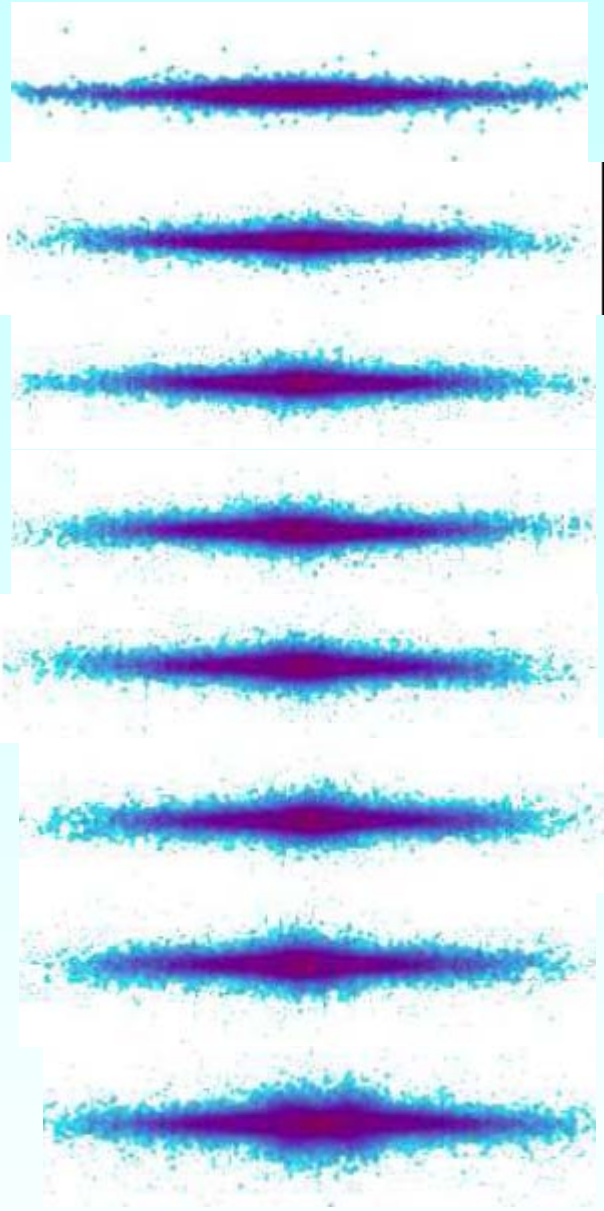
Secular evolution and assembly of bulges



Outline:

➔Secular evolution & bulges, gas flows

➔Bar destruction, re-formation, role of gas

➔Bars & bulge stats: B/T, n, high z evolution

➔Mergers and bulge formation scenarios

Françoise Combes

Austin, 11 November 2008

l'Observatoire de Paris | LERMA

Laboratoire d'Étude du Rayonnement et de la Matière en Astrophysique

Secular evolution and bulges

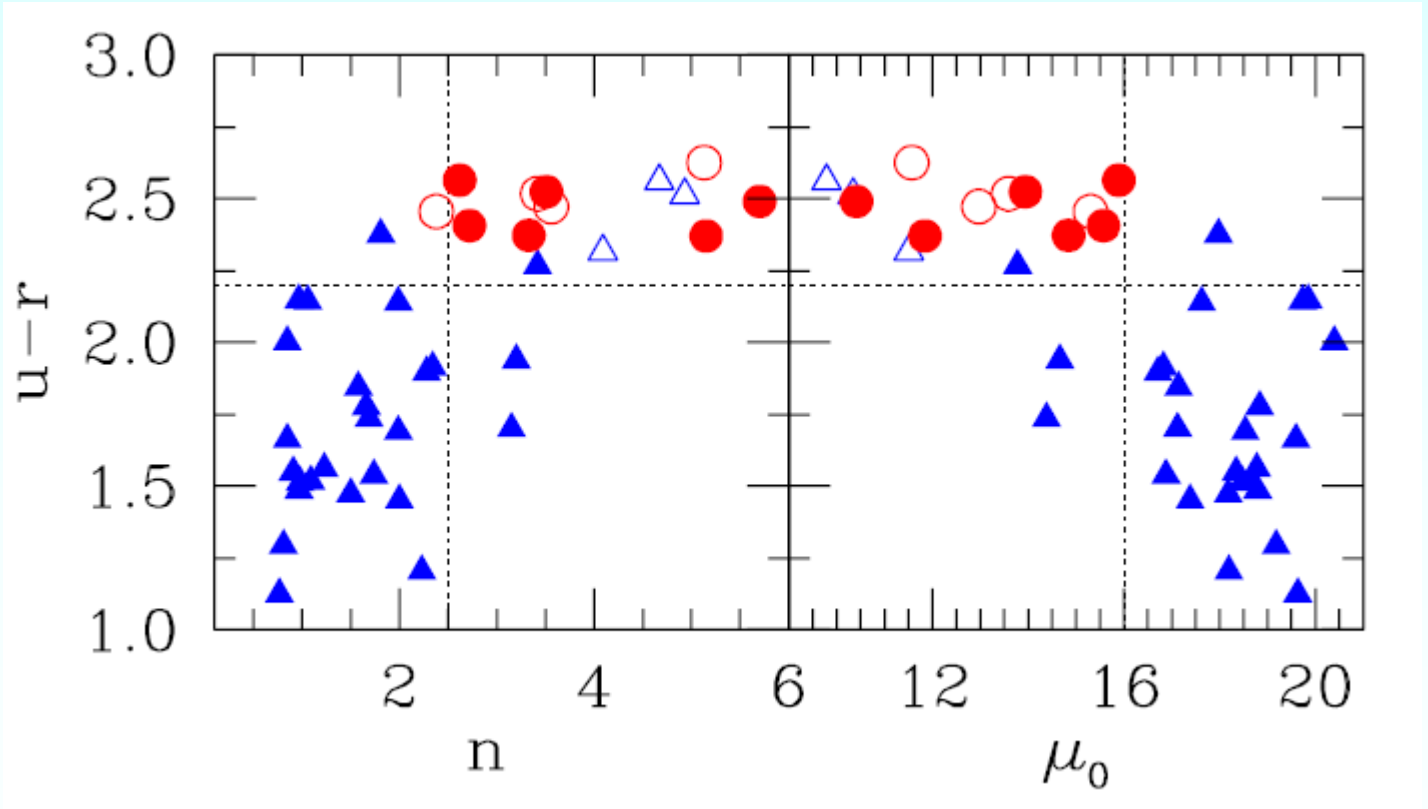
Secular evolution reviews, Kormendy & Kennicutt 2004, Jogee 2006

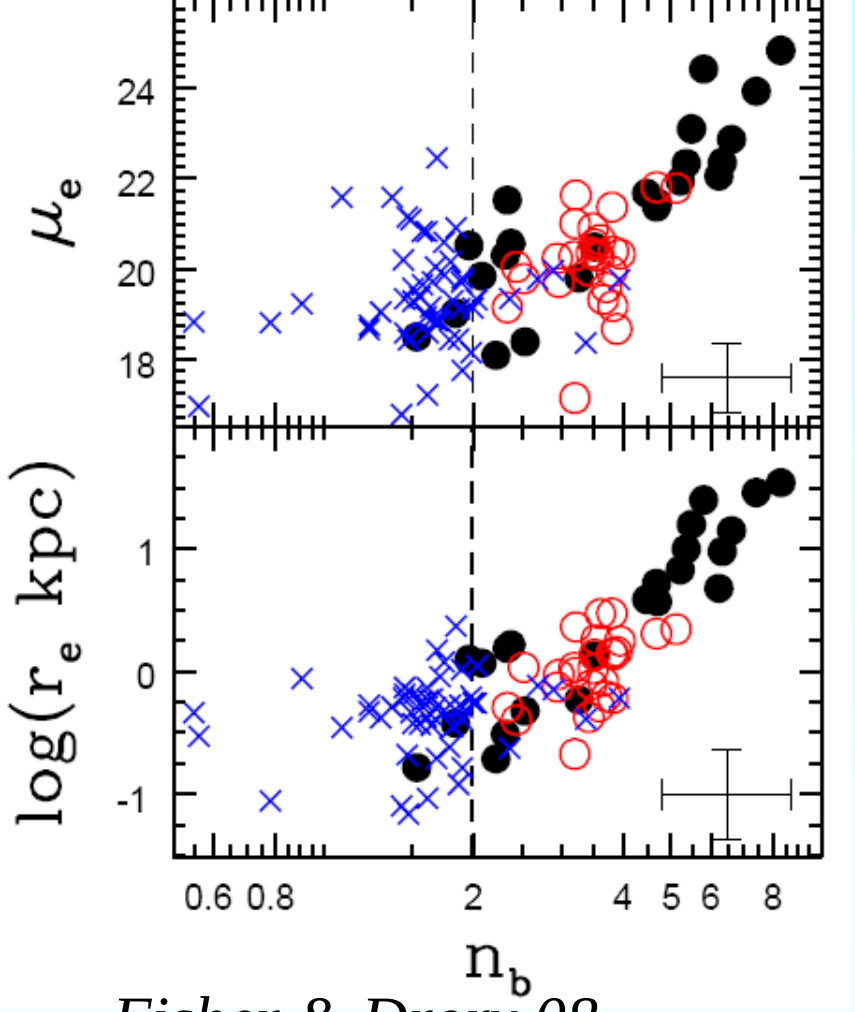
➔IAU 245 on "Formation and Evolution of Bulges", 2007

Clear distinction between classical bulges and pseudo-bulges,

Much more similar to disk: flattening, rotation, Sersic index, color..

➔ bimodality blue & red sequences *Drory & Fisher 2007*





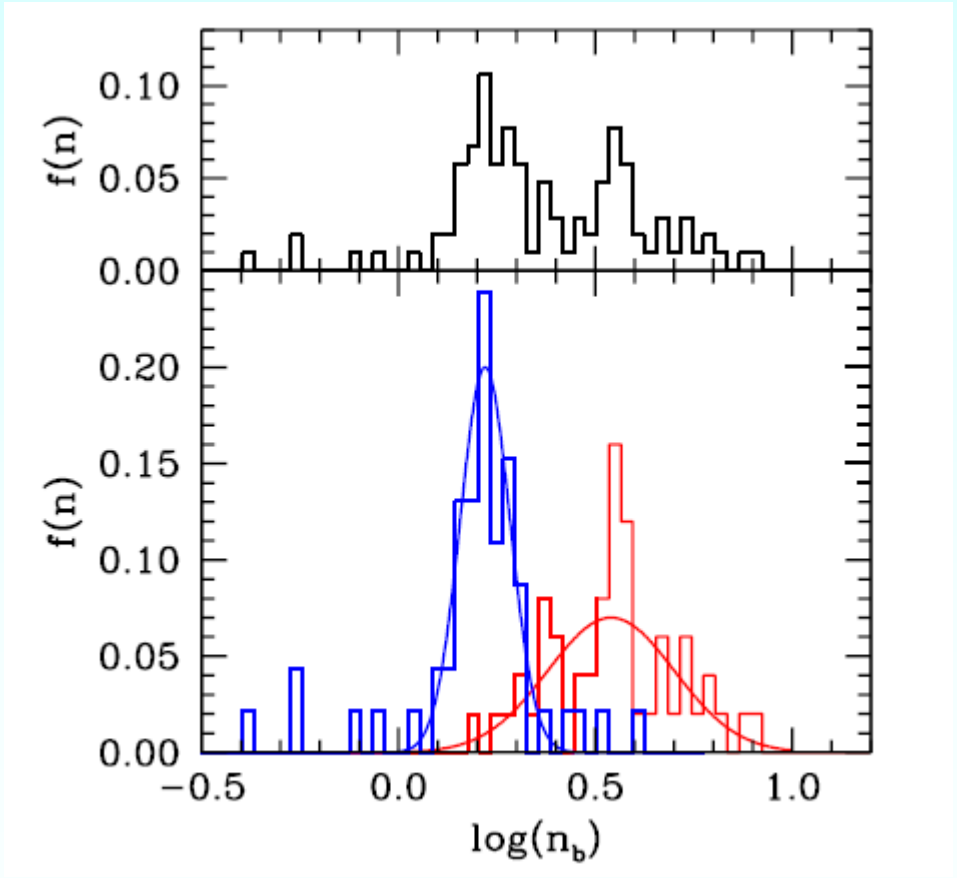
Fisher & Drory 08

Black dots= Elliptical galaxies
n=4 de Vaucouleurs law

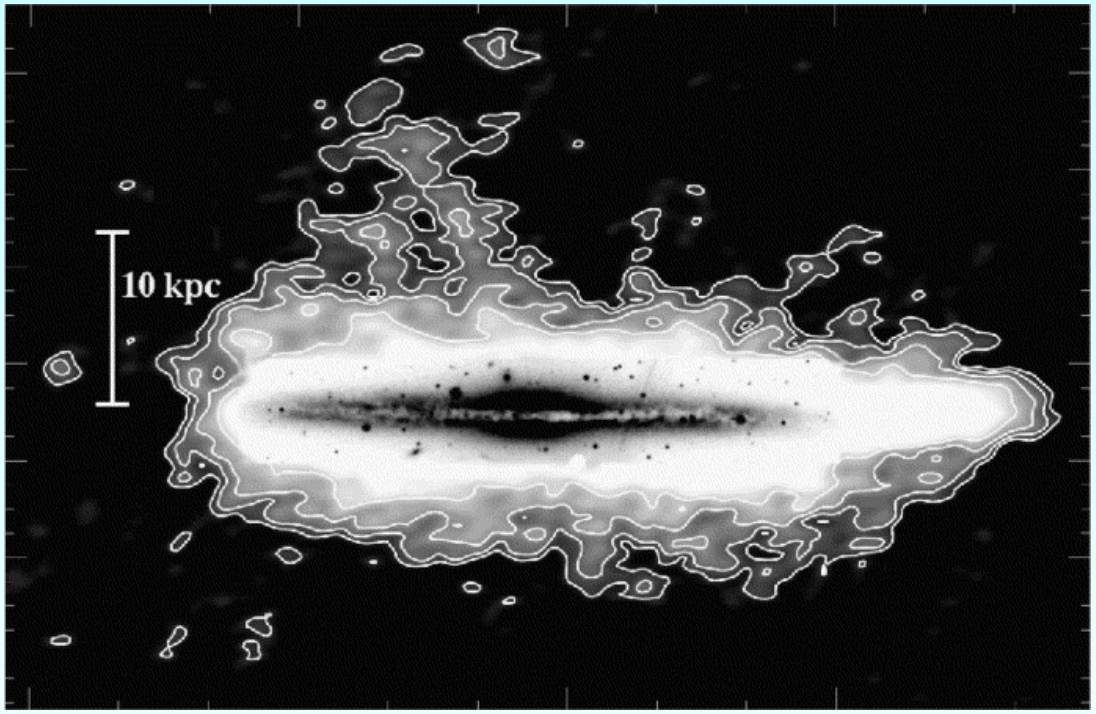
Blue sequence= pseudo-bulge
Red sequence = classical

Pseudo-bulge n=1-2

Bimodality in Sersic index



Gaseous haloes around galaxies

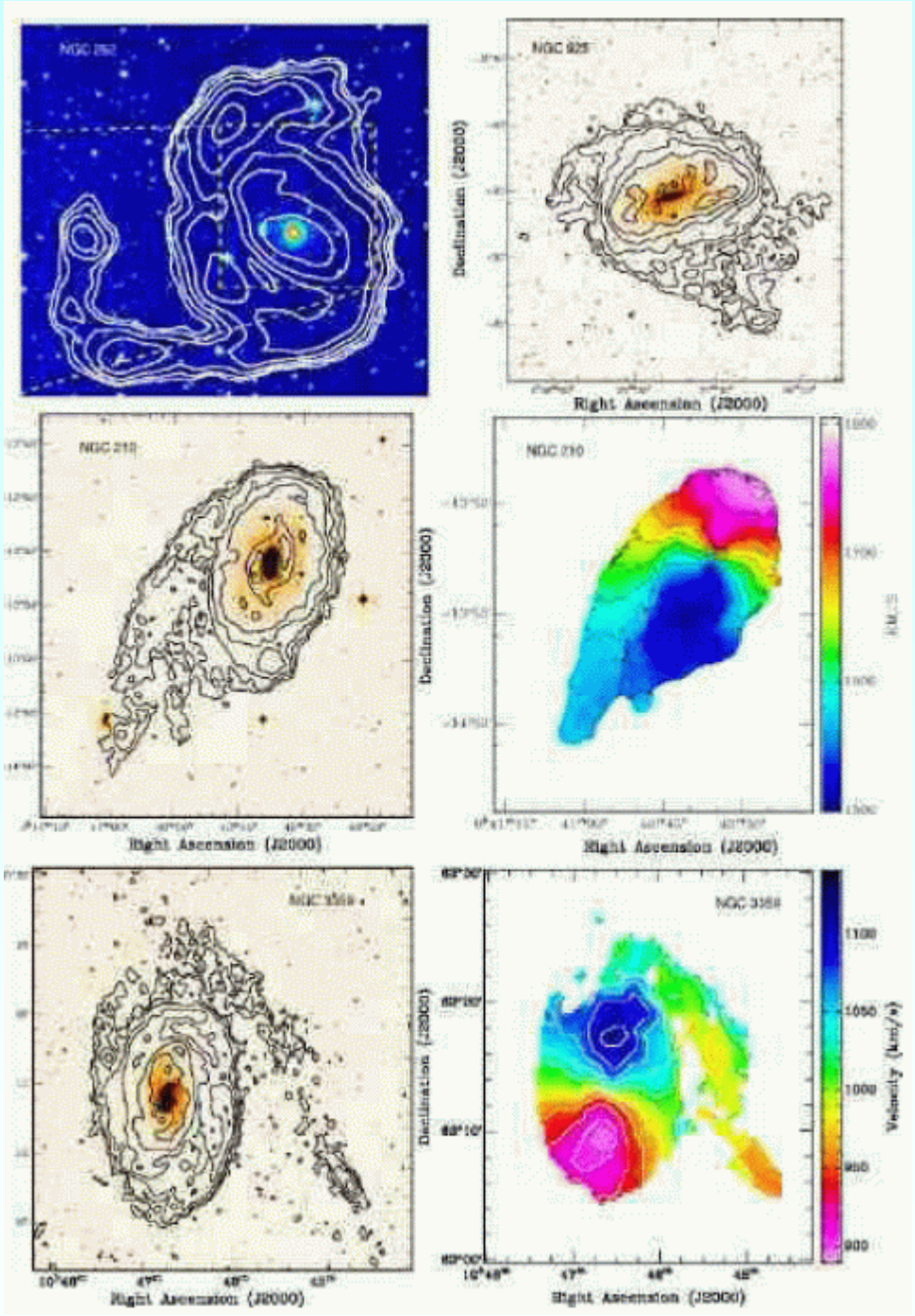


N891, Fraternali et al 2007

z~8kpc, or even up to 20kpc
Rotation decreases with z

Not all from galactic fountain, which will conserve AM

Modelisation with the fountain effect shows outflows (N2403)
While inflow is observed ➔ like HVC, IVC in the MW
Gaseous haloes require **accretion of external gas**
(Fraternali & Binney 2006)



Extra-planar gas, and signs of accretion

Sancisi et al 2008

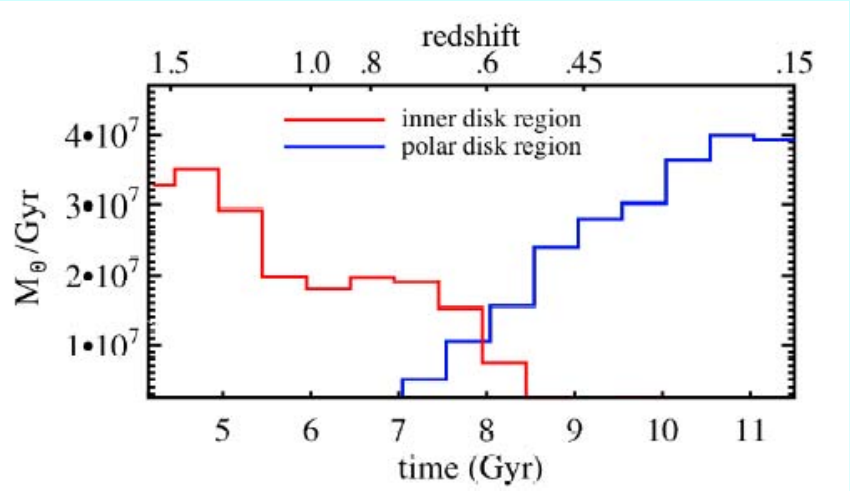
Evidence is mounting
in parallel to tidal streams

Part due to dwarf companions

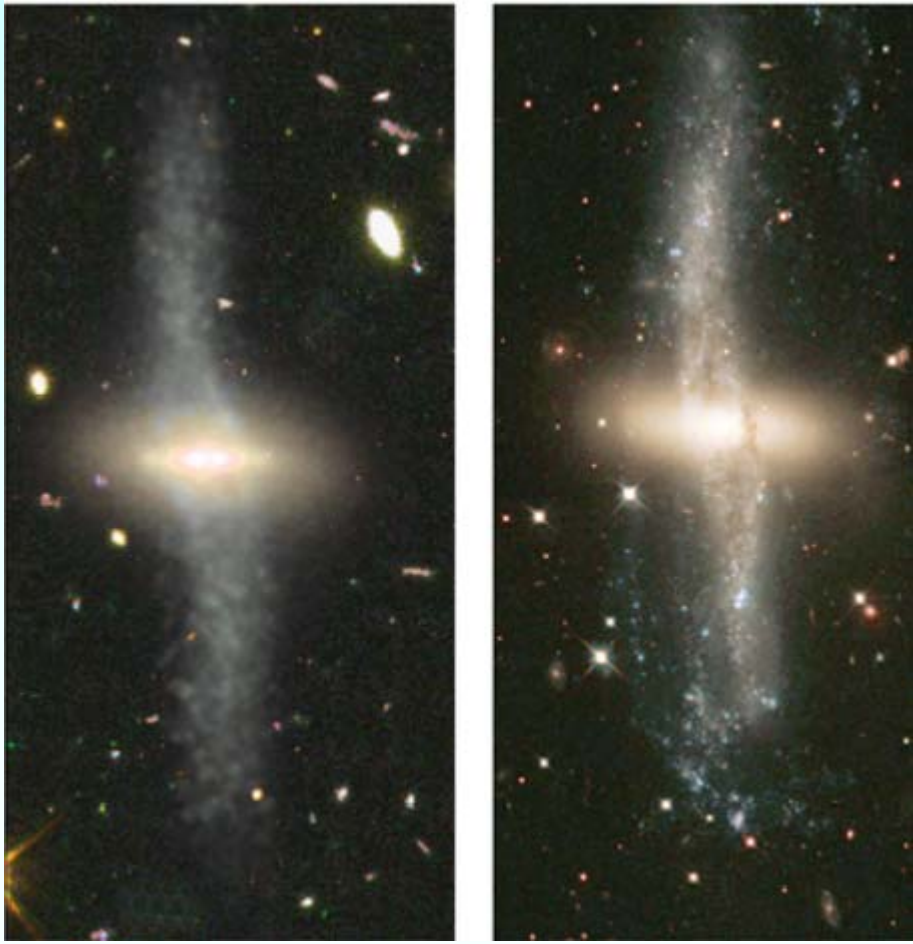
But most **extragalactic gas**

➔lopsideness, SF

Polar rings from cosmic gas accretion

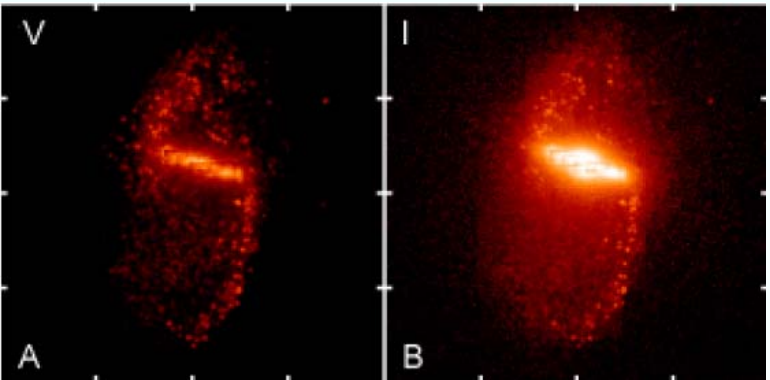


Brook et al 2008



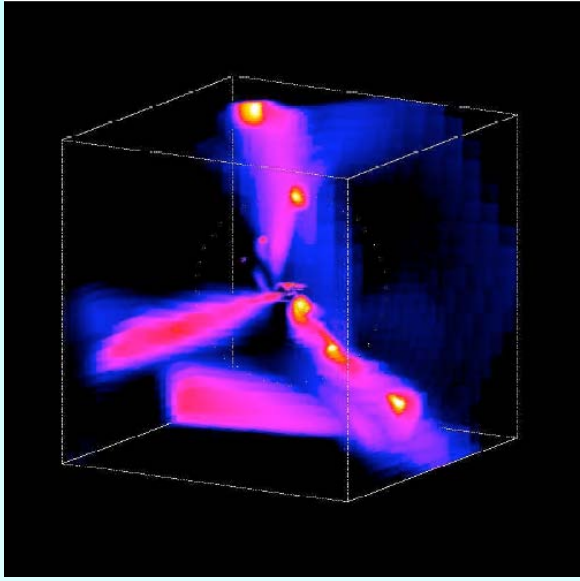
➔After 1.5 Gyr, interaction between the two disks destroys the PRG

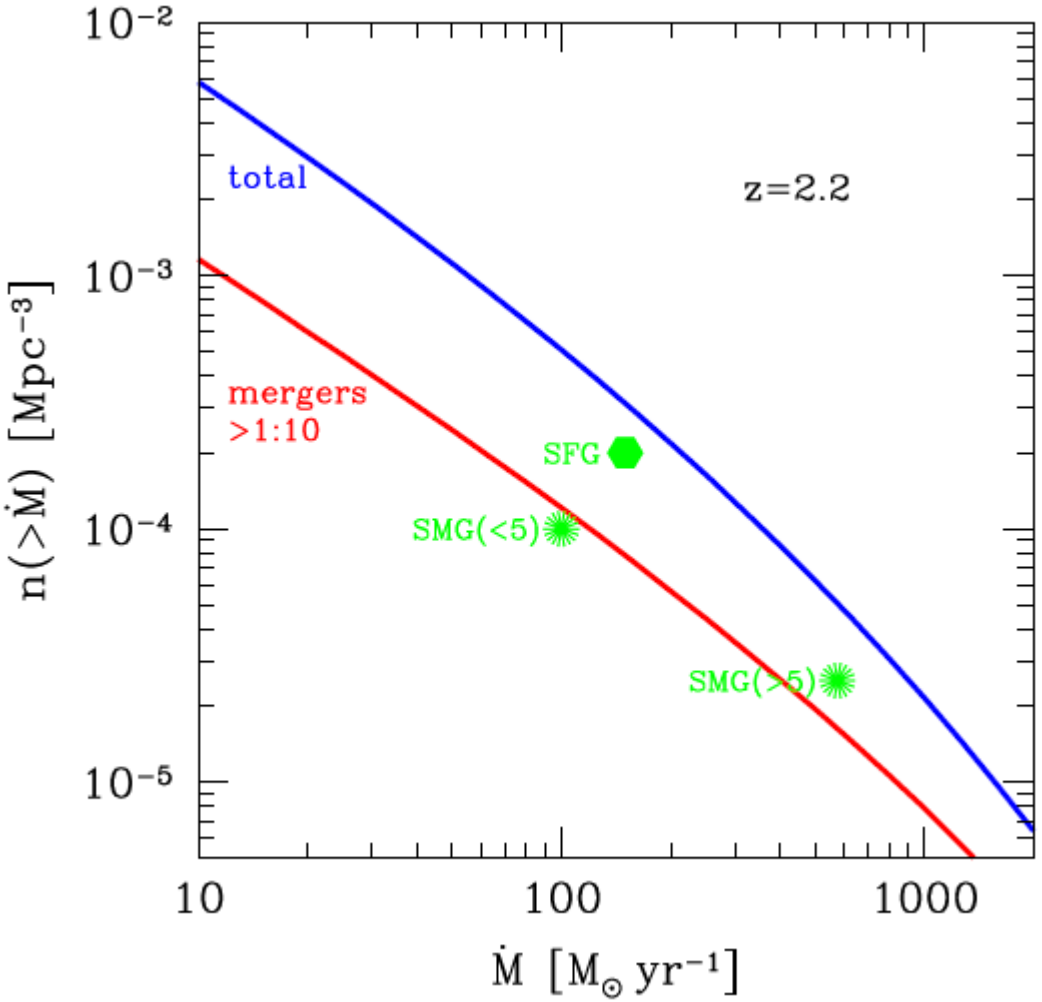
➔Velocity curve about the same in both equatorial and polar planes



Relative role of gas accretion and mergers

Dekel et al (2008)





Analysis of results from a cosmological simulation with gas and SF (Horizon) shows that most of the starburst are due to smooth flows

Inflow rates are sufficient to assemble galaxy mass (10-100 Mo/yr)

Outline:

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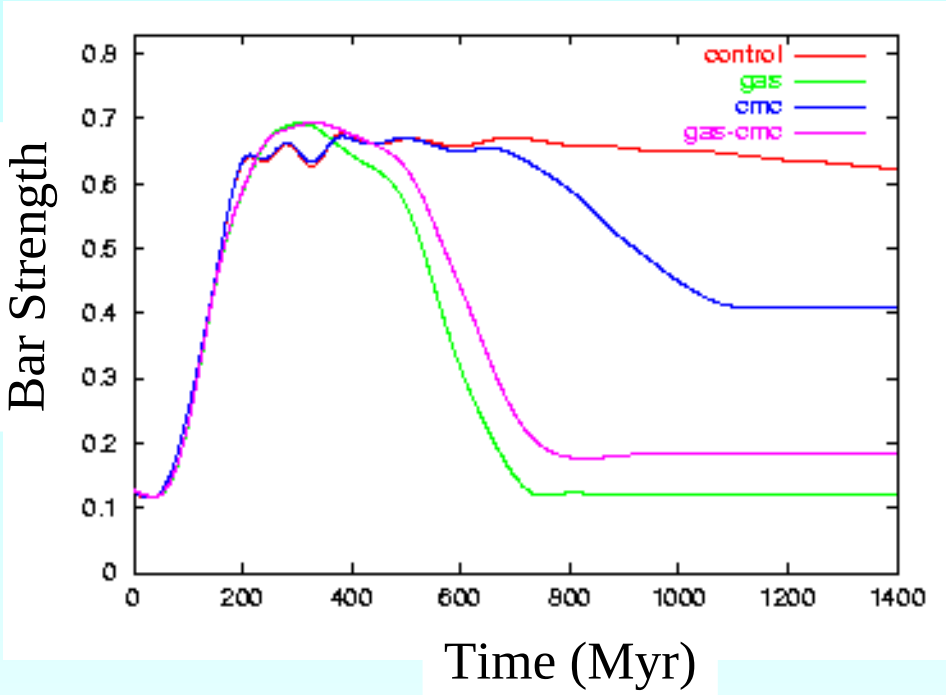
➔Mergers and bulge formation scenarios

Re-formation of bars



Self-regulated cycle:

➔Formation of a bar in a cold disk

➔Bar produces gas inflow, and

➔Gas inflow destroys the bar

+gas accretion

2% of gas infall is enough to transform a bar in a lens

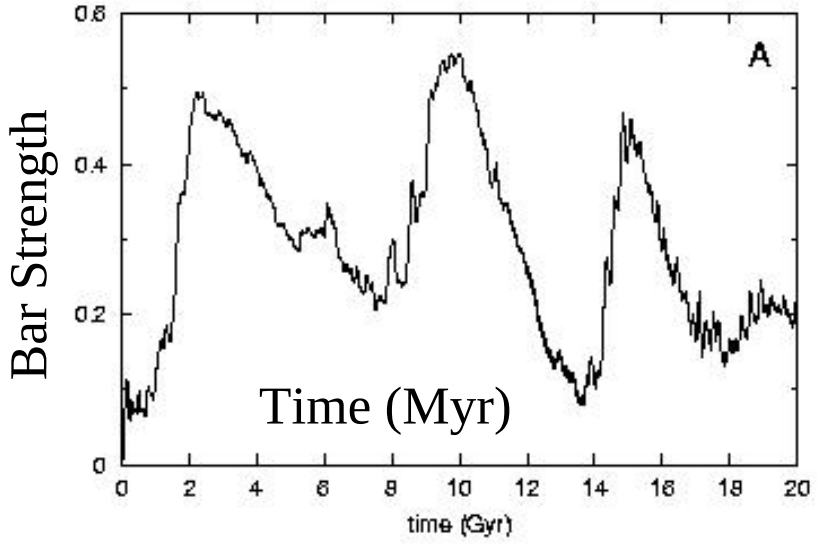
(Friedli 1994, Berentzen et al 1998, Bournaud & Combes 02, 04)

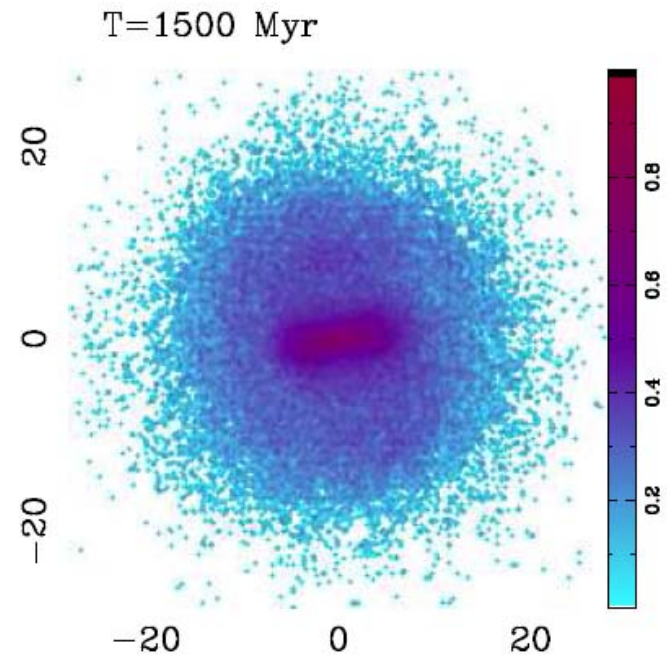
Gas accretes by intermittence

First it is confined

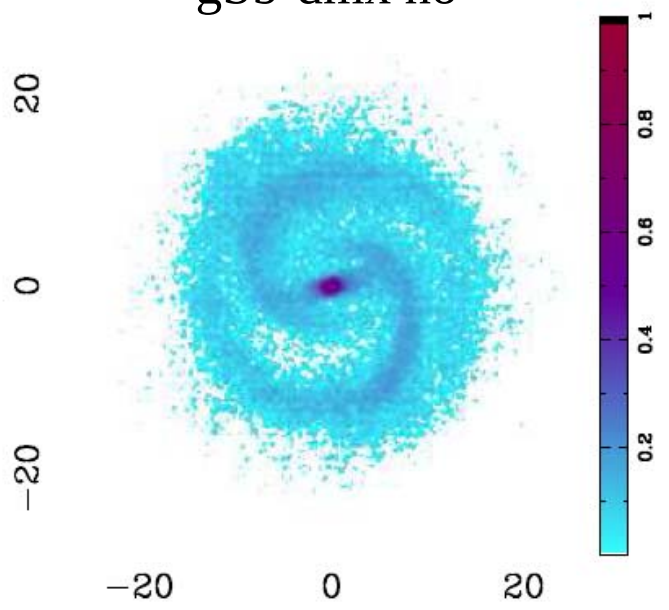
outside OLR until the bar weakens,

then it can replenish the disk, to make it unstable again to bar formation

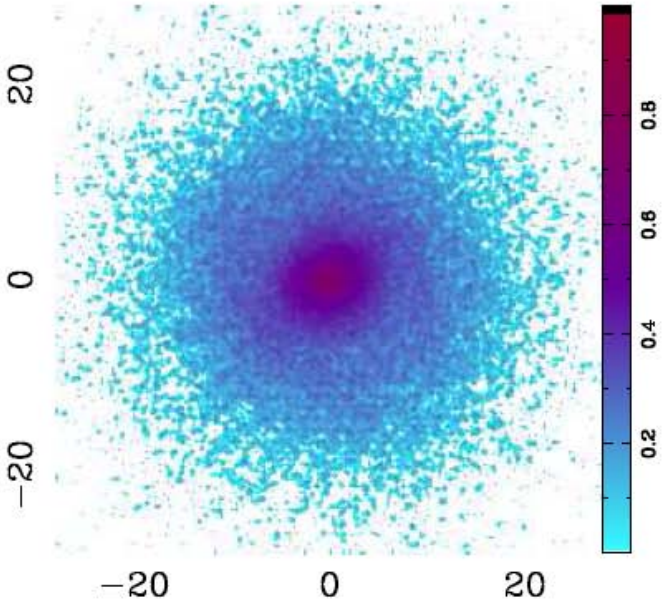


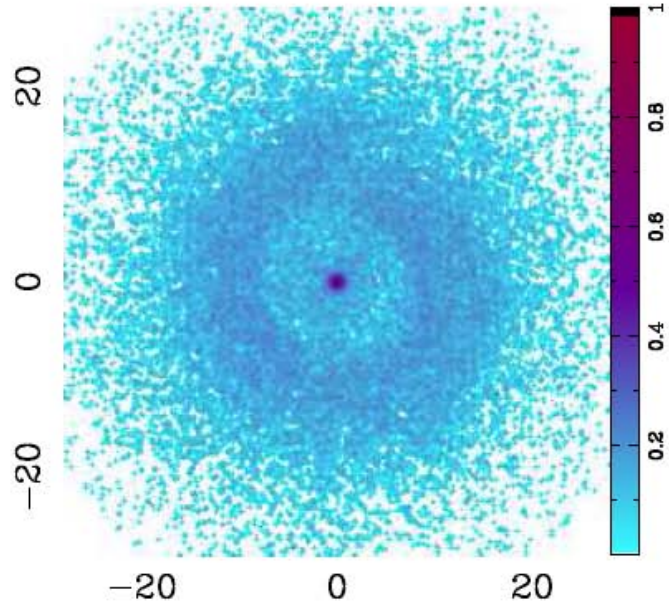


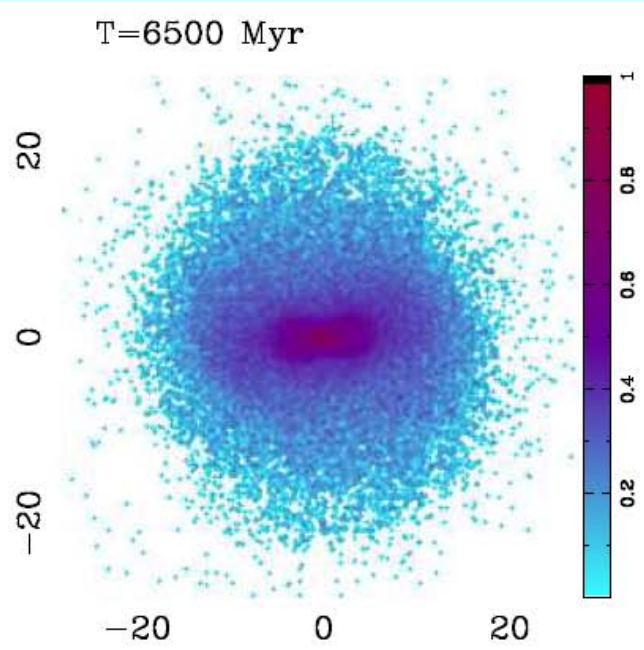
gSb-dmx no



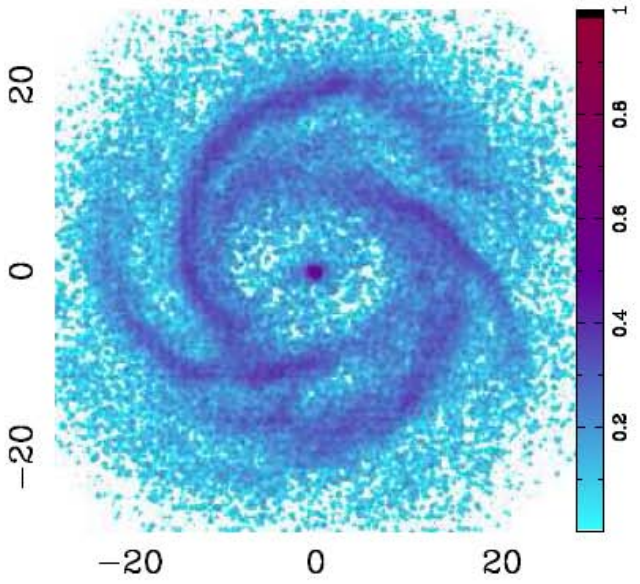
No gas accretion



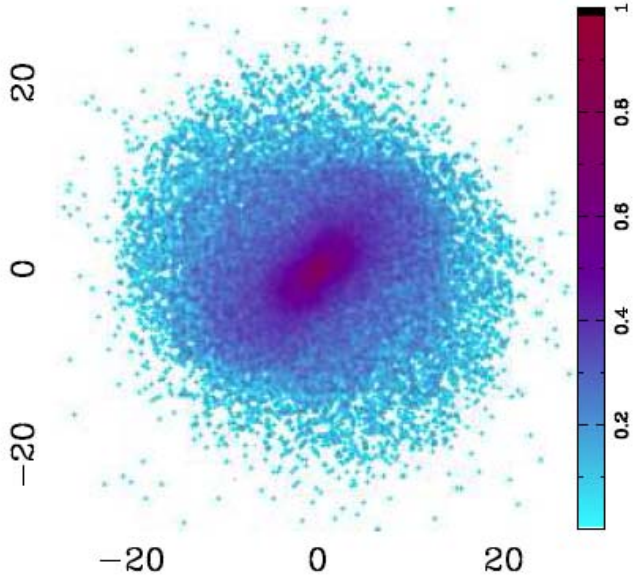


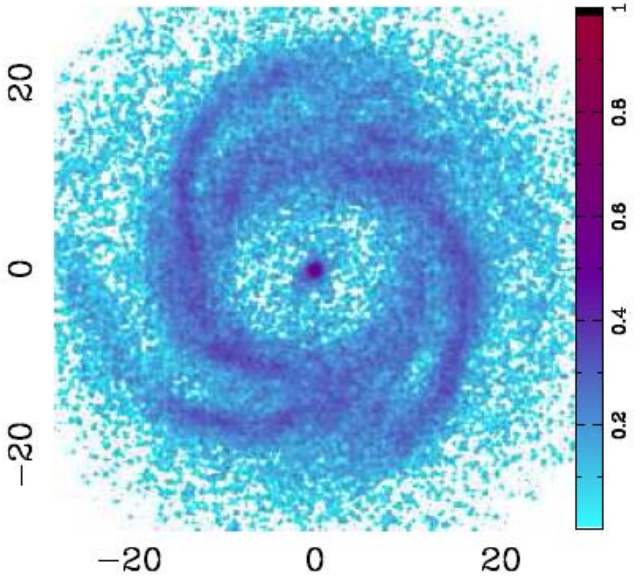


gSb-dmx ac



With gas accretion



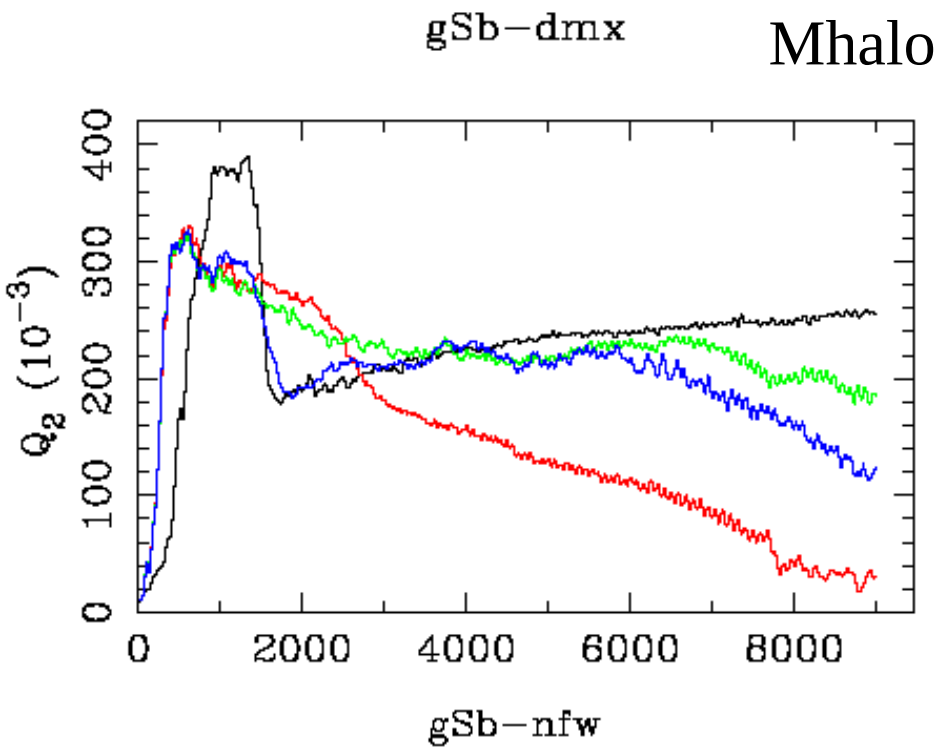


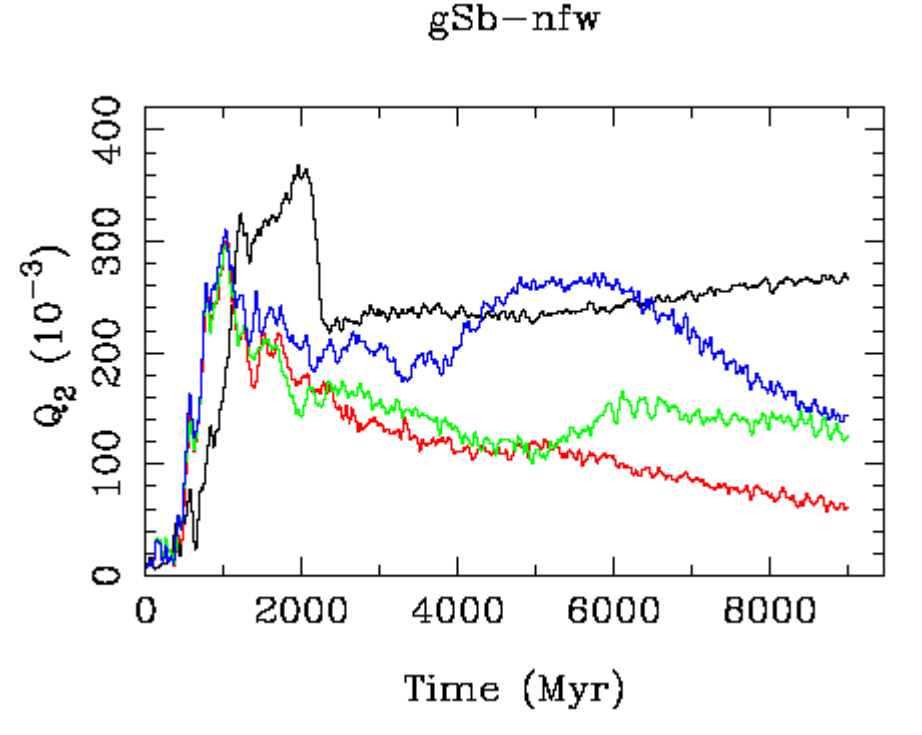
Mhalo=Mbar

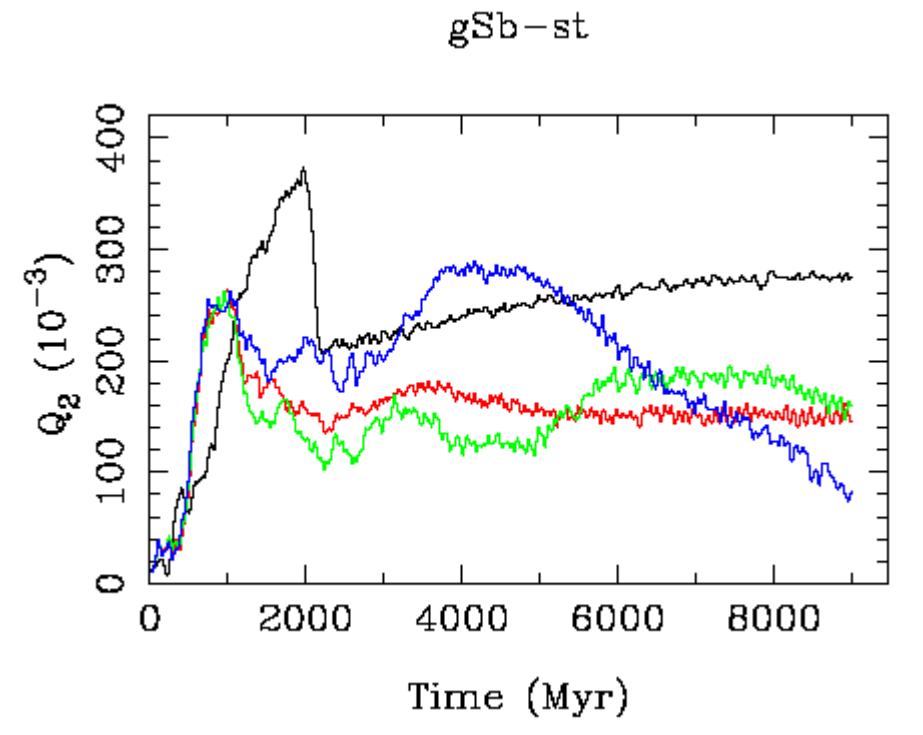
gSb models

Mbulge=1.1E10 Mo
Mdisk=4.6E10 Mo
Mhalo=17.2E10 Mo

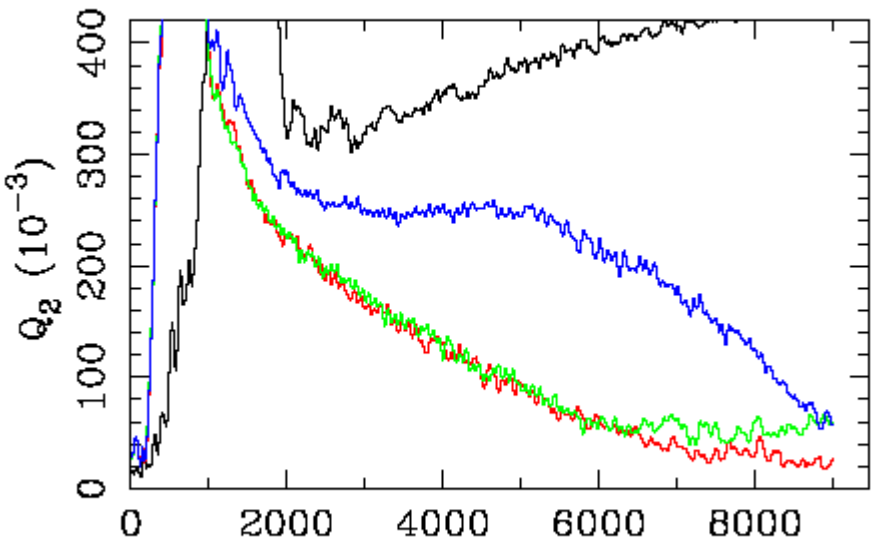
Mgas= 0.9E10 Mo (4%)







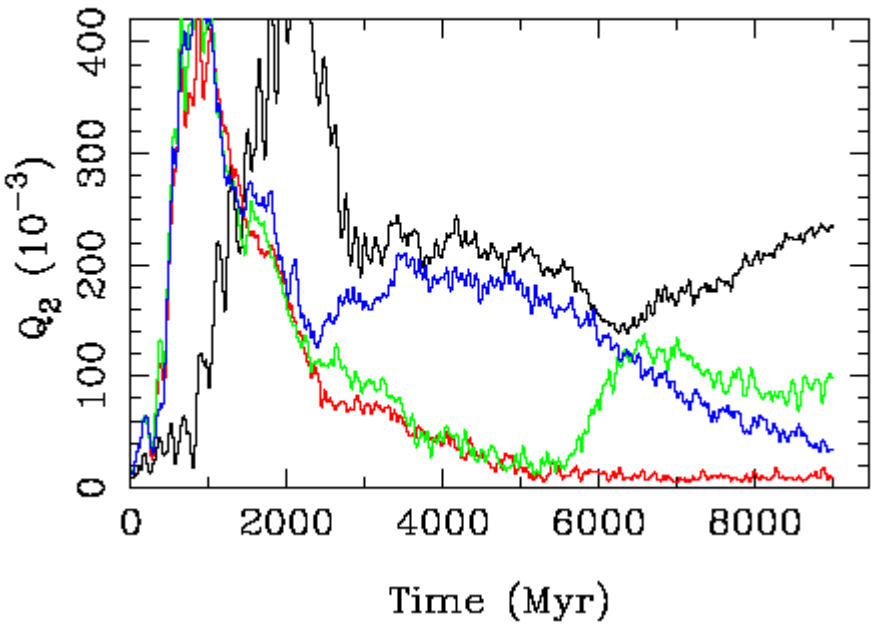
Mhalo=Mbar

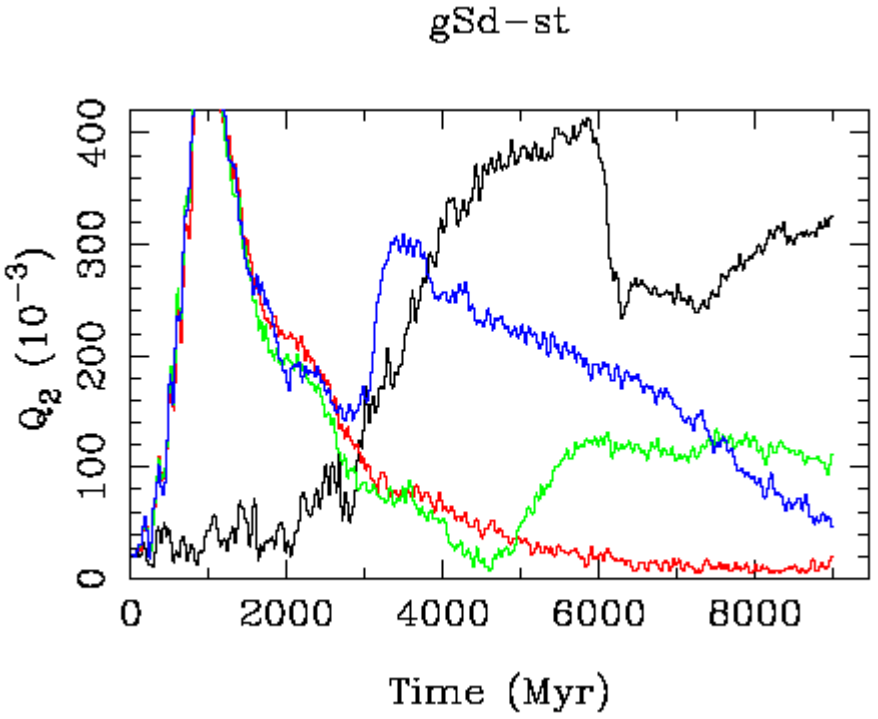


gSd models

Mbulge= 0
Mdisk=5.7E10 Mo
Mhalo=17.2E10 Mo

Mgas= 1.7E10 Mo (7%)

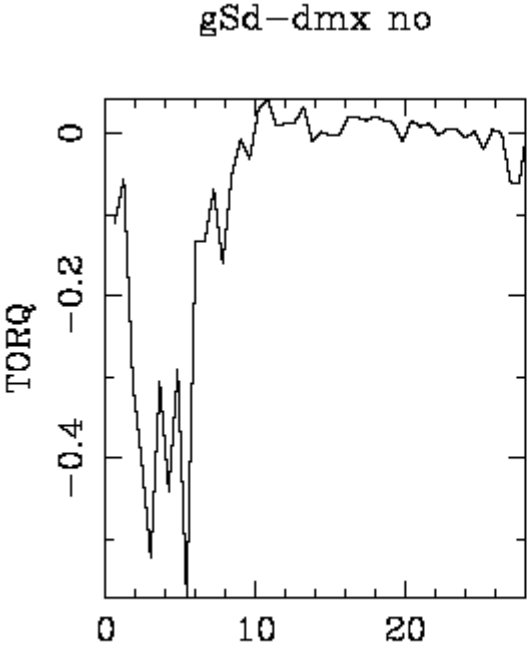


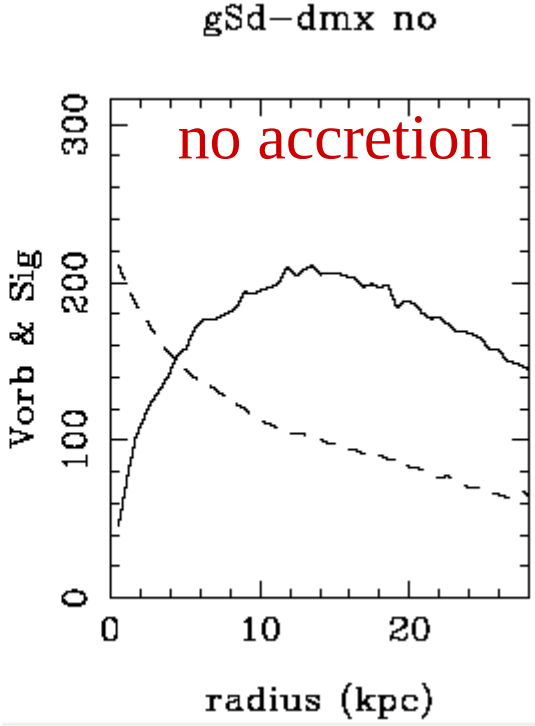


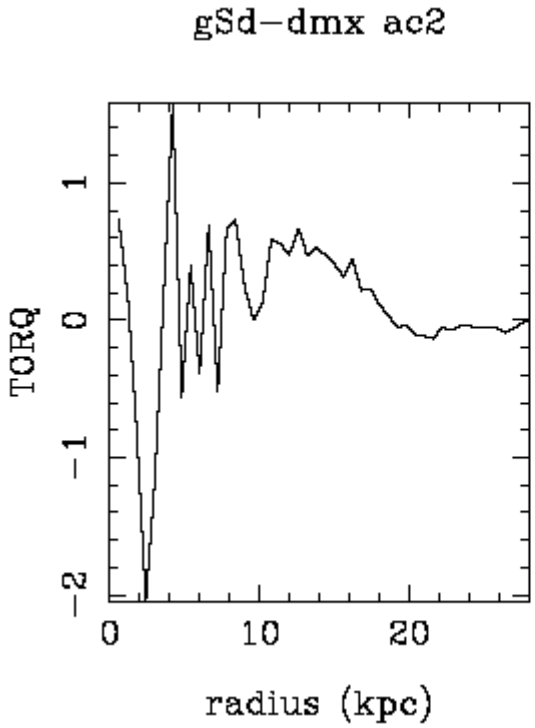
Sd-dmx

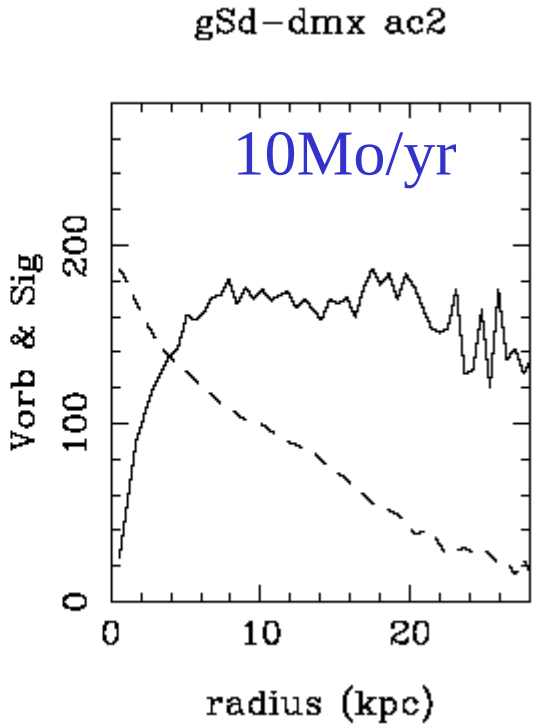
Gravity torques on the gas

➔Redistribution of matter in the disk

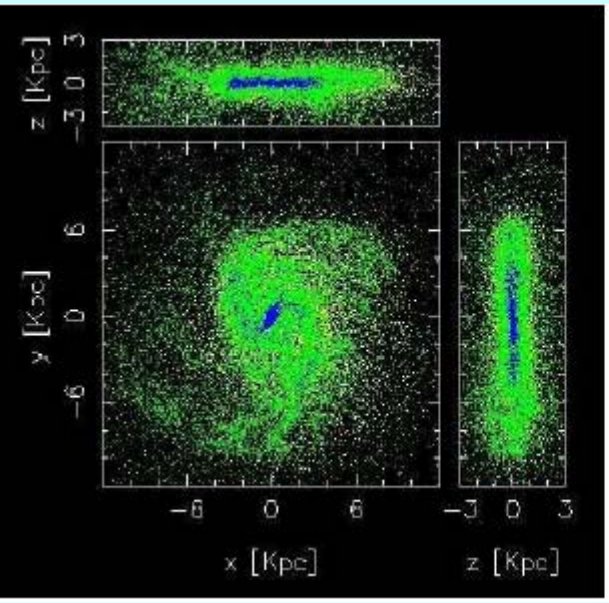


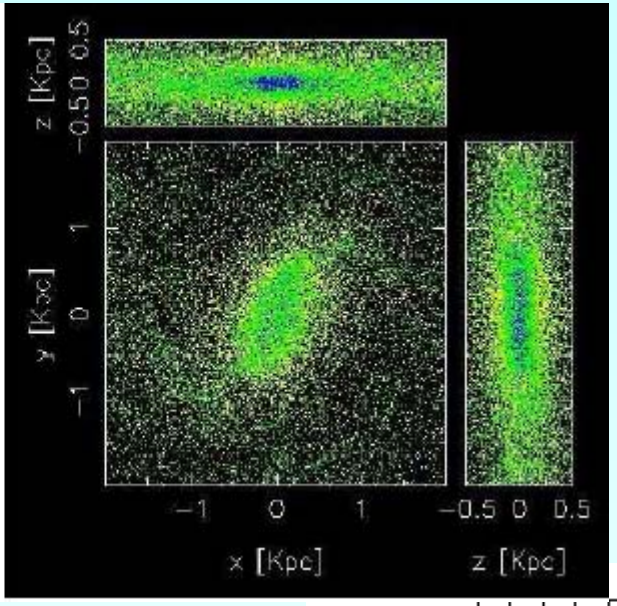






Formation in a cosmological context

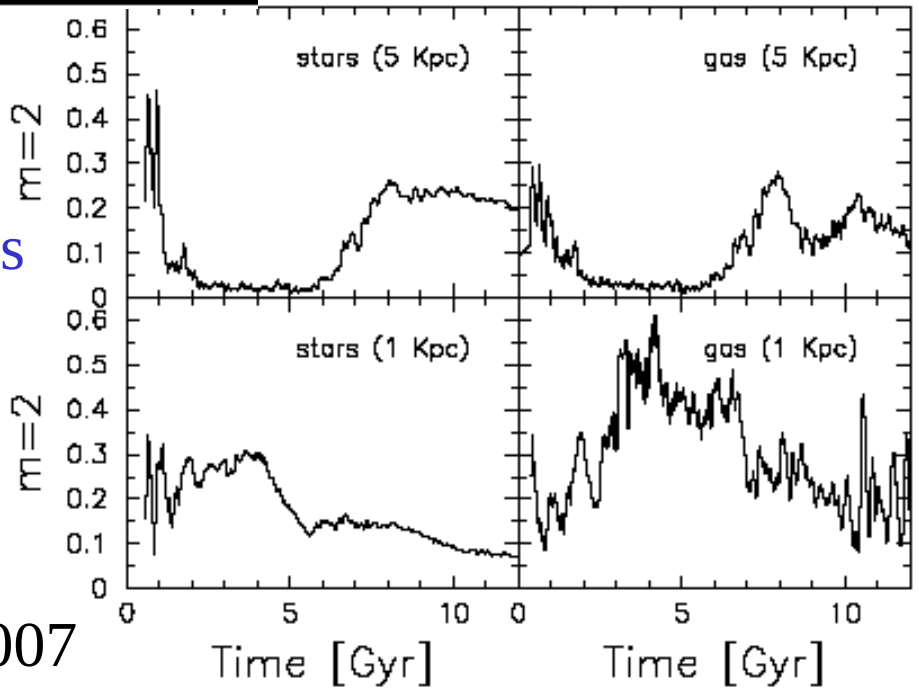




Bars form,
destroy and reform

Gas flows, and accretion

Influence of isothermal/adiabatic gas
Star formation and feedback, etc..

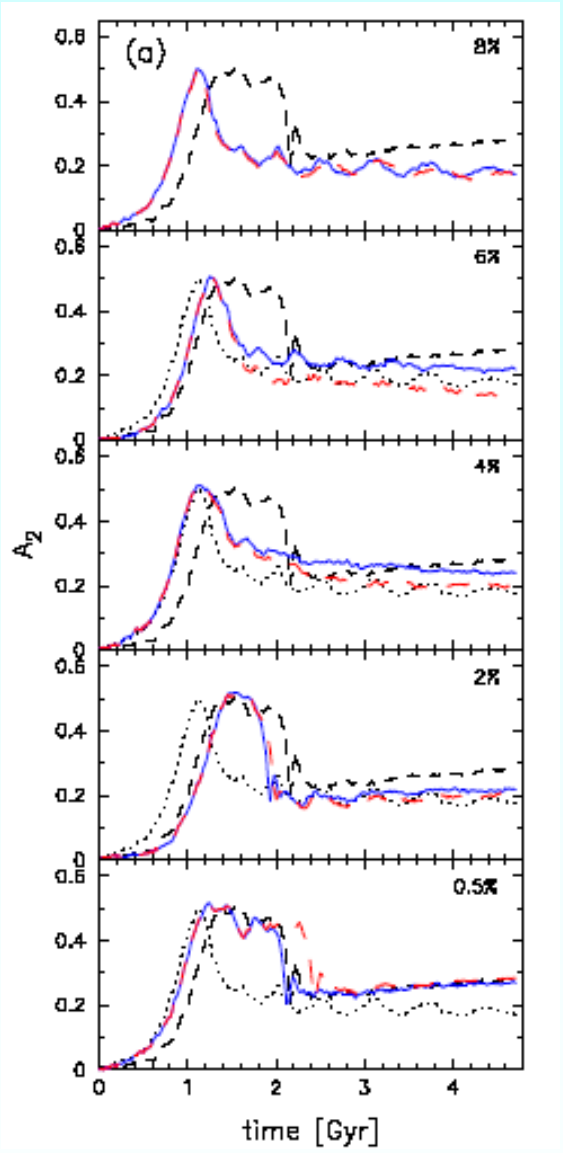


Heller, Shlosman & Athanassoula 2007

Angular Momentum transfers with DM

More important in DM-dominated galaxies (fgas < 8%)

Berentzen et al 2007

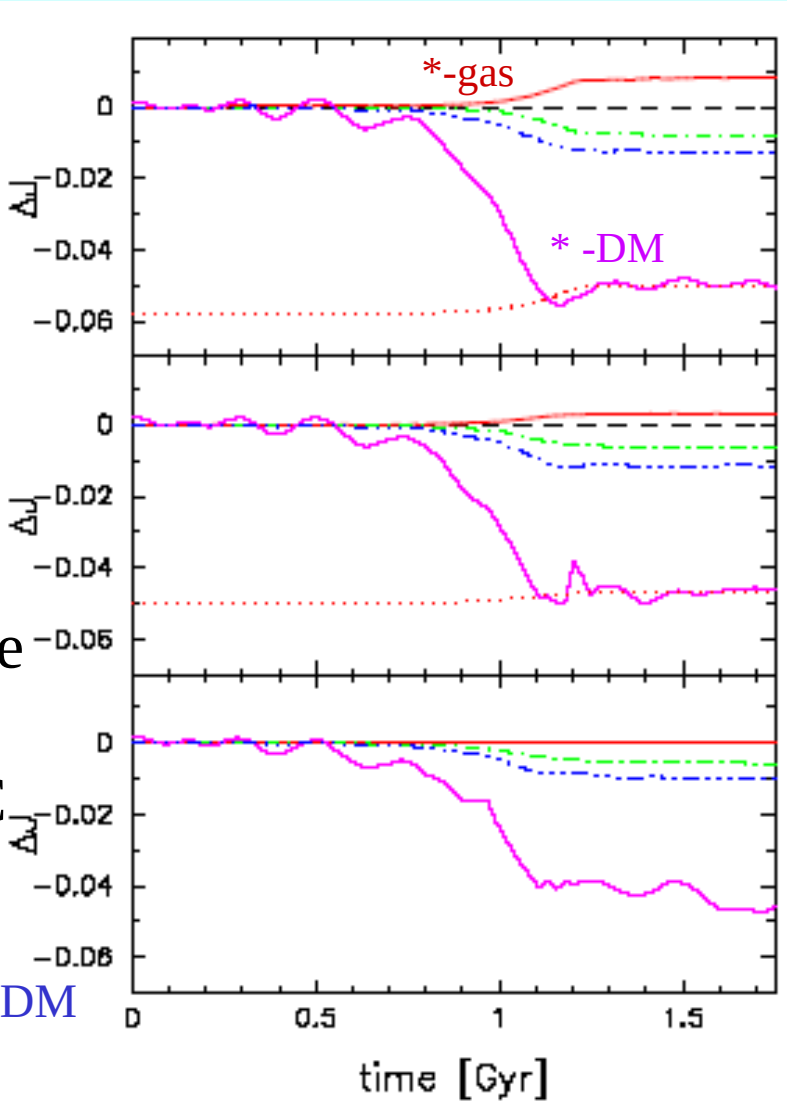


However, bar destroys more quickly with gas

Interpreted as a function of destruction of vertical resonance

Help of the CMC

Fgas should be higher
In presence of massiveDM



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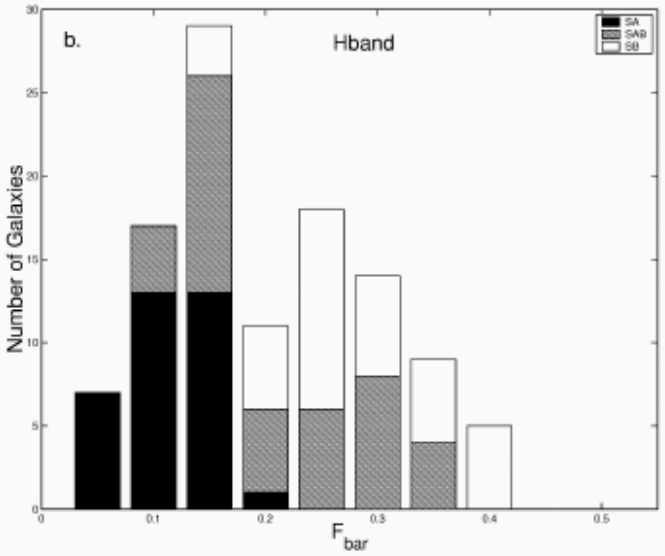
➔Mergers and bulge formation scenarios

Bar frequency

Whyte et al 2002

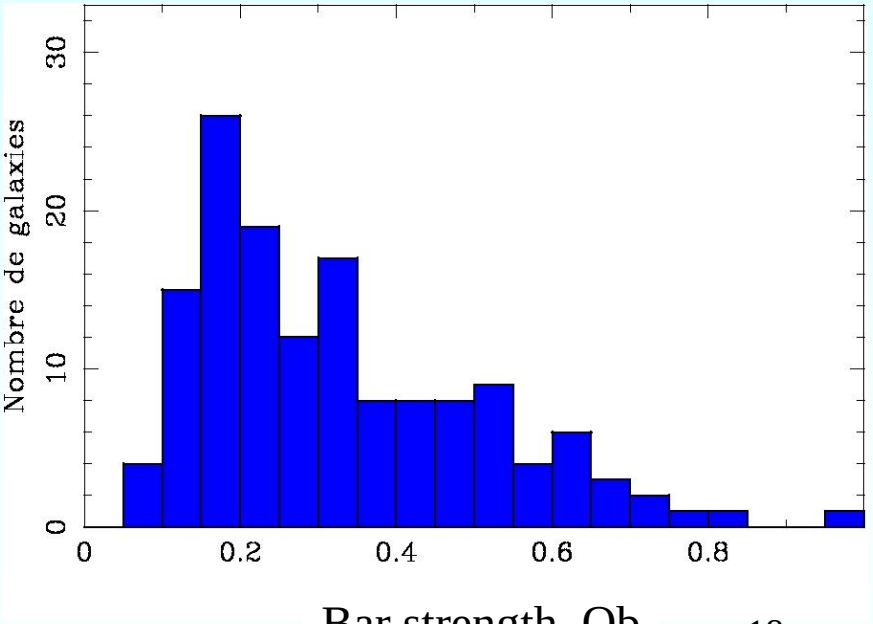


OSU NIR sample (Eskrige et al 02)

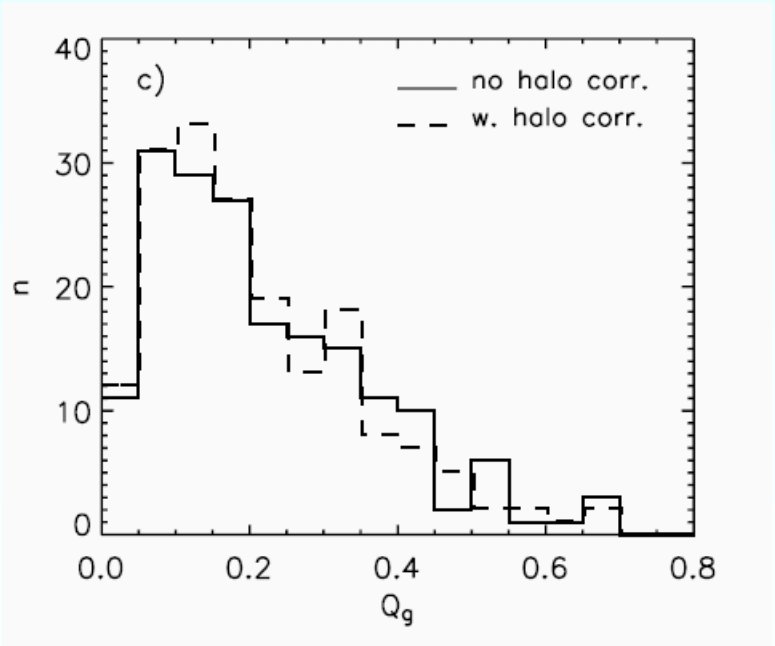
➔Paucity of weak bars

Marinova & Jogee 06

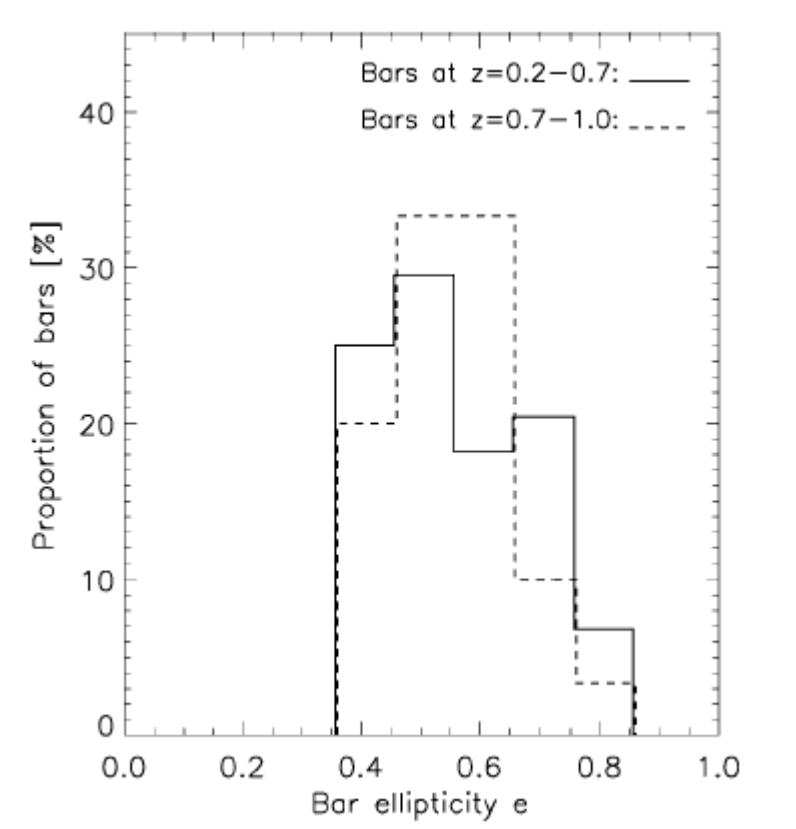
Block et al 2002

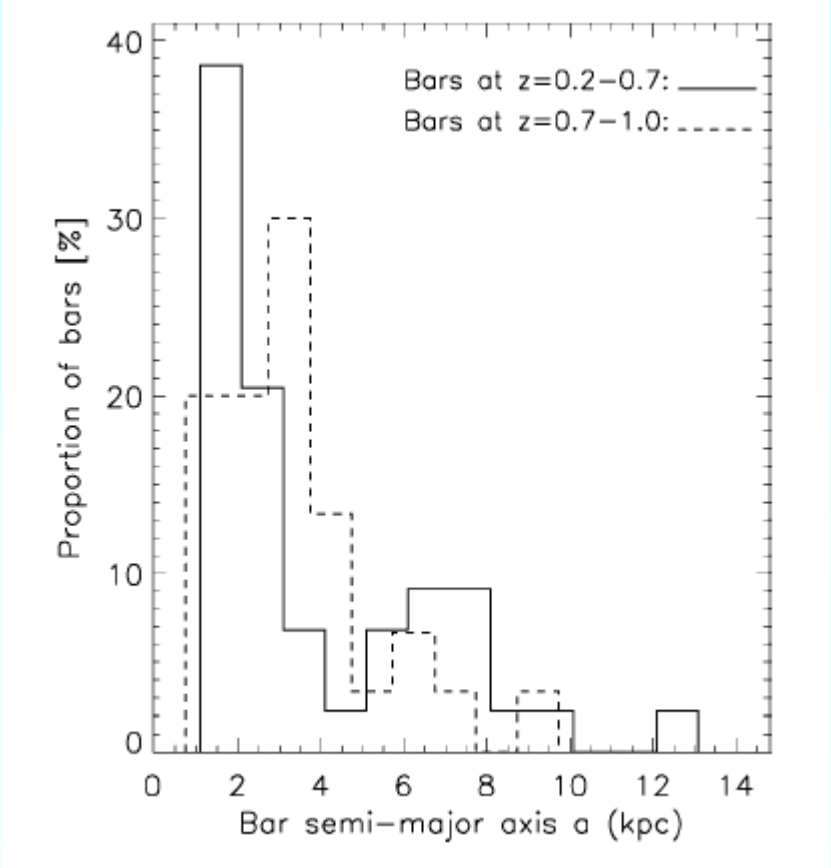


Buta et al 04



Bar frequency with redshift





— z=0.2-0.7,T=2-6 Gyr

----z=0.7-1.0, T=6-8 Gyr

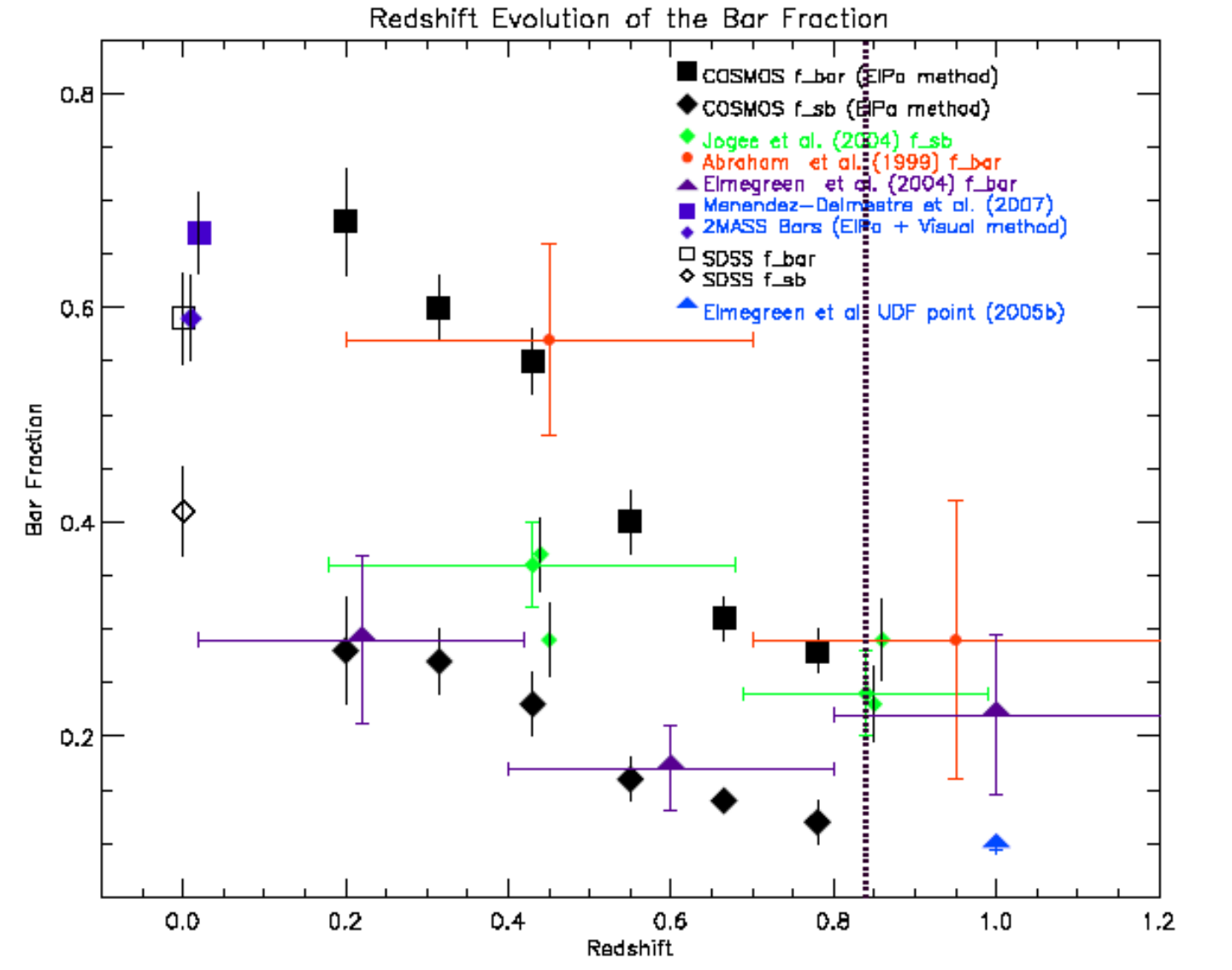
Strong bars e>0.4

in the optical, remain ~~ 30%

Jogee et al 2004 from GEMS

Bar fraction from COSMOS

Sheth et al 2008



B/T and n statistics

146 bright spirals in H-band *(Weinzirl, Jogee, Khochfar et al 2008)*
2/3 of galaxies are barred (OSU sample)

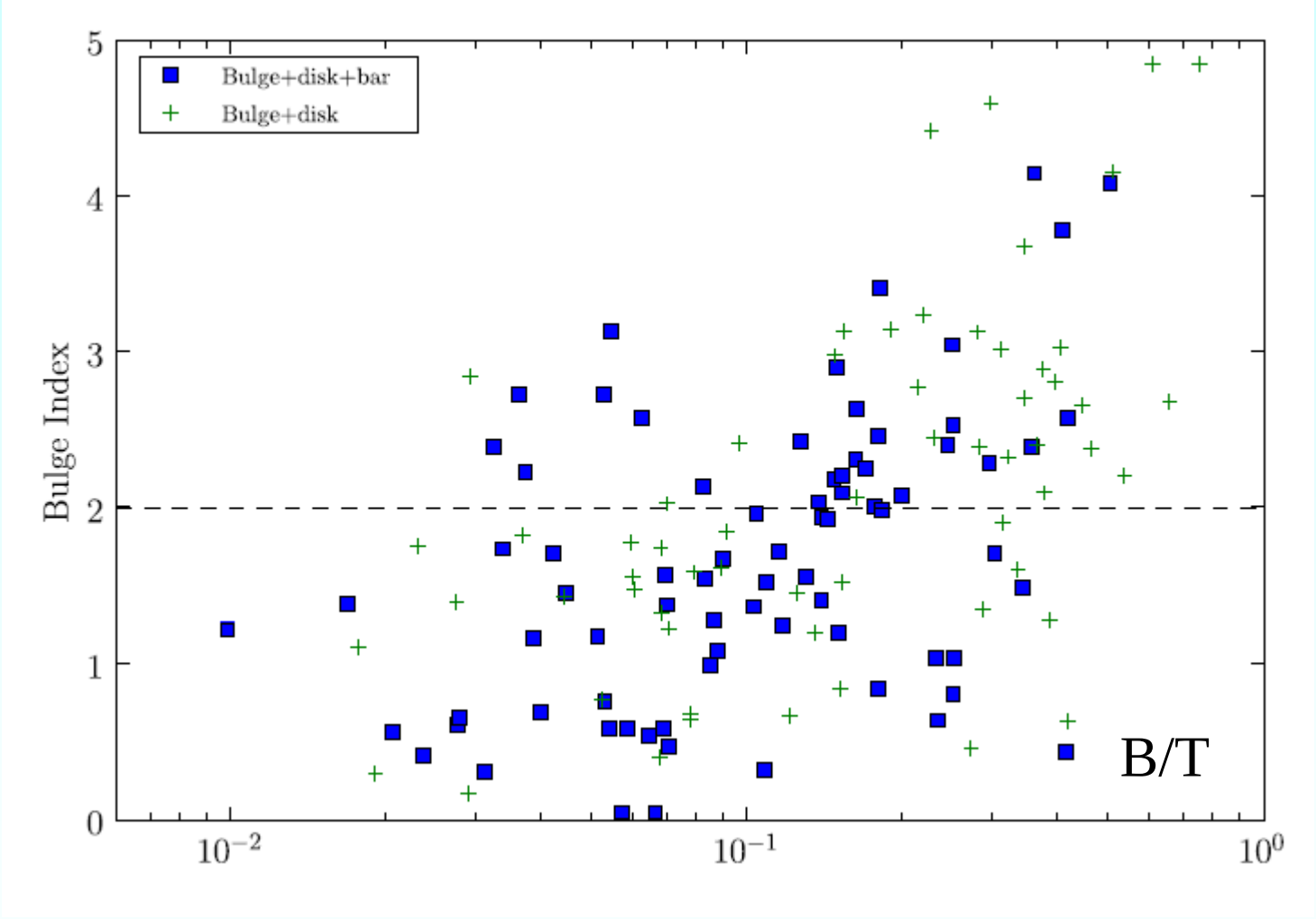
➔ 60% have n<2, and B/T < 0.2, barred or not
2/3 of these have bars

In ΛCDM, a B/T<0.2 galaxy requires no merger since 10 Gyr (z>2)
The fraction of these low-bulge bright spiral is 15 times lower than observed (*Weinzirl et al 08)*

2/3 of these low-bulge bright spirals must be explained either by rare minor mergers or secular evolution

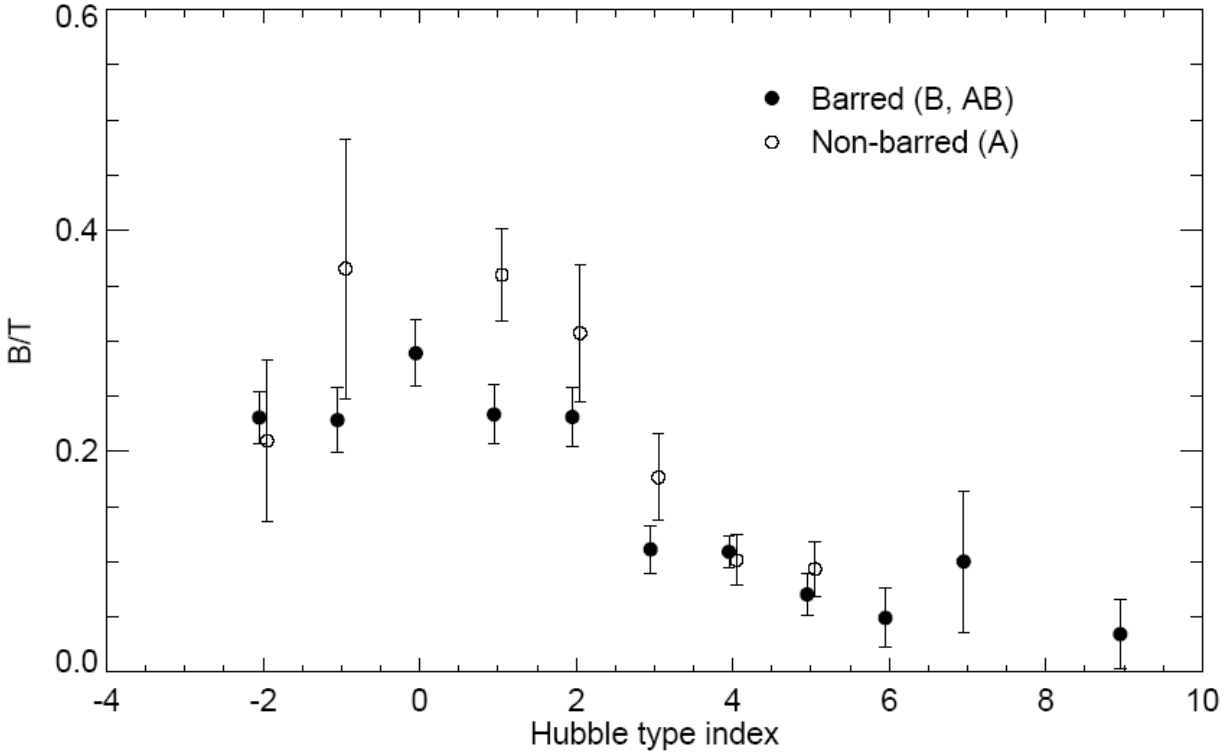
Koda et al (2007) could be the tail of the distribution ?
But semi-analytical criteria

Sersic index n versus B/T

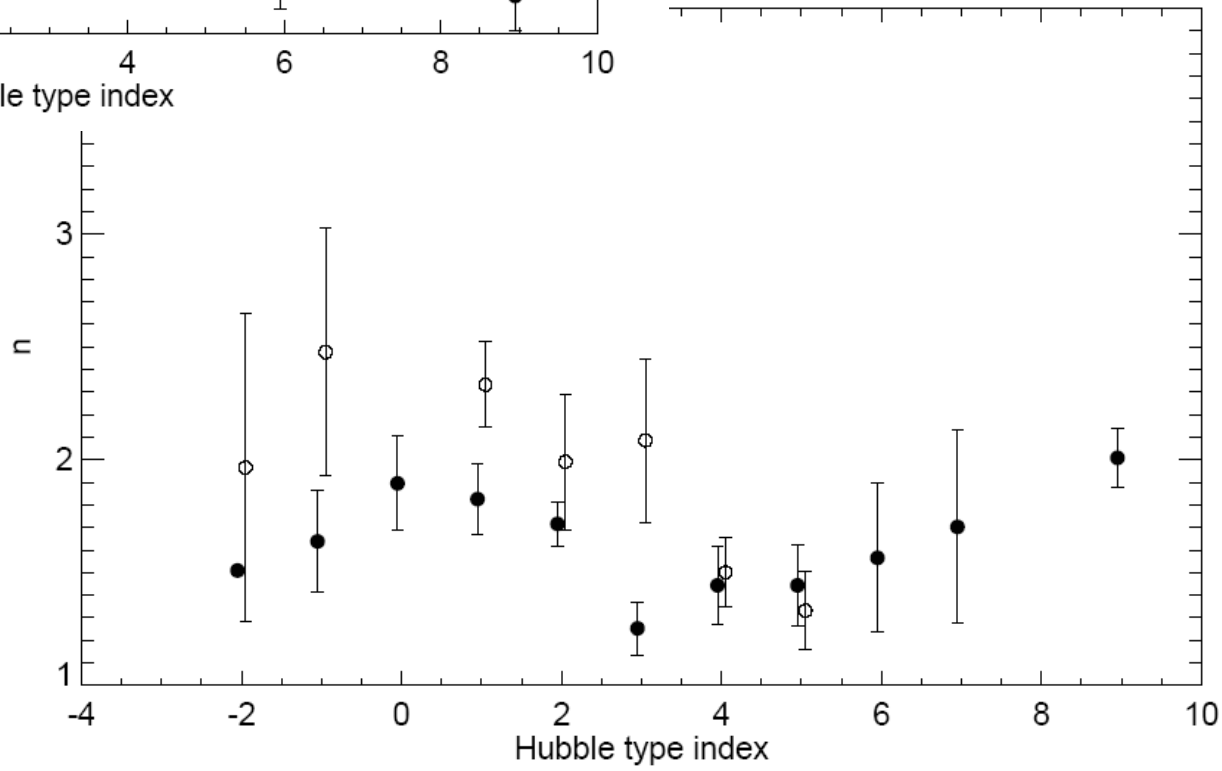


(*Weinzirl et al 08*)

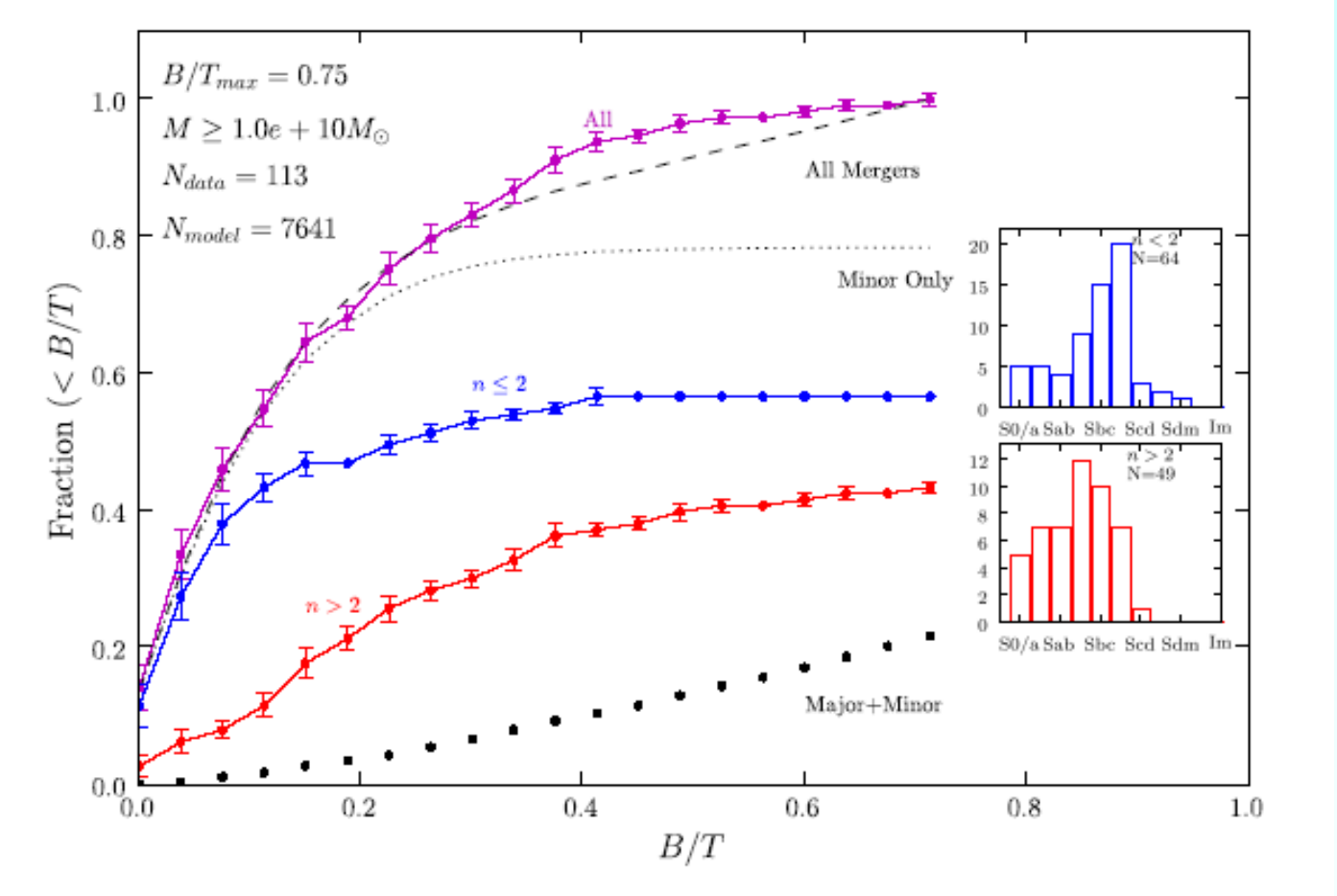
B/T, n



Laurikainen et al 07
216 galaxies
NIR



Comparison with predicted B/T



Semi-analytic models, with major mergers (mass ratio <1/4)
Weinzirl et al 2008

Frequency of bulge-less galaxies

Locally, about 2/3 or the bright spirals are bulgeless, or low-bulge
Kormendy & Fisher 2008, Weinzirl et al 2008
Some of the rest have both a classical bulge and a pseudo-bulge
Plus nuclear clusters *(Böker et al 2002)*

Frequency of edge-on superthin galaxies *(Kautsch et al 2006)*
1/3 of galaxies are completely bulgeless

SDSS sample : 20% of bright spirals are bulgeless until z=0.03
(Barazza et al 2008)
Disk-dominated galaxies are more barred than bulge-dominated ones

How can this be reconciled with the hierarchical scenario?

Outline:

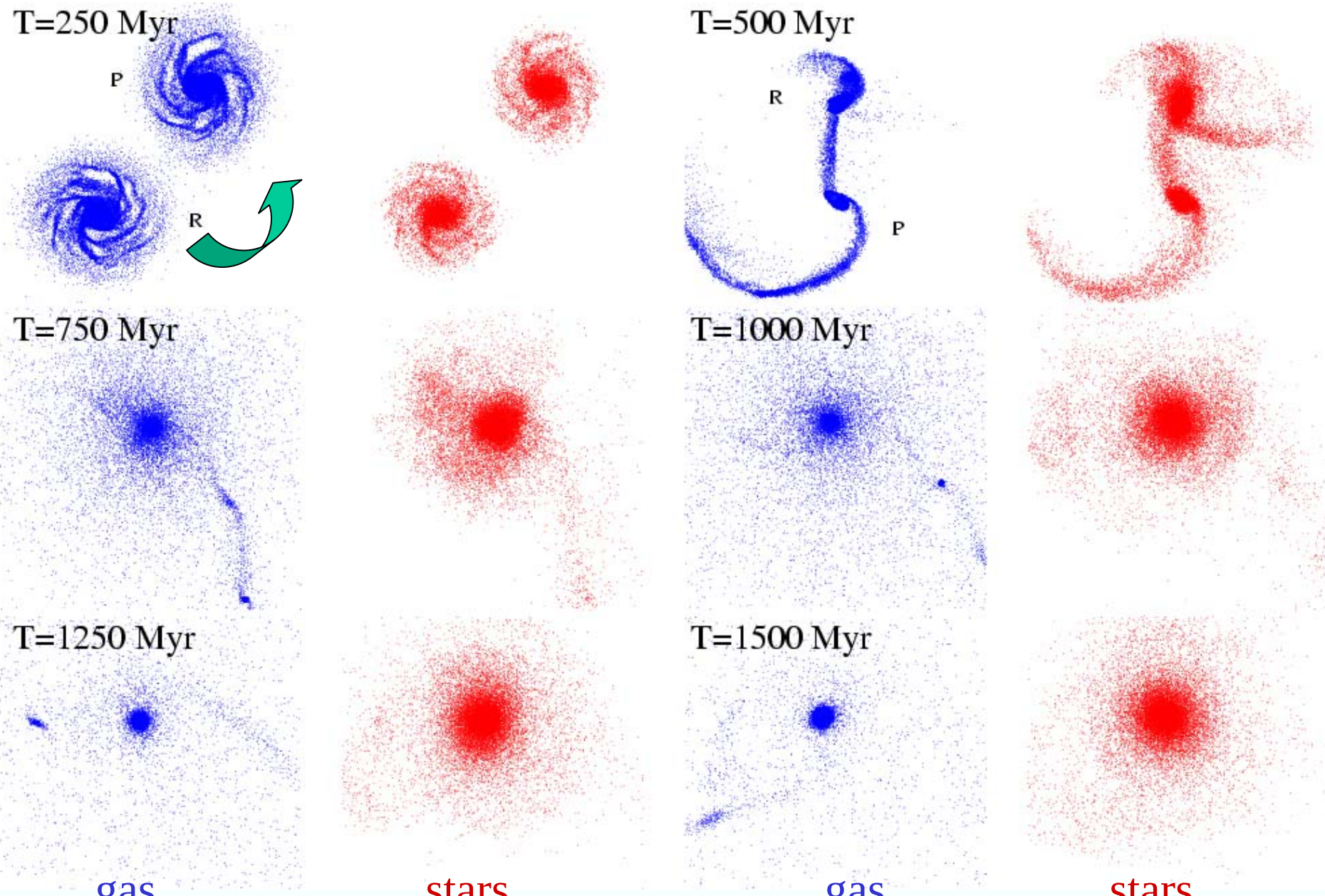
➔Secular evolution & bulges, gas flows

➔Bar destruction, re-formation, role of gas

➔Bars & bulge stats: B/T, n, high z evolution

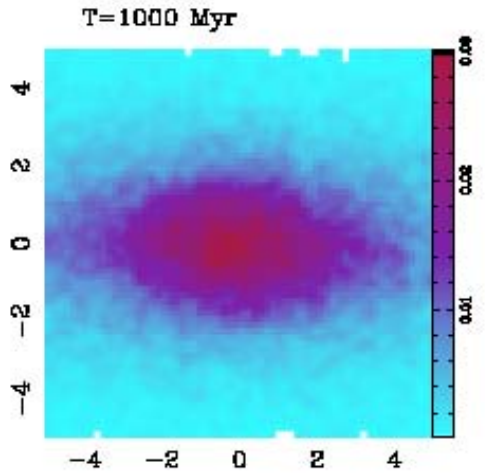
➔Mergers and bulge formation scenarios

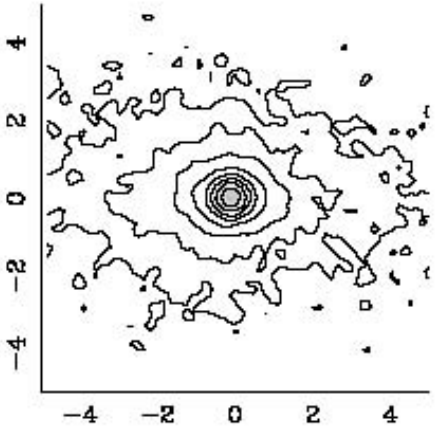
Major merger, N4550 prototype ➔ bulge formation

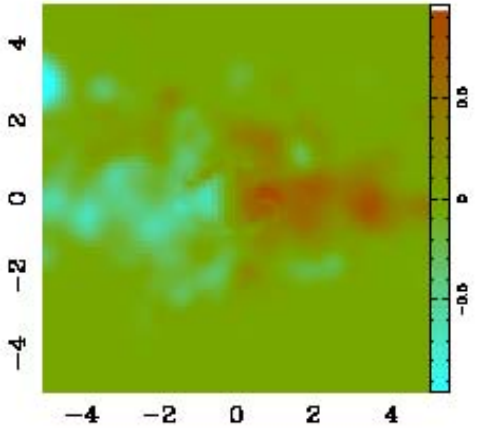


Formation of the counter-rotating disk

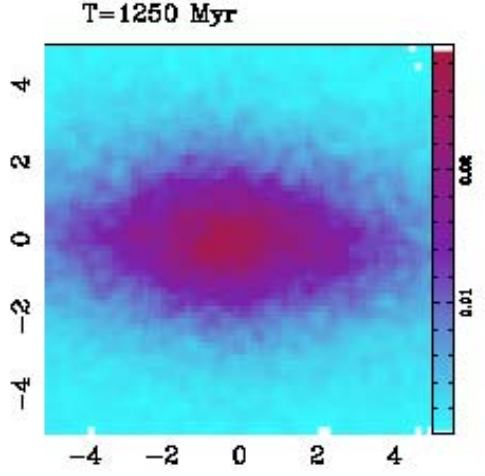
Gas settles in the prograde sense.

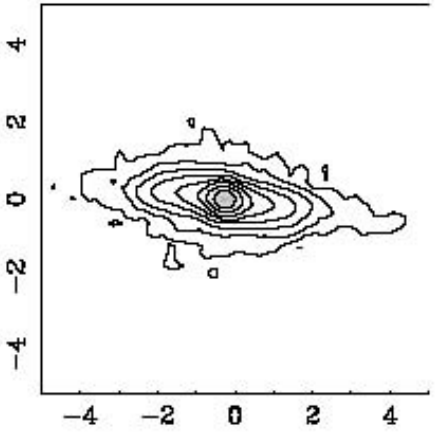


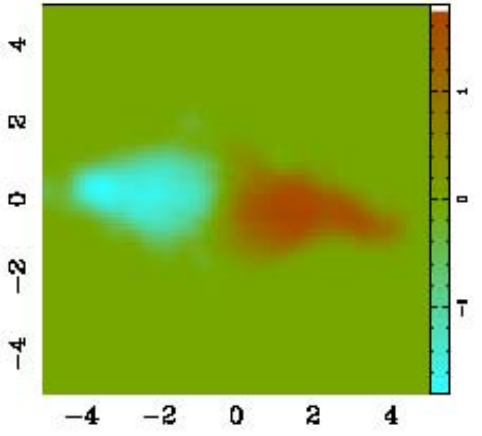




stars gas gas velocity

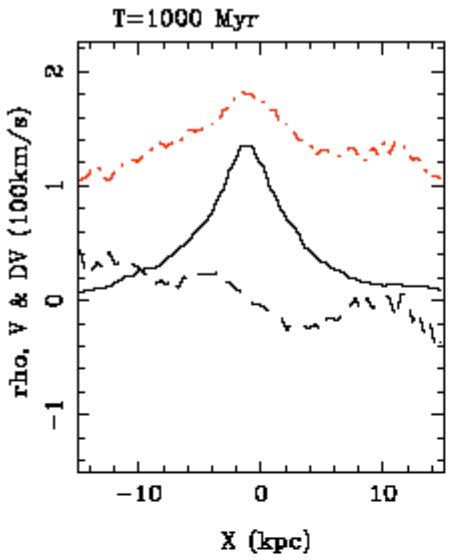


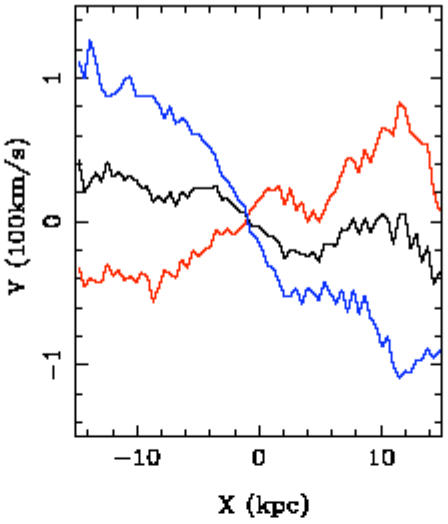


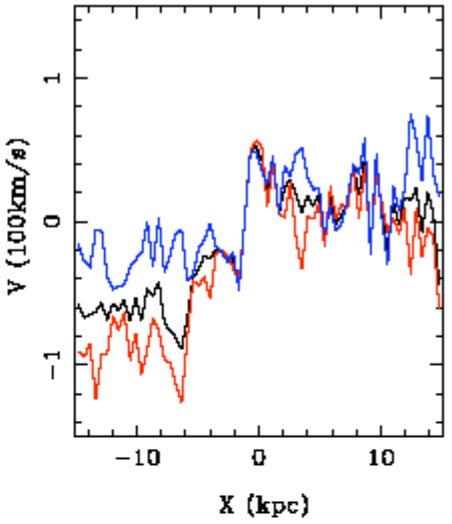


2 CR stellar disks, but only one gas rotation

Red= prograde galaxy, Blue= retrograde galaxy, Black=total

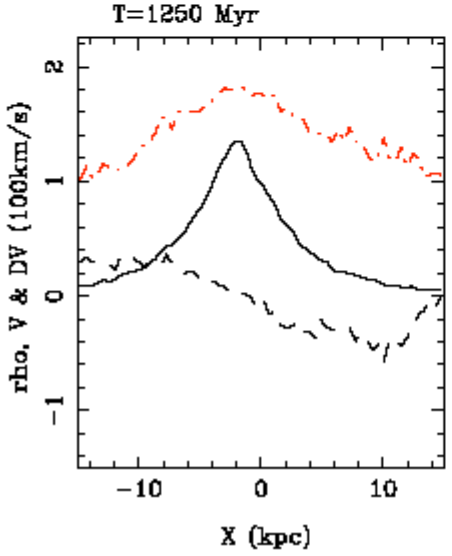


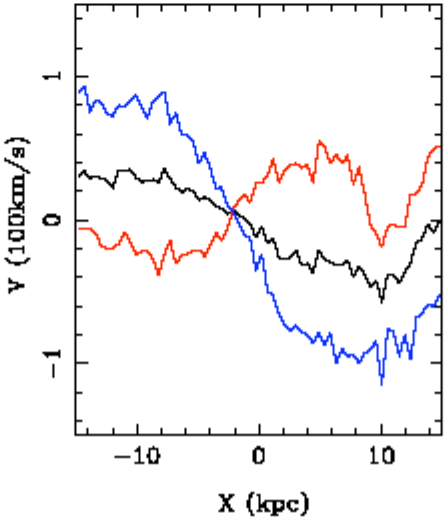


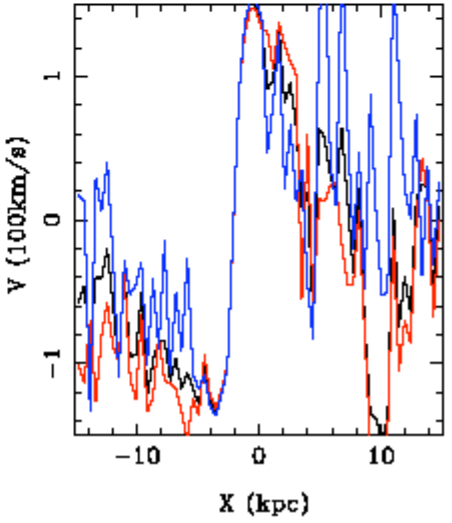


stars

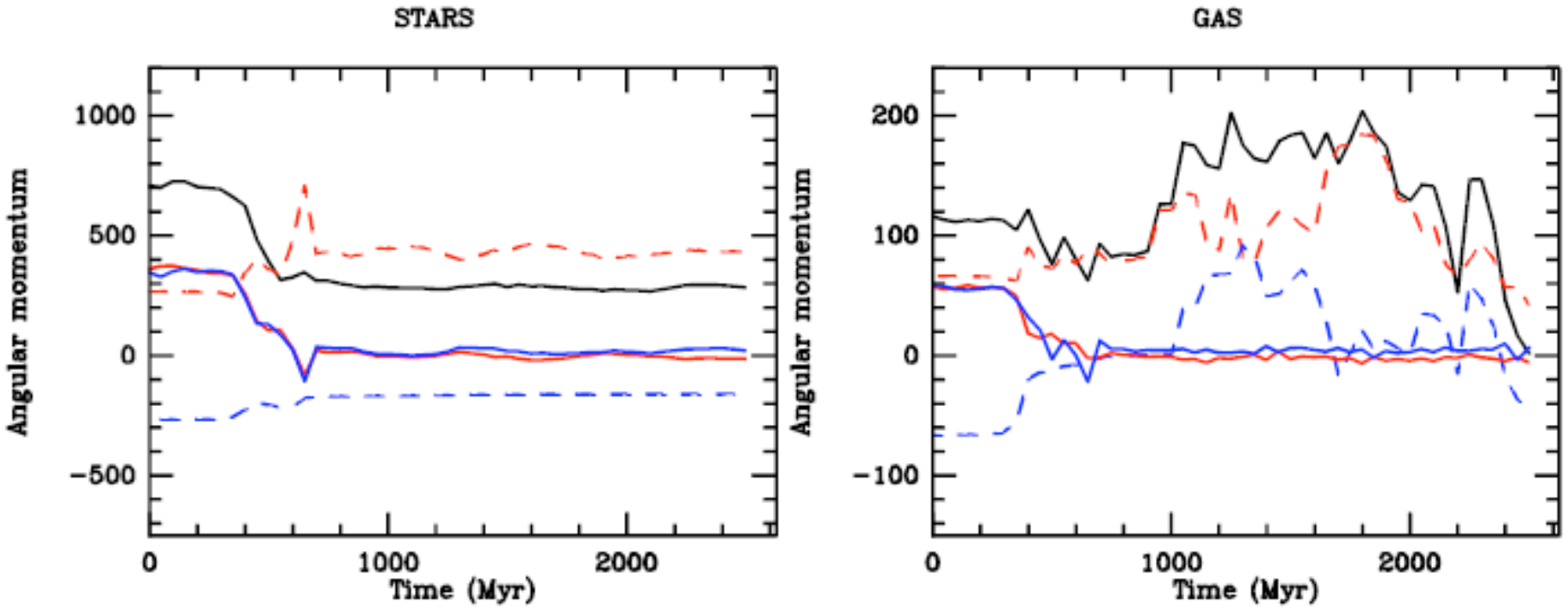
gas







Angular momentum exchange



Red= prograde galaxy, Blue= retrograde galaxy, Black=total
Full lines= orbital AM, Dash lines= individual spins

The gas settles in corotation with the thicker, more perturbed, disk
Formation of a bulge with low n ~1-2
Special geometry, of aligned or anti-aligned spins

Crocker et al 2008

Scenarios of bulge formation

❶Major mergers ❷Minor mergers ❸Bars ❹Clumps

In major mergers, the tidal trigger first forms strong bars in the partner galaxies, which drive the gas inward
➔Formation first of a pseudobulge

Then the merger of the two galaxies could provide a classical bulge
Which will then co-exist with the pseudo ones

Alternatively, after a classical bulge has formed
subsequent gas accretion, could re-form a bar, and a disk
and drive the gas towards the center, ➔ pseudobulge

Clumpy galaxies at high z ➔ bulge formation
Again problem for the bulgeless galaxies

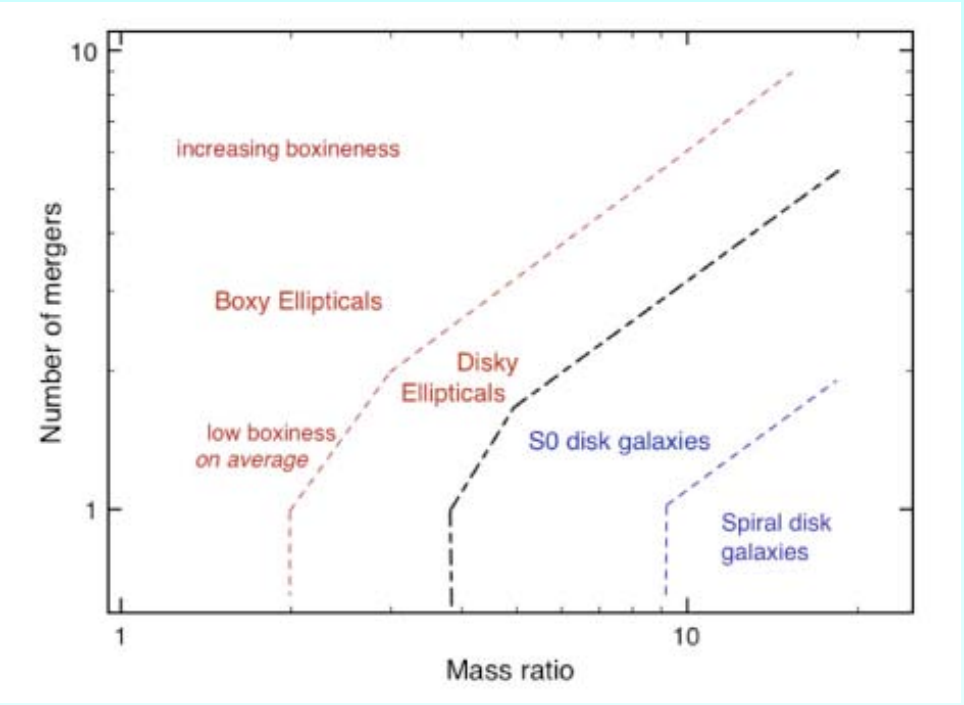
Clues from high z galaxies

Spheroids appear in place quite early (*Conselice 2007)*
Deficit of disk galaxies at z=1
Bias of the observations? K-correction?
Or disky galaxies have formed only recently? In poor environment

Big disks in rotation are however observed
(Genzel et al 2008, Neichel et al 2008)

Massive bulges (B/T >2) and ellipticals have the
same early formation GOODS 0.1 <z <1.2 *(MacArthur et al 2008)*
SF History compatible with a single early burst

Degeneracy however: same SFH if mass is assembled more recently from dry mergers

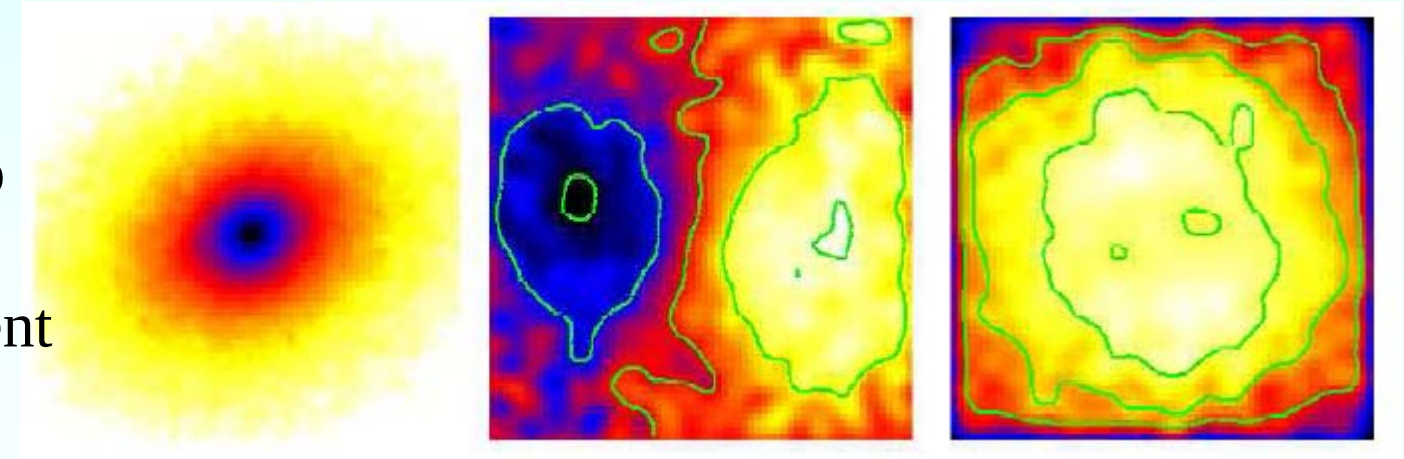


Multiple minor mergers

The issue is not the mass ratio of individual mergers
But the total mass accreted
If 30-40% of initial mass
➔ Formation of an elliptical

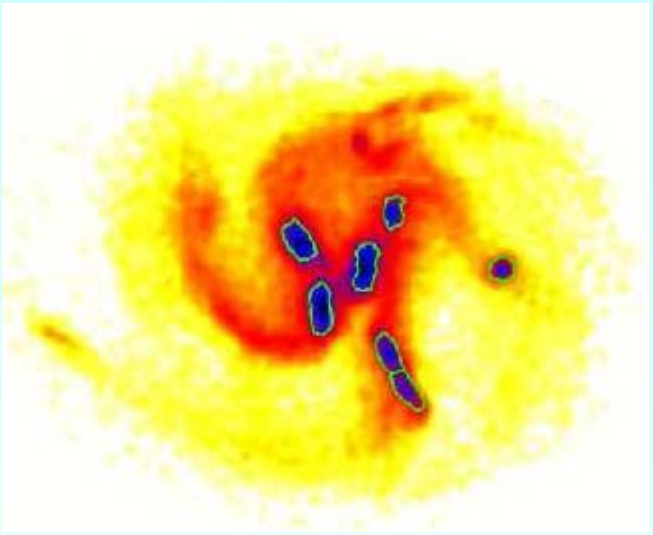
50 mergers
of 50:1 mass ratio

Even more frequent
Than 1:1



Bournaud, Jog, Combes 2007

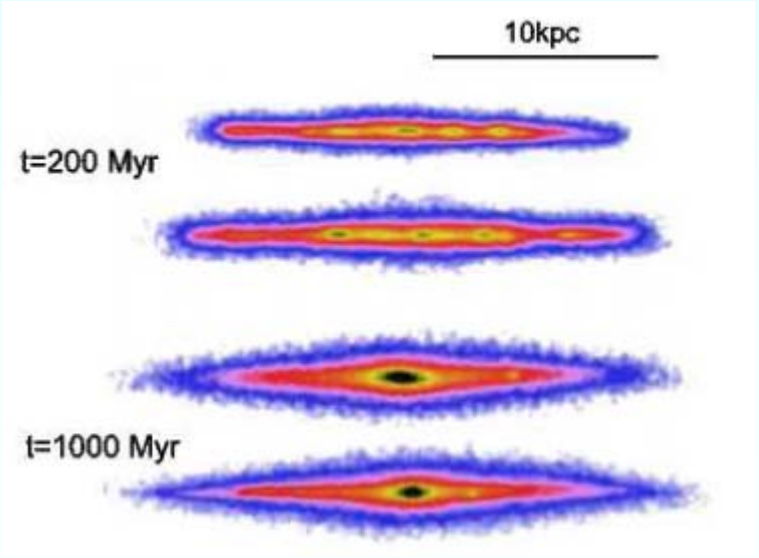
Formation in clumpy galaxies



Rapid formation of exponential disk and bulge, through dynamical friction
Noguchi 1999, Bournaud et al 2007

Chain galaxies, when edge-on

Evolution slightly quicker than with spirals/bars?



CONCLUSION

➔ Secular evolution (bars) plays a role in **pseudo-bulge formation**

➔ Bars re-formation requires **cold gas accretion**, from cosmic filaments

➔ Bars were destroyed more frequently at high z (more gas)

➔ Fraction of bulgeless galaxies: challenge for hierarchical scenario?

➔ Difficult to find high-z precursors: disks formed recently?

➔*Bulge formation: coexistence of many processes*
Some major mergers could keep a disk
Multiple minor mergers lead to spheroids
Clumpy galaxies at high-z