



# The Ultraviolet Spectra of Lyman Break Galaxies at $z=4$ : Outflows in the First 2 Billion Years

Tucker Jones (Caltech – CGE/UCSB)  
with Richard Ellis (Caltech) & Dan Stark (Arizona)

The Baryon Cycle, 16 June 2012

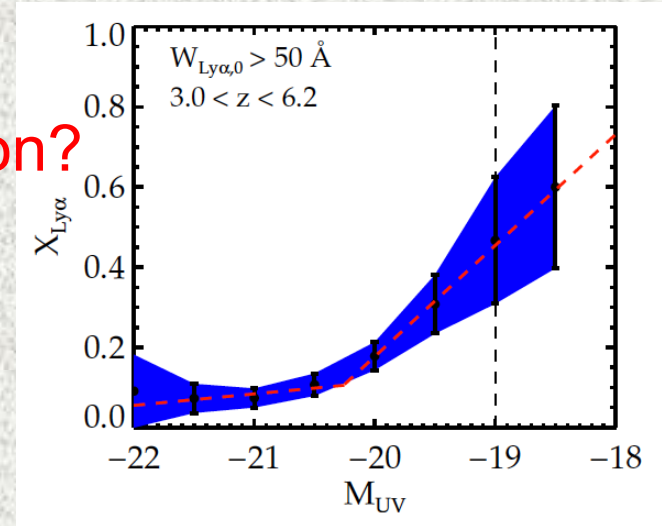
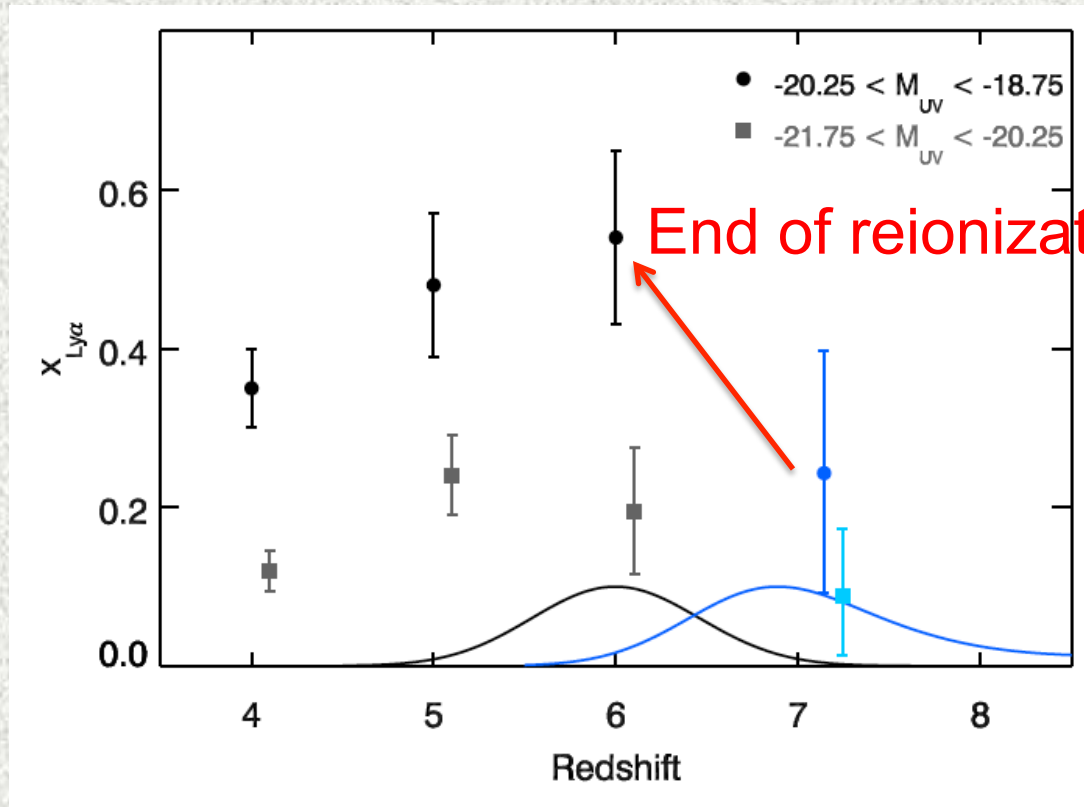


# Neutral Gas Around High Redshift Galaxies

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# Ly $\alpha$ emission fraction



Stark+10,11  
Schenker+11

- Ly $\alpha$  emission depends on redshift and galaxy properties
  - Neutral IGM at  $z > 7$
  - Neutral hydrogen in CGM, ISM changes with redshift

# Topics

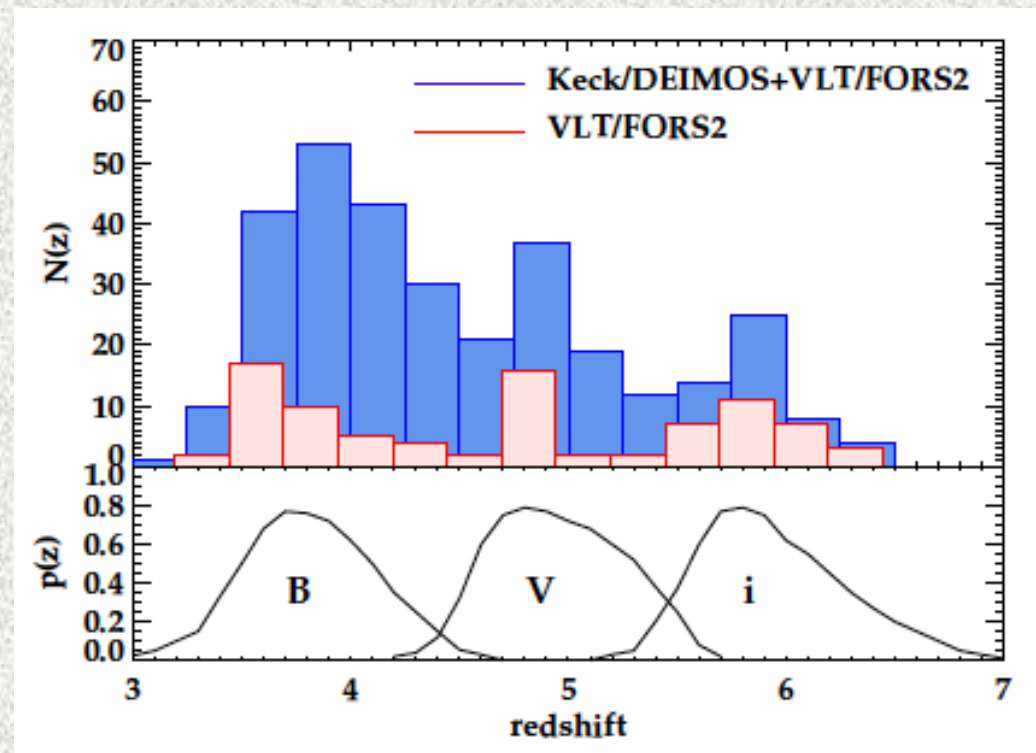
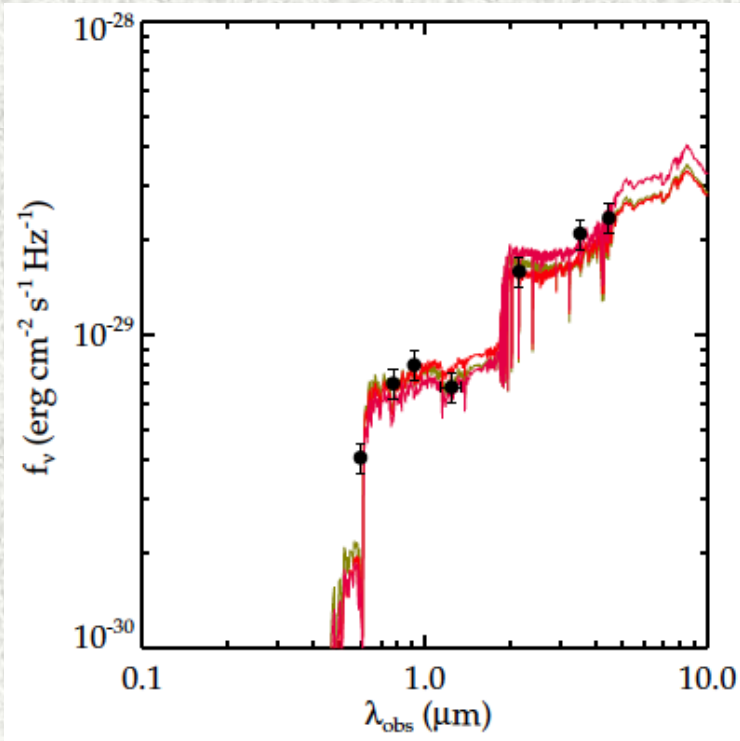
1. What governs Ly $\alpha$  emission?

(answer: neutral HI gas, dust)

2. What is the distribution of neutral gas around high redshift galaxies?

3. Implications for reionization

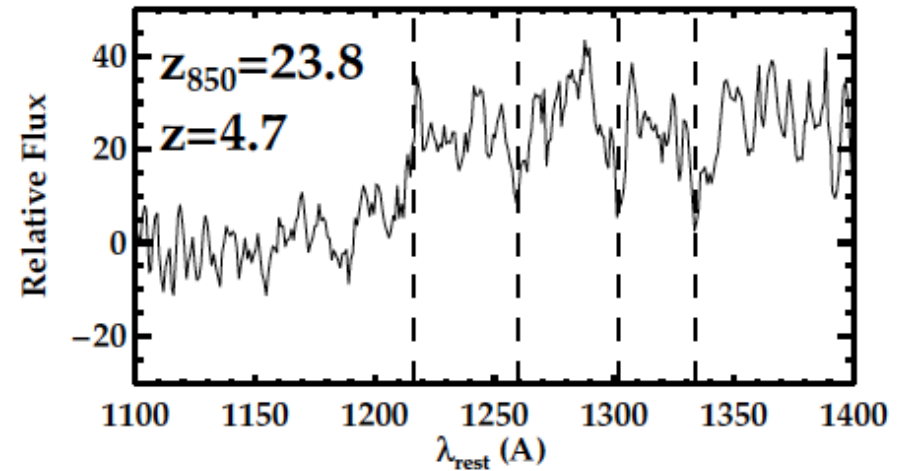
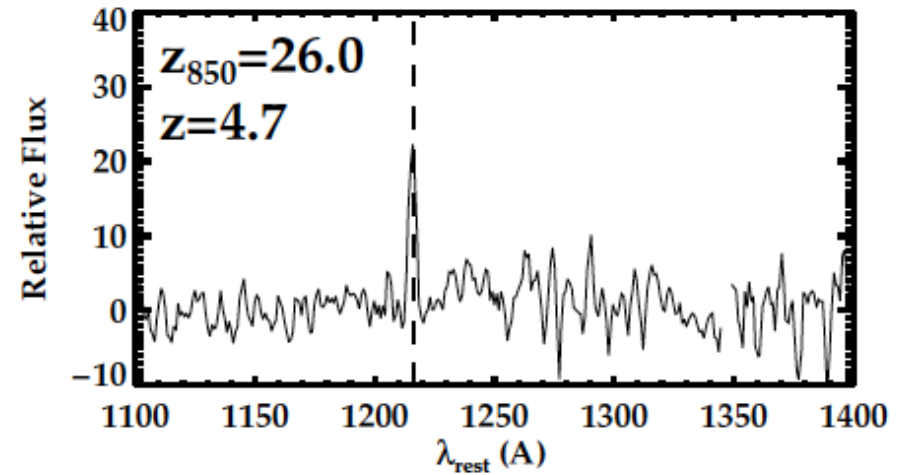
# Survey Overview



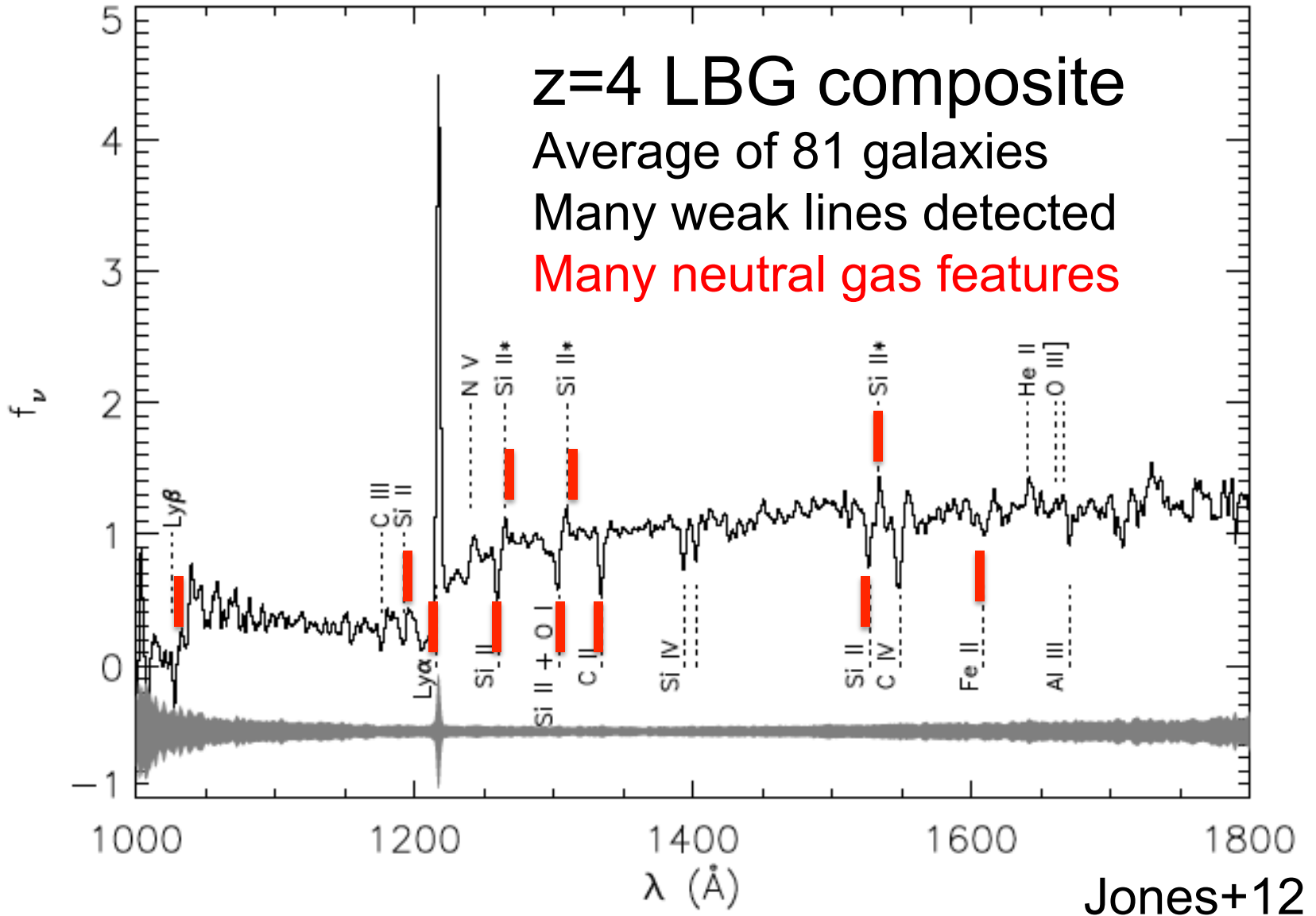
- Spectroscopic survey of Lyman Break Galaxies at  $z=3-7+$ 
  - Deep photometric data from GOODS and CANDELS
- Over 600 galaxies observed to date
  - Largest spectroscopic sample at these redshifts

# Keck/DEIMOS Spectra

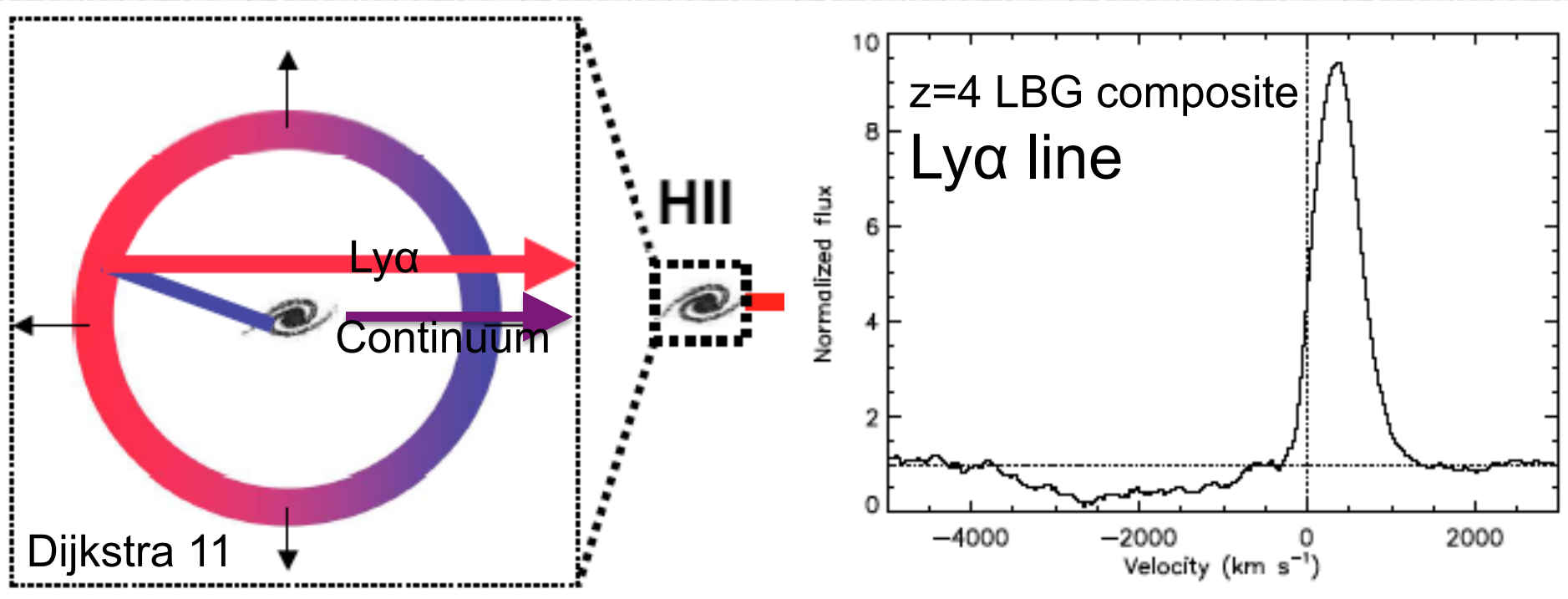
- 5-12 hour exposures
- $R \approx 2000$  ( $\Delta v \approx 150$  km/s)
- Optical magnitudes as faint as  $m_{AB} = 27.5$ 
  - Good continuum detection for  $m_{AB} < 25.5$
- Strong Ly $\alpha$  emission easily identified
  - Stack many spectra to detect weaker lines



# Composite Spectra



# Outflow Kinematics



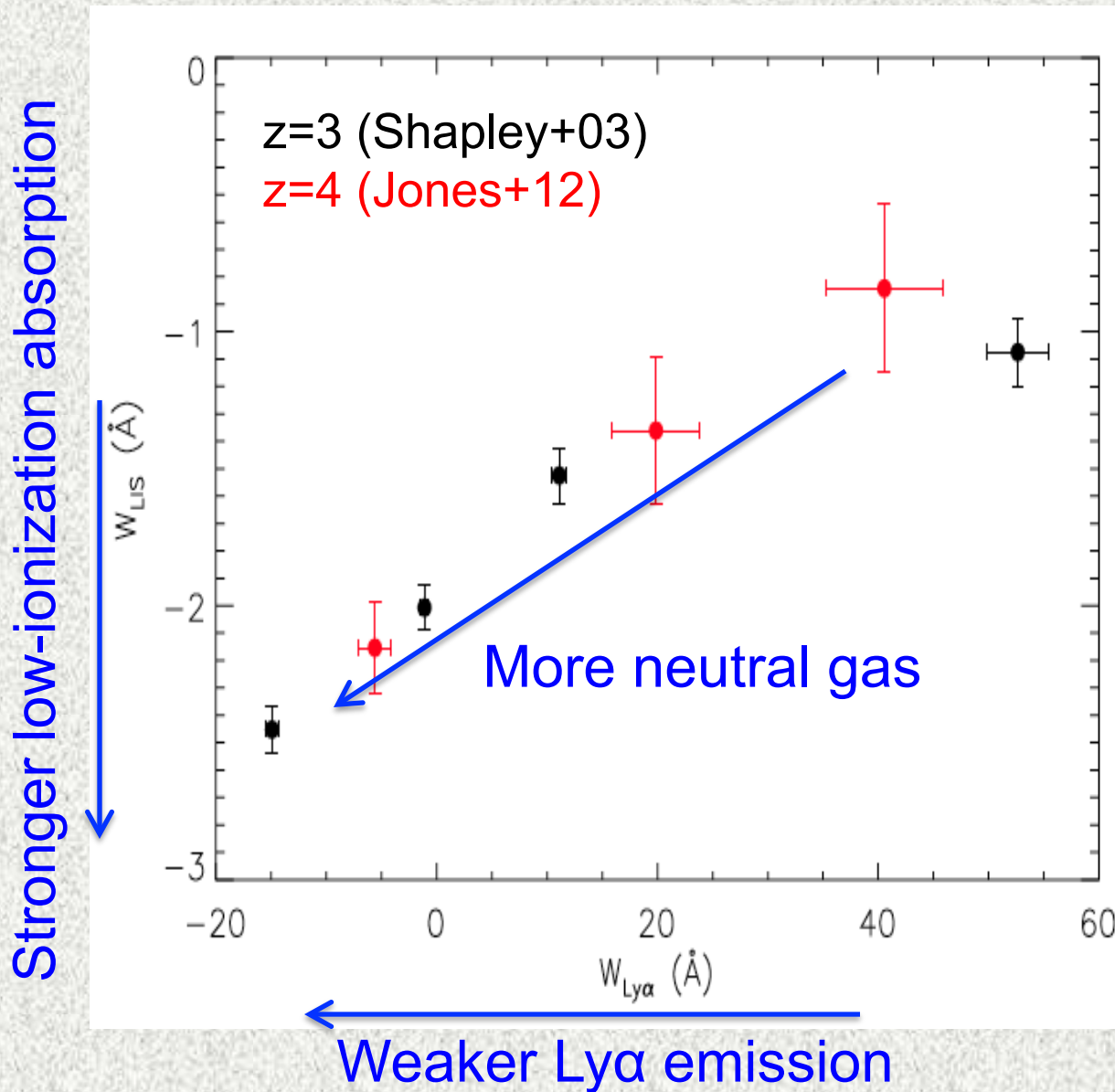
blueshifted absorption  
in both HI and low-ionization  
metal transitions

redshifted emission  
in Ly $\alpha$

More neutral gas  $\rightarrow$  stronger low-ionization metal absorption,  
lower Ly $\alpha$  equivalent width



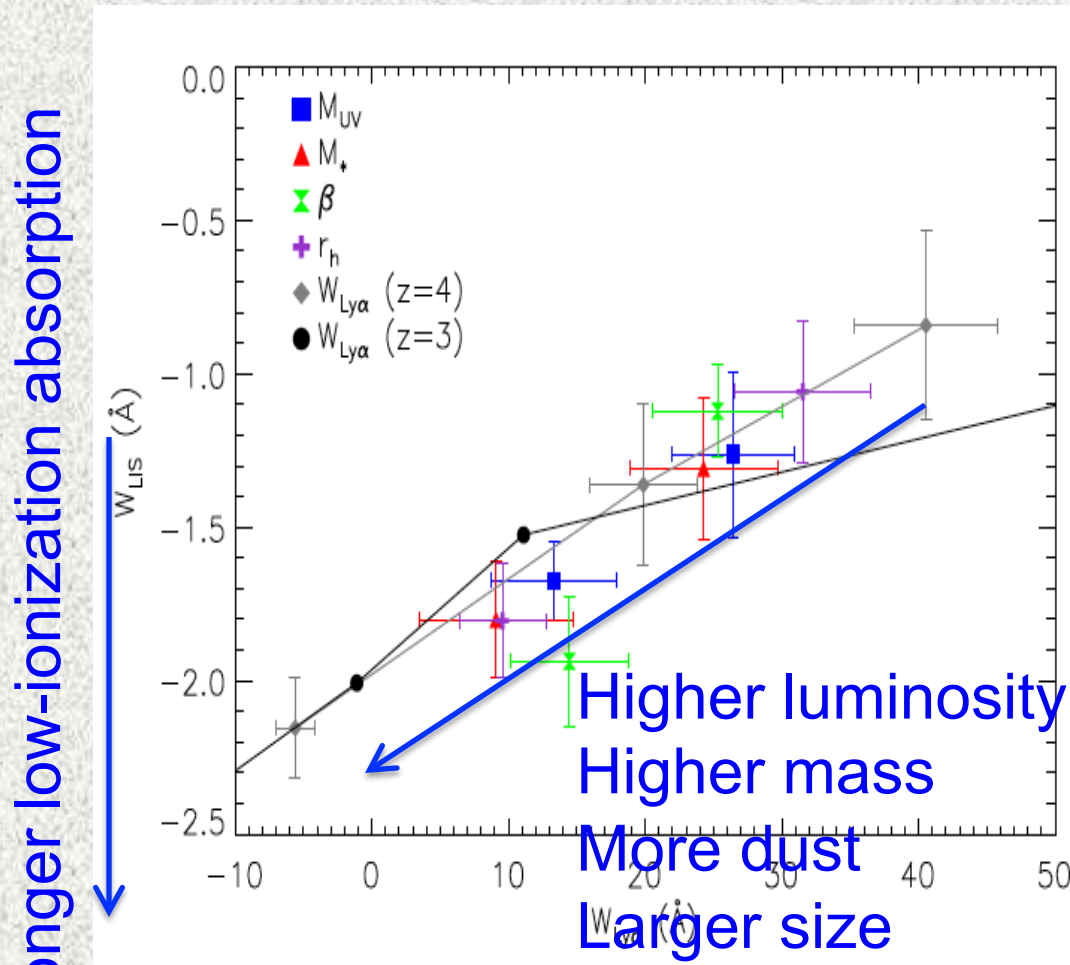
# Results: Neutral Gas at High $z$



Ly $\alpha$  strongly correlated with low-ionization absorption

Similar relation at  $z=3$  and  $z=4$

# Results: Galaxy Properties



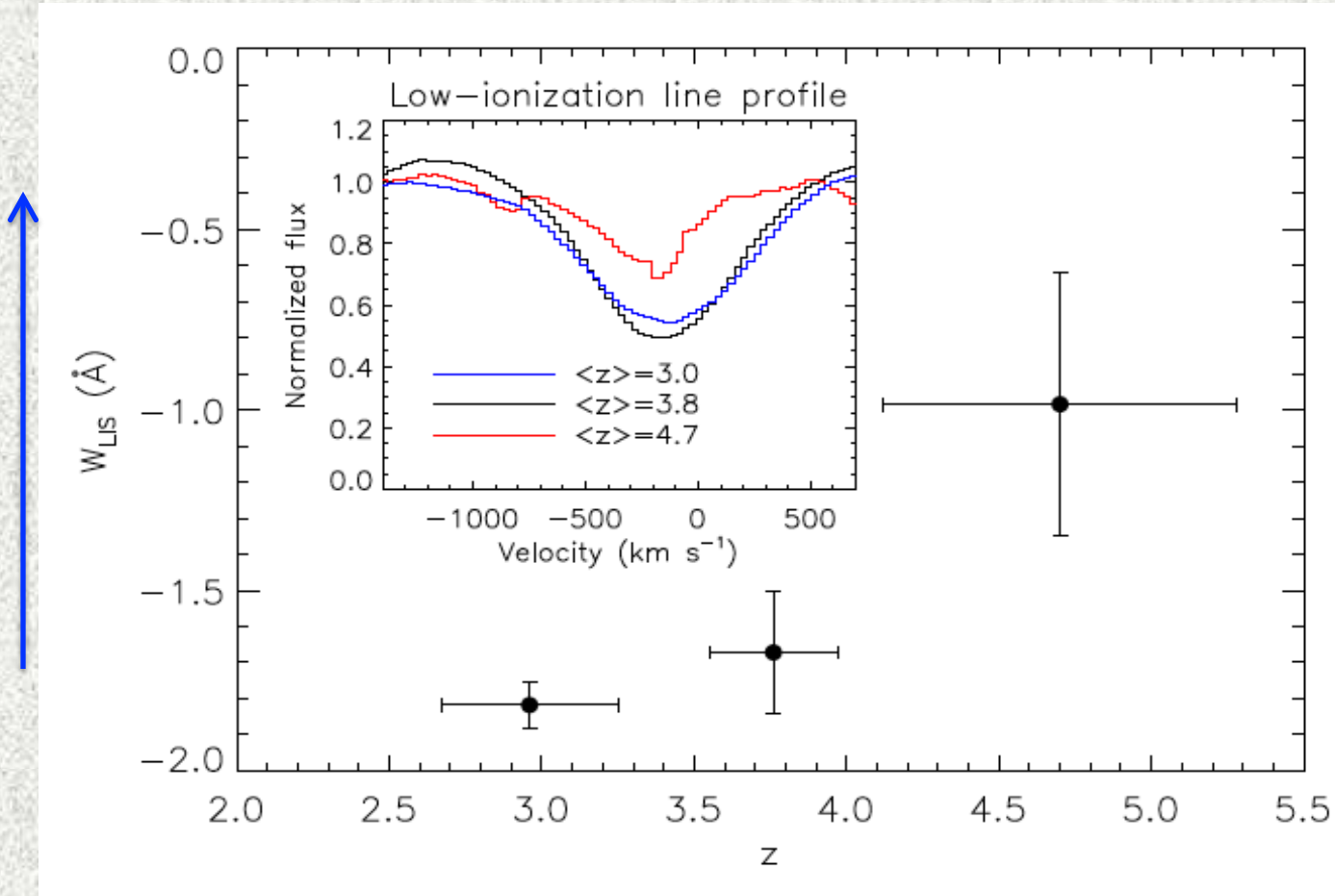
More evolved galaxies have more neutral gas in CGM

Relation between Ly $\alpha$  and low-ionization absorption is independent of galaxy properties

← Weaker Ly $\alpha$  emission

# Evolution with Redshift

Weaker low-ionization absorption  
Less neutral gas in outflows

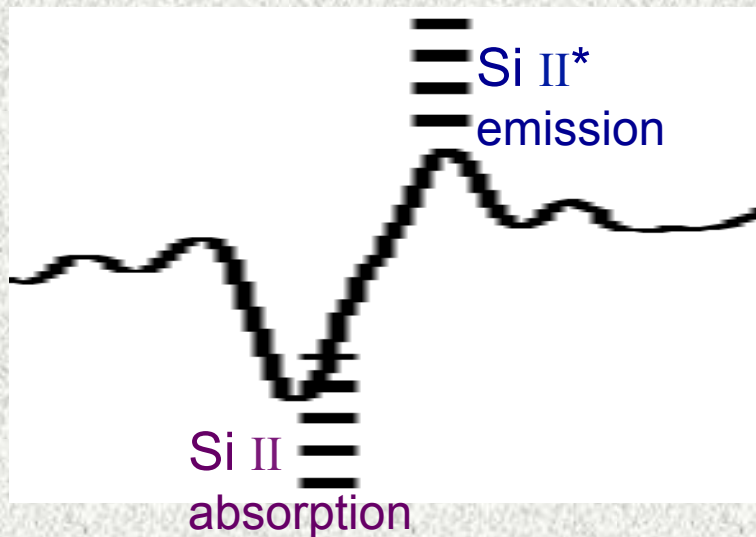
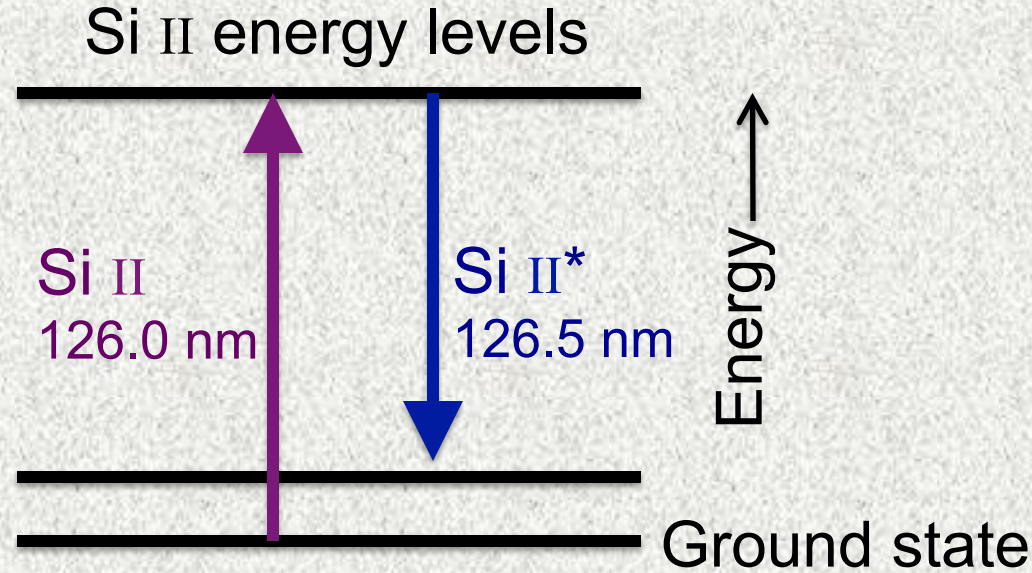


For fixed galaxy properties, low-ionization absorption is *weaker* at higher  $z$

- “Less” neutral gas
- Lower covering fraction and/or velocity range

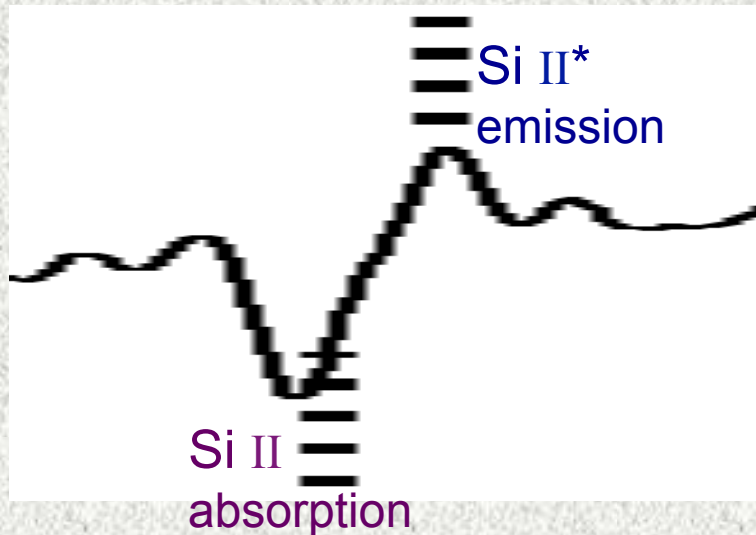
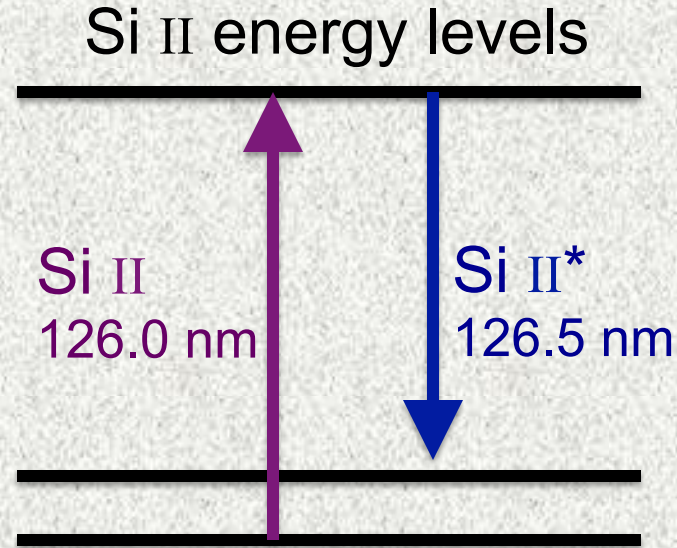
Difficult to distinguish, but we’re trying with lensed galaxies

# Fine Structure Emission



Composite z=4 spectrum

# Fine Structure Emission



Photons absorbed from ground state and re-emitted.

Decay to ground state (Si II) or excited ground state (Si II\*)

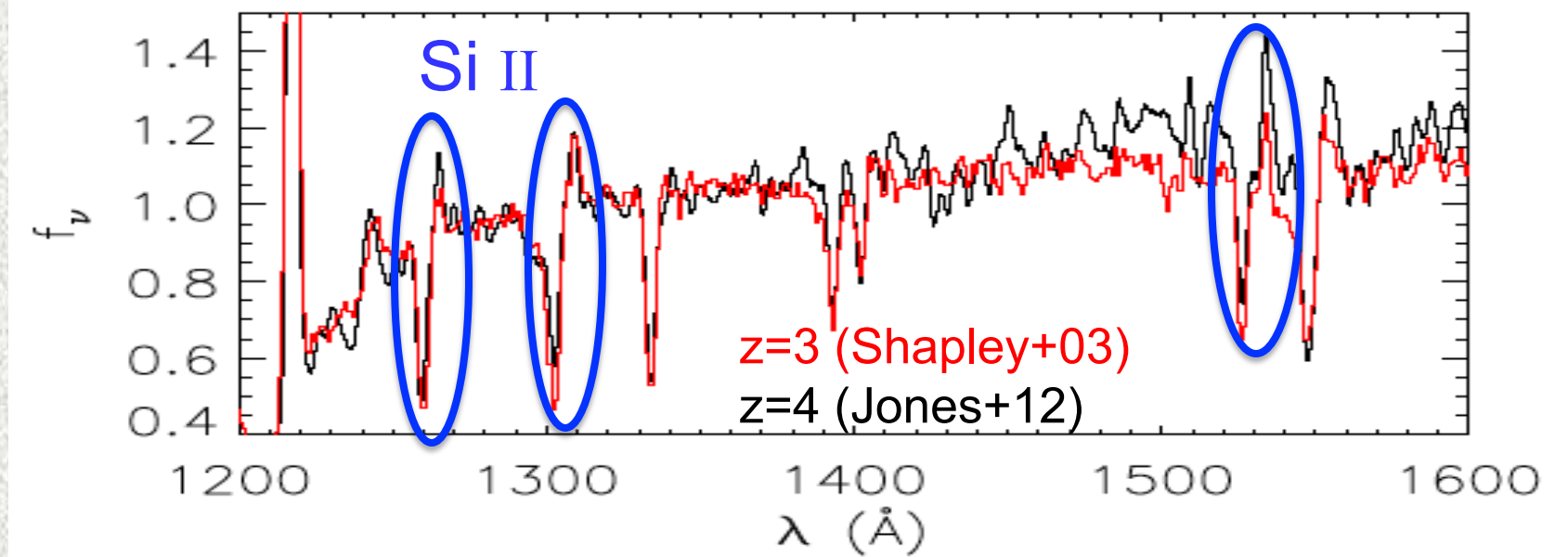
Ground state transitions are optically thick.

→ Si II emission re-absorbed, eventually emitted as Si II\*

$$W_{\text{Si II}^*} = -W_{\text{Si II}}$$

But only a fraction of Si II\* is contained within slit, depending on size of emitting region.

# Fine Structure Emission



Fraction of Si II\* emission is contained within slit:

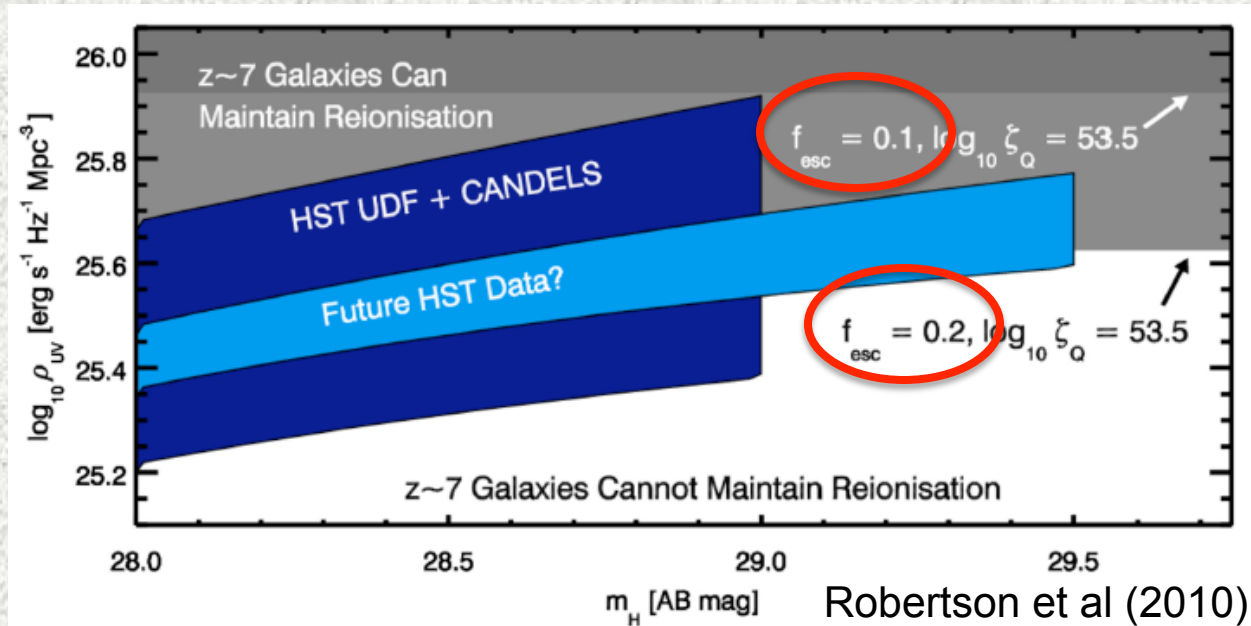
$$f = -W_{\text{Si II}^*} / W_{\text{Si II}}$$

$f = 0.17 \pm 0.04$  at  $z=3$ , within  $\approx 5.5$  kpc radius

$f = 0.53 \pm 0.17$  at  $z=4$ , within  $\approx 3.5$  kpc radius

→ At higher redshift, neutral gas absorption/emission is concentrated at smaller radii

# Implications for Reionization



- Did star-forming galaxies reionize the universe?
  - Maybe. What is  $f_{esc}$ ?
- $f_{esc}$  determined by the covering fraction of neutral gas
- Weaker absorption may indicate lower covering fraction
  - If so, galaxies can maintain reionization at earlier times
  - Could also indicate lower outflow velocity
  - ➔ Need to disentangle velocity and covering fraction

# Summary

- Neutral outflowing gas traced by Ly $\alpha$  and low-ionization metal lines in UV spectrum
- Fine structure emission lines probe size scale of absorbing gas
- Ly $\alpha$  and low-ionization line strengths evolve systematically with redshift
  - Smaller spatial extent of neutral gas at higher  $z$
  - Lower covering fraction of neutral gas at higher  $z$ ?  
Would have interesting implications for reionization.  
Need to disentangle covering fraction and kinematics.  
... we're working on it