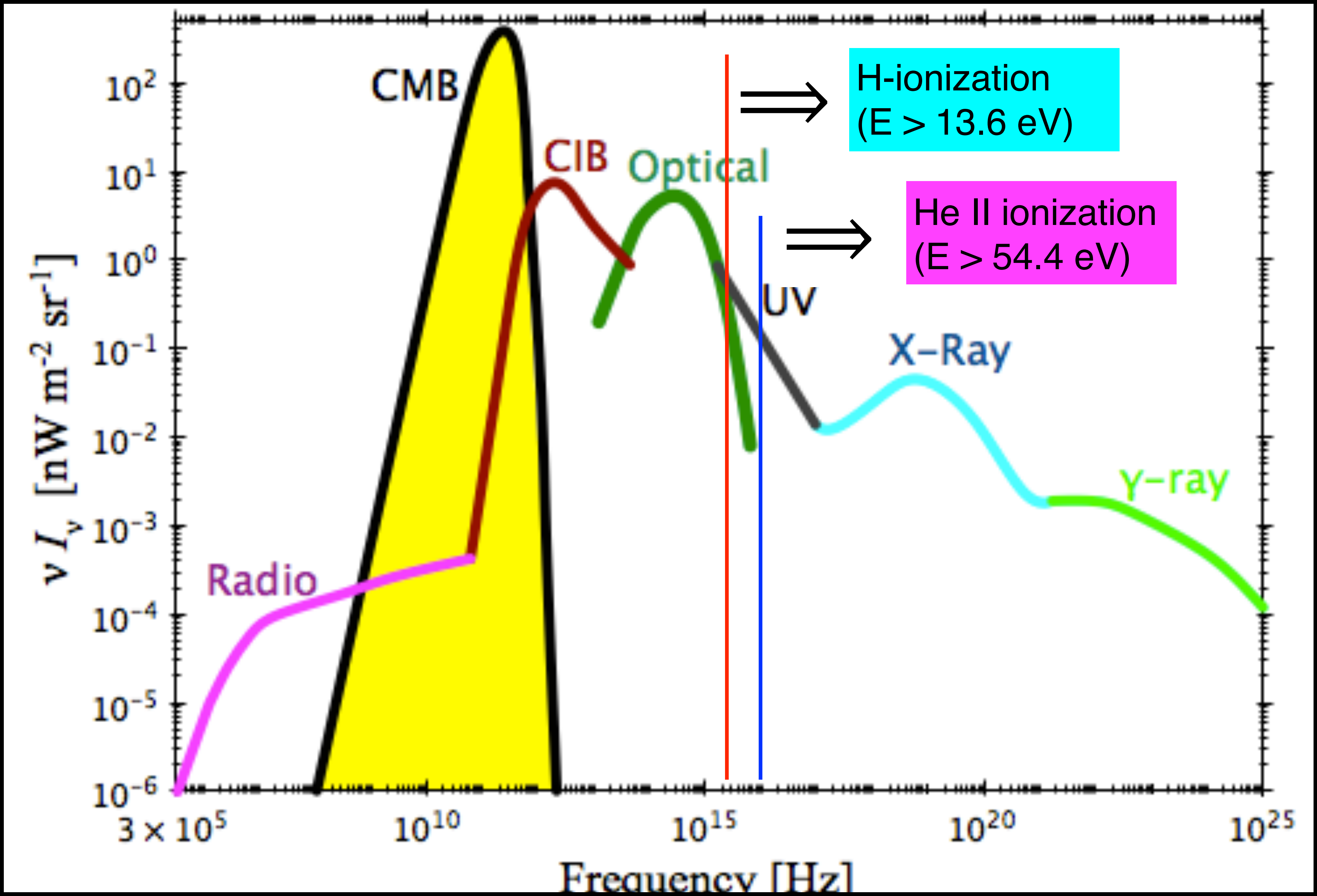
Metagalactic Ionizing Radiation

Contributions from Hot Stars and Quasars

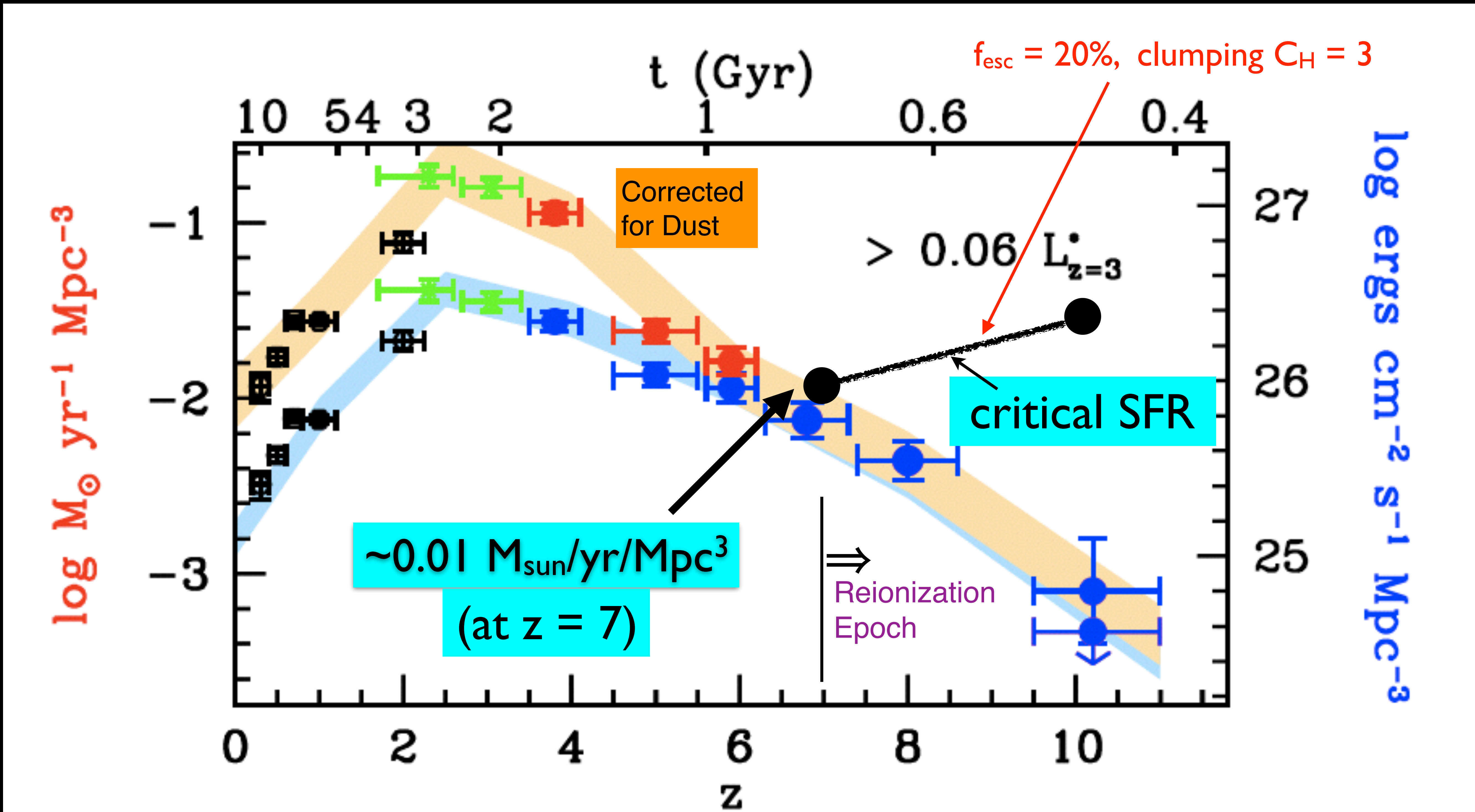
Michael Shull *(Univ of Colorado)*



Kavli Symposium/Cambridge - Sept 18, 2019

Global Star-Formation Rate (density)

Bouwens et al. (2011) Comoving Units: $M_{sun}\ yr^{-1}\ Mpc^{-3}$



CMB Optical Depth (fully ionized IGM)

$$\tau_e(z_{\rm rei}) = \int_0^{z_{\rm rei}} n_e \sigma_{\rm T} (1+z)^{-1} \, [c/H(z)] \, dz$$

$$\approx \left(\frac{c}{H_0}\right)\left(\frac{2\Omega_b}{3\Omega_m^{1/2}}\right)\left[\frac{\rho_{\rm cr}(1-3Y/4)\sigma_{\rm T}}{m_{\rm H}}\right](1+z_r)^{3/2}$$

$$\approx (0.0522)\left[\frac{(1+z_r)}{8}\right]^{3/2}$$

$(1+z_{rei}) >> (\Omega_\Lambda/\Omega_m)^{1/3}$
$[z_r >> 0.3]$

Helium (He^+, He^{+2}) is 8% of the total, with Y = 0.2477

IGM appears to be fully ionized back to $z_{rei} \gtrsim 7$

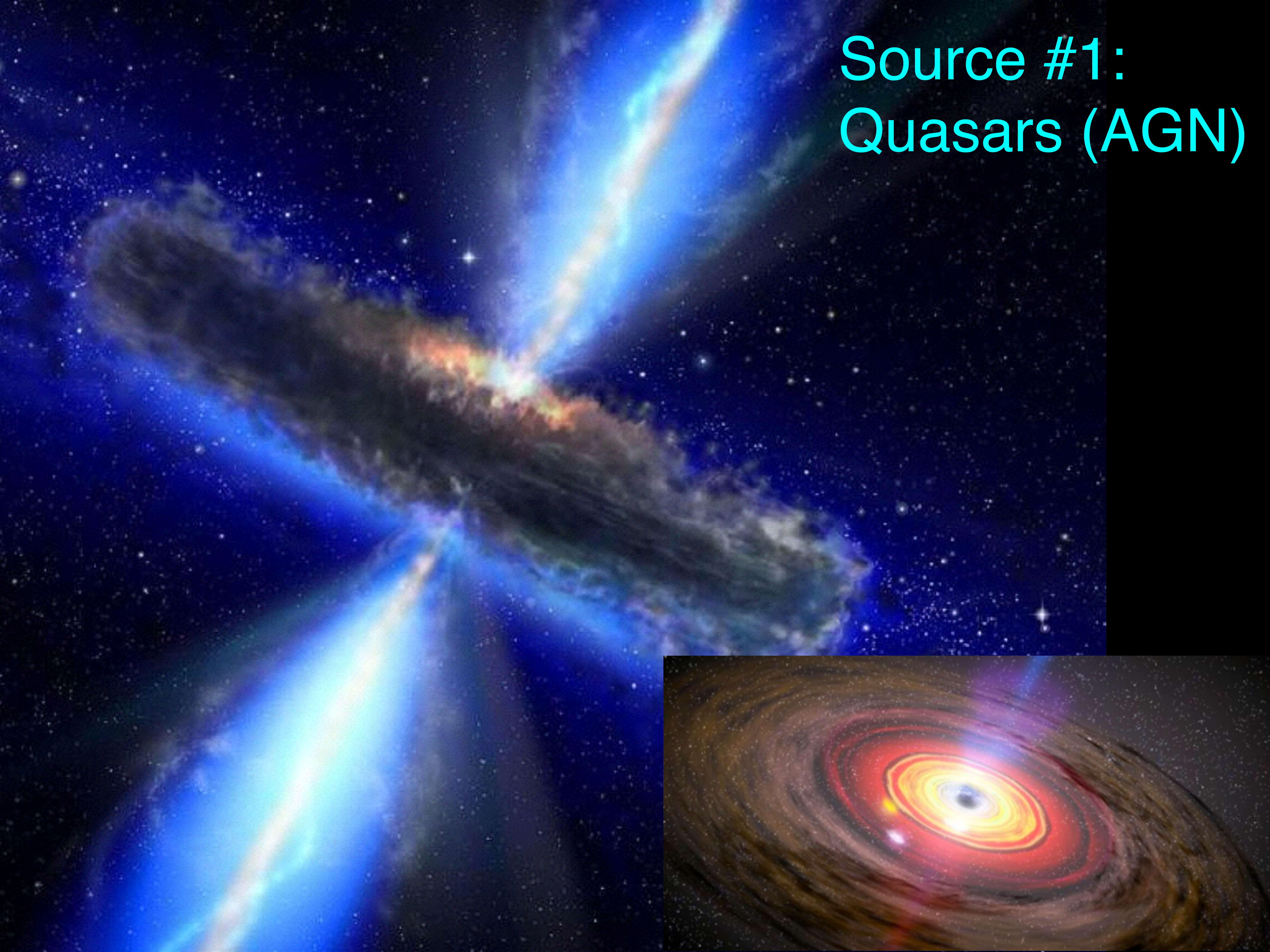
(by a mixture of AGN and massive stars)

Shull & Venkatesan 2008
ApJ, 685, 1

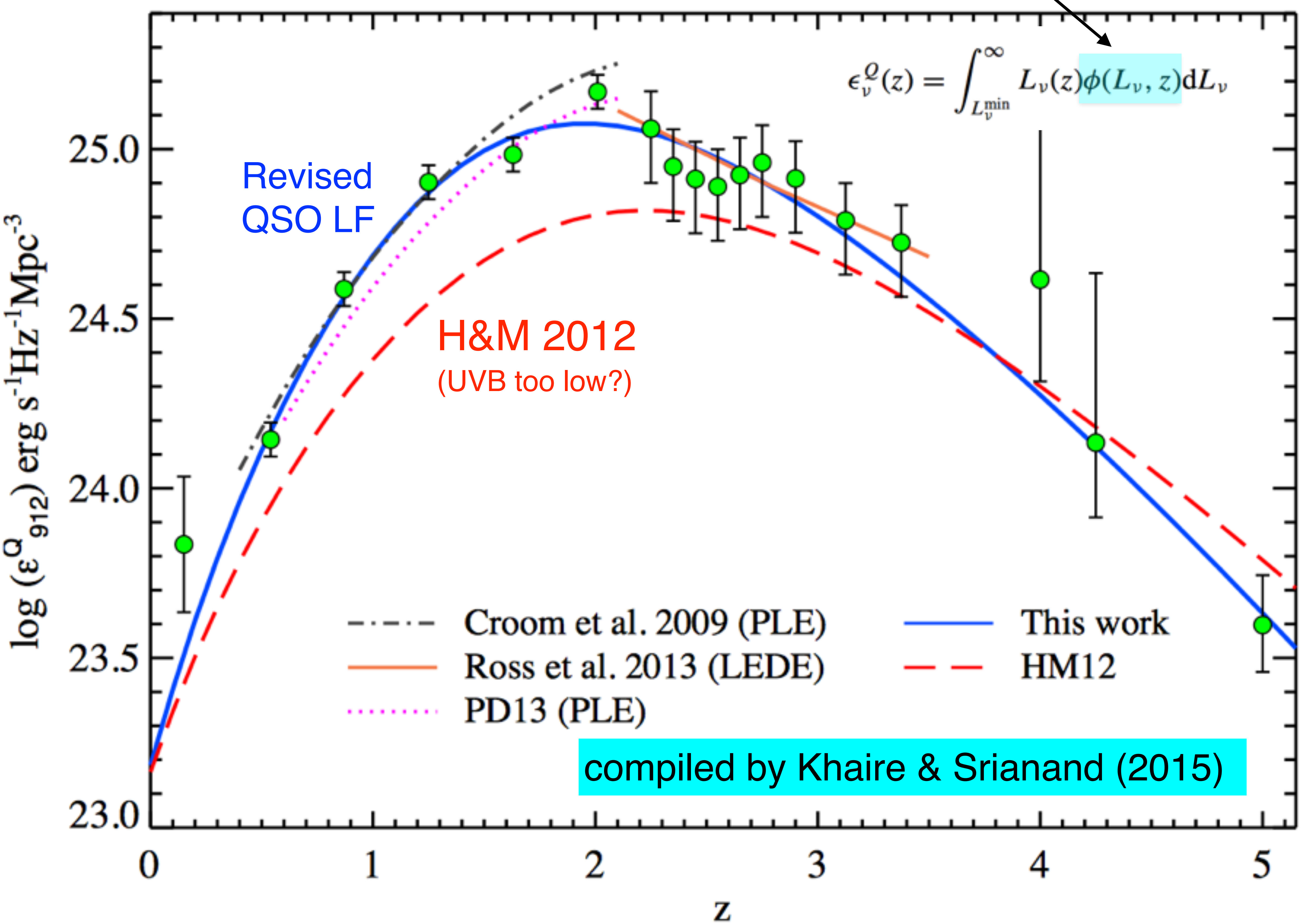
Shull et al. 2012,
ApJ, 747, 100

$\tau_e = 0.0544 \pm 0.007$
(Planck 2018)

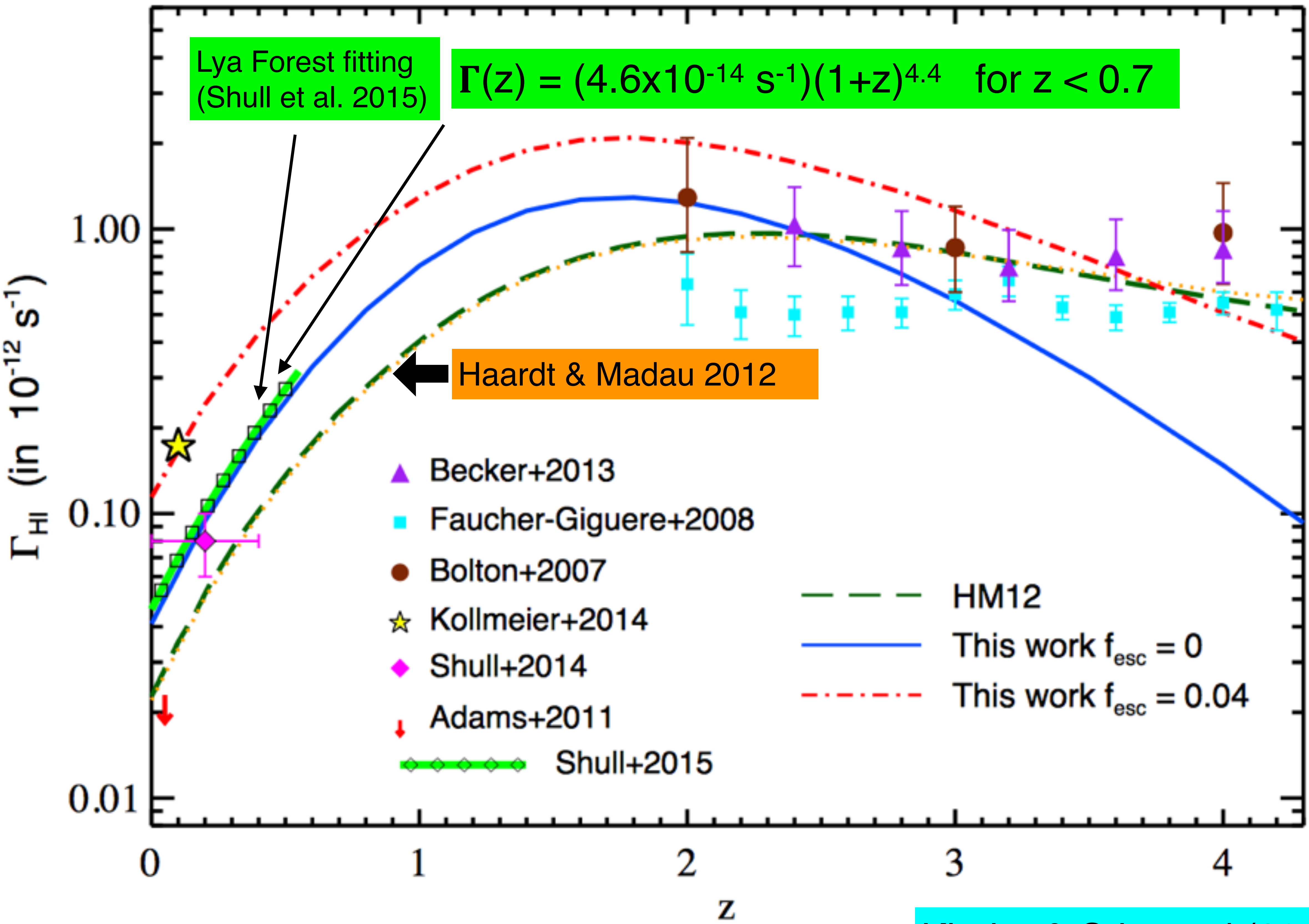
Source #1: Quasars (AGN)



QSO Emissivity (new luminosity functions SDSS-III)



Hydrogen Photoionization Rate $\Gamma_H(z)$

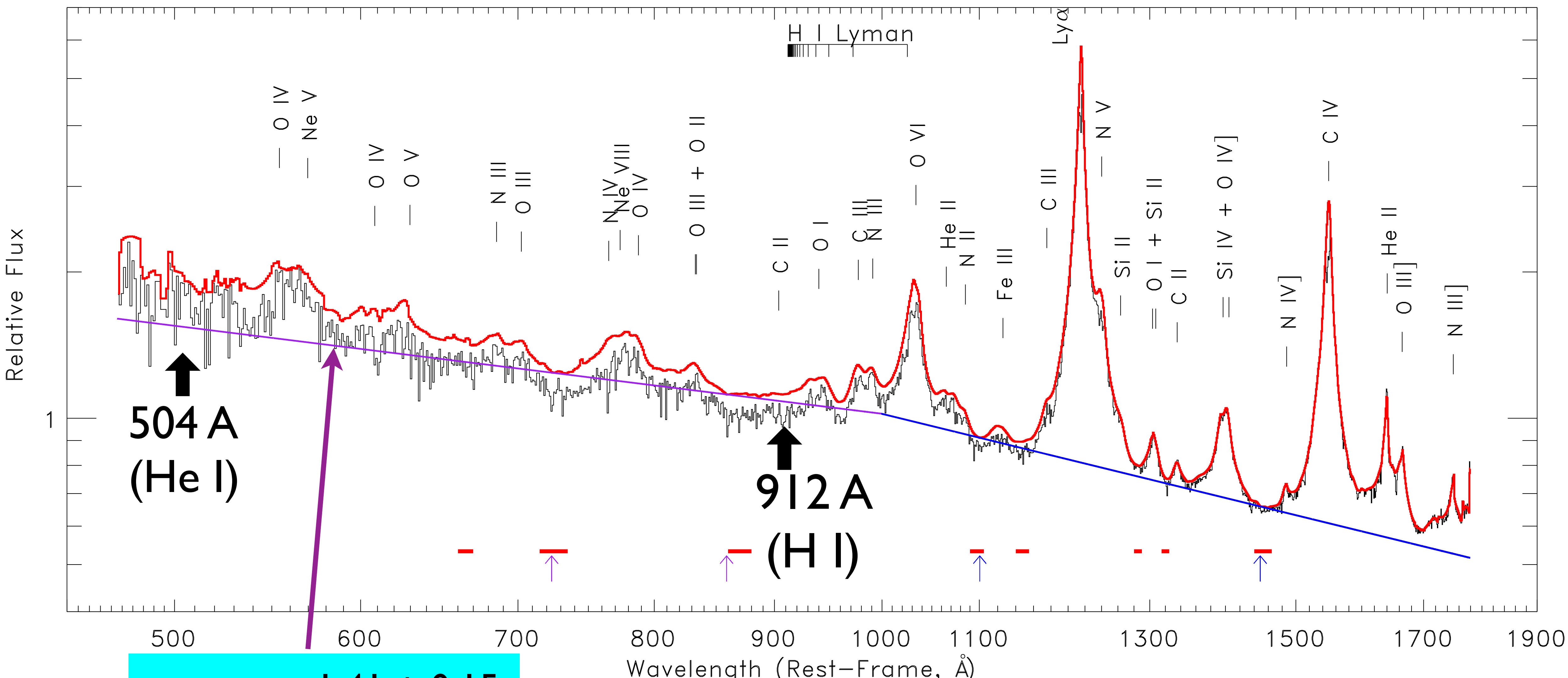


Khaire & Srianand (2015)

Composite UV and EUV (rest-frame) spectrum

159 AGN observed by *Hubble*: (COS G130M/G160M)

Continuum fitted underneath strong UV emission lines and corrected for absorption-line blanketing from the intervening IGM



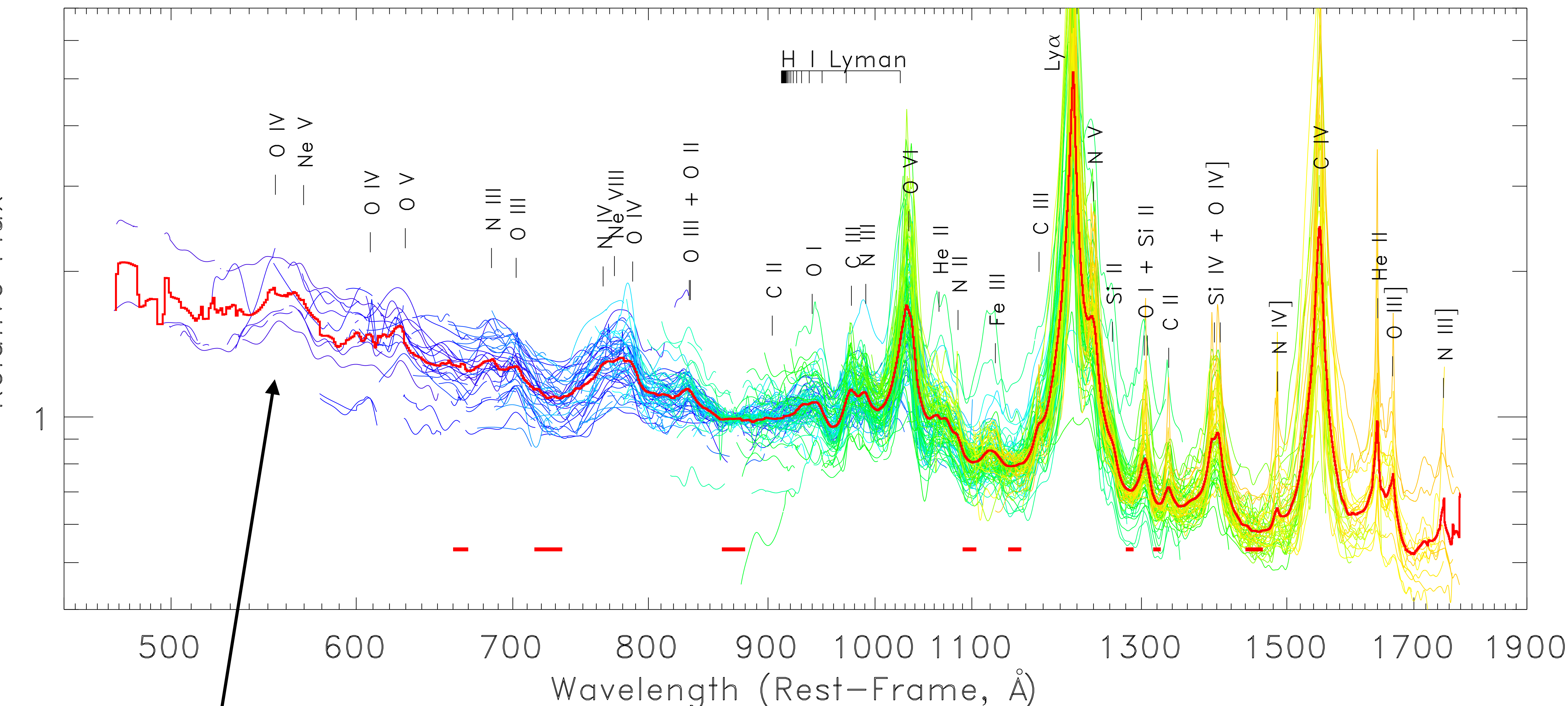
$F_\nu \sim \nu^{-1.41 \pm 0.15}$

AGN spectrum (1-2 ryd)

Shull, Stevans, & Danforth (2012)
Stevans, Shull, Danforth & Tilton (2014)

Variations in rest-frame AGN Spectra

$F_\nu \sim \nu^\alpha$ where $\langle\alpha_\nu\rangle = -1.41 \pm 0.15$

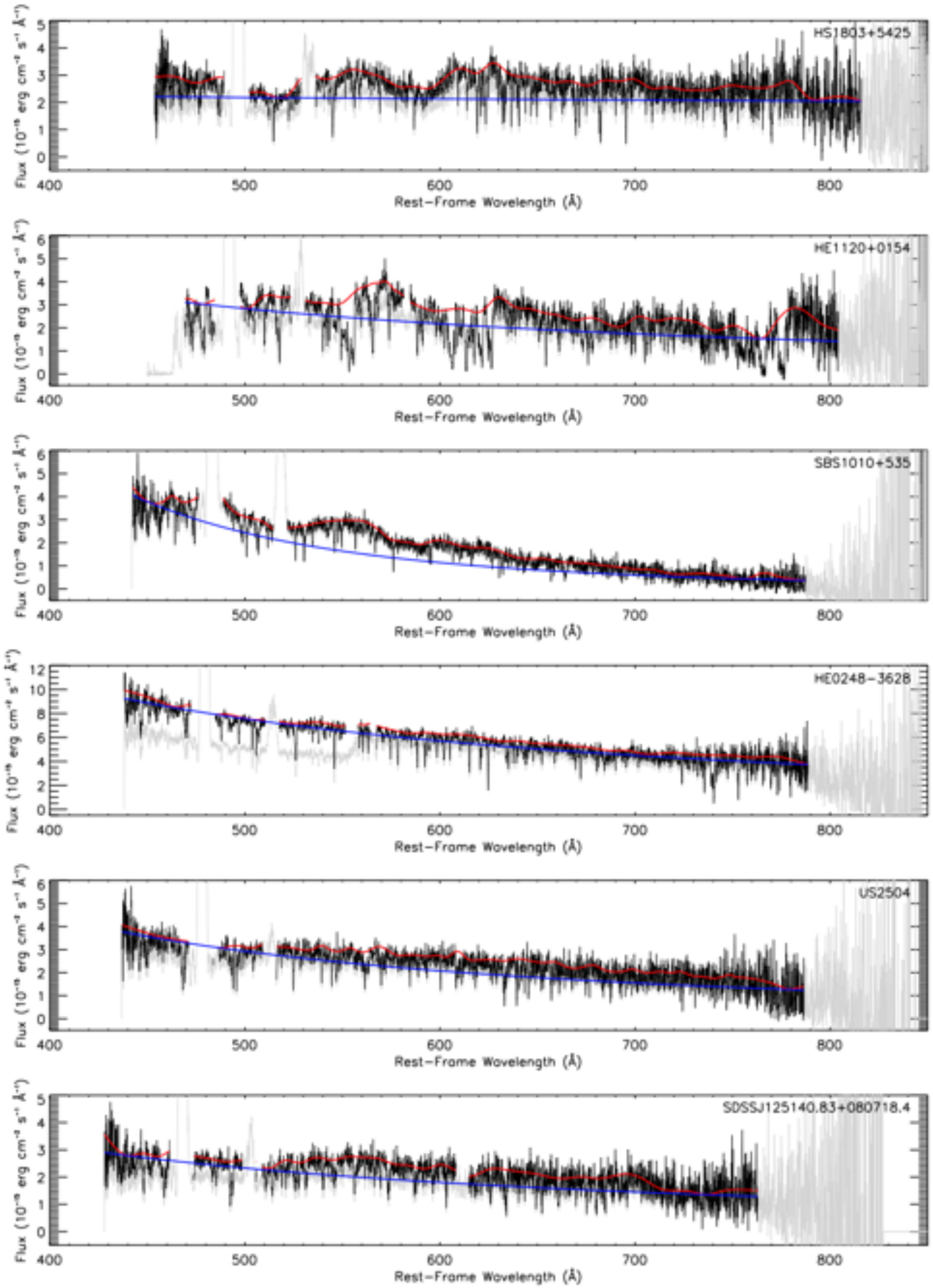


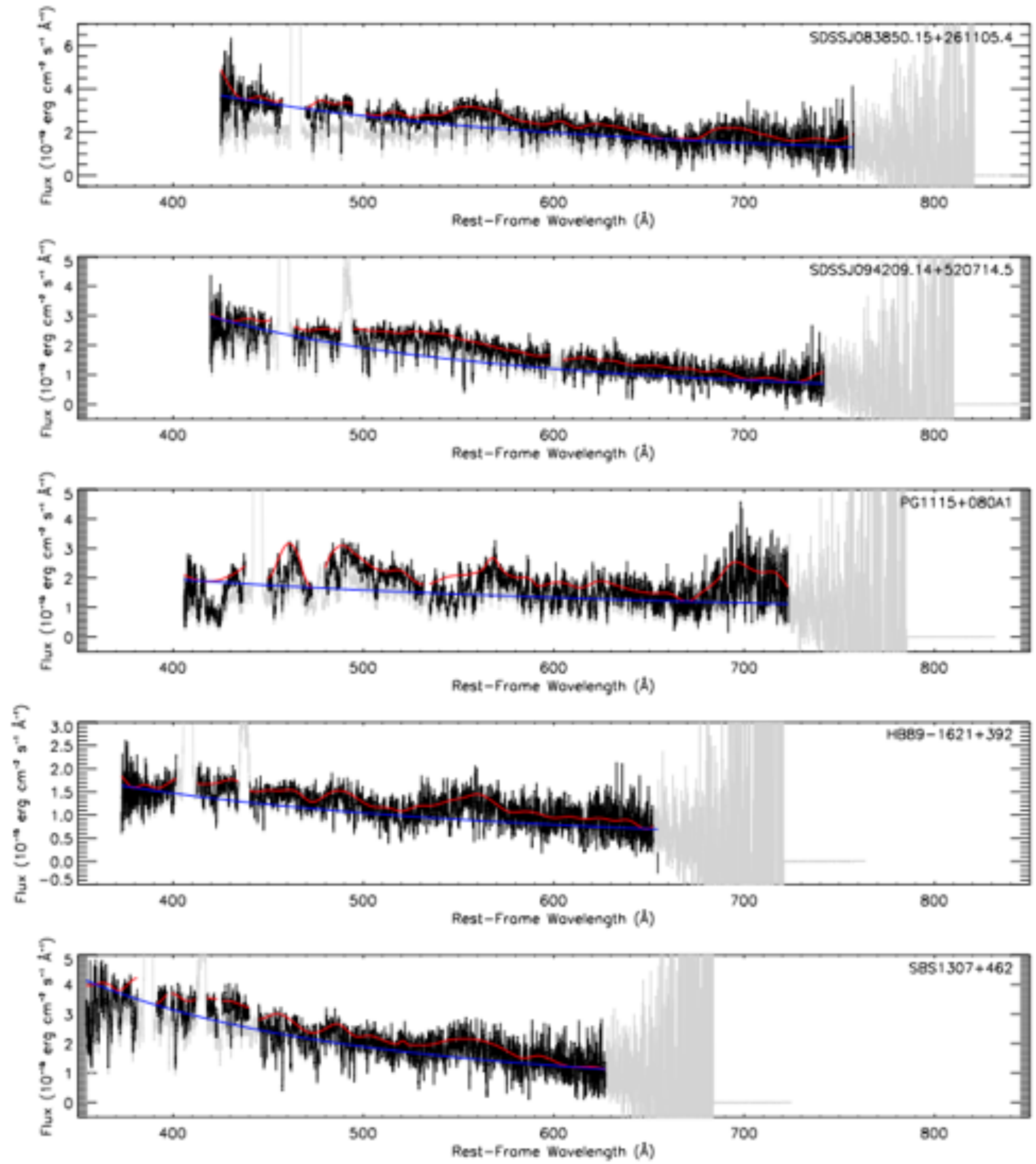
Small numbers of AGN at $\lambda_{rest} < 600$ A

Observed 17 more AGN
(z = 1.5-2.1) Hubble Cycles 21-25

New survey of 17 QSOs (z_{QSO} = 1.448 - 2.142) with Hubble COS/G140L

Probing rest-frame EUV spectra of quasars down to 350-400 A





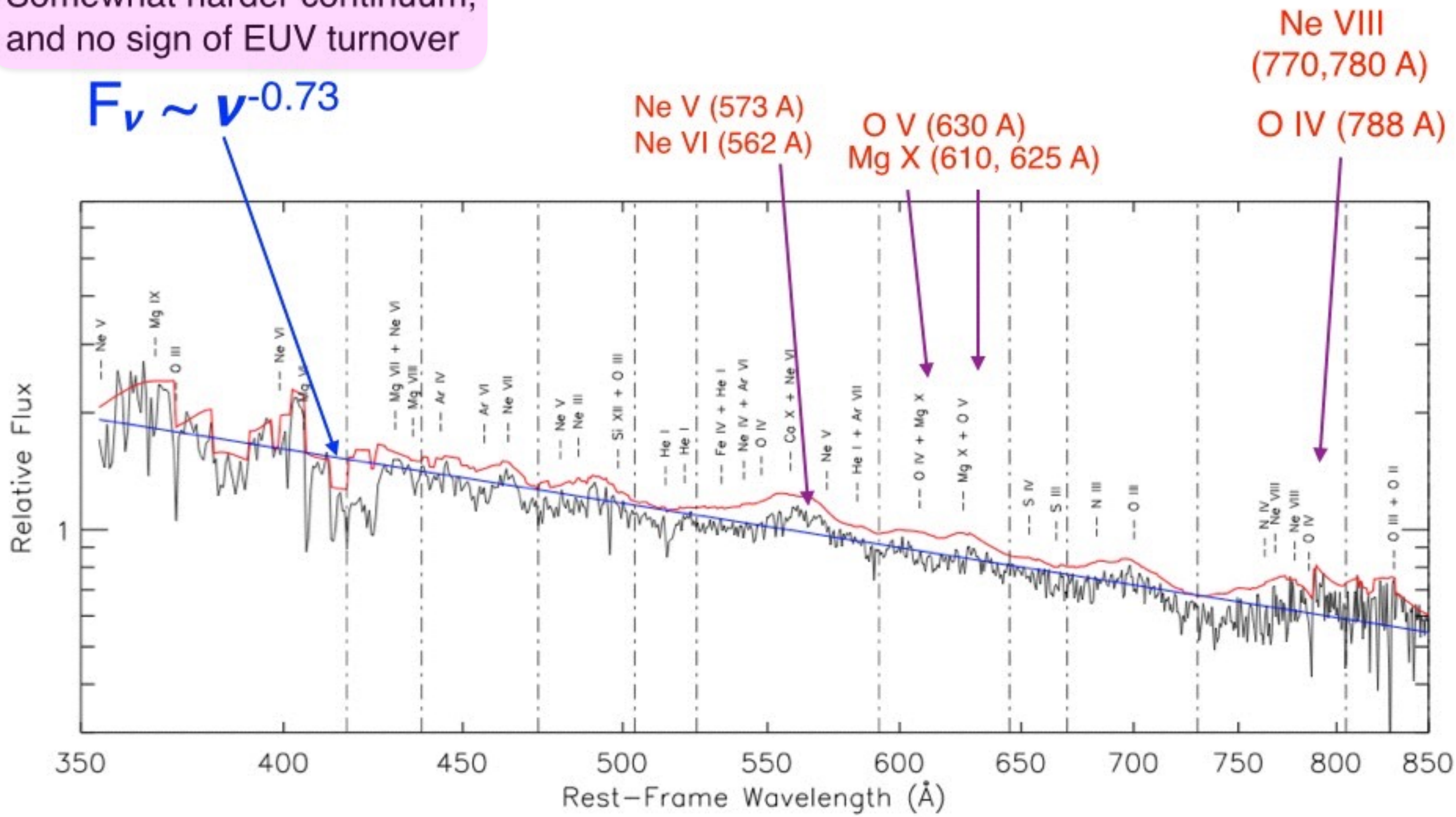
EUV Composite Spectrum (λ_{rest} = 425 - 850 A)

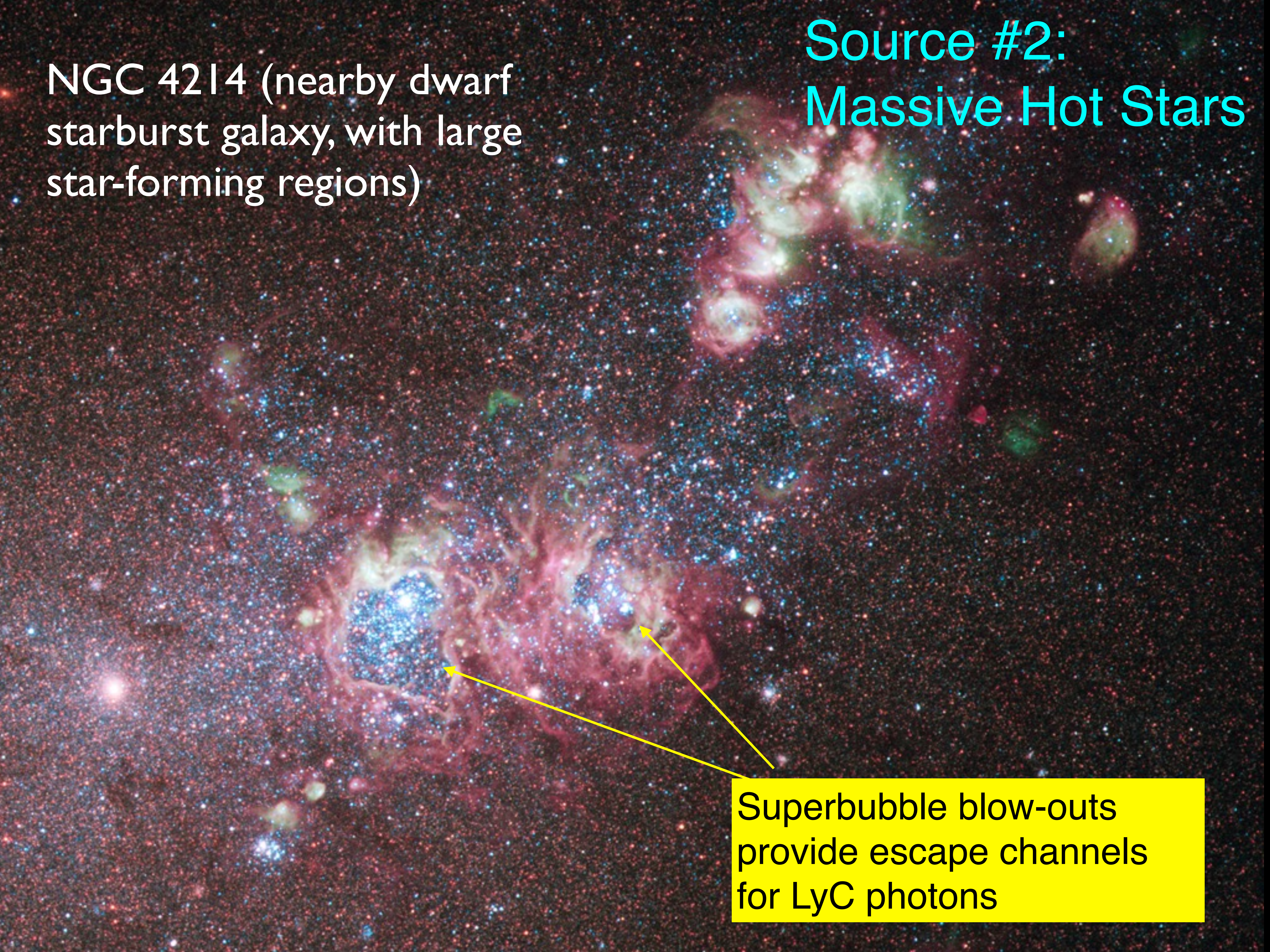
Continuum was fitted below many broad EUV emission lines.
Mostly O and Ne ions, plus the Mg X doublet (610, 625 A)

Tilton et al. 2016, ApJ, 817, 56

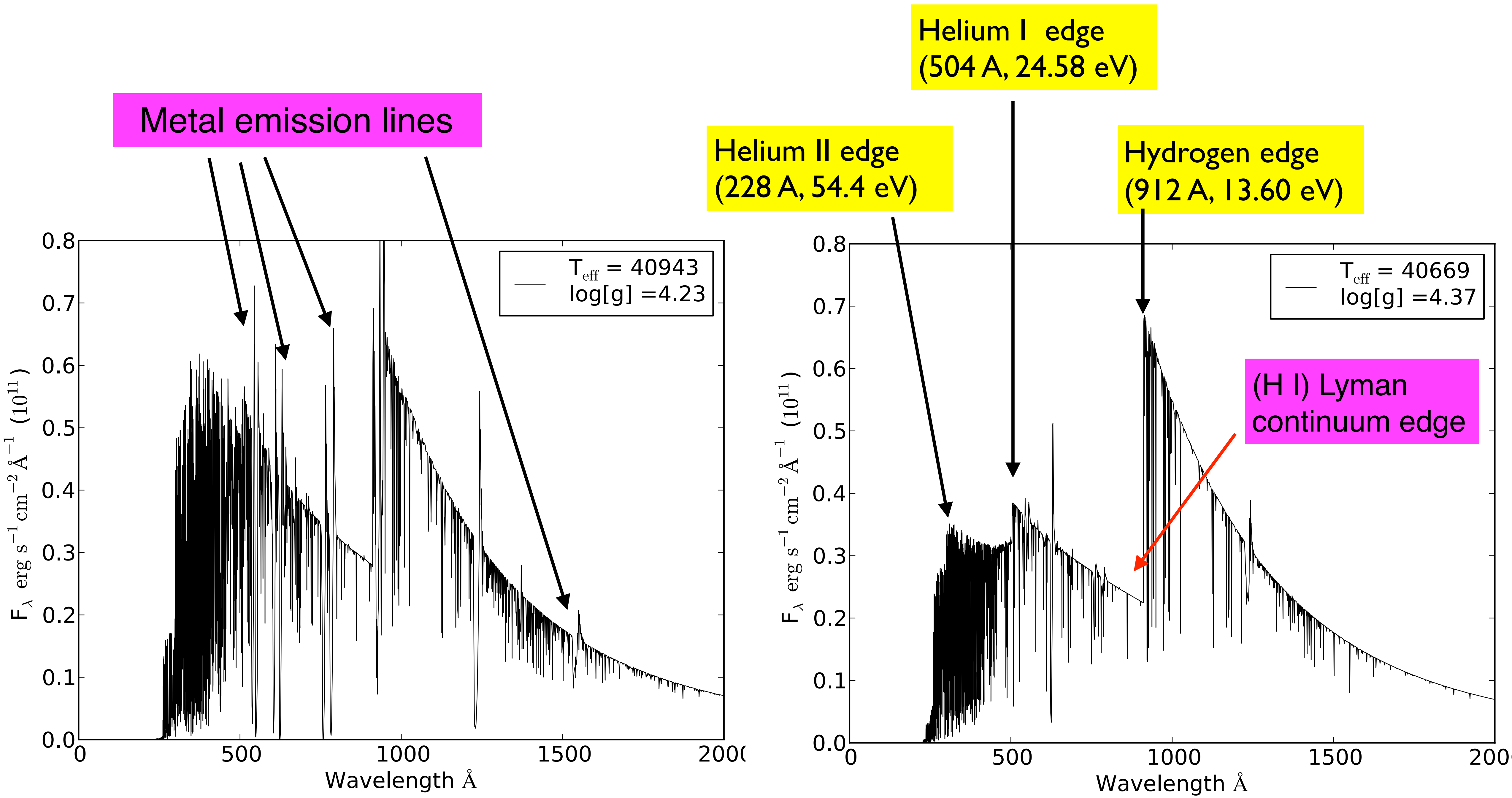
Somewhat harder continuum, and no sign of EUV turnover

$F_\nu \sim \nu^{-0.73}$




Source #2:
Massive Hot Stars
NGC 4214 (nearby dwarf starburst galaxy, with large star-forming regions)
Superbubble blow-outs provide escape channels for LyC photons

The Ionizing Continua of Massive O- Stars



Solar Metallicity (Z = 0.014)

30% Solar Metallicity (Z = 0.004)

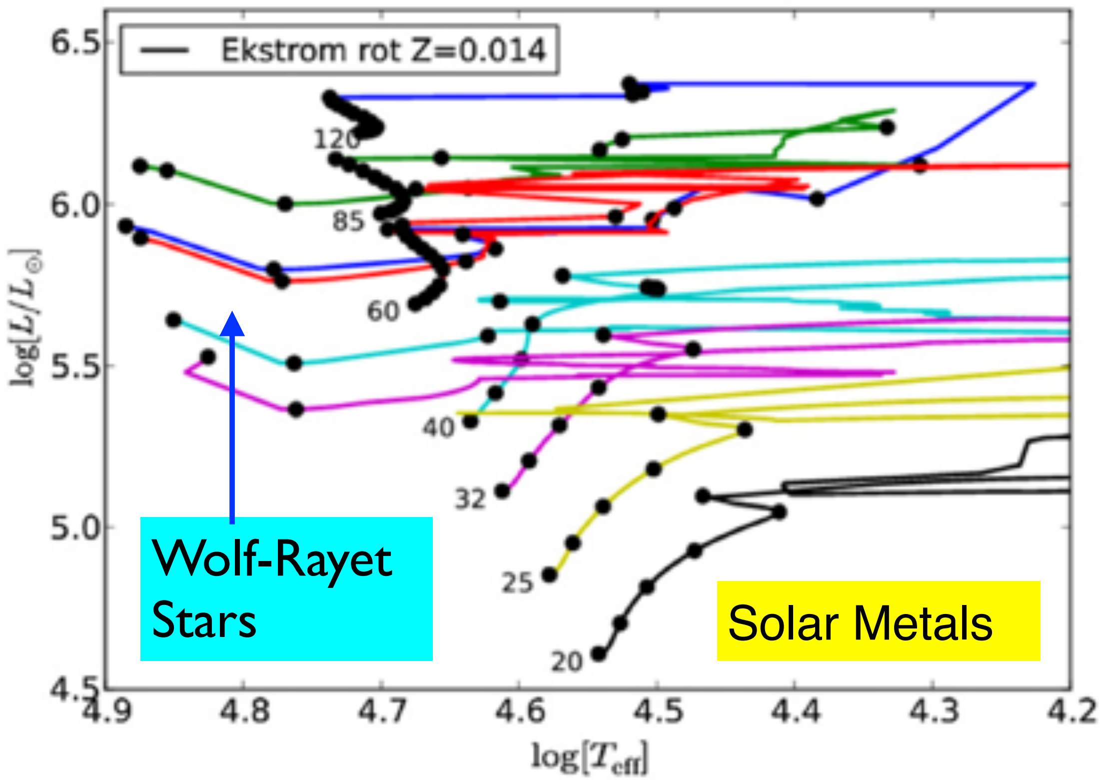
Model stellar atmospheres (WM-BASIC code)

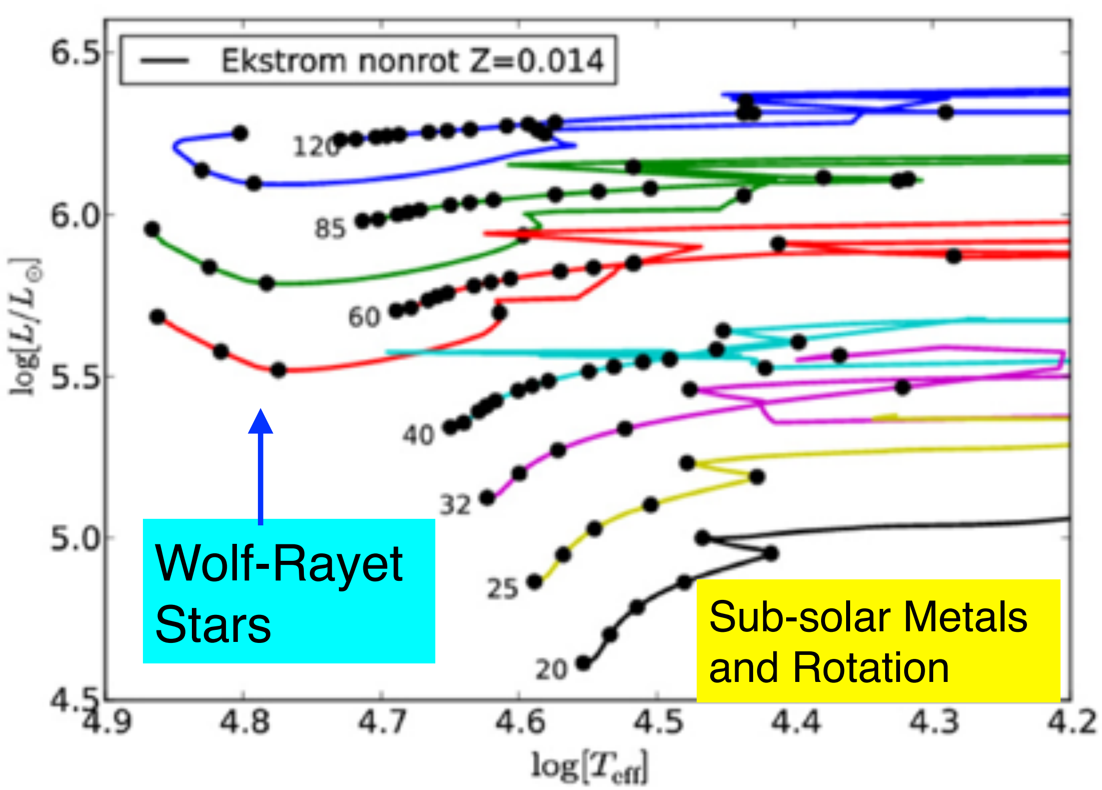
Topping & Shull 2015, ApJ, 800, 97

THE EFFICIENCY OF STELLAR REIONIZATION: EFFECTS OF ROTATION, METALLICITY, AND INITIAL MASS FUNCTION

Michael W. Topping[1] and J. Michael Shull[2]

ApJ, 800, 97 (2015)





Revised calibration of LyC production, using new evolutionary tracks + NLTE atmospheres.

$$10^{53.3\pm0.2} \text{ photons s}^{-1} \text{ per } M_\odot \text{ yr}^{-1}.$$

50% increase over the previous calibration, for Salpeter, Kroupa, Chabrier IMFs.

O-star binaries can prolong LyC timescale (Stanway, Eldridge, & Becker 2016).

Mass-transfer rejuvenates secondary star. Late mergers may produce more massive stars late in evolution (t > 10 Myr).

SFR density needed to sustain a photoionized IGM against recombinations

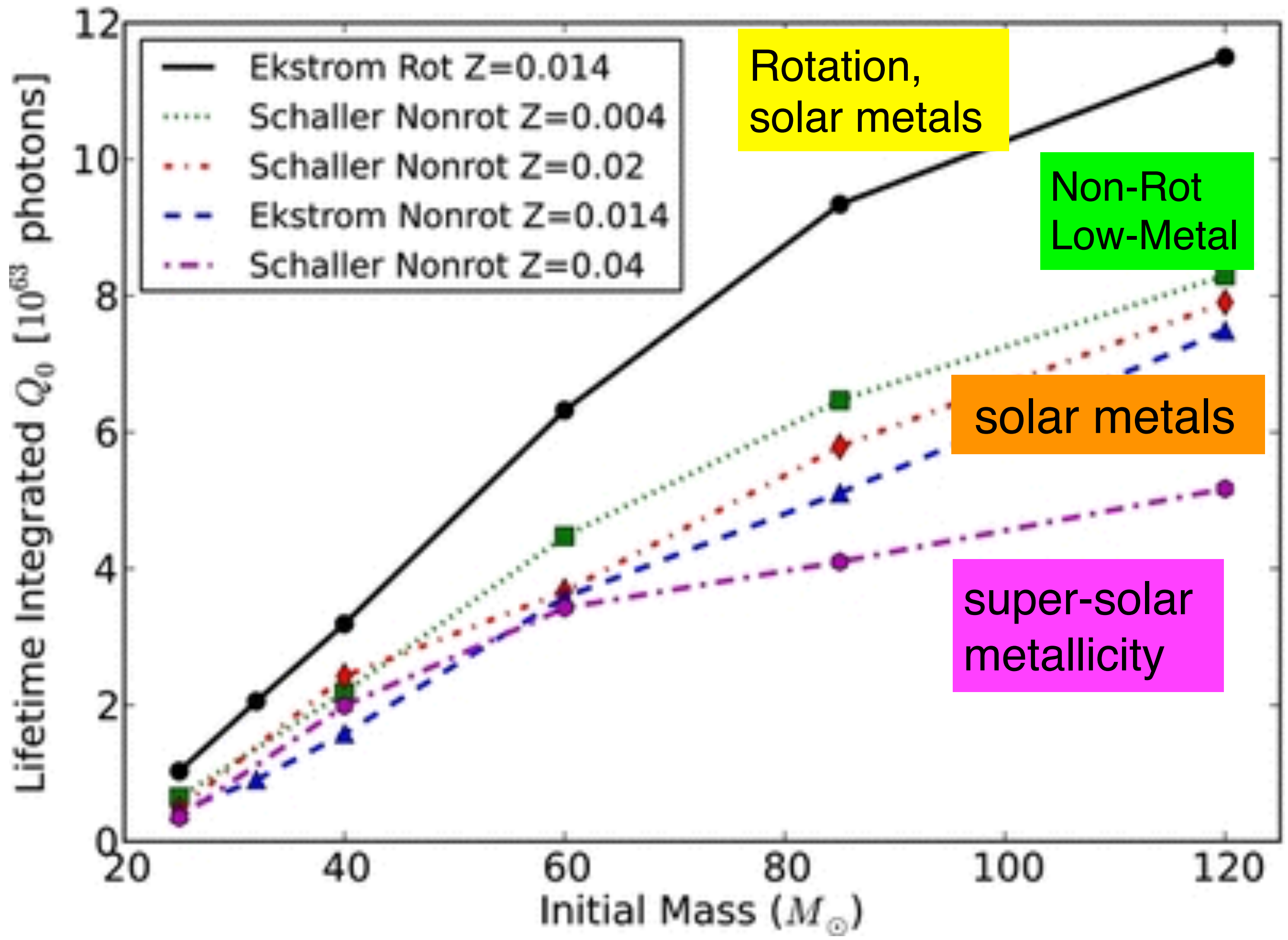
$$\dot{\rho}_{\rm SFR} = (0.012\ M_\odot\ {\rm yr}^{-1}\ {\rm Mpc}^{-3}) \left[\frac{(1+z)}{8}\right]^3 \left(\frac{C_H/3}{f_{esc}/0.2}\right) \left(\frac{6\times 10^{60}\ {\rm phot}/M_\odot}{Q_{LyC}}\right) T_4^{-0.845}$$

$H^+ + e^- \Leftrightarrow H^o + \gamma$

IGM clumping factor (C_H = 3)
LyC escape fraction (f_{esc} = 0.2)

$$Q_{LyC} = (6 \pm 2) \times 10^{60}\ {\rm LyC\ photons}$$

per $M_\odot$ of star formation
(over lifetime of coeval starburst)



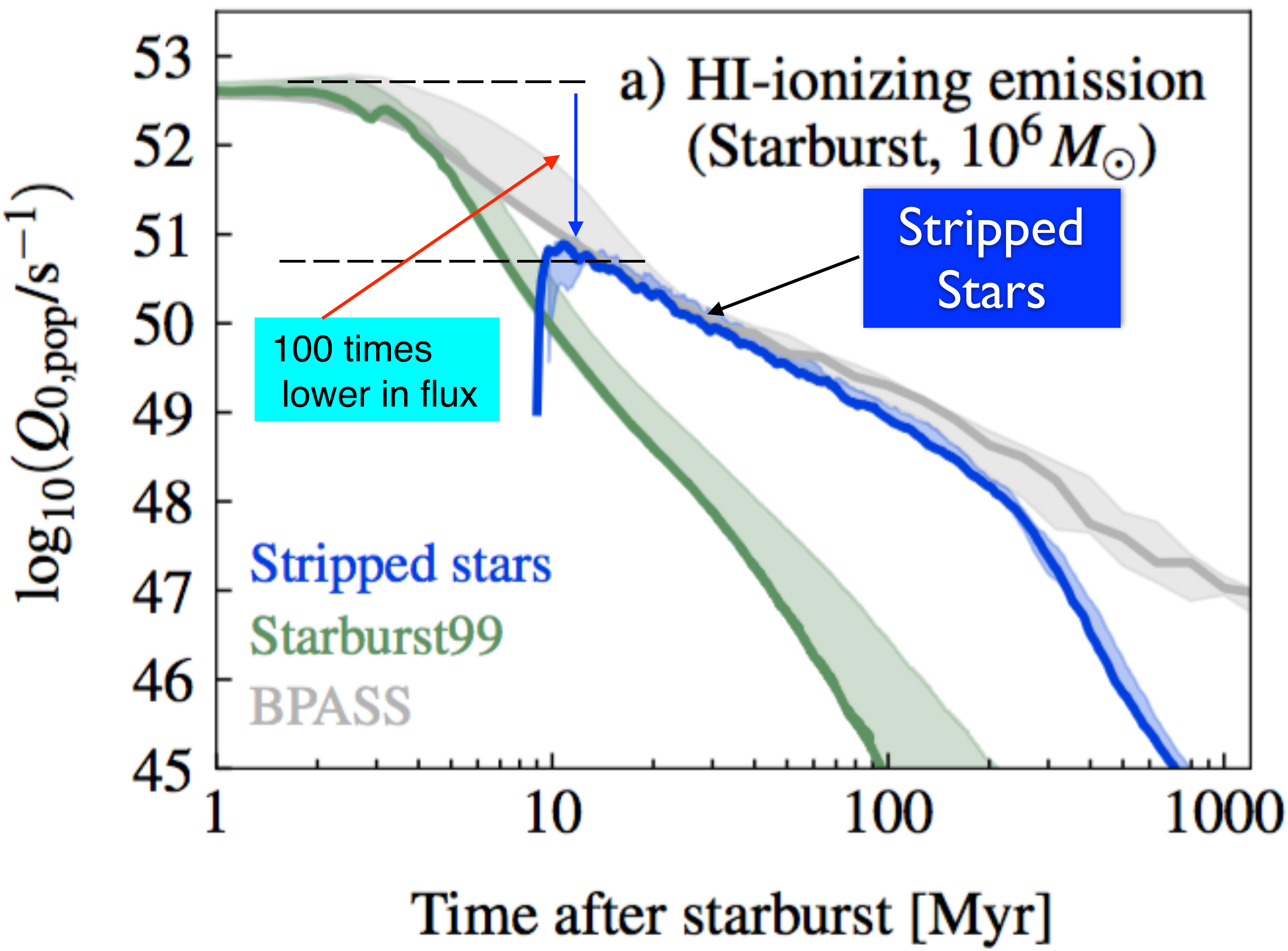
Full range is a factor of 3
(3-9) x 10^{60} photons/M_{sun}

LyC production increases for low-metallicity stars and also for stars with rapid rotation.

Gotberg et al. (2019) preprint (A&A)

(arXiv:1908.06102)

New possibility (and controversy) Binaries and Stripped Stars ?

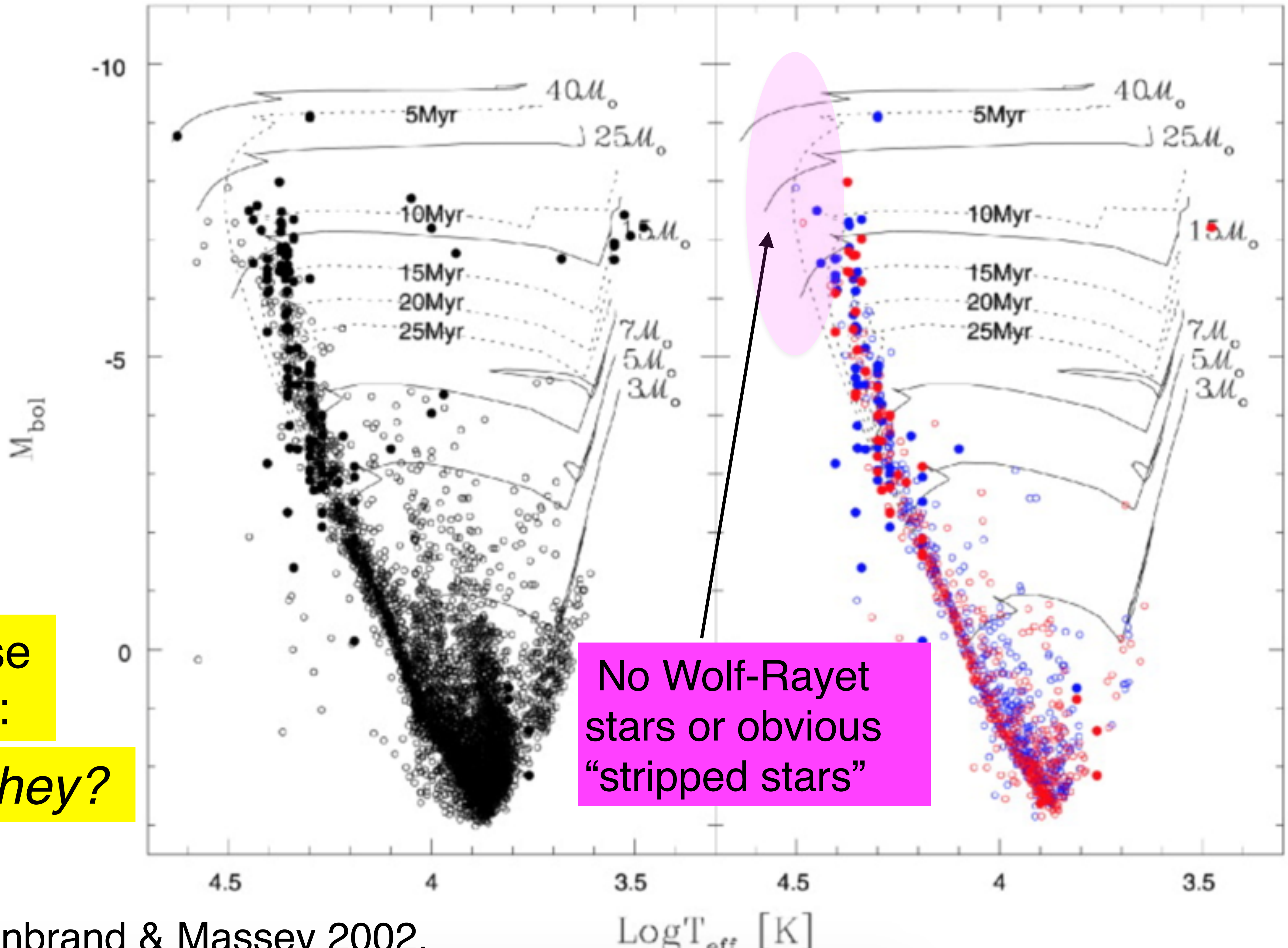



h and χ Persei
12.8 ± 1.0 Myr star clusters
No Wolf-Rayet Stars
or clear evidence for
“stripped stars”

h and Chi Persei (Color-Magnitude Diagram)

Γ=-1.3+/-0.2, indistinguishable from a Salpeter value.

Age 12.8 ± 1.0 Myr



No Wolf-Rayet stars or obvious "stripped stars"

To paraphrase Enrico Fermi:

Where are they?

Slesnick, Hillenbrand & Massey 2002, ApJ, 576, 880

Key Points for Reionization

(by both AGN and massive stars)

(1) The composite ionizing spectrum (EUV) of quasars is fairly hard ($F_\nu \sim \nu^{-1.41}$ at $z < 1.5$) and may be even harder (possibly $\nu^{-0.73}$ at higher redshifts, $z > 1.5$). More heating!

(2) The LyC photon production efficiency of O-stars depends on stellar IMF, metallicity, rotation, and binary evolution. But the rate could be different at z = 7-10 than "today".

$$10^{53.3\pm0.2}\ \text{photons s}^{-1}\ \text{per}\ M_\odot\ \text{yr}^{-1}.$$

(3) Maintaining an ionized IGM at z = 7 requires a SFR density of $0.01\ M_{sun}\ yr^{-1}\ Mpc^{-3}$, rising steeply at higher z.

$$\dot{\rho}_{\rm SFR} = (0.012\ M_\odot\ {\rm yr}^{-1}\ {\rm Mpc}^{-3})\left[\frac{(1+z)}{8}\right]^3 \left(\frac{C_{\rm H}/3}{f_{\rm esc}/0.2}\right) T_4^{-0.845}$$