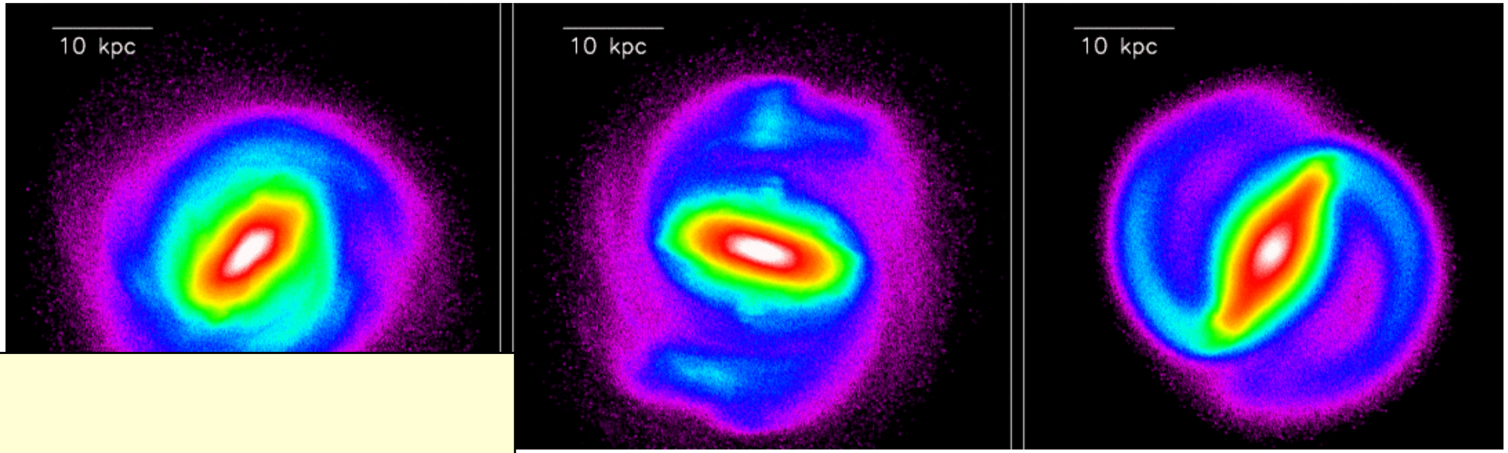
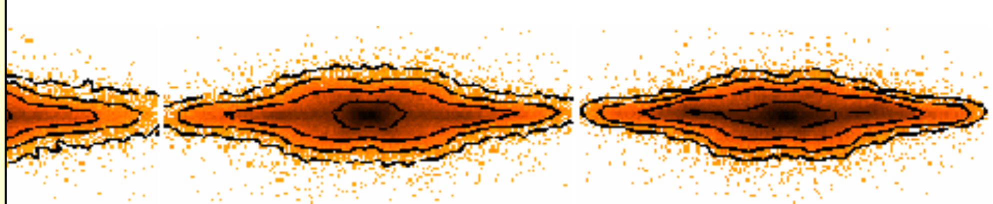
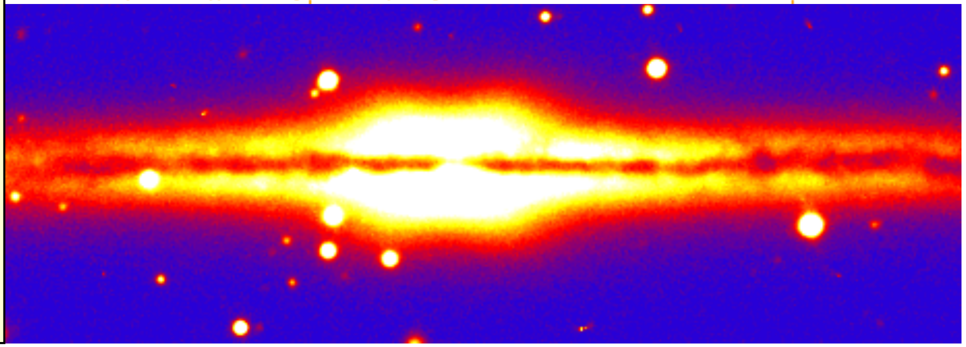
Secular Evolution of Galaxies







Outline:

➔Disk size evolution

➔ Bar fraction vs mass & color

➔AM transfers, radial migrations

➔Bulges, thick disks

Françoise Combes

Durham, 19 July 2011

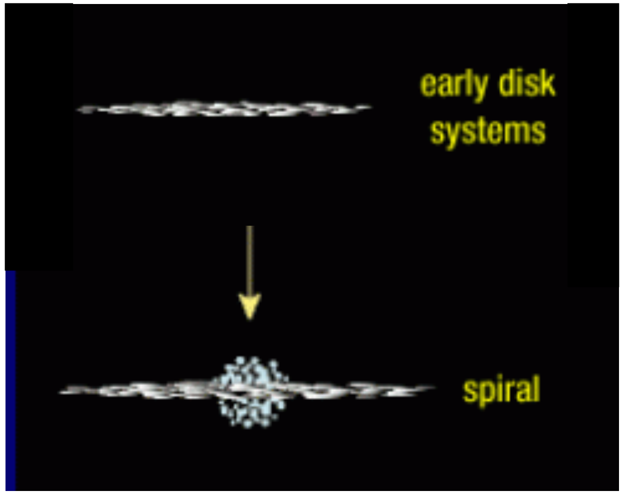
Laboratoire d'Étude du Rayonnement et de la Matière en Astrophysique

Two modes to assemble and redistribute mass

➔according to epochs and environment

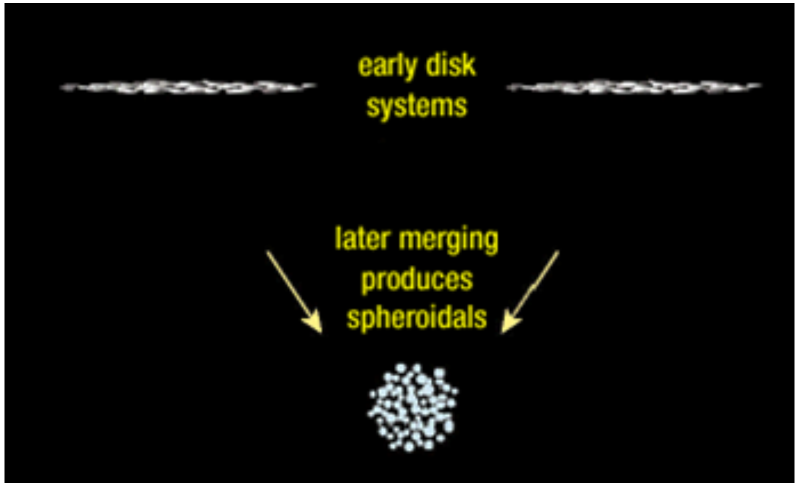
Secular evolution

Internal slow evolution
Through bars, spirals,
+gas accretion

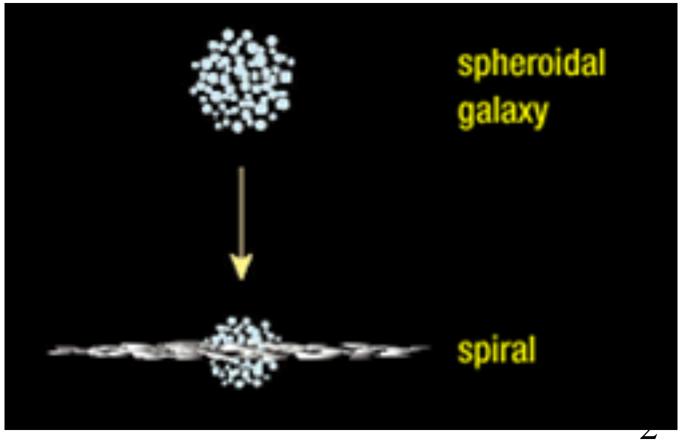


Hierarchical scenario

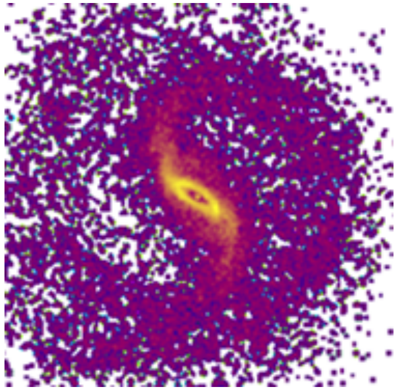
Spheroids form through major spiral mergers



Gas accretion can then reform disks



Disk evolution & Angular Momentum

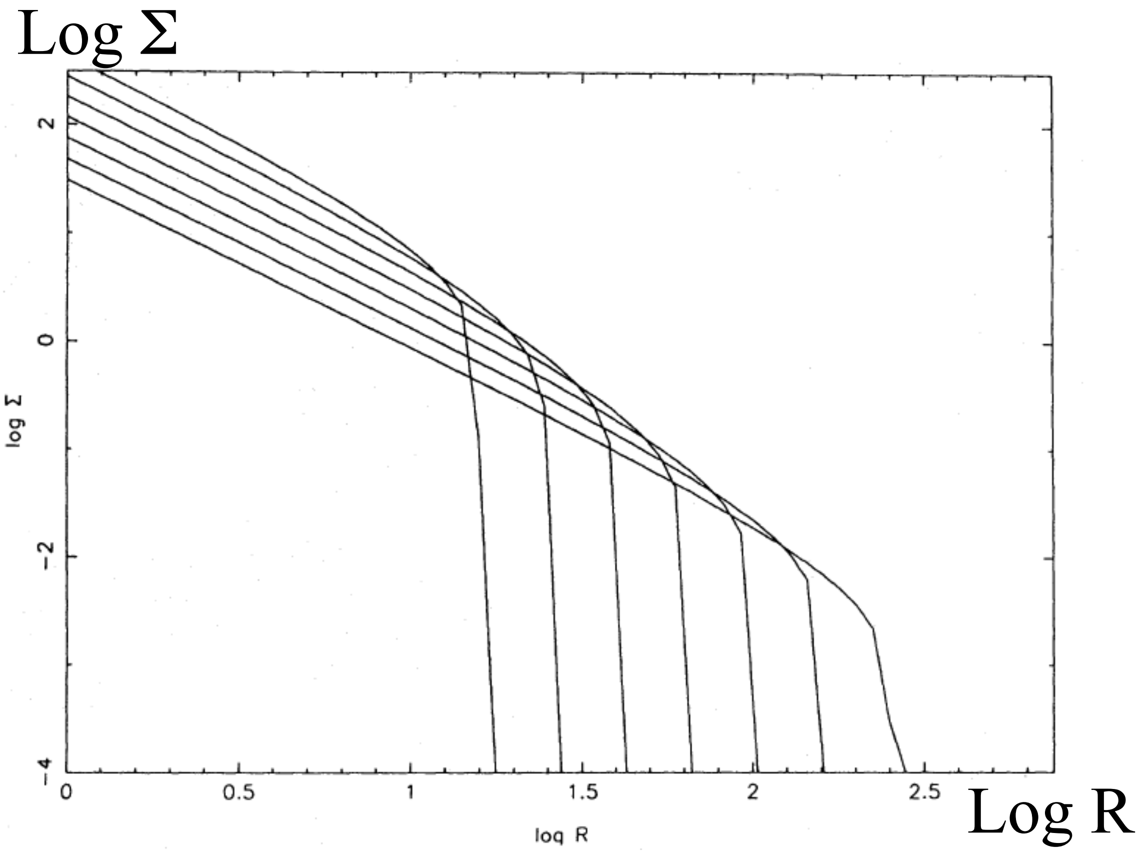


In mergers: AM lost on DM: very small disks

Bars and spirals re-distribute AM

Effective kinematic viscosity (Lin & Pringle 1987)

Unstable scales $L_J < L < L_{crit}$ Jeans length and scale of shear



When instabilities occur, they transfer momentum on scale L_{crit} with time scale Ω^{-1}.

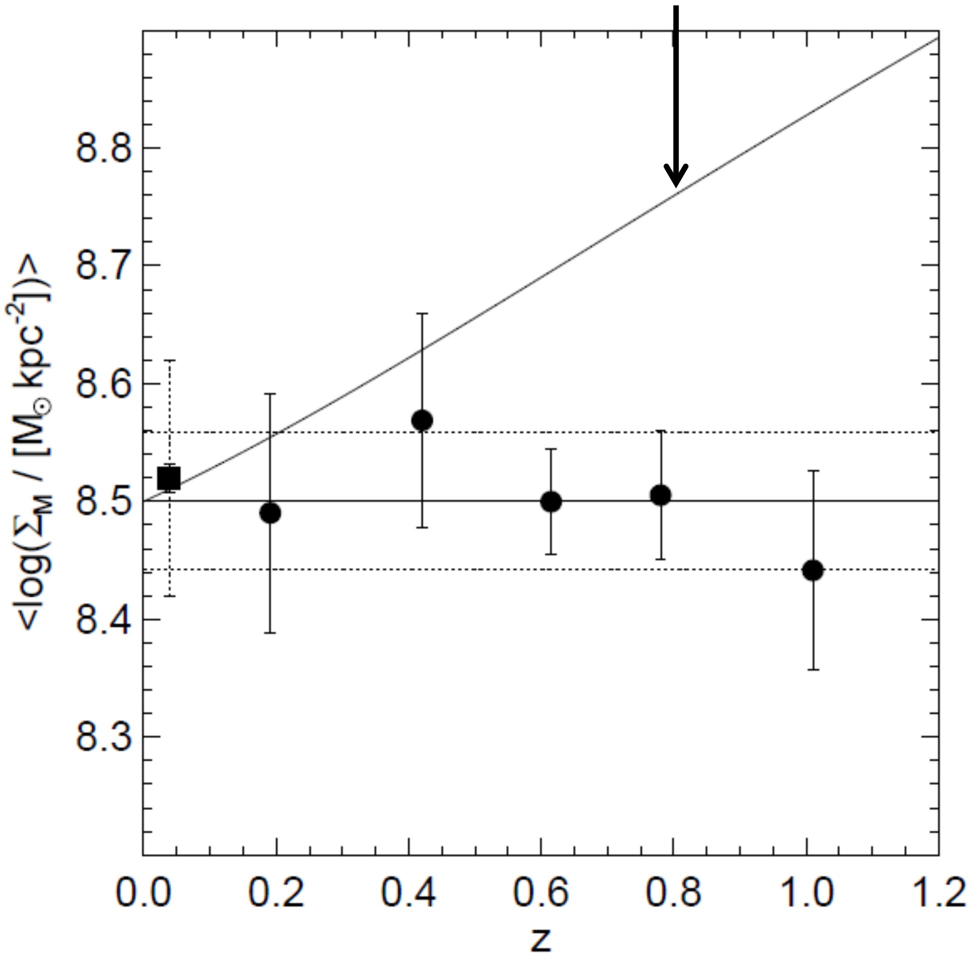
➔ a prescription for **effective viscosity**

$\nu \sim L_{crit}^2/\Omega^{-1} \sim Q^{-2} H_r^2 \Omega$

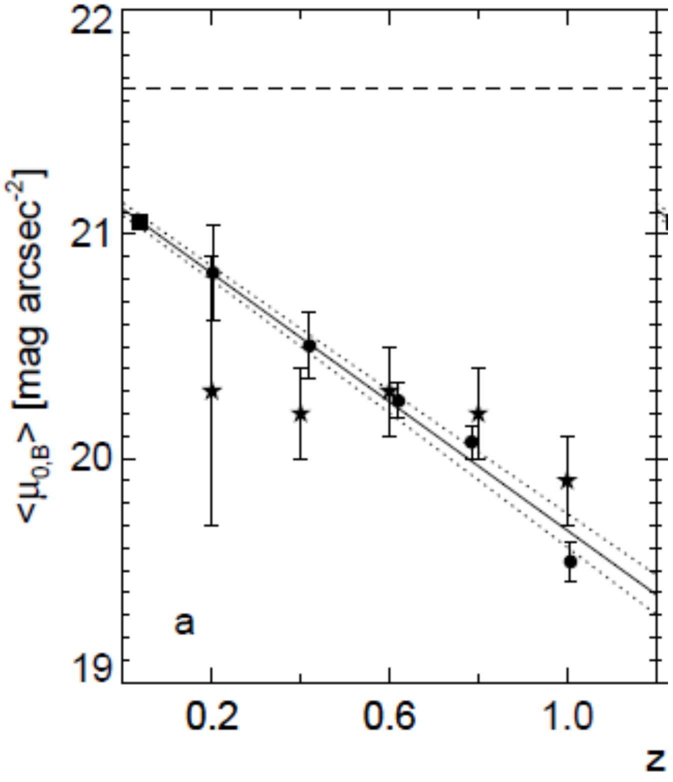
If $t_\nu \sim t_*$, exponential disk

Surface density evolution

Surface density of disks do not vary, while they were 10 times brighter in the last 8 Gyr ➔ passive evolution

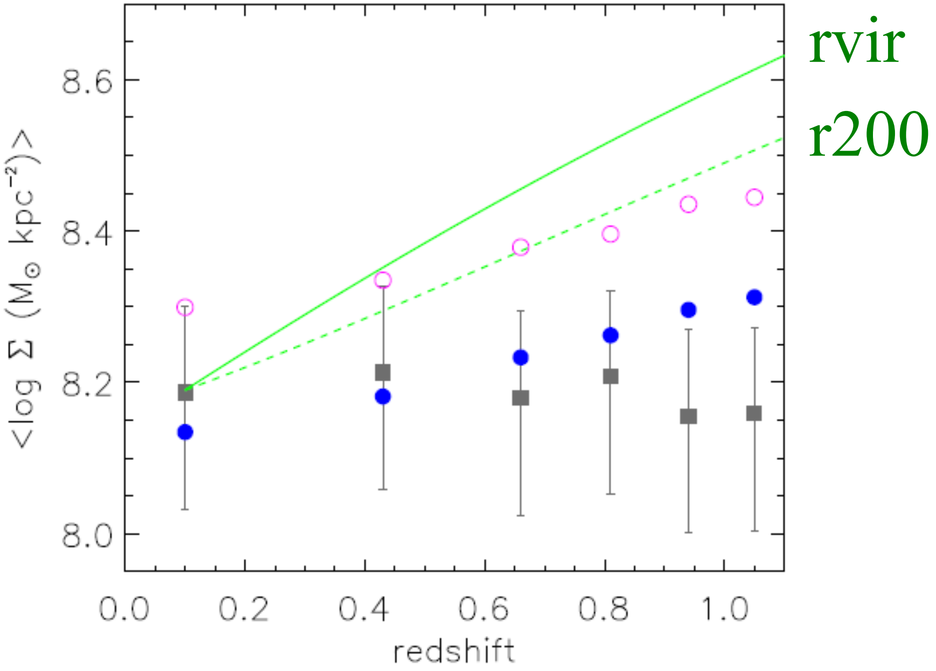

Mo et al 1998 (rd~λrvir)

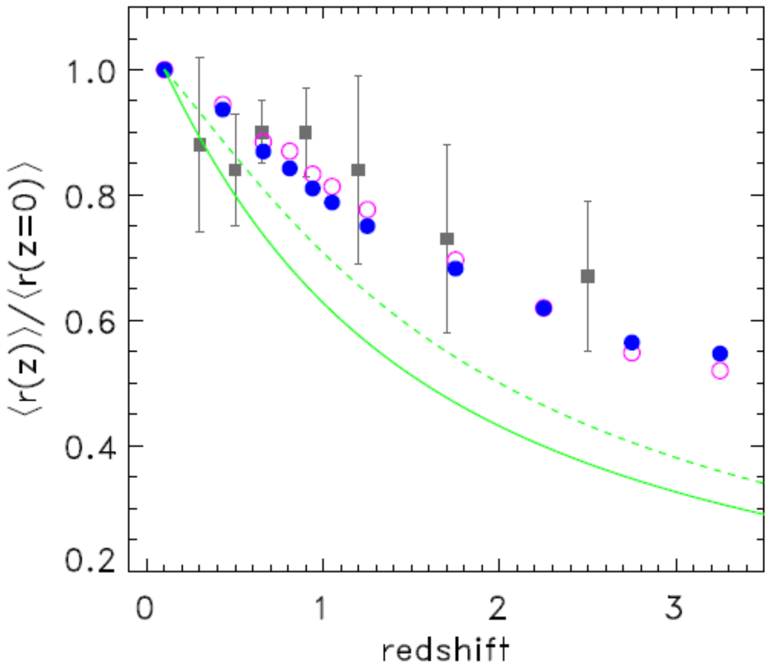
Barden et al 2005



Size evolution with redshift

SDSS and GEMS data (black)





- ○ NFW all disks
- ● NFW stable disks

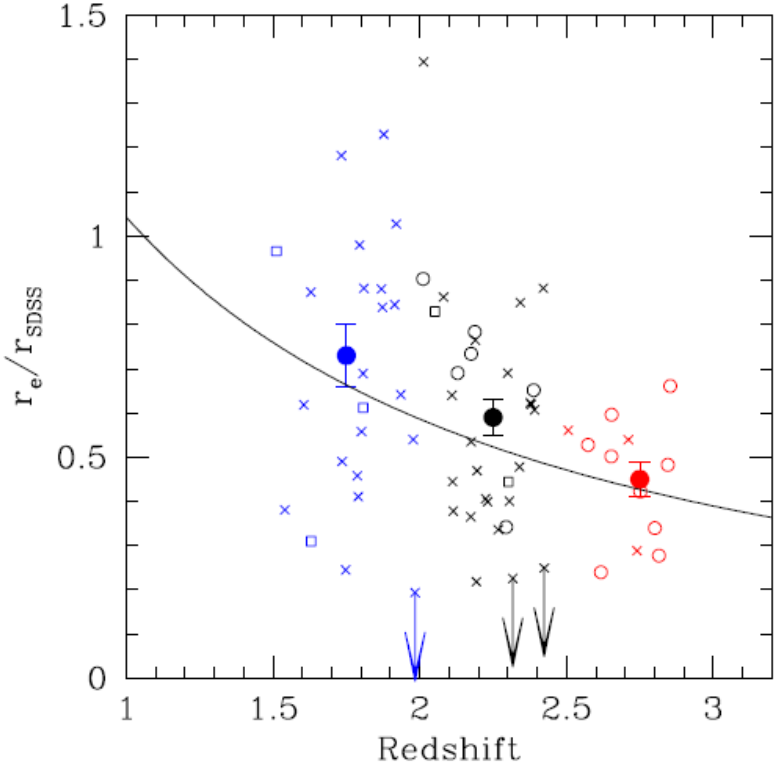
Stellar radii at a given mass are ~half lower, at z=2-3

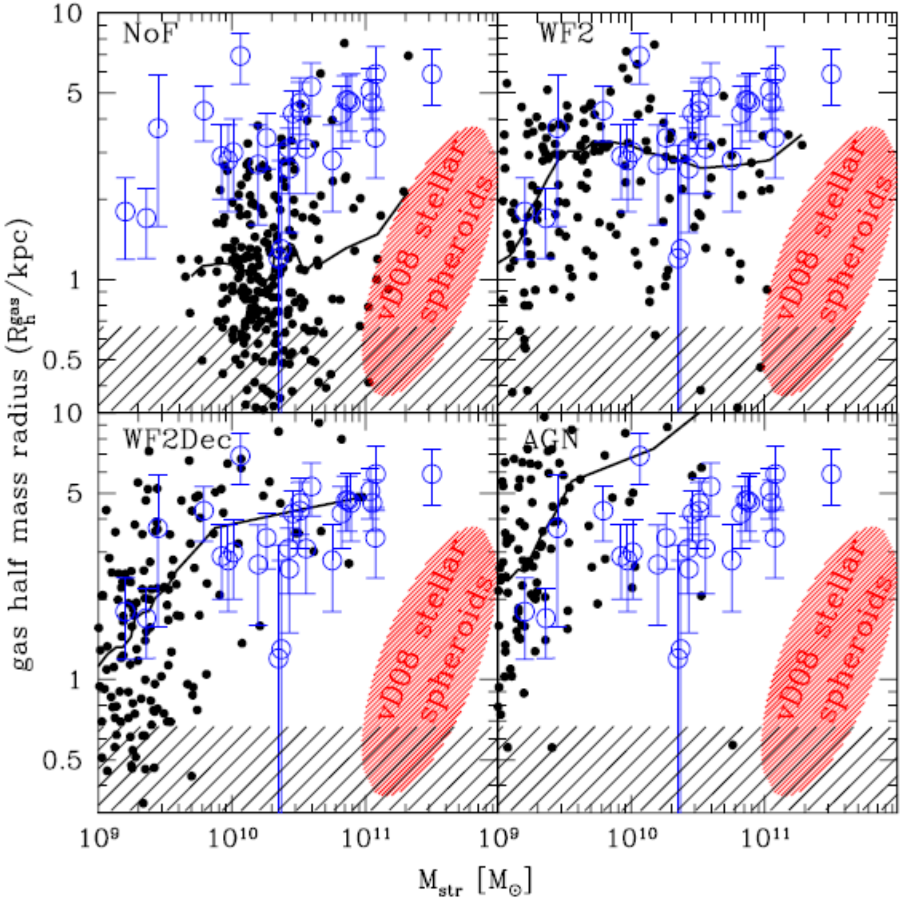
Sommerville et al 2008

DM radii are in $(1+z)^{-1}$
rs = cst, *Bullock et al 2001*

Size evolution with redshift (2)

102 SF galaxies at z=1.5-3 , about half the radius of local galaxies
Nagy et al 2011, z=2-3 Weinzirl et al 2011





re ~$(1+z)^{-\alpha}$

α=1.4 Nagy et al 2011

α=1.3 van Dokkum et al 2010

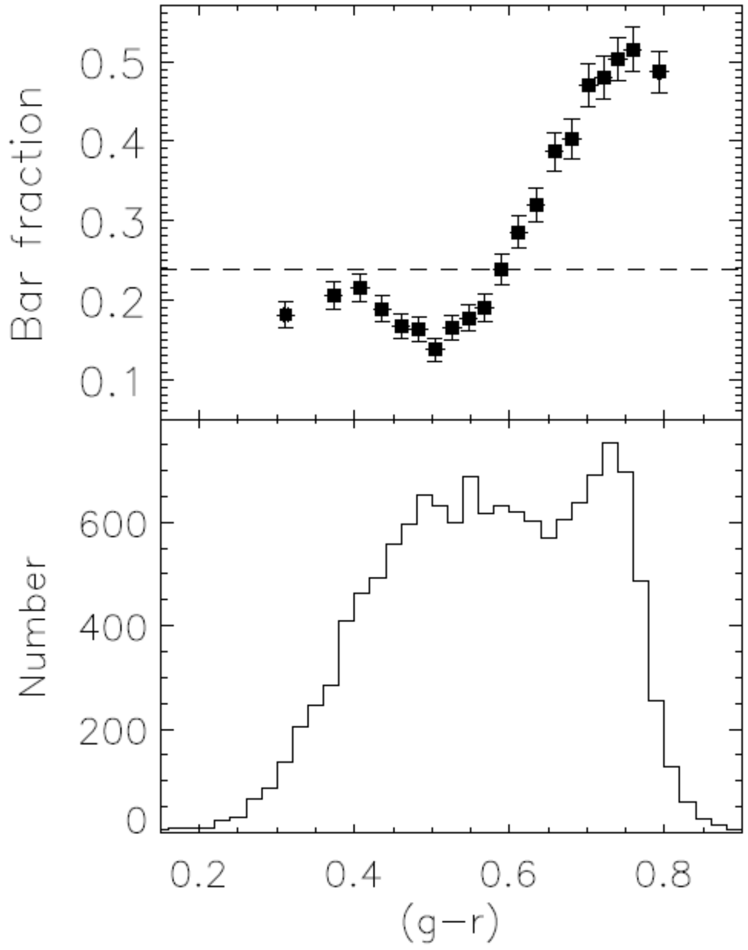
α=1.1 Mosleh et al 2011

Sales et al 2010

The feedback can be adjusted to fit larger disks at z=2

Disk Stability & Bar Fraction

Bulges and bars are more frequent for redder and bulge-dominated galaxies (Masters et al 2011, Galaxy Zoo)



Low-mass galaxy disks are thicker

Gas layer is thin, for **Vc > 120 km/s**

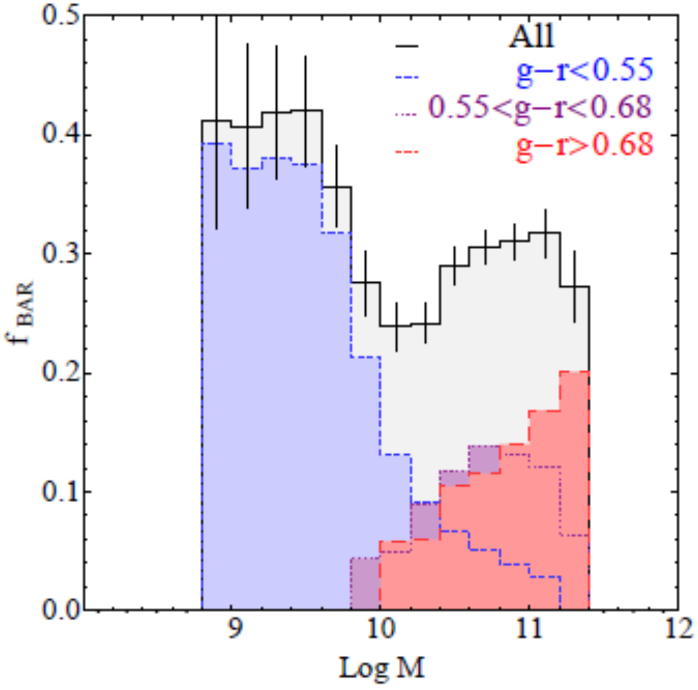
And thick for Vc< 120km/s (Dalcanton et al 2004)

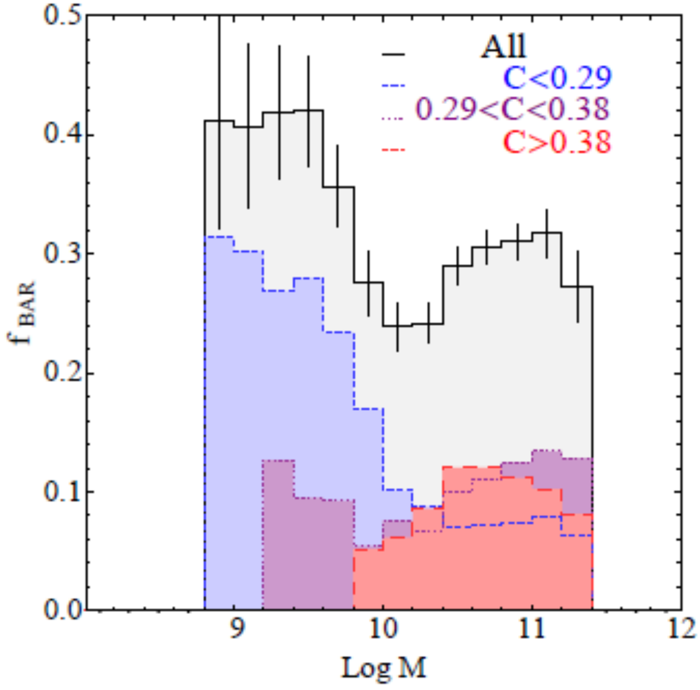
There is a sudden drop, due to the stability criterium

Half of the bar fraction at z~1 (Sheth et al 2008, COSMOS)

Bar fraction & mass/color

Bar fraction depends on mass (Nair & Abraham 2010)
Bimodality linked to the blue and red sequence





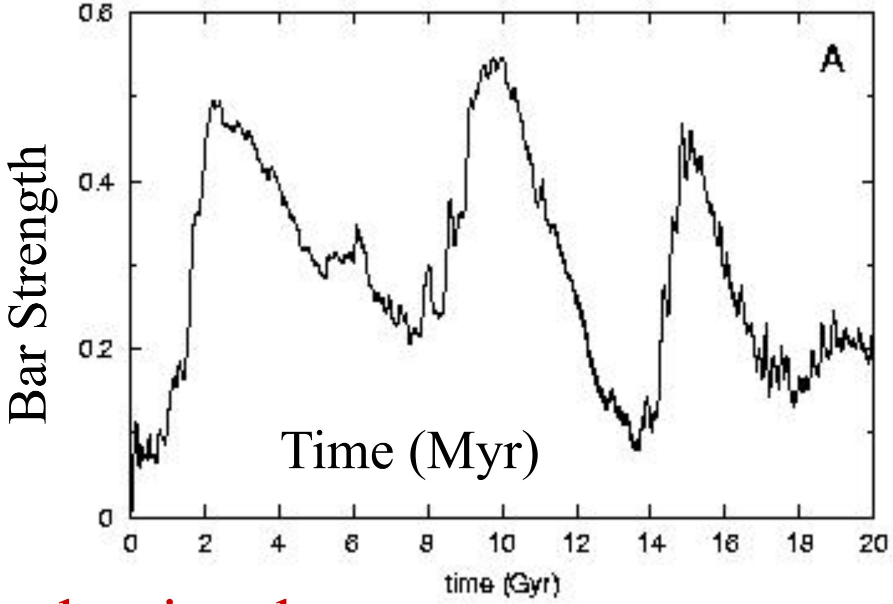
On a given path from the blue cloud, a barred galaxy loses its bar and regain it, when passing to the red sequence

Bars formation and destruction

Self-regulated cycle:

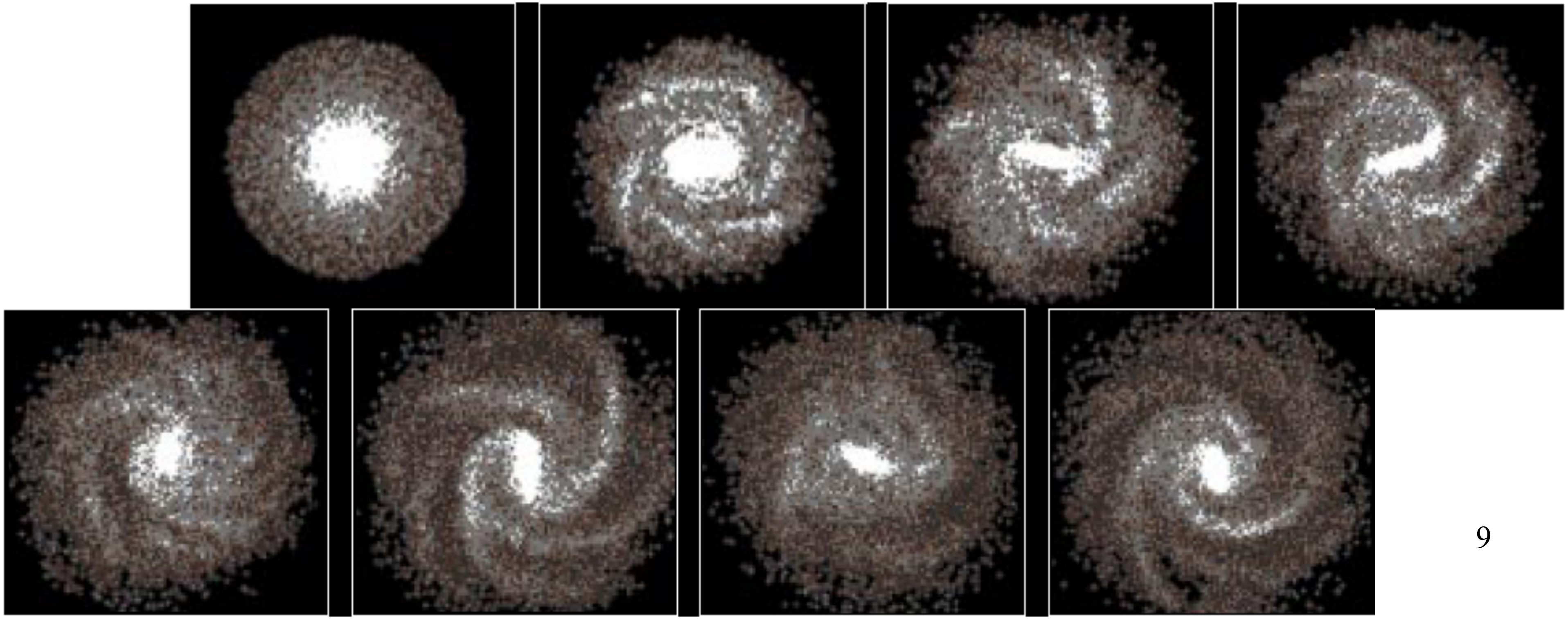
➔Bar produces gas inflow, and

➔Gas inflow destroys the bar

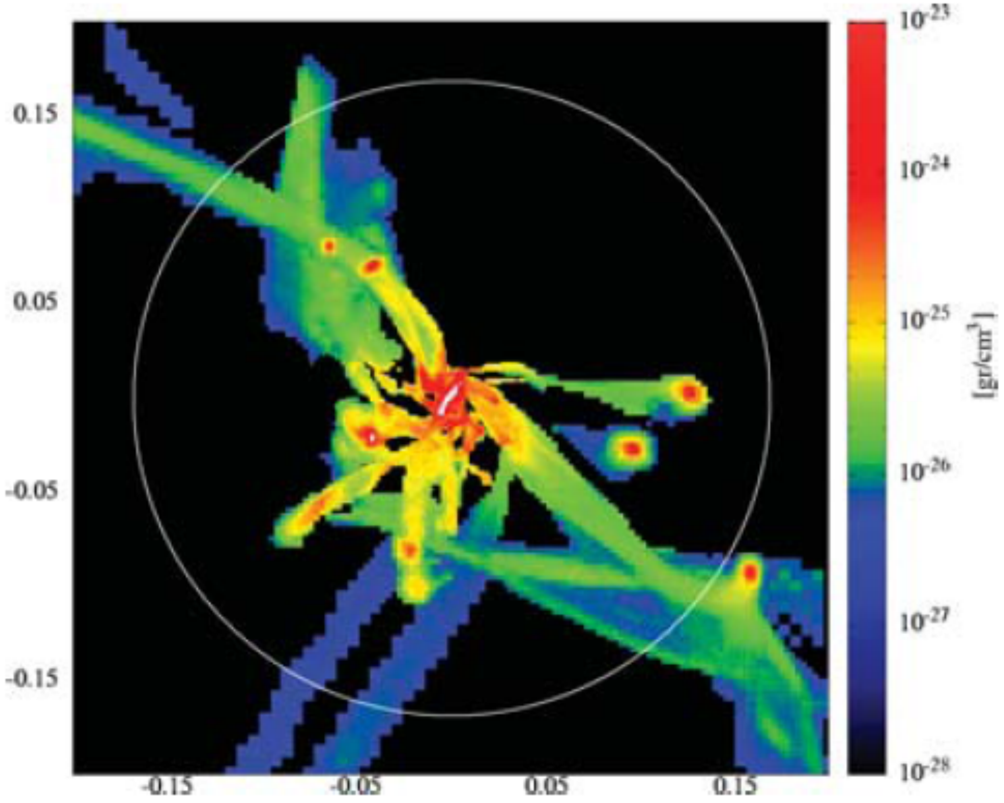


2% of gas infall is enough to transform a bar in a lens

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



Cold gas inflow in filaments

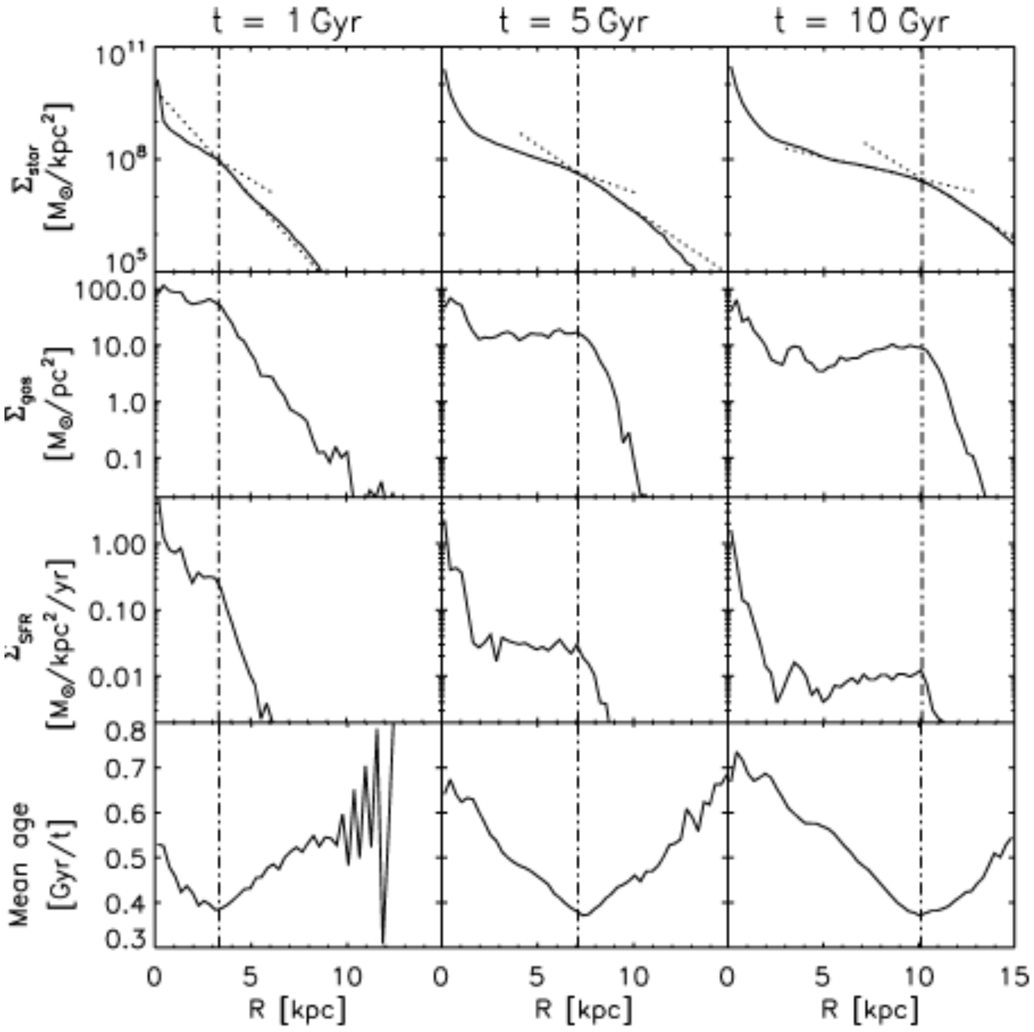


Rate of gas accretion sufficient
to maintain bars:
Mass doubling in 7 Gyrs

Keres et al 2005, Dekel & Birnboim 2006, Ceverino et al 2010

Inside out disk formation

TreeSPH simulation of collapse, with gas accretion: gas break and Toomre Q increase: SF at the break



Stars

Gas

SFR

Age

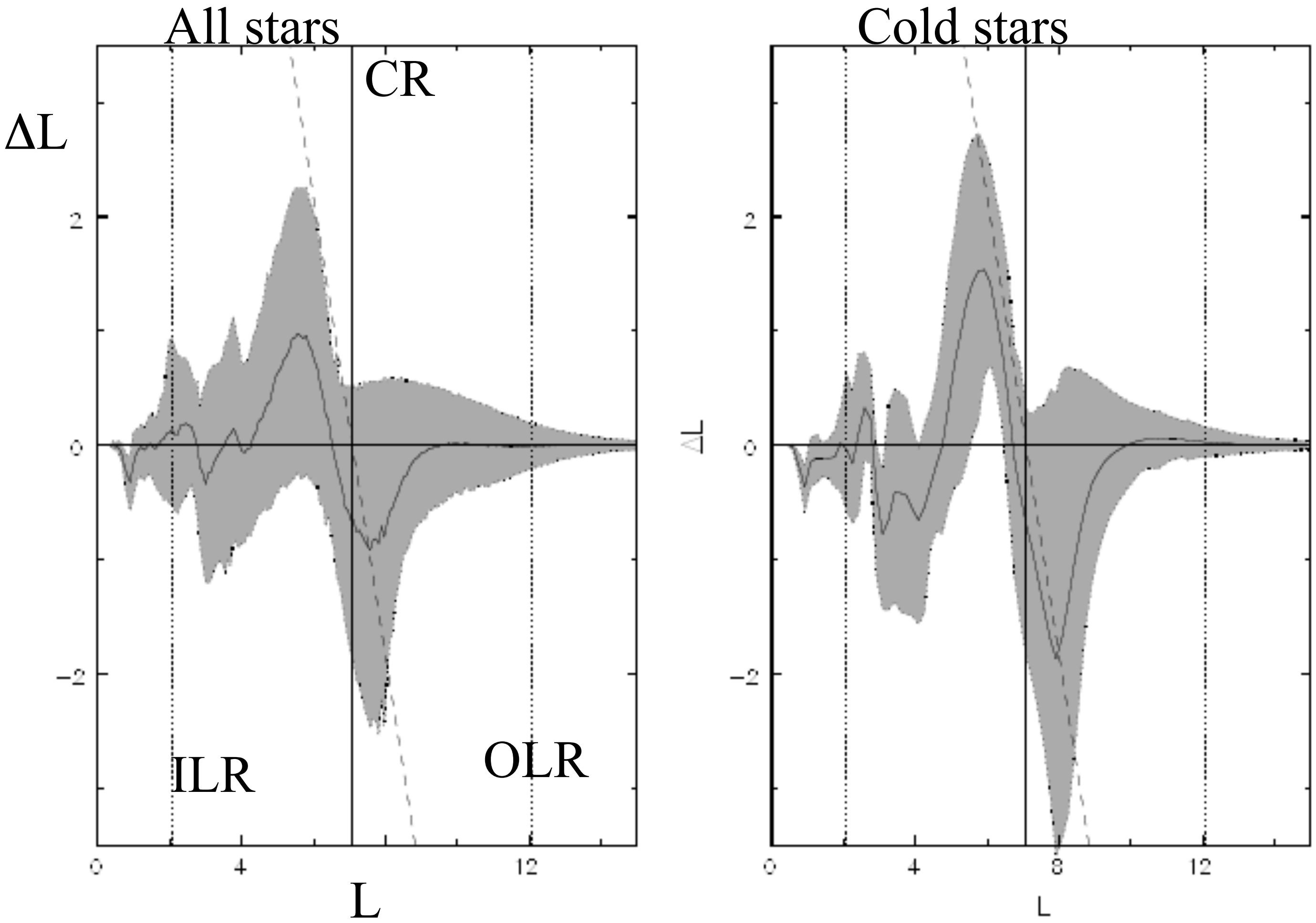
➔Spirals and bar transfer inner stars to the outer parts

Roskar et al 2008

Radial migrations of stars and gas

Resonant scattering at resonances

➔ Exchange of angular momentum



Sellwood & Binney 2002

ΔL exchange without heating

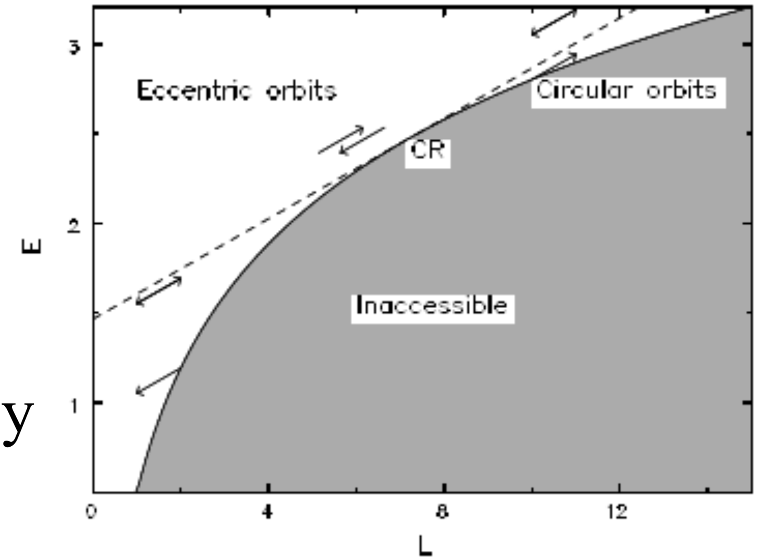
Invariant: the Jacobian

$E_J = E - \Omega_p L$ ➔ $\Delta E = \Omega_p \Delta L$

$\Delta J_R = (\Omega_p - \Omega)/\kappa \, \Delta L$

If steady spiral, exchange at resonance only

In fact, spiral waves are transient



The orbits which are almost circular will be preferentially scattered

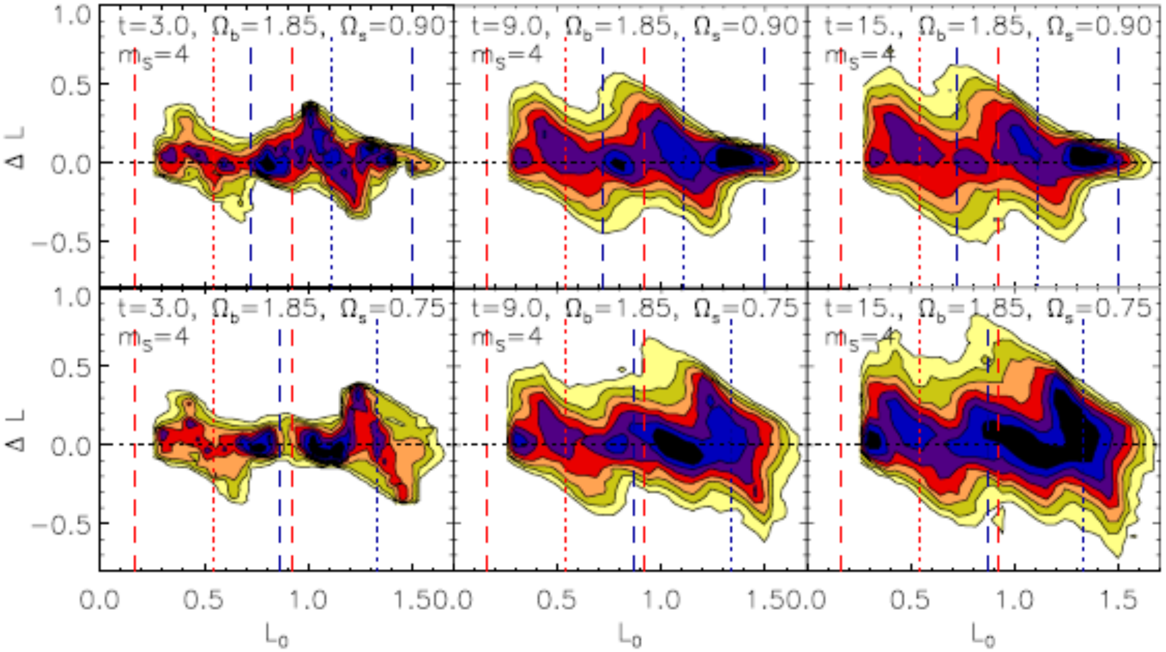
Sellwood & Binney 2002

Effect of coupled patterns

Time evolution of the L transfer with bar and 4-arm spiral, in the MW

Top: spiral CR at the Sun

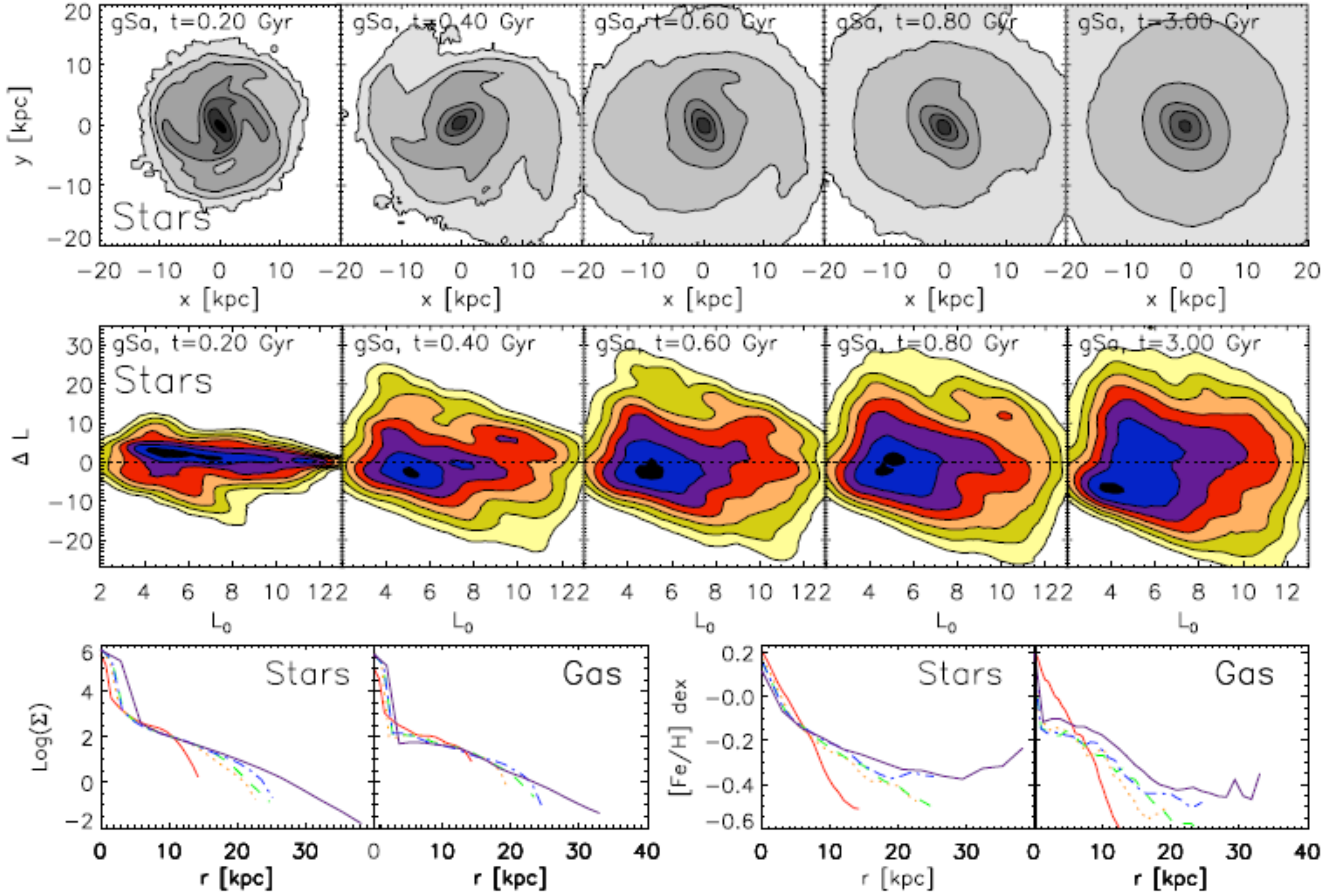
Bottom: near 4:1 ILR



Minchev et al 2010

Bar+spiral migrations

Overlap of resonances



Minchev et al 2010

Scenarios of bulge formation

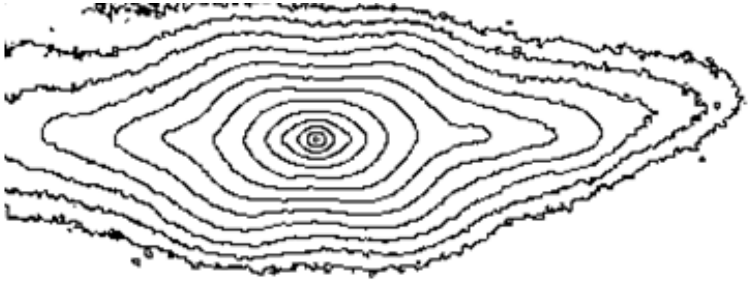
Mergers:
Major mergers form generally a spheroid
In minor mergers, disks are more easily kept and enrich the classical bulge

Secular evolution:
bars and vertical resonance elevate stars in the center
into a pseudo-bulge: intermediate between a spheroid and a disk
More frequent for late-type galaxies

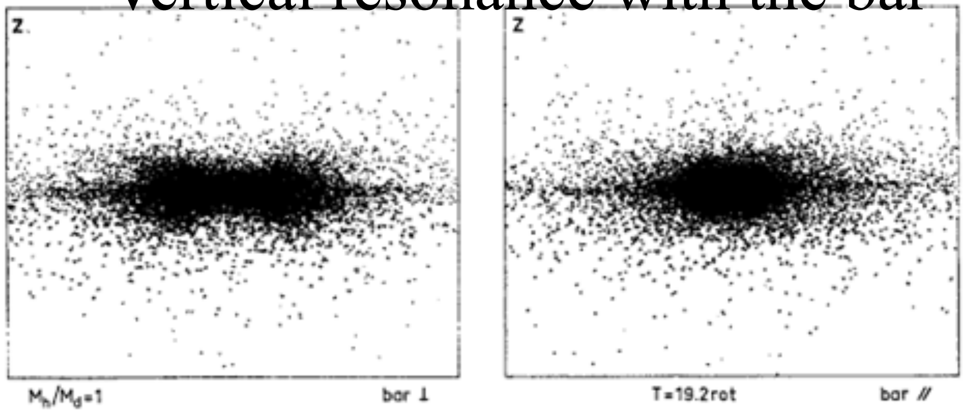
Clumpy galaxies at high z can also form a bulge, through dynamical friction

➔ Problems to form bulgeless galaxies

Pseudo-bulge formation



Vertical resonance with the bar



Combes & Sanders 1981

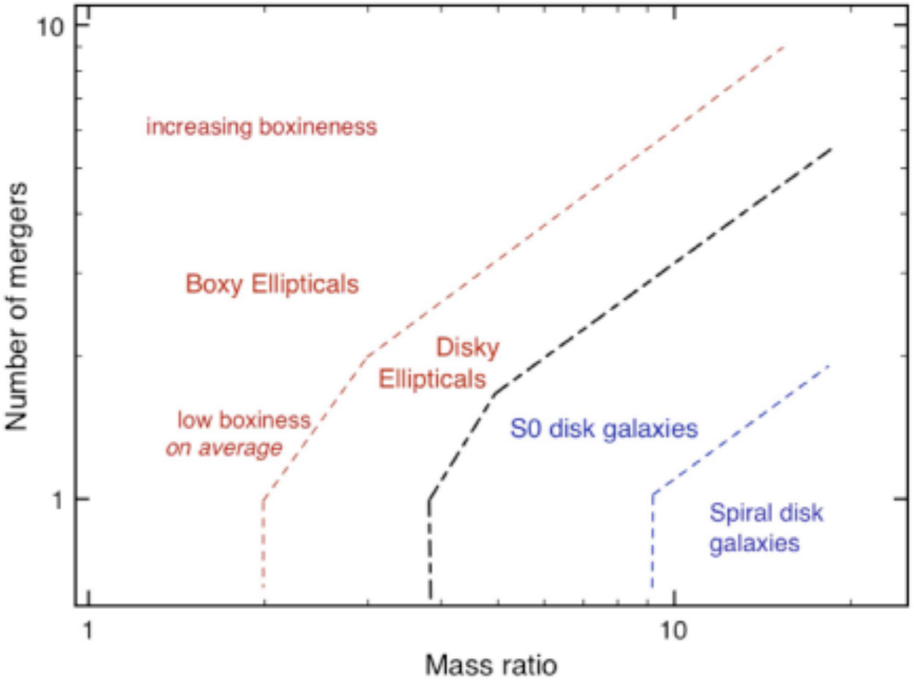
Pseudobulges have characteristics intermediate between a classical bulge (or Elliptical) and normal disks *(Kormendy & Kennicutt 2004)*

➔Sersic index $\mu \sim r^{1/n}$, with n =1-2 (disks: n=1, E: n=4 or larger)

➔Flattening similar to disks, box/peanut shapes ➔ Bluer colors

➔Kinematics: more rotation support than classical bulges

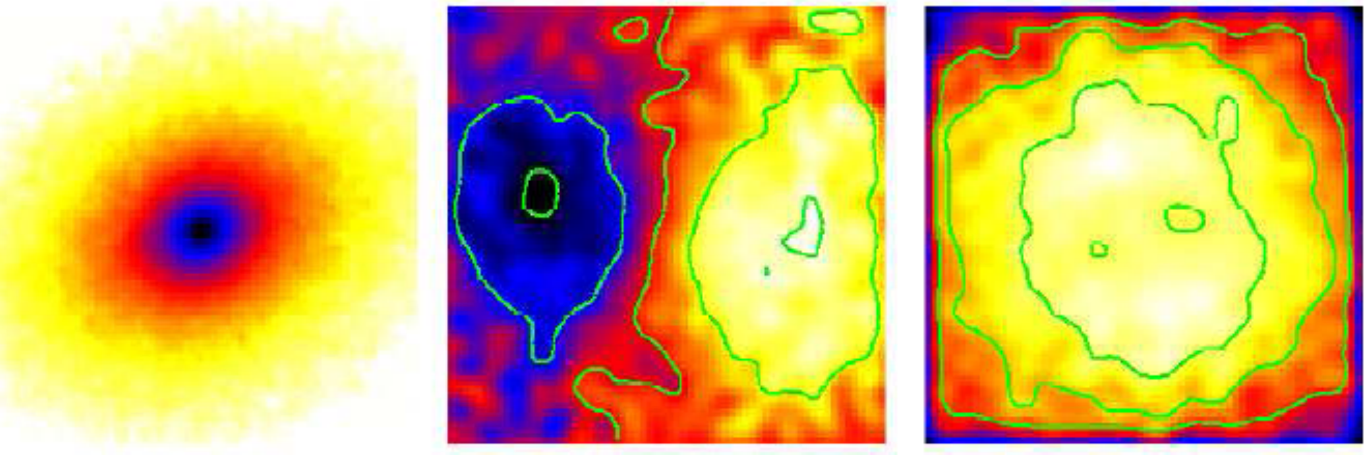
Multiple minor mergers



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

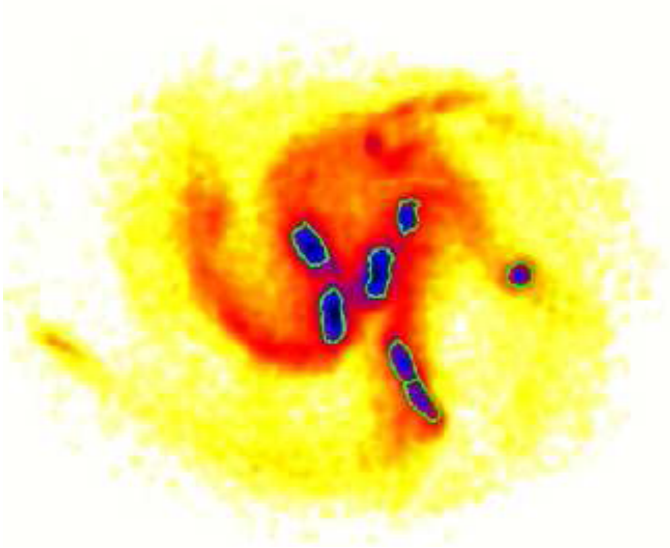
50 mergers
of 50:1 mass ratio

Even more frequent
Than 1:1



Bournaud, Jog, Combes 2007

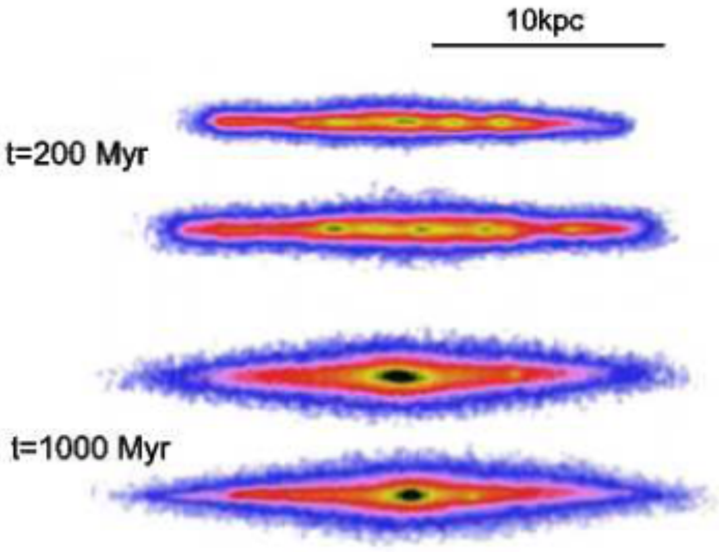
Formation in clumpy galaxies



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?



Frequency of bulge-less galaxies

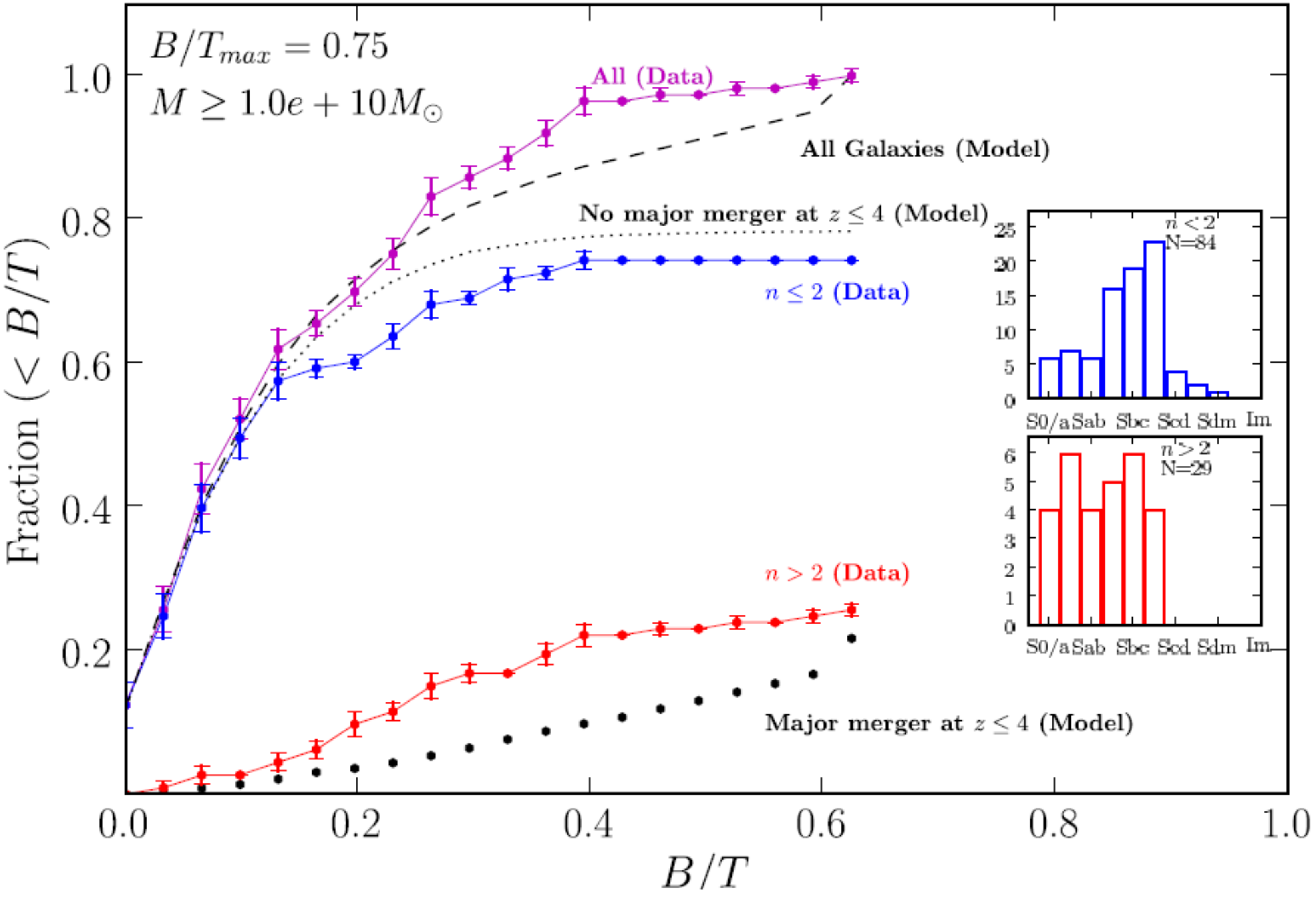
Locally, about 2/3 or the bright spirals are bulgeless, or low-bulge
Kormendy & Fisher 2008, Weinzirl et al 2009
Some of the rest have both a classical bulge and a pseudo-bulge
Plus nuclear clusters *(Böker et al 2002)*

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?

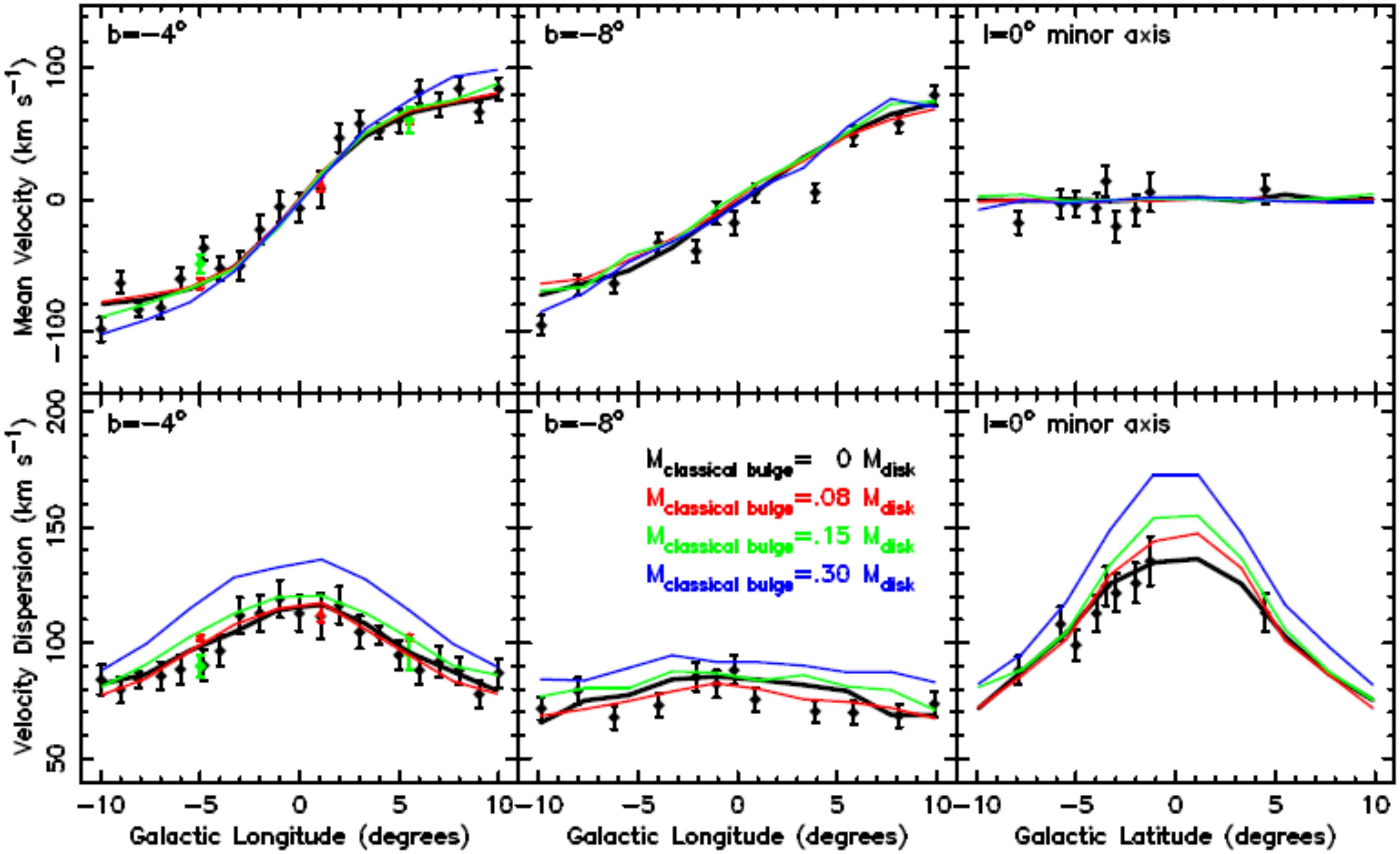
Low Bulge Mass in spiral galaxies



Weinzirl et al 2009

Milky Way: No possible classical bulge

Even a classical bulge of 8% Mdisk worsens the fit to the data



Older, low Fe/H stars have been scattered at high z, for a longer time

Several bars?

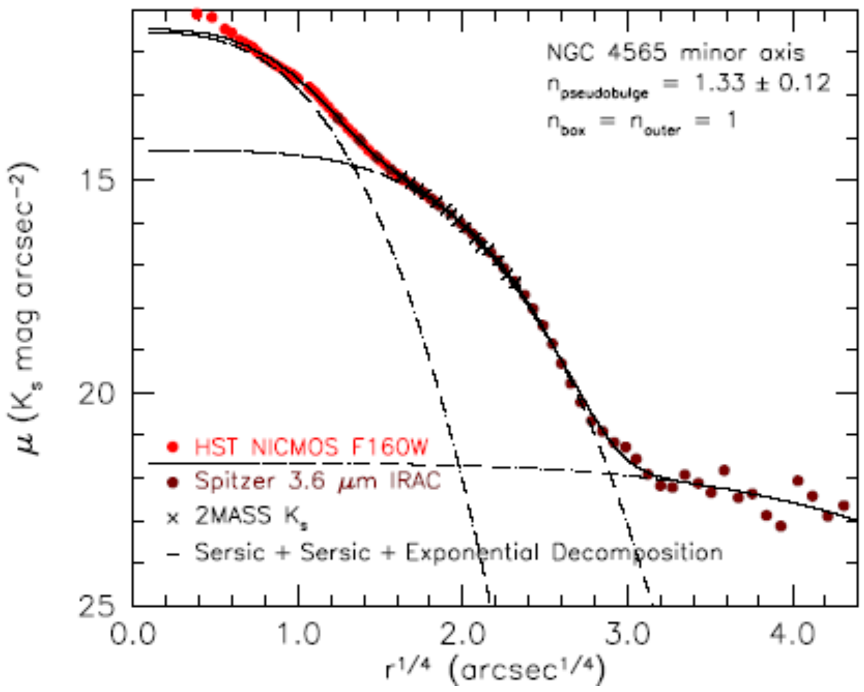
Shen et al 2010

NGC 4565: SBb, No classical bulge

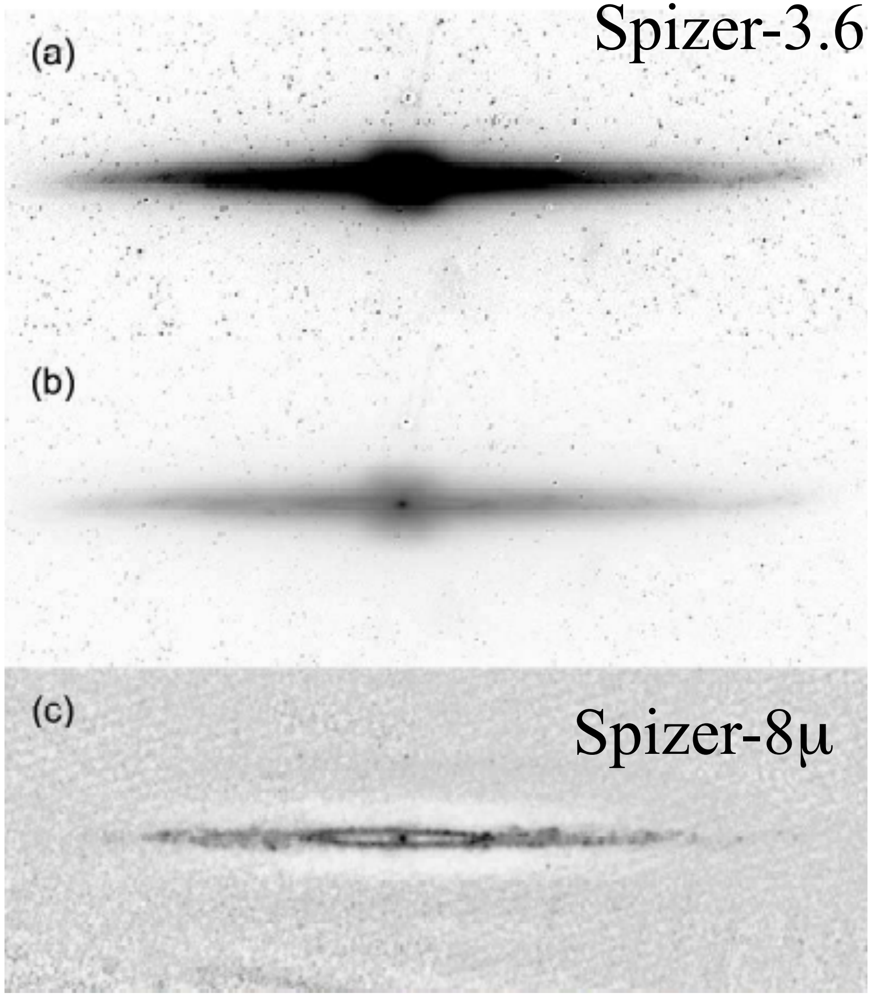
In addition to the bar, a pseudo-bulge of 6% in mass

Pseudo, since flattened, and
Sersic index 1.3-1.5

HST 1.6μm



Spizer-3.6μ



Spizer-8μ

Kormendy & Barentine 2010

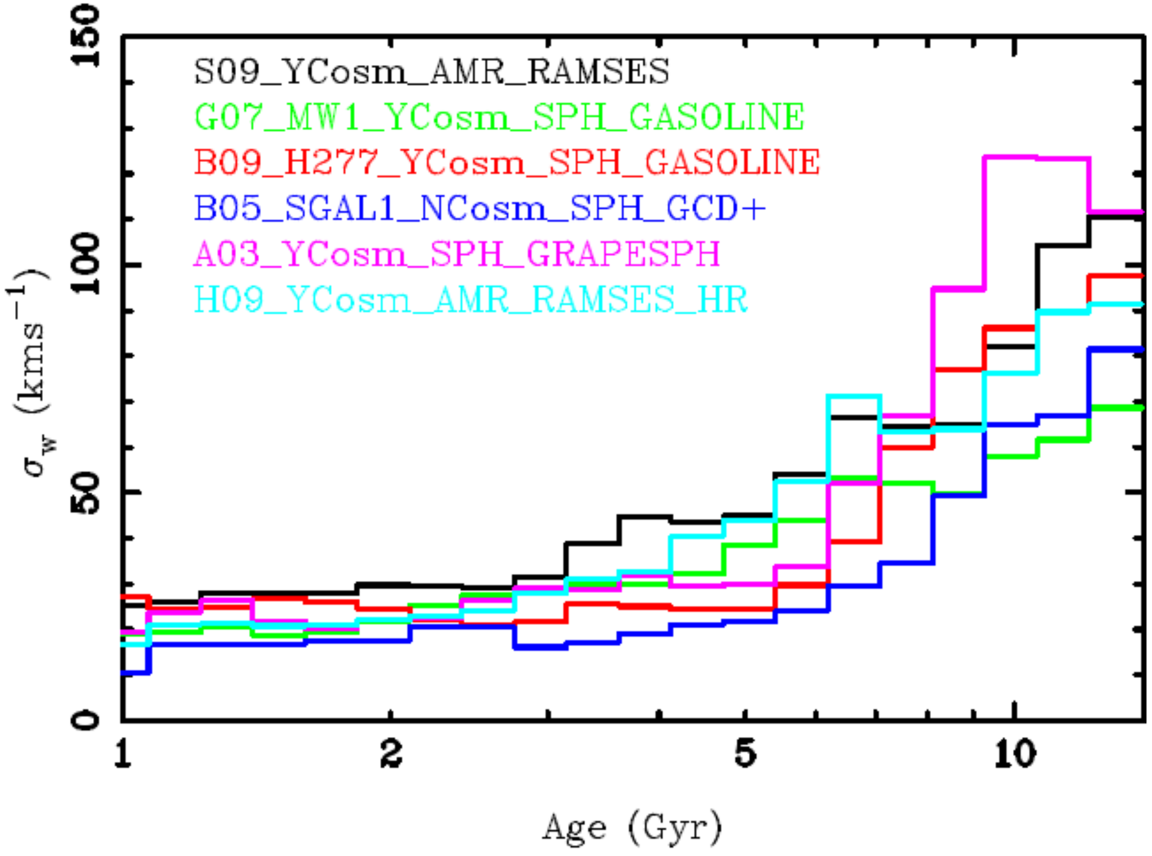
Disk Heating

➔Rapid, due to mergers
➔Slow due to secular evolution

Presence of thin and thick disks as two independent components
Thick disks could be due to mergers and/or turbulent ISM at high z

House et al 2011

Too hot in simulations
High σ floor
Due to low ρ threshold



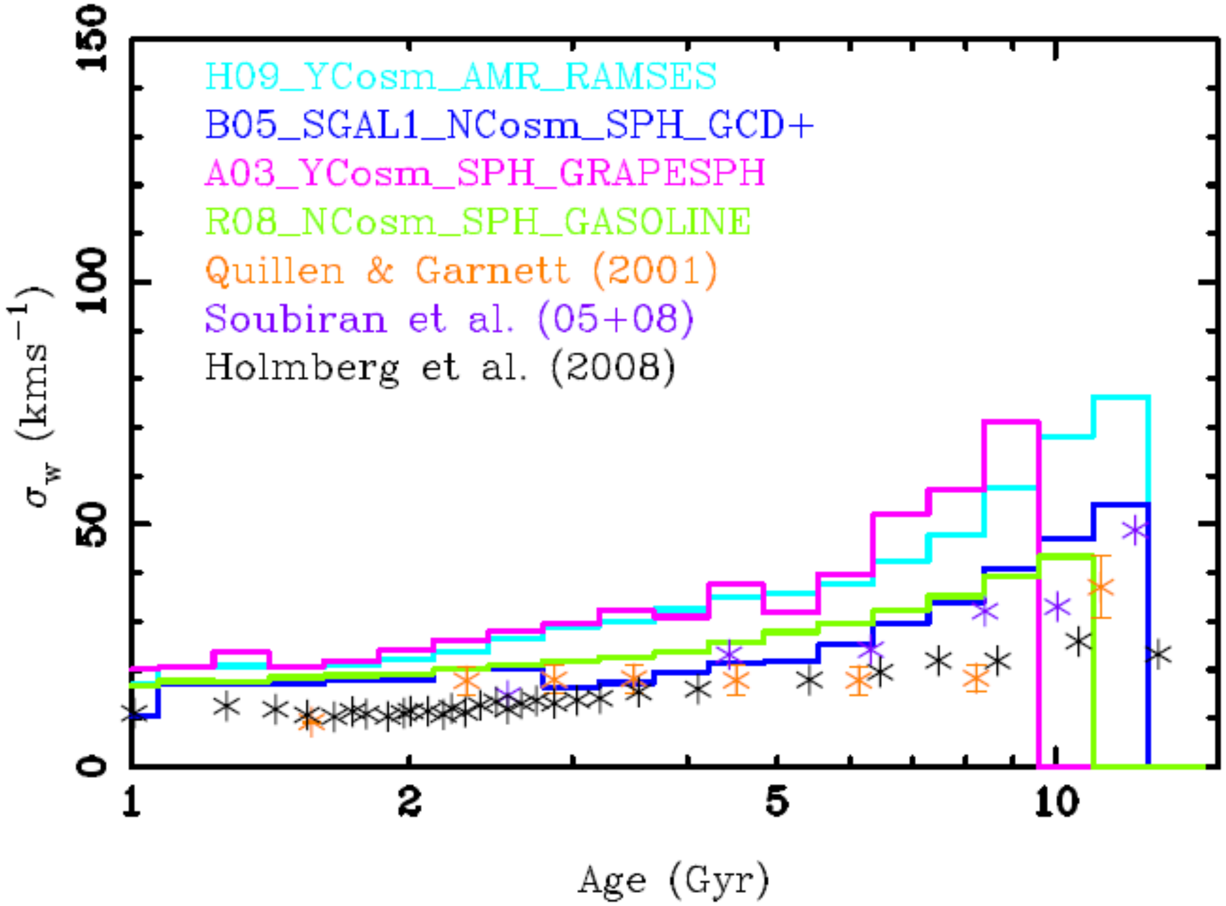
Disk Heating

Presence of the old thin disk➔ problem for the hierarchical scenario

House et al 2011

Comparison with the observations

In-situ stars



Thick disk formation

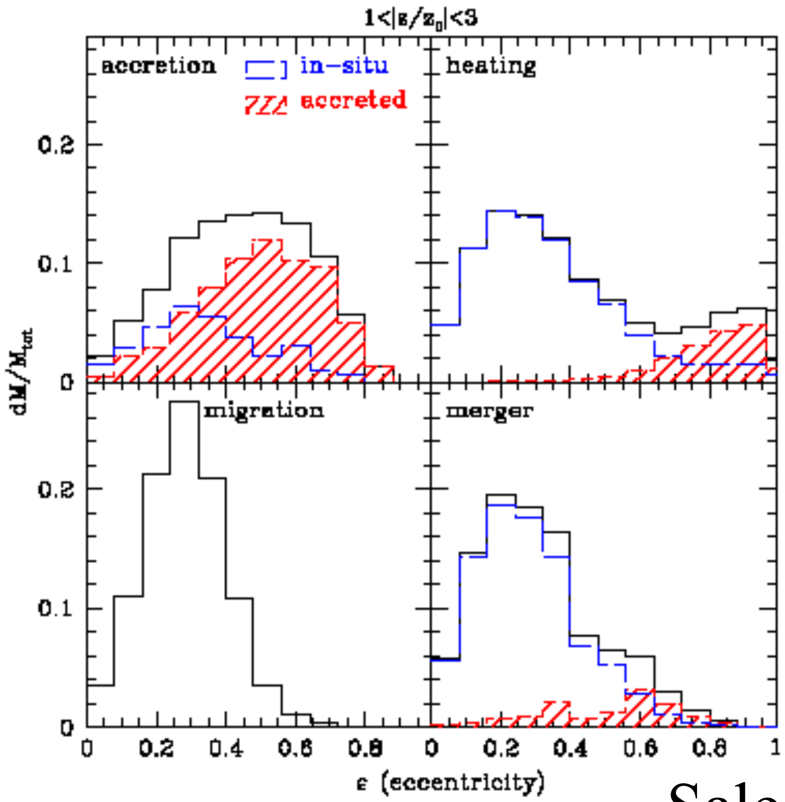
At least 4 scenarios:

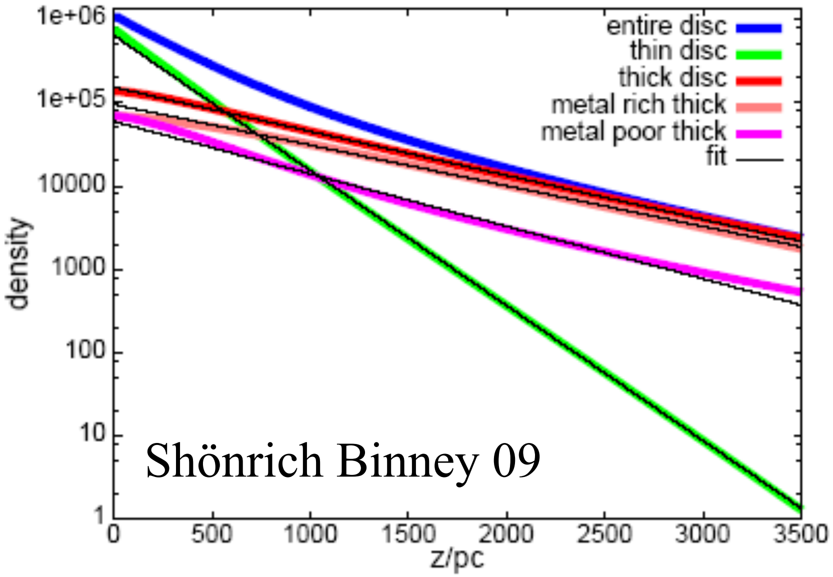
1) Accretion and disruption of satellites (like in the stellar halo)

2) Disk heating due to minor merger

3) Radial migration, via resonant scattering

4) In-situ formation from thick gas disk (mergers, or clumpy galaxies)





Shönrich Binney 09

➔Orbit excentricity of stars could help to disentangle

Sales et al 2009, cf di Matteo et al 2011

CONCLUSION

➔ Importance of mergers: more frequent in Early-type Galaxies (ETG)
However, 86% Fast rotators, 14% Slow rotators (Emsellem et al 2011)

➔ Bars efficient to AM exchange, gas radial flows

➔ Radial migration, resonant scattering by spirals, large disks

➔Bulge formation: partly mergers
But also vertical resonance with bars, secular evolution
Or clumpy galaxies at high-z

➔ Thick disk formation: mergers, or secular evolution?