# Early Star Forming Galaxies and Cosmic Reionization

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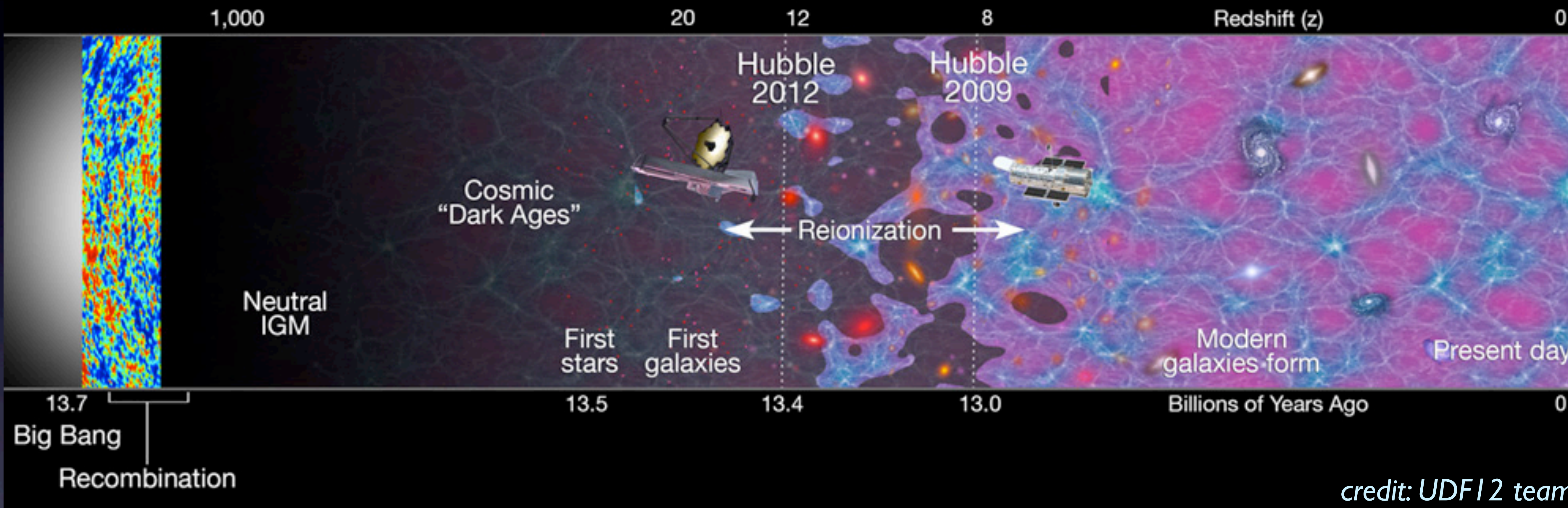
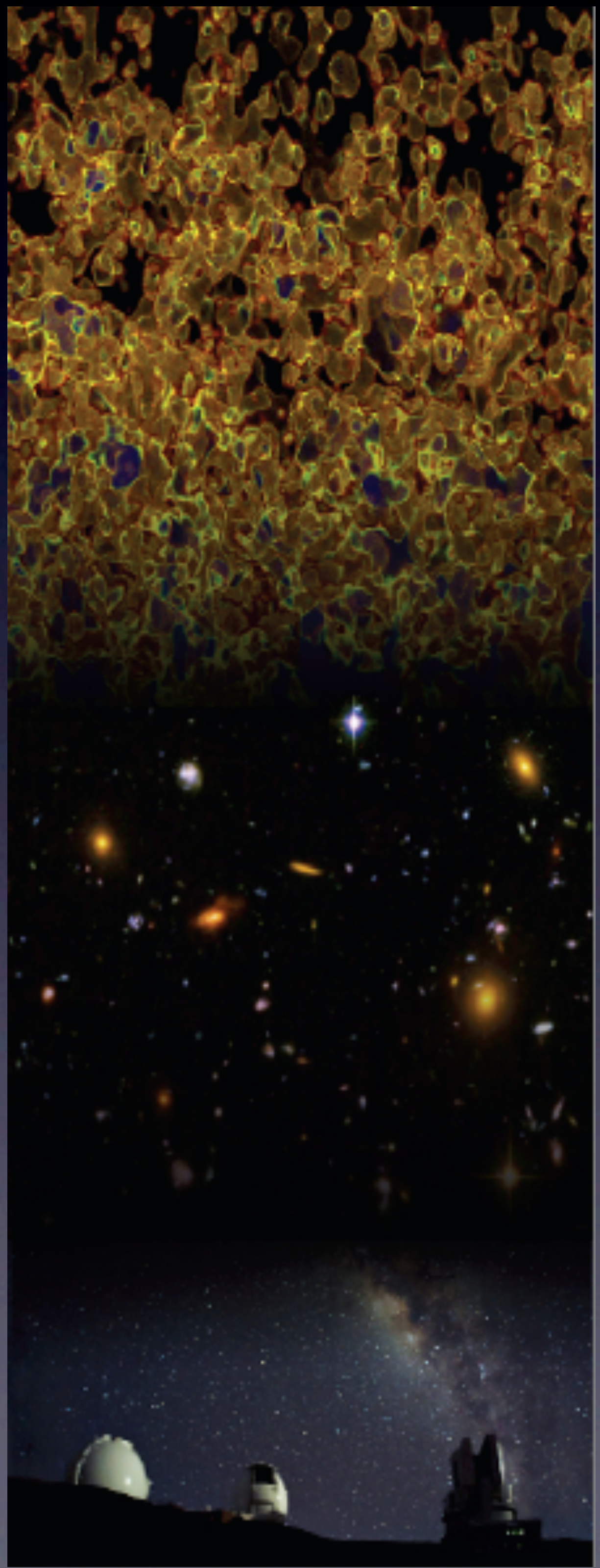
# Cosmic reionization: the latest frontier




- One of few remaining unobserved periods of cosmic history
- Promises insight into the first generation of stars/galaxies
- Major science driver for future observations (JWST, GSMT, SKA)

# The Big Questions

- When did reionization occur?
  - Begins early (WMAP/Planck optical depth)
  - Highly ionized IGM at z<6 (quasars)



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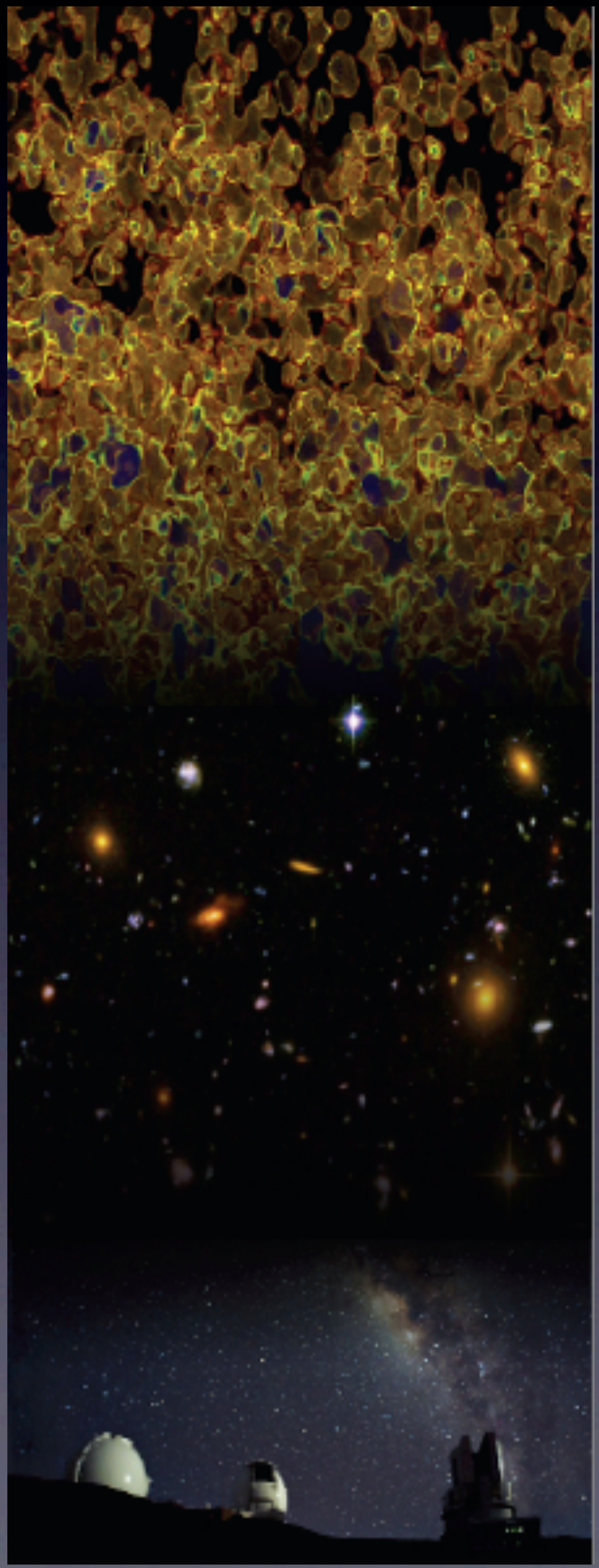
  - Can star forming galaxies drive process?



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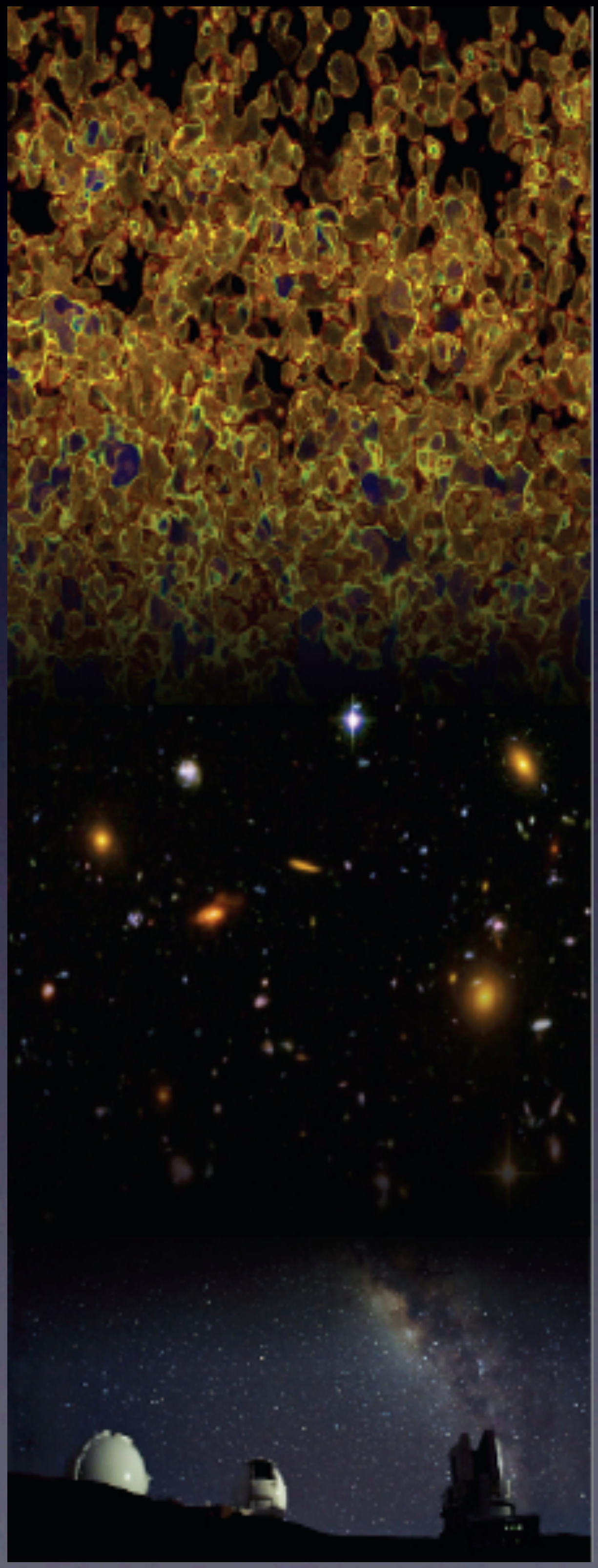

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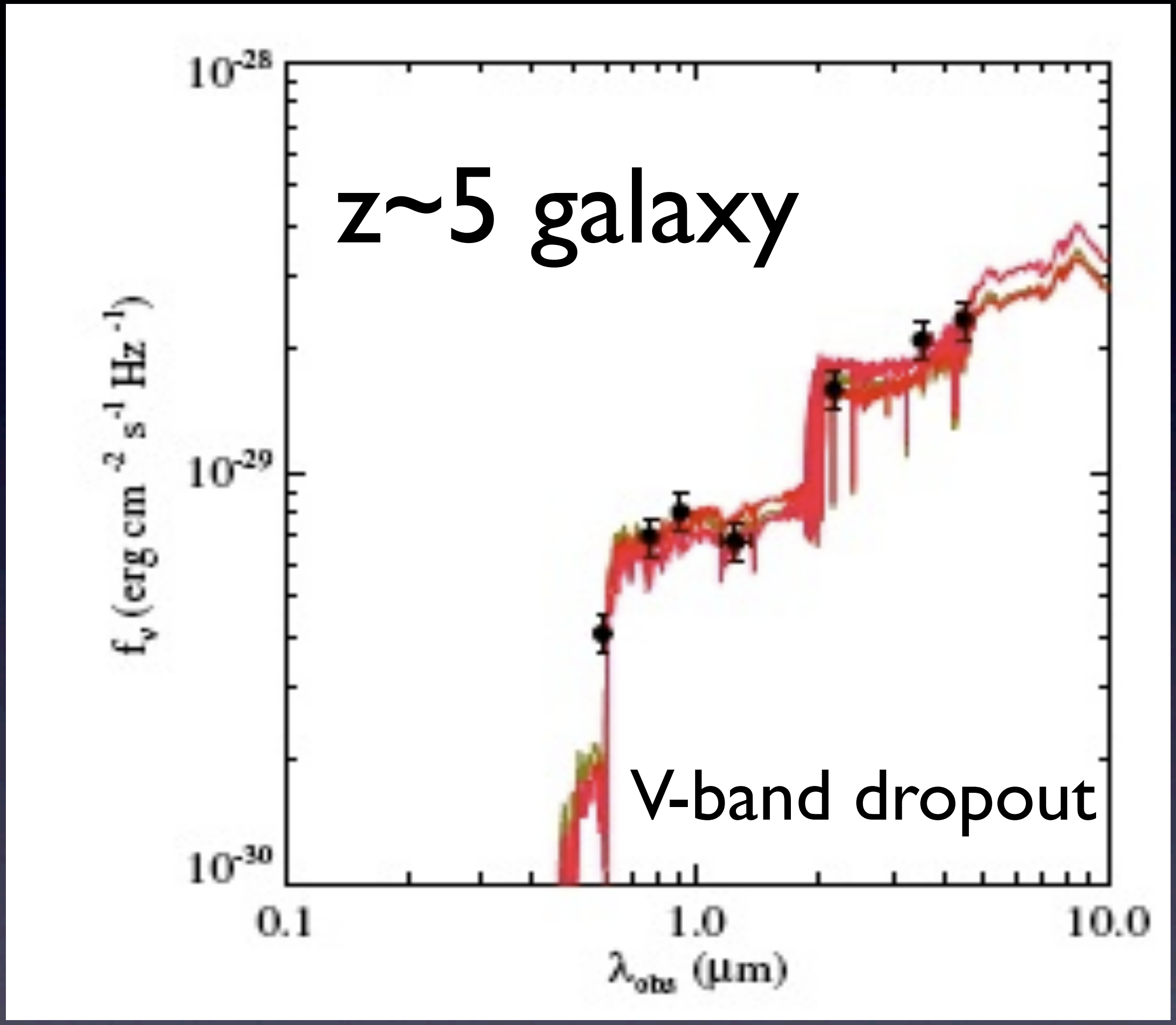
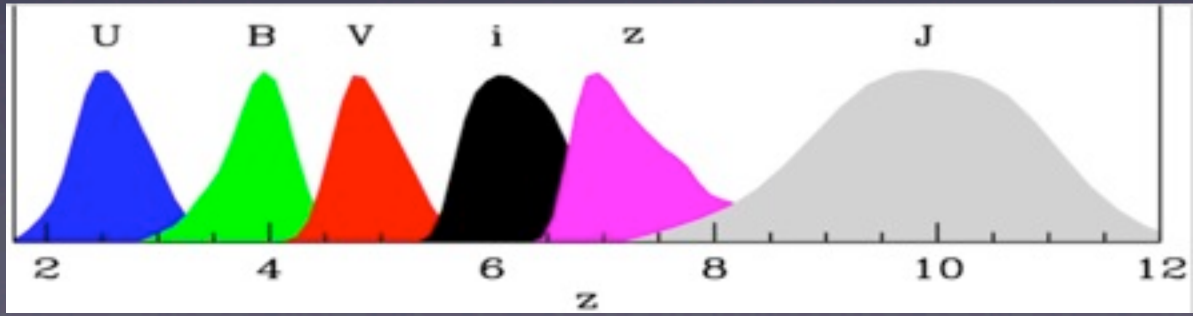
  - Can star forming galaxies drive process?
- Early galaxy assembly
  - Evolution UV + stellar mass functions (now)
  - Early chemical enrichment (near future)

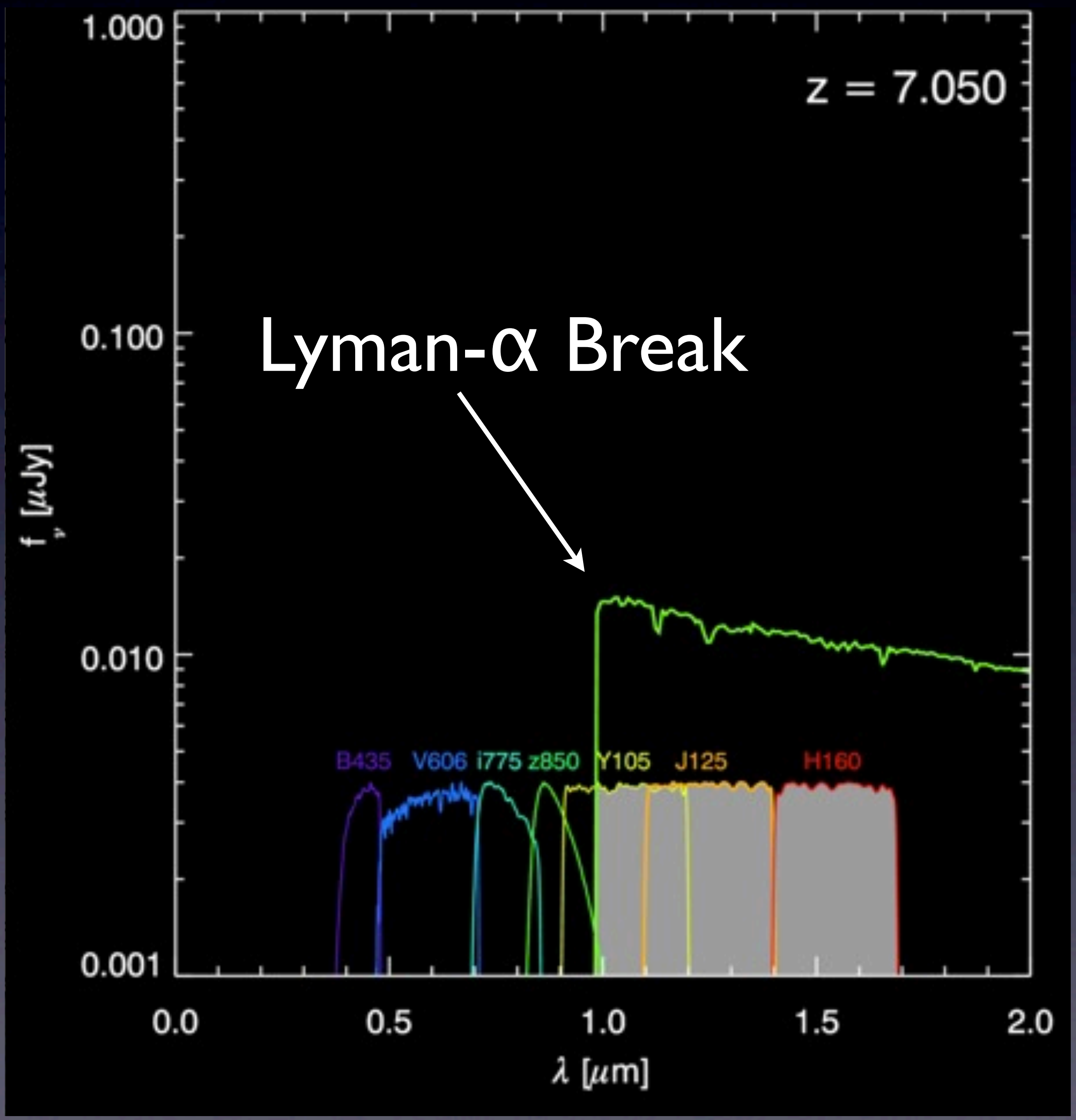
# Locating Early Galaxies




- Between 3<z<6, Lyman break shifted into optical window.
- 4000+ z~4, 1000+ z~5, 600+ z~6, UV-continuum selected galaxies from HST imaging surveys.
- To explore reionization era, must extend test to z>7.

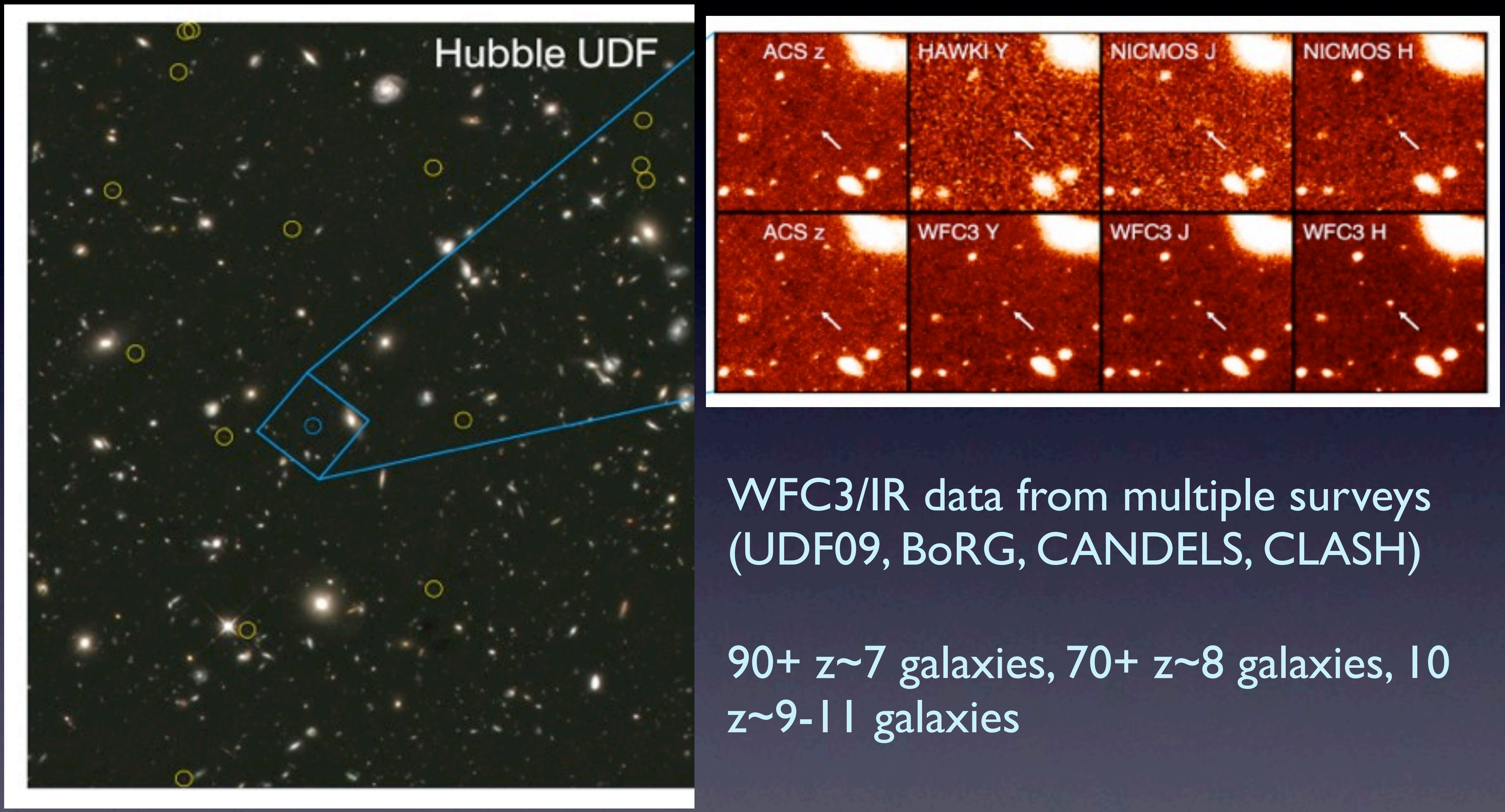
# Extension to z~7 is Difficult




- Just ~200 Myr earlier than z~6, but much more difficult.
- Lyman-α Break redshifted to Y-band (0.97 [1+z/7] μm)
- Requires deep J and H-band imaging for selection.

# Hubble Delivers First Large z>7 Samples

*Robertson et al. 2010*



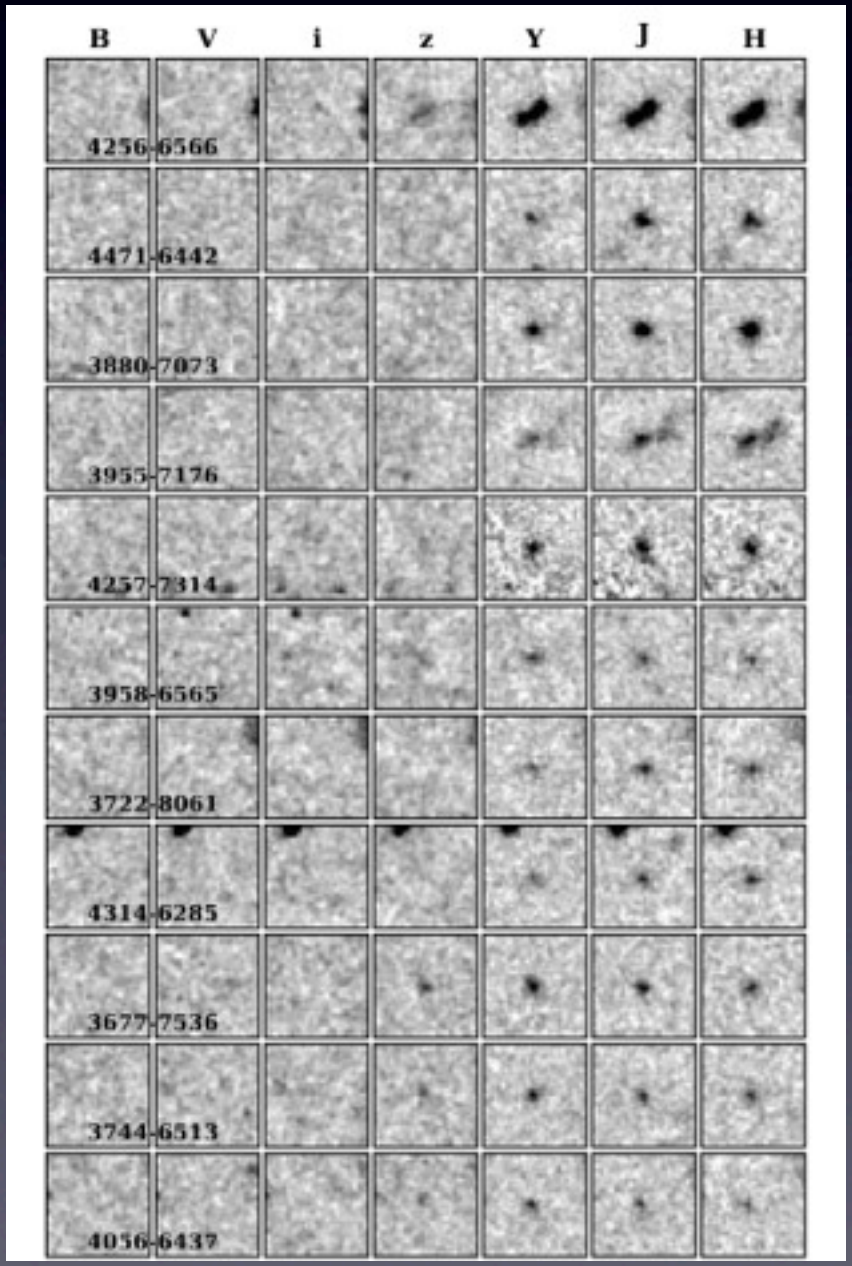

*(e.g., Bouwens et al. 2010, Oesch et al. 2010, Bunker et al. 2010, McLure et al. 2010, Finkelstein et al. 2010, Yan et al. 2010, Wilkins et al. 2010, Trenti et al. 2011, Bradley et al. 2012,+ many more papers)*

WFC3/IR data from multiple surveys (UDF09, BoRG, CANDELS, CLASH)

90+ z~7 galaxies, 70+ z~8 galaxies, 10 z~9-11 galaxies

*First census of star formation in reionization era*

# Examples of z~7 Galaxies in Hubble Ultra Deep Field Imaging




*Oesch et al. 2010*

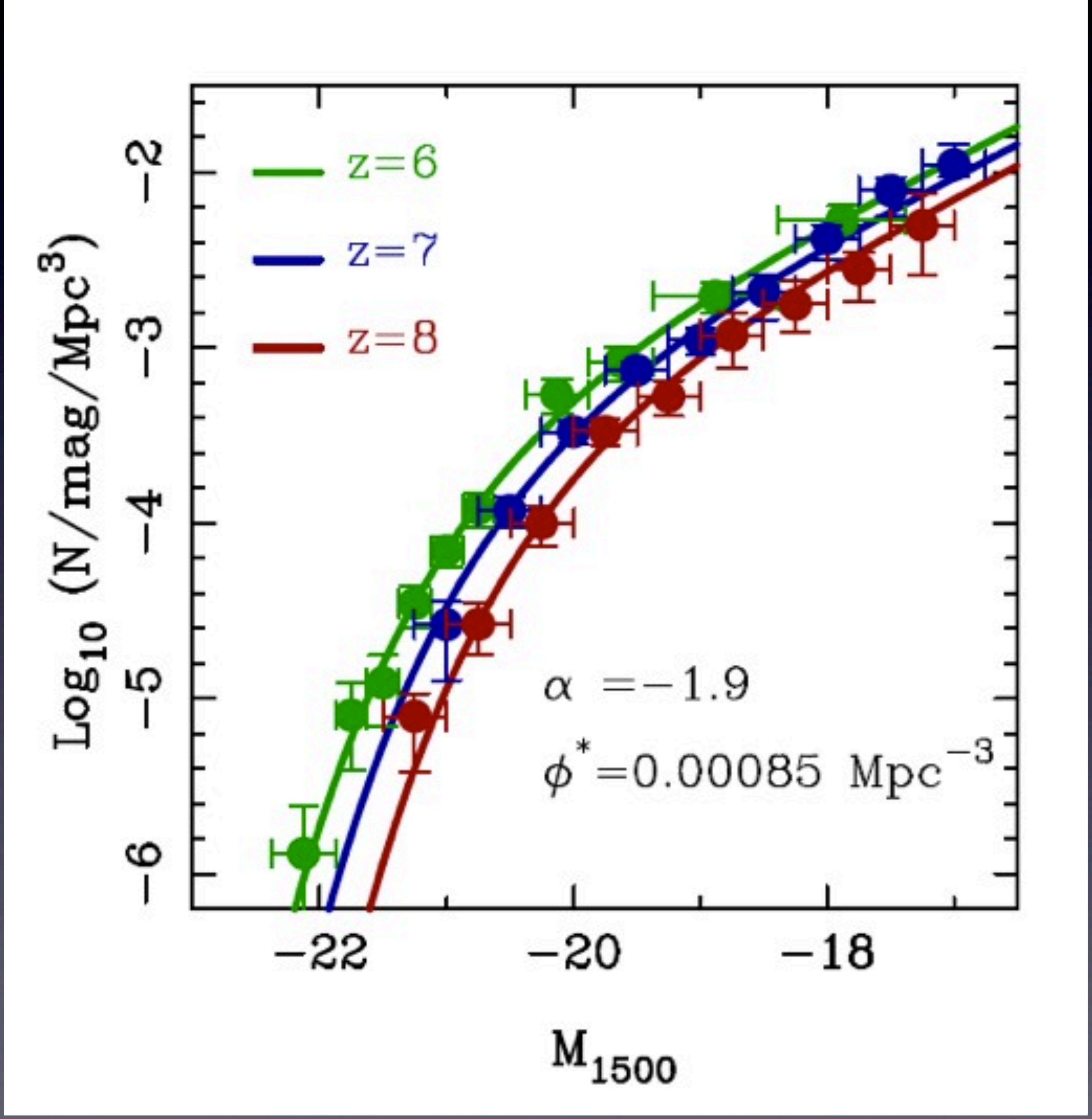
Non-detection in deep optical imaging, confidently detected in near-IR (rest-frame UV) with HST.

Compact in rest-UV (half light radii of 0.3-0.4 kpc).

Photometric redshifts for most of sample, most too faint for spectroscopy.

# UV Luminosity functions

*McLure + DS and UDF12 team, 2013*




L★ galaxy has J~27 and SFR of ~ 9 M⊙/yr.

Steep faint-end slope (α~-1.90+/-0.15).

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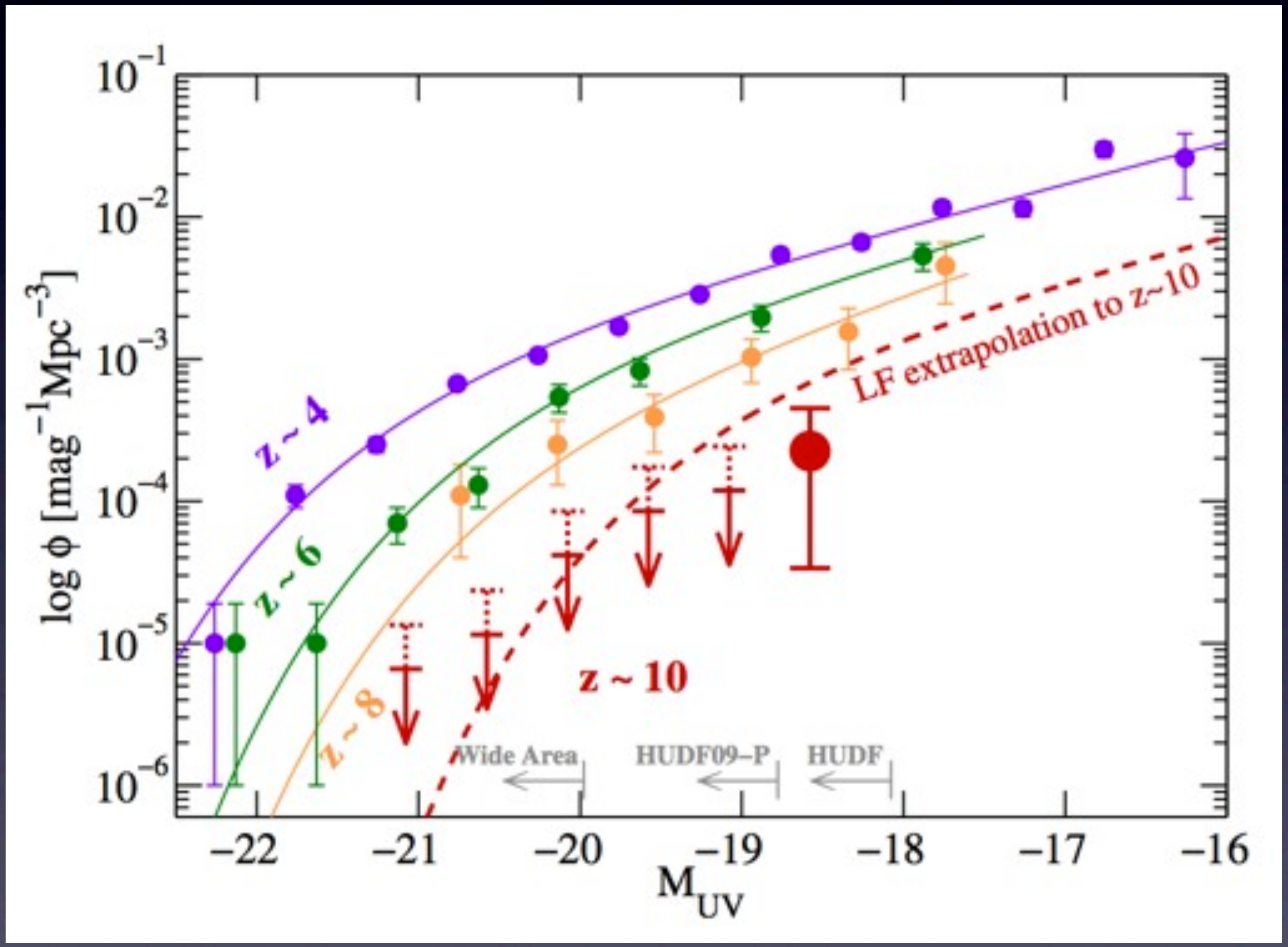
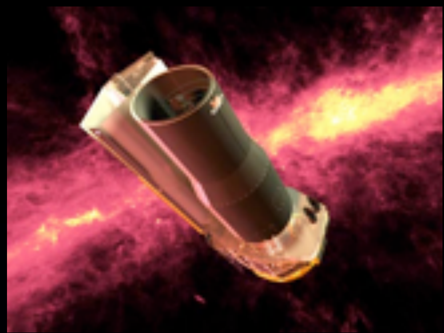



L★ galaxy has J~27 and SFR of ~ 9 $M_\odot$/yr.

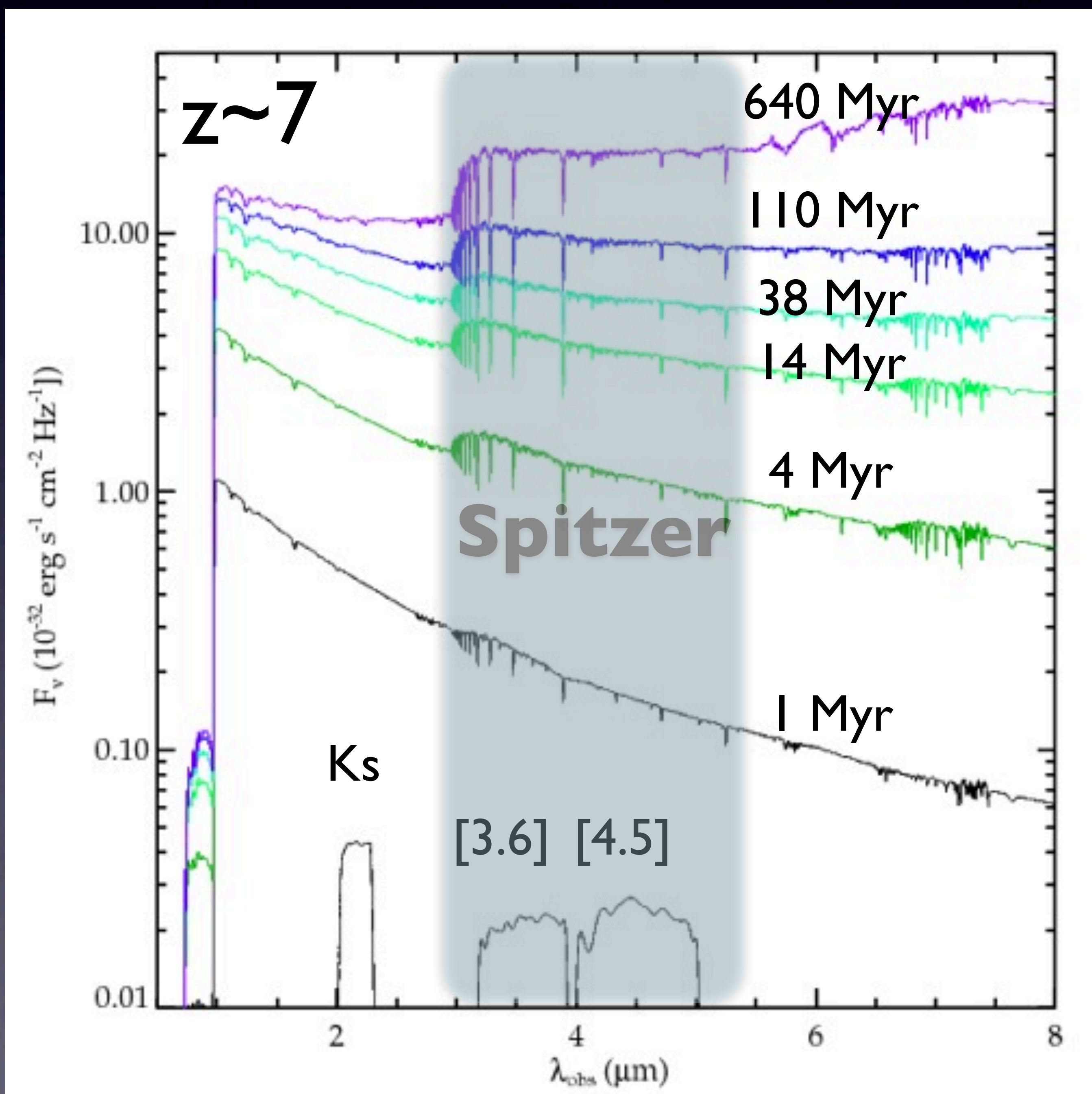
Steep faint-end slope (α~-1.90+/-0.15).

Number density of UV luminous galaxies rapidly decreases at z>4

*UV output at z>7 dominated by low luminosity galaxies*



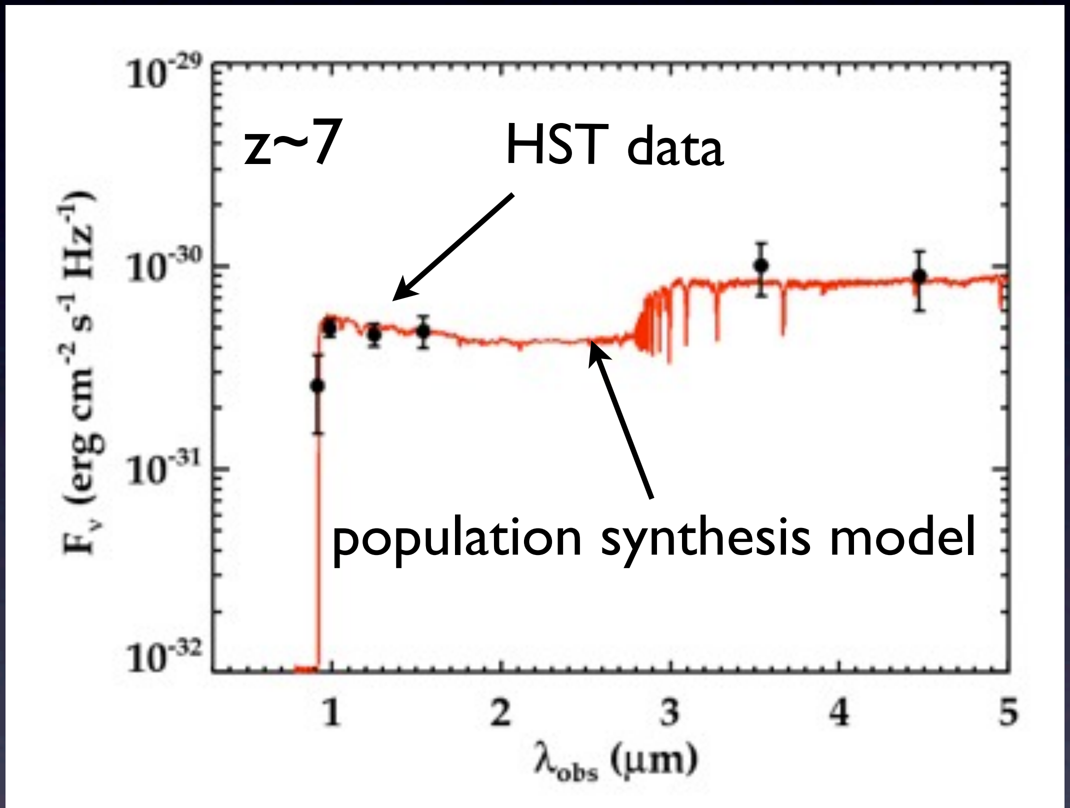
# How much stellar mass already formed in z>7 galaxies?



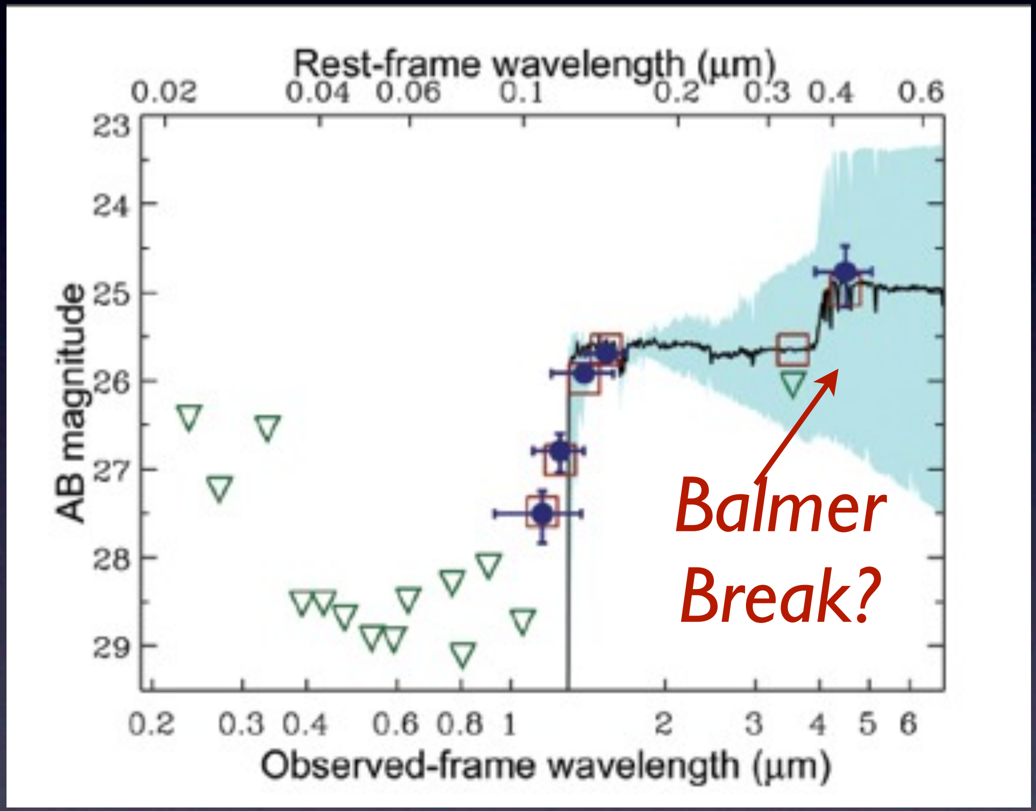

- HST probes rest-UV continuum (light from young massive stars).
- Rest-optical flux necessary to characterize contribution from earlier generations of stars.
- Need Spitzer/IRAC 3.6 and 4.5μm

# Spitzer Detections are Common at z>7

*Stark et al. 2013*



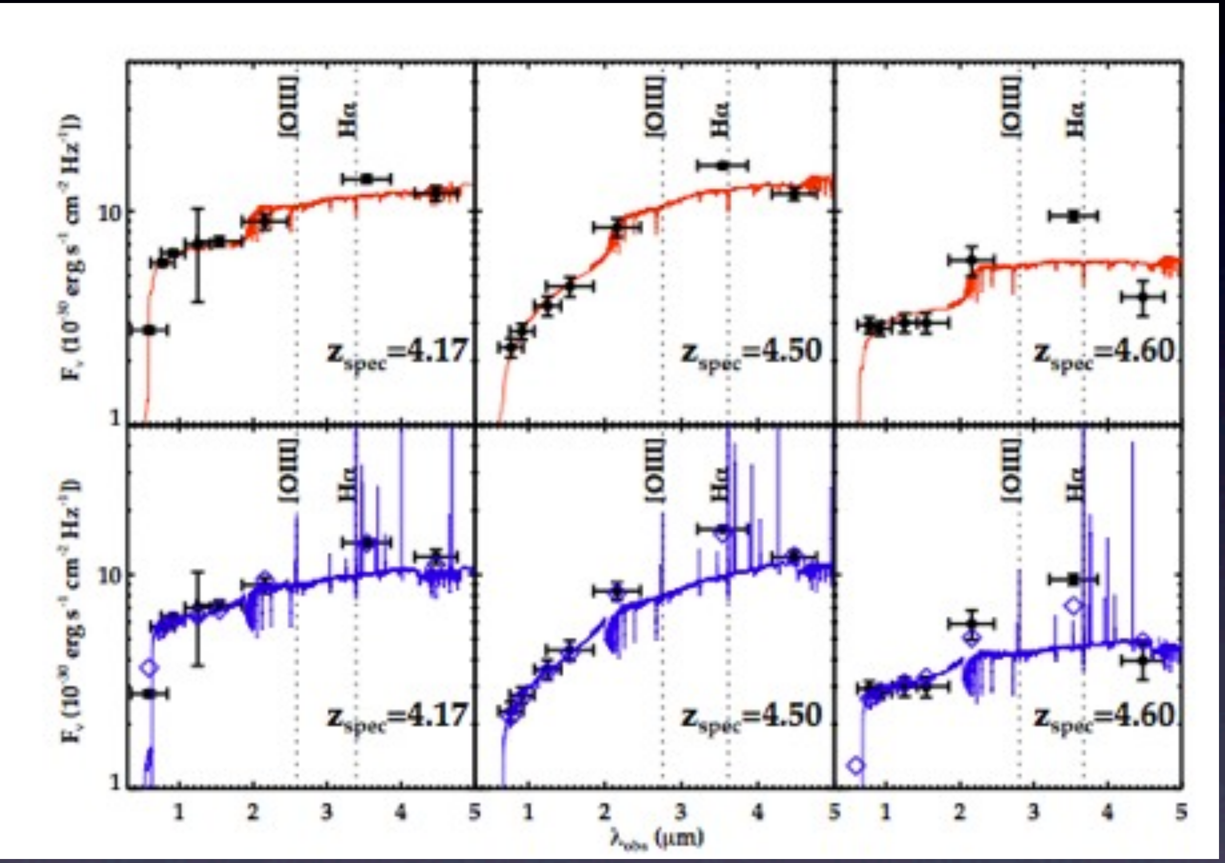

*Zheng et al. 2012*



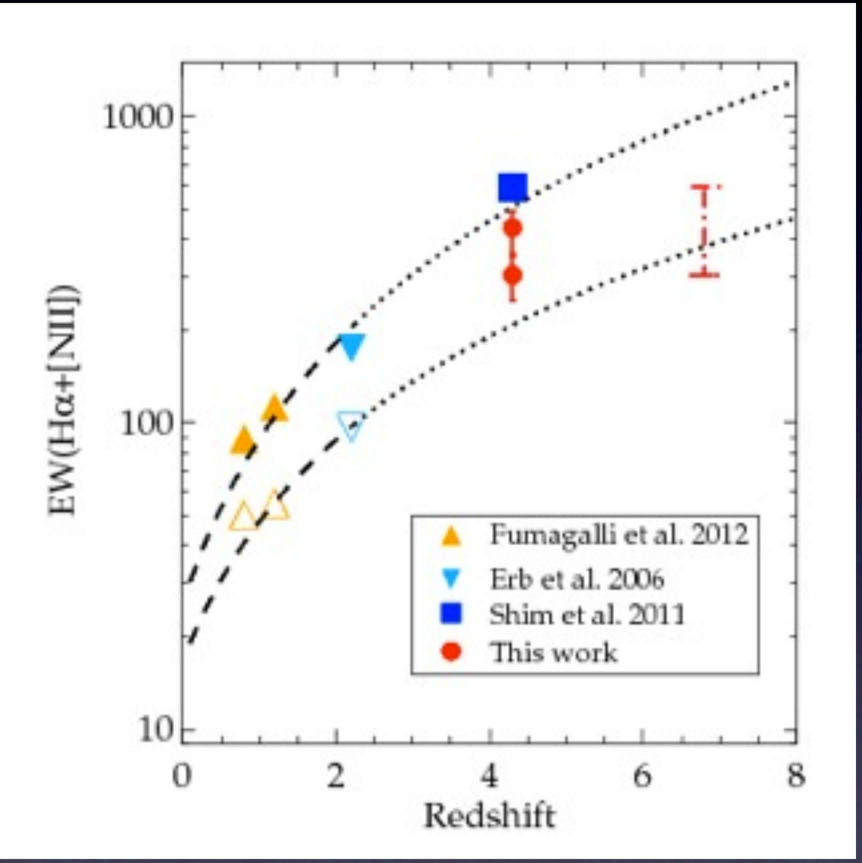

- 2000+ SEDs characterized at 4<z<8 (Stark+07,09,13)
- Stellar masses and SFRs inferred through population synthesis models.

# Emission Lines are Stronger at Higher Redshift

*Stark et al. 2013*




*Stark et al. 2013*




- Median Hα EW of ~300 Å at z~4-5.
- [OIII] + Hβ and Hα expected to contribute ~50% of flux in Spitzer bands

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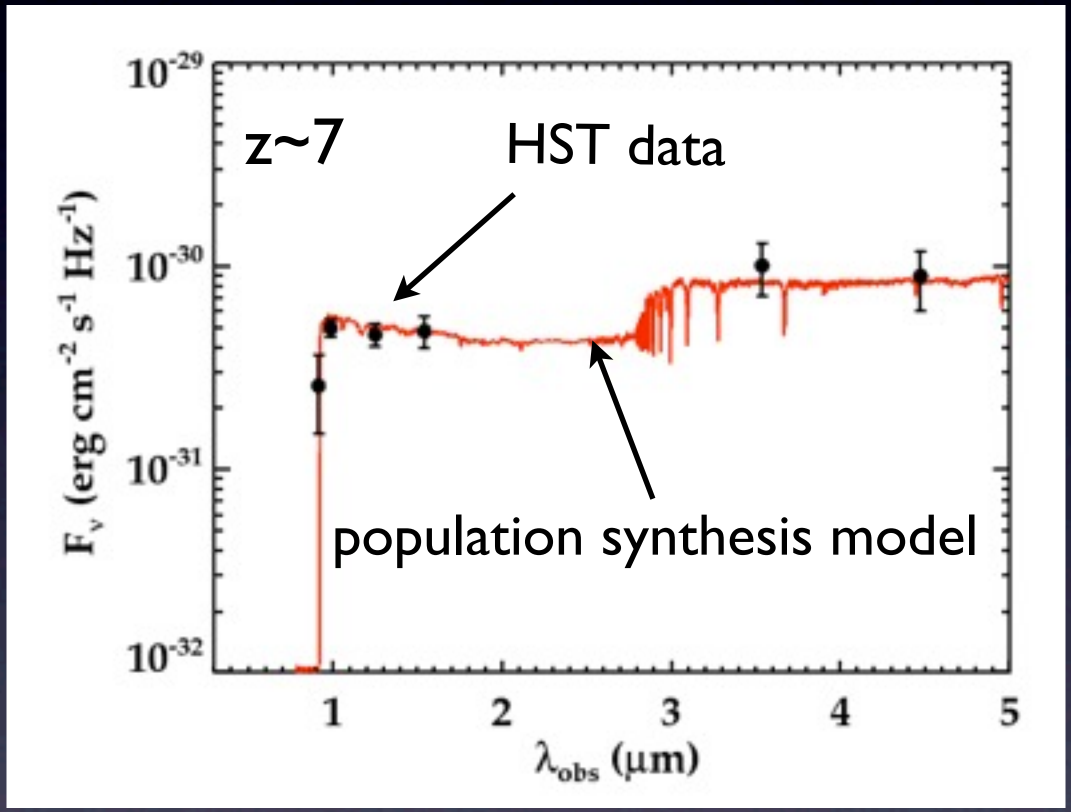


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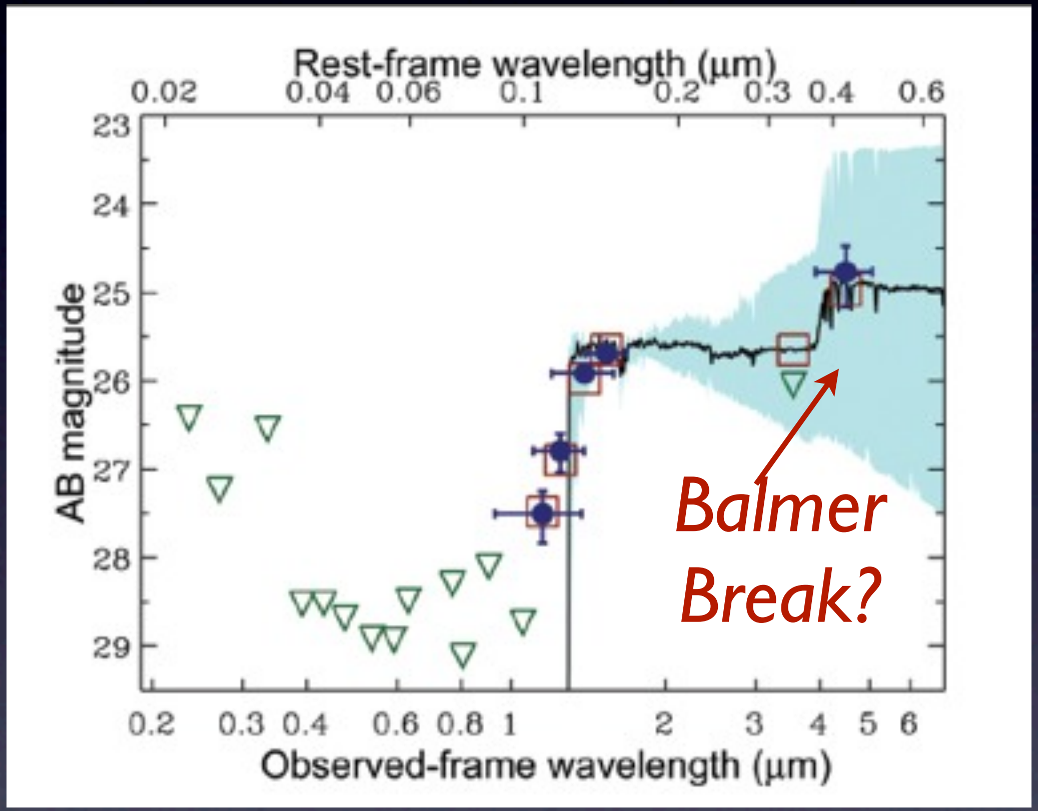
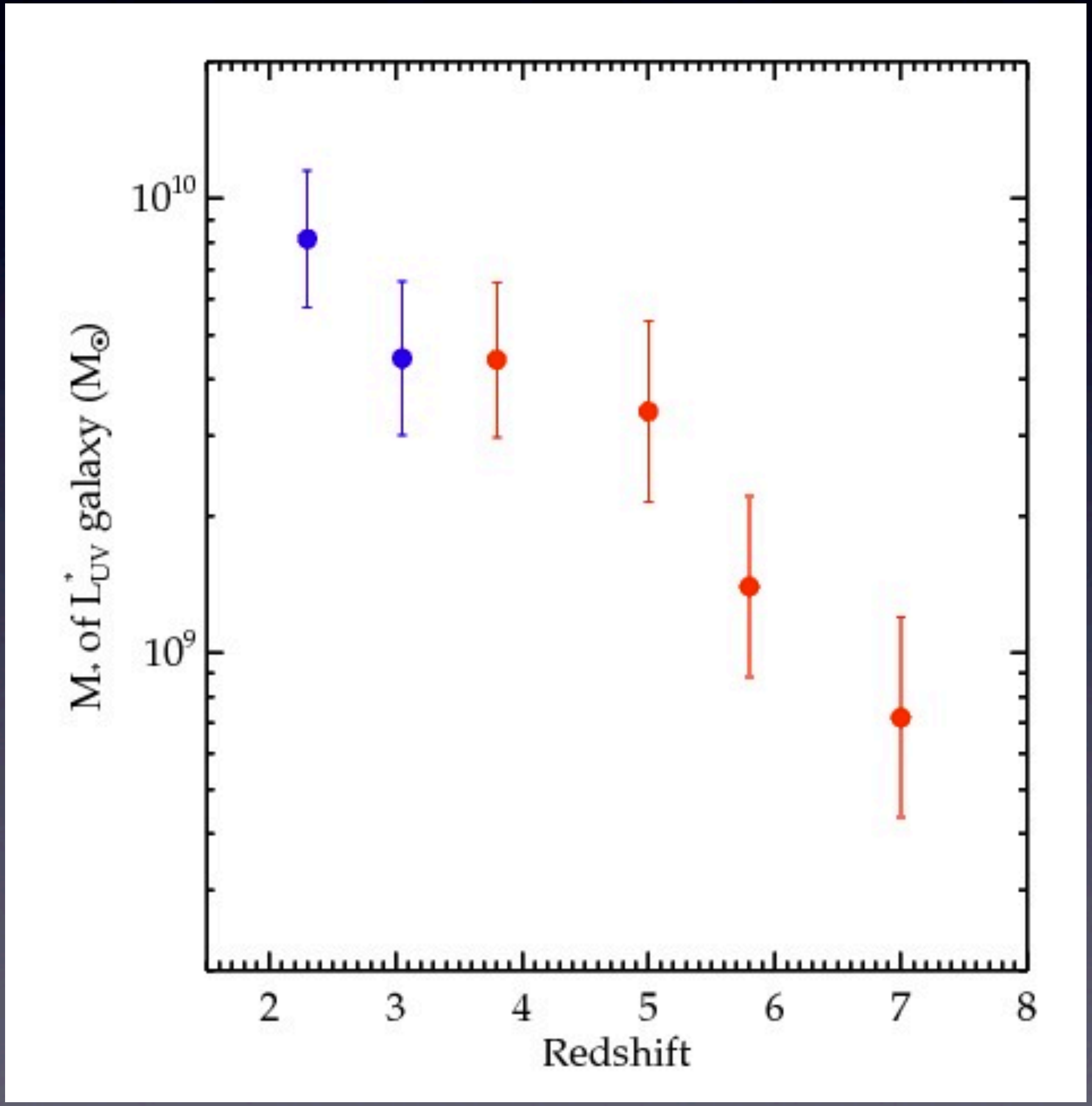



- 2000+ SEDs characterized at 4<z<8 (Stark+07,09,13)
- Stellar masses and SFRs inferred through population synthesis models.
- Balmer Breaks remain common at z>7 after correction for nebular contamination.
- Indicative of significant past activity

# Galaxy evolution over 2<z<7

*Stark et al. 2013*



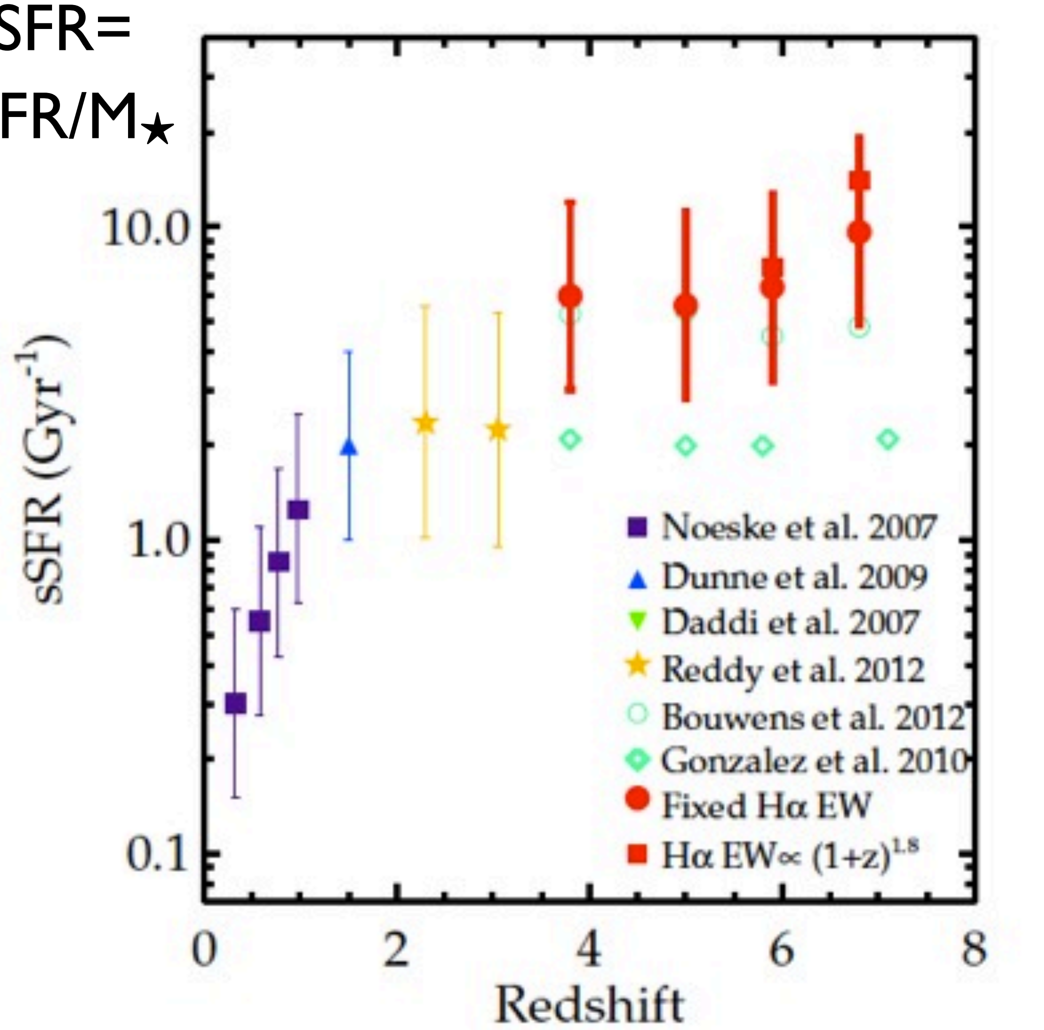

- Stellar mass of ~$7 \times 10^8$ $M_\odot$ for $L^*$ LBGs at z~7.

- ~10x lower than typical stellar mass at z~2.

# Galaxy evolution over 2<z<7

*Stark et al. 2013*

sSFR=
SFR/M★



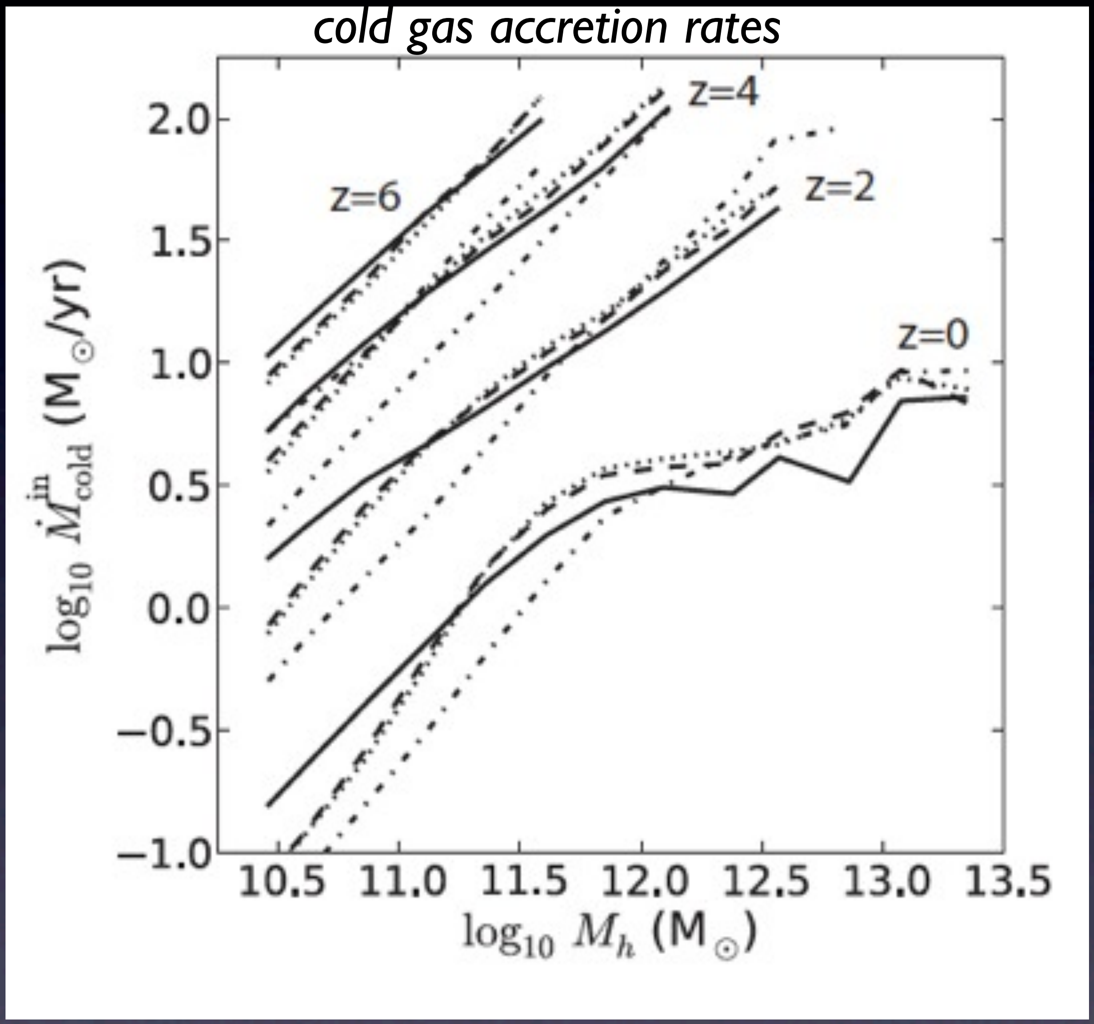

- Stellar mass of ~7x10$^8$ M$_\odot$ for L* LBGs at z~7.

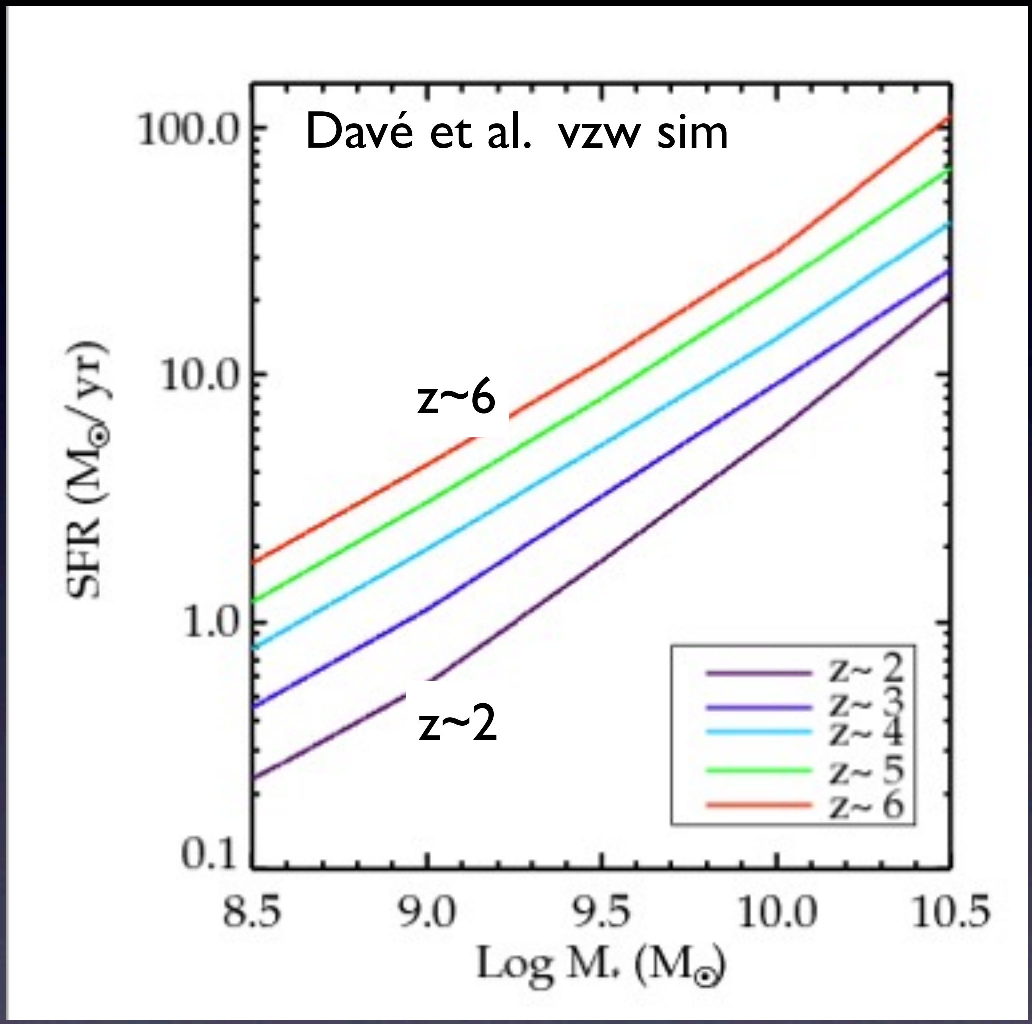
- ~10x lower than typical stellar mass at z~2.

- Large specific star formation rate at z~2 (~5x greater than at z~2)

# Expect Evolution in Specific Star Formation Rate

Faucher-Giguère, Kereš, & Ma 2012

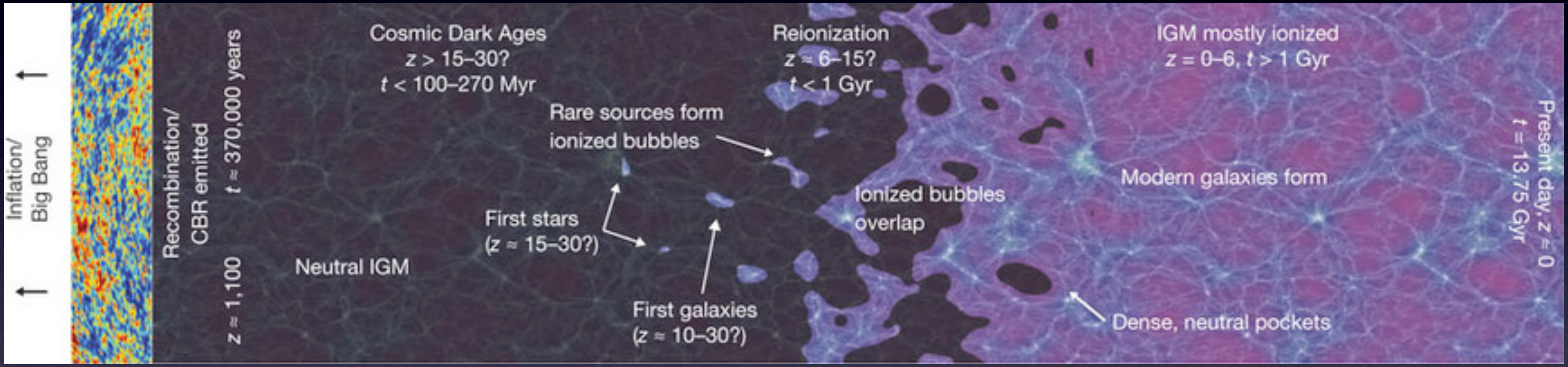



Baryon accretion rates onto fixed mass halos increase rapidly with redshift

Specific star formation rates (SFR/M★) expected to increase rapidly with redshift

# What causes the IGM to be reionized?

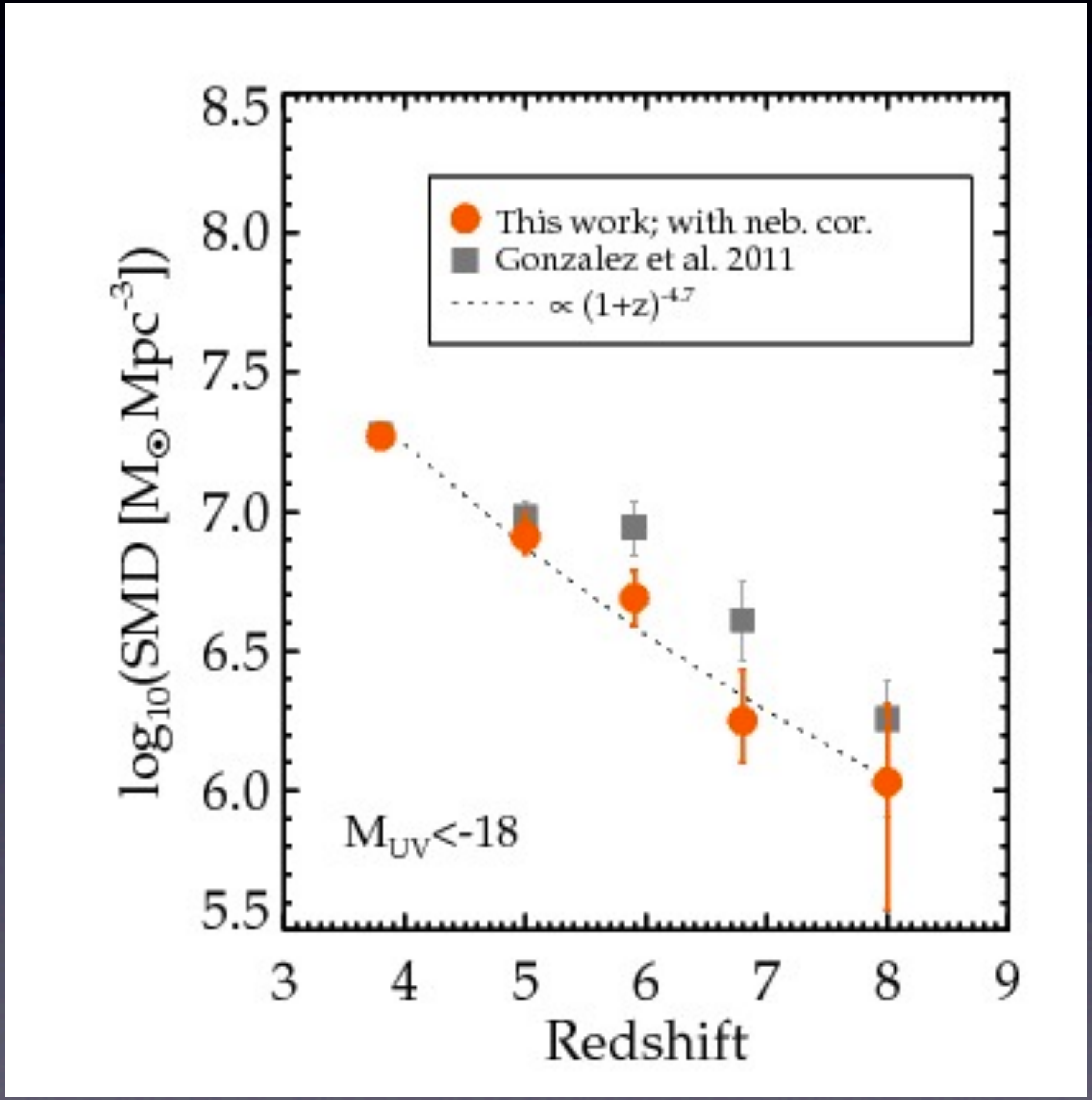



I. Star formation in Galaxies?

II. Low luminosity AGN?

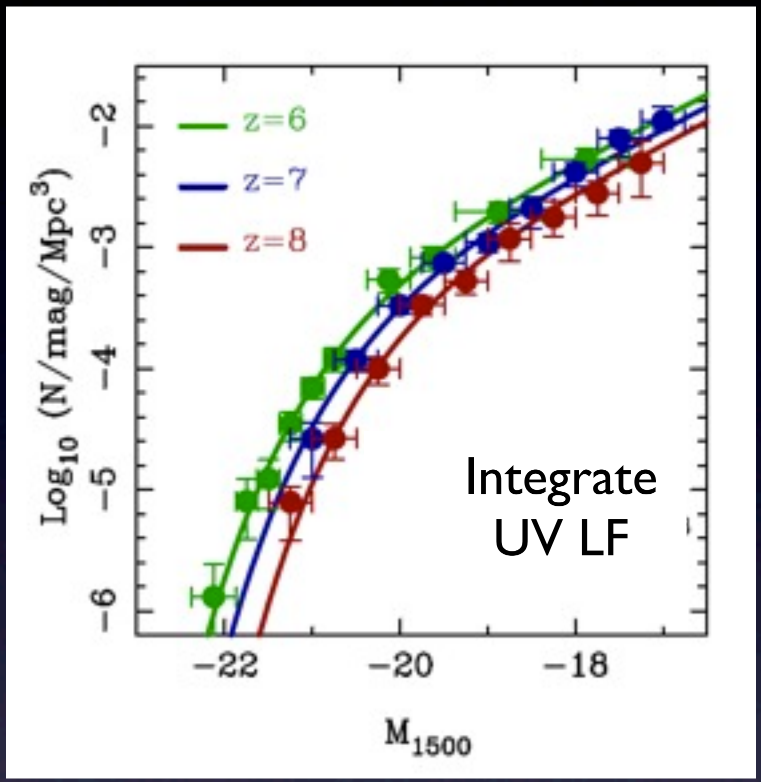
# Stellar Mass Density at z~7-8

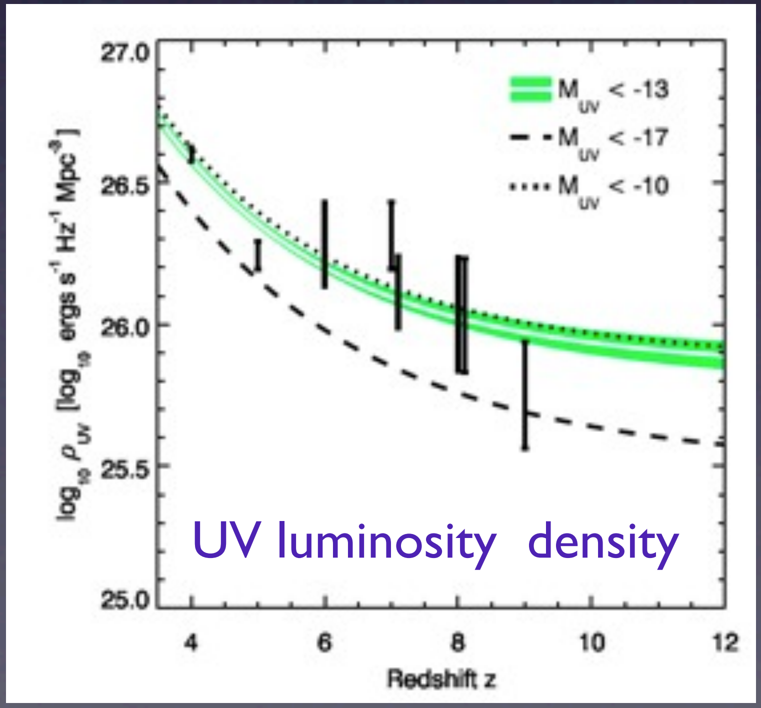
*Stark et al. 2013*




- Integral constraint on earlier activity.
- Balmer Breaks at z~8 is indicative of significant star formation at z~8-10 (for most star formation histories).
- Enough star formation for reionization?

# Contribution of Galaxies to Reionization




*Robertson et al. 2013*

**Method:**

- Estimate ionizing photon contribution from galaxy population
- Recombination rate taken from estimates from simulations
- Compute evolution in filling factor of HII, $Q_{HII}$,
- Reionization is complete when $Q_{HII} = 1$

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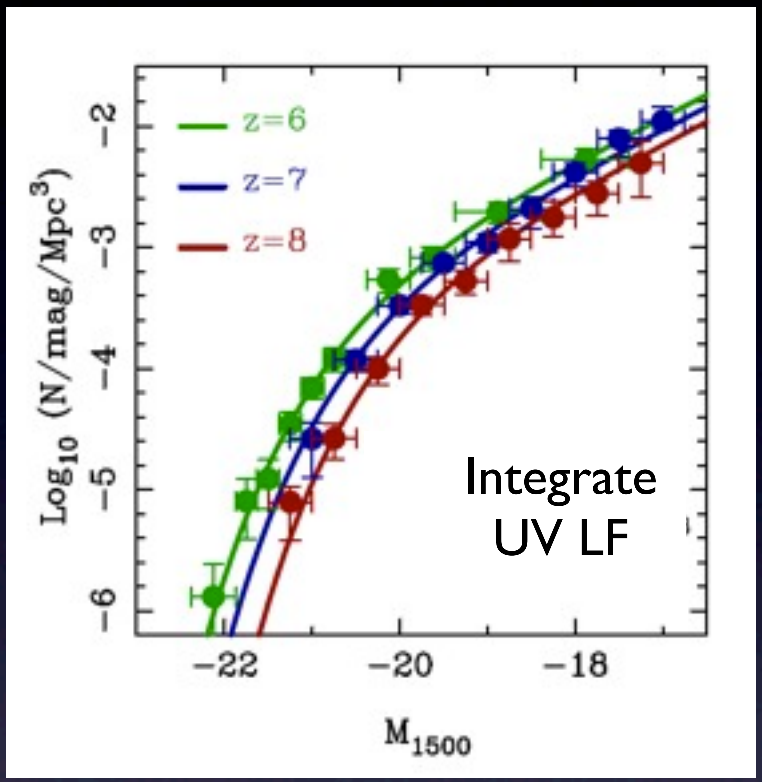


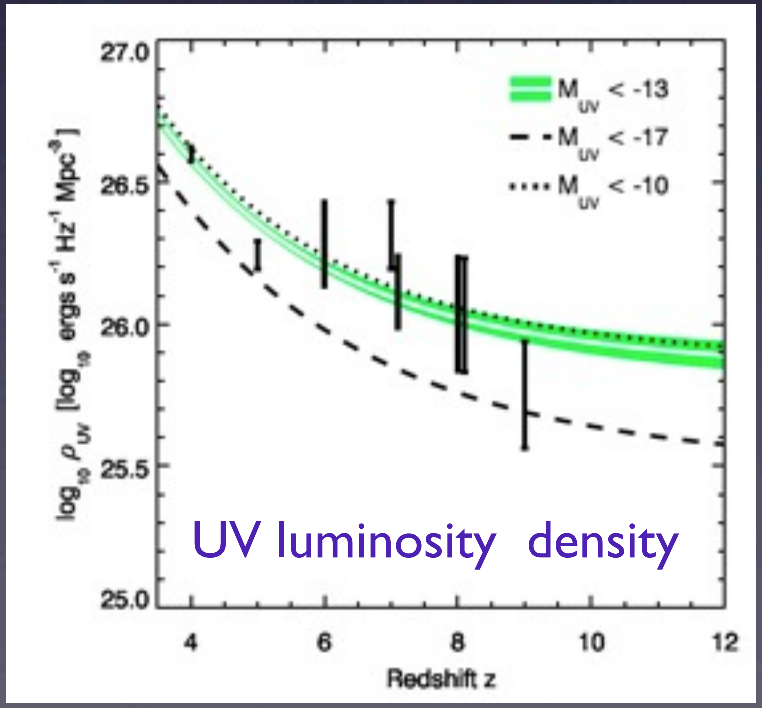


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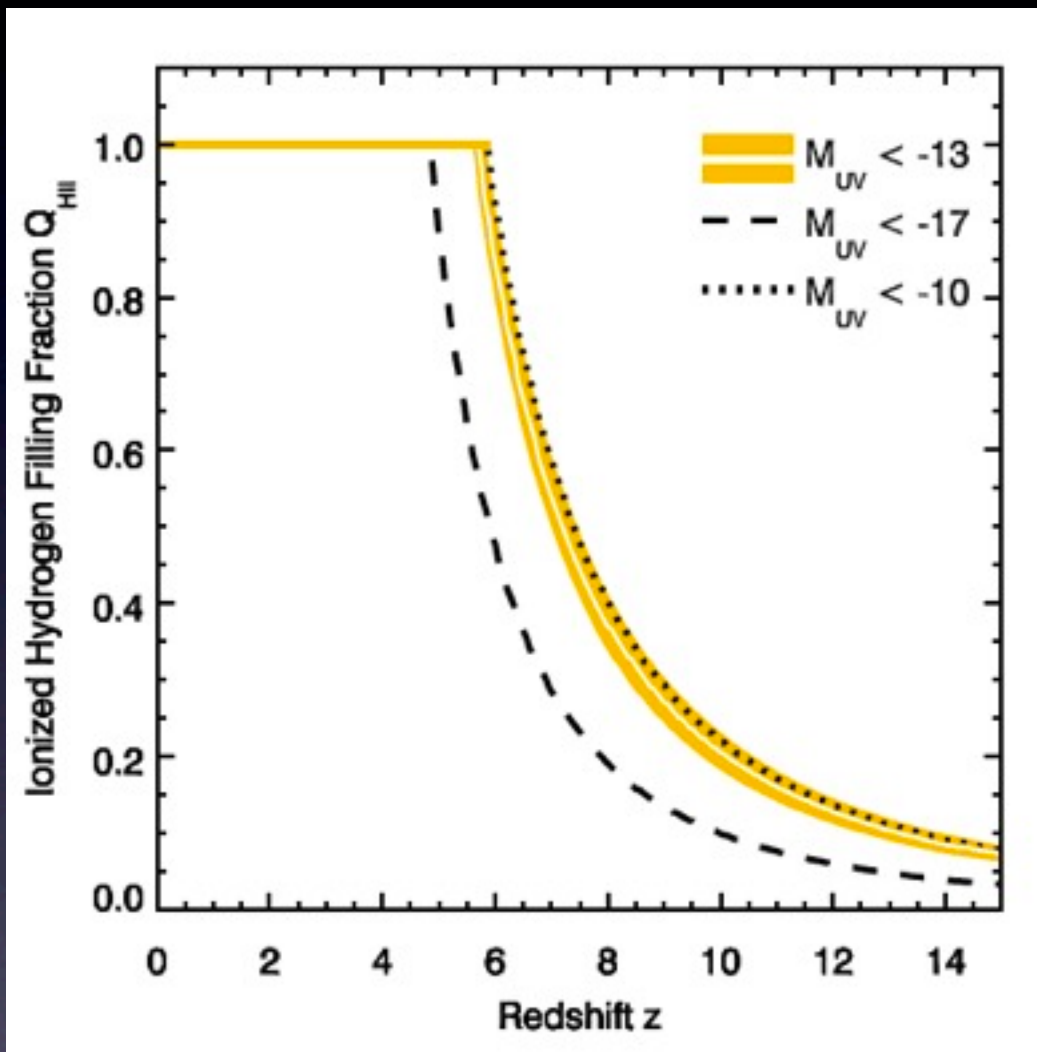
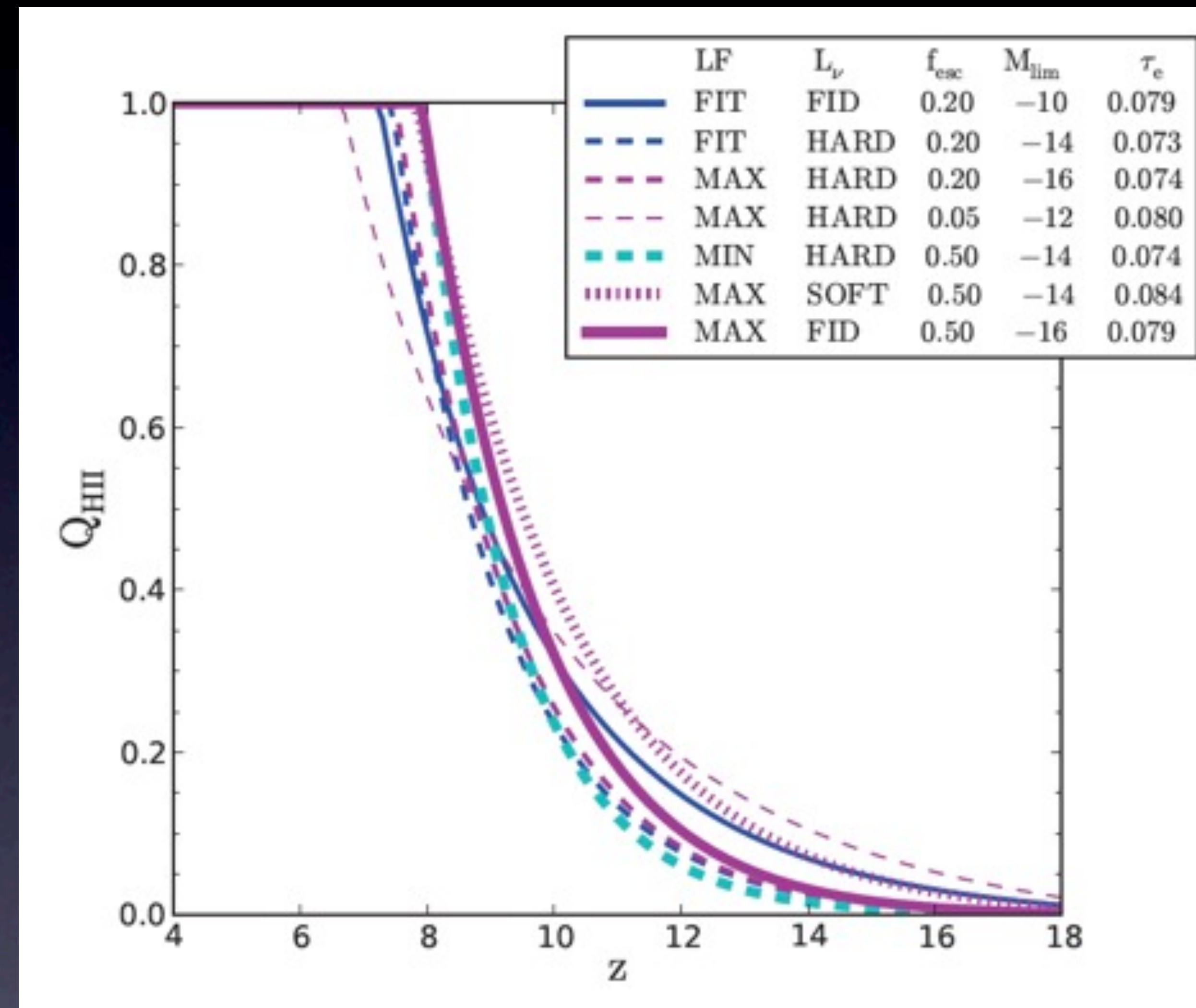
**Necessary Ingredients:**
- Robust measure of UV luminosity function
- Hardness of UV spectrum
- Escape fraction of ionizing radiation

# Contribution of Galaxies to Reionization

*Robertson and UDF12 team 2013*




*Kuhlen & Faucher-Giguere 2013*



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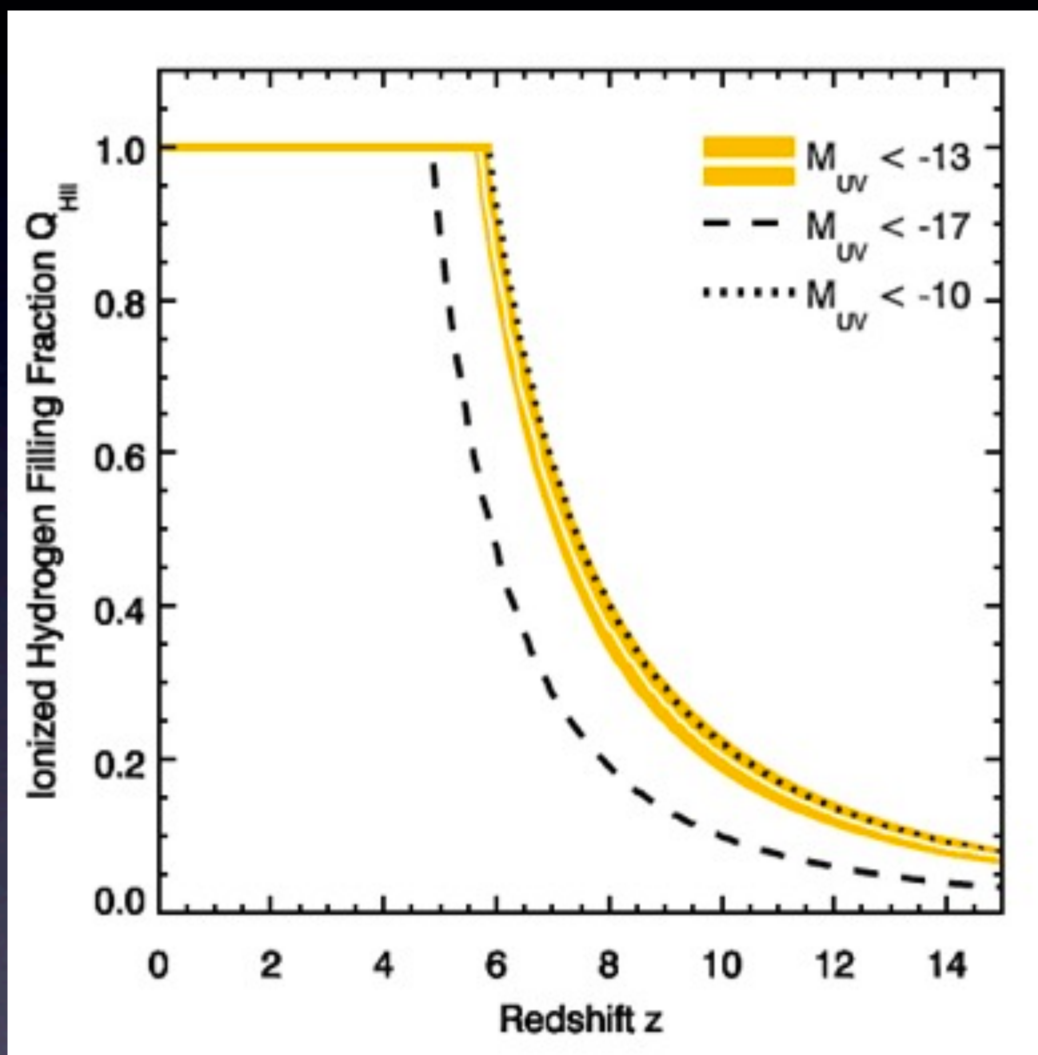


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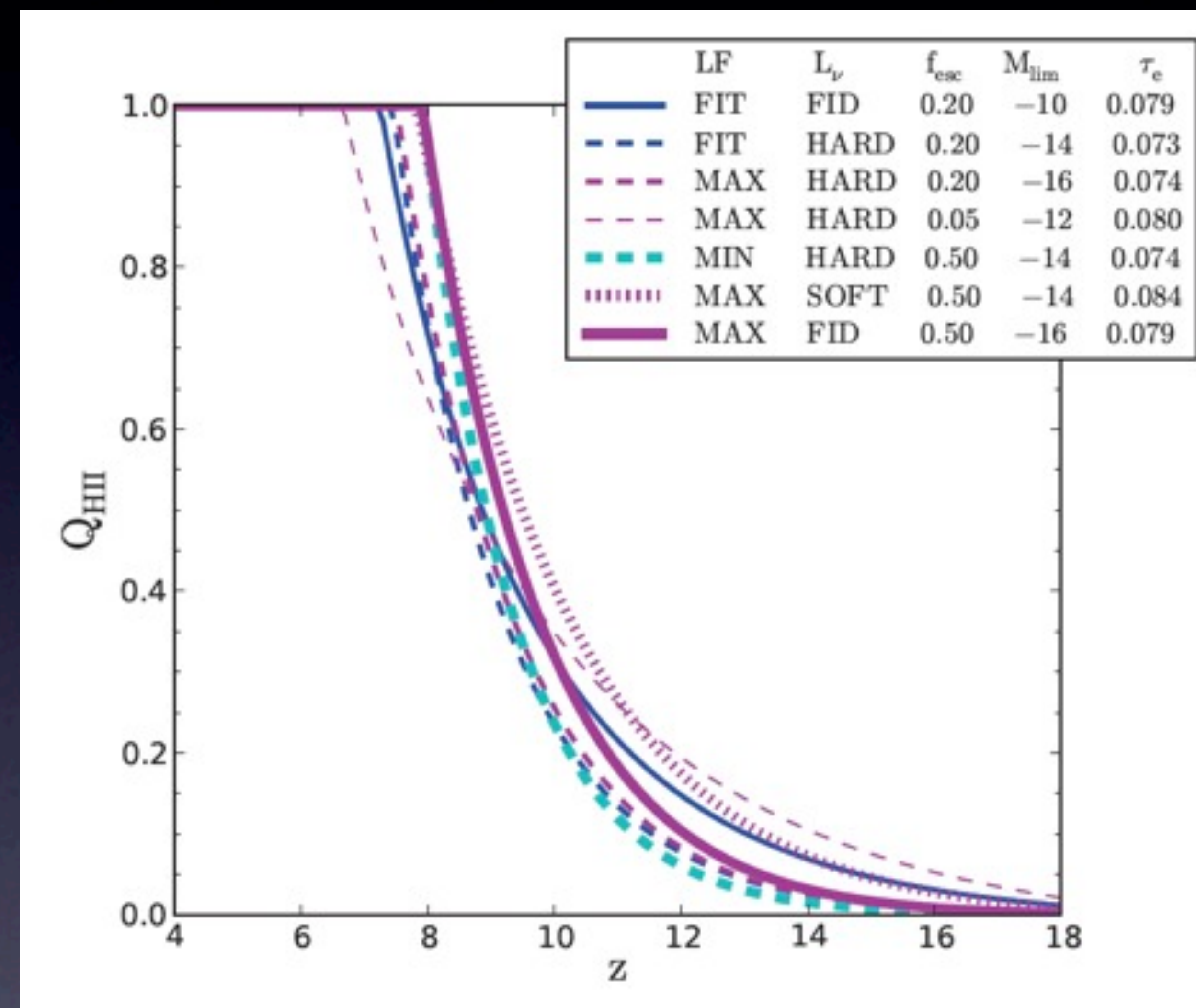


## Reionization requirements:

- Luminosity function must extend 4-7 mags below UDF12 detection limits
- Escape fraction increases with redshift (20% at $z>7$ c.f. 5% at $z\sim3$) OR
- Hard ionizing spectra in $z>7$ galaxies

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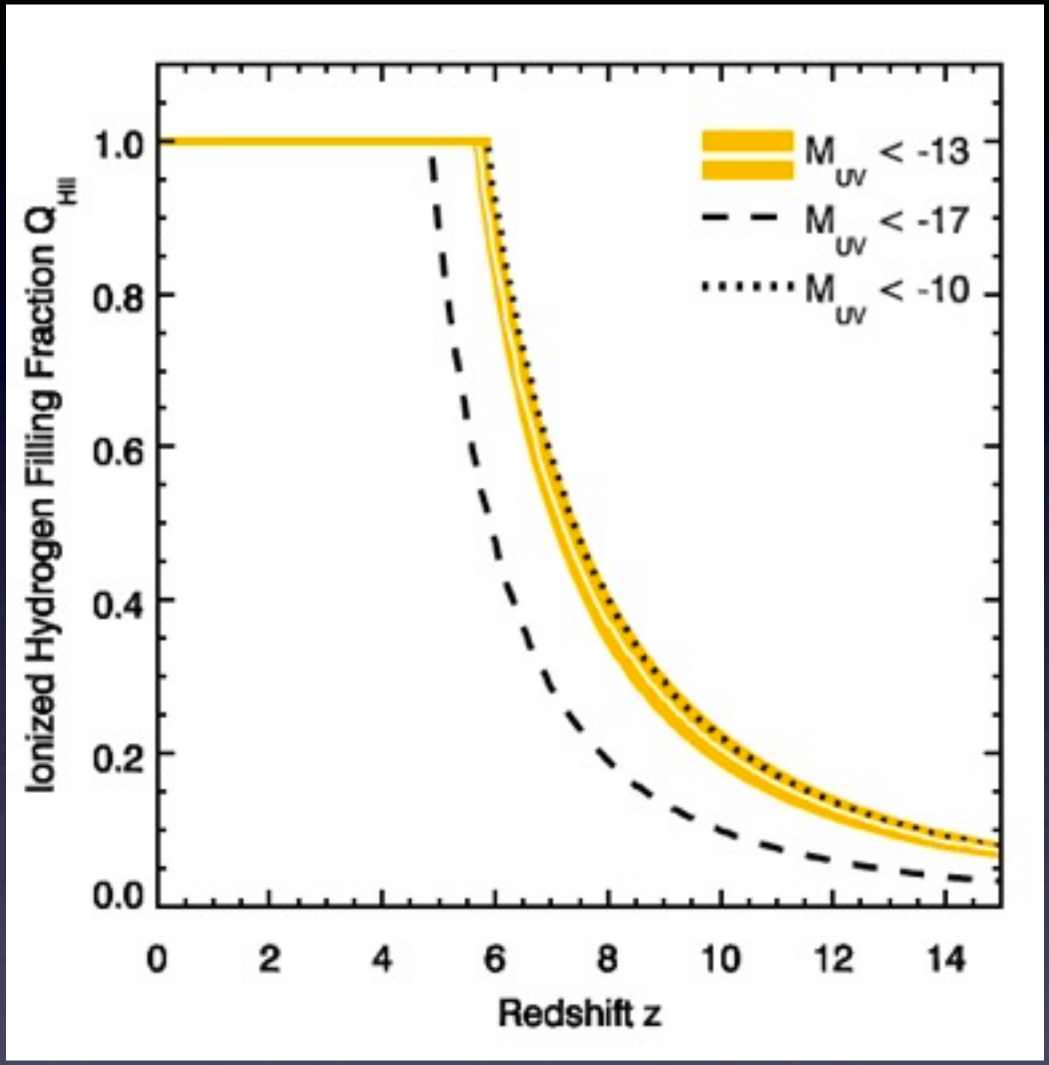


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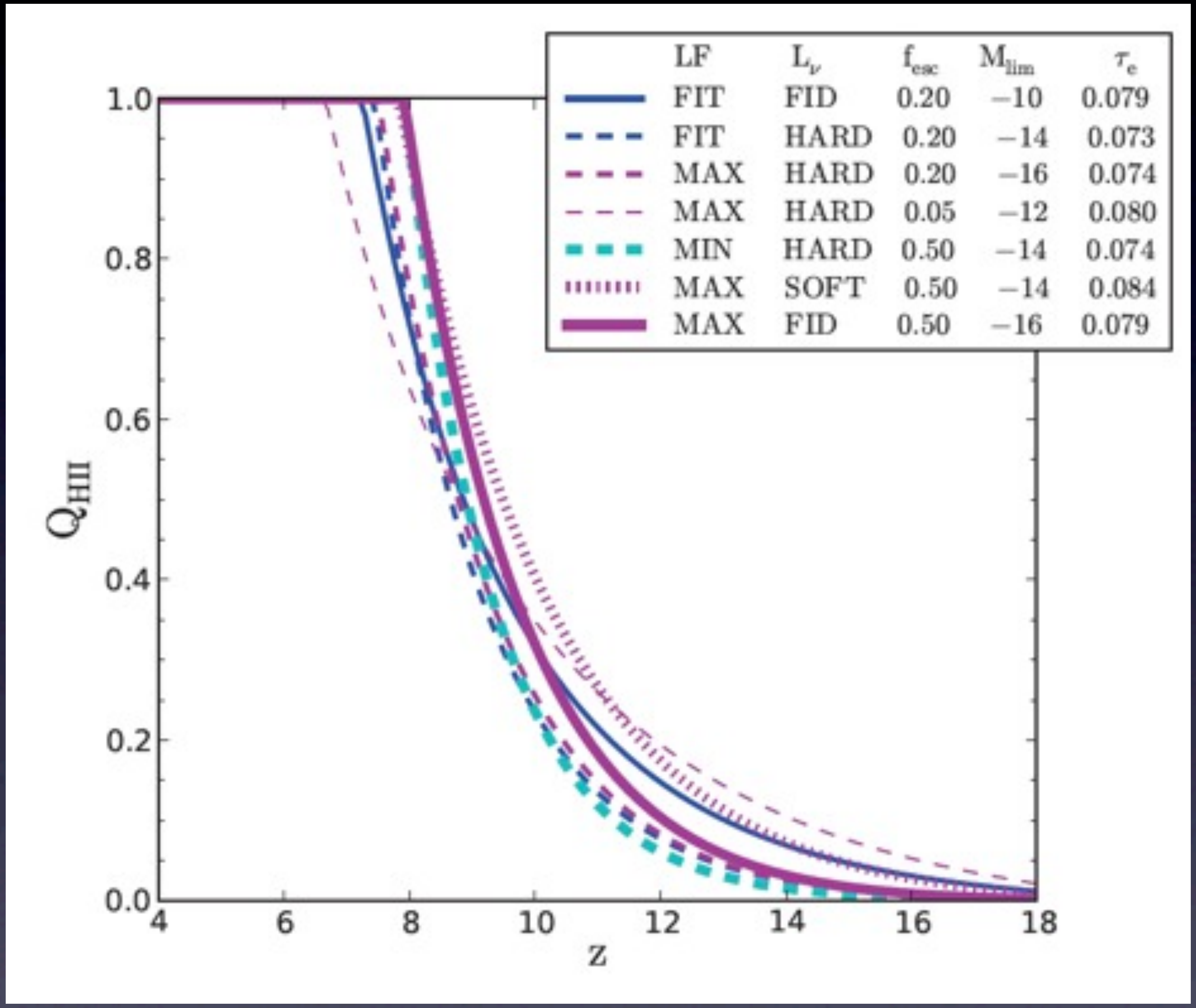


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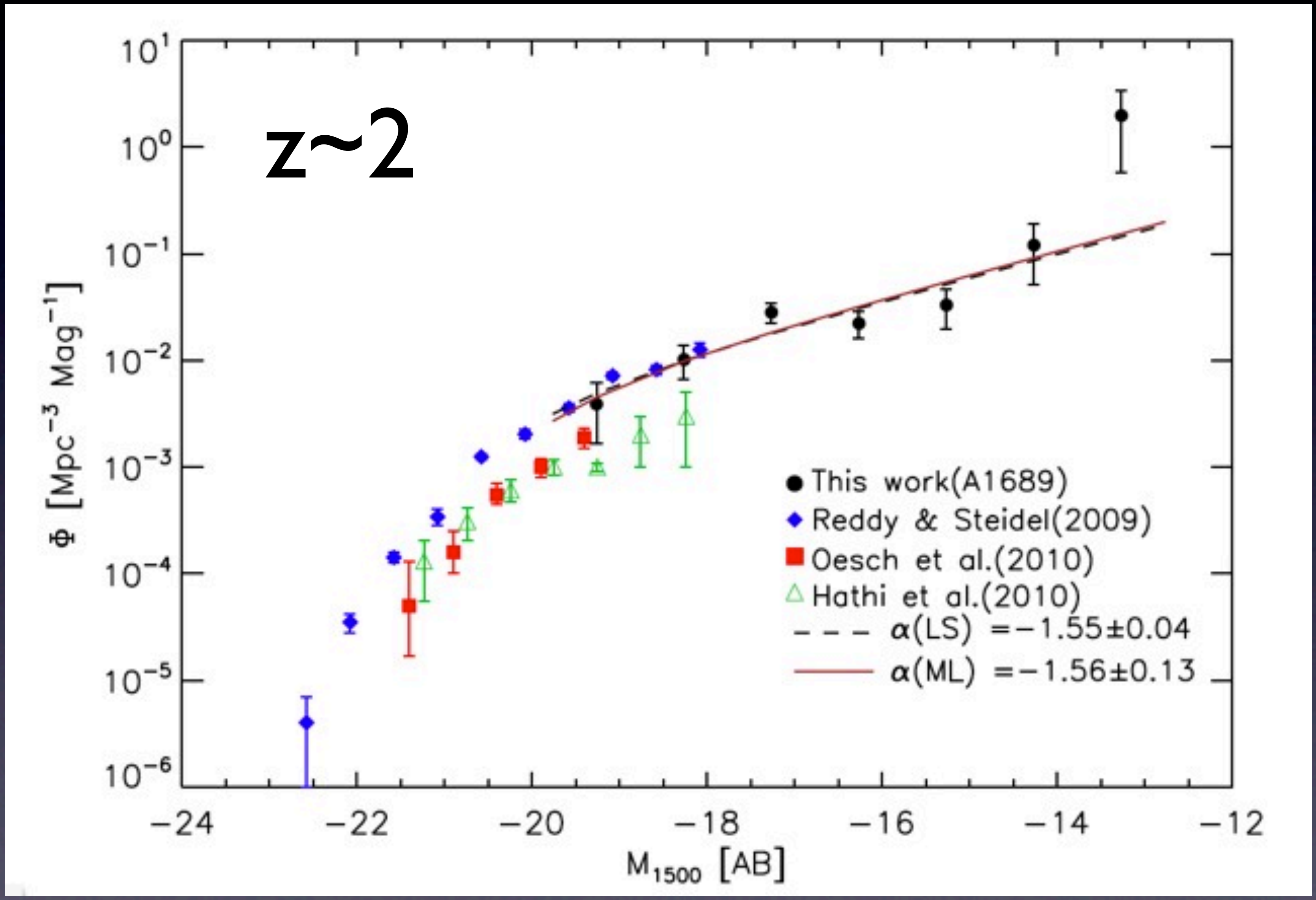
# No Evidence for Luminosity Function Floor

Alavi et al. 2013




New measurement of UV luminosity function from faint lensed galaxies.

UV luminosity function rises to $M_{UV}$~-13 at z~2.

No evidence for turnover in luminosity function.

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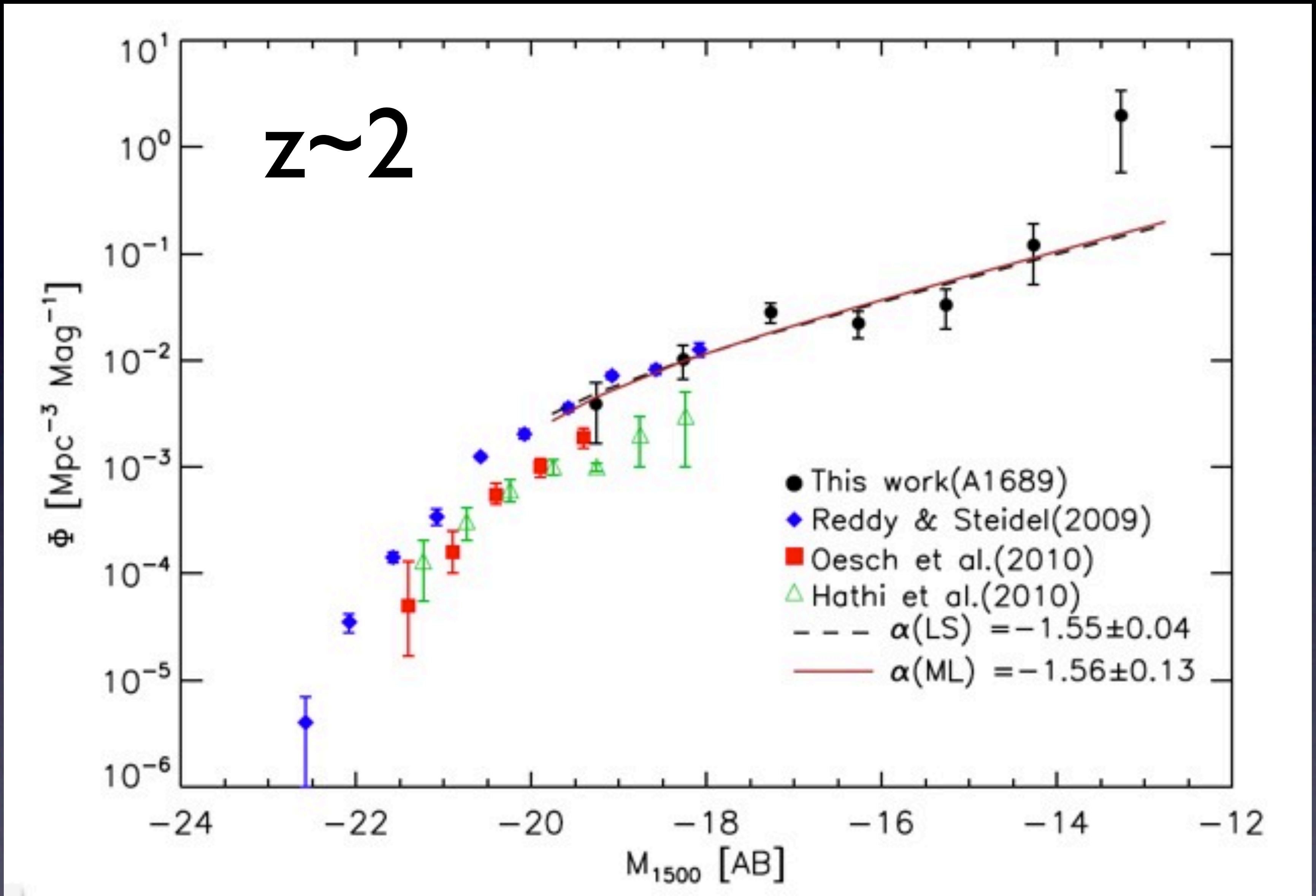


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No evidence for turnover in luminosity function.

*HST Frontier Field imaging will soon enable analogous measurements at z~7*

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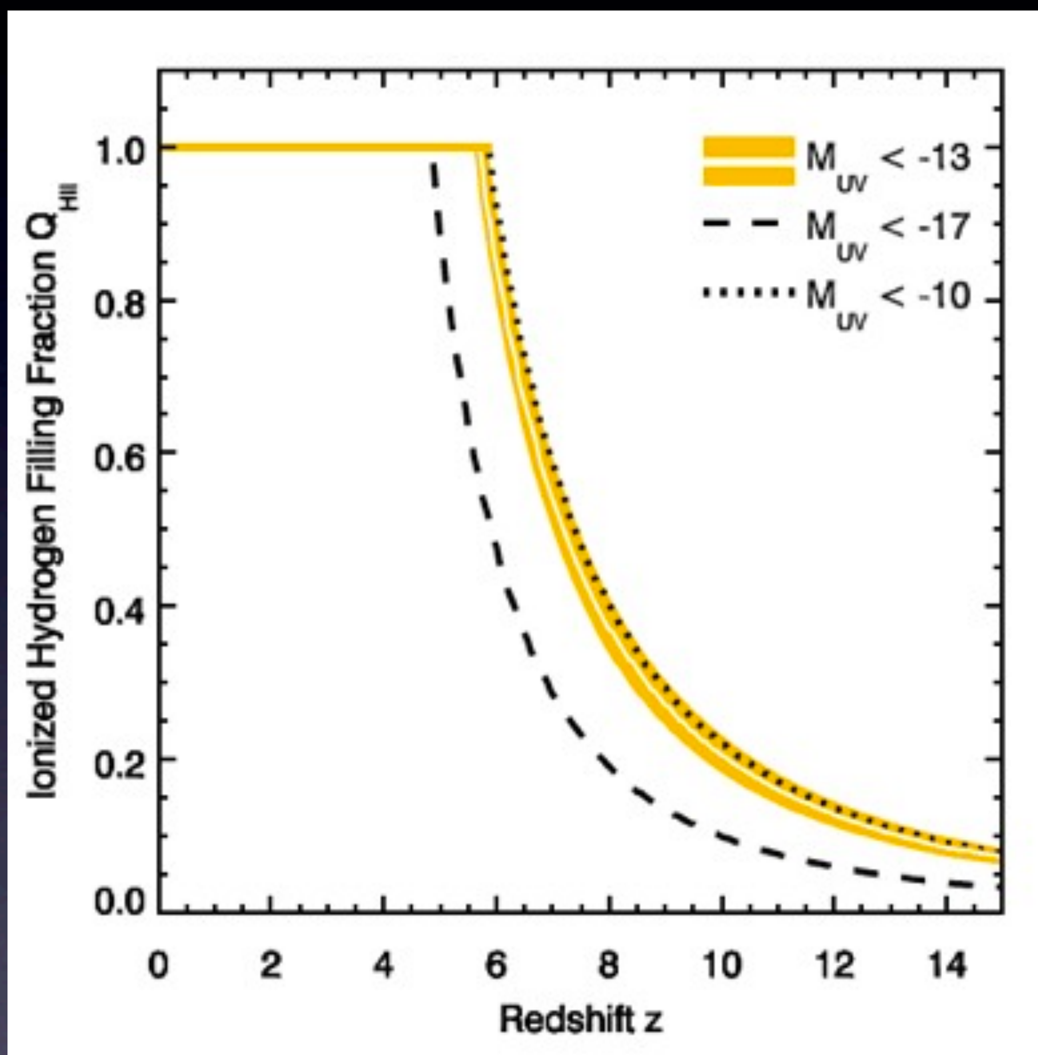


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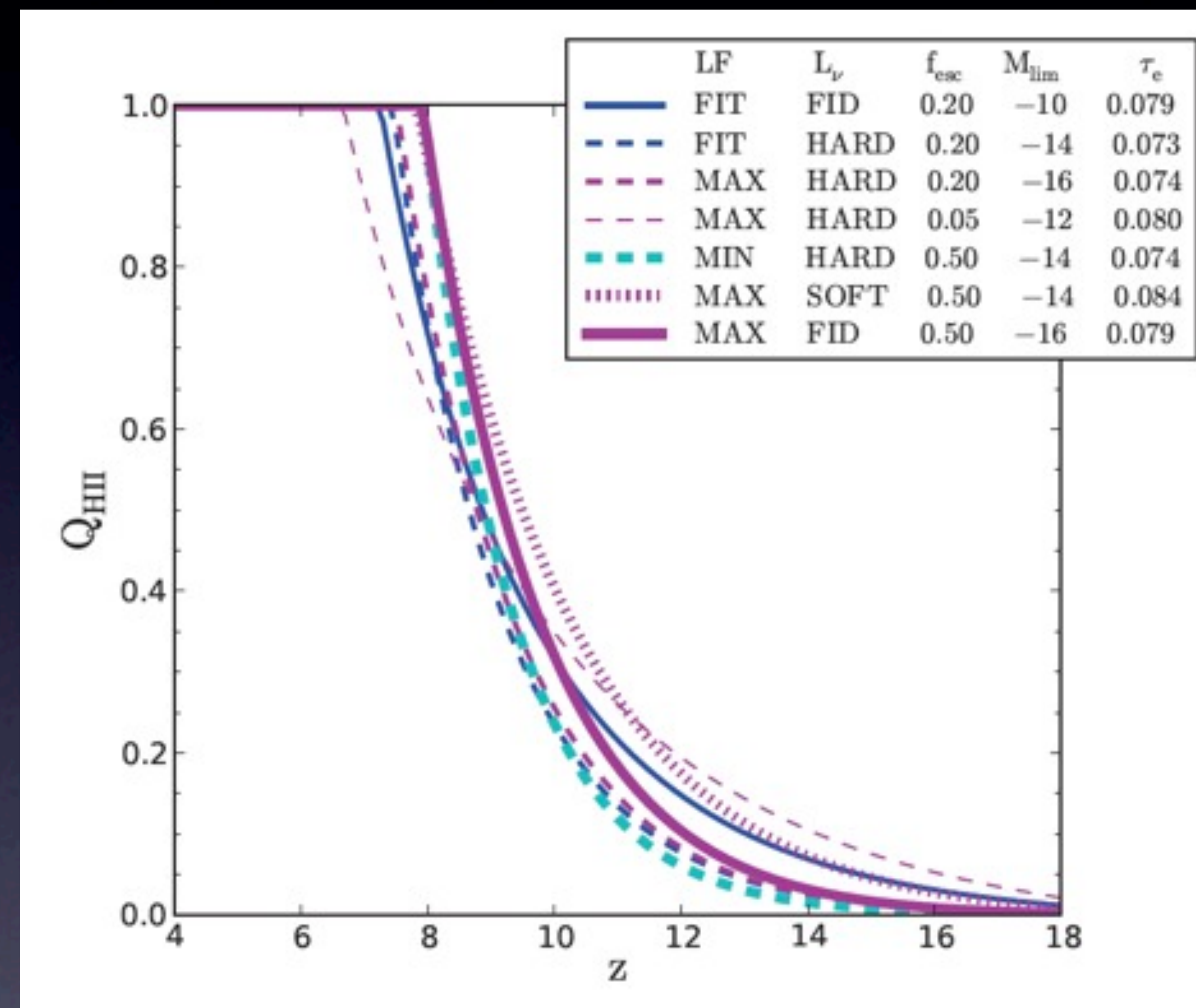


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# Why is it so difficult for ionizing radiation to escape?

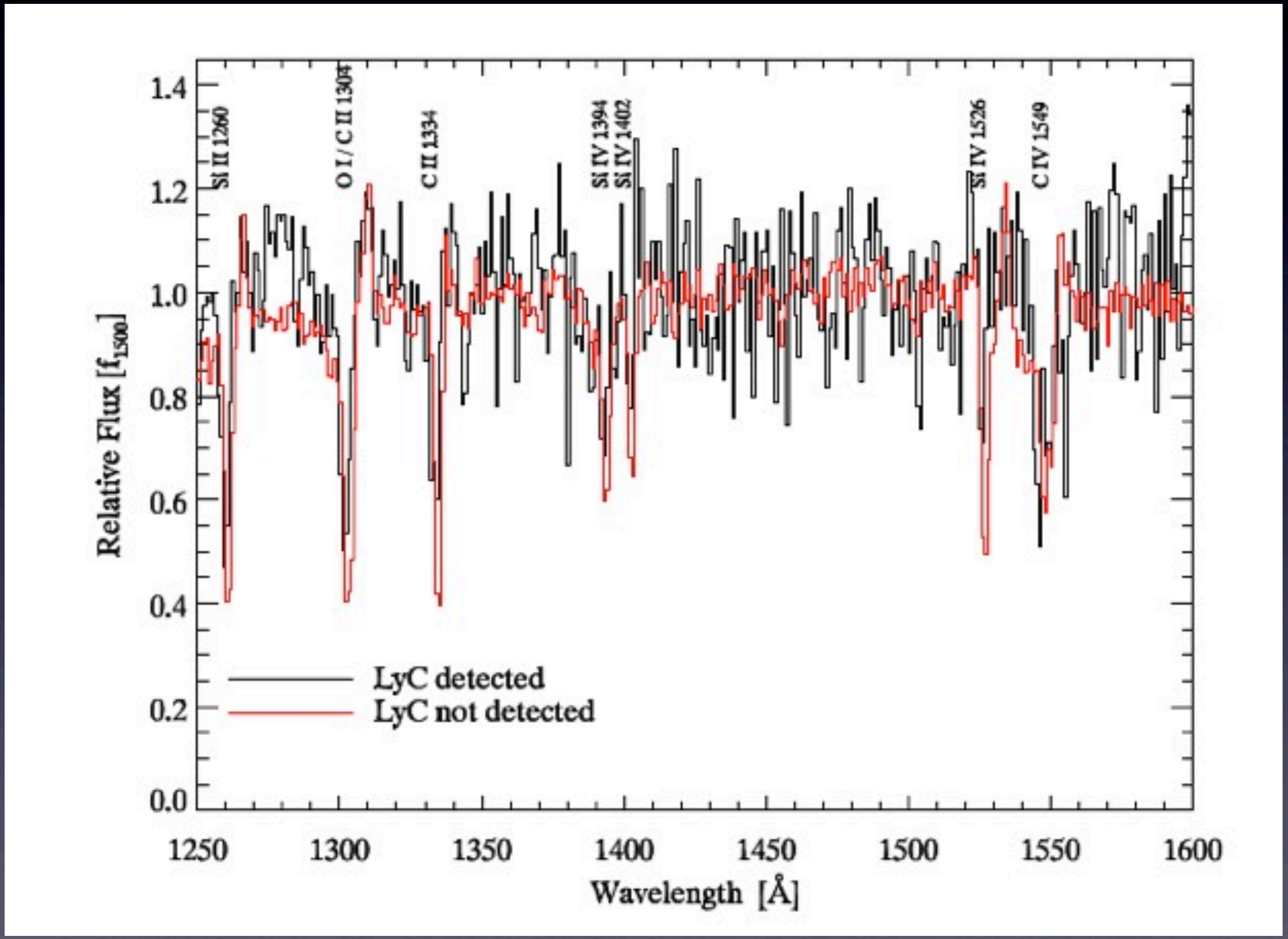
Ionizing radiation must escape large columns of HI around galaxies.

(I) What conditions are condusive to escape of ionizing radiation at z~3?

(II) Might distribution of circumgalactic gas evolve with redshift?

# What governs escape of ionizing radiation at z~3?

Bogosavljević, 2010, (Steidel et al. 2013, in prep,)

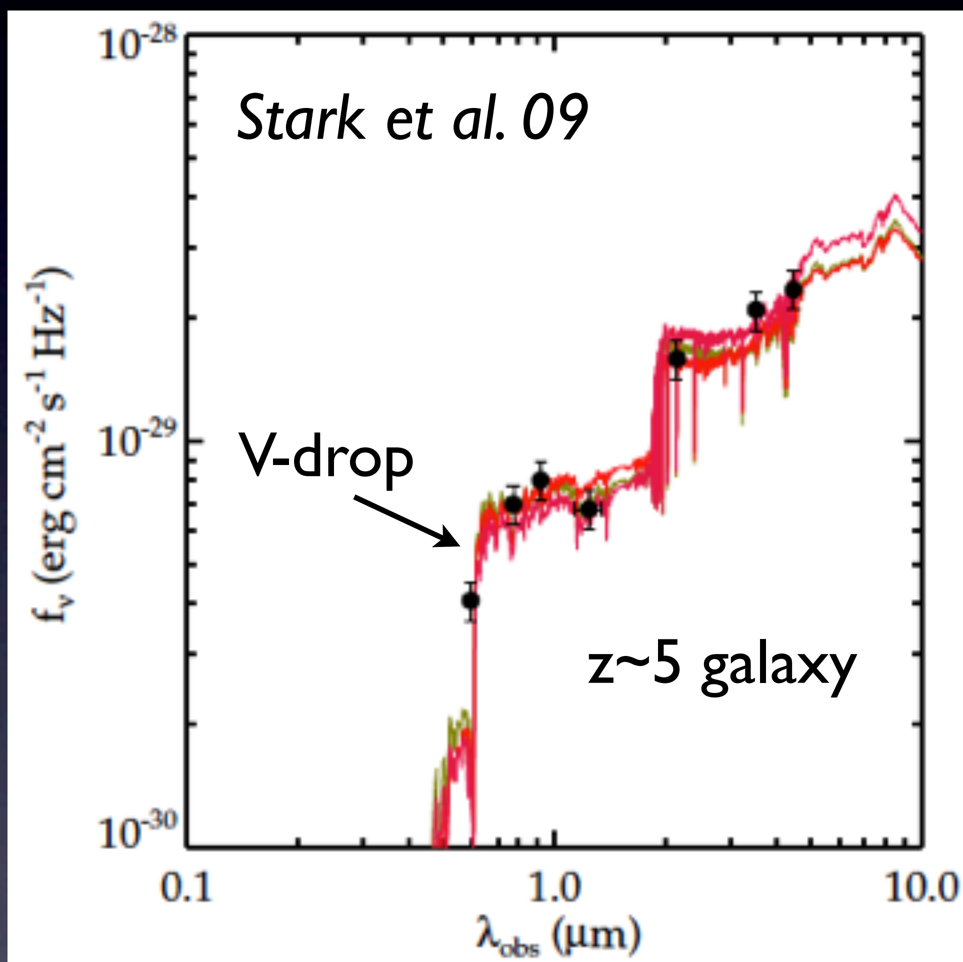




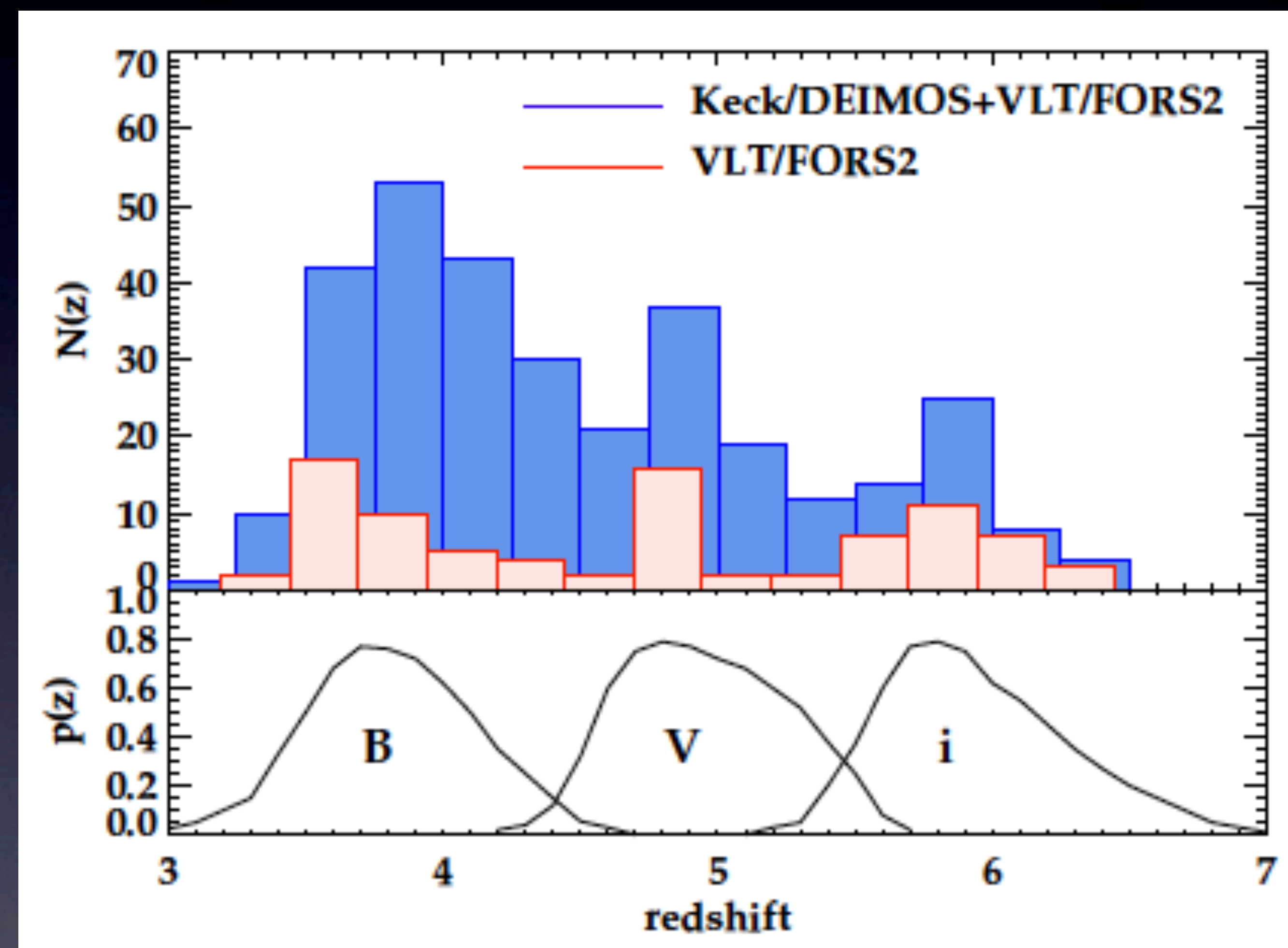
- Composite spectrum of z~3 galaxies with LyC detections (Steidel+)
- Weak low ionization absorption.
- Partial coverage of neutral gas.

*Does partial gas coverage become more common at higher redshift?*

# Spectroscopic Samples of z>4 LBGs



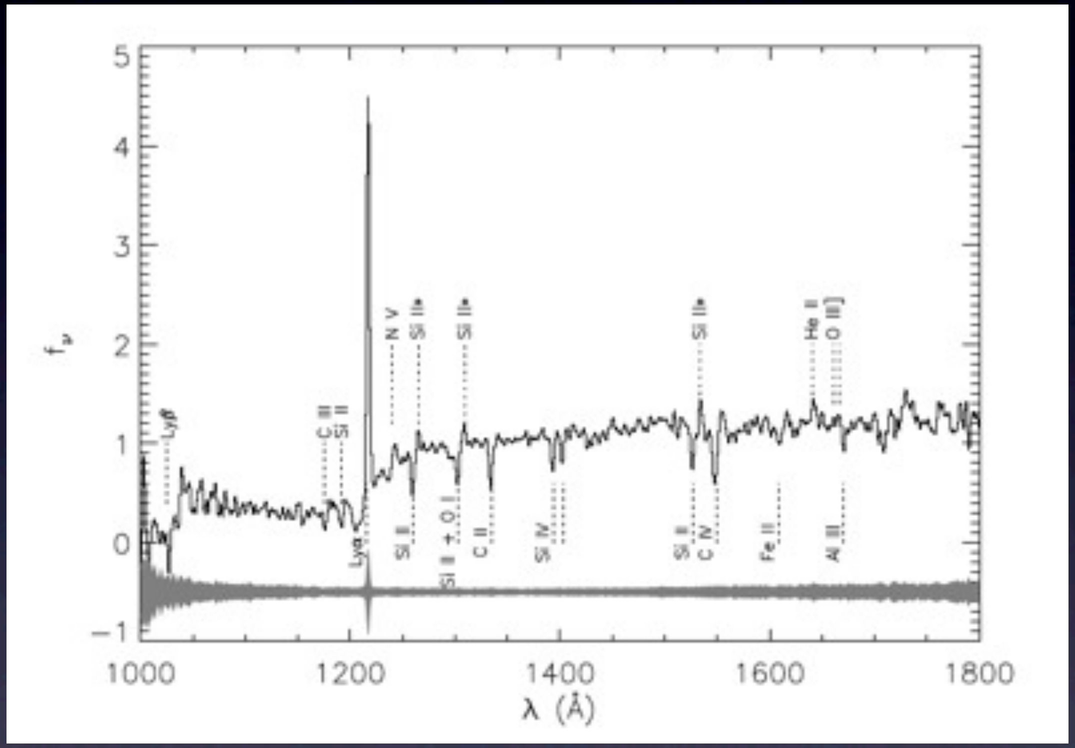

*Stark et al. 2010, 2011*

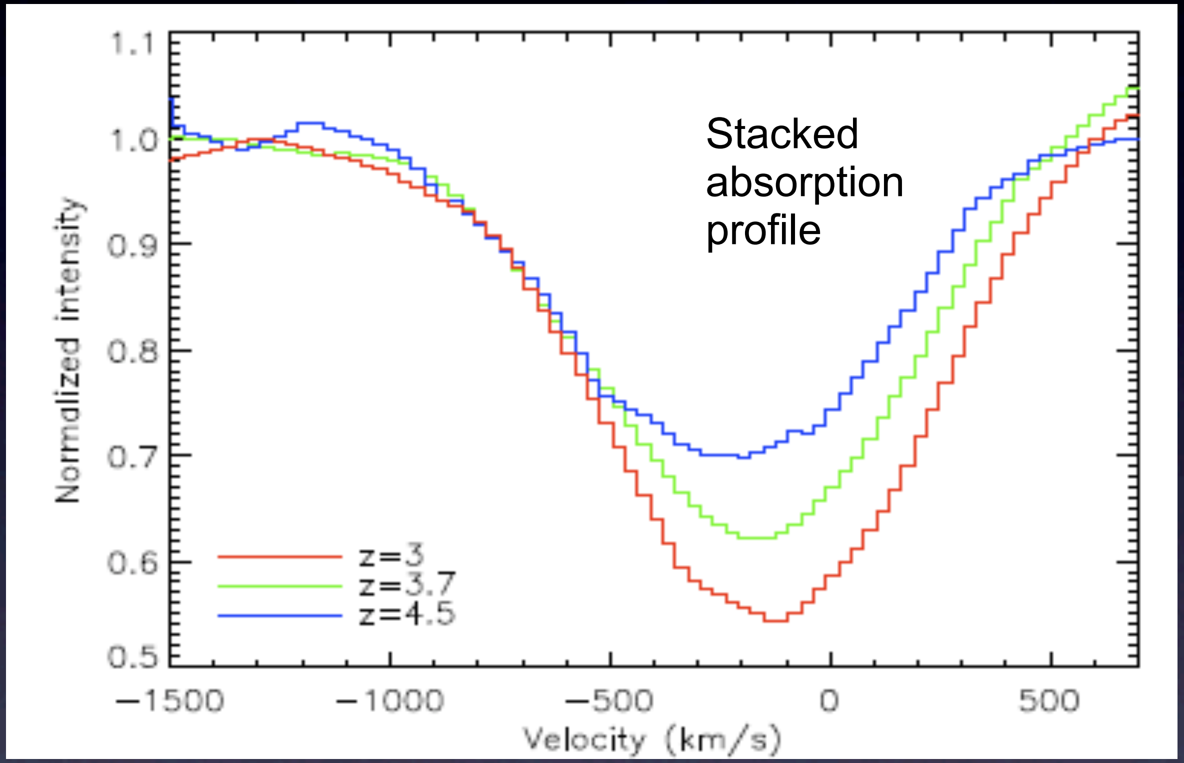



- Input photometric catalog from 2000+ 4<z<6 LBGs (Stark+ 2009)
- Deep (5-12 hr) Keck spectra of ~450 4<z<6 LBGs taken with DEIMOS
- With VLT/FORS spectra, 600+ z>4 LBGs with deep spectra

# How do absorption lines evolve with redshift?

Stark+2010; Jones, Stark, & Ellis 2012

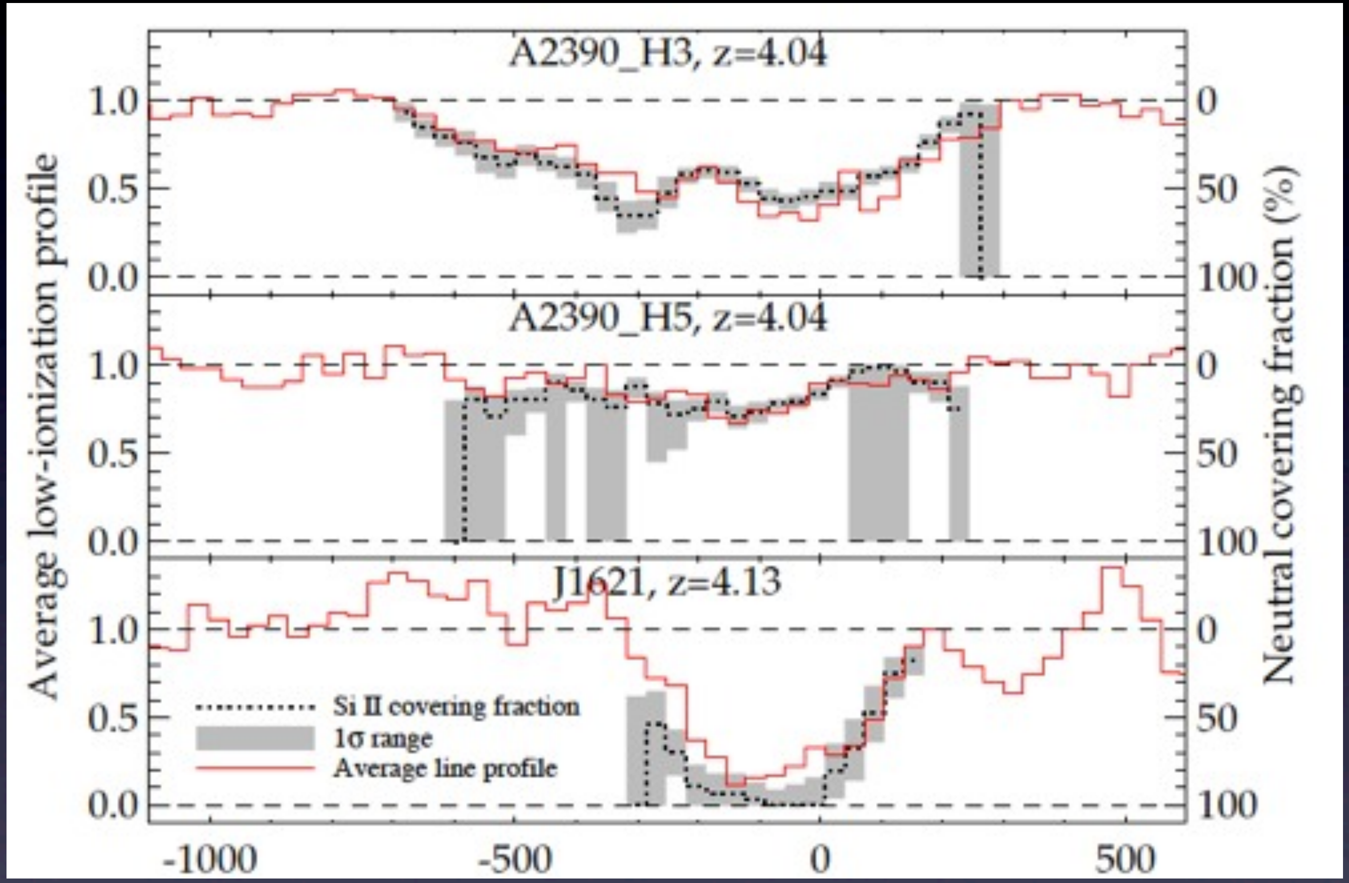


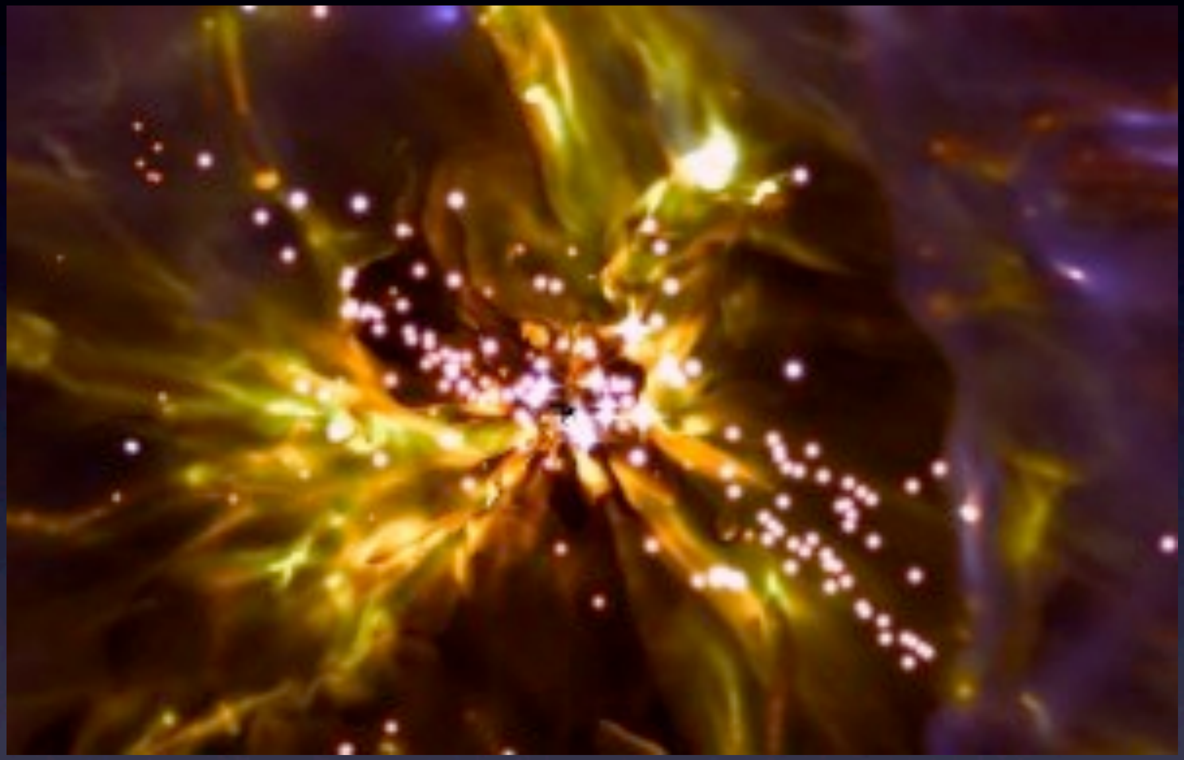




- EW of low ionization absorption lines decreases at z>3.
- Absorption lines are optically thick (not metallicity effect).
- Could be due to a variety of outflow parameters (need higher resolution data).

# Gas covering fractions are lower at z~4

*Jones et al. 2013, arXiv:1304.7015*



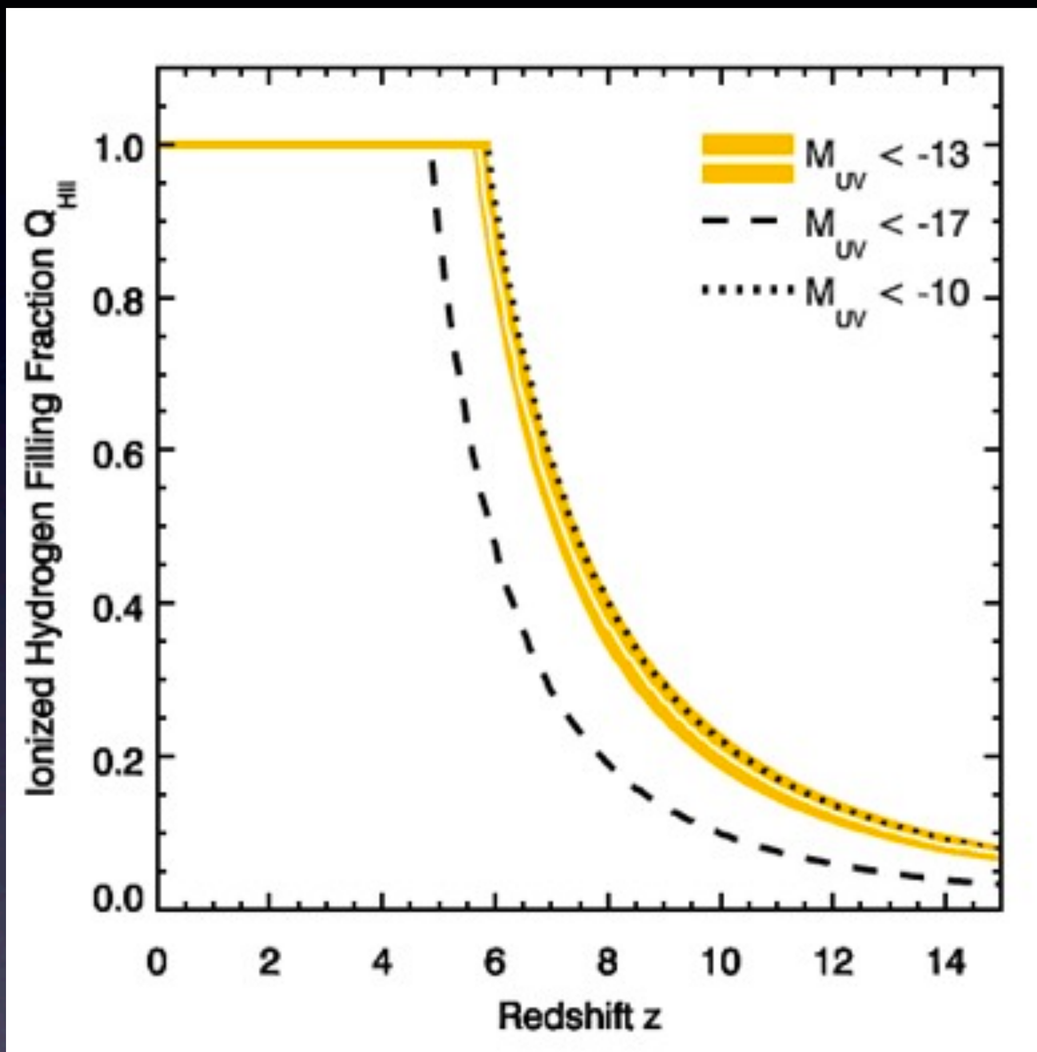
credit: Wise/Kaehler

- Covering fractions derived from Si II absorption lines in bright lensed z~4 galaxies
- Neutral gas only partially covers young stars in z>4 galaxies.

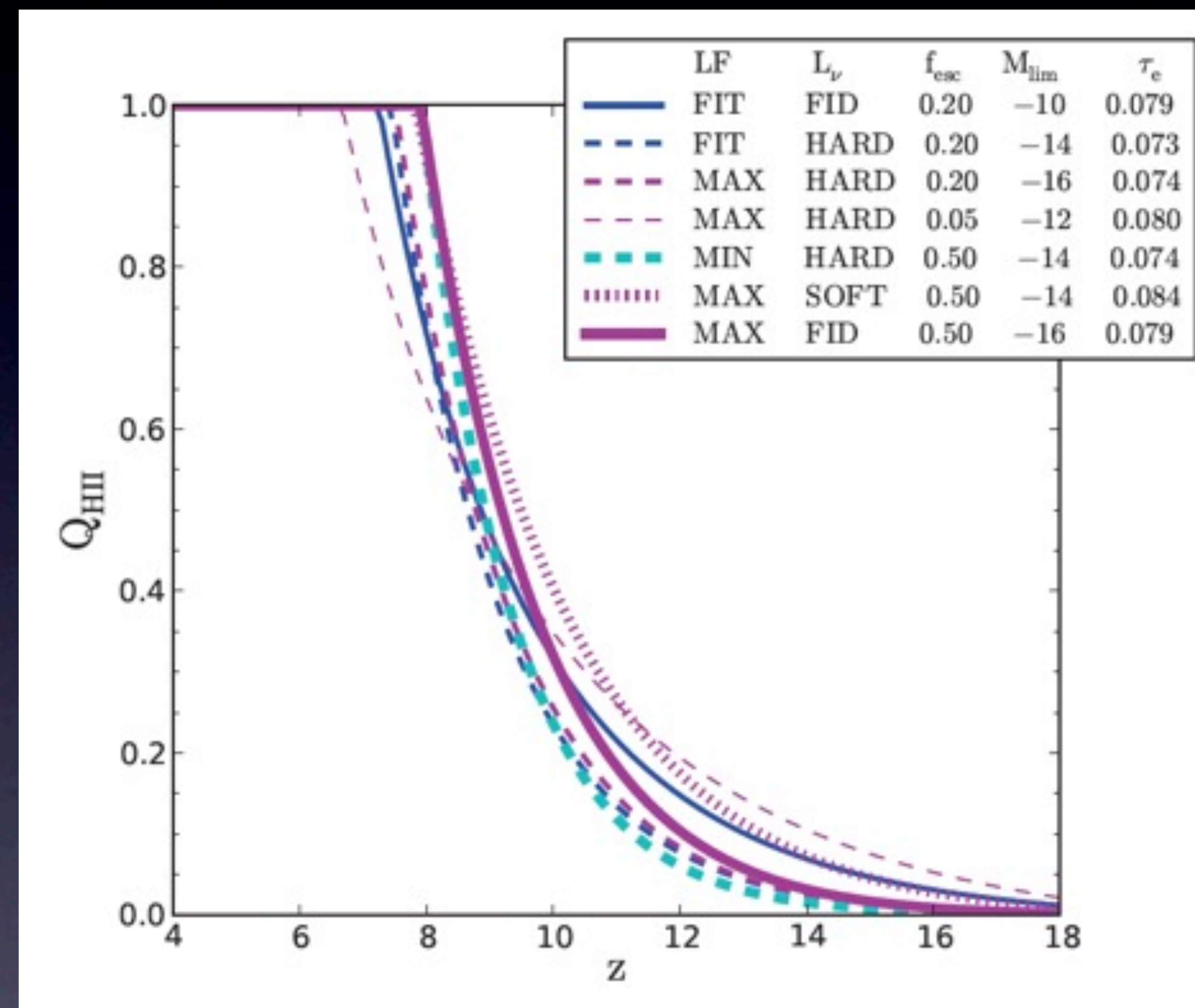
*Early galaxies appear to have conditions which support large escape fractions*

# Contribution of Galaxies to Reionization

*Robertson and UDF12 team 2013*




*Kuhlen & Faucher-Giguere 2013*

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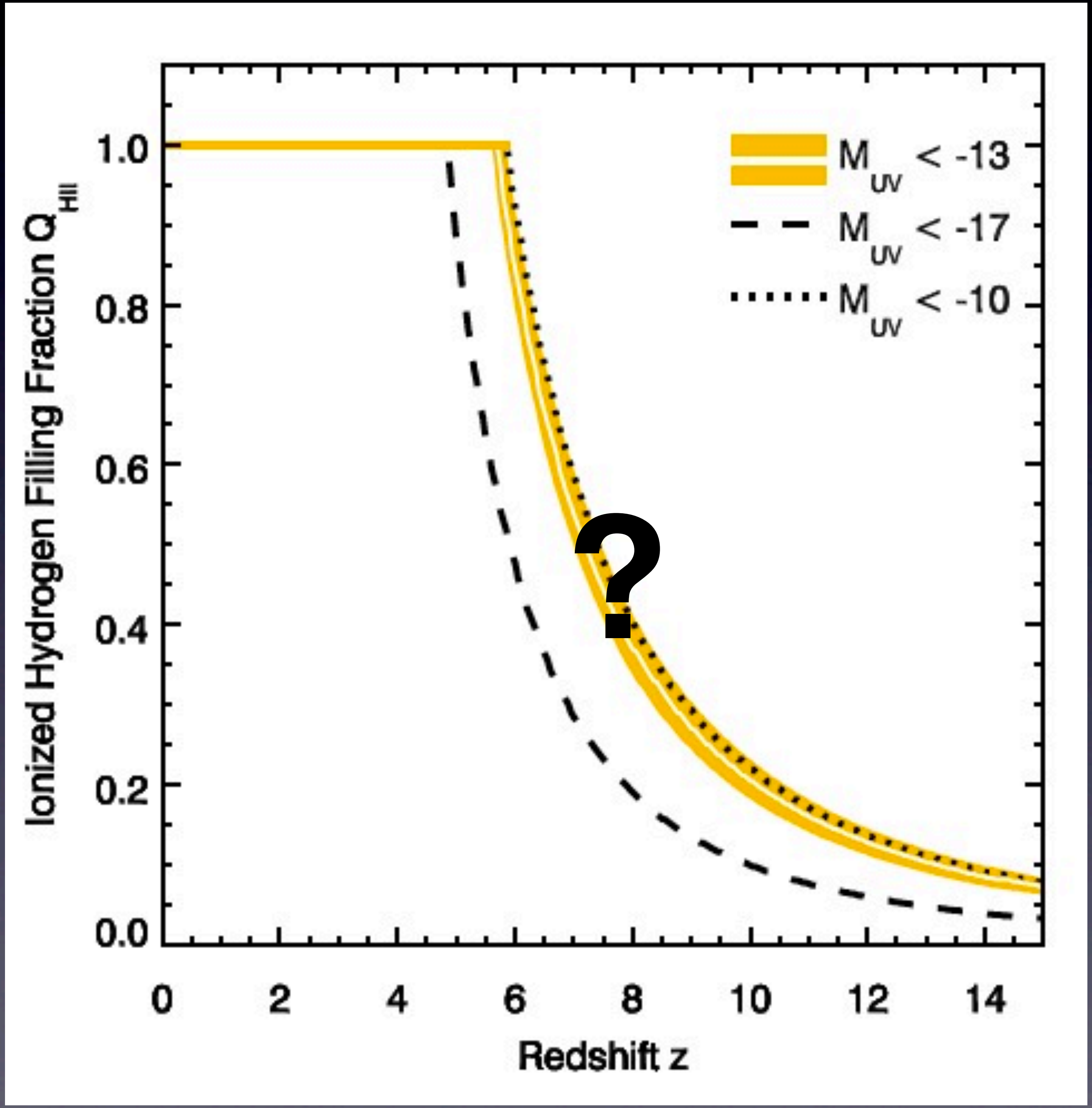
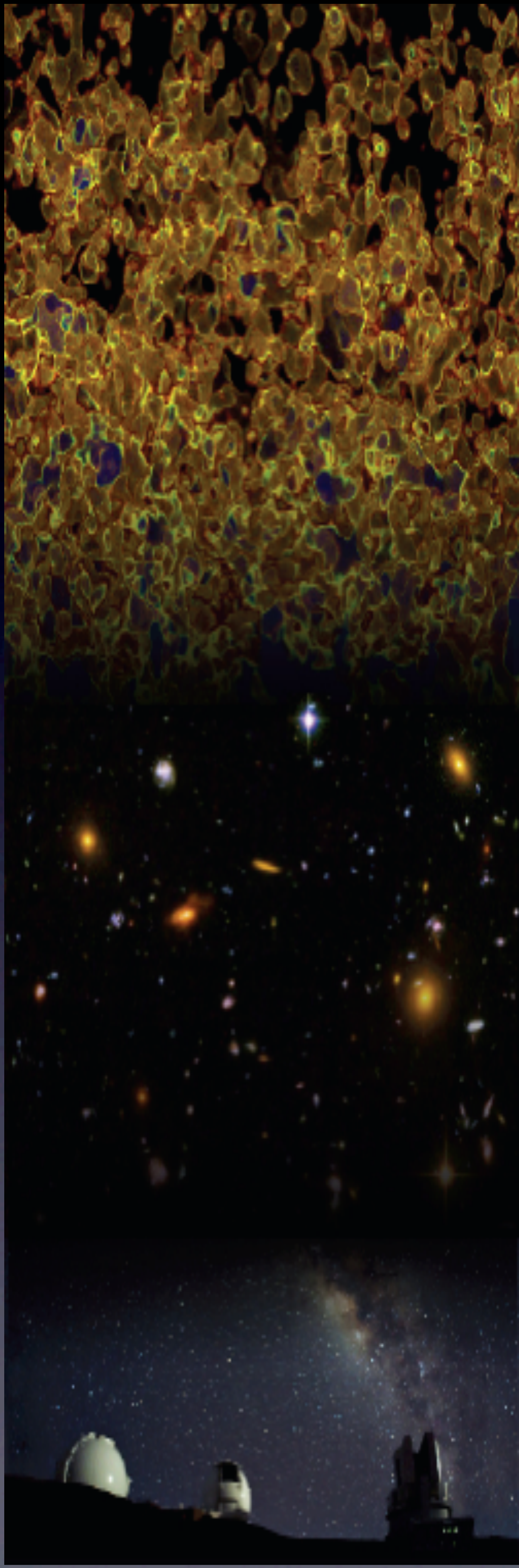
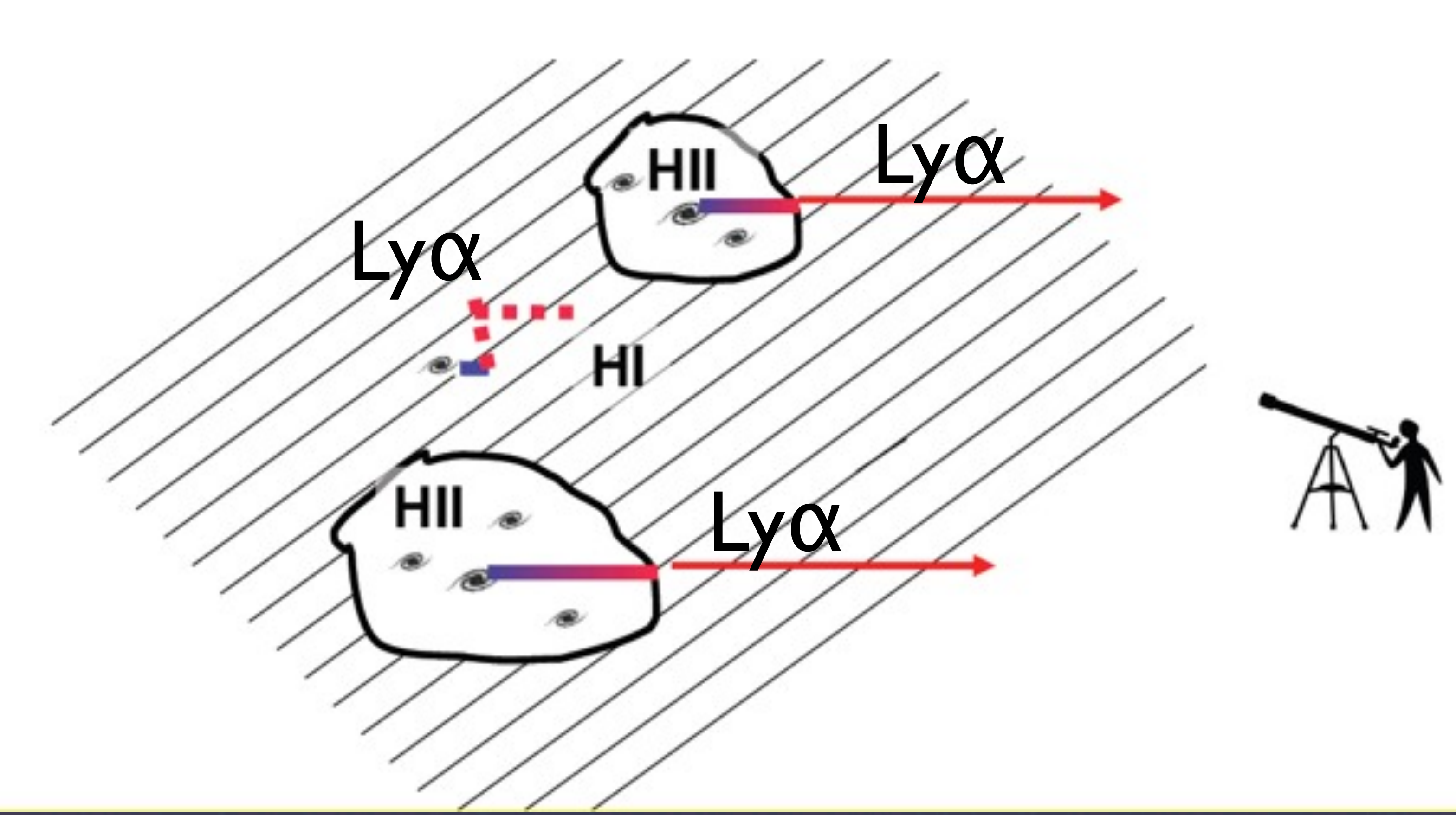
# When Does Reionization Happen?



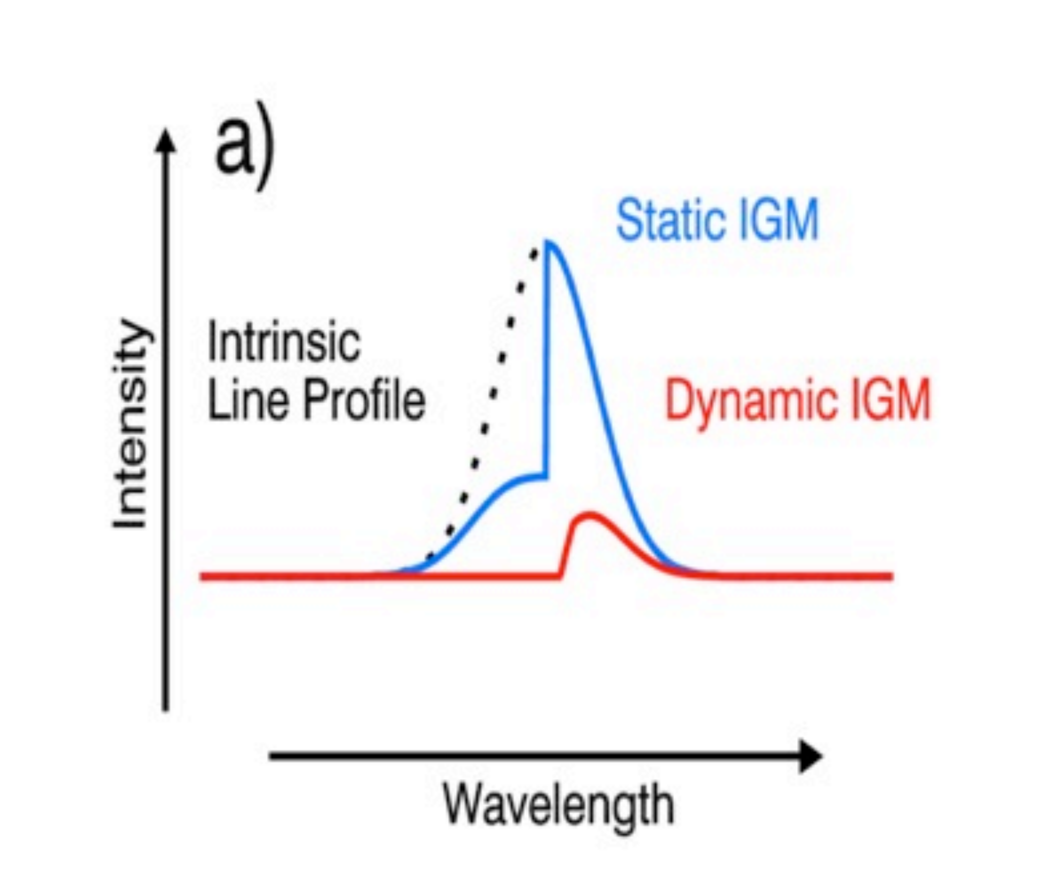



*Can we use new z>7 UV-selected galaxies to constrain IGM?*

# Galaxies as Probes of Reionization




credit: *Mark Dijkstra*




credit: *Brant Robertson*

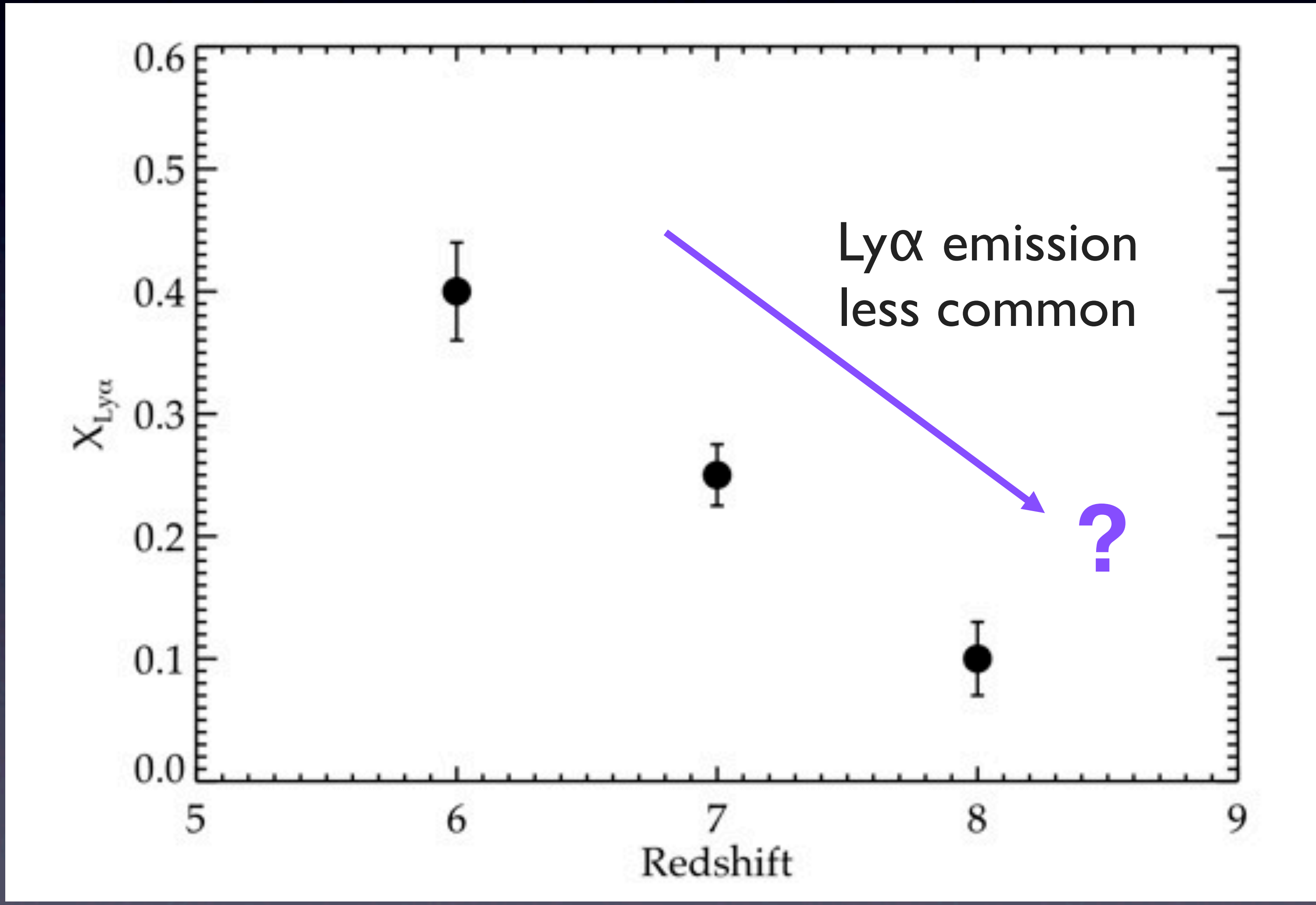
- UV-selected galaxies should emit strong Lyα radiation
- Partially neutral IGM will attenuate Lyα line through resonant scattering

# Reionization Test with LBGs

*what we might hope to see...*

Fraction of LBGs with Lyα emission above a fixed EW threshold:

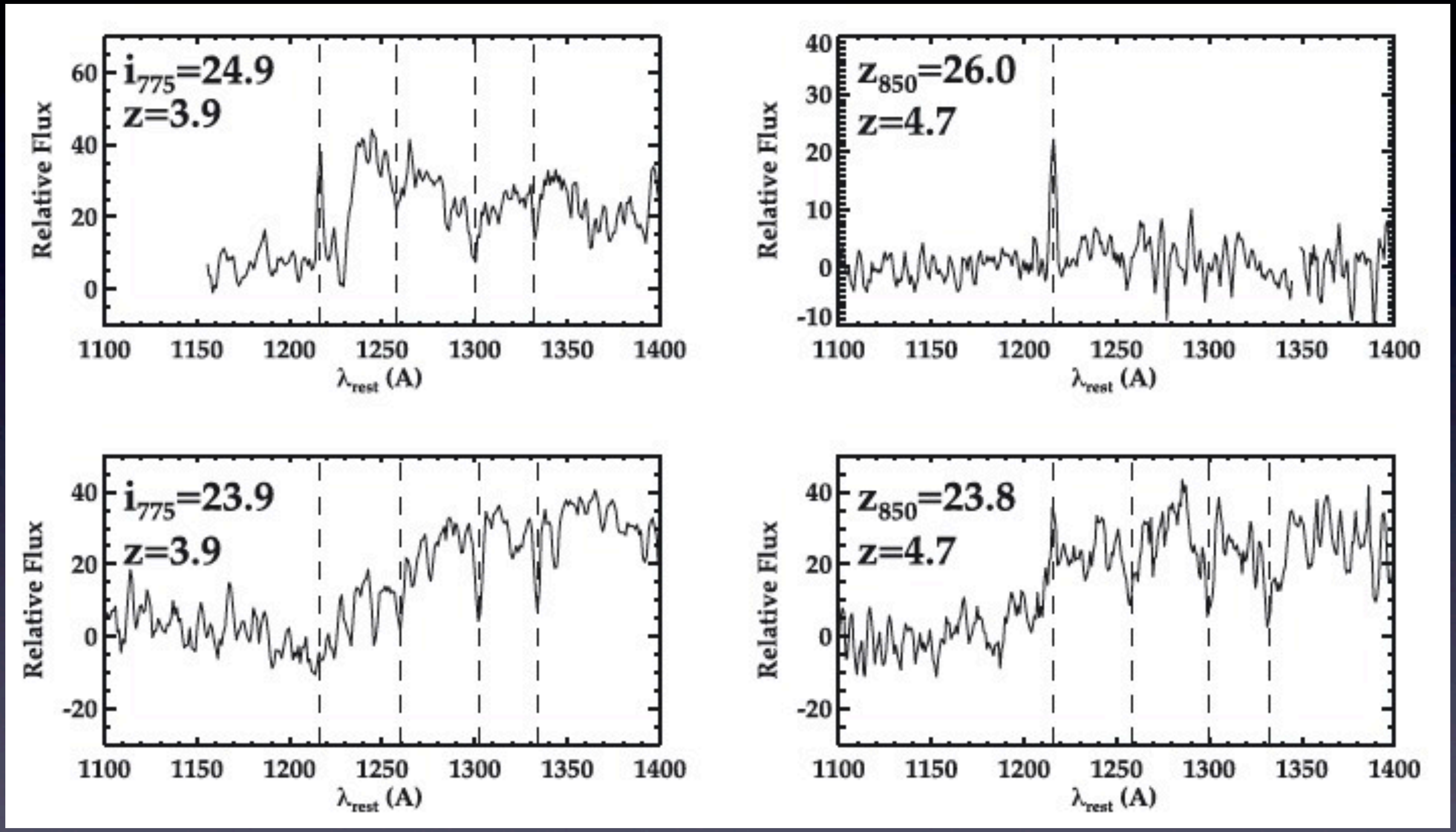
$$X_{Ly\alpha}(z) = \frac{p\, N_{Ly\alpha}}{N_{tot}}$$




*as introduced in Stark+2010,2011*

# Control measurement in ionized IGM

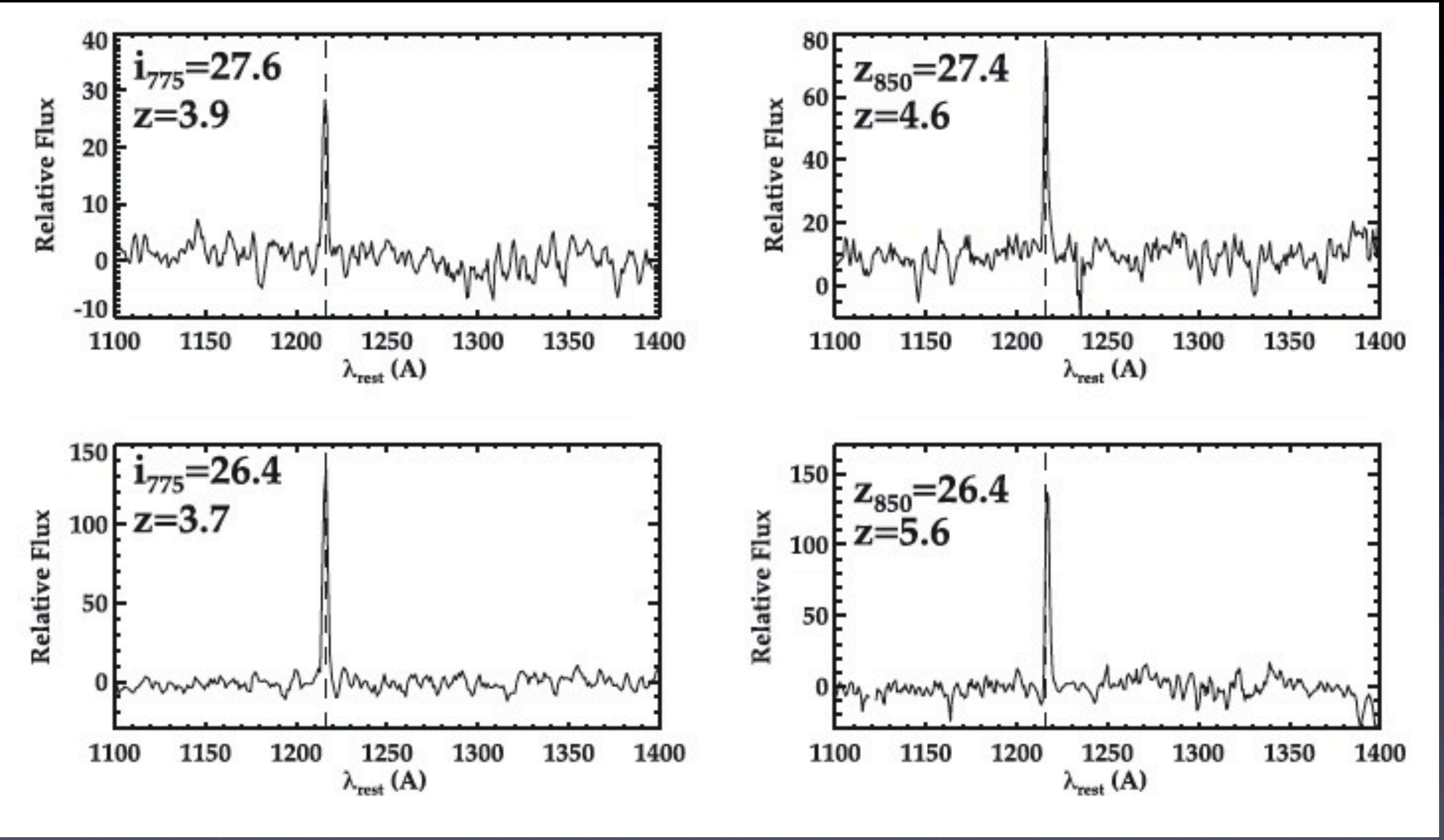
*Stark et al. 2010, 2011*




- Deep (5-12 hr) Keck spectra of ~450 4<z<6 LBGs taken with DEIMOS
- With VLT/FORS spectra, 600+ z>4 LBGs with deep spectra

# Control measurement in ionized IGM

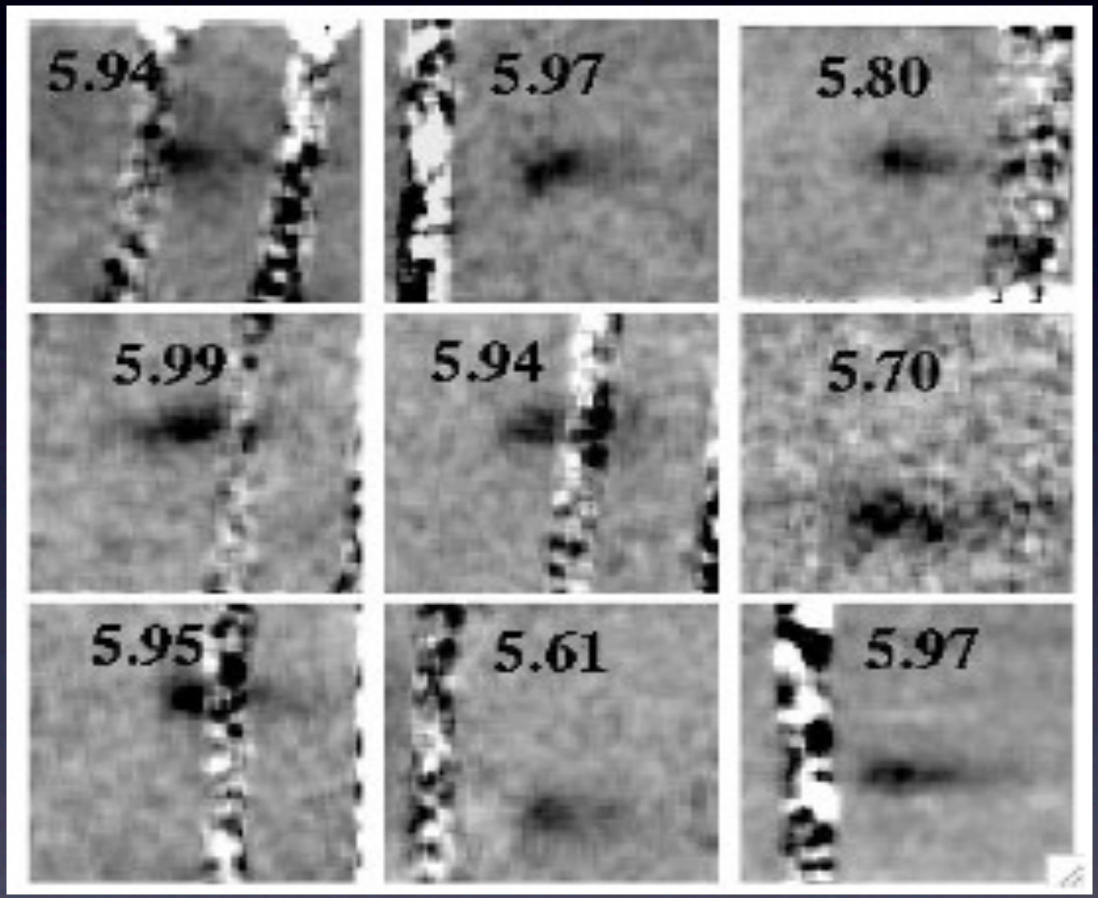
*Stark et al. 2010, 2011*

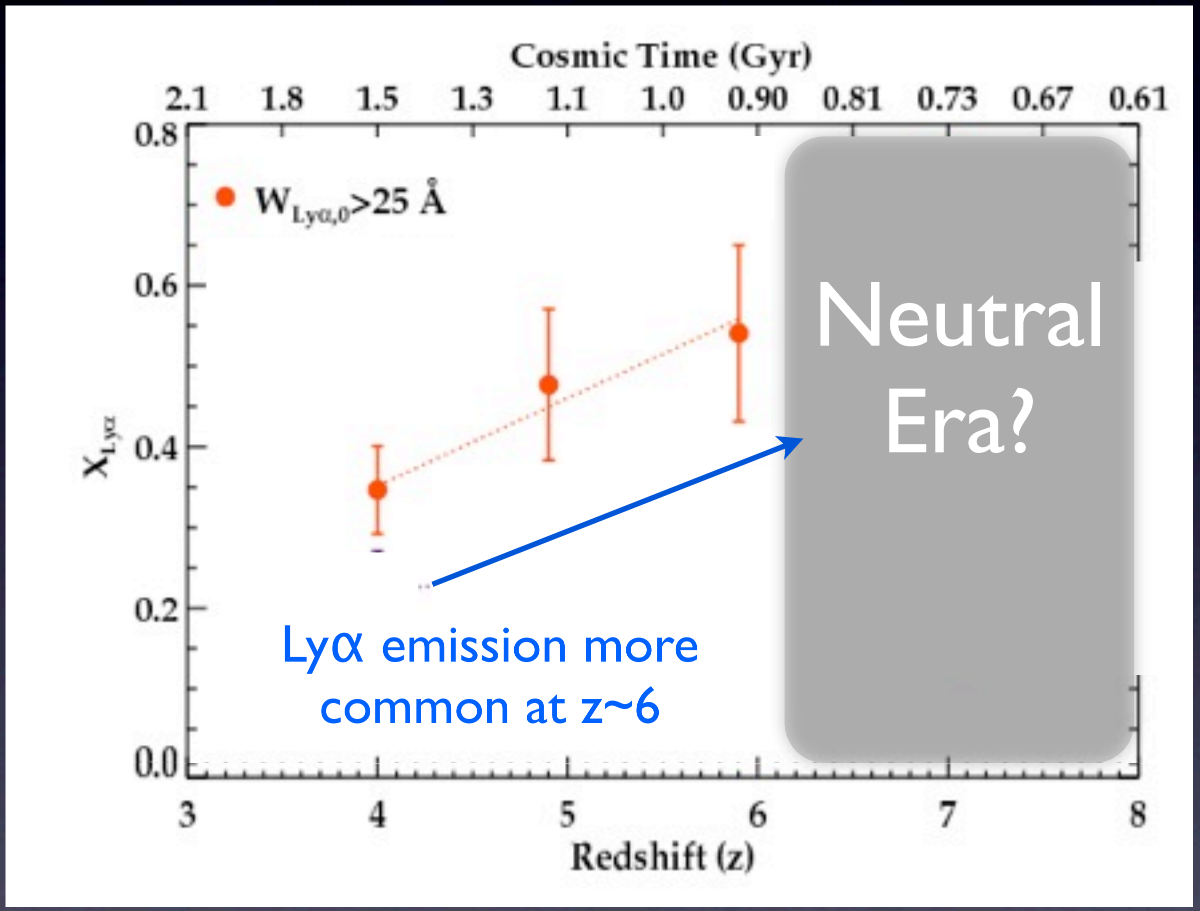



- Deep (5-12 hr) Keck spectra of ~450 4<z<6 LBGs taken with DEIMOS
- With VLT/FORS spectra, 600+ z>4 LBGs with deep spectra

# Baseline Measurement: z~6 Lyα Emission

*Stark et al. 2011*



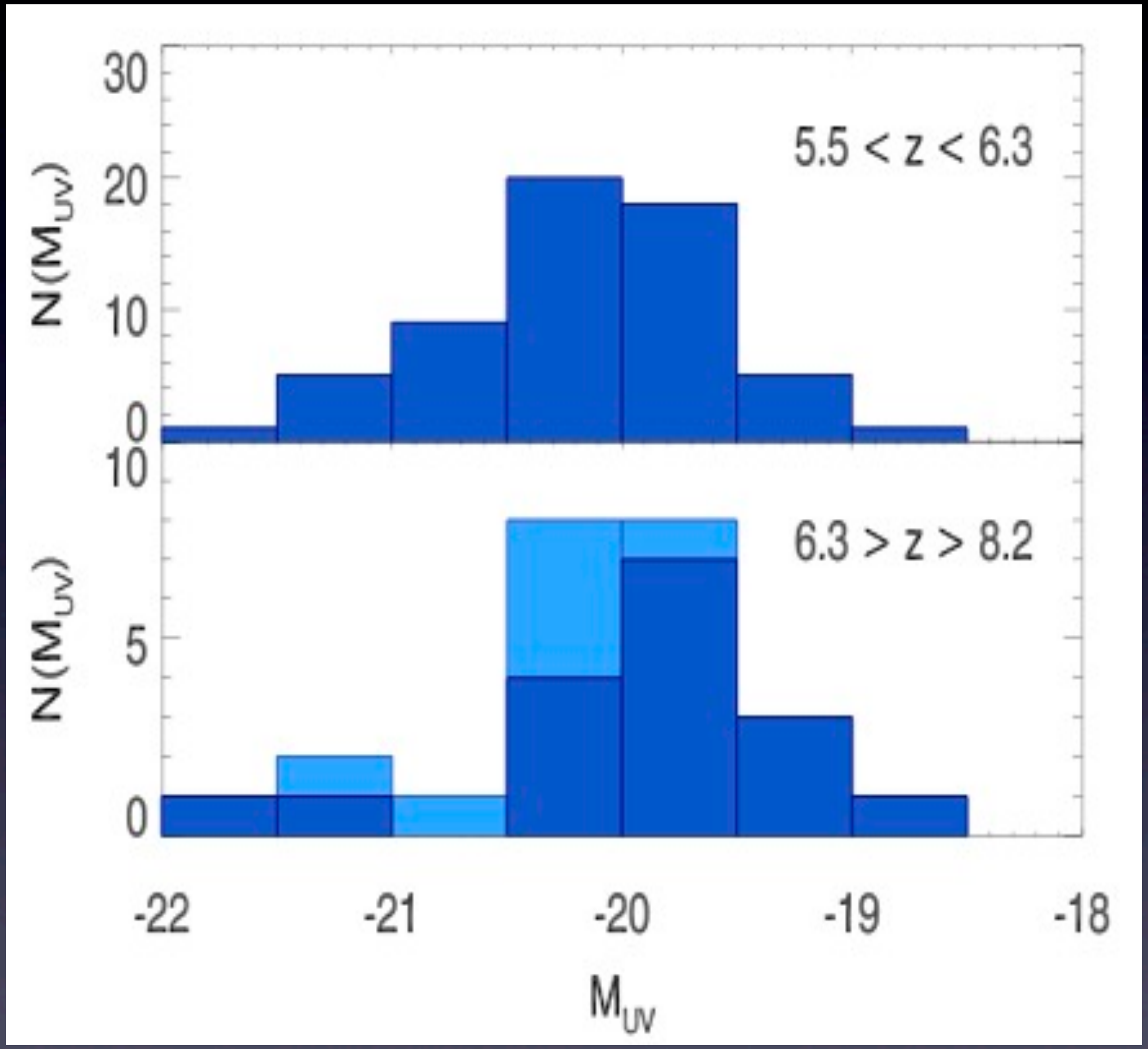




- Strong Lyα emission seen in ~50% of low luminosity z~6 galaxies
- Should be detectable in new z~7 galaxy samples

# Spectroscopy of z~7-10 galaxies

- Keck (2009-)
  Sample: 24 galaxies with $6.3<z_{phot}<8.8$
  5-7 hr exposures
  More data to come in March-April

- LBT (2012-)
  Sample: 15 galaxies with $7 < z_{phot} < 10$
  3-5 hr exposures
  luminous galaxies

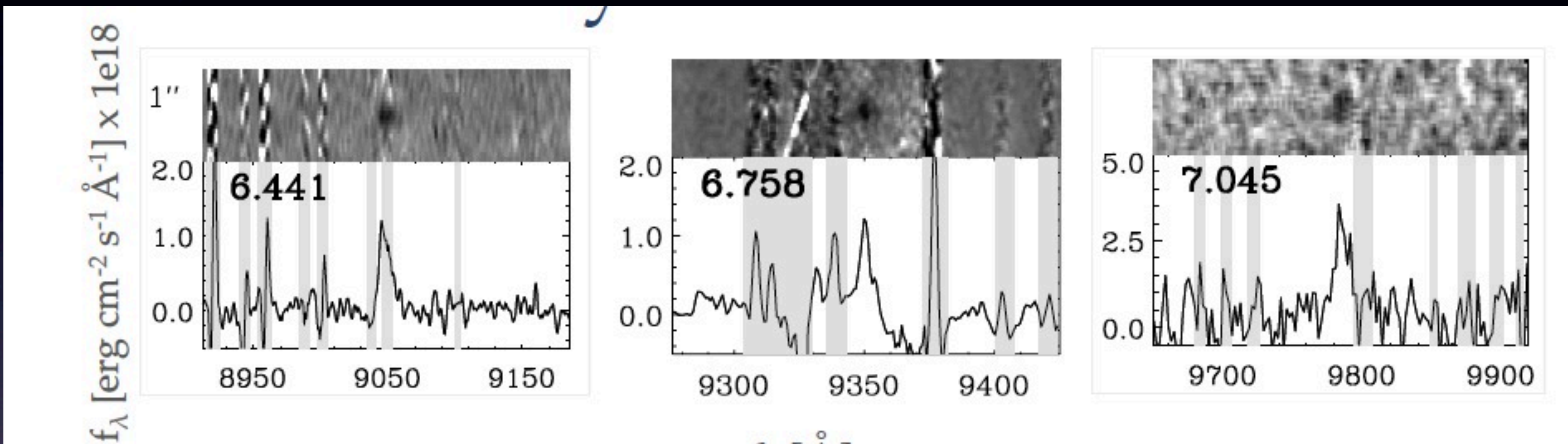



*Schenker, DS et al. 2012*

Sensitive to Lyα EW of 10-50 Å, depending on source magnitude and redshift

# Lyα Detections in z~6-7 LBGs

*Schenker, DS et al. 2012*

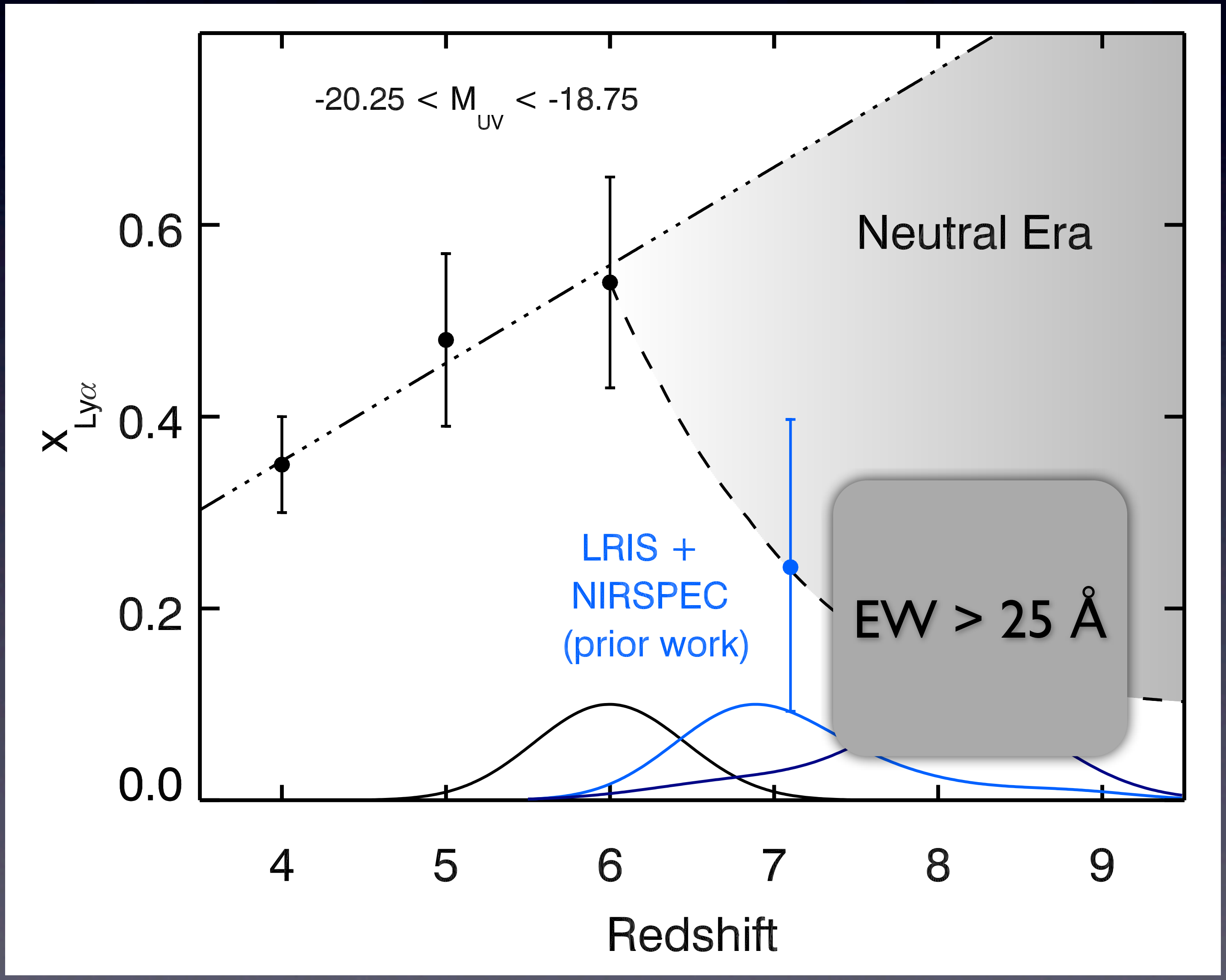



- One of 3 was found at z=7.045, first Lyα emission seen in z>7 galaxy with NIR spectrograph.
- Lyα detected in 3 of 24 galaxies in Keck survey.

*Is Lya emission less common at z>6.5?*

# Lyα Fraction Decreases over 6<z<7

Schenker, Stark et al. 2012

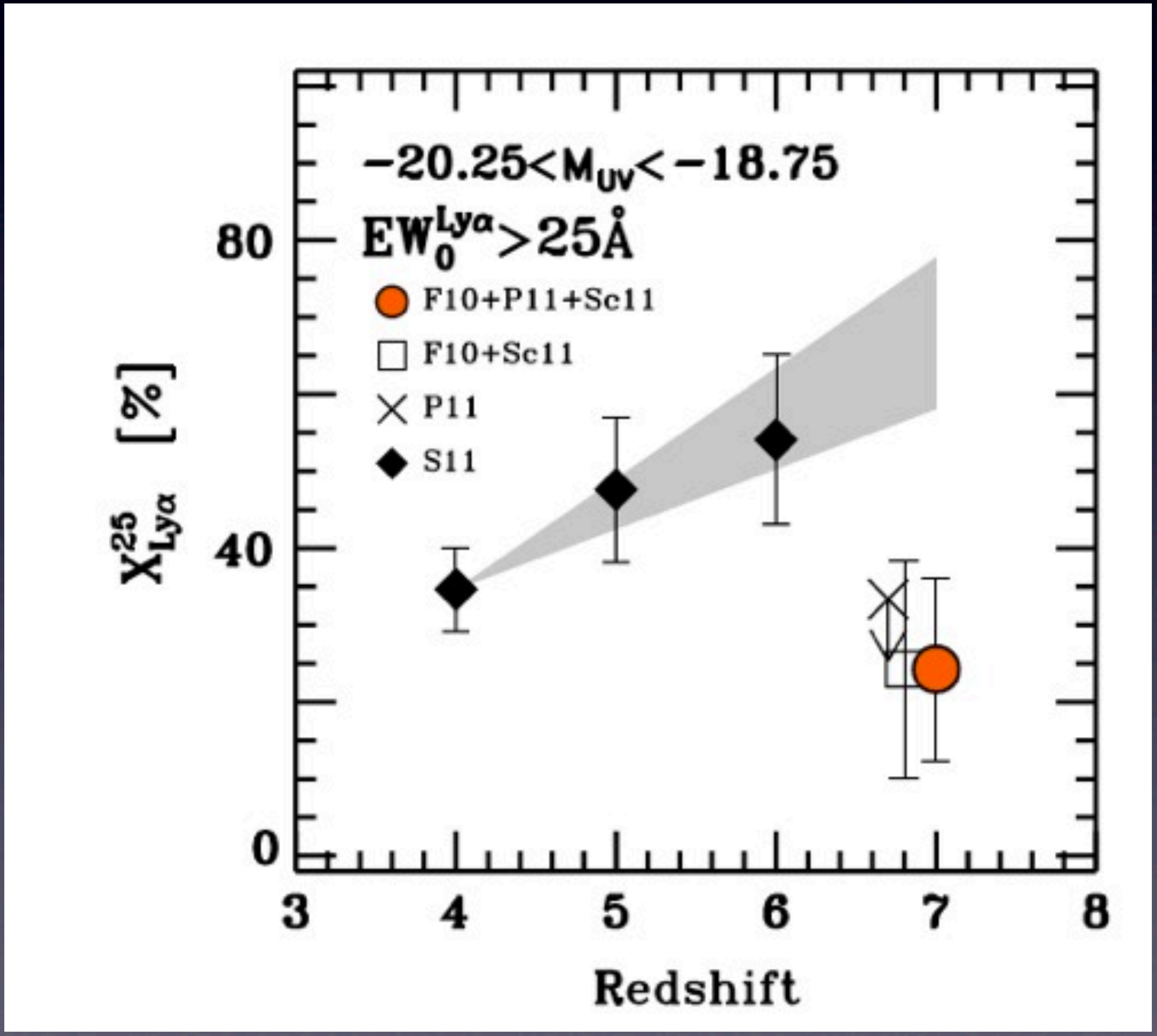



Lyα transmission decreases in 200 Myr period spanning 6<z<7.

see also Ono et al. 2012, Pentericci et al. 2012, Treu et al 2012

# Lyα Fraction Decreases over 6<z<7

Ono et al. 2012

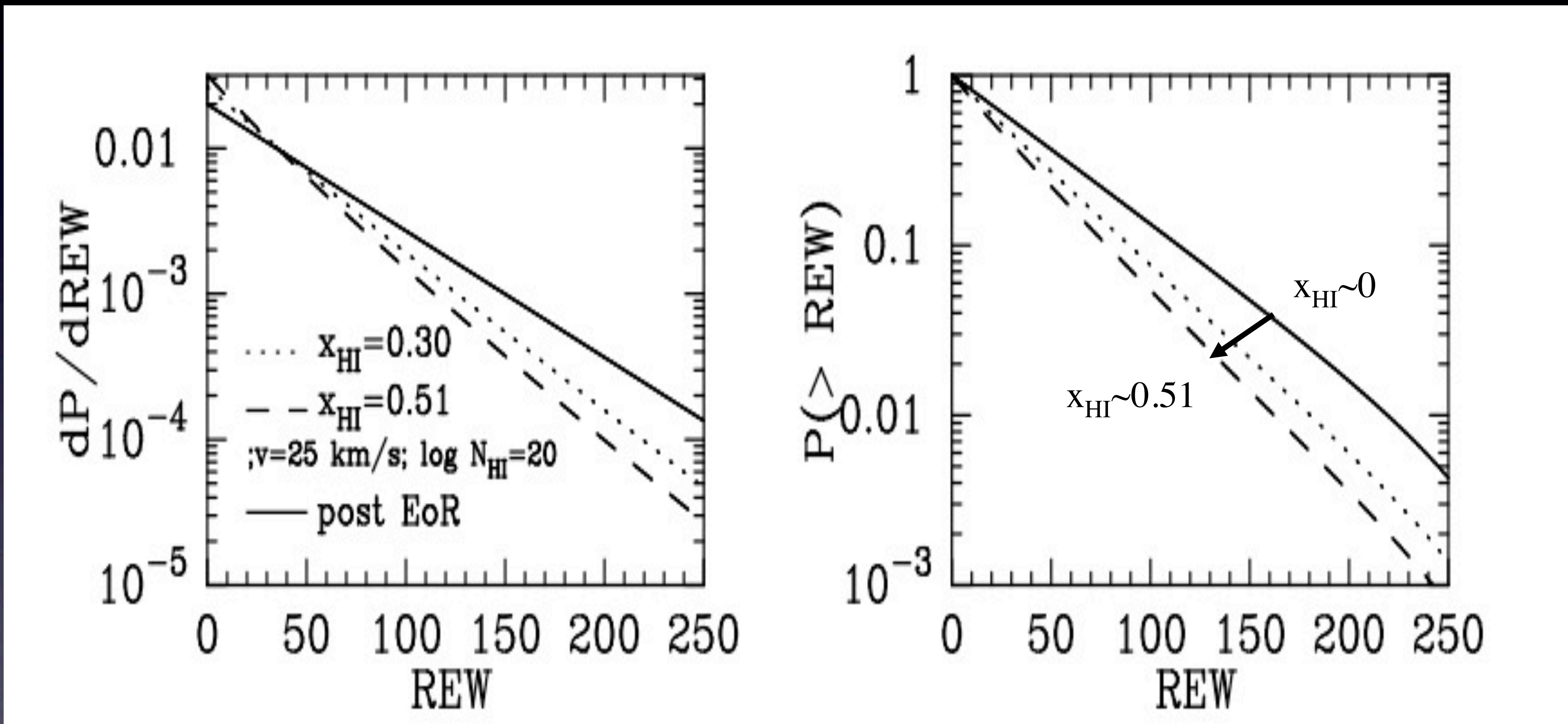



Lyα transmission decreases in 200 Myr period spanning 6<z<7.

Similar results from independent samples in different fields.

# Implications for Reionization

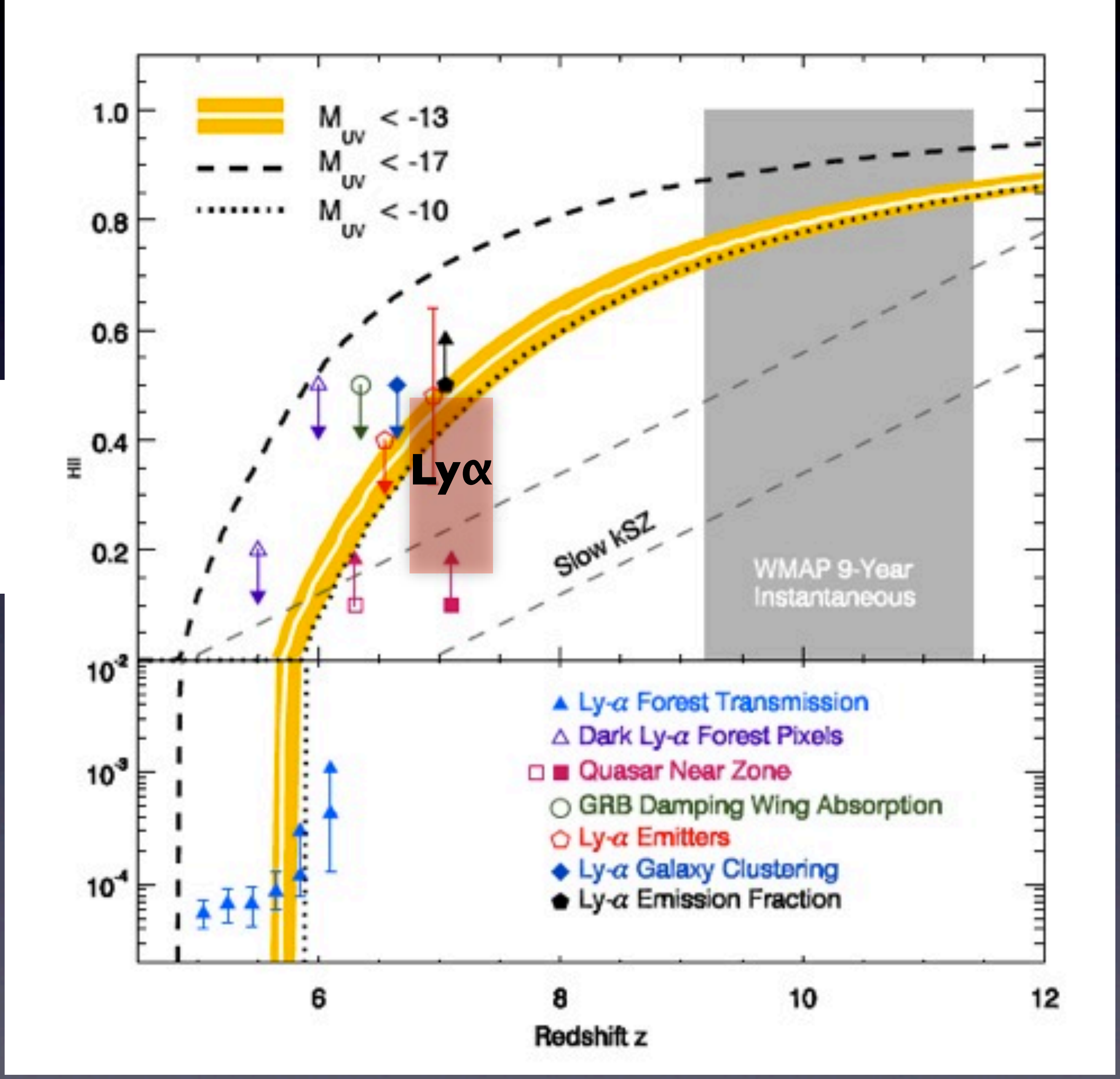
Dijkstra, Mesinger, & Wyithe, 2011, arXiv:1101.5160




~40% decrease in Lyα fraction with EW > 50 Å requires IGM neutral HI fraction of $x_{HI}$>0.1 at z~7

# Updated Reionization constraints

IGM HI Filling Factor

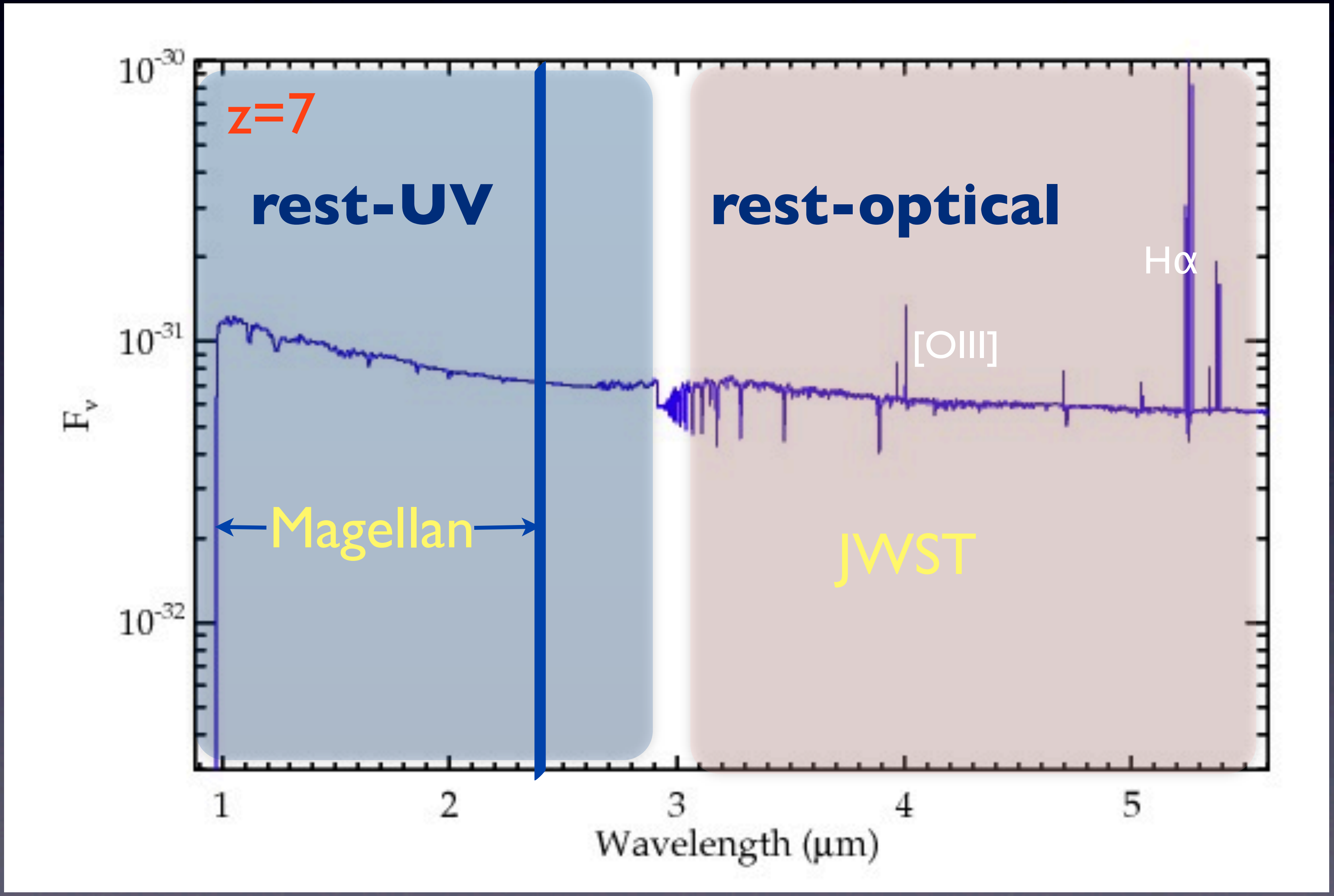



*compilation in Robertson et al. 2013*

Decrease in Lyα fraction consistent with 10-50% HI fraction at z~7.

10% HI fraction consistent with inferences from quasar near zone size evolution at z>6.

# Can we learn more about low mass reionization-era galaxies?



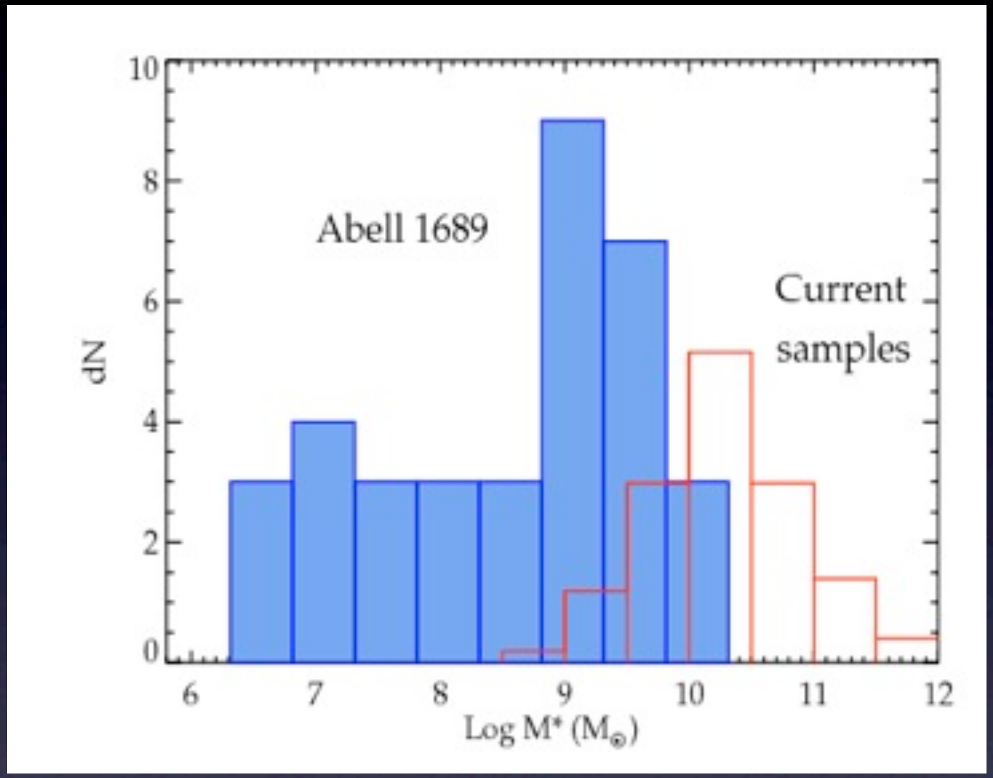

Rest-optical inaccessible until JWST

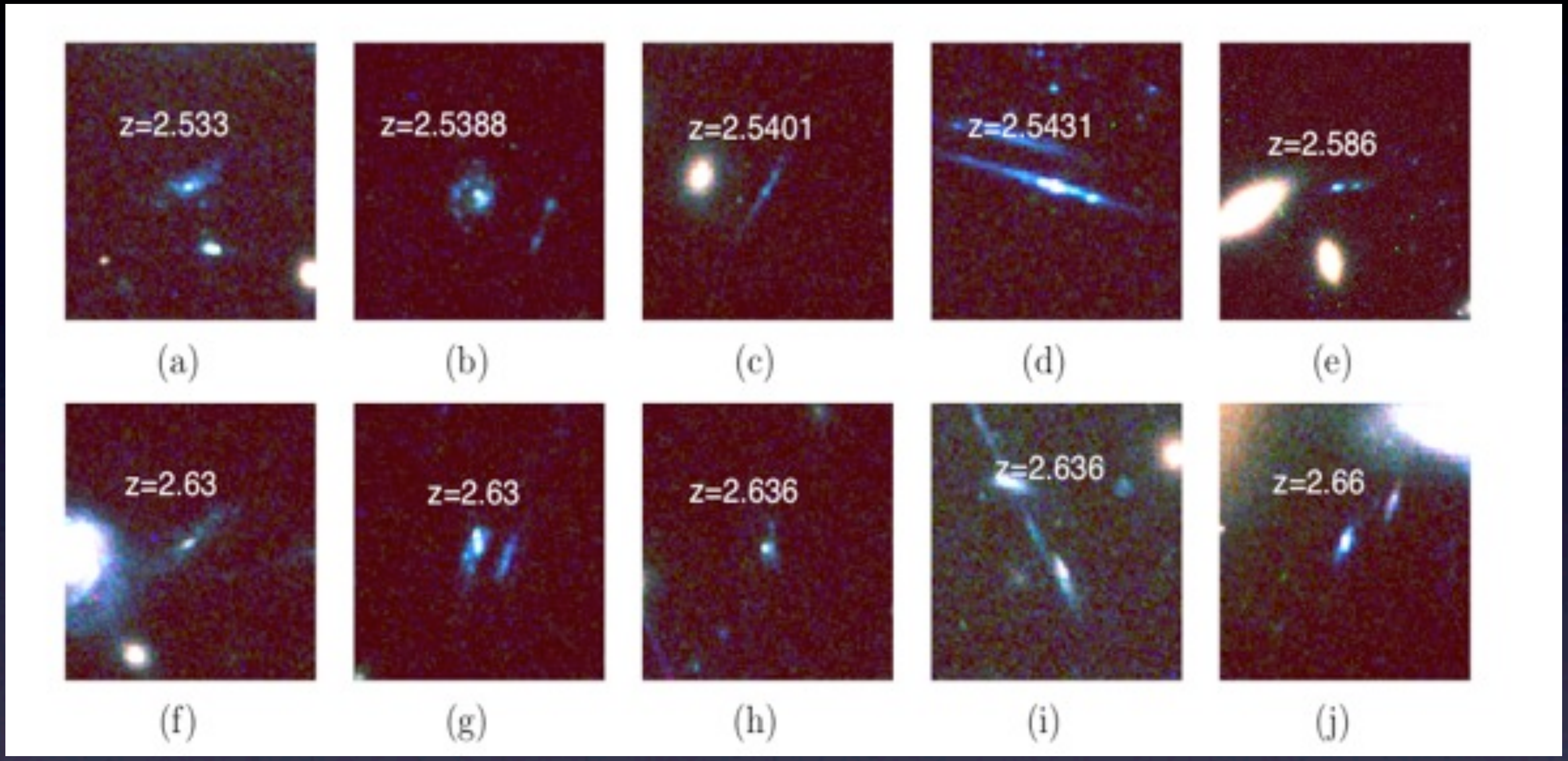
Few emission lines in rest-UV of luminous galaxies, *particularly if Lyα obscured at z>7.*

*Might reionization era systems have different UV spectra?*

# Stellar Populations of Low Stellar Mass, Metal Poor Galaxies at z~2

*Stark et al. 2013, in prep*

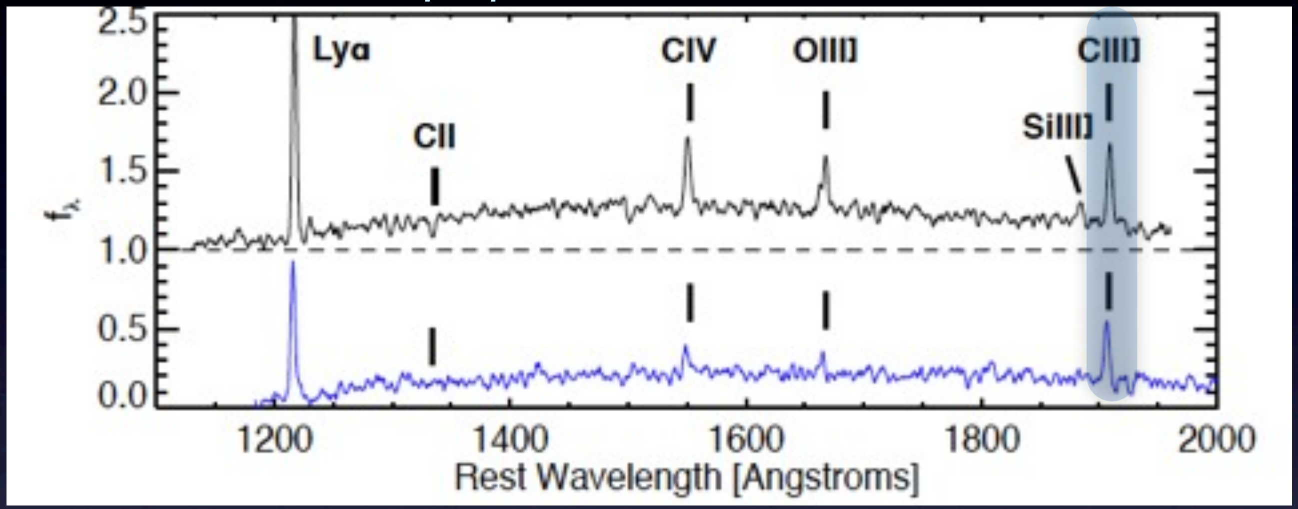


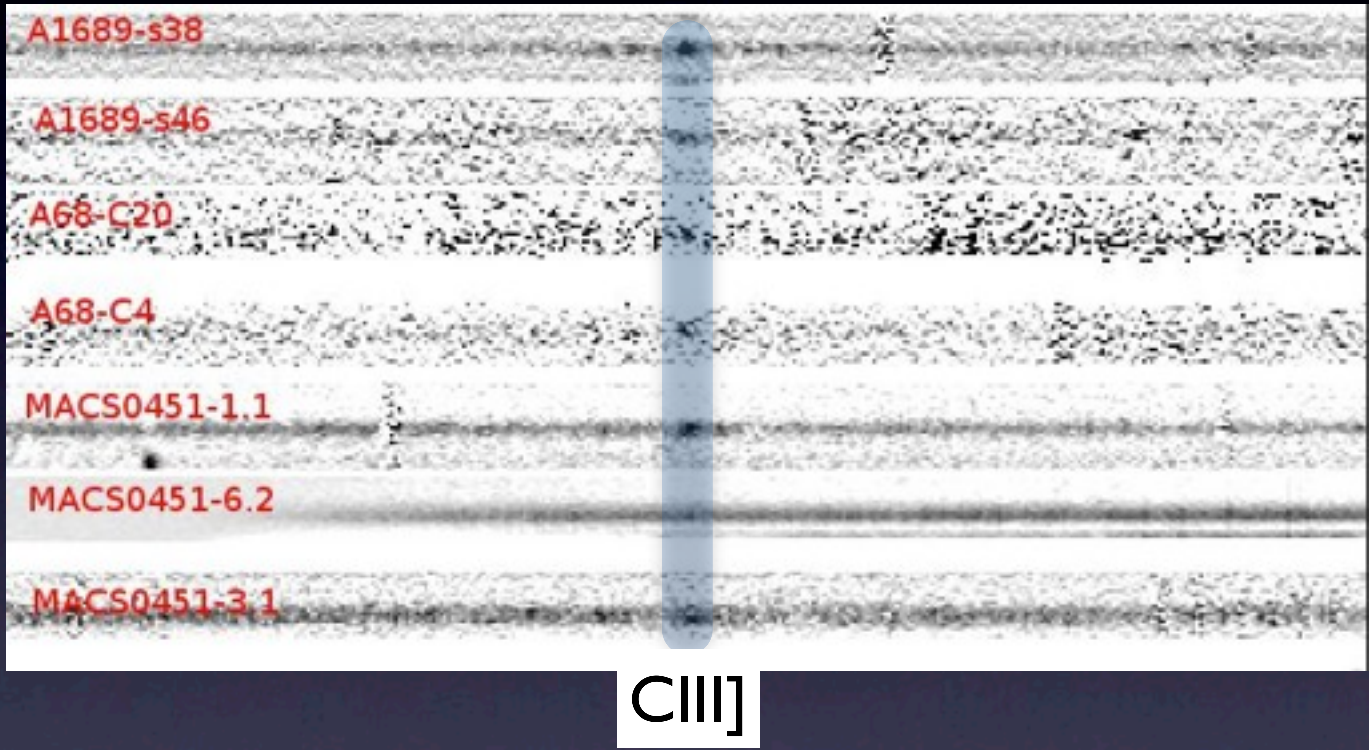



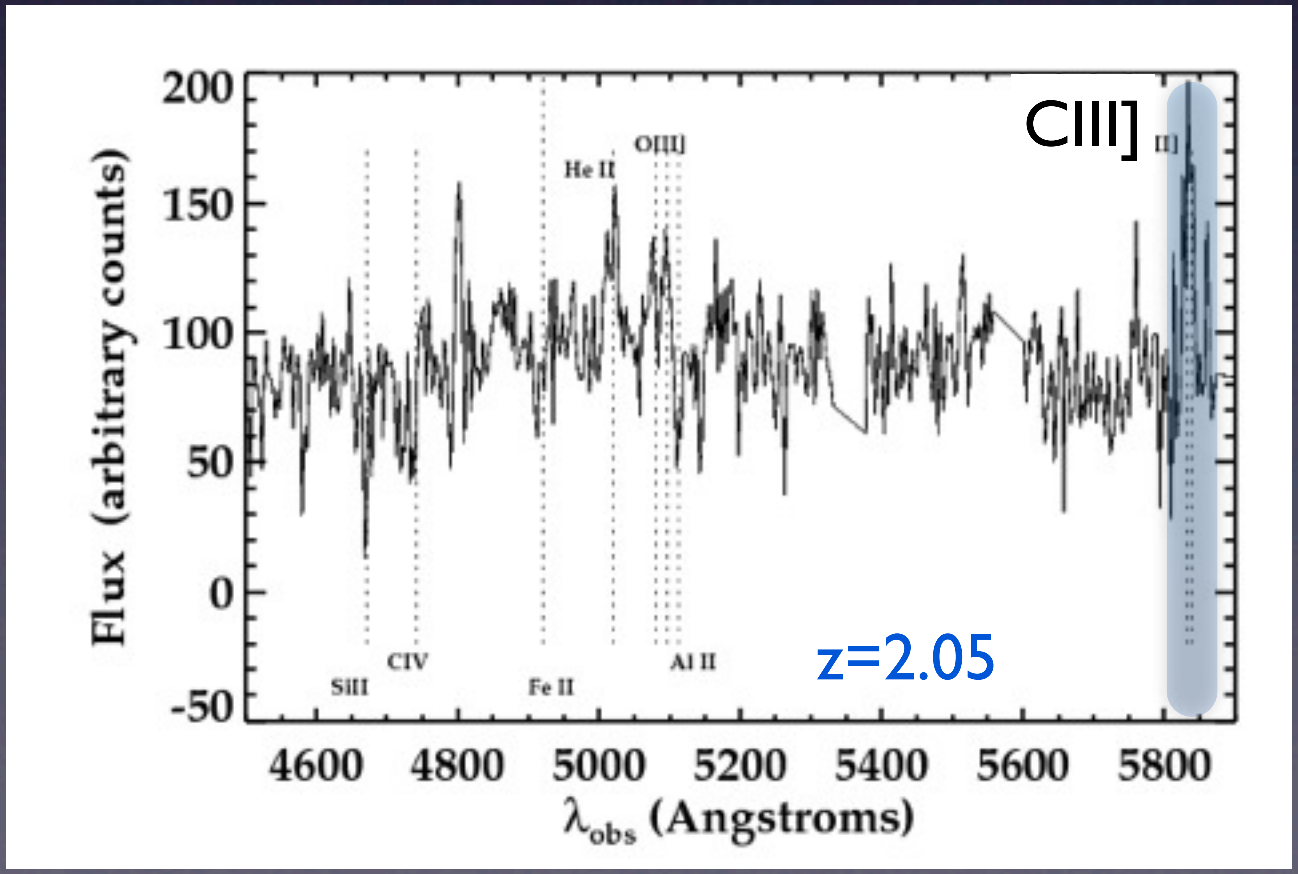

- Spectroscopic sample of $10^{6\text{-}9}$ $M_\odot$ galaxies (stellar mass)
- Sizes range between 0.3 and 2 kpc, SFR as low as 0.1 $M_\odot$/yr
- Rest-UV spectra (VLT/Keck), Rest optical spectra (Magellan/FIRE)

# High Ionization Emission Features

*Stark et al. 2013, in prep*



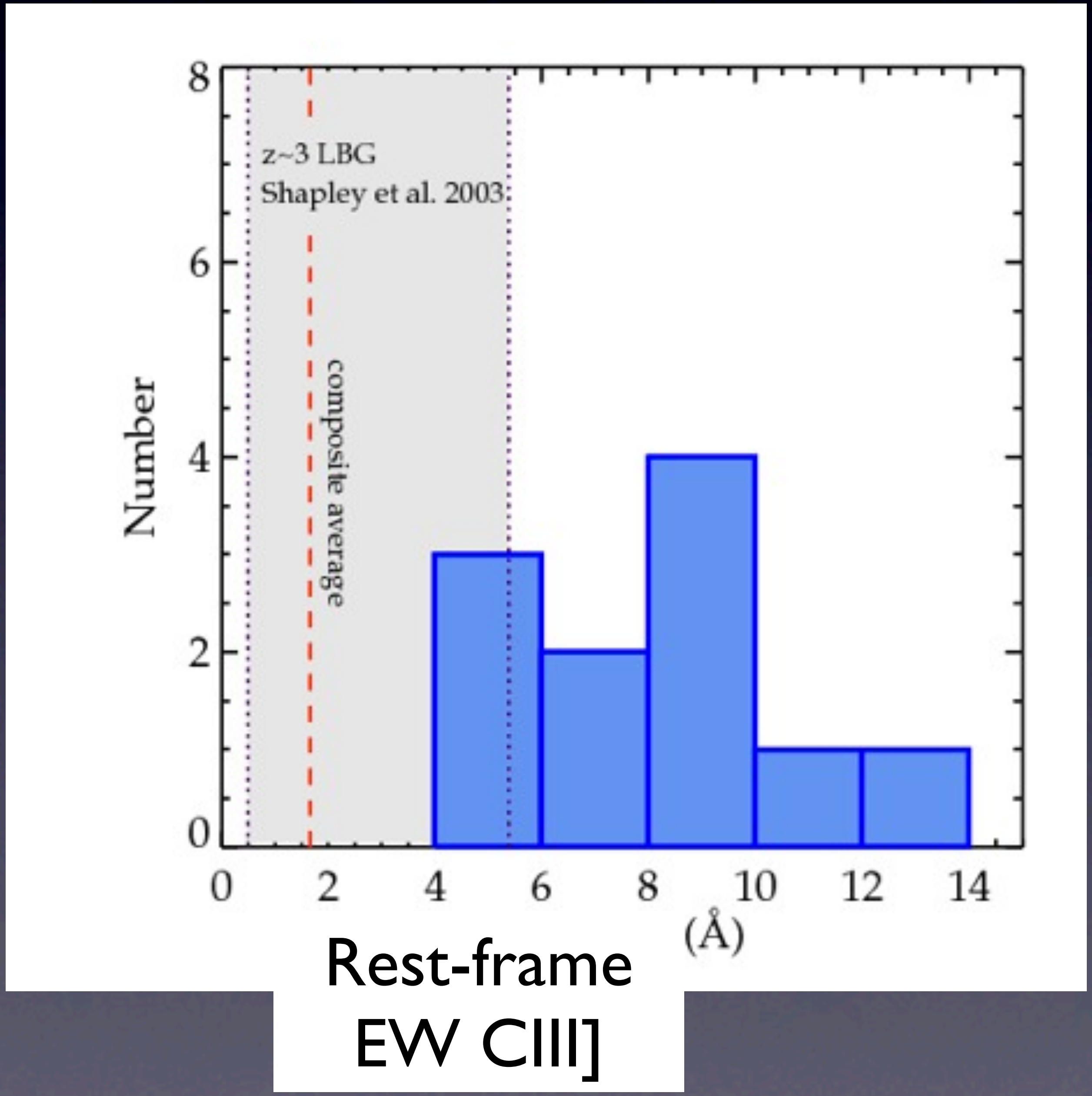




Strong CIII] emission is seen in every single lensed galaxy spectrum with <$10^9$ $M_\odot$

He II and CIV in select systems.

# Comparison to more massive galaxies

*Stark et al. 2013, in prep*




Rest-frame CIII] EW of low mass lensed galaxies at z~2-3 is 4.5-18 Å.

Composite stack of $10^{10-11}$ $M_\odot$ LBGs at z~3 has CIII] EW of 1.7Å.

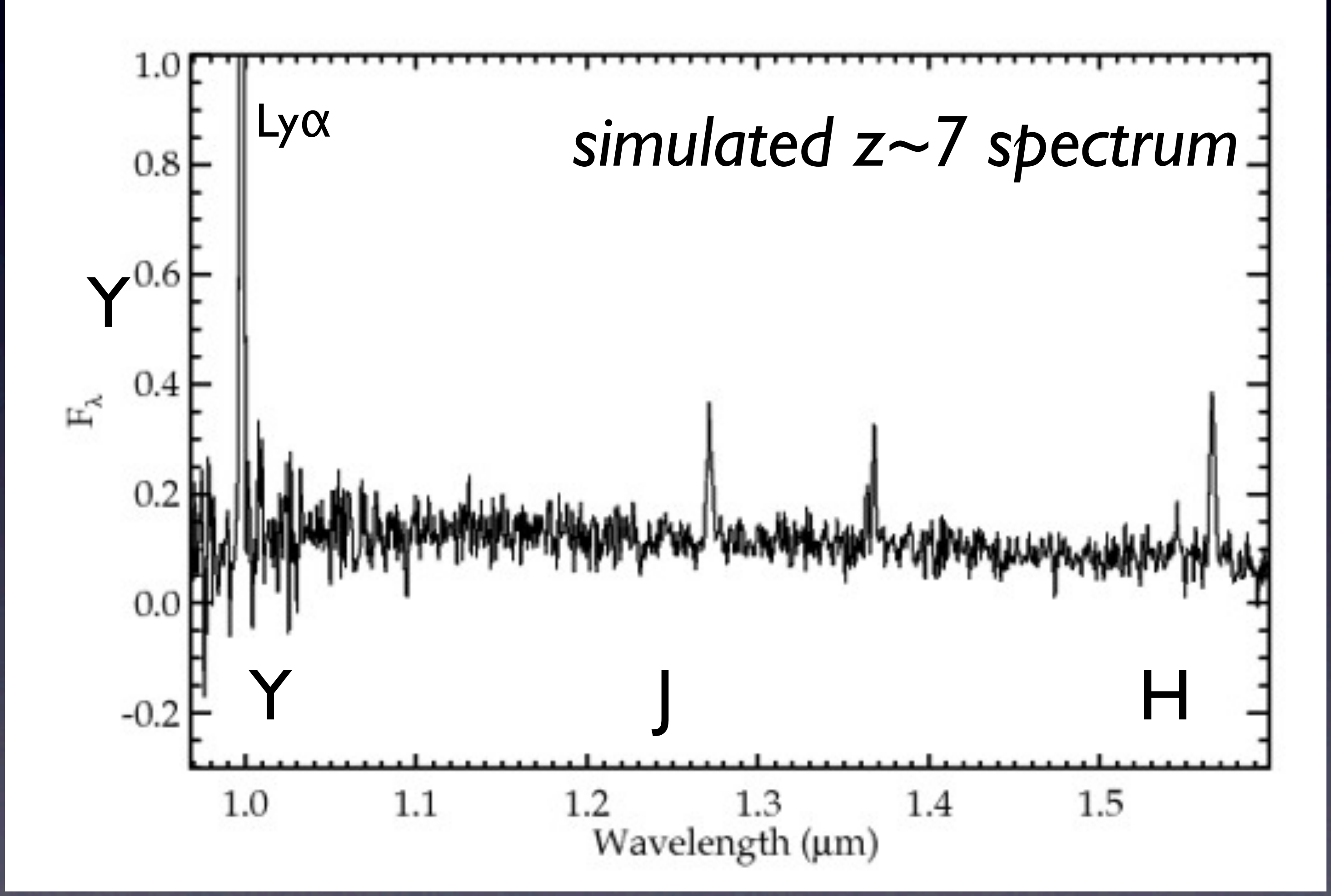
CIII EW is ~5-10x greater in low mass (<$10^9$ $M_\odot$) galaxies.

Points to harder ionizing spectrum!

# Next step: Extend to z~7 Galaxies

Current generation near-IR spectrographs can detect CIII] in bright z~7 galaxies.

Composite stack will yield constraints/detections of CIV He II, OIII, and CIII.




*First insight into chemistry and massive stellar populations at z~7 coming soon*

# Summary

- Early star forming galaxies and reionization
  1. Low stellar mass and high sSFR at z>7.
  2. Galaxies can achieve reionization if star formation efficient below detection limits and escape fraction of ionizing radiation is ~20%.

- When did Reionization happen?
  1. Ly$\alpha$ emission visibility decreases over 6<z<7.
  2. Consistent with HI fraction in range 0.1-0.5 at z~7.

- Lessons from gravitational lensing
  1. Escape fraction evolution likely.
  2. Harder ionizing spectra in low mass, metal poor galaxies
  3. Strong nebular lines in rest-UV opens door for extracting physics from z~7 galaxies.