Morphological transformations in clusters and groups: the origin of early-type dwarfs

Lucio Mayer

University of Zurich

Collaborators

Stelios Kazantzidis (Ohio State Uni
Chiara Mastropietro (CEA-Saclay)
Robert Feldmann (Fermilab)
Simone Callegari (U. Zurich)
Ewa Lokas (Copernicus Center)
Victor Debattista (UCLAN)
Thomas Quinn (U.Washington)
Fabio Governato (U. Washington)
Ben Moore (U. Zurich)
James Wadsley (Mc Master U.)
Juerg Diemand (U.Zurich)

Early-type dwarfs and dense environments

-Morphology-density relation. Early-type galaxies (E, S0s, dEs, dSphs, dS0s) dominate in cluster cores Lisker et al. 2006;2007; Wilman et al. 2008). For low mass galaxies (e.g dwarfs) morphological segregation evident in all nearby groups (e.g Local Group) Karachentsev et al. 2005;2006)
dEs located closer to disks than to Es/SOs in scaling relations (Ferguson & Binggeli 1994; Kormendy 1985;2009; but see Misgeld et al. 2008;2009)
Early-type dwarfs with disky features discovered in clusters (Barazza et al. 2003; Lisker et al. 2007) --→ *transitional class reflecting morphological transformation in action?*

-Faint end of the luminosity function (down to Mb=-10) steeper than in the field (SDSS + LG and nearby groups) for nearby clusters (e.g. Virgo, Coma, Hydra, Fornax) (Trentham et al. 2005; Sabatini et al. 2003, 2005; Milne et al. 2006; Misgeld et al. 2008;2009)

-Clusters (especially cores) have the highest dwarf-to-giant ratios among all known environments. Excess of dwarfs due to red, early type dwarfs, dEs and dS0s (Ferguson & Sandage 1988; Yamamani et al. 2007).
Dwarf-to-giant ratio decreases out to z ~ 0.5

-Mean star formation (SF) rate different in different environments – SF truncation in clusters and groups (Balogh et al. 2004; Christlein & Zabludoff 2005; Poggianti et al. 2006;2008; Peng et al. 2010 w/ zCOSMOs +SDSS for non-central galaxies) + correlation between specific SF rate and HI deficiency (see Gavazzi's talk yesterday, Hα^3 survey)

ORIGIN OF EARLY TYPE DWARFS: OUTLINE

(1) Tidally induced transformation of low disk mass galaxies – origin of the cluster/group population of early type dwarfs (dEs, dSphs, UCDs)

(2) The ICM-galaxy interaction – gas removal from ram pressure

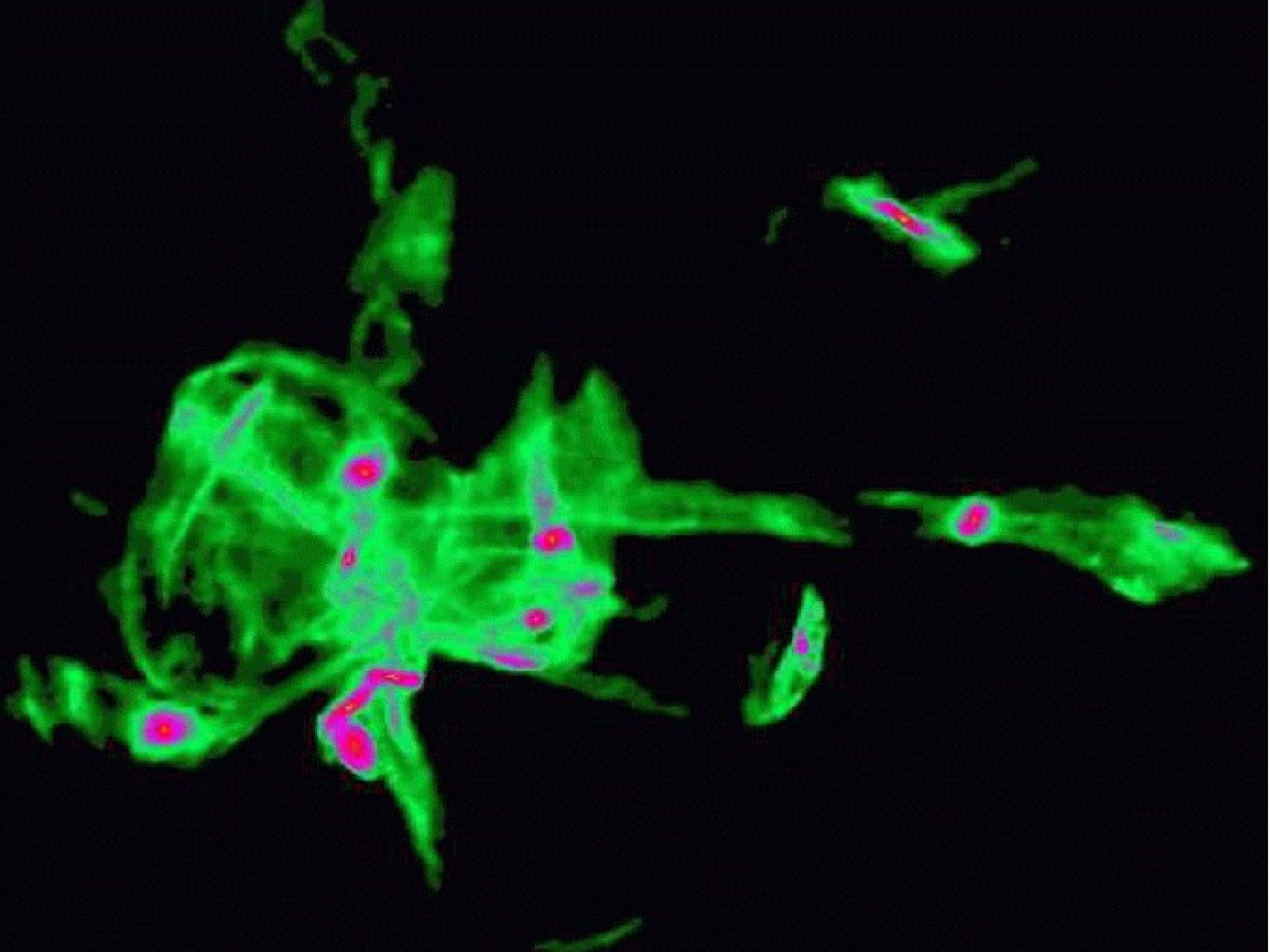
- Cluster cores: high ICM densities, high velocities

- Cluster outskirts/groups: low ICM densities, low velocities

TOOL: TAILORED SIMULATIONS OF GALAXY INTERACTIONS

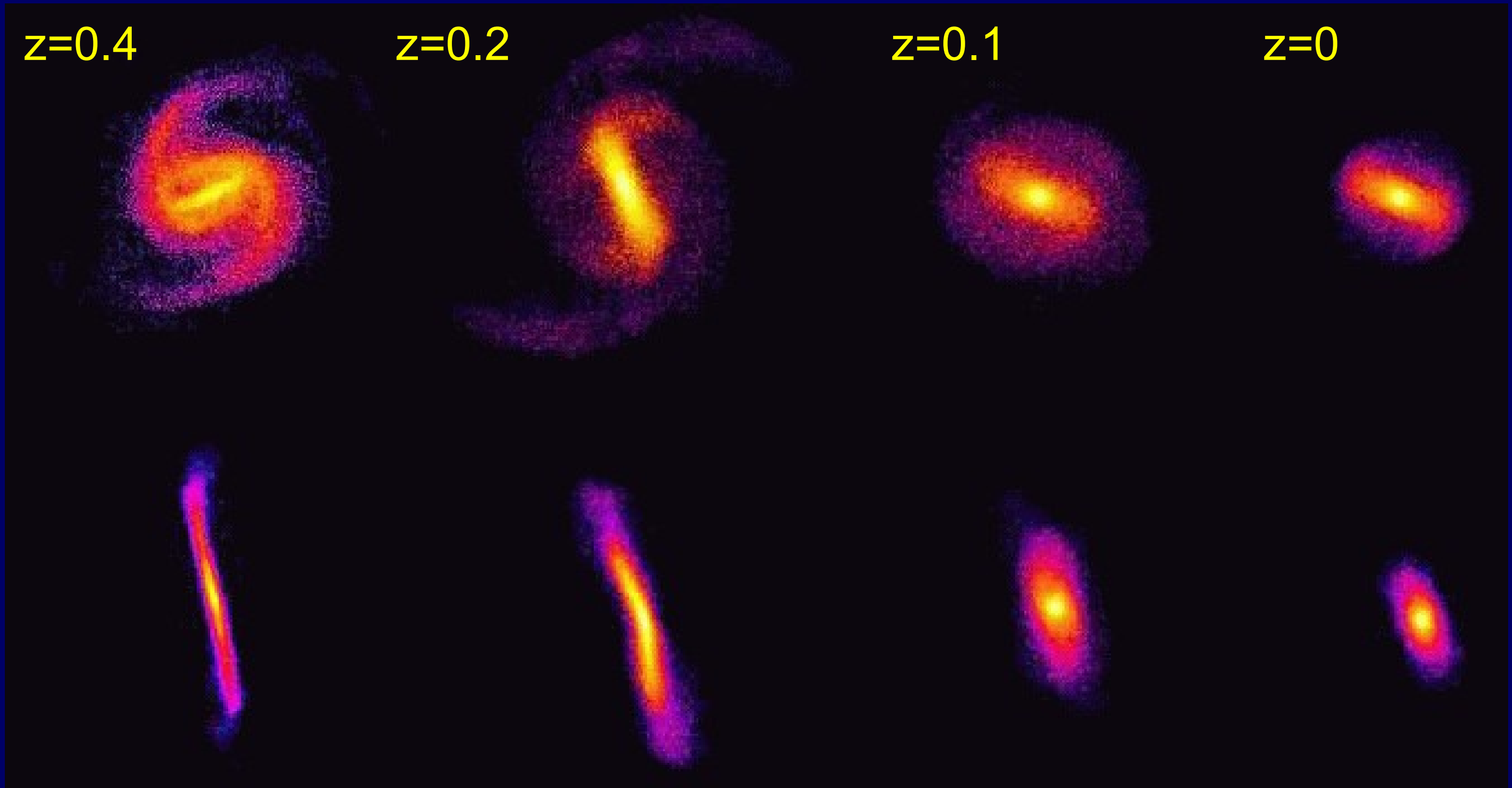
(3) Morphological transformation of a representative (small) galaxy population

TOOL: COSMOLOGICAL HYDRODYNAMICAL SIMULATIONS



Harassment (repeated fast tidal encounters with massive galaxies – Moore et al. 1996;1998) + tidal stirring (repeated tidal shocks during pericenter passages in cluster/ group core - Mayer et al. 2001,2007; Gnedin 2003) turn late-type spirals into low luminosity spheroidals

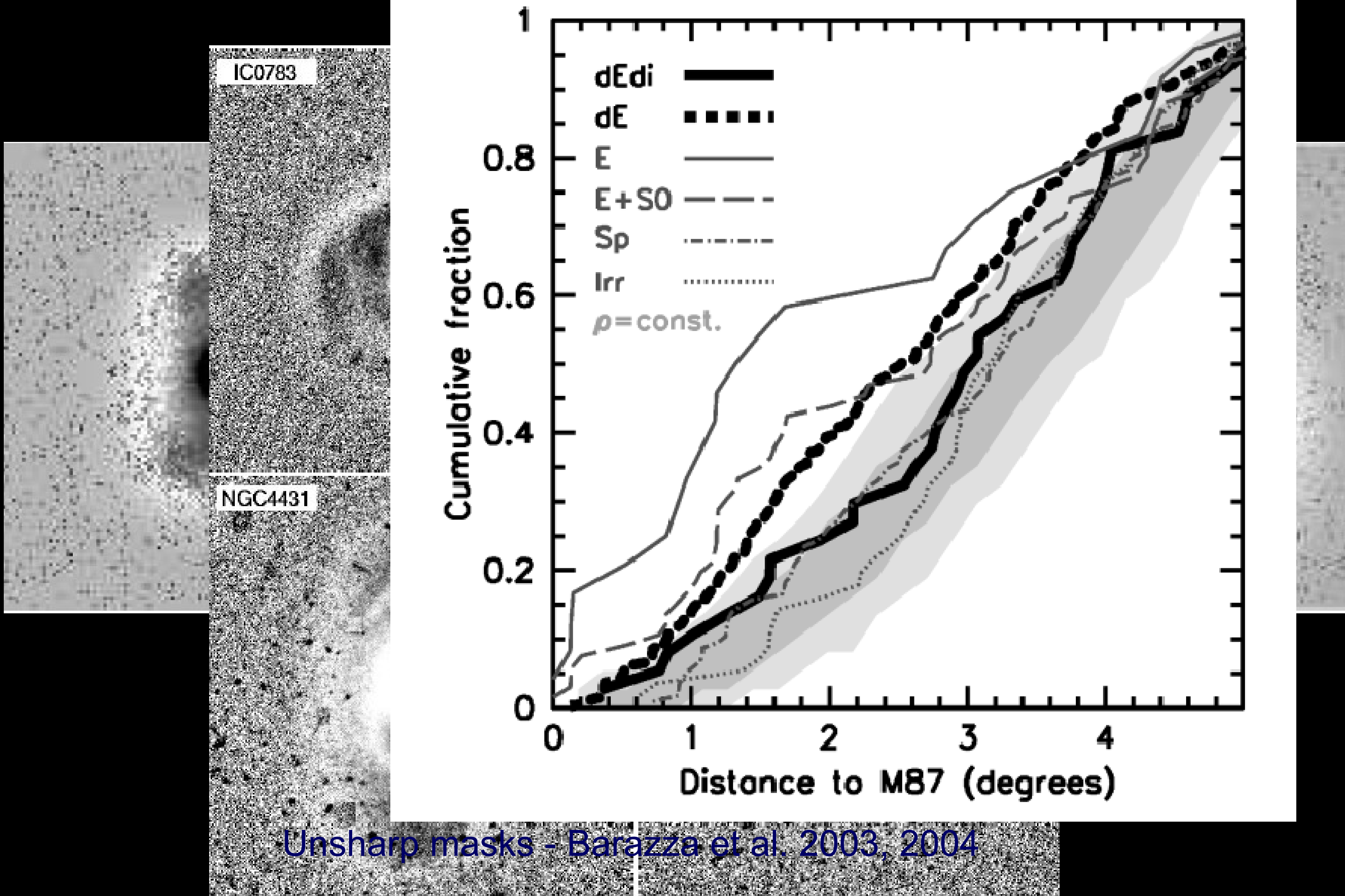
Tidal heating/stripping + bar/buckling instabilities increase σ, reduce J



Transformation takes a few orbits ~ a few Gyr after infall into cluster

How “complete” the transformation will be after several Gyr in the cluster depends on pericenter/orbital time and density profile of galaxy

Prediction: late-type population falling into clusters at z < 1
evolves into dE ... als

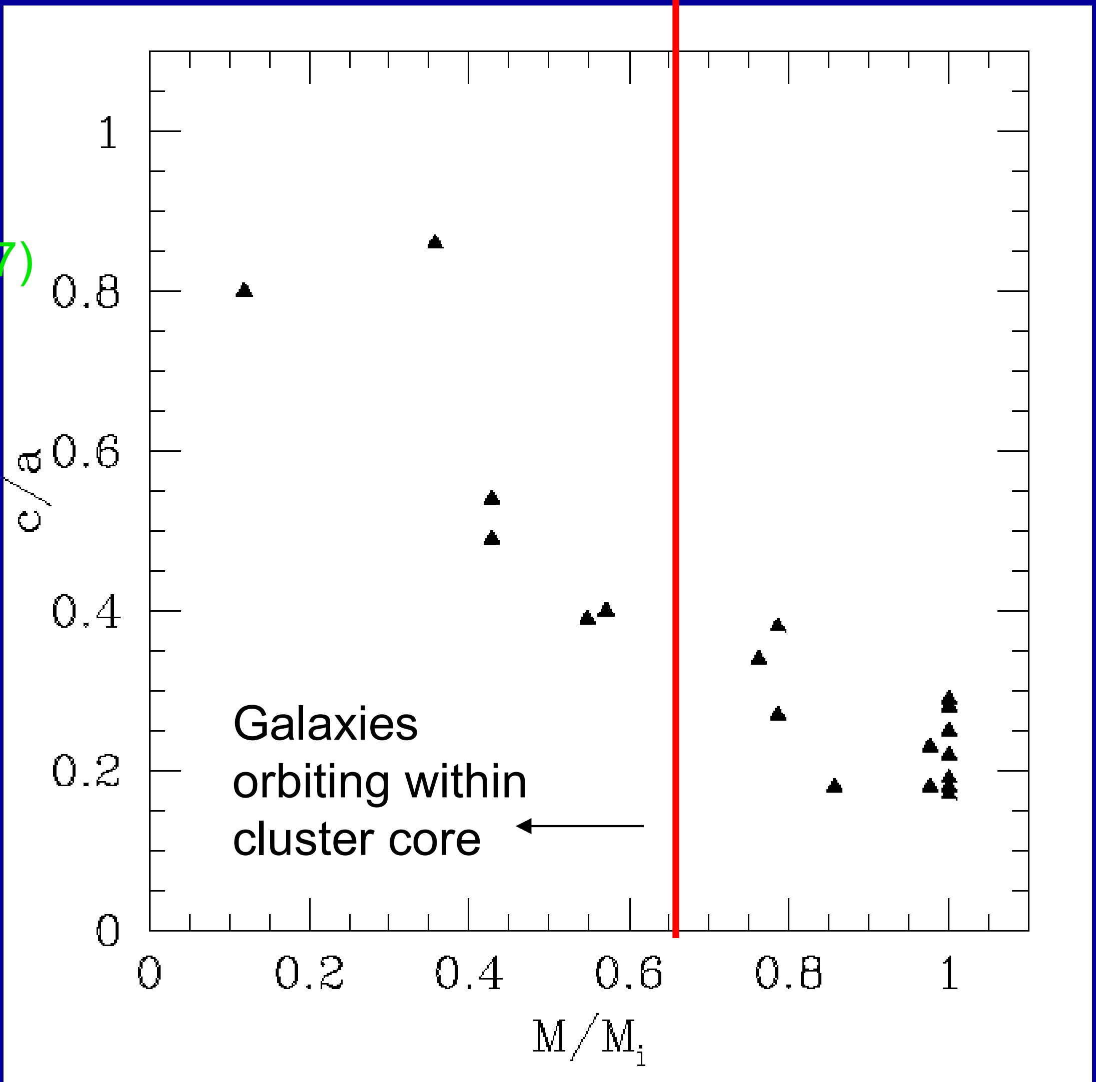


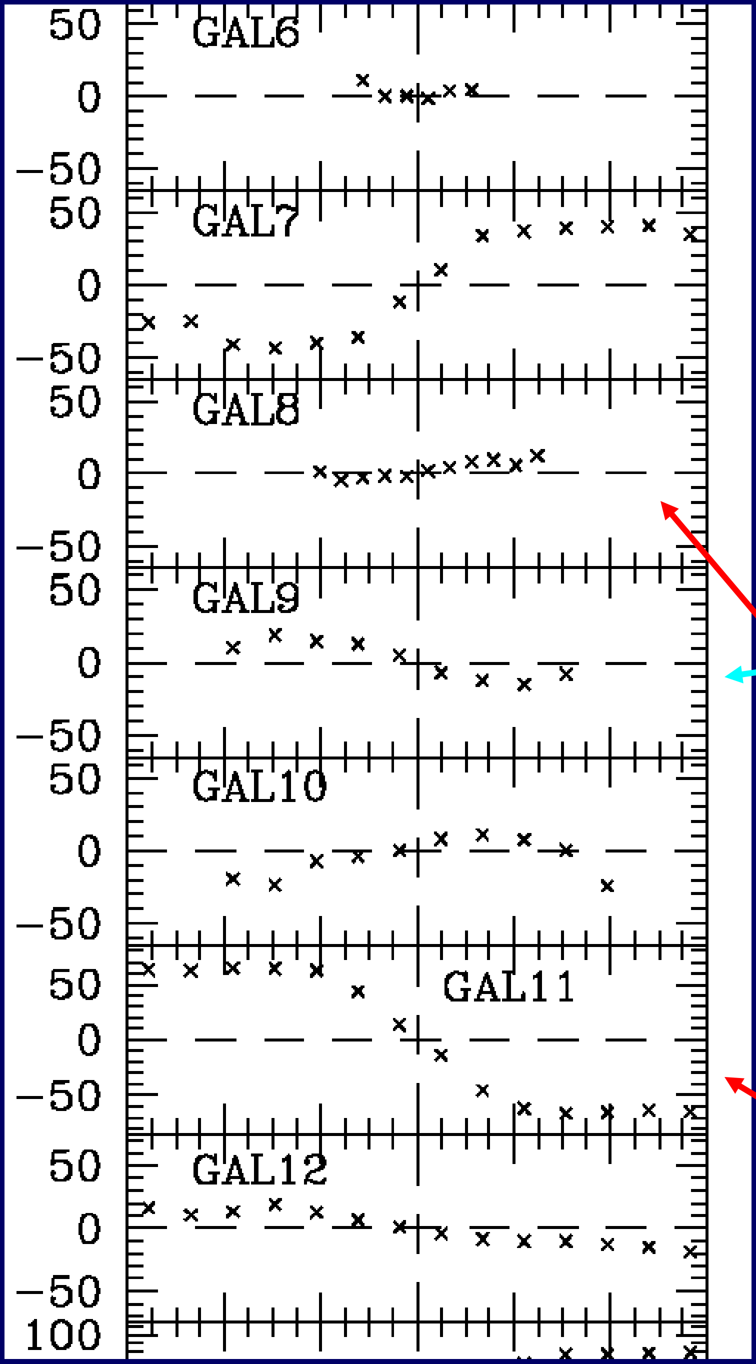
Morphology-density relation in Virgo (Lisker et al. 2007)

Unsharp masks - Barazza et al. 2003, 2004

(1)Galaxies lose up to 90% of their mass, but none is completely destroyed. More mass loss for galaxies with orbits well within the cluster core, final luminosities down to Mb ~ -15.5 ----> higher dwarf-to-giant ratio in the core + increase of dwarf-to-giant ratio with time.

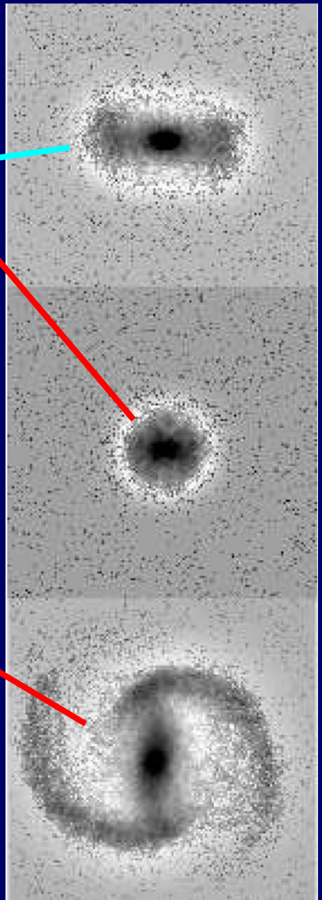
(2)Shorter orbital times, higher stellar mass loss <------→ more spheroidal remnant Prediction: dEs and dSphs faintest galaxies in clusters + transitional dwarfs brighter than dEs (e.g. Lisker et al. 2006;2007)





Transformation involves removal of angular momentum from the stellar component (induced by stellar bar + tidal torques)

Spheroidal-looking remnants completely supported by velocity dispersion as bone-fide dEs ($v/\sigma << 1$), those with disky features still rotate significantly



Importance of orbital eccentricity in tidal stirring

Kazantzidis et al. (2011); a large survey of parameters space using initial disky dwarfs models constructed with the Widrow & Dubinski method (very stable equilibrium ICs) with Vc ~ 20-40 km/s inside Milky-Way sized galaxies (→ Vc ~ 100-150 km/s in Virgo)

ICs:

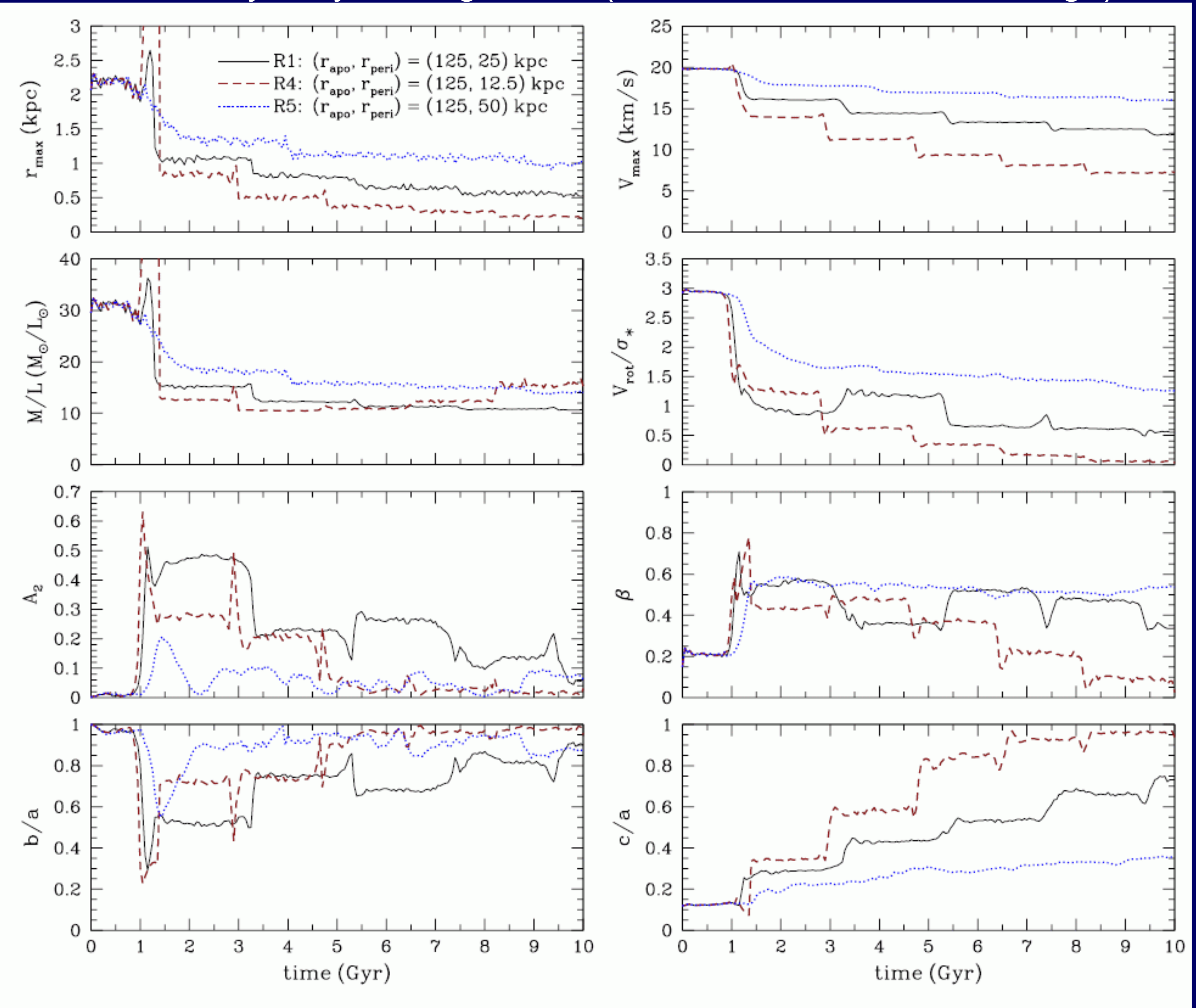
NFW halo c=20

M_{halo} = 10^9 Mo

Mstar = 0.01 Mhalo

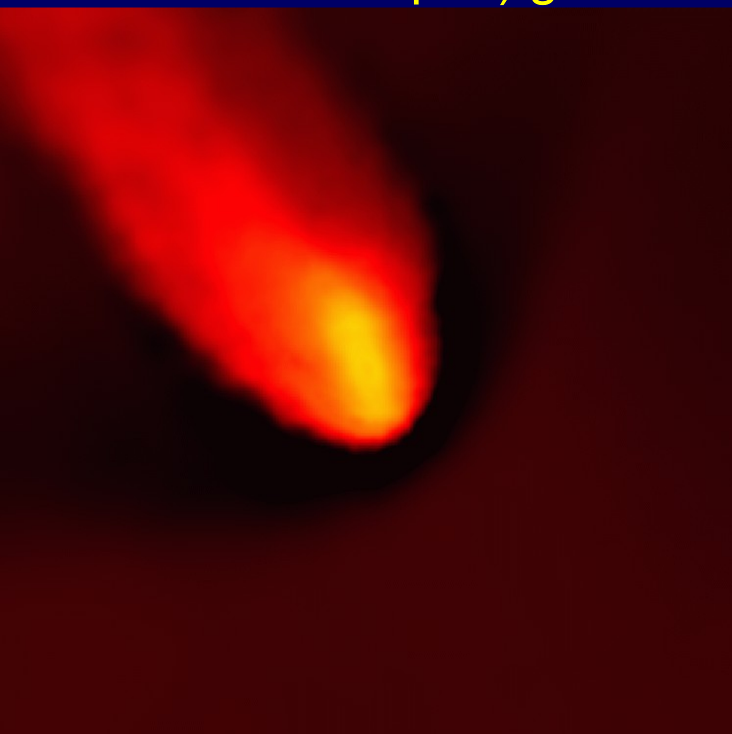
No gas in dwarf at at t=0

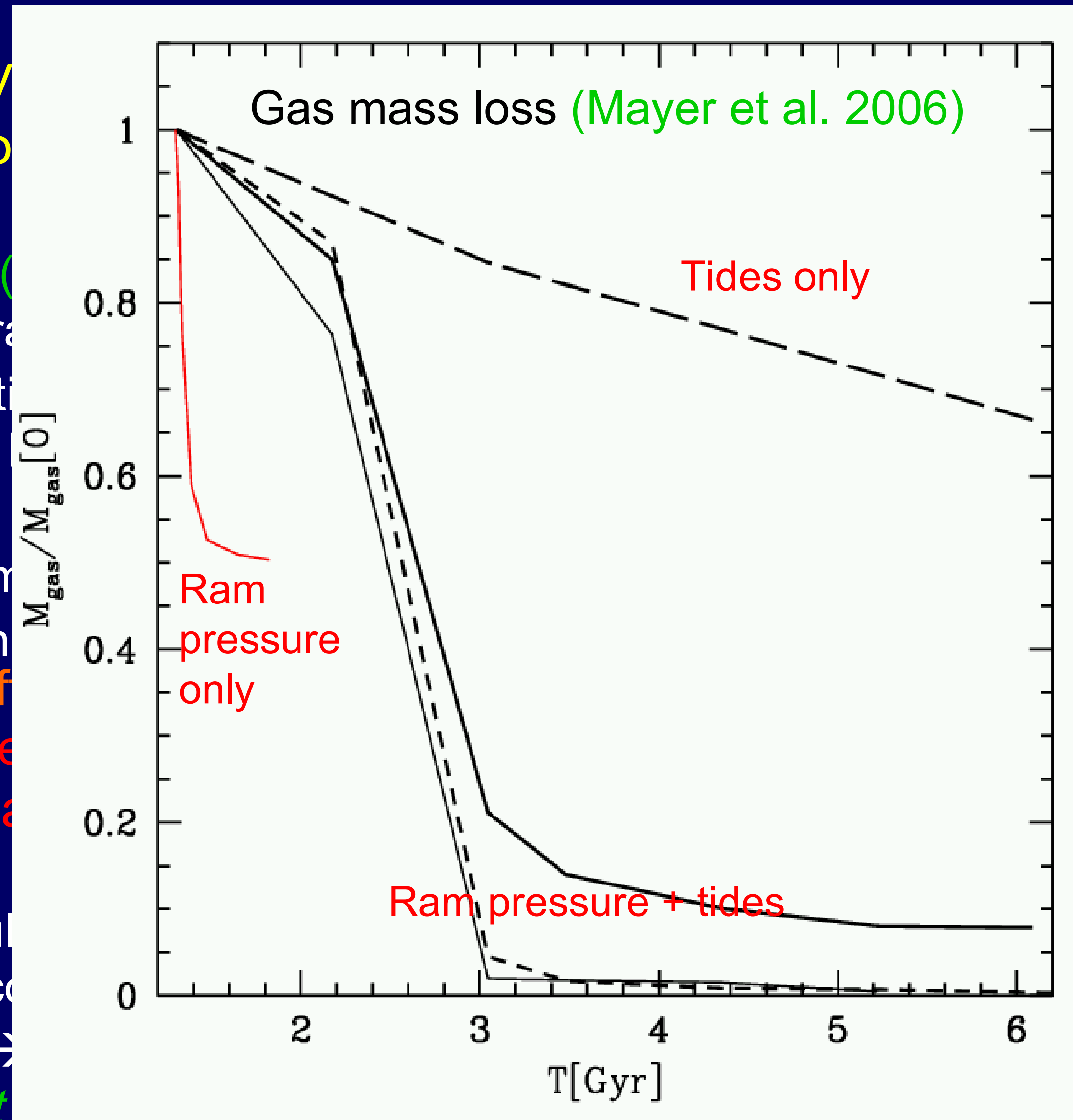
Live primary model disk +bulge+halo model of the (A2 model of the MW by Klypin et al. 2002)



Both harassment and tidal stirring cannot remove most of the gas (eg Mayer et al. 2006)

For low mass spirals/dIrrs (V
of dEs and dSphs) gas remo



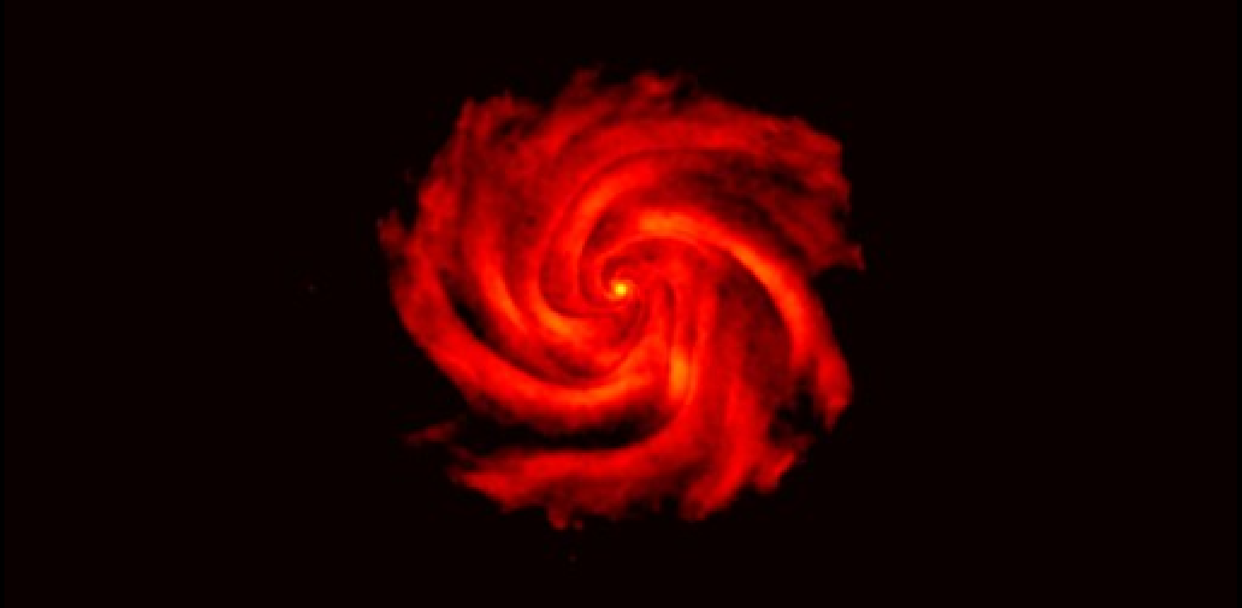


Rescaling from Local Group simul
~ 1-2 orbits sufficient to remove co
km/s even outside cluster cores-→
outside the cluster core (Lisker et
gas removal faster than morphological transformation of stellar component (see eg Boselli et al. 2008)

A tidal stirring + disruption scenario for UCDs in clusters (Goerdt et al. 2008 – see also Bekki et al. 2003)

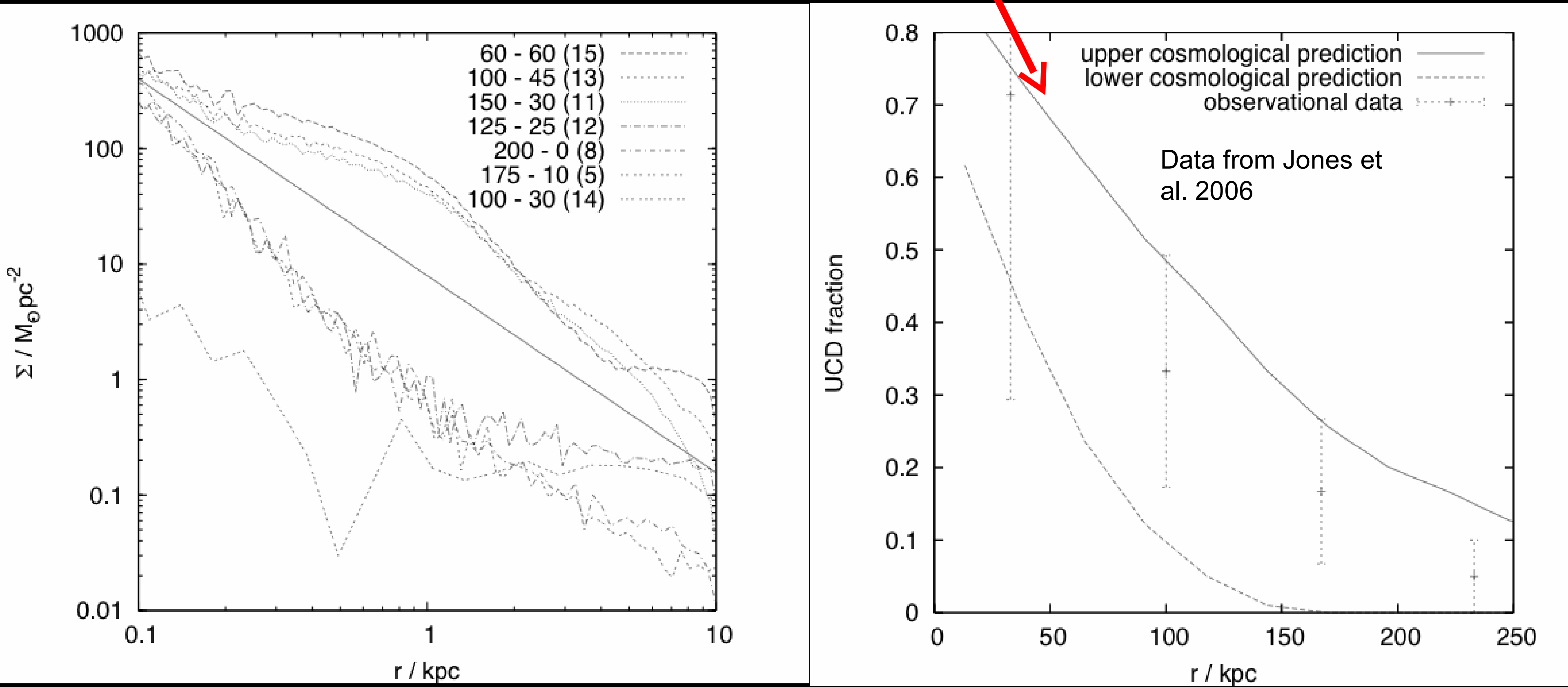
Tidal disruption of nucleated dwarf galaxies on the most eccentric among innermost cluster orbits (Rapo <= 200 kpc, Rperi <= 30 kpc in a Virgo-sized cluster- note no such orbits considered in Mastropietro et al. 2005)

A three-Step morphological evolution sequence:
Low luminosity nucleated Spiral -→ dE(N) -→ UCD



Initial condition: an M33-like galaxy (Vvir ~ 115 km/s, Mdisk ~ 10^{10} Mo, $M_{nucleus}$ ~ 10^7 Mo) evolved in static NFW cluster halo (Virgo-sized) with SPH (Gasoline) including cooling but no star formation/feedback

- Galaxy tidally destroyed, only the nucleus survives, including its dark matter → UCD wth M/L ~ 4-5 predicted
- If not tidally destroyed produces a nucleated dE (dE(N)).
- Predicted radial distribution of dE(N)s and UCDs from completely disrupted subhalos in cosmological simulation of Virgo-sized galaxy cluster



Above: UCD fraction = n(UCD)/ n(UCD+ n(dE(N))

Scenario consistent with the notion theat UCDs and nuclei of dEs are structurally similar (Paudel et al. 2010) – same formation channel (from nucleated late-type galaxies) - *simply tidal disruption more advanced in UCDs than in dE(N)*

Hi-res cosmological dwarf galaxy formation

Governato, Brook, Mayer et al., Nature, 463, 203, 2010

TWO SIMS FOR TWO OBJECTS (DG1, DG2)

Vc_{halo} ~ 50 km/s
NSPH ~ 2 x 10^6 particles
Ndm ~2 x 10^6 particles
(Msph ~ 10^3 Mo)
spatial resolution
(grav. softening) 86 pc

-Cosmic UV background
(Haardt & Madau 2008)
- High SF threshold
100 atoms/cm^3
-Supernovae blastwave feedback model (Stinson et al. 2006)

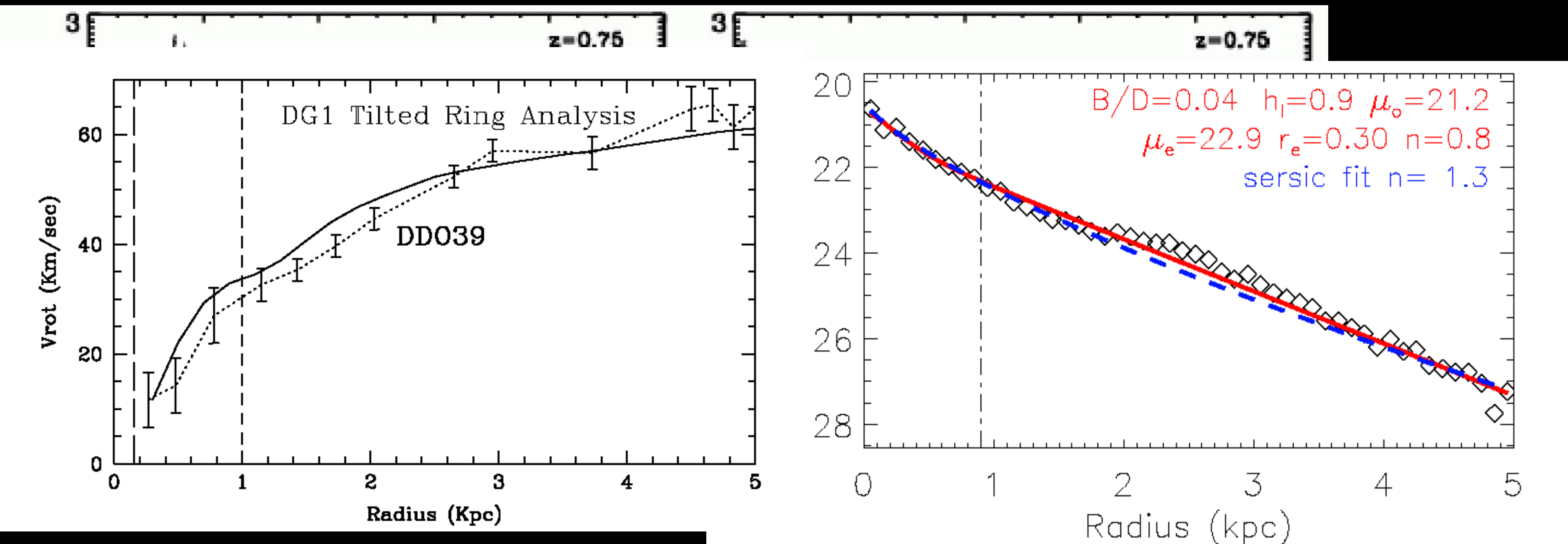
- Final baryonic mass fraction within Mvir < 0.3 x f_cosmic fraction
- Final disk mass (stars + gas) <= 0.2 x f_cosmic
- Final gas/stars ratio in disk ~ 2.5 (DG1) ,4 (DG2)

(galaxy formation efficiency < 10% - see Guo et al. 2010)

→ M_I ~ -16.8 (DG1), - 15.9 (DG2) → *analogs of NGC 6822, NGC3109 dIrrs*

Frame = 15 kpc on a side
color-coded gas density
Evolution from z=100
to z=0 (DG1)

First realistic late-type dwarfs in cosmological simulations;
Star formation and sup. feedback in *inhomogeneous* ISM



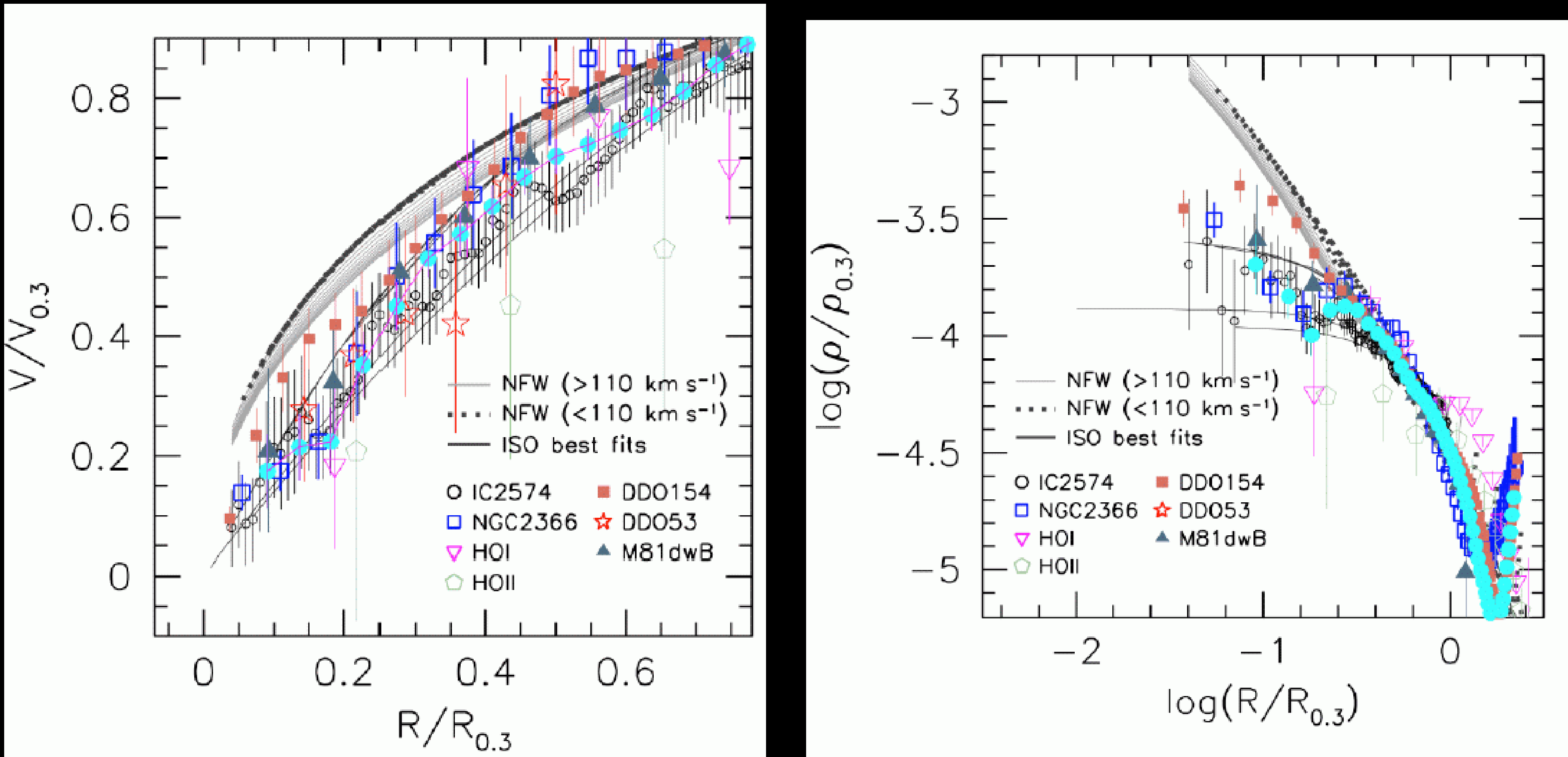
Star formation in resolved, dense "molecular" phase (GMCs):

- Star formation more localized, only in high density peaks
-→ LOCALLY stronger effect of outflows because more energy deposited in smaller volume via blastwaves (more gas heated at $T > T_{vir}$, outflows at ~ 100km/s
-→ final baryonic fraction ~ 1/4 of cosmic value)

- Outflows mostly in the center of galaxy where density peaks higher
-→ *selectively remove low angular momentum material at the center*
-→ *suppress bulge formation and produce exponential profile for stars*
-→ *flatten dark matter profile to repeated impulsive dynamical heating* ($\rho \sim r^{\beta}$, $\beta <= -0.6$))

Independent analysis by the THINGS survey team + comparison with late-type dwarfs in THINGS survey shows excellent agreement (Oh et al. 2011)

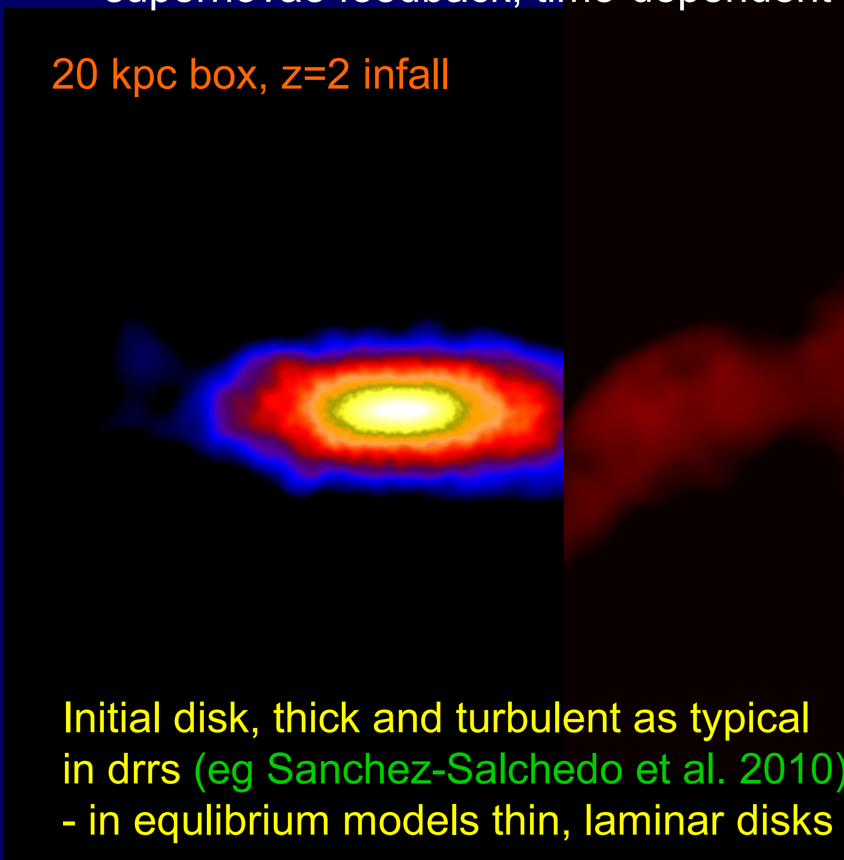
slope - 0.29 (mean slope THINGS) sample - 0.31
Note: no explicit correction for non-circular motions
(we obtain ~ - 0.5 from direct measure of the dm profile)

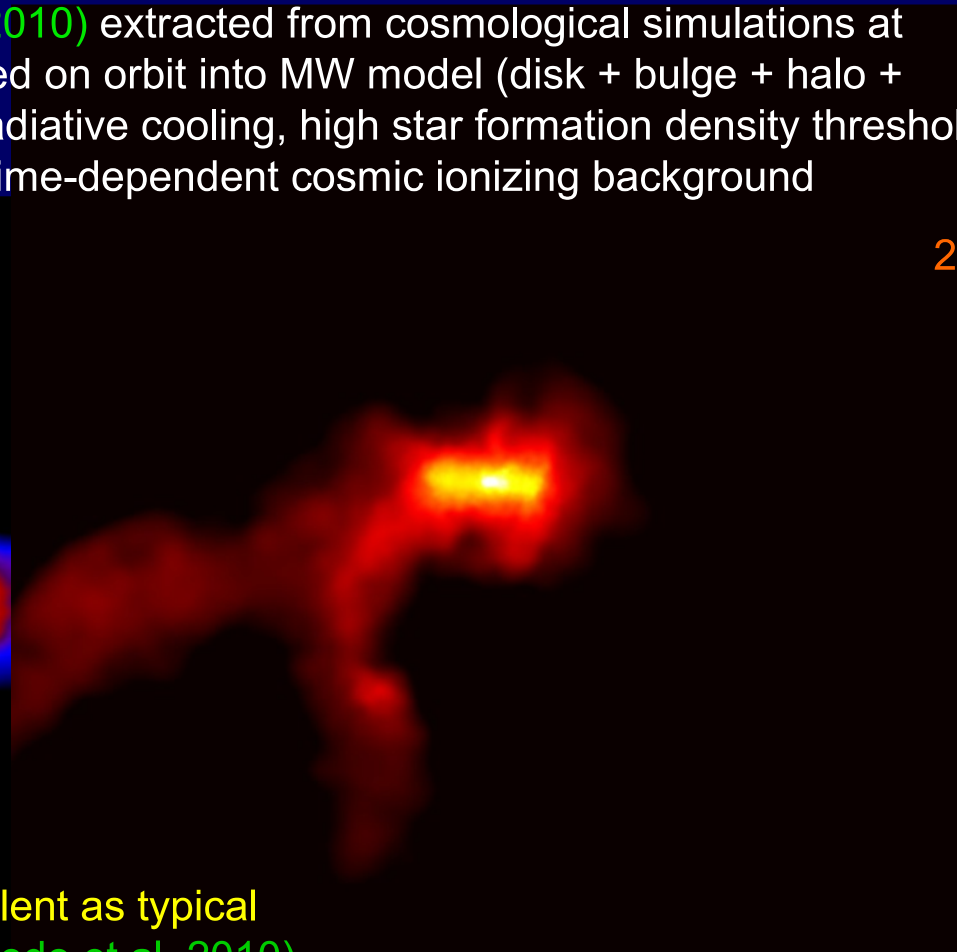


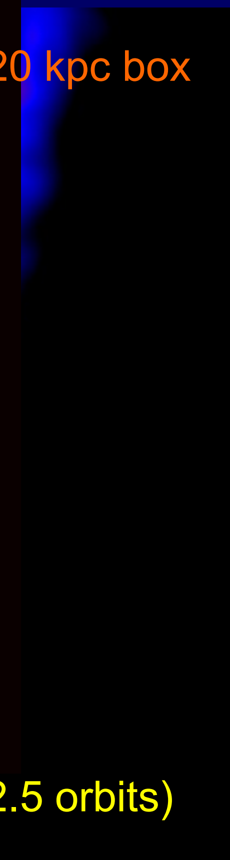
Interaction simulations with "cosmological dwarf"

Mayer 2011; Mayer, Callegari, Kazantzidis in prep.

DG2 (Governato et al. 2010) extracted from cosmological simulations at z=1 and z=2 and inserted on orbit into MW model (disk + bulge + halo + gaseous corona) with radiative cooling, high star formation density threshold, blastwave supernovae feedback, time-dependent cosmic ionizing background





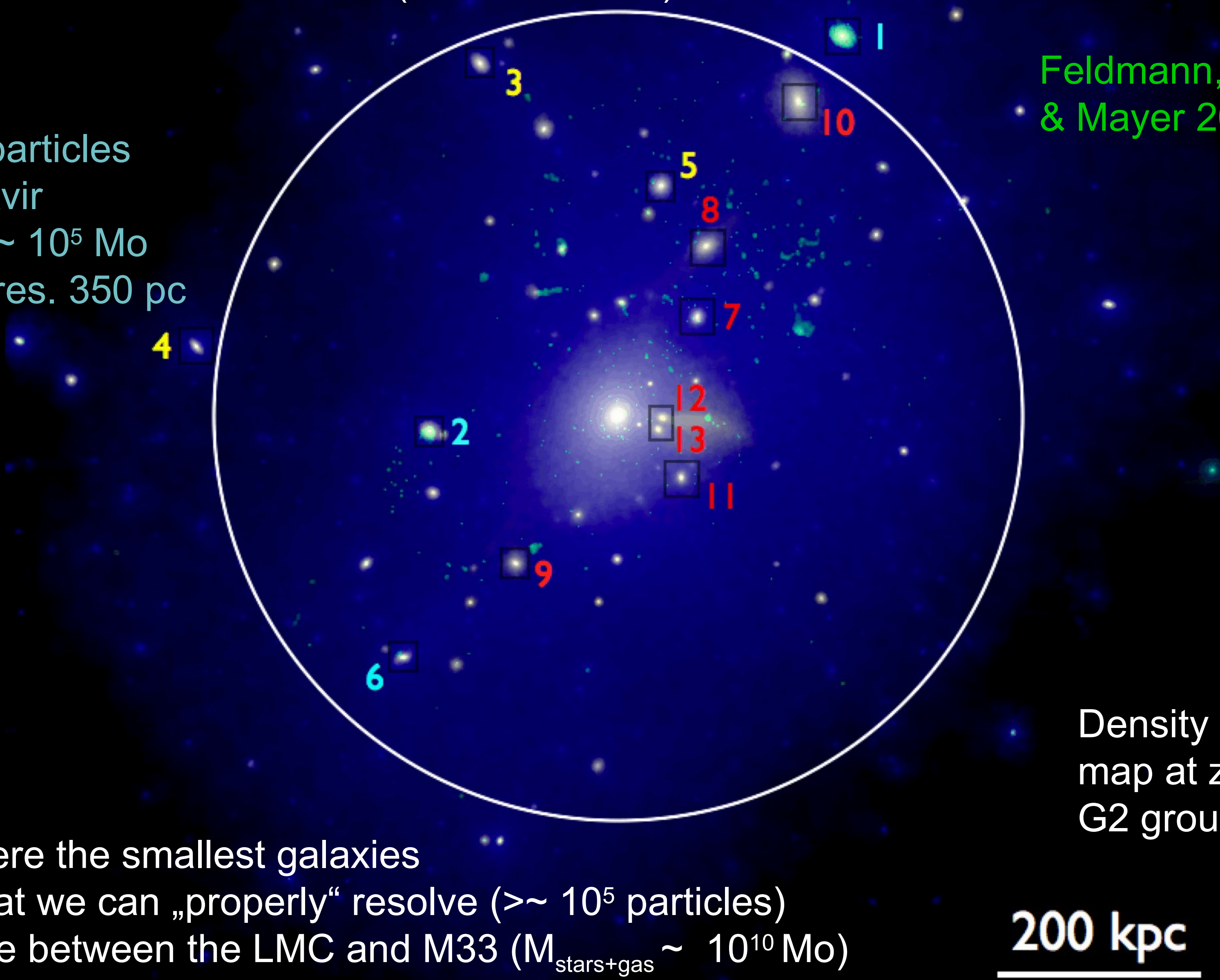


Transformation dIrr -→ dSph confirmed BUT:
WEAK BAR INSTABILITIES, STRONGER TIDAL HEATING

MORPHOLOGICAL TRANSFORMATION OF A GALAXY POPULATION:
COSMOLOGICAL ZOOM-IN HYDRO SIMULATIONS ON THE GROUP SCALE (Mvir ~ 10^{13} Mo)

Feldmann, Carollo & Mayer 2011

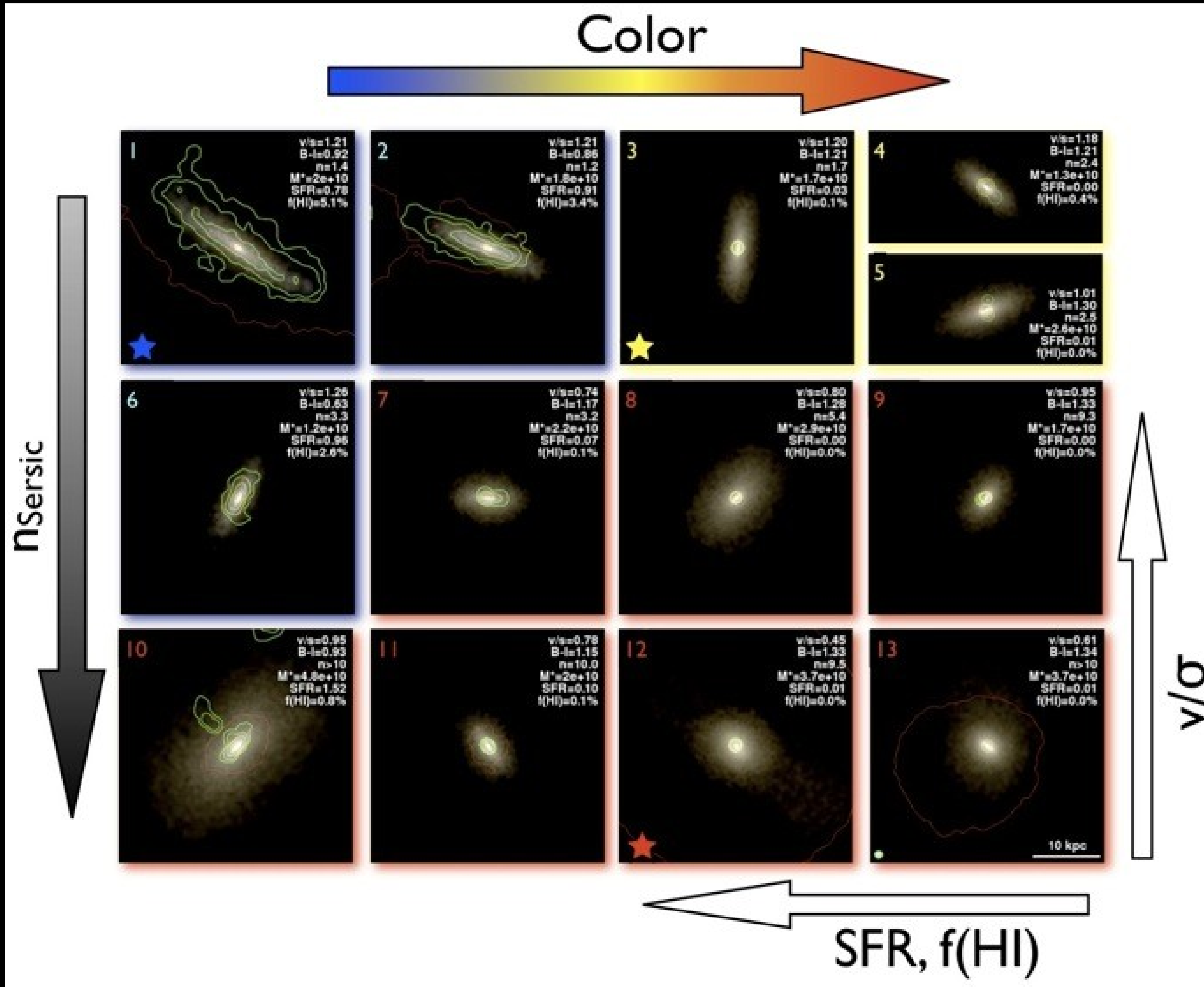
<~ 10^7 particles within Rvir
Mstar >~ 10^5 Mo
Spatial res. 350 pc



Density map at z=0 for G2 group

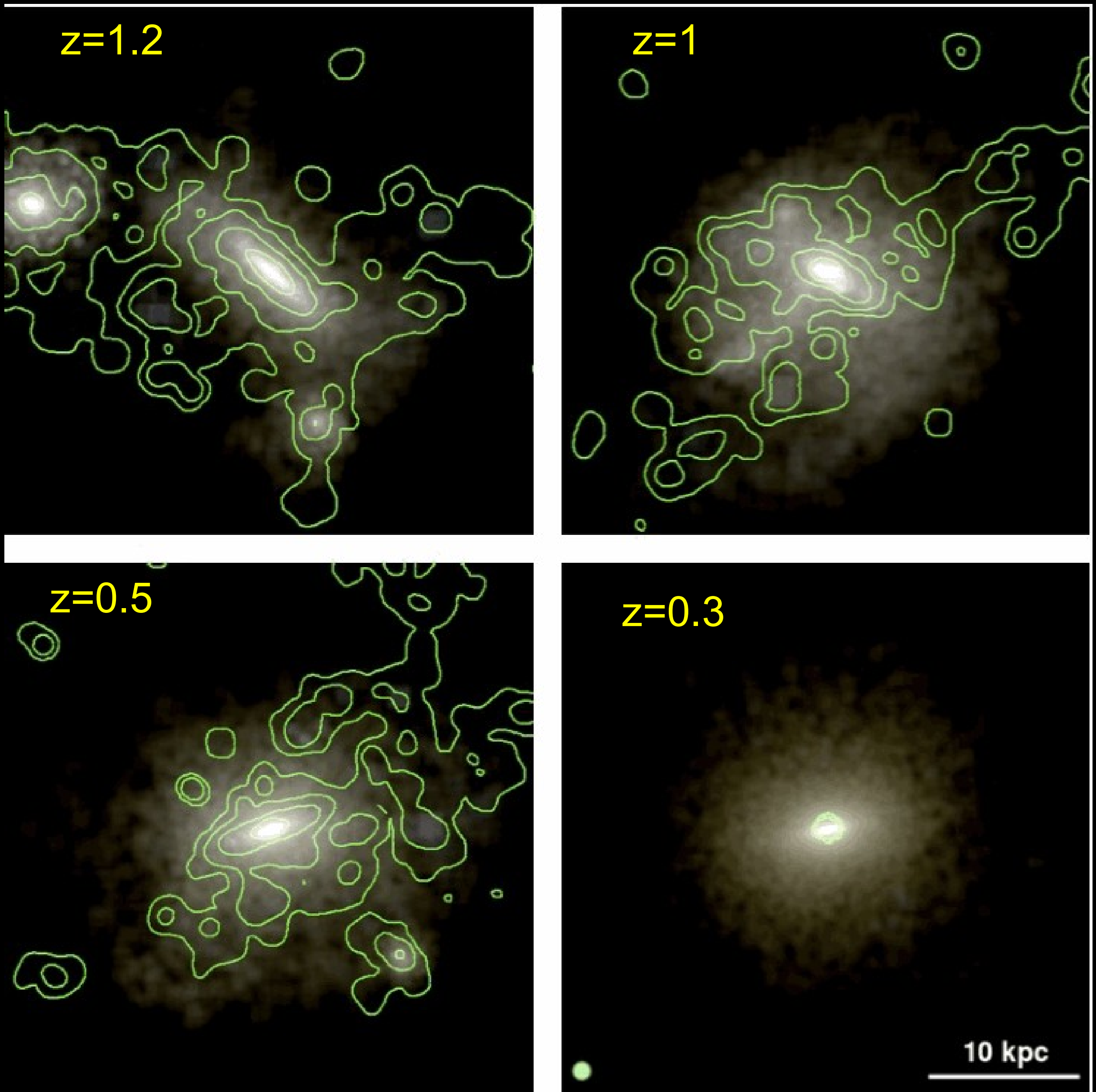
Here the smallest galaxies that we can „properly“ resolve (>~ 10^5 particles) are between the LMC and M33 ($M_{stars+gas}$ ~ 10^{10} Mo)

A ZOO OF MORPHOLOGIES....



TRANSFORMATION FROM DISK TO SPHEROID *VIA COMBINATION OF SEVERAL MECHANISMS* INCLUDING MERGERS PRIOR TO INFALL

Galaxy shown here has 1:2 merger at z ~ 1.1 plus ram pressure stripping after infall into group potental at z ~ 0.5



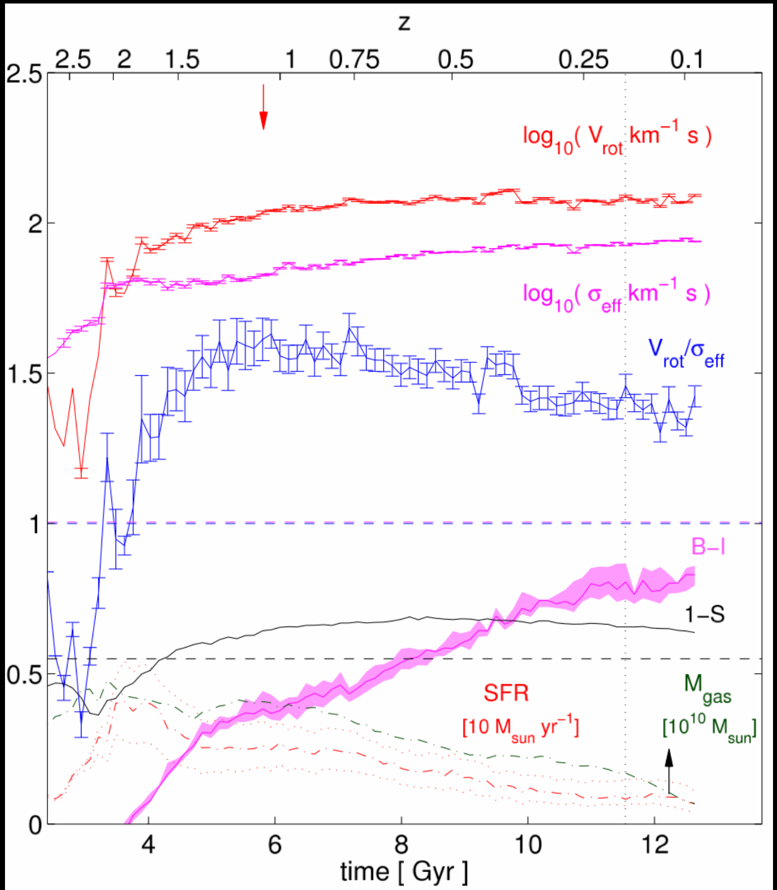
Shown:
Stellar density in grey scale
HI contours in green

In a cluster one expects similar evolutionbut different timing (mergers occur earlier on in protocluster, when relative velocities still small, and galaxies become „satellites“ earlier)

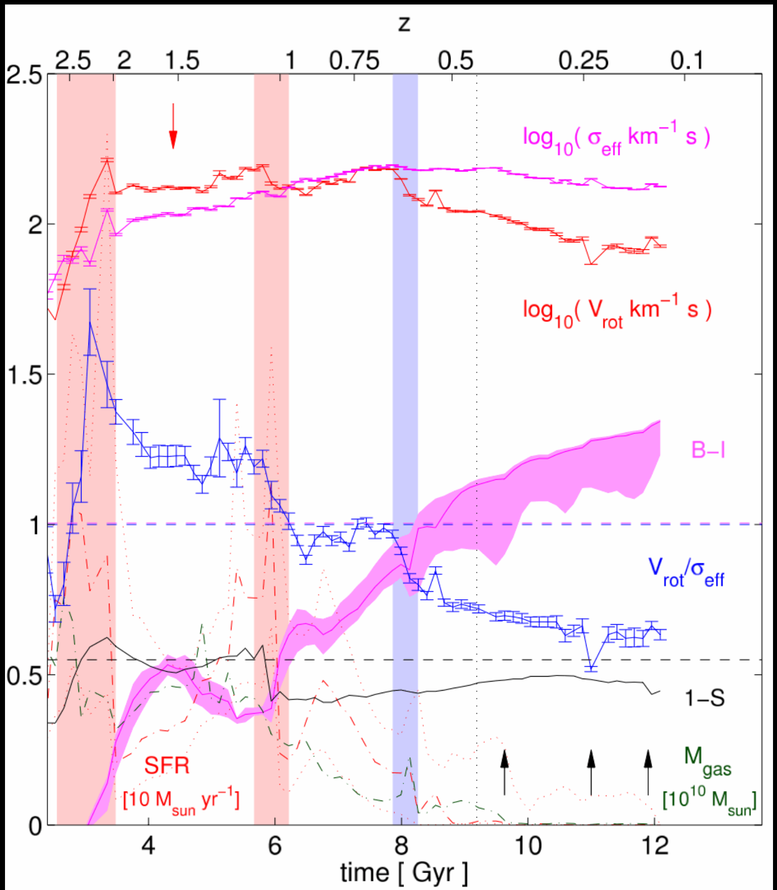
EVIDENCE FOR TIDAL STIRRING/HARASSMENT IN EVOLUTION OF KINEMATICS AFTER INFALL IN GROUP POTENTIAL + TRUNCATION OF STAR FORMATION VIA GAS STRIPPING (RAM PRESSURE + TIDAL)

INFALL TIME IS KEY TO EFFECTIVE TRANSFORMATION

DISK DOMINATED GALAXY FALLING LATE (z ~ 0.25) REMAINS DISKY AND GAS-RICH
(black arrows mark pericenter pass.)



S0-like GALAXY FALLING RELATIVELY EARLY (z ~ 0.5) BECOMES SPHEROIDAL AND DEVOID OF GAS
(black arrows mark pericenter pass.,
red stripes mergers, blue stripe a fly-by)



CONCLUSIONS

(1) Tidal stirring + harassment turn rotating disky dwarfs/dIrrs (Vrot <~ 50-100 km/s) into pressure supported early type dwarfs (dEs/dSphs).

-tidally induced bar-bluckling instabilities shed angular momentum outwards and increase velocity dispersion along with tidal heating

-in clusters harassment more important than in groups because of higher relative velocities and higher number of massive perturbers/galaxies.

- Significant population of dEs/dSphs can be formed at z < 1 in clusters + dEs with disky features naturally explained as transitional objects
- Fainter/older dE/dSph population formed in groups that later accrete onto cluster?

(2)Gas lost by ram pressure *COMBINED* with tides that decrease depth of potential well

(3) UCDs can be understood the tidally driven transformation scenario as surviving nuclei of disrupted nucleated dEs produced by nucleated spiral progenitors on most plunging orbits

(4) Cosmological simulations (group scale for now) confirm qualitatively the crucial role of tidal stirring and ram pressure stripping in producing low-luminosity spheroidals from gas-rich disks (caveat: resolved mass scale not yet in the dwarf regime). However they also show that early mergers (at z > 1) in sub-groups before infall into main potential play a role in initiating the disk-spheroid transformation

Can dSphs Form by Mergers of Disky Dwarfs?

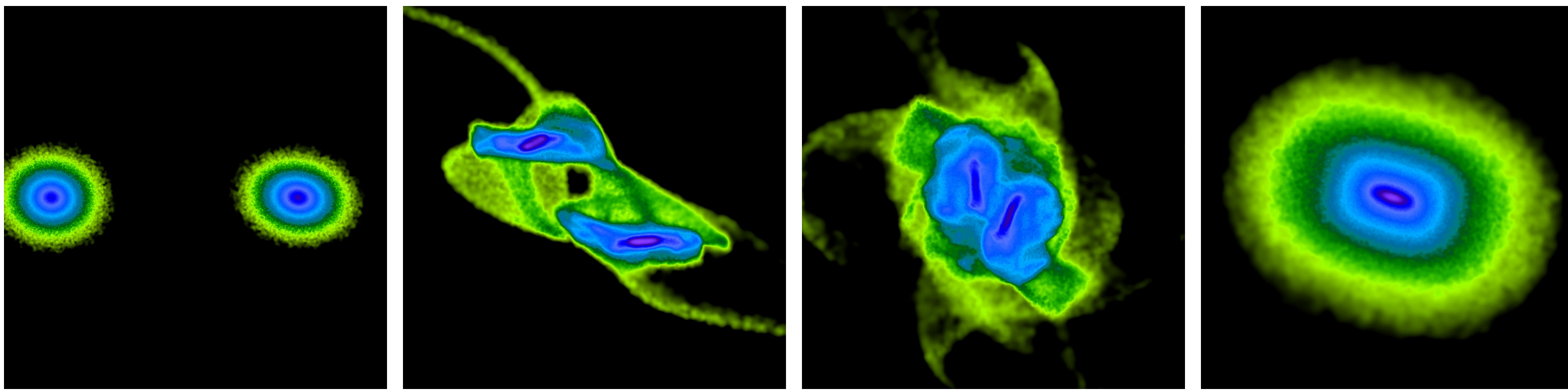
Kazantzidis et al. (2010b), in preparation

Ø Binary mergers of dwarfs identified in constrained cosmological simulation of the Local Group (Klimentowski et al. 2010)

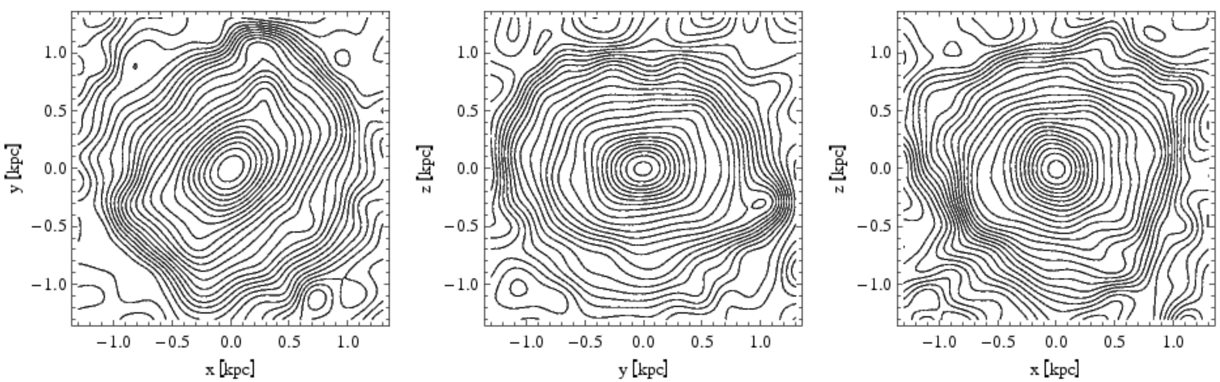
ØMost mergers happen at very early times (z ~ 2-3) well outside the virial radius of the host. Dwarfs can be accreted by the main halo at much lower z.

Major merger between two dwarfs with $M_{total} \sim 10^{7}\ M_{0}$ at $z \sim 2.5$

Stellar Density



Surface number density of stars



Ø Final system exhibits the properties of classical dSphs with $V/\sigma < 1$ and projected axis ratio of ~ 0.85

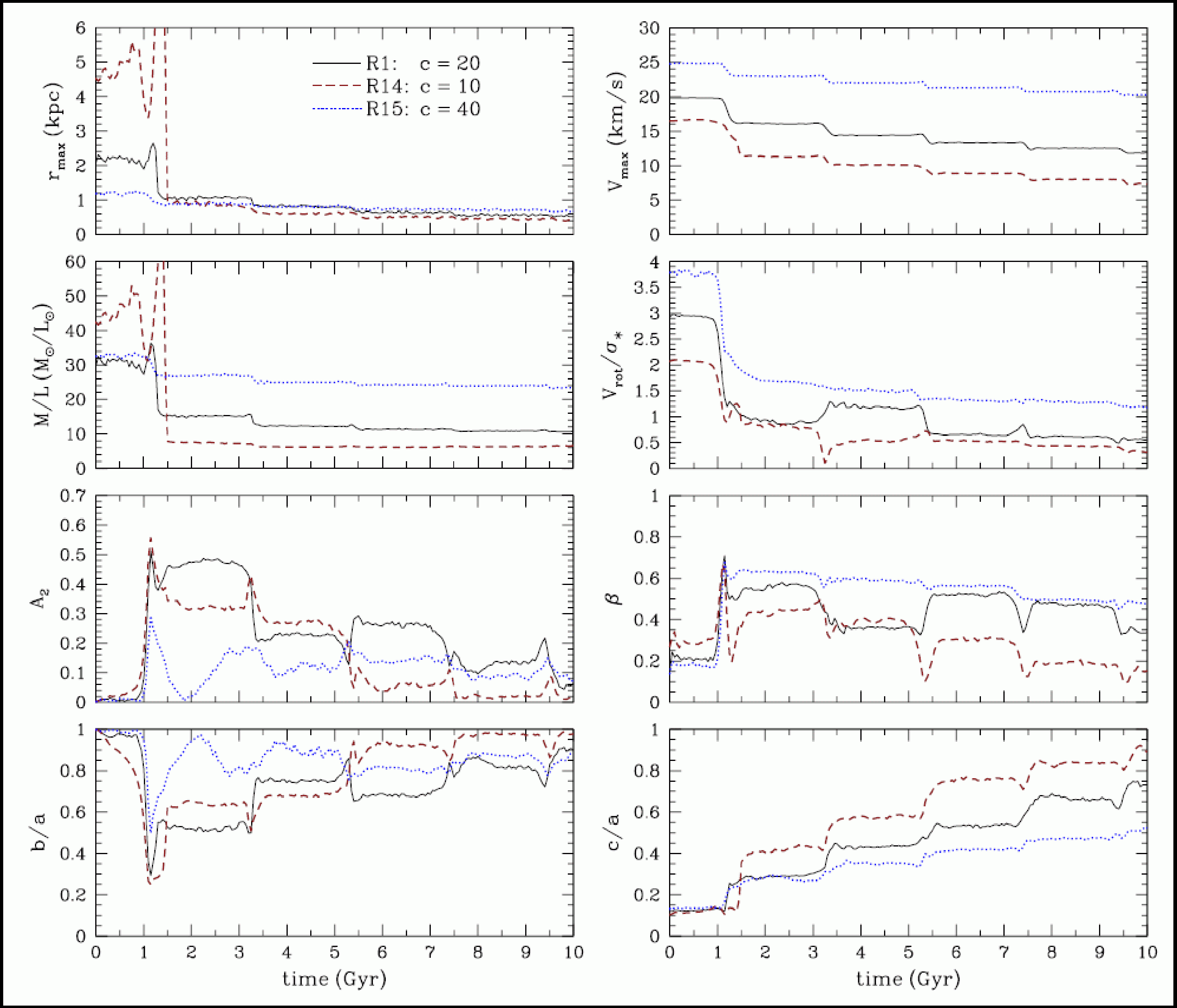
Importance of halo concentration in tidal stirring

Mhalo = 10^9 Mo

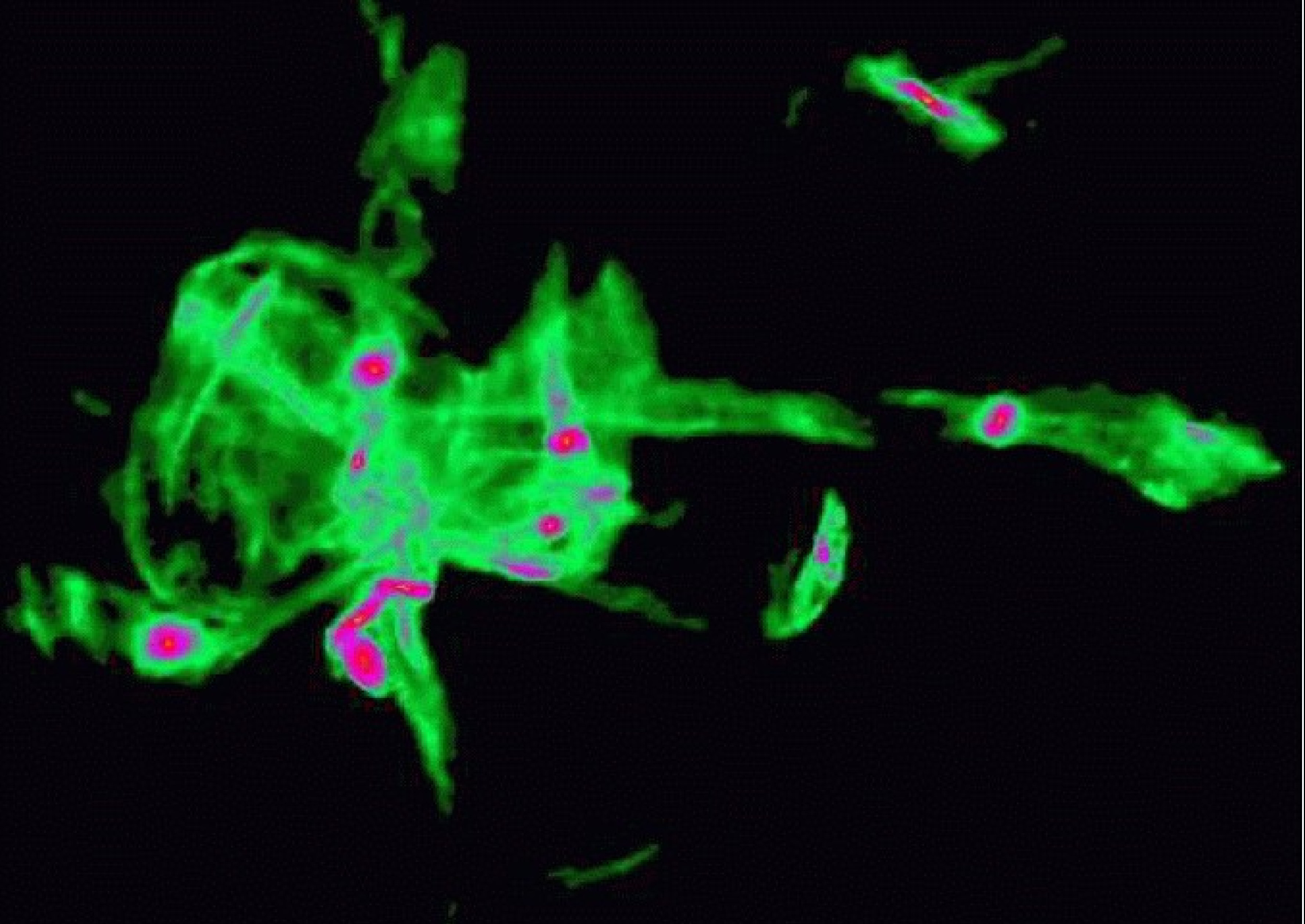
Mstar = 0.01 Mhalo

No gas in dwarf at at t=0

Live primary model disk +bulge+halo model of the (A2 model of the MW by Klypin et al. 2002)



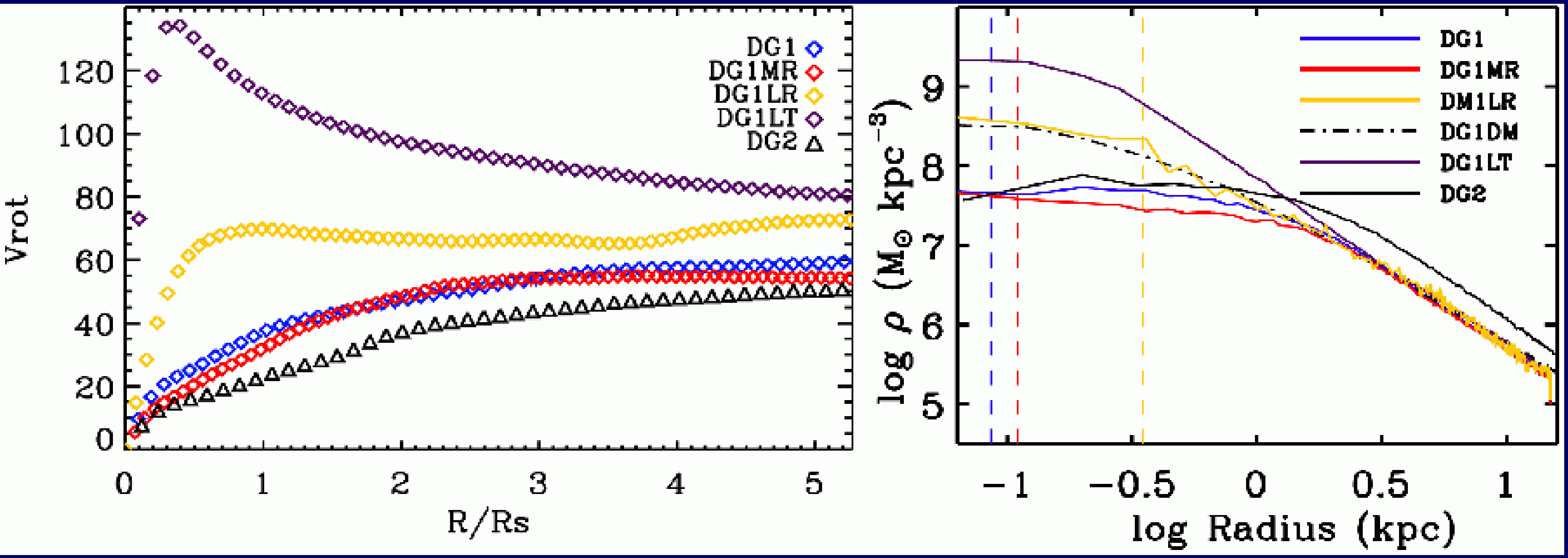
MAKING dEs from late-type disks IN GALAXY CLUSTERS



Enlightening numerical tests

"Erosion" of dark matter density cusp occurs only at high resolution and high star formation density threshold

--> only in such configuration prominent baryonic clumpiness + outflows do occur



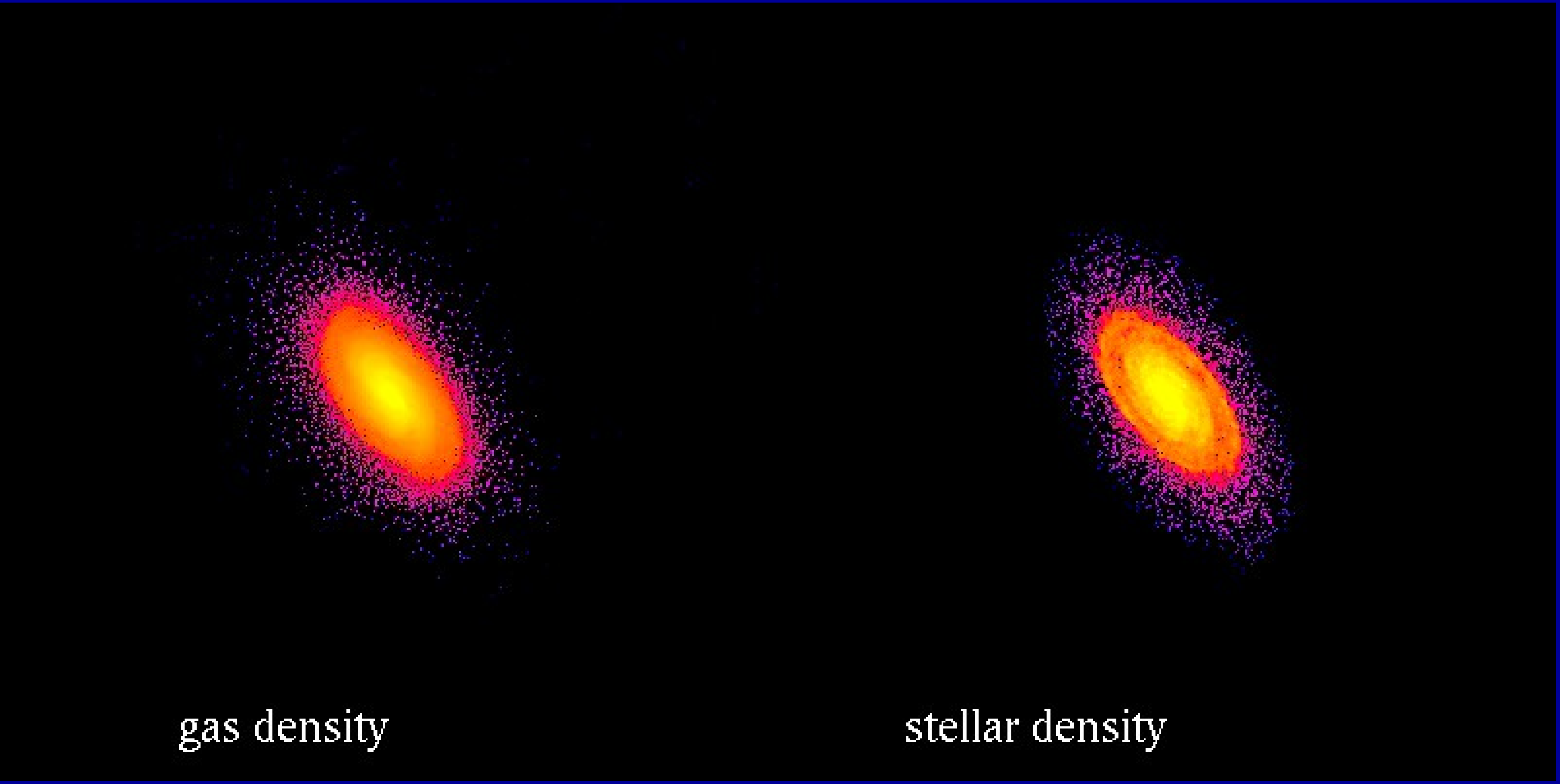
Tides + ram pressure in action

A “big dwarf”’ on a wide orbit (conservative case for all stripping effects)

Vpeak= 60 km/s

Apocenter = 250 kpc, Pericenter= 30 kpc, gaseous halo profile ~ dm halo profile (NFW)

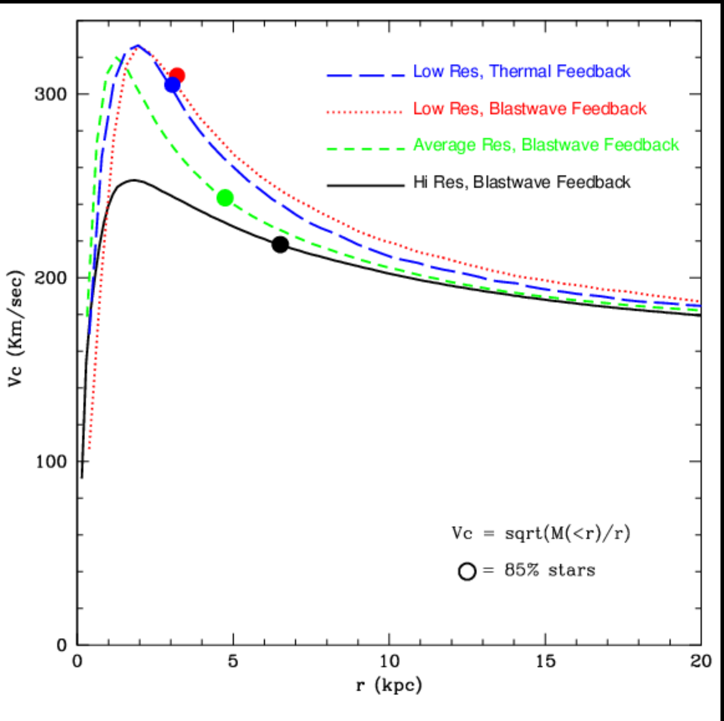
ρ_{gas} (50 kpc) = 8 x 10^{-5} cm^{-3}



Ram pressure stripping continues on subsequent orbits because potential well o dwarf becomes shallower as a result of tidal shocks

No disk dominated galaxies in CDM simulations = no progenitors of dEs

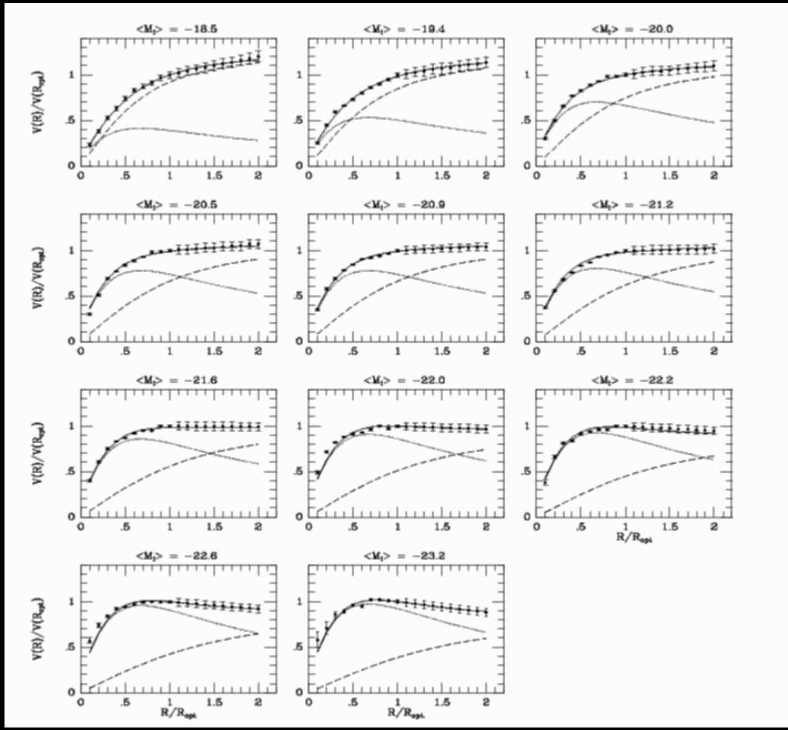
Simulations



Mayer et al. 2008

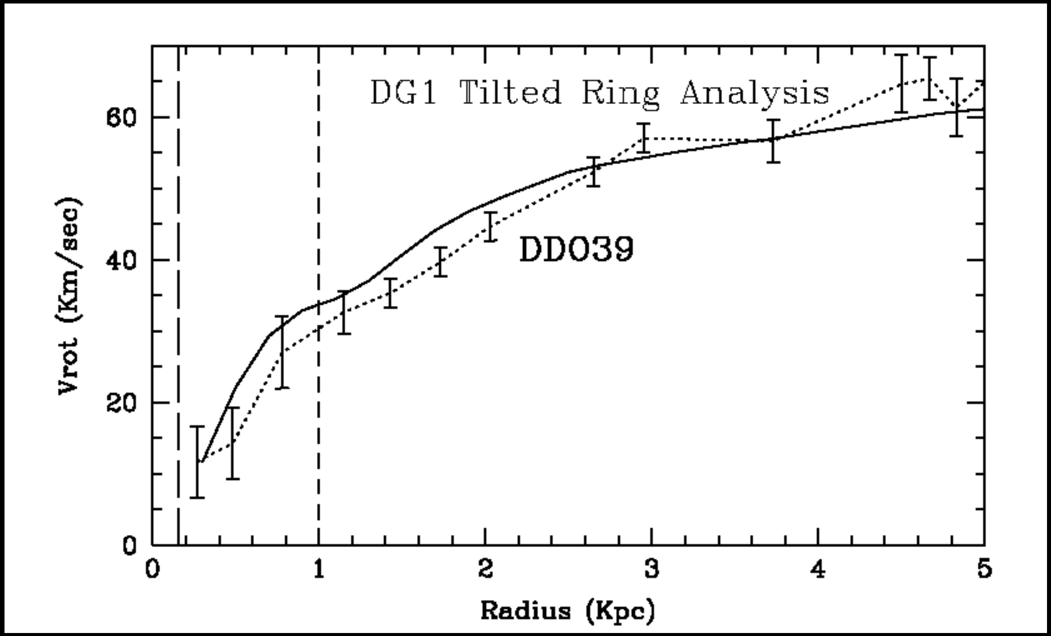
-→ implied inner slope ~ r^{-2}

Observations



Cosmological sims that model collisionless dark matter + dissipational baryonic component with radiative cooling, heating, star formation, feedback processes exhibit a mass concentration problem: disk galaxies always form with massive bulges --- no analog of late-type disks/dIrrs!

A slowly rising rotation curve produced



How?

(1) Removal of baryons (baryonic mass fraction ~ 0.04 at z=0, so 4 times lower than cosmic fb) + (2) flattening of dark matter profile

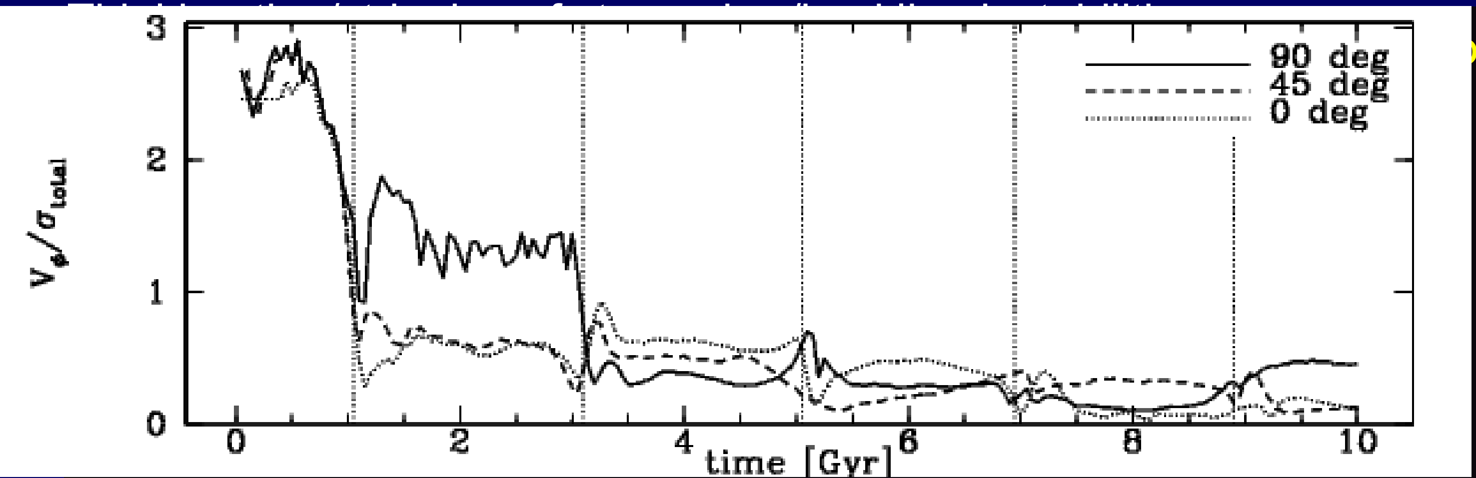
--During strongest outflows (at z > 1) inner dark matter mass expands as a result of impulsive removal of mass + transient gas clumps transfer energy due to dynamical friction

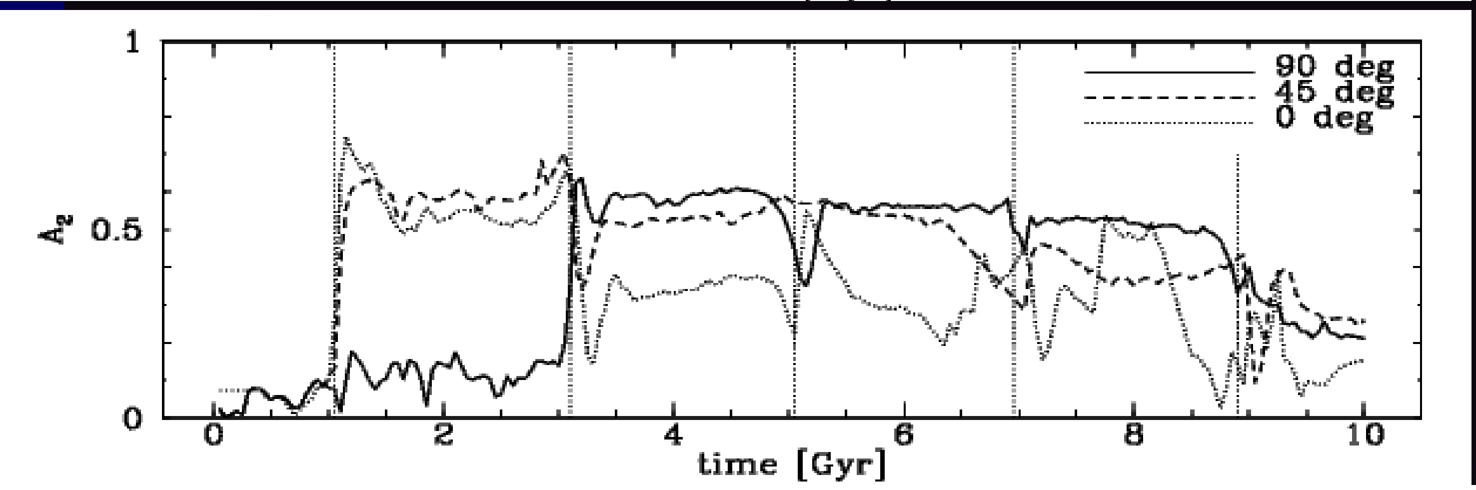
(confirms earlier models of e.g. Navarro et al. 1996; Read & Gilmore 2003; Maschchenko et al. 2008 – see also Ceverino & Klypin 2009)

Dark matter density decreases by a factor of ~ 2 at r < 1 kpc and density profile becomes shallower ~ $r^{-0.5}$ rather than ~ $r^{-1.3}$

The response of disky dwarfs to tidal forcing

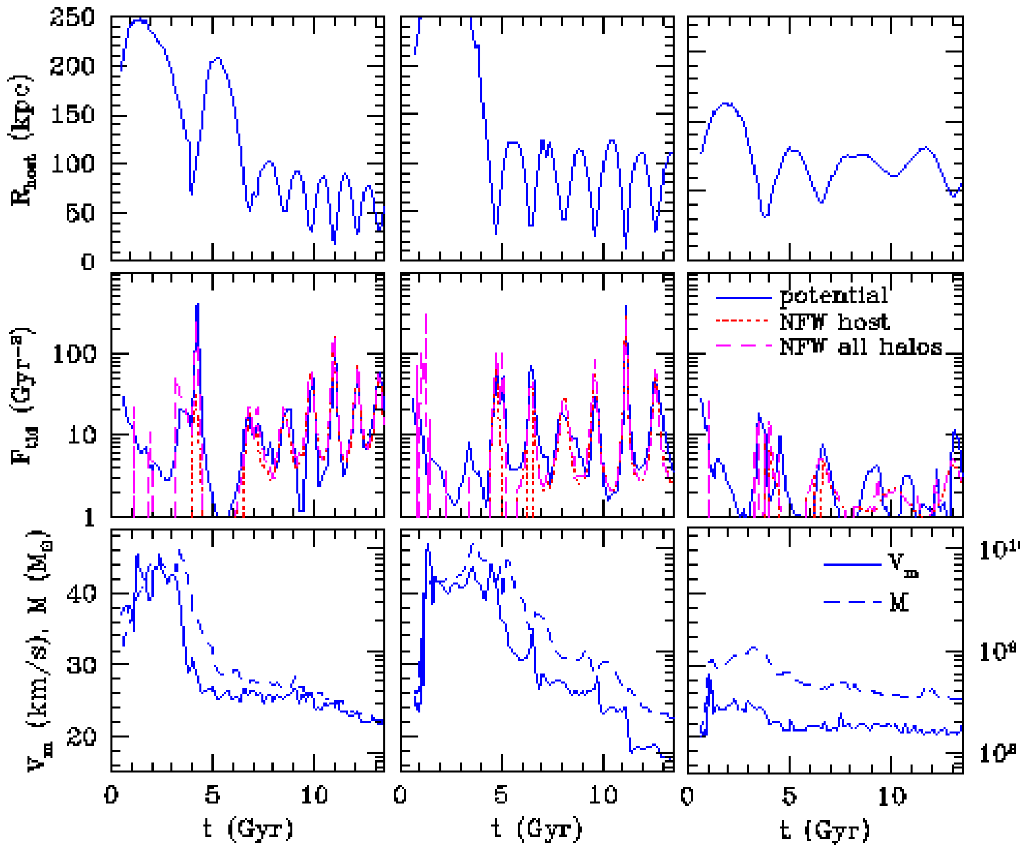
Tidal stirring = repeated tidal shocks at pericenters with primary galaxy (Weinberg 1994; Gnedin, Hernquist & Ostriker 1999) turn rotationally supported late-type dwarf ($v/\sigma >> 1$) into faint spheroidals with low $v/\sigma < 0.5$ (Mayer et al. 2001, 2002; Klimentowski et al. 2008,2009) INITIAL CONDITION IS EQUILIBRIUM DISK+HALO MODEL PLACED ON COSMOLOGICAL ORBIT





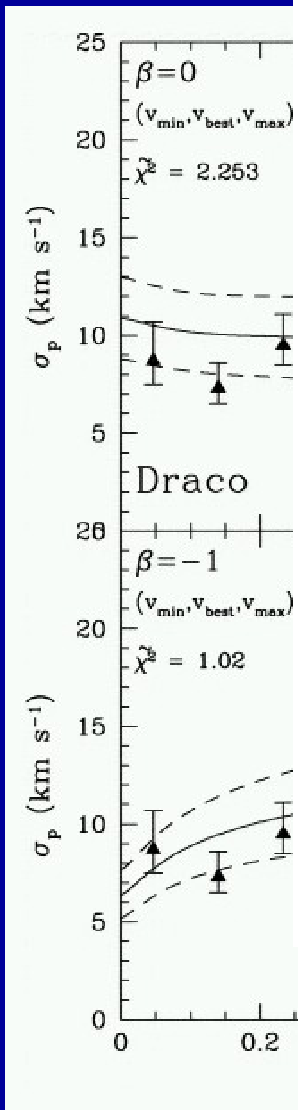
Masses

Vpeak > 30 km/s, or M > 10 [9]Mo before accretion (Mayer 2005; Kravtsov et al. 2004, Diemand et al. 2007;) – too massive for squelching by reionization to be effective



Hi-res cosmological (dm-only) simulations: subhalos lose between 30% and 99% of their mass (Madau et al. 2008; Stadel et al. 2008; Springel et al. 2008)

Modeling of k
Vpeak >~ 20



dis, Mayer
4

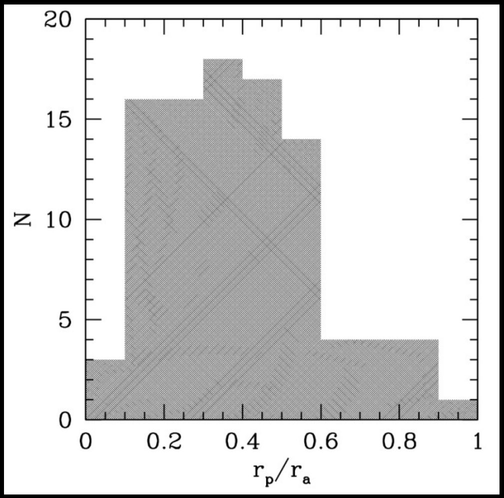
d
ng Jeans
e "modified"
und for
subhaloes
l sims

model for
ion

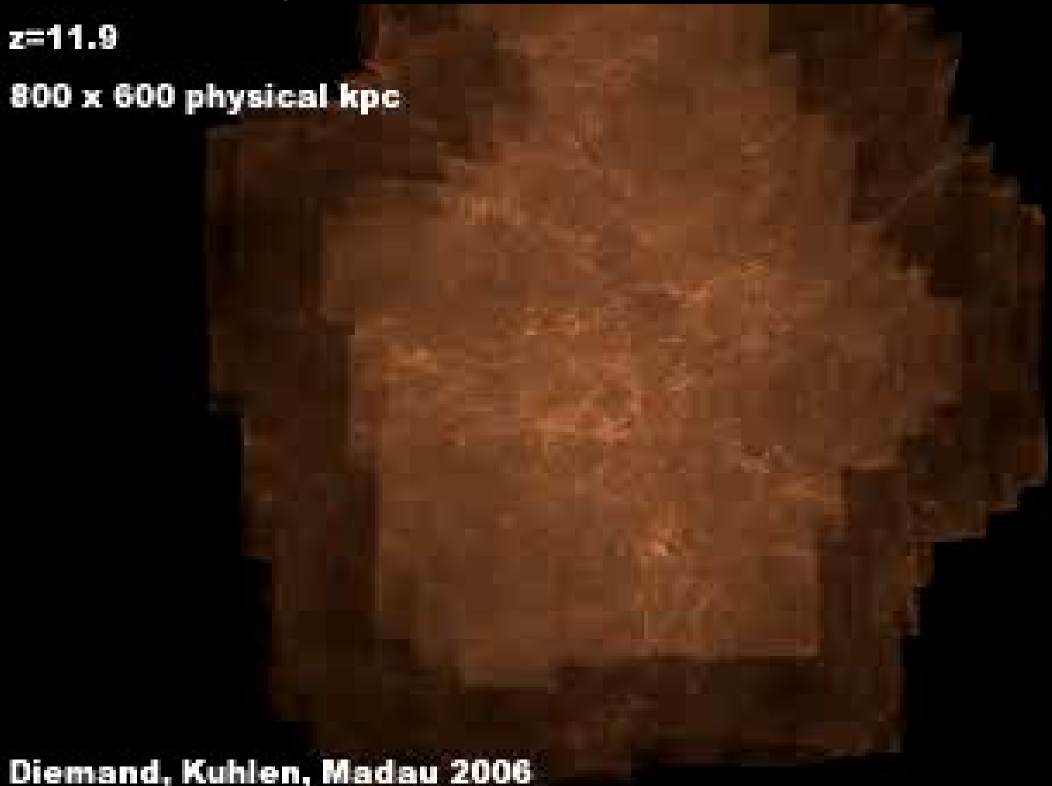
as 2004,
n et al.
more et
al. 2007; Strigari et al. 2006, 2007; Lokas 2009; Strigari, Frenk & White 2010

The hosts of dwarf spheroidals: dark matter subhalos surviving to z=0

- In CDM models subhalos evolve on eccentric orbits (apo/peri = 5:1-20:1)
- Subhalos surviving until the present time have undergone several pericenter passages within the primary halo, being (1) Tidally truncated and (2) repeatedly tidally shocked (Taylor & Babul 2001; Taffoni, Mayer, et al. 2003; Hayashi et al. 2003; Penarrubia et al. 2006; 2008;2010)



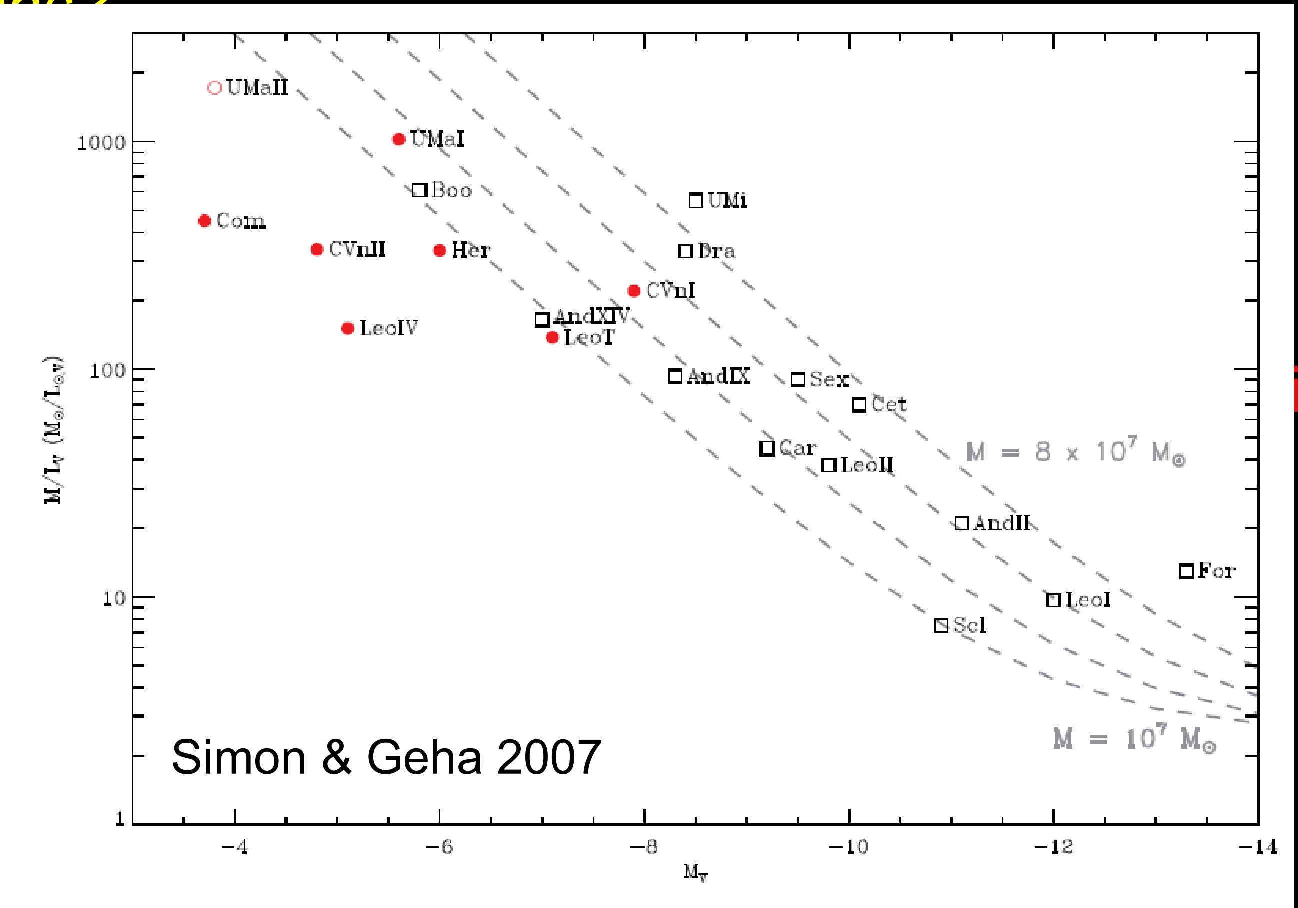
From (cosmological) constrained simulation of the LG (Klimentowski et al. 2010)



Mass-to-light ratios

- *How do we explain very high M/L (> 100 for Draco and UMinor) in the tidal stirring + ram pressure stripping scenario?*

- *And how do we explain that M/L correlates with L for dSphs?*



-→ Gas … into

primary …

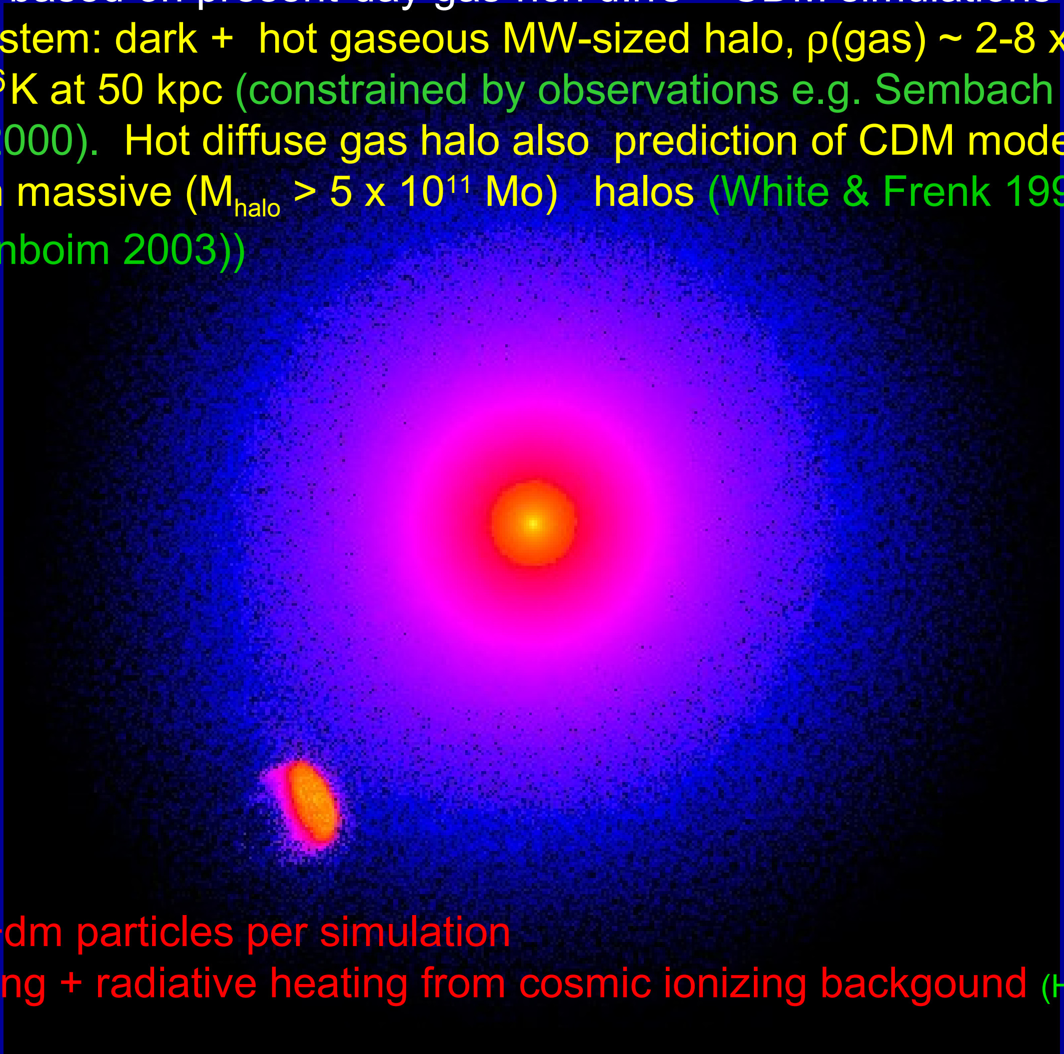
Mayer, Ka…

Tides + Ram Pressure Stripping

(Mayer & Wadsley 2003, Mayer et al. 2006, 2007)

-Dwarf model = N-Body +SPH equilibrium model w/disk of gas and stars + NFW halo on cosmological orbit (apo/peri =5:1 – 6:1). Initial structural parameters based on present-day gas-rich dIrrs + CDM simulations

-Primary system: dark + hot gaseous MW-sized halo, ρ(gas) ~ 2-8 x 10^{-5} atoms/cc and T ~ 10^6K at 50 kpc (constrained by observations e.g. Sembach et al. 2003; Blitz & Robishaw 2000). Hot diffuse gas halo also prediction of CDM models - leftover of galaxy formation in massive (M_{halo} > 5 x 10^{11} Mo) halos (White & Frenk 1991; Maller & Bullock 2004; Dekel & Birnboim 2003))



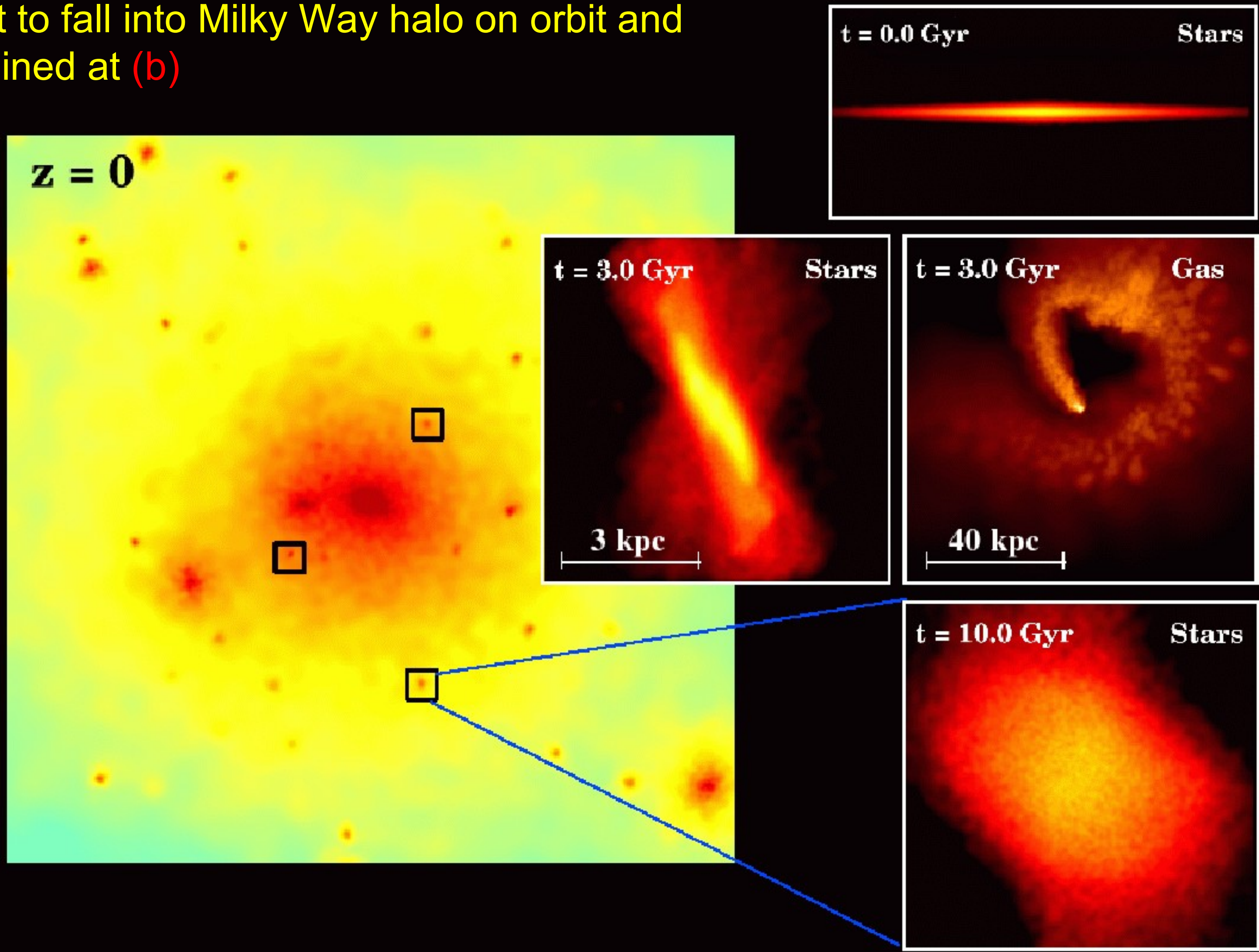
~ 2 million SPH+dm particles per simulation

W/radiative cooling + radiative heating from cosmic ionizing backgound (Haardt & Madau 1996+2003)

(a) Pick satellites with Vmax ~20-25 km/s today (consistent with kinematics of darkest classical “dSphs”, Draco and Umin) and within 100 kpc from MW in hi-res cosmological ΛCDM dark matter-only simulation

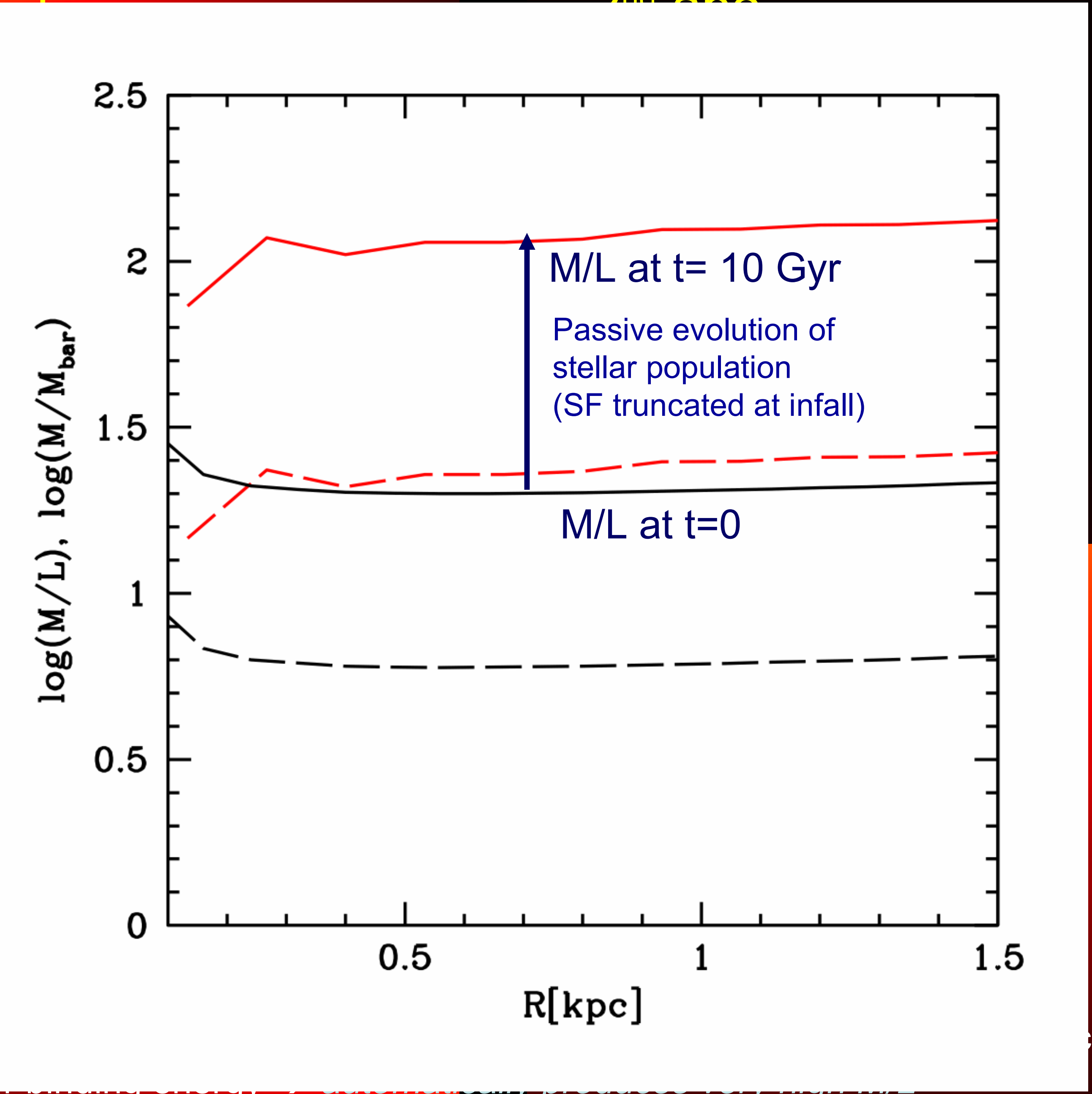
- (b) Trace the orbit back in time --→ > 50% are “old” accreted satellites that fell in at z > 1.5 → *exposed to high cosmic UV bg at accretion*
- (c) Hi-res model of gas dominated disk-like progenitor (gas/stars = 8:1) set to fall into Milky Way halo on orbit and at infall time determined at (b)

Mayer, Kazantzidis, Mastropietro & Wadsley
Nature, 2007



1st pe

2nd apo



Orbit fro ... 1<z<2)

Half

- Gas is complete ... cause
tidal shocks lowe
- SF suppressed because gas ionized and below density threshold for H2 formation

Implications/Predictions for stirring+ gas stripping scenario

(1) Final M/L driven by initial gas fraction in disky progenitor

Larger initial fgas (> 0.9 normal for present-day dIrrs – Geha et al. 2006; McGaugh et al. 2009) -→ for early infall final M/L up to 10^3

Prediction: dSphs with Vmax ~ 10-30 km/s with M/L >> 100 should exist (some of the ultra-faint dwarfs, e.g. Ursa Major I)
-→ helps to solve missing satellites problem at high mass end where reionization alone would fail (Vmax ~ 15-30 km/s – see Kravtsov 2010)

(2) M/L and SF history dependent on infall epoch

Naturally explains why Draco and Fornax have similar σ (Vmax) but M/L different by a factor of 10 → *Fornax infall at z < 1 (weaker ram pressure+tidal stripping+ weak UV=more baryons retained)*

Predictions:

(1) Positive correlation between M/L and timescale of SF

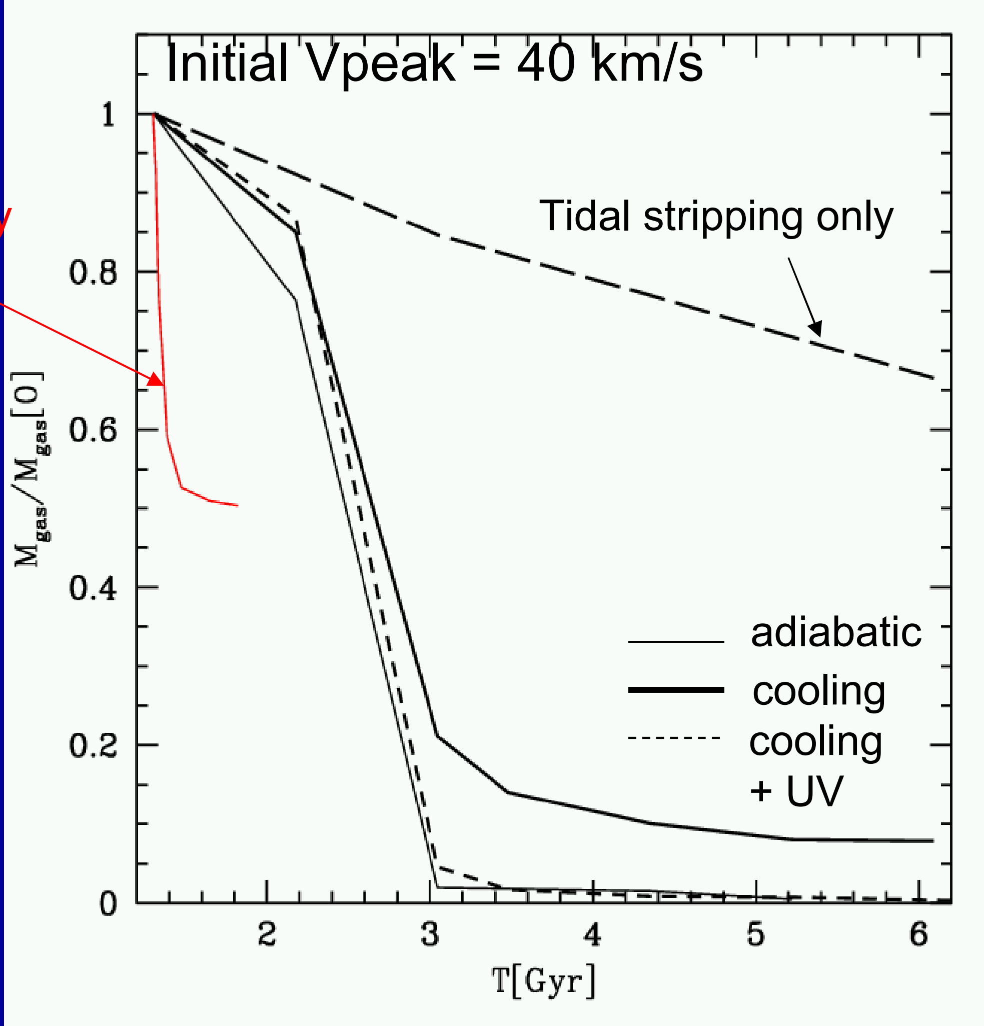
(2) Anticorrelation between M/L, L, mean orbital distance

Test case: Fornax should be on wider orbit than Draco

Gas mass loss: tides + ram pressure + UV

- Ram pressure produces higher gas 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 (V_{peak} drops)
- With high intensity of cosmic UV bg (z > 1) gas is warmer and more diffuse
---→ *is more efficiently stripped*

Ram pressure only



ORBIT FIXED:
Apo=150 :kpc
Peri=30 kpc

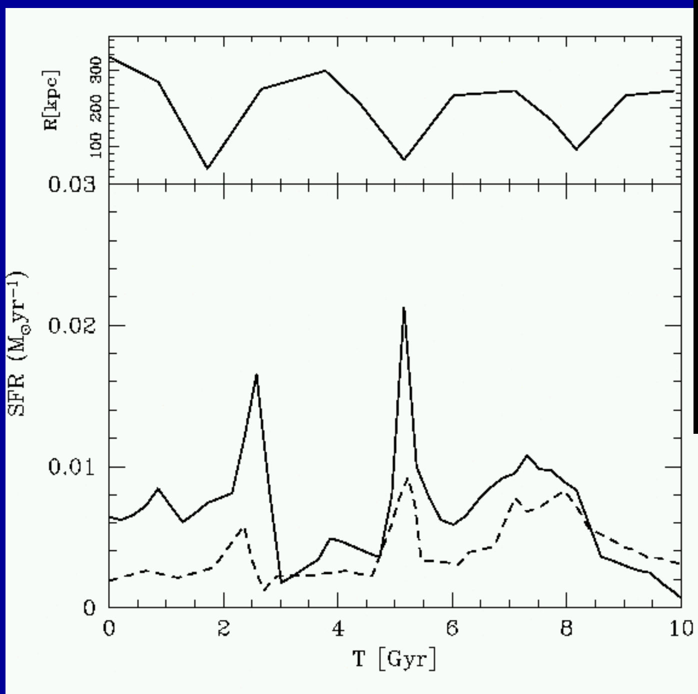
"standard" uniform high-z cosmic UV bg (Haardt & Madau)
Assumes infall at z=2
(UV bg ~ 10 times higher than at z=0)

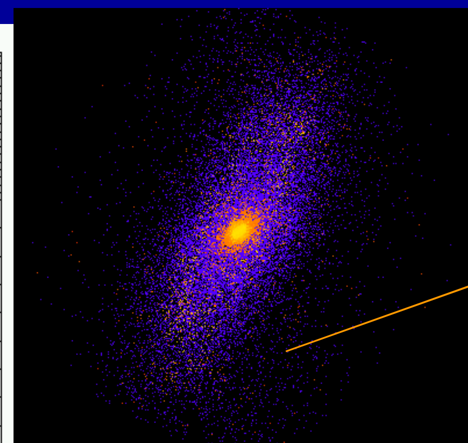
Mayer et al. 2006

Satellites accreting late (z < 1): gas retained for many orbits + extended SF history because effect of UV bg weak

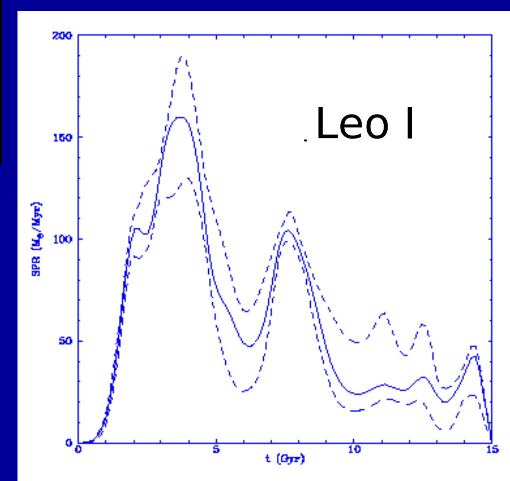
(Mayer et al. 2007, Mayer 2010)

SF computed with Kennicutt-Schmidt law





new SF concentrated central region → age gradient as a function of distance
(Mayer 2010)
See E. Grebel's talk



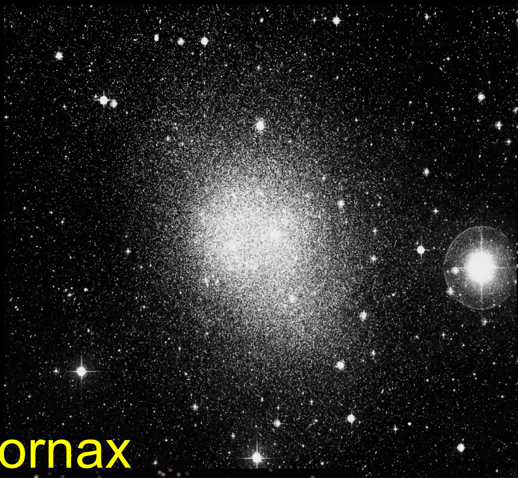
From Hernandez et al. (2000)

Star formation is periodic: gas driven bar inflow and tidal compression at pericenter passages

---→ Different infall times drive variety of SF histories

Dwarf spheroidals (dSphs)

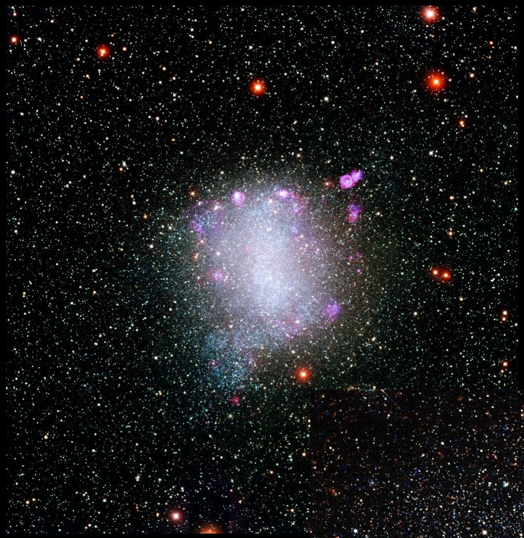
Dwarf irregulars (dIrrs)



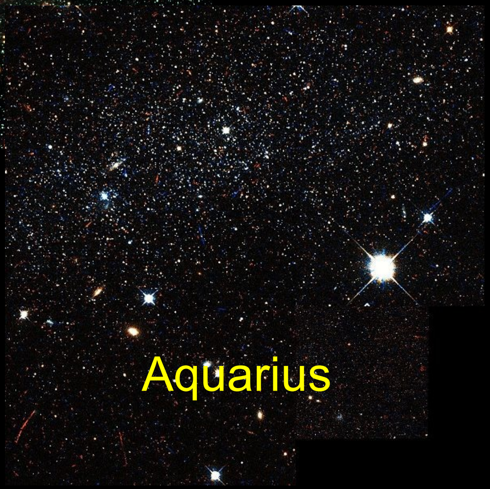
Fornax

Carina

Bootes



NGC6822



Aquarius

- dark matter dominated (M/L ~ 10-1000)
- faint, low surface brightness ($M_B > -18$, $\mu_B > 23$ mag arcsec^{-2})
- Low angular momentum content, $v/\sigma < 0.5$ for dSphs, high angular momentum for gas-rich dwarfs (dIrrs), some dwarfs in between (e.g. $v/\sigma \sim 1$ for Tucana – Fraternali et al. 2009)
- Very low gas content for dSphs (<< Mstar), very high gas content for dIrrs (~> Mstar),

- MORPHOLOGY-DENSITY RELATION (Grebel '99; Karachentsev '08 - E. Grebel's talk)

dSphs clustered near primary galaxy (R < Rvir), dIrrs in the field (R > Rvir)→

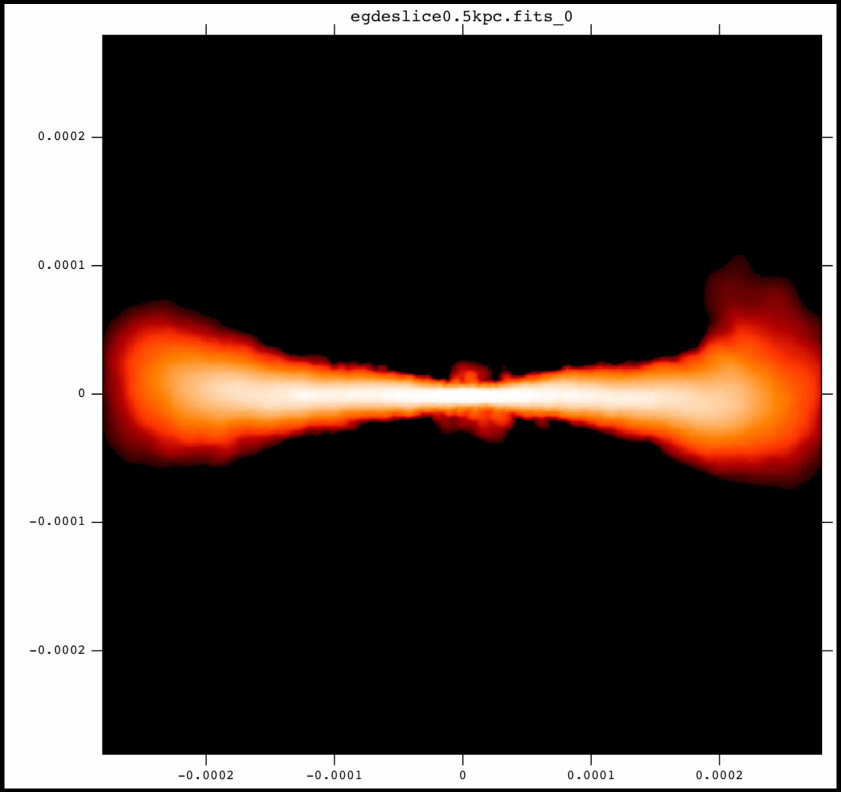
--→ role of environmental mechanisms important

On ultra-faint dSphs and "isolated" dSphs

▪Many ultra-faint dwarfs have very low σ (< 5 km/s) -→ live in lower mass halos compared to classical dSphs: even accounting for stripping halo mass before accretion < 10^8 Mo (Mayer 2010) -→ subject to photoevaporation by UV bg at high z (Susa & Umemura 2004) or blow-out by sup. feedback (Sawala et al. 2010).
Possibly reionization fossils (Ricotti & Gnedin 2005; Ricotti 2010), tidal stirring marginal if already "hot" + tiny stellar system before infall into primary (Mayer 2010, Kazantzidis et al. 2010).

▪Some ultra faint-dwarfs could be satellites of satellites (e.g. Segue 2 – Belokurov et al. 2009) which suffered tidal stirring by their larger dwarf companion before infall into primary

▪Distant dSphs (e.g. Cetus/Tucana – Monelli's and Hidalgo's talks) ar R > Rvir: observations suggest $v/\sigma \sim 1$ -→ consistent with non-complete transformation by tidal stirring because large pericenter/few pericenter passages but still would require extreme orbit (apo/per > 10:1) and/or resonant stripping if dwarf's disk prograde with primary's disk (d'Onghia al. 2010).
-- Tucana and Cetus are receding from primaries; perhaps ejected by three-body scattering (Sales et al. 2007)→ if were on smaller orbit before, tidal stirring origin more likely
-- Different formation mechanism, e.g. blow-out by supernovae feedback (Sawala et al. 2010 but Tucana's halo mass quite high for effective blow-out) *OR……*


egdeslice0.5kpc.fits_0
0.0002
0.0001
0
-0.0001
-0.0002
-0.0002
-0.0001
0
0.0001
0.0002

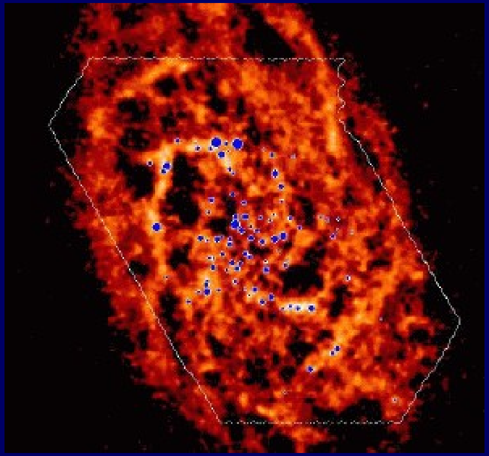
The star formation density threshold: tests with hi-res isolated galaxy models

"Low" SF density threshold (corresponds to warm neutral medium - adopted in all cosmological simulations by all groups till 2009)

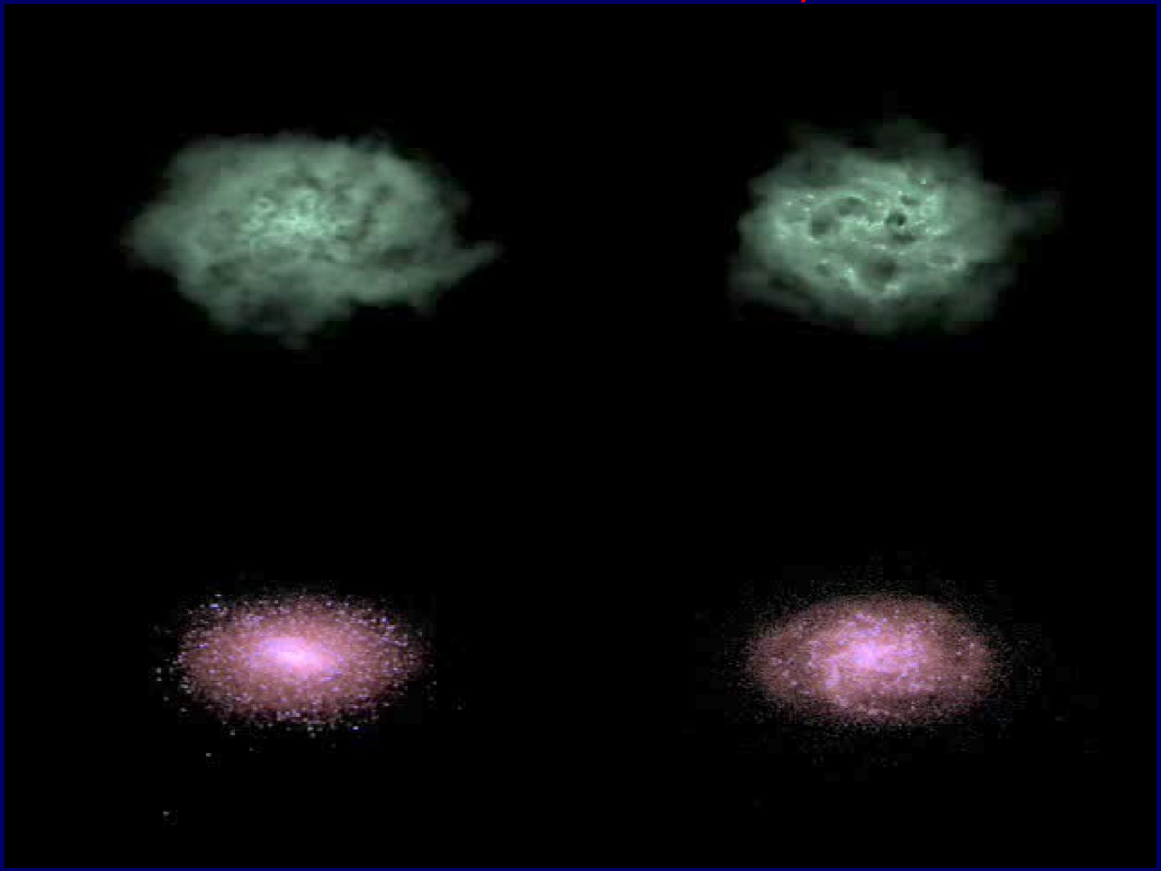
$\rho > 0.1 \text{ cm}^{-3}$

"High" SF density threshold (corresponds to molecular gas), feasible only at hi-res

$\rho > 100 \text{ cm}^{-3}$



HI map M33
(Blitz et al. 2006)

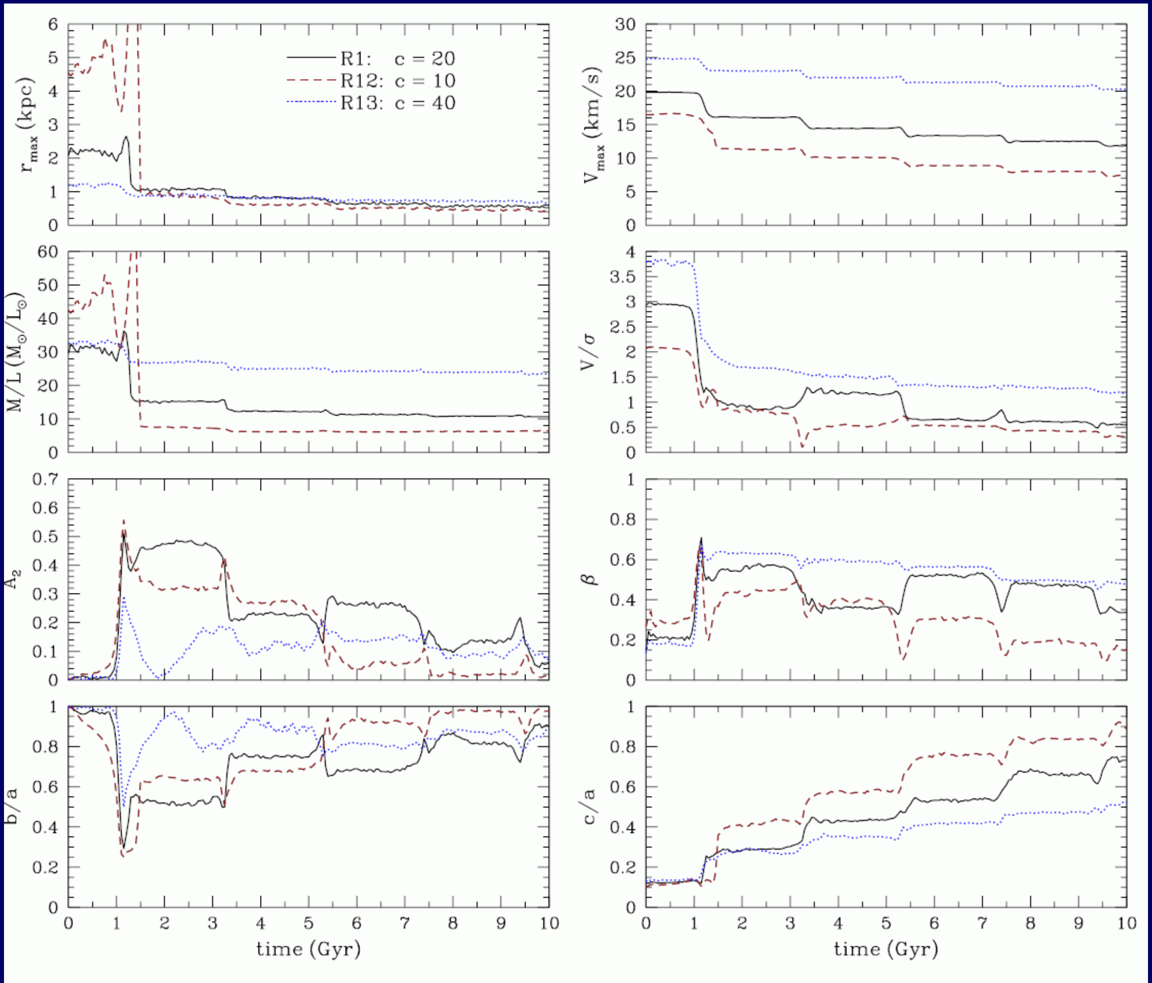


Callegari, Brook, Mayer, Governato, 2009

See also Robertson & Kravtsov 2008; Gnedin et al. 2009; Pelupessy et al. 2009 on the importance of molecular gas to model SF correctly

Tidal stirring more effective if dwarf has shallower potential well (response more impulsive)

Trend with concentration of NFW halos suggests tidal stirring would be even more efficient if dwarfs' halo shallower than NFW as predicted by Governato et al. (2010)
-→ likely easier to explain most distant dSphs (Leo I-II, perhaps Tucana, Cetus)

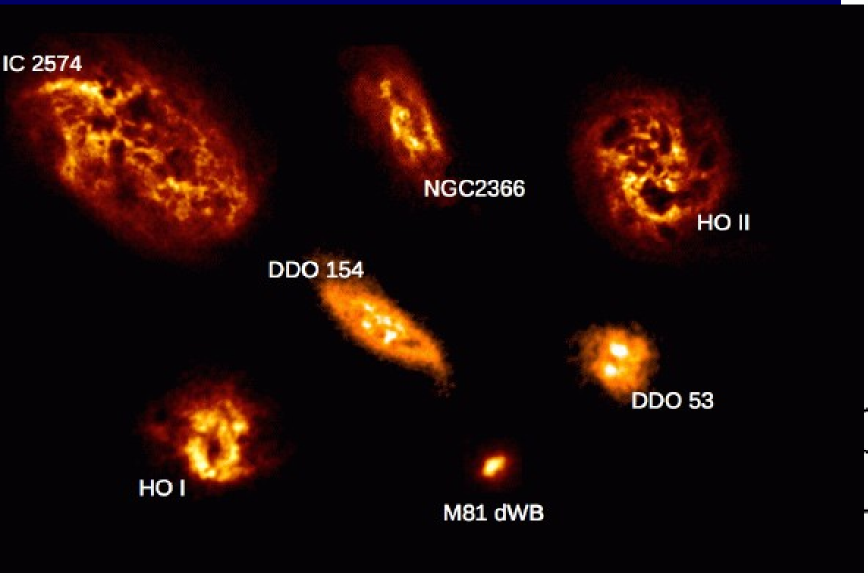


Runs have same initial model for stellar disk + same initial orbit (peri= 25 kpc, apo=125 kpc)

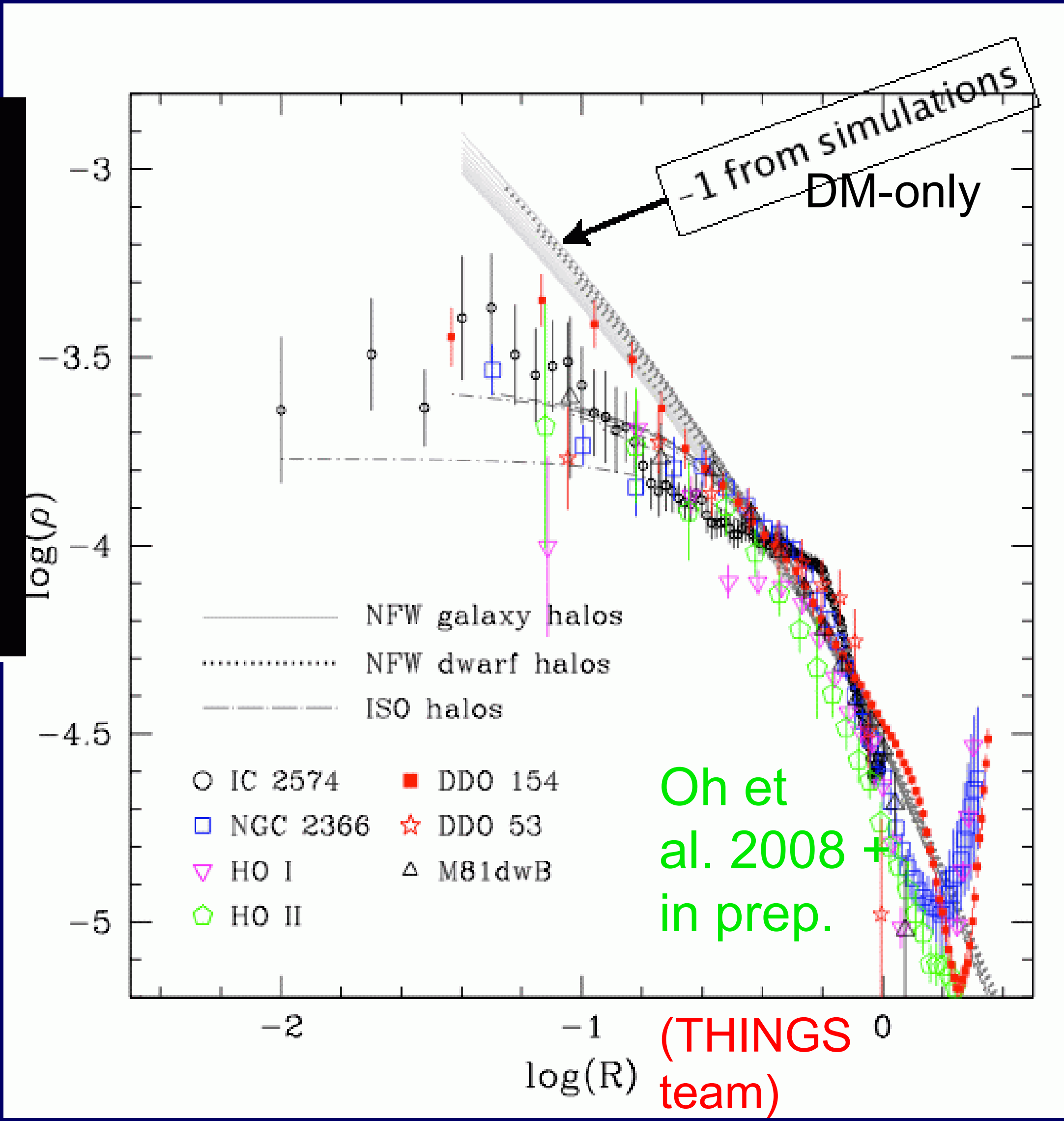
Kazantzidis et al. 2010

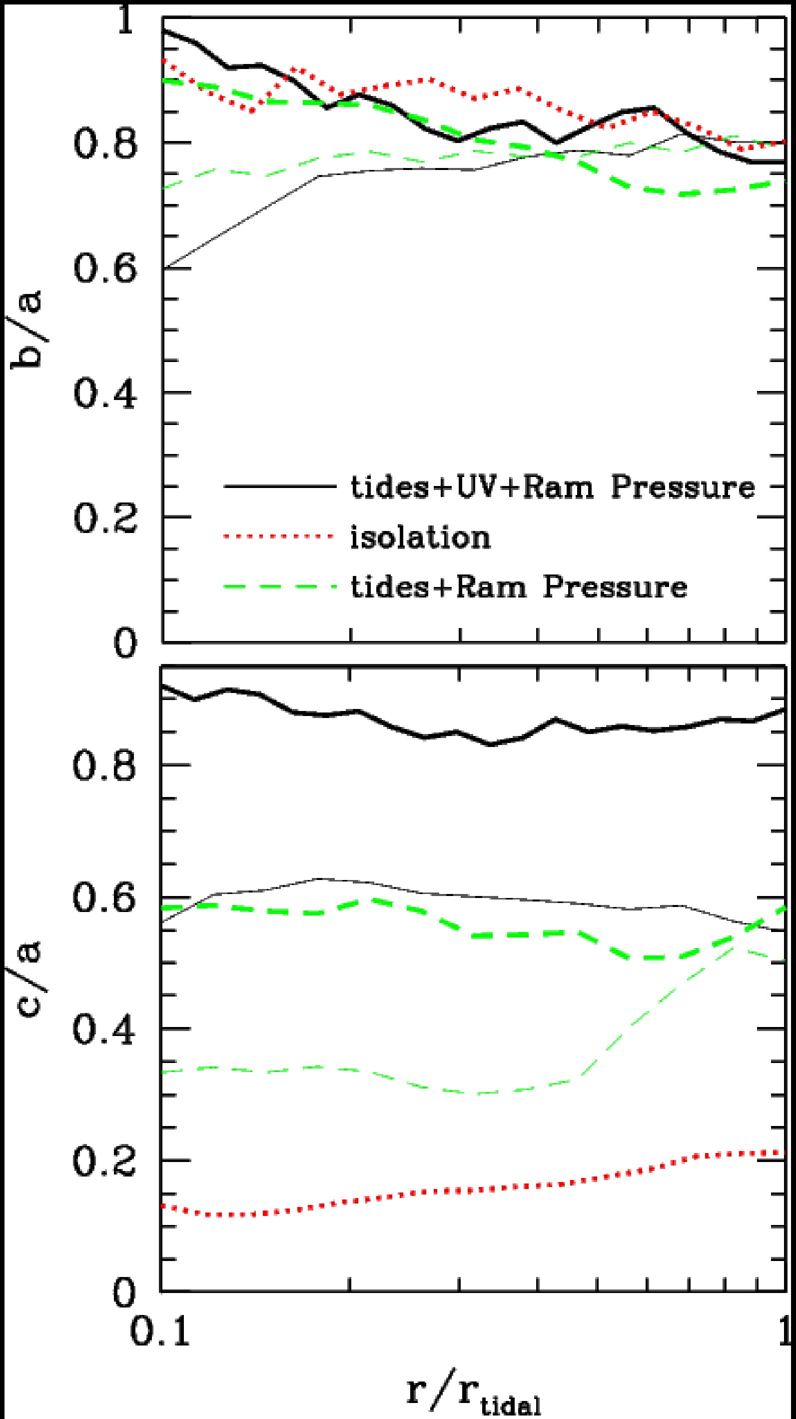
Dark matter in gas-rich dwarfs; cusps or cores?

See de Blok (2010) for a recent review



State-of the art HI observations
From the THINGS survey
(2D velocity fields)

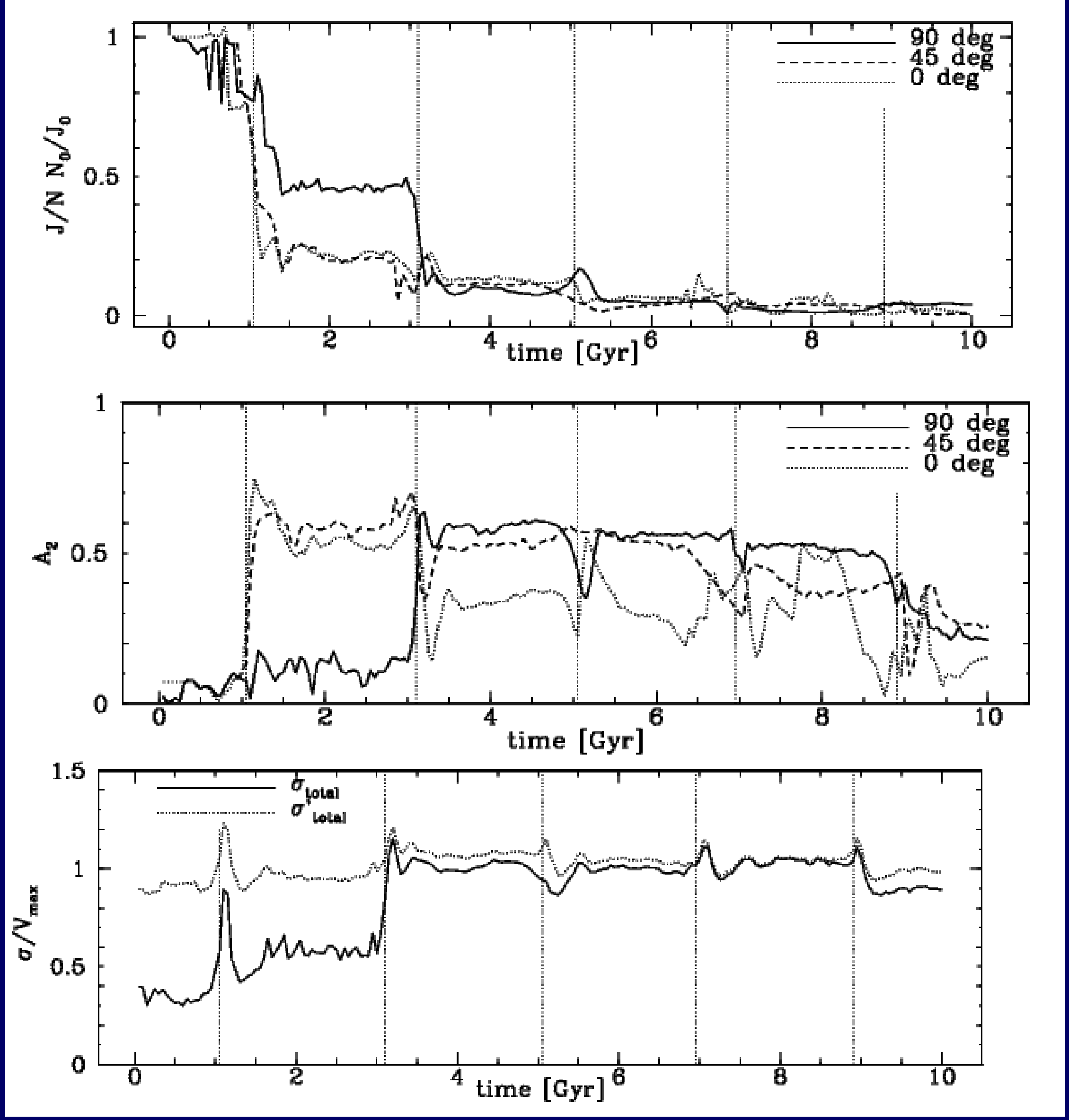




Strong connection between dynamical and hydrodynamical processes

-Complete gas removal (w/UV) is crucial for effective tidal heating into a spheroidal over 10 Gyr

-If gas is retained bar-driven inflow stifles tidal heating by increasing the central depth of the potential (response to tides more adiabatic, see Supp. Material on *Nature*)



New detailed analysis of tidally stirred dwarfs by Klimentowski et al. 2009 (MNRAS, in press))

Supports mapping $V_{max} = 3^{1/2}$ s for velocity distribution of substructure. For missing satellites problem it means solutions in which V_{max} very large (Vmax ~ 3s – e.g. Stoehr et al. 2002; Penarrubia et al. 2007) unlikely

So far:

§Tides+ram pressure stripping at $z > 1$ (high UV radiation) explain complete gas removal in dSphs with initial V_{peak} ~ 20-50 km/s

§Tides transform high v/s disks into low v/s spheroidals

§Both processes more efficient the closer the distance from the primary -□ naturally explain the morphology-density relation

But how to explain very high M/L in some dSphs (and lower in others)? dIrrs have M/L ~ 10-30 (comparable with e.g. Fornax but not with e.g. Draco)

Model described has a major caveat: the initial conditions before the interaction are somewhat arbitrary

Next step:

Repeat interaction experiments use fully cosmological simulations of dwarf galaxy formation to set the initial conditions (Kazantzidis, Mayer & Callegari, in prep.), Including distribution of initial stellar ages and stellar/gas metallicities

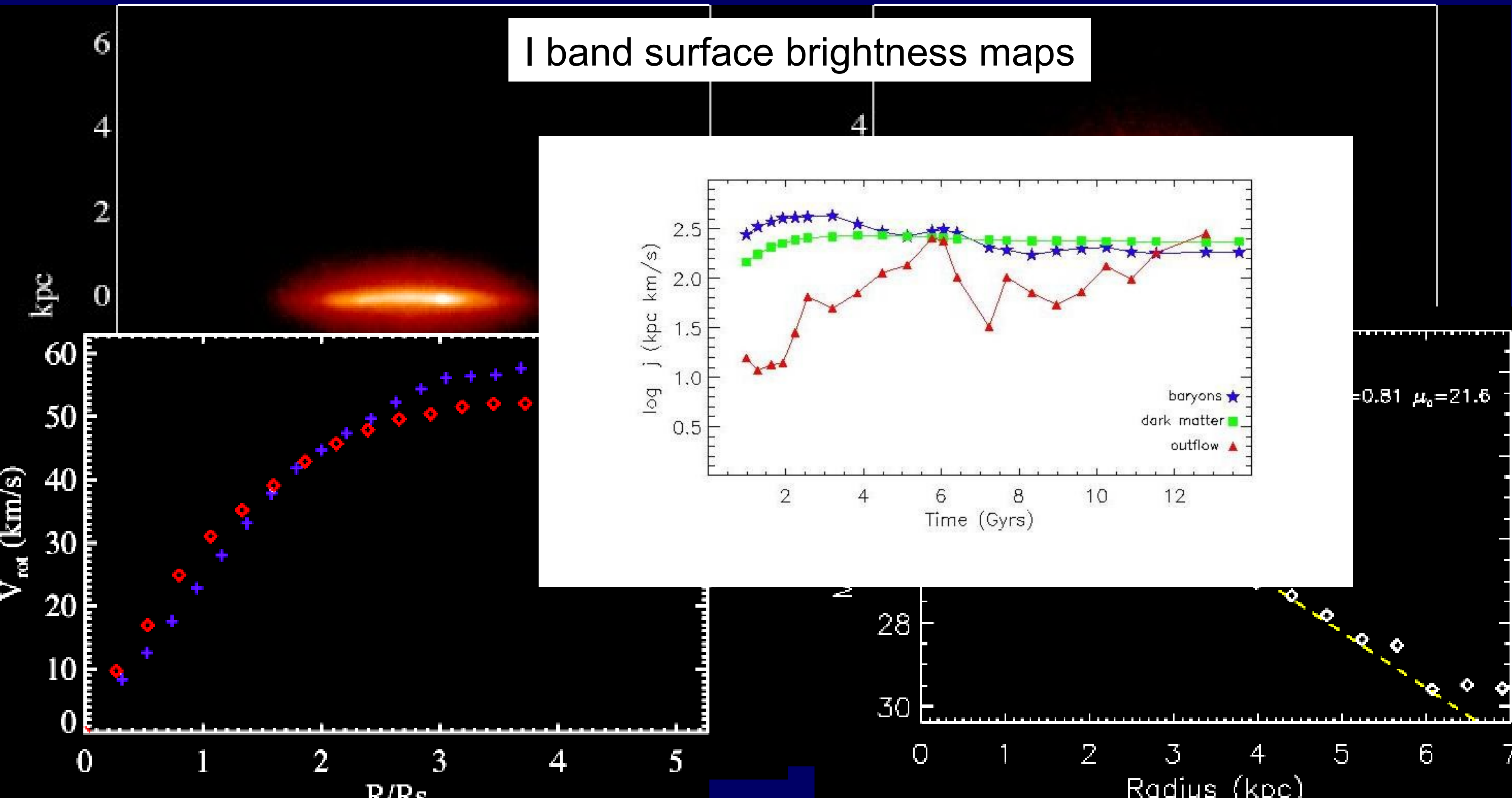
Cosmological simulations employed are the first to produce a realistic, bulgeless gas-rich dwarf galaxy (slowly rising rotation curve, exp. disk) thanks to unprecedented resolution and a more realistic star formation model based on molecular gas densities

Hi-res dwarf galaxy formation simulations

Vpeak (z=0) ~ 60 km/s
NSPH ~ 2 x 10^{6} particles
Ndm ~2 x 10^{6} particles
(Msph ~ 1000 Mo –
we resolve GMCs)

Color coded
gas density
Shown

(Governato,
Brook,
Mayer et al. 2009)

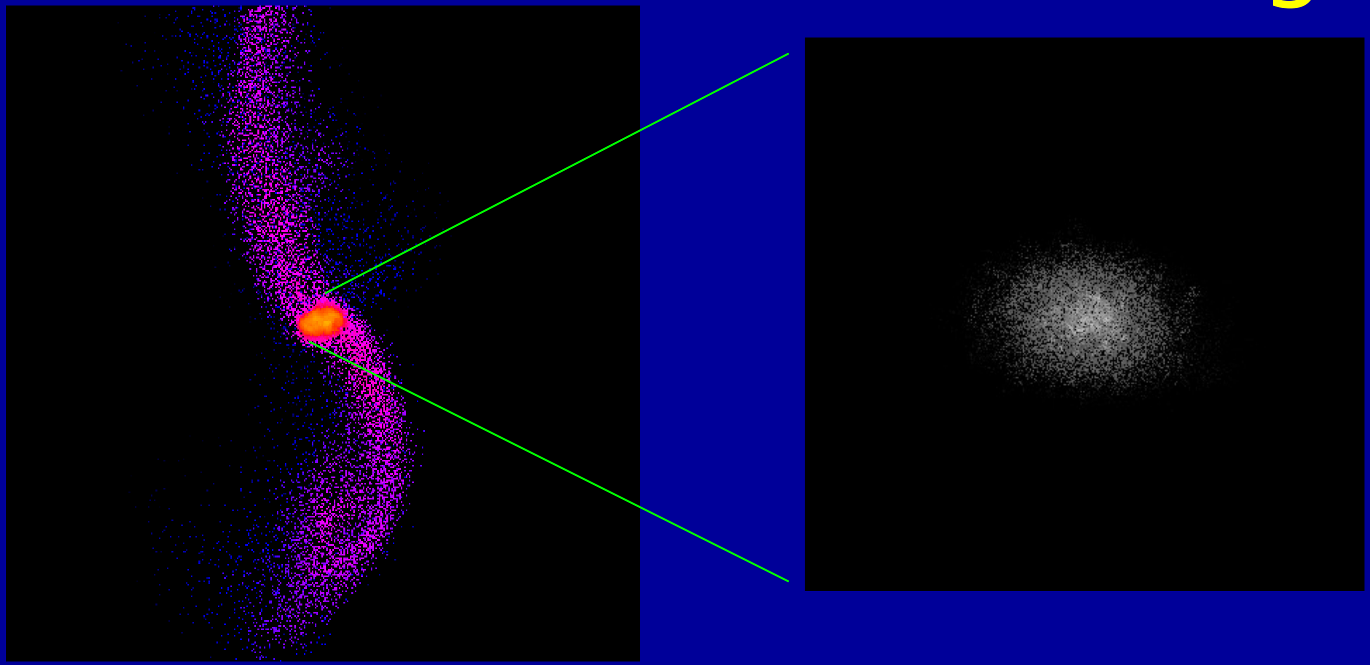


M_I= -17.4 MHI/L_B=1.1 – high gas fraction Vrot~55km/s u-r = 1.5

Baryon Fraction ~0.067 No Bulge, Exponential profile, Slowly Rising Rotation Curve

….and…ends up with cored halo from NFW (see also Read & Gilmore

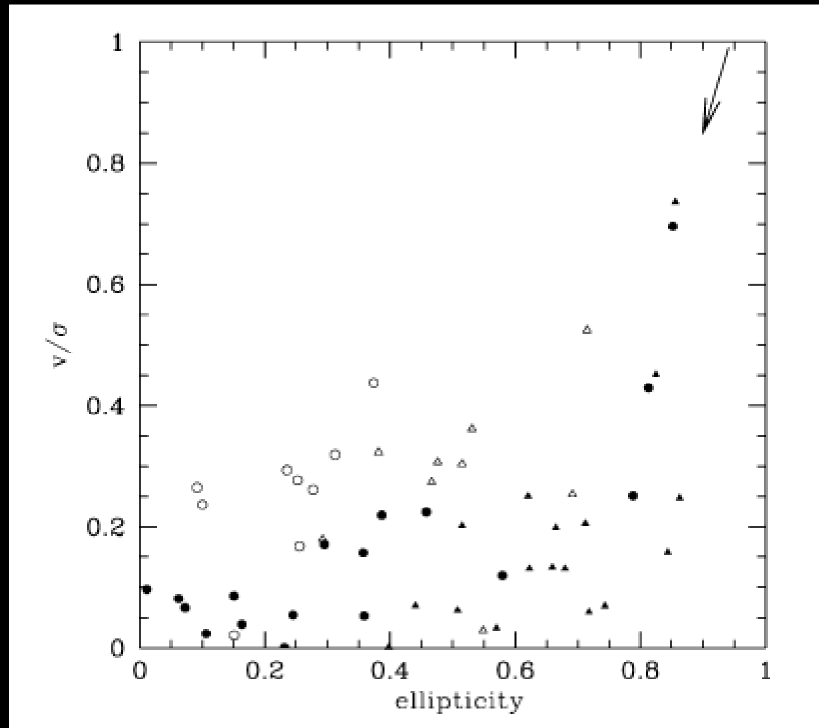
But tides do not remove enough gas



--up to 50% of the gas stripped while another >~30% of the gas is consumed in star formation. The rest stays!

Typical final Mgas/Mstars >~ 0.1 in sims (Mayer et al. 2001; Mayer 2005) while M(HI)/Mstars <0.05 required to match dSphs (e.g. Mateo 1998).

Final V/ (after ~ 10 Gyr)



Large suite of different initial models and different orbits

Within R=Re

Mayer et al. 2001, 2002

Ρεμναντσ αρε μοδερατελψ τριαξιαλ

Διφφερεντ σψμβολσ ρεφερ το λινε οφ σιγητσ αλονγ διφφερεντ αξεσ

Φιλλεδ Σψμβολσ=ΛΣΒ δισκσ, > 23 μαγ αρχσεχ $^{-2}$

Οπεν Σψμβολσ=ΗΣΒ δισκσ, < 23 μαγ αρχσεχ $^{-2}$

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

Τιδαλ στιρρινγ προδυχεσ πρεσσυρε συππορτεδ ρεμναντσ ασ δΣπησ

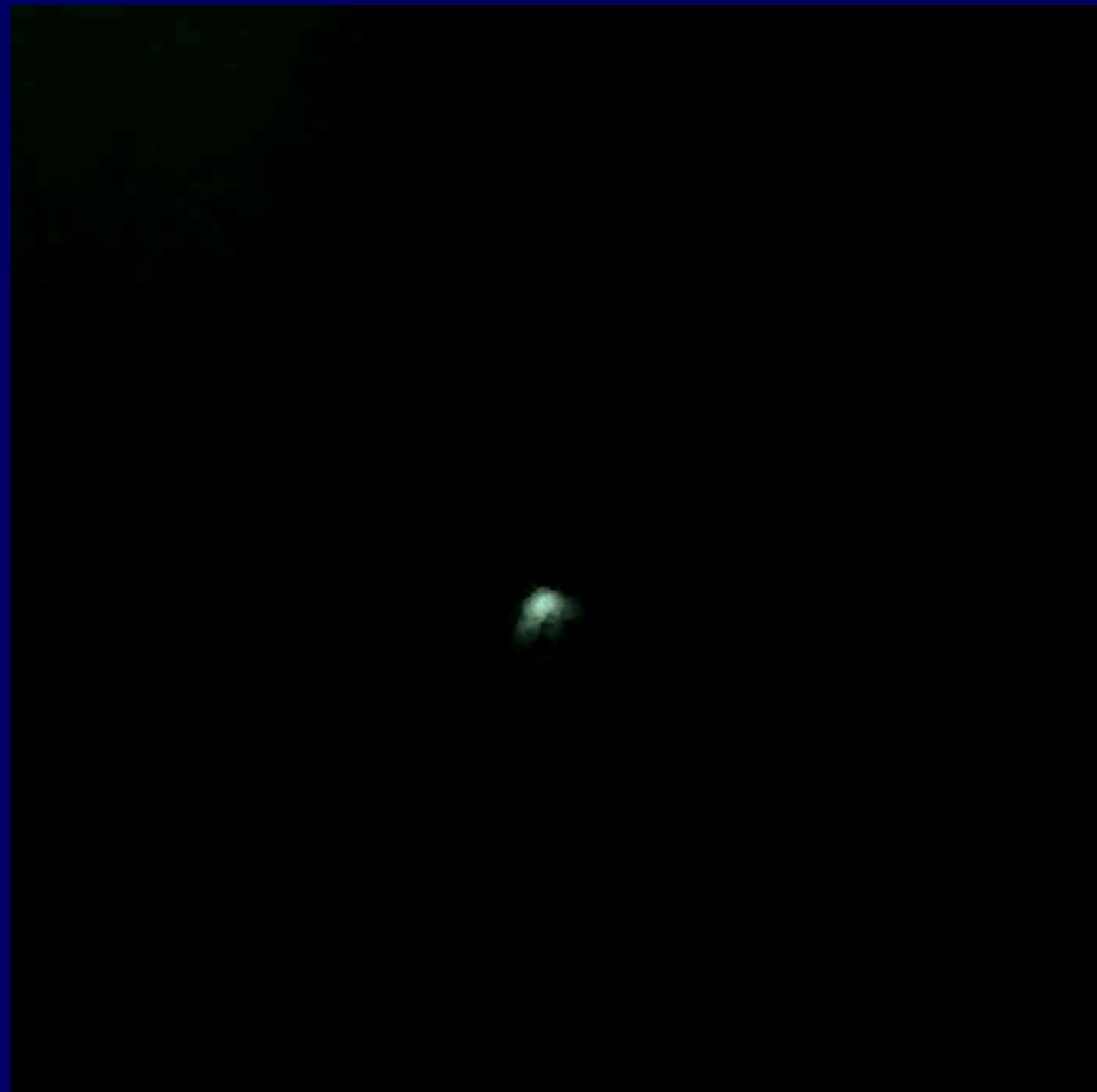
Hi-res dwarf galaxy formation simulation

Vc_{halo} ~ 50 km/s
NSPH ~ 2 x 10^6 particles
Ndm ~2 x 10^6 particles
(Msph ~ 10^3 Mo)
spatial resolution
(grav. softening) 75 pc

- High SF threshold
100 atoms/cm^3

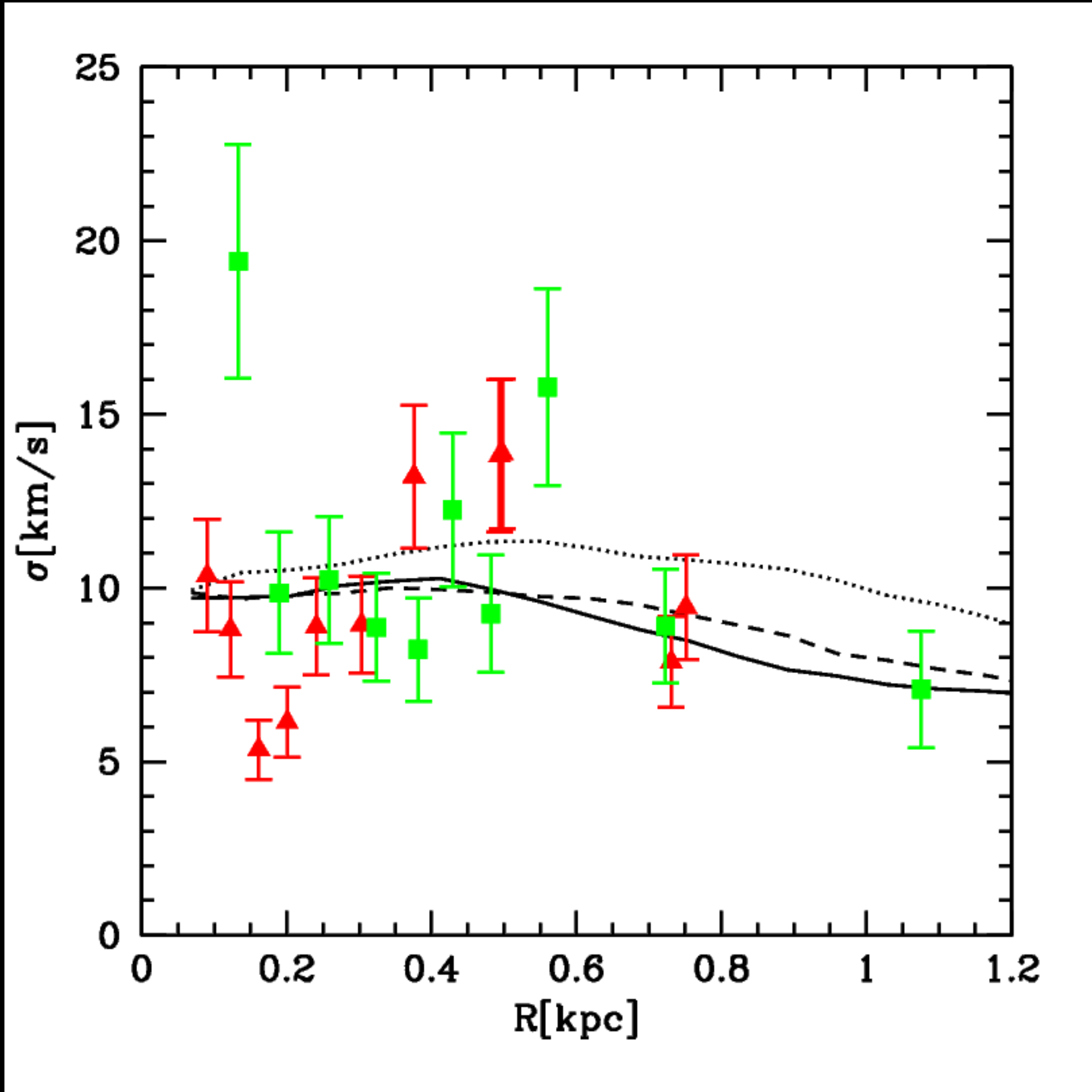
- Cooling function includes
metal lines (gas cools
below 10^4 K)
+ heating by cosmic
UV background

Simulation goes
to z=0

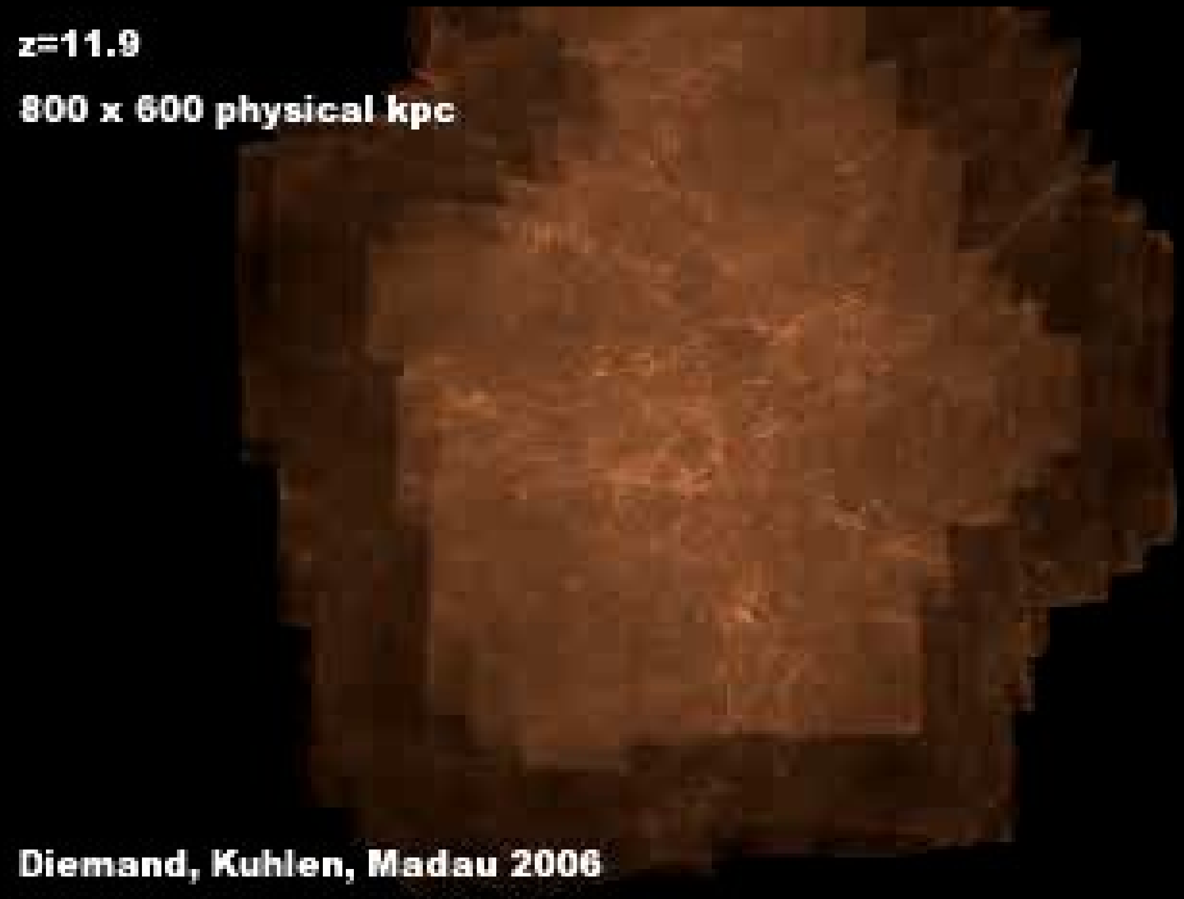


Good match with kinematics of dSphs (e.g. Draco)

In general dSphs show nearly flat velocity dispersion profiles (Walcher et al. 2006;Gilmore et al. 2007; Munoz et al. 2006, 2007) as those predicted by our simulations



The theoretical perspective; dwarf satellites as CDM subhaloes evolve (mass,size) while continously interacting with host halo



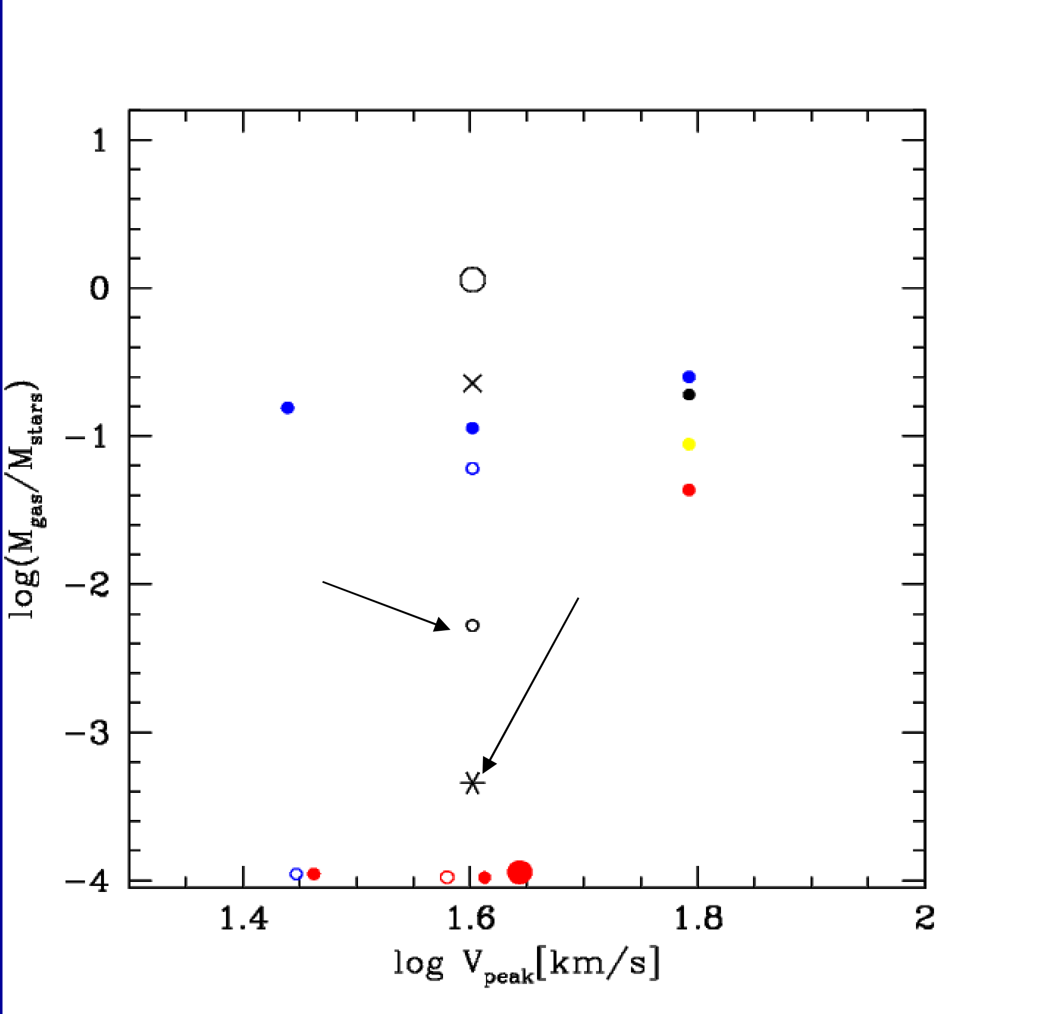
Via Lactea - (Diemand et al. 2007)

300 million particles MW halo with our parallel treecode PKDGRAV

In progress: proximity effect , i.e. local UV radiation from MW

Starbursting MW at z=2 as bulge forms (SFR ~ 50 Mo/yr, like LIRG):
- Within 50 kpc 5-10 times higher flux than cosmic bg (satellites infalling at z > 1 have all pericenters << 50 kpc, see Diemand et al. 2007)

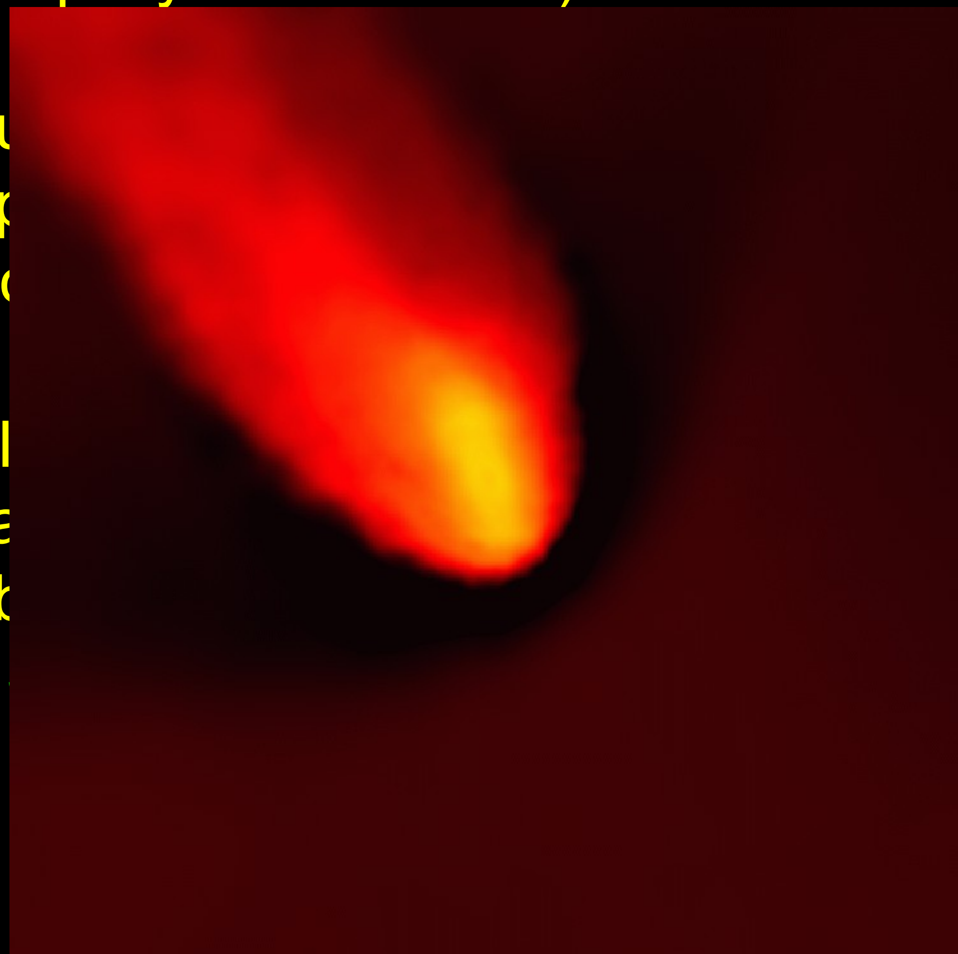
Also will look at effect in clusters:
Preliminary calculations including only effect of BCGs suggest galaxies with Vmax ~< 120 km/s strongly affected in cluster core.
Might be crucial to understand faint end of LF.



Mayer 2005

Mayer & Porciani in preparation

-Star formation suppressed because gas density always too low (mainly because of photoheating by UV bg, note that Vmax drops rapidly to < 30 km/s)



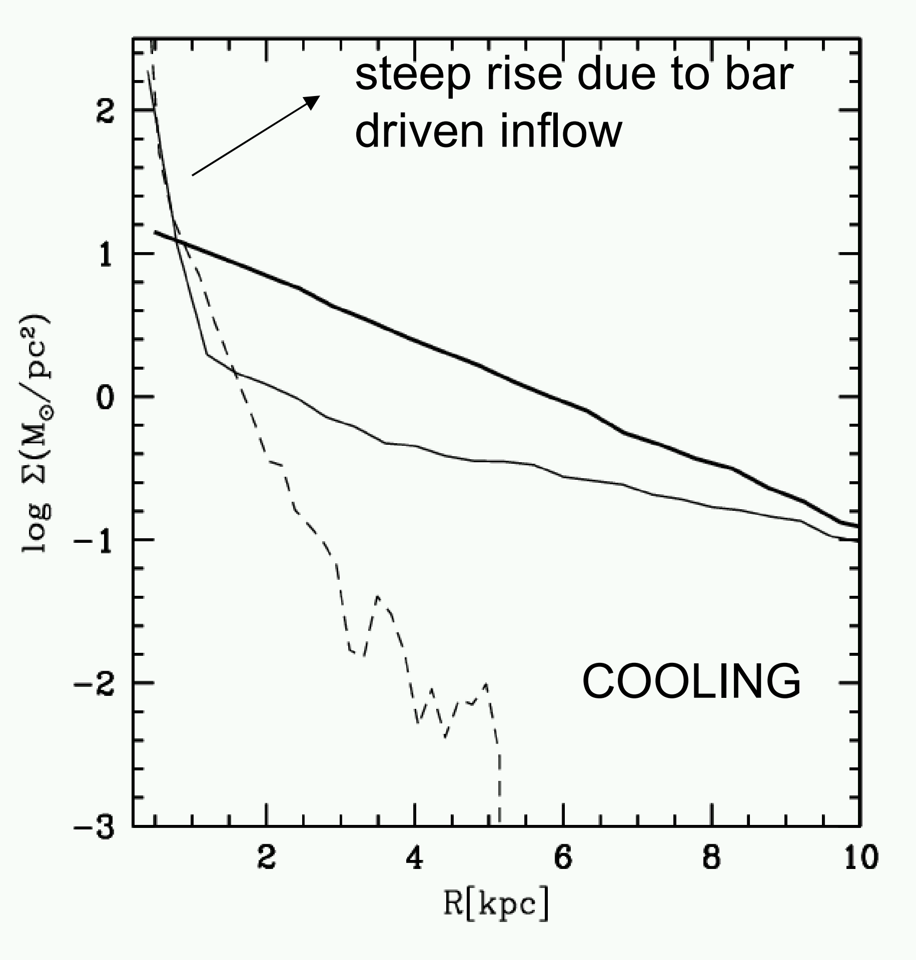
-Instantaneou ... enter passages (V ... + continous (laminar visc ... ~ a few T_{orb}

-Dwarfs stabl ... no ablation of ga ... use of stabilization b ... atter content, see ... T_{orb}

TIDAL AND RAM PRESSURE FORCES DON'T JUST SUM UP….

Bar instability + cooling opposes stripping by driving gas to smaller radii, deeper in the potential well of the dwarf.
Gas within bar radius not stripped unless heating source expands gas again

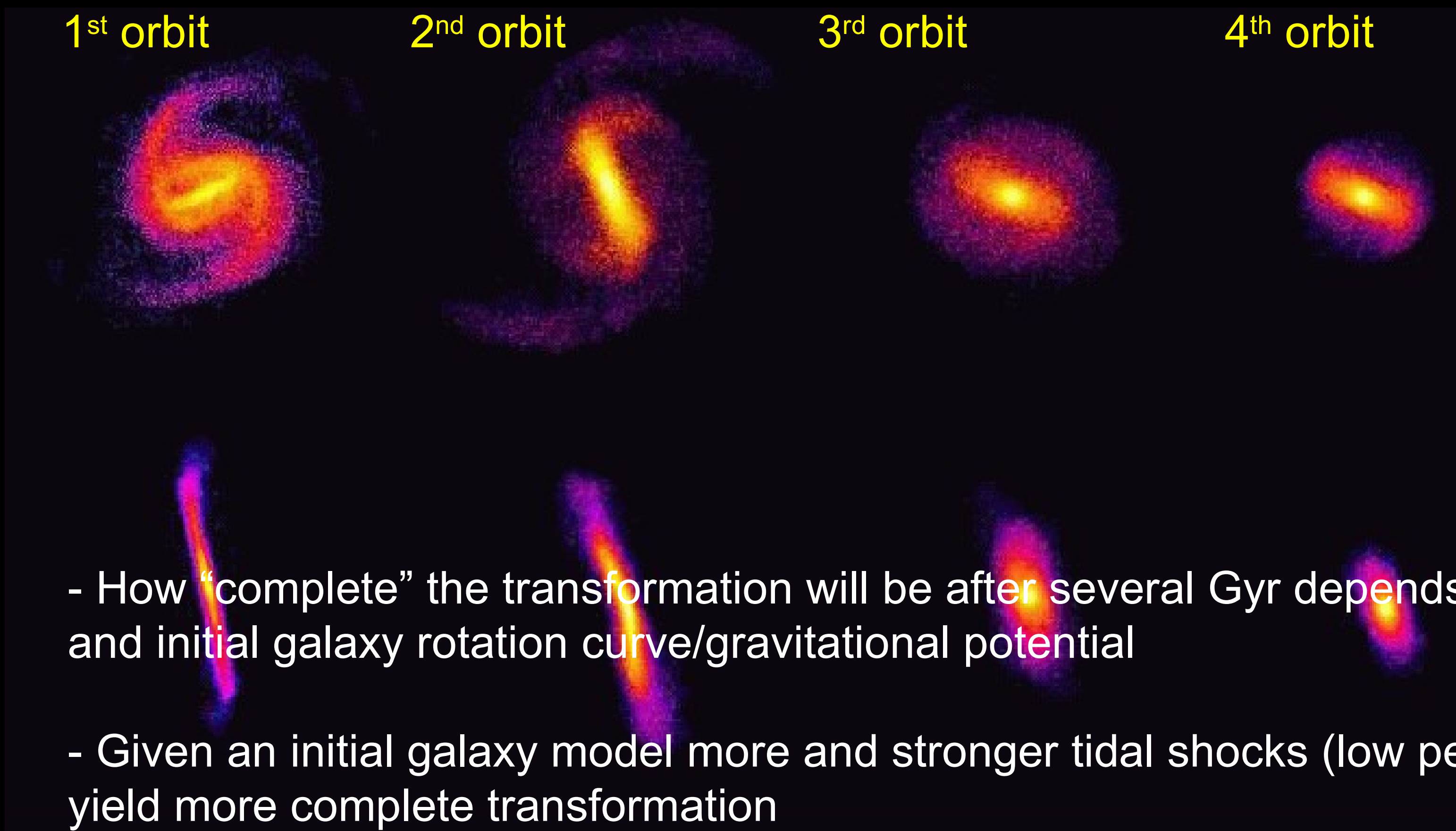
Evolution of gas surface density profiles, dwarf with initial Vpeak = 60 km/s



Tidal stirring = repeated tidal shocks at pericenters with primary galaxy (Weinberg 1994; Gnedin, Hernquist & Ostriker 1999) turn late-type dwarf (dIrrs) into faint spheroidals (Mayer et al. 2001a,b; 2002)

Physics: Tidal heating/stripping + bar/buckling instabilities

Bar tidally triggered, galaxy stable in isolation due to low surface density



- How "complete" the transformation will be after several Gyr depends on orbit and initial galaxy rotation curve/gravitational potential

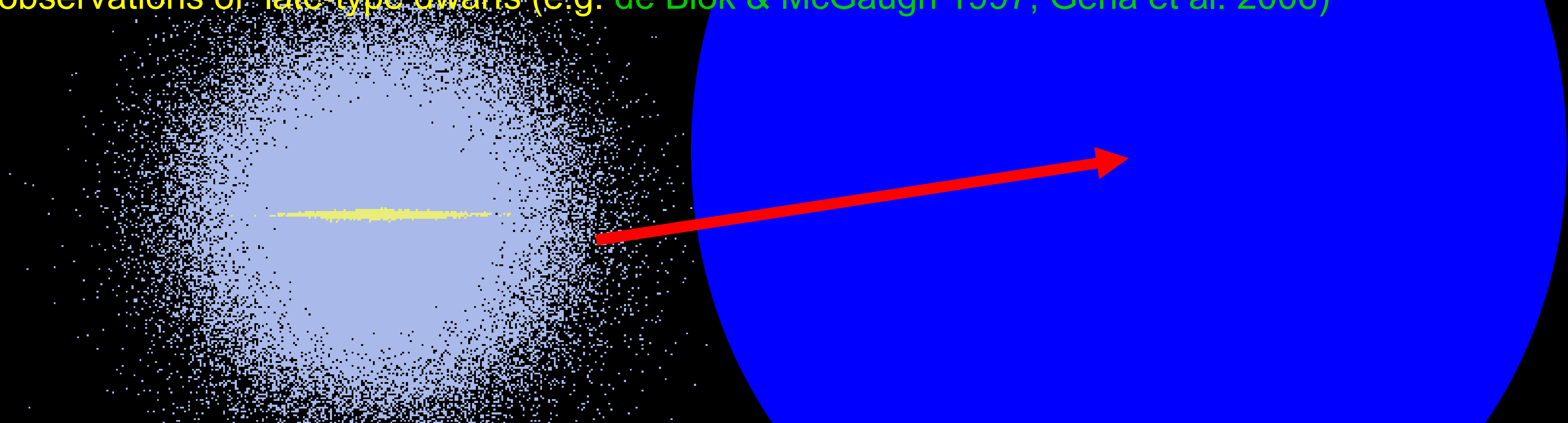
- Given an initial galaxy model more and stronger tidal shocks (low peri) yield more complete transformation

Need help from very hi-res controlled simulations.

Example: interaction simulations to study origin of morphology-density relation

Hi-res N-Body+SPH models of disky dwarfs (Hernquist 1993) -- Vc ~ 30-70 km/s
Assumption: dwarf disky at formation since baryons collaps ... ning halos
in CDM (White & Rees 1978; see also Kaufmann, W ...

Initial conditions
(1) orbits and structure of galaxies/halos (NFW) from cosmological runs + scaling relations between baryonic disk and halo from Mo, Mao & White (1998)
(2) free parameters (e.g. disk mass fraction, gas fraction in disk) chosen based on observations of late-type dwarfs (e.g. de Blok & McGaugh 1997; Geha et al. 2006)



•Throw them in a massive MW-sized galaxy halo

Hypothesis to verify: transformation of late type dwarfs into early type dwarfs driven by tidal interaction with massive primary halo

Mayer et al. 2001, 2002, 2003, 2006

What's next?

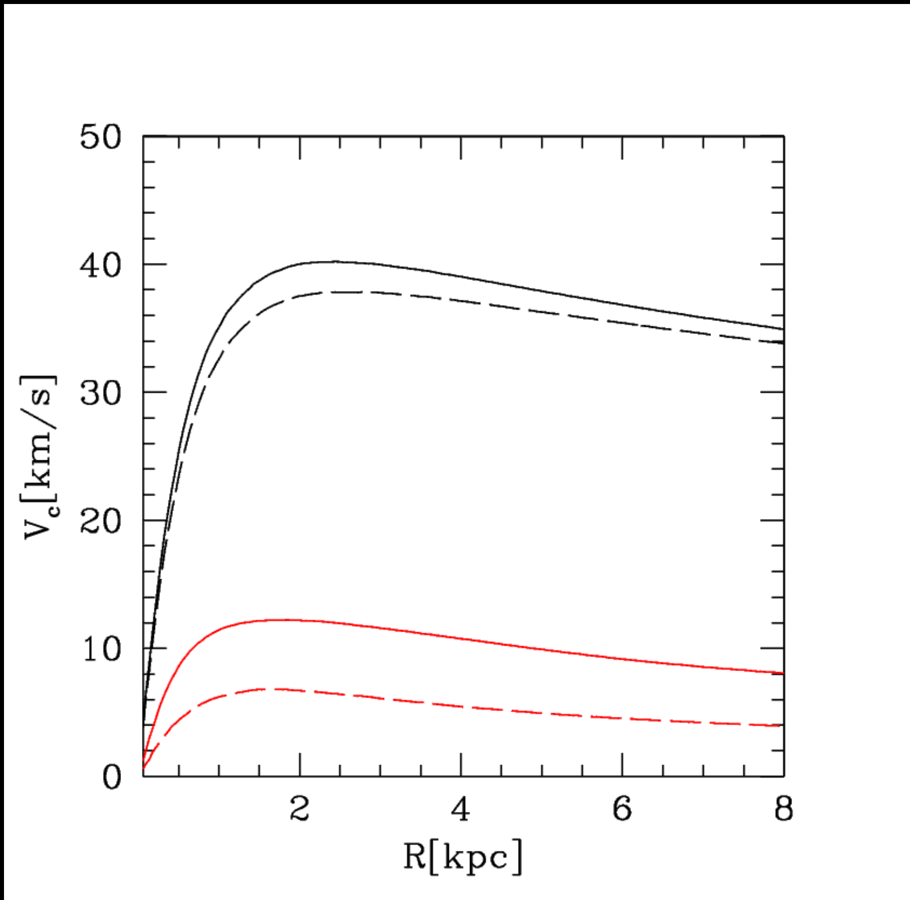
-Verify model with new generations of cosmo+hydro simulations, i.e. look at statistics of a satellite population as opposed to simulating individual cases (w/Beth Willman and Fabio Governato)

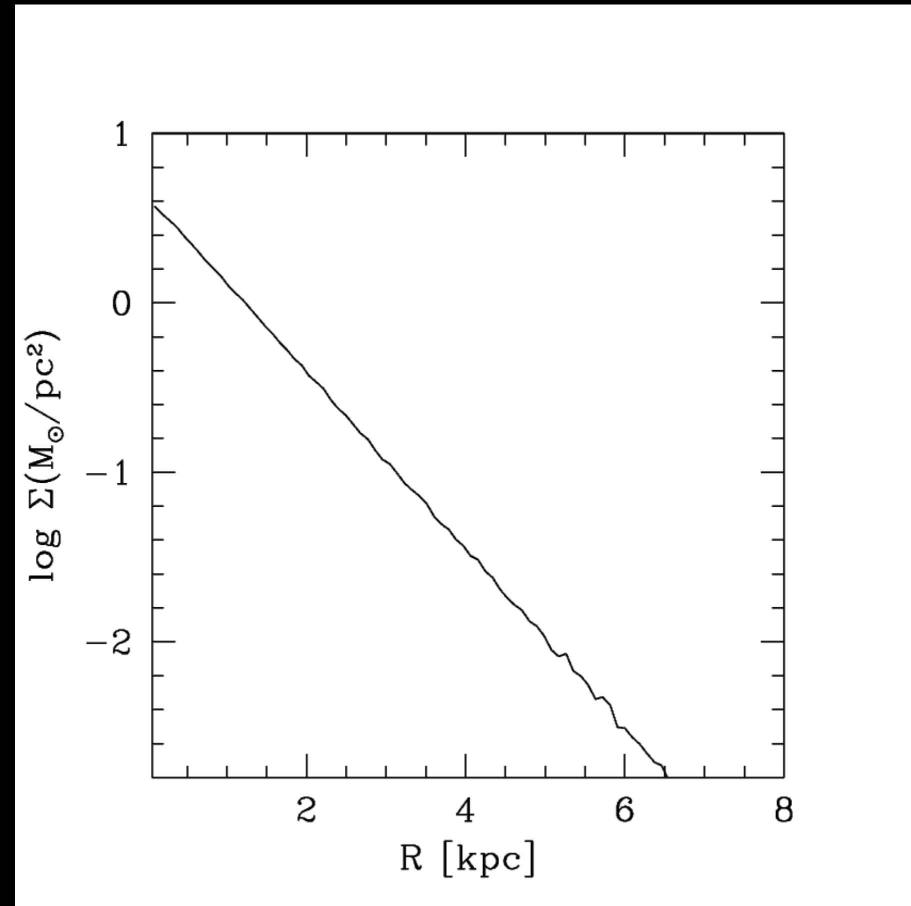
-Compare with upcoming proper motions (e.g. GAIA) that should measure the orbits of the satellites. Expected is trend between orbital time and M/L (while now only distance is known) easy to falsify model

-Study origin and evolution of "field" dwarfs (dirrs) as opposed to dSphs. Use simulations combined with new detailed SF histories of LG dIrrs obtained within the LCID program with ACS/HST (Minnesota/Michigan/IAC/STIS)
Idea: limited effect of environment, better tracers of cosmic reionization

Evolution of a gas dominated dwarf in MW potential

Mayer, Kazantzidis, Mastropietro, Wadsley, *Nature, 2007, 445, 738*



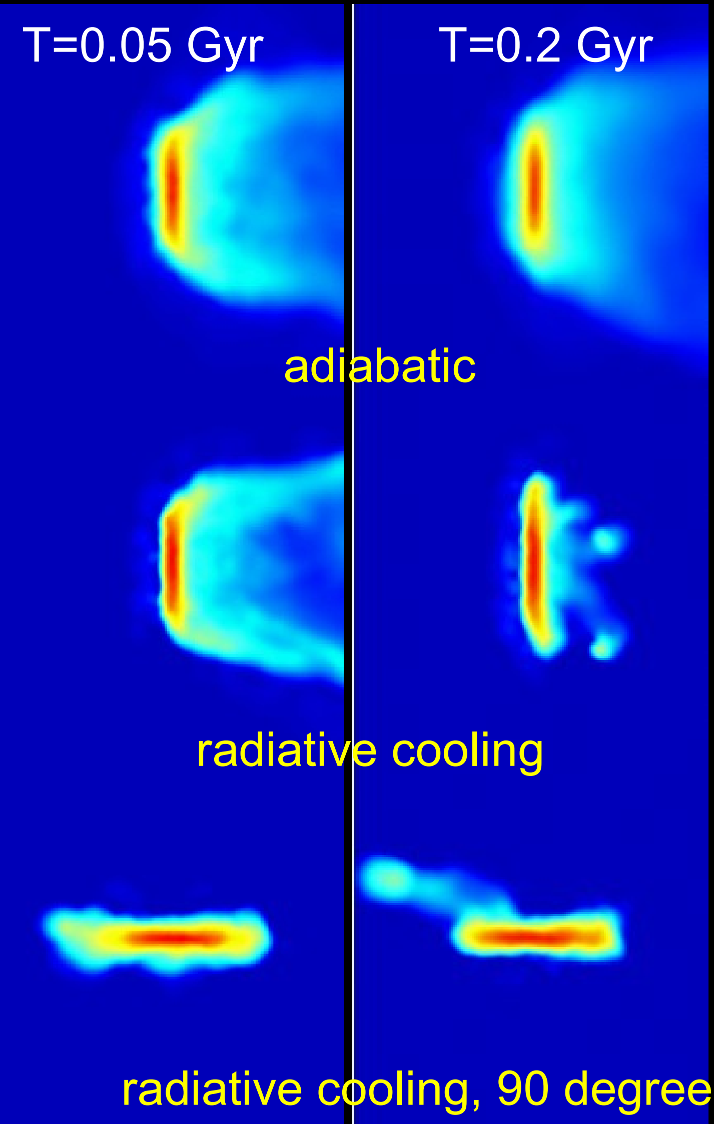


Mgas/Mdisk ~ 0.8, consistent with assumed baryonic surface density based on Li, MacLow & Klessen 2005

Tube Flow runs: ram pressure only

2 million SPH particles to control numerical artifacts

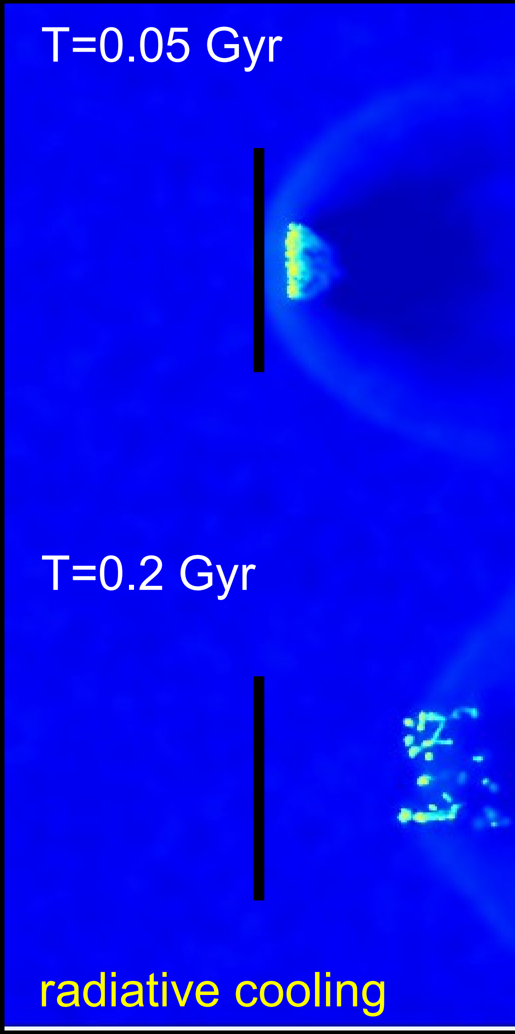
Vpeak=40 km/s



-- Complete stripping requires Vpeak < 30 Km/s (also Marcolini, Brighenti & Matthews 2003 with eulerian code)

-- Stripping reduced with cooling, less gas leaves the disk + fall back of some gas that leaves the disk

Vpeak=25 km/s



Cosmological simulations with dm + baryons

Formation of a Milky Way-sized galaxy

(Ngas, Ndm > 10^6 within R < Rvir)
Gravity+Hydro+SF+sup. feedback

(Governato,Willman, Mayer et al. 2007)
Mayer, Governato and Kaufmann 2008;
Governato et al., 2008)

Frame size =
200 kpc comoving

Movie shows color-coded density

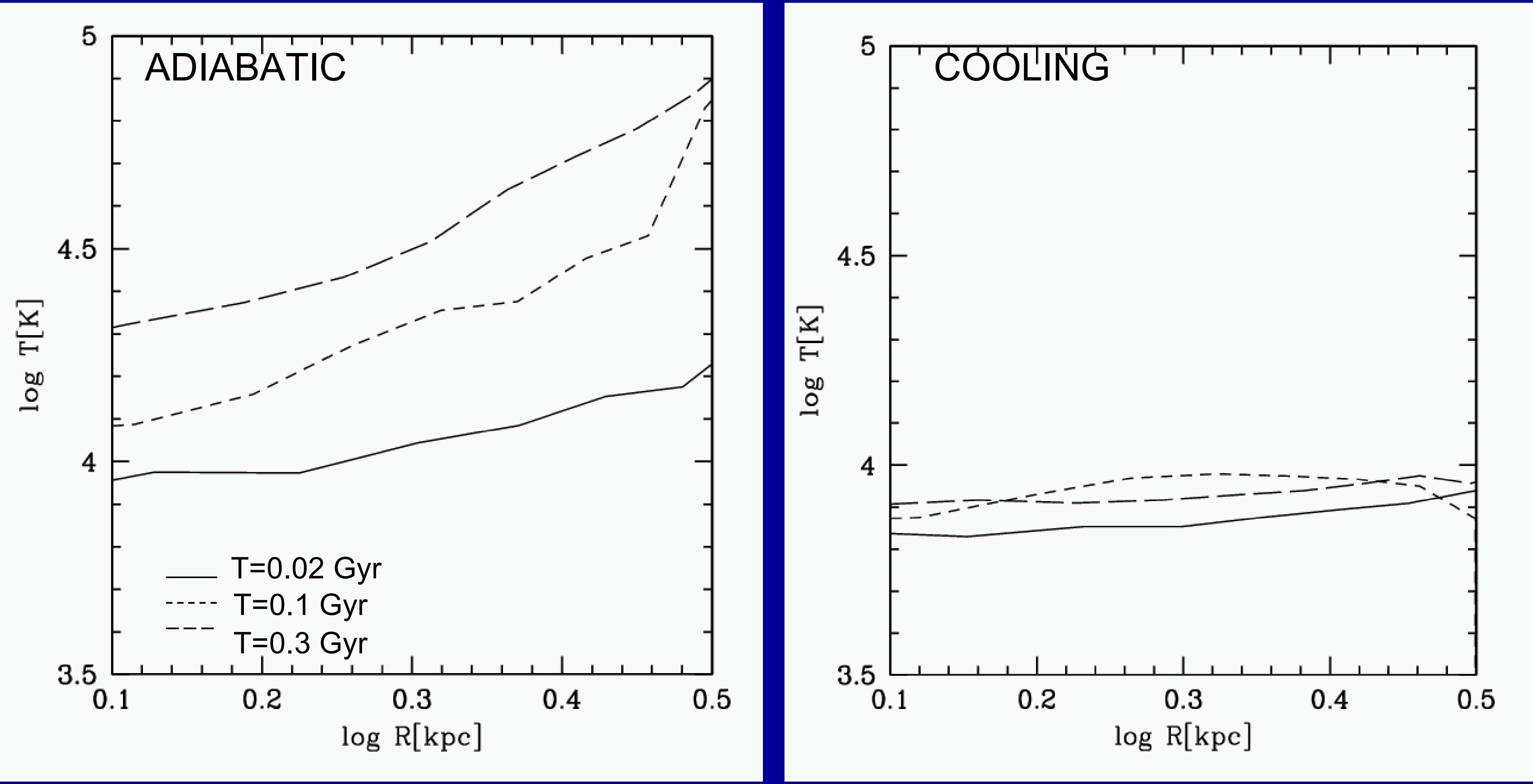
Green=gas
Blue= young stars
Red=old stars

Numerical resolution issue:
10^5-10^6 SPH and DM particles needed in individual objects to control numerical two-body heating, numerical loss of angular momentum and overcooling (Mayer 2004; Kaufmann, Mayer et al. 2007) – now possible for central galaxy but not (yet) for satellites

Why stripping more effective with no radiative cooling?

1)Gas of the dwarf heated by compression from external medium (galaxy moves mildly supersonically)

2) *Without radiative cooling adiabatically expands and becomes easier to strip, with radiative cooling cools much faster than it can expand.*



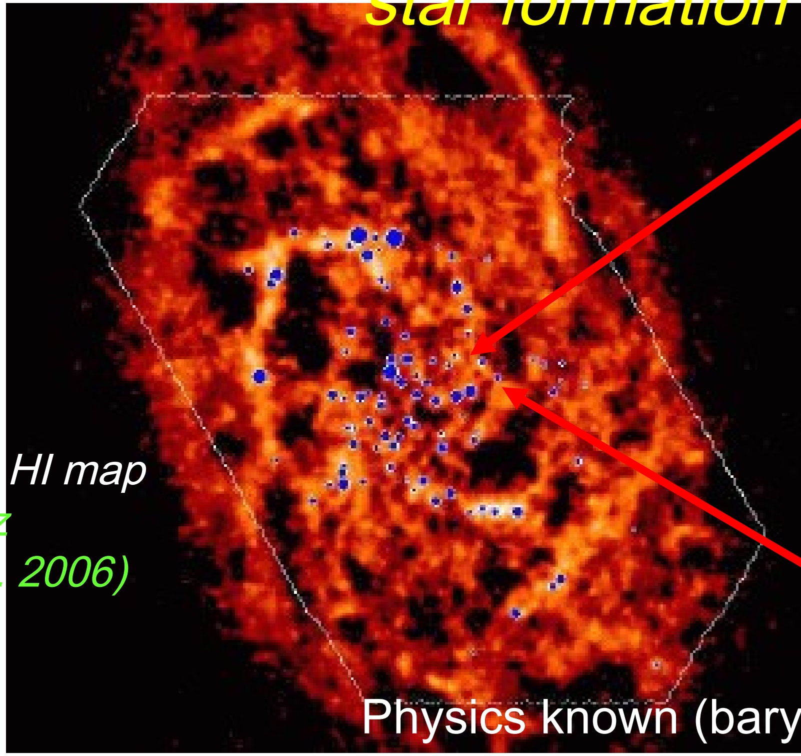
Why do we care about LG dwarf satellites?

- They are the closest and thus best studied among dwarf galaxies ----> galaxy formation

- They are the most dark matter dominated galaxies known -□ nature of dark matter

- They are associated with the CDM crisis at small scales, namely the missing satellite problem -□ structure formation

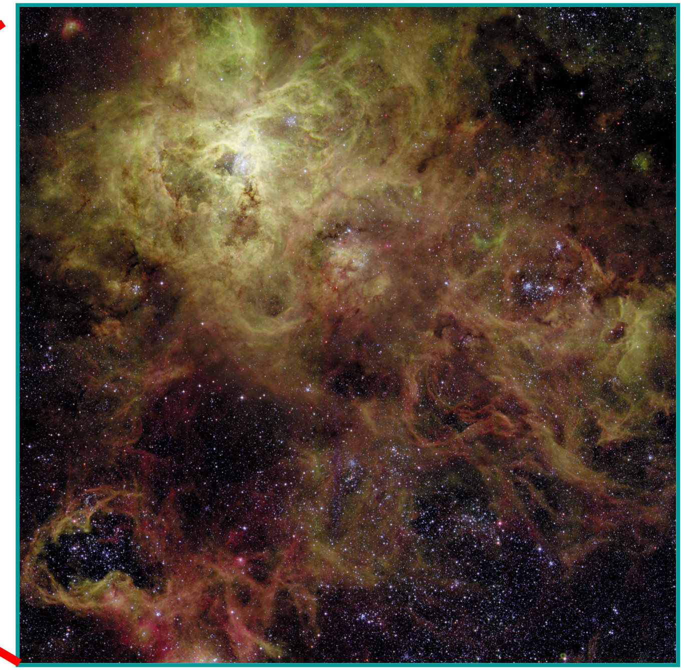
Complexity: *Physics of the interstellar mediu star formation (SF)*



HI map

(Blitz et al. 2006)

Physics known (bary

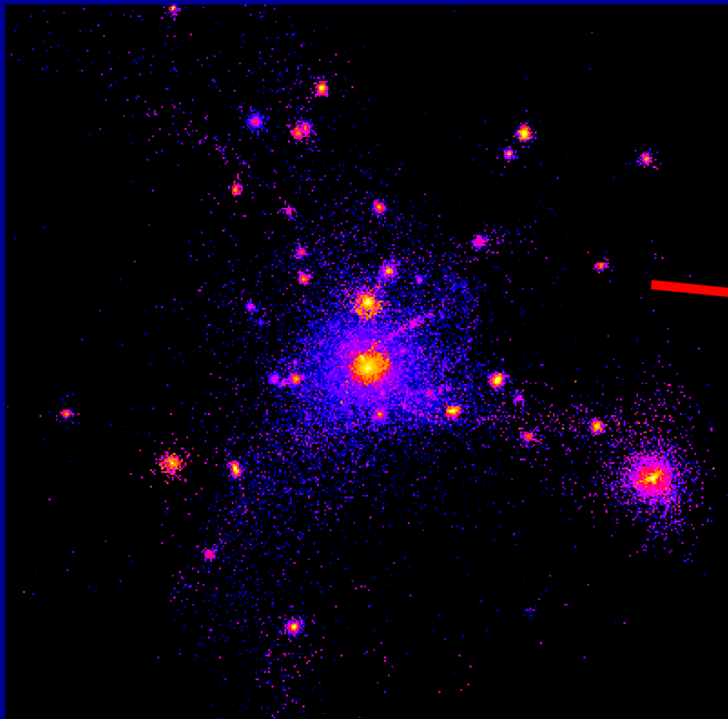


- Multi-scale (< 1 pc to 1 kpc) – resolution of numerical models of cos formation was only ~ 1 kpc till 2004, <100 pc today

- Multi-process: cooling, heating, phase transitions (e.g. from HI to H_2 star formation, stellar explosions, self-gravity, MHD phenomena, visc (what source viscosity?). Some of these processes not completely understood plus require interplay between many scales

"Decently" resolved satellites (Npart > 1000) in LCDM simulation

Mayer 2005

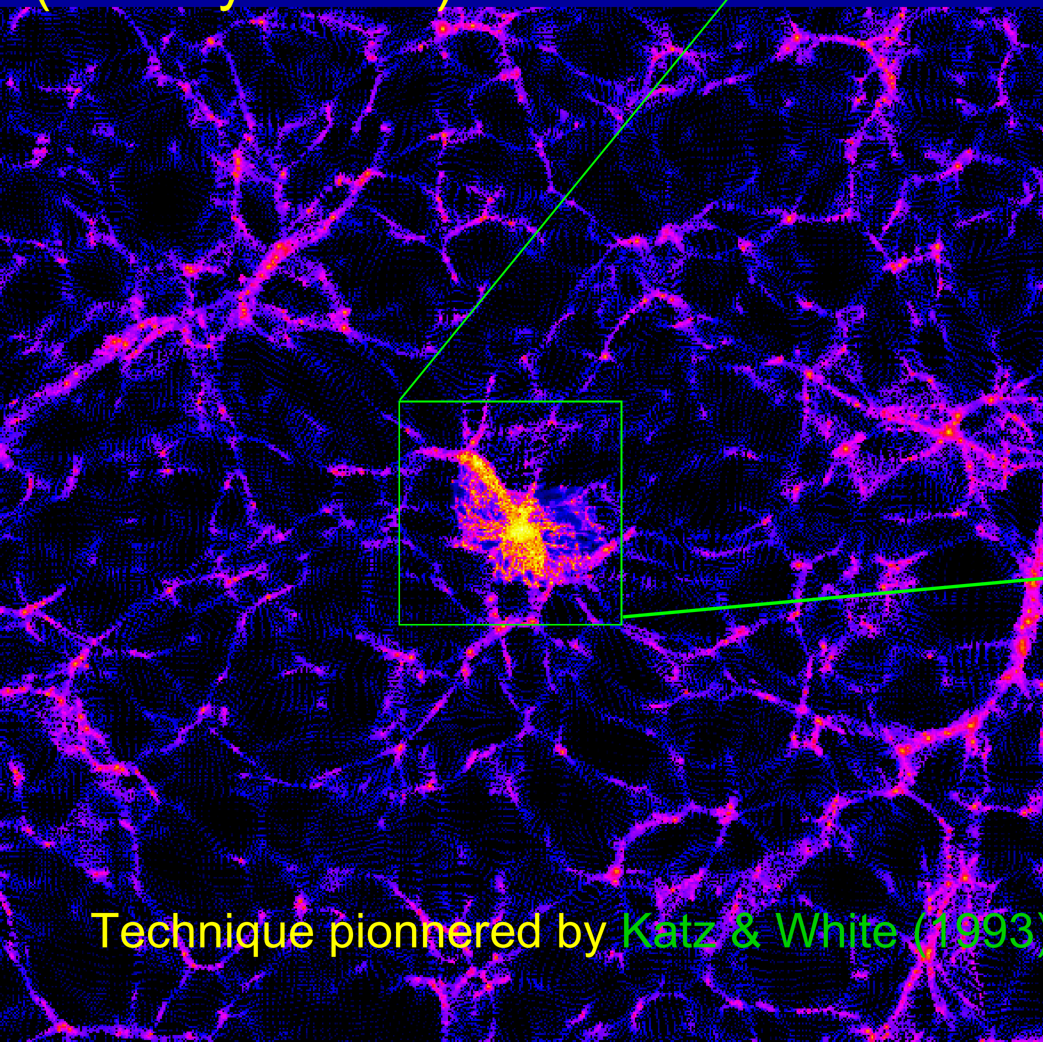


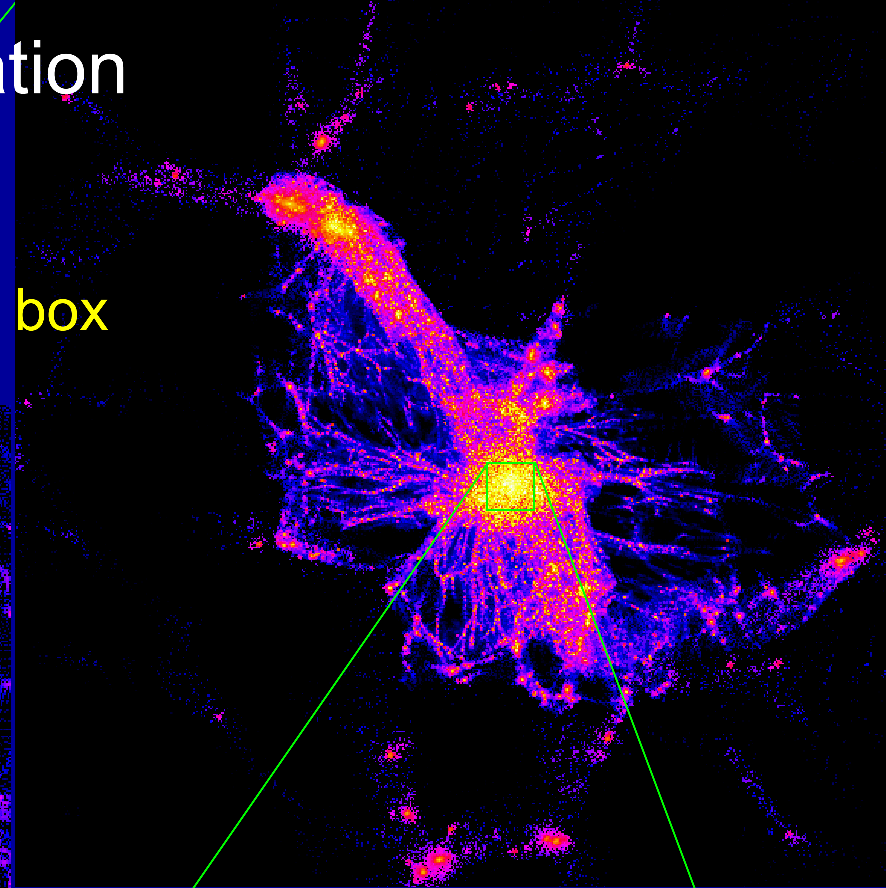
ong correlation between kinematics of the stellar component
dwarfs and the number orbits.
t satellites within 200 kpc from the primary completed more
n one orbit and have v/s << 1 like dSphs.
ital time is the key parameter governing *Tidal Stirring*
yer et al. 2001b).

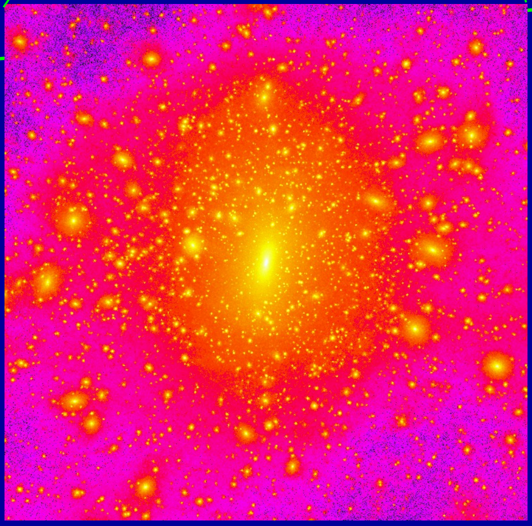
High resolution galaxy formation

(Governato, Mayer et al. 2004, 2005)

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

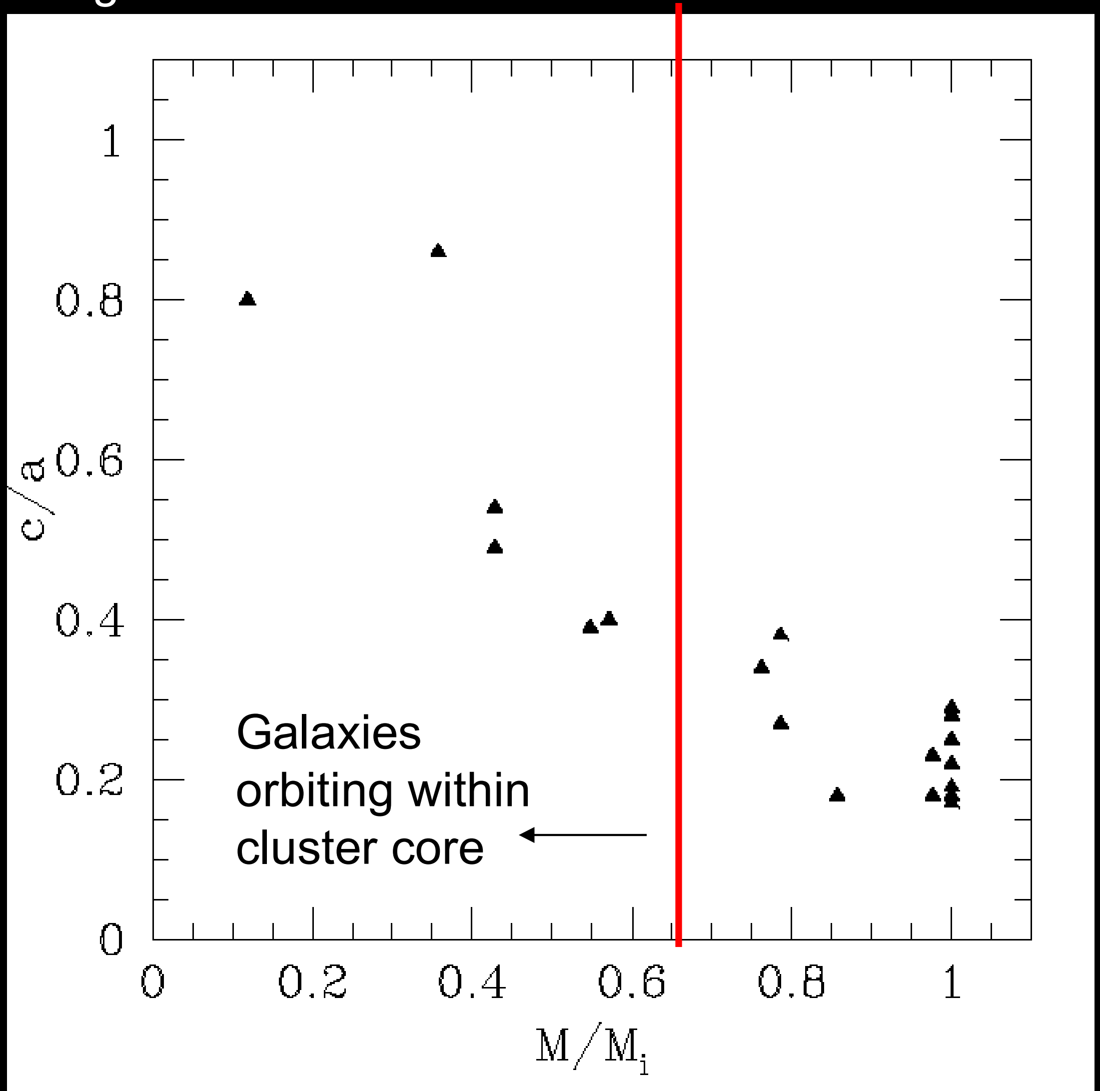


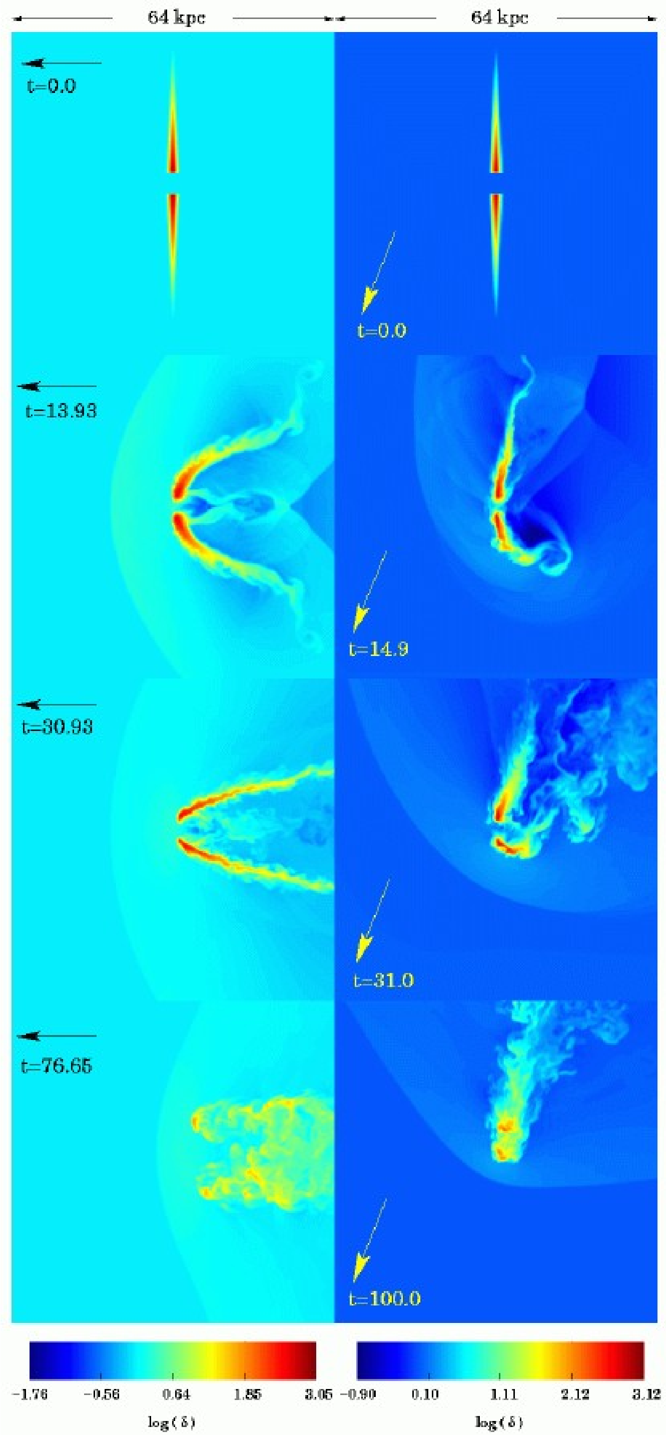




Technique pionnered by Katz & White (1993)

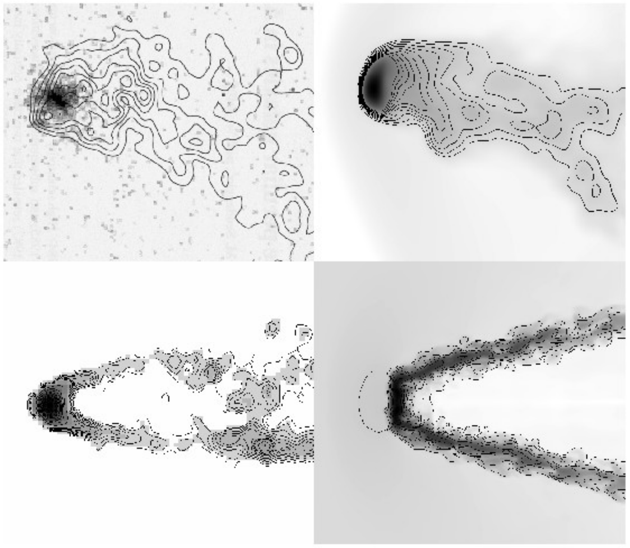
(1)Galaxies lose up to 90% of their mass, but none is completely destroyed.
More mass loss for galaxies with orbits well within the cluster core, final luminosities down to Mb ~ -15.5 ----> higher dwarf-to-giant ratio in the core + increase of dwarf-to-giant ratio with time.
(2)Higher stellar mass loss <------ more spheroidal remnant
Indeed dEs faintest galaxies in clusters

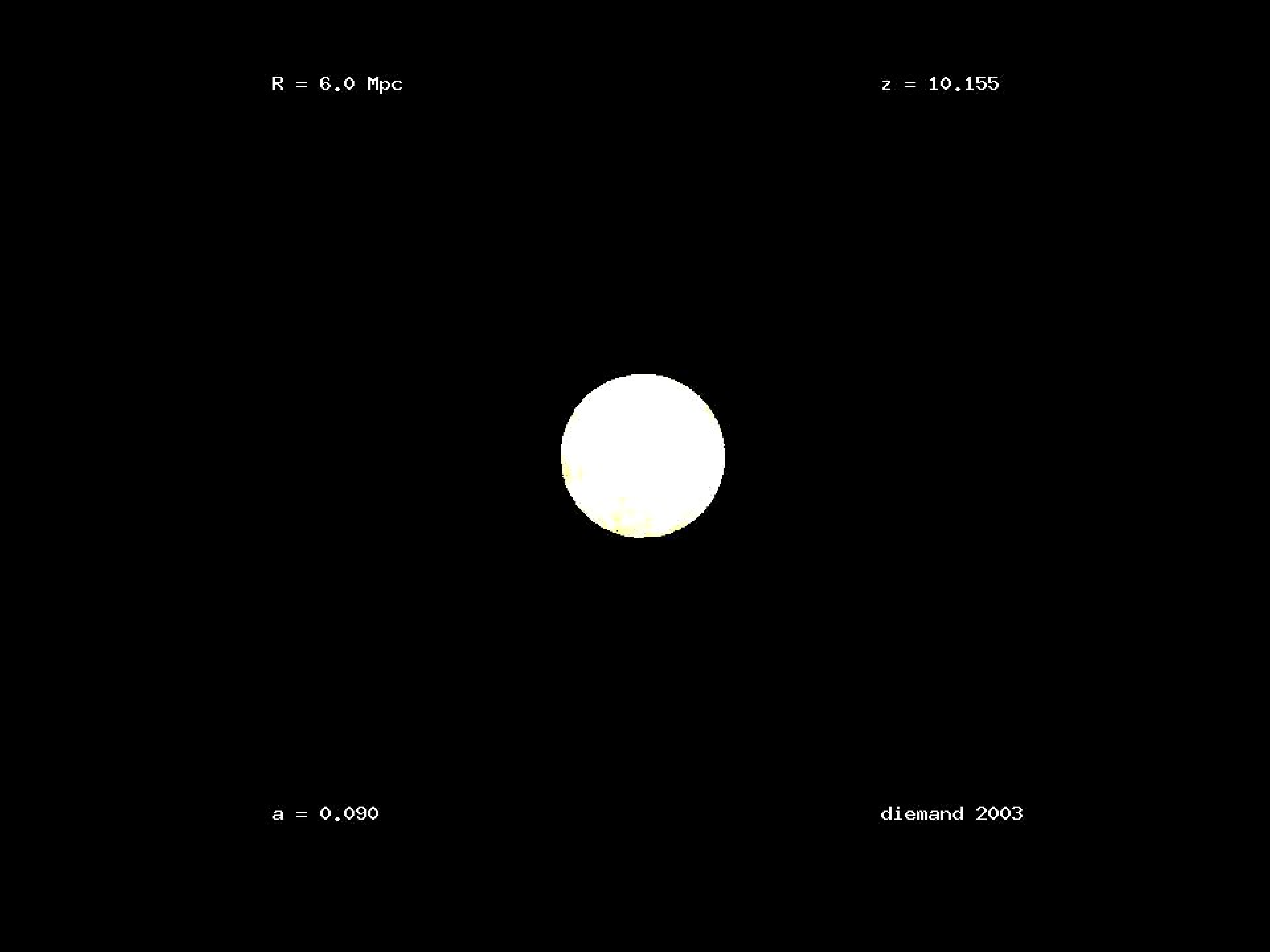




(Quilis et al. 2000)

Result: truncation of star formation, passive spiral or S0 (but tides crucial to shape morphology – see next talk by Oleg Gnedin)




R = 6.0 Mpc
z = 10.155
a = 0.090
diemand 2003

Questions

What has determined the present-day structure, star formation histories and spatial distribution of dwarf satellites?

- What is more important, internal mechanisms -- e.g feedback from star formation -- or environmental mechanisms -- e.g. tidal effects, ram pressure? Or is the key a combined role of both??

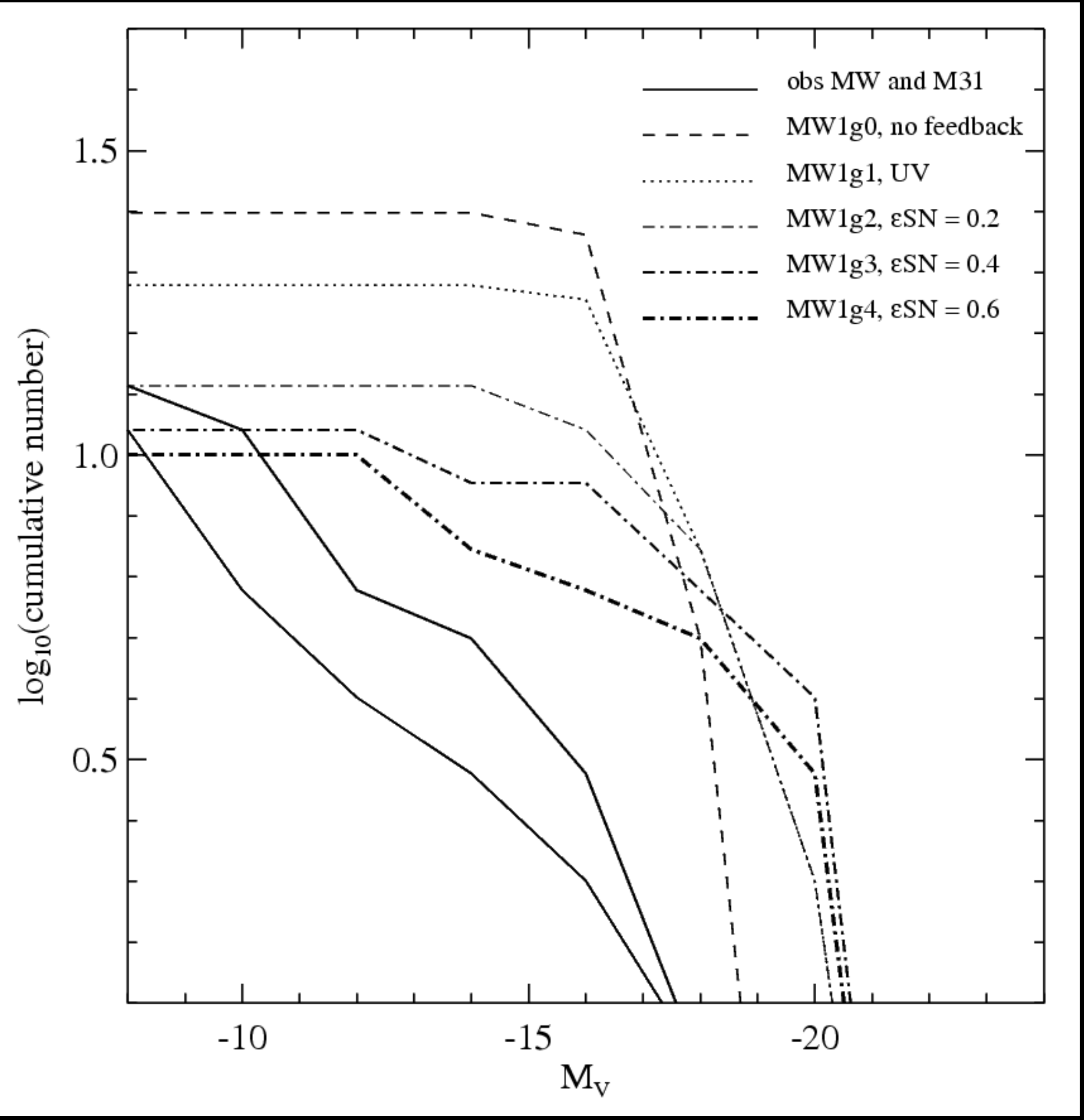
- How massive are the satellites of the Milky Way?

- Is the missing satellites problem still a problem?

-What is the relation, if any, between dwarf satellites and reionization? Where most of their stars formed before or after reionization?

Luminosity function of satellites

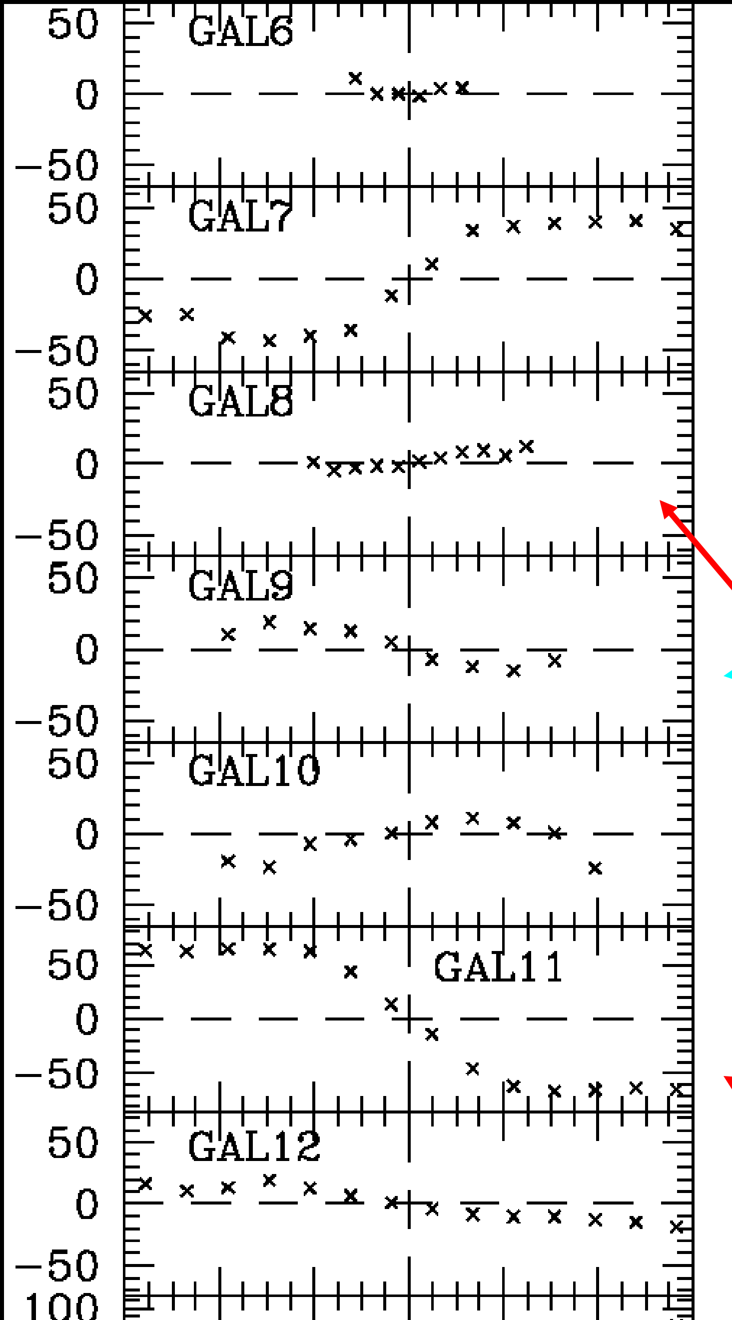
Governato, Willman, Mayer et al. 2006



UV + SN feedback nearly reproduce the correct number of satellites expected within a Milky Way sized halo (see also Bullock et al. 2000, Somerville 2002)

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

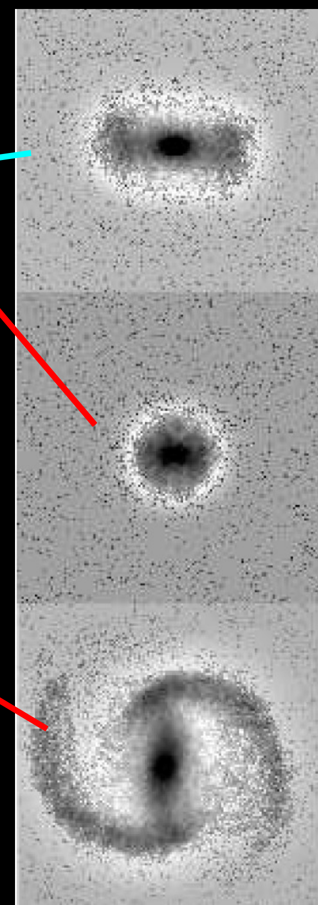
However still



Mastropietro, Moore, Mayer et al. 2005

Transformation involves removal of angular momentum from the stellar component.

Spheroidal-looking remnants supported by velocity dispersion as bone-fide dSphs (v/s << 1), when disky features still present rotation still significant

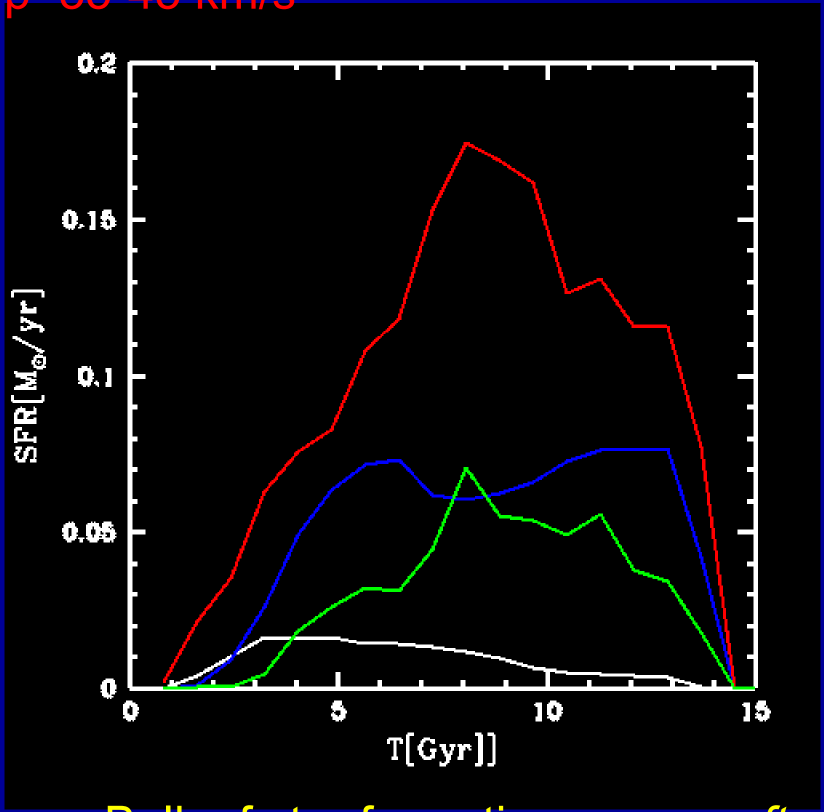


(to be tested with obs., see Geha et al. 2003)

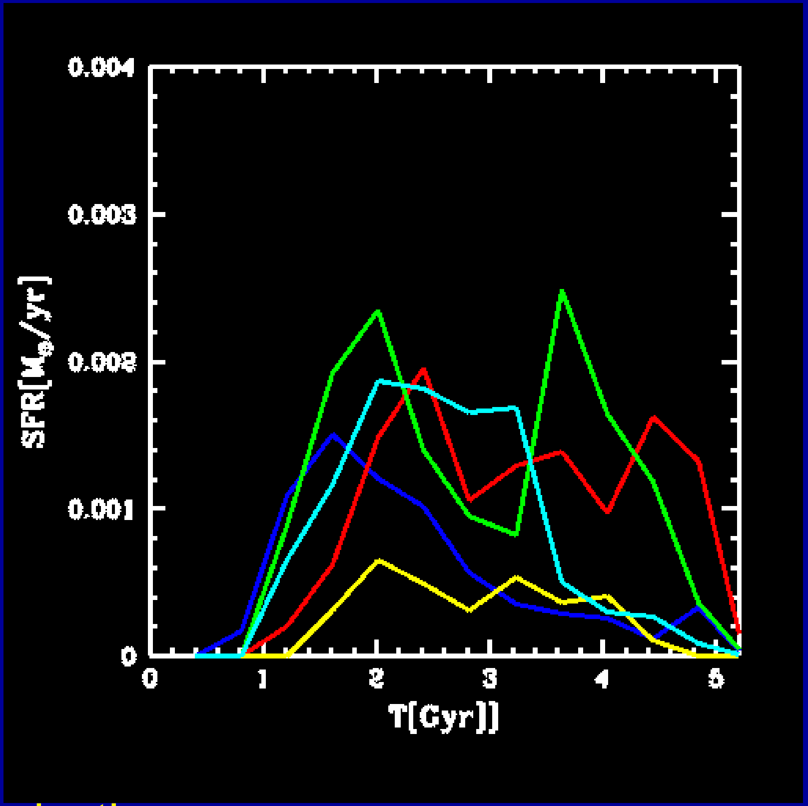
Population of transitional dwarfs “dEdis”recently discovered in Virgo by Barazza et al. 2004 and Lisker et al. 2006
Should be many more in clusters because much larger population of recent infallers, in MW-halo disky features already erased by t=0 because more tidal shocks

Star formation histories of satellites in cosmo. sim

"Small satellites" in LR sim, Vp=35-45 km/s



Small satellites in HR sim, Vp=18-35 km/s at z = 1



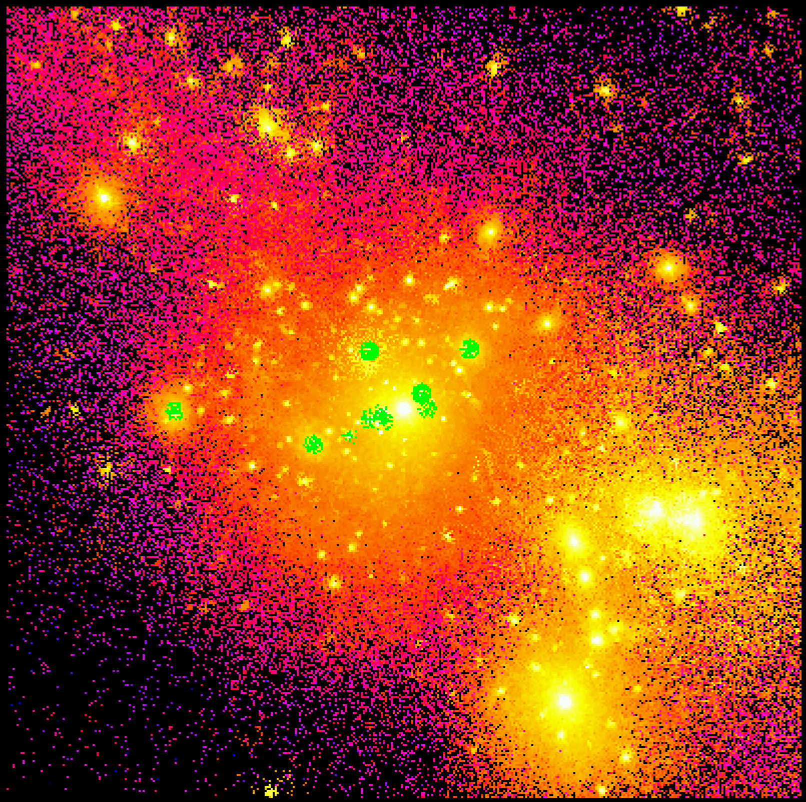
•Bulk of star formation occurs *afte*r reionization

•Wide variety of star formation histories is seen; more extended star formation histories for bigger satellites and satellites with larger pericenters. No satellite With SF lasting for less than 2.5-3 Gyr (implications for metallicity)

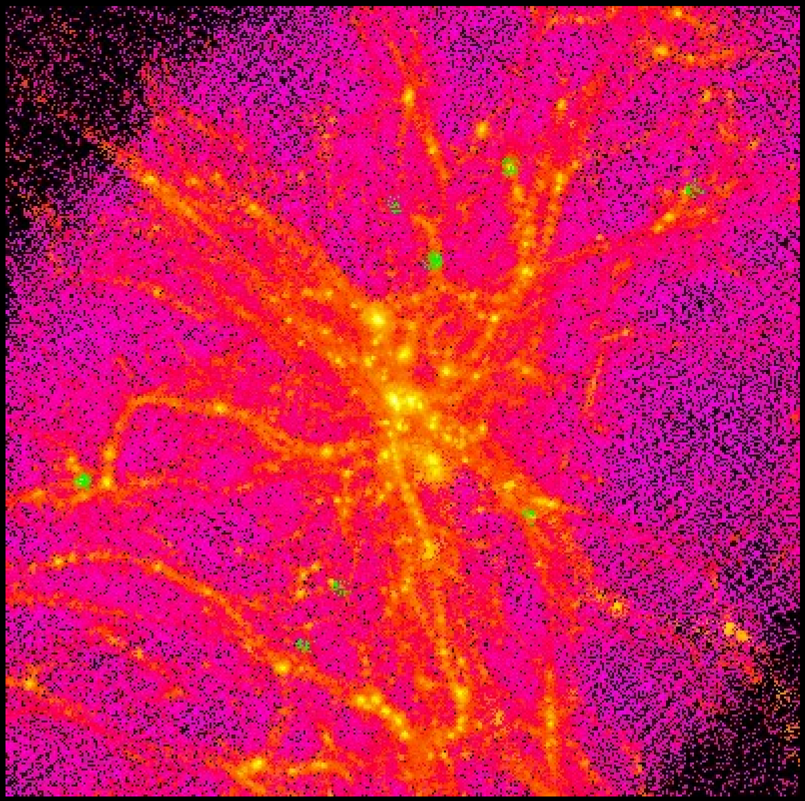
•Peaks of star formation *sometimes* correlated with pericenter passages

Where do the z=0 galaxy satellites come from?

Mayer, Willman 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 s peaks) at z=6. They were just starting to collapse.

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

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

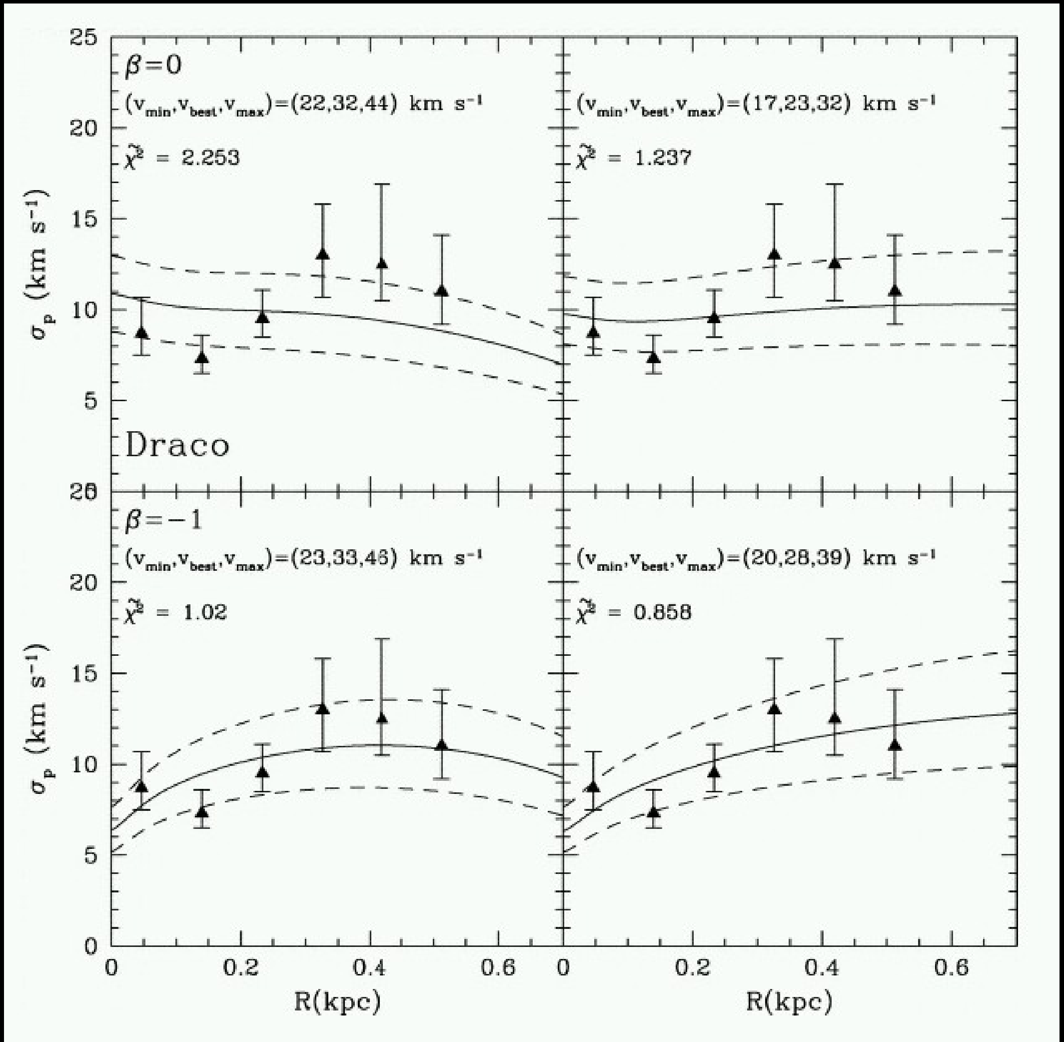
3)Start at high z and go on until z=0 to compare with the data that we have.

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….

Masses of dwarf spheroidals and reionization

They live in fairly big halos, Vpeak > 20 km/s today, were Vpeak > 30 km/s when they first fell into the primary (see Kravtsov et al. 2004; Mayer 2005).
---> feedback by supernovae (MacLow & Ferrara 2000; Mori et al. 2003) and photoevaporation by cosmic UV bg effective at *lower* Vpeak, < 20 km/s (Susa & Umemura 2004, 2005)



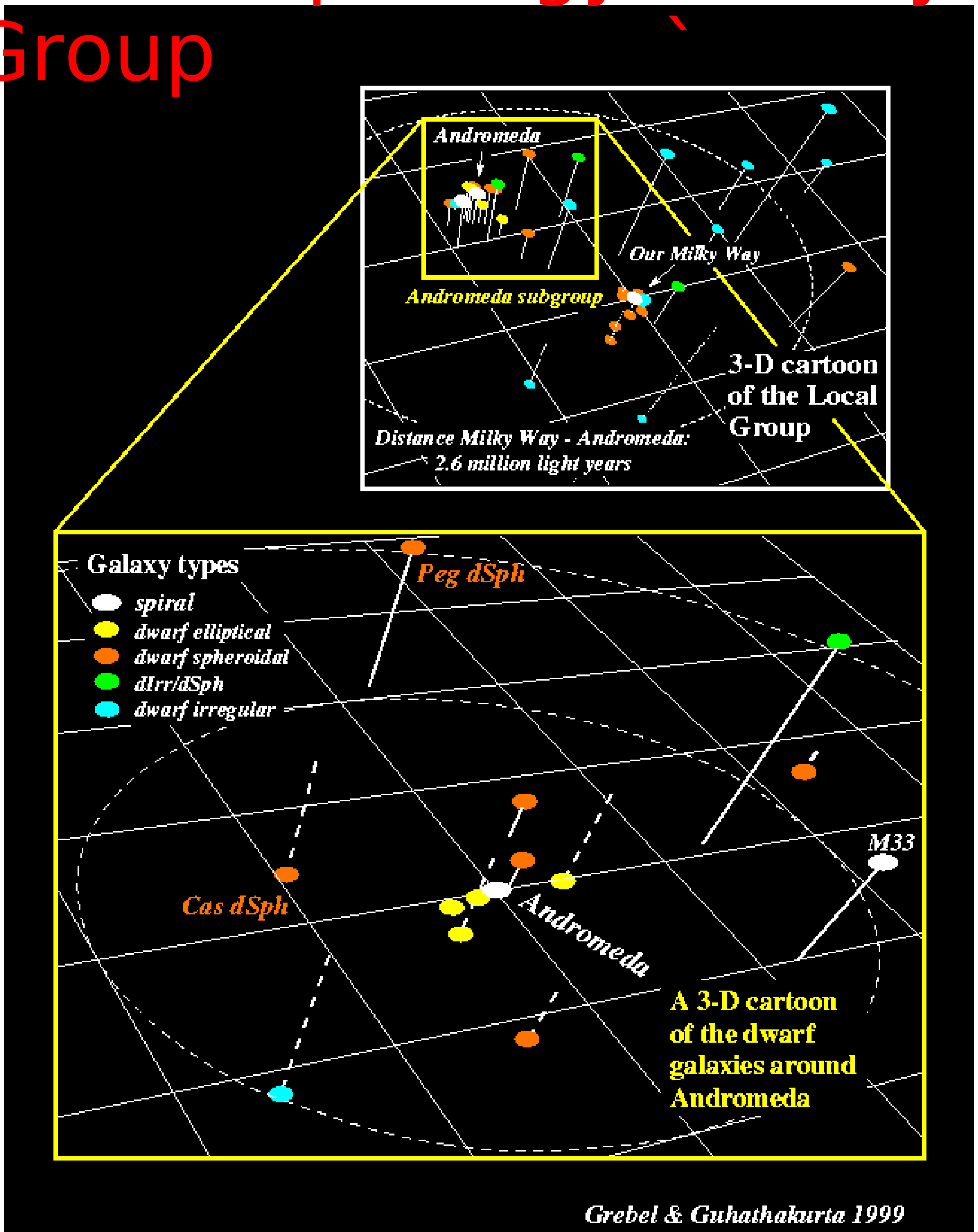
Kazantzidis, Mayer et al. 2004

Fitting observed kinematics in cuspy tidally stripped subhaloes using Jeans equation

King model for stellar distribution

also Lokas 2004, Wilkinson et al. 2005, Strigari et al. 2006, 2007

The morphology-density relation in the Local Group



- 2 Γιαντ σπιραλσ
- > 60 Δωαρφσ

  40% δΙρρσ
- (Γασ ριχη, ϖροτ/s > 1
- *Low surface brightness,*
- *exp. stellar profiles*♦
- 40% δΣπησ
- 5% δΕσ
- (Gas poor, vrot/s < 1,
- *Low surface brightness,*
- *exp. stellar profiles*)

  15% τρανσιτιον

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

Gas=red

Stars=white

Milky Way As Klypin, Zhao & Somerville 2001,

Vc ~ 160 km/s

SFR

Stellar Rz/Rdisk ~ 0.3

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

Cold Gas turbulence ~ 20Km/sec

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

EVEN DWARFS WITH MASSIVE HALOS TRANSMUTE

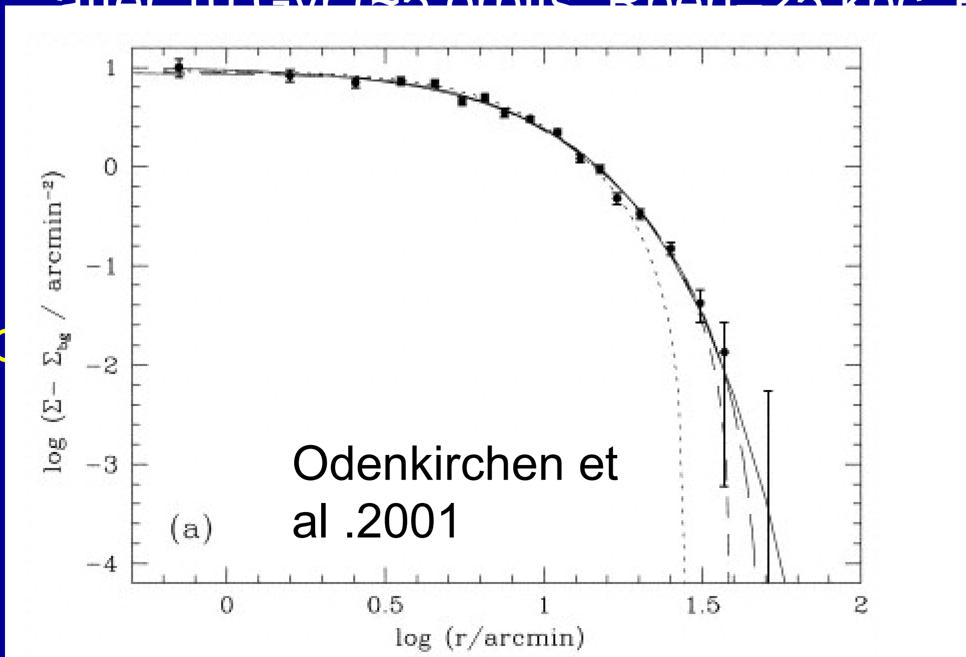
Initial Vpeak=35 km/s, fdisk=4% c=16 NFW HALO, shown is morphology after 10 Gyr (~5 orbits, Rperi=25 kpc, Rapo=120 kpc). Final (M/L)e ~ 40

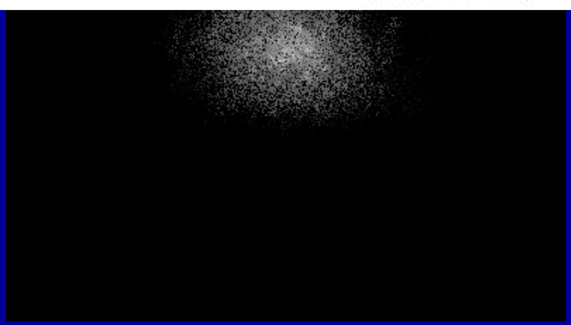
out heating and instabilities

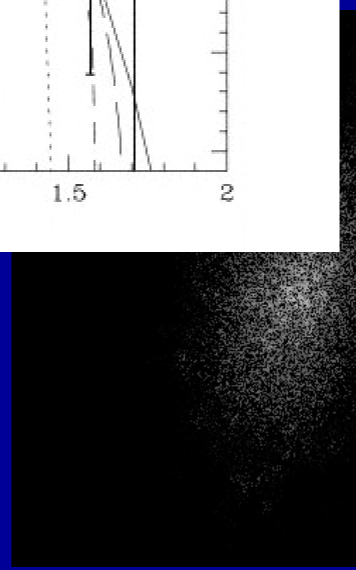
d et al. 2006; Gnedin et al. 1999)

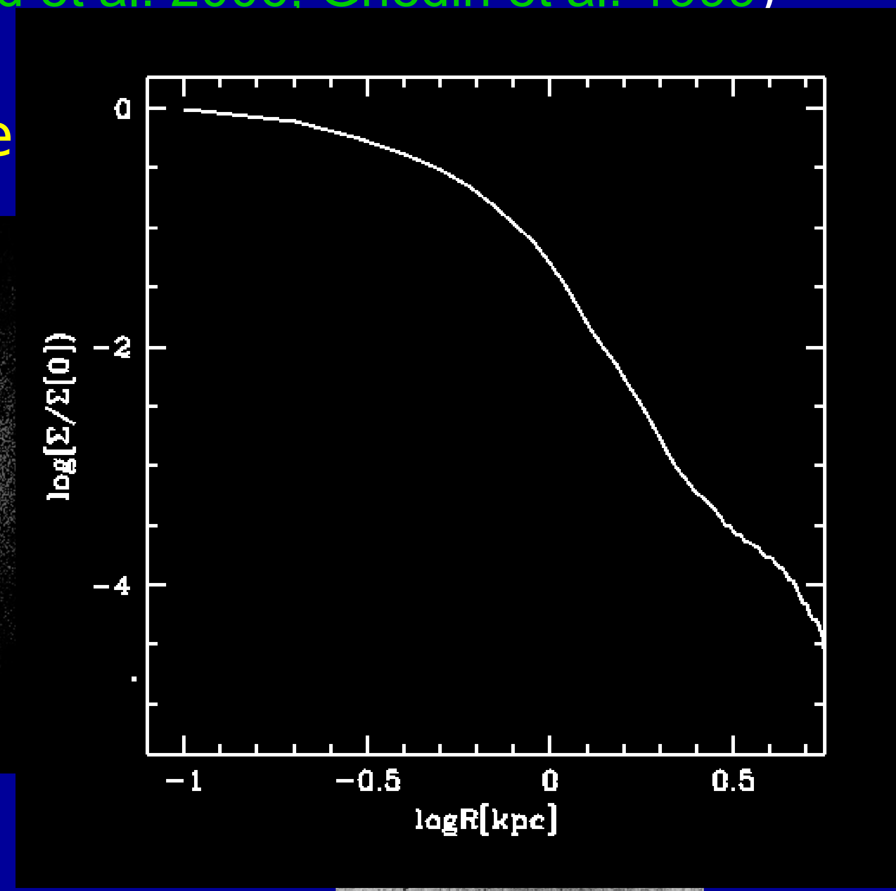
kp

e





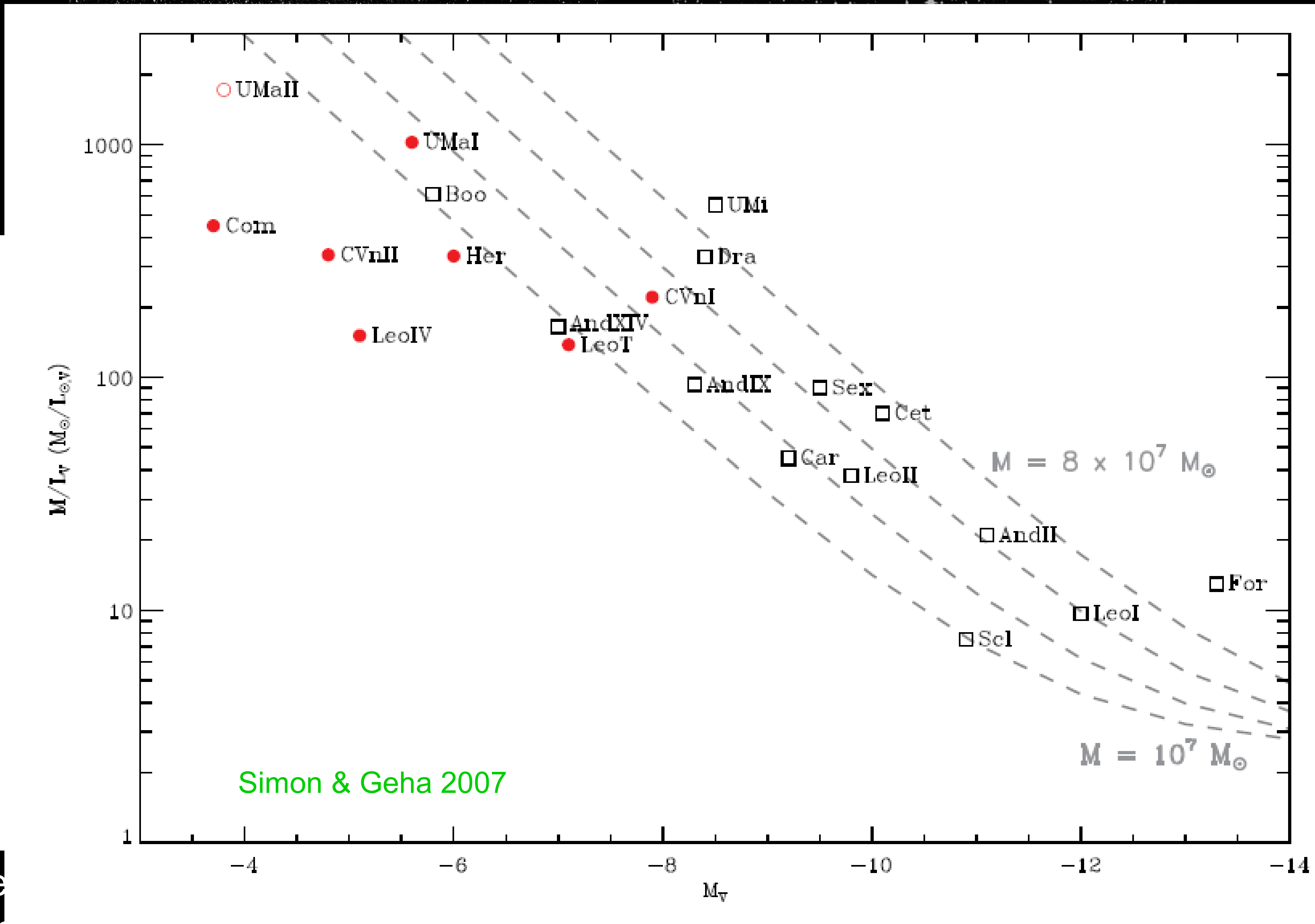




Dwarf galaxies have shallow potential wells (total mass 10^7-10^9 Mo) ---> low binding energy means several internal and external processes can remove baryons (stars and gas) if they deposit enough thermal or kinetic energy to them.

Example: photoevaporation = UV photons during reionization heat the gas to a few 10^4 K, > virial temperature of a 10^8 Mo halo (Babul & Rees 1992; Quinn et al. 1997; Bullock, Kravtsov & Weinberg 2000)

Very small halos could lose their baryons completely and remain dark explaining why they are not seen!



§d

§fa

§L

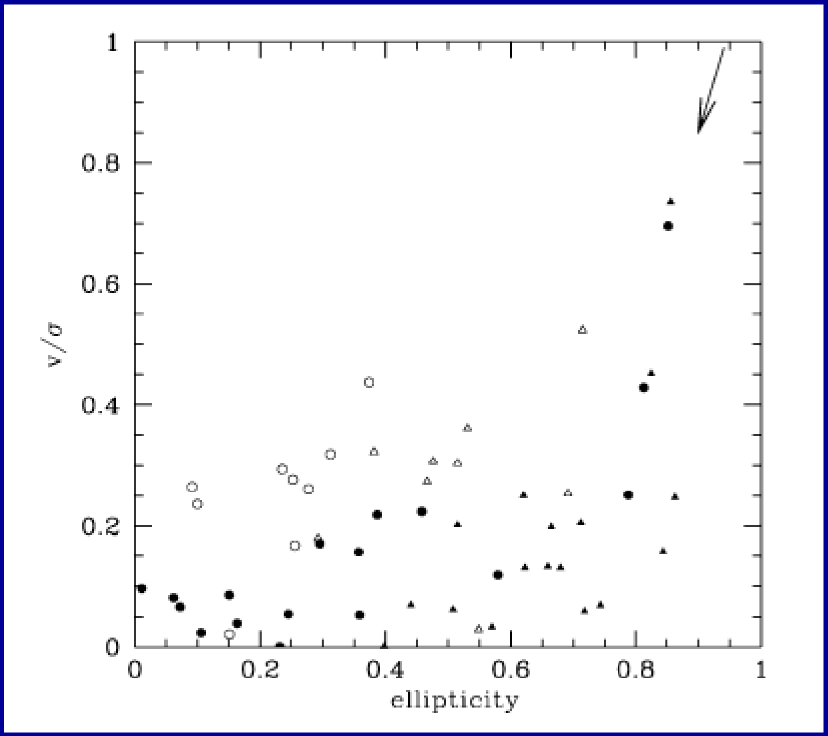
§Ve

Mgas < 0.1 Mstar < 0.1 Mdark (Gallagher, Grebel & Harbeck 2003)

MHI < 0.01 Mstar

§Variety of SF histories, truncated or extended (Skillman 2005; Dolphin et al. 2006)

V/ after 8 Gyr



Suite of different initial models
and different orbits

Within R=Re

Mayer et al. 2001a

Ρεμναντσ αρε μοδερατελψ τριαξιαλ

Διφφερεντ σψμβολσ ρεφερ το λινε οφ σιγητσ αλονγ διφφερεντ αξεσ

Φιλλεδ Σψμβολσ=ΛΣΒ δισκσ, > 23 μαγ αρχσεχ -2

Οπεν Σψμβολσ=ΗΣΒ δισκσ, < 23 μαγ αρχσεχ -2

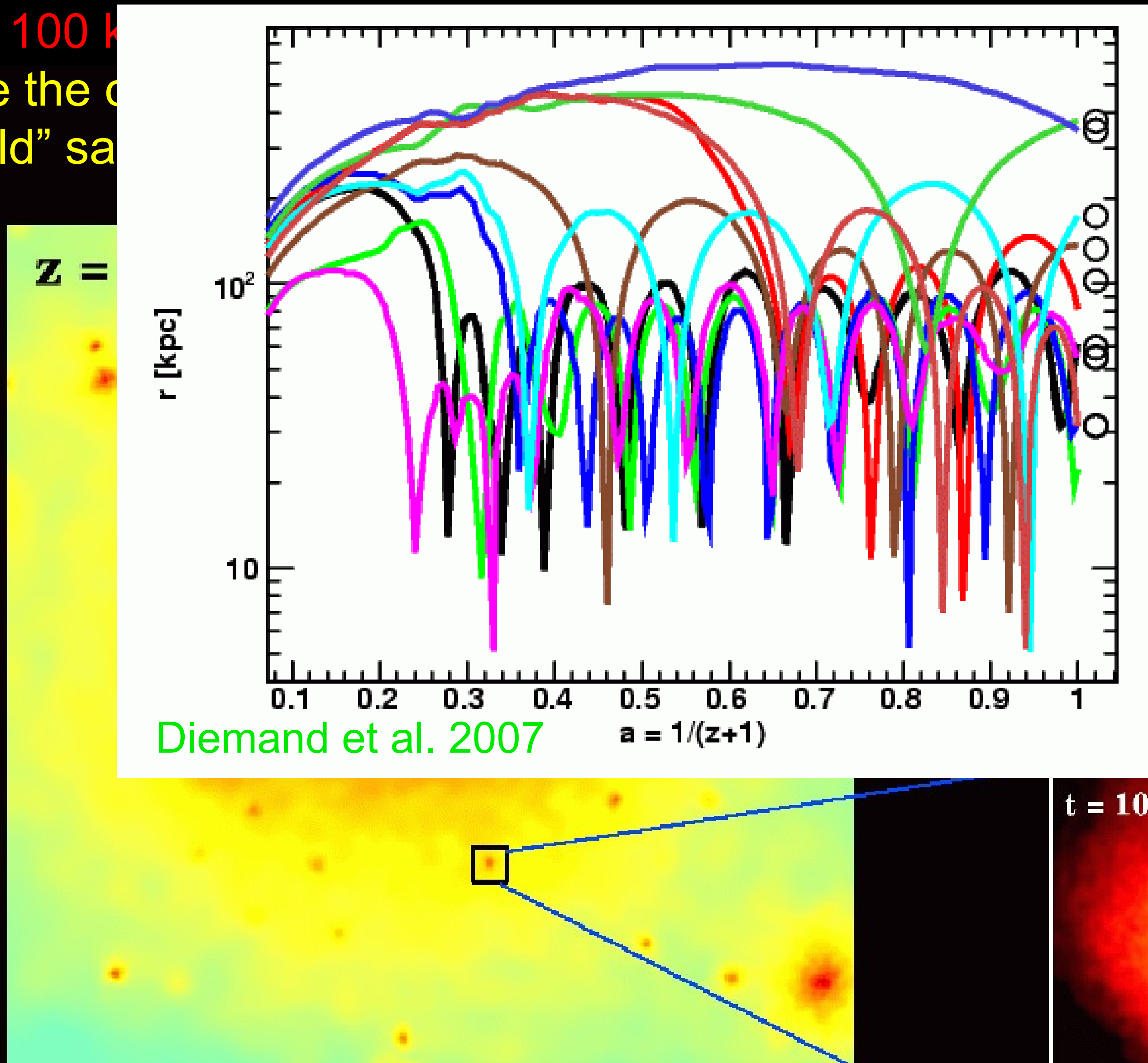
Loss of angular momentum due to bar instability (vt) + ↓
heating by tides/buckling ( ) ↑

Τιδαλ στιρρινγ προδυχεσ πρεσσυρε συππορτεδ ρεμναντσ ασ δΣπησ

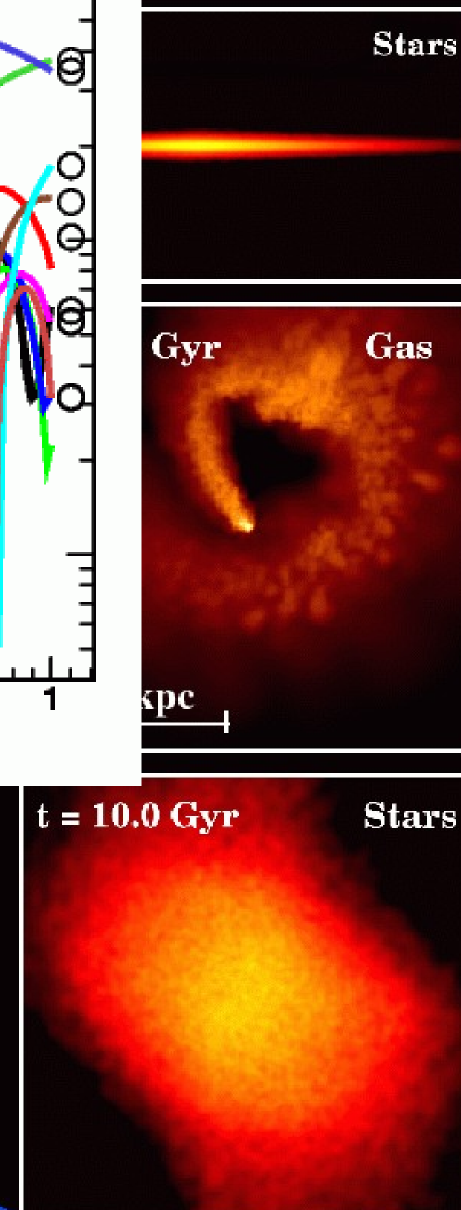
-Pick satellites with Vmax ~20-25 km/s today (consistent with kinematics of darkest dSphs, Draco and Umin) and within 100 k

-Trace the c

are “old” sa



Diemand et al. 2007



Τιδεσ ινδυχε βαρ/βυχκλινγ ινσταβιλιτιεσ Τυρν δισκ ιντο σπηεροιδαλ

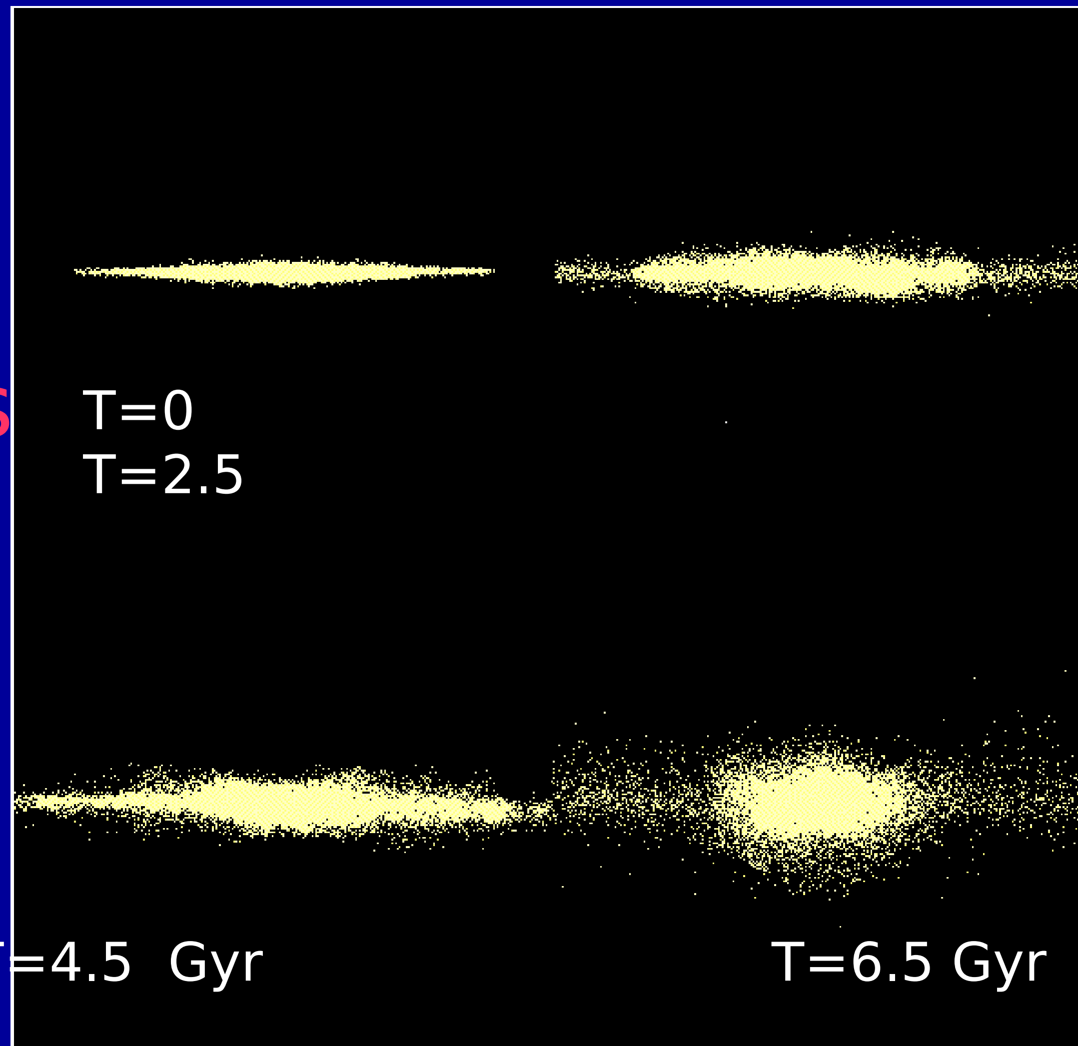
LSB disk

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)

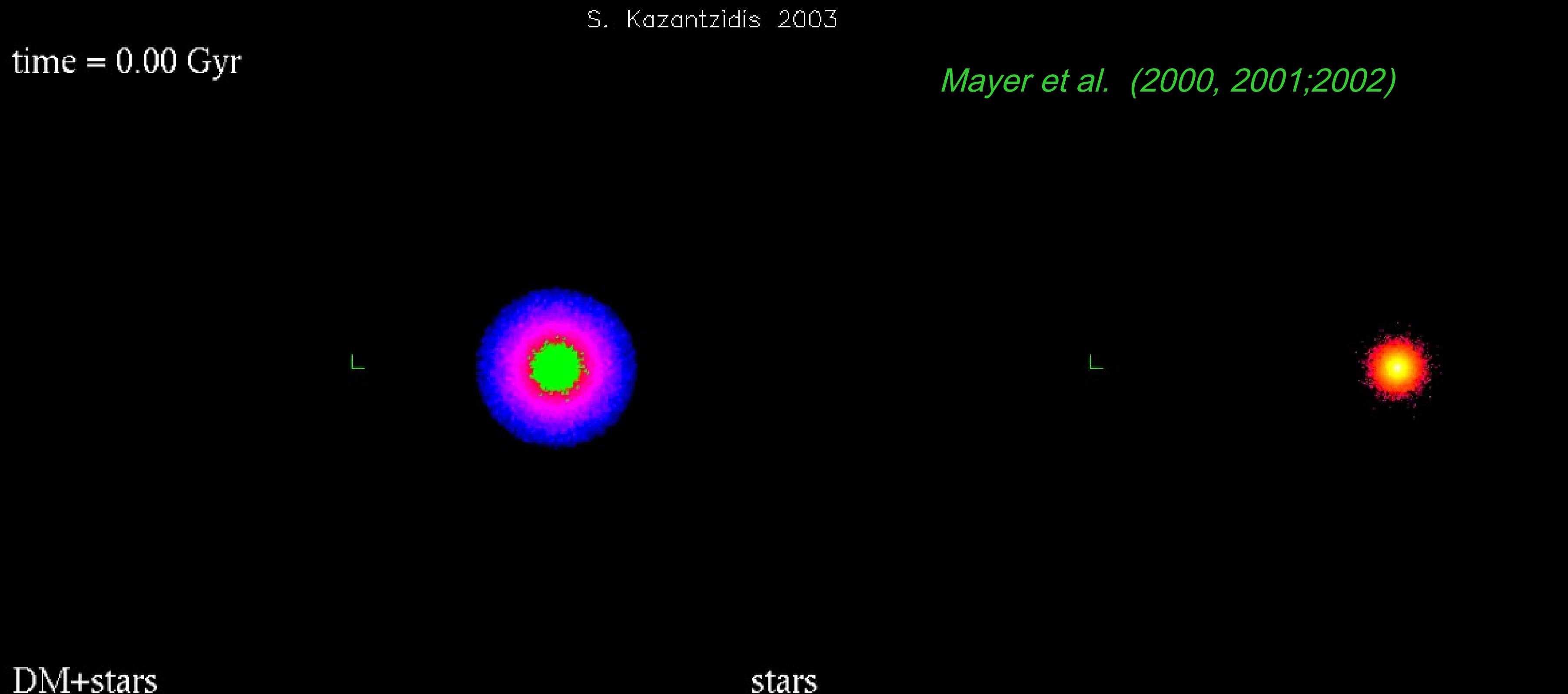
OUTLINE?

TIDAL STIRRING of dwarf galaxy satellites

Not enough resolution in subhalos of cosmological simulations with hydro ---->
study interaction between a dwarf galaxy and a massive spiral with hi-res N-Body + SPH sims (with GASOLINE), a few million particles per single dwarf model.

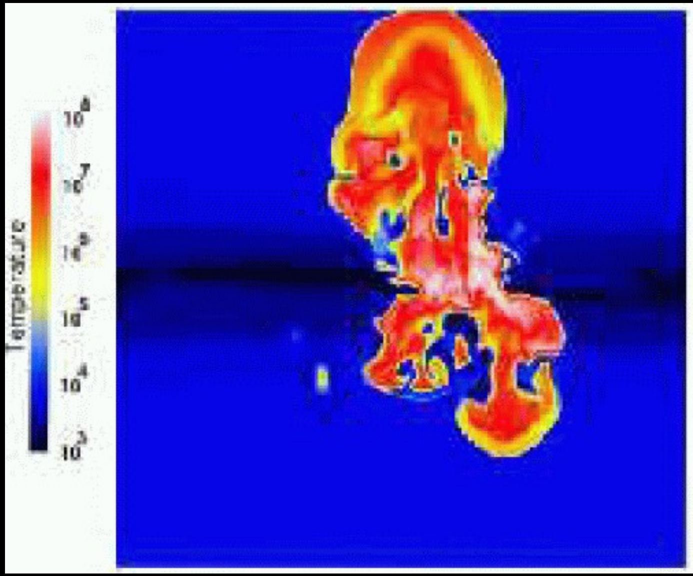
Initial conditions
(1) orbits and structure of galaxies/halos (NFW) from cosmological runs + scaling relations between baryonic disk and halo from Mo, Mao & White (1998)
(2) free parameters (e.g. disk mass fraction, gas fraction in disk) chosen based on observations of late-type dwarfs (e.g. de Blok & McGaugh 1997; Geha et al. 2006)

Mayer et al. (2000, 2001;2002)



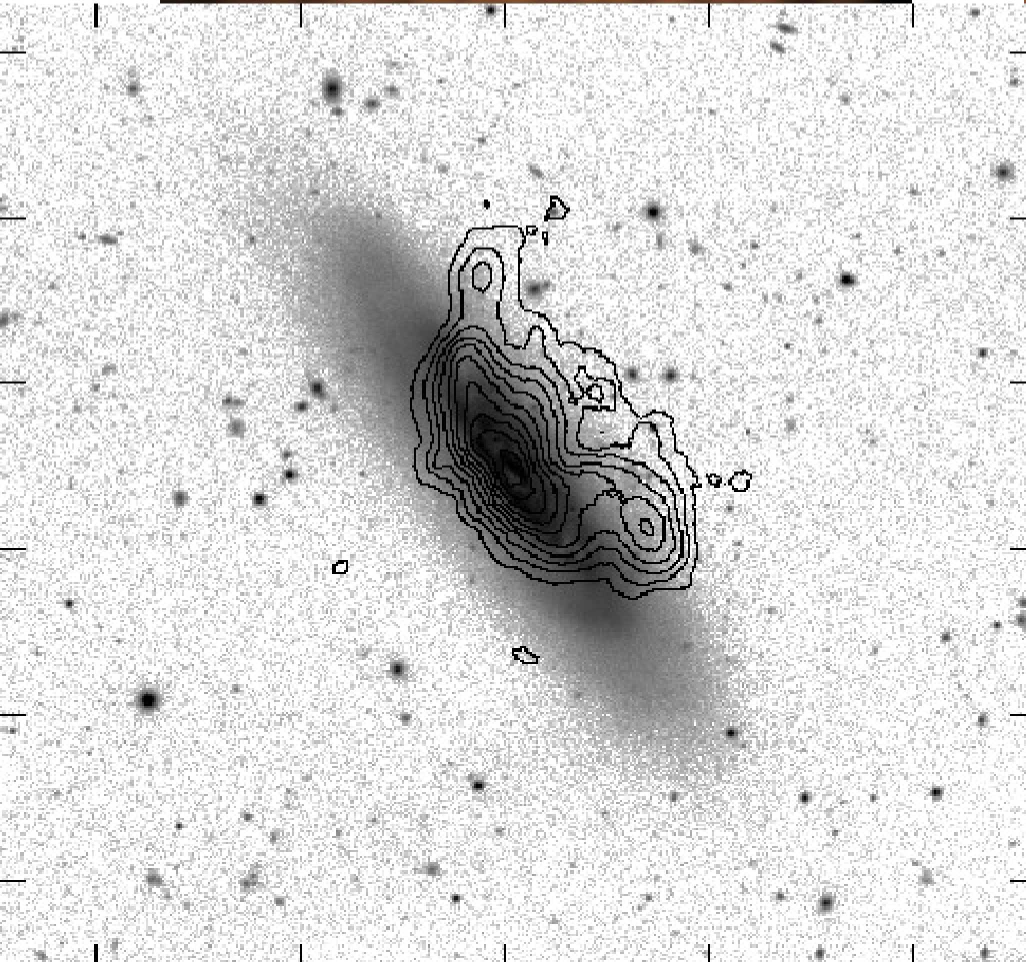
How did dwarf spheroidals lose their gas?

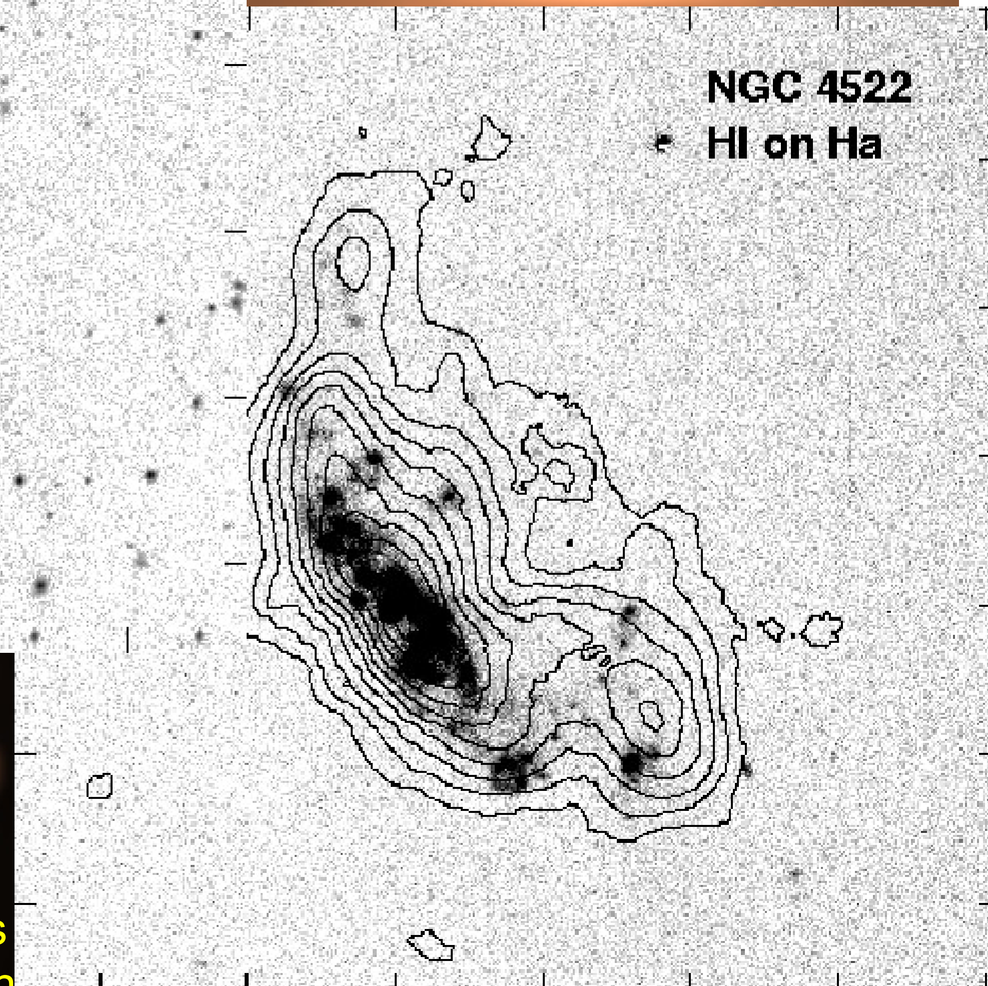
-Feedback from supernovae (Dekel & Silk 1987) Blow-out of most gas only at very small halo masses, $M_{vir} < 10^7$ Mo (Mac Low & Ferrara 1999; Mori et al. 2001; Read, Pontzen & Viel 2006;Ceverino & Klypin 2008)

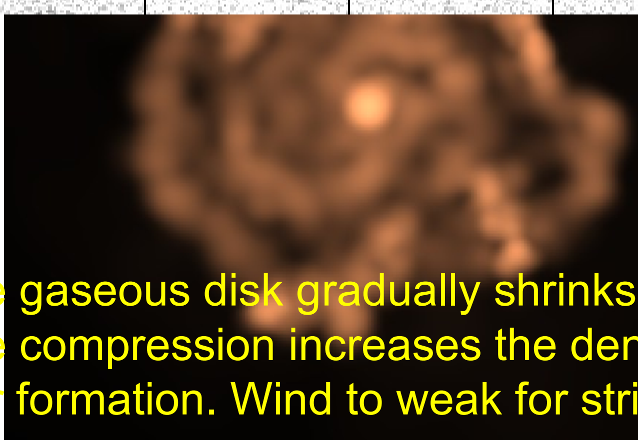


-Suppression of gas accretion or photoevaporation due to the cosmic UV radiation (Babul & Rees 1992; Quinn et al. 1996, Bullock, Kravtsov & Weinberg 2000, Gnedin 2000)

Most recent simulations including self-shielding indicate Vpeak < 20 km/s ($M < 10^8$ Mo) required for gas fraction to drop to < 0.01 Mdark (Susa & Umemura 2004, 2005)







The gaseous disk gradually shrinks
The compression increases the den
star formation. Wind to weak for stripping, only the disk edges ablated.

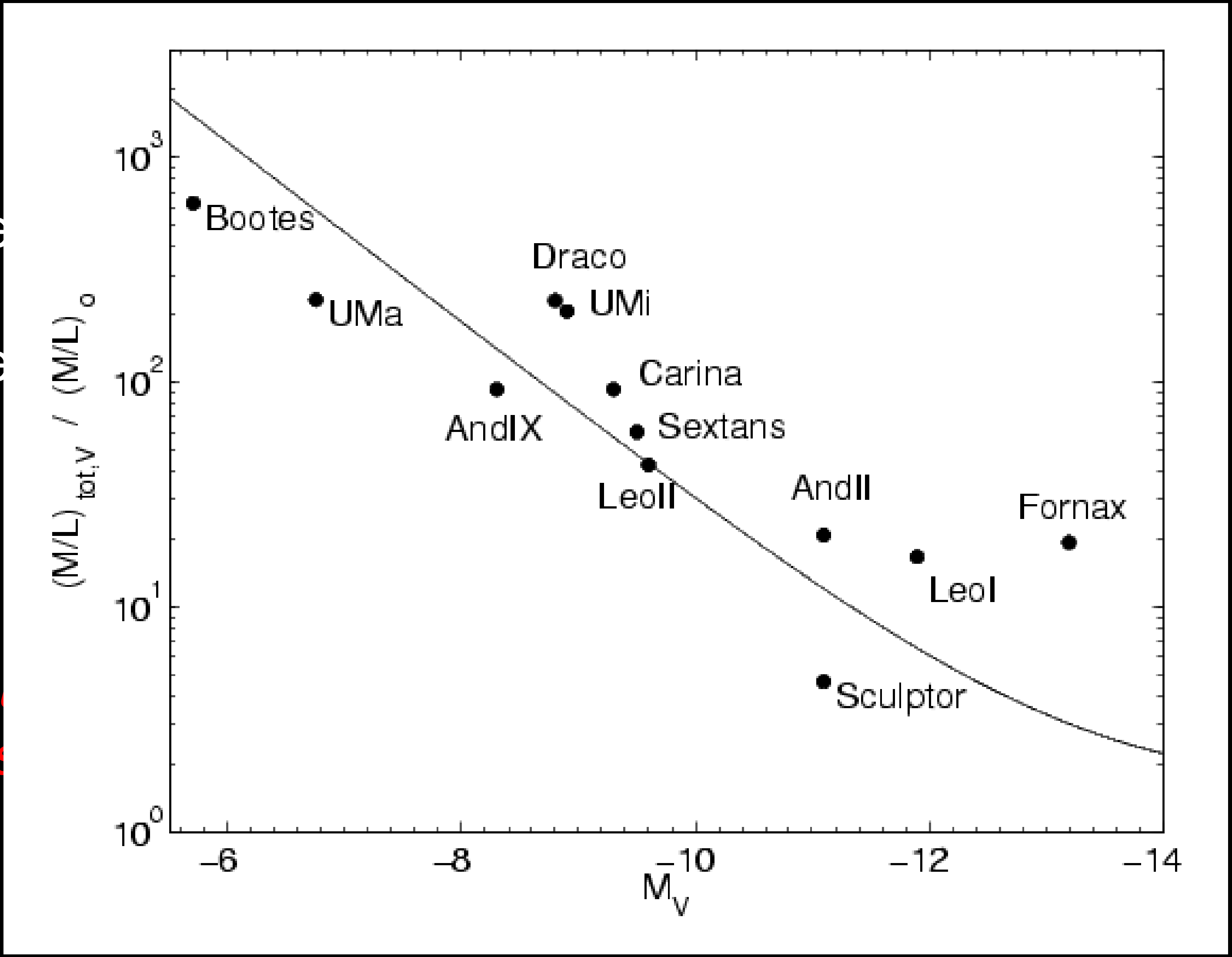
Key questions

(1) What is

(2) Why are

(3) Why are

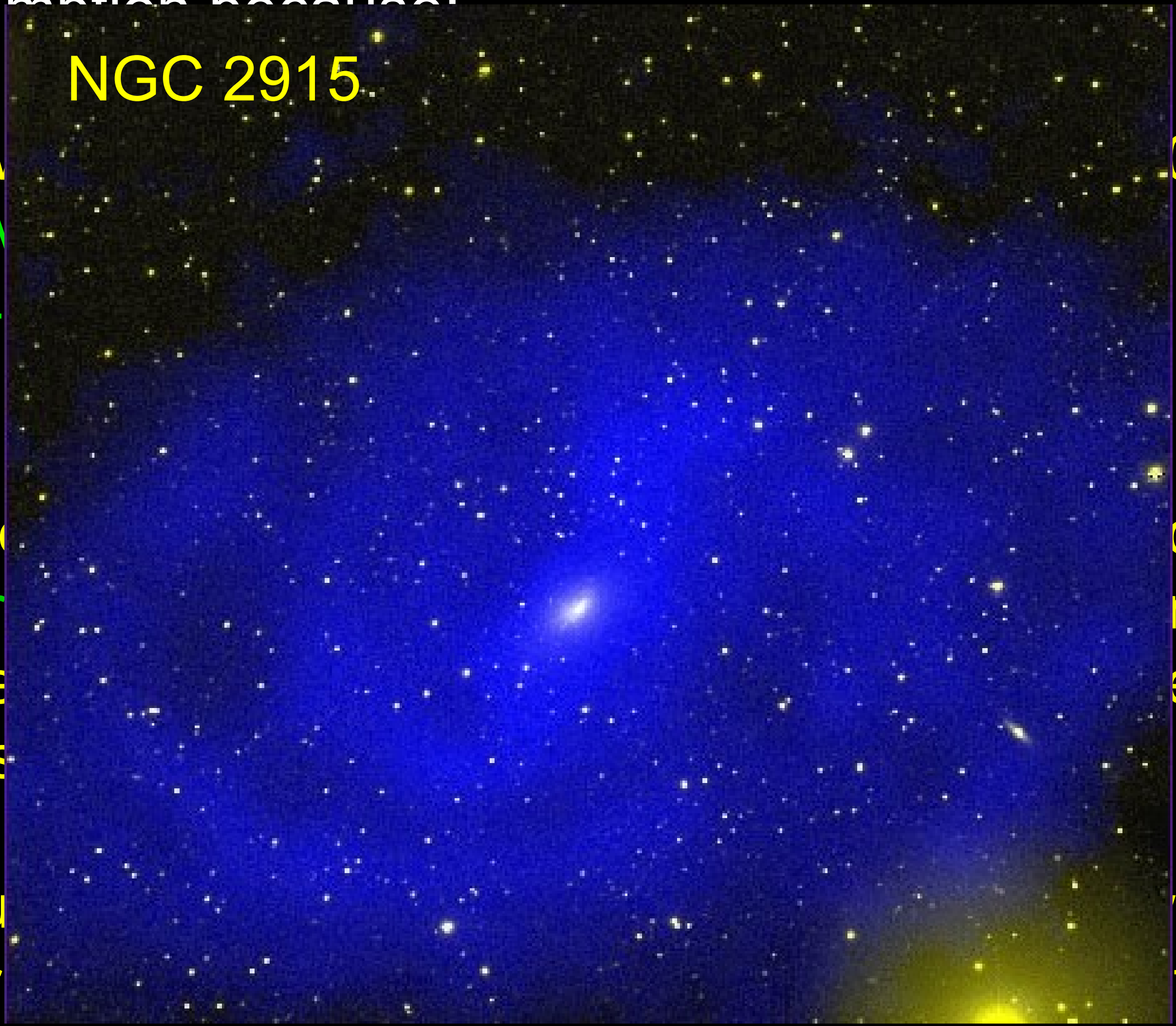
(4) Can we
by trying to



(1) s
of dis

What if the progenitor was gas dominated?

Plausible assu…



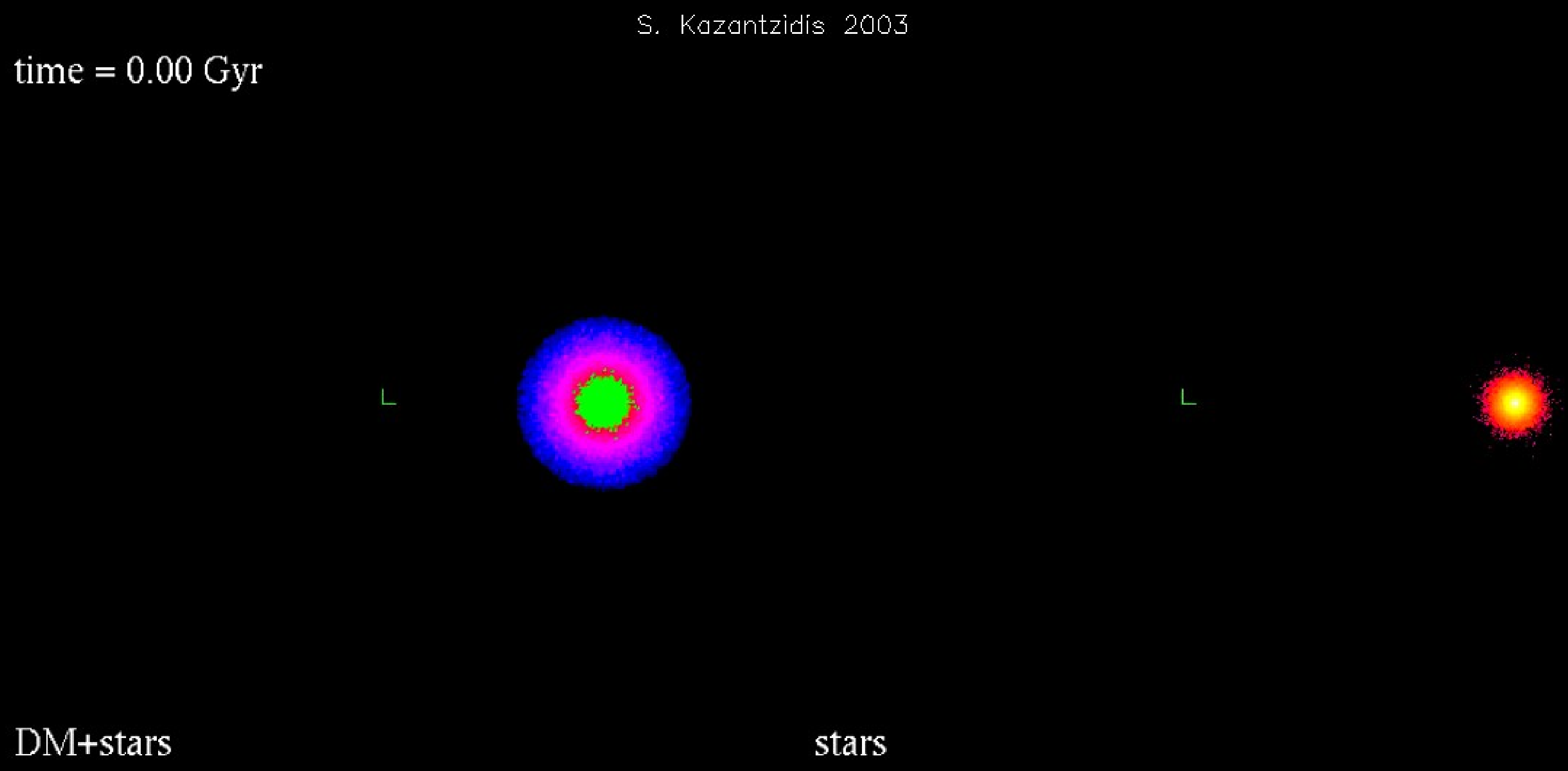
(1)Late-type dv… 0.5 today (e.g. M… Moore 2004…

(2)Simple anal… should be To… …ce density (Ver… …mre Q ~ 1 not ne… …eshold at dwarf scales…

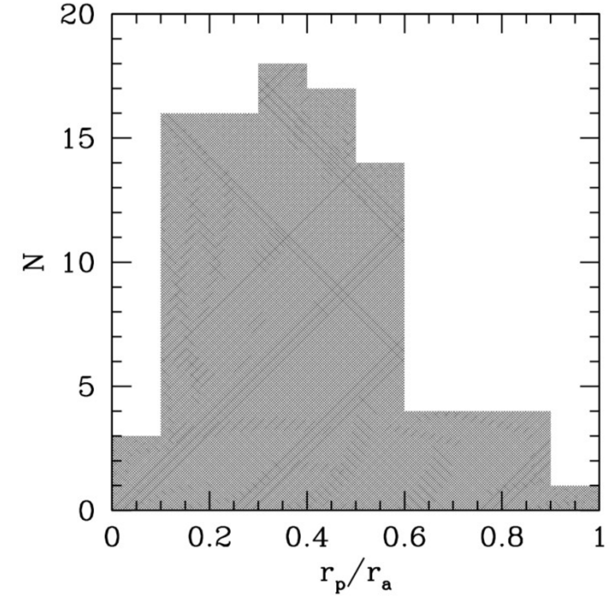
(3) Hydro simu… …ould predict near… …ty, Q > 1.5 gas disk as that of dIrrs (Li, MacLow & Klessen 2005; Robertson et al., in prep.)

TIDAL STIRRING WITHIN THE MW HALO

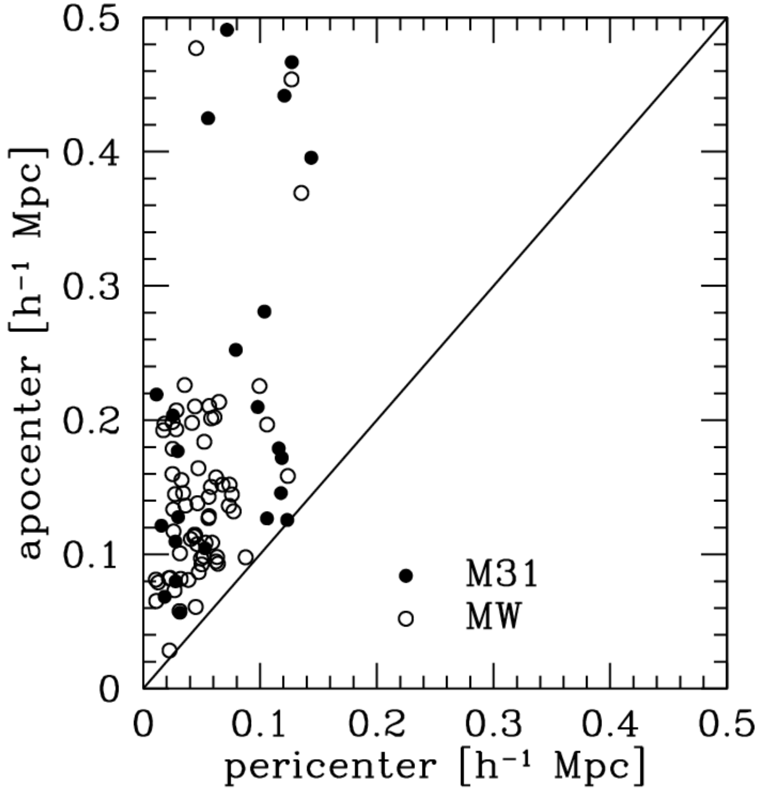
Mayer et al. (2000, 2001a,b, 2002)



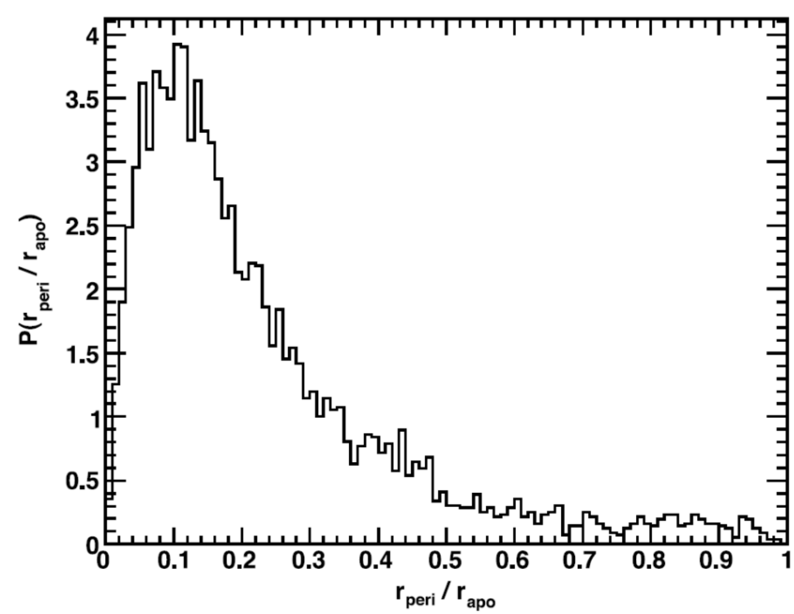
Orbits of subhaloes



✶⑤②⑥❾⑦☎⑧▯▦④② ❾☎ ❺⑤❍



❾⑦☎⑧▯▦④② ❾☎ ❺⑤❍ ✓➔➔➔



✢②❾⑥❺⑦❽ ❾☎ ❺⑤❍ ✓➔

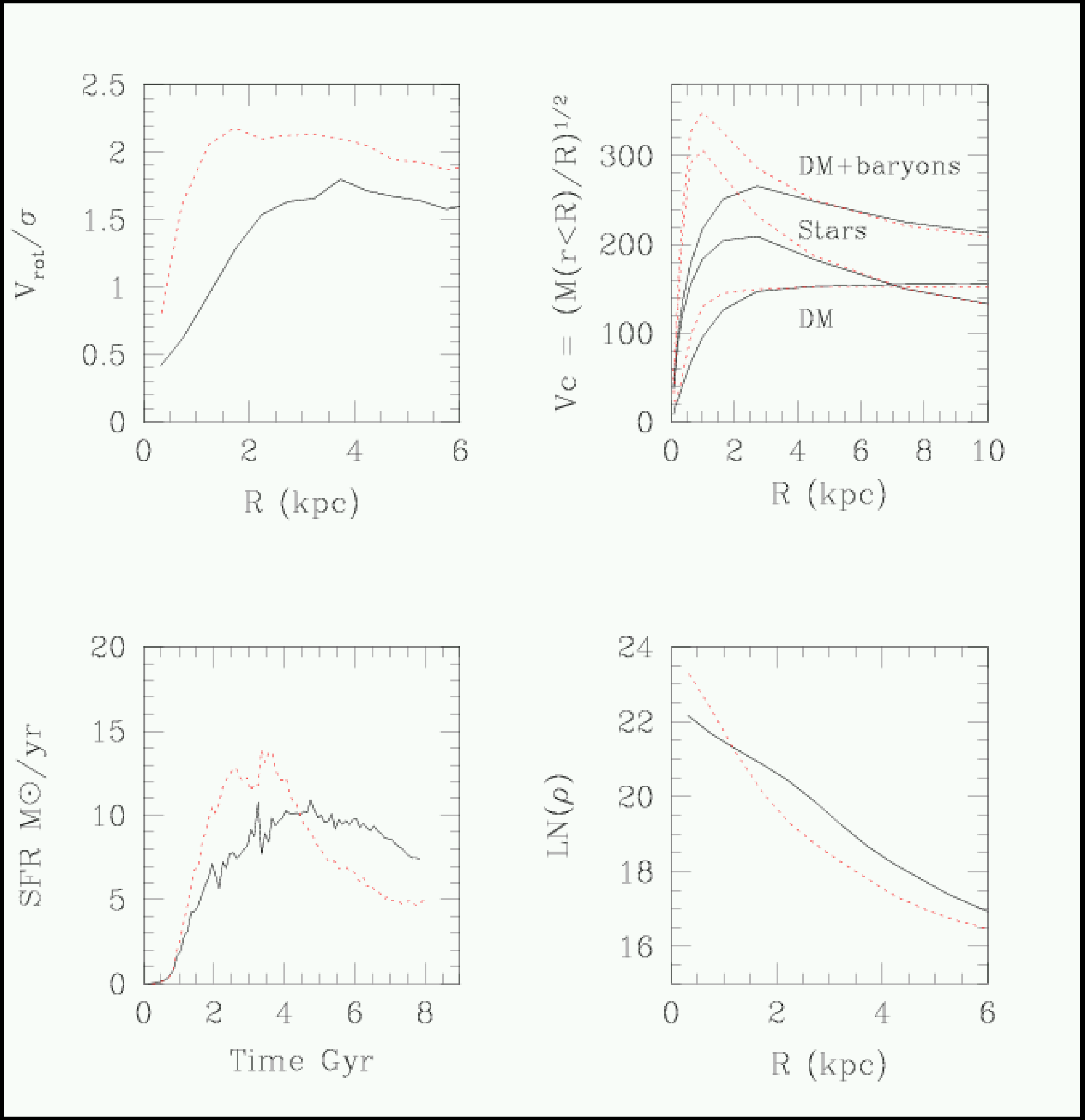
Typical orbits of subhaloes are eccentric

Example of numerical effects due to limited resolution

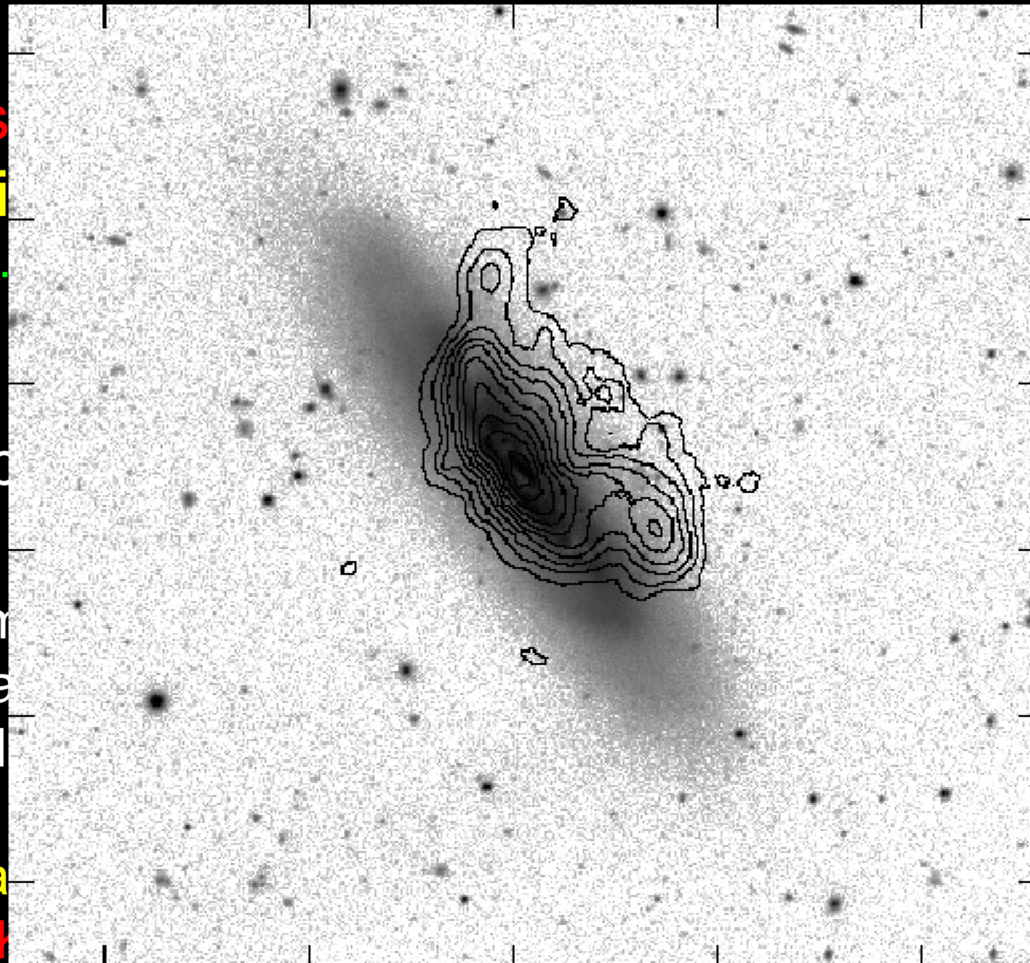
Primary MW-sized halo

Artificial angular momentum loss (e.g. Kaufmann, Mayer et al. 2006)

Numerical effects X10 for satellites that have 100 times less particles than primary



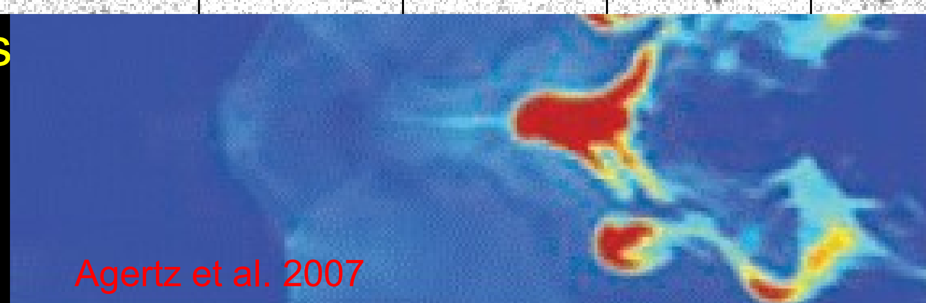
Ram press… …es through intergalacti… …Robishaw 2000; Marcolini et al.…



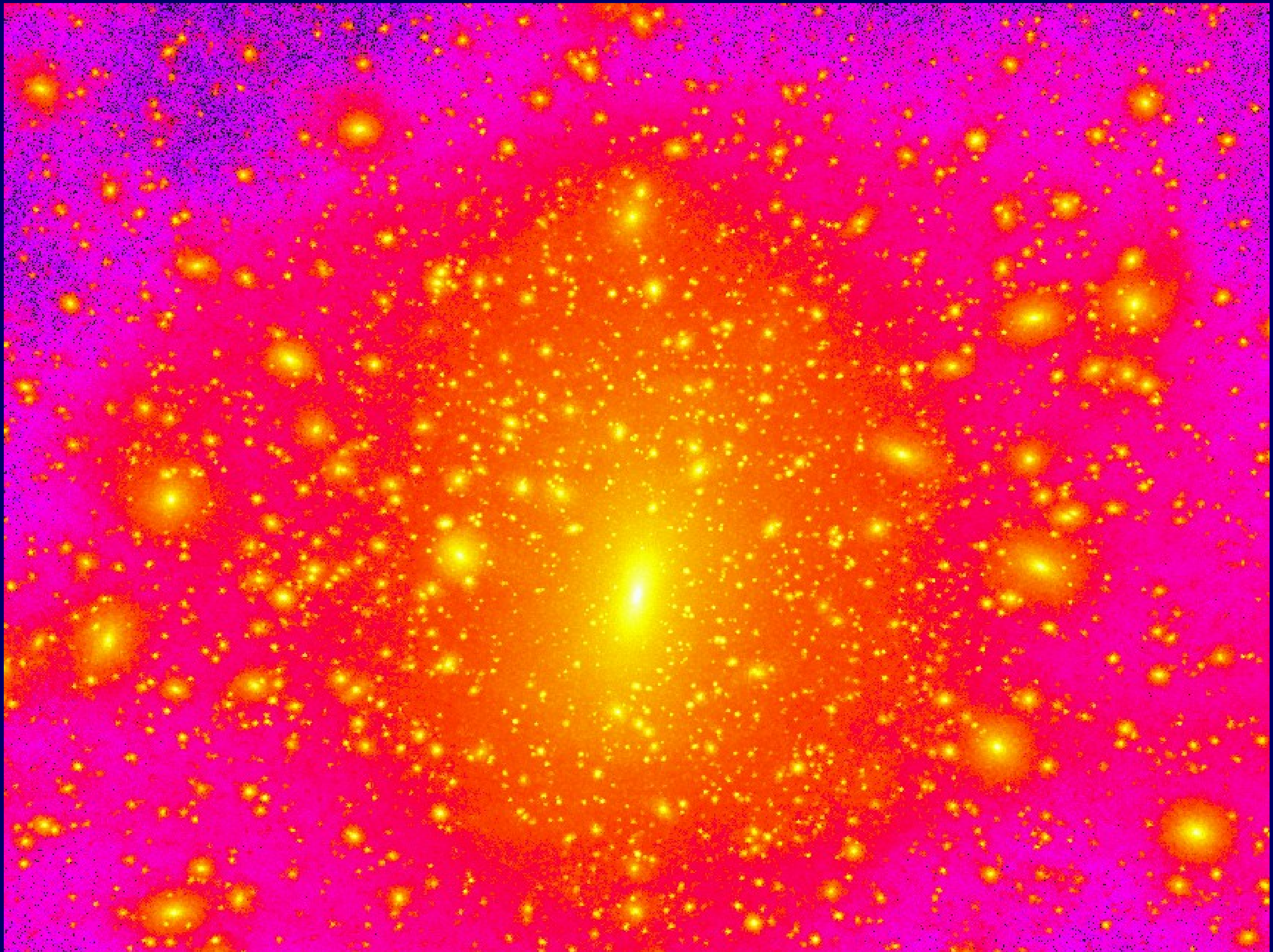
Gas is strip…

In general tim… …l on a non-circular orbit (both r a… …endent in general if gal… …e.g. tidal effects.

Additional ga… …amical instabilities (K… …“turbulent stripping”) and vis…

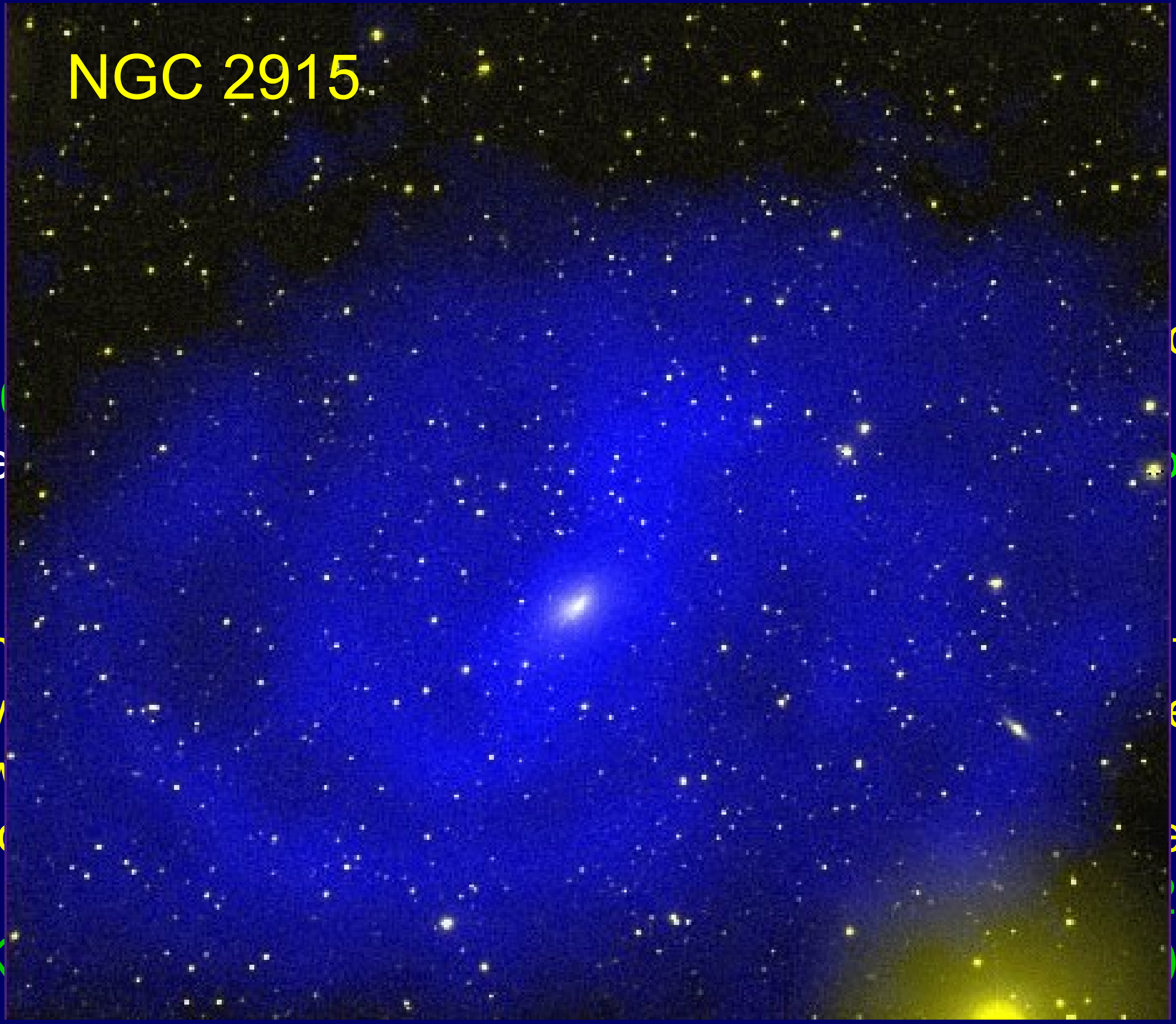


Theoretical perspective: counting subhalos in dm-only cosmologi
simulations - “missing satellites problem”



Gas dominated progenitors for darkest dSphs

Mayer, Kazantzidis, Mastropietro, Wadsley, *Nature, 2007, 445, 738*

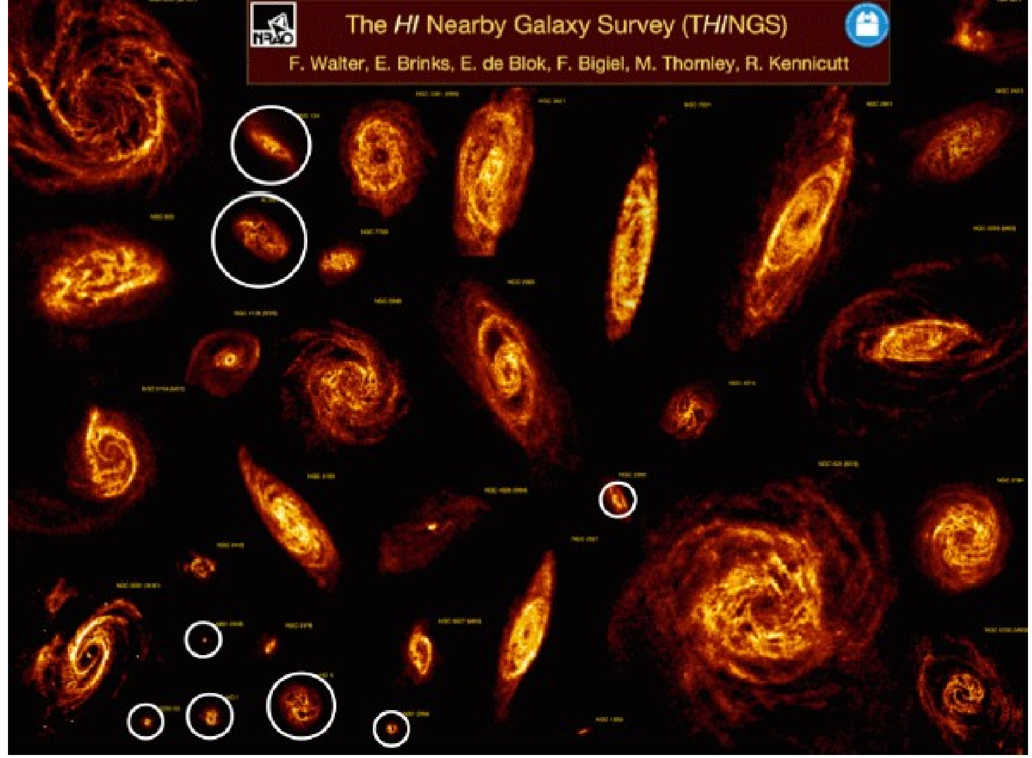


Plausible assu

(1) Most late-type day (e.g. McGaugh 200 THINGS surve by et al. 2009)

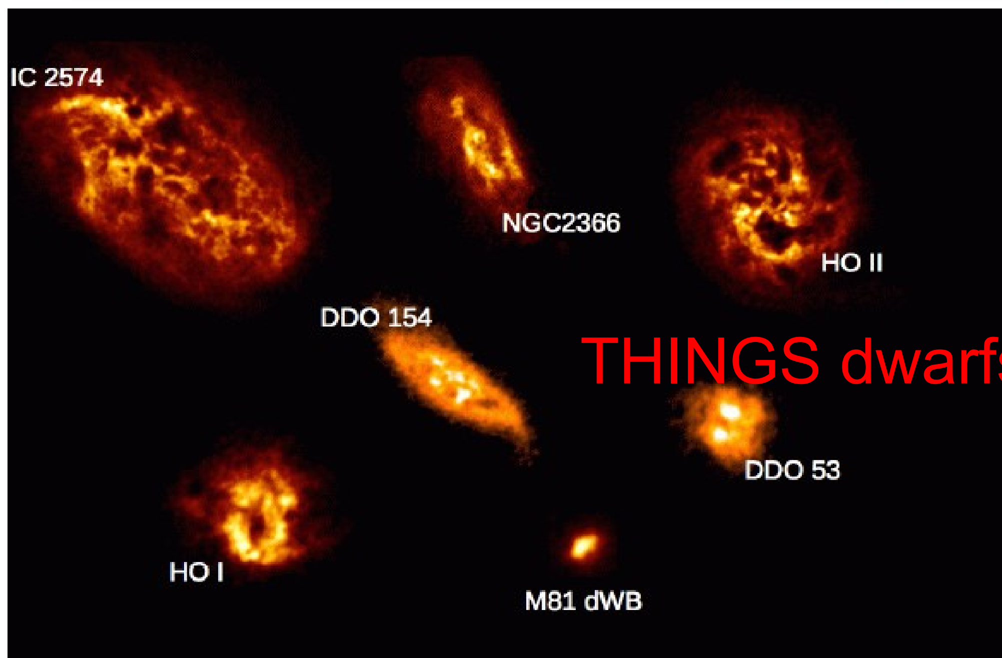
(2) Both hydro sim turally obtain that low ency because of low due to UV ionizing ra ent molecular gas 2005; Robertson & K)

State-of-the-art survey of atomic hydrogen (HI) in nearby galaxies at NRAO Very Large Array (VLA) (combined with Spitzer photometry)



Walter et al. 2008 ,2009

Hi-res 2D velocity fields



THINGS dwarfs sample

Key questions

(1) What is the origin of the morphology-density relation?

(2) Why are dSphs devoid of gas?

(3) Why are some dSphs extremely dark matter dominated ("darkest" galaxies known!) and some less? Why mass-to-light ratio anticorrelates with luminosity?

(4) Can we shed light on the missing satellite problem in trying to answer (1)-(3)?

All these problems involve the mapping between dm and light

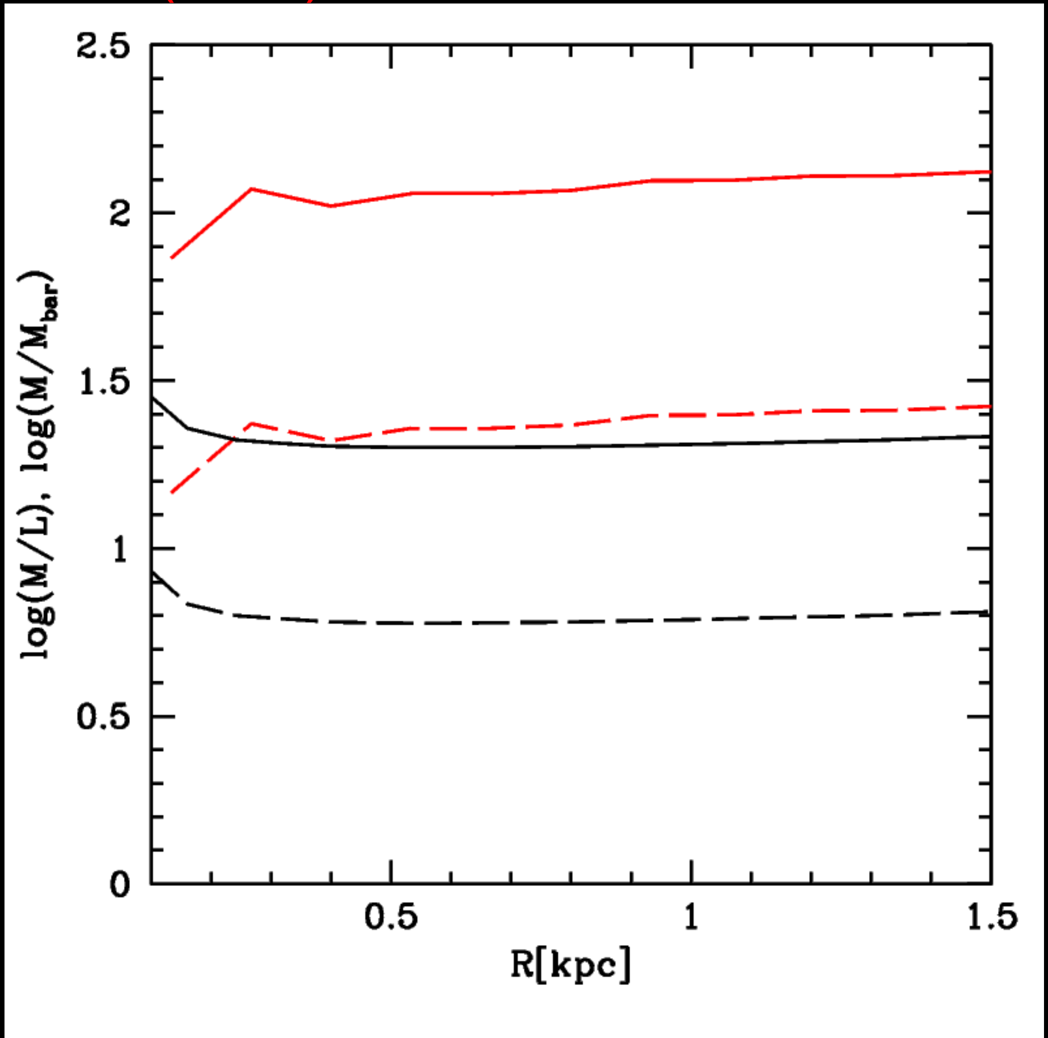
Dark matter and stars are only partially stripped (suffer only tidal effects) and are stripped at similar rate ---->

M_{dm}/M_{stars} ~ constant = final Mdm/Mbaryon > 100!

Naturally obtain very large mass-to-light ratio starting from a normal mass-to-light ratio (~ 20)

Dashed = log(Mtot/Mbaryon)
Solid = log (M/L)

Black: Initial values
Red = Final values (i.e. after 10 Gyr of orbital evolution)



Formation and morphological evolution of dwarf galaxies in a hierarchical Universe

Institute for Theoretical Physics
ZURICH

ETH

Lucio Mayer

Collaborators:

Stelios Kazantzidis (CCAPP Ohio State Univ.), Simone Callegari (PhD student, University of Zurich), Chiara Mastropietro (LERMA, Paris) James Wadsley (McMaster Univ.), Ewa Lokas (Copernicus AC), Fabio Governato (UW), Chris Brook (UCLAN), Alyson Brooks (Caltech), Beth Willman (Haveford), Thomas Quinn (UW), Jaroslaw Klimentowski (Copernicus AC), Jorge Penarrubia (IoA Cambridge), Greg Stinson (UCLAN), LCID collaboration and many others….