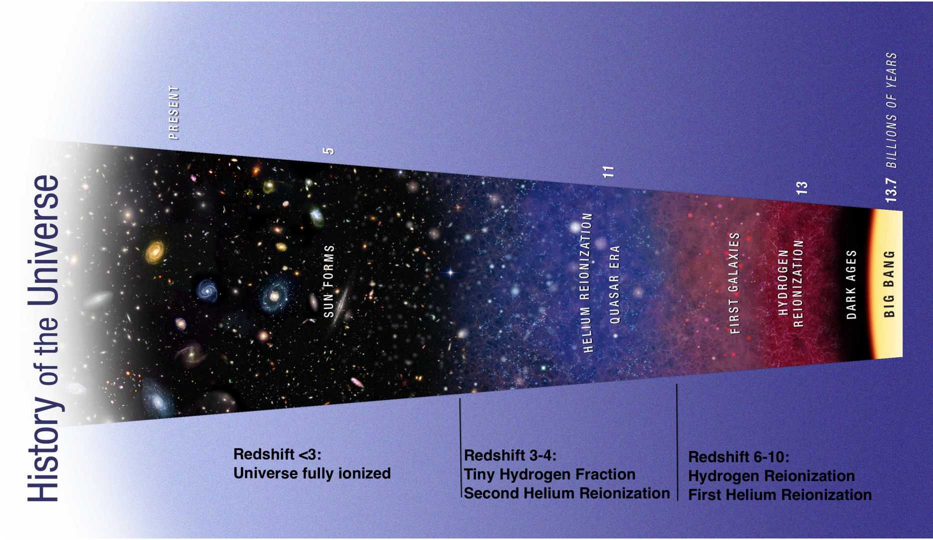
Probing the Two Epochs of Reionization in Absorption: Status and Issues

Gábor Worseck

Intergalactic Interconnections

Marseille, July 9–13, 2018

Reionization Events – Two Baryonic Phase Transitions

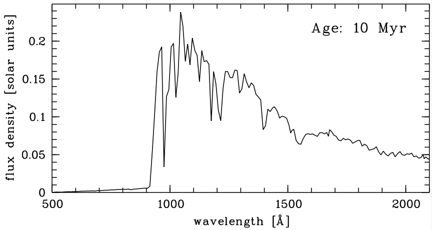


Credits: NASA, ESA, and A. Feild (STScI)

Sources of the UV Background

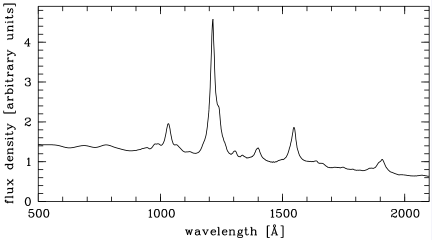
Star-forming galaxies

- High space density
- Small (?) escape fraction
- Soft UV radiation



Quasars

- Low space density
- Unity (?) escape fraction
- Hard UV radiation



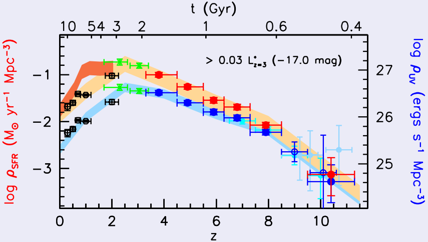
Emissivity of Quasars and Star-Forming Galaxies

Star-forming galaxies

- Lyman limit emissivity

$$\epsilon_{\nu,912} = {\color{red}f_{\rm esc}} f_{\nu,912}/f_{\nu,\rm UV} \times \epsilon_{\nu,\rm UV}\left(> L_{\rm UV,min}, z\right)$$

- $\epsilon_\nu(\nu) = \epsilon_{\nu,912} \times {\color{red}?}$



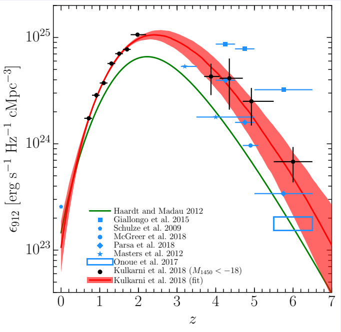
Bouwens et al. (2015)

Quasars

- Lyman limit emissivity

$$\epsilon_{\nu,912} = f_{\nu,912}/f_{\nu,\rm UV} \times \epsilon_{\nu,\rm UV}\left(> L_{\rm UV,min}, z\right)$$

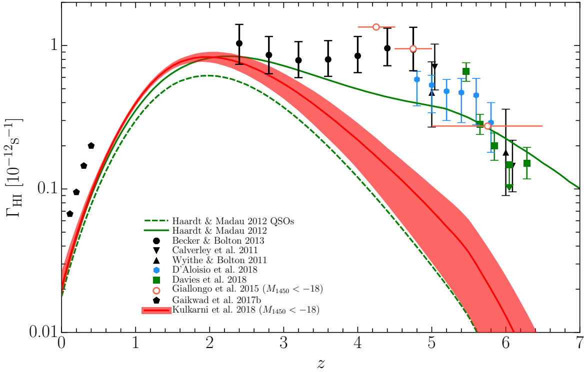
- $\epsilon_\nu(\nu) = \epsilon_{\nu,912}\left(\nu/\nu_{912}\right)^\alpha$



Kulkarni, Worseck & Hennawi (2018)

- Method 1: Adjust H I photoionization rate in optically thin numerical simulation until Lyα effective optical depth matches observations
- Method 2: Quasar proximity effect
- Comparison to UV background synthesis models based on source population and IGM absorber model

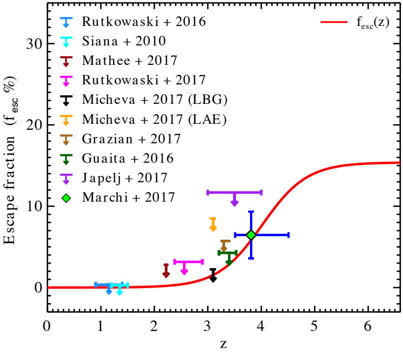
$\longrightarrow$ Quasars+galaxies needed to explain $\Gamma_{\mathrm{HI}} \simeq$ const at $z = 3$–5

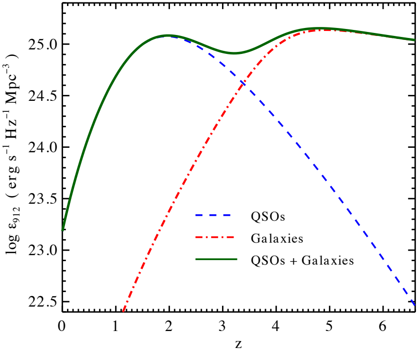


Kulkarni, Worseck & Hennawi (2018)

The High-Redshift Photon Underproduction Crisis

- Strong redshift evolution of Lyman continuum escape fraction required to explain inferred H I UV background at $z > 3$!
- $z \sim 3$: $f_{\rm esc} \lesssim$ few % (but see Steidel et al. 2018)
- Source population for H I reionization not well constrained





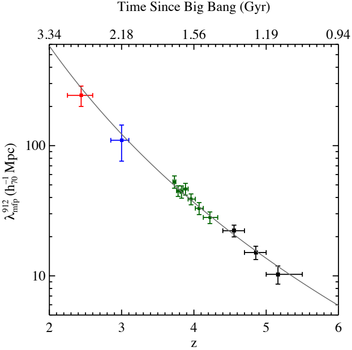
Khaire & Srianand (2018)

The H I Reionization History

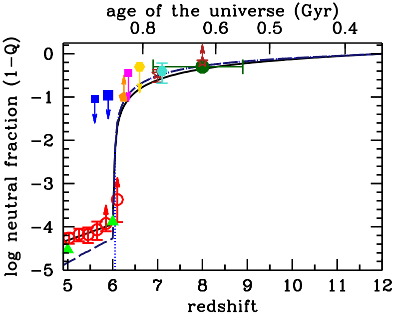
- Rest-frame stacks of QSO spectra $\longrightarrow \lambda_{\rm mfp}(z) = 37\left(\frac{1+z}{5}\right)^{-5.4}$ pMpc
- Madau 2017: Modified reionization eq. to account for residual H I

$$\frac{dQ_{\rm HII}}{dt} = \frac{\langle \dot{n}_{\rm ion}\rangle}{\langle n_{\rm H}\rangle}\left(\frac{1}{1+\frac{1}{\lambda_{\rm mfp}\langle n_{\rm H}\rangle(1-Q_{\rm HII})\sigma_{\rm HI}}}\right) - \frac{Q_{\rm HII}}{\langle t_{\rm rec}\rangle}$$

- Madau 2017: $\langle \dot{n}_{\rm ion}\rangle/\langle n_{\rm H}\rangle = 2.9$/Gyr fits observational constraints (Lyα forest, IGM damping wings, Planck, Lyα emitter fraction)

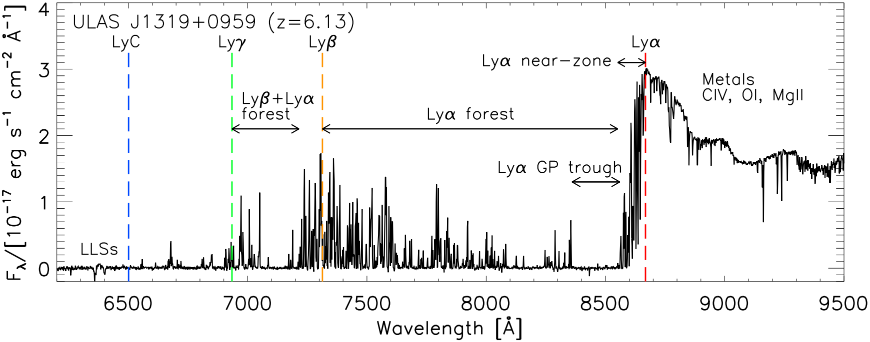


Worseck et al. (2014)



Madau (2017)

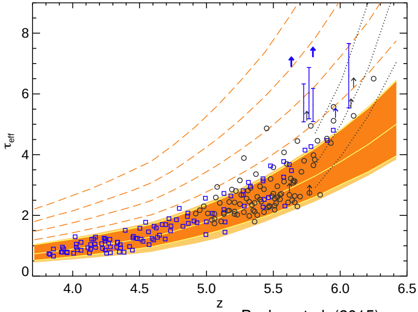
Quasar Sightlines Probe the Reionization Epochs



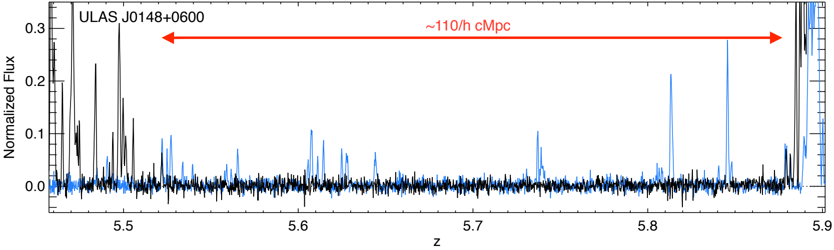
Becker, Bolton & Lidz (2015)

Scatter in H I Lyα Effective Optical Depth

- H I Lyα scattering optical depth
  $\tau(z) \simeq 3.85 \times 10^5 \langle x_{\rm HI} \rangle \left(\frac{1+z}{7}\right)^{3/2}$
- $z \sim 6$: $\tau_{\rm eff} = -\ln\left\langle e^{-\tau}\right\rangle \gtrsim 6$
  $\longrightarrow x_{\rm HI} = n_{\rm HI}/n_{\rm H} \gtrsim 10^{-4}$
- $\tau_{\rm eff}$ scatter larger than expected from density field ($r = 50/h\,$cMpc)
  $\longrightarrow \langle x_{\rm HI} \rangle$ variations (factor $\gtrsim 3$)
  $\longrightarrow$ UV background fluctuations



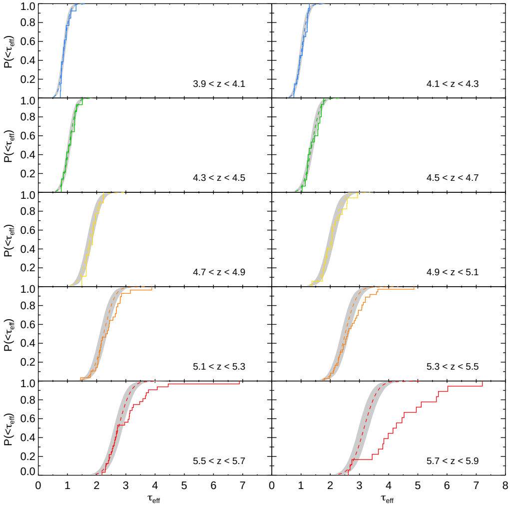
Becker et al. (2015)



Becker et al. (2015)

Statistical Description

- Cumulative distribution of τ_{eff} among sightlines
- Statistical comparison to simulations
  $\longrightarrow$ Constrain models
- Realistic mock data from simulations required

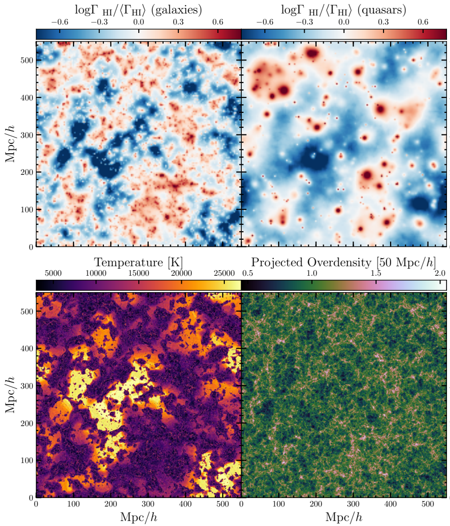


Becker et al. (2015)

Potential Explanations for the Large $\tau_{\rm eff}$ Scatter

1. Temperature fluctuations after patchy reionization
   (D'Aloisio et al. 2015)
2. UV background fluctuations due to spatially varying $\lambda_{\rm mfp}$
   (Davies & Furlanetto 2016,
   D'Aloisio et al. 2018)
3. UV background fluctuations due to rare UV sources / QSOs
   (Chardin et al. 2015, 2017)

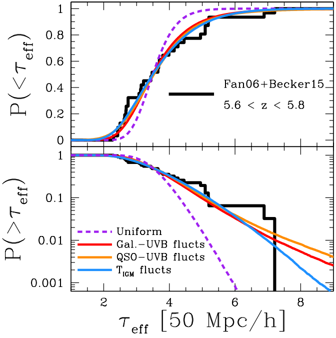
- Predictions for GP troughs:
  - T fluct.: Cooling overdensities
  - $\Gamma_{\rm HI}$ fluct.: Voids with $\lambda_{\rm mfp} \to 0$
  - QSOs: Range of densities

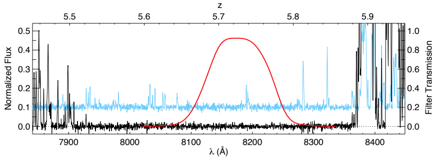


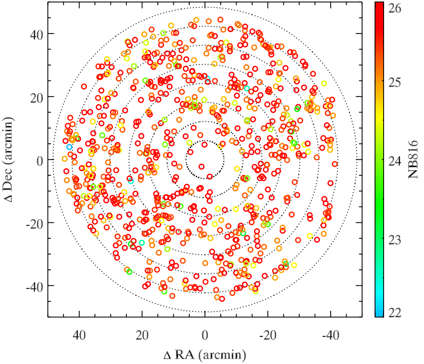
Davies et al. (2018), Becker et al. (2018)

Evidence for UV Background Fluctuations: Underdensity of Lyα Emitters near GP Trough

- Survey for Lyα emitters near $z \simeq 5.7$ GP trough
- Underdensity of Lyα emitters at $R < 20/h\,$cMpc ($P_{\rm random} = 3 \times 10^{-5}$)



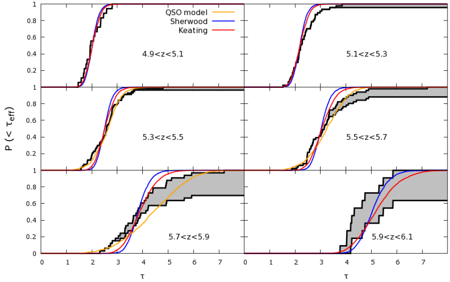




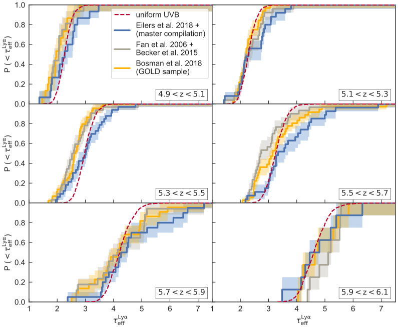
Davies et al. (2018), Becker et al. (2018)

More Data – More Puzzles

- Bosman et al. (2018): τ_{eff} measurements in 62 $z_{\text{em}} > 5.7$ QSOs
- Treatment of non-detections: 2σ upper limit of transmission <u>or</u> $\tau_{\text{eff}} \to \infty$ for all non-detections
- Comparison to forward-modeled simulations
  $\longrightarrow$ No considered model matches data at $z > 5.2$
- Eilers et al.: Different results on largely the same data



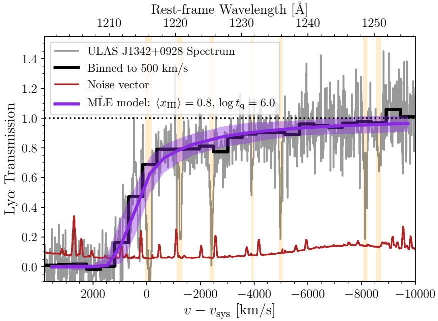
Bosman et al. (2018)



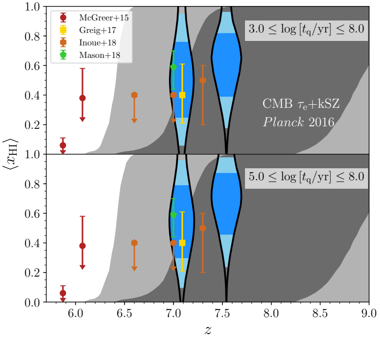
Eilers et al. (2018)

IGM Damping Wing: Significant H I Fraction at $z \gtrsim 7$

- Significantly neutral IGM $\longrightarrow$ IGM damping wing in QSO spectra
- Davies et al. 2018: Seminumerical sim. of reion. topology + 1D radiative transfer through high-res. sim.
  $\longrightarrow$ Model IGM damping wing including biased QSO halos, proximity effect and QSO lifetime
  + Modeling of uncertain QSO continuum
  $\longrightarrow$ Joint constraints on x_{HI} and QSO lifetime

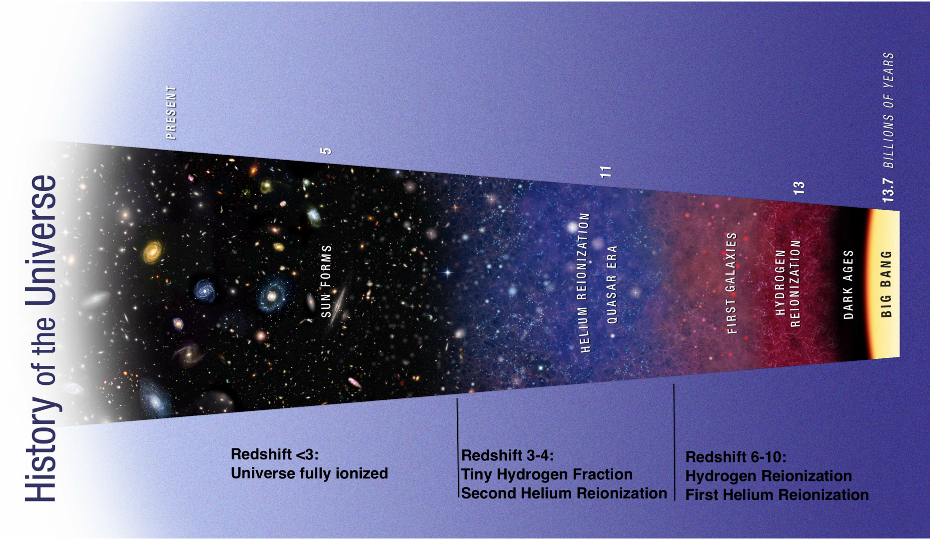


Davies et al. (2018)



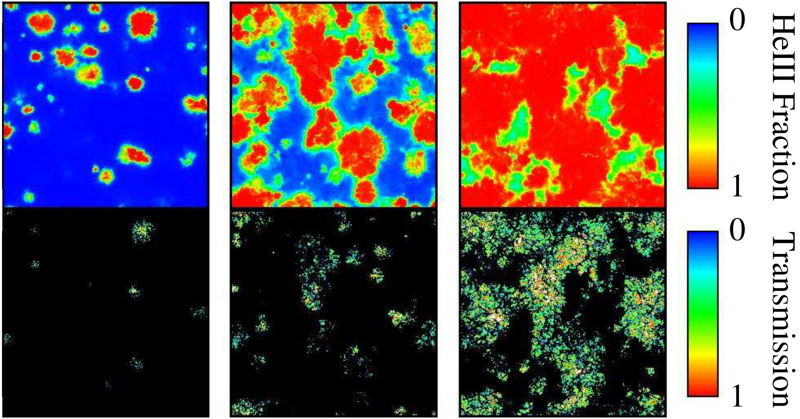
Davies et al. (2018)

Cosmic Reionization Ends at $z \sim 3$!



Credits: NASA, ESA, and A. Feild (STScI)

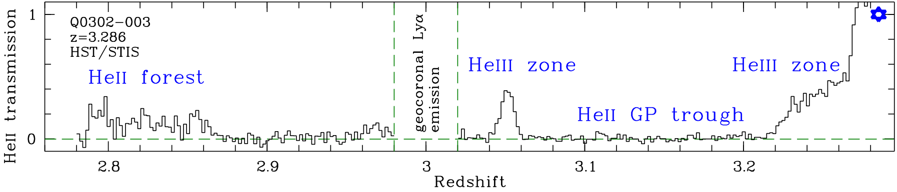
- Semi-analytic models and radiative transfer simulations
- Prediction: Inhomogeneous and extended He II reionization ($\sim$ 1Gyr, $3 \lesssim z \lesssim 4$)



McQuinn et al. (2009)

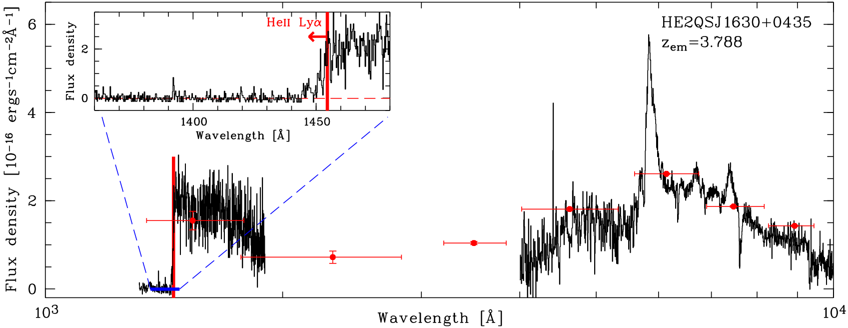
Handful of Historic He II Sightlines: $z_{\mathrm{reion}} \sim 3$

- Direct tracer of He II reionization: He II Lyα ($\lambda_{\mathrm{rest}} = 303.78$ Å) analogous to H I Lyα at $z \sim 6$
- Before GALEX: Blind surveys for UV-bright quasars
- Until 2009: 5 sightlines (HST/STIS, FUSE)
- Main features:
  - Gunn-Peterson trough at $z > 3$
  - Patchy He II absorption at $2.7 < z < 3$
  - He II Lyα forest at $z < 2.7$
- He III zones around quasars



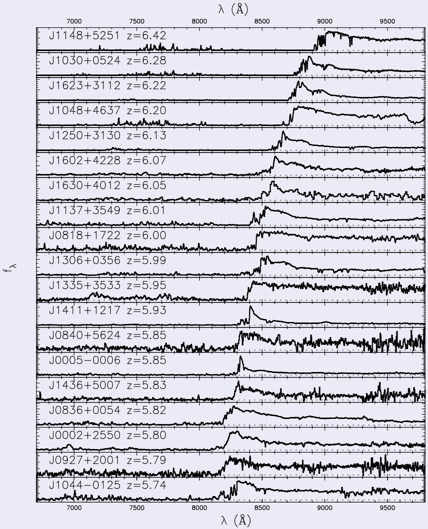
The GALEX + HST/COS Revolution

- GALEX: Pre-selection of UV-transparent quasar sightlines
- Dedicated survey for UV-bright quasars (2–3 m tel.)
- HST/COS follow-up spectroscopy
- 22 new science-grade He II sightlines ⟶ First statistical sample
- Helium Reionization Survey (HERS):
  Homogeneous reduction and analysis (Worseck et al. 2016, 2018)



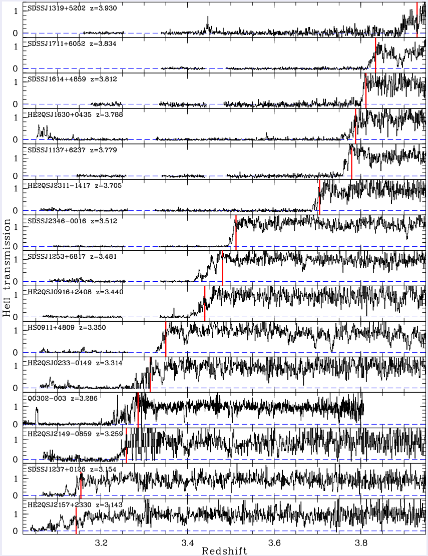
Fluctuating Lyα Absorption

Optical: H I at $z \sim 6$



Fan et al. (2006)

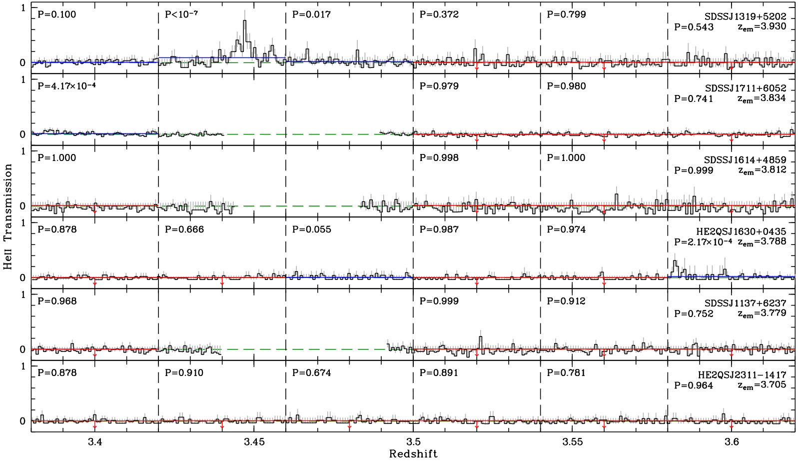
Far UV: He II at $z \sim 3.5$



Worseck et al. (2011, 2016, 2018)

He II Transmission Spikes at $z \sim 3.5$

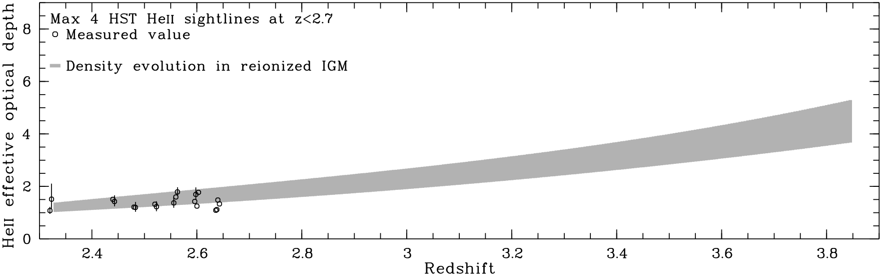
- Unexpected based on handful of pre-COS He II spectra
- Disagreement with quasar-driven He II reionization models predicting ubiquitous Gunn-Peterson troughs at $z > 3$



Worseck et al. (2018)

Very Extended He II Reionization Ends at $z_{\mathrm{reion}} \simeq 2.7$

- Measurements: He II effective optical depth on $\sim$ 40 cMpc
- $z \lesssim 2.7$: Agreement with numerical simulation of photoionized IGM



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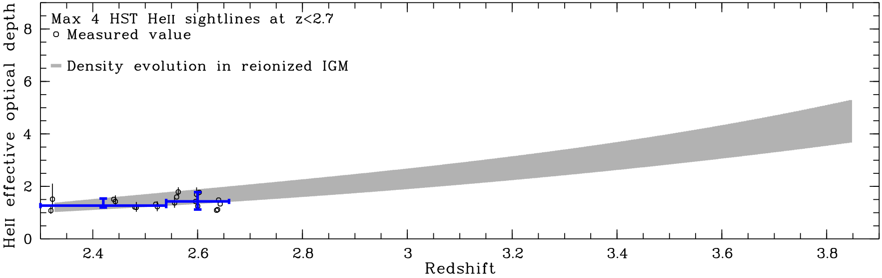

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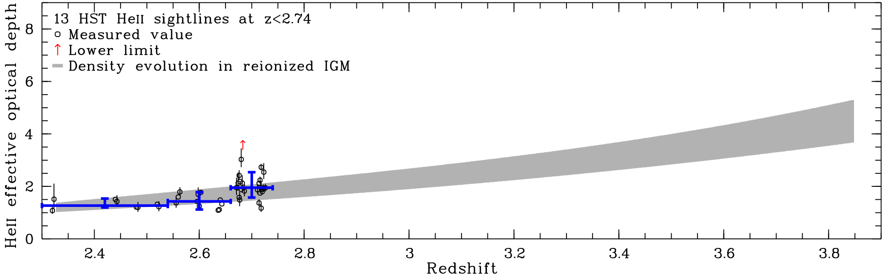

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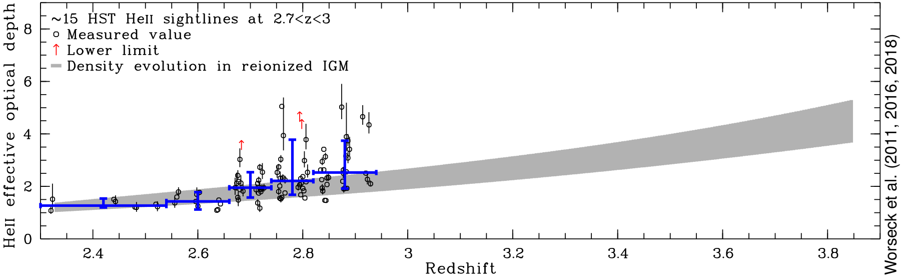
- $2.7 \lesssim z \lesssim 3$: Gradual increase & scatter



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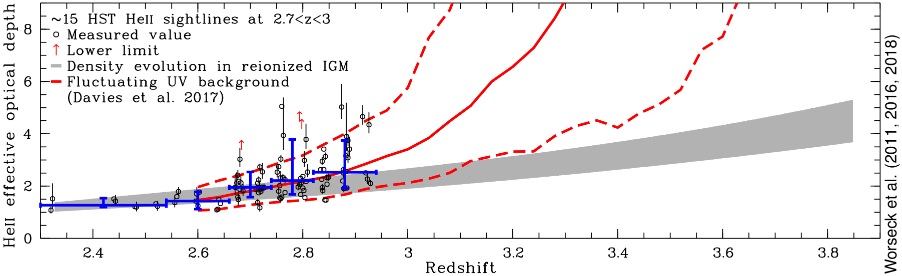
  $\longrightarrow$ fluctuating UV background, $z_{\text{reion}} \simeq 2.7$



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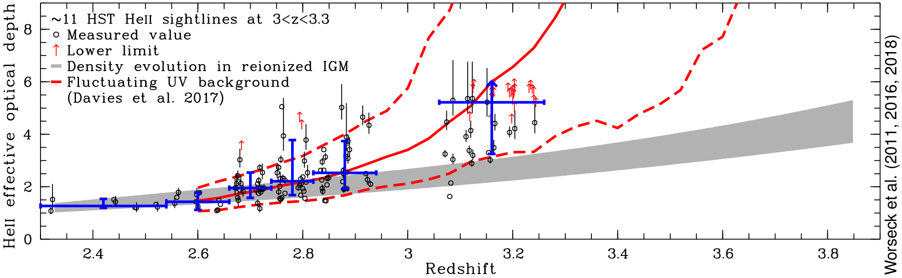
- $z \sim 3.2$: Low effective optical depths, gradual He II reionization



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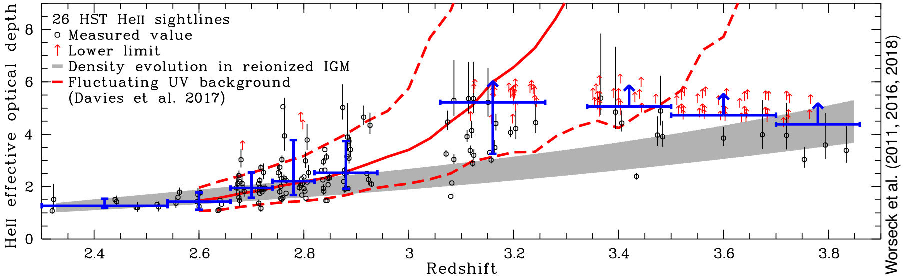
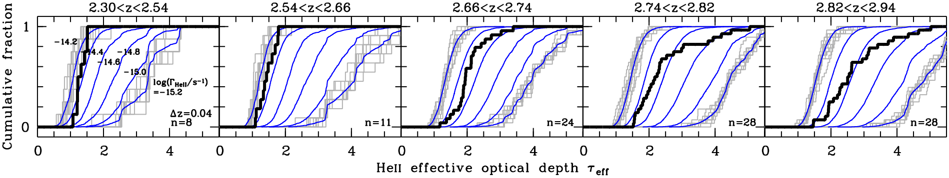
- $2.7 \lesssim z \lesssim 3$: Gradual increase & scatter
  $\longrightarrow$ fluctuating UV background, $z_{\rm reion} \simeq 2.7$
- $z \sim 3.2$: Low effective optical depths, gradual He II reionization
- $z \sim 3.6$: One third of the IGM consistent with $\sim$ 1% He II fraction
  $\longrightarrow$ He II reionization well underway at $z \sim 4$



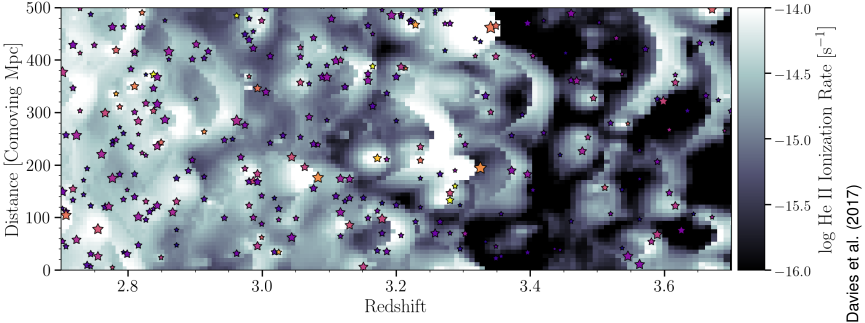
The He II-Ionizing Background Fluctuates at $z > 2.74$

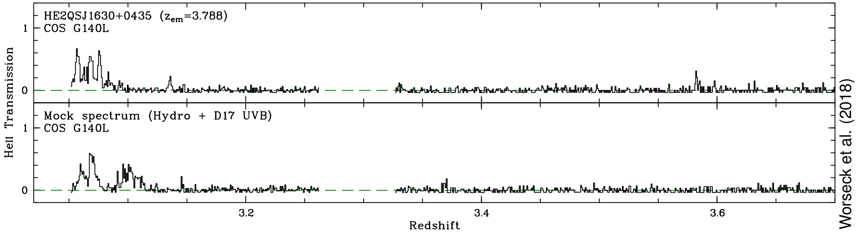
- Forward-model He II spectra for grid in $\Gamma_{\rm HeII} = $ const.
  - $100/h$ Mpc 4096^3 Eulerian hydrodyn. sim. (Nyx; Lukić et al. 2015)
  - Realistic mock He II spectra, redshift subsamples
- $z > 2.74$: $\tau_{\rm eff}$ scatter exceeds expectations for $\Gamma_{\rm HeII} = $ const.
  $\longrightarrow$ He II-ionizing background fluctuates at $z > 2.74$
  $\longrightarrow$ Standard UV background spectra only applicable at $z < 2.7$



Worseck et al. (2018)

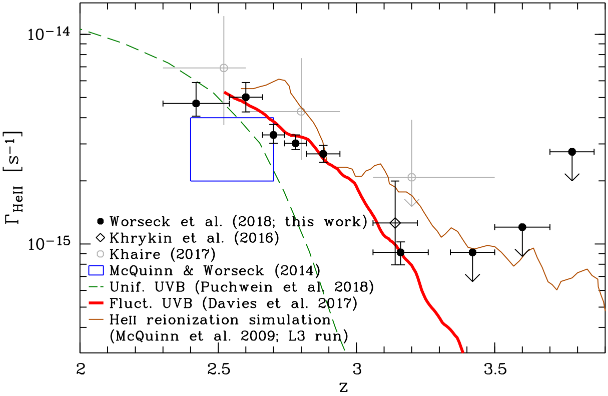
UV Background Fluctuations at the End of He II Reion.





The Evolution of the He II Photoionization Rate

- Match mock and observed median effective optical depth
  $\longrightarrow$Median Γ_{HeII} drops by factor 5 between $z = 2.6$ and $z = 3.1$



Worseck et al. (2018)

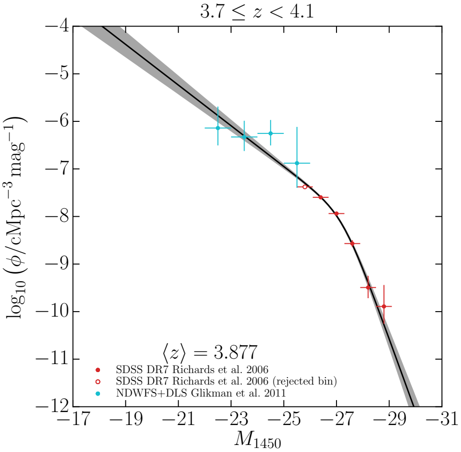
Implications for He II-Reionizing Source Population

- He II reionization in progress at $z \sim 4$ and ends at $z \simeq 2.7$
- Tension with reionization models with rapidly evolving quasar emissivity

- Exotic sources
  - X-ray binaries?
  - Thermal emission from shock-heated gas?

- Reassessment of $z < 7.5$ quasar luminosity function

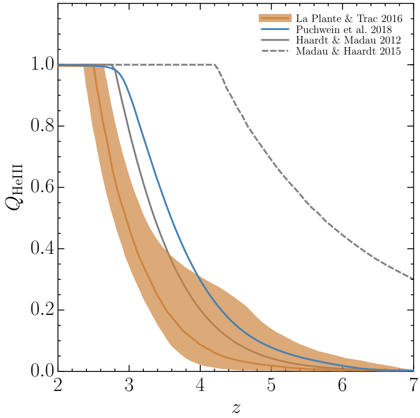
- Homogenized sample from credible quasar surveys (z_{spec}, selection function)



Kulkarni, Worseck & Hennawi (2018)

The He II Reionization History

- Reionization equation
  $$\frac{dQ_{\mathrm{HeIII}}}{dt} = \frac{\dot{n}_{\mathrm{ion}}}{\langle n_{\mathrm{He}} \rangle} - \frac{Q_{\mathrm{HeIII}}}{\langle t_{\mathrm{rec,He}} \rangle}$$
- Emission rate given by QSO luminosity function and SED



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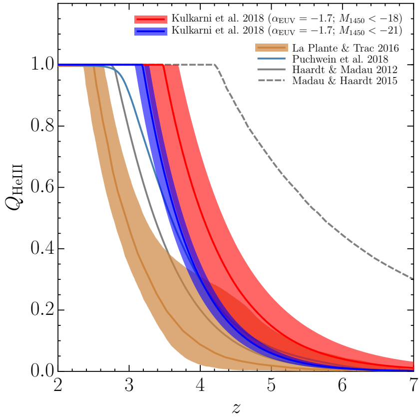
- Emission rate given by QSO luminosity function and SED
- Vanilla model:
  $z_{\mathrm{reion}} \simeq 3.5$ for $M_{1450} < -18$



Kulkarni, Worseck & Hennawi (2018)

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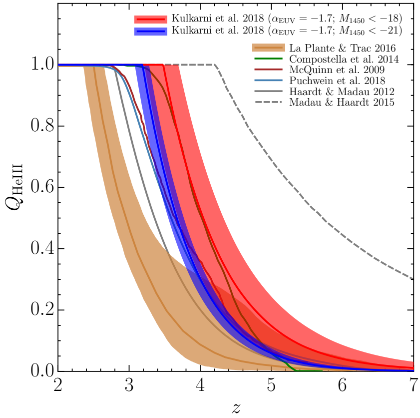
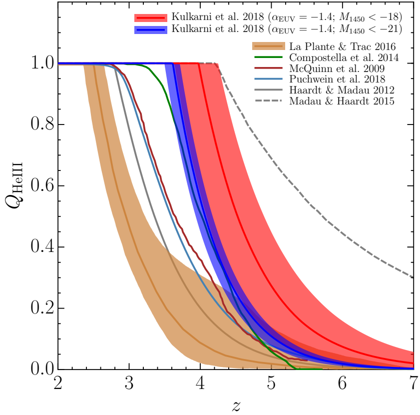
- Emission rate given by QSO luminosity function and SED
- Vanilla model:
  $z_{\mathrm{reion}} \simeq 3.5$ for $M_{1450} < -18$
- But: End of reionization delayed by Lyman limit systems
  (Bolton et al. 2009, Madau 2017)
- $Q \to 1$ overestimates z_{reion}



Kulkarni, Worseck & Hennawi (2018)

The He II Reionization History: Parameter Variations

- Harder SED
  ($\alpha_\nu = -1.4$, Stevans et al. 2014)
  $\longrightarrow z_{\text{reion}} \simeq 3.9$ for $M_{1450} < -18$
- Other parameter choices:
  - Fainter AGN ($M_{1450} > -18$)
  - Luminosity-dependent f_{esc}
  - Clumping factor evolution
- Radiative transfer simulations of He II reionization are needed



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- ✓ Comparison to simple models
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  $\longrightarrow$ Ongoing H I reionization at $z \simeq 7$

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