Do Quasars Dominate the UV Background at $z > 4$?

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&

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Illuminating the Dark Ages

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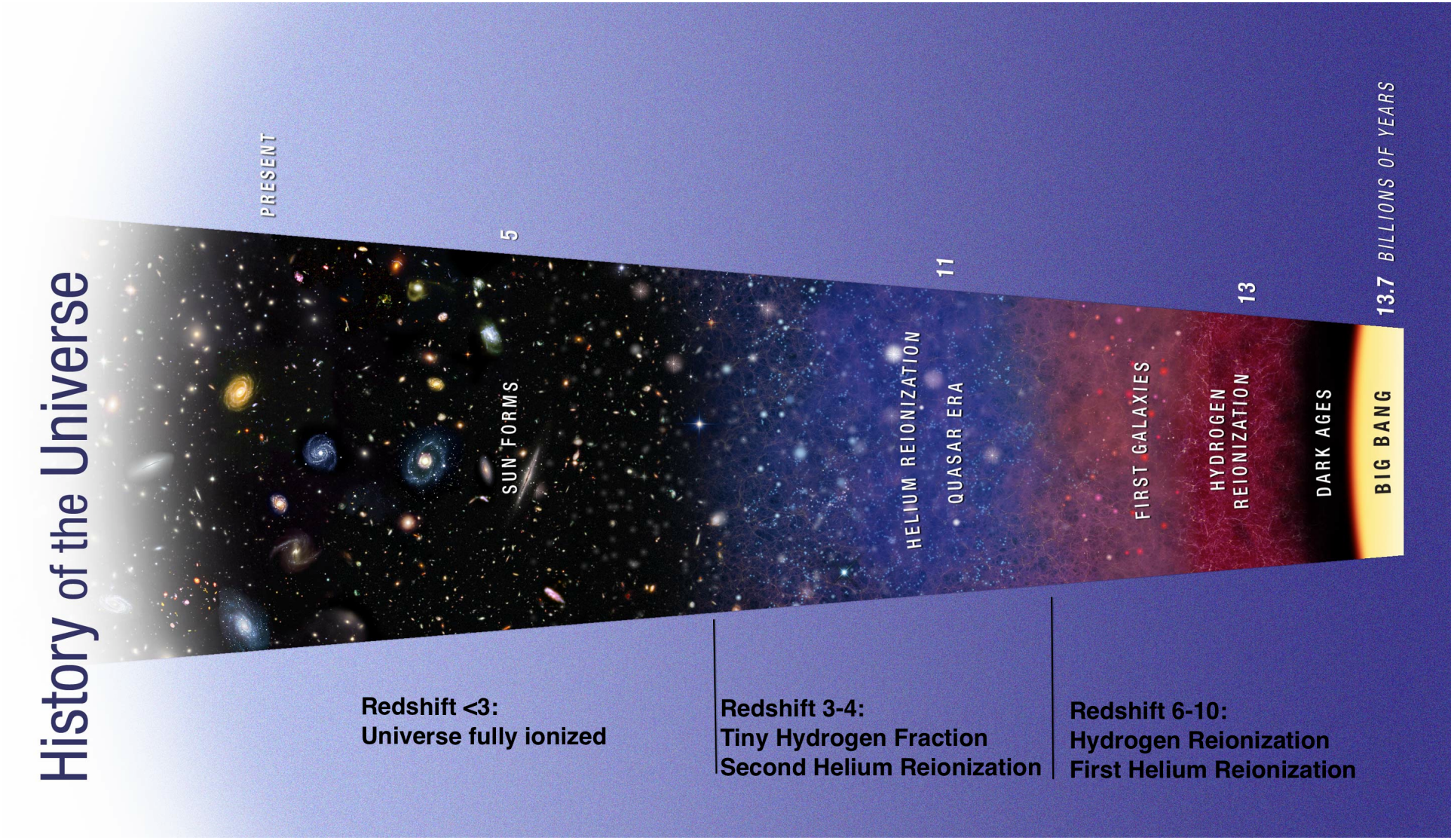
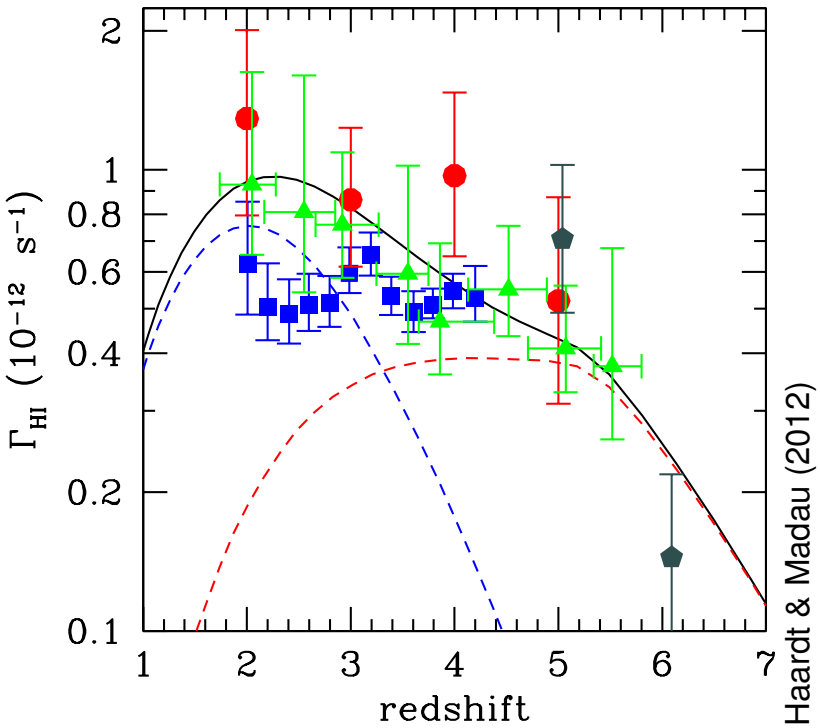
Reionization Events – Two Baryonic Phase Transitions

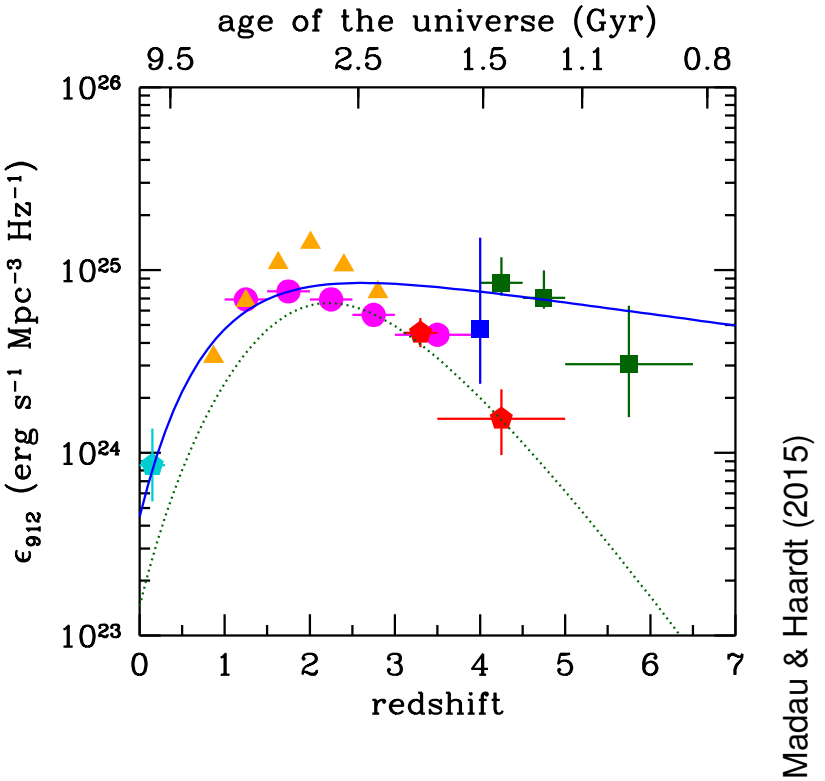


Credits: NASA

The QSO Contribution to the UV Background

- Goal: Relative contribution from QSOs and galaxies to UV background measured from the Lyα forest
- Photoionization rate: $\Gamma_{\rm HI}(z) = \int_{\nu_{912}}^{\infty} \frac{4\pi J_\nu(\nu,z)}{h\nu} \sigma_{\rm HI}(\nu) {\rm d}\nu$
- $z > 4$: MFP$\ll$Horizon$\longrightarrow$ local-source approximation
  $4\pi J_\nu(\nu, z) \simeq \lambda_{\rm mfp}(\nu, z)\,(1+z)^3\,\epsilon_\nu(\nu, z)$

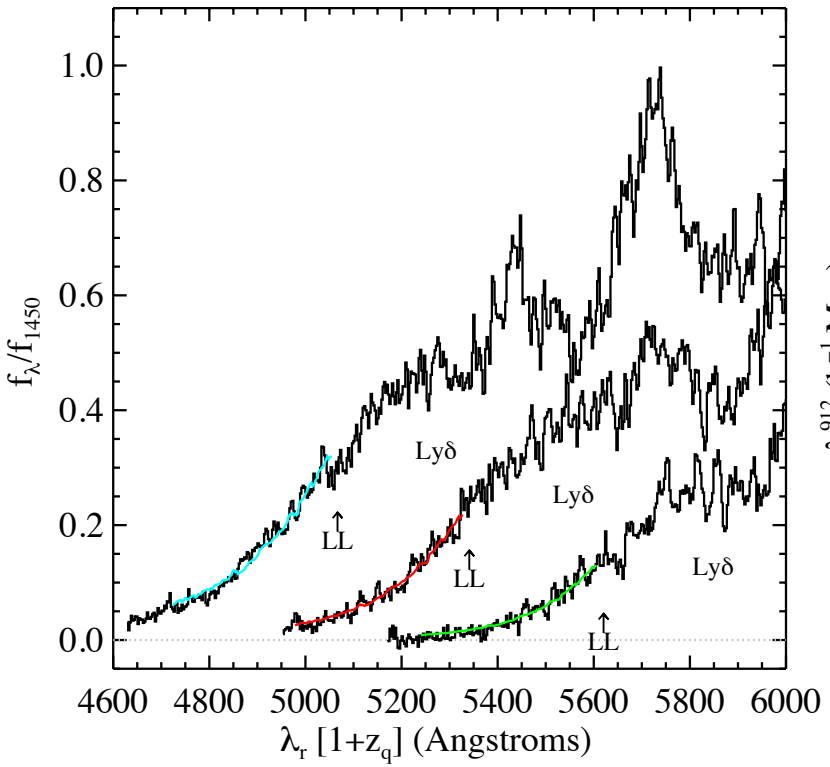


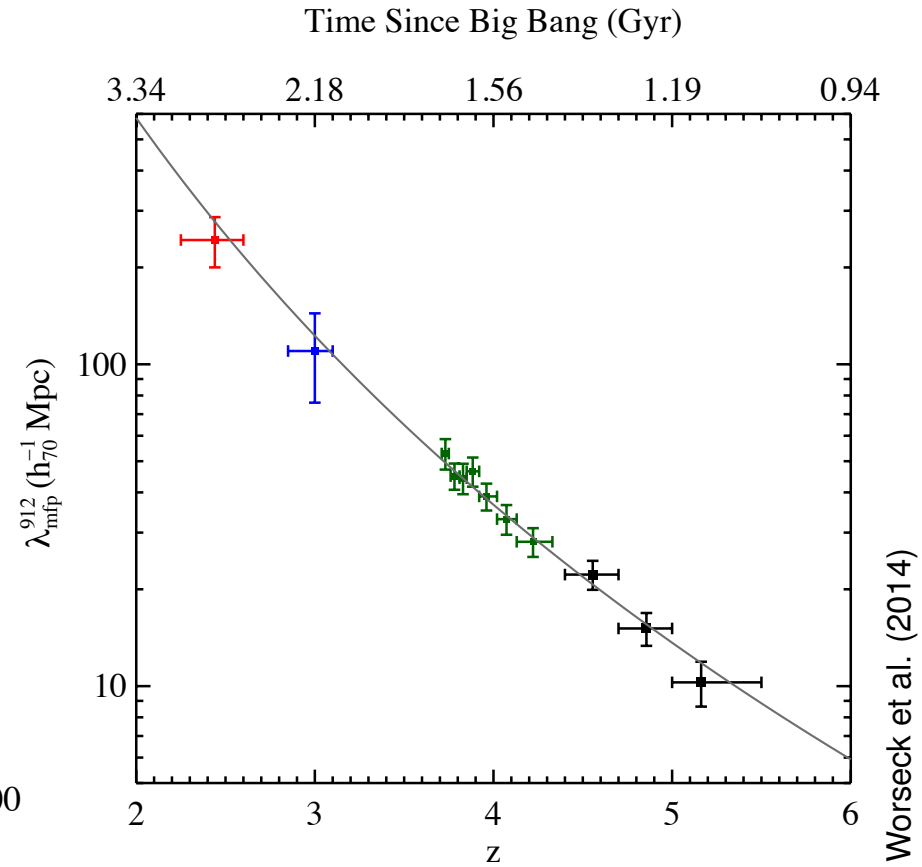


1. The Mean Free Path to Lyman Continuum Photons

- Rest-frame stacks of QSO spectra $\longrightarrow \lambda_{\rm mfp,912}(z)$

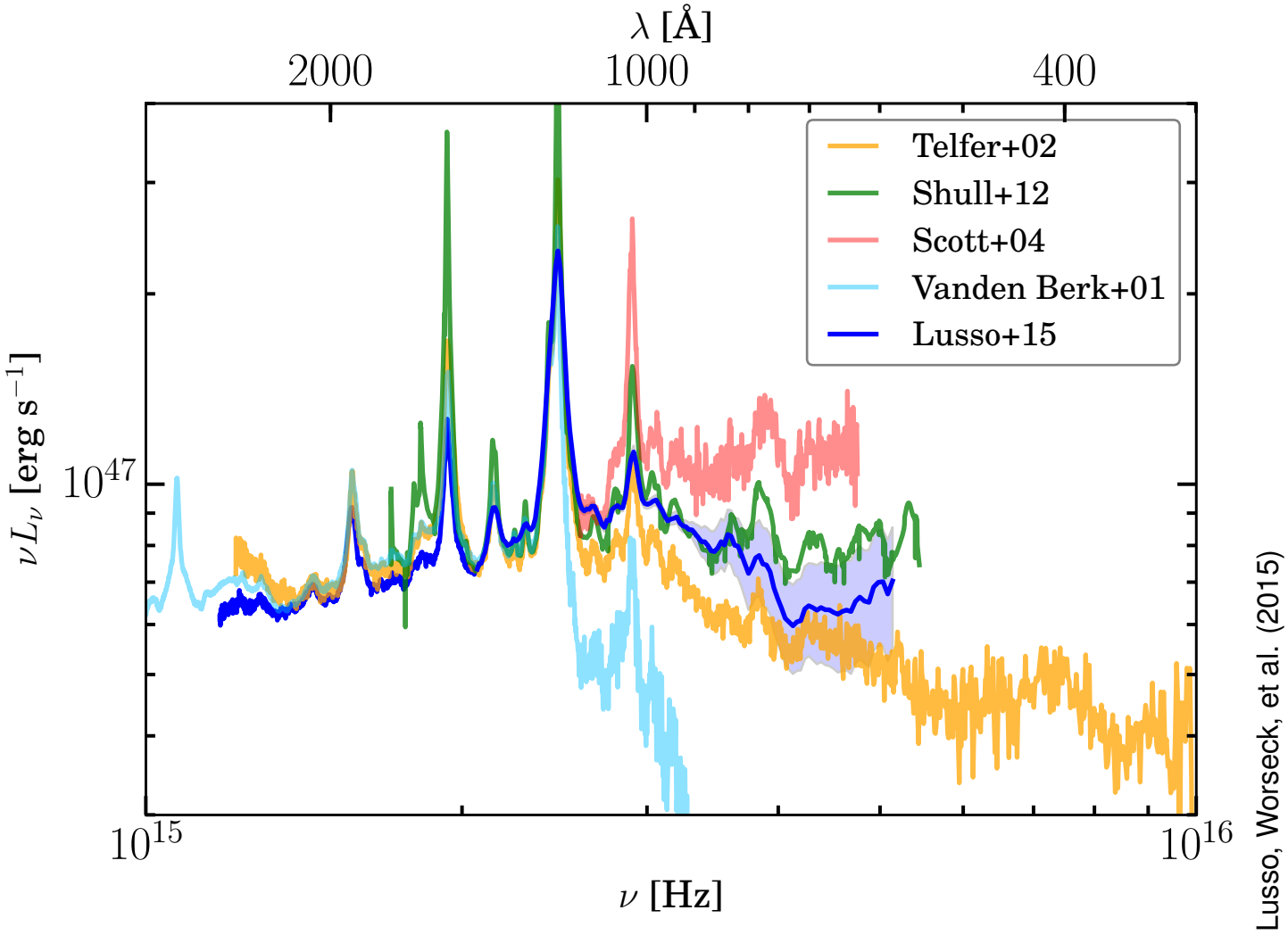
$$\lambda_{\rm mfp}(\nu, z) \approx \lambda_{\rm mfp,912}(z) \left(\frac{\nu}{\nu_{912}}\right)^{1.5} = 37 \left(\frac{1+z}{5}\right)^{-5.4} \left(\frac{\nu}{\nu_{912}}\right)^{1.5} \text{pMpc}$$





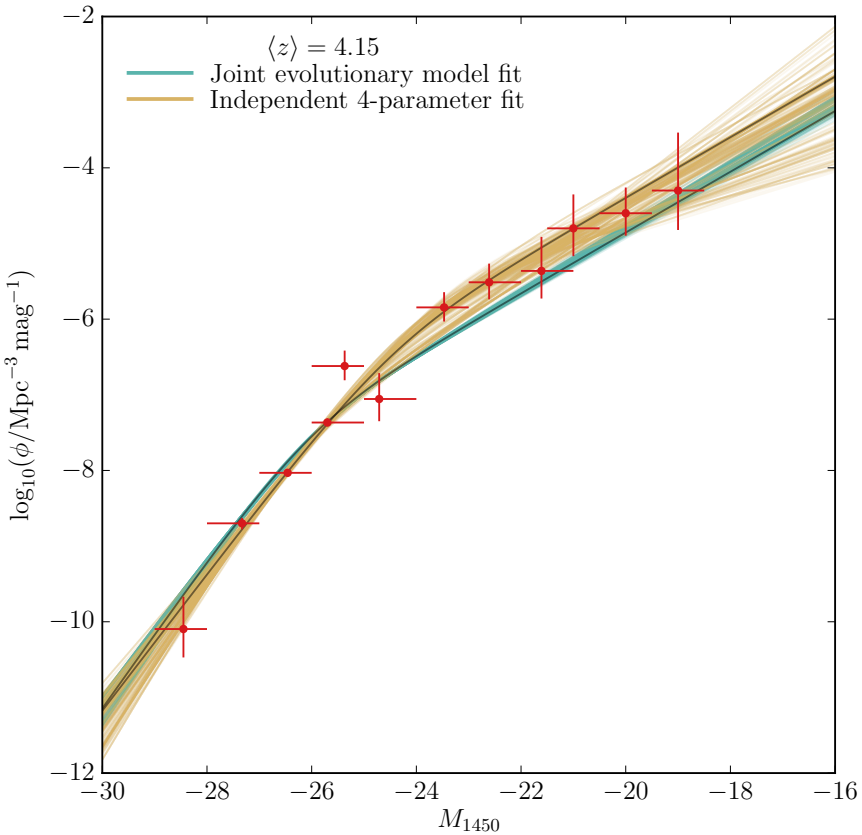
2. QSOs Have Hard SEDs

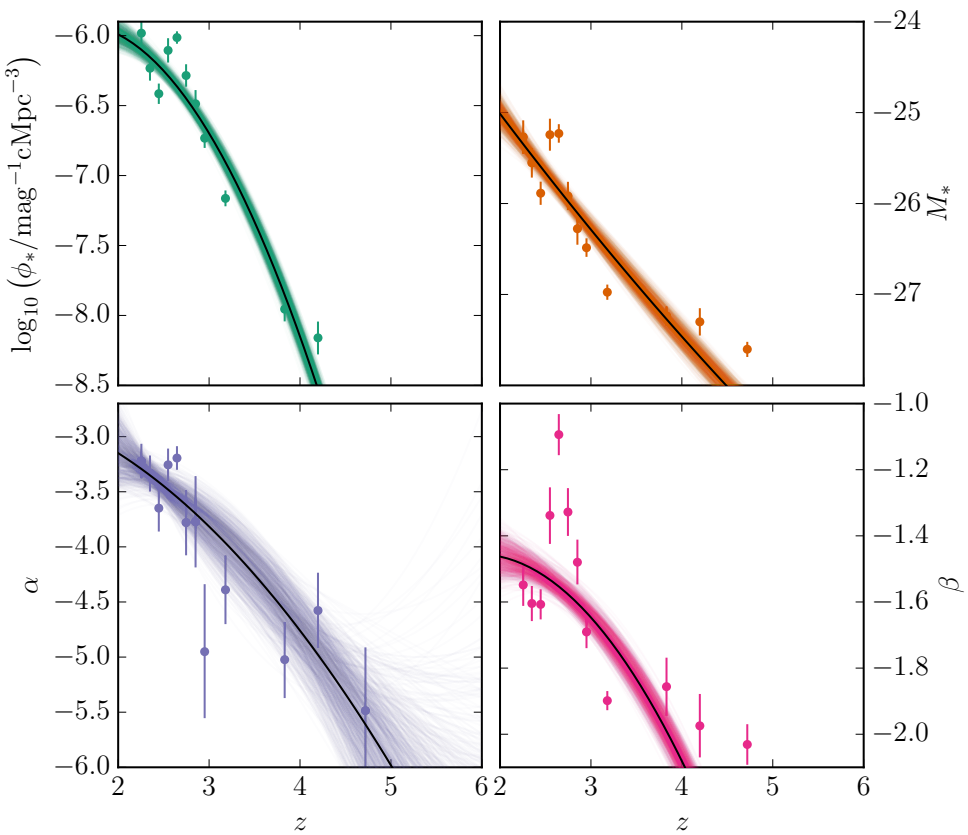
- No SED break at $\lambda \sim 1200$Å$\longrightarrow$ Emissivity increases by $\sim 30\%$



3. Reassessment of the QSO UV Luminosity Function

- MCMC analysis of $2 < z < 6$ QSO UV luminosity function data
- Homogenous re-analysis (K correction, targets, selection functions)
- All QLF parameters evolve with redshift
- Scatter of parameters in small z intervals $\longrightarrow$ survey systematics

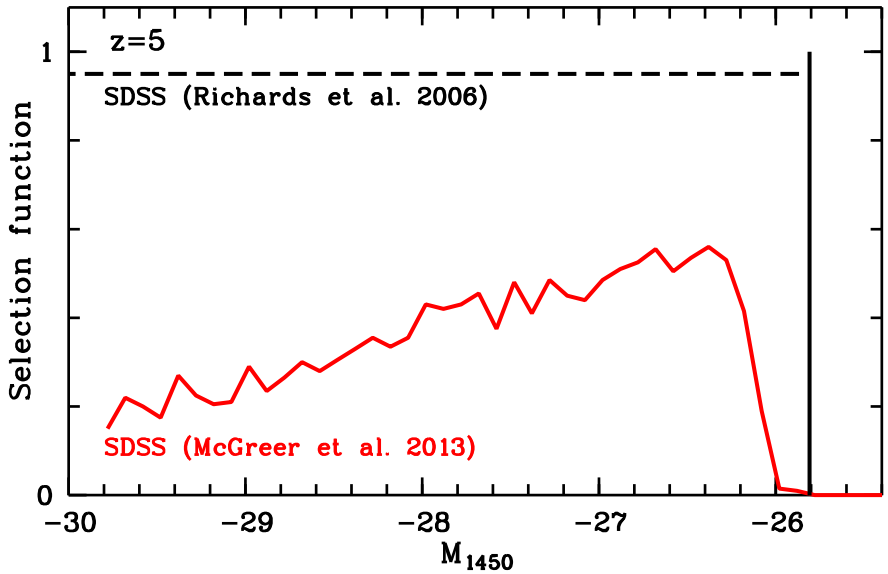


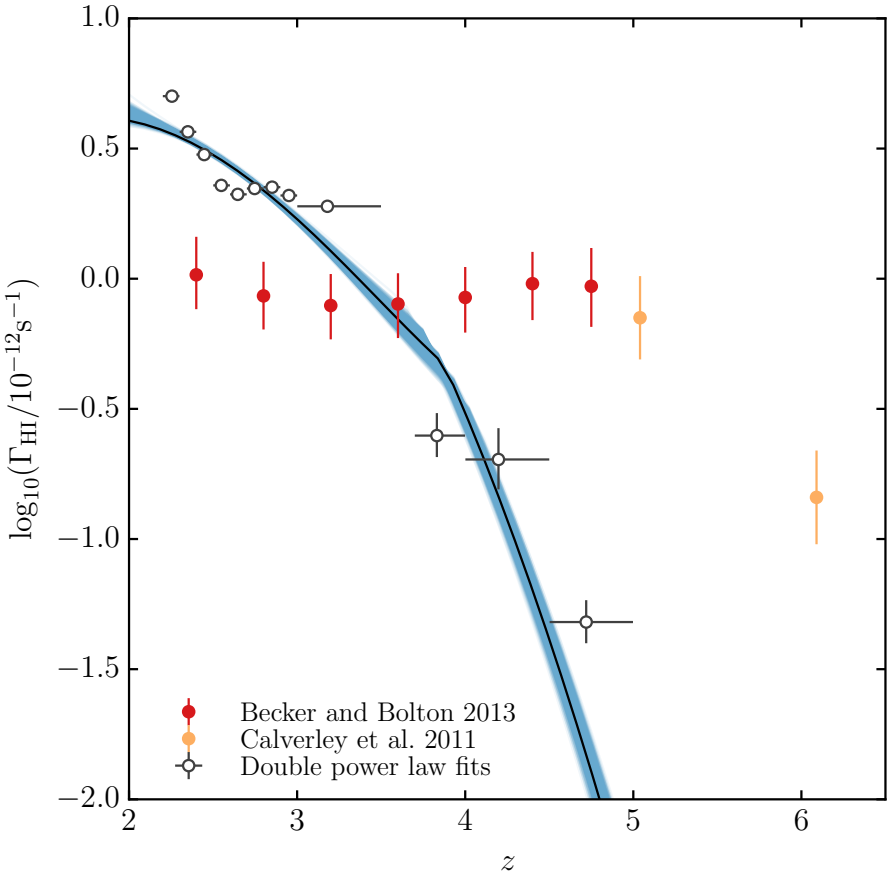


Kulkarni, Worseck & Hennawi in prep.

Are QSOs dominatating the UV background?

- QSO emissivity depends on $M_\star$ and faint end slope
- Faint end of $z > 4$ QSO luminosity function poorly determined
- Severe systematics in selection functions (factor 2–5 at $z = 5$)
- Current data: UV background not QSO-dominated at $z > 4$

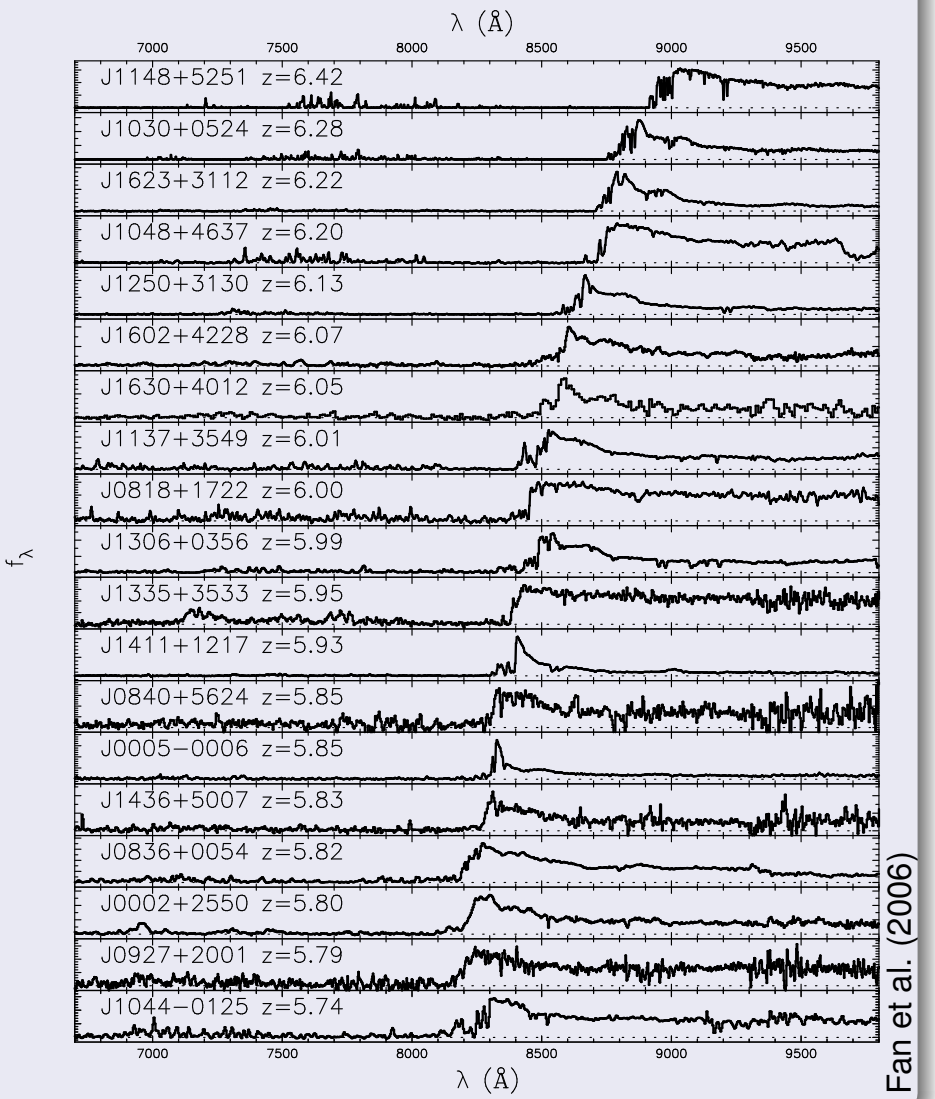




Kulkarni, Worseck & Hennawi in prep.

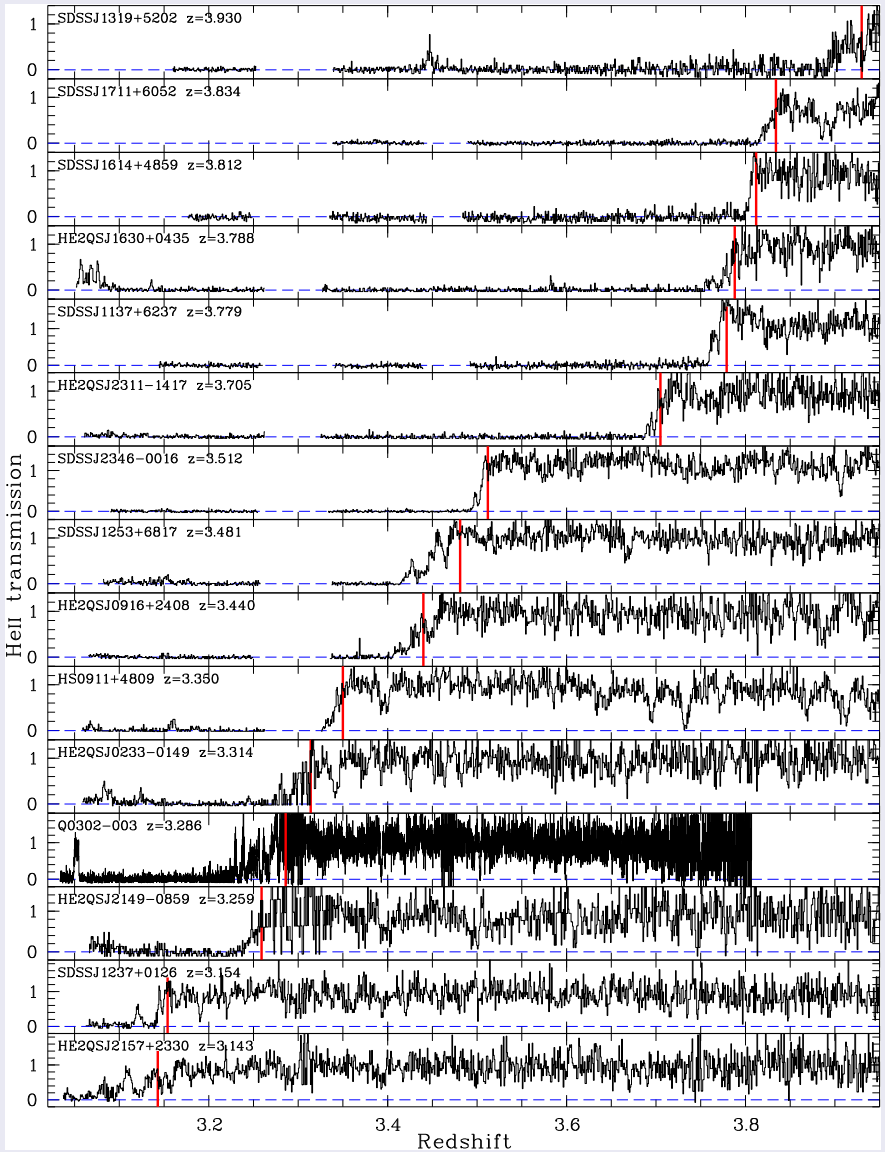
Fluctuating Gunn-Peterson troughs

Ground: H I at $z \sim 6$



Fan et al. (2006)

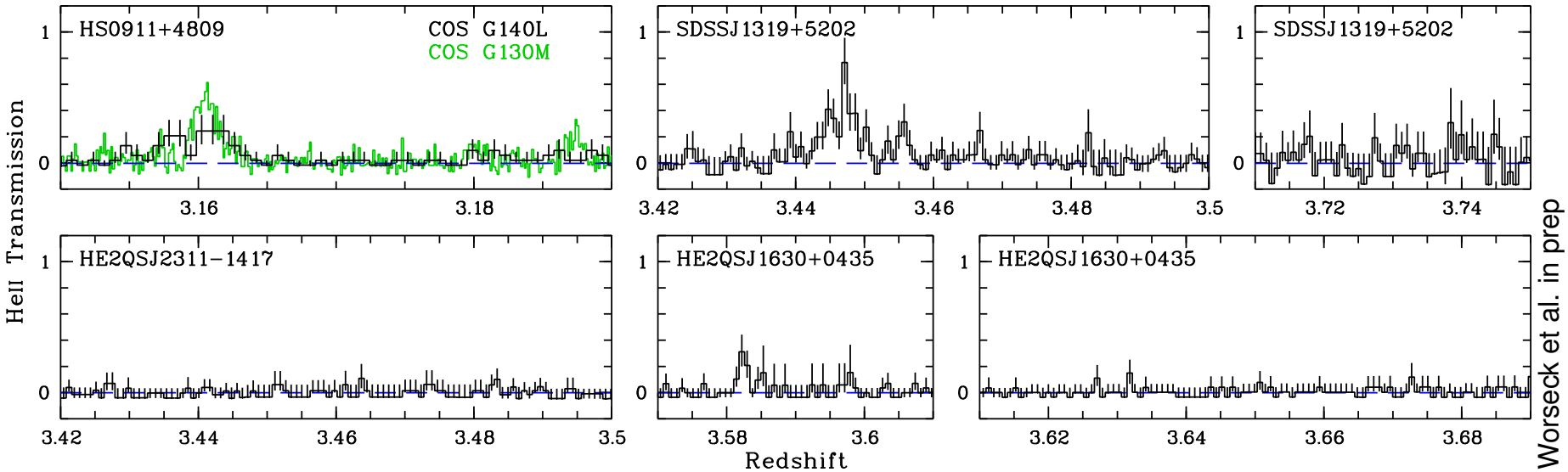
Far UV: He II at $z \sim 3.5$



Worseck et al. (2011, 2016); Worseck et al. in prep.

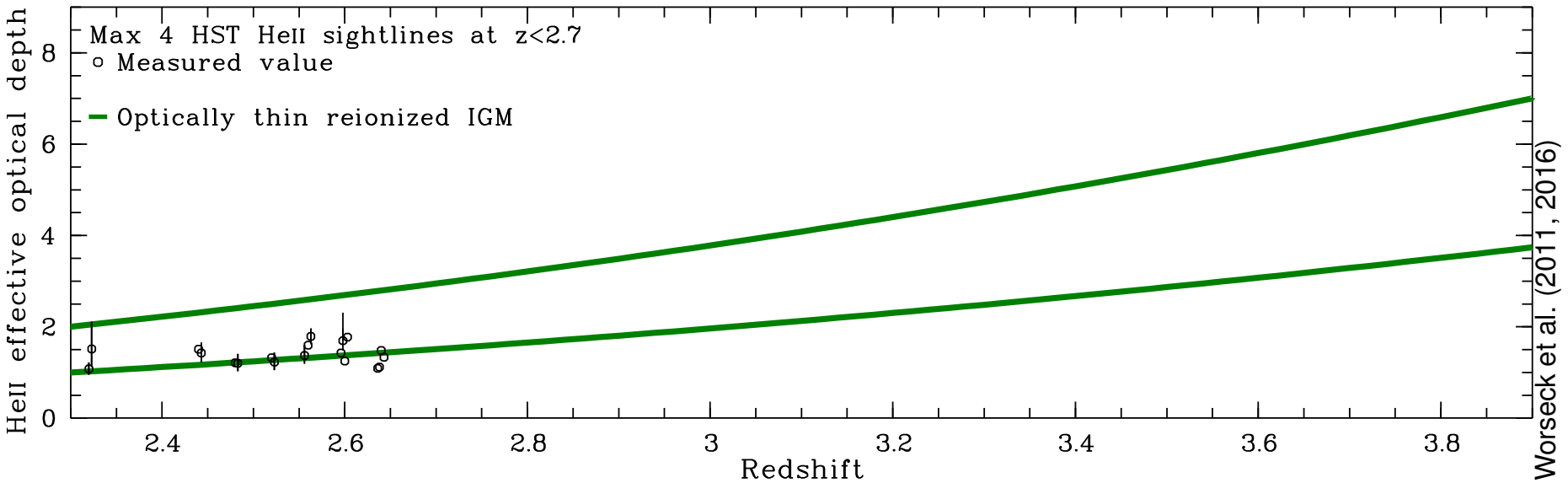
He II transmission spikes at $z \sim 3.5$

- Unexpected based on handful of pre-COS He II spectra
- Unexpected based on quasar-driven He II reionization models
- Possibly due to transverse proximity effect
  (Tobias Schmidt's poster)



Very extended He II reionization ends at $z_{\rm reion} \simeq 2.7$

- Measurements: He II effective optical depth on ~ 10 proper Mpc
- $z \lesssim 2.7$: Agreement with semi-analytic model of photoionized IGM



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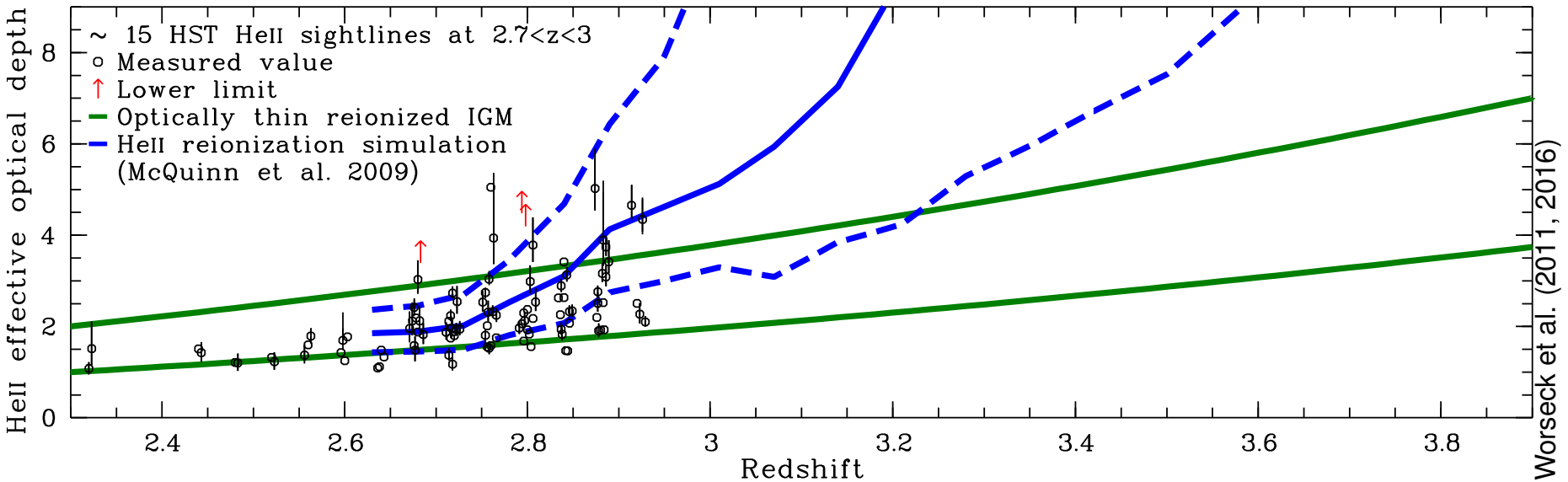

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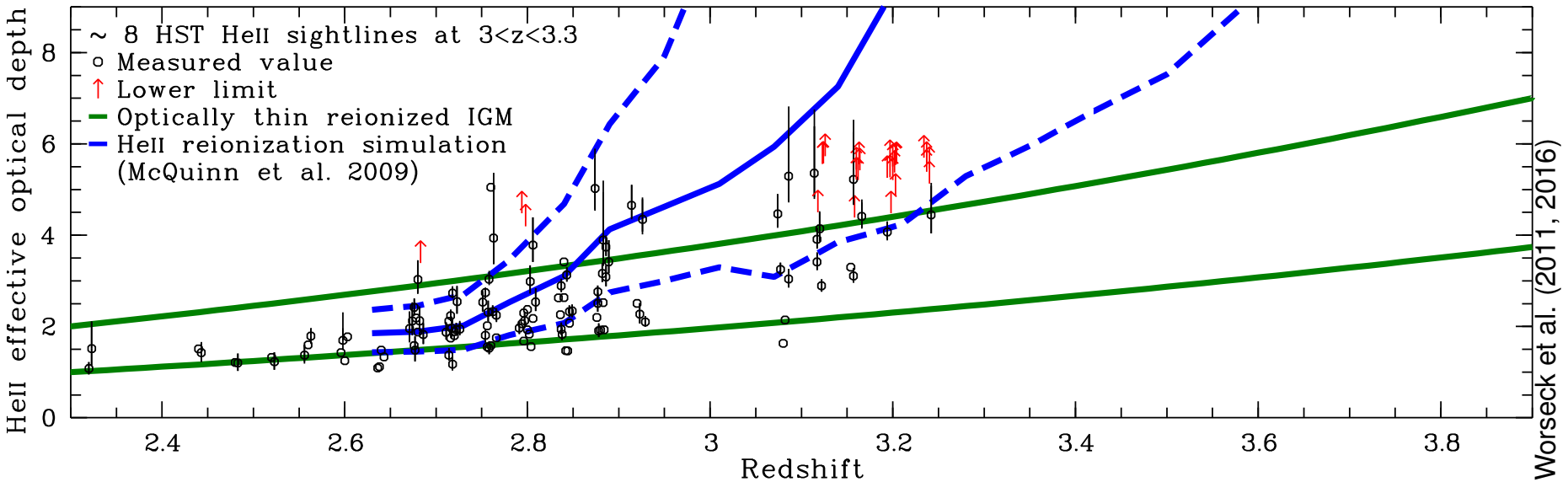
- $z \sim 3.2$: low effective optical depths, gradual He II reionization



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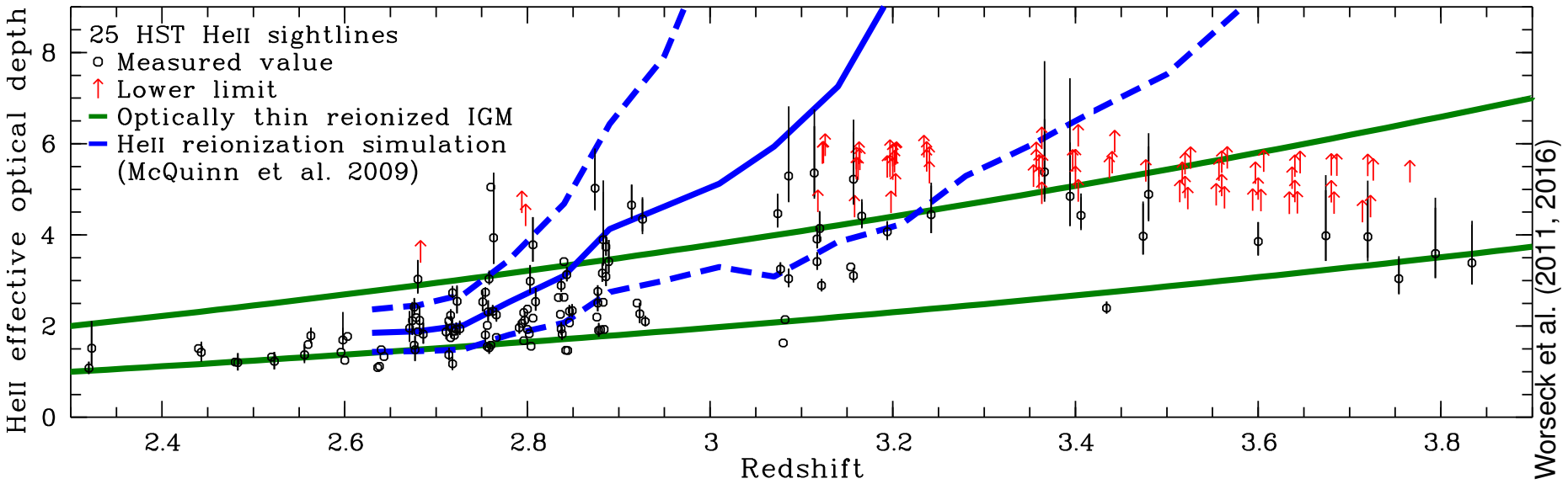
- $z \sim 3.2$: low effective optical depths, gradual He II reionization
- $z \sim 3.6$: One third of the IGM consistent with $\sim 1\%$ He II fraction
  $\longrightarrow$ He II reionization well underway at $z \sim 4$



Conclusions

- Reassessment of QSO UV luminosity function at $z > 2$
  - Homogeneous MCMC analysis of QSO UV luminosity function data
  - Redshift evolution of QLF parameters $\longrightarrow$ QSO emissivity
- UV background may not be dominated by QSOs at $z > 4$
  - Survey selection functions disagree for the same survey!
  - Large surveys need sophisicated modeling of selection effects
- Early and extended He II reionization by faint QSOs?
  - 25 He II sightlines probing $2.3 < z < 3.8$
  - Low effective optical depths
    $\longrightarrow$ One third of the pathlength fully reionized at $z \sim 3.6$
    $\longrightarrow$ He II reionization must have begun at $z \gg 4$
  - Modeling of QSO-driven He II reionization requires accurate luminosity function