A two-phase model of galaxy formation: clumpy and bursty star formation in the early Universe

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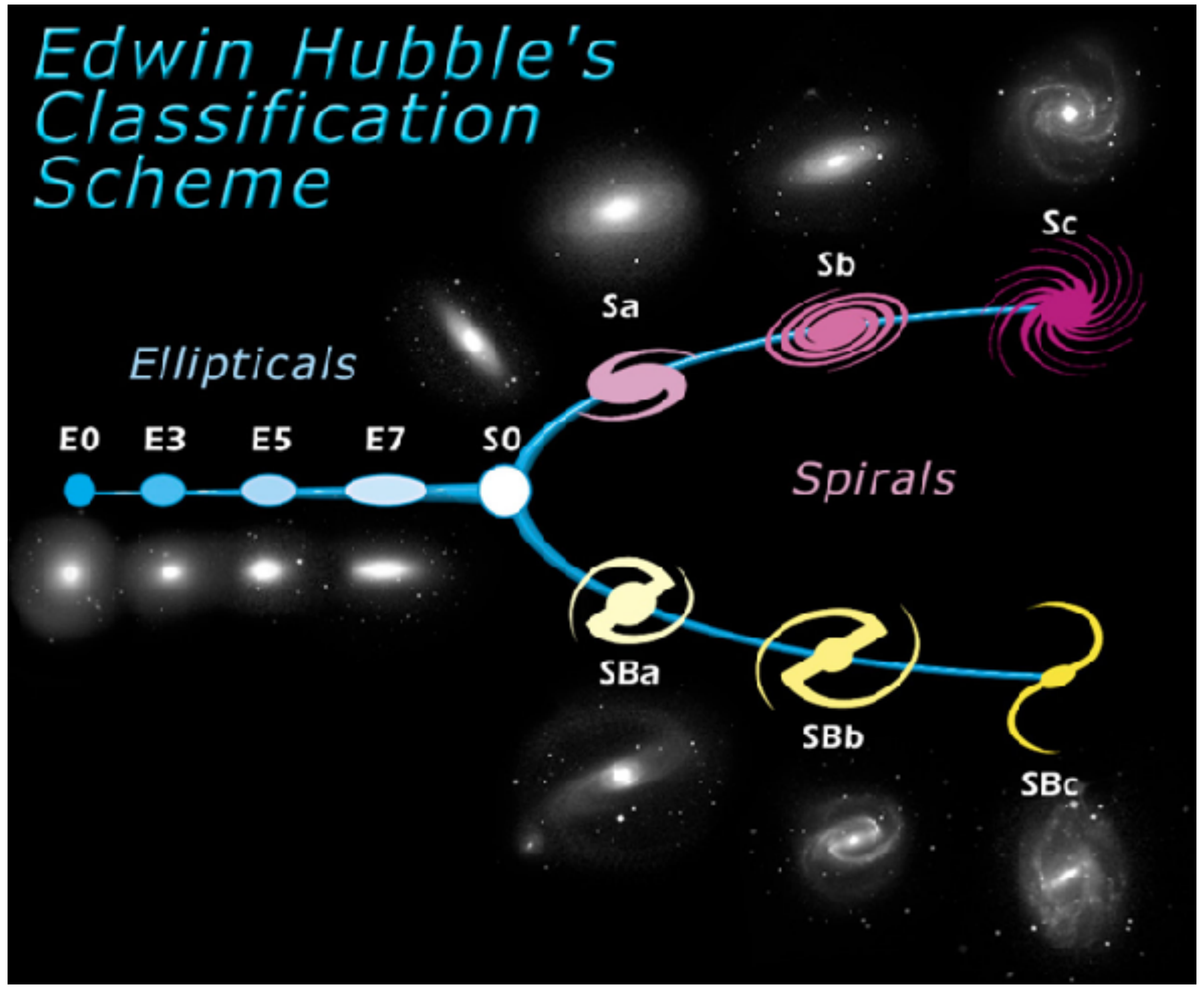
MoChenWang 2023, arXiv: 2311.05030

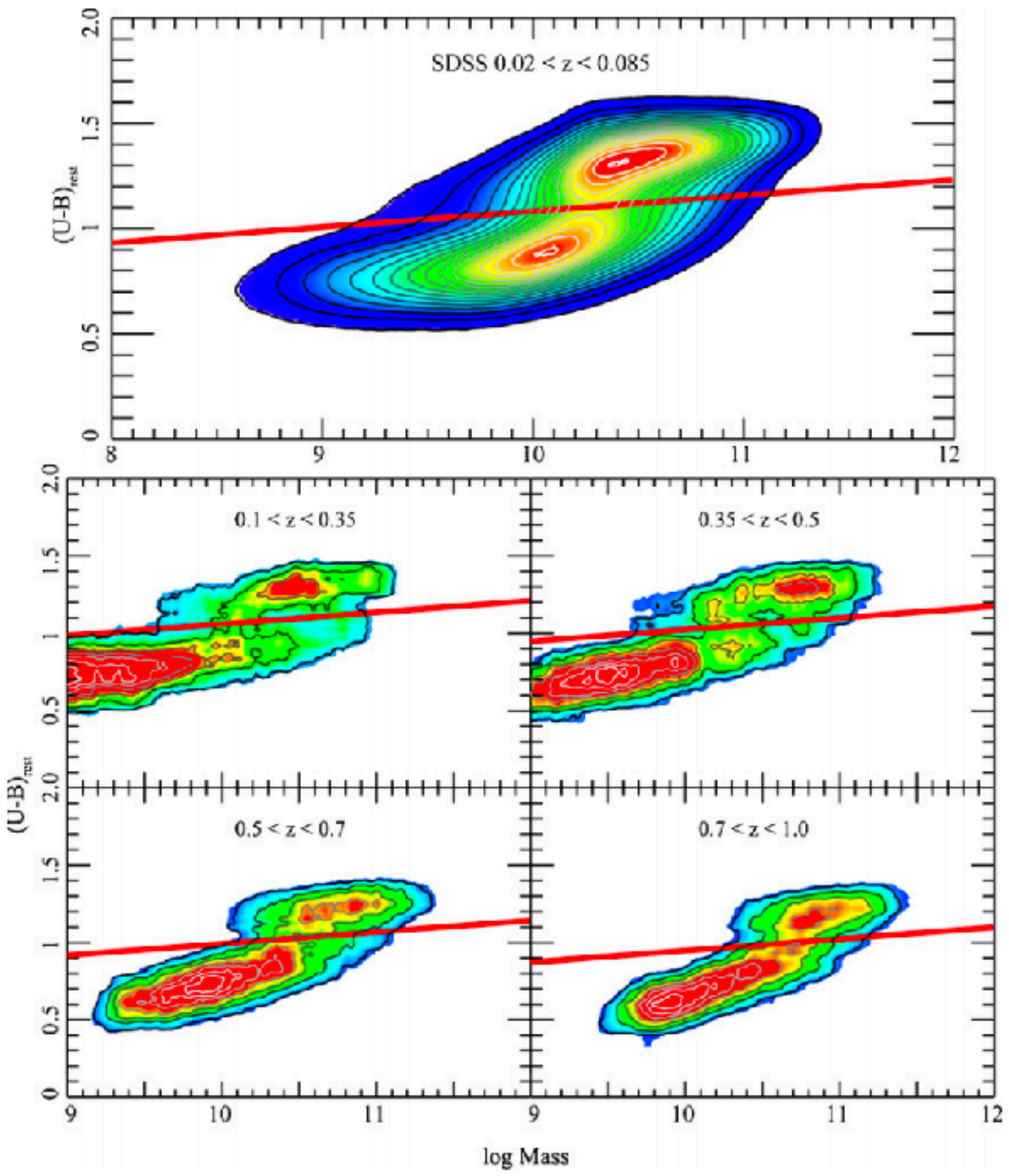
The ‘everywhere’ bimodality

Galaxy morphology



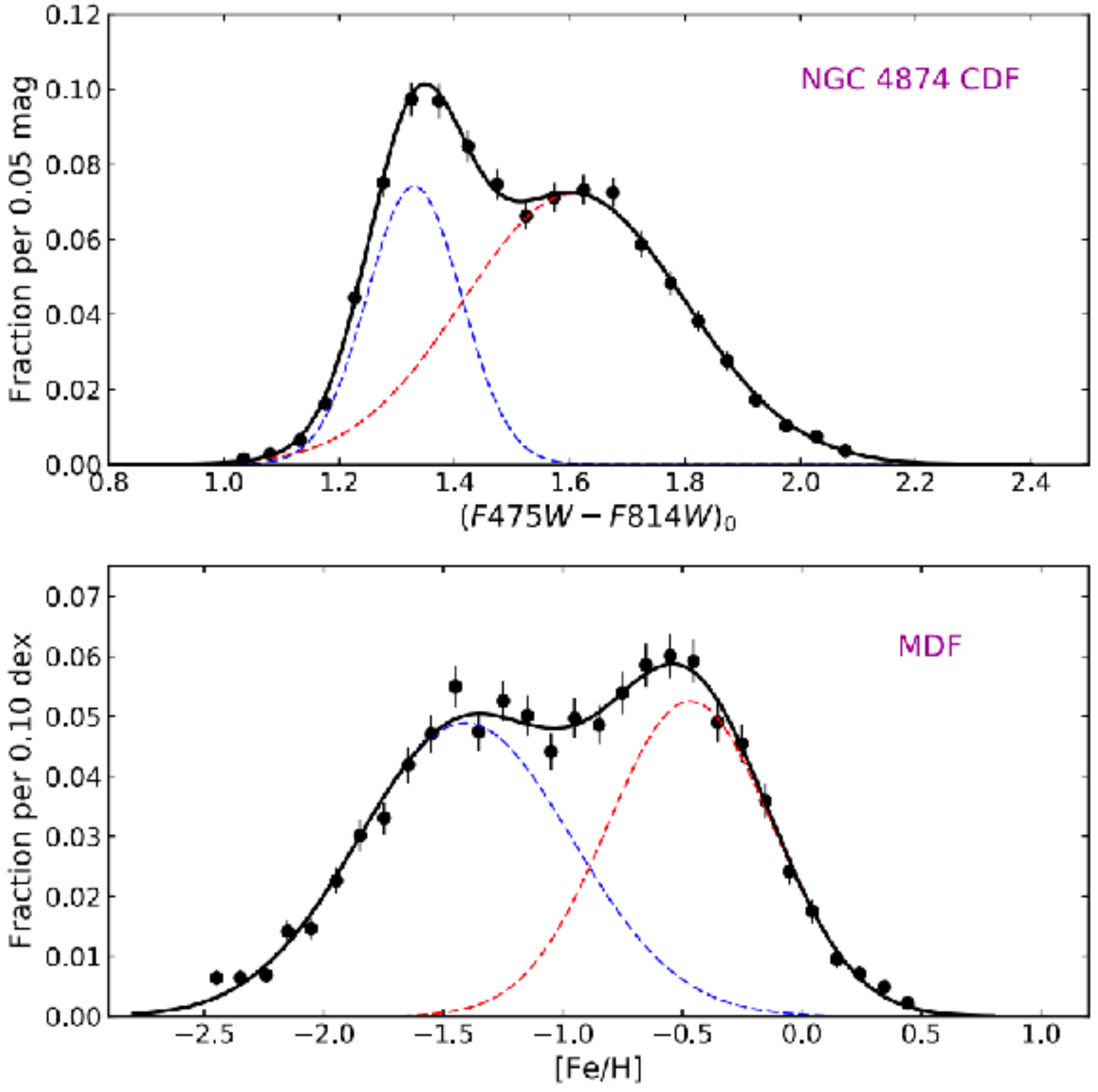
NASA & ESA

Galaxy color



Peng 2010

Globular star cluster color



Harris 2023

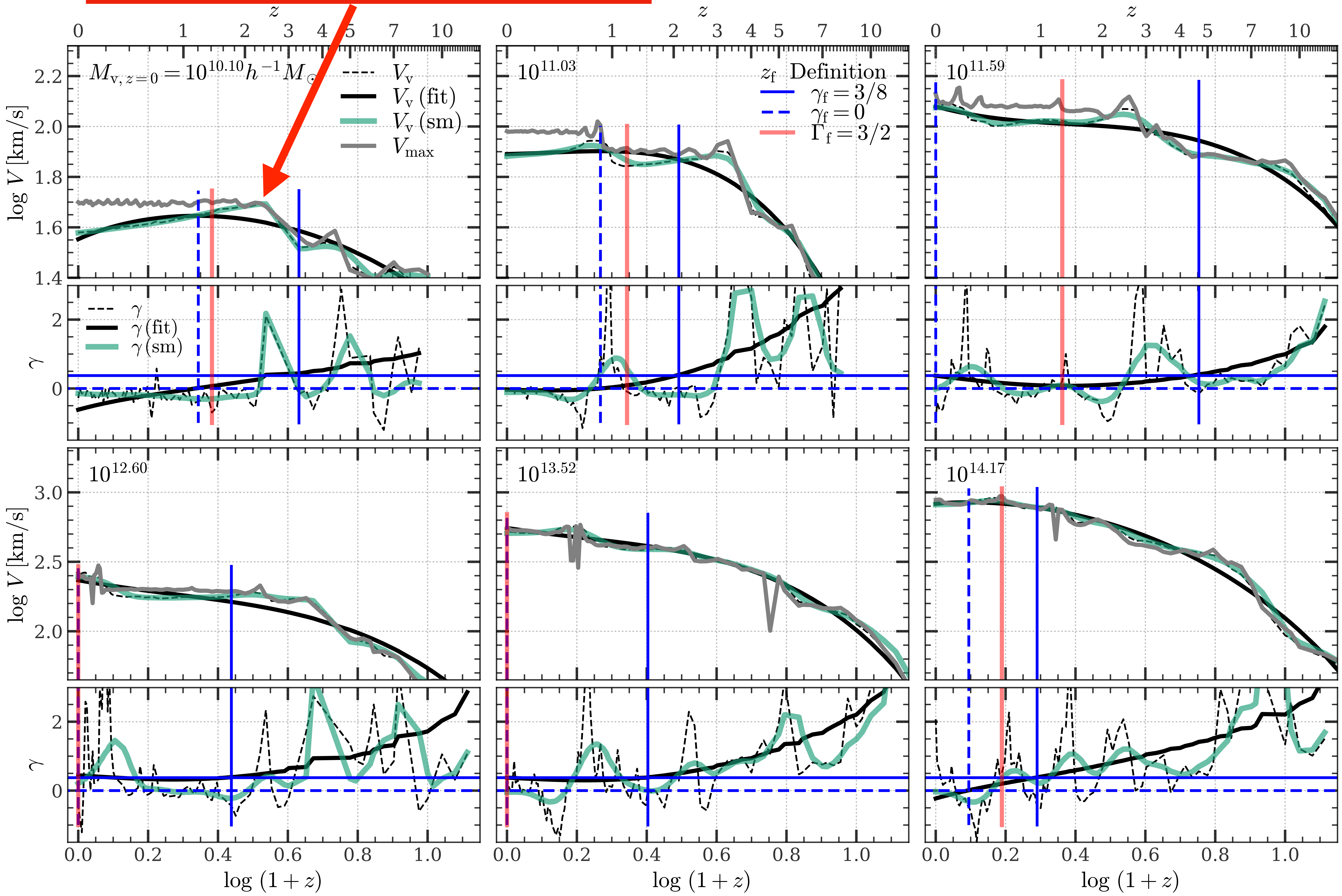
What is the origin of the 'everywhere' bimodality?

Let's start from dark matter halo.

Halo specific growth rate

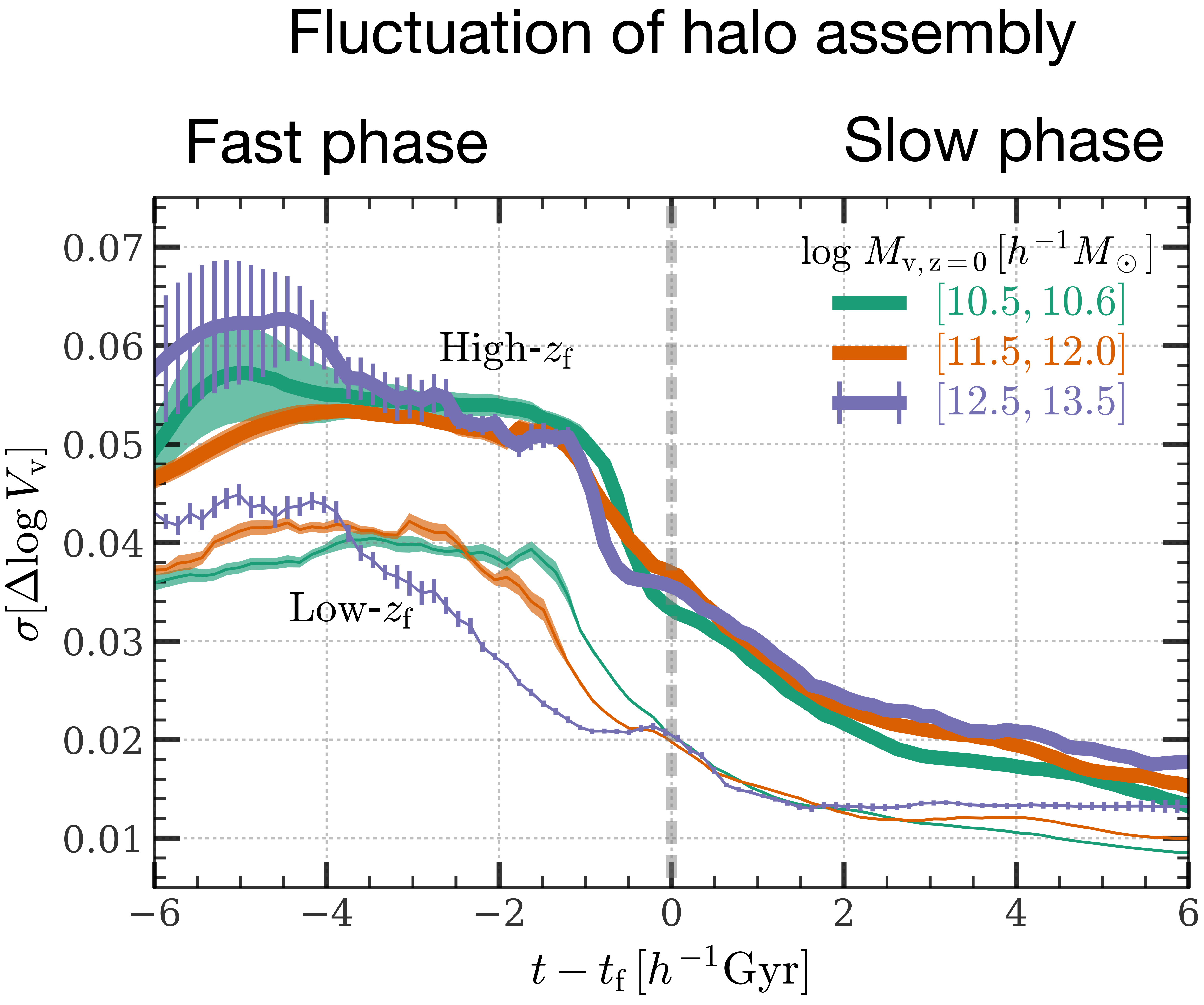
$$\gamma = \frac{\dot{V}_{\rm v}}{H(z)V_{\rm v}}$$

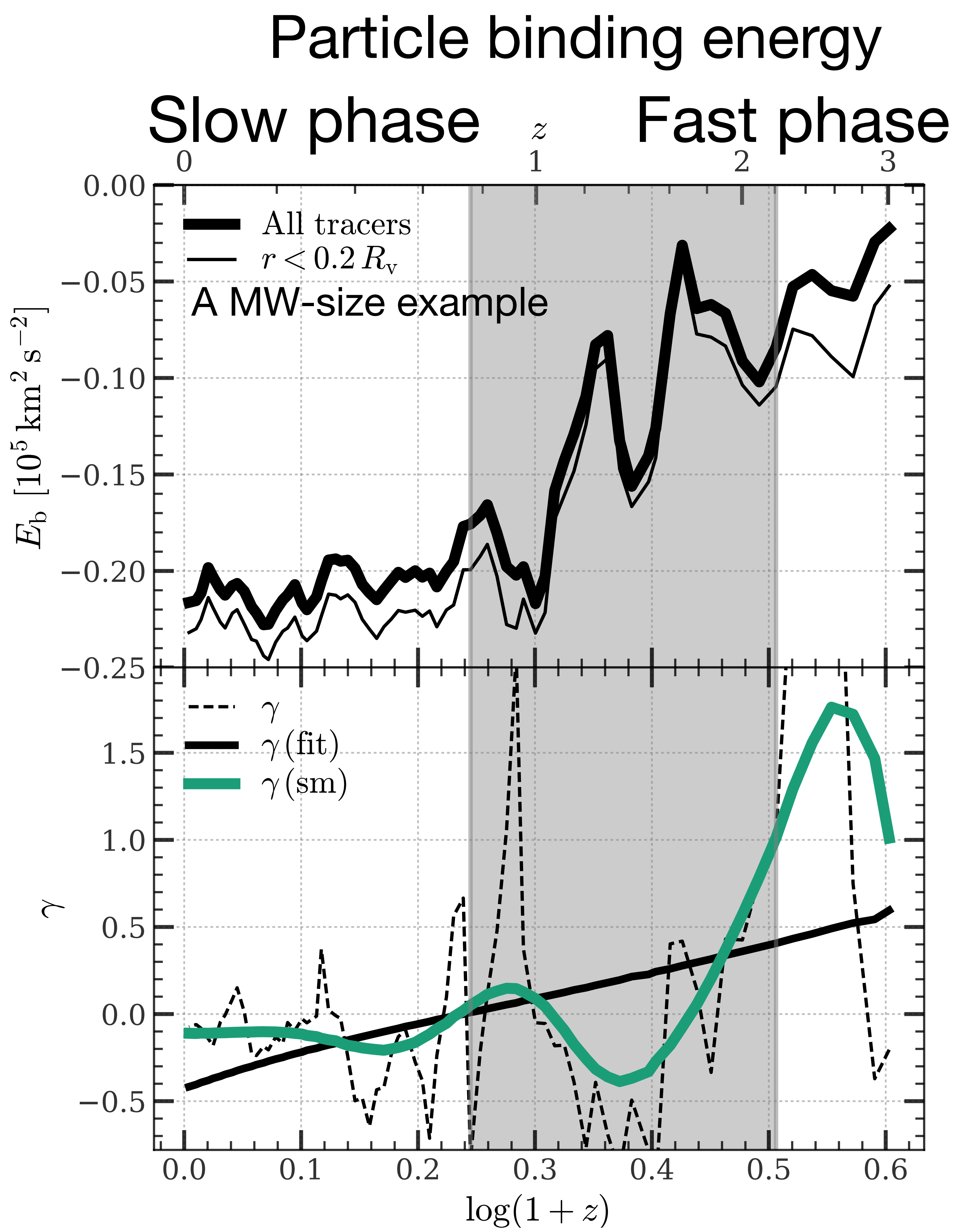
A transition from fast to slow accretion



See also Donghai Zhao+ 2003

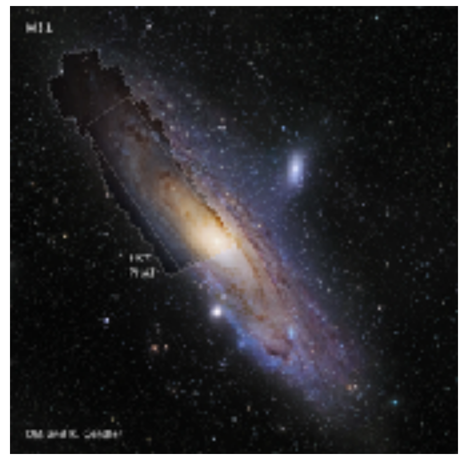
Dark matter halos and their assembly





Hao Li, in prep

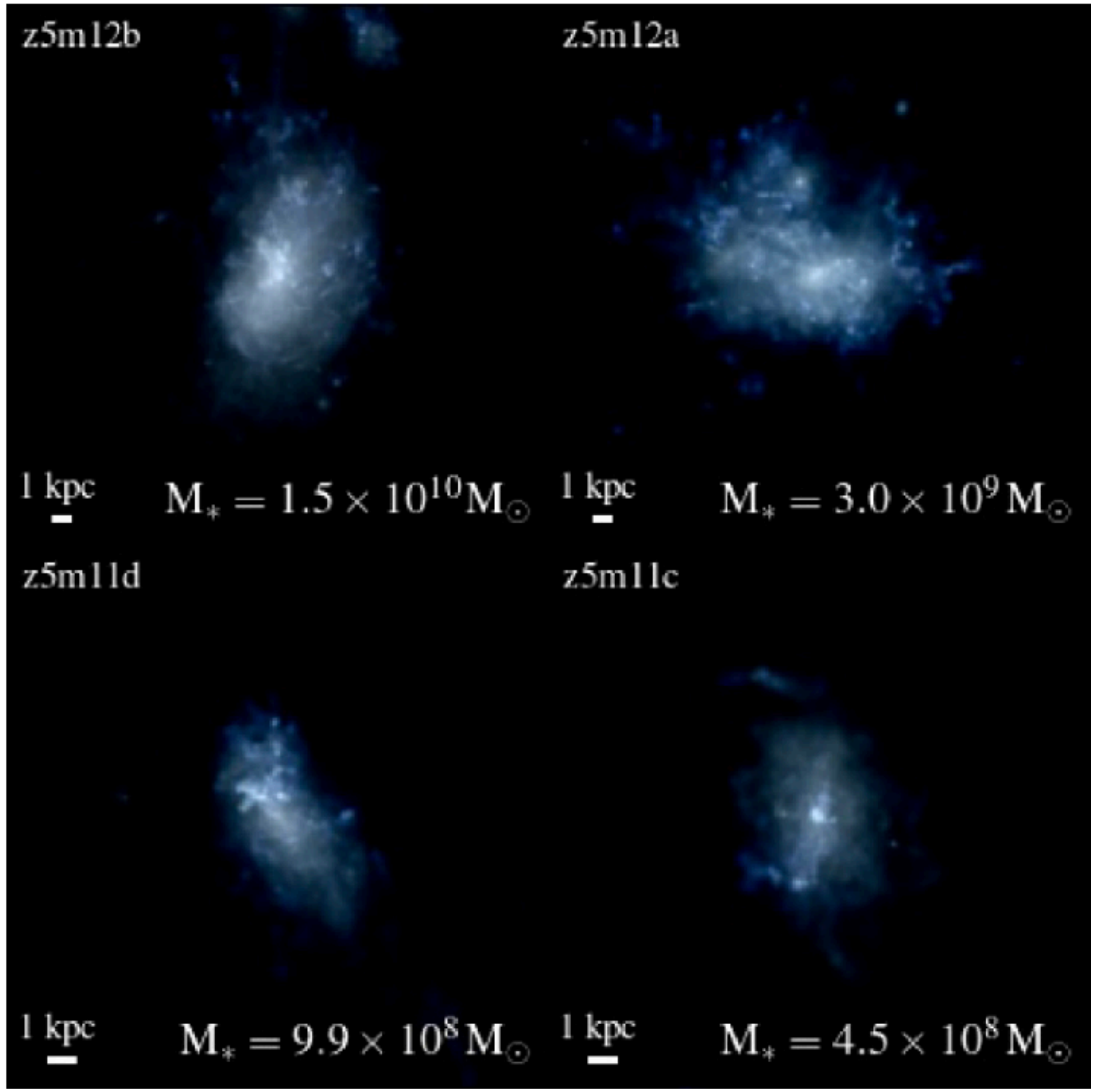
M31



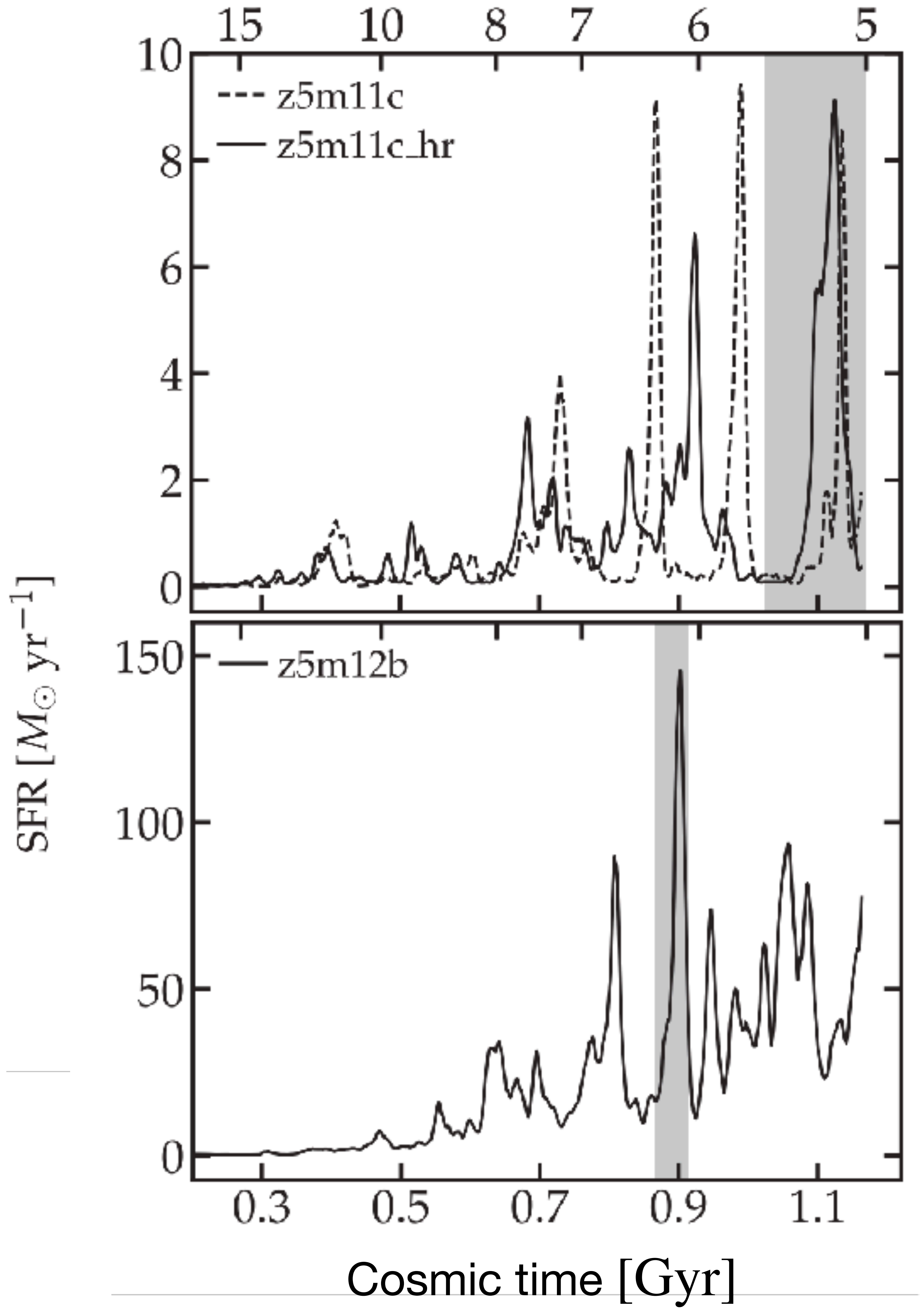
Galaxy formation in the early universe

Hydrodynamical simulations z=5

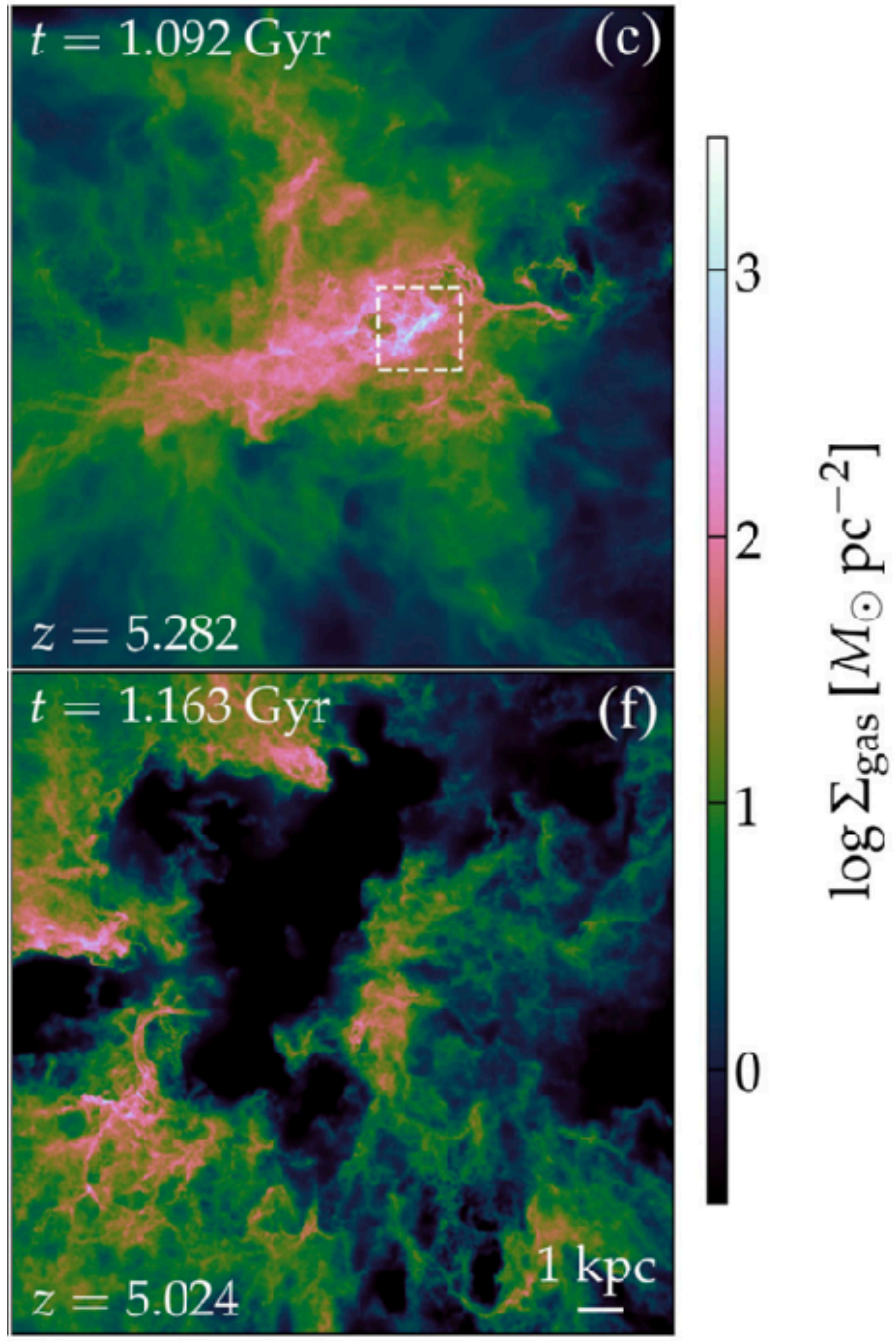
Clumpy and irregular



Bursty



Gas-rich and turbulent



FIRE-2 and its zoom-in runs, XC Ma 18, 20

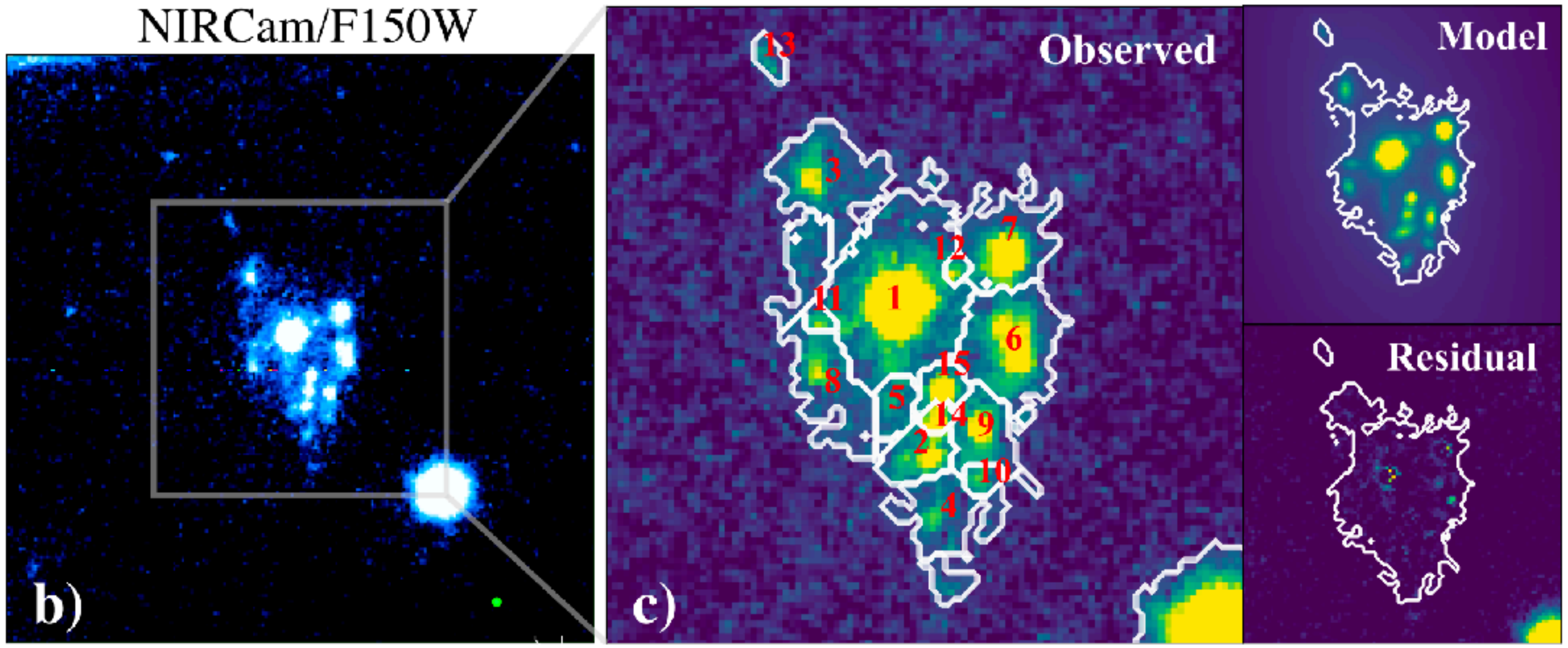
Galaxy formation in the early universe

JWST observations of strongly lensed galaxies

SF clumps with 10 - 60pc sizes

$\Sigma_{\rm gas} \sim 10^{3-5} M_\odot/{\rm pc}^2$

containing ~ 70% total flux

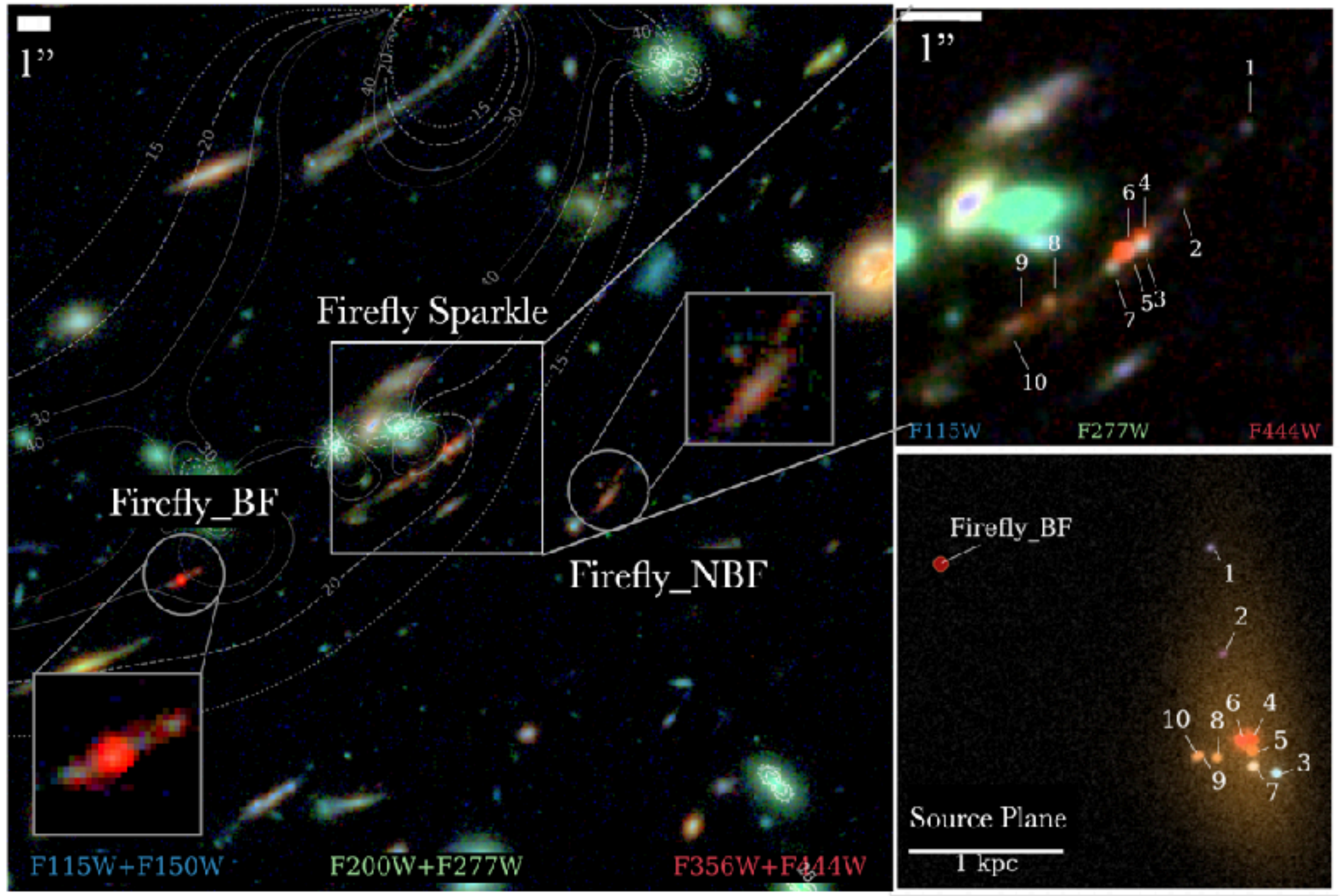


Fujimoto 24, z = 6.072

Star cluster masses ~ $10^{5.5} M_\odot$

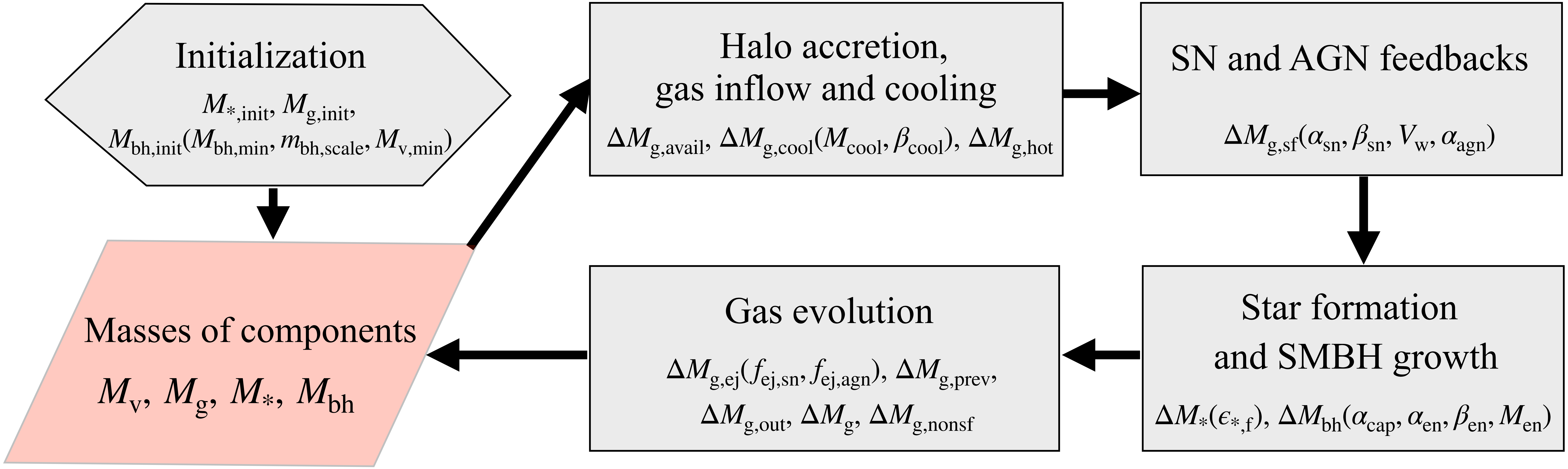
Containing ~ 50% total mass

$\Sigma_* \sim 10^{3-4} M_\odot/{\rm pc}^2$



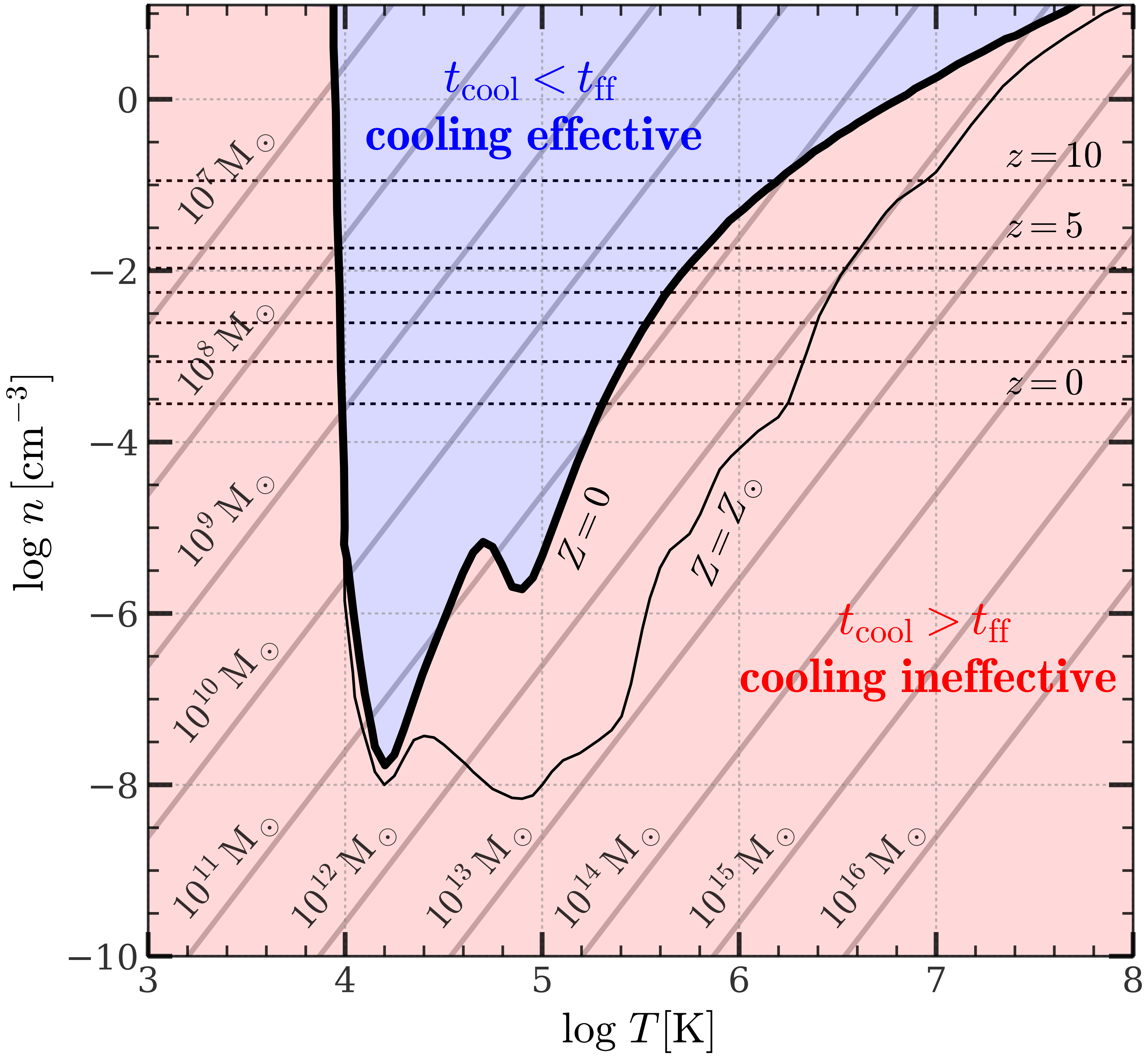
Mowla 24, at z = 8.304

A general pipeline for the modeling galaxy formation

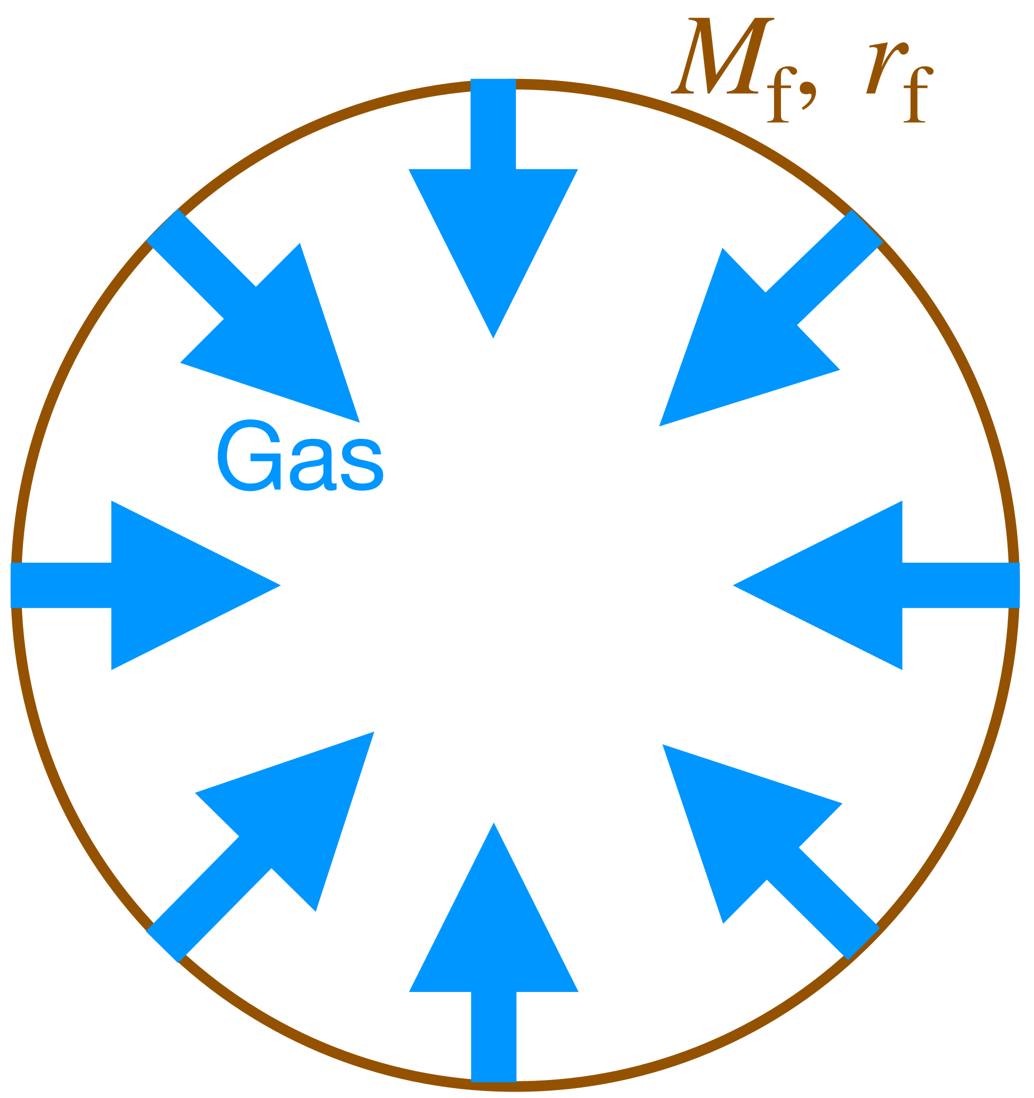


The cooling at halo scale and the formation of SGC

Cooling diagram



At high z, gas can inflows into halo core without any support from thermal pressure.



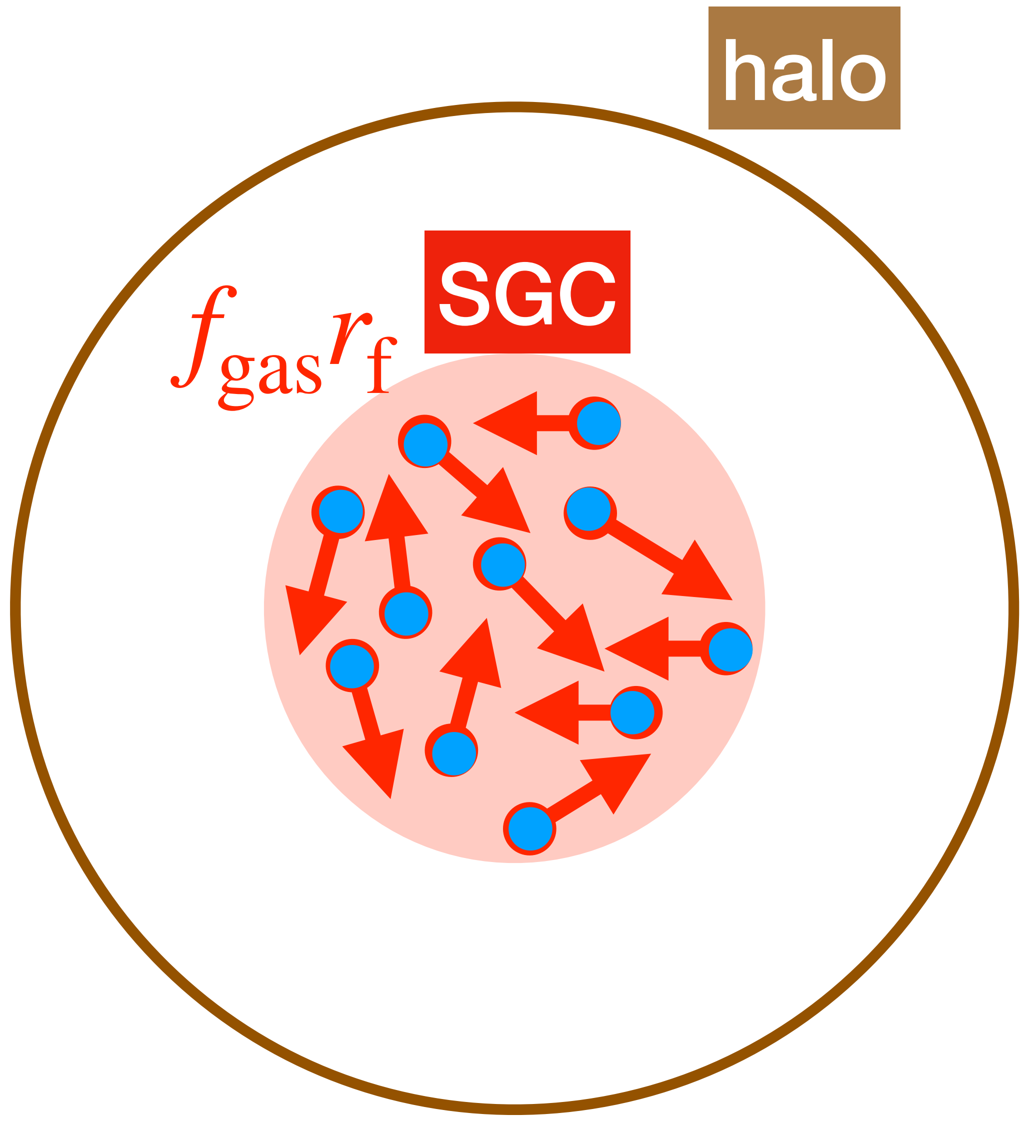
Self-gravitation condition: $V_{\rm gas}^2 \propto G\dfrac{M_{\rm f}}{r_{\rm f}} = G\dfrac{f_{\rm gas}M_{\rm f}}{f_{\rm gas}r_{\rm f}}$

Galaxy (self-gravitating cloud) size: $r_{\rm sgc} \propto f_{\rm gas} r_{\rm f}$

SGC density:

$$n_{\rm sgc} = \frac{f_{\rm str} f_{\rm gas} M_{\rm v}}{(4\pi/3)(f_{\rm gas}R_{\rm v})^3 \mu m_{\rm p}} = 663.24\mathrm{cm}^{-3}\,(1+z)_{10}^3$$

Gas dynamics within SGC



Ballistically moving sub-clouds

Gravitational instability of SGC leads to its fragmentation, and the formation of sub-clouds.

Jeans mass gives the typical sub-clouds mass:

$$M_{\rm J} = 5\times10^7\left(\frac{c_s}{10\,{\rm km\,s^{-1}}}\right)^3\left(\frac{n_{\rm sgc}}{1\,{\rm cm^{-3}}}\right)^{-1/2}$$
$$\sim 10^6 - 5\times10^7 M_\odot$$

Collision of inflow gas with pre-existing gas generates turbulence and raises the density of sub-clouds:

$$\rho_{\rm sc}/\rho_{\rm sgc} \sim \mathscr{M}^2 \sim V_{\rm v}^2 + V_{\rm w}^2$$

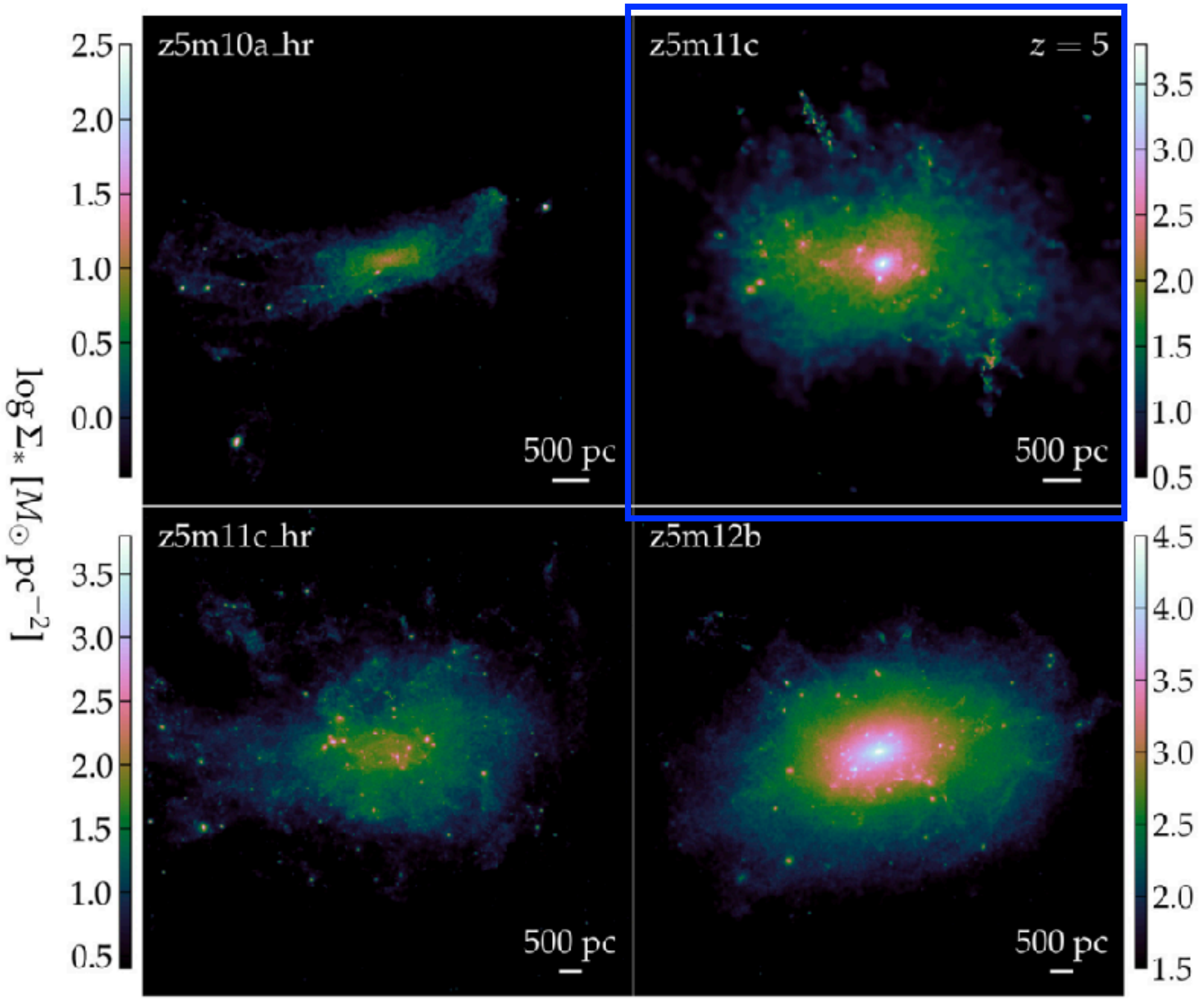
$$\mathscr{M}_{\rm v} \sim V_{\rm v}/c_{\rm s} \sim 8.00 M_{\rm v,10}^{1/3}(1+z)_{10}^{1/2} \sim 13.86 M_{\rm v,11.5}^{1/3}(1+z)_3^{1/2}$$

$$\mathscr{M}_{\rm w} \sim V_{\rm w}/c_{\rm s} \sim 25$$

Sub-clouds is like a tiny bullet, moving without drag force/collision within the SGC.

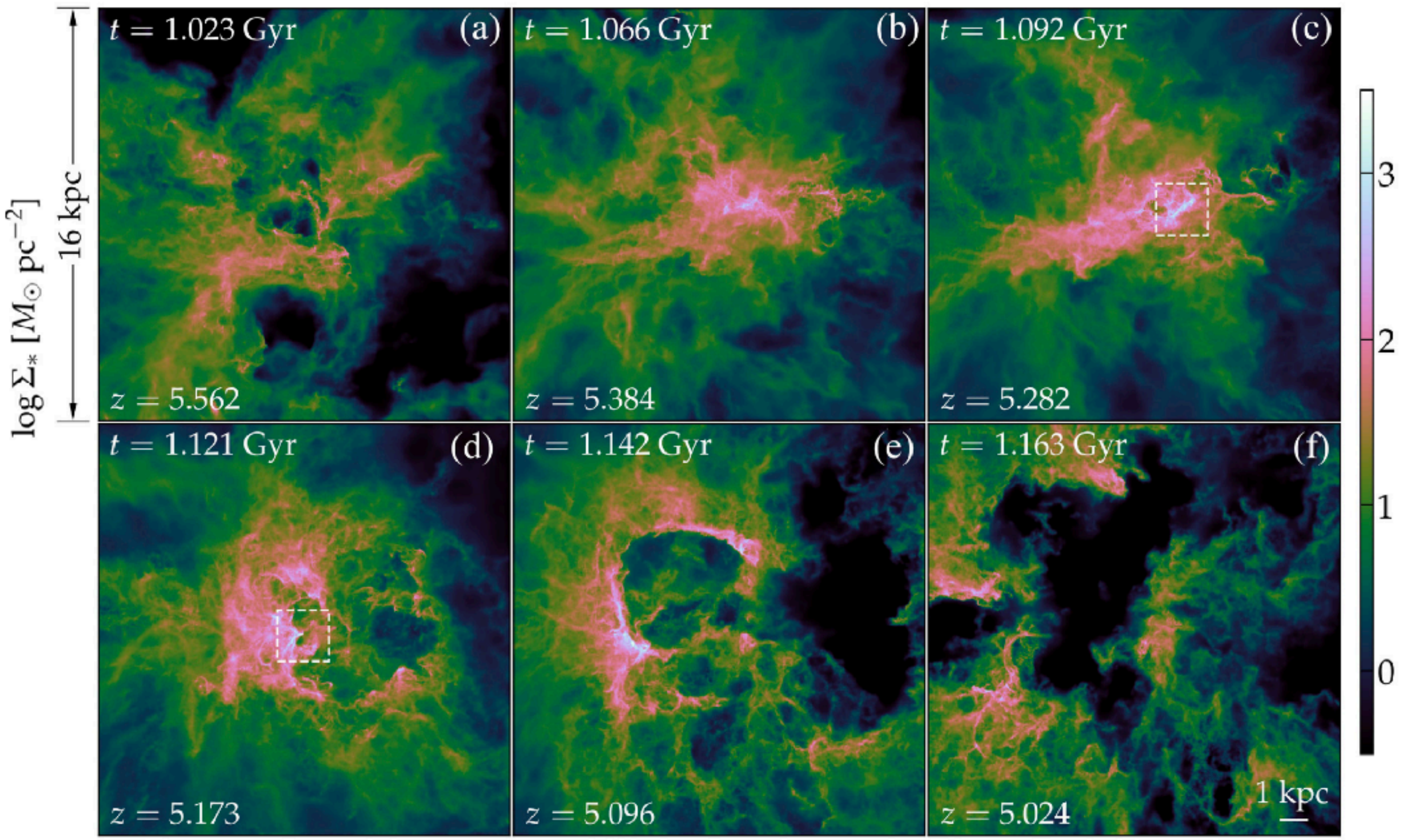
For $f_{\rm gas} \sim 0.16 > \lambda \sim 0.04$, rotation support does not appears. The sub-clouds form a dynamically hot system.

Ma+ 2020, FIRE-2 zoom-ins

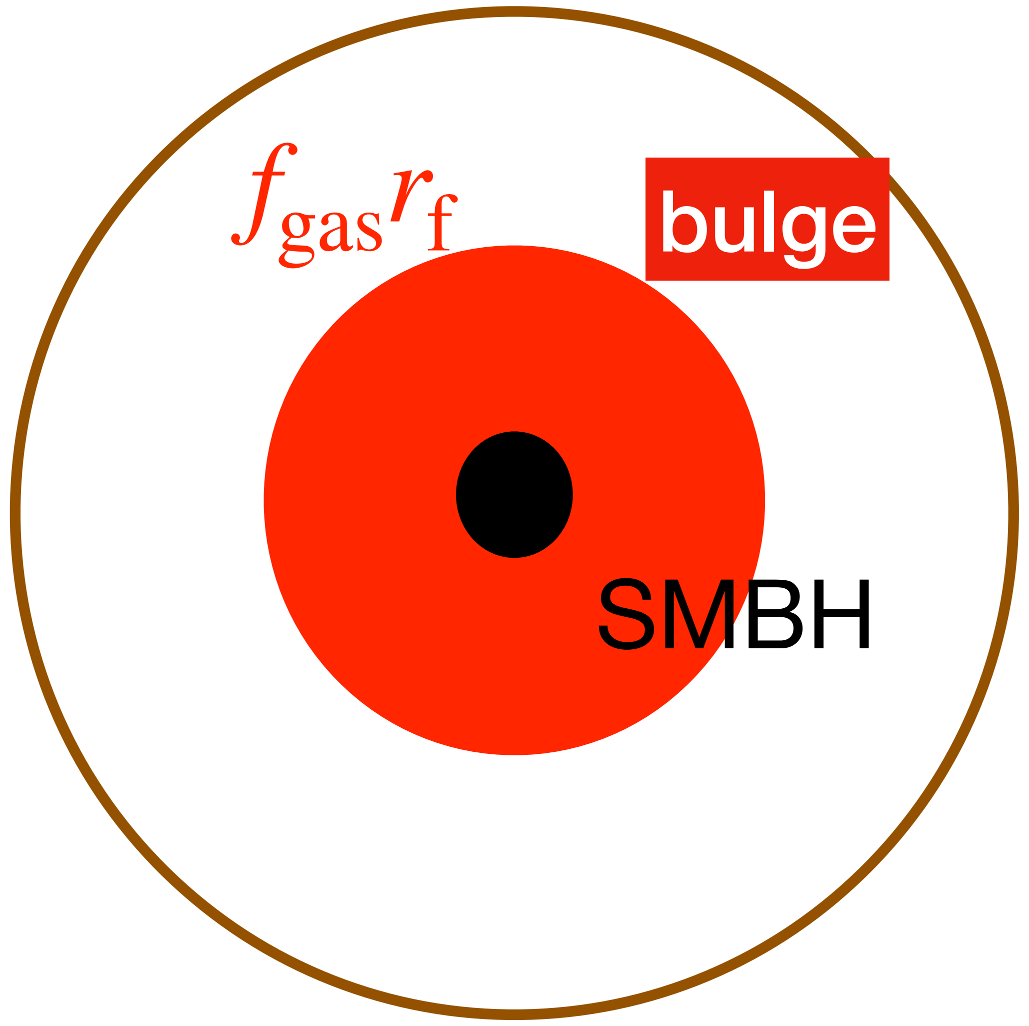


Formation of one cluster triggers more

A 'breathing FIRE' - bursty SFH



Star formation within SGC



Star formation in sub clouds leads to a stellar bulge (early-type galaxy).
The total amount of formed stars:

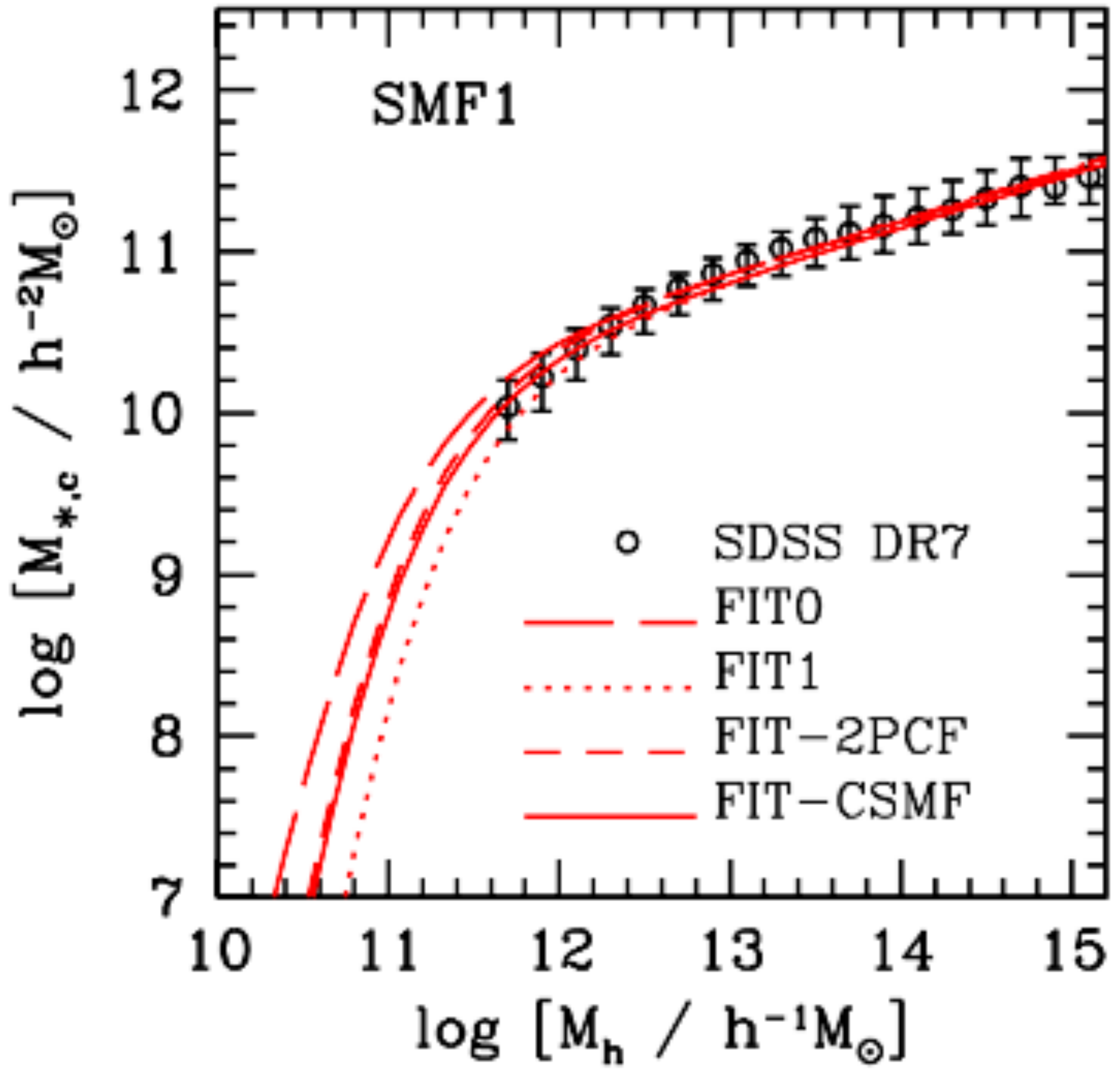
$$\Delta M_* = \epsilon_* \Delta M_{\rm v} F_{\rm cool} F_{\rm sn} F_{\rm agn}$$

with $\epsilon_* \sim 1$ and

$$F_{\rm cool} = \frac{1}{1 + (M_{\rm v}/M_{\rm cool})^{\beta_{\rm cool}}},$$

$$F_{\rm agn} = 1 - \frac{\alpha_{\rm agn} M_{\rm bh} c^2}{M_{\rm g} V_{\rm g}^2},$$

$$F_{\rm sn} = \frac{\alpha_{\rm sn} + (V_{\rm g}/V_{\rm w})^{\beta_{\rm sn}}}{1 + (V_{\rm g}/V_{\rm w})^{\beta_{\rm sn}}}.$$



Yang+ 2012

SMBH accretion in SGC

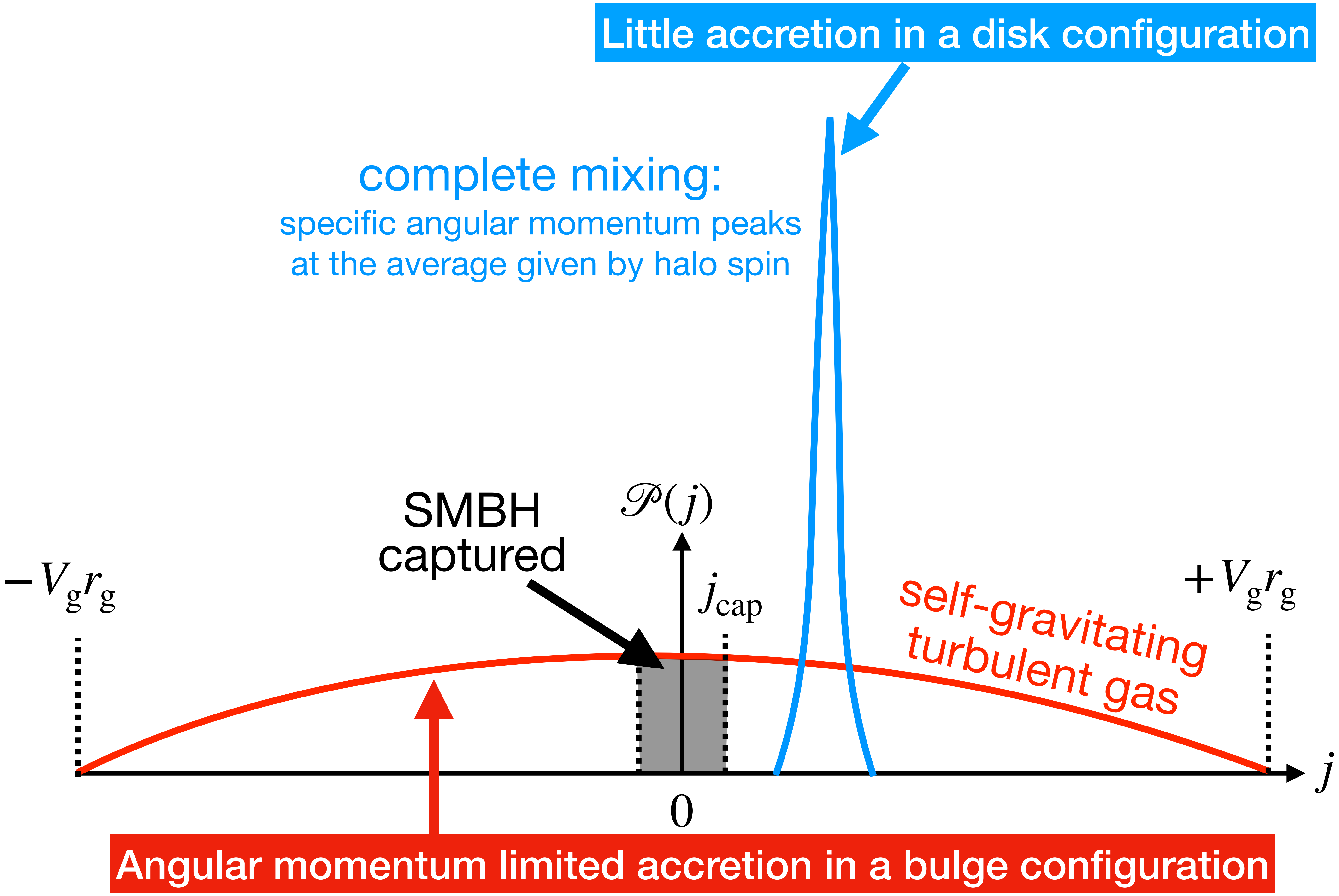
The fraction of 'dynamically hot' gas capture by the SMBH:

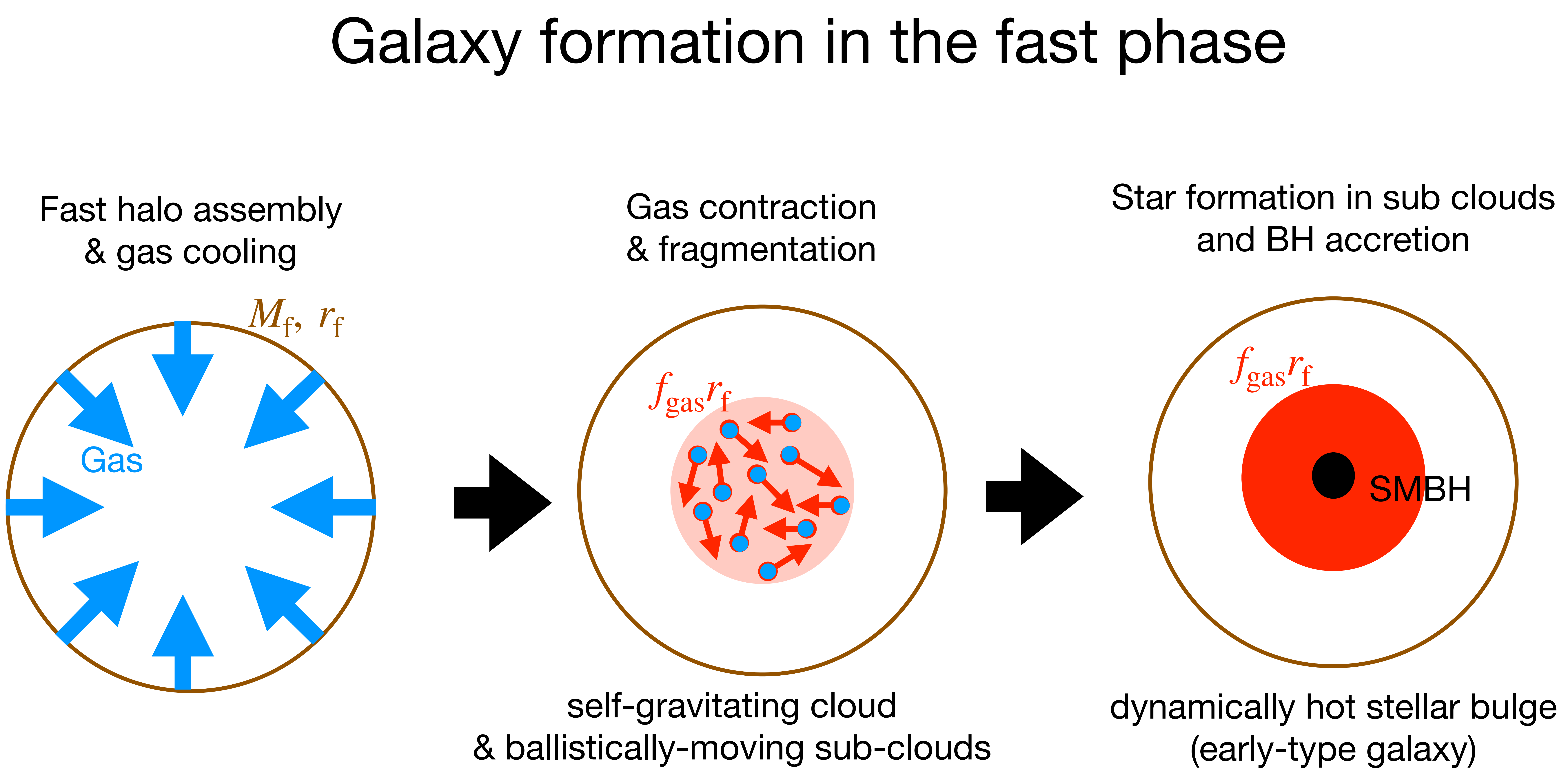
$$\frac{\Delta M_{\rm acc}}{\Delta M_{\rm g}} = \frac{j_{\rm cap}}{j_{\rm turb}} = \frac{V_{\rm g} r_{\rm cap}}{V_{\rm g} r_{\rm g}} = \frac{V_{\rm g}^2 r_{\rm cap}}{V_{\rm g}^2 r_{\rm g}} \propto \frac{G M_{\rm bh}}{G M_{\rm g}}$$

$$\boxed{\frac{\Delta M_{\rm acc}}{\Delta M_{\rm g}} = \alpha_{\rm cap} F_{\rm en} \frac{M_{\rm bh}}{M_{\rm g}}}$$

Regenerated low-j gas by a positive SN feedback

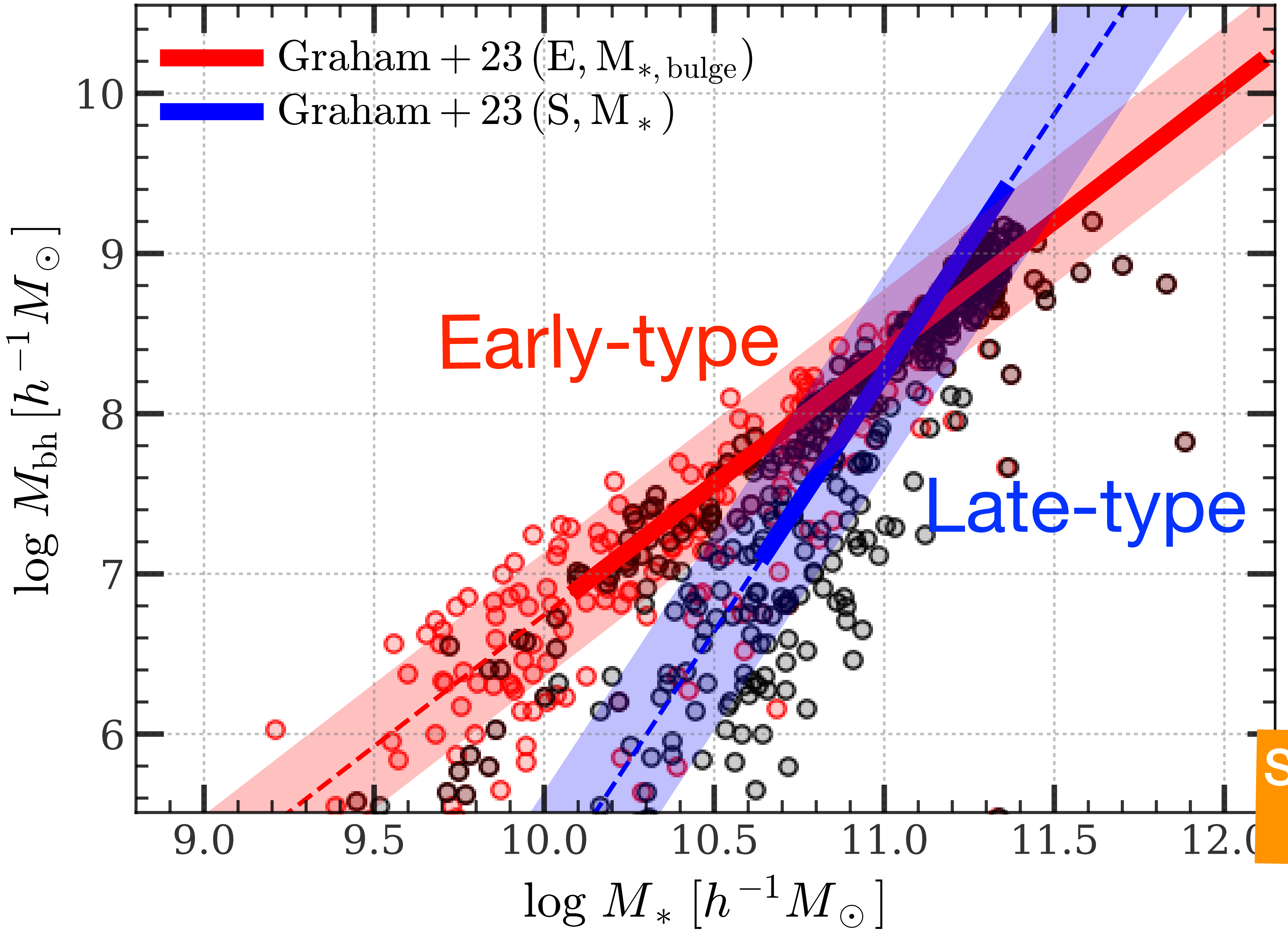
$$F_{\rm en} = \frac{\alpha_{\rm en} + (M_{\rm v}/M_{\rm en})^{\beta_{\rm en}}}{1 + (M_{\rm v}/M_{\rm en})^{\beta_{\rm en}}}$$

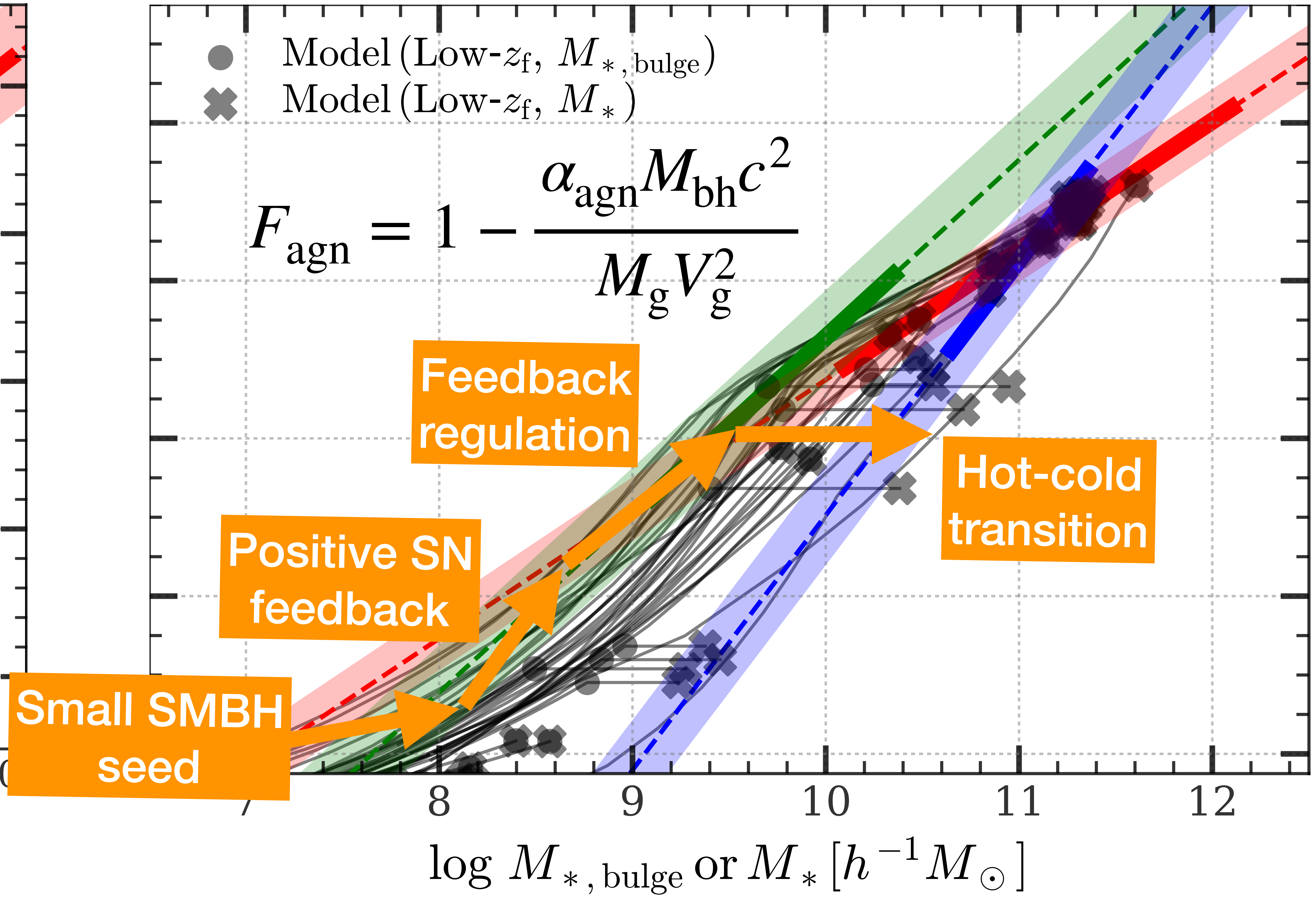



Galaxy formation in the fast phase
Fast halo assembly
& gas cooling
$M_{\rm f}$, $r_{\rm f}$
Gas
Gas contraction
& fragmentation
$f_{\rm gas} r_{\rm f}$
self-gravitating cloud
& ballistically-moving sub-clouds
Star formation in sub clouds
and BH accretion
$f_{\rm gas} r_{\rm f}$
SMBH
dynamically hot stellar bulge
(early-type galaxy)

Prediction and explanation for the SMBH mass-stellar mass scaling

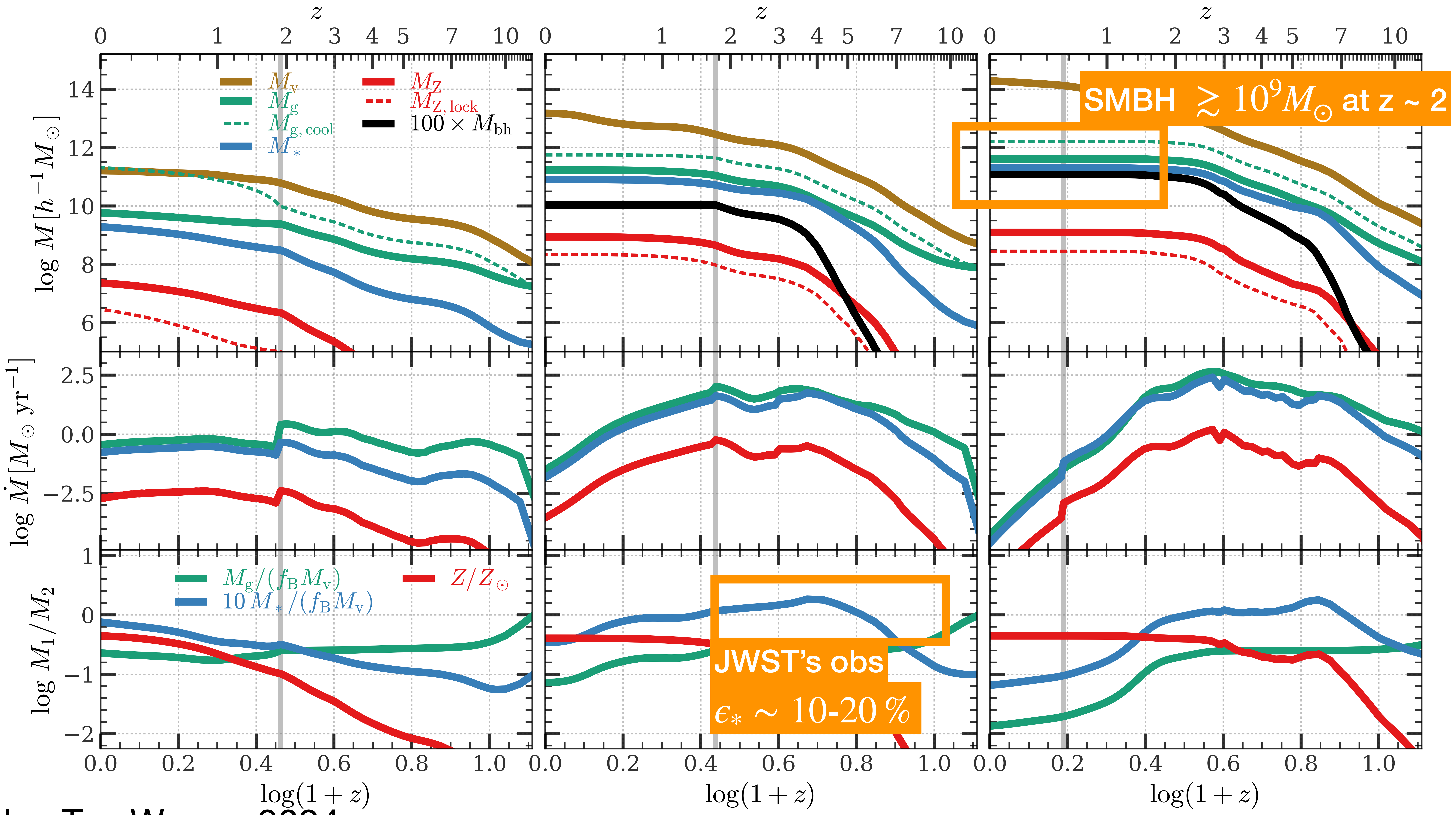
- The model reproduces SMBH-stellar scaling relations in the low-z Universe.
- The growth of SMBH can be separated into four stages, each driven by a distinct physical mechanism.





See also Hui Hong+ 2023; Hao Li+ in prep.

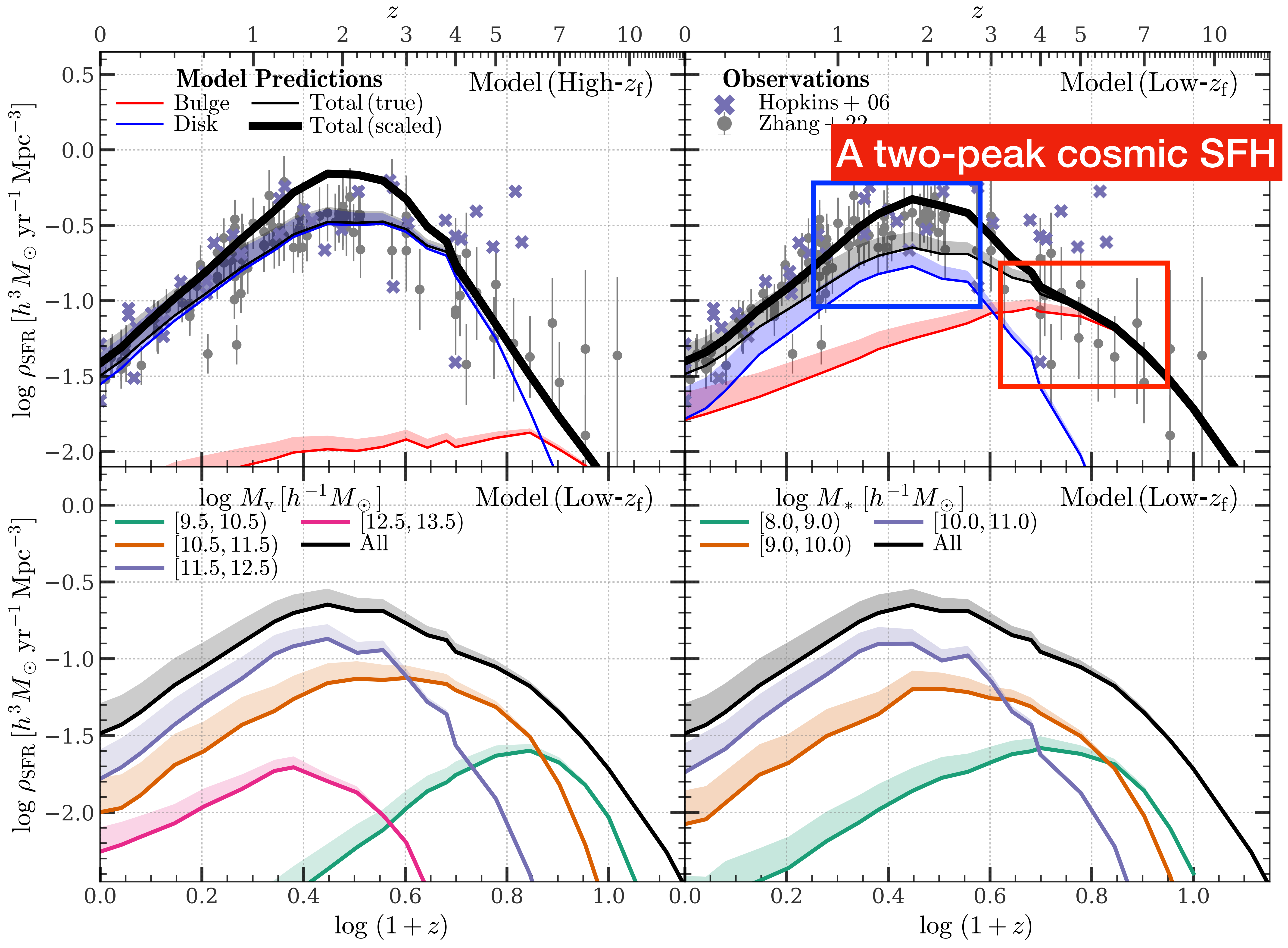
Predicted evolution history of individual galaxies

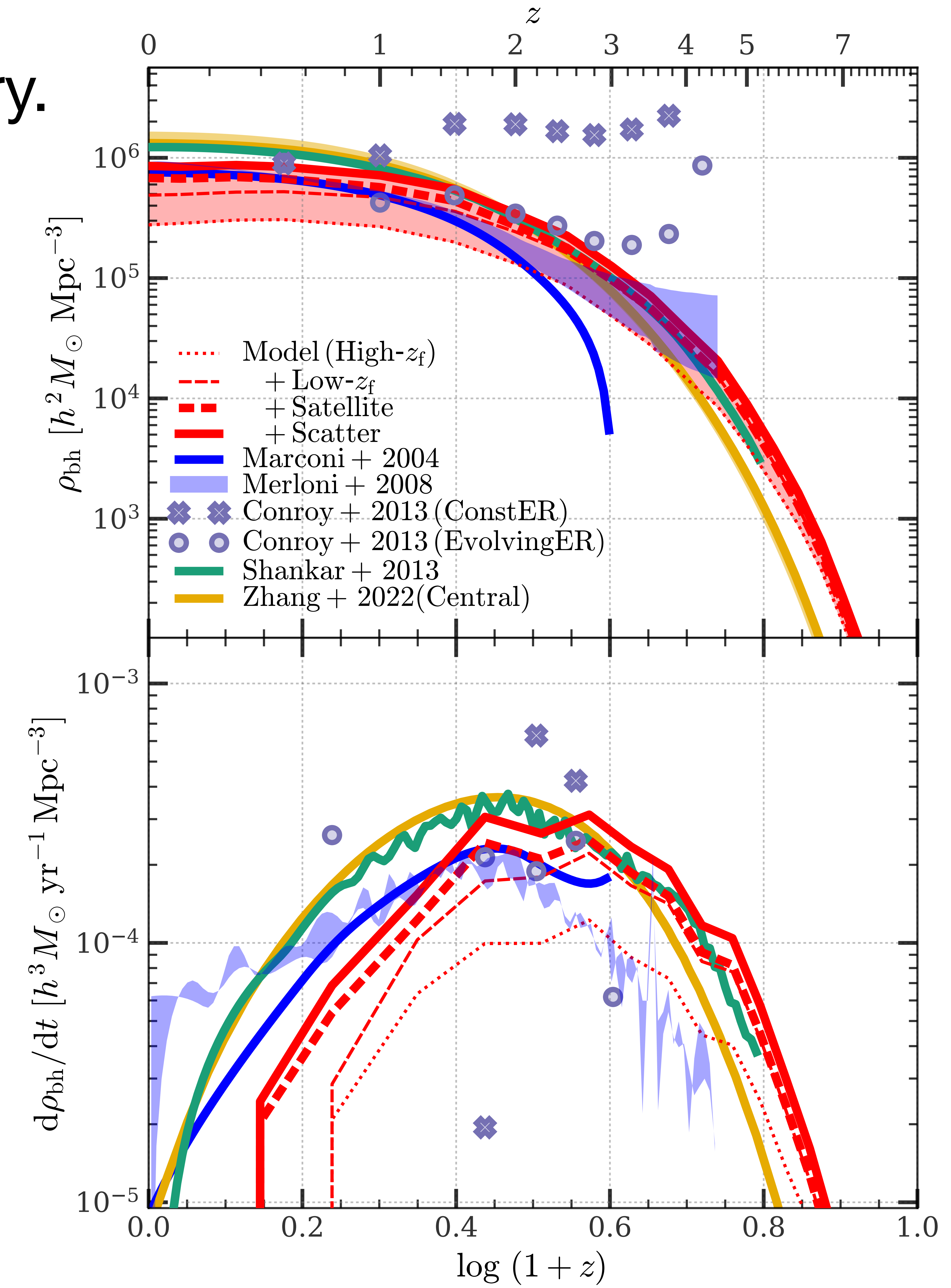


See also Tao Wang+ 2024

More predictions

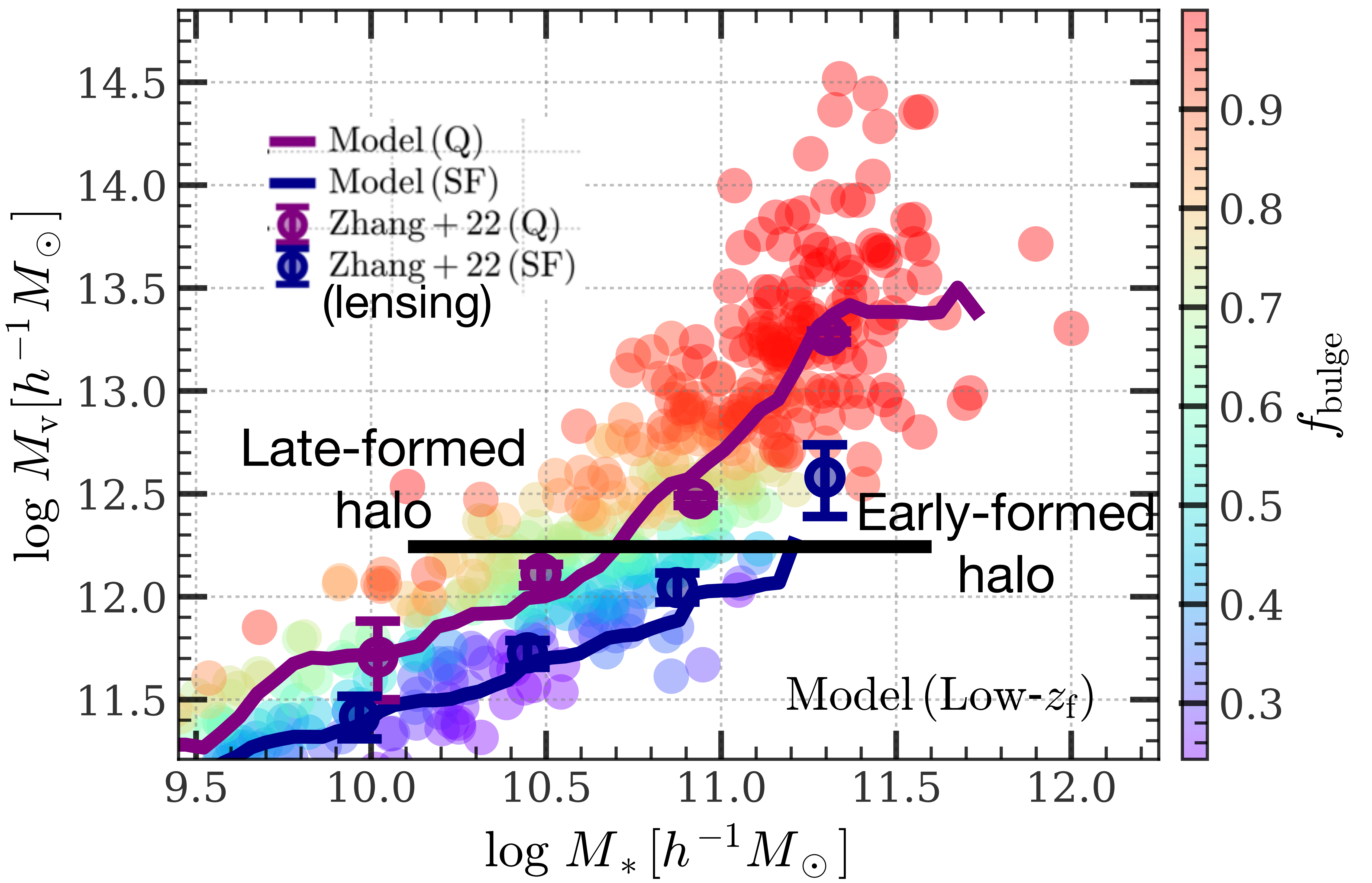
- Cosmic SMBH accretion and star formation history.
- SMBH and stellar mass functions.

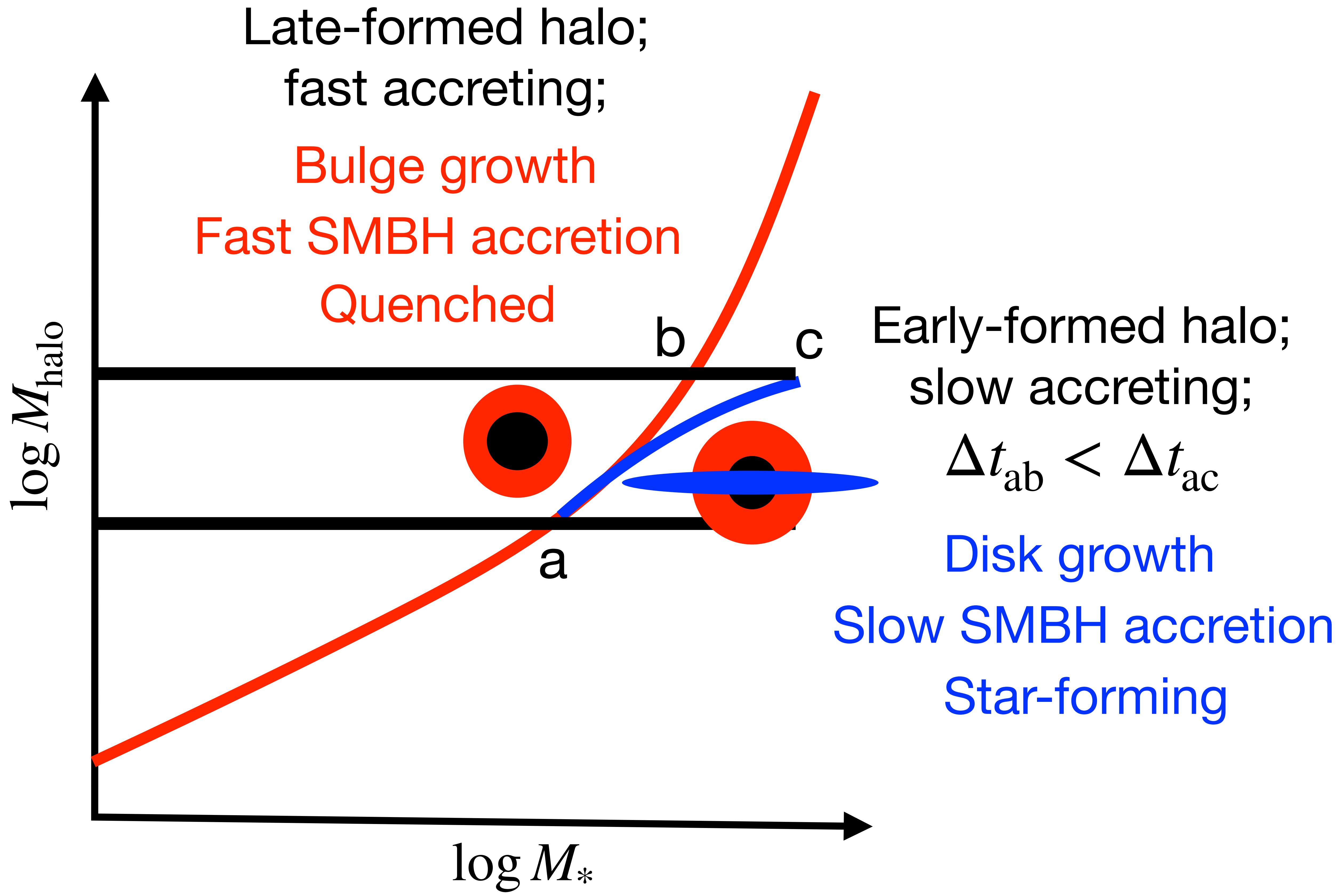




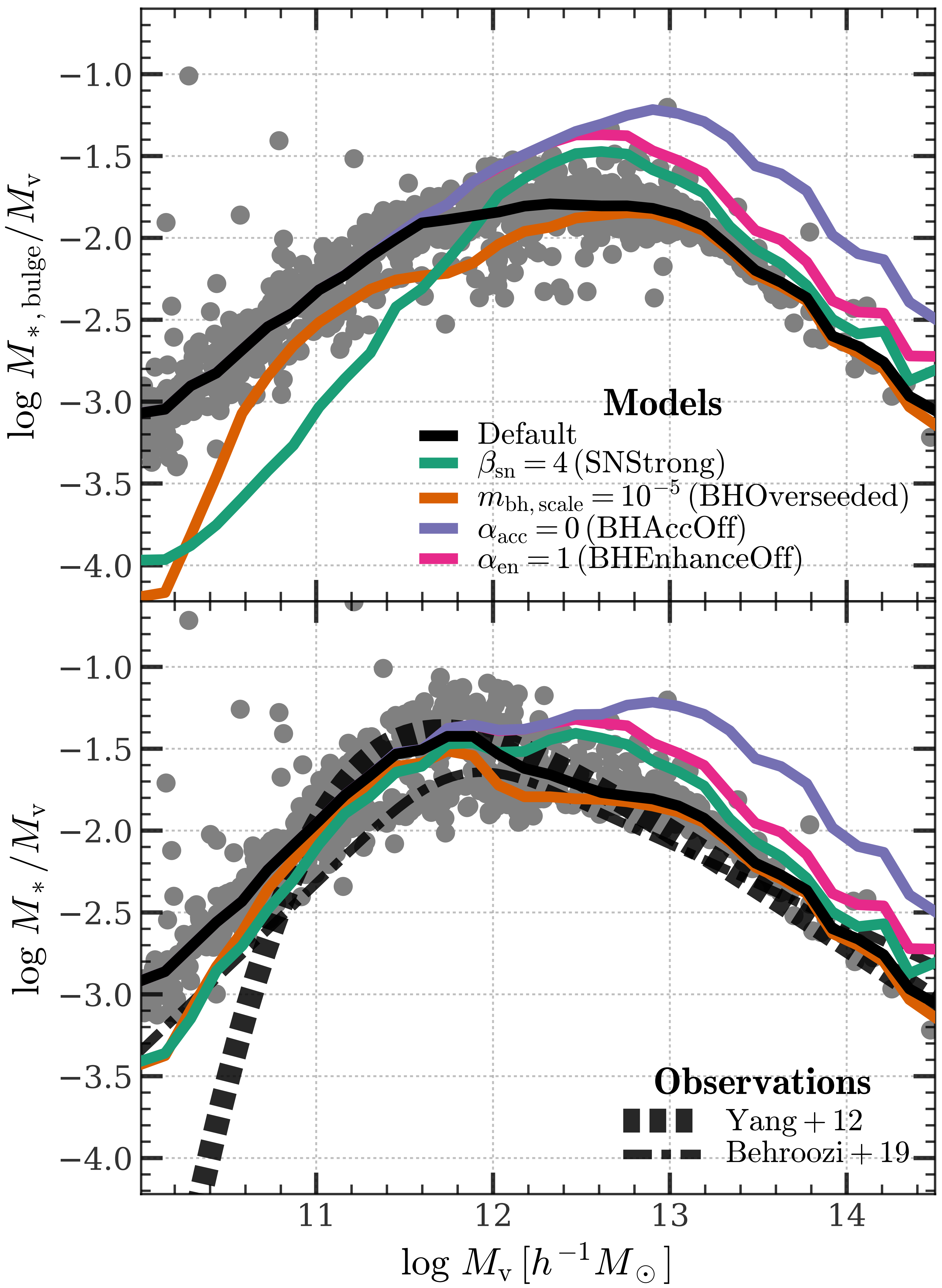
An interesting consequence: early formed halo prefers to host star-forming galaxy

- There are indirect evidences of the counter-intuitive z_{form}-quenching relation (e.g. Kai Wang 2023).
- We find that this is a natural outcome of early bulge-to-disk transition in early-formed halo.

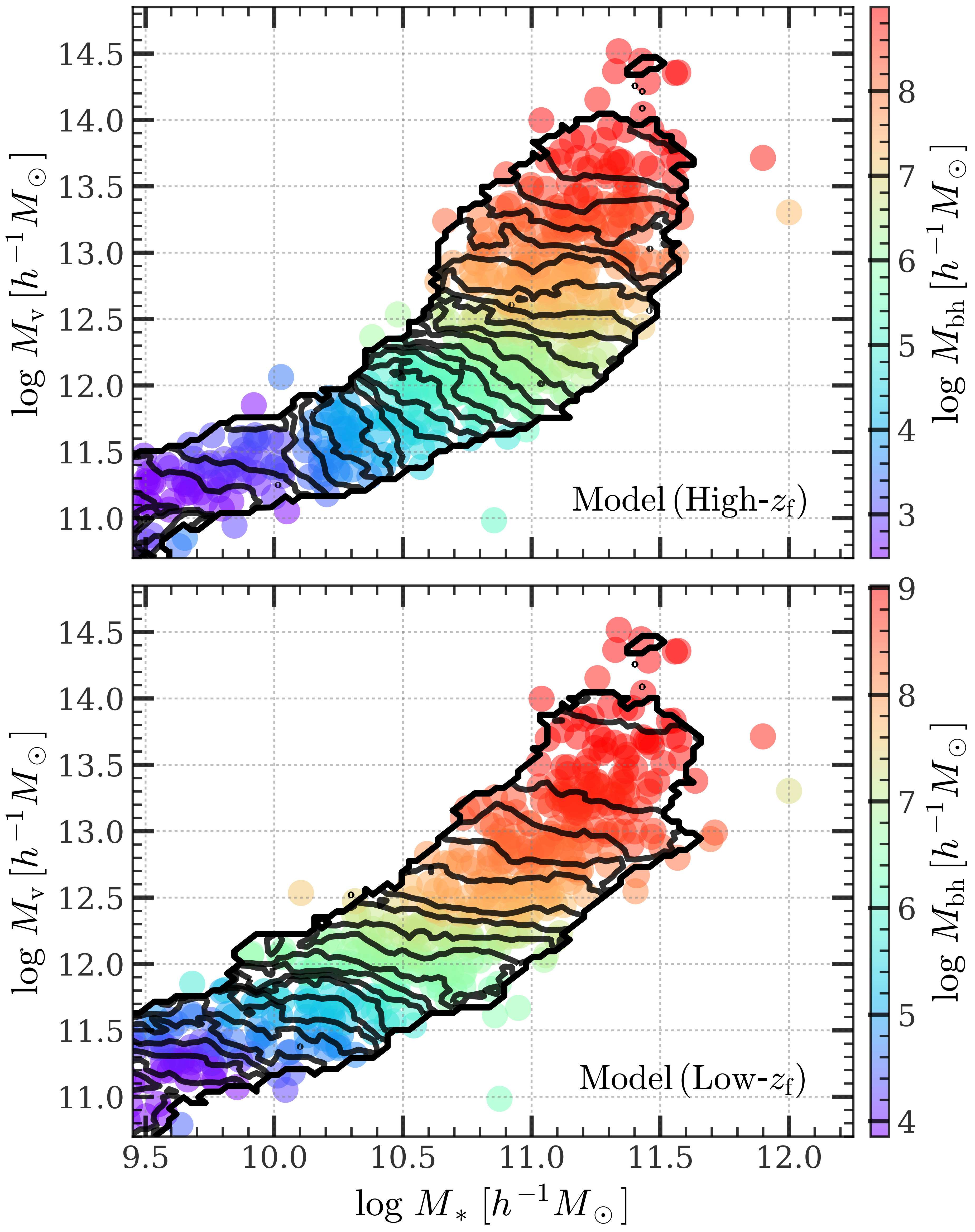


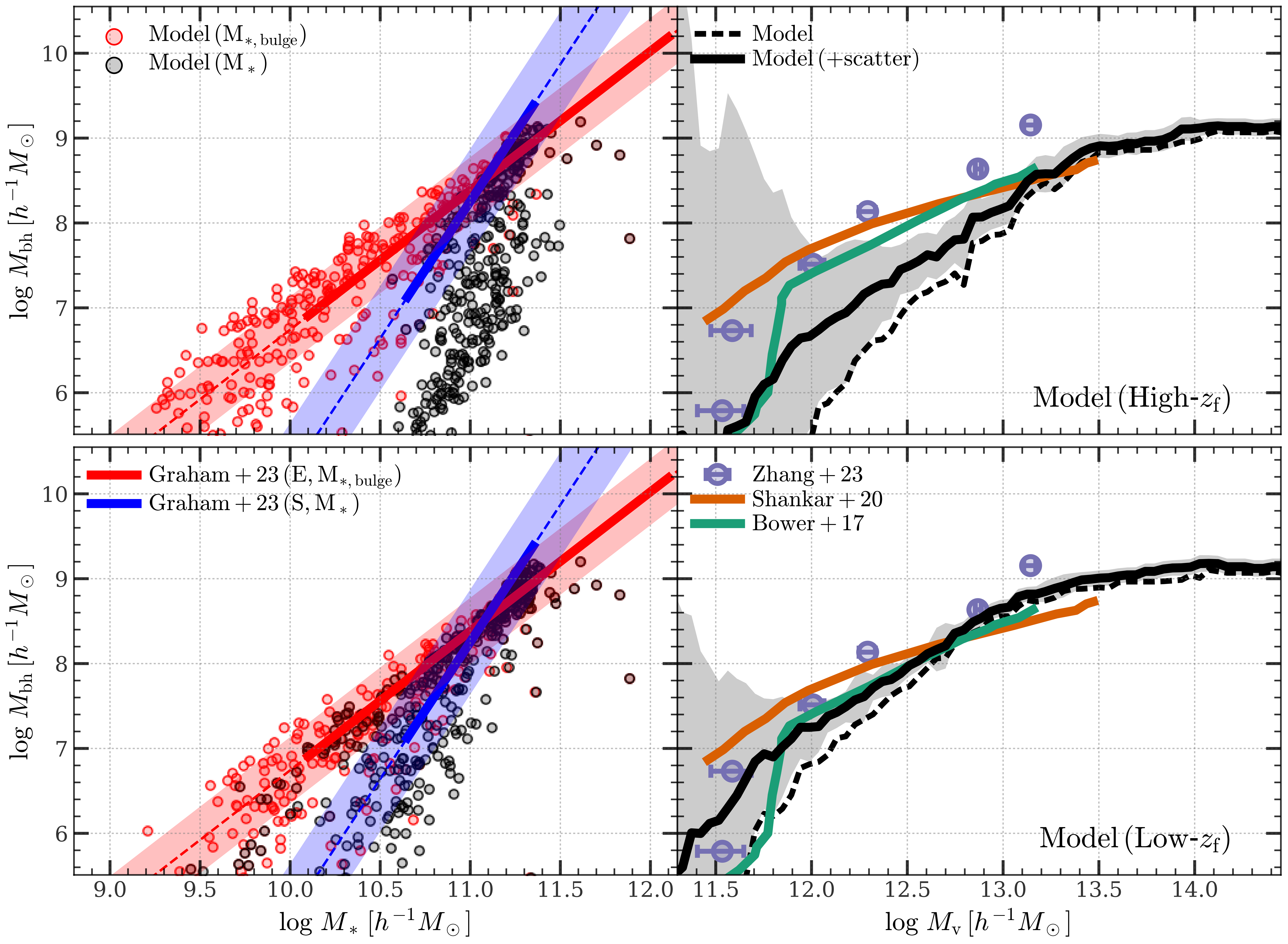


The double-power-law SMHM relation



The SMHMBH relation



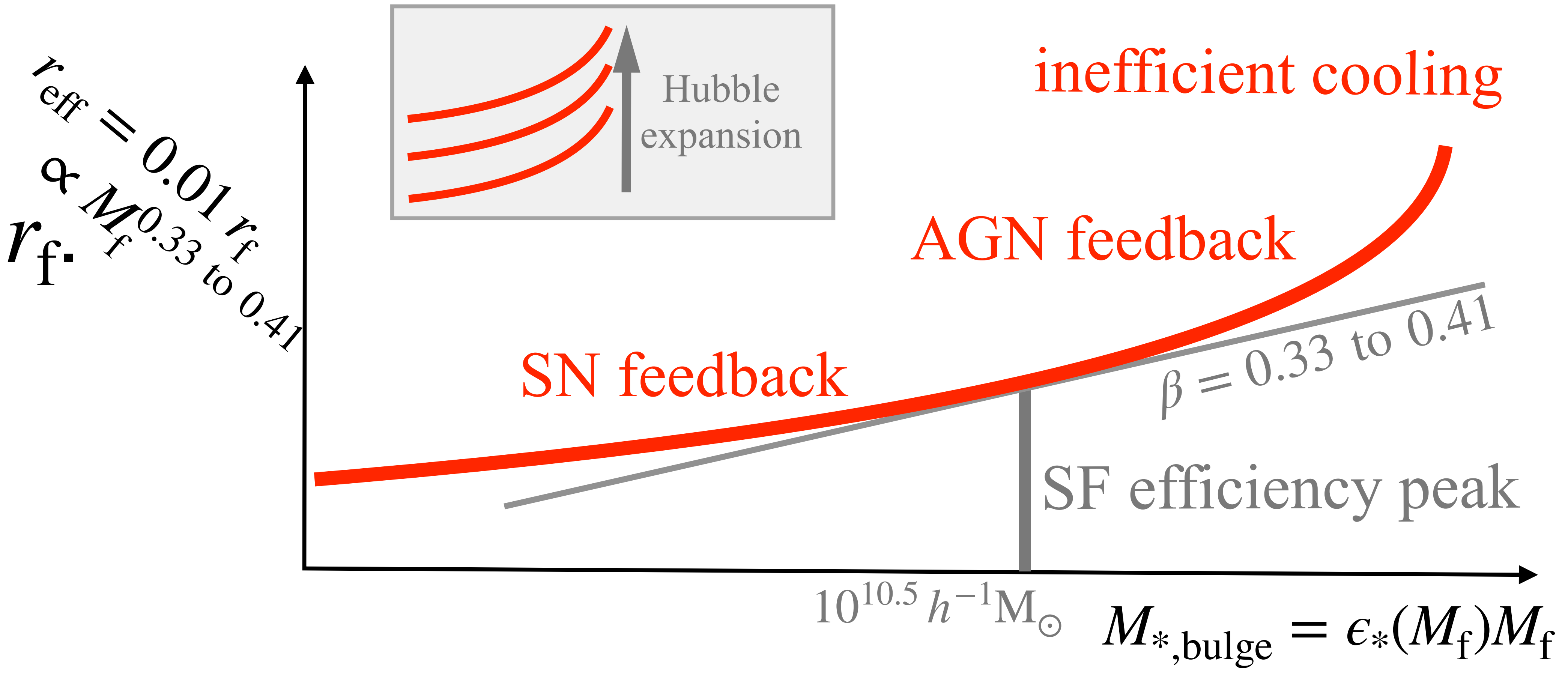


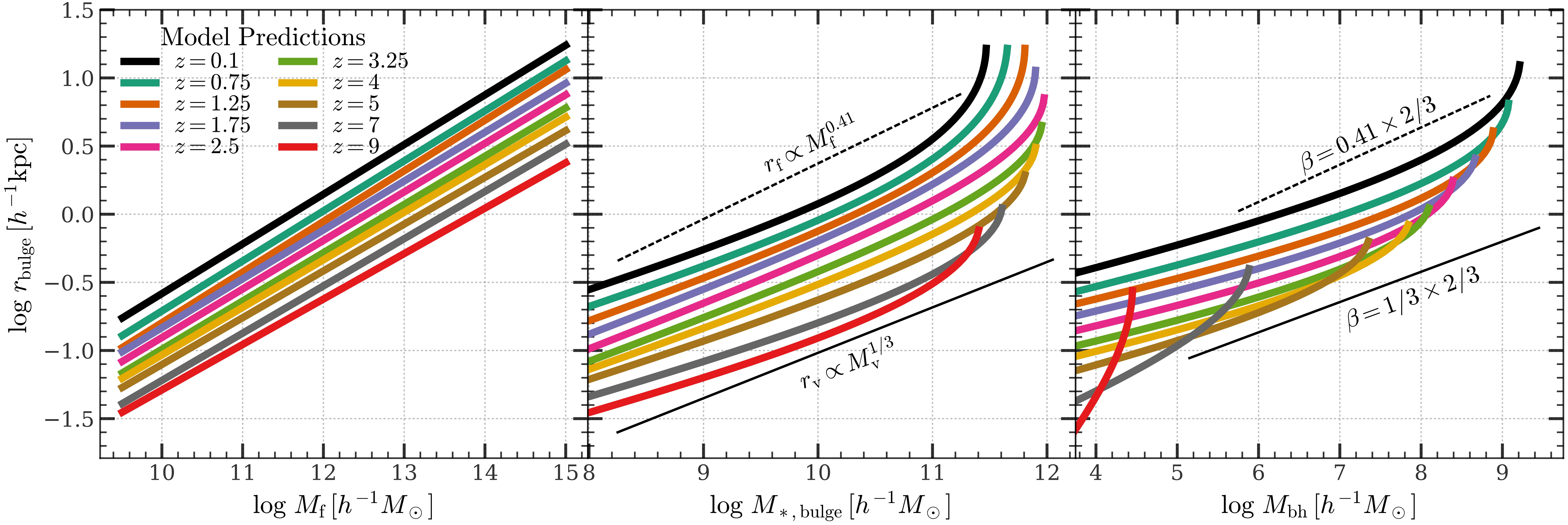
See also Ziwen Zhang+ 2023

The bulge size-(halo, bulge, SMBH) masse relations

- starting from the galaxy-halo homology relation, $r_{eff} = 0.01 r_{\rm f}$.
- Combining non-linear mass-mass relations step by step.

Size - mass relation of dynamically hot galaxies



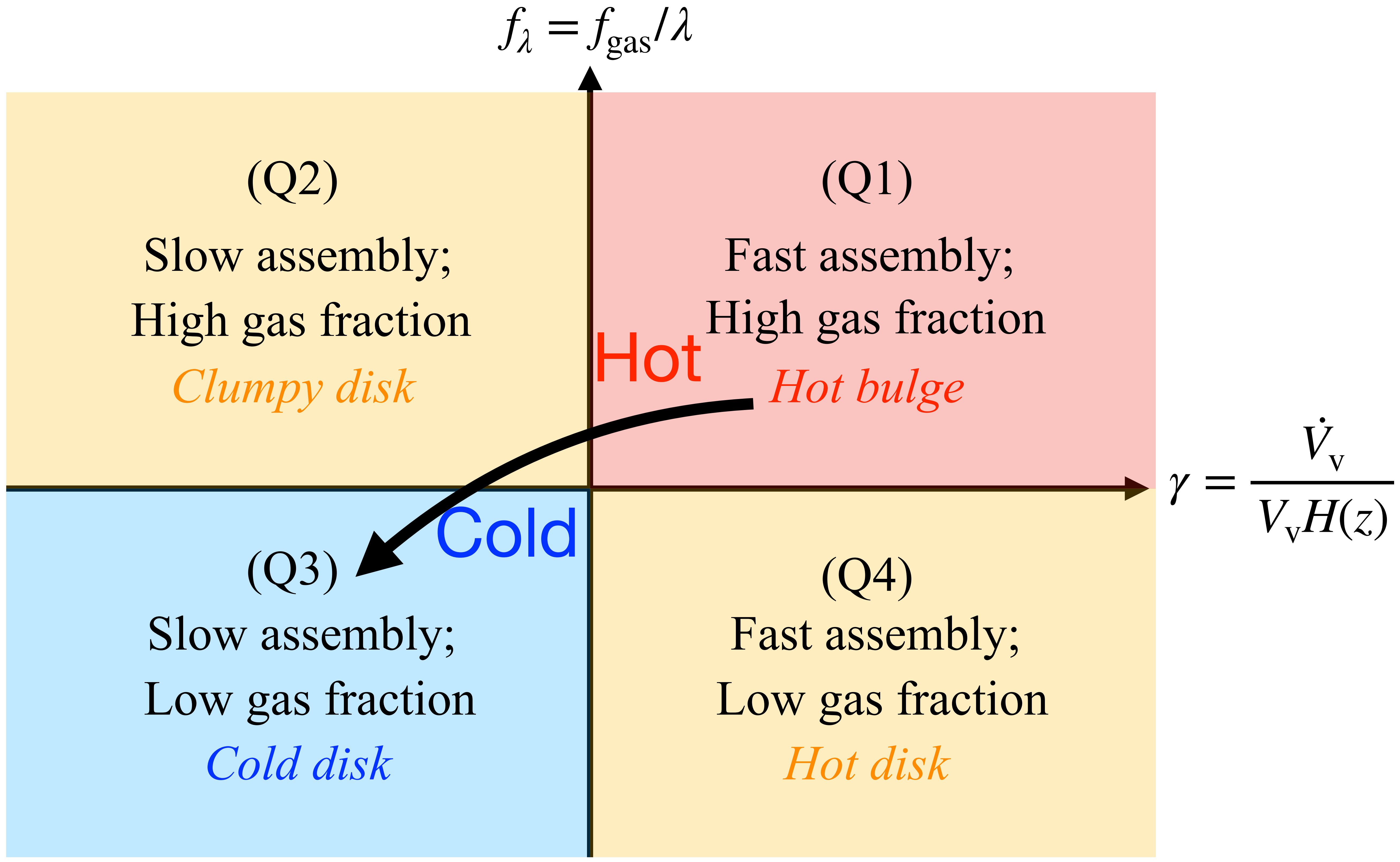


ChenMoWang 2023 (next talk)

The picture of two-phase galaxy formation

Star formation is bursty and concentrates in dense sub-clouds, driven by fast inflow, cold streams, wet mergers.

Basic model assumption: the transition of halo from fast to slow drives the transition of galaxy from dynamically hot to cold.



Star forms smoothly in disks, driven by steady gas inflow

A multi-scale semi-analytical model of galaxy formation

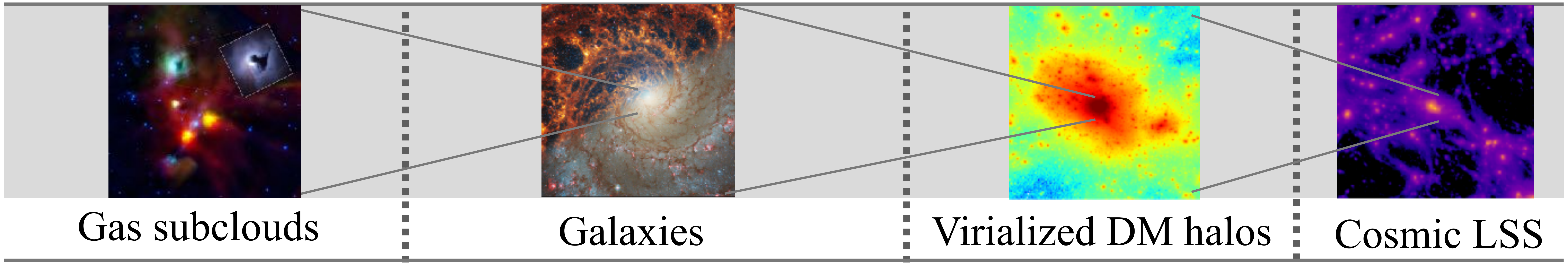
Key idea: model the larger-scale structure first, and use
it as the environment of smaller-scale structure.

A model for star (globular) clusters

Shock compression, metal cooling,
fragment and star formation,
cloud-scale feedbacks

N-body

Determine halo mass, concentration,
shape, formation history, etc.



Cosmology

A ‘two-phase’ model

Determine available gas, inflow, cooling,
feedbacks, stars, SMBH

ChenMoWang+ in prep

Globular clusters as tracers of large-scale and small-scale environment

ChenMoWang+ in prep