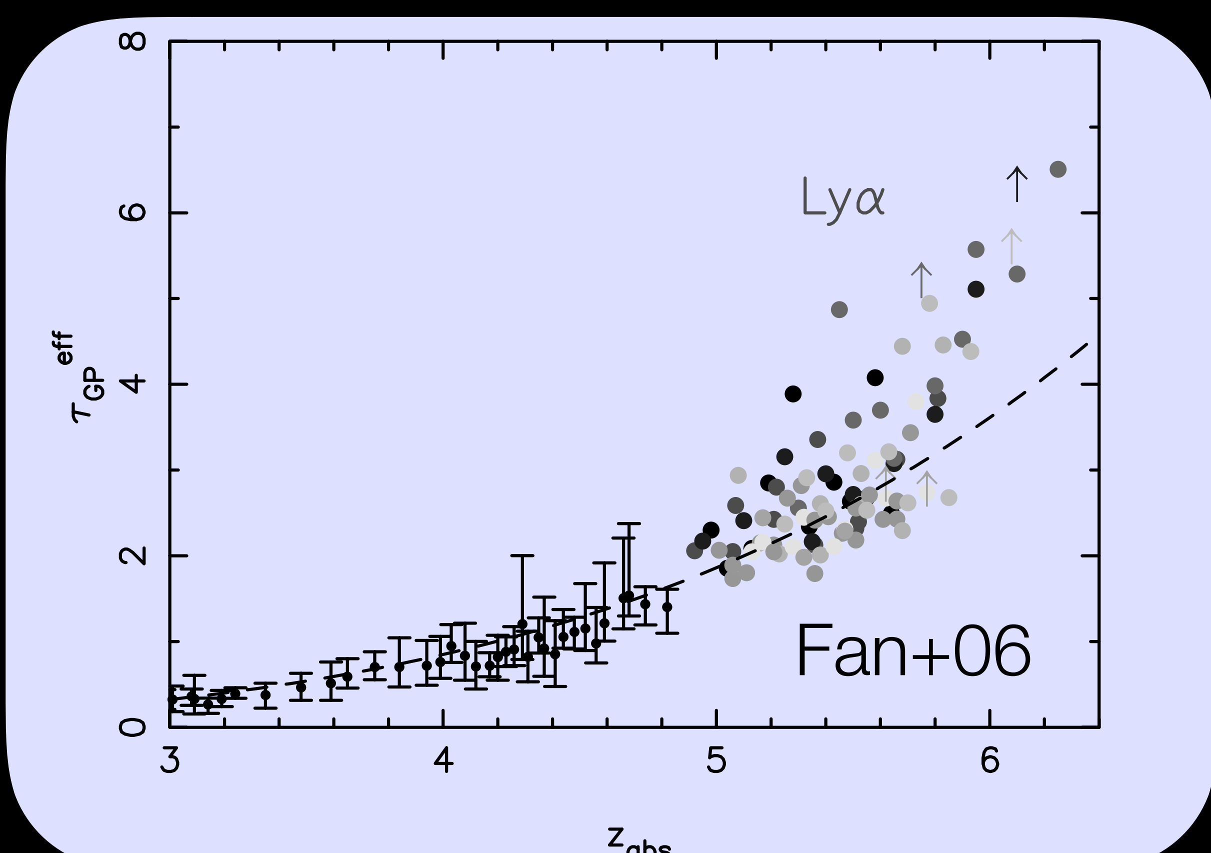
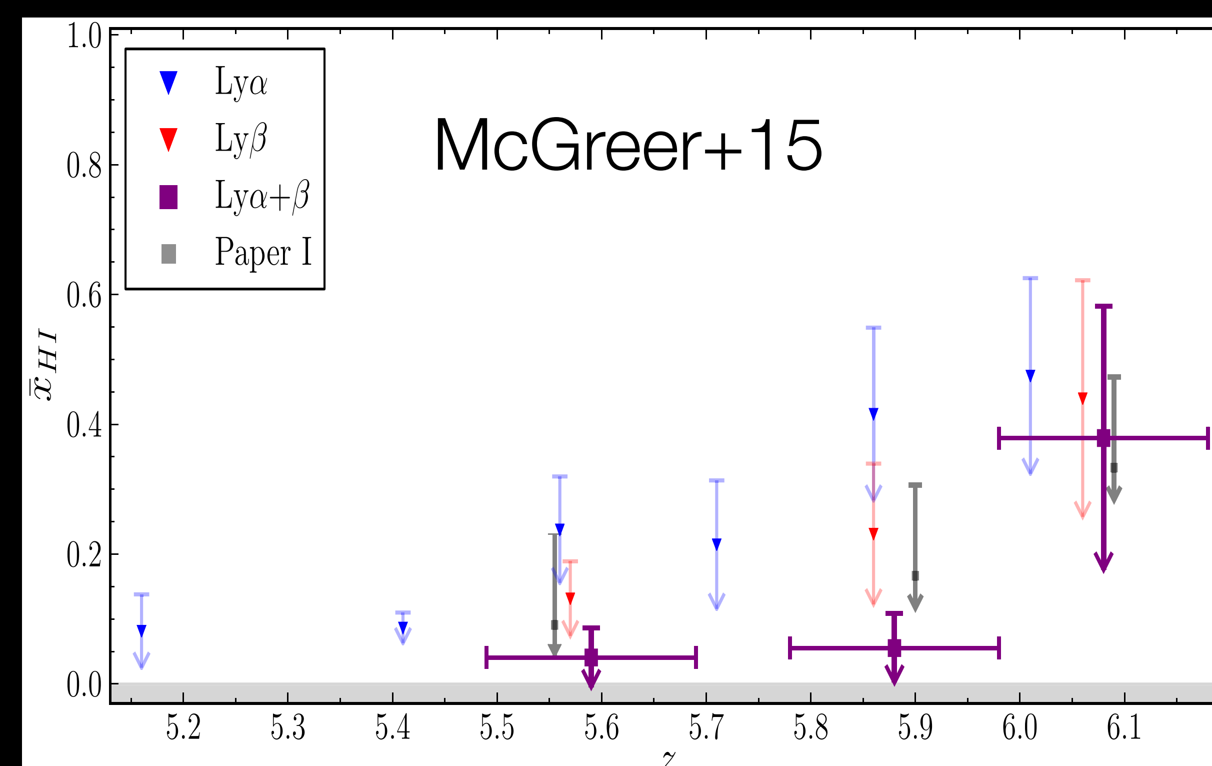
WHAT ARE THE ROBUST OBSERVATIONAL CONSTRAINTS ON REIONIZATION?

- Several observational probes available of either the actual ionization state of the IGM, or of the prevalenc
    - Quasars: Studying absorption in t   t quasars directly probes the neutr called Gunn-Peterson optical dep

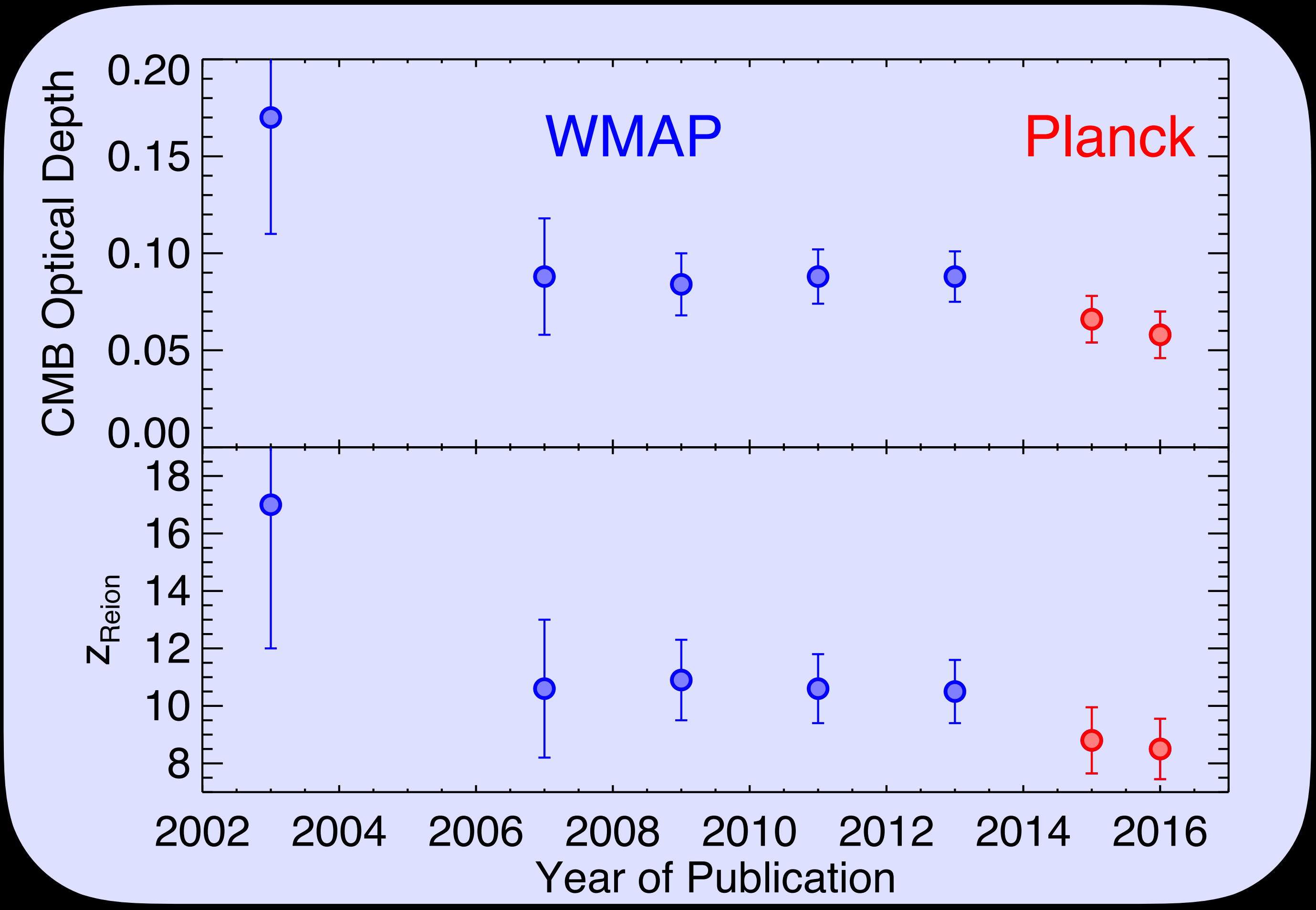
Model-independant constraints:
$x_{HI} < 0.04 \pm 0.05$ @ $z=5.6$
$x_{HI} < 0.06 \pm 0.05$ @ $z=5.9$





WHAT DO WE KNOW ABOUT REIONIZATION?

- Cosmic microwave background: CMB photons scatter off of free electrons on their way from the surface of last scattering to our telescopes. This optical depth can be measured via polarization data from CMB experiments.
  - This does not tell us anything about the temporal or spatial inhomogeneity about reionization, it simply tells us about the number of electrons along the line of sight, and one can approximate this as an instantaneous reionization redshift.



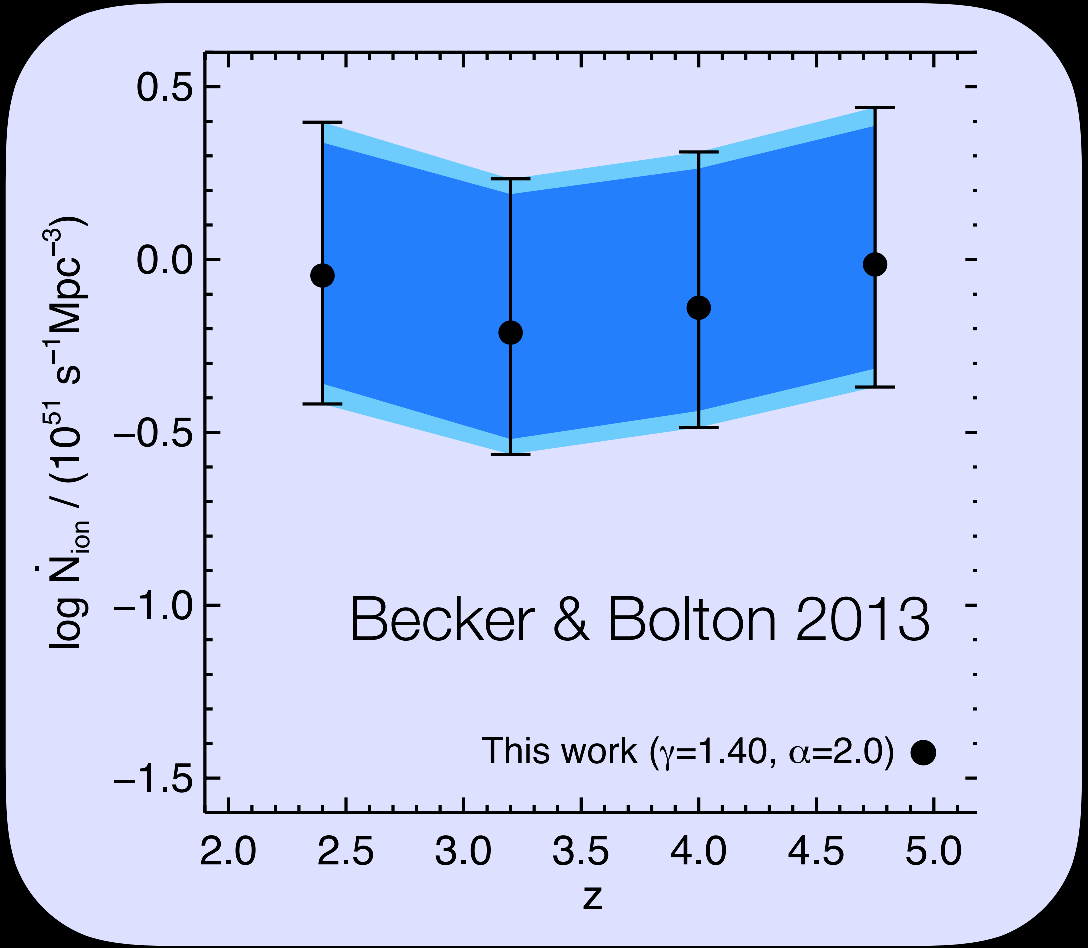
<u>Planck constraints:</u>

$\boldsymbol{\tau_{es} = 0.066 \pm 0.012}$ **(2015)**

$\tau_{es} = 0.058 \pm 0.012$ (2016)

WHAT DO WE KNOW ABOUT REIONIZATION?

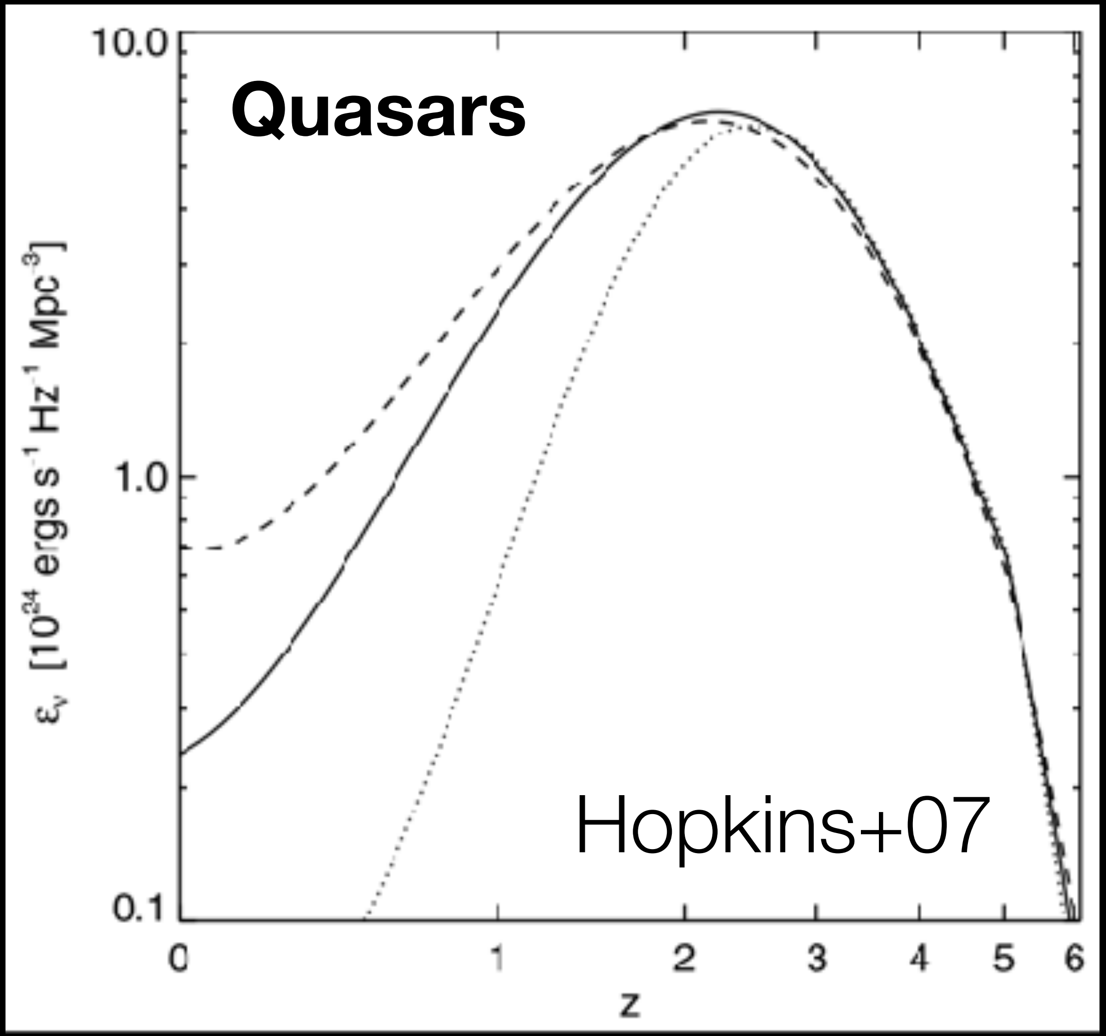
- Ionizing emissivity: Using quasar spectra to infer/measure the gas temperatures and opacities of Lyα and ionizing photons, one can infer the ionizing emissivity in the IGM at various epochs.
  - Does require some assumptions, including that the mean free path to ionizing photons is somewhat short.

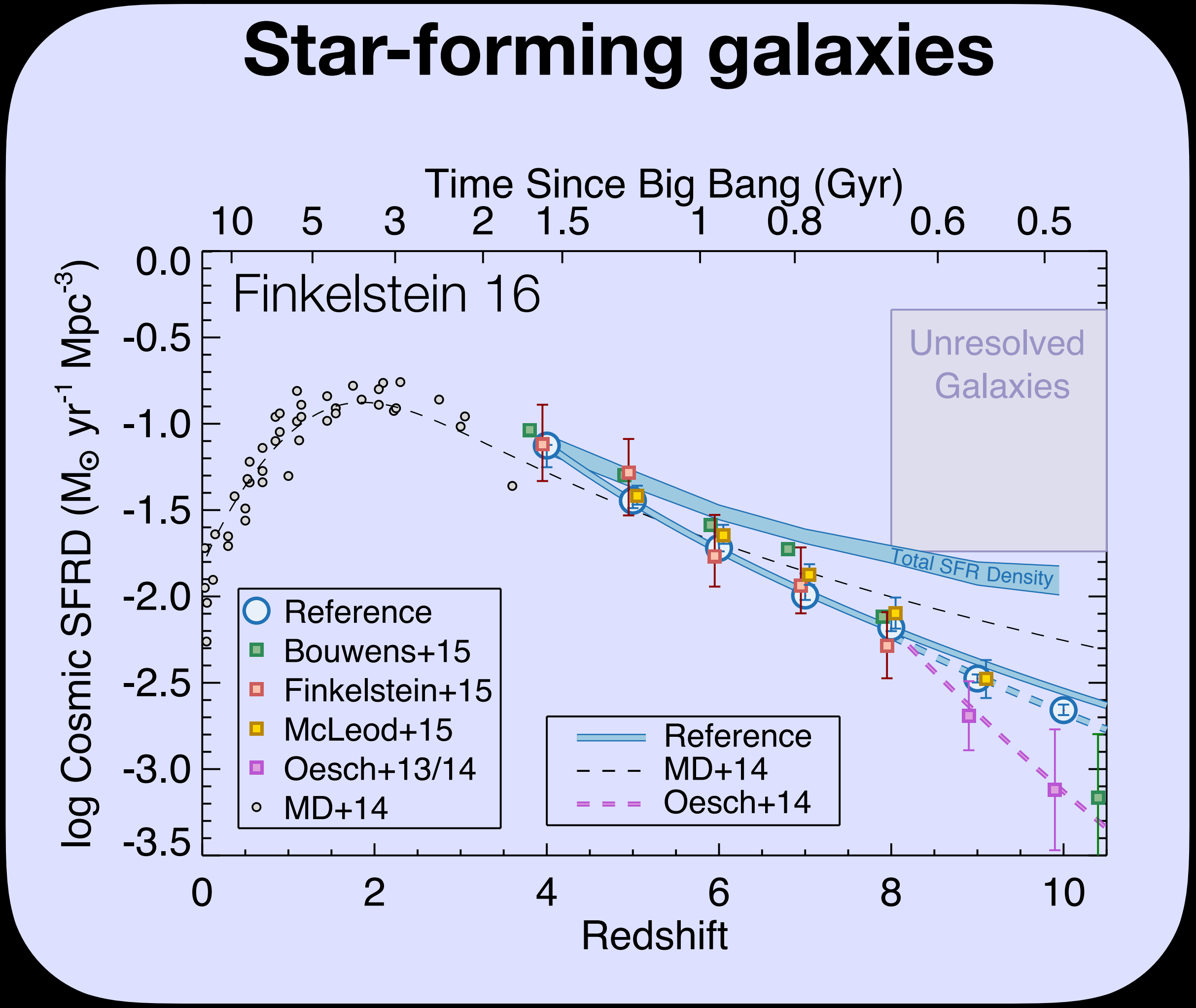


Not a direct constraint on the neutral fraction of the IGM, but whatever the ionizing sources are must match these observations.

GALAXIES ARE THE MOST LIKELY IONIZING SOURCES

- Estimates of the potential contribution from quasars show that it dies off steeply at z > 3, while galaxies exhibit a more modest decline.





QUANTIFYING THE CONTRIBUTION OF GALAXIES TO REIONIZATION

- From a galaxy standpoint, we need to understand three things:
  - **The UV luminosity density ρ_{UV}**
    - Integral of the UV luminosity function, to some limiting faint magnitude.
  - **The conversion from UV luminosity density to ionizing photon density**
    - ξ_{ion}, or the Lyman continuum photon production efficiency

Common assumptions (e.g., Finkelstein+12, 15; Robertson+13, 15)

M_{lim}=-13

log ξ_{ion}=25.2 (modestly metal-poor stars)

QUANTIF… …TION OF GALAXIES

The product of these three numbers gives the escaping ionizing emissivity at a given epoch

- From a galaxy standpoint, we need to understand three things:
  - **The UV luminosity density ρ_{UV}**
    - Integral of the UV luminosity function, to some limiting faint magnitude.
  - **The conversion from UV luminosity density to ionizing photon density**
    - ξ_{ion}, or the Lyman continuum photon production efficiency
  - **The escape fraction of ionizing photons.**
    - Where we have the least knowledge

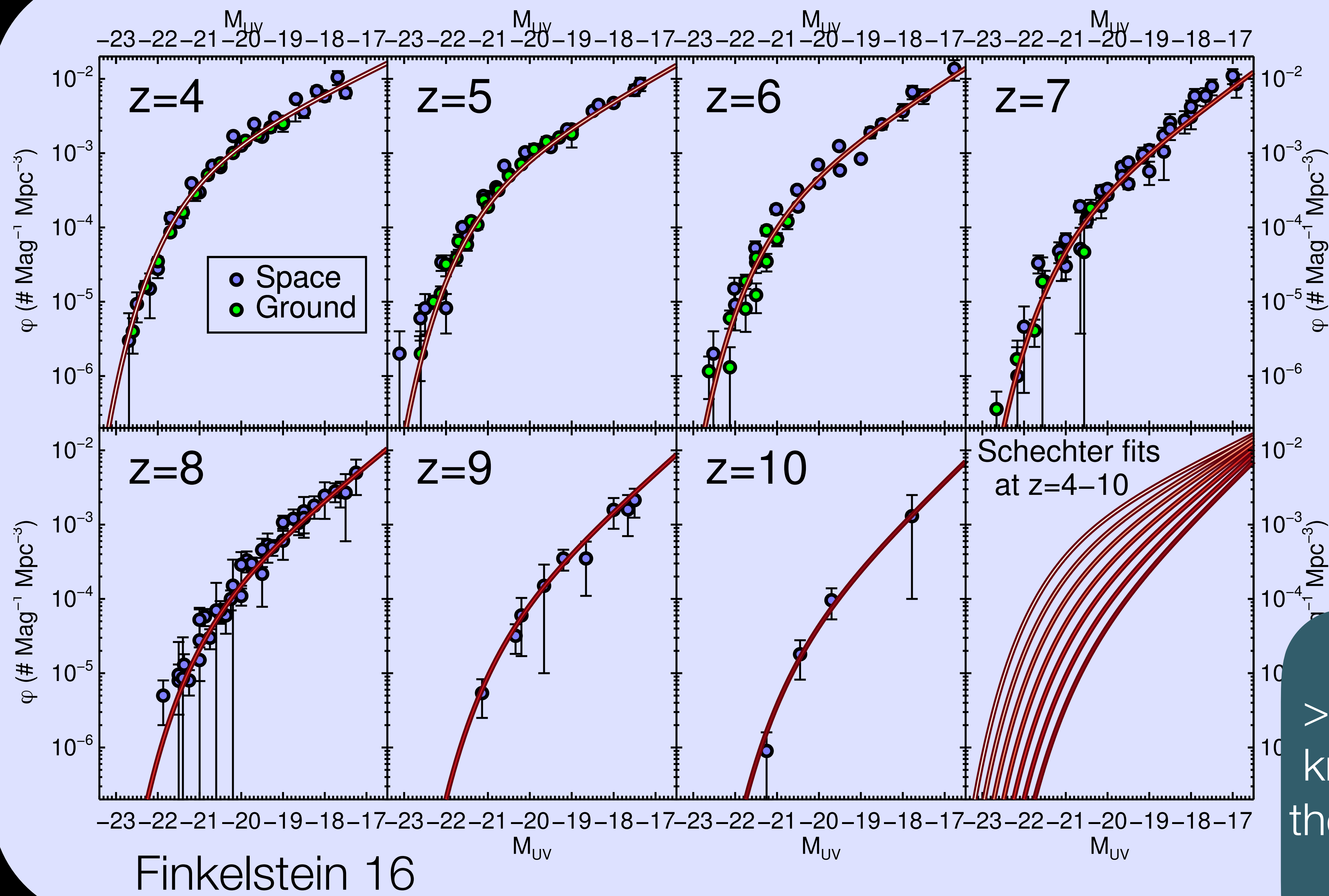
Common assumptions (e.g., Finkelstein+12, 15; Robertson+13, 15)

M_{lim}=-13

log ξ_{ion}=25.2 (modestly metal-poor stars)

f_{esc} = 0.1 - 0.5

REFERENCE LUMINOSITY FUNCTIONS: SIMULTANEOUS CONSTRAINTS FROM ALL RECENT STUDIES



Data from:

Bouwens+15ac

Bowler+14,15

Castellano+10

Finkelstein+15

McLeod+15,16

McLure+09

McLure+13

Oesch+13,14

Schenker+13

Schmidt+14

Tilvi+13

van der Burg+10

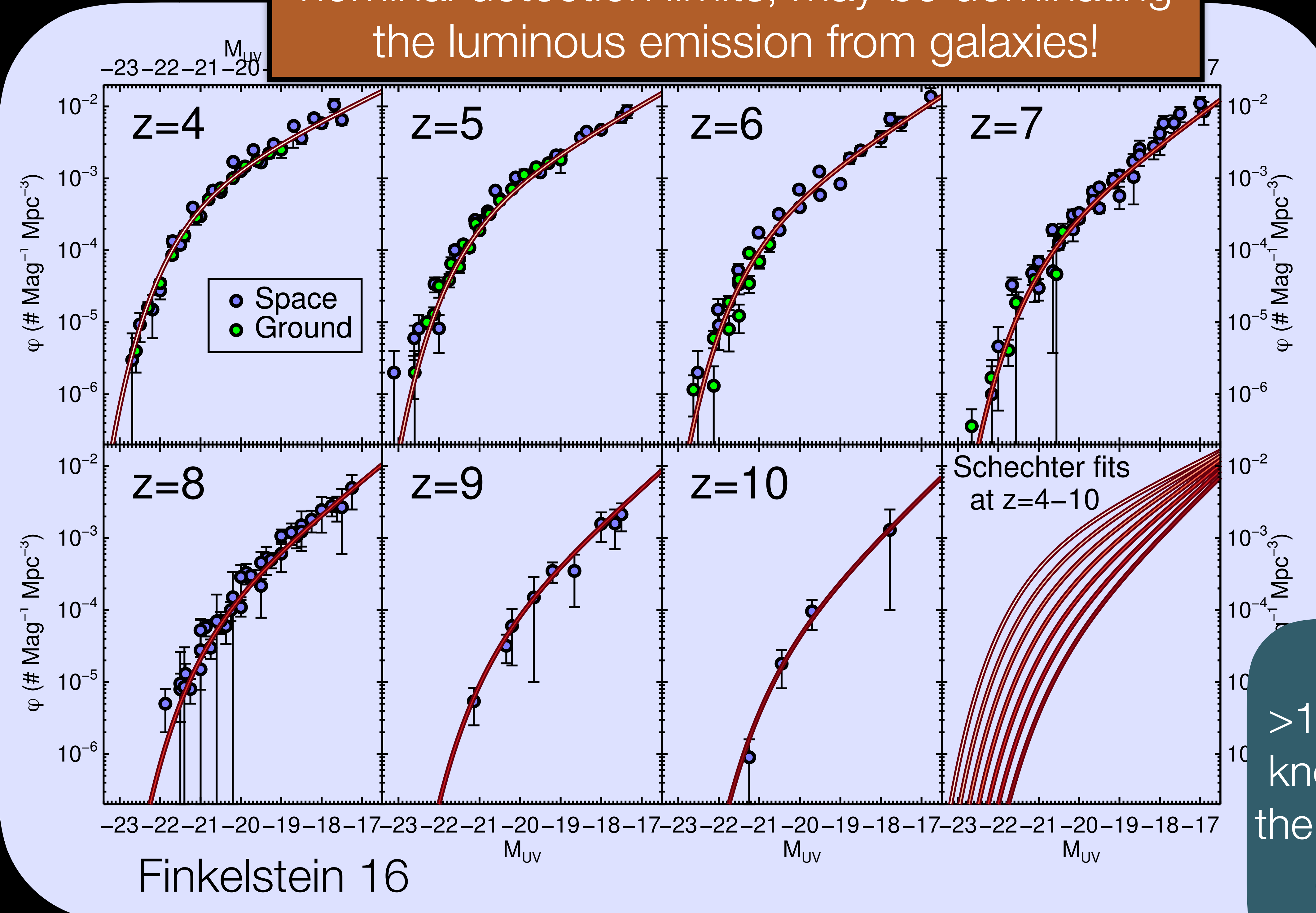
Based off of >1000 galaxies now known at z > 6 from the CANDELS, HUDF and UltraVISTA surveys.

REFERE MULTANEOUS
CONST ES

Note the steepening faint-end slopes!

$\boldsymbol{\alpha}(z) = -1.91 - 0.11(z-6)$

This implies that faint galaxies, below our nominal detection limits, may be dominating the luminous emission from galaxies!



Finkelstein 16

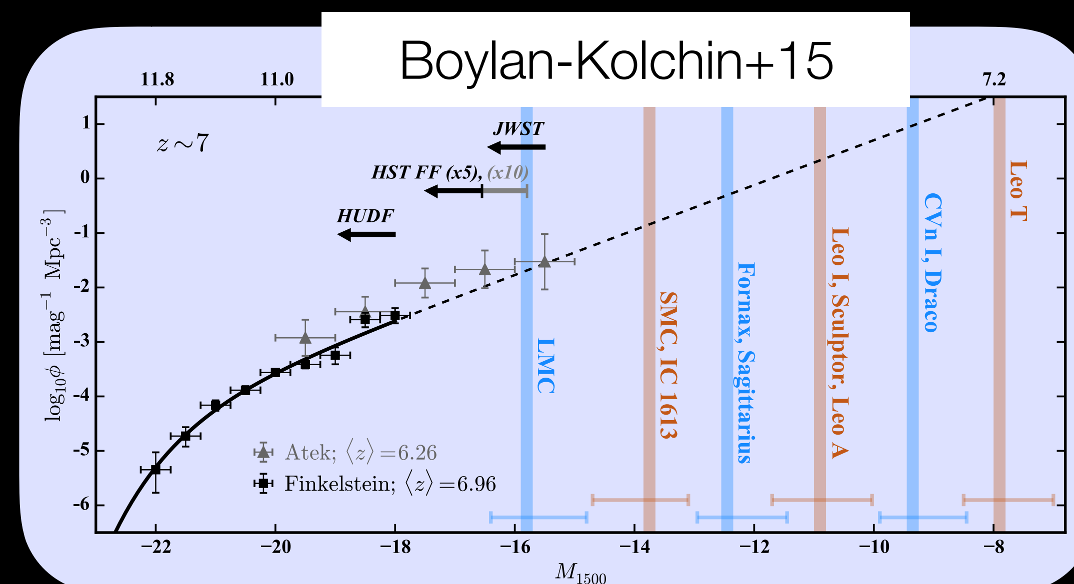
<u>Data from:</u>

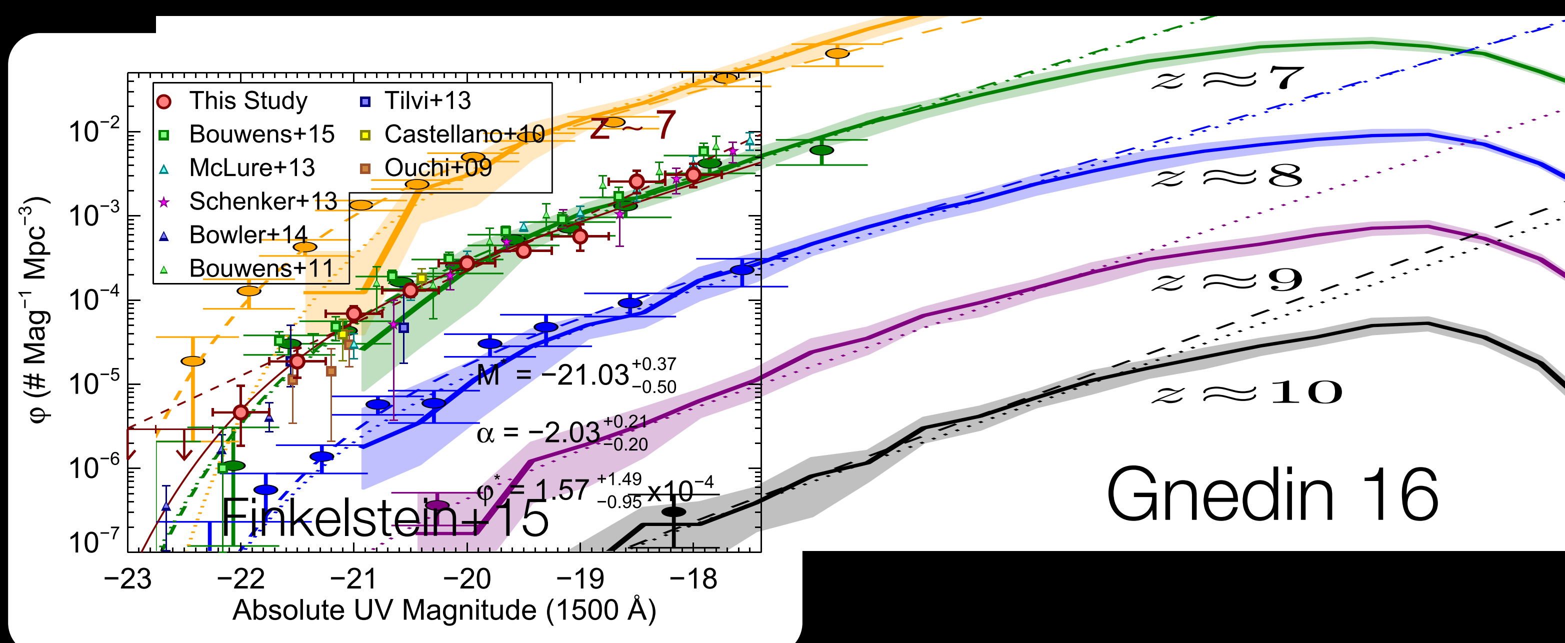
Bouwens+15ac
Bowler+14,15
Castellano+10
Finkelstein+15
McLeod+15,16
McLure+09
McLure+13
Oesch+13,14
Schenker+13
Schmidt+14
Tilvi+13
van der Burg+10

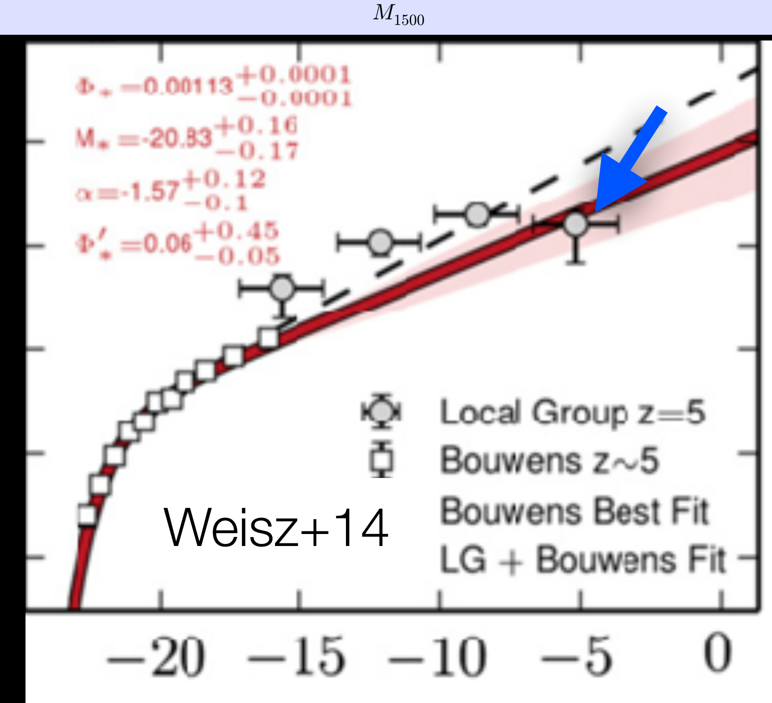
Based off of >1000 galaxies now known at z > 6 from the CANDELS, HUDF and UltraVISTA surveys.

THE LIMITING MAGNITUDE IS THE LARGEST PART OF THIS UNCERTAINTY

- While we now have excellent constraints on the luminosity function, what is the shape of the LF below our detection limits?



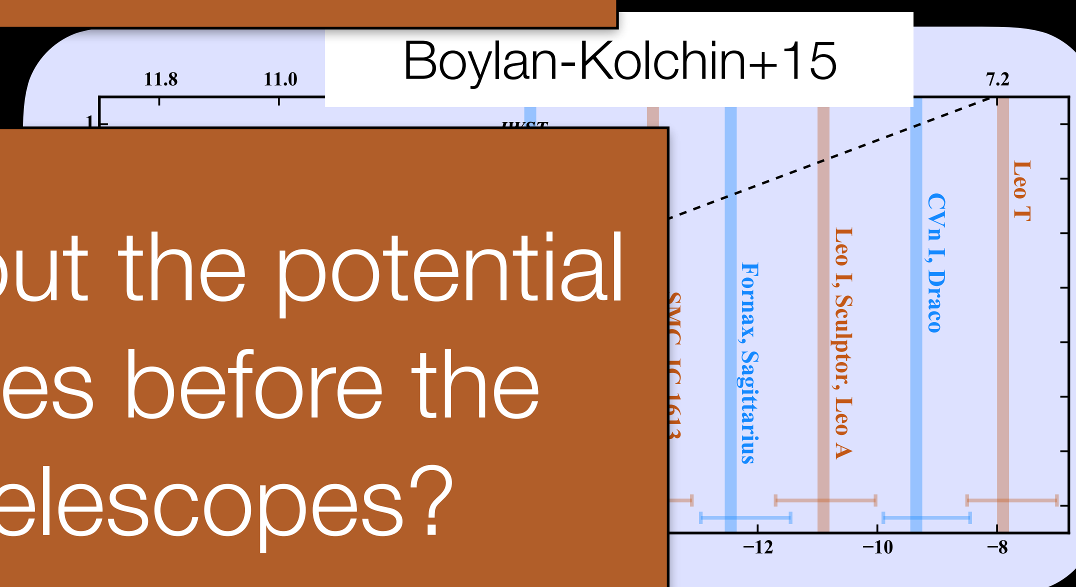




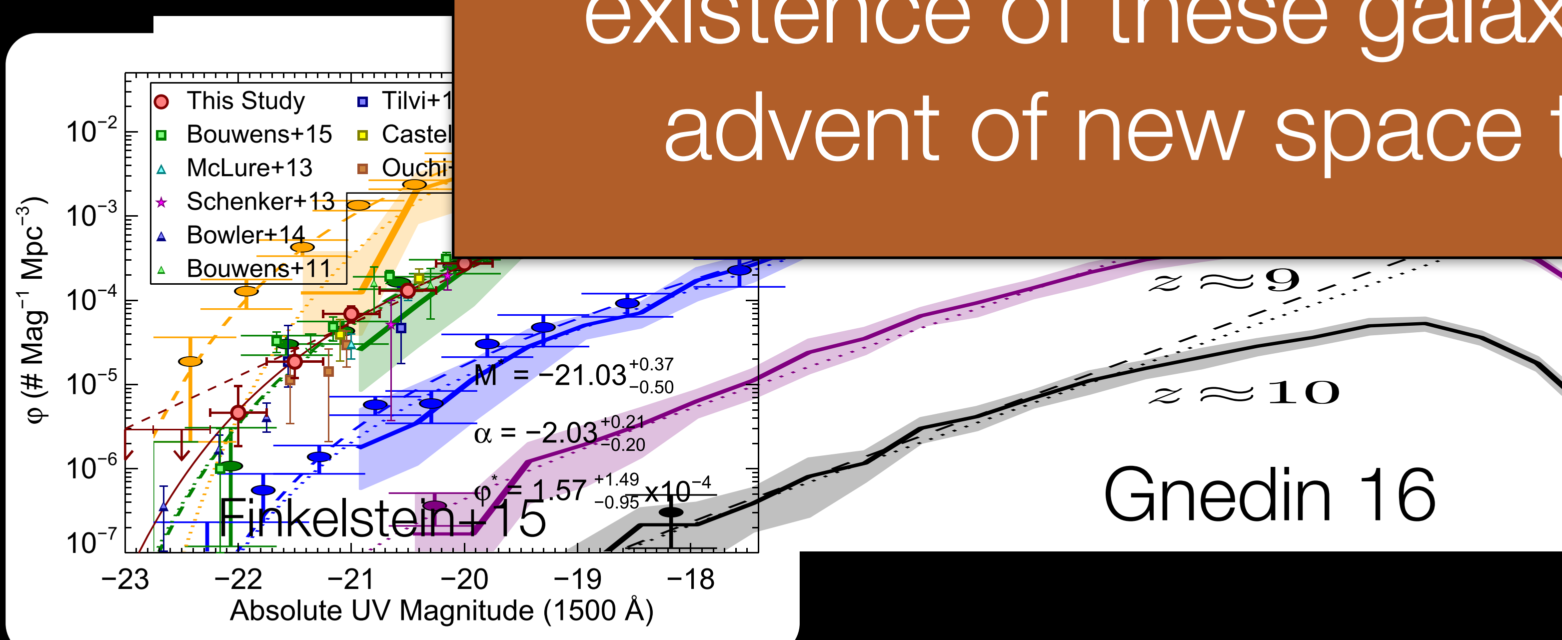
THE L… LARGE… …INTY

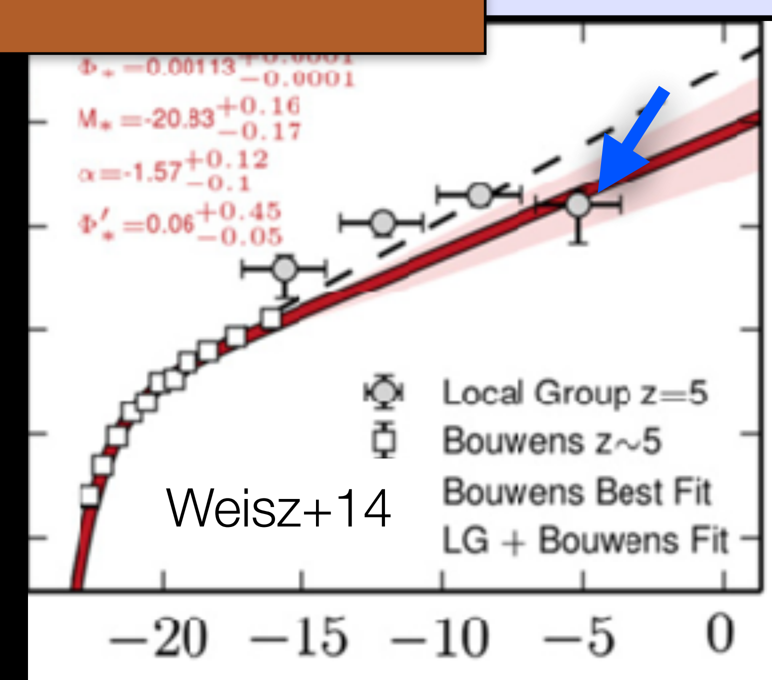
- While … e lumin… F below our detection limits?

If the luminosity function maintains a steep slope to M=-13, blank-field HST studies have seen only ~35% of the total luminosity density at z=7 (a JWST UDF-like program would only get to 60%).



Can we learn anything about the potential existence of these galaxies before the advent of new space telescopes?





THE HUBBLE FRONTIER FIELDS WAS DESIGNED TO FIND THE GALAXIES WHICH DOMINATED REIONIZATION

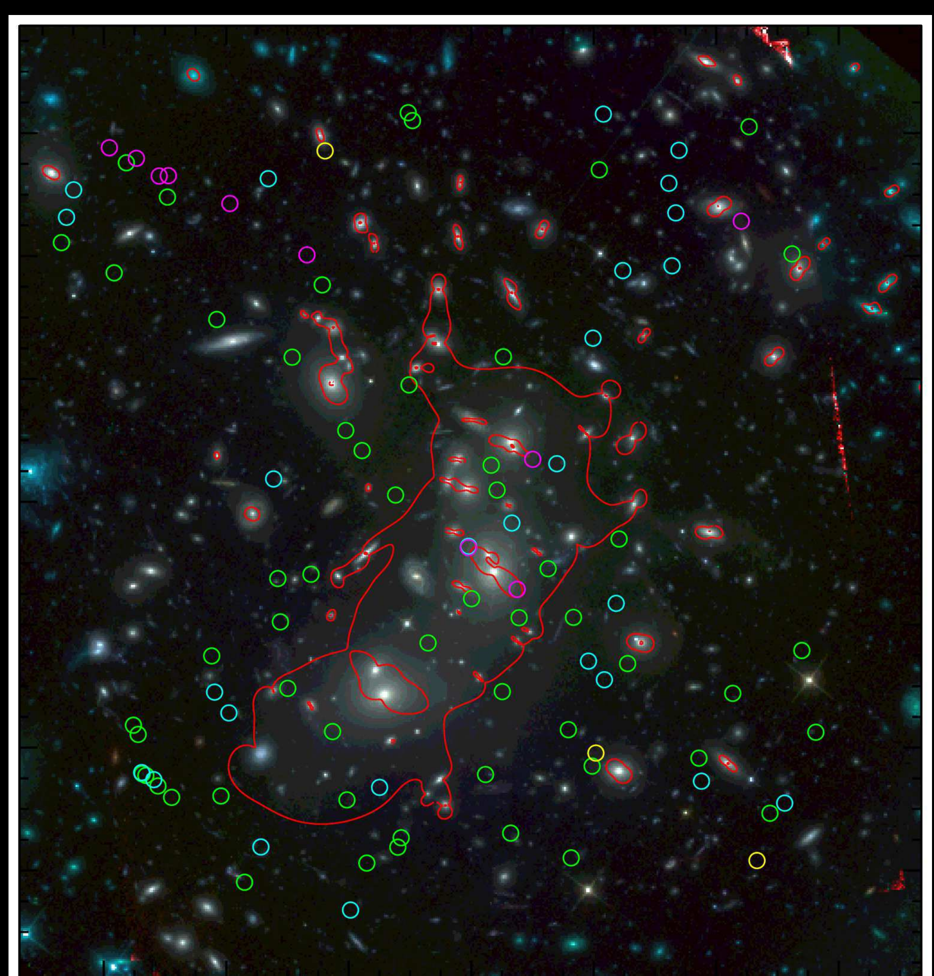
DIRECTLY OBSERVING THE GALAXIES LIKELY RESPONSIBLE FOR REIONIZATION

R. C. Livermore[1] and S. L. Finkelstein
The University of Texas at Austin, 2515 Speedway, Stop C1400, Austin, TX 78712, USA

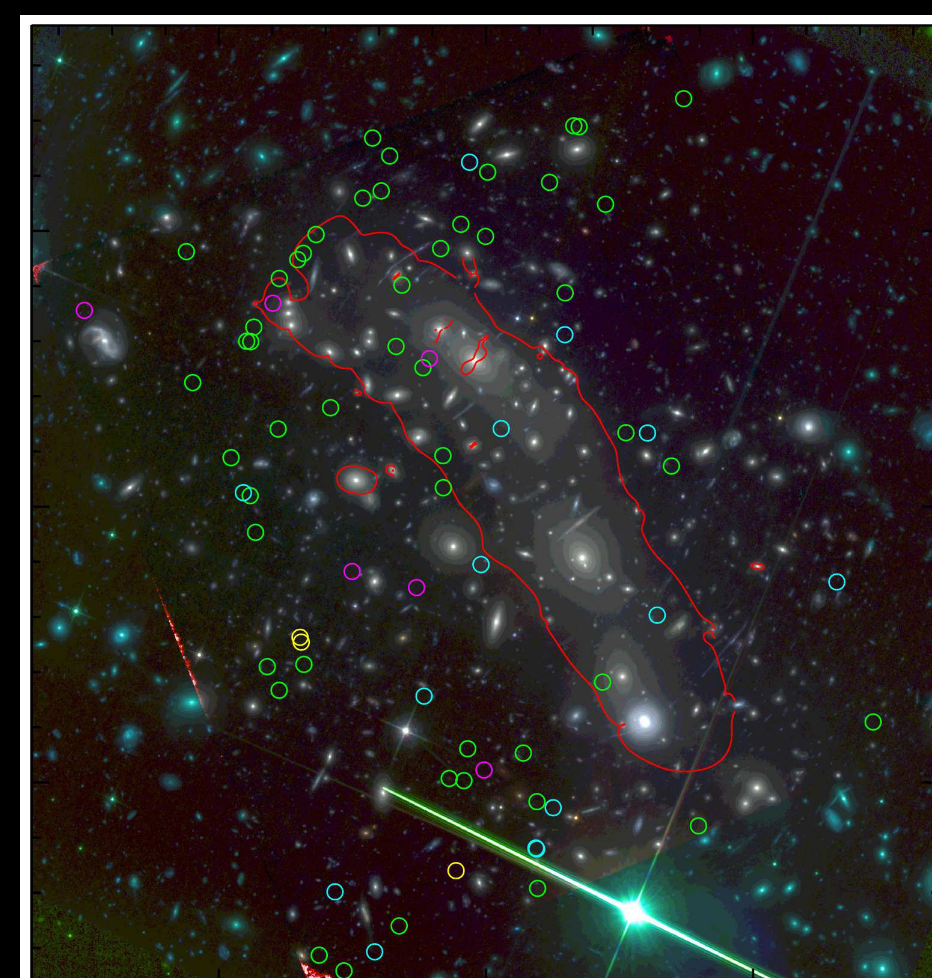
J. M. Lotz
Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA

FRONTIER FIELDS

Abell 2744

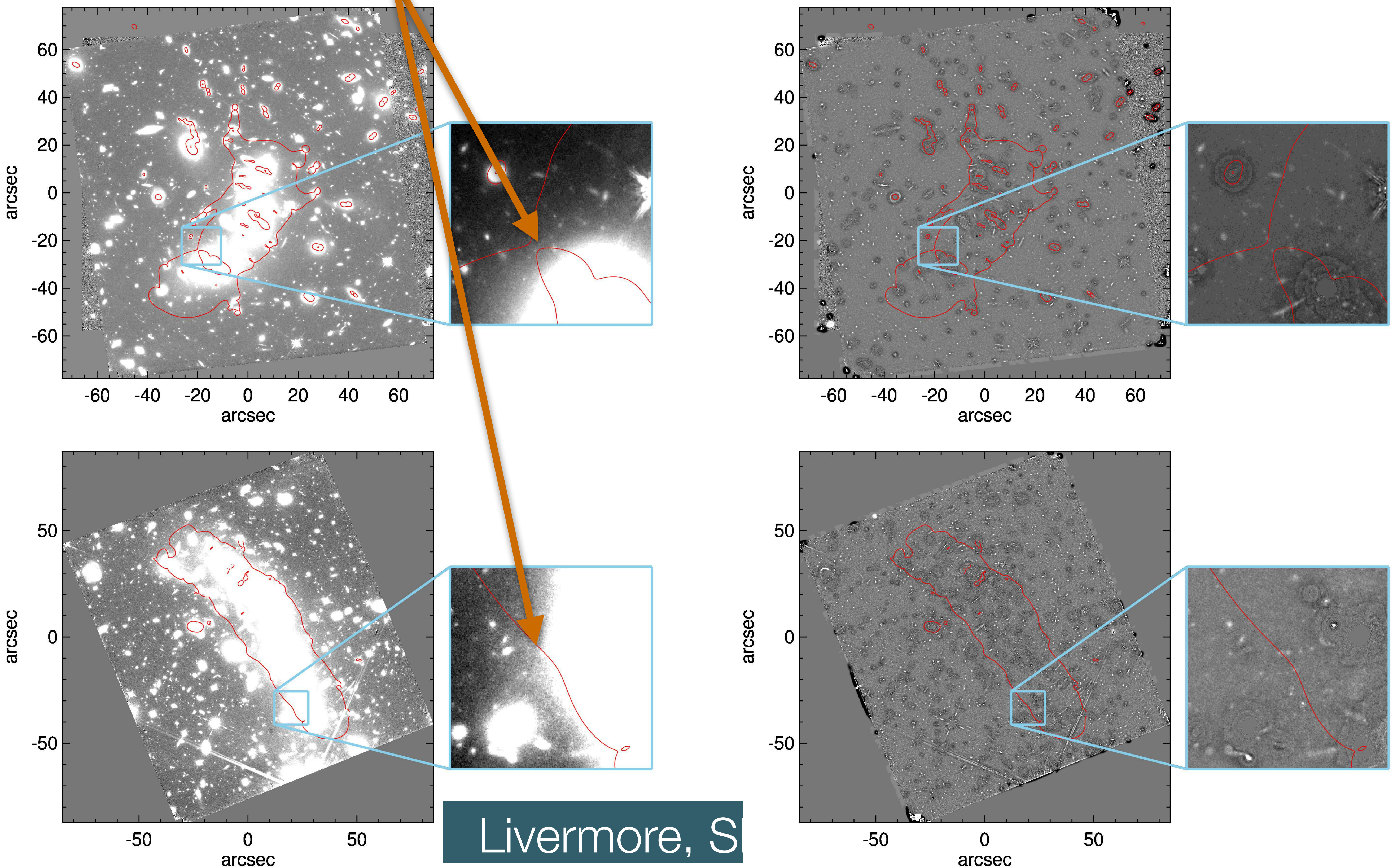


MACS 0416



The cluster blocks the highest magnification regions

Removed ICL and large cluster galaxies via wavelet decomposition
(see similar analyses w/ other techniques by Castellano+16, Merlin+16, Bouwens+16)



Livermore, SI

The cluster blocks the highest magnification regions

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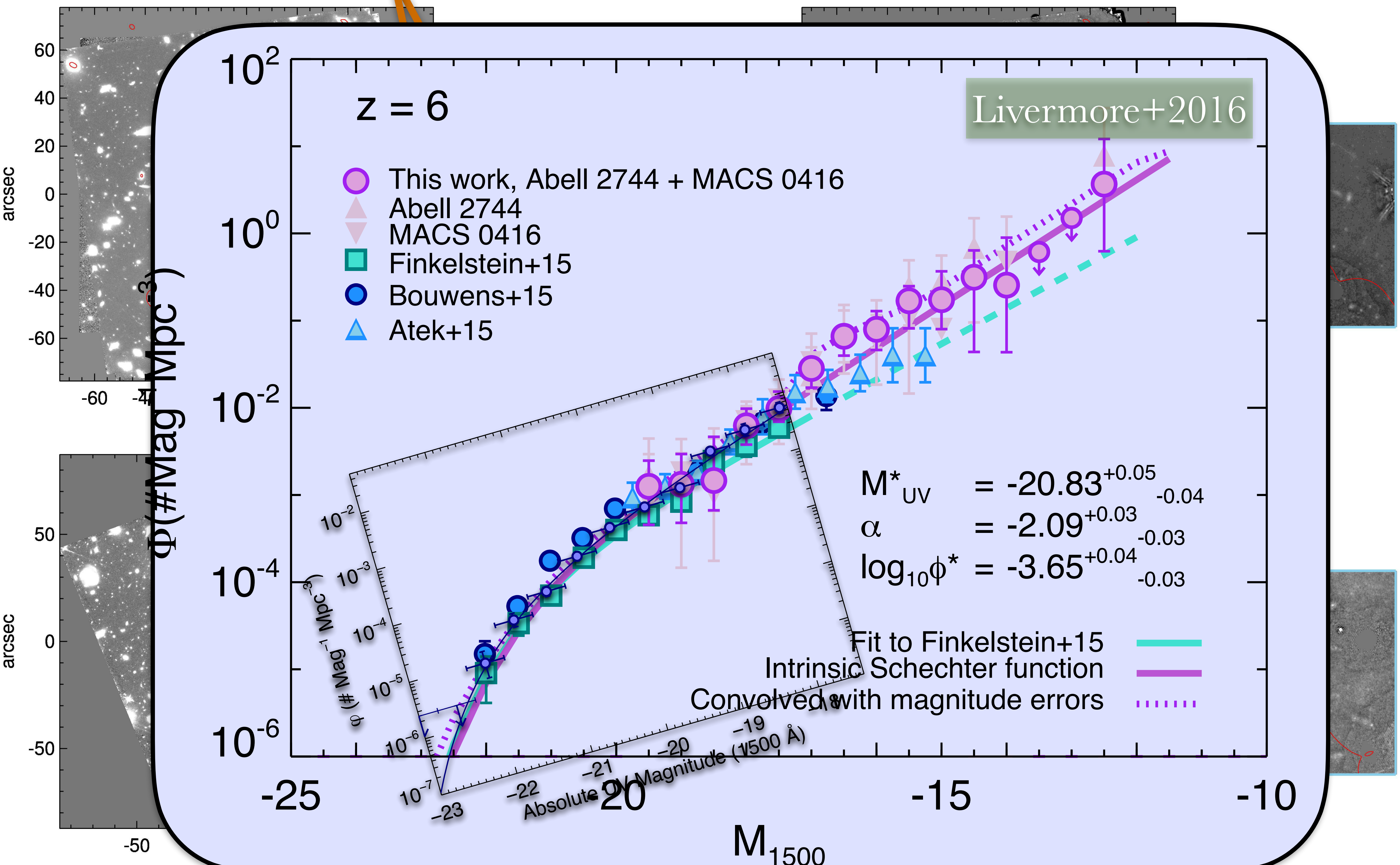
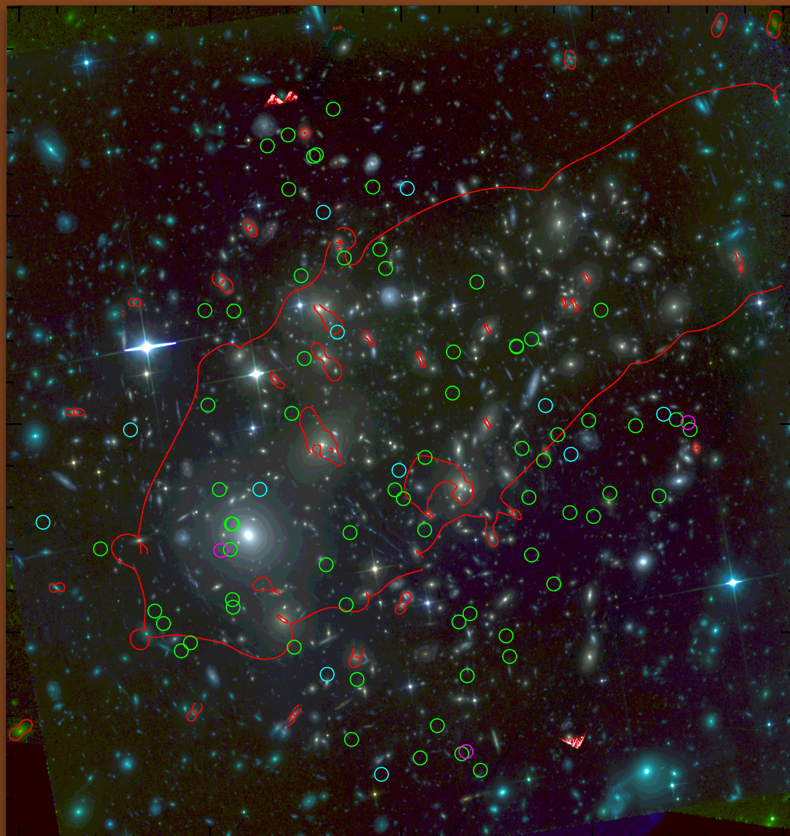
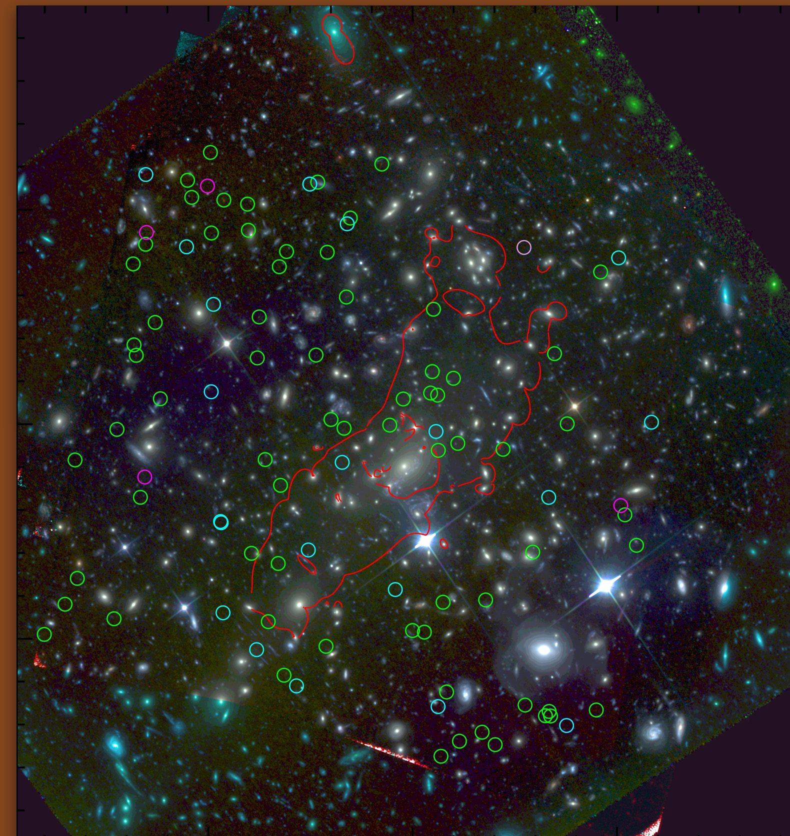
(see similar analyses w/ other techniques by Castellano+16, Merlin+16, Bouwens+16)

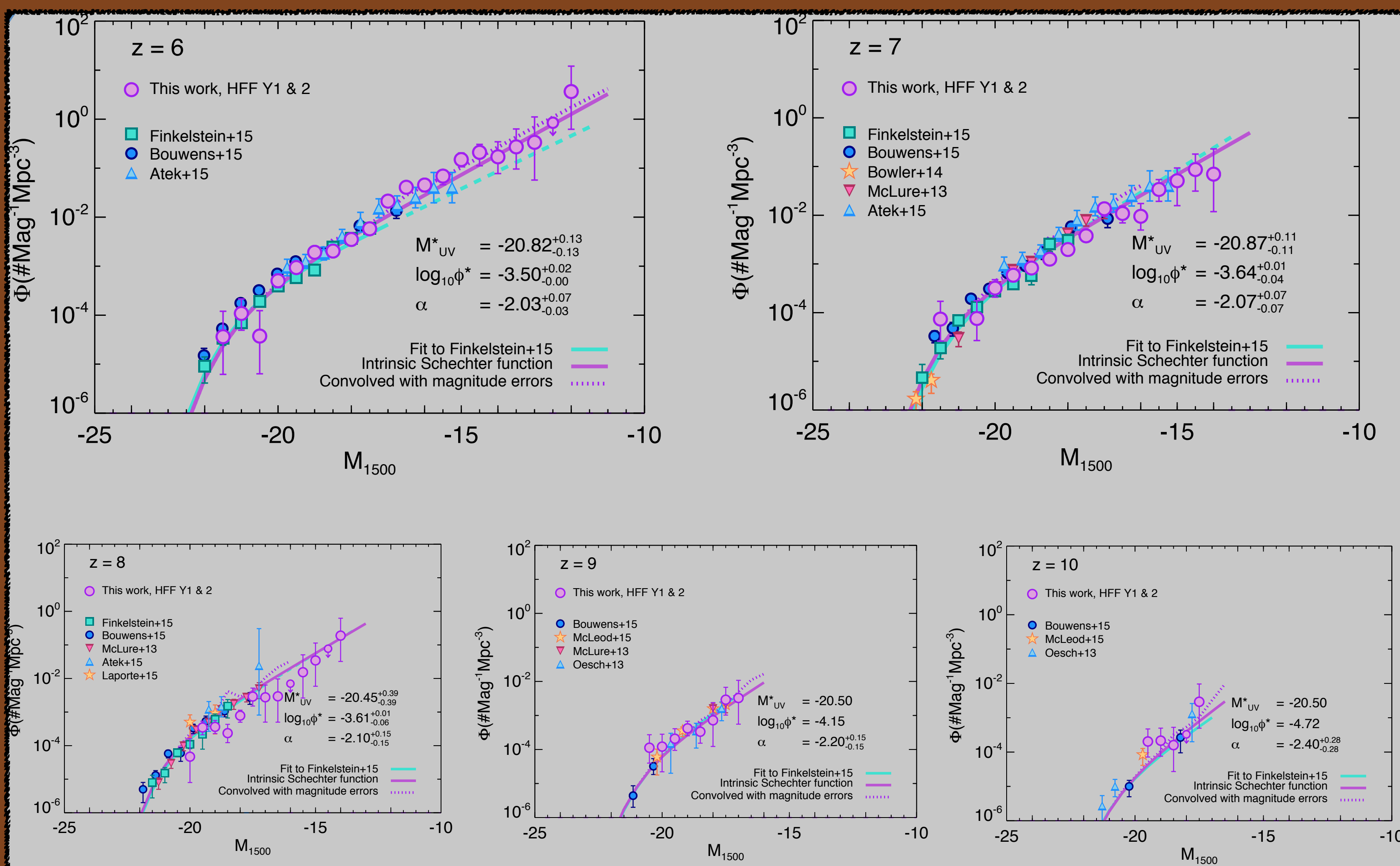






Updated analysis using Year 2 clusters, now extending to z=9,10.

680 total galaxies over four clusters+parallels



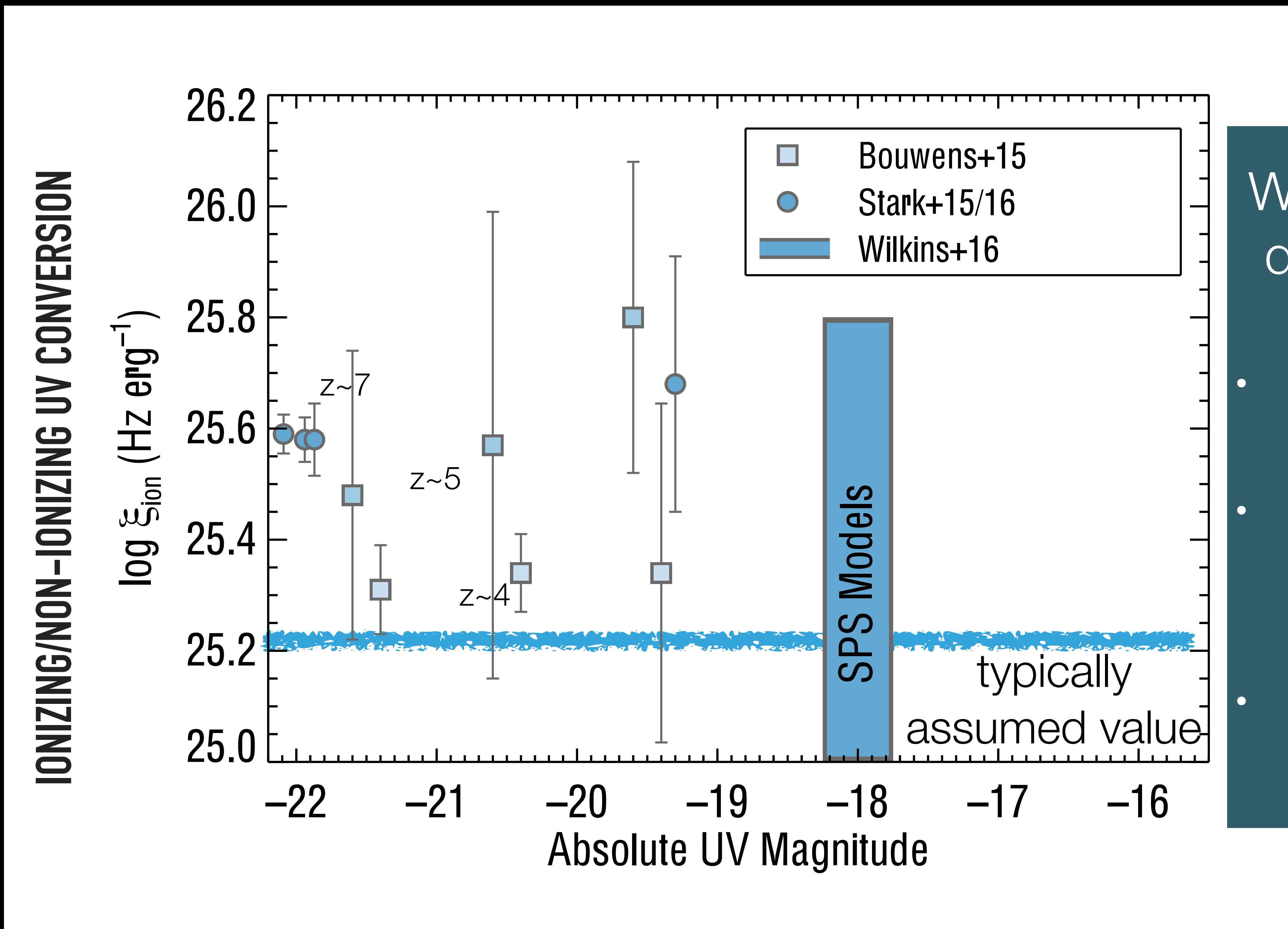
Confirms at higher significance our previous result that the luminosity function continues unbroken to M=-13 (at least at z=6).

Livermore,SF+in prep

QUANTIFYING THE CONTRIBUTION OF GALAXIES TO REIONIZATION

- From a galaxy standpoint, we need to understand three things:
  - **The UV luminosity density**
    - ~~Includes the UV luminosity function, and knowledge of the limiting magnitude.~~ **~ish**
  - **What about these assumptions?**
    - **The conversion from UV luminosity density to ionizing photon density**
      - ξ_{ion}, or the Lyman continuum photon production efficiency
    - **The escape fraction of ionizing photons.**
      - Where we have the least knowledge

PROBABLY NEED TO ASSUME THAT STELLAR POPULATIONS EVOLVE WITH REDSHIFT

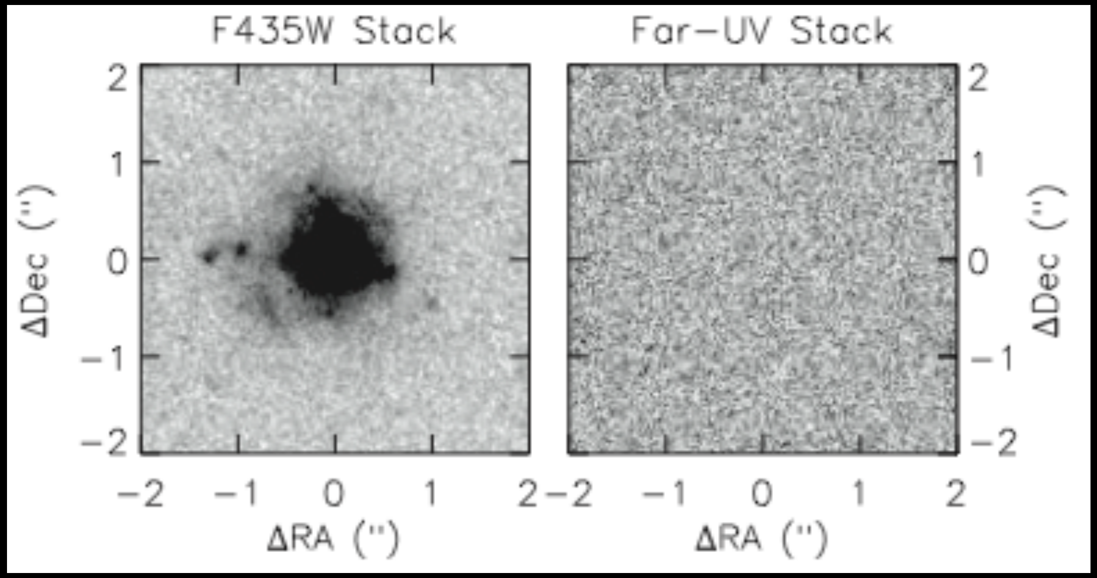


What could cause this quantity to increase?

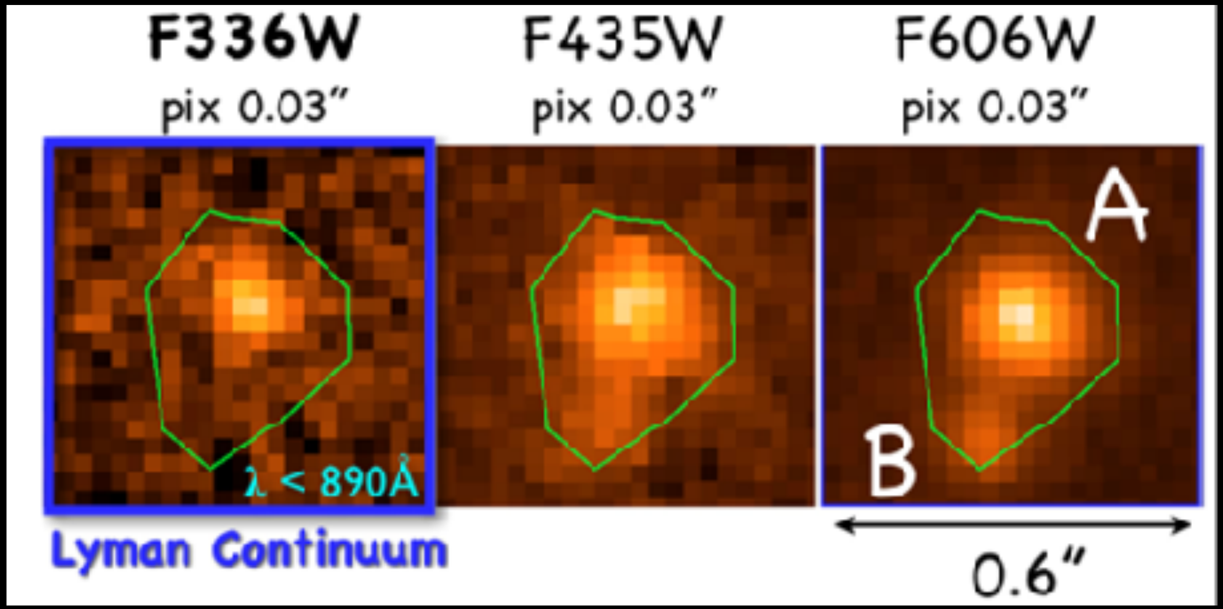
- Lower metallicities
- Binary Stars (X. Ma+2015)
- Faster stellar rotation (J. Choi + 17)

ALL GALAXIES LIKELY DO NOT HAVE UNIFORMLY HIGH IONIZING PHOTON ESCAPE FRACTIONS

- Almost all observations of escaping ionizing radiation from lower redshift galaxies result in non-detections.
    - Those we do see appear to be “oddballs”, and not necessarily representative of the general population.
    - Implies that most galaxies have very low escape fractions (<2%), with a small fraction with higher (>10%) escape fractions.

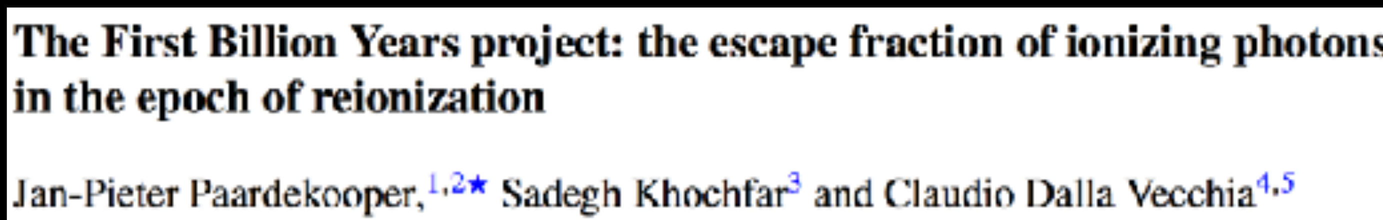


Siana et al. 2010



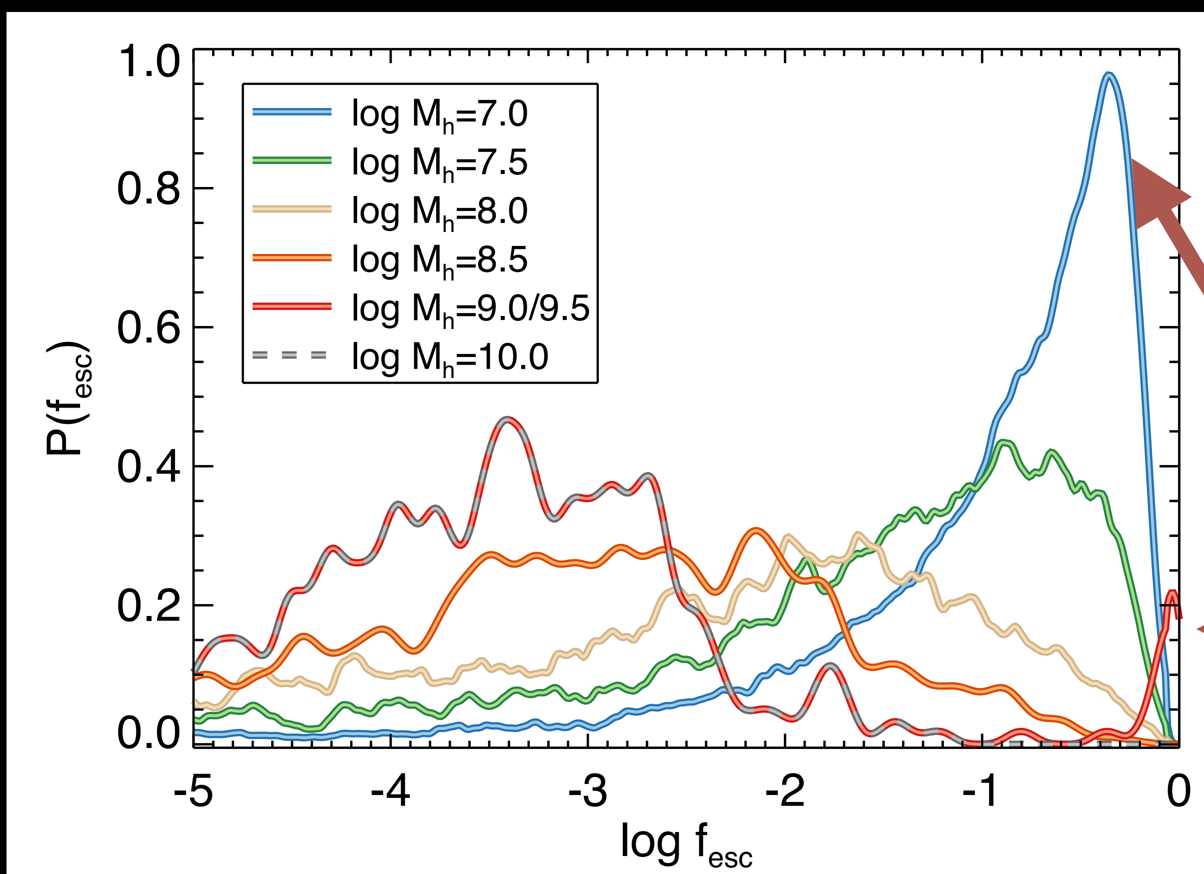
Vanzella et al. 2015

SIMULATIONS SAY ESCAPE FRACTIONS IN MASSIVE GALAXIES


The First Billion Years project: the escape fraction of ionizing photons in the epoch of reionization

Jan-Pieter Paardekooper,[1,2★] Sadegh Khochfar[3] and Claudio Dalla Vecchia[4,5]

Could galaxies reionize the universe with escape fractions this low?



Parameterize escape fraction as a function of halo mass. Independent of redshift.

Notice - very high escape fractions common only for very small halos. Exception is for a subset of log M ~9-10 halos undergoing an extreme starburst, where SNe have evacuated gas, allowing a high f_{esc}.

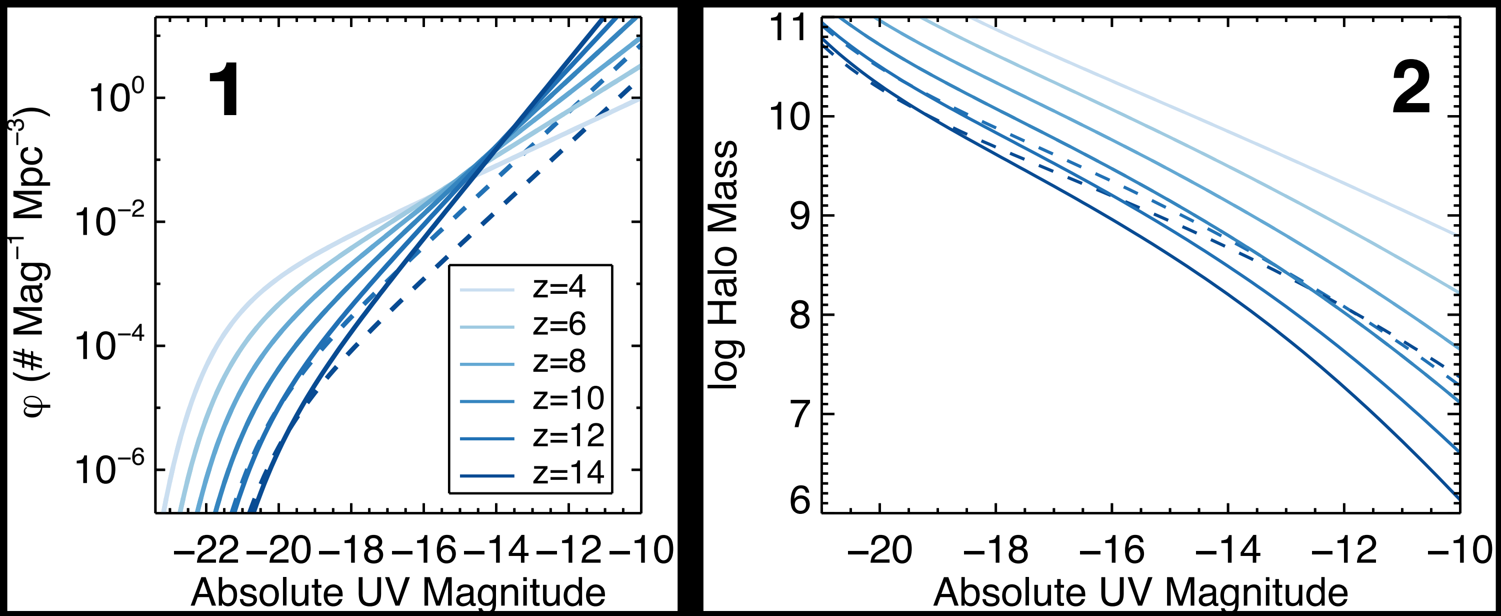
Similar to results from Renaissance simulations (Xu, Norman+16)

CAN GALAXIES REIONIZE THE IGM WITH LOW ESCAPE FRACTIONS?

- Motivated by these theoretical results, we set out to reconsider the contribution of galaxies to reionization, with an emphasis on physically-motivated values for the needed assumptions.
  - We do this within an MCMC framework, using the observations of the IGM neutral fraction (McGreer+15), CMB τ_{es} (Planck 2015), and ionizing emissivity at z~4-5 (Becker & Bolton 13) to constrain our free parameters.

Step 1: Assume a set of luminosity functions (Finkelstein+16, extrapolated to z=20).

Step 2: Perform abundance matching (Behroozi+13) to calculate the relation between M_h and M_{UV}.

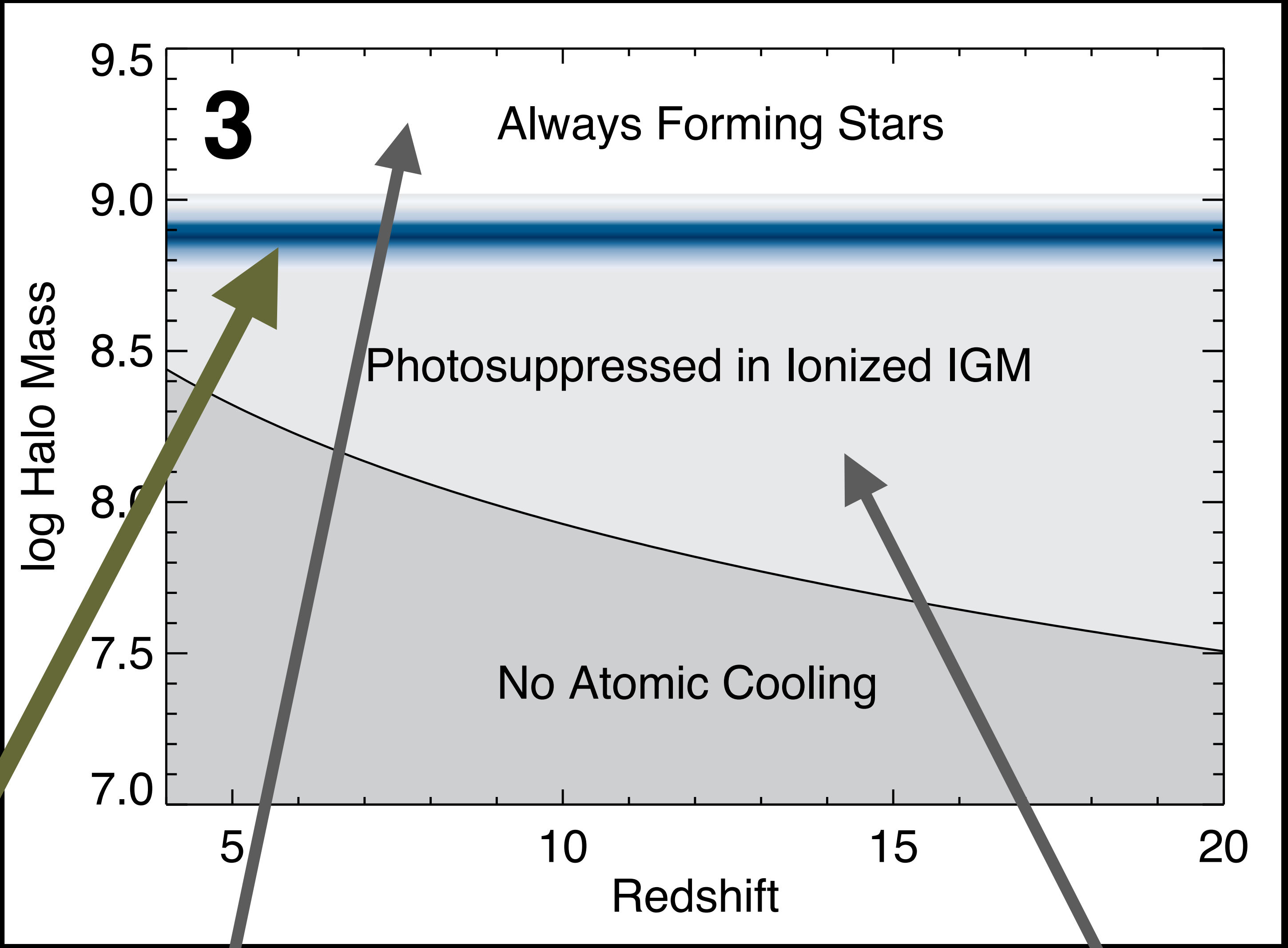


Finkelstein+17, in prep

THERE IS ARE TWO DIFFERENT PHYSICAL REASONS FOR A TURNOVER IN THE LUMINOSITY FUNCTION

Free parameter: $\mathbf{M_{supp}}$

Step 3: Assume a limiting halo mass, rather than a limiting halo magnitude. Prior to reionization, this is the atomic cooling limit (T_{vir} ~10^4 K). After reionization, galaxies with $T_{vir} < T_{IGM}$ will no longer accrete new gas, and so will be "photo-suppressed". This is the photo suppression mass (***M_{supp}***) is a free parameter.



Fiducial result: log $M_{supp}/M_\odot$ ~ 8.9, consistent with simulations (e.g., Iliev+07, Mesinger+08, Okamoto+08, Alvarez+12).

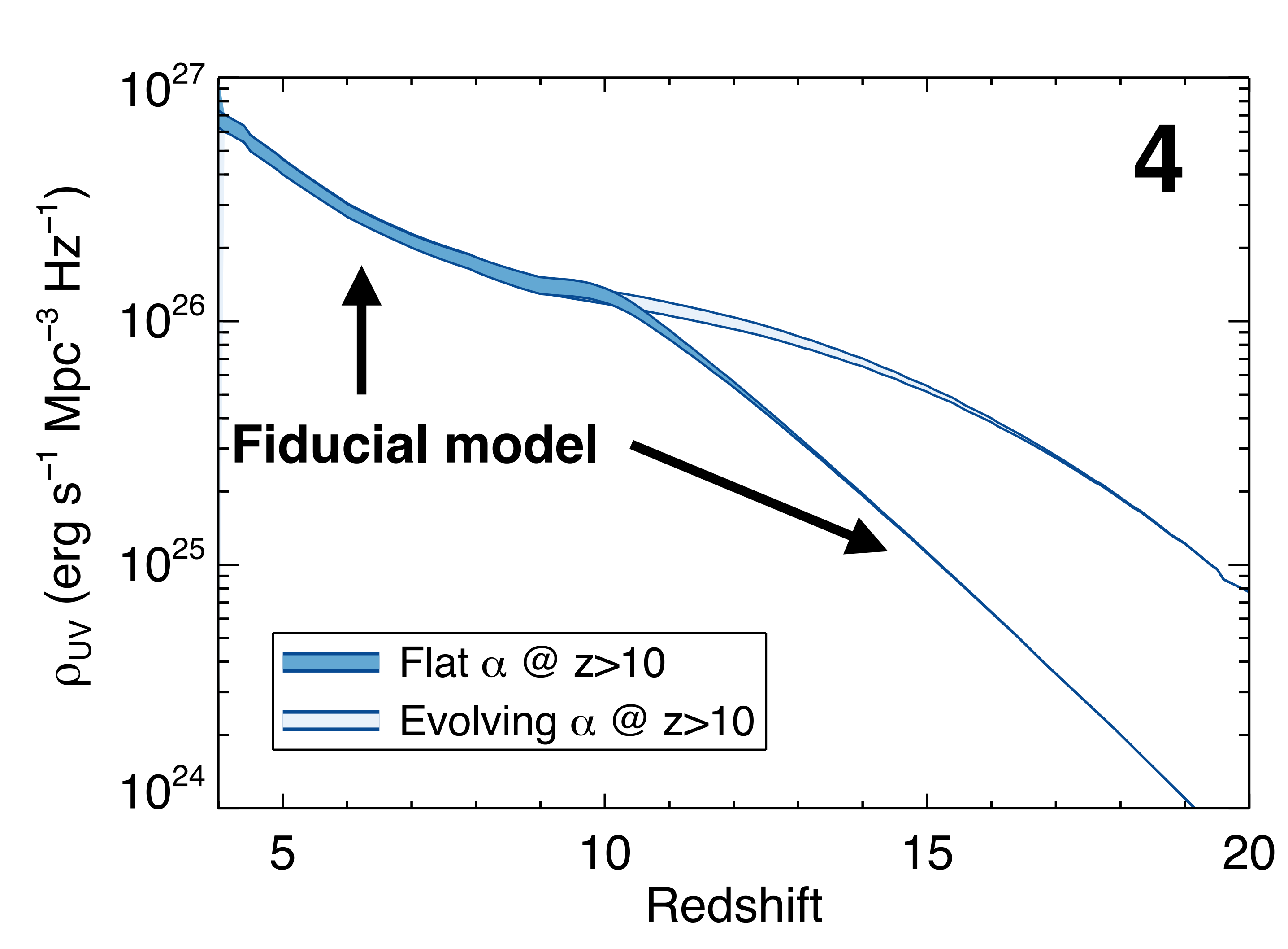
<u>Calculated on the fly as:</u>

$\rho_{UV}(z)=\rho_{UV}(M>M_{supp})+(1-Q_{HII})*\rho_{UV}(M_{supp}>M>M_{atomic})$

COMBINE EVERYTHING THUS FAR TO CALCULATE THE NON-IONIZING UV LUMINOSITY DENSITY

Step 4: Integrate the luminosity function down to the UV magnitude which corresponds to the appropriate limiting halo mass.

For our fiducial model, we fix the faint-end slope to stop evolving at $z > 10$ (stays at α=-2.35). We find that if we allow it to evolve, too many ionizing photons are produced at high redshift (violates CMB τ_{es}).



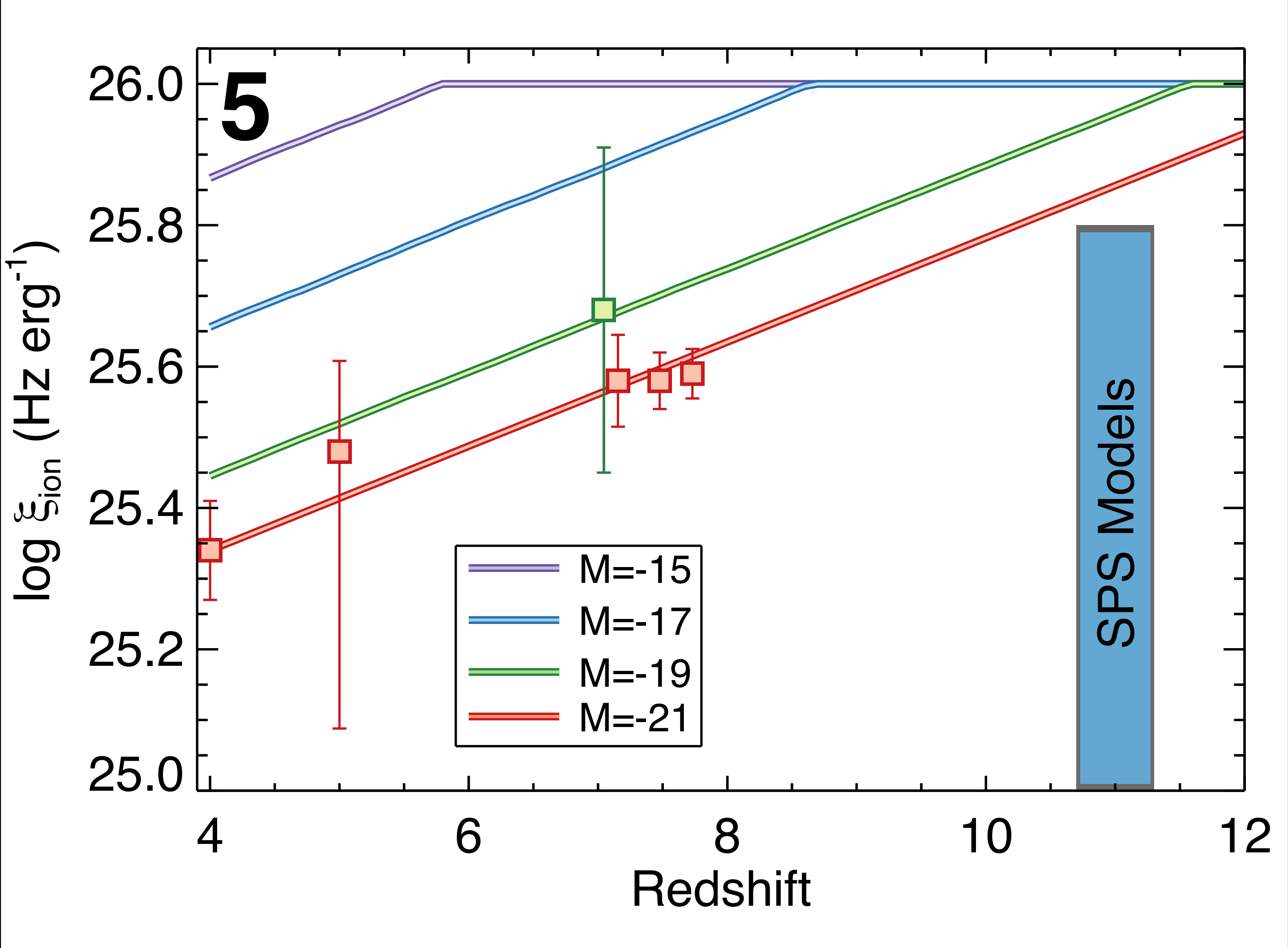
Gives us the first number: $\rho_{UV}(z)$

MODEL PREFERS HIGHER IONIZING PHOTON PRODUCTION EFFICIENCY AT HIGHER REDSHIFT AND FAINTER MAGNITUDE

Step 5: Assume an ionizing photon production efficiency, and convert UV luminosity density into ionizing emissivity. We fix this quantity to be equal to observations for bright (M_{UV}=-20) galaxies at z=4 (Bouwens+16), and allow it to evolve with both increasing redshift and magnitude.

Free parameters: **dξ/dz and dξ/dm**

Fiducial result: Modest evolution preferred in both (~0.05-0.1), shown by the colored lines in this figure. Interestingly, this evolution matches observations, which were ***not*** imposed as constraints.



$$\xi_{ion}(z,M) = 25.34 + (z-4)\frac{d\xi_{ion}}{dz} + (M - M_{ref})\frac{d\xi_{ion}}{dM}$$

-20

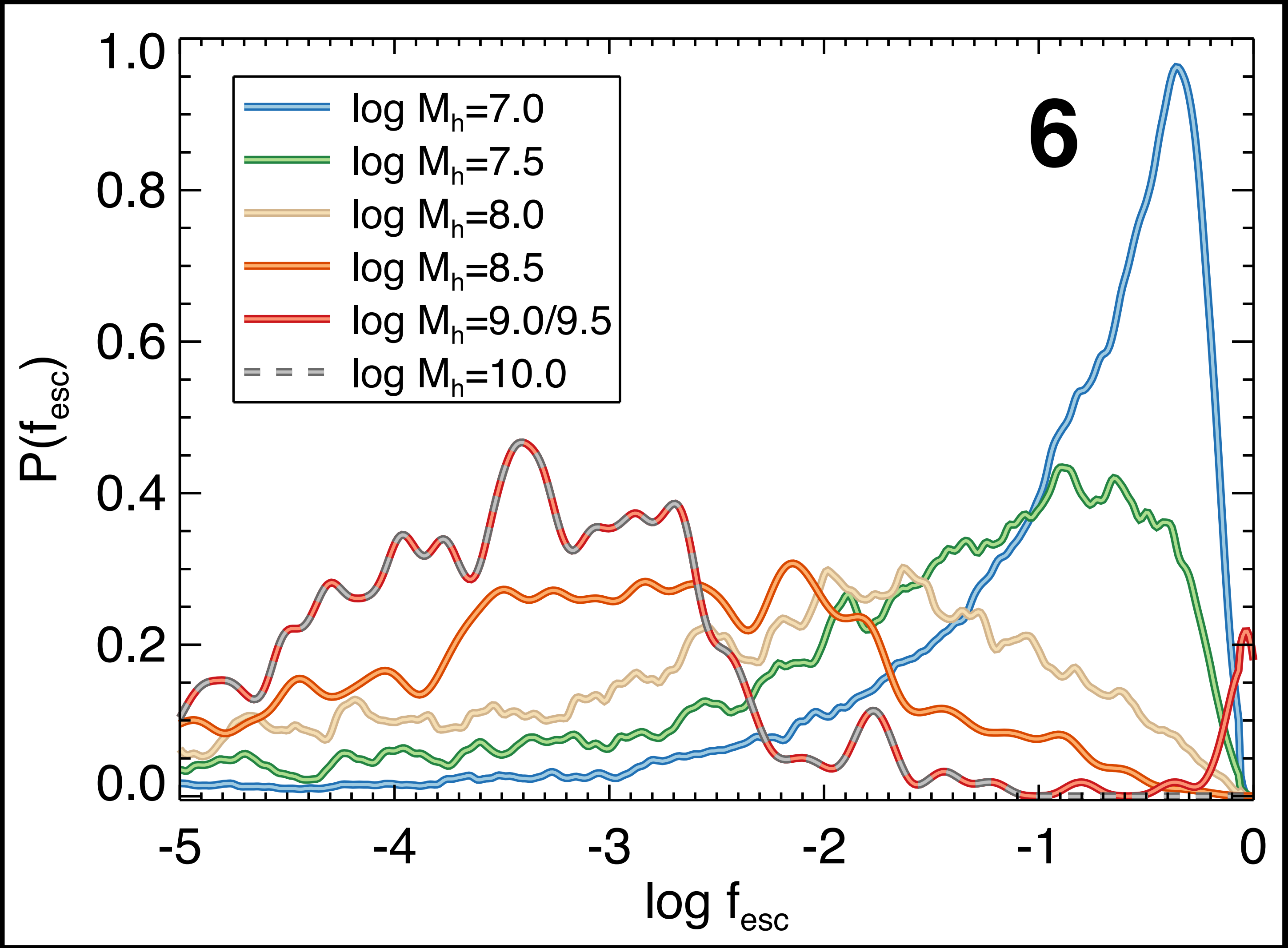
MARGINALIZE OVER F_{ESC} PROBABILITY BY SAMPLING PDFS DURING THE MCMC

Step 6: Apply escape fractions from Paardekooper+15, randomly drawing from the f_{esc} PDF according to the halo mass.

We then apply a scale factor ($f_{esc,scale}$) to account for the fact that the simulation does not resolve the birth cloud of the star particles, and those that do often find a higher escape fraction as the porosity of the gas is better accounted for (e.g., Paardekooper+11).

Free parameter: $\mathbf{f_{esc,scale}}$

Fiducial result: Scale factor of ~2-3 is preferred by the model.

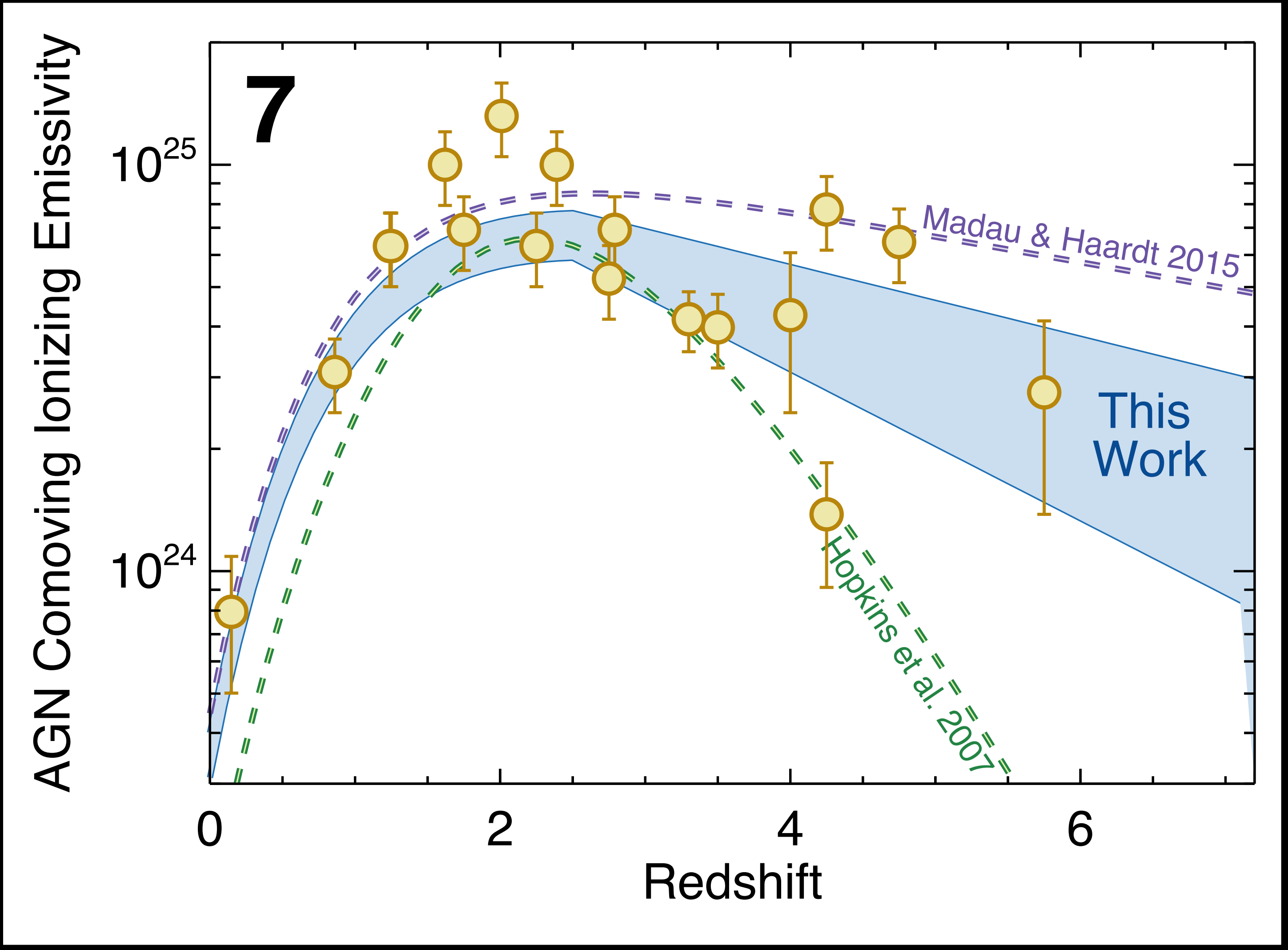


RECENT RESULTS IMPLY WE SHOULD AT LEAST CONSIDER THE POSSIBILITY OF AGNS

- While we're focusing on galaxies, several recent results imply that AGNs may still play a role.
  - Giallongo+15: X-ray flux seen at positions of z=4-6 galaxies, hinting at steeper than expected faint-end slope of AGN luminosity function.
  - Tilvi+16: Potential NV detection in z=7.5 galaxy.
  - Worseck+16: Find low HeII fractions in IGM at z~3.4, implying HeII reionization was mostly done (earlier than previously thought; z~2.7).
  - Chardin+15: Fluctuaions in UV background can be matched by a model where QSOs provide half the ionizing flux at z=5.5-6.
    - See also though
      - Finlator+16 (traced ionizing hardness via IGM metal absorption features)
      - D'Aloisio+16 (all quasars inconsistent with IGM temperature observations).
        - Both imply if AGN are present, they likely did not dominate.

ALLOWING AGNS:

Step 7: Allow an ionizing contribution from AGNs by assuming a functional form equal to Madau & Hardy (2015) at z=2.5, and, at higher redshift, equal to a single power law, constrained to be between previous observations by these three parameters:



Free parameters:

AGN_{slope} = The slope of the power-law, constrained to be between -1.05 (~Hopkins+07) and -0.13 (~MH15)

$z_{AGN,max}$ = Maximum redshift of AGNs

$f_{esc,AGN}$ = A scale factor applied to the emissivity, effectively an AGN escape fraction.

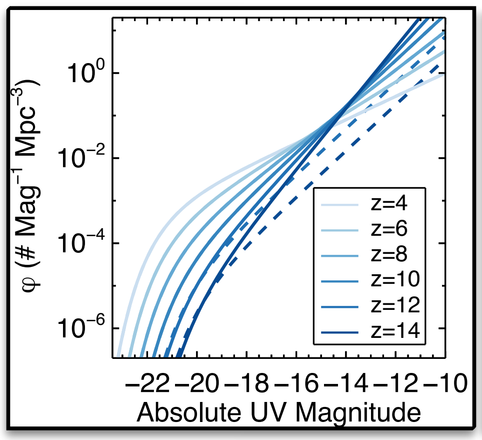
Fiducial result: The model prefers a redshift evolution lower than MH15, but still shallower than Hopkins+07, implying AGNs contribute at least somewhat to reionization.

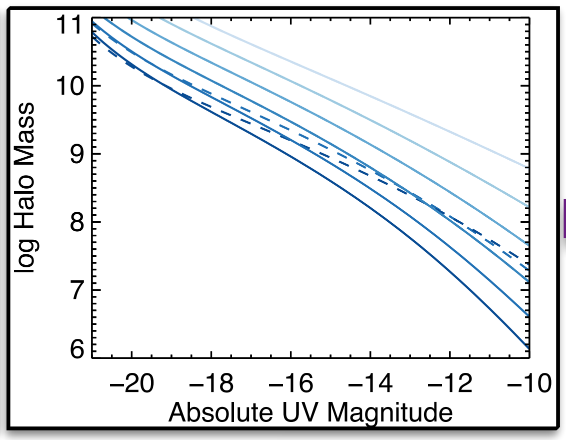
METHOD SUMMARY:

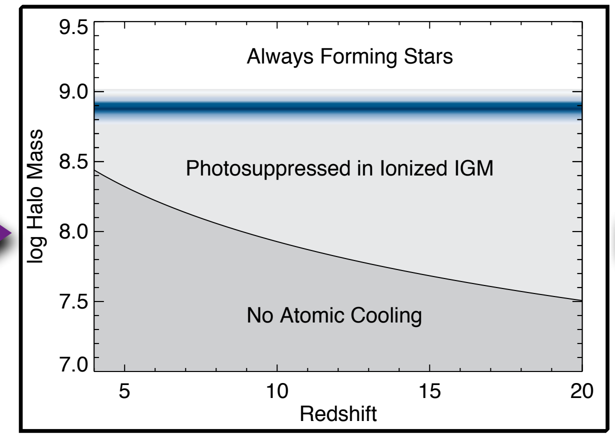
Uses the IDL implementation of emcee (Foreman-Mackey+13), translated by Russell Ryan, with the affine-invariant ensemble sampler

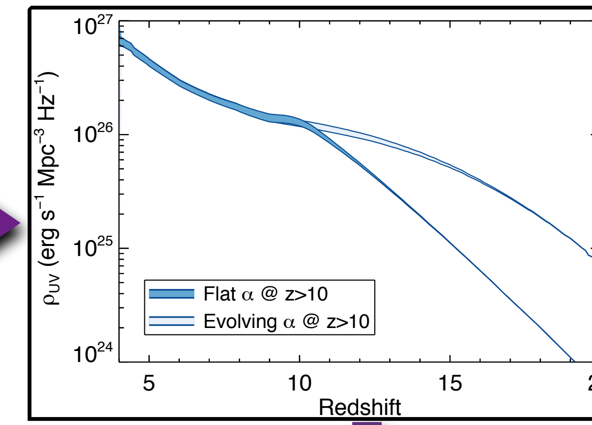
Assume a set of:

M_{supp}, $d\xi/dz$, $d\xi/dm$, $f_{esc\ scl}$, $z_{agn\ max}$, $f_{esc\ AGN}$, AGN_{slope}.

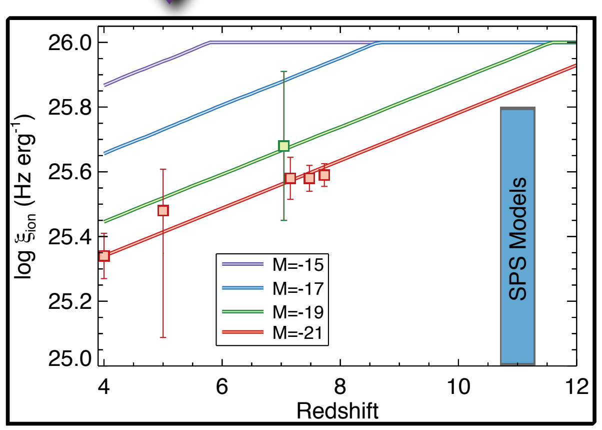


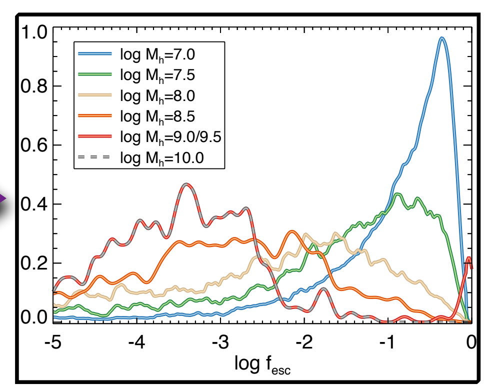






MCMC

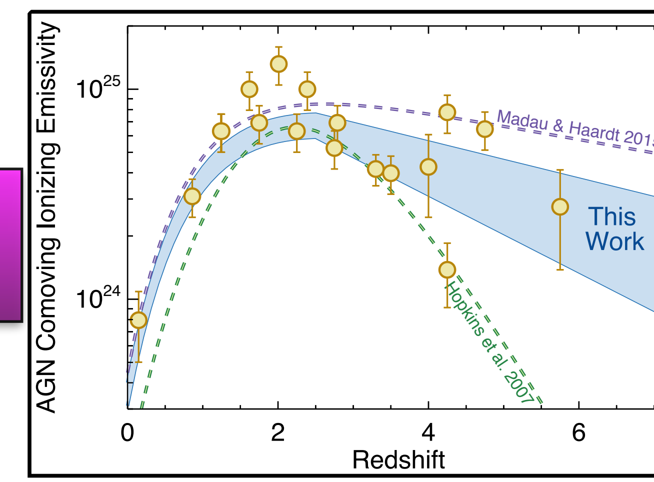




Galaxy Ionizing Emissivity

+

AGN Ionizing Emissivity



Total Ionizing Emissivity

Solve this ODE to calculate $Q_{HII}(z)$ (and also $Q_{HeIII}(z)$), and then calculate τ_{es}.

$$\dot{Q}_{HII} = \frac{\dot{n}_{ion}}{\langle n_H \rangle} - \frac{Q_{HII}}{t_{rec,H}}$$

<u>Calculate likelihood:</u>

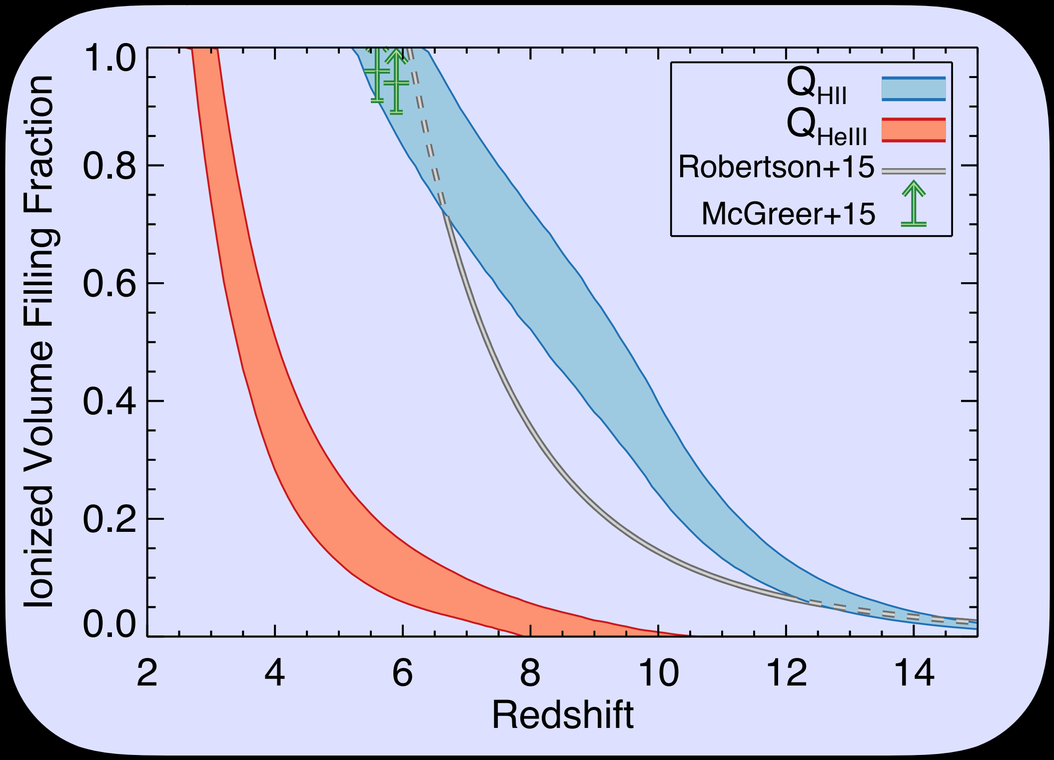
1) $\dot{N}_{total}(z=4.0,4.75)$ vs Becker & Bolton 2013

2) $Q_{HII}(z=5.6,5.9)$ vs McGreer+15

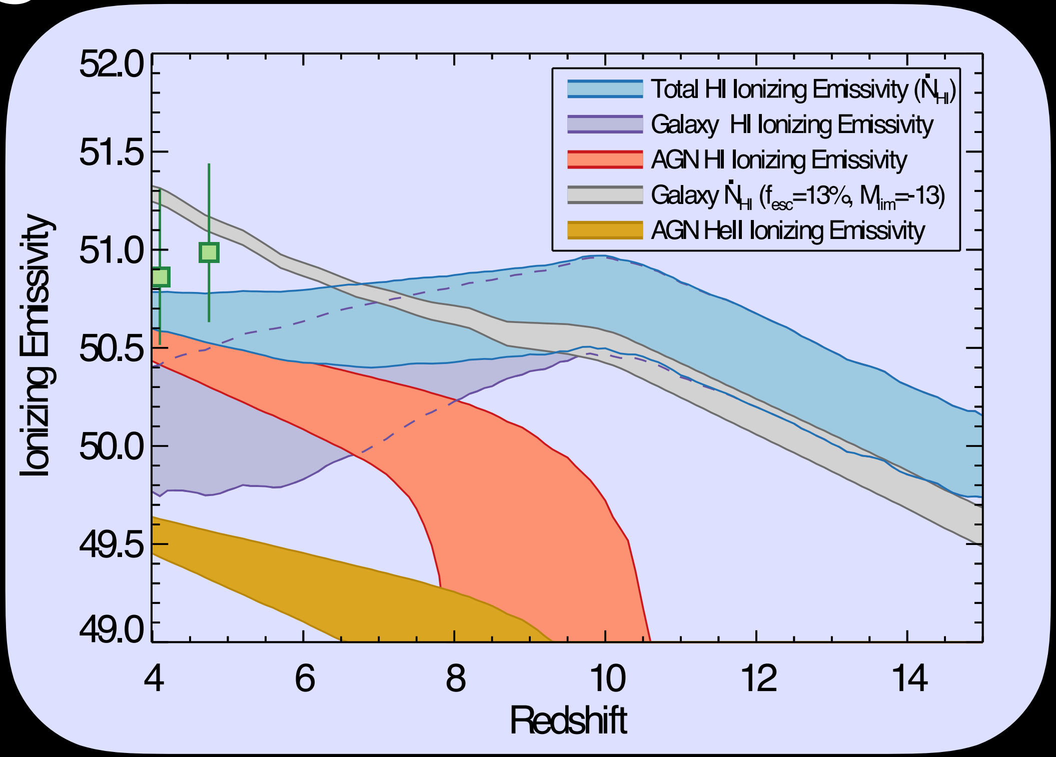
3) τ_{es} vs Planck 2015 measurement

Finkelstein+17, in prep

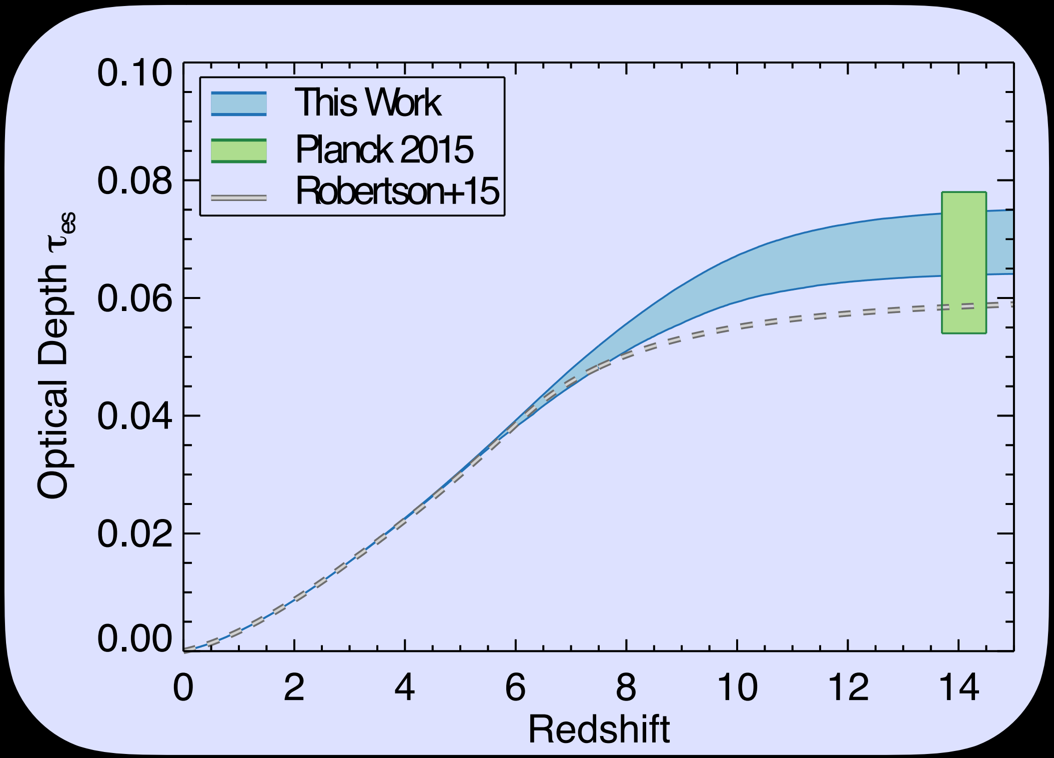
RESULTS



H reionization (blue) completes by z~6, in agreement with observational limits. It is more extended than previous models (50% ionized at z~9, rather than z~8 for Robertson+15). HeII reionization (red) completes by z~3.

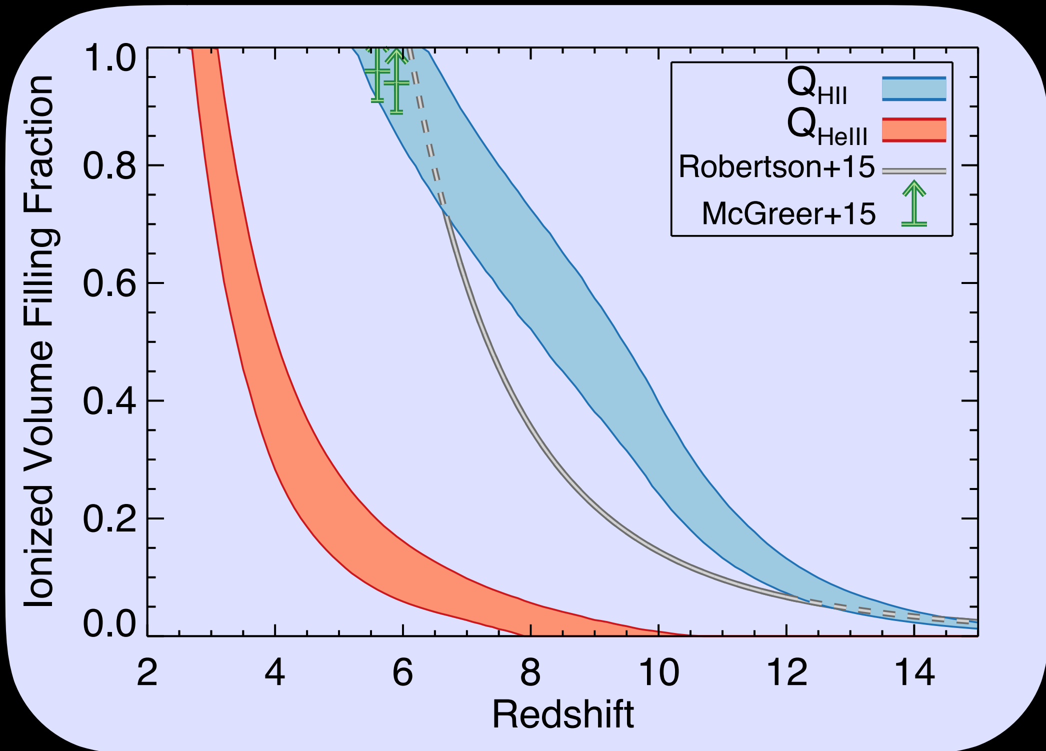


Total emissivity (blue) matches observations. AGNs (red) begin to dominate emissivity over galaxies (purple) at z < 6.



CMB optical depth also a good match, more at the upper end of the allowable range than Robertson+15.

RESULTS



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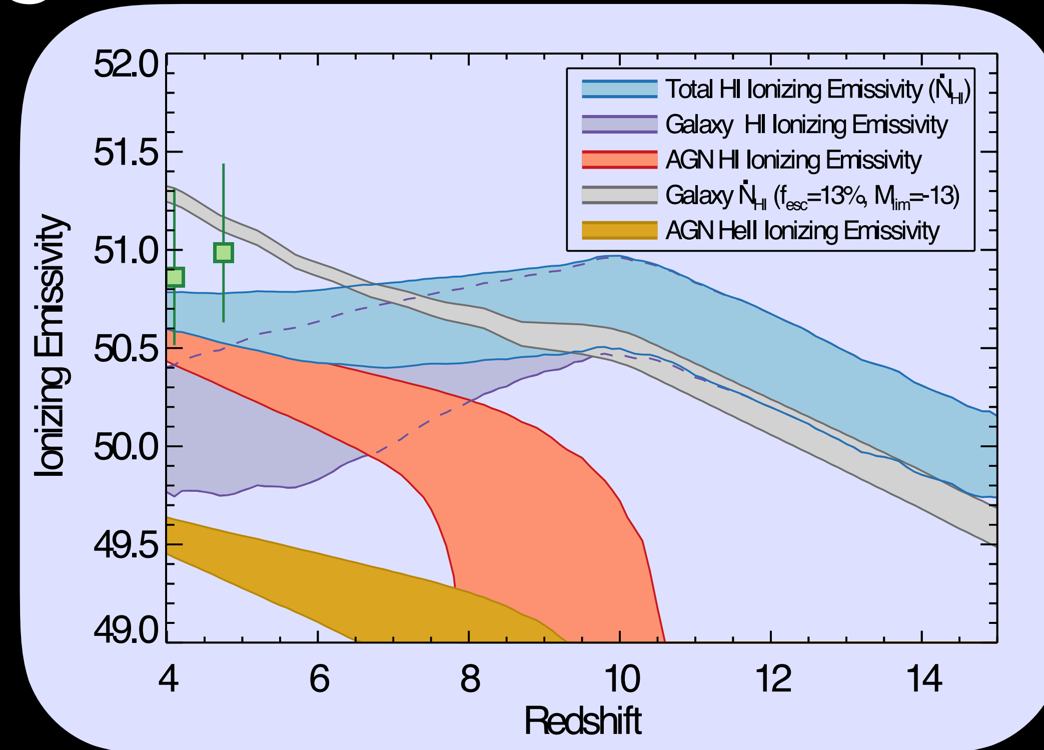

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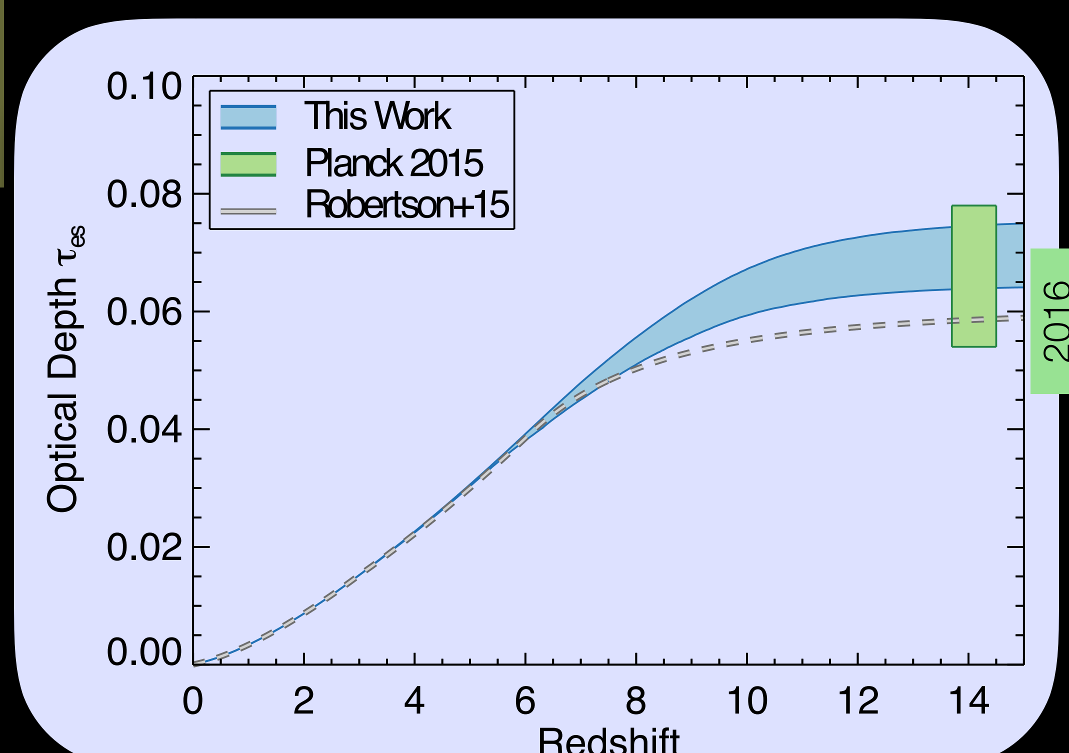
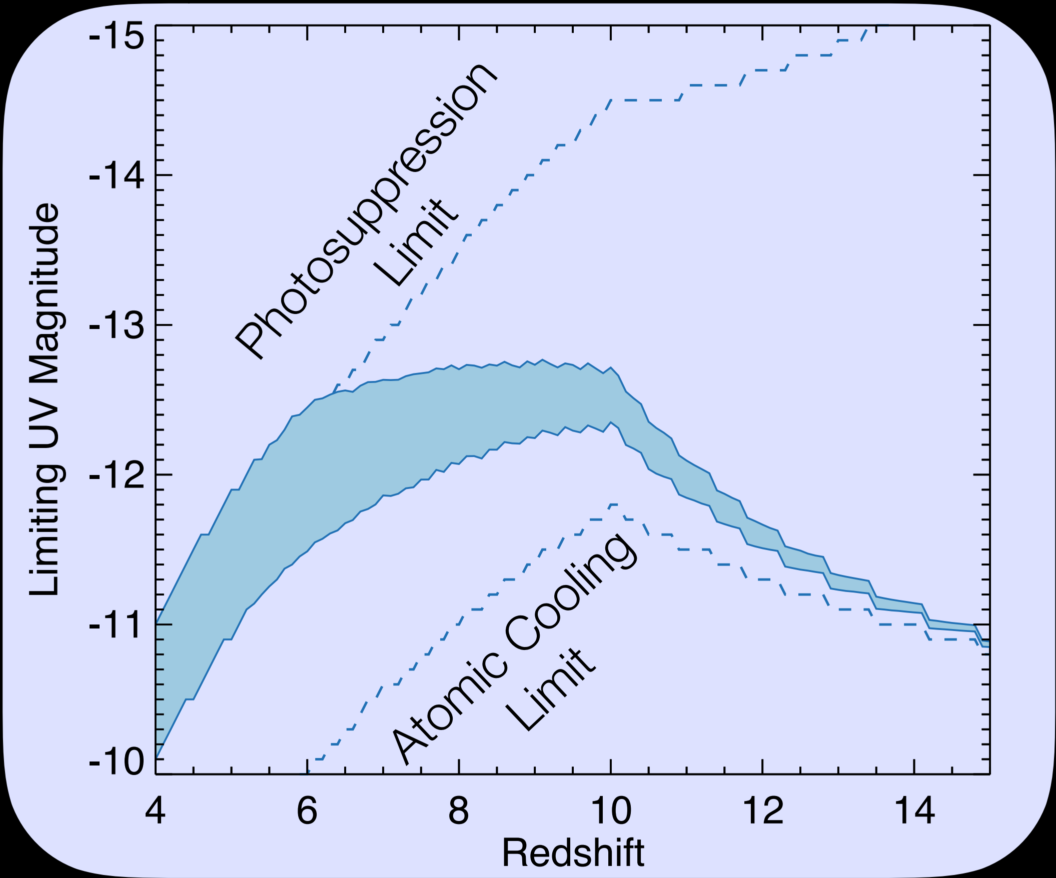
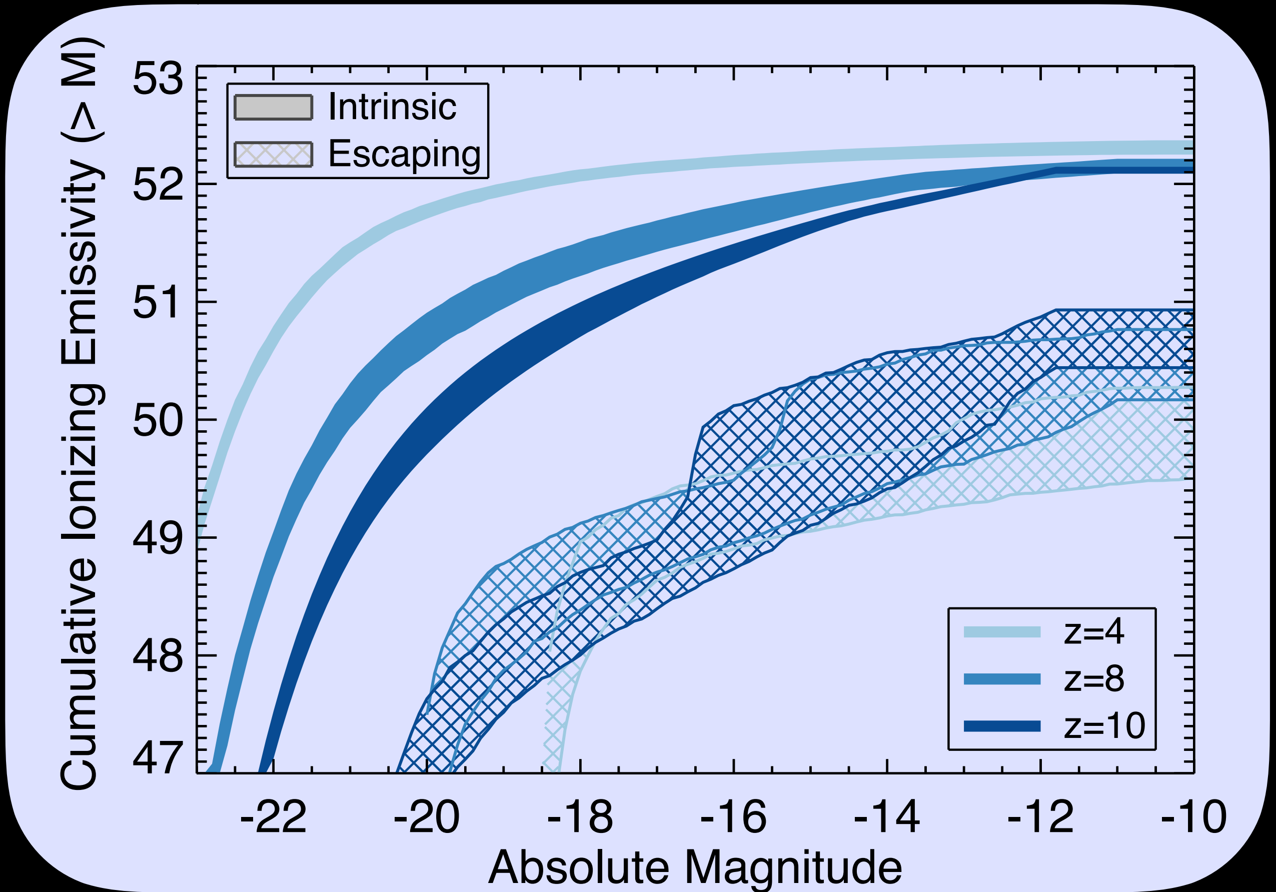


CMB optical depth also a good match, more at the upper end of the allowable range than Robertson+15.

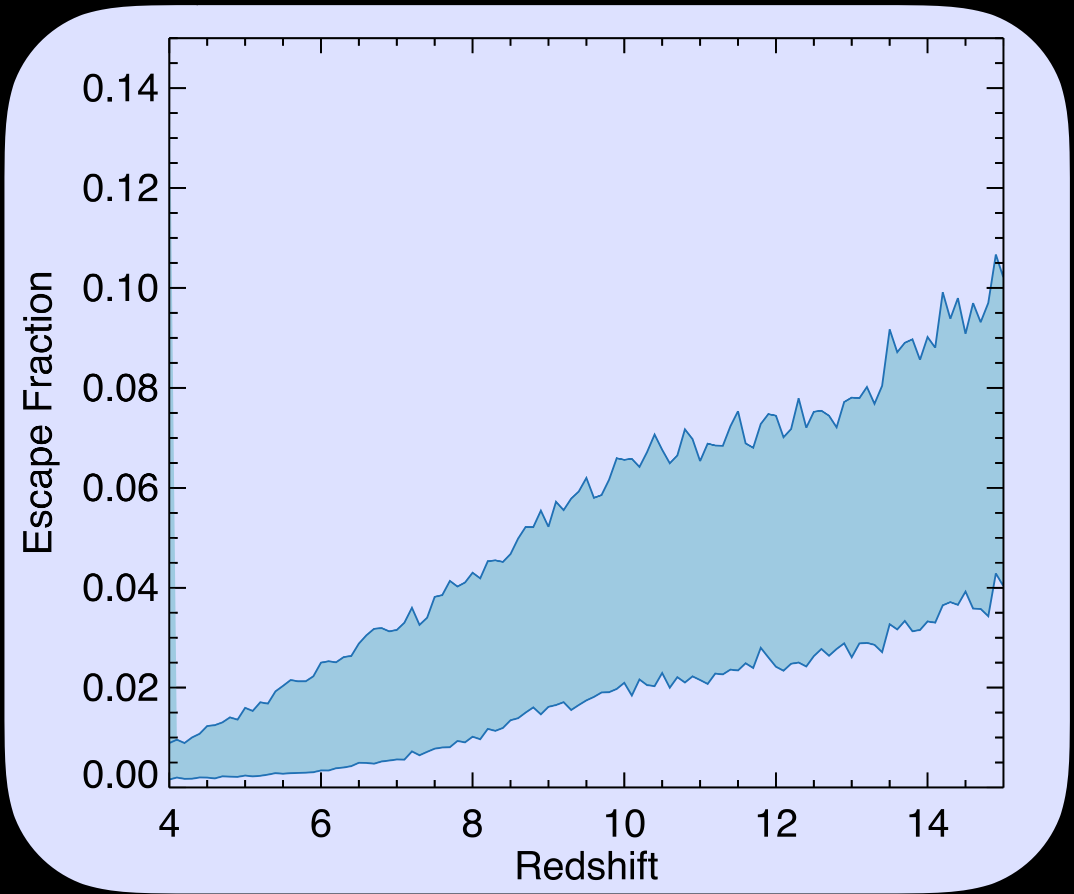
Effective limiting magnitude is always fainter than -13.

RESULTS





The steeper faint-end slope with increasing redshift, combined with the evolution of the halo mass function, means that z=10 galaxies emit *more* ionizing photons that z=4 galaxies, even though their non-ionizing specific UV luminosity is lower.



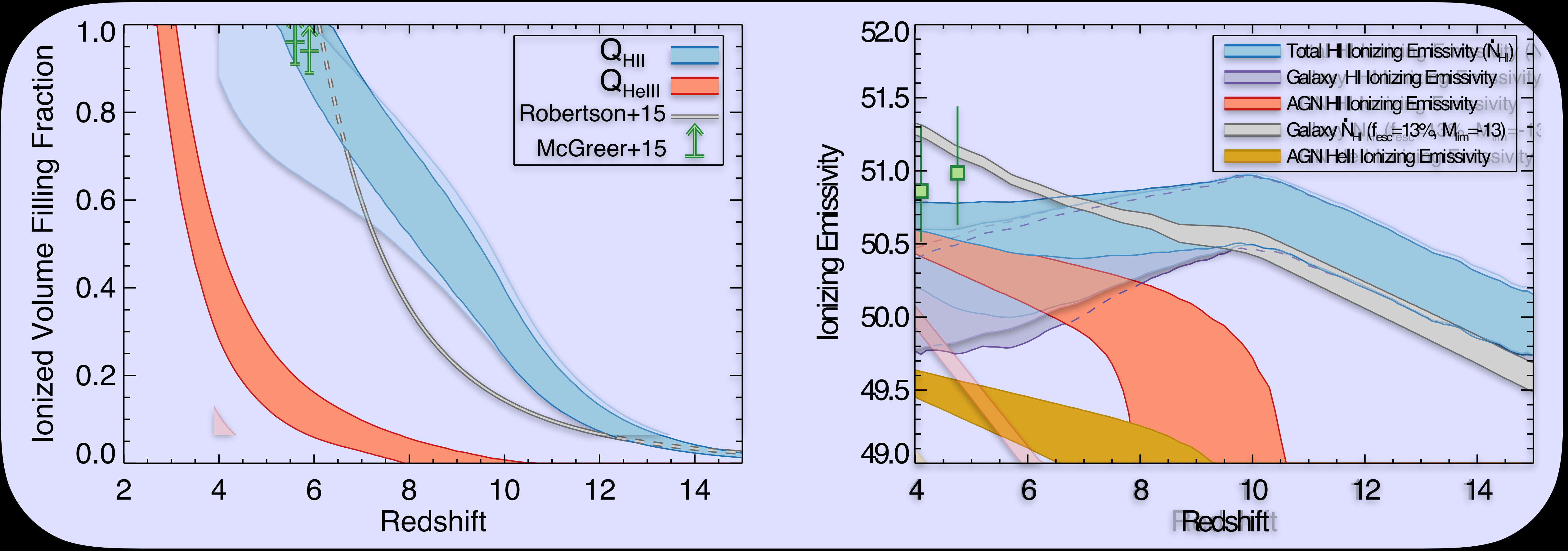
The *average* escape fraction (total number of escaping ionizing photons divided by total number created), does evolve with redshift, but is <5% at z < 10.

TOO MANY PARAMETERS?

- We tested whether all free parameters were required by running our MCMC algorithm for a variety of scenarios keeping some parameters fixed, with both a flat and evolving faint-end slope (at $z > 10$). We found that the model with the full set of seven parameters with a constant faint-end slope at $z>10$ was strongly preferred compared to all alternative scenarios.

BACK TO THE QUESTION AT HAND: WHAT REIONIZED THE UNIVERSE?

- Our model included both galaxies and AGNs. Which was more important?
  - Lets compare to a run of the model with "no" AGN (AGN are truly there, but assigned according to the Hopkins+2007 steep evolutionary slope).



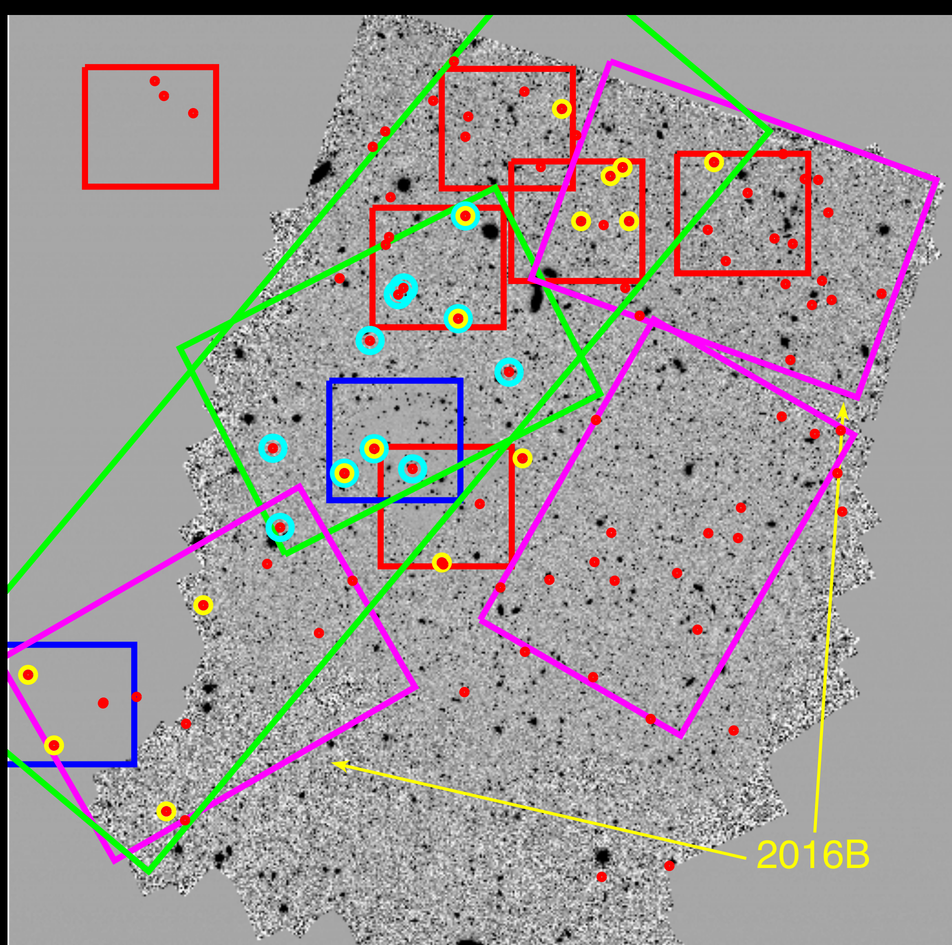
Conclusion: ***If*** these escape fractions have some basis in reality, galaxies can still accomplish the bulk of reionization, but they probably need a little help from AGN/QSOs at the end to finish things by z~5.5-6.

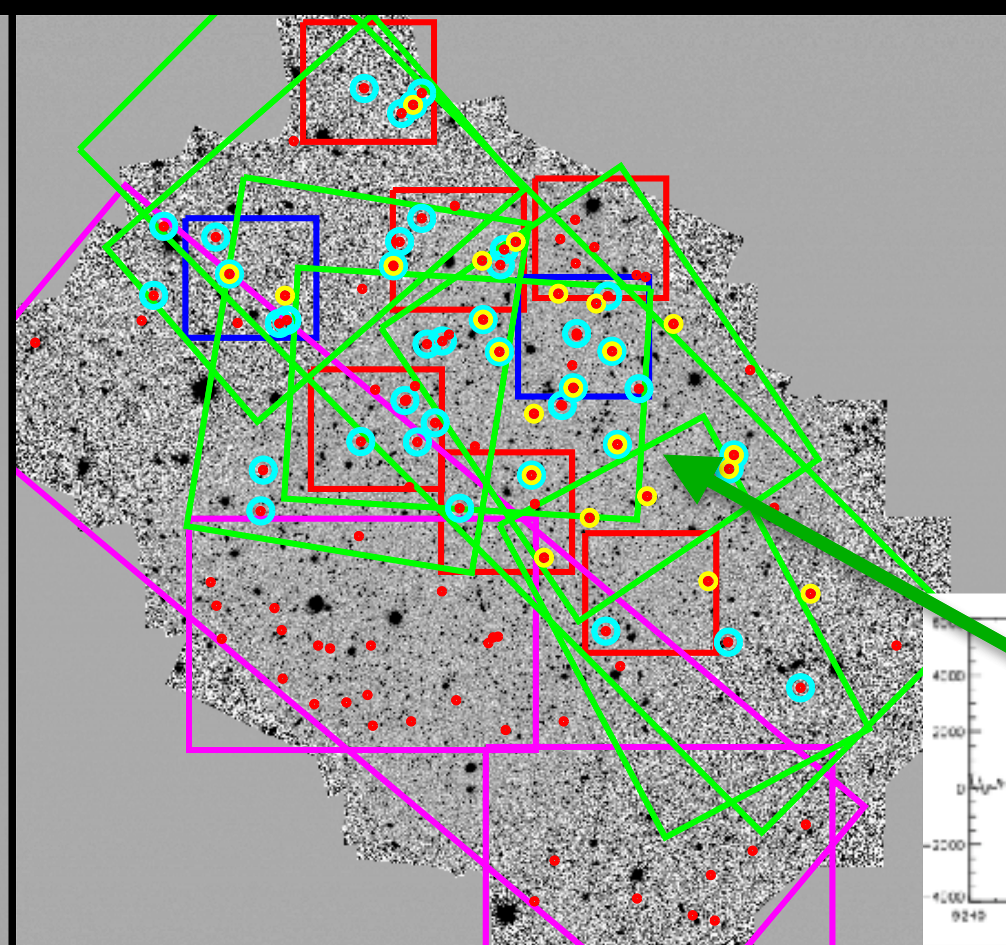
BETTER OBSERVATIONAL CONSTRAINTS CAN TIGHTEN UP THIS MODEL

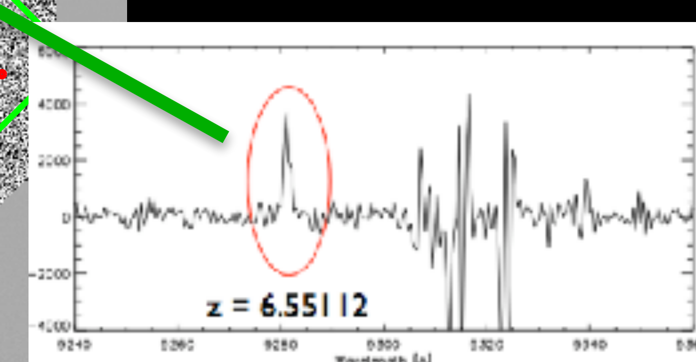
- While we're unlikely to see a new CMB satellite fly soon, measurements from quasars can continue to improve constraints on $\dot{N}(z)$ and $Q_{HI}(z)$.
  - Would be great to push these measurements to $z > 6$, but requires a significant increase in $z > 6.5$ quasars.
- A complementary probe of the IGM is available from Lyα emission from galaxies. While Lyα is nearly ubiquitous at $z\sim6$, it should start to be much more difficult to observe as the IGM grows more neutral.

LYMAN ALPHA AS A PROBE OF REIONIZATION

- While there has seemingly been a dearth of Lyα detections at z > 6.5, the observed samples have been relatively small, and there have been some notable exceptions (z=7.5, 7.7, 8.7 from Finkelstein+13, Oesch+15, Zitrin+15).
    - We in the midst of the first magnitude limited survey for Lyα in the epoch of reionization, using ~20 nights of Keck DEIMOS+MOSFIRE observations (primarily through NASA).

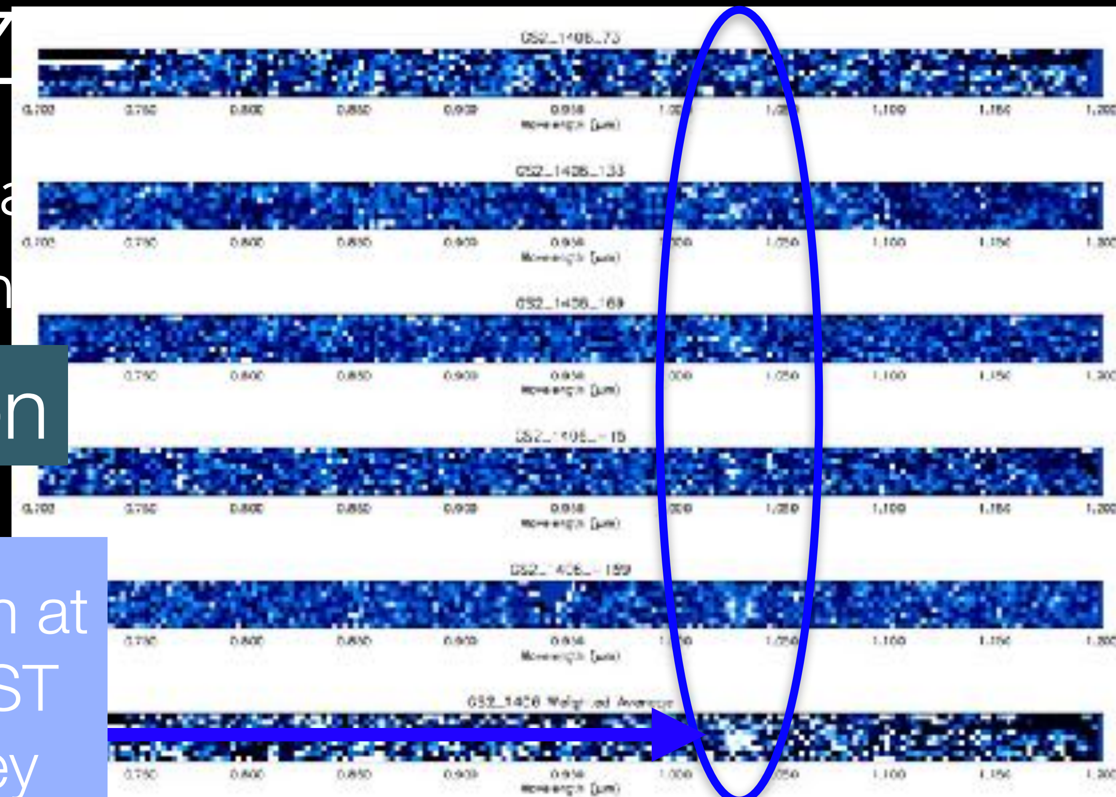






ALPHA AS A PROBE OF

Rebecca Larson



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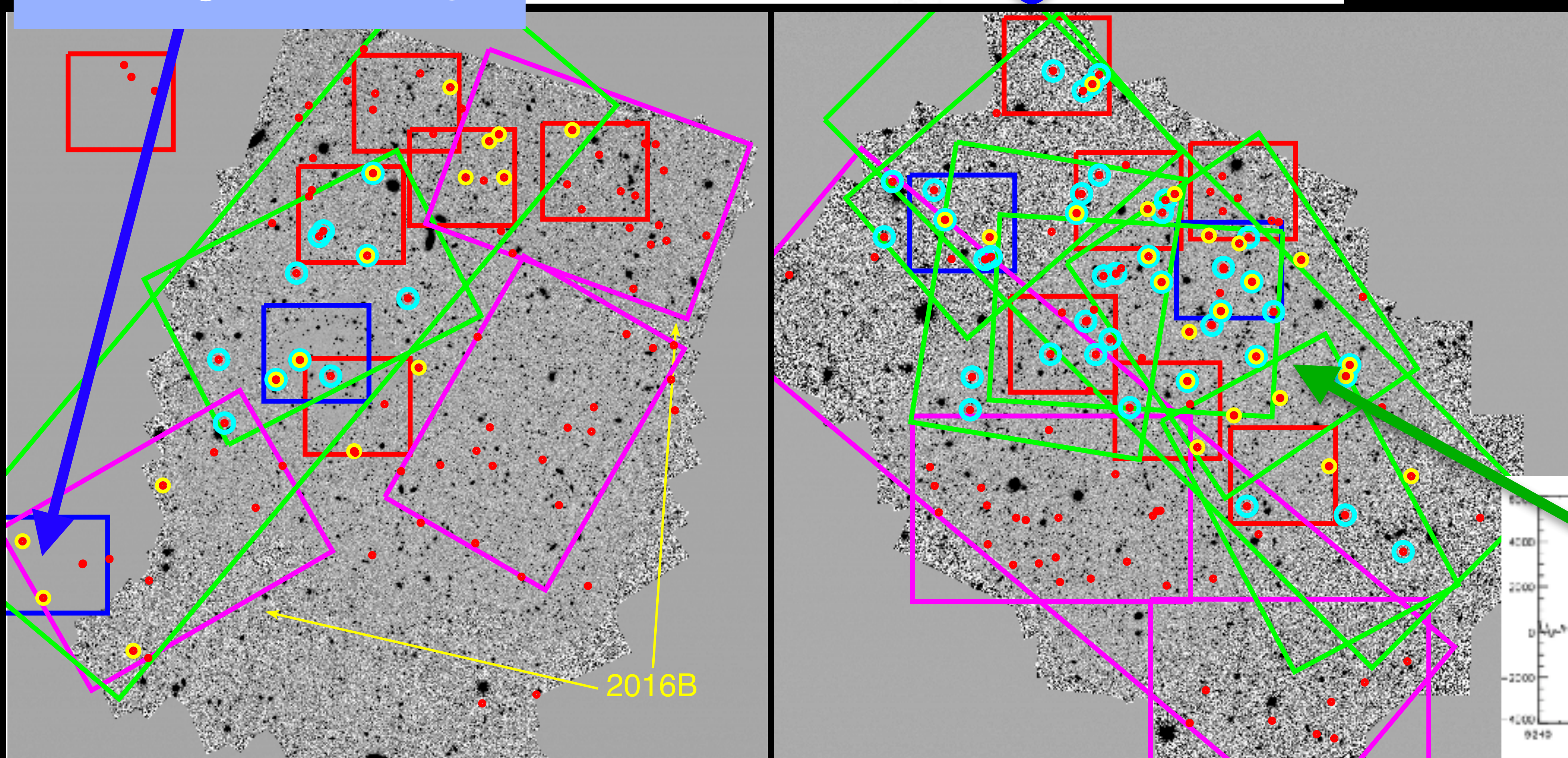
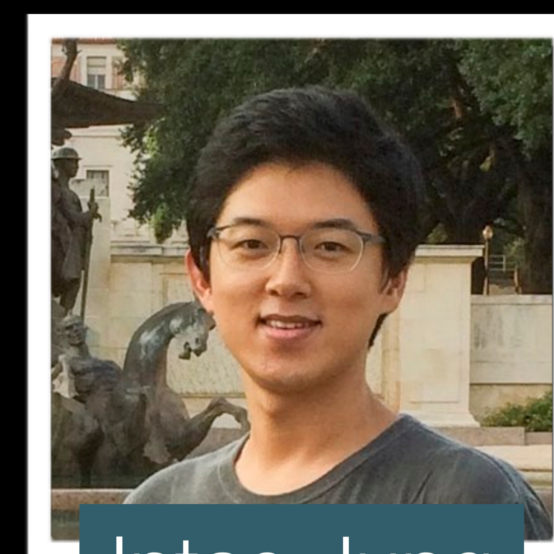
here have been some
+13, Oesch+15, Zitrin+15).

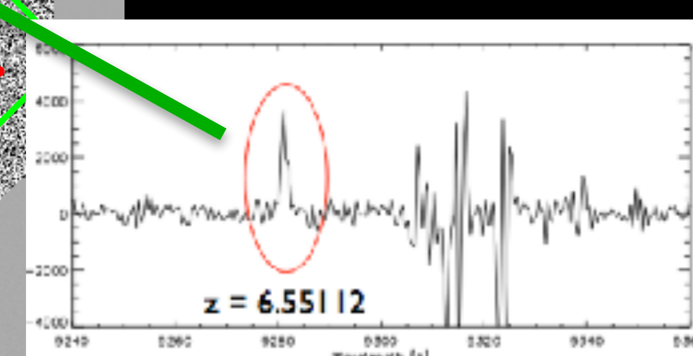
urvey for Lyα in the epoch
DS+MOSFIRE observations

Likely Lyα emission at z=7.4 from the HST FIGS grism survey





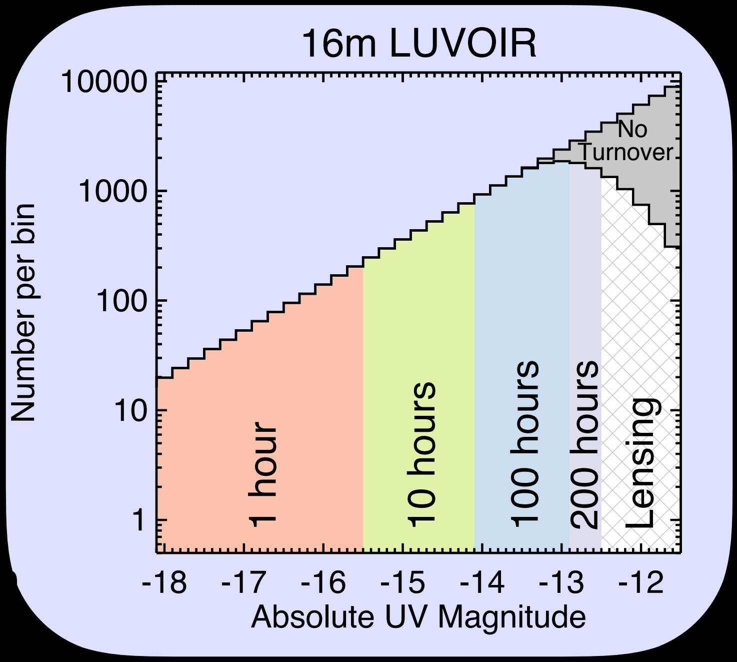
Intae Jung



IMPROVEMENTS WITH THE NEXT NASA FACILITIES

- JWST: Spectroscopic confirmation in *minutes* of many sources via strong [OIII] emission; understanding ionizing environment via rest-UV emission lines; push faint-ward of M=-13 with lensing.
    - Some improvement in Lyα, but JWST throughout at <1.3μm isn't great.

- WFIRST: Pushing for addition of a blue grism (0.9-1.35 μm), to allow spectroscopy over a field ~100X larger than WFC3/IR, ultimately potentially mapping ionized bubbles in Lyα.
- LUVOIR: Get close to the expected turnover in the UV luminosity function ***without lensing***, see progenitors of MW faint companions with lensing.



TAKE-AWAY POINTS

- Going from observations of galaxies to their contribution to reionization is not straightforward, and previous assumptions were not all that physically motivated.
- It is possible for galaxies to accomplish the bulk of reionization with small escape fractions if:
  - the galaxy luminosity function evolves smoothly at z=6-15
  - galaxies become more proficient at making ionizing photons
- Even then, a stronger-than-expected contribution from AGNs at z=4-6 may be necessary to complete reionization "on time".