From oligarchic reionization to the formation of bulges

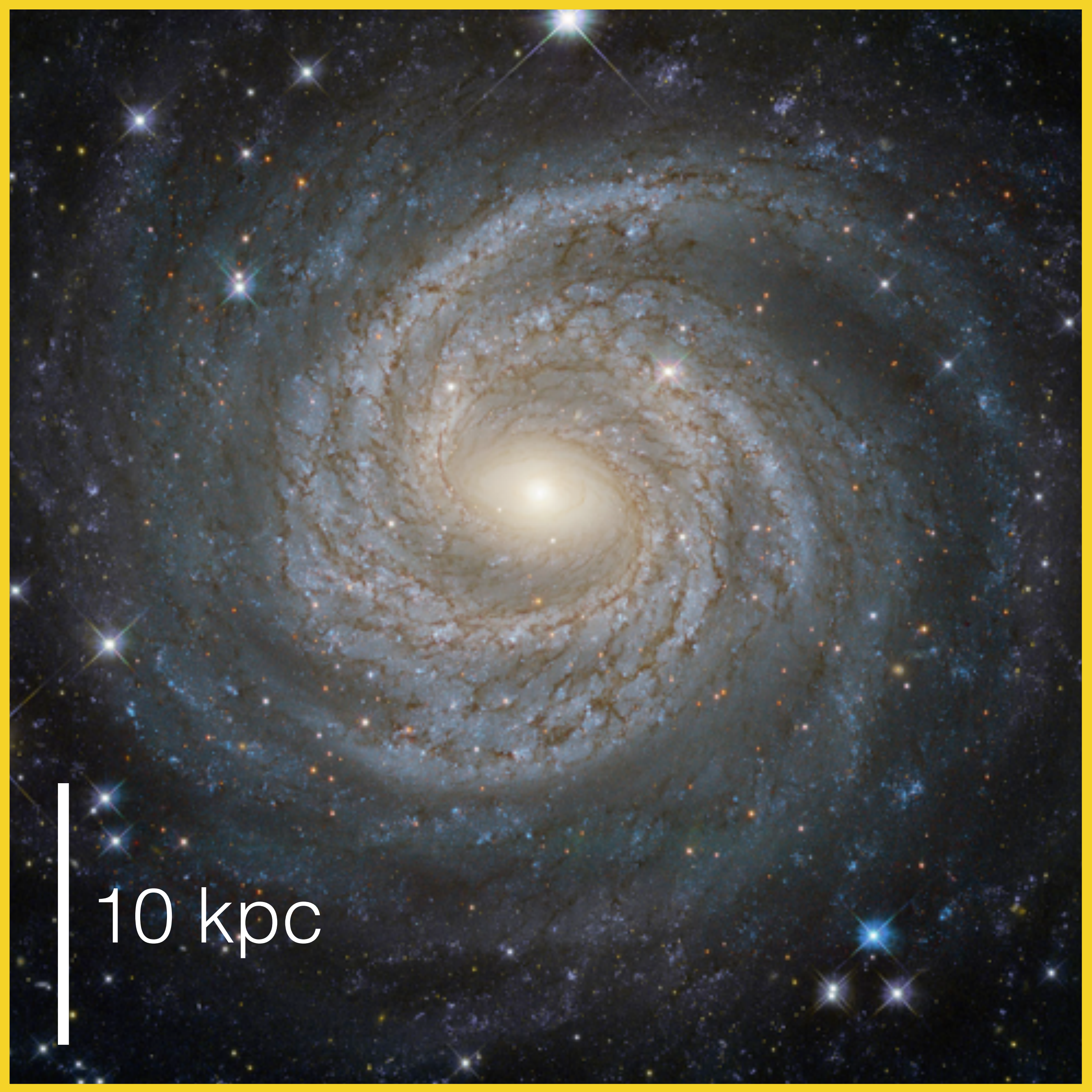
- galaxies at z~1-4: mature bulges
- simple empirical model
- protagonists of reionization are already known

Sandro Tacchella
CfA Fellow

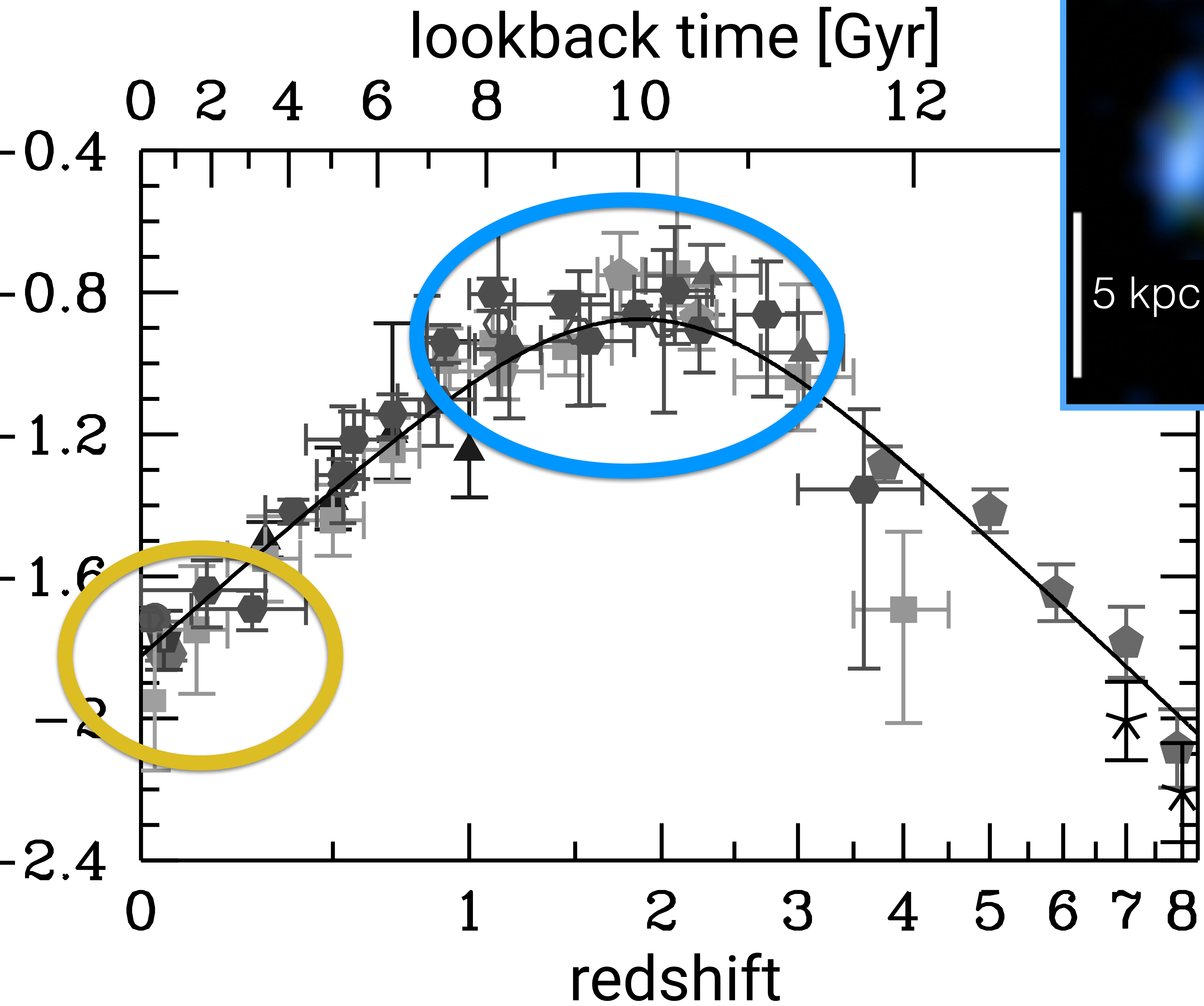
CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

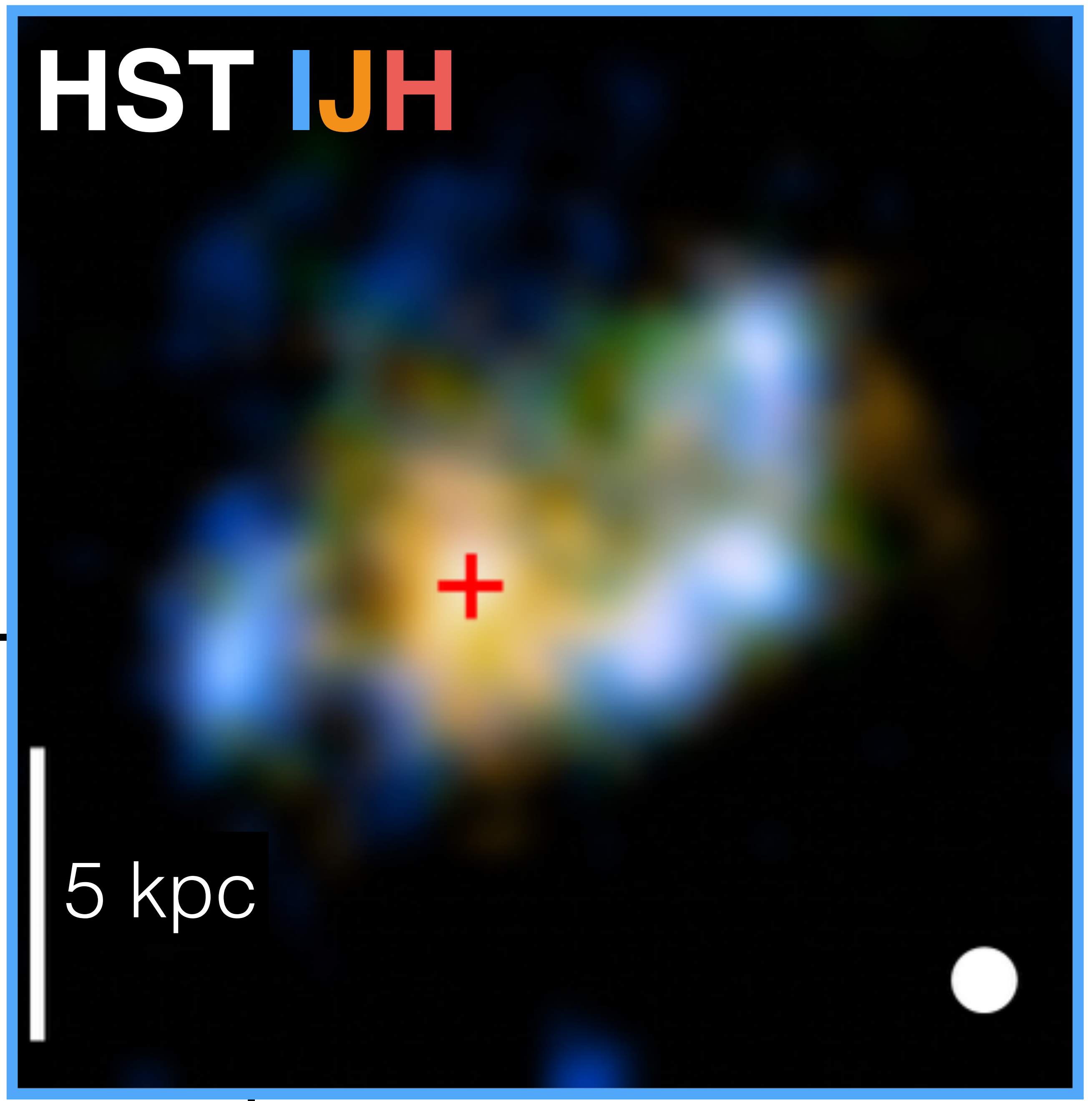
In collaboration with:
R. Naidu, S. Bose, A. Dekel, C. Conroy, L. Hernquist, M. Carollo,
D. Eisenstein, S. Lilly, R. Genzel, N. Förster Schreiber, A. Renzini, et al.

Star-forming galaxies evolve



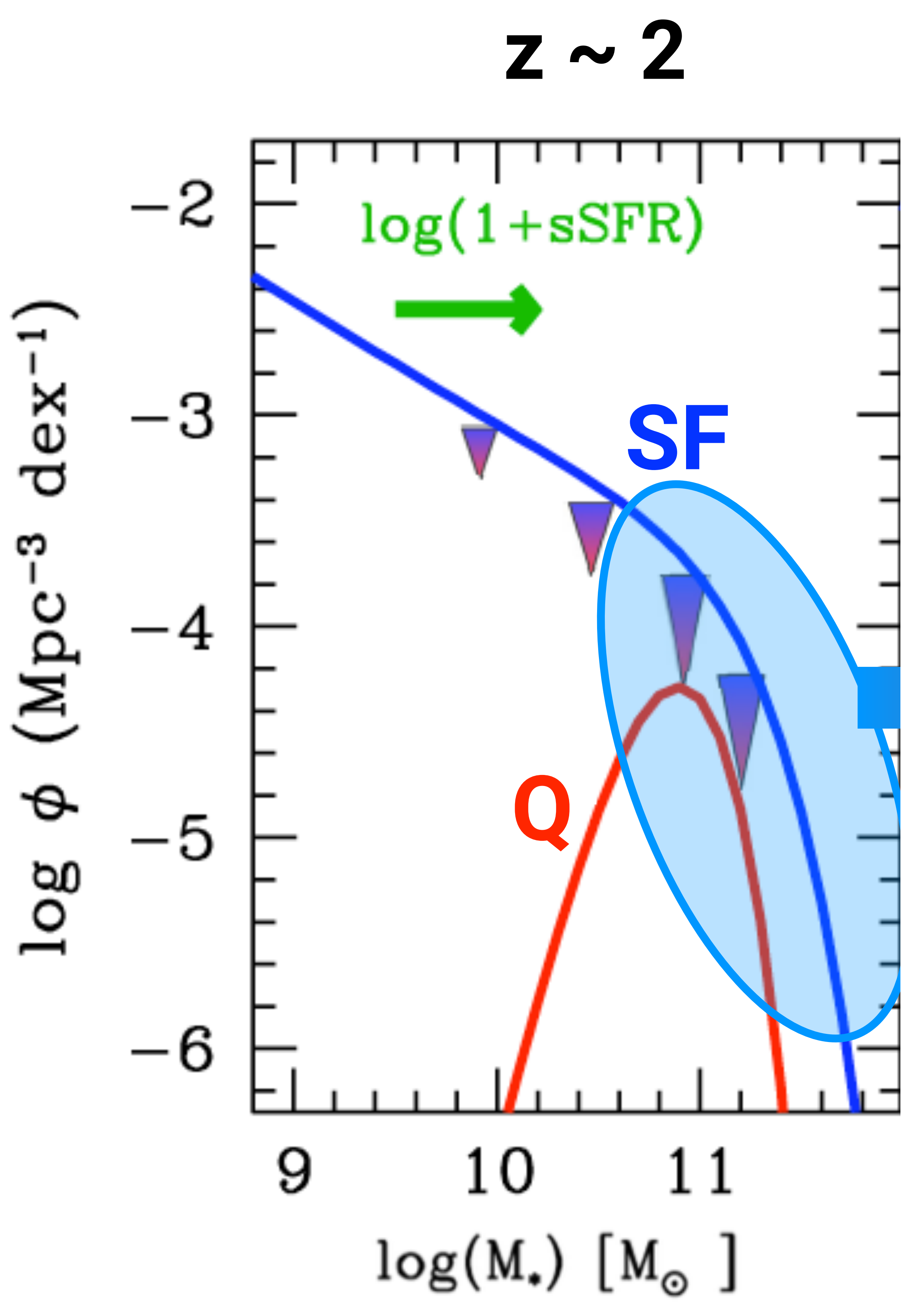
$M_\star \sim 3 \times 10^{10}\ M_\odot$
SFR ~ 4 $M_\odot$/yr
$v_{rot}/\sigma_0 \sim$ 10-20





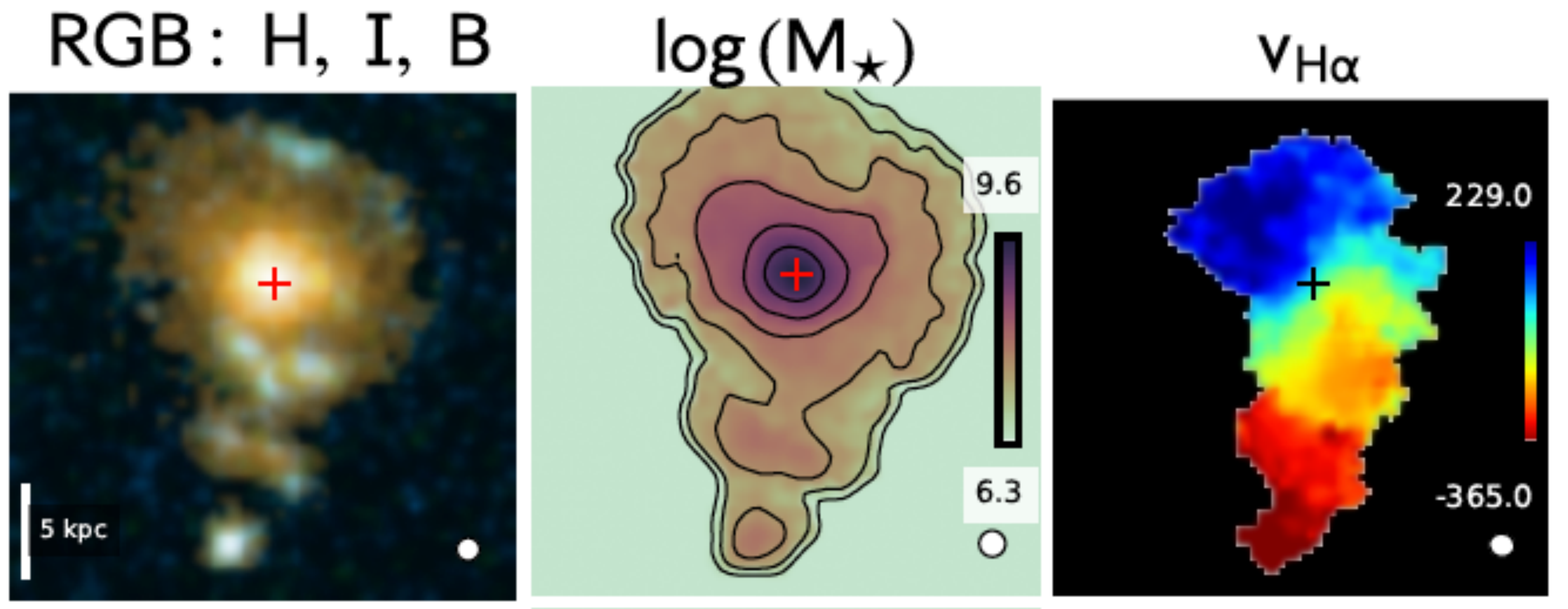
$M_\star \sim 2 \times 10^{10}\ M_\odot$
SFR ~ 100 $M_\odot$/yr
$v_{rot}/\sigma_0 \sim$ 1-6

Galaxies at z~2: mature bulges



e.g. Illbert+13; Muzzin+13; Peng+10

Although we can not track individual galaxies, these observations are consistent with **no morphological transformation during quenching.** (see also Tacchella+19 for IllustrisTNG analysis)

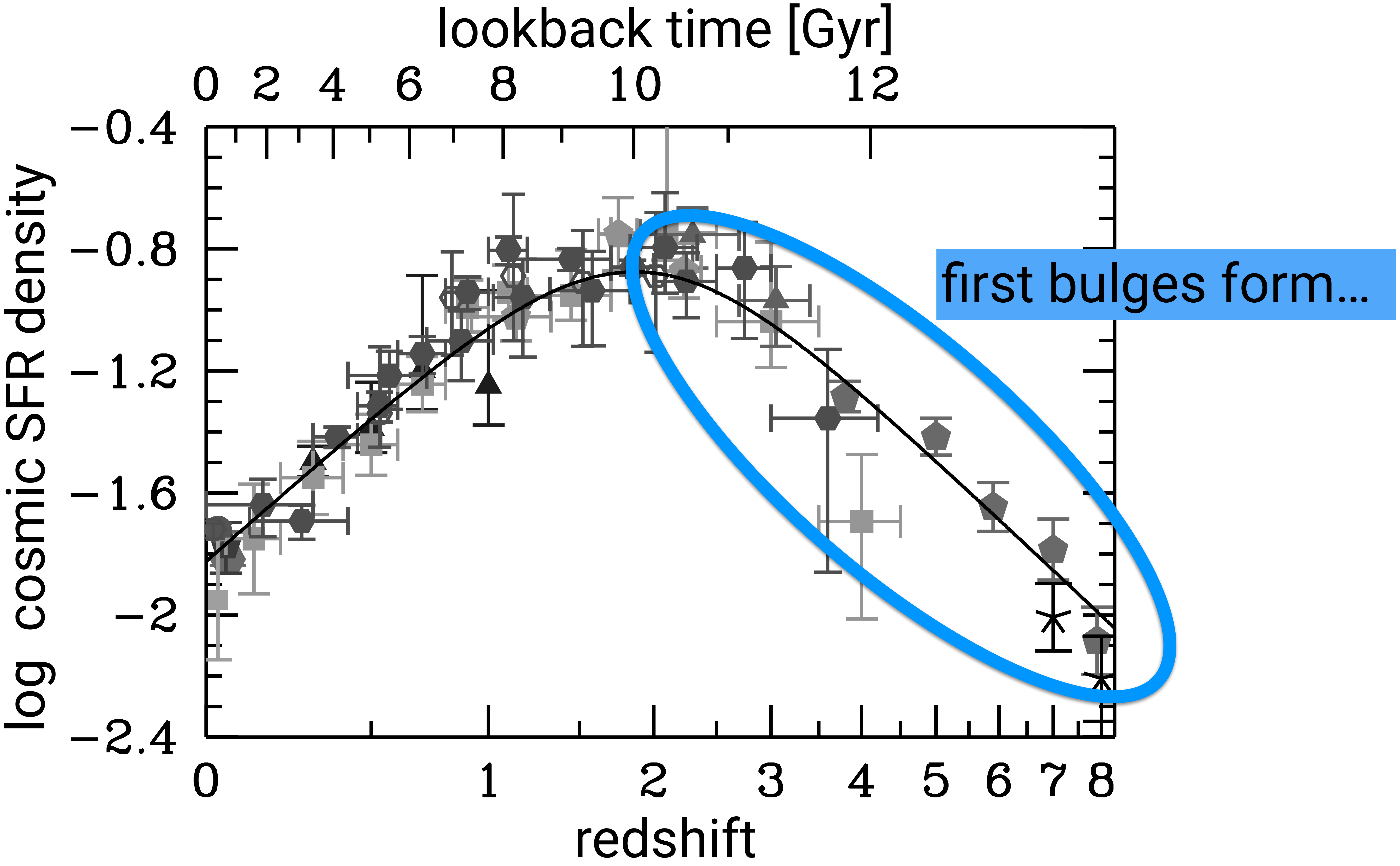


Tacchella+15ab,18

- high central stellar mass density: comparable local ETGs (see also, e.g., van Dokkum+ 2010)
- started quenching inside-out
- star-forming disk component with rotation, $v_{rot}/\sigma_0 \sim 5$ (see also, e.g., Förster Schreiber+ 2018)

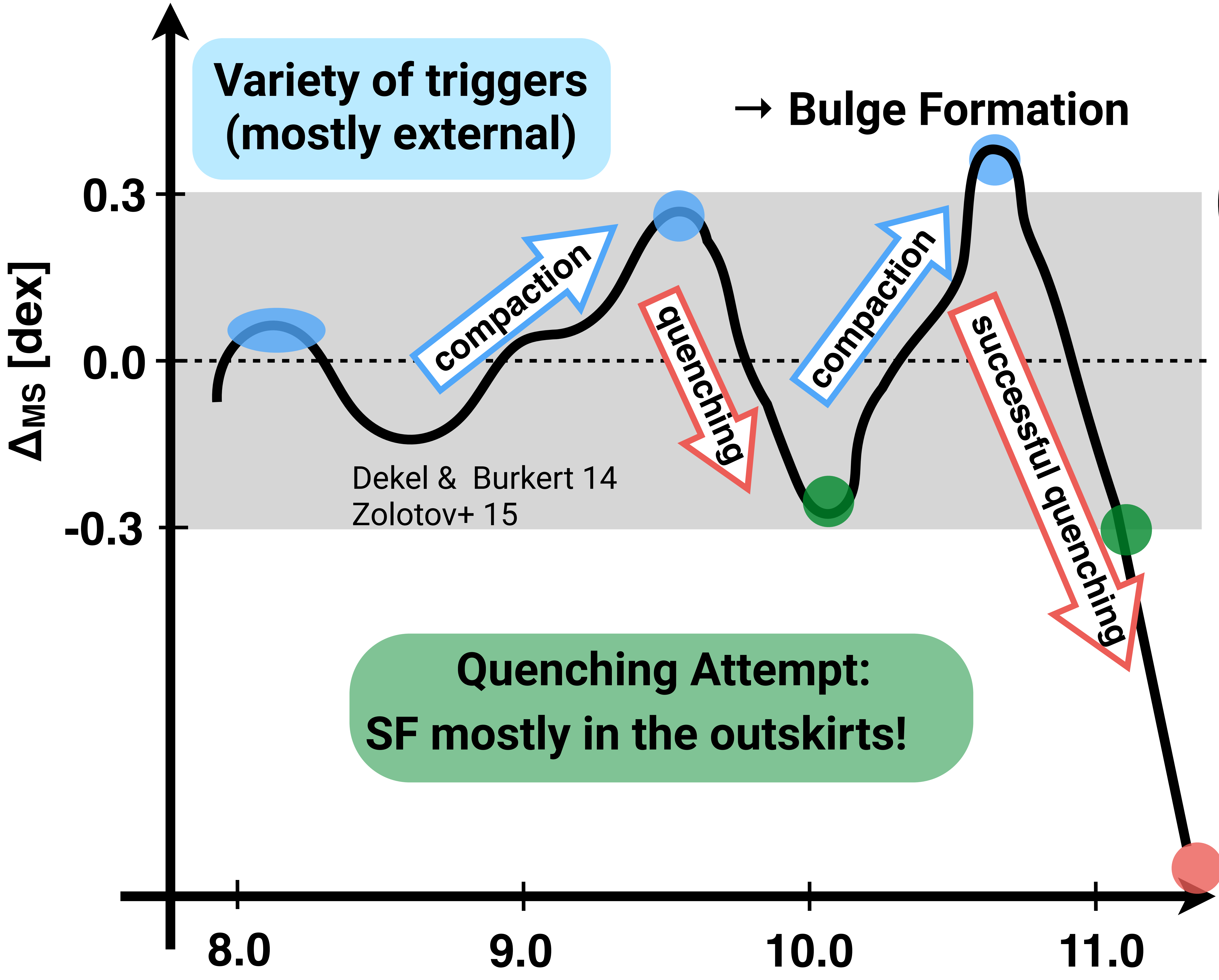
Star formation in the universe

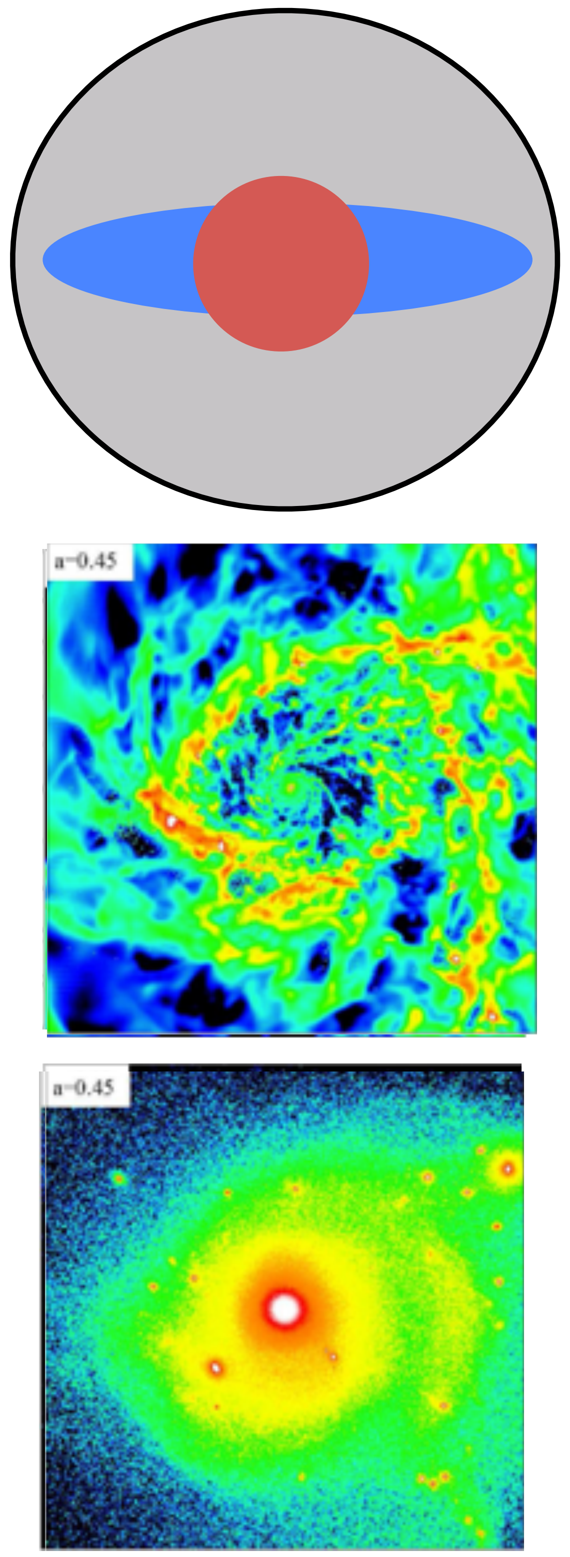
Lilly+ 1996
Madau+ 1996; 1998
Madau & Dickinson 2014

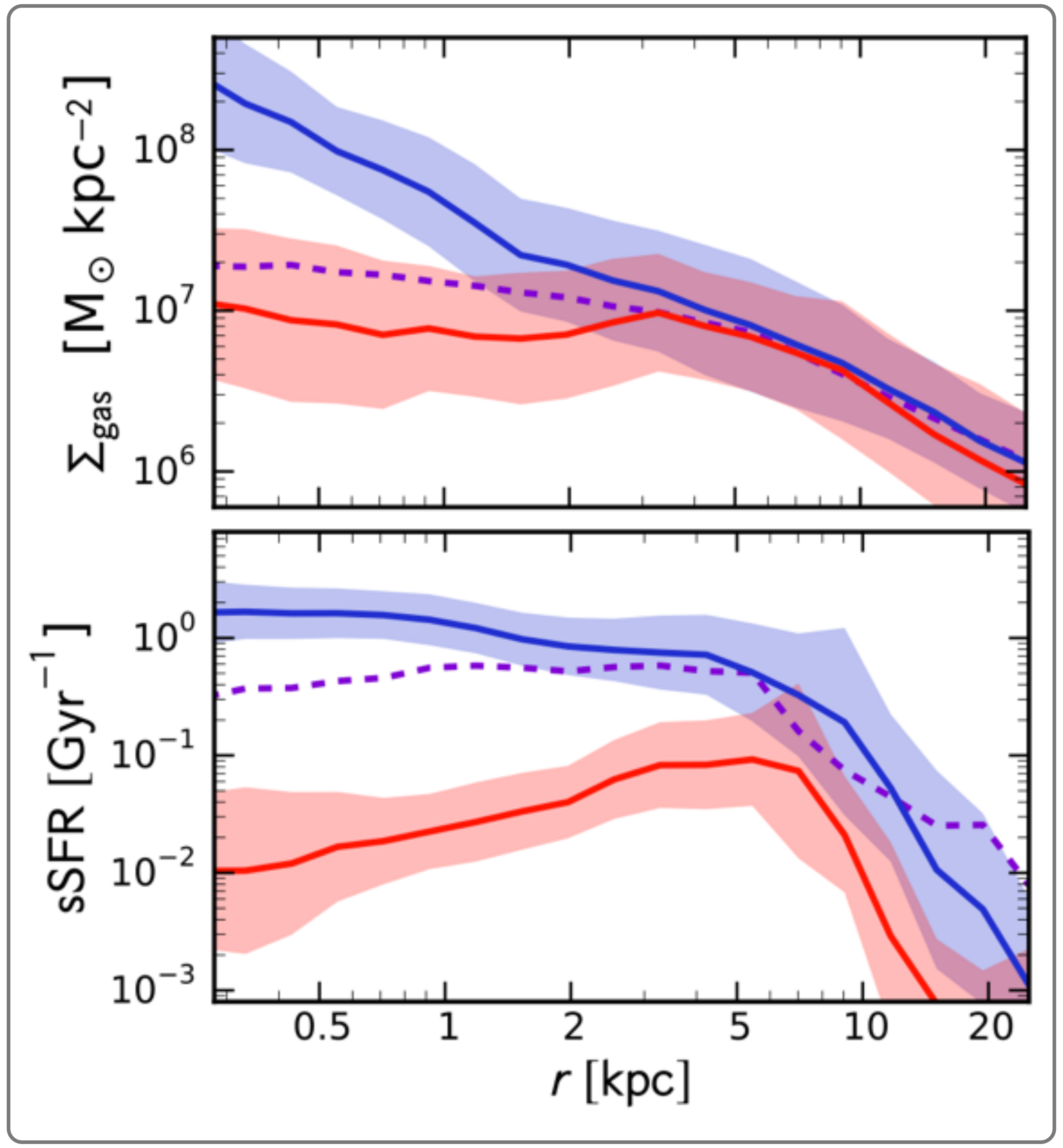


Formation of bulges in typical star-forming galaxies at z>2

based on VELA zoom-in simulations, see talk by A. Dekel







→ observational tests with JWST

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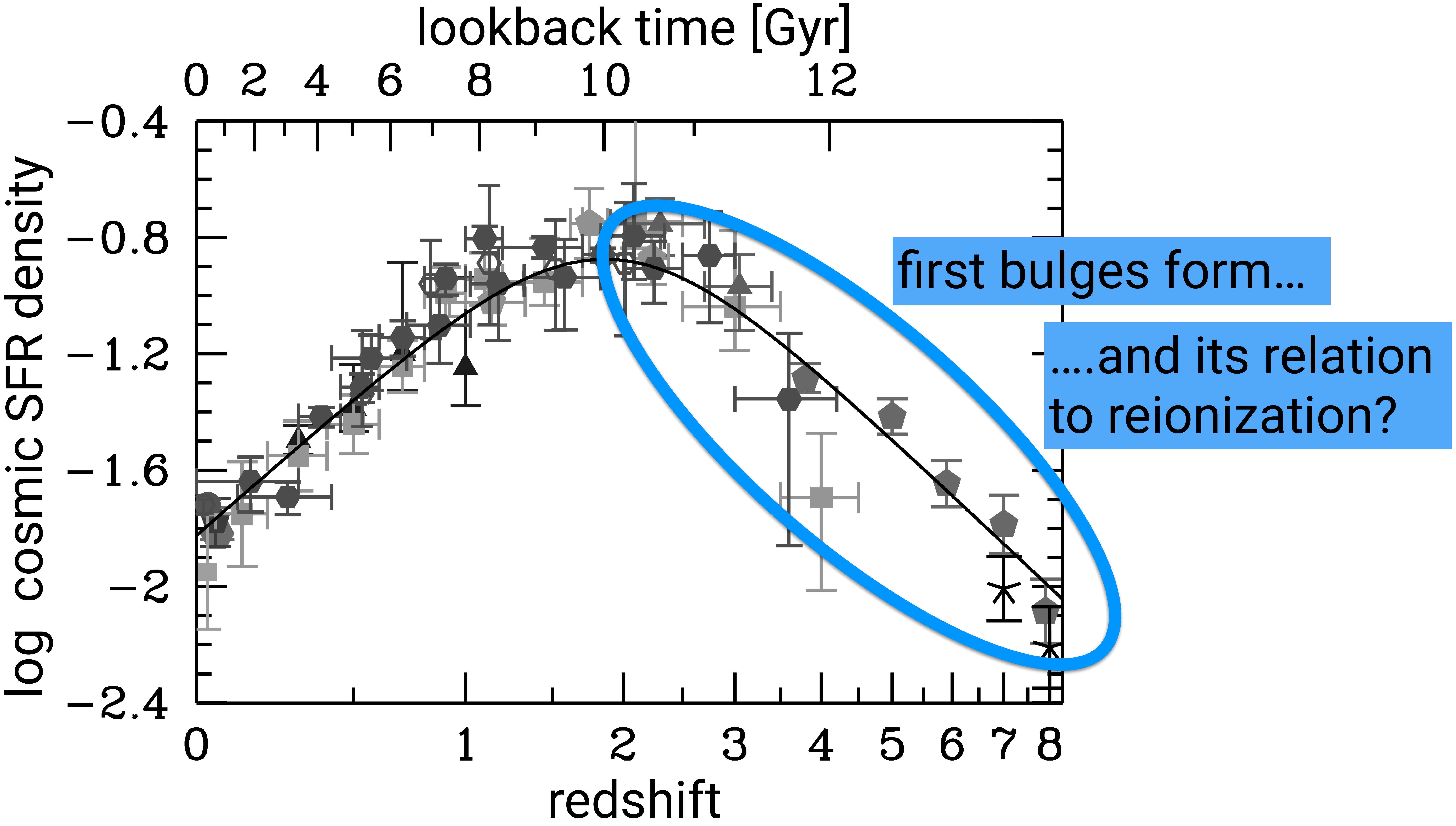
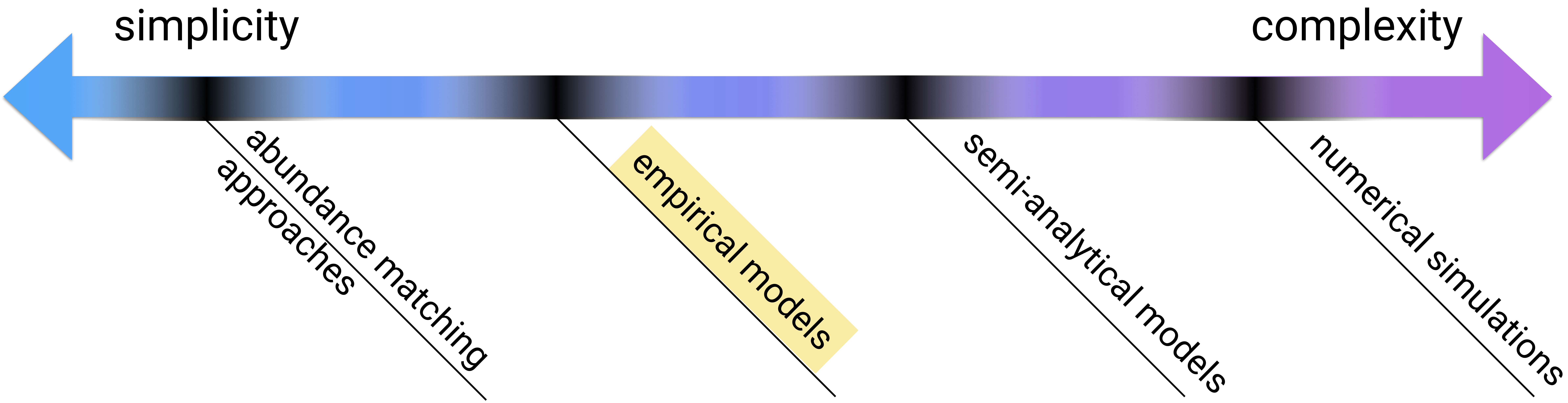
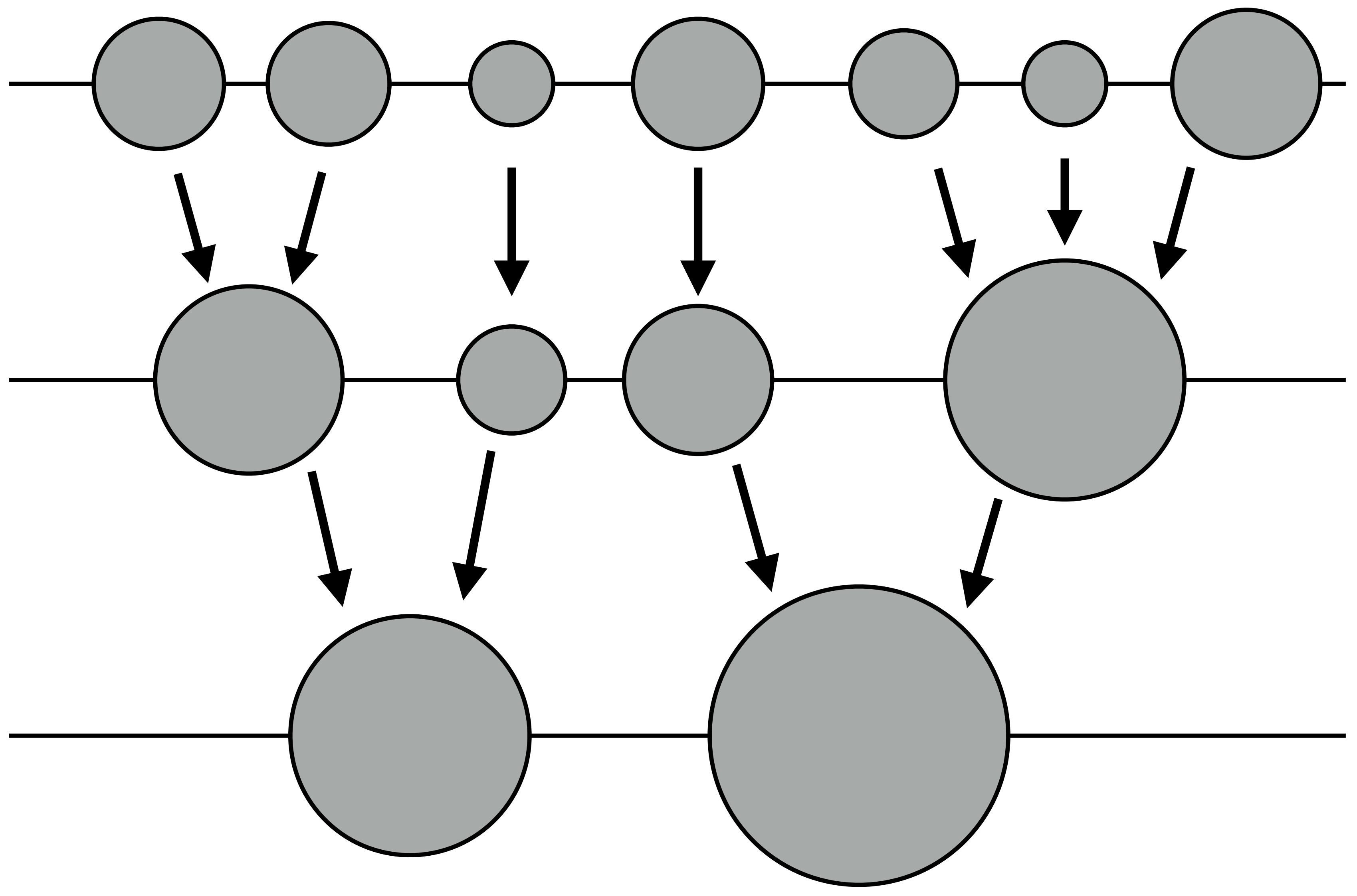


Motivation for an empirical model



- “marginalizing” over poorly understood baryonic physics
- planning future surveys (JWST, WFIRST, …)
- interpretation of the observations, including modeling of biases
- constrain the relevant physical processes in ab initio models
  (f.e. to fix unconstrained parameters in the sub-grid models of hydrodynamic simulations)

Modeling star formation in halos



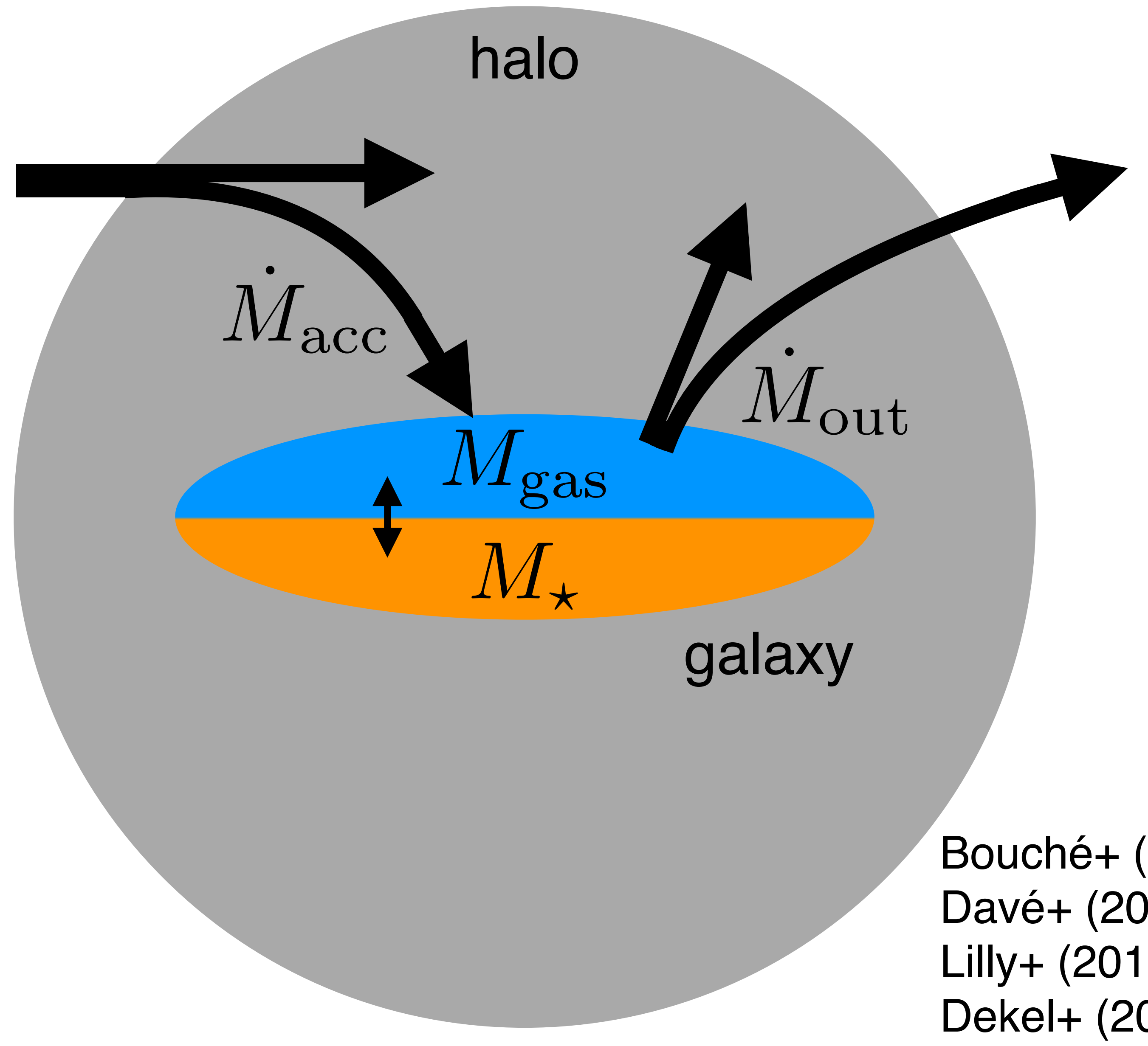
regulator model (“bathtub model”):

$$\mathrm{SFR} \propto \dot{M}_{\mathrm{acc}}$$

$$\mathrm{SFR}(M_h, z) = \varepsilon(M_h) \times f_b \times \frac{\mathrm{d}\widetilde{M_h}}{\mathrm{d}t}$$

- redshift-independent efficiency
- calibrated via UV LF at z=4

- time-delayed DM accretion rate
- COLOR N-body simulations (Hellwing+16)
- 70.4 Mpc/h box
- $m_{DM} = 6\times10^6\ M_\odot$



Bouché+ (2010)
Davé+ (2012)
Lilly+ (2013)
Dekel+ (2014)
Peng+ (2014)

based on Tacchella+ (2013; 2018b)

Modeling star formation in halos

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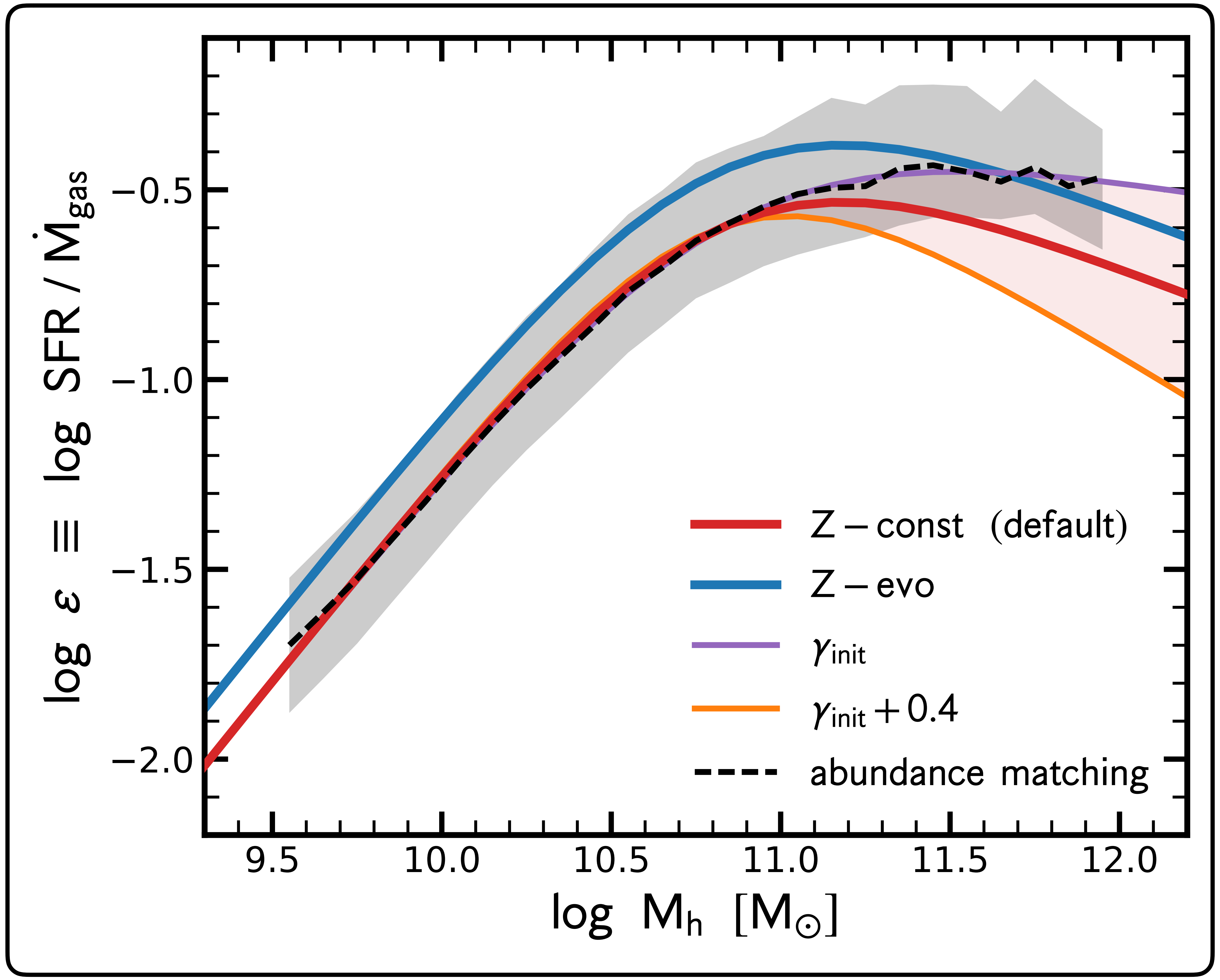
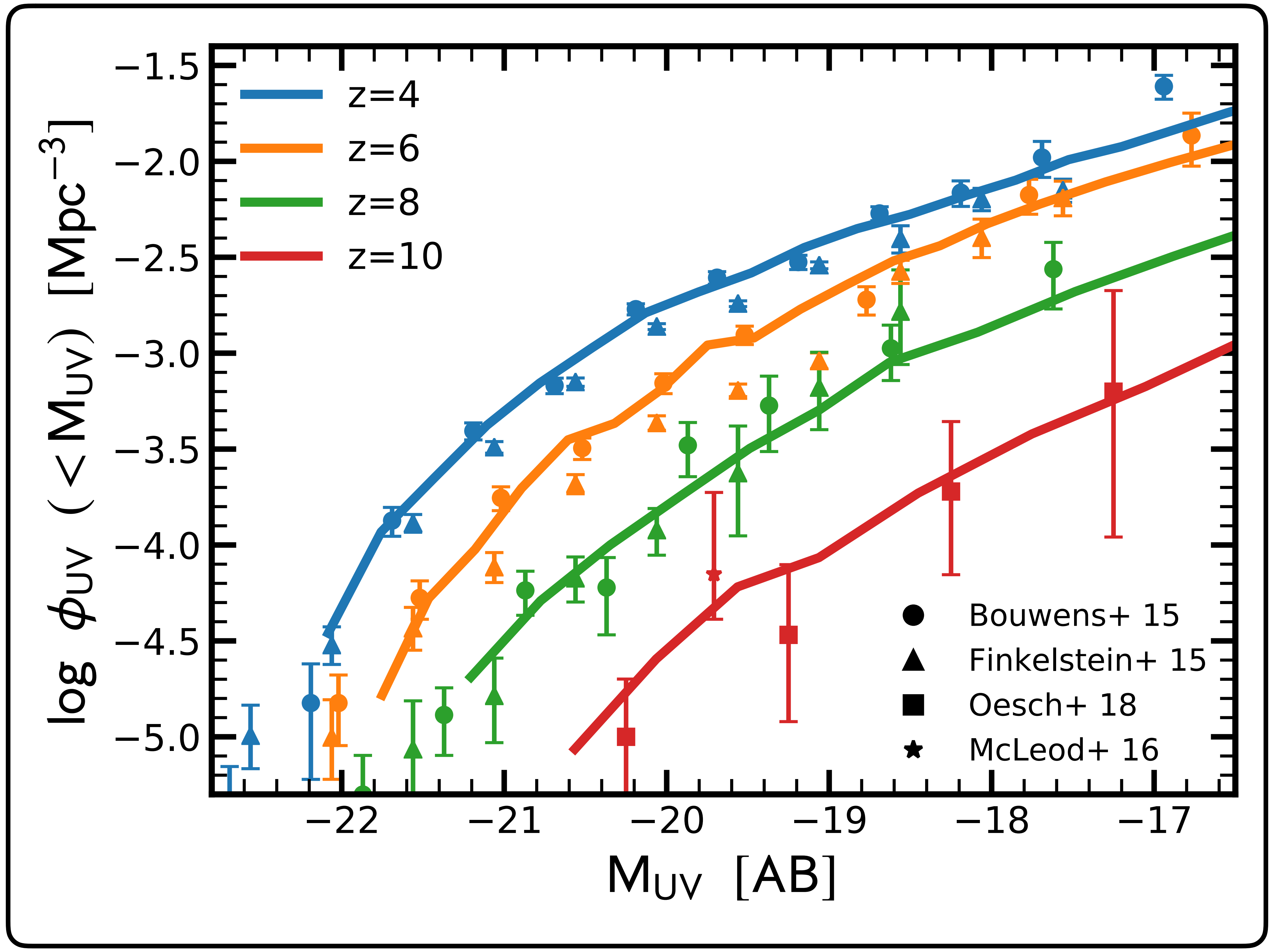
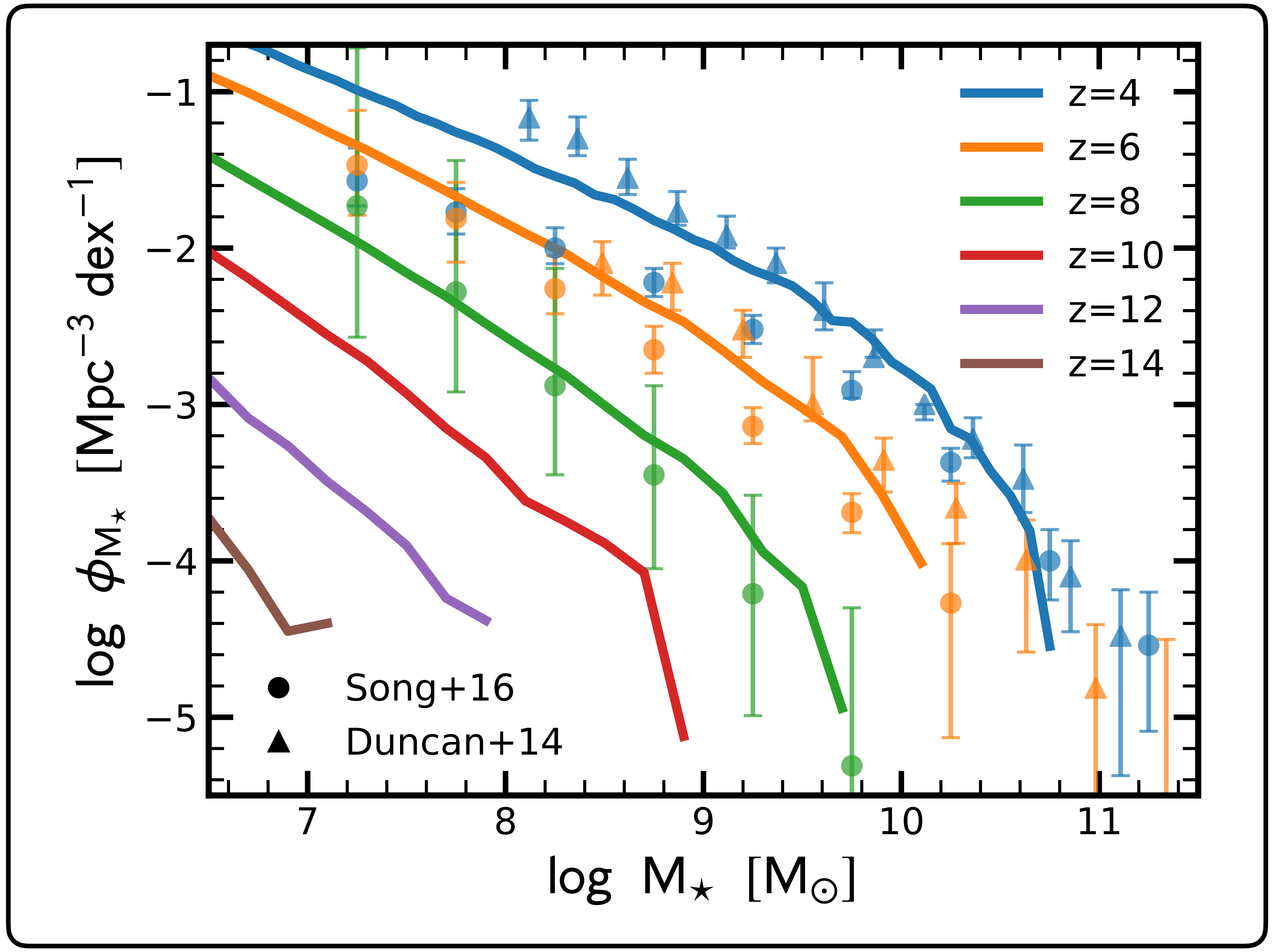


UV luminosity and stellar mass functions

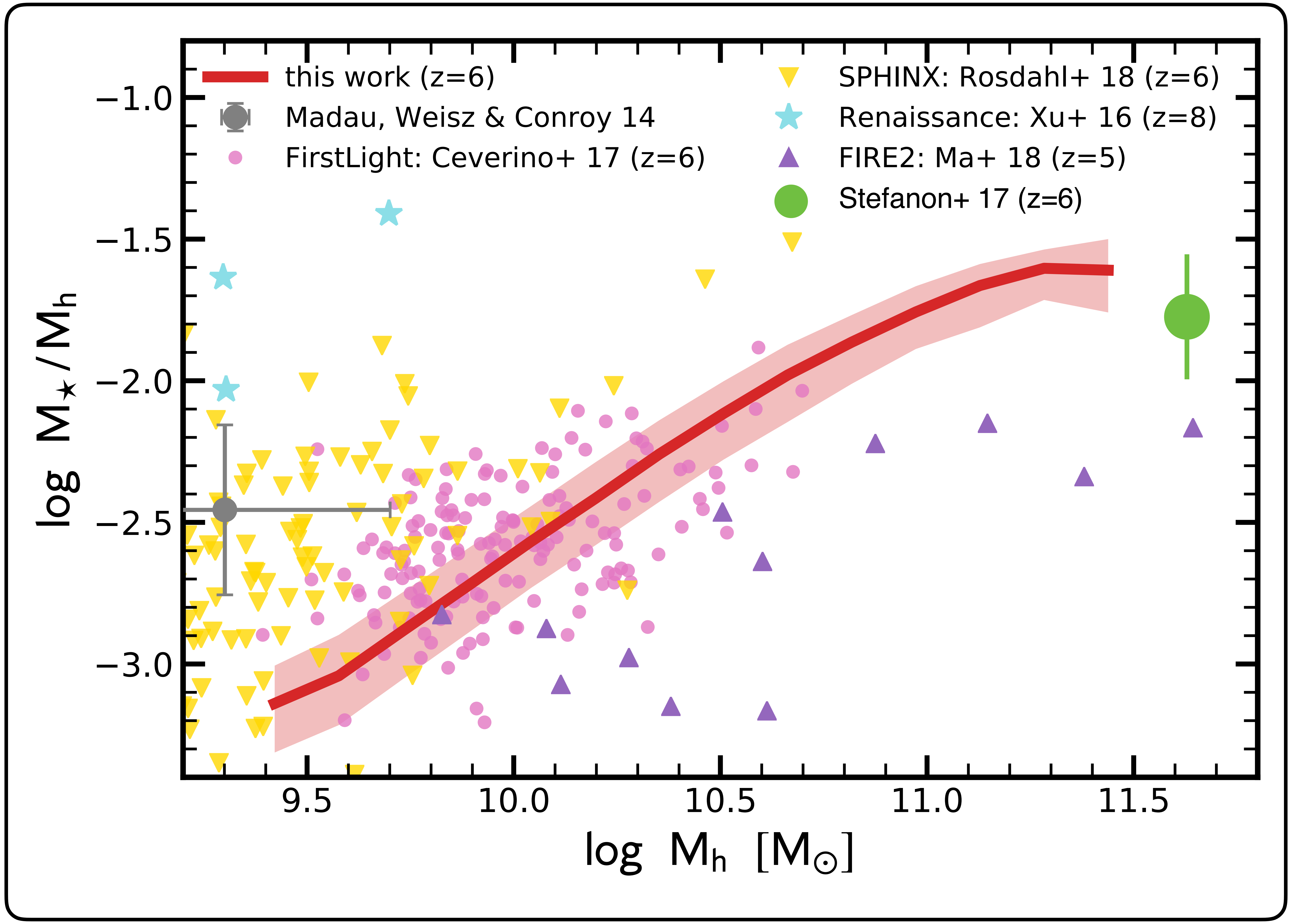




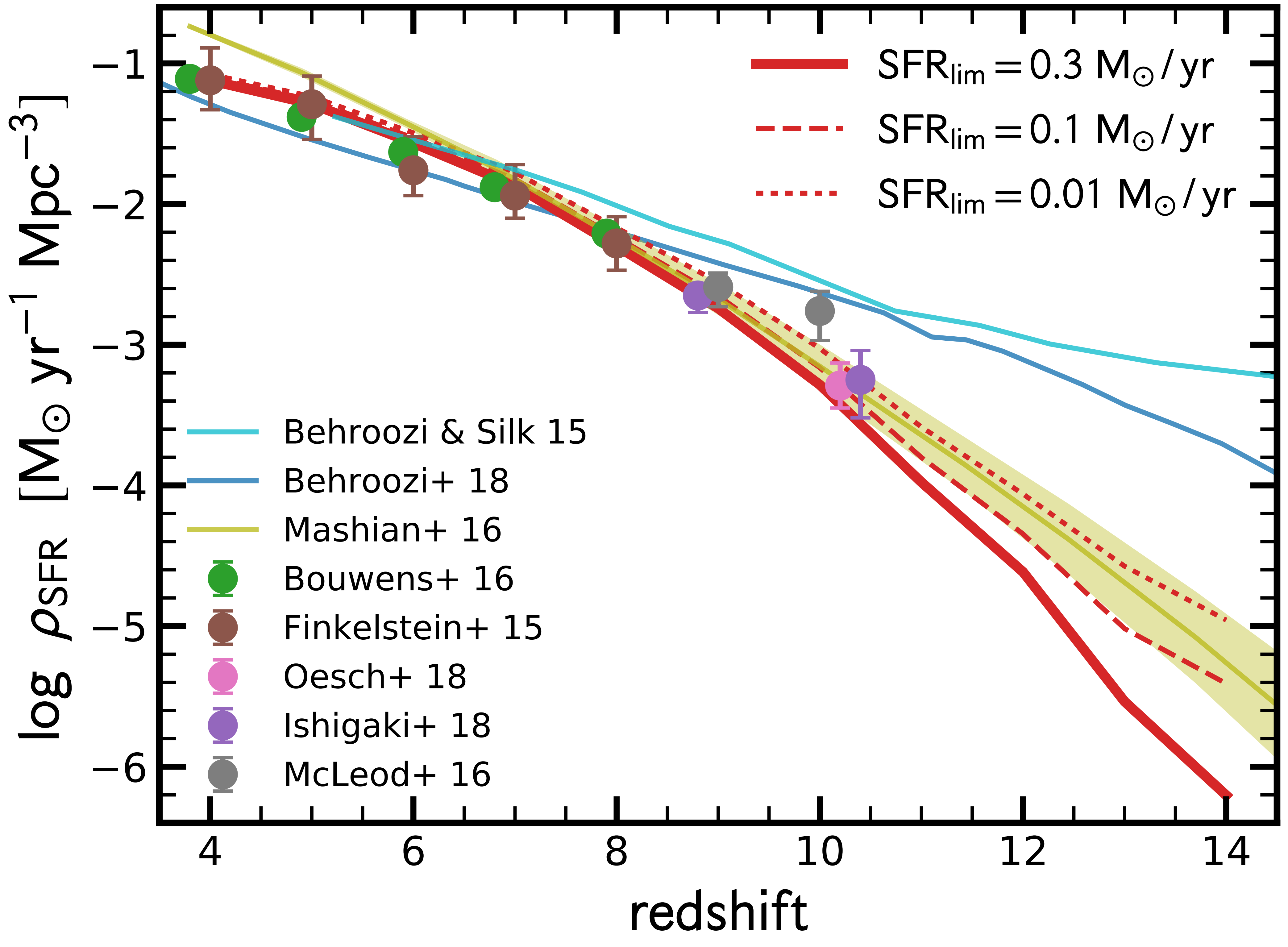
- match at z=4 by construction (redshift of calibration)
- remarkably consistent with observations at z>4
- steepening of the faint-end slope

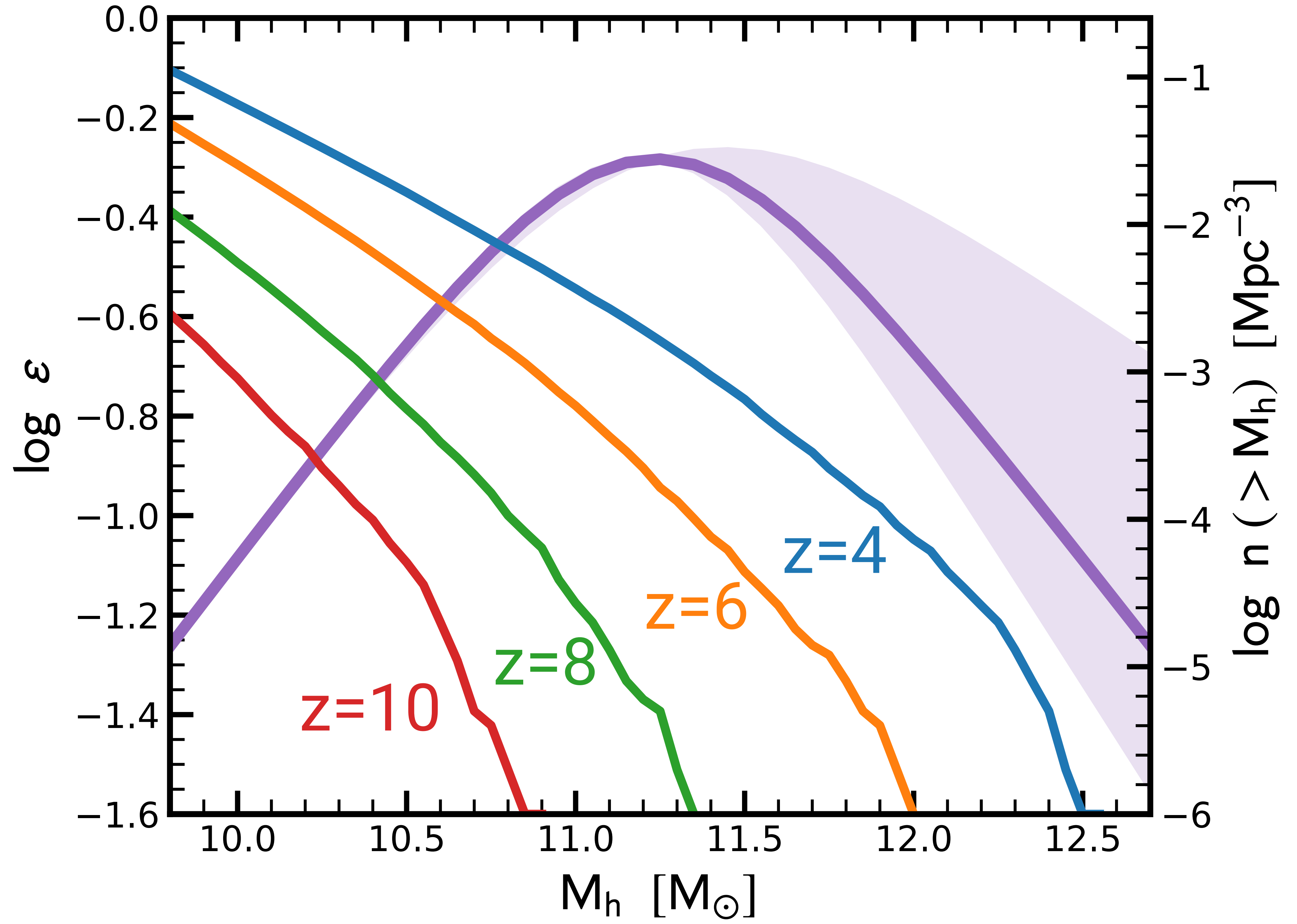
- observations are still uncertain (prior dominated)
- roughly consistent with observations
- too few high mass galaxies? size of box / merging
- steepening of the low-mass end slope

Stellar-halo mass relation



Cosmic SFR density

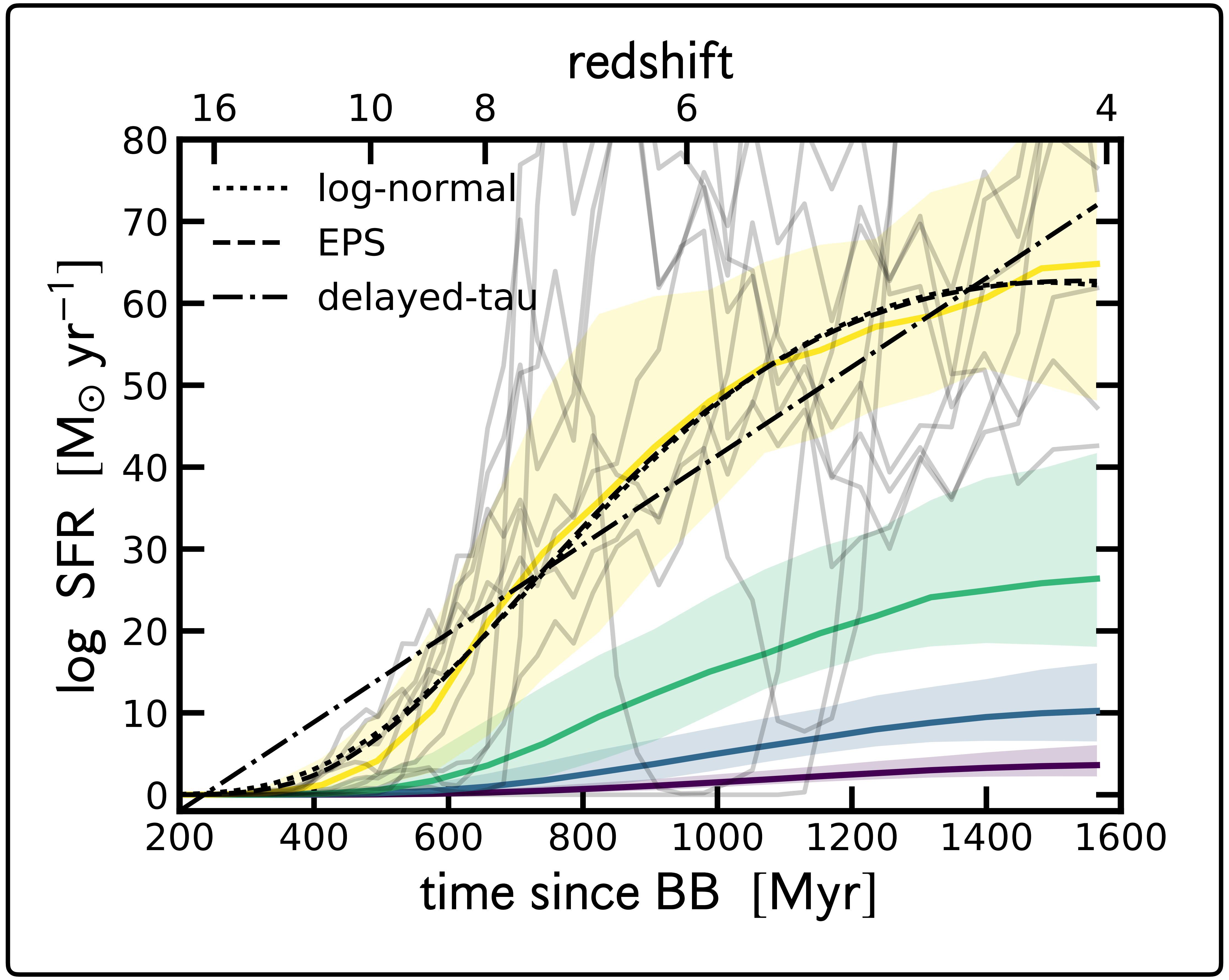


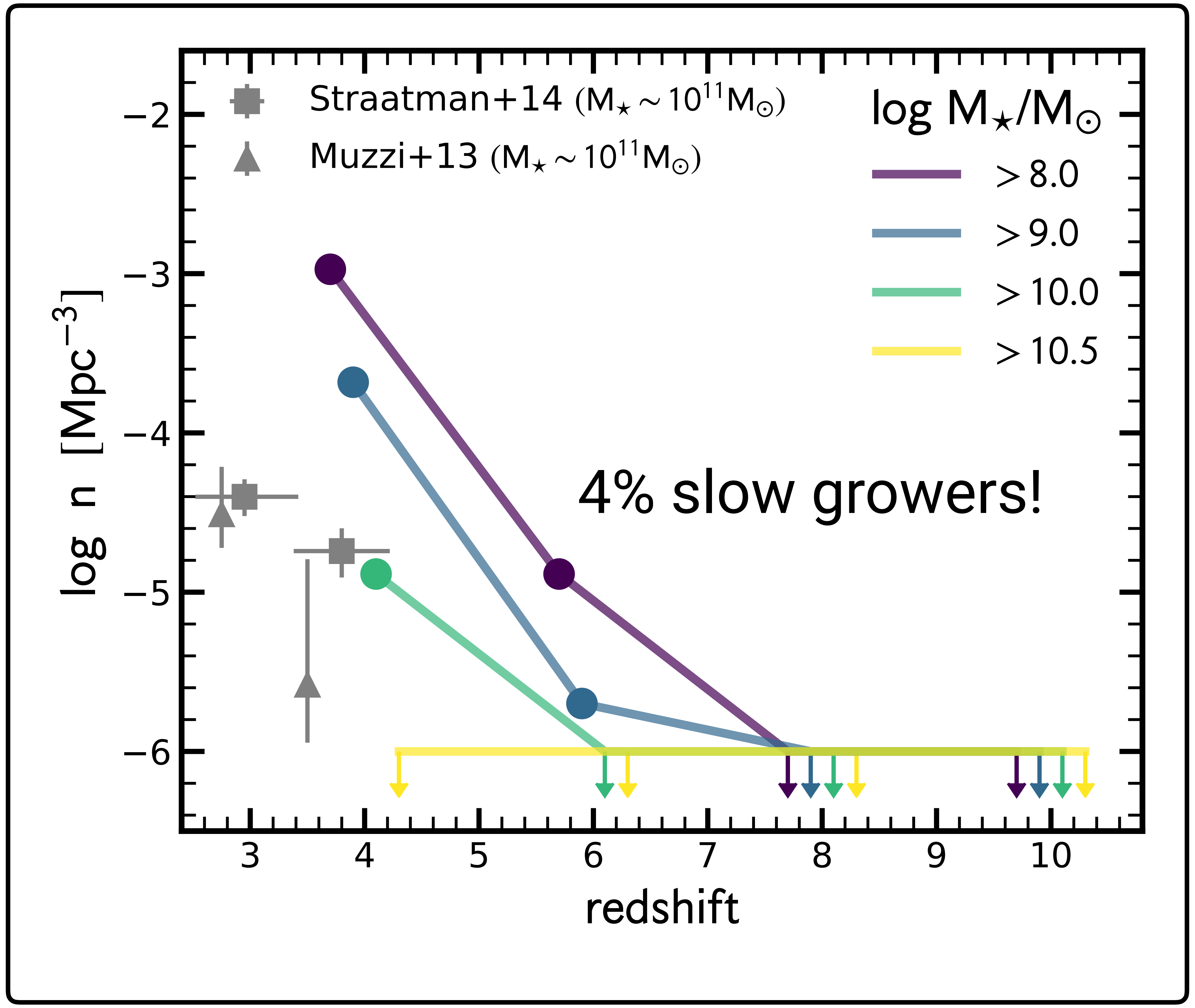


- steep decline of the cosmic SFRD at high redshifts, but consistent with observations
- other models (e.g., Behroozi+18) predict higher cosmic SFRDs

- fast build-up of the cosmic SFRD consistent with the evolution of the halo mass function
- M* moves in into the star-formation efficient region

Star-formation histories





- average star-formation histories are increasing with time and well described by a log-normal or EPS-like equation
- however, individual galaxies have a lot of variation

- linear relation between the SFR and $M_\star$
- scatter of SFMS decreases toward higher redshift
- 4% of galaxies are growing slowly (sSFR < t_H^{-1})

JWST number counts

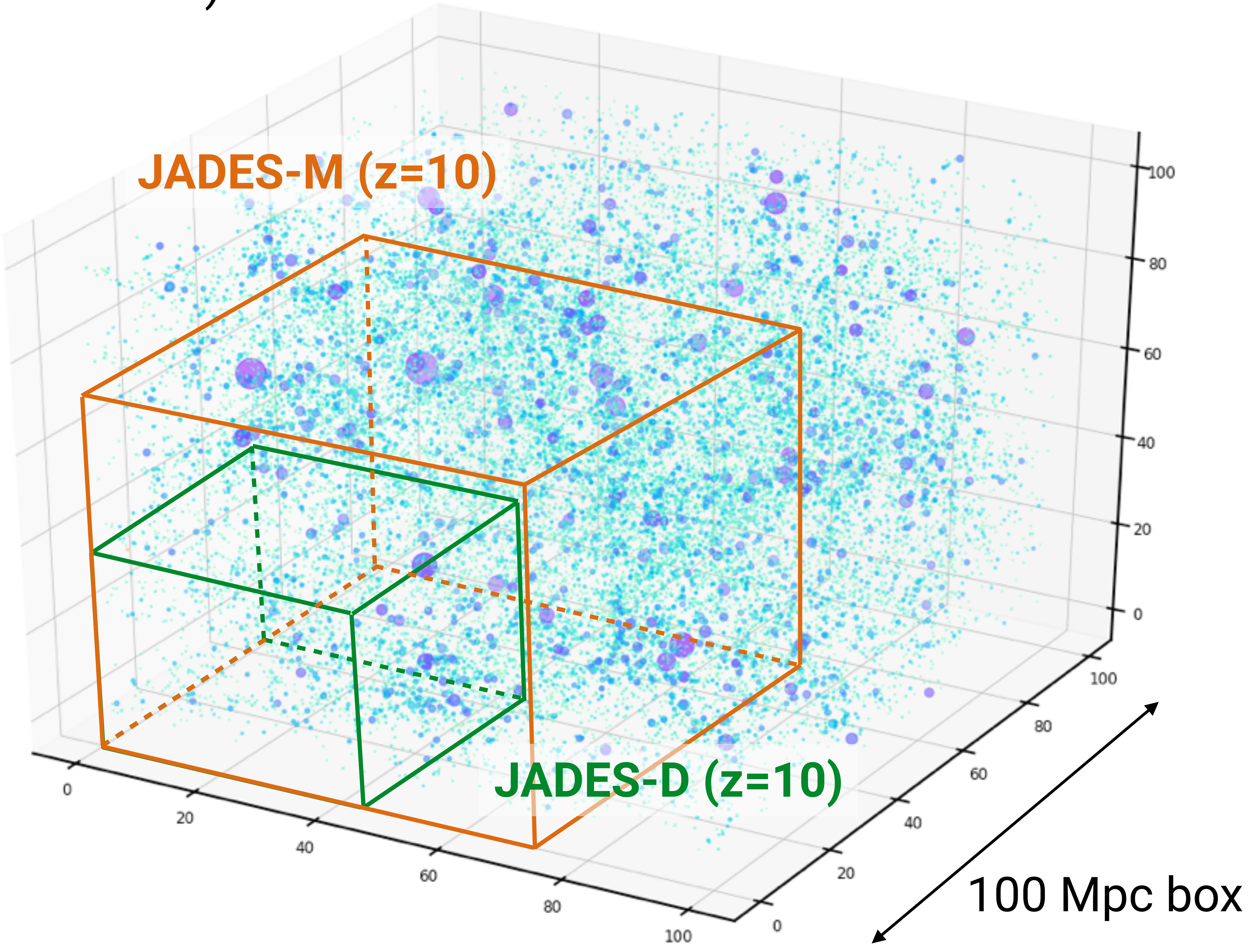
<u>JADES: **J**WST **A**dvanced **D**eep **E**xtragalactic **S**urvey</u>

- joint program of the NIRCam and NIRSpec Guaranteed Time Observations (GTO) teams
- Marcia Rieke (NIRCam PI); Daniel Eisenstein (extra-galactic team lead)
- ~800+800 hr (prime + parallel) NIRCam, NIRSpec & MIRI
- NIRCam/Deep: 46 arcmin^2, 10σ limits of m~29.7
- NIRCam/Medium: 190 arcmin^2, 10σ limits of m~28.7

<u>CEERS: **C**osmic **E**volution **E**arly **R**elease **S**cience Survey</u>

- ERS program (PI Steve Finkelstein)
- ~35+35 hr (prime + parallel) NIRCam, NIRSpec & MIRI
- NIRCam imaging: 100 arcmin^2, 10σ limits of m~28.0

	z=6	z=8	z=10
CEERS	921	106	8
JADES-M	3582	495	45
JADES-D	1779	270	31



Reionization: recent developments

ionizing photon budget = $\rho_{\mathrm{SFR}} \times \xi_{\mathrm{ion}} \times f_{\mathrm{esc}}$

- galaxy evolution: new measurements of the cosmic SFR density out to z=10
  (e.g. Bouwens+16, Ishigaki+17, Oesch+18)
- ionizing efficiency: SED models with rotation and binaries
  (e.g. Stanway & Eldridge 16, Choi+16, Casey+18, Lam+19, Bouwens+16, Shivaei+18)

} progress with JWST

- new generation of Lyman continuum escape fraction measurements
  (e.g. Naidu+17, Izotov+16,18, Vanzella+16,18, Shapley+16, Bian+17, Matthee+18, Borthakur+14, Leitherer+16, Jones+13, Leethochawalit+16, Fletcher+19, Steidel+18, Marchi+17, Kakiichi+18)

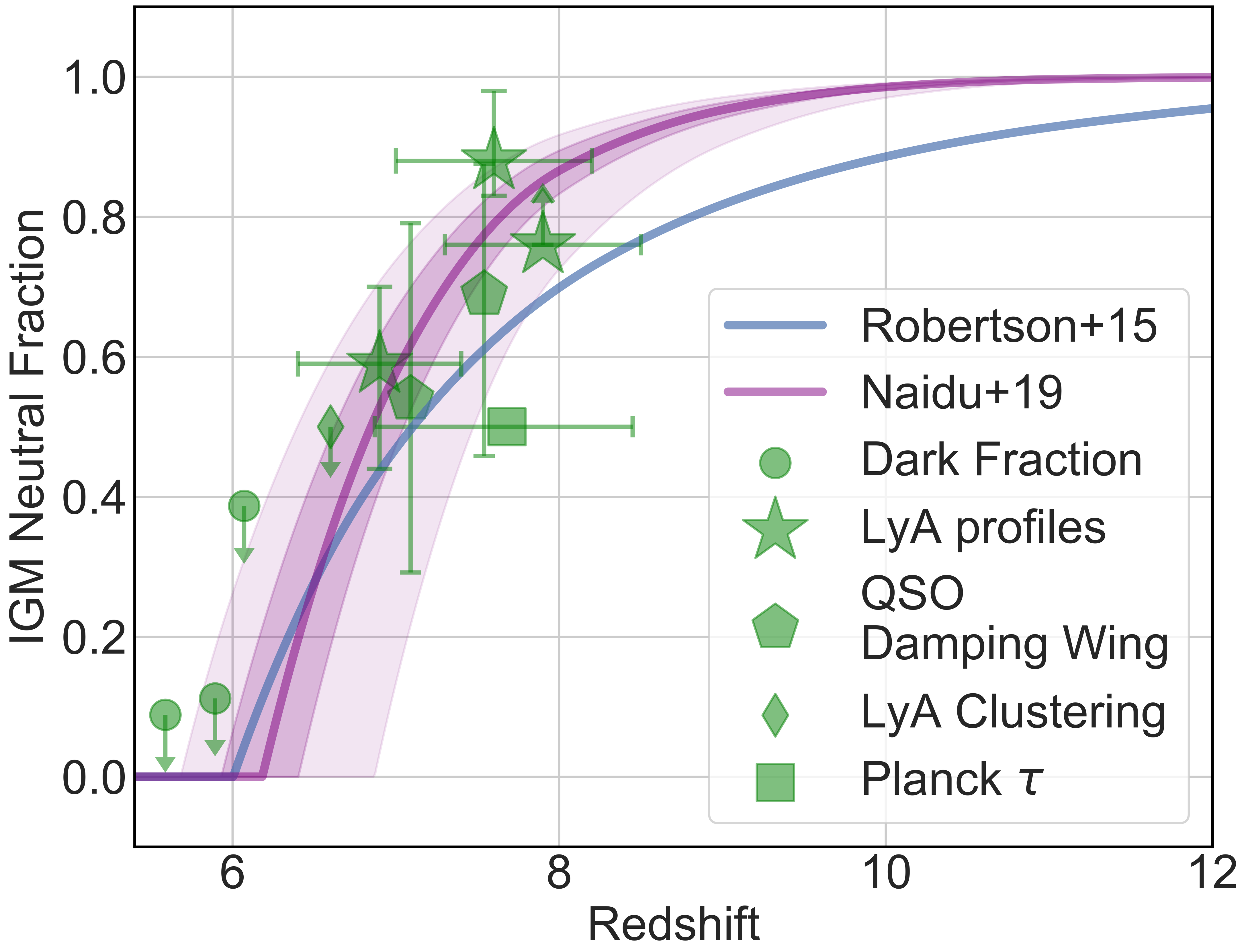
} direct detection during reionization epoch impossible!

Idea: constrain f_{esc} from the observed IGM reionization history, assuming empirical model for the intrinsic number of ionizing photons

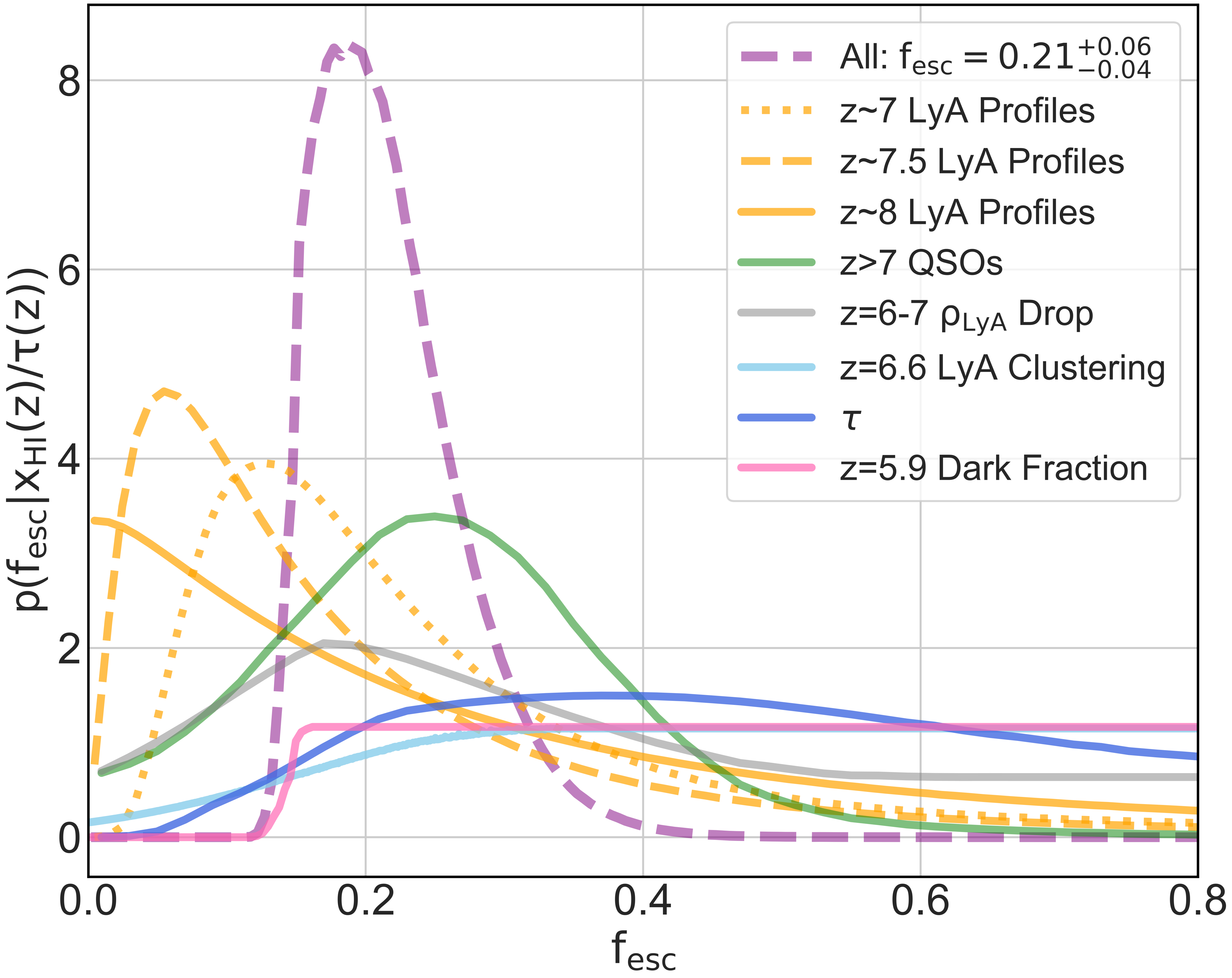
work submitted (Naidu, Tacchella+ 2019; arXiv:1907.13130)

Late & rapid reionization: z=8 (10%) to z=6 (100%)

Assumptions:
- Average f_{esc} is constant across reionization
- Muv > -13.5 galaxies do not contribute



joint constraint: f_{esc} = 21^{+6}_{-4} %



Naidu, Tacchella+ (2019)

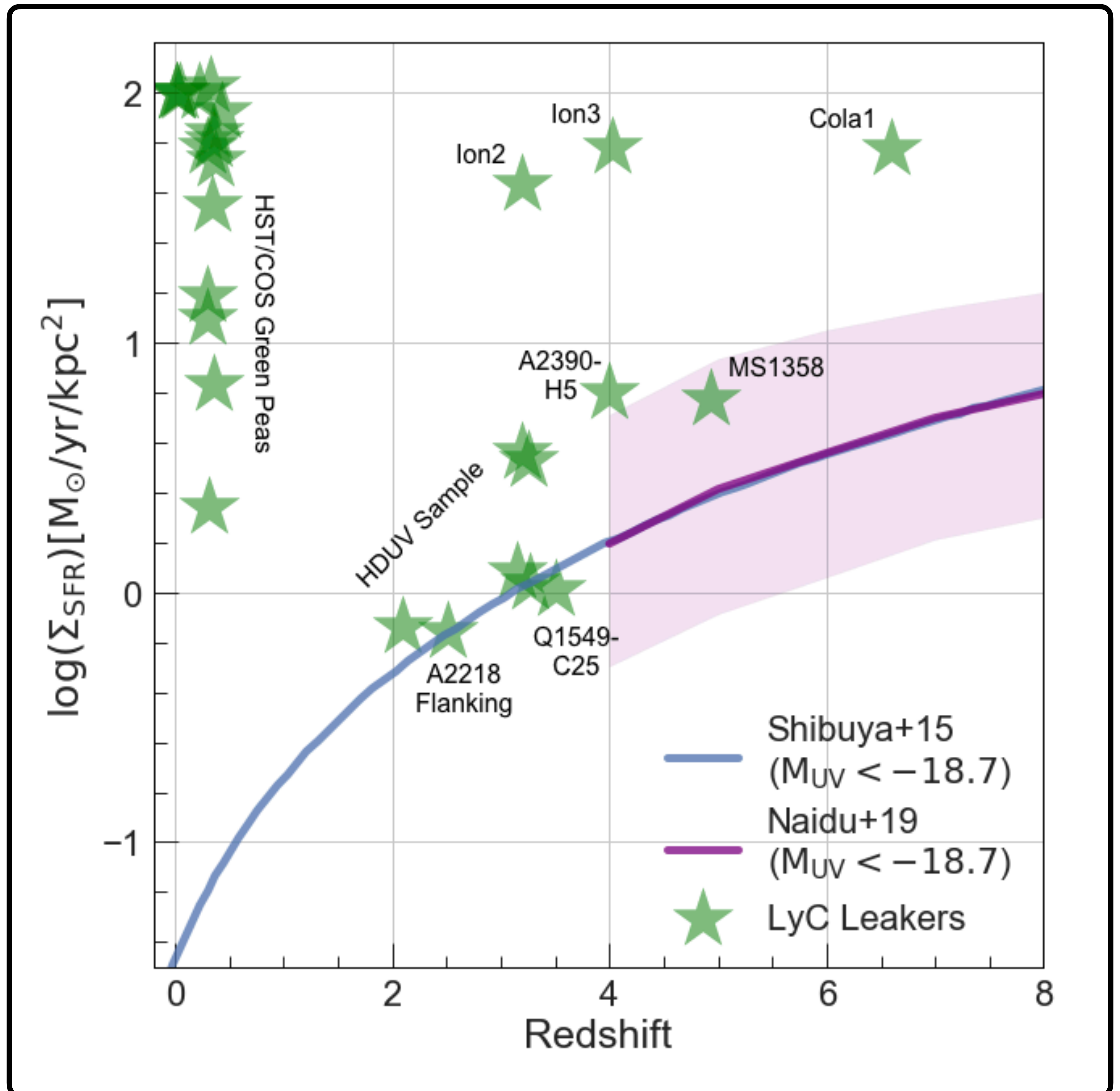
But f_{esc} = 20%?

- Emerging picture of average f_{esc}~10% at z=2-3 for M_{UV} < -18 galaxies (Steidel+18, Marchi+18, Fletcher+19, Oesch+ in prep.)
- How do we go from ~0% at z=0, to ~10% at z=3, and ~20% at z=6-10 in a self-consistent manner?

Idea: link f_{esc} to some galaxy property
here we assume SFR surface density: $f_{\rm esc} \propto \Sigma_{\rm SFR}^{\alpha}$

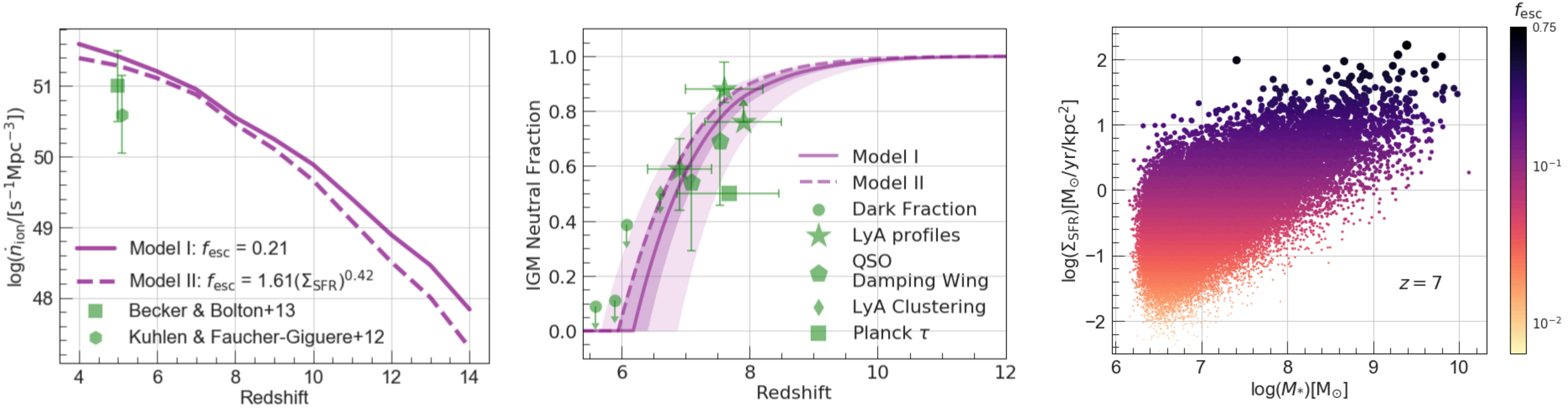
Motivations:
- Observations: LyC leakers tend to be extremely compact, highly star-forming
(Naidu+17, Izotov+16,18, Vanzella+16,18, Shapley+16, Bian+17, Matthee+18, Borthakur+14, Leitherer+16, Jones+13)

- Simulations/Theory: Spatially concentrated SF creates turbulence and carves channels in ISM for photons to escape
(Heckman+11, Ma+16, Sharma+16, Trebitsch+17, Katz+18, Rosdahl+18, Kakiichi&Gronke19)



Naidu, Tacchella+ (2019)

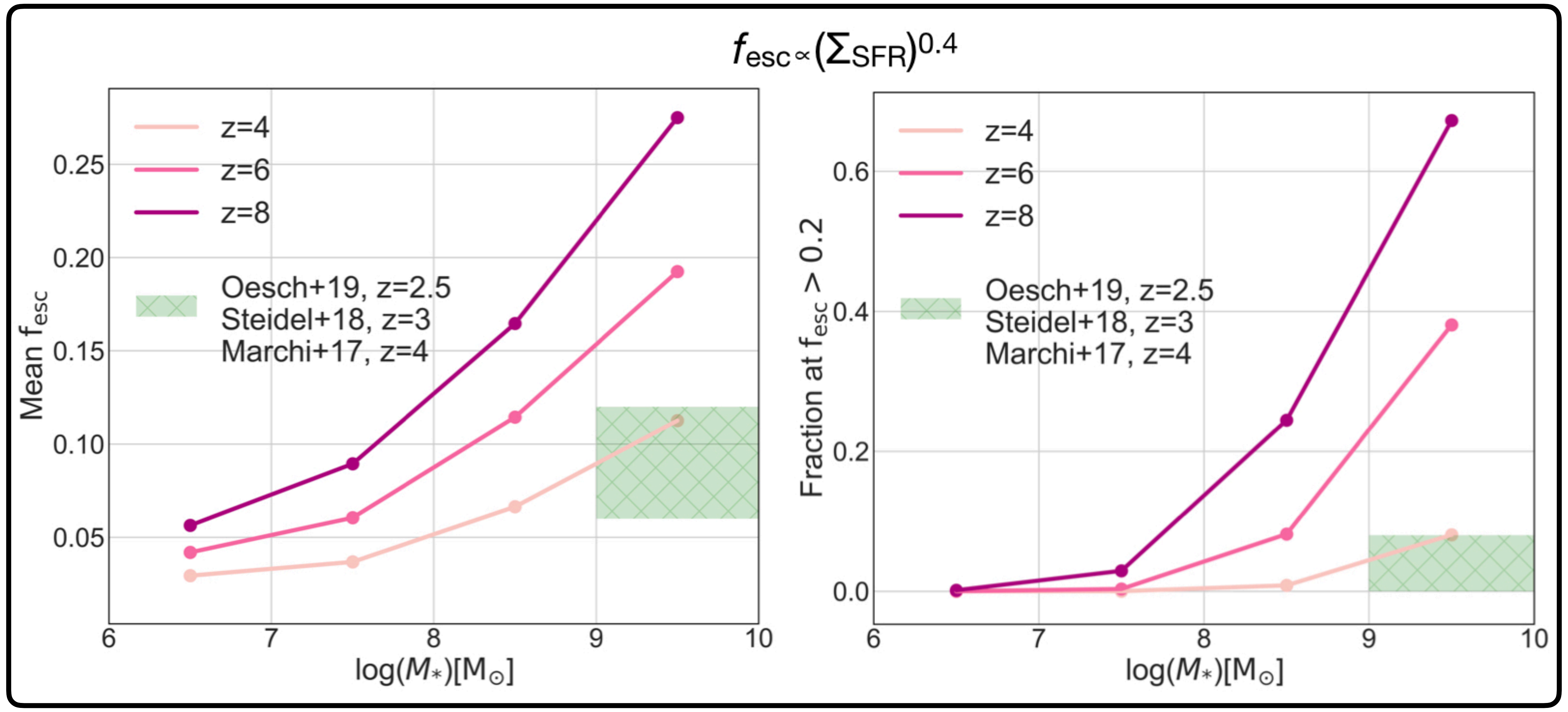
Link f_{esc} to SFR surface density

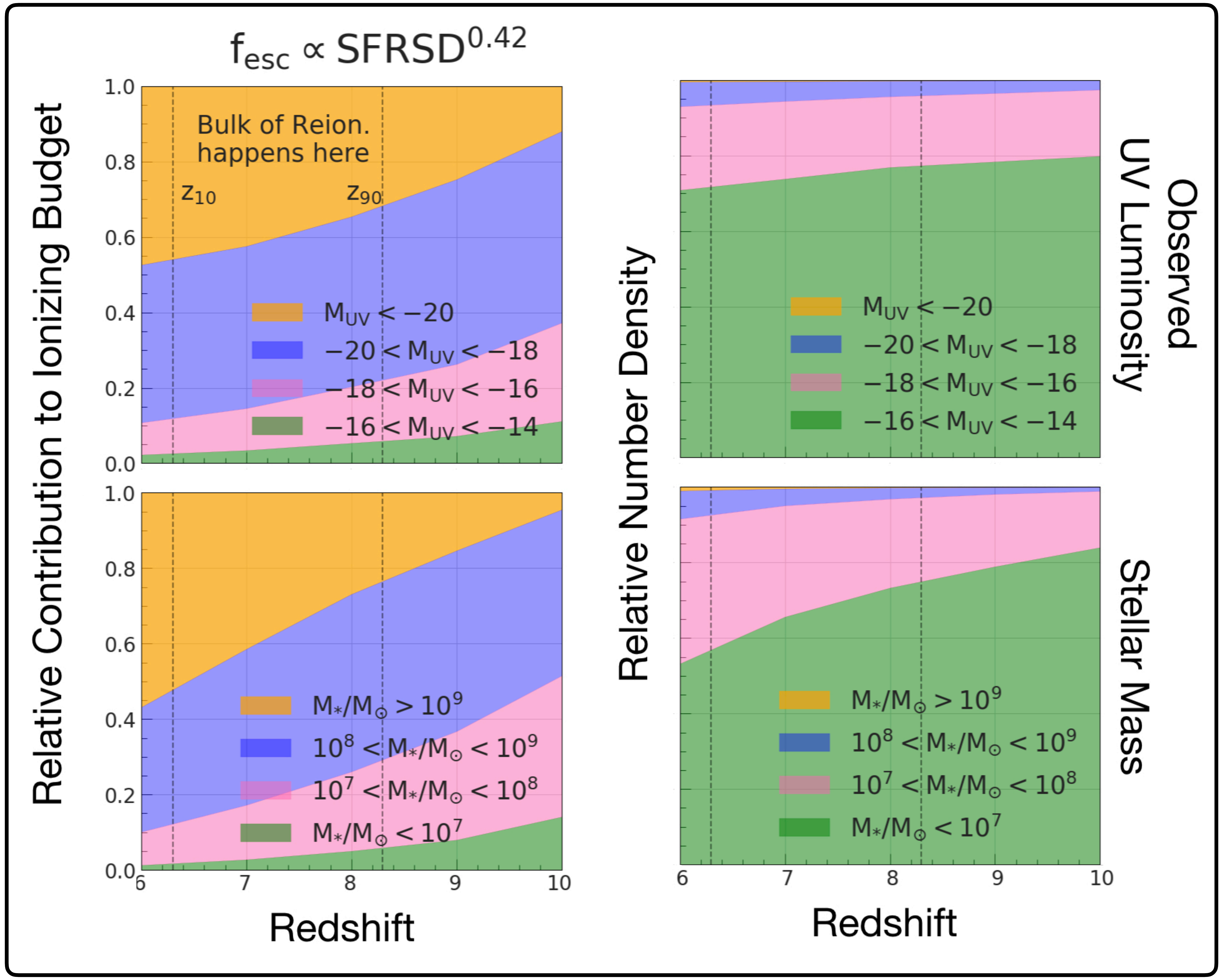


- $f_{esc} \propto \Sigma_{SFR}^{0.4}$ produces similar global reionization histories to the constant f_{esc} model
- … but $f_{esc} \propto \Sigma_{SFR}^{0.4}$ produces a differently distributed reionization budget

Which galaxies reionize the universe?

- More than ~80% of the reionization budget is controlled by <5% of galaxies — the “oligarchs”
- Great match to current observational picture: humble mean f_{esc}, but a small proportion of sources are “oligarchs”





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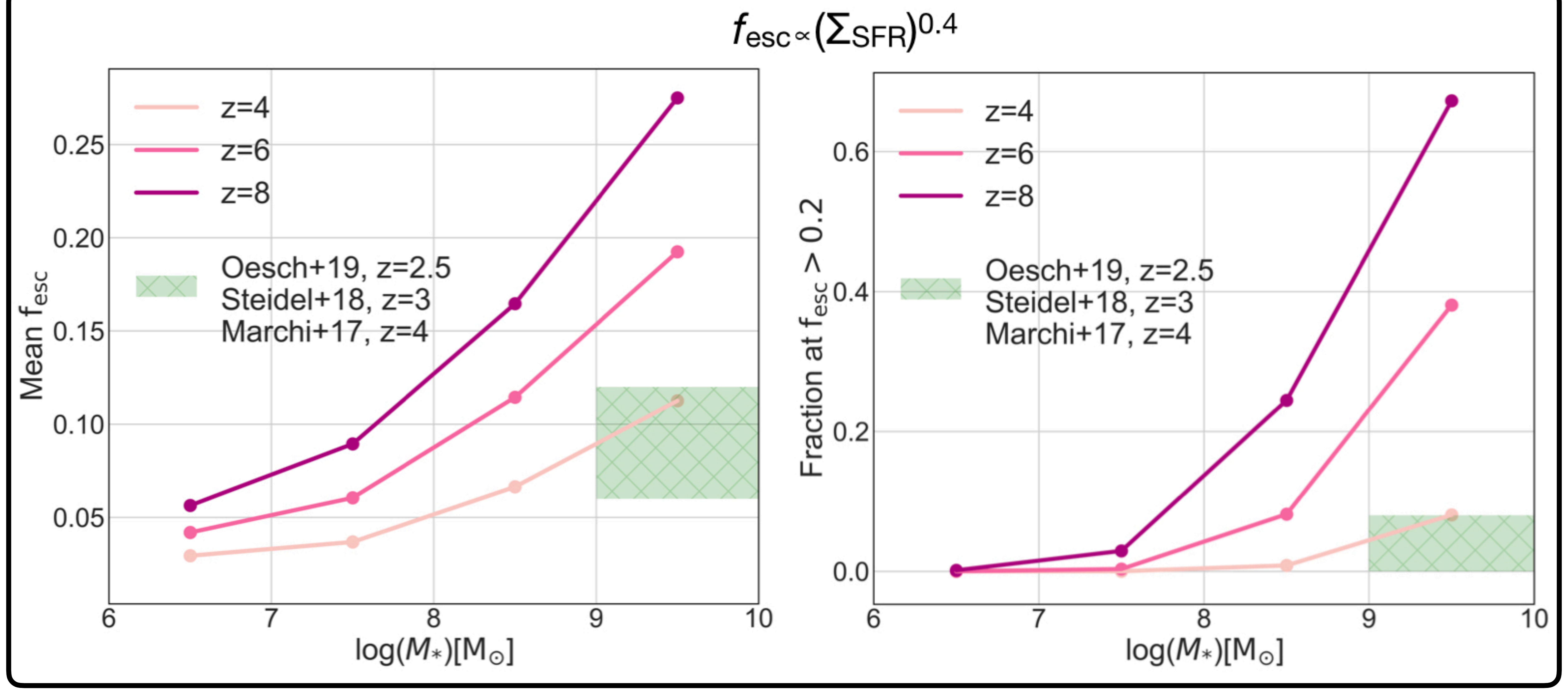
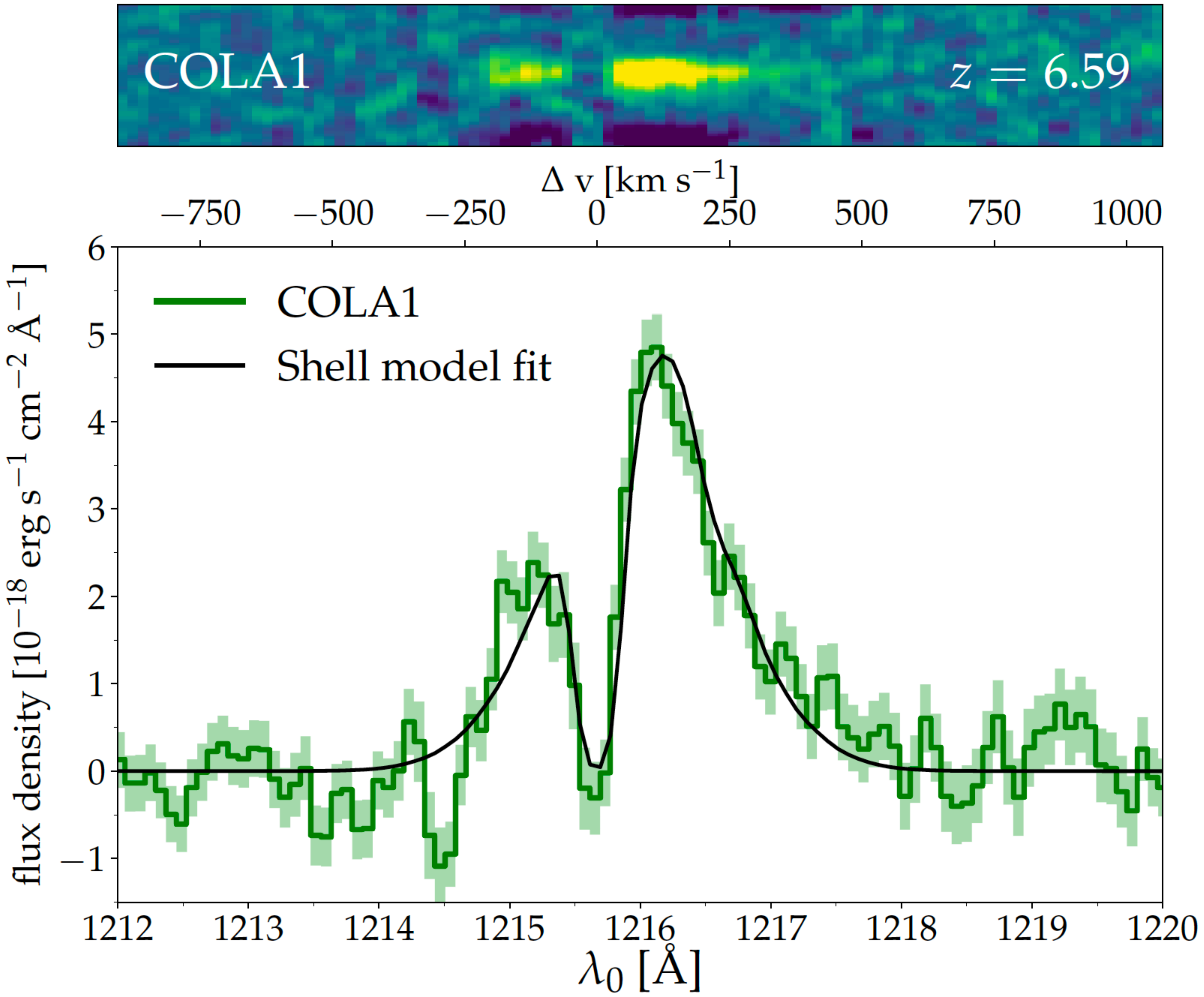


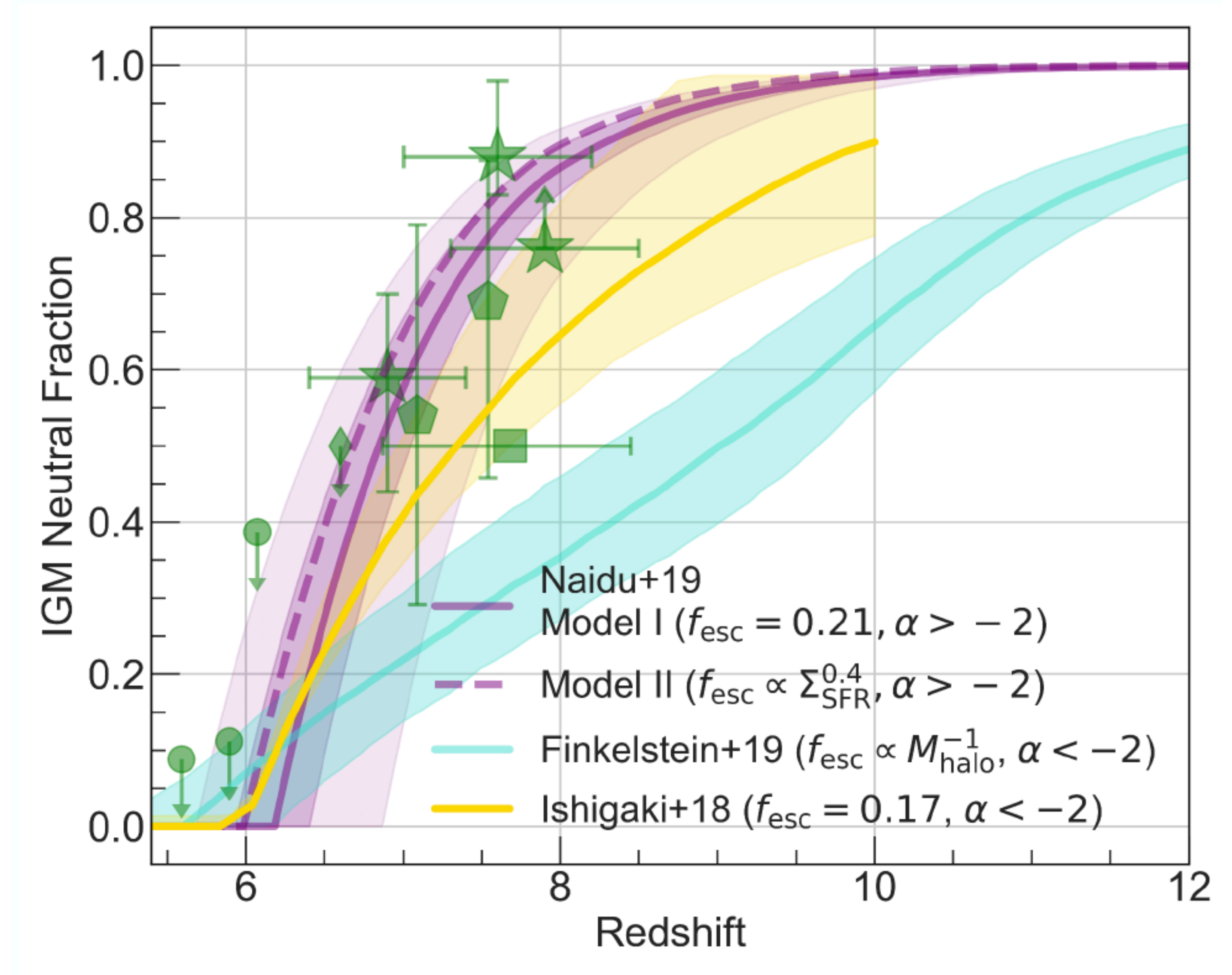
COLA1 at z=6.6 is a poster-child oligarch (f_{esc}~30%, M_{UV}~-21; Matthee+18)



see Anne Verhamme’s talk

What about “democratic” reionization?

- In state-of-the-art models where faint-galaxies dominate the budget, reionization is too slow (Finkelstein+19, Paardekooper+15, Khochfar+19)



Conclusions

- galaxies at z~1-4:
  - **mature bulges** in the most massive galaxies
  - star-forming disk component with rotation, v_{rot}/σ_0 ~ 2-5
- **gas compaction** leads to bulge formation while galaxies are on the main sequence
  ➜ high Σ_{SFR} for ~ dynamical time ➜ impact on reionization?
- simple empirical model (SFR $\propto$ dark matter accretion rate x z-indep. star-formation efficiency):
  - **buildup of dark matter halo** is a key driver of galaxy evolution
  - decline of the cosmic SFRD: fewer and fewer halos that are massive enough to be able to form stars efficiently
- reionization prediction:
  - linking f_{esc} to Σ_{SFR} naturally produces an evolving f_{esc} that reaches 20+% during reionization and explains humble f_{esc}~0 at z~0.
  - reionization is very rapid (z=6-8), and driven by “oligarchs” (>$10^8 M_\odot$)

  ➜ **protagonists of reionization are not hidden across the faint-end of the luminosity function but are already known to us** — testable!