Star-Forming Galaxies in the z > 4 Universe

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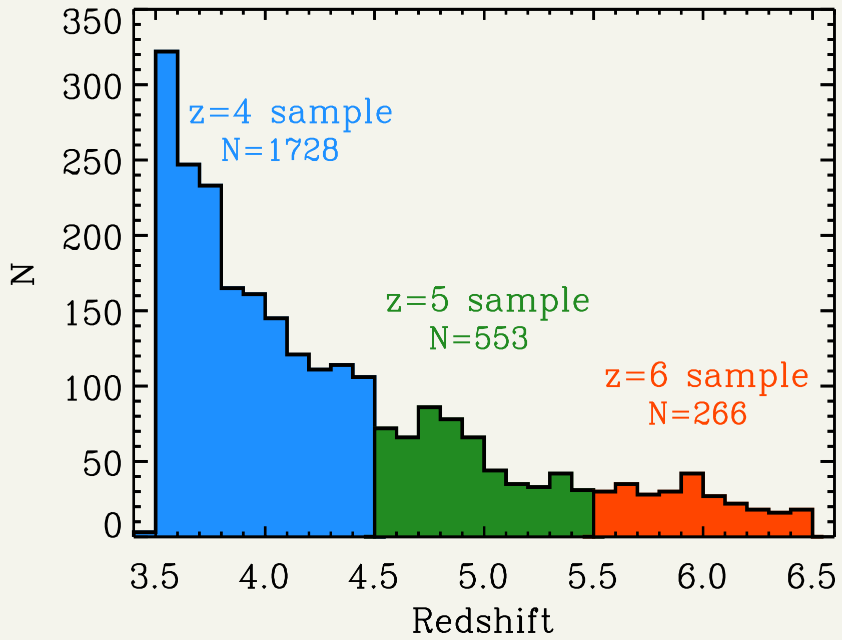
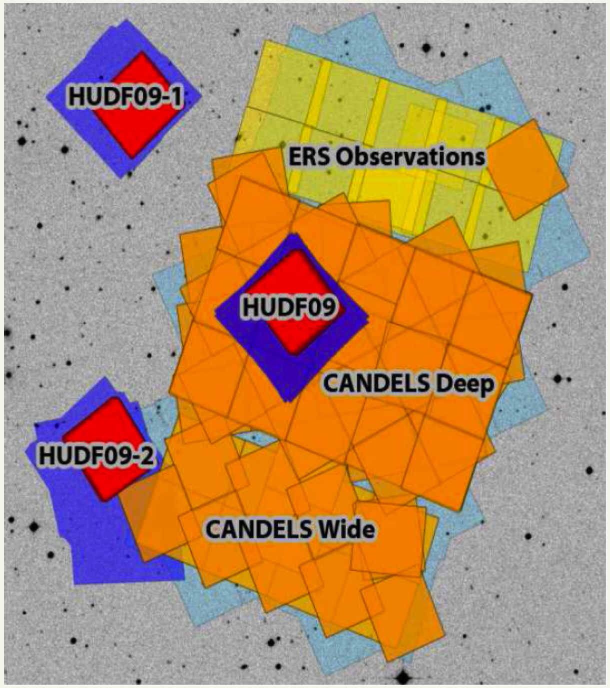
Outline

- Lessons learned at high z
  - A Bayesian approach to SED fitting
  - UV SFR improvements
  - Dust attenuation
  - The star-formation and stellar mass relation
- Star Formation Histories
- Summary

CANDELS Data

- Benefits: DEEP, large volume, and rest-frame optical
- Fields: GOODS-S DEEP & WIDE + ERS + HUDF
- H_{160}-band selected catalog (Guo et al. 2013)
- 18 Bands
  - ACS: B_{435} , V_{606} , i_{775} , I_{814} , and z_{850}
  - WFC3: Y_{098}, Y_{105}, J_{125}, JH_{140}, and H_{160}
  - IRAC (3.6, 4.5, 5.8, and 8.0 μm)
  - CTIO/MOSAIC and VLT/VIMOS *U*-bands
  - VLT ISAAC K_S and HAWK-I K_S





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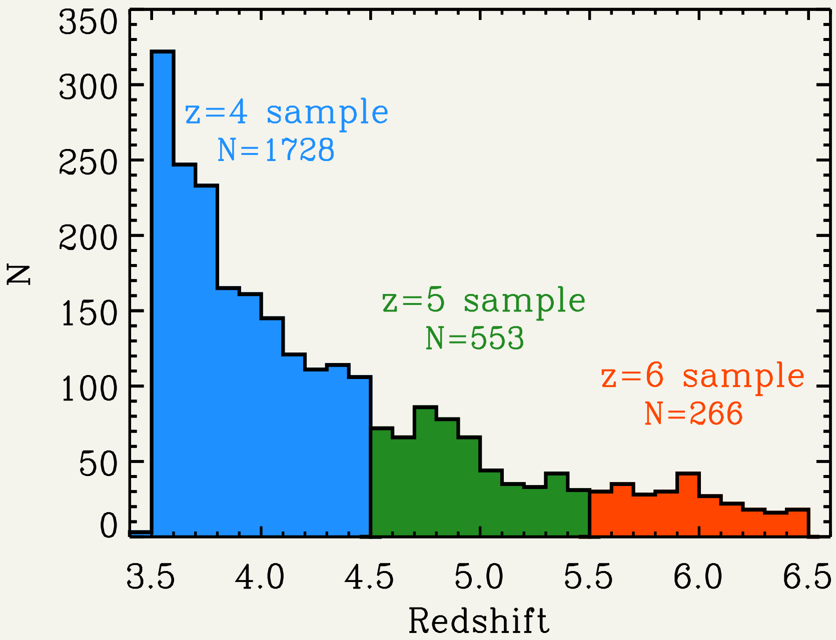
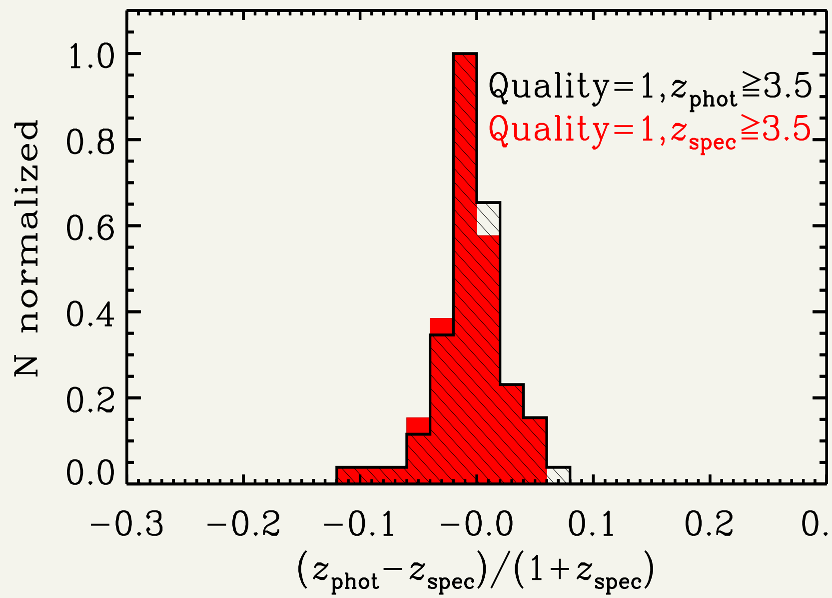
- Photometric redshift selection 3.5<z<6.5

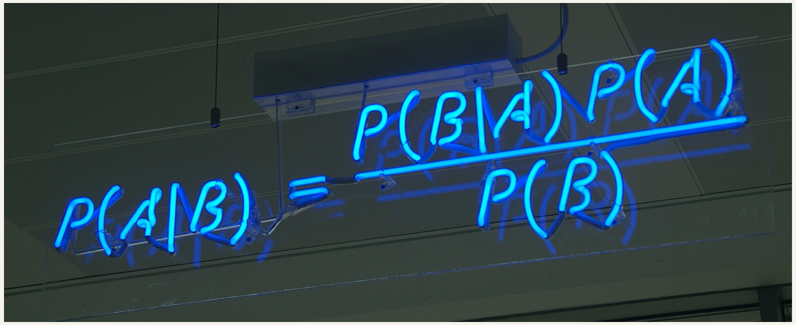




Bayesian Approach SED Fitting

- Bayesian techniques quickly find the best model, given prior knowledge and all available information
- Already used in astronomy to determine the patchiness of the IGM during reionization (Tilvi+14, Pentericci+14)
- We use a Bayesian SED fitting procedure that calculates the posterior on each galaxy and marginalizes over nuisance parameters

Reads "Posterior of A given B = "



A = fitted parameters B = Data

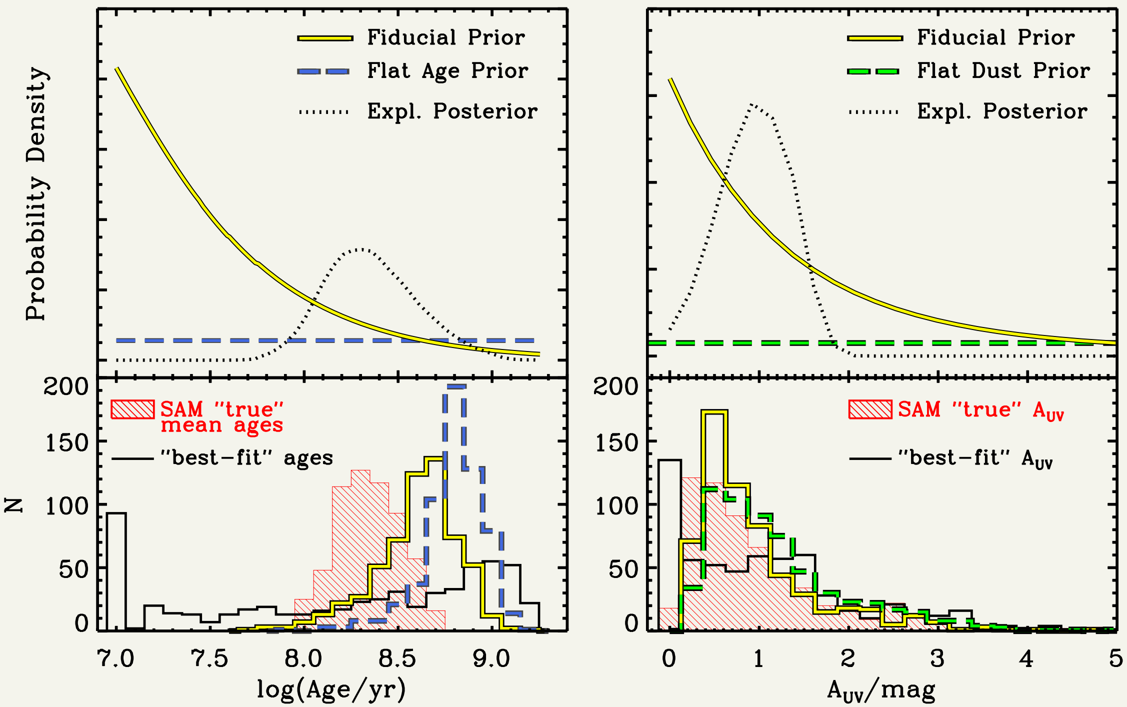
P(A) = prior, the knowledge you already have. ie., that galaxies cannot be older than the age of the Universe

Bayesian Approach SED Fitting

$$p(D|\Theta') = \prod_{i=1}^{n} \frac{1}{\sqrt{2\pi}\sigma_i} e^{-(f_i - M f_\Theta(\lambda_i))^2/(2\sigma_i^2)}$$

$$p(\Theta') = \left(\sum_{i=1}^{n} f_\Theta^2(\lambda_i)/\sigma_i^2 \right)^{1/2}$$

- The process of marginalization requires the above prior, which is effectively dependent on the template fluxes, f_Θ
- Tests on SAM objects show that inducing other priors shift the distributions as expected
- The best fit is not always the best answer. Individual solutions can be very sporadic across the parameter space



Bayesian Approach SED Fitting

- The p
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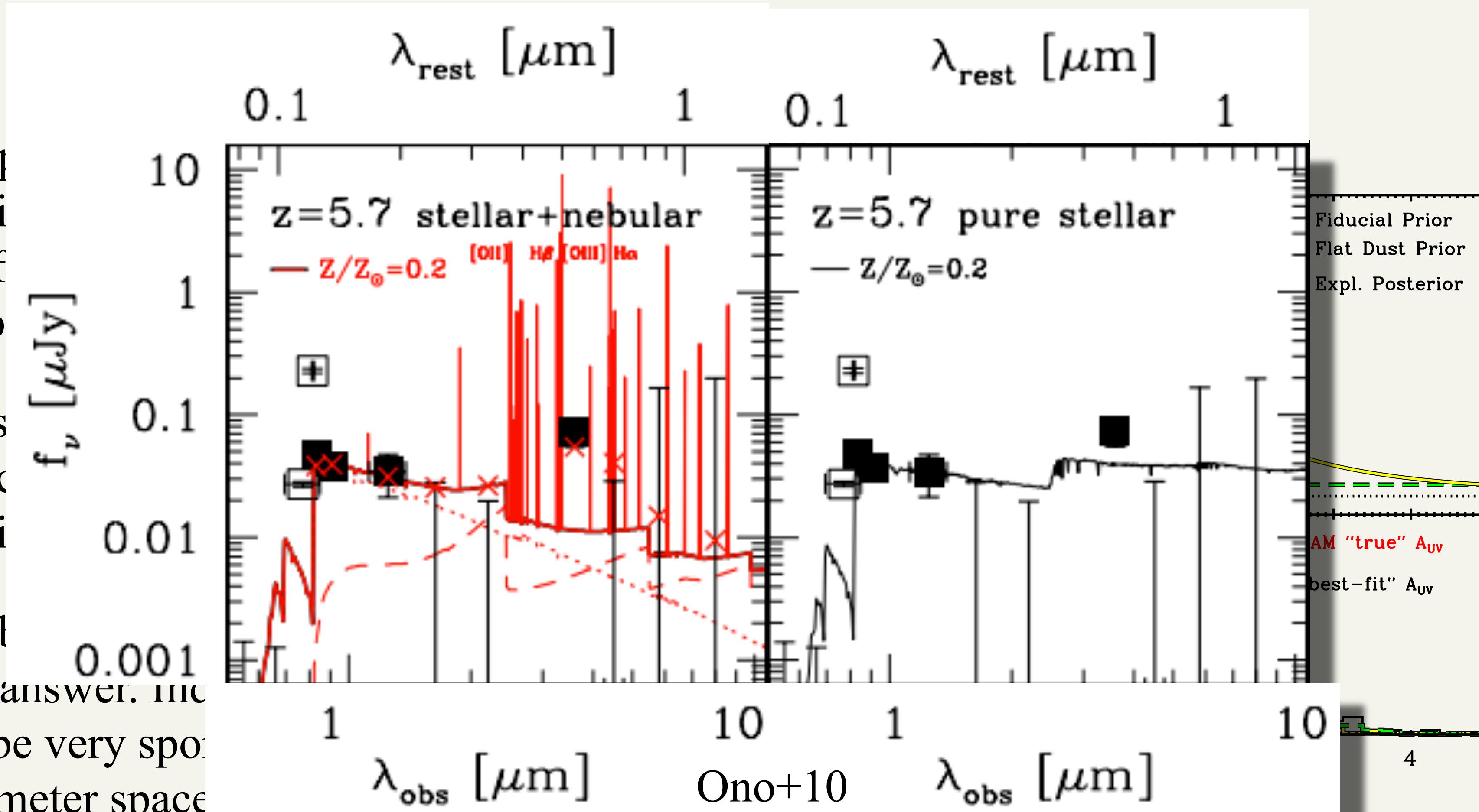
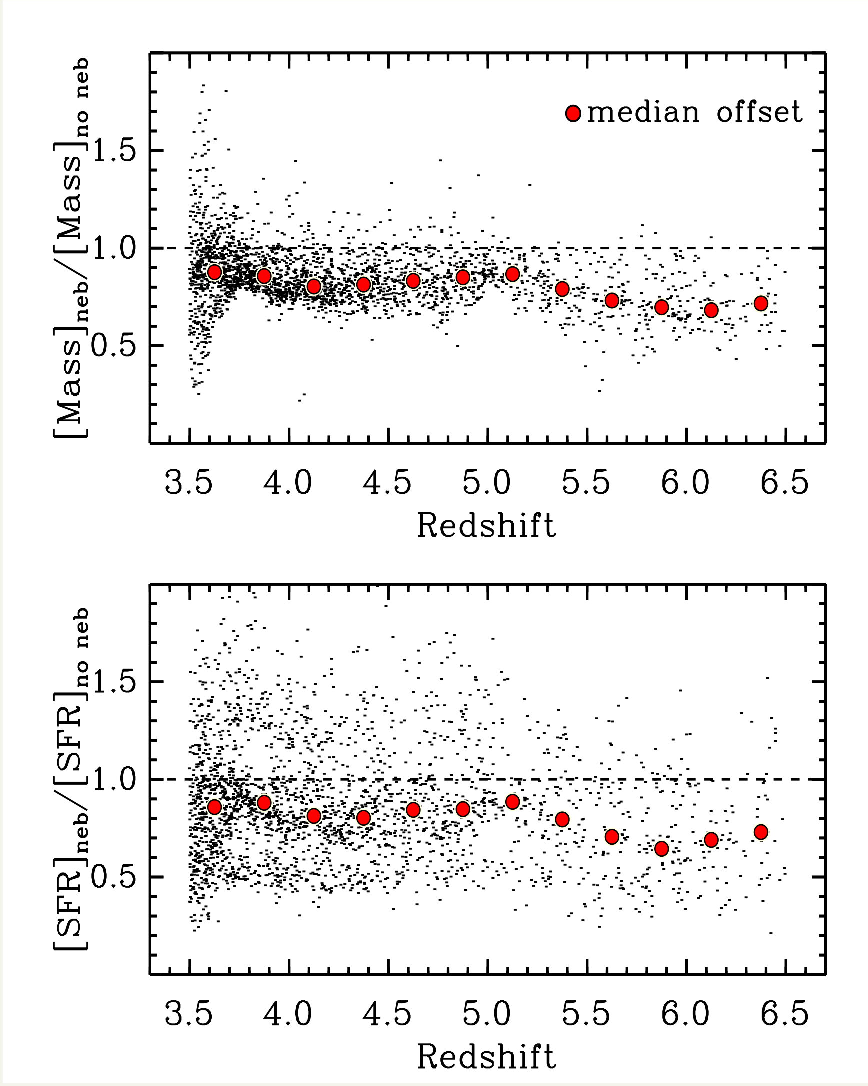


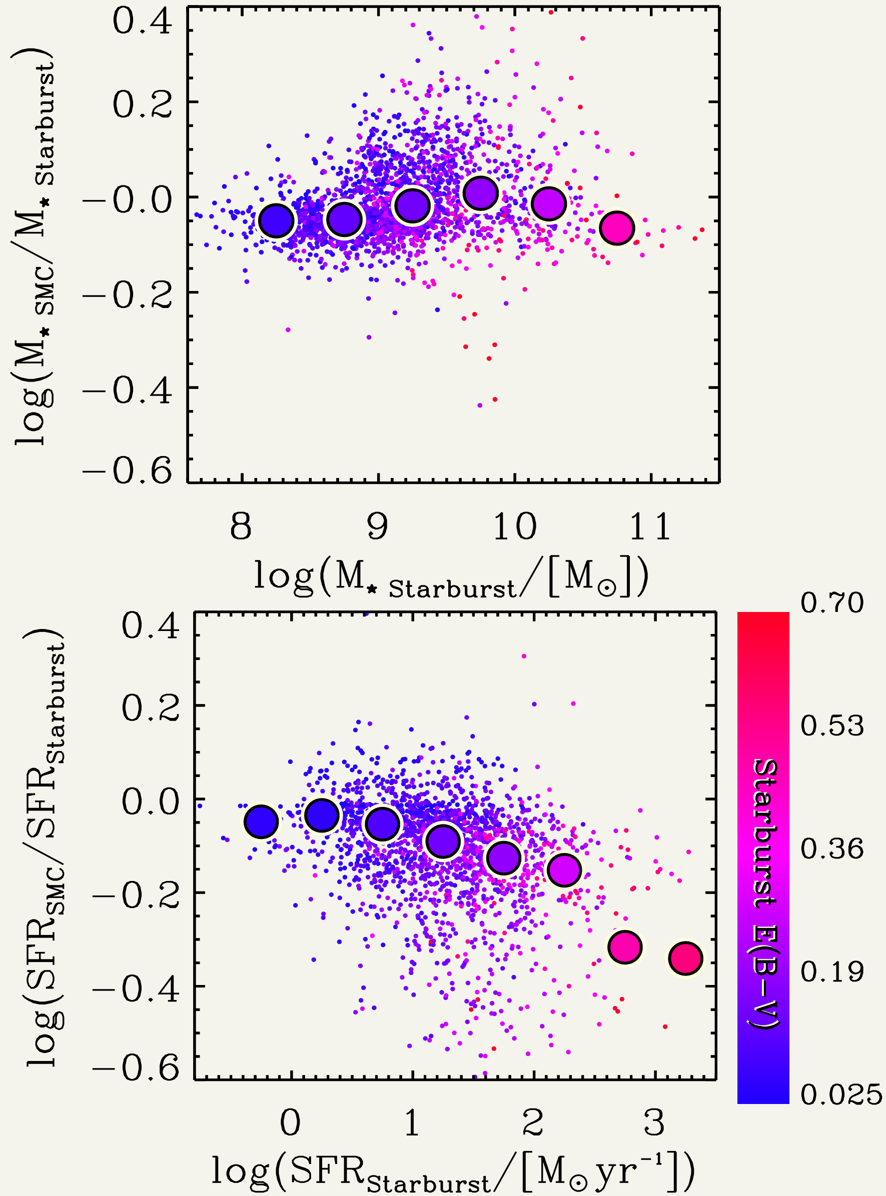
Ono+10

Sensitivity of Best Fits to Template Assumptions

Nebular Emission

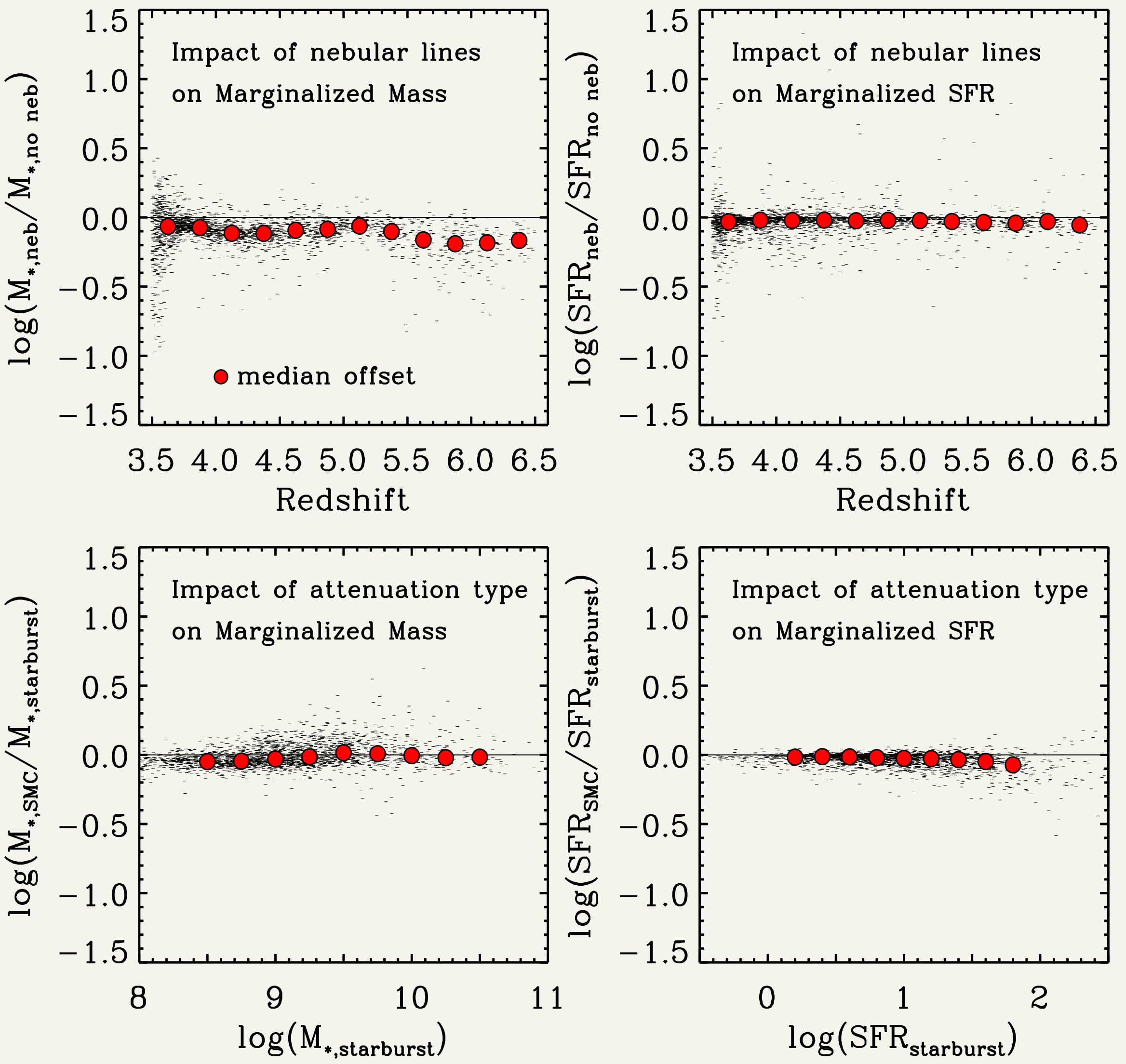


Attenuation slope



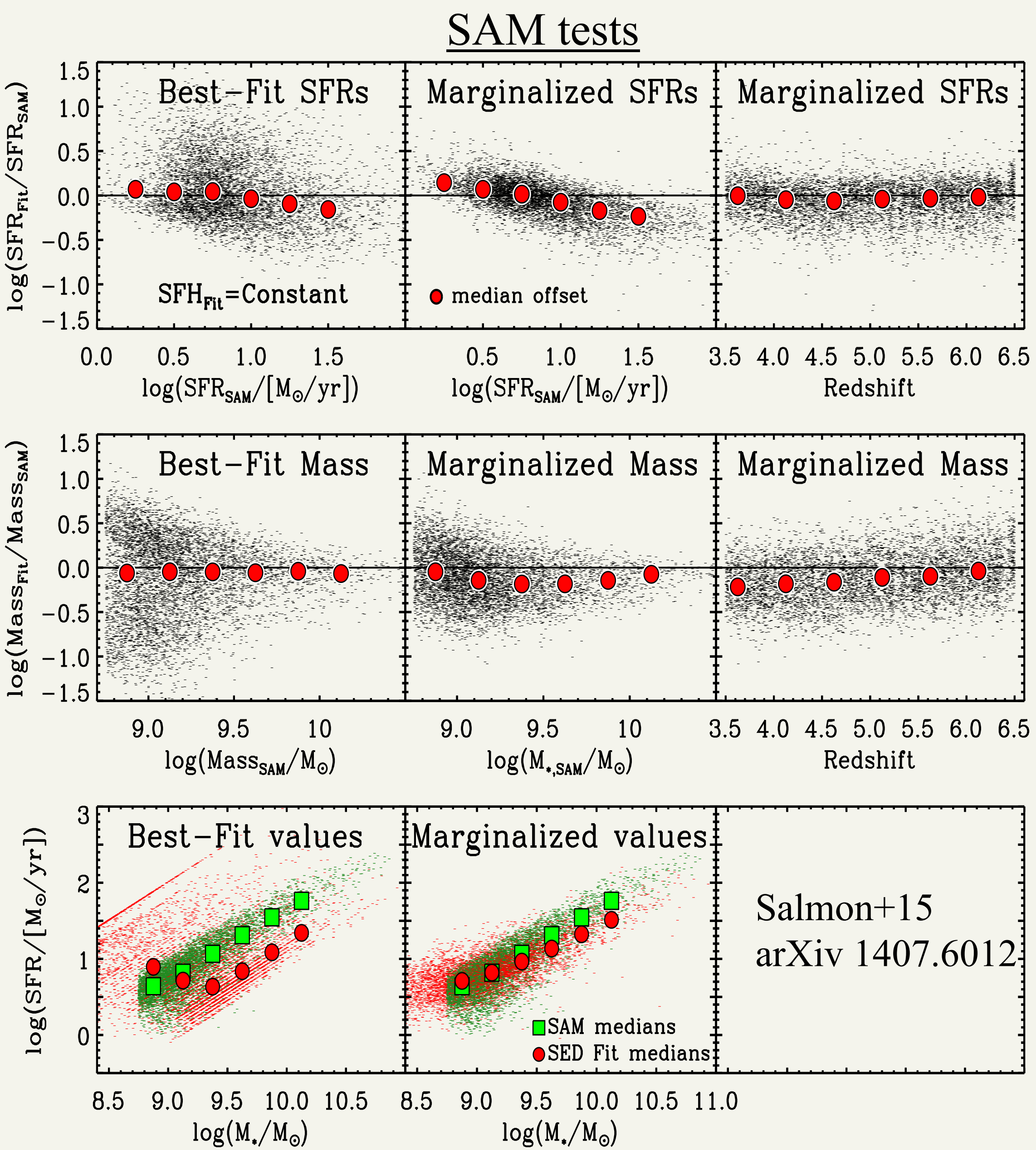
Sensitivity of Marginalized Values to Template Assumptions

- When marginalizing over posterior, some template assumptions become less pronounced
- Inclusion of nebular emission still displays a (small) decrement to stellar mass
- Effects of nebular emission or attenuation type on the SFR are now negligible



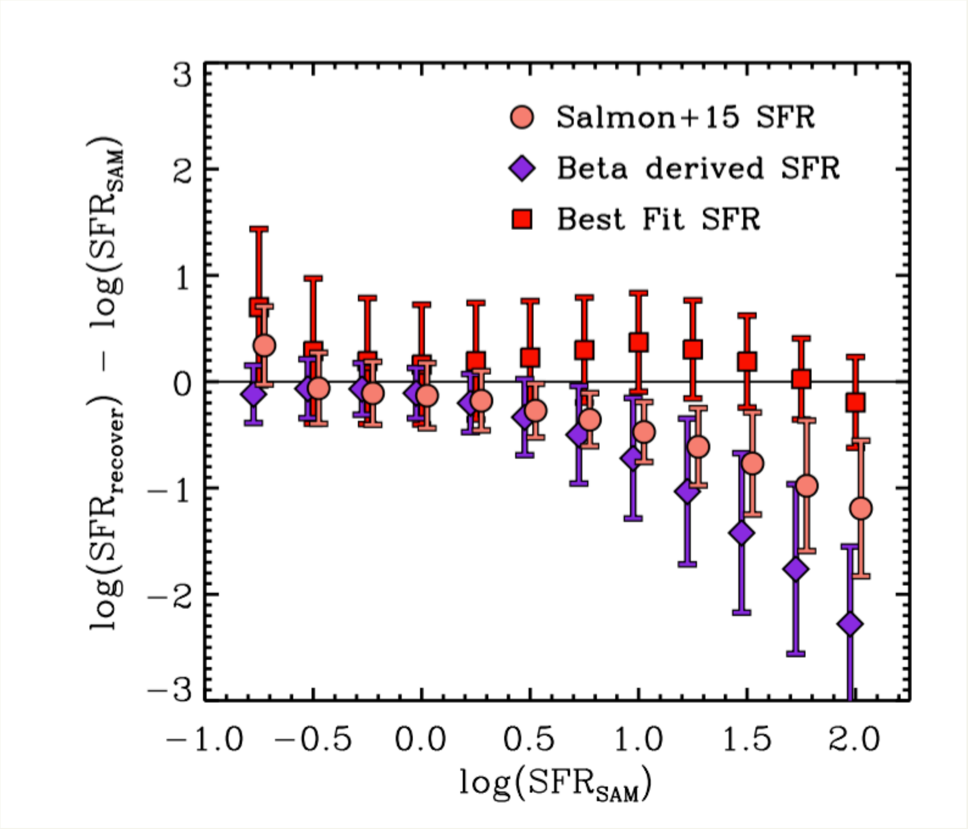
Sensitivity of Marginalized Values to Template Assumptions

- We quantify our ability to derive SFR and $M_\star$ by comparing to the Somerville et al. SAMs.
- SAM fluxes are perturbed by CANDELS-like uncertainties, and used as inputs
- The "best-fit" SED is less reliable at recovering SFR and $M_\star$ than using the median of the marginalized likelihood.



Improvements to UV SFR

- The L_{UV} is corrected for dust according to the marginalized A_{UV} posterior. Then, L_{UV} is converted to SFR according to an age-dependent Kennicutt relation.
- The right shows recovery of SFR from SAM objects after CANDELS-like flux perturbations
- Beta-derived A_{UV} is severely underestimated at high SFRs
- A deeper investigation with the SAM dust law is needed



Salmon+15 (in prep)

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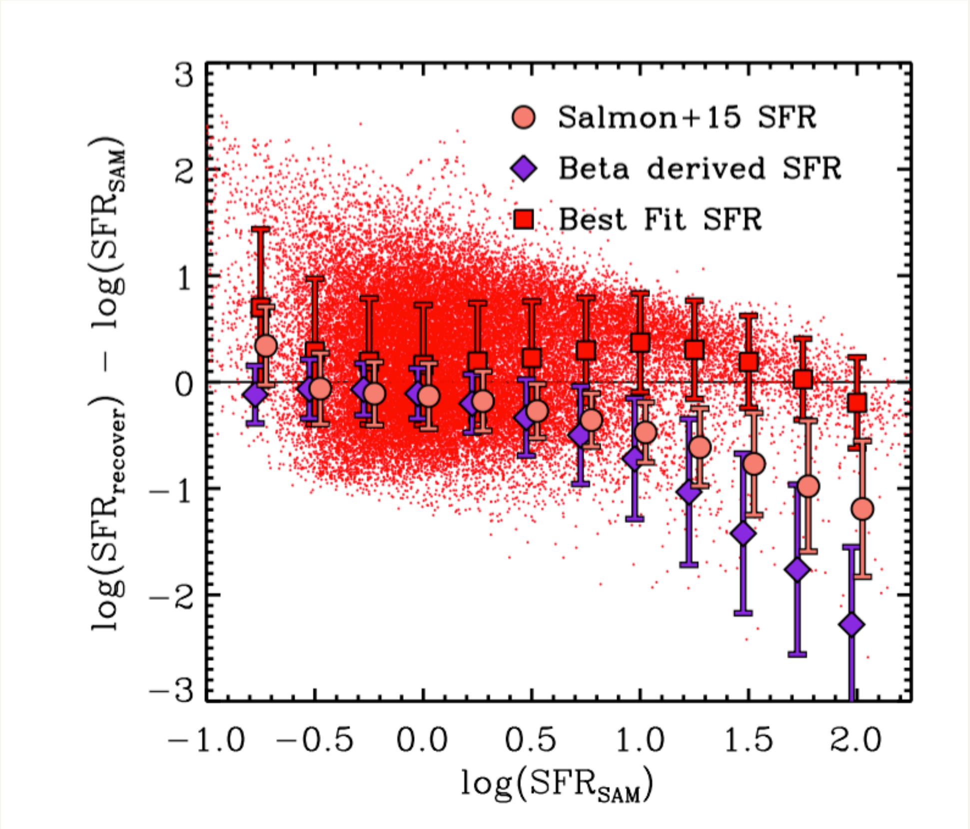

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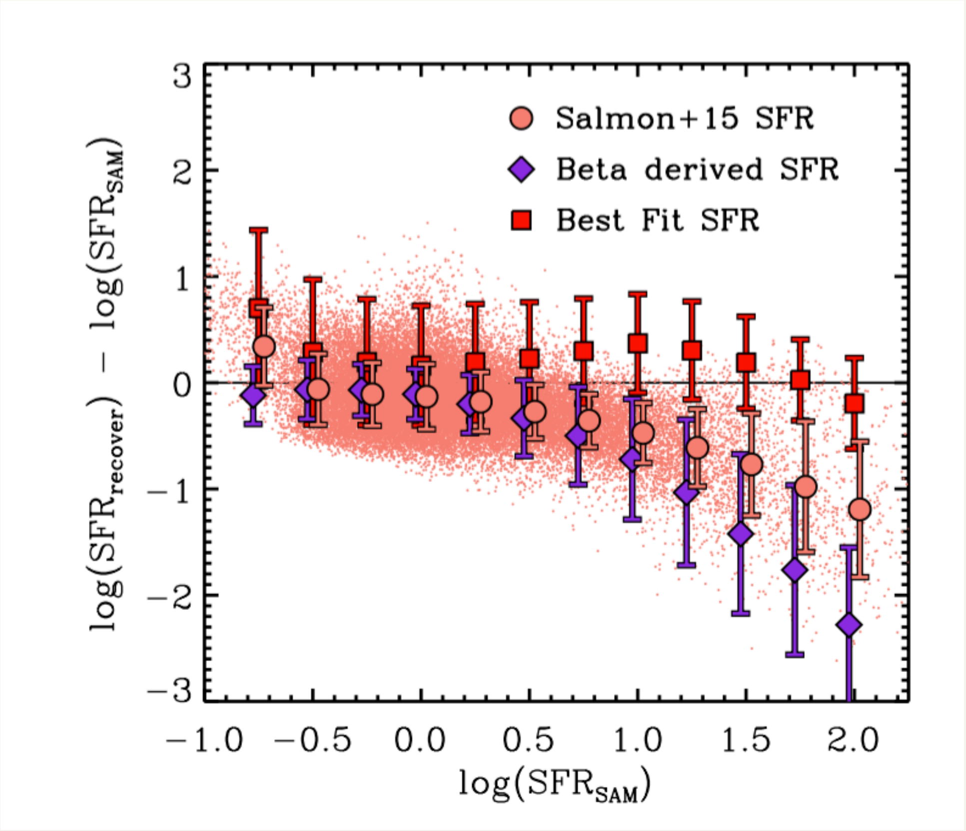

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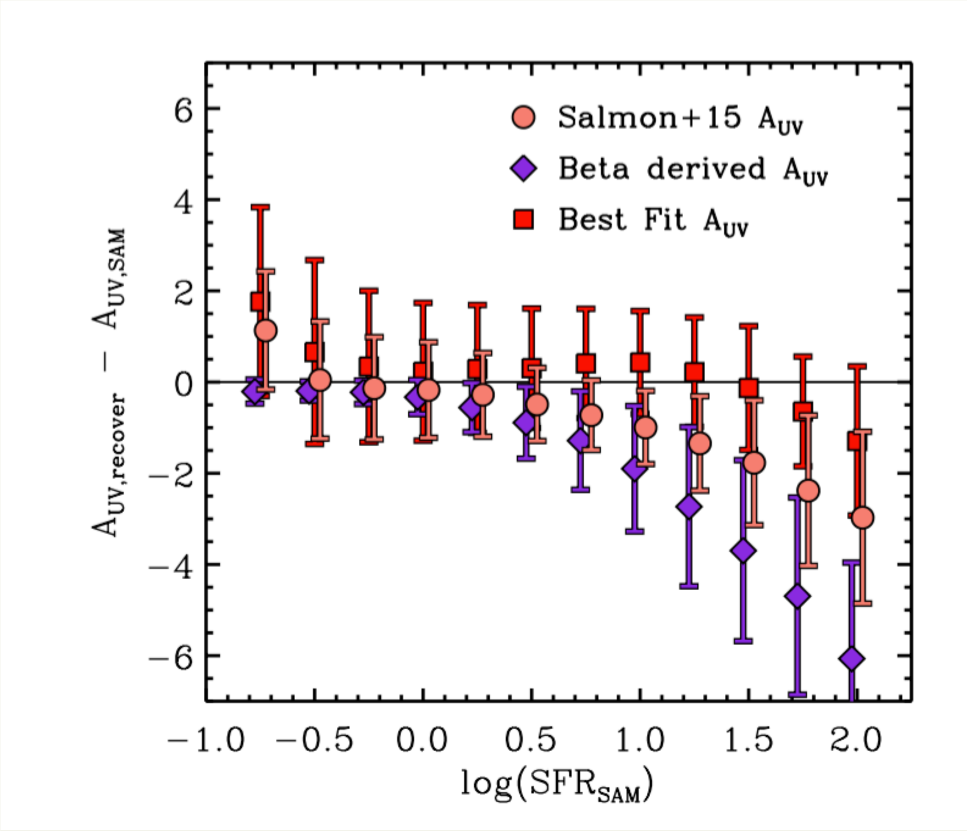
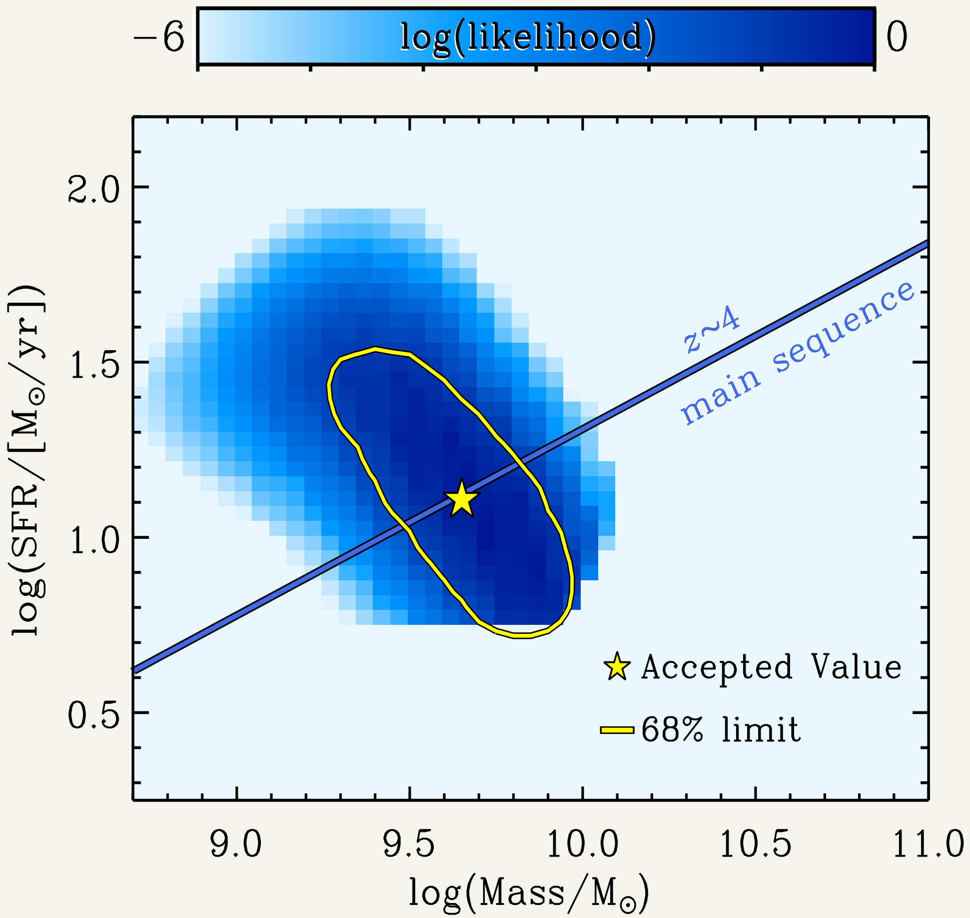


Salmon+15 (in prep)

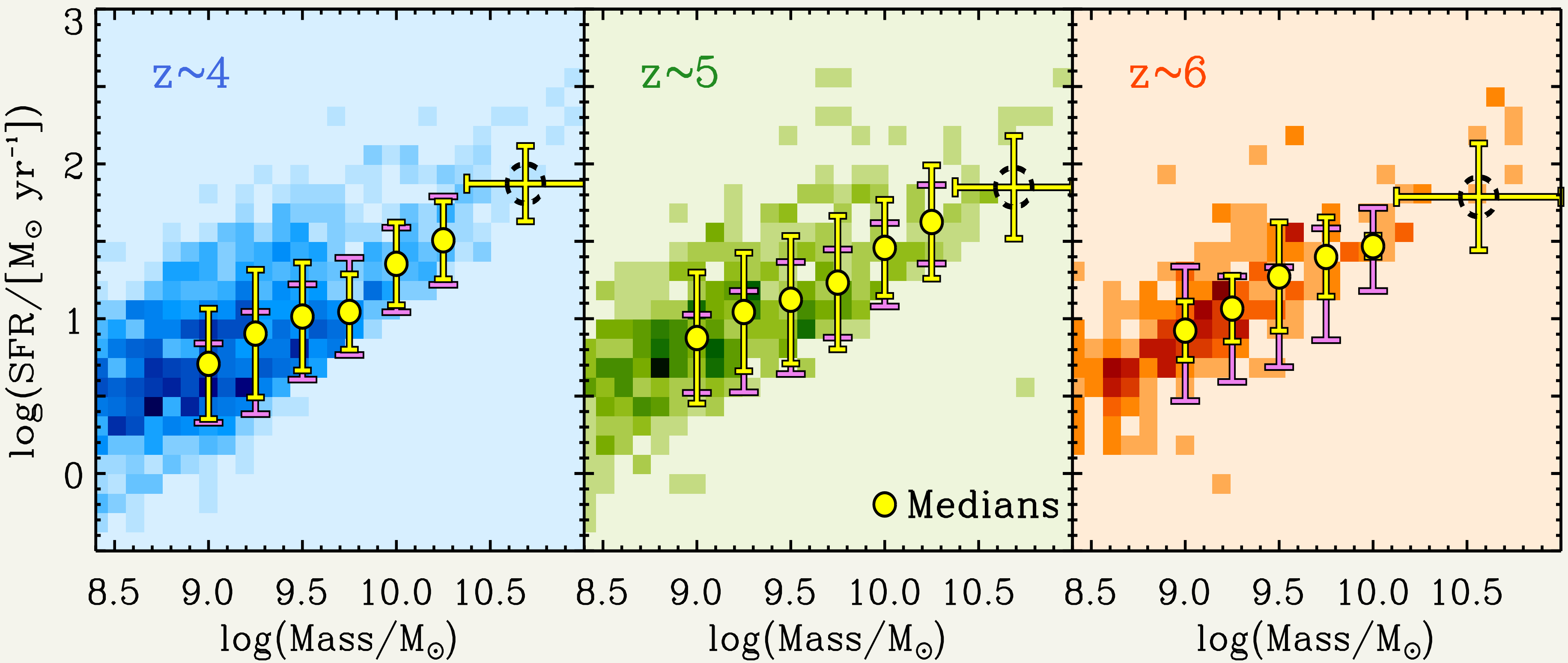
SFR-$M_\star$ in CANDELS

Single Object Scatter in SFR-$M_\star$ Plane

- Right: an individual object's 2D likelihood in the plane of SFR-$M_\star$
- The scatter in determining a single object's SFR or $M_\star$ is orthogonal to the main relation (from age-dust degeneracies)
- These observational uncertainties contribute scatter to the SFR-$M_\star$ plane, and must be accounted for with Monte Carlo simulations



Result: Slope of SFR-$M_\star$ remains un-evolving up to z~6



- log(SFR) ≈ α log($M_\star$), α remains <1 (about α=0.6 across all redshift)

Salmon+15 (accepted)

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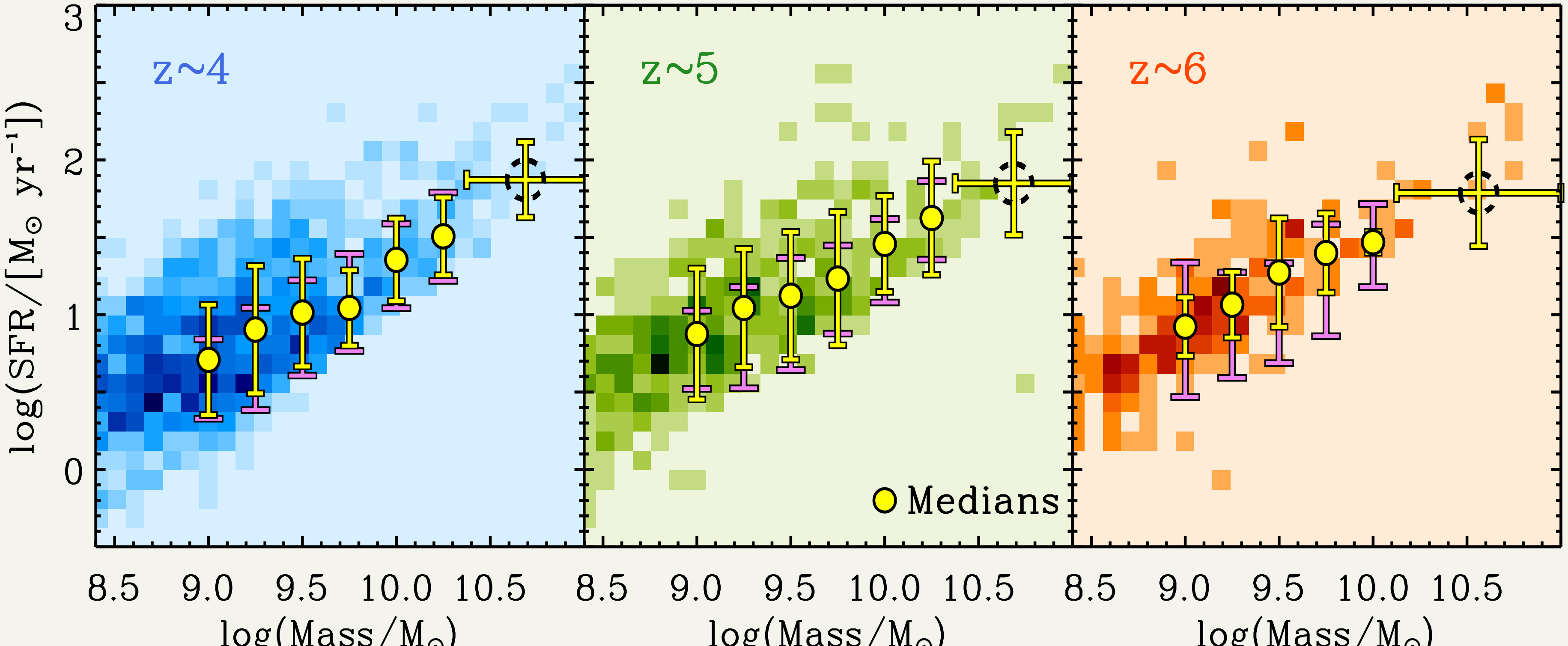
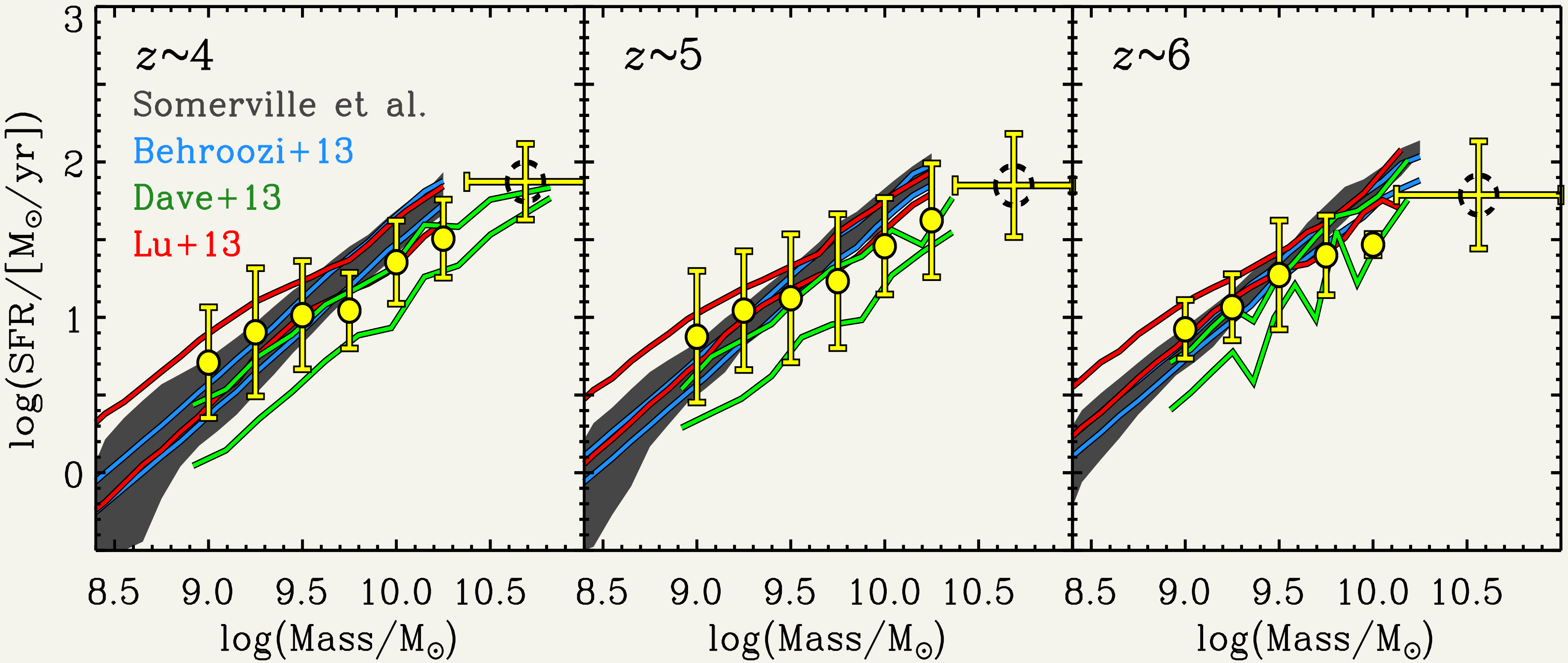


- log(SFR) ≈ α log($M_\star$), α remains <1 (about α=0.6 across all redshift)

- Considering most observational uncertainties (purple), the "true" intrinsic scatter in SFR-$M_\star$ is as much as 0.2-0.3 dex

Salmon+15 (accepted)

Result: SFR-M$_\star$ is consistent with many theoretical models



- If SFR traces the net gas inflow, then the "true" scatter in the inflow rate is 0.2-0.3 dex.
- Does this imply that, on average, early galaxy growth history is not stochastic?

Salmon+15 (accepted)

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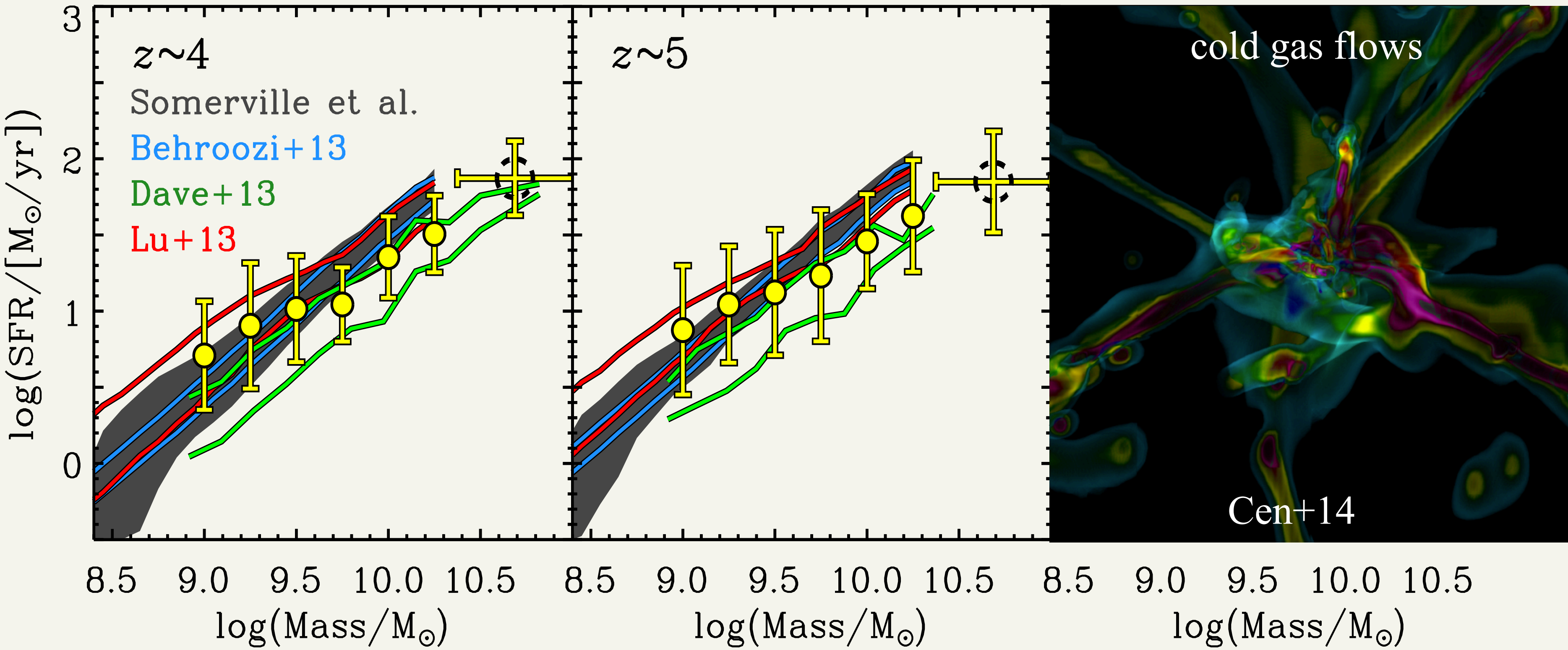
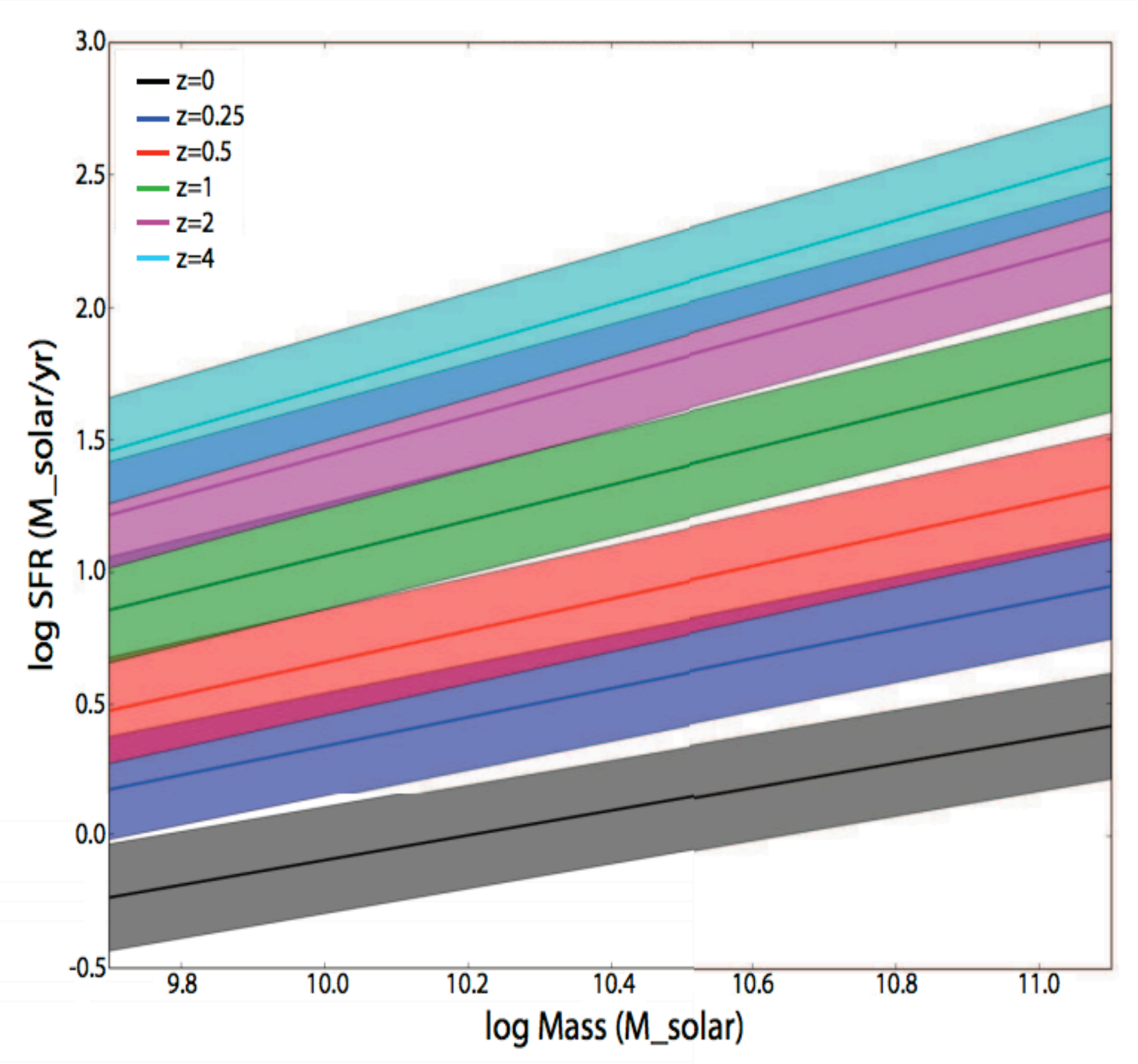


- If SFR traces the net gas inflow, then the "true" scatter in the inflow rate is 0.2-0.3 dex.
- Does this imply that, on average, early galaxy growth history is not stochastic?
- These observations favor smooth gas accretion over these redshifts and stellar masses

How Does this SFR-$M_\star$ relation evolve over time? and in the literature?

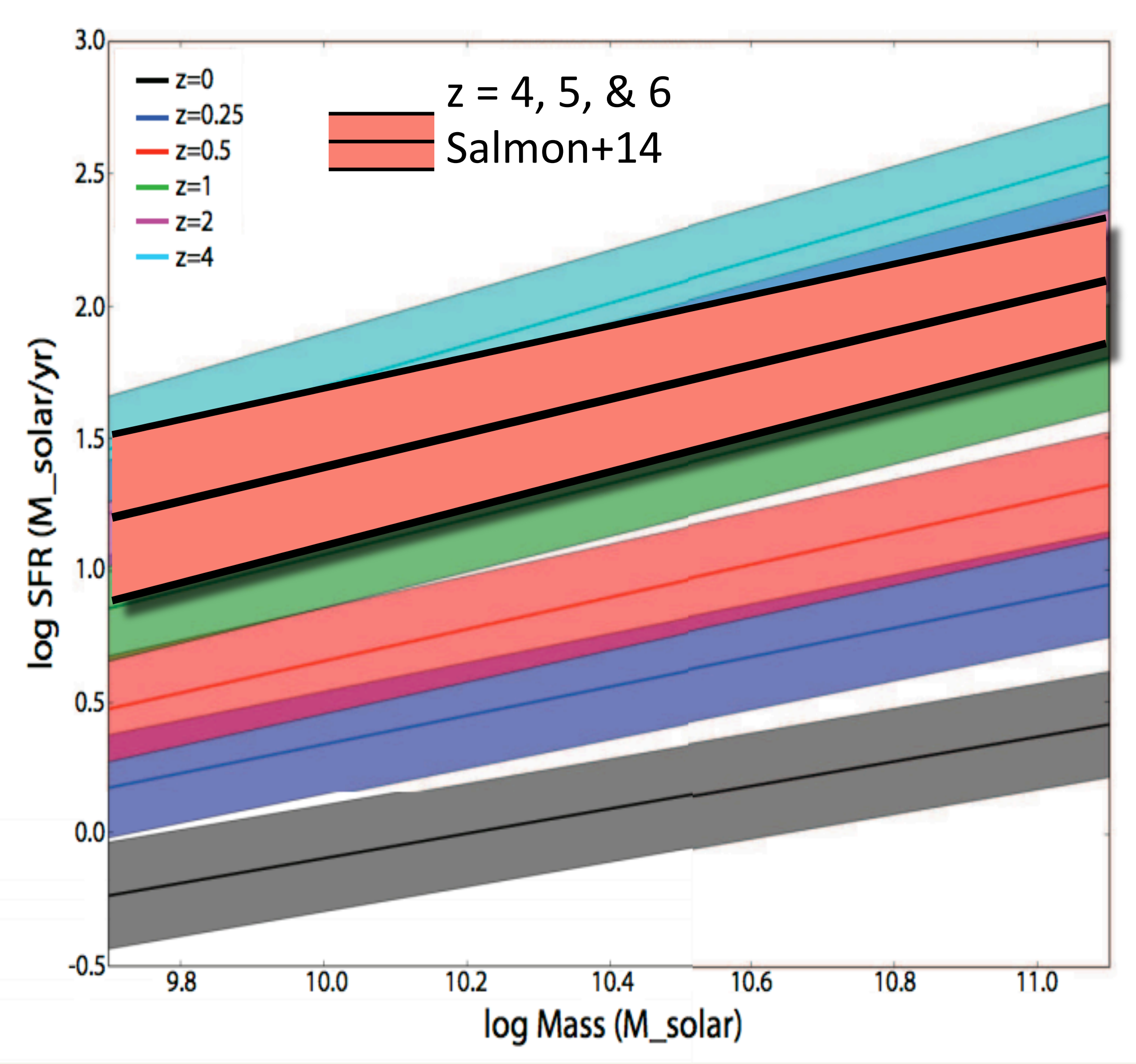
- At least since the first 800 Myr of the Universe, the scatter in SFR at a given mass is small (~0.2-0.3 dex after taking into account observational uncertainties).
- The SFH can be best described as a power law SFR = $(t/\tau)^\gamma$, where γ=1.4 at high redshift (z>4).



Speagle+14

SFR-$M_\star$ evolves little in slope, and decreases in scale over cosmic time

- At least since the first 800 Myr of the Universe, the scatter in SFR at a given mass is small (~0.2-0.3 dex after taking into account observational uncertainties).
- The SFH can be best described as a power law SFR = (t/τ)^γ, where γ=1.4 at high redshift (z>4).
- The slope and scatter at high redshift is consistent with low-z results in the literature.

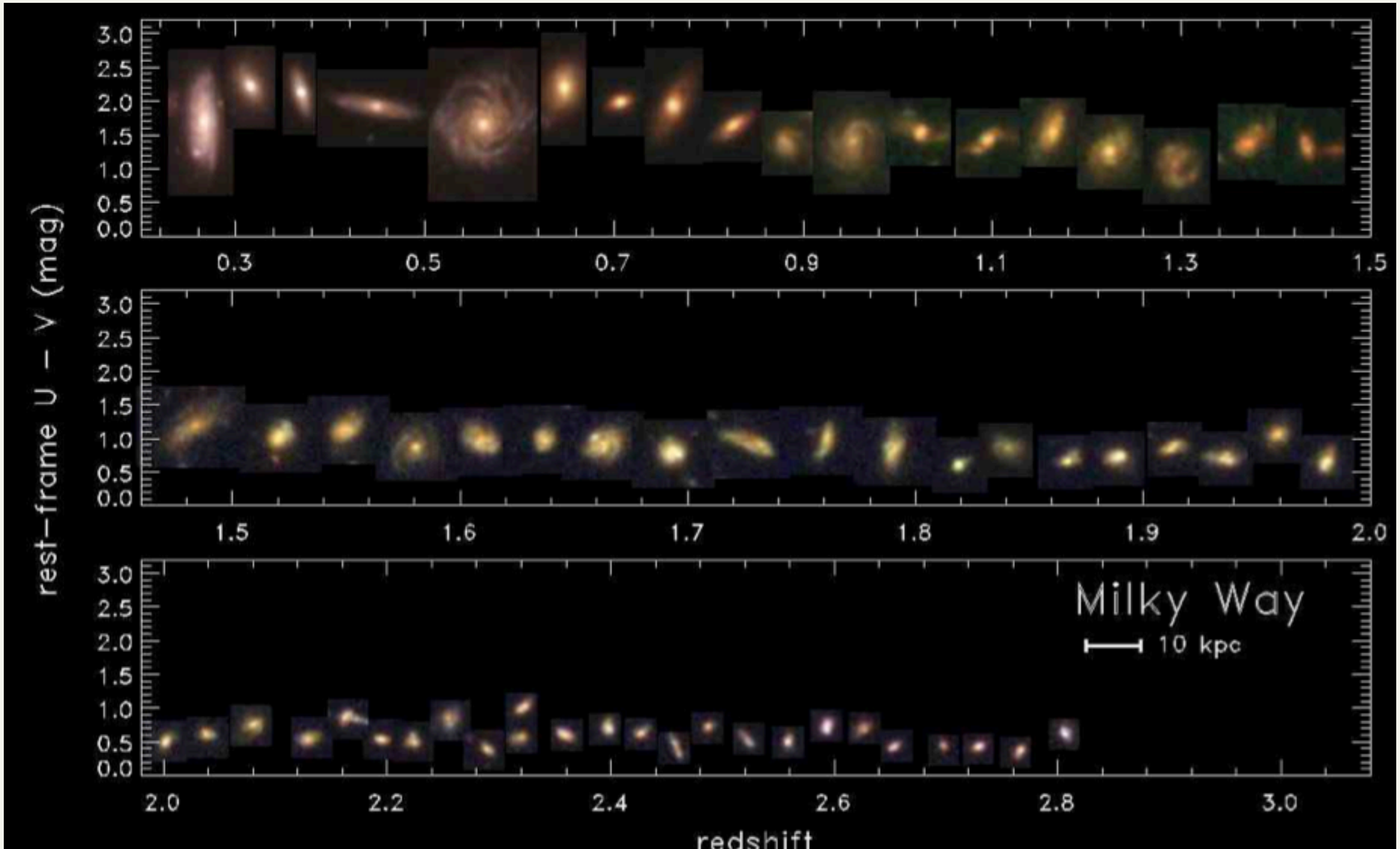


Speagle+14

Star-Formation Histories

A Test: What Does the History of These Galaxies Look Like?

- A number-density selection can track the progenitor-to-descendant evolution across redshift.
- The most massive galaxies in a comoving volume, will be the progenitors of the most massive galaxies at a later time



Papovich+15(accepted)

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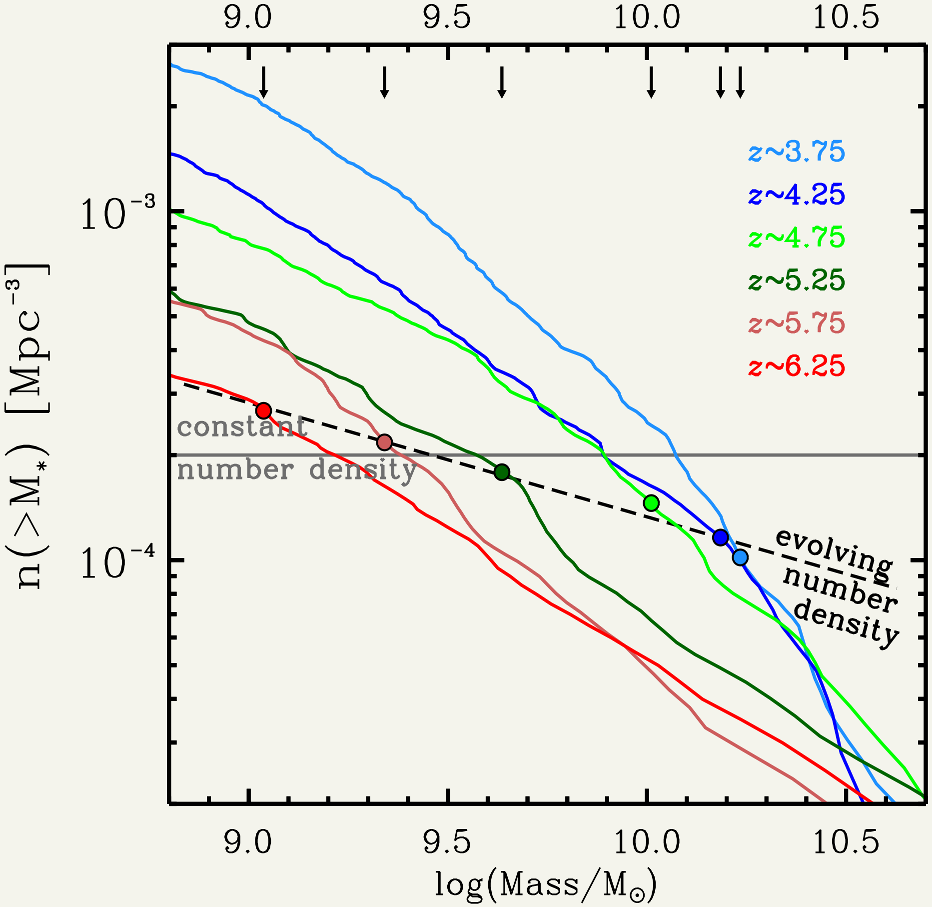
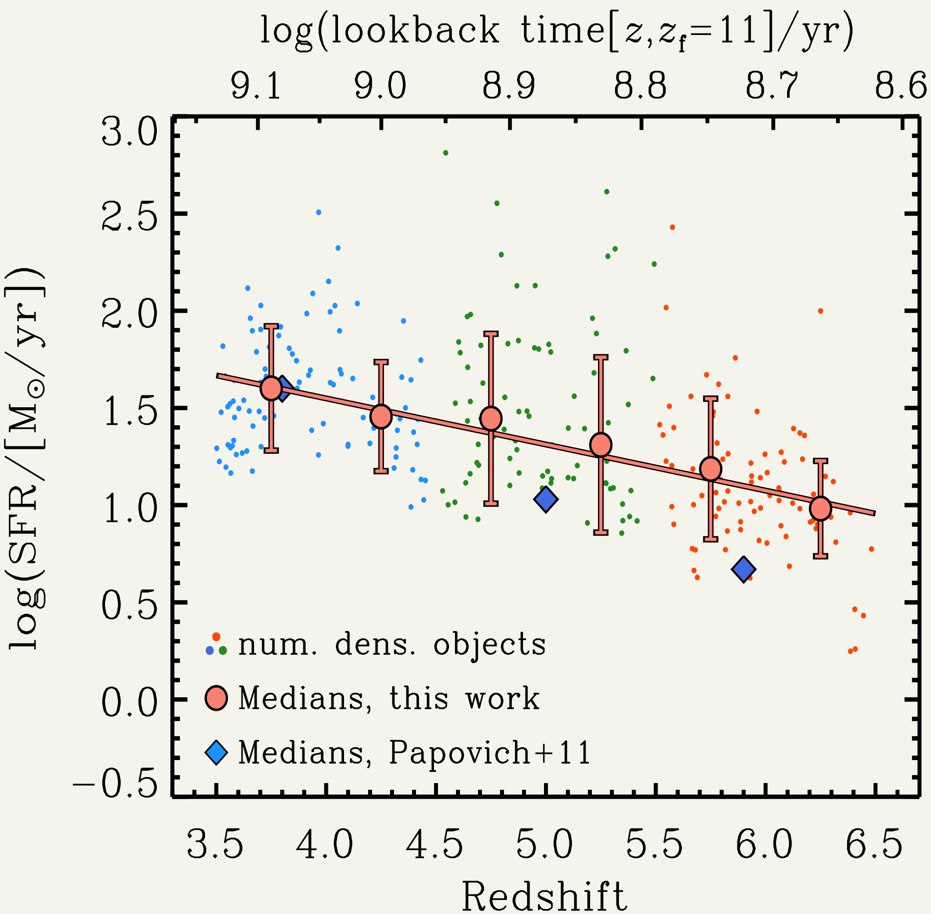


- Objects were selected according to an evolving number density in stellar mass, as predicted by dark matter abundance matching (Behroozi+13b)

Salmon+15 (accepted)

A Test: What Does the History of These Galaxies Look Like?

Does it match the observed SFR-$M_\star$ relation?



- Objects were selected according to an evolving number density in stellar mass, as predicted by dark matter abundance matching (Behroozi+13b)
- We find a rising SF history at high redshift,
  as expected, with SFR = (t/τ)^γ and γ=1.4
- Now, let's feed this history into a stellar population synthesis model

Salmon+15 (accepted)

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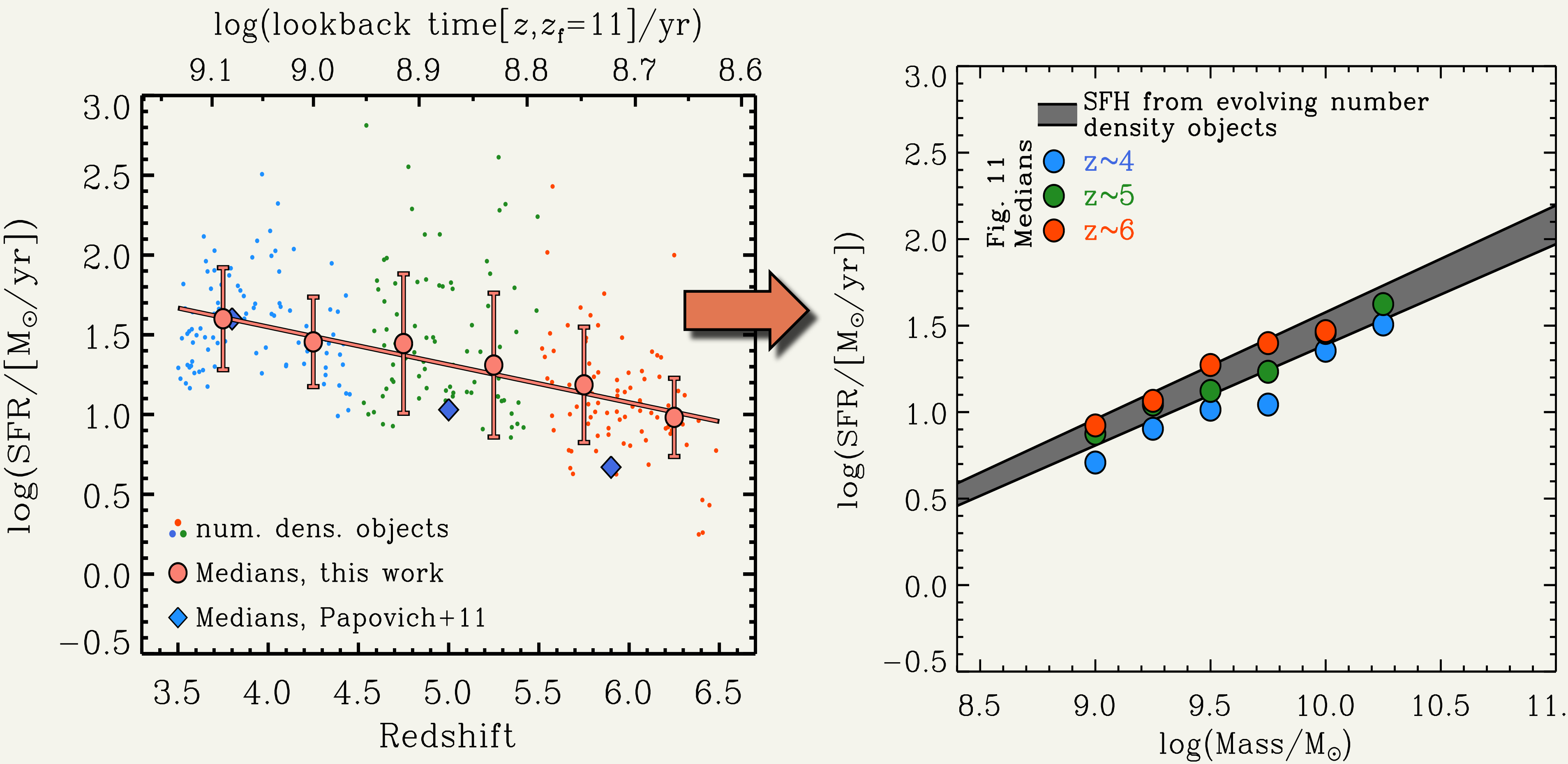
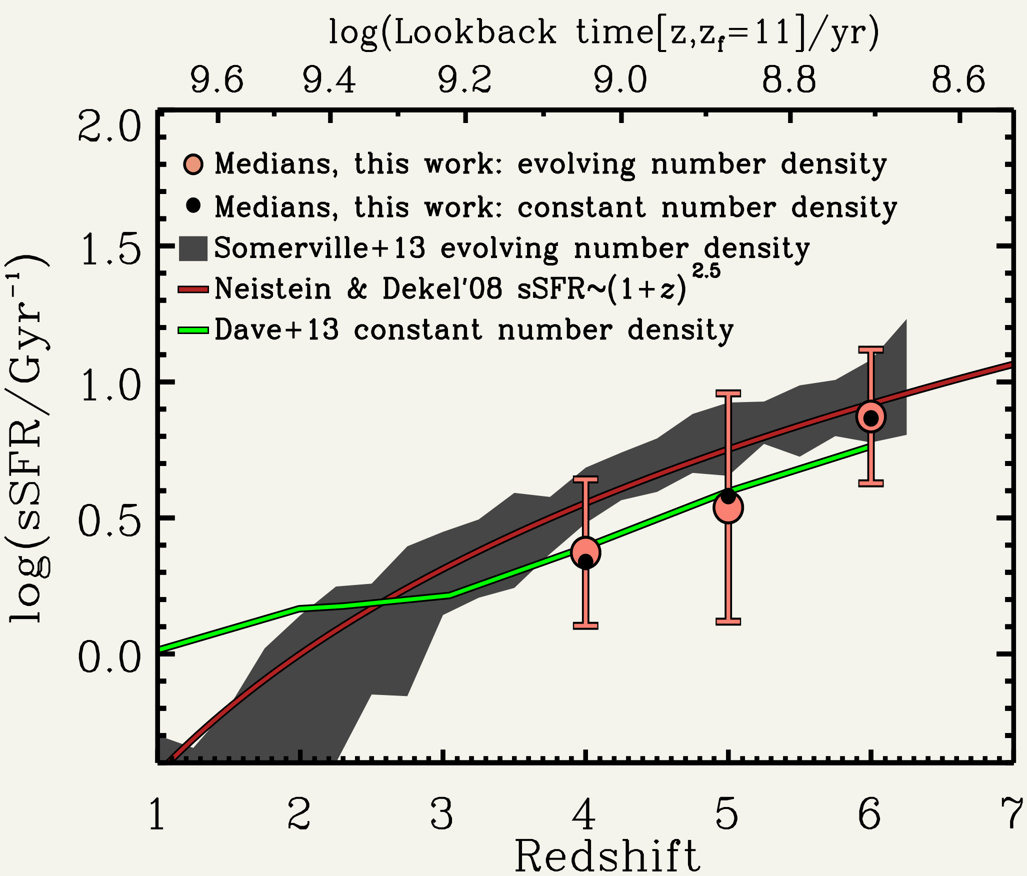


Salmon+15 (accepted)

We need dust measurements of high-z galaxies to constrain the SFR efficiency

- Theory predicts a rapidly evolving gas-mass fraction with redshift.
- Data is broadly consistent with trend, but scatter in sSFR is still depending on SED modeling
- Must turn to [CII] from ALMA to determine the dusty IR SFR, constraining the total UV+IR SFR
- We also need gas masses to find the cause of the SFR-$M_\star$ scatter (is it SF efficiency or scatter in galaxy formation time?)

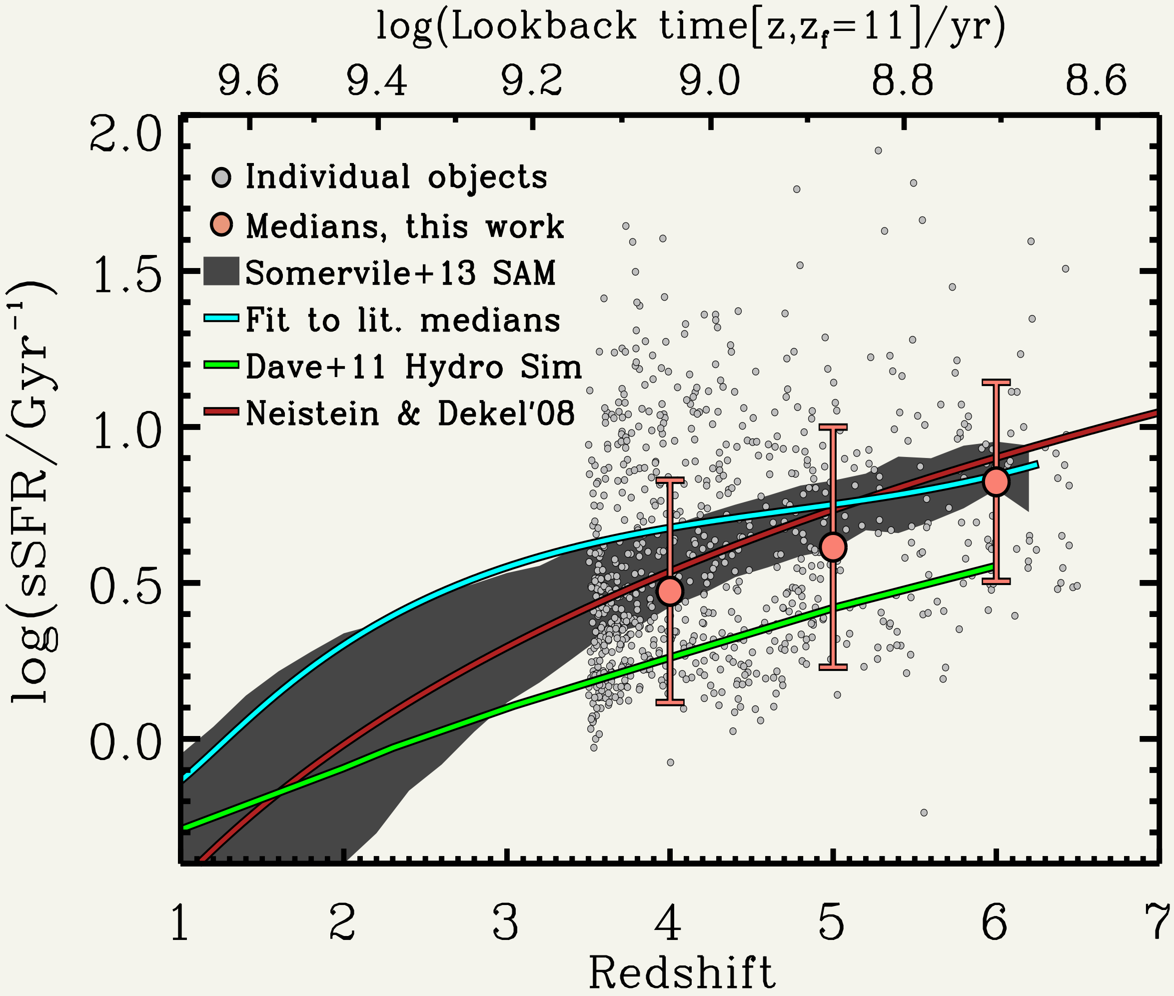


Observational uncertainties are still too high to make model constraints

Salmon+15 (accepted)

Summary

- Whenever possible, use marginalized information instead of best-fit results. However, this will introduce a prior that is dependent on the assumed templates
- The marginalized approach to the UV SFR seems favorable, though further tests to SAMs are needed
- The relation between SFR and $M_\star$ for star-forming galaxies evolves little in slope, and declines in scale since the 1^{st} Gyr of the Universe (Wuyts+11, Panella+14).
- The scatter in SFR at a given mass is small at all redshifts (~0.2-0.3 dex after taking into account observational uncertainties). If SFR traces the net gas inflow rate, then this result favors smooth, cosmological gas accretion onto galaxies.
- The SFH can be best described as a power law SFR = $(t/\tau)^\gamma$ at high redshift ($z>4$, $\gamma=1.4$), or a delayed-tau model across the age of the Universe (Salmon+15).

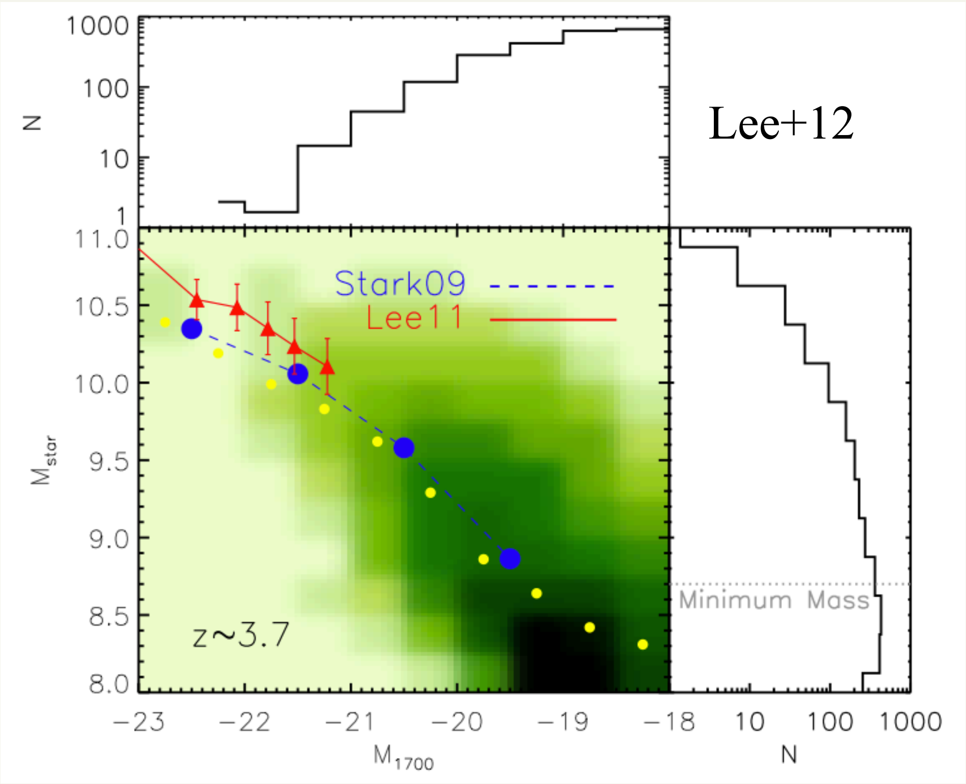


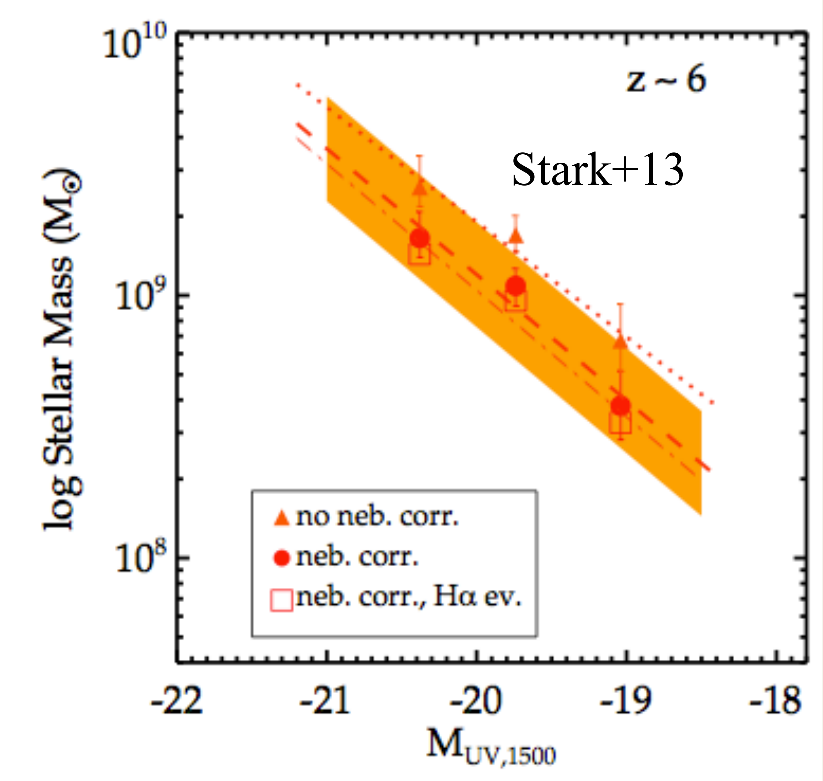
log(Lookback time[z,z_f=11]/yr)
9.6
9.4
9.2
9.0
8.8
8.6
2.0
1.5
1.0
0.5
0.0
log(sSFR/Gyr^-1)
Individual objects
Medians, this work
Somervile+13 SAM
Fit to lit. medians
Dave+11 Hydro Sim
Neistein & Dekel'08
1
2
3
4
5
6
7
Redshift

What do we know?

Dust is important, lending to scatter in M_{UV}–$M_\star$

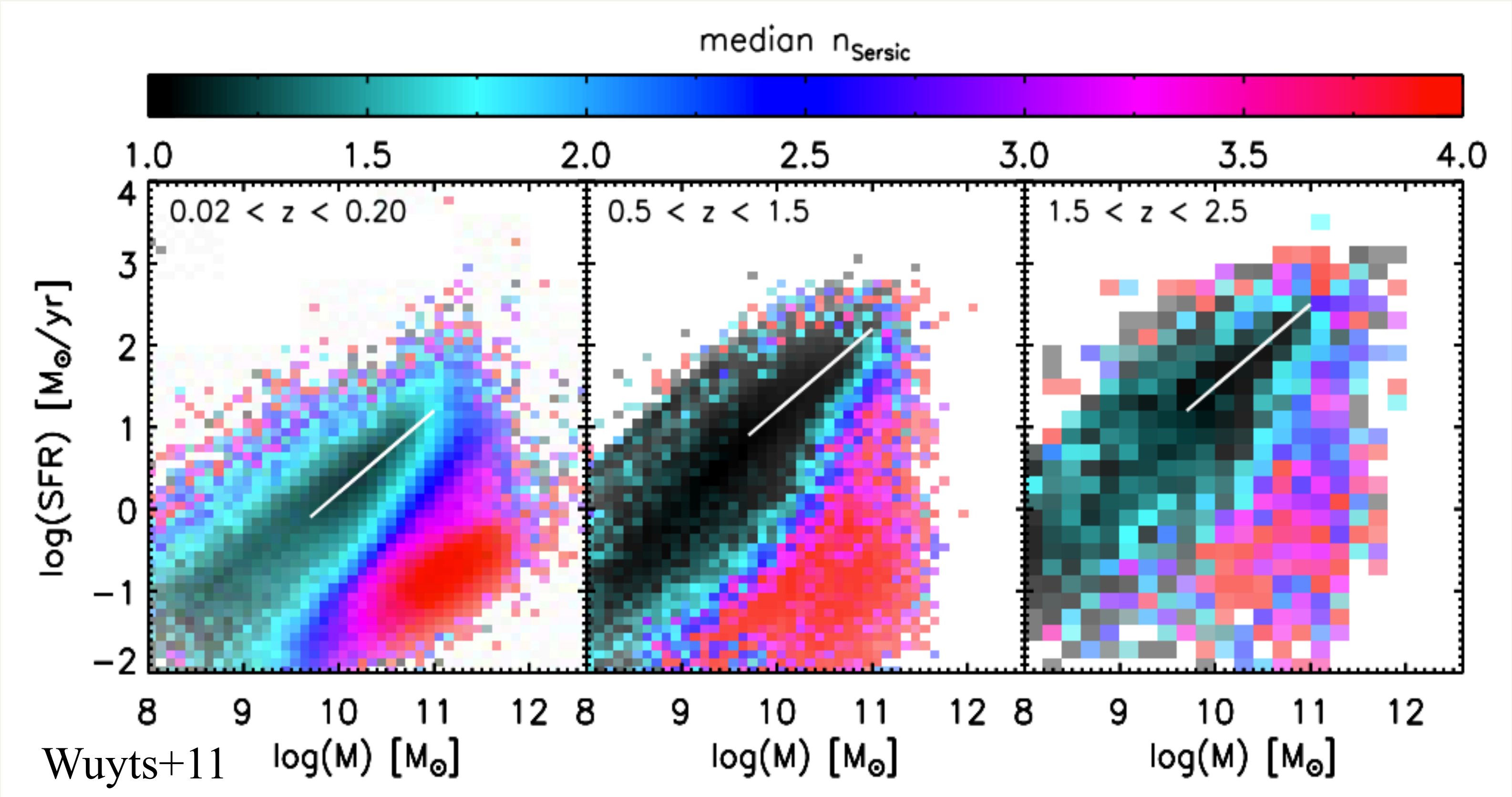
- There is an observed correlation between MUV and stellar mass, but with significant scatter
- The scatter may be physical, or due to a range of dust attenuations at a given stellar mass. The answer lies in the scatter about the main sequence of SFR-$M_\star$





What do we know?

The relation between SFR and $M_\star$ reveals interesting galaxy physics



- SFR-$M_\star$ can distinguish between star-forming, elliptical, and starburst galaxies
- A relation means the current SFR is proportional to the integral of SFR over time
- The scatter about SFR-$M_\star$ can be due to
  - scatter in the net inflow rate of gas to fuel star formation
  - scatter in the galaxy formation time

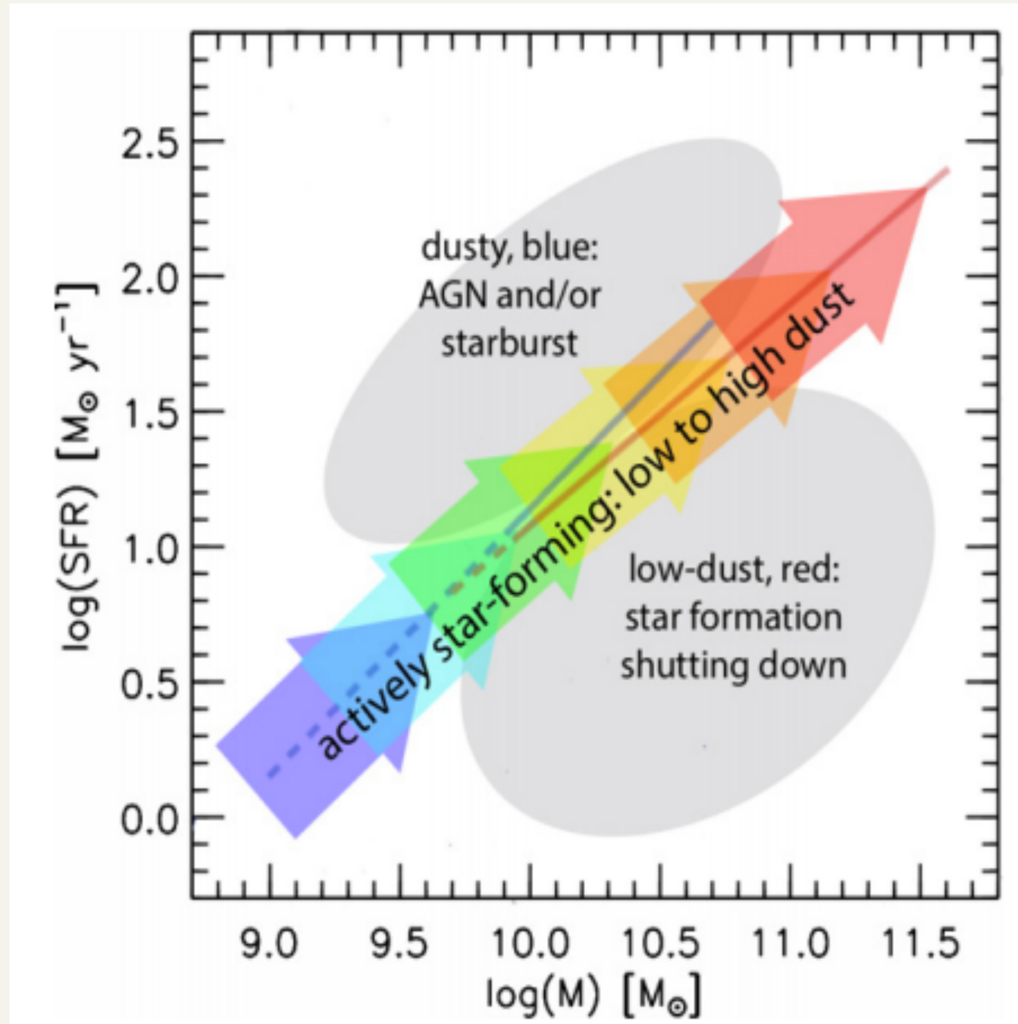
What drives galaxies off the SFR-$M_\star$ relation?

and with what uncertainties?

- Physical causes:
  - Starbursts, AGN
  - Stochastic SF histories
  - Star-formation quenching (mainly at low redshift)

- $M_\star$ correlates strongly with UV dust attenuation (Panella+14).

  If the scale of SFR-$M_\star$ decreases with time, then galaxies with the same amount of SF are *less* attenuated at higher redshift (it is hosted by a less massive, less metal rich galaxy).



Whitaker+12