The Cosmic Ionizing Background

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with Lars Hernquist, Adam Lidz, & Matias Zaldarriaga

+ Matt McQuinn & J. X. Prochaska

(see also work by Becker, Bolton, Calverley, and others!)

Proximity effect: Faucher-Giguère et al. 2008a, ApJ, 673, 39

Lyα opacity measurement: Faucher-Giguère et al. 2008b, ApJ, 681, 831

Implications: Faucher-Giguère et al. 2008c, ApJ, 688, 85

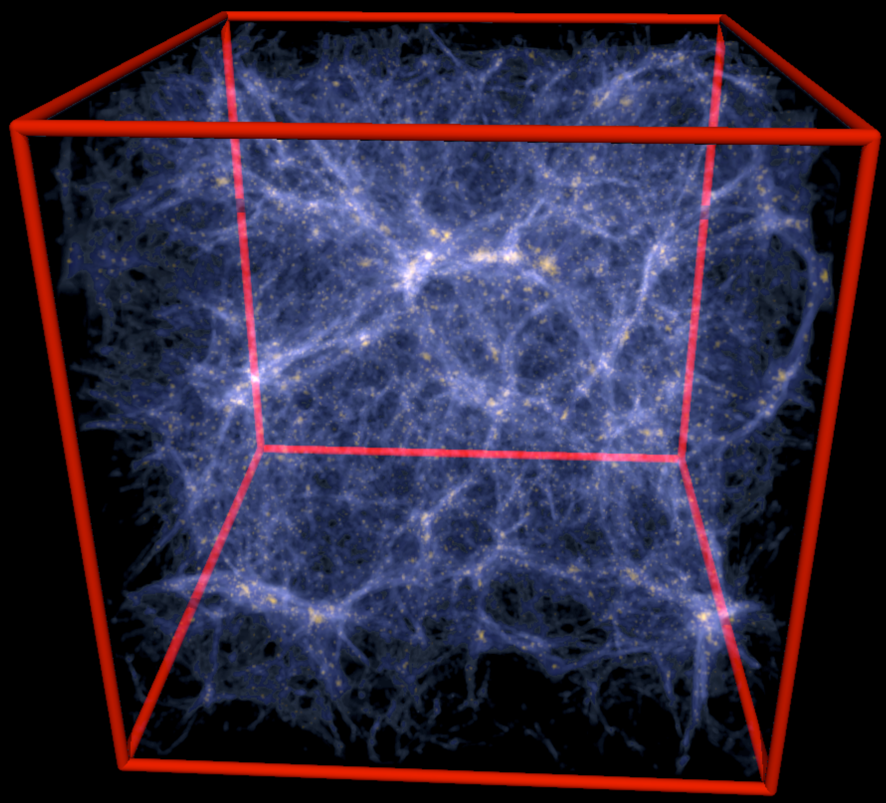
Faucher-Giguère et al. 2008d, ApJL, 682, 9

UV background spectrum: Faucher-Giguère et al. 2009, ApJ, 703, 1416

IGM temperature: Lidz, Faucher-Giguère et al., ApJ, submitted (arXiv:0909.5210)

Outline

- Intro and importance
- Observational constraints
- Evolution, sources, and spectrum
- HeII reionization

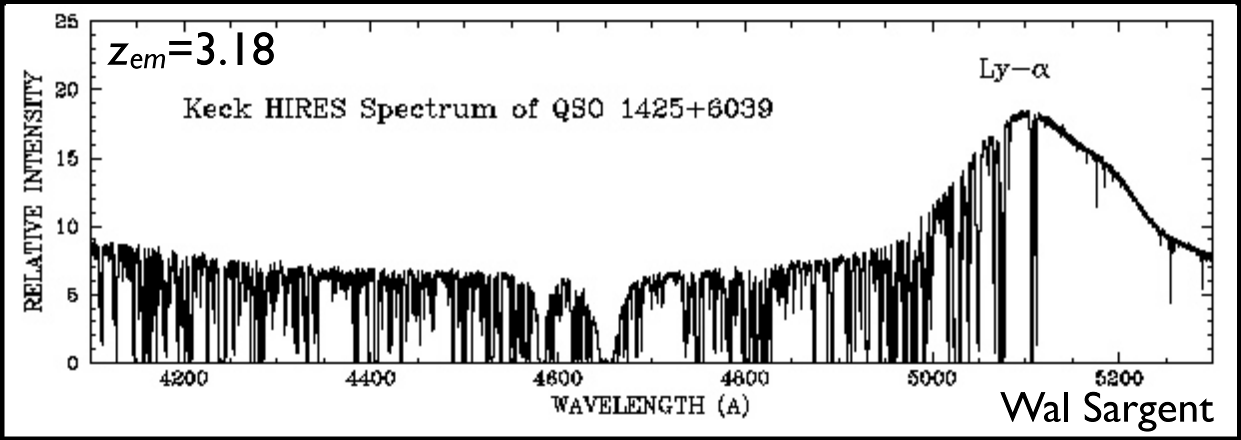


Springel & Hernquist (2003)

Intro and Importance

- Background of photons with energy sufficient to ionize HI (>13.6 eV; UV and X-ray) that permeates the Universe
- Know it is there because otherwise the Lyα forest would be completely saturated (Gunn & Peterson 1965)

$$\Gamma_i \equiv 4\pi \int_{\nu_i}^{\infty} \frac{d\nu}{h\nu} \sigma_i(\nu) J_\nu$$

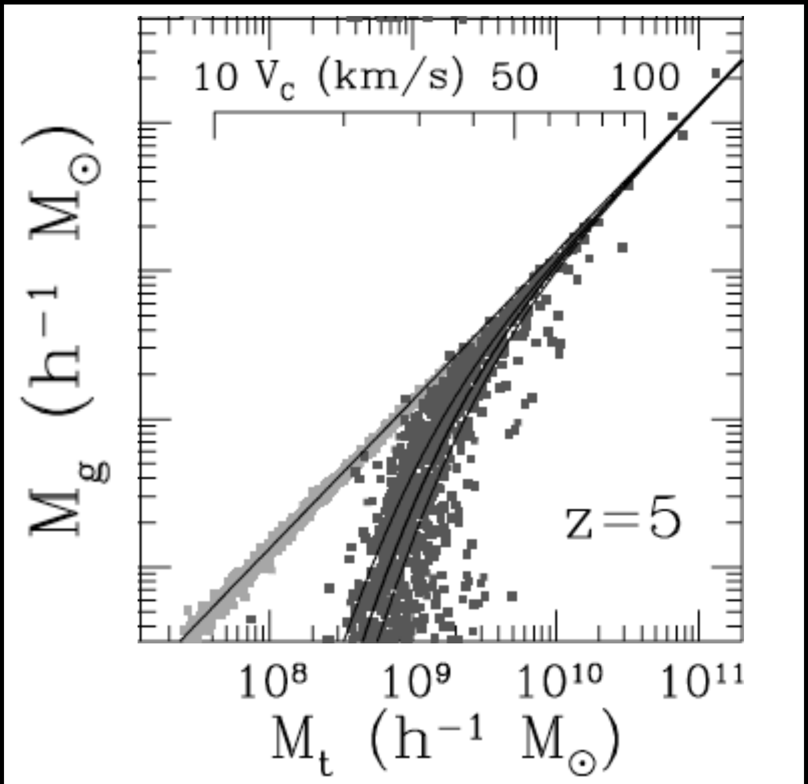


- Sets the ionization state of H, He, and metals
- Determines the thermal evolution of cosmic gas through photoheating: IGM and galaxy formation

More Concretely...

- IGM:
  - ➡ transmission of the Lyα forest
  - ➡ temperature of the IGM
  - ➡ its characteristic (Jeans) scale
  - ➡ ionization corrections for metal enrichment studies
- Galaxy formation:
  - ➡ modifies heating and cooling functions
  - ➡ keeps gas out of shallow potential wells

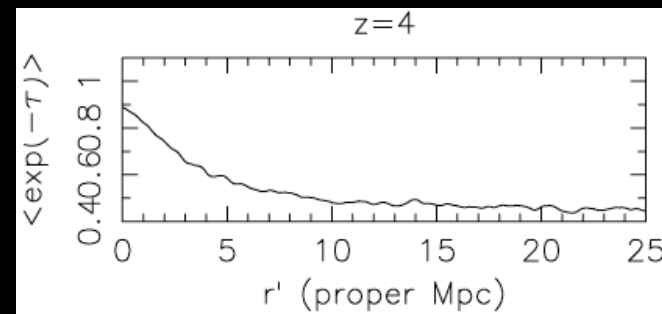
Low-mass galaxies



Gnedin (2000)

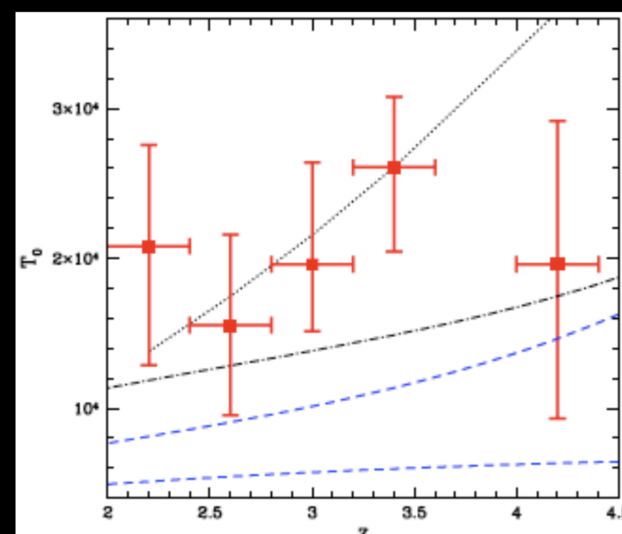
Observational Techniques

- Proximity effect:
  - ➡ look at Lyα forest near the quasar source vs. away from it
  - ➡ measure the ratio $\Gamma_{\rm HI}^{\rm QSO}/\Gamma_{\rm HI}^{\rm bkg}$
  - ➡ solve for $\Gamma_{\rm HI}^{\rm bkg}$ given the quasar luminosity
  - ➡ systematics: quasar redshifts, quasar variability, local overdensity
    (but perhaps better at z≳5, see Calverley talk)



CAFG et al. (2008a)

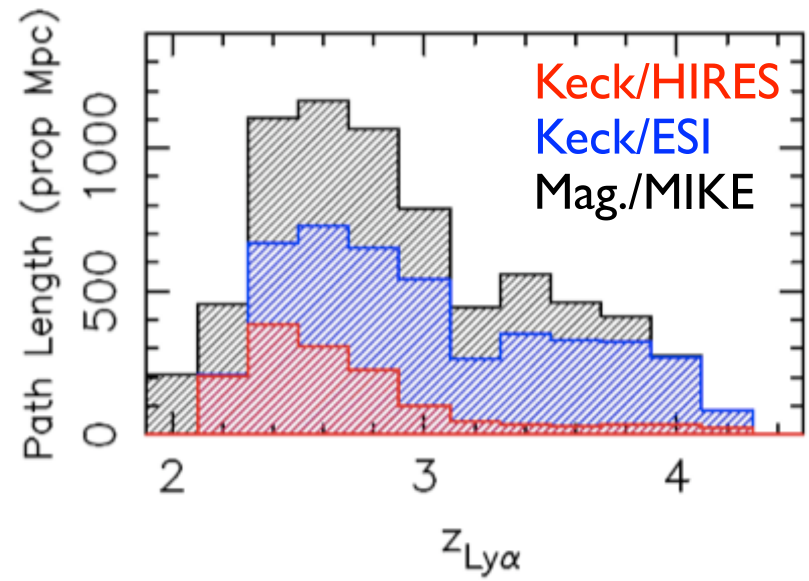
- Mean flux decrement:
  - ➡ consider mean Lyα forest transmission
  - ➡ solve for $\Gamma_{\rm HI}^{\rm bkg}$ using $\tau \propto T^{-0.7}/\Gamma_{\rm HI}^{\rm bkg}$
  - ➡ also has systematics: *T* degeneracy, gas density PDF
  - ➡ but more tractable: *T* measurement, simulations

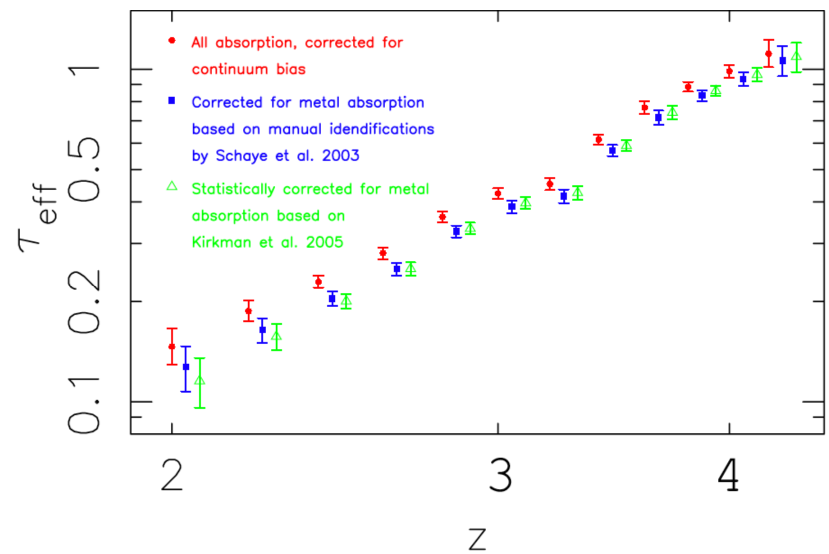


Lidz, CAFG, et al., submitted

Lyα Opacity Measurement

- 86 high-resolution, high S/N spectra obtained with Keck and Magellan
- Covers $2 \leq z_{Ly\alpha} \leq 4.2$
- Correct for continuum bias and metal absorption



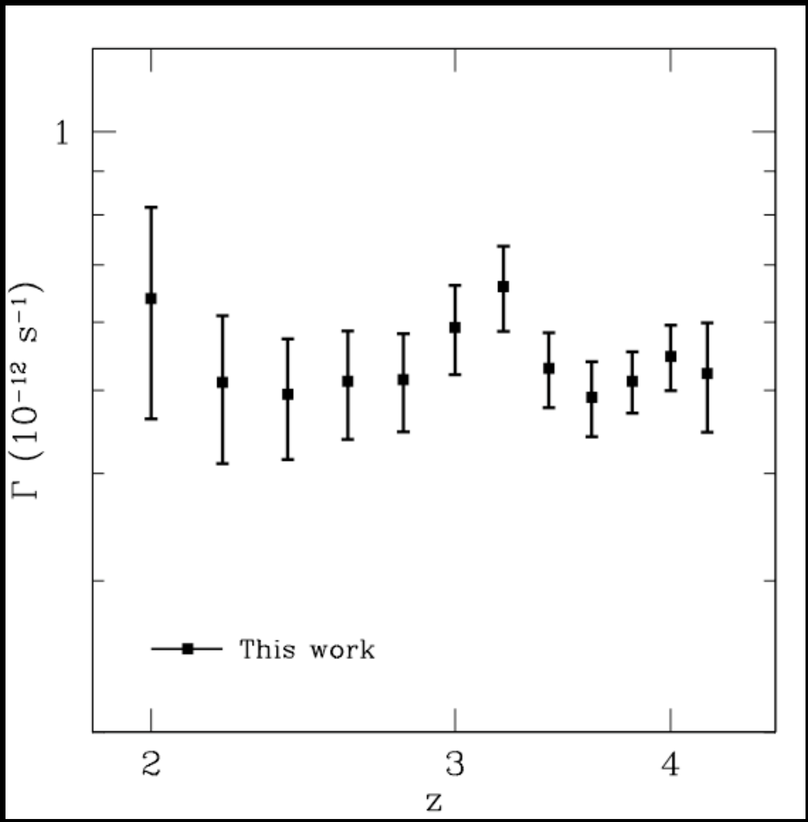


CAFG et al. (2008b)

Integral Constraints on J_ν

- $\Gamma_{\rm HI}$ from $\tau_{\rm eff}$
- $\Gamma_{\rm HeII}/\Gamma_{\rm HI}$ from $N_{\rm HeII}/N_{\rm HI}$

  (Zheng et al. 2004, Bolton et al. 2006)
- HI must be reionized by z=6 (HI Lyα forest)
- HeII must be reionized by z~3 (HeII Lyα forest)



CAFG et al. (2008c,d)

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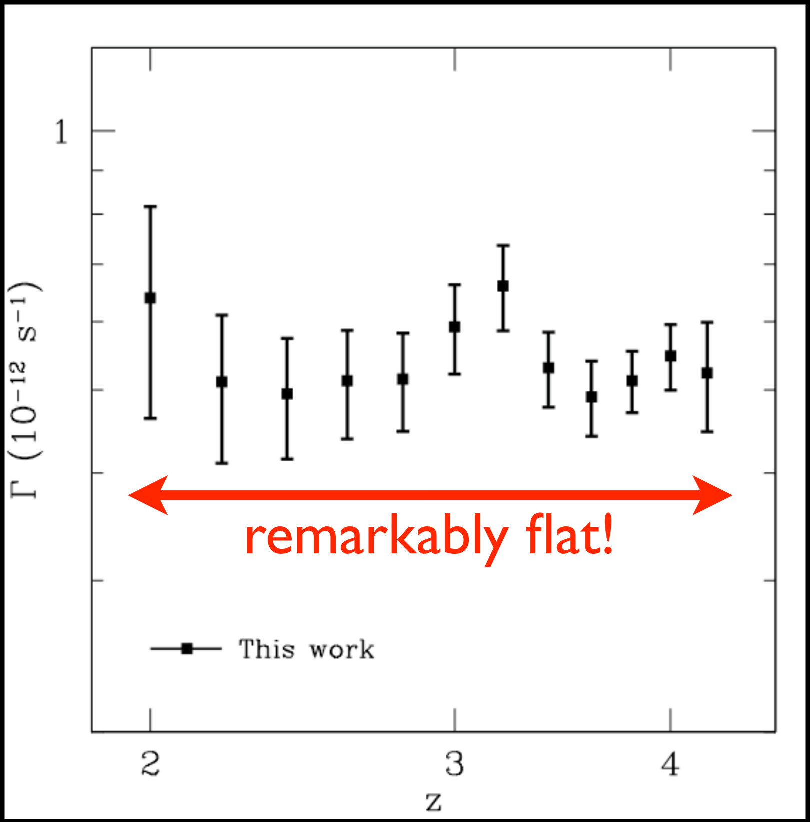
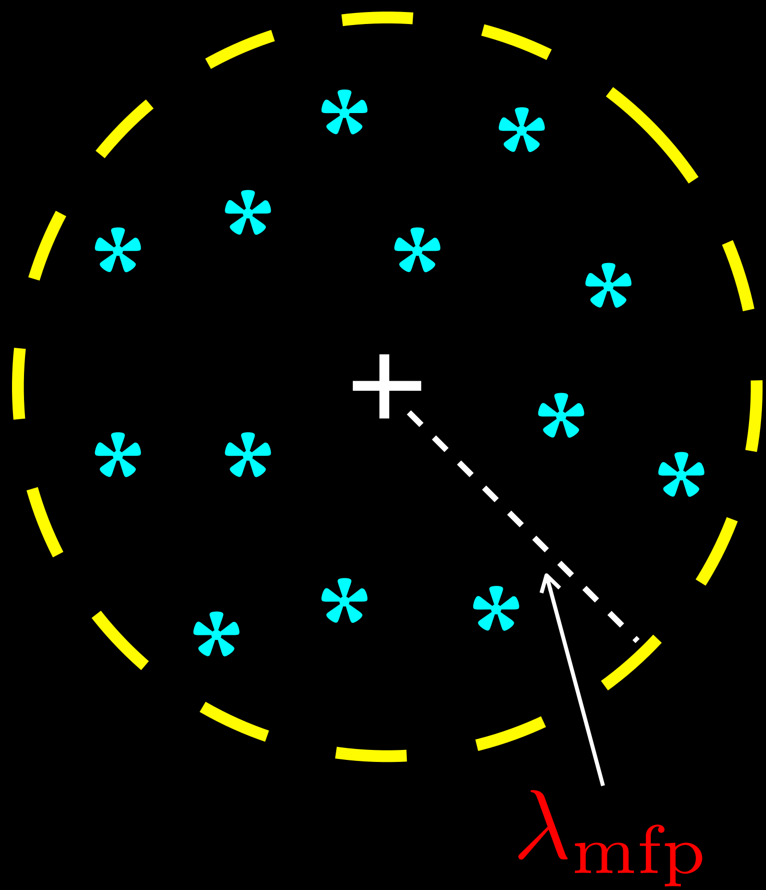


CAFG et al. (2008c,d)

From Γ to Emissivity

$$\epsilon_{912} \approx \langle n_{\rm src} \rangle \langle L^{\rm src}_{912} \rangle$$



- Only sources within an ionizing mean free path contribute to local ionizing background:

$$J_{912} \approx \frac{\epsilon_{912} \lambda_{\rm mfp}}{4\pi} \Rightarrow \Gamma \propto \epsilon_{912} \lambda_{\rm mfp}$$

- Mean free path determined by LLS:

$$\lambda_{\rm mfp} \propto (1+z)^{-4}$$

$$\text{for } dN_{\rm LLS}/dz \propto (1+z)^{1.5}$$

(Strengler-Larrea et al. 1995)

$$\Rightarrow \Gamma \propto \epsilon_{912} (1+z)^{-1}$$

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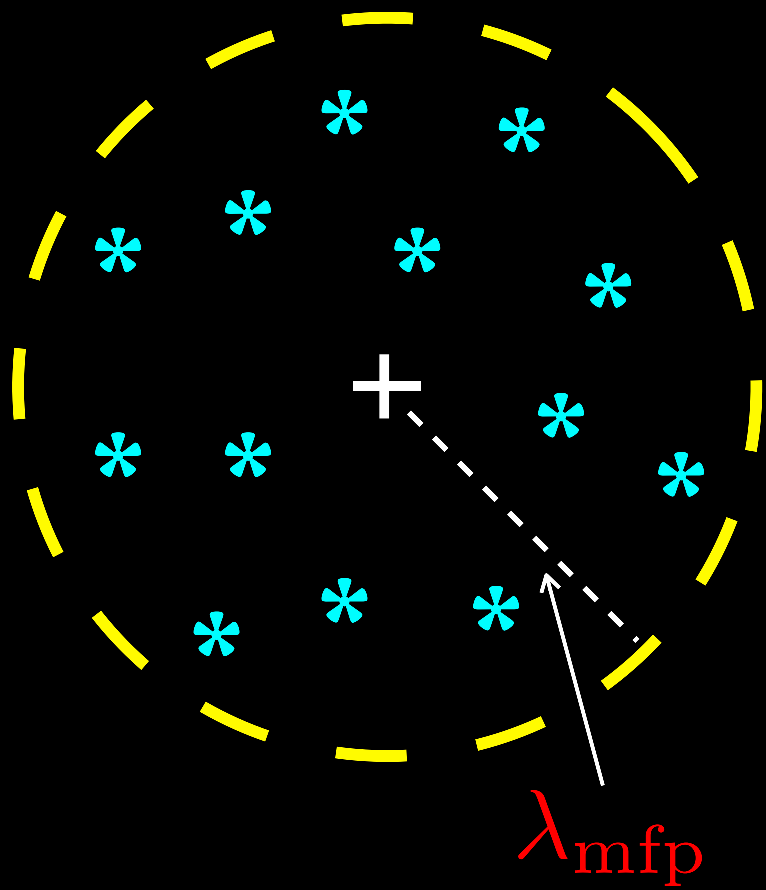

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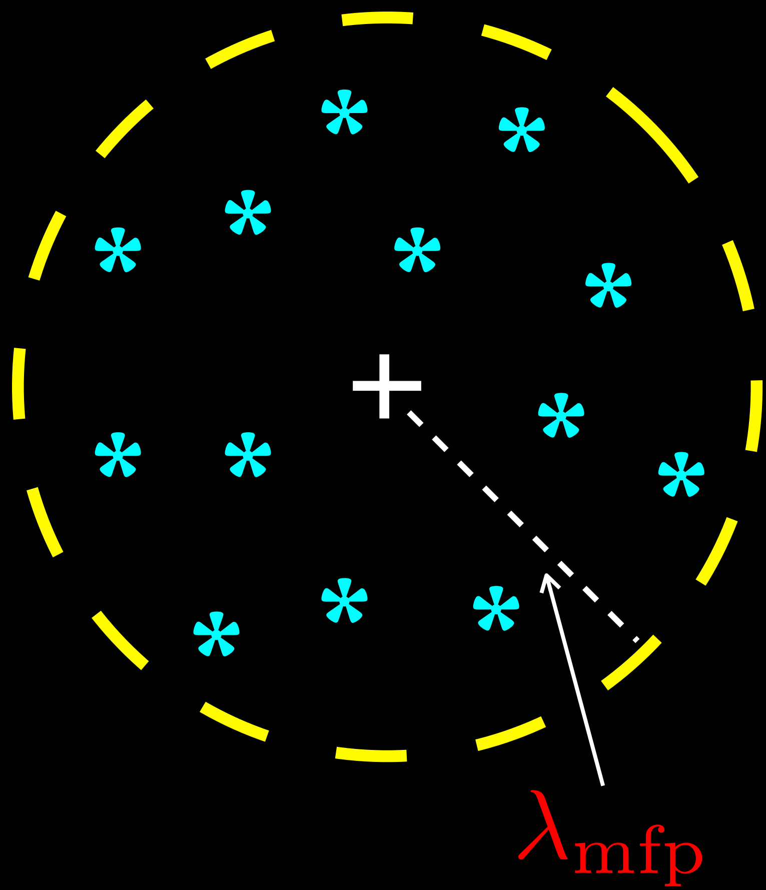

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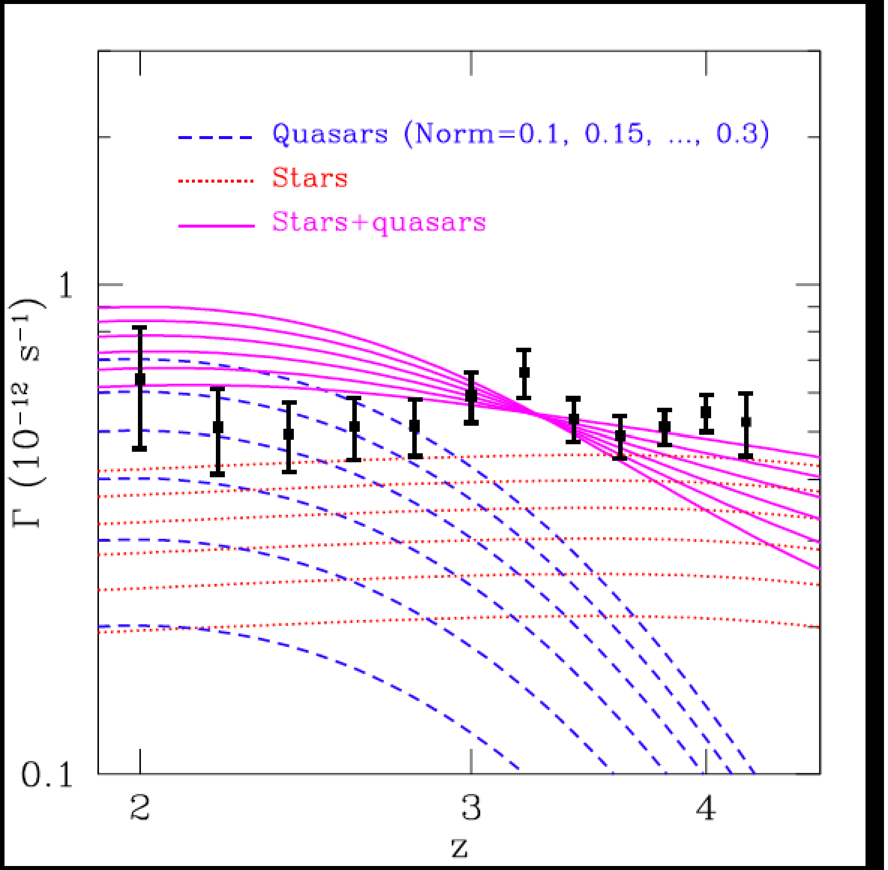
Ionizing Background Sources

- Given priors on the evolution of the QLF and SFH, and spectra, fit for the superposition quasars+stars that satisfies the IGM constraints
- Quasars:
  - ➡ Hopkins et al. (2007) luminosity function
  - ➡ α_{QSO}=1.6 (Telfer et al. 2003)
- Stars:
  - ➡ star formation tracing Hernquist & Springel (2003) model
  - ➡ α_{*}=1 at 1-4 Ryd, no emission beyond 4 Ryd (Kewley et al. 2001)



CAFG et al. (2008c)

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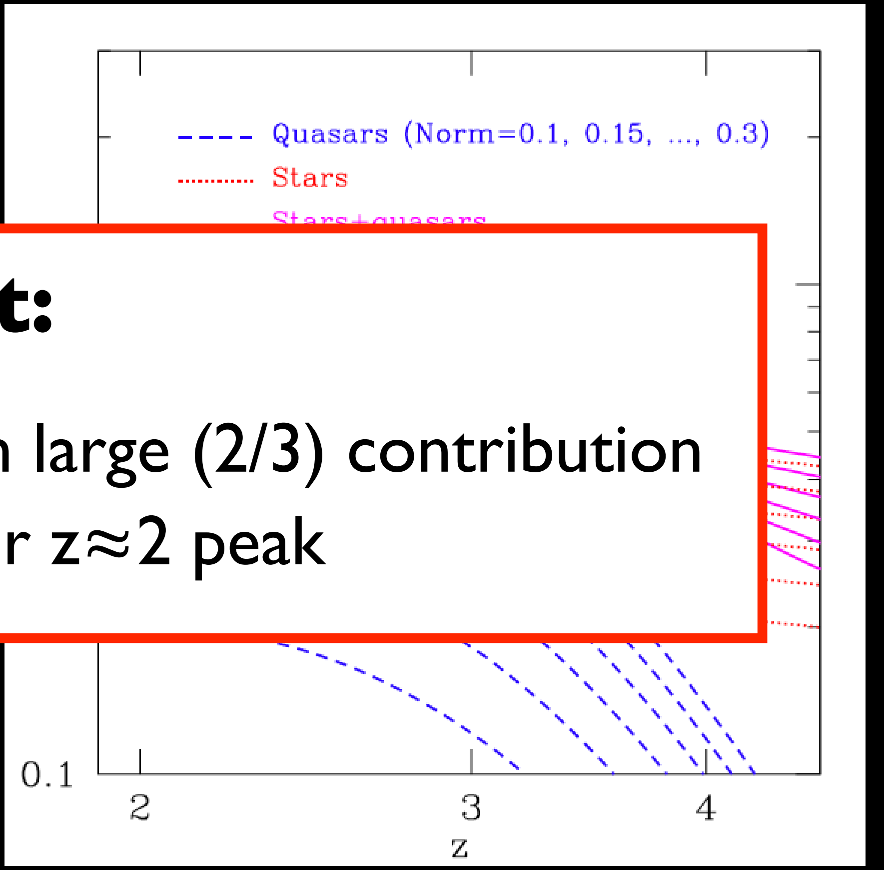
In short:

stellar-dominated at z≳3, but with large (2/3) contribution from quasars at their z≈2 peak

- Stars:
  - ➡ star formation tracing Hernquist & Springel (2003) model
  - ➡ $\alpha_* = 1$ at 1-4 Ryd, no emission beyond 4 Ryd (Kewley et al. 2001)



CAFG et al. (2008c)

Spectrum Calculation

- Solution to the radiative transfer equation:

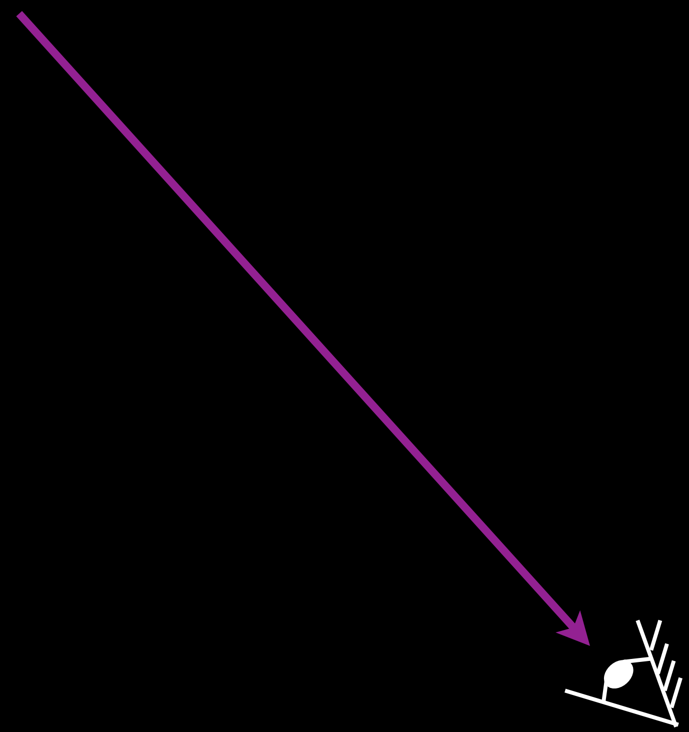
$$J_{\nu_0}(z_0) = \frac{1}{4\pi}\int_{z_0}^{\infty} dz\,\frac{dl}{dz}\,\frac{(1+z_0)^3}{(1+z)^3}\,\epsilon_\nu(z)\,\exp[-\bar{\bar{\tau}}(\nu_0, z_0, z)]$$

- Emissivity is sum of quasars, stars, and recombinations:

$$\epsilon_\nu(z) = \epsilon_\nu^{\rm QSO}(z) + \epsilon_\nu^{\star}(z) + \epsilon_\nu^{\rm rec}(z)$$

- Absorption arises from intergalactic HI and HeII:

$$\tau_\nu = N_{\rm HI}\sigma_{\rm HI}(\nu) + N_{\rm HeII}\sigma_{\rm HeII}(\nu)$$



CAFG et al. (2009)

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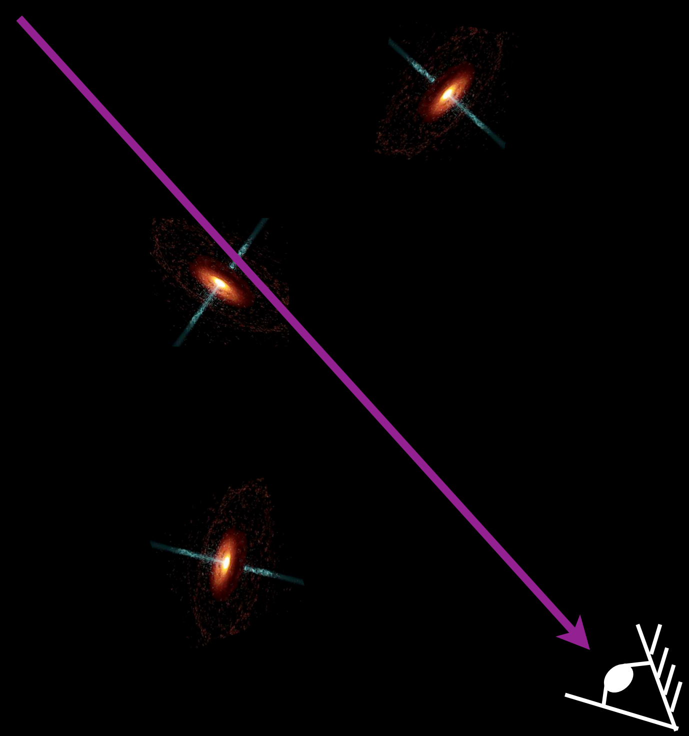

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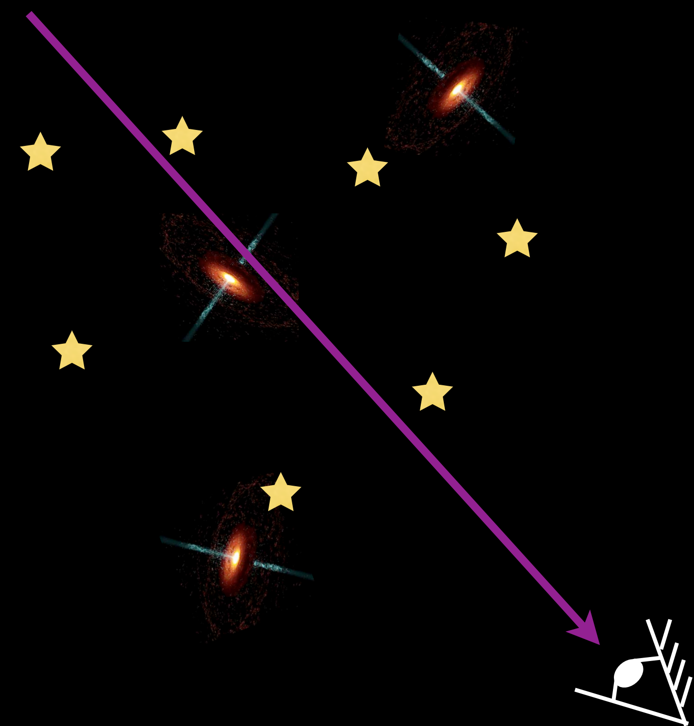

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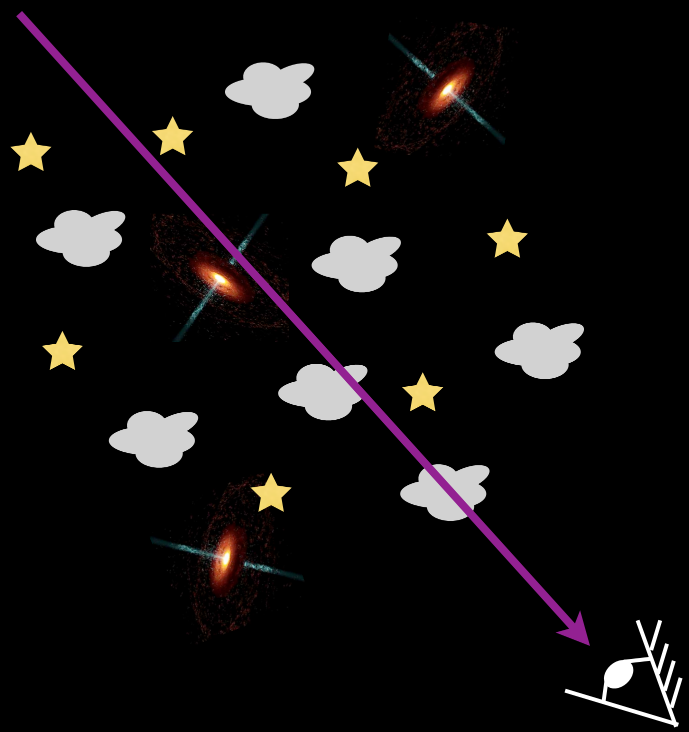

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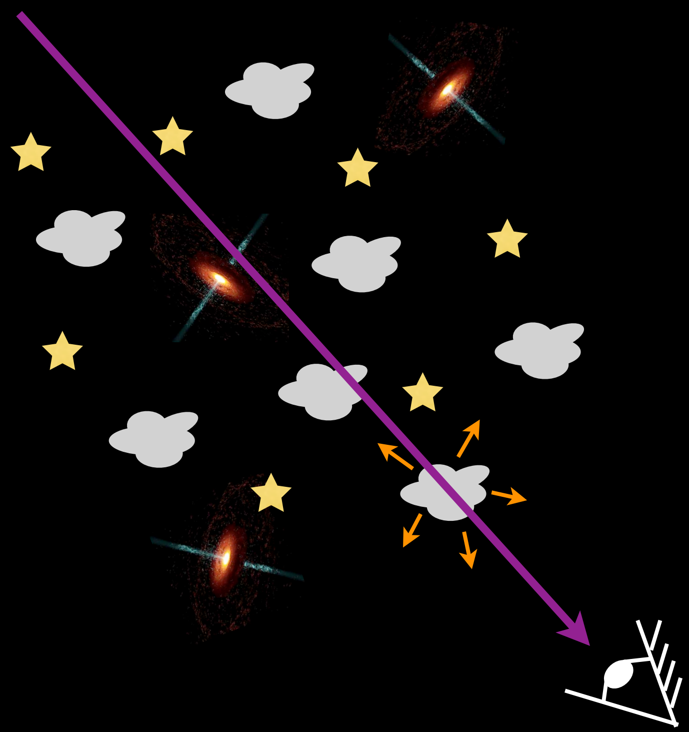
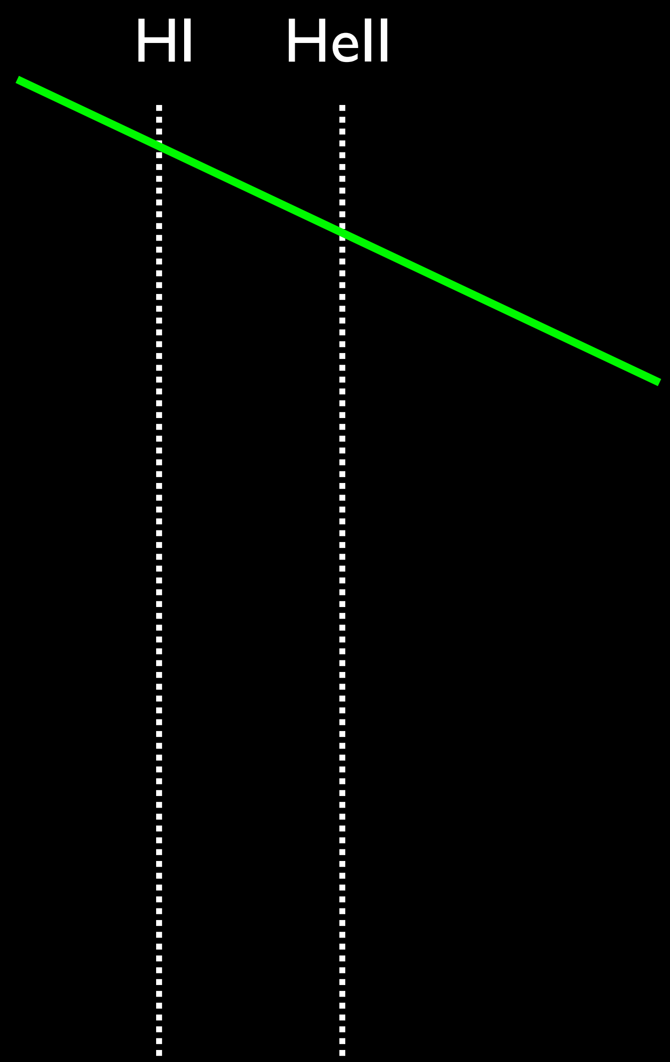


CAFG et al. (2009)

Spectral Features

- UV background spectrum is shaped by:
  - ➡ source spectra



CAFG et al. (2009)

Spectral Features

- UV background spectrum is shaped by:
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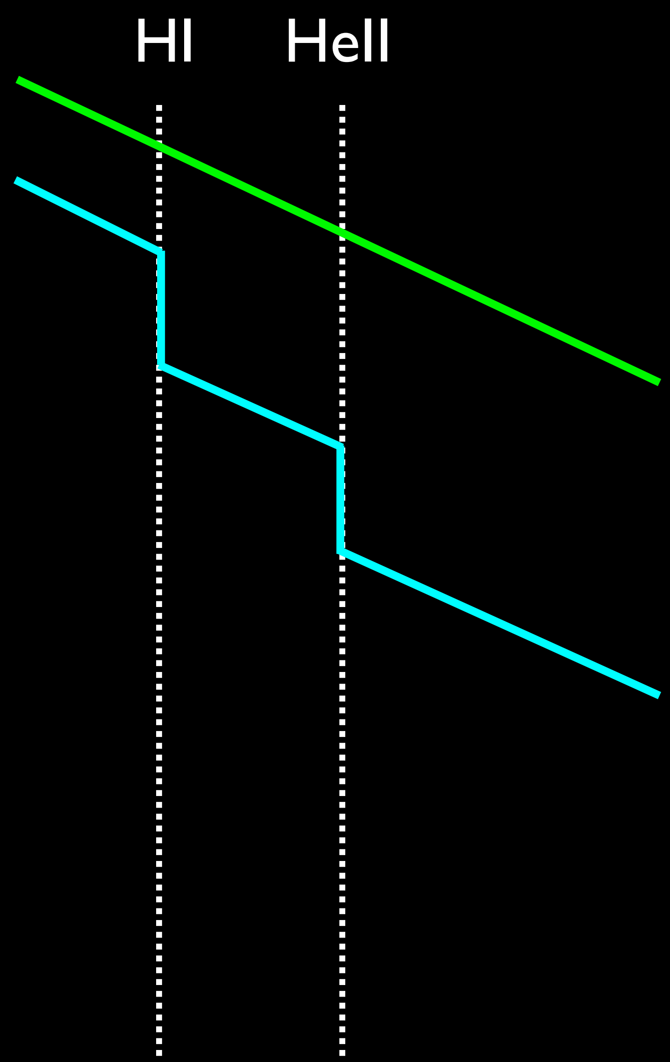

CAFG et al. (2009)

Spectral Features

- UV background spectrum is shaped by:
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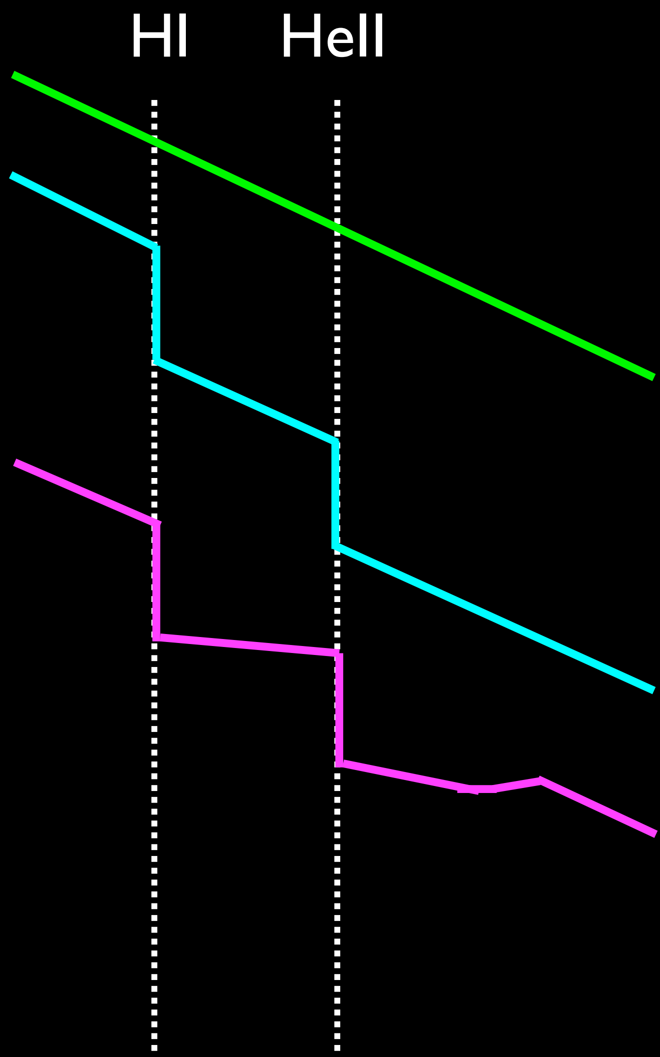
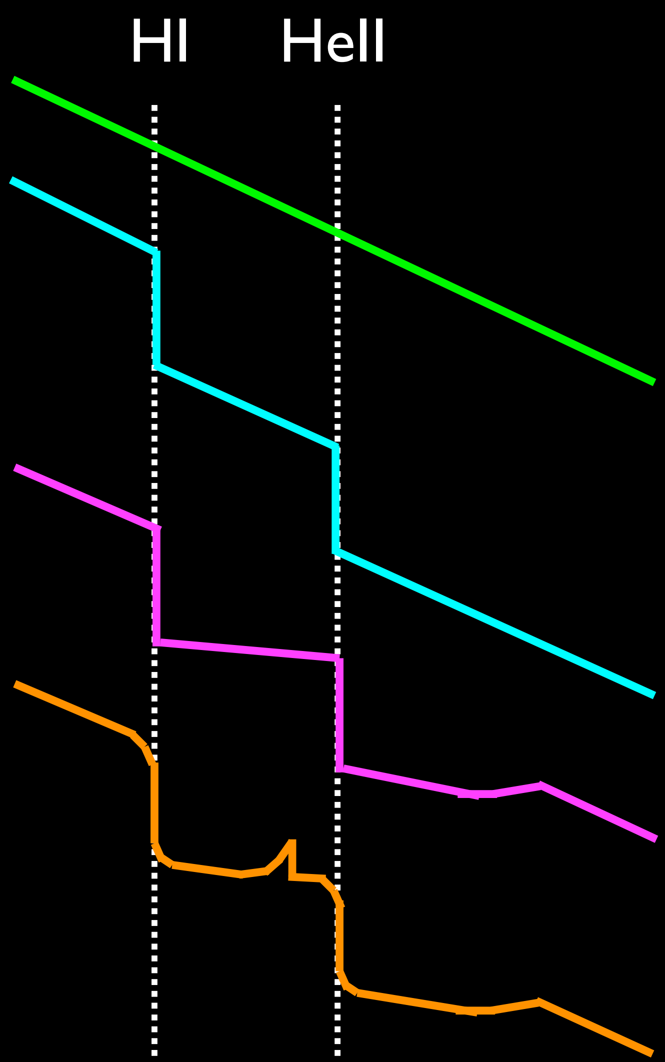
  - ➡ photoelectric absorption edges
  - ➡ spectral hardening above ionization edges



CAFG et al. (2009)

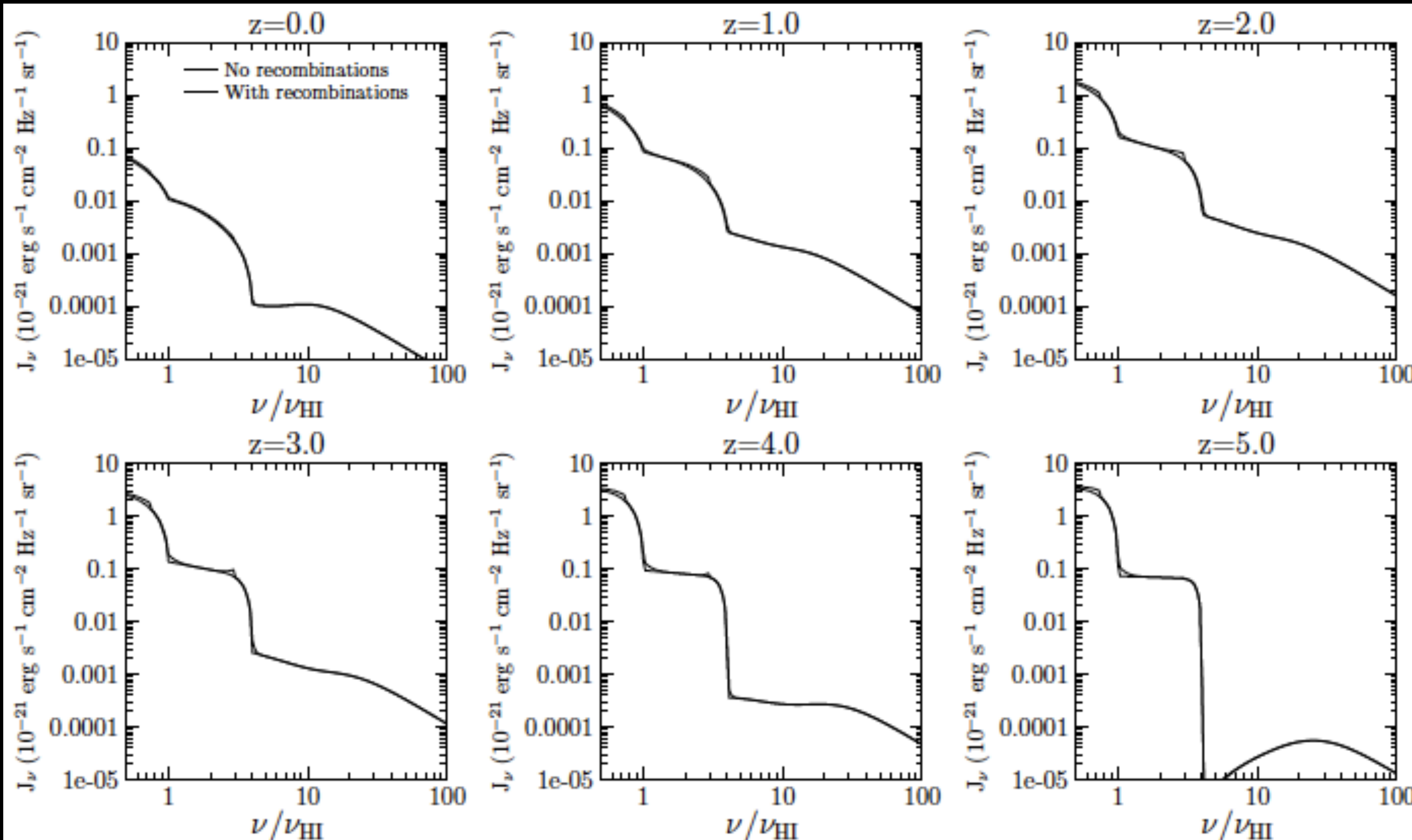
Spectral Features

- UV background spectrum is shaped by:
  - ➡ source spectra
  - ➡ photoelectric absorption edges
  - ➡ spectral hardening above ionization edges
  - ➡ recombination emission



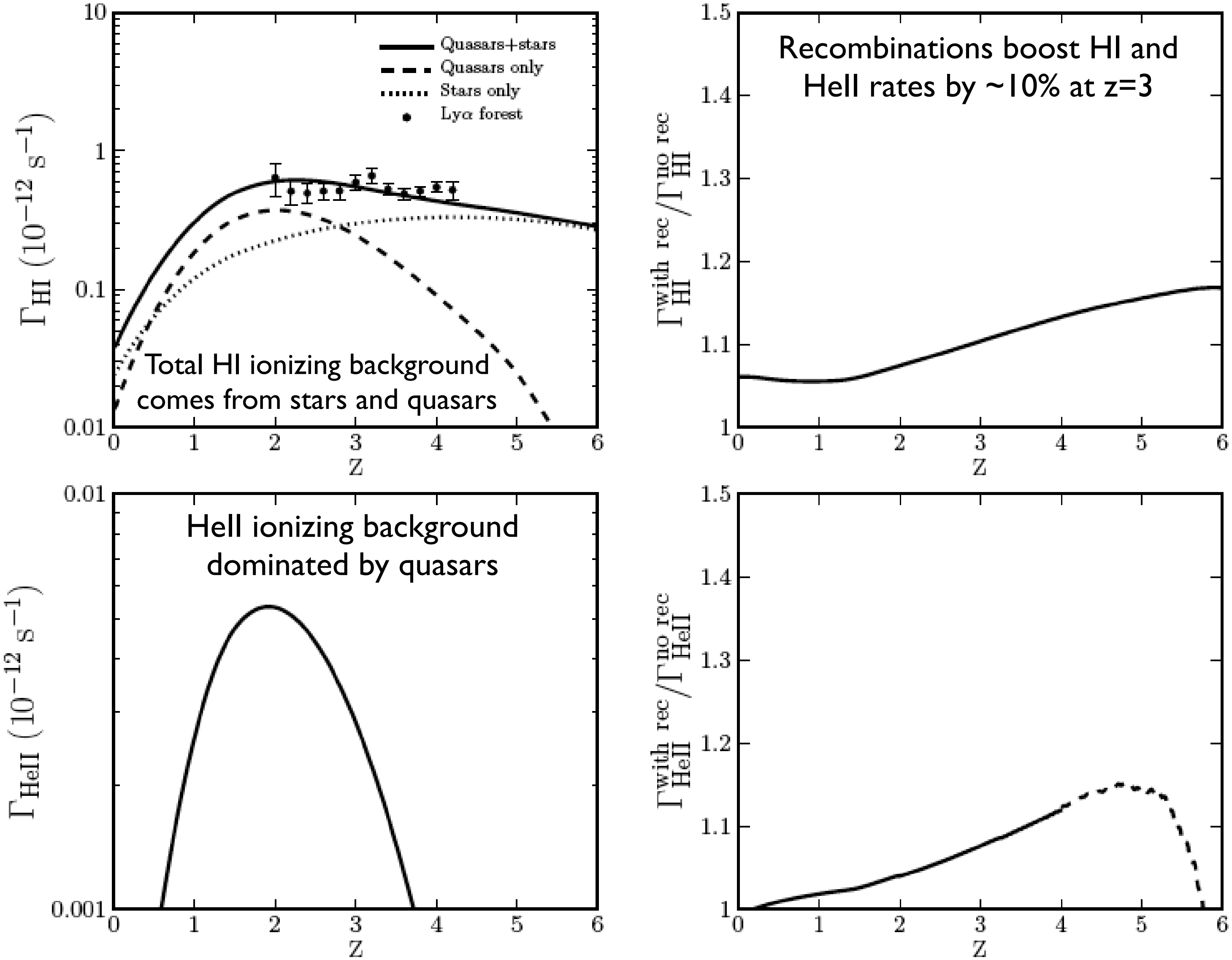
CAFG et al. (2009)

Spectrum Results



CAFG et al. (2009)

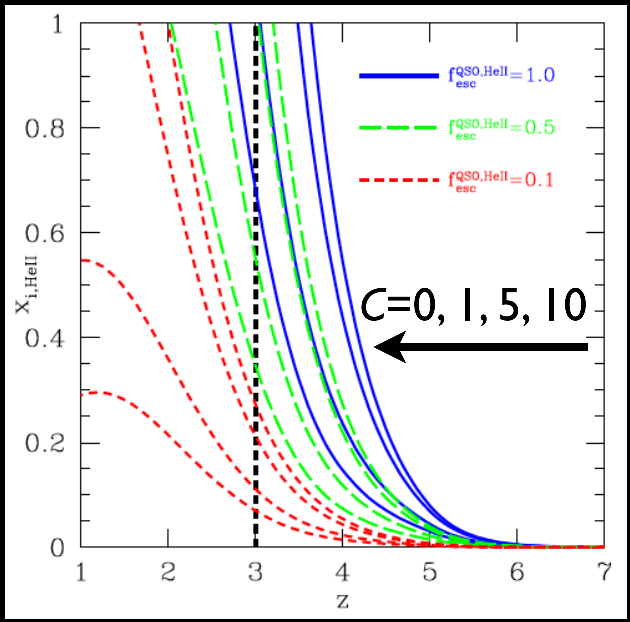
Corresponding Rates



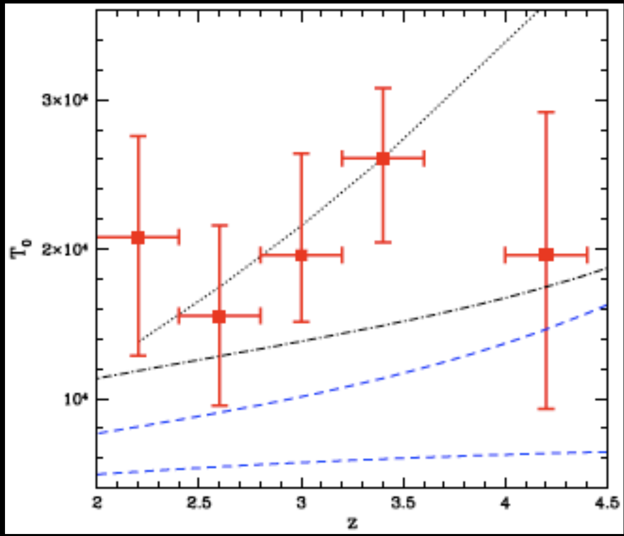
CAFG et al. (2009)

HeII Reionization

- Until now, neglected HeII reionization
- For an escape fraction of HeII ionizing photons ~1, the quasar luminosity function predicts that HeII is reionized by z~3
- Several, though not yet conclusive, observational lines of evidence:
  - ➡ HeII Lyα forest
  - ➡ HI Lyα forest temperature
  - ➡ metal line ratios?
  - ➡ HI Lyα forest mean transmission?



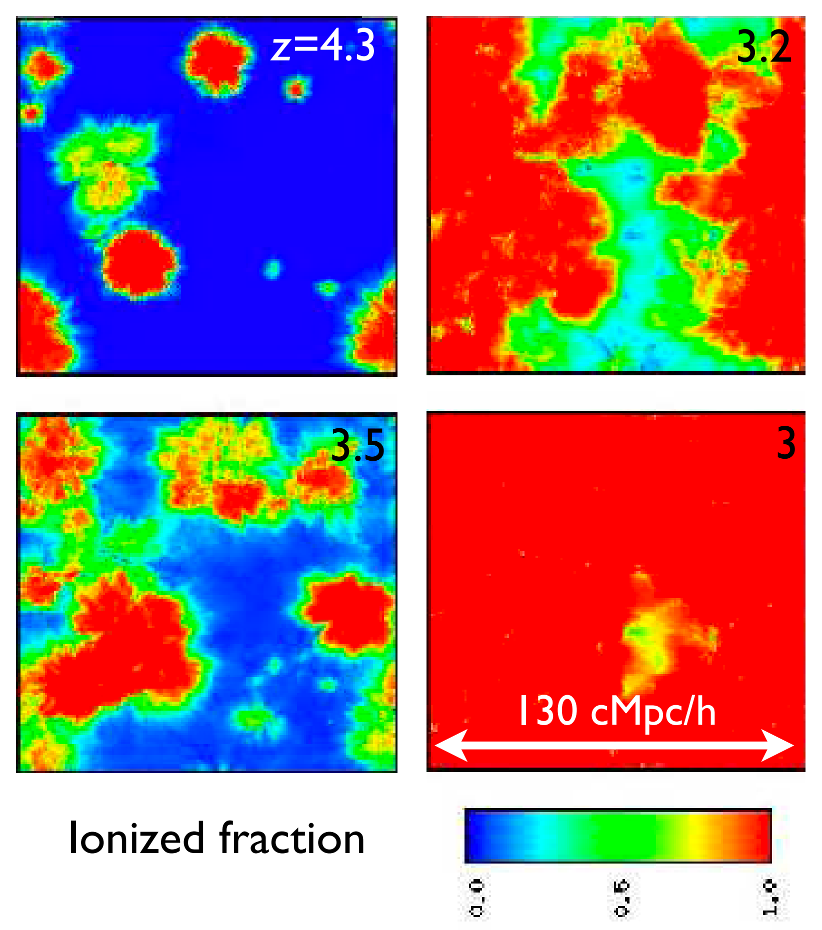
CAFG et al. (2008c)



Lidz, CAFG, et al., submitted

HeII Reionization: Picture and Scales

HeII Reionization Simulation



McQuinn et al. (2009, w/ CAFG)

- Before and during HeII reionization: extremely opaque large patches of HeII
- Quasars are rare:
  - ➡ mean quasar separation
  - ➡ HeIII bubble radii
  - ➡ HeII ionizing mean free path

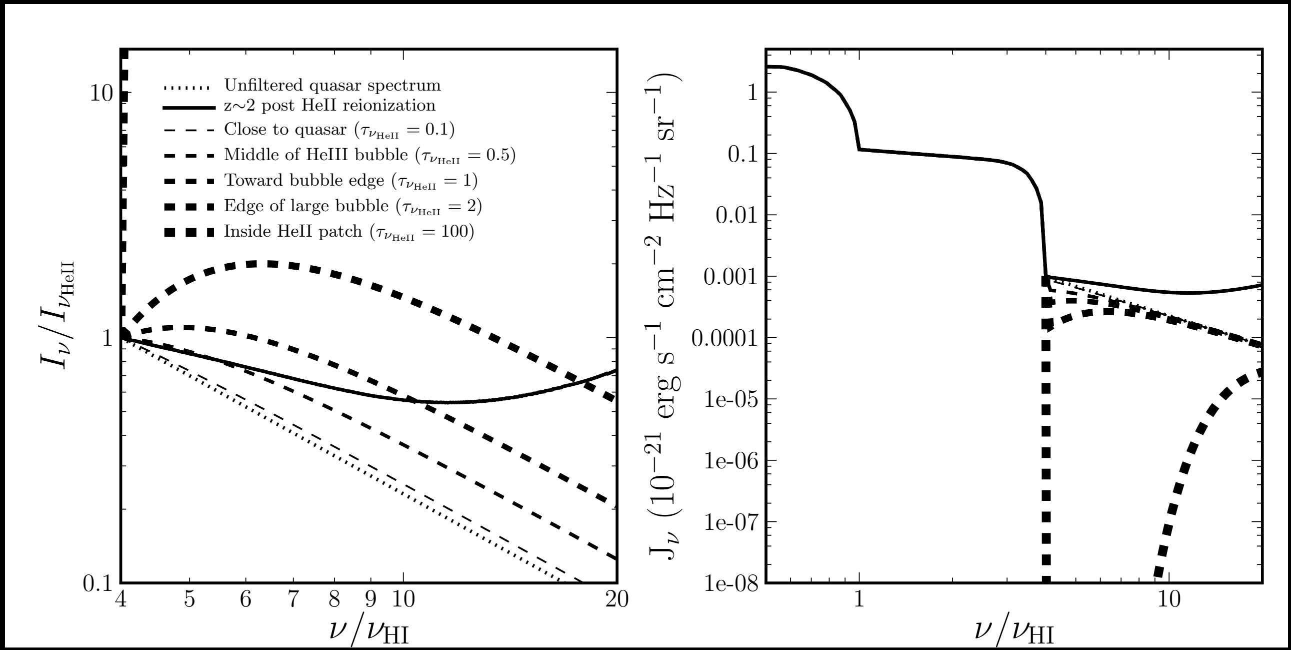
  are of comparable size, 10-100 cMpc
- HeII ionizing background inhomogeneous, with large fluctuations

HeII Reionization: Spectral Effects

- Spectrum is hardened by residual HeII beyond 4 Ryd as it propagates away from the source quasar
- Almost completely suppressed just above HeII photoionization edge outside ionized regions (see also Madau & Haardt 2009 sawtooth):

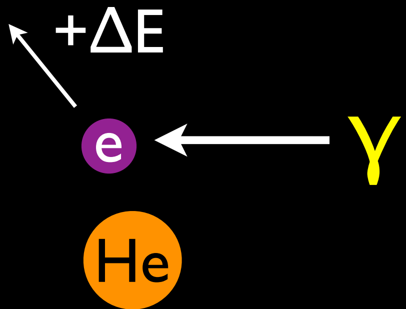
$$\tau_{\nu_{\rm HeII}}^{\rm neutral} = 318 \left(\frac{1+z}{4.5}\right)^4 \left(\frac{L}{10 \text{ comoving Mpc}}\right)$$

- Recovers as $\nu \to \infty$ and $\sigma_{\rm HeII}(\nu) \to 0$, resulting in a high-energy background



CAFG et al. (2009)

HeII Reionization: Thermal Effects



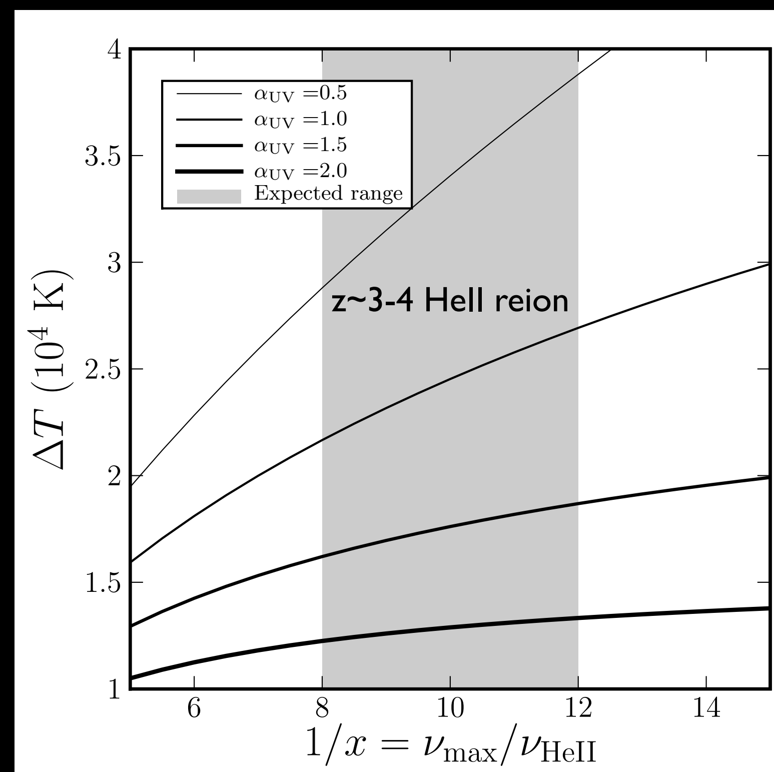
- Ionizations inject residual photon energy as heat into IGM

- Temperature increase = mean energy per ionization distributed over all particles:

$$\Delta T_{\rm HeII} = \frac{2}{3k}\frac{n_{\rm He}}{n_{\rm tot}}\langle E_i \rangle$$

- Mean energy per ionization is determined by the quasar spectral index and maximum absorbed frequency:

$$\langle E_i \rangle = \frac{\int_{\nu_{\rm HeII}}^{\nu_{\max}} d\nu/(h\nu)(h\nu - h\nu_{\rm HeII})\nu^{-\alpha_{\rm UV}}}{\int_{\nu_{\rm HeII}}^{\nu_{\max}} d\nu/(h\nu)\nu^{-\alpha_{\rm UV}}}$$



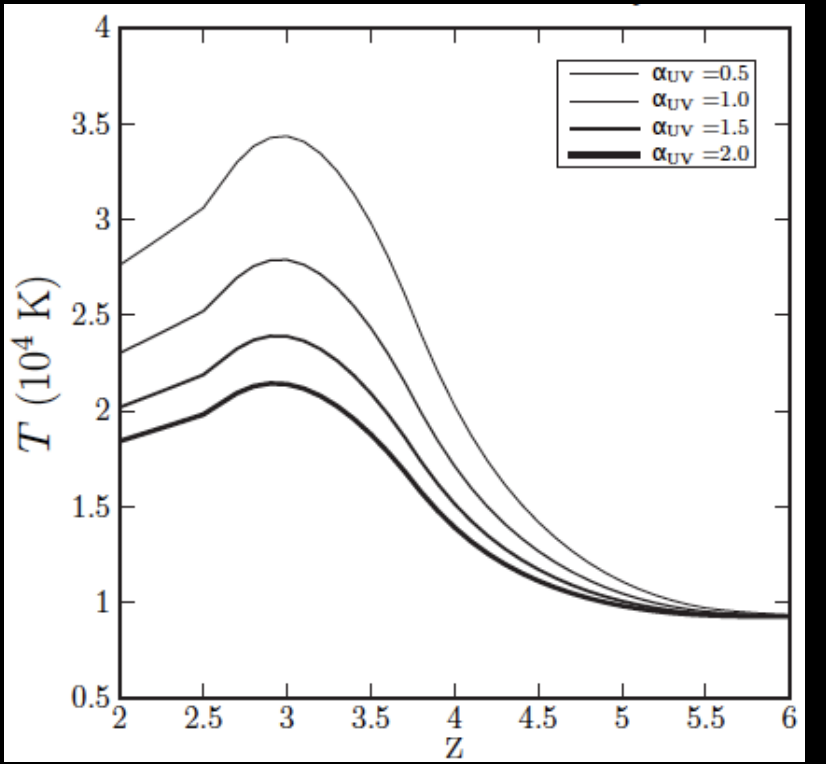
CAFG et al. (2009)

HeII Reionization: Thermal Effects

- Can formalize and include time-dependence:
  - ➡ use the quasar luminosity function to calculate the HeII ionization history, $y_{III}(z)$=ionized fraction(z)
  - ➡ photoheating and adiabatic cooling dominate at z≲6

$$\Delta T_{\rm HeII}(z) = \frac{2}{3k}\frac{n_{\rm He}}{n_{\rm tot}} y_{\rm III}(z)\langle E_i\rangle(z)$$

$$\Delta T(z) = \int_\infty^z dz' \frac{d\Delta T_{\rm HeII}(z')}{dz'}\left(\frac{1+z}{1+z'}\right)^2$$

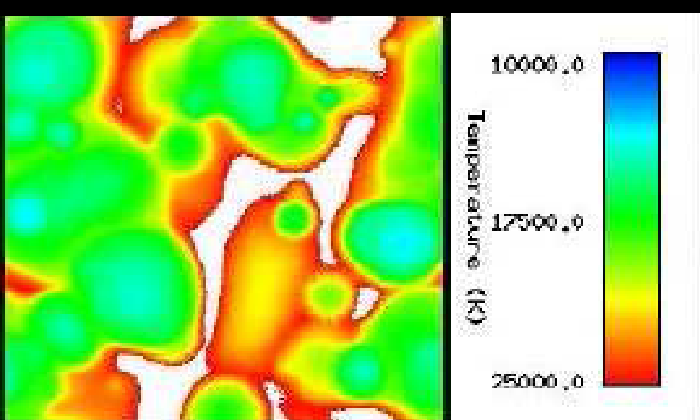


CAFG et al. (2009)

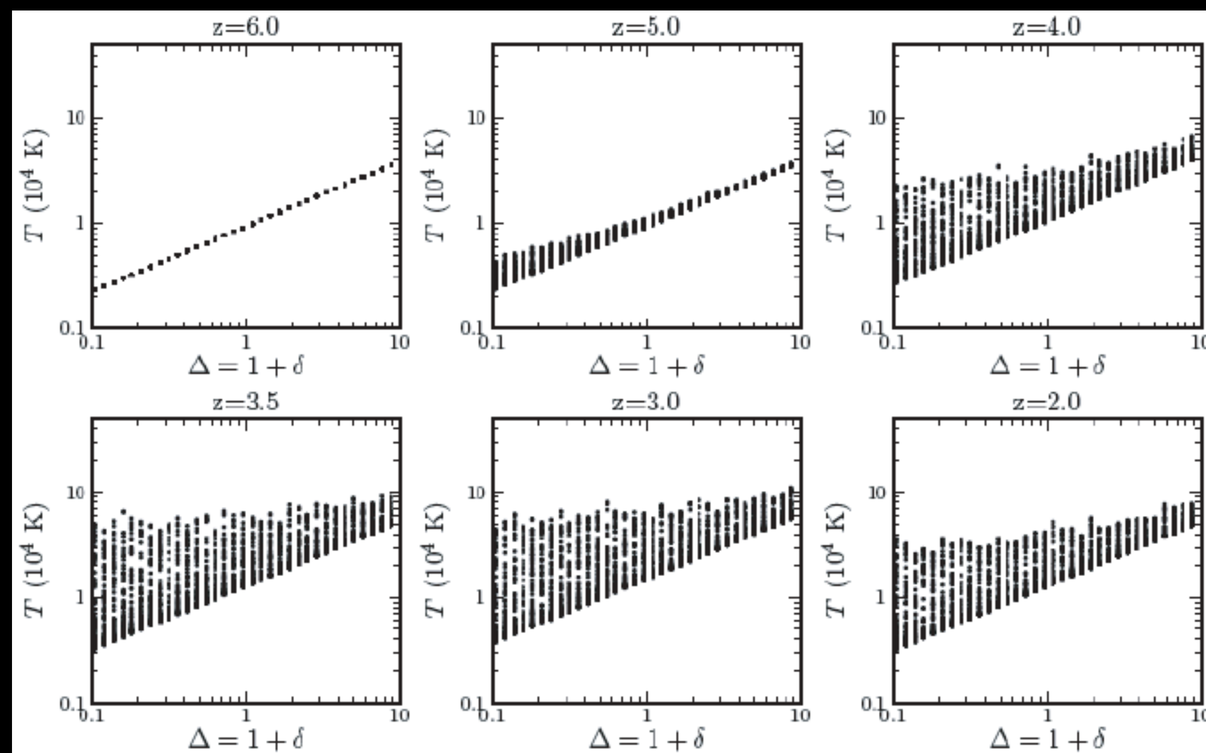
HeII Reionization: *T*-Δ Relation

- In reality, homogeneities lead to a temperature-density relation
- In the limit of early HI reionization, $T(\Delta) \approx T_0 \Delta^{0.6}$ (Hui & Gnedin 1997)
- HeII reionization modifies the relation:
  - ➡ injects heat at all Δ → flattens the relation, but not to isothermal
  - ➡ introduces a large scatter from different reionization times

Analytic model based on QLF and heating ~ exposure to high-energy background →



McQuinn et al. (2009, w/ CAFG)



CAFG et al. (2009)

Summary

- The cosmic ionizing background is fundamental to IGM and galaxy formation studies
- We have constrained its evolution and sources, and calculated its spectrum versus redshift:
  - ➡ quasars and stars contribute about equally to the HI ionization rate at $z=3$, with stars dominating at $z\gtrsim3$
  - ➡ quasars are the dominant contributors to the HeII ionization rate
- HeII reionization induces fluctuations at >54.4 eV, heats the IGM, and modifies the temperature-density relation
- Ionizing Background Resources:

http://www.cfa.harvard.edu/~cgiguere/uvbkg.html

with data in electronic form, including GADGET TREECOOL file