BEYOND THE HORIZON:

What is left to learn after *Hubble* about the first billion years?

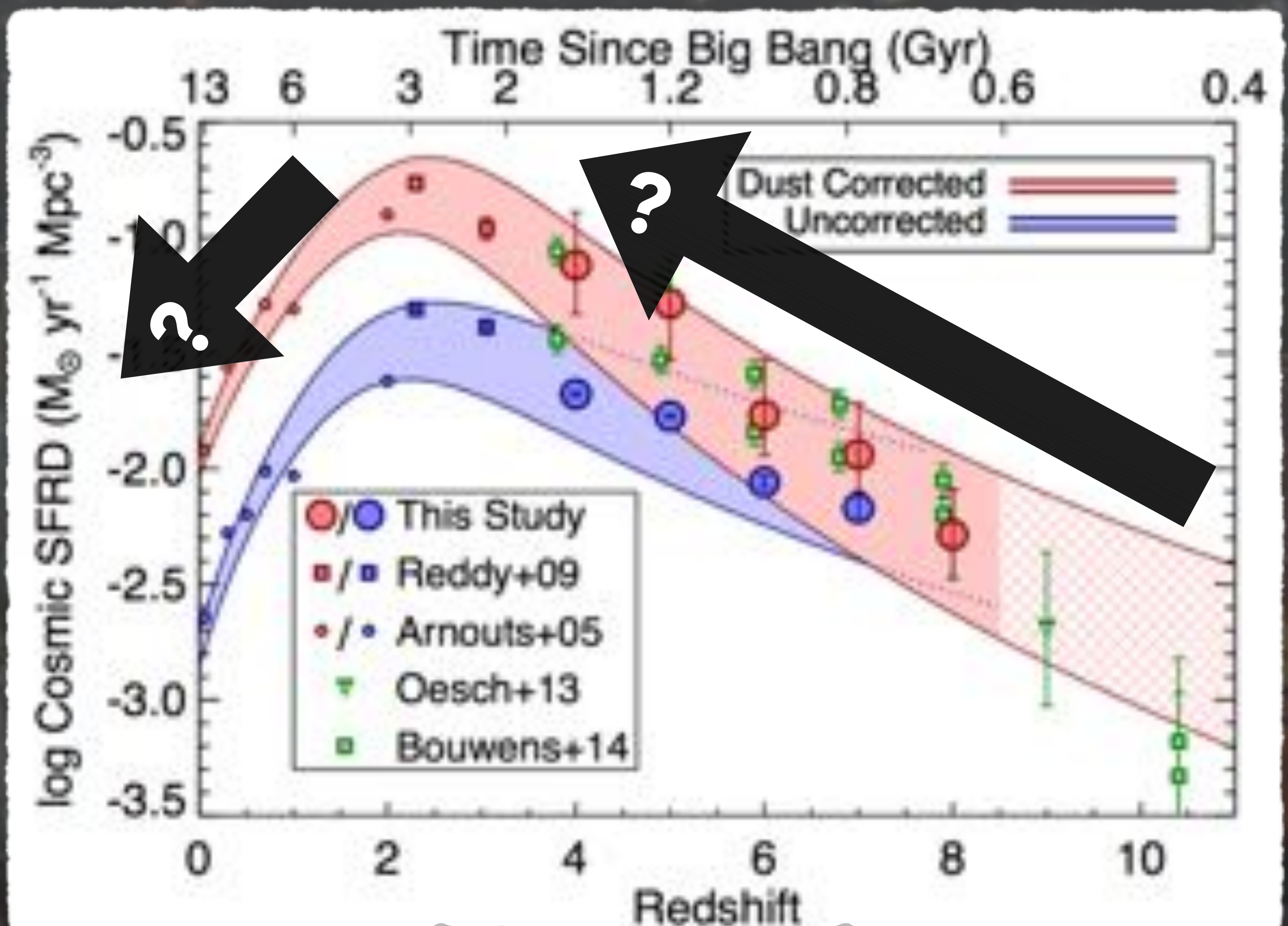
STEVEN FINKELSTEIN
THE UNIVERSITY OF TEXAS AT AUSTIN

NASA/Goddard ATLAST Colloquium

July 15th, 2015

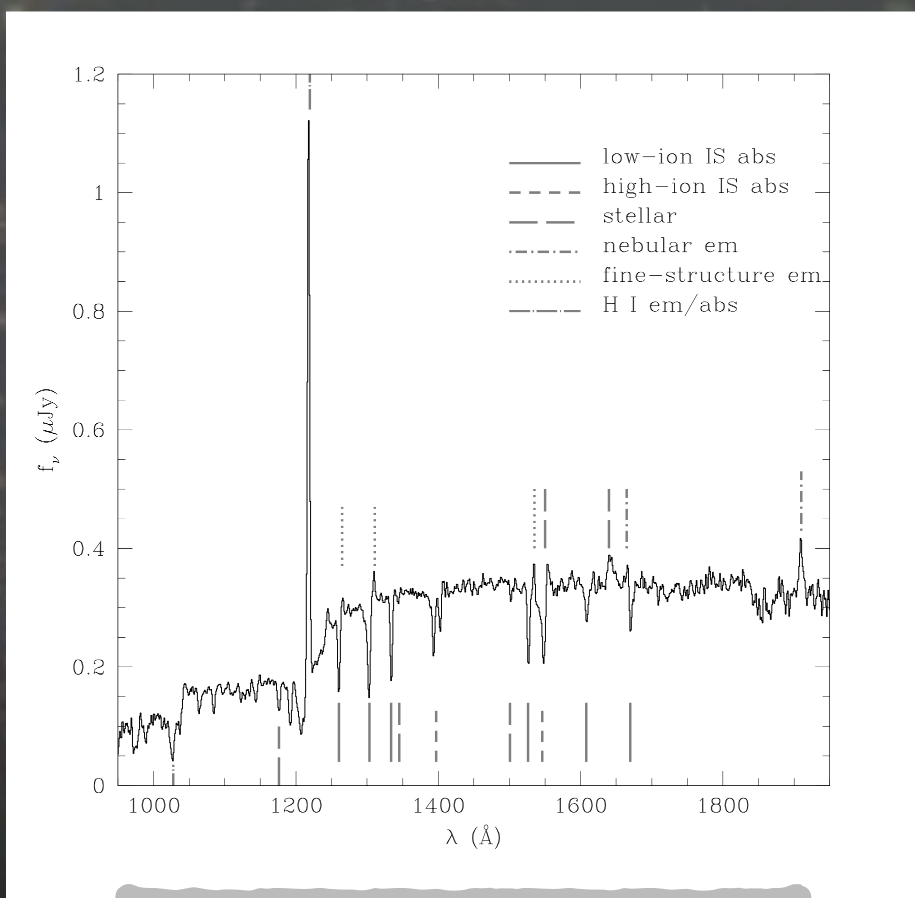
GALAXY EVOLUTION

- What are the (changing?) physical effects responsible for the rise and fall of the cosmic star-formation rate density?

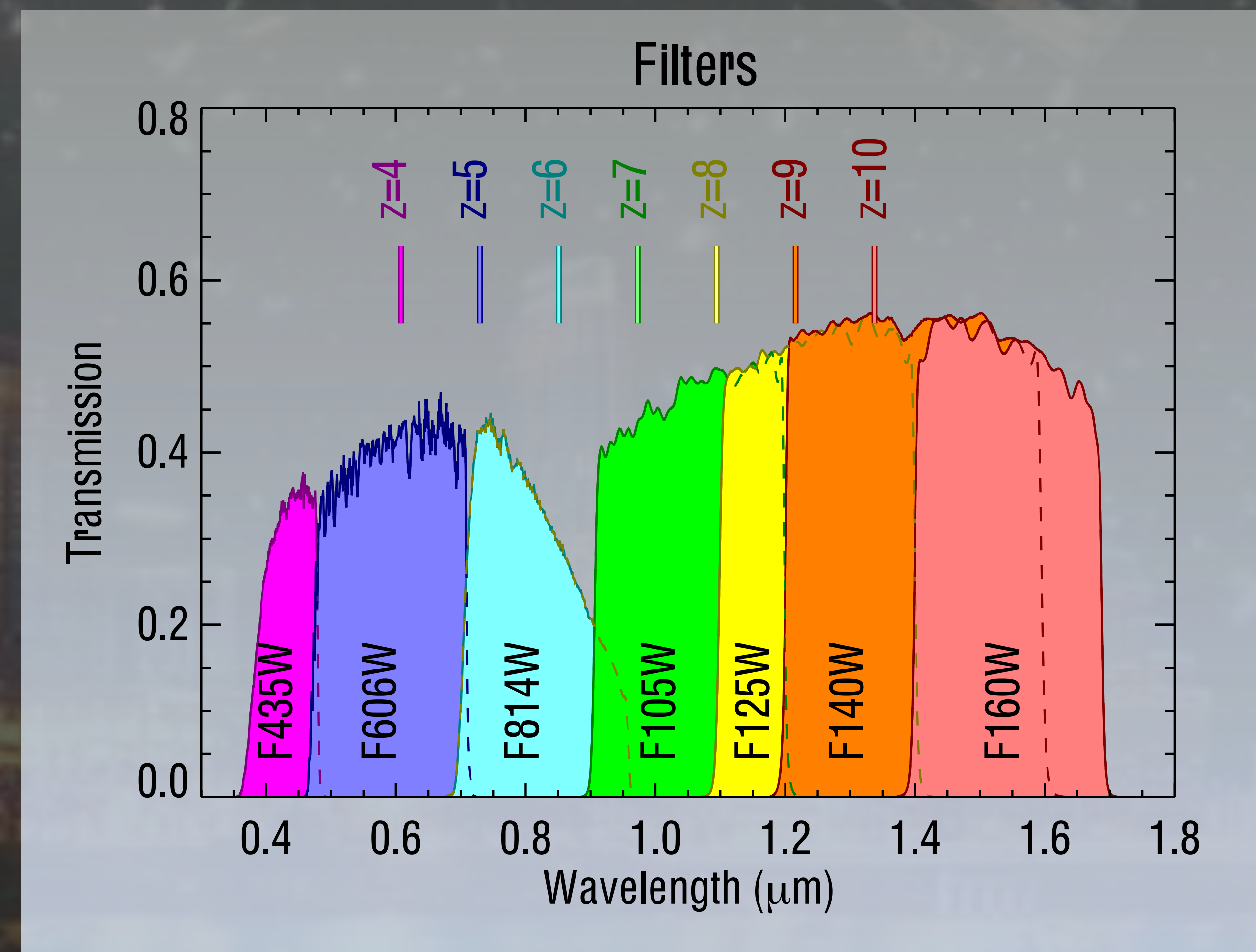


SF+2015

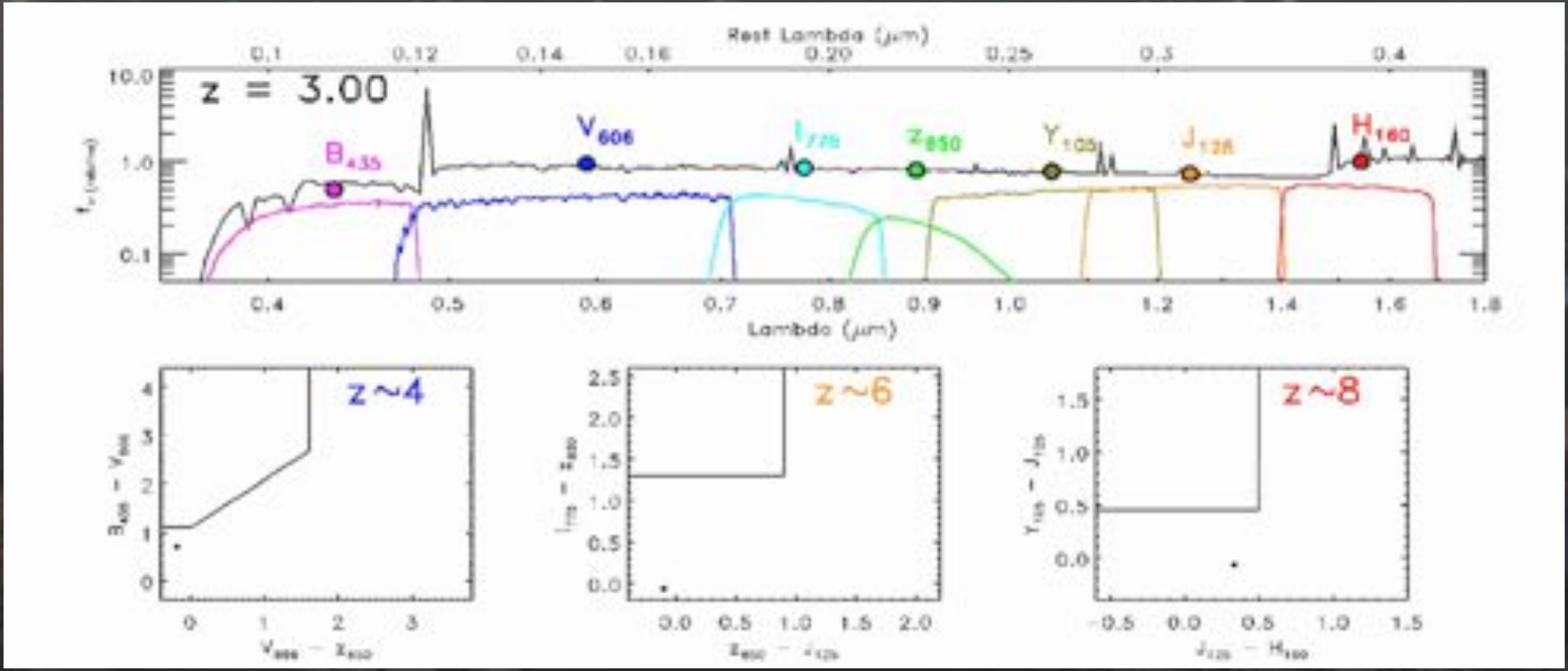
GALAXY SELECTION



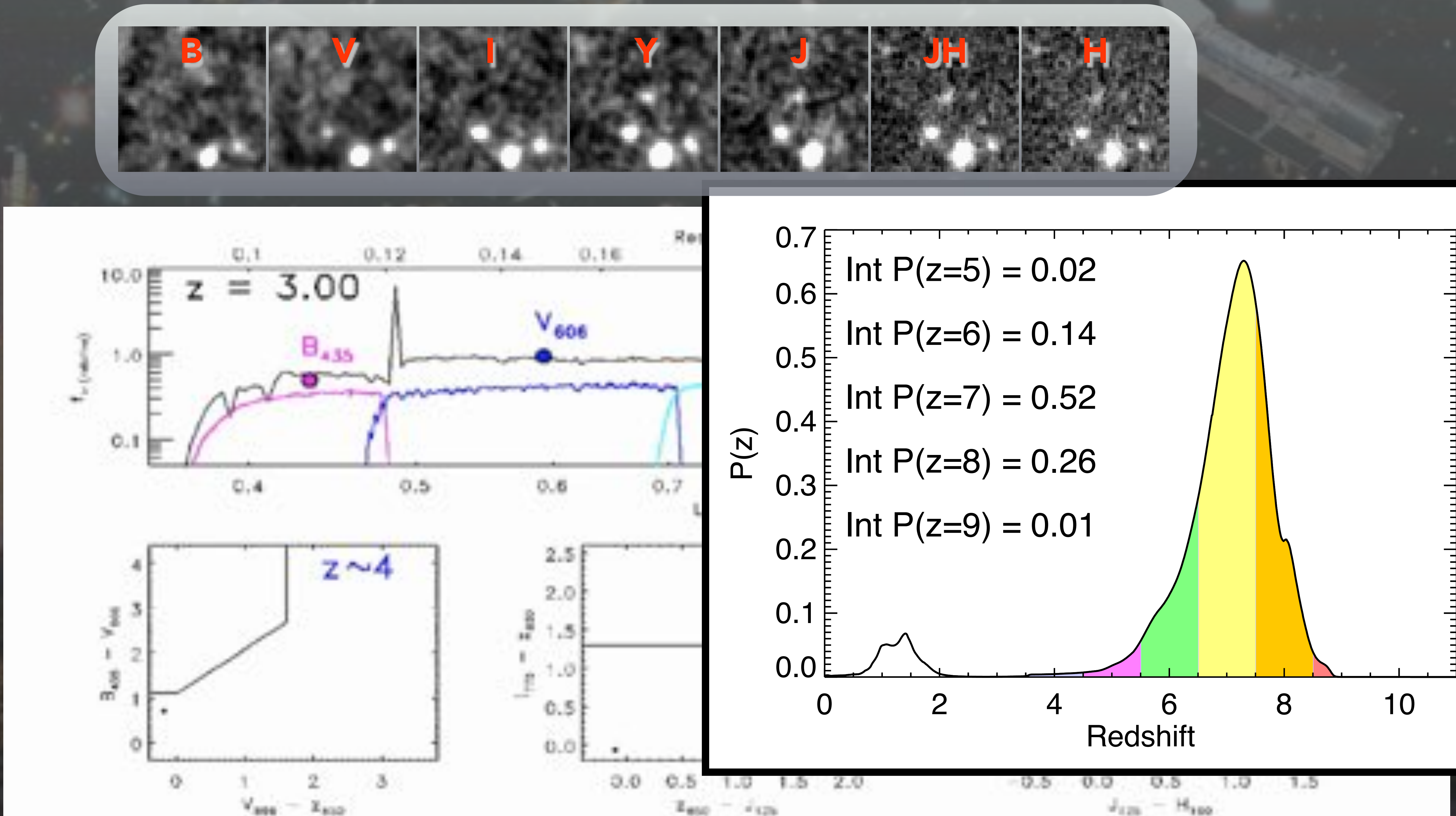
SHAPLEY+2003



GALAXY SELECTION



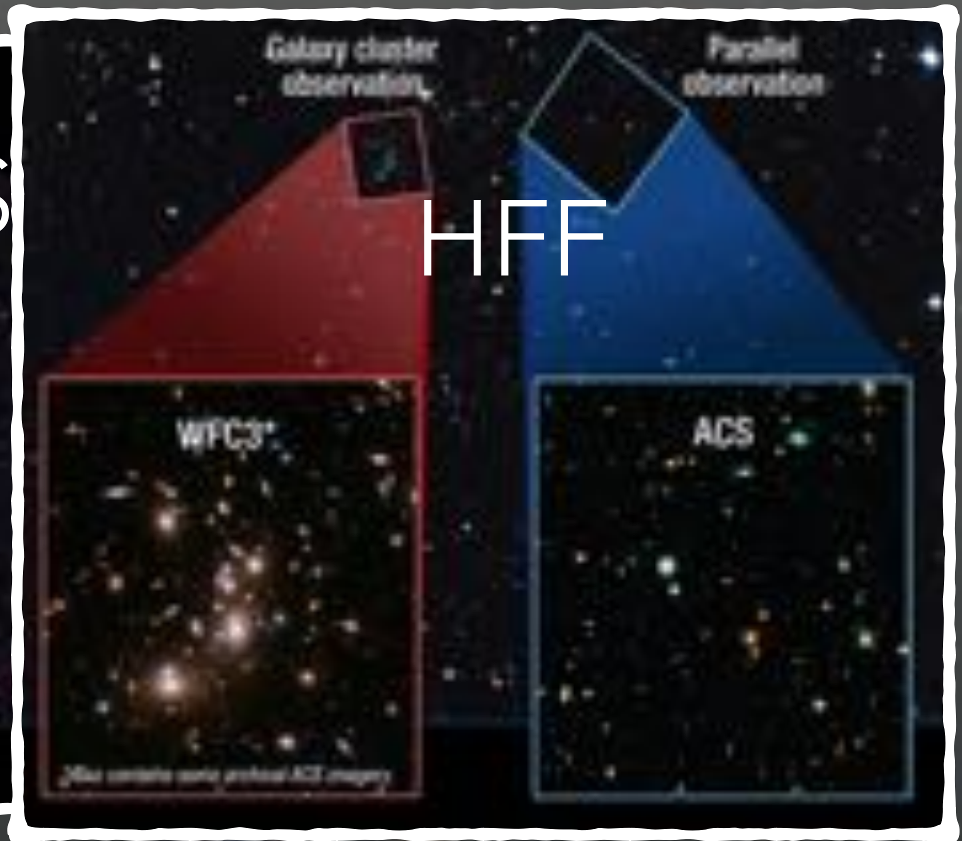
GALAXY SELECTION



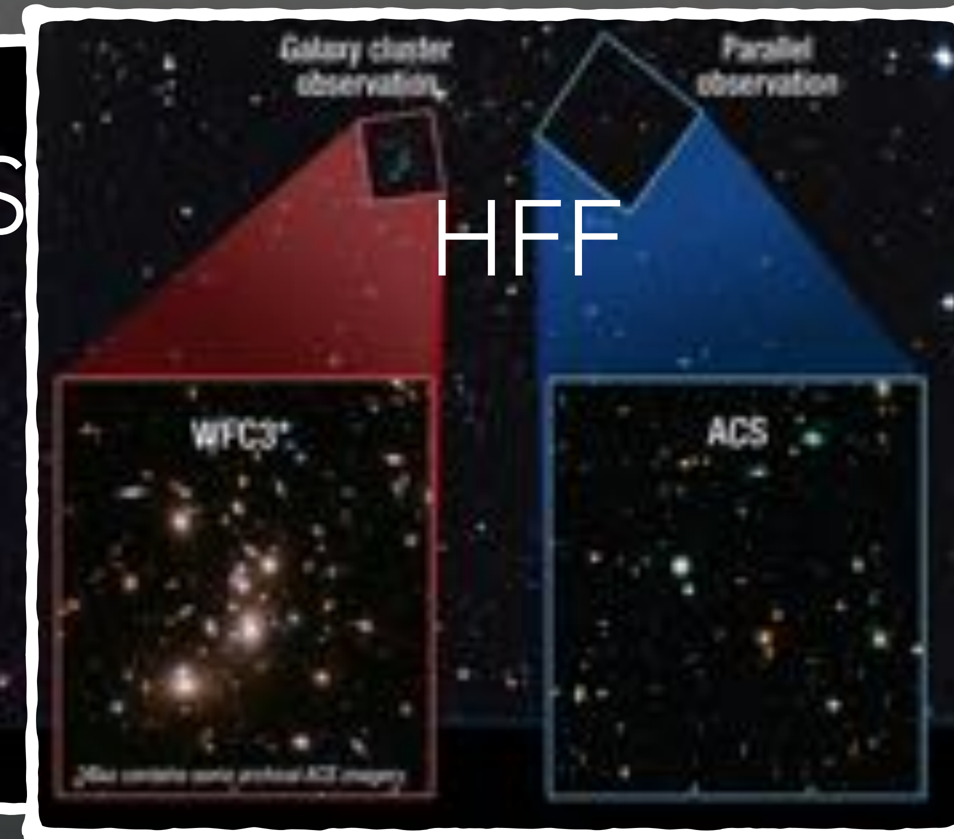
OUR TOOLBOX

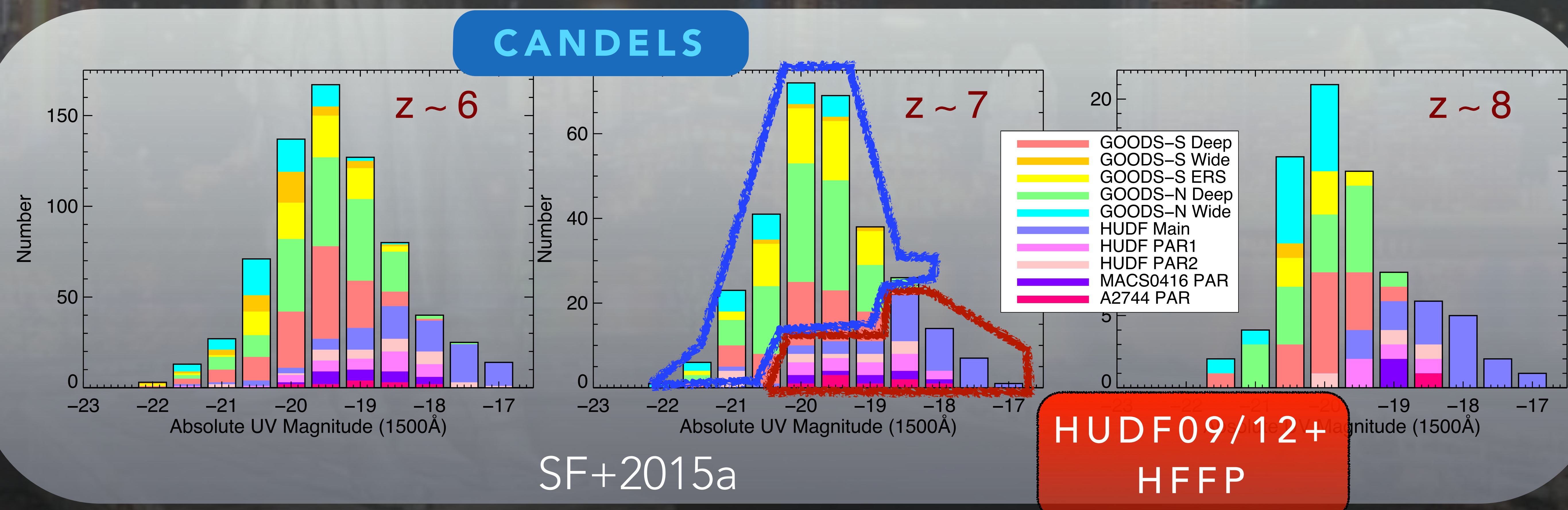

HUDF


CANDELS/GOODS


HFF
Galaxy cluster observation
Parallel observation
WFC3*
ACS

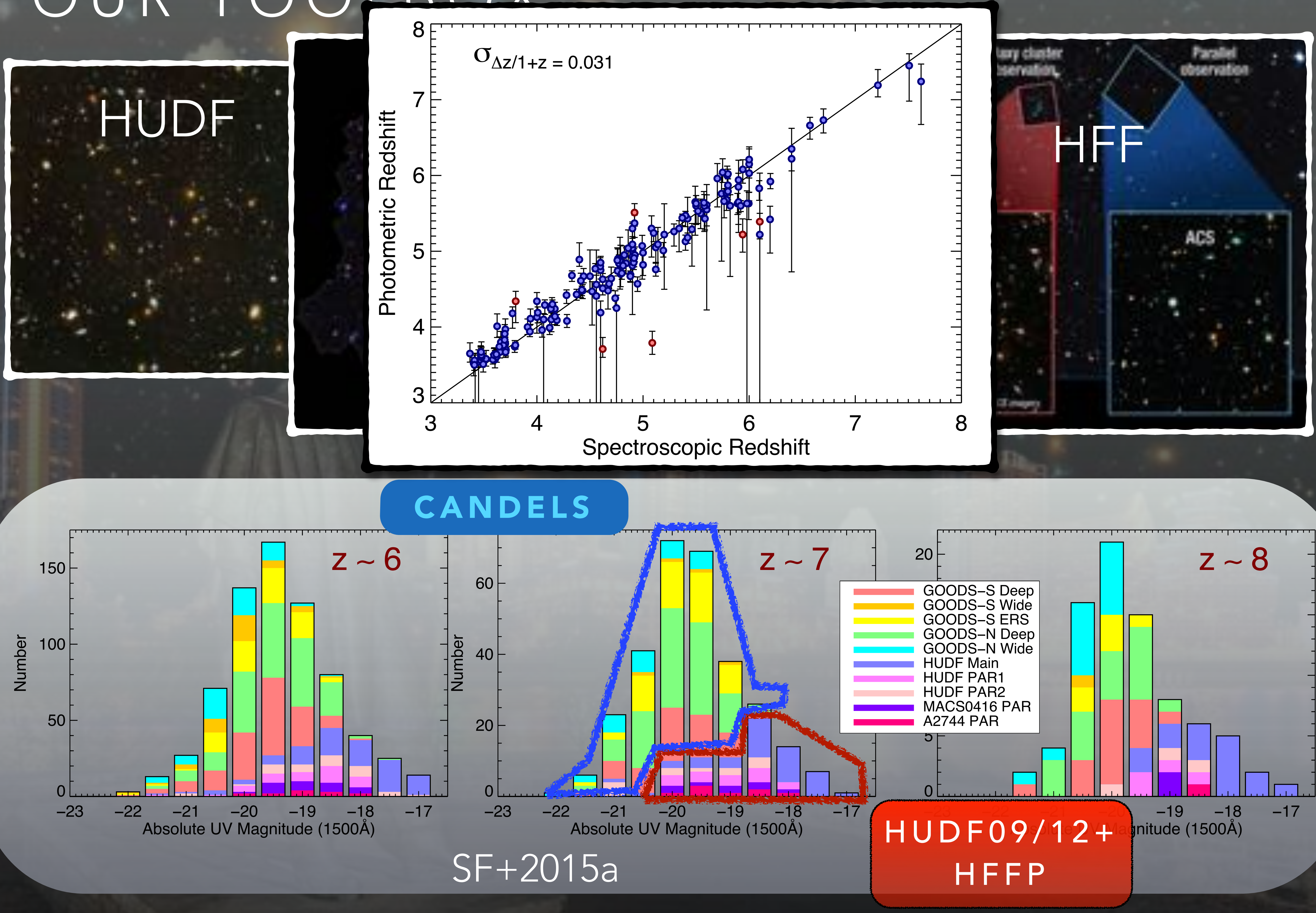
OUR TOOLBOX

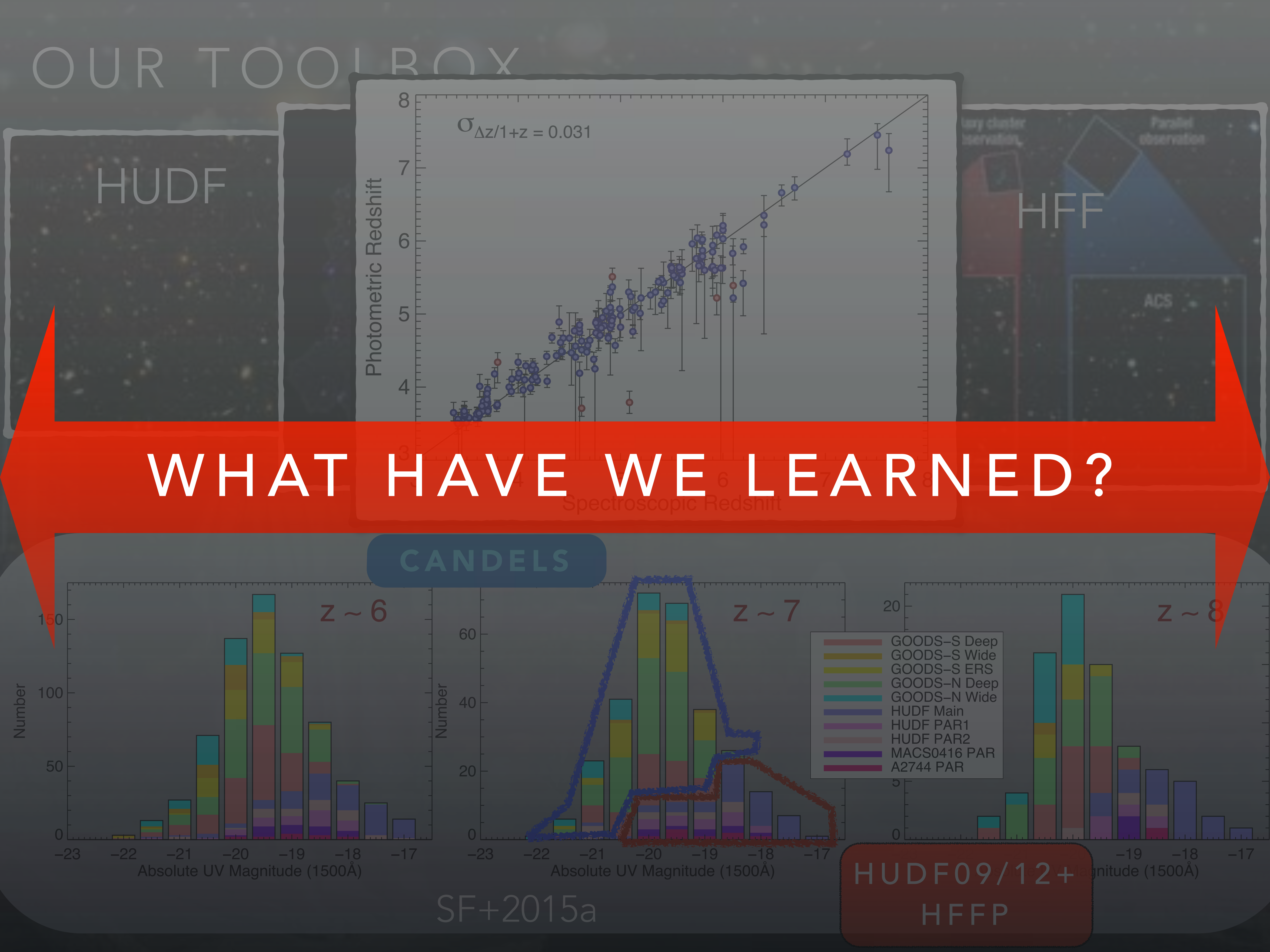




SF+2015a

OUR TOOLBOX


HUDF
HFF
$\sigma_{\Delta z/1+z}$ = 0.031
Photometric Redshift
Spectroscopic Redshift
CANDELS
z ~ 6
z ~ 7
z ~ 8
Number
Absolute UV Magnitude (1500Å)
GOODS−S Deep
GOODS−S Wide
GOODS−S ERS
GOODS−N Deep
GOODS−N Wide
HUDF Main
HUDF PAR1
HUDF PAR2
MACS0416 PAR
A2744 PAR
HUDF09/12+
HFFP
SF+2015a


OUR TOOLBOX
HUDF
HFF
CANDELS
$\sigma_{\Delta z/1+z} = 0.031$
Photometric Redshift
Spectroscopic Redshift
WHAT HAVE WE LEARNED?
z ~ 6
z ~ 7
z ~ 8
Number
Absolute UV Magnitude (1500Å)
GOODS–S Deep
GOODS–S Wide
GOODS–S ERS
GOODS–N Deep
GOODS–N Wide
HUDF Main
HUDF PAR1
HUDF PAR2
MACS0416 PAR
A2744 PAR
SF+2015a
HUDF09/12+
HFFP

CHEMICAL ENRICHMENT

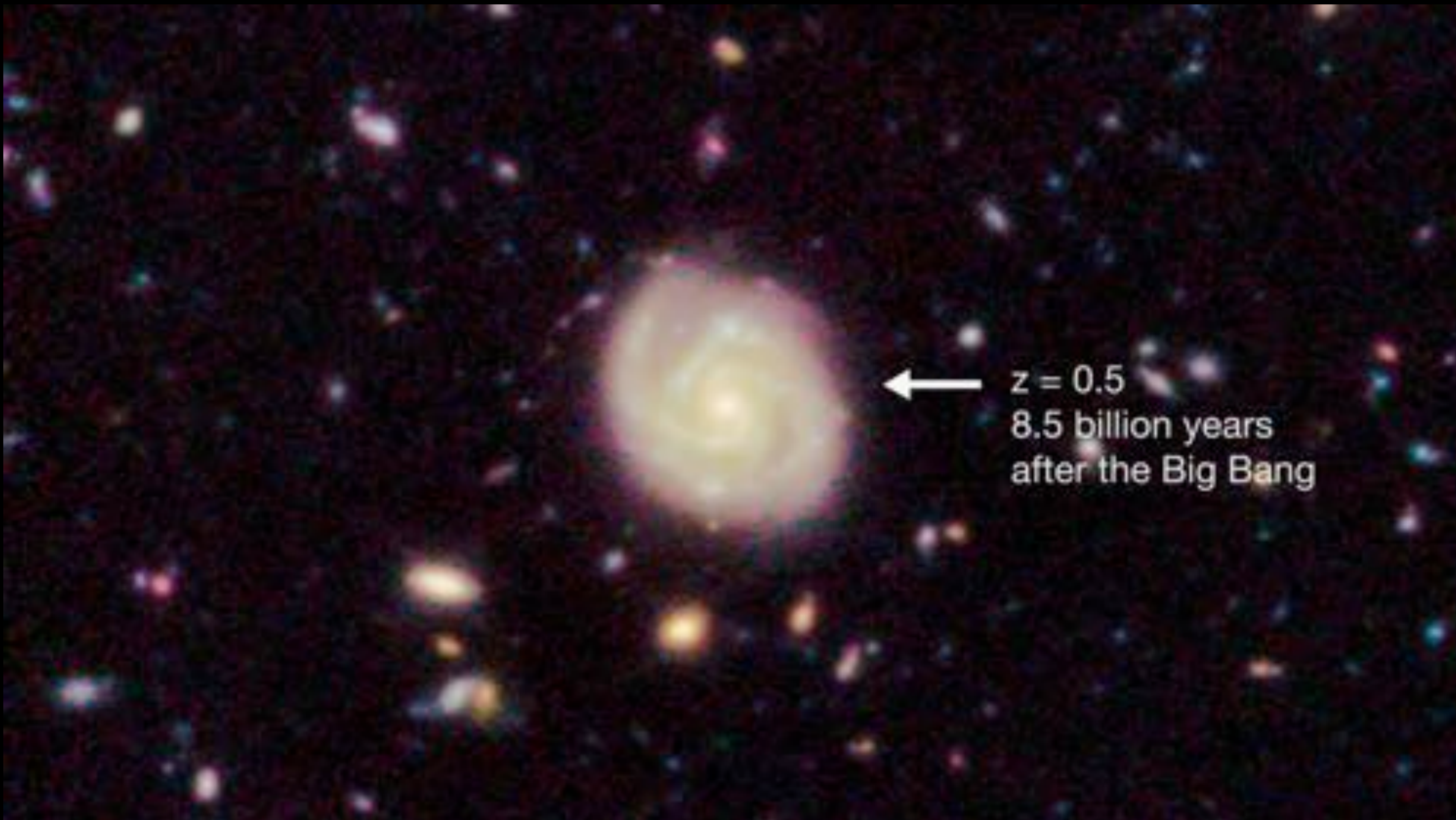
WHEN DO THE FIRST GALAXIES FORM?

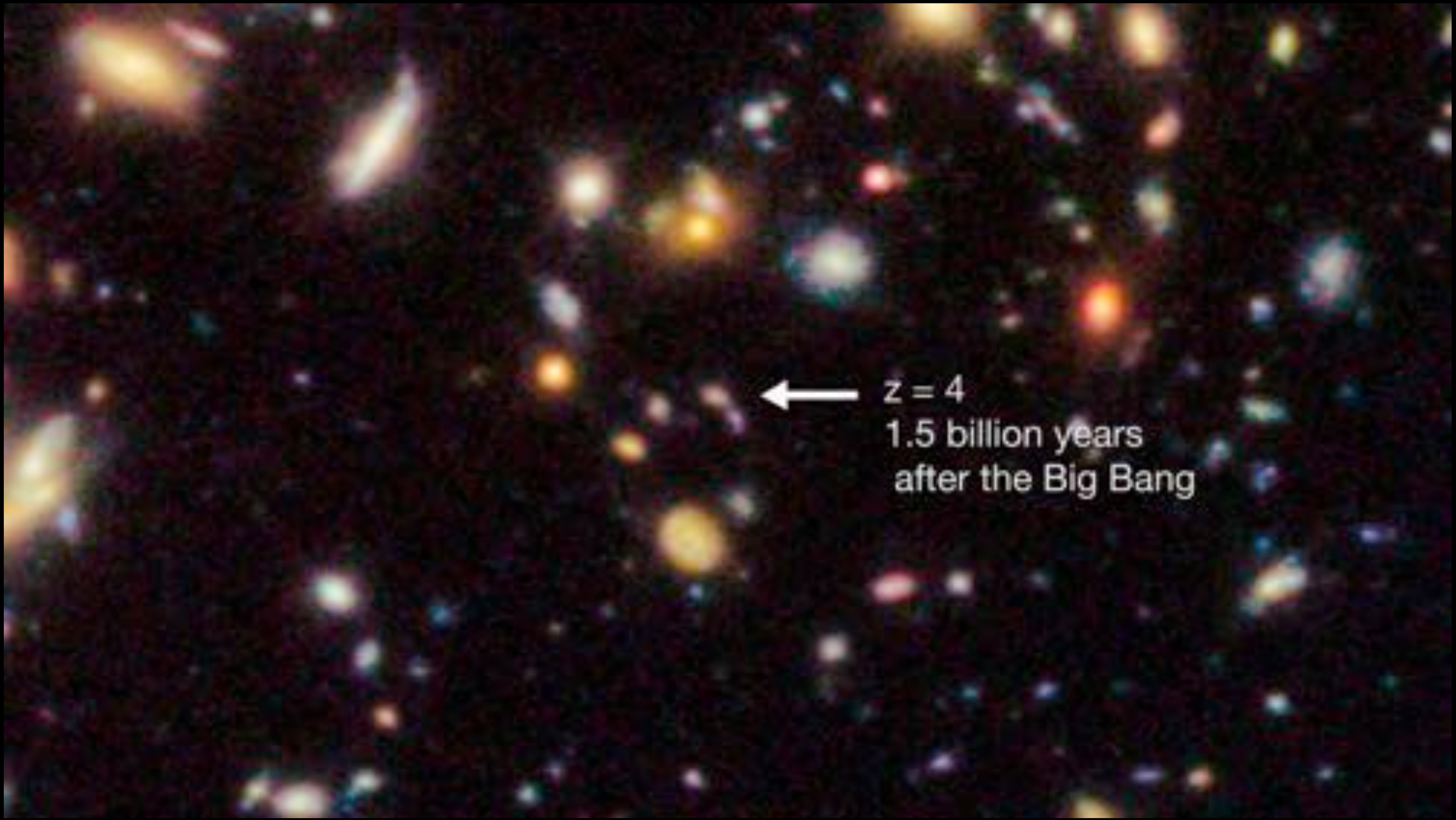
HOW EARLY DO METALS FORM?

Credit: Tiffany Davis - STScI

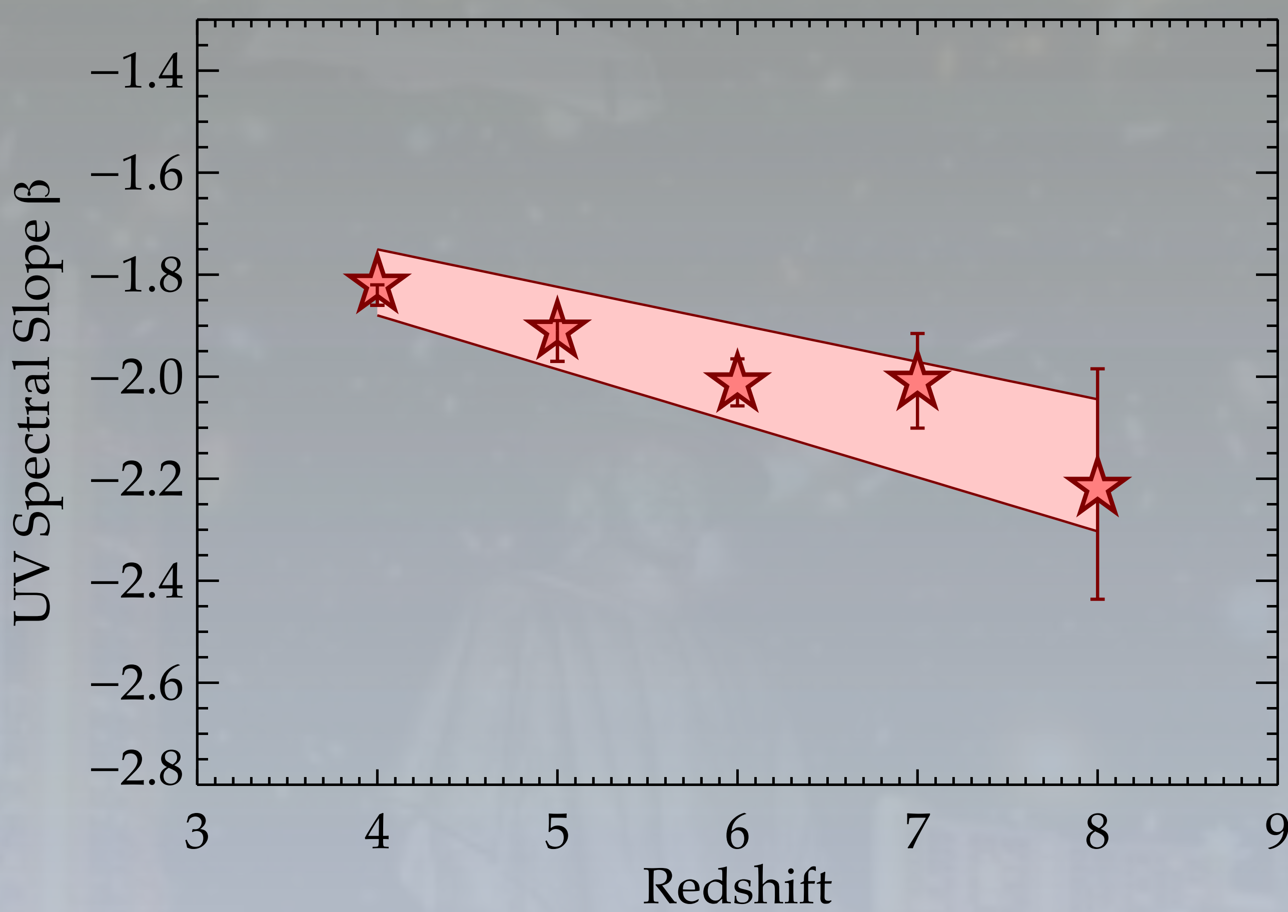
CHEMICAL ENRICHMENT

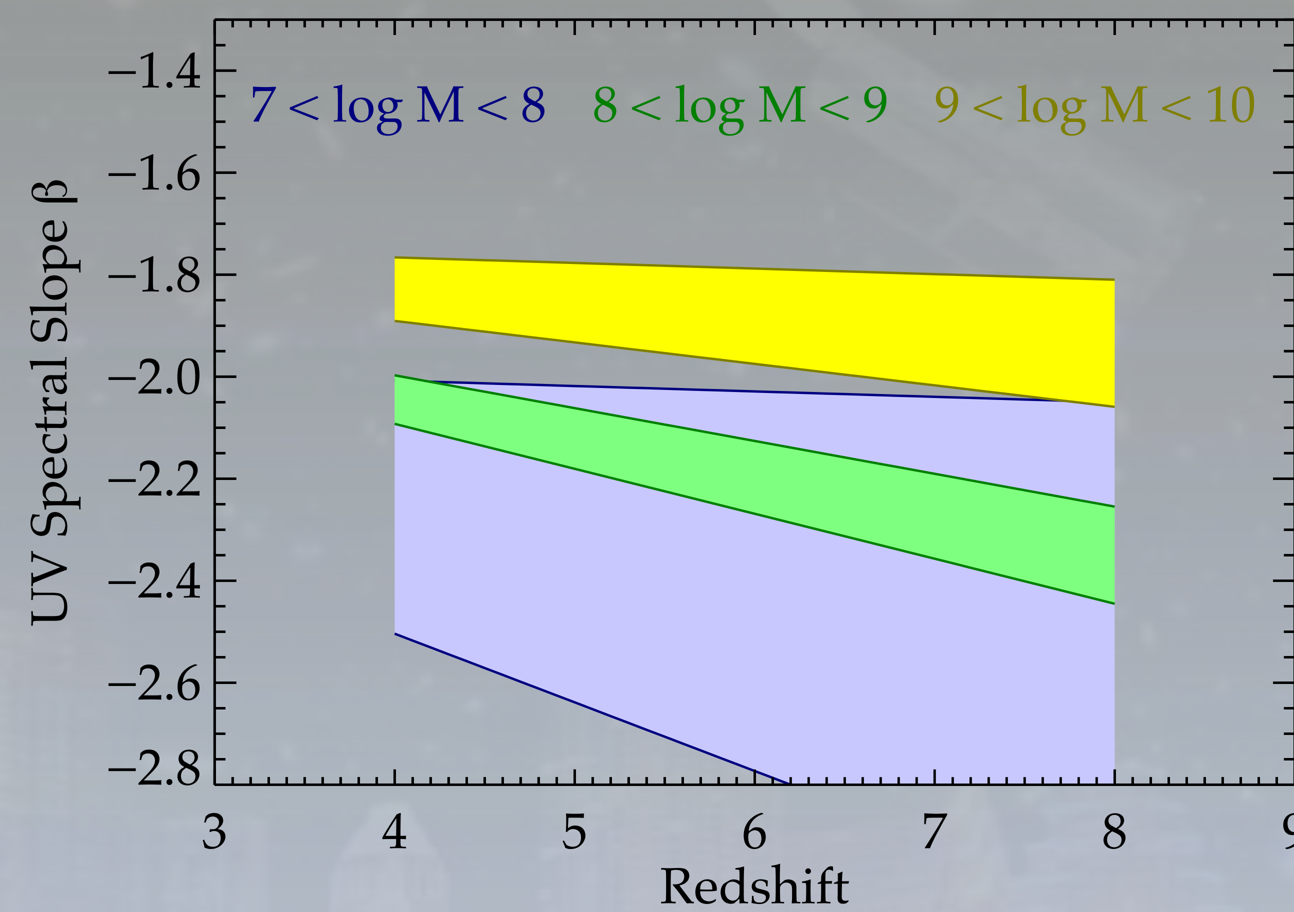
Credit: Tiffany Davis - STScI


z = 0.5
8.5 billion years
after the Big Bang


z = 4
1.5 billion years
after the Big Bang

CHEMICAL ENRICHMENT



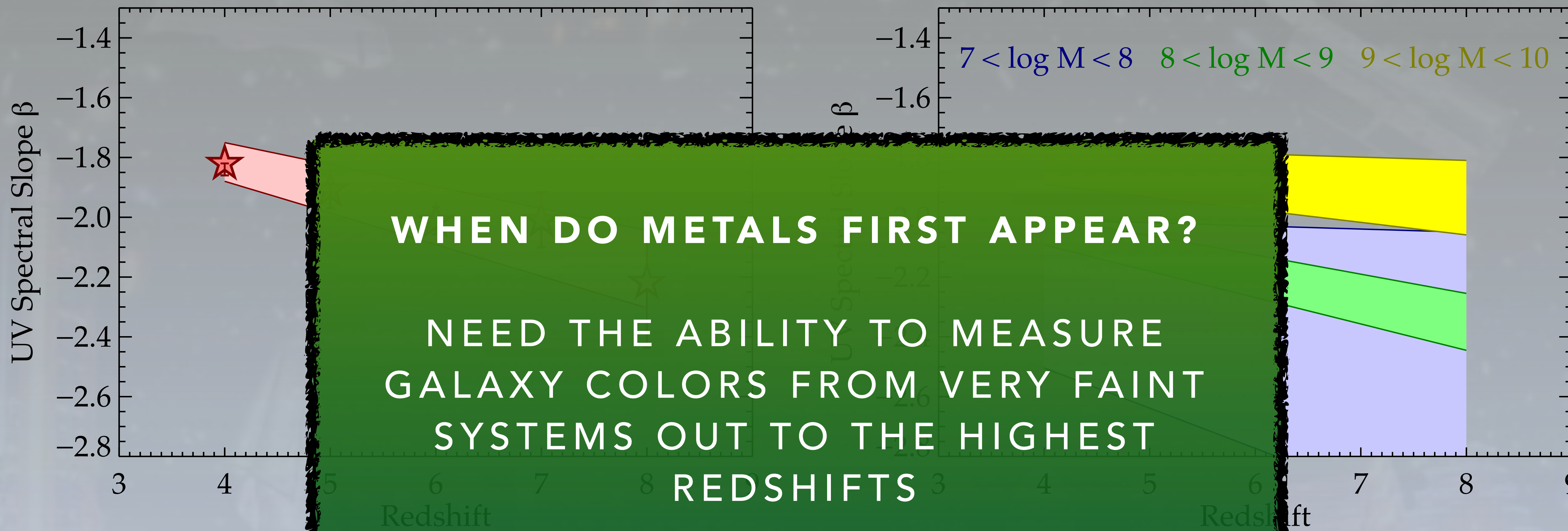


GALAXIES ON AVERAGE ARE LESS DUSTY WITH INCREASING REDSHIFT

THE MOST MASSIVE GALAXIES APPEAR DUSTY, EVEN AT Z=7. LOW-MASS GALAXIES ARE LESS DUSTY, THOUGH NOT METAL-FREE.

SF+2012A,2015B

CHEMICAL ENRICHMENT



WHEN DO METALS FIRST APPEAR?

NEED THE ABILITY TO MEASURE GALAXY COLORS FROM VERY FAINT SYSTEMS OUT TO THE HIGHEST REDSHIFTS

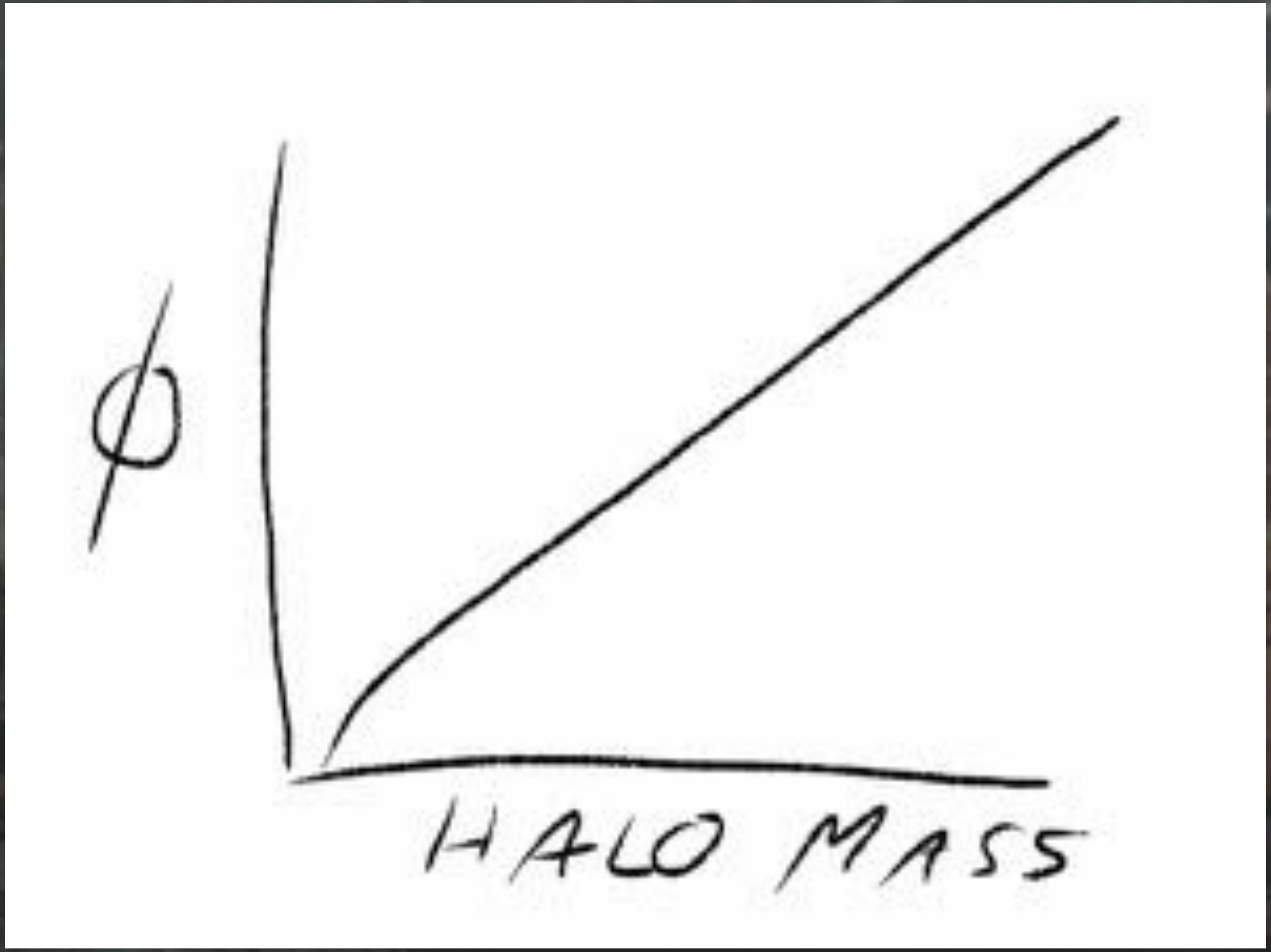
GALAXIES ON AVERAGE ARE LESS DUSTY WITH INCREASING REDSHIFT

THE MOST MASSIVE GALAXIES APPEAR DUSTY, EVEN AT Z=7. LOW-MASS GALAXIES ARE LESS DUSTY, THOUGH NOT METAL-FREE.

SF+2012A,2015B

LUMINOSITY FUNCTIONS

- Much effort has been spent computing the rest-frame UV luminosity functions.



LUM

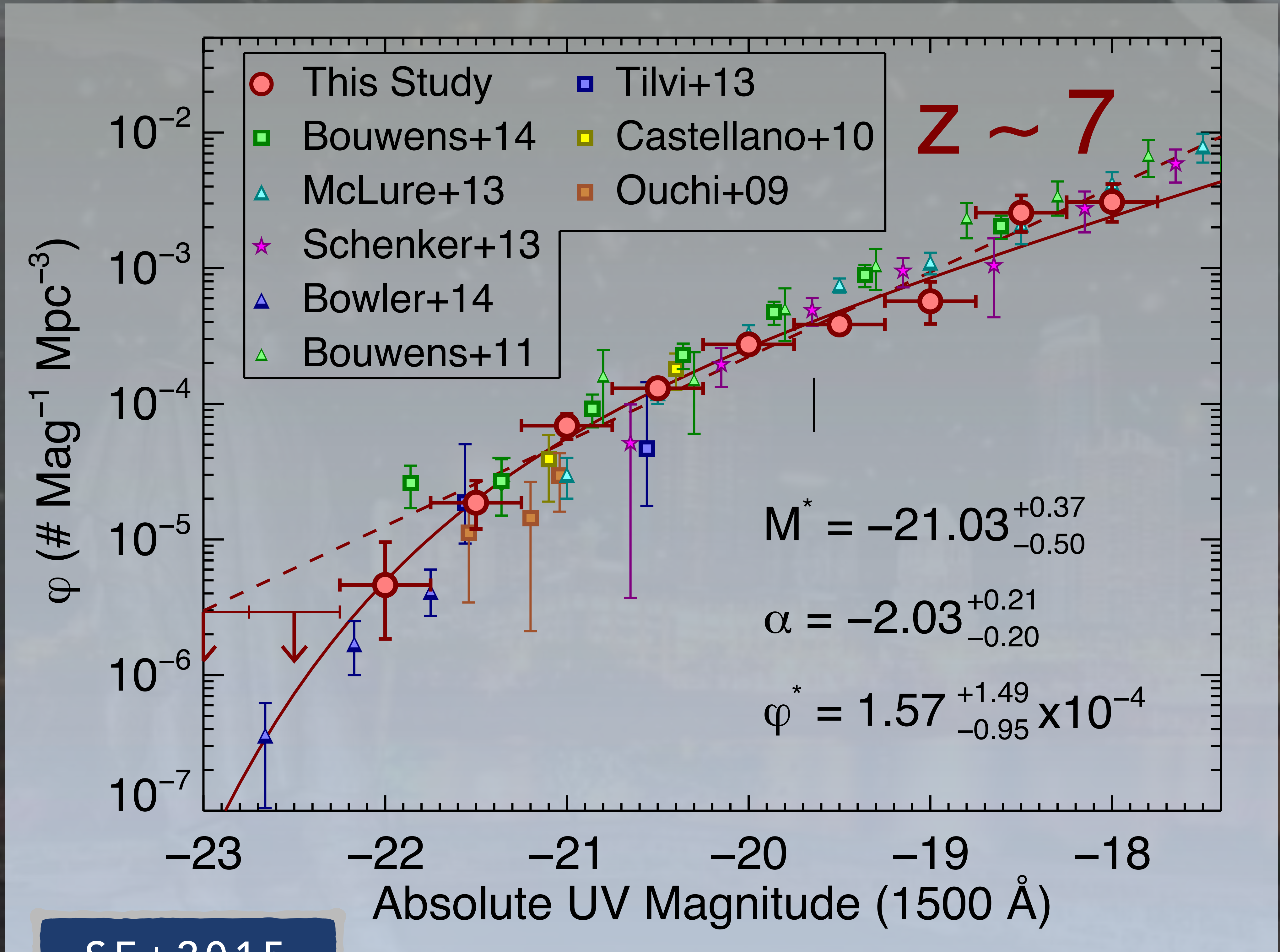
Mu frame

UV

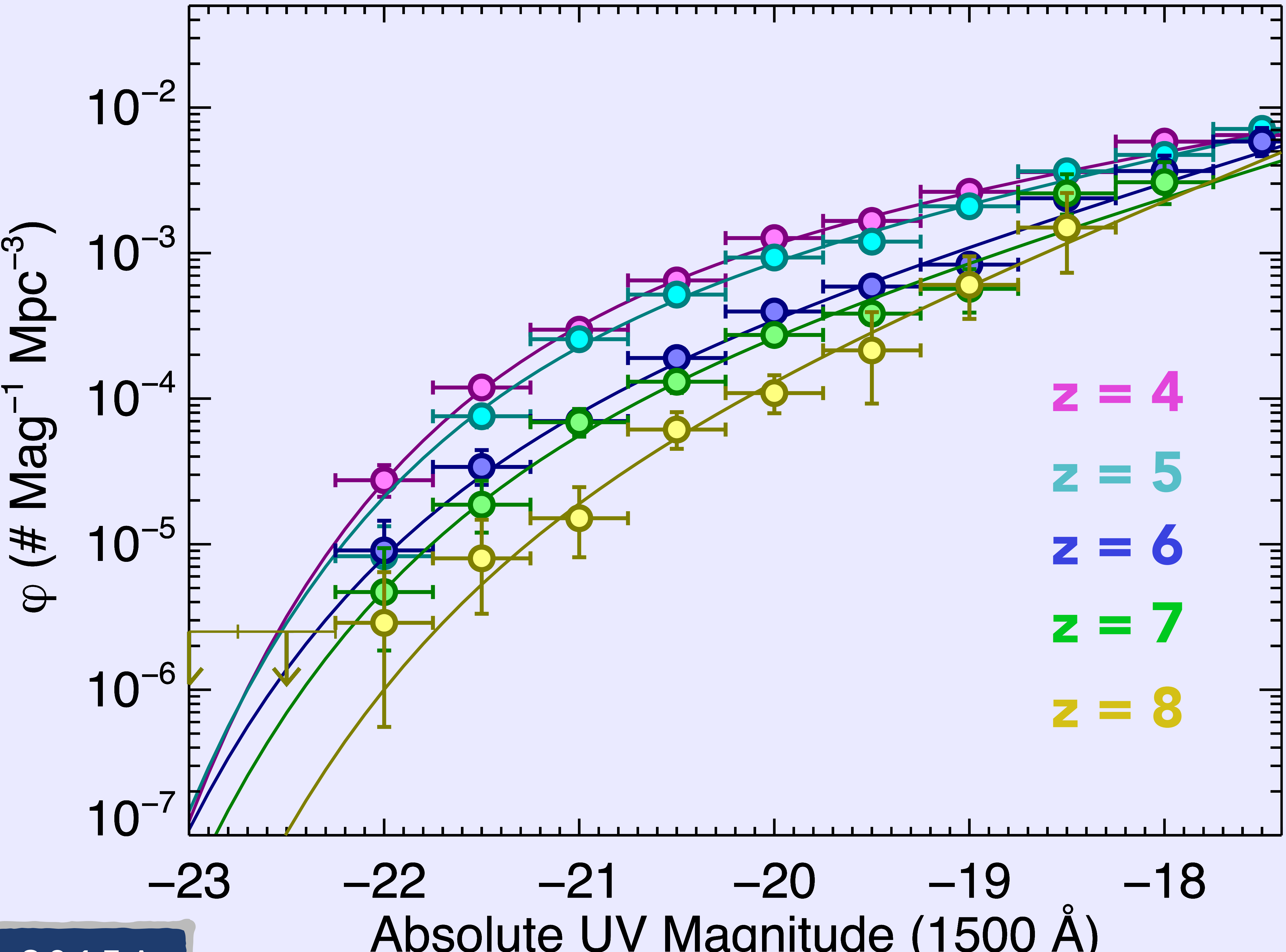
LUMINOSITY FUNCTIONS CAN TELL US ABOUT THE PHYSICAL PROCESSES REGULATING STAR-FORMATION IN THE DISTANT UNIVERSE

THE REST-UV LUMINOSITY FUNCTION ALSO ALLOWS US TO CALCULATE THE STAR-FORMATION RATE DENSITY

THE GOOD NEWS



SF+2015

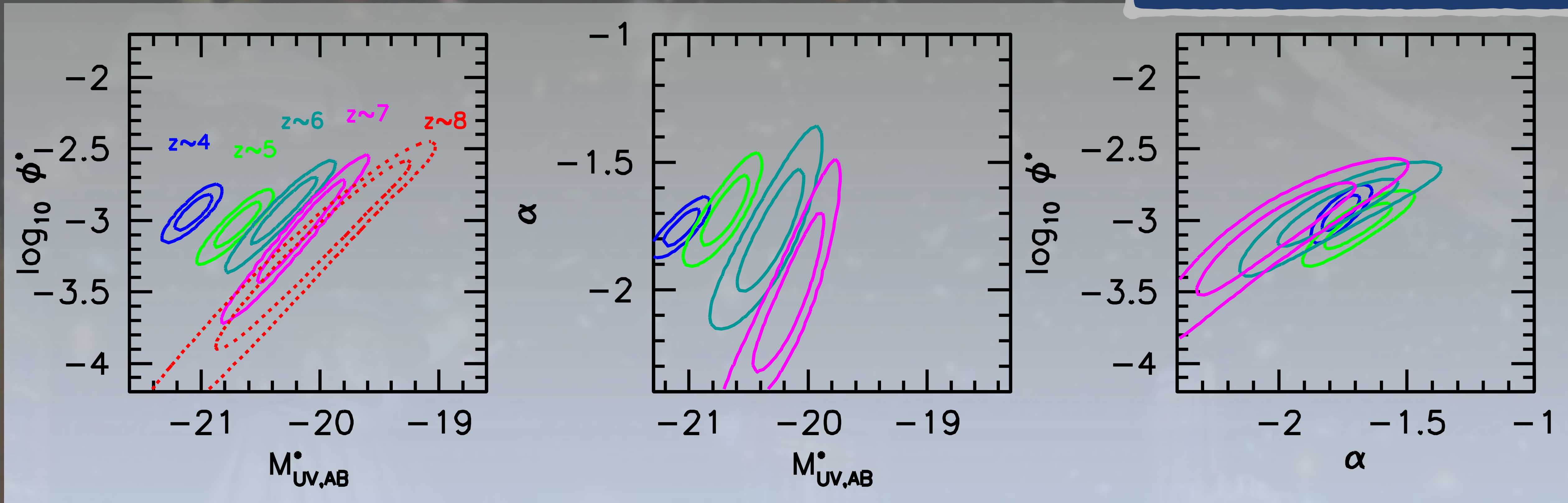


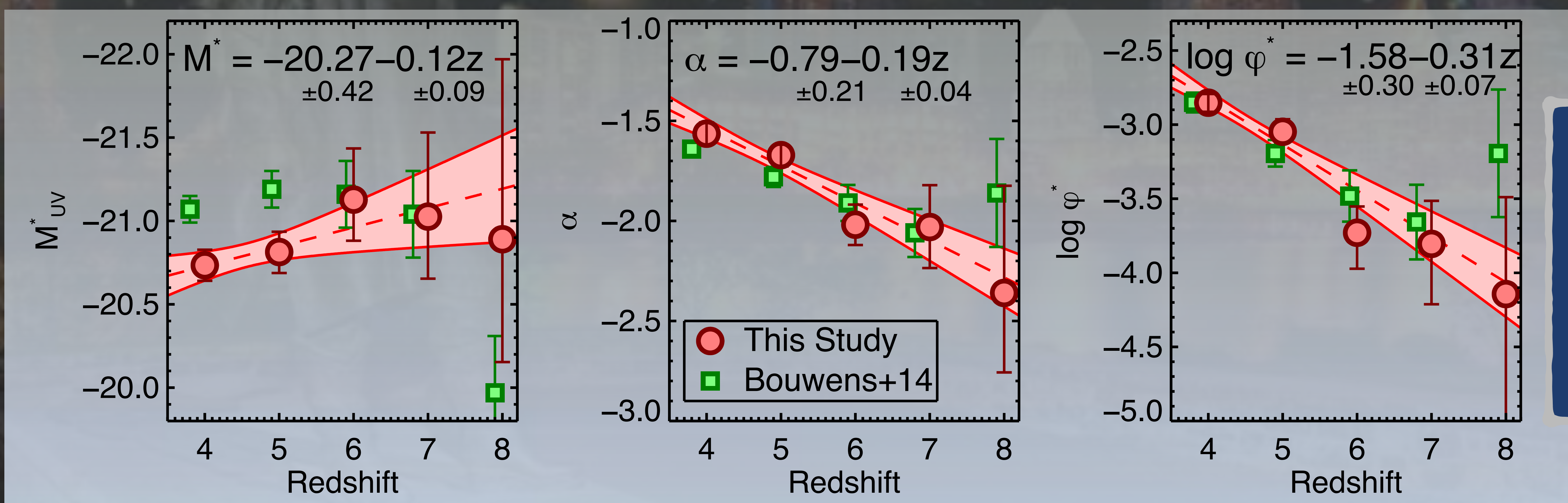
φ (# Mag^{-1} Mpc^{-3})
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
−23
−22
−21
−20
−19
−18
Absolute UV Magnitude (1500 Å)
z = 4
z = 5
z = 6
z = 7
z = 8

SF+2015A

A SURPRISE!

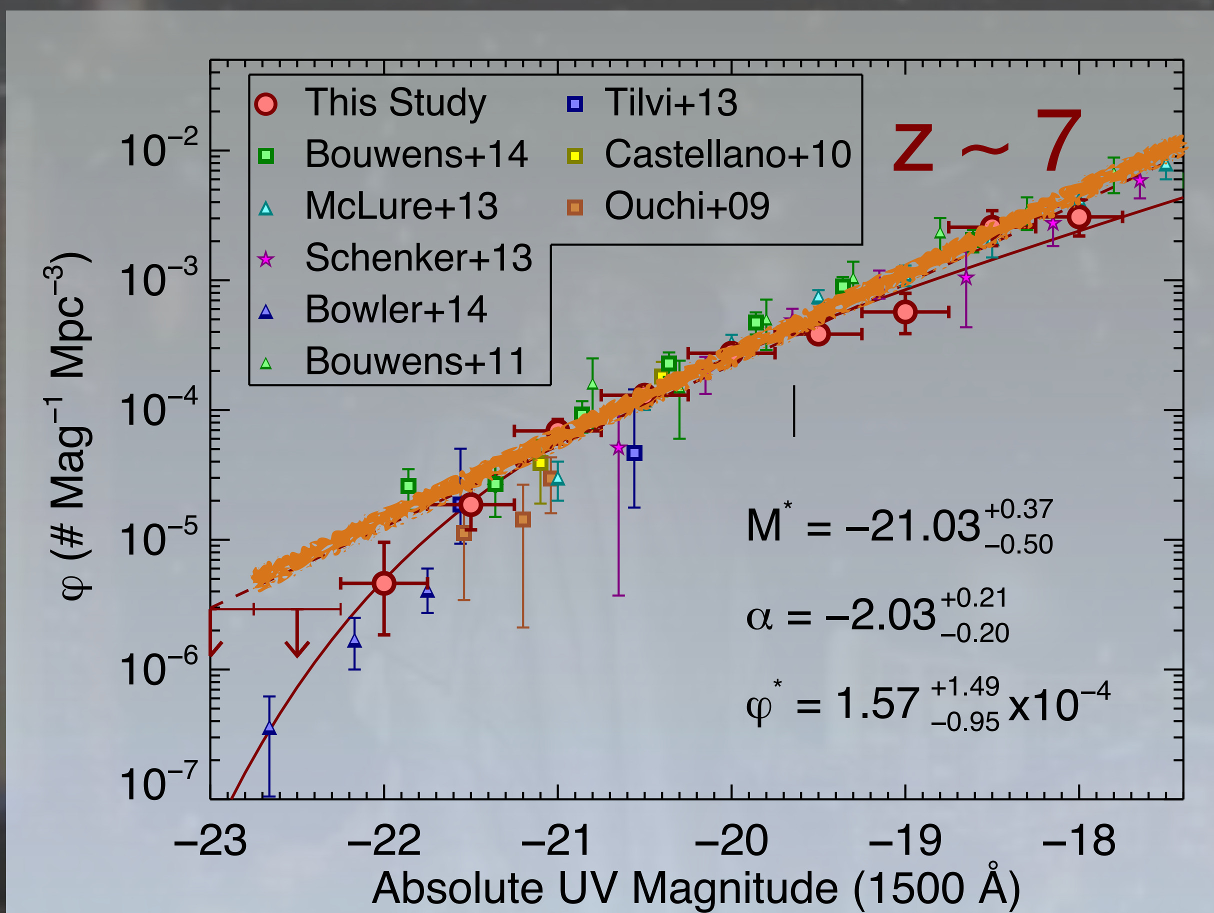
BOUWENS+2011

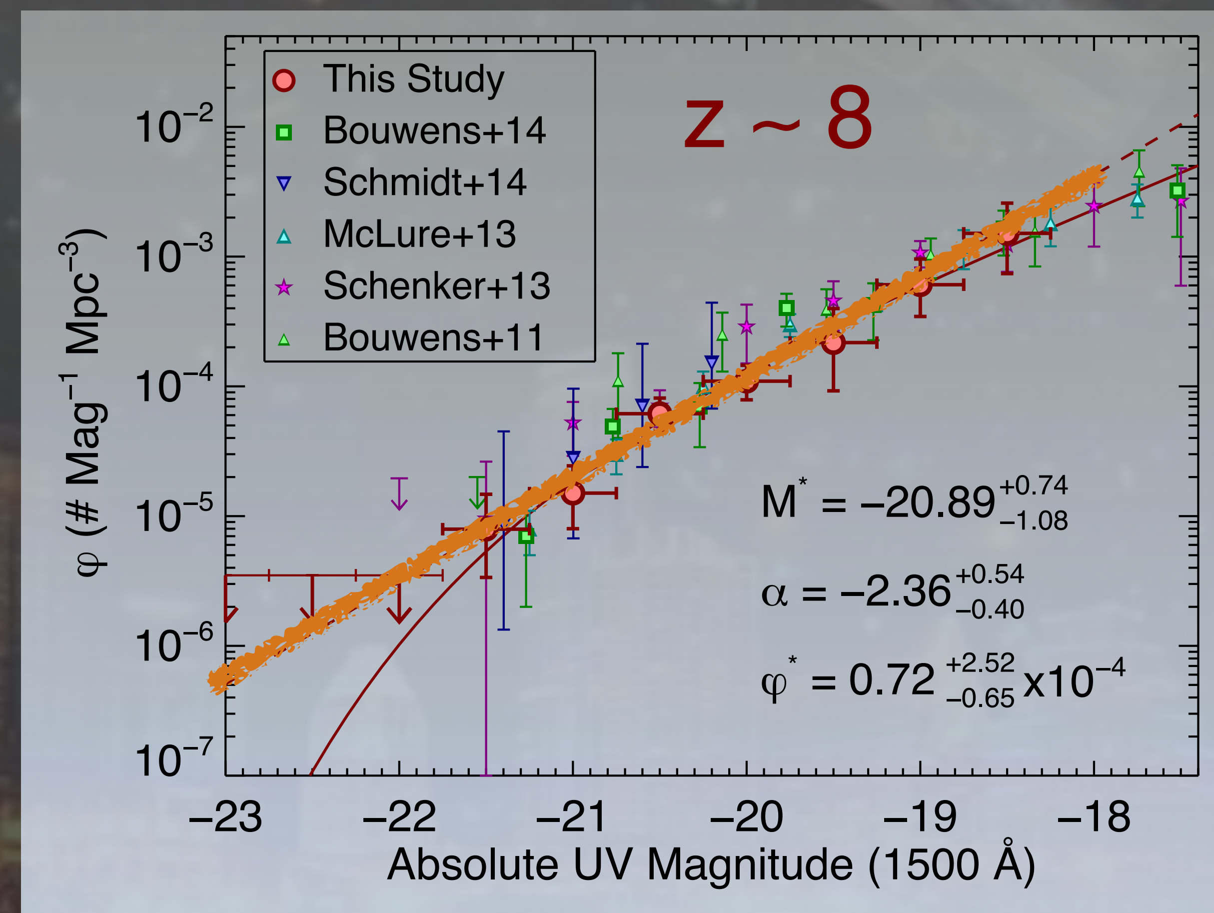




SF+2015

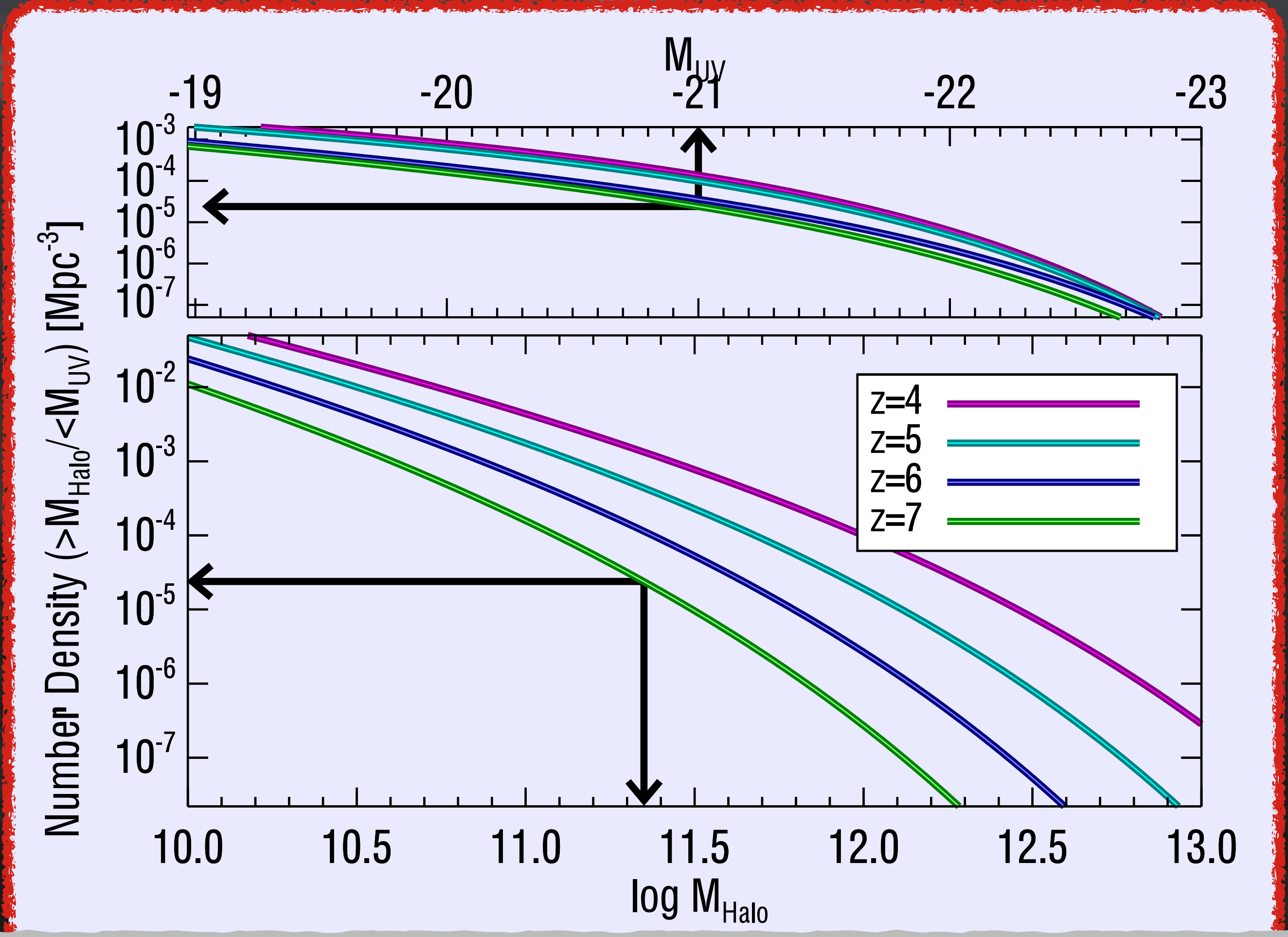
WHATS HAPPENING AT THE BRIGHT END?



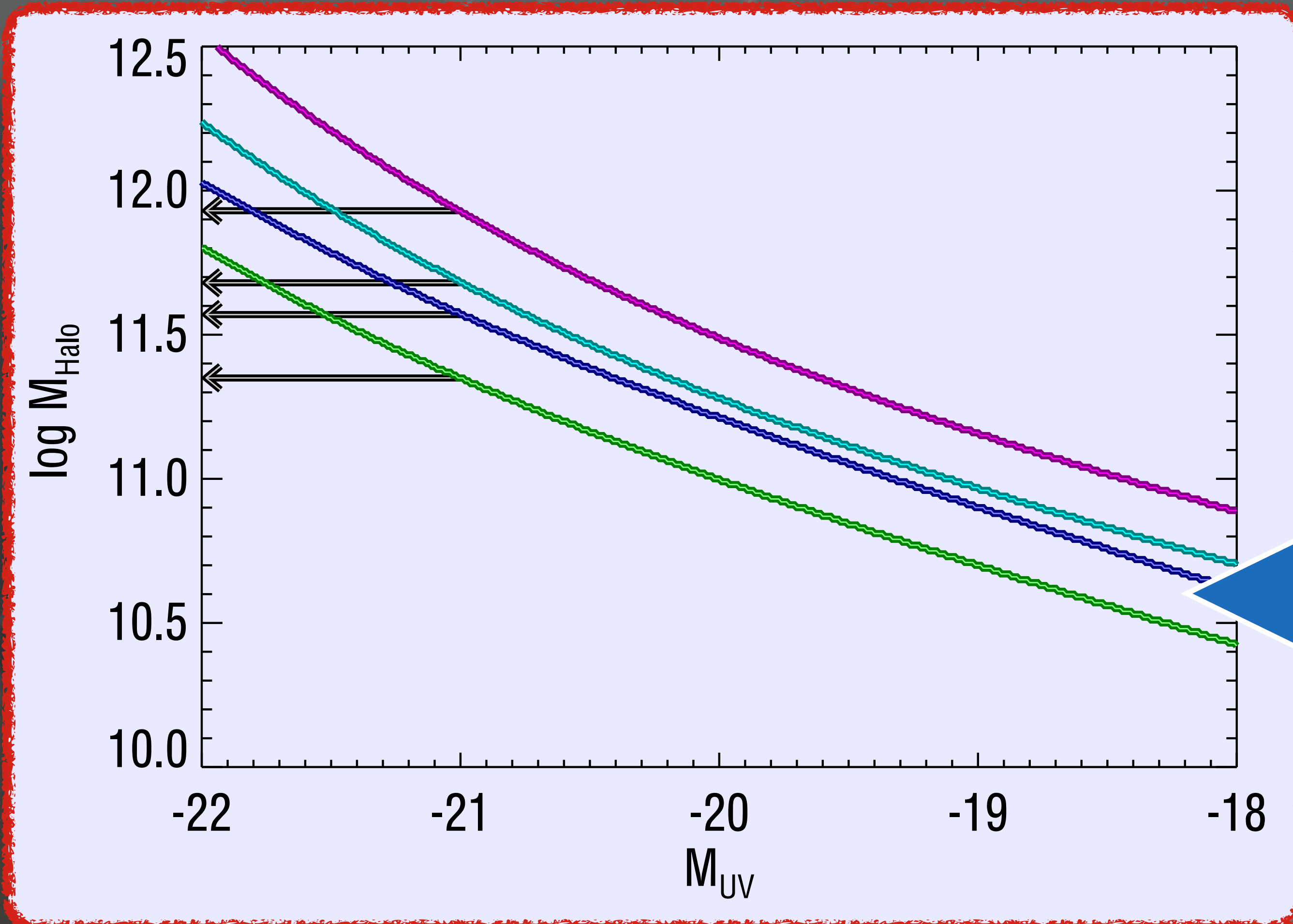


CAN WE UNDERSTAND THE INTERESTING EVOLUTION AT THE BRIGHT END?

- To put this in context, we set out to measure the stellar mass growth of galaxies in context of their dark matter halos.
  - For this study, we considered M_{UV}=-21 galaxies (~L*)
  - We can detected them with IRAC, and thus obtain more robust physical property measurements.
  - Halo masses estimated via abundance matching.



SF, MIMI SONG, PETER BEHROOZI+2015B



D THE INTERESTING
RIGHT END?

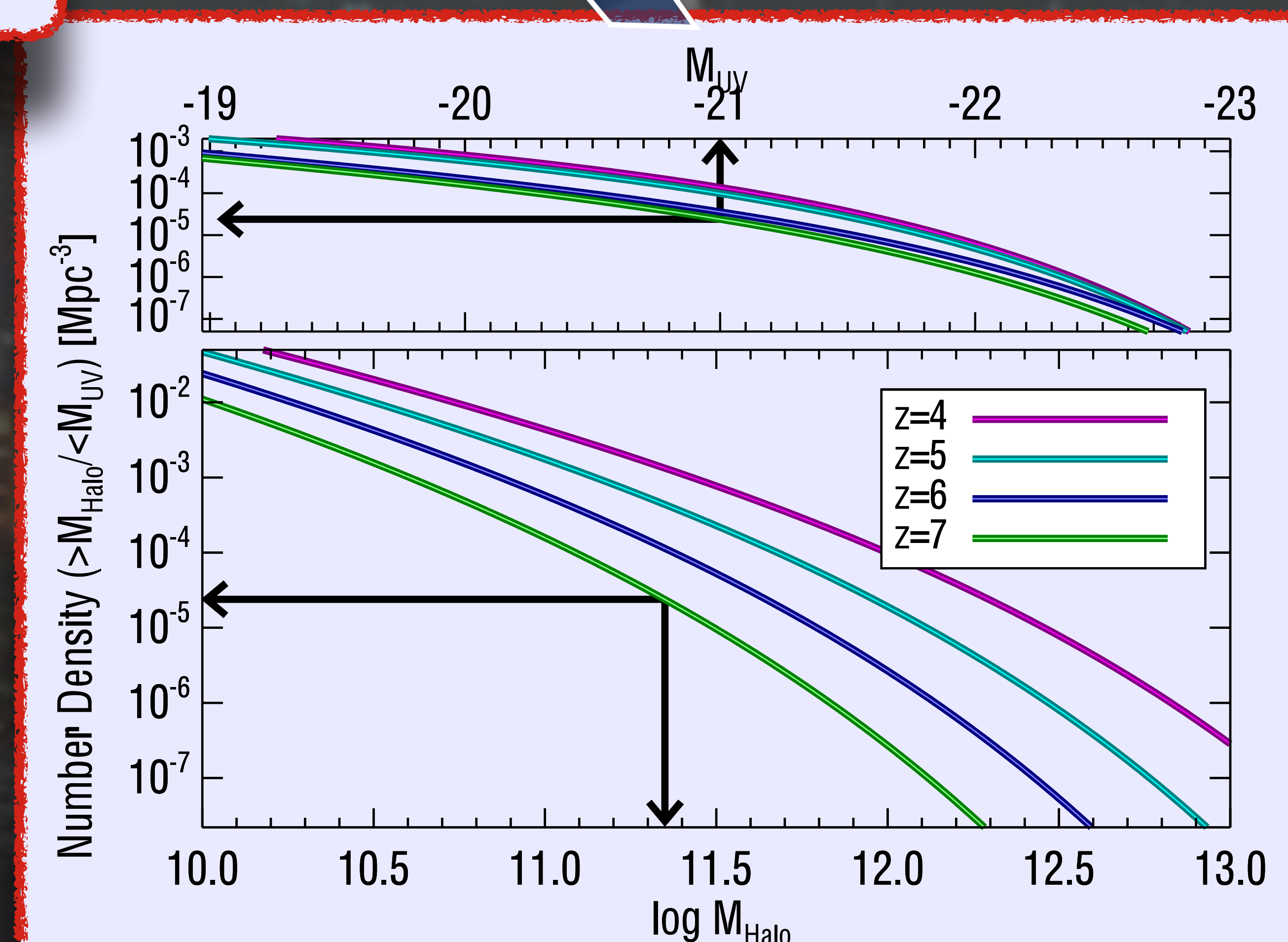
ut to measure the stellar mass
heir dark matter halos.

M_{UV}=-21 galaxies (~L*)

- We c ... em with ... obtain more ... l prop ... ents.

Redshift	log M_{halo}
4	**11.9**
5	**11.7**
6	**11.6**
7	**11.4**

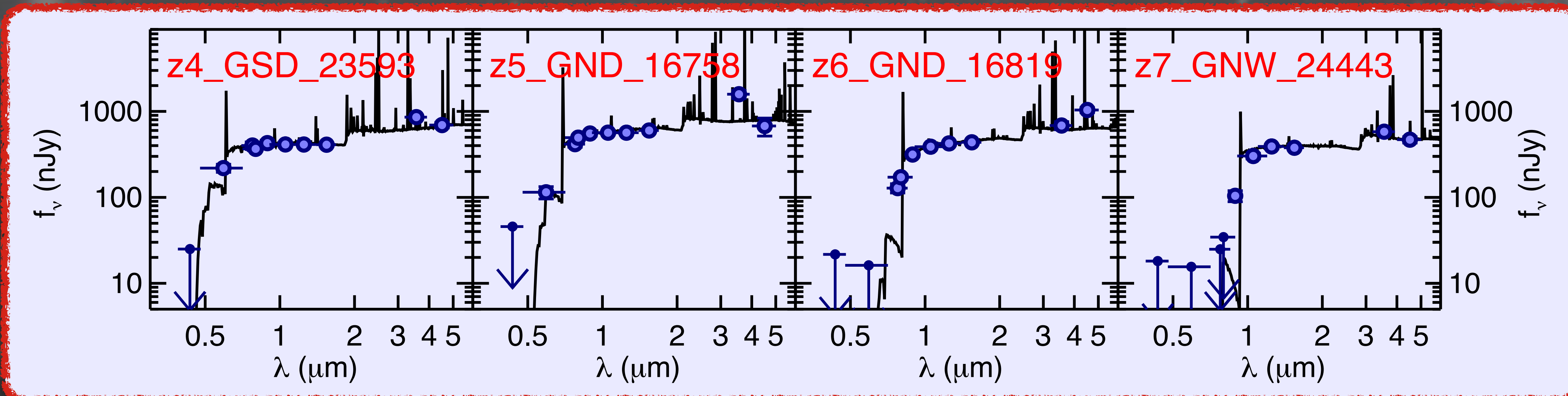
- Halo masses estimated via abundance matching.



SF, MIMI SONG, PETER BEHROOZI+2015B

A CHANGING ISM SHOULD REVEAL ITSELF IN THE STAR-FORMING PROPERTIES OF DISTANT GALAXIES

- Measured stellar masses via SED fitting using HST ACS +WFC3 and *deep* (50+ hr) IRAC imaging.



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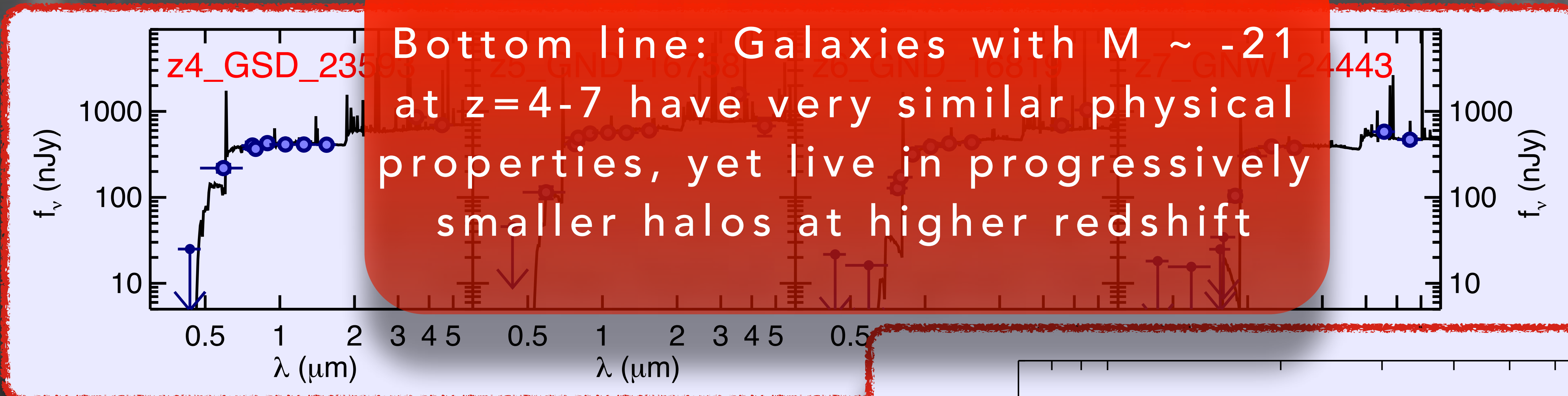
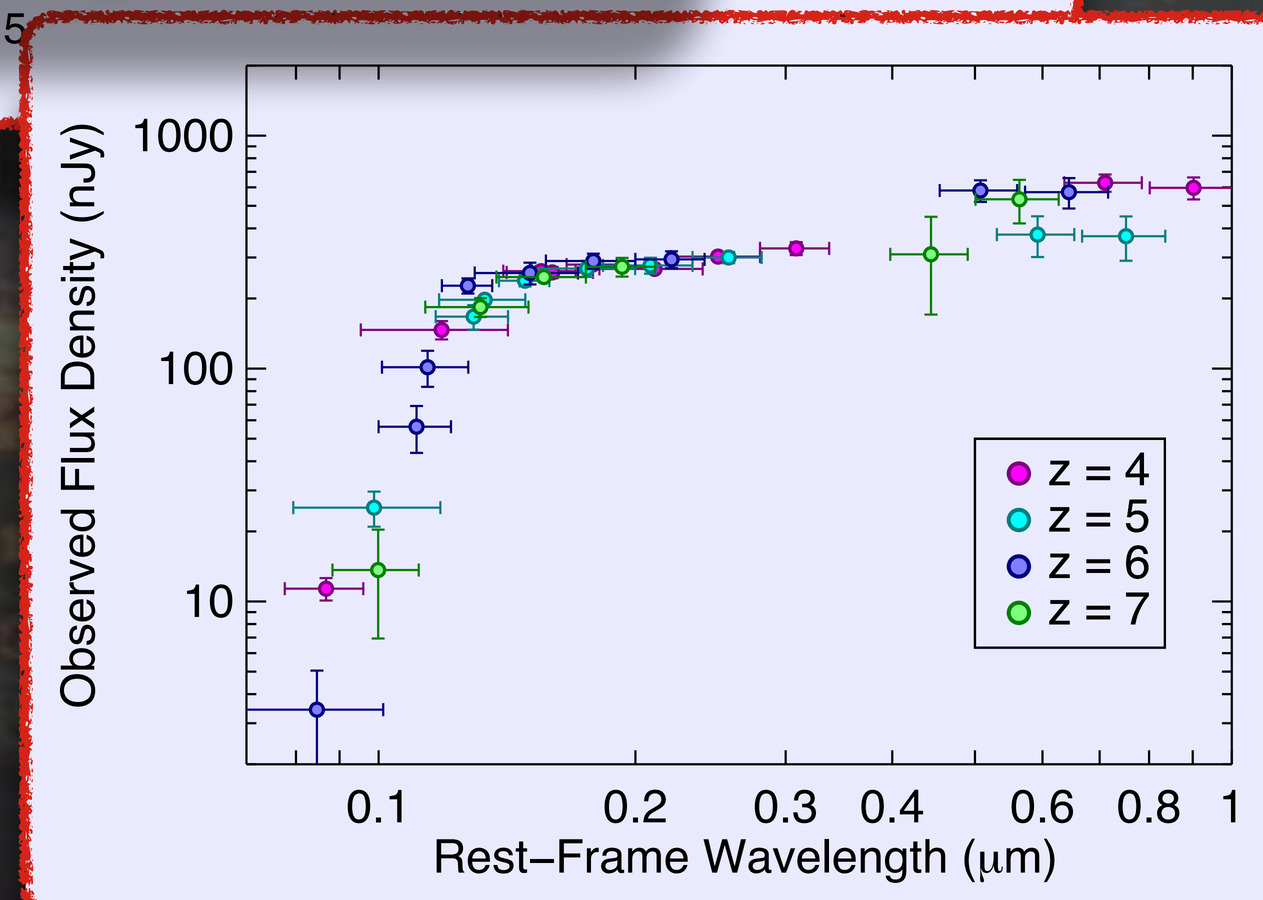


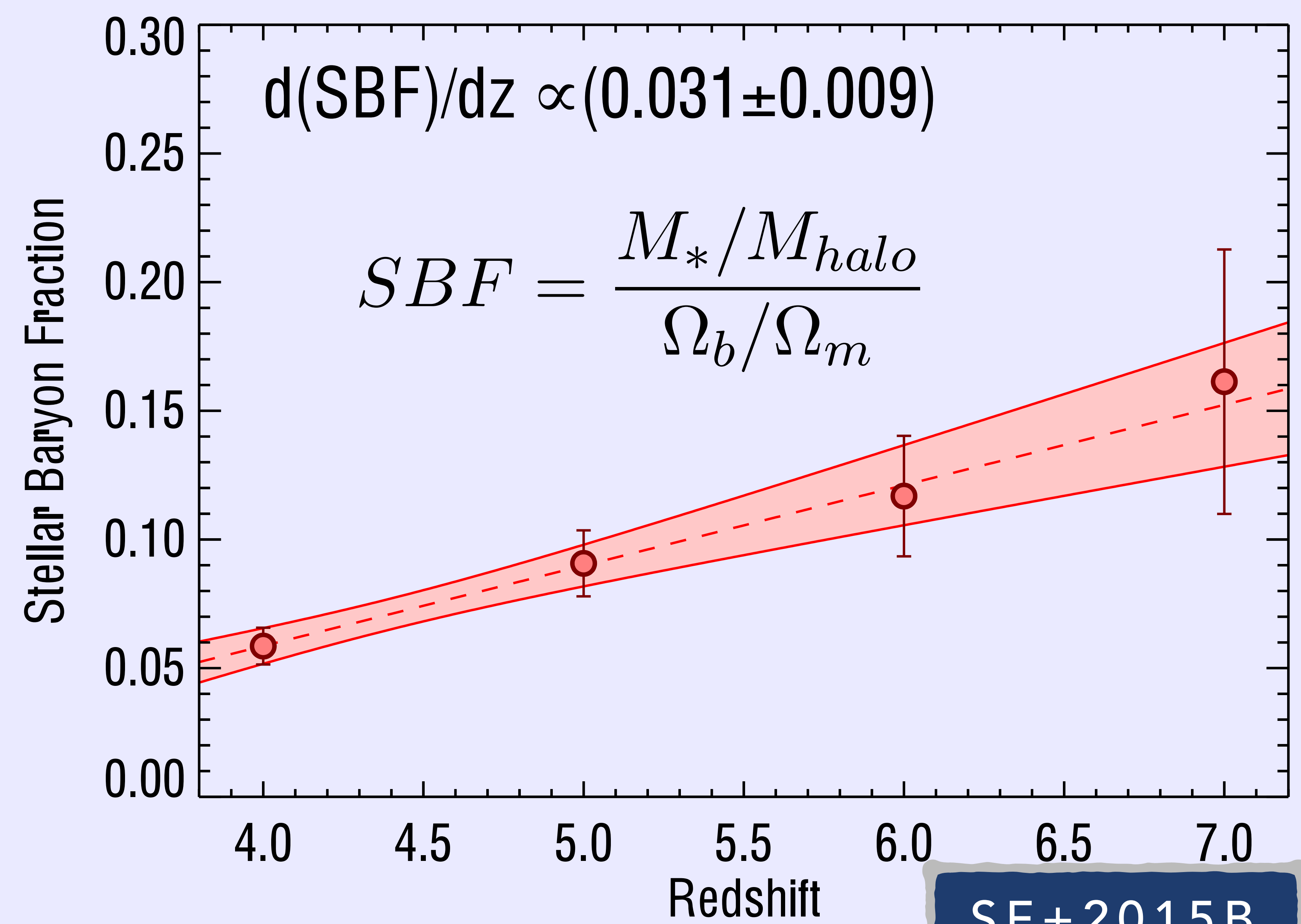
Bottom line: Galaxies with M ~ -21 at z=4-7 have very similar physical properties, yet live in progressively smaller halos at higher redshift

Redshift	log M_{halo}	log M_*
4	11.9	9.9
5	11.7	9.9
6	11.6	9.9
7	11.4	9.8



A CHANGING ISM SHOULD REVEAL ITSELF IN THE STAR-FORMING PROPERTIES OF DISTANT GALAXIES

z	log M_{halo}	log M_*	SMHM	SBF
4	11.9	9.9	0.010	0.06
5	11.7	9.9	0.015	0.09
6	11.6	9.9	0.020	0.12
7	11.4	9.8	0.027	0.16



SF+2015B

A CHANGING ISM SHOULD REVEAL ITSELF IN THE STAR-FORMING PROPERTIES OF DISTANT GALAXIES

- What physical effects could cause this result?
  - **A) Galaxies have a higher star formation efficiency.**
    - Increased redshift ➜ increased gas density ➜ faster freefall time ➜ more star formation
    - More star formation happens in self-gravitating clumps, which have high SFE (e.g., Dekel+2009, Ceverino+2010; Genzel+2011)
  - **B) Galaxies have more fuel available for star formation.**
    - Higher gas density leads to more gas in the cool phase.
    - Weaker feedback leads to more gas available for star formation.
      - Higher gas density could lead to more energy from SNe being radiated away (e.g., Creasey+2013).
      - Less dust leads to less momentum-driven radiative feedback (e.g., Murray+2010, Andrews and Thompson 2011).
      - Less/zero AGN feedback.

Redshift

SF+2015B

A CHANGING ISM SHOULD REVEAL ITSELF IN THE STAR-FORMING PROPERTIES OF DISTANT GALAXIES

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  - **B) Galaxies have more fuel available for star formation.**

If Scenario B is the answer, it could have a dramatic effect on the escape of Lyα photons from galaxies.

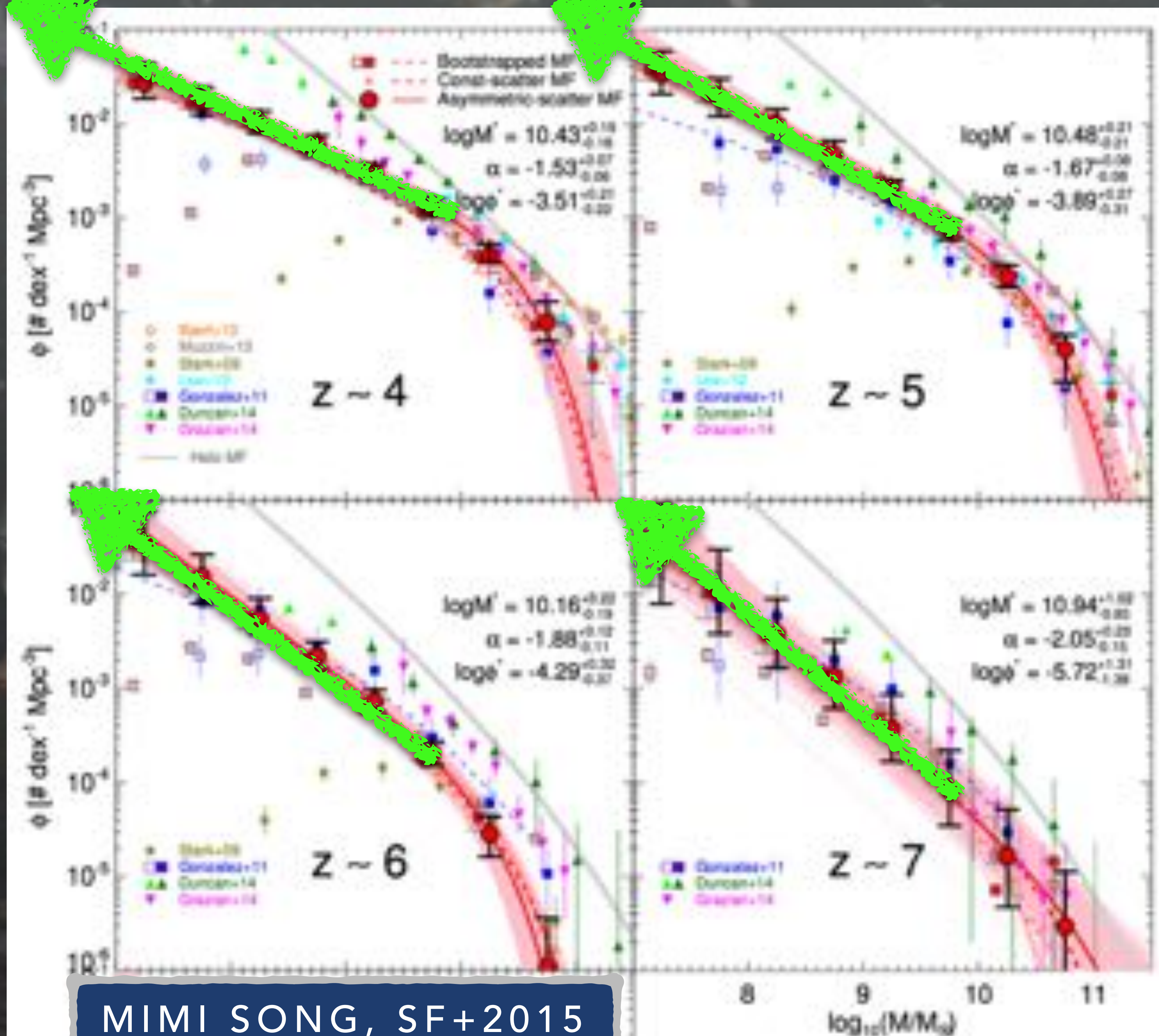
Can test this scenario directly with ALMA, by measuring the redshift evolution of the gas-to-stellar mass ratio.

Redshift

SF+2015B

OTHER EVIDENCE FOR LACK OF FEEDBACK / INCREASED SFE?

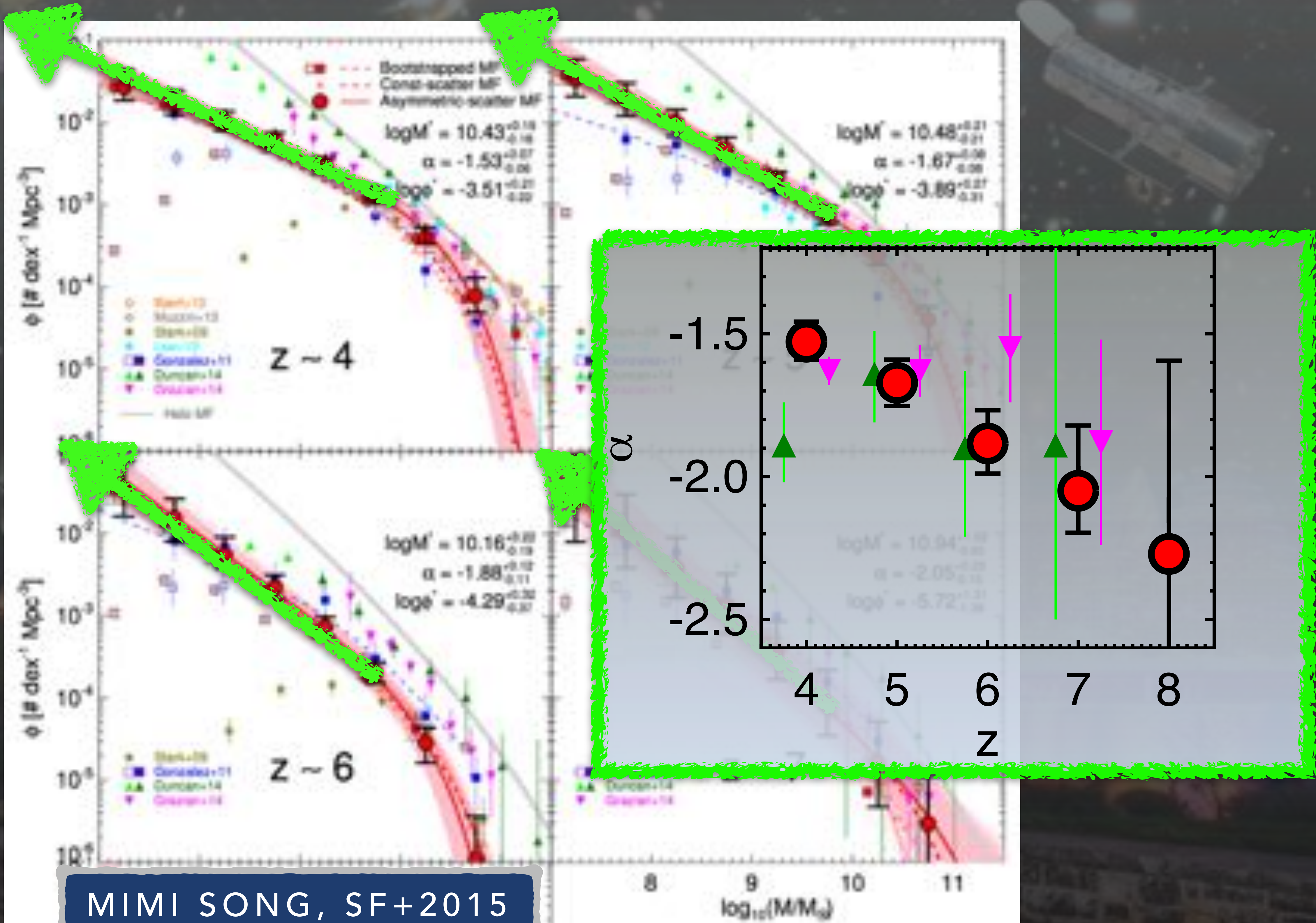
STELLAR MASS FUNCTIONS



MIMI SONG, SF+2015

OTHER EVIDENCE FOR LACK OF FEEDBACK / INCREASED SFE?

STELLAR MASS FUNCTIONS

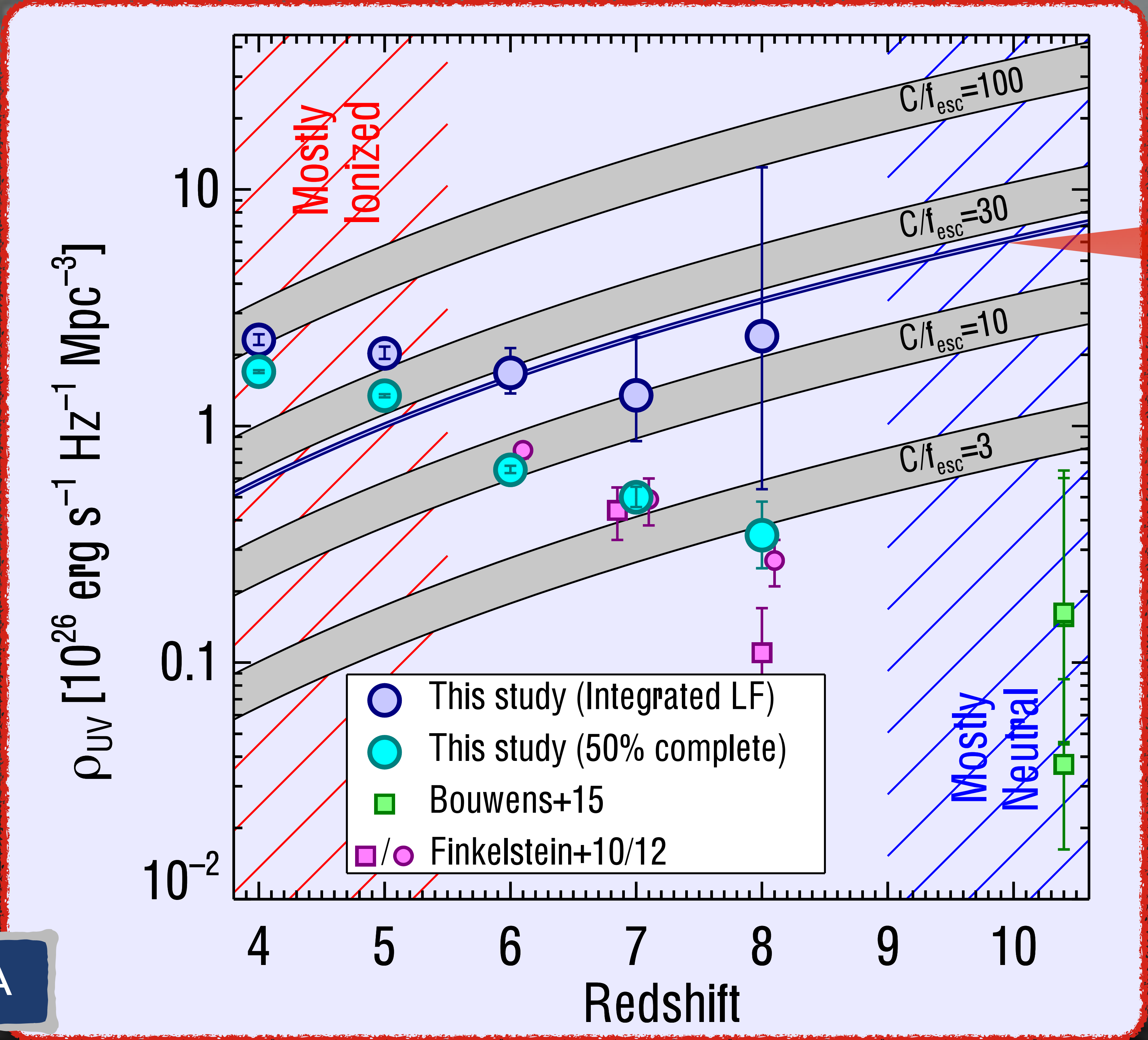


MIMI SONG, SF+2015

HOW DO WE OBTAIN REIONIZATION CONSTRAINTS FROM THE LUMINOSITY FUNCTION?

- Step 1: Integrate the UV LF to obtain the specific UV luminosity density: ρ_{UV} [erg s^{-1} Hz^{-1} Mpc^{3}]
  - Assumption: Need to assume a minimum value of M_{UV} (especially when α < 2).
    - Common values in the literature: -17, -15, -13, -10
    - We see galaxies down to -17, so its likely fainter. We assume M_{lim}=-13, though this bears watching from the theoretical side (e.g., Jaacks+12, O'Shea+15).
- Step 2: Choose a reionization model.
    - Assumptions: Madau (1999) model, C=3, f_{esc}=13% (upper limit at z=6 from SF+2012b), conversion from ionizing to non-ionizingg UV for a Salpeter IMF, and 20% Solar metallicity.

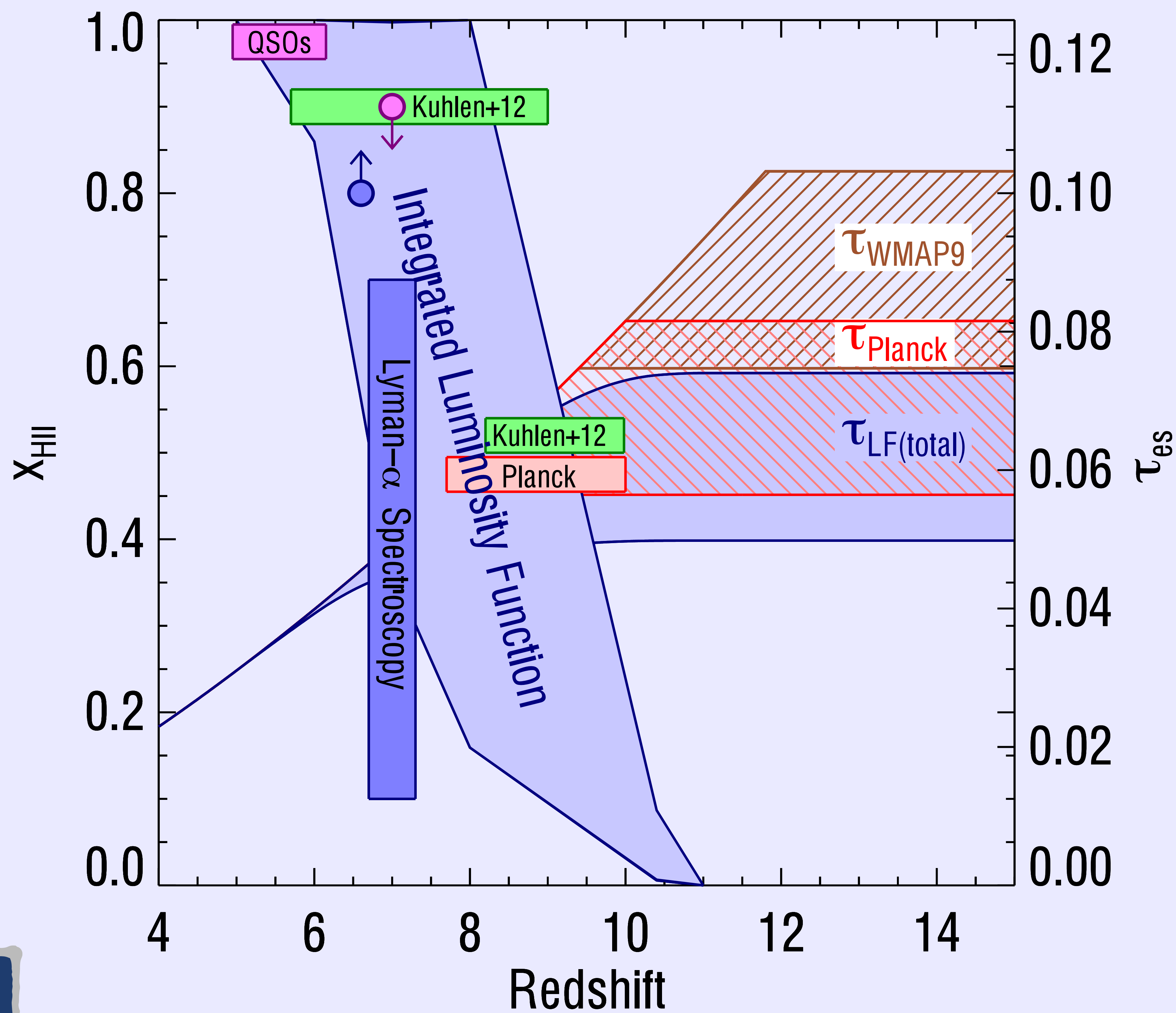
HOW DO WE OBTAIN REIONIZATION CONSTRAINTS FROM THE LUMINOSITY FUNCTION?



OUR FIDUCIAL MODEL

SF+2015A

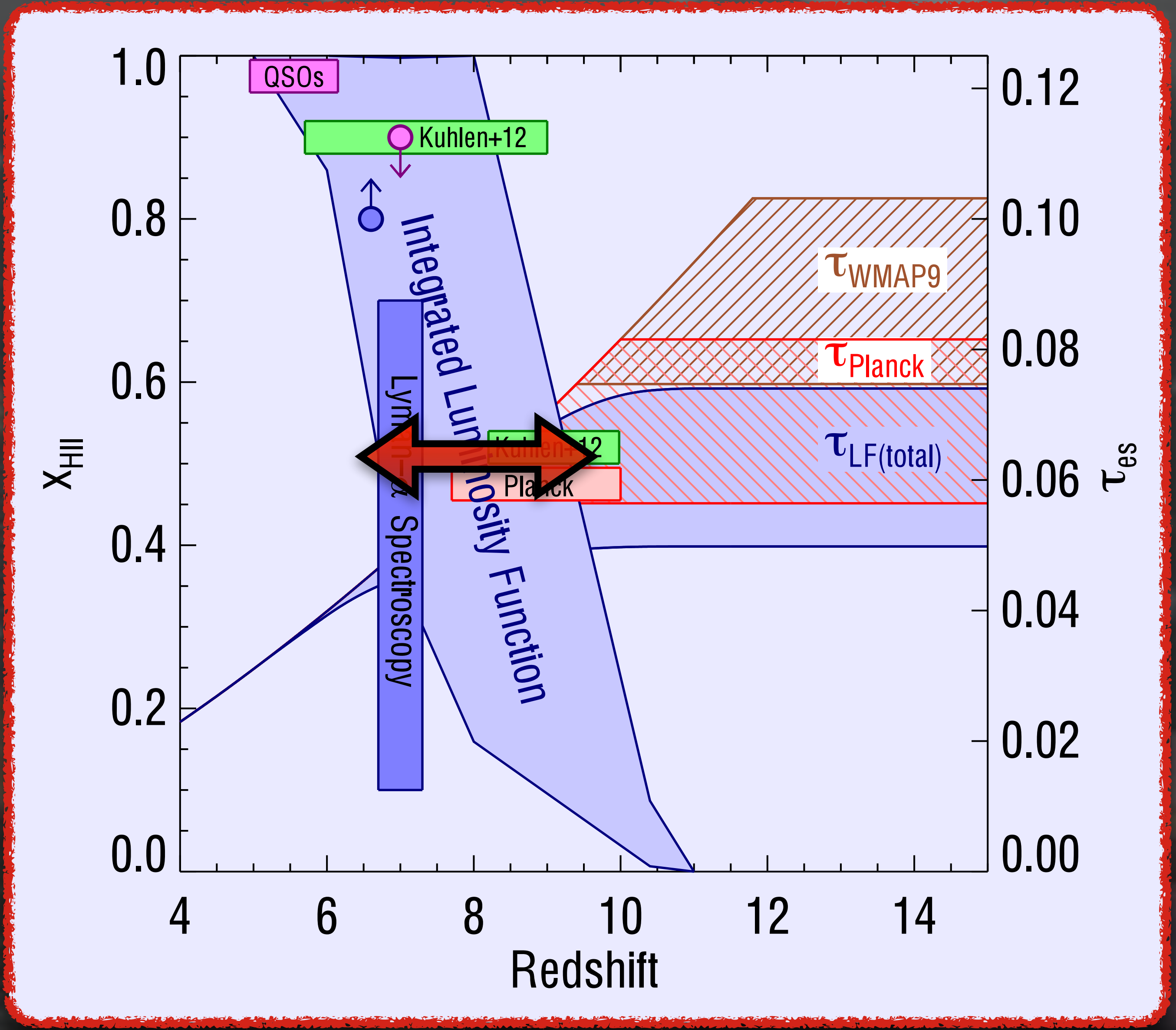
CONSTRAINTS ON THE REIONIZATION HISTORY



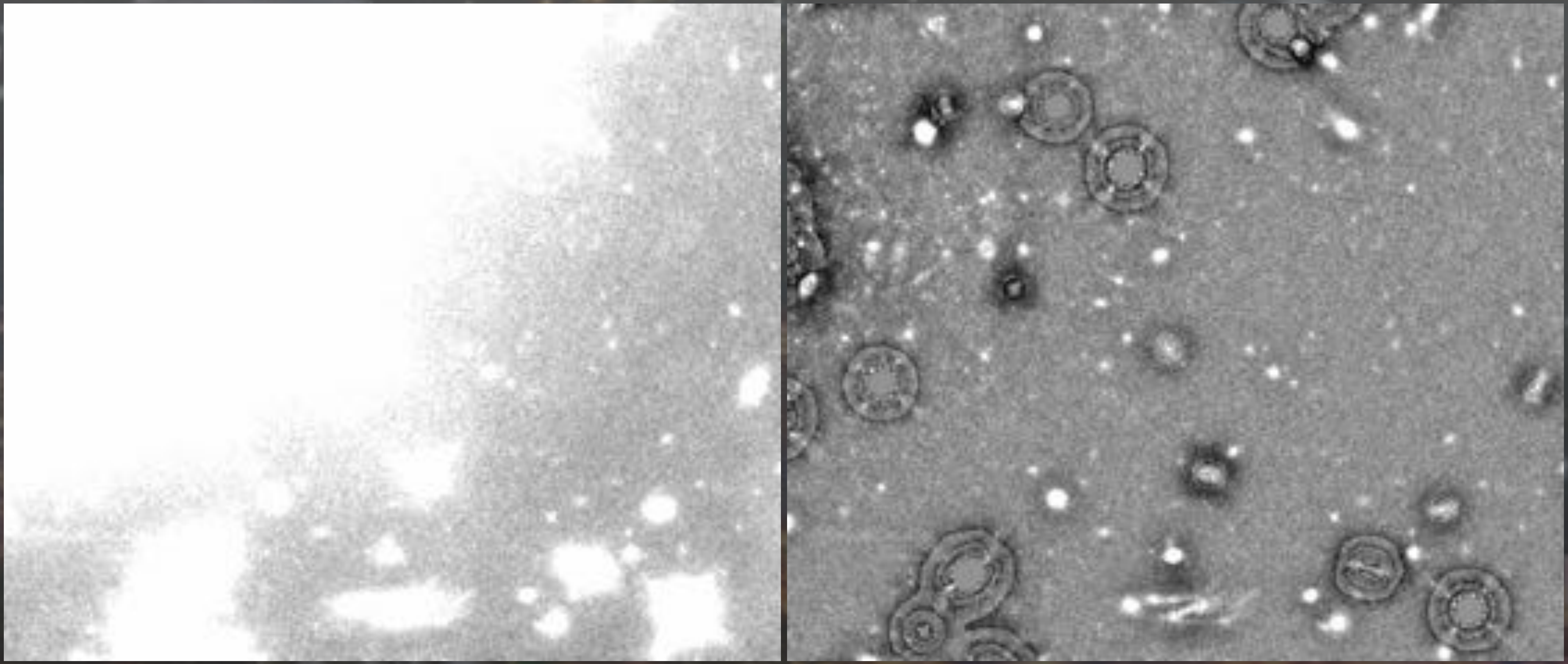
SF+2015A

NEEDED IMPROVEMENTS

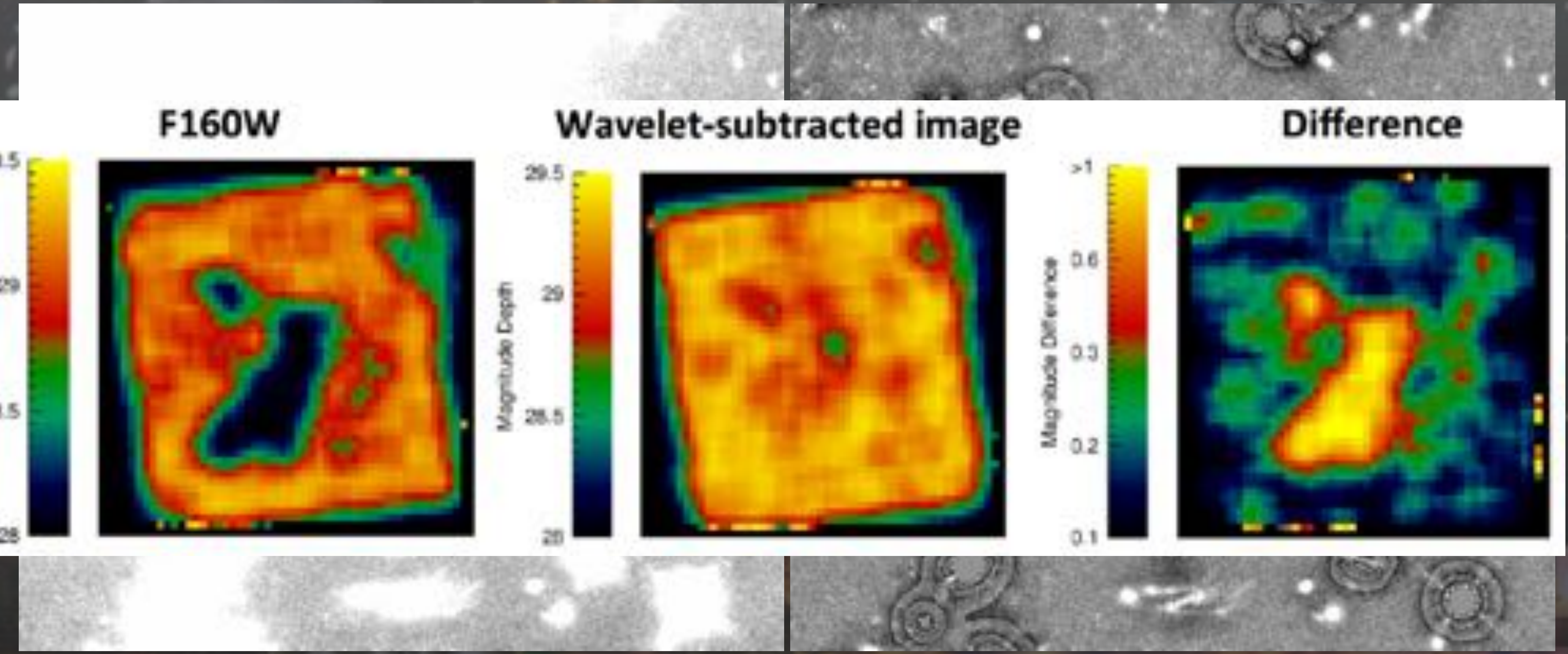
- Our current constraints from the LF give 68% confidence range on the 50% reionization redshift of 6.7 < z < 9.4.
- This uncertainty is driven by the fact that faint galaxies dominate the photon budget, and the current uncertainties on α are large.
- Improvements will happen with JWST, but we are cracking this door open right now with the Hubble Frontier Fields.
    - Will not only improve LF at M ~ -17 to 19, but can also probe to ~ -16 to test assumptions on M_{lim}.



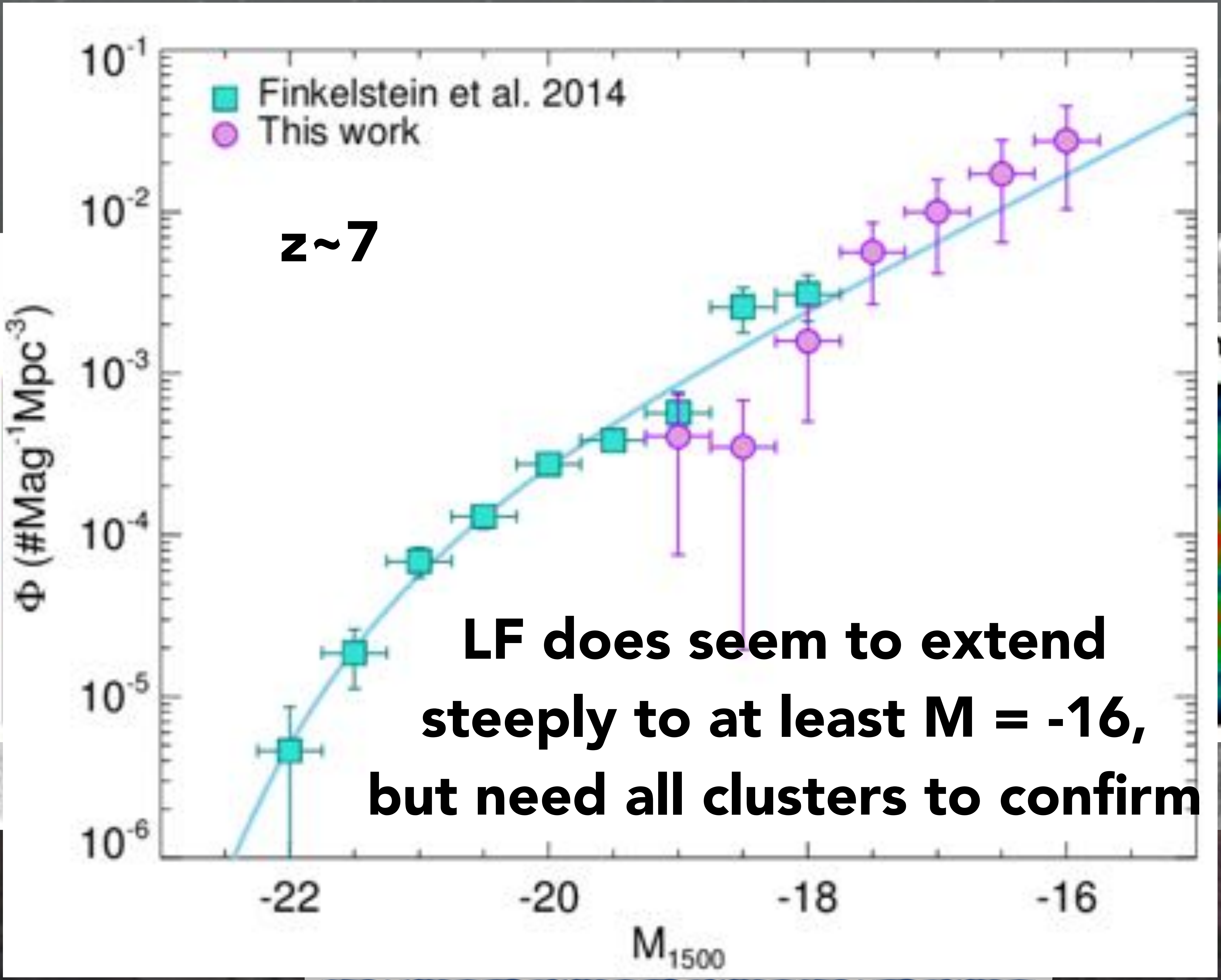
FINDING THE FAINT GALAXIES



FINDING THE FAINT GALAXIES

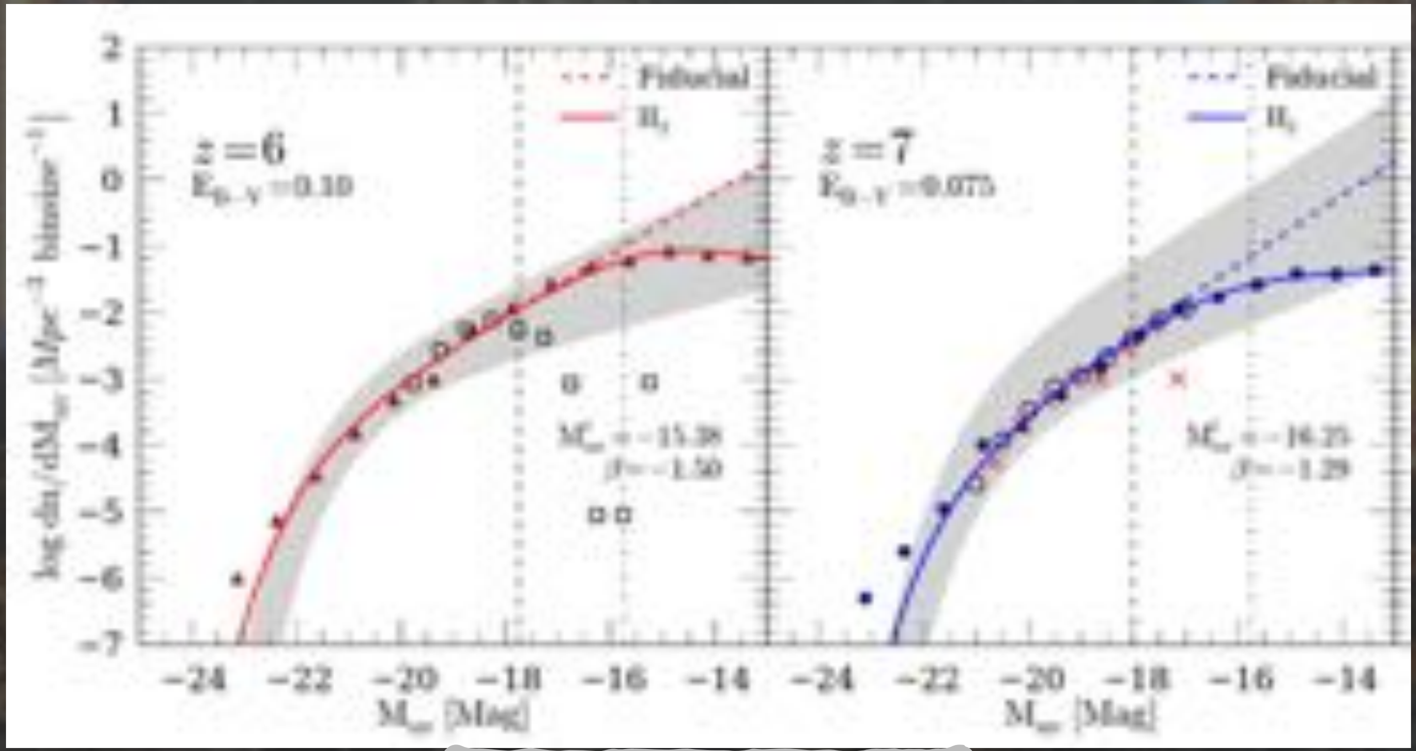


RACHAEL LIVERMORE, SF+2015

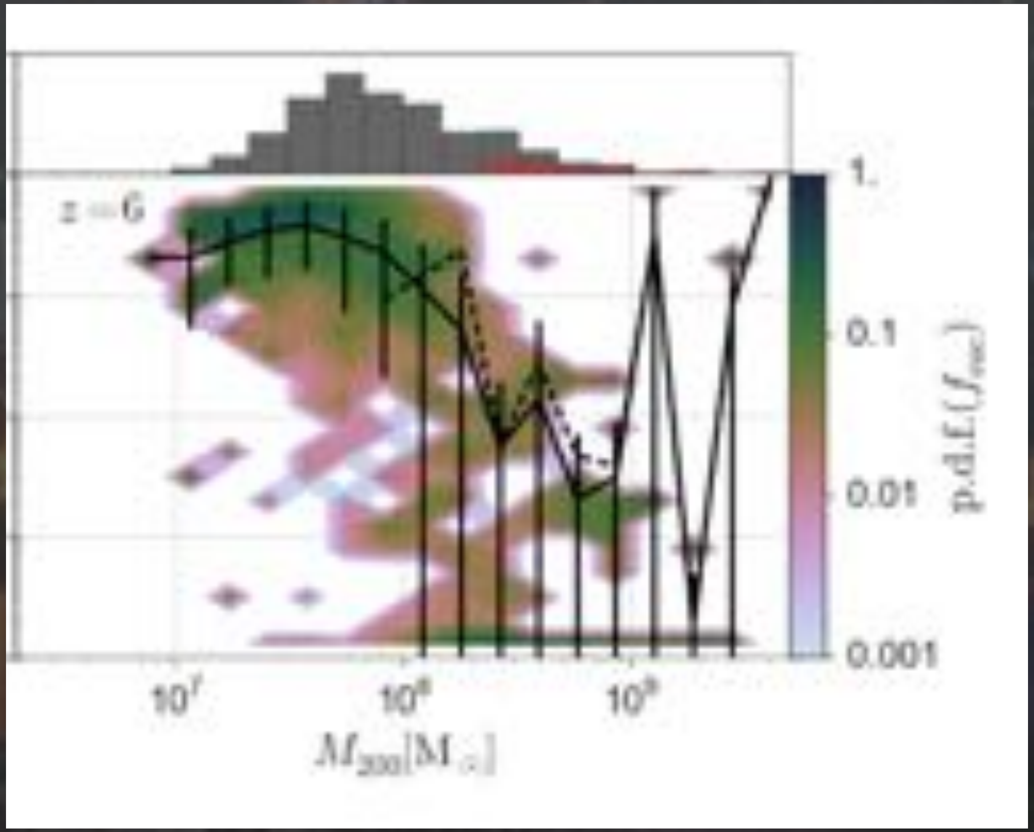

Finkelstein et al. 2014
This work
z~7
LF does seem to extend steeply to at least M = -16, but need all clusters to confirm
Φ (#Mag⁻¹Mpc⁻³)
M1500
-22
-20
-18
-16

WHAT DO WE NEED?

- We need to understand the luminosity function down to -13. If it turns over at brighter magnitudes, we have a photon production crisis.
  - JWST deep fields will only reach around -15.5 or so in UV absolute magnitude.

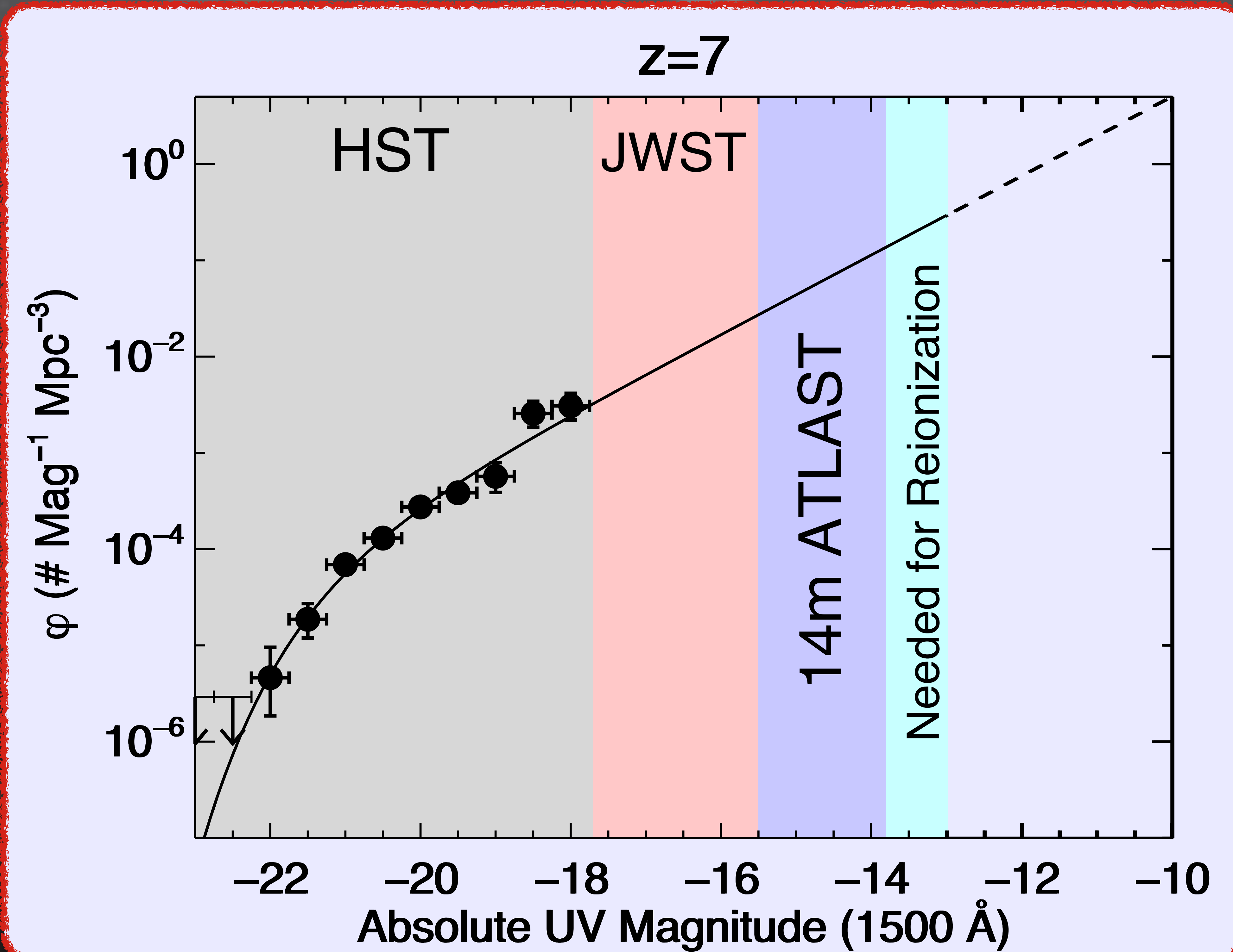


JAACKS+13



PAARDEKOOPER+15

ACCOUNTING FOR ALL REIONIZING PHOTONS



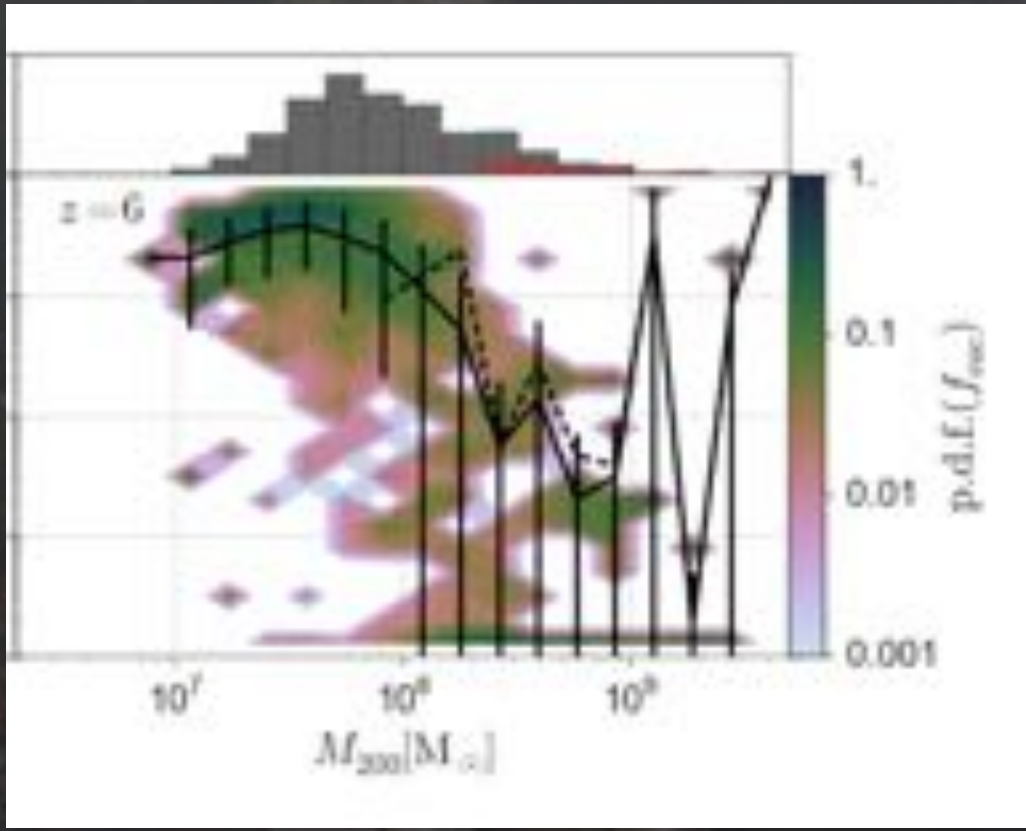
TELESCOPE	FRACTION OF REIONIZING PHOTONS ACCOUNTED
HST	35%
JWST	60%
ATLAST (14M)	90%

ACCOUNTING FOR ALL REIONIZING PHOTONS

- So a 14m ATLAST can a
~90% of the needed ior

- But, we need to conside

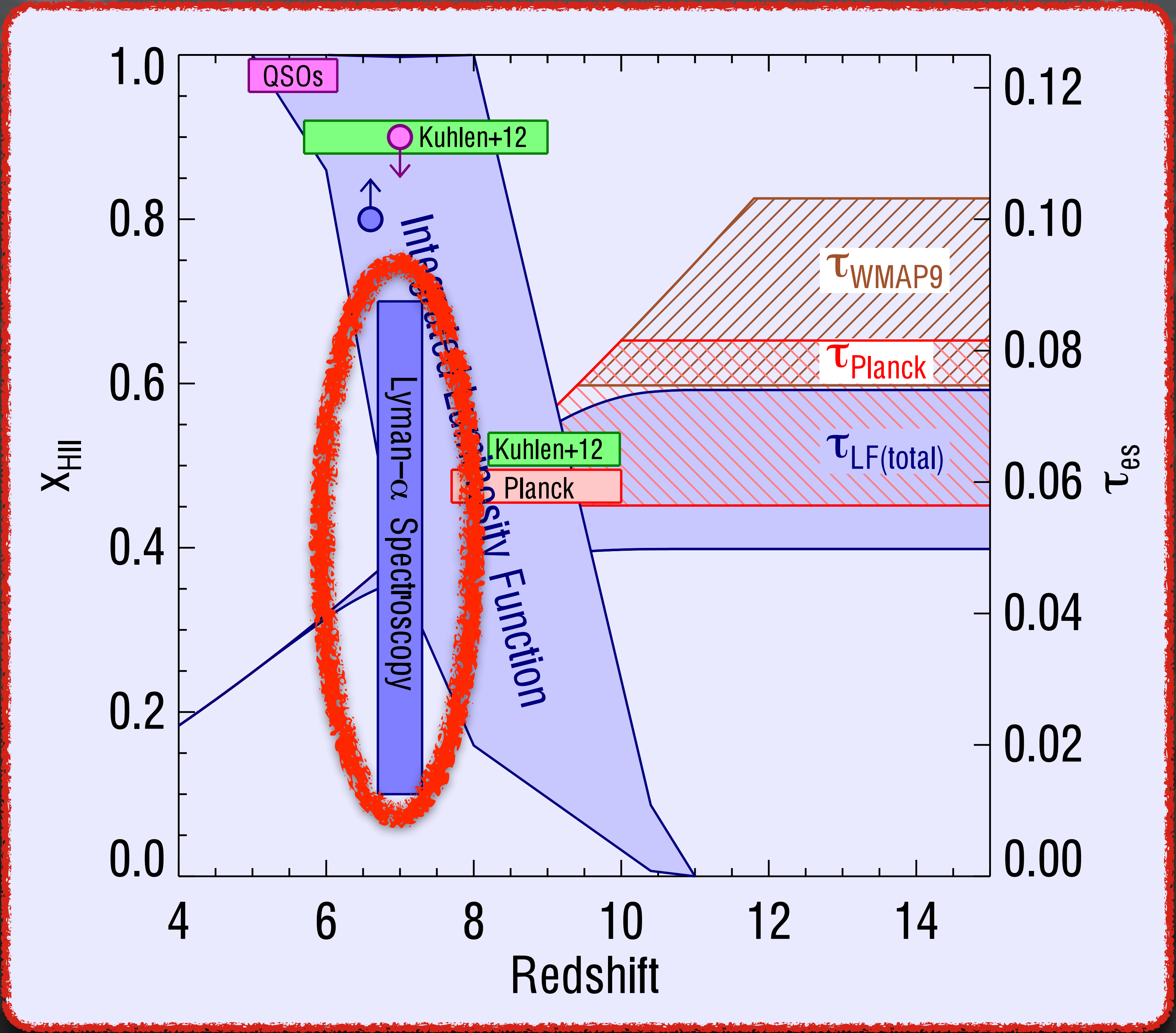
- What if we assume that halos with M > 10^{10} M_{sol} do not have any escaping ionizing radiation?



PAARDEKOOPER+15

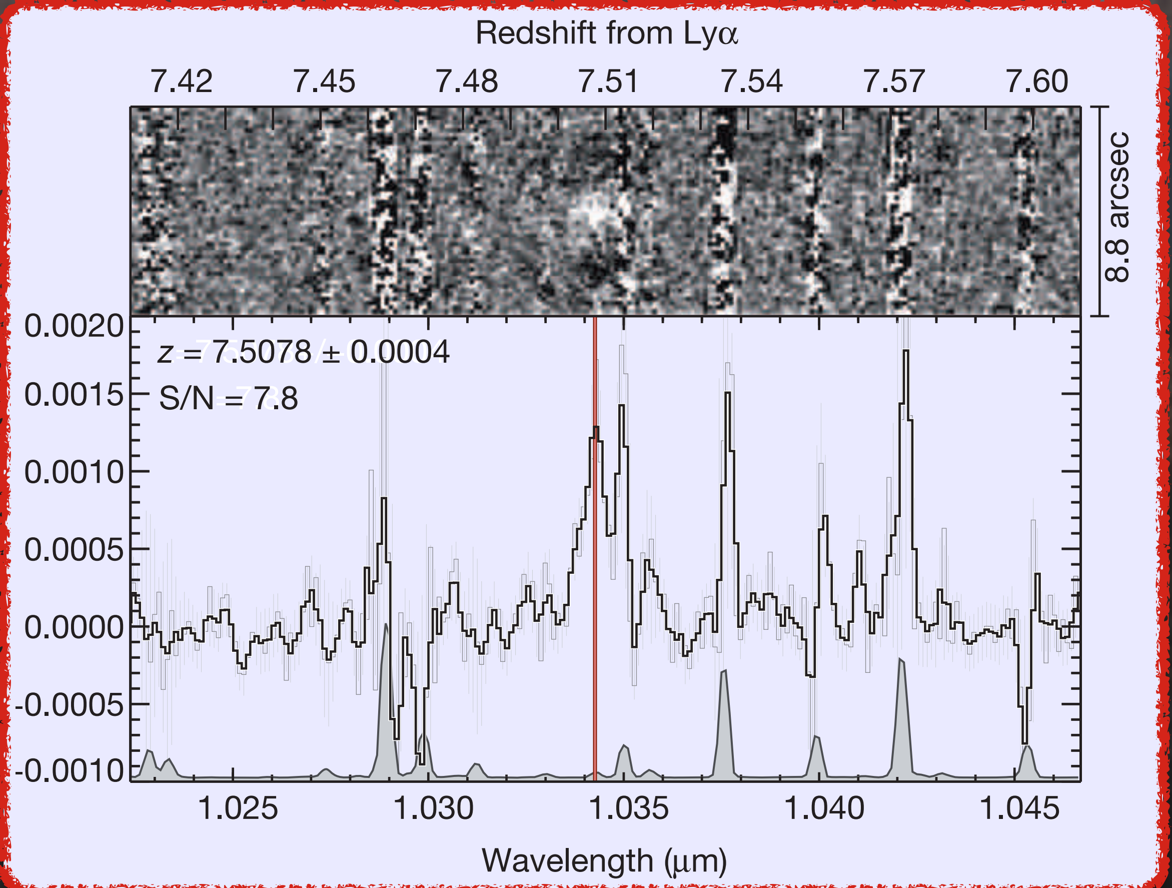
TELESCOPE	FRACTION OF REIONIZING PHOTONS ACCOUNTED
HST	5%
JWST	45%
ATLAST (14M)	80%

HOW ELSE CAN WE BETTER CONSTRAIN REIONIZATION?

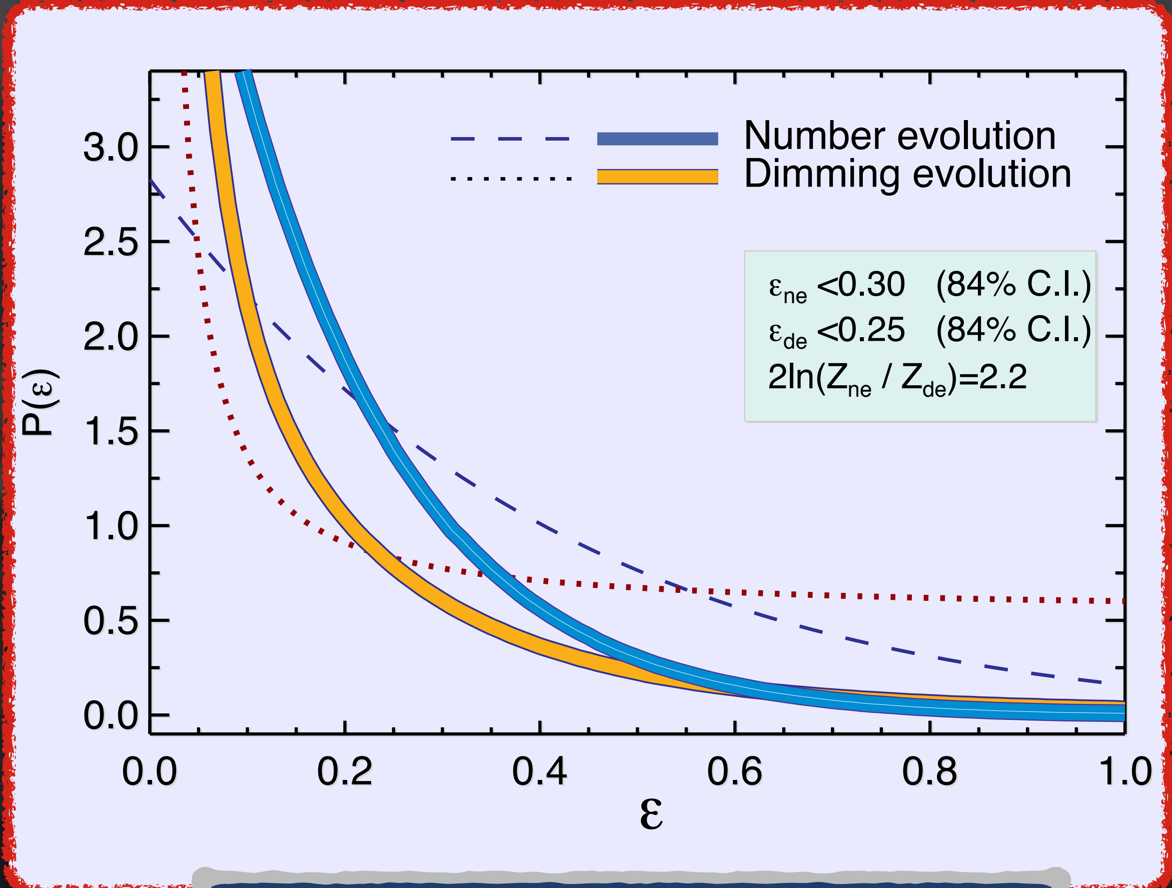


LYMAN ALPHA EMISSION

- Over the past few years we have been collecting Keck spectroscopic data on our z > 6 galaxy candidates.
    - Rather than hitting as many galaxies as possible for short integrations (similar to other MOSFIRE programs), we go deep, at least 5, and up to 20 hr/object.
    - First run was in April 2013.



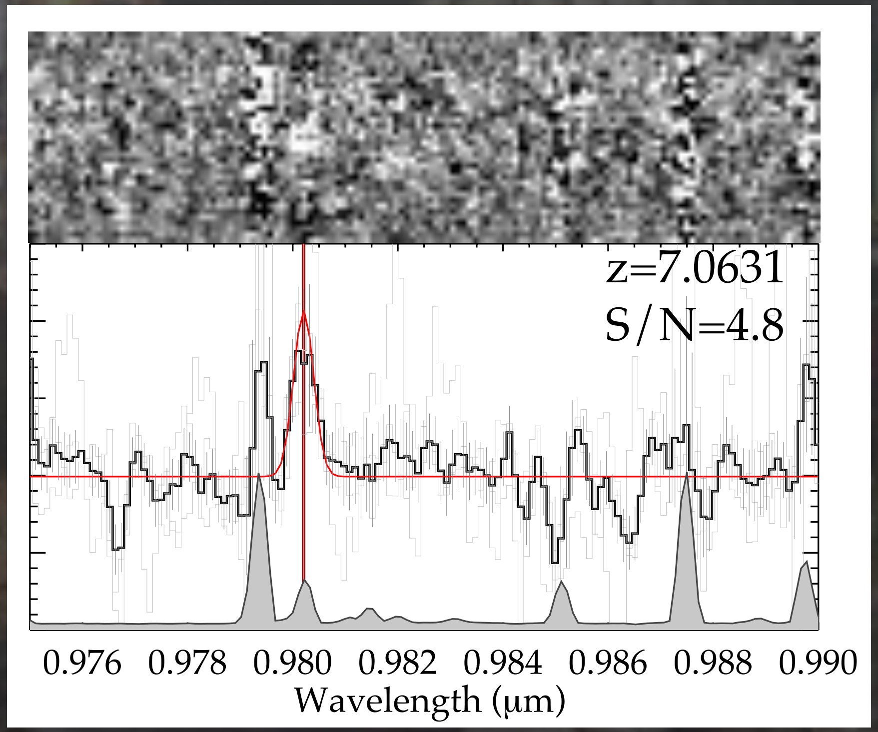
SF+2013

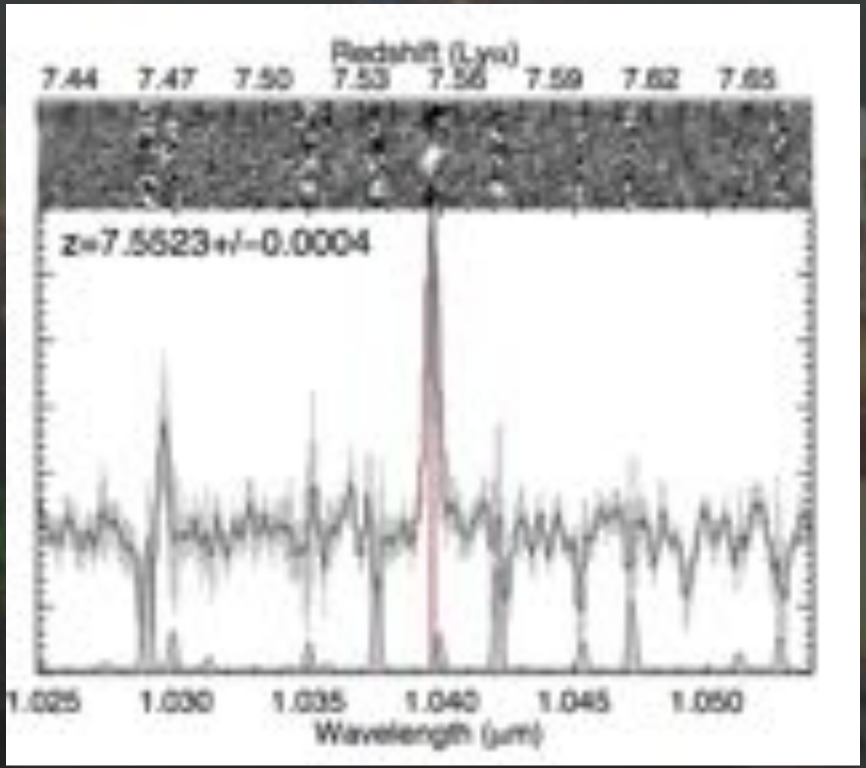


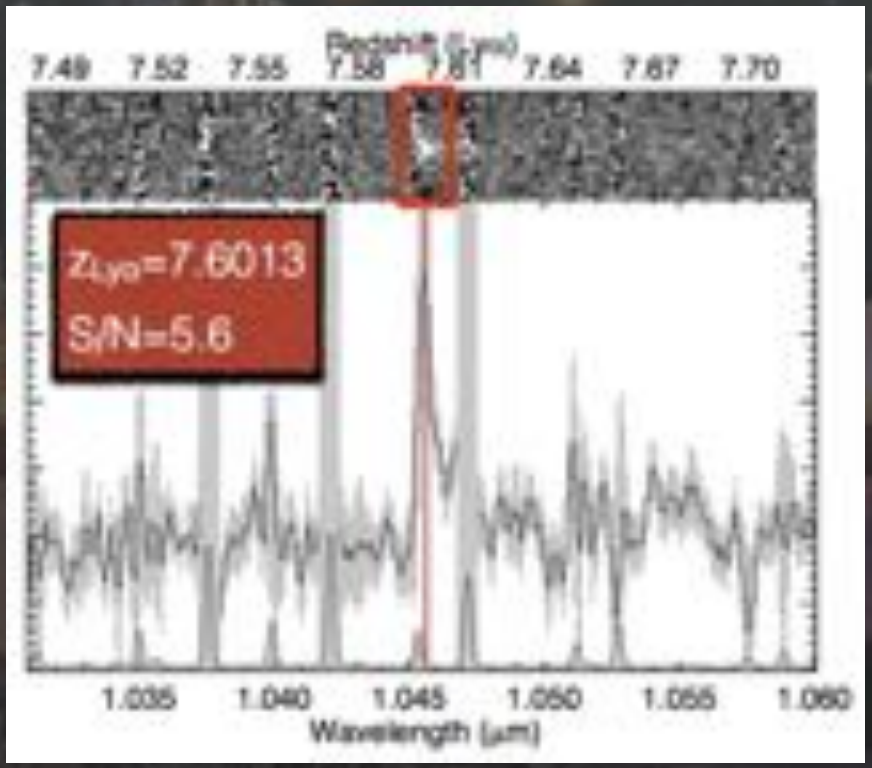
TILVI, CP, SF+2014

LYMAN ALPHA EMISSION

- We have continued to observe, obtaining data over 13.5 nights over the past two years (primarily through NASA, but also with collaborators at UC).
  - We have observed ~40 candidate z > 7 galaxies at J < 27 to at least 5 hr depth, and these long integrations allow us to pick out more lines.

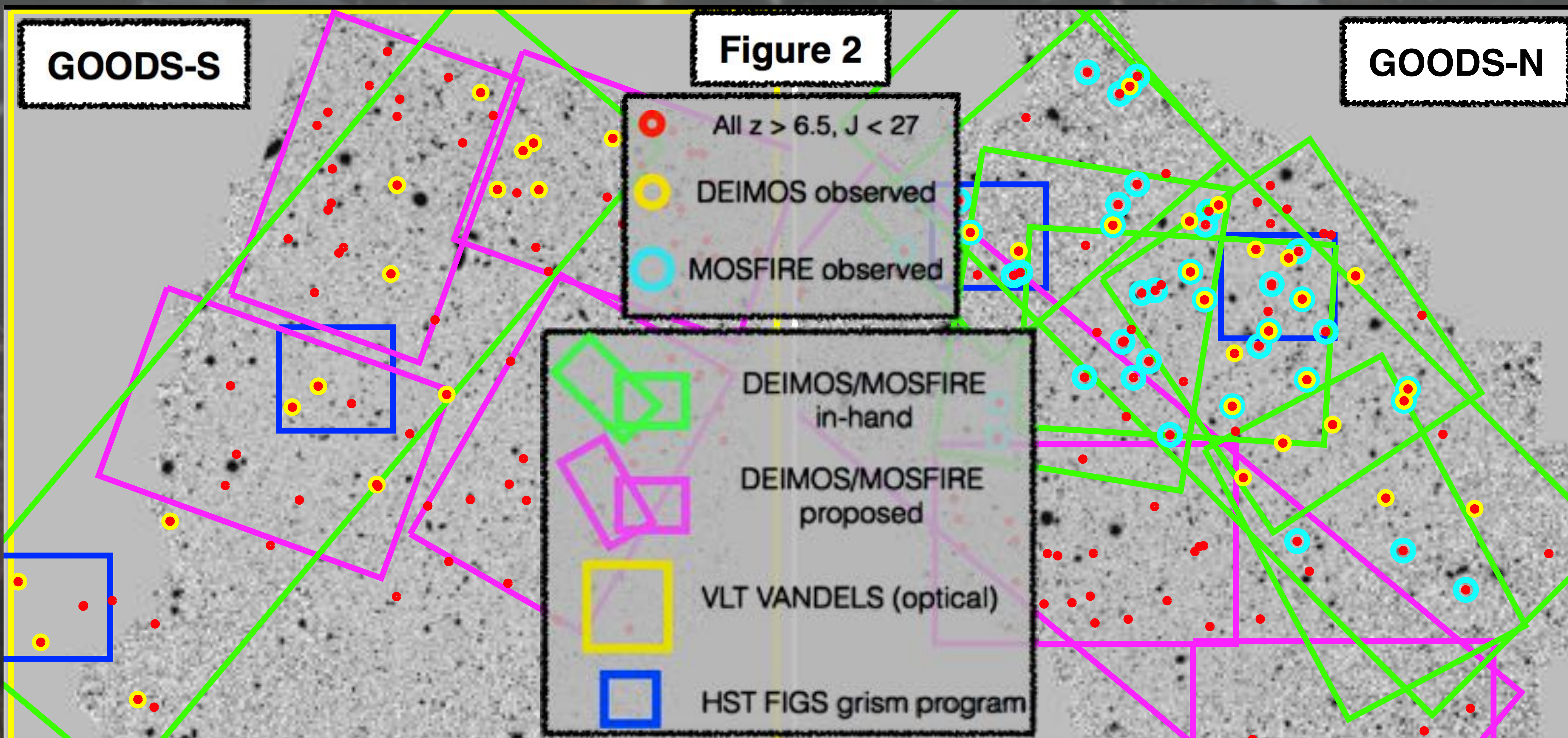






LIVERMORE, SF, IN PREP

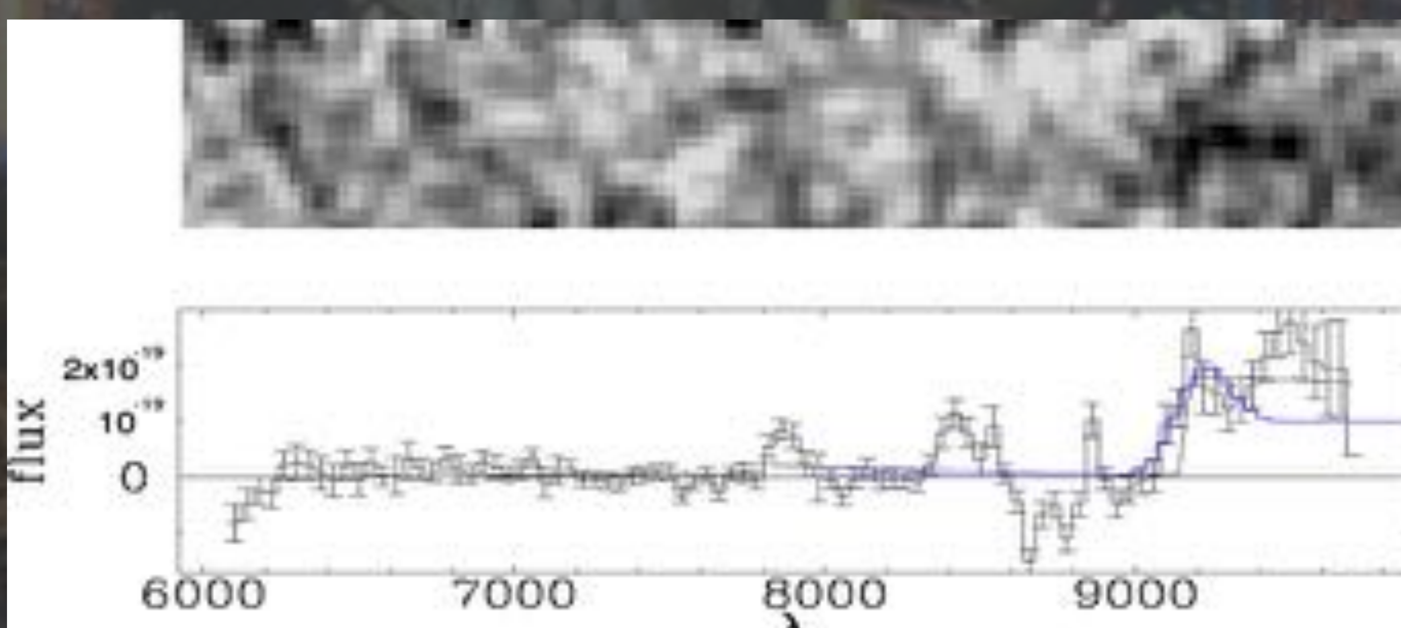
FROM THE GROUND: AN EW-LIMITED SURVEY OF LYMAN ALPHA EMISSION AT 5.5 < z < 8.2

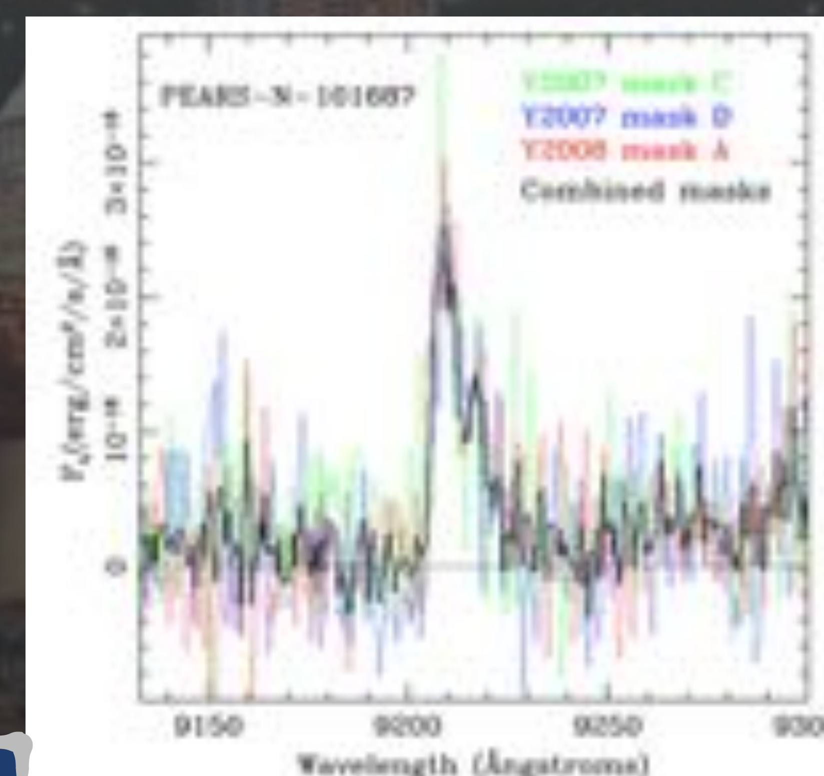


Will constrain EW < 15 (5) Å for 200 (30) J < 27 (26) galaxies

FROM SPACE: HST GRISMS

- The HST grisms are an untapped resource for spectroscopic studies of z > 6 galaxies.
  - The exquisite sensitivity can allow spectroscopic confirmations from the *break*, with our without a line.





RHOADS+13

FROM SPACE: HST GRISMS

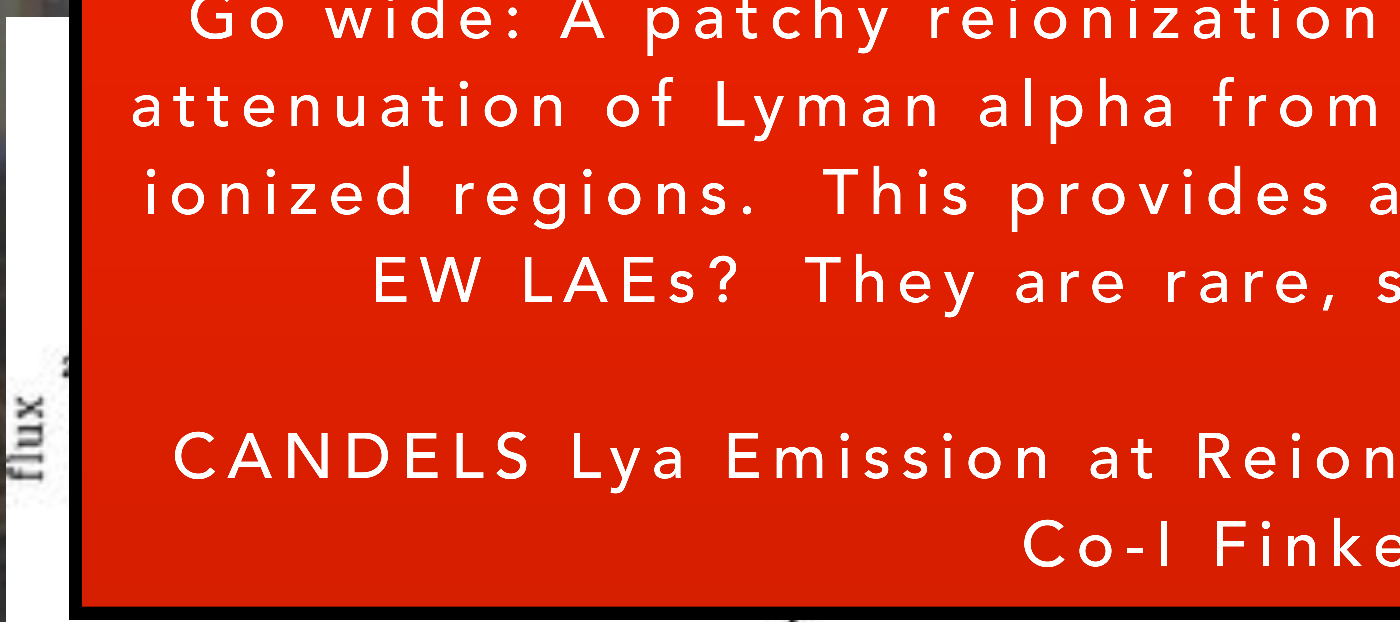
How can we make progress?

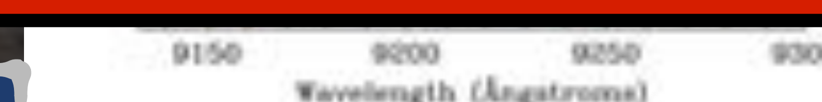
Go deep: Lyman alpha emission is clearly faint. by going deep, we can detect lyman breaks *spectroscopically* at z > 7 (as well as faint Lyman alpha lines).

Faint Infrared Grism Survey (FIGS; PI Malhotra; Co-I Finkelstein)

Go wide: A patchy reionization process should result in the attenuation of Lyman alpha from neutral regions, but not from ionized regions. This provides a simple test: do you see high EW LAEs? They are rare, so you need to go wide.

CANDELS Lya Emission at Reionization (CLEAR; PI Papovich; Co-I Finkelstein)





RHOADS+13

THE FUTURE

- Current surveys can really only hope to detect Lyα emission from bright (J < 27 galaxies), and even then, we have maxed out (more or less) with 10m-class ground-based telescopes.
- JWST will have the capability to explore these lines to somewhat fainter flux levels.
    - At best, a factor of ~4 fainter in an ultradeep (30 hr) survey. Likely not nearly enough to detect Lya from faint galaxies at z > 7.
    - And this only over a small field, and for a <10 year lifetime.
- The future is with the GSMTs, and future very large aperture space missions.
    - For example, the GMT will have a sensitivity at least as good as JWST between night sky lines. This, coupled with a wide field of view, will create a powerful reionization machine.
- ATLAST can do even better - by being above the atmosphere, we will be able to access Lya over the *full* redshift range for distant galaxies, with no night sky lines to block us.
    - With no lines, lower resolution can be used to achieve even higher sensitivities, allowing detection of Lyα for the newly discovered faint galaxies from JWST.

CONCLUSIONS

- We have made significant progress over the past few years understanding the high-redshift universe.

THREE THINGS WE'VE LEARNED

OBSERVABLE GALAXIES AT Z=7 ARE NOT METAL FREE, EVEN THE FAINT ONES.

GALAXIES LIKELY REIONIZED THE UNIVERSE BY Z=6

LYMAN ALPHA SURVEYS IMPLY A RAPIDLY RISING NEUTRAL FRACTION AT Z > 6.5

THREE THINGS WE DON'T KNOW

WHEN DID METALS FIRST FORM, AND ARE THERE METAL-FREE POPULATIONS AT Z < 10?

CAN WE ACCOUNT FOR ALL THE NEEDED IONIZING PHOTONS?

WHAT IS THE TEMPORAL AND SPATIAL EVOLUTION OF REIONIZATION, AND CAN LYA EMISSION TELL US?