Reionization Overview: Latest predictions, constraints, & prospects

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image credit: Norman, Xu, O’Shea, & Wise

Outline for Today

CMB ~ 100 Myr ~ 1 Gyr Today

1. Backdrop: standard practice in EoR modelling and measurements (last ~10 years)
2. New ideas: latest modelling results and new constraints (last ~2 years). What's changed?
3. Looking forward: near-future prospects for improved constraints (next ~5 years). What can we expect?

Loeb 2006, Scientific American

Outline for Today

CMB ~ 100 Myr ~ 1 Gyr Today

Goal: set stage for rest of the session, leave details to speakers!

Recent modelling efforts:

- Talks by S. Mukherjee (kSZ, B modes), X. Wu (CMB & PopIII stars)

New constraints on IGM:

- Talk by by J. Dillon (via 21-cm PS w/ HERA)

Near-future possibilities

- Talks by P. Breysse (LIM), T. Namikawa (y x tau), P. La Plante (CMB x 21-cm)

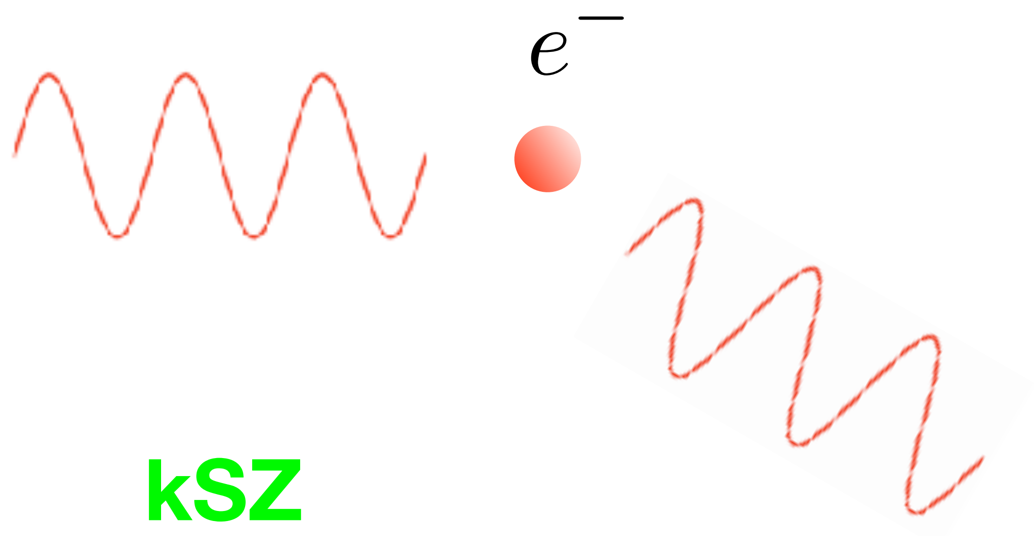
I'll focus largely on progress in galaxy models/obs., which are often used to frame expectations and results.

Loeb 2006, Scientific American

Observational & Theoretical Landscape

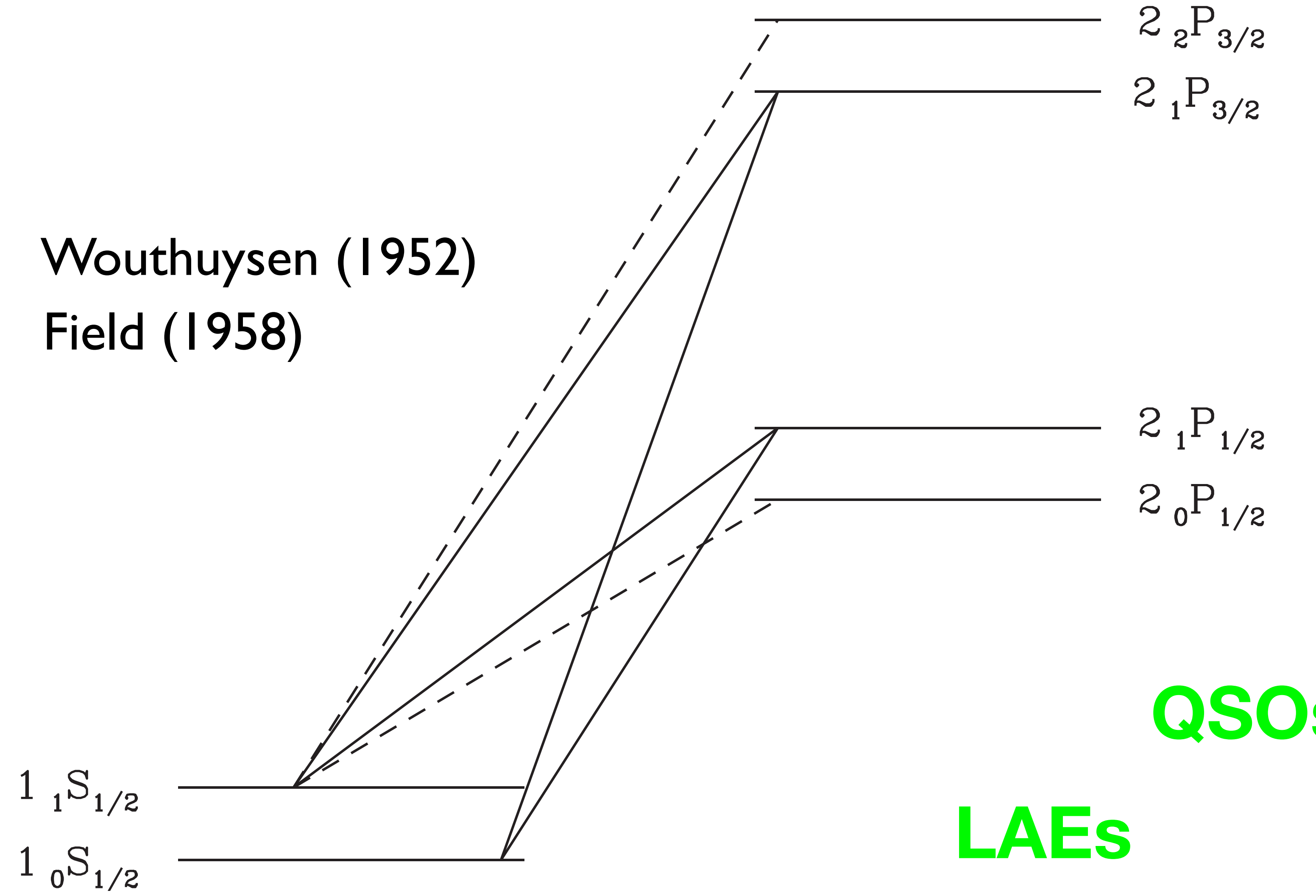
Measuring Reionization

1. Free electrons scatter w/ photons



τ_e **kSZ**

2. Hydrogen atoms emit/absorb Ly-a photons



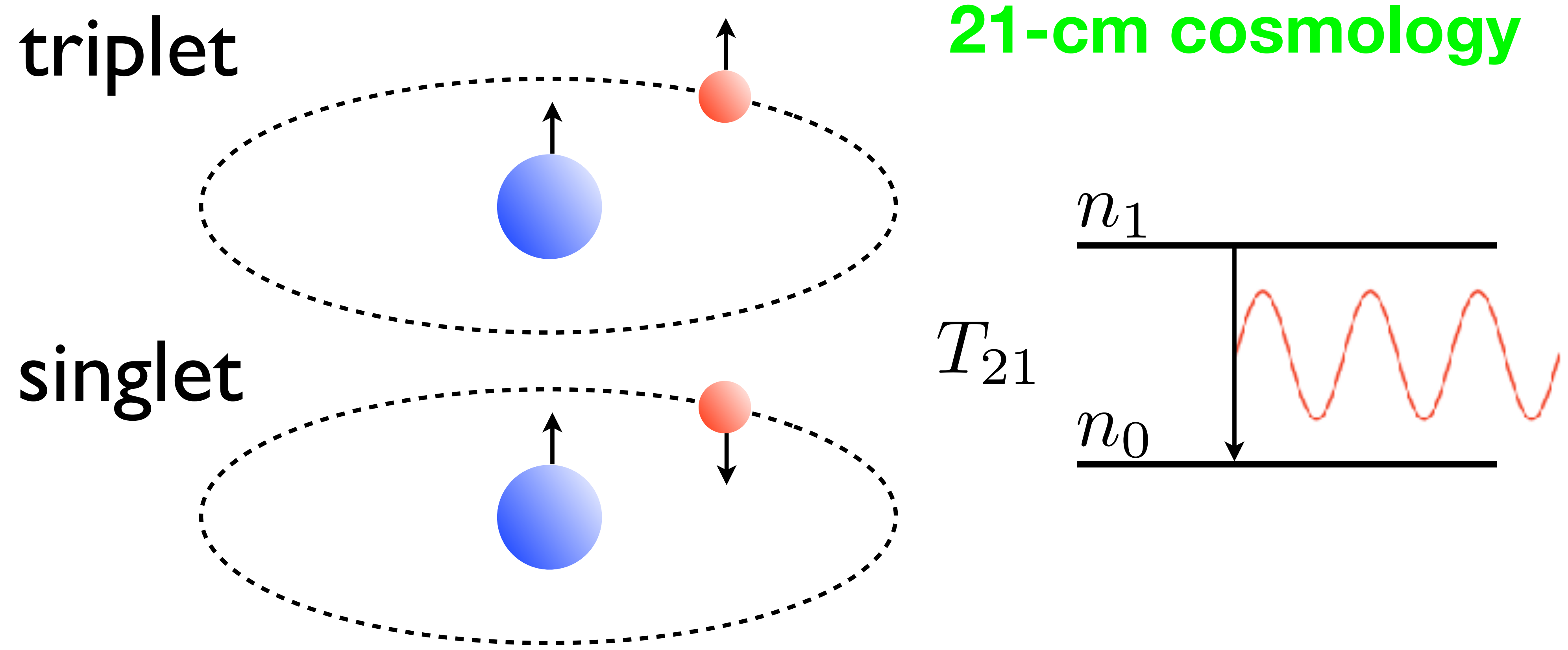
Wouthuysen (1952)
Field (1958)

QSOs

LAEs

3. Hydrogen atoms emits 21-cm photons

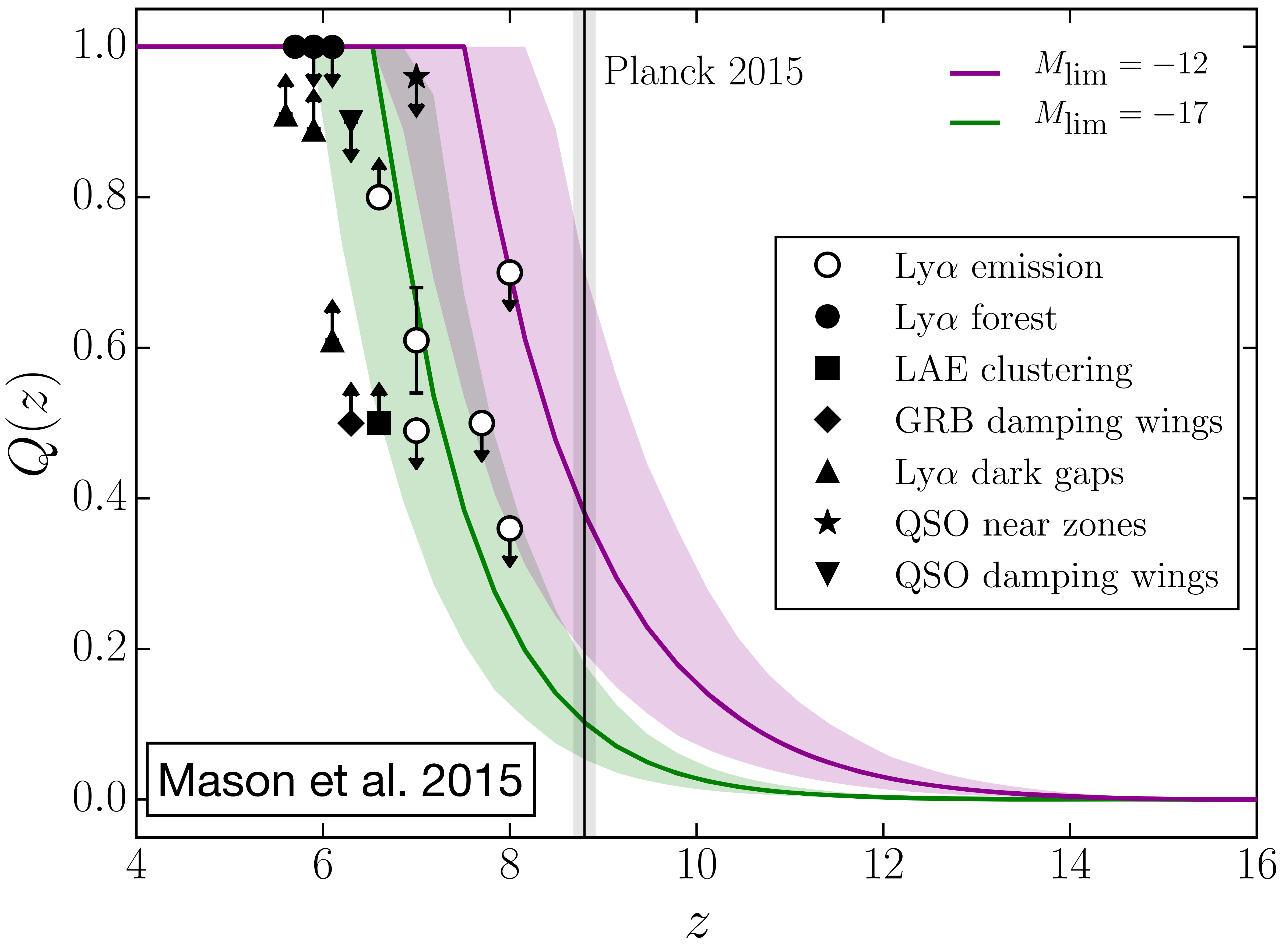
21-cm cosmology



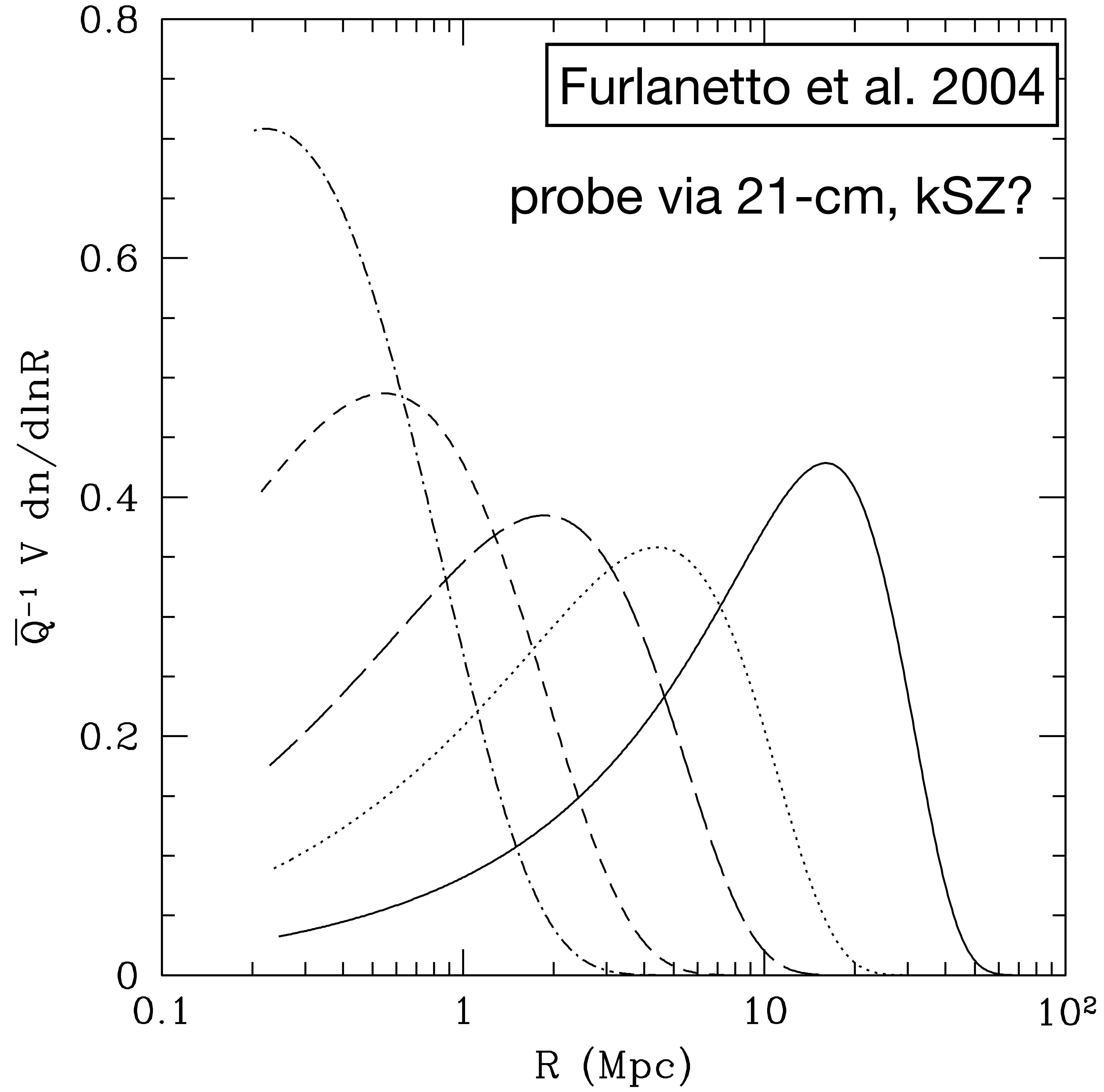
$\lambda = 21$ cm

Measuring Reionization

Mean history
(e.g., xHI(z), tau(z), etc.)



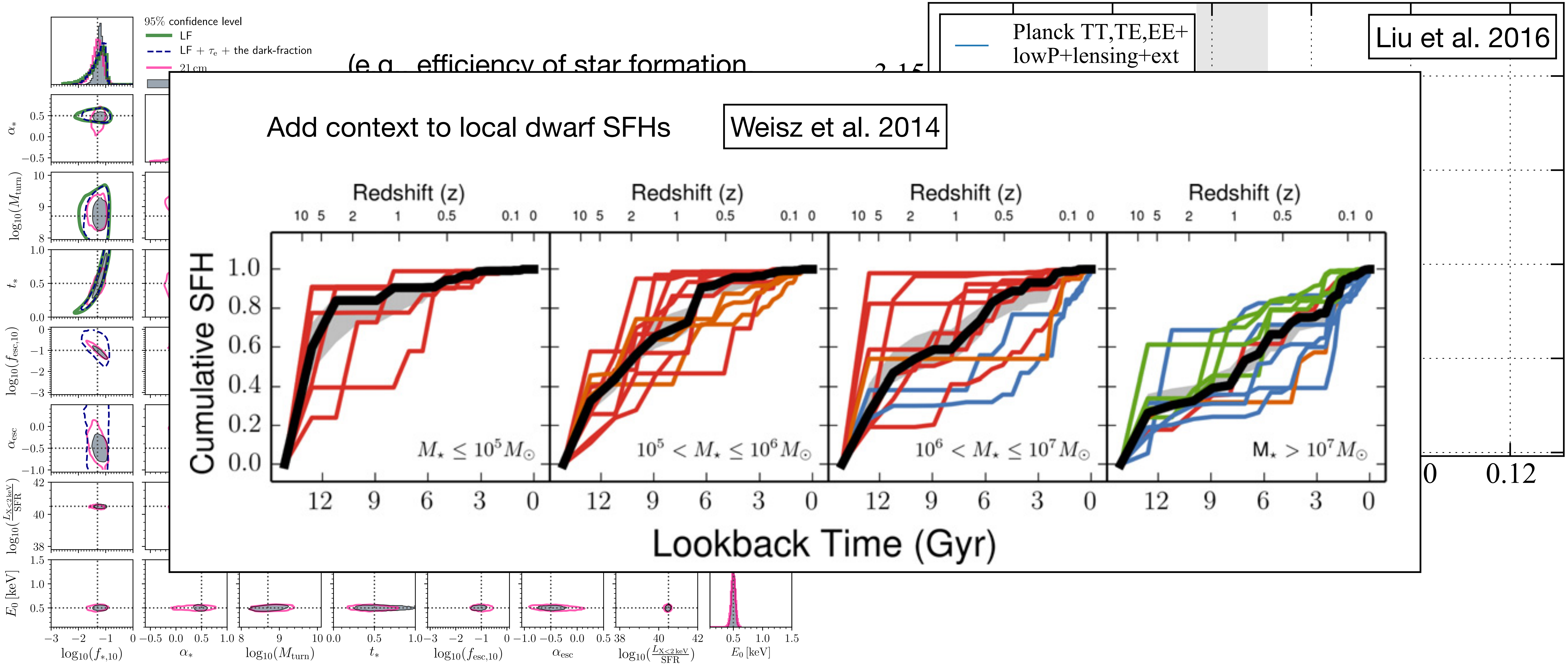
Topology
(e.g., bubble size distribution)



What’s the point?

Constrain properties of high-z galaxies

Improve constraints on cosmology



Modeling the EoR

The problem: counting photons

We often think of reionization in the following, highly-idealized, one-zone model:

$$\dot{Q}_{\rm H\,II} \propto \underbrace{\dot{\rho}_* N_{\rm ion} f_{\rm esc}}_{\rm sources} - \underbrace{\alpha_{\rm H\,II} n_e}_{\rm sinks}$$

Each quantity here is potentially very complicated to model and/or infer:

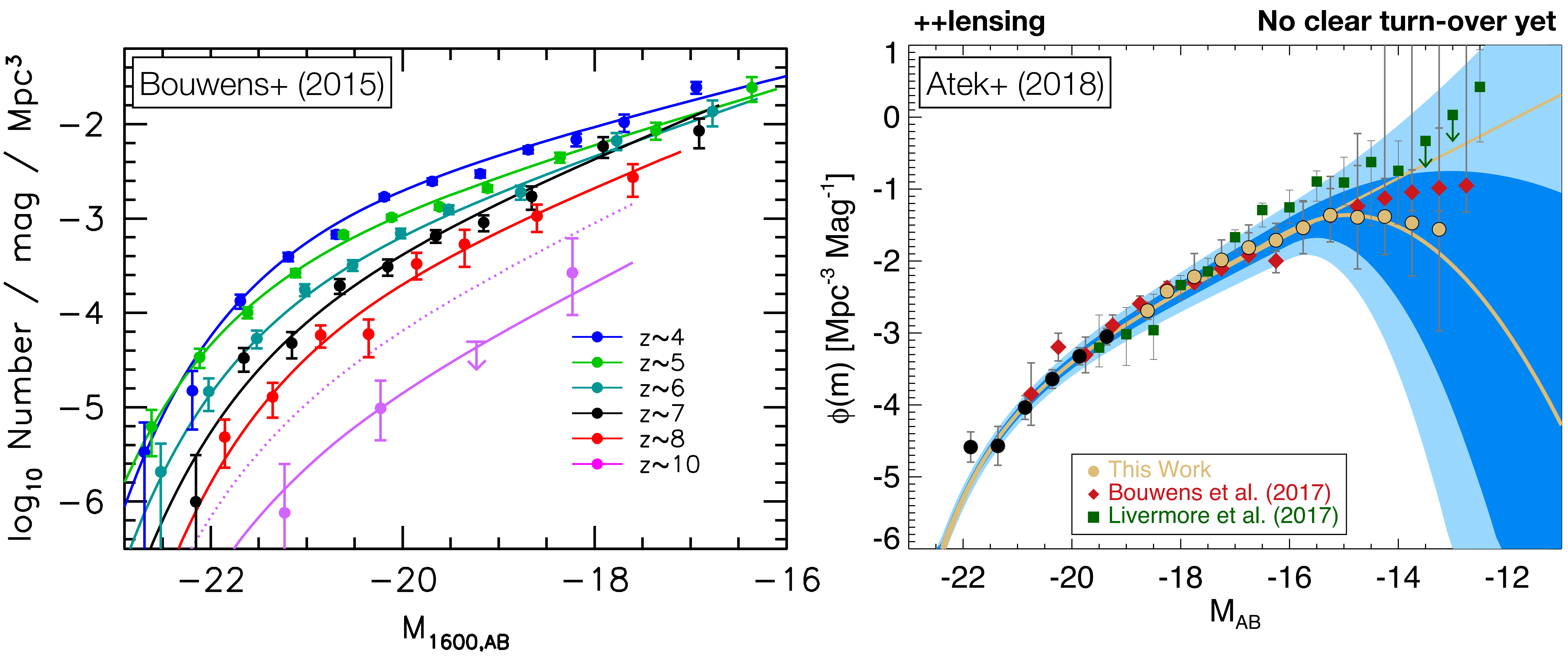
$\dot{\rho}_*$ **star formation rate density:** encodes stellar feedback physics, though averaged over galaxy population

$N_{\rm ion}$ **# of ionizing photons produced per stellar baryon:** encodes stellar atmospheres, IMF, metallicity, binarity

$f_{\rm esc}$ **escape fraction:** encodes topology of interstellar medium, possibly circumgalactic medium

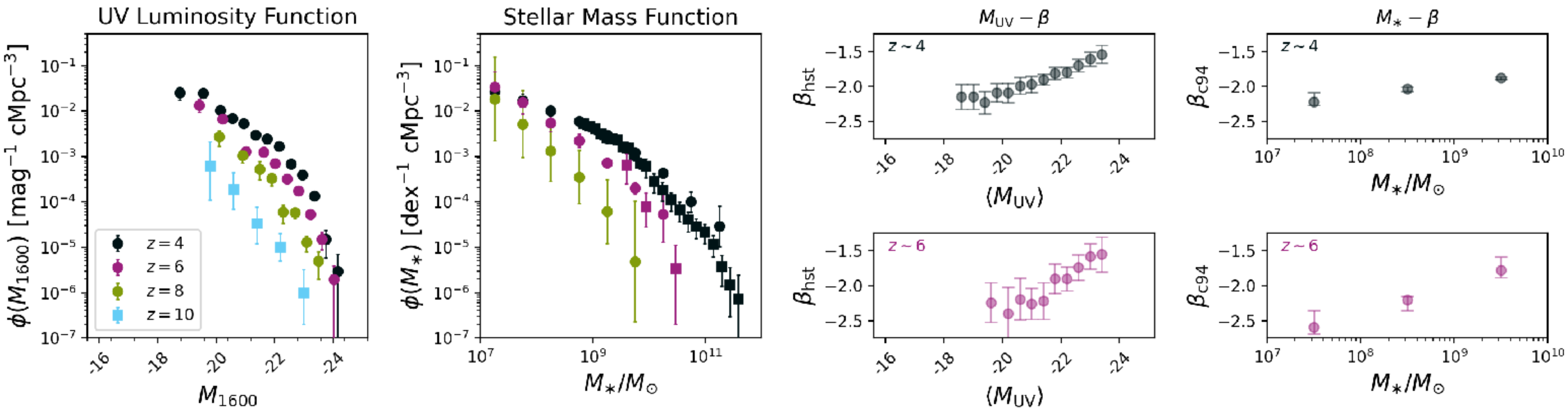
Reionization is “patchy.” Can think about this problem in small patch or entire Universe.

How to infer galaxy SFRs?



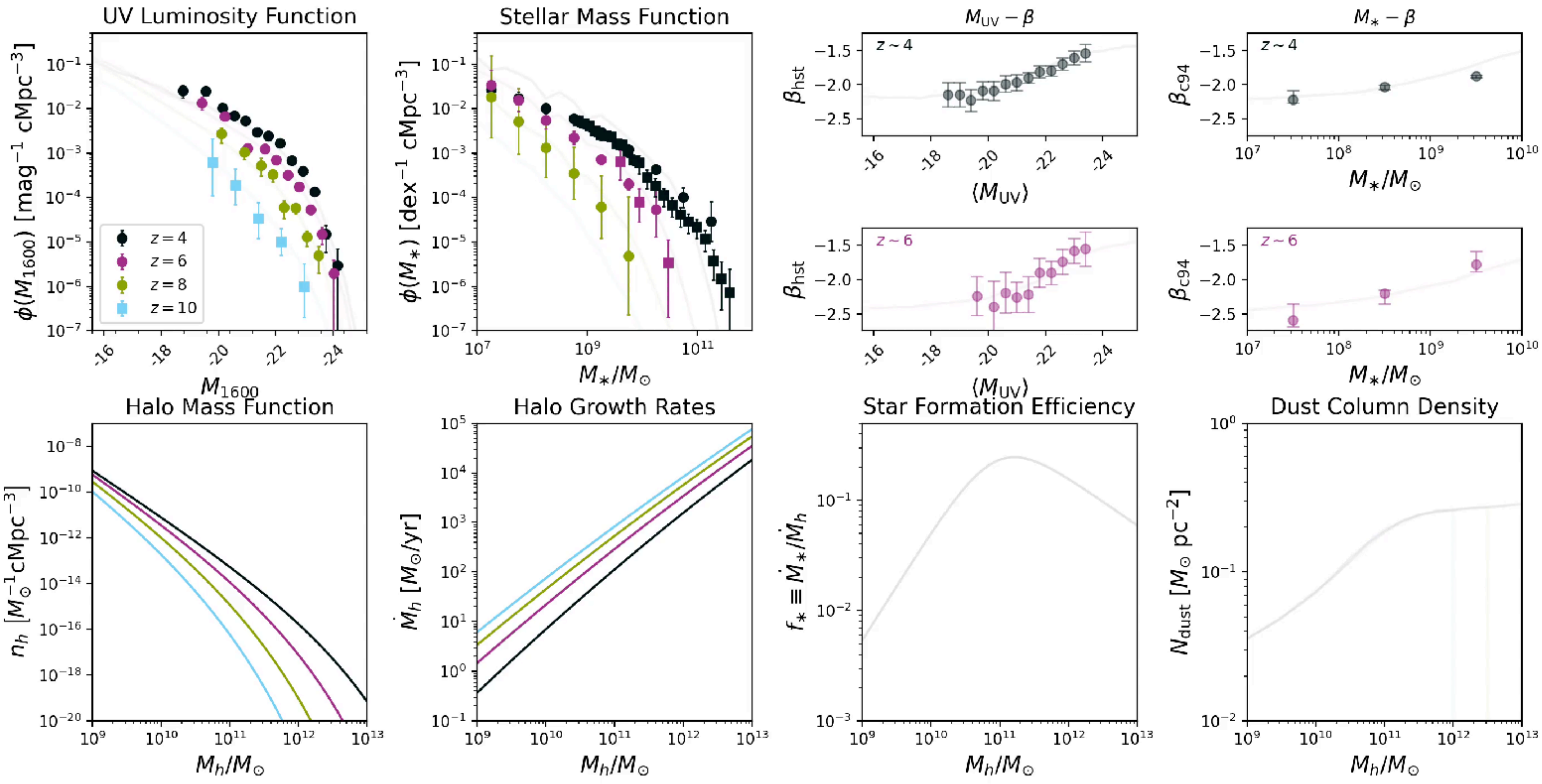
see also, e.g., Finkelstein+ (2016), McLure+ (2013), recent update in Bouwens et al. (2102.07775)

Empirical Models: Basic Procedure



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

Empirical Models: Basic Procedure



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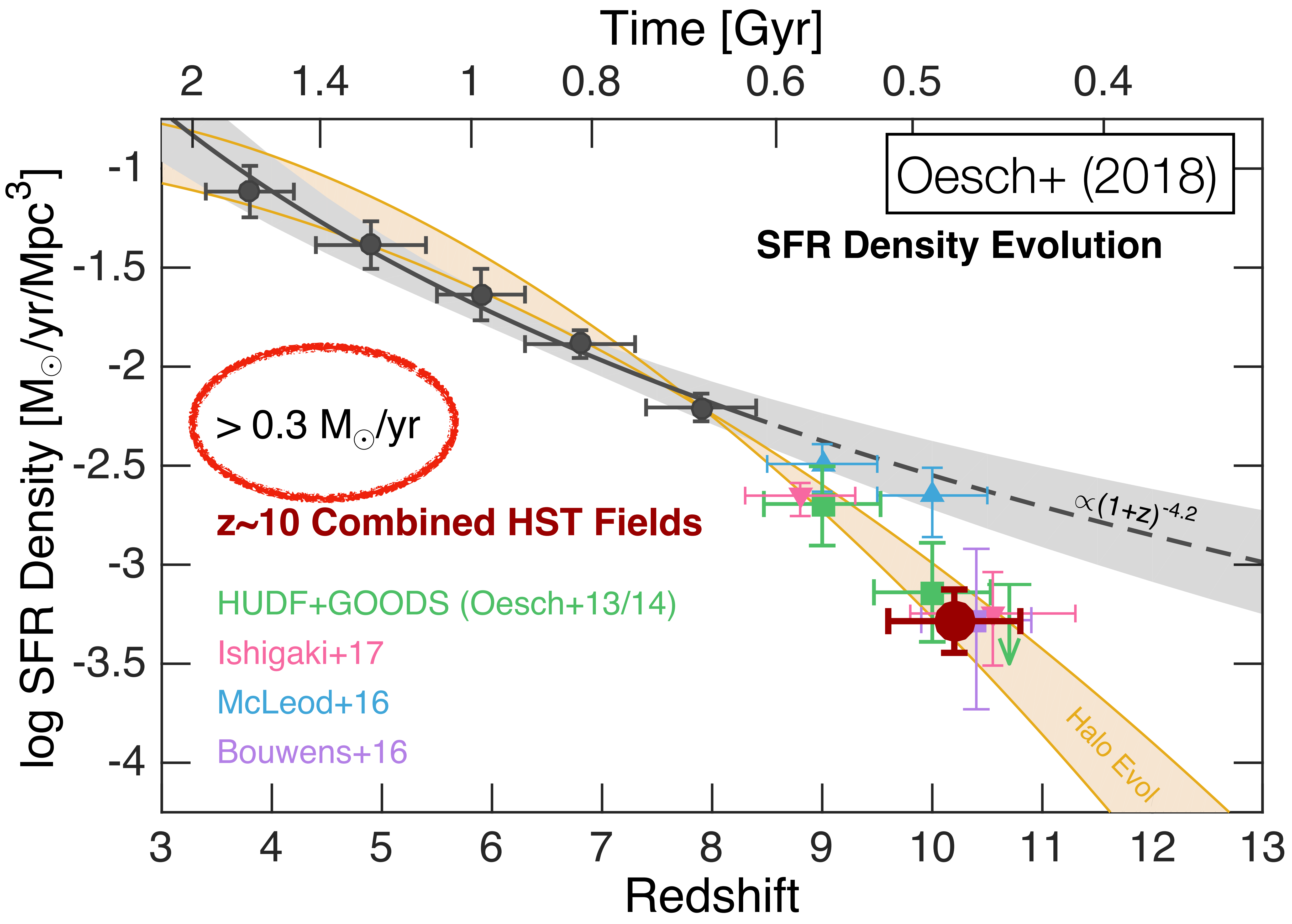
Main result: SFRD steep



SFRD depends on extrapolation:

$$\dot{\rho}_* = \int_{m_{\rm min}}^{\infty} \dot{m}_* \frac{dn}{dm} dm$$

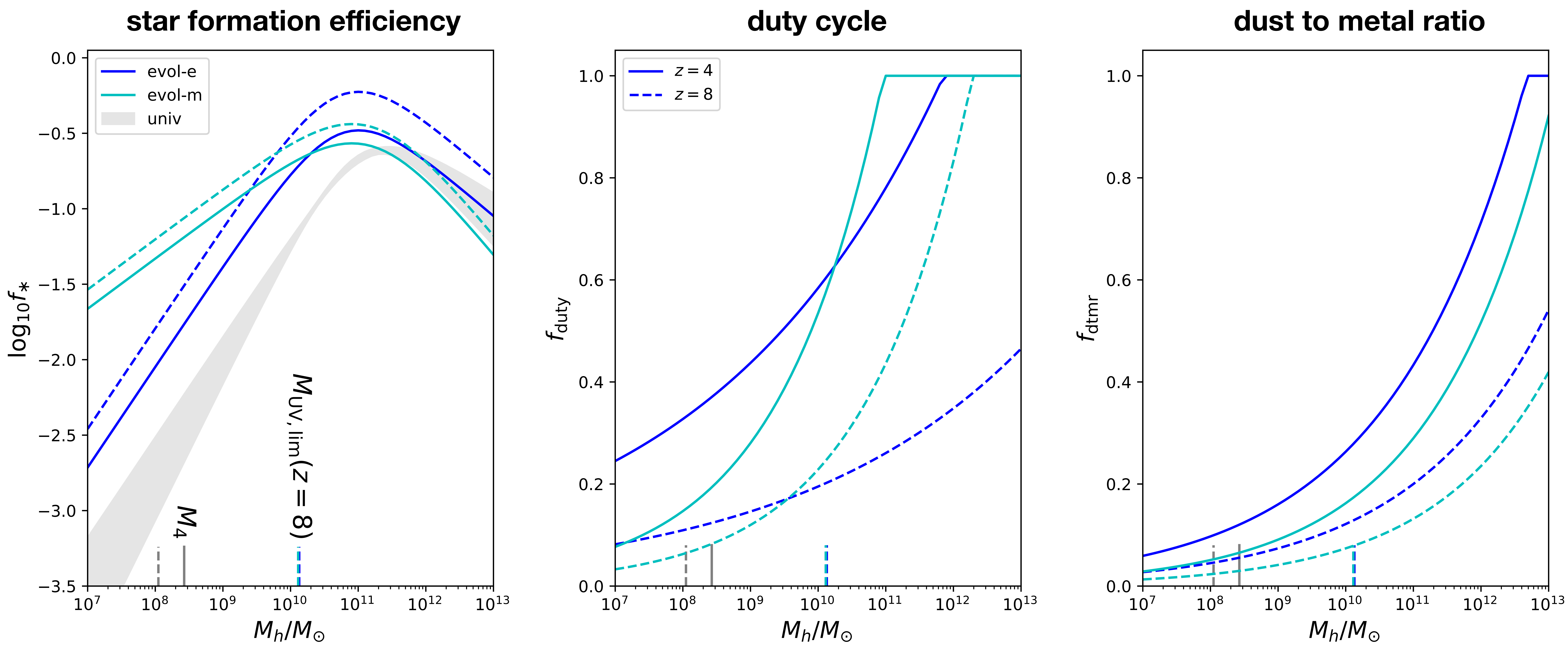
$$= \int_{m_{\rm min}}^{\infty} f_* \dot{m} \frac{dn}{dm} dm$$

and stellar/dust properties:

$$l_{1600} = f_* \dot{m} \kappa_{1600}^{-1}$$

Any wiggle room here?

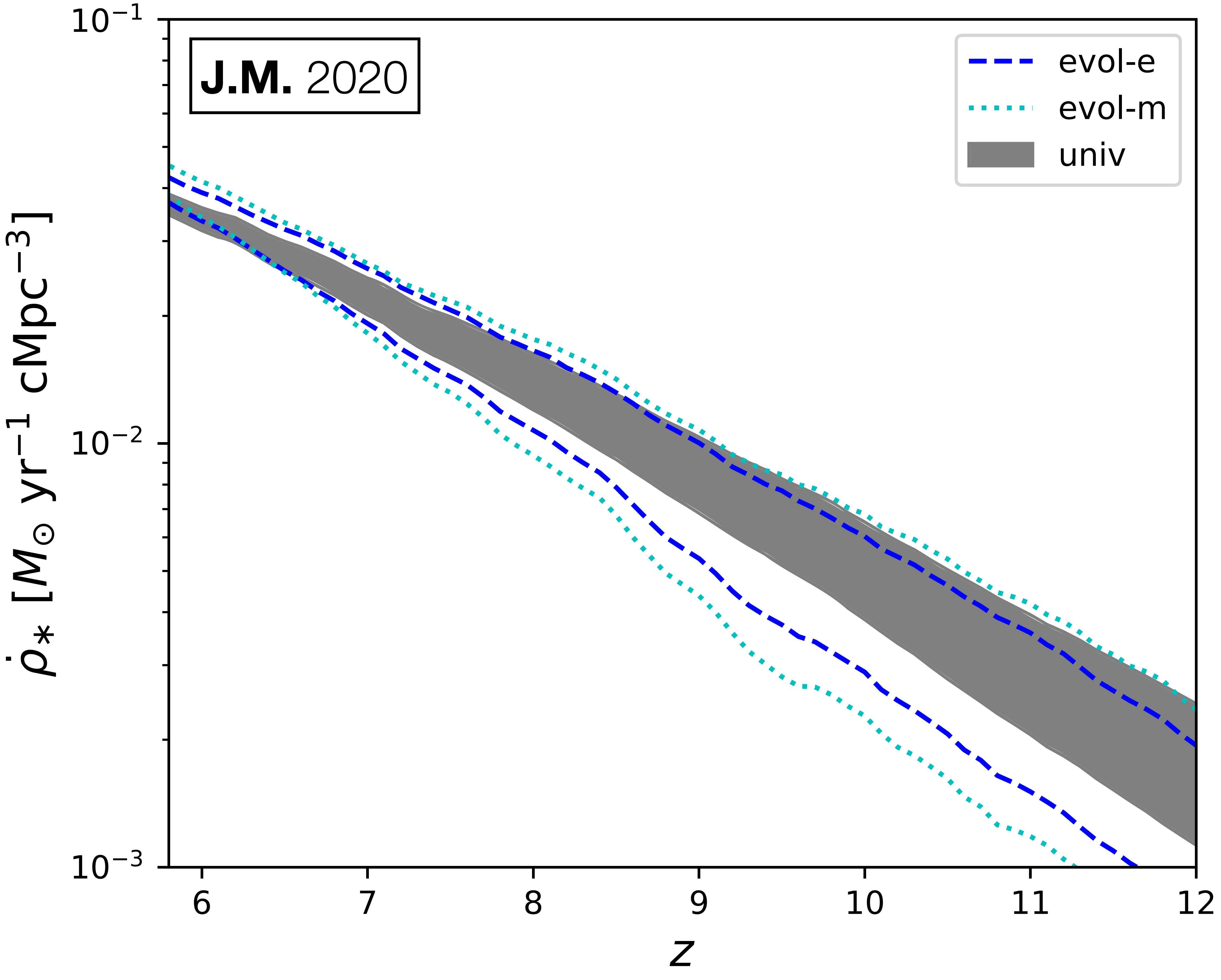
Results model-dependent?



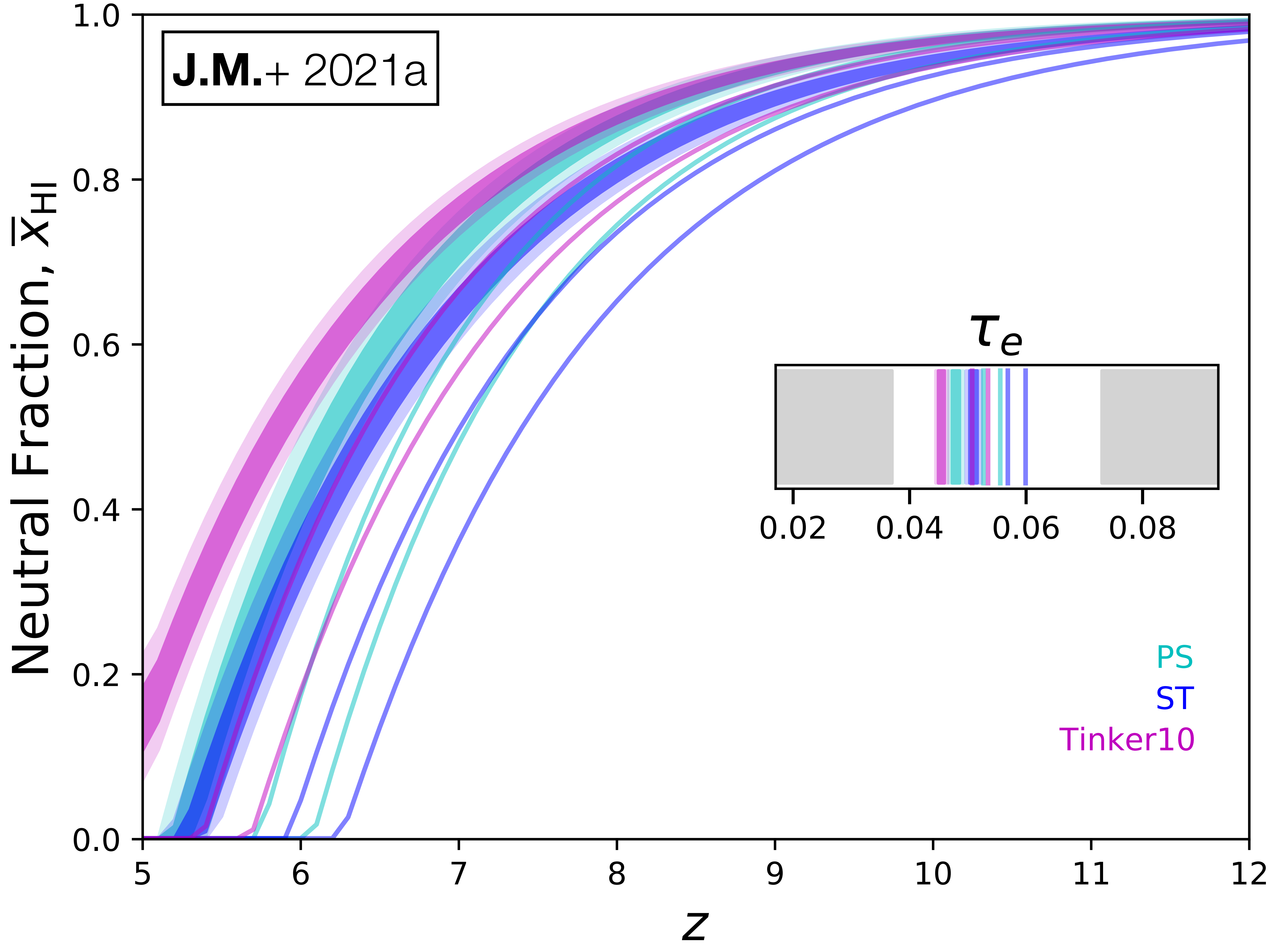
J.M. 2020

Results model-dependent?

If SFE, f_{duty}, f_{dtmr} power laws to all the way down, steep SFRD emerges from UV data consistently.



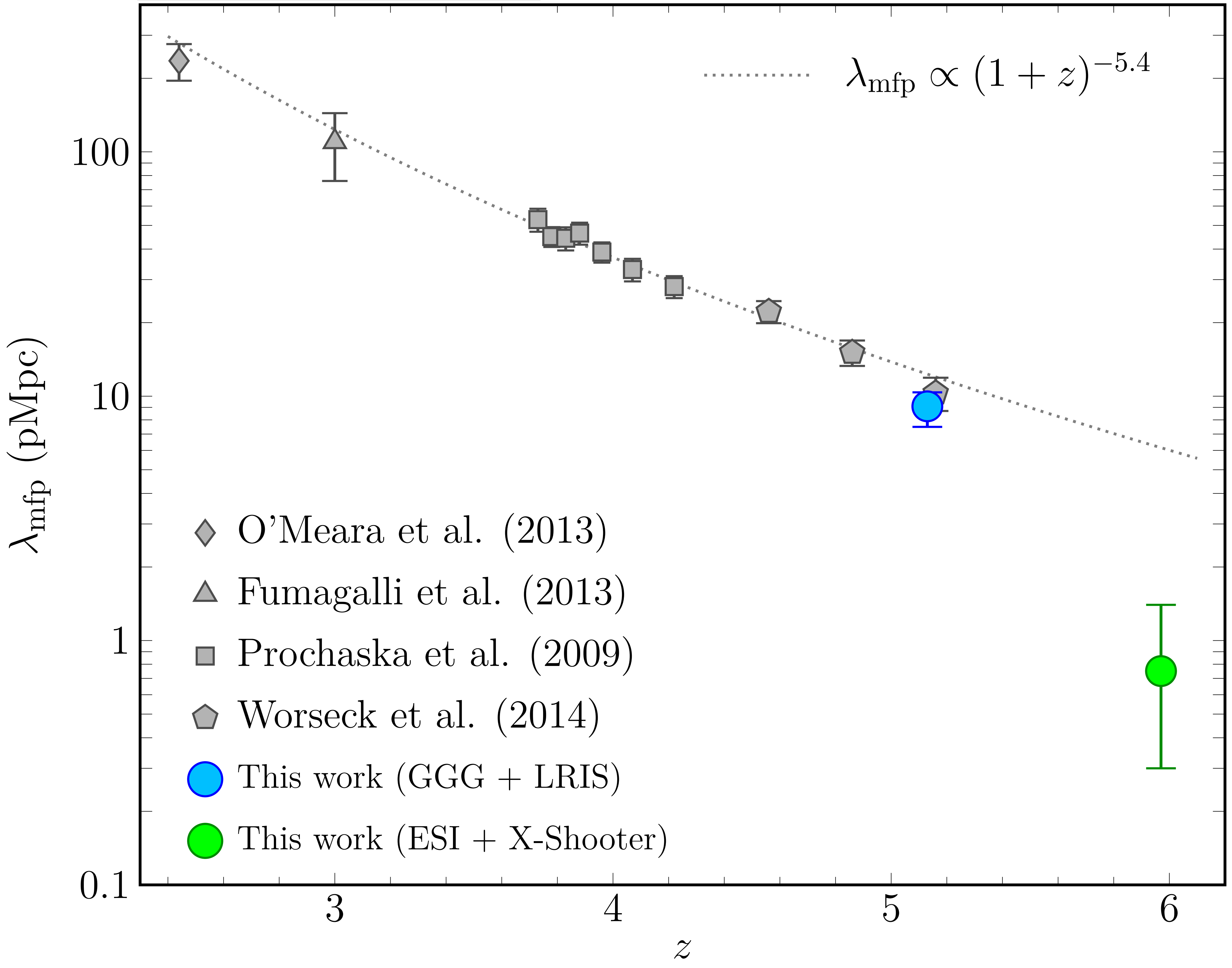
Some systematics to worry about, e.g., high-z HMF, stellar models, but largely normalization issues.



What about f_{esc}? Sinks?

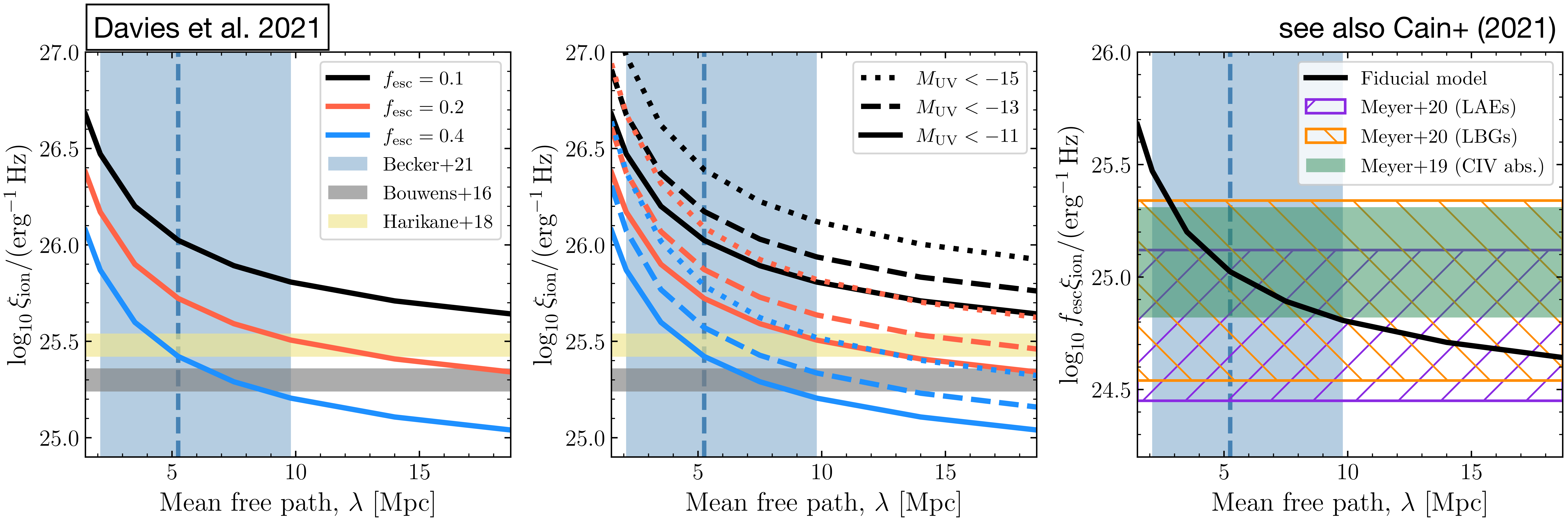
Short mean free path?

Becker et al. 2021



- Sharp decline in MFP of ionizing photons between z~5 and z~6.
- Consistent with ~20% neutral IGM at z~6 (or even more neutral).
- How to ionize IGM with such short MFP? Increased demand on f_{esc} and/or intrinsic photon production.

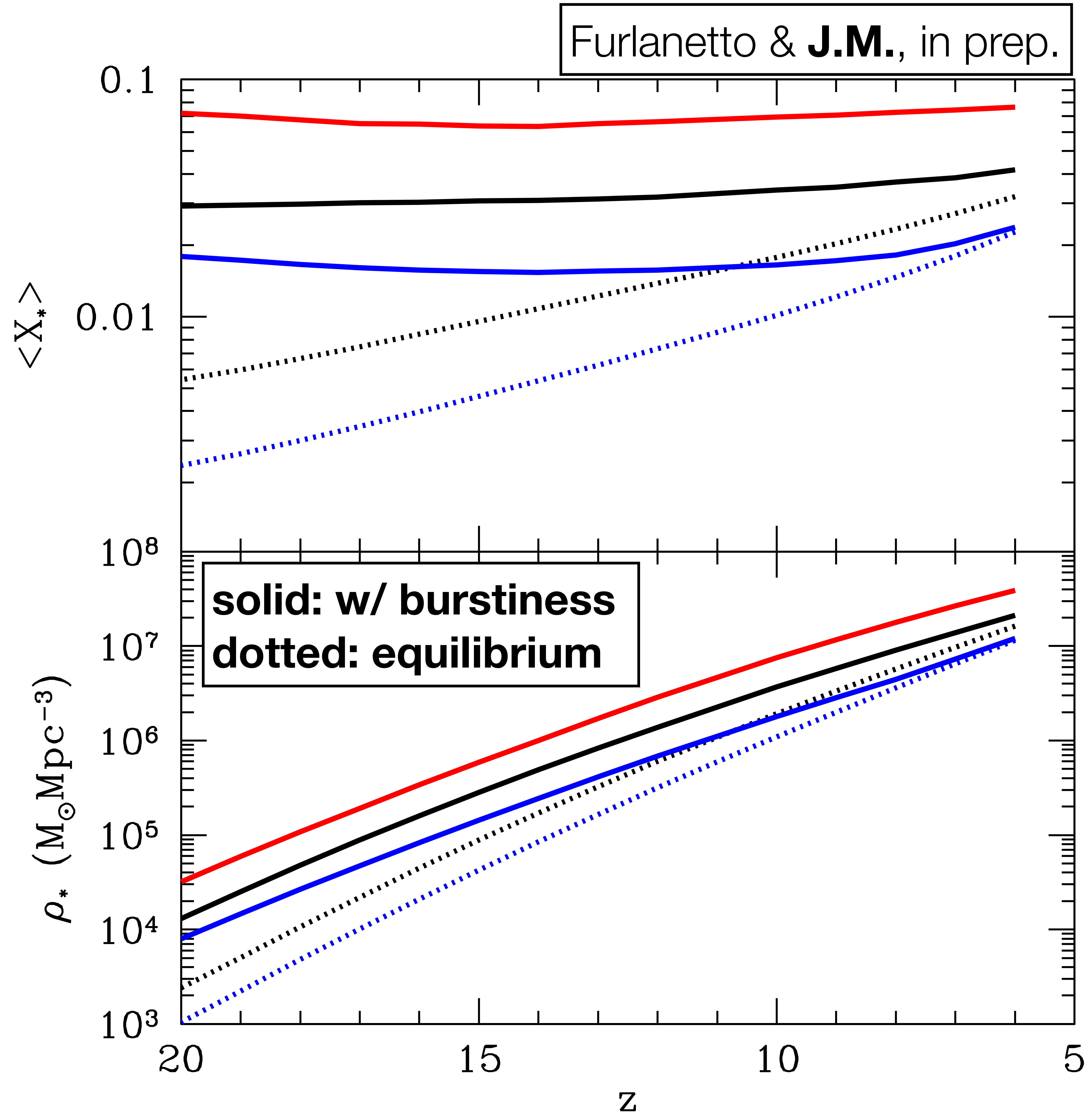
Short mean free path?



Need > 20% fesc, ~3x higher than z~3 galaxies (e.g., Pahl et al. 2021), and/or small $M_{\rm UV,lim}$.

Boost from 'burstiness'?

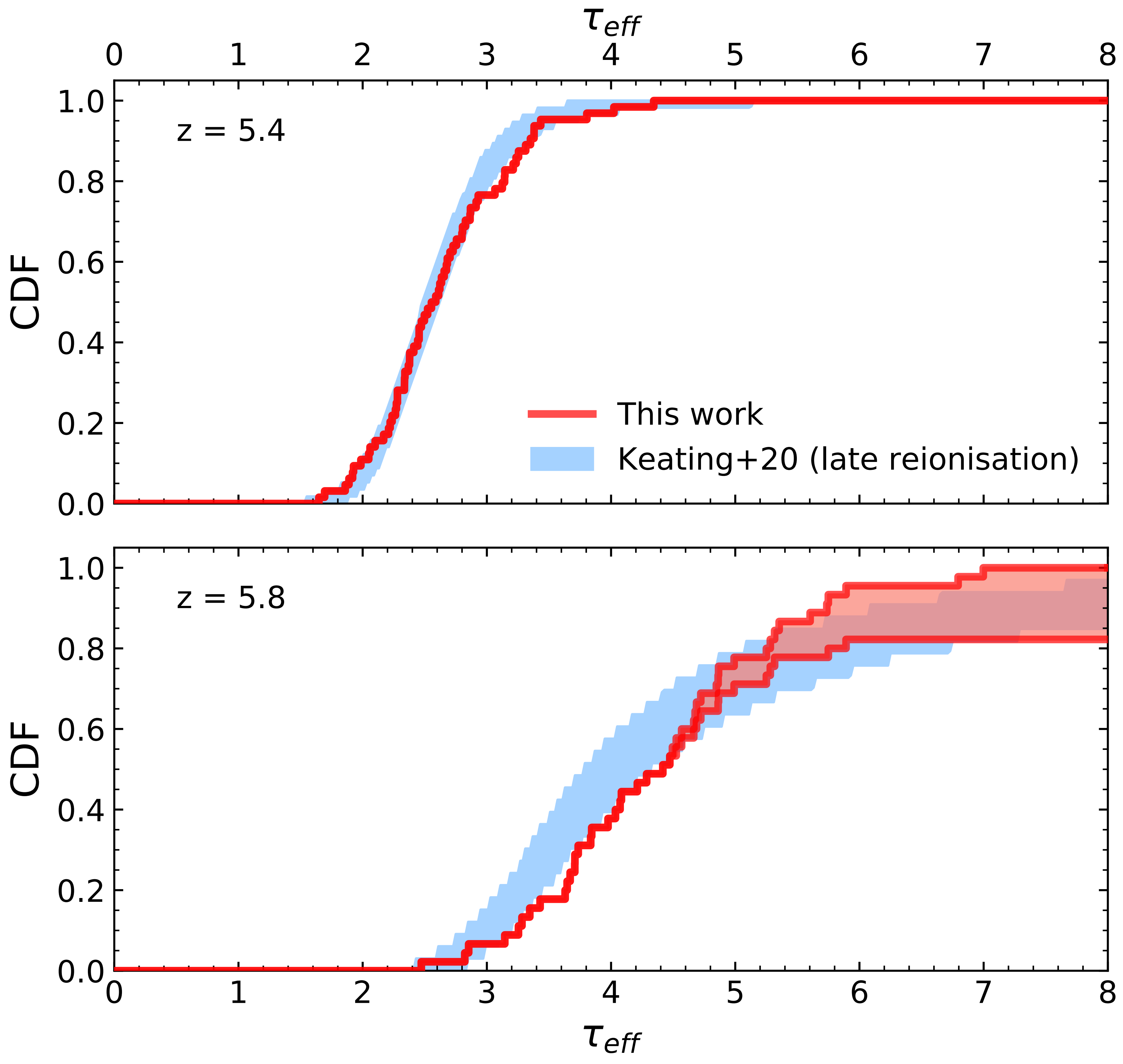
- General interpretation of steep decline in SFRD is that feedback is strong in low-mass galaxies (shallow potentials).
- Only works if feedback injected quickly relative to halo growth timescale.
- At high-z, $t_{SN} \sim t_{dyn}$, could result in failure of feedback, overshoot in SFR and photon production, perhaps by ~2-3x.



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

Late(r) reionization

Bosman et al. (2108.03699)



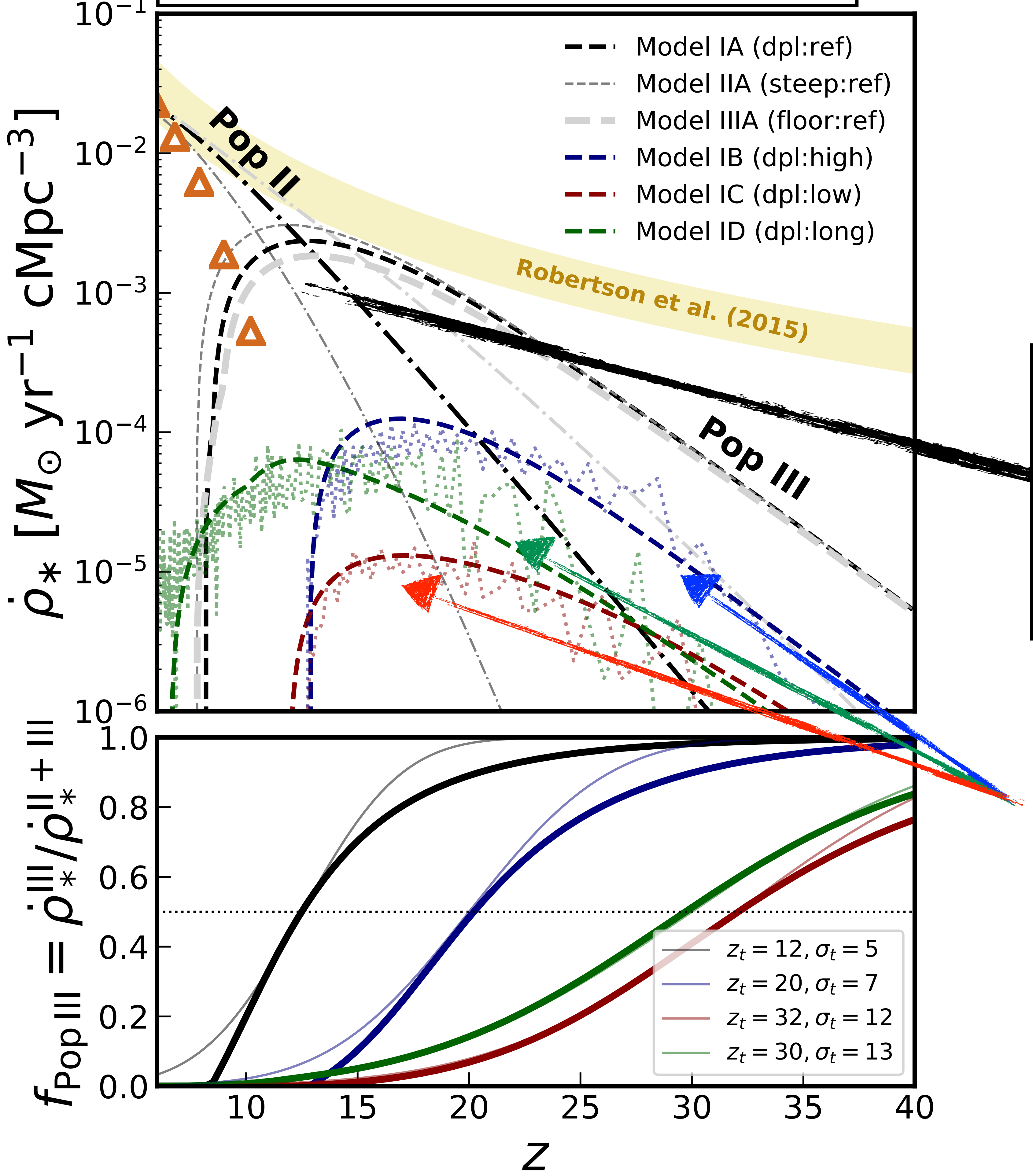
- Reionization not complete until z~5.3?
- Need neutral islands to explain distribution in Ly-a forest opacity PDF.
- Based on Ly-a forest, which means sensitive to small xHI only, but ~10% neutral at z~5.6 possible.

see also, e.g., Becker+ (2015), Kulkarni+ (2019), Keating+ (2020)

Near-future prospects

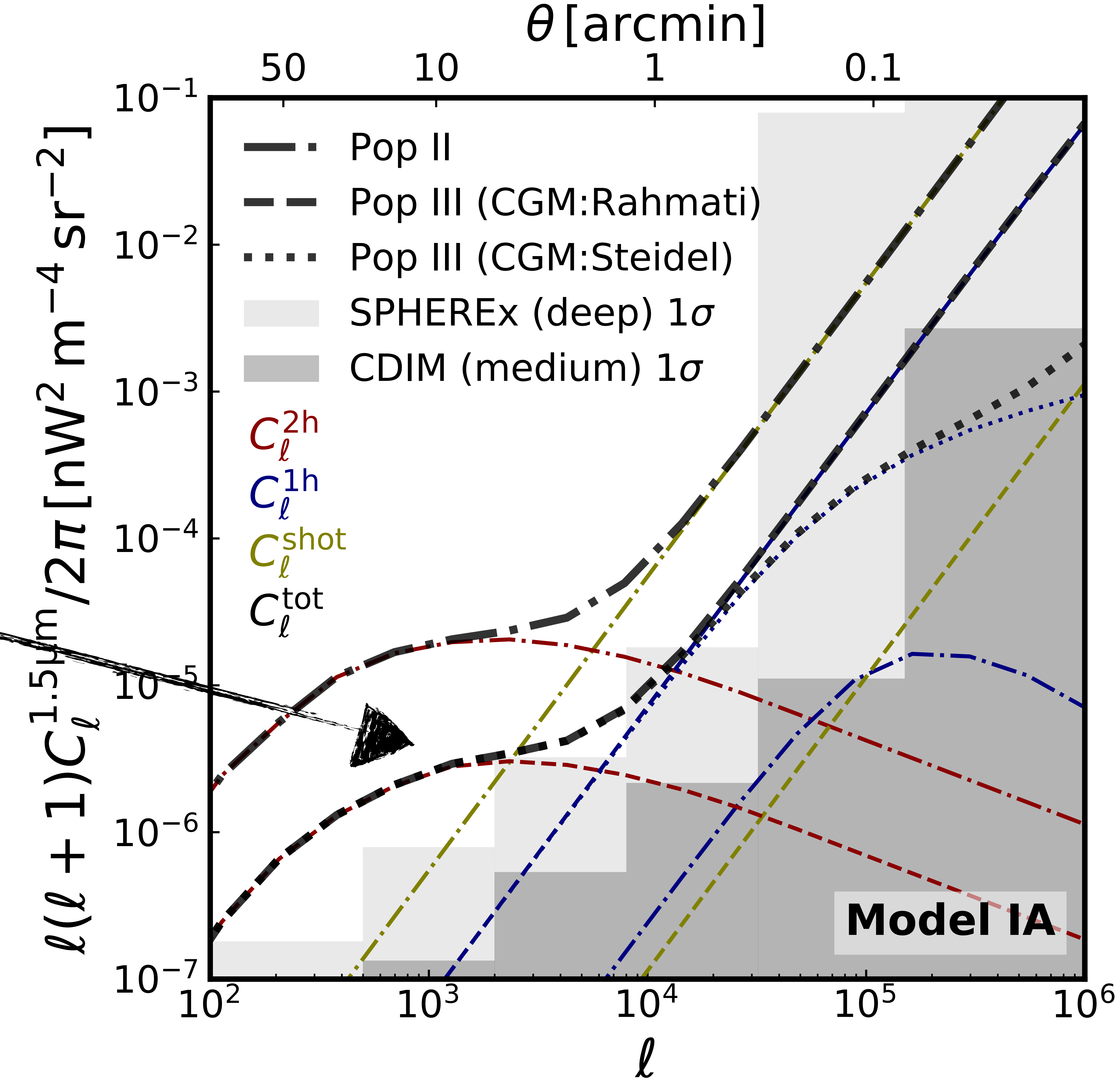
PopIII: visible in NIRB?

Sun, **J.M.**, et al. (2107.09324)



Extreme* PopIII scenarios detectable w/ SPHEREx?

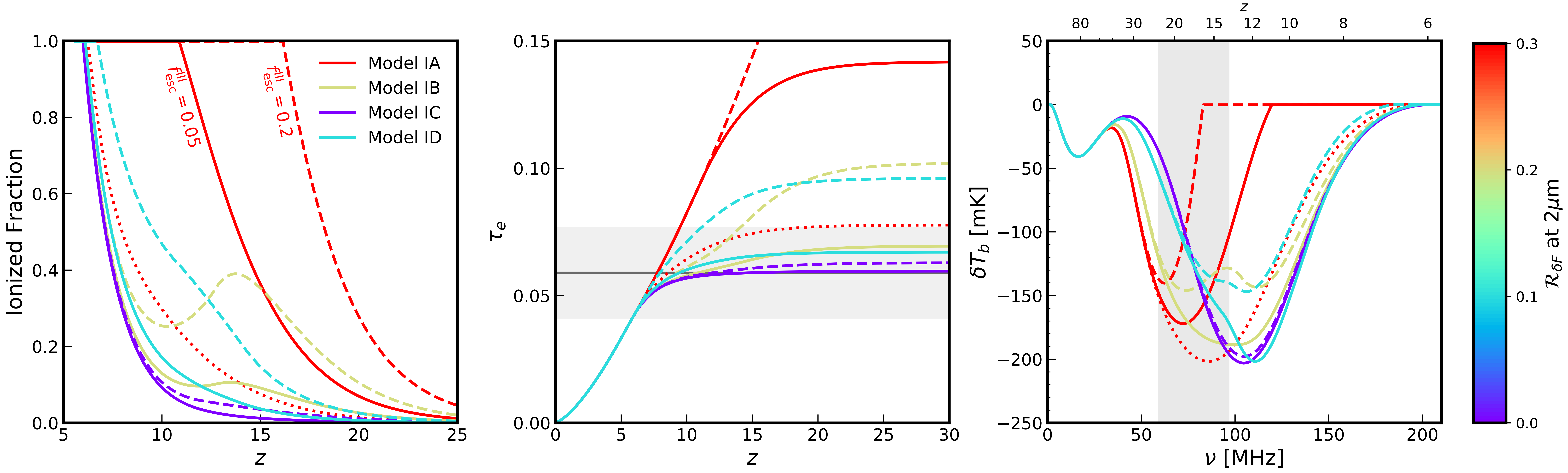
Semi-analytic models from Mebane+ (2018) w/ LW feedback, metal enrichment curbs PopIII SFRD.



see also, e.g., Fernandez+ (2006,2013), Cooray+ (2012), Yue+ (2013), Helgason+ (2016)

Multi-Probe Prospects

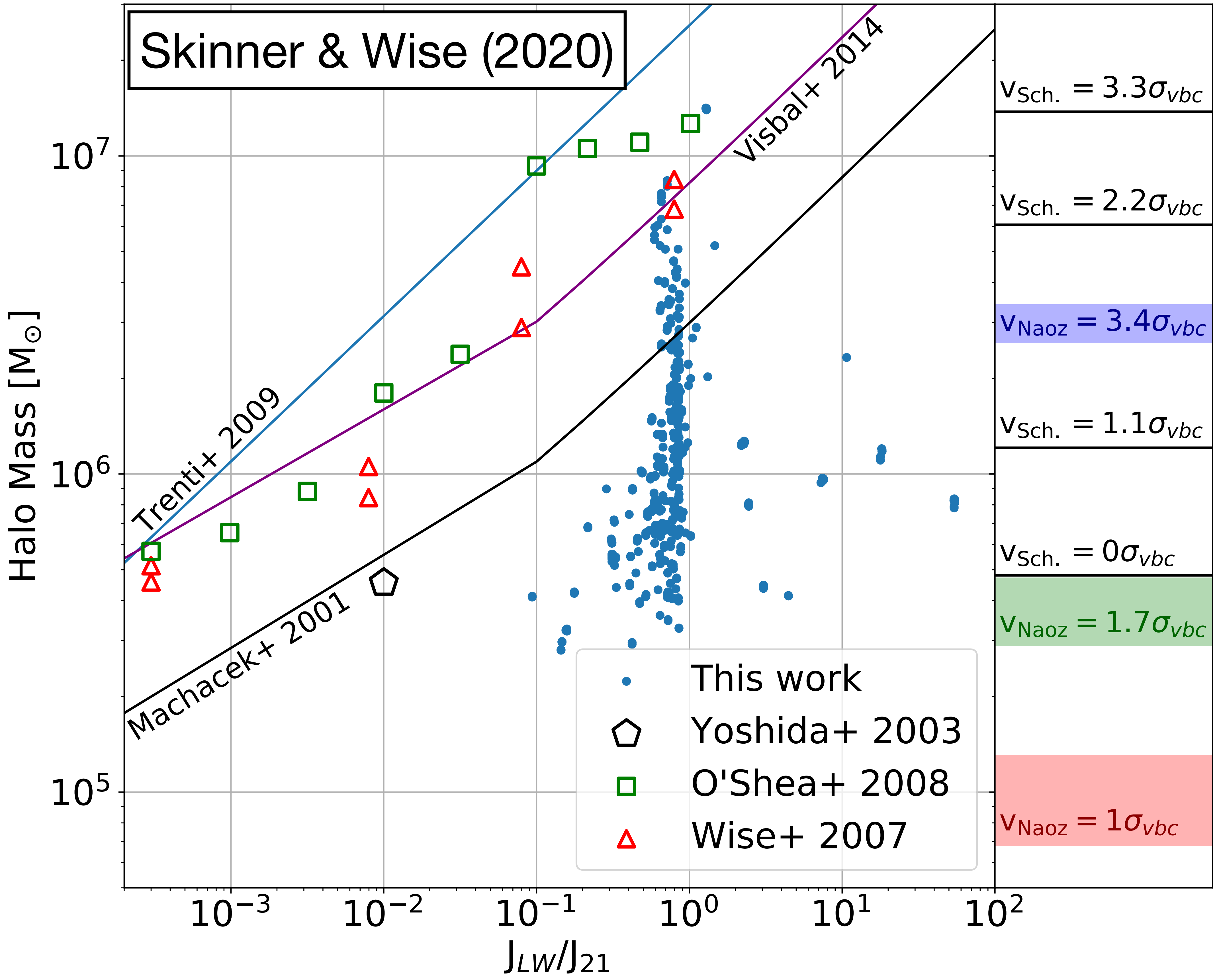
Efficient PopIII star formation drives early reionization, global 21-cm signal, and comprises ~30% of high-z NIRB.



Sun, **J.M.**, et al. (2107.09324)

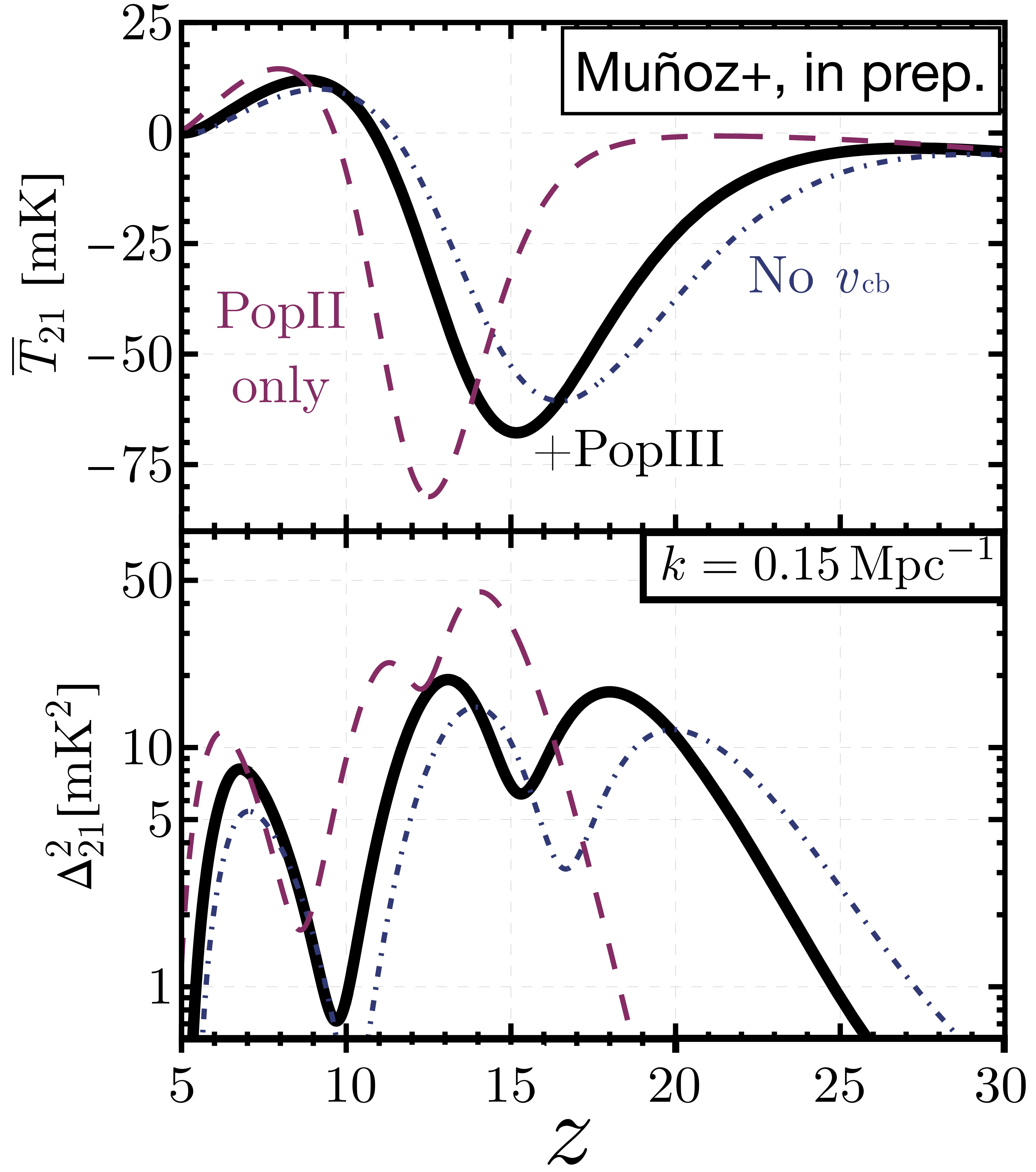
LW feedback: in decline?

Latest hydro sims w/ self shielding show halos more resilient to LW feedback.



see also, e.g., Kulkarni, Visbal, & Bryan (2021)

If higher ~10^{-3} Msun/yr/cMpc³ PopIII SFRD plausible, 21-cm signatures also strong.



see also, e.g., Qin+ (2020), **J.M.**+ (2018), Mebane+, in prep.

Summary

- The late reionization picture is still holding up. Inefficient star formation in low-mass halos drives steep decline in SFRD w/ z, pretty robust to modelling assumptions.
    - Escape fraction still a problem, exacerbated by short mean free paths. Binarity & burstiness help! 21-cm observations should help with M_h dependence.
    - LW feedback getting weaker in simulations. More PopIII expected?
    - Efficient PopIII should have discernible impact on NIRB (**SPHEREx**), 21-cm GS/PS.
- Could be surprises in store. Reliant on rest-ultraviolet observations, extension to rest-optical at $z > 6$ with **JWST** is a huge advance. Pushing UVLF limits fainter helps constrain current extrapolations. **ALMA** results probe dust more directly. Stay tuned!

Questions?