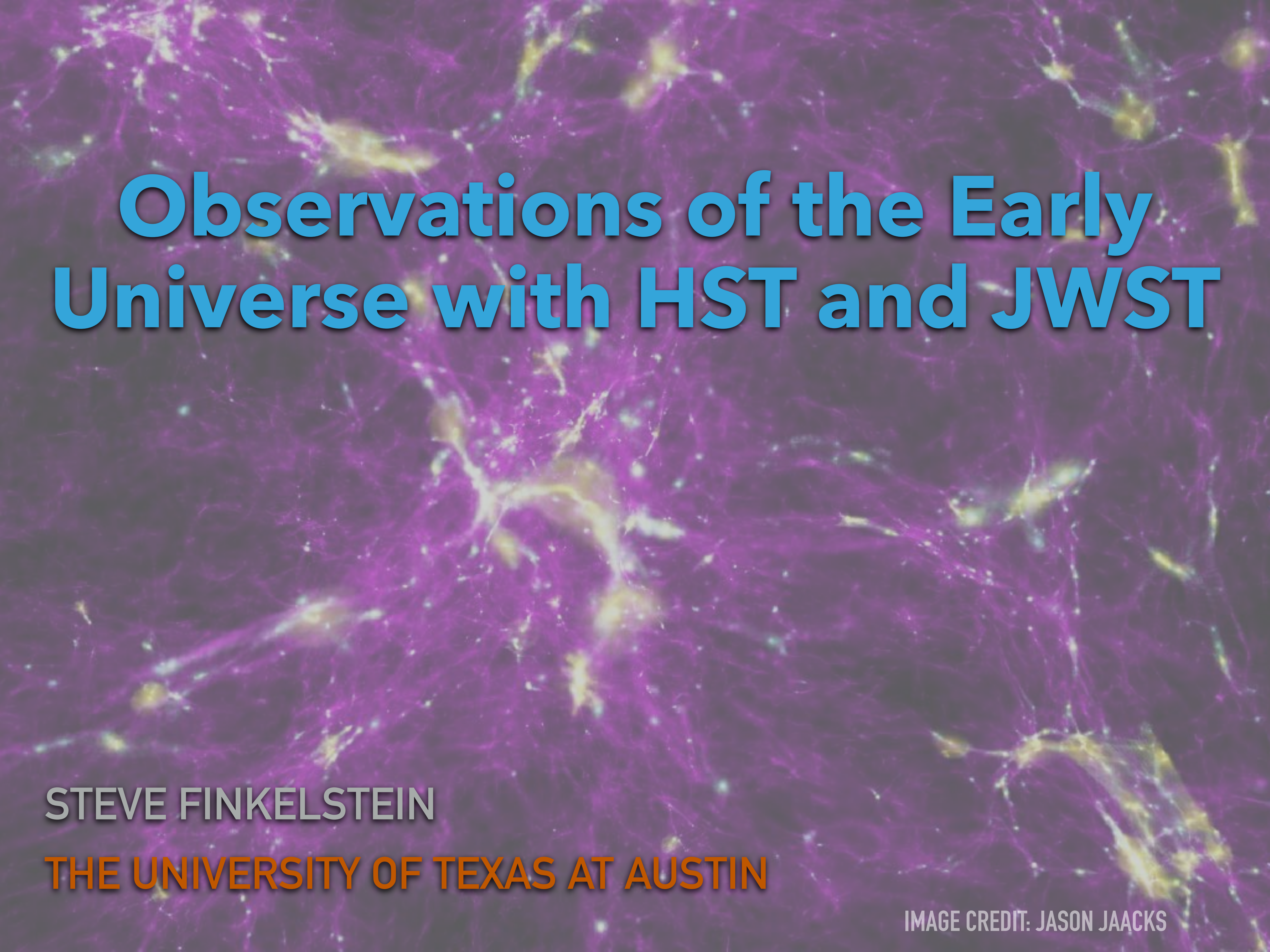

Observations of the Early Universe with HST and JWST

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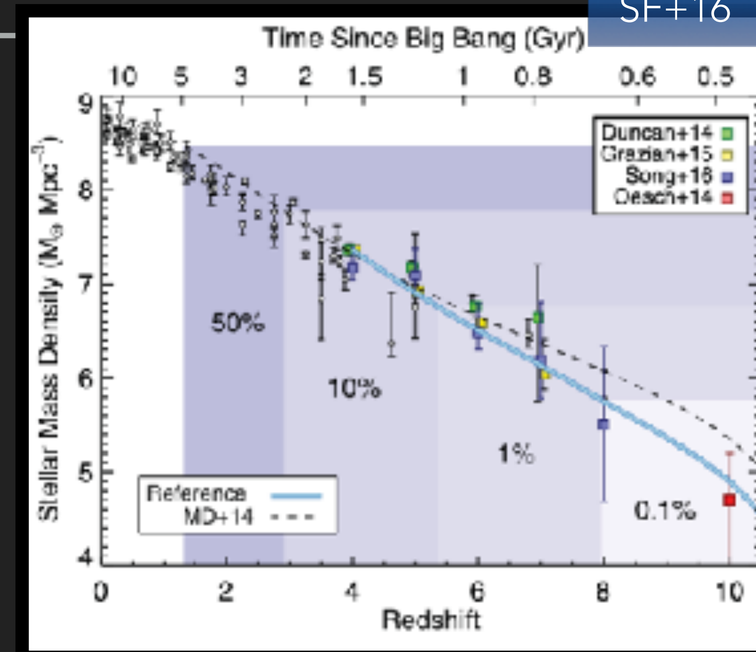
IMAGE CREDIT: JASON JAACKS

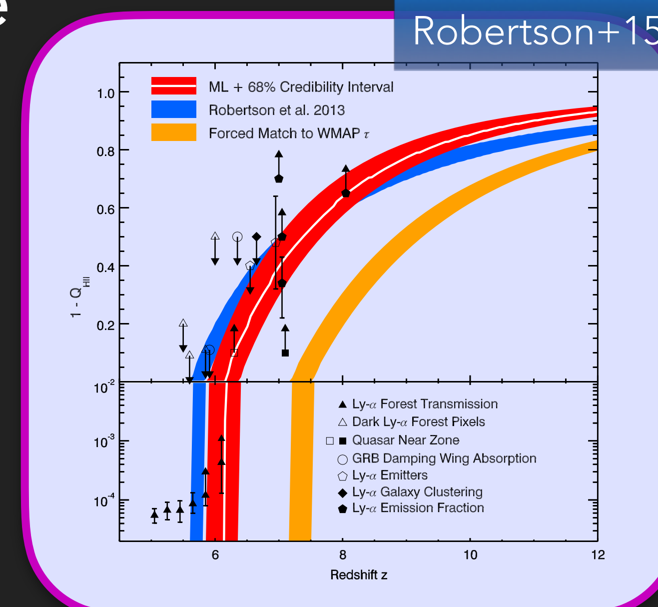
(SOME) OPEN QUESTIONS FOR JWST

- Do we have the full picture on star-formation at high redshift?
    - Are the rest-UV morphological structures representative of the full underlying stellar populations?
    - Have we found all of the galaxies, or is there a quiescent population?
- When does reionization start and end, and can galaxies contribute all needed ionizing photons?
- What is the true redshift distribution of photometric candidates, and what can we learn about their stellar populations from spectroscopy?

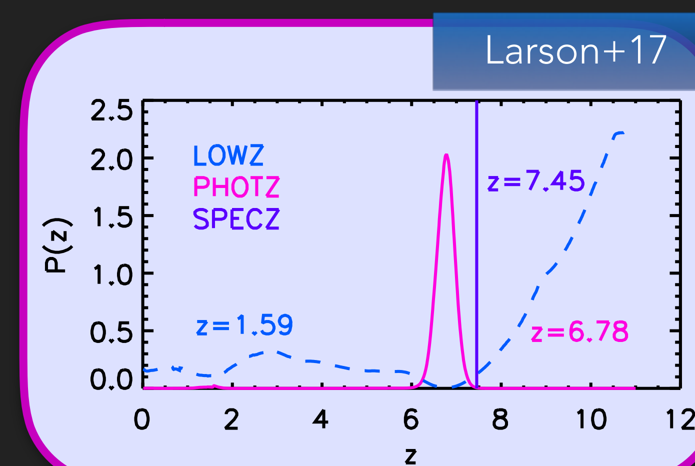
SF+16



Robertson+15



Larson+17

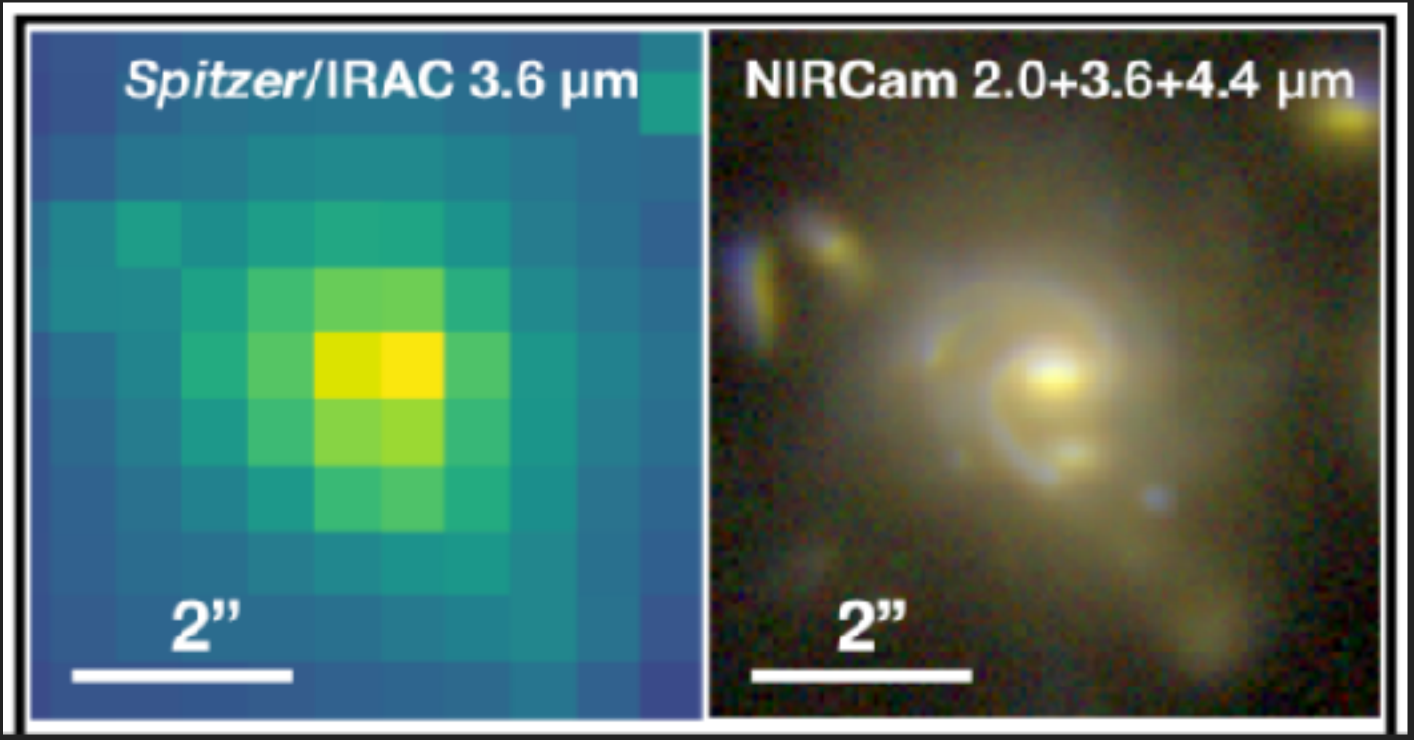


THIS IS AN INHERENTLY MULTI-WAVELENGTH PROBLEM

- While JWST opens up several new observational windows, past and future Hubble data have advantages in key areas, including:
  - Optical (<1μm) imaging probes the rest-frame non-ionizing UV at z < 5.
  - This imaging also probes below the Lyman break at z=4-7.
  - Vast samples of galaxies at z=3-10 have been discovered with Hubble, which will comprise a reference set of early-cycle JWST spectroscopic targets.
  - Only Hubble can probe escaping Lyman continuum radiation at z=0-4, answering key questions about reionization.

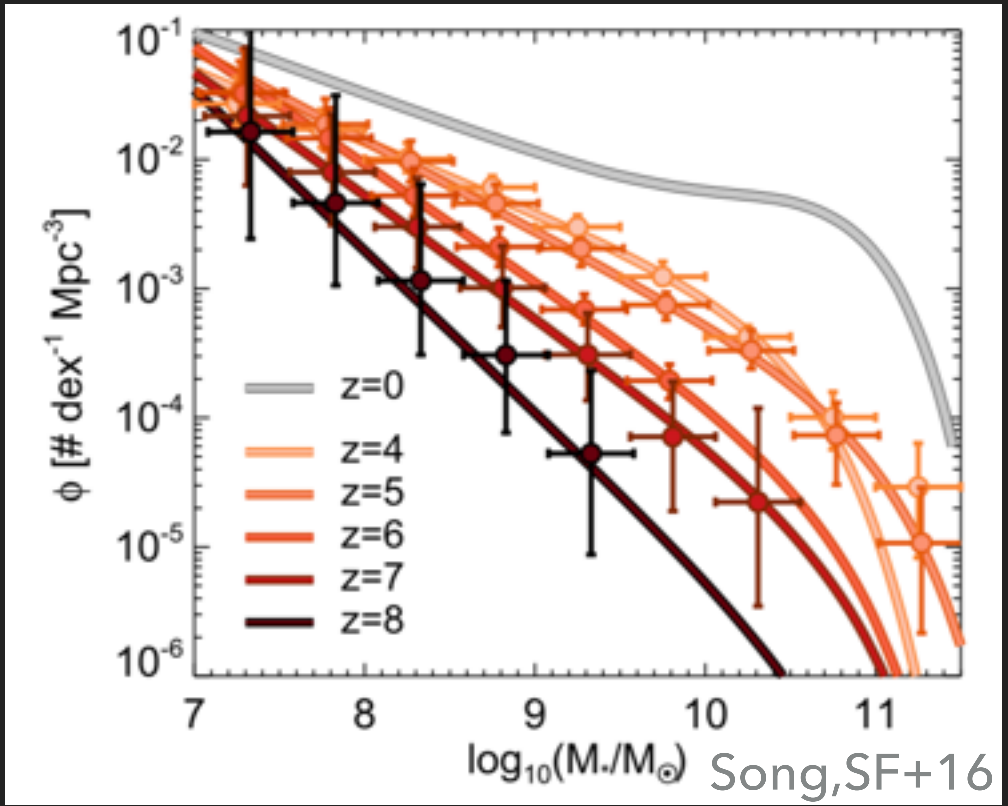
1. A FULL VIEW OF STARLIGHT FROM GALAXIES

- At z > 3, we currently only have a rest-UV view of galaxies. This gives us wonderful information on the level and extend of their unobscured star-formation, but we are lacking knowledge of whether older stellar populations exist.
  - Deep imaging at λ > 2μm is needed to probe the rest-frame optical at z > 3. A comparison of the morphologies across rest-UV and optical will allow us to better understand the formation of early galaxies.
  - While Spitzer/IRAC probes these wavelengths, the resolution does not permit us to understand whether the rest-optical and rest-UV are coincident.



1. A FULL VIEW OF STARLIGHT FROM GALAXIES

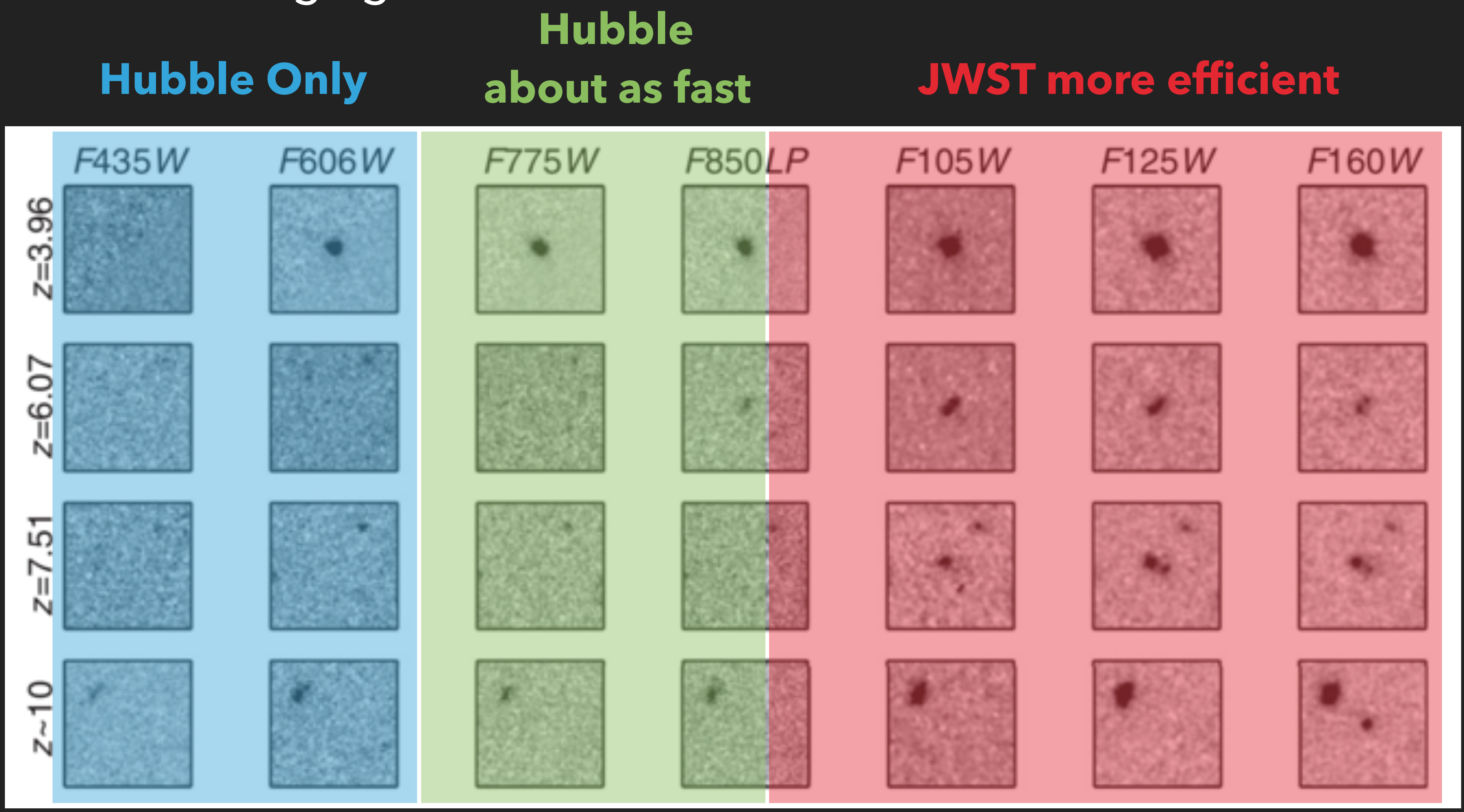
- A related topic - much work has gone into measuring the stellar mass function at high-redshift, but this is based purely on rest-frame UV light at z > 4.
  - Combining *Hubble* optical with *Webb* NIR imaging will not only improve stellar mass measurements from star-forming galaxies, it will allow for us to quantify the presence of weakly star-forming yet massive galaxies, which would be invisible in current *Hubble* surveys (e.g., SMUVS paper).



Song,SF+16

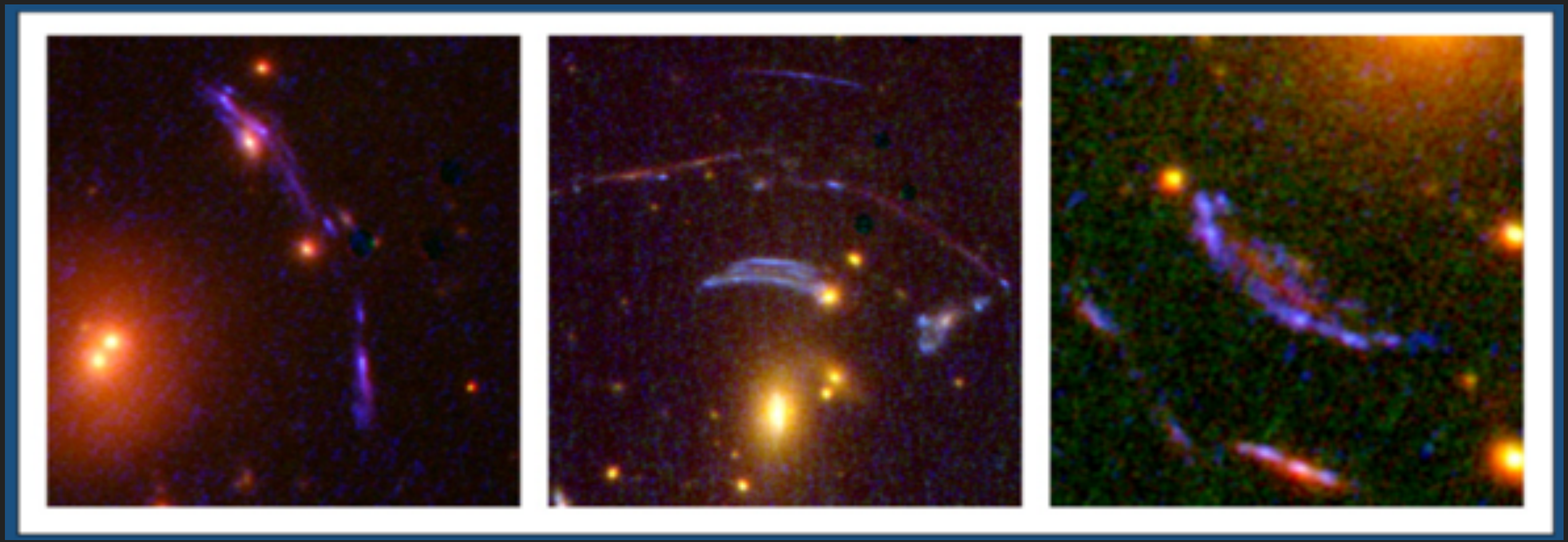
2. LYMAN BREAK SELECTION AT Z > 4

- While JWST is excellent at detecting the rest-UV and optical emission at z > 7, it cannot probe blue enough to reach below the Lyman break.
    - Hubble imaging at < 1um is necessary for robust photometric selection of distant galaxies. We'd like to understand these populations for a number of reasons, but one is to constrain the total amount of star formation in the universe at all times.
    - One reason why all early programs are in well-studied HST fields. New fields will require new blue-optical *HST* imaging.



3. ULTRAVIOLET SPECTROSCOPY

- Deep JWST imaging surveys will better constrain the total non-ionizing UV emissivity from galaxies, and spectroscopic surveys will inform us on the stellar populations, and thus the conversion from non-ionizing to ionizing.
- The major unknown is the ionizing photon escape fraction.
    - This can only be done at z ~ 0-3 (perhaps 4) due to the opacity of the IGM, which requires deep imaging or spectroscopy at $\lambda < 4000$ Å.
    - Thus, combining Hubble UV observations with JWST imaging and spectroscopic surveys can significantly improve our understanding of how reionization was completed.

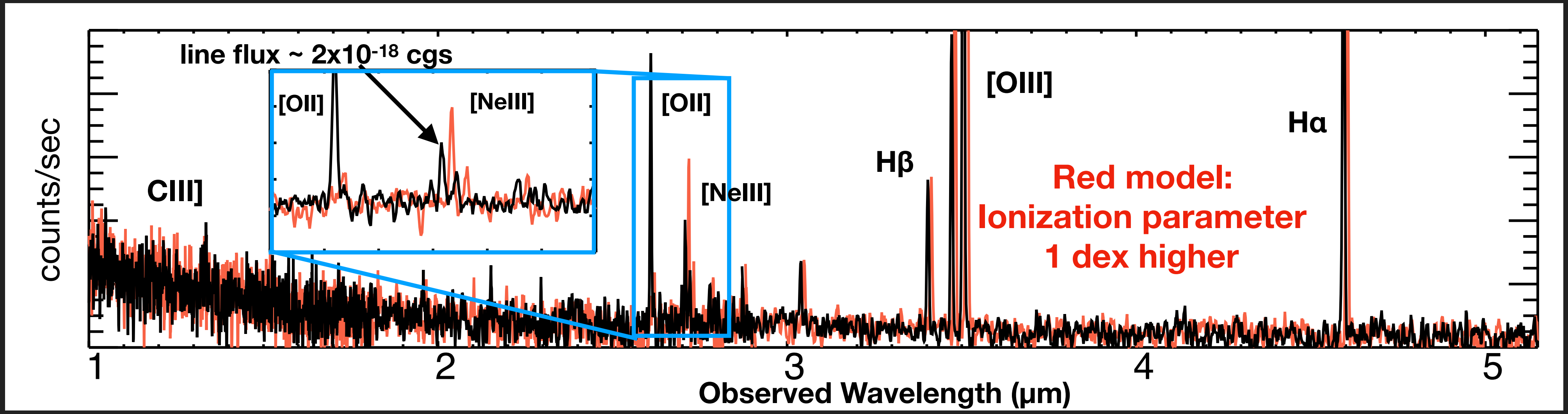


COS-targeted lensed galaxies (poster by Allyssa Riley; PI Harry Ferguson) See also recent programs by Anne Jaskot, Brant Robertson, among others.

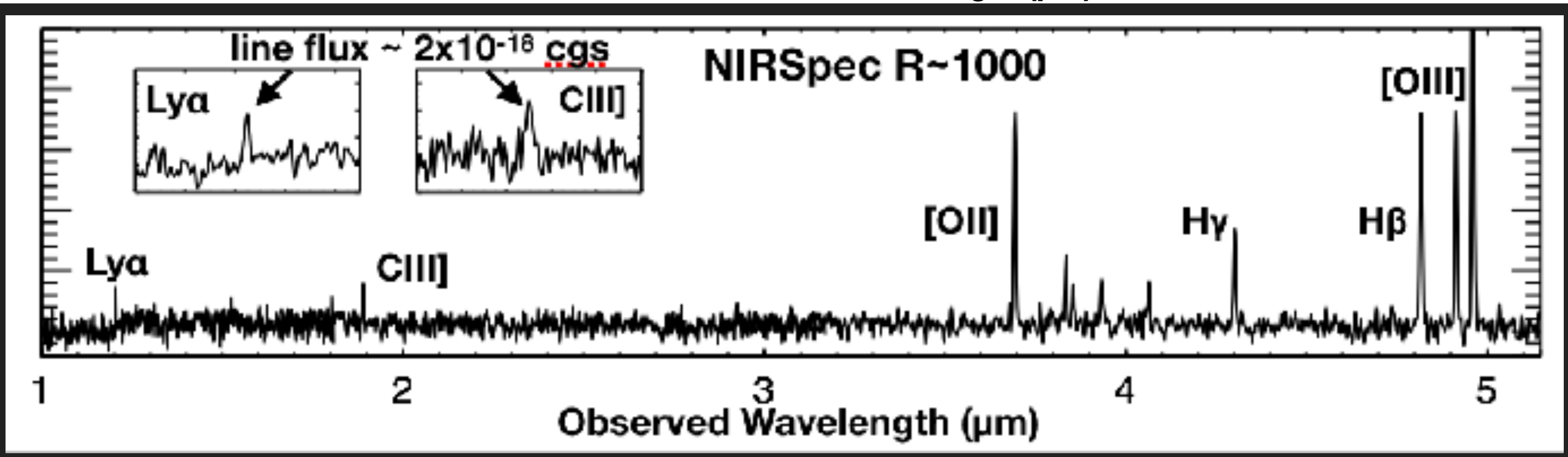
4. EARLY-CYCLE SPECTROSCOPIC TARGETS

- One of the early-Webb most impactful results will be spectroscopic studies of high-z galaxies.
  - While followup of faint Webb-discovered galaxies will be interesting, the most astrophysical knowledge will be learned from followup of HST-discovered galaxies, which are bright enough for a large number of diagnostic lines to be well-detected.

z~6



z~9



SUMMARY

- Previous and future HST imaging and spectroscopic observations are needed to complement (and in some cases make possible) some of the key science goals of JWST, including:
  - Resolved galaxy studies at high redshift*
  - Complete stellar mass functions*
  - Lyman break selection at $z < 10$*
  - Spectroscopic observations of known galaxies*
  - Direct measurements of ionizing photon escape fractions.
- *These will all be trialed by the Cosmic Evolution Early Release Science program.