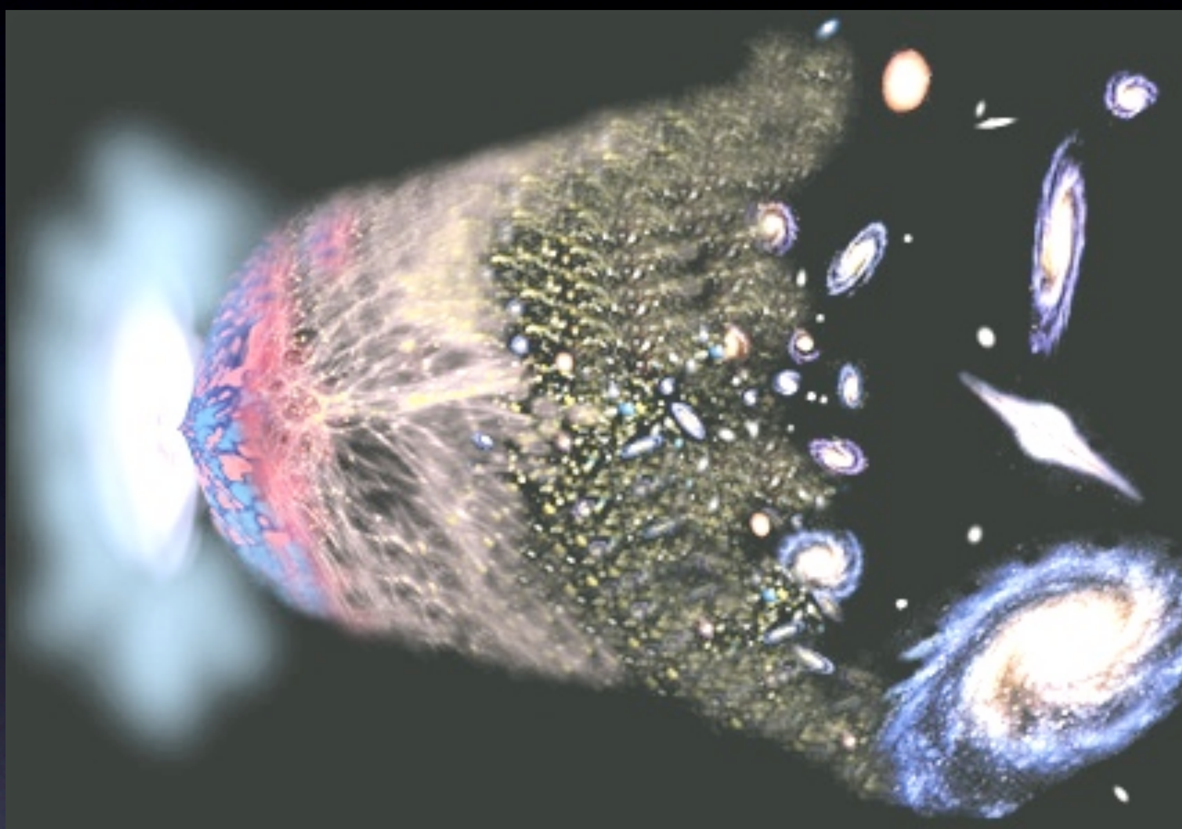
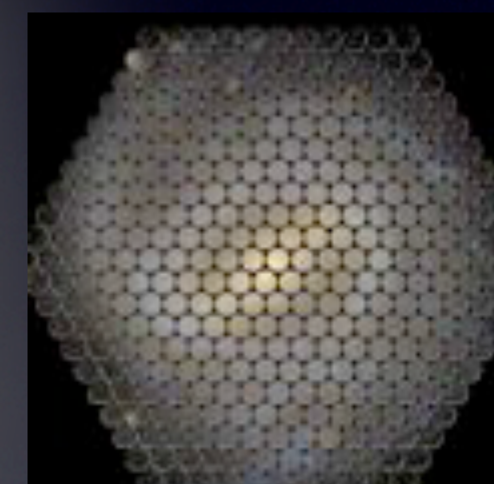
Constraints to disk galaxy evolution from IFS observations





Vladimir Avila-Reese
Instituto de Astronomía, UNAM

Contents

- Theoretical background: the dark and bright side of galaxy formation
- The semi-empirical picture, downsizing
- Models and simulations of disk galaxies, some examples of possible constraints from IFS
- Conclusions

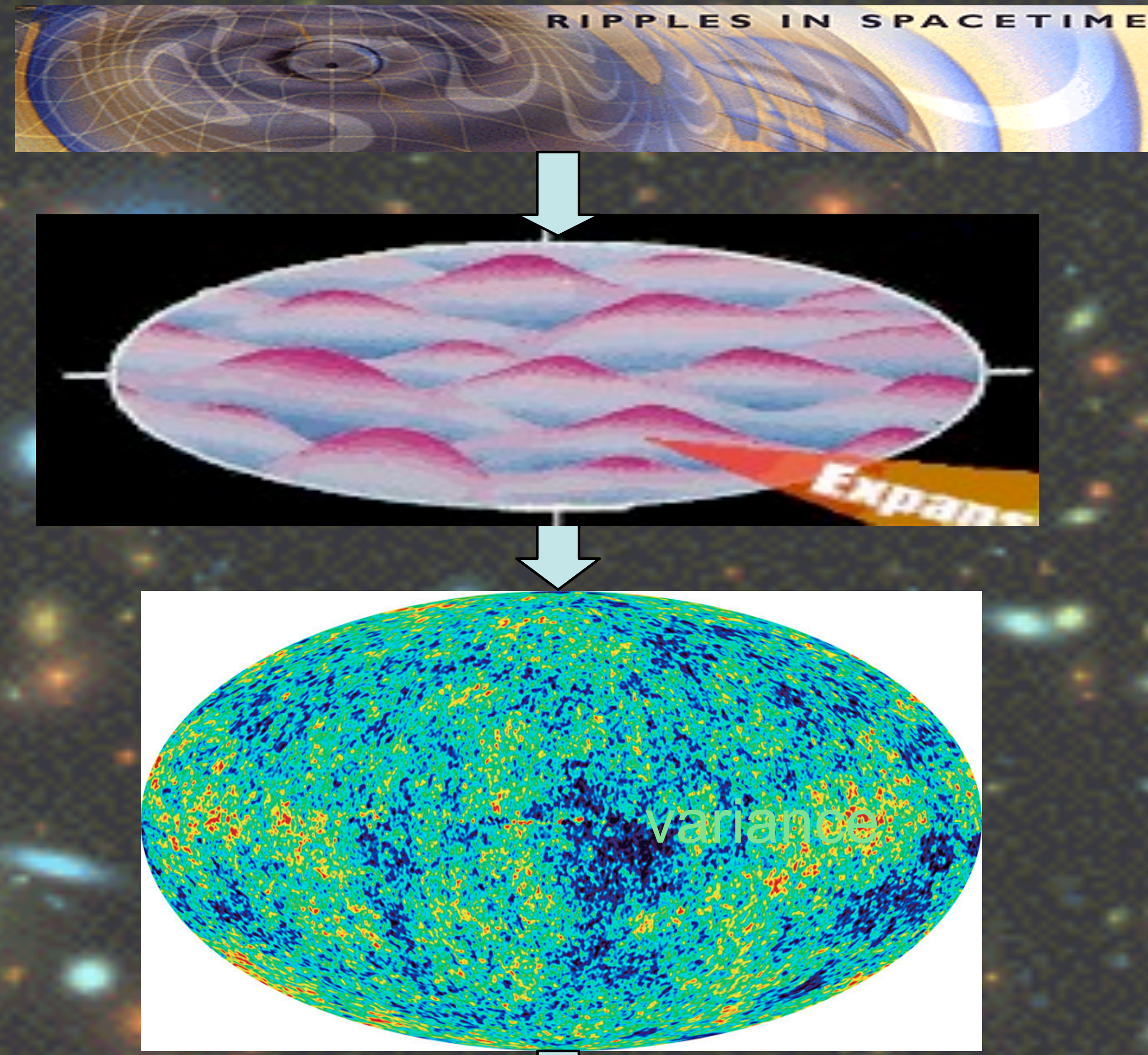
Primordial fluctuations + Background universe (matter-energy content)

⇓

Linear gravitational evolution *(CDM is necessary to form protogalaxies)*

⇓

Processed power spectrum at recombination



Inflation (*from quantum to classical fluctuations)*
10^{-33} s

Hot universe
(radiative pressure, damping processes)

Cosmic Microwave Background radiation
380,000 años

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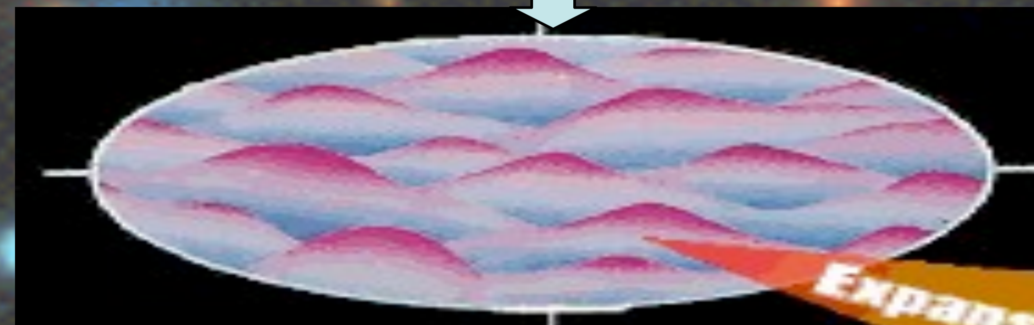

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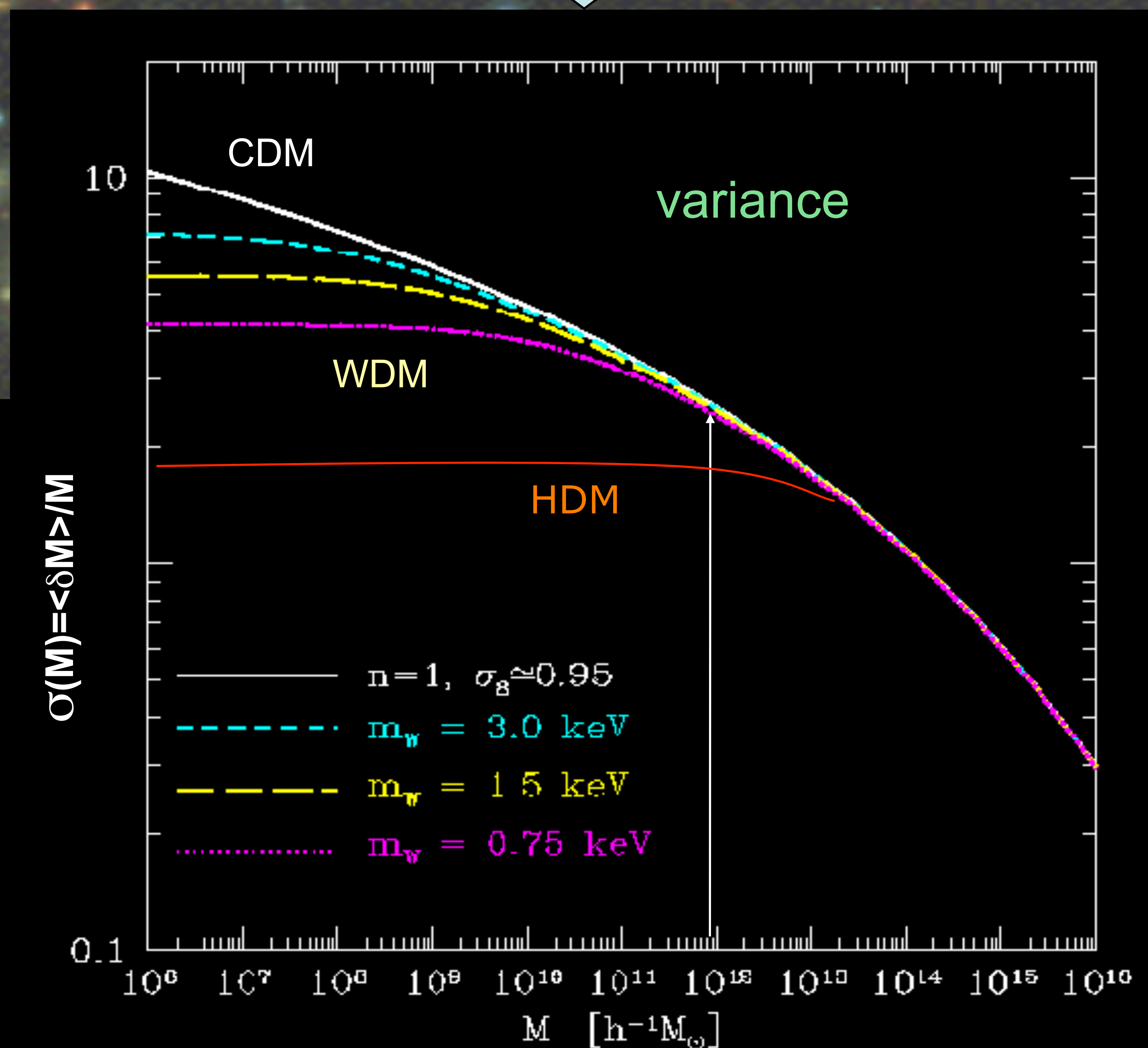
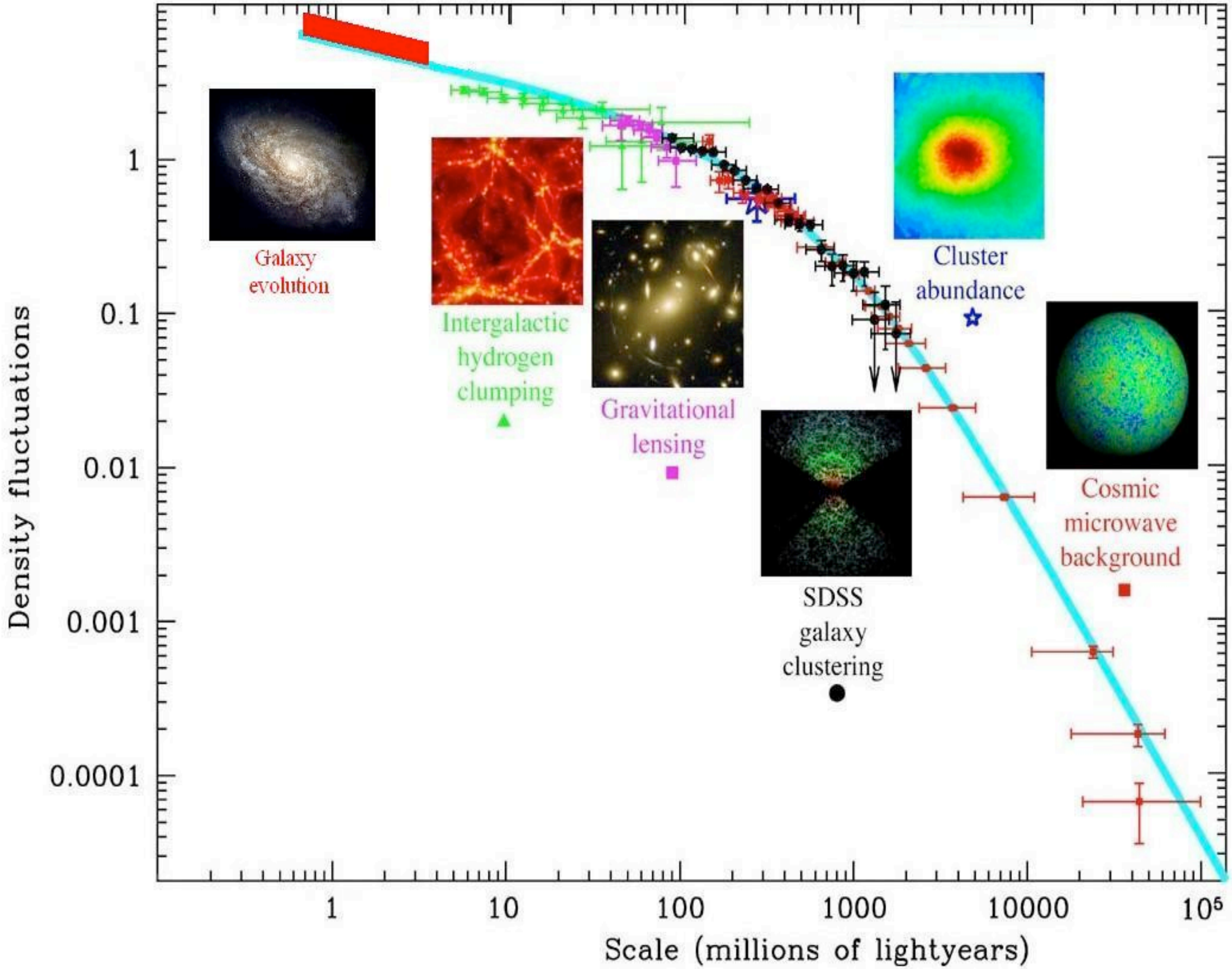


the initial conditions for non-linear cosmic structure evolution *(variance, from the PS)*

CDM: the simplest model
(no cut-off, collisionless, no self-interacting)

The LCDM PS agrees very well w/a large body of observations at large scales!

Is there a cut-off at small scales?--> WDM



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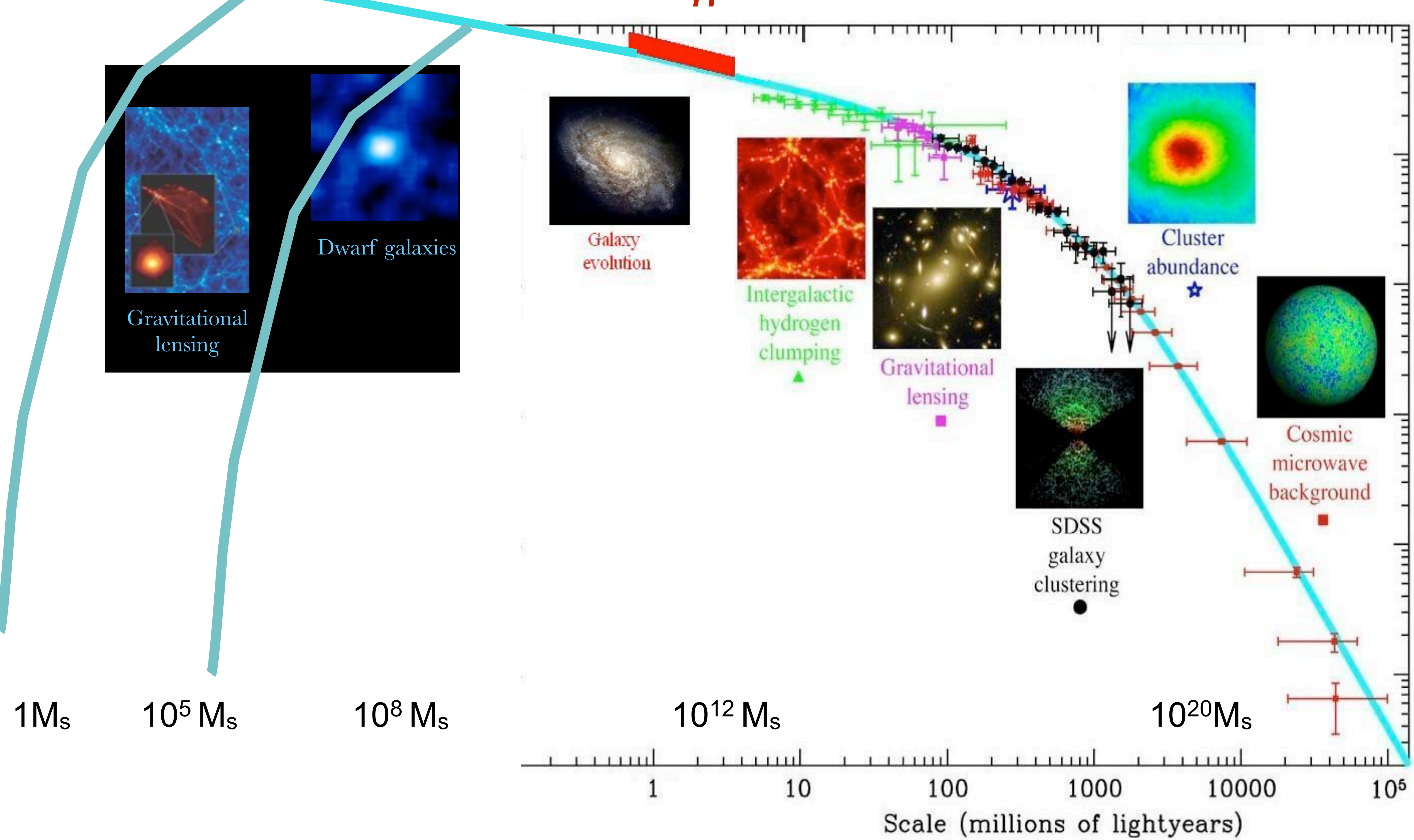


Primordial fluctuations + Background universe (matter-energy content)

⇓

Linear gravitational evolution ***(CDM is necessary to form protogalaxies)***

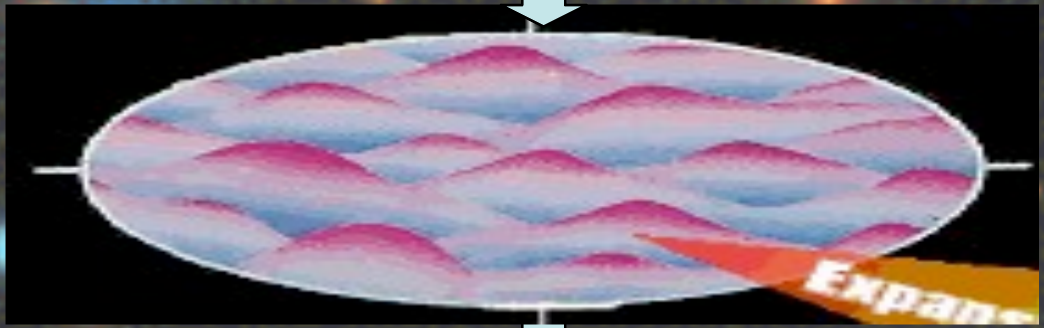
⇓

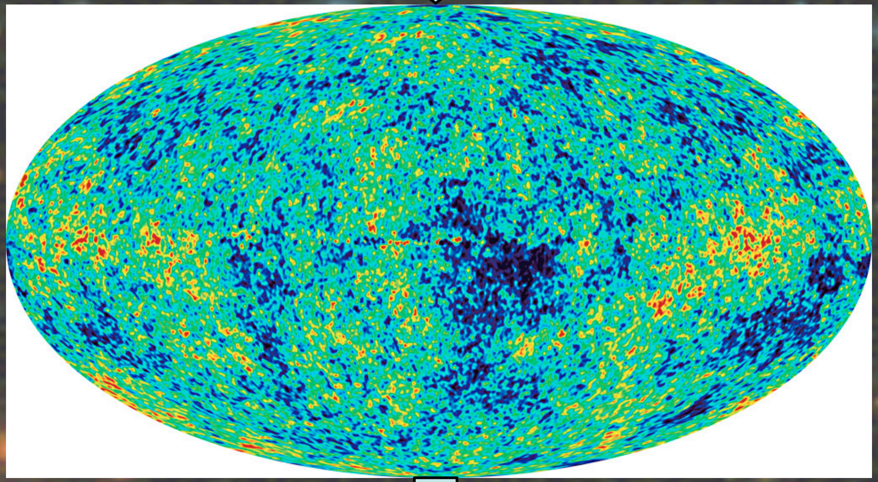
Processed power spectrum at recombination

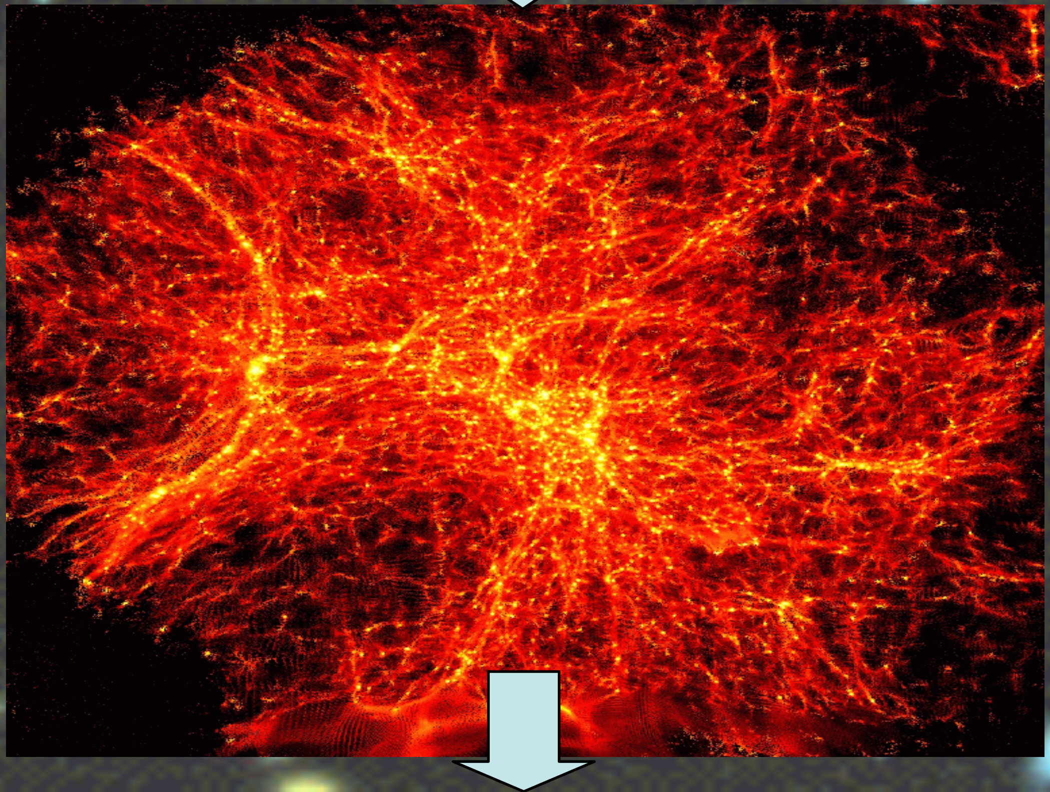
N-body simulations of the **gravitational clustering**

⇓

CDM halos and LSS: filaments, clusters, voids







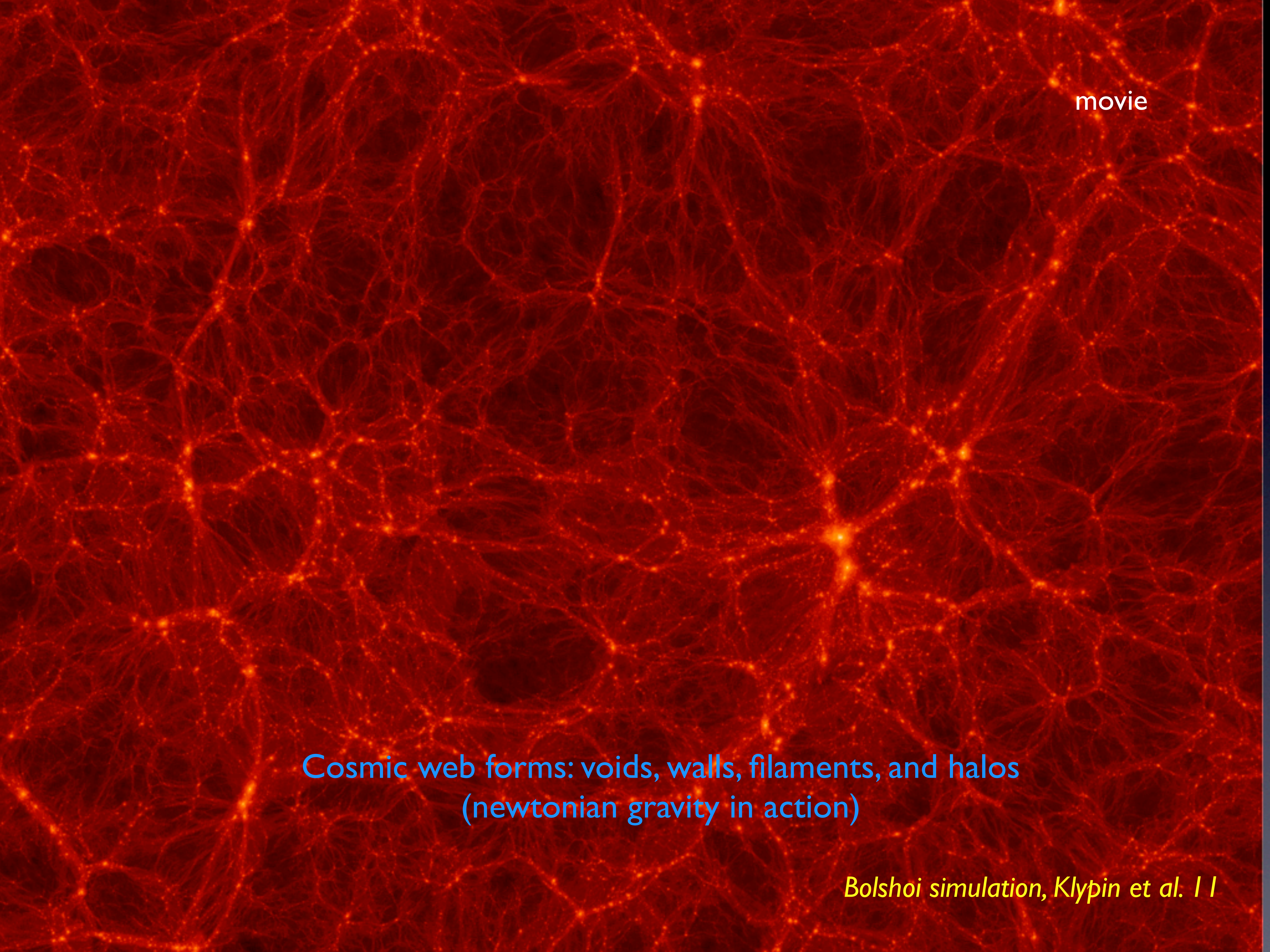
Inflation *(from quantum to classical fluctuations)*
10^{-34} s

Hot universe *(radiative pressure, damping processes)*

Cosmic Microwave Background radiation
380,000 años

Gravitational collapse

(first collapsed halos form at 10^{8}-10^{9} y)



movie

Cosmic web forms: voids, walls, filaments, and halos
(newtonian gravity in action)

Bolshoi simulation, Klypin et al. 11

Dark halo formation is different in different environments

(Avila-Reese et al. 2005)

Cluster6 *(M_{res}=4E7M_s/h; 3E8M_s/h)*

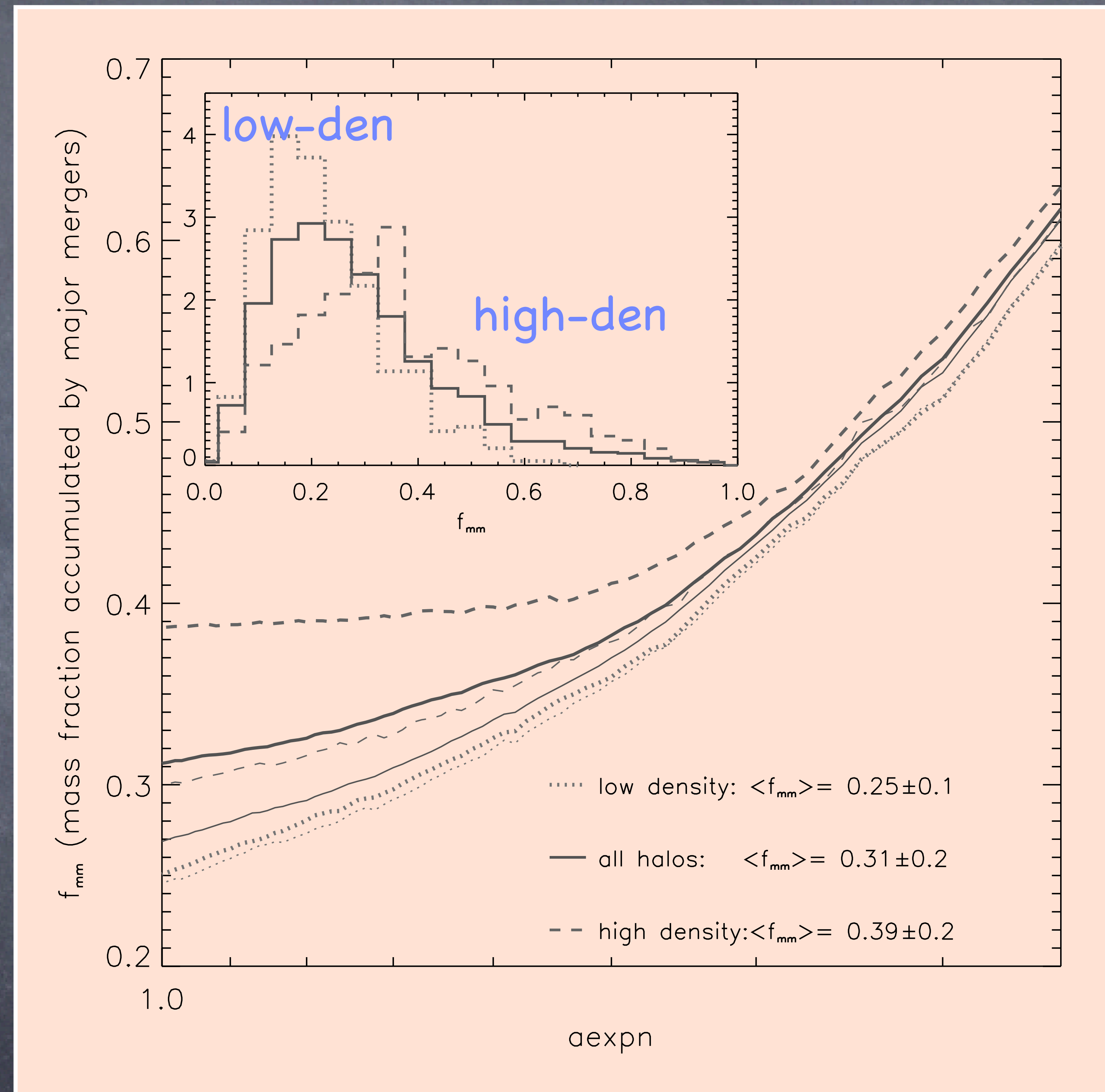
Void5 (*M_{res}=4E7M_s/h*)

movies

Halo mass assembly: A common myth around the LCDM scenario is that mergers and violence is the rule in cosmic structure formation

Merger dominated tree

Even at the level of dark matter halos, this is not true



Maulbetsch+ 07, ApJ: most of halos assembled only ~10-30% of their masses in mergers larger than 1:4. See also Genel+10; Wang+10 with the MS)

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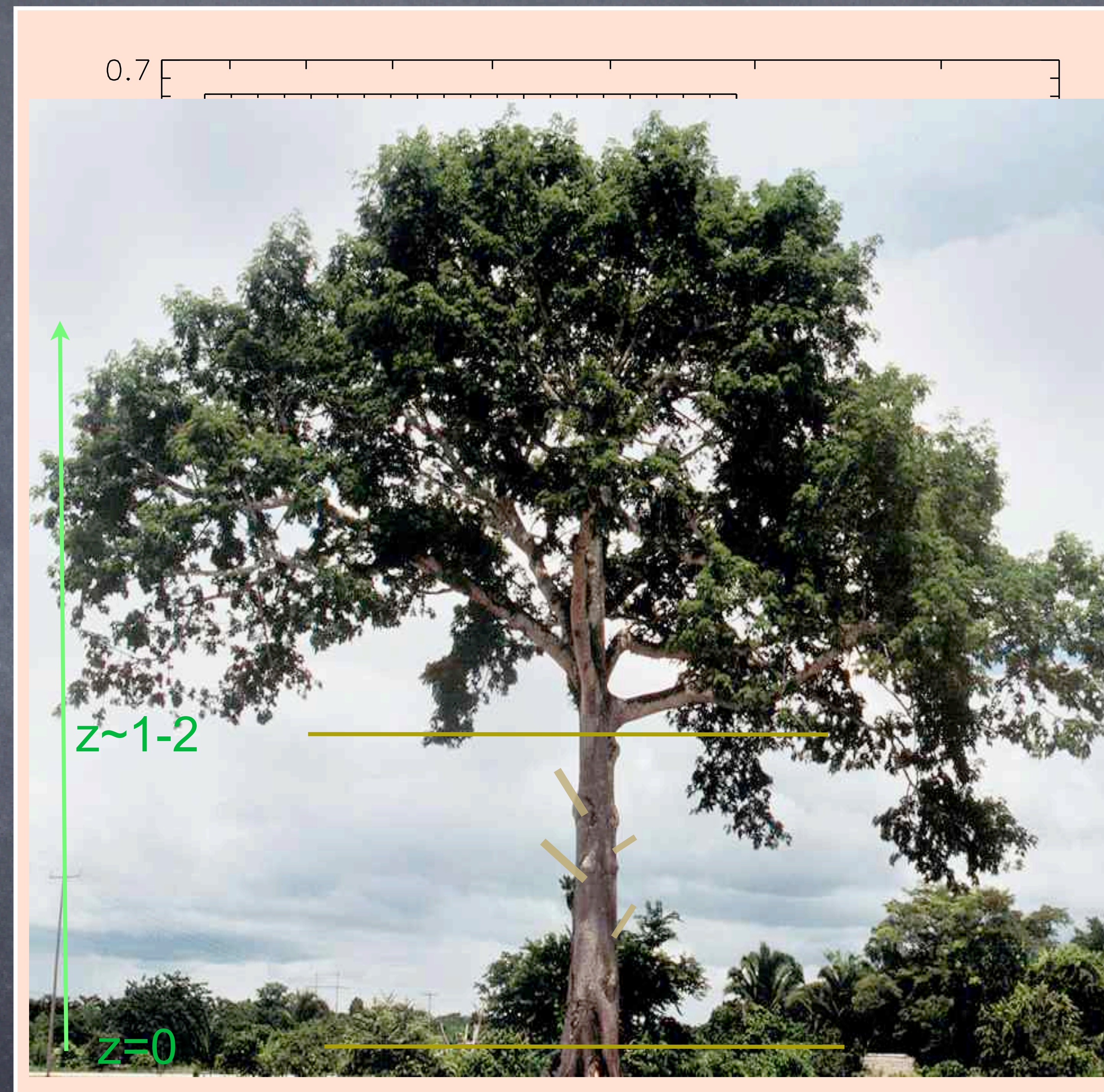

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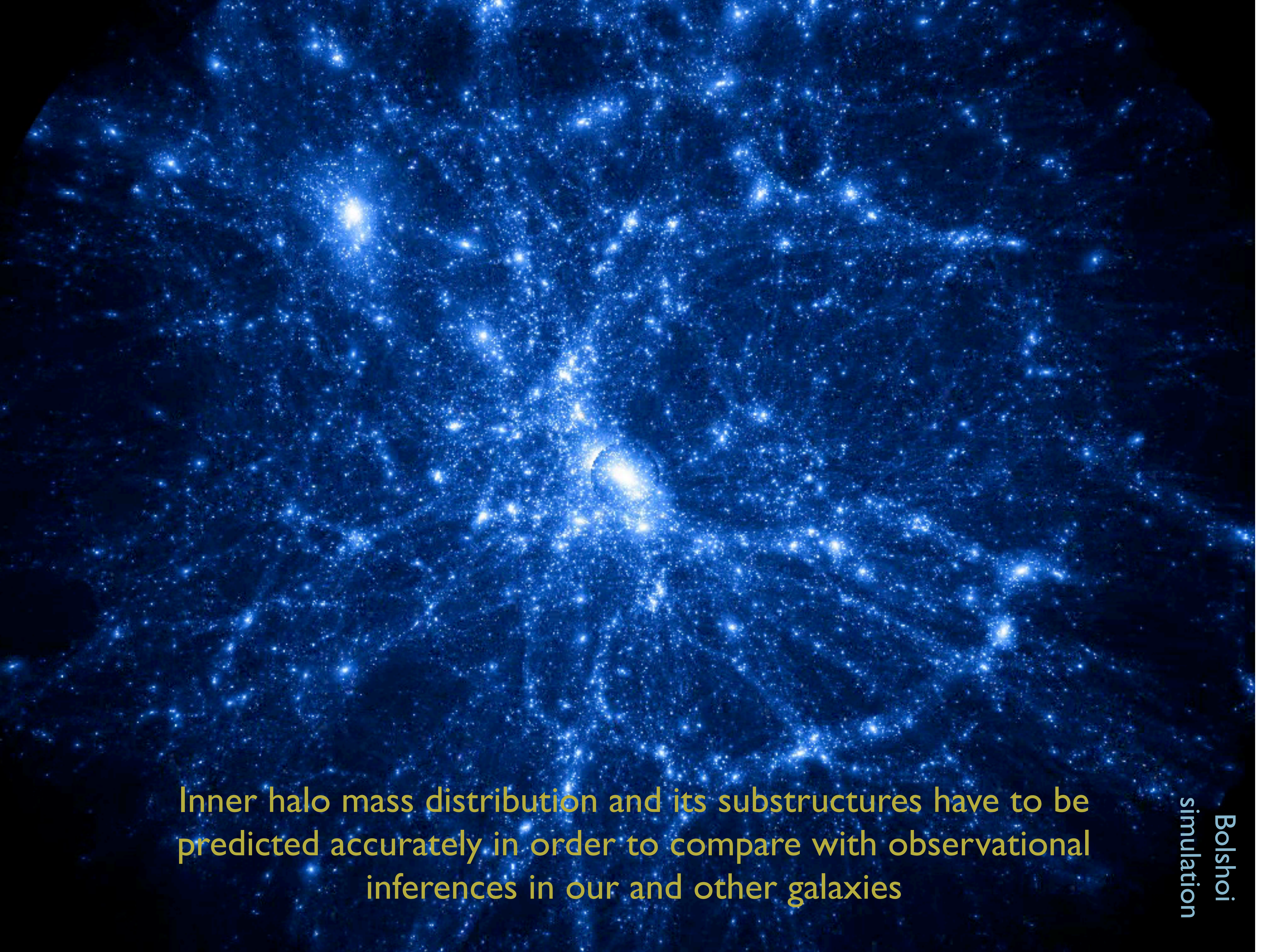


Inner halo mass distribution and its substructures have to be predicted accurately in order to compare with observational inferences in our and other galaxies

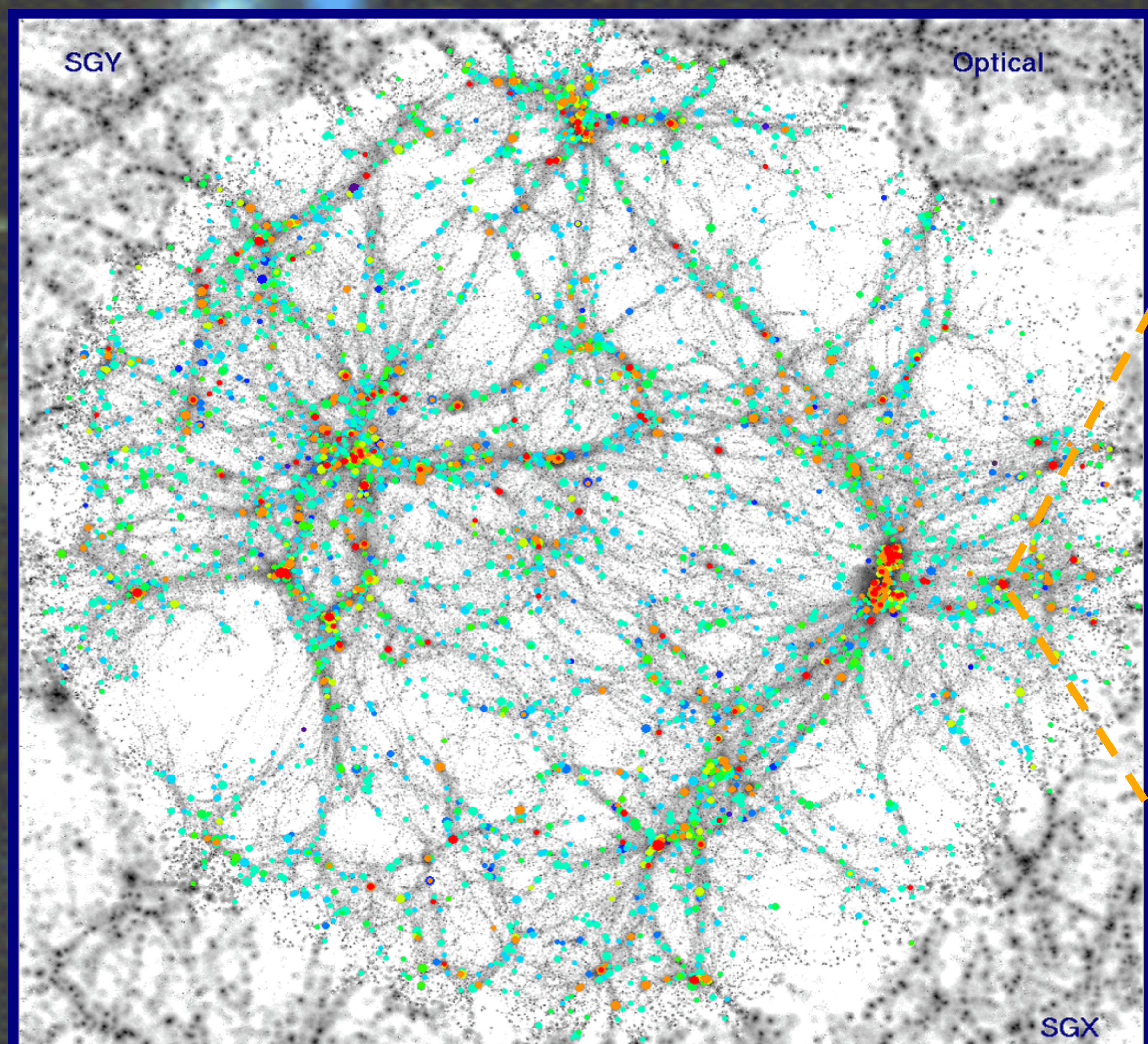
Bolshoi simulation

GASTROPHYSICS

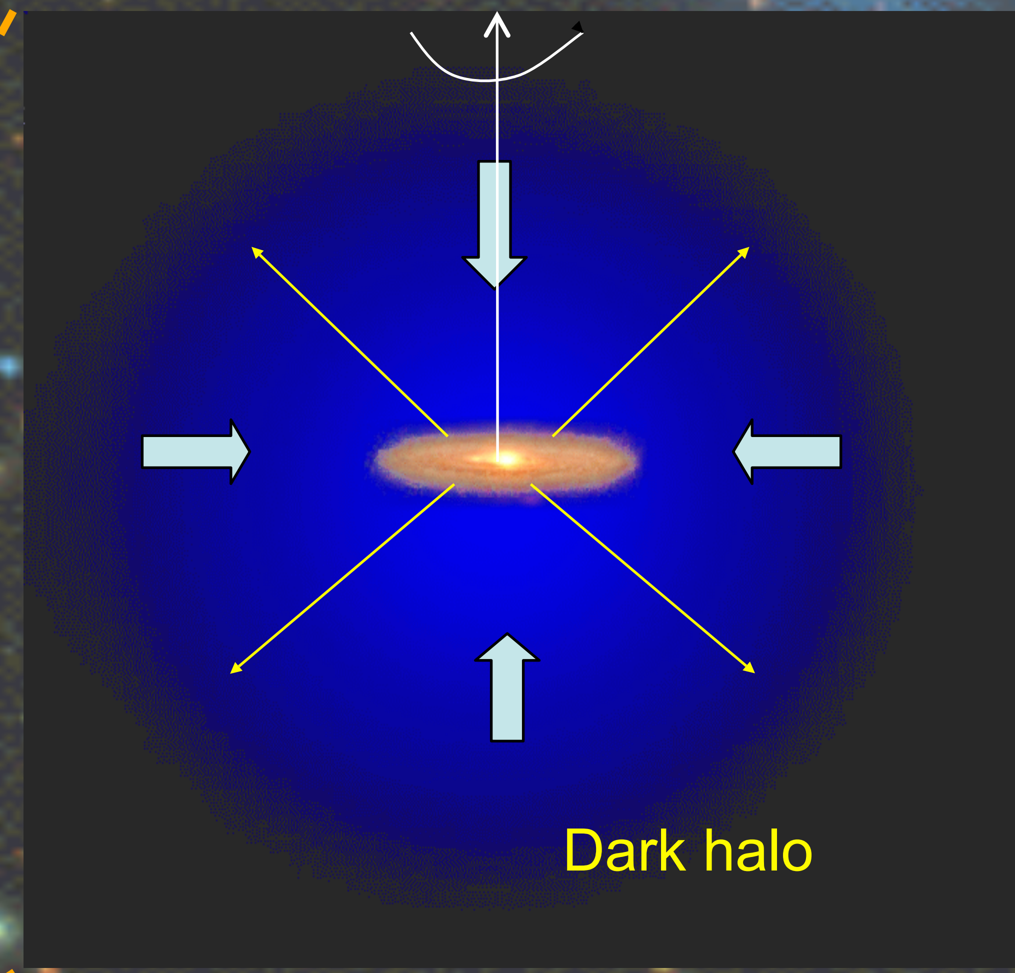
Cooling and hydrodynamics of the baryon gas ⇒ intergalactic medium and protogalaxies

Disk assembly, star formation and feedback. Mergers→spheroids

Cosmic web



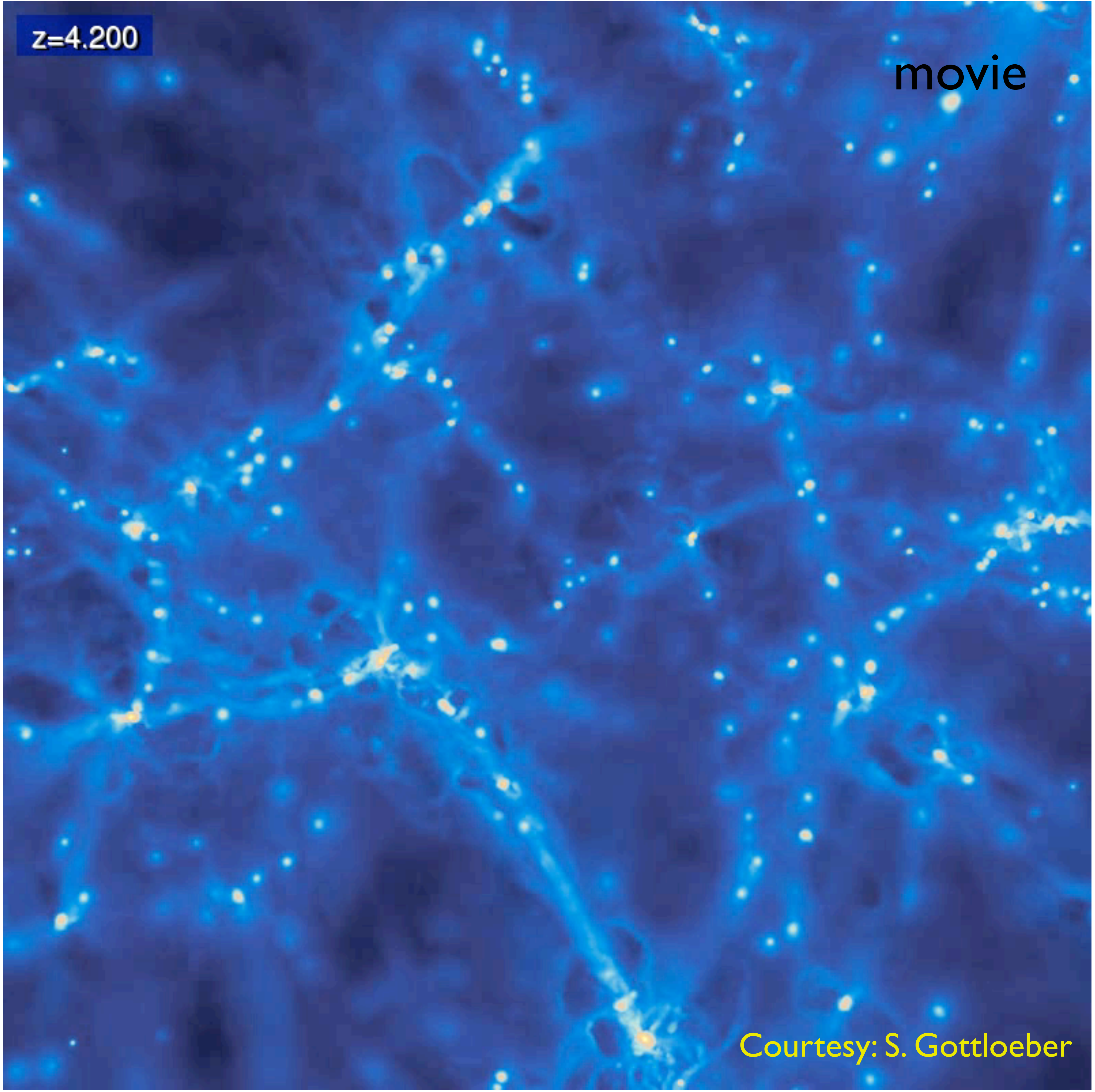
Benson et al.



-Does galaxy assembly follow the DM halo assembly? (memory of initial cond's)
- Do the DM halo environment affect the galaxy properties?

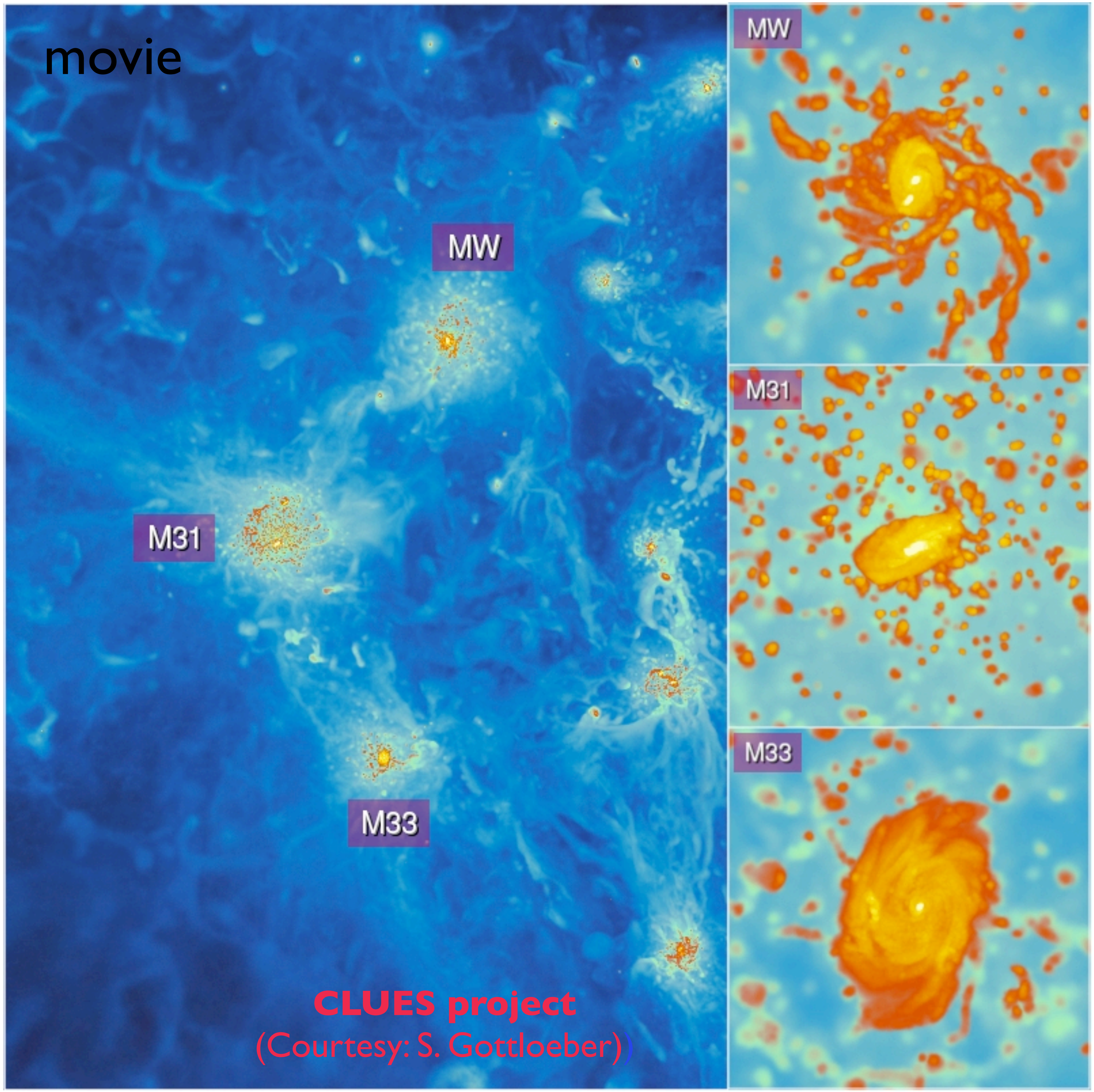
N-body/hydro simulations

Non-linear gravitational evolution + baryonic physics *(yet not well understood at the smallest scales , <50 pc)* make difficult to follow the evolution of a whole population of galaxies (cosmological box) resolving at the same time the galaxy physics *(molec. clouds, stellar feedback, etc.)*



Zoomed or constrained simulations of a few objects allow to explore galaxy evolution and present-day properties.

Simulations may help to understand biases and selection effects in the IFS observations and how to optimize them at the time of making inferences



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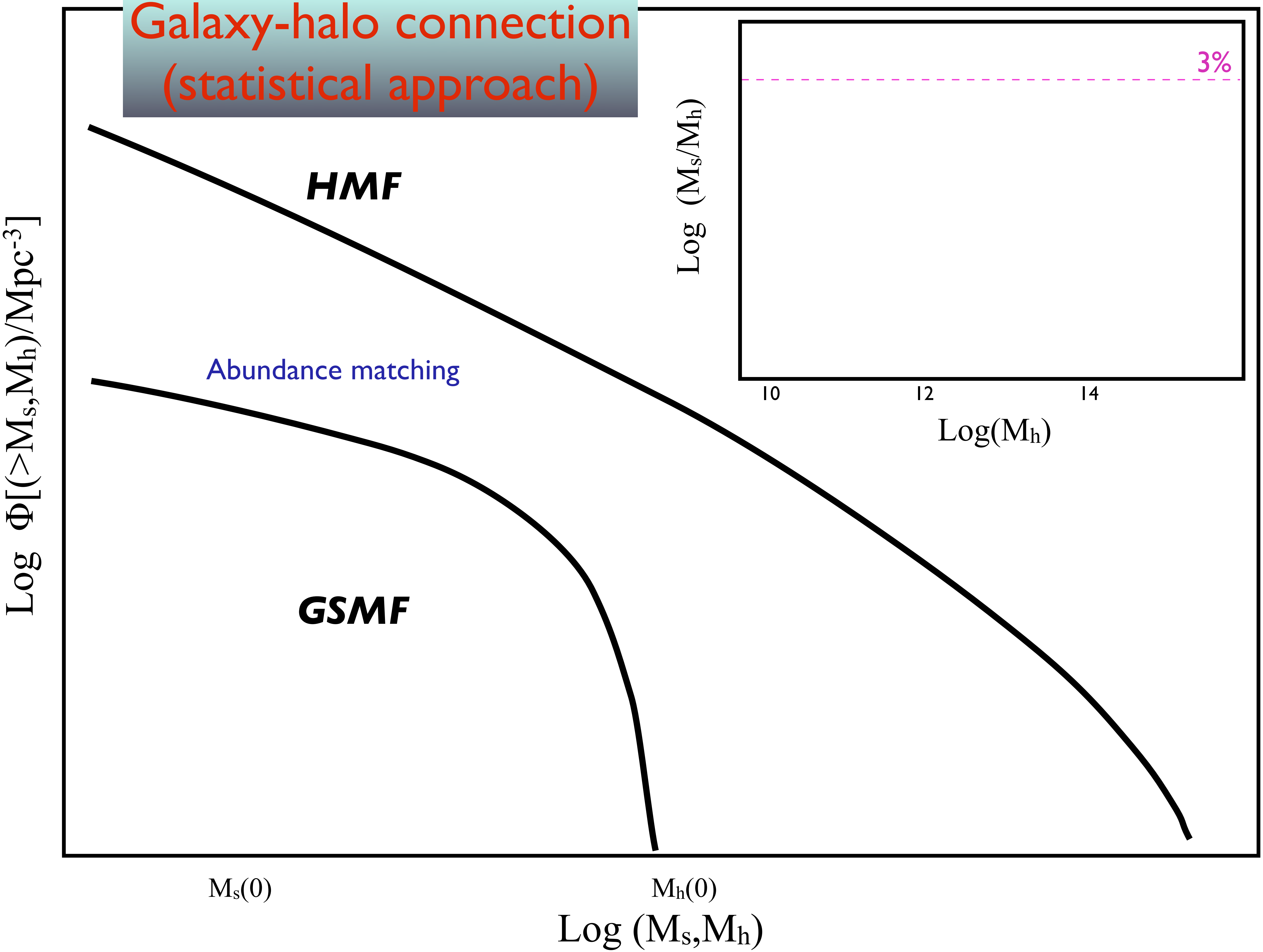
Galaxy-halo connection (statistical approach)



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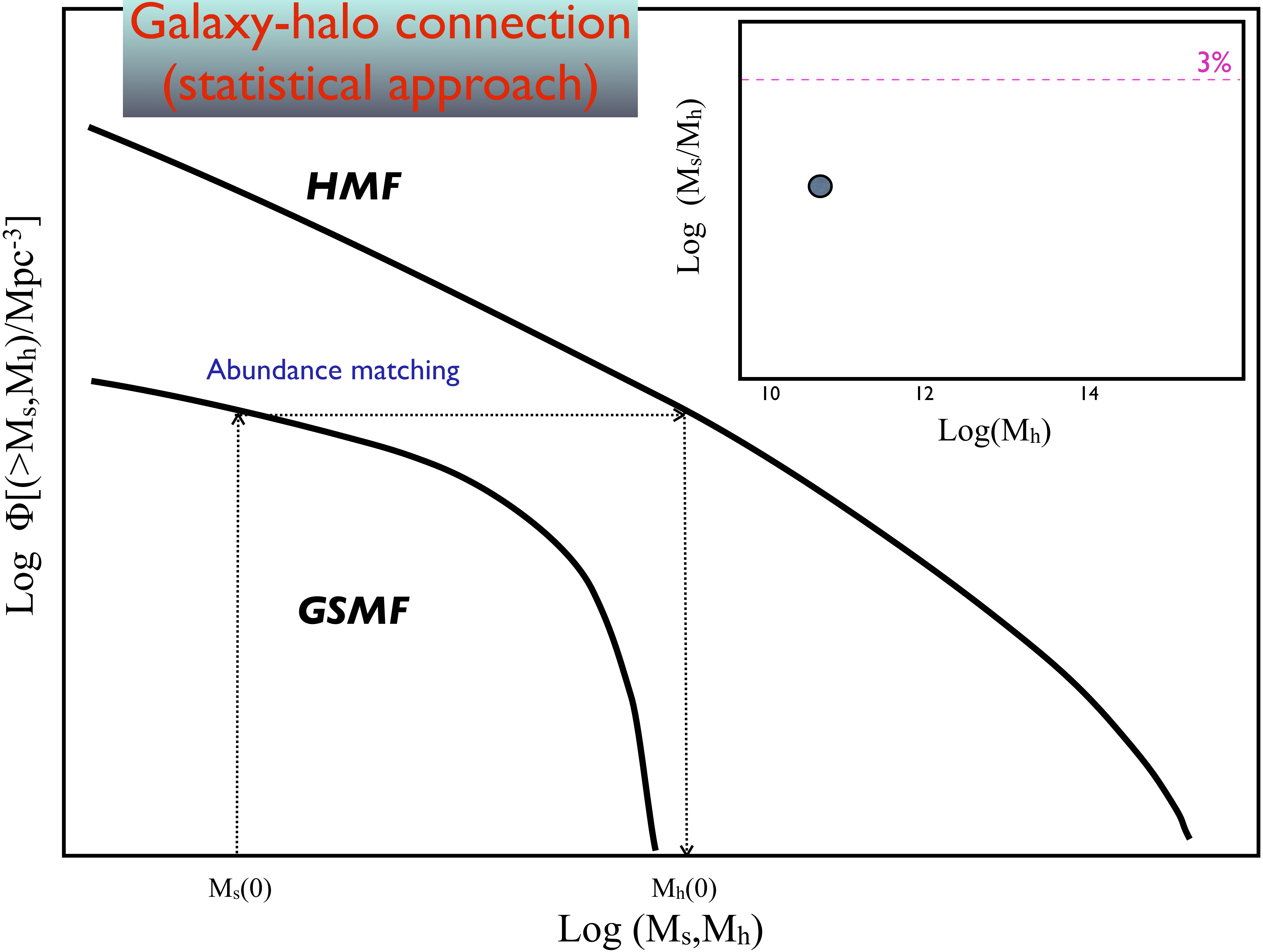

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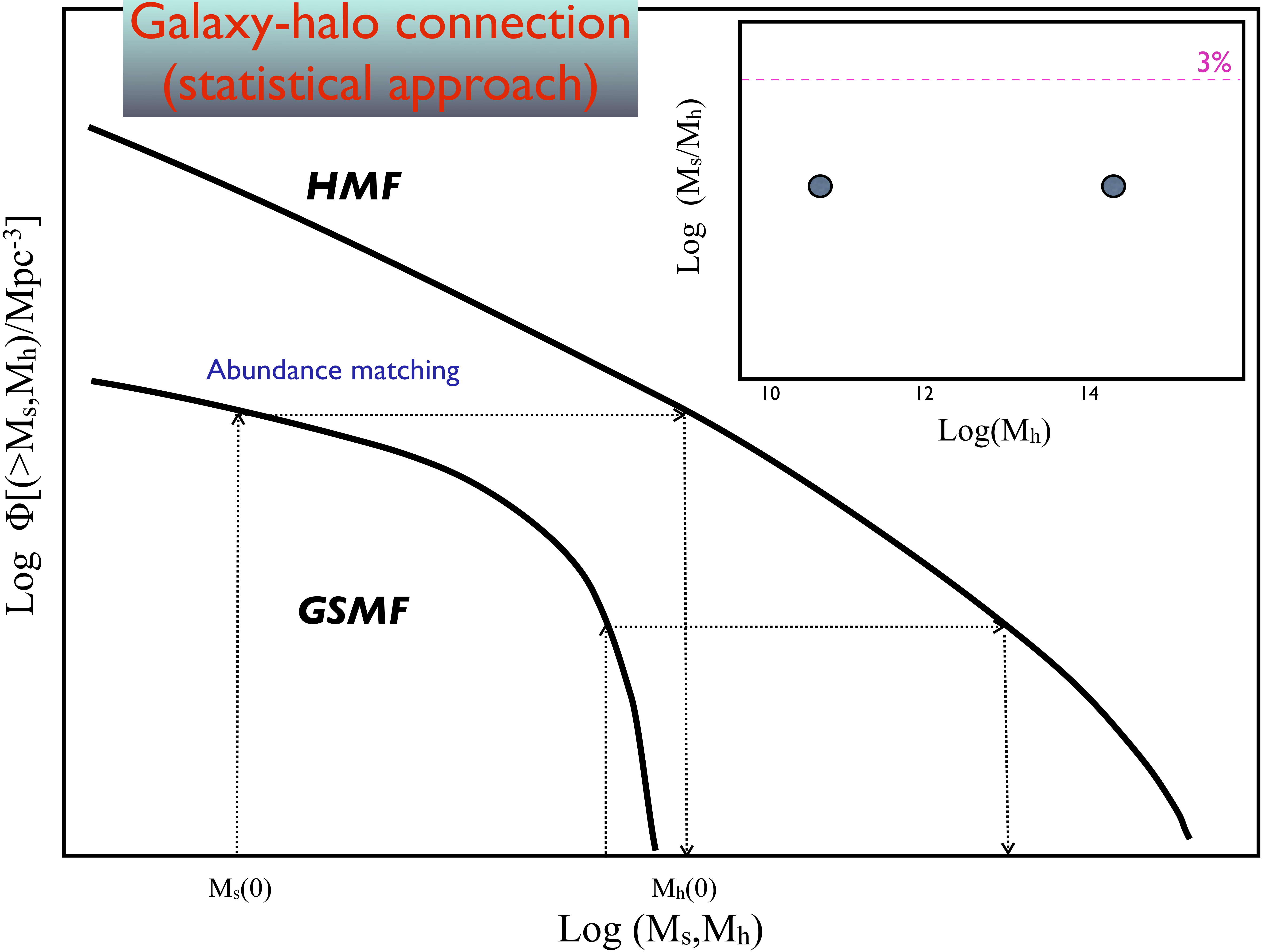

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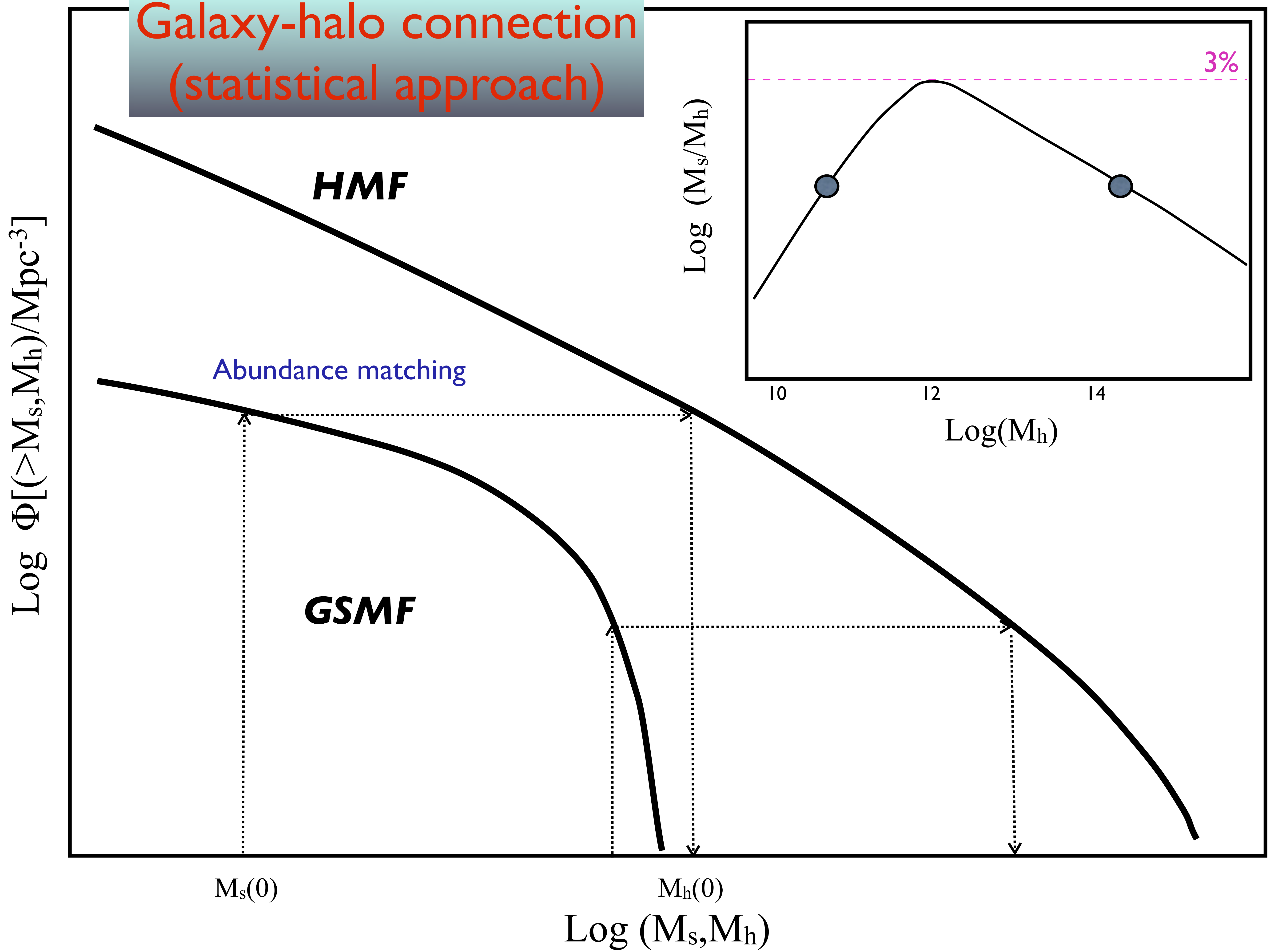
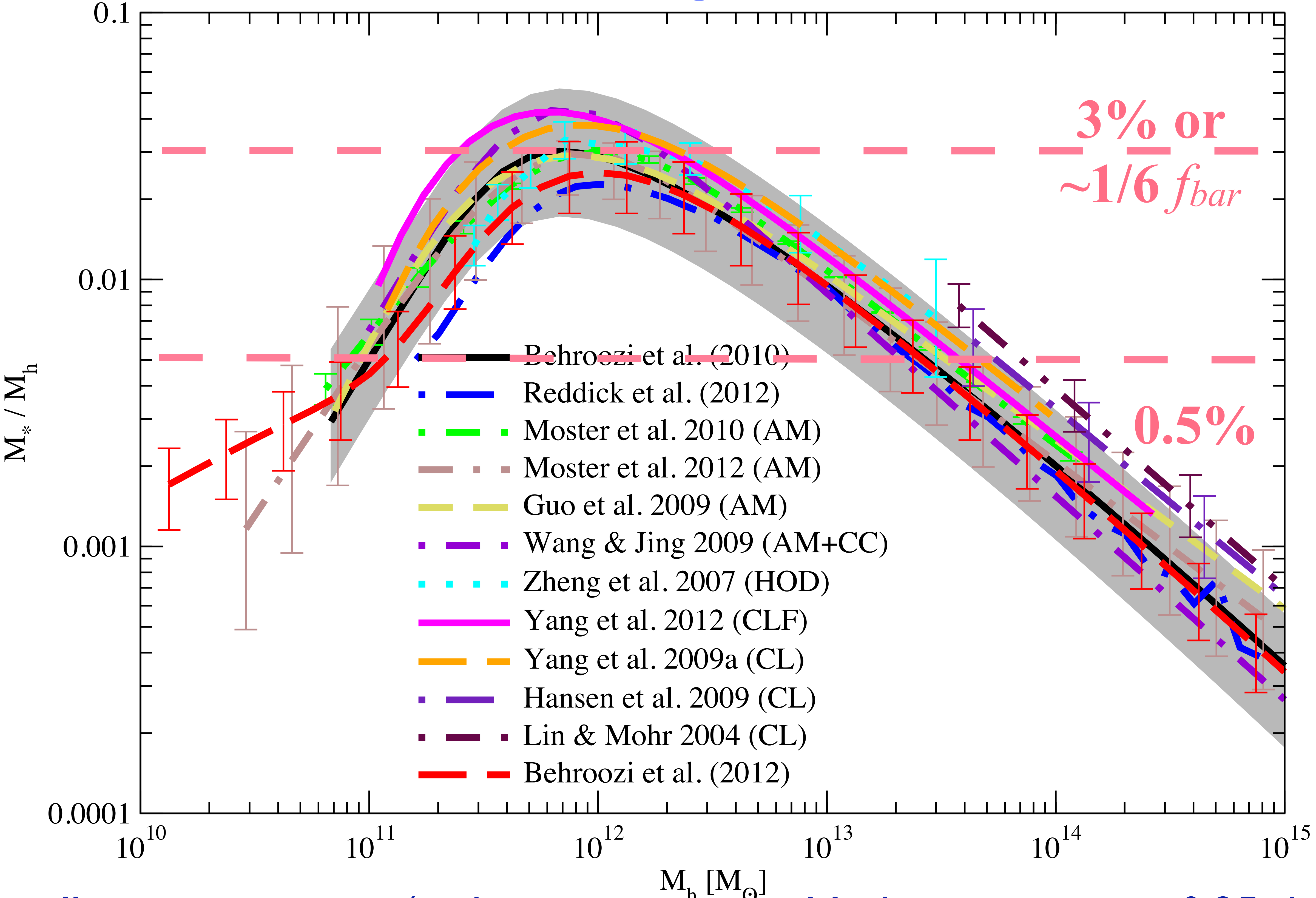
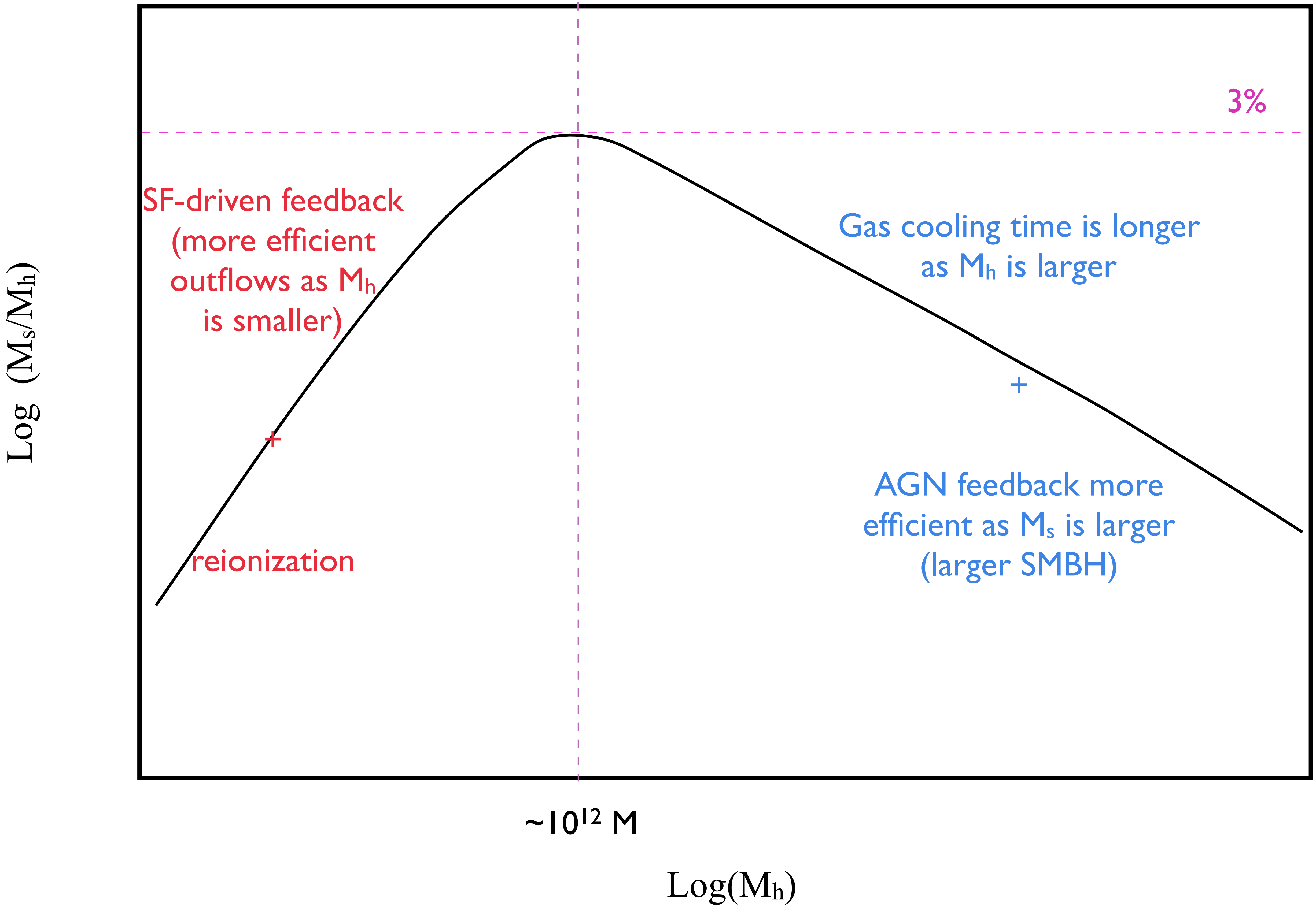


$M_s(M_h)$ at z=0; comparison among several works and methods (e.g., the direct ones)



Small intrinsic scatter (< the uncertainty in M_s determination, ~0.25 dex)

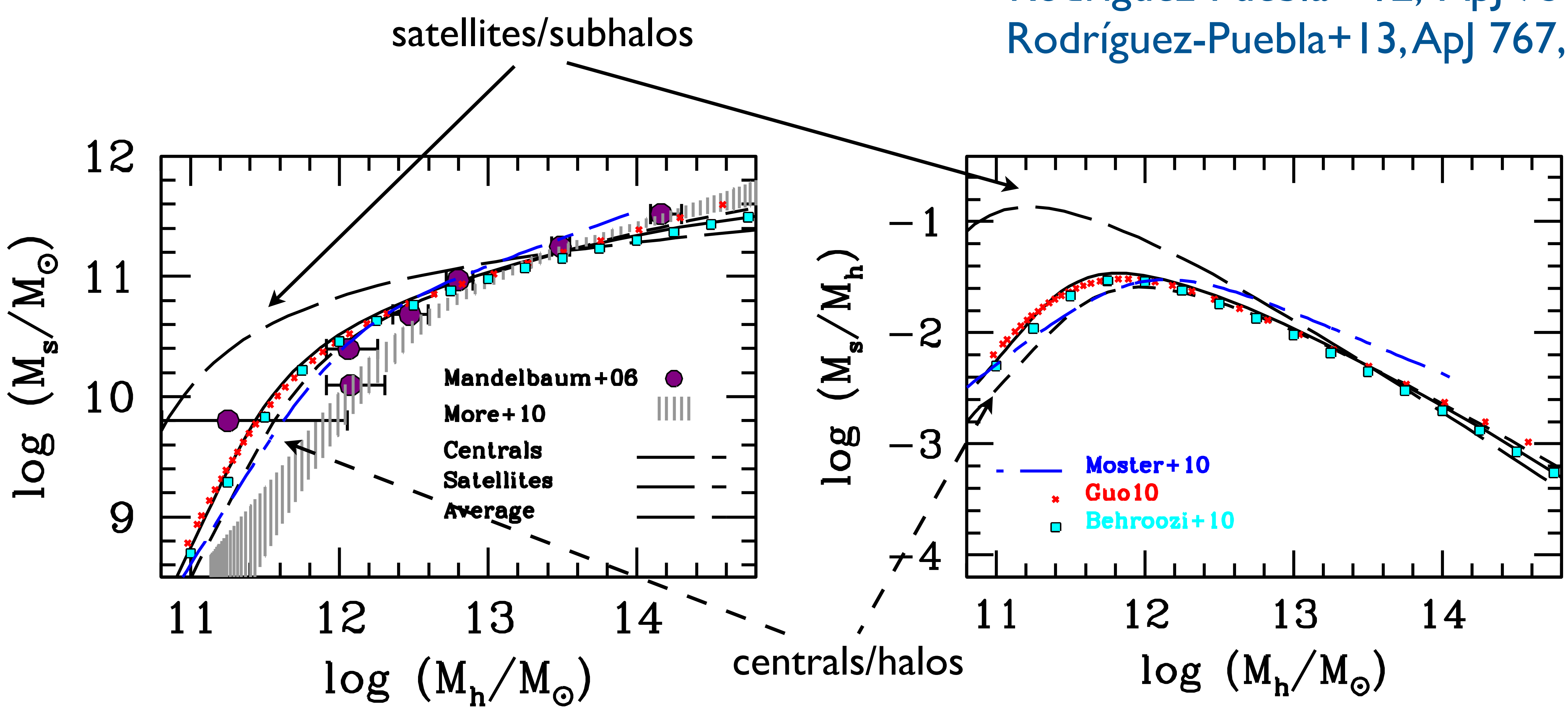
M_s/M_h ~ efficiency of galaxy stellar mass growth in a given halo



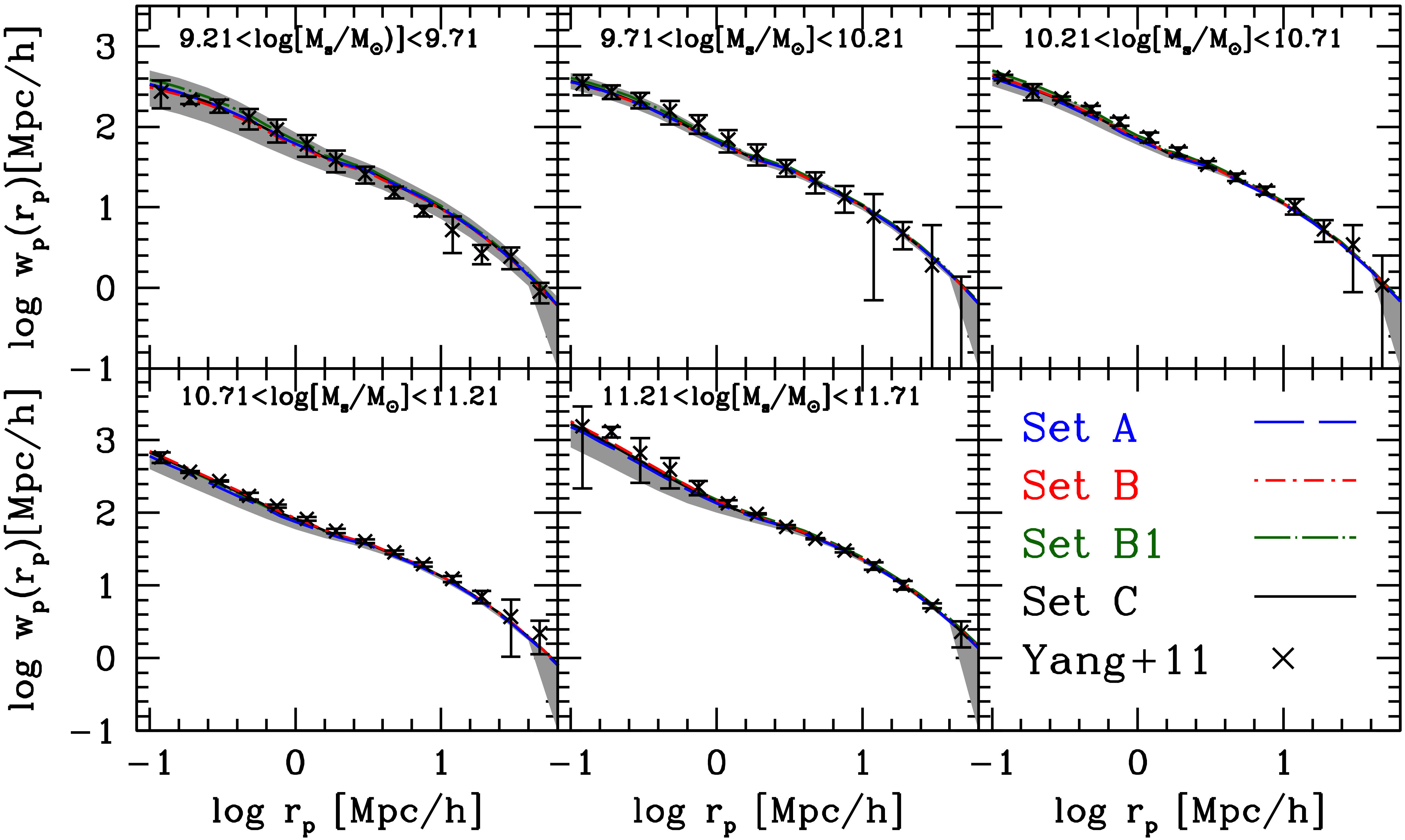
Combining the abundance matching w/Halo Occupation model and the Conditional Mass Function formalism:

One takes into account centrals/satellites and the 2-point Correlation Function: the M_s-M_h relation remains almost the same but it improves on the uncertainties

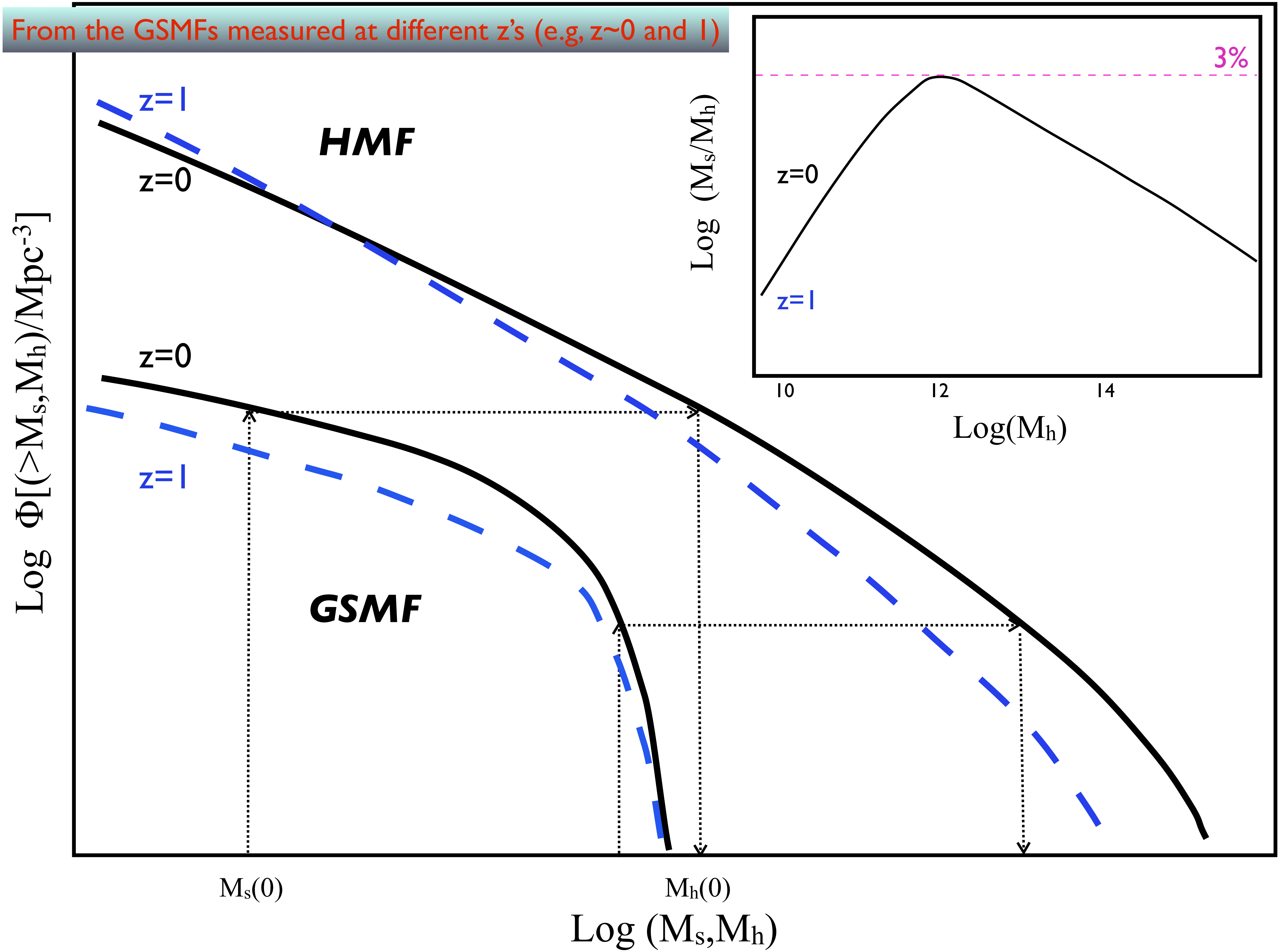
Rodríguez-Puebla+ 12, ApJ 756,2
Rodríguez-Puebla+13, ApJ 767, 92



Projected correlation function (sampled in different stellar mass bins)

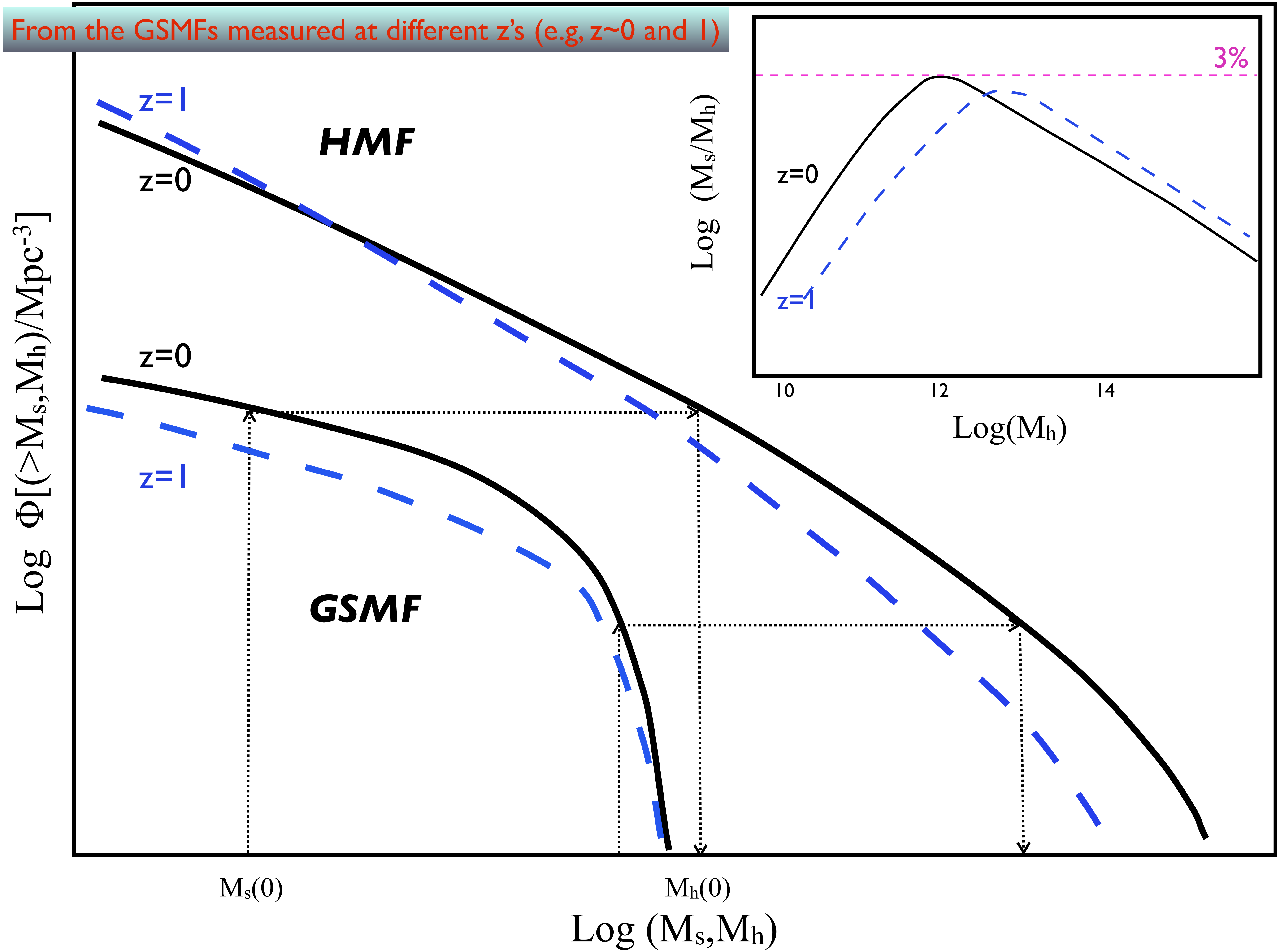


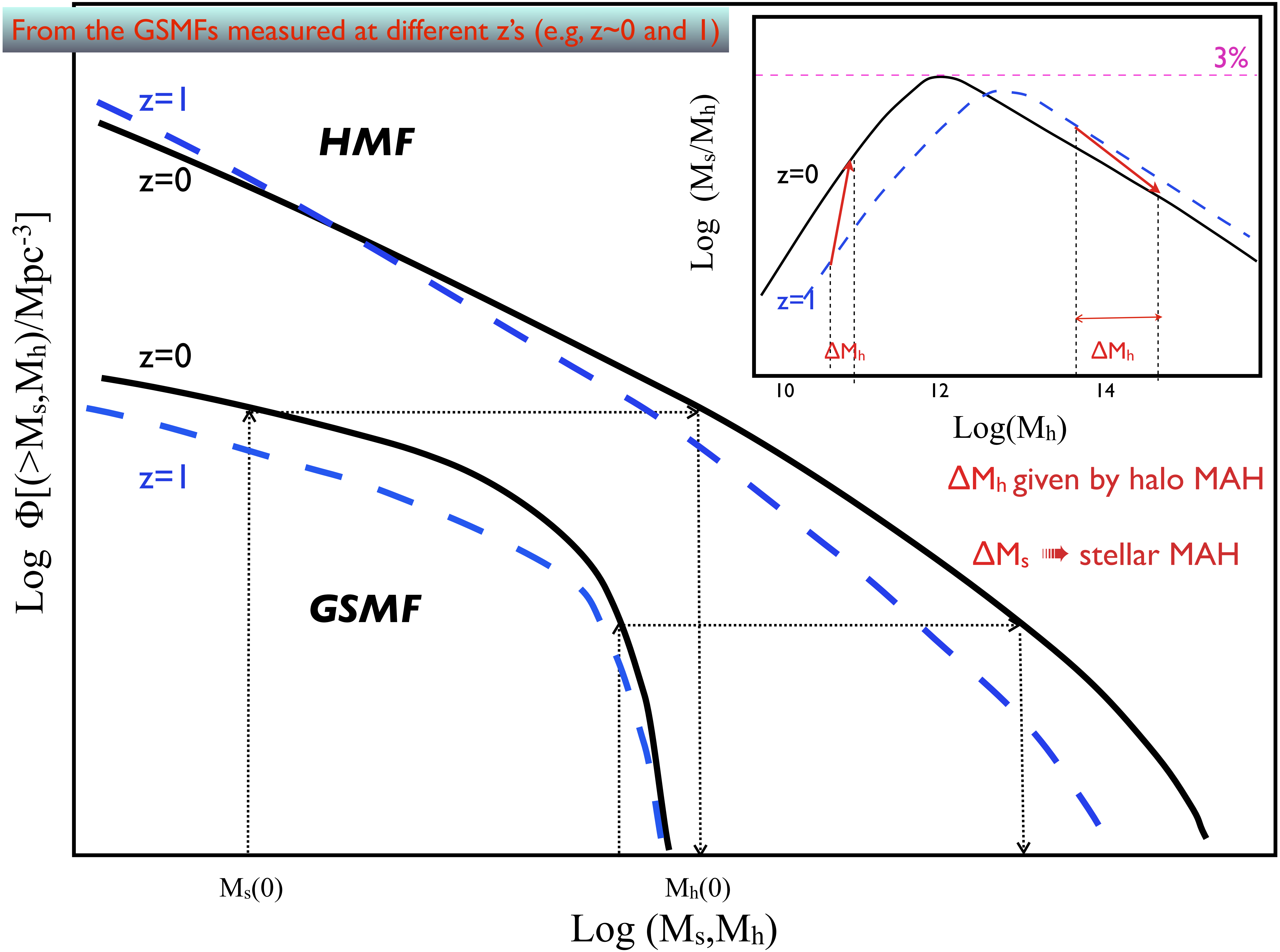
The semi-empirical model, through the galaxy-halo connection, describes very well the observed central/satellite GSMFs, 2-point correlations functions and satellite CSMFs *(Rodríguez-Puebla+13)*



From the GSMFs measured at different z's (e.g, z~0 and 1)
HMF
z=1
z=0
z=0
z=1
GSMF
3%
Log (Ms/Mh)
z=0
z=1
10
12
14
Log(Mh)
Log Φ[(>Ms,Mh)/Mpc-3]
Ms(0)
Mh(0)
Log (Ms,Mh)

From the GSMFs measured at different z's (e.g, z~0 and 1)





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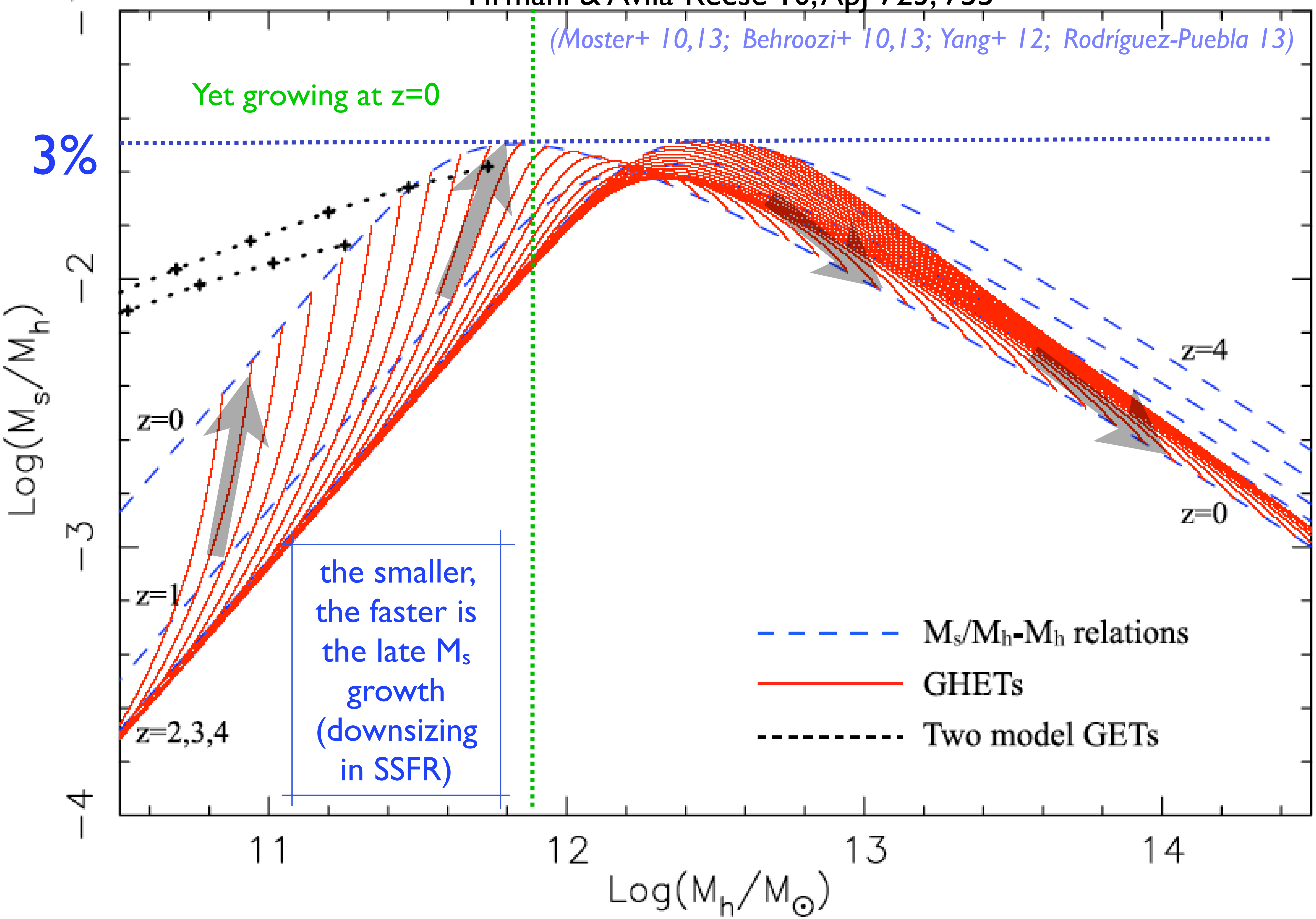
z=1
HMF
z=0
z=0
z=1
GSMF
Log Φ[(>Ms,Mh)/Mpc-3]
Ms(0)
Mh(0)
Log (Ms,Mh)
3%
Log (Ms/Mh)
z=0
z=1
ΔMh
ΔMh
10
12
14
Log(Mh)
ΔMh given by halo MAH
ΔMs ➟ stellar MAH

Stellar mass downsizing vs halo mass upsizing (?)

Firmani & Avila-Reese 10, ApJ 723, 755



Stellar mass downsizing vs halo mass upsizing (?)

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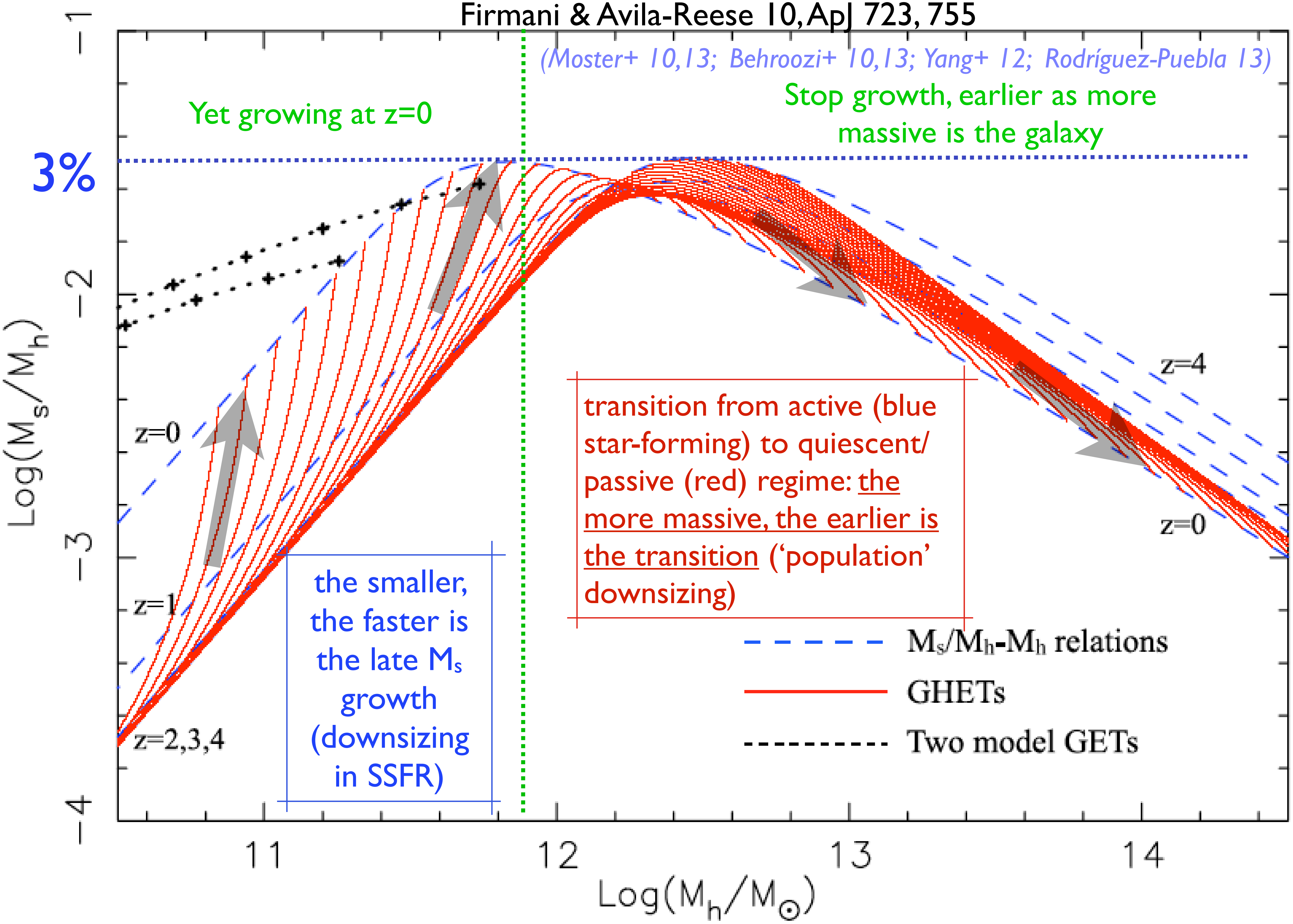
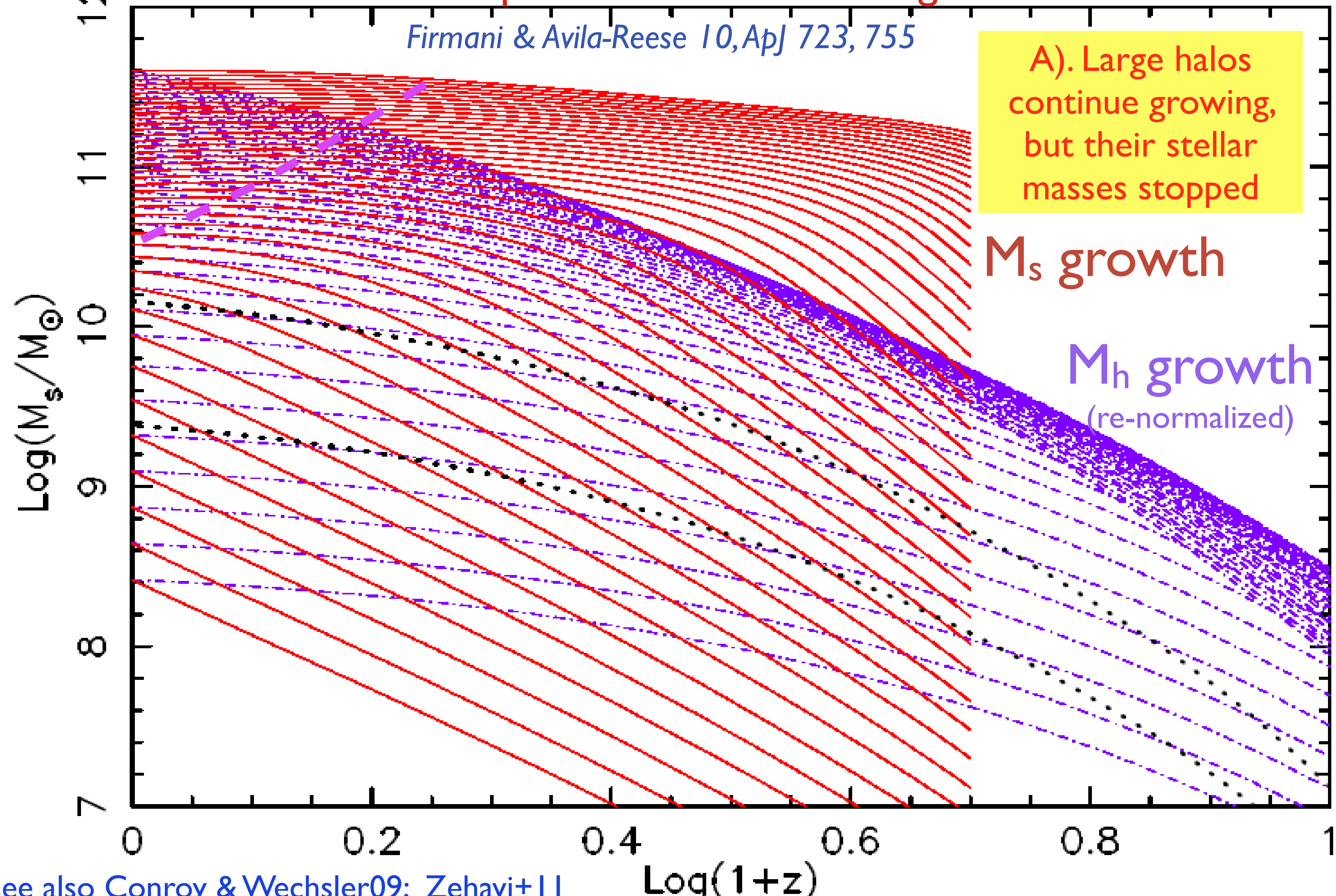


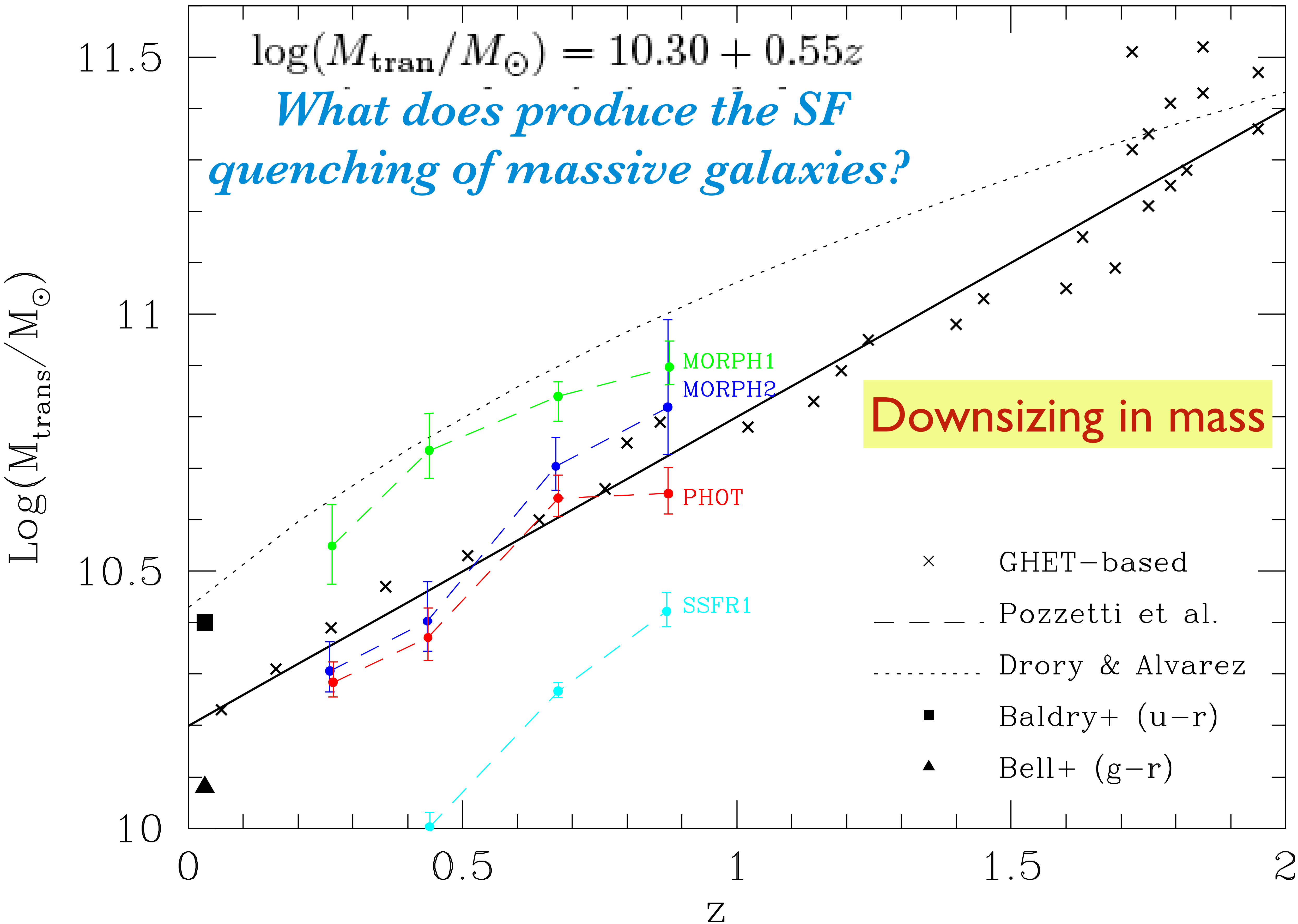
Semi-empirical inferences of M_s growth



see also Conroy & Wechsler09; Zehavi+11

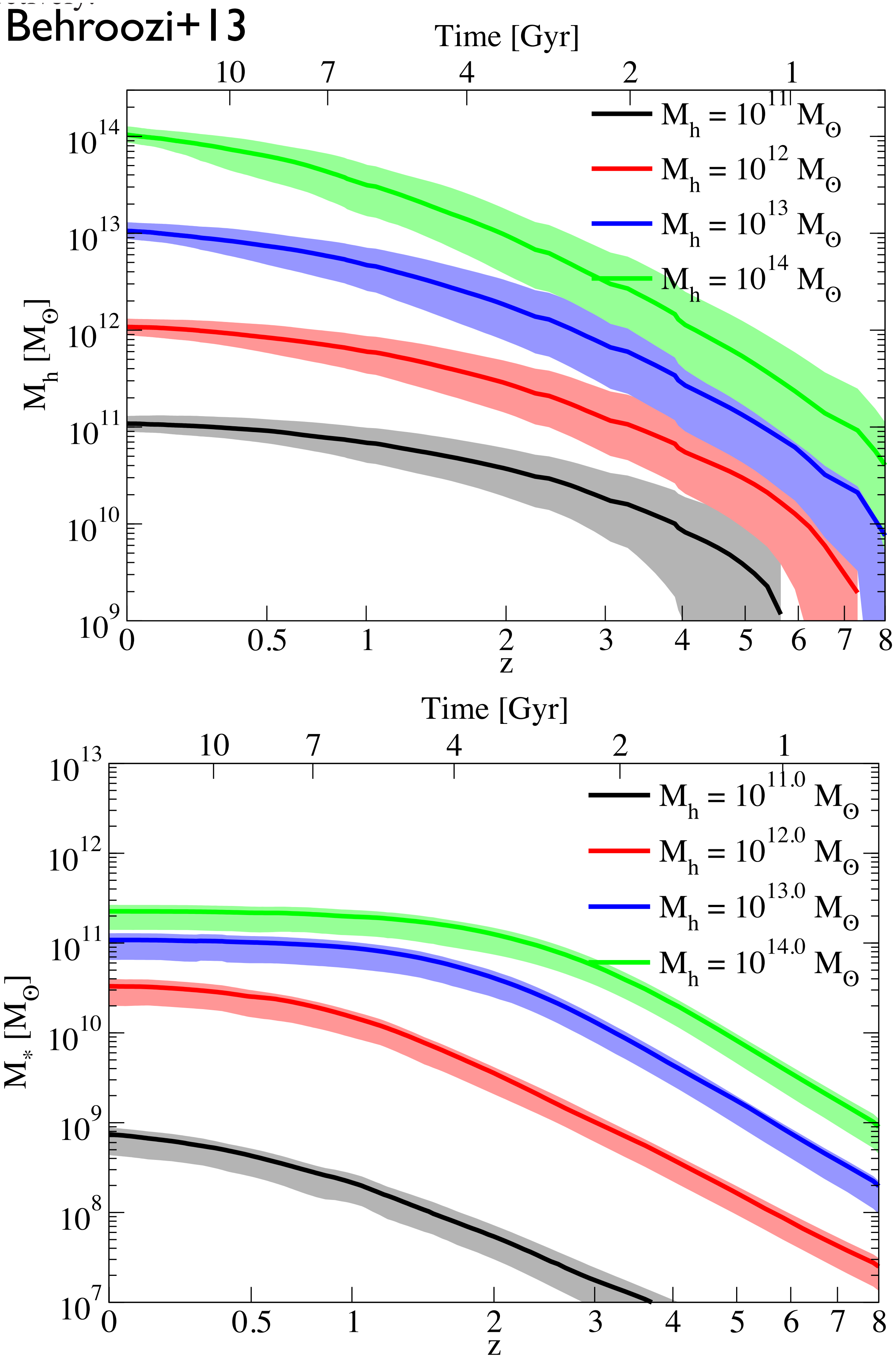
B). Small halos assemble earlier than more massive ones BUT their stellar masses assemble much later (downsizing in SSFR).

A) Characteristic mass of transition from active to passive regime (when the SSFR strongly falls)



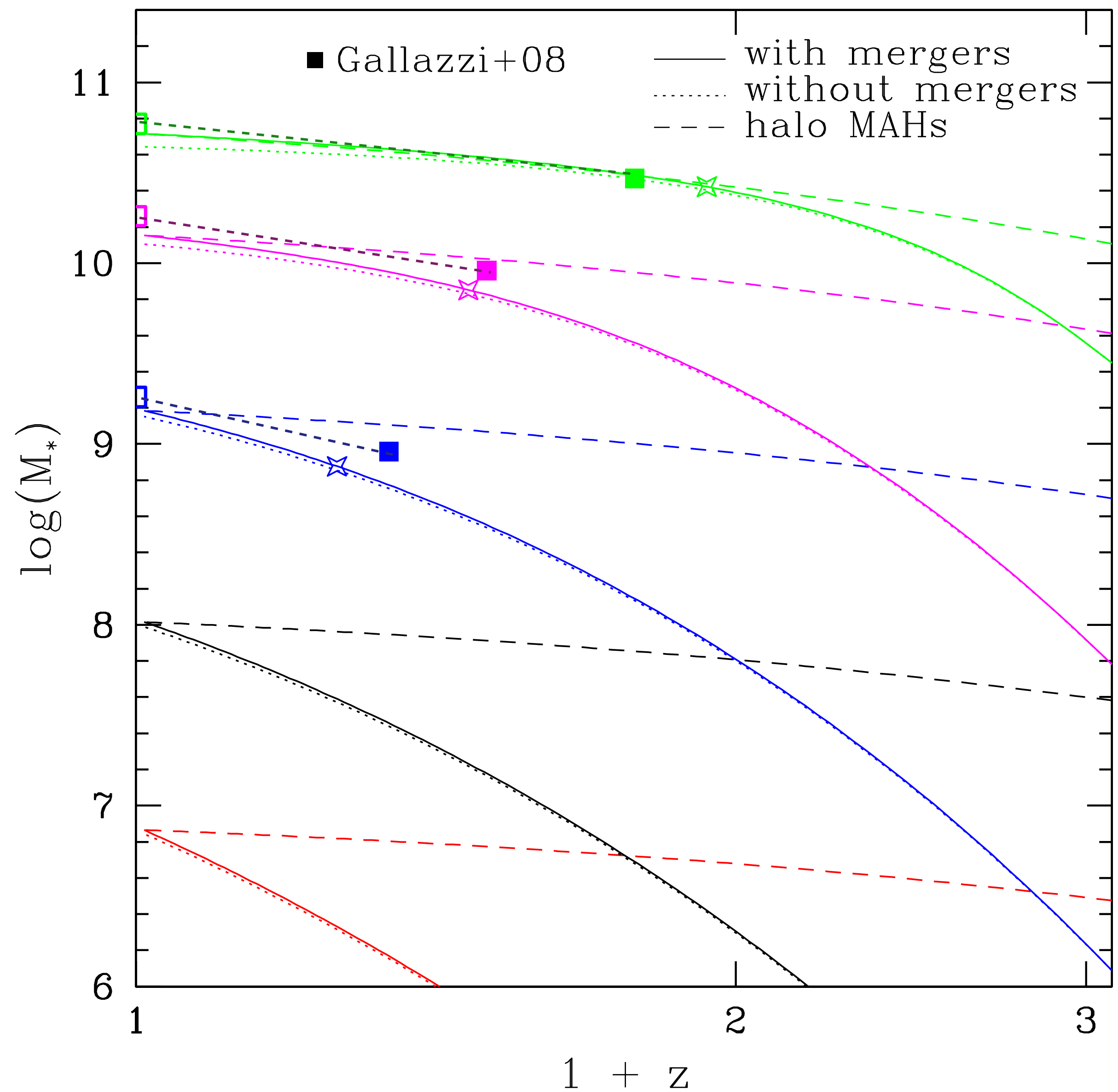
Another inference

Behroozi+13



Archeological (SPS) inferences

Present-day SEDs + SPS: M_s growth inference

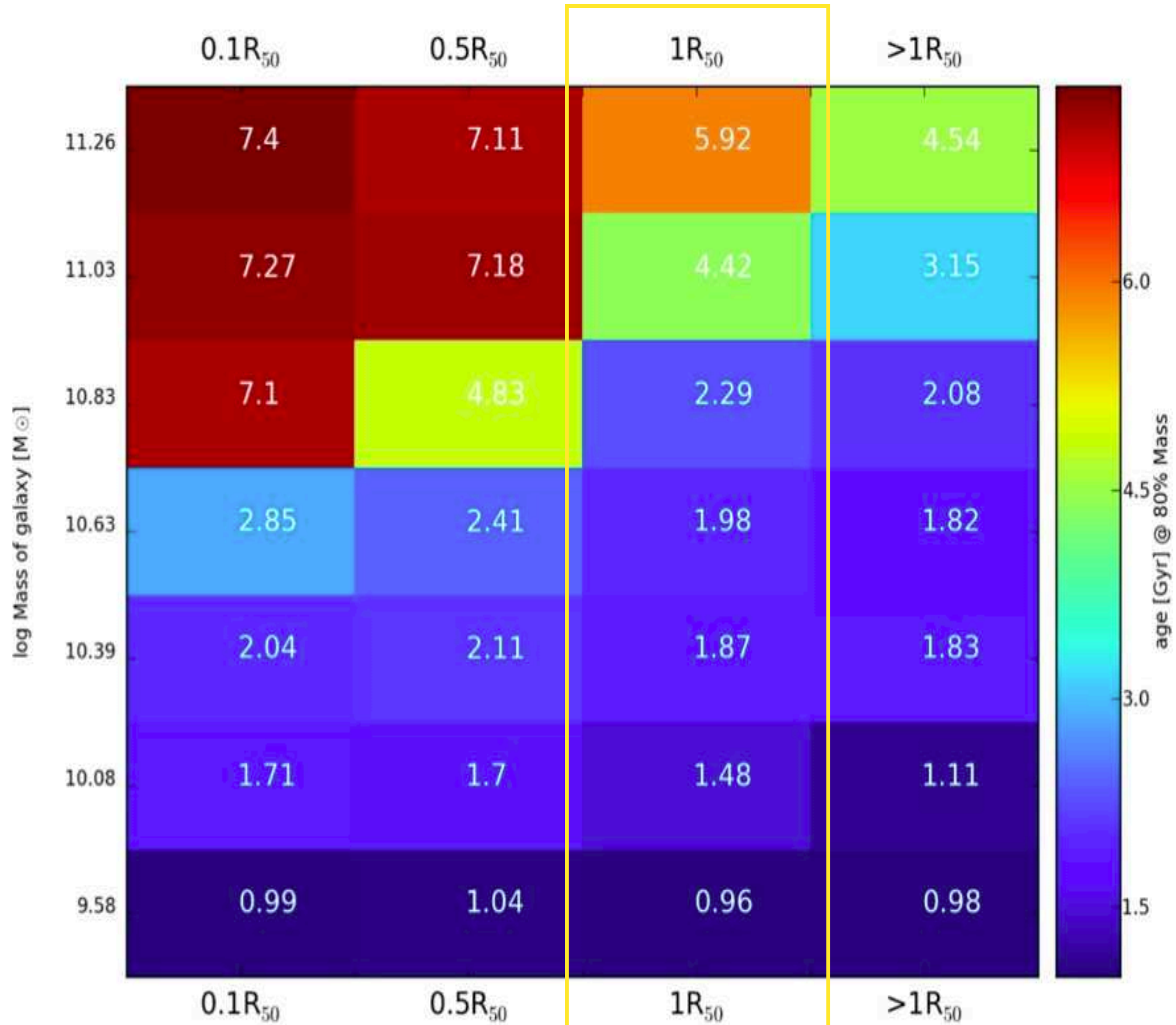


Look-back time-based vs archeological inferences

(de Rossi+ 13, MNRAS, accepted)

Perez+ 2013, ApJL (CALIFA + STARLIGHT)

look-back time at which 80% of M_s has been attained



IFS allows to infer not only the whole galaxy M_s growth, but resolved at different radii!

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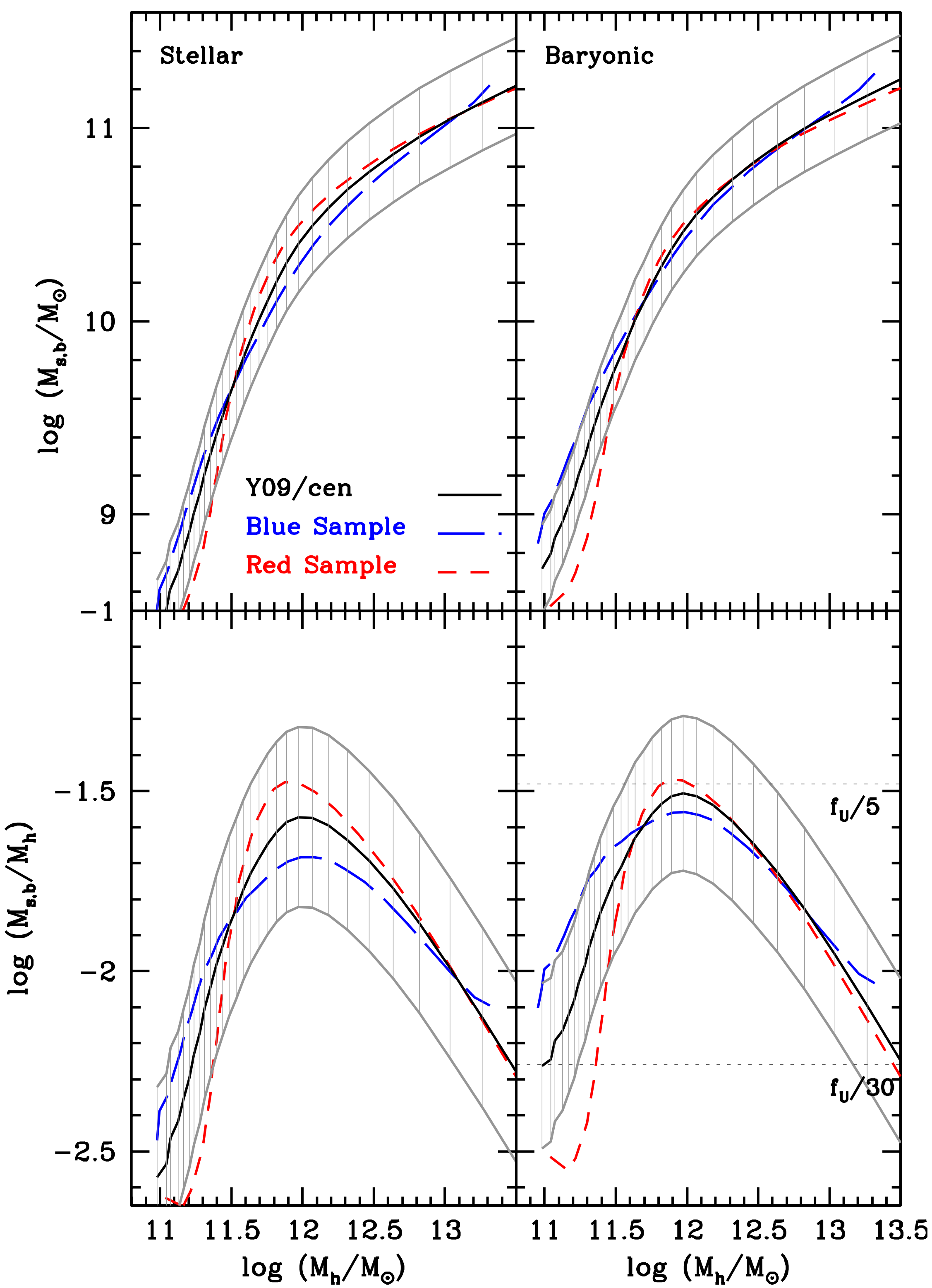
Mapping the M_s-M_h (or M_b-M_h) relation onto the scaling relations of disk galaxies

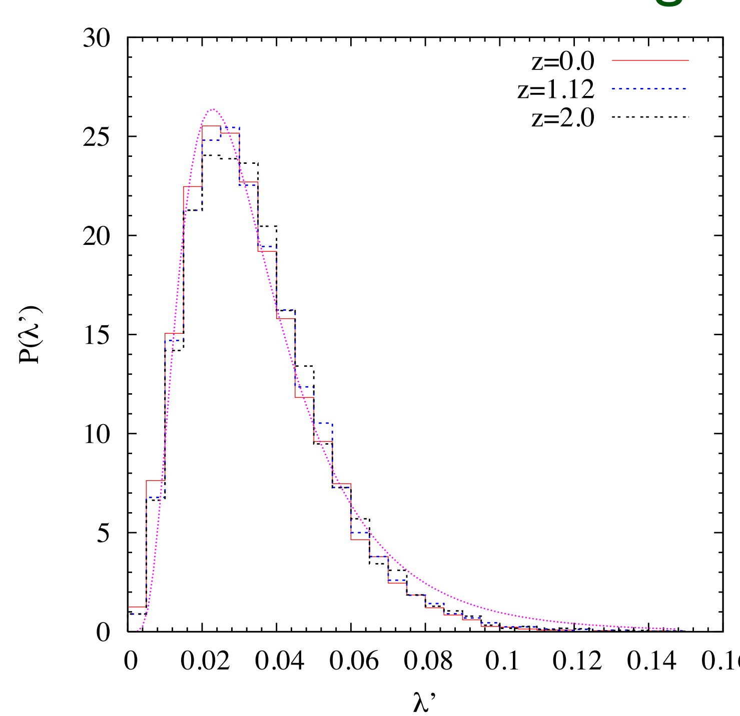
Rodríguez-Puebla+ 11: SHMR for blue & red galaxies



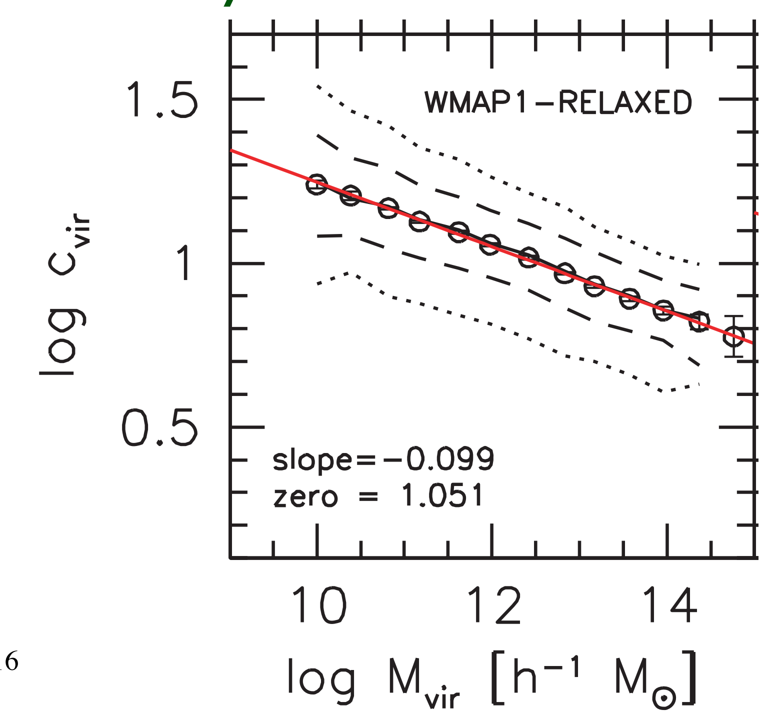
Model for seeding disk galaxies in centr. eq. inside CDM halos, taking into account the halo contraction and star formation (improved Mo-Mao-White model).

Initial conditions: halo M_h, spin parameter λ, concentration & baryon fraction (blue gal's)

from cosmological N-body simulations



lognormal distributed, <λ>~0.03, no Mh dependence



c_{vir} depends on Mh, wide lognormal distribution

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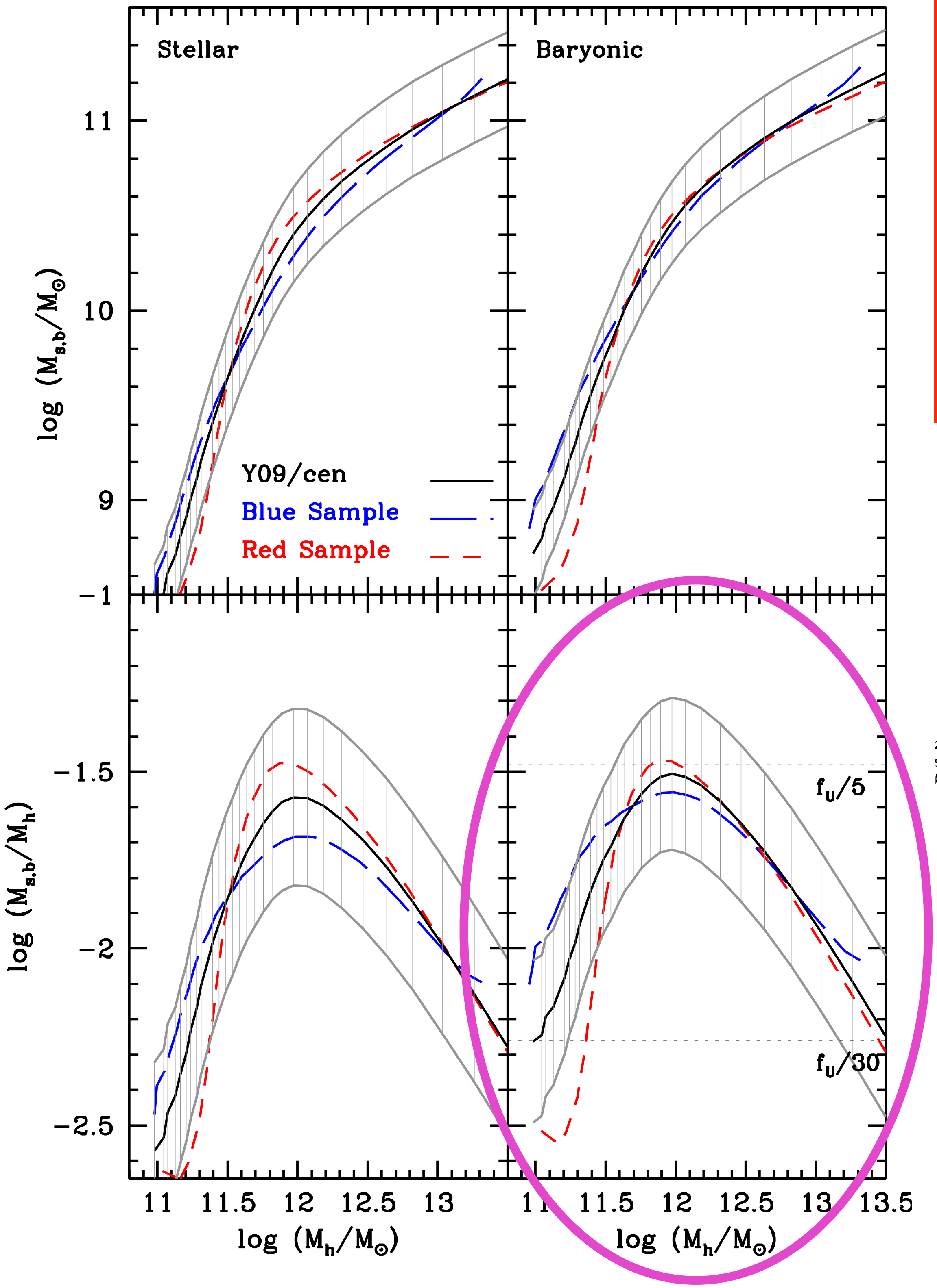

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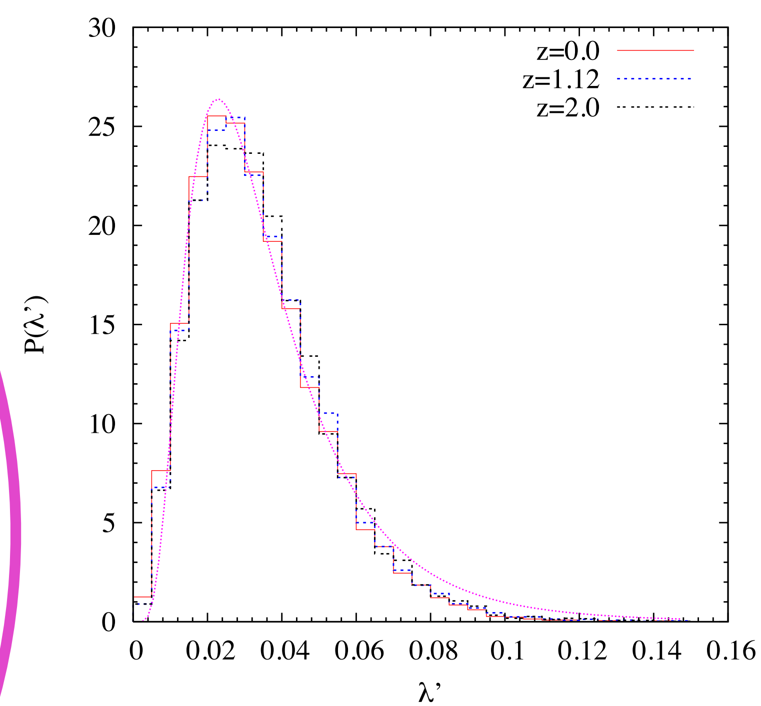
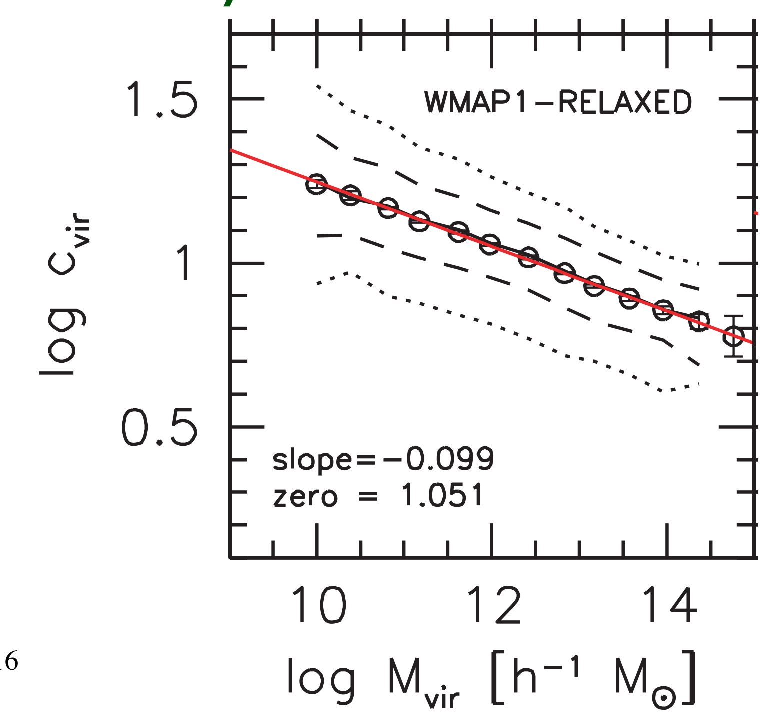


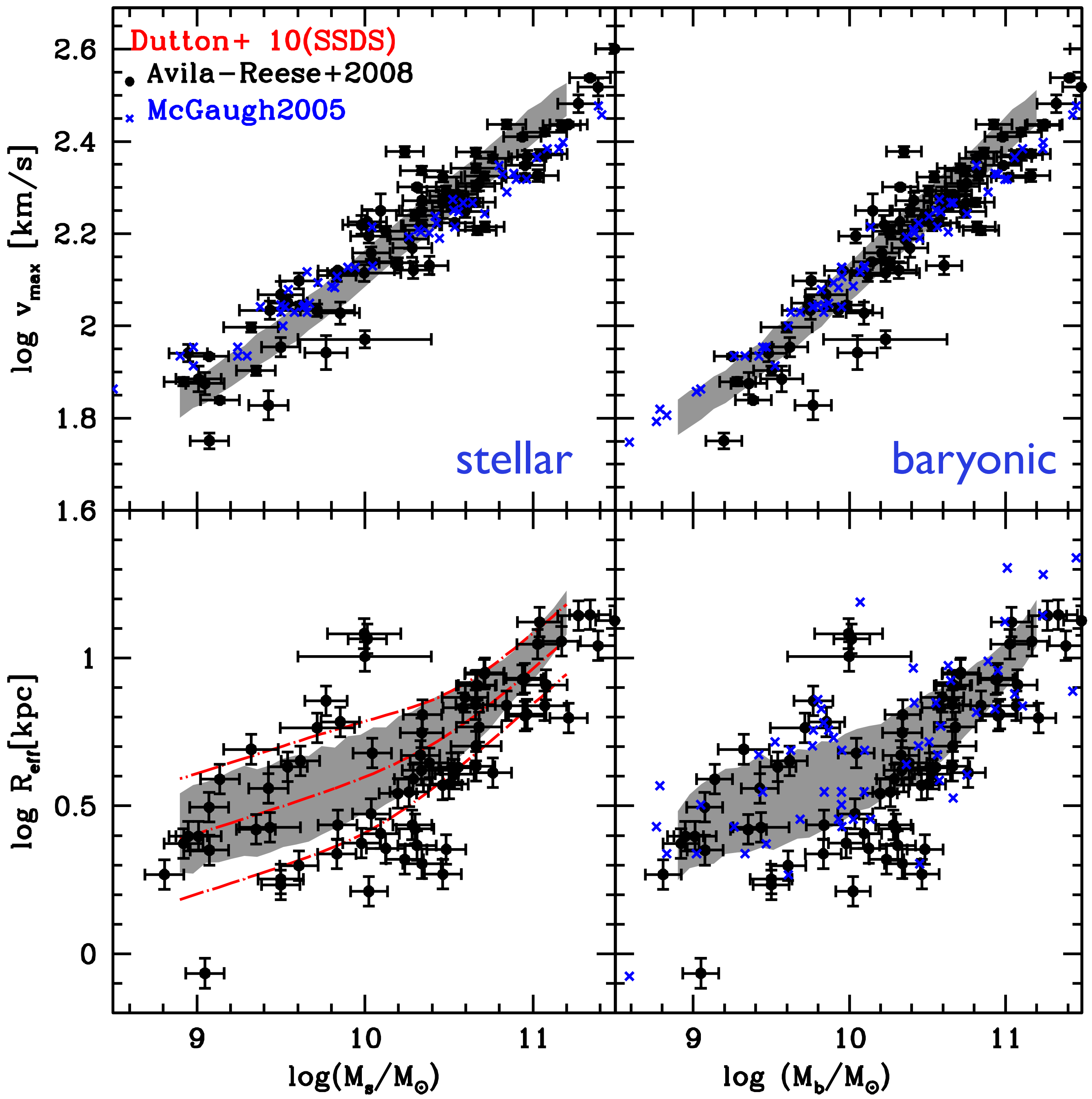
lognormal distributed, $\langle\lambda\rangle \sim 0.03$, no Mh dependence



c_{vir} depends on Mh, wide lognormal distribution

Disks are loaded in a population of CDM halos *(Rodríguez-Puebla 13)*

Scaling relations



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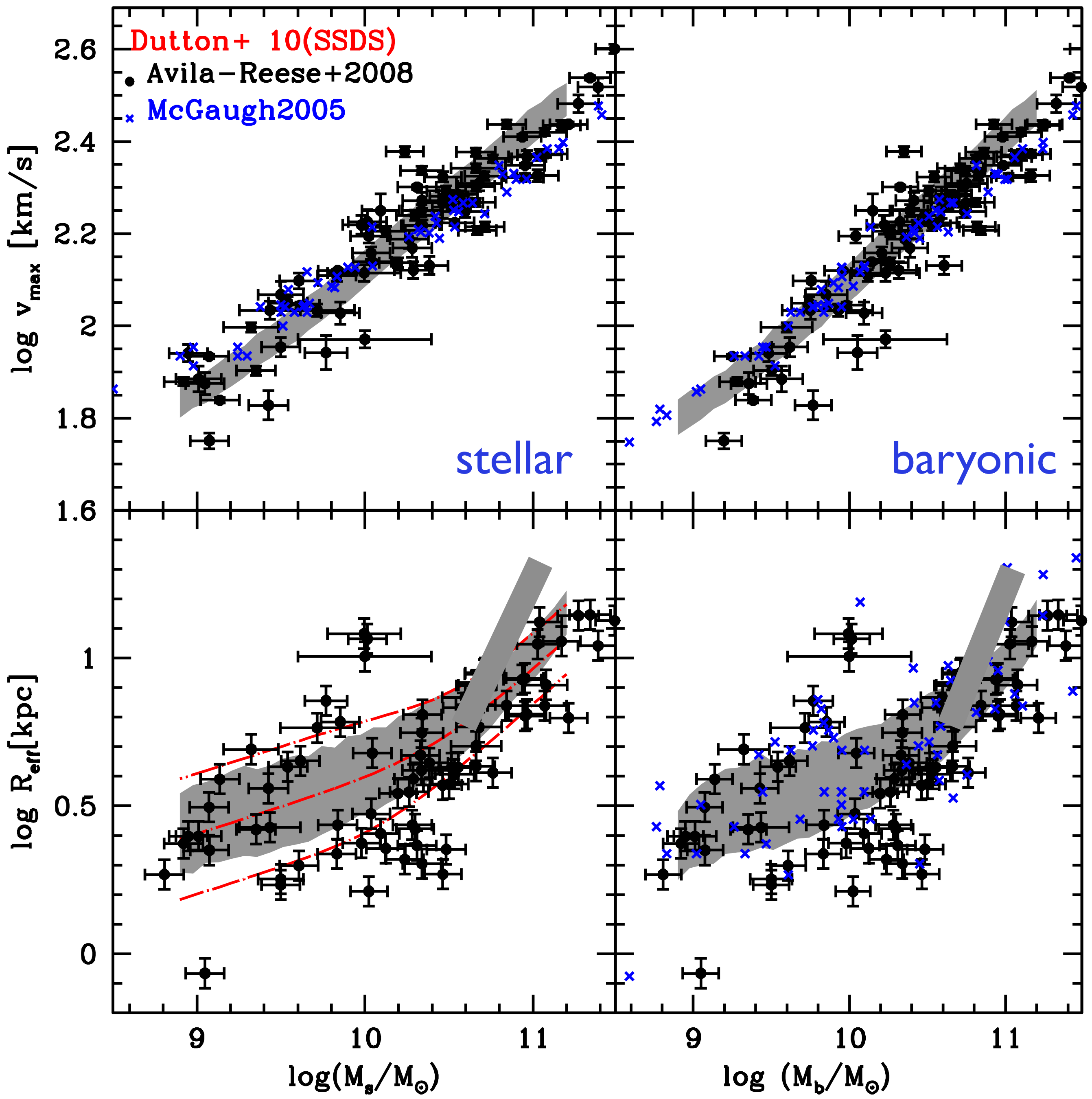

<λ> is reduced as M_h is larger (massive galaxies had major mergers--> transfer of ang.mom.)

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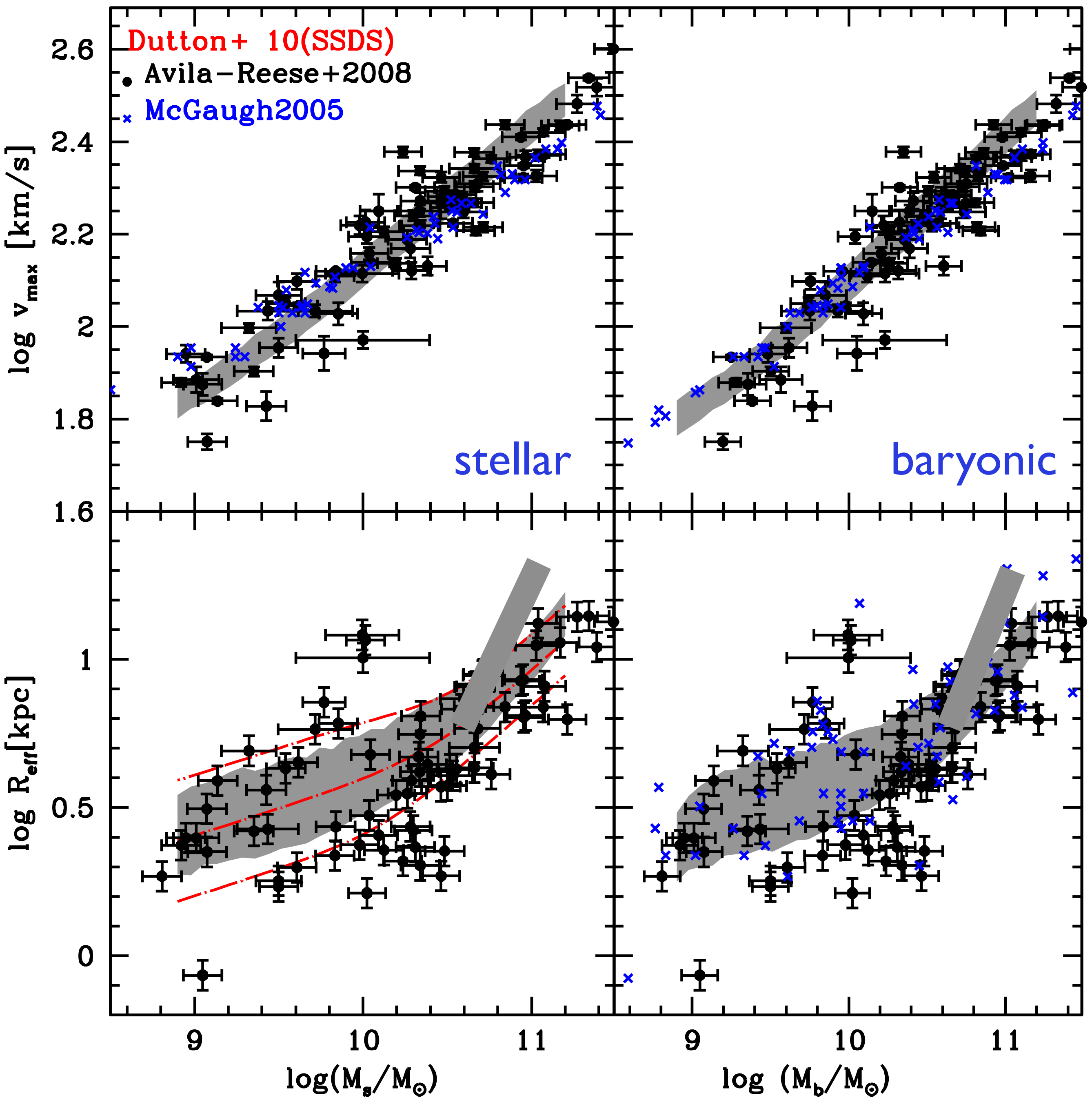

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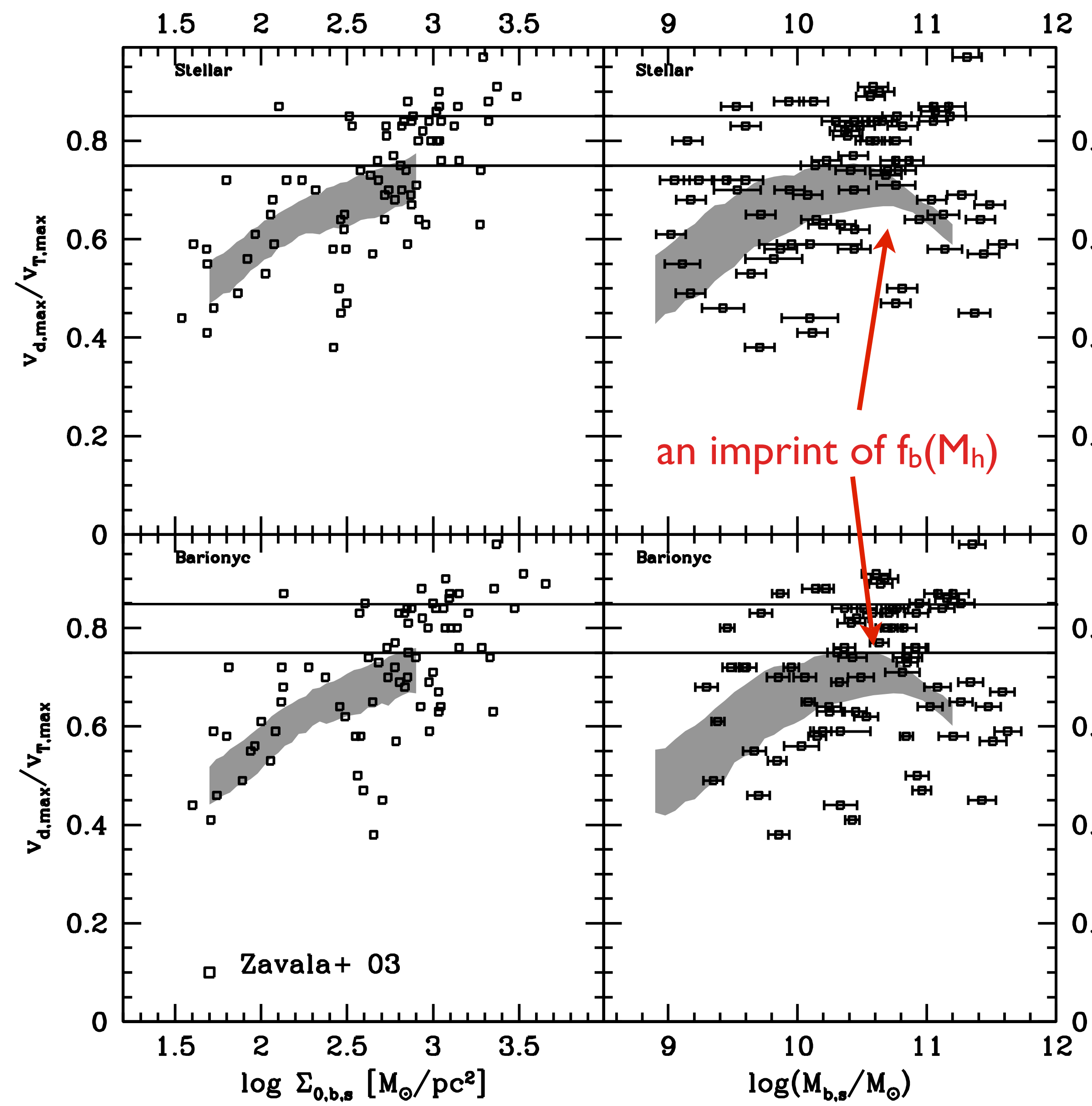
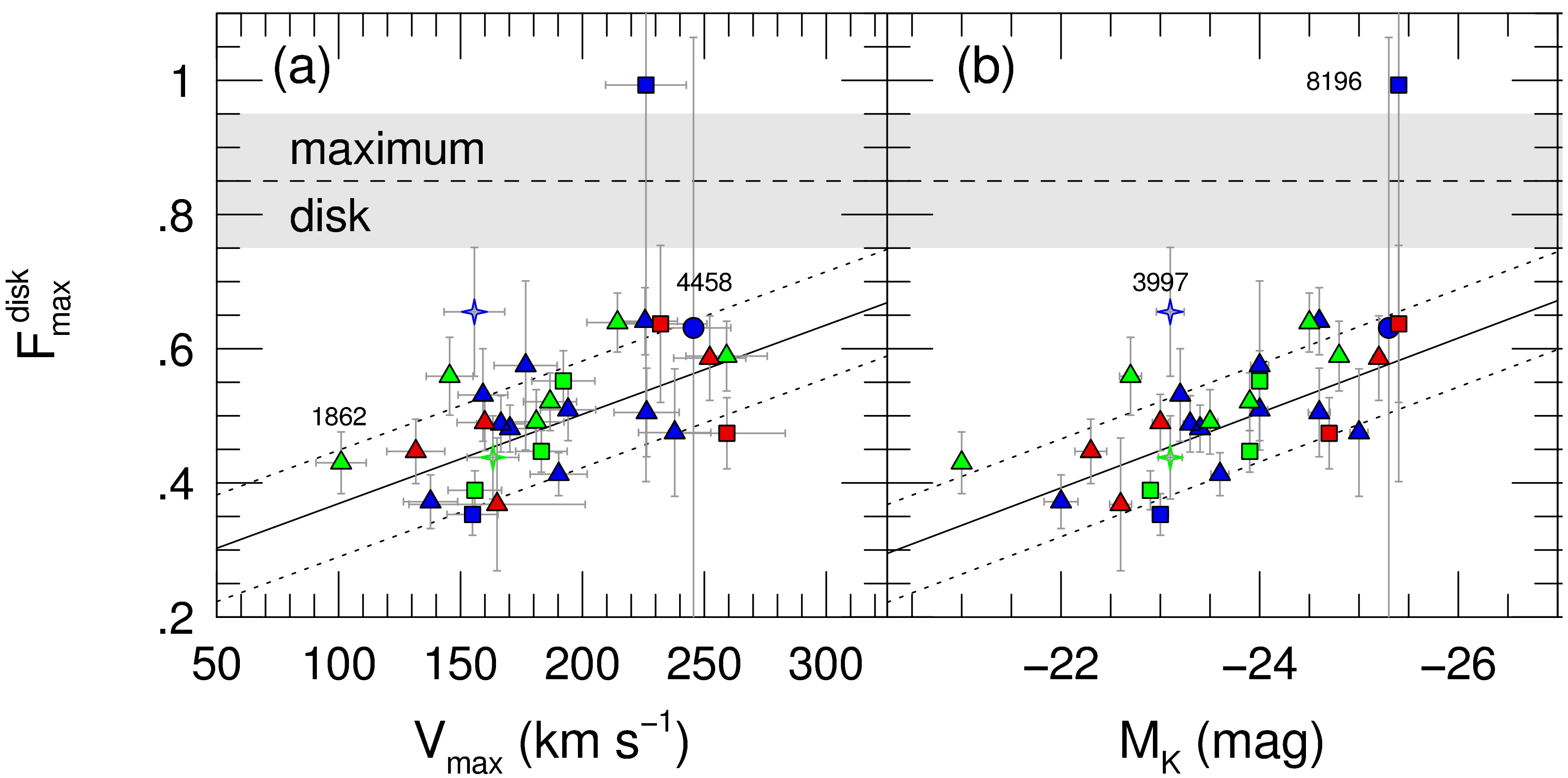
Disk-to-dyn. mass ratio



All gal's (1σ) are submaximal!

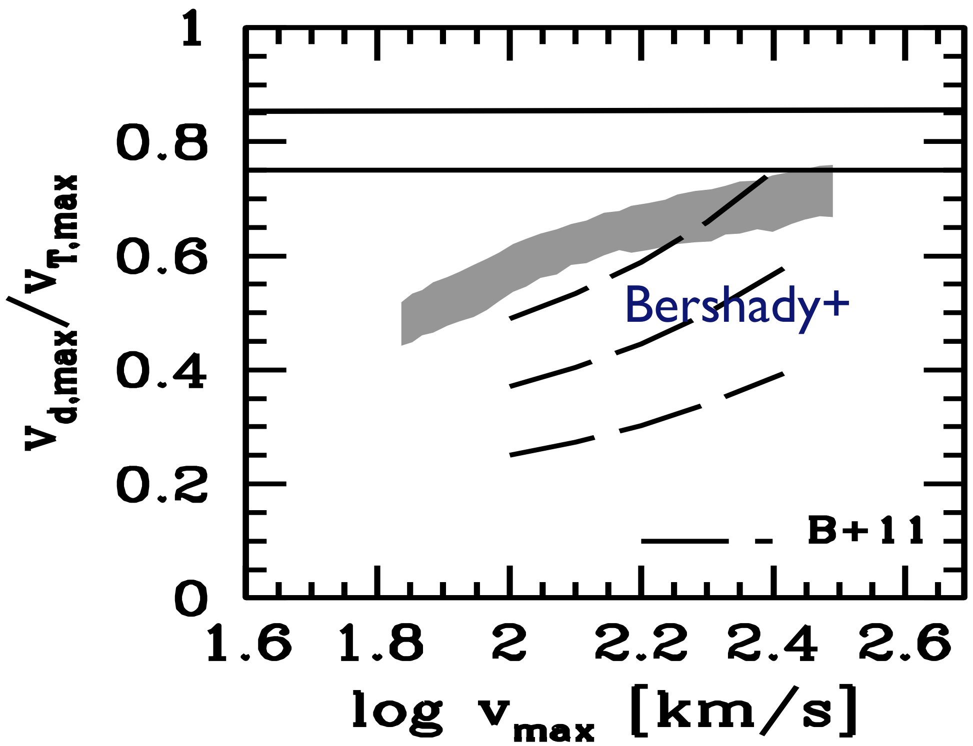
Observations: 81 gal's from the literature (Zavala+03 & Avila-Reese+08). V_d inferred from photometry

Recent accurate measures of disk mass --> V_d calculated directly *(see Kyle's talk)*



Bershady+11, from the DiskMass Survey, w/IFS

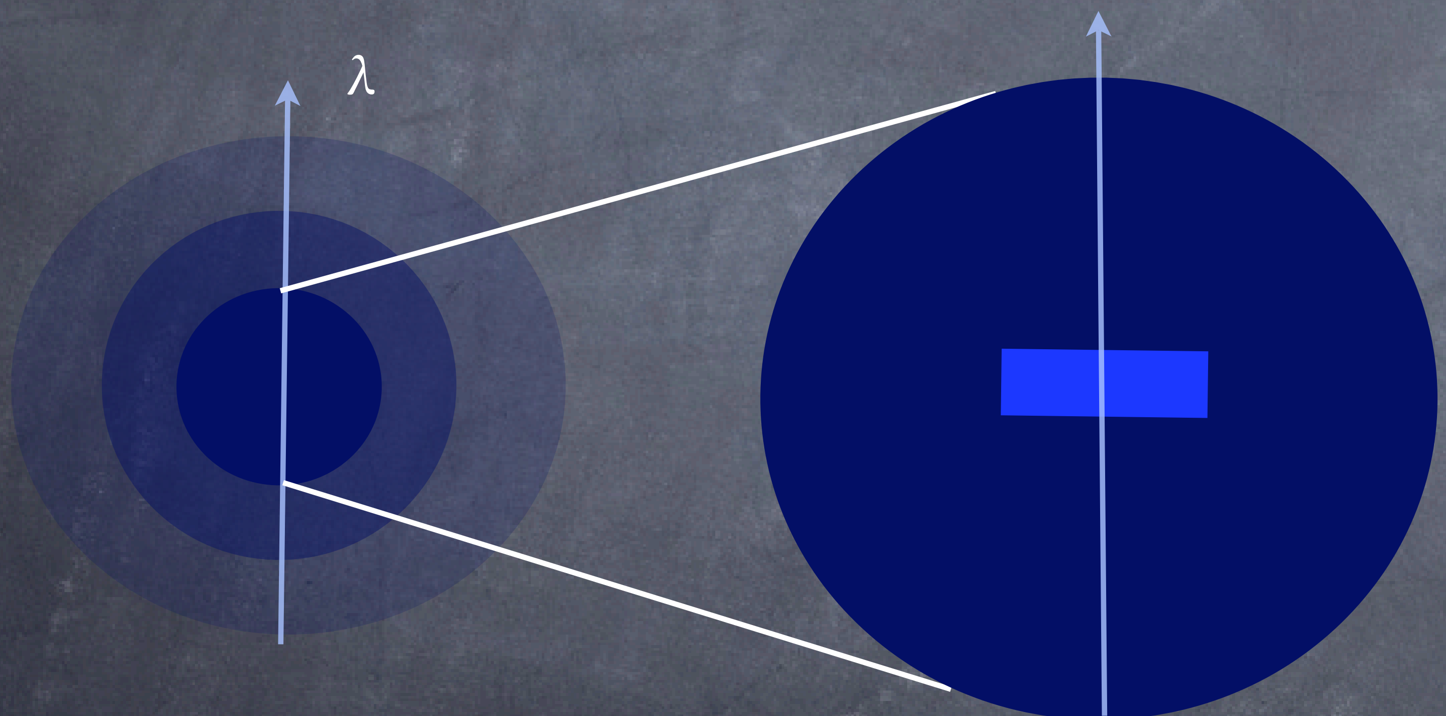
Model prediction



- Real gal's are more dark matter dominated than those formed in CDM halos?
- The adiabatic contraction should be stronger than in the model? *(Dutton+07, 11 claim that instead of AC there is an adiabatic expansion!)*
- More observational data are needed; ***IFS surveys may provide them! (V_{max}, σ, R_e, M_s, Σ, M_{dyn})***

The evolution of disk galaxies

•Semi-numerical evolutionary models allow to simulate the internal evolution of disk galaxies inside growing CDM halos and to model pop's of galaxies.



Cosmology + LCDM power spectrum ➟ Hierarchical halo mass and angular momentum growing

Gas cooling and infall & disk in centrifugal equilibrium formation. Halo adiabatic contraction

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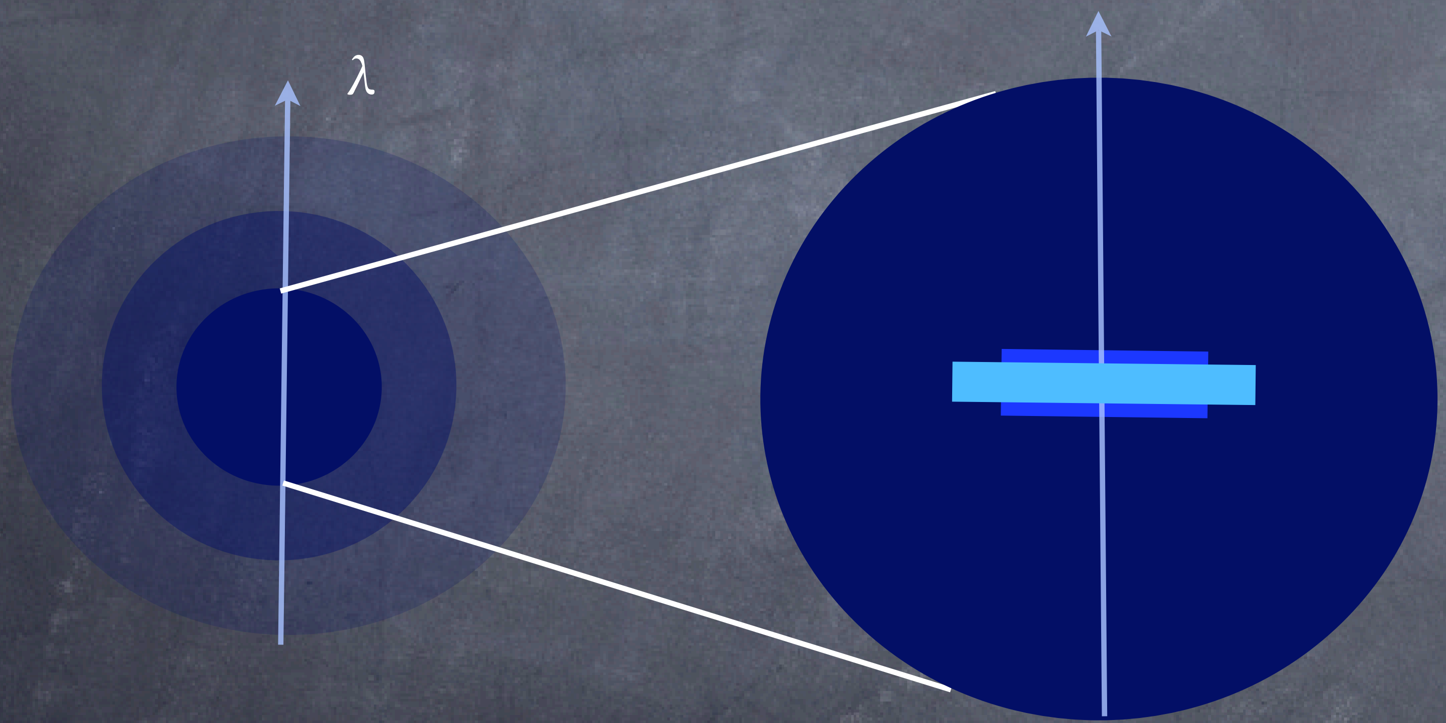

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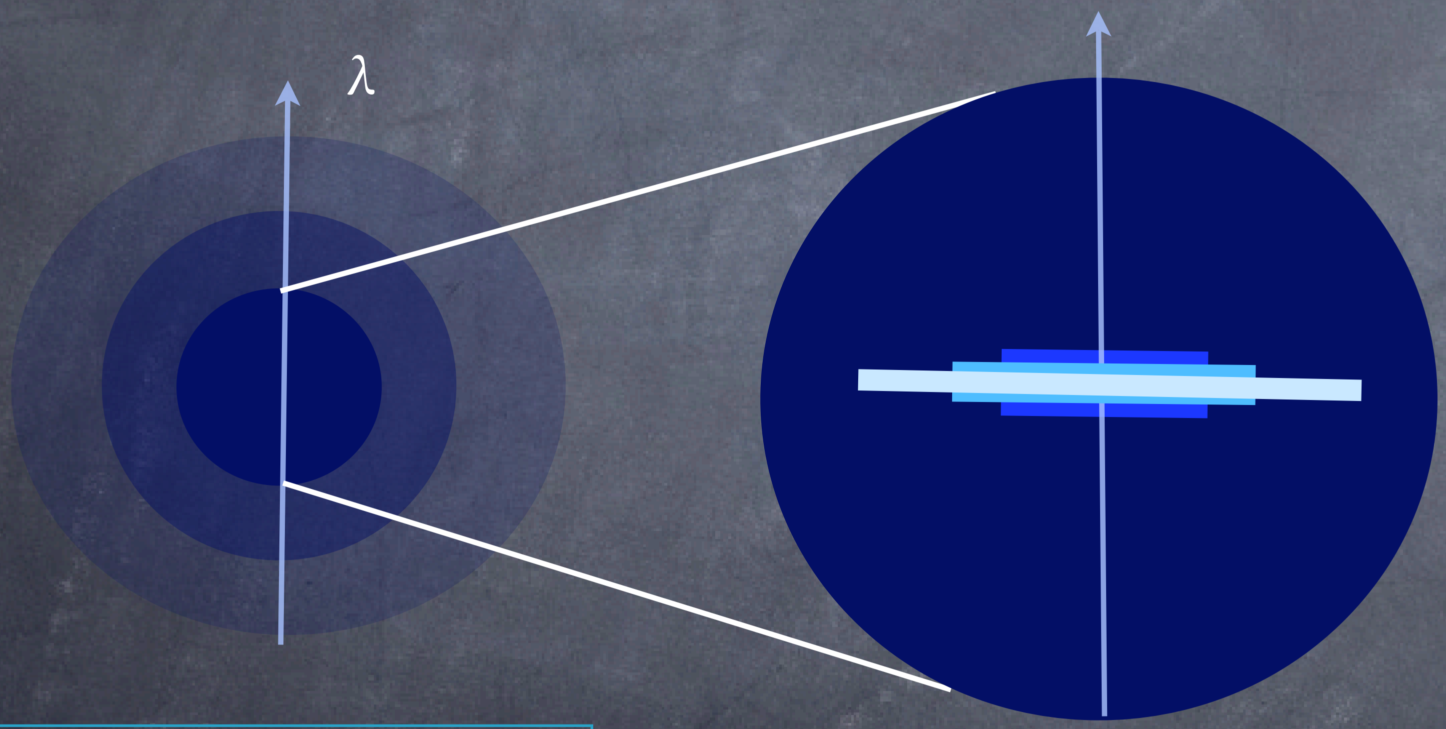

Cosmology + LCDM power spectrum ➟ Hierarchical halo mass and angular momentum growing

Gas cooling and infall & disk in centrifugal equilibrium formation. Halo adiabatic contraction

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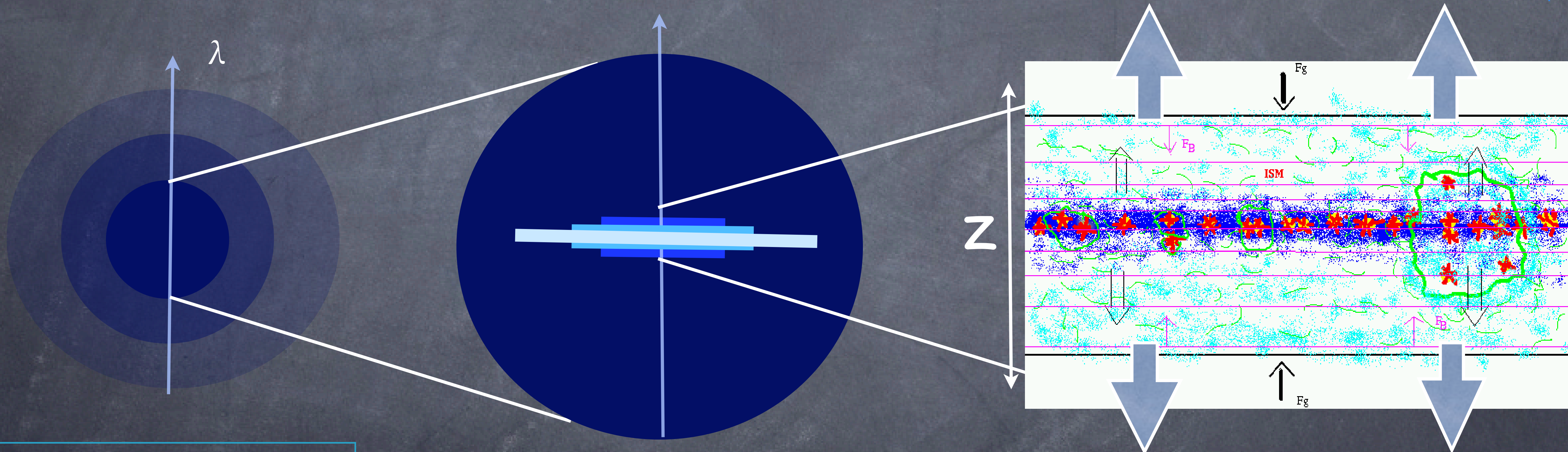

Cosmology + LCDM power spectrum ➡ Hierarchical halo mass and angular momentum growing

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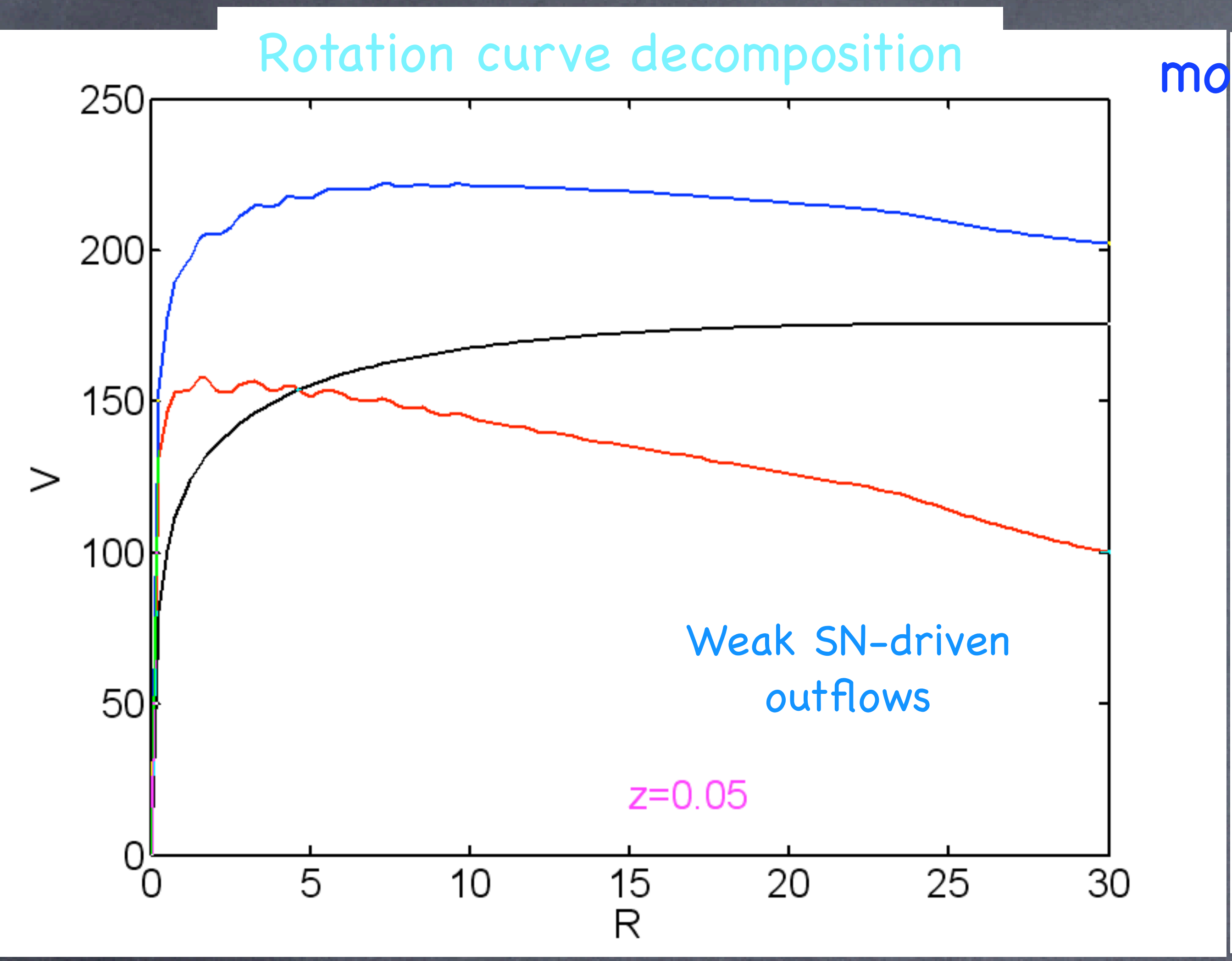
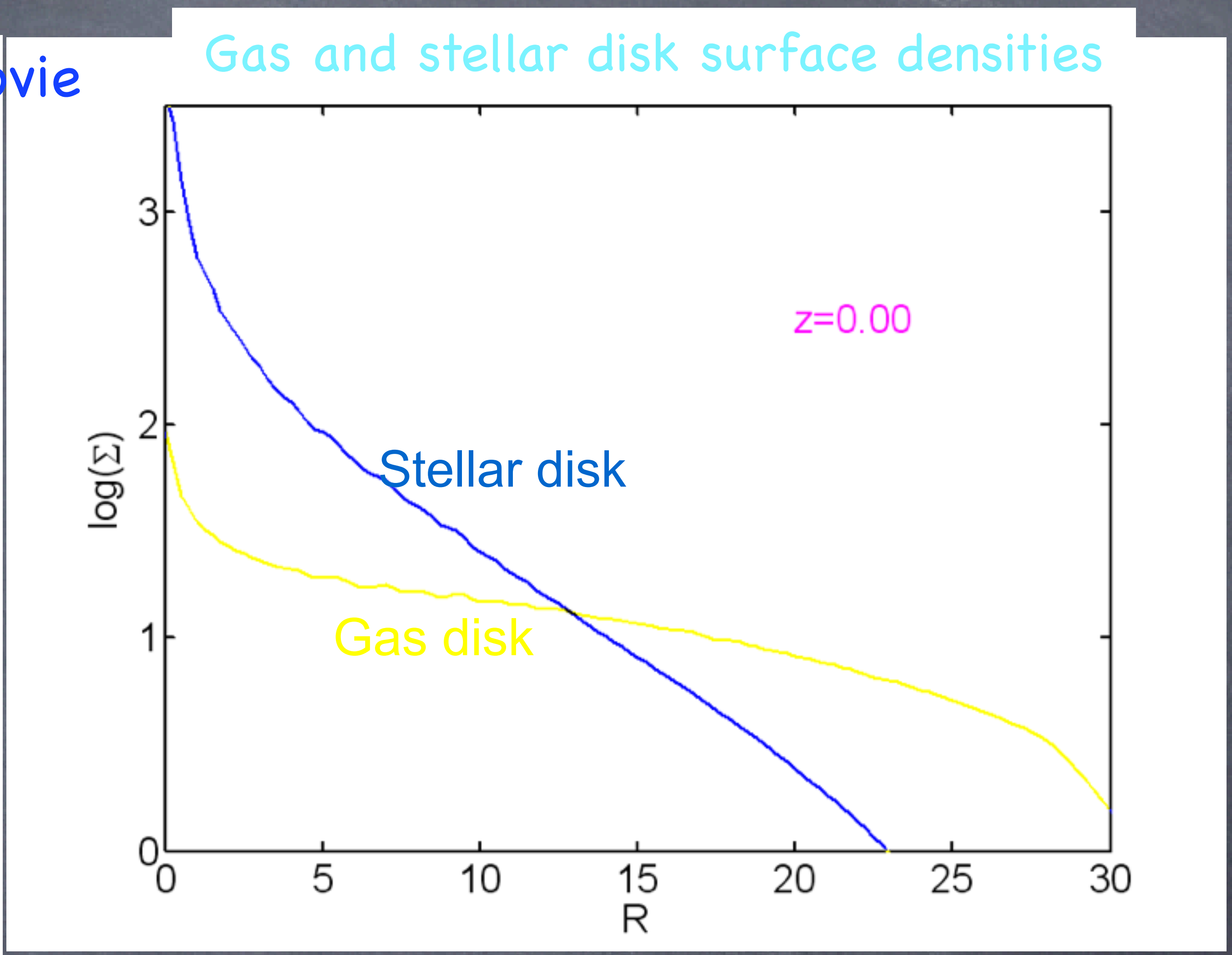
Toomre instability parameter + **vertical** E balance *(SN feedback and turbulent dissipation)* = **self-regulated SF.** Outflows

The model in action

Firmani & Avila-Reese 00; Avila-Reese+ 00, 08; Firmani+ 10



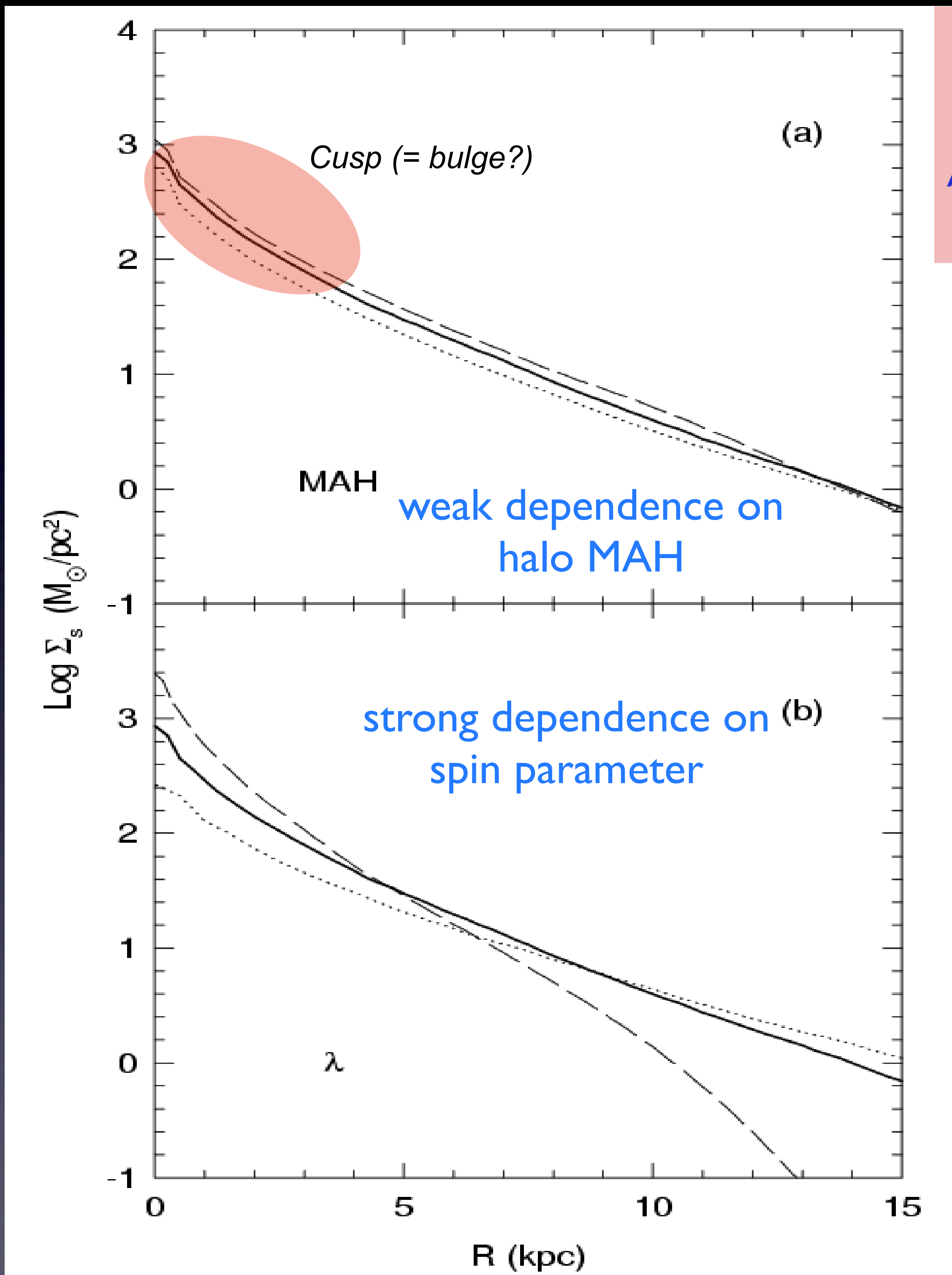
movie



Inside-out disk galaxy formation. The SD profiles of stars, light and gas are different: R_d increases, respectively.

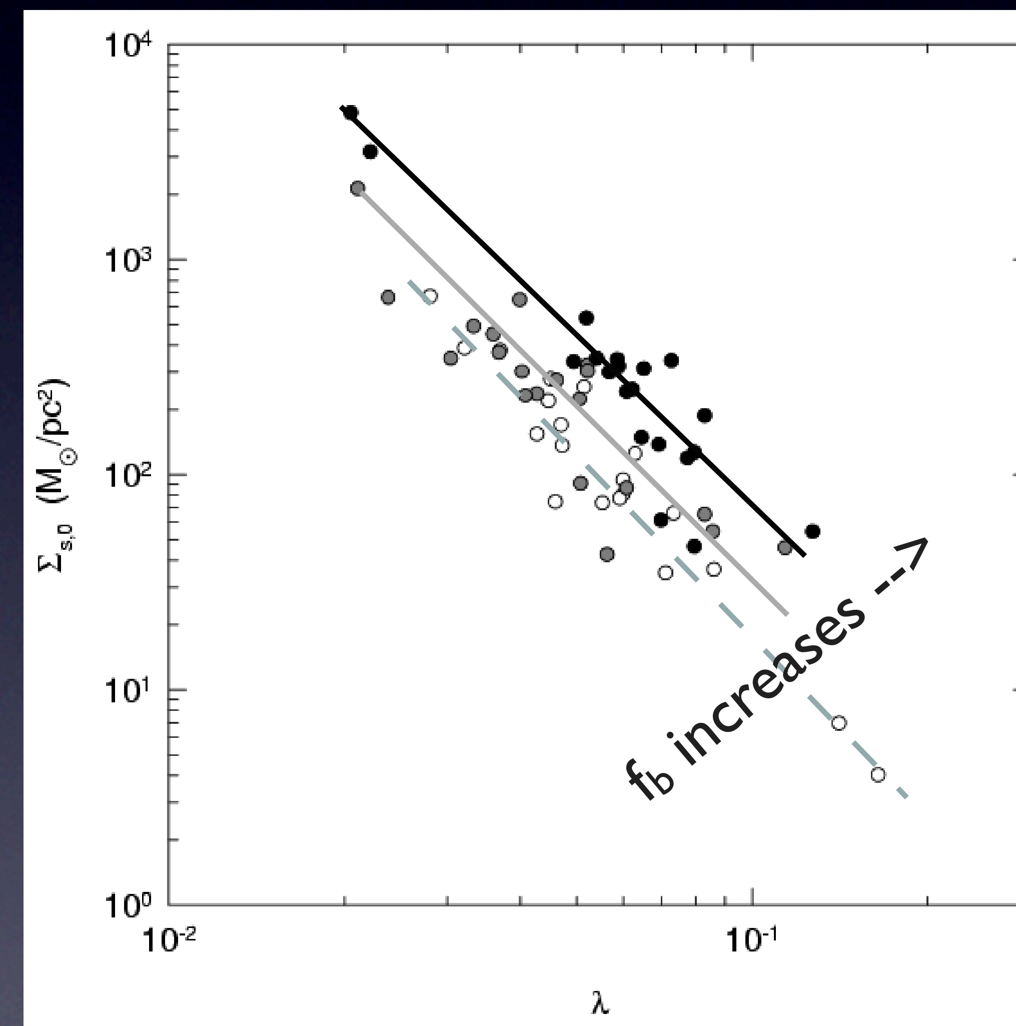
CALIFA IFS analysis shows evidence of inside-out growth for late-type, $Ms<7\ 10^{10}M$ gal's (Roberto's talk)

The SD and R_d as well as the RC decomposition depend on λ and f_b. By comparing models w/accurate IFS observations, λ and f_b can be constrained.



Toomre unstable regions = pseudobulge (realistic b/d ratios for late-type galaxies, A-R & Firmani 00, RevMexAA). IFS observations may help to disentangle the nature of the bulges

λ and f_b incluence on the SD



HSB → LSB (spin parameter)

Simulated disks have in most of cases negative color gradients (depends mainly on the halo MAH)

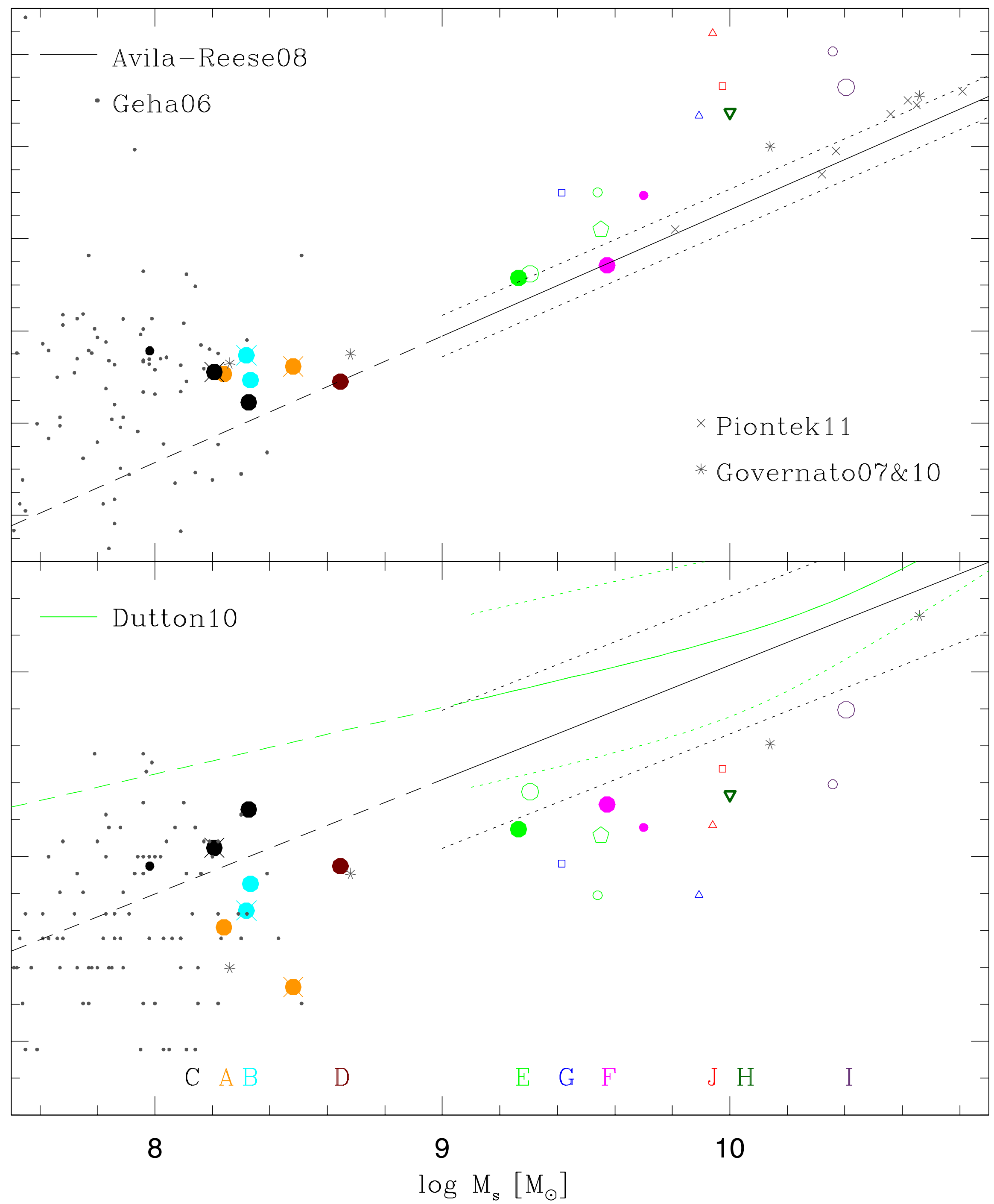
N-body/hydrodynamical simulations, the case of low mass galaxies ($<3\ 10^{10}$ M)

"Zoomed" simulation of low-mass galaxies

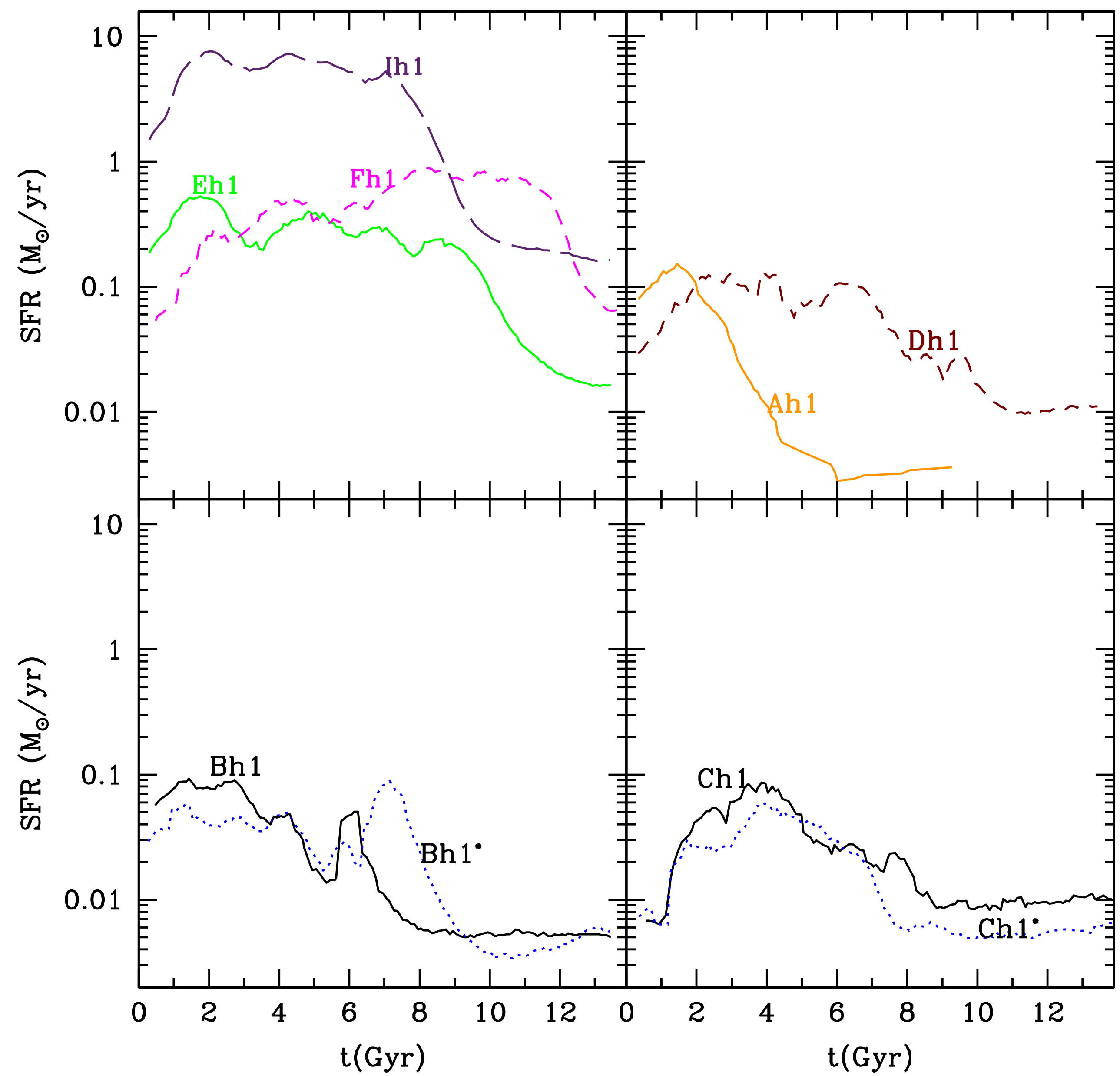
($M_h \sim 2\times10^{10}$-$4\times10^{11} M_\odot$) *Colin+ 10 (ApJ, 713, 535) and Avila-Reese+ 11 (ApJ, 736, 134)*

Hydrodynamics ART code (Kravtsov+97,03)

Scaling laws



SFR histories



In all cases the SFR strongly decreases since z~1-0.5

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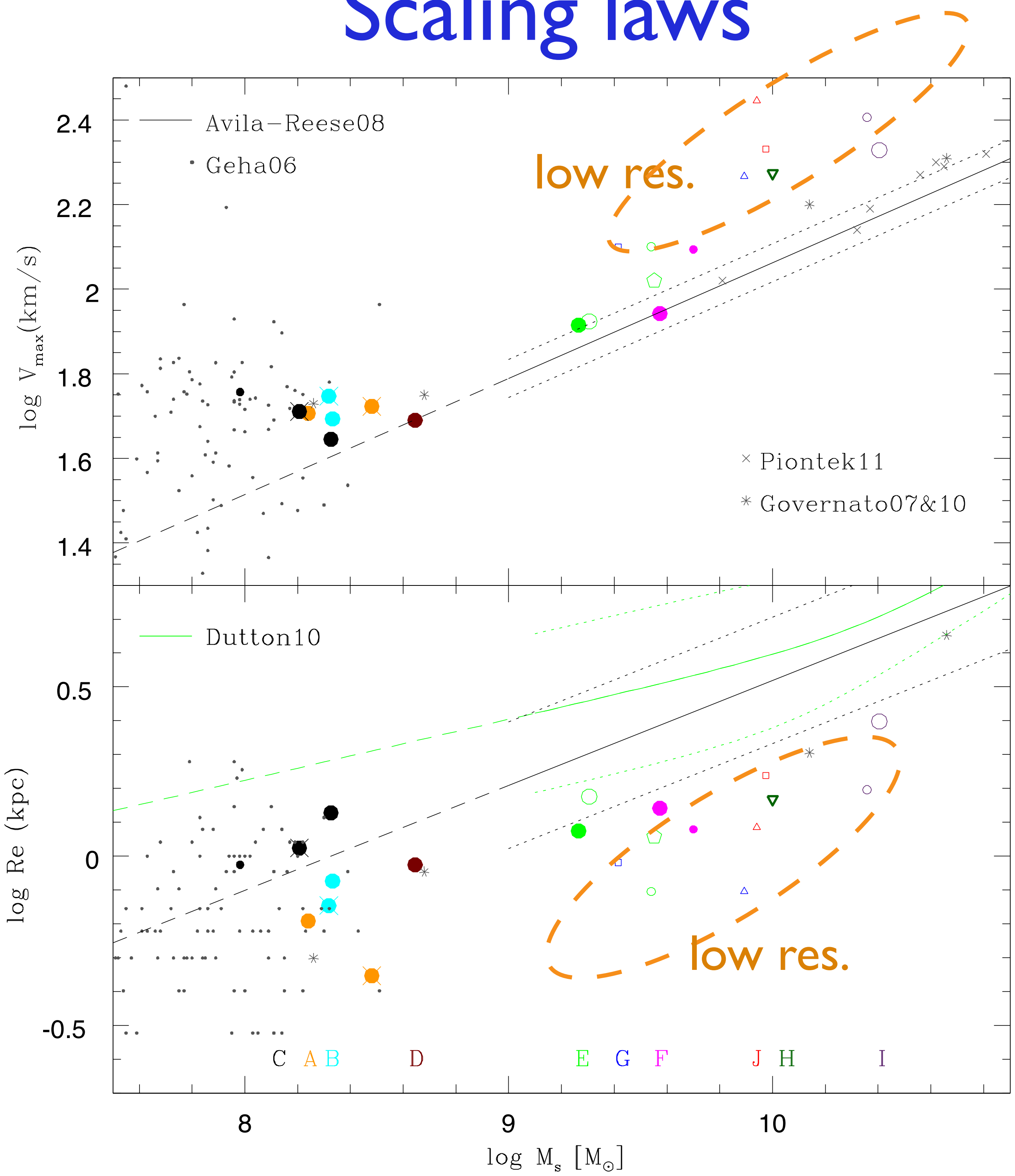

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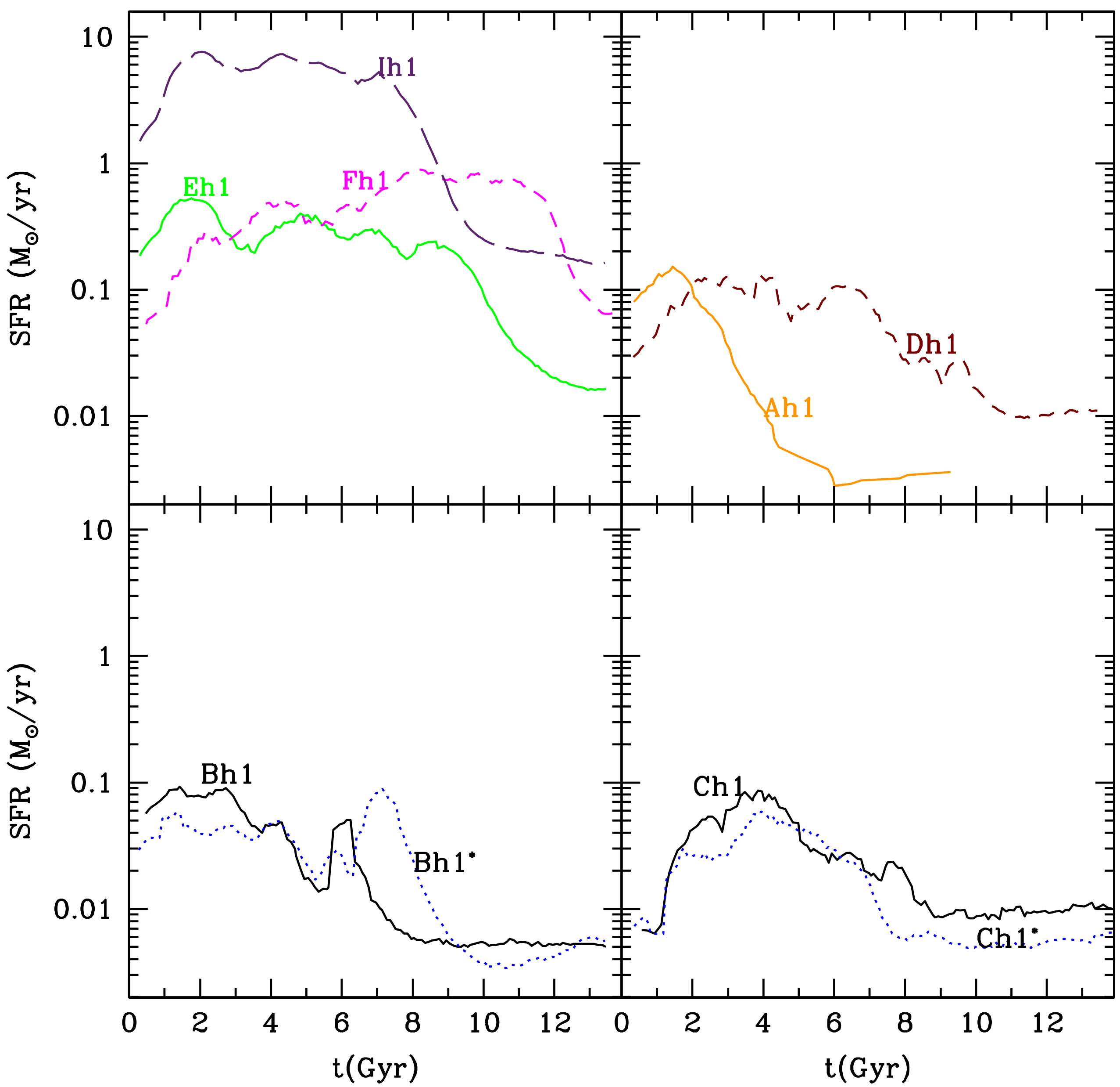

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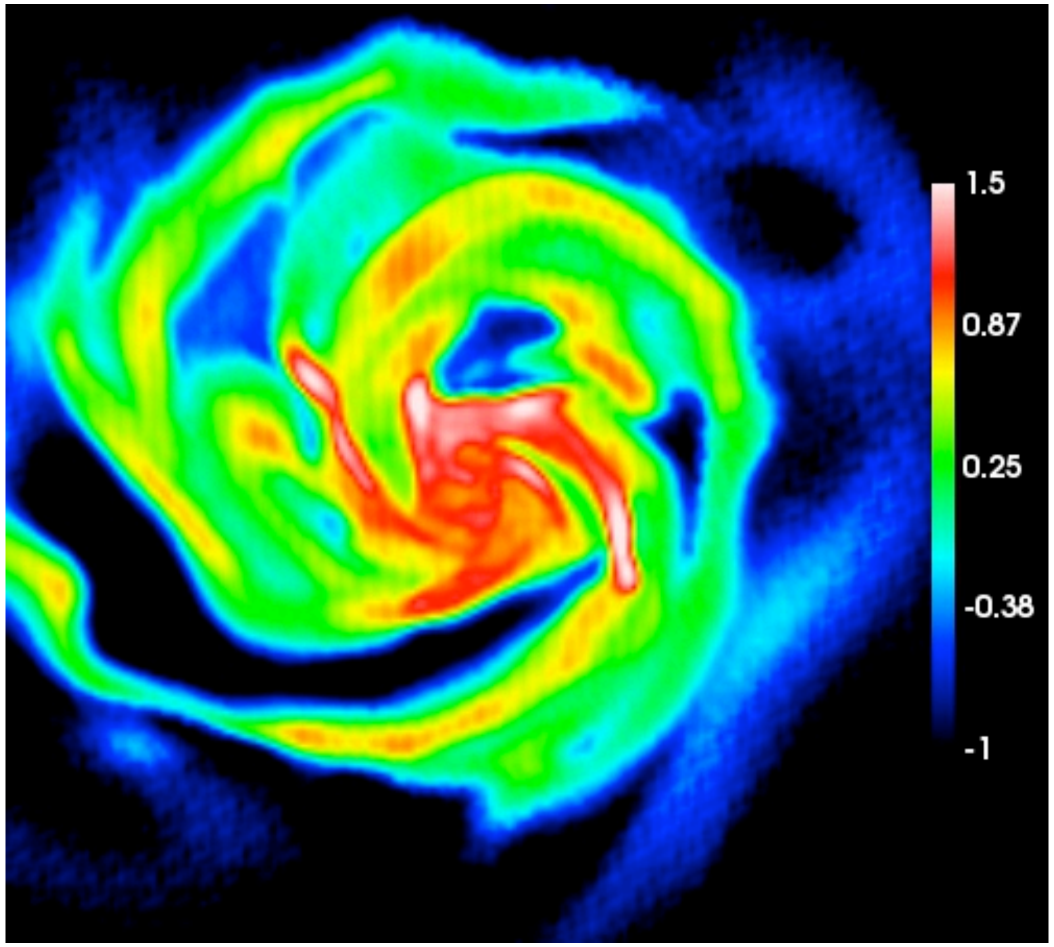
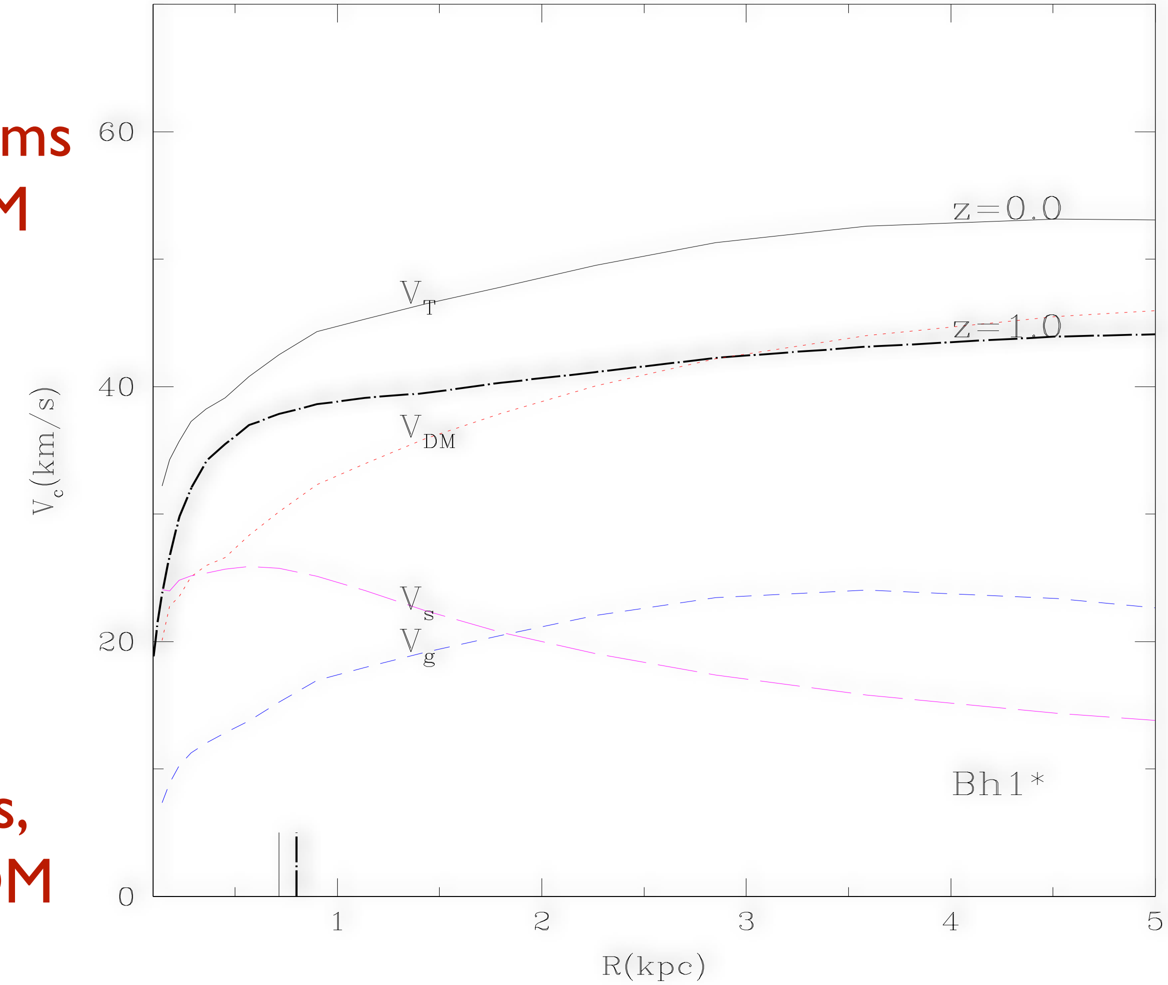


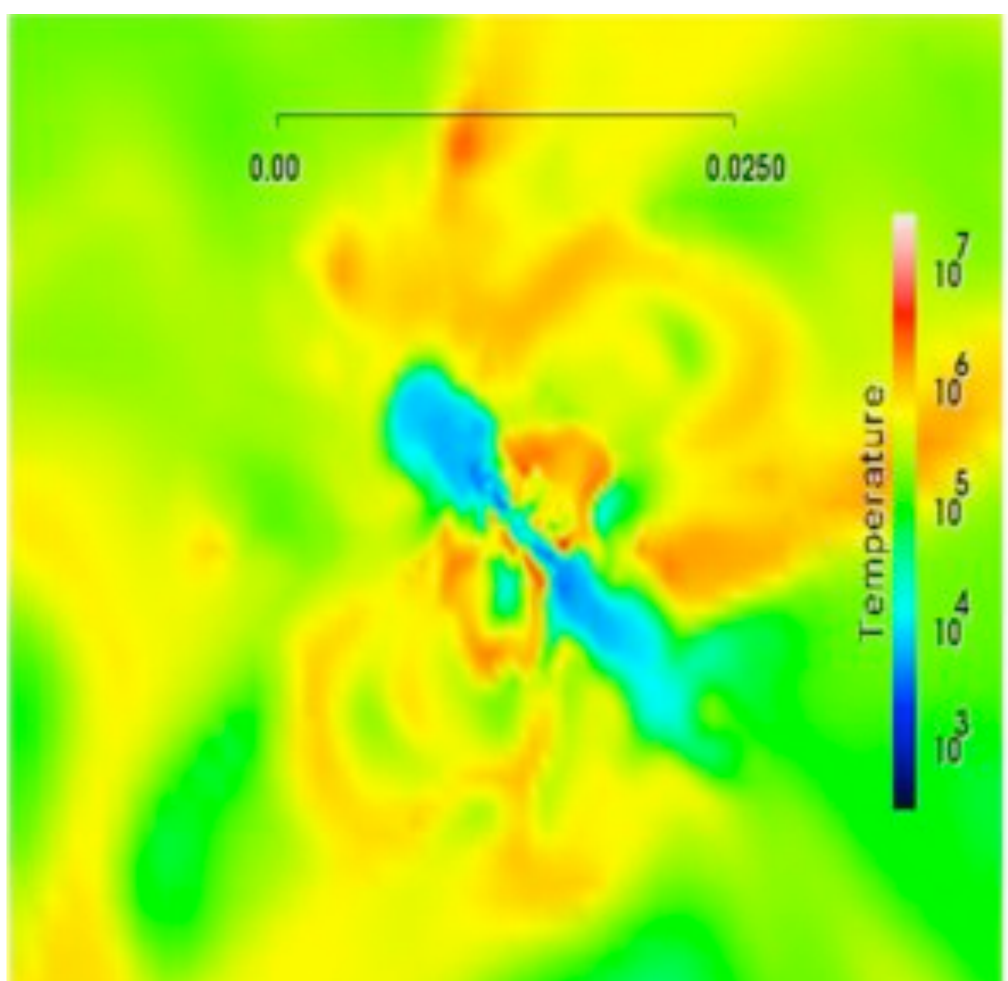
Disks w/spiral arms and realistic ISM properties

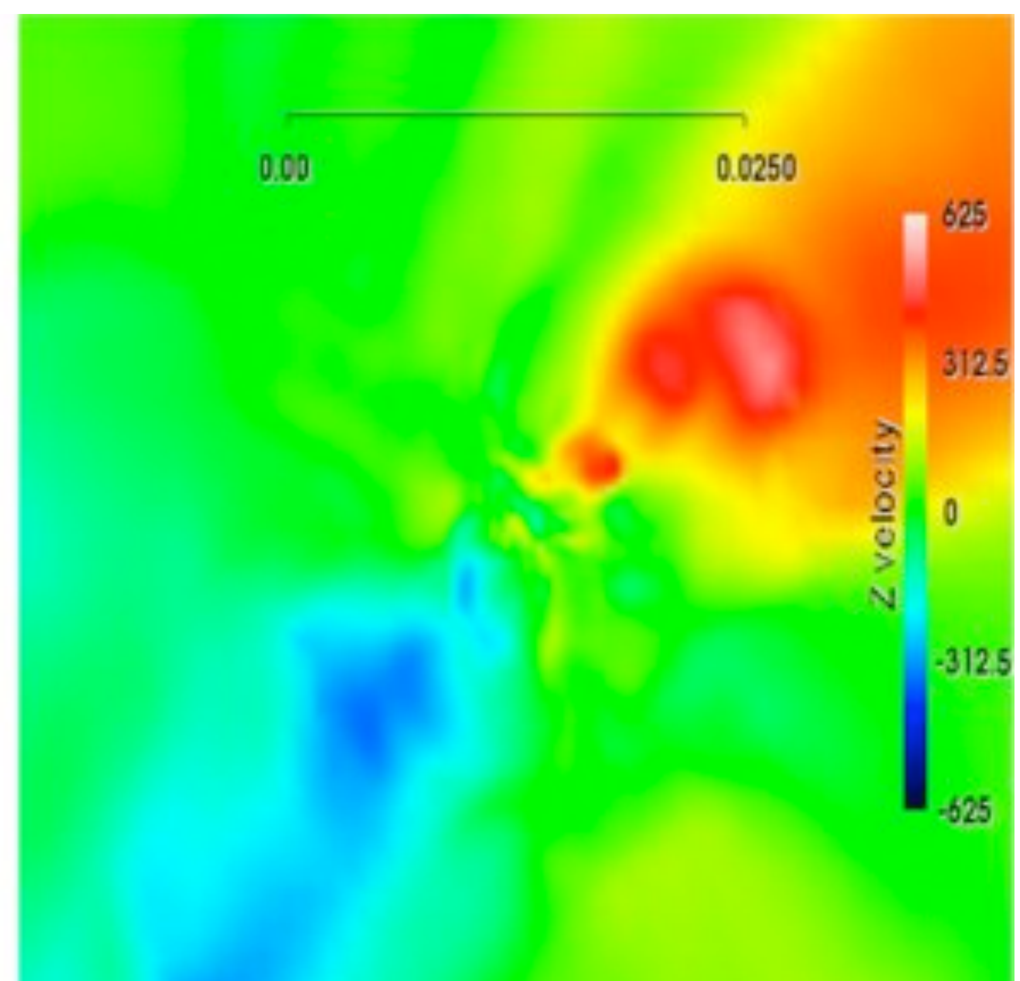
Nearly flat RCs, dominated by DM



Strong SN-driven outflows (supergalactic winds)

IGM: infalling and outflowing gas



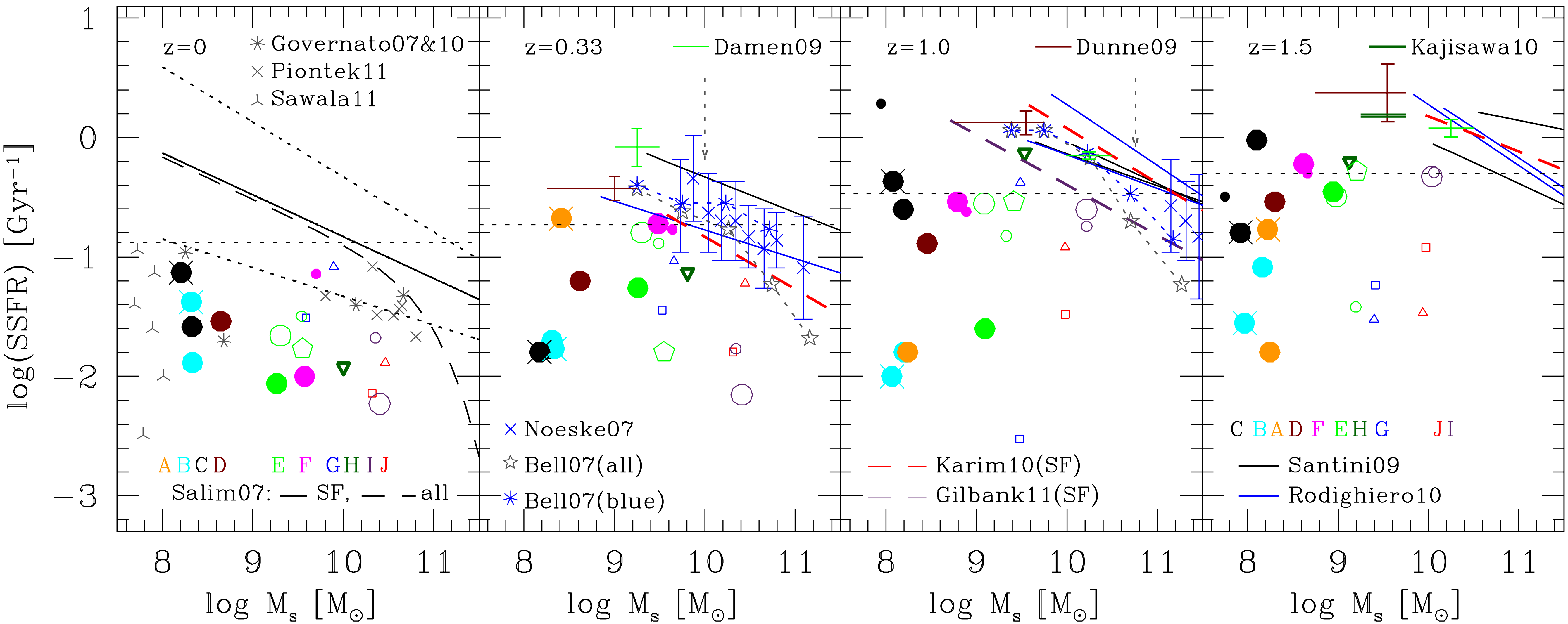


Measured SSFR vs M_s at four epochs

SSFR= SFR/M_s (current to average past SFR)

.... const SFR case

Avila-Reese+ 11 (ApJ, 736, 134)



The LCDM numerical simulations show that the SSFR is too low out to z~1 w.r.t. obs's

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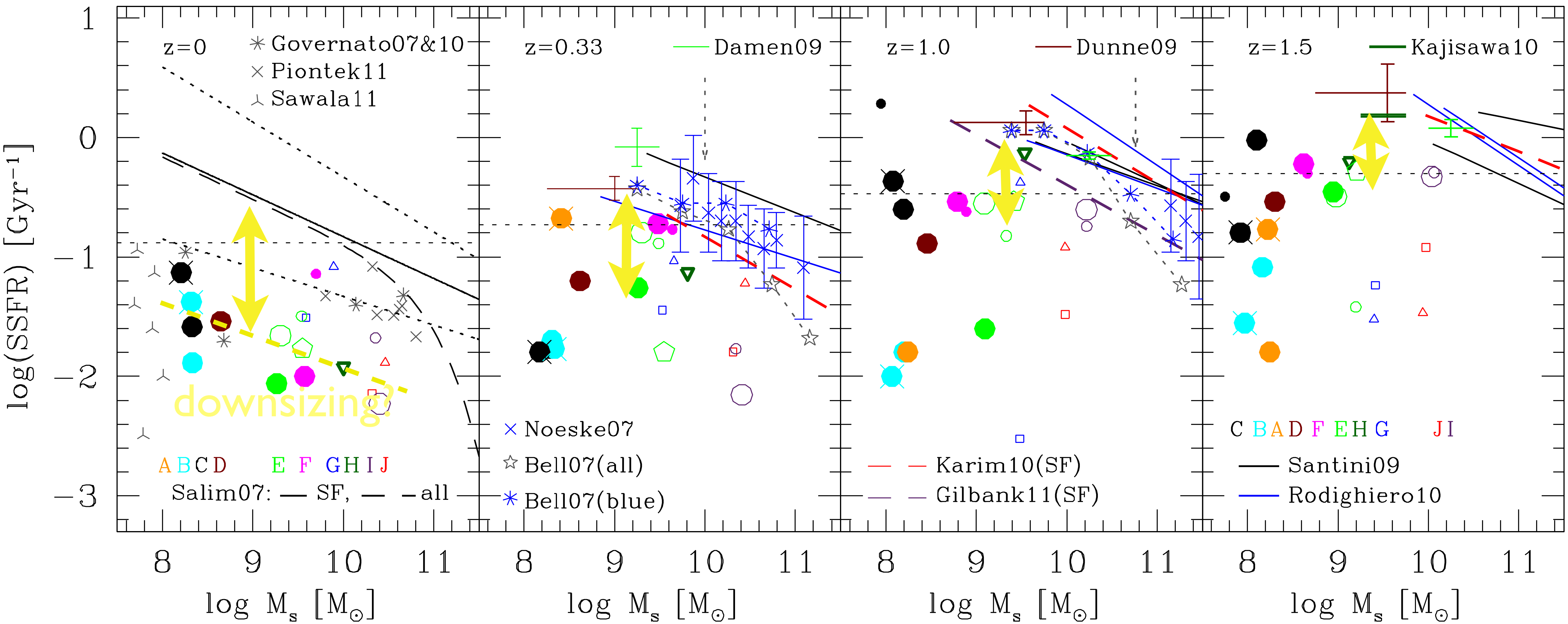

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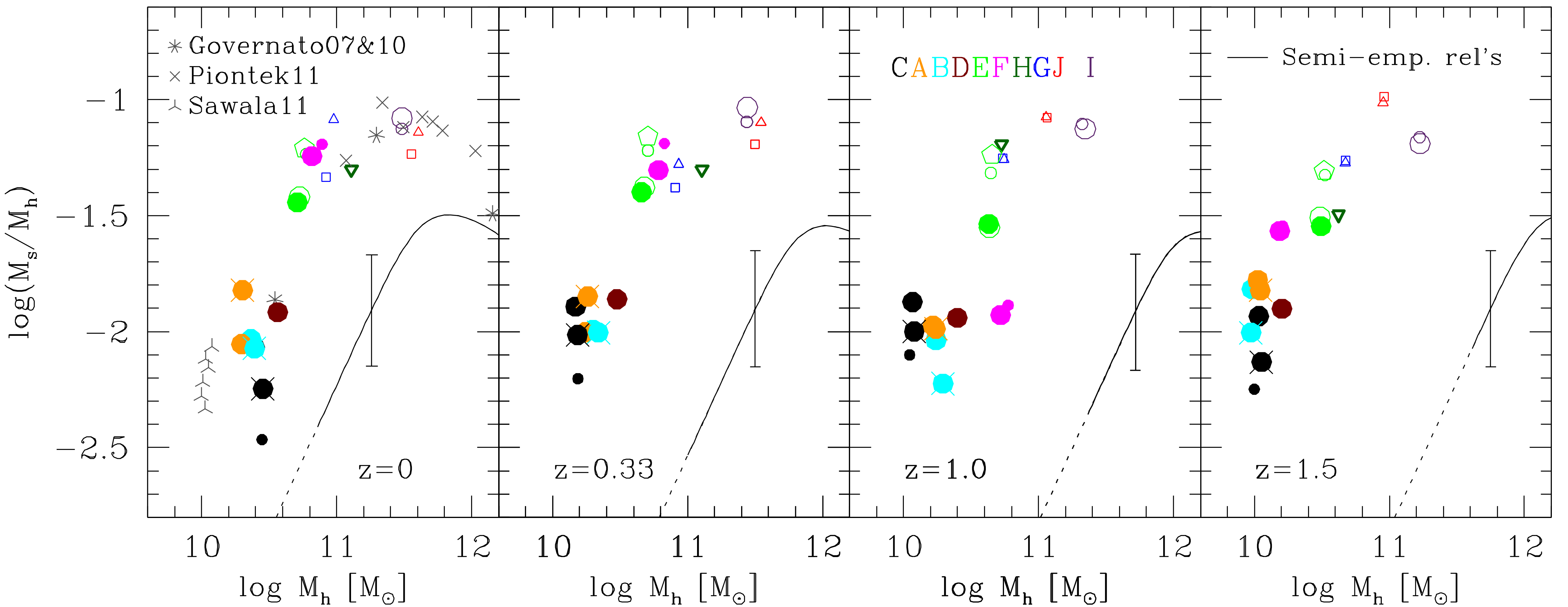
A related problems is the one of the stellar mass fraction (M_s/M_h) evolution

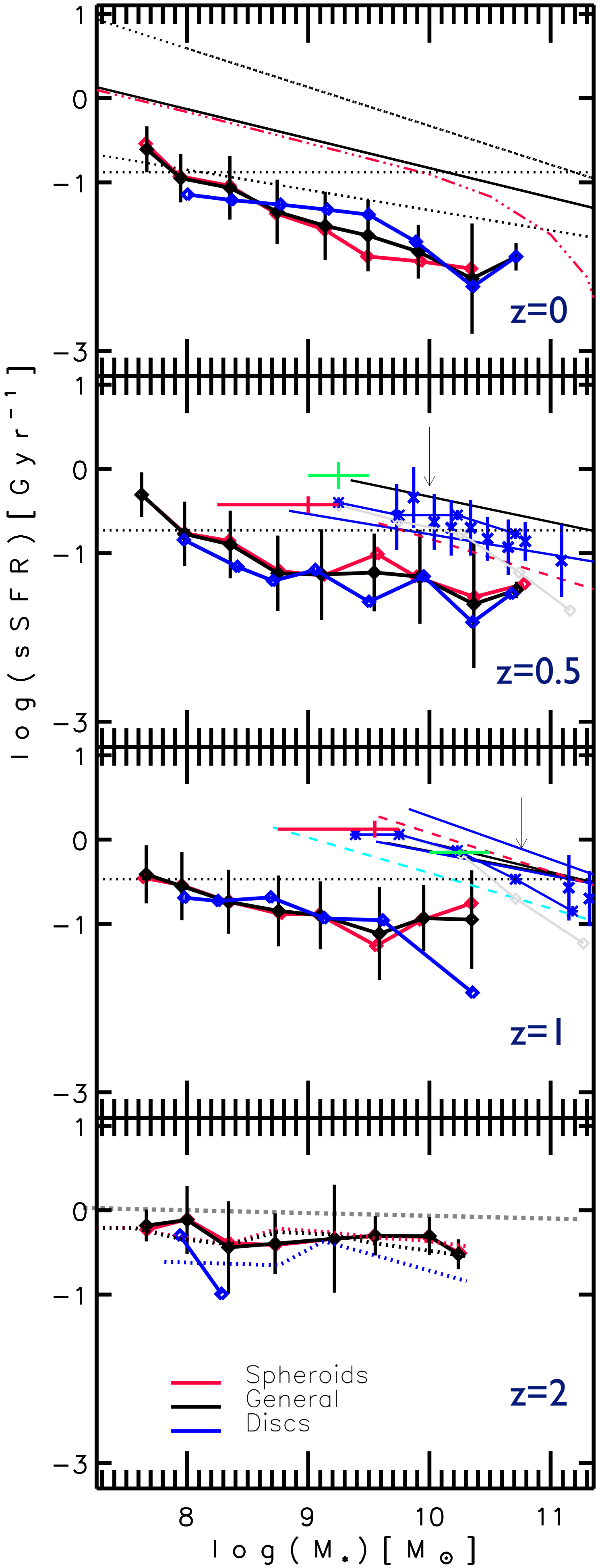


Avila-Reese+ 11 (ApJ, 736, 134)

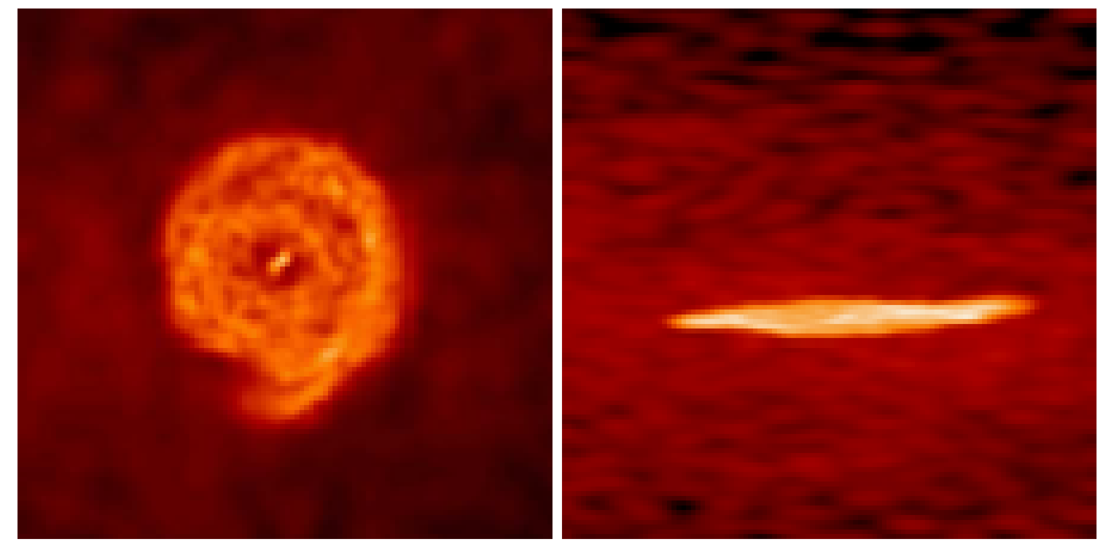
Even with SN-driven galaxy outflows, simulations have difficulties in reproducing the too low M_s/M_h ratios inferred from observations, ***in special its evolution***

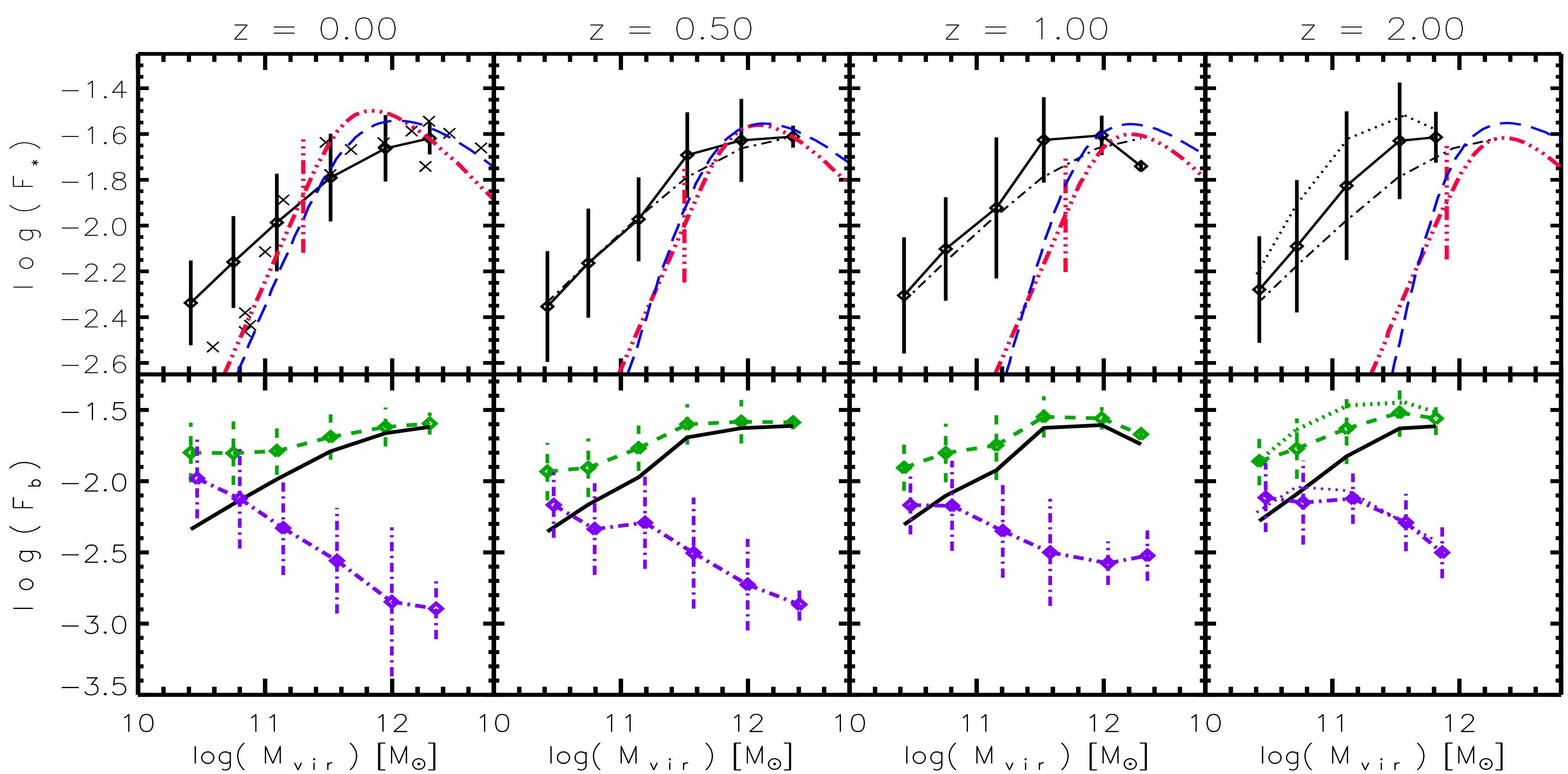
•**Another simulation**: a whole cosmic volume (14Mpc, ~300 galaxies at z=0 with more than 2000 particles; lower resolution but good statistics)

•*GADGET-3 SPH Code* with **multiphase ISM** and SN feedback grafted into this medium (Scannapieco+06,08)



de Rossi et al. 2013, MNRAS, accepted





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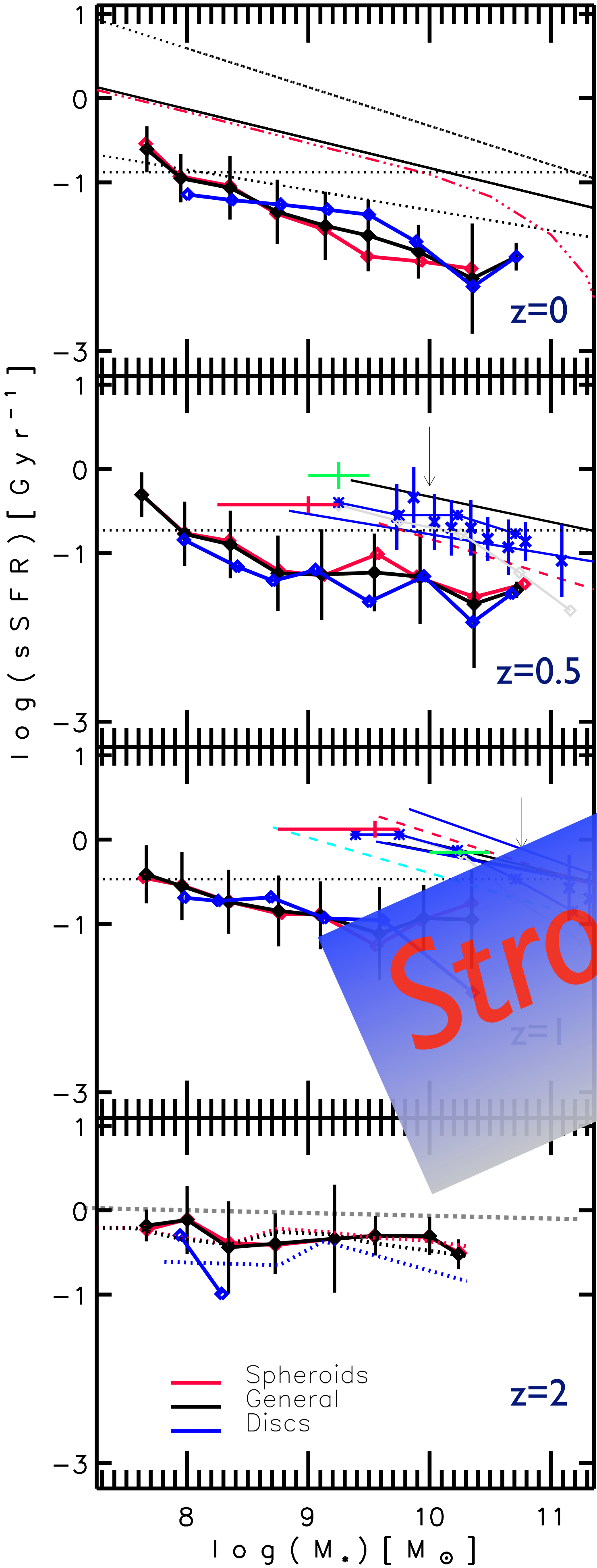
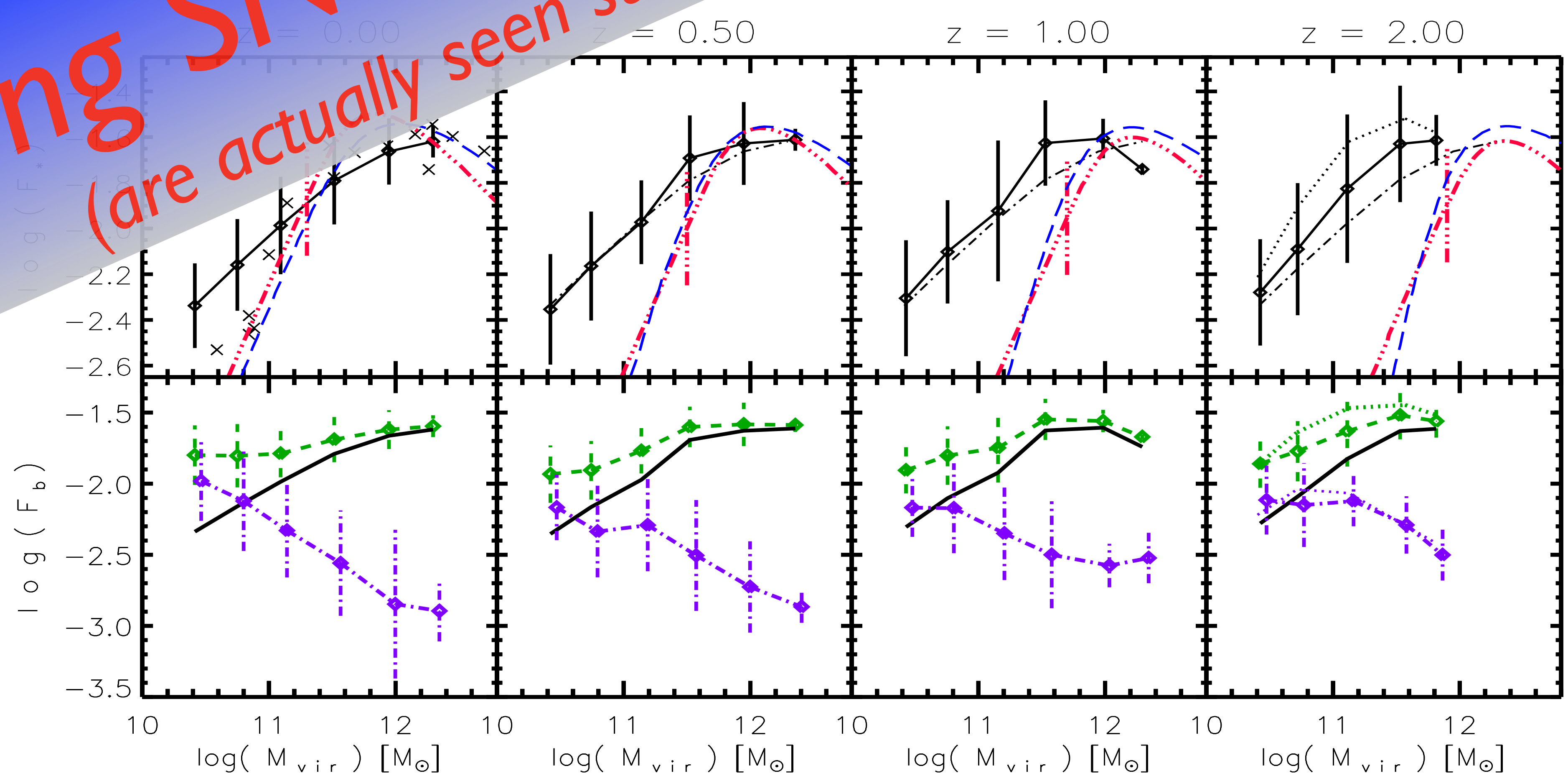


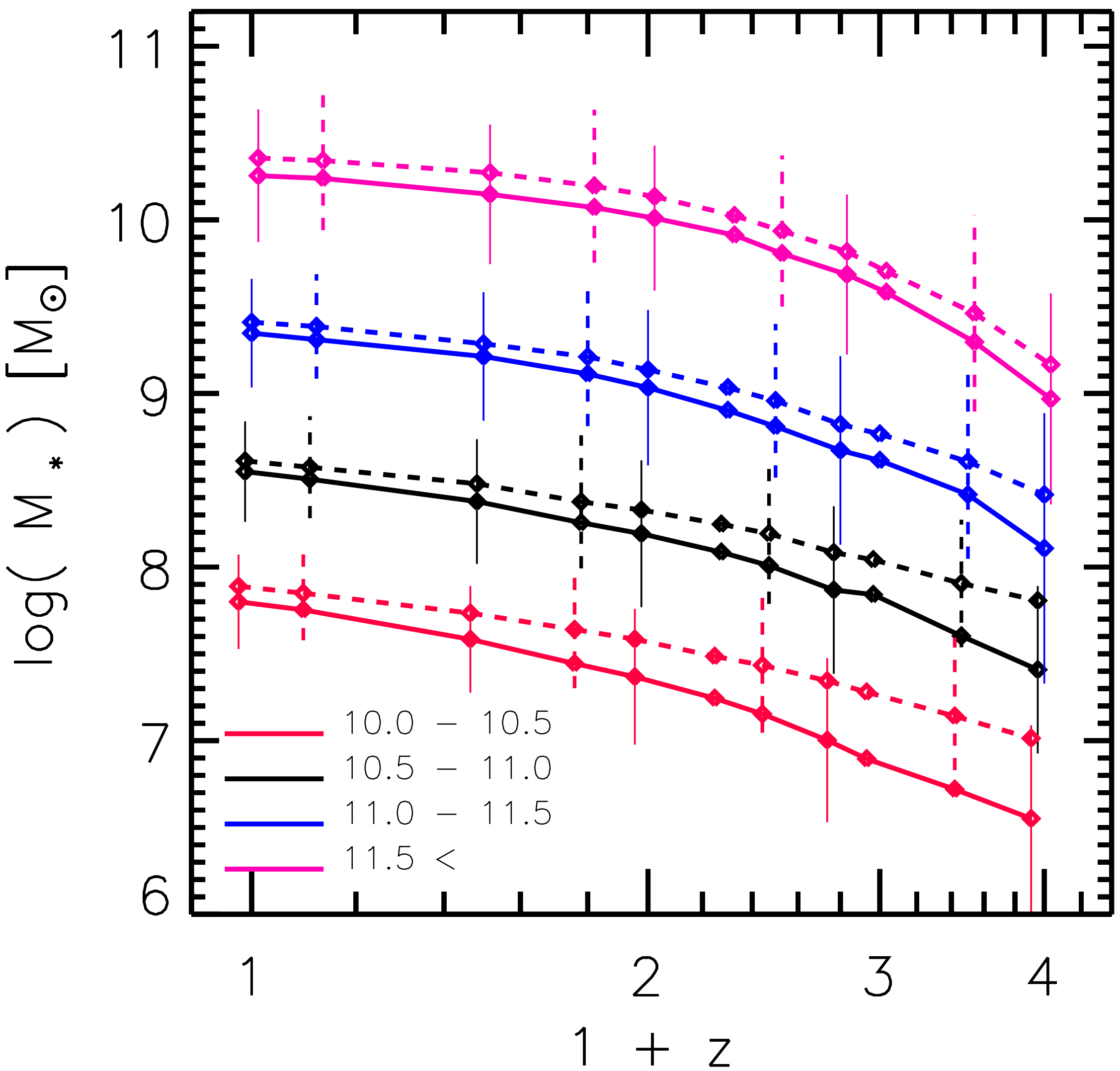


Strong SN-driven feedback

(are actually seen strong outflows?)

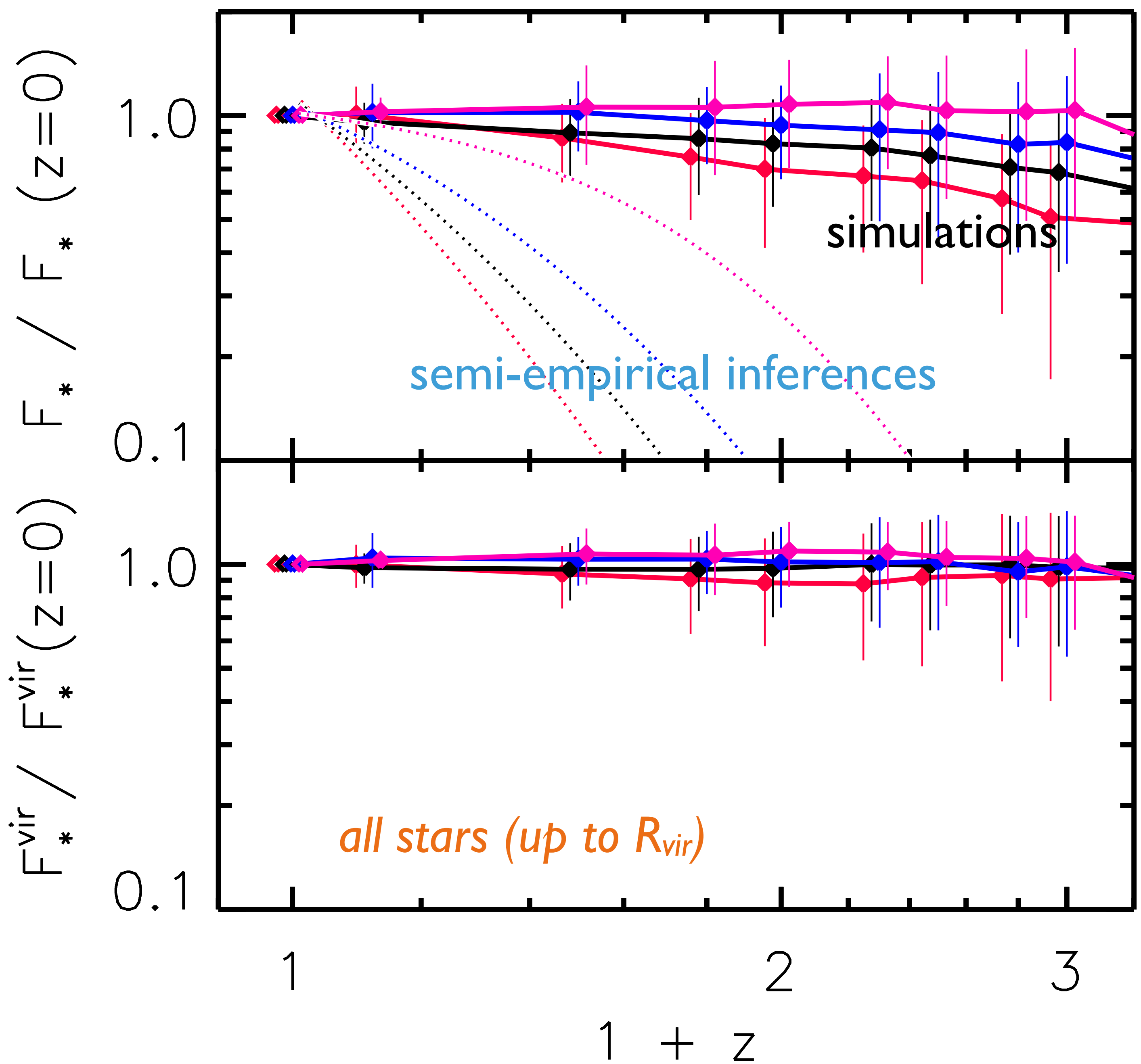
Average stellar mass growth histories

de Rossi+ 13, MNRAS



solid line: inside R_{opt}
dashed line: inside R_{vir}

$F_* = M_s/M_h$ evolution as a function of mass (normalized to the z=0 ratio)



Less massive halos assemble their central galaxy stars later than more massive ones do it: downsizing. BUT not as strong as inferred semi-empirically for galaxies less massive than $\sim 3\times10^{10}$ M_{sun}.

- **Caveats:** **a)** Are there systematics in M_s inferred with the SPS models? *(subestimated at low masses w.r.t. BC03)* **b)** Is the IMF constant in space and time? *(higher low-M cut-off as the smaller is the galaxy and for higher z's?).* **c)** Are the measured SFRs reliable? (different tracers, e.g., Bauer+11). Sample completeness and biases associated to a bursty SFH (no strong evidences in <11Mpc small galaxies, e.g., Lee+ 07, Bothwell+09, James+ 09). Environment (sSFR-M_s is ~ the same for different environments; COSMOS: Peng+ 10, McGee+ 10) .

Crucial questions to be answered, IFS may help

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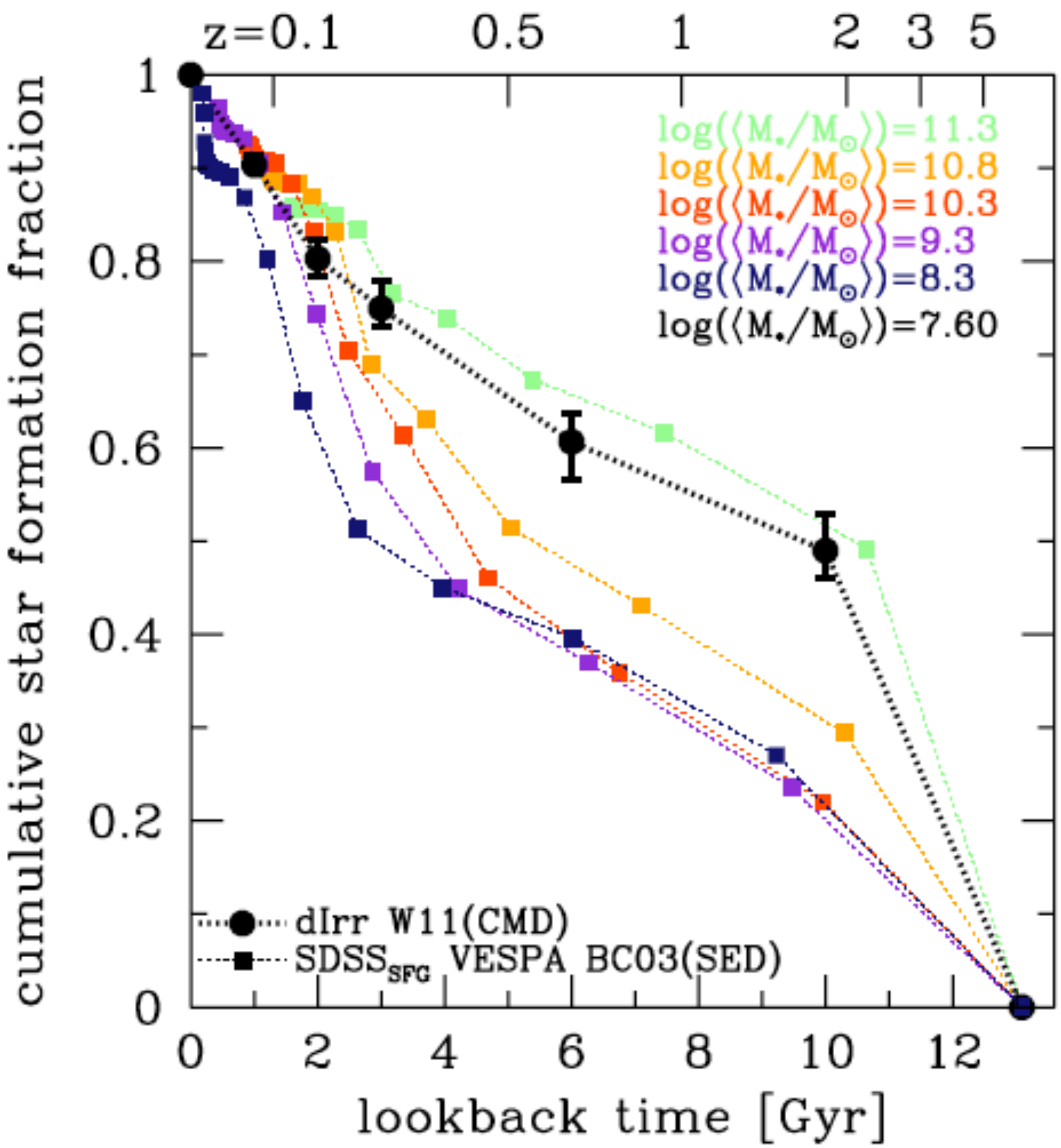

Leitner12, ApJ: Archeological inferences (DR7 SDSS in VESPA) agree qualitatively with evolutionary (toy model) inferences: ***downsizing.***

However, the trend is reversed for local dwarf galaxies! (CMD inferences, *Holtzman+06;Weisz+11a,b*

Crucial questions to be answered, IFS may help

<u>Bulge growth in disk galaxies:</u> 1) does the LCDM merger rates allow for the large fraction of observed "bulgeless" gal's? 2) Do bulges grow by mergers of from stars from the unstable disk?

Zavala+ 12, MNRAS 427,1503: disks are seeded in halos from the MS-1 and MS-2 simulations, according to the Ms-Mh and Mg-Ms relations at each z. Bulges grow by 3 channels: a) stars from the merged secondary, b) stars from the primary disk perturbed by the merger, c) stars formed in bursts from the gas deposited in the center.

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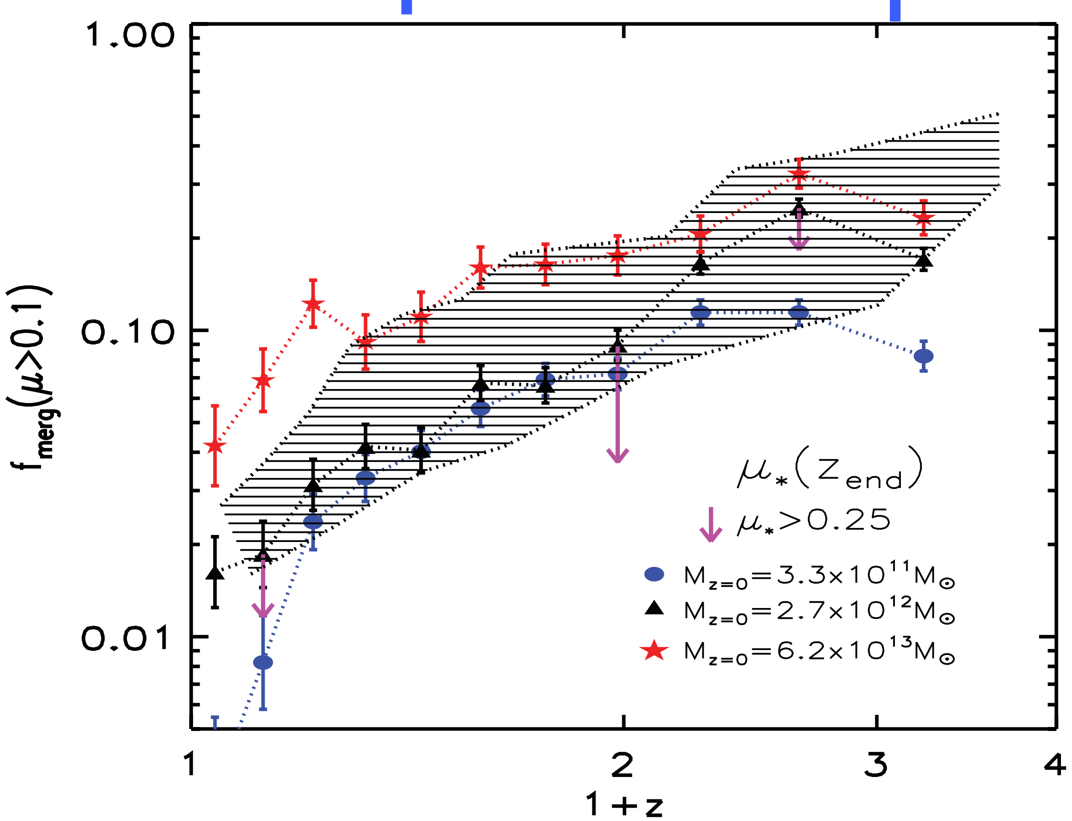
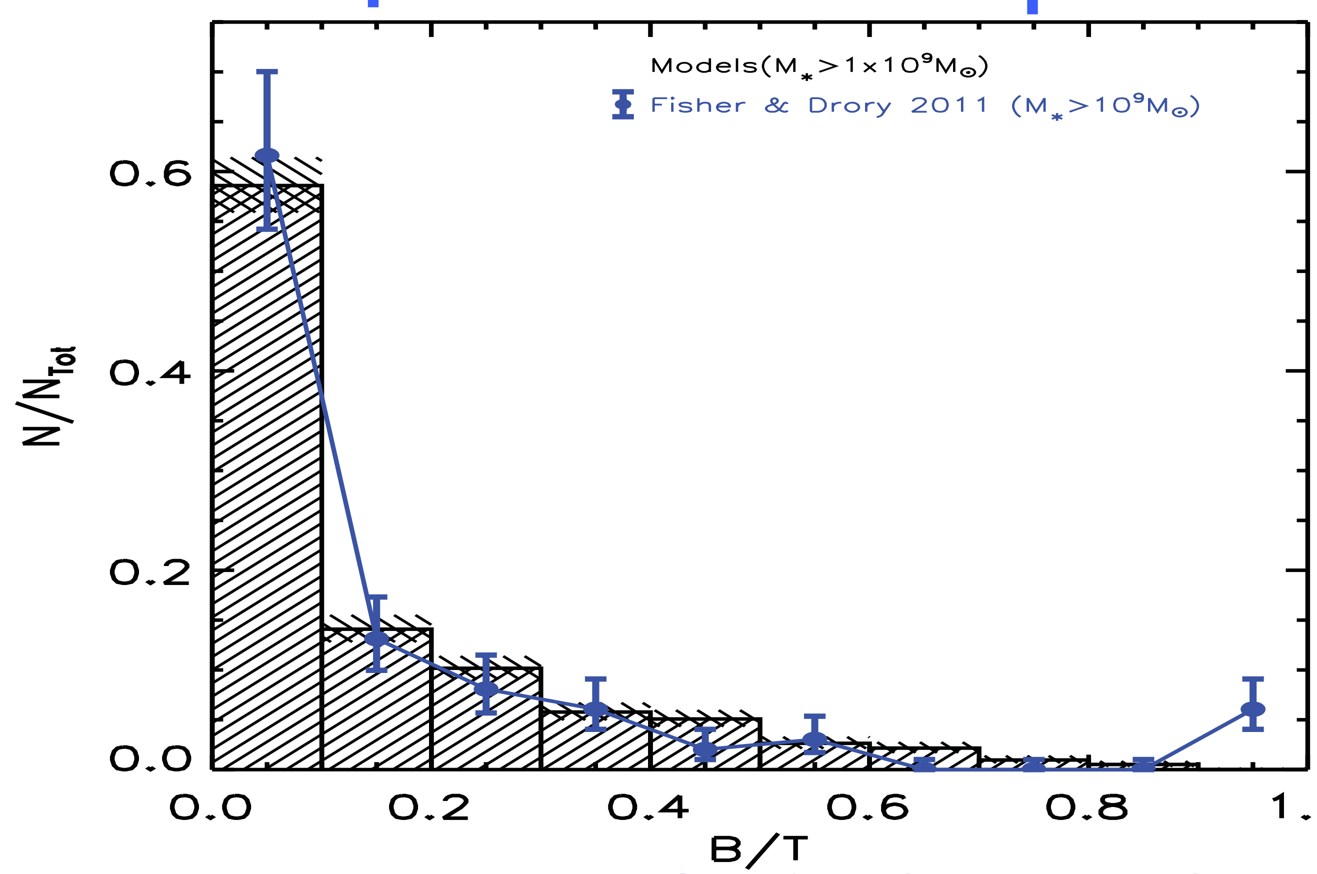
Merger rates



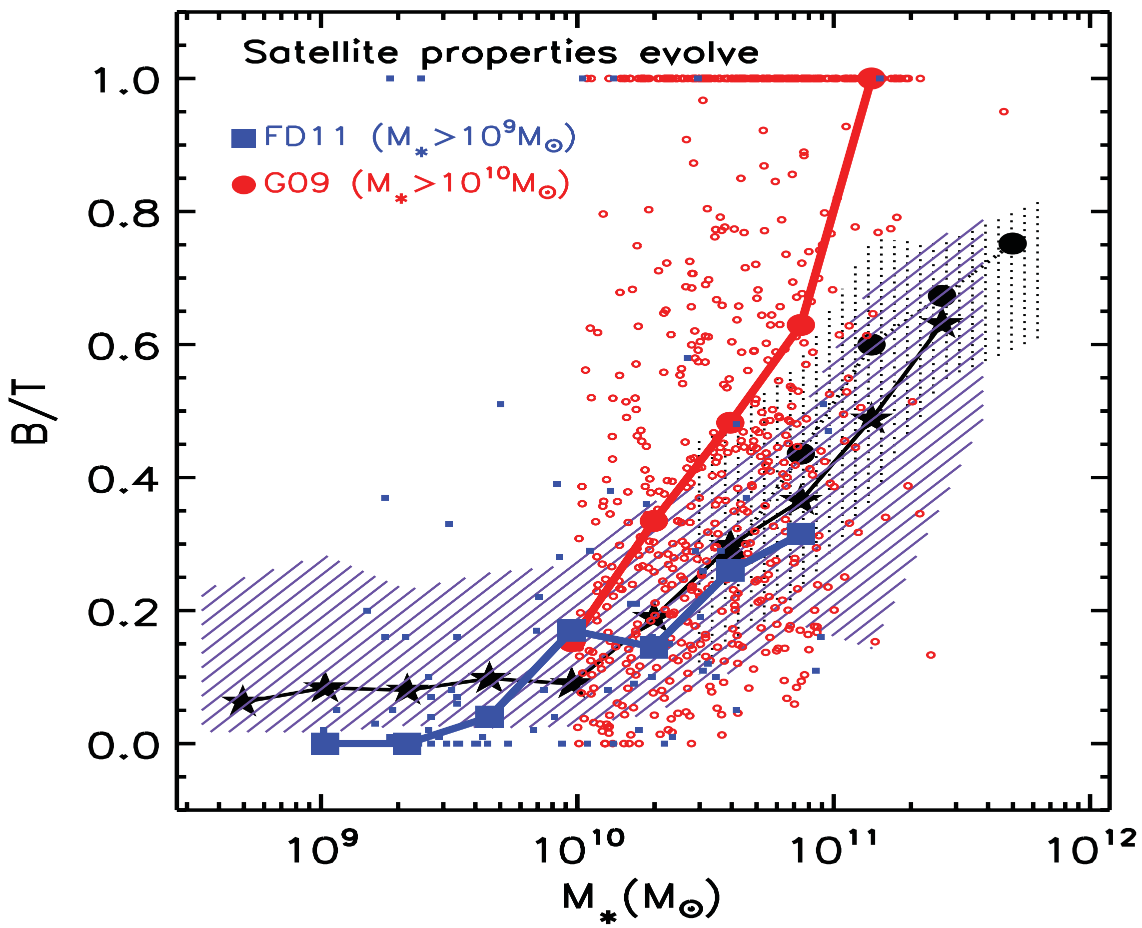
Good agreement w/observed stellar merger rates

B/T demographics

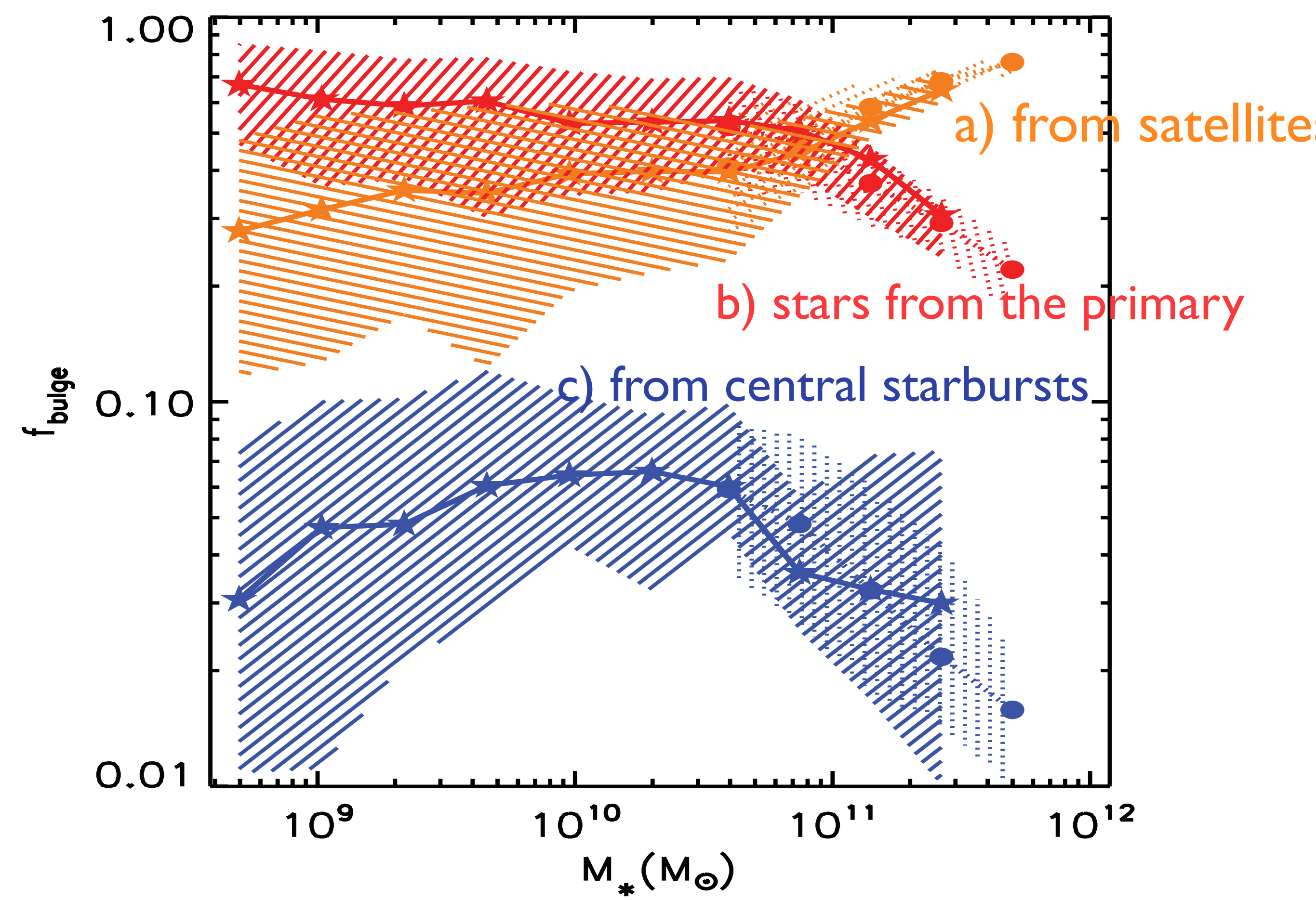


Dominate the B/T<0.1 (low-mass) gal's, in agreement w/observations

B/T vs M_s



Fraction of mass due to the 3 bulge-growth mechanisms

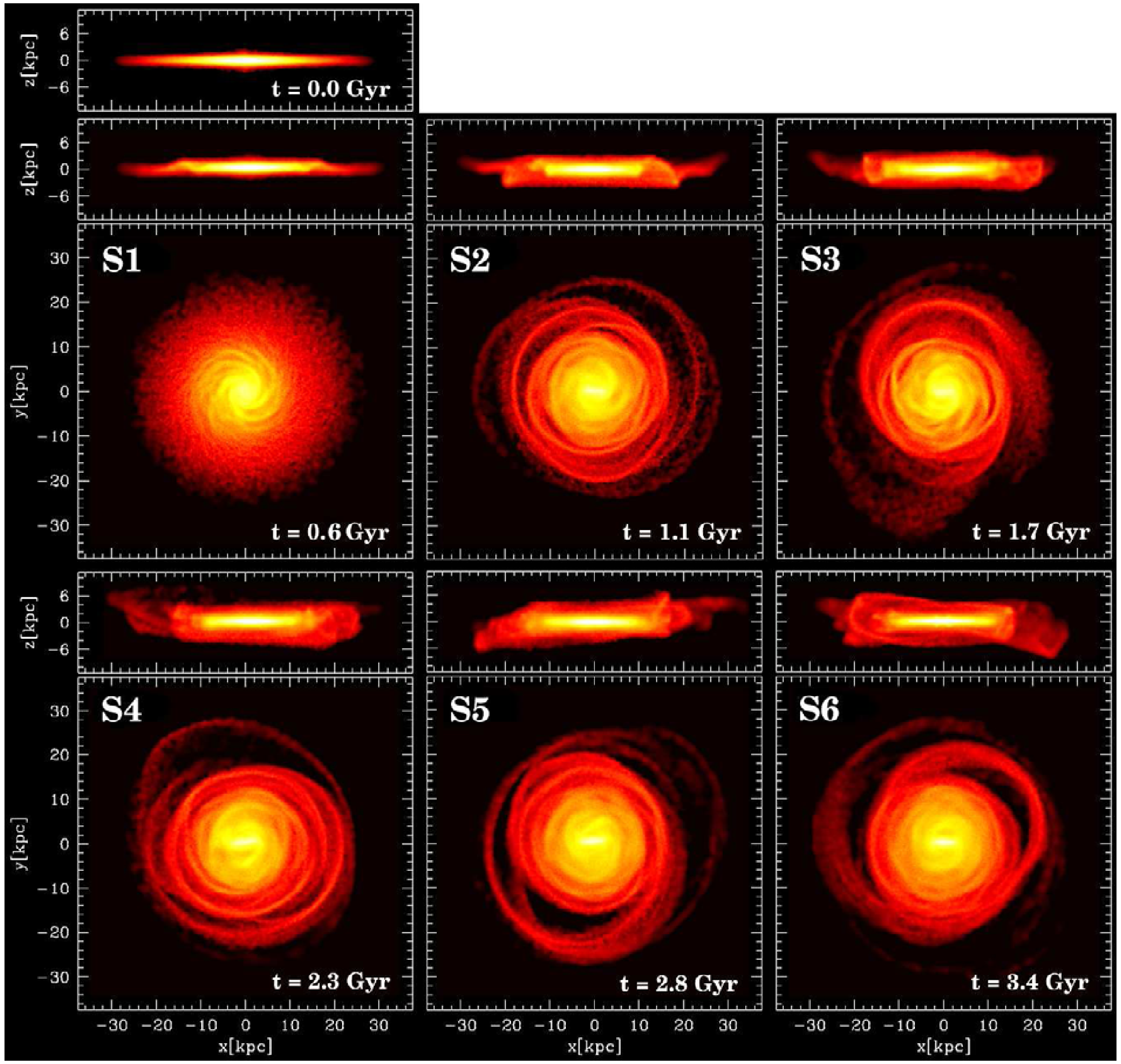


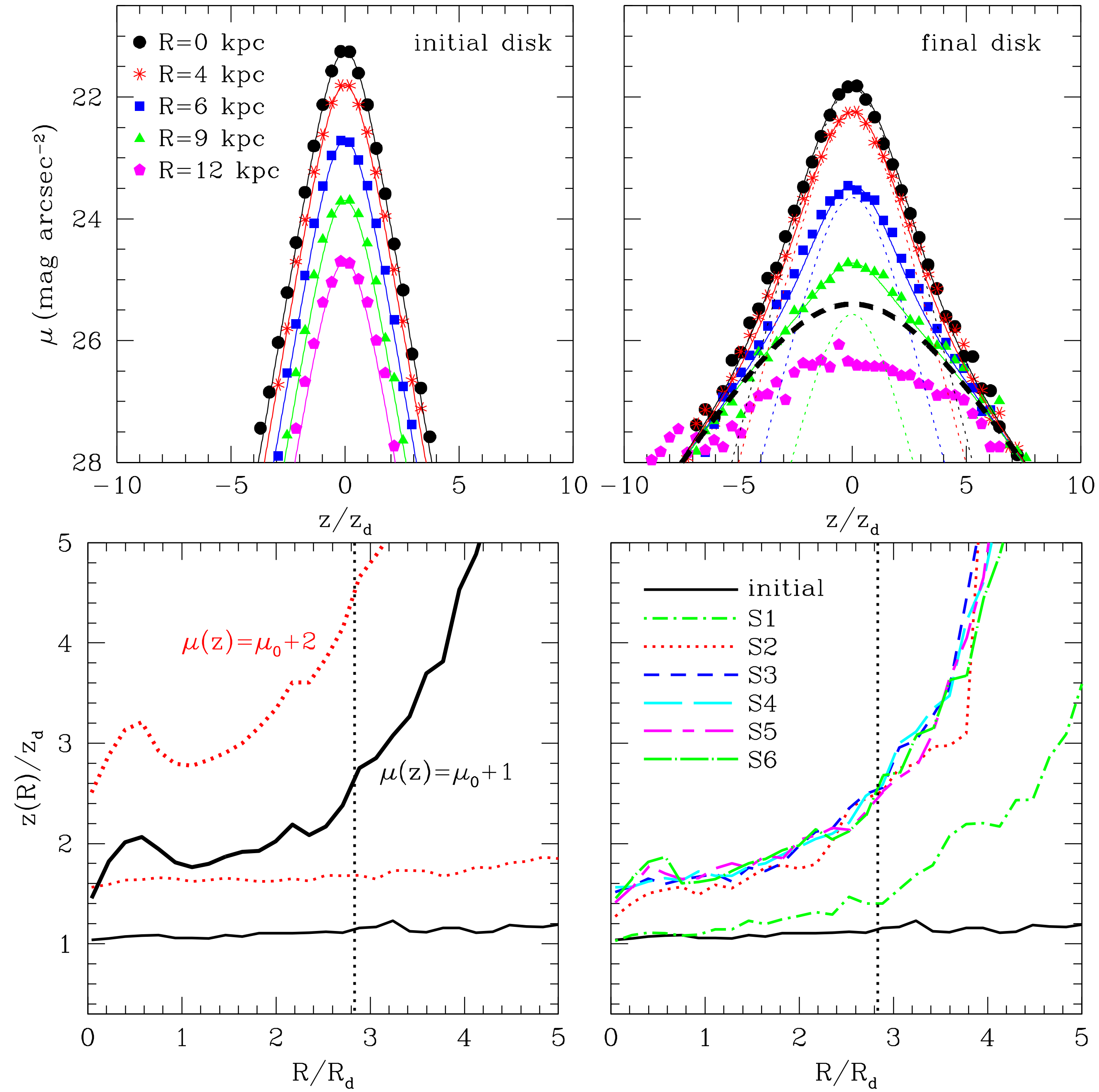
- Bulges are composite: they grow up with stars from the secondaries (classical), from the primary disk (pseudo), and from local starbursts. The former one dominates only in the most massive gal's

IFS may help to constrain the kinematics of the bulge-inner disk regions + the stellar pop's --> constraints to bulge formation

Effects of dark matter subhalo accretion on the disk galaxies

(Kazantzidis+08,09)





Several subhalo passages/infalls since z=1: non-axisymmetric structures (warps, outer rings), bar, vertical thickening and heating, flares, lopsidness, filamentary structure in the disk seen in the configuration space. *IFS studies of close disk galaxies can be used to detect these features*

Concluding remarks

- The current LCDM-based models make concrete predictions for the scaling relations of disk galaxies. IFS surveys can test these predictions.

- The well constrained Ms-Mh (Mb-Mh) relation mapped onto the internal properties of disk galaxies, which can be obtained by means of IFS, allows to probe the LCDM model.

- The semi-empirical picture shows strong downsizing in SSFR for low-mass galaxies (the smaller they are, the later they assemble). Numerical simulations cannot reproduce that. Is it a problem with interpreting the observations or new gastrophysics should be introduced? IFS studies of the SPop's of galaxies may help to find the answer.

- Merger-driven bulge formation in the LCDM is in agreement with observations. However, the kinematical/stellar pop nature of the bulges should be yet understood (classical, pseudo, composite).