Observing the First Galaxies
Part II: Galaxy Properties & Implications

Dunlop 2012

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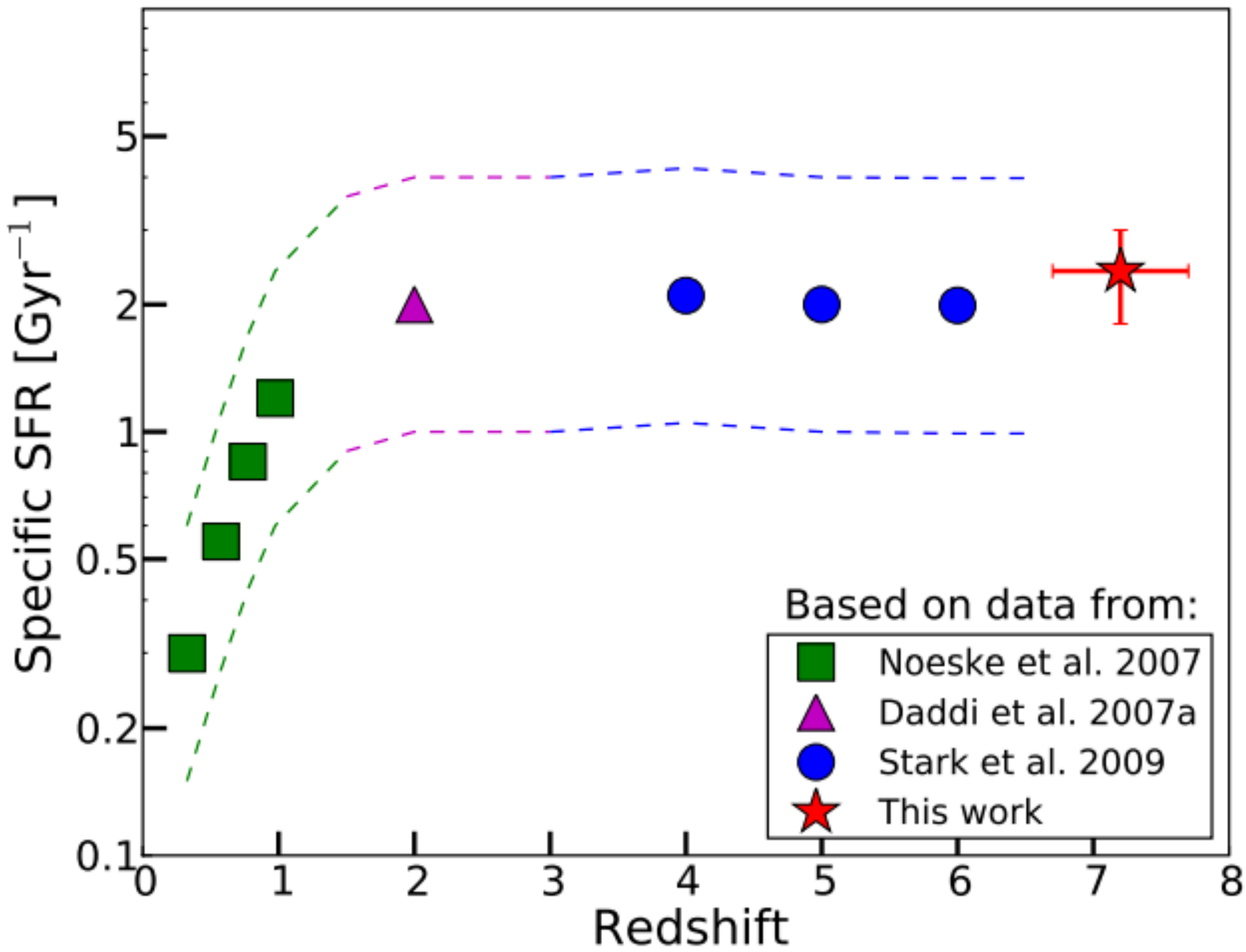
Stellar Masses (5.1)

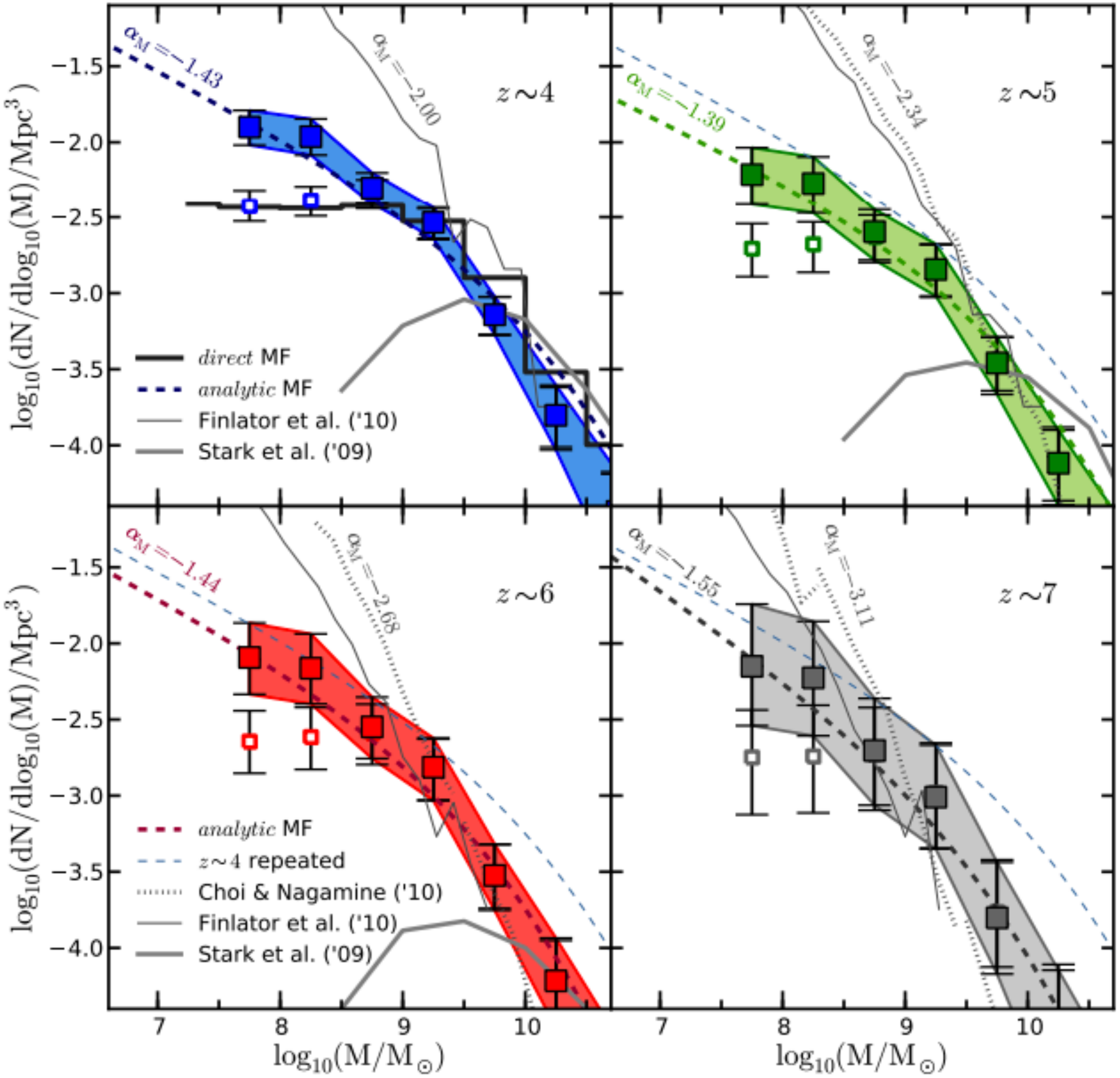
- Why are they useful?
  - Time integral of past star formation activity
  - Enable comparisons with galaxy formation models
- Hard to derive from UV data only
  - IMF is dominated by short-lived massive stars -> depends strongly on recent SF
  - Dust extinction is large
- Best stellar mass constraints are from near-IR
  - Not practical until JWST
  - Any photometry at wavelengths > 400 nm is helpful to reduce uncertainty
  - Spitzer IRAC – rest-frame optical – must assume SFR

Stellar Masses ctd. (5.1)

- Multi-band SED fitting is the best way to estimate currently, but:
    1. Requires combining HST and Spitzer (order of mag. different resolution)
    2. Depends somewhat on your population synthesis model
    3. Significant degeneracies between age, metallicity, and extinction
    4. Difficult to disentangle stellar and nebular/ISM emission
    5. Must assume an IMF, since low-mass stars are not detected
- IMF is not *that* big an issue, though
    - Can still compare with theory usefully despite factor of ~1.8 difference
    - Specific star formation rate (sSFR = SFR/M_stars) is relatively unaffected

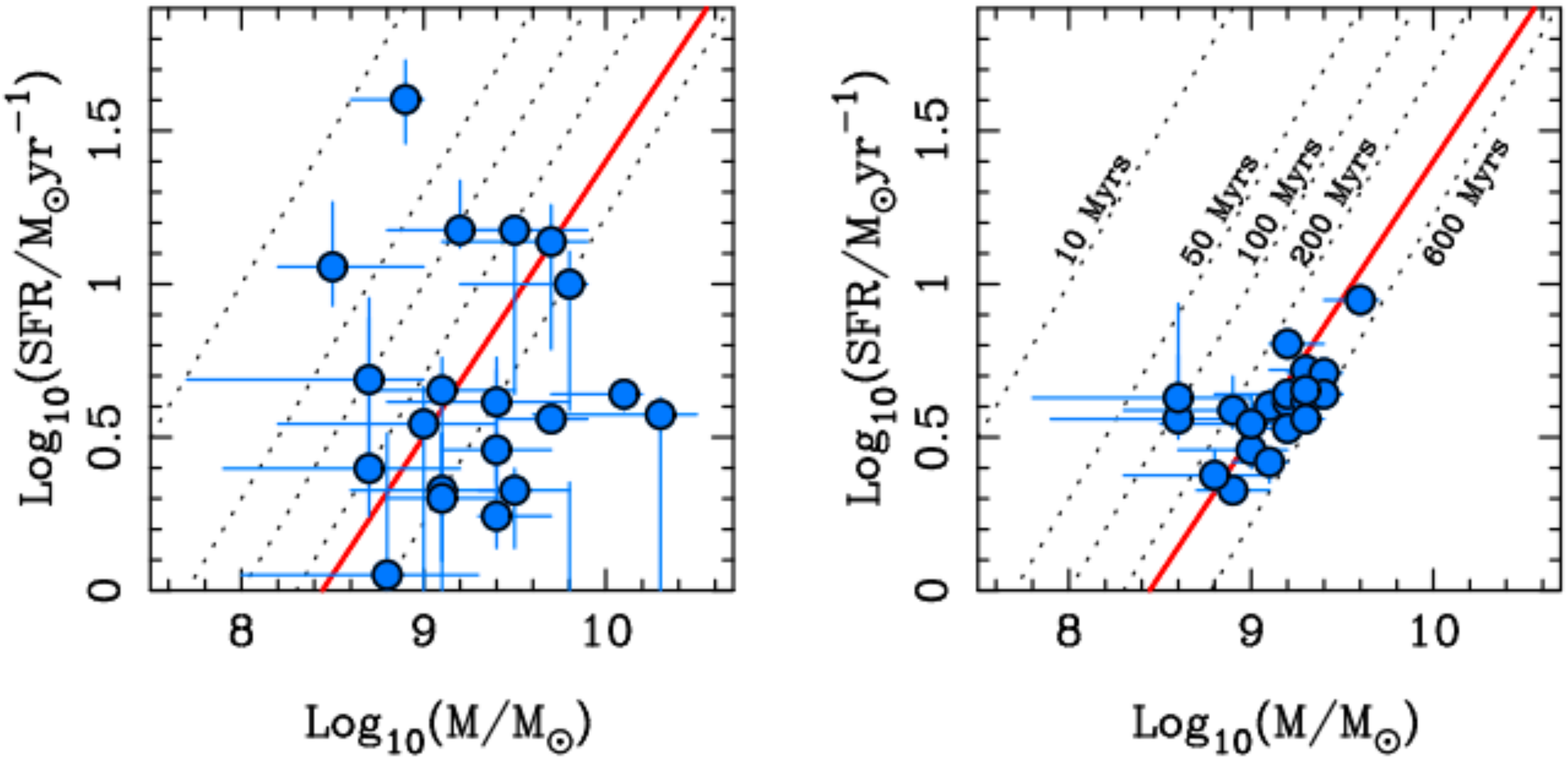


Specific SFR [Gyr^{-1}]
5
2
1
0.5
0.2
0.1
0
1
2
3
4
5
6
7
8
Redshift
Based on data from:
Noeske et al. 2007
Daddi et al. 2007a
Stark et al. 2009
This work



$$M_{star} \propto L_{1500}^{1.7}$$

- Apply above relation derived for z ~ 4 to higher z
- Theoretical models predict steeper slopes (more low mass galaxies)
- All points assume same M-L relation
- Constant SFR is assumed



Left panel – Perform SED fitting over a wide range of metallicities, SFHs, reddenings, choose best fitting model for each point; get mass, SFR from that

Right panel – Force constant SFR, then do the same thing

Dashed lines – relation for model galaxies with constant SFR, reddening

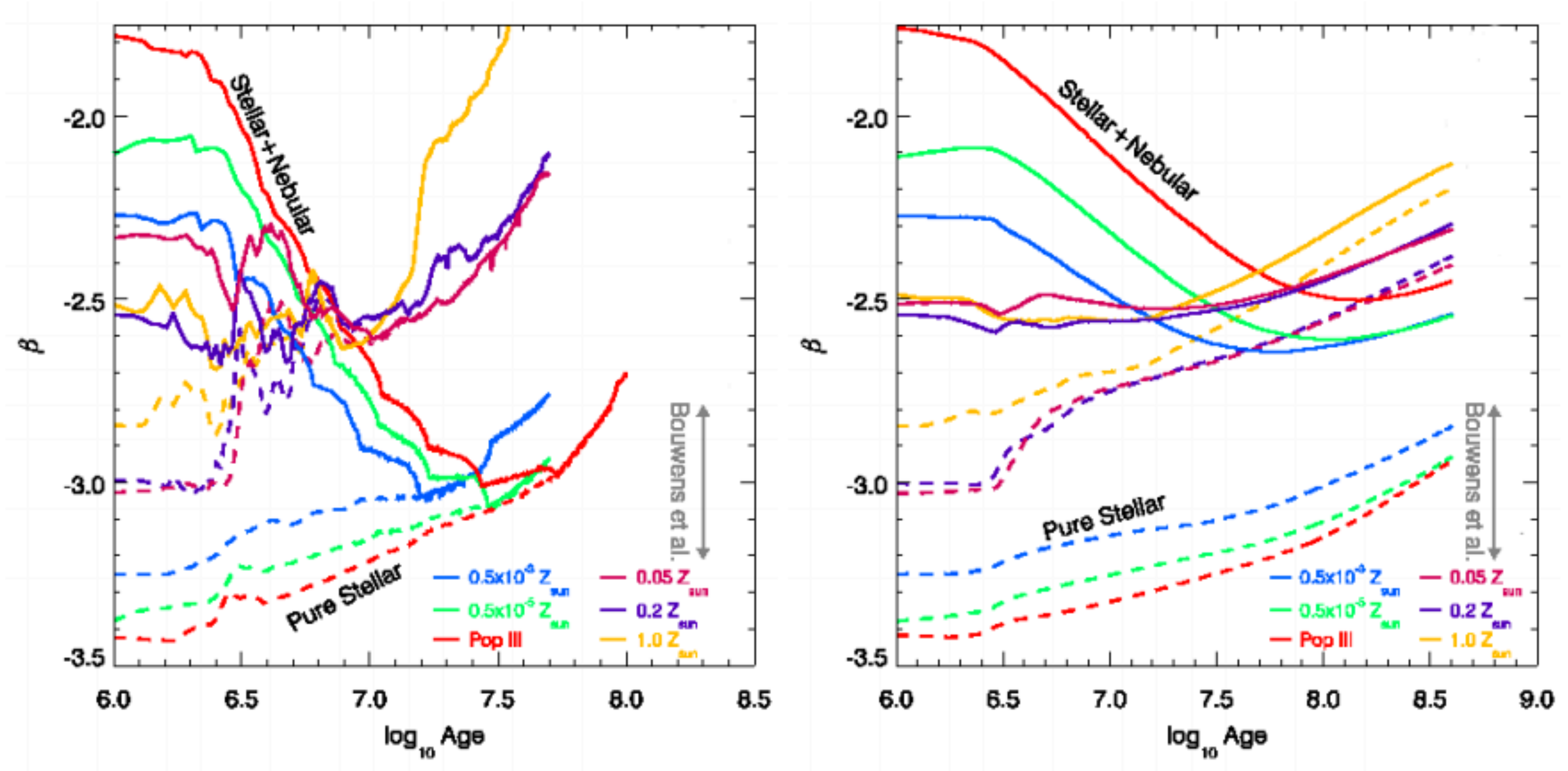
Star formation histories (5.2)

- Since sSFR is roughly constant, is SFR increasing exponentially?
  - Not all galaxies grow the same, but basically, yes – must be something close
  - This is confirmed by most data from z = 8 to z = 3
  - Consistent with the latest hydro simulations
    - However, these want sSFR to increase with z, tracking halo mass accretion rate
    - Need more feedback
- Hard to say basically anything else about SFHs without high-res spectroscopy
  - Probably episodic, different by galaxy
  - Degeneracies from nebular emission, dust, metallicity

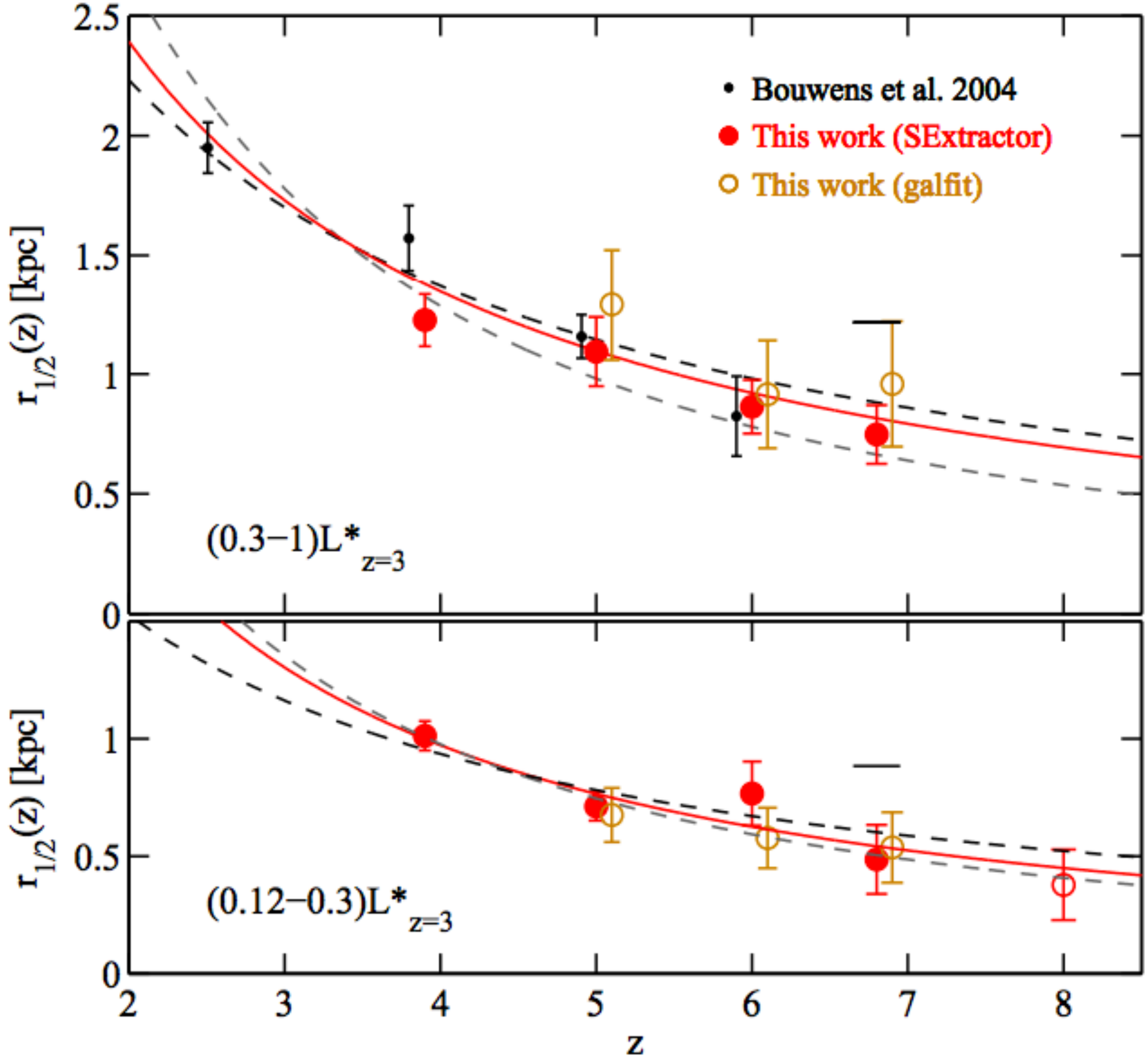
Ultraviolet Slopes (5.3)

- Extremely low metallicity, dust free, high-z galaxies are expected to be much bluer than anything at $z < 6.5$
- Can constrain this using rest frame UV photometric continuum slopes parameterized by power law index β
- $\beta \sim -2$ for the bluest galaxies at $z = 3$-4
- $\beta \sim -3$ is possible for young, low metallicity populations if:
    1. Population is very young, i.e. $t < 30$ Myr
    2. Completely free of dust extinction
    3. No contamination from nebular continuum
- Important implications for reionization – β is related to UV escape fraction
- For brightest galaxies, $\beta \sim -1.5$ at $z \sim 3$-4 but $\beta \sim -2$ at $z \sim 6$
    - Interpreted as changing extinction

Instantaneous starburst　　　　Continuous SFR



** Interpreting moderate β values like those observed is not straightforward

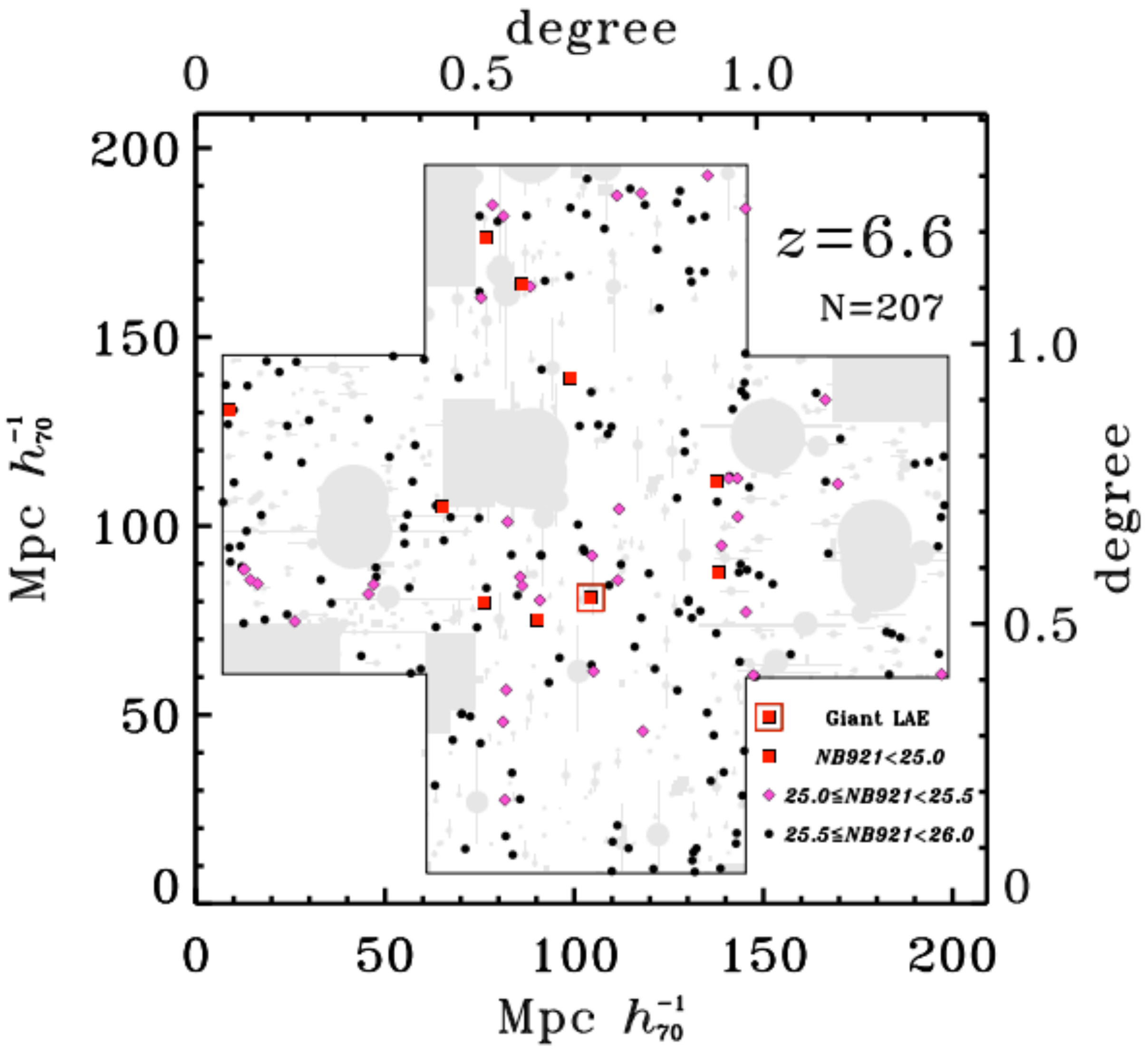


Sizes & Morphologies (5.4)

Size evolution of Lyman break galaxies with redshift. Effect of HST's selection bias for galaxies with high surface brightness isn't fully understood – need more data and JWST

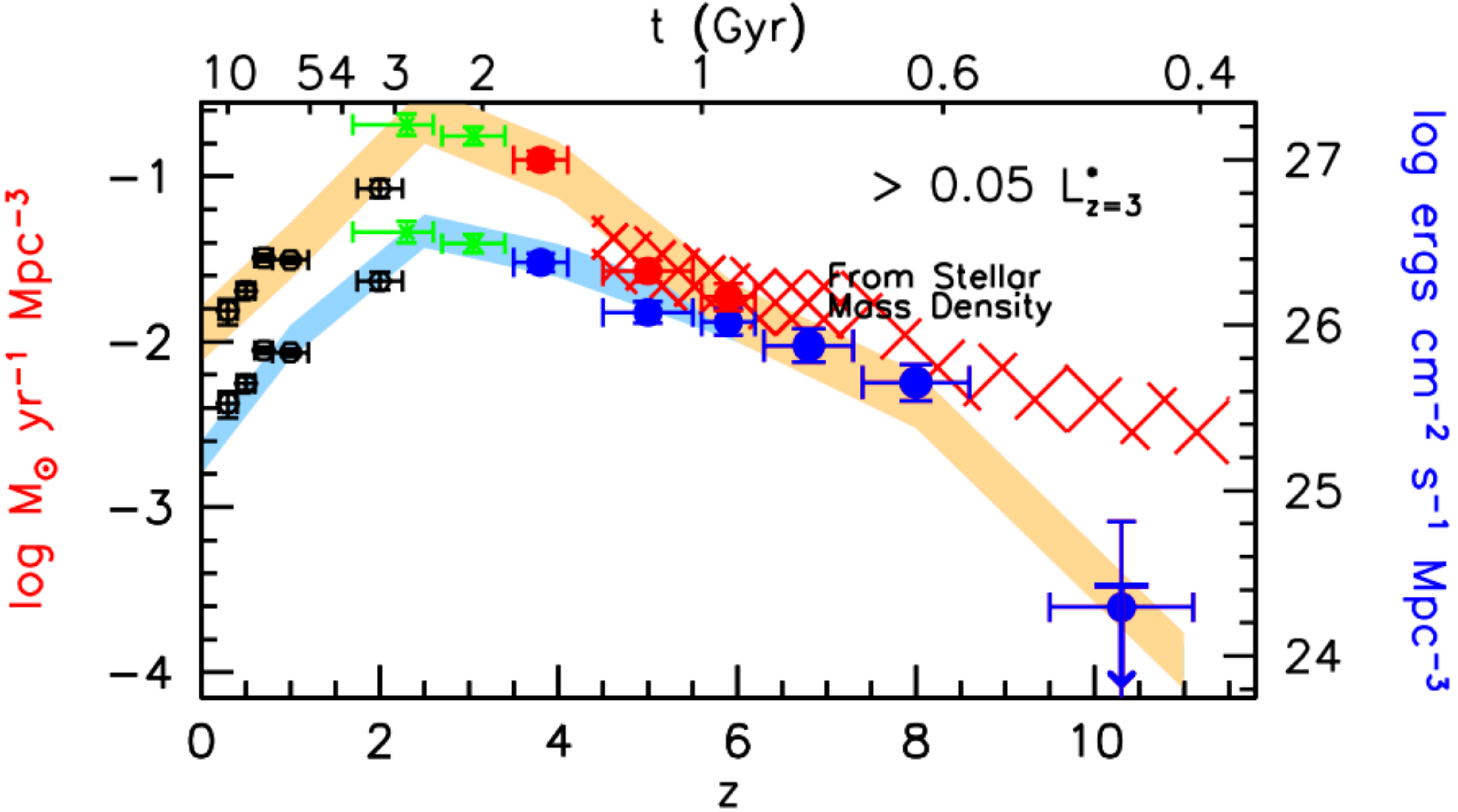
Clustering (5.5)

- Clustering measurement -> estimate DM halo occupation fraction
- At z ~ 5, observations are limited severely by small number statistics
- Best observations are in Subaru images, and they do detect clustering
  - Lyman alpha emitters -> correlation length 3-7 Mpc -> log(M_halo) ~ 10-11
  - Lyman break galaxies -> correlation length 6-10 Mpc -> log(M_halo) ~ 11.5-12
  - Difference makes sense – LBGs are rarer and more massive

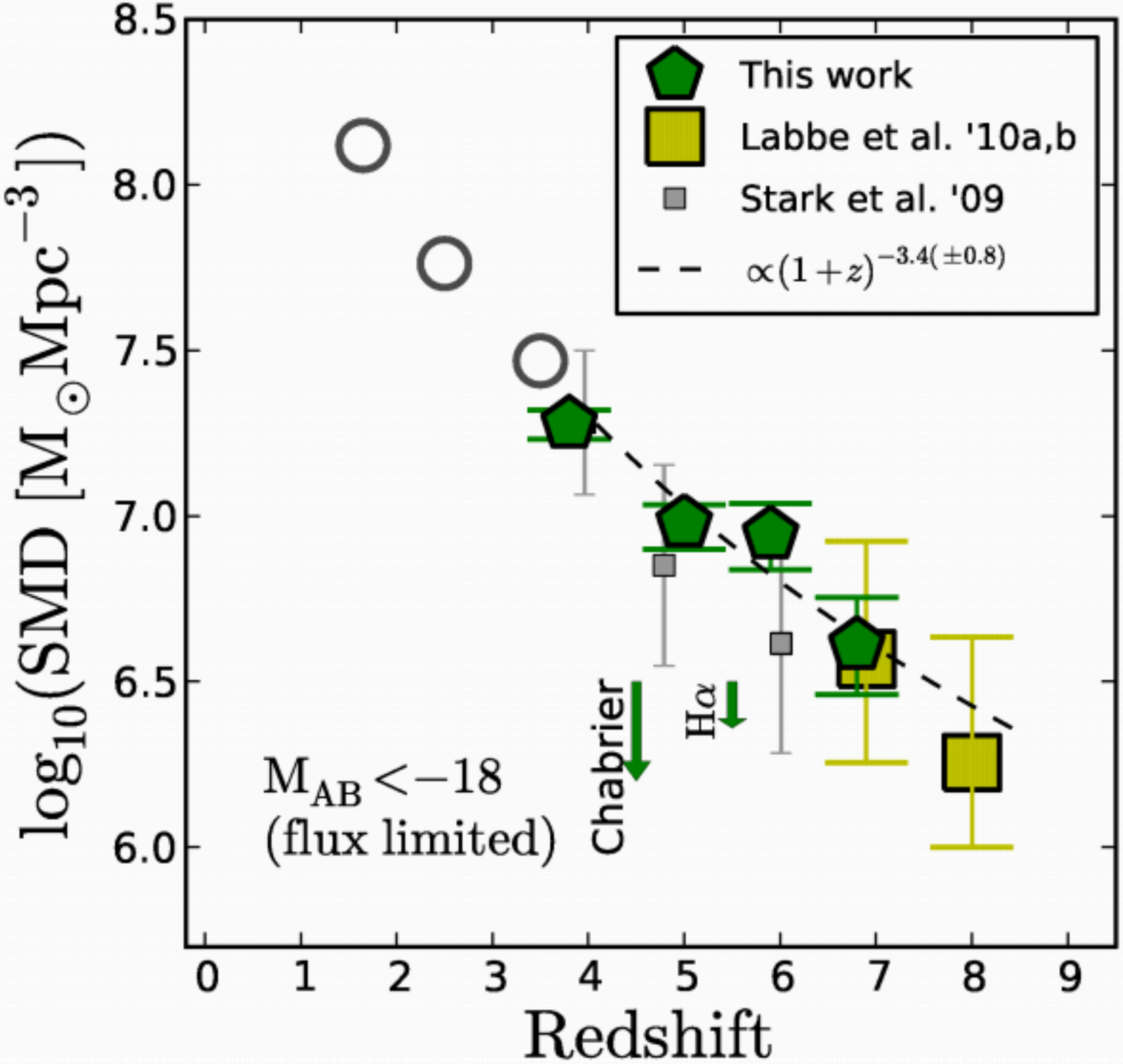


Cosmic Star Formation History (6.1)

- UV luminosity function -> comoving UV luminosity density -> star formation density over cosmic time
- This measurement requires several extrapolations
  - Galaxy luminosity function extrapolated to low luminosities
  - Stellar mass function extrapolated to low masses
  - Mass/time dependence of dust must be accounted for
  - Selection effects – highly dust-obscured galaxies may not be detectable
- Alternatively, differentiate the stellar mass density over cosmic time
- Reasonable but imperfect agreement – dust extinction at high redshift may be necessary



t (Gyr)
10
54
3
2
1
0.6
0.4
log M⊙ yr⁻¹ Mpc⁻³
−1
−2
−3
−4
27
26
25
24
log ergs cm⁻² s⁻¹ Mpc⁻³
> 0.05 L*z=3
From Stellar
Mass Density
0
2
4
6
8
10
z

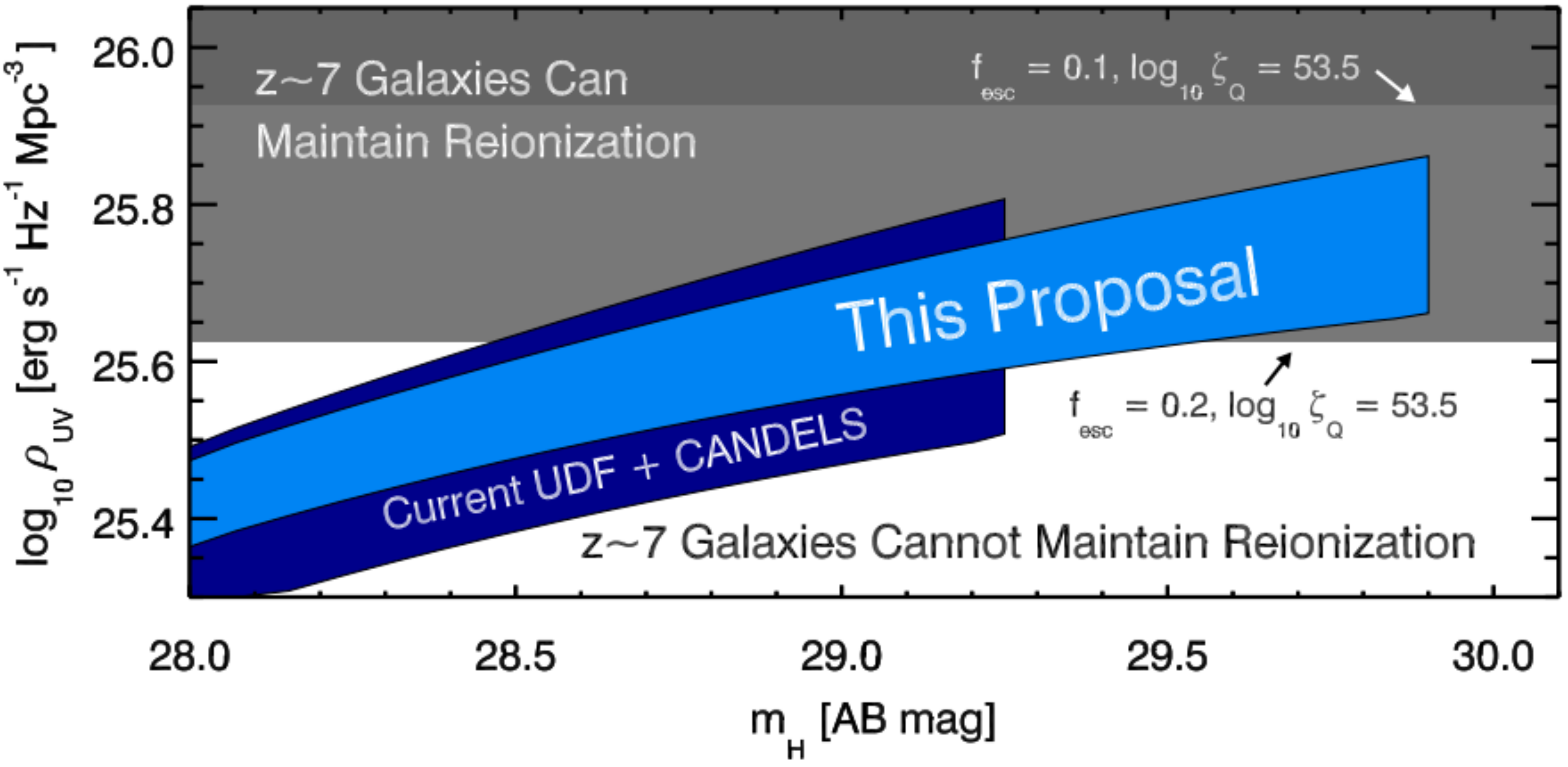


This work
Labbe et al. '10a,b
Stark et al. '09
$\propto (1+z)^{-3.4(\pm 0.8)}$
$\log_{10}(\mathrm{SMD}\,[\mathrm{M_\odot Mpc^{-3}}])$
Redshift
$\mathrm{M_{AB}} < -18$
(flux limited)
Chabrier
$\mathrm{H}\alpha$
8.5
8.0
7.5
7.0
6.5
6.0
0
1
2
3
4
5
6
7
8
9

Reionization (6.2)

- At what z, if at all, can the galaxy population reionize the Universe?
- Need sustained Lyman continuum photons, $\lambda < 91.2$ nm
- Hard to constrain because these photons are absorbed by hydrogen (as they reionize the Universe…)
- Guess their abundance by observing UV luminosity density at longer λ
  - Estimate rate of ionizing photons per star formation rate
  - Estimate escape fraction
  - Estimate clumpiness of IGM

  All three highly uncertain
- Ly-α emission as probe of IGM ionization state
  - Luminosity function of Ly-α emitting galaxies (LAEs) may evolve
  - Ly-α escape fraction should evolve with ionization state
  - Shape of lines should evolve
  - Clustering of LAEs should increase with redshift



Proposal is UDF12 imaging program with Hubble

Future Prospects – JWST (7)