M31 and galaxy formation

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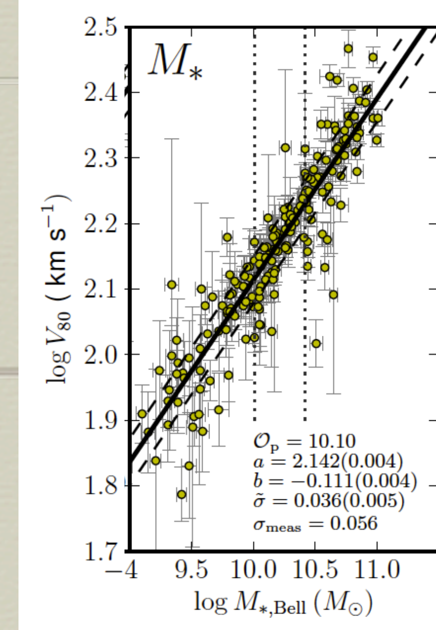
Why Study M31?

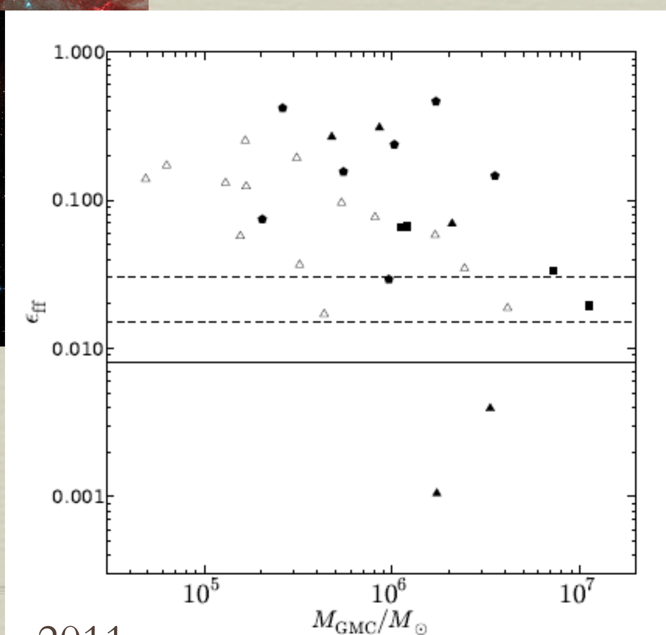
- unique opportunity to study internal structure/kinematics of a large spiral galaxy, that we are not buried within
- resolved stellar population studies can provide ‘archaeological’ record of star formation and chemical enrichment history
- puzzle in galaxy formation: diversity & complexity of ‘small scale’ processes, yet relative regularity of galaxy scaling laws

star formation efficiency shows complex dependence on local environment and conditions

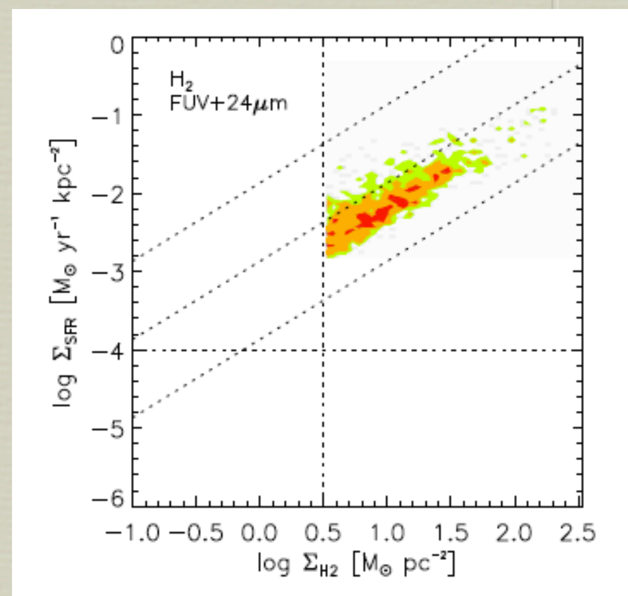


Reyes et al. 2011

yet somehow galaxies obey sometime very tight global scaling relations

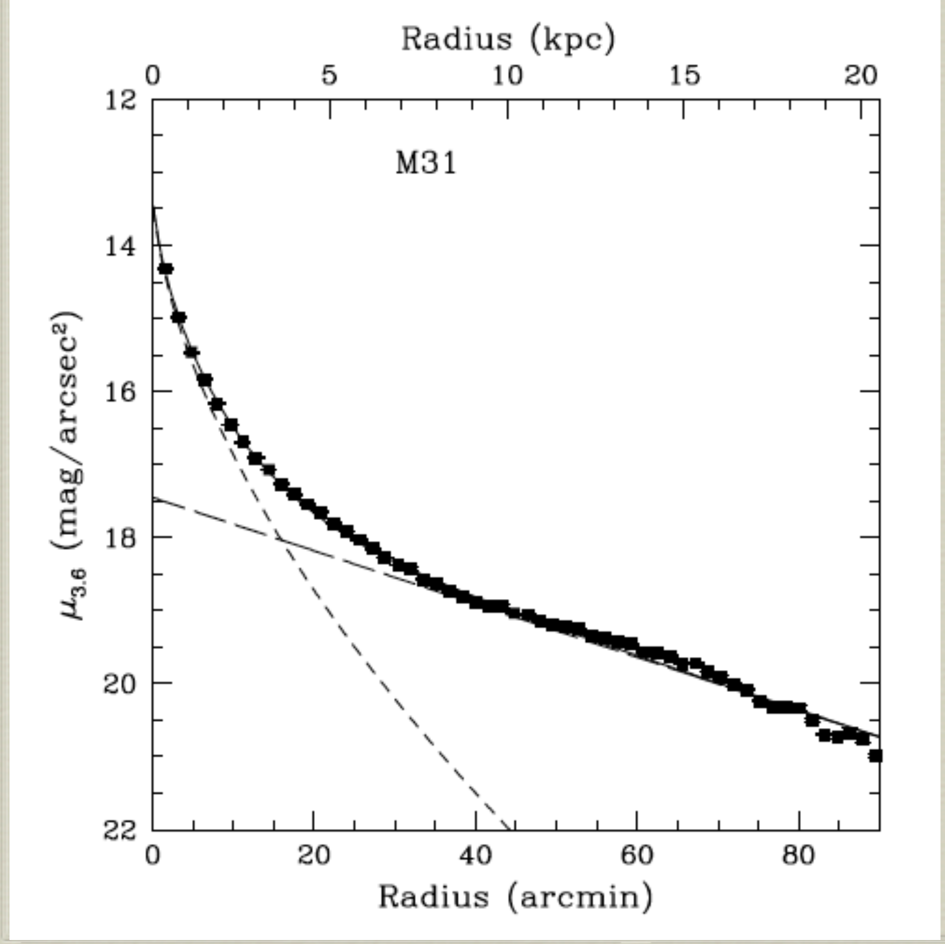


Murray 2011



Bigiel et al. 2008

M31 global properties

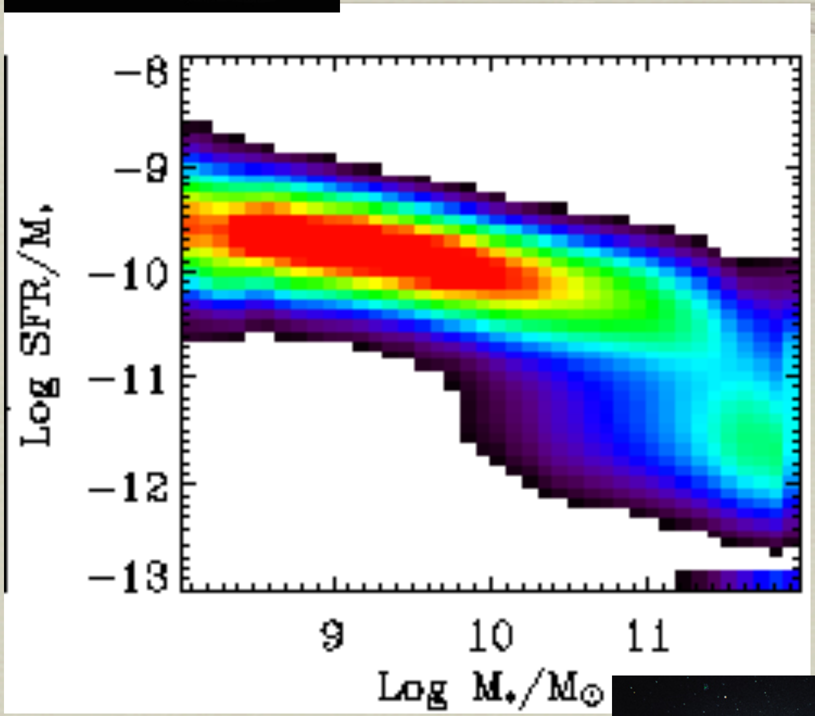


m* ~ 9E10-1E11 Msun
Hubble type: SA(s)b (de V. 2001)
B/D = 0.57+/-0.02
rd = 5.91
rb = 1.93
n_bulge = 1.71

KZS02: Mh=(1.4-1.6)E12 M_{sun}
c(NFW)=12

SBB06: Mh = (7.3-8.9)E11 M_{sun}
c(NFW)=16-51

Seigar, Barth & Bullock 2006; Klypin, Zhao & rss 2002

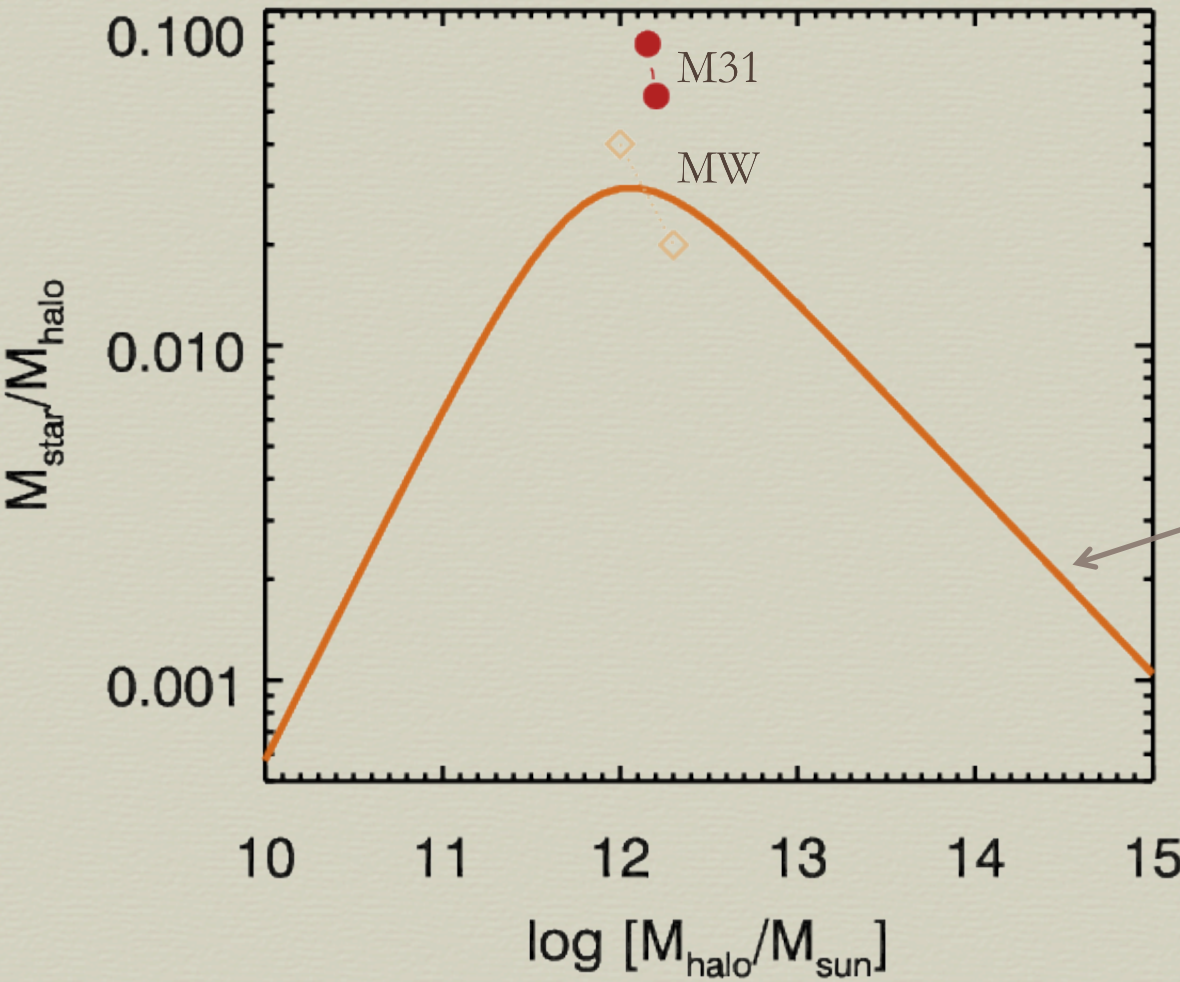


Brinchmann et al. 2003

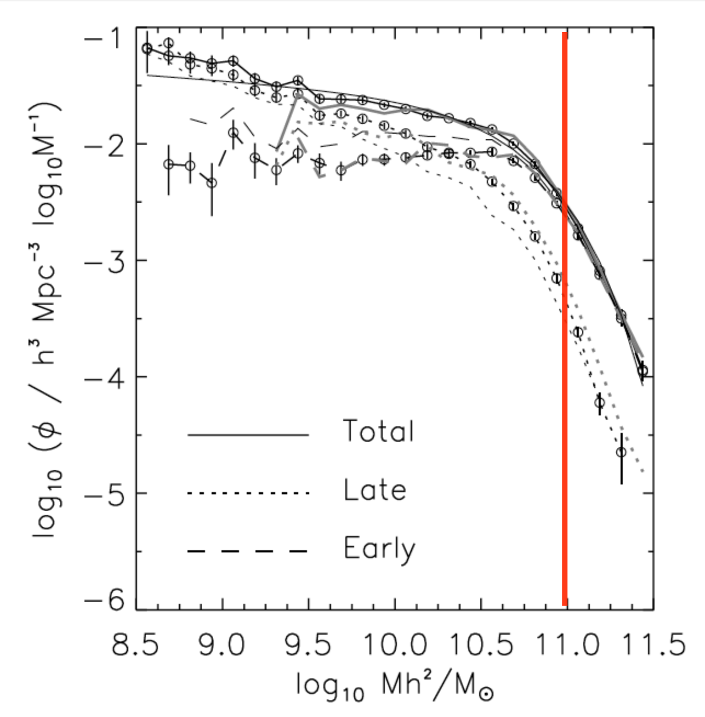
is M31 a transitional object?

- M31 lies close to, or slightly above, the 'transition mass' scale (Kauffmann et al. 2003) that marks:
- disk dominated→ spheroid dominated
- star forming→ passive

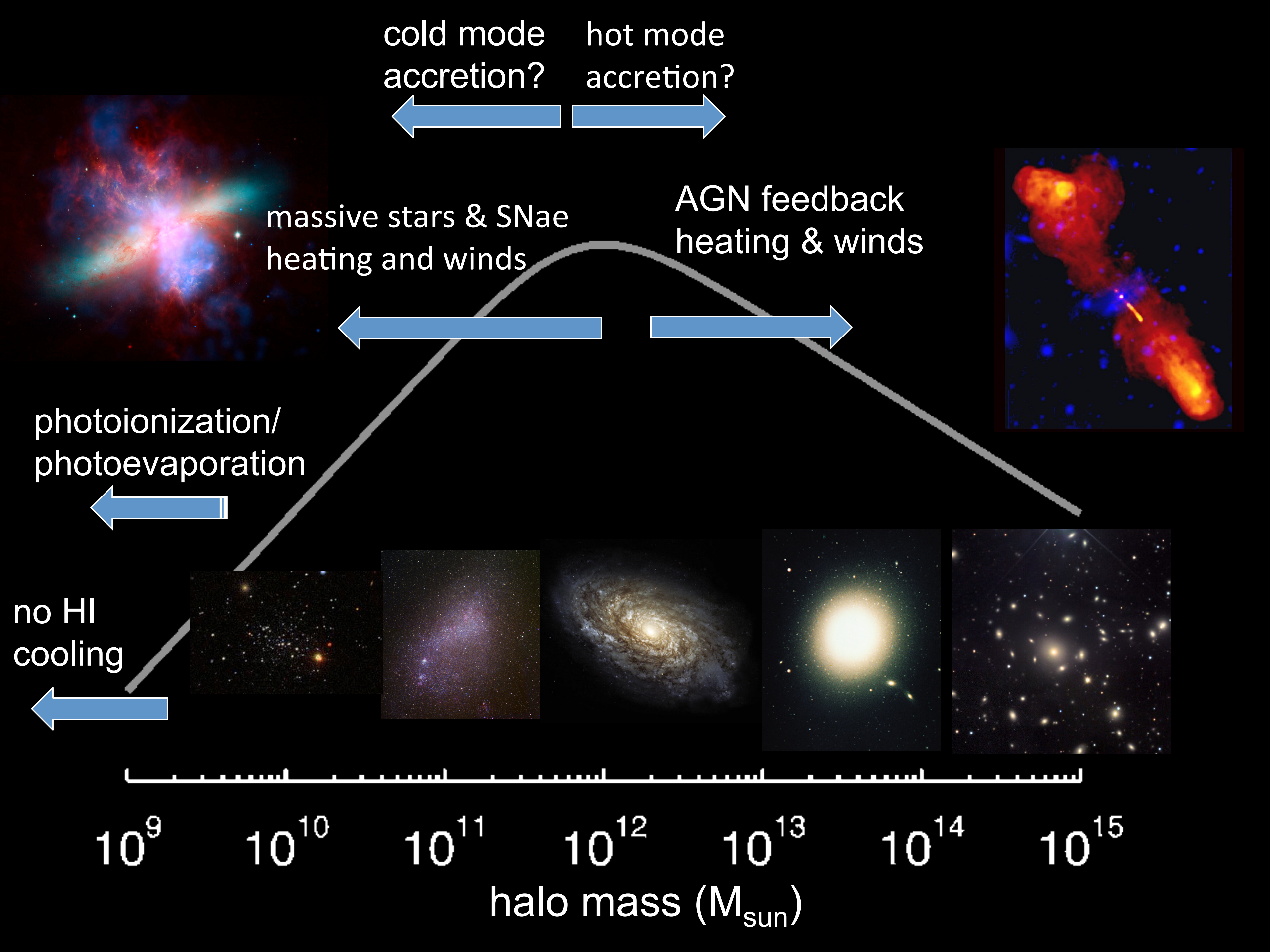
is M31 a typical disk galaxy?



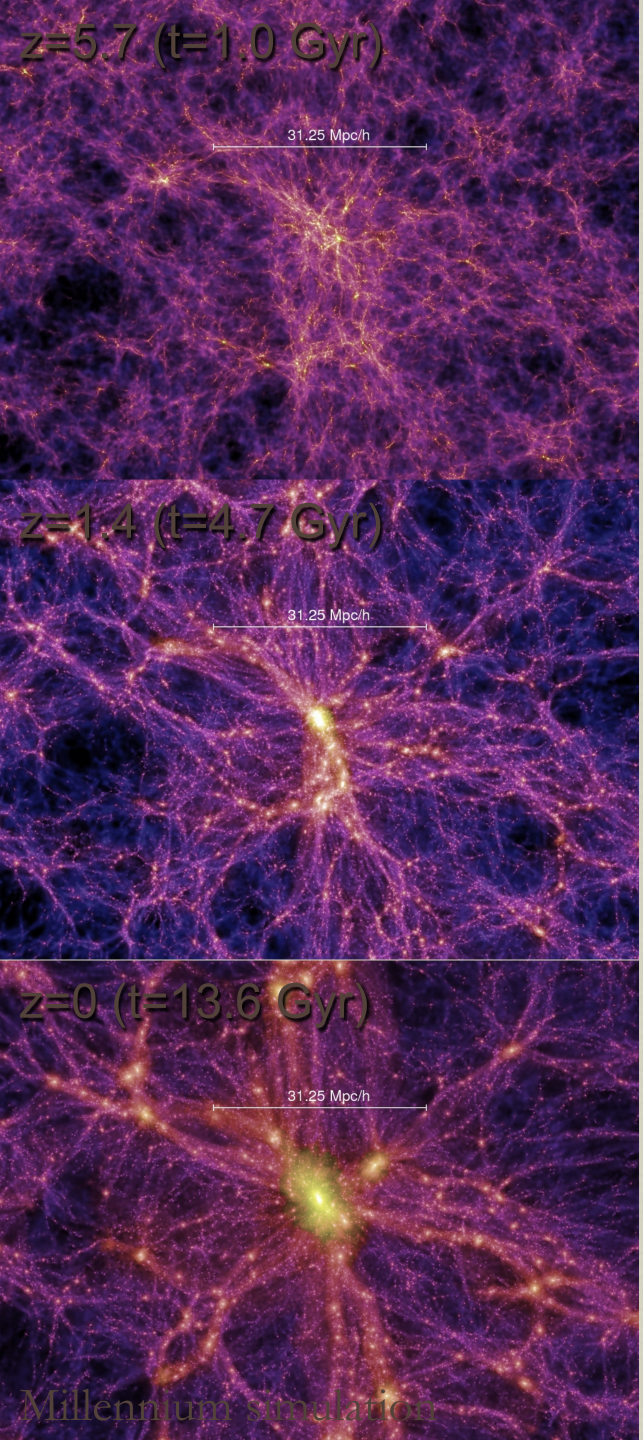
abundance matching
Moster, rss et al. 2008



Bell et al. 2003



cold mode
accretion?
hot mode
accretion?
massive stars & SNae
heating and winds
AGN feedback
heating & winds
photoionization/
photoevaporation
no HI
cooling
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
halo mass (M_{sun})



Modern paradigm of galaxy formation

- gravitationally bound structures (halos) form as predicted by LCDM
- gravity also causes gas to accrete into halos and galaxies
- accretion may be suppressed in halos below the "filtering mass" by the presence of a photoionizing background
- cold dense gas can form stars (Kennicutt relation)
- cold gas is heated and removed from galaxies by stellar & SNae-driven winds
- metals produced by stars enrich cold gas and blown around by winds

major uncertainties in galaxy formation modeling

- how does gas get into galaxies: modes of accretion, the "hot vs. cold" mode debate
- how does gas turn into stars: what processes regulate star formation? how does SF efficiency depend on local environment? is there a universal "star formation law"?
- how does gas get out of galaxies: stellar, SNae, and AGN driven winds
- how do the internal structure and kinematics of galaxies correlate with their formation history and global properties?

theoretical challenges

- making extended, disk-dominated galaxies with flat rotation curves
- making dwarf galaxies with rising rotation curves (cusps instead of cores)
- making galaxies with the observed number of satellites
- making galaxies with star formation histories consistent with observations (downsizing)

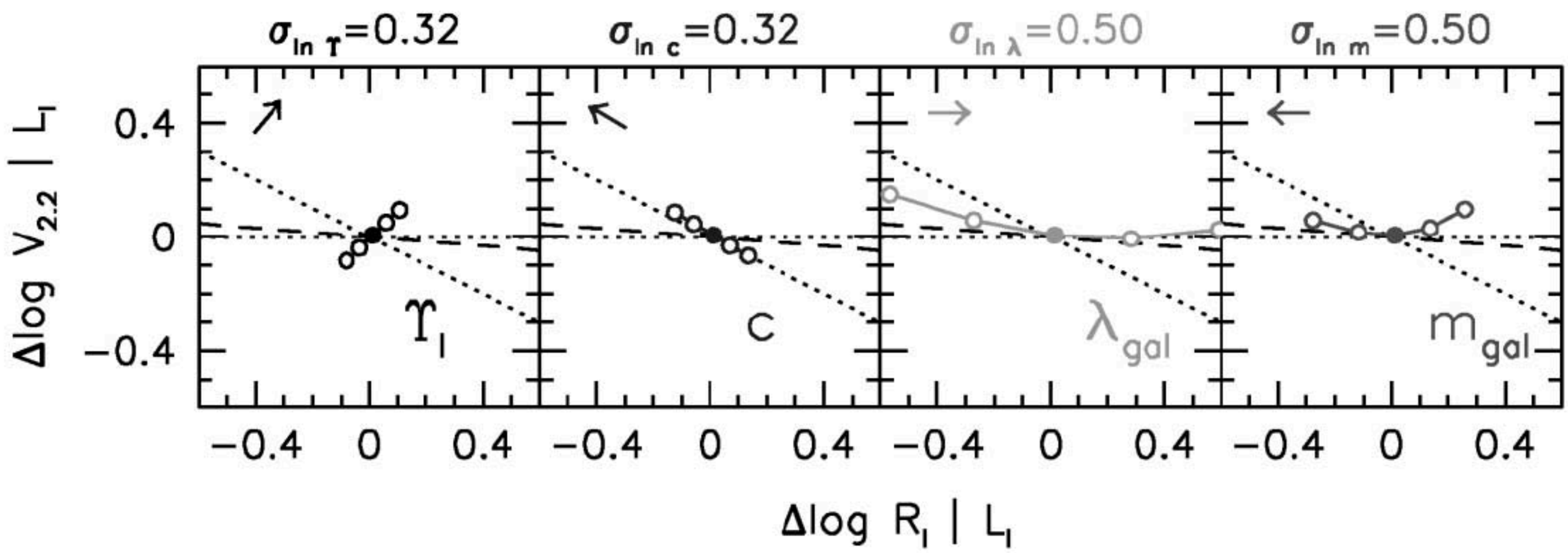
disk formation: simplest analytic models

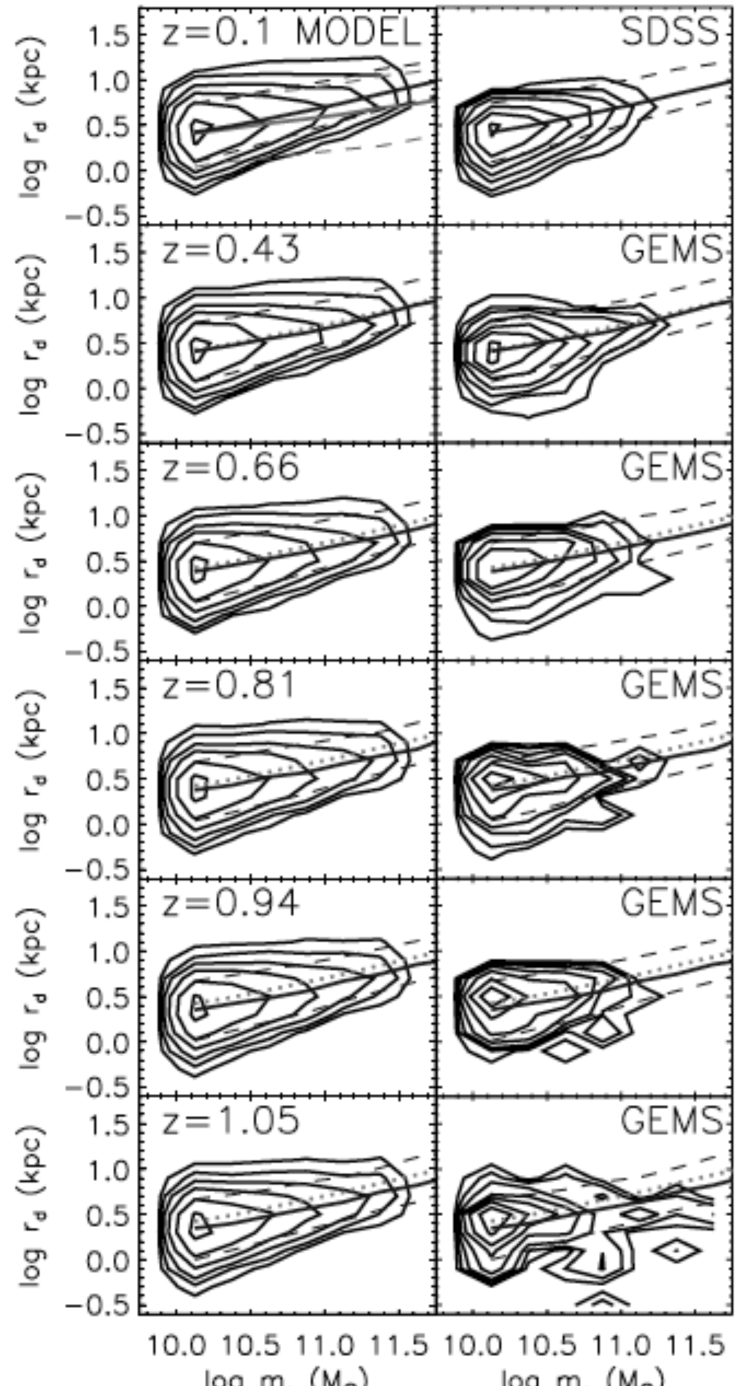
- average spin of DM halos described by a non-evolving, nearly universal log-normal distribution ($\lambda \sim 0.04$, $\sigma_{\log\lambda} \sim 0.5$)
- assume gas has same j as DM and final disk profile is exponential
- conservation of angular momentum (no shell crossing) + *adiabatic contraction* → estimates of disk size and rotation velocity

e.g. Fall & Efstathiou 1980; Blumenthal et al. 1986;
Mo, Mao & White 1998; Dutton et al. 2007

disk collapse factor

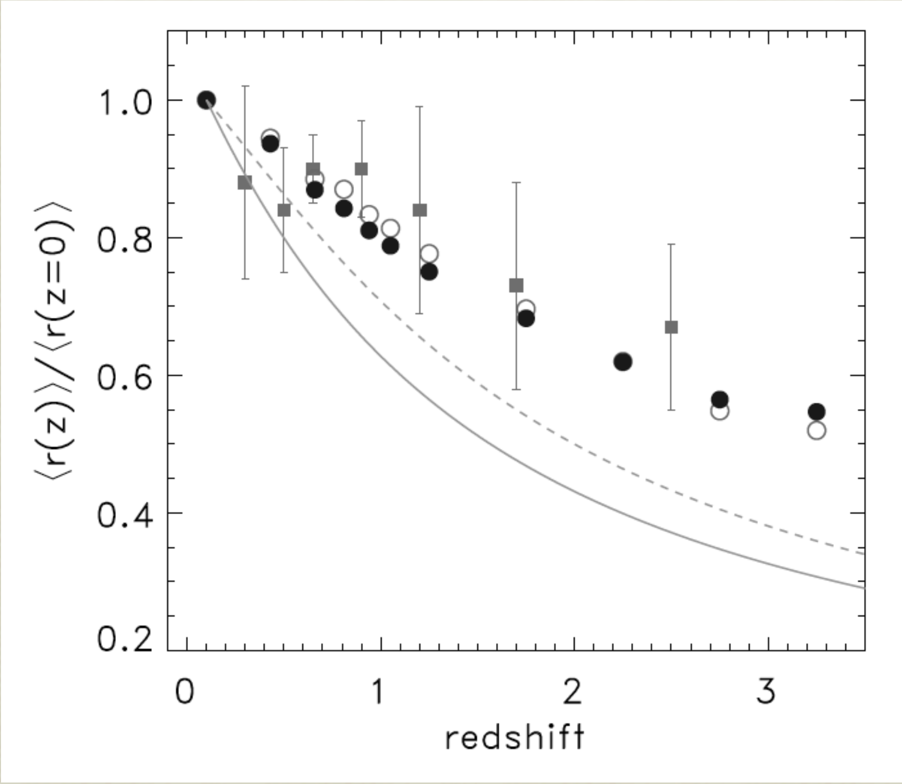
$$r_d \sim \lambda \, r_H \, f(c, \lambda, f_d)$$





simple model assuming
-exponential disk profiles
-no shell crossing
-conservation of angular momentum

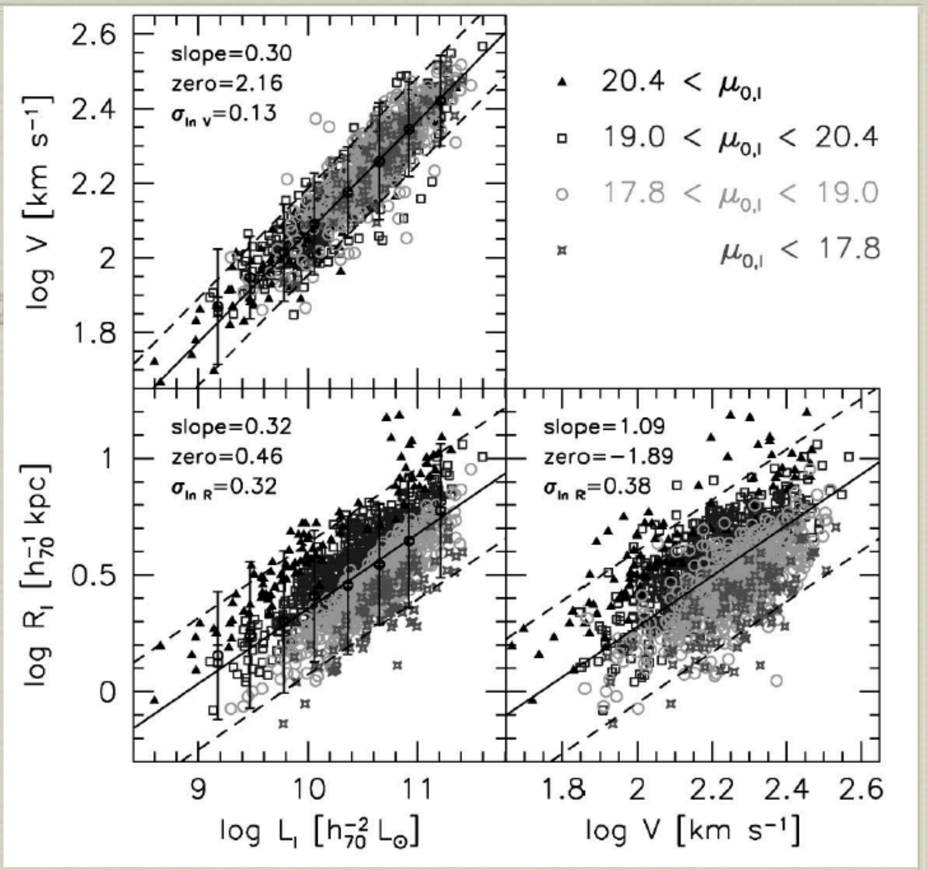
reproduces observed disk sizes up to z~2
predicts slower evolution than 'naïve' r_{vir} scaling



Somerville et al. 2008

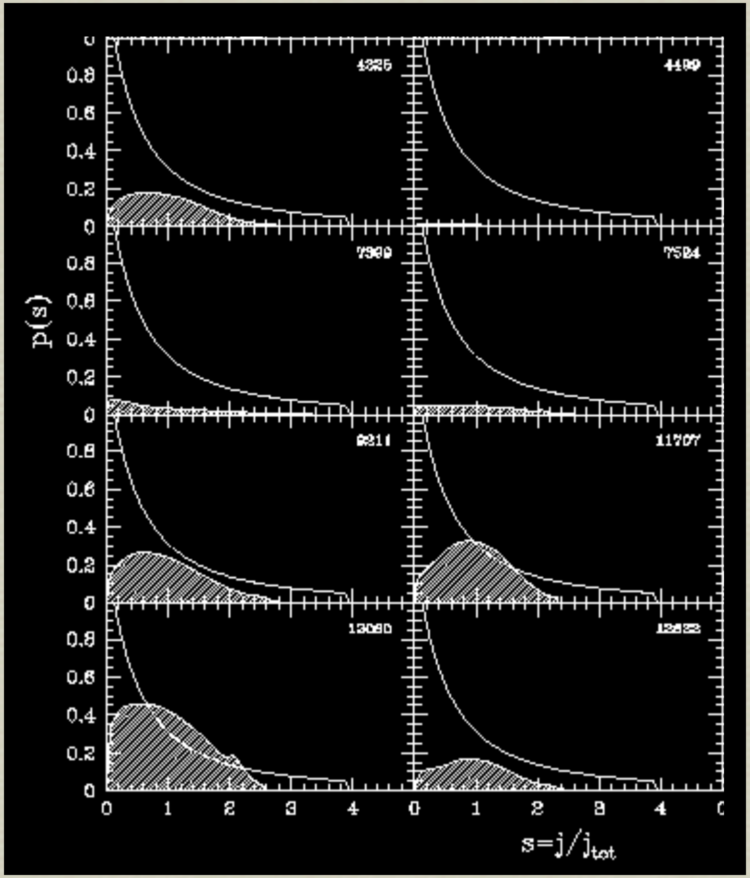
The 'Adiabatic Contraction' debate

- Dutton et al. found that models with AC could not simultaneously reproduce size-mass and L-V relations for disks, unless a strange IMF or very low halo concentrations were adopted
- they proposed a model with low spin, low baryon fraction in disk, and halo expansion rather than contraction



angular momentum distribution

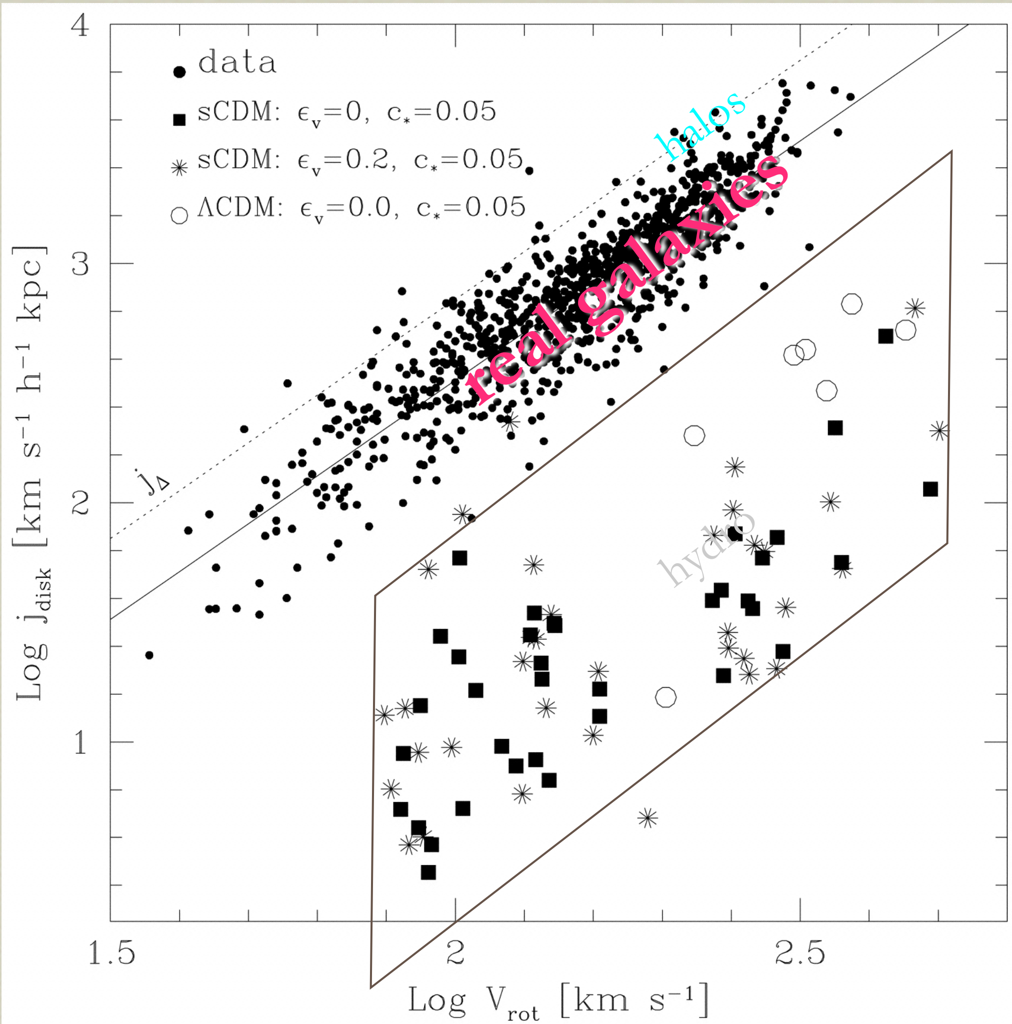
- angular momentum distribution of DM within halos characterized (Bullock et al. 2001)
- if stars+gas in galaxies a 'fair census' of j_{DM}, observed profiles violated
- need to remove low j material, which corresponds to early accretion → *connection between SFH and internal structure of disks* (see also Maller & Dekel 2002)



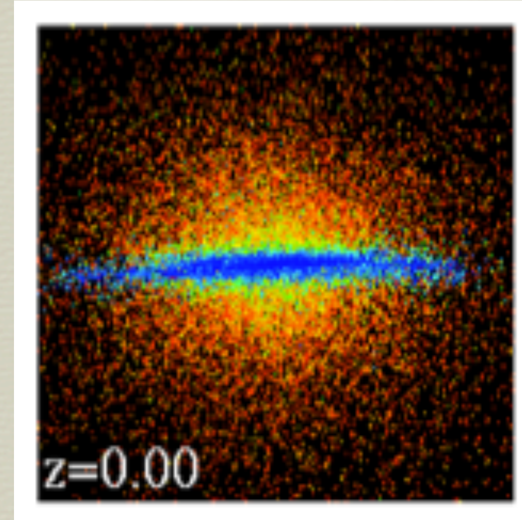
van den Bosch & Burkert 2001

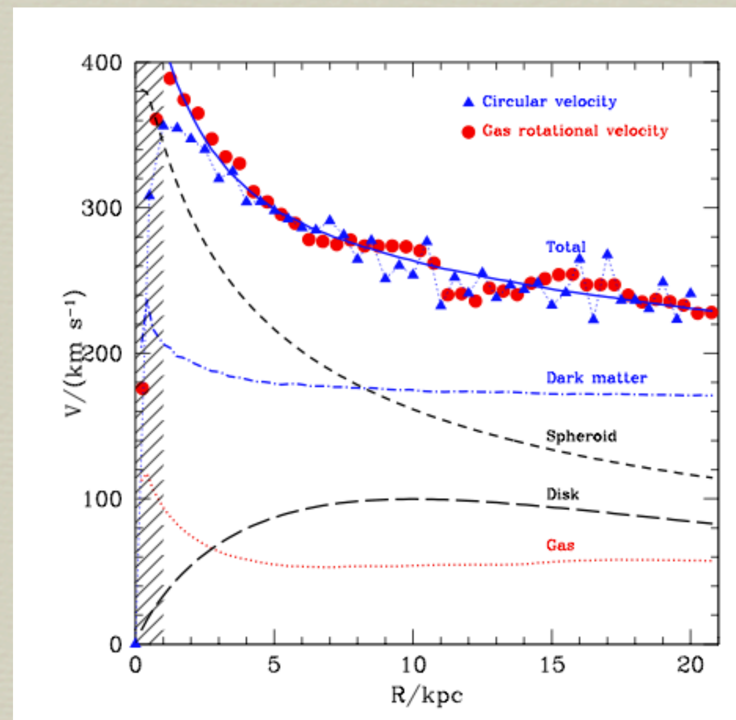
The Angular Momentum Catastrophe

specific angular momentum



rotation velocity



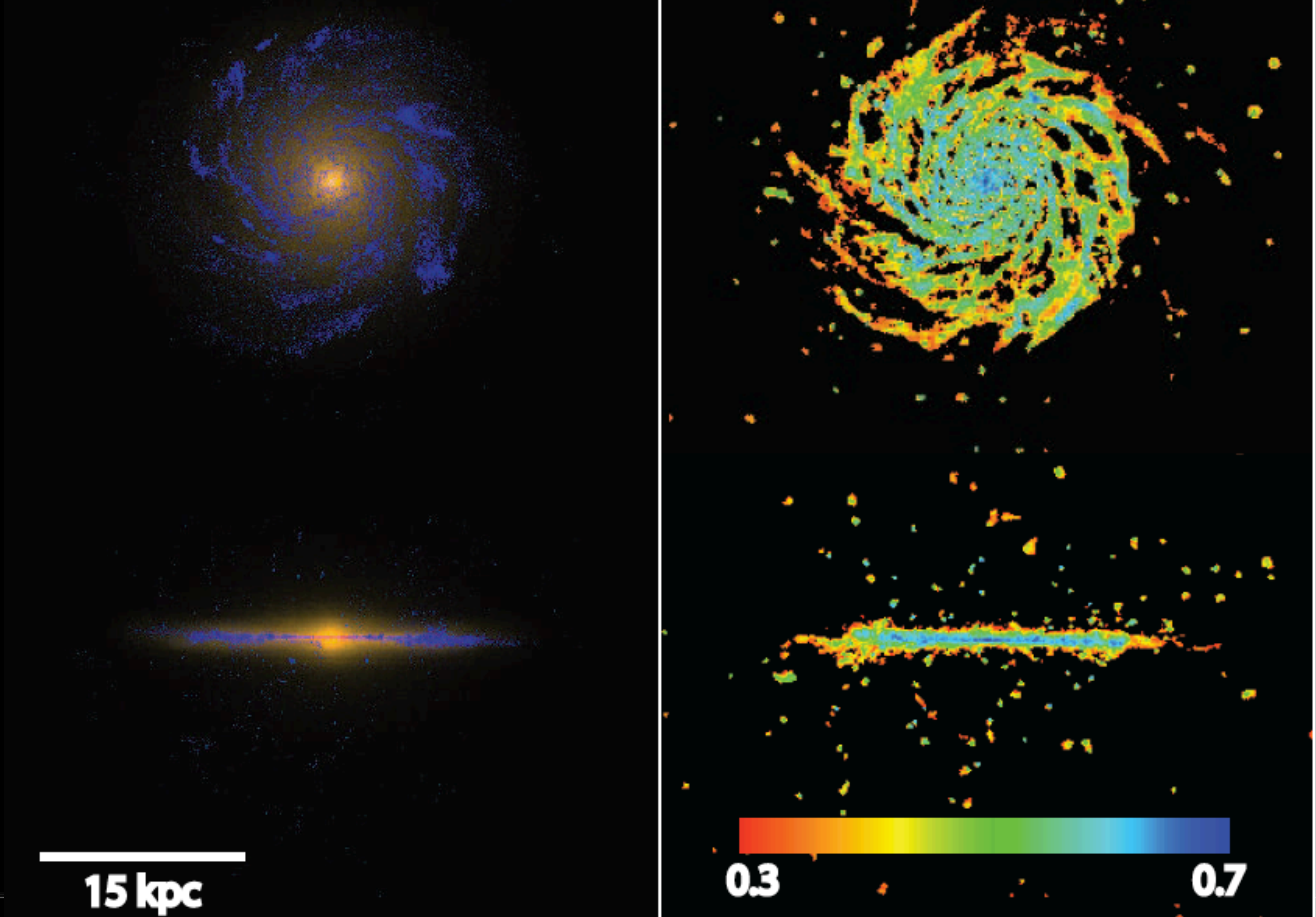


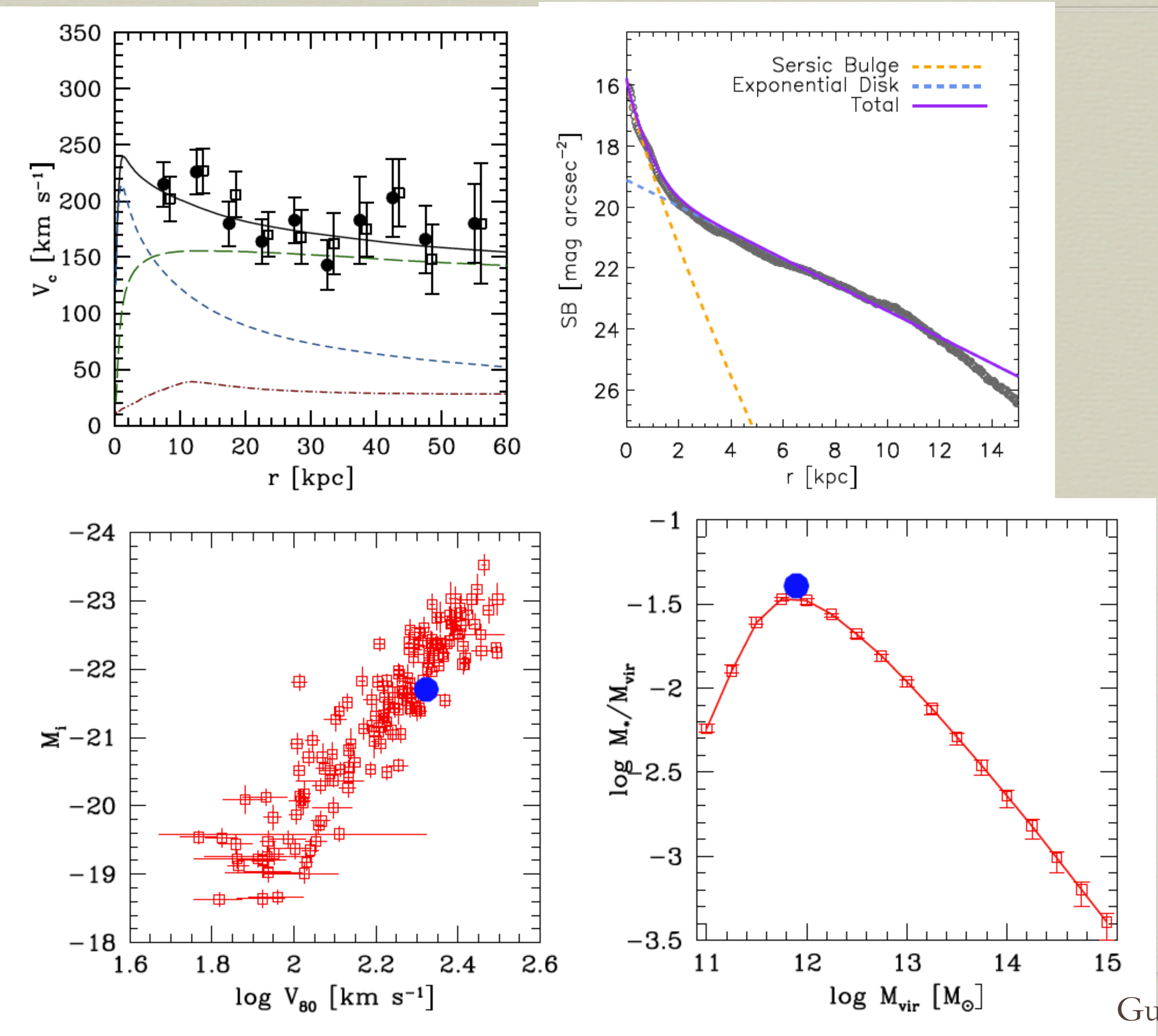
deconstructing the AM Catastrophe

- numerical resolution or spurious numerical effects leading to too much loss of angular momentum
- modelling of “sub-grid” processes like star formation and stellar/SNae feedback
- nature of dark matter (too much power on small scales)

ERIS Simulation
Guedes et al. 2011
Shen et al. 2012

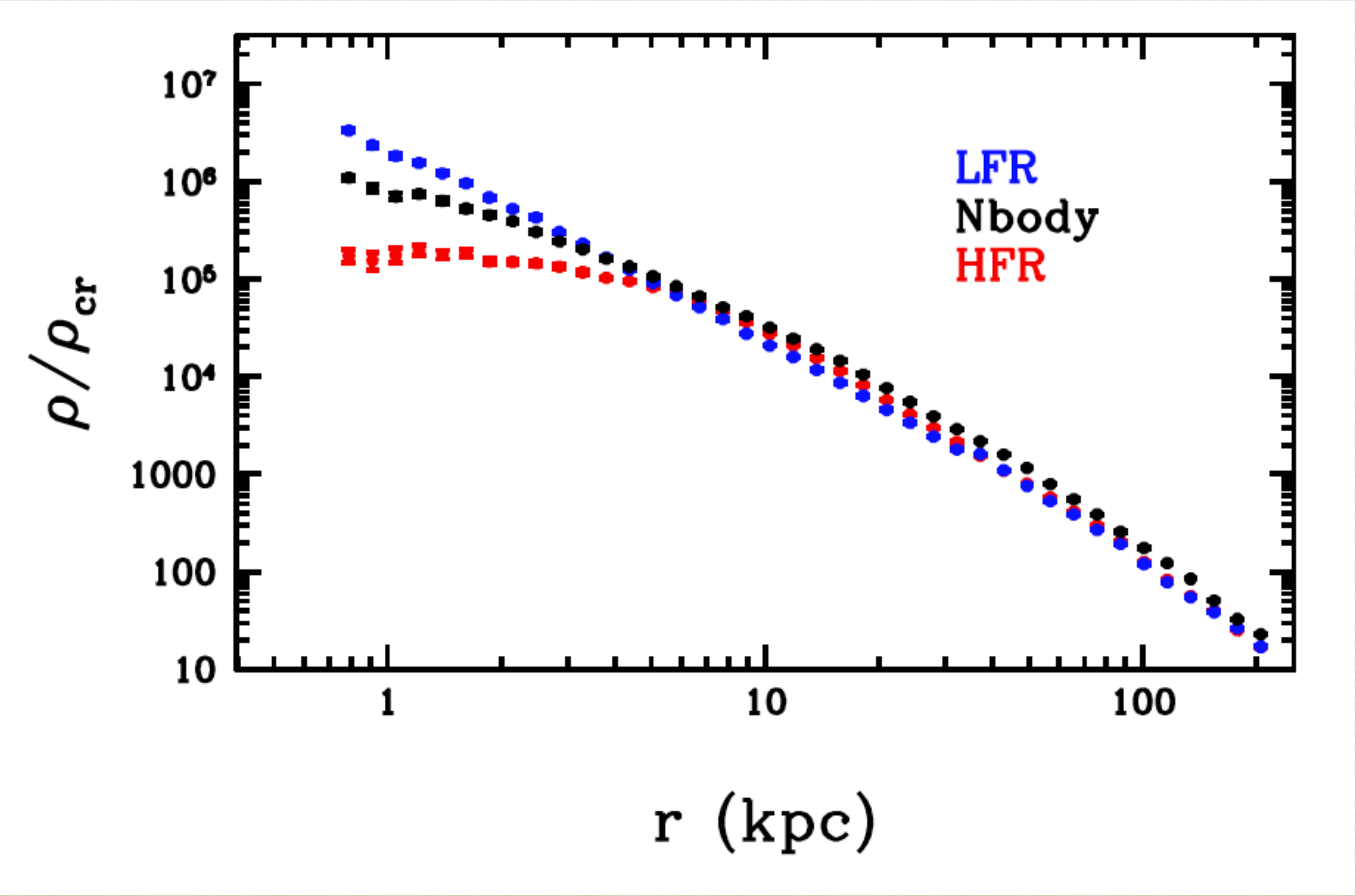
18 million particles
120 pc resolution





Guedes et al. 2011

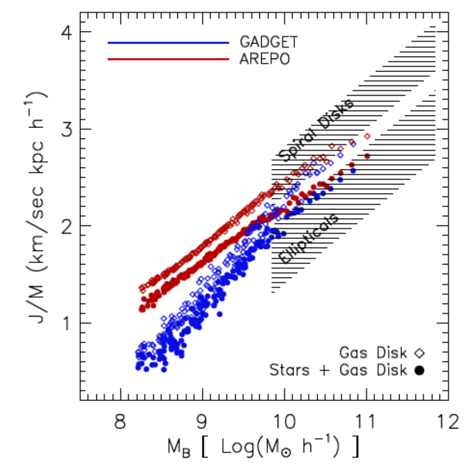
strong feedback appears to be able to cause “halo expansion” even in MW/M31-mass halos



Maccio et al. 2011

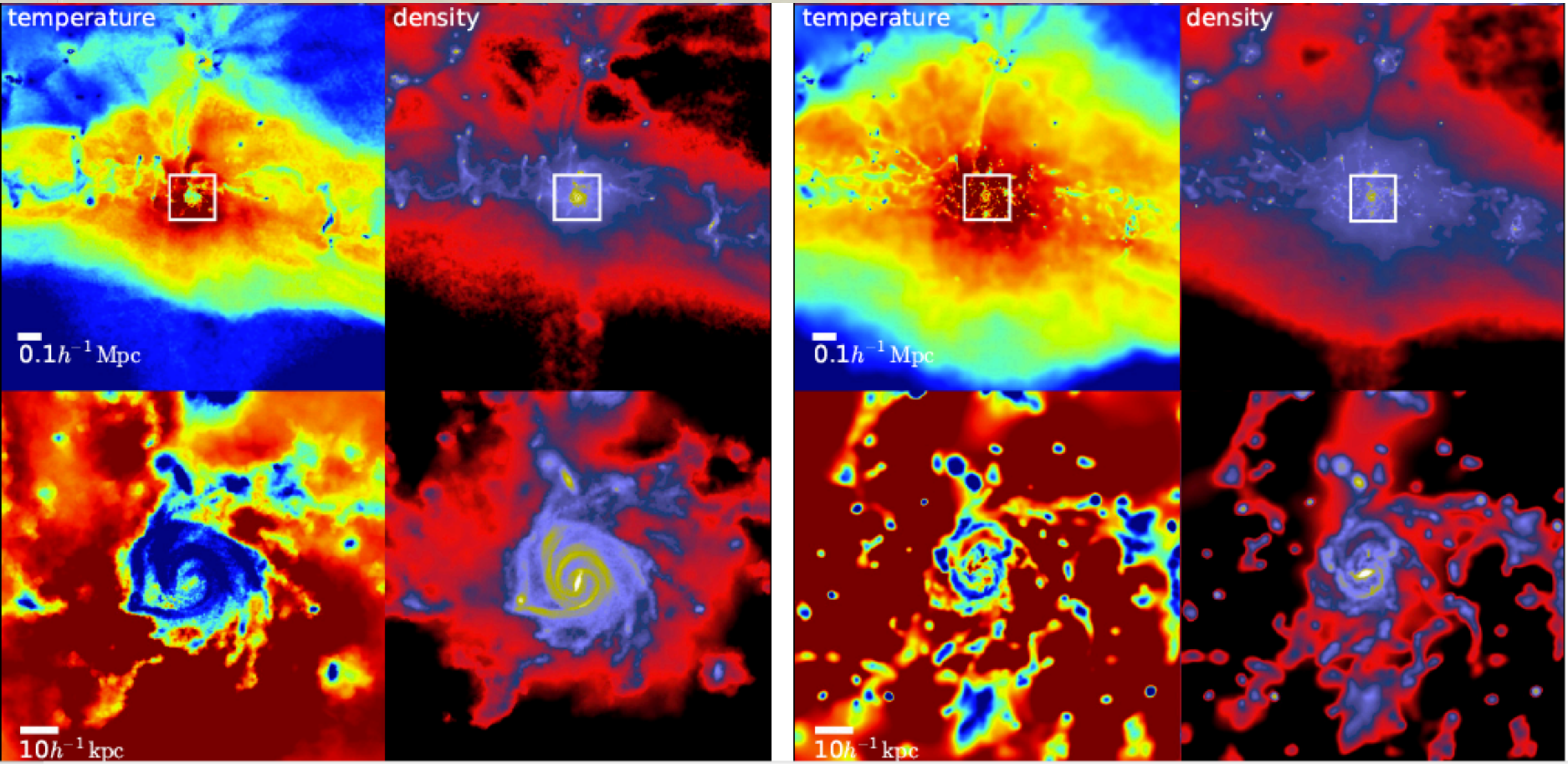
size and structure of galactic disks significantly different in moving mesh (AREPO) code vs. vanilla SPH (GADGET)

Torrey et al. 2011
Keres et al. 2011
Vogelsberger et al. 2011

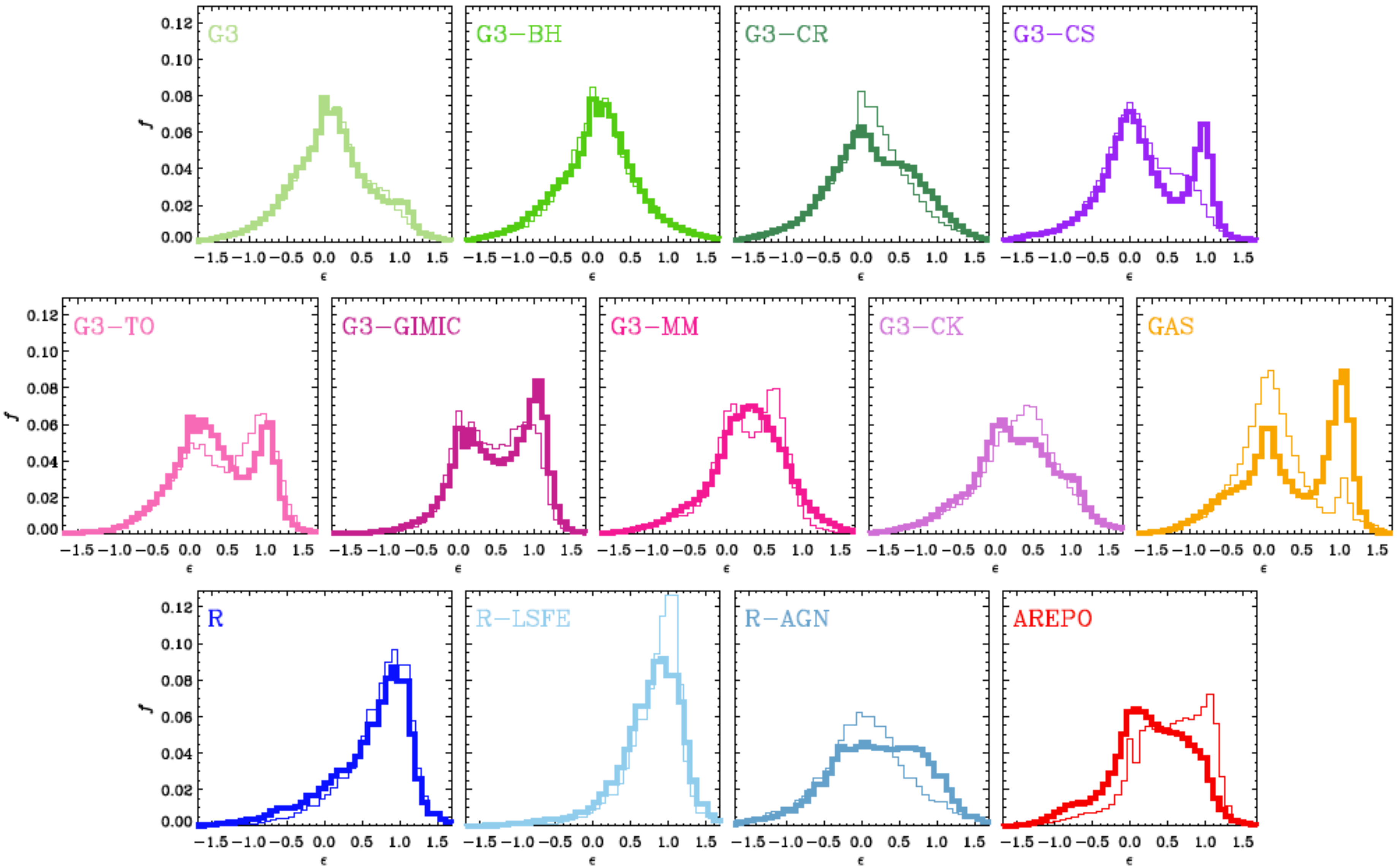


AREPO

GADGET



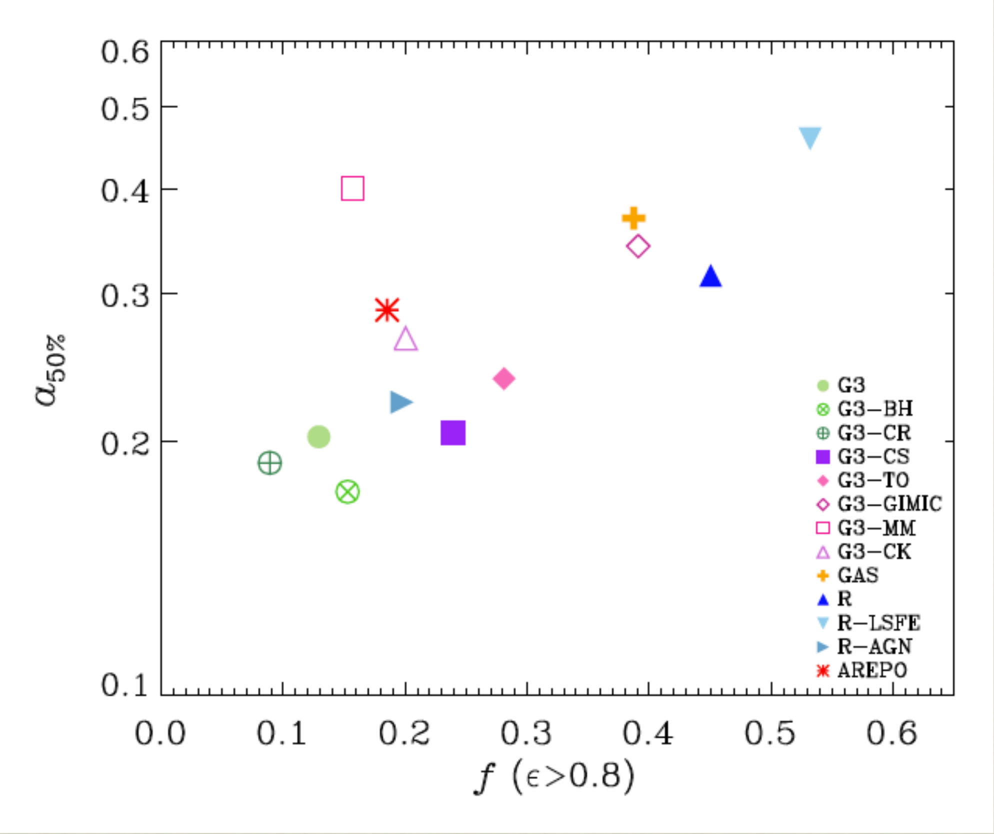
The Aquila Project



e=jz/jc: z-component of j in units of j of circular orbit at that radius

Scannapieco et al. 2011

all ‘solutions’ to the angular momentum catastrophe rely on suppressing star formation in low mass objects (typically via strong stellar FB) and accreting disk material *late*



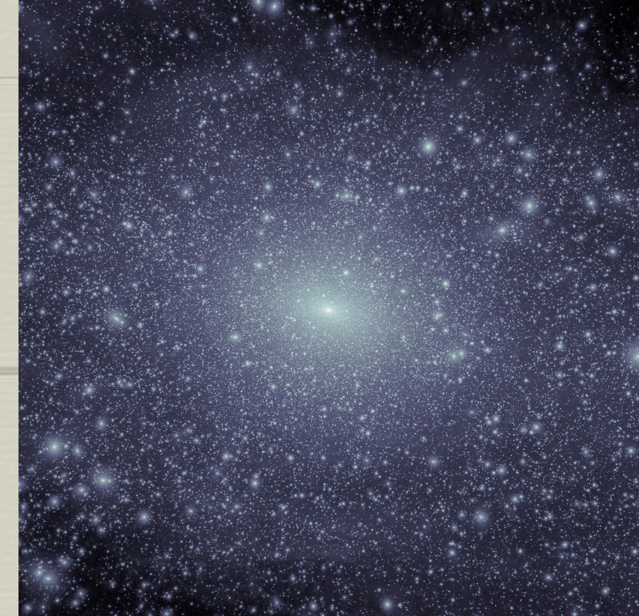
therefore expect a correlation between galaxy internal structure and star formation history--
not clear whether this is supported observationally!

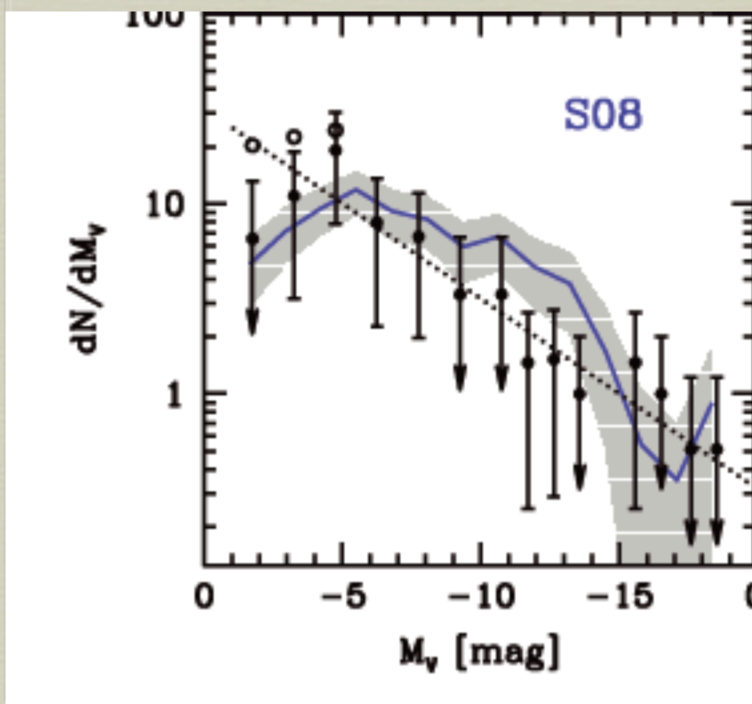
showing that the observed scaling of SFH with mass (downsizing) works too would be even better!
current simulations do NOT reproduce this trend.

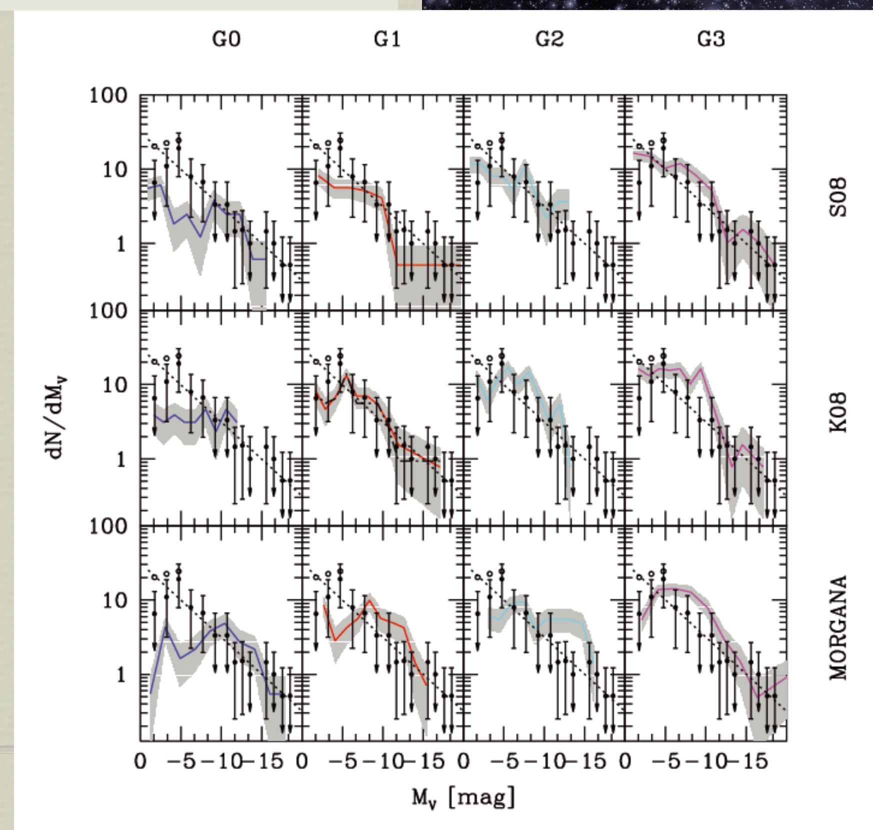
Scannapieco et al. 2011

satellite/substructure problems

- many works have shown that photoionization 'squelching' can plausibly reduce the number of MW/M31 satellites to agree with observations (Bullock et al. 2001; rss 2002; Benson et al. 2002; Kravtsov et al. 2004)

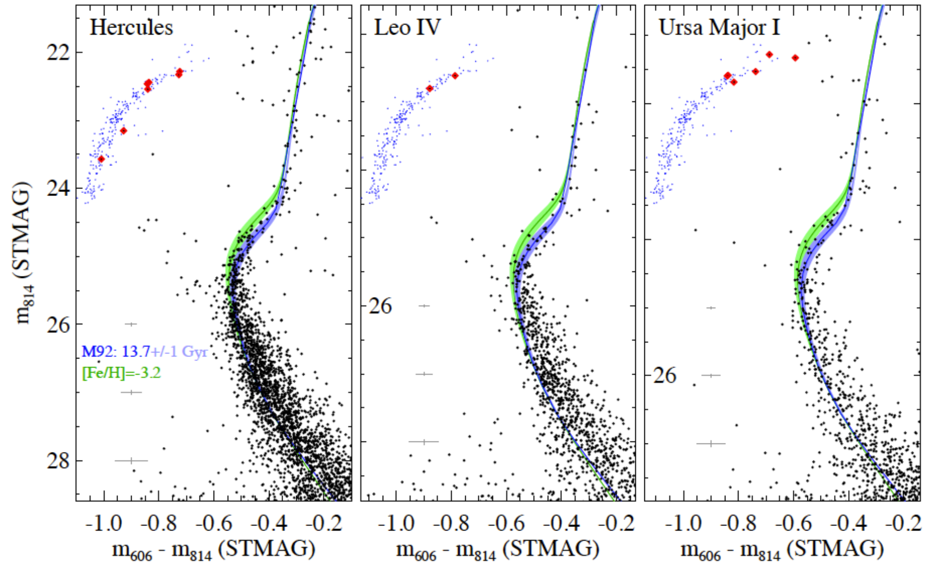






Maccio et al. 2010

this picture predicts that galaxies below the 'filtering mass' would have had their star formation truncated at an early time…



THE PRIMEVAL POPULATIONS OF THE ULTRA-FAINT DWARF GALAXIES[1]

THOMAS M. BROWN[2], JASON TUMLINSON[2], MARLA GEHA[3], EVAN N. KIRBY[4,5], DON A. VANDENBERG[6], RICARDO R. MUÑOZ[7], JASON S. KALIRAI[2], JOSHUA D. SIMON[8], ROBERTO J. AVILA[2], PURAGRA GUHATHAKURTA[9], ALVIO RENZINI[10], AND HENRY C. FERGUSON[2]

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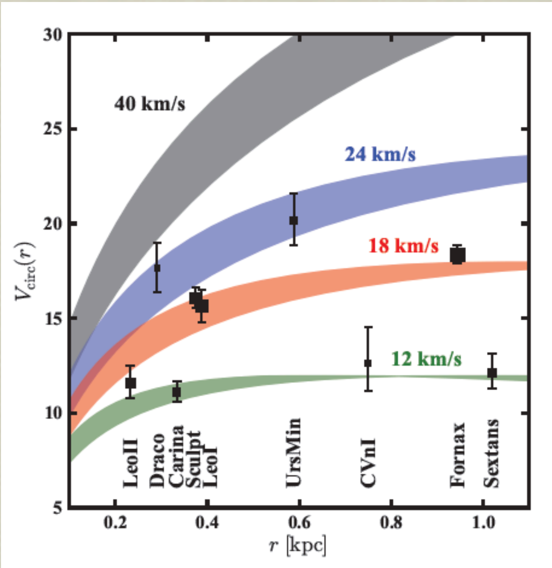
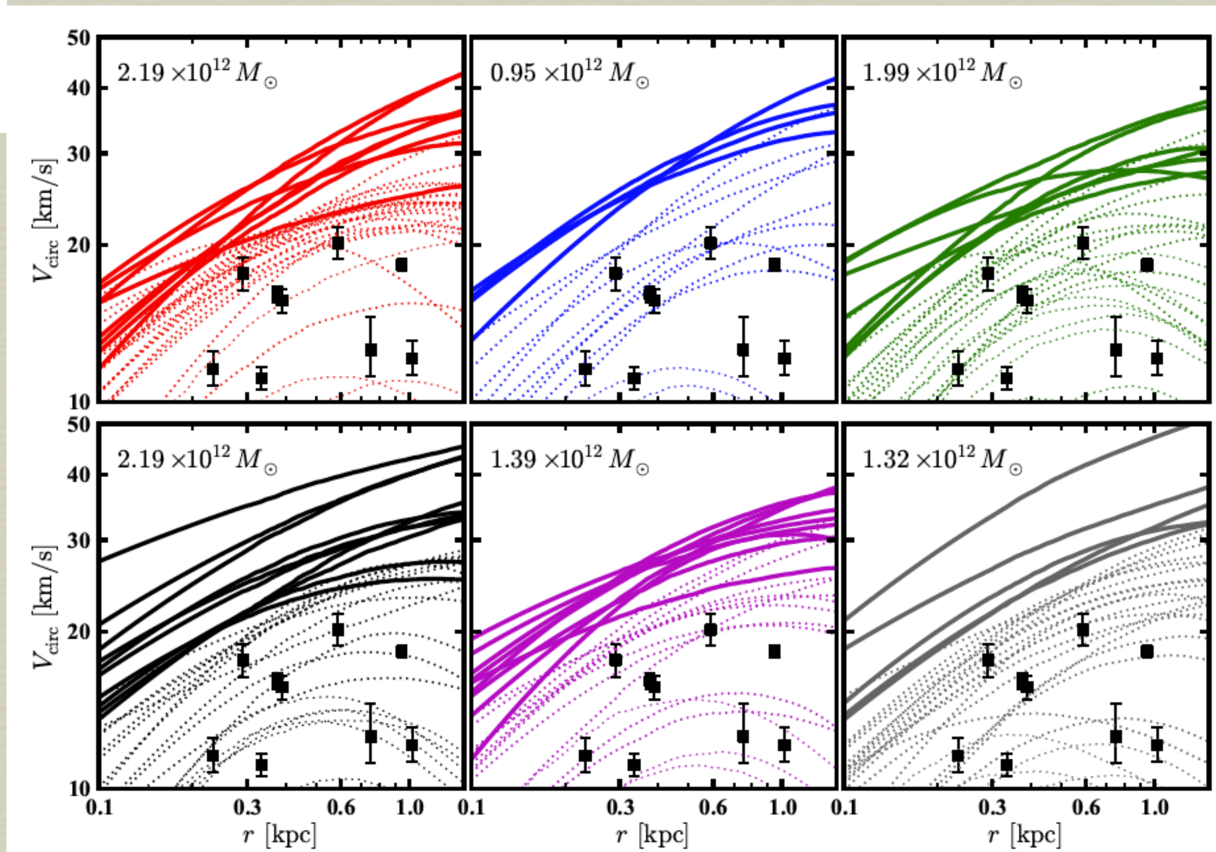
ABSTRACT

We present new constraints on the star formation histories of the ultra-faint dwarf (UFD) galaxies, using deep photometry obtained with the *Hubble Space Telescope (HST)*. A galaxy class recently discovered in the Sloan Digital Sky Survey, the UFDs appear to be an extension of the classical dwarf spheroidals to low luminosities, offering a new front in efforts to understand the missing satellite problem. They are the least luminous, most dark-matter dominated, and least chemically-evolved galaxies known. Our *HST* survey of six UFDs seeks to determine if these galaxies are true fossils from the early universe. We present here the preliminary analysis of three UFD galaxies: Hercules, Leo IV, and Ursa Major I. Classical dwarf spheroidals of the Local Group exhibit extended star formation histories, but these three Milky Way satellites are at least as old as the ancient globular cluster M92, with no evidence for intermediate-age populations. Their ages also appear to be synchronized to within ~1 Gyr of each other, as might be expected if their star formation was truncated by a global event, such as reionization.

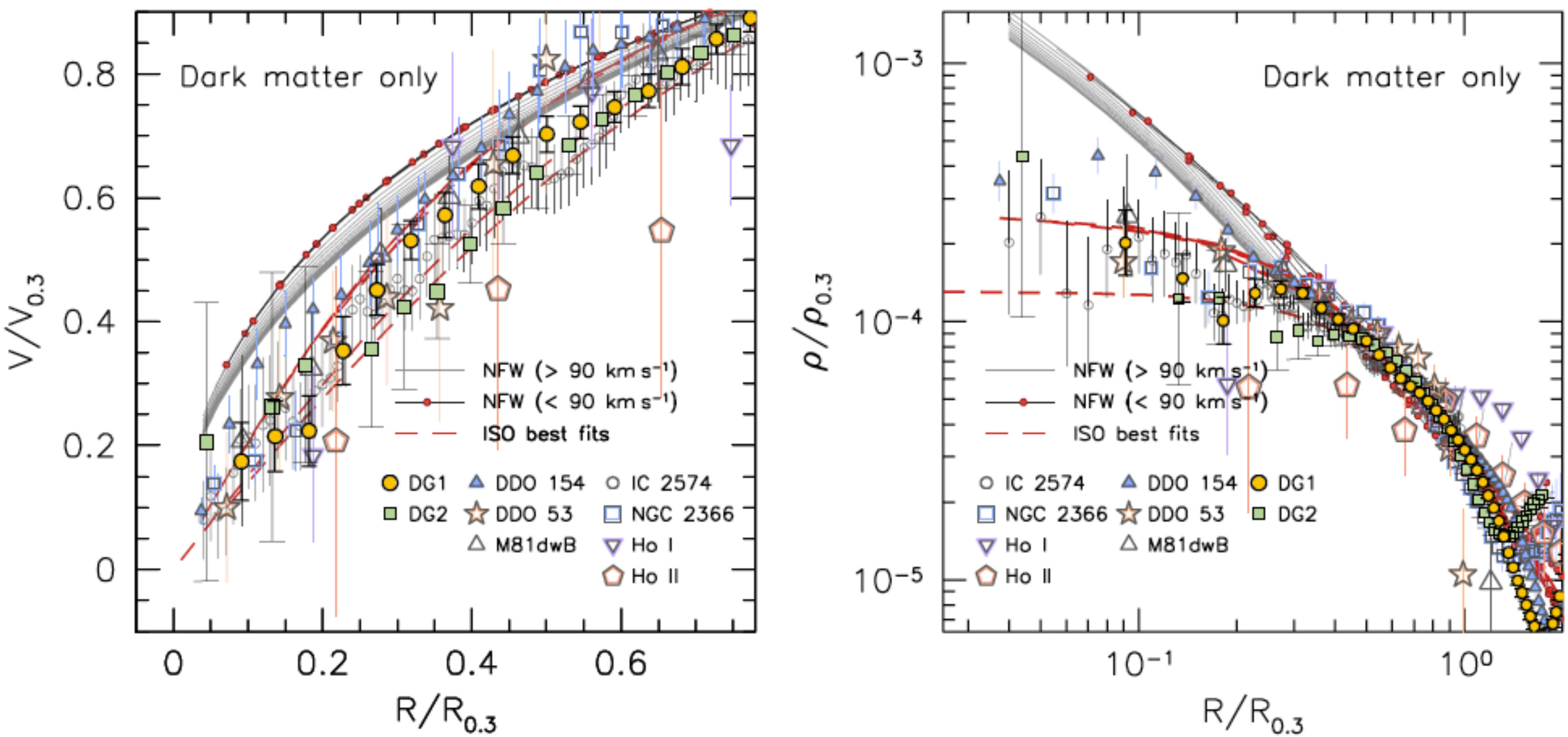


Too Big to Fail: kinematics of Milky Way dwarf satellites are in conflict with predictions of dissipationless LCDM simulations



Boylan-Kolchin et al. 2011a,b

but powerful, stochastic injections of energy from stars and SNae may be able to create 'cores' in low-mass halos (Governato et al. 2010; Pontzen & Governato 2011)



Oh et al. 2011

Summary

- if we could make *even a single galaxy* that matched all available and upcoming observations of M31 (and her companions) it would be a major accomplishment for galaxy formation theory
- key to making nice disks: keep baryon fraction in disks low, but make sure you keep the *right* baryons (with relatively high j).
- may be able to accomplish this with strong stellar/SNae feedback. having high enough resolution to get close to GMC scales seems to be key (high SF threshold). impact of numerics still unclear.
- combination of detailed structural/kinematic data and archeological record (SFH, Z) extremely powerful (disks, dwarfs)