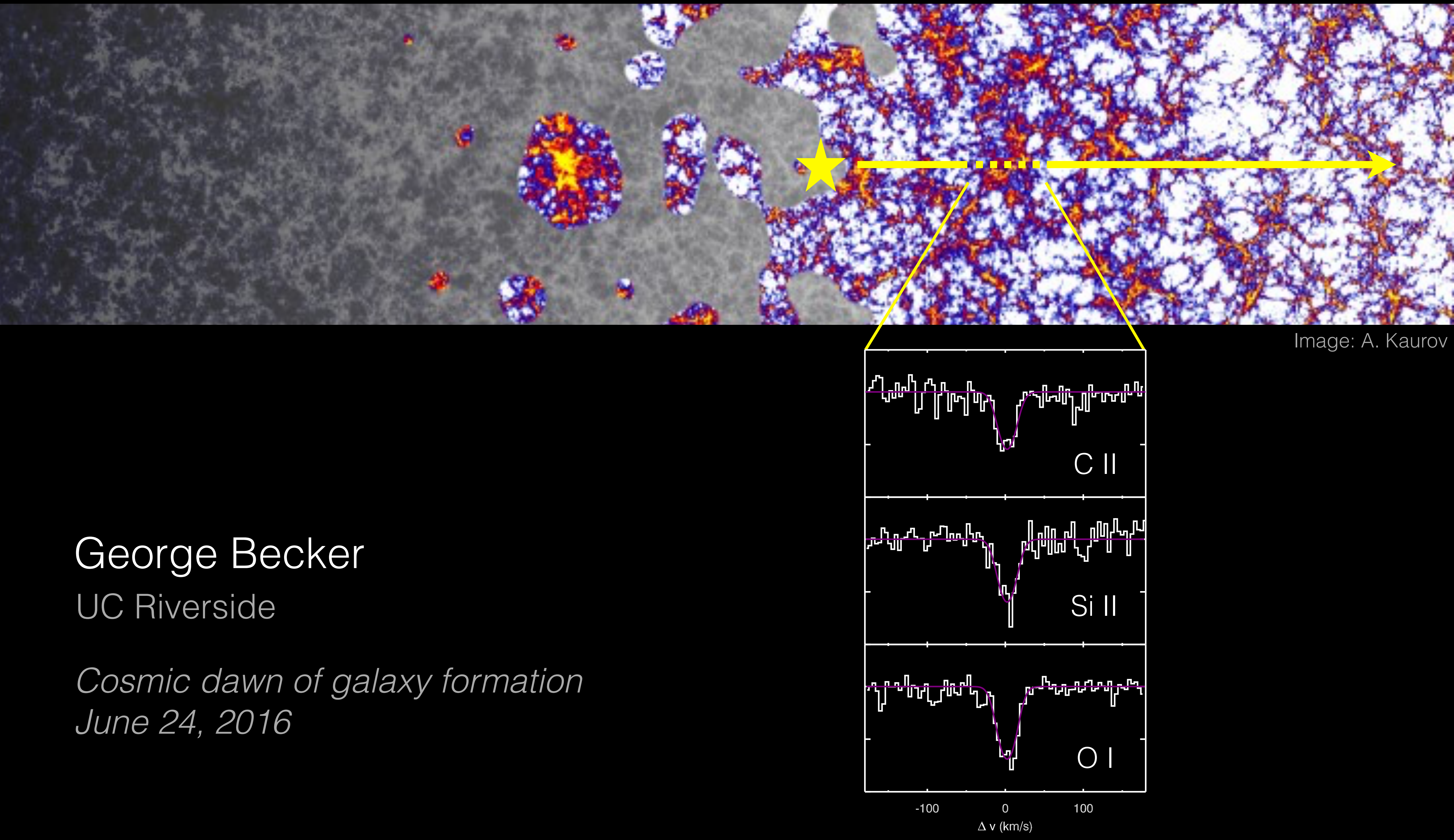
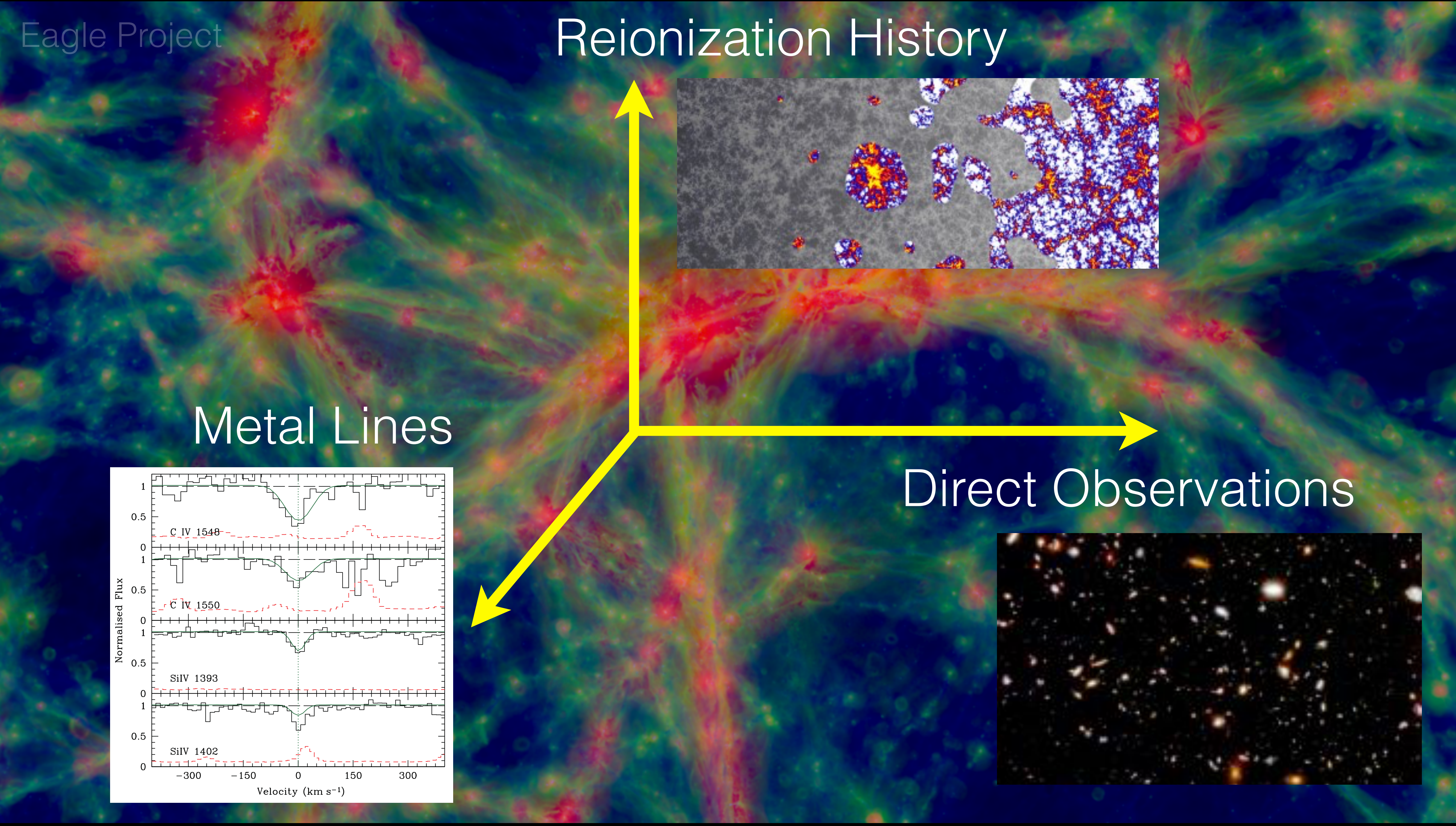
Metal Absorption Lines near the Reionization Epoch



George Becker
UC Riverside

Cosmic dawn of galaxy formation
June 24, 2016

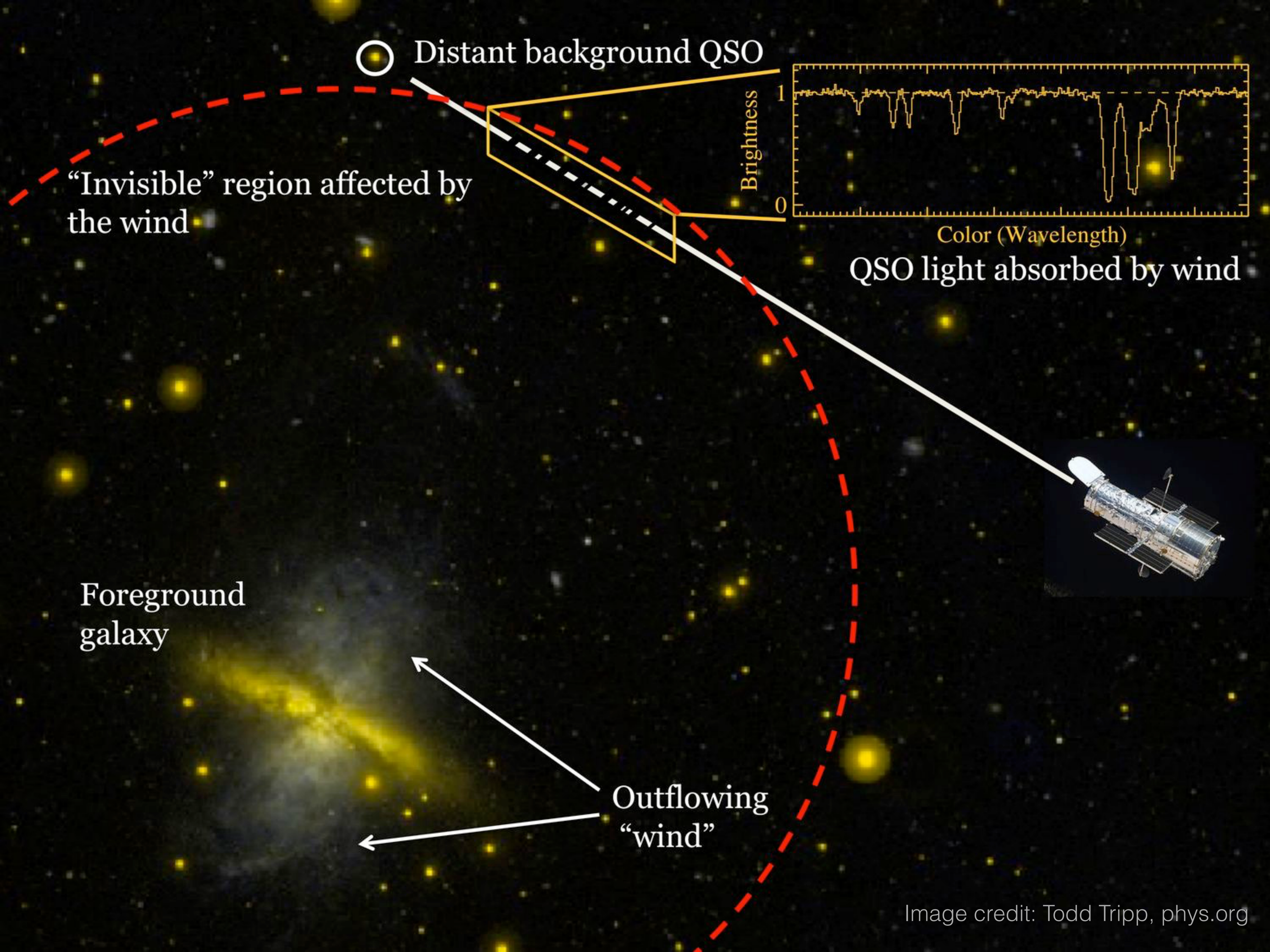
Studying high-z galaxy formation



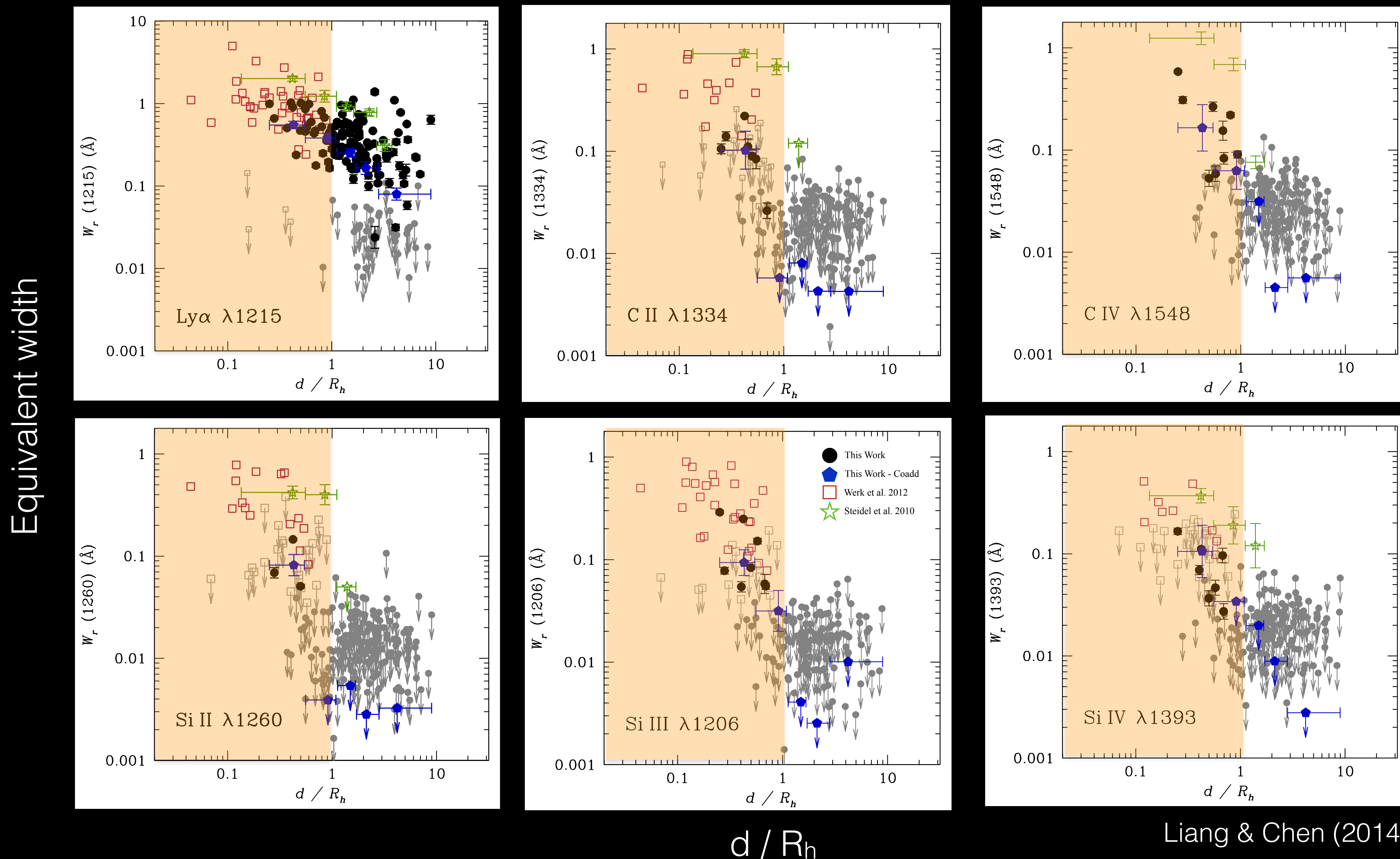
Metal absorbers: Highlights from z~0-4

Setting the scene: The IGM at z~5-6

Metals near reionization


Distant background QSO
"Invisible" region affected by the wind
Brightness
1
0
Color (Wavelength)
QSO light absorbed by wind
Foreground galaxy
Outflowing "wind"
Image credit: Todd Tripp, phys.org

Where are metals found? Around galaxies! The "CGM".

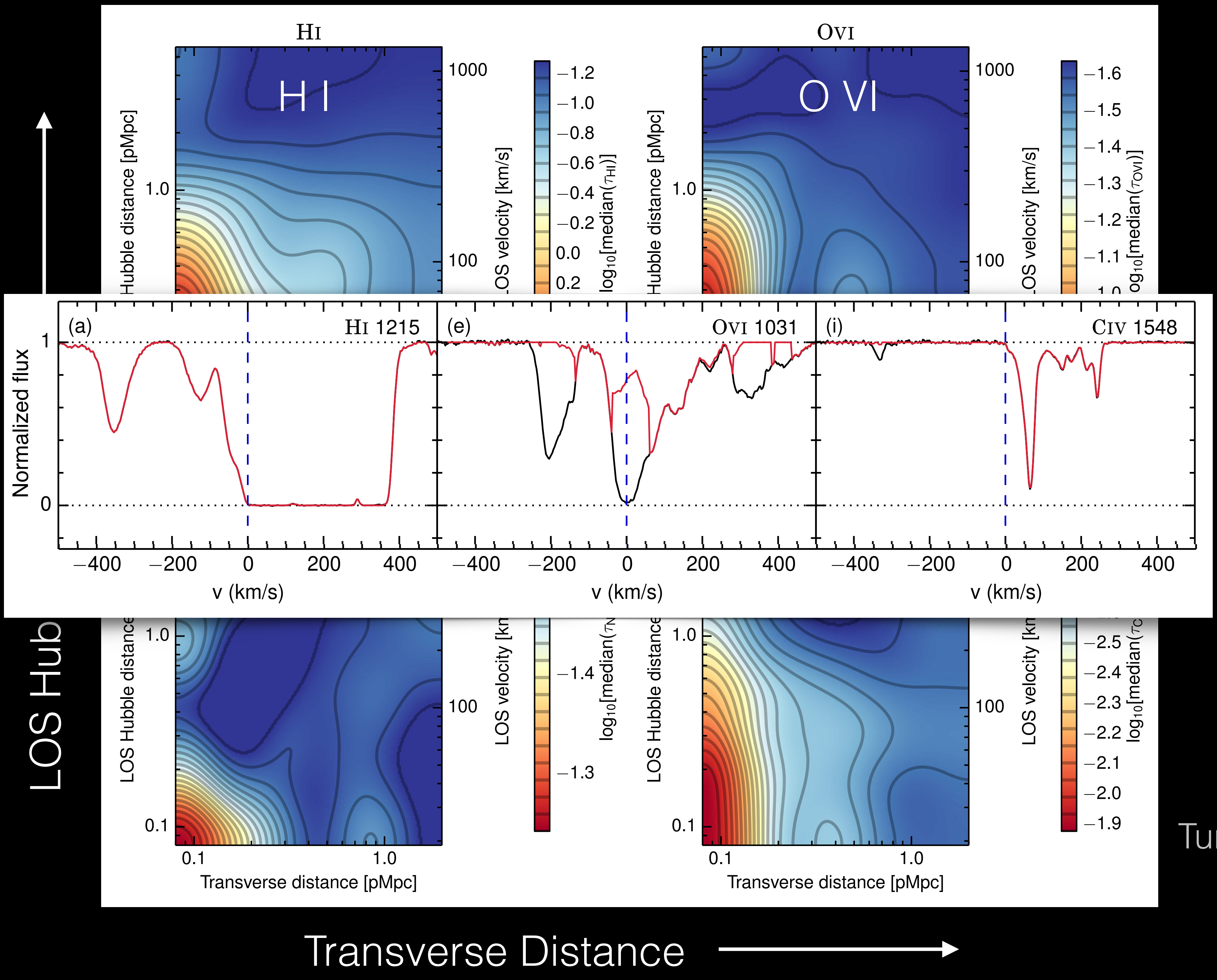


Liang & Chen (2014)

z < 0.2: Metals generally found within the halo radius

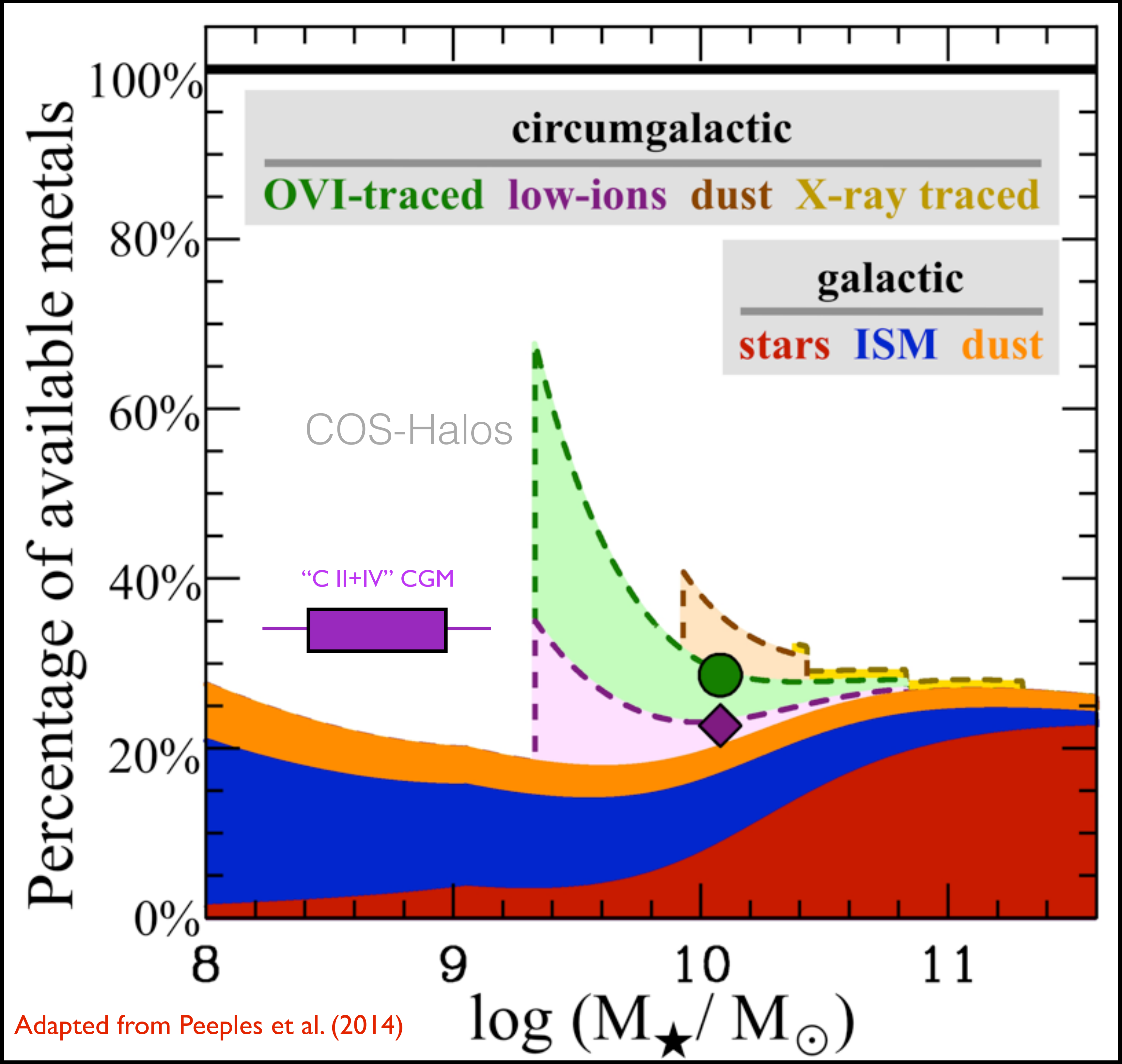
Metals absorbers have kinematics indicative of inflows & outflows.

Keck Baryonic Structure Survey, z~2.3 (PI: Steidel)



Turner et al. 2014

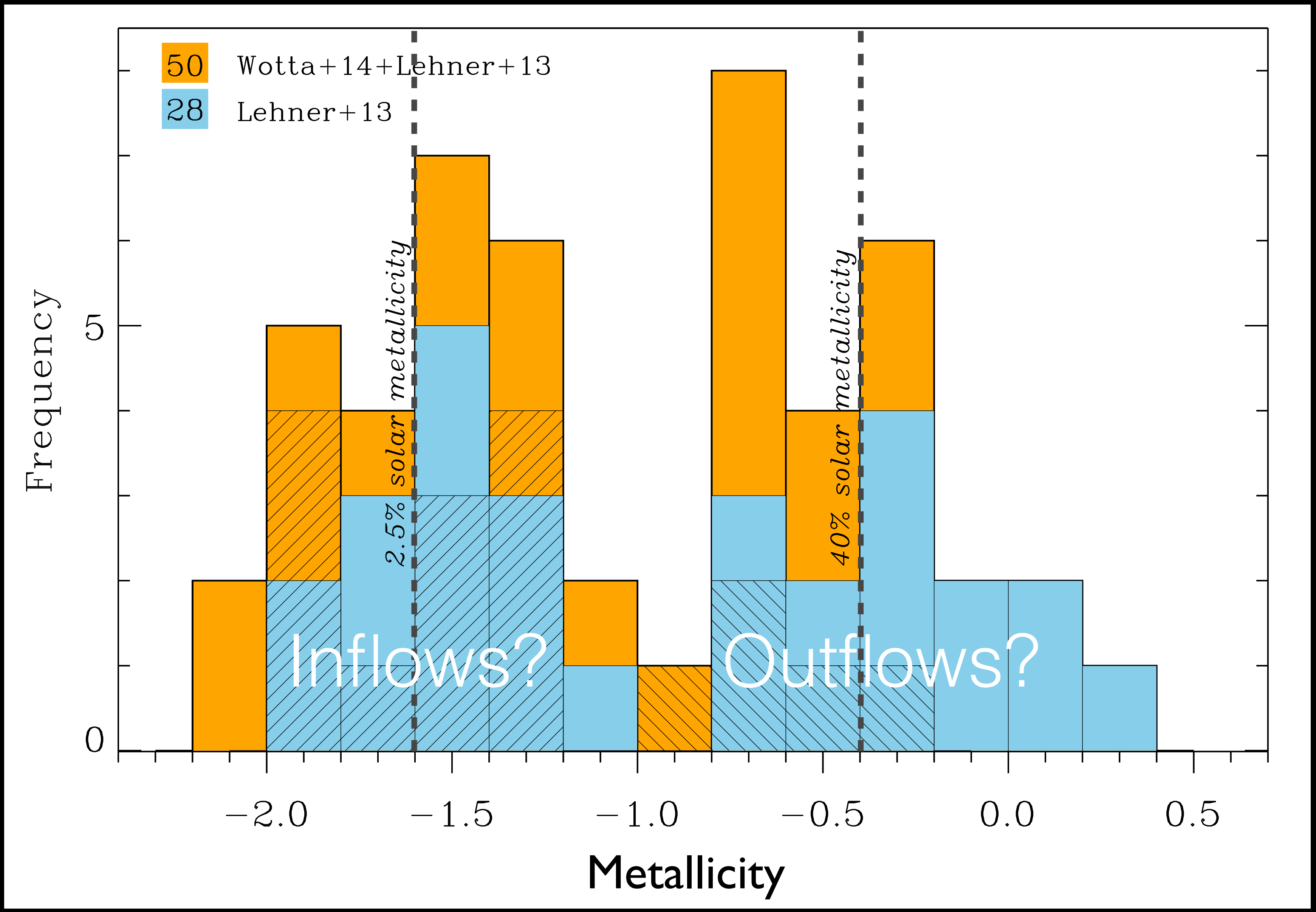
Total Inventory of Galactic Metals (z~0)



Typical star forming galaxies have ejected at least as many metals as they have retained.

Credit: Peeples, Tumlinson et al.

Metallicities provide further evidence of inflows and outflows.



"CGM-like" absorbers (Lyman limit systems)
COS + ground-based data

Typical star forming galaxies. . .

. . . have a CGM that outweighs their ISM and maybe their stars. . .

. . . have ejected at least as many metals as they have retained . . .

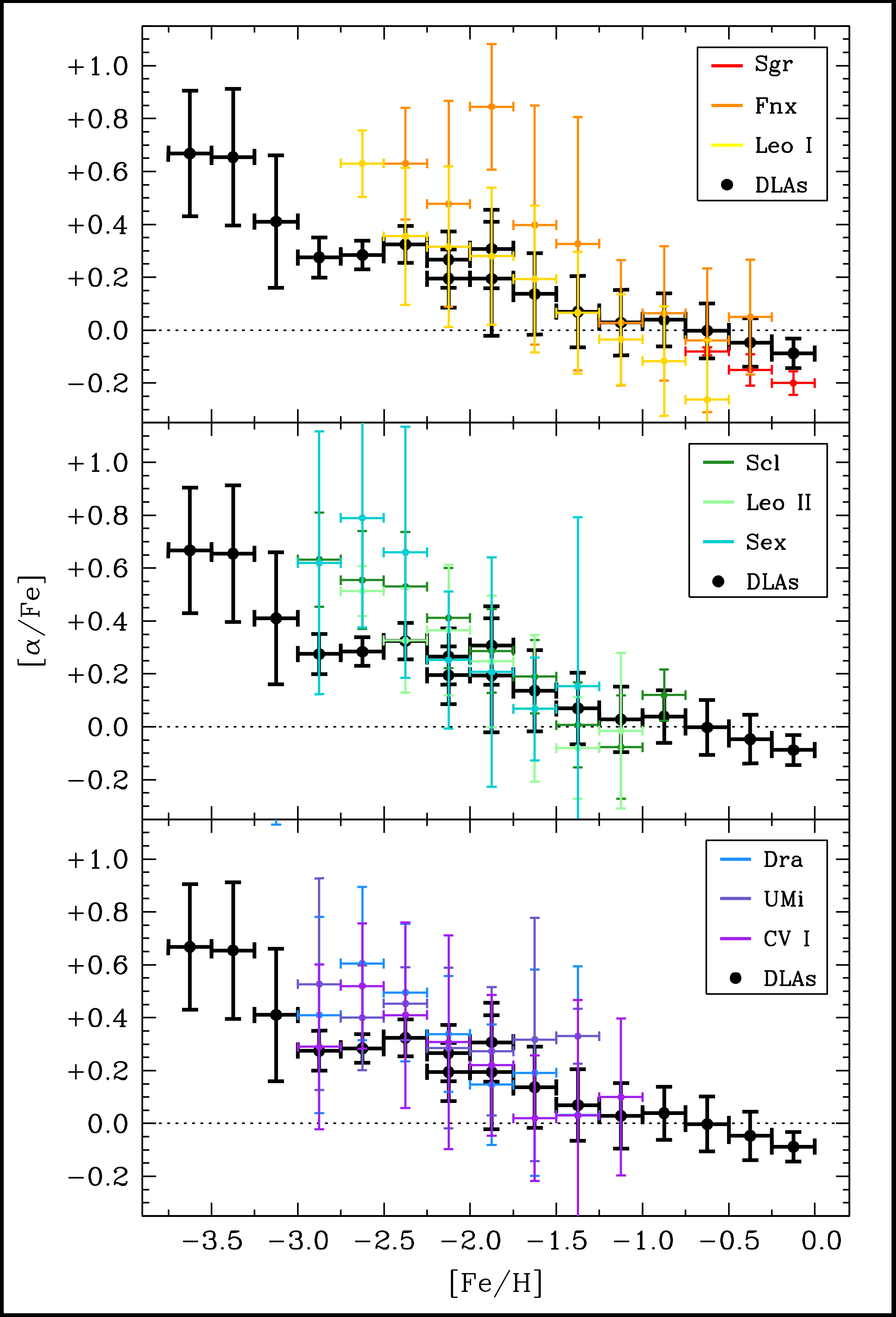
. . . yet appear to retain both pristine and metal-enriched material in their halos. . .

Credit: J. Tumlinson

Abundances in metal absorbers

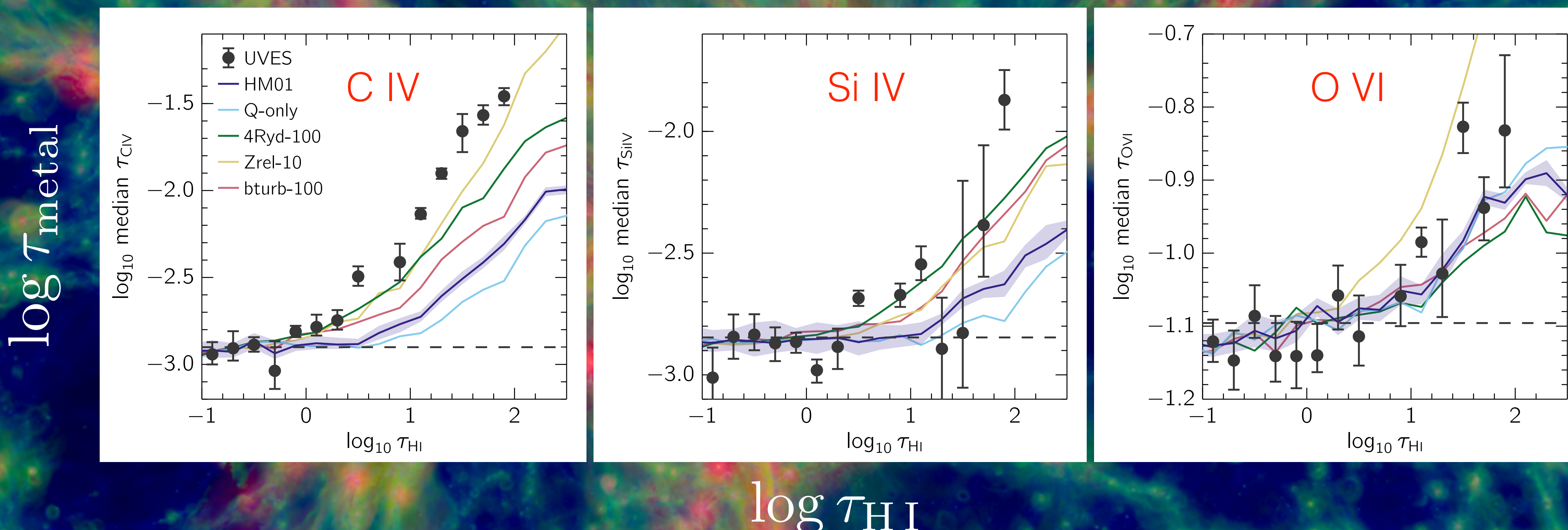
- Can often be measured accurately (especially in DLAs)
- Constrain star-formation histories in high-z galaxies.

For example, DLA abundances resemble those of dwarf galaxies.



Cooke, Pettini, & Jorgenson (2015)

Simulations struggle to produce enough metals in the IGM/CGM and/or metals in the right phases.



UVES data at z~3.5 compared to predictions from Eagle simulations (Turner et al. 2016, but see, e.g., Oppenheimer+2008)

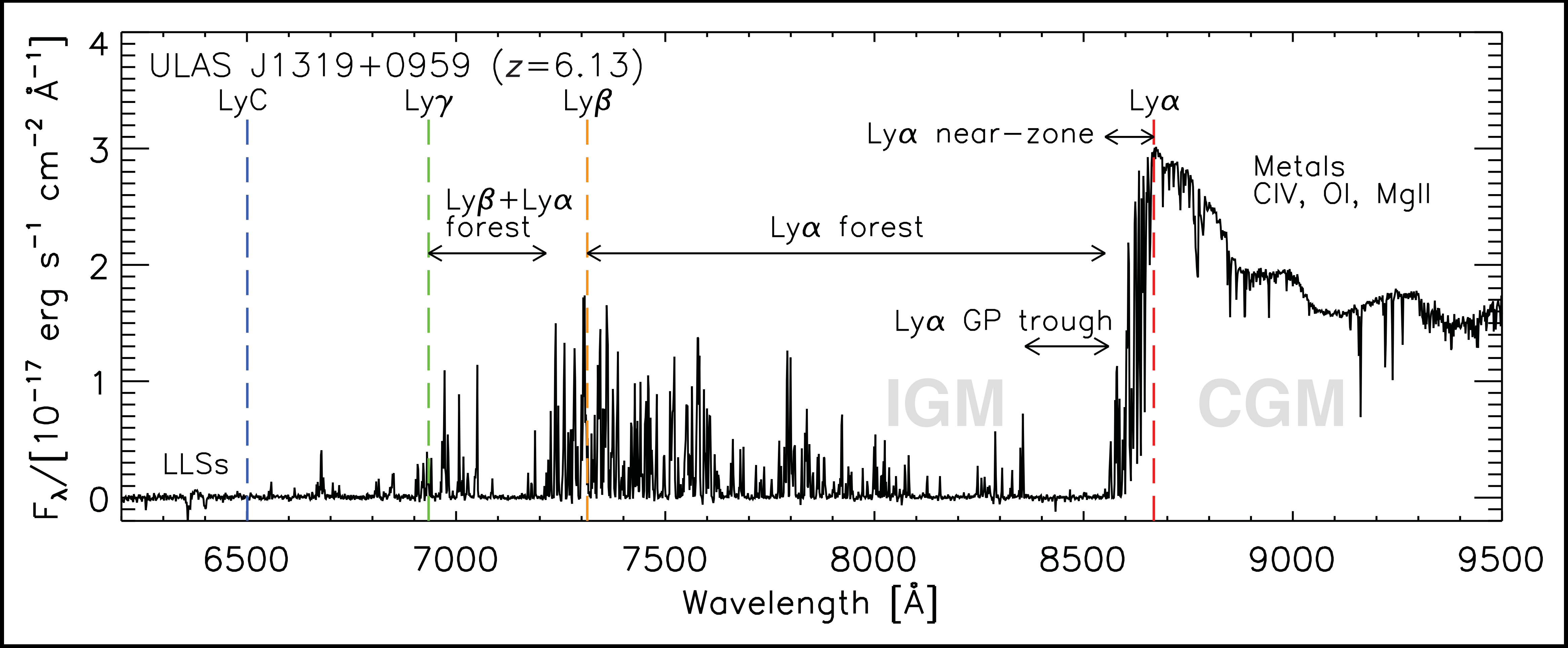
THE EAGLE PROJECT

Metal absorbers: Highlights from z~0-4

Setting the scene: The IGM at z~5-6

Metals near reionization

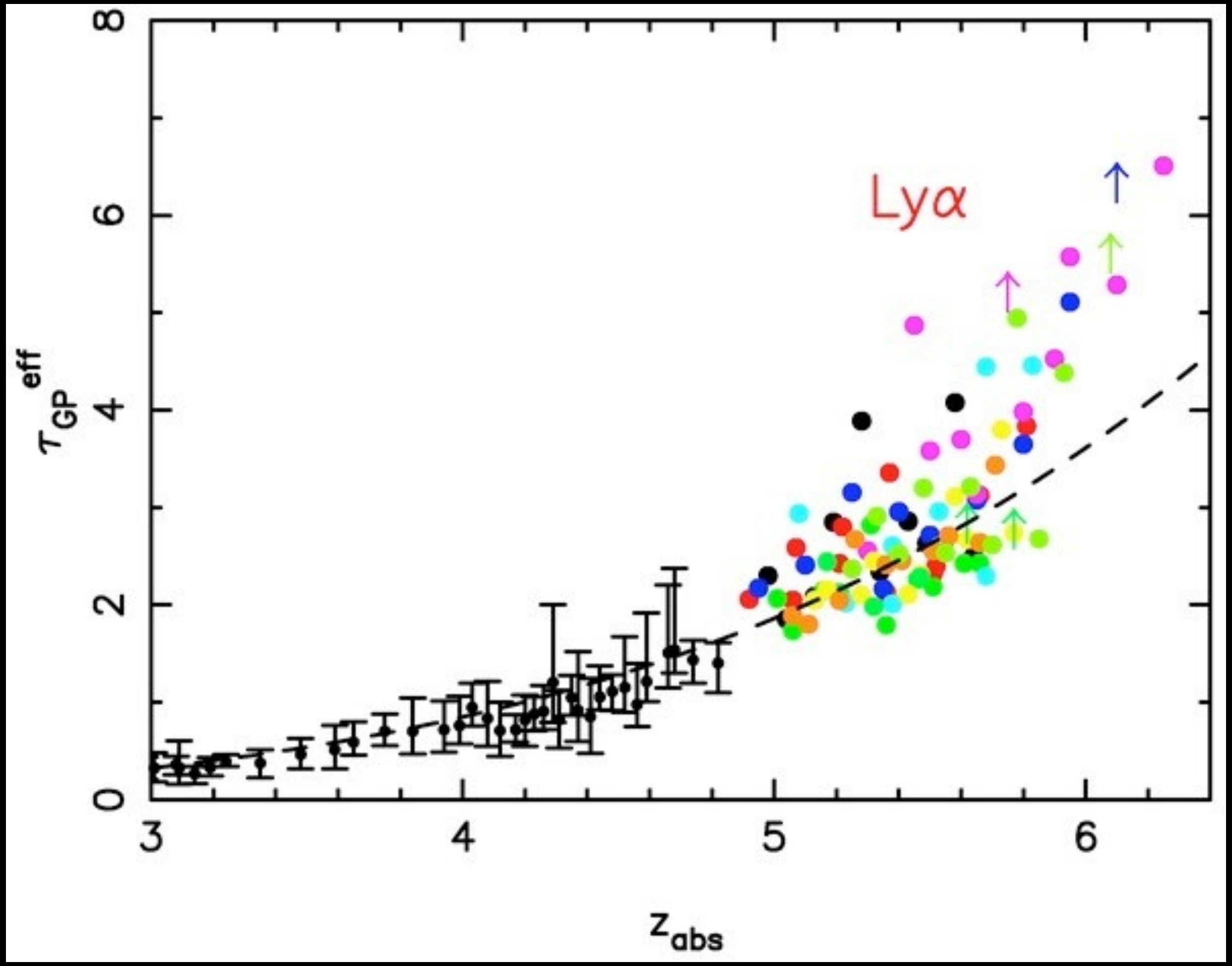
Anatomy of a high-z QSO spectrum

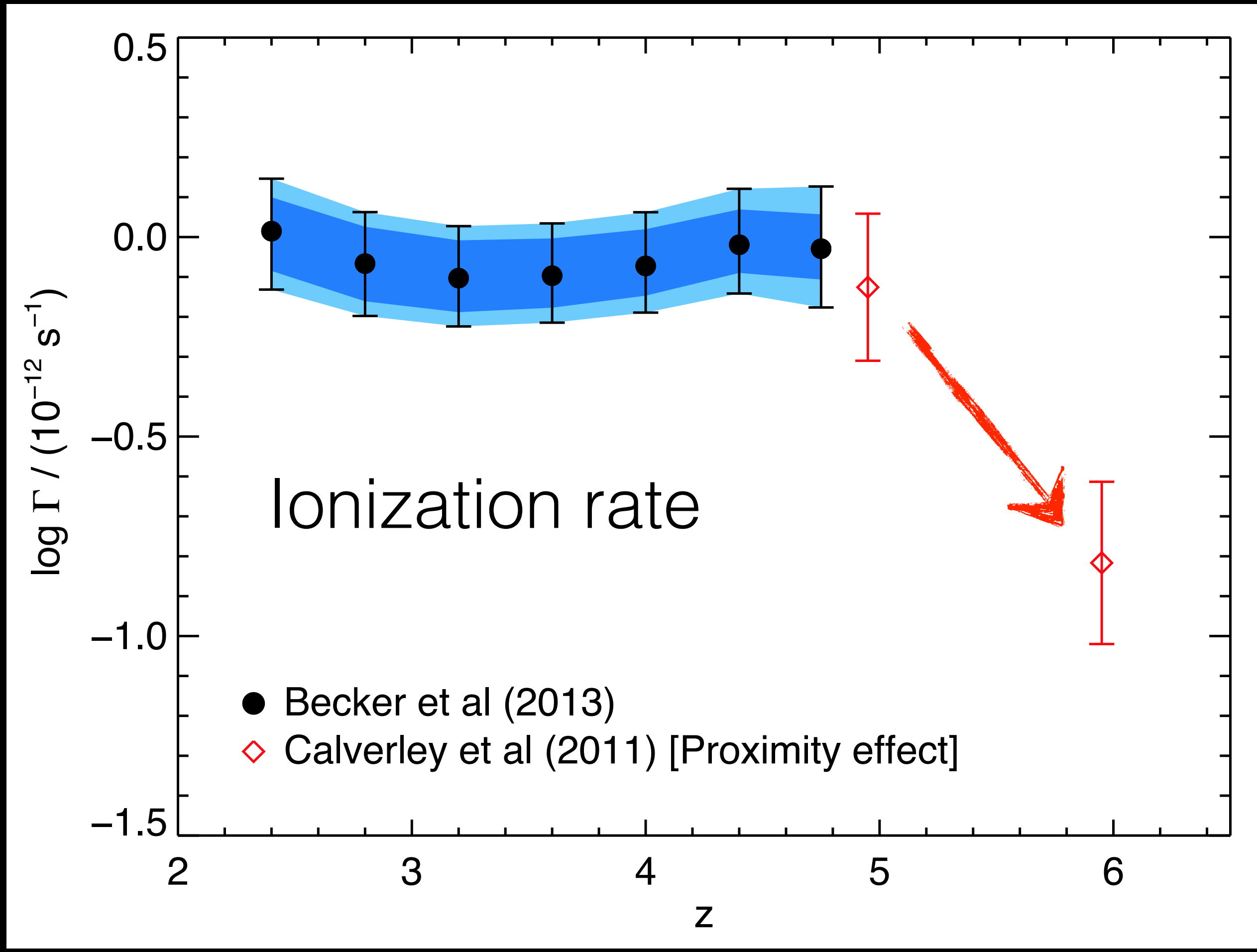


Becker, Bolton & Lidz (2015) PASA Review

Lyα forest at z > 5

Increasing Lyα opacity ⟶ Declining UV background

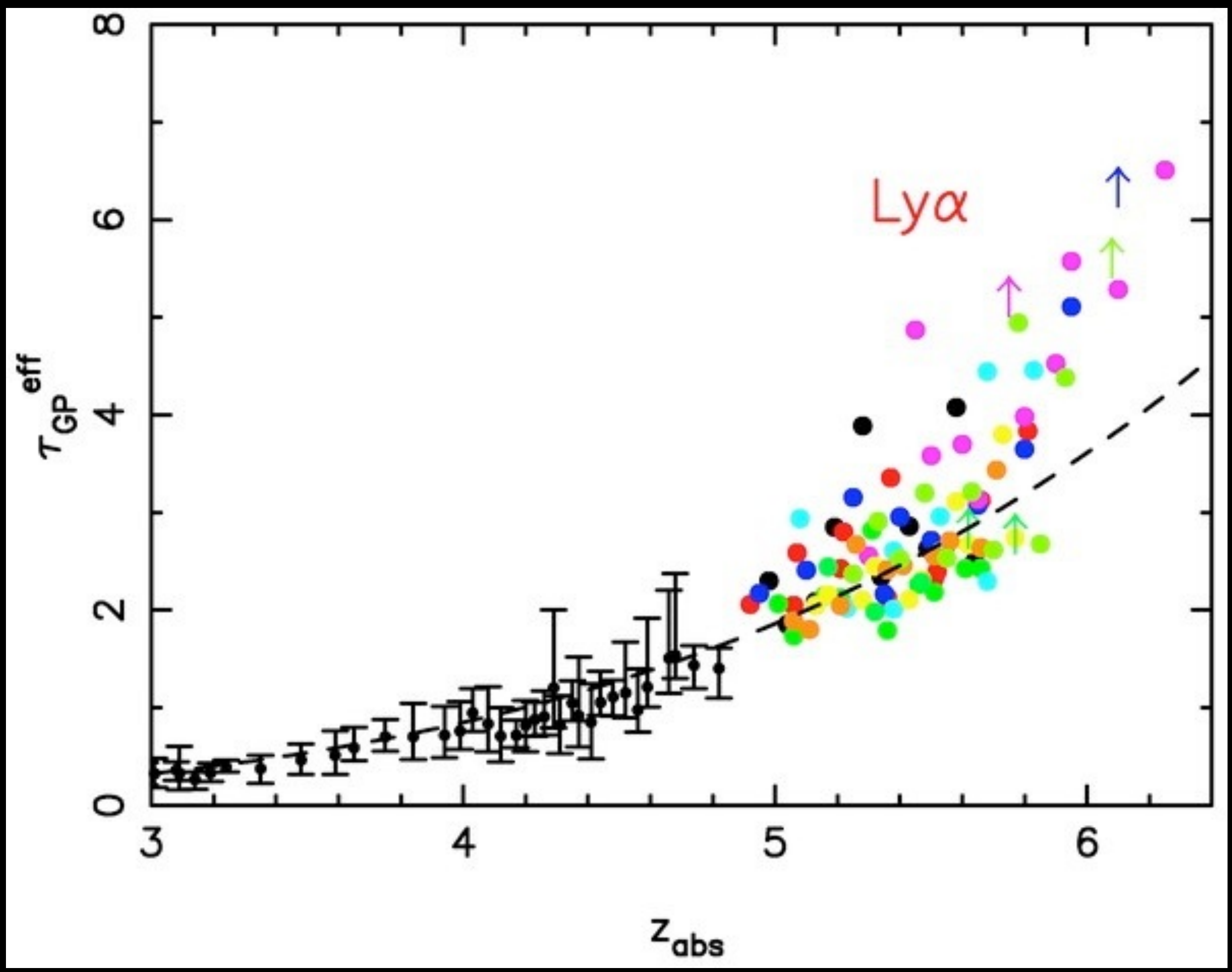




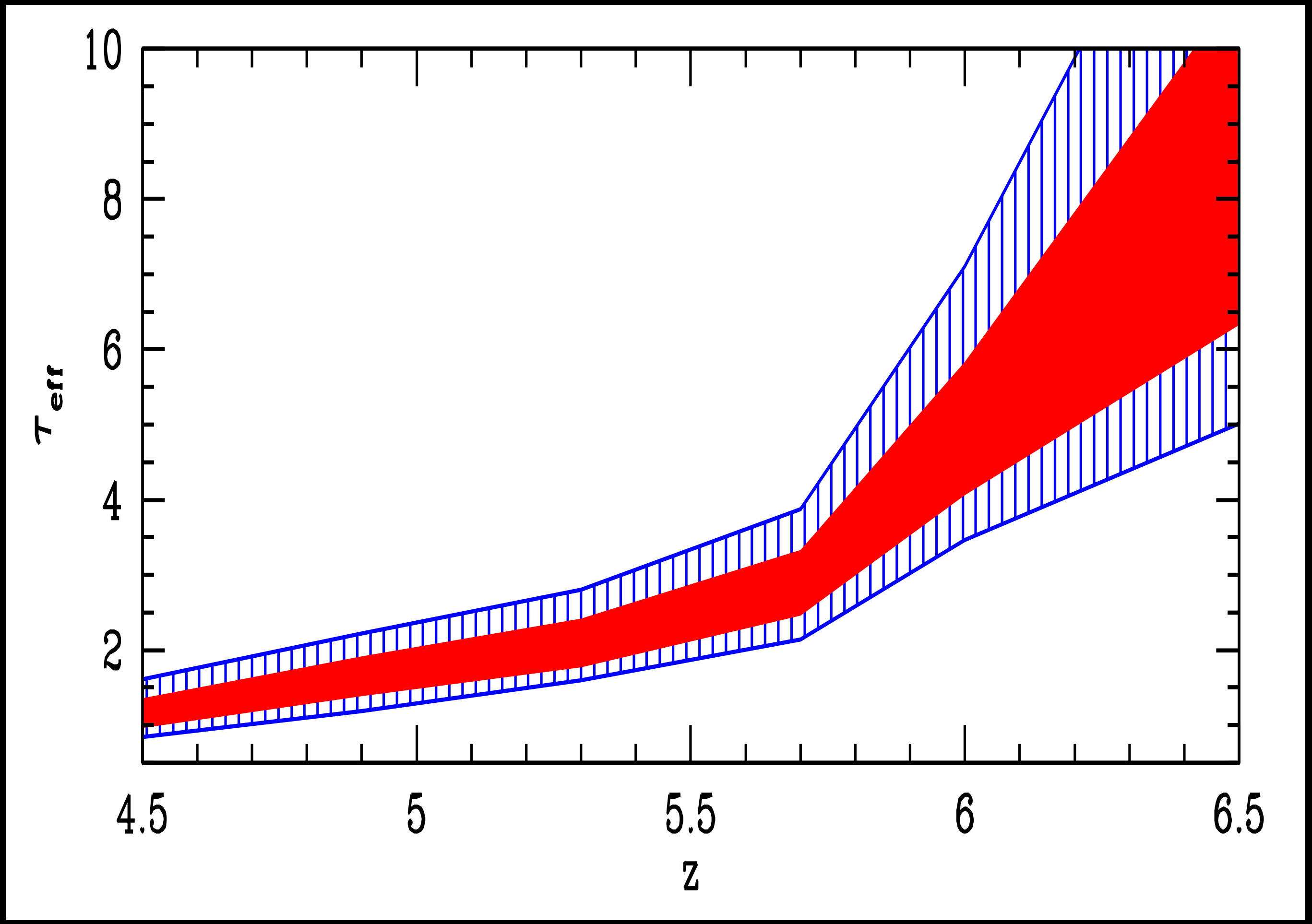
Fan+06

Lyα forest at z > 5

Scatter in Lyα Opacity = Reionization?



Fan+06

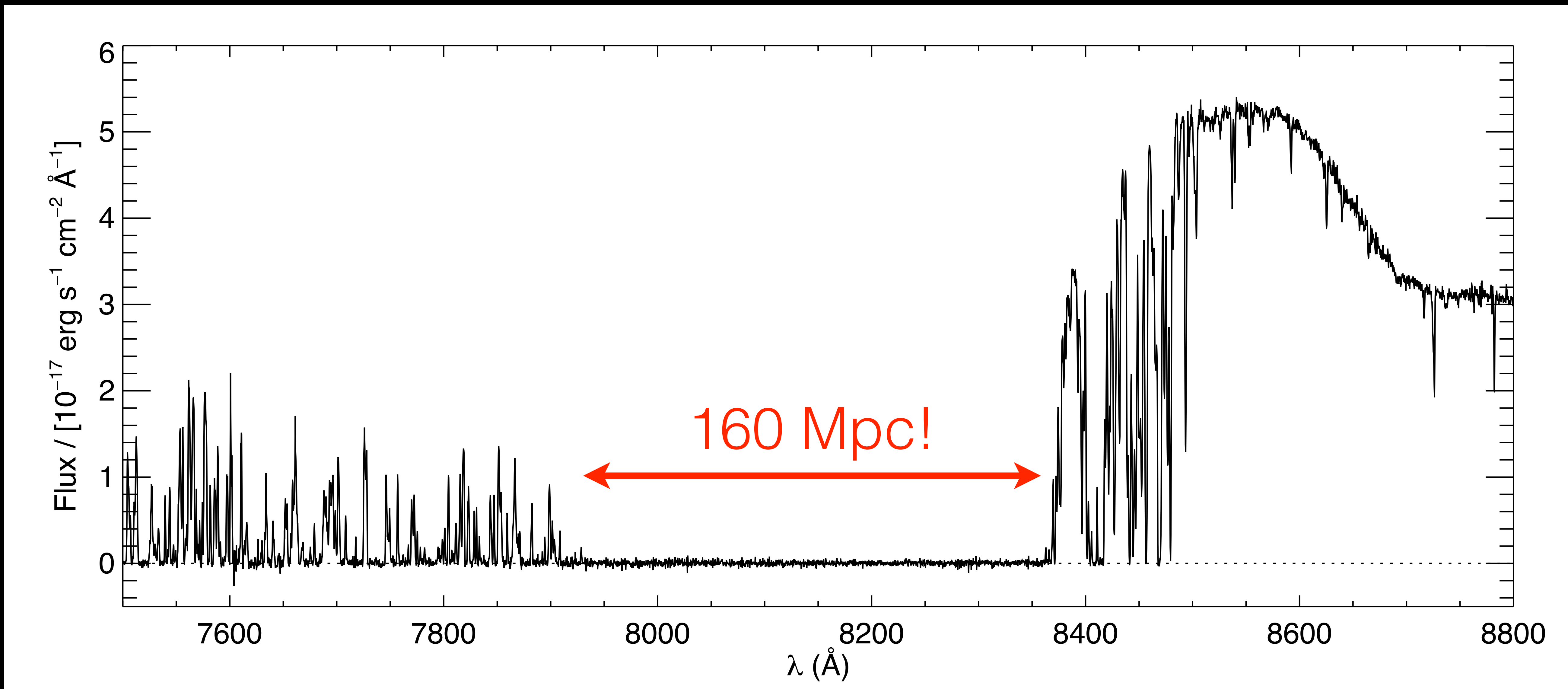


Lidz et al (2006)

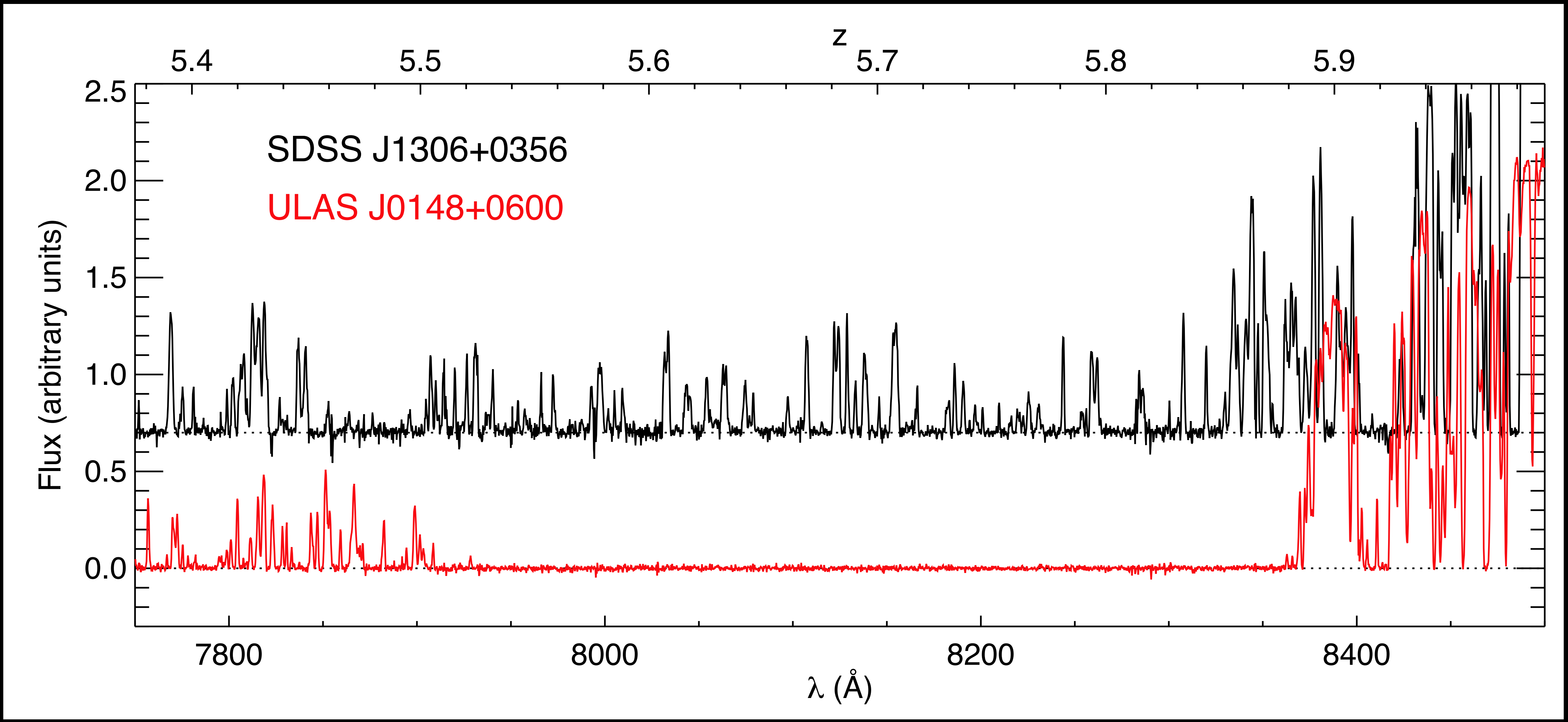
Get large scatter in Lyα opacity from the density field ***alone***.

ULAS J0148+0600

$z_{em} = 5.98$

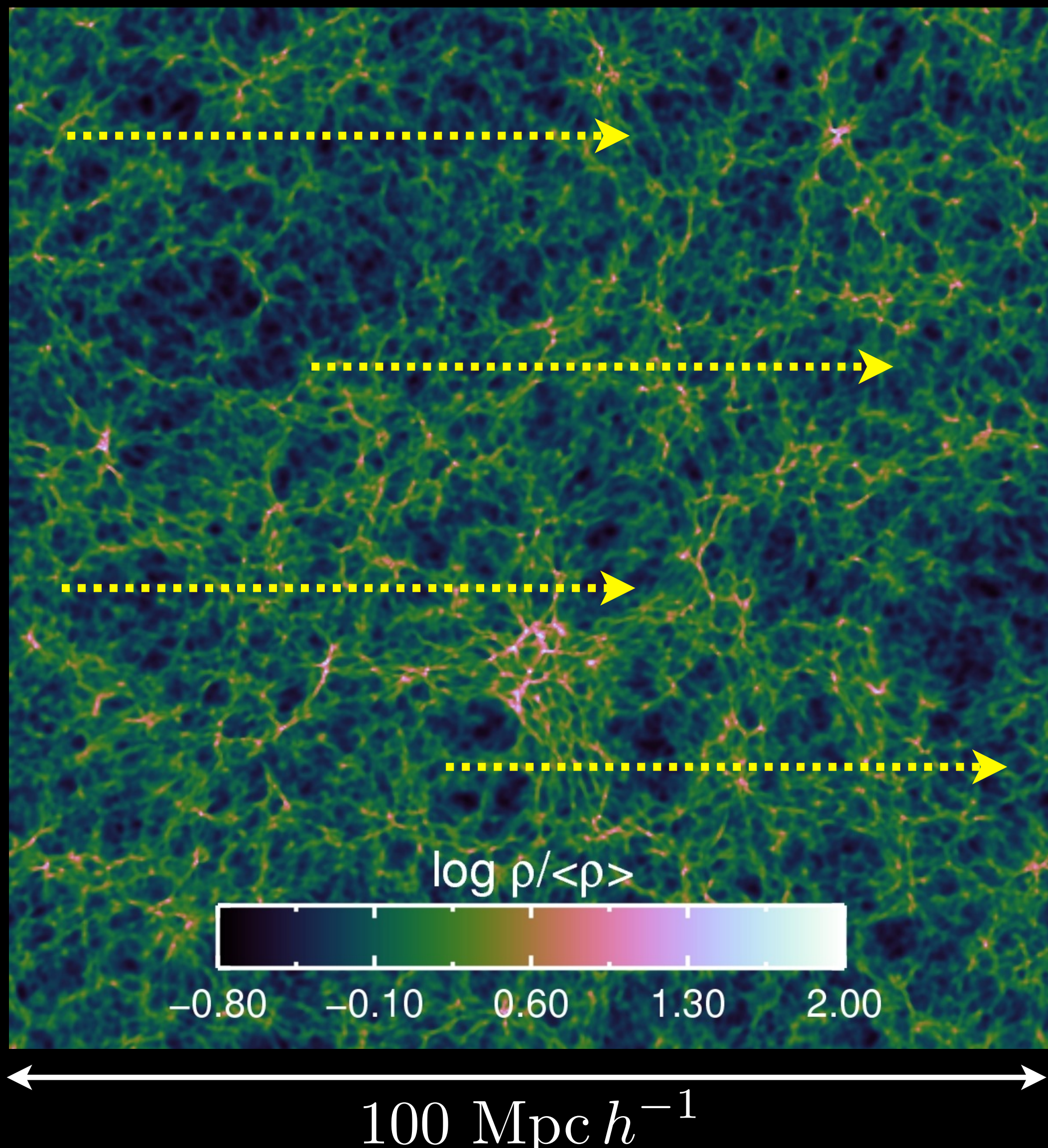


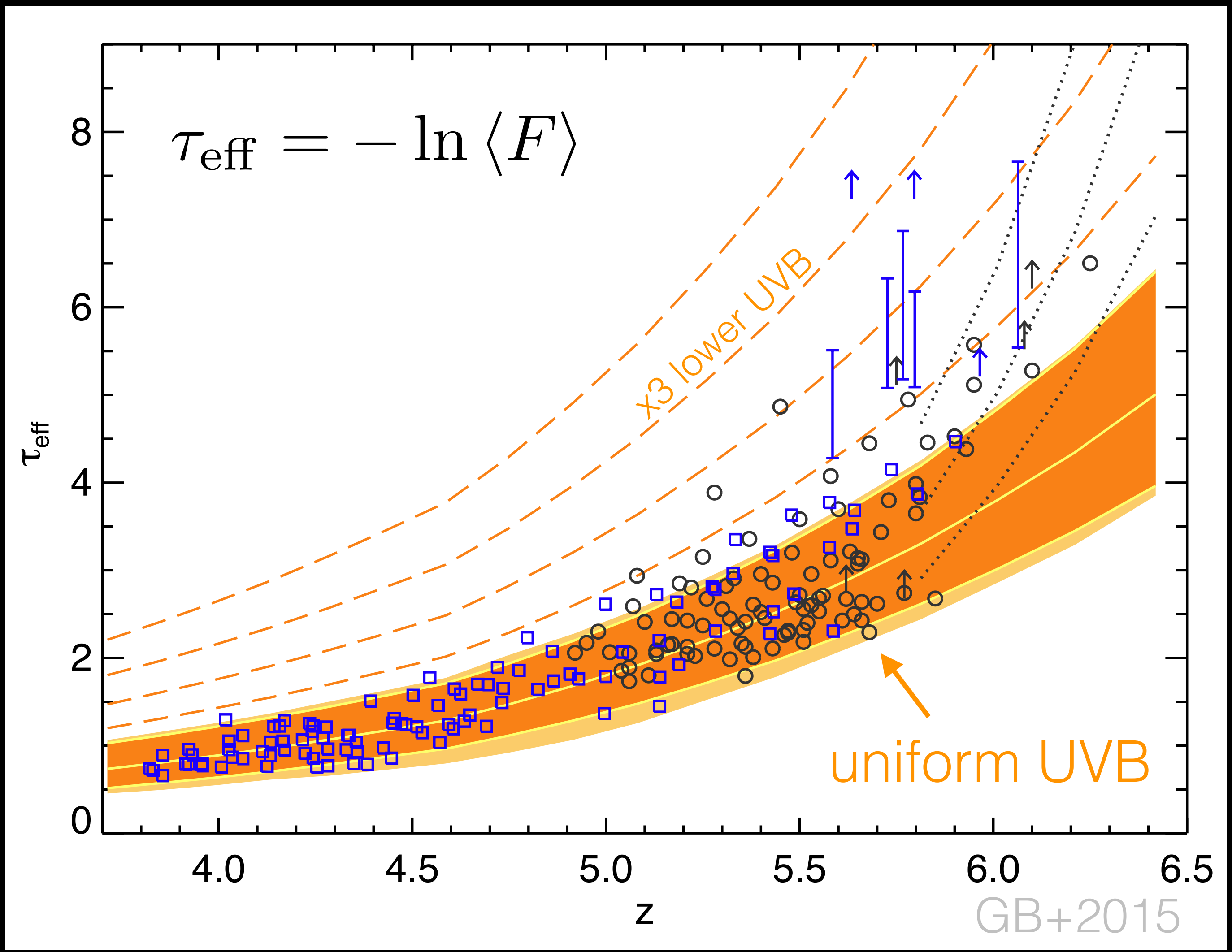
10 hr VLT/X-Shooter Spectrum



What drives this difference in opacity?

It must be more than density fluctuations…





Factor of >3 fluctuations in neutral fraction required.

- UVB fluctuations due to bright sources? (Chardin+2015 & in prep)
- Temperature fluctuations from reionization? (D'Aloisio+2015)
- UVB fluctuations due to mean free path? (Davies & Furlanetto 2016)
- Radiative-transfer effects? (Gnedin+2016)

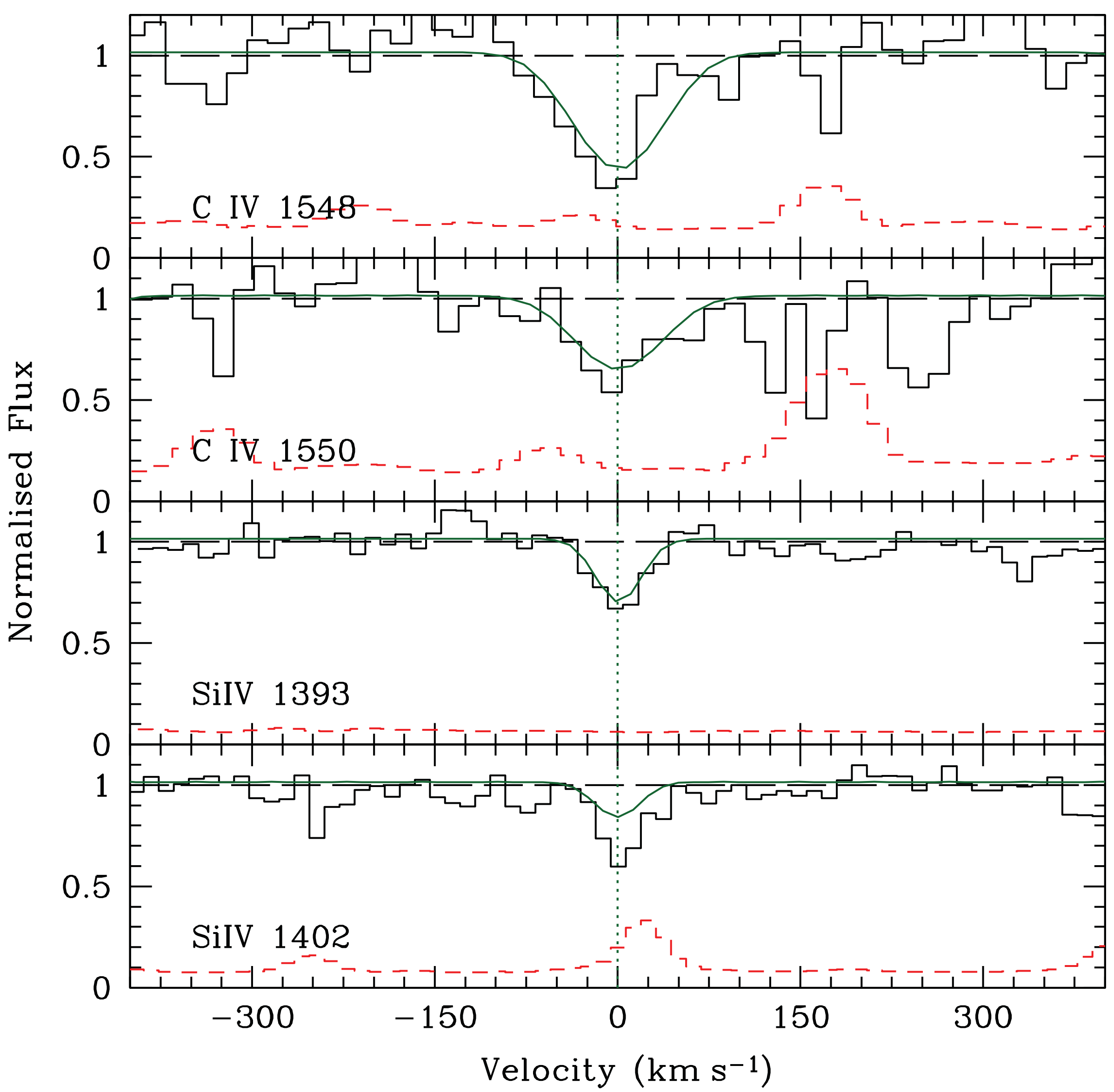
Metal absorbers: Highlights from z~0-4

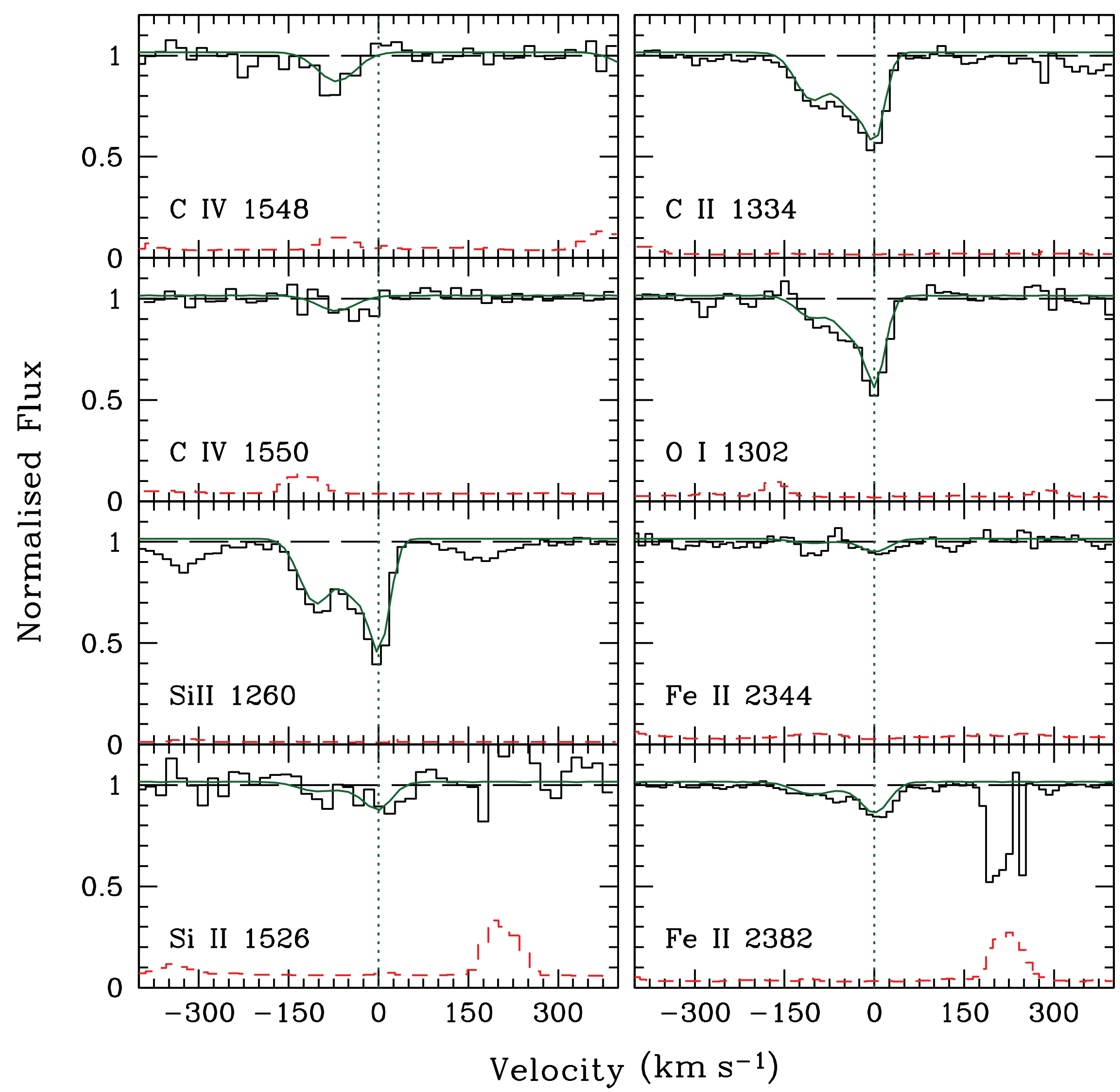
Setting the scene: The IGM at z~5-6

Metals near reionization

High ionization "C IV" system

Low ionization "O I" system

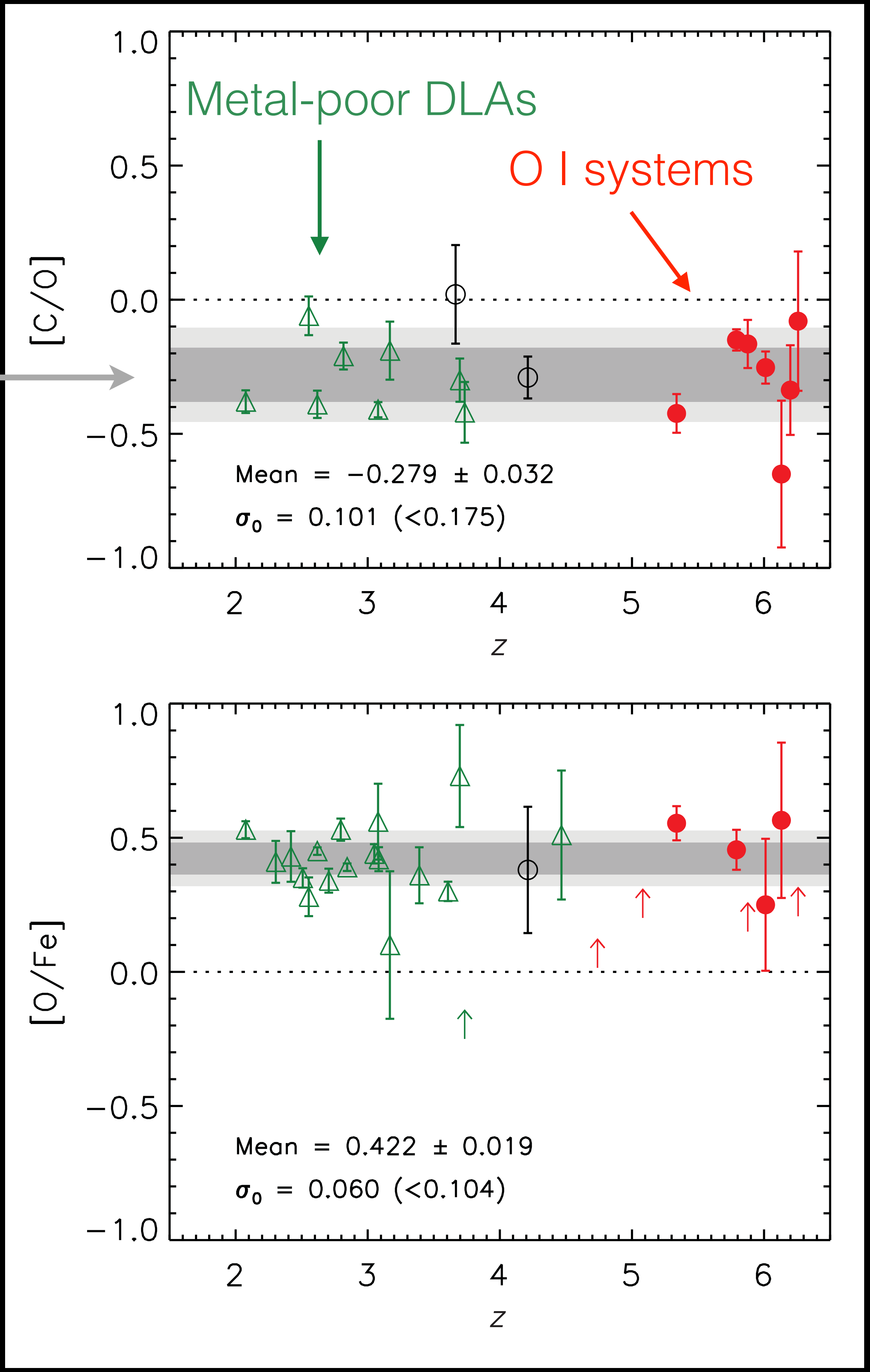




X-Shooter data, D'Odorico et al. (2013)

Relative abundances constrain early stellar populations.

As seen in z~2.4 LBGs (Steidel+), nearby low-metallicity galaxies (Berg+), metal-poor stars…

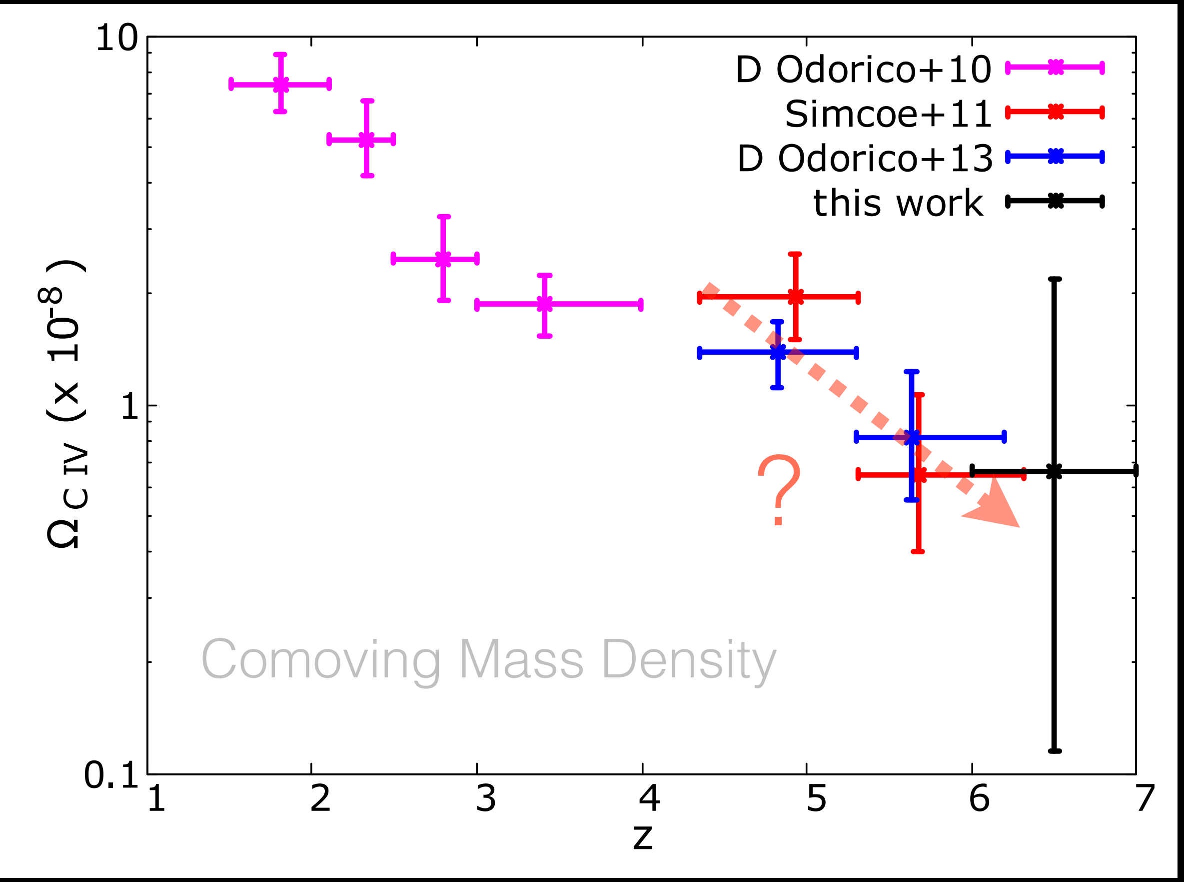


z > 5: GB+2012

z < 5: DLAs from Cooke+2011, sub-DLAs from Dessauges-Zavadsky+2003, Péroux+2007

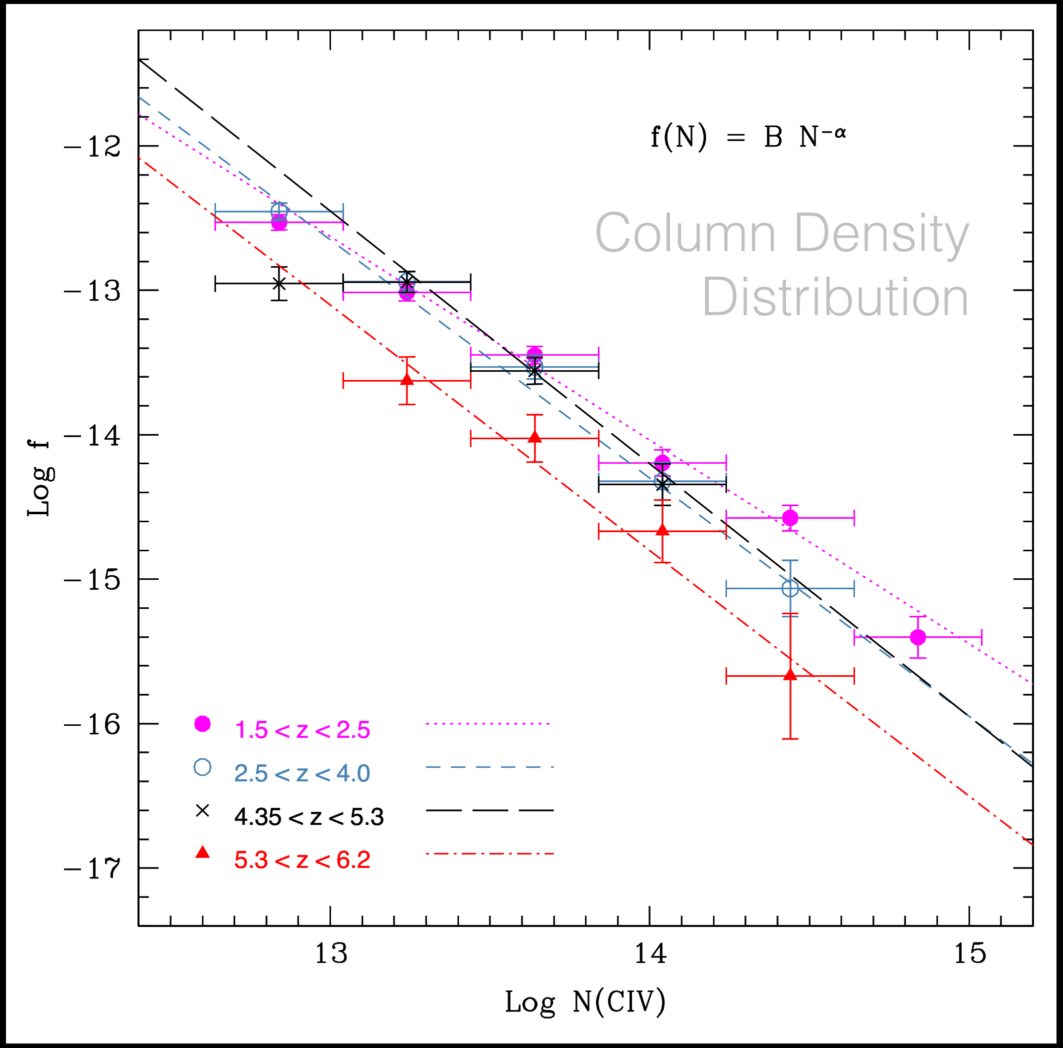
C IV at z > 5

Global mass density of C IV: declining rapidly?



From Bosman+ in prep
See also Ryan-Weber+2009

C IV systems are certainly becoming more rare.



D'Odorico+2013

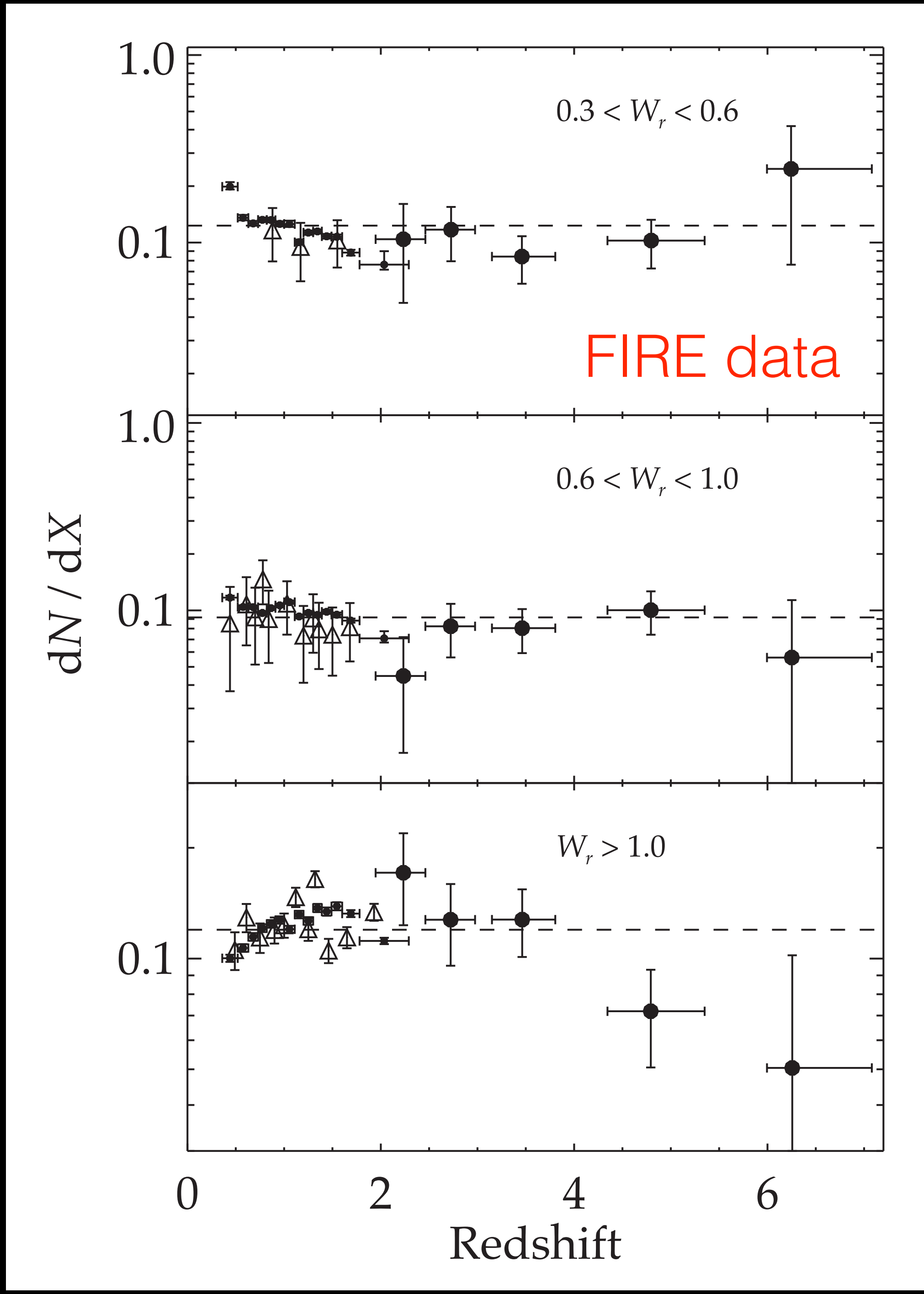
Modeling: z~5-6 C IV requires exceptionally strong feedback
(Oppenheimer+2009; Finlator+2015; Keating 2016)

Mg II at z > 2

Weak systems (oddly?) constant with redshift

Strong systems echo evolution of global SFR density

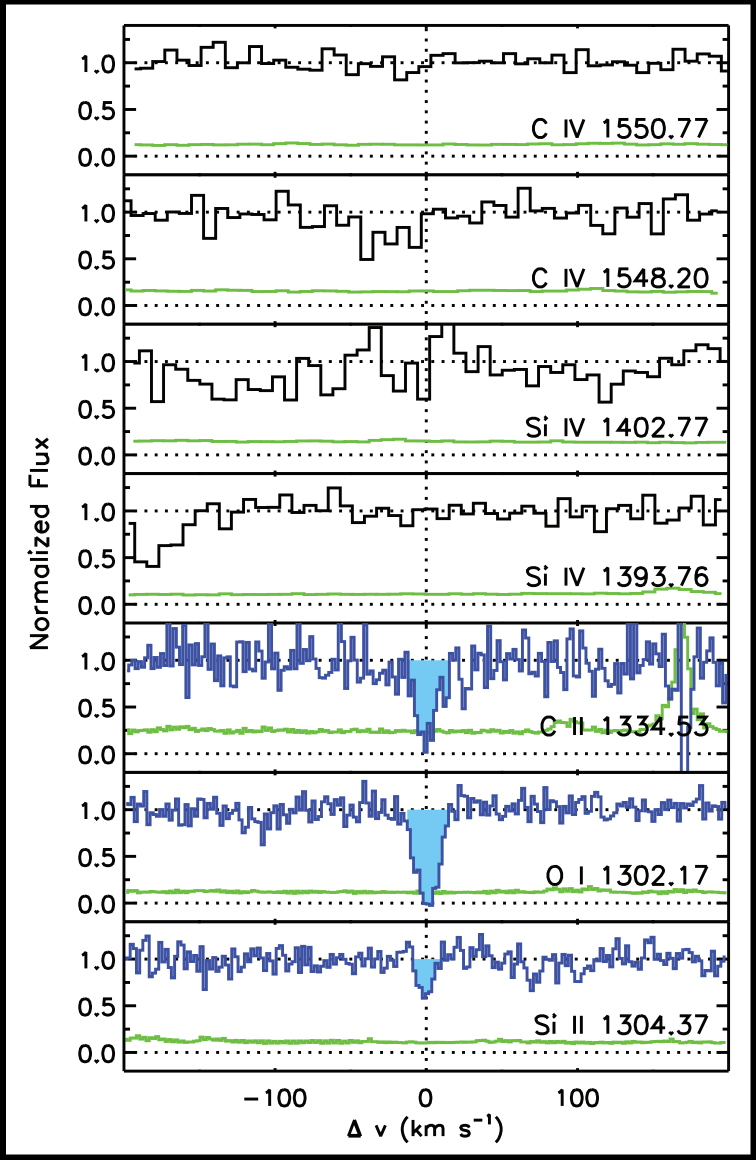
Line-of-sight Number Density



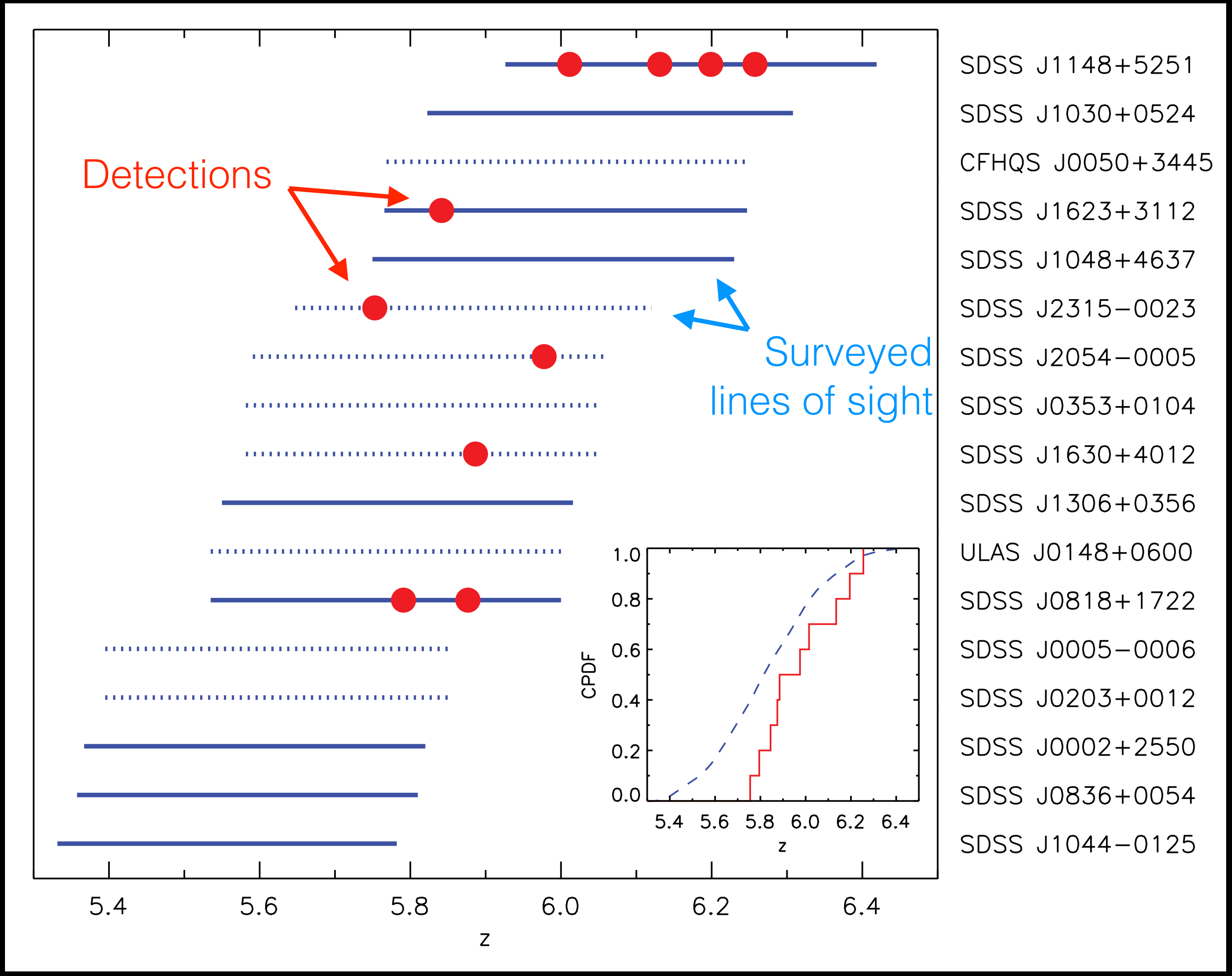
z > 2: Matejeck+2012; Chen, Simcoe+ in prep
z < 2: Nestor+2005, Syeffert+2013

O I systems at z > 5.4

An example at z=6.131



Evolution?



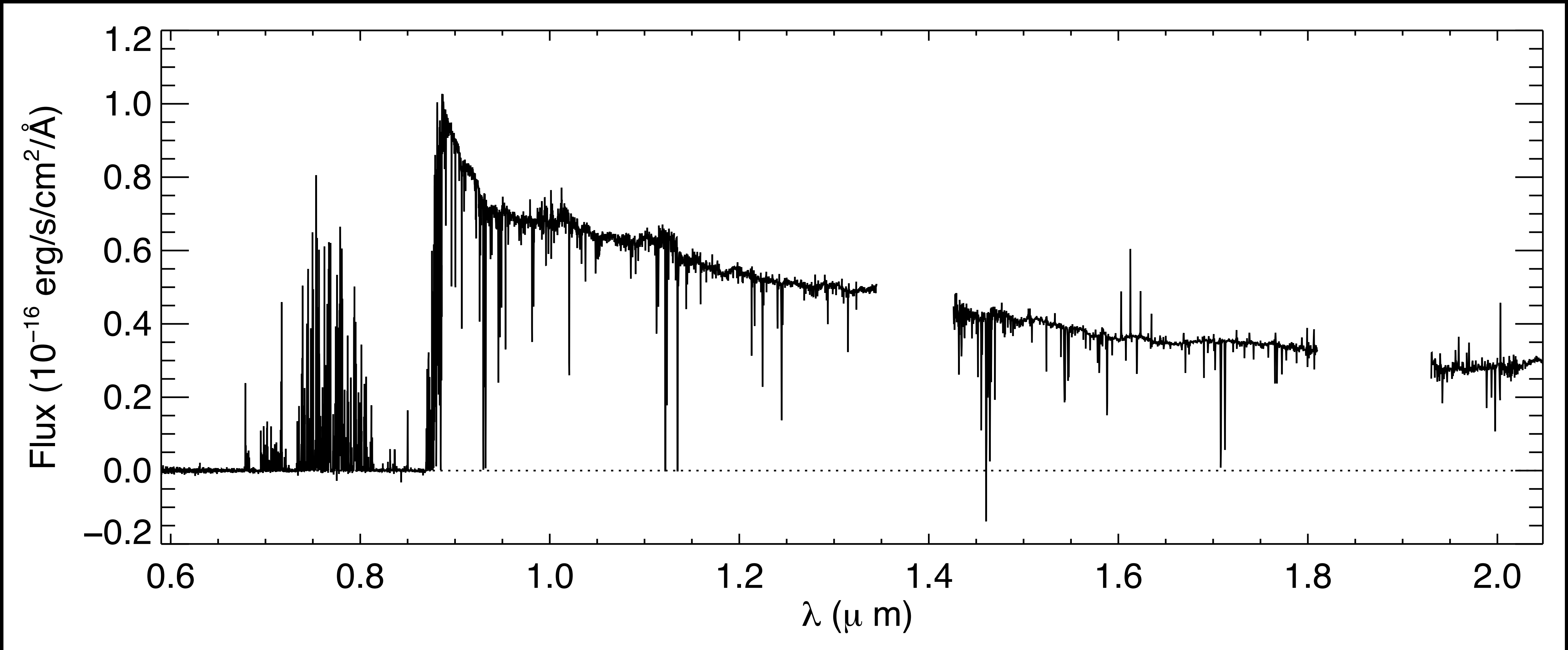
GB+2011

Modeling: Consistent with CGM enrichment and an evolving, patchy UVB

(Keating+2014; Finlator+2015,2016)

SDSS J0100+2802 (z=6.3)

3 hours with VLT/X-Shooter, PI: Pettini



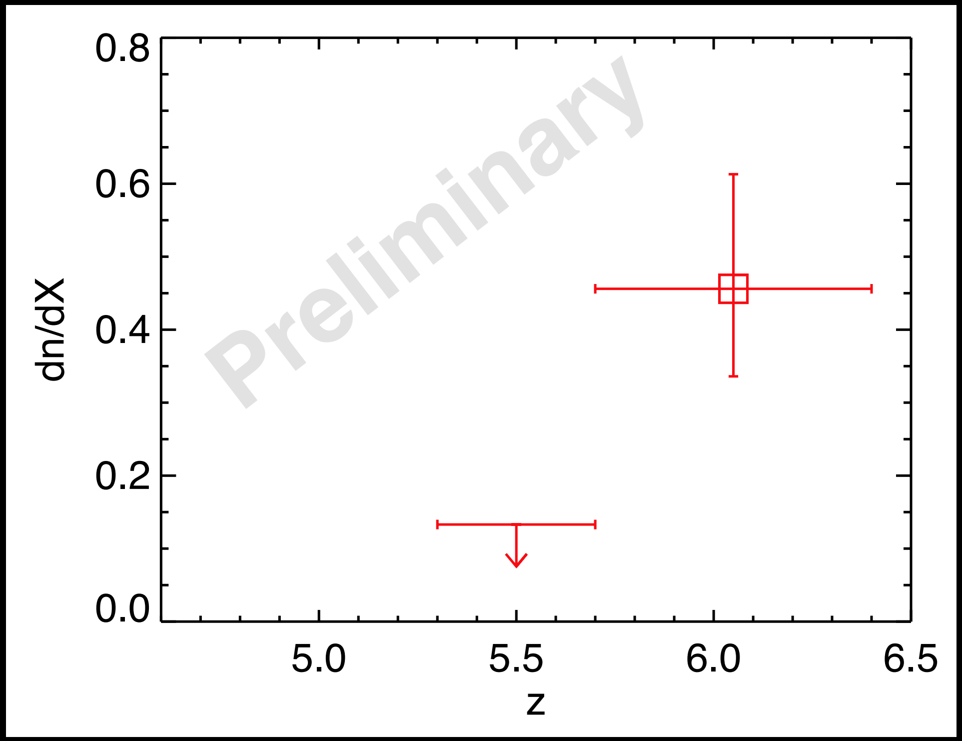
4 O I systems over $5.8 < z < 6.1$

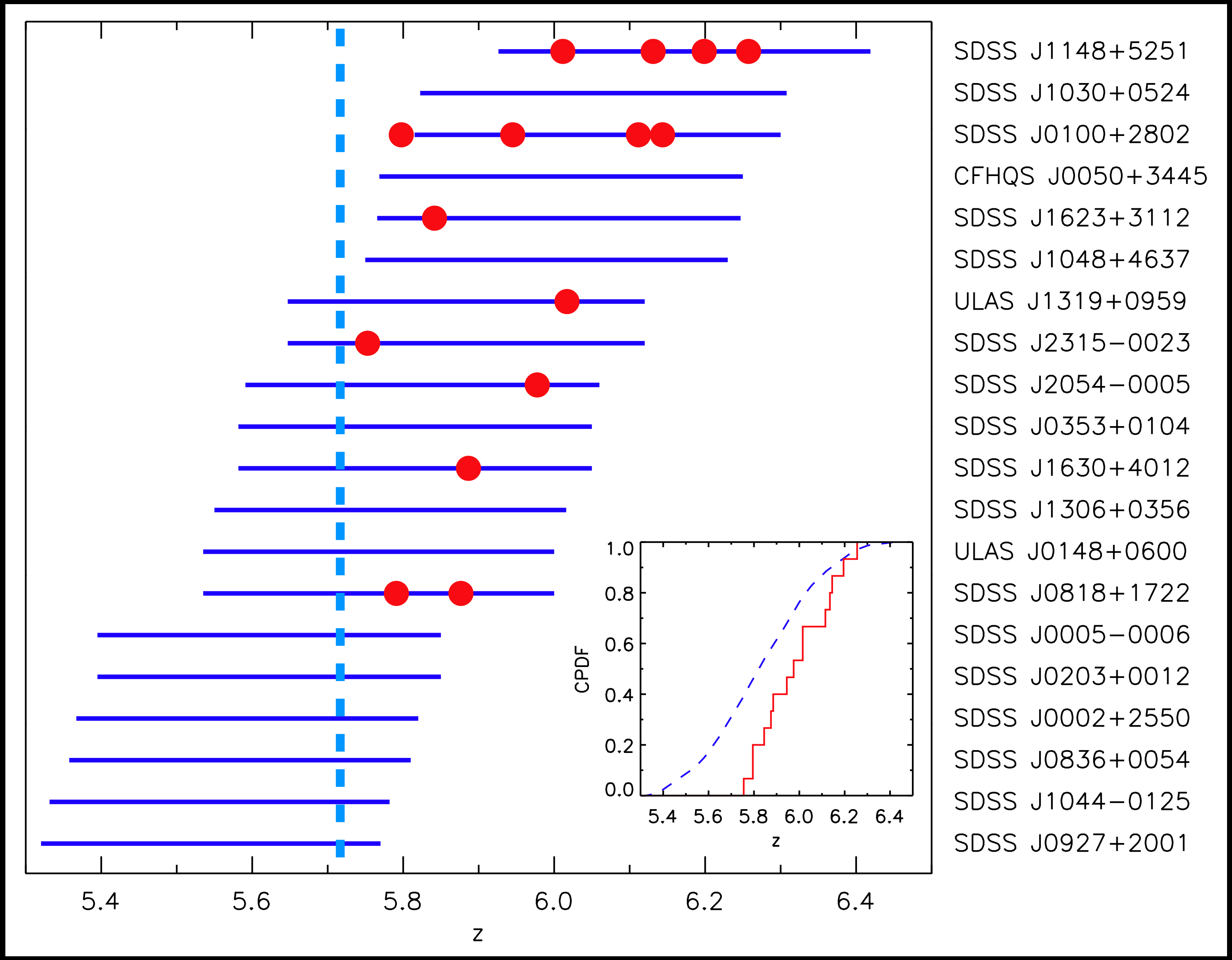
O I systems at z > 5.4

Evolution? Yes. (Probably.)

Number density off neutral metal absorbers appears to suddenly increase at z > 5.7 (>99% conf).

Line-of-sight Number Density

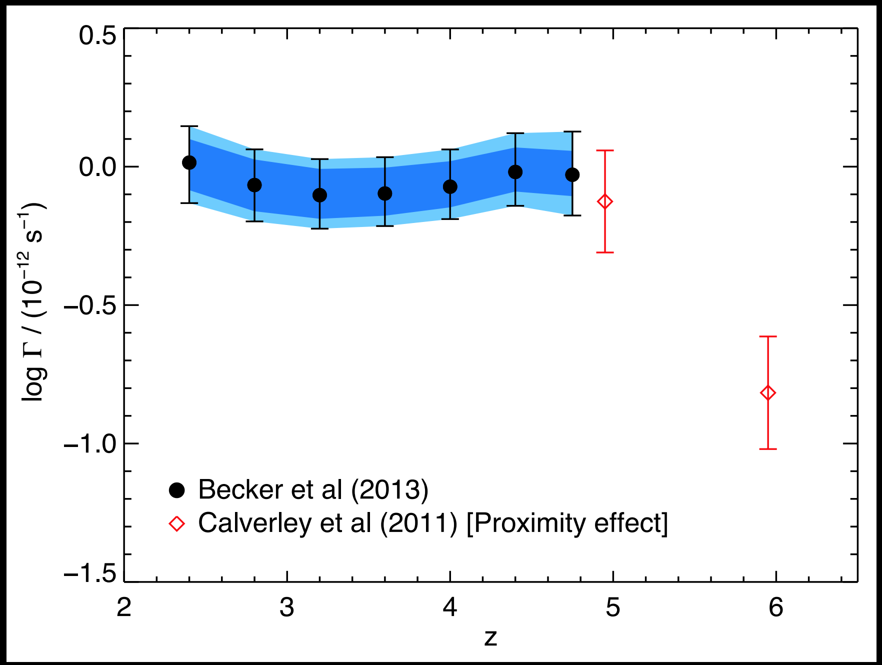




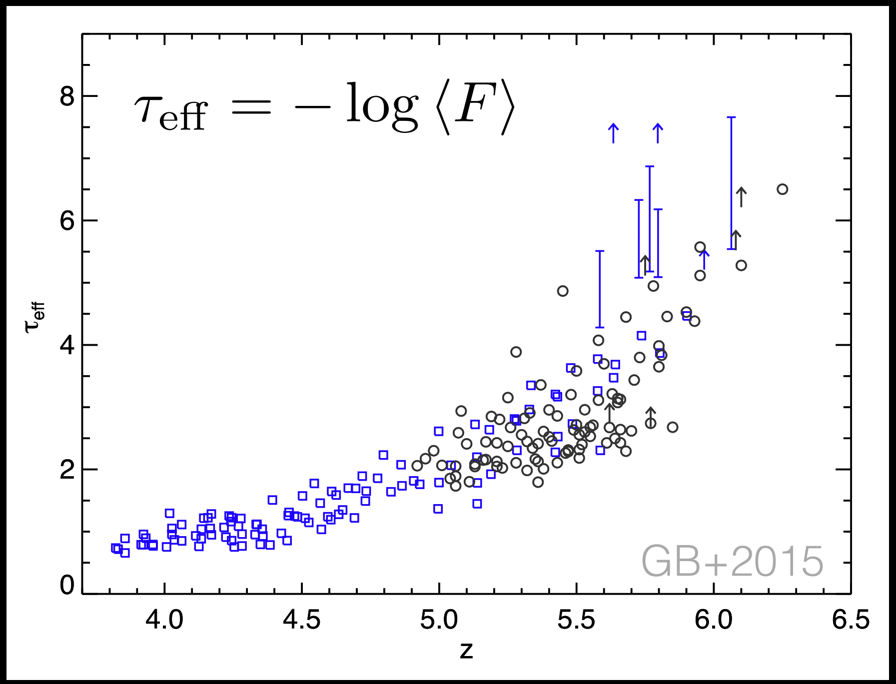
Becker & Pettini, in prep

The IGM and CGM are in transition at z~5.5-6

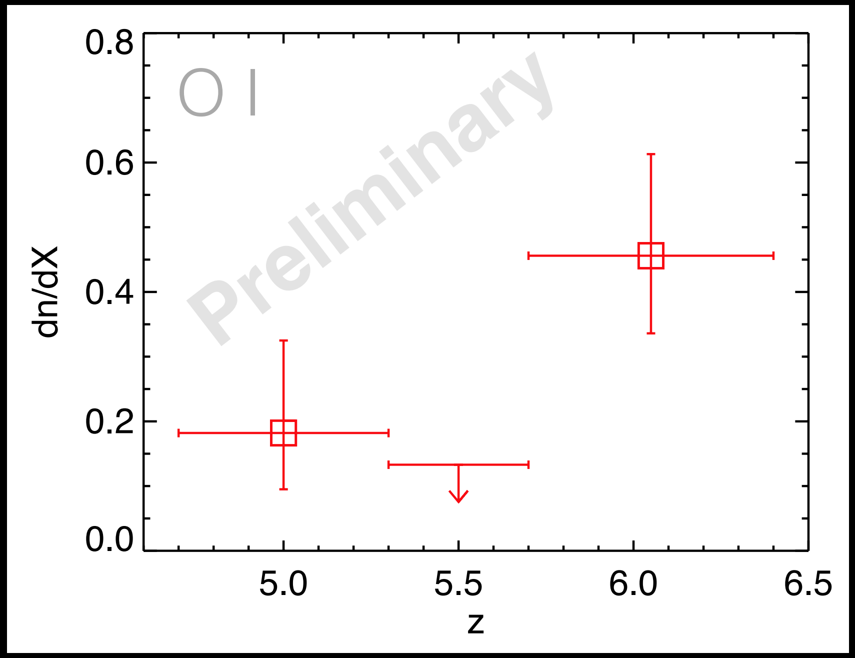
Declining UV background



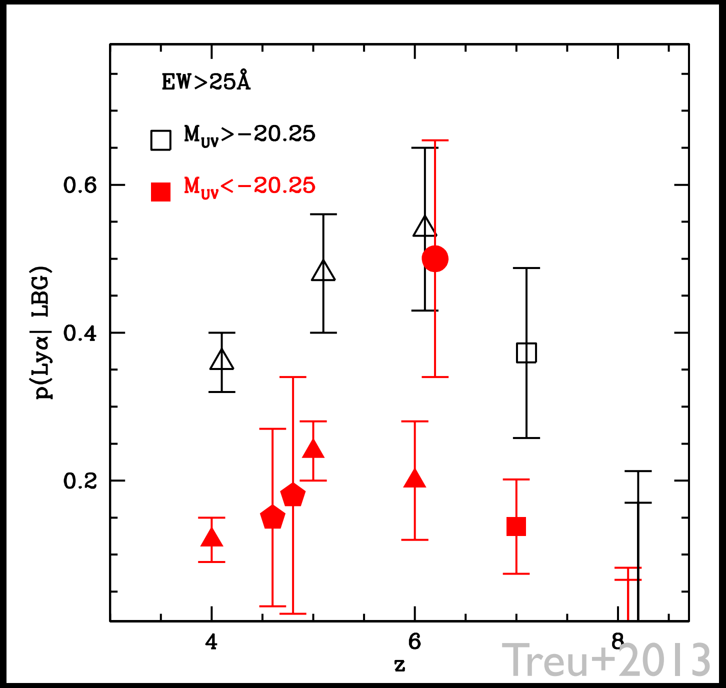
Scatter in Lyα opacity



Increase in O I systems, decline in C IV



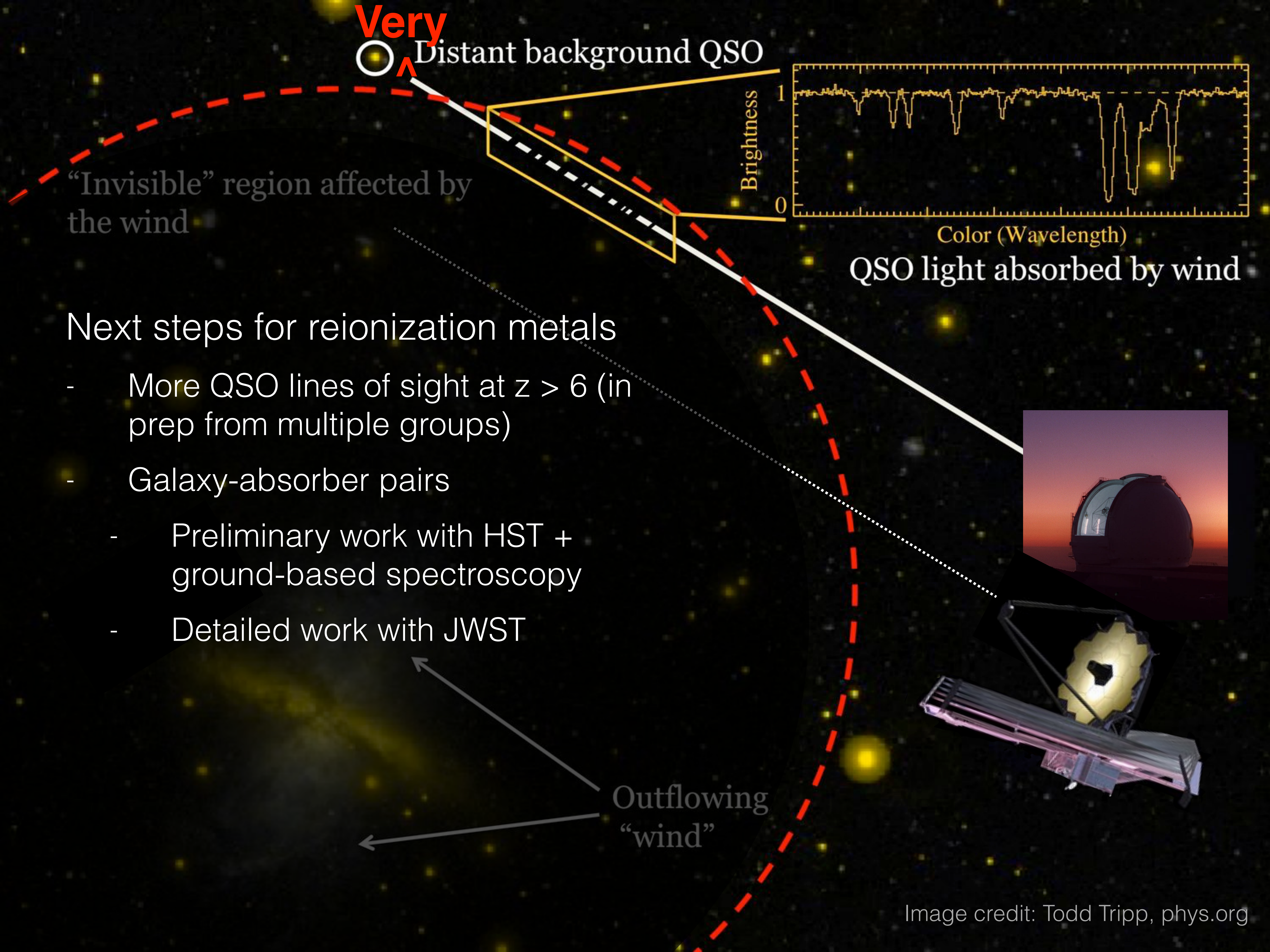
Declining galaxy Lyα fraction



Can this all be explained by a declining UVB, or are we witnessing the end stages of reionization?

Next steps for reionization metals

- More QSO lines of sight at z > 6 (in prep from multiple groups)
- Galaxy-absorber pairs
  - Preliminary work with HST + ground-based spectroscopy
  - Detailed work with JWST



Summary

- Metal absorption lines are a powerful tool to constrain galaxy evolution at all redshifts.
- Surveys for metals at $z > 5$ are rapidly expanding, largely due to new instrumentation.
- Trends in metal lines, along with other observations, point to a rapidly evolving IGM/CGM near $z \sim 5.5$-6 — a highly observable epoch for joint galaxy/CGM/IGM studies.
- Strong constraints on feedback in reionization galaxies will come from studying galaxy-absorber pairs at $z > 5$.