The Main Sequence of Star-Forming Galaxies from CANDELS

Brett Salmon[1], Casey Papovich[1], Steven L. Finkelstein[2], Vithal Tilvi[1], Kristian Finlator, Peter Behroozi, Tomas Dahlen, Romeel Davé, Avishai Dekel, Mark Dickinson, Henry C. Ferguson, Mauro Giavalisco, James Long, Yu Lu, Naveen Reddy, Rachel S. Somerville, Risa H. Wechsler

[1]Texas A&M University, [2]University of Texas

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High redshift = z >2-3

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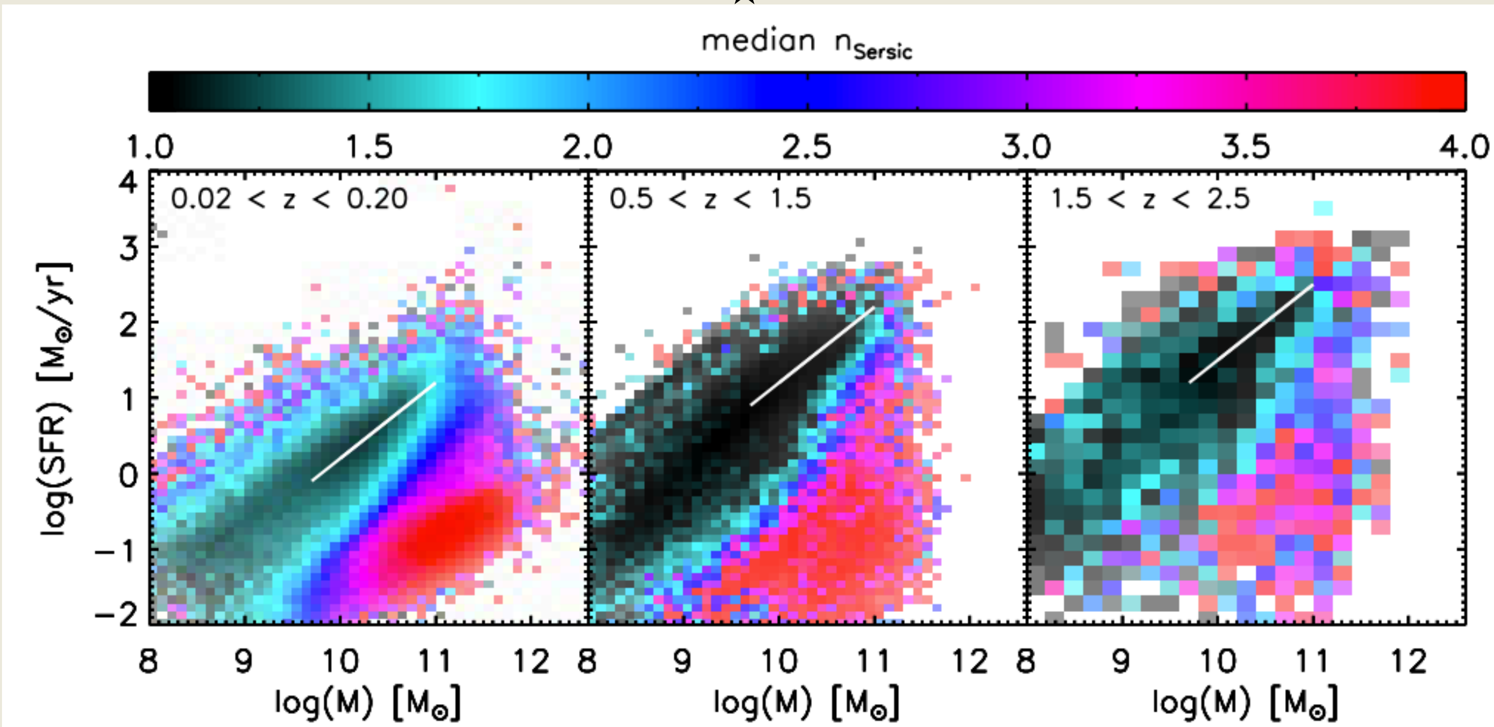
What do we know?

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



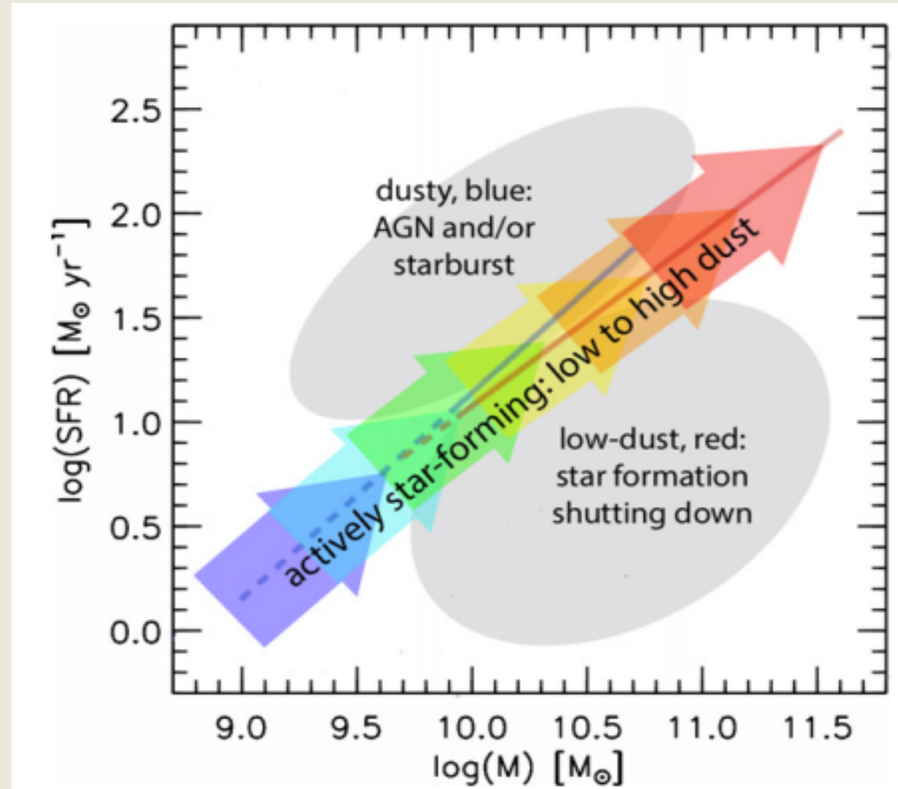
- SFR-$M_\star$ can distinguish between star-forming, elliptical, and starburst galaxies
- The scatter about SFR-$M_\star$ can be due to
  - scatter in the net inflow rate of gas to fuel star formation
  - scatter in the galaxy formation time

Wuyts+11

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

and with what uncertainties?

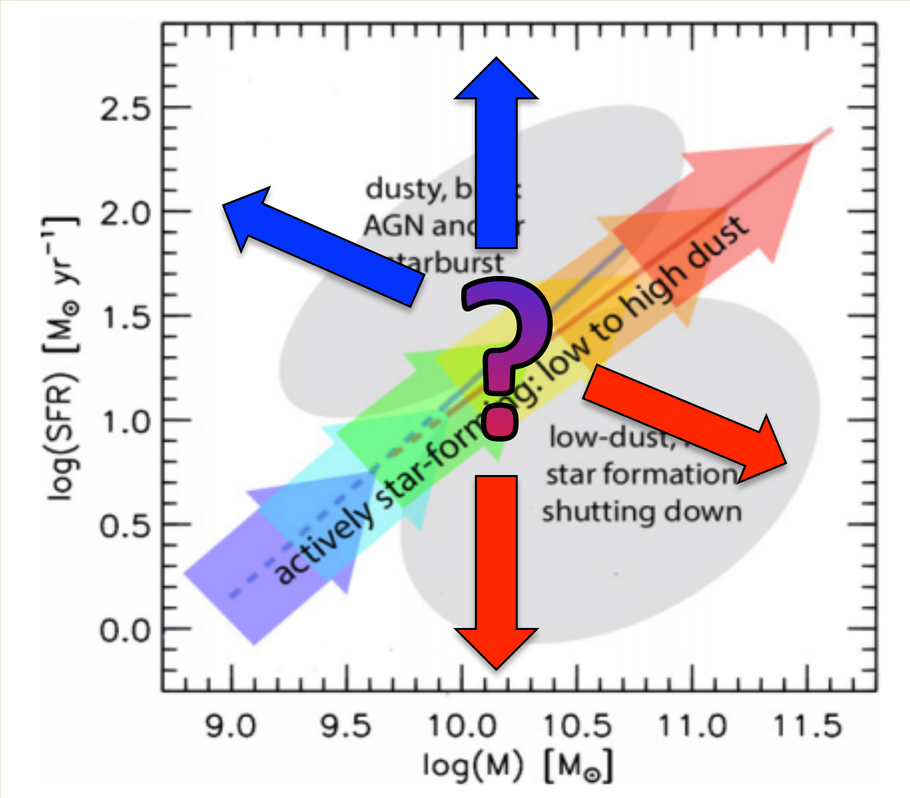
- Physical causes:
  - Starbursts, AGN
  - Stochastic SF histories
  - Star-formation quenching (mainly at low redshift)
- $M_\star$ correlates strongly with UV dust attenuation (Panella+14). Thus, galaxies with the same amount of SF are *less* attenuated at higher redshift (it is hosted by a less massive, less metal rich galaxy).



Whitaker+12

What drives galaxies off the SFR-$M_\star$ relation, and with what uncertainties?

- SED fitting methods
- Template assumptions
- Redshift uncertainties
- Sample selection
- SFR indicators

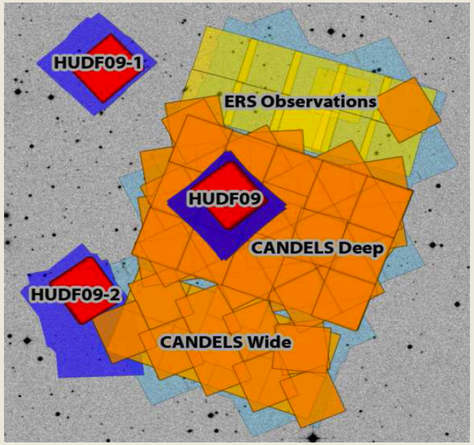


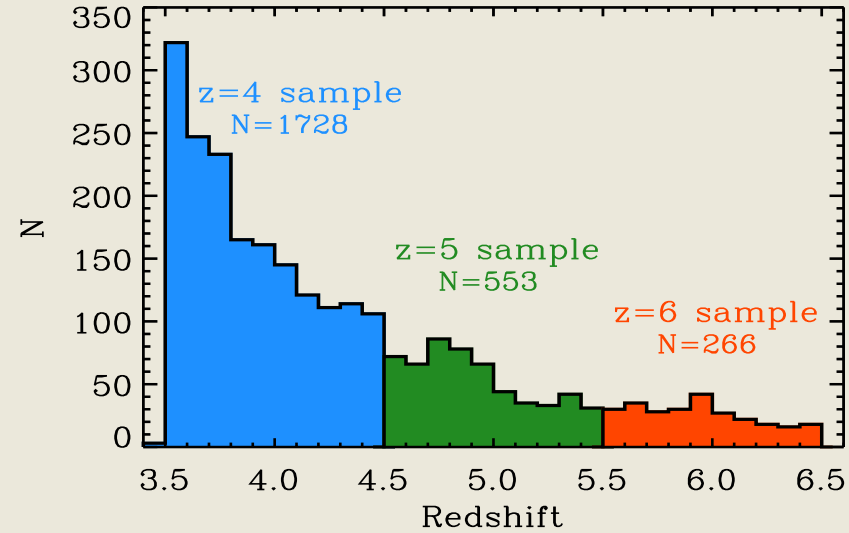
Whitaker+12

Sample: CANDELS GOODS-S, photometric-redshift selection

What can broadband photometry tell us?

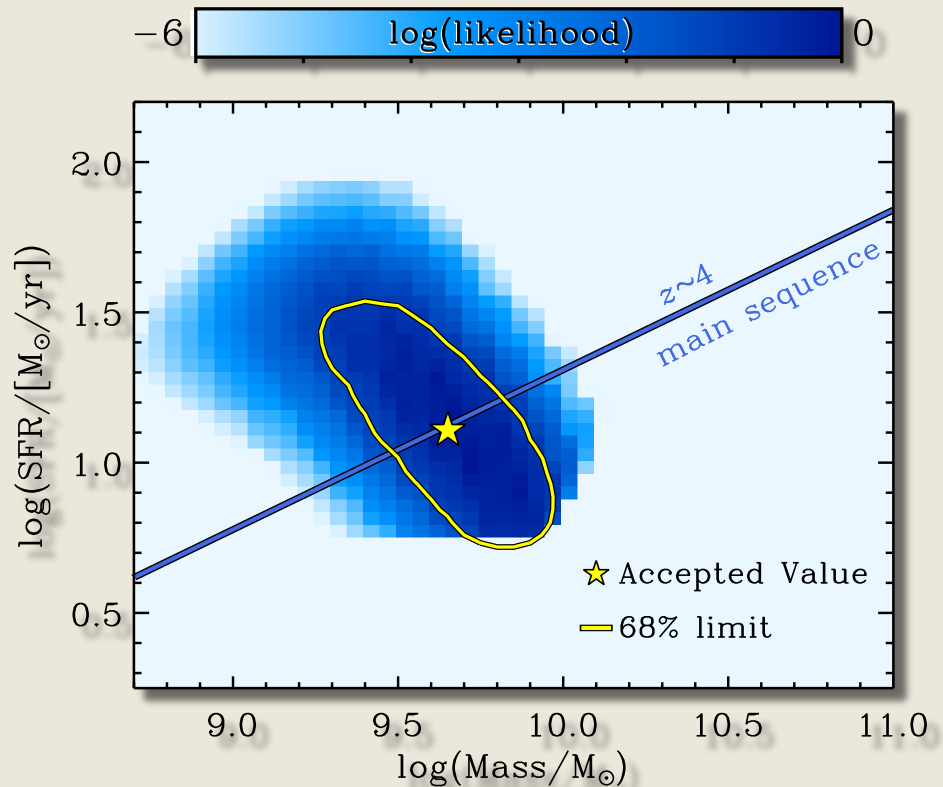
- We use a Bayesian SED fitting procedure that calculates the posterior on each galaxy and marginalizes over nuisance parameters.
- UV SFRs calculated using an age-dependent Keniccutt 1998 conversion
- See Salmon+14 (arXiv 1407.6012) for details





What drives galaxies off the SFR-$M_\star$ relation, and with what uncertainties?

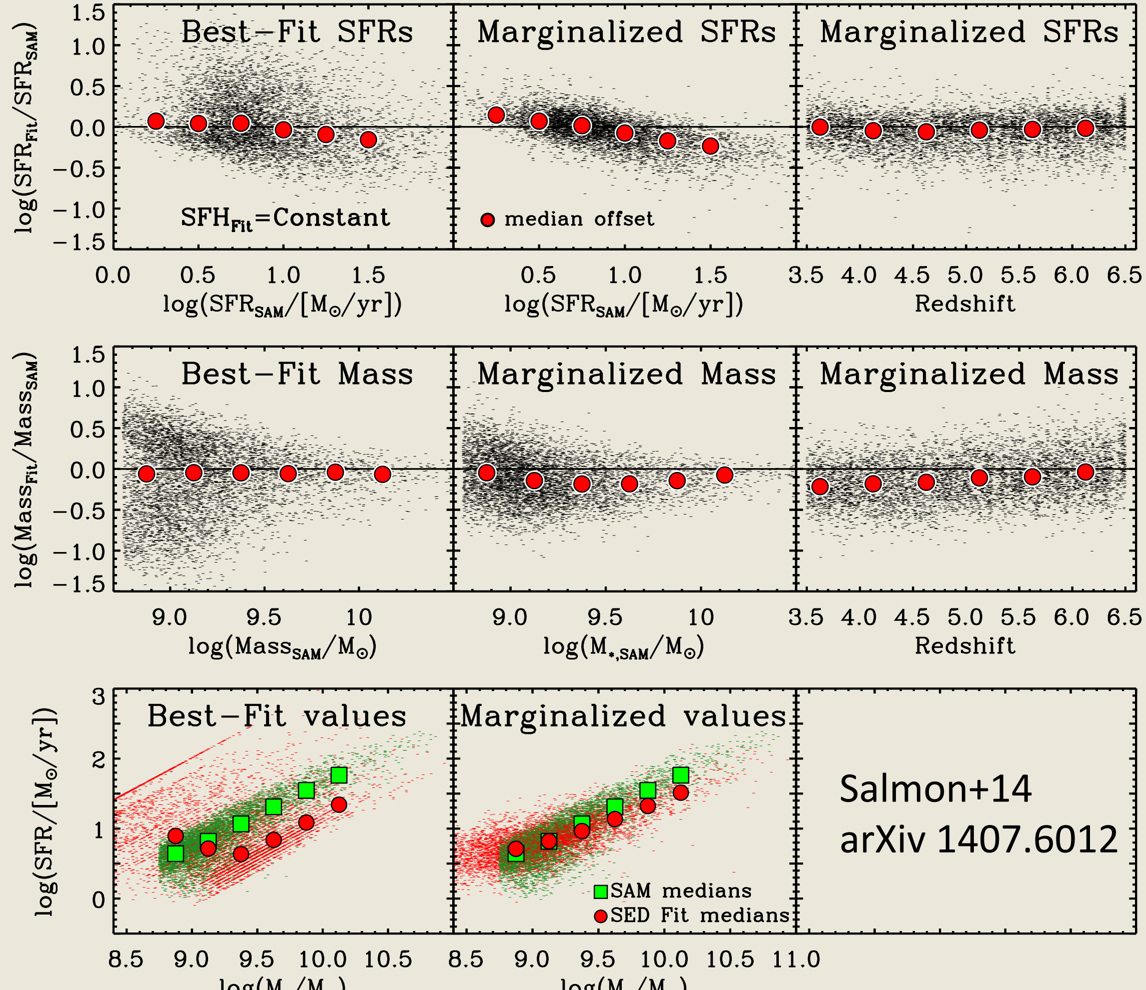
- Right: an individual object's 2D likelihood in the plane of SFR-$M_\star$
- The scatter in determining a single object's SFR or $M_\star$ is orthogonal to the main relation (from age-dust degeneracies)
- These observational uncertainties contribute scatter to the SFR-$M_\star$ plane, and must be accounted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



Salmon+14 (arXiv 1407.6012)

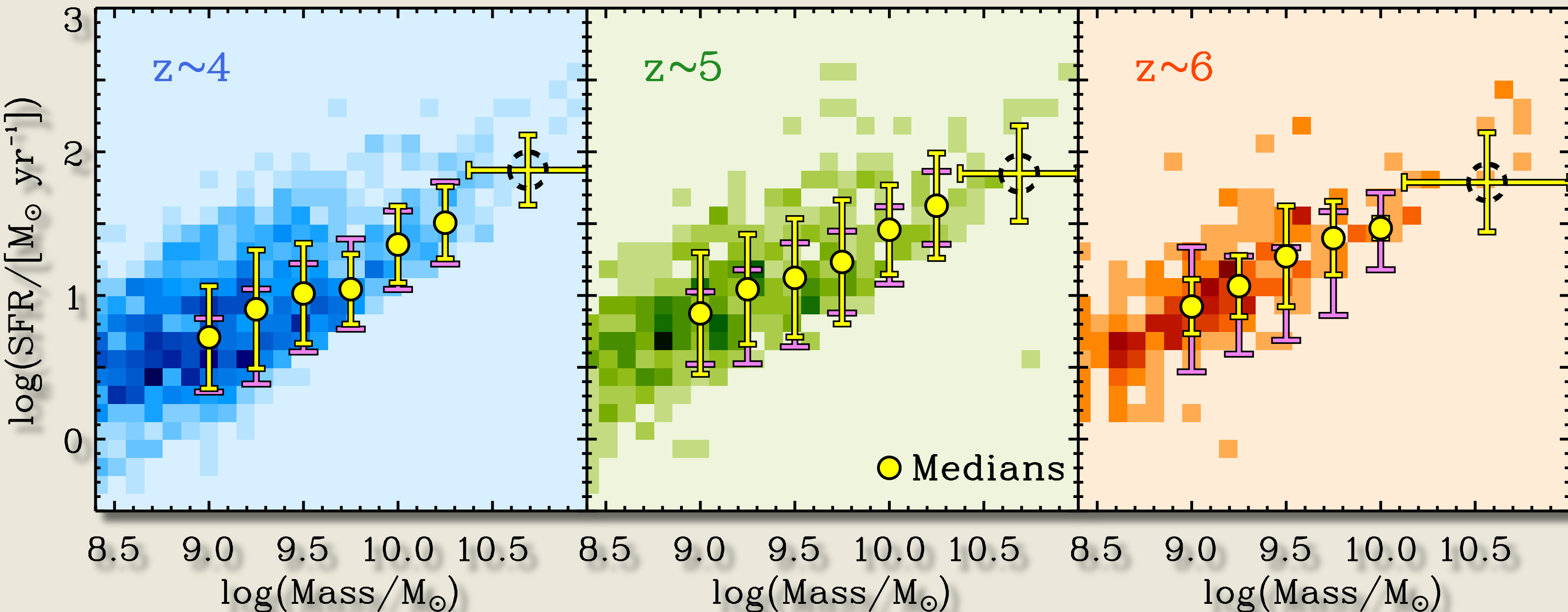
What drives galaxies off the SFR-$M_\star$ relation, and with what uncertainties?

- 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.



Salmon+14
arXiv 1407.6012

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+14 (arXiv 1407.6012)

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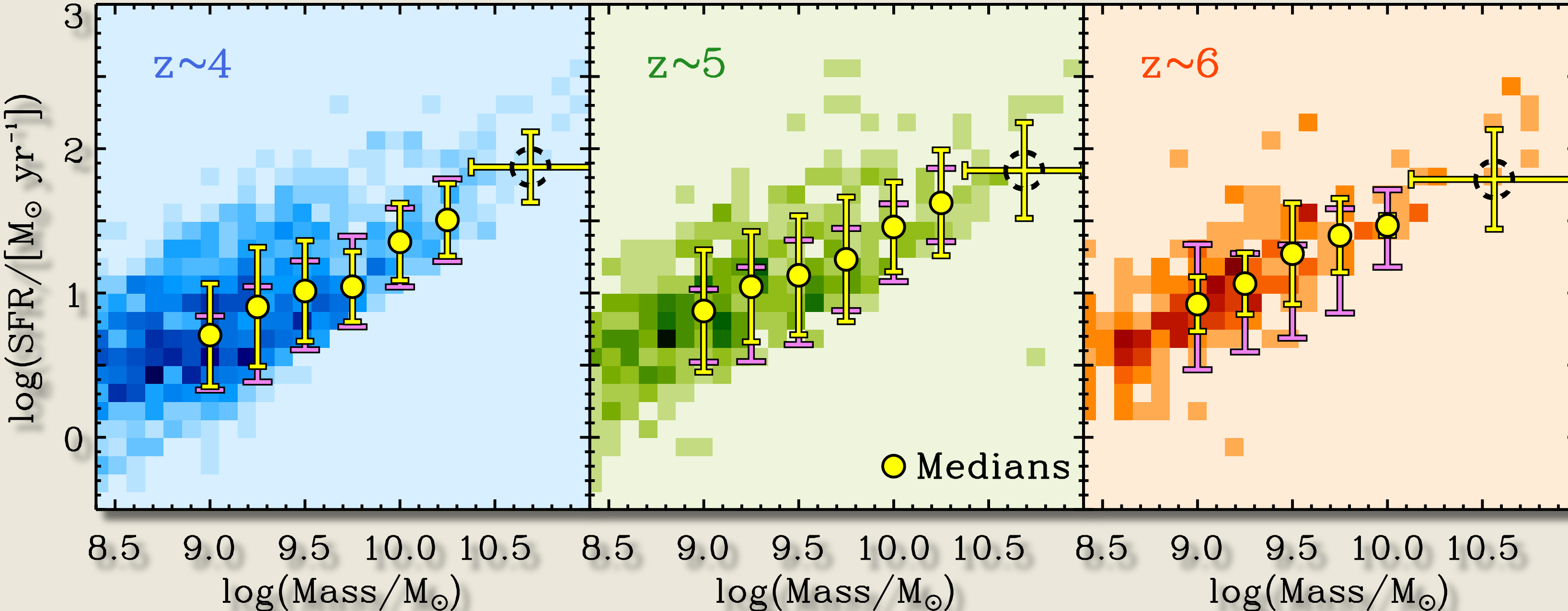
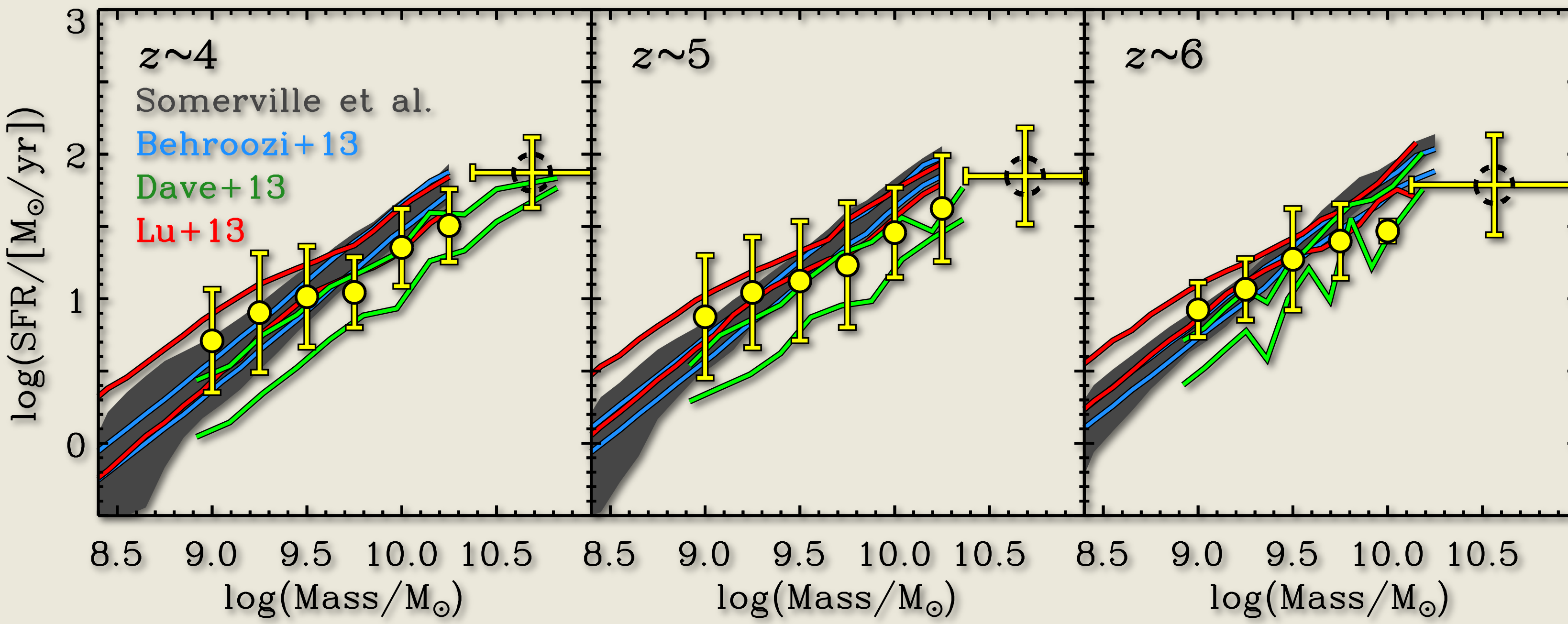


- log(SFR) ≈ α log($M_\star$), α remains <1 (about α=0.6 across all redshift)

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

Salmon+14 (arXiv 1407.6012)

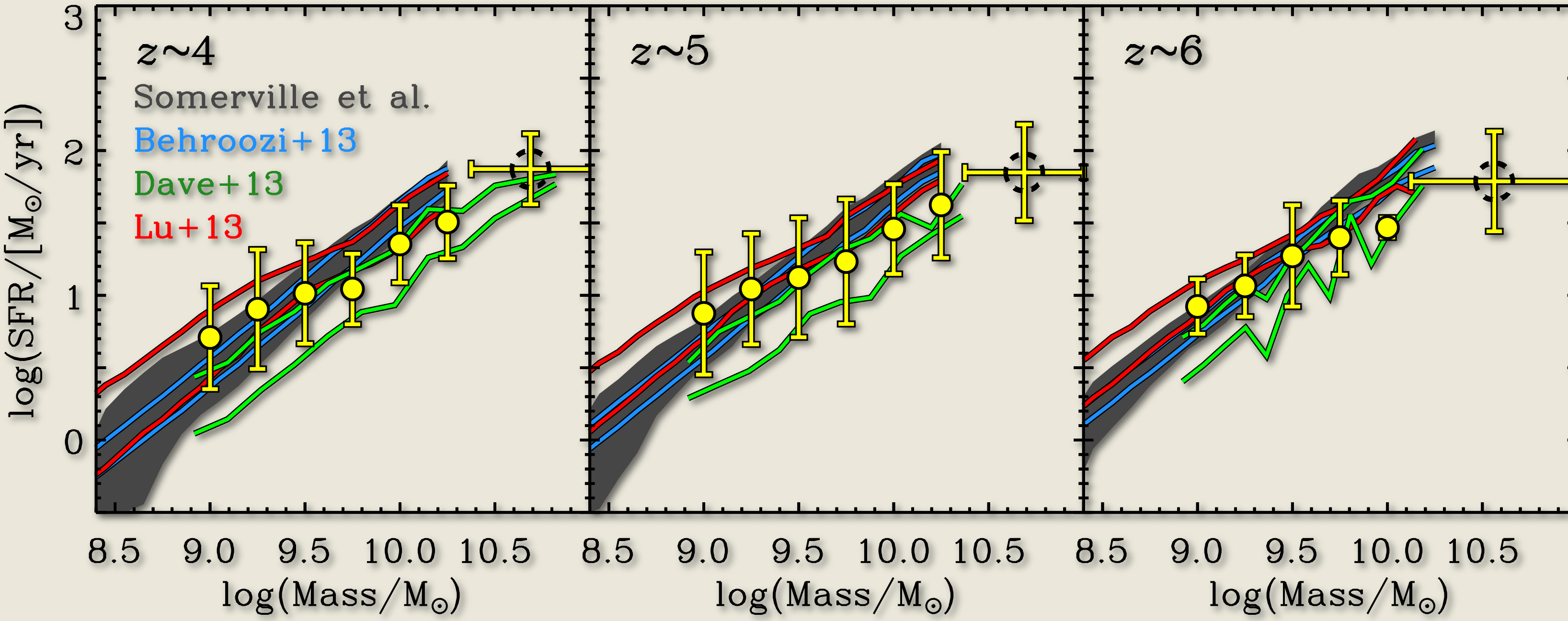
Result: SFR-$M_\star$ is consistent with many theoretical models



- If SFR traces the net gas inflow, then the "true" scatter in the inflow rate is 0.2-0.3 dex.
- These observations favor smooth gas accretion over these redshifts and stellar masses

Salmon+14 (arXiv 1407.6012)

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

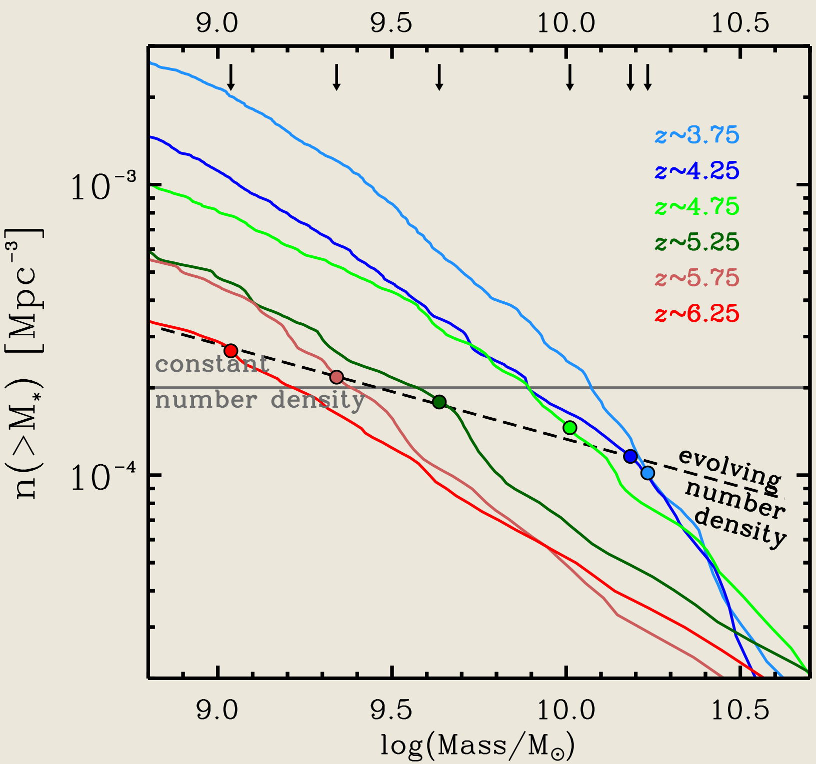


- If SFR traces the net gas inflow, then the "true" scatter in the inflow rate is 0.2-0.3 dex.
- These observations favor smooth gas accretion over these redshifts and stellar masses
- Need ALMA to observe the gas-fraction scatter, thereby constraining the SFR efficiency

Salmon+14 (arXiv 1407.6012)

How does the SFR evolve at these redshifts?

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



- A number-density selection can track the progenitor-to-descendant evolution across redshift.
- Objects were selected according to an evolving number density in stellar mass, as predicted by dark matter abundance matching (Behroozi+13b)

Salmon+14 (arXiv 1407.6012)

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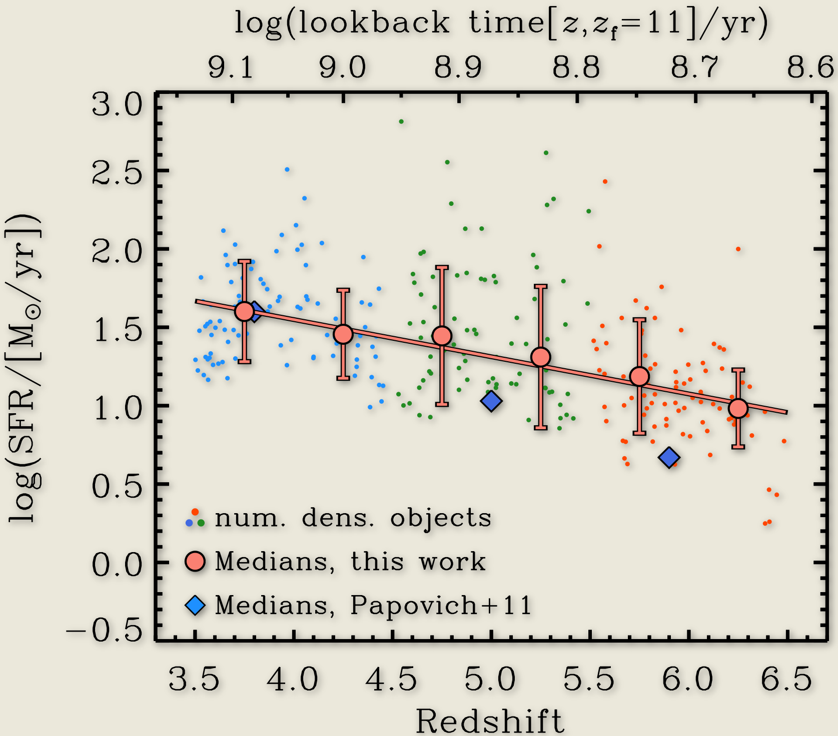
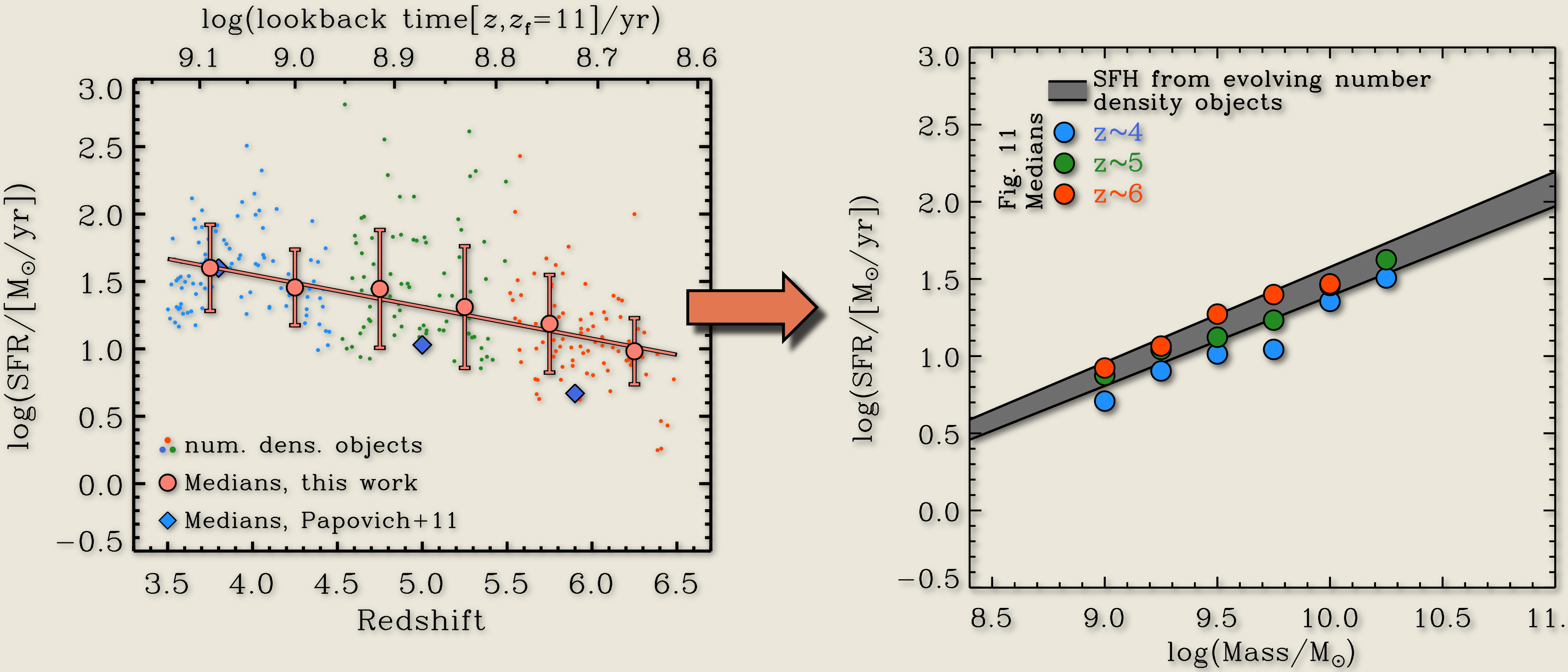


- A number-density selection can track the progenitor-to-descendant evolution across redshift.
- Objects were selected according to an evolving number density in stellar mass, as predicted by dark matter abundance matching (Behroozi+13b)
- We find a rising SF history at high redshift, as expected, with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

Salmon+14 (arXiv 1407.6012)

Does the SFR evolution match the observed SFR-M$_\star$ relation?

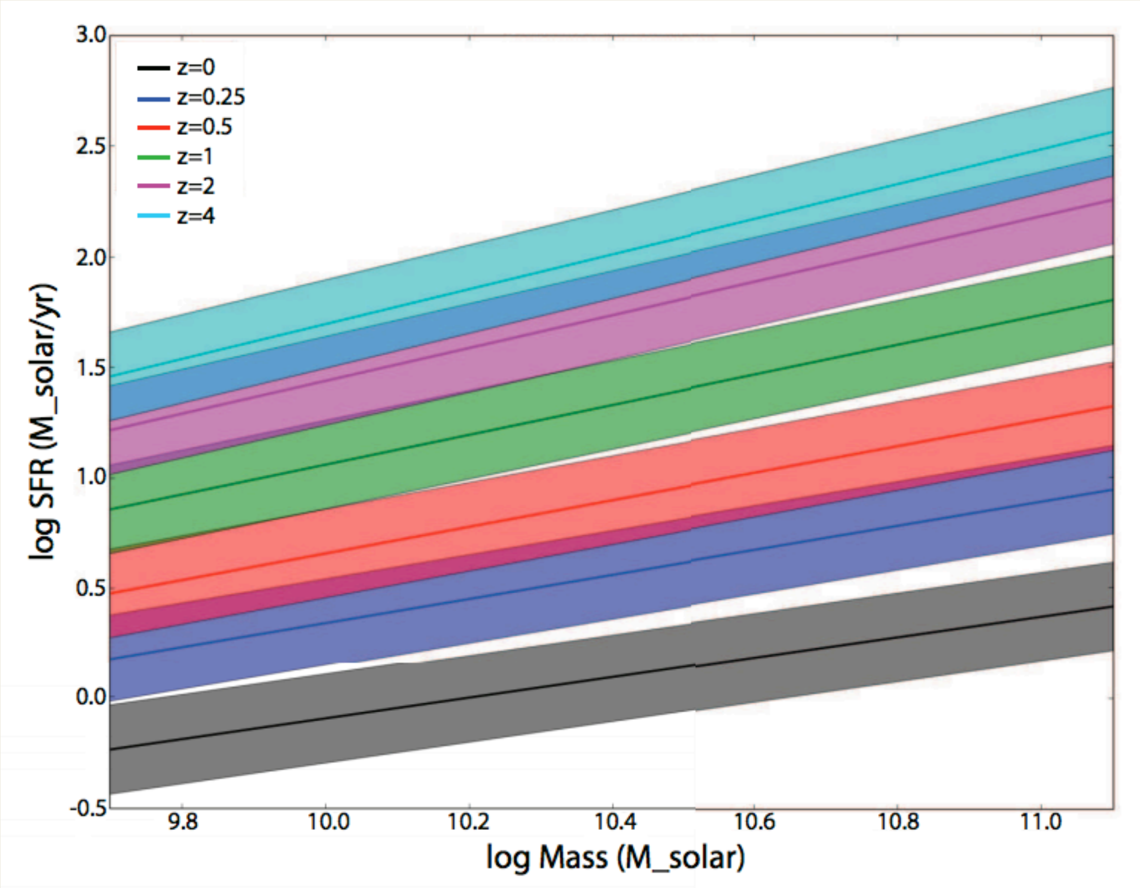


Salmon+14 (arXiv 1407.6012)

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 = $(t/\tau)^\gamma$, where γ=1.4 at high redshift (z>4).



Speagle+14

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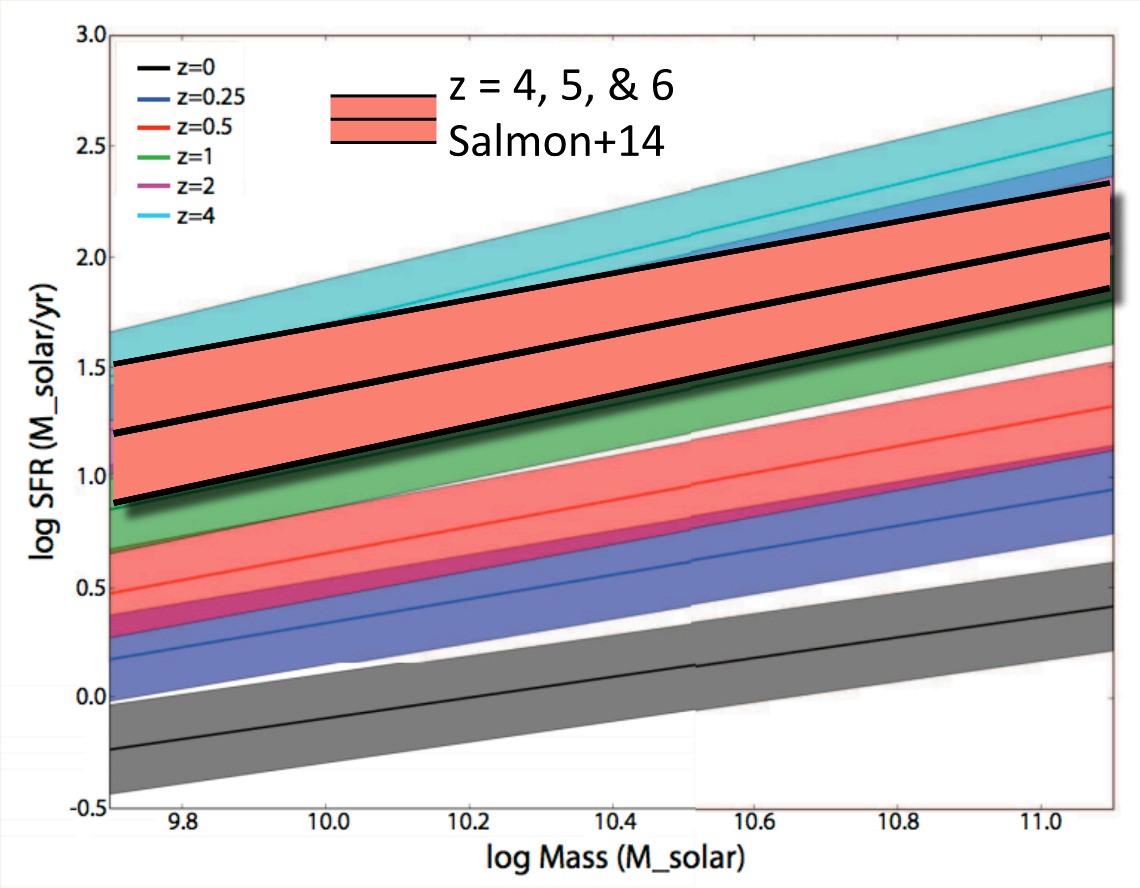
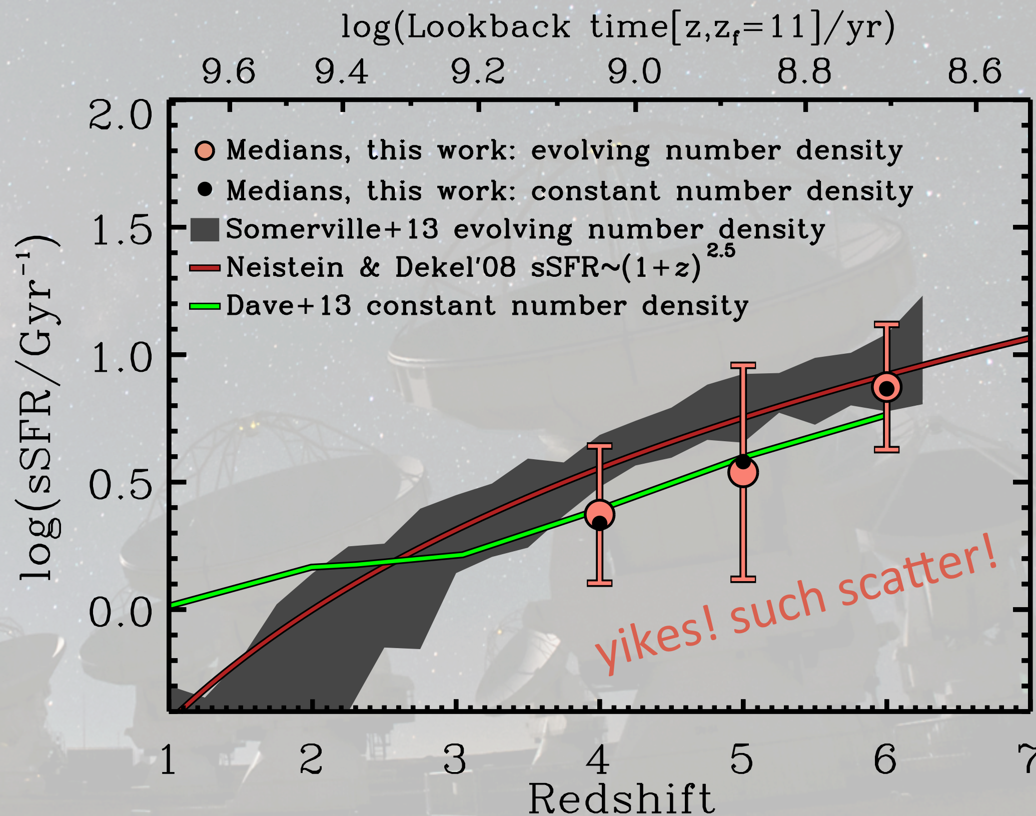


Speagle+14

ALMA: We need gas-mass fractions of high-z galaxies to constrain the SFR efficiency

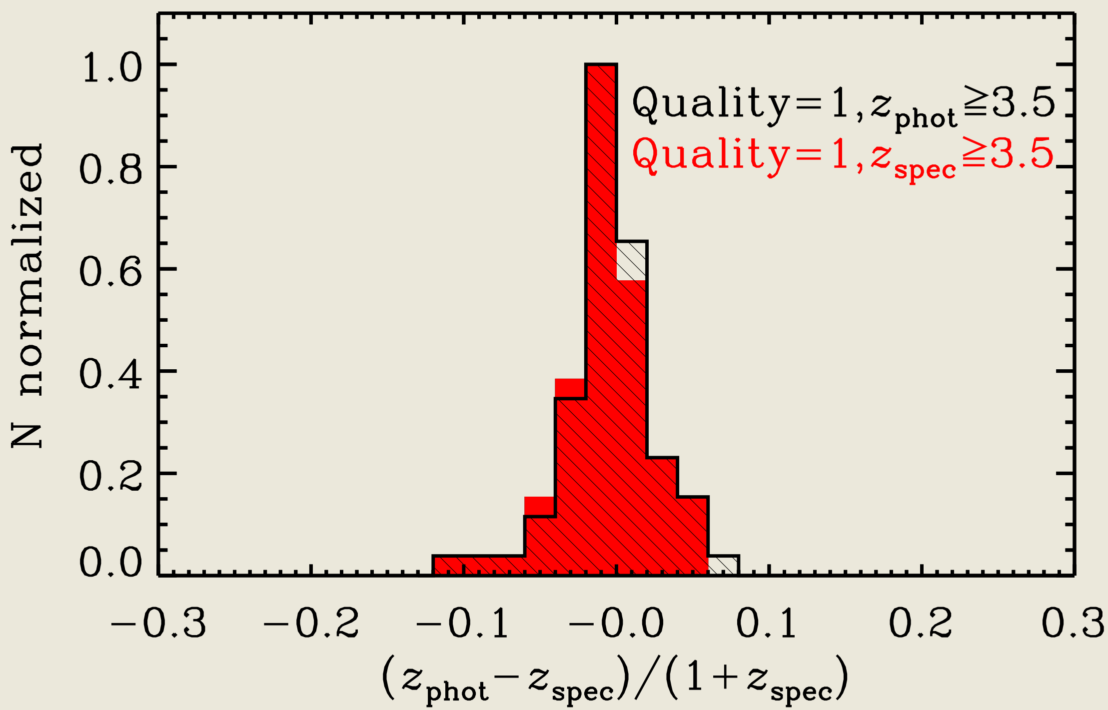
- Theory predicts a rapidly evolving gas-mass fraction with redshift.
- CO emission can tell us dynamical mass, and therefore the gas-mass fraction. [CII] can tell us the dusty IR SFR, constraining the total UV+IR SFR
- ALMA can find the cause of the SFR-$M_\star$ scatter (is it SF efficiency or scatter in galaxy formation time?)



Salmon+14 (arXiv 1407.6012)

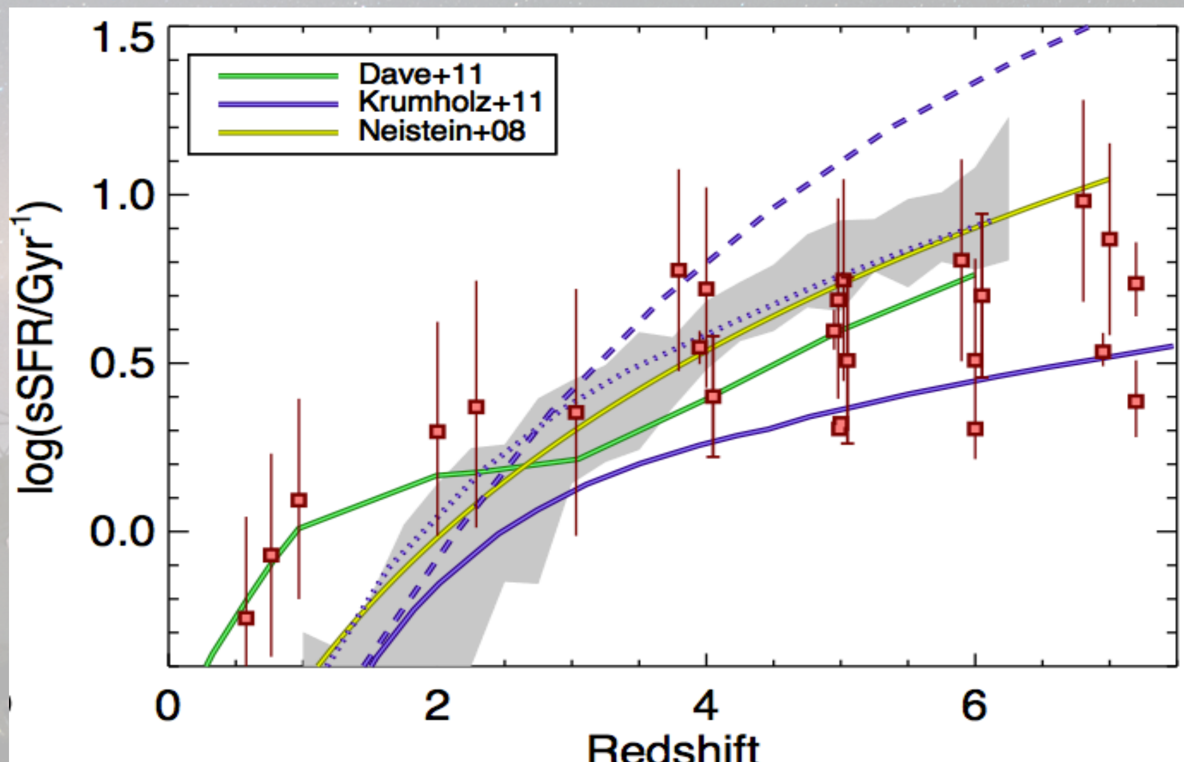
Summary

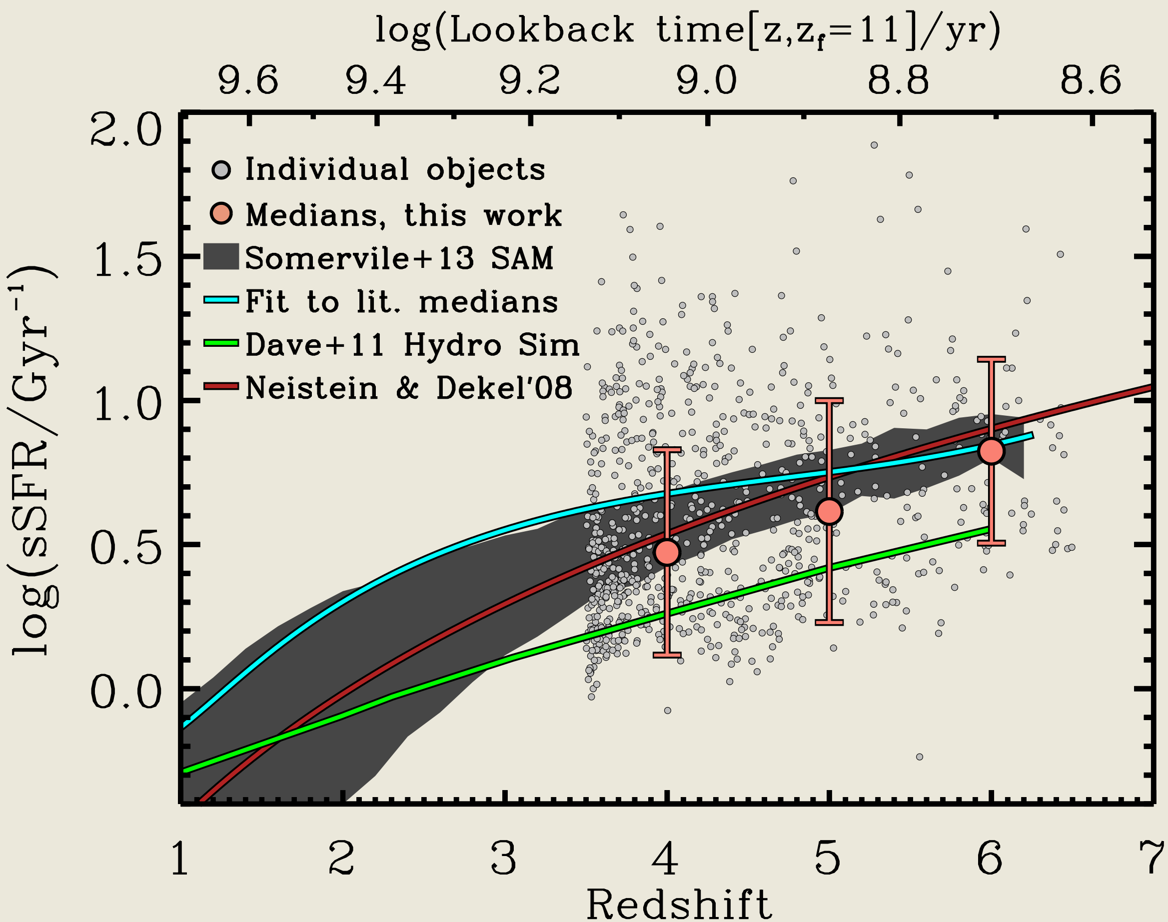
- The relation between SFR and $M_\star$ for star forming galaxies evolves little in slope, and declines in scale since the 1^{st} Gyr of the Universe (Wuyts+11, Panella+14).
- The scatter in SFR at a given mass is small at all redshifts (~0.2-0.3 dex after taking into account observational uncertainties). If SFR traces the net gas inflow rate, then this result favors smooth, cosmological gas accretion.
- 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+14, arXiv 1407.6012)
- ALMA can constrain the gas-mass fraction, and place important limits on high-redshift SFR efficiency.



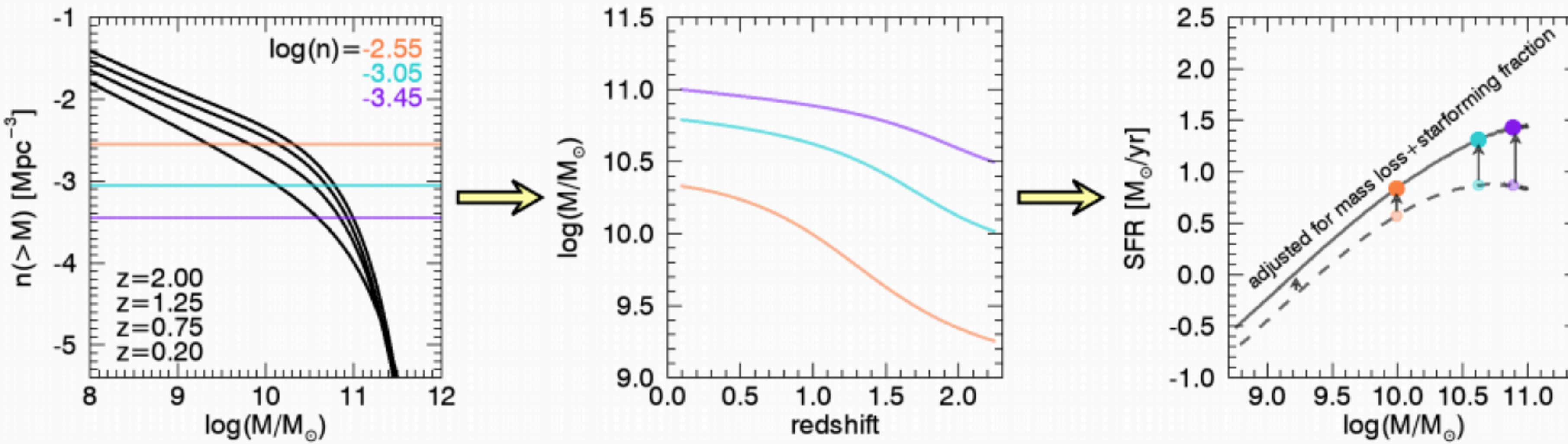
Quality=1, z_{phot}≧3.5
Quality=1, z_{spec}≧3.5
N normalized
1.0
0.8
0.6
0.4
0.2
0.0
−0.3
−0.2
−0.1
−0.0
0.1
0.2
0.3
$(z_{phot}-z_{spec})/(1+z_{spec})$

ALMA: We need gas-mass fractions of high-z galaxies to constrain the SFR efficiency




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

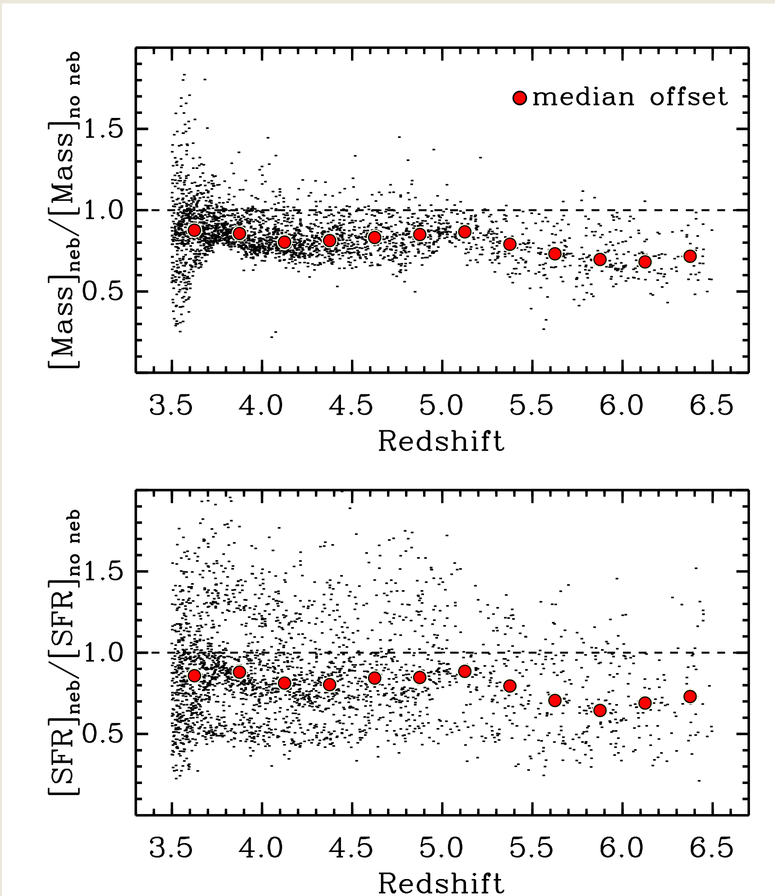
How does this relate to the Stellar Mass Function?

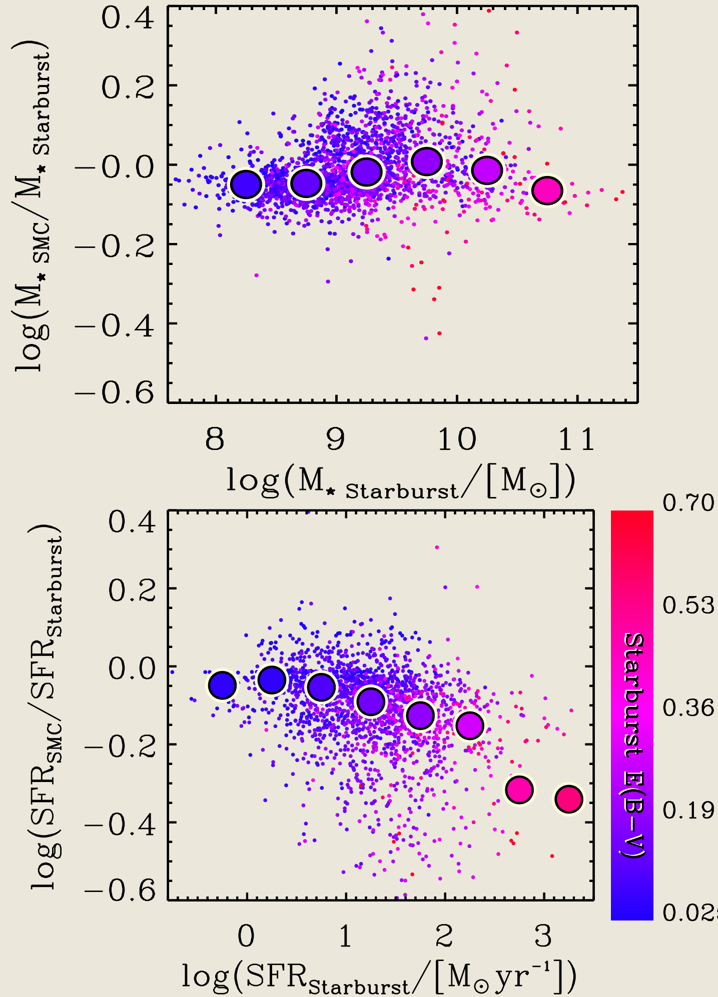


- Implies star formation evolves differently in galaxies of different masses.
- SFR-Mass slope *cannot* be <1 at all masses and redshifts

See Leja+14

What drives galaxies off the SFR-$M_\star$ relation, and with what uncertainties?





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