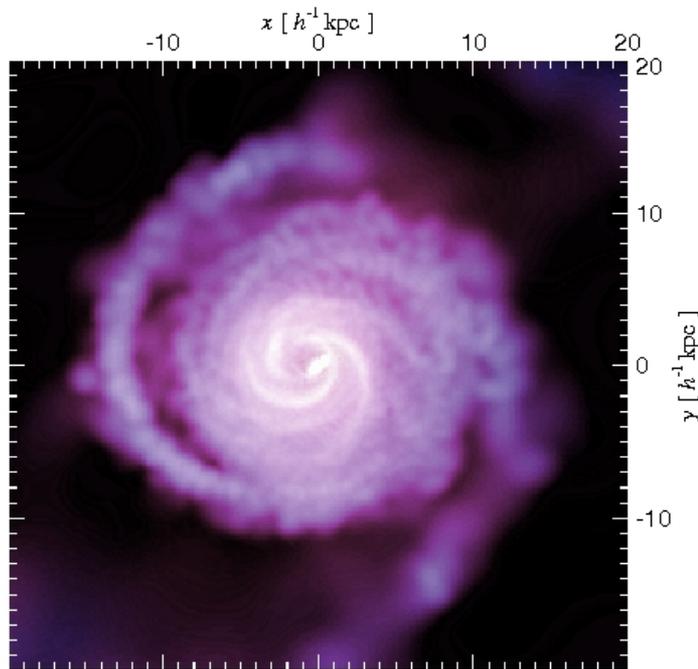
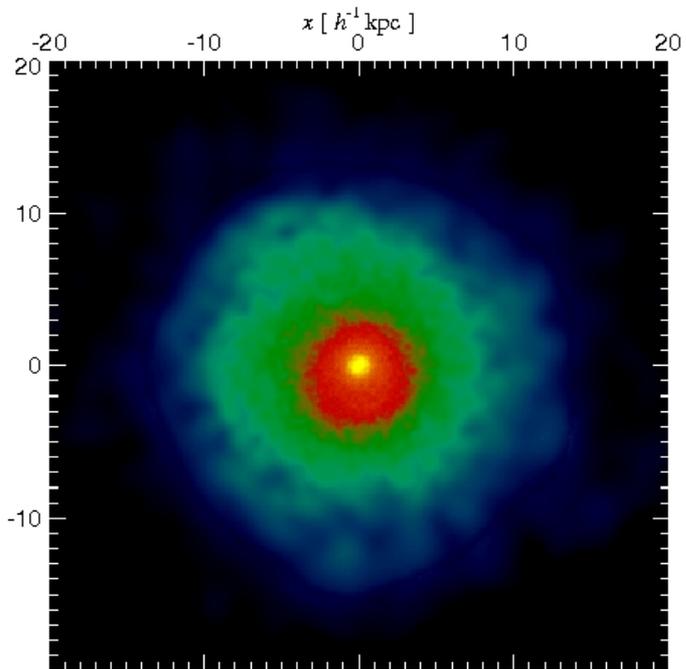
Toomre & Toomre 72; Barnes & Hernquist 92; Barnes 98; Naab & Burkhard 03;
Naab, Khochfar, Burkhard 06 etc

but also

Disc + Disc = Disc

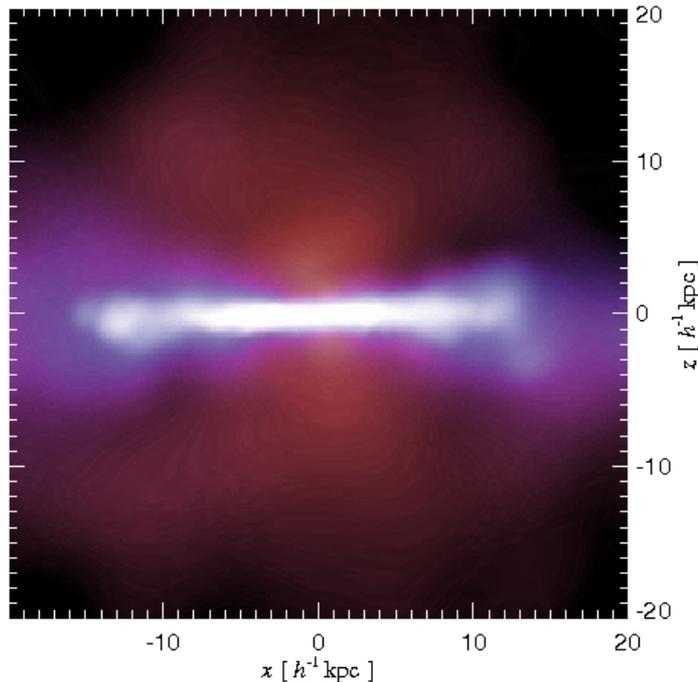
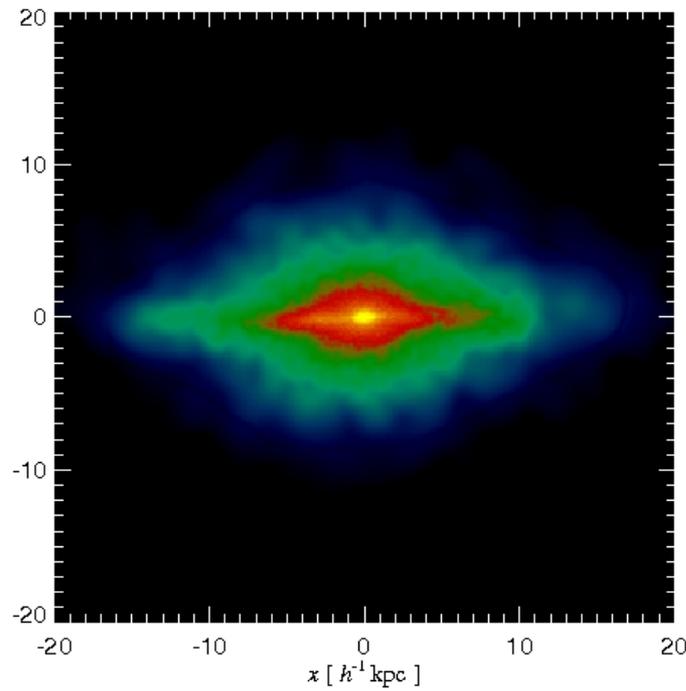
Observational starting point: Hammer et al 05, 09

Simulations: Dominguez-Tenreira et al. 98; Barnes 02; Scannapieco,
Tissera 03; Brook et al 04, 07; Springel & Hernquist 05;
Robertson et al 06,08, Hopkins et 08; Governato et al 07, 08; Stewart et al 09

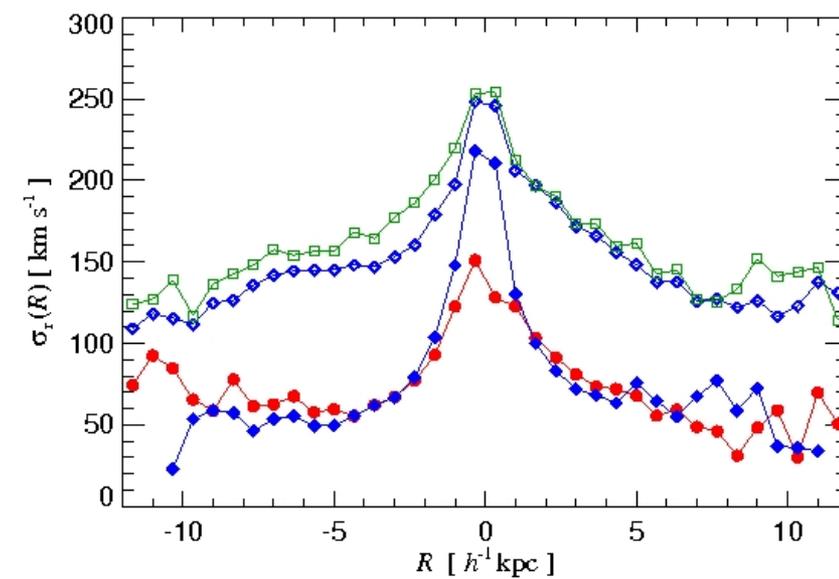
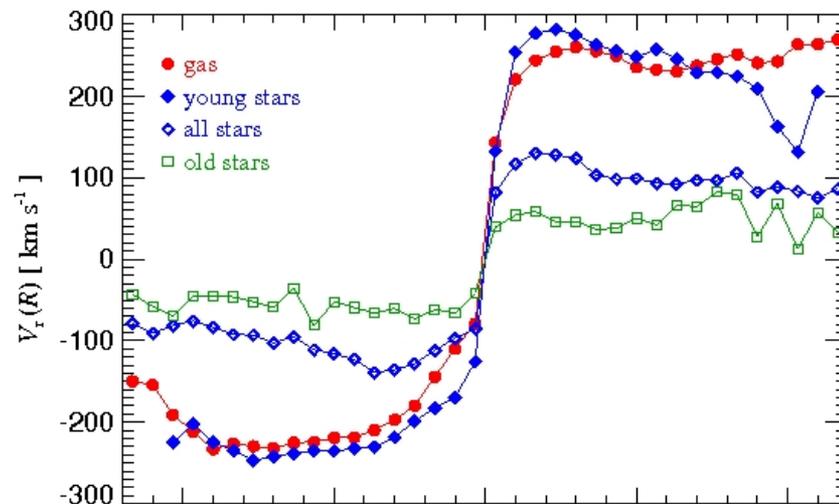
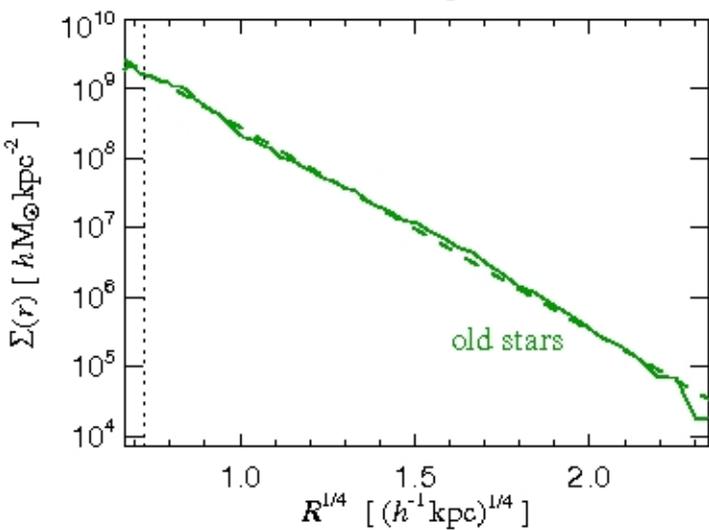
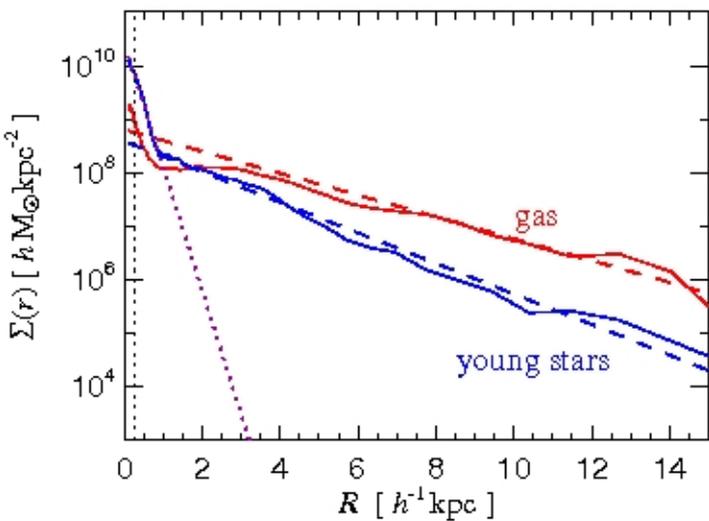


Equal mass
progenitors

No bulge



Springel and
Hernquist 2005

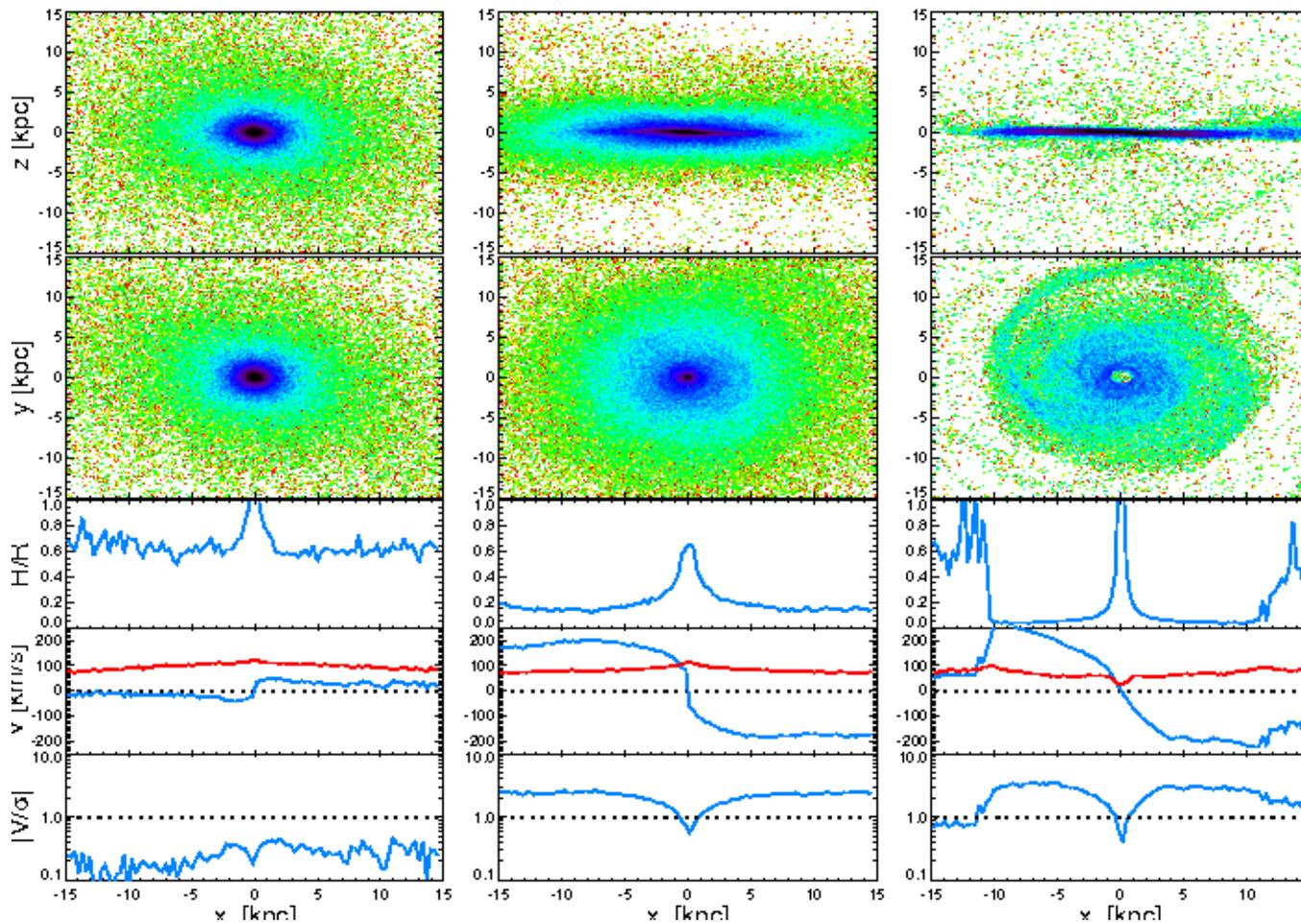




Bulge

Stellar disc

Gas



1:2 mass ratio merger with 20% gas

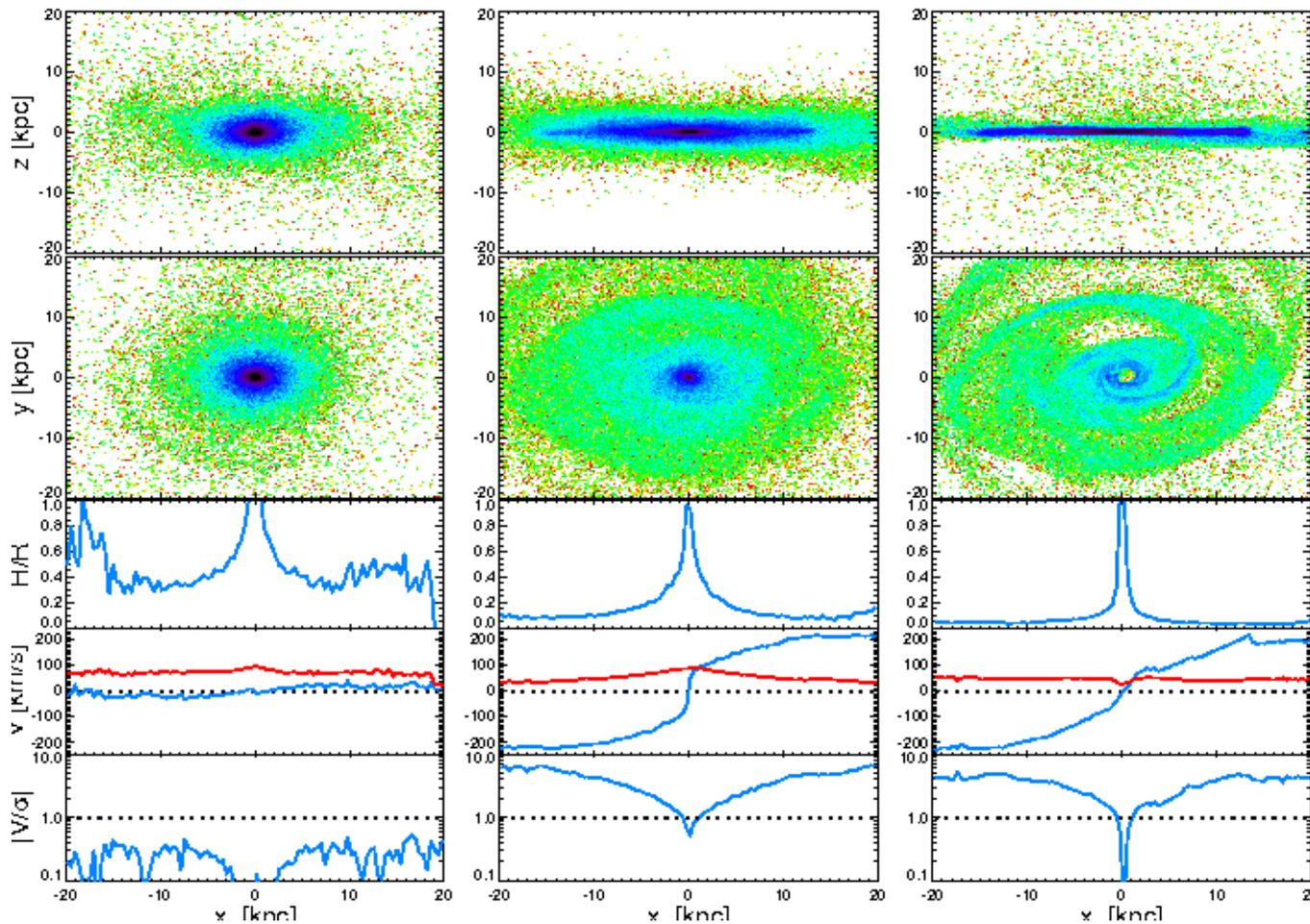
Hopkins et al 2008



Bulge

Stellar disc

Gas



1:6 mass ratio merger with 15% gas

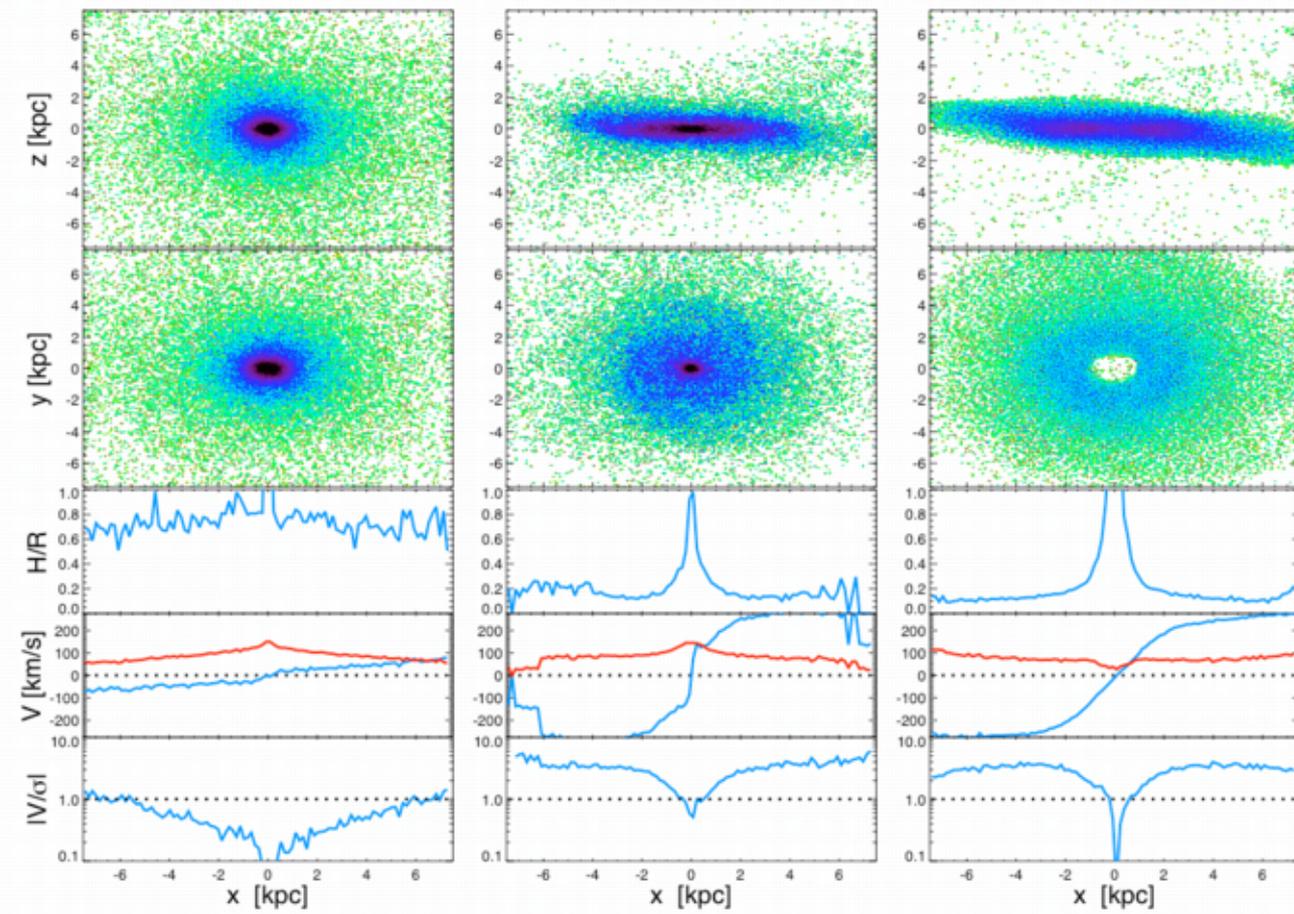
Hopkins et al 2008



Bulge

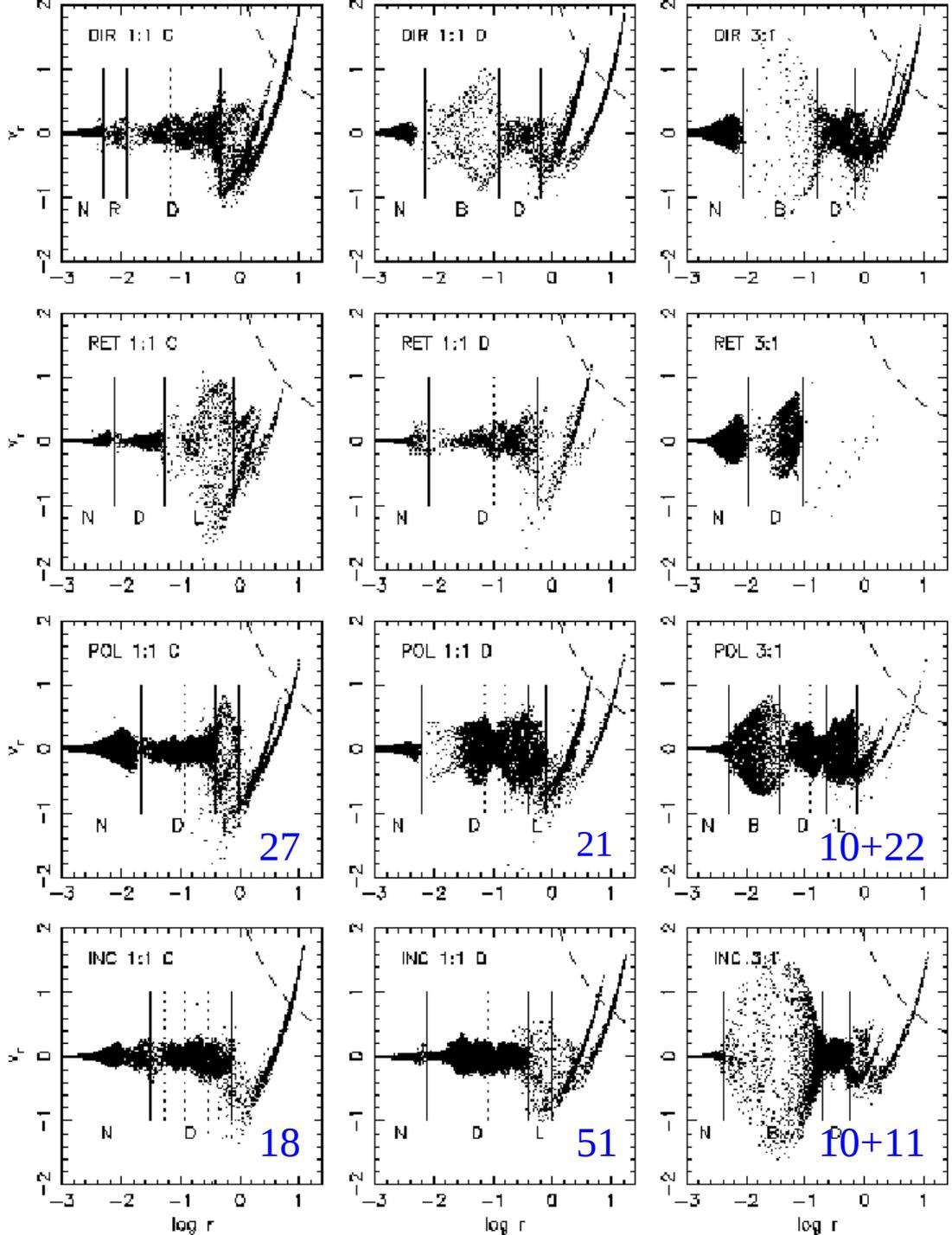
Stellar disc

Gas



1:1 mass ratio merger with 20% gas

Hopkins et al 2008



Barnes 02



Bulge definitions

Definition 1

From morphology:

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.

Definition 3

From kinematics:

From the V/σ plot

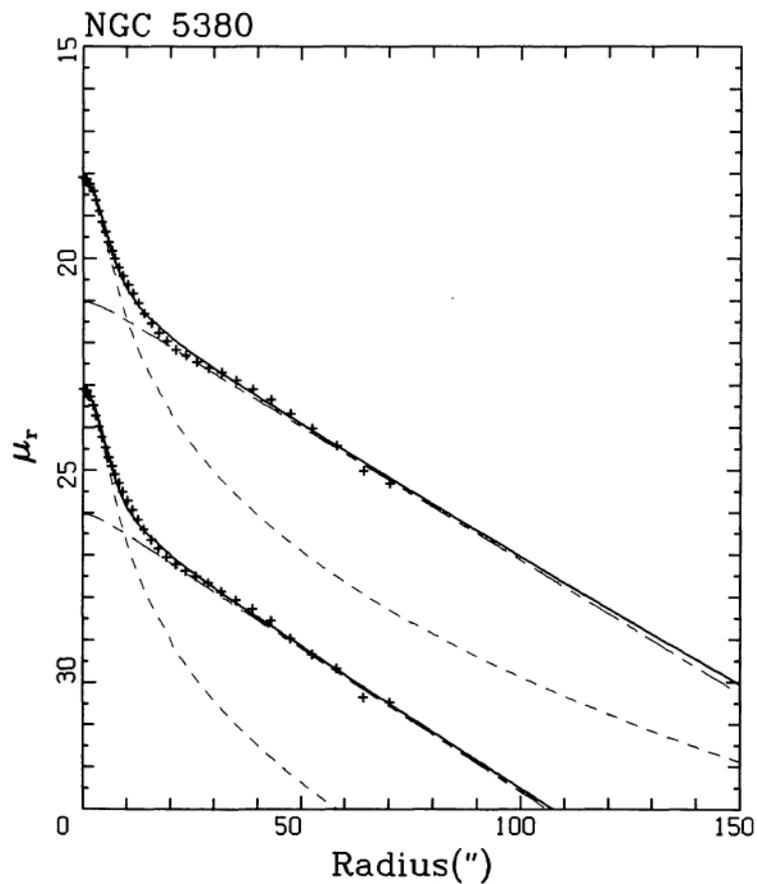
Bulges





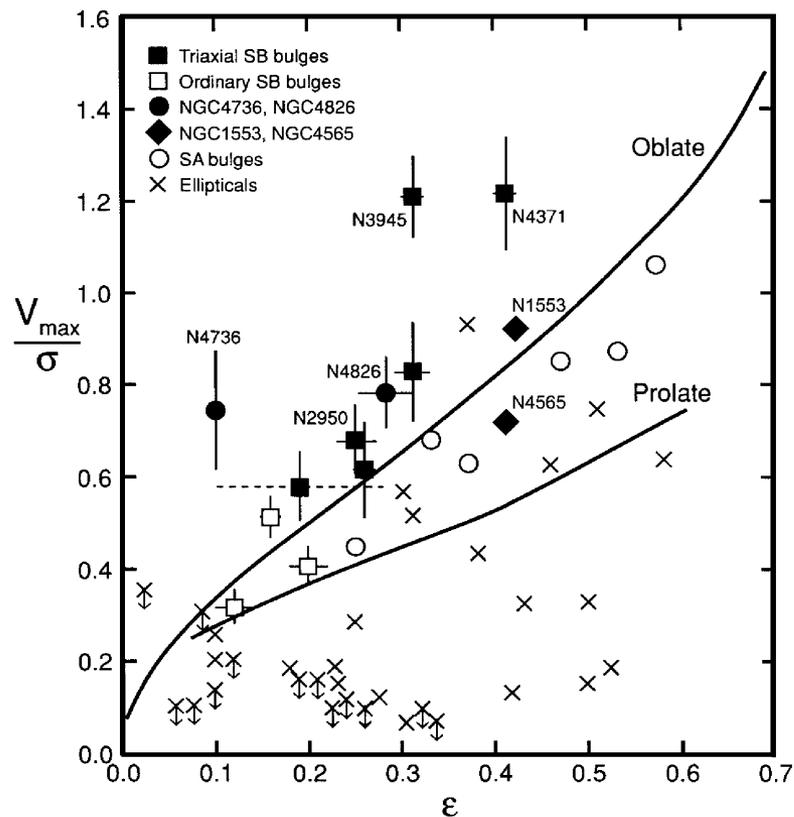
Bulge definitions

Photometric definition



Kinematic definition

Binney 78, 05





Types of bulges (1)

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

1) Classical Bulges

Formed by gravitational collapse, or hierarchical merging and corresponding dissipative processes. Occurs early on in the formation process and is 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), Athanasoula (1999), Aguerri, Balcells & Peletier (2001), Fu, Huand & Deng (2003)

2) Box/peanut bulges

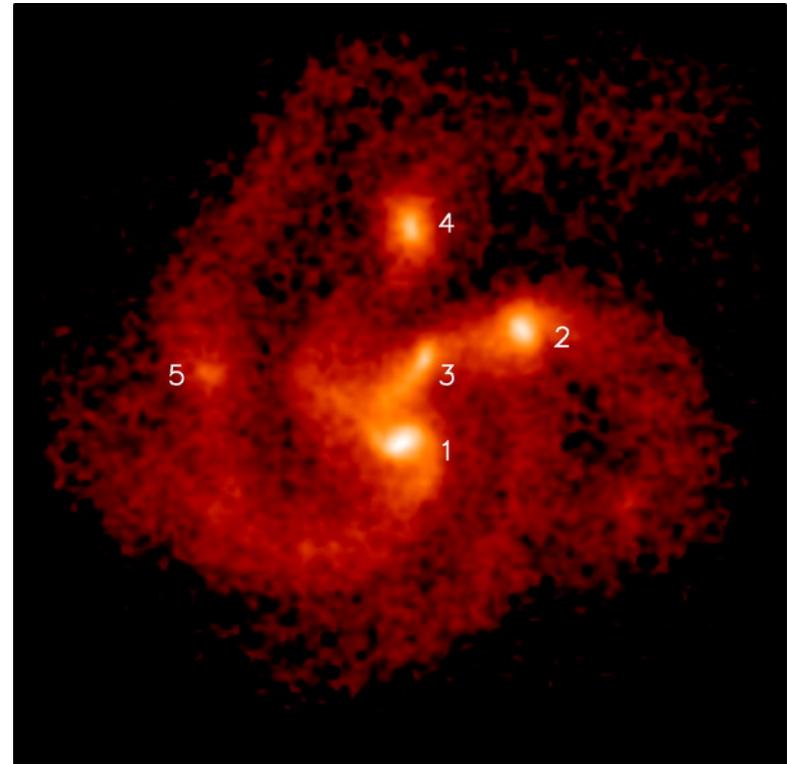
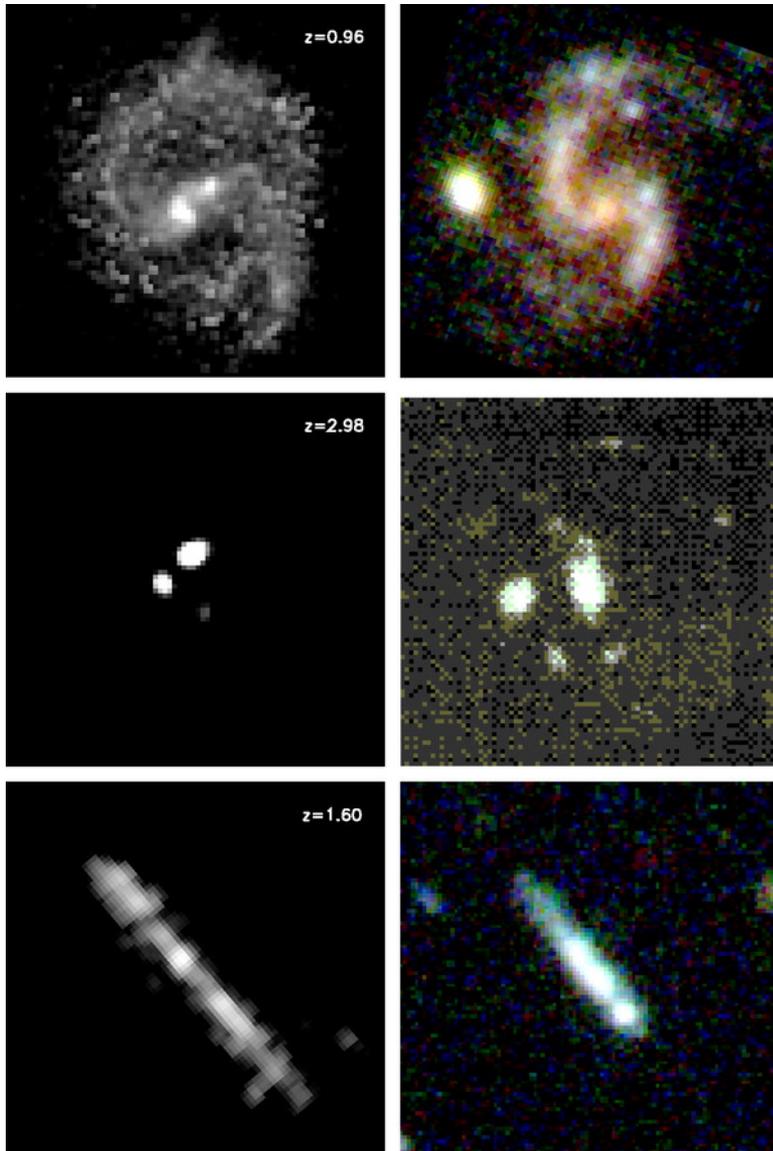
They are parts of bars seen edge-on

3) Discy-bulges

Inflow of gas to the central regions and subsequent star formation



Formation from clumps in the proto-disc



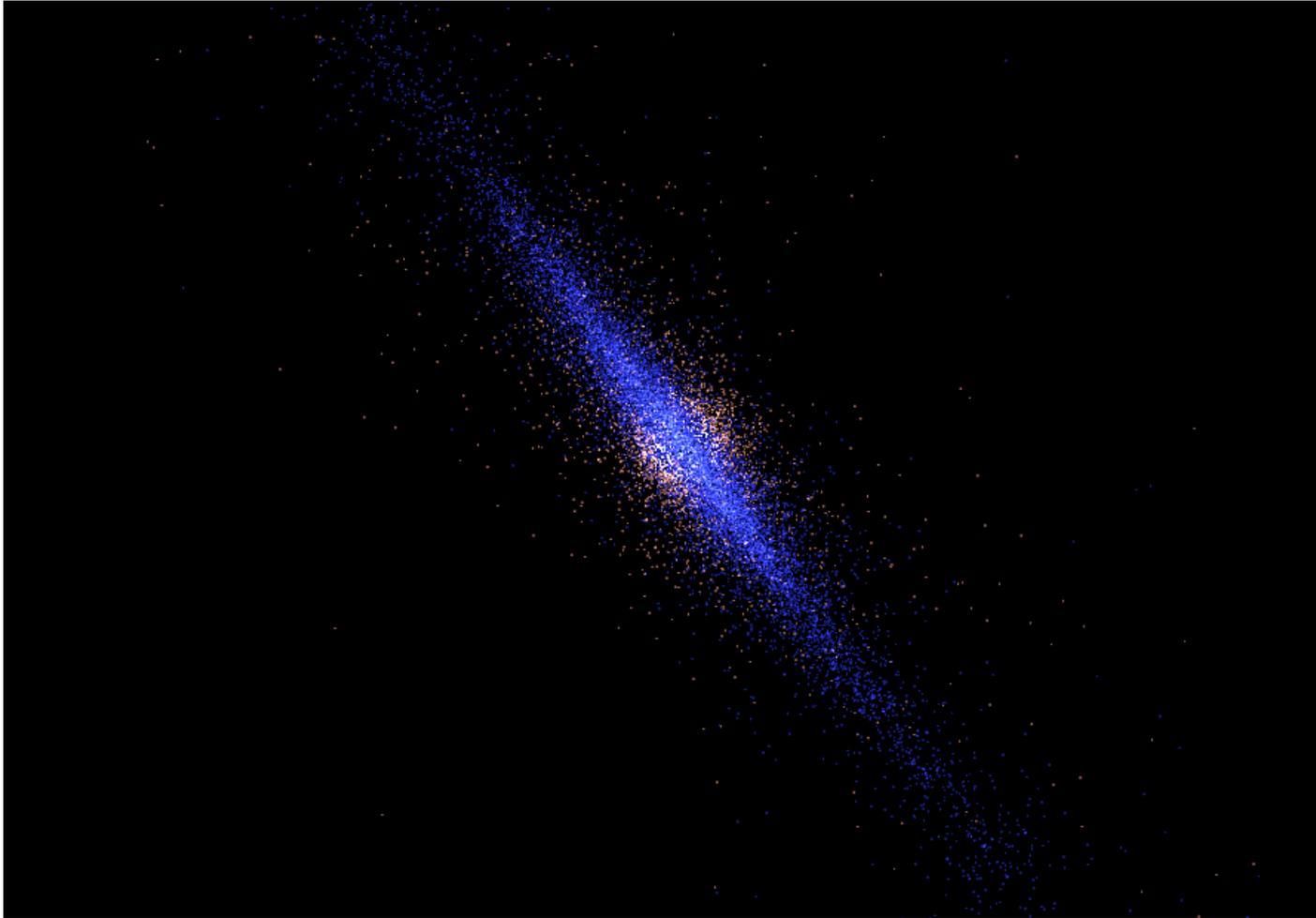
Noguchi (1998, 1999)

Immeli et al (2004a,b)

Bournaud et al 2008, 2009



Classical bulge formation : companion infall



Pfenniger 91, Athanassoula 1999, Aguerri et al. 01, Fu et al. 03, Eliche-Moralet al. 06



Types of bulges (2)

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

1) Classical Bulges

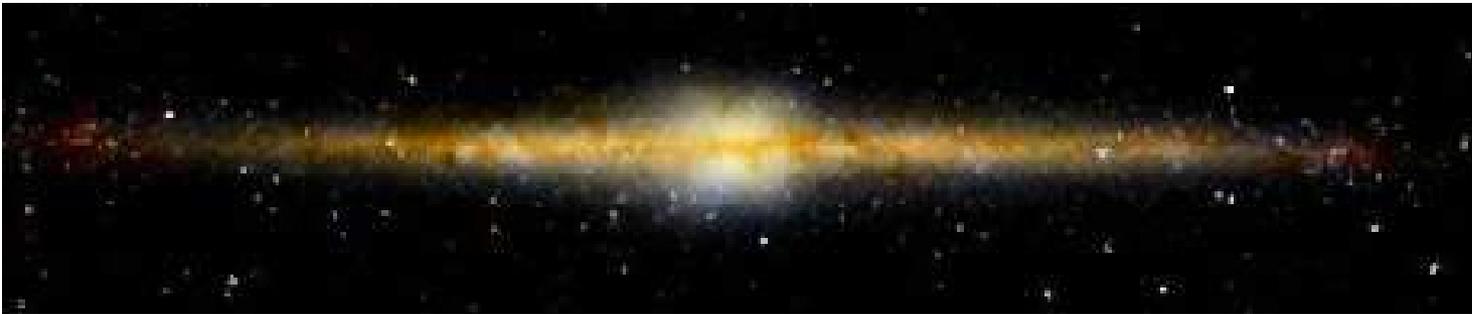
2) **Box/peanut bulges**

They are parts of bars seen edge-on.



N-body simulations : [Combes & Sanders 81](#); [Combes et al 90](#); [Raha et al 91](#);
[Athanassoula & Misiriotis 02](#); [Athanassoula 03, 05](#); [O'Neil & Dubinski 03](#);

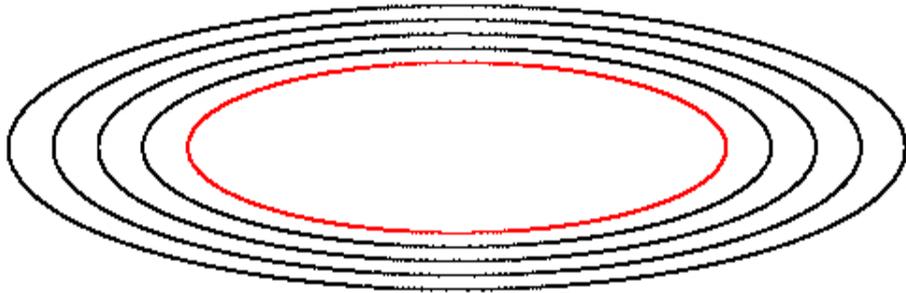
Orbital structure : [Pfenniger 84](#); [Skokos, Patsis & Athanassoula 02a,b](#);
[Patsis, Skokos & Athanassoula 02, 03](#);; [Martinez-Valpuesta et al 04, 06](#)



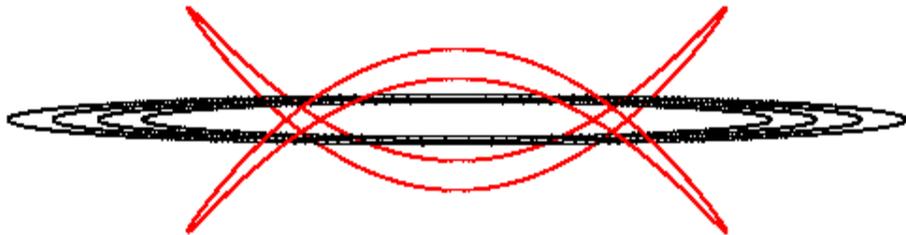
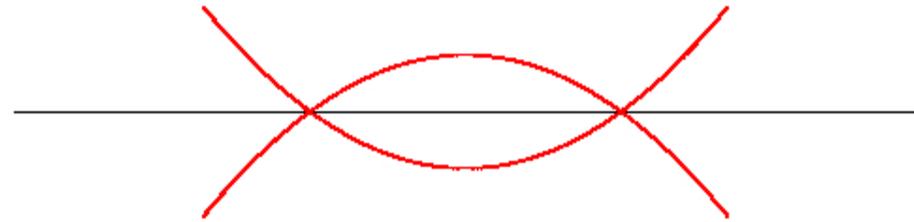


Orbits (schematic)

Face-on



Edge-on

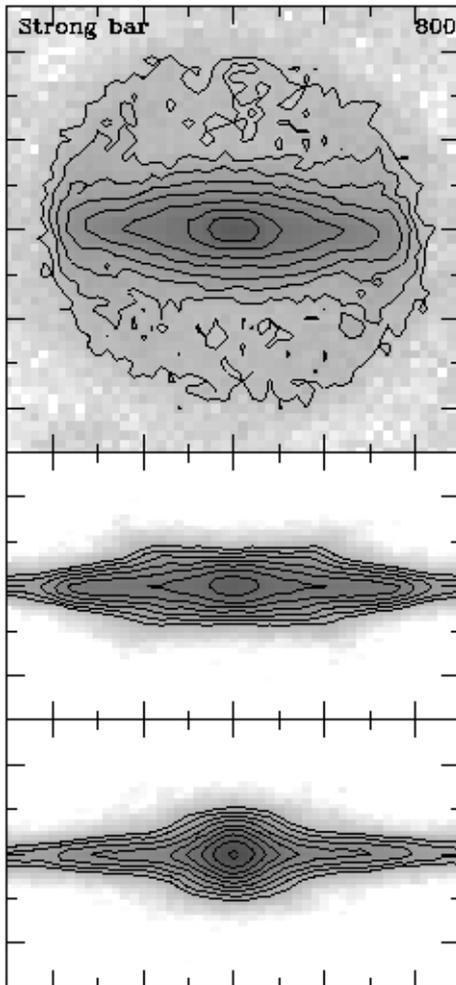


At an angle



N-body simulations

A bar seen :



Face-on

Edge-on and side-on

Edge-on and end-on



Types of bulges (3)

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

1) Classical Bulges

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.

By bars and/or by interactions

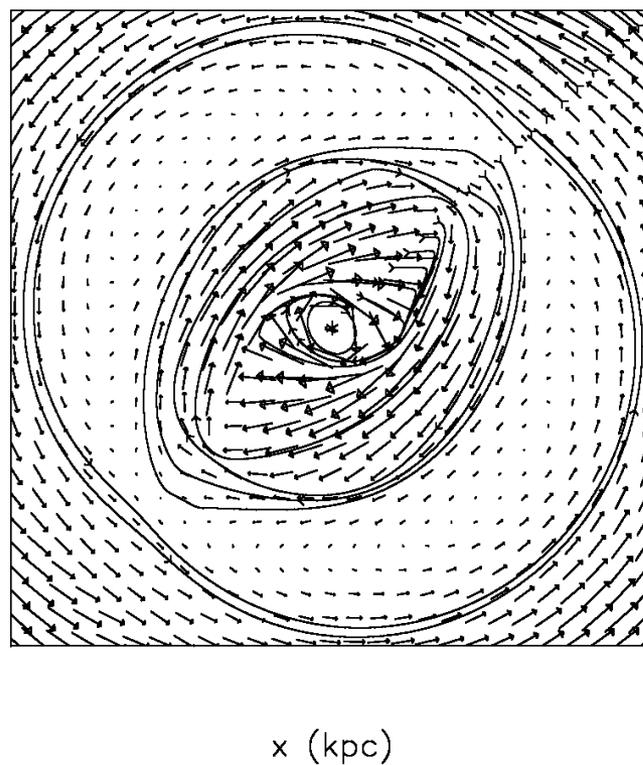
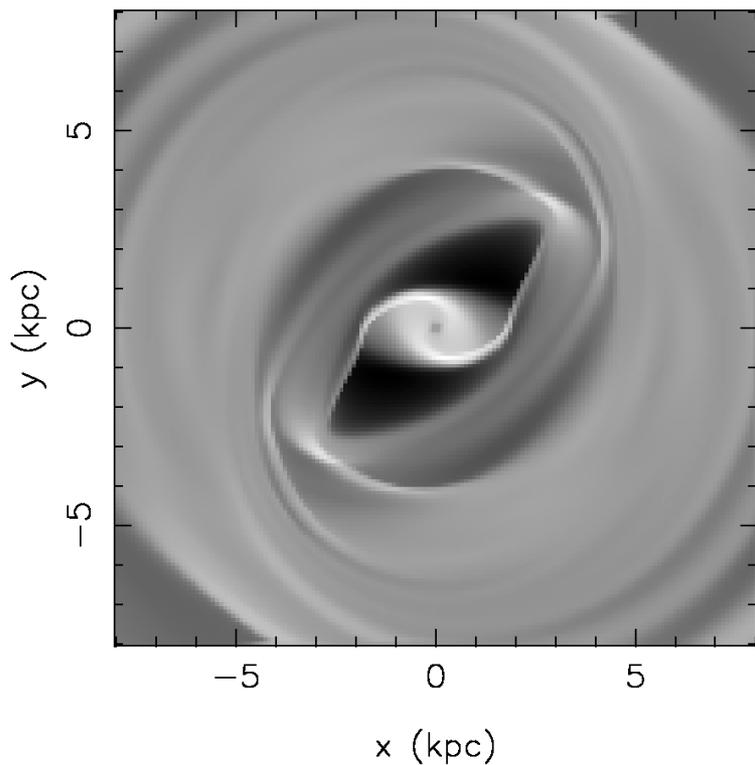
Observations : Carollo, Stiavelli & Mack 1998; Carollo & Stiavelli 1998;
Kormendy 1993; Kormendy & Kennicutt 2004

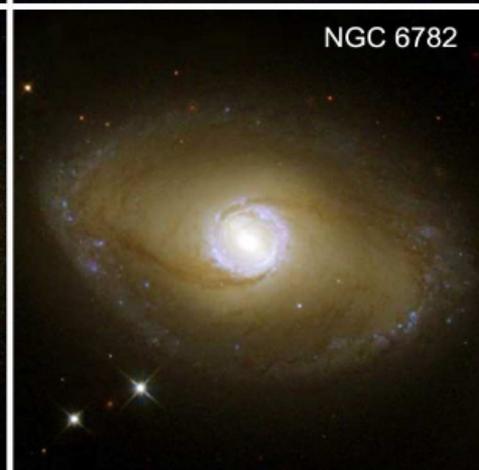
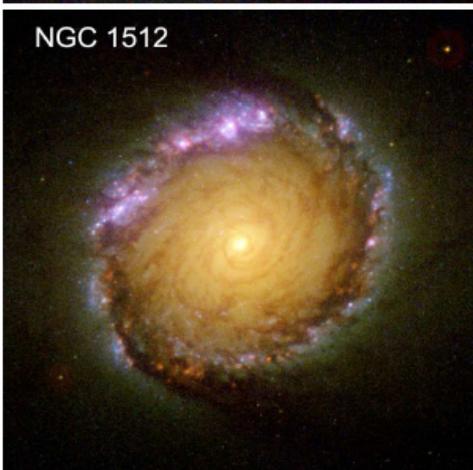
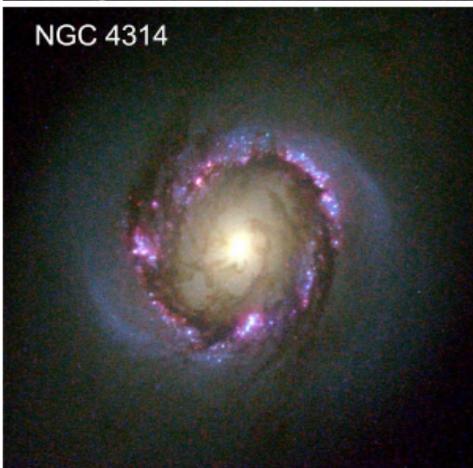
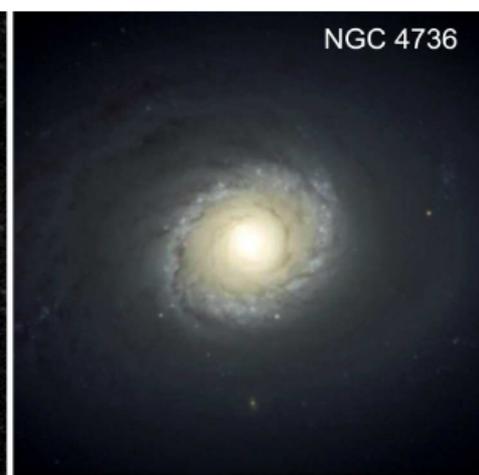
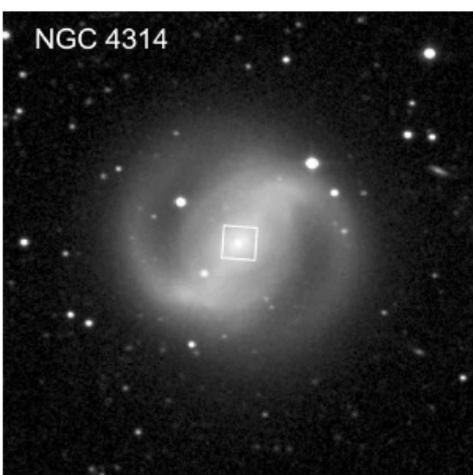
Simulations : Athanasoula 1992; Friedli & Benz 1993; Heller & Shlosman 1994;
Regan & Teuben 2004

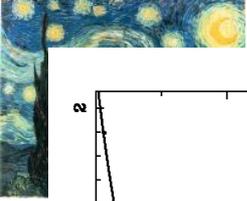


Discy bulges

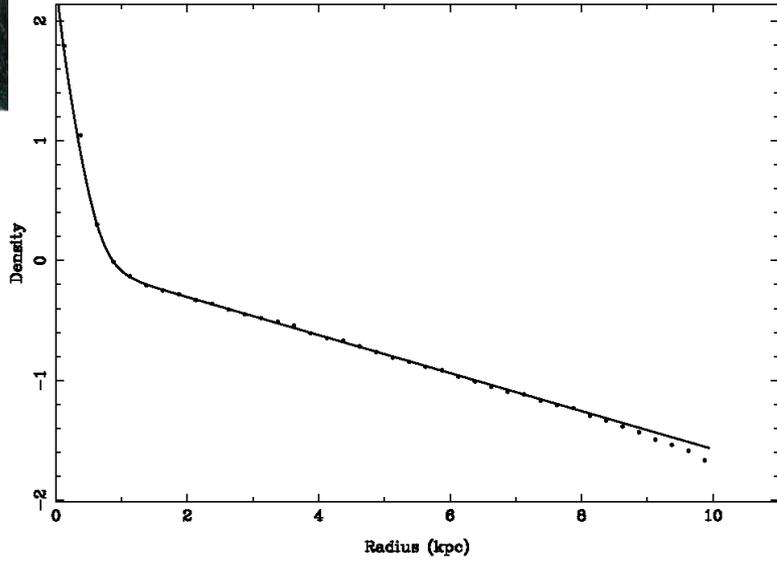
Gas inflow : bars or interactions/mergings



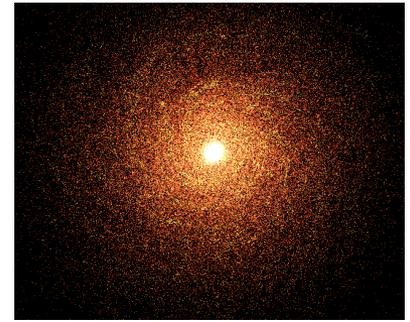




D17 t= 200.000



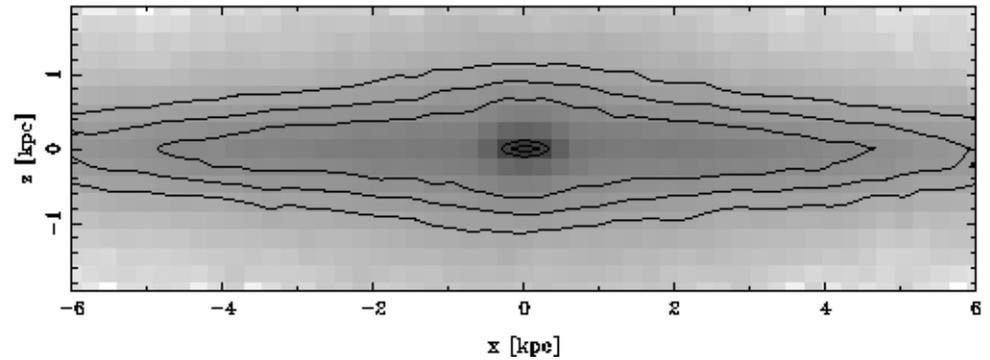
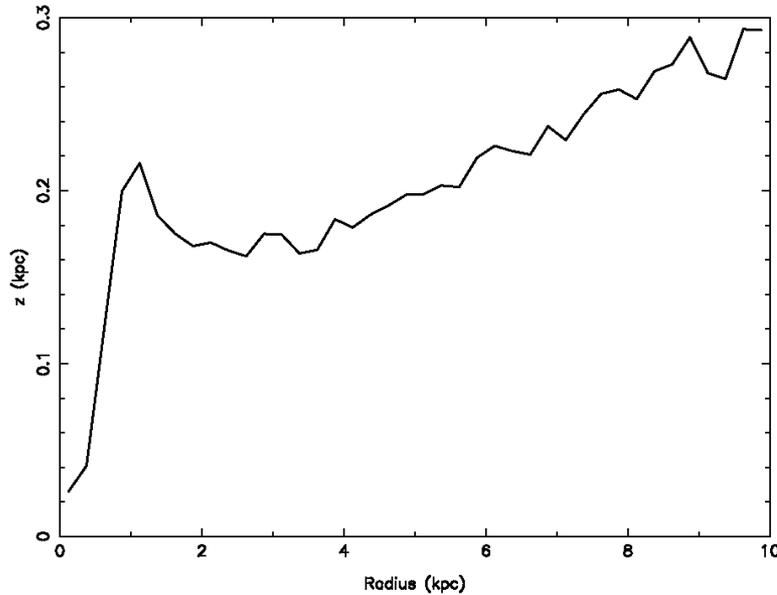
Discy bulges



Sersic index = 1

in general Sersic Index < 2

D17 t= 200.000



Face-on, it often has an oval shape or includes a bar (inner bar)



Summary (bulge types)

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

1) Classical Bulges

Both nature and nurture.

2) Box/peanut bulges

They are parts of bars seen edge-on

Nature

3) Discy-bulges

Inflow of gas to the central regions and subsequent star formation

Both nature and nurture

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



Bars

Bar formation

Evolution driven by angular momentum exchange within the galaxy

Bars strength is proportional to the amount of angular momentum it lost

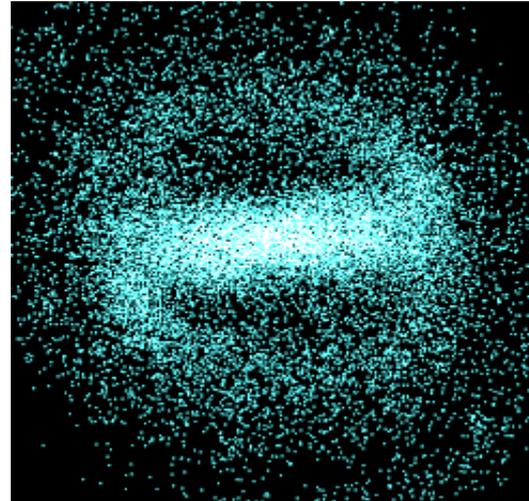
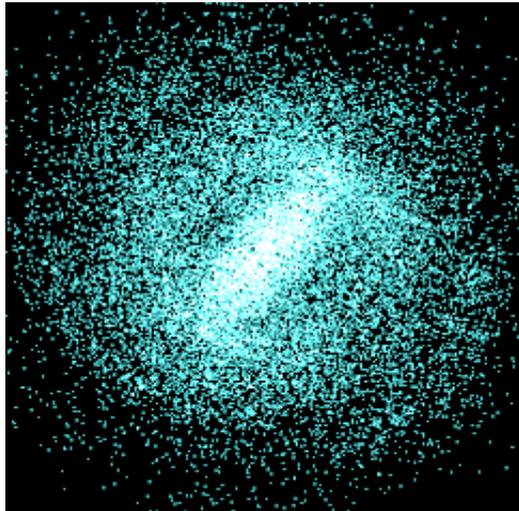
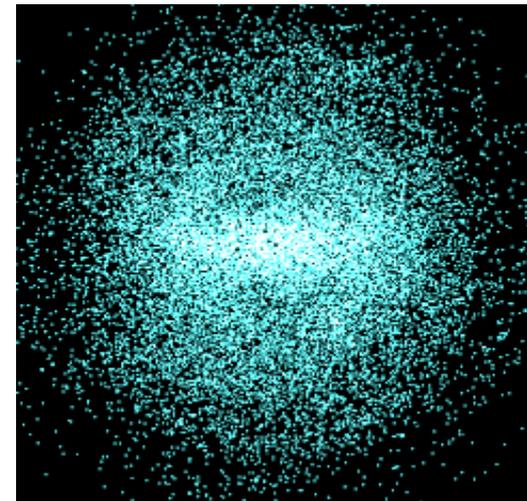
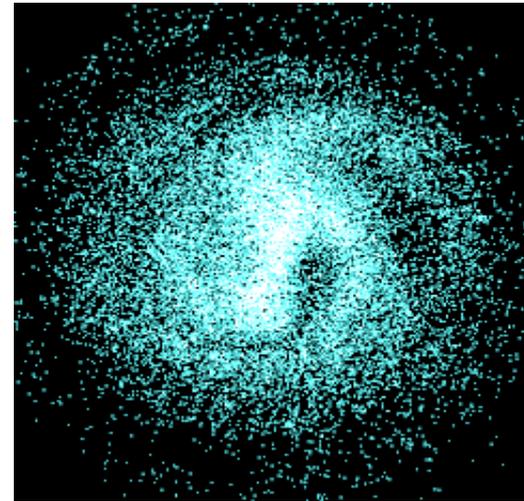
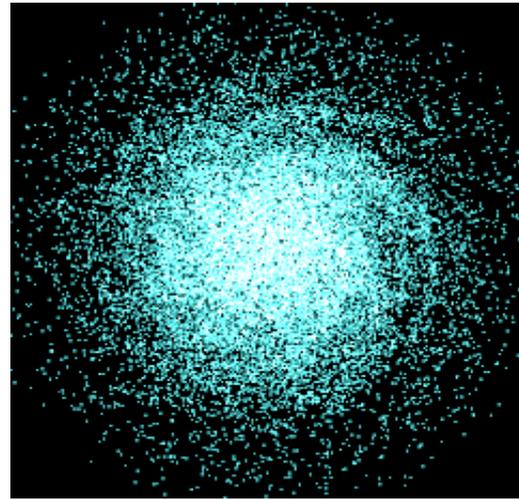
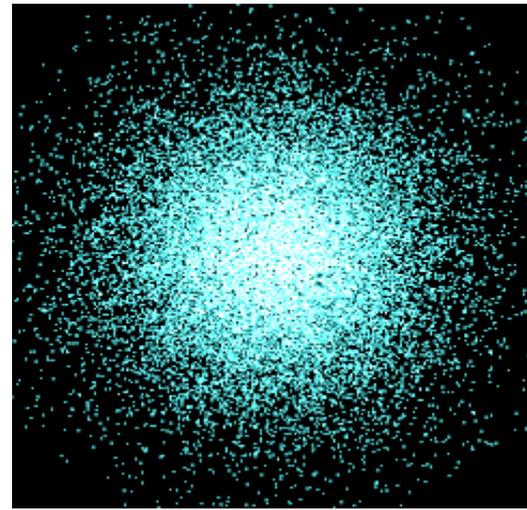
The angular momentum emitted by near-resonant material in the bar region is absorbed by near-resonant material in the outer disc and in the halo

Nature, although interactions may change the properties of the bar since the companion can participate in the angular momentum exchange

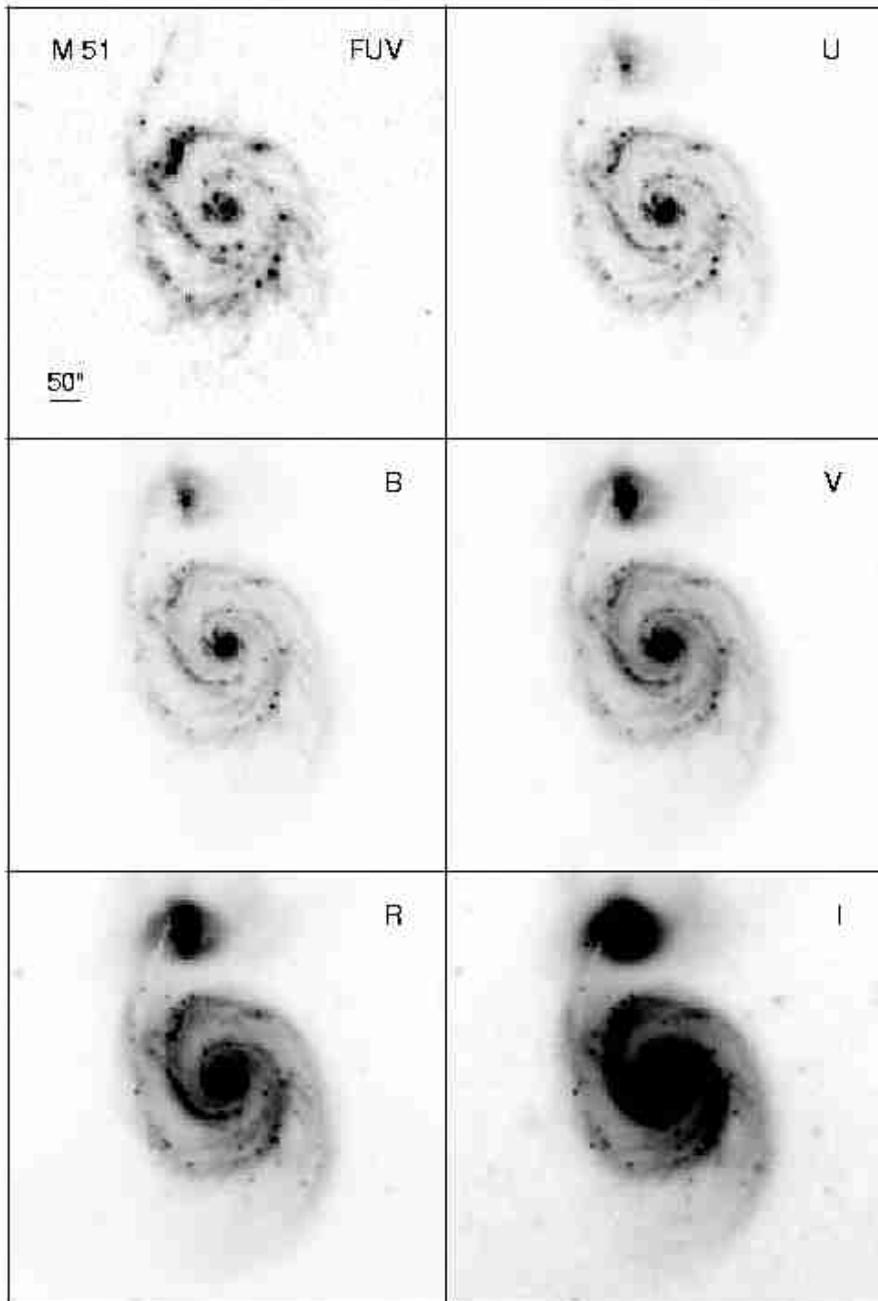


Time evolution

Face-on view



Spirals

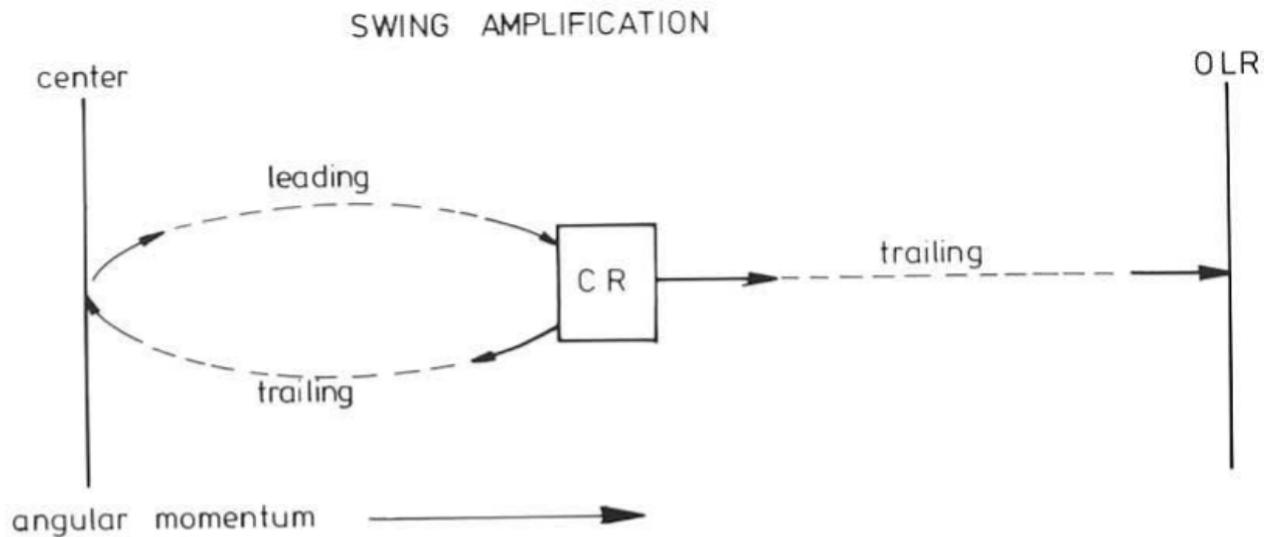


Companion-driven spirals



Spirals

Swing amplified spirals

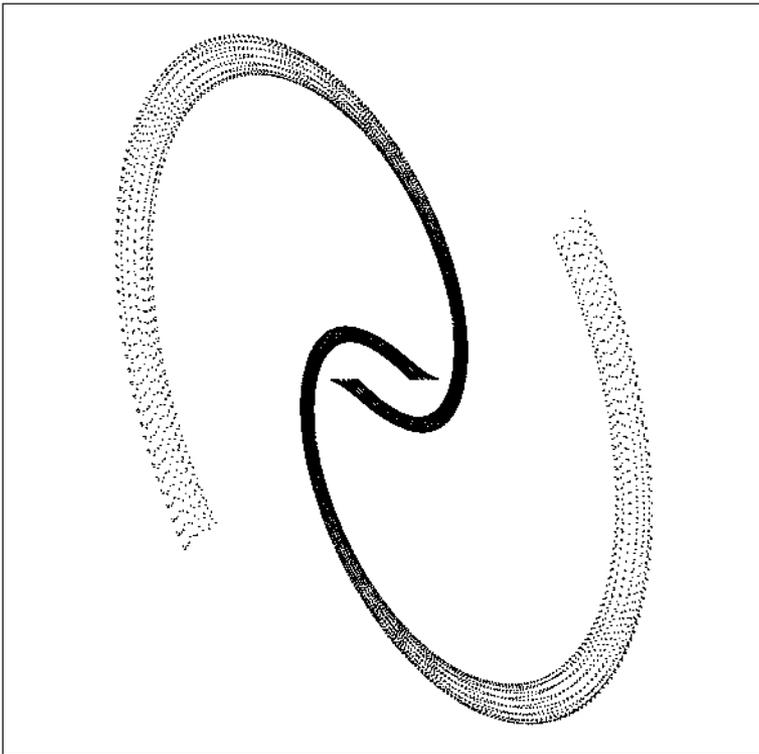


Both for grand design and flocculent spirals
Observations?

Toomre 81

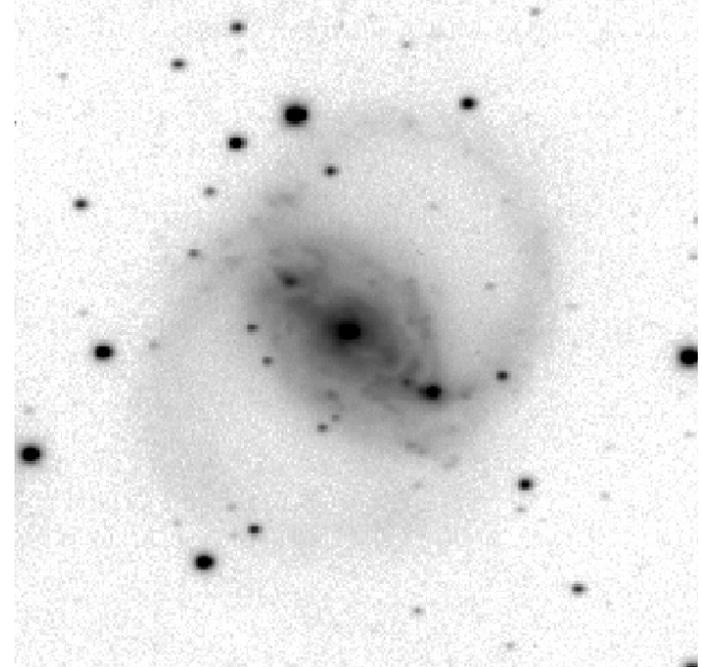


Spirals in barred galaxies



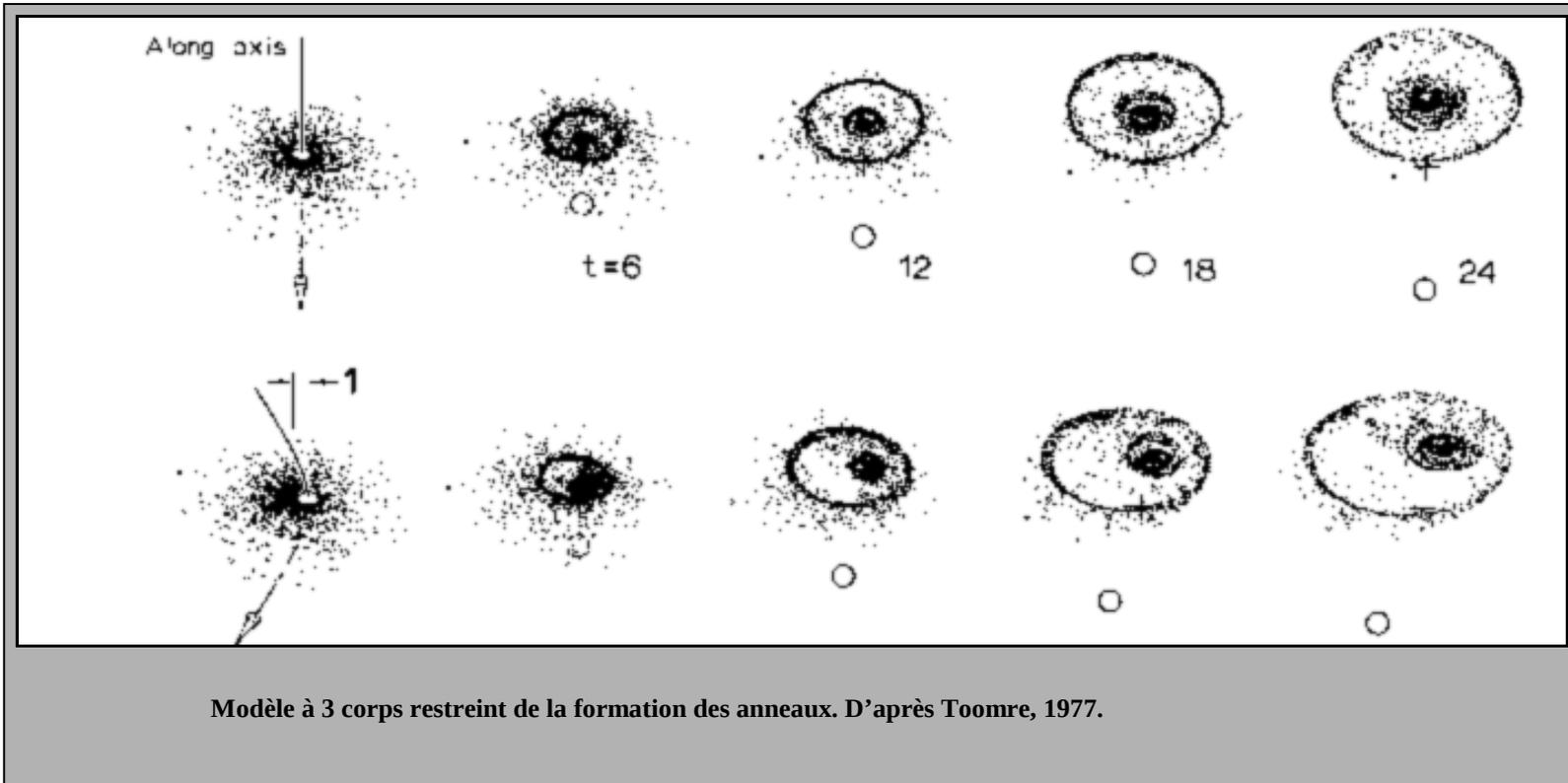


Rings



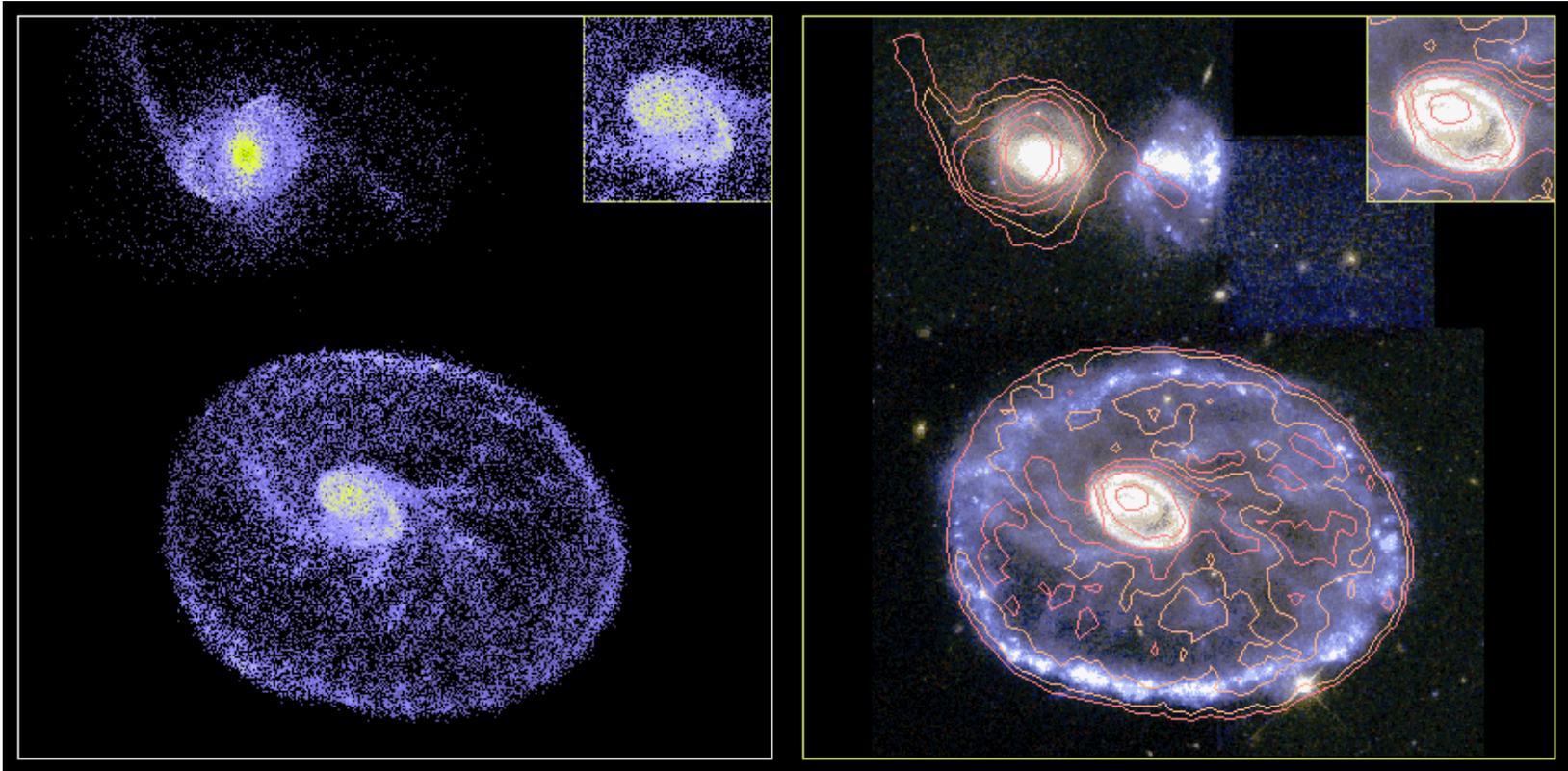


Rings: Ring galaxies

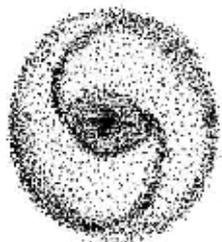
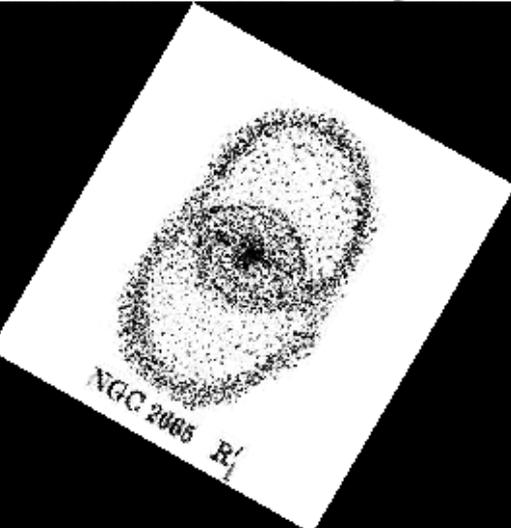
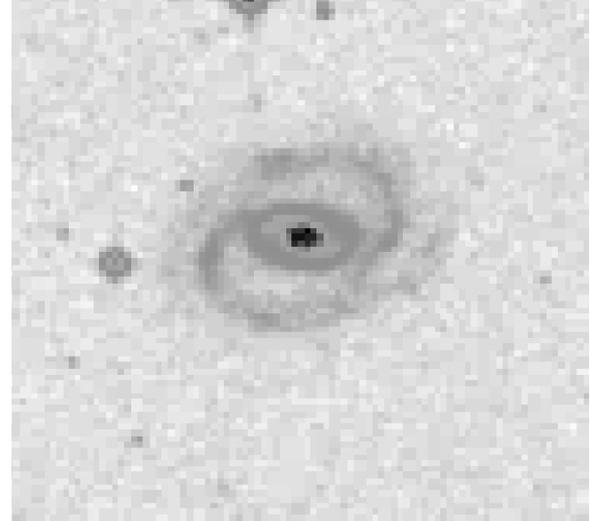
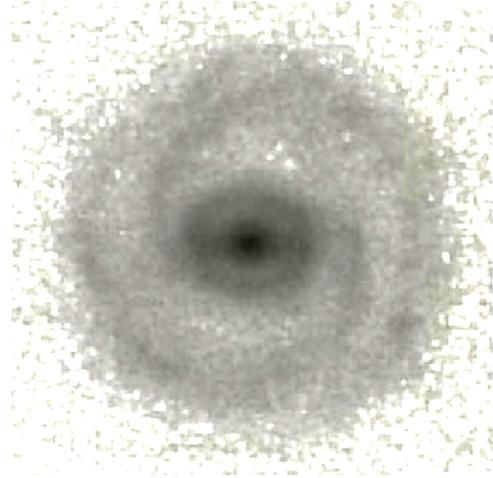
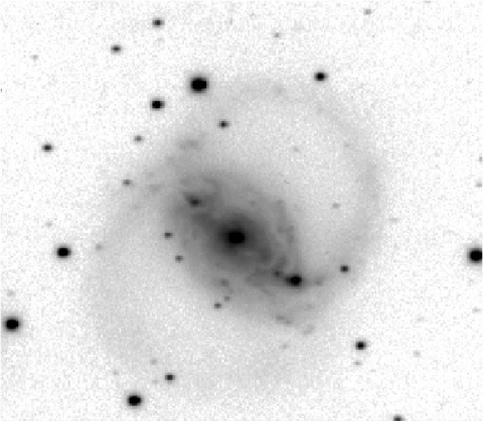




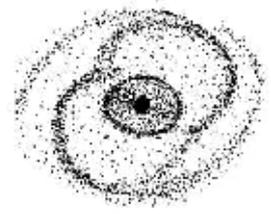
Rings: Ring galaxies



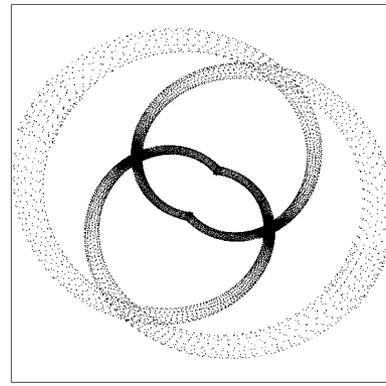
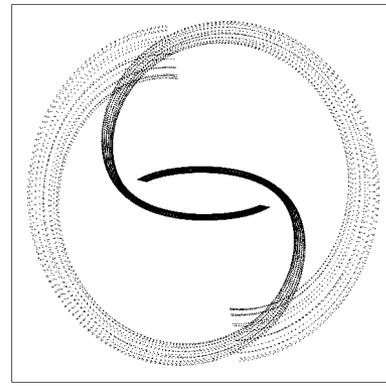
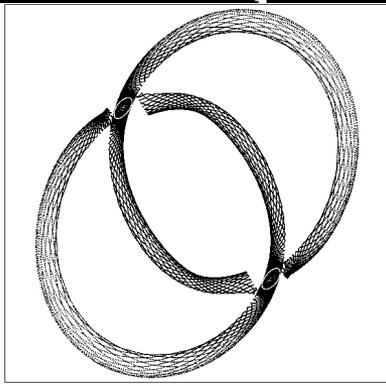
Villa-Vargas & Athanassoula, unpubl.



ESO 325-28 R'_2

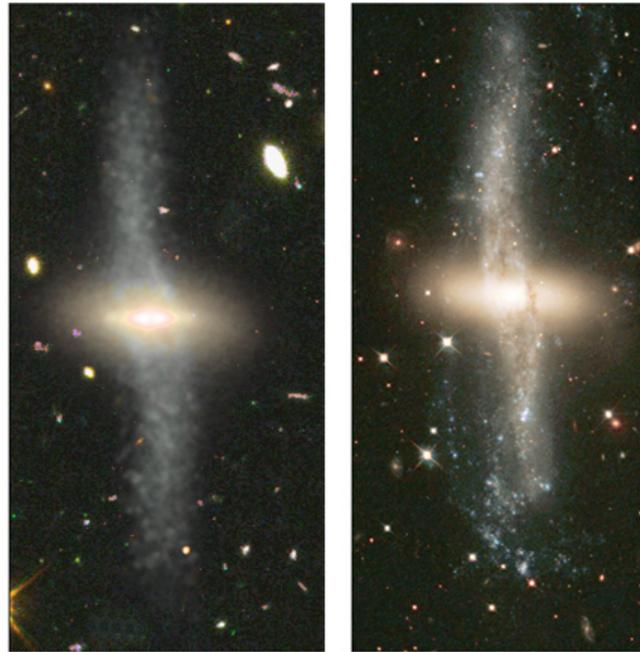


ESO 507-16 $R_1R'_2$





Rings: Polar rings



Sparke 86; Arnaboldi & Sparke 94; Dubinski & Christodoulou 94;
Bekki 97, 98; Tremain & Yu 00; Bournaud & Combes 03; Macio et al. 06



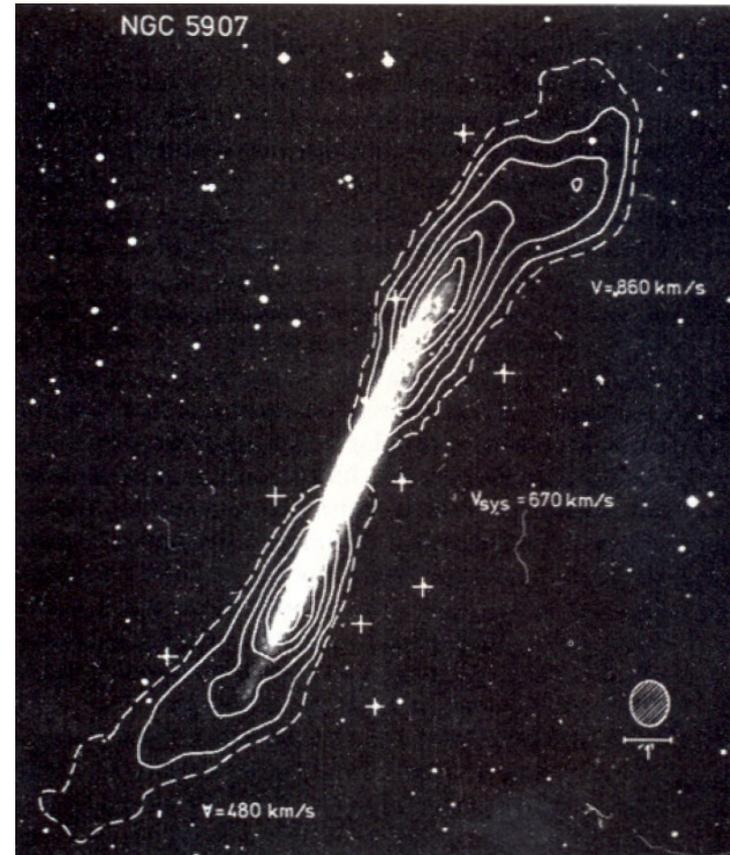
Warps

Disc only : only if outer disc truncation is unrealistically sharp (Hunter & Toomre 69)

Effect of the halo (flattened, misaligned) (Toomre 83; Dekel & Shlosman 83; Sparke & Casertano 88; Kuijken 91; Ideta et al 00; Nelson & Tremaine 95; Dubinski & Kuijken 95; Binney et al 98; Debattista & Sellwood 99)

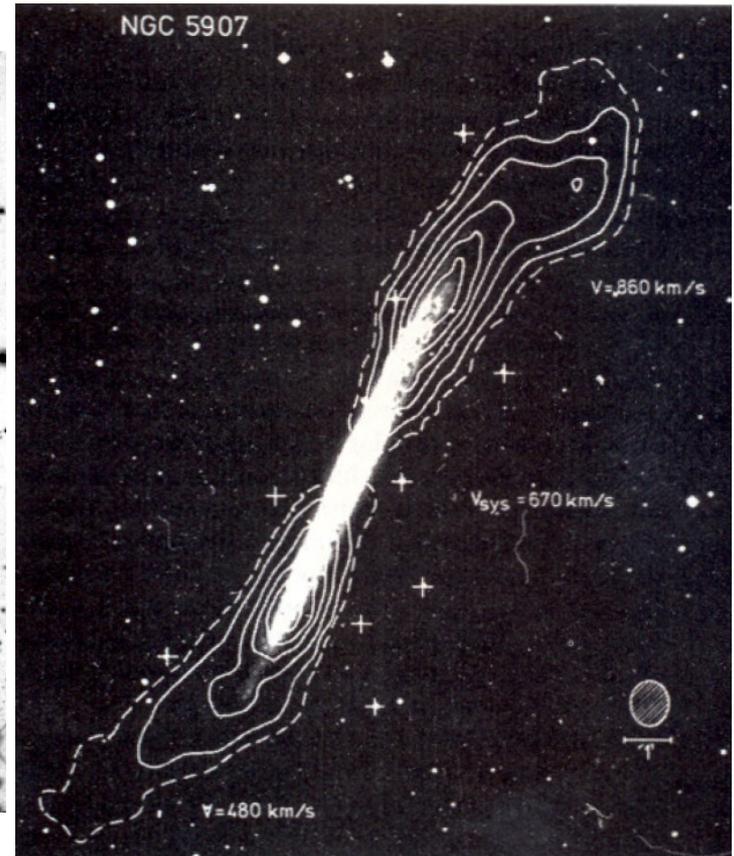
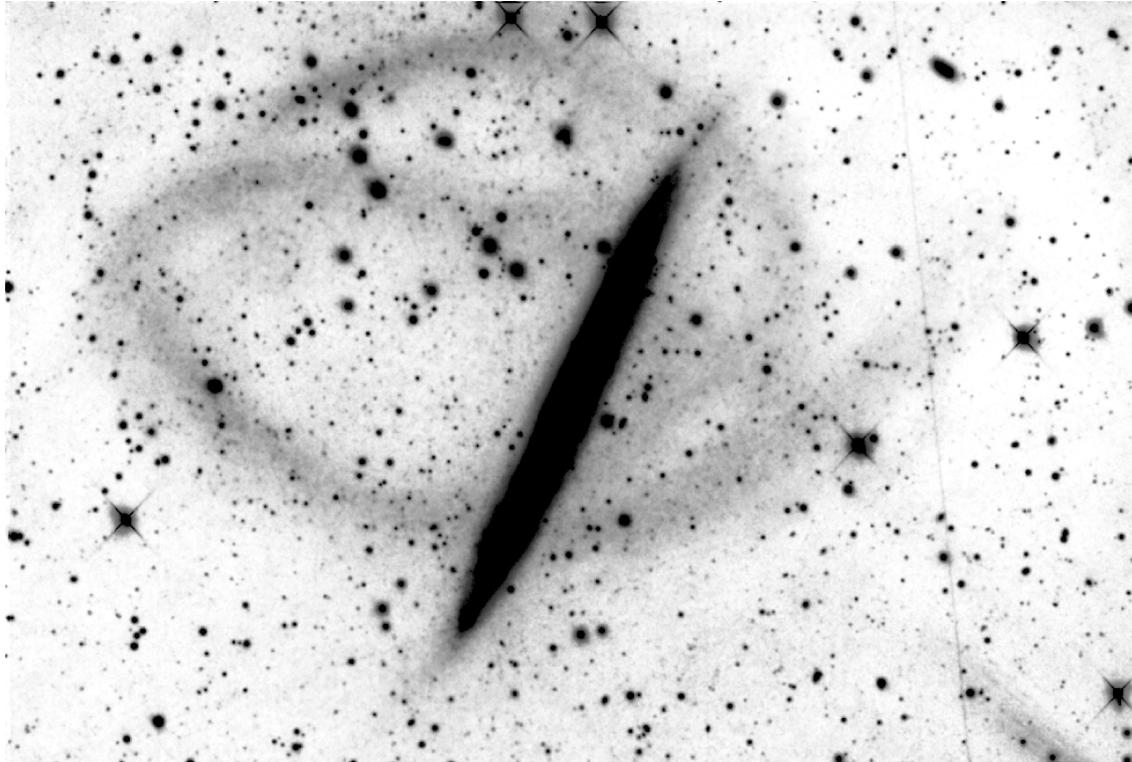
– Cosmic infall (Ostriker & Binney 89; Binney 91; Quinn & Binney 92; Jiang & Binney 99; Lopez-Corredoira et al. 02; Shen & Sellwood 06; Jeon et al 09)

– Companions (Hernquist 91; Bailin & Steinmetz 03)



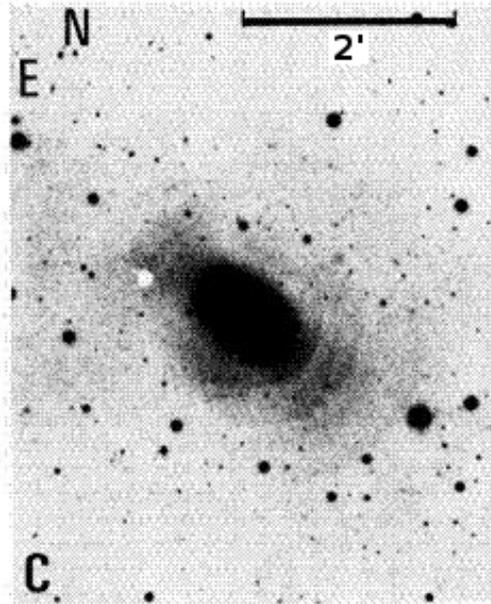
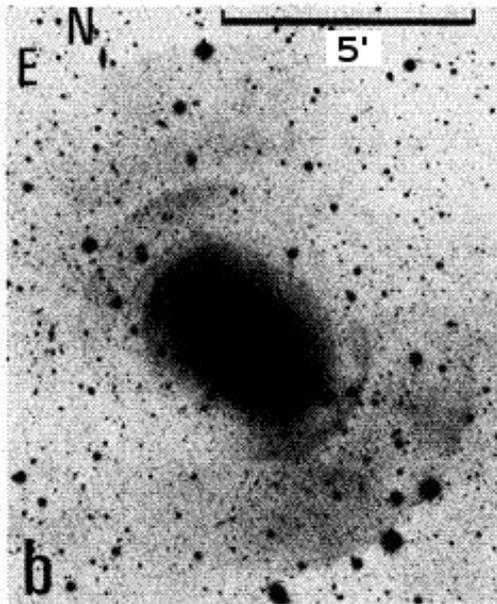
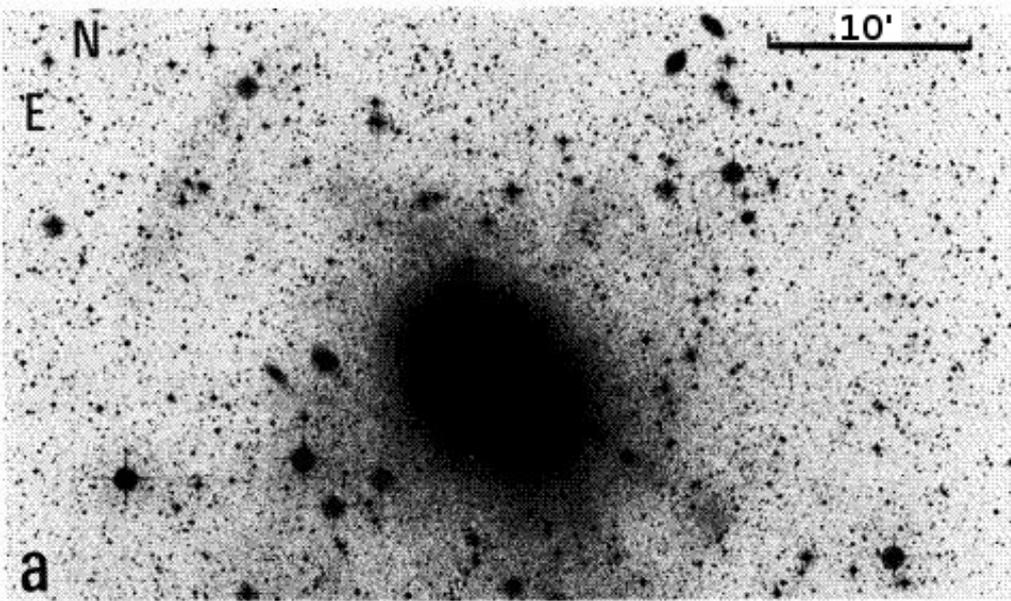


Warps



Hunter & Toomre 69; Toomre 83; Dekel & Shlosman 83; Mathur 84;
Sparke 84; Christodoulou & Tohline 86; Sparke & Casertano 88; Ostriker & Binney 89; Binney 91;
Hernquist 91; Kuijken 91; Christodoulou et al 93; Hoffner & Sparke 93, 94; Nelson & Tremaine 95;
Masset & Tagger 97; Binney et al. 98; New et al. 98; Debattista & Sellwood 99; Brada & Milgrom 00;
Ideta et al 00; Lopez-Corredoira et al. 02; Bailin & Steinmetz 03; Shen & Sellwood 06; Jeon et al 09

Shells and ripples



Nature

Quinn 82, 84; Athanassoula & Bosma 85;
Huang & Stuart 85, 87;
Dupraz & Combes 86, 87;
Hernquist & Quinn 87, 88, 89;
Loewenstein et al 87;
Heisler & White 90;
Thomson & Wright 90, 91;
Weil & Hernquist 93;
Ehlerova et al. 97;
Merrifield & Kuijken 98

Nature

Fabian et al. 80; Williams & Christiansen 84



Disc Galaxies

Disc

Bulge (classical, **boxy/peanut**, discy)

Bar

Spiral

Warps

Bridges and tails

Thick discs

Rings (ringed galaxies, polar rings,
rings in barred spirals)

Ellipticals

Shells and ripples

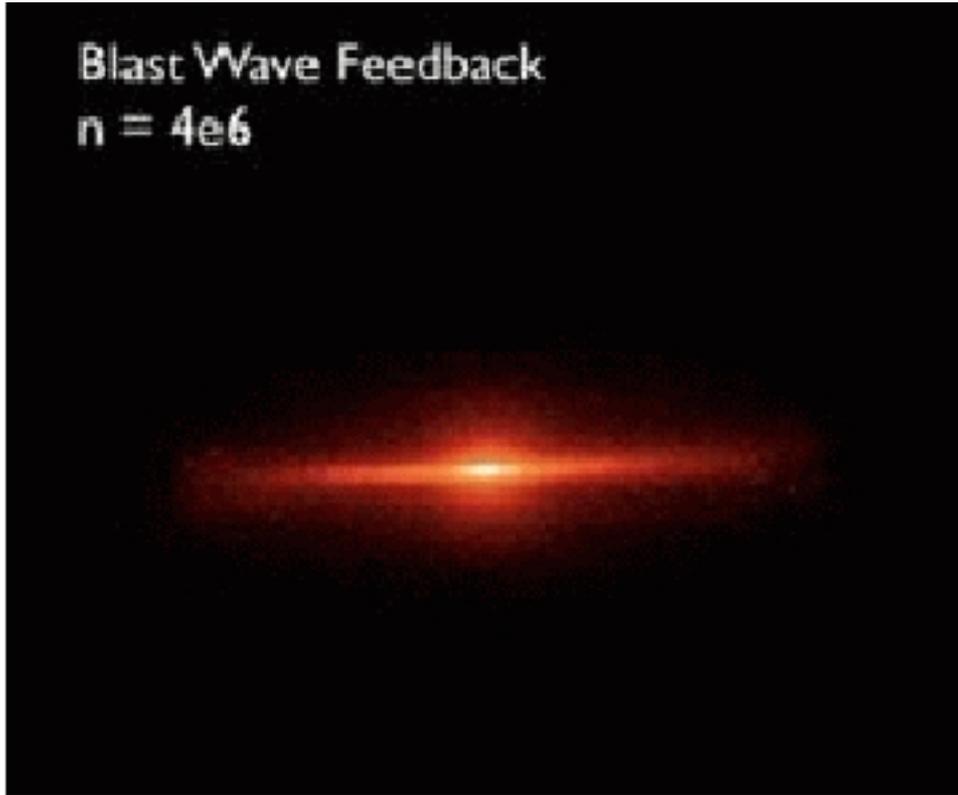
Dust lanes with
peculiar kinematics



The end

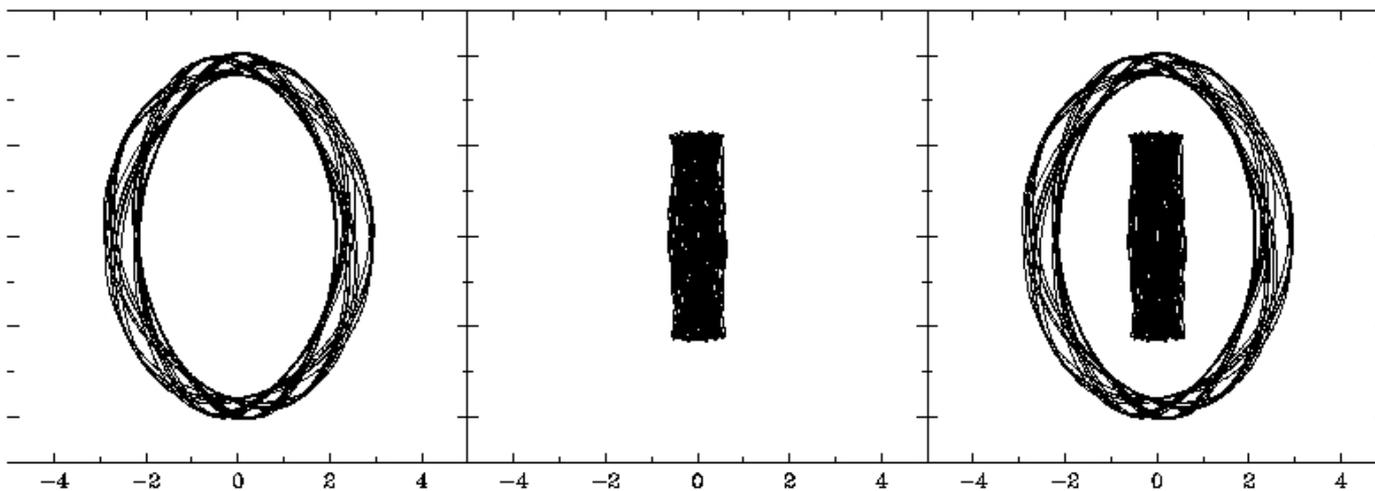
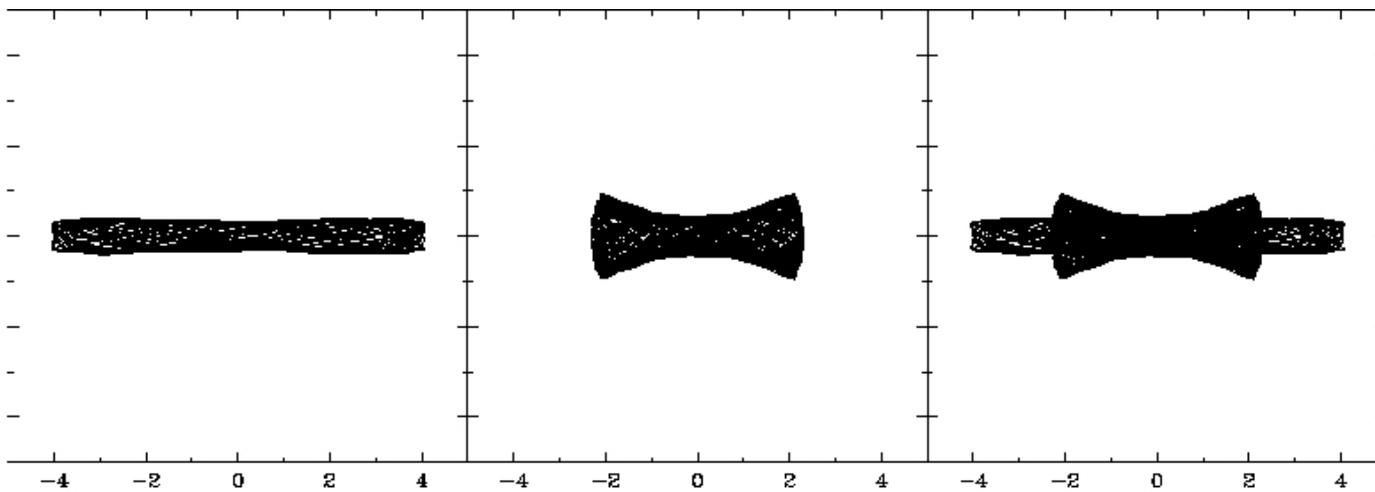


Blast Wave Feedback
 $n = 4e6$





Orbits (cont.)





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

Galaxies viewed edge-on with observations :

... (Athanassoula and Misiriotis 2004)

... king (Aronica, Athanassoula, Bureau, Bosma et al 2003,

... 'tation' (Athanassoula and Misiriotis 2002)

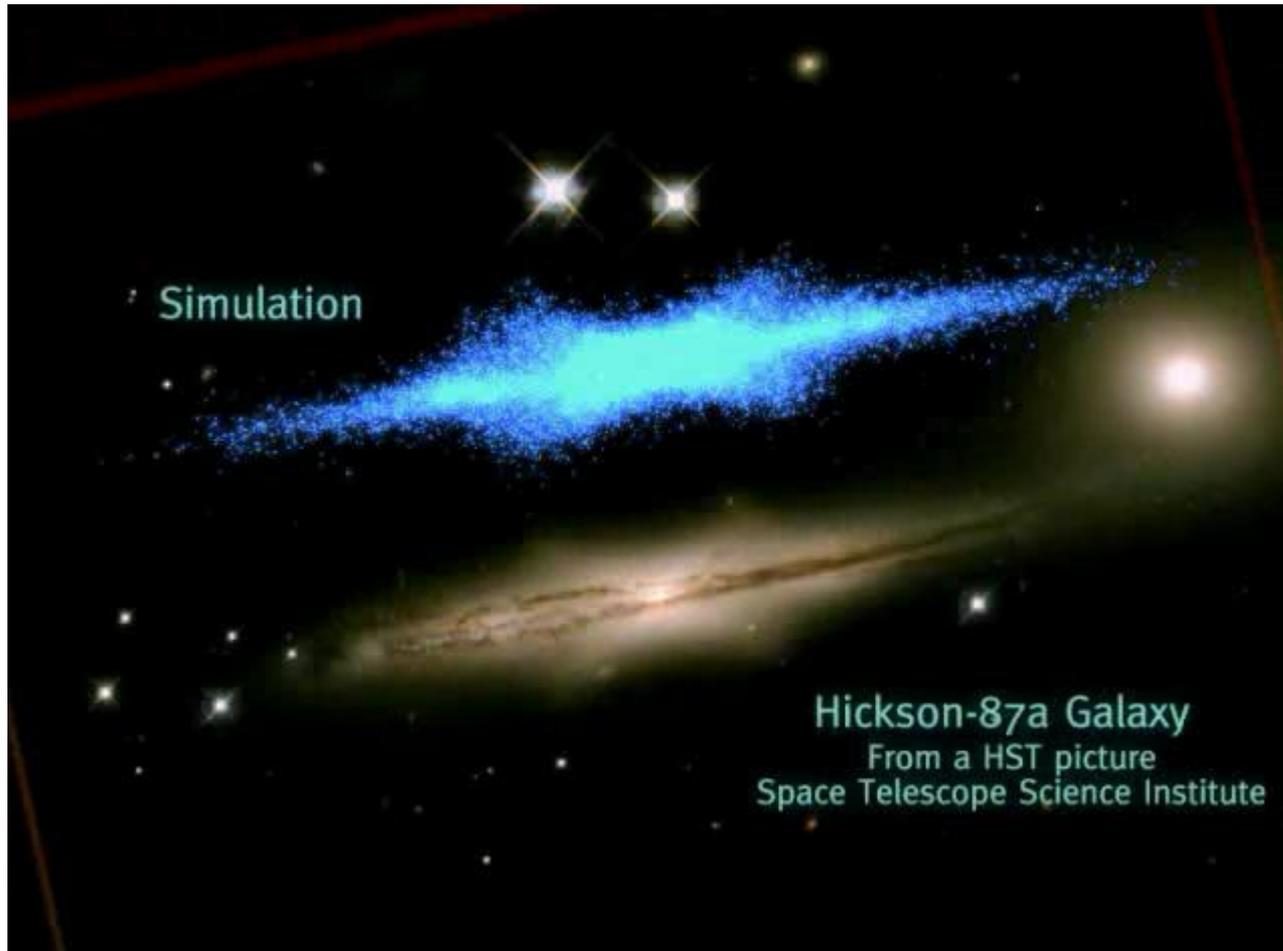
... and Athanassoula 2004, Athanassoula 2004)

... ttista, Carollo, Mayer and Moore 2004)

... and Kennicutt 2004 for other references

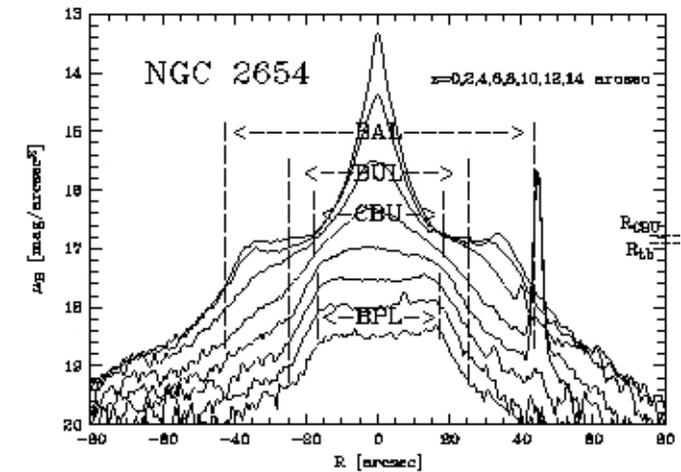
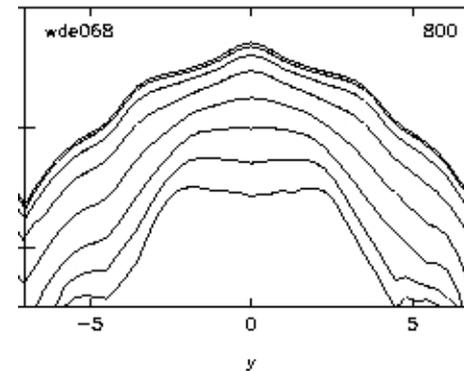
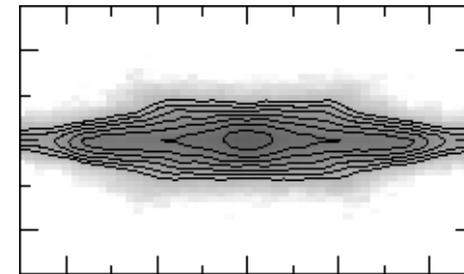
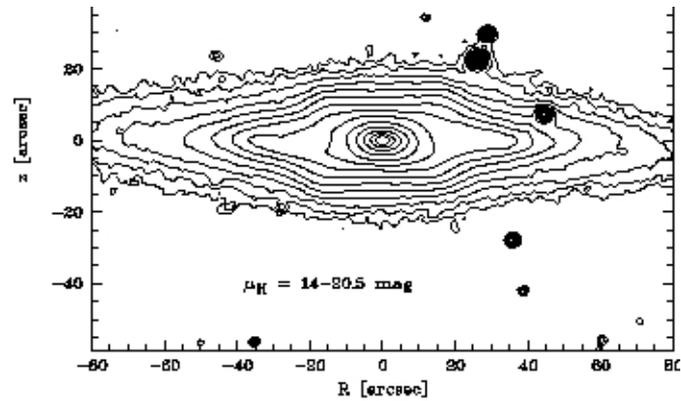


N-body simulations





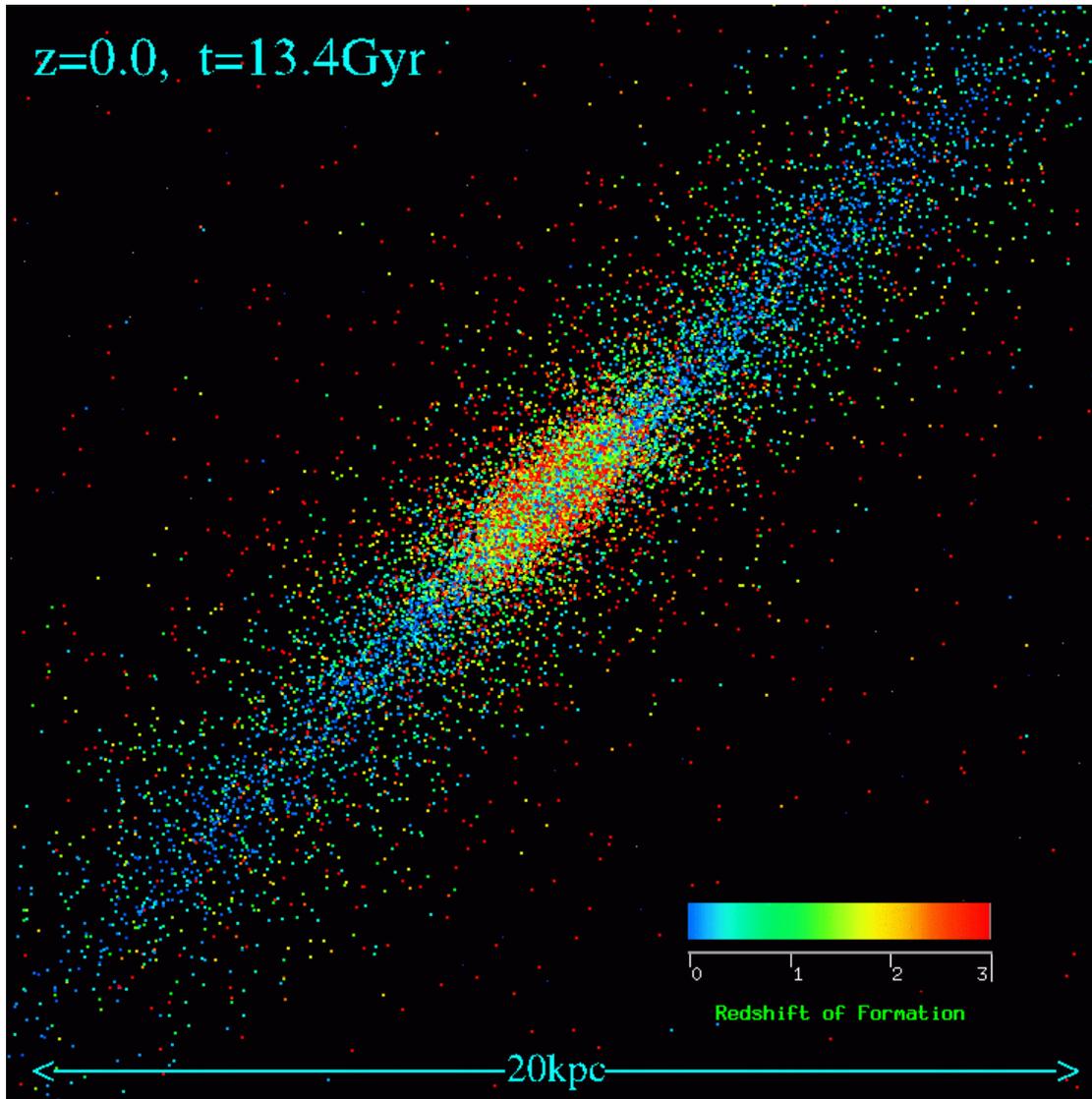
Horizontal cuts



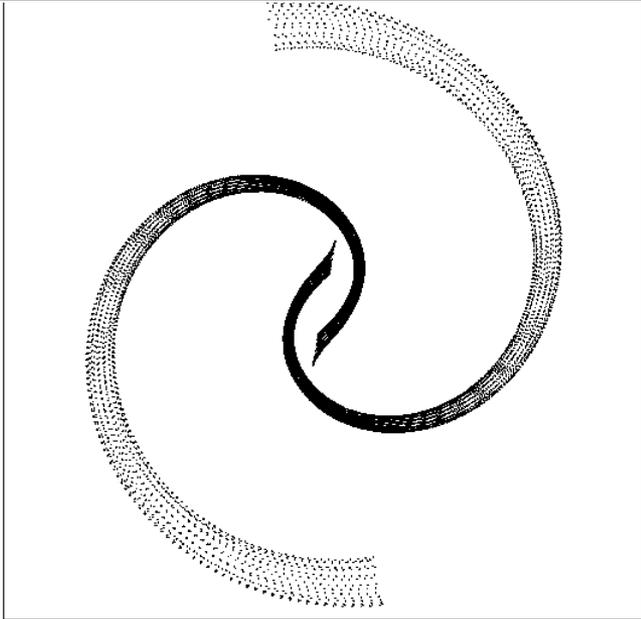
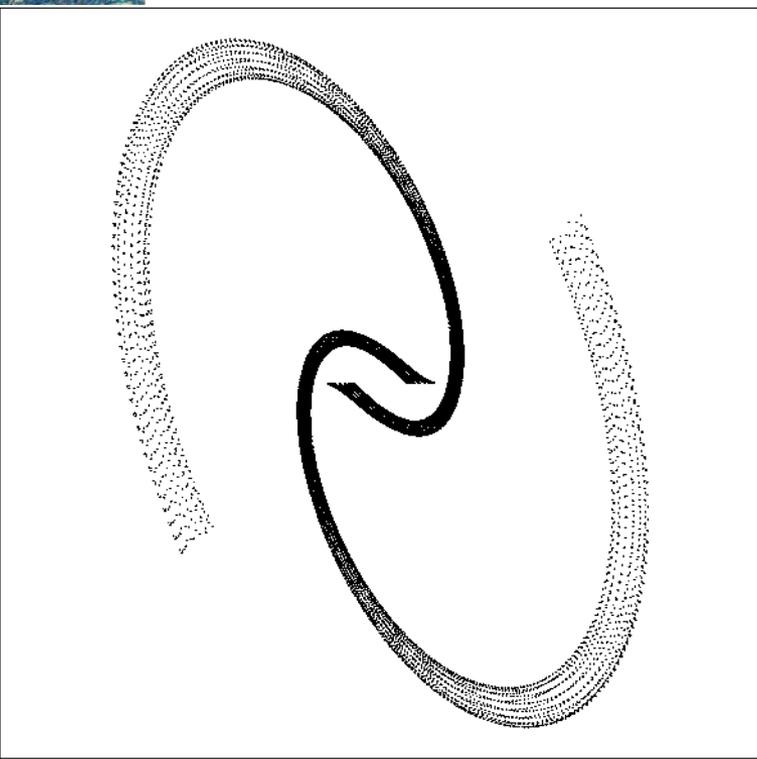
Athanassoula 2005 (also Athanassoula and Misiriotis 2002)



Formation of classical bulges : collapse and merging

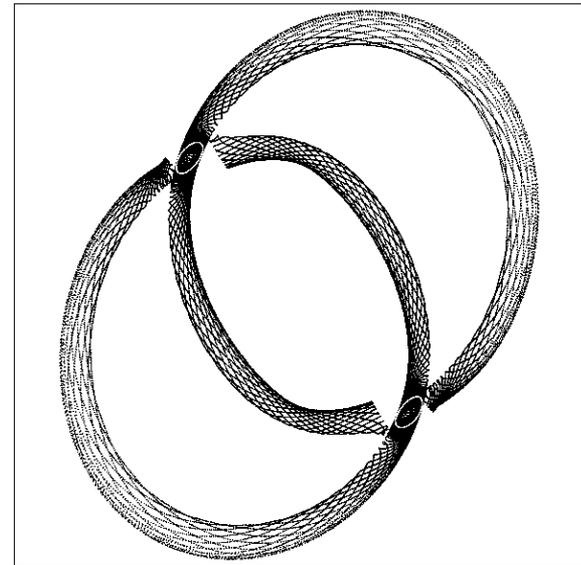
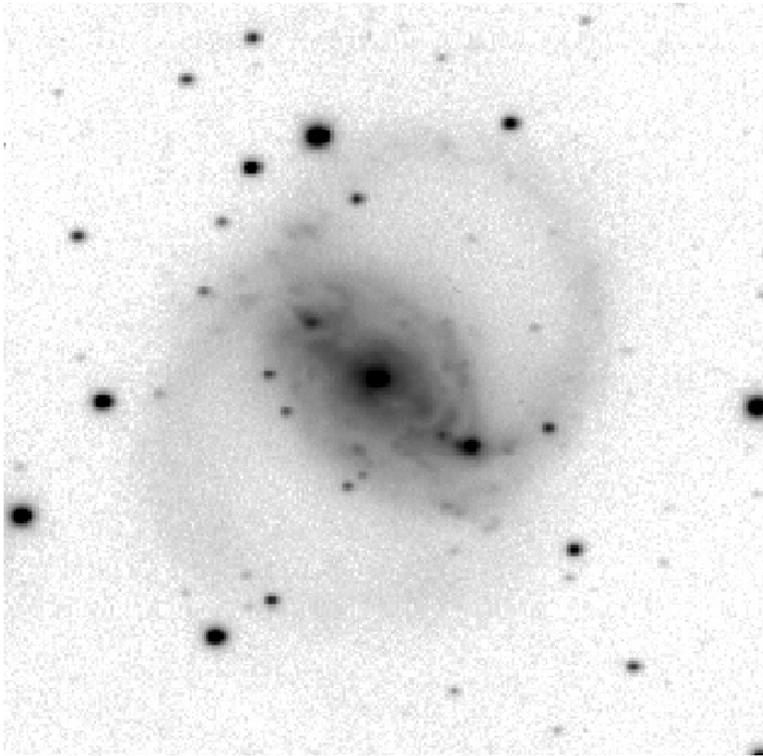


Sommer-Larsen et al (2005)





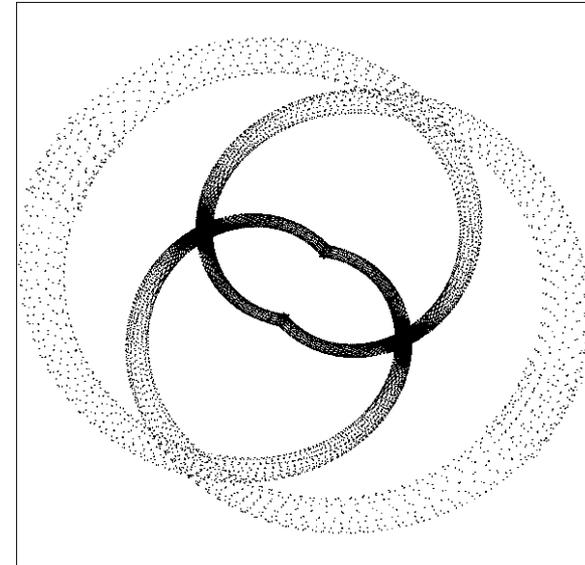
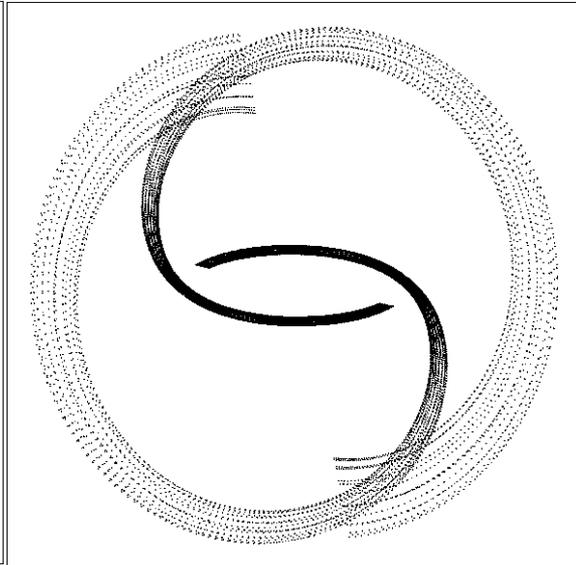
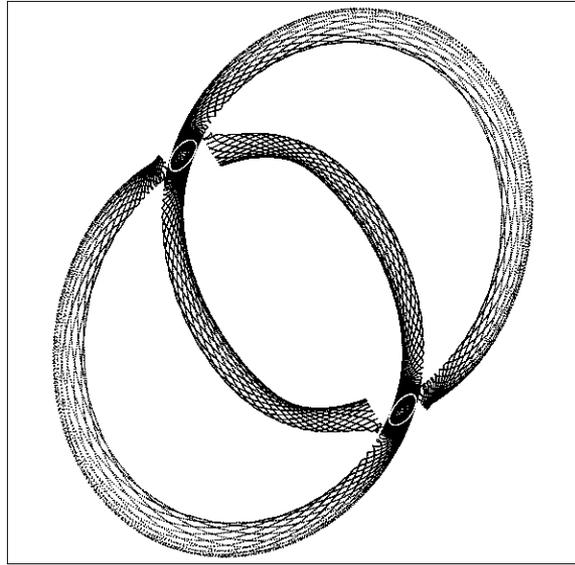
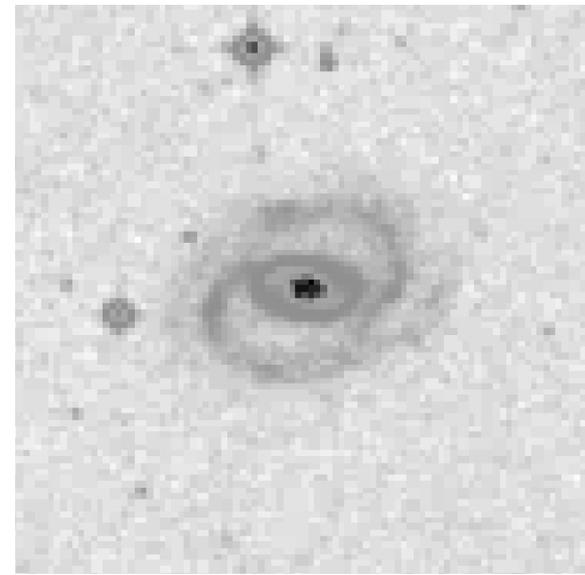
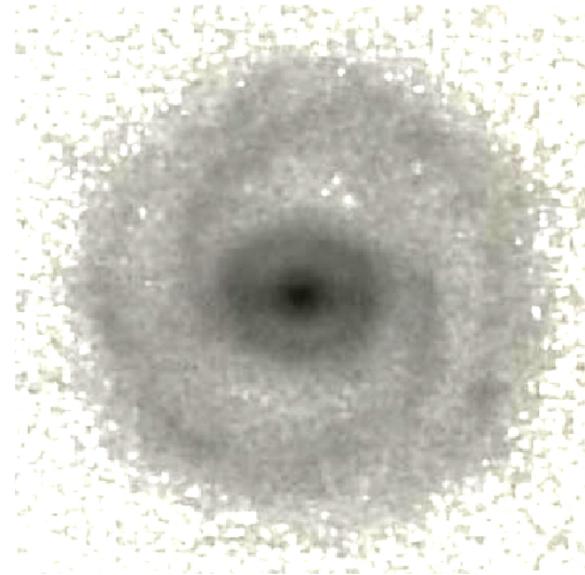
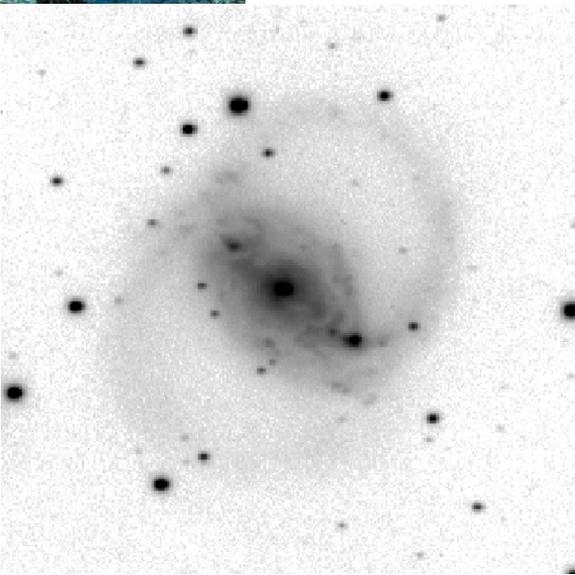
Rings



Schwarz 81, 84, 85; Romero-Gomez et al. 06, 07; Athanassoula et al. 09



Rings



Schwarz 81, 84, 85; Romero-Gomez et al. 06, 07; Athanassoula et al. 09



Warps

Disc only : only if outer disc truncation is unrealistically sharp (Hunter & Toomre 69)

Rigid flattened, misaligned halo (Toomre 83; Dekel & Shlosman 83; Sparke & Casertano 88; Kuijken 91; Ideta et al 00)

Live halo: Dynamical friction will damp the warp (Nelson & Tremaine 95; Dubinski & Kuijken 95; Binney et al 98; Debattista & Sellwood 99)

Origin?

– Cosmic infall (Ostriker & Binney 89; Binney 91; Quinn & Binney 92; Jiang & Binney 99; Lopez-Corredoira et al. 02; Shen & Sellwood 06; Jeon et al 09)

– Companions (Hernquist 91; Bailin & Steinmetz 03)

