The Local Group of galaxies in a cold dark matter Universe

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Why should we care about the Local Group?

- It is the best known sample of galaxies in the Universe, hence the most important testbed for theories of galaxy formation

- We need to understand the origin and history of present-day galaxies if we want to understand the high redshift Universe. The history of LG galaxies can tell us a lot about history of mass, light and chemistry in the Universe

➢> 100 “subhaloes” but only 10 dwarf satellites around the MW and M31

➢with baryons in the simulations galactic disks are ten times smaller than real disk (e.g. Navarro & Steinmetz 2000)

How to simulate the formation of the MW and its satellites?

Proper simulations with dark matter+baryons in a cosmological context extremely complex. One should:

1)Include the baryons and all the relevant processes, both internal (star formation, feedback) and environmental (tidal stripping, ram pressure, reionization)

2)High resolution to resolve dwarf galaxy-sized objects

3)Start at high z and go on until z=0 to compare with the data that we have.

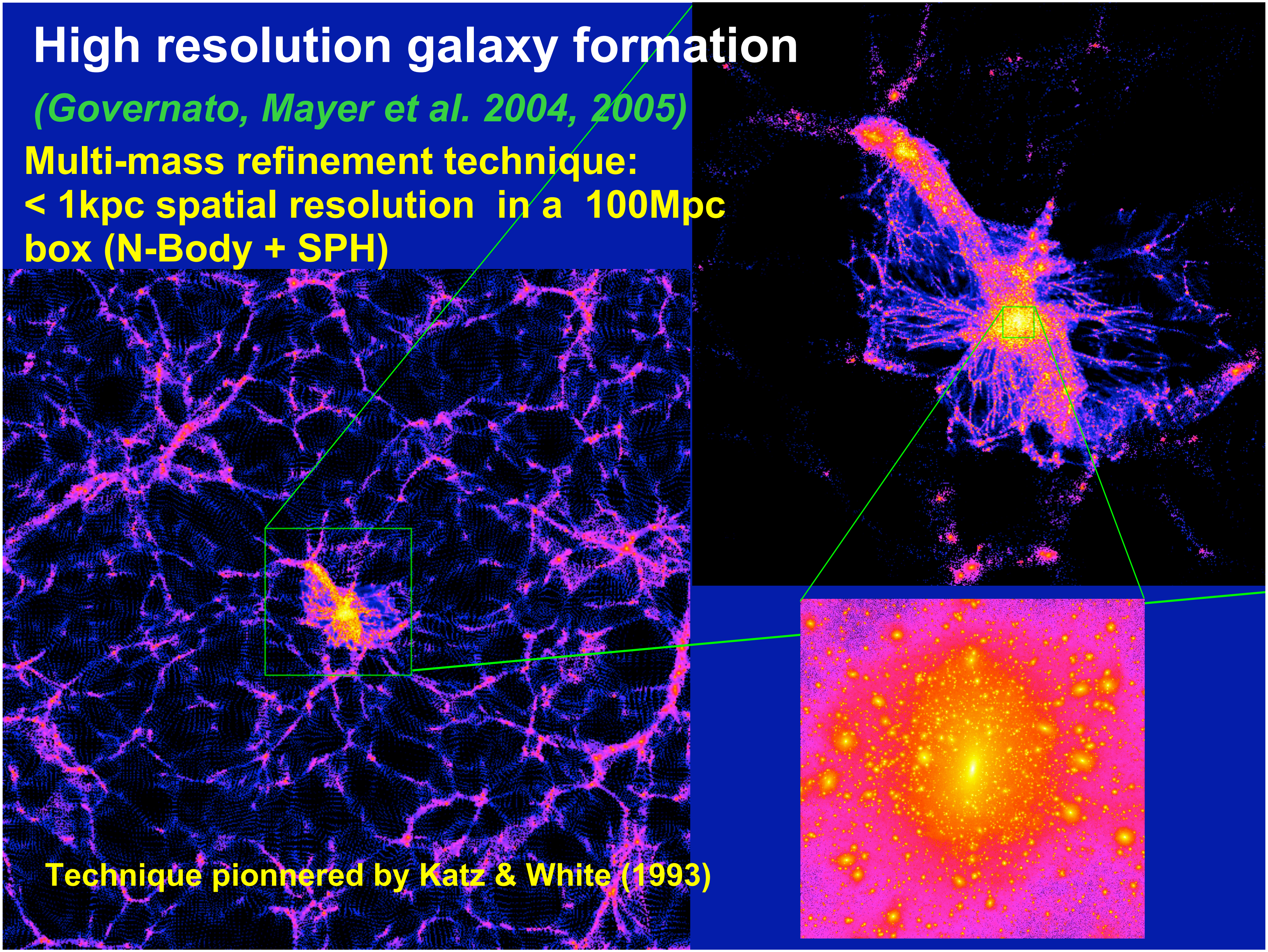
Uncertain modeling of physics in (1) plus (2,3) too many Tflops/s even on the best available parallel machines with current computational techniques

Need some compromises….

High resolution galaxy formation

(Governato, Mayer et al. 2004, 2005)

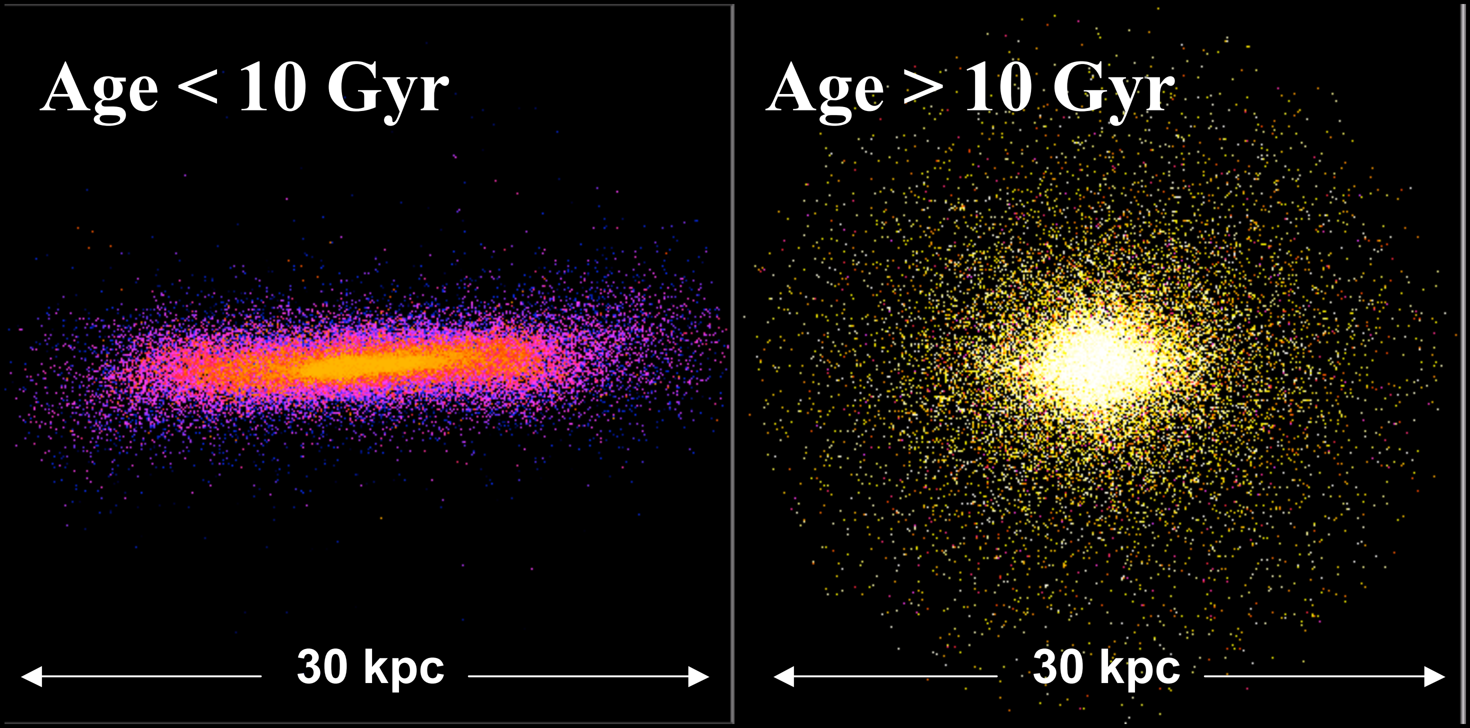
Multi-mass refinement technique:
< 1kpc spatial resolution in a 100Mpc box (N-Body + SPH)



Technique pionnered by Katz & White (1993)

LCDM galaxy at z=0

GM04
and
Mayer
(2004)



Disk (+ bar)

Bulge + Stellar Halo

A realistic disk galaxy forms thanks to high mass and force resolution in the simulation (Ndm and Nbaryon $> 10^5$)

No angular momentum catastrophe of older simulations (e.g. Navarro & Steinmetz 2000)

LCDM simulations with feedback

With Fabio Governato (UW), Beth Willman (NYU), Greg Stinson (UW), Alyson Brooks (UW) and James Wadsley (McMaster)

Use SF+SN feedback algorithm in **LCDM simulations** ***to study the ab initio formation of*** **three** ***disk galaxies over a range of masses:***

3e11 Mo **(small galaxy),** 1e12 Mo **(Milky Way like),** 3e12 Mo **(giant spiral)**

Res- a)*Spatial resolution: 0.3-0.6kpc*
Mass resolution for MW sim: 5e1e6 Mo DM particles, 5e10e5 Mo gas particles

Res-b)*Spatial resolution: 0.1-0.3kpc*
Mass resolution for MW sim: 6e10e5 Mo DM particles, 6e10e4 Mo gas particles

Simulations carried to z=0

Halos picked with a quiet merging history (last major merger at z>2)
typical formation time for their halos: ~ z=0.9-0.7

Star formation + feedback recipe

-Gas is eligible to form stars when cold, dense and in covergent flow (Miller-Scalo IMF assumed)

-Gas receives thermal energy from nearby SNII + is not allowed to radiate energy for a timescale related to ISM turbulence decay (Thacker & Couchman 2000)

-Gas is metal enriched by SN I&II

Parameters:

-Star Formation Efficiency: *fraction of gas turned into stars – free parameter*
-Efficiency of SN Winds: *fraction of energy of supernovae explosion that goes into the wind – free parameter*
-Turbulence of the IGM: *"entrainment factor" i.e. amount of gas affected by the wind + timescale for decay of turbulence (following McKee & Ostriker 1977) – determined by local gas properties (T,ρ)*

Strategy: test algorithms with compound N-Body/SPH galaxy models of a Milky Way and a dwarf galaxy trying to reproduce observed properties at z=0:

-SFR as from SDSS on a wide mass range
-Reproduce Schmidt Law in MW model
-Stellar Rz/Rdisk ratio
-Volume ratio Cold Gas/Hot gas (Porosity)
-Cold Gas turbulence

Tests with isolated galaxy N-Body+SPH models

(Stinson et al. 2005)

SF efficiency 0.05/Tdyn

SN efficiency = 0.6 * 10^{51} erg

Gas Rich Dwarf Galaxy Vc ~70Km/sec

Gas=white

SFR

Stellar Rz/Rdisk ~ 0.3

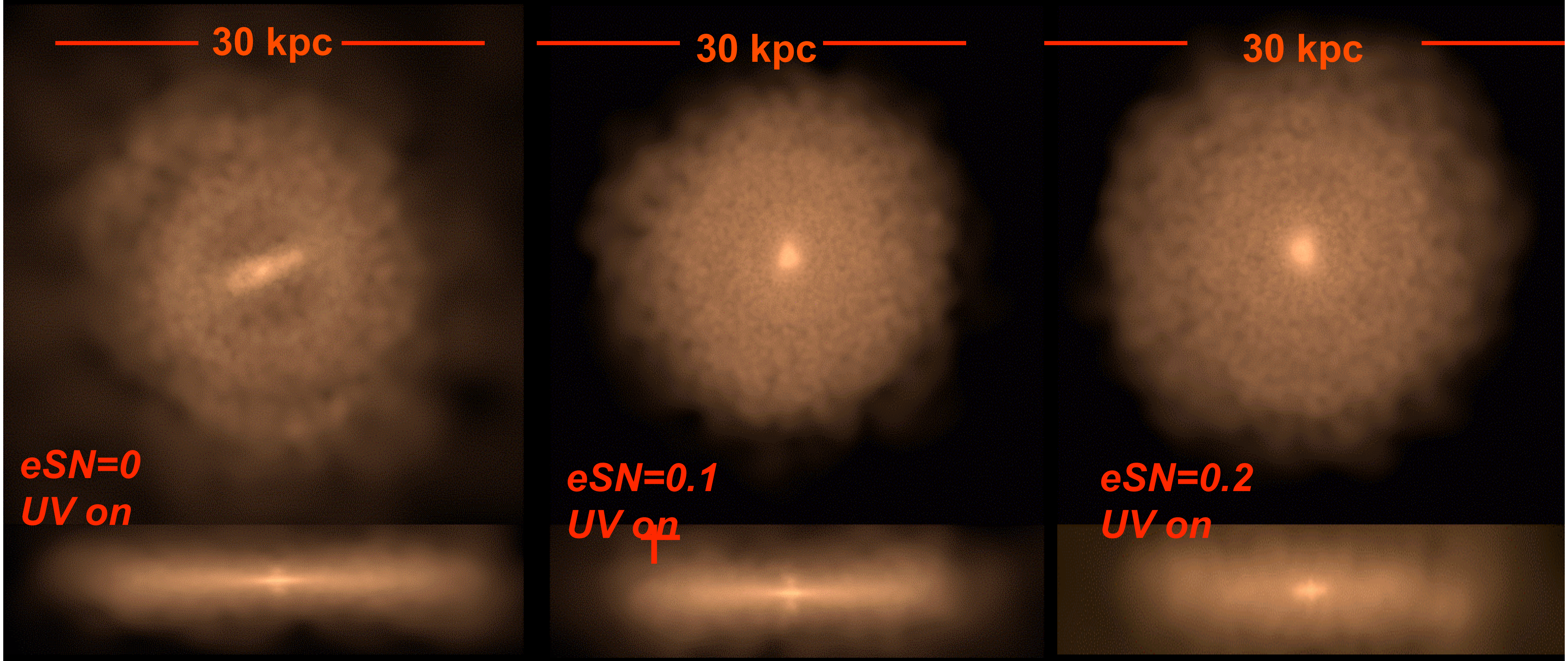
Volume ratio Cold Gas/Hot gas ~ 0.5-1 within stellar disk

Cold Gas turbulence ~ 20Km/sec

Milky Way As Klypin, Zhao & Somerville 2001, Vc ~ 160 km/s

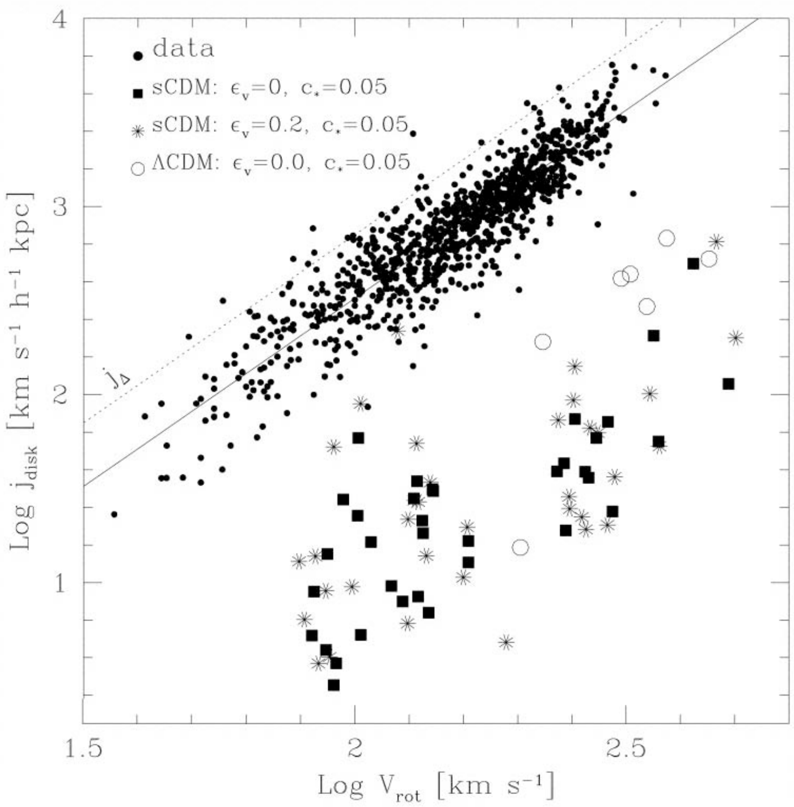
Gas=red
Stars=white

MW DISK SIZE AND MORPHOLOGY AT z=0

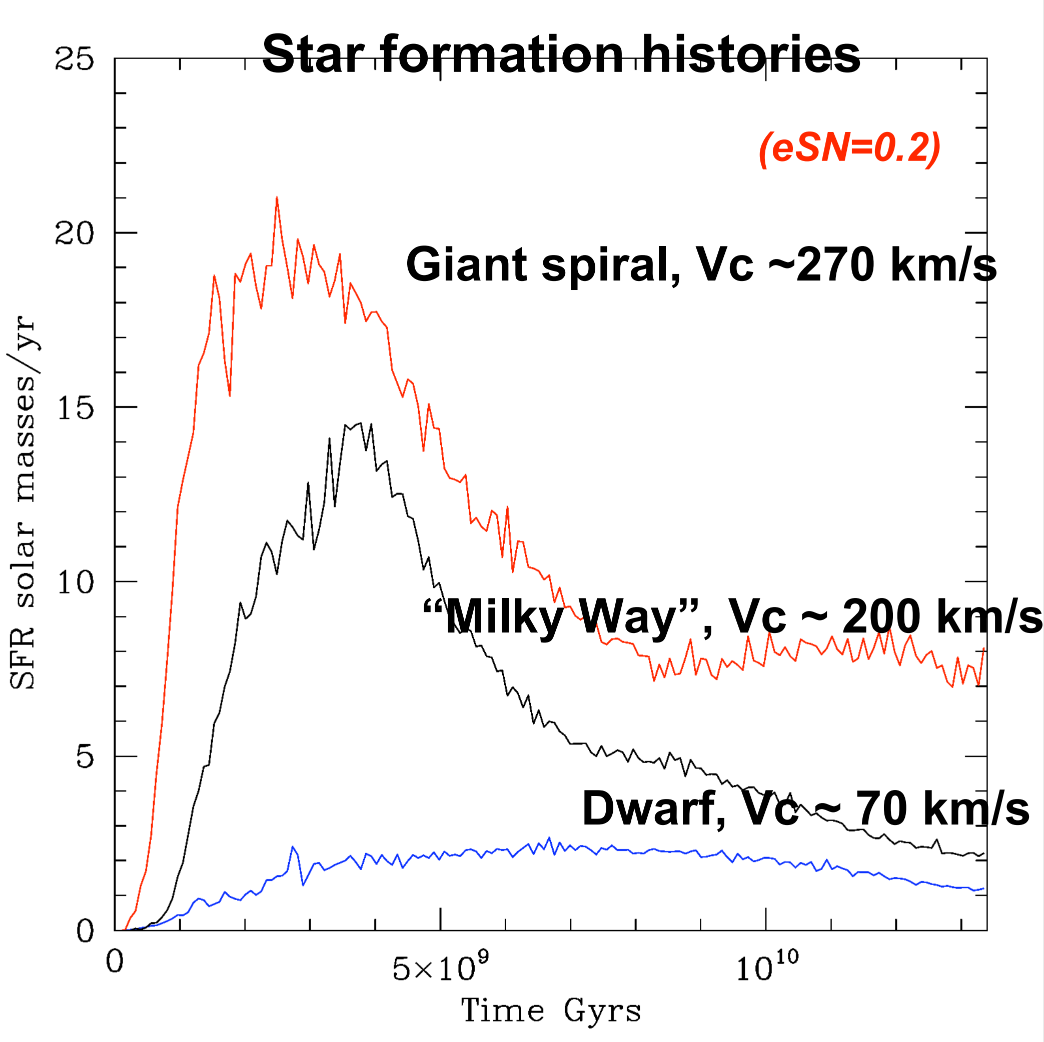


- DISK SIZE AT z=0 REALISTC + *NEARLY INDIPENDENT* ON FEEDBACK

- MORPHOLOGY (e.g. BAR FORMATION) AND STELLAR KINEMATICS *DEPEND* on FEEDBACK.


data
sCDM: ϵ_v=0, c_*=0.05
sCDM: ϵ_v=0.2, c_*=0.05
ΛCDM: ϵ_v=0.0, c_*=0.05
j_Δ
Log j_{disk} [km s^{-1} h^{-1} kpc]
Log V_{rot} [km s^{-1}]
1.5
2
2.5
1
2
3
4

But feedback is important!



SN Feedback reproduces the observed Vrot vs stellar age trend ---> *"anti-hierarchical" galaxy formation possible in CDM (e.g McArthur & Courteau 2004)*

Formation of the Milky Way and its satellites

Red: stars

Blue: gas

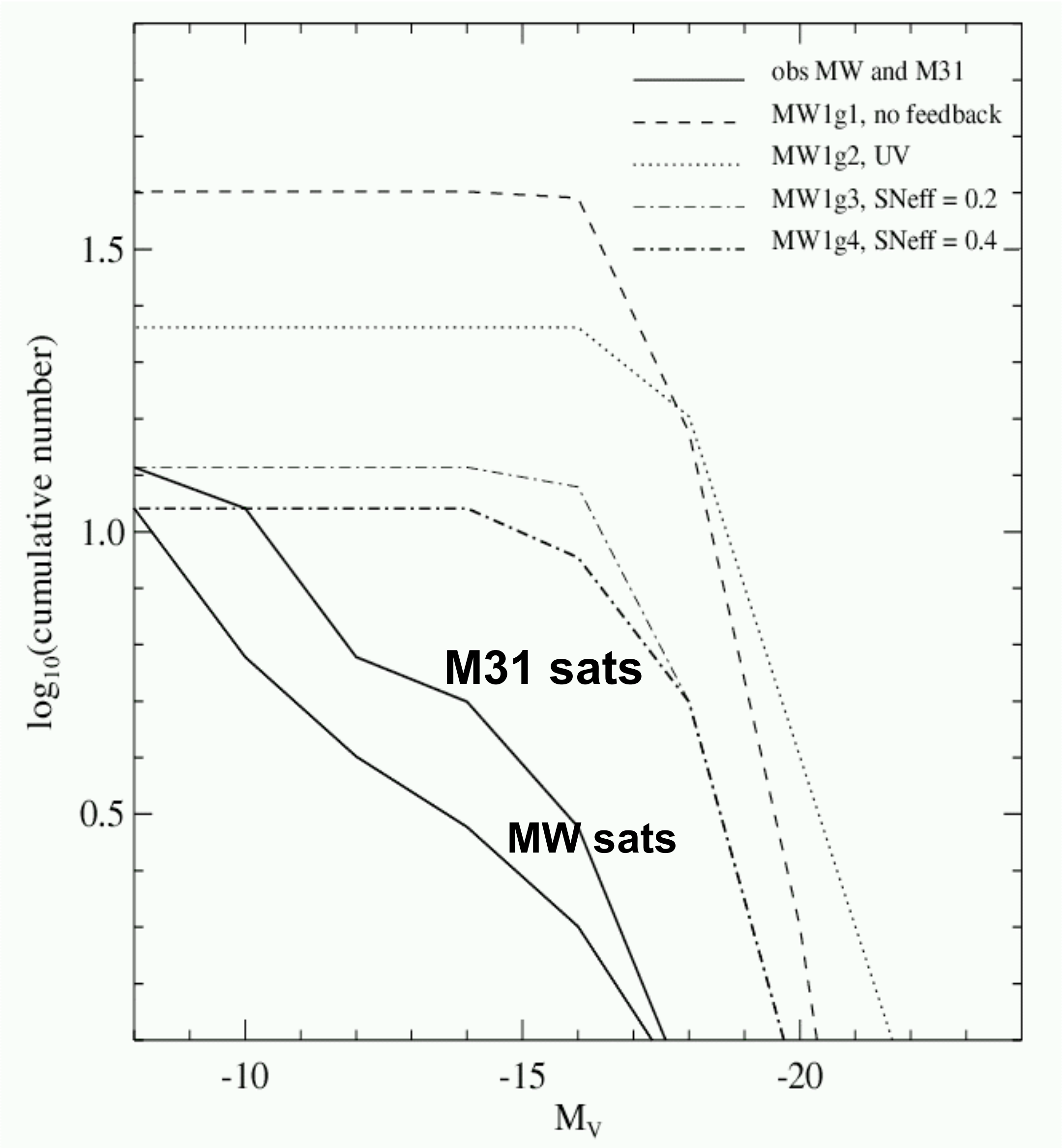
Total Mass 3e12 Msol
Spin Parameter = 0.035
Vrot Max 270 Km/sec
Formation time z = 0.75
Last major merger z=2.5
Frame size ~ 200 Kpc

UV+SN Feedback
(UV bg model from Haardt & Madau 1999)

No Feedback, No UV

Feedback + UV inhibit dwarf galaxy formation at Vc < 30 km/s

Luminosity function of satellites



Mayer, Willman,
Governato et al., in prep.

UV + SN feedback nearly reproduce the correct number of satellites expected within a Milky Way sized halo.

These satellites are all gas poor at z=0 (as dSphs and dEs)

However still too many bright satellites!

Can we fix completely the substructure problem?
Can we lower further the baryon fraction?

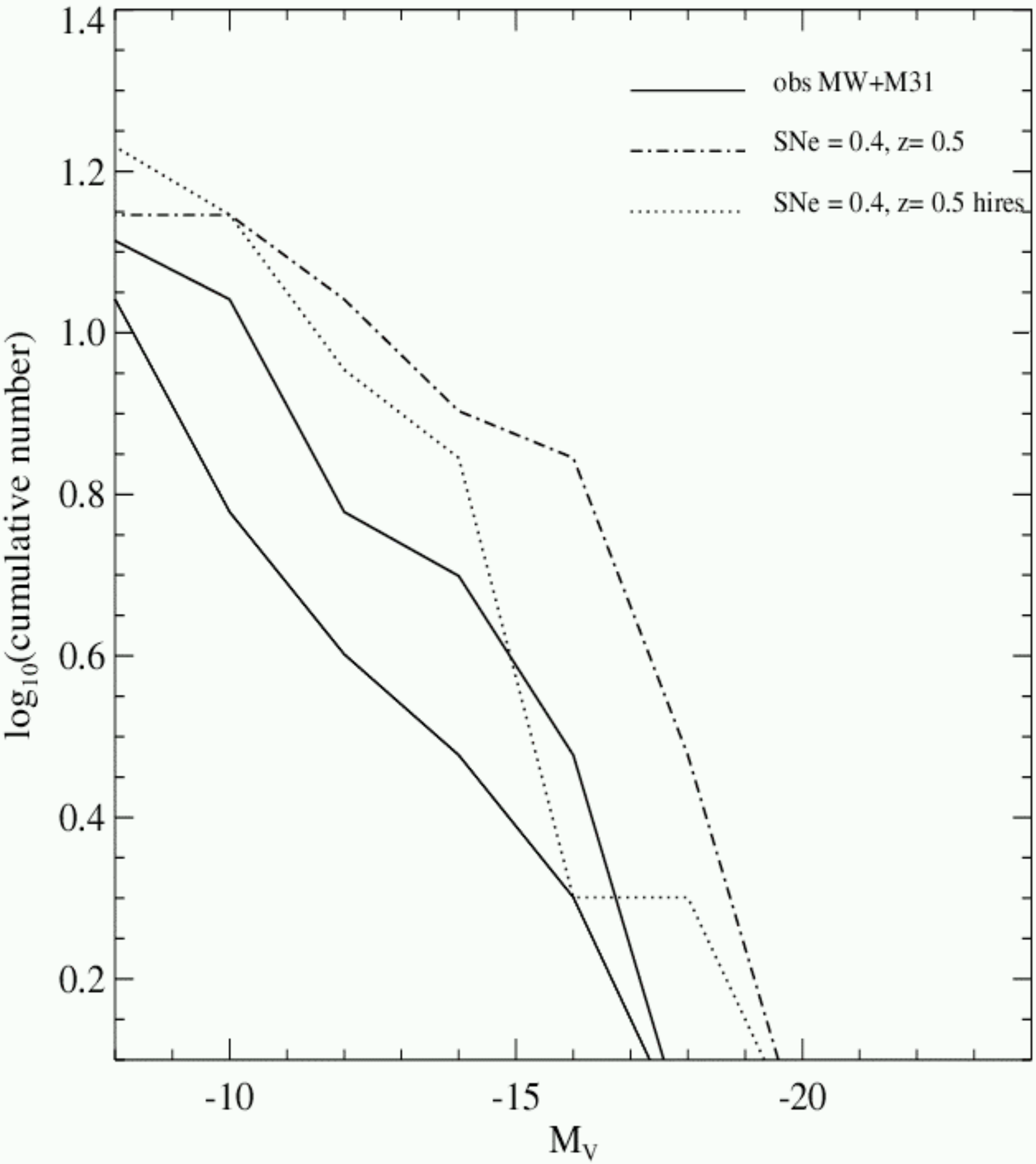
Yes, tremendous room for improvement:

(1) Direct effect of increasing resolution; less catastrophic angular momentum loss → less dense gaseous concentration -> less star formation.
Especially at high redshift subhaloes are poorly resolved!

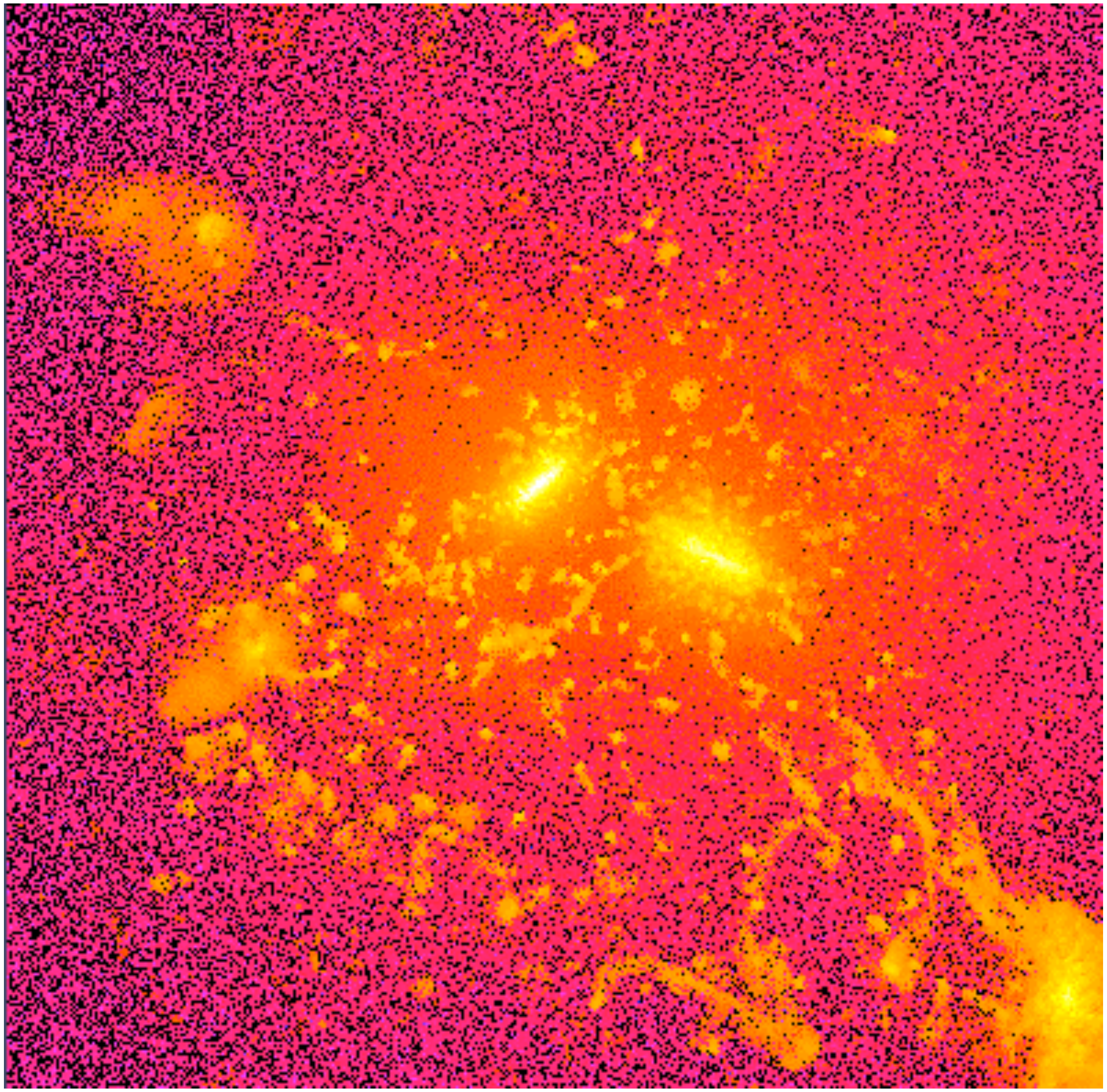
(2) Indirect effect of increasing resolution; less star formation implies satellites have a higher gas fraction by the time they approach the primary galaxy ---> they would then be more susceptible to gas mass loss from environmental mechanisms

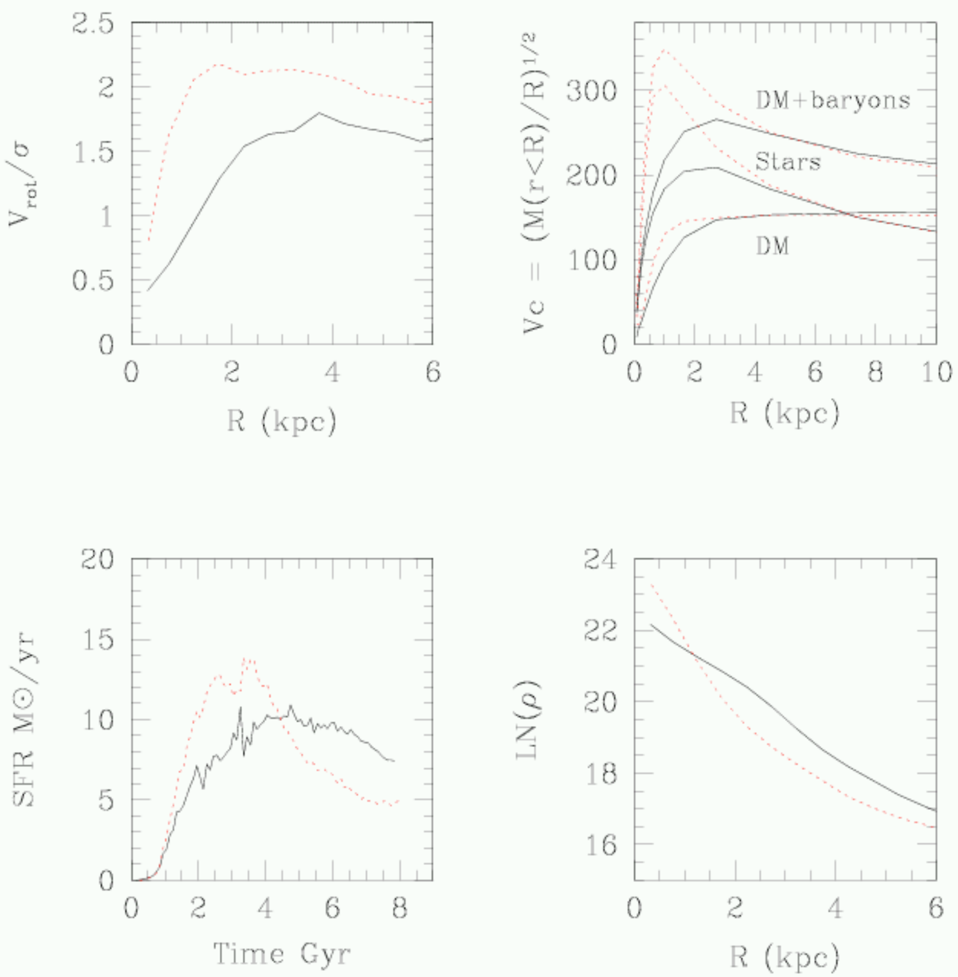
(3) Stronger/earlier UV + supernovae feedback from top-heavy IMF to reduce gas mass fraction in progenitor lumps

(4)Proximity effect, i.e. photoionization from primary galaxy, can be important even after UV bg fades (Mayer 2005)



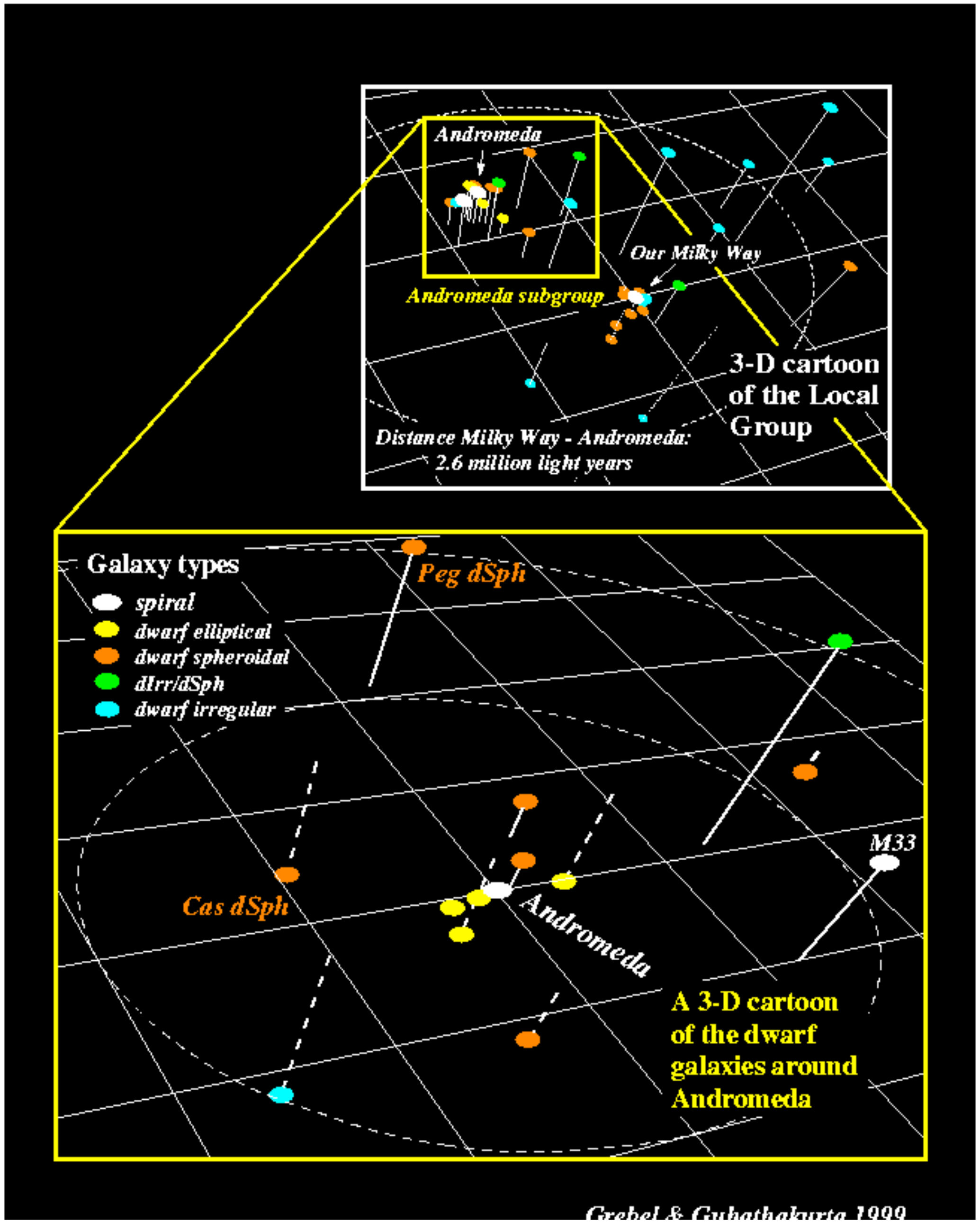
obs MW+M31
SNe = 0.4, z= 0.5
SNe = 0.4, z= 0.5 hires
log$_{10}$(cumulative number)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
-10
-15
-20
M$_V$





V_{rot}/σ
2.5
2
1.5
1
0.5
0
0
2
4
6
R (kpc)
$Vc = (M(r<R)/R)^{1/2}$
300
200
100
0
DM+baryons
Stars
DM
0
2
4
6
8
10
R (kpc)
SFR M⊙/yr
20
15
10
5
0
0
2
4
6
8
Time Gyr
LN(ρ)
24
22
20
18
16
0
2
4
6
R (kpc)

The LG morphology-density relation



- **2 Giant spirals**
- **40 Dwarfs**
- **45% dIrrs**
- **(Gas rich, vrot/$\sigma > 1$)**
- **30% dSphs**
- **15% dEs**
- **(Gas poor, vrot/$\sigma < 1$)**
- **10% transition**

From Grebel (1999)

Even state-of-the art cosmological hydrodynamical simulations do not have enough resolution to probe the internal structural evolution of the satellites yet!

Need some help from another type of simulations. Recipe:

- **Build high resolution models of dwarf galaxies**

**Mayer et al. 2000,
2001a,2001b,
2002, 2003, 2005**

Even state-of-the art cosmological hydrodynamical simulations do not have enough resolution to probe the internal structural evolution of the satellites yet!

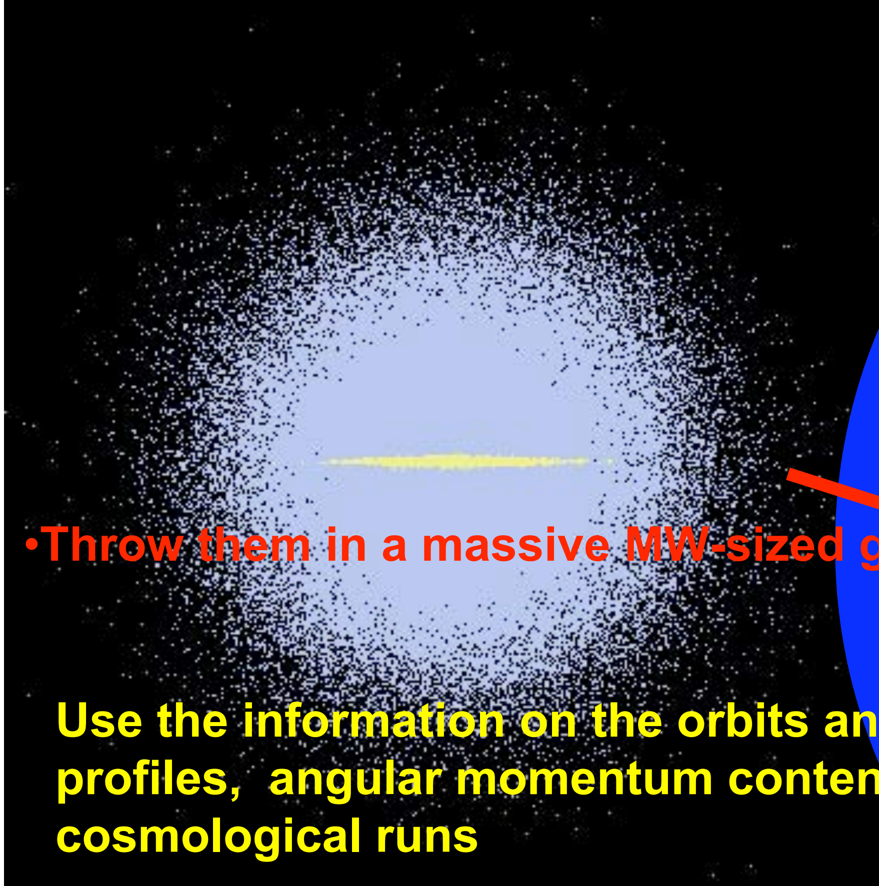
of simulations. Recipe:

galaxies

- Throw them in a massive MW-sized galaxy halo

Mayer et al. 2000, 2001a,2001b, 2002, 2003, 2005

Even state-of-the art cosmological hydrodynamical simulations do not have enough resolution to probe the internal structural evolution of the satellites yet!



of s

•Throw them in a massive MW-sized galaxy halo

Use the information on the orbits and structure of galaxies (halo density profiles, angular momentum content, baryon fraction etc..) that comes from cosmological runs

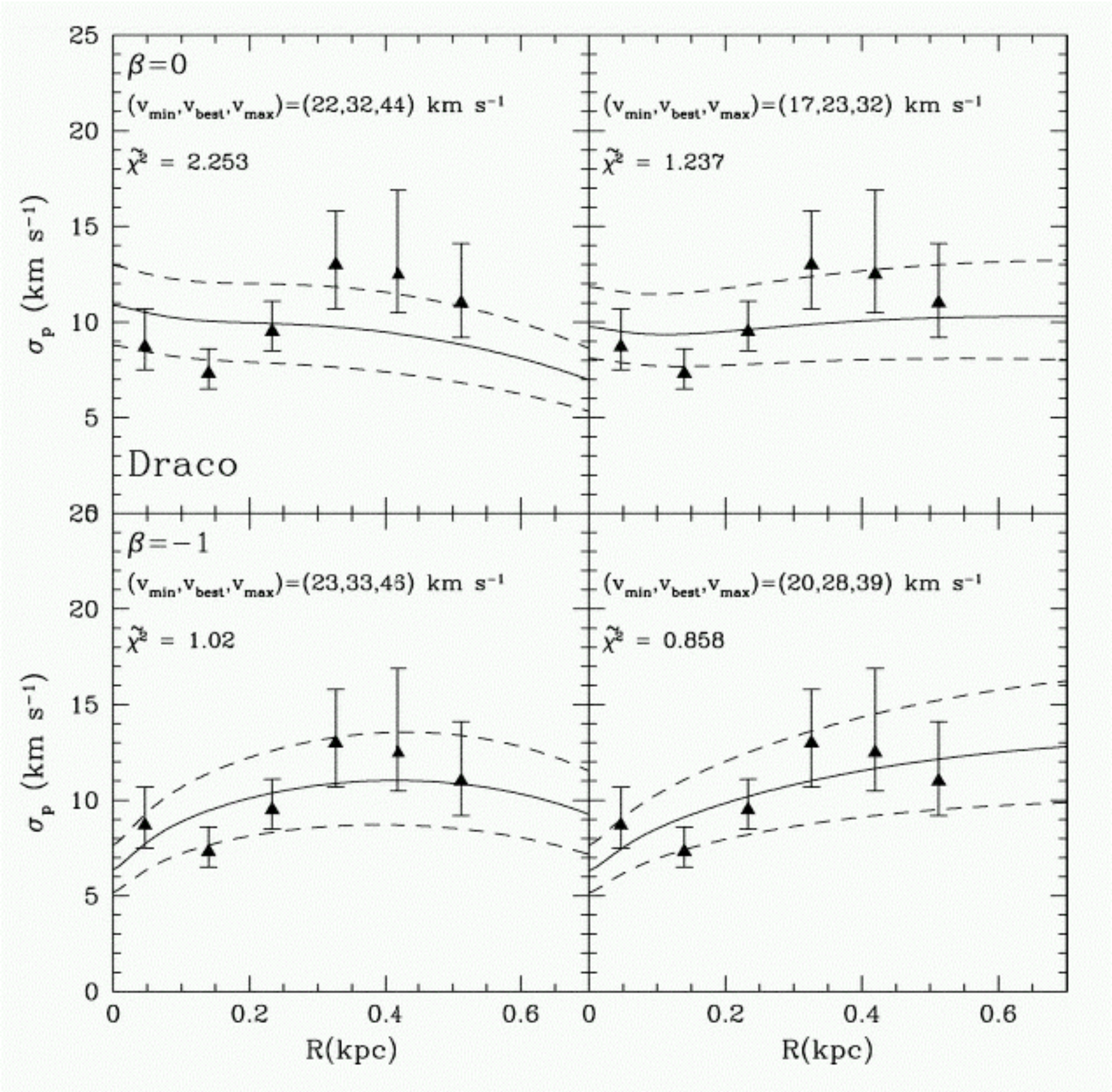
Mayer et al. 2000,
2001a,2001b,
2002, 2003, 2005

The masses of dwarf spheroidals

They live in fairly big halos, Vmax > 20 km/s today, Vmax > 30 km/s, or M > 10^9 Mo, before tidal stripping

(Kravtsov et al. 2004)

Kazantzidis, Mayer et al. 2004



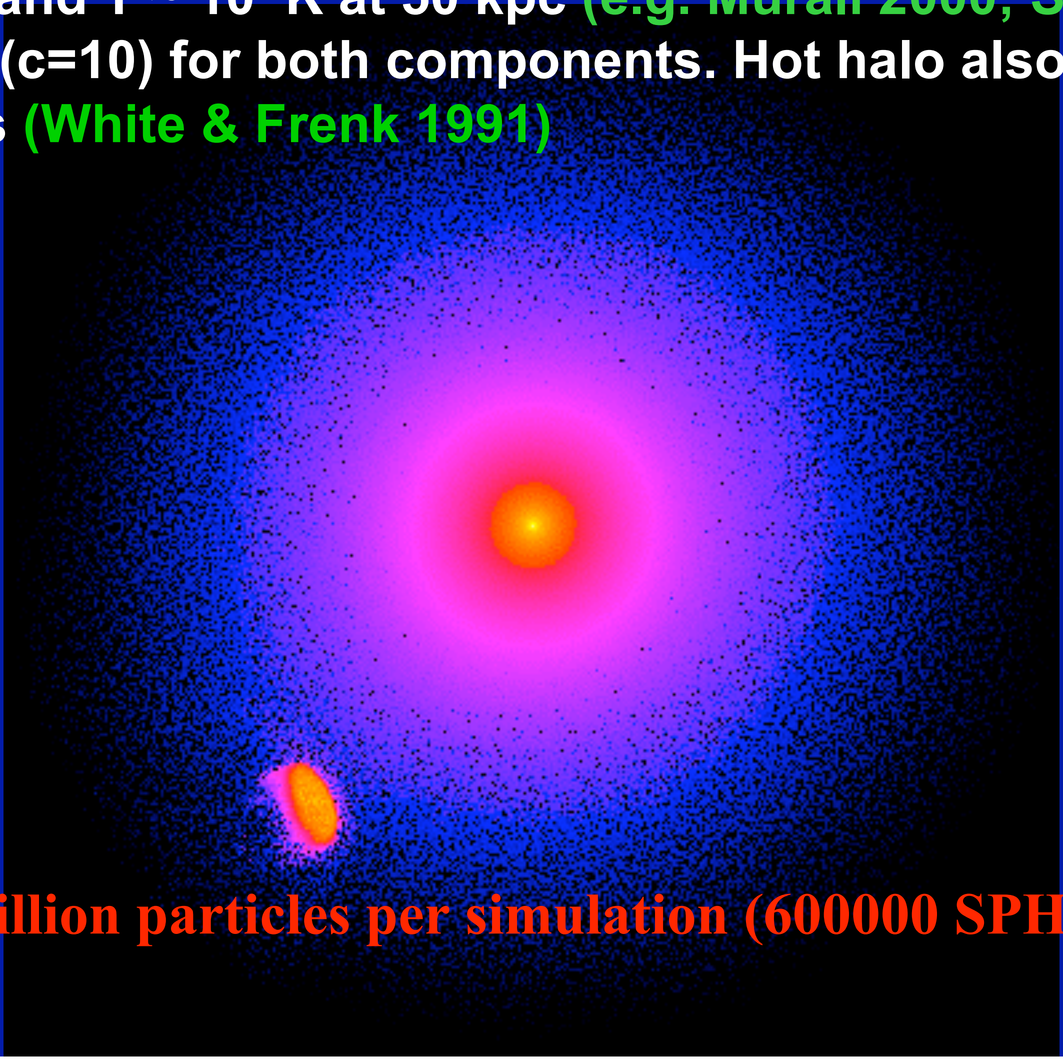
Fitting observed Kinematics in NFW subhaloes using Jeans equation

also Lokas 2004 and Wilkinson et al. 2005

Tides + Ram Pressure Stripping

(Mayer & Wadsley 2003, Mayer et al. 2005)

-Primary system: dark + hot gaseous MW-sized halo, ρ(gas) ~ 2-8 x 10^{-5} atoms/cm^3 and T ~ 10^6K at 50 kpc (e.g. Murali 2000; Sembach et al. 2003). NFW profile (c=10) for both components. Hot halo also prediction of CDM models (White & Frenk 1991)



Ntotal ~ 2 million particles per simulation (600000 SPH particles)

Tides + Ram Pressure Stripping

(Mayer & Wadsley 2003, Mayer et al. 2005)

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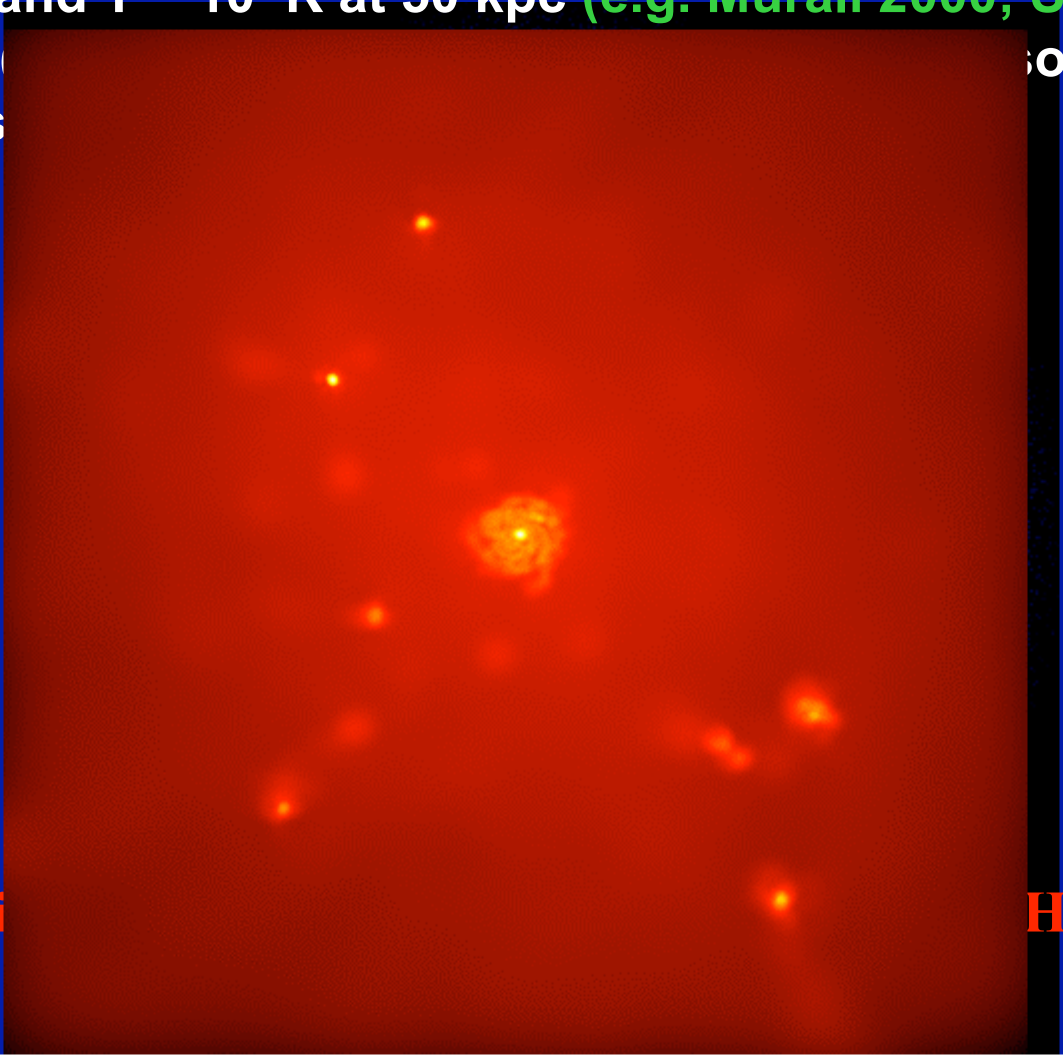
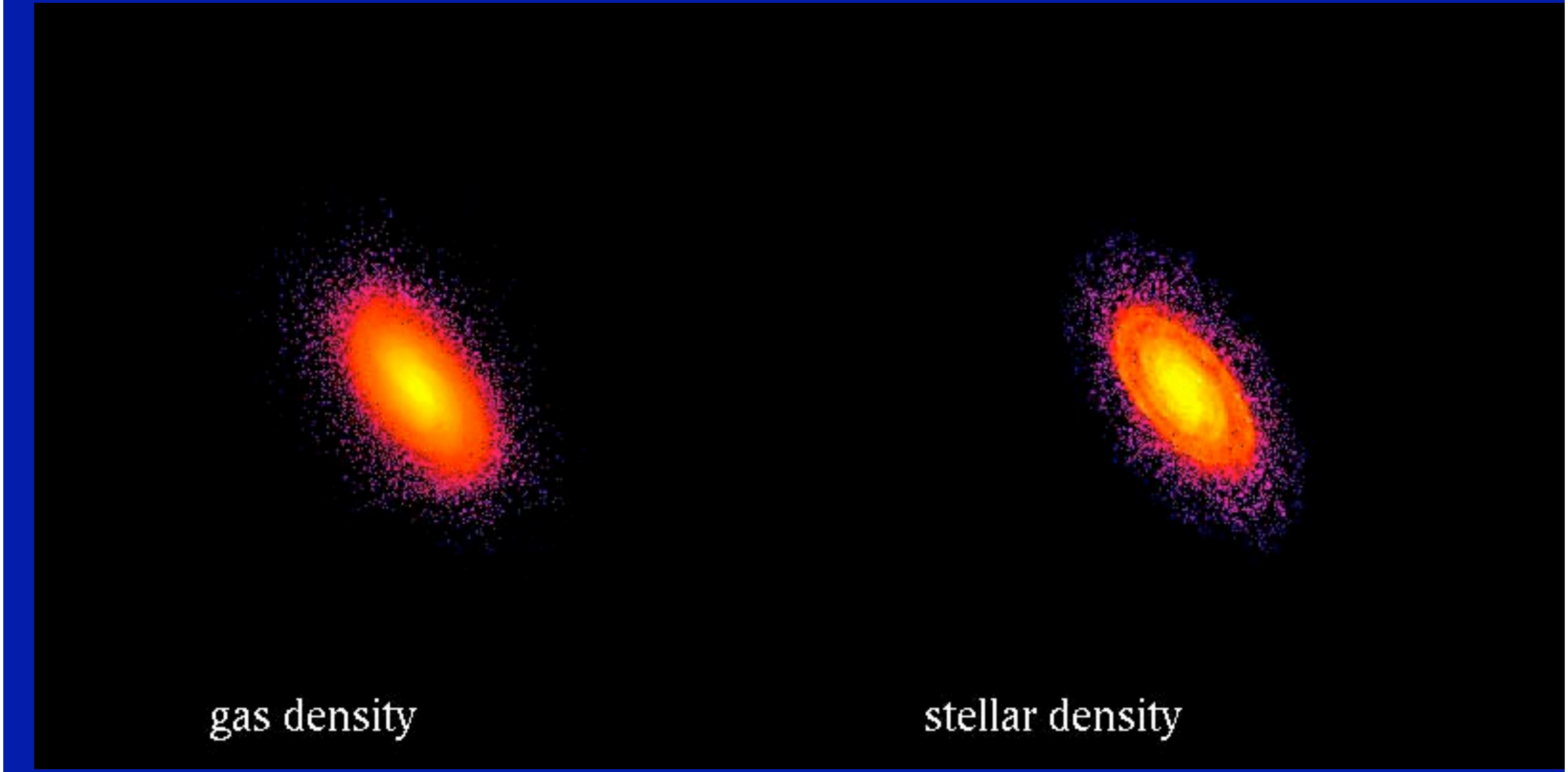
CDM models



Ntotal ~ 2 mi

H particles)

A “big dwarf”’ – Vpeak= 60 km/s, c=5 (M/L~ 30)
Apocenter = 250 kpc
Pericenter= 50 kpc



Tides induce bar/buckling instabilities Turn disk into spheroidal

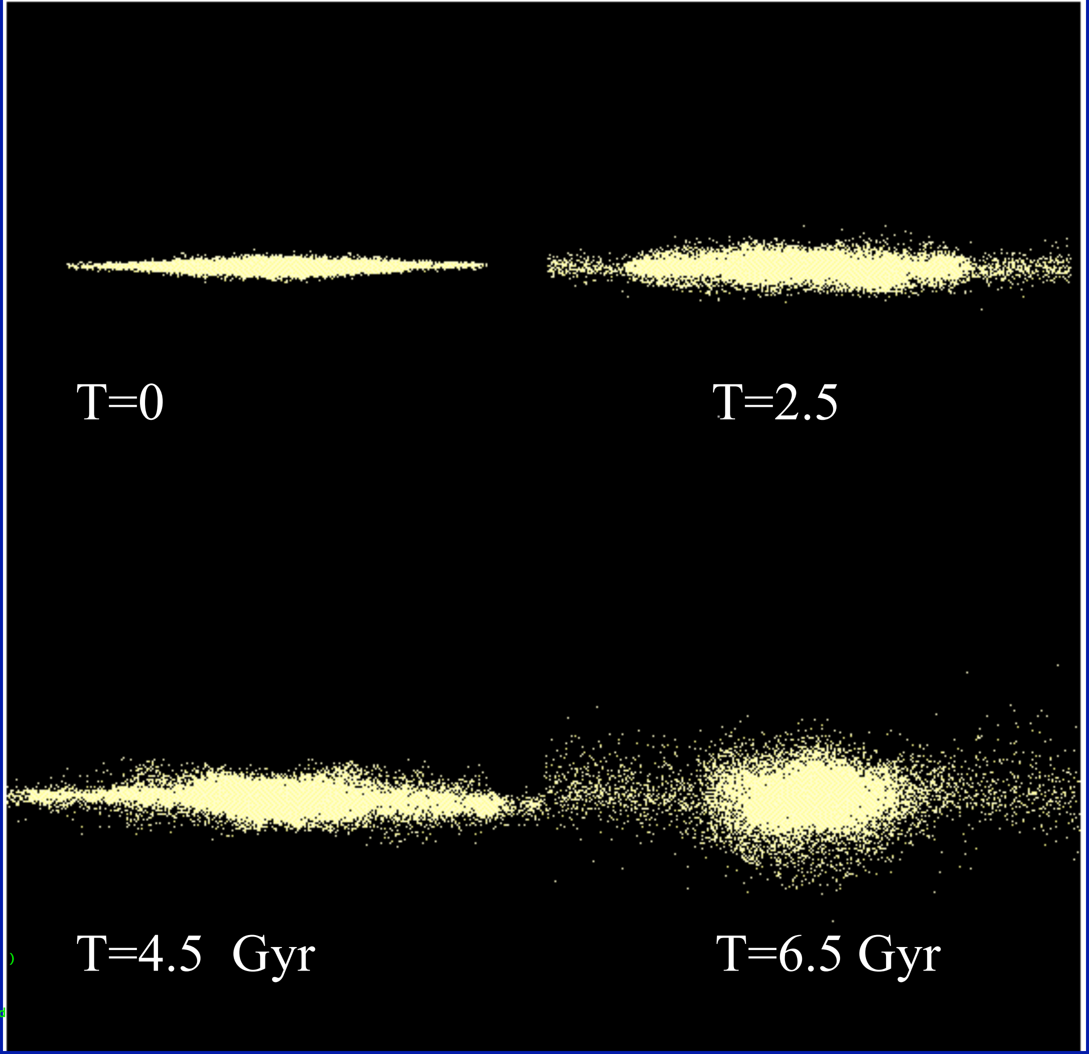
LSB disk

apo/peri = 5

Apo= 250 kpc

Peri= 50 kpc

Star particles shown



10 x 10 kpc

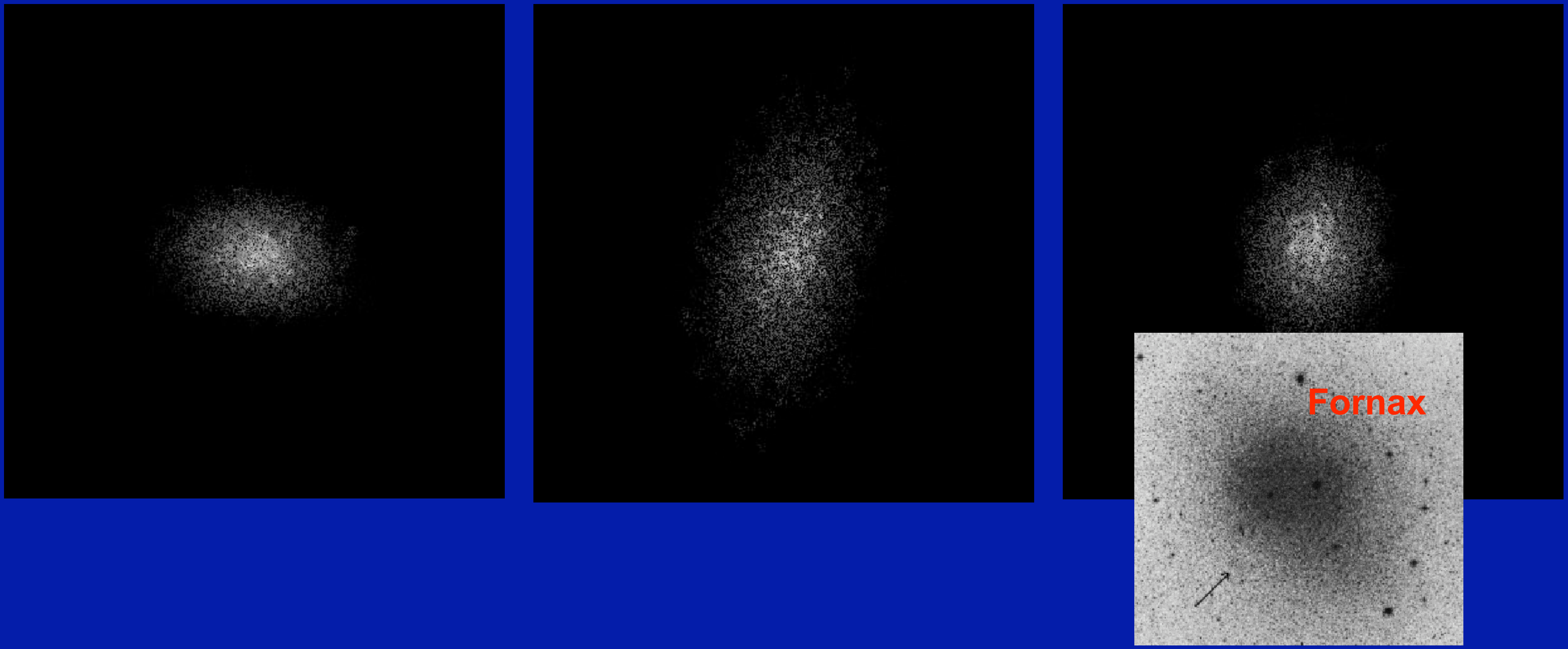
Mayer et al. 2001a,b
Mayer et al. 2002

See also
Raha et al. (1991)
Merritt & Sellwood
(1994), Combes
et al. (1990)

EVEN DWARFS WITH MASSIVE HALOS TRANSMUTE

Initial Vpeak=35 km/s (initial M/L=200) c=16 NFW HALO, shown is morphology after 10 Gyr (~5 orbits, Rperi=25 kpc, Rapo=120 kpc). Final (M/L)e ~ 40 (for a stellar M/L~ 3).
Only 10% of the stellar mass stripped but tidally induced instabilities effective!

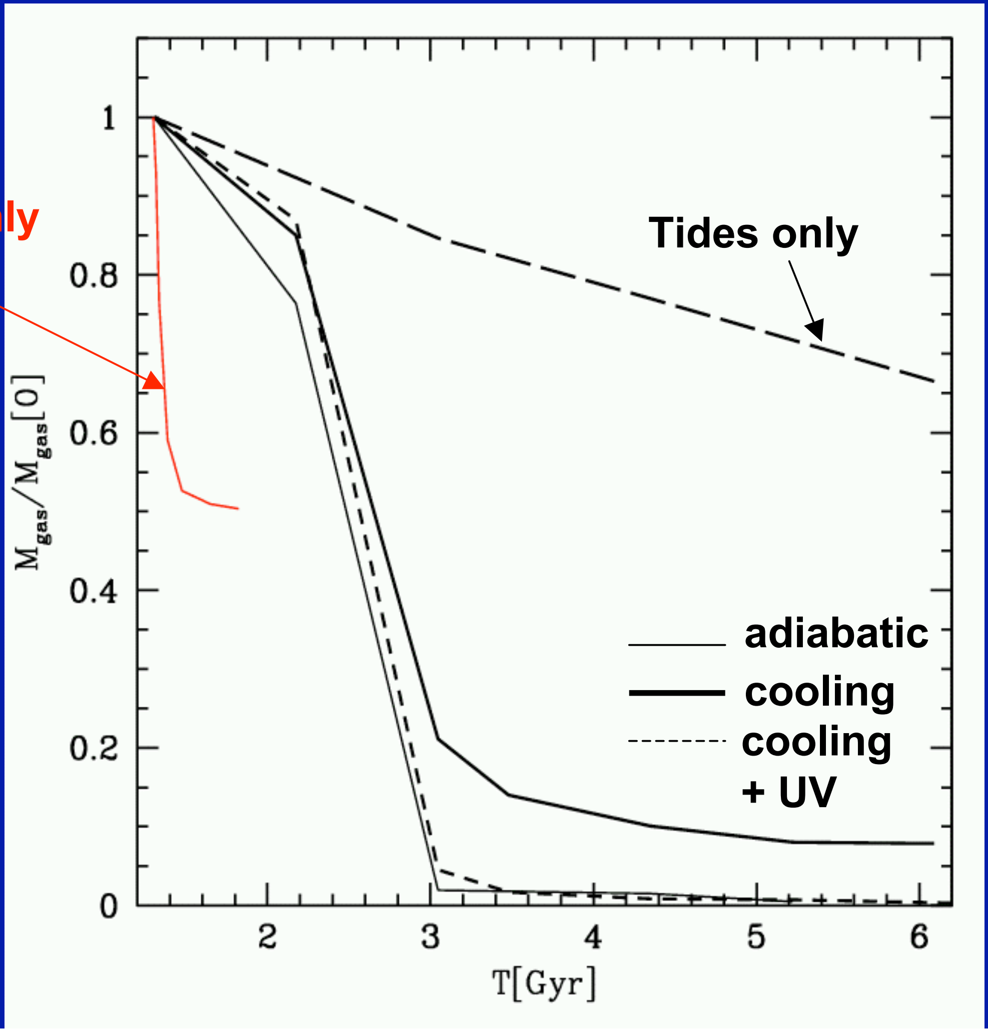
3 kpc field, limiting surface brightness ~ 27 mag arcsec^{-2} (B band)



Gas mass loss: tides + ram pressure

- Ram pressure produces higher mass loss relative to tides.
- Stripping with tides + ram pressure higher relative to ram pressure only since potential well of the dwarf is substantially weakened (Vpeak drops)

Initial Vpeak = 40 km/s, Vpeak=30 km/s after 4 Gyr



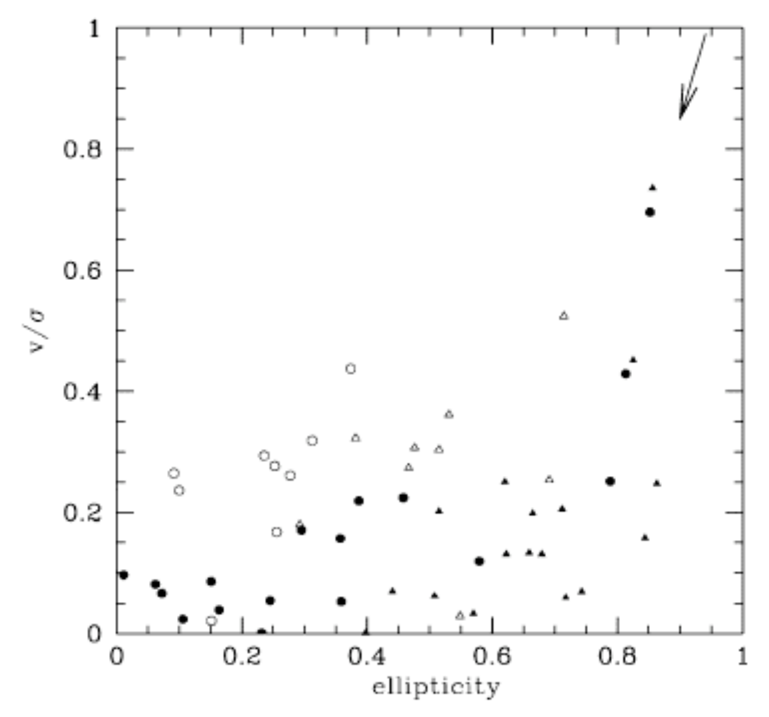
Ram pressure only

ORBIT:
Apo=150 kpc
Peri=30 kpc

"standard" cosmic UV bg (Haardt & Madau 1999) for dwarf falling into MW halo at z ~ 3

Mayer et al. 2005

V/σ after 8 Gyr



Within R = Re

Mayer et al. 2001a

Remnants are moderately triaxial
Different symbols refer to line of sights along different axes
Filled Symbols=LSB disks, > 23 mag arcsec $^{-2}$
Open Symbols=HSB disks, < 23 mag arcsec $^{-2}$

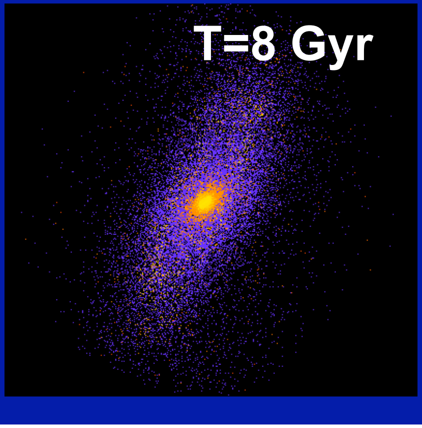
**Loss of angular momentum due to bar instability (vt↓) +
heating by tides/buckling (σ↑)**

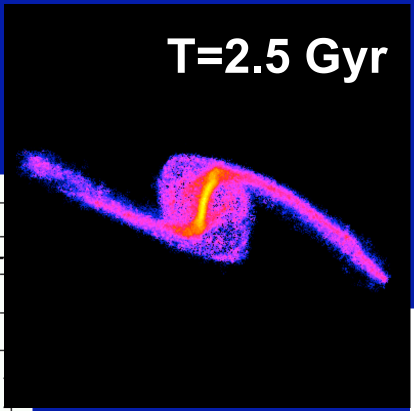
**Tidal stirring produces pressures supported
remnants resembling dSphs**

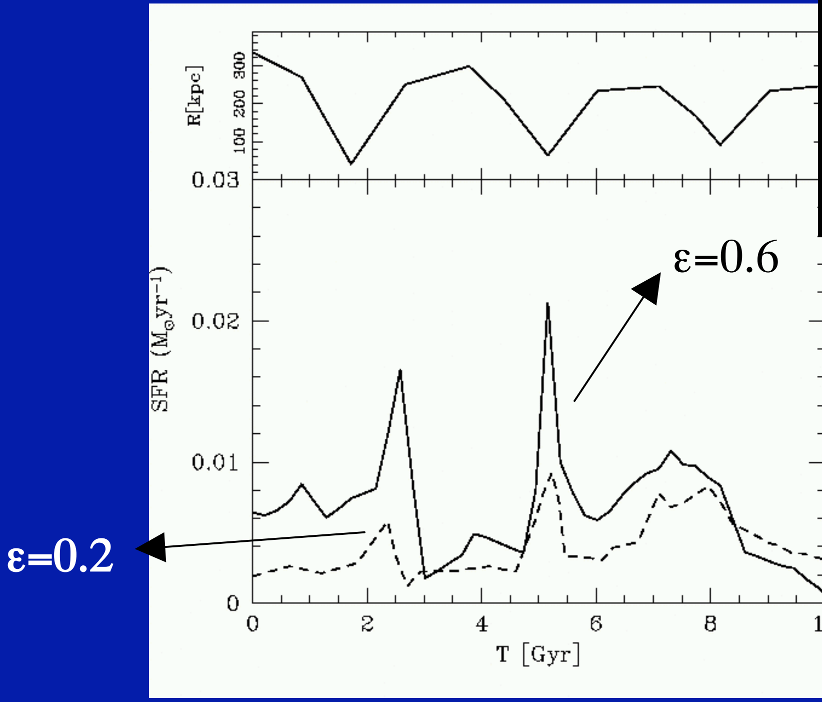
SPH runs with radiative cooling:

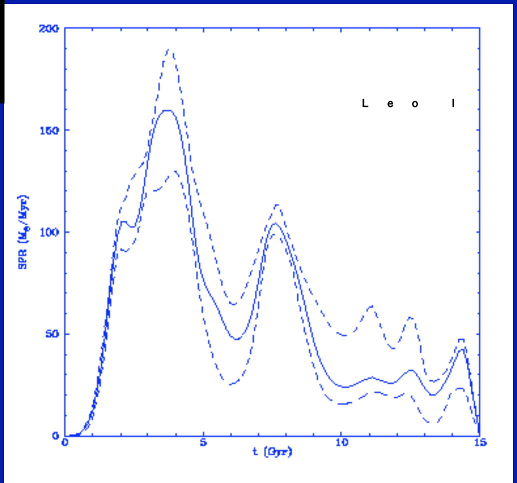
The star formation history of LSB satellites

$\Sigma_* = \varepsilon \, (\Sigma_{gas}/t_{dyn})$ (Kennicutt 1998)





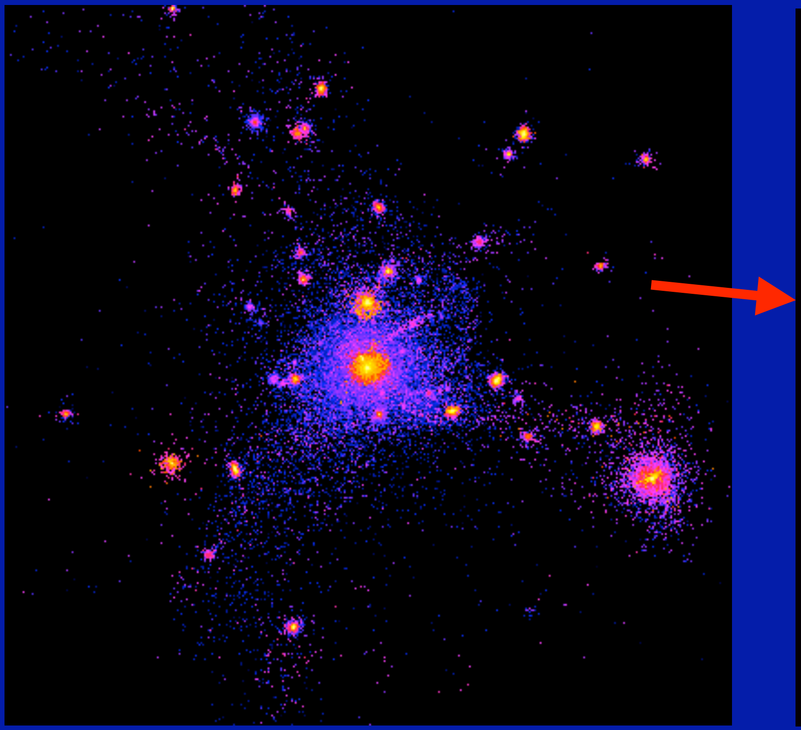


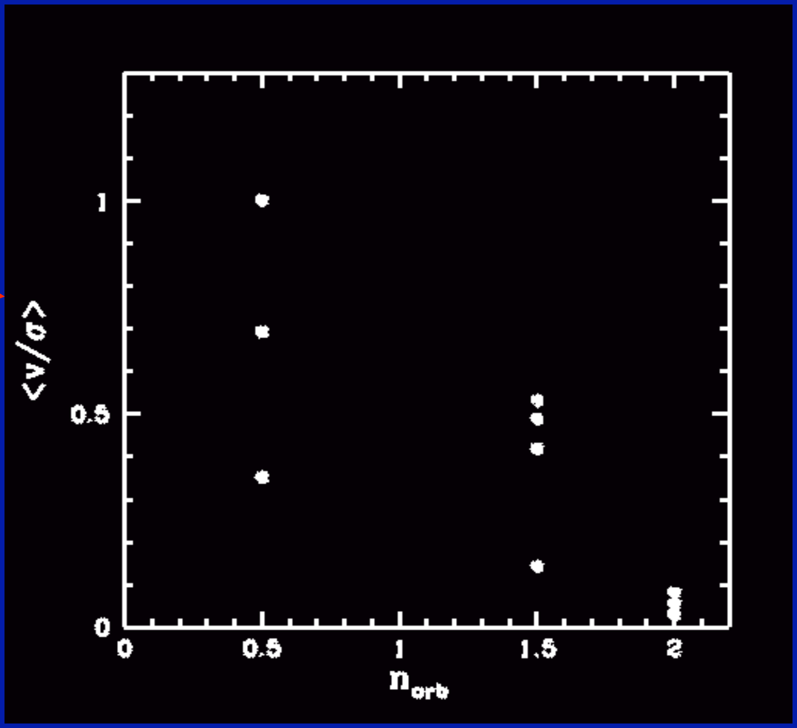


From Hernandez et al. (2000)

Star formation is periodic: gas inflow in the bar and tidal compression produce enhanced SF at pericenters.

What about “decently” resolved satellites (Npart > 1000) in our hi-res LCDM simulations?





Strong correlation between kinematics of the stellar compon

the dwarfs and the number orbits.

Most satellites within 200 kpc from the primary completed m

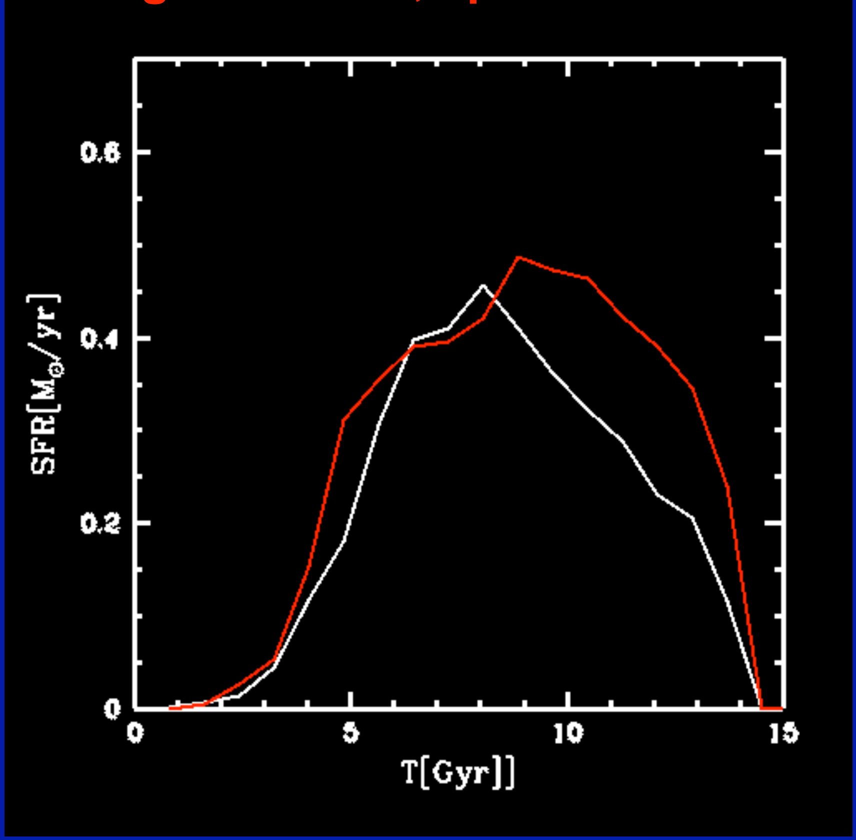
than one orbit and have $v/\sigma << 1$ like dSphs.

Orbital time is the key parameter governing *Tidal Stirring*

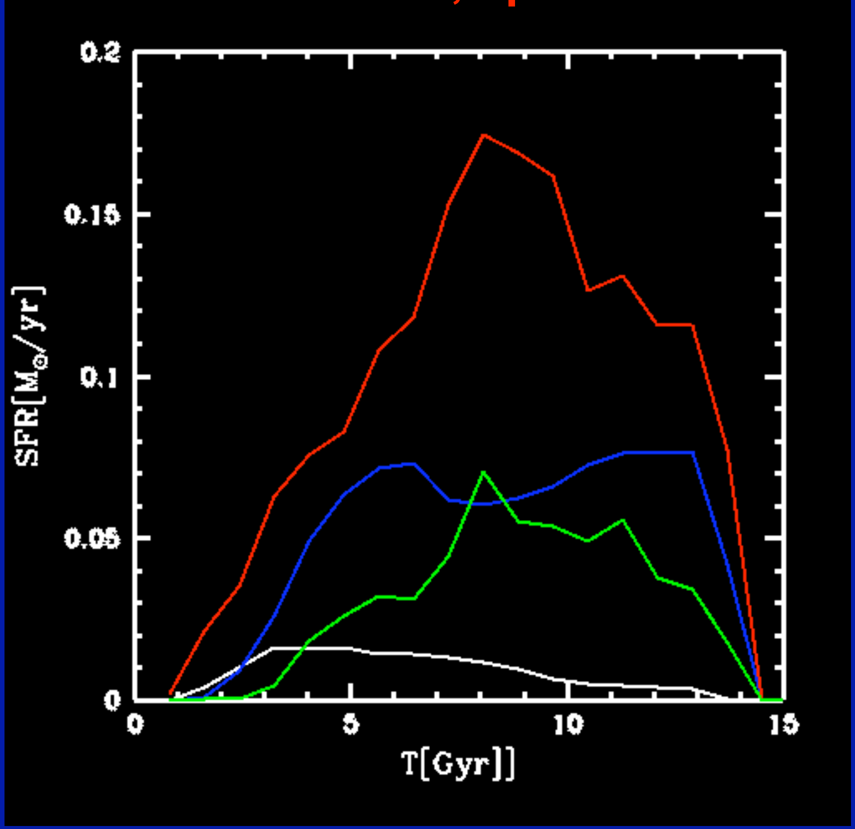
(Mayer et al. 2001b).

Star formation histories of satellites

"Big satellites", vpeak=65-75 km/s



"Small satellites", vpeak=30-45 km/s



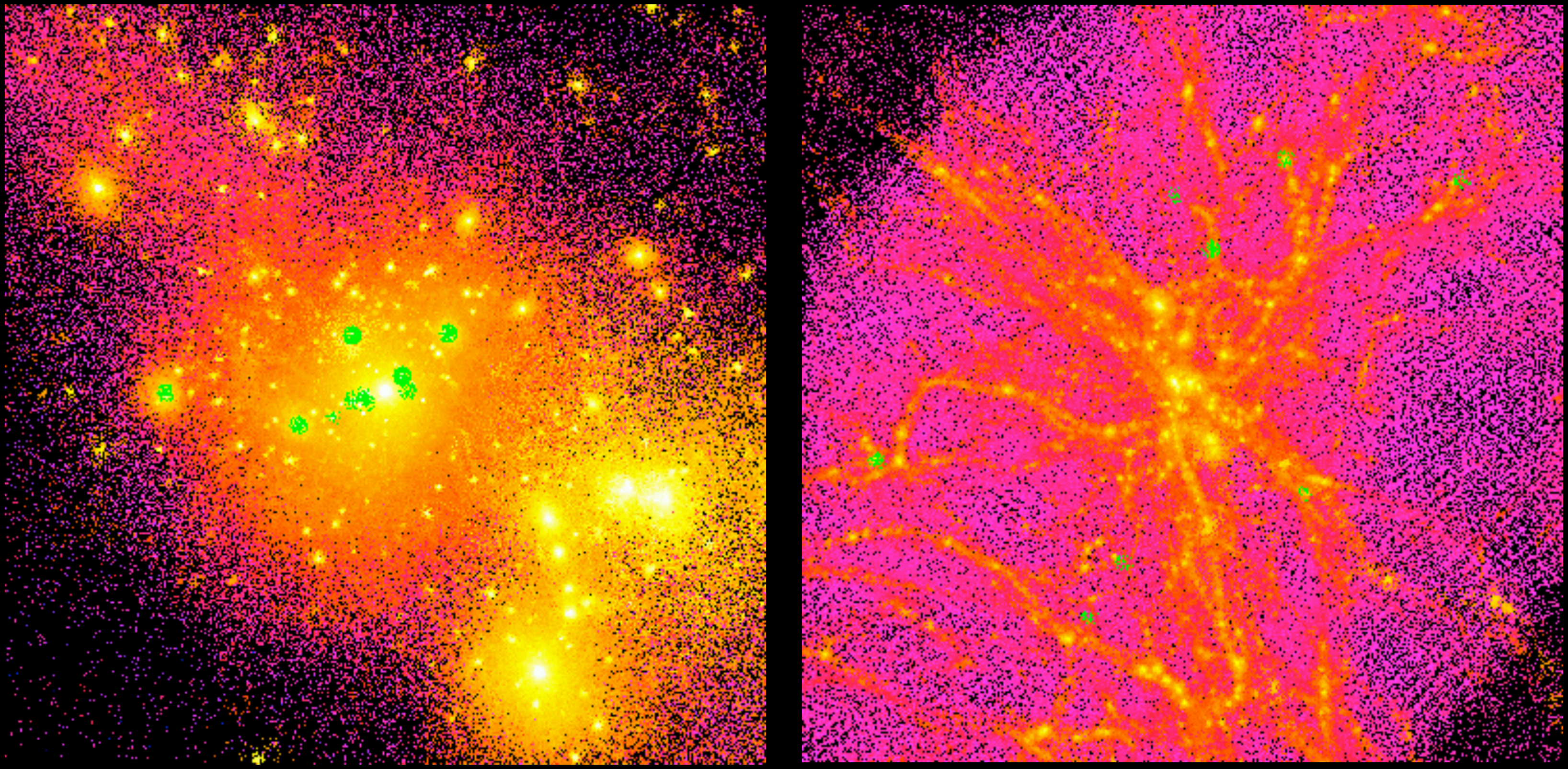
- Bulk of star formation occurs *after* reionization, between z=3 and z=1

- Wide variety of star formation histories is seen; more extended star formation histories for bigger satellites and satellites with longer orbital times

- Peaks of star formation *sometimes* correlated with pericenter passages

Where do the z=0 galaxy satellites come from?

Mayer et al., in prep.



500 kpc box z=0

50 kpc box z=6

Present-day satellites come from regions that were mildly overdense (~1.5 σ peaks) at z=6. They were just starting to collapse.

The highest (> 3.5 σ) peaks at z > 6 merged and formed the bulge, stellar halo and maybe the GC system (see also Diemand, Madau & Moore 2005)

CONCLUSIONS

(1) Disk galaxy fomation in LCDM models is in now in a good shape

-Angular momentum catastrophe disappears at high resolution – realistic disk forms

-Supernovae feedback (without superwinds) decouples the history of baryons from the history of their halos enough to reproduce observations

(2) The substructure problem Is solvable (and is nearly solved) again thanks to the decoupling of baryons from their halos due to feedback + reionization

(3) Present-day dwarf galaxy satellites collapsed between z=7 and z=5, form the bulk of their stars after reionization, so they are not a good tracer of reionization

-Their halos are fairly massive, $M > 10^9$ Mo today and even larger before tidal mass loss within the MW/M31 halos. This is why they were not affected by reionization (see also Bullock et al. 2000 and Kravtsov et al. 2004)

-their progenitors were disky dwarfs like dIrrs that were tidally stirred into spheroidals. This explains the morphology-density relation.

-their present-day low gas fractions result from ram pressure + tidal stripping