He II: Reionization and Post-Reionization Epochs

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Ayers Rock Conference
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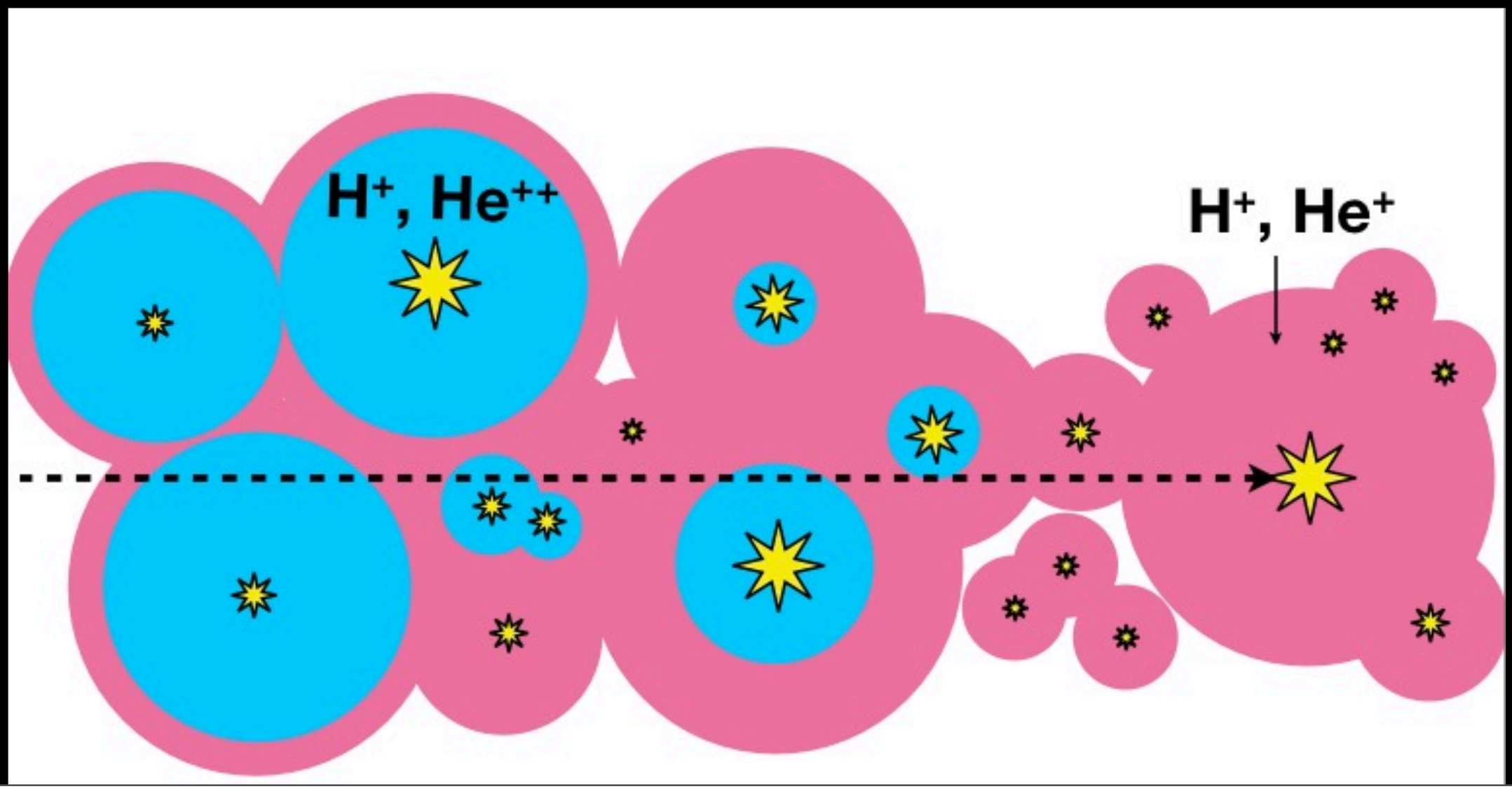
HST/COS work with David Syphers, Charles Danforth, Kevin France, Britton Smith



The High-Redshift Universe

Re-ionization of He II (11 Gyr ago)

probably photoionized by
quasars (4 ryd radiation)

COS Observations of Three Bright He II Quasars:

* HE 2347-4342 (z = 2.886)
* HS 1700+6416 (z = 2.748)
* Q 0302-003 (z = 3.286)

Re-ionization of H I (13 Gyr ago)

probably photoionized by
hot stars (1 ryd radiation)

(complete by z ≈ 7)

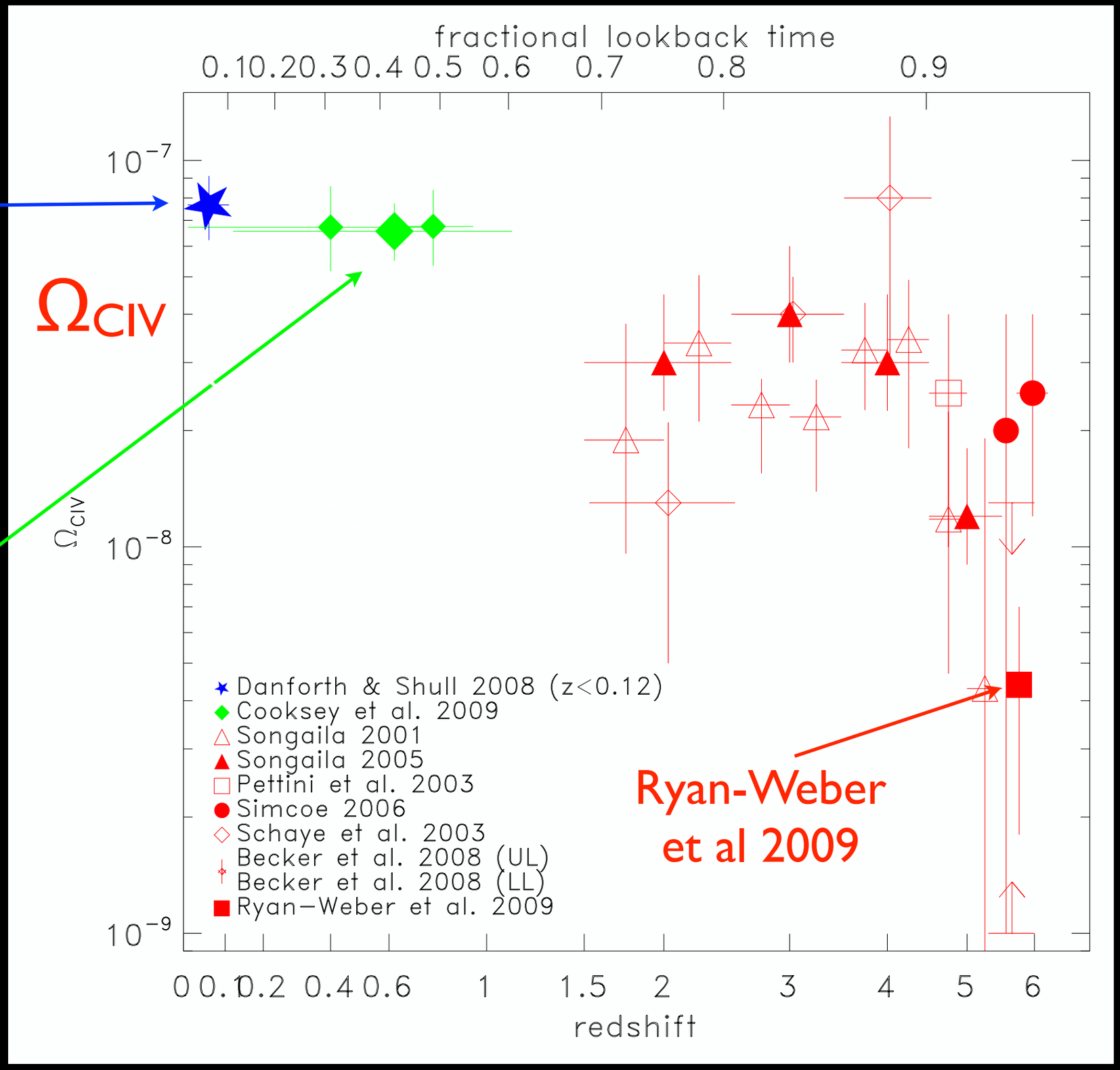
Metal Evolution in the IGM (rapid at z = 3-6)

(Traced by C IV)

STIS/E140M survey
(Shull & Danforth 2010)

$\Omega_{CIV} \approx 8 \times 10^{-8}$

STIS/E230M survey
(Cooksey et al 2009)

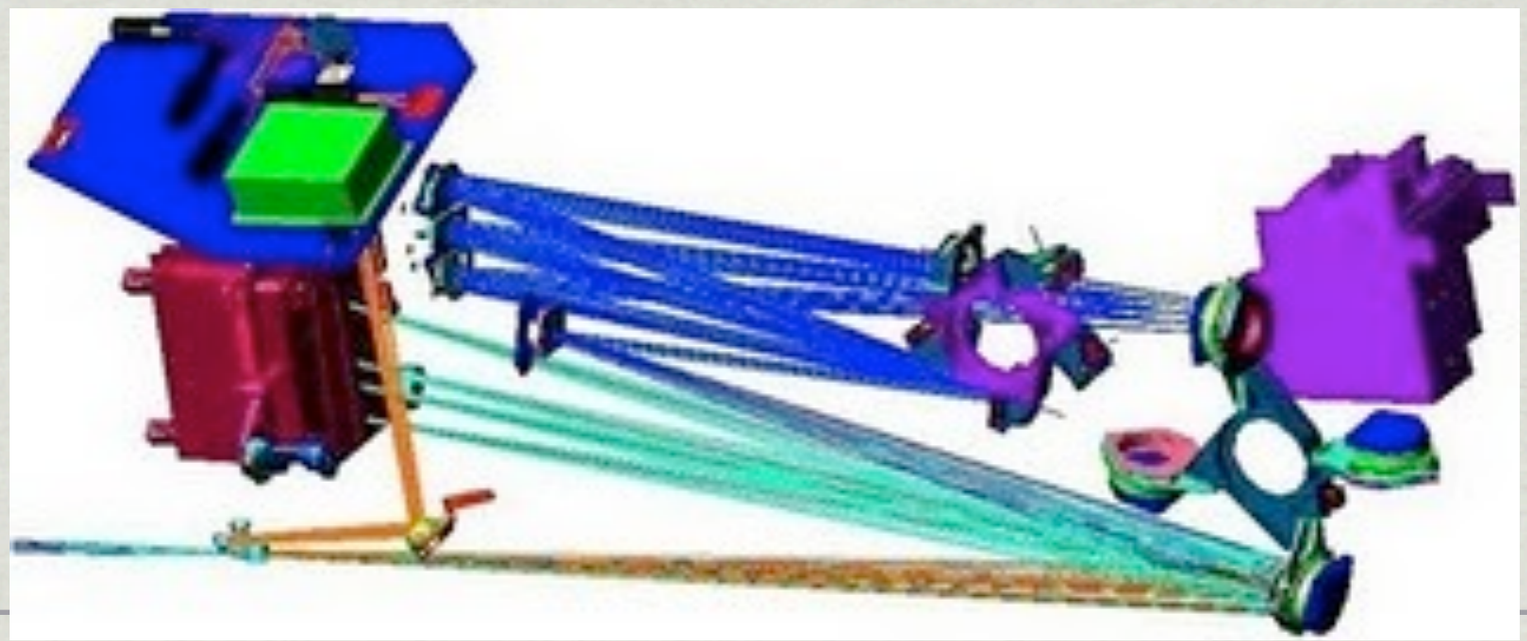


Cosmic Origins Spectrograph:

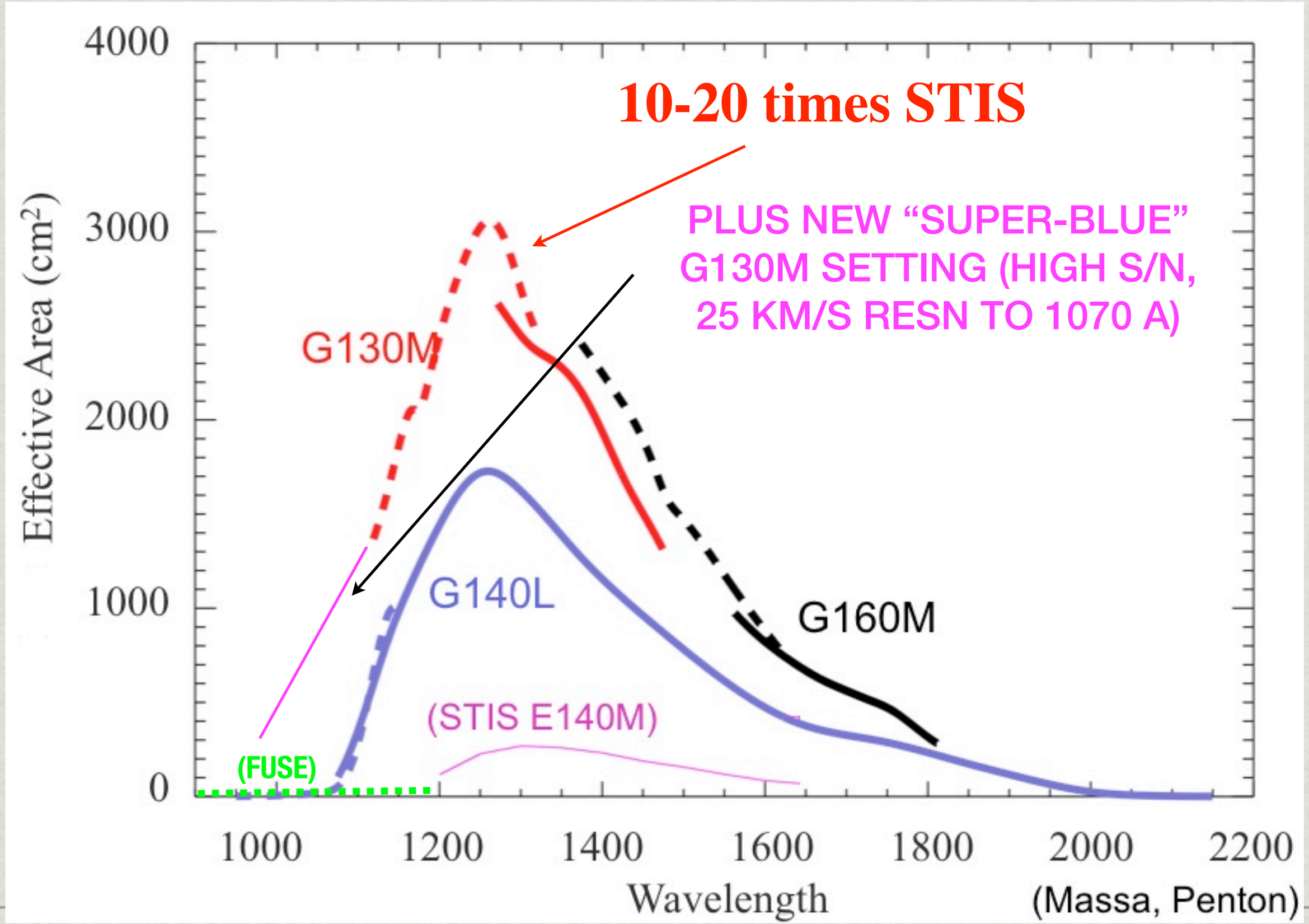
Instrument Overview

- 4th-generation UV Spectrograph on HST
- FUV (1140-1800 Å)
  NUV (1700-3150 Å)
- High-sensitivity “quasar gun” for studying ISM/IGM (and AGN, O stars, White Dwarfs)
- Moderate resolution (R≈18,000 ; 17 km/s)

Resolves weak lines at high S/N > 30



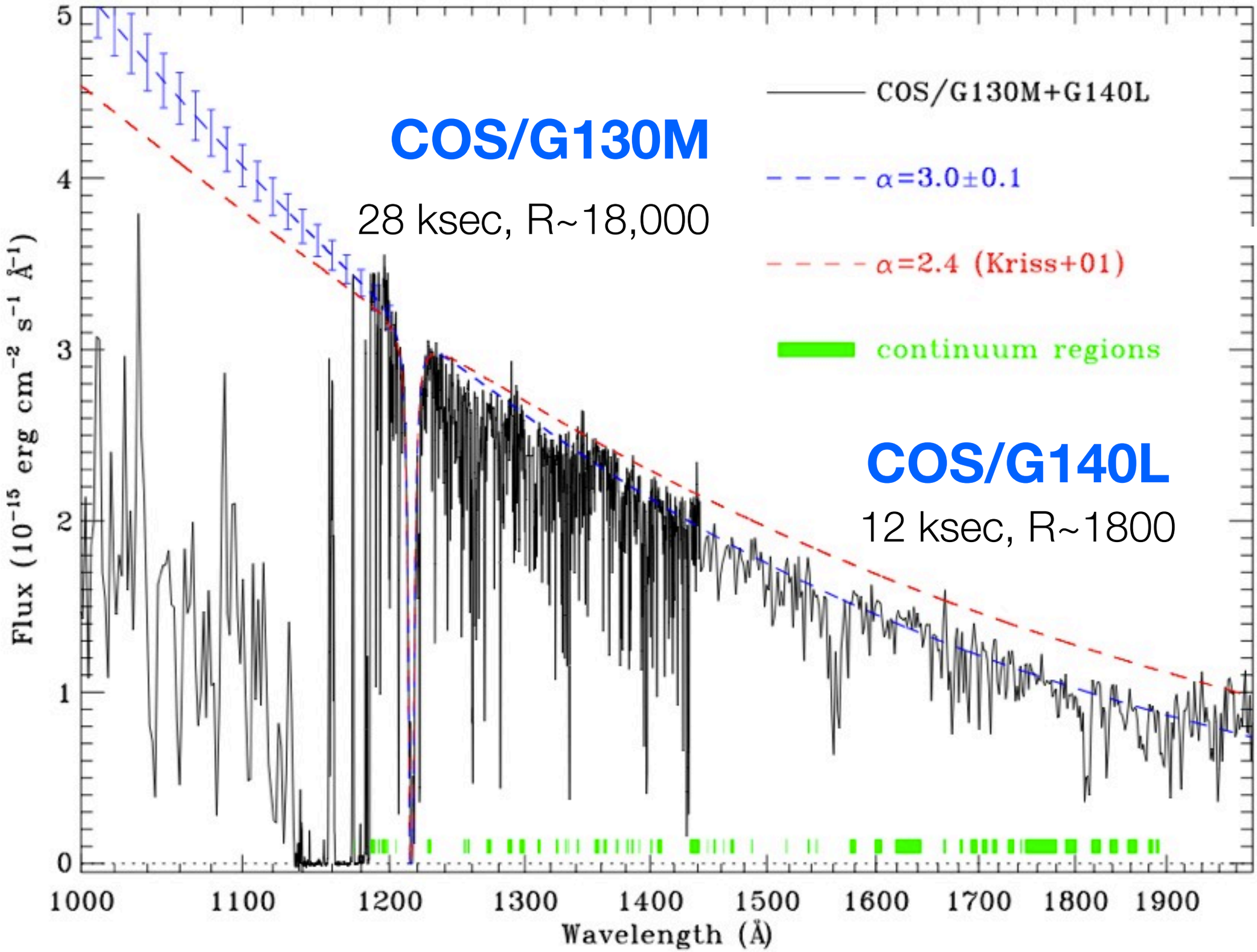
COS Detector Performance



Hubble/COS Spectrum of HE 2347-4342

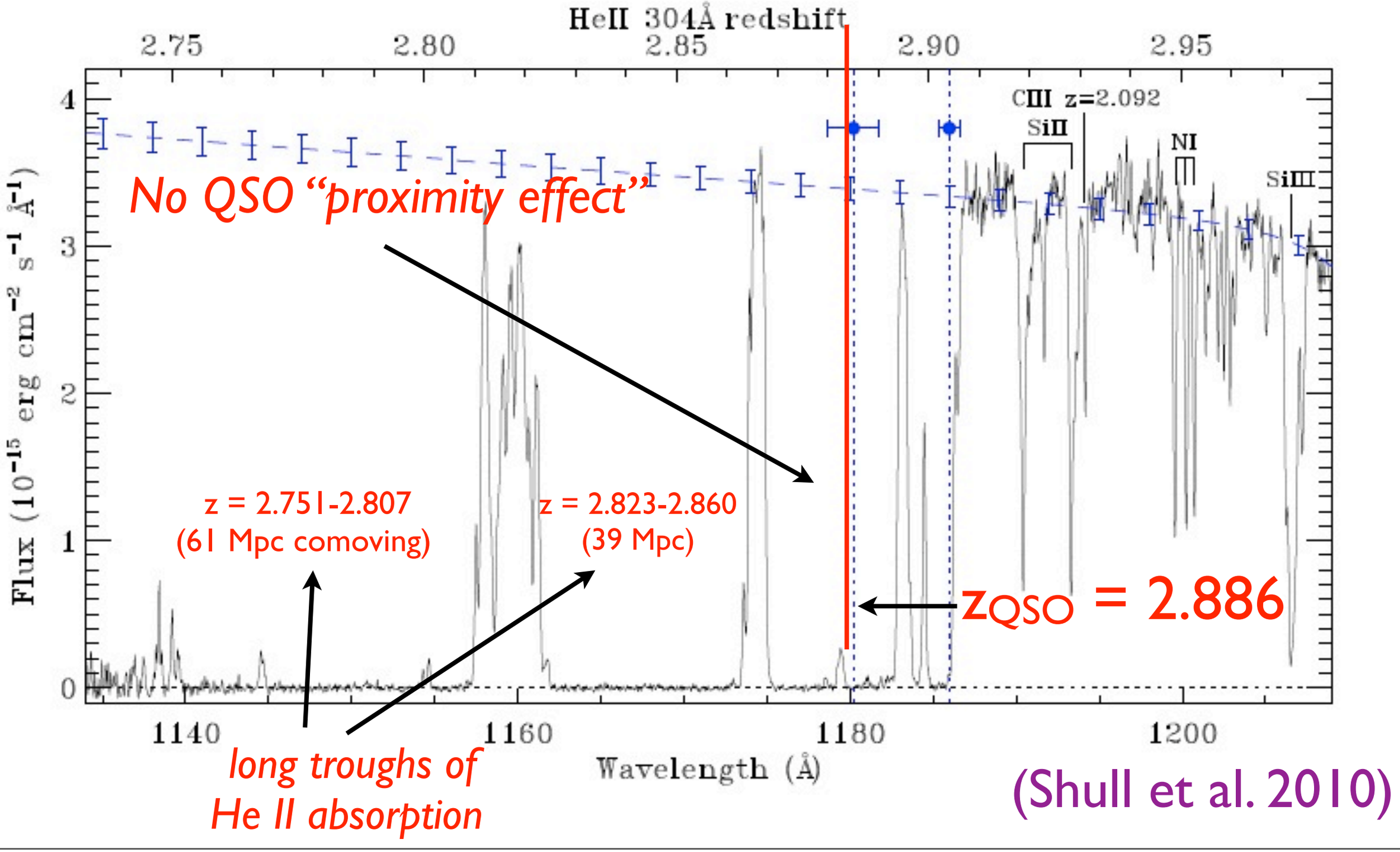
z = 2.886

Shull, France, Danforth, et al. (2010 ApJ)



Patchy He II Reionization (z ≈ 2.7-2.9)

HE 2347-4342

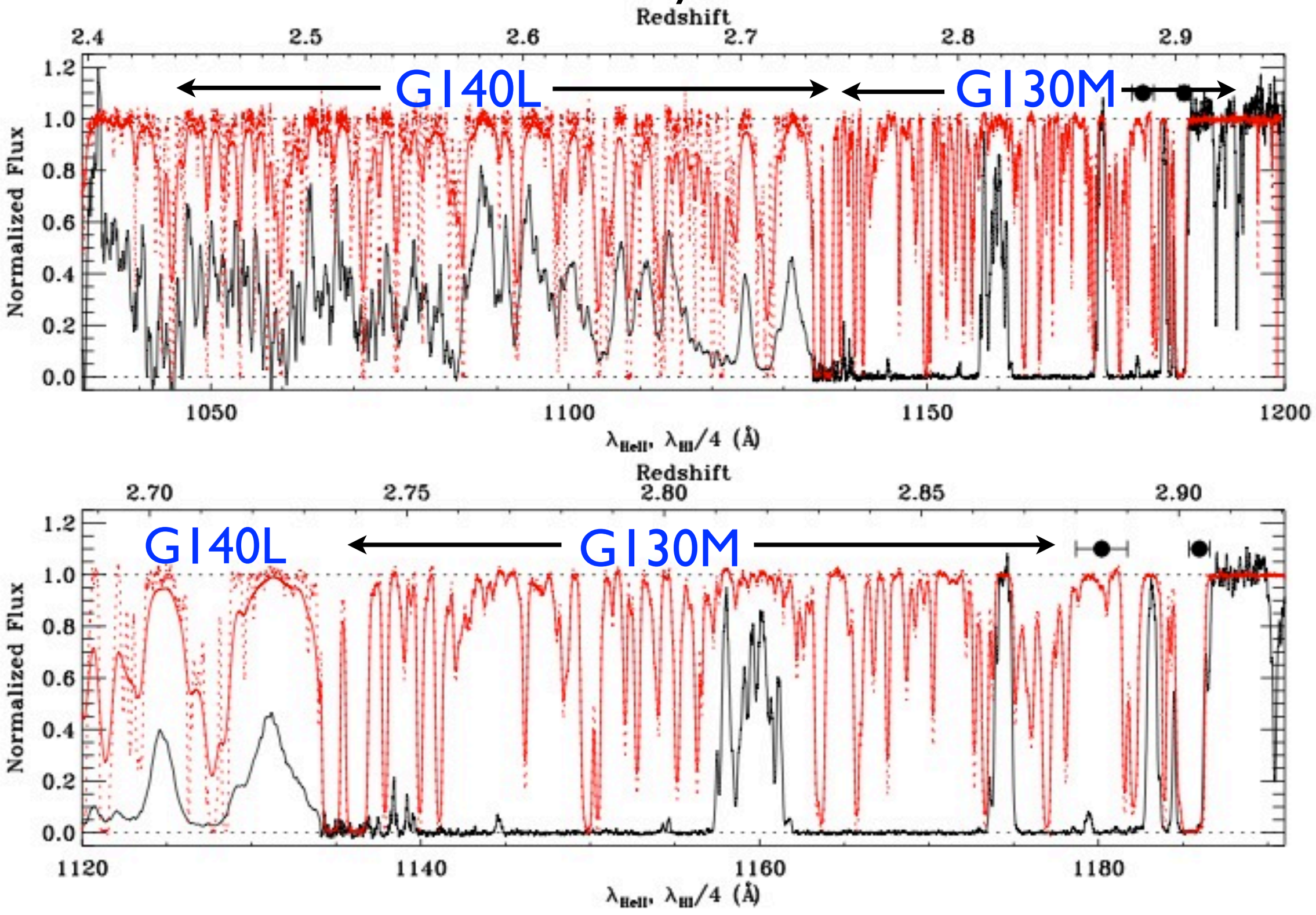


(Shull et al. 2010)

HE 2347-4342

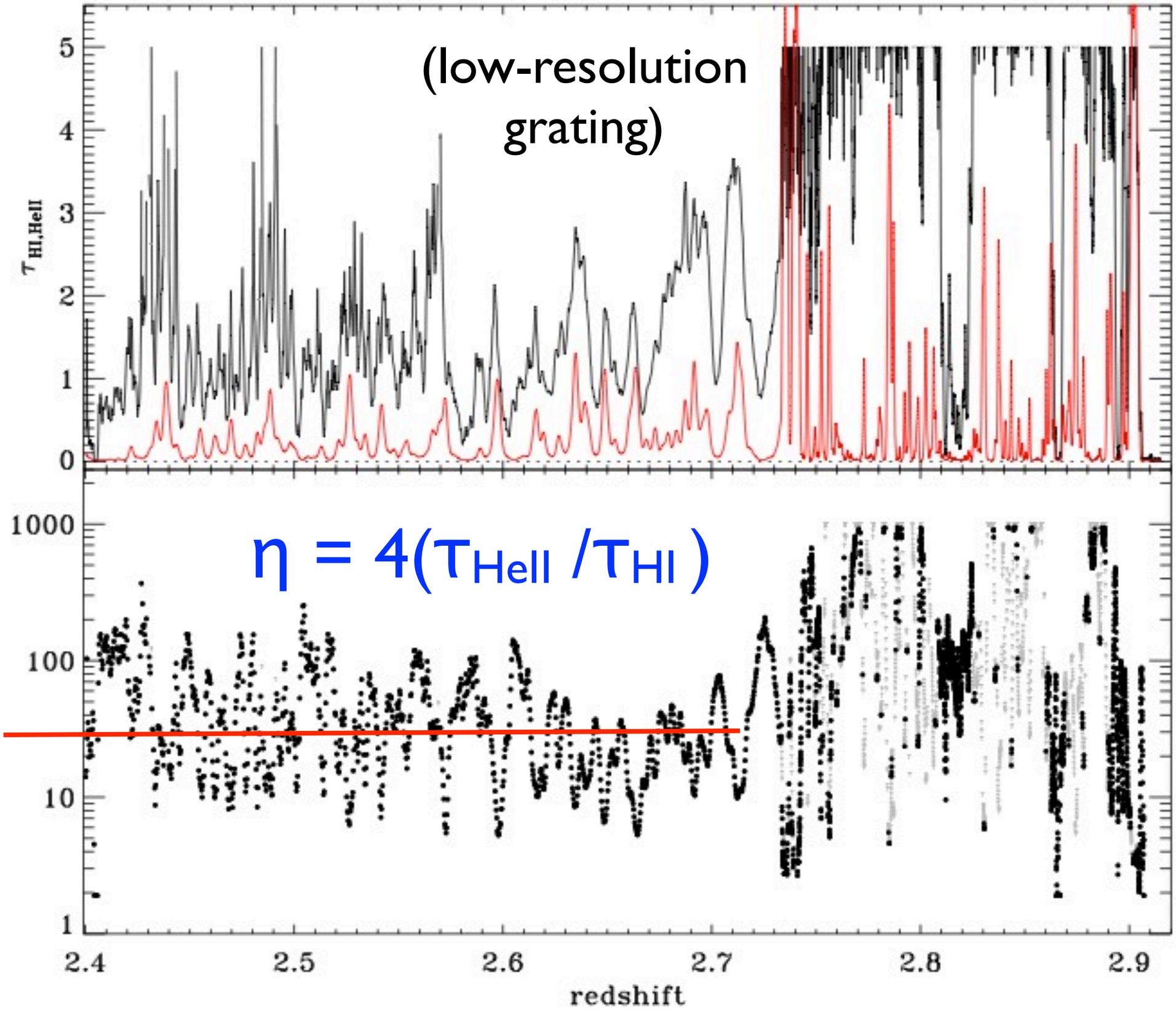
Flux transmission in Lyα forest

He II H I



HE 2347-4342

G140L G130M



Gunn-Peterson Optical Depth (He II)

$$\tau_{GP} = (3520)\,[(1+z)/4]^{3/2}\; f_{HeII}\,(z)\; \Delta_b$$

$$\tau_i(z) = \left(\frac{\pi e^2}{m_e c}\right) \frac{\lambda_i\, f_i\, n_i}{H(z)}\;;$$

ionization fraction n_{HeII} / n_{He}

baryon overdensity $\rho_b / < \rho_b >$

At z = 2.7, even an ionization fraction $f_{HeII} = 10^{-2}$ in a void ($\Delta_b = 0.1$) will produce $\tau_{GP} = 3$

$$x_{\rm HeII} = (0.015)\left[\frac{\tau_{\rm HeII}}{5}\right]\left[\frac{(1+z)}{3.8}\right]^{-3/2}\left[\frac{\delta_{\rm He}}{0.1}\right]^{-1}$$

He II troughs ($\tau > 5$) require S/N > 150 (binned) and well-characterized COS backgrounds

The "η-ratio" -- N(He II) / N(H I)

Assume photoionization equilibrium at $T = (10^{4.3}\ \mathrm{K})\, T_{4.3}$

$$\frac{N(\mathrm{He\ II})}{N(\mathrm{H\ I})} = \frac{n_{\mathrm{HeIII}}\ \alpha_{\mathrm{HeII}}\ \Gamma_{\mathrm{HI}}}{n_{\mathrm{HII}}\ \alpha_{\mathrm{HI}}\ \Gamma_{\mathrm{HeII}}} \approx (1.81)\, Y_{25}\, (T_{4.3})^{0.042}\, \frac{J_{\mathrm{HI}}}{J_{\mathrm{HeII}}}$$

(10-100)

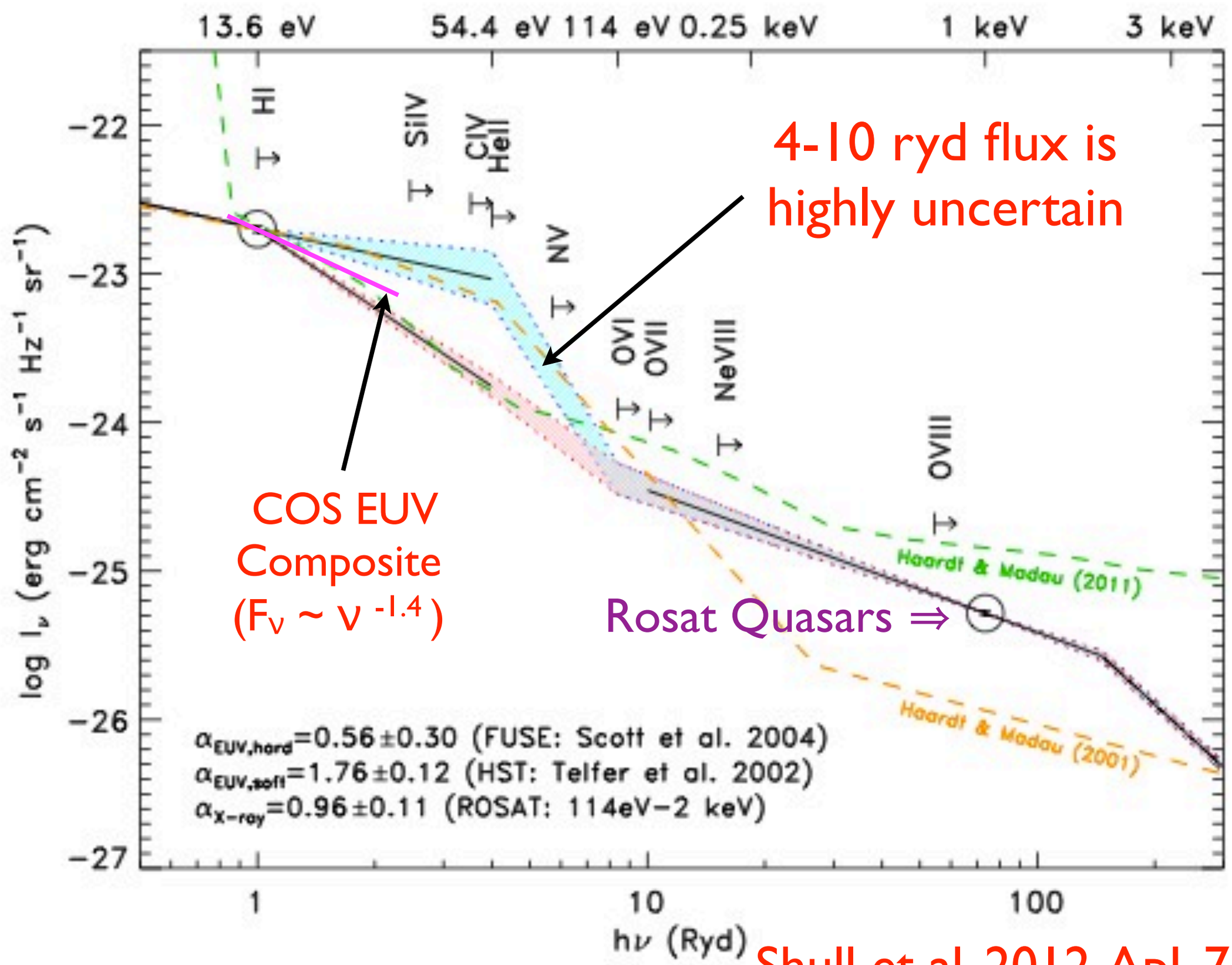
Ratio of ionizing intensities at 1 ryd (H I) and 4 ryd (He II)

Photoionization rates: $\Gamma_{\mathrm{HI}} / \Gamma_{\mathrm{HeII}} \approx 4\ (J_{\mathrm{HI}} / J_{\mathrm{HeII}})\ \frac{(\alpha_{\mathrm{HeII}} + 3)}{(\alpha_{\mathrm{HI}} + 3)}$

Recombination rates: $\alpha_{\mathrm{HeII}} / \alpha_{\mathrm{HI}} \approx 5.42\ (T_{4.3})^{0.042}$

Number densities: $n_{\mathrm{HeIII}} / n_{\mathrm{HII}} \approx 0.0833$ $(Y_{\mathrm{He}} = 0.25\, Y_{25})$

The Metagalactic Ionizing Spectrum



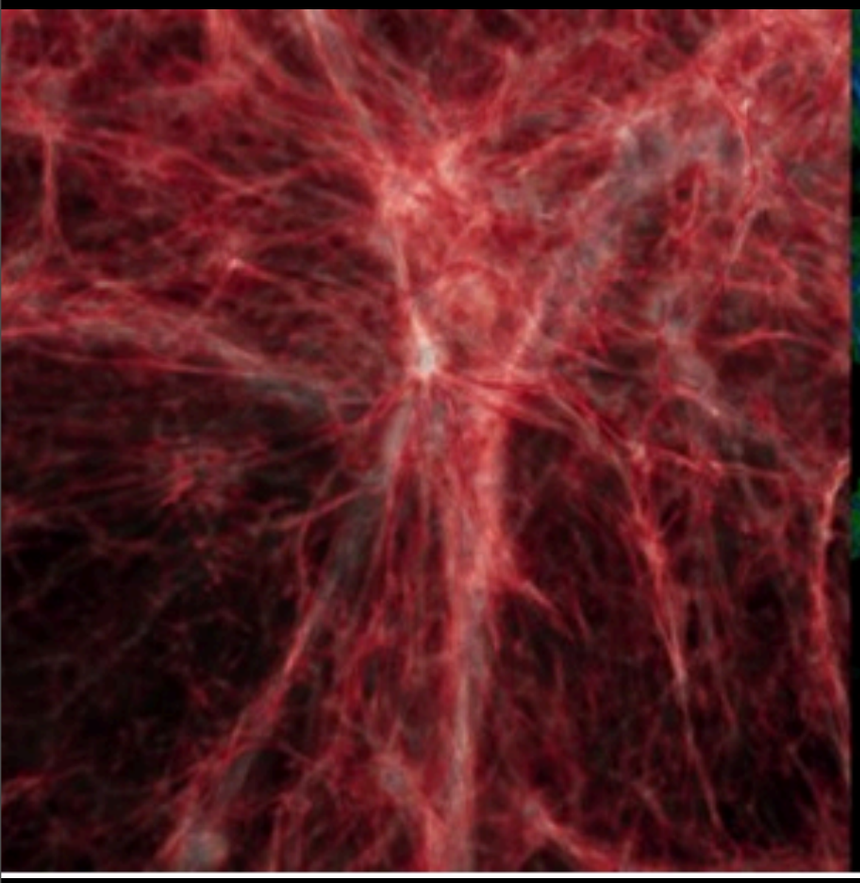
4-10 ryd flux is highly uncertain

COS EUV Composite ($F_\nu \sim \nu^{-1.4}$)

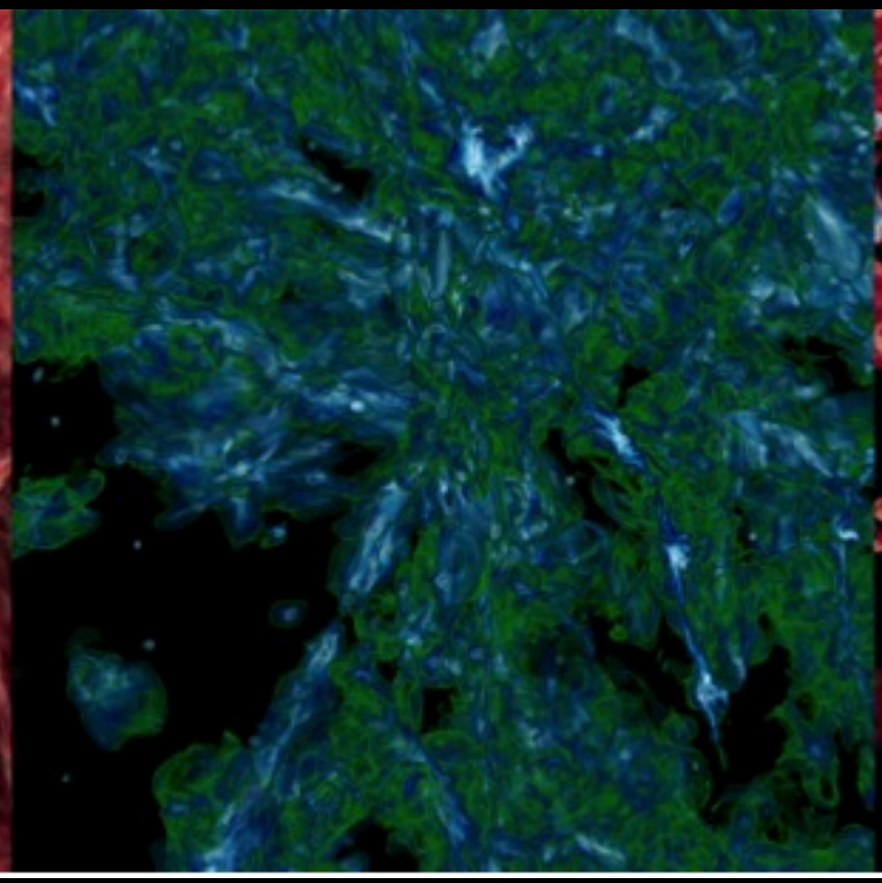
Rosat Quasars ⇒

Shull et al. 2012, ApJ, 762, 162

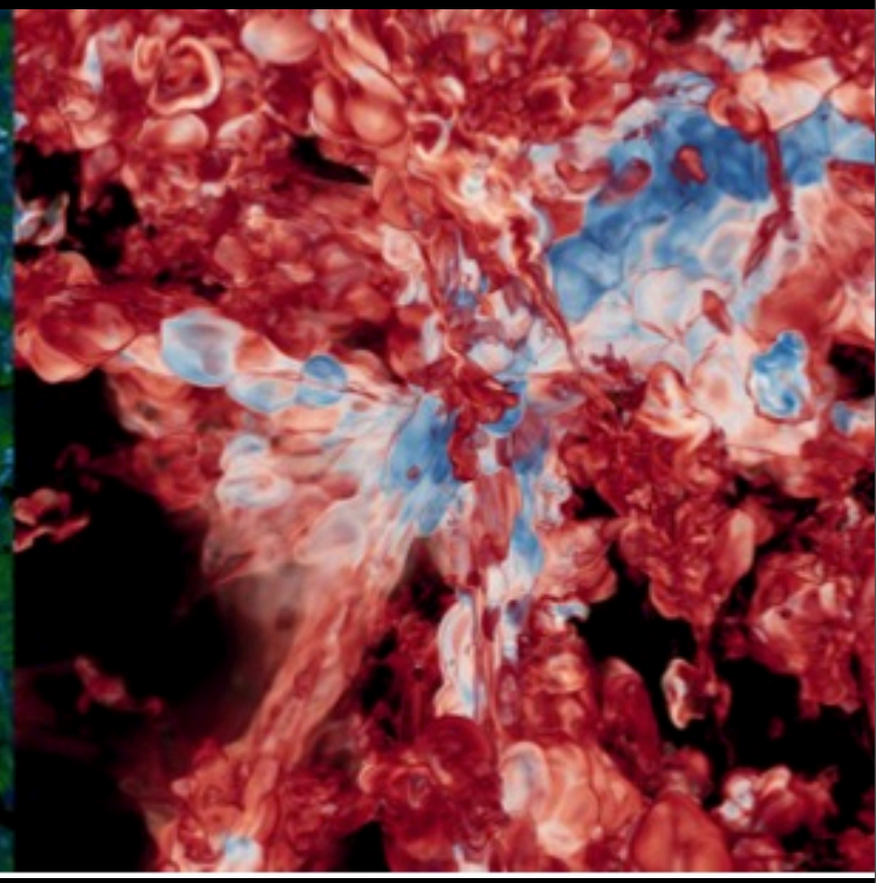
Grid-code (Enzo) simulations of the low-redshift IGM structure



Gas Density



O VI Density

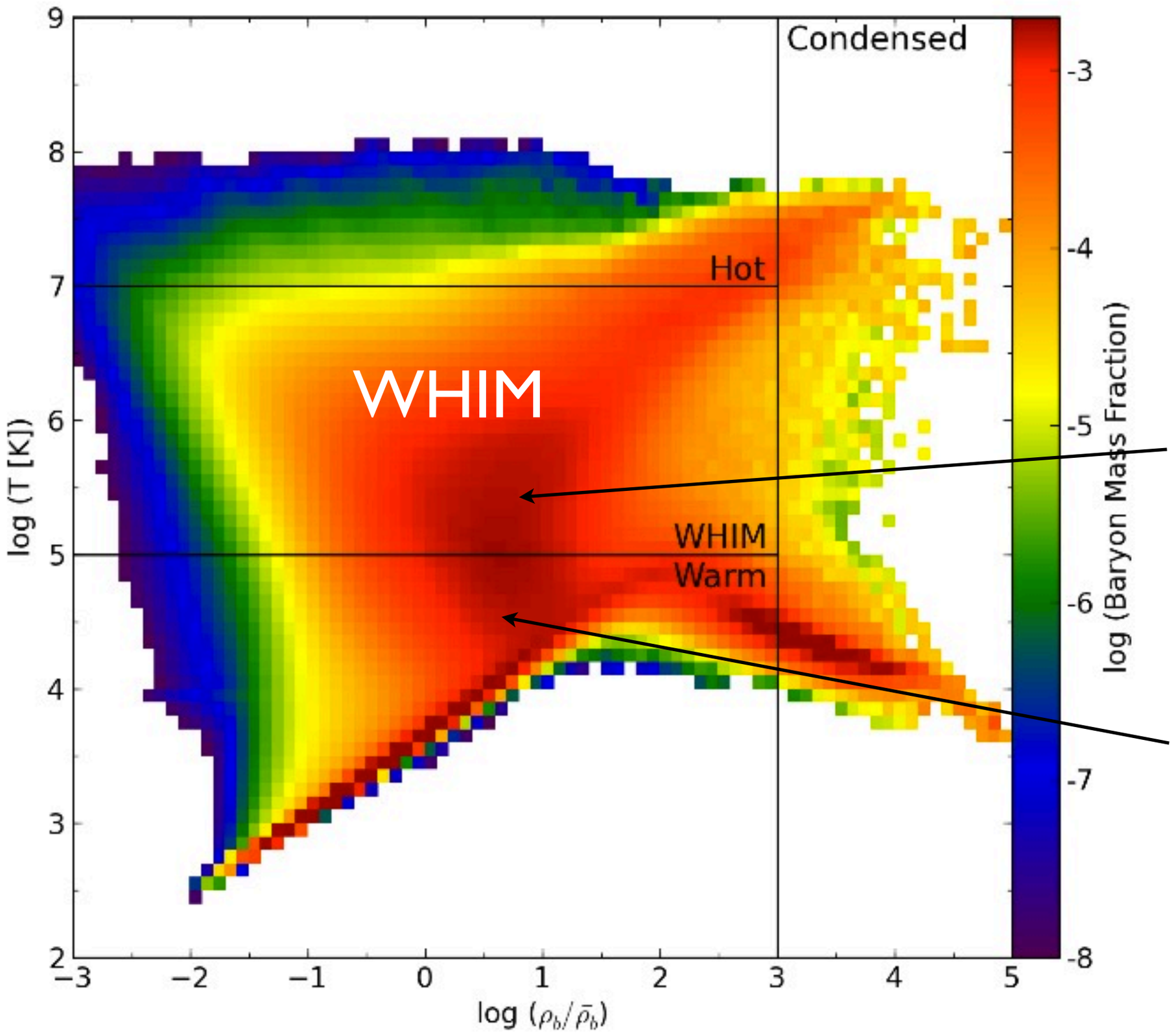


Temperature

Britton Smith and the Colorado IGM Theory Group

10^5 K (red)
10^7 K (blue)

Baryon "phase plot" (Temperature - Density)



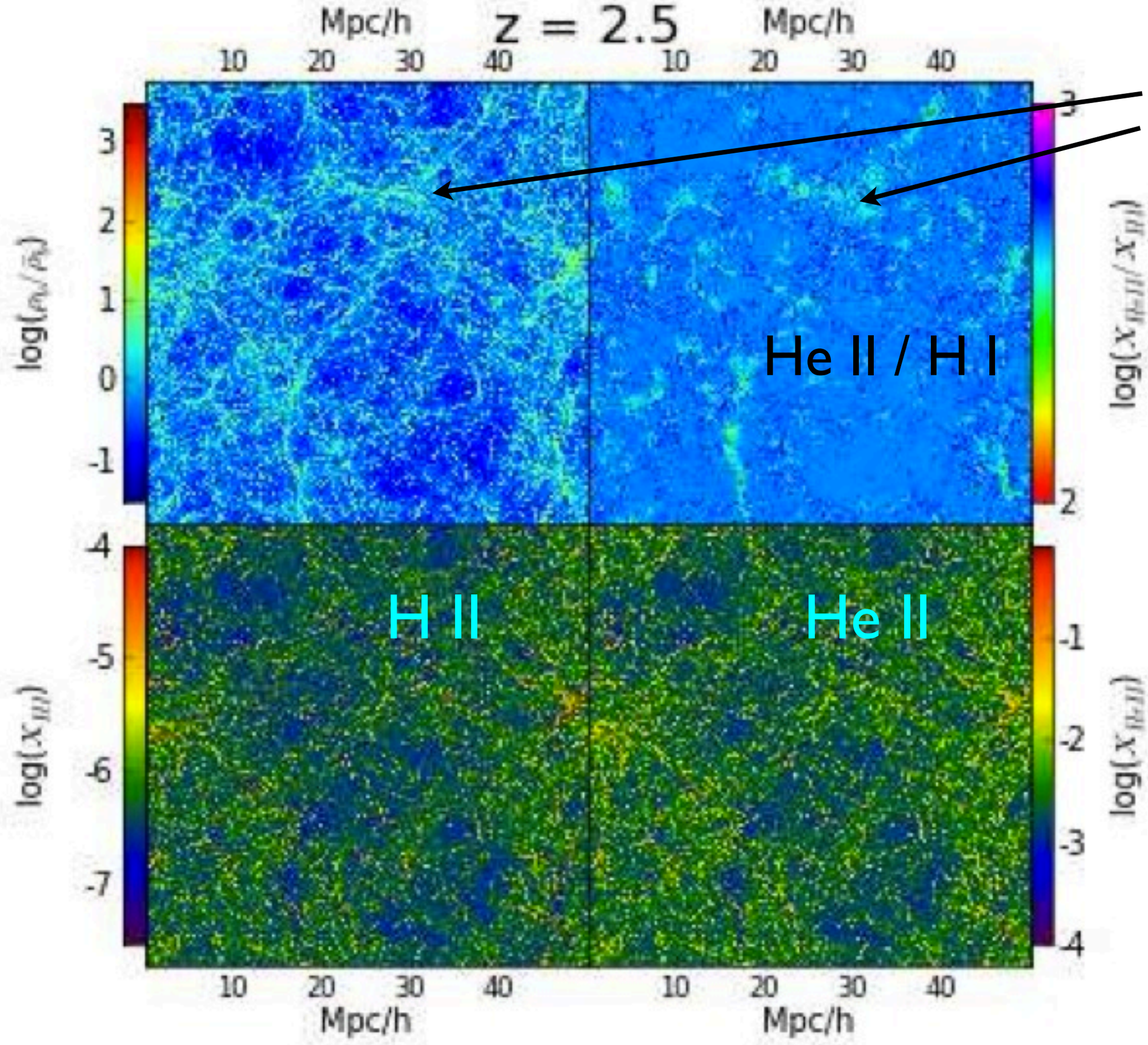
Simulations color-coded by gas mass

1024^3 and 50 Mpc/h

Collisionally Ionized ($10^{5.5}$ K)

Photoionized ($T \sim 10^{4.3}$ K)

Shull, Smith, & Danforth 2012



Collisionally Ionized He II (IGM filaments)

$x_{HeII}/x_{HI} \approx 500$

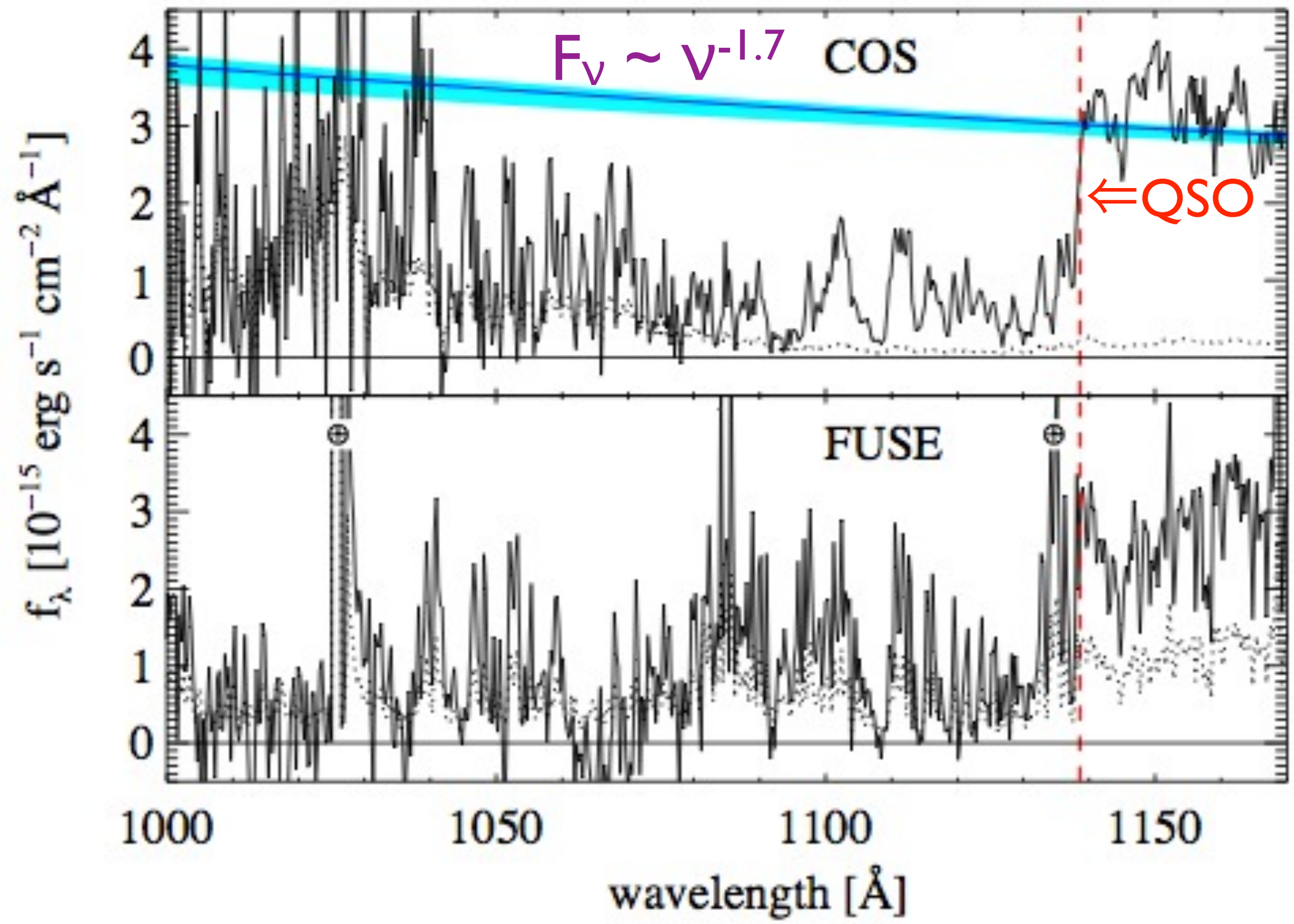
($\eta \approx 40$)

for $y \approx 0.08$

Shull et al. 2010
Smith et al. 2011

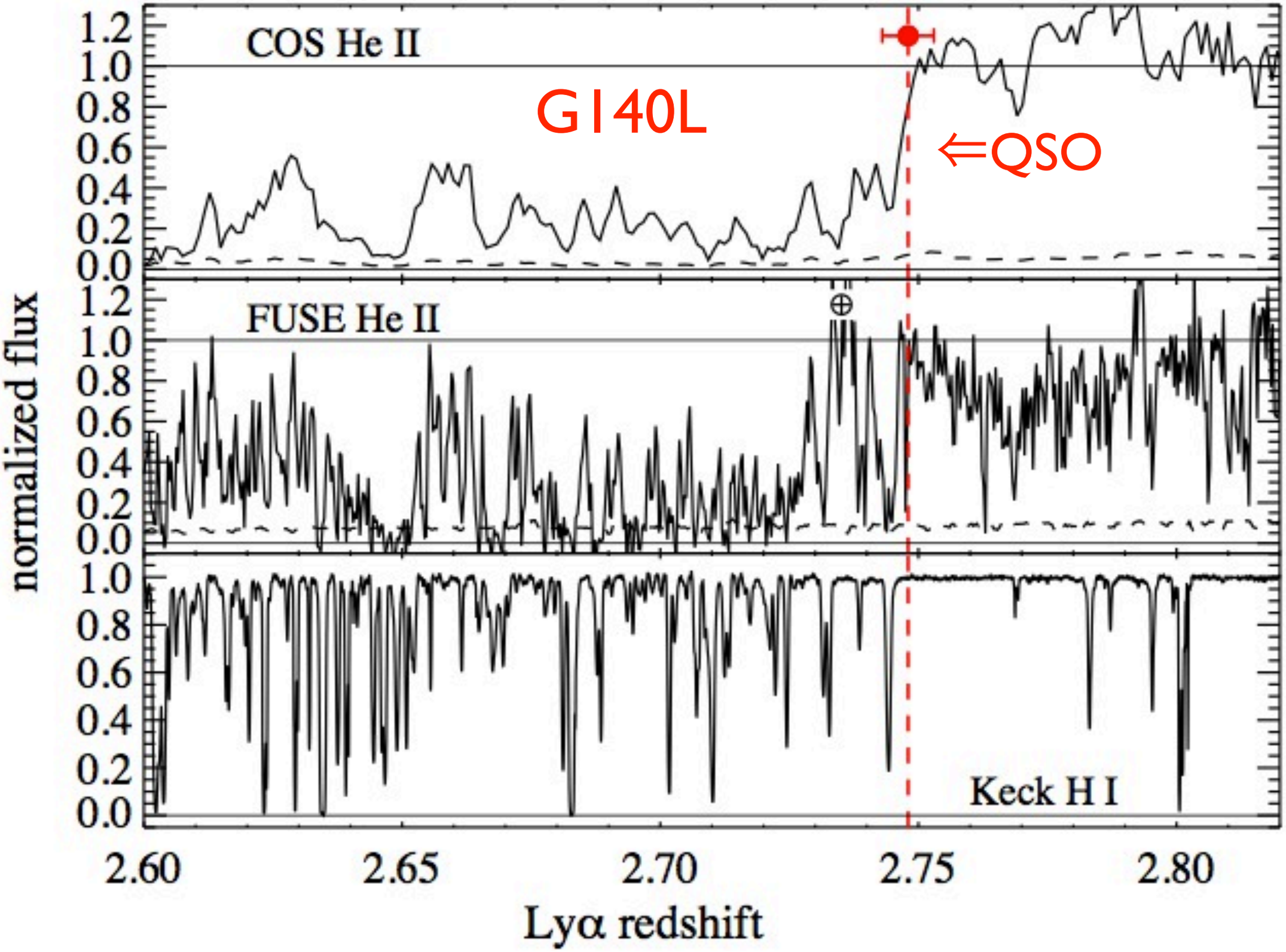
Hubble/COS Spectrum of HS 1700+6416

G140L z = 2.748 (Syphers & Shull 2013a, ApJ, 765, 119



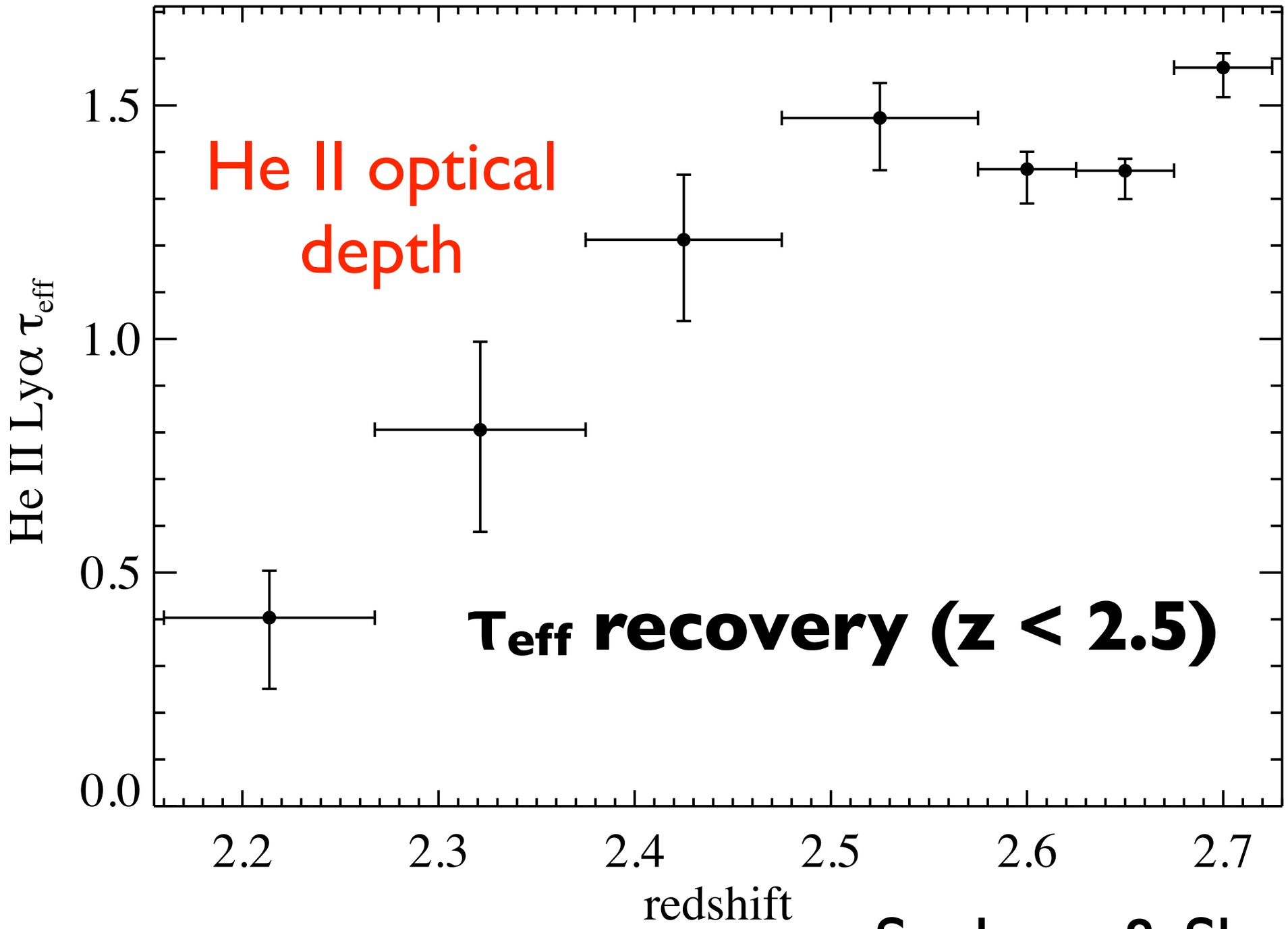
HS 1700+6416 (low-resolution spectrum)

η_{med} = 32 (Syphers & Shull 2013a)



HS 1700+6416 (z = 2.748)

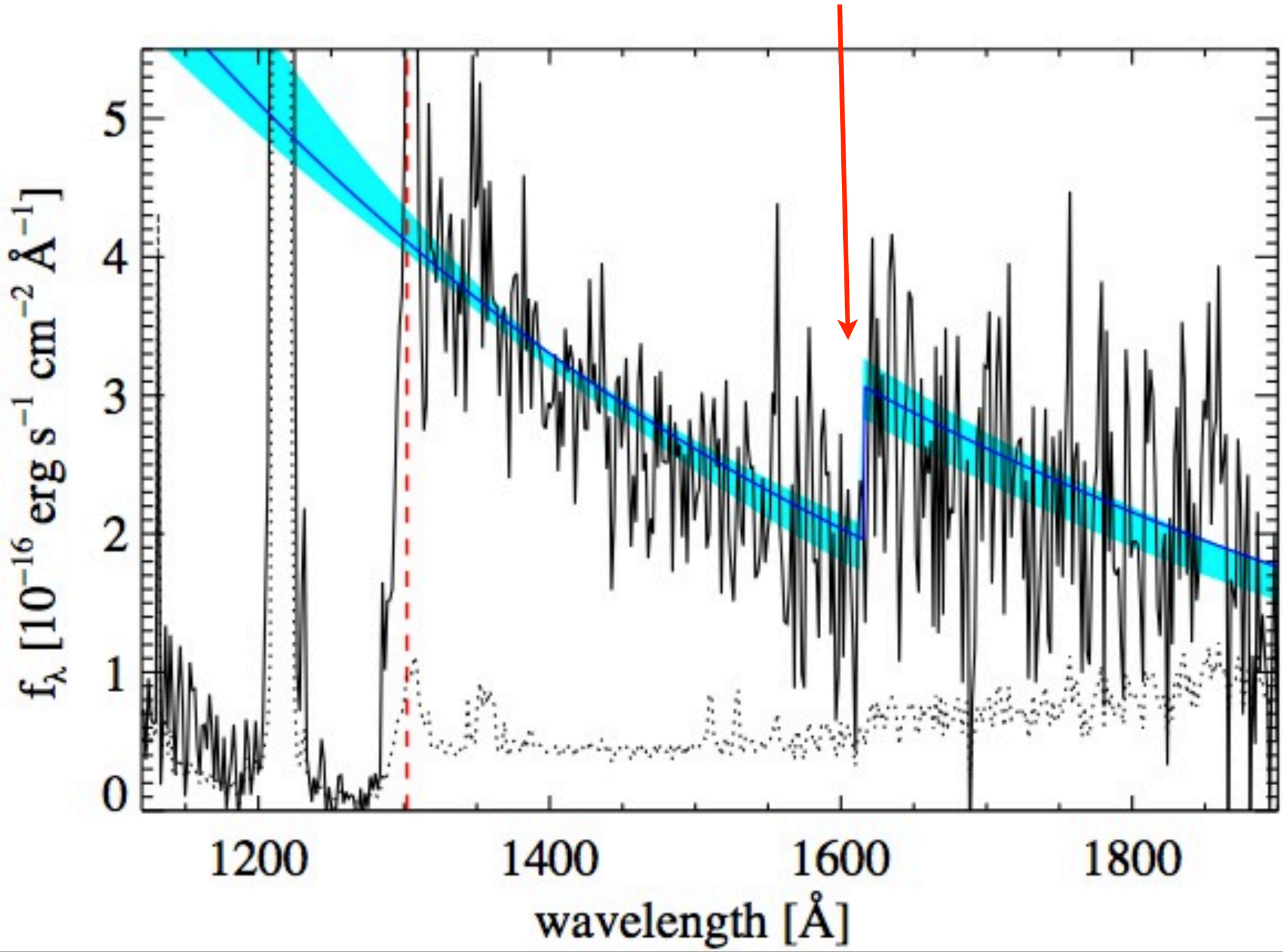
COS (G140L) low-res'n spectrum



Syphers & Shull 2013a

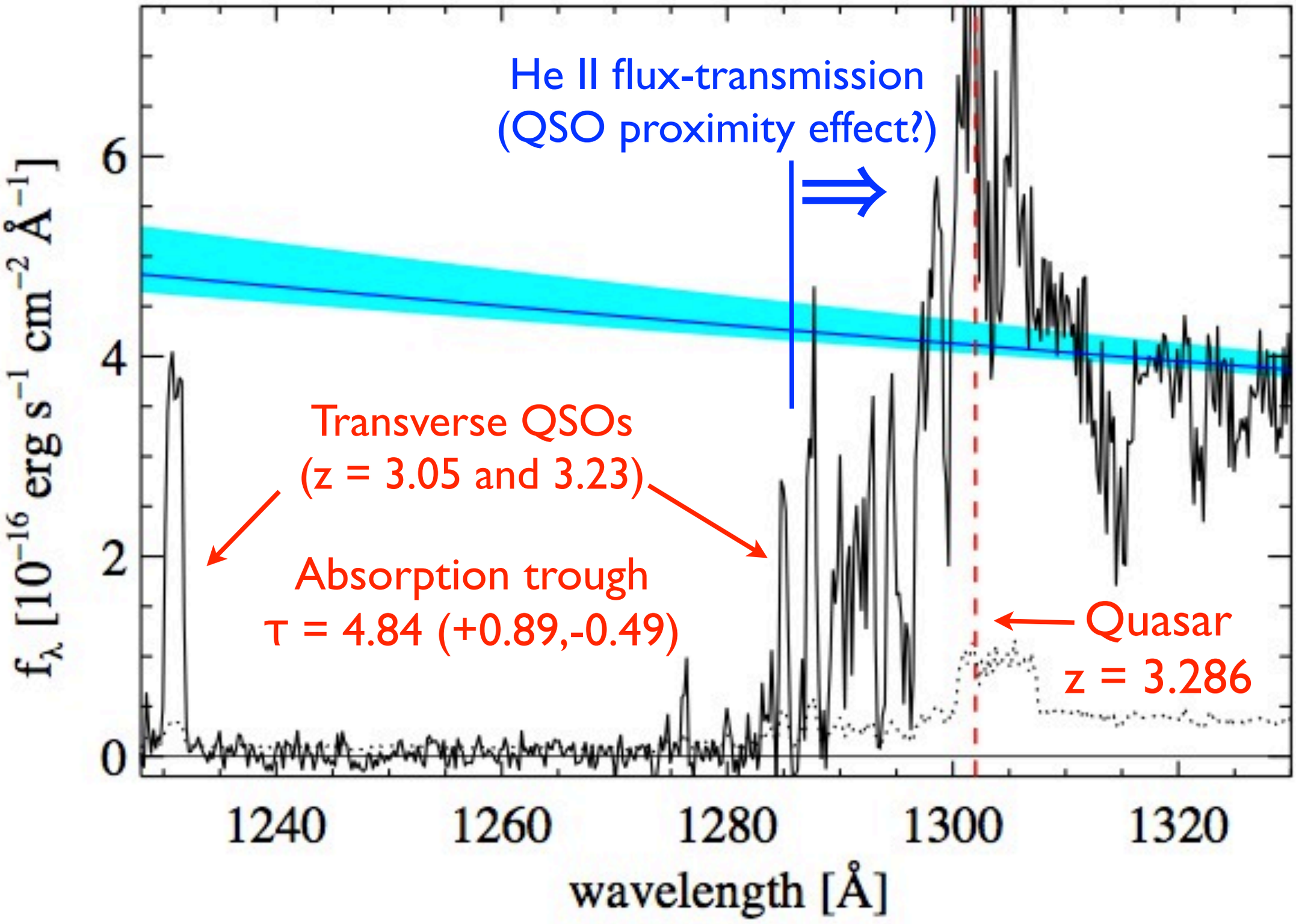
Q0302-003 (Syphers & Shull 2013b)

De-reddened underlying spectrum: $F_\nu \sim \nu^{-0.82}$
(partial LLS, z = 0.771, log N_{HI} = 16.85)

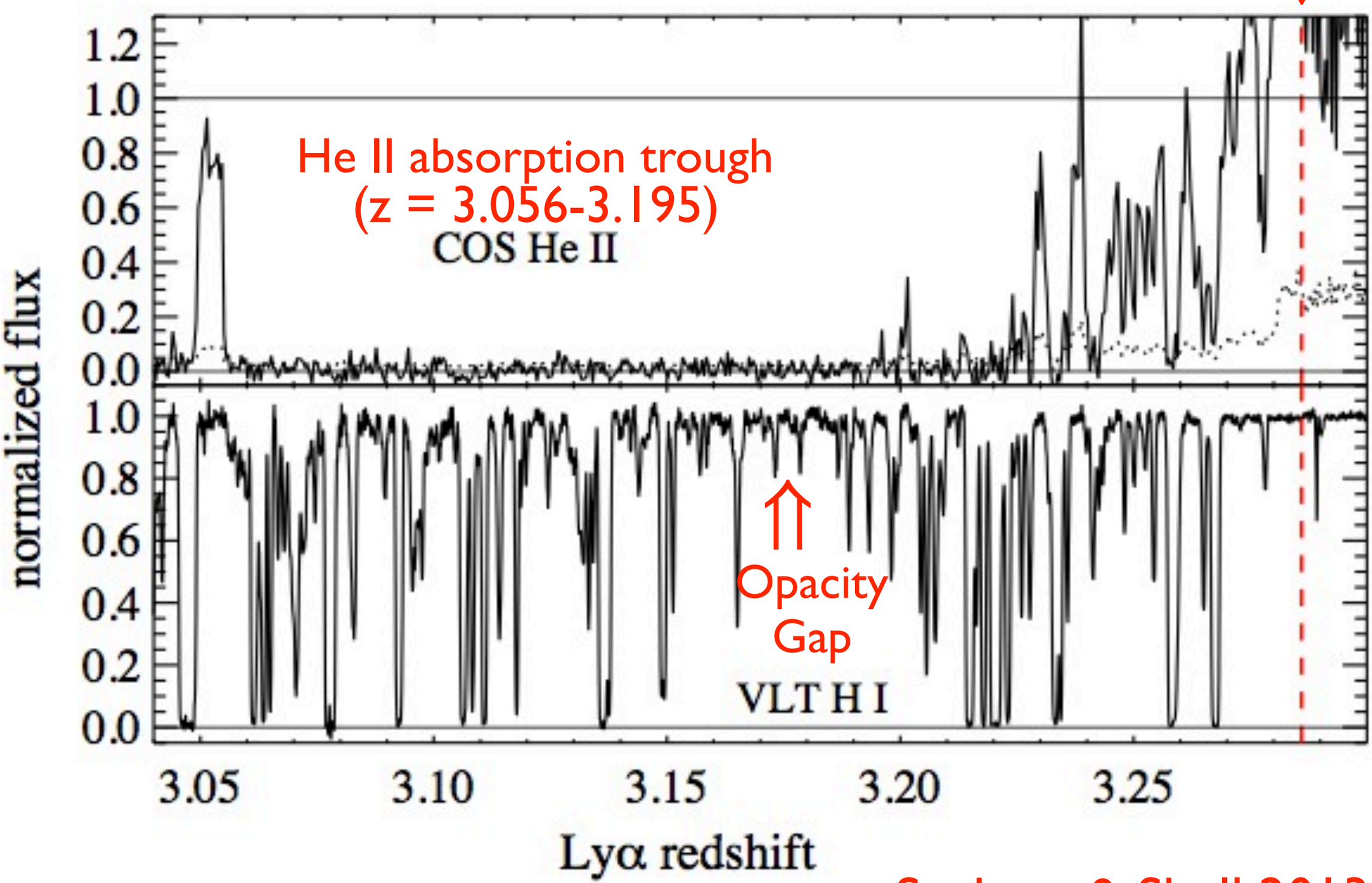


New HST/COS data (Q0302-003)

z = 3.286 (Syphers & Shull 2013b)



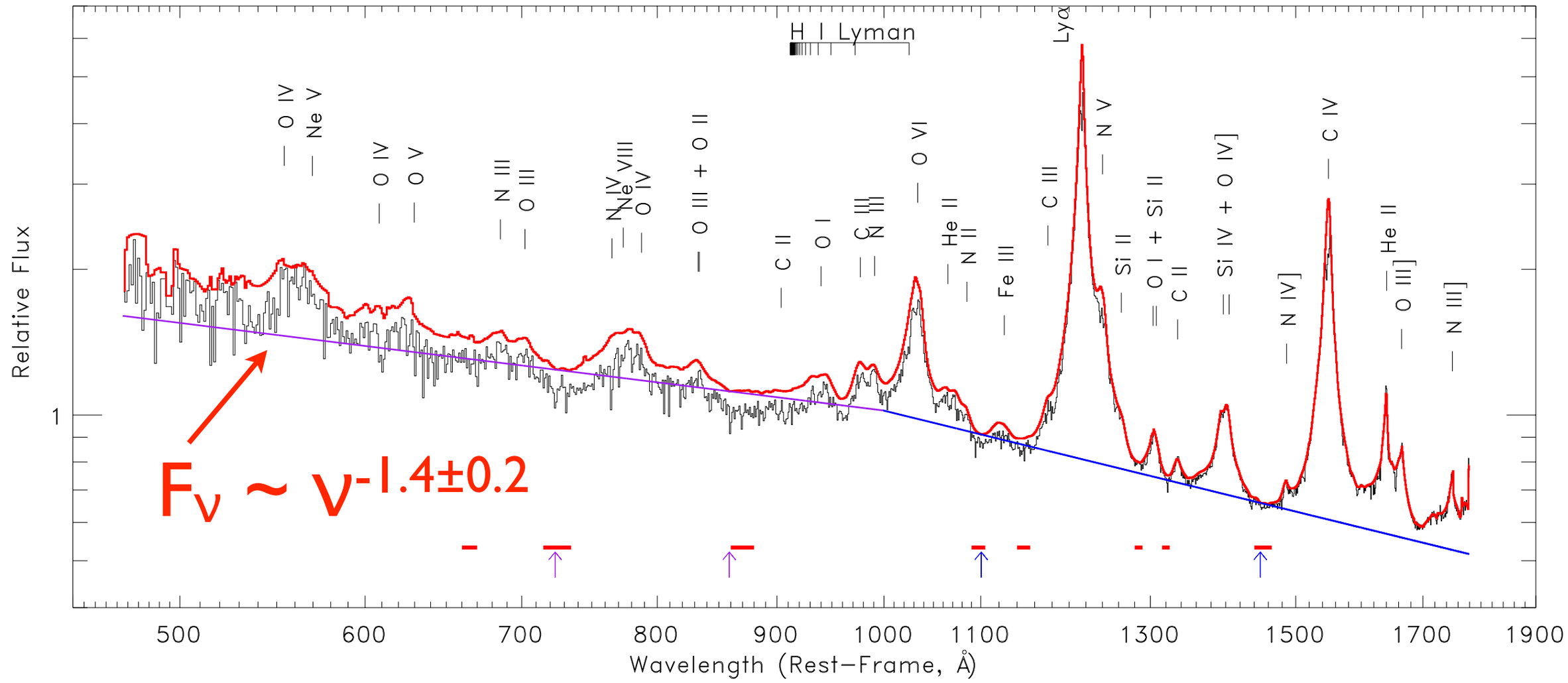
Q0302-003
(He II and H I absorption)



Syphers & Shull 2013b

Composite UV and EUV (rest-frame) spectrum (158 AGN observed by COS)

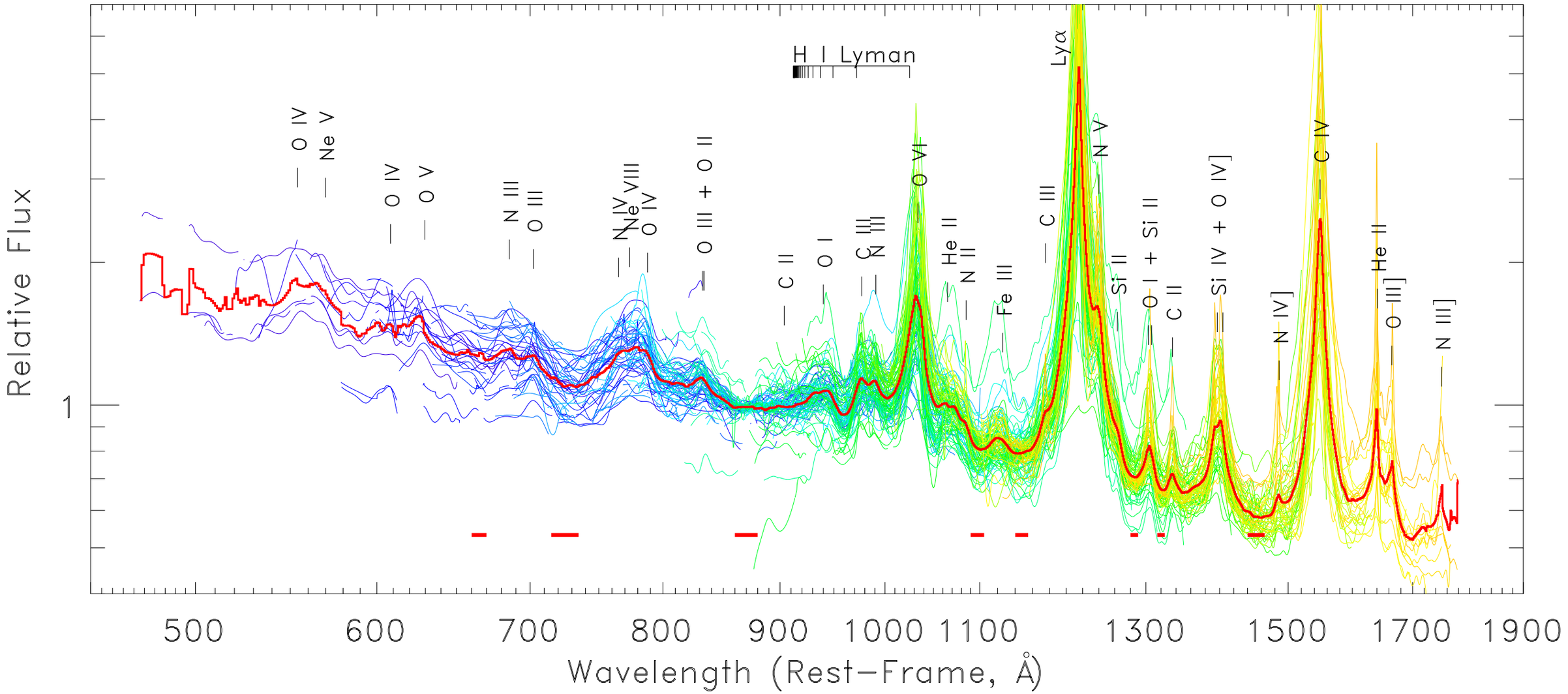
Continuum fitted underneath strong EUV emission lines



Shull, Stevans, & Danforth (2012, ApJ)

Stevans et al. (2013, in preparation)

Composite QSO Spectrum (showing range of EUV spectral indices)



$F_\nu \sim \nu^{-\alpha}$ $(\alpha = 1.4 \pm 0.2)$

(500-1000 A in rest frame)

HST - Cycle 21 Programs

(1) Two bright He II Quasars at Medium-Resolution

HE 2347-4342 (15 orbits)

HS 1700+6416 (20 orbits)

using new G130M "super-blue setting" (down to z = 2.5) at 25 km/s resol'n

(2) Rest-frame quasar EUV spectra down to 350 A)

Two orbits (with G140L) on each of 11 QSOs at intermediate redshift (z_{QSO} = 1.45-2.10)

This will increase the rest-frame EUV spectral coverage (350-600 A) from 2-4 to 13-15 QSOs