



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

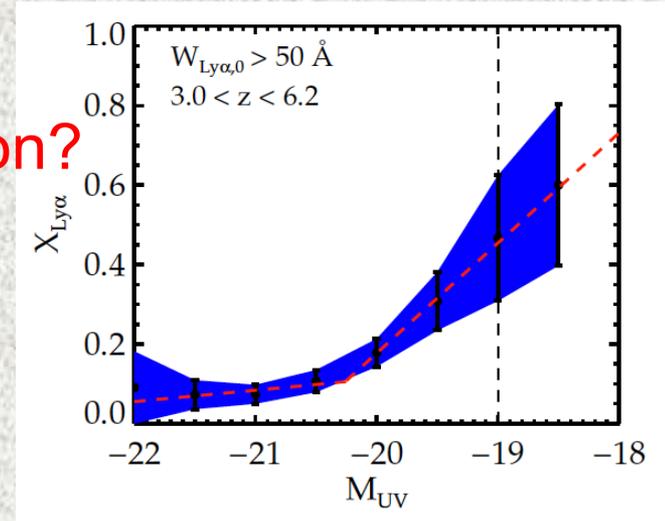
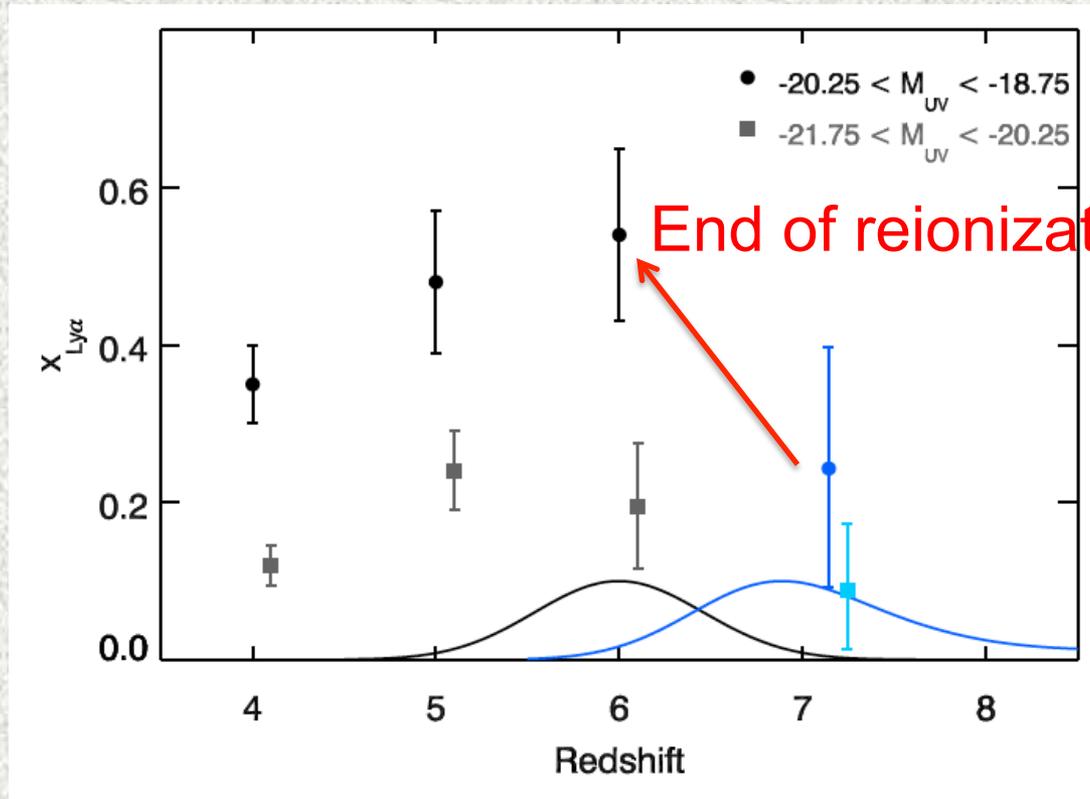


Neutral Gas Around High Redshift Galaxies

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Ly α emission fraction



Stark+10,11
Schenker+11

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

Topics

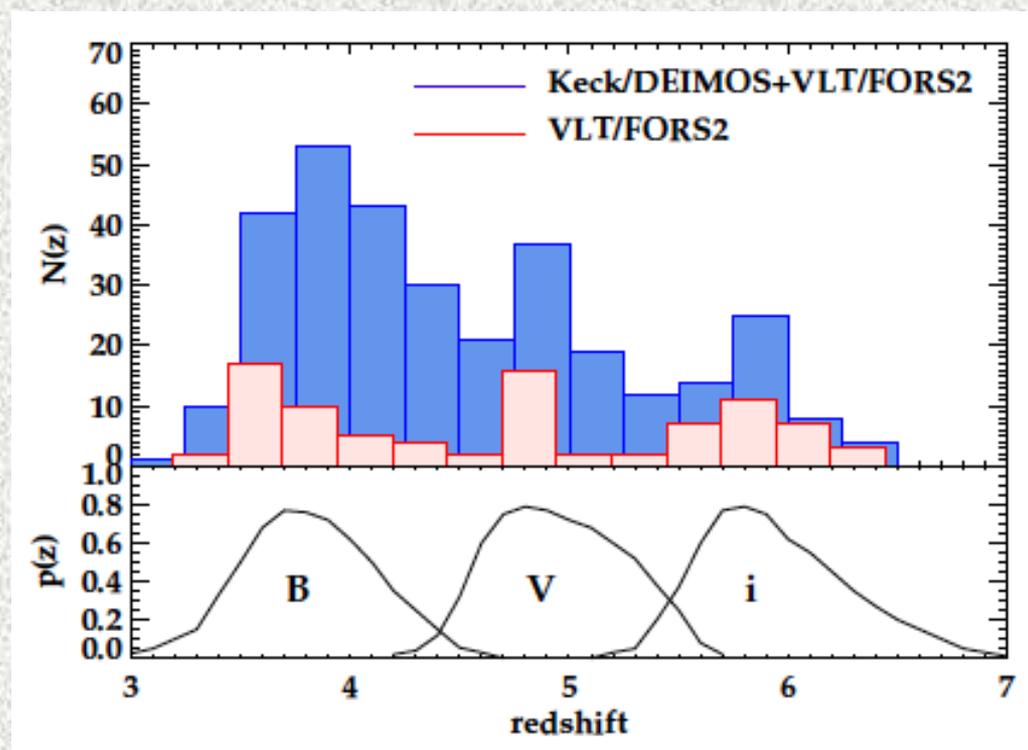
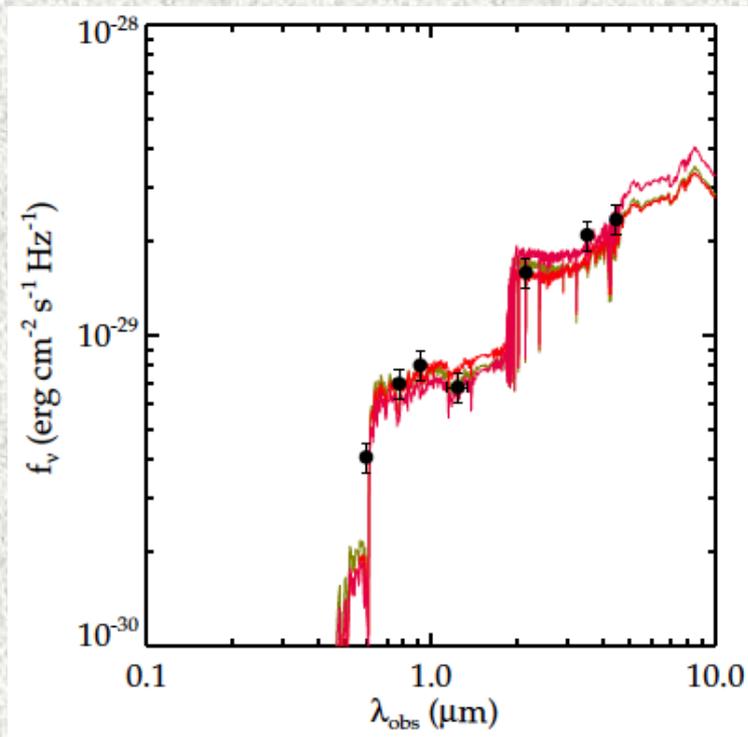
1. What governs Ly α emission?

(answer: neutral HI gas, dust)

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

3. Implications for reionization

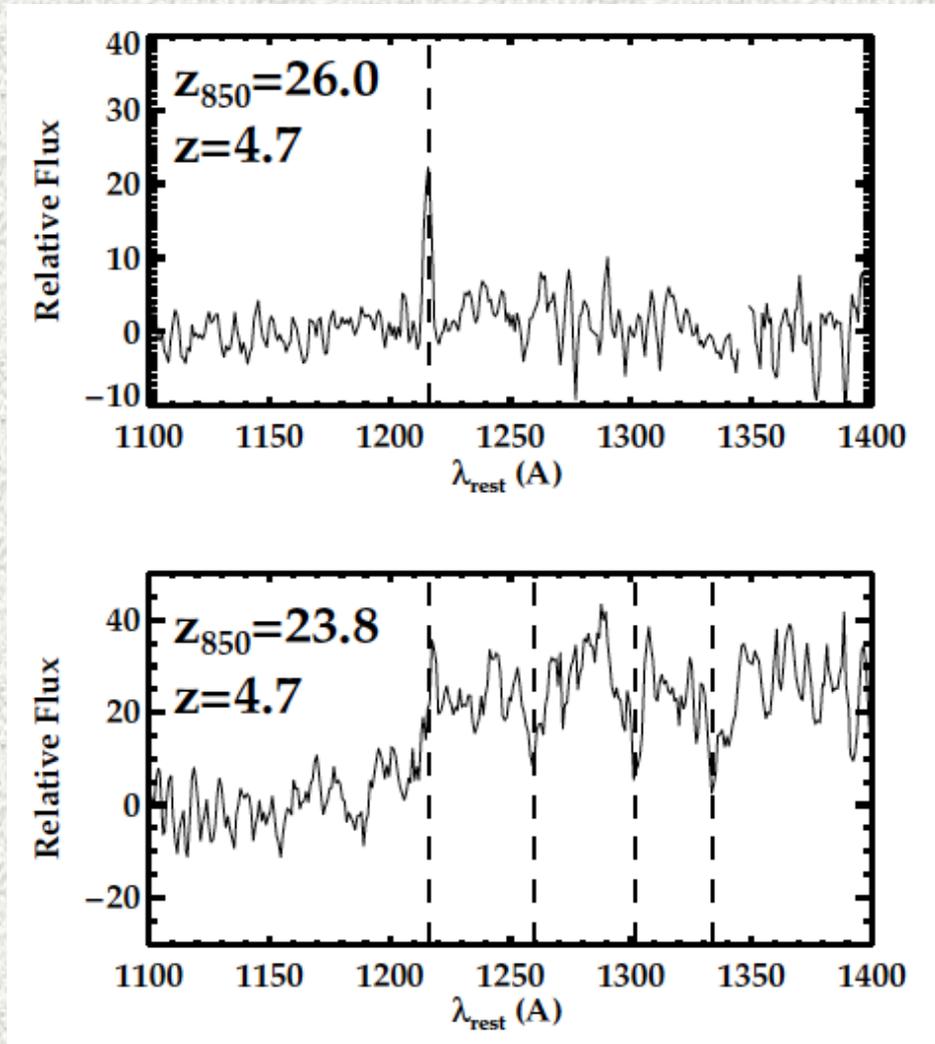
Survey Overview



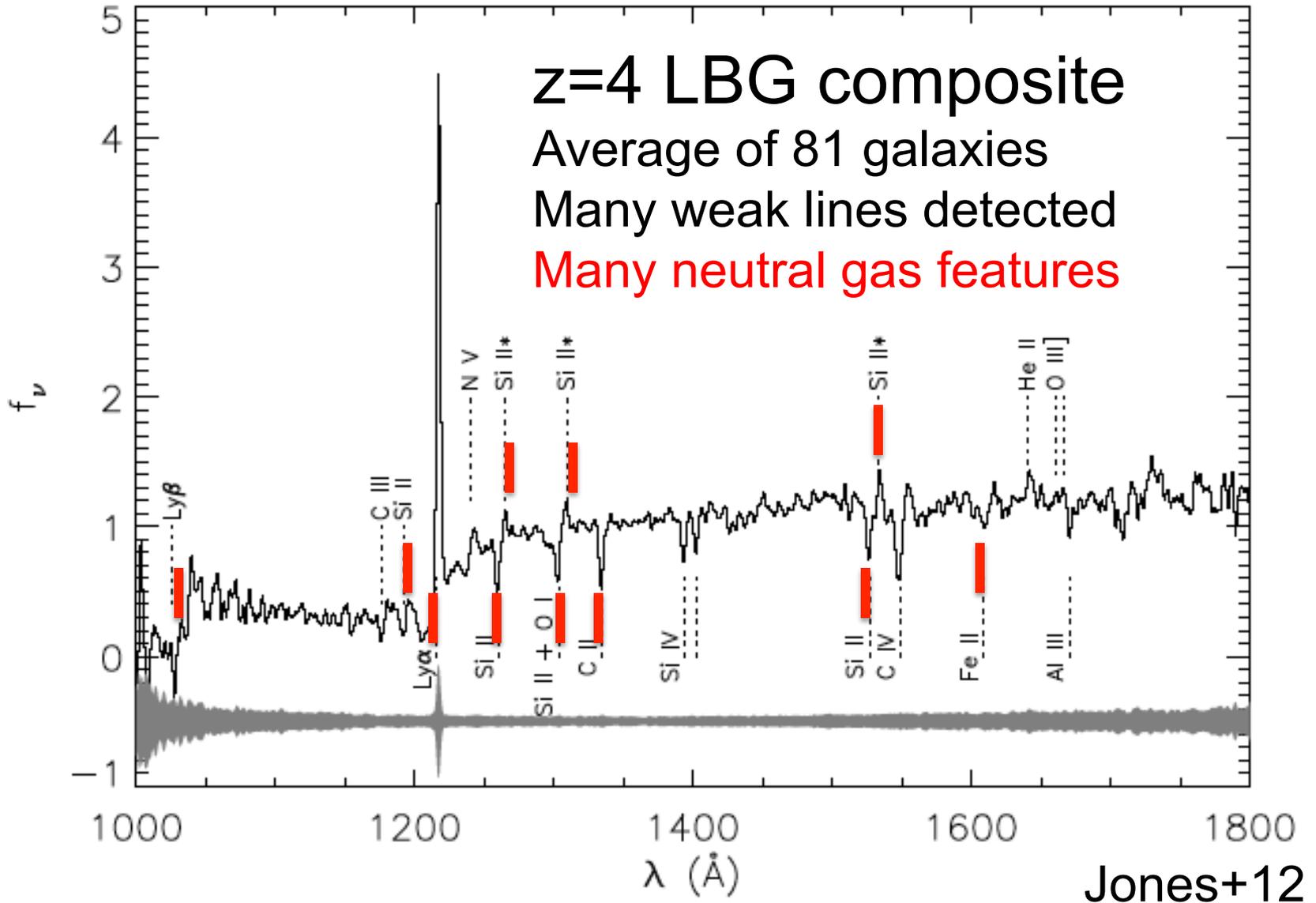
- Spectroscopic survey of Lyman Break Galaxies at $z=3-7+$
 - Deep photometric data from GOODS and CANDELS
- Over 600 galaxies observed to date
 - Largest spectroscopic sample at these redshifts

Keck/DEIMOS Spectra

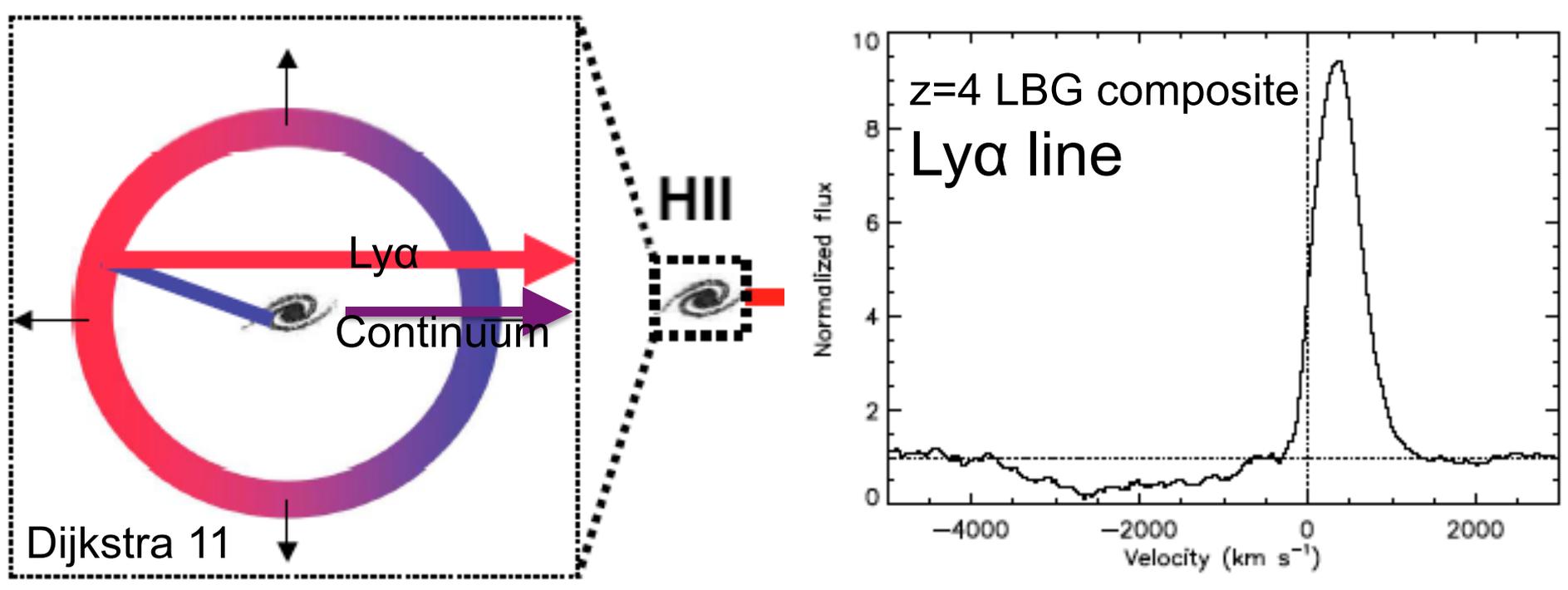
- 5-12 hour exposures
- $R \approx 2000$ ($\Delta v \approx 150$ km/s)
- Optical magnitudes as faint as $m_{AB} = 27.5$
 - Good continuum detection for $m_{AB} < 25.5$
- Strong Ly α emission easily identified
 - Stack many spectra to detect weaker lines



Composite Spectra



Outflow Kinematics

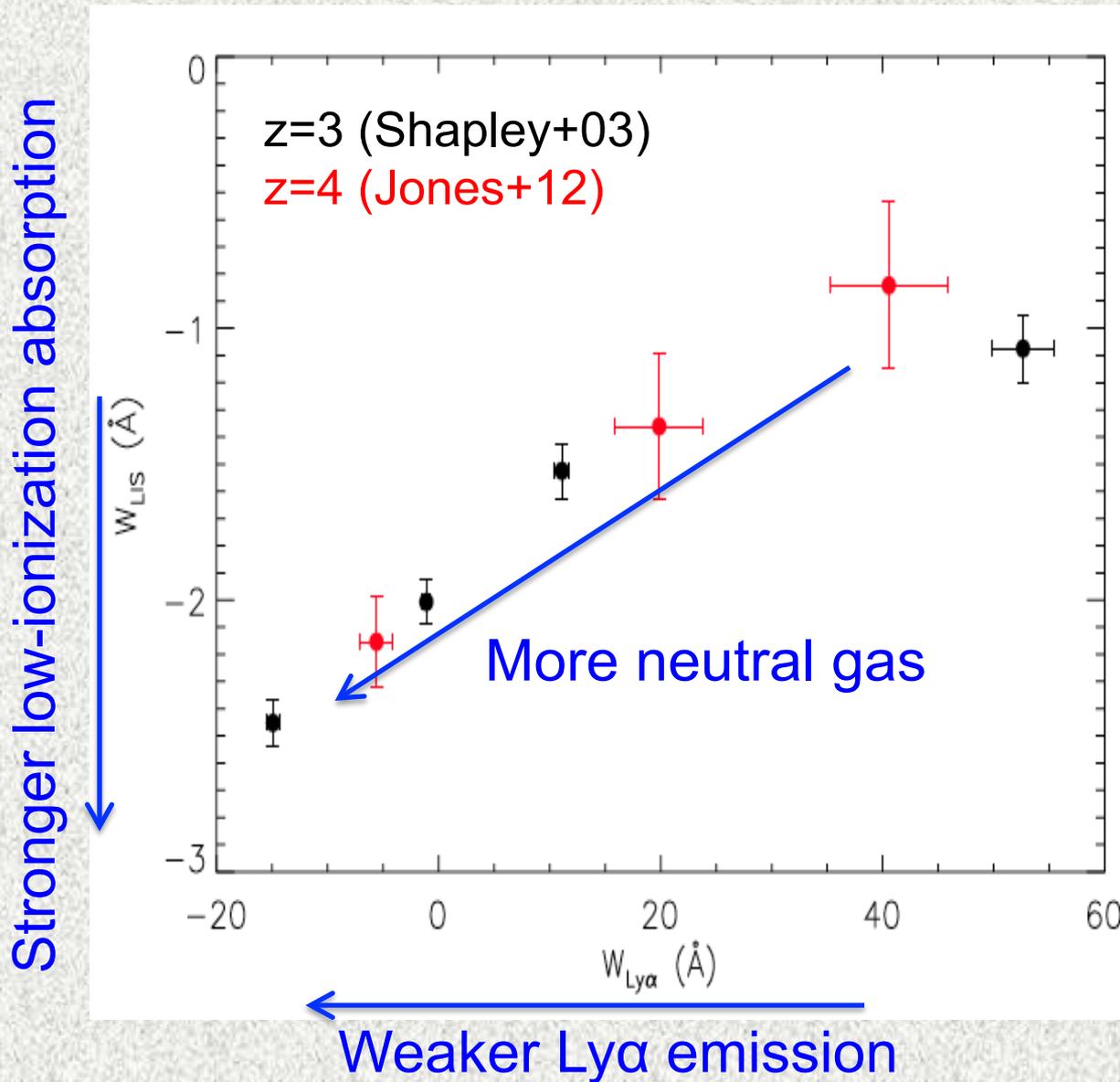


blueshifted absorption
in both HI and low-ionization
metal transitions

redshifted emission
in Ly α

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

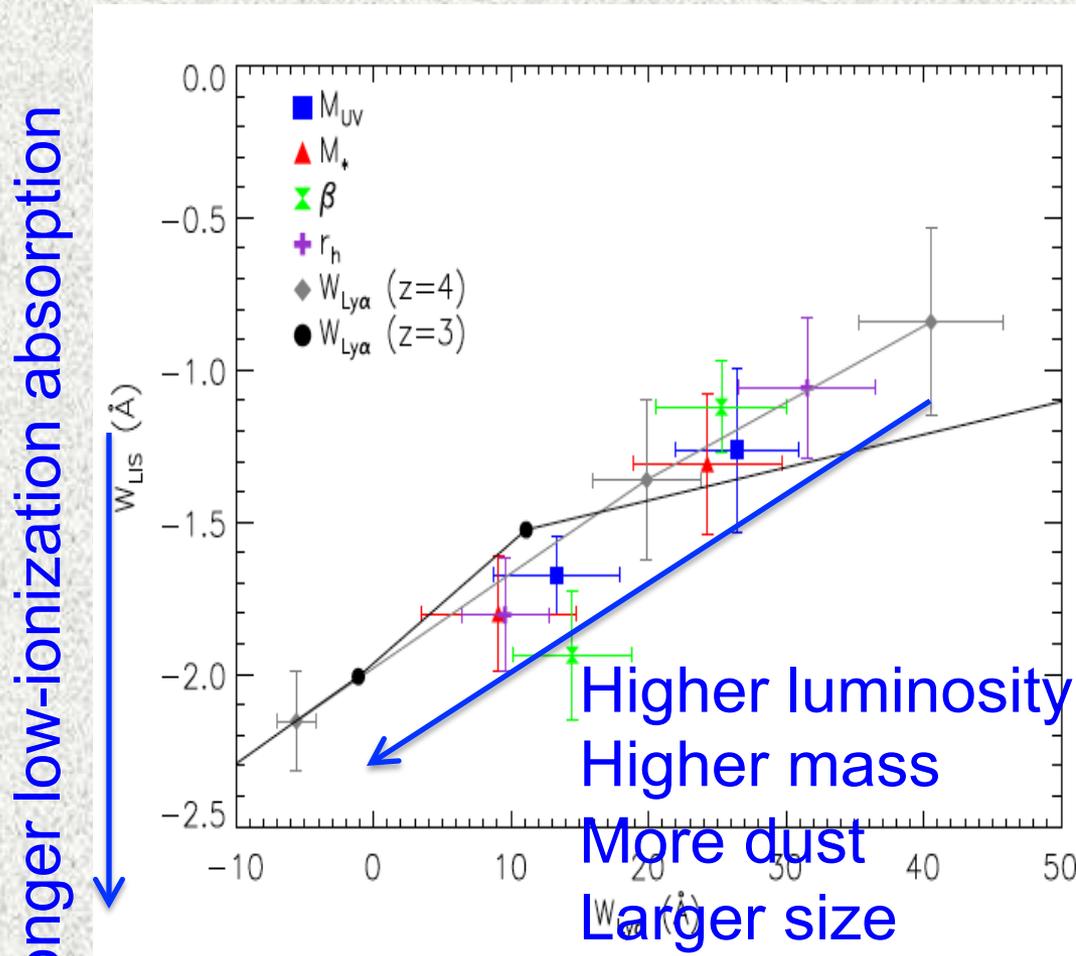
Results: Neutral Gas at High z



Ly α strongly correlated with low-ionization absorption

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

Results: Galaxy Properties

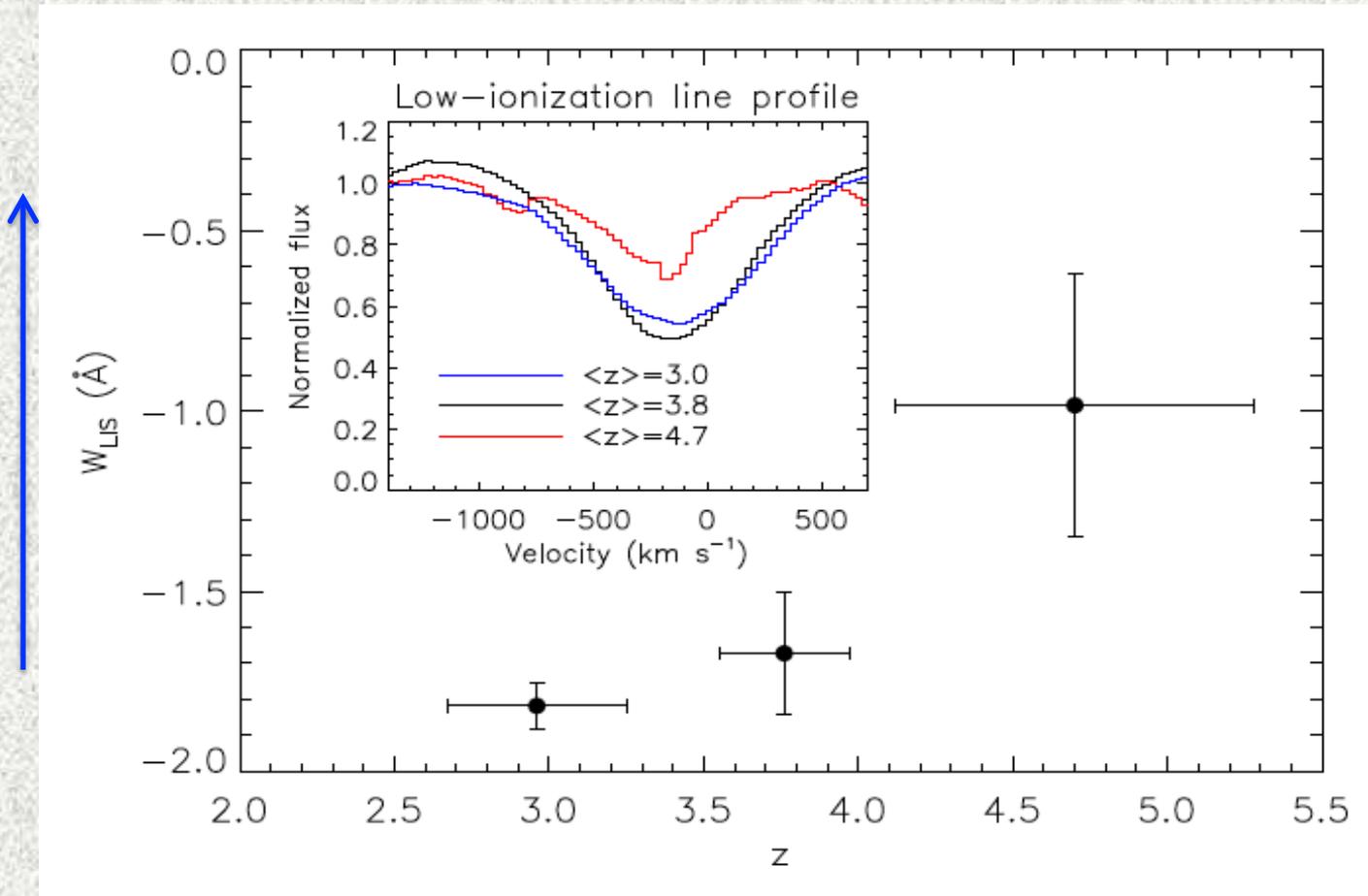


More evolved galaxies have more neutral gas in CGM

Relation between Ly α and low-ionization absorption is independent of galaxy properties

Evolution with Redshift

Weaker low-ionization absorption
Less neutral gas in outflows

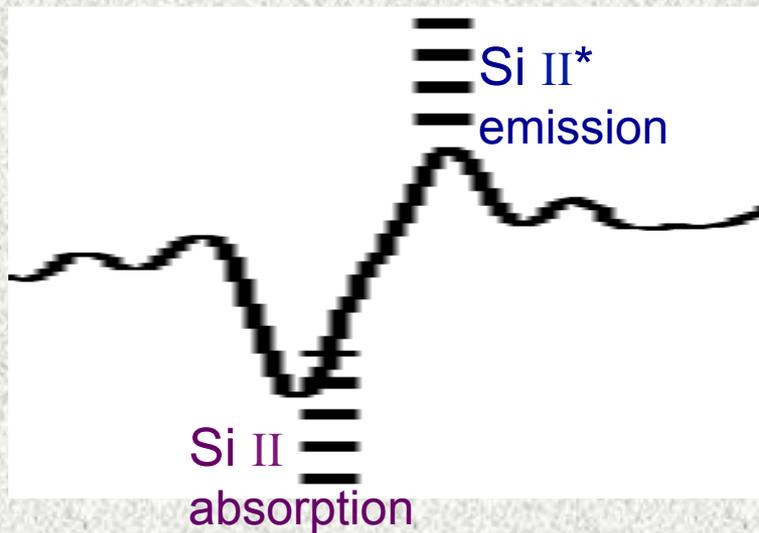
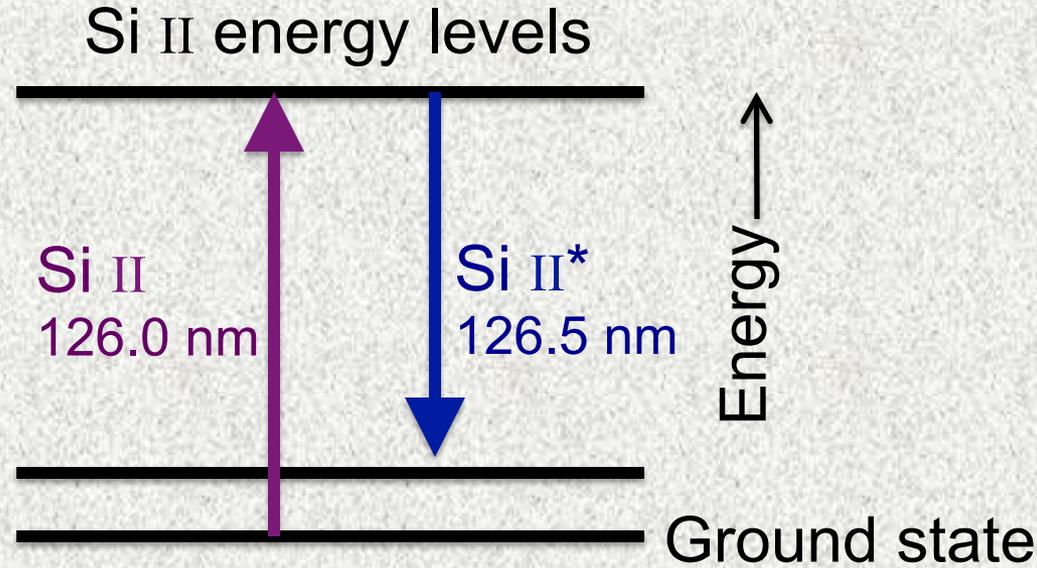


For fixed galaxy properties, low-ionization absorption is *weaker* at higher z

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

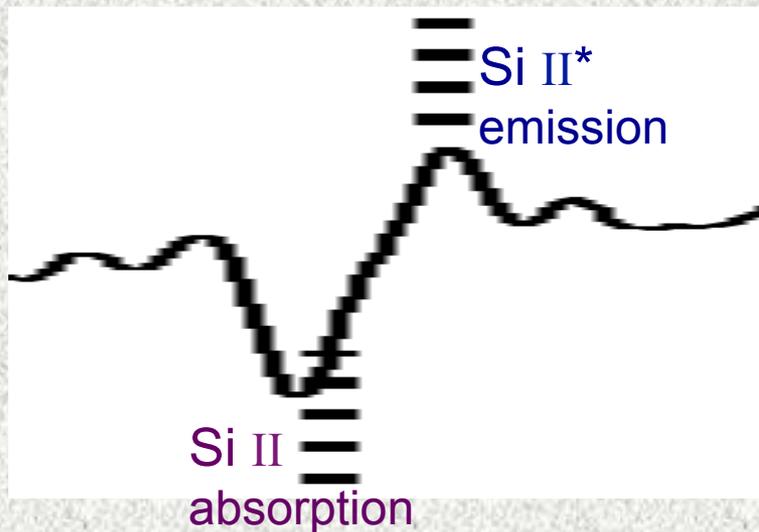
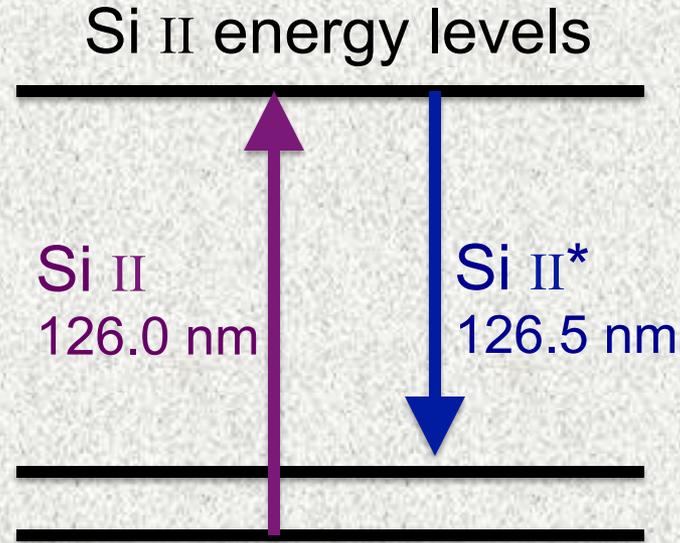
Difficult to distinguish, but we’re trying with lensed galaxies

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*)

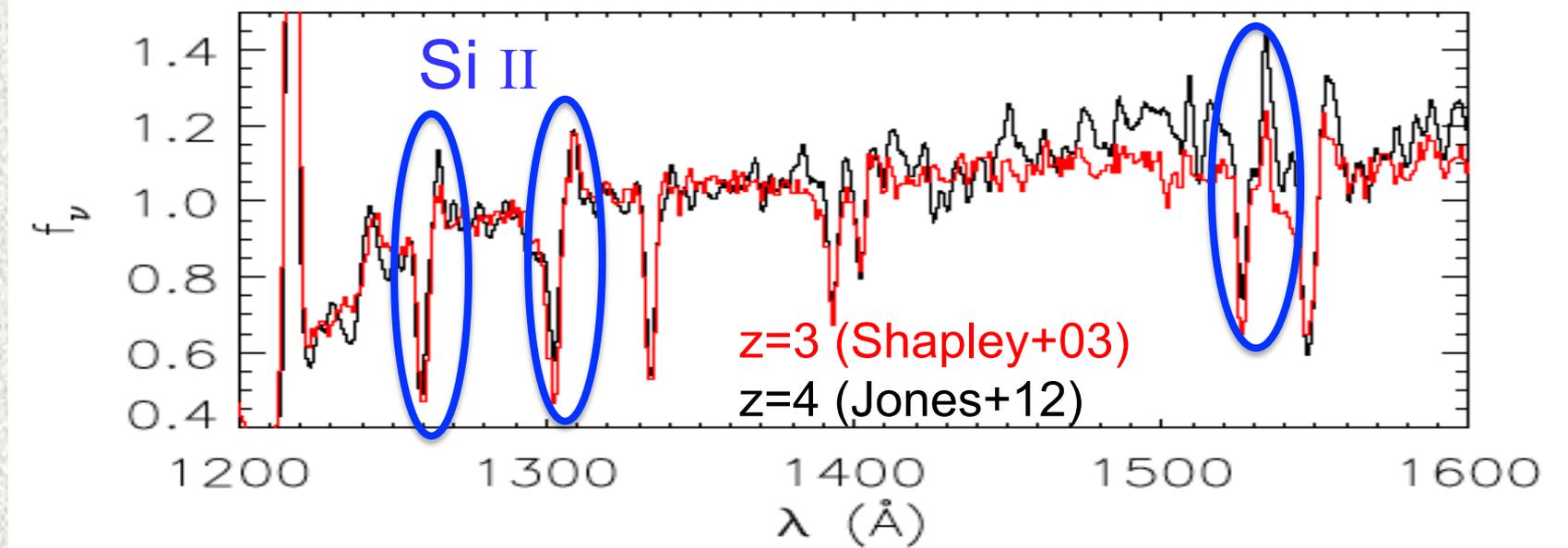
Ground state transitions are optically thick.

→ 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:

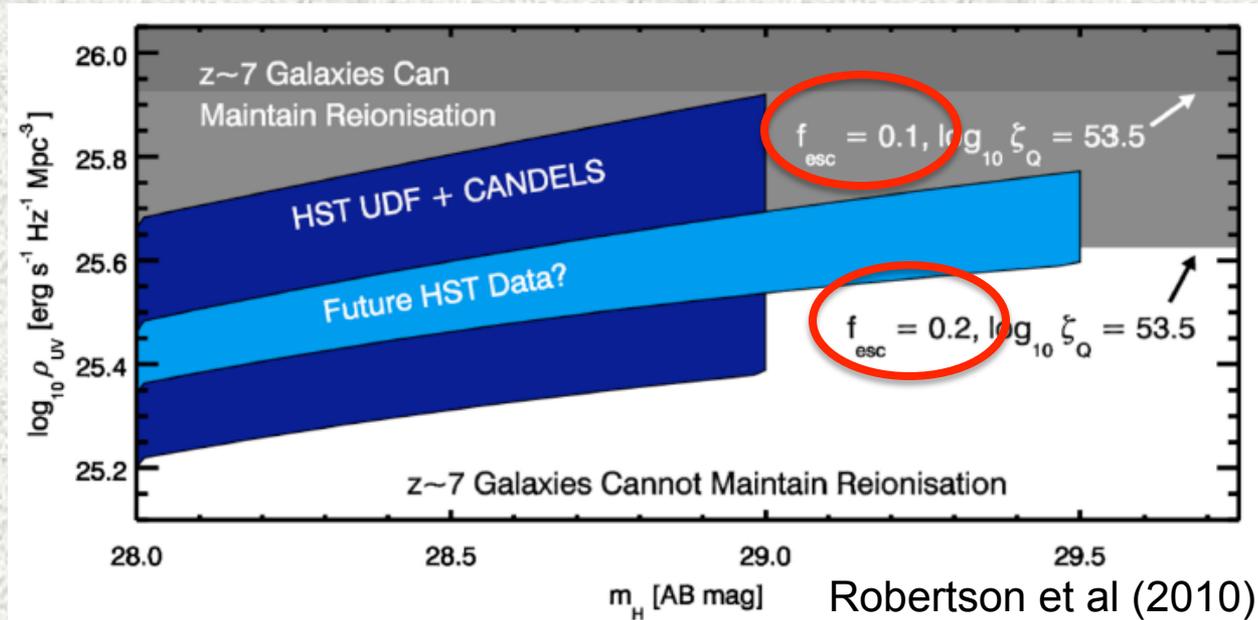
$$f = -W_{\text{Si II}^*} / W_{\text{Si II}}$$

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

$f = 0.53 \pm 0.17$ at $z=4$, within ≈ 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 α and low-ionization metal lines in UV spectrum
- Fine structure emission lines probe size scale of absorbing gas
- Ly α 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