Disk Formation and the Angular Momentum Problem

Presented by: Michael Solway

Papers

1. Vitvitska, M. et al. 2002, *The origin of angular momentum in dark matter halos*, ApJ 581: 799-809

2. D'Onghia, E. 2008, *How galaxies gain and lose their angular momentum*, Proceedings of the International Astronomical Union, 245: 51-54

3. Burkert, A. 2009, *Galactic Disk Formation and the Angular Momentum Problem*, arxiv:0908.1409

4. Zavala, J., Okamoto, T., & Frenk, C. S. 2008, *Bulges versus discs: the evolution of angular momentum in cosmological simulations of galaxy formation*, MNRAS 387: 364-370

5. Scannapieco, C. et al. 2009, *Effects of Supernova Feedback on the Formation of Galaxy Disks*, IAU Symposium and Colloquium Proceedings Series, 254: 369-374

6. Governato, F. et al. 2007, *Forming Disk Galaxies in ΛCDM Simulations*, MNRAS 374:1479-1494

7. Governato, F., Mayer, L., & Brook, C. 2008, *The Formation of Galaxy Disks*, Ast. Soc. Pacific Conf. Series, ed. J. Funes & E. Corsini, Vol. 396: 453-+

Angular momentum of disks

Whether a disk can form at all depends on the amount of angular momentum present in the infalling gas

During early collapse stages, gas and dark matter are well mixed
So they have a similar specific angular momentum distribution

Gas loses some angular momentum during infall

After the disk forms, secular disk evolution becomes important on timescales longer than the infall timescale

Angular momentum redistribution by torques and viscous effects

How halos gain angular momentum

Primordial turbulence and vorticity (von Wiezsacker 1951, Gamow 1952):

- Ruled out: velocities not due to gravitation decay in an expanding universe

Tidal torques (Hoyle 1949): Gravitational coupling from surrounding matter

- Well-developed (Peebles 1969, Doroshkevich 1970, White 1984) and widely accepted

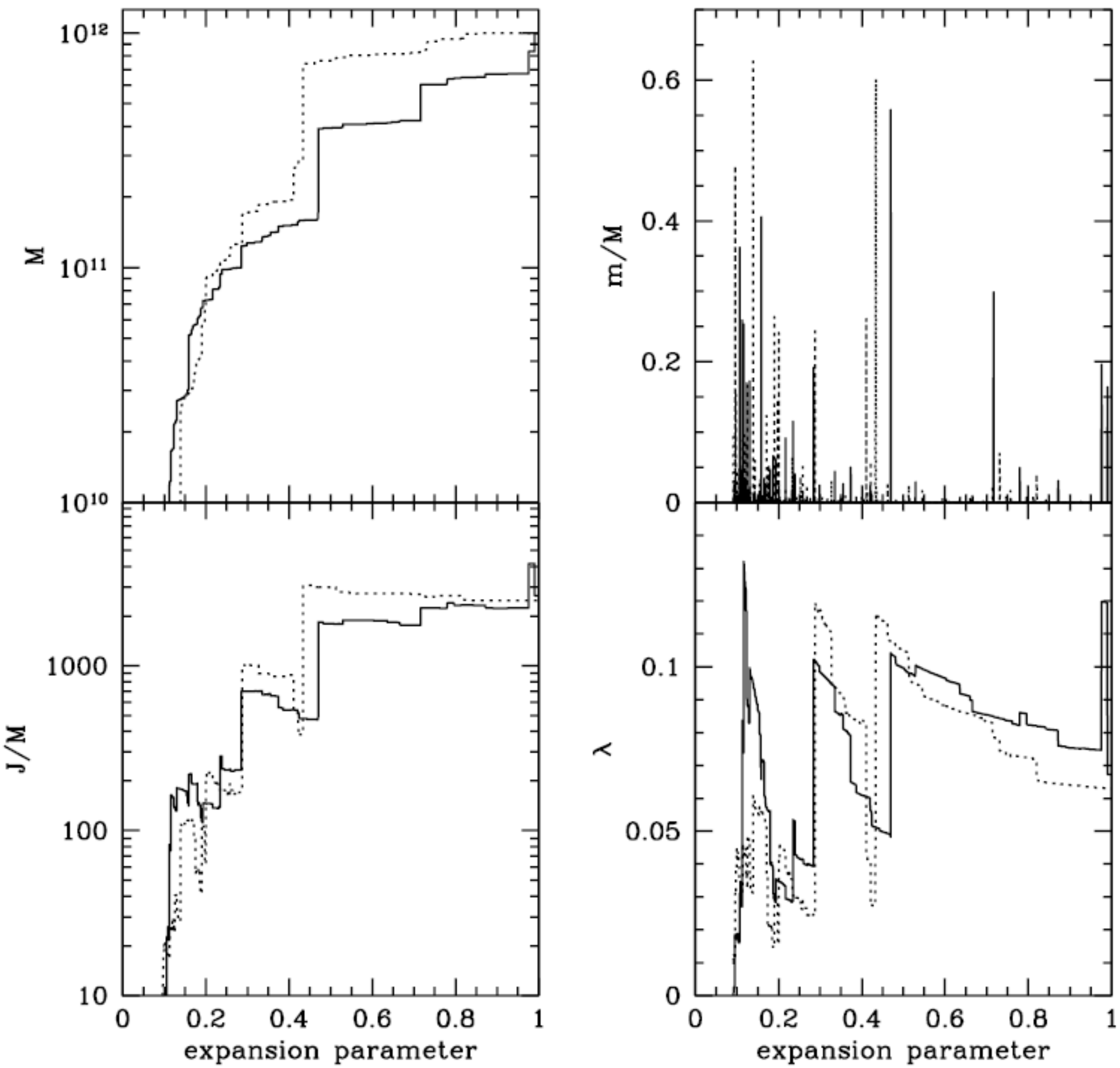
Agreement with N-body simulations:

- Considering all the mass that at $z = 0$ ends up inside a given halo, its angular momentum grows linearly with time at early collapse stages
- At later times, the growth slows down

Disagreement: due to nonlinear effects

- Angular momentum is overestimated by a factor of ~ 3
- Large scatter in angular momentum and direction of the spin parameter

Satellite accretion theory (Vitvitska et al. 2002)



Halos cumulatively acquire angular momentum from satellite accretion

Buildup of angular momentum is a random walk process associated with the mass assembly history of the halo's major progenitor

Extended Press-Schechter approximation is used for calculations

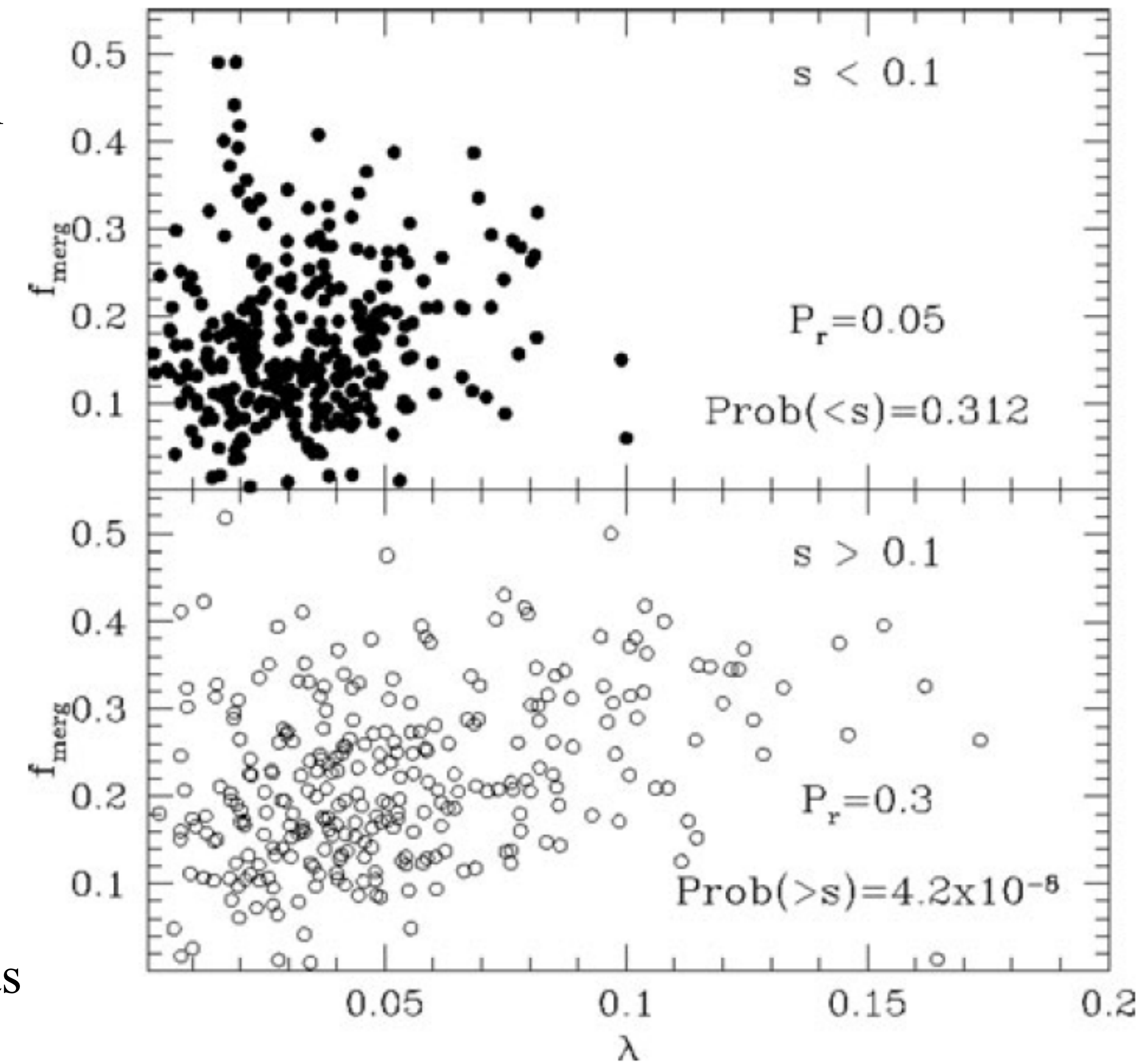
$$\lambda \equiv \frac{J|E|^{1/2}}{GM^{5/2}}$$

Equilibrium vs. non-equilibrium systems

Merging history and spin are uncorrelated in equilibrium halos, but are correlated in non-equilibrium ones

Major mergers have higher-than-average spins only for unrelaxed systems

Virialization should lead to a net decrease of angular momentum in gas



(D'Onghia 2008)

Does infalling gas lose angular momentum?

The tidal torques theory predicts that gas conserves its angular momentum

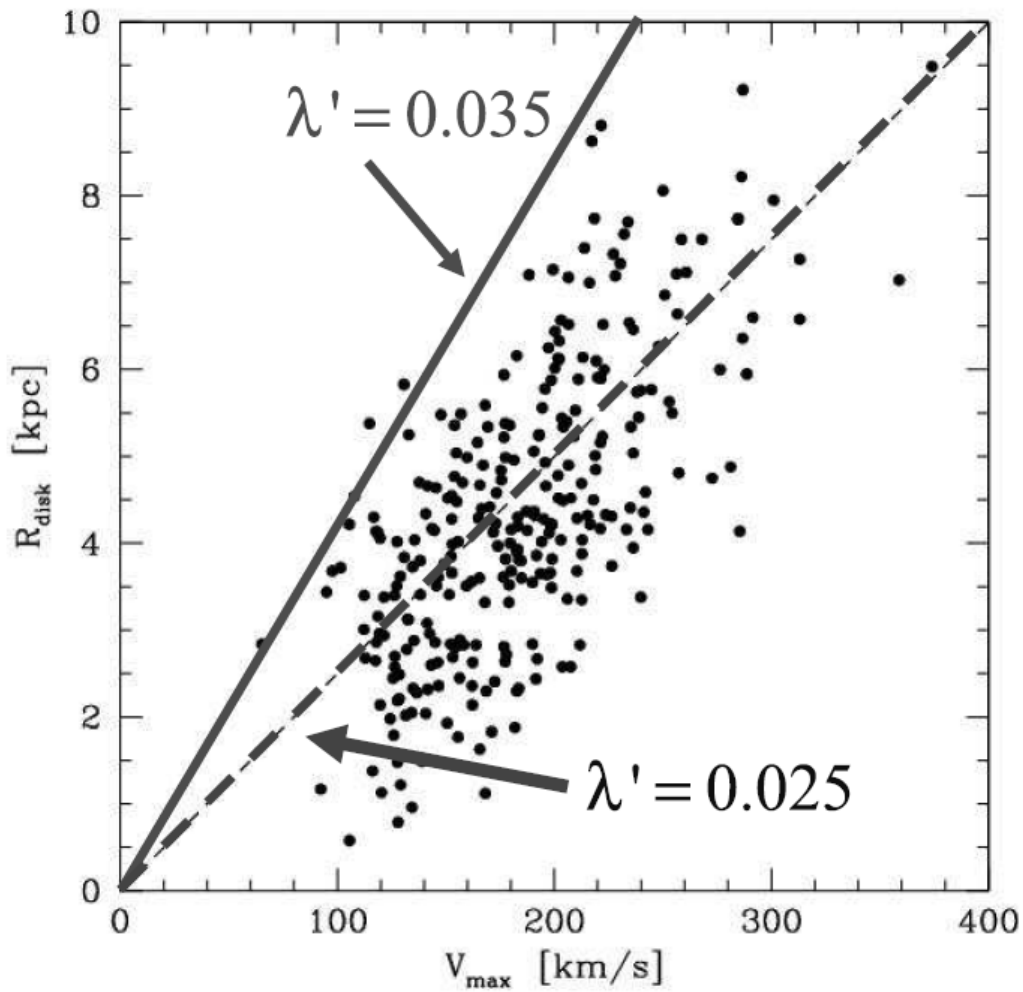
Then, the resulting disk size should be directly related to the halo's specific angular momentum λ'

Assuming a flat rotation curve,

$$R_d \approx 8 \left(\frac{\lambda'}{0.035}\right)\left(\frac{H_0}{H}\right)\left(\frac{v_{max}}{200km/s}\right) kpc$$

Observations suggest that the gas does lose angular momentum during infall

$$\lambda' = \frac{J}{\sqrt{2} M_{vir} V_{vir} R_{vir}}$$



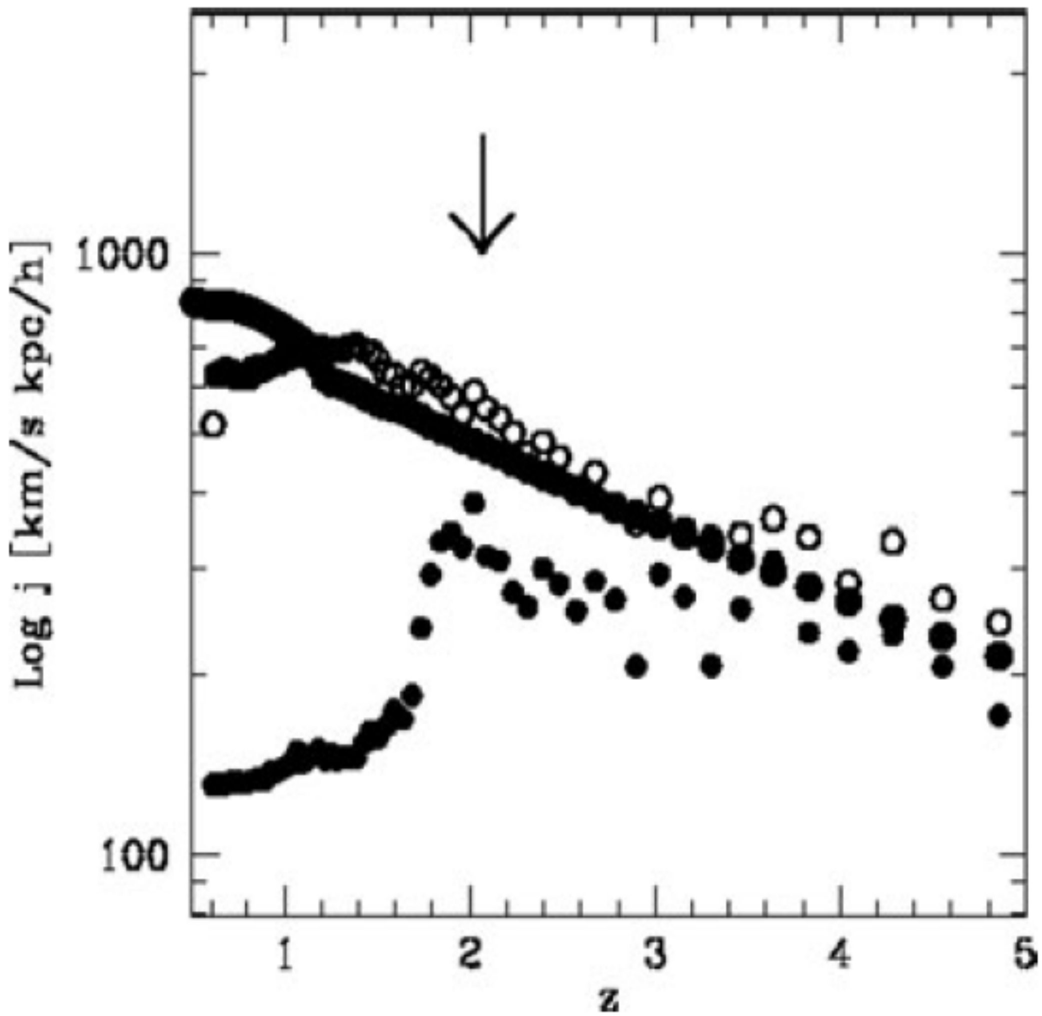
(Burkert 2009) Data from Courteau (1997)

It does in N-body simulations of satellite accretion

Redistribution of mass and angular momentum during a major merger likely effects baryons and dark matter unevenly

Angular momentum distributions of gas and dark matter are similar until a major merger at z ~ 2 with a mass ratio of 5 : 1

A new extended disk begins to form from gas that was not involved in the merger



(D’Onghia 2008)

Problems with ΛCDM N-body simulations

- Catastrophic angular momentum loss of gas during disk formation
  - Formed disks have unrealistically small scale lengths
  - And very large surface densities
- Inability to produce disk-dominated and bulgeless galaxies
- Production of too many satellite galaxies

Blamed processes:

- Dynamical friction of infalling gas clumps with the halo
- Low numerical resolution
- Major mergers
- Absence of important processes: star formation , feedback

Empirical Kennicutt relations (1998, 2007)

Simplified and observationally motivated descriptions of star formation

Correlation between the star formation rate per surface area Σ_{SFR} and the gas surface density Σ_g, averaged over the whole galaxy:

$$\Sigma_{SFR}^{(K1)} = 2.5 \times 10^{-4} \left(\frac{\Sigma_g}{M_\odot / pc^2} \right)^{1.4} \frac{M_\odot}{kpc^2 \ yr}$$

Including a dependence on the typical orbital period τ_{orb} of the disk:

$$\Sigma_{SFR}^{(K2)} = 0.017 \left(\frac{\Sigma_g}{M_\odot / pc^2} \right) \left(\frac{10^8 yrs}{\tau_{orb}} \right) \frac{M_\odot}{kpc^2 \ yr}$$

Combined: $\Sigma_g \sim \tau_{orb}^{-2.5} \sim \left(\frac{v_{rot}}{R_{disk}} \right)^{2.5}$

Star Formation and Feedback (Zavala et al. 2008)

N-body + SPH simulations

<u>Bulge-dominated galaxy</u>

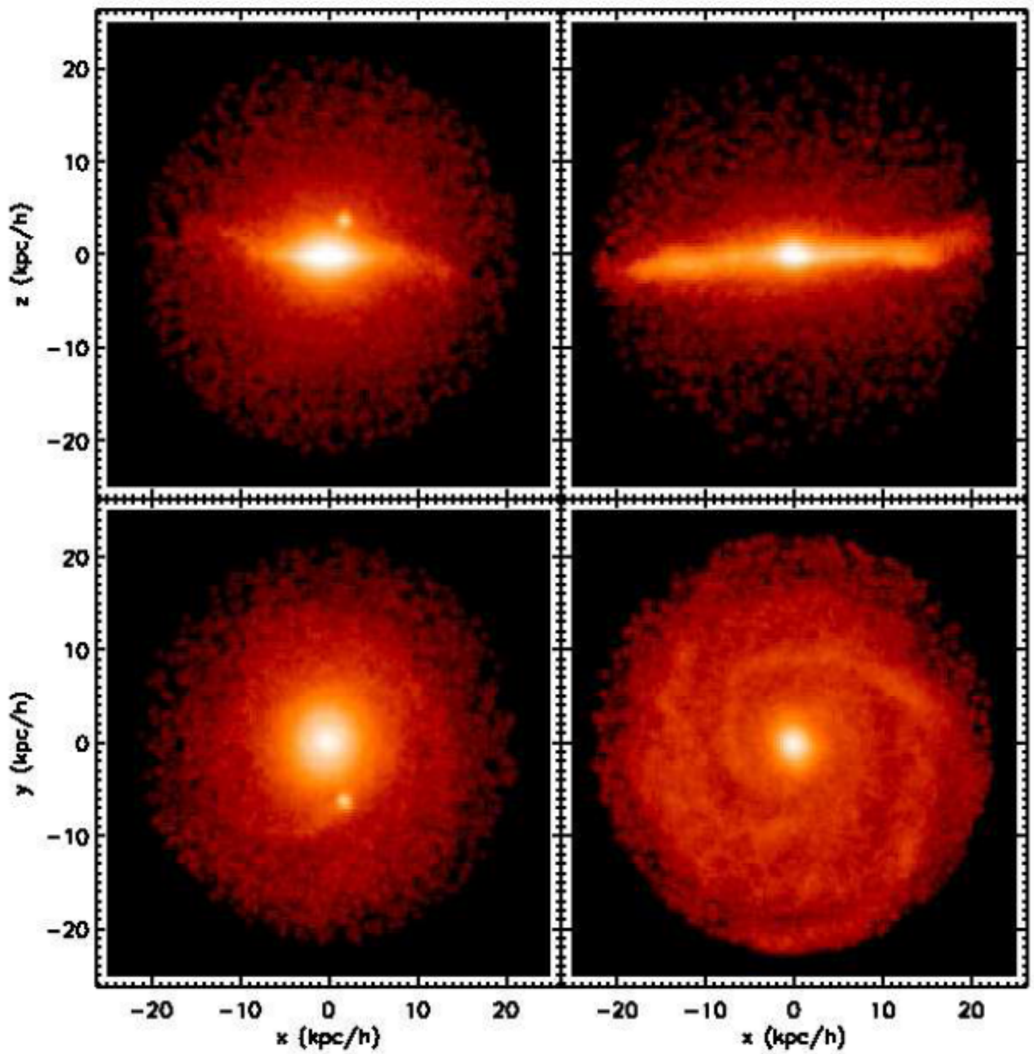
Star formation:

- Tuned to reproduce the first Kennicutt relation

<u>Disk-dominated galaxy</u>

Supernova heating:

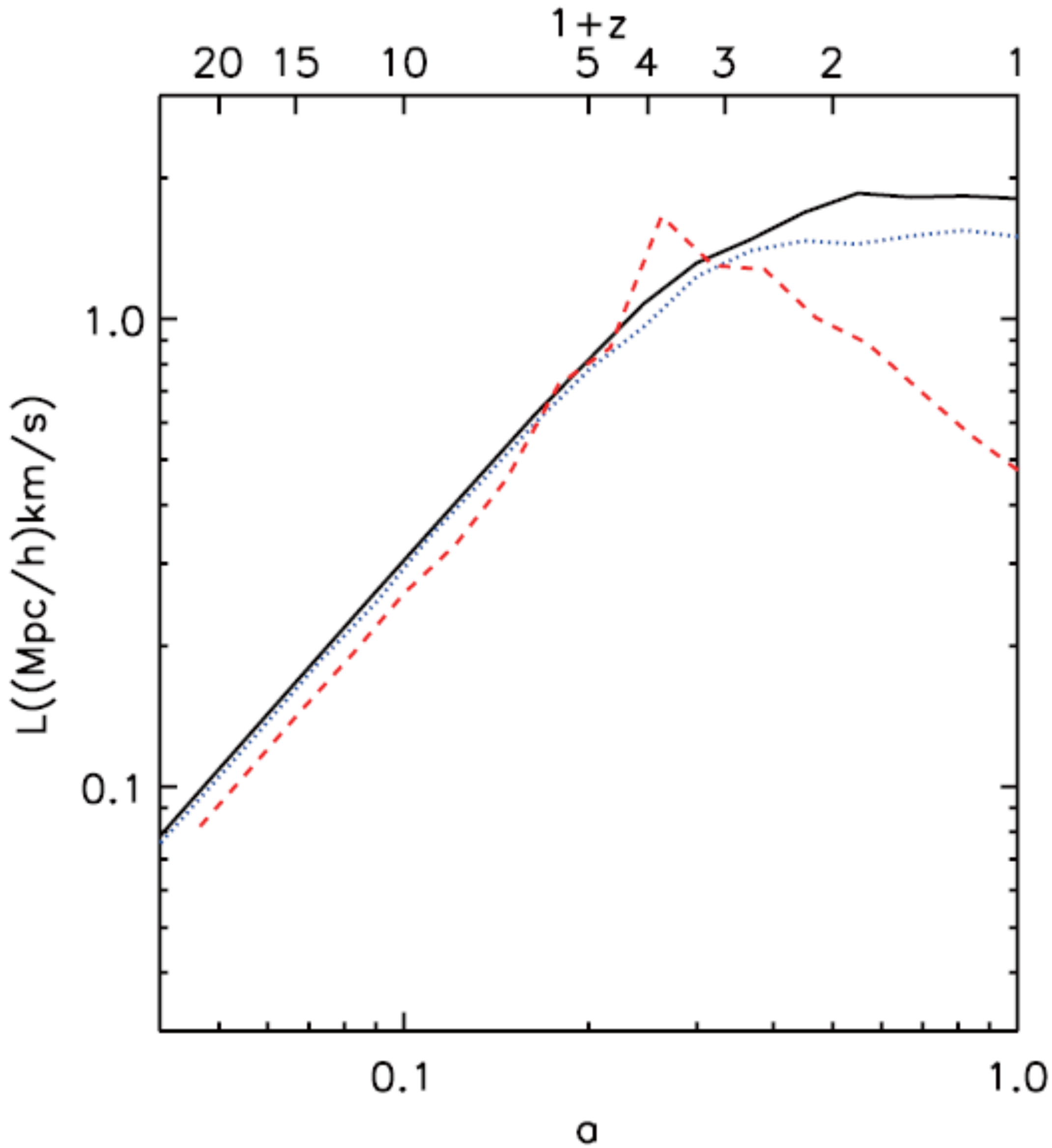
- Star formation efficiency is higher than average in recently shock-heated gas
- Stars formed from this gas are assumed to have a top-heavy IMF



Bulge- vs. disk-dominated galaxies (cont.)

The shape and value of the specific angular momentum is similar for the disk-dominated baryons and the halo

These simulations support the standard tidal torque theory

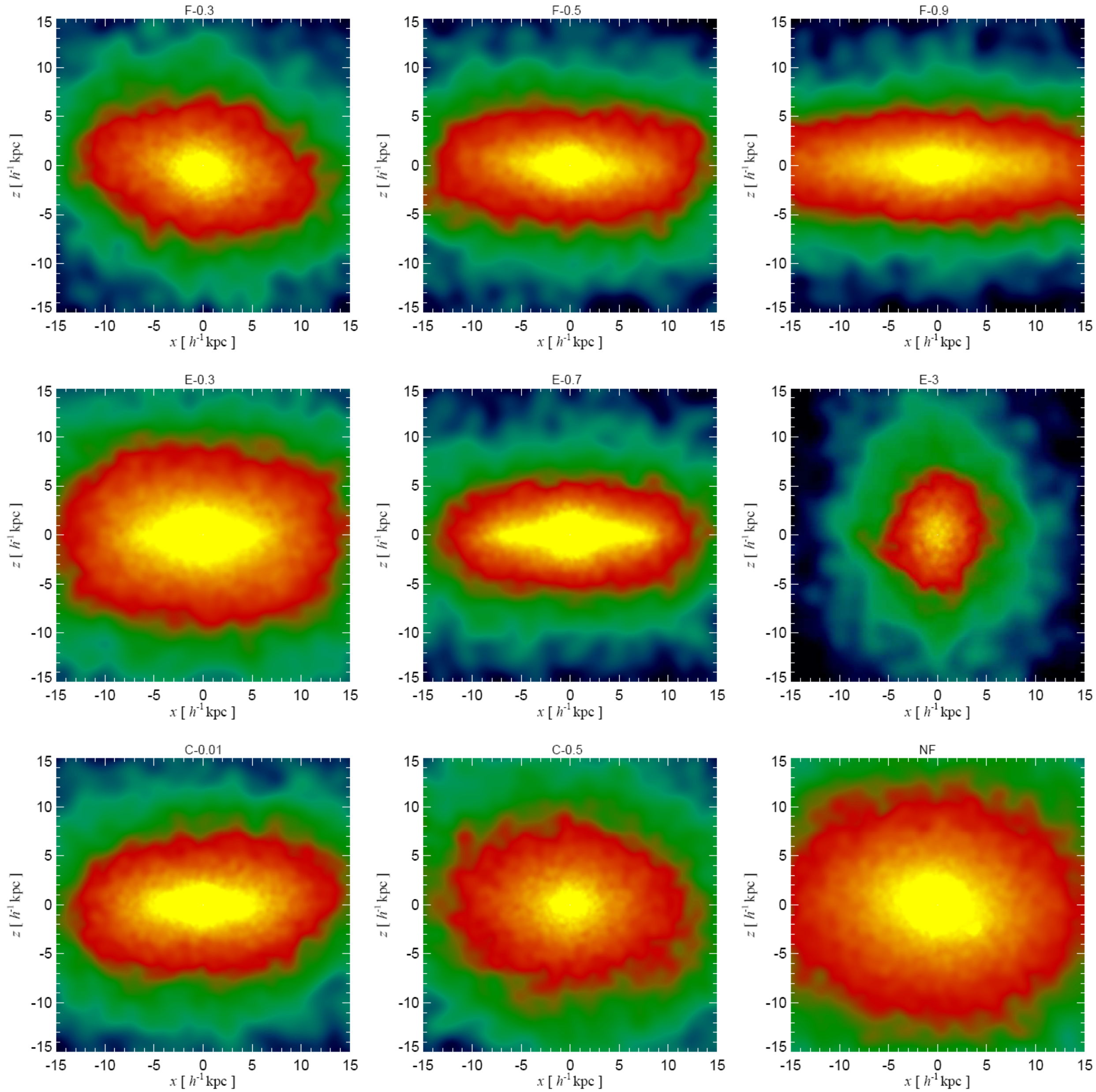


(Zavala et al. 2008)

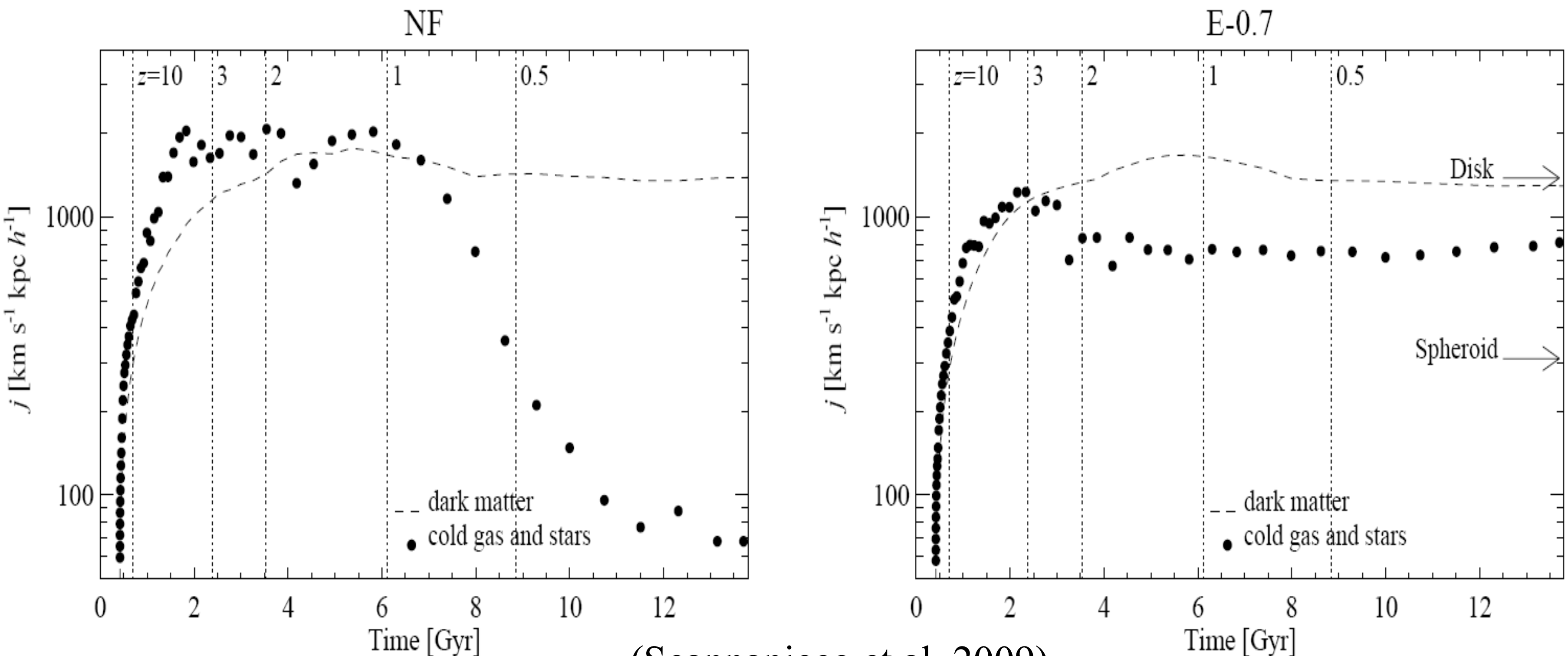
Supernova feedback (Scannapieco et al. 2009)

Star formation and feedback prescriptions are set based upon isolated models of present day galaxies

Same initial conditions could produce either disk or elliptical galaxies depending on the used efficiency of gas heating



Supernova feedback (cont.)



(Scannapieco et al. 2009)

SN feedback: regulates star formation efficiently, pressurizes the gas, and generates mass-loaded galactic winds

Allows Large galactic disks to form

Still not efficient enough to generate disk-dominated late-type galaxies

More realistic simulations (Governato et al. 2007)

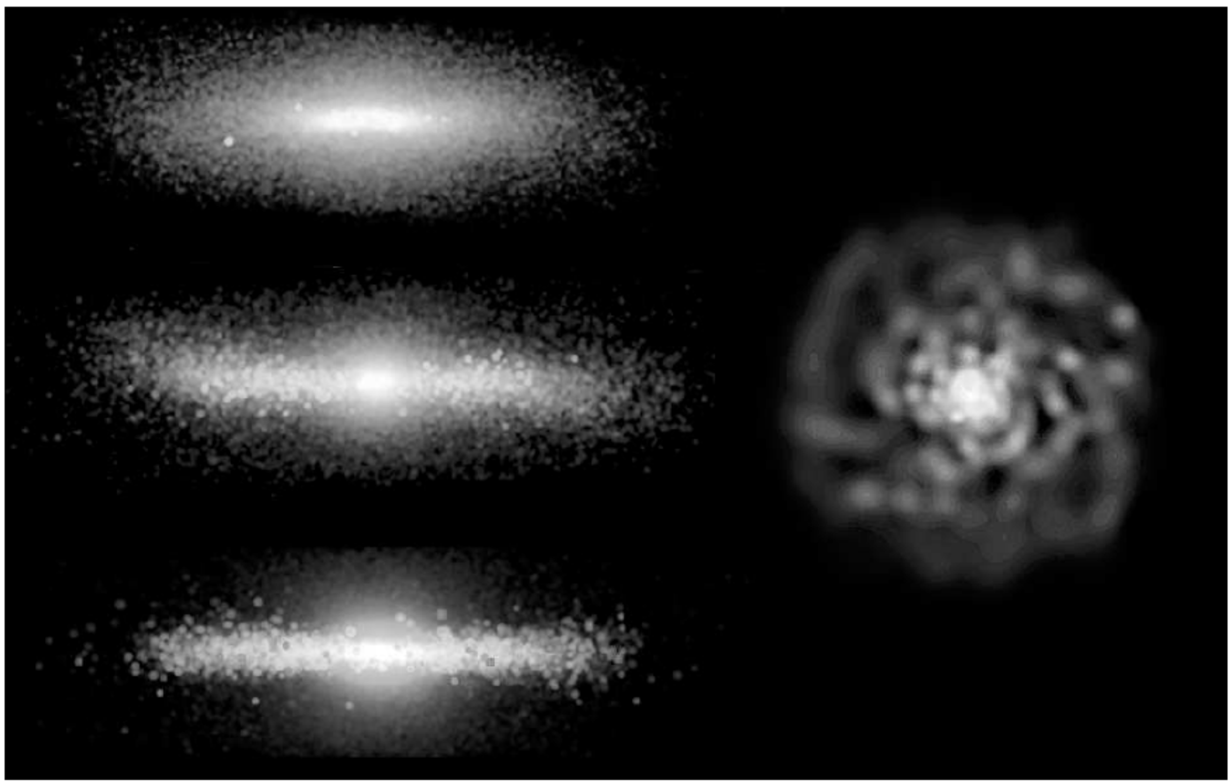
Star formation and feedback based on isolated present-day galaxy models

Compton and radiative gas cooling

Pressure support of gas turbulence and multiphase treatment of the ISM

Effects of a time-dependent, but uniform UV background

High mass and force resolutions

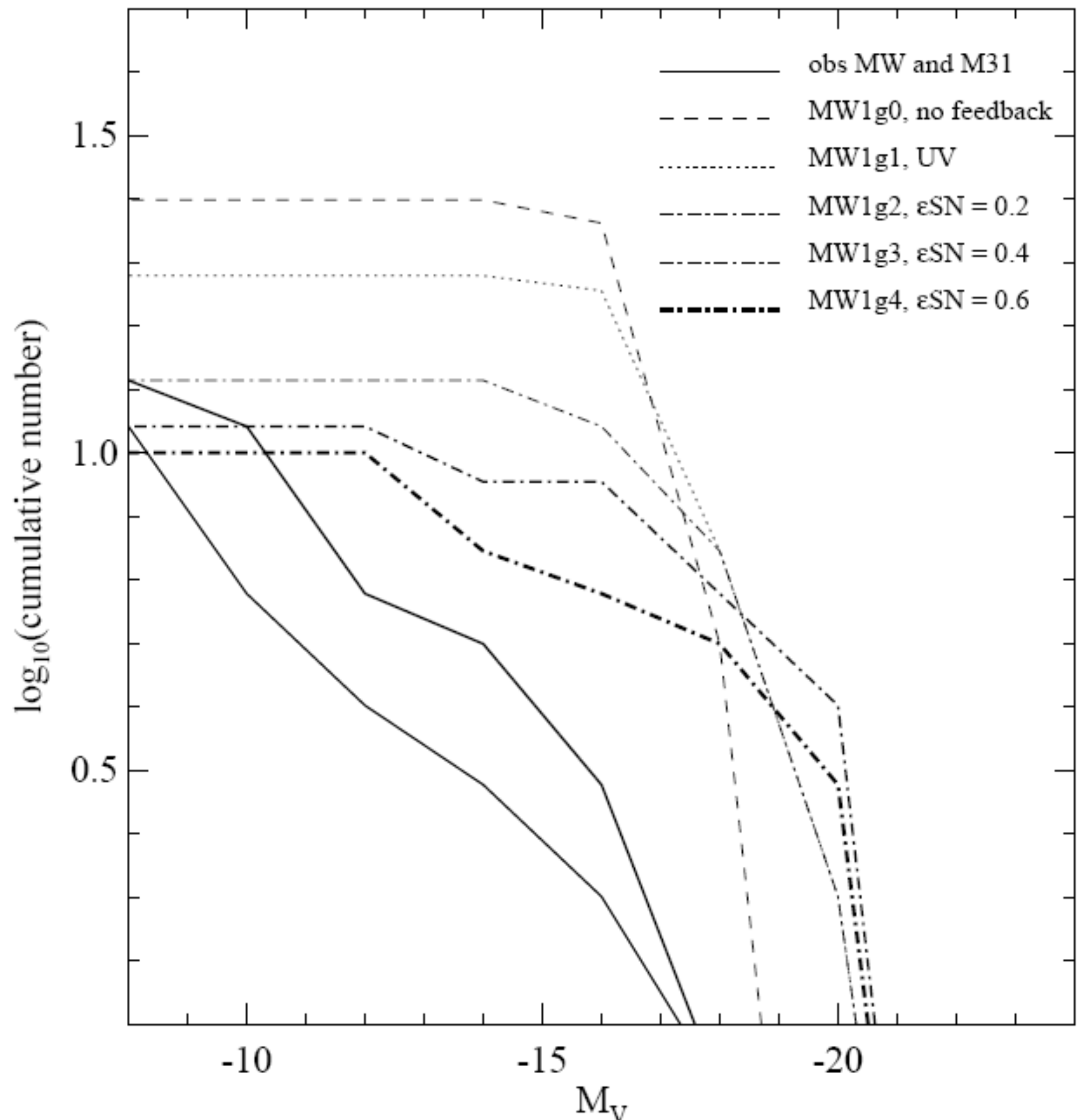


Realistic simulations: Number of satellites

The 2 runs without SN feedback produce too many satellites

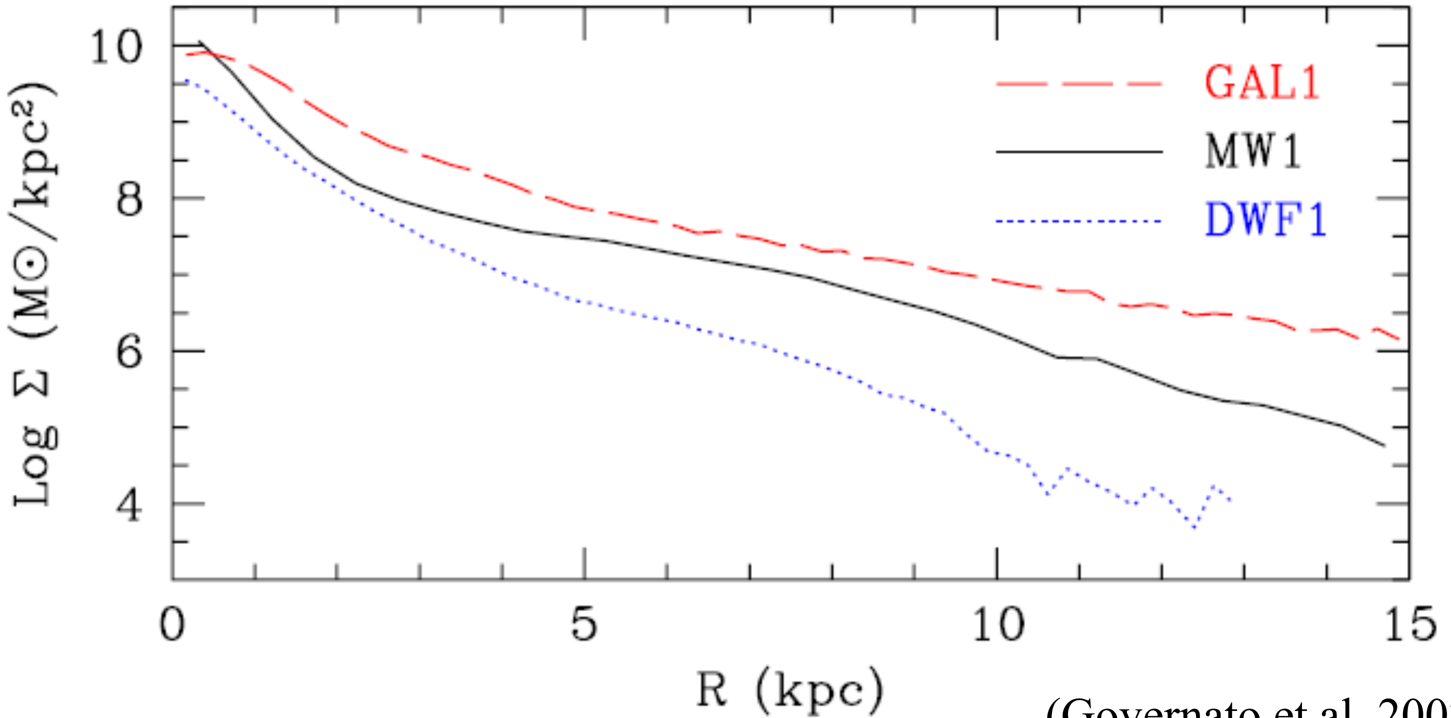
The 3 runs with feedback produce reasonable satellite numbers,

But they are still too bright



(Governato et al. 2007)

Realistic simulations: Stellar density profile



(Governato et al. 2007)

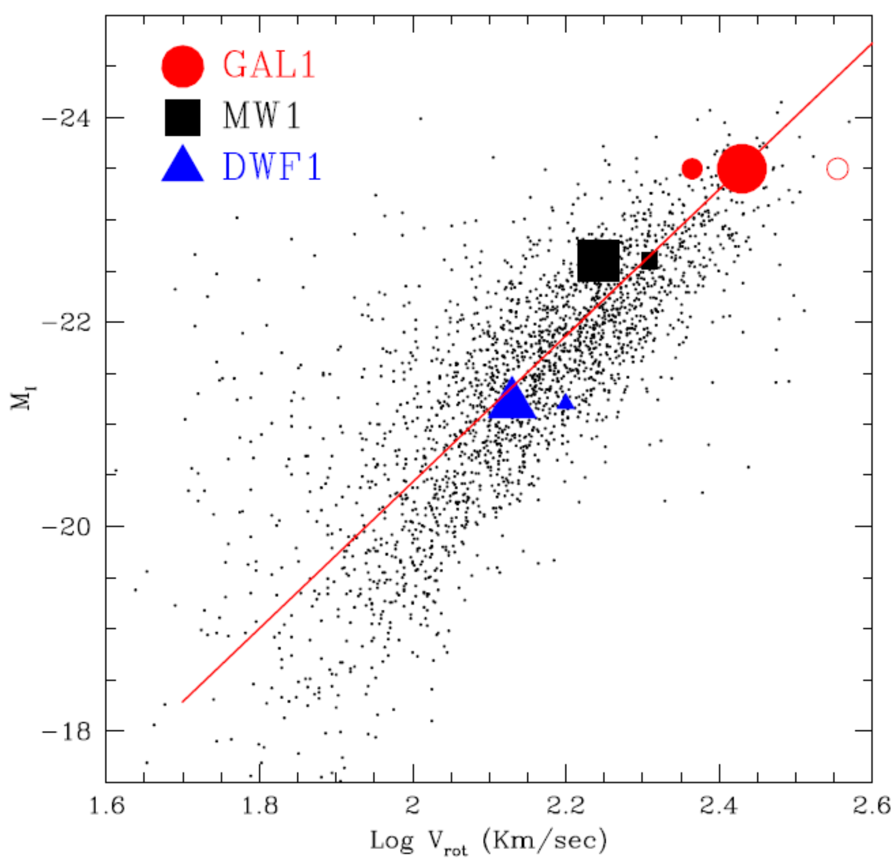
The stellar disk component is well fit by an exponential distribution between 1 and 3 disk scale lengths

There is evidence for a central steeper component extending to 1 or 2 kpc

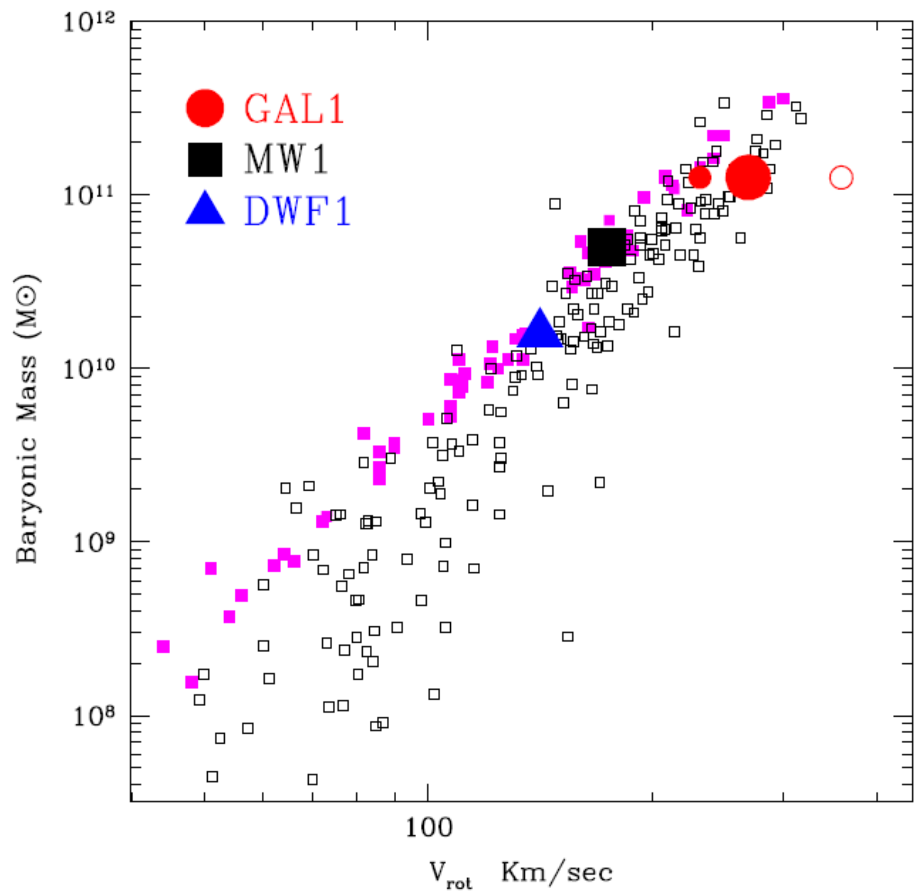
Realistic simulations: Tully Fisher relations

TF relation: a galaxy's characteristic rotational velocity connected to its total absolute magnitude

Baryonic TF: same for the total disk mass



(data from Giovanelli 2005)



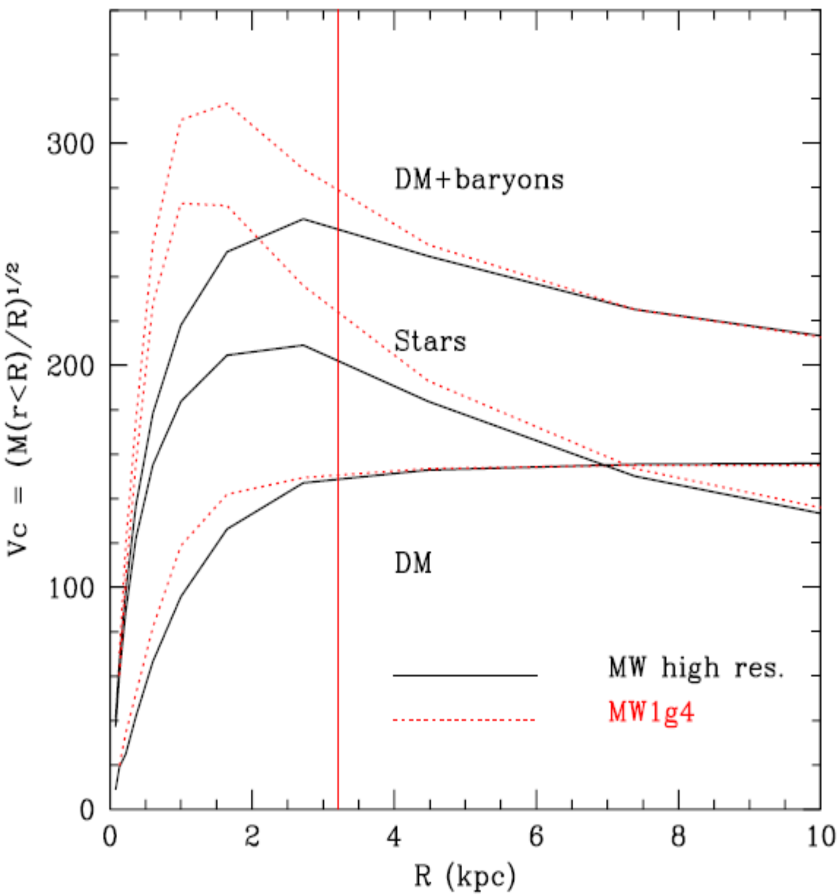
(Governato et al. 2007)

(data from McGaugh 2005)

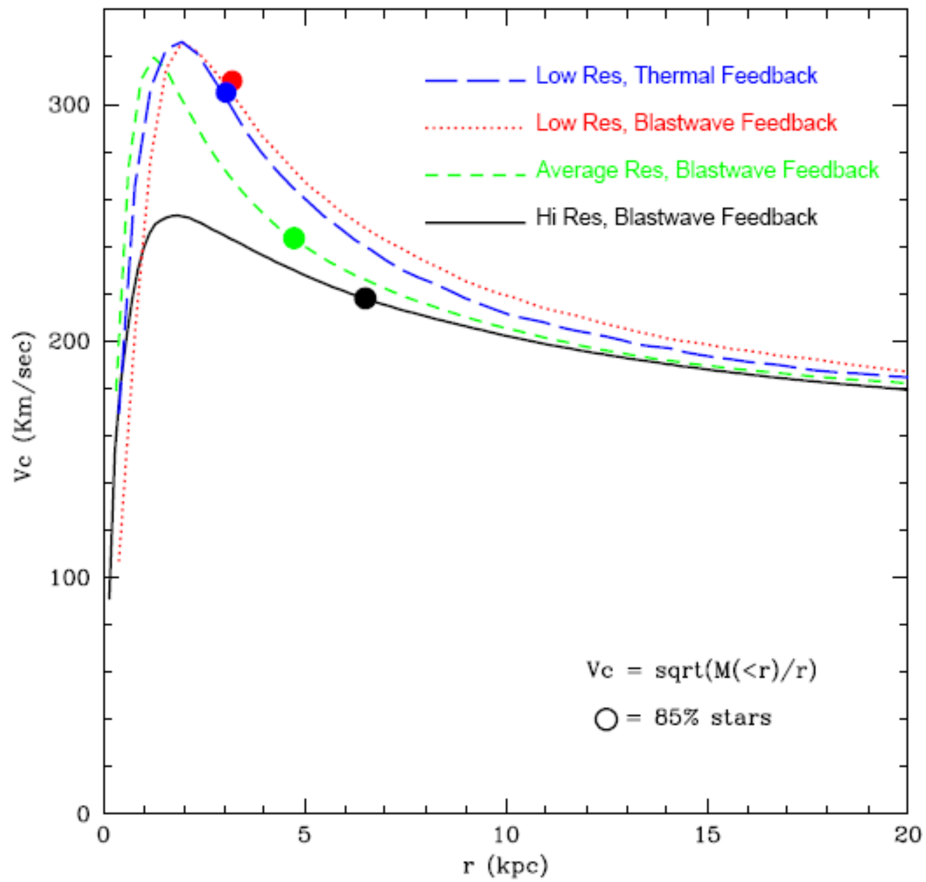
Rotation curves and a resolution test

The high resolution simulations have flatter rotation curves

They also yield larger I-band disk scale lengths, and smaller B/D ratios

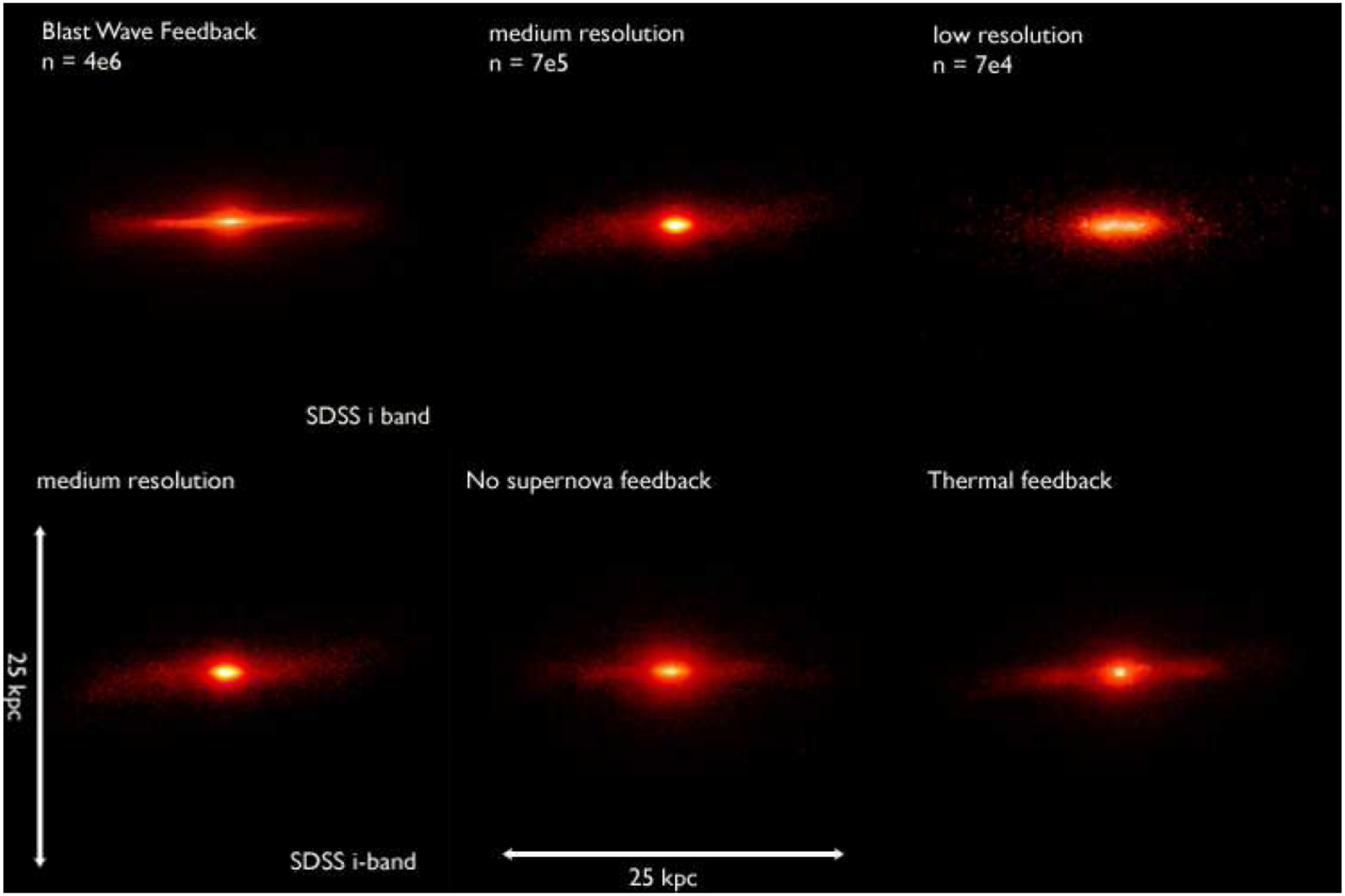


(Governato et al. 2007)



(Governato et al. 2008)

High resolution simulations (Governato et al. 2008)



Conclusions

- The tidal torques theory disagrees with observations that infalling gas loses angular momentum
- But the satellite accretion theory, when checked with simulations, yields an angular momentum loss that is too big
- The same problem, among others, is present in simple N-body simulations
- Realistic star formation, feedback, and high resolution play important roles in allowing N-body + SPH simulations to form realistic disks and solve the missing satellites problem
- The satellites in simulations are still too bright