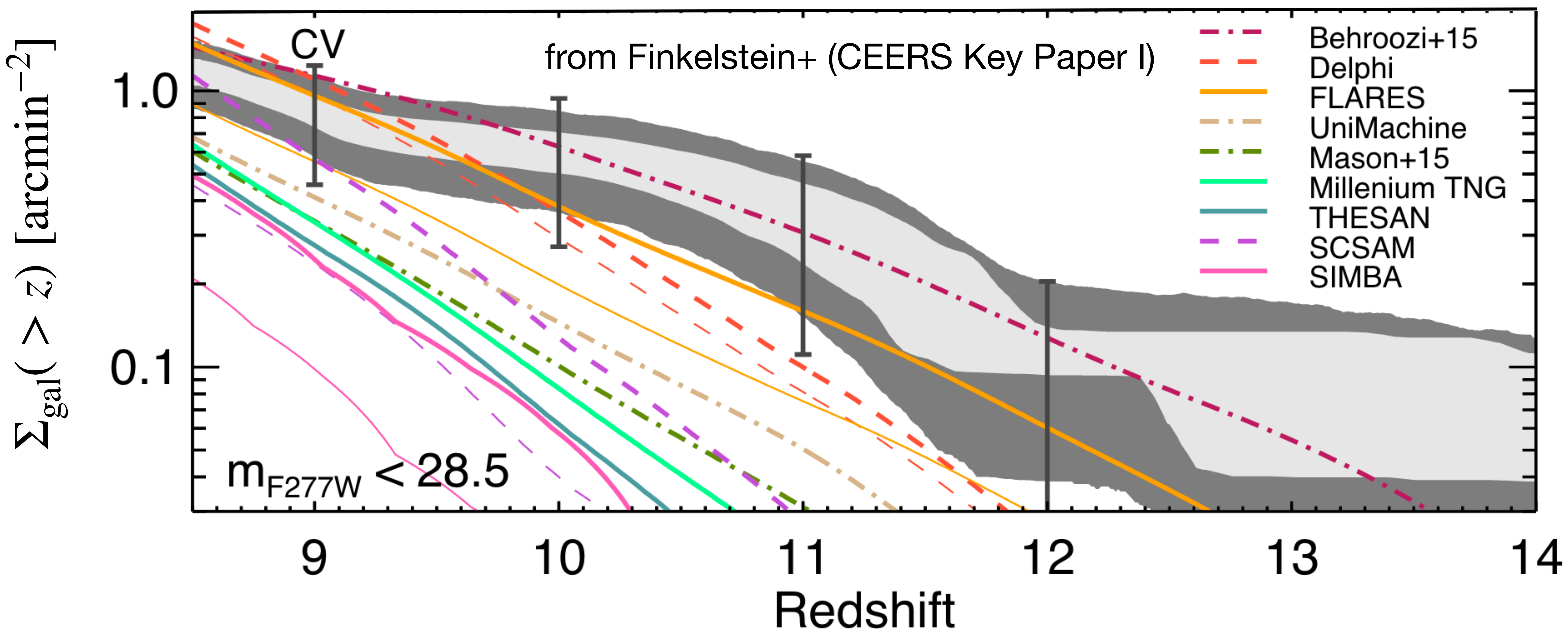
A new era in studies of the cosmic dawn: constraints from galaxy surveys, redshifted 21-cm signals, and the extragalactic background light

Jordan Mirocha (McGill → NASA/JPL)

based on **JM** & Furlanetto (arXiv:2208.12826)



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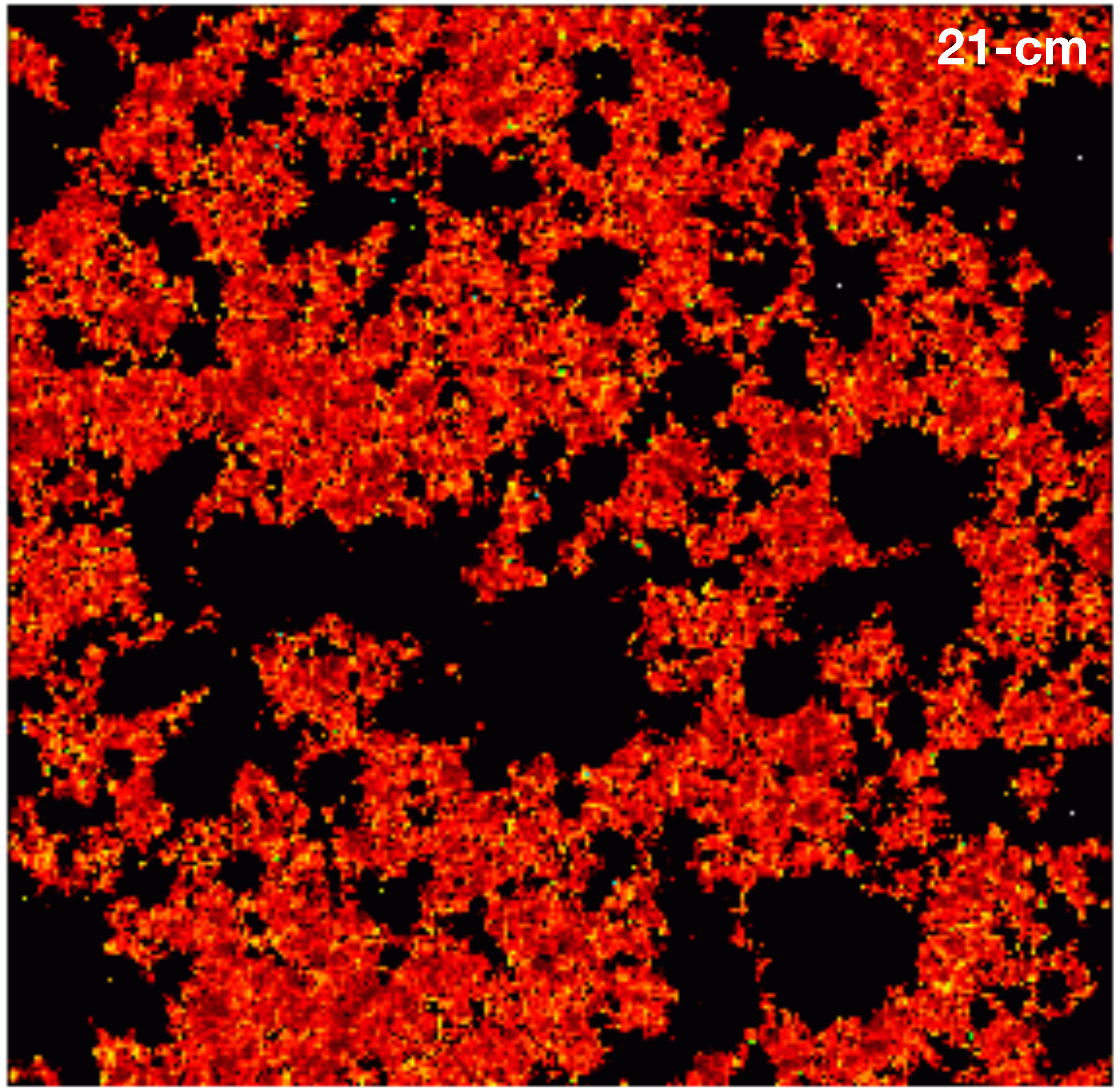
Plan for today

1. Hubble view of high-z galaxies.
How do we currently understand galaxy evolution at $z \gtrsim 4$?

2. First observations w/ JWST.
Can we accommodate early measurements in context of HST-era constraints?

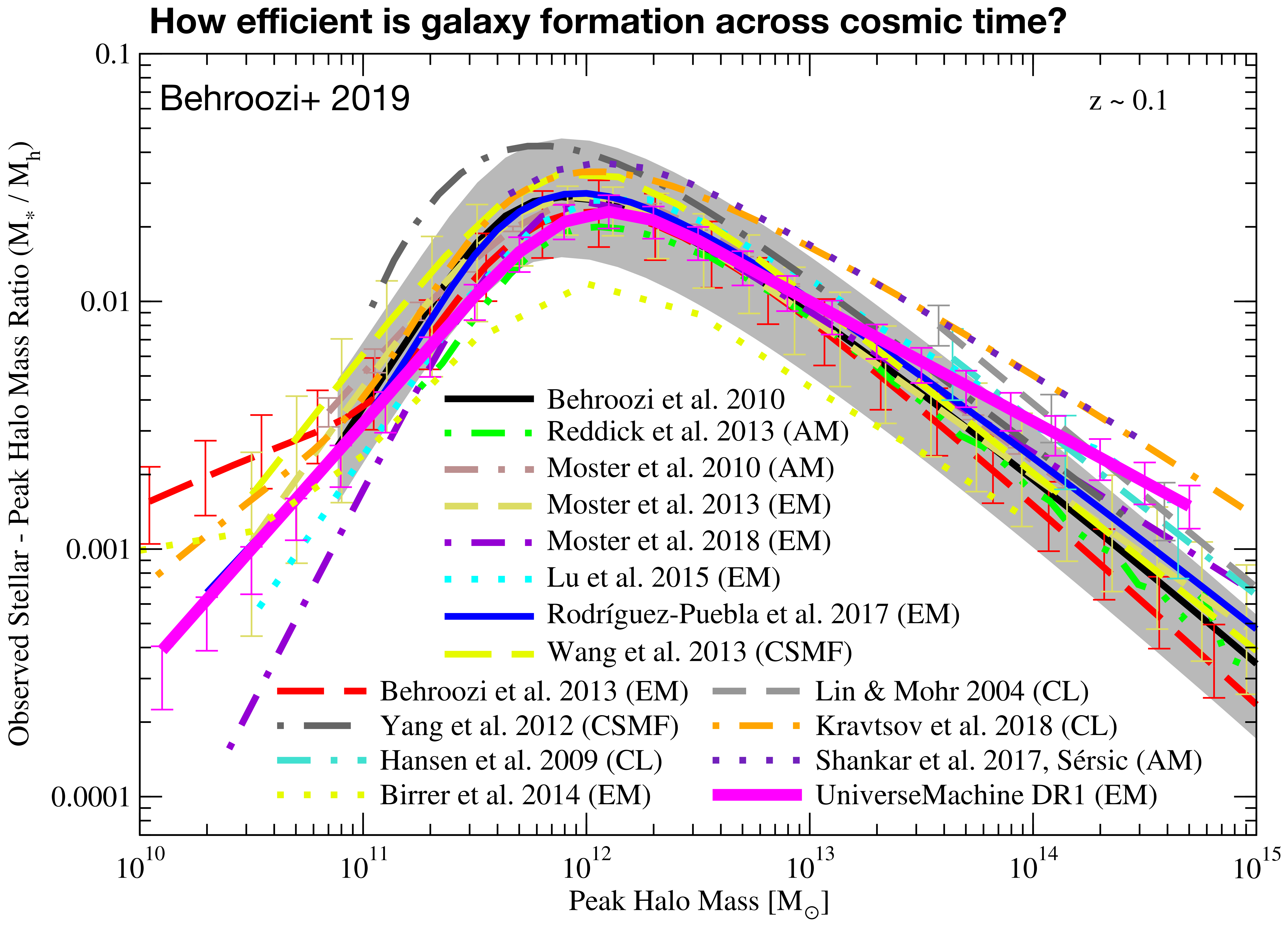
3. What else is going on?
Current / near-future input from EDGES, HERA, Roman, SPHEREx.



from Lidz+ 2009

Part I. High-z Galaxies (pre-JWST)

Big picture motivation



- Star formation efficiency (SFE) and related stellar-mass-halo-mass relation strong functions of halo mass.
- Case at high-z not so clear. Does it evolve?
- Low-mass regime virtually unconstrained.
- What does this tell us about <u>feedback</u>?

Big picture motivation

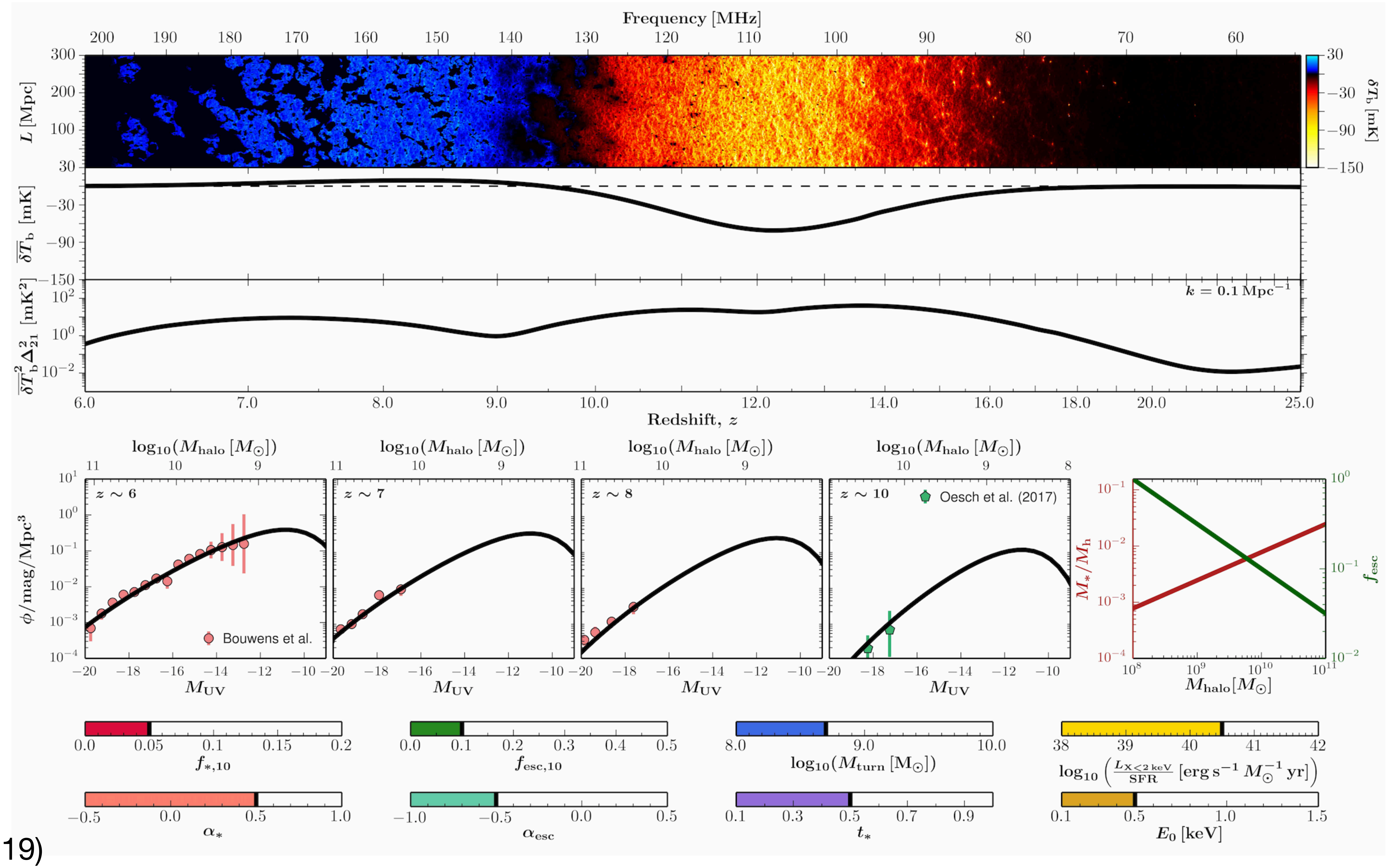
light cone

global signal

power spectrum

UVLFs

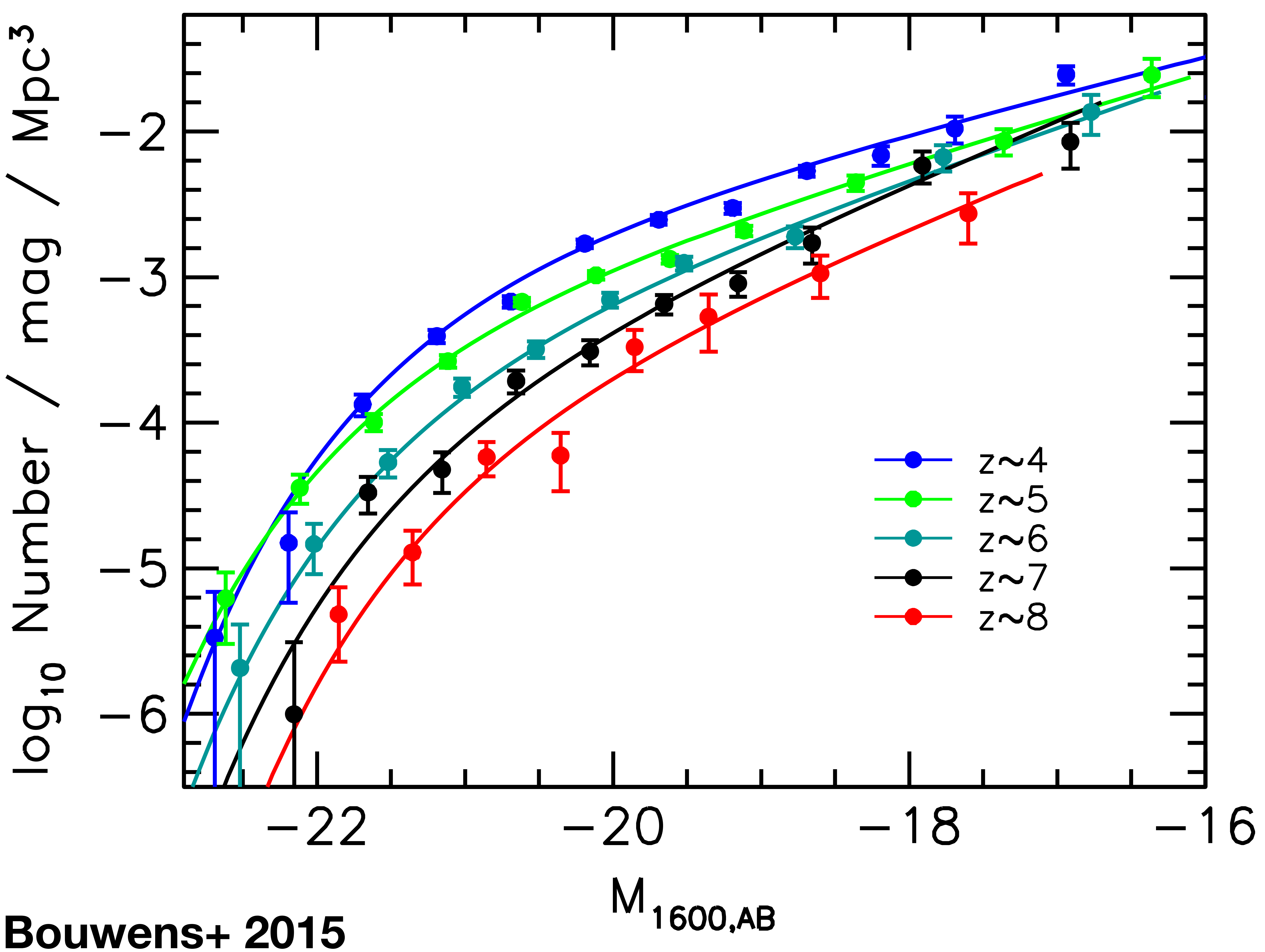
parameters



from **Park+** (2019)

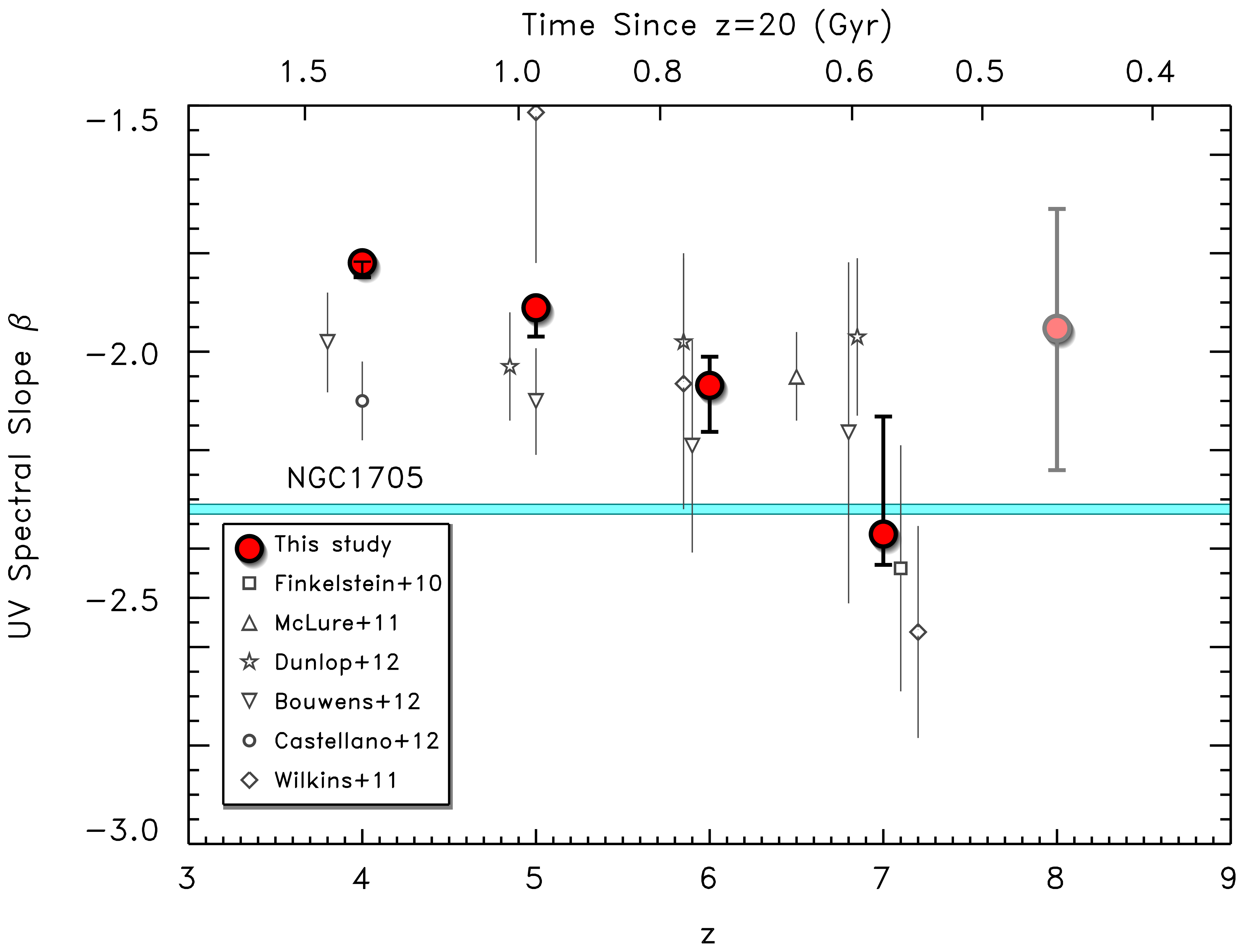
What we know: counts and colors at z~4-8

Rest-ultraviolet luminosity functions (UVLFs)
[just histogram of galaxies vs. mag]



Bouwens+ 2015

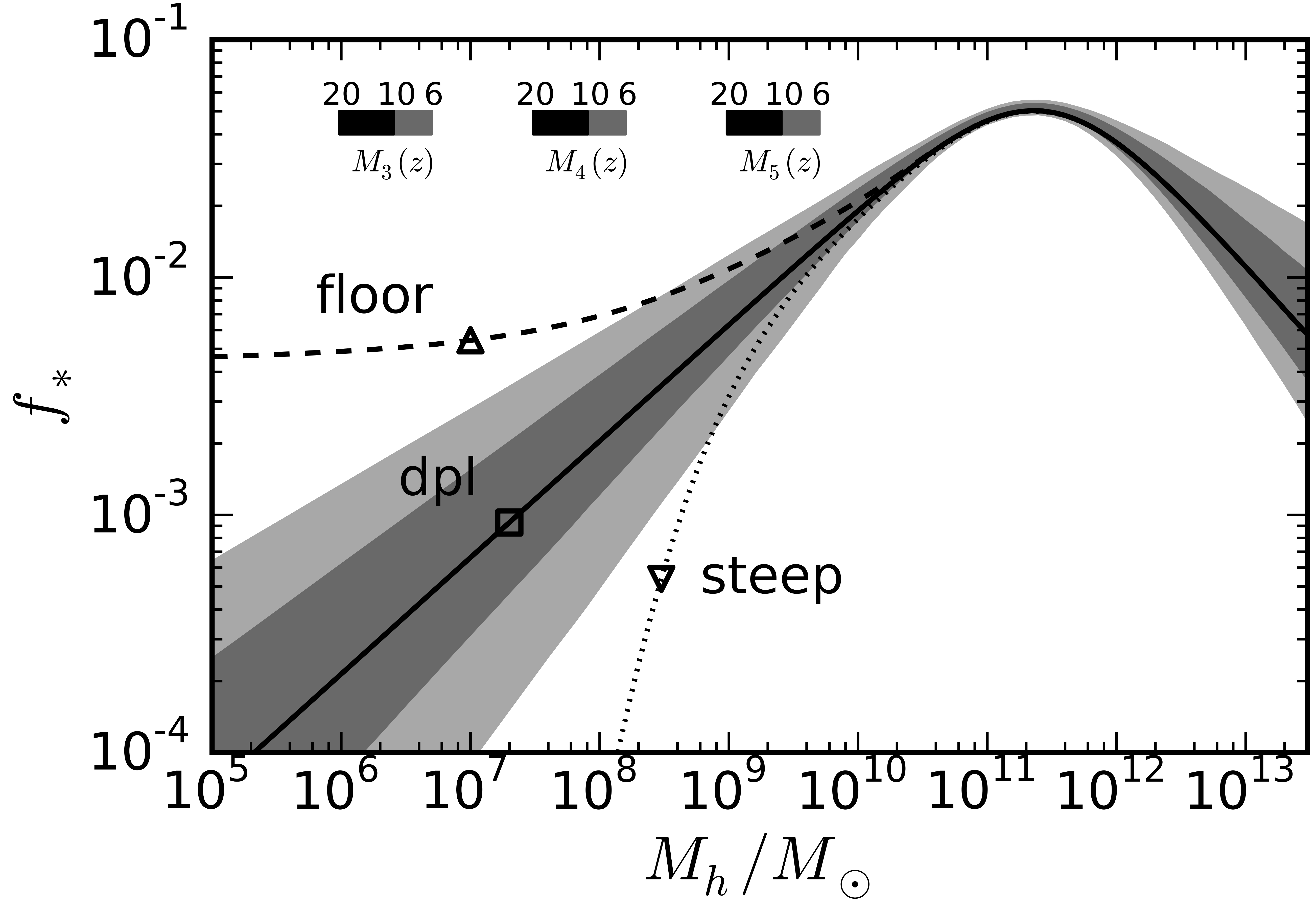
Rest-ultraviolet colours (spectral slope vs. z)



Finkelstein+ 2012

[know more than this, but this is easiest stuff for theorists to use]

Semi-empirical SFE model



Assume we know:

- halo mass function, dn_h/dM_h.
- halo mass accretion rates (MAR), $\dot{M}_h$.

Assume star formation tracks MAR.

$$L_{\mathrm{UV}} \propto \mathrm{SFR} = \mathrm{f}_* \left(\frac{\Omega_{\mathrm{b}}}{\Omega_{\mathrm{m}}}\right) \dot{\mathrm{M}}_{\mathrm{h}}$$

Can fit for f_* parameters via fitting rest-UV luminosity functions (UVLFs).

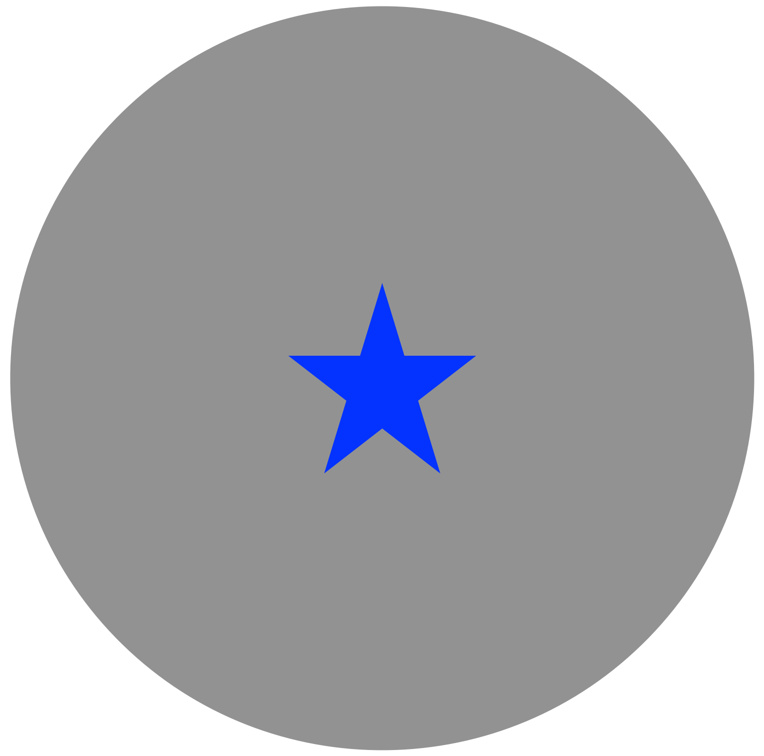
$$\frac{dn_{\mathrm{gal}}}{dM_{\mathrm{UV}}} = \frac{dn_h}{dM_h} \frac{dM_h}{dM_{\mathrm{UV}}}$$

JM, Furlanetto, & Sun 2017

Semi-empirical dust model

Avoid IRX-β:

$$
\begin{aligned}
L_\lambda &= L_{\lambda,0} \exp\{-\tau_\lambda\} \\
&= L_{\lambda,0} \exp\{-\rho_d R_d \kappa_\lambda\} \\
&= L_{\lambda,0} \exp\{-(3 M_Z f_{\mathrm{dtmr}} / 4\pi R_d^2) \kappa_\lambda\}
\end{aligned}
$$



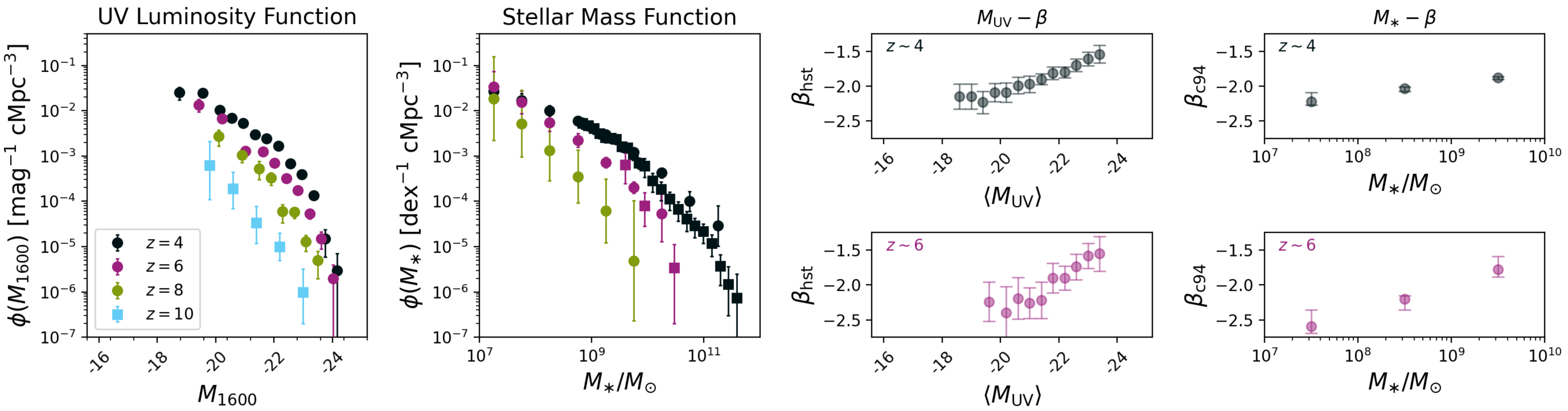
Relate dust production to star formation via f_{dtmr} parameter and invoke dust scale length, R_d, to get column density.

Synthesize SED of each model galaxy, redden, and "observe" through HST filters relevant for redshift.

This looks like a pt. src w/ spherical screen, but we can also think of this as some *effective* dust column density to get away from geometrical interpretation.

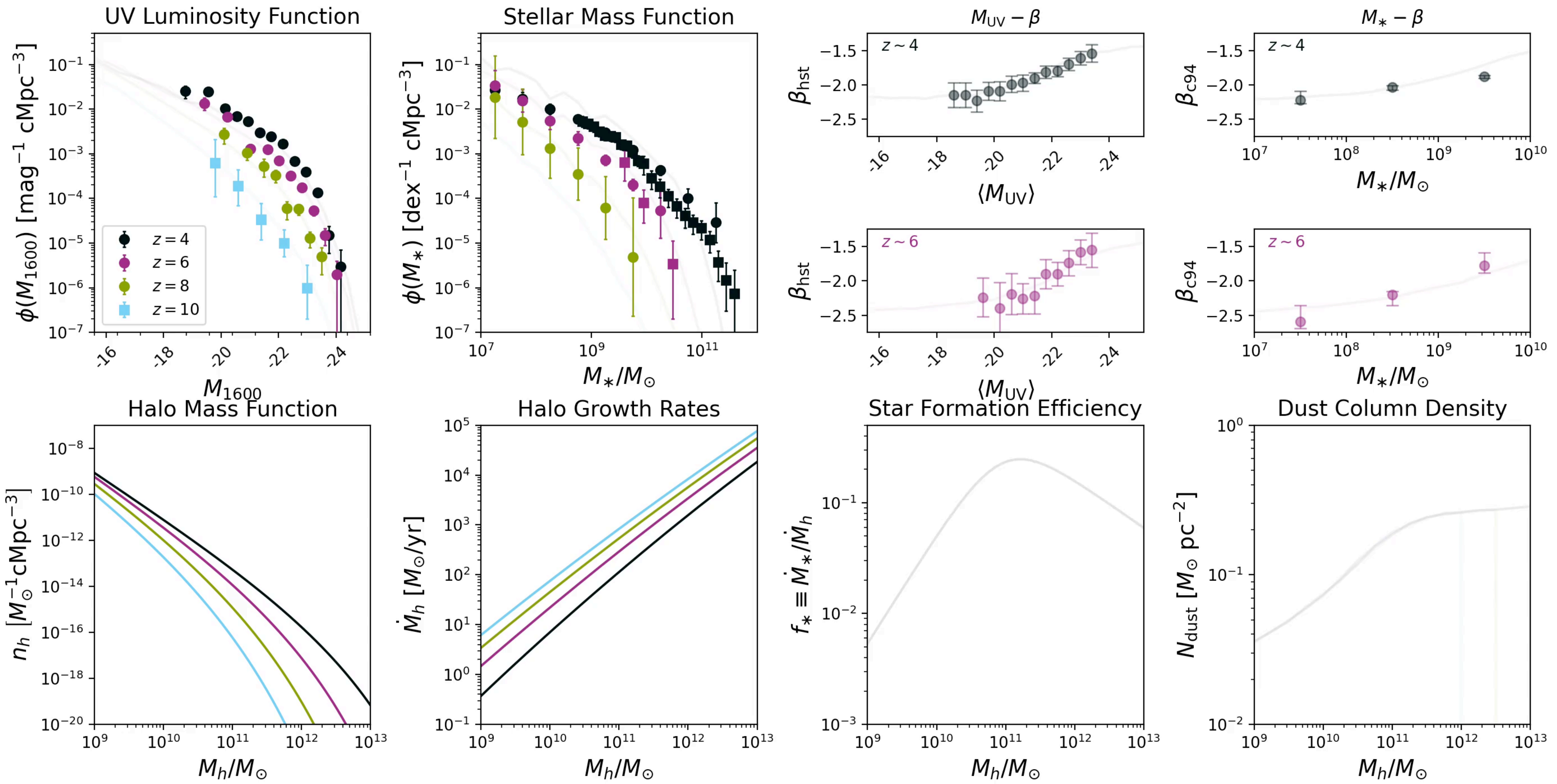
JM, Mason, & Stark 2020

Model calibration



JM, Mason, & Stark (2020), see also, e.g., Sun & Furlanetto (2016), Tacchella+ (2018), Behroozi+ (2019), +many others

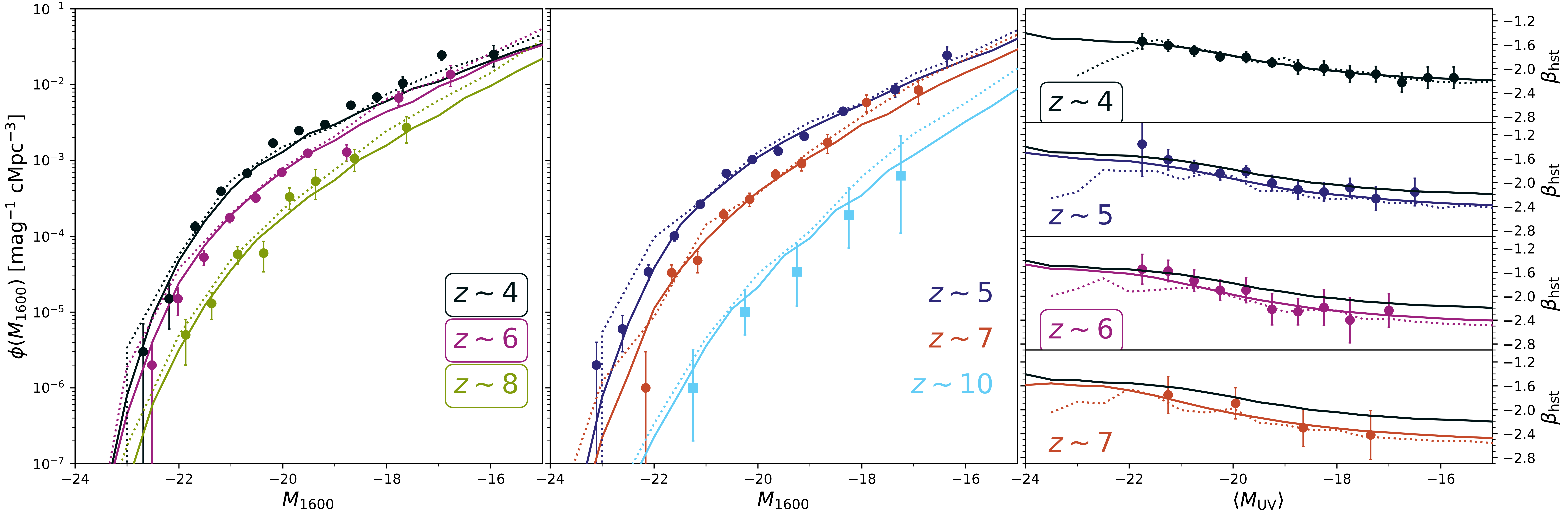
Model calibration



JM, Mason, & Stark (2020), see also, e.g., Sun & Furlanetto (2016), Tacchella+ (2018), Behroozi+ (2019), +many others

Universal SFE & dust results

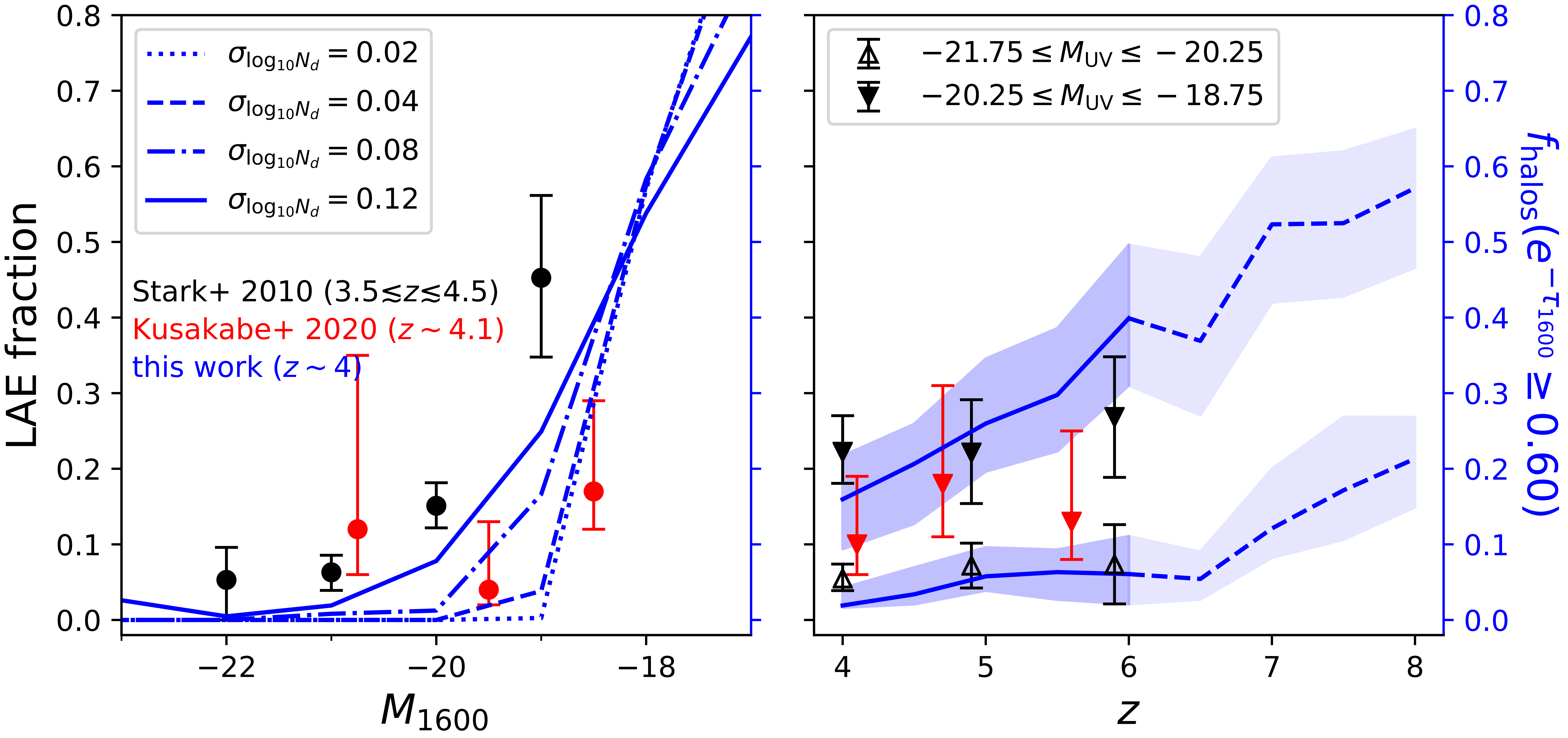
Colour evolution matches up with observations even without SFE, f_{dtmr}, or R_d evolution.



JM, Mason, & Stark 2020

note: solid (dotted) curves assume double power-law (power-law) R_d

Side note: LAEs too?



JM, Mason, & Stark 2020

So: SFE, R_d, f_{dtmr}, need not evolve to match UVLF & color evolution…

…but shouldn't they evolve?

Feedback: SFE=SFE(z)

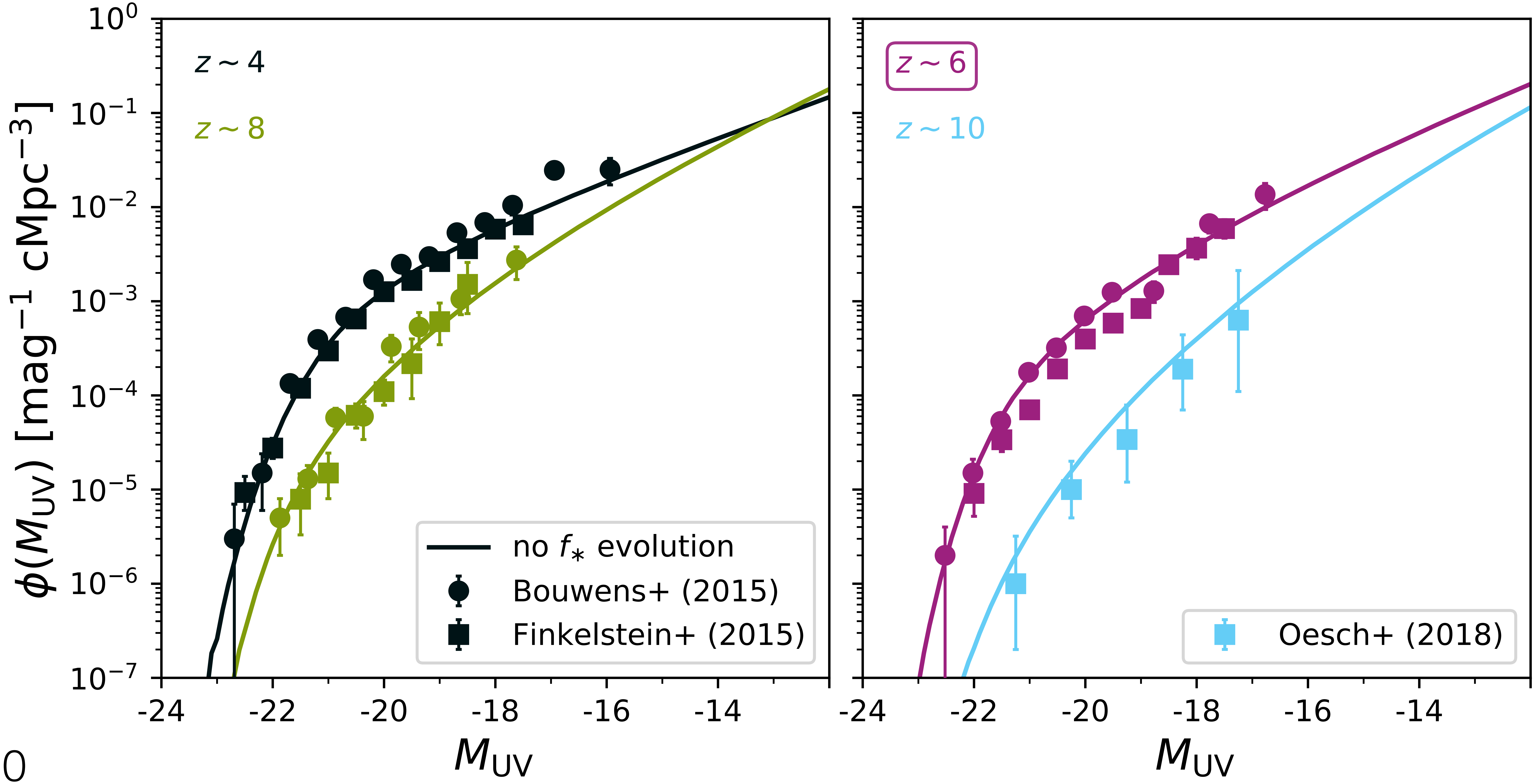
Balance star formation, inflow, outflow:

$$\dot{M}_* = \dot{M}_b - \dot{M}_w$$

$$\frac{1}{2}\dot{M}_w v_{\rm esc}^2 = \dot{M}_* \epsilon_k \omega_{\rm SNe}$$

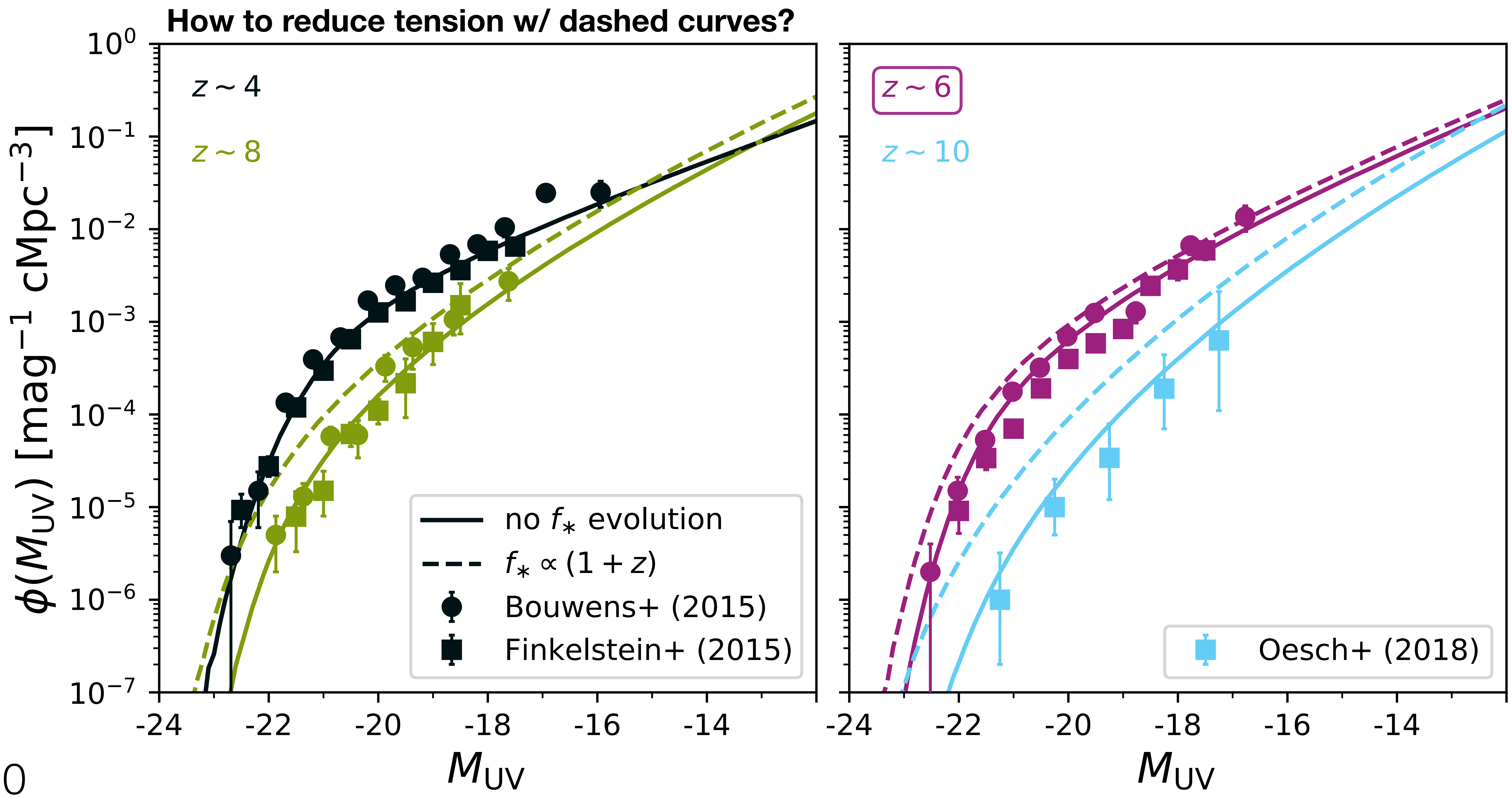
see, e.g., Furlanetto, **JM**+ 2017,
and most semi-analytic models (e.g., Somerville+ 2012, Dayal+ 2013, …)

Tension in Physical Models



JM 2020

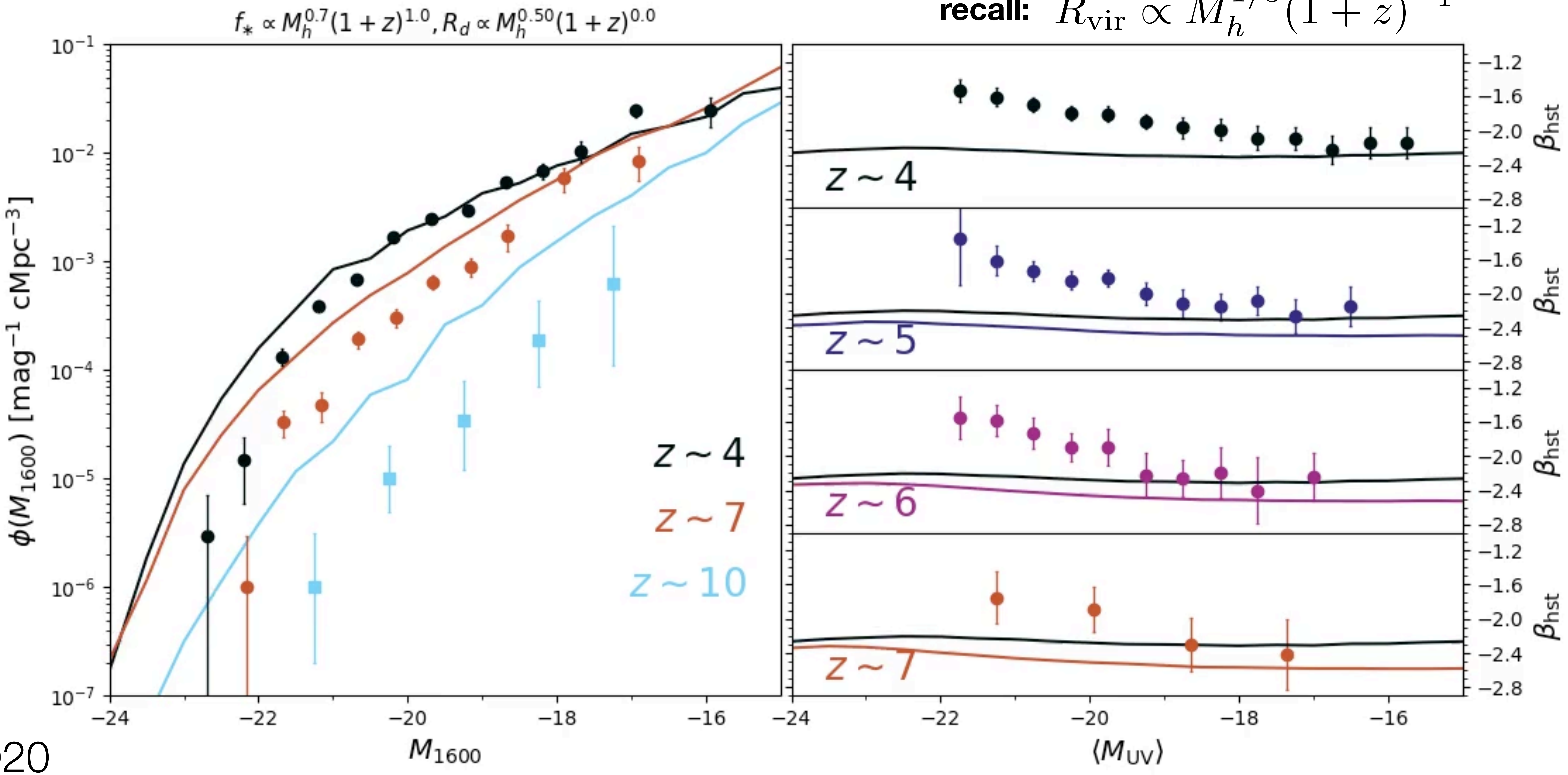
Tension in Physical Models



JM 2020

Rapid contraction → over-reddening

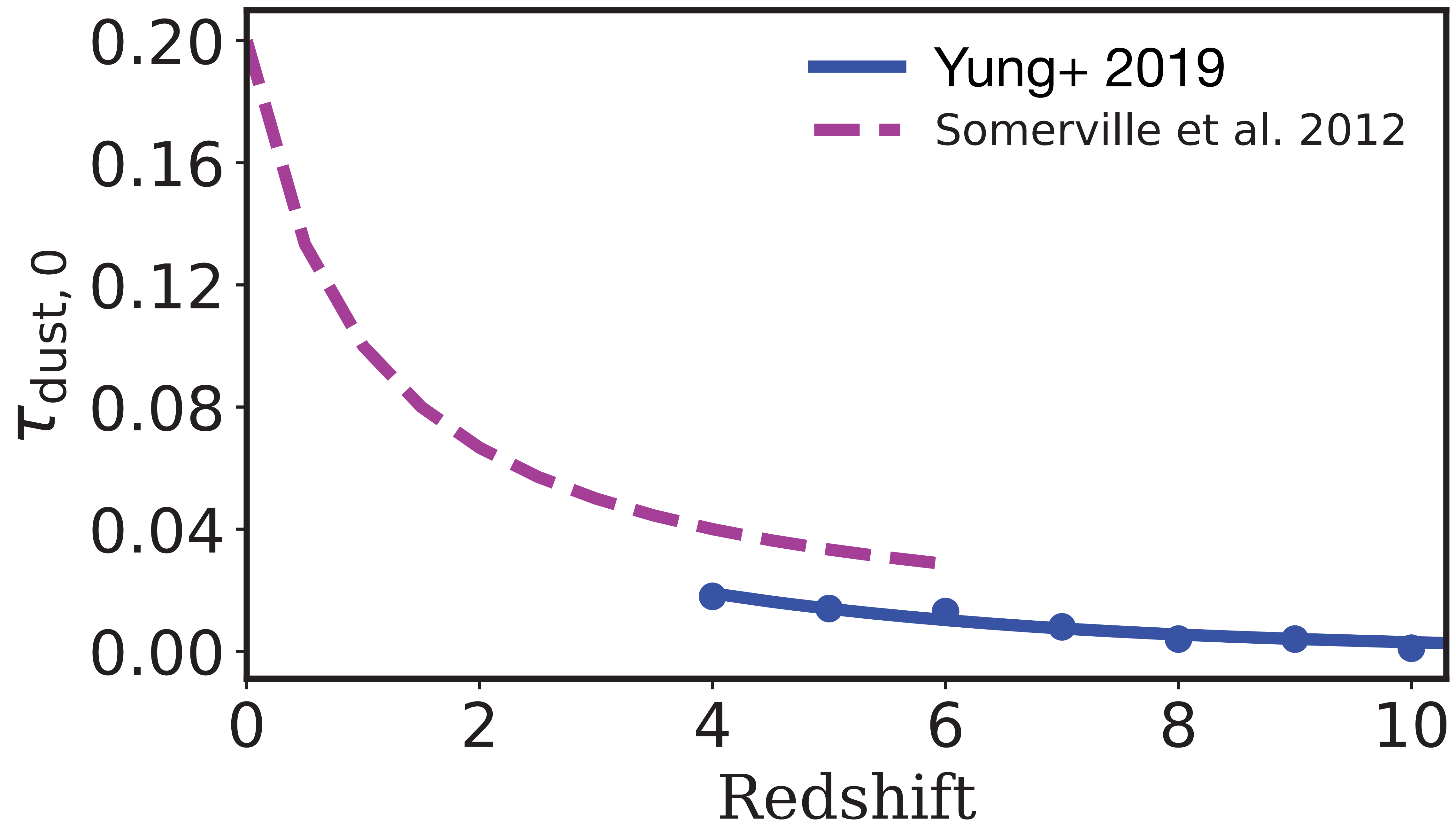
recall: $R_{\rm vir} \propto M_h^{1/3}(1+z)^{-1}$



JM 2020

Remedies

Invoke redshift evolution in the dust opacity?



In this work: allow M_h or redshift dependent f_{dtmr} and f_{duty}:

$$f_{\rm dtmr} = f_{\rm dtmr,10} \left(\frac{M_h}{10^{10} M_\odot} \right)^{\alpha_{\rm dtmr}} \left(\frac{1+z}{5} \right)^{\gamma_{\rm dtmr}}$$

$$f_{\rm duty} = f_{\rm duty,10} \left(\frac{M_h}{10^{10} M_\odot} \right)^{\alpha_{\rm duty}} \left(\frac{1+z}{5} \right)^{\gamma_{\rm duty}}$$

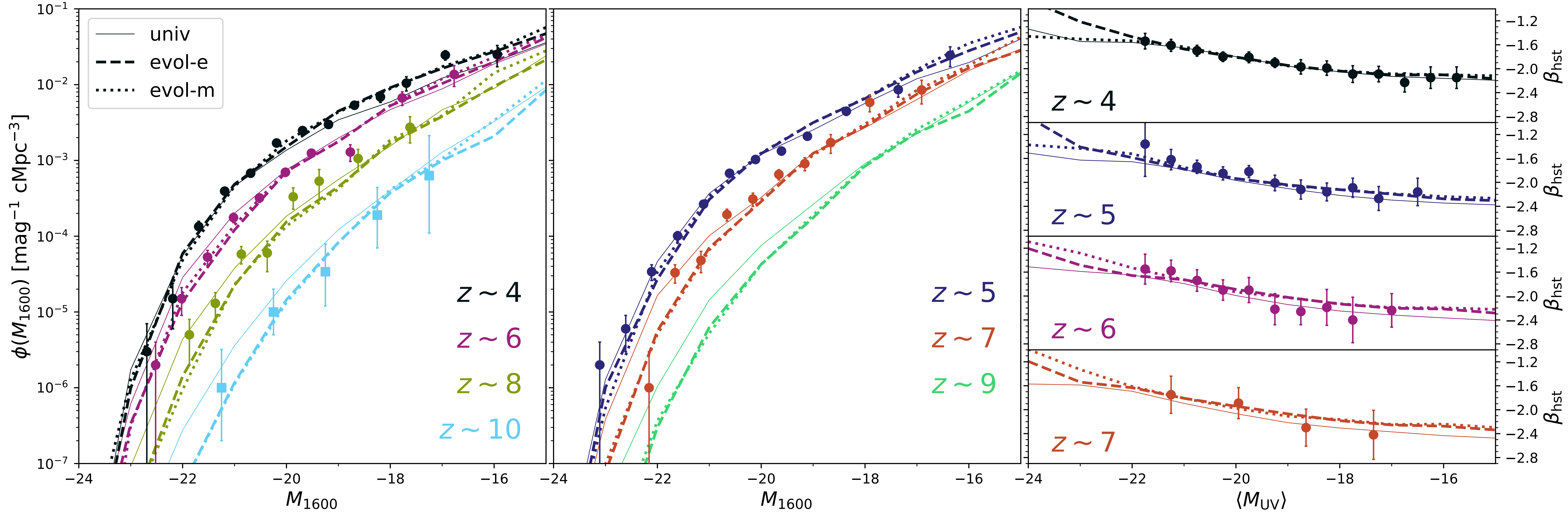
Force SFE to energy-regulated case.
Force R_d to track R_{vir}.

JM 2020 (see also, e.g., Vogelsberger+2019, Qiu+ 2019)

Fit Results

MCMC fit to z~4,6,8 UVLFs and colours (8-9 parameters)

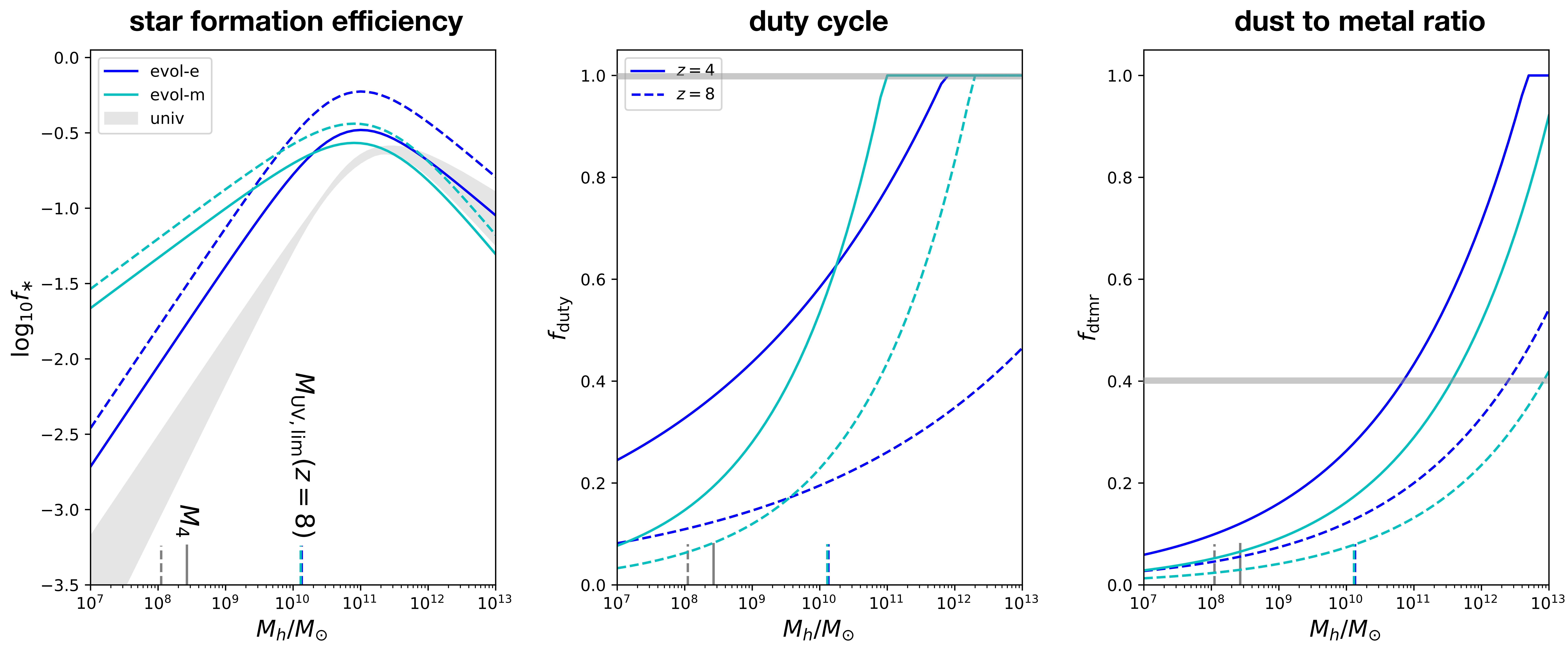
data from Bouwens+ 2014,2015



JM 2020

How different are these three models “under the hood”?

Constraints on properties of galaxies

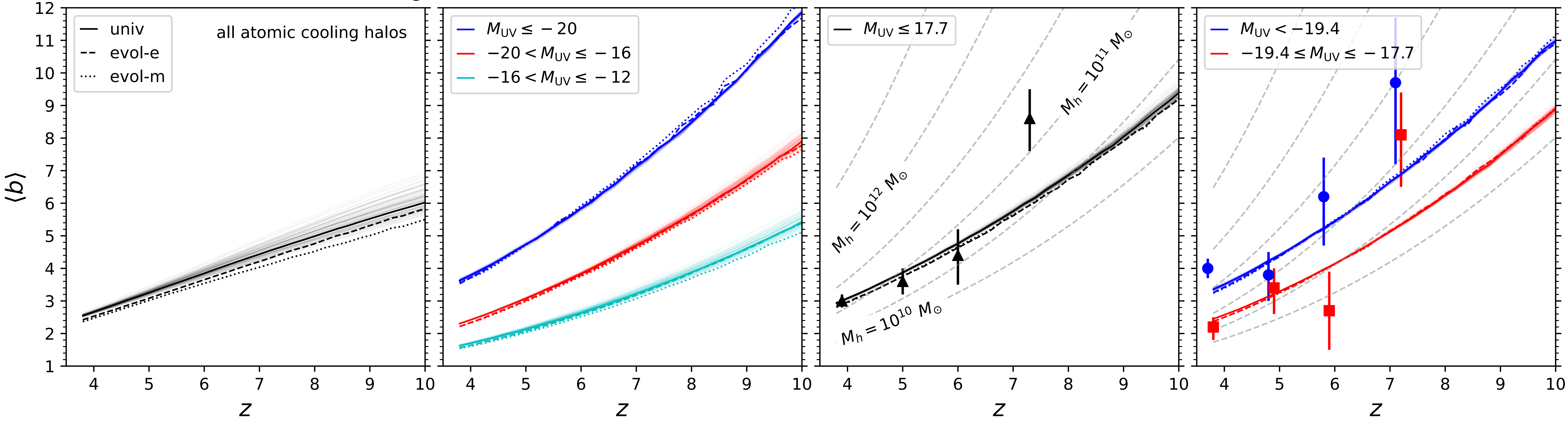


JM 2020

Each scenario here can fit all UVLFs and colours — need more (and different) data!

Clustering signal

Evolution of the mean bias of galaxies with redshift.



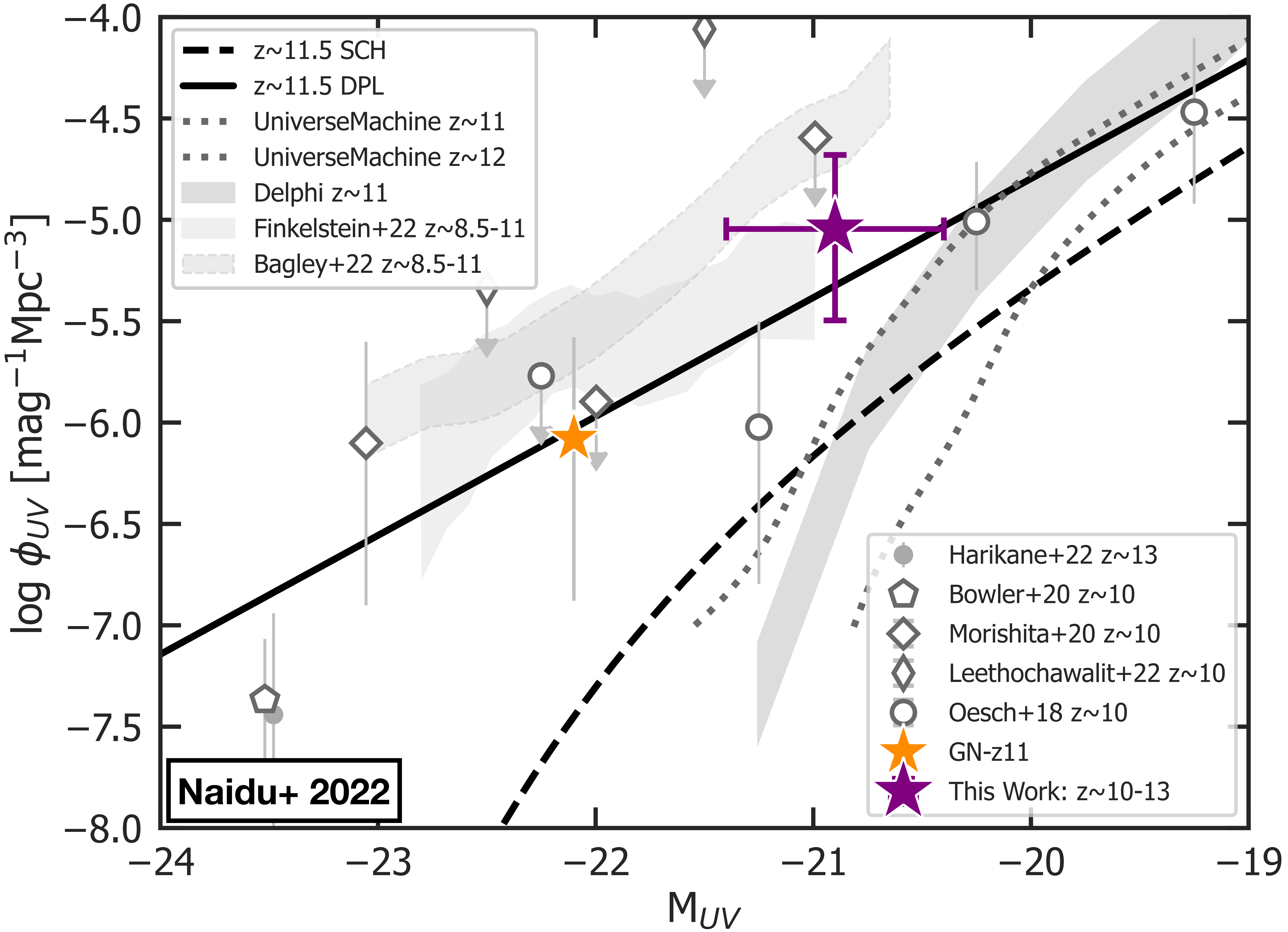
How to differentiate models, given ease with which UVLFs and colors can be matched?

JM 2020

data from Barone-Nugent, Trenti+ (2014)

Part II. First wave of JWST results

Definitely learning if *all* models are wrong!

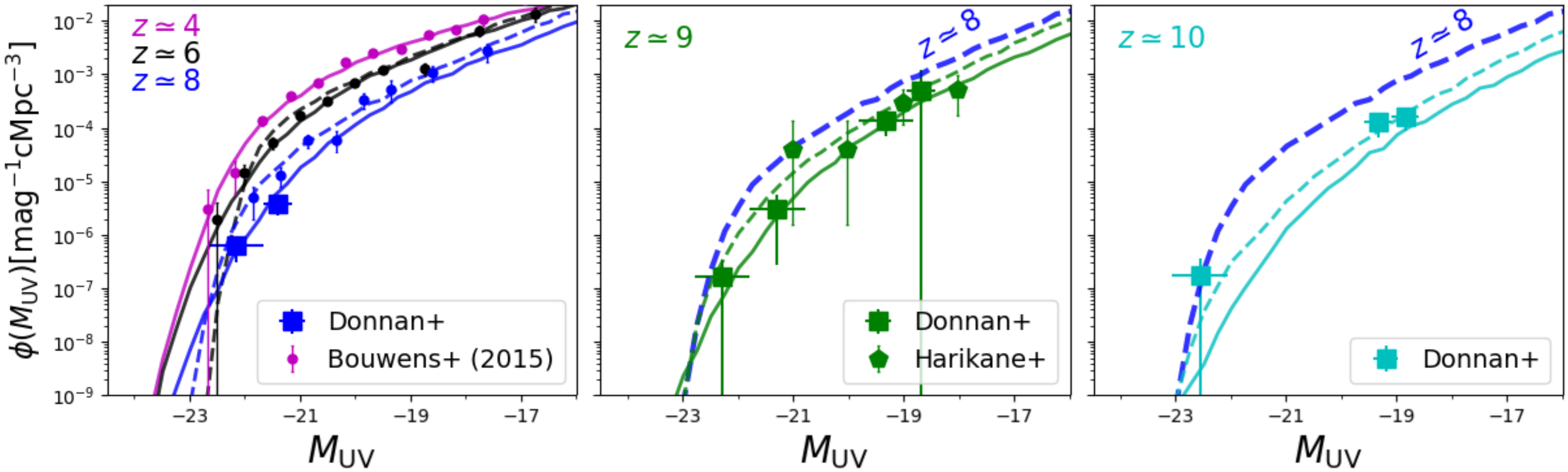


Some of the first high-z galaxies from JWST…are there too many? Are they too bright? Are they all interlopers?

see also Donnan+, Harikane+, interpretations from Mason+, Ferrara+, Zavala+, Naidu+ **…**

Agreement w/ HST-based models at $z \lesssim 10$

Small symbols: HST Big symbols: JWST



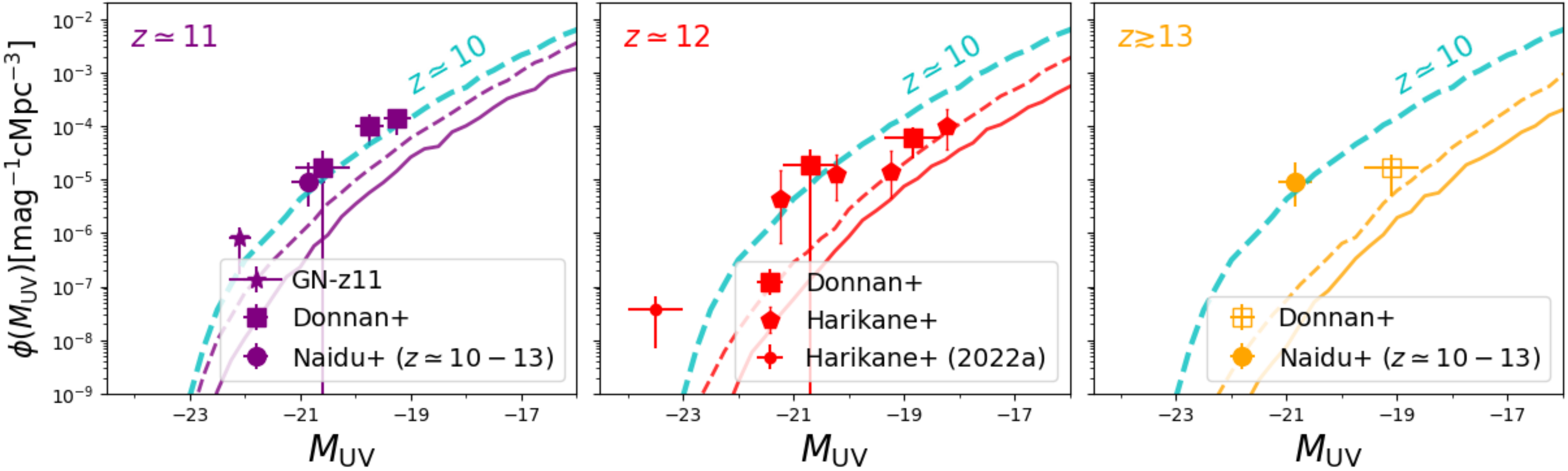
Solid: energy-regulated f_* model, with dust and 0.3 dex scatter in SFR(M_h)

Dashed: 'universal' f_* model, **no dust** or scatter in SFR(M_h)

JM & Furlanetto (arXiv:2208.12826)

Abundances high, ~constant at $z \gtrsim 10$

Small symbols: HST Big symbols: JWST



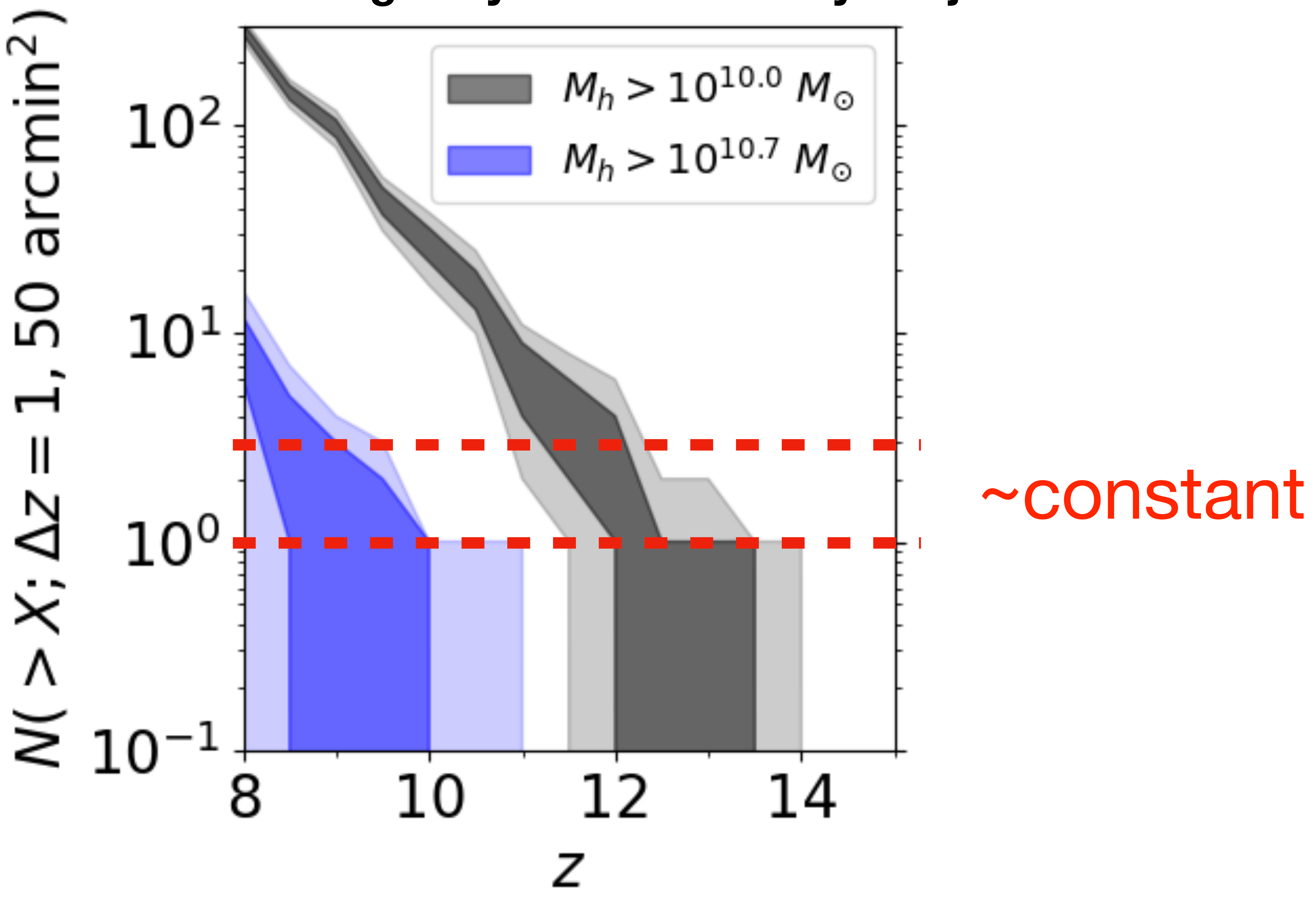
Solid: energy-regulated f_* model, with dust and 0.3 dex scatter in SFR(M_h)

Dashed: 'universal' f_* model, **no dust** or scatter in SFR(M_h)

JM & Furlanetto (arXiv:2208.12826)

Abundances ~constant by chance?

Halo/galaxy surface density subject to Poisson sampling and cosmic variance…

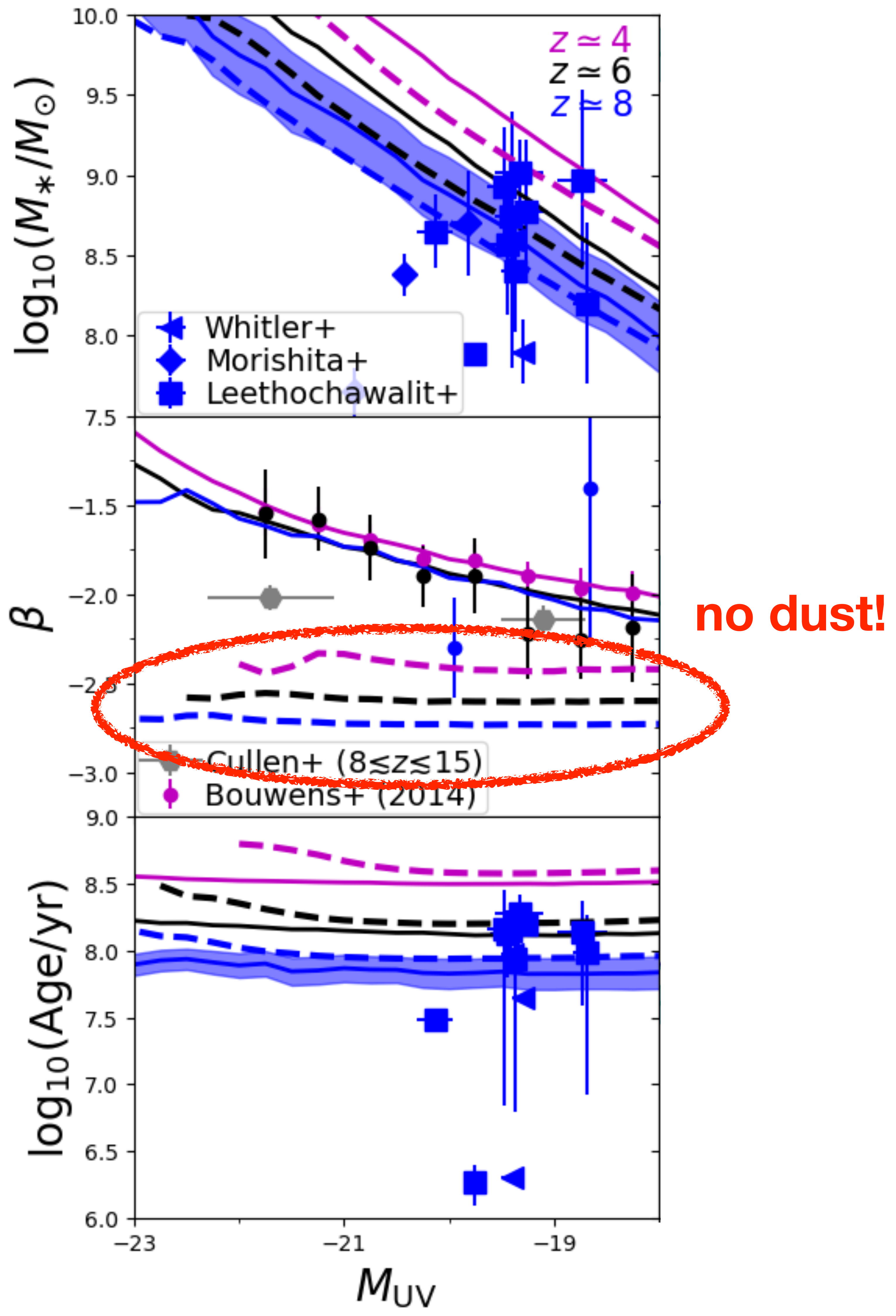


Dark: 68% of realizations
Light: 95% of realizations

$$L_{\rm UV} \propto \mathrm{SFR} \propto \mathrm{f}_* \times \mathrm{MAR}$$

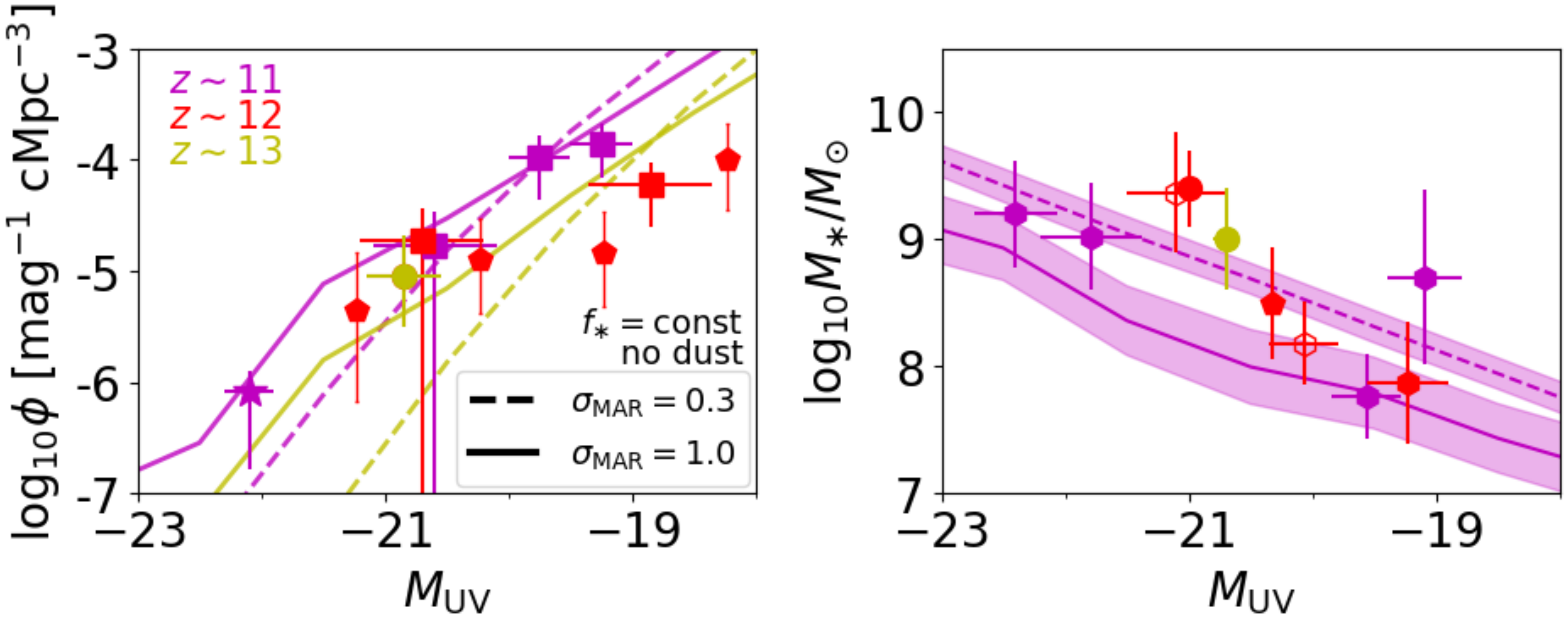
JM & Furlanetto (arXiv:2208.12826)

Masses, rest-UV colors, ages ~OK?



JM & Furlanetto (arXiv:2208.12826)

Need flat f_*, high scatter, *and* dust

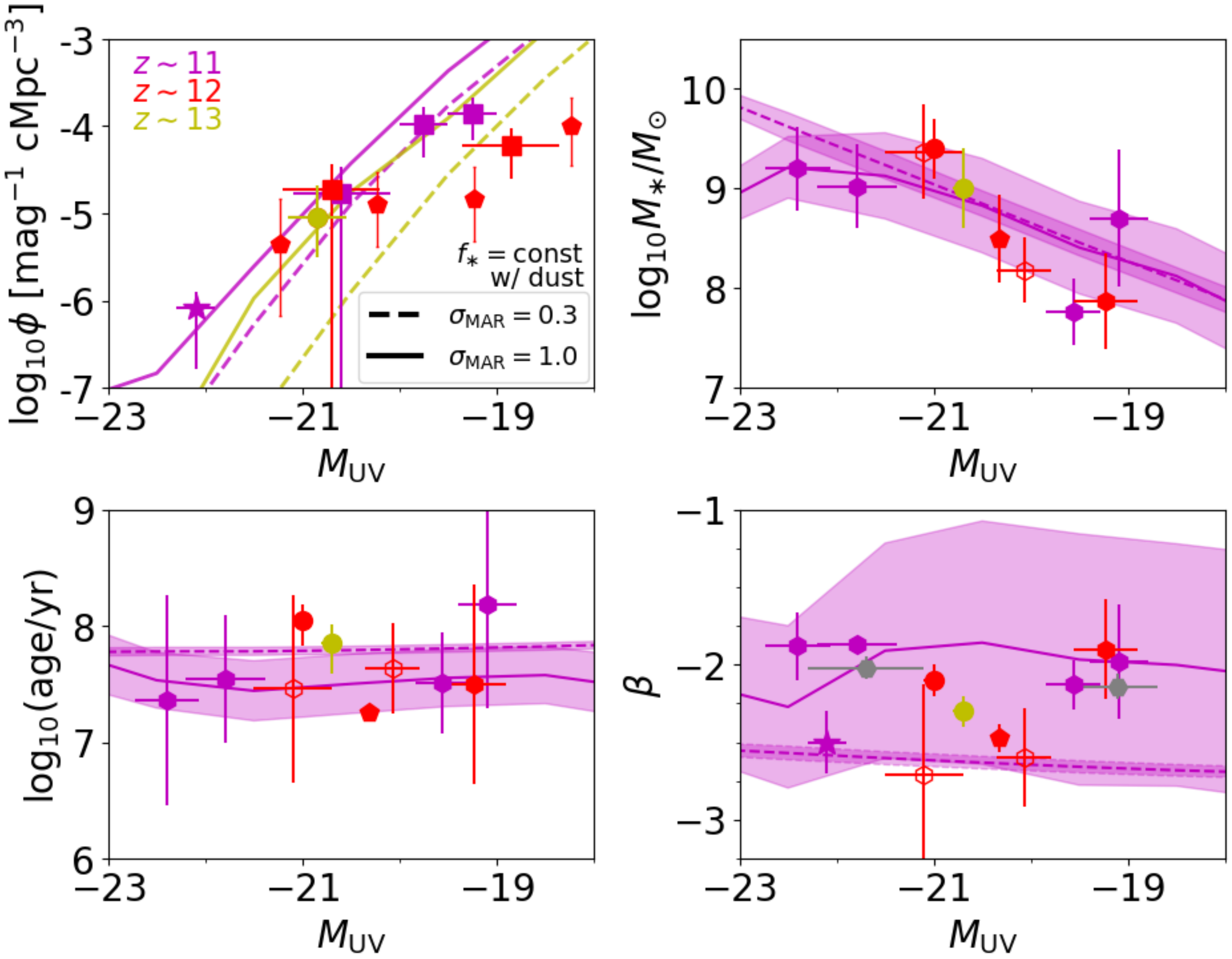


Many moving parts here:

- Scatter 'props up' bright-end.
  - see also Mason+
- Flat f_* slows UVLF evolution.
  - see also Inayoshi+
- Without dust, UV too blue!
  - Still need some dust?
  - Or, *very* rapid disappearance of dust (see Ferrara+) *and,* e.g., strong nebular continuum (e.g., Endlsey+, Topping+)? More complex SFHs (e.g., Kelson+, Tacchella+)?

JM & Furlanetto (arXiv:2208.12826)

Need flat f_*, high scatter, *and* dust



Many moving parts here:

- Scatter 'props up' bright-end.
- Flat f_* slows UVLF evolution.
- Without dust UV too blue!

- Adding dust:
  - Reddens colors
  - Requires boost in f_*, drives ages and masses up too.

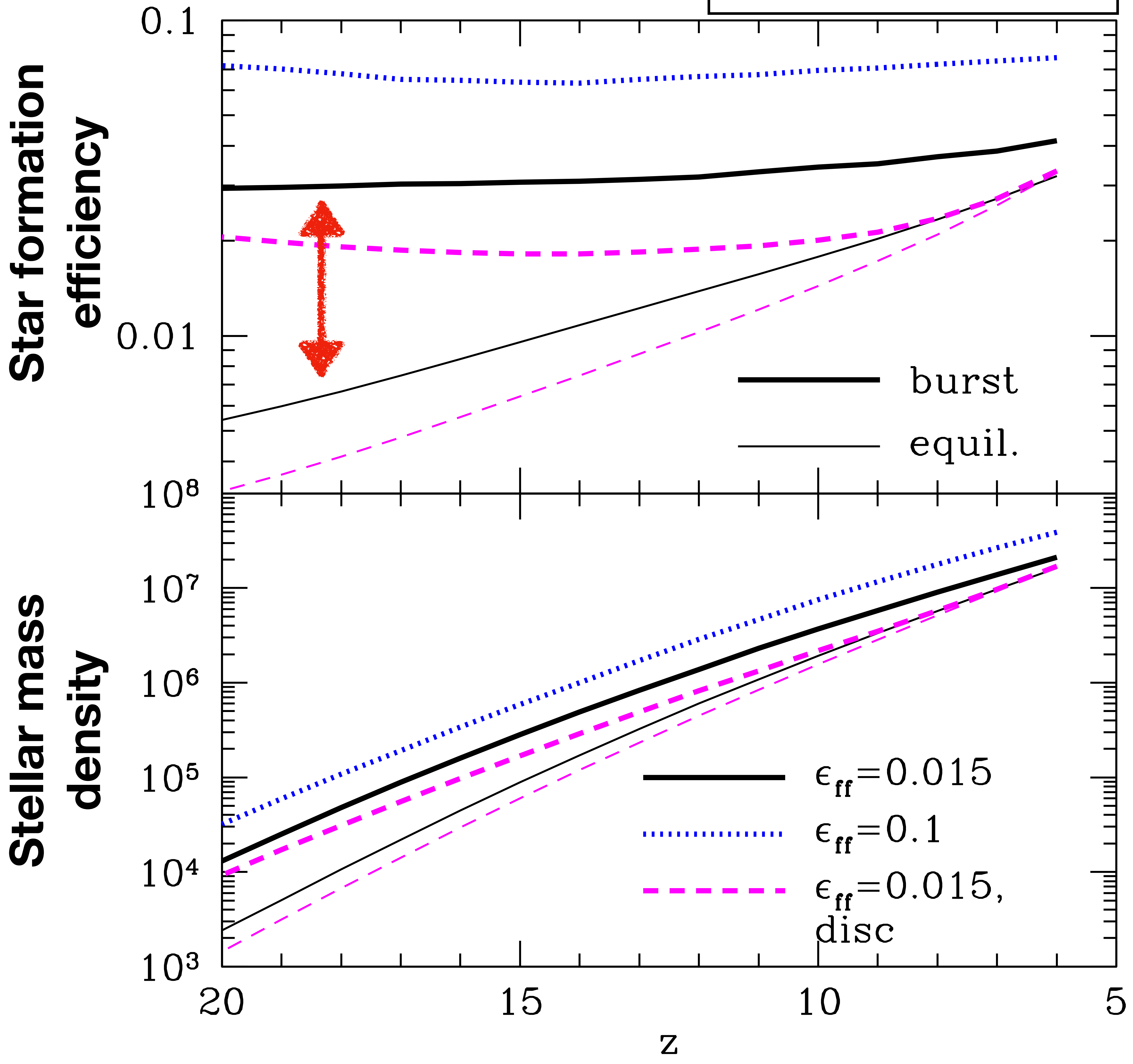
JM & Furlanetto (arXiv:2208.12826)

Constant f_* and scatter: package deal?

- General interpretation of steep decline in f_* at low M_h is that feedback is strong in low-mass galaxies (shallow potentials).
- Only works if feedback injected quickly relative to halo growth timescale.
- At high-z, $t_{SN} \sim t_{dyn}$, could result in failure of feedback, overshoot in SFR in ~2-3x bursts.
- Does not help with the many very bright galaxies detected with JWST 'out of the box,' which suggest ~1 dex scatter in SFR(M_h). This model naturally yields ~2-3x, more to think about.

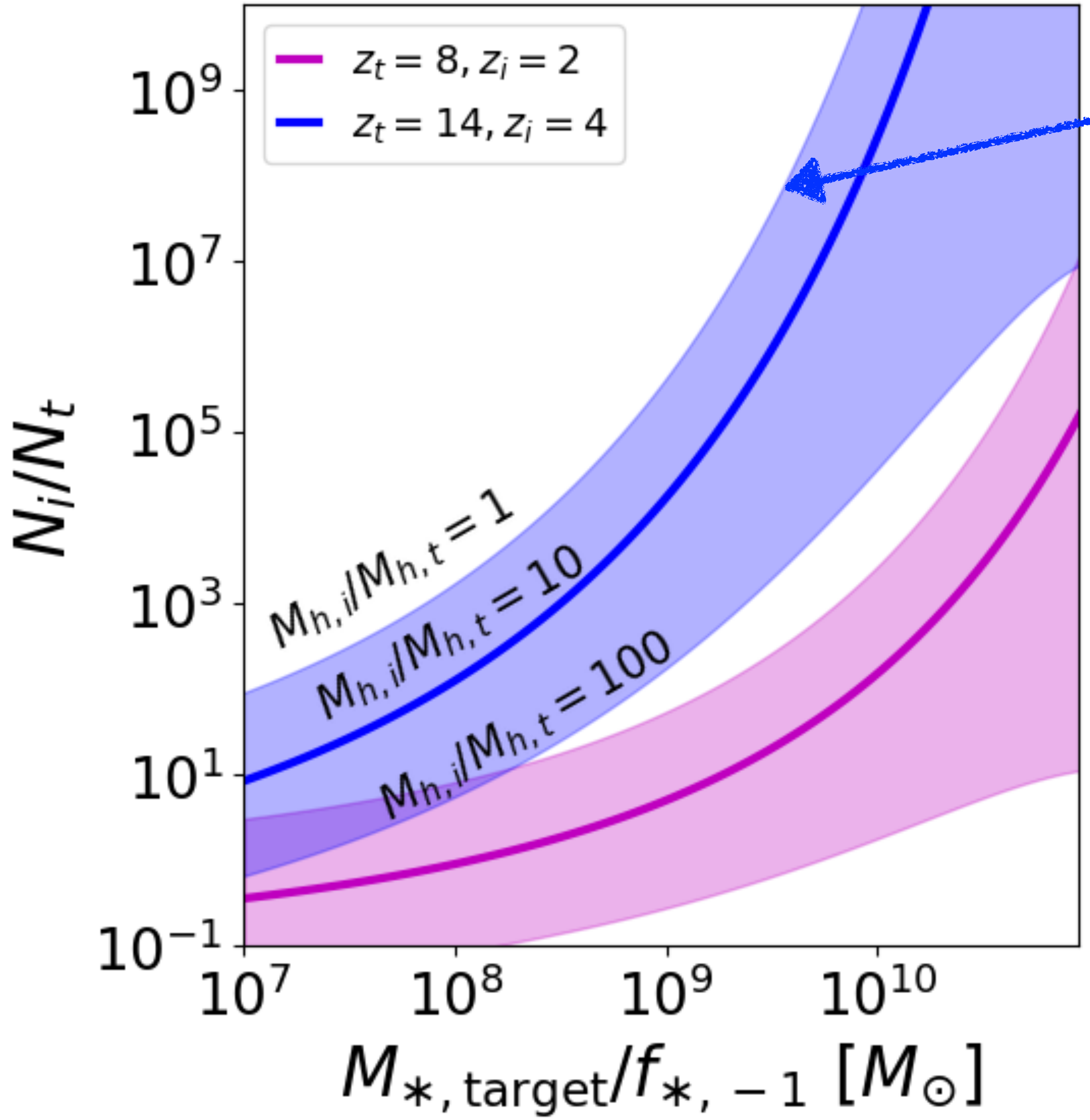
see also, e.g., Faucher-Giguère (2018), Orr+ (2019).

Furlanetto & **JM** 2021

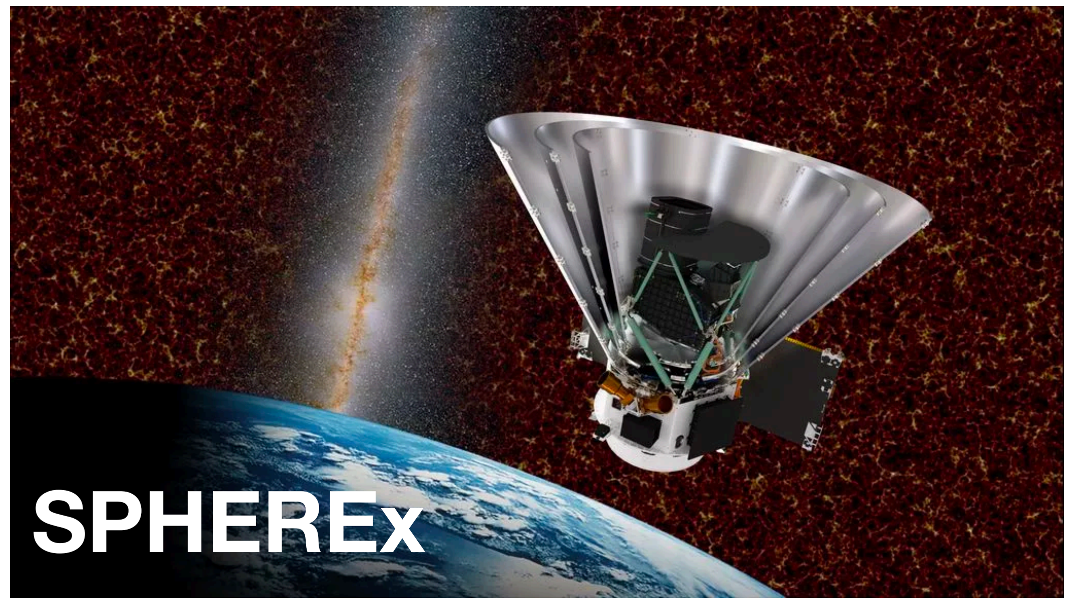


Interlopers?

Furlanetto & **JM** (arXiv:2208.12828)



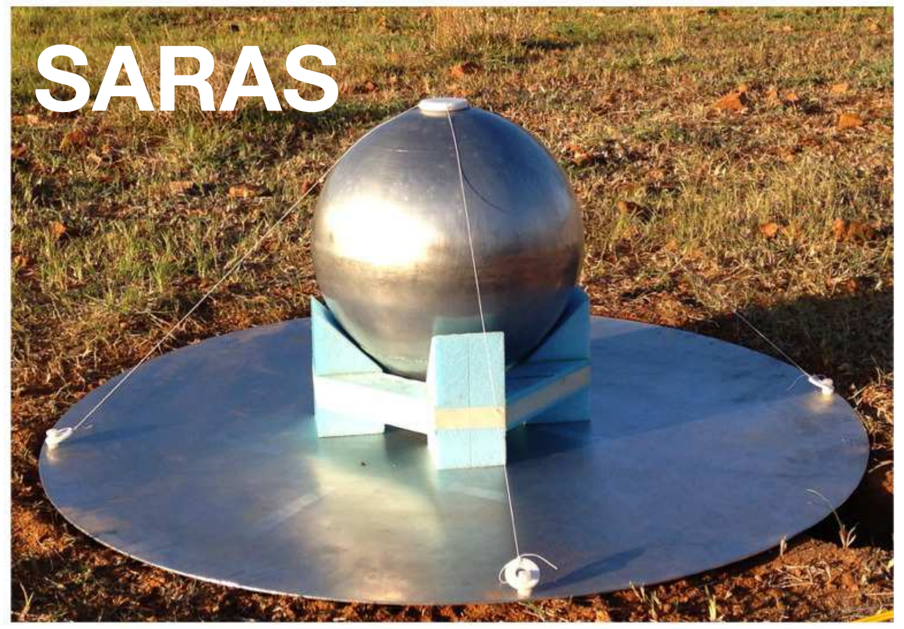
- For M_{UV} ~ -22, ~Gyr ages of interlopers, $M_{h,i}/M_{h,t}$ ~ 1 (see Fig. 2 in paper).
  - Interlopers / targets evolves *very* rapidly at $z \gtrsim 10$ for massive halos.
- This is, of course, a known challenge (see, e.g., Zavala+, Rodighiero+, Glazebrook+, McKinney+).
- Key point here: how well do we understand the prior volume in SED fitting? Prior on individual objects (very reasonably uninformative), wrong for whole population.
- Fujimoto+ (today; 2301.09482), ~90% confirmation rate at z~9 (CEERS).

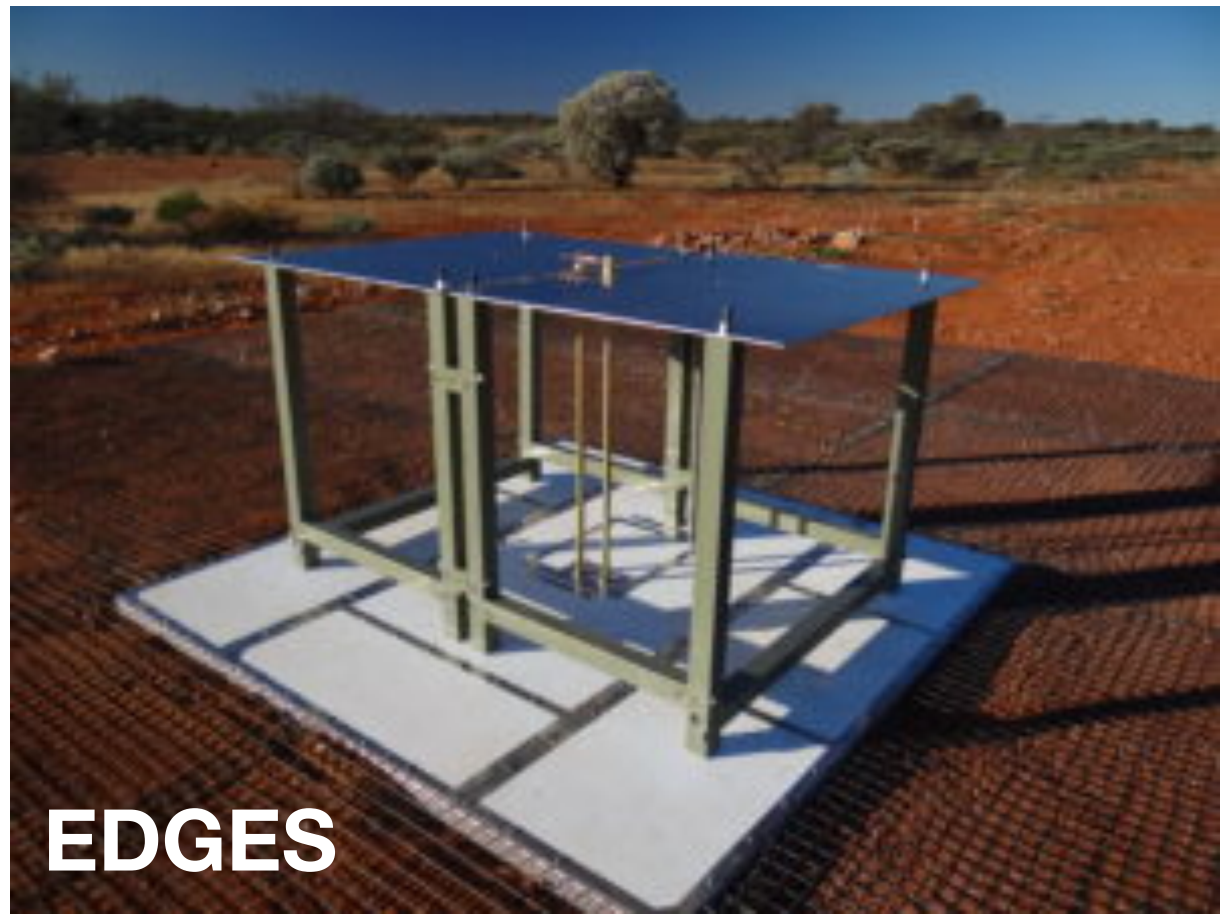


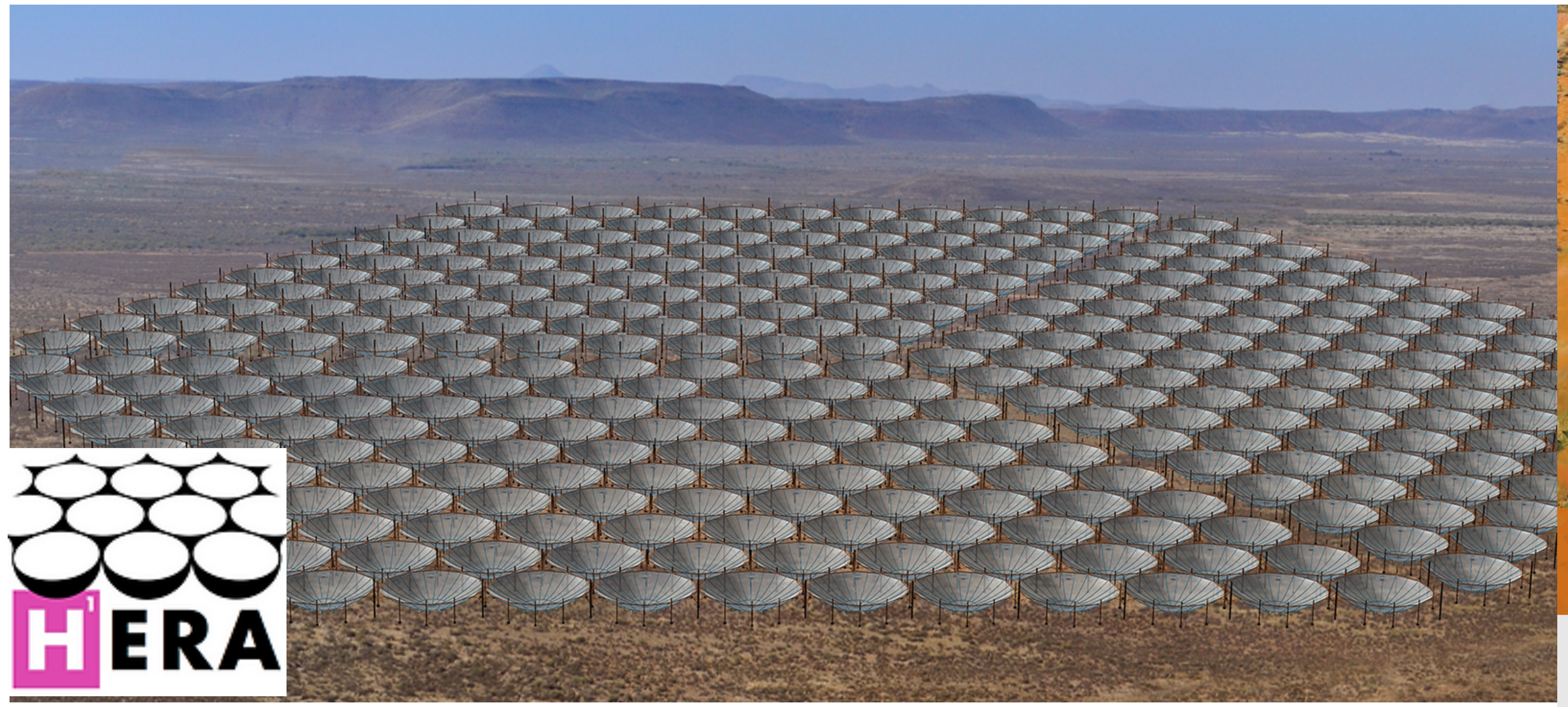
VERA C. RUBIN OBSERVATORY

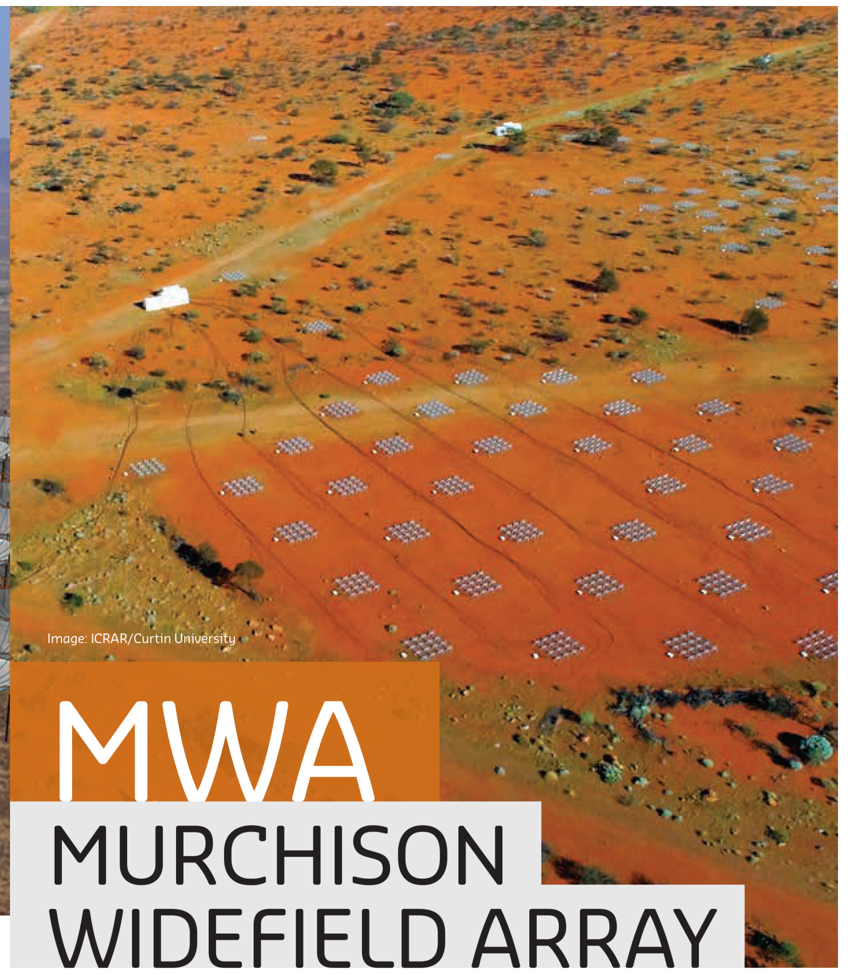
esa euclid

Part III. 21-cm, EBL, cross-correlation opportunities









RESEARCH, SCIENCE & ENVIRONMENT, TECHNOLOGY & ENGINEERING

Were galaxies much different in the early universe?

By Robert Sanders, Media relations | JANUARY 24, 2023

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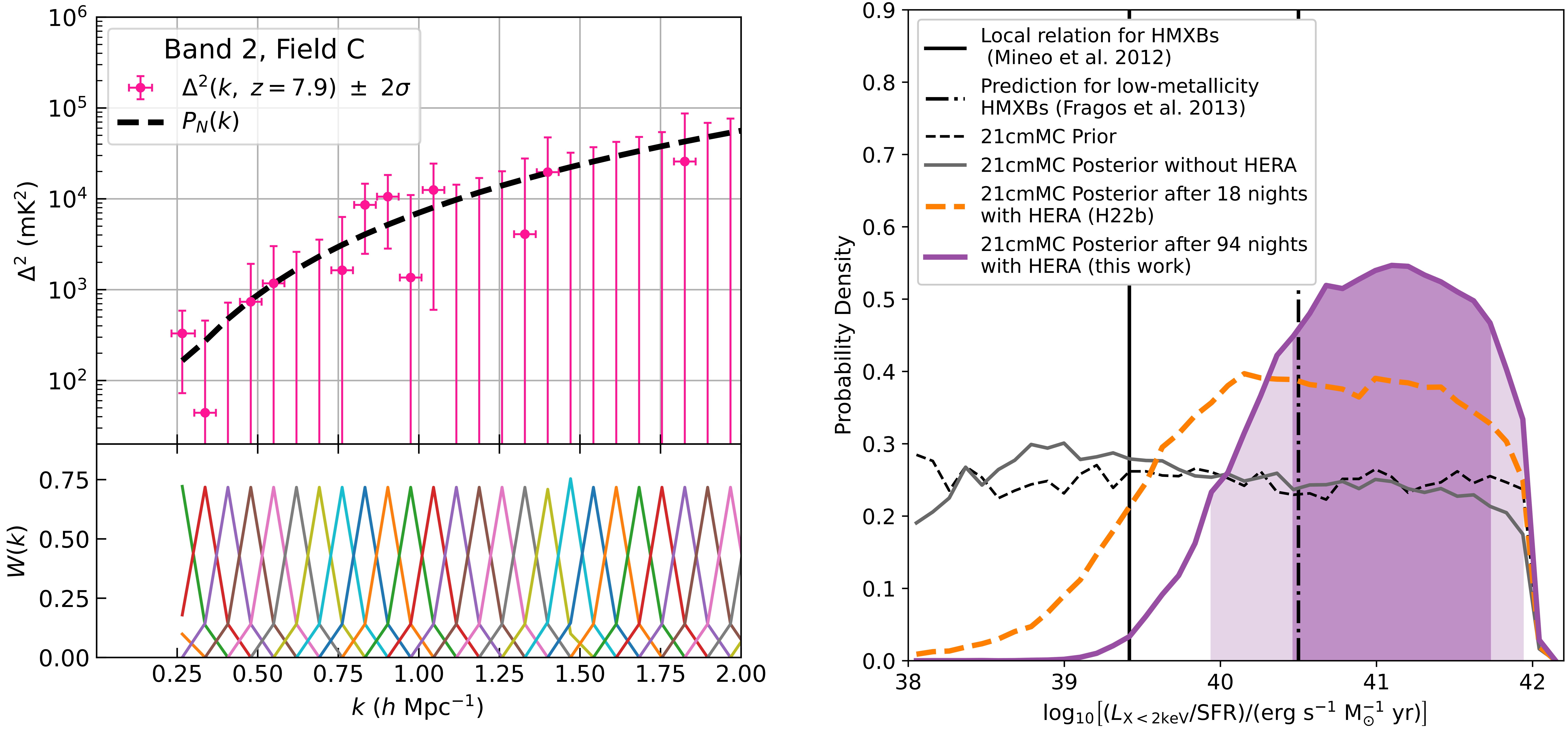
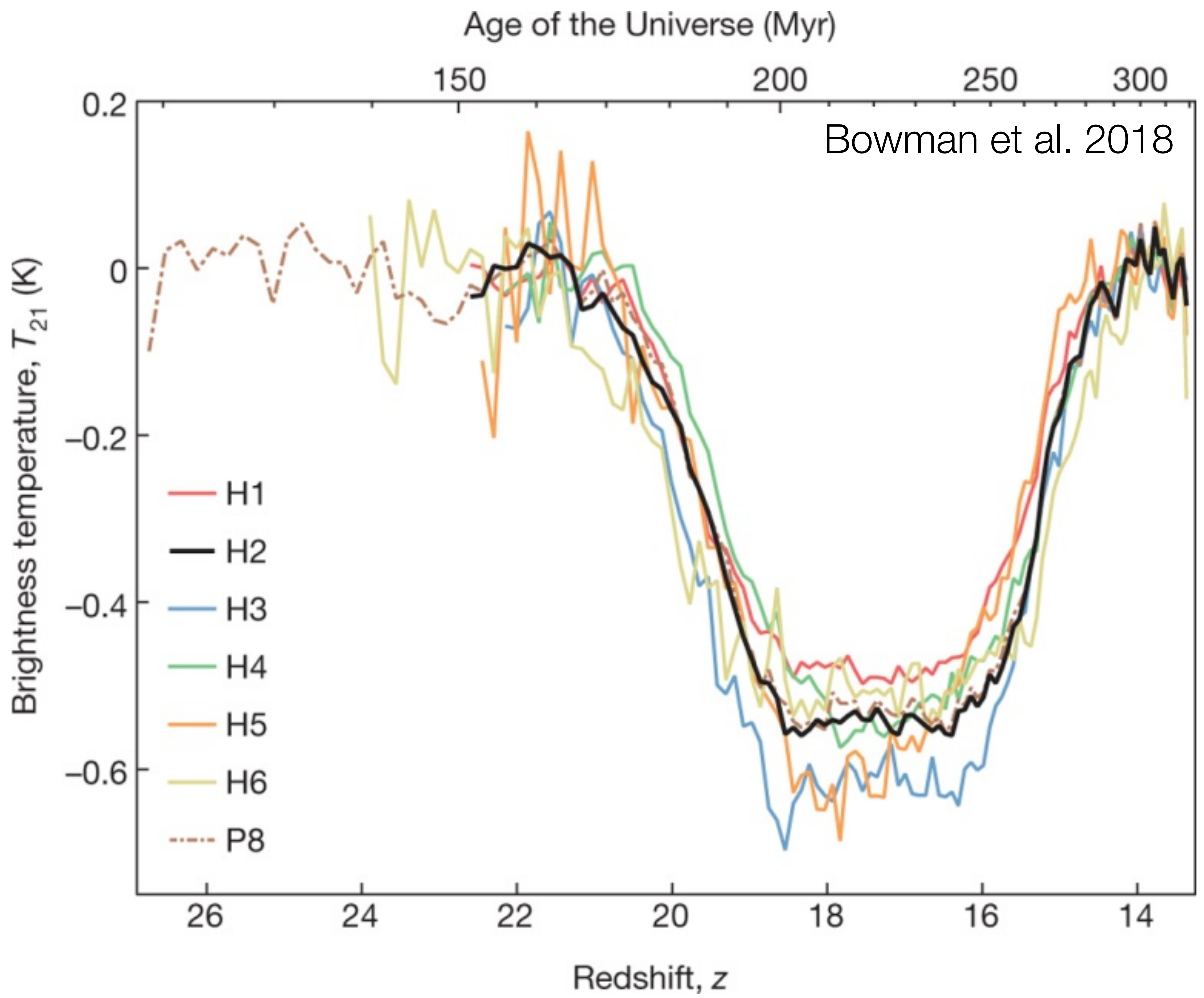
The HERA radio telescope consists of 350 dishes pointed upward to detect 21-centimeter emissions from the early universe. It is located in a radio-quiet region of the arid Karoo in South Africa. (Photo credit: Dara Storer, 2022)

Constraints on L_X/SFR from HERA

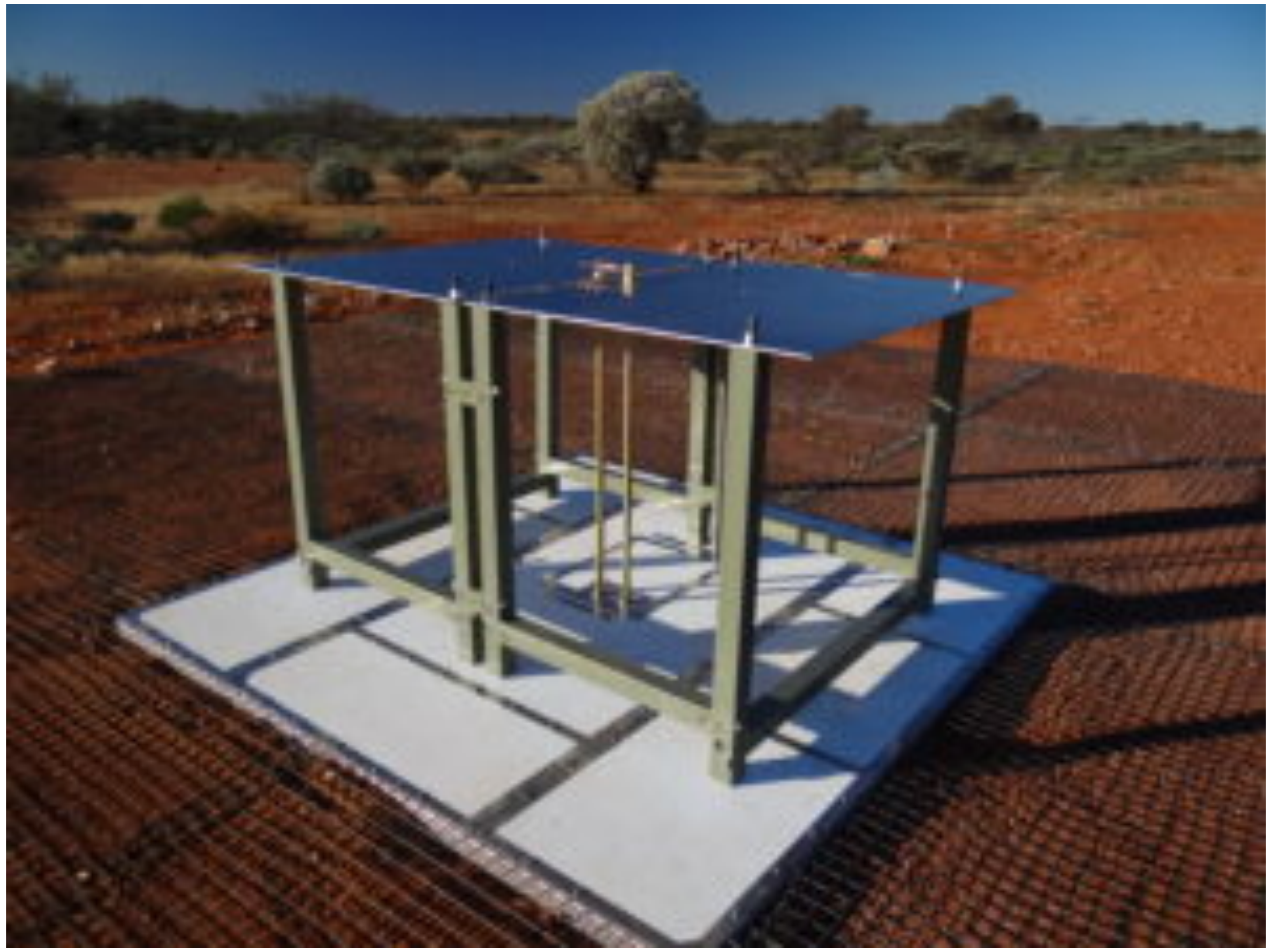


HERA Collaboration et al. (2022a, 2023)

Implications of EDGES for early galaxies

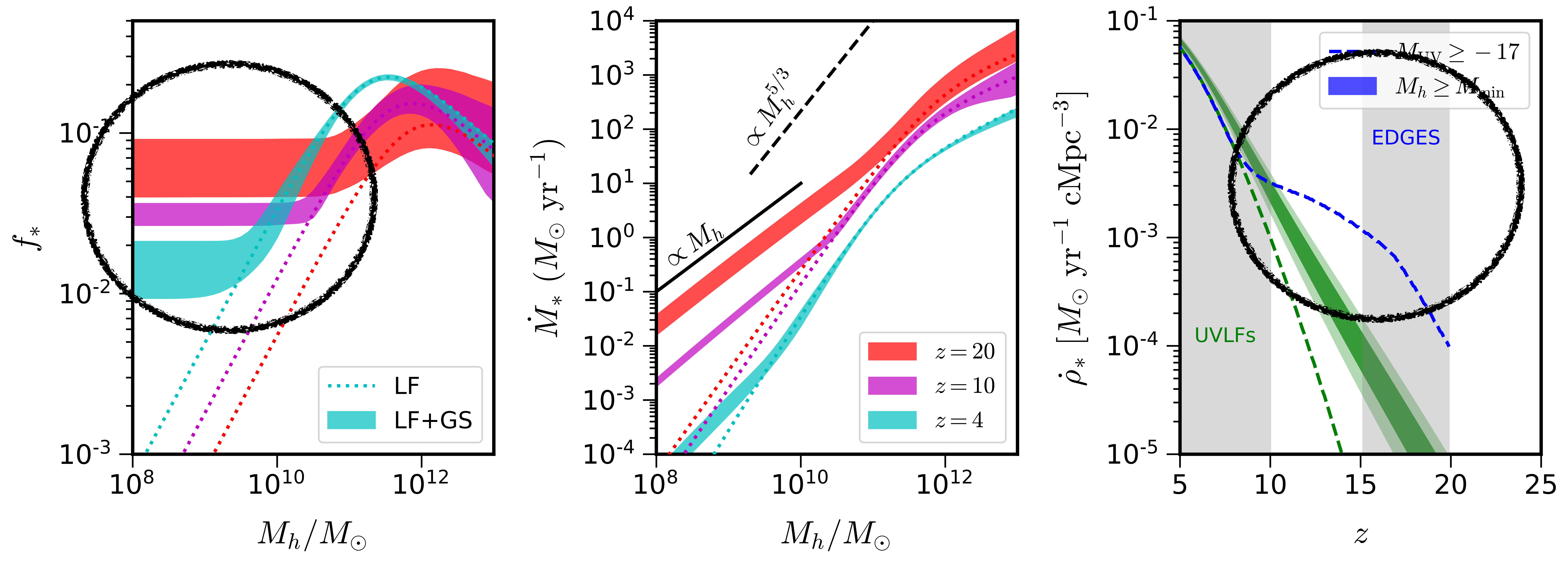


Observing site:
Murchison Radio Observatory (W. Australia)



See also, e.g., Bowman & Rogers (2010), Mozdzen et al. (2016), Monsalve et al. (2017)

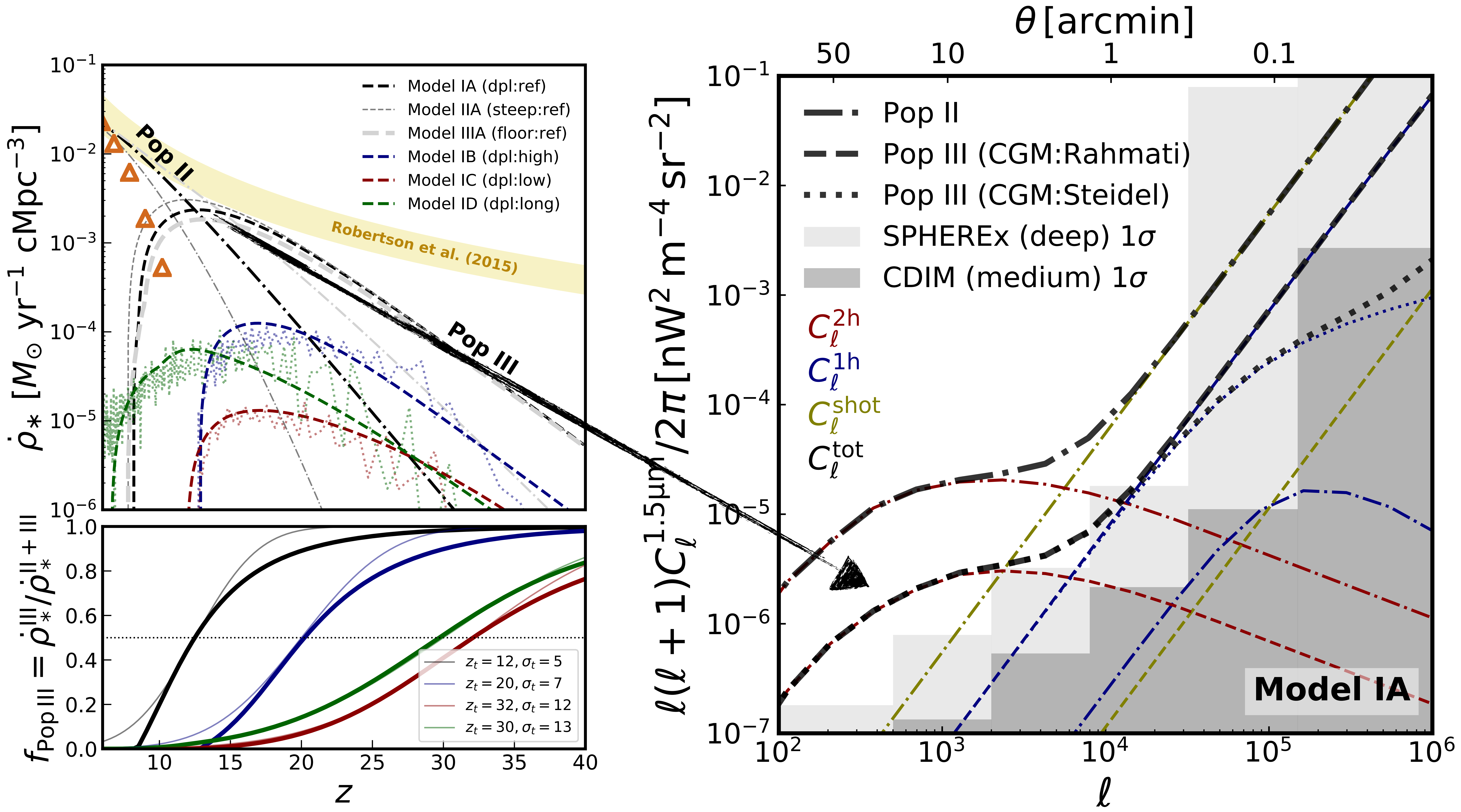
EDGES needs a lot of star formation relative to HST/UVLF-based predictions



JM & Furlanetto (2019)

Flattened SFE here phenomenological, allowed to vary in fit.

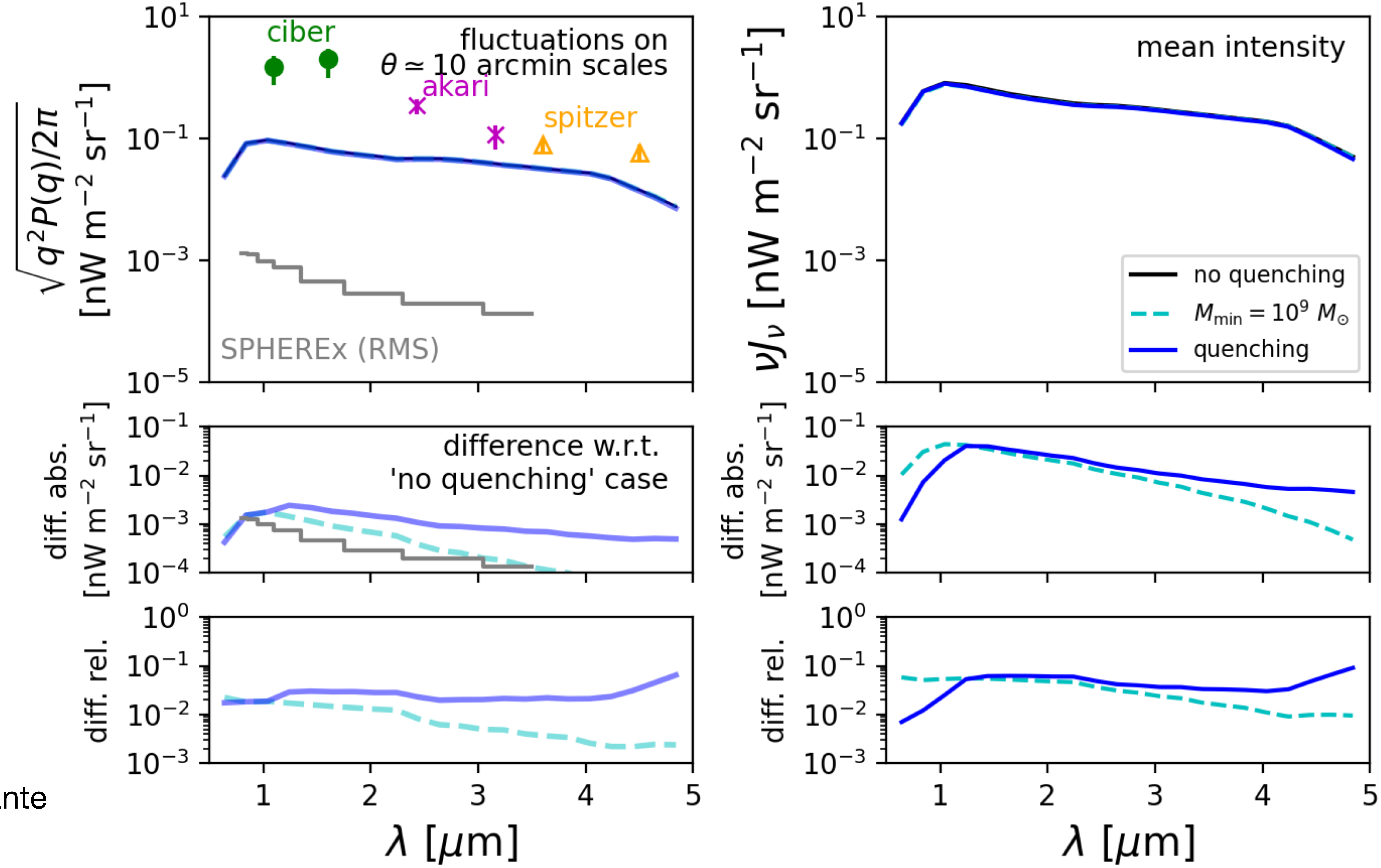
PopIII via near-infrared fluctuations?



Extreme PopIII star formation models in principle detectable with SPHEREx!

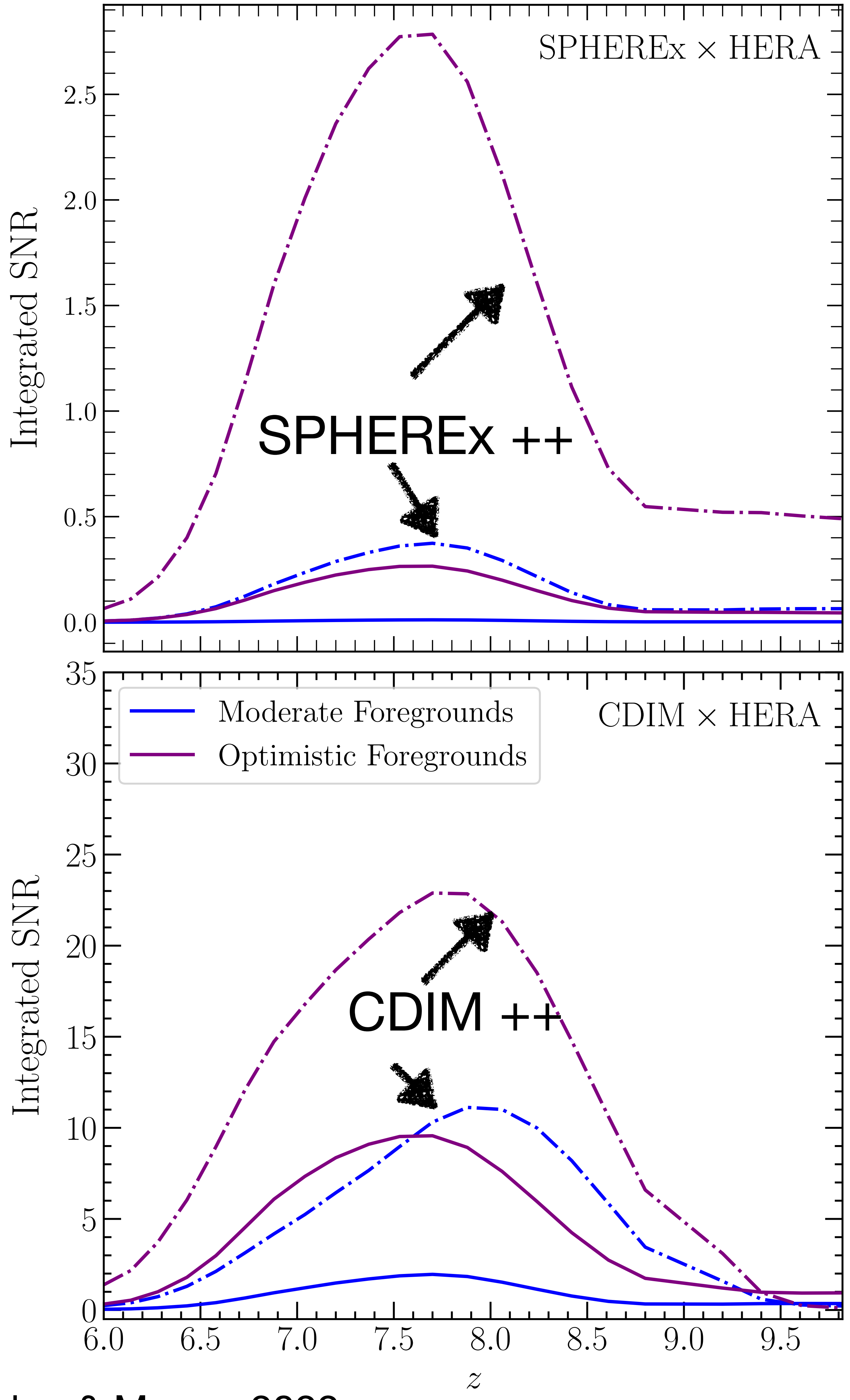
Sun, **JM**+ (2021)

Turn-over in galaxy luminosity function via NIRB?



JM, Liu, & La Plante (2205.14168)

HERA x SPHEREx?



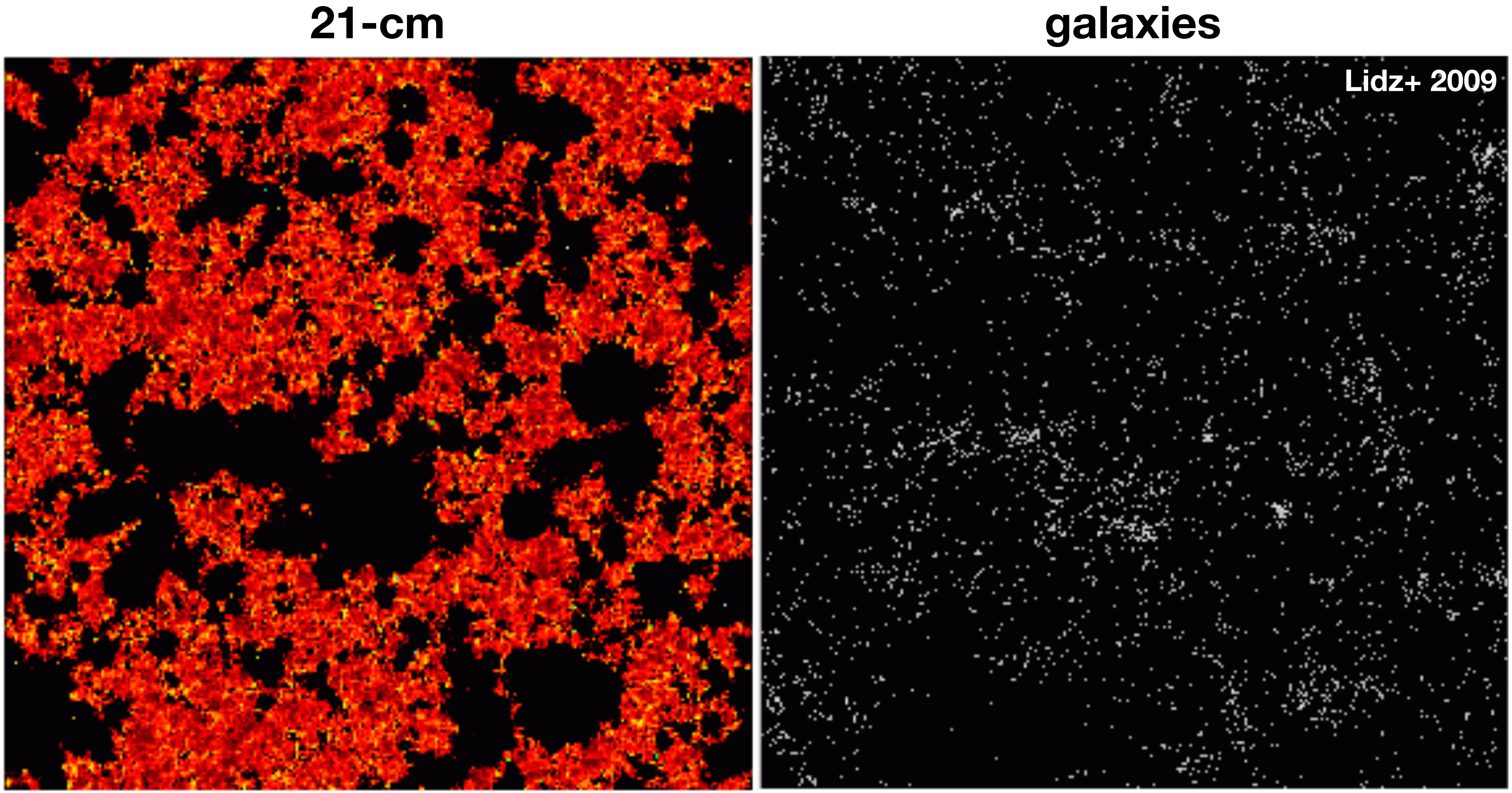
Cox, Jacobs, & Murray 2022

Outlook for HERA x SPHEREx Ly-a not great, but HERA x CDIM more promising (Cox+ ’22; left).

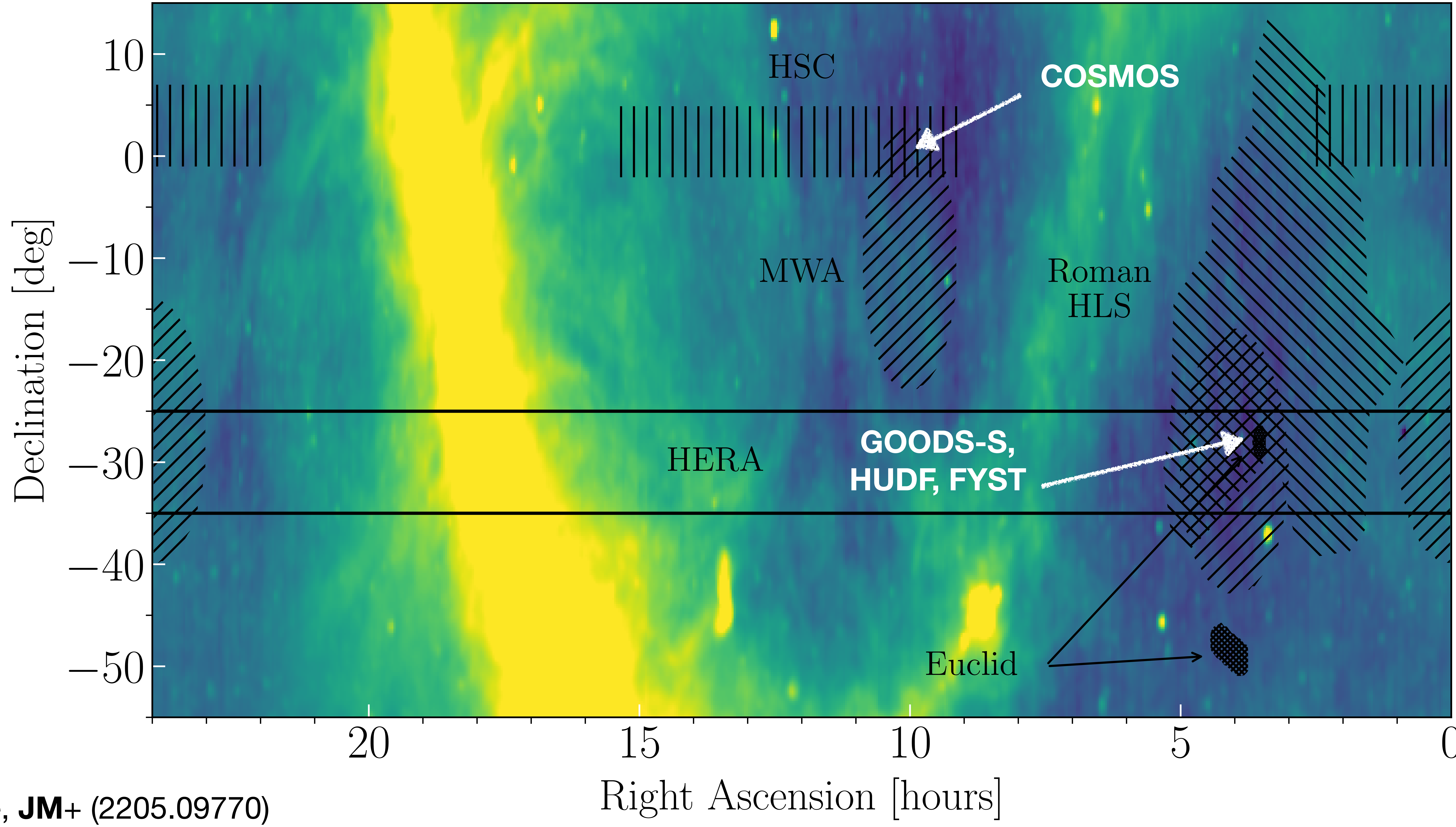
HERA cannot leverage SPHEREx deep fields at poles…maybe LoFAR would have better luck?

SKA x CDIM very promising (see Feng+ 2017, Heneka & Cooray ’21)

21-cm x galaxies



21-cm & wide-field surveys



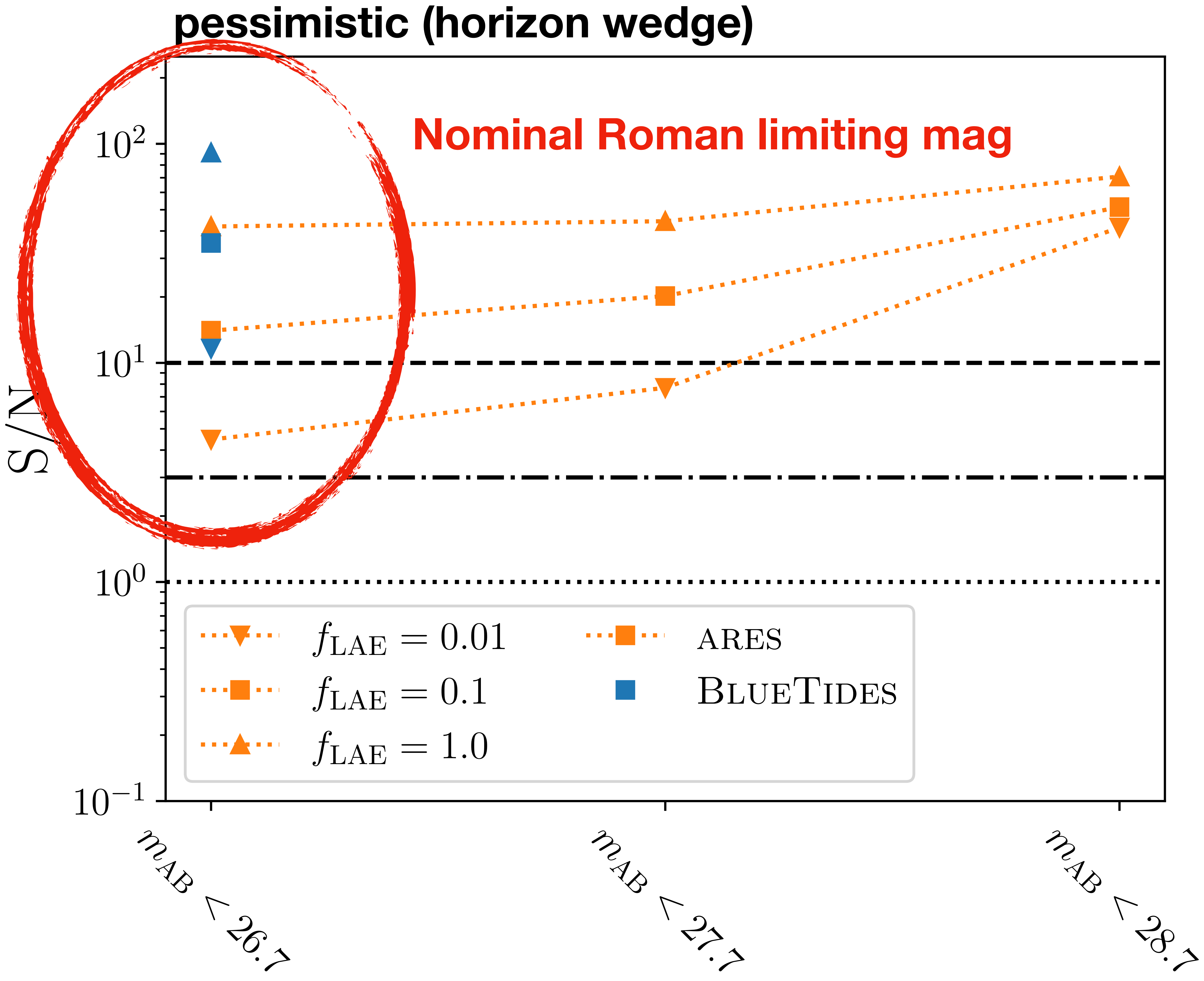
LoFAR, GMRT

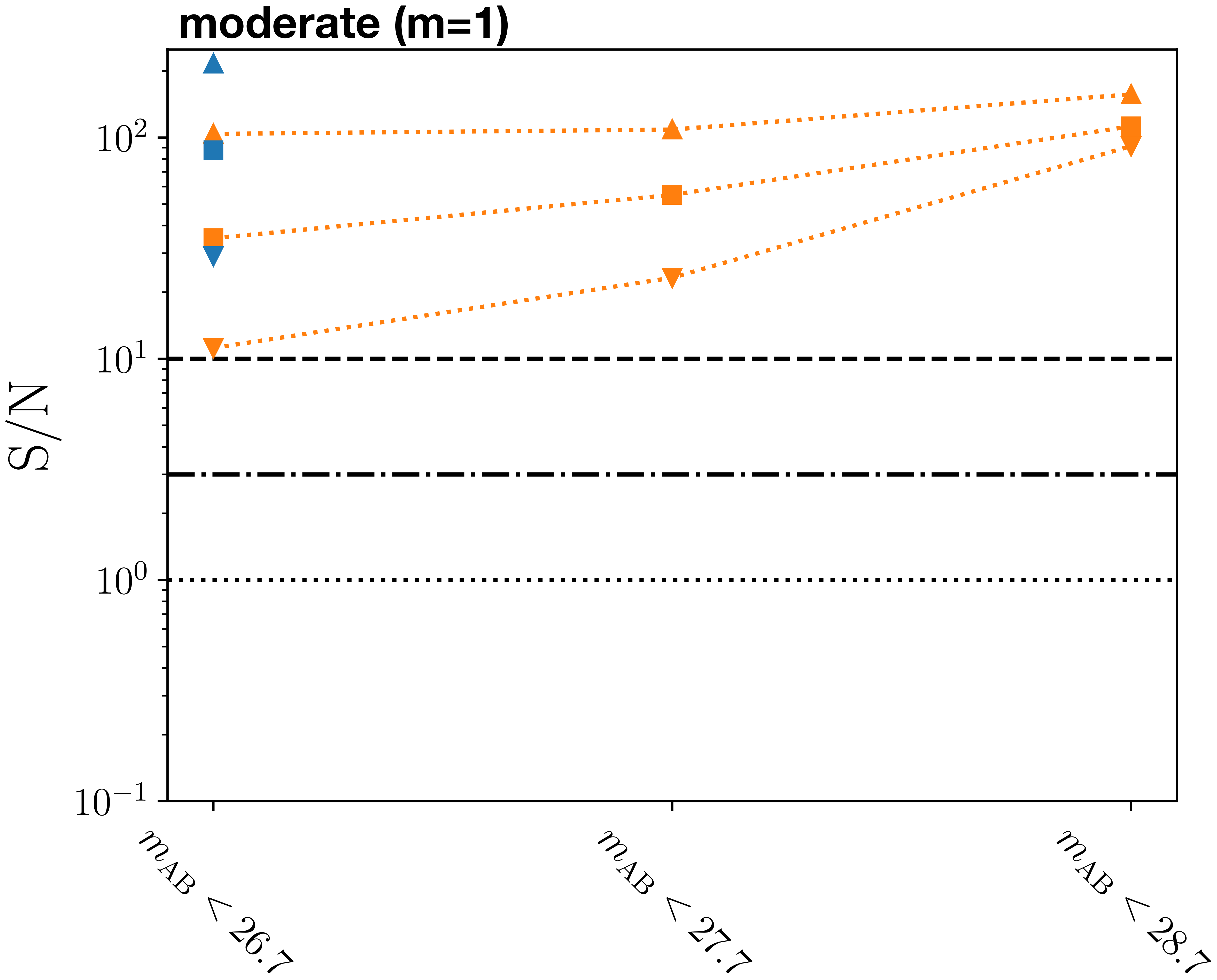
HERA+HLS: ~500 deg²

Euclid deep fields are comparable to HLS depth

La Plante, **JM**+ (2205.09770)

HERA x Roman Forecast





La Plante, **JM**+ (2205.09770)

Summary

- Overabundance of $z \gtrsim 10$ JWST galaxies: not a single quick fix for models.
  - Unlikely to be due to shot noise or cosmic variance.
  - M_h-independent f_* does help to slow evolution in UVLF.
  - Still need ~1 dex of scatter in SFR(M_h) to 'prop up' bright end of UVLF.
    - M_h-independent f_* and scatter sign of bursts (e.g., Furlanetto & **JM** 2021)?

- Dust-free model still under-produces UVLF if anchored to $z \lesssim 8$
  - Need dust to get UV colors right! Helps with ages and masses indirectly.
  - Less dust needed than at $z \lesssim 8$, but non-negligible (though complex SFHs or strong nebular continuum might work too; see, e.g., Kelson+, Tacchella+, Topping+, Endsley+)