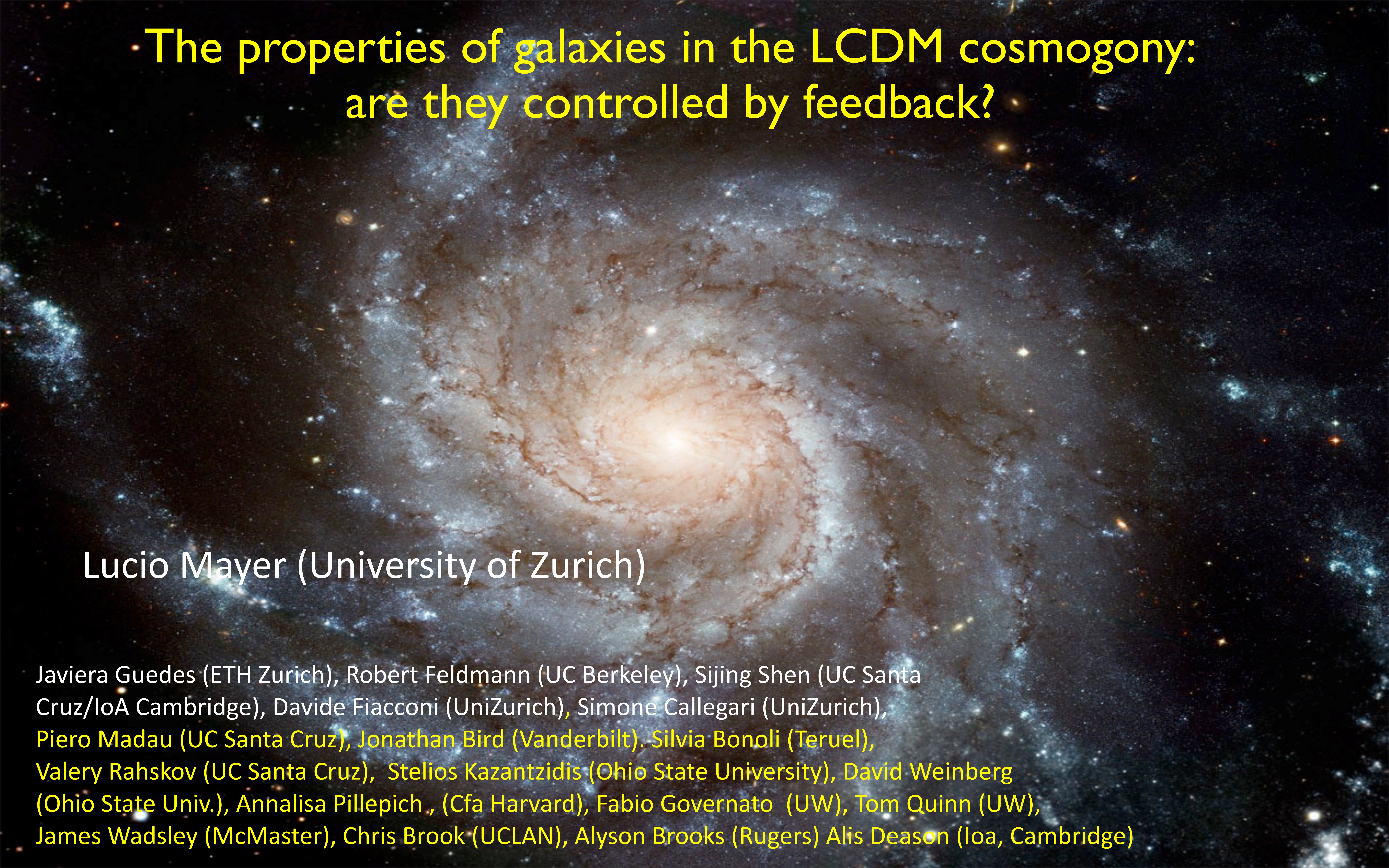


The properties of galaxies in the LCDM cosmogony: are they controlled by feedback?

Lucio Mayer (University of Zurich)

Javiera Guedes (ETH Zurich), Robert Feldmann (UC Berkeley), Sijing Shen (UC Santa Cruz/IoA Cambridge), Davide Fiacconi (UniZurich), Simone Callegari (UniZurich), Piero Madau (UC Santa Cruz), Jonathan Bird (Vanderbilt). Silvia Bonoli (Teruel), Valery Rahskov (UC Santa Cruz), Stelios Kazantzidis (Ohio State University), David Weinberg (Ohio State Univ.), Annalisa Pillepich , (Cfa Harvard), Fabio Governato (UW), Tom Quinn (UW), James Wadsley (McMaster), Chris Brook (UCLAN), Alyson Brooks (Rugers) Alis Deason (Ioa, Cambridge)

LONG STANDING PROBLEMS IN ΛCDM SIMULATIONS OF GALAXY FORMATION

(a)OVERSIZED STELLAR BULGES (= excesse of low angular momentum material)

(b)STEEP ROTATION CURVES (Vpeak ~ 300 km/s for MW-sized galaxies)

(c)EXCESSE STELLAR MASS (2-5 times larger than observed at given halo circular velocity)

UNDERLYING PHYSICS:
ANGULAR MOMENTUM TRANSPORT, THERMODYNAMICS OF THE GAS PHASE (OVERCOOLING), RATE OF CONVERSION OF COLD GAS INTO STARS

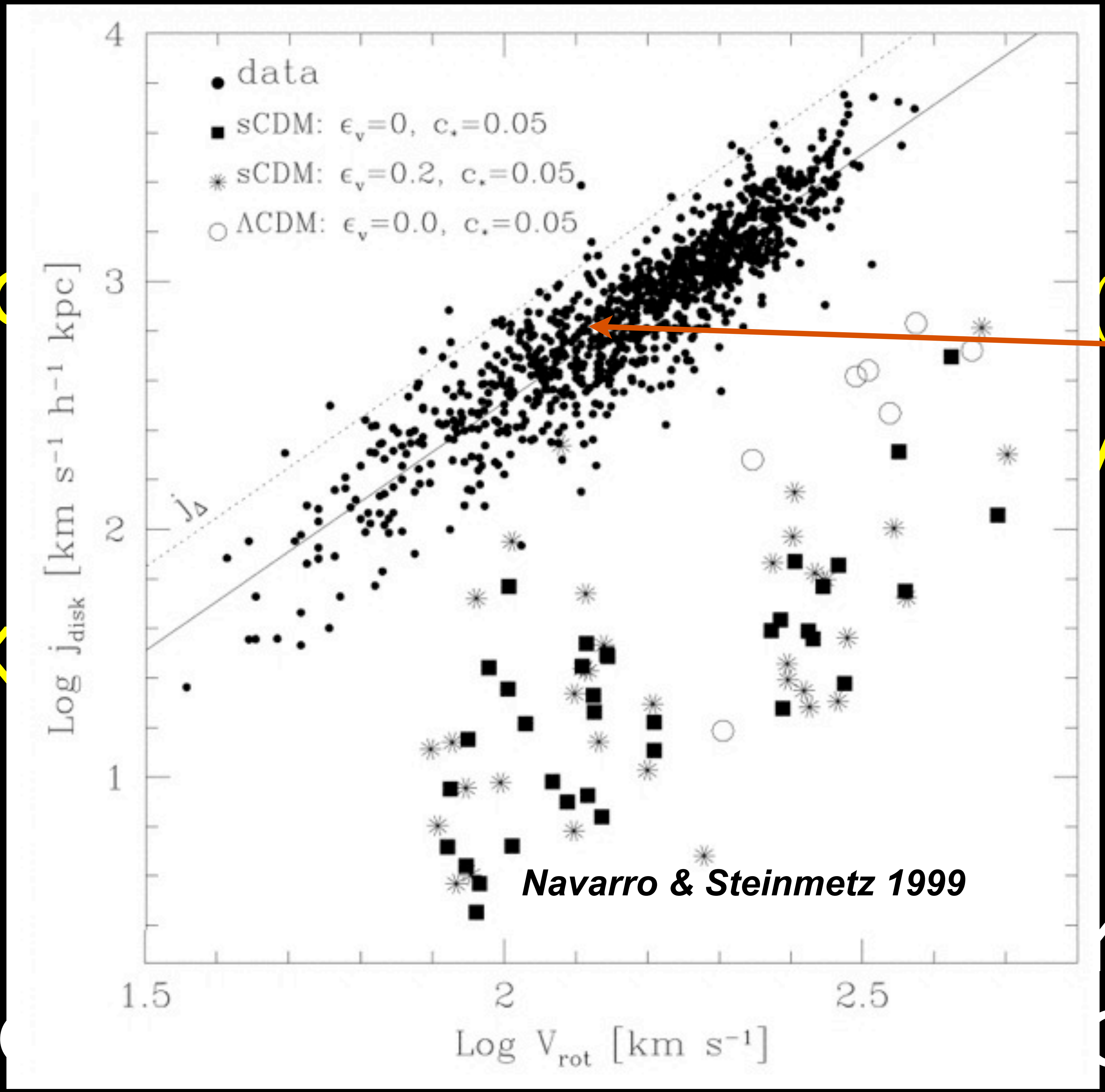
UNDERLYING NUMERICAL ISSUES: ANGULAR MOMENTUM DISSIPATION, TWO-BODY HEATING, SPURIOUS HYDRO DRAG...

LONG STANDING PROBLEMS IN ΛCDM SIMULATIONS OF GALAXY MA

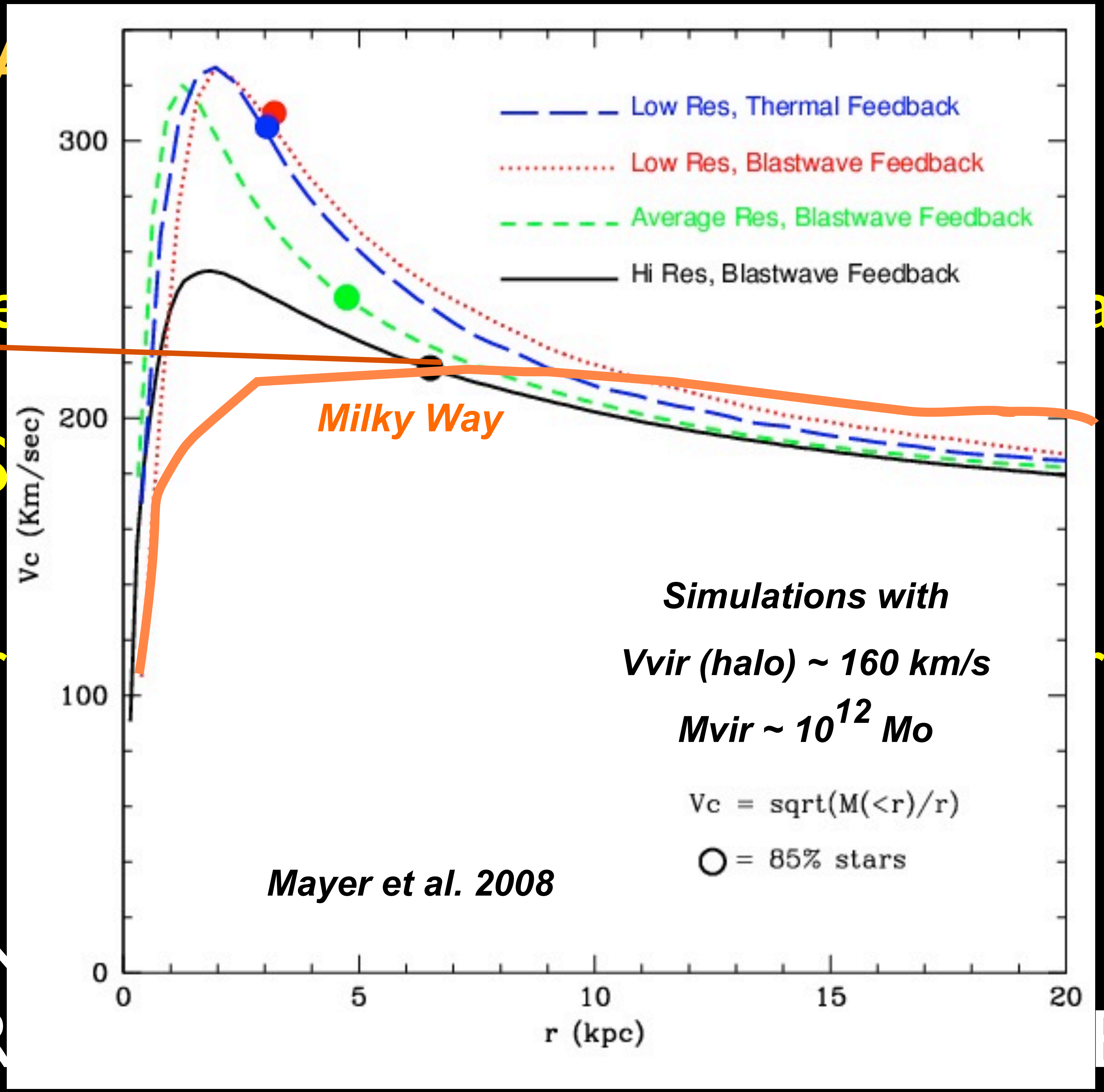
(a)C (= e aterial)

ES

(c)EX lar velocity)



Navarro & Steinmetz 1999



Simulations with

Vvir (halo) ~ 160 km/s

Mvir ~ 10^{12} Mo

Vc = sqrt(M(<r)/r)

○ = 85% stars

Mayer et al. 2008

YIN

ANG OR E GAS PHASE (OVERCOOLING), RATE OF CONVERSION OF COLD GAS INTO STARS

UNDERLYING NUMERICAL ISSUES: ANGULAR MOMENTUM DISSIPATION, TWO-BODY HEATING, SPURIOUS HYDRO DRAG...

SUB-GRID "Blastwave" Supernovae Feedback

Cooling shut-off in local volume heated by supernovae type II blastwave for
t_s ~ 10 million years (Stinson et al. 2006 - see also J.Rosdahl's and A.Brooks' talks)

- Based on time of maximum expansion of supernova type II blast wave (Sedov-Taylor phase + snowplow phase). Radius of blastwave calculated based on McKee & Ostriker (1977)

Note: resulting cooling shut-off timescale similar order of decay time for ISM turbulence

- Blastwave generated by simultaneous sub-grid explosion of many supernovae type II (recall time resolution as well mass resolution limited – single star particle ~ 10^3-10^4 Mo represents star cluster in which more than one type II supernovae can explode)

Dwarf galaxy (M ~ 10^{10} Mo)

Milky Way-sized galaxy (M ~ 10^{12} Mo)

- Supernovae heating efficiency, i.e. what fraction of the energy of supernovae is converted into thermal energy of the gas, is free parameter ---> eSN=0.4-0.8 (x 10^{51} erg per supernovae explosion) after calibration with isolated galaxy models to reproduce a range of properties in present-day galaxies across wide mass range (cold/hot gas volume ratio, gas turbulent velocities, disk thickness, star formation rates - see Stinson et al. 2006)

- Thermal energy input also by type Ia supernovae but no delayed cooling

THE STAR FORMATION DENSITY THRESHOLD

STARS FORM IN MOLECULAR CLOUDS, i.e. in gas at densities in range 10-100 cm^{-2} (depends on metallicity, ambient UV flux)

TILL 2010 IN COSMOLOGICAL SIMULATIONS OF GALAXY FORMATION STARS FORMED BASED ON A SCHMIDT LAW , $d\rho_{star}/dt \sim \varepsilon\rho_{gas}^{1.5}$ (ε=0.05-0.1) AT GAS DENSITIES > 0.1 cm^{-3} (typical density of Warm Neutral Medium in Milky Way!)
(eg Abadi et al. 2003; Governato, Mayer+, 2004; Governato et al. 2007, Mayer+ 2008; Piontek & Steinmetz 2010; Scannapieco et al. 2010; Agertz et al. 2011; Naab et al. 2007)

TO CAPTURE COLD DENSE MOLECULAR PHASE:
FIRST STEP IS TO RESOLVE REGIONS OF CORRESPONDING DENSITY
IN SPH >~ 2 SPH kernels per Jeans mass ~ 10^6 Mo, eg Bate & Burkert 1997
required mass resolution 10^4 Mo ---> hi-res zoom-in cosmo sim

CASE STUDY 1: FORMATION OF GAS-RICH DWARFS (10^8-10^{11} Mo)
(Governato, Brook, Mayer et al., Nature, 2010, Governato et al. 2012; Shen et al. 2013)
CASE STUDY 2: FORMATION OF LATE-TYPE SPIRAL GALAXIES (~ 10^{12} Mo)
(Guedes, Callegari, Madau & Mayer 2011, Mayer 2012; Guedes, Mayer et al. 2013)
CASE STUDY 3: FORMATION OF MASSIVE EARLY-TYPES (Feldmann & Mayer 2014)
(~ 10^{13} Mo)

with SPH code GASOLINE (Wadsley et al. 2004)

“Clustered” Star Formation powers-up feedback

The K-S relation of each particle:

$$\frac{d\rho_*}{dt} = \frac{\epsilon_{\rm SF}\rho_{\rm gas}}{t_{\rm dyn}} \propto \rho_{\rm gas}^{1.5} \qquad \rho > \rho_{\rm \ thres}$$

SN feedback (blast-wave):

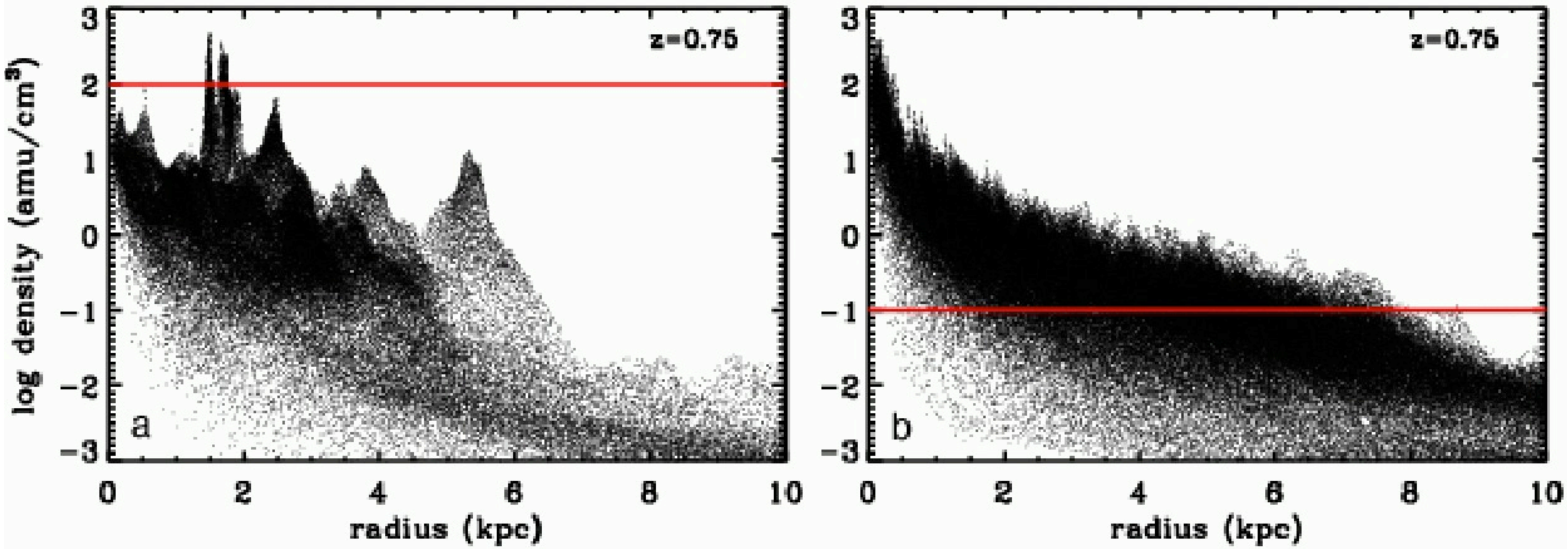
$$E_{\rm SN} = \epsilon_{SN} \times 10^{51}\,{\rm erg\,s^{-1}}$$

Radius of blastwave R_E set by local density/temperature/energy injection, ~ 30-50 pc in typical conditions

$$\frac{\rm N_{new*}}{\rm m_{gas}} \propto \sqrt{n_{\rm SF}} \longrightarrow$$

Higher supernovae rate per gas mass “unit” as threshold rises, so *enhanced effect of feedback where stars can form*

Stronger local feedback further amplified by the fact that ISM becomes more inhomogeneous and clumpy with high SF threshold



Hi-res dwarf galaxy formation: blowing the wind

TWO Ics (DG1 and DG2, different mass assembly history)
Vvir ~ 50 km/s
NSPH ~ 2 x 10^6 particles
Ndm ~2 x 10^6 particles
Msph ~ 10^3 Mo
gravitational softening = 86 pc
WMAP5 cosmology

-Schmidt-law SF w/high density threshold of 100 atoms/cm^3
-Supernovae blastwave feedback model (Stinson et al. 2006)
-Cooling to 300 K owing to metal lines
-Heating/ionization by cosmic UV bg (Haardt & Madau 2006)

Frame = 15 kpc on a side: color-coded gas density of DG1 from z=100 to z=0

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

-- Final baryonic mass fraction within Mvir = 0.3 x f_b (cosmic)
-- Final stellar mass ~ 0.05 f_b (cosmic) <~ 0.01 Mvir
(see Oh et al. 2011 for comparison with dwarf galaxies in THINGS survey and other datasets)
-- Final gas/stars ratio in disk ~ 2.5

Hi-res dwarf galaxy formation: blowing the wind

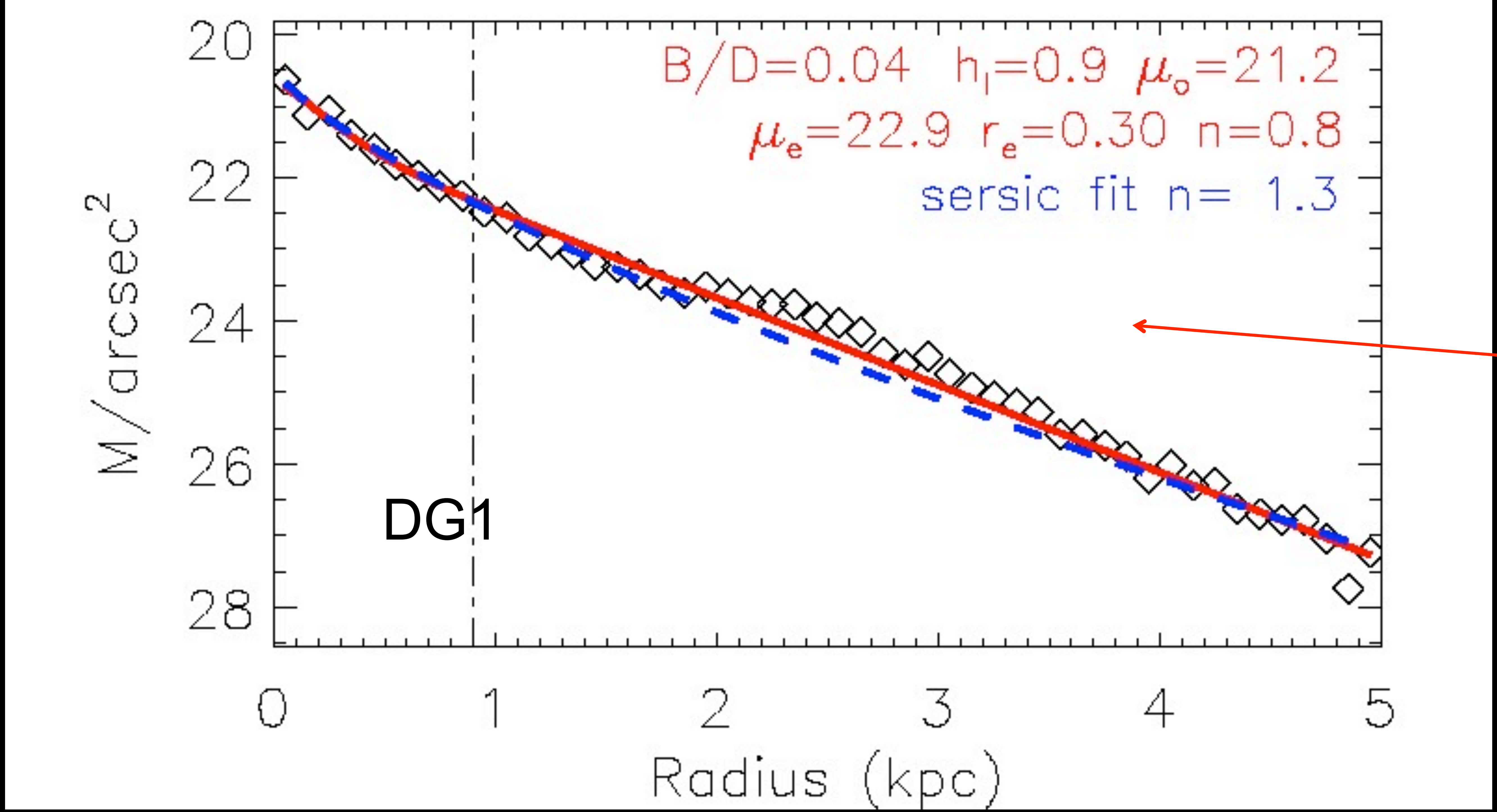
TWO Ics (DG1 and DG2, different mass assembly history)
Vvir ~ 50 km/s
NSPH ~ 2 x 10^6 particles
Ndm ~2 x 10^6 particles
Msph ~ 10^3 Mo
gravitational softening = 86 pc
WMAP5 cosmology

-Schmidt-law SF w/high density threshold of 100 atoms/cm^3
-Supernovae blastwave feedback model (Stinson et al. 2006)
-Cooling to 300 K owing to metal lines
-Heating/ionization by cosmic UV bg (Haardt & Madau 2006)

Frame = 15 kpc on a side: color-coded gas density of DG1 from z=100 to z=0

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

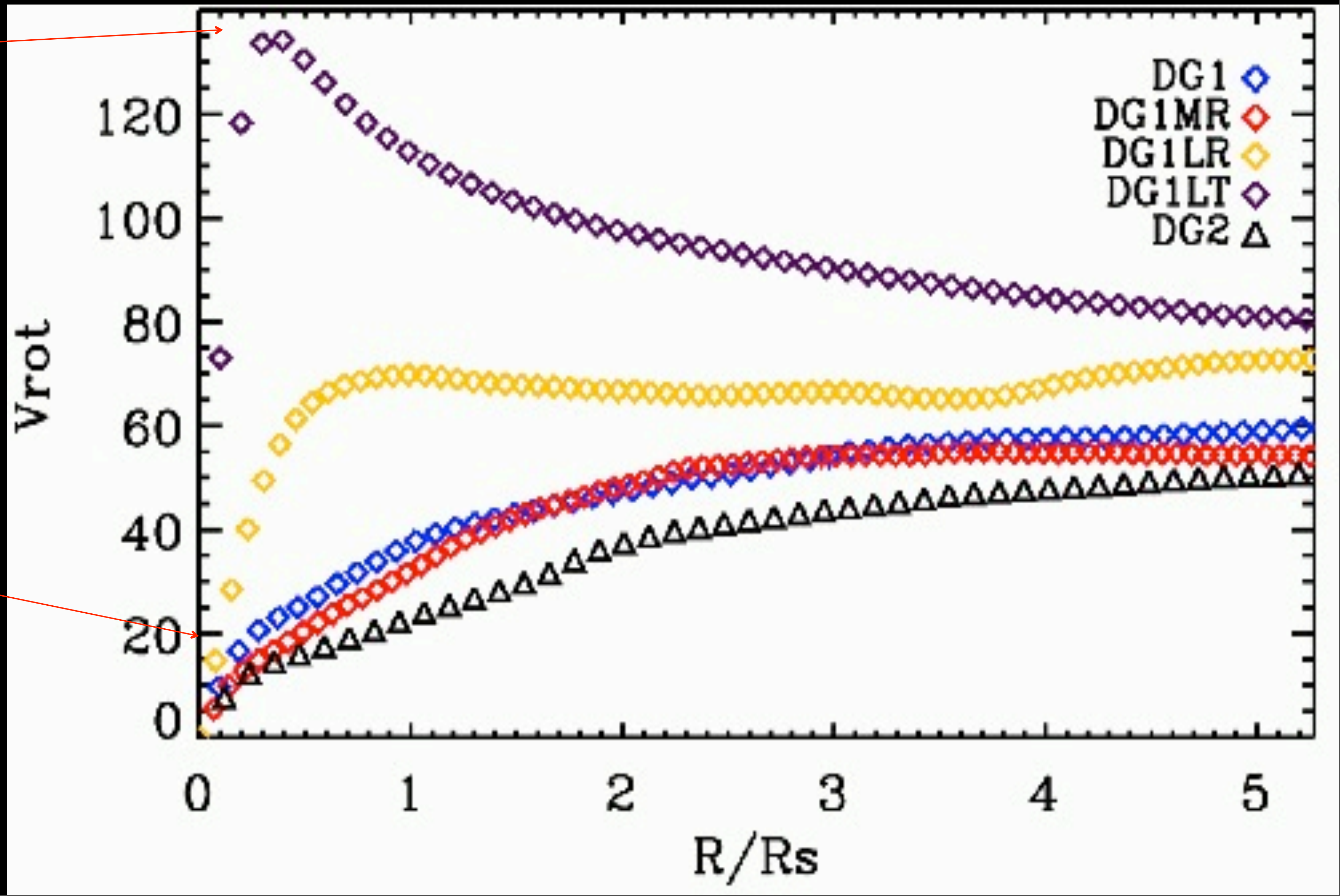
-- Final baryonic mass fraction within Mvir = 0.3 x f_b (cosmic)
-- Final stellar mass ~ 0.05 f_b (cosmic) <~ 0.01 Mvir
(see Oh et al. 2011 for comparison with dwarf galaxies in THINGS survey and other datasets)
-- Final gas/stars ratio in disk ~ 2.5



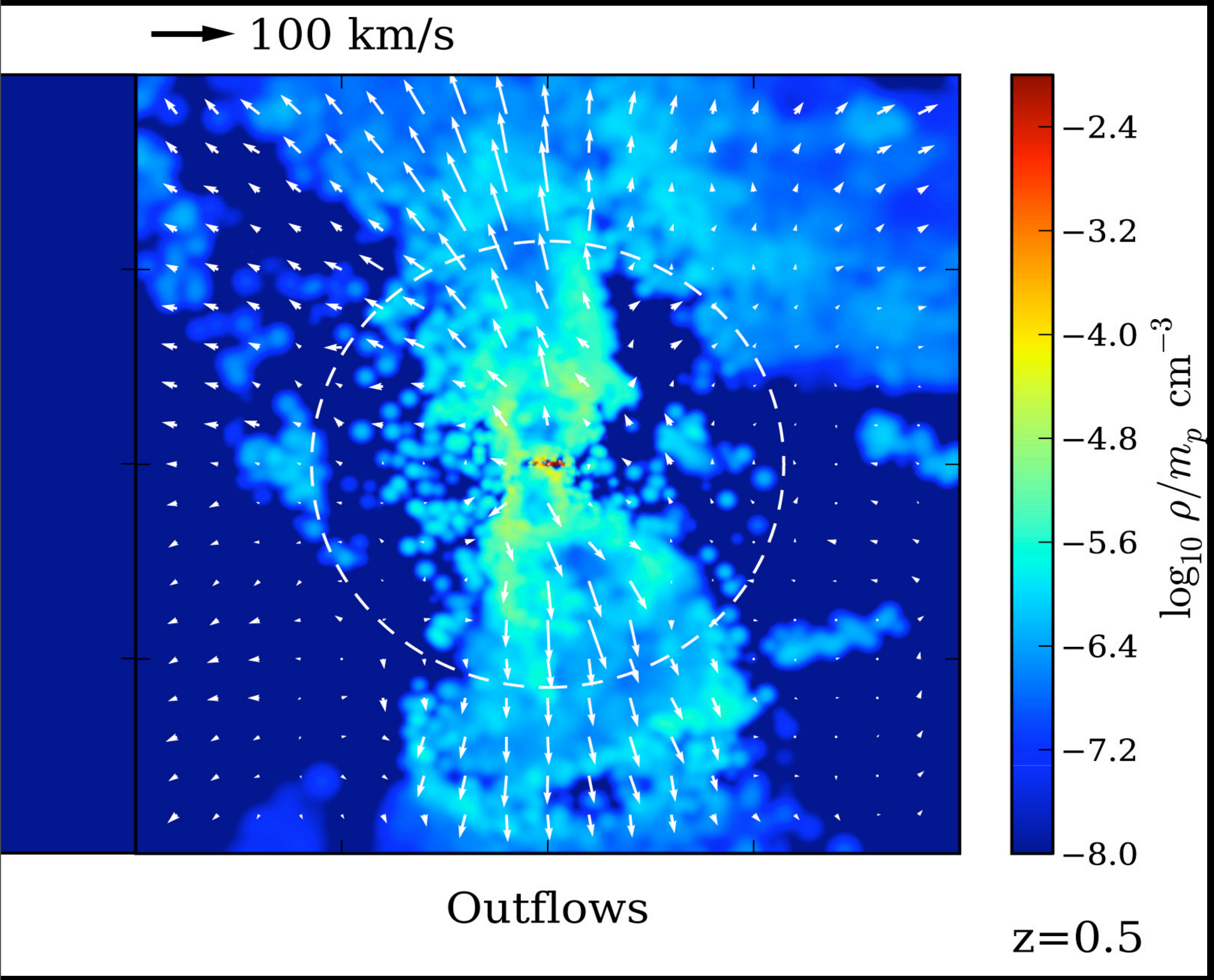
Bulgeless
exponential
disk
(instead B/D ~ 0.3 in run
with conventional
low SF threshold)

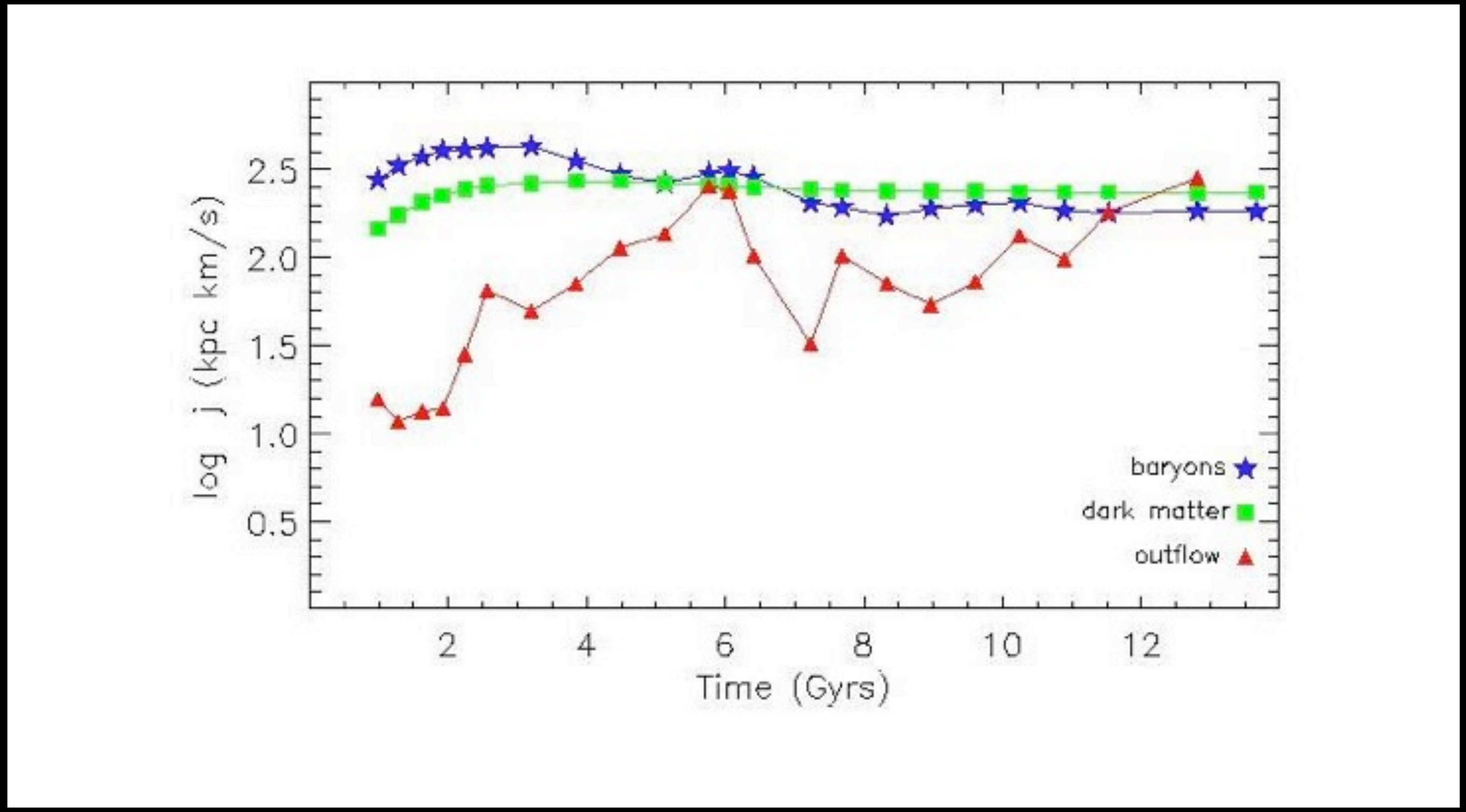
From unrealistic steep rotation curves at low SF threshold to realistic slowly rising rotation curves at high SF threshold

Inner dark matter profile flattened to ~r $^{-0.5}$ by expansion following impulsive supernovae outflows producing potential fluctuations – see Pontzen+Governato 2011 (also Navarro, Frenk & Eke 1996; Read & Gilmore 2005; Maschenko et al. 2008)



Strong supernovae winds with high SF density threshold





- star formation CLUSTERED rather than DISTRIBUTED, mainly in high density peaks with scales ~ GMCs ---> stronger heating produces stronger gas outflows compared to runs with "standard" low SF threshold (more gas heated at T > Tvir at z ~ 1-3, outflows at ~ 100km/s --**> final baryonic fraction ~ 1/3 of cosmic**)

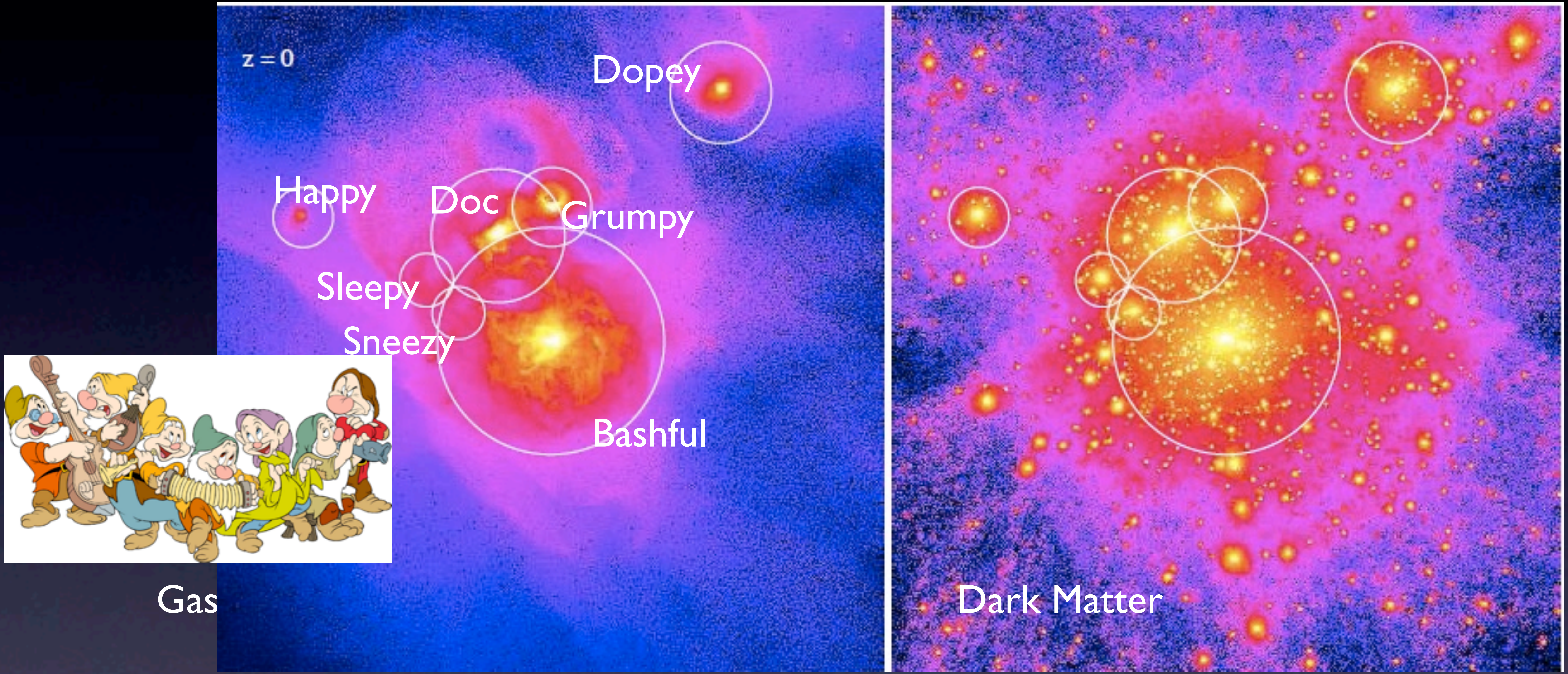
- Outflows correlated with peaks in SFR, in turn correlated with mergers (hence occur preferentially at z > 1) – see Brook et al. (2010) for details

- Outflows mostly in the center of galaxy where star forming density peaks higher
---> selective removal of lowest angular momentum material (eg Binney et al. 2001)
---> **suppress bulge formation and produce exponential profile**

Formation of gas-rich field dwarfs in cosmological hydro simulations across a spectrum of mass scales

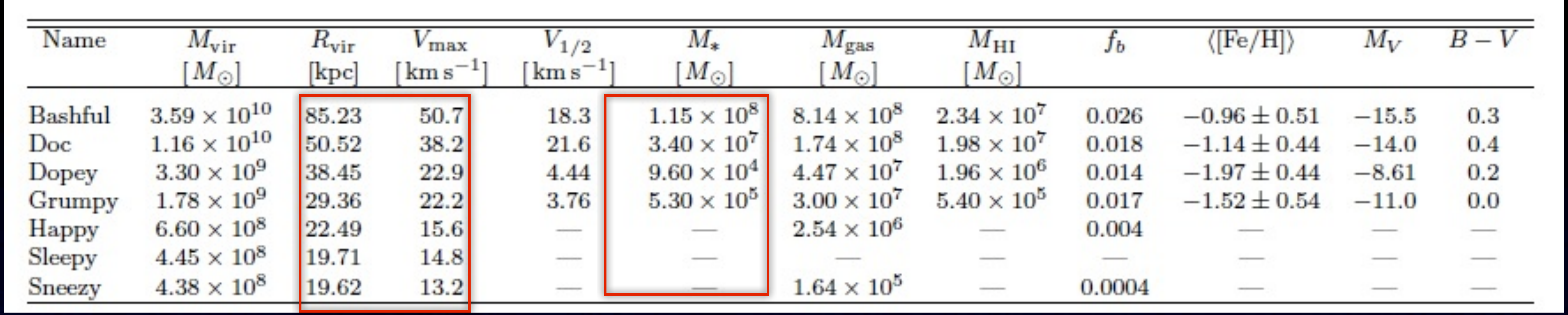
Shen et al. 2013

Sijing Shen, Charley Conroy, Piero Madau, Lucio Mayer, Fabio Governato

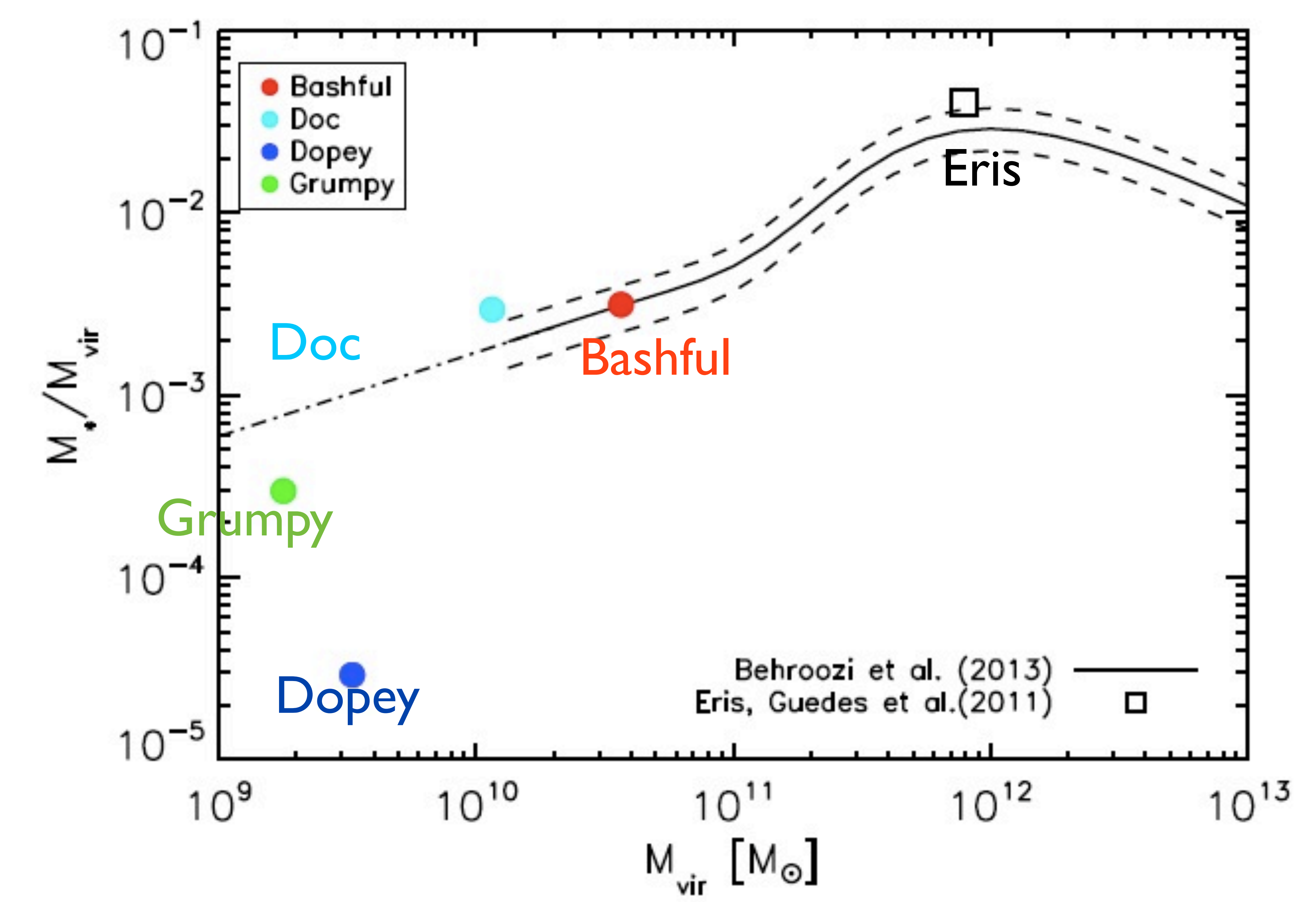


- •Resolution: DM 1.6×10^4 M_{sun}; Gas 3300 M_{sun}; Star 1000 M_{sun}; force resolution 86 pc
- •“Field” dwarfs: nearest massive halo > 3 Mpc away
- • Include metallicity-dependent cooling using CLOUDY, ionization equilibrium (but for H and He rates for non-equilibrium ionization), high SF density threshold of 100 cm^{-3}, blastwave feedback (Stinson et al. 2006), new UV background from stars and QSOs (Haardt & Madau 2013)
- • 4 Luminous galaxies with stellar mass ranges from 10^5 to 10^8 $M_{sun,}$ and halo mass ranges from 1.8×10^9 to 3.6×10^{10} M_{sun}
- •3 DARK DWARFS where gas accretion and SF are suppressed by the UVB (see also Kuhlen+13)

Stellar Mass of the Group of Seven (Shen et al. 2013)

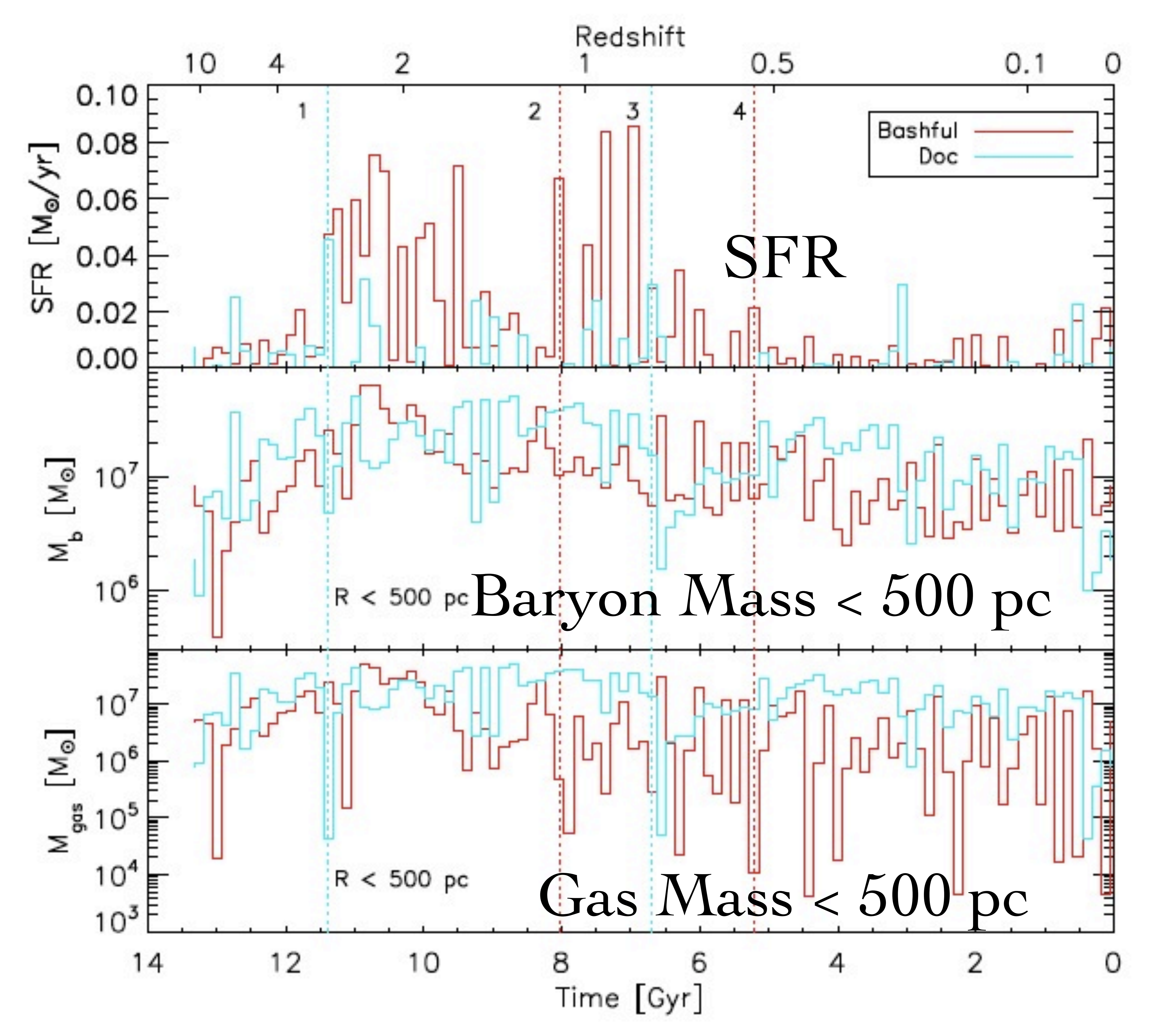


Name	$M_{\rm vir}$ $[M_\odot]$	$R_{\rm vir}$ [kpc]	$V_{\max}$ $[{\rm km\,s^{-1}}]$	$V_{1/2}$ $[{\rm km\,s^{-1}}]$	M_* $[M_\odot]$	$M_{\rm gas}$ $[M_\odot]$	$M_{\rm HI}$ $[M_\odot]$	f_b	$\langle[{\rm Fe/H}]\rangle$	M_V	$B-V$
Bashful	3.59×10^{10}	85.23	50.7	18.3	1.15×10^{8}	8.14×10^{8}	2.34×10^{7}	0.026	-0.96 ± 0.51	−15.5	0.3
Doc	1.16×10^{10}	50.52	38.2	21.6	3.40×10^{7}	1.74×10^{8}	1.98×10^{7}	0.018	-1.14 ± 0.44	−14.0	0.4
Dopey	3.30×10^{9}	38.45	22.9	4.44	9.60×10^{4}	4.47×10^{7}	1.96×10^{6}	0.014	-1.97 ± 0.44	−8.61	0.2
Grumpy	1.78×10^{9}	29.36	22.2	3.76	5.30×10^{5}	3.00×10^{7}	5.40×10^{5}	0.017	-1.52 ± 0.54	−11.0	0.0
Happy	6.60×10^{8}	22.49	15.6	—	—	2.54×10^{6}	—	0.004	—	—	—
Sleepy	4.45×10^{8}	19.71	14.8	—	—	—	—	—	—	—	—
Sneezy	4.38×10^{8}	19.62	13.2	—	—	1.64×10^{5}	—	0.0004	—	—	—



- •4 luminous dwarfs, with M* from 9.6×10^4 $M_{\rm sun}$ to 1.1×10^8 $M_{\rm sun}$
- •Bashful & Doc: M_*/M_h on the Behroozi + (2013) curve
- •Dopey & Grumpy: very small stellar fraction
- •Dopey is H I rich: $M_{\rm HI} \sim 20\ M_*$

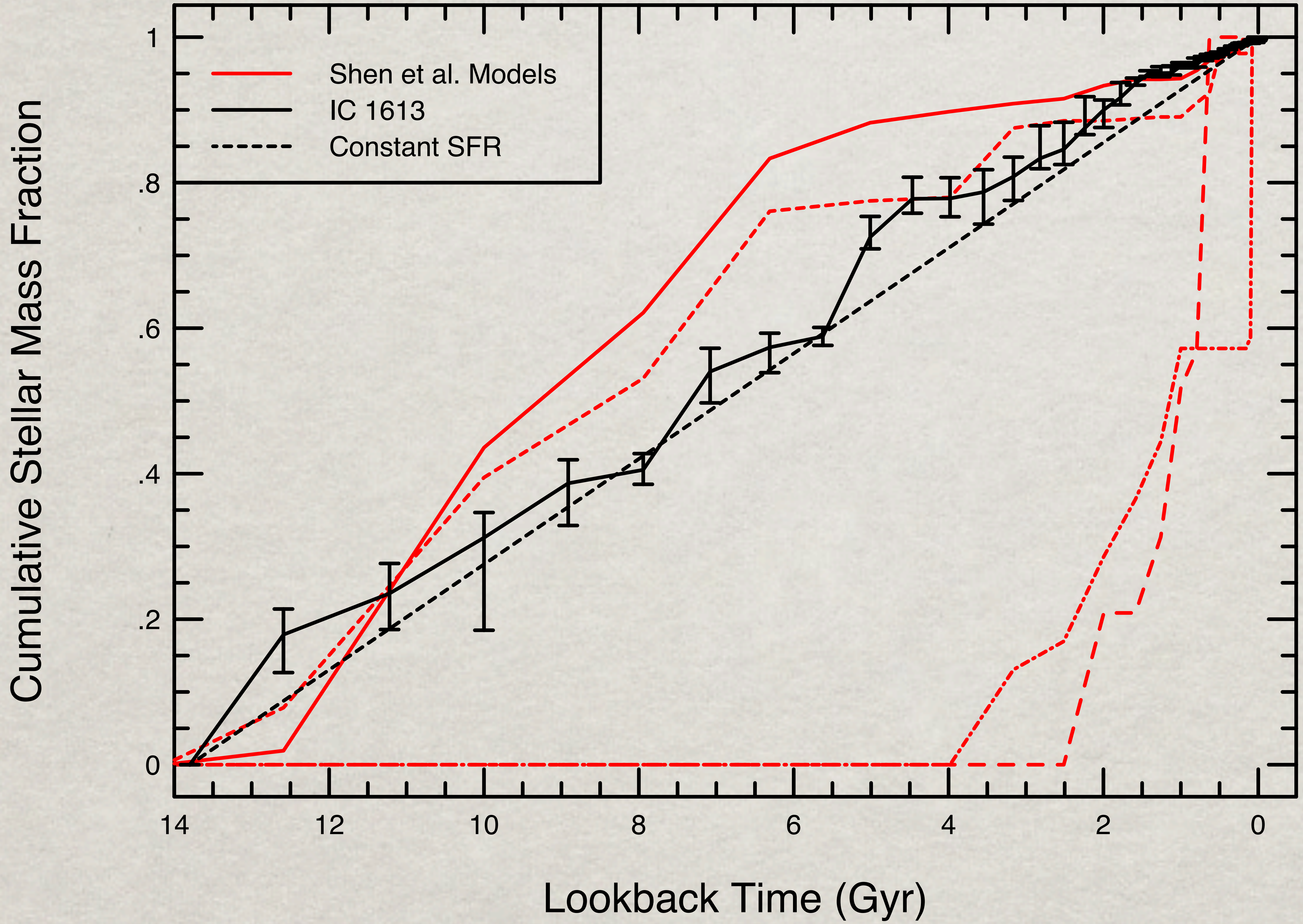
BURSTY STAR FORMATION + LATE STELLAR MASS ASSEMBLY



SF burst followed by decrease in M_b and M_{gas}

Rapid change of central potential, transfer energy into DM and generate cores (Pontzen & Governato 12, Teyssier+ 13)

BURSTY STAR FORMATION + LATE STELLAR MASS ASSEMBLY

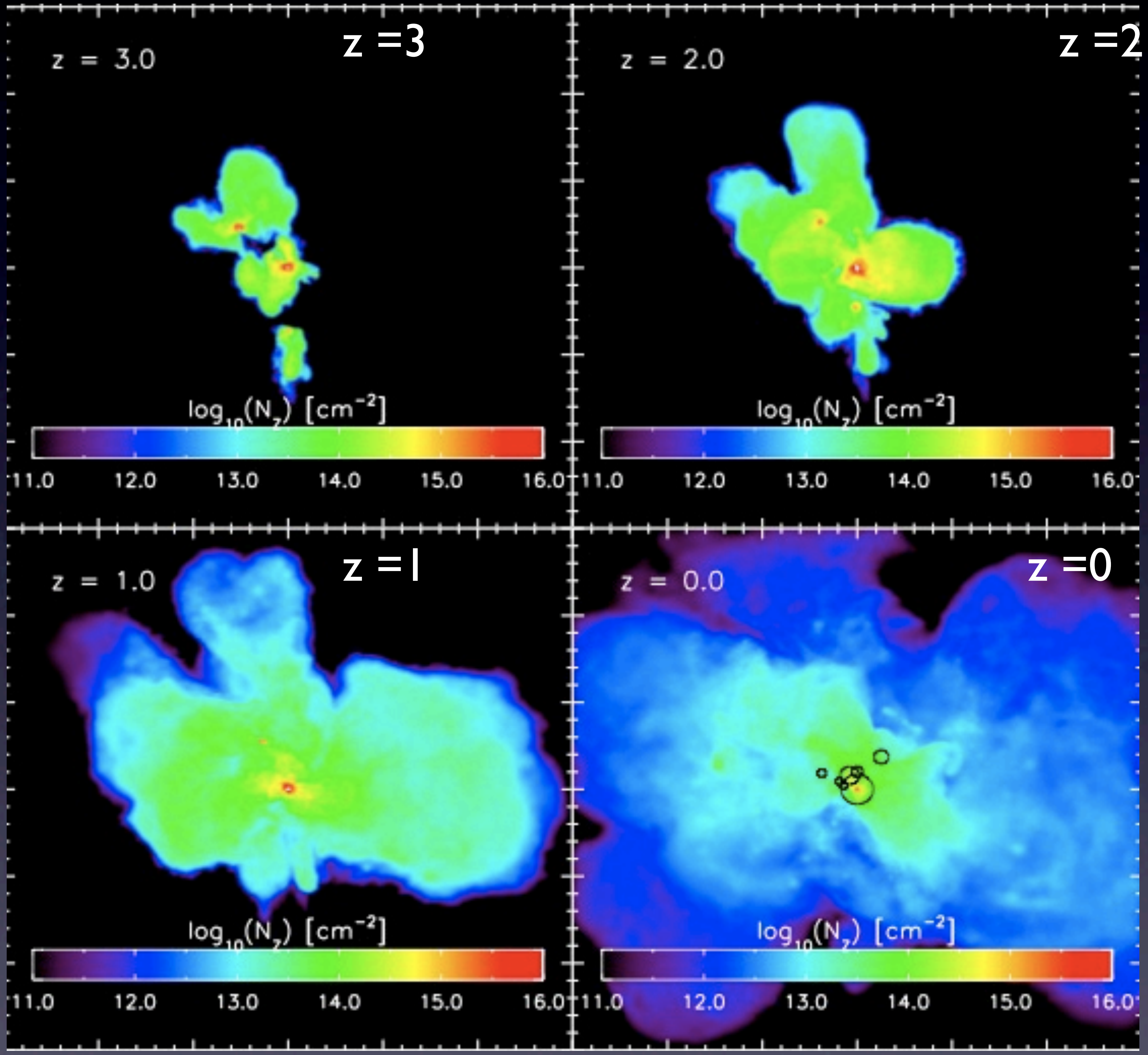


SF burst followed by decrease in M_b and M_{gas}

Rapid change of central potential, transfer energy into DM and generate cores (Pontzen & Governato 12, Teyssier+ 13)

Skillman et al. 2013
(LCID collaboration - unique LG field dwarf observational program with HST)

Evolution of the CGM around Dwarf Galaxies



- The extent of enriched region is:
  - 6 R_{vir} of Bashful at z ~ 2
  - 10 R_{vir} at z = 1
  - 16 R_{vir} at z = 0 (1.4 Mpc!)

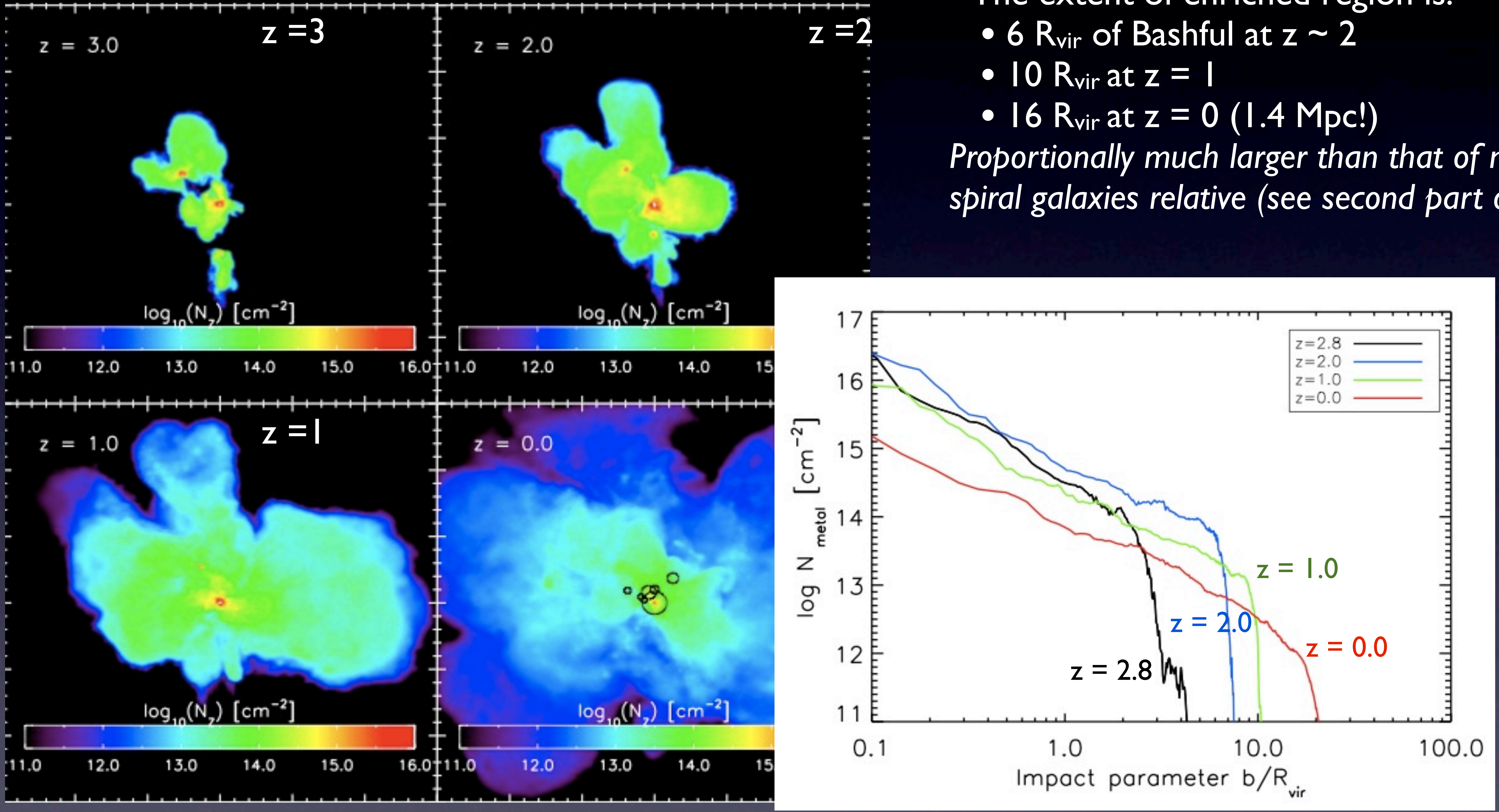
Proportionally much larger than that of massive spiral galaxies relative (see second part of talk)

Box size: 3 comoving Mpc on a side
Centered at the most massive dwarf

Evolution of the CGM around Dwarf Galaxies

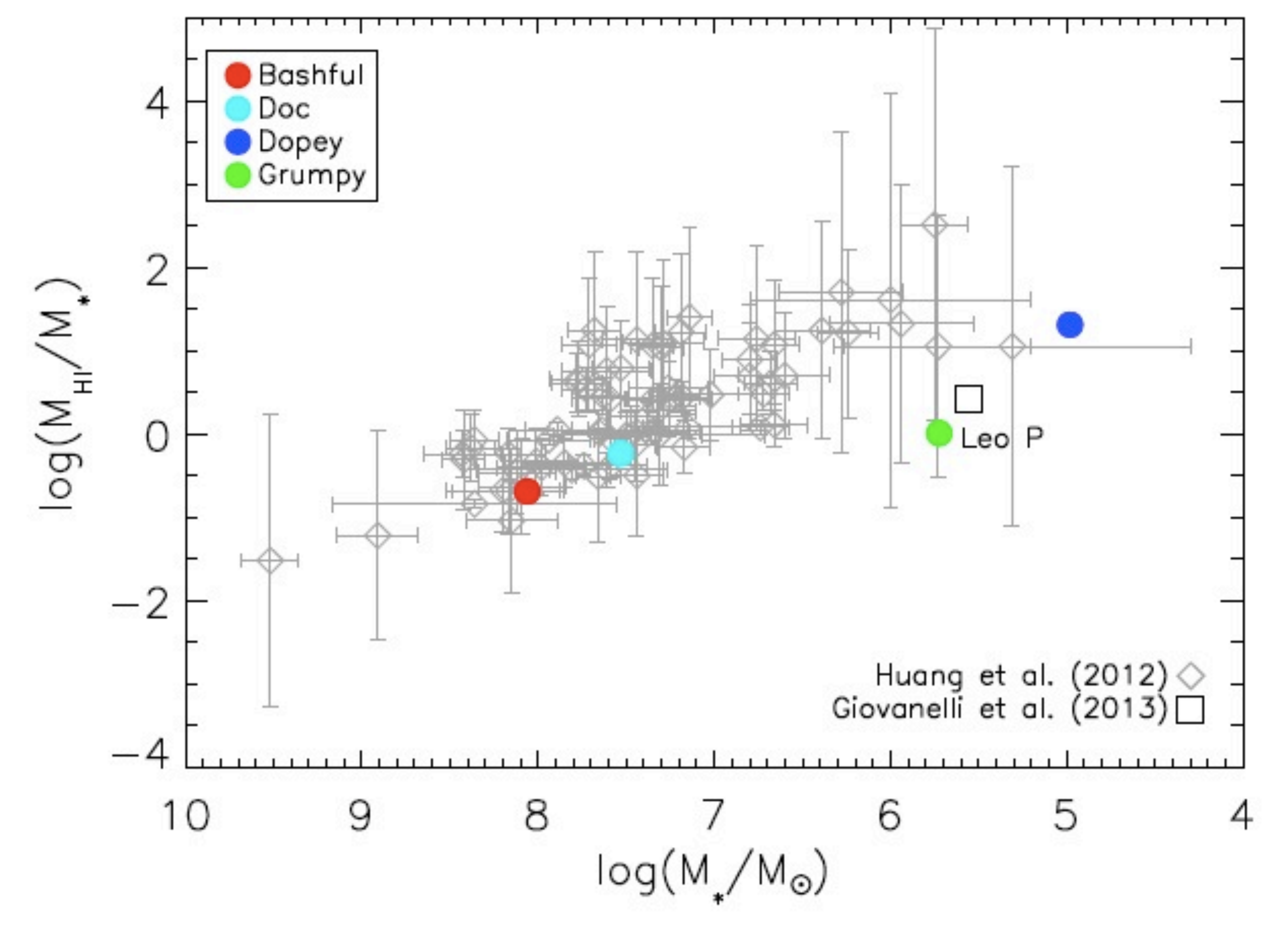
- The extent of enriched region is:
  - 6 R_{vir} of Bashful at z ~ 2
  - 10 R_{vir} at z = 1
  - 16 R_{vir} at z = 0 (1.4 Mpc!)

Proportionally much larger than that of massive spiral galaxies relative (see second part of talk)



Box size: 3 comoving Mpc on a side
Centered at the most massive dwarf

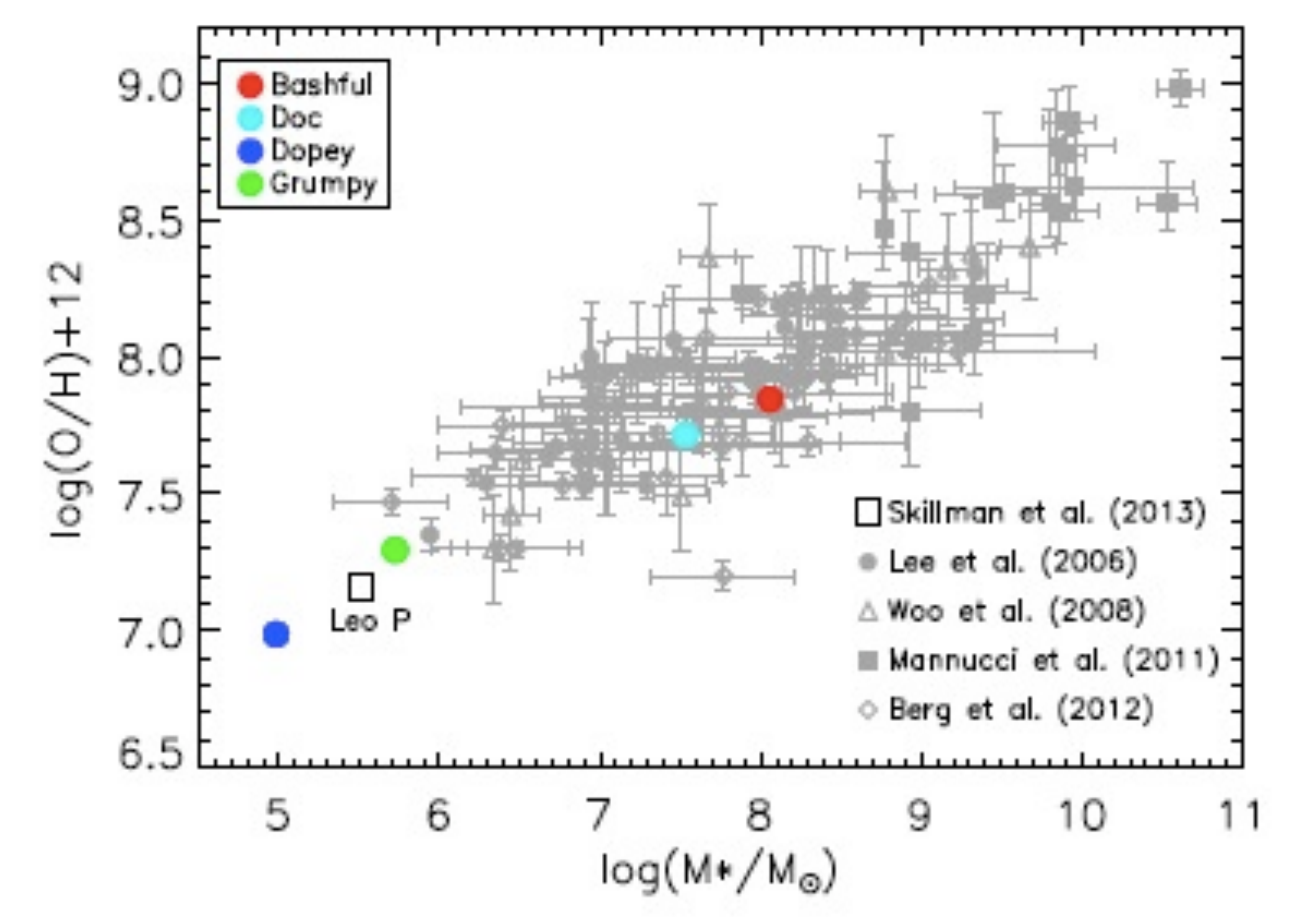
Cold Gas Fractions



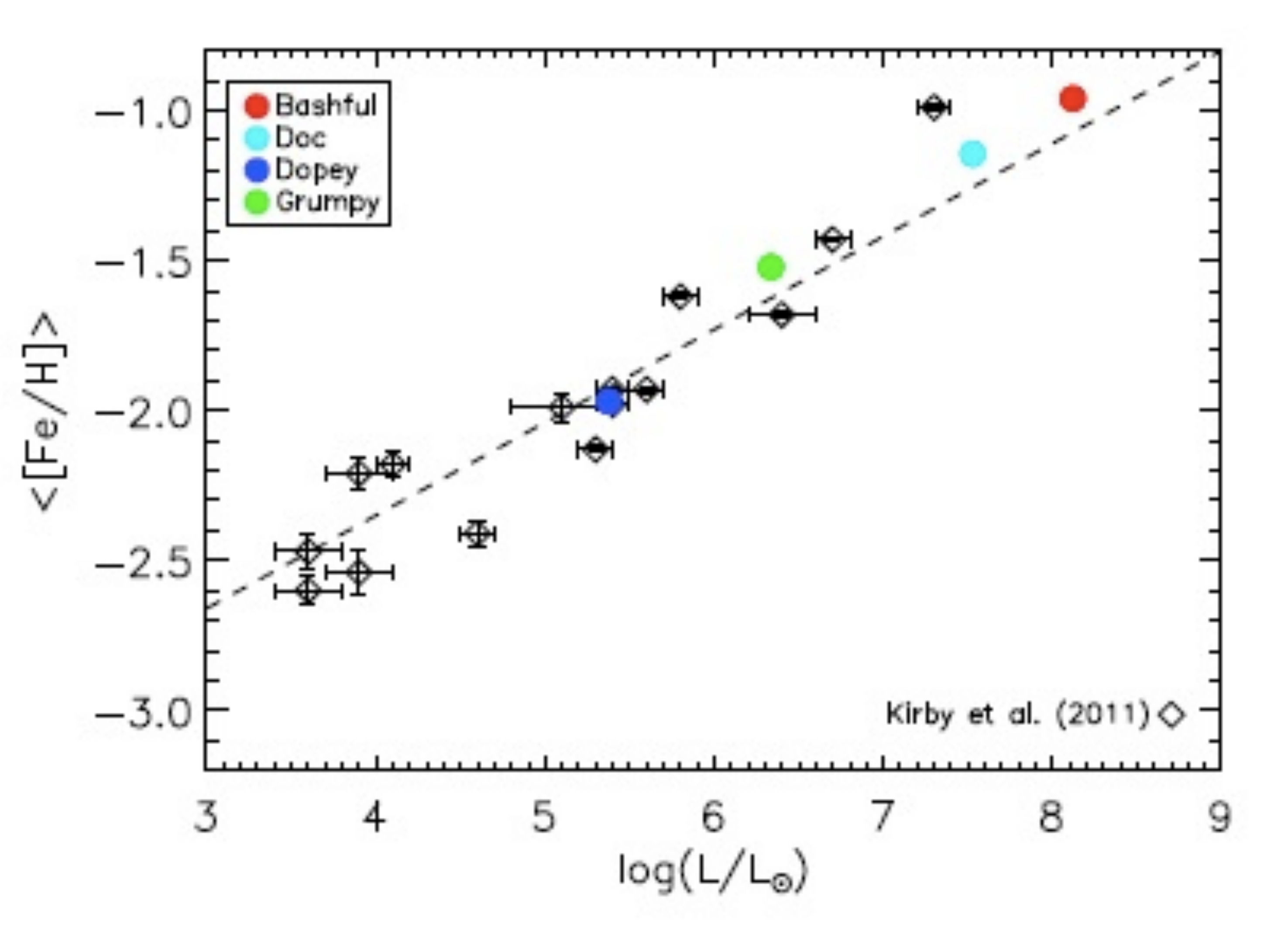
- Low stellar mass dwarfs in the ALFALFA sample are on average more HI gas rich (however here some gas is stripped due to dwarf-dwarf interactions)
- Low star formation efficiencies are not necessarily result of blowing out all gas (Bashful and Doc retain significant fraction of baryons)

Mass(Luminosity)-Metallicity Relationship: an important constraint on the feedback model

Gas



Stars



- Oxygen abundances in the ISM for the 4 dwarfs lie on the mass metallicity relationship and in good agreements with observations of local group dwarfs, nearby dwarf irregulars, low luminosity galaxies in the local volume (Lee+2006, Woo+2008, Mannucci+2011, Berg+2012)
- Dopey and Grumpy are extremely metal poor galaxies, but still on the MZR. Similar to a very recently discovered H I-rich dwarf, Leo P (Giovanelli+2013)
- Stellar metallicity - V band luminosity relation consistent with Milky Way's dSphs from Kirby+(2011)

ERIS: The Basics

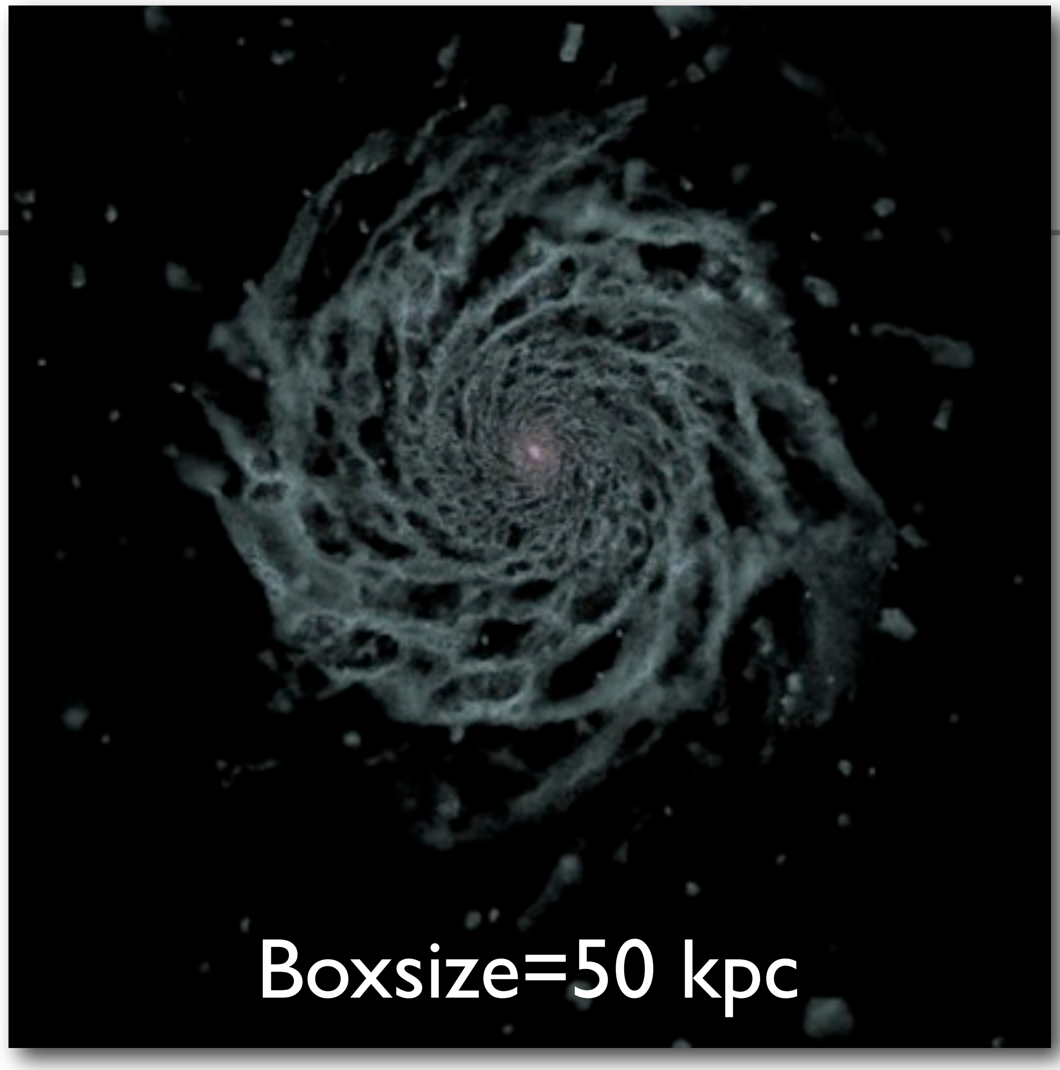
✳ Eris is a product of **GASOLINE.**
✳ Follows the formation of a light Milky Way galaxy of mass
$M_{vir} = 8\times10^{11}\ M_{sun}$
✳ Selected to have a quiet merger history. No mergers larger than 1:10 after z=3.
✳High mass and spatial resolution: 18.6 million particles within the virial radius. ε_G=120 pc

✳ Physics: metal dependent gas cooling (only for T <~ 10^4K,) UVB heating, SN Type Ia and Type II (blastwave) thermal feedback.
✳ High SF gas density threshold:
nSF=5 atoms cm^{-3}, + control run ErisLT with low SF threshold (*nSF* = 0.1 atoms cm^{-3}) and other runs with lower resolution or lower SF efficiency
✳ Expensive: 9 months per single run at NASA Pleiades and "Rosa" Cray at Swiss National Supercomputing Center using up to1024 cores.

What is missing: High Temperature metal cooling, H_2 cooling, metal and thermal diffusion diffusion, radiative feedback from stars, AGN feedback.....(see Eris2 runs later)

Eris: Basic Features at z=0


Boxsize=76 kpc


Boxsize=50 kpc

	M_{vir} [$10^{12} M_{sun}$]	V_{sun} [km/s]	M* [$10^{10} M_{sun}$]	f_b	B/D	R_d [kpc]	M_i	SFR [M_{sun} yr^{-1}]
Eris	0.79	206	3.9	**0.12**	0.35	2.5	-21.7	1.1
MW	1±0.2	221±18	4.9-5.5	?	0.33	2.3±0.6	?	0.68-1.45

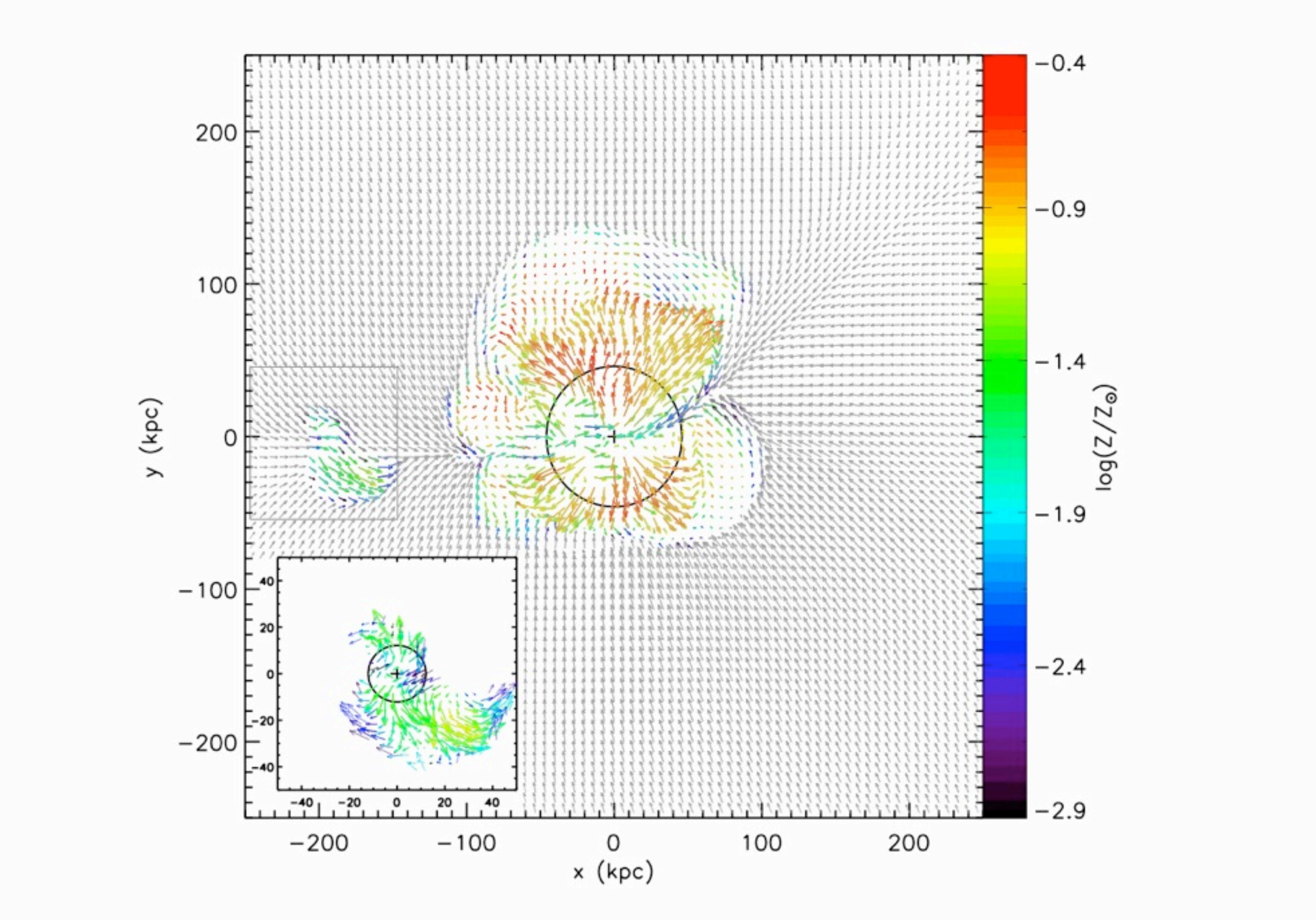
	N	ε [kpc]	m_{dark} [10^4 M_{sun}]	m_{gas} [10^4 M_{sun}]	n_{SF} [cm^{-3}]
Eris (Guedes et al. 2011; Mayer 2012)	18.6 M 3M+7M+8.6M (gas+dark+star)	0.12	9.8	2	5
Marinacci et al. 2013 (w/AREPO)	8.5 M	0.34	22	5	0.1
Scannapieco et al. 2009, 2010 (GADGET3)	1 M	0.7-1.4	26	56	0.05

AS IN DWARF GALAXY SIMULATIONS OUTFLOWS ARE PRODUCED BY **BLASTWAVE (THERMAL) FEEDBACK** WITH CLUSTERED SF IN INHOMOGENEOUS ISM -->

FINAL BARYON FRACTION within R_{vir} ~ 0.12 (~30% lower cosmic)

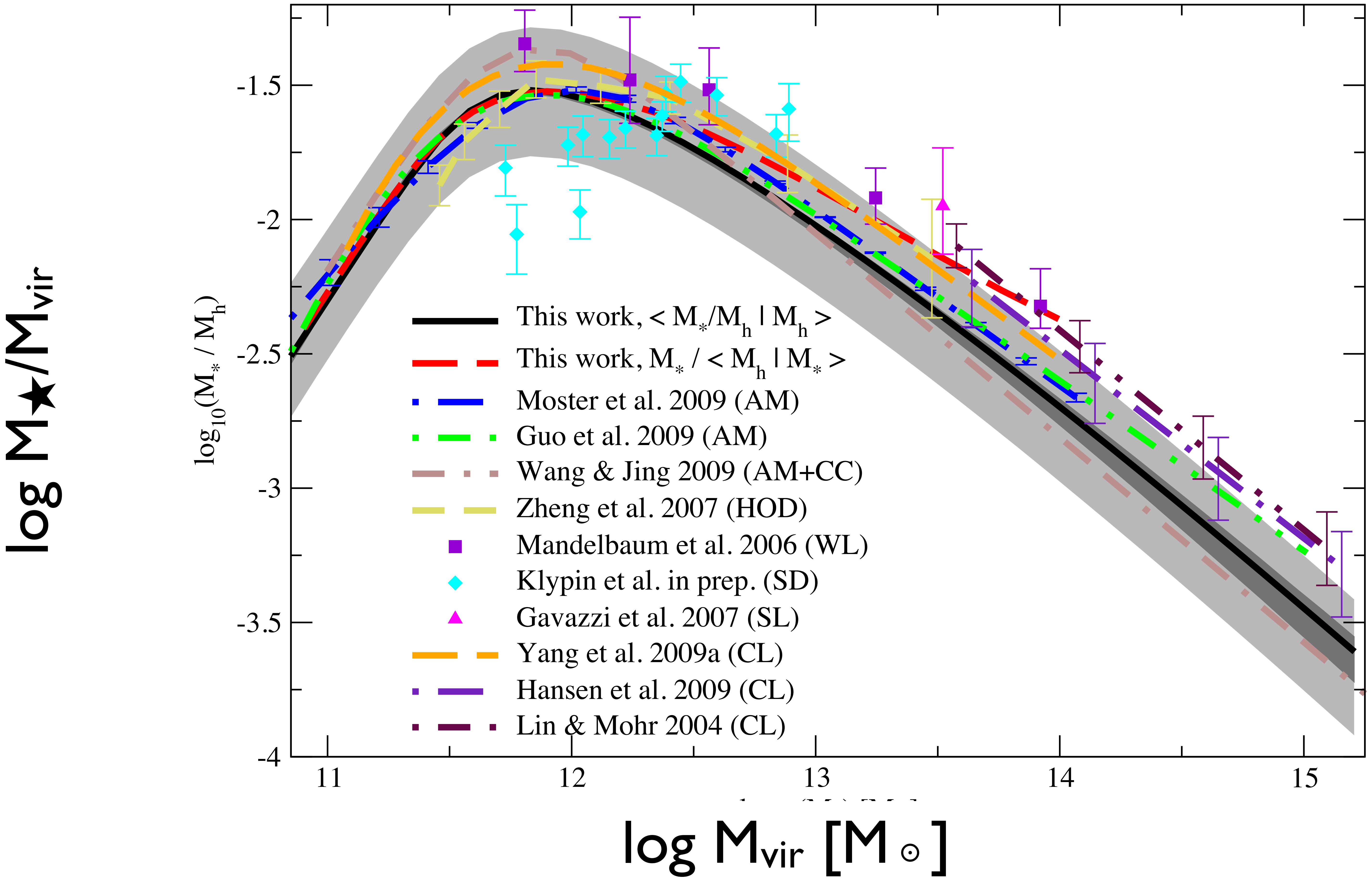
OUTFLOWS WELL TRACED BY METALS: IN FIGURE BELOW METALLICITY BUBBLES SHOWN FOR MAIN GALAXY AND A SATELLITE AT z=3 (Shen et al 2013, circle marks virial radius) OUTFLOWS CONFINED to ~ 2 Rvir though (10 Rvir for dwarfs)

Maximum length of velocity vectors ~ 260 km/s



The M_{star}-M_{halo} Relation

Behroozi et al 2010



● Brooks et al. 2011

● Eris ● ErisLT

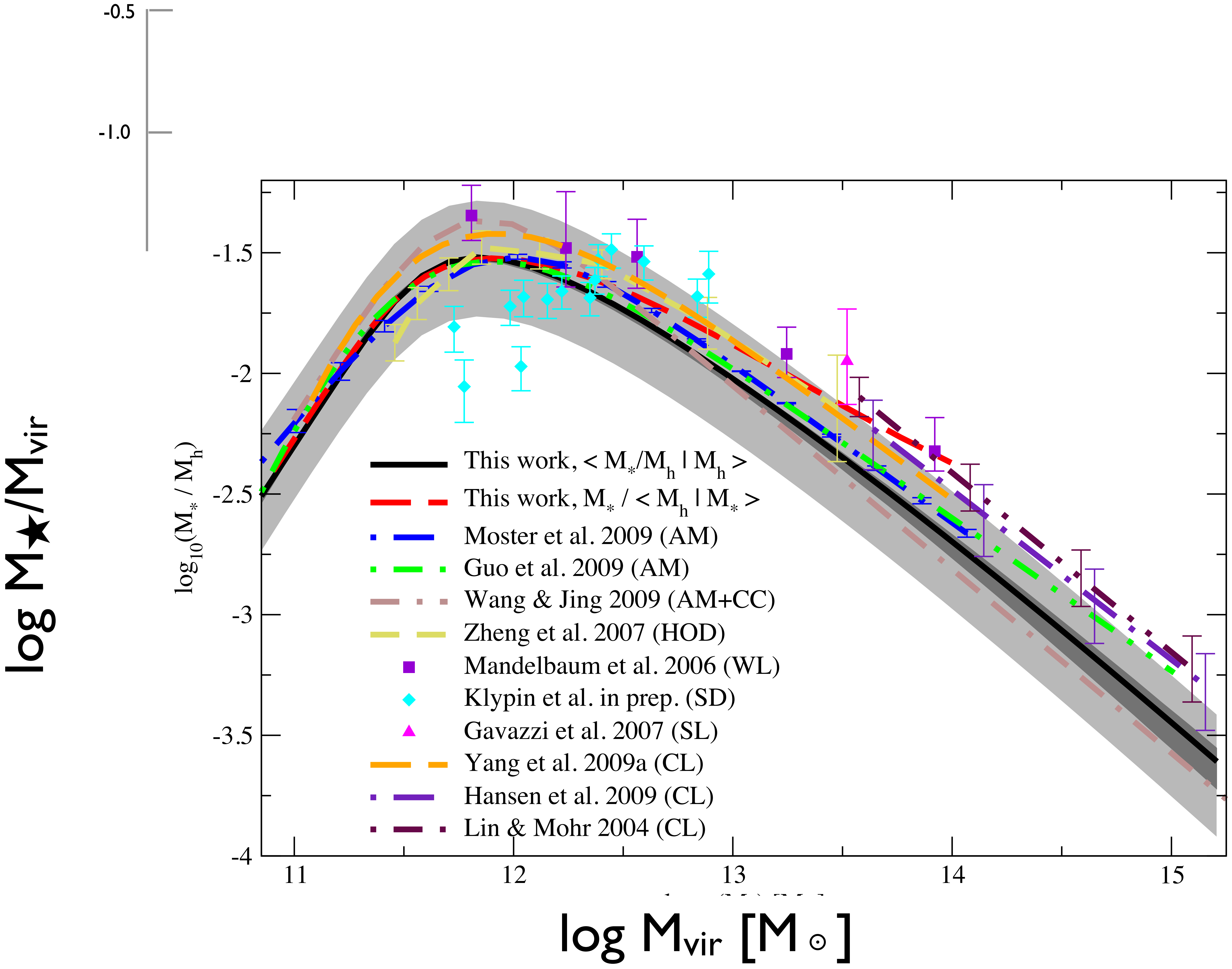
● Brook et al. 2012

● Feldmann et al. 2010;2011

In 2012-2014 other groups have simulated hi-res galaxies that agree with AM at z=0 (eg Stinson et al. 2013 and Munshi et al.2013, Marinacci et al. 2013; Roskar et al. 2013; Phil's and Dusan's talks)

The M_{star}-M_{halo} Relation

Behroozi et al 2010



● Brooks et al. 2011

● Eris ● ErisLT

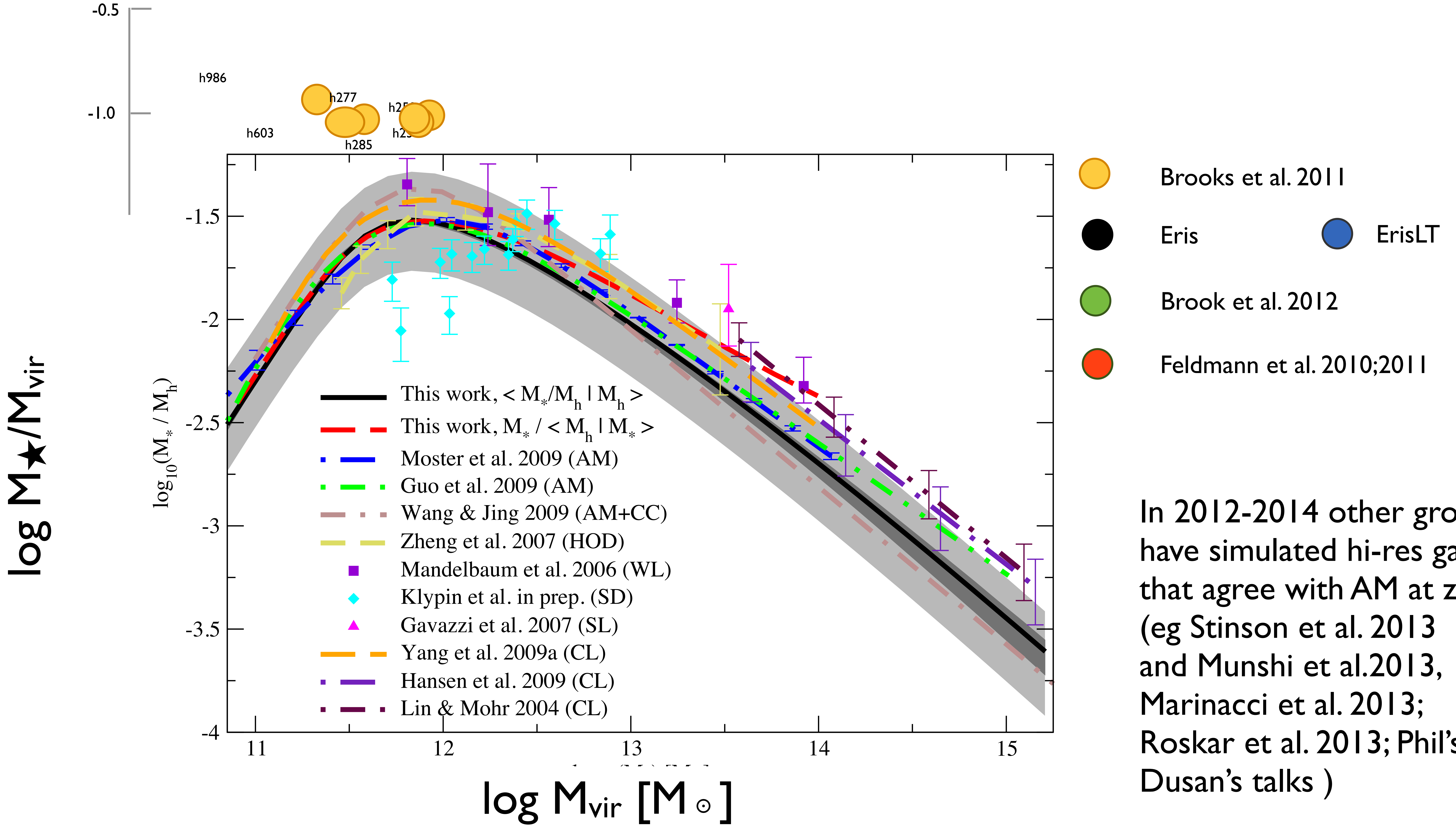
● Brook et al. 2012

● Feldmann et al. 2010;2011

In 2012-2014 other groups have simulated hi-res galaxies that agree with AM at z=0 (eg Stinson et al. 2013 and Munshi et al.2013, Marinacci et al. 2013; Roskar et al. 2013; Phil's and Dusan's talks)

The M_{star}-M_{halo} Relation

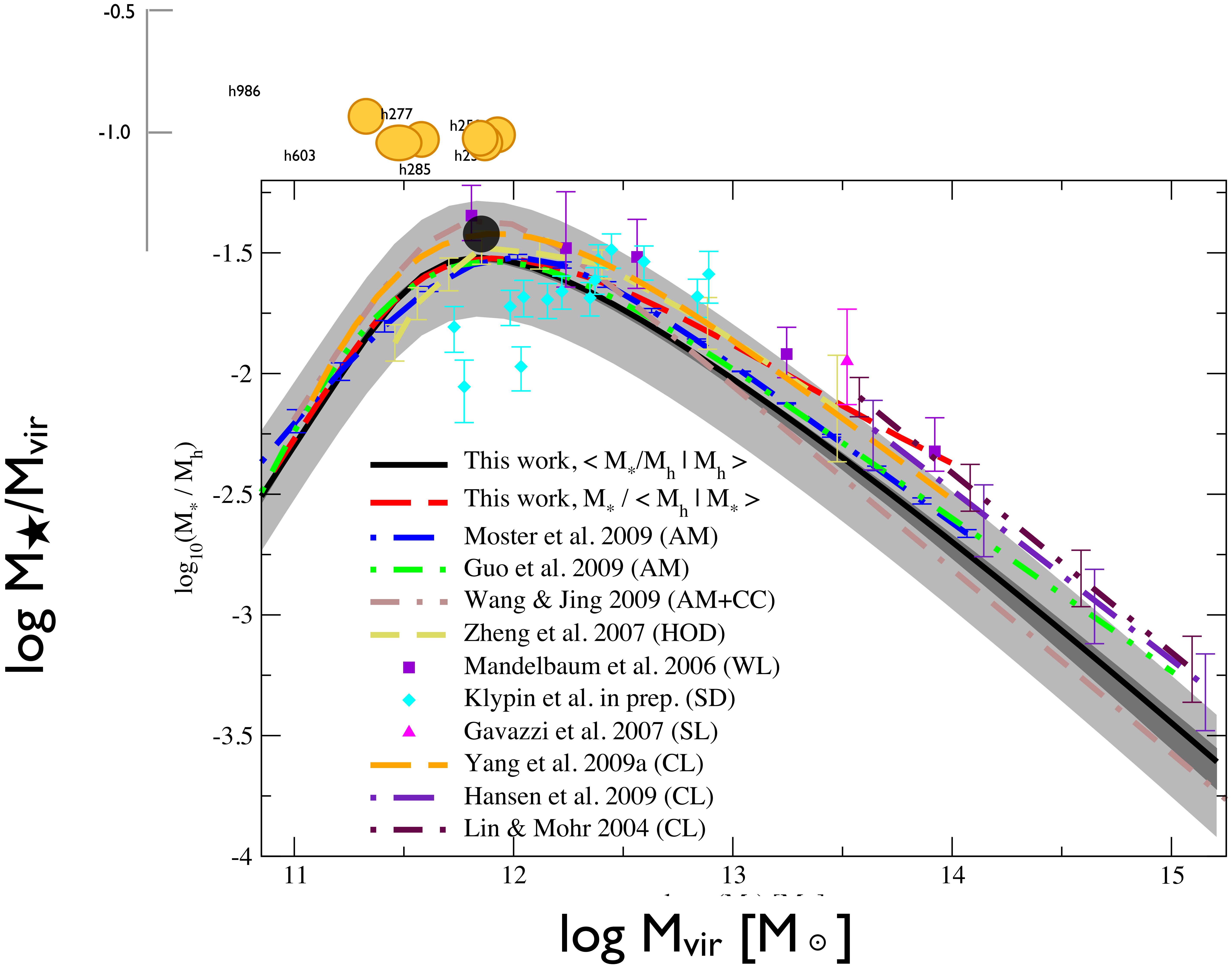
Behroozi et al 2010



In 2012-2014 other groups have simulated hi-res galaxies that agree with AM at z=0 (eg Stinson et al. 2013 and Munshi et al.2013, Marinacci et al. 2013; Roskar et al. 2013; Phil's and Dusan's talks)

The M_{star}-M_{halo} Relation

Behroozi et al 2010



● Brooks et al. 2011

● Eris ● ErisLT

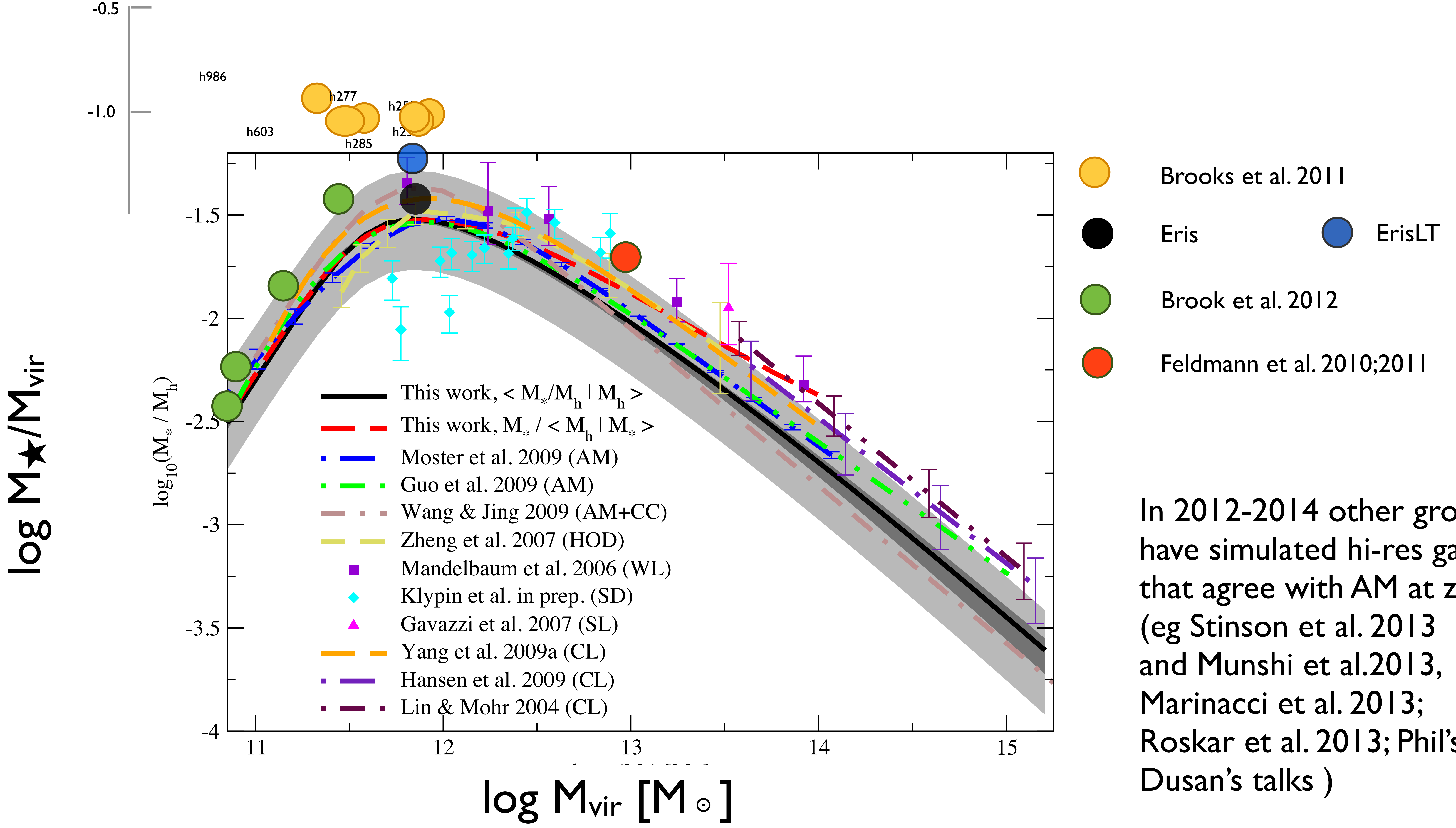
● Brook et al. 2012

● Feldmann et al. 2010;2011

In 2012-2014 other groups have simulated hi-res galaxies that agree with AM at z=0 (eg Stinson et al. 2013 and Munshi et al.2013, Marinacci et al. 2013; Roskar et al. 2013; Phil's and Dusan's talks)

The M_{star}-M_{halo} Relation

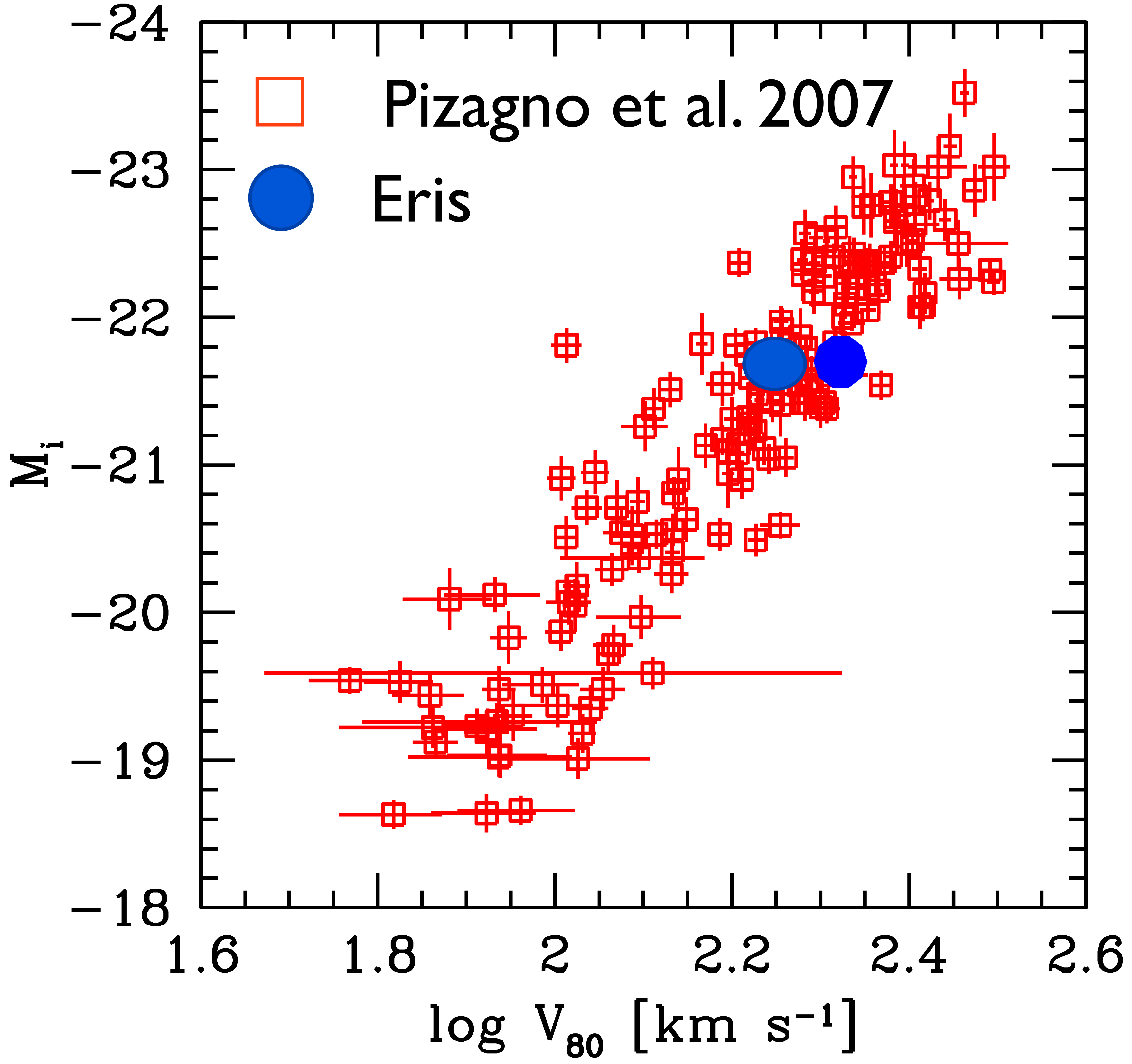
Behroozi et al 2010



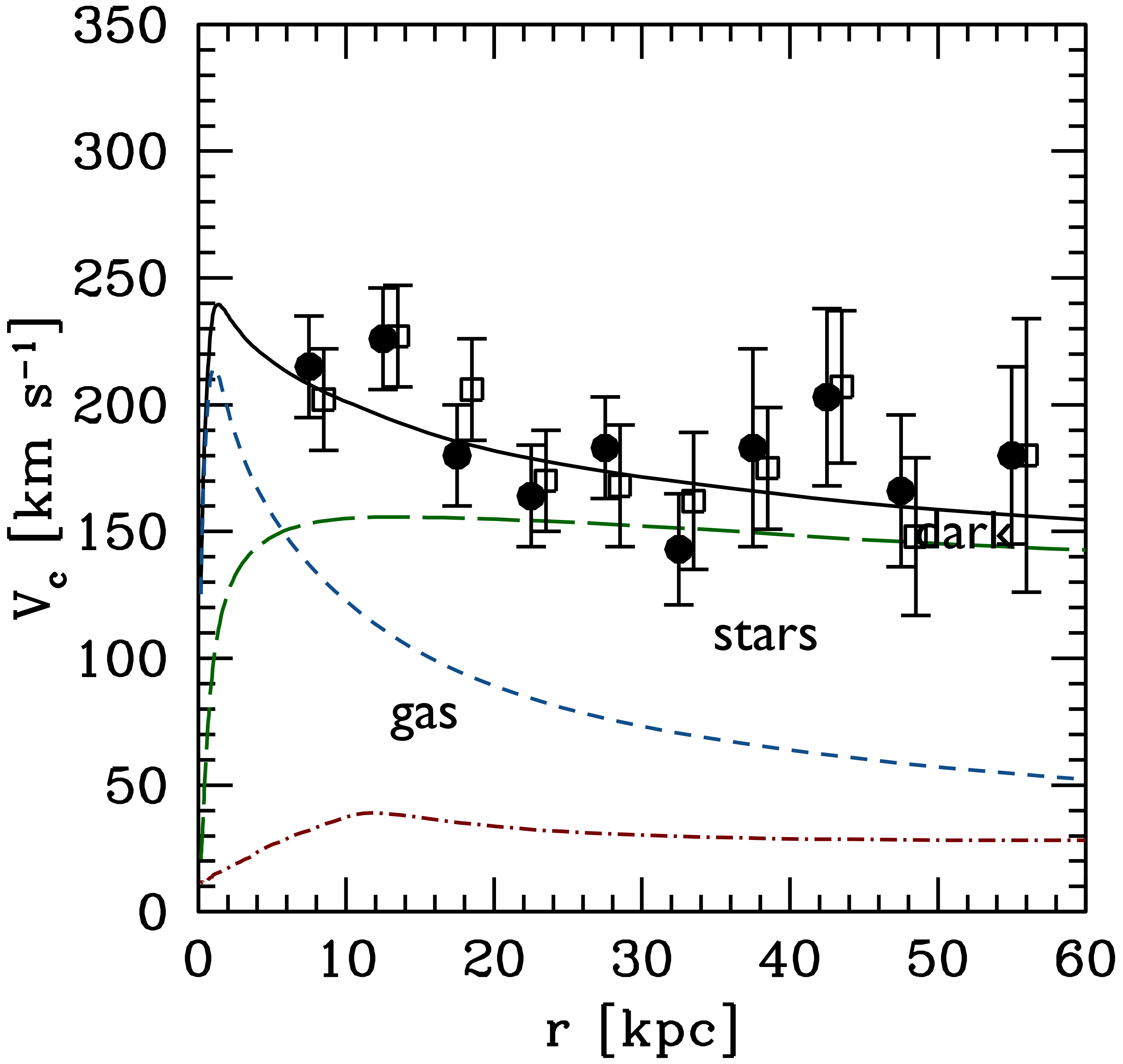
In 2012-2014 other groups have simulated hi-res galaxies that agree with AM at z=0 (eg Stinson et al. 2013 and Munshi et al.2013, Marinacci et al. 2013; Roskar et al. 2013; Phil's and Dusan's talks)

Mass and Light Distribution

Tully-Fisher Relation and rotation curve: the distribution of the stellar mass in the galaxy is in agreement with observed nearby spirals.



data points from SDSS blue HB stars in MW (Xue et al. 2008)

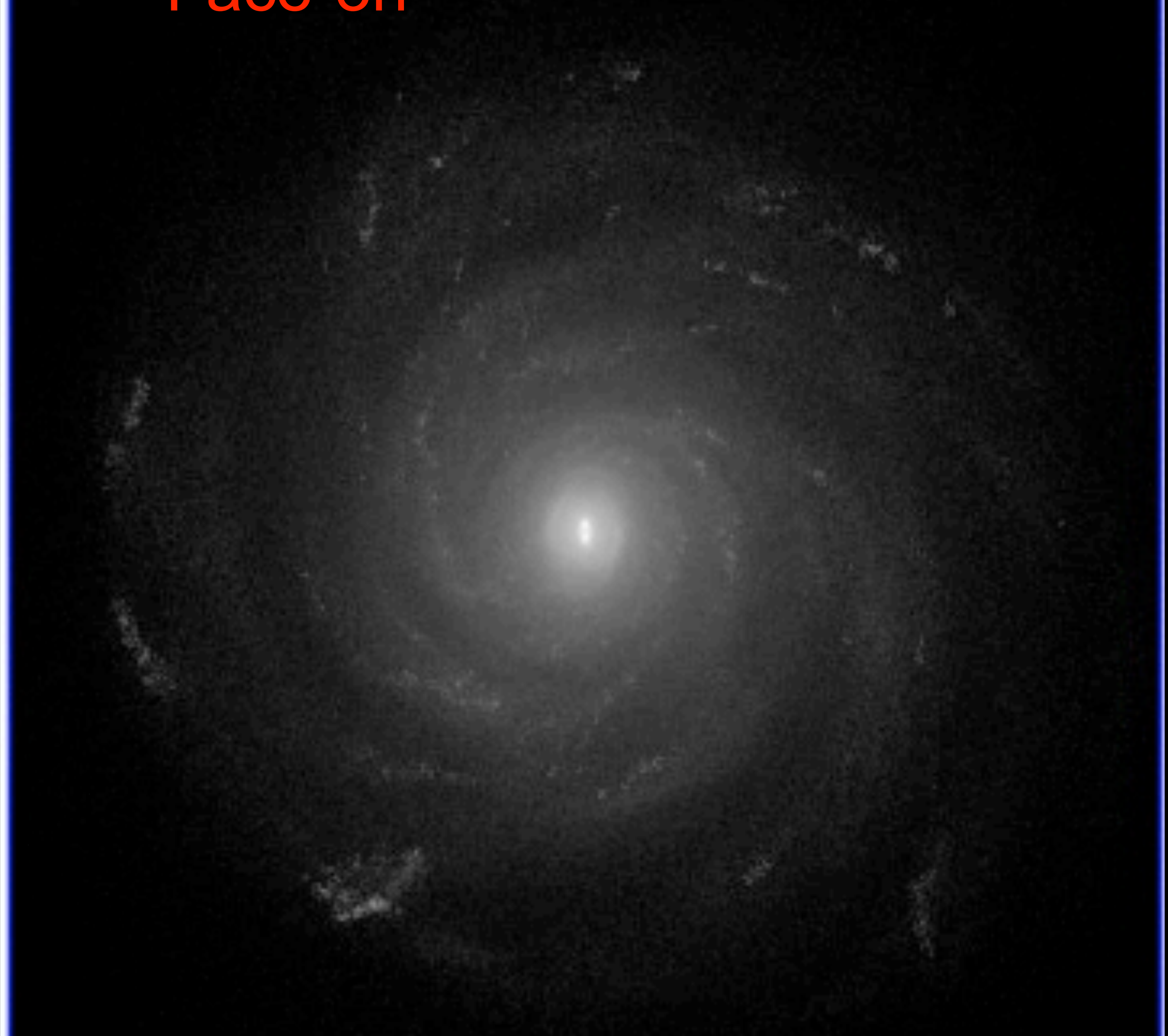


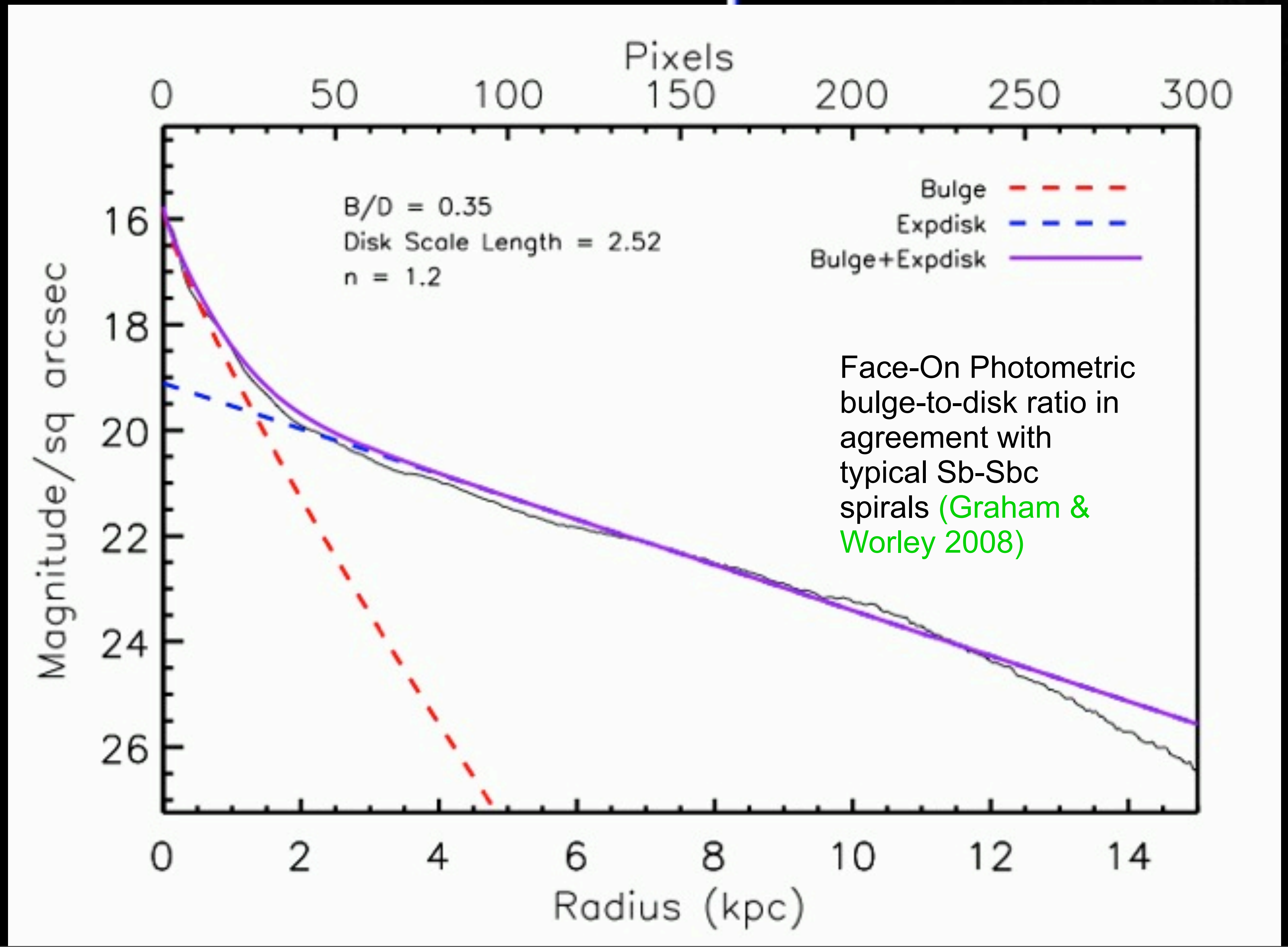
ERIS: I-Band mock imaging+photometry z=0 (w/SUNRISE - P. Jonsson 2010)

Boxes
40 kpc on a side

Edge-on

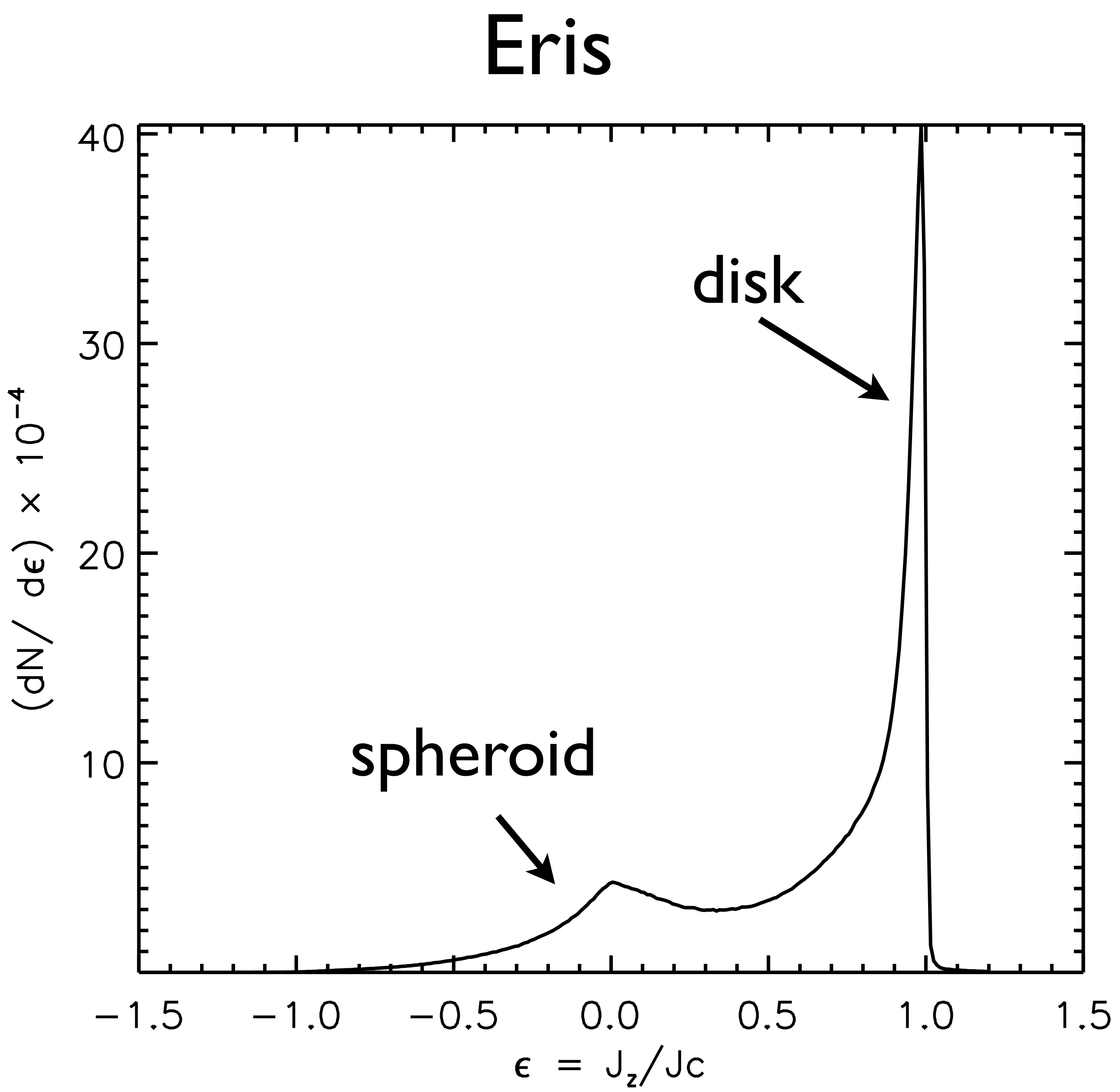
Face-on

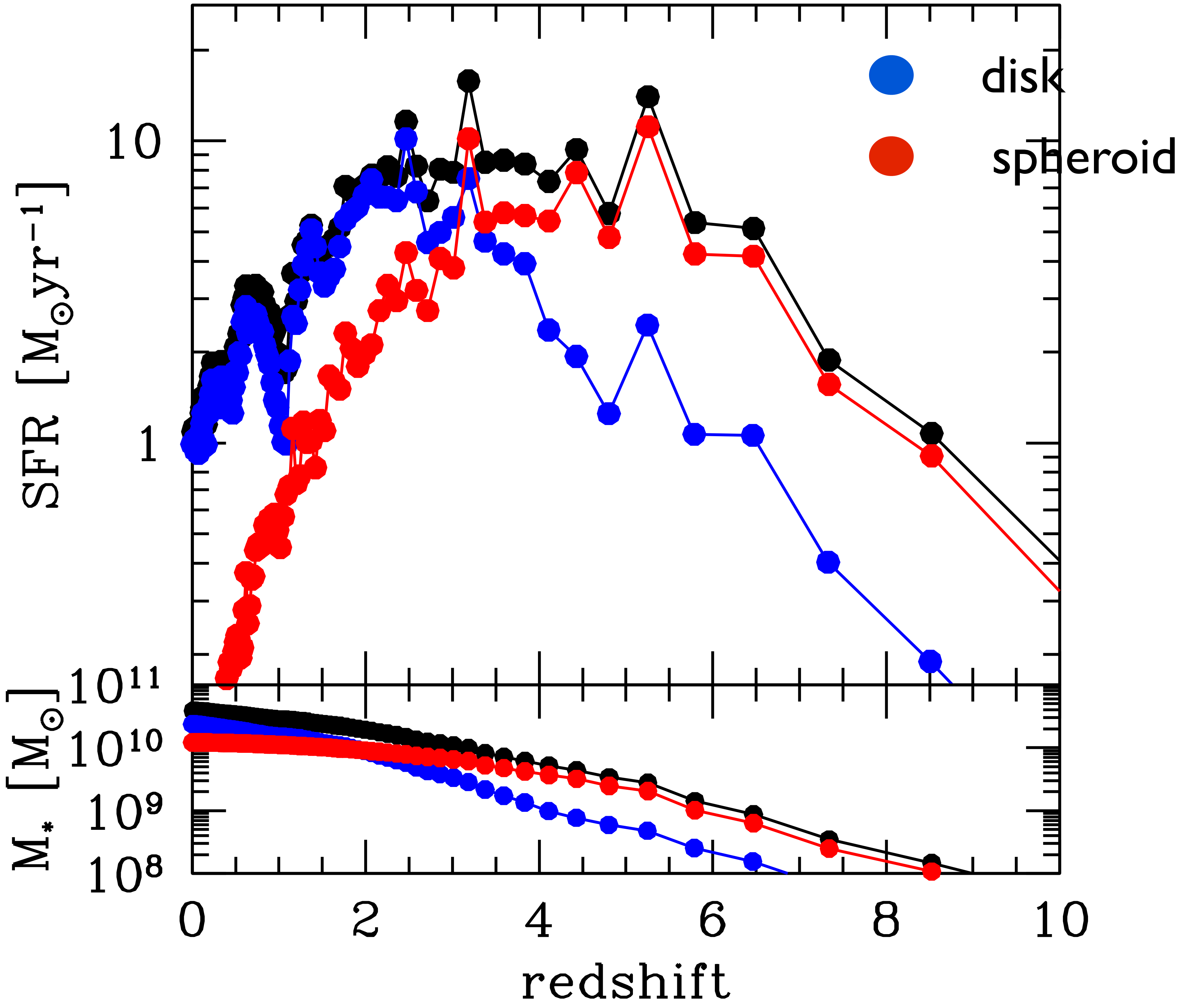




Face-On Photometric bulge-to-disk ratio in agreement with typical Sb-Sbc spirals (Graham & Worley 2008)

Structural Properties: Kinematic Decomposition

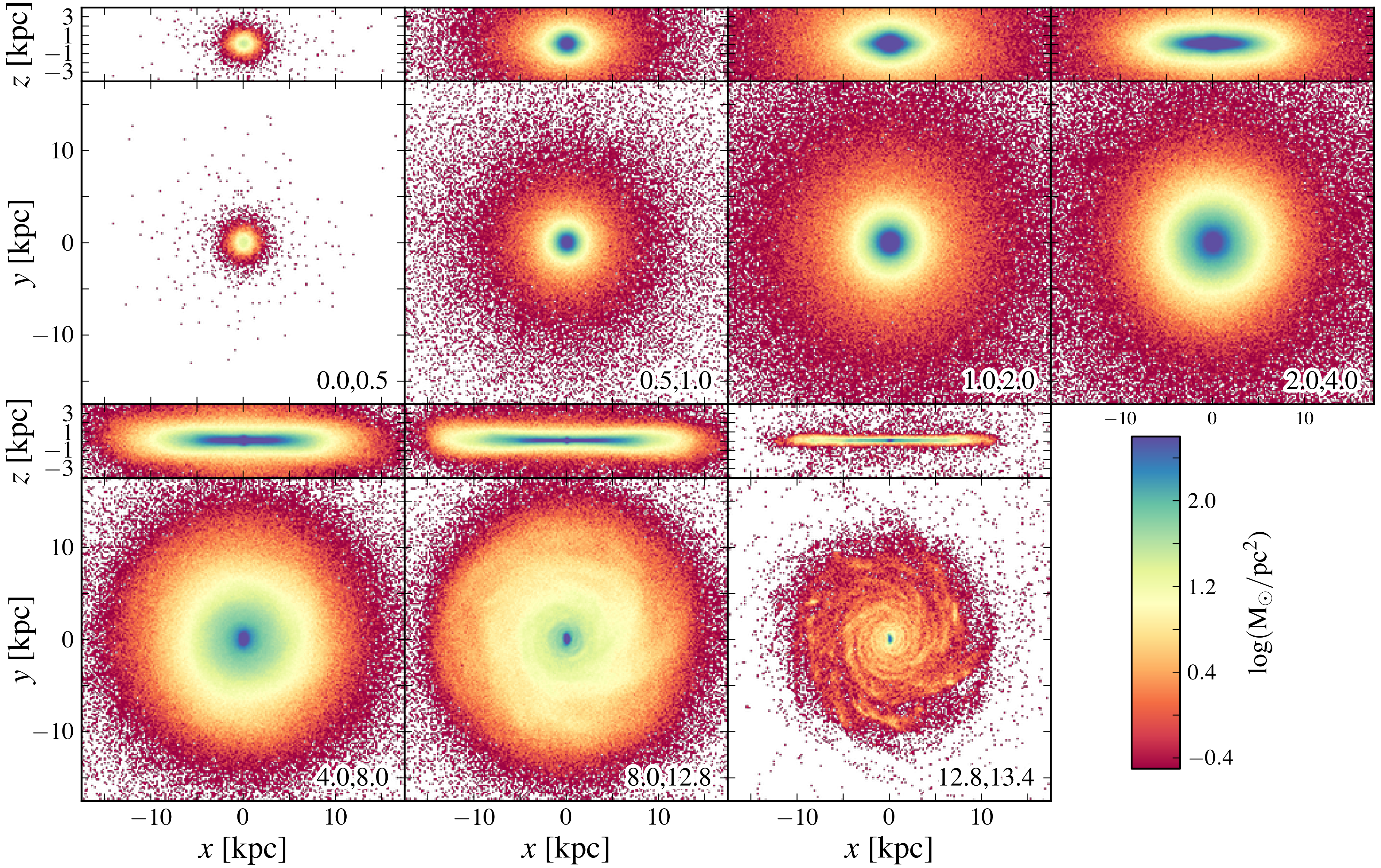




- ✳ The spheroid forms early and is quenched late.
- ✳ The formation of the disk begins later, but it is sustained down to z=0 at a rate of 1.1 M_{sun} yr^{-1}

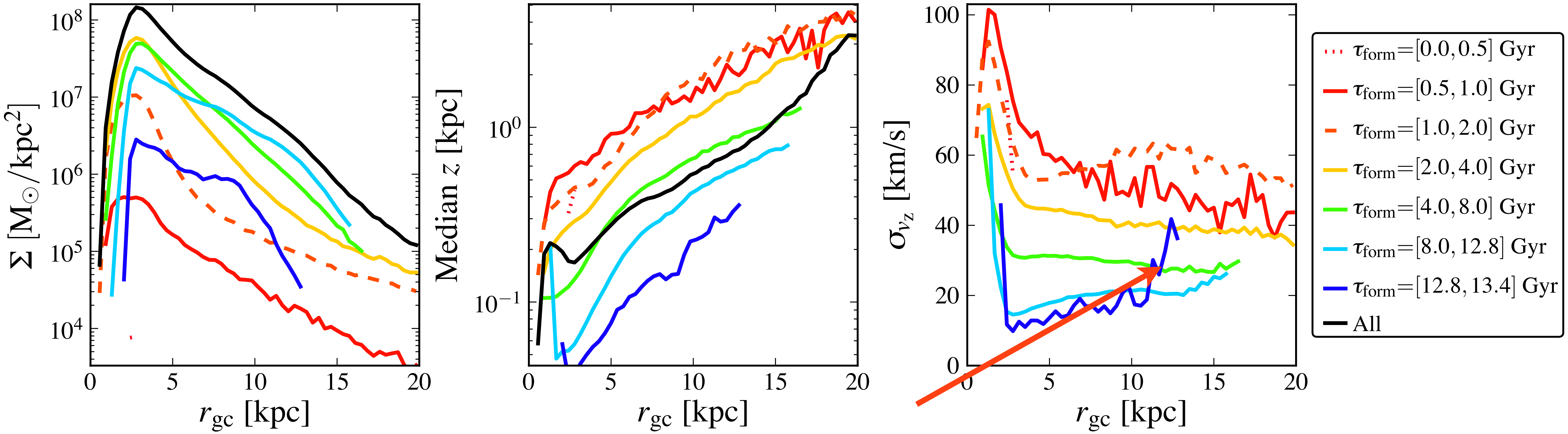
Important figure of merit: Age-Kinematics relation

Young/thin/
kinematcally
cold disk
+
Continuum between
sub-components



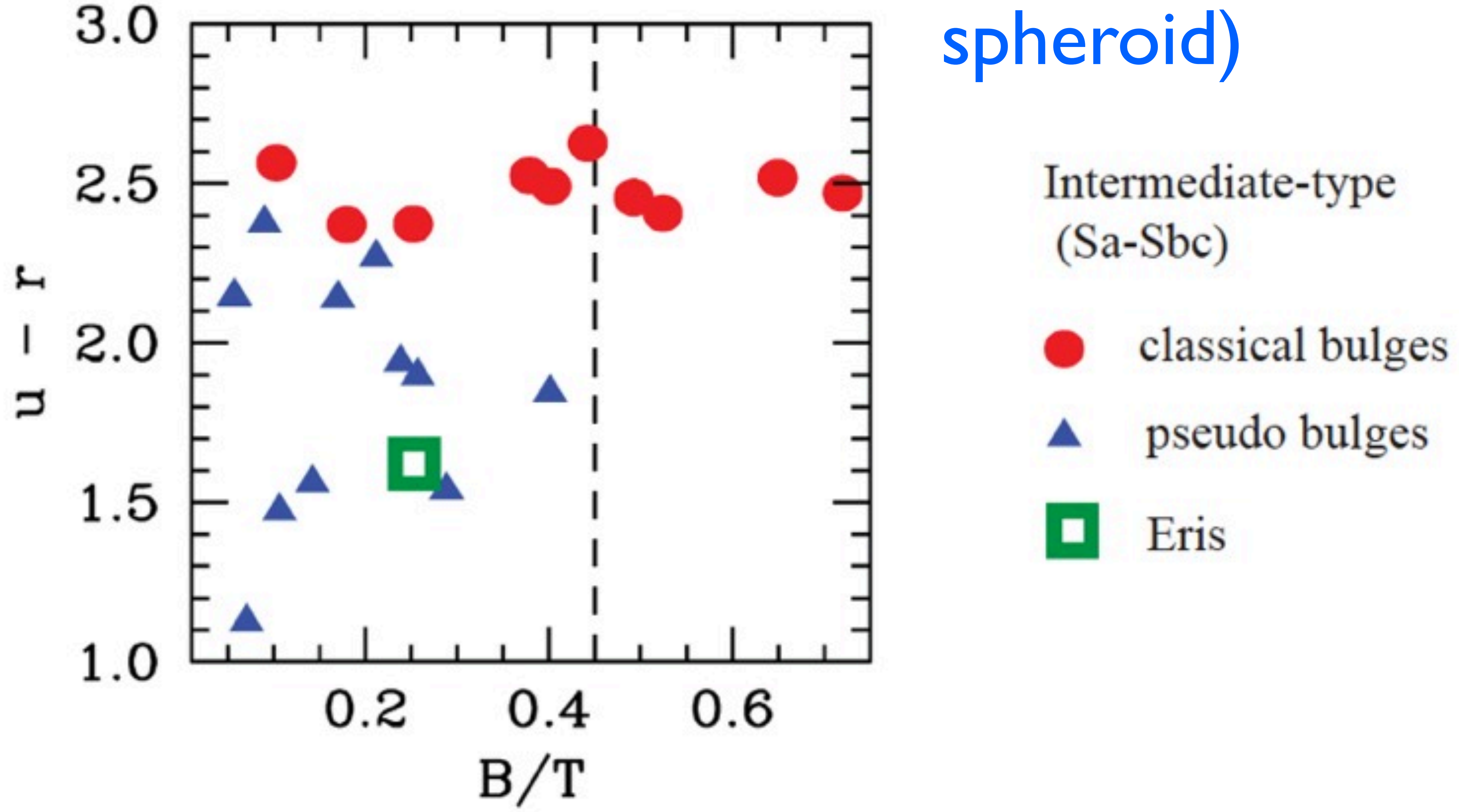
Bird et al. 2013

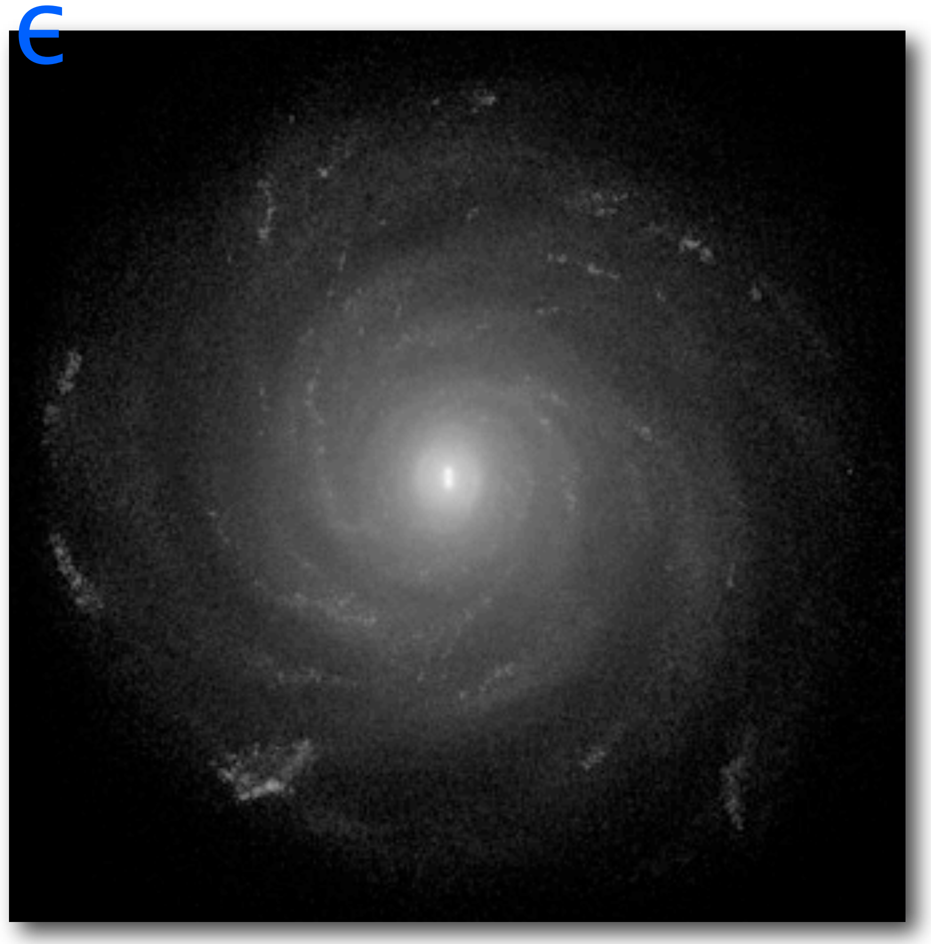
Very good agreement with age-kinematics of disk stars in the MW (w/SEGUE - Bovy+ 2011; 2012)

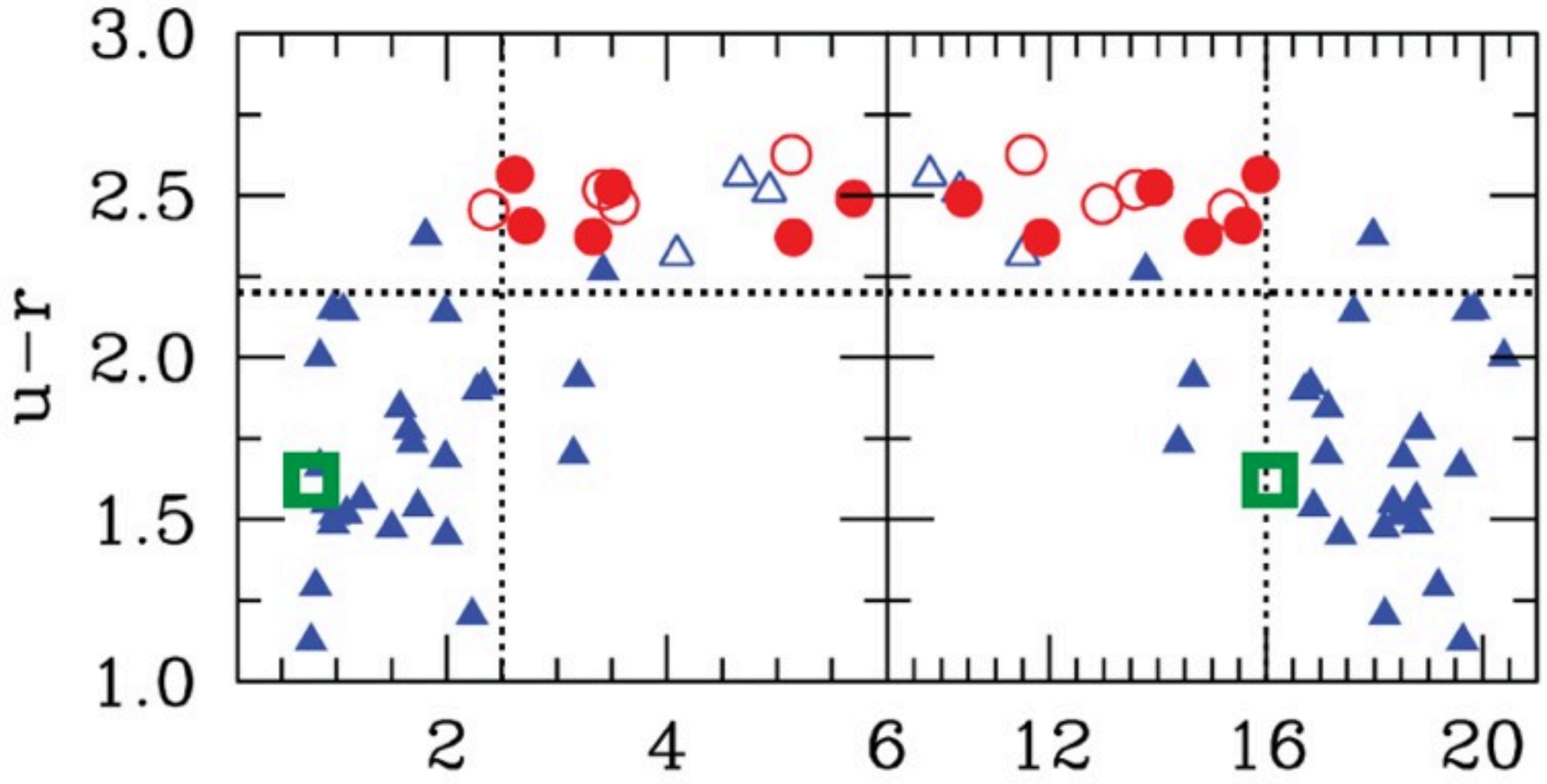


Eris has a pseudo-bulge triggered by bar formation at z >~ 4 (Guedes, Mayer et al. 2013)

Bulge = stars at R < 2 kpc with ε < 0.2 (subset of spheroid)







Pseudobulges have low Sersic index (n <~ 2) and:
- exhibit rotation
- can have blue colors
- are often associated with bars and are typical of late-type spirals

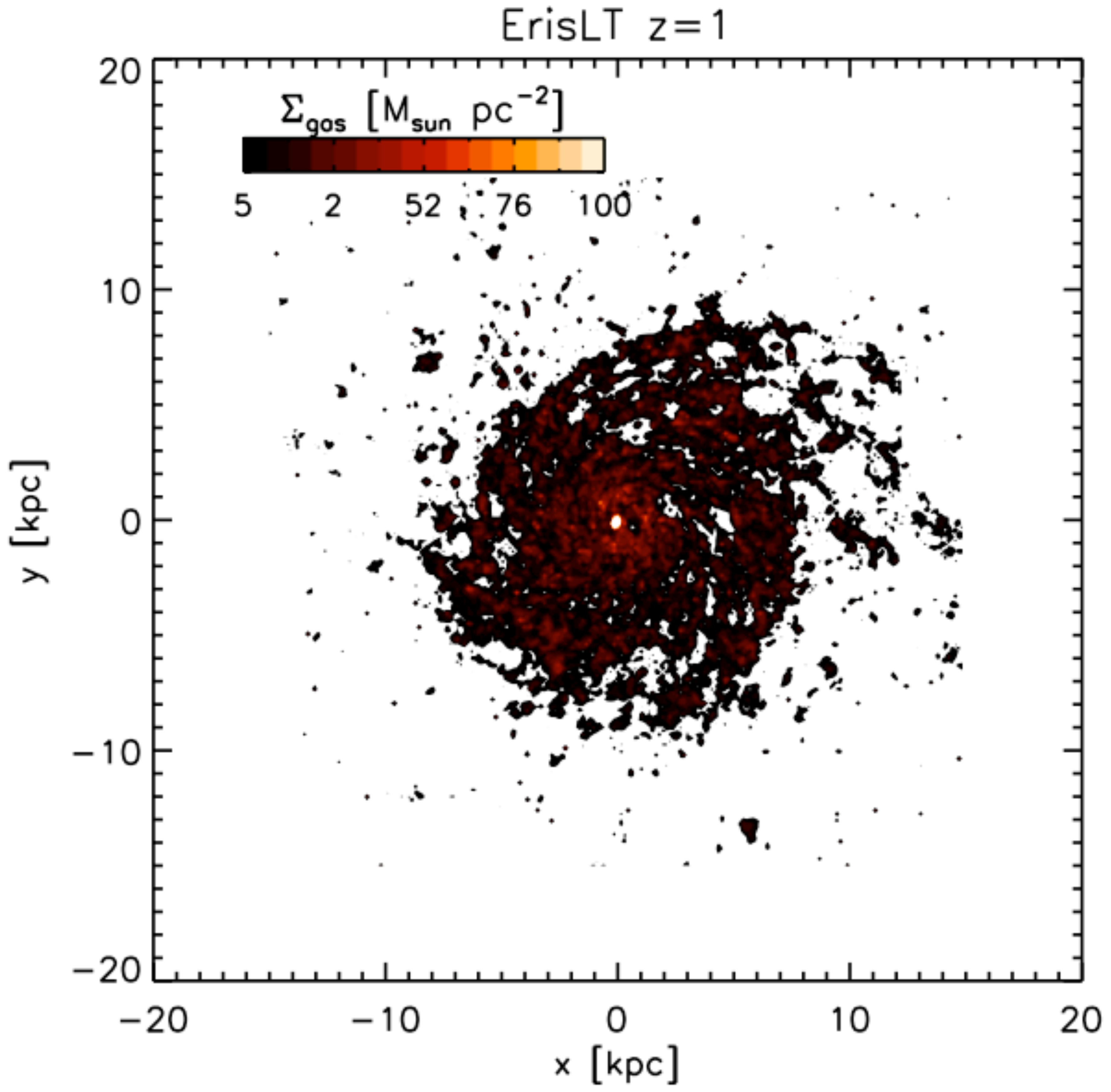
data from
Drory & Fisher 2007

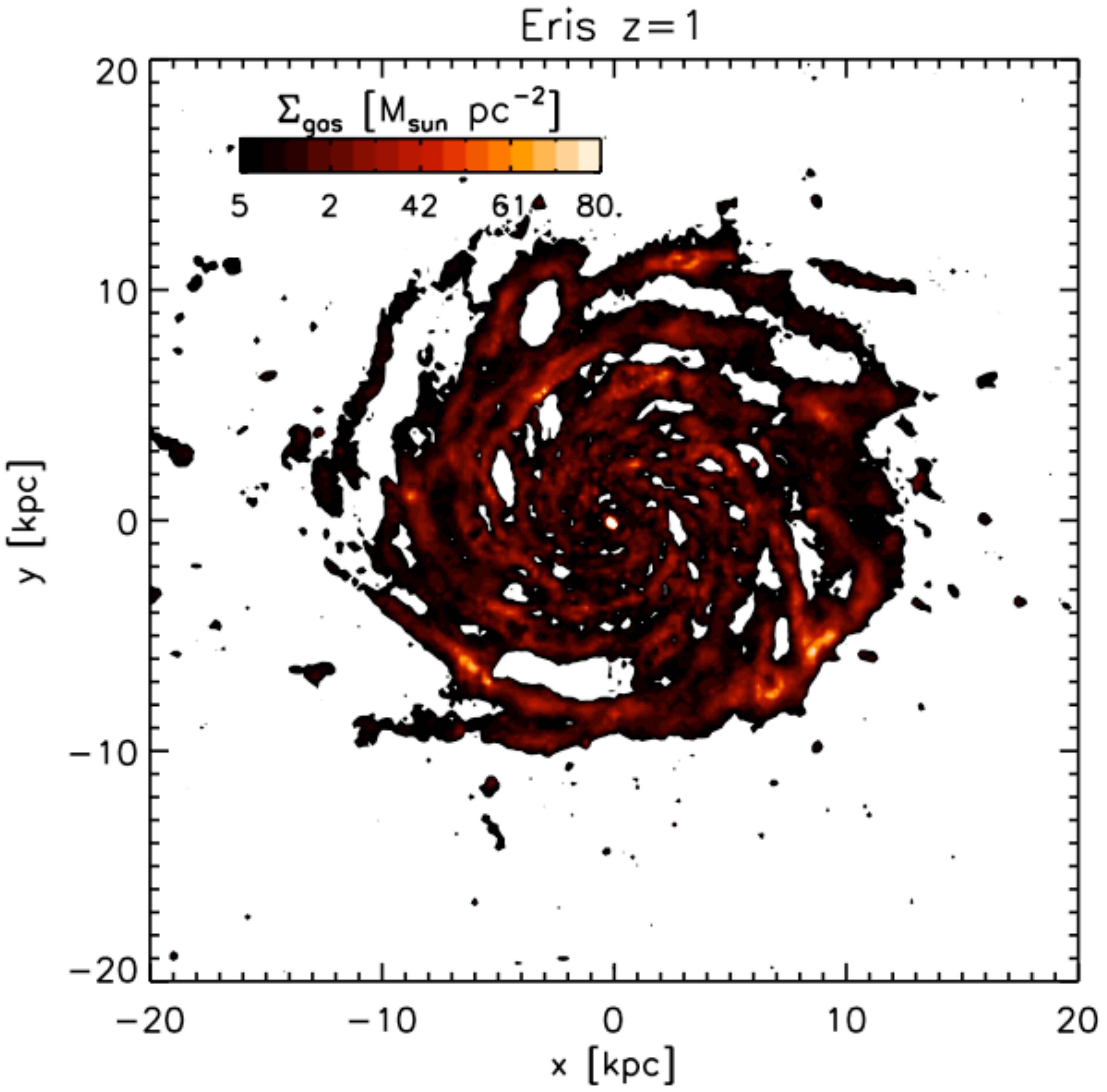
Low vs. high star formation threshold: effect on disk size/angular momentum

With higher threshold, Eris' disk at z=2 compared to ErisLT is:

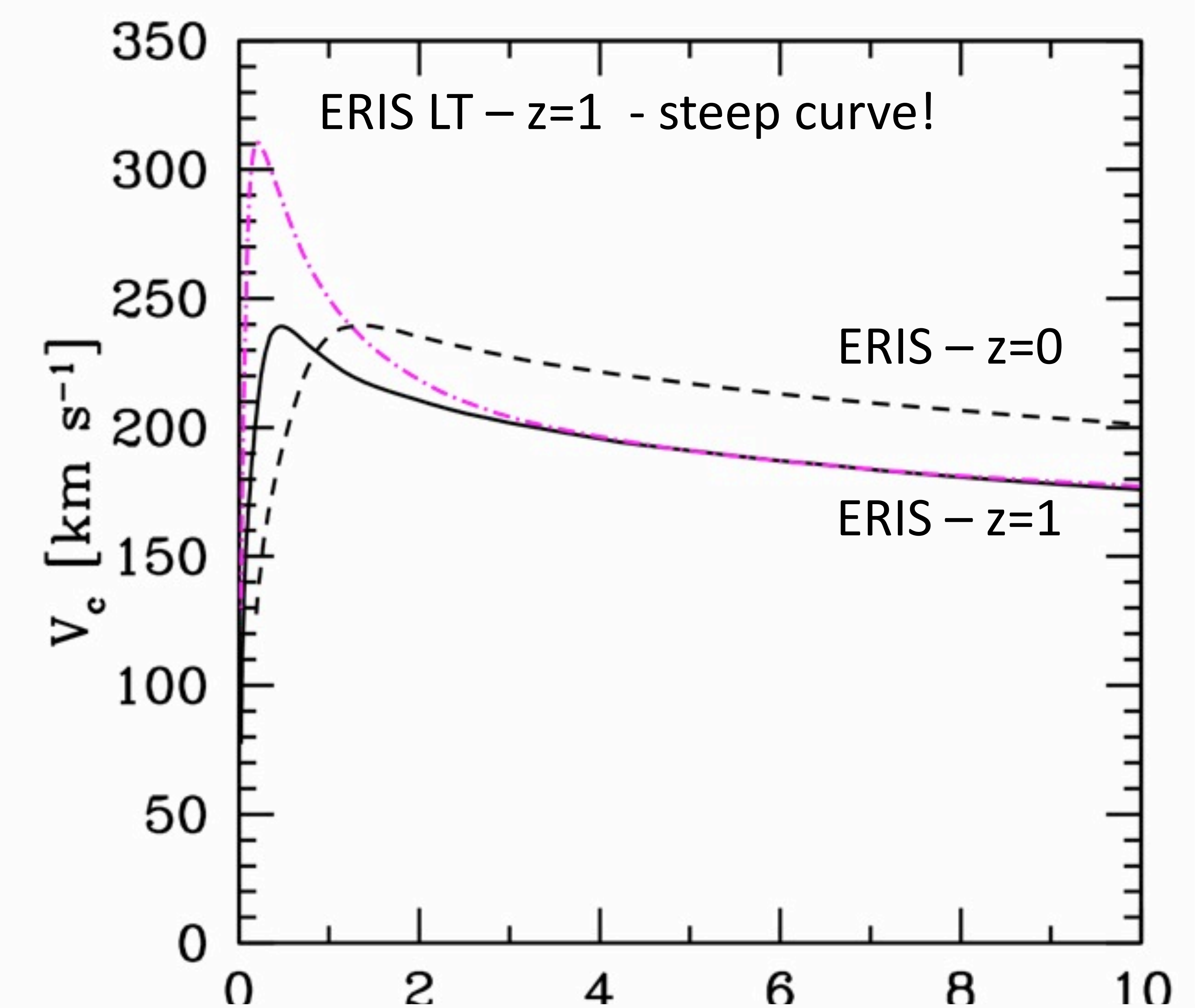
50% larger
30% less massive
30% higher gas fraction
5x lower density at r < 1 kpc

Difference is result of stronger effect of feedback in Eris vs. ErisLT (baryon fraction in Eris ~ 0.12 in Eris, 0.16 in ErisLT)





Circular velocity and stellar density profiles: Eris vs. ErisLT



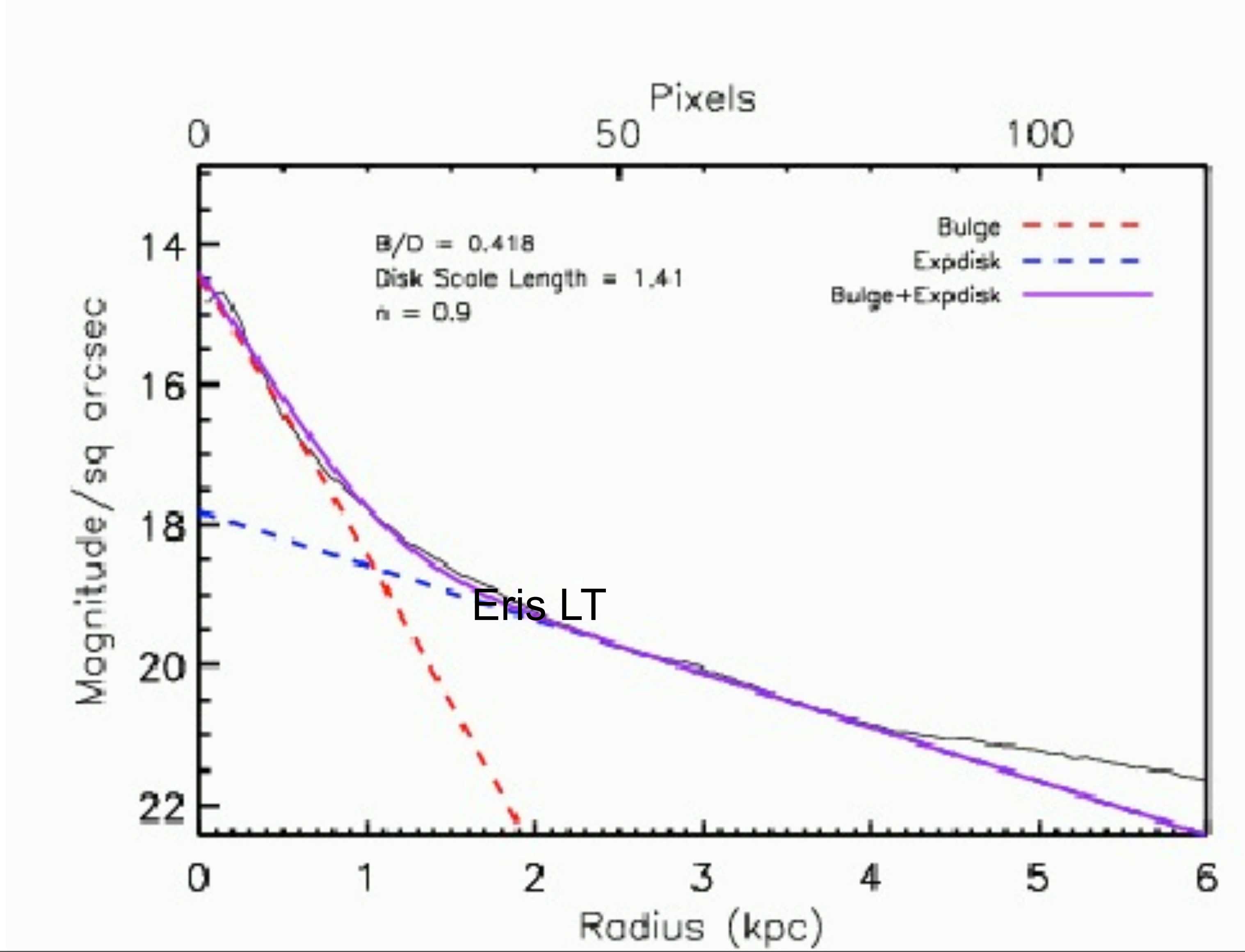
ERIS LT – z=1 - steep curve!

Stronger feedback w/ SF threshold

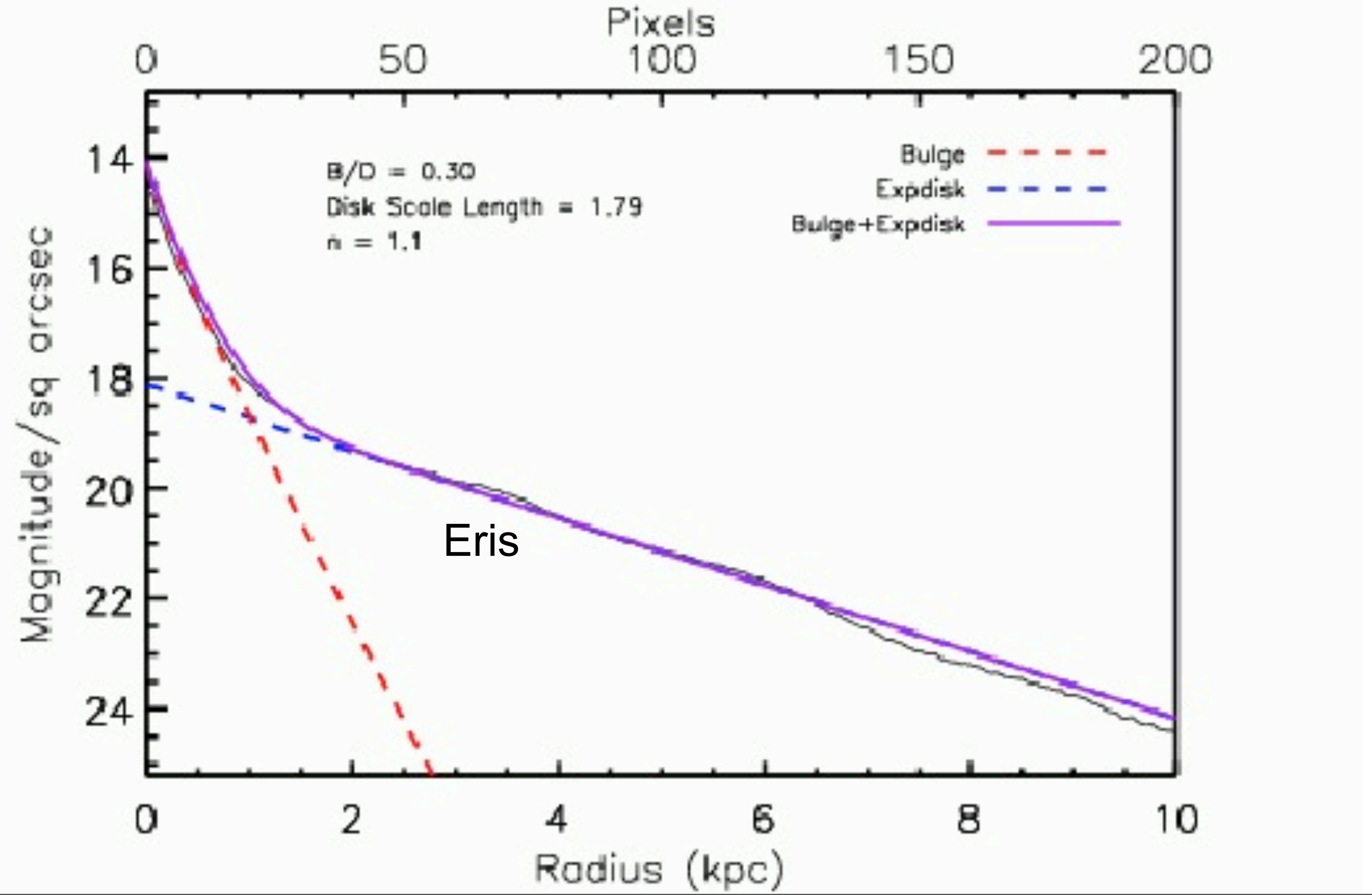
---> ejection of low angular momentum material

---> reduces contribution of inner bulge

Steeper rotation curves in ERIS LT run reflecs its higher B/D + more compact disk (runs compared at z=1)



Eris LT



Eris

The forming-too-many-stars-at-high-z catastrophe?

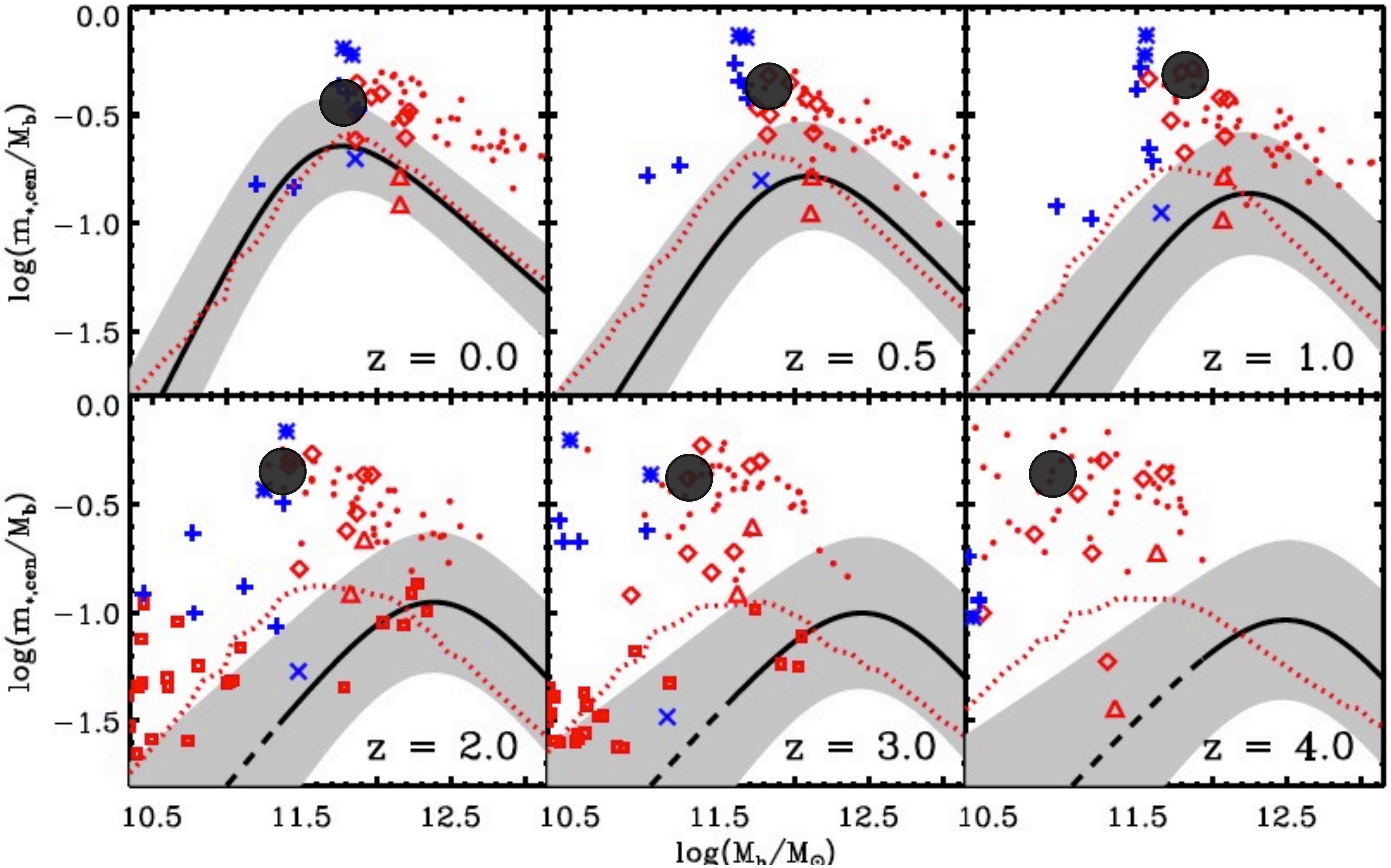


Figure 12. Comparison between central galaxy formation efficiencies found in numerical simulations at different redshifts. Each panel corresponds to the indicated redshift. The solid black lines give the average conversion efficiencies needed to fit the observed SMFs and the shaded areas indicate the 1σ confidence levels. The symbols show the results of hydrodynamical zoom-in simulations run with the GASOLINE code (blue asterisks: Brooks et al. 2011, pluses: Governato et al. 2012, crosses: Stinson et al. in prep.) and the GADGET code (red dots: Oser et al. 2010, diamonds: Scannapieco et al. 2011, squares: Genel et al. 2012, triangles: Okamoto 2012). The colored lines show the conversion efficiencies predicted by the semi-analytic model by Guo et al. (2011, red dotted line). While many simulations agree well with the predicted conversion efficiency at $z = 0$, most have too high values at earlier epochs, indicating that they form their stars too early.

Abundance matching curves from Moster et al. 2012

Important caveat: the Eris runs did not take into account metal line cooling for gas at $T > 10^4$ K

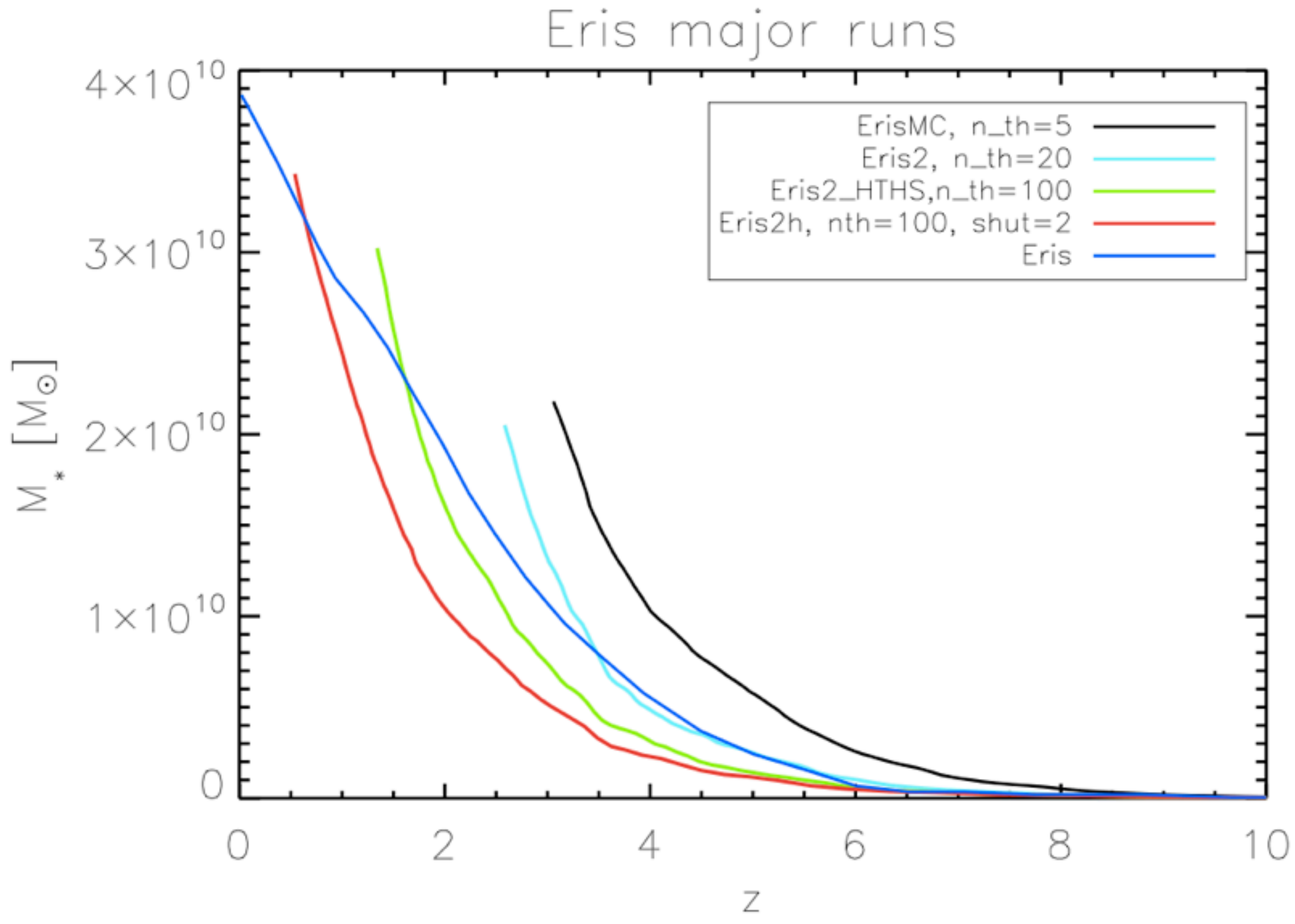
Galaxies with virial masses below 10^{12} Mo assemble primarily via cold mode accretion (Tgas <~ 10^4 K) (Keres et al. 2003; Dekel & Birnboim 2003;Brooks et al. 2008)

However supernovae ejecta are more metal rich than bulk of ISM and have T >~ 10^5 K...

Important caveat: the Eris runs did not take into account metal line cooling for gas at T > 10^4 K

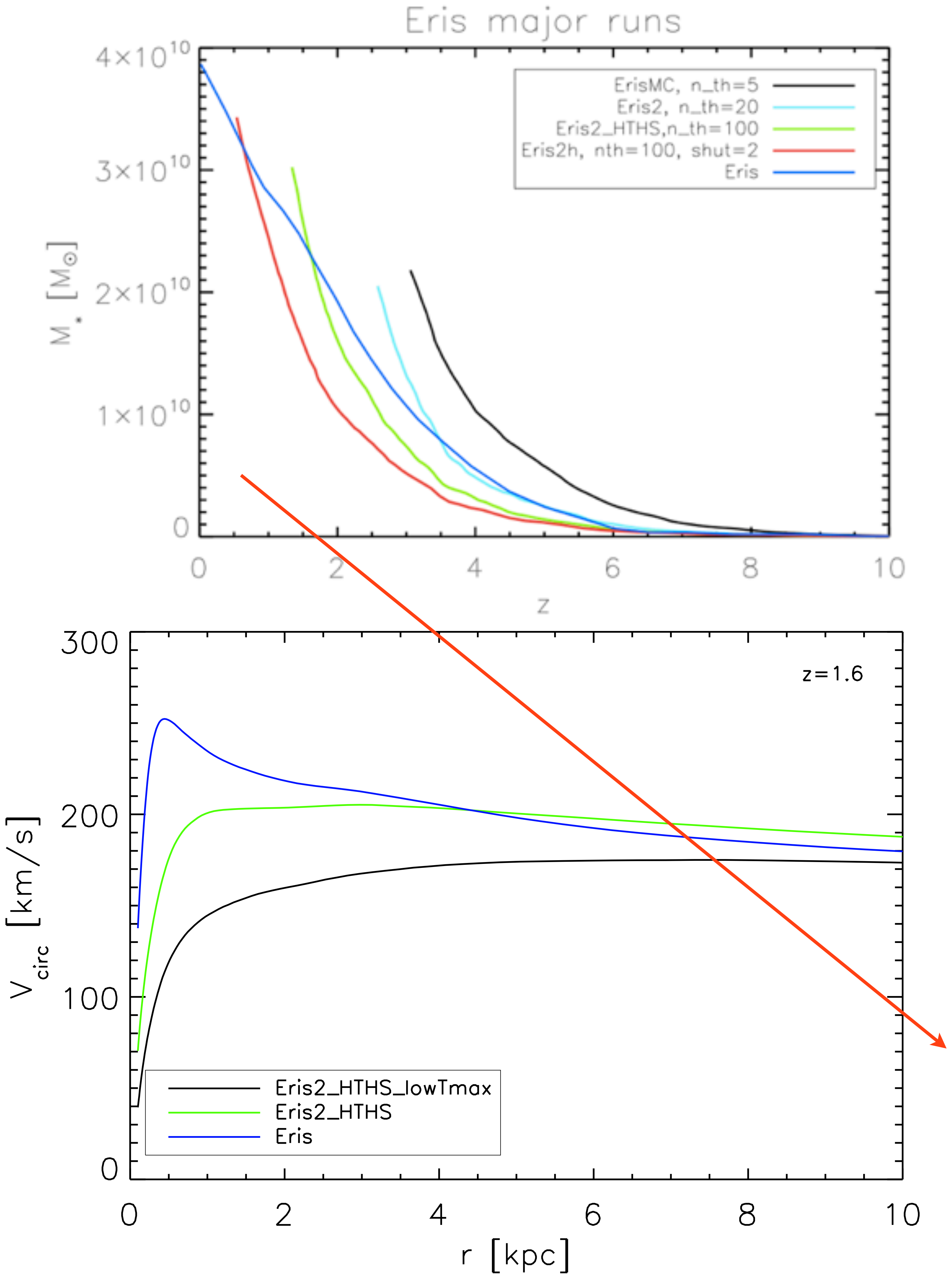
Galaxies w ia cold mode

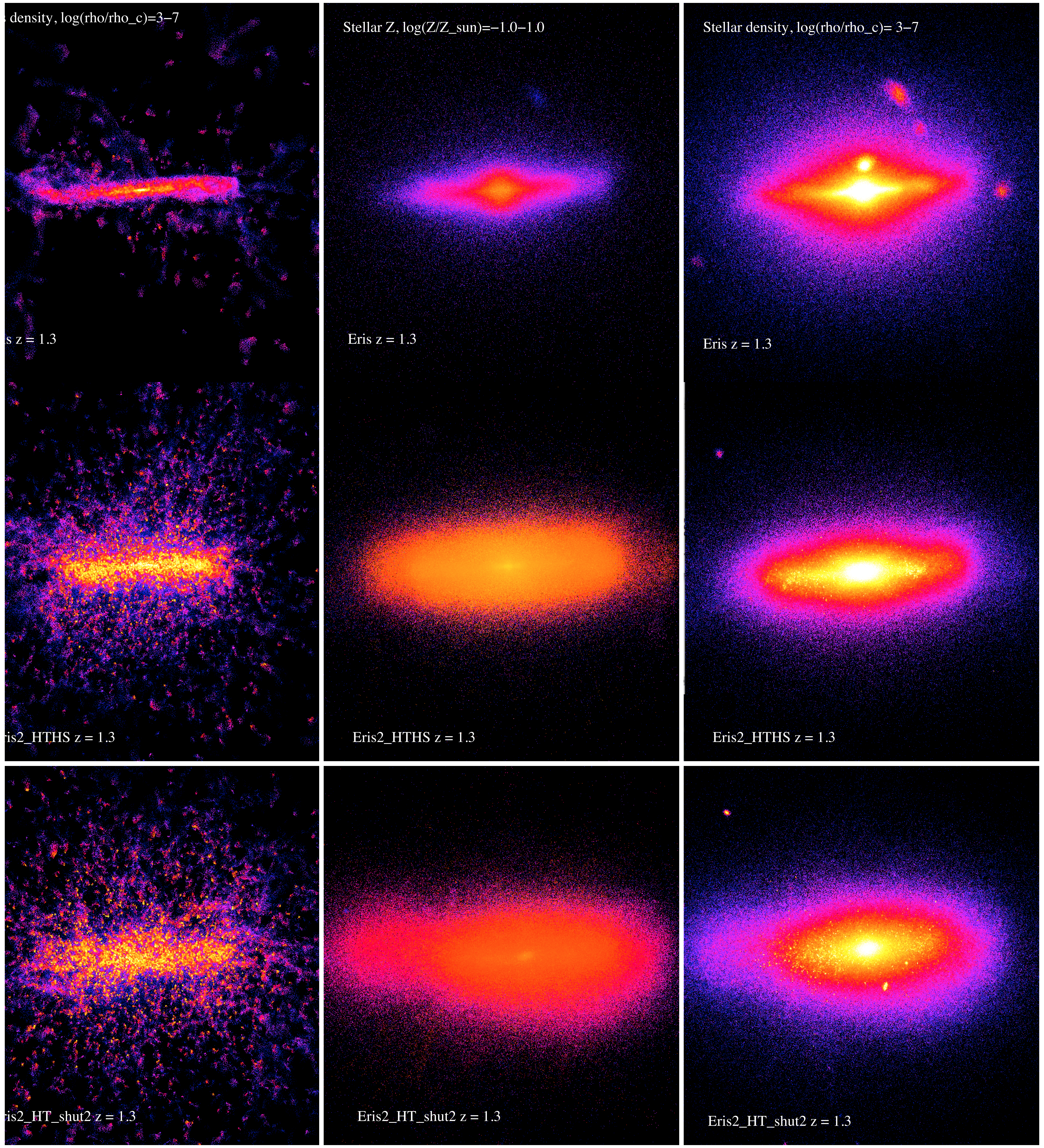
accretion (T 2003;Brooks et



The new Eris2 simulations (Shen et al. in prep)

Exploration of sub-grid models: SF density threshold (20-100 atoms/cc) + high T metal line cooling, new Haardt & Madau (2013) cosmic ionizing background, Chabrier IMF, varying feedback efficiency, modified SPH with thermal energy and metal diffusion term, (Shen et al. 2010), non-thermal pressure to mimic sub-grid turbulence





Lesson from Eris2 runs

Stronger feedback(s) allows to match M^*-M_{halo} at but precludes formation of realistic kinematically cold, thin disk component.

Same conclusion also reached by Roskar, Teyssier et al. (2013) with AMR simulations using the RAMSES code.

Hence current biggest challenge in disk galaxy formation:

Reproduce stellar masses AND SIMULTANEOUSLY thin kinematically cold stellar/gaseous disk

Should be achieved by maintaining a larger fraction of the disk gas in a warm, non-star forming phase BUT without stirring/pressurizing the whole ISM!

A case study of a massive galaxy

Argo Simulation

Feldmann & Mayer 2014; Fiacconi, Feldmann & Mayer, in prep..

Goals:

- study the formation/evolution of z≥2 galaxies with high fidelity and address critically the role of feedback(s)
- study a massive high z galaxy

A case study of a massive galaxy

Argo Simulation

Feldmann & Mayer 2014; Fiacconi, Feldmann & Mayer, in prep..

Goals:

- study the formation/evolution of z≥2 galaxies with high fidelity and address critically the role of feedback(s)
- study a massive high z galaxy

Details:

- cosmological zoom-in simulation
- halo mass ~ 2 x 10^{13} $M_\odot$ at z=0 (~ M*), average density environment and merging history
- 3 different resolutions;
  HR: Δx ~100 pc, m_{SPH} ~10^4 $M_\odot$; **MR, LR with 8, 16 times less resolution**
- efficient SN feedback, **no AGN** feedback (heretic approach?)

A case study of a massive galaxy

Argo Simulation

Feldmann & Mayer 2014; Fiacconi, Feldmann & Mayer, in prep..

Goals:

- study the formation/evolution of z≥2 galaxies with high fidelity and address critically the role of feedback(s)
- study a massive high z galaxy

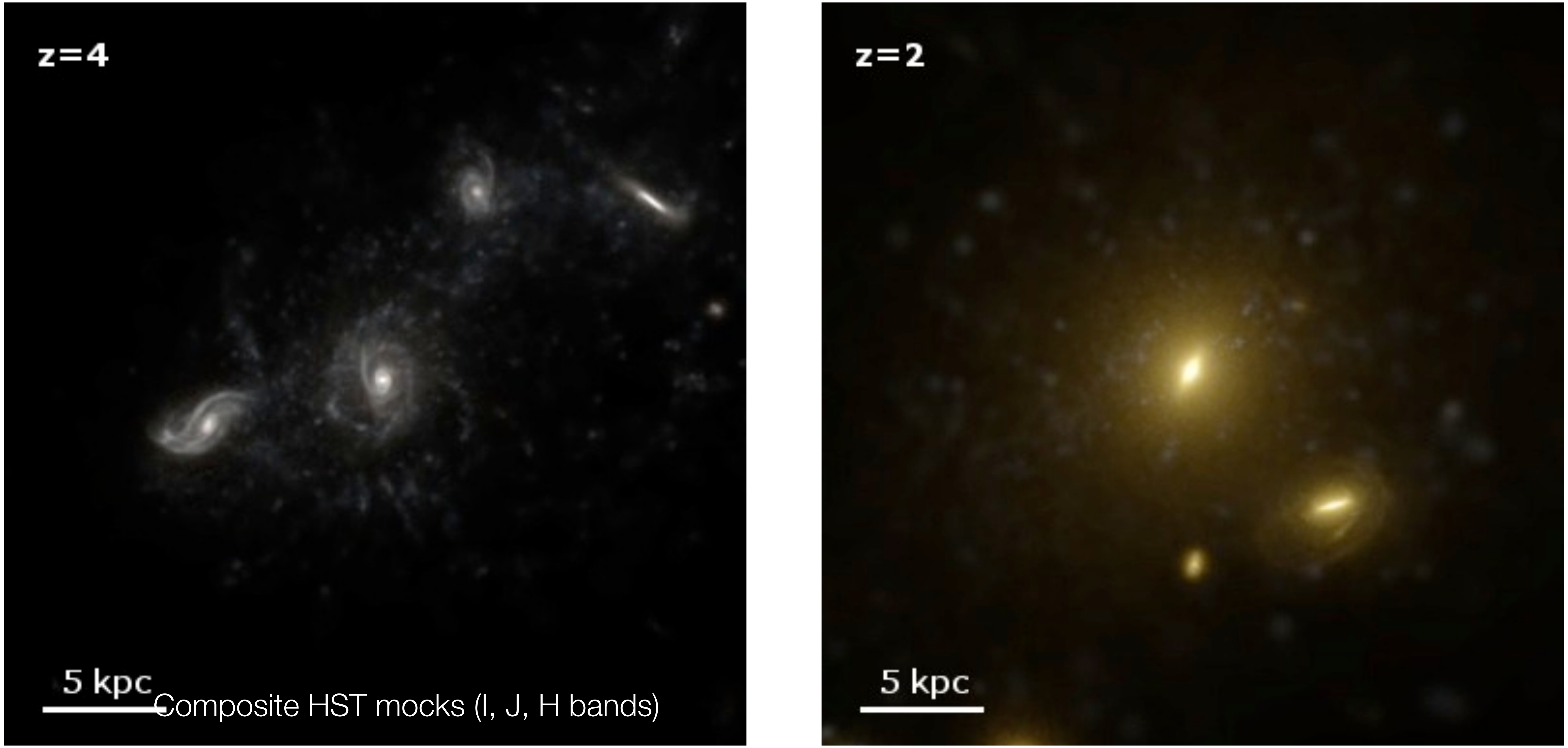
Details:

- cosmological zoom-in simulation
- halo mass ~ 2 x 10^{13} M⊙ at z=0 (~ M*), average density environment and merging history
- 3 different resolutions;
  HR: Δx ~100 pc, m_{SPH} ~10^4 M⊙; **MR, LR with 8, 16 times less resolution**
- efficient SN feedback, **no AGN** feedback (heretic approach?)

- same radiative cooling, star formation, feedback model, resolution as
  - "seven dwarfs" (Shen+13) (dwarf galaxies)
  - "Eris" (Guedes+11) (MW-like galaxy)

A case study of a massive galaxy

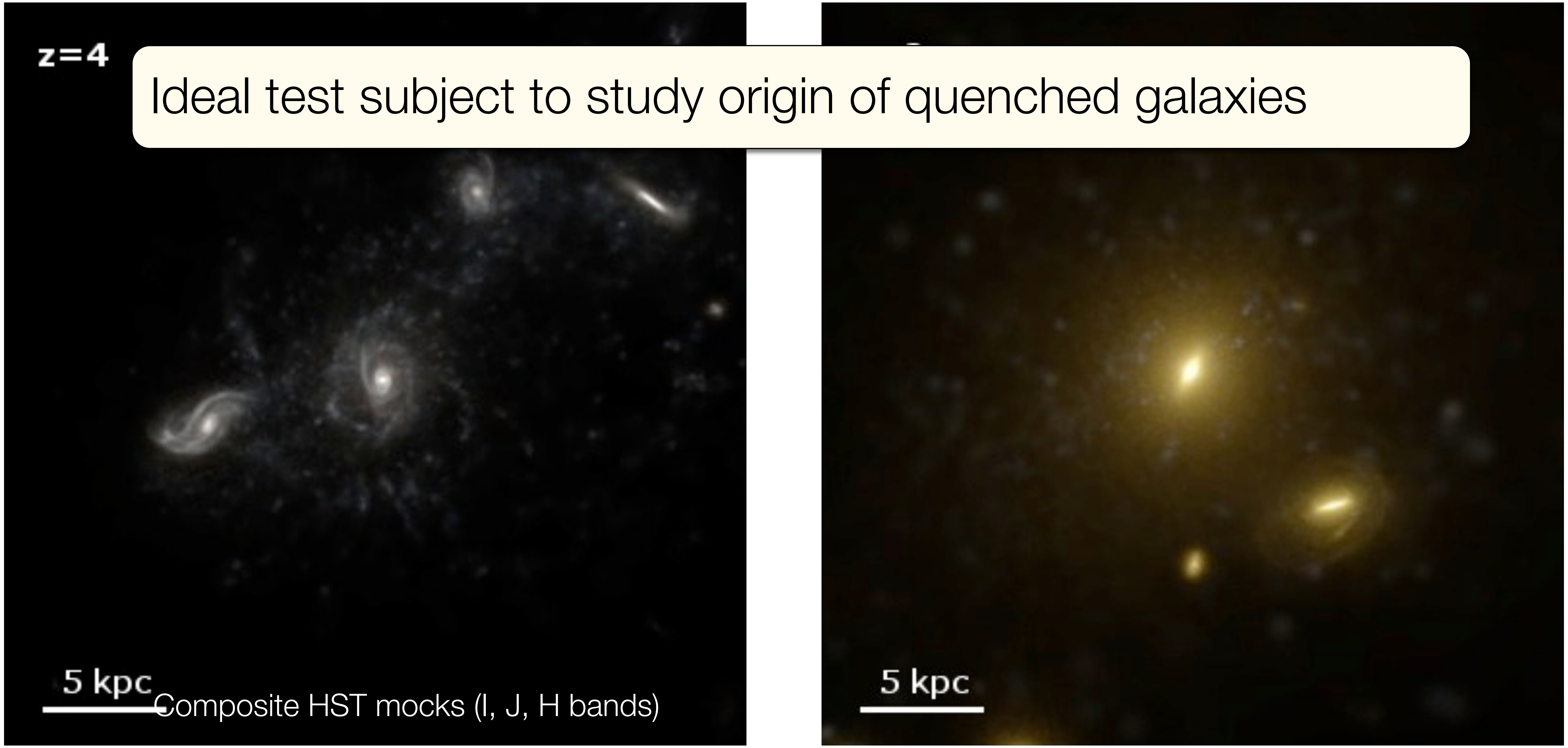
- at z~4 compact, blue, disk galaxy
- at z~2 massive, red, quiescent galaxy
- at z = 0 companion low-res simulations (Feldmann et al. 2010) produce massive gas-poor early type galaxy, $M^* \sim 2 \times 10^{11}$ Mo)



Composite HST mocks (I, J, H bands)

A case study of a massive galaxy

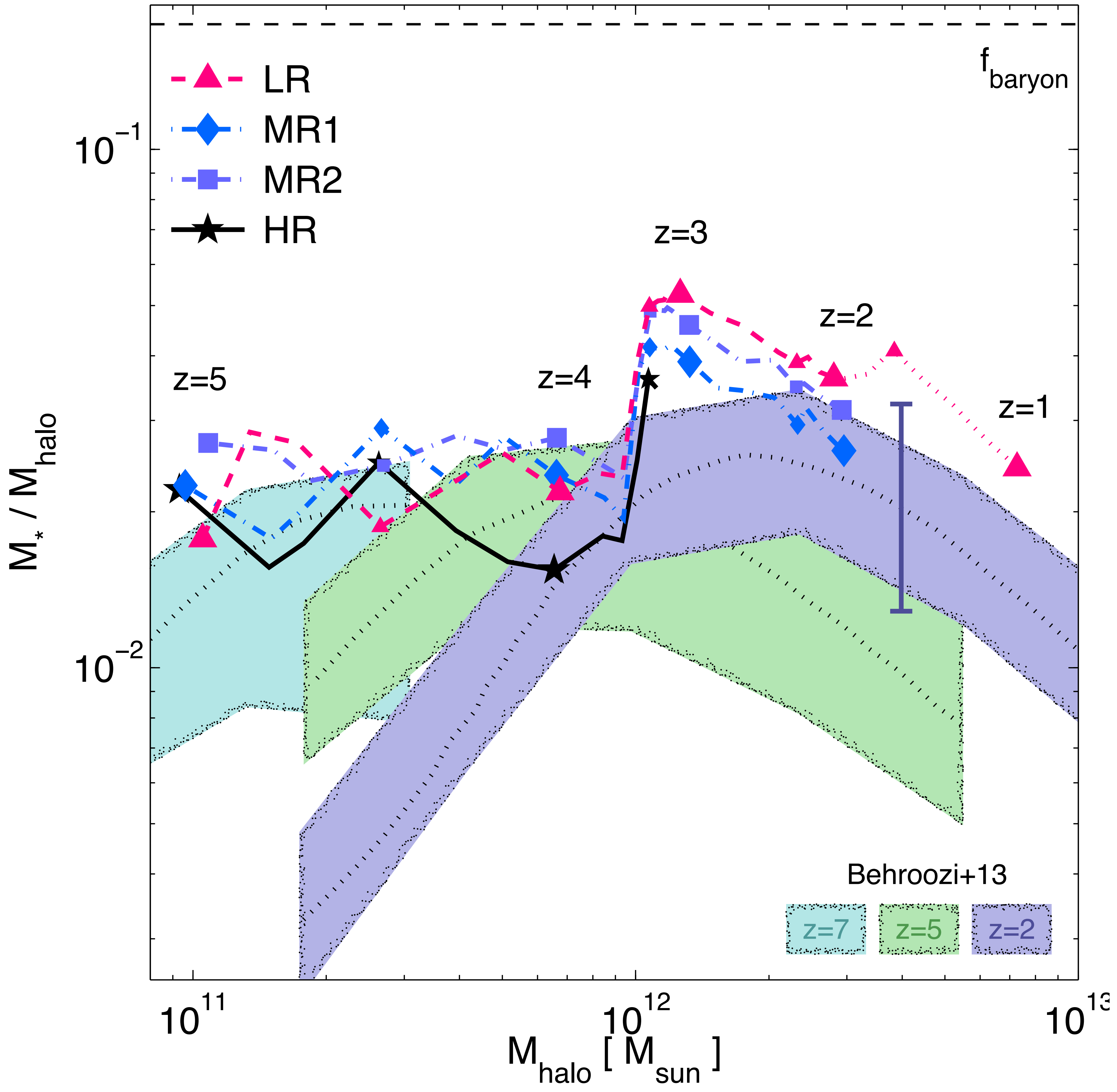
- at z~4 compact, blue, disk galaxy
- at z~2 massive, red, quiescent galaxy
- at z = 0 companion low-res simulations (Feldmann et al. 2010) produce massive gas-poor early type galaxy, M*~ 2 x 10^{11} Mo)

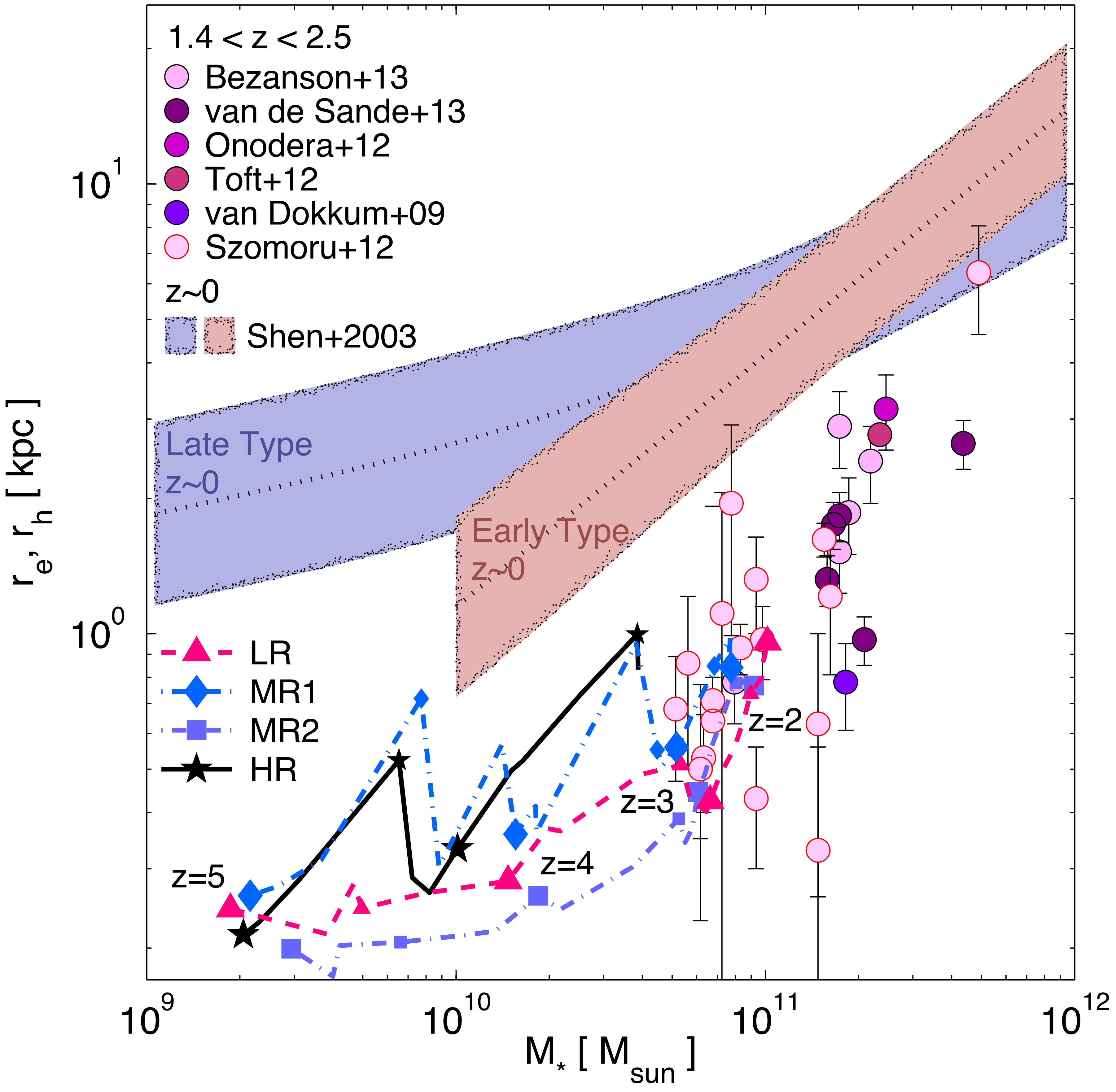


Ideal test subject to study origin of quenched galaxies

Composite HST mocks (I, J, H bands)

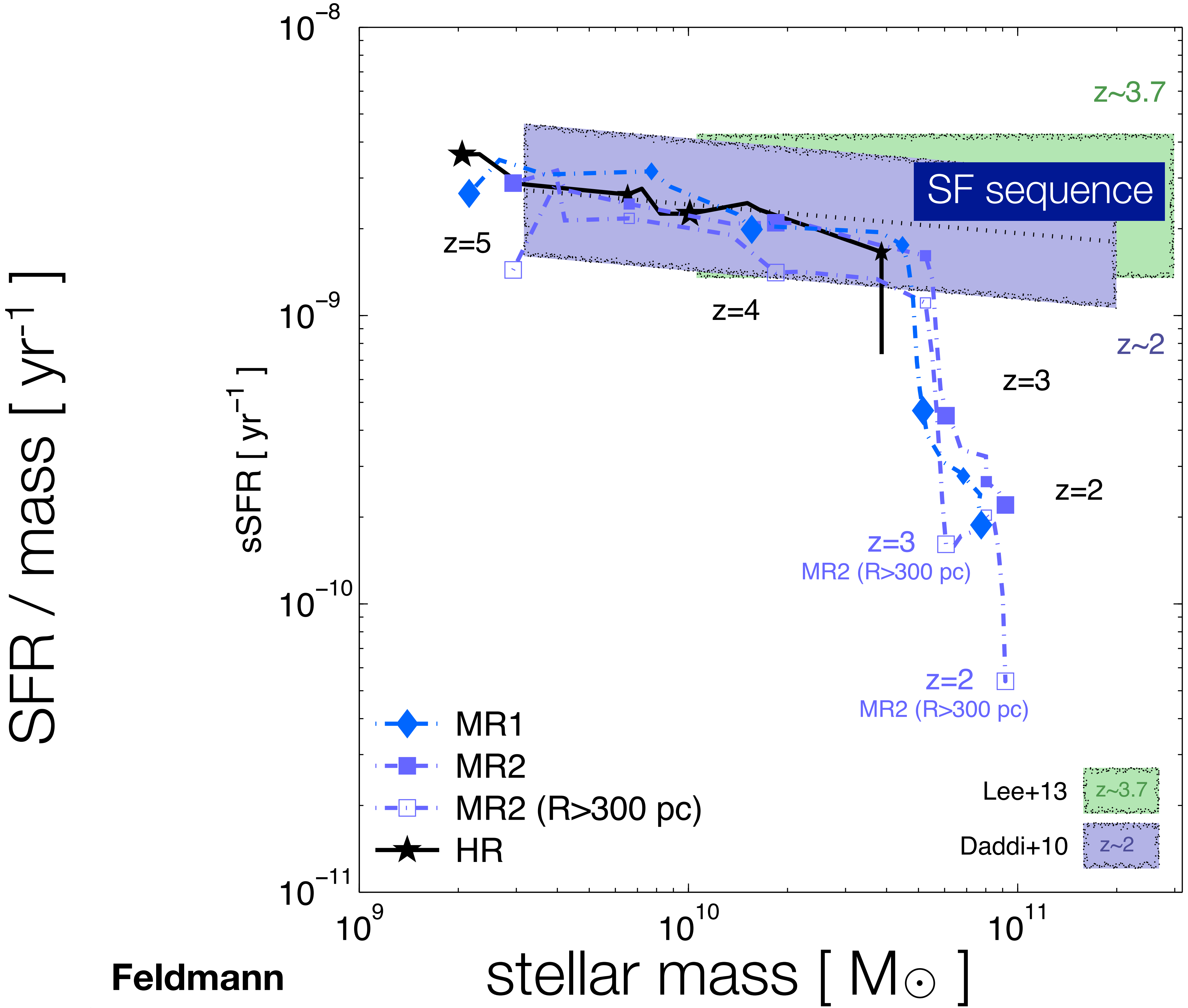
Global galaxy properties agree with observations





- stellar mass to virial mass ratio in agreement with abundance matching at z≤4
- stellar fraction ~ constant, slight increase (x2) during mergers
- size ~ 1 kpc at z~2; consistent with sizes of massive, quiescent galaxies

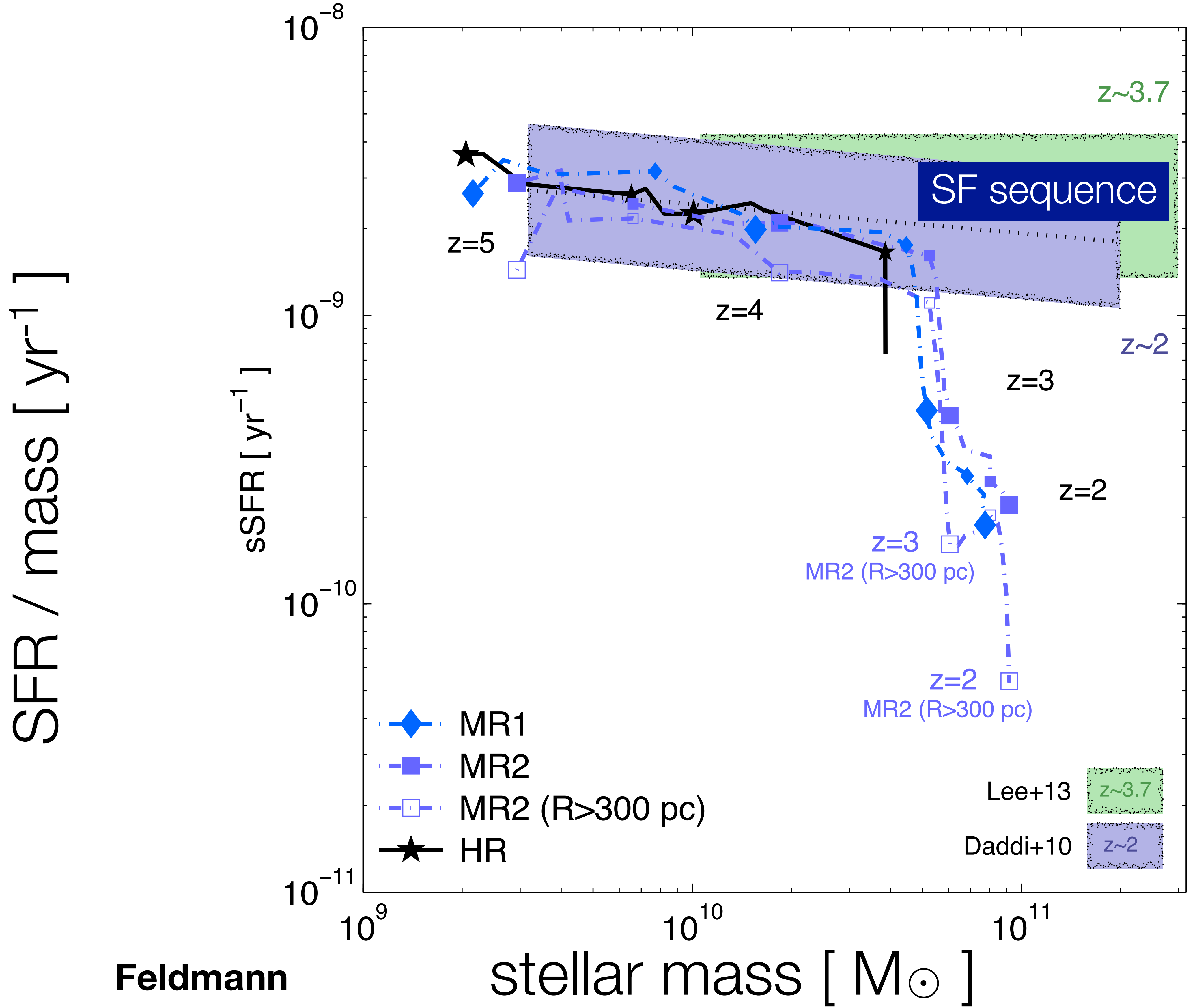
A case study of a massive galaxy

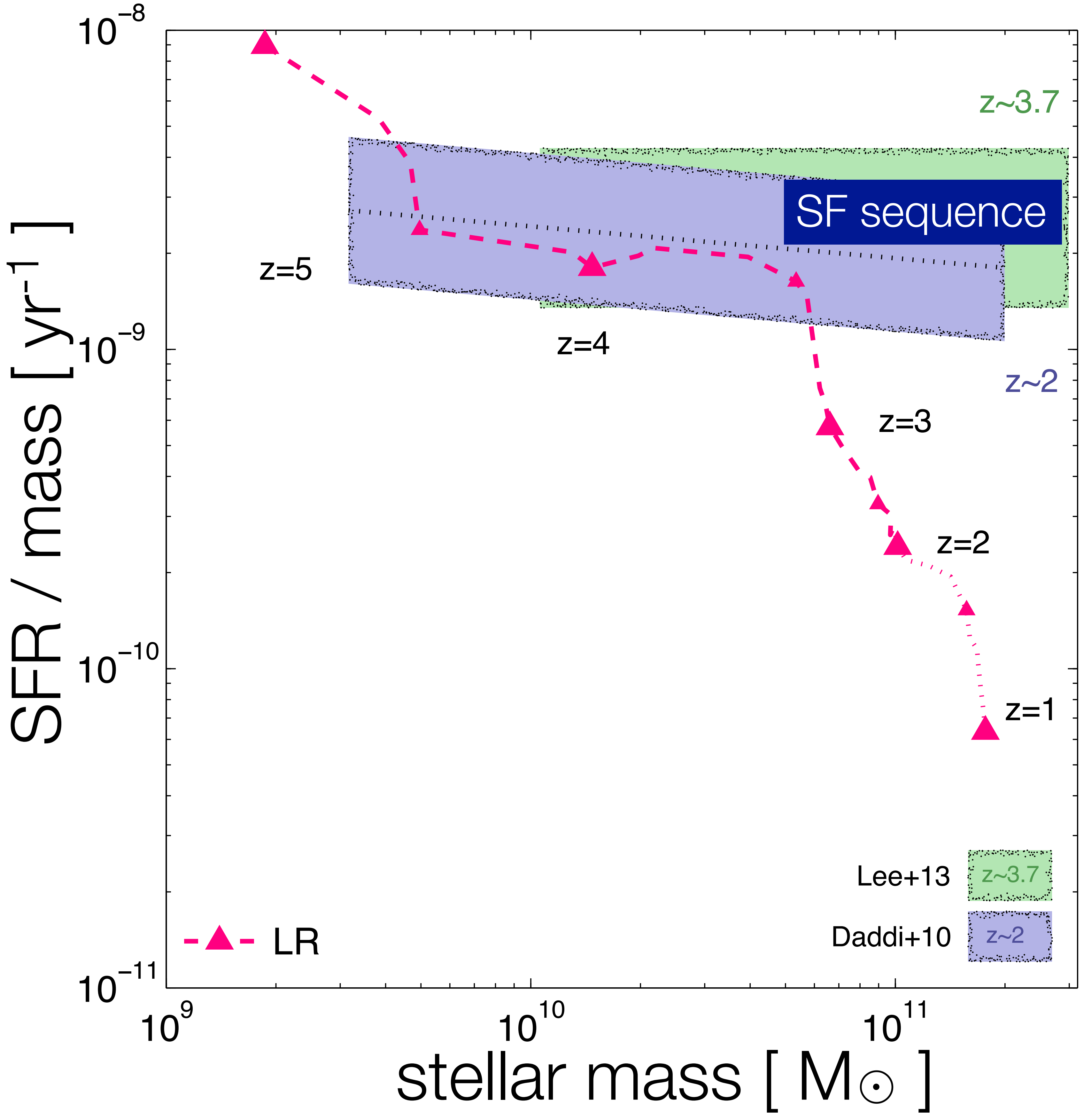


Feldmann & Mayer 2014

- on star formation sequence at z>3.5
- drops off the SF sequence at z~3.5
- early quenching prompted by observations at z ~ 2-2.5 (Brammer et al. 2011)

A case study of a massive galaxy

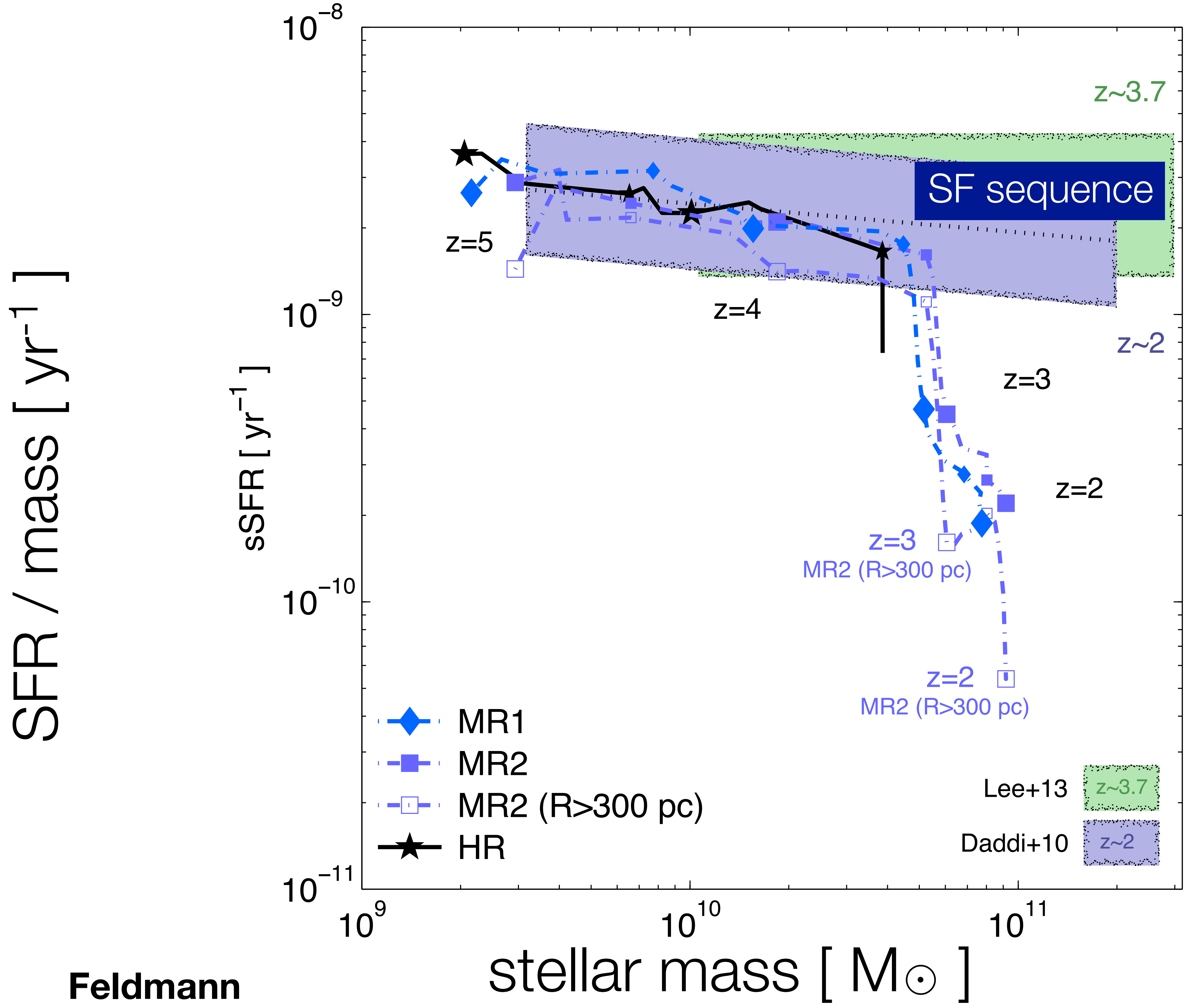




Feldmann & Mayer 2014

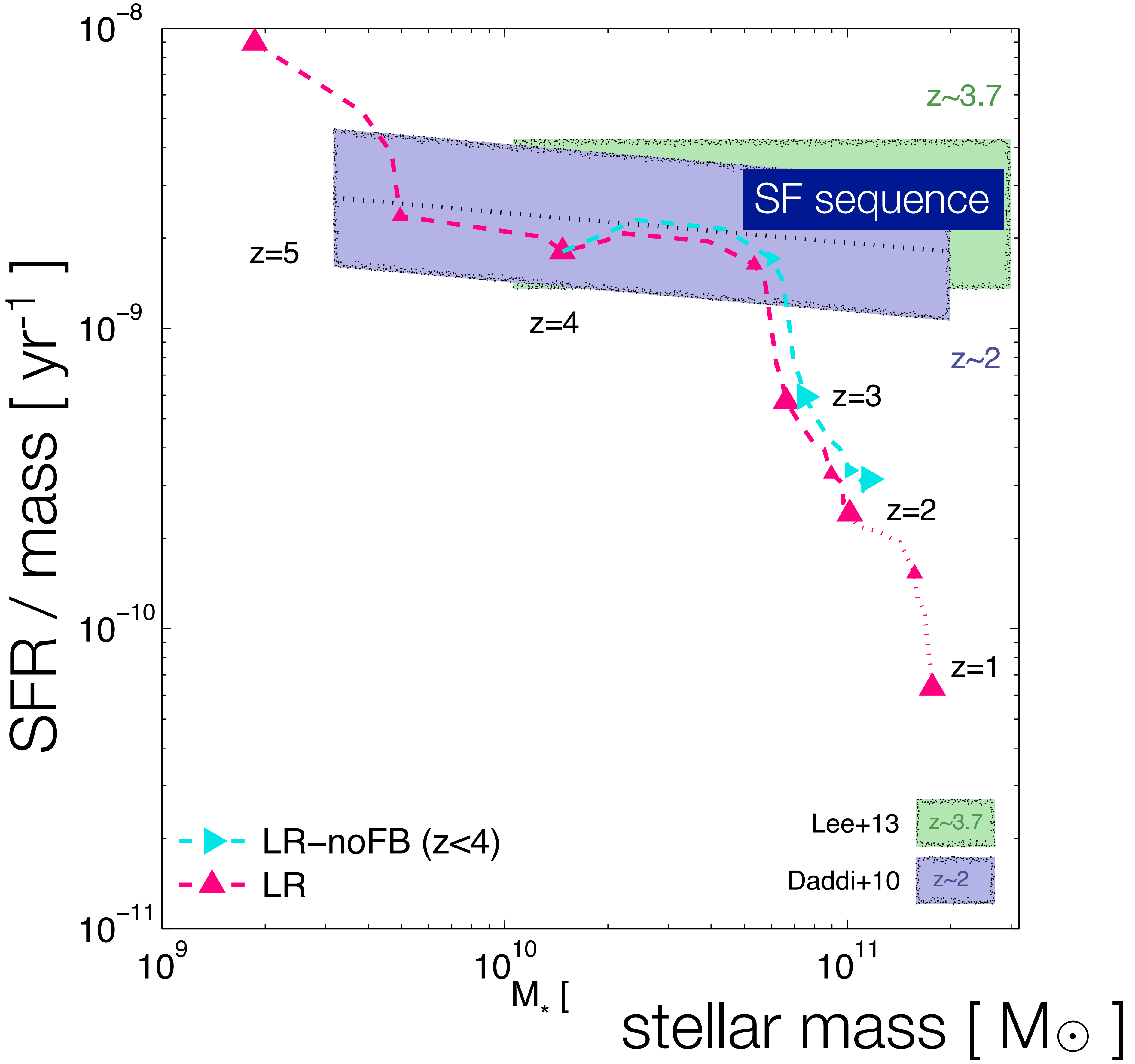
- on star formation sequence at z>3.5
- drops off the SF sequence at z~3.5
- early quenching prompted by observations at z ~ 2-2.5 (Brammer et al. 2011)

A case study of a massive galaxy



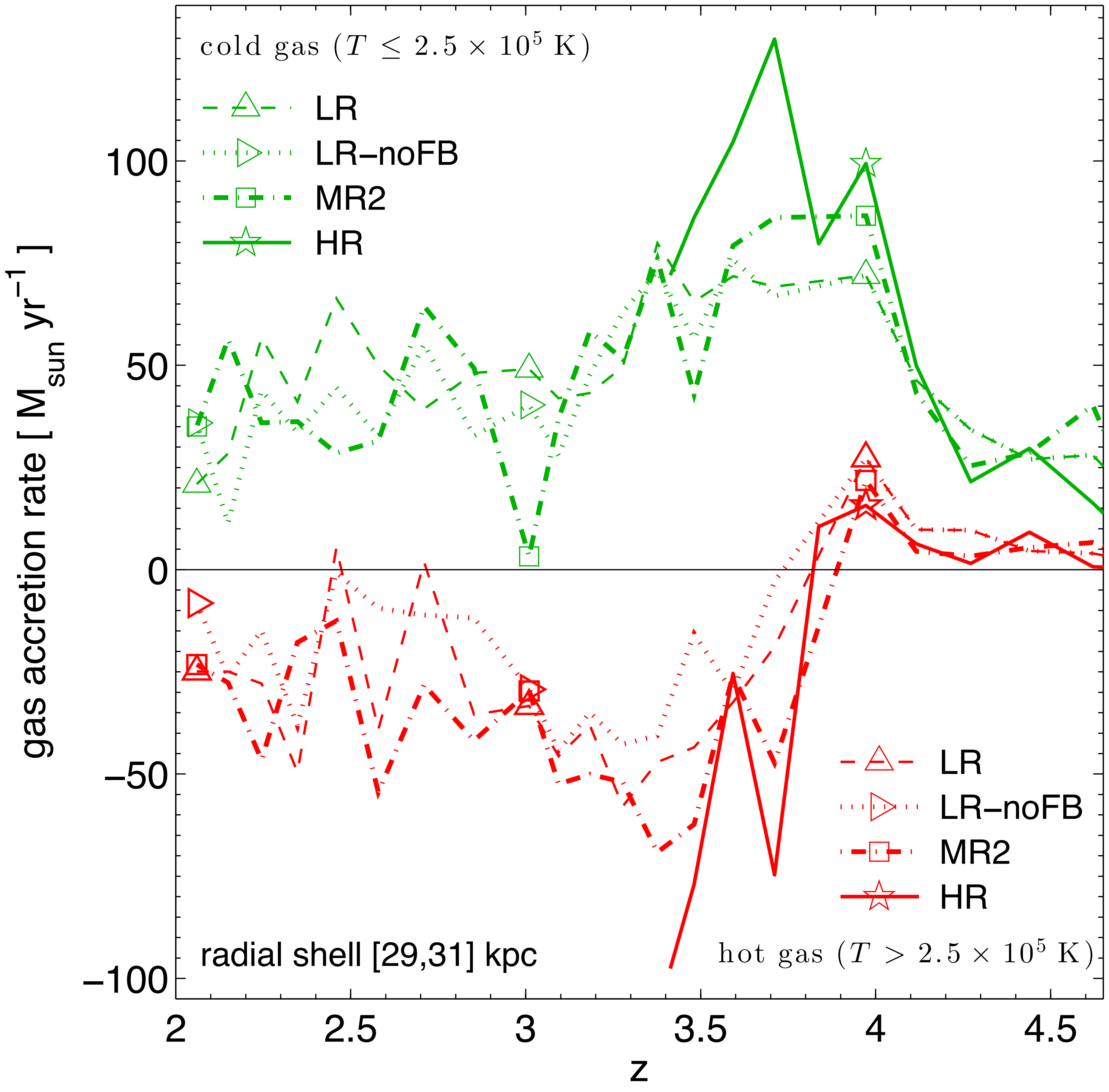
Feldmann & Mayer 2014

- on star formation sequence at z>3.5
- drops off the SF sequence at z~3.5



- the initial drop not caused by FB
- FB necessary to:
  - reduce SF to less than ~ few M☉ yr^{-1}
  - suppress SF in central few 100 pc

Inflow vs Outflow



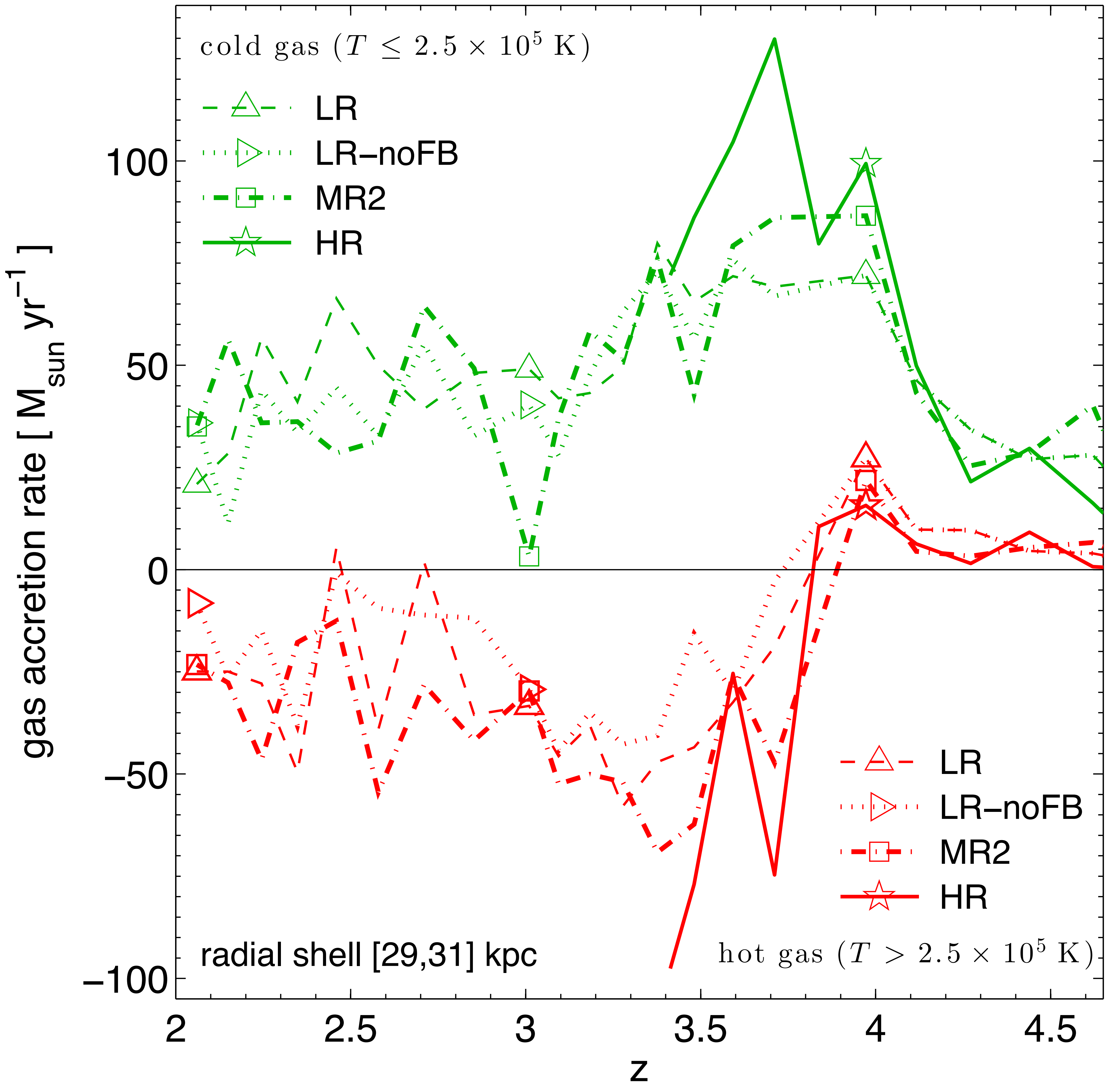
- SF at z>3.5 sustained by accretion of cold (≲ 10^5 K) gas
- at later times: cold gas accretion rate and hot gas expansion rate ~ balanced

- inflow / outflow

  of cold gas offset w.r.t. SFR (~100 Myr)

  of hot gas not offset w.r.t. SFR

Inflow vs Outflow

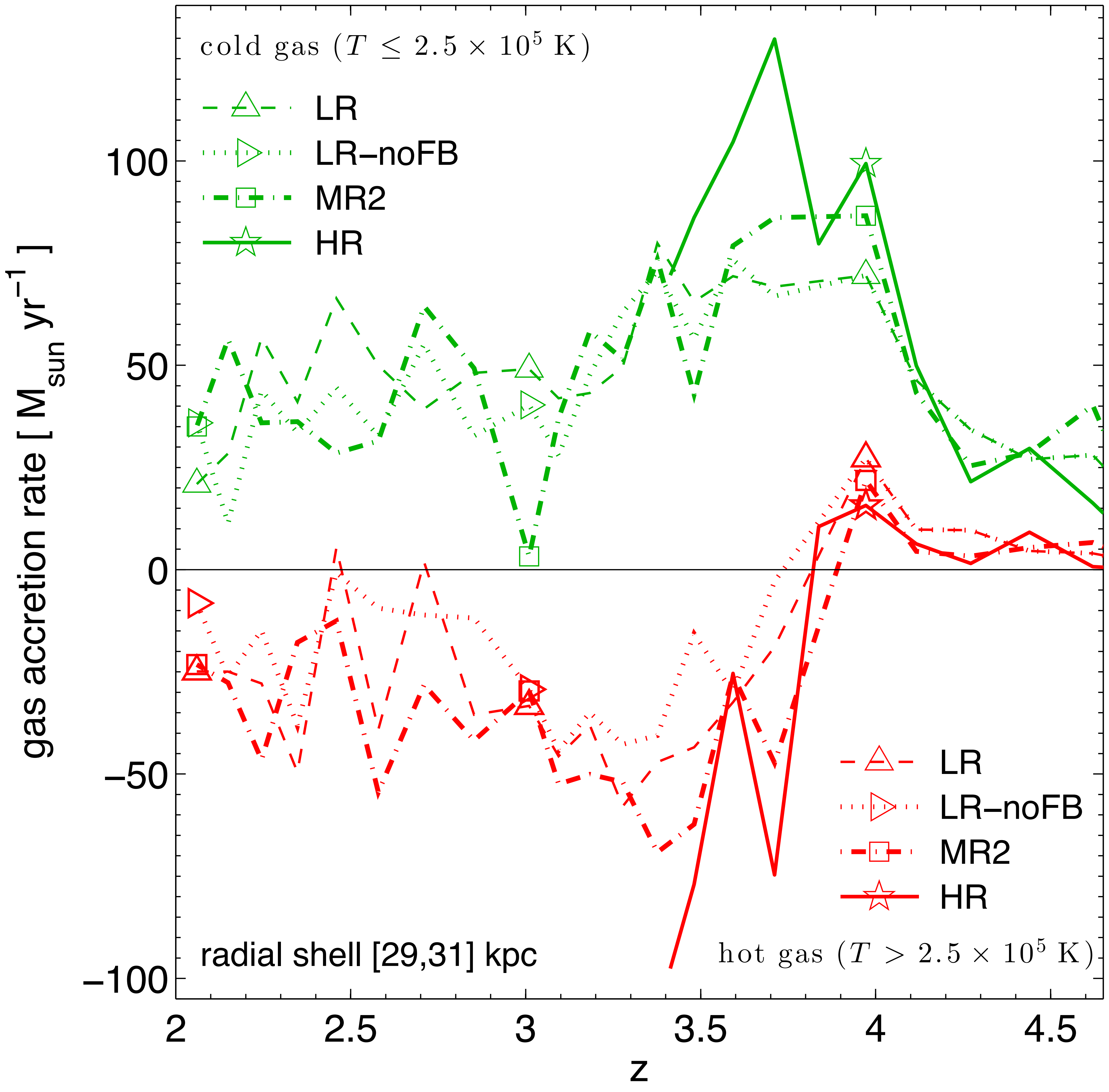


- SF at z>3.5 sustained by accretion of cold (≲ 10^5 K) gas
- at later times: cold gas accretion rate and hot gas expansion rate ~ balanced

- inflow / outflow
  of cold gas offset w.r.t. SFR (~100 Myr)
  of hot gas not offset w.r.t. SFR

SF shuts down after cold gas accretion decreases

Inflow vs Outflow



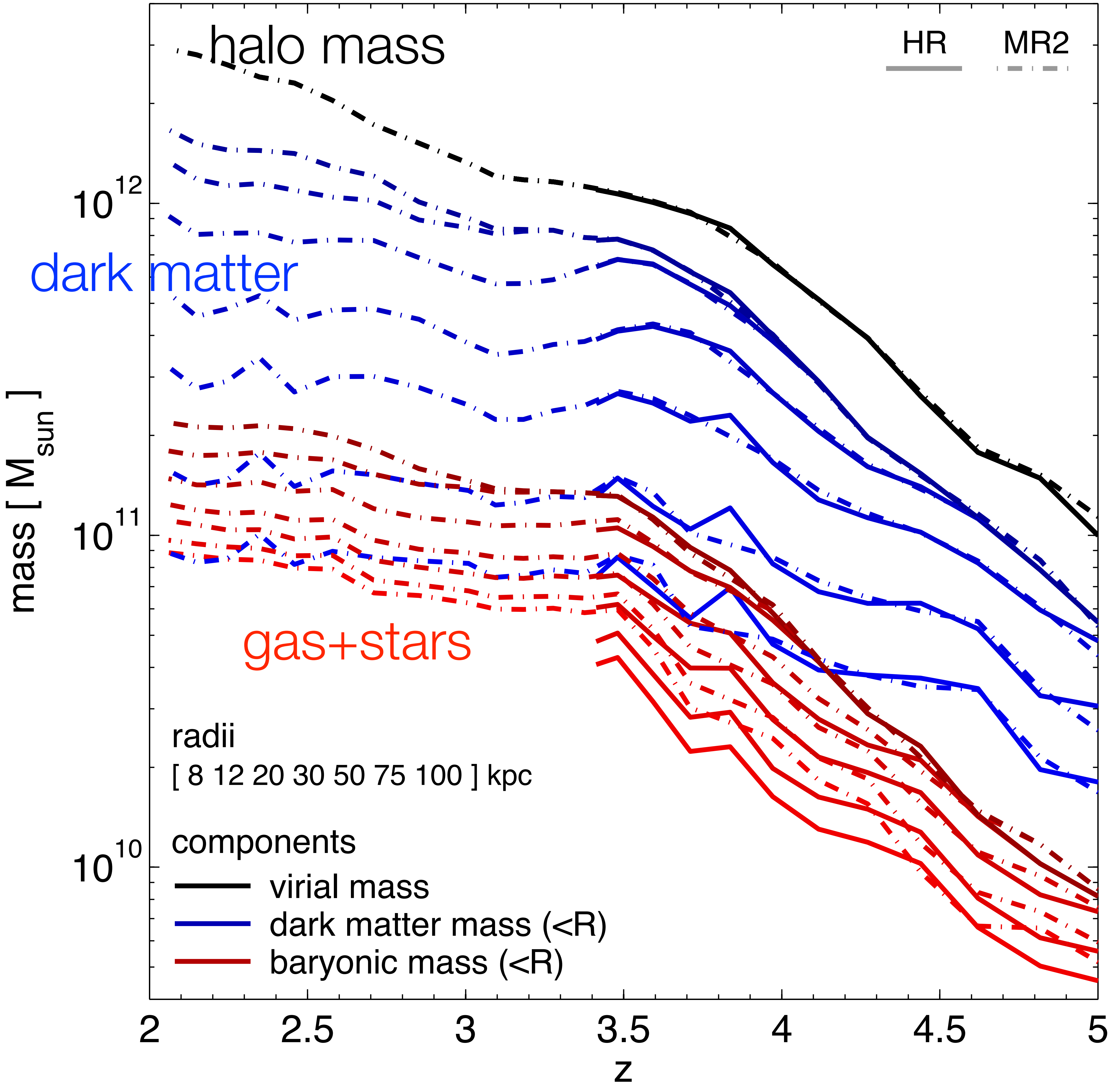
- SF at z>3.5 sustained by accretion of cold (≲ 10^5 K) gas
- at later times: cold gas accretion rate and hot gas expansion rate ~ balanced

- inflow / outflow
  of cold gas offset w.r.t. SFR (~100 Myr)
  of hot gas not offset w.r.t. SFR

SF shuts down after cold gas accretion decreases

What reduces the gas accretion?

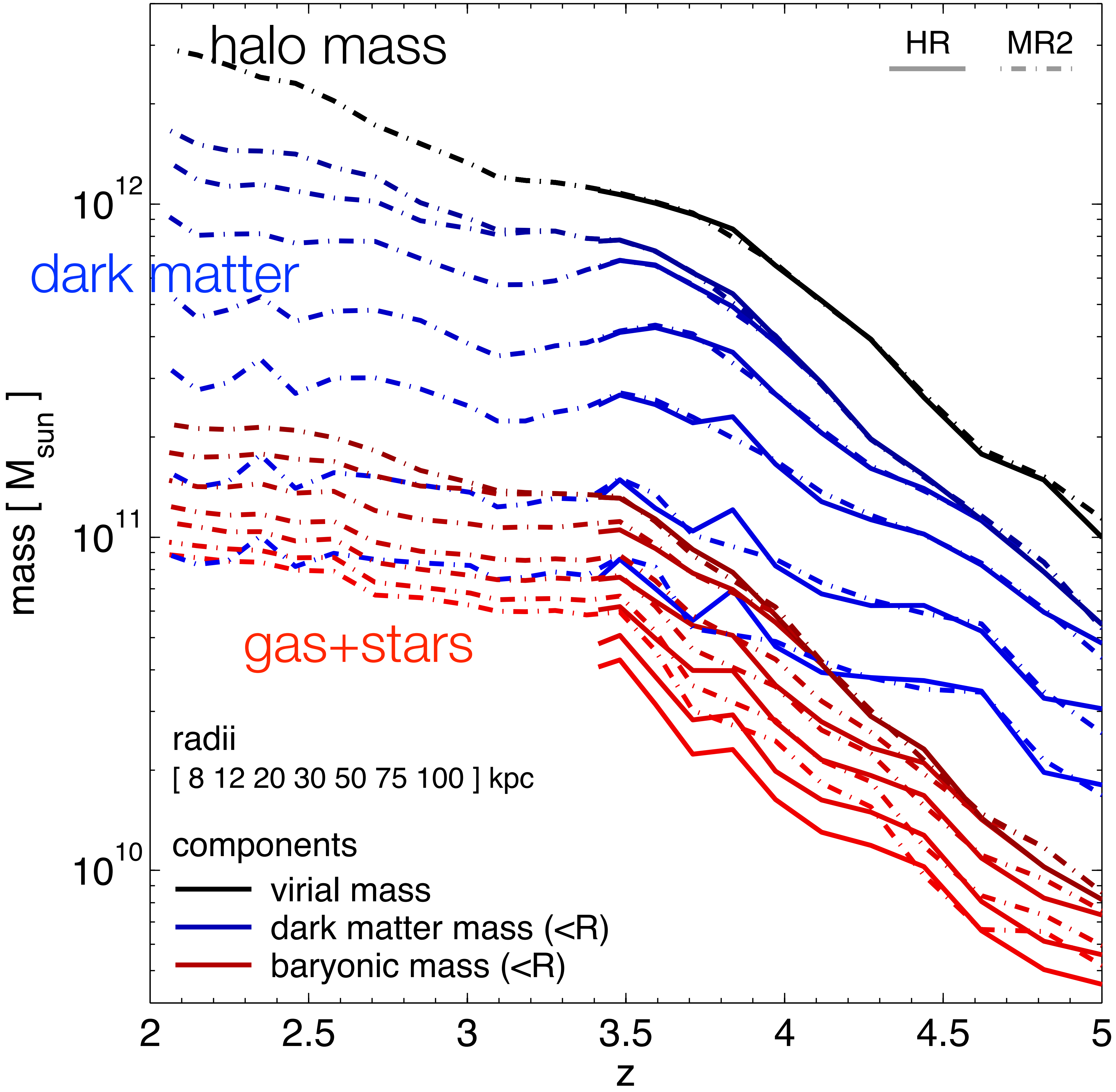
A case study of a massive galaxy



- gas & dark matter grow together
- at z~3.5 accretion within fixed physical radii nearly stops

Feldmann & Mayer
2014

A case study of a massive galaxy



Feldmann & Mayer 2014

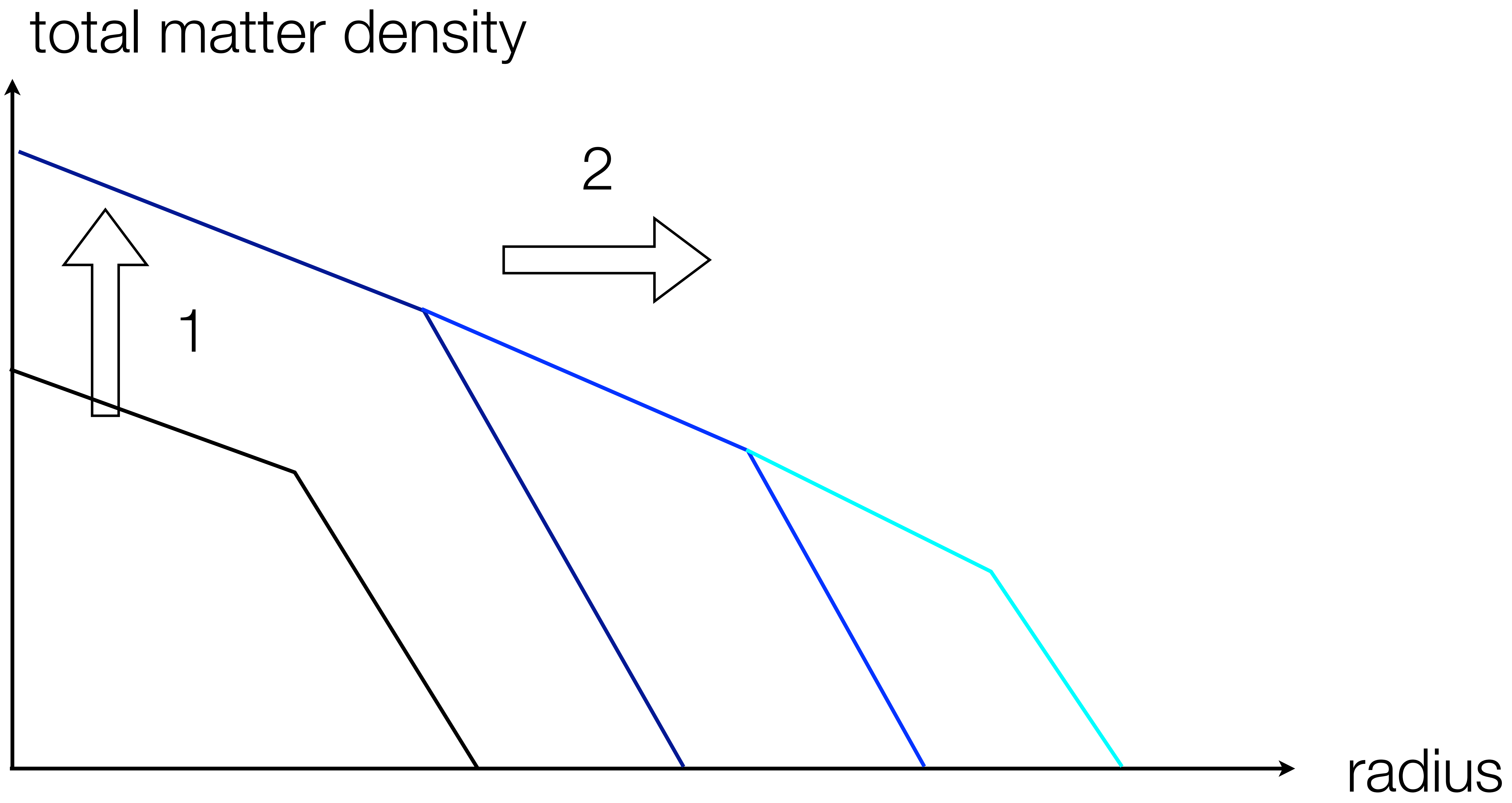
- gas & dark matter grow together
- at z~3.5 accretion within fixed physical radii nearly stops

Cosmological Starvation

- accretion levels off
- SF (nearly) runs out of fuel => (nearly) shuts down

How do massive galaxies stop forming stars?

2 distinct stages

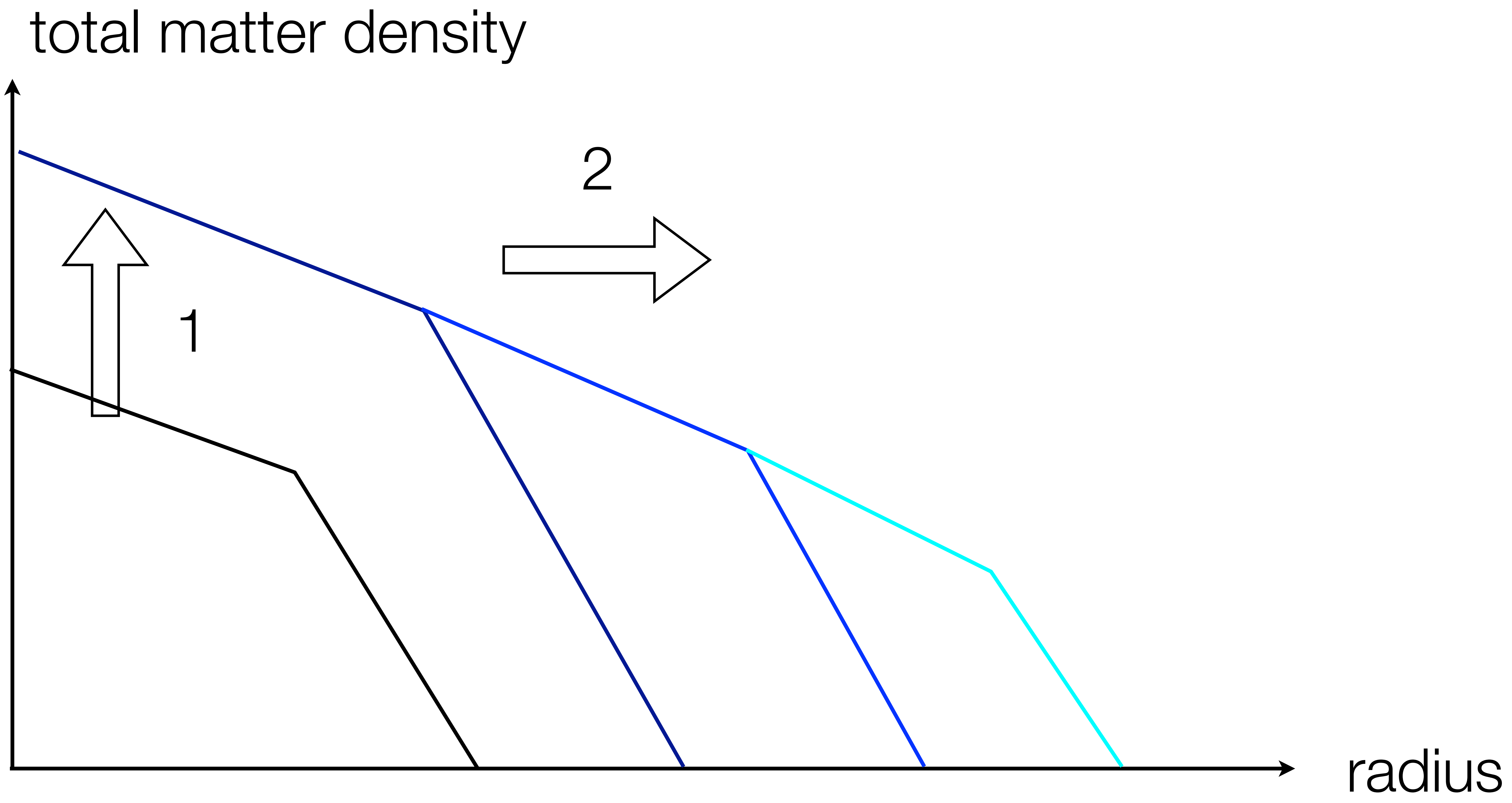


How do massive galaxies stop forming stars?

2 distinct stages

Collapse:

- sets density structure in the center
- high inflow rates of dark matter and gas
- galaxies are growing fast and are star forming

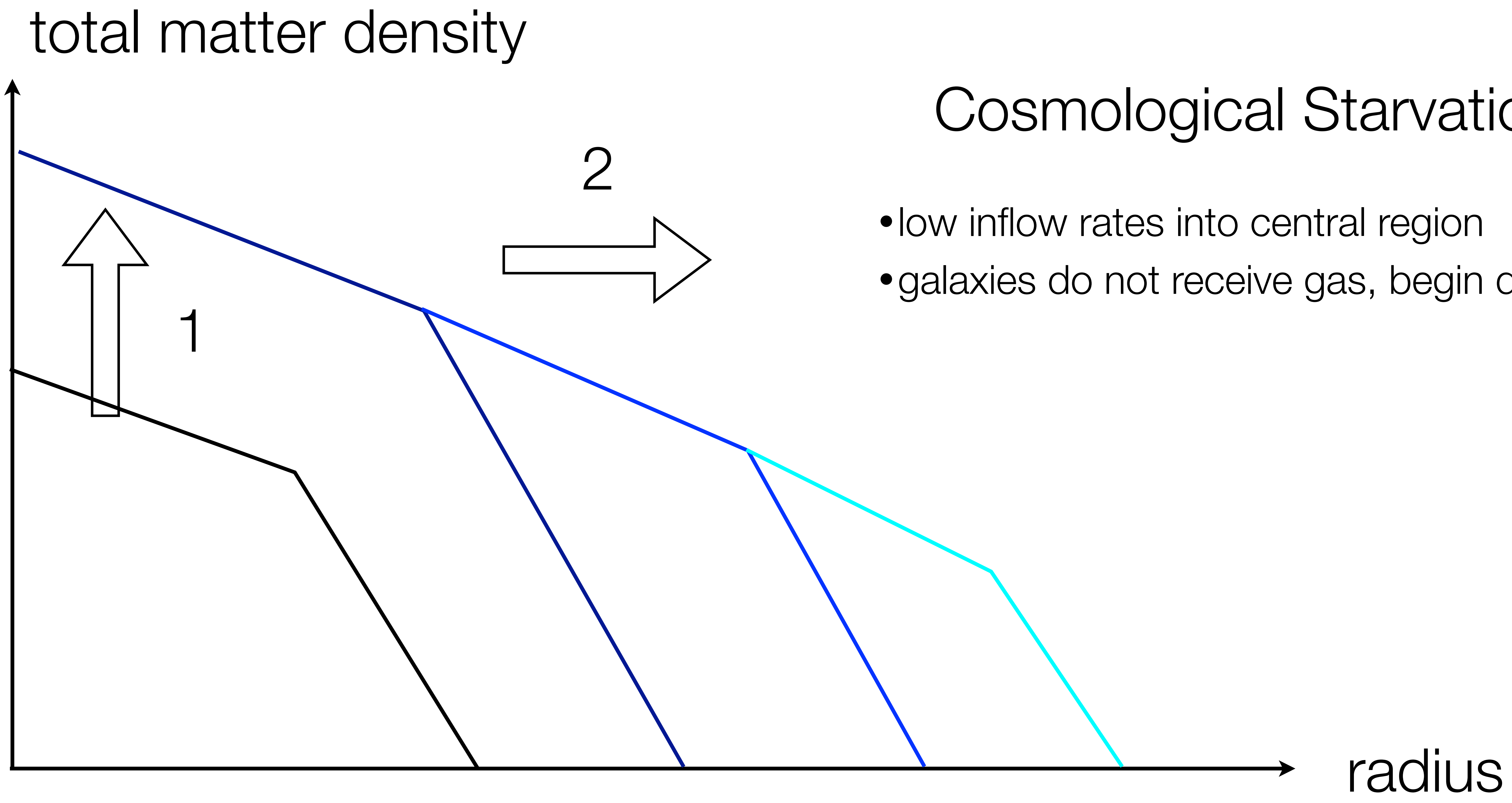


How do massive galaxies stop forming stars?

2 distinct stages

Collapse:

- sets density structure in the center
- high inflow rates of dark matter and gas
- galaxies are growing fast and are star forming

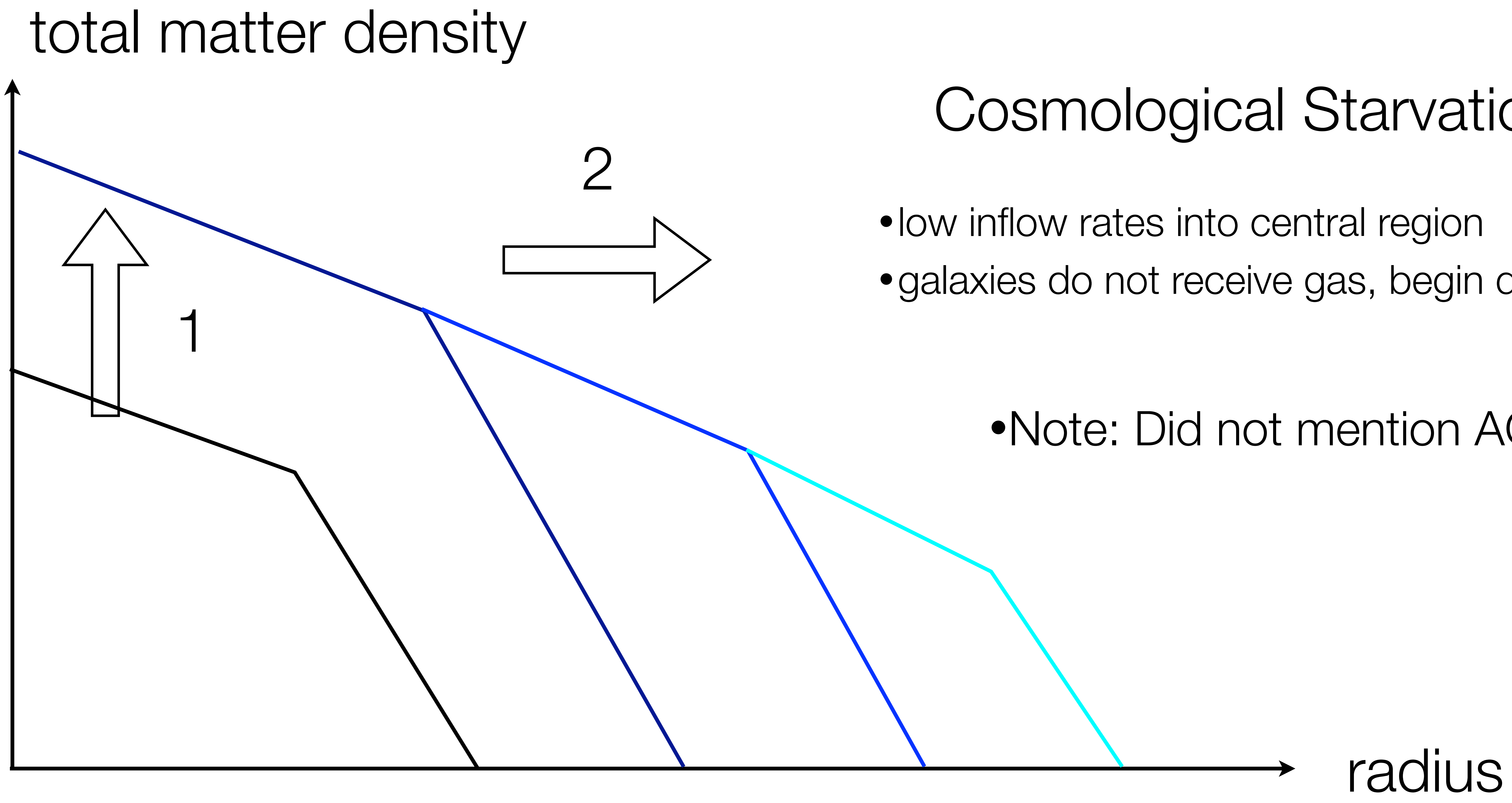


Cosmological Starvation:

- low inflow rates into central region
- galaxies do not receive gas, begin quiescent phase

How do massive galaxies stop forming stars?

2 distinct stages



Collapse:

- sets density structure in the center
- high inflow rates of dark matter and gas
- galaxies are growing fast and are star forming

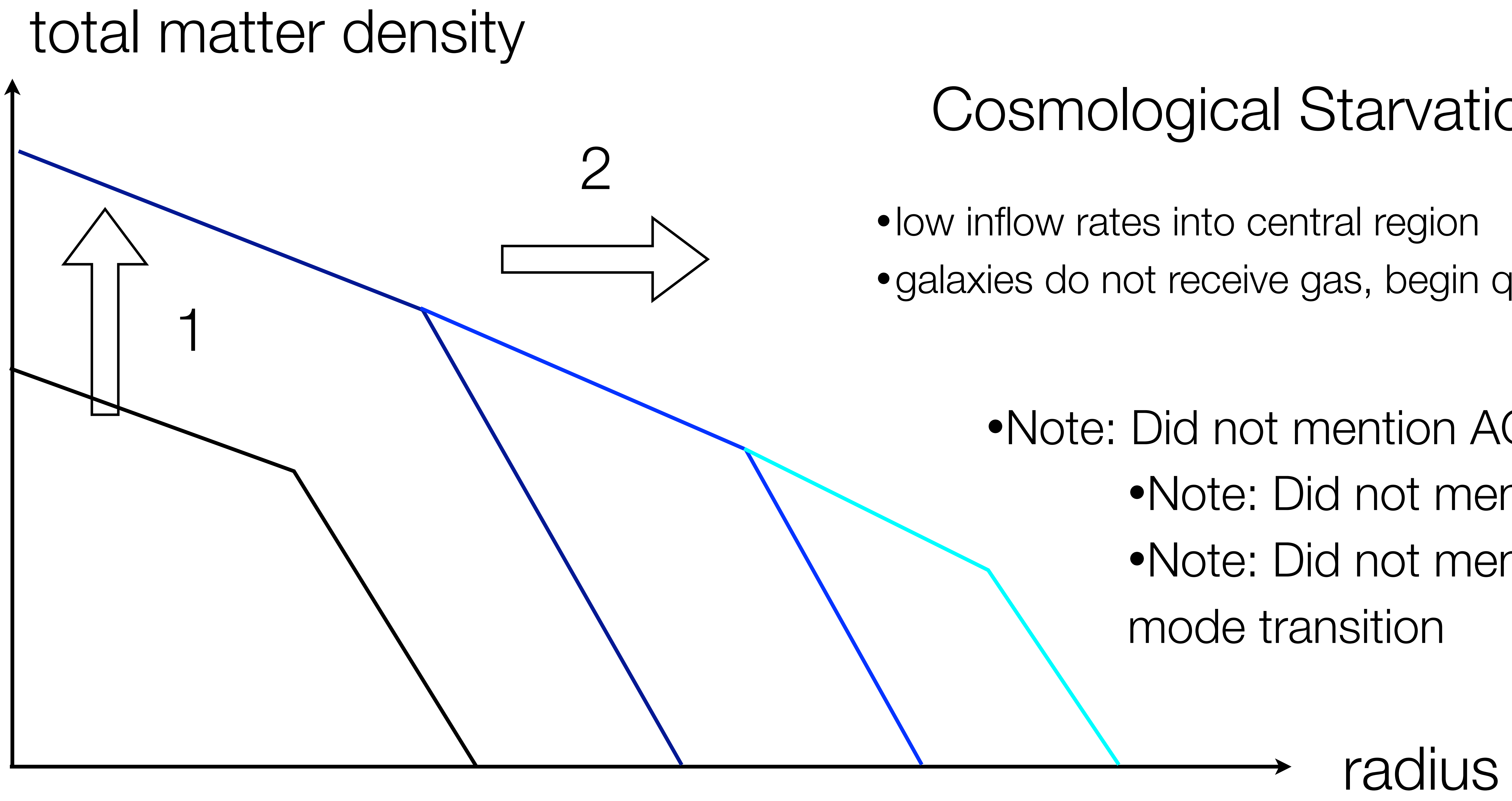
Cosmological Starvation:

- low inflow rates into central region
- galaxies do not receive gas, begin quiescent phase

- Note: Did not mention AGN feedback

How do massive galaxies stop forming stars?

2 distinct stages



Collapse:

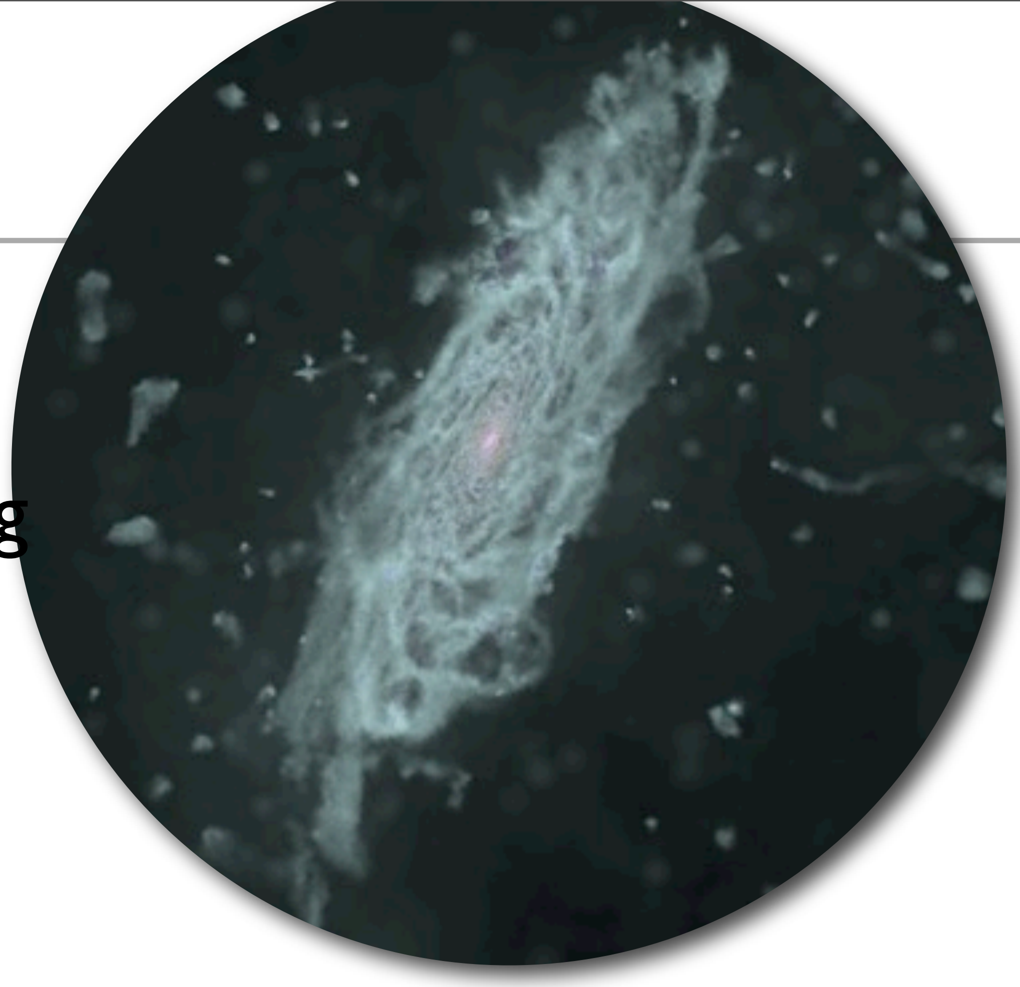
- sets density structure in the center
- high inflow rates of dark matter and gas
- galaxies are growing fast and are star forming

Cosmological Starvation:

- low inflow rates into central region
- galaxies do not receive gas, begin quiescent phase

- Note: Did not mention AGN feedback
- Note: Did not mention mergers
- Note: Did not mention cold/hot mode transition

Summary



✳ The Eris simulations and the dwarf galaxy simulations do match all main observables of late-type spirals and dwarfs at z=0, both in terms of global scaling relations and detailed internal structural properties. *No fine-tuning of sub-grid parameters - the same SF+feedback sub-grid model has been used for two very different mass scales*

✳ The major improvement in Eris was its high resolution which allowed us to use a high density threshold for star formation. *The high SF threshold coupled with blastwave thermal feedback allows to drive outflows and regulate both baryonic mass accretion and star formation to the required level*

✳ Eris has a pseudobulge as typical for late-type spirals: it forms in situ, at high redshift, as a result of repeated bar-instabilities that are dynamical rather than secular in nature.
The trends in scale length, scale height, age and kinematics of disk stellar populations agree very well with the results for the MW and show there is a continuum between thin and thick disk -- this has to be connected with star formation history and gas thermodynamics, hence with feedback model

✳ A big challenge (for all simulations); the M*-Mhalo relation as a function of redshift.
SFR *too high at high z unless much stronger feedback is employed at the expense of creating unrealistic thick, turbulent disks* (eg Eris2 runs). This likely reflects limitation of the SF+feedback recipes.

✳ Massive galaxies (M* >~ 10^{11} Mo, Mvir ~ 10^{13} Mo) appear to (begin) quench due to cosmological starvation quite irrespective of feedback (especially without requiring AGN feedback). Need to assess how general this quenching mode is. A long lasting transition to "red and dead" may still require a maintenance feedback mode such as the radio mode AGN feedback.