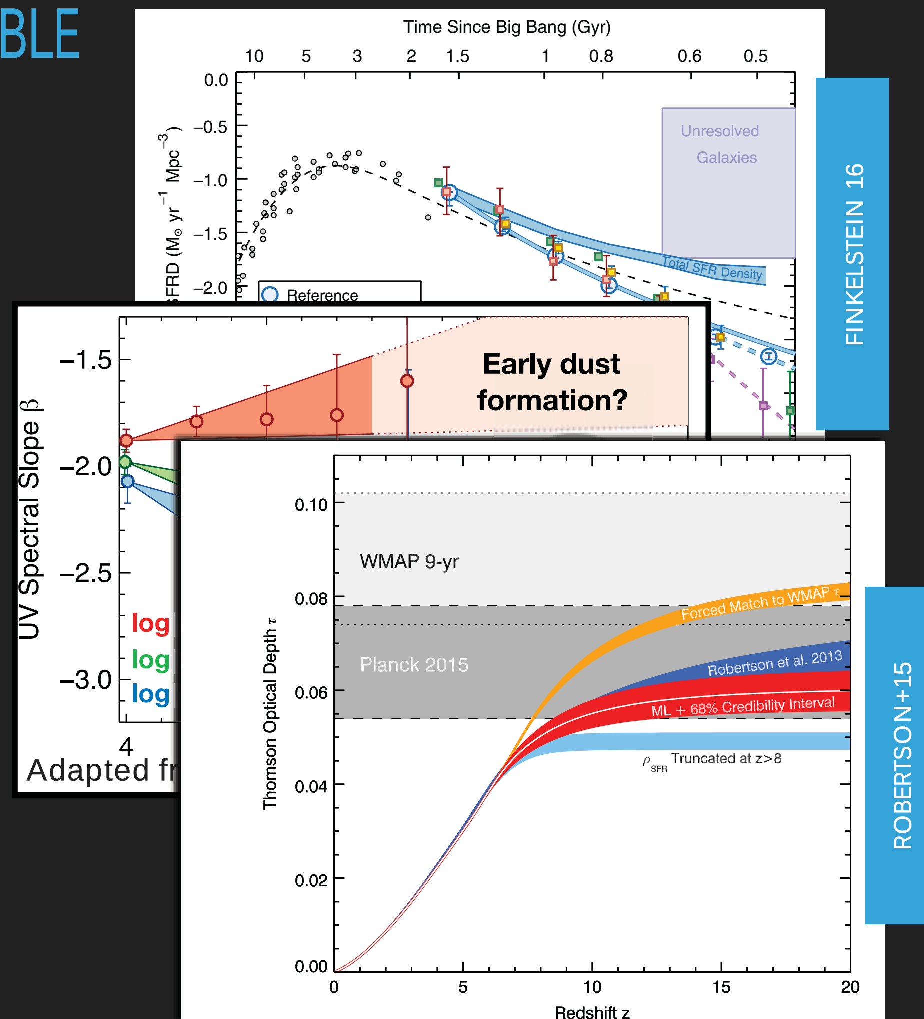
THE UNIVERSITY OF TEXAS AT AUSTIN

Galaxy Evolution in the Early Universe

Steven Finkelstein - The University of Texas at Austin

(SOME) QUESTIONS WE HAVE ANSWERED WITH HUBBLE

- Galaxies exist in great number between 500 Myr and 1 Gyr after the Big Bang, and the cosmic star-formation rate density evolves smoothly upward from z=8 to z=4 (e.g, work by Bowler+, Bouwens+, Oesch+, McLeod+, McLure+, Ishigaki+, Finkelstein+).
- Even the smallest galaxies we can see with Hubble are still enriched by previous generations of star-formation (e.g., Bouwens+12,14, Dunlop+13, Rogers+14, Smit+15, Finkelstein+12).
- Galaxies alone could reionize the universe if their ionizing photon escape fractions are relatively high, >10% (e.g., Kuhlen 12, Robertson+13,15, Bouwens+15b, Livermore+17 . Finkelstein+12,15).



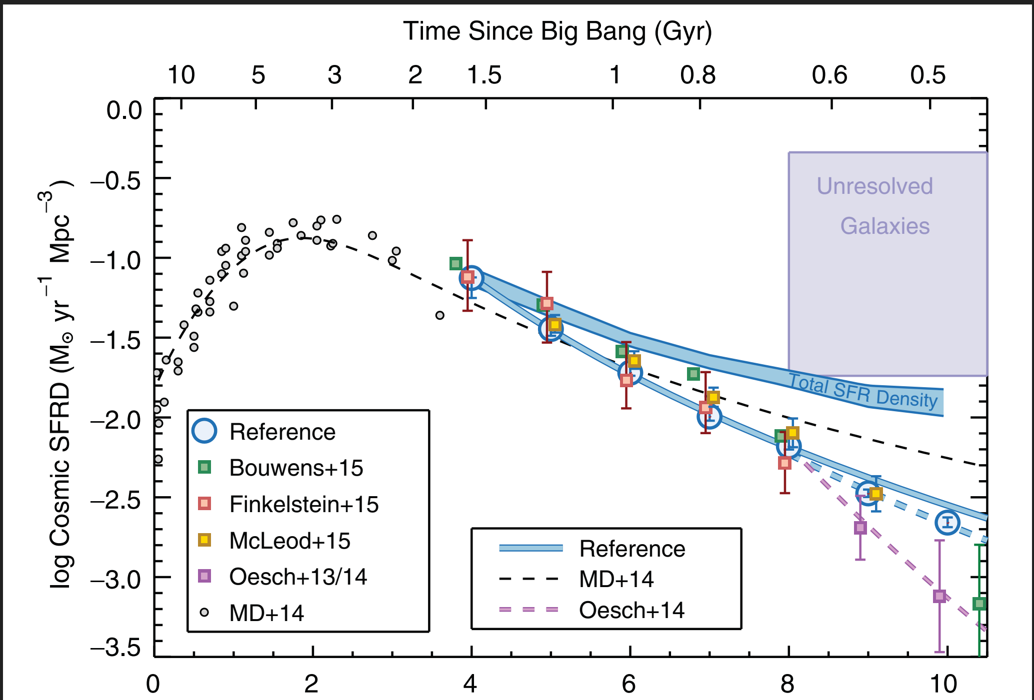
WHAT ARE THE OPEN QUESTIONS WE CAN ANSWER WITH MM/RADIO FACILITIES?

- 1) How important are dusty star-forming galaxies at high redshifts?
- 2) Is the star-forming efficiency evolving at higher redshifts?
- 3) Do the changing gas properties of galaxies impact Lyα as a probe of reionization?

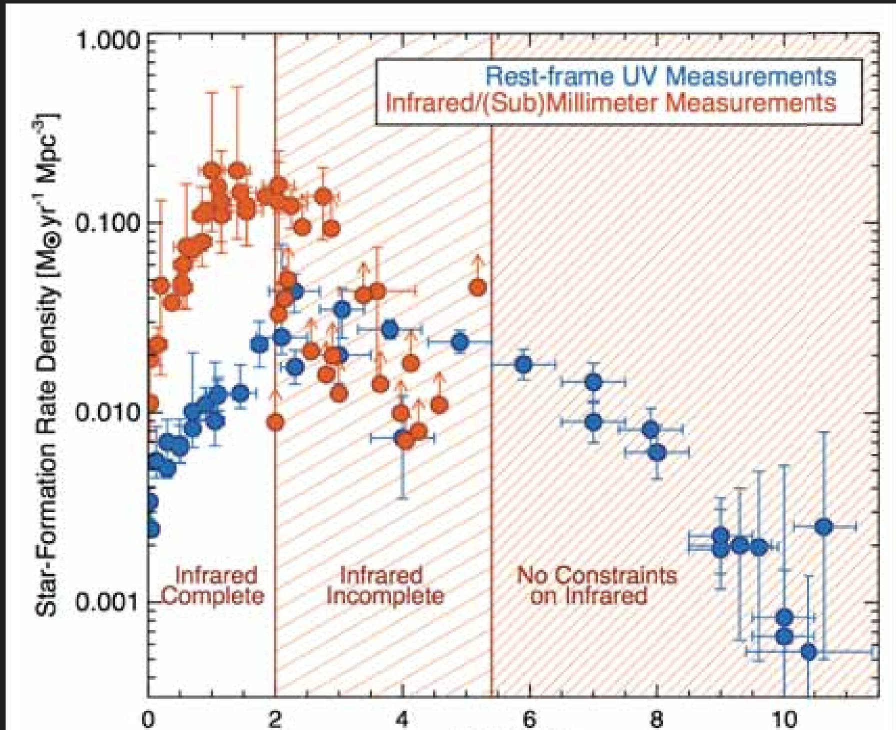
Part 1:

The danger of a UV-only view of star-formation at high redshift

HAVE WE FOUND ALL THE STAR-FORMATION AT HIGH REDSHIFT?

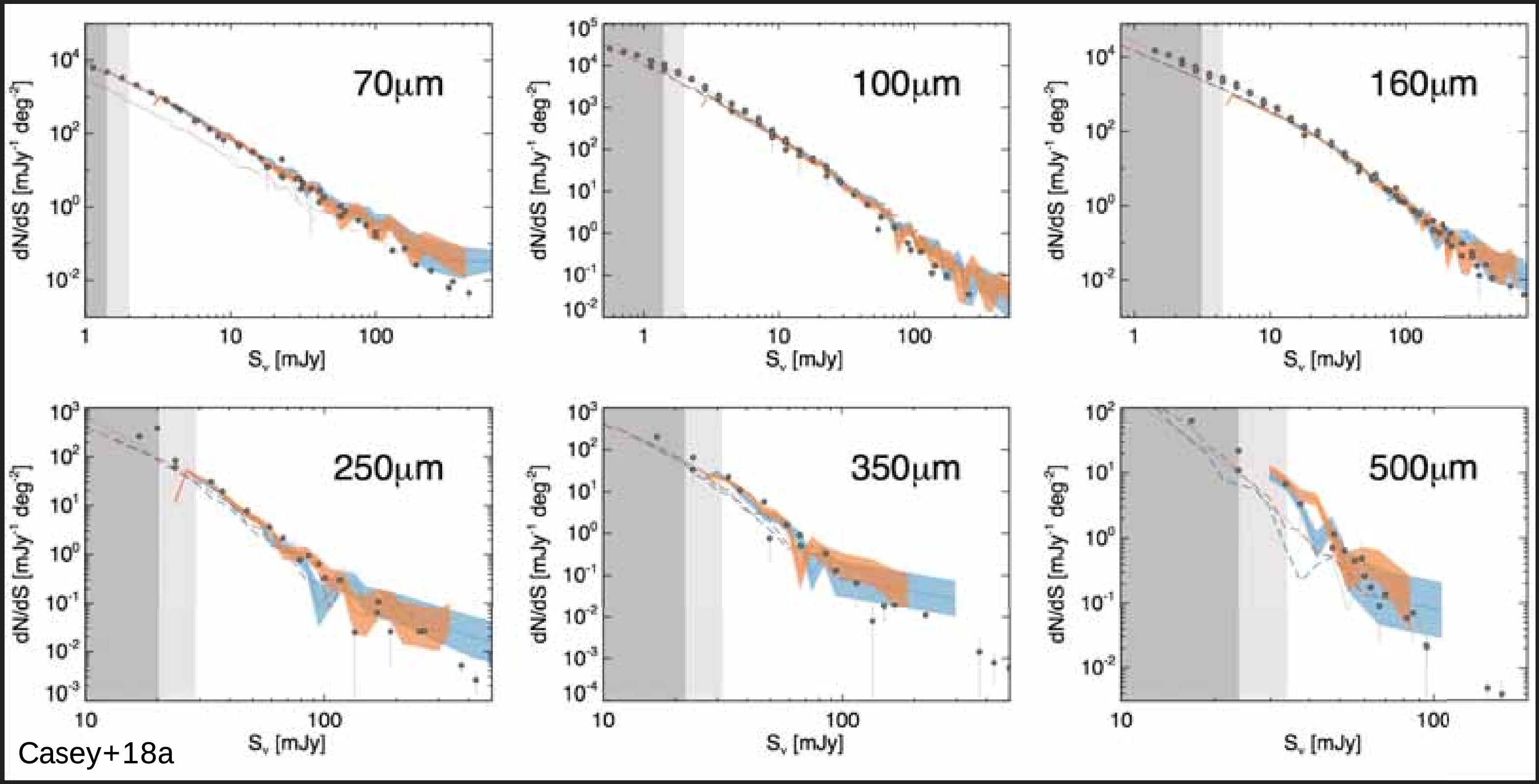


Finkelstein 16



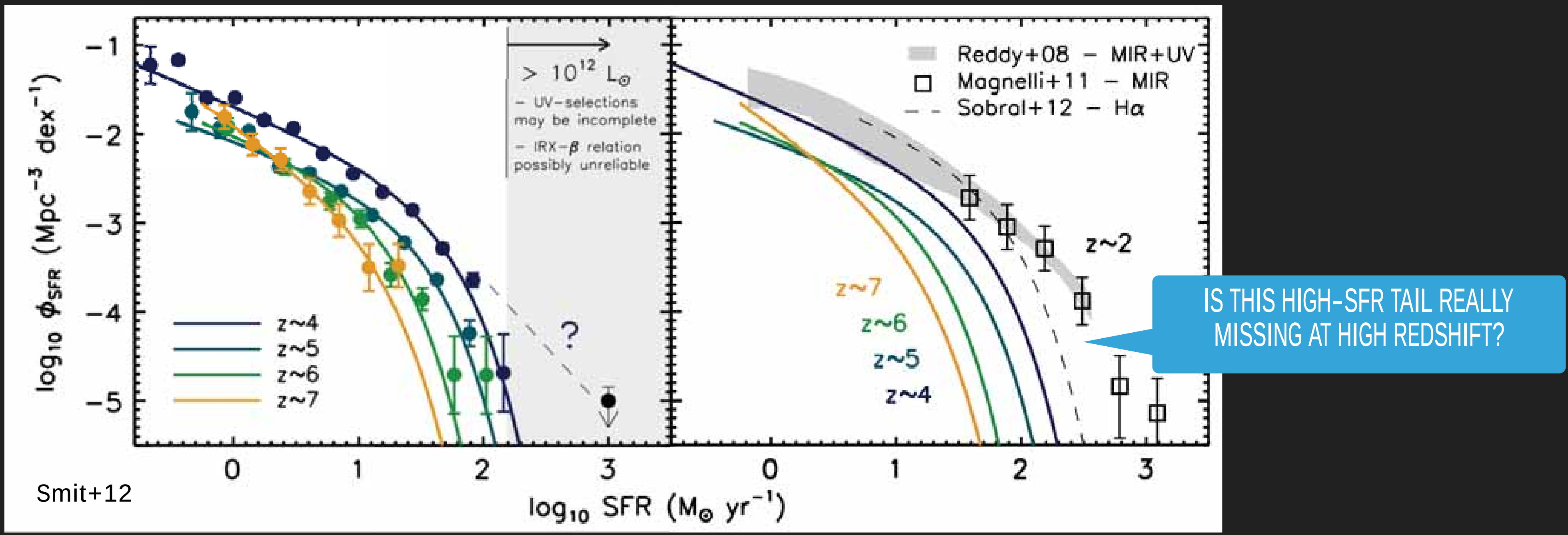
Casey+18a

CAN PREVIOUS OBSERVATIONS RULE OUT SIGNIFICANT OBSCURED SFR AT HIGH REDSHIFT?

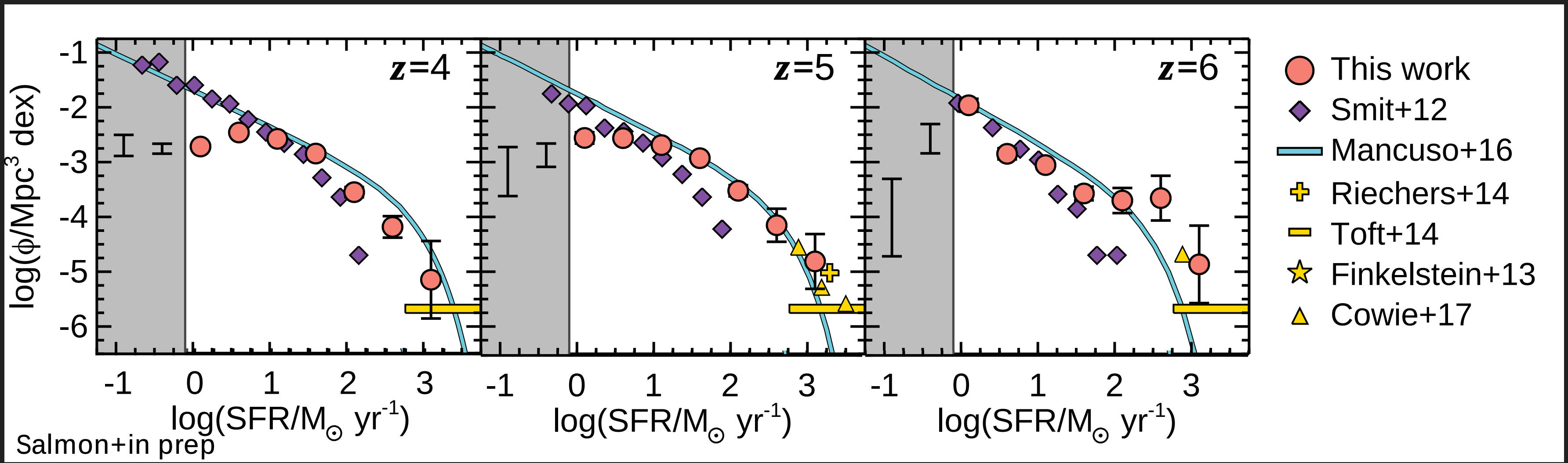


- Blue: DSFGs contribute < 10% of SFR density at z > 4.
- Red: DSFGs contribute >90% of SFR density at z > 4.

DO WE HAVE ANY CLUES FROM HST FOR THIS “MISSING” COMPONENT?



THERE IS AN EXTENDED HIGH-SFR TAIL!



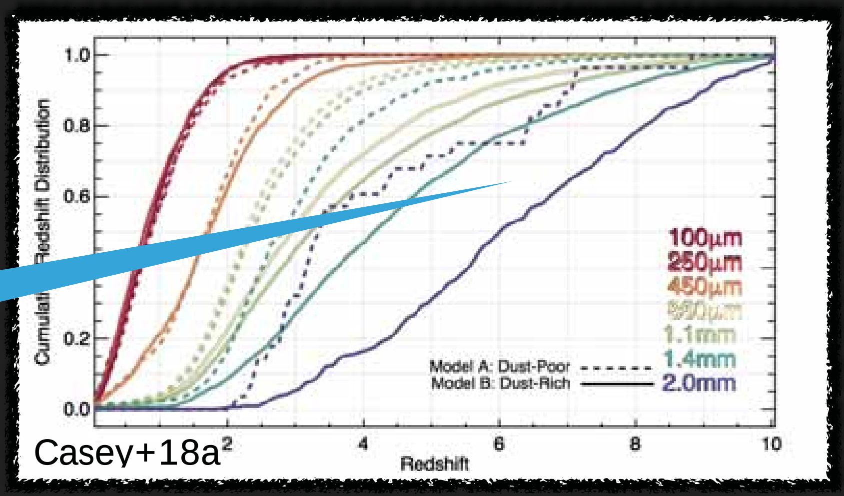
- In-prep work by Brett Salmon (postdoc at STScI), applying individual dust corrections to galaxies within CANDELS. Finds that there is a tail of UV-faint, high-E(B-V) galaxies, which populate the high-SFR end of the SFR function.
- Number densities begin to tie together UV-selected and FIR-selected galaxies!

HIGH-Z OBSCURED STAR-FORMATION: ACTION ITEMS

- **Near-term**: Followup of galaxies with large dust corrections to directly measure obscured SFR.

- Long(er)-term: Wide-field 2mm surveys, ideally with ALMA.

Tamura+18: Detection of dust emission at z=8.3



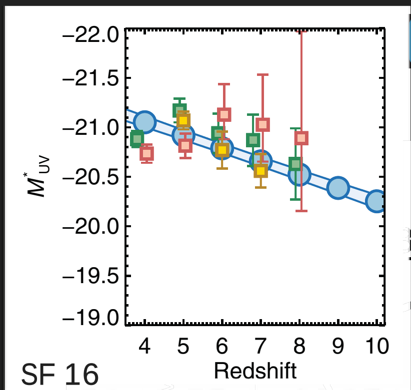
Casey+18a[2]

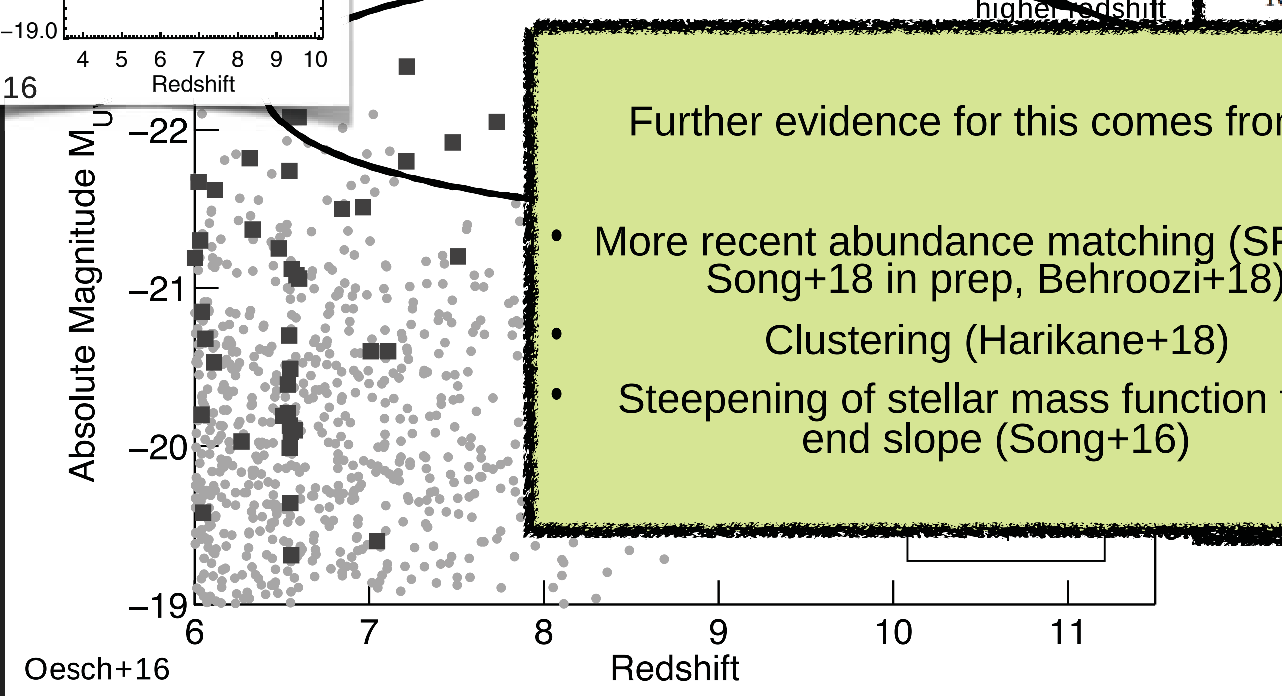
A WIDE-AREA 2MM SURVEY COULD DISTINGUISH BETWEEN THESE MODELS

Part 2:

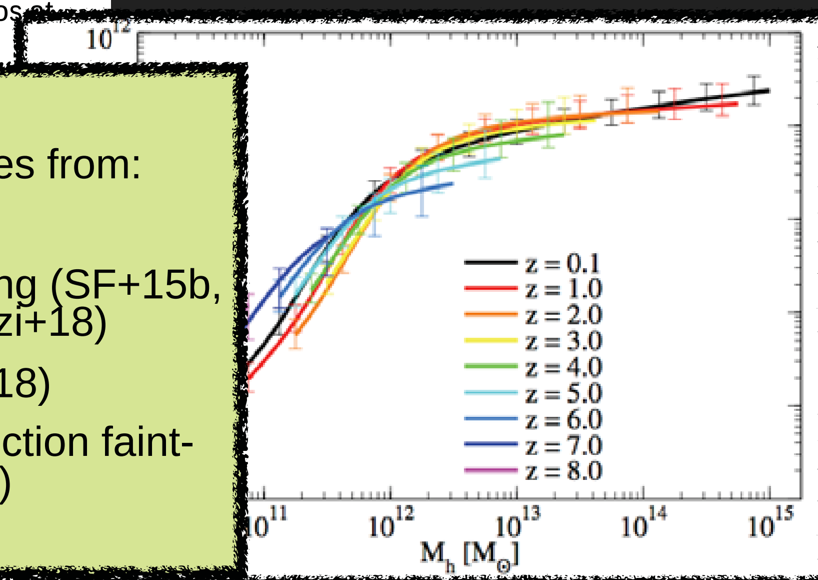
Are the physics of star-formation changing at high redshift?

GALAXIES BETTER AT FORMING STARS AT HIGH REDSHIFT?





At fixed stellar mass, galaxies are living in lower-mass halos at higher redshift



Further evidence for this comes from:

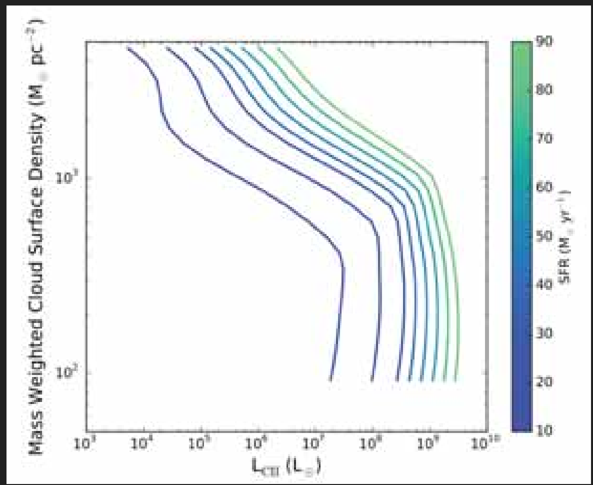
- More recent abundance matching (SF+15b, Song+18 in prep, Behroozi+18)
- Clustering (Harikane+18)
- Steepening of stellar mass function faint-end slope (Song+16)

HOW TO CONSTRAIN CHANGING STAR-FORMATION PHYSICS

- The gas rich and compact nature of distant galaxies implies that gas densities are similar to those seen only in extreme starbursts in the local universe.

- This could lead to a steeper dependence of the SFR on the gas density (e.g., Krumholz, McKee & Tumlinson 2009; Ostriker & Shetty 2011).

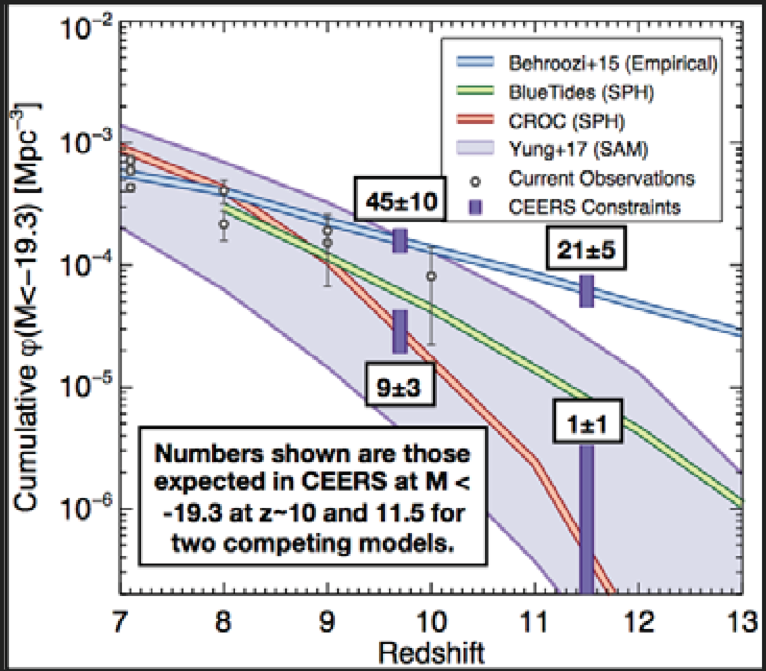
  - We cannot measure these densities directly, but can make inferences from models. For example, Narayanan and Krumholz (2017) show that the size of the [CII] emitting layer in clouds is intimately tied to the cloud surface density and global galaxy SFR.



STAR-FORMATION EFFICIENCY: ACTION ITEMS

- **Near-term**: ALMA measurements of [CII] (and ideally FIR SFRs) for a large sample of galaxies can begin to fill out this space, and place constraints on gas densities on scales of only 10-100 pc.

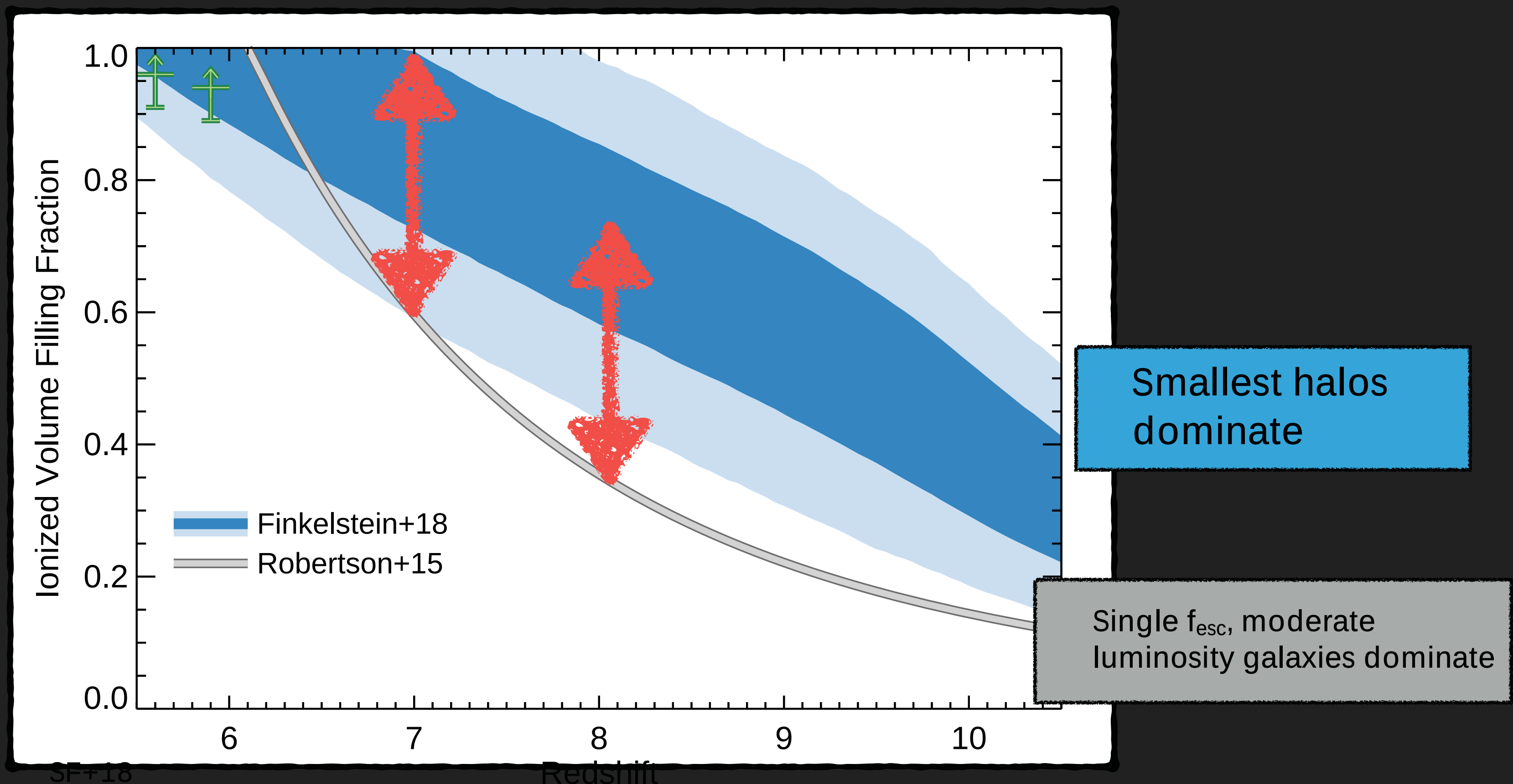
- **Long(ish)-term**: Simply counting galaxies at very-high redshifts with JWST can also help. Models with Kennicutt-Schmidt-like scaling predict very few galaxies at z > 10, while $\Sigma_{SFR} \propto \Sigma_{H2}^2$ is much more optimistic.



Part 3:

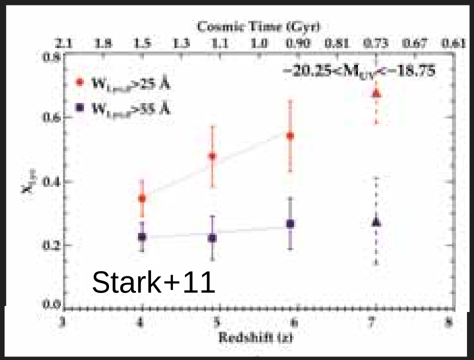
Does the changing gas properties of galaxies affect our ability to use Lyα emission to constrain reionization?

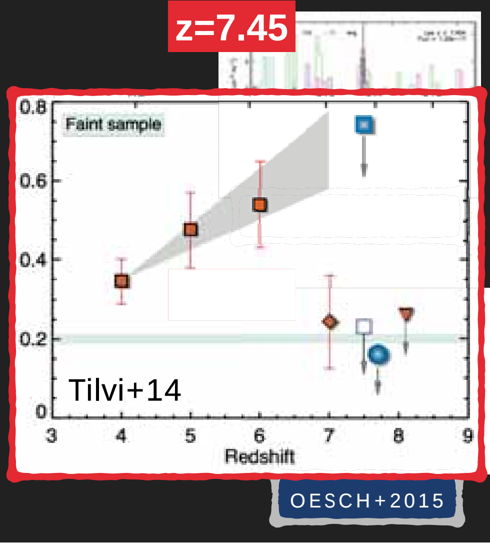
UNCERTAINTIES AT THE END OF REIONIZATION

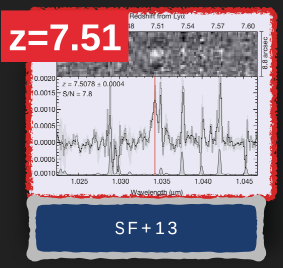


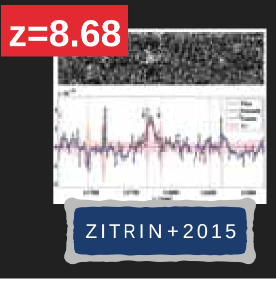
PROBING REIONIZATION WITH LYMAN ALPHA EMISSION

- Lyα is resonantly scattered by neutral hydrogen, so if it is emitted from a galaxy with a surrounding neutral IGM, it will be significantly spatially diffused, well beyond detectable levels (e.g., Miralda-Escude+98, Malhotra & Rhoads 04, 06; Dijkstra+07).
  - Also, it is relatively “abundant” at z=6, just after the end of reionization.
- Many successes (e.g., Shibuya+12, Finkelstein+13, Rhoads+13, Oesch+15, Zitrin+15, Roberts-Borsani+16, Song+16, LaPorte+17)
- However, the majority of galaxies go undetected with spectroscopic followup, leading to the inference that the IGM at z ≥ 7 is highly neutral (e.g., Pentericci+11, 14, Treu+13, Fontana+10, Tilvi+14).

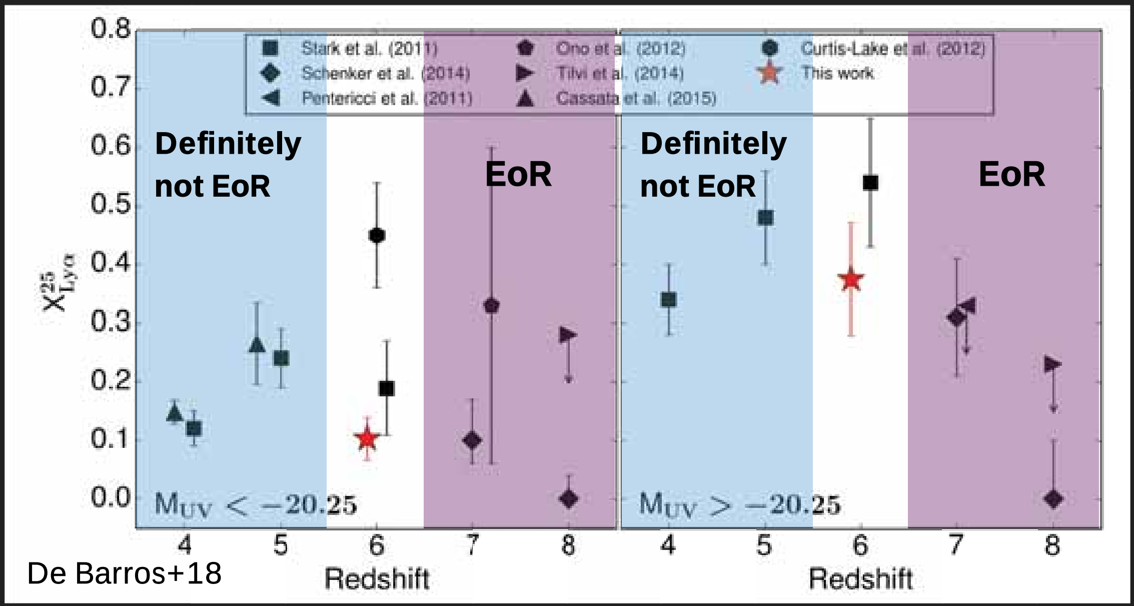






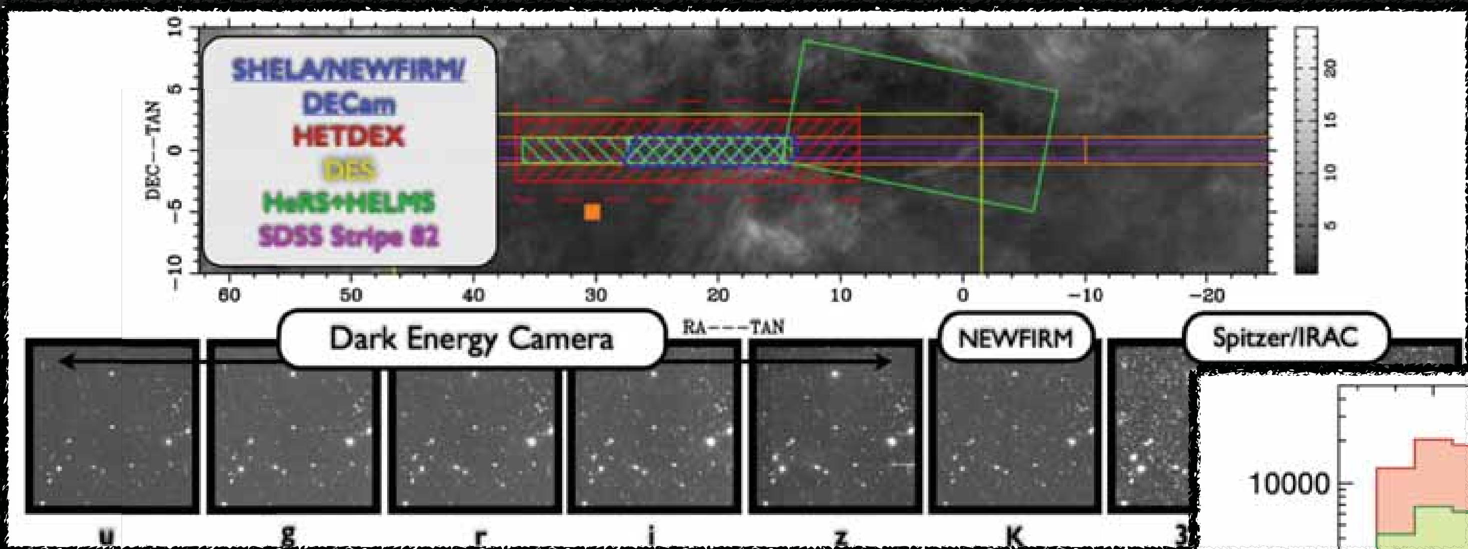


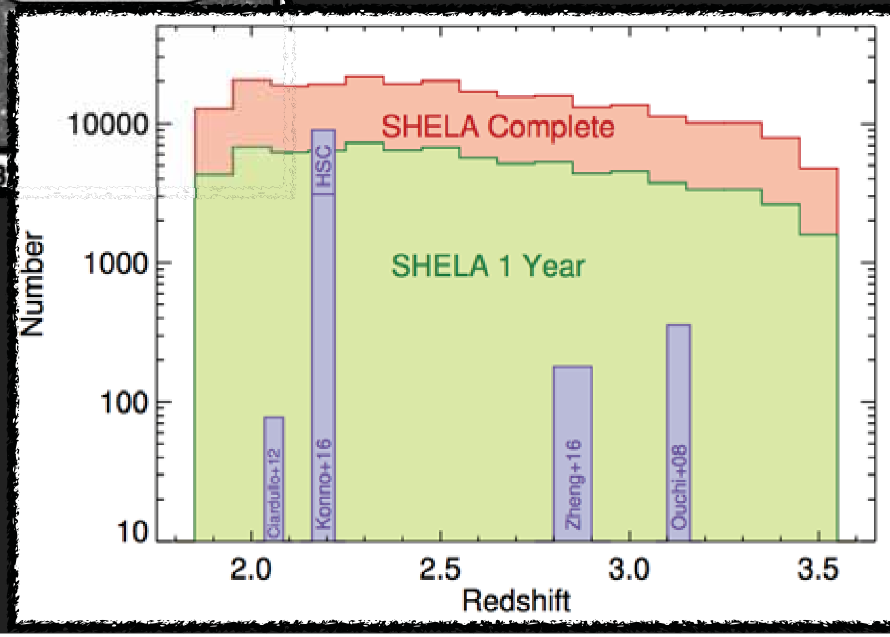
WHAT ELSE COULD CAUSE LYA TO GO MISSING?



- Lyα is certainly not ubiquitous at z~3-4, when it cannot be the IGM.
- What about gas content, dust content, ISM geometry and kinematics?
  - To study this, would need a very large sample of Lyα-emitting galaxies not in the EoR, and try to correlate Lyα strength with physical properties.

LEVERAGING LARGE SAMPLE OF LYA EMITTERS FROM HETDEX



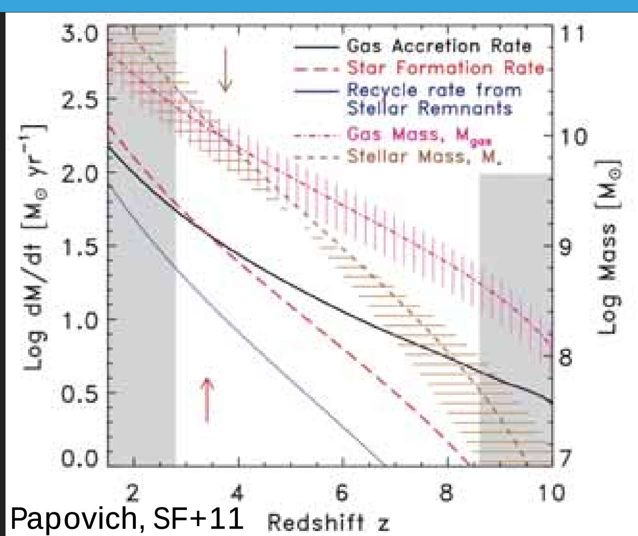


- Will study correlations of Lya line strength with physical properties measured from SED fitting (M*, E(B-V), SFR).
  - Isolate those galaxies most likely to exhibit strong Lyα emission, and then followup ***those*** types of galaxies in the EoR.

WHAT ABOUT GAS?

- While this will be highly useful, it will not tell us about the potential impact of gas reservoirs on the detection of Lyα, a

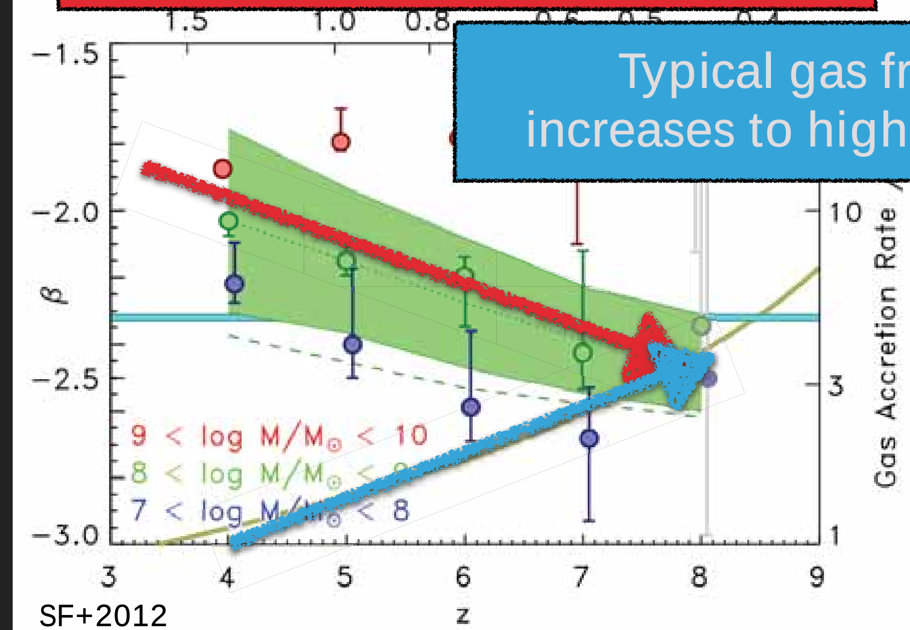
Prediction based on observed M* and SFRs of galaxies.



Papovich, SF+11

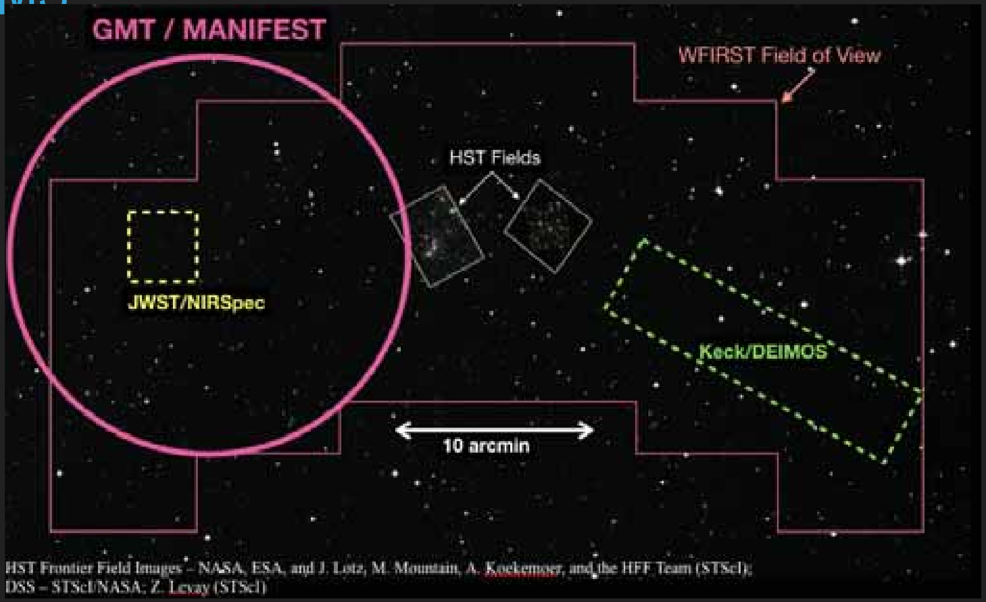
- Typical dust attenuation decreases to high-z. Lyα=😀

Typical gas fraction increases to high-z. Lyα=😟



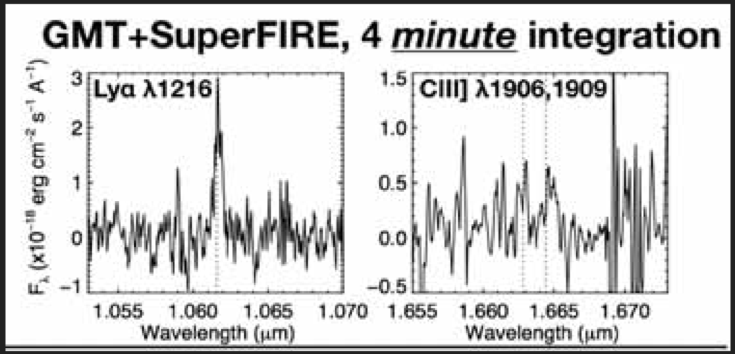
SF+2012

LYA AND REIONIZATION: ACTION ITEMS



- **Near-term**: ALMA measurements of gas mass (CO? Dynamical mass via [CII]? RJ tail?) for a statistically significant sample of galaxies with Lyα measurements (must be at $z < 5$ to avoid IGM issues). HETDEX is ideal, as it is a blind spectroscopic sample, though the redshift range ($2 < z < 3.5$) presents observational issues for [CII].

- **Long-term**: WFIRST identification of large numbers of galaxies over larger areas, GMT measurements of Lyα.



- **Long-term**: Use NGVLA to probe CO(1-0) at higher redshift in a (potentially) more direct probe of gas.

SUMMARY

- Direct observations of gas and dust are necessary to complete our picture of galaxy evolution at high-redshift.

  - **Part 1:** There are hints that dusty-star-forming galaxies may be more prevalent at high-redshifts than typically assumed.
    - **Action Item:** Observations of dust emission, particularly at $\lambda > 1$mm, are necessary to constrain their importance.

  - **Part 2:** There are a surprising number of highly star-forming high-redshift galaxies.
    - **Action Item:** Measurements of gas densities can inform us whether the star-formation efficiency is impacted.

  - **Part 3:** Lyα is our most promising near-term probe of the evolution of reionization, but we have little constraints on the ISM transmission.
    - **Action item:** Studies of the impact of gas fraction on Lyα detectability can help resolve this major systematic issue.