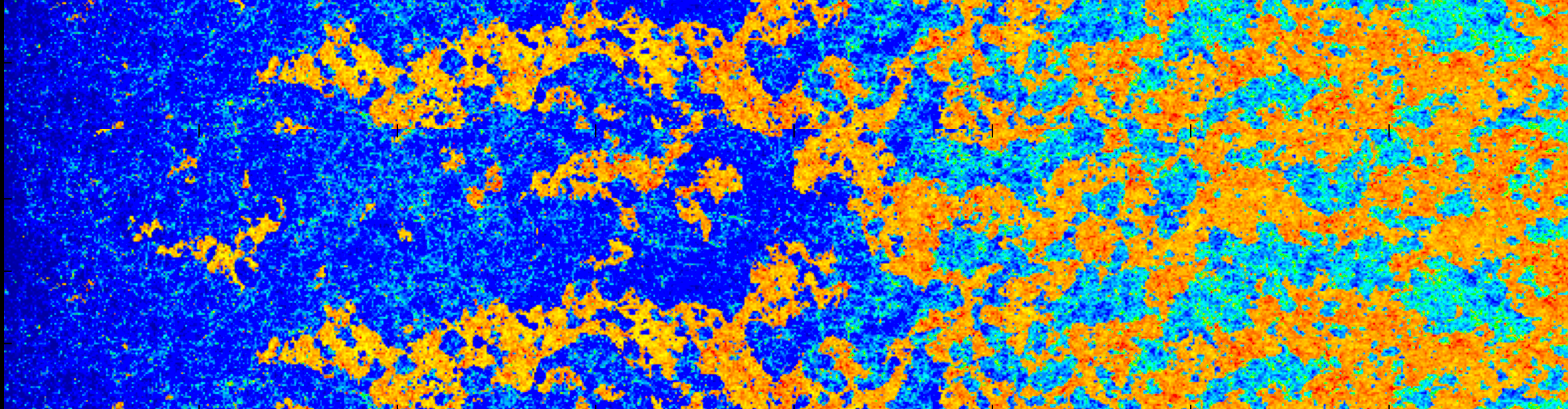

Evolution of the Quasar Luminosity Function: Implications for EoR-21cm

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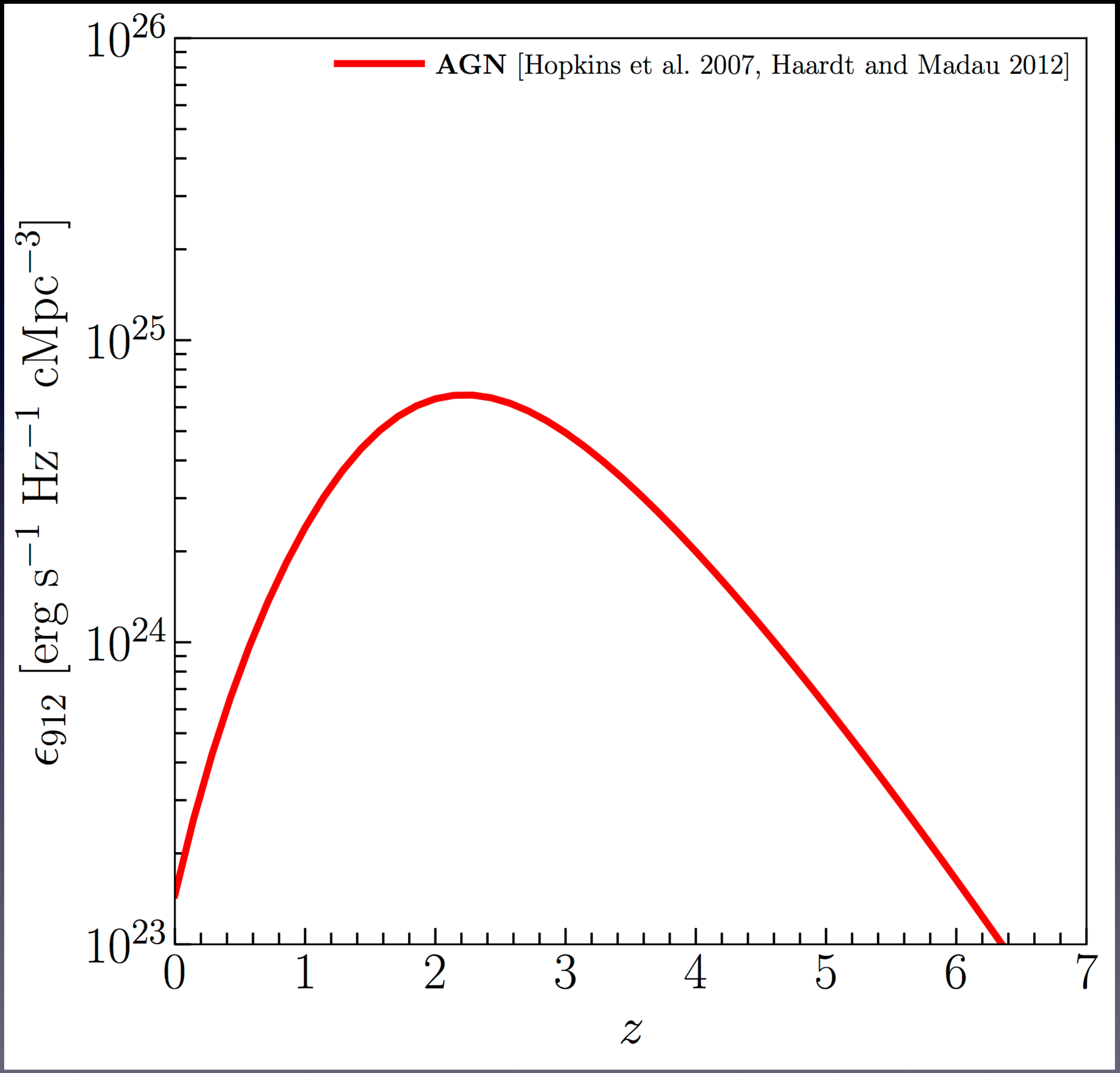
5 October 2017 — Dubrovnik

Reionization by Quasars—c. 2012

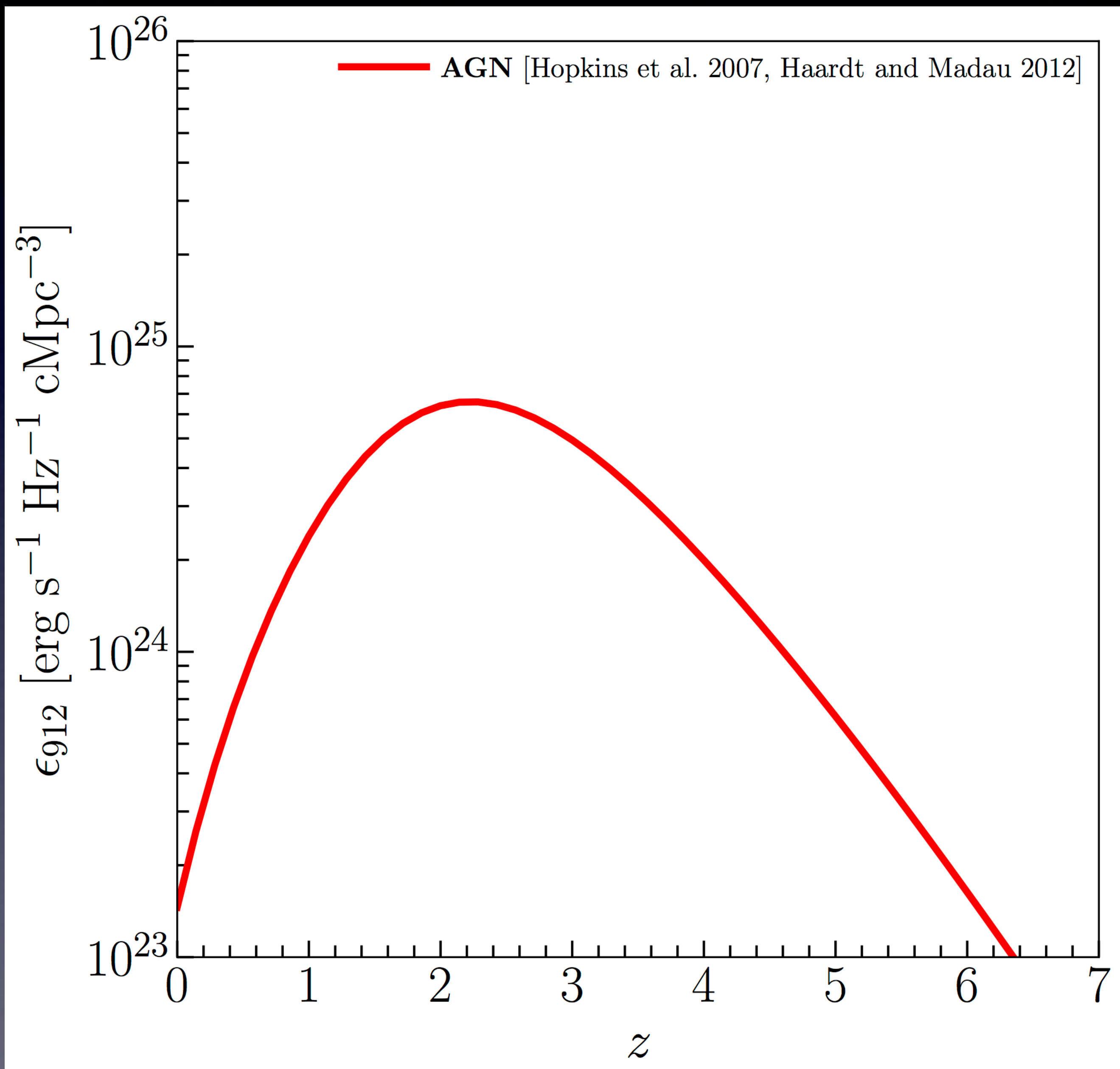
Ionizing Emissivity



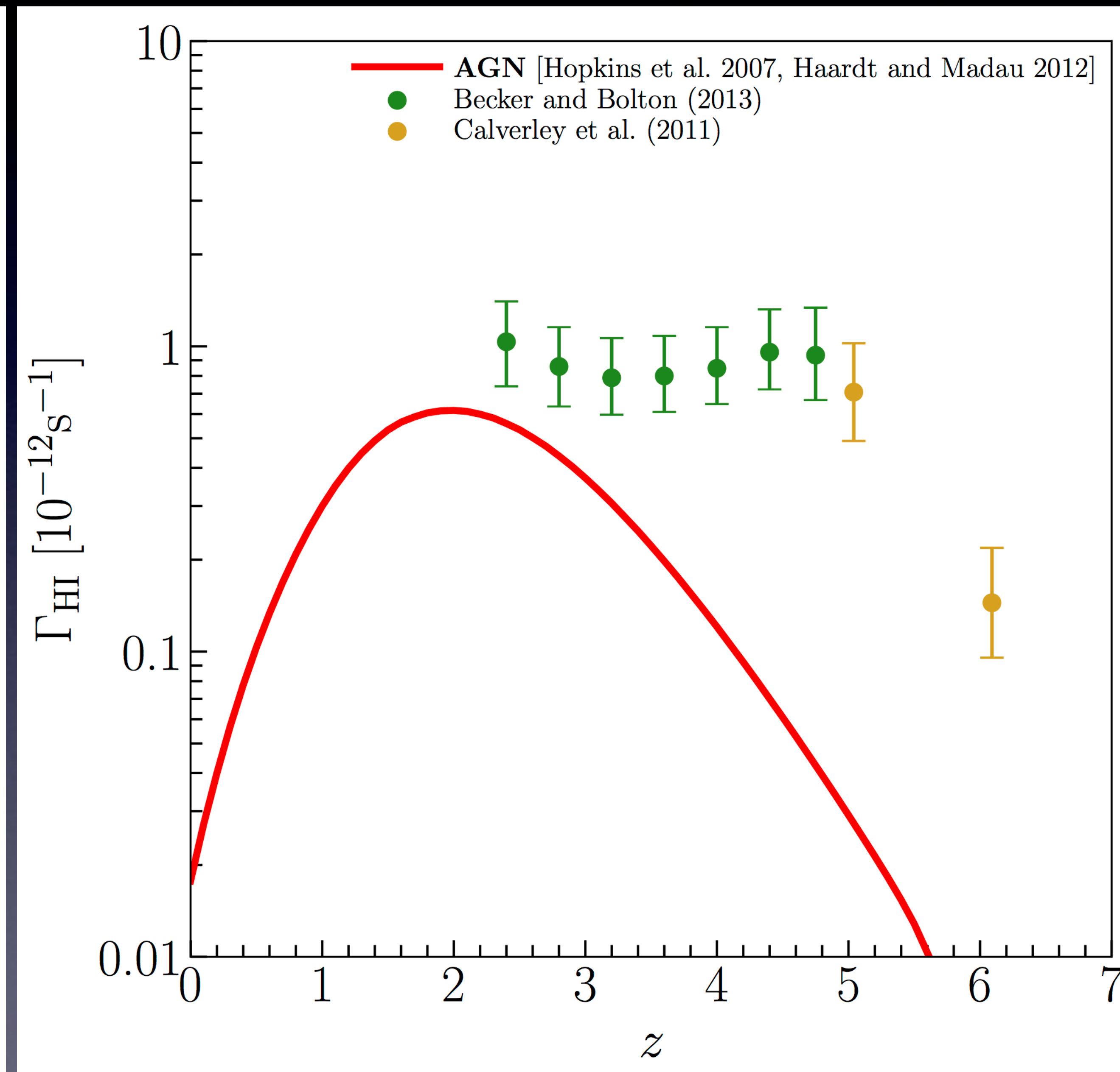
LyC emissivity of quasars peaks at z ~ 2 and **drops steeply at high redshifts** (Hopkins et al. 2007; Haardt and Madau 2012)

Reionization by Quasars—c. 2012

Ionizing Emissivity



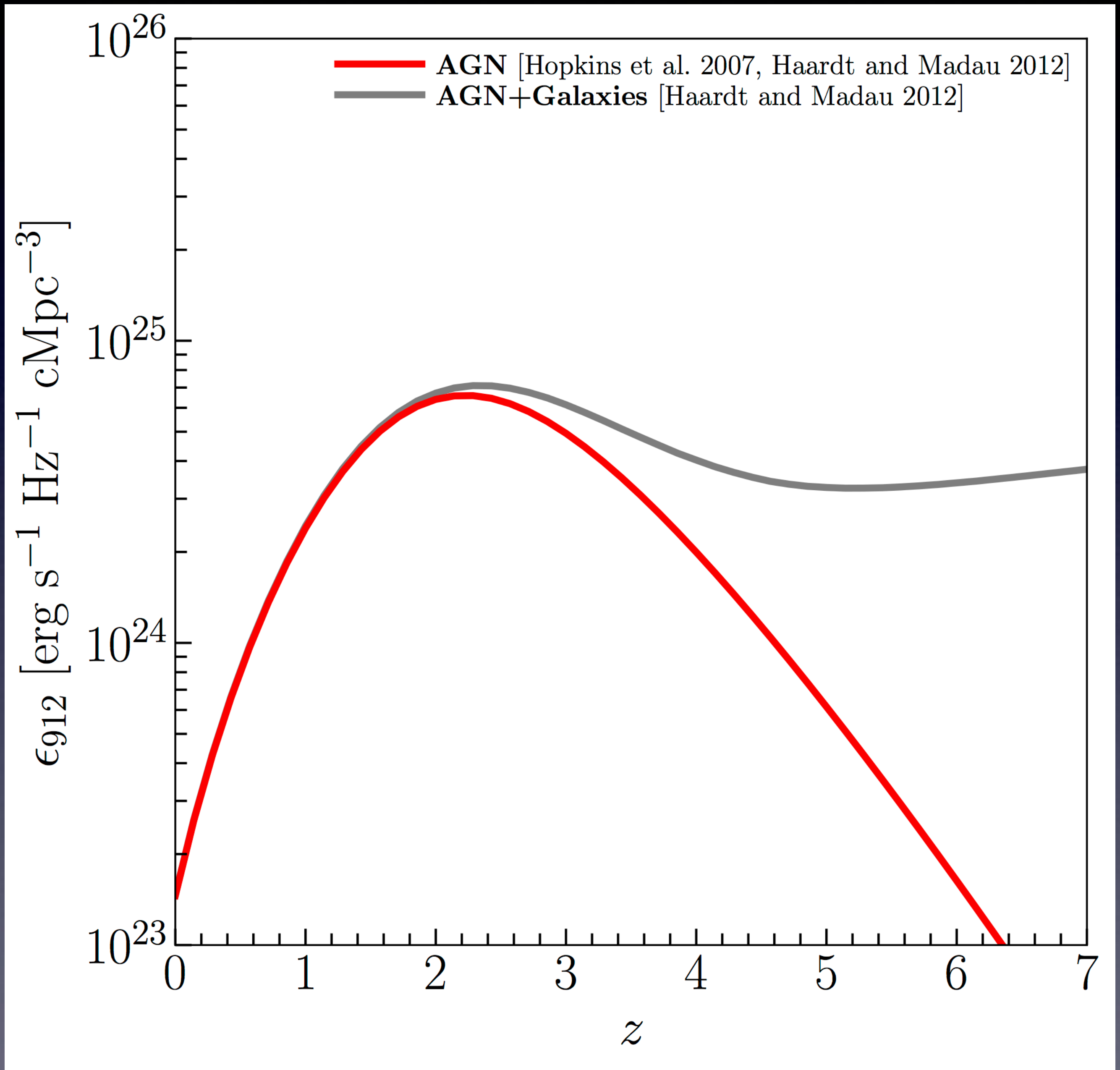
Photoionization Rate



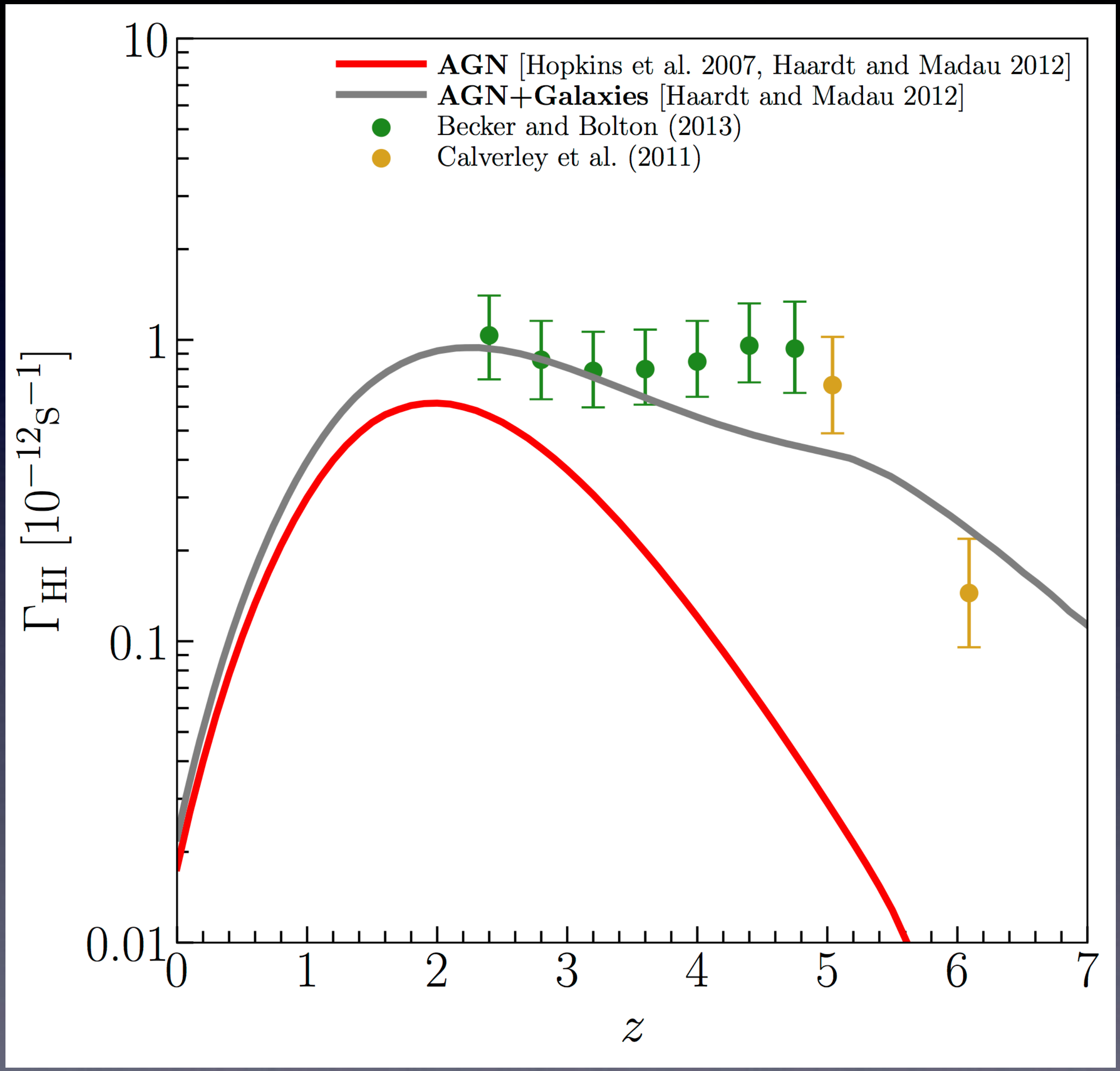
Quasar contribution falls short of the photon budget implied by Lyα data (e.g., Becker and Bolton 2013; Calverley et al. 2011)

Reionization by Quasars—c. 2012

Ionizing Emissivity



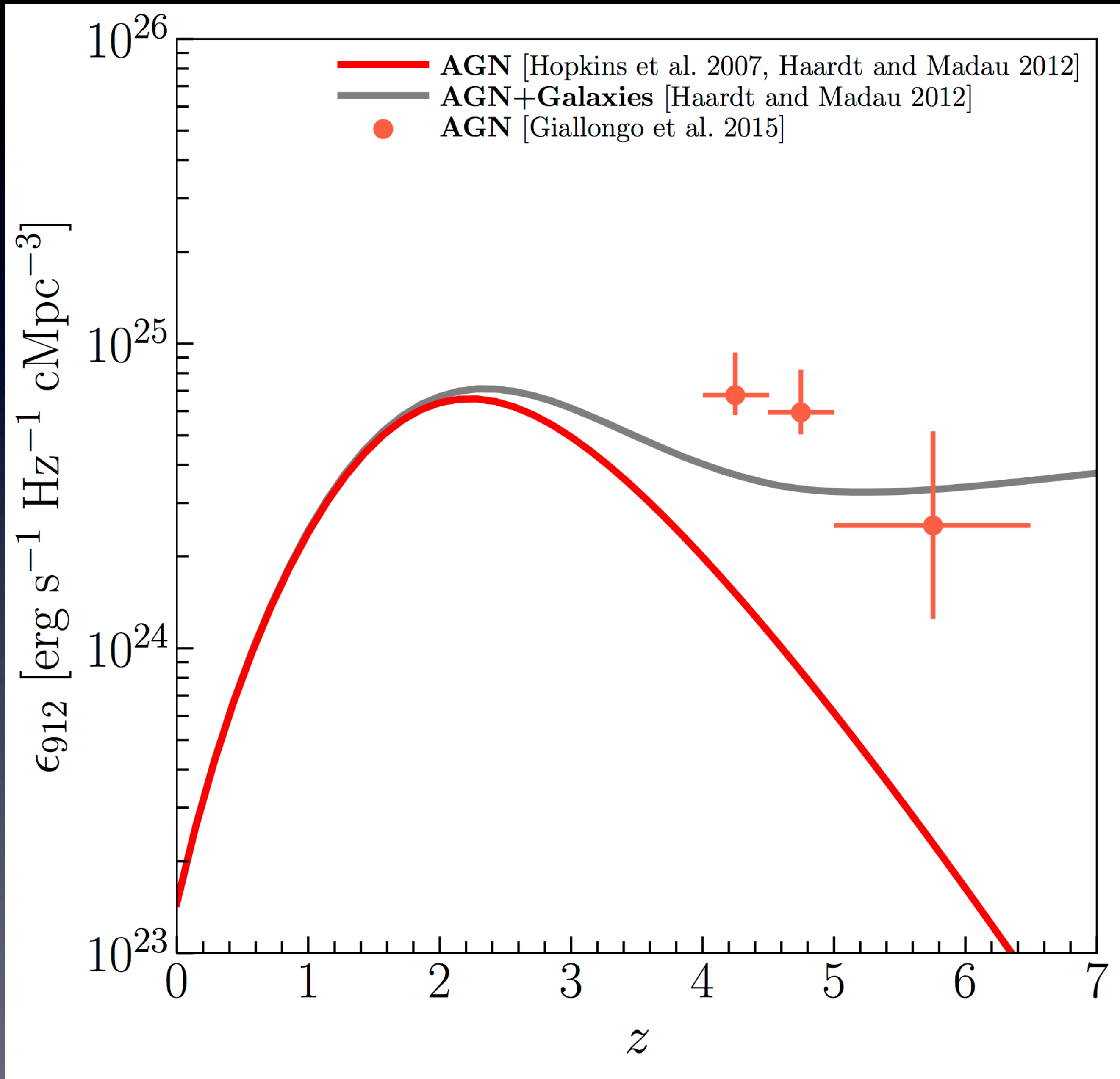
Photoionization Rate



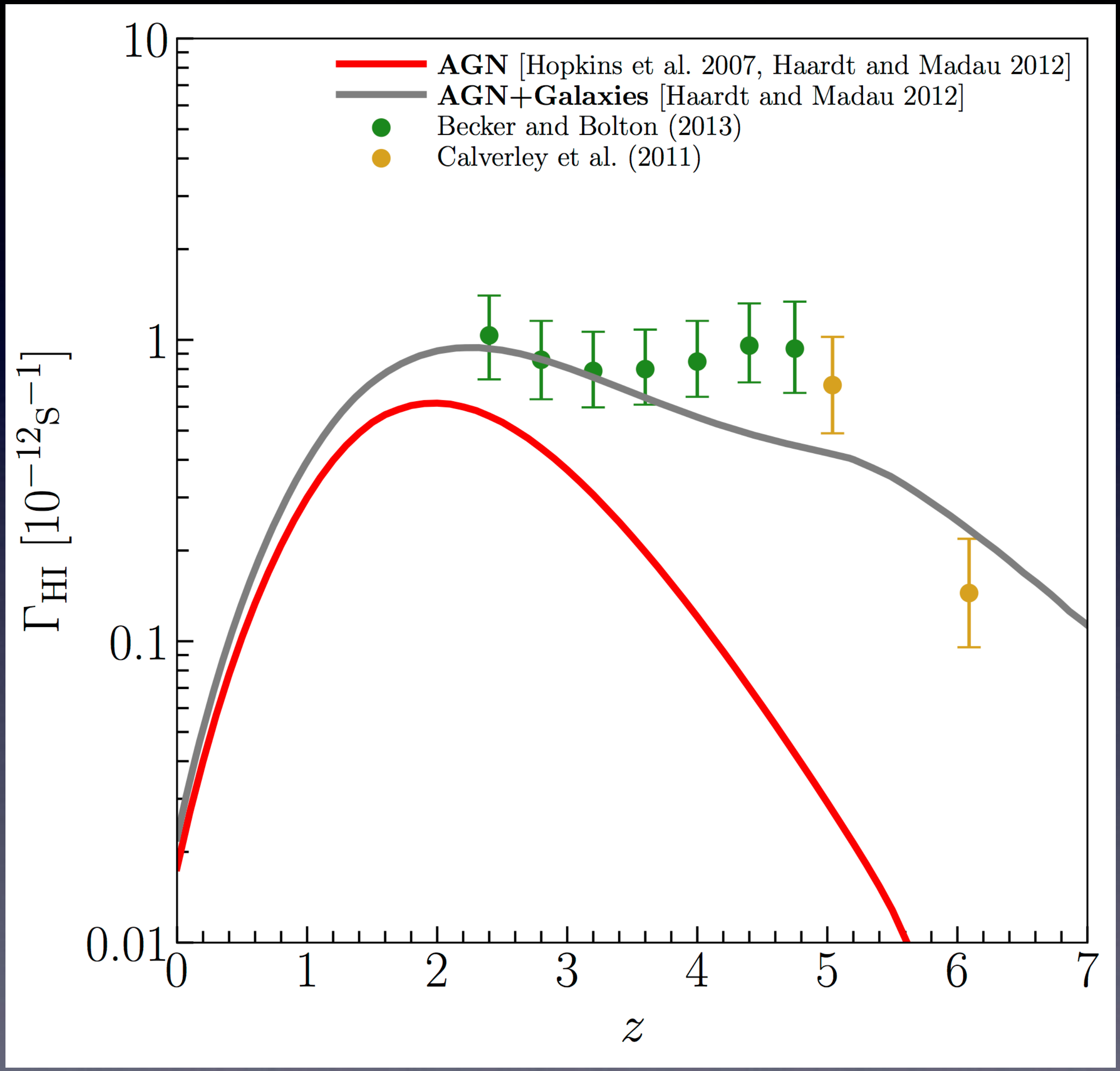
Deficit can be balanced by invoking escape of LyC photons from galaxies (e.g., Haardt and Madau 2012; Mitra et al. 2016)

Reionization by Quasars—today

Ionizing Emissivity

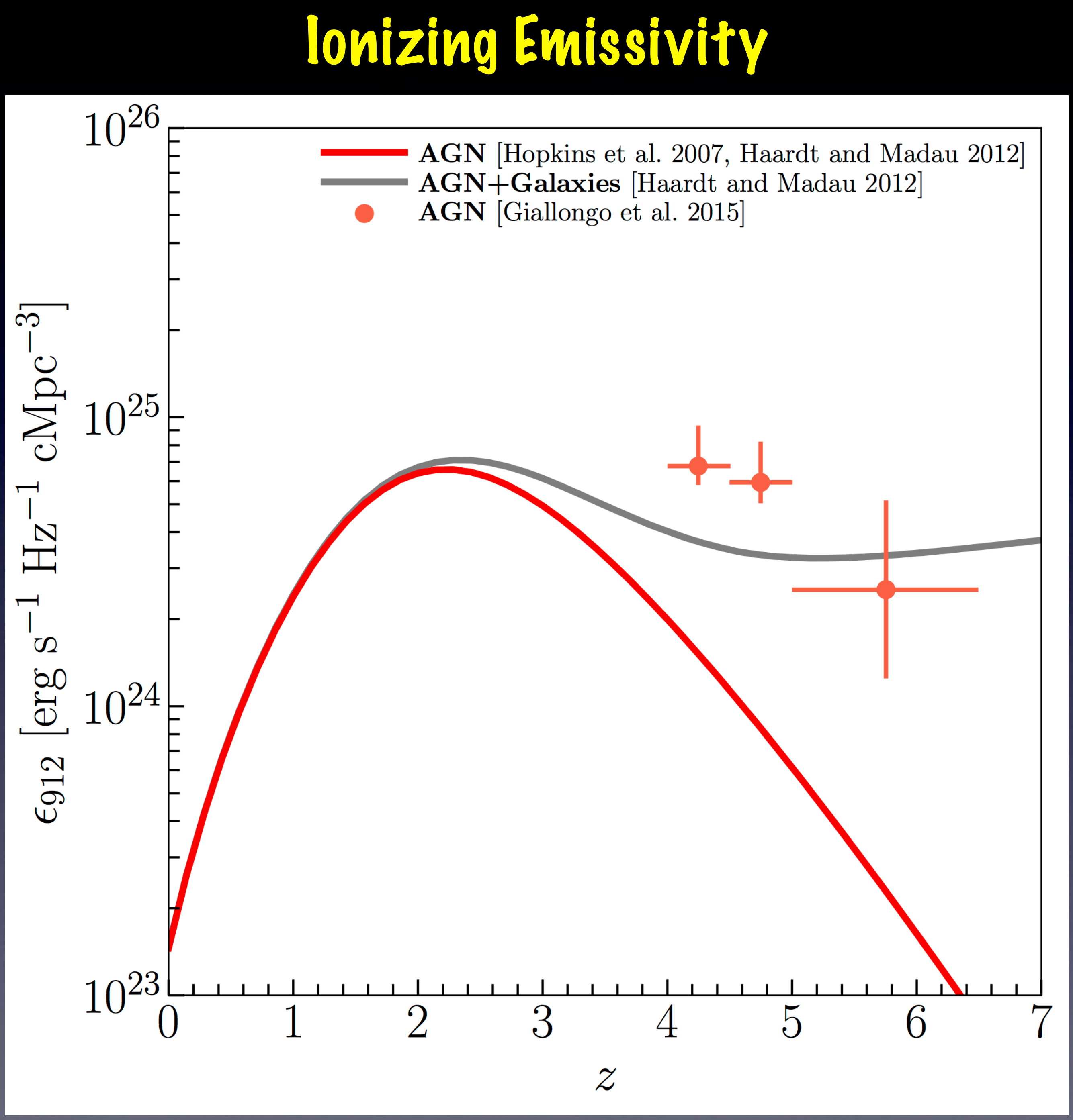


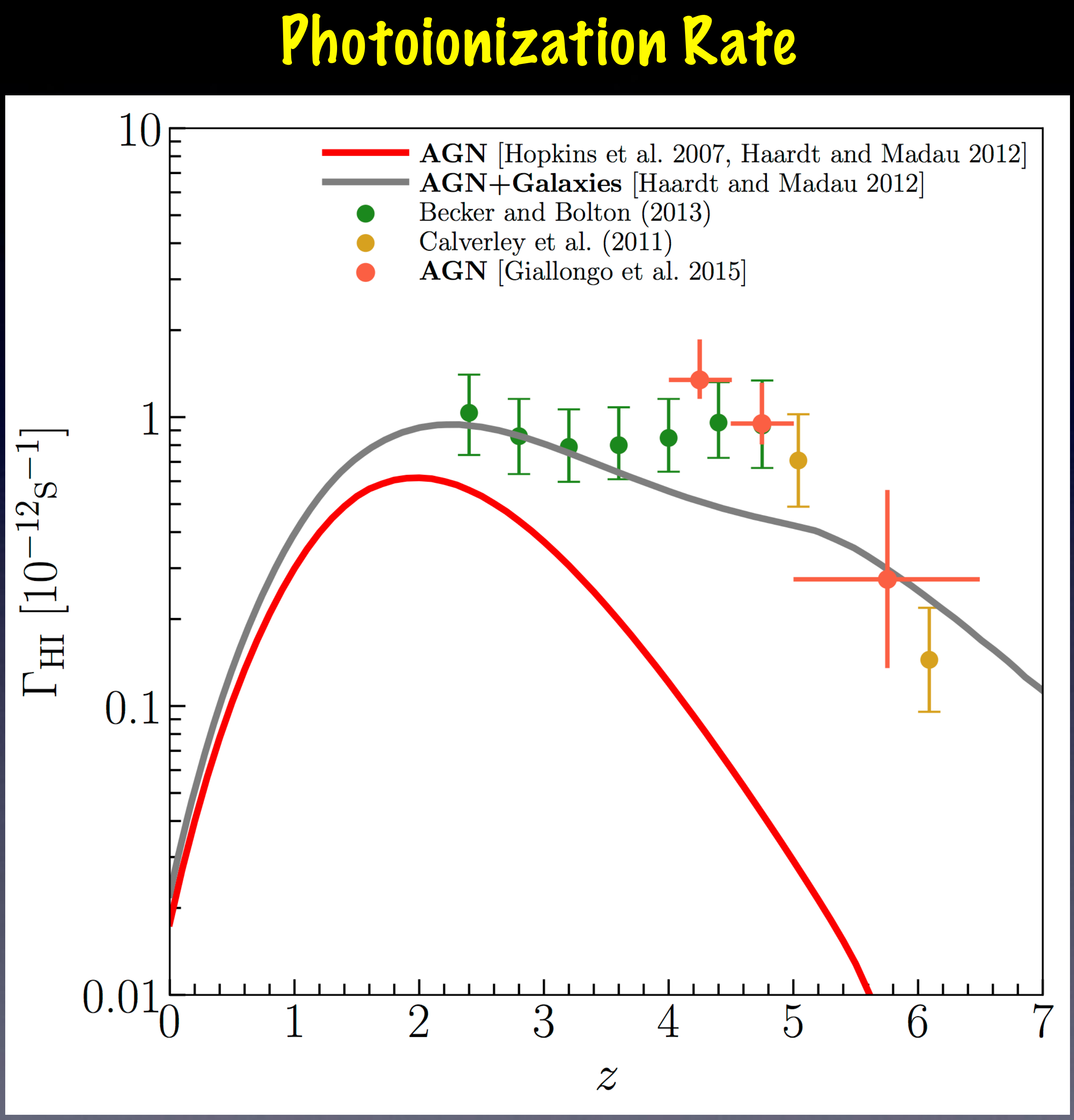
Photoionization Rate



19 new faint AGN at z = 4–6 via photometric X-ray/NIR selection suggest much higher AGN number density (Giallongo et al. 2015)

Reionization by Quasars—today



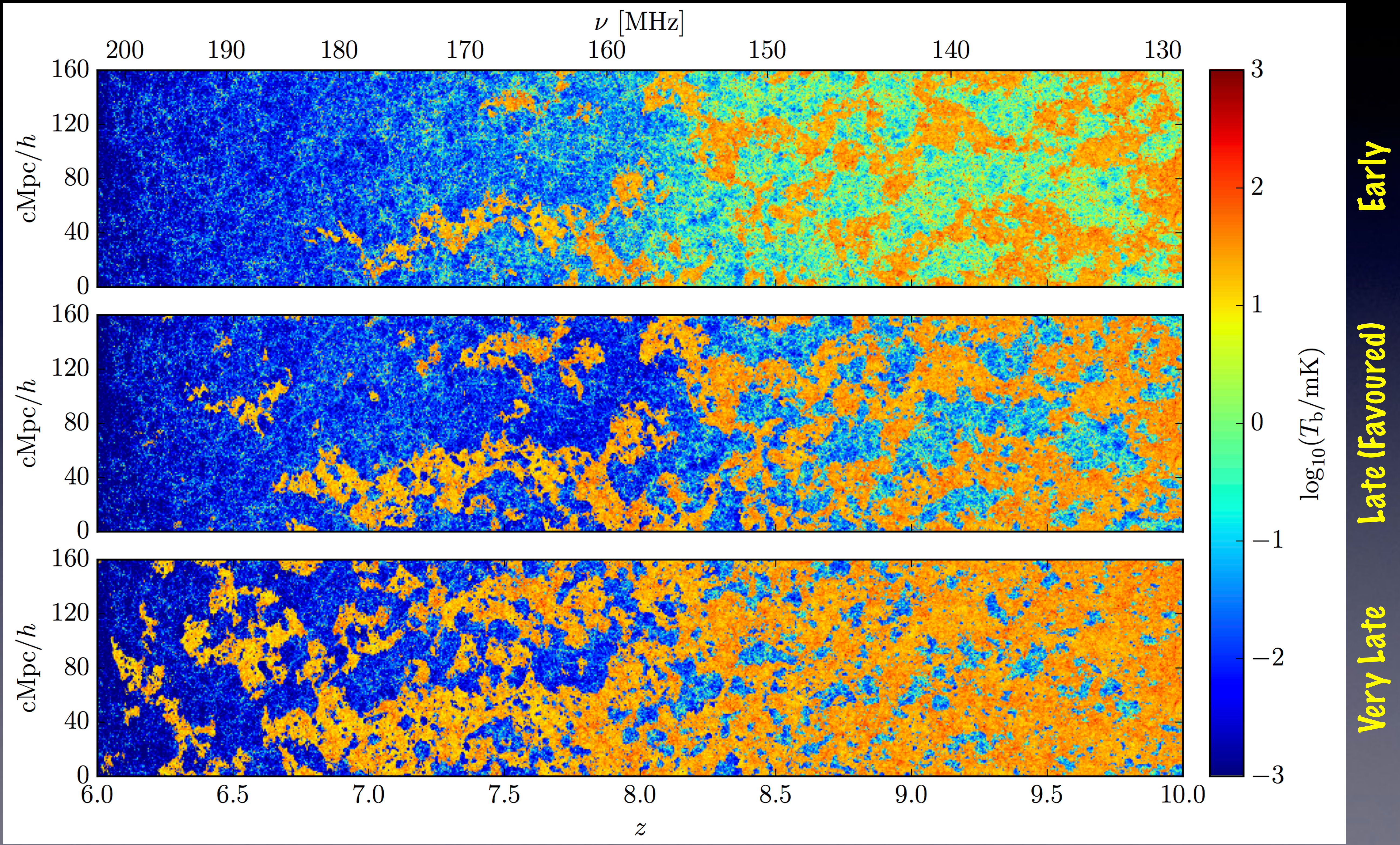


Consistency with Lyα data all the way up to z = 6 suggests that **AGN *can* reionize the universe** (Giallongo et al. 2015)

1. What are the implications for 21 cm?

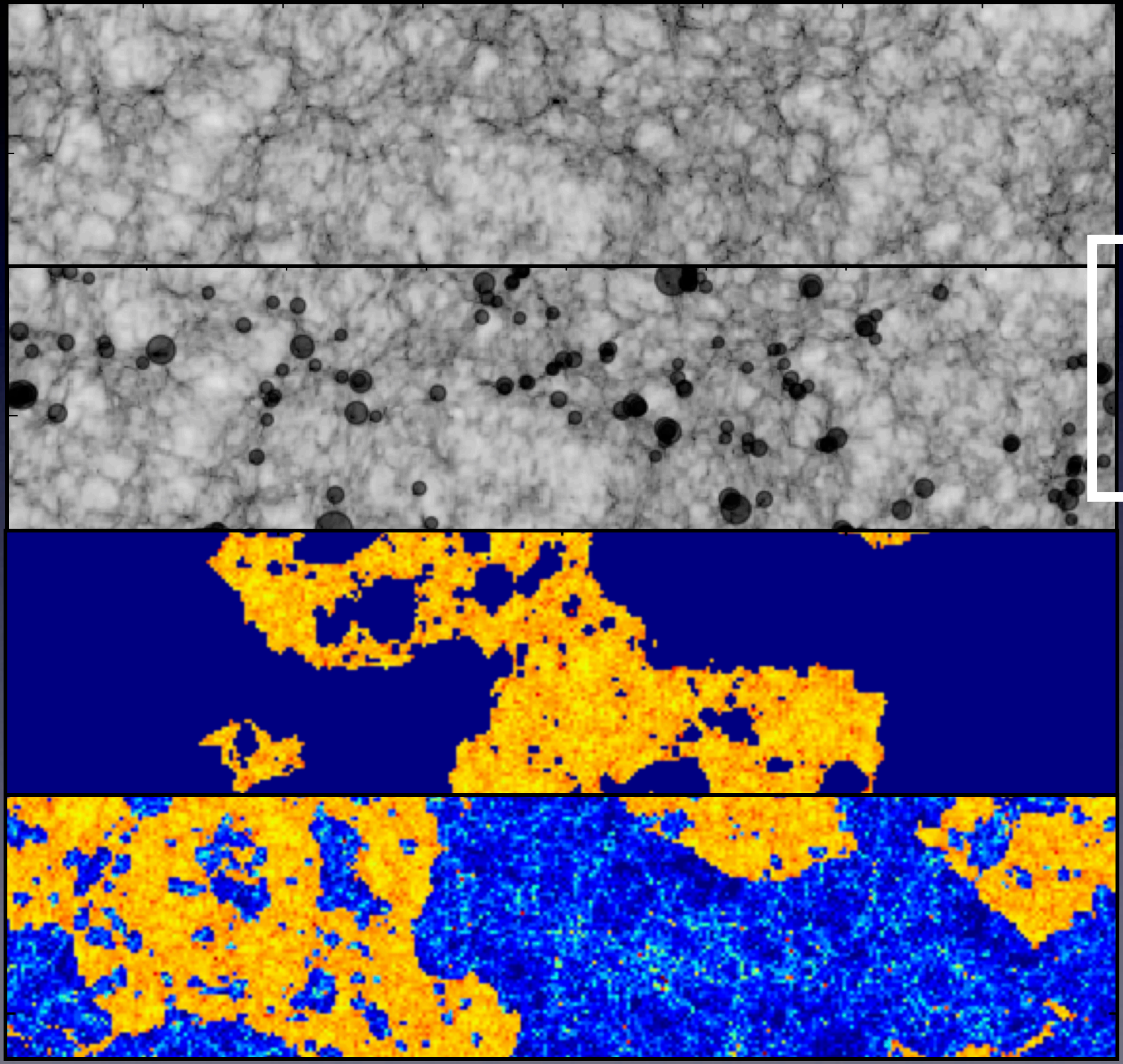
2. Did quasars really reionize the Universe?

High-dynamic-range 21 cm simulations



Kulkarni et al. 2016

High-dynamic-range 21 cm simulations



1. Cosmological density field

SPH simulations using Gadget-3
Box size 160 Mpc/h
Resolution ~50 kpc

2. Sources of LyC photons

Haloes down to ~10^8 M⊙
$N_\gamma \propto M_{\rm halo}$

3. Use Excursion Sets

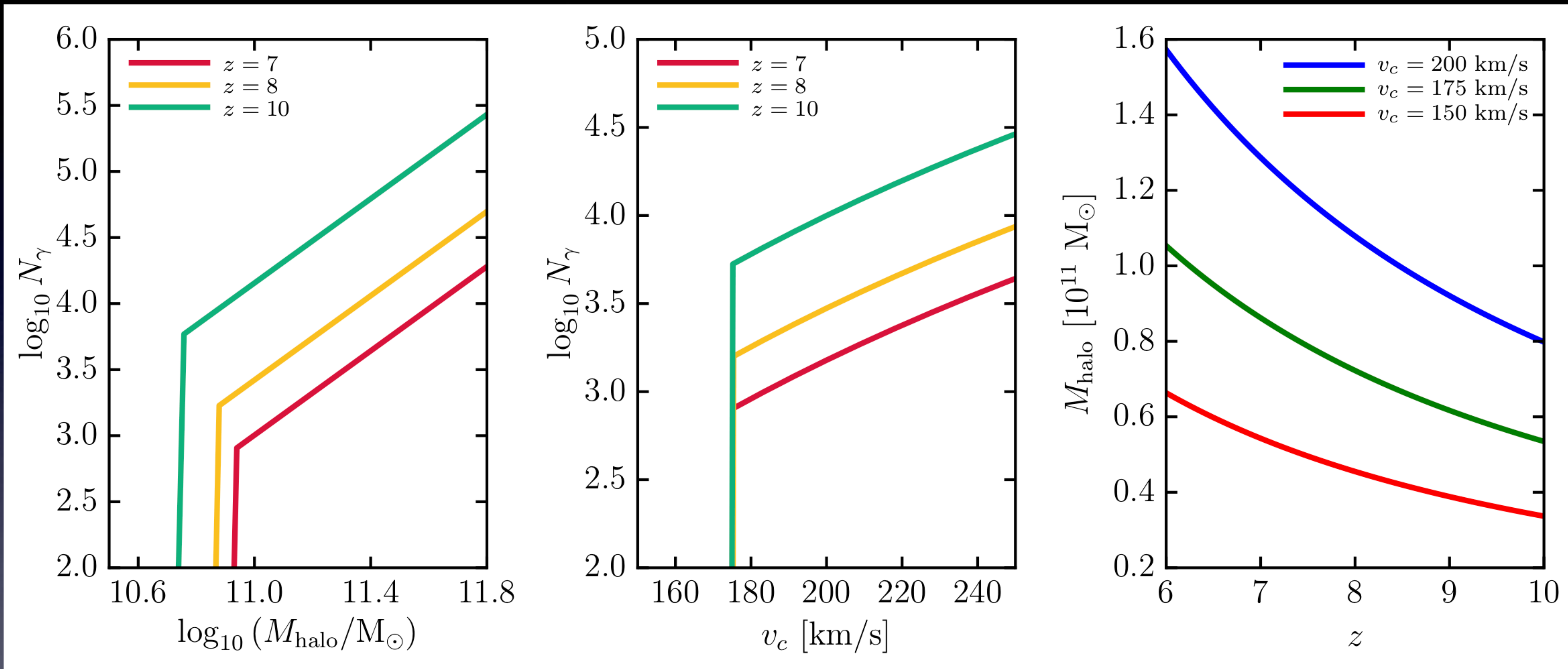
Get large-scale ionization field
$\zeta_{\rm eff} f(\mathbf{x}, R) \geq 1$

4. Calibrate to Lyα and CMB

Also fixes small-scale structure
$\delta T_b \propto x_{\rm HI} \Delta_{\rm gas}$

Kulkarni et al. 2016

$N_\gamma \propto \cancel{M_{\rm halo}}\ M_{\rm bh}$

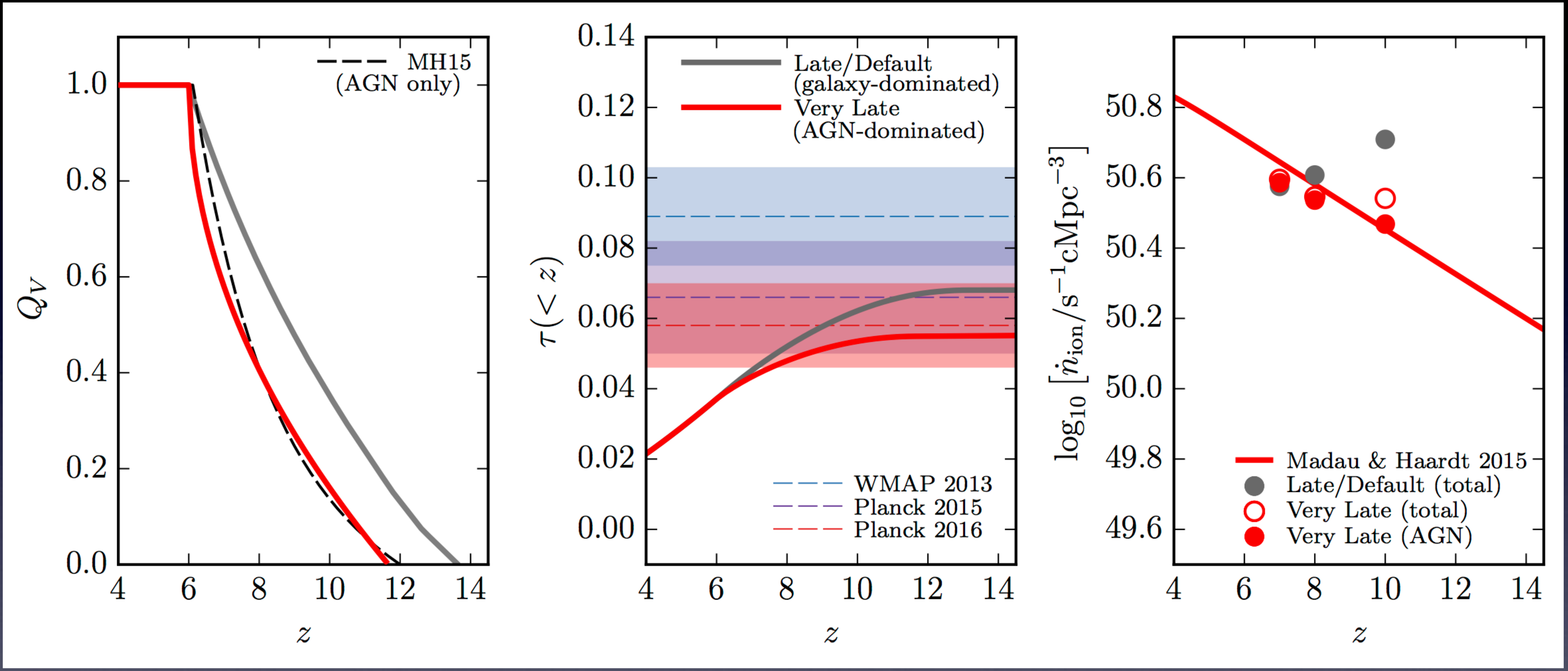


Kulkarni et al. 2017

$$\frac{M_{\rm bh}}{10^8 {\rm M}_\odot} = 0.12\left(\frac{M_{\rm halo}}{10^{12}{\rm M}_\odot}\right)^{1.6}(1+z)^{3/2}$$

Model quasars using M–σ relation in haloes above circular velocity of 175 km/s (Haehnelt and Kauffmann 2002, Kelly and Merloni 2012)

AGN-dominated reionization history



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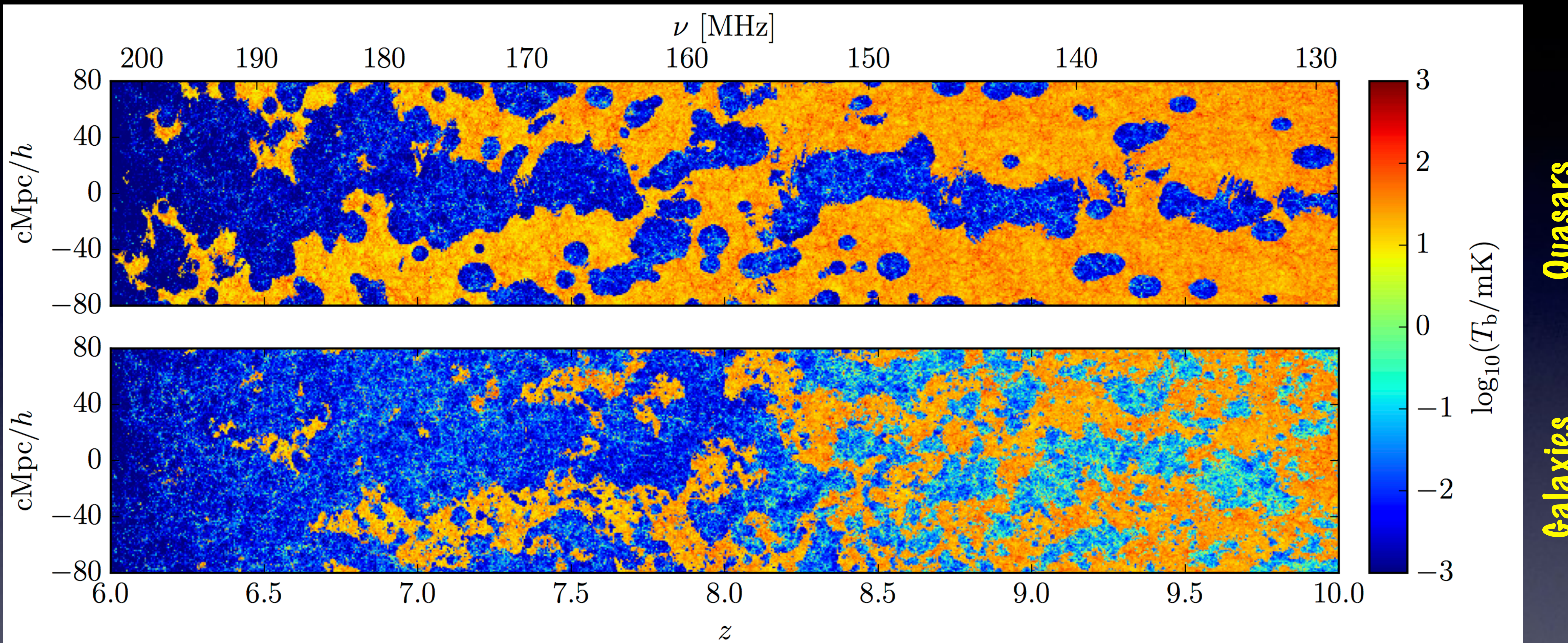
Reionization history is close to the “Very Late” model.

21 cm signal from Quasar-dominated Reionization



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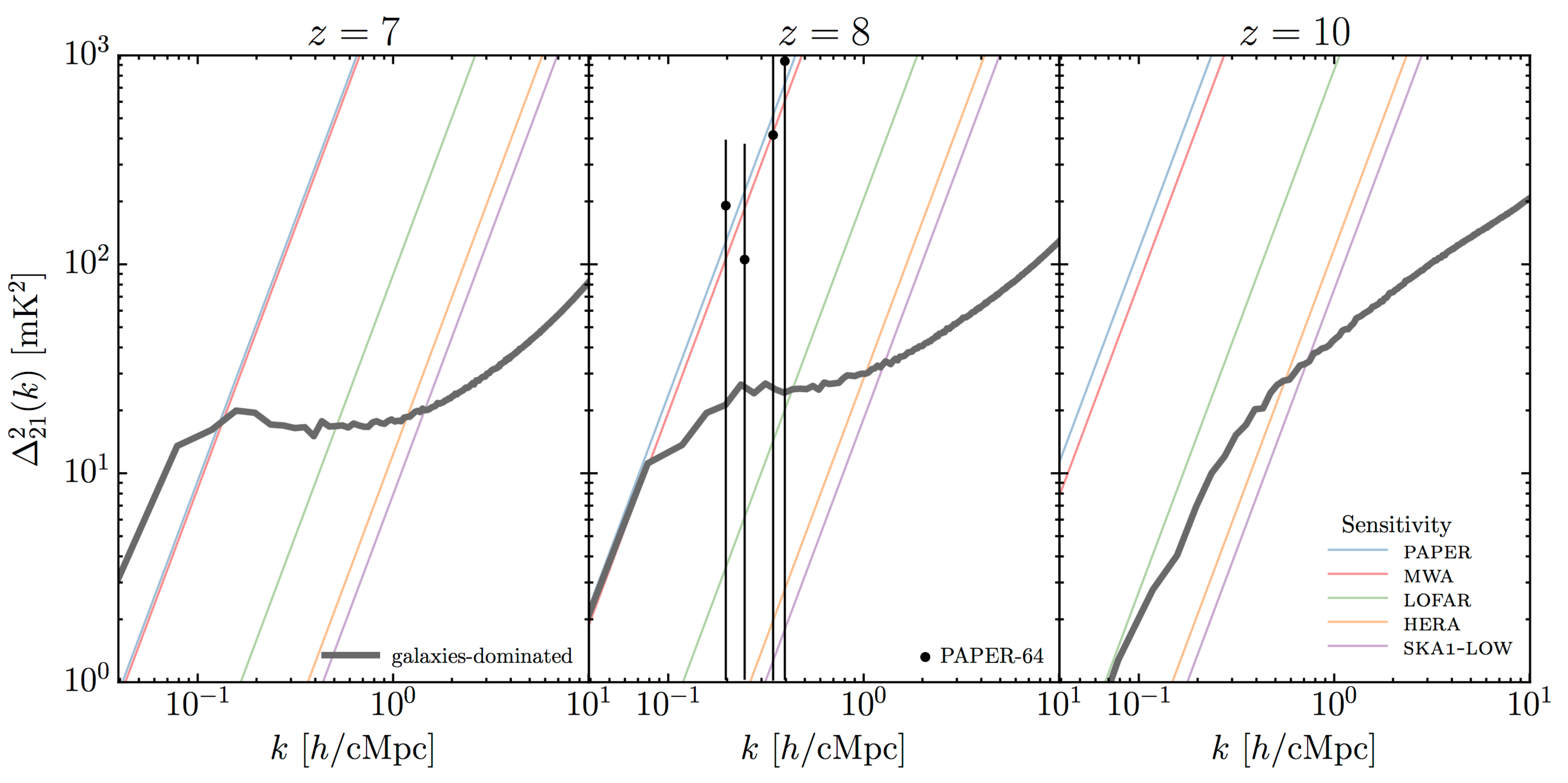
- 21 cm distribution dominated by large bubbles.
- Reionization happens later but ionised regions are now ~10 cMpc in size

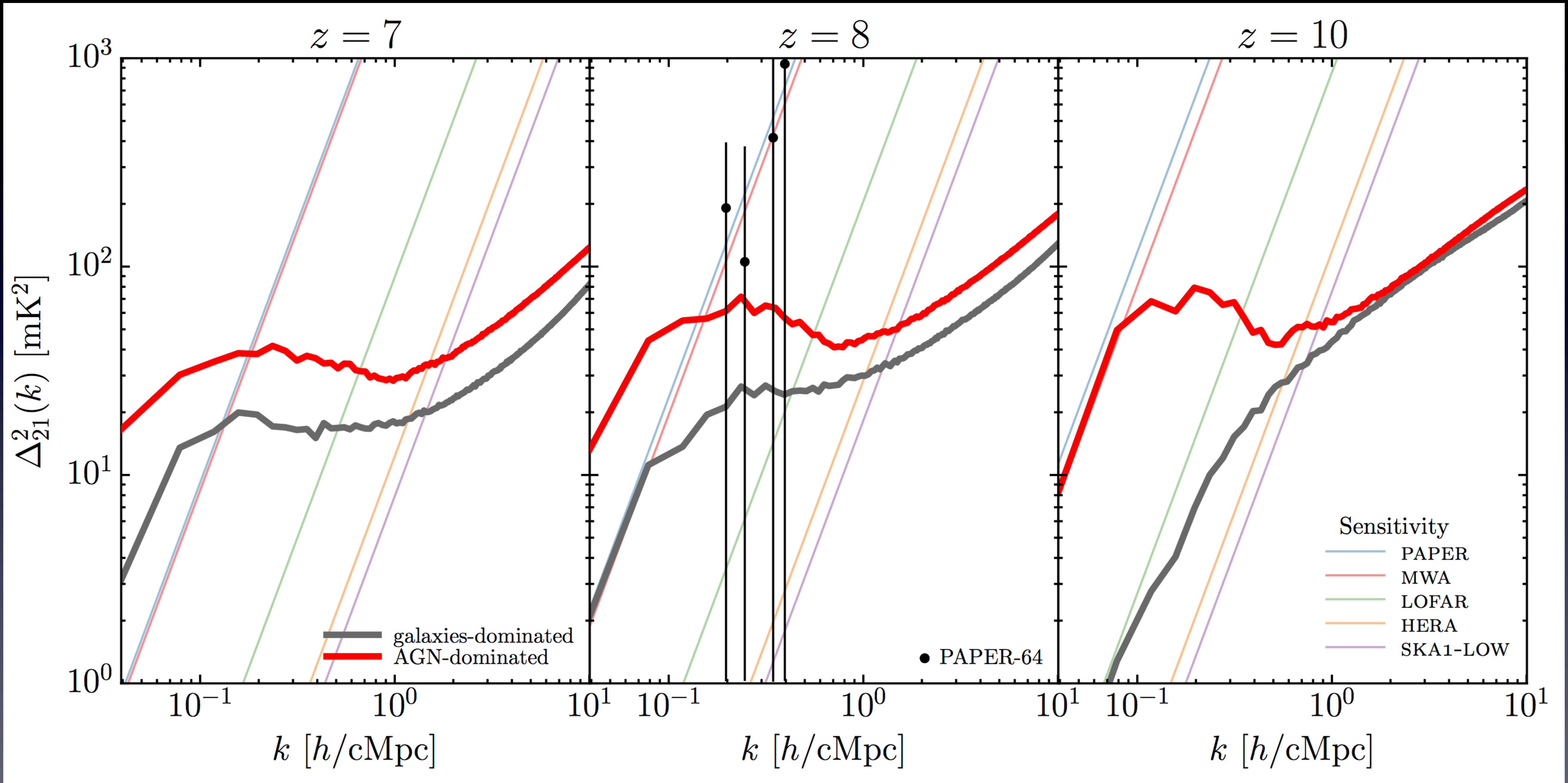
Compare with the galaxies-dominated case



Diagonal lines: sensitivities; Points: PAPER-64 (Ali et al. 2010)

Kulkarni et al. 2017

Factor of 5–10 increase in power



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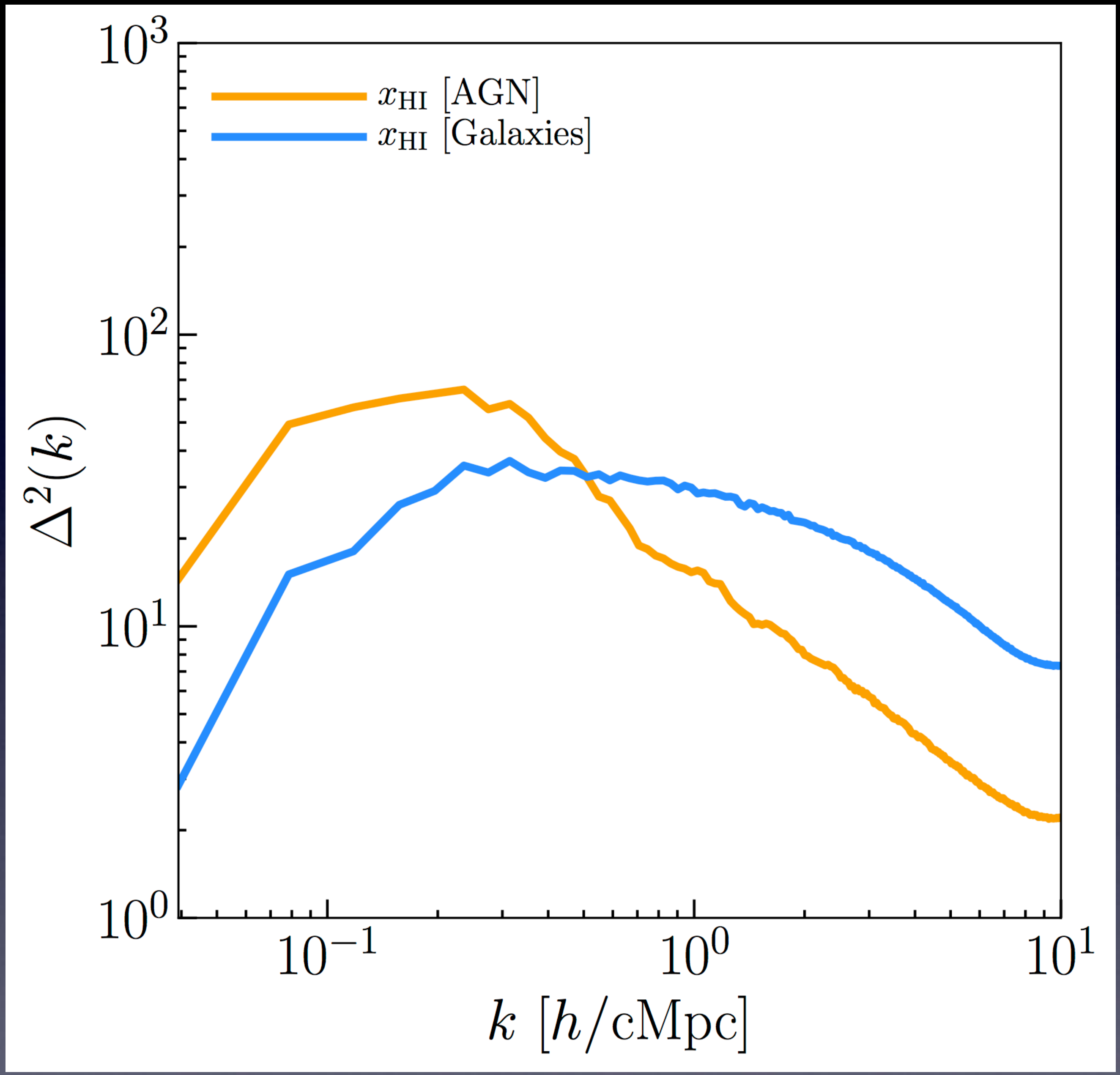
Peak power is only factor of ~2 smaller than PAPER limits. Potential source of constraint on high-z quasars.

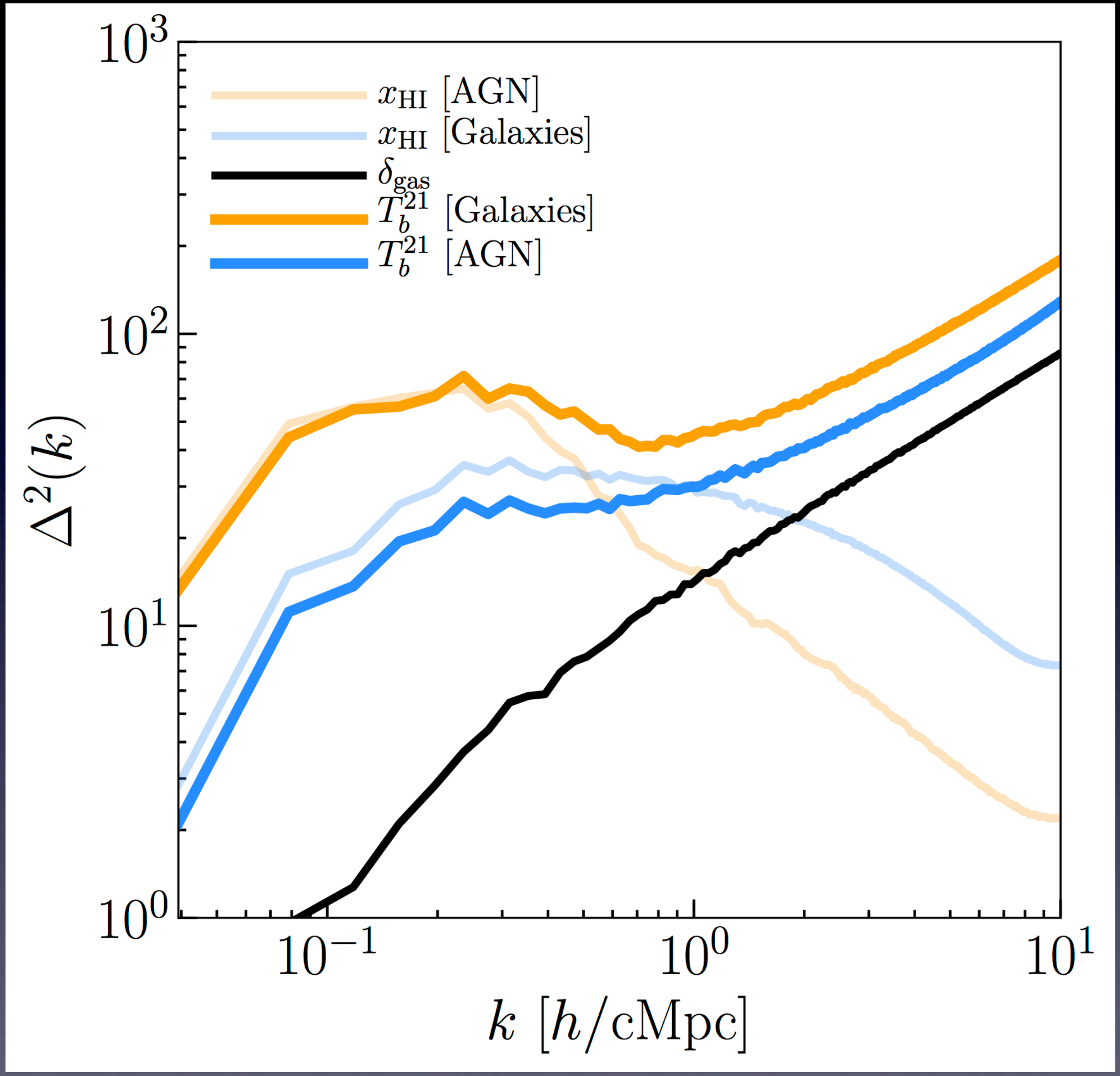
Increase in 21 cm power due to quasar clustering



$$\Delta^2_{21}(k) = b_\delta \Delta^2_\delta(k) + b_x \Delta^2_{x_{\rm HI}}(k) + \text{cross-correlations}$$

Enhanced clustering of quasars results increases 21 cm power on large scales

Increase in 21 cm power due to quasar clustering



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Enhanced clustering of quasars results increases 21 cm power on large scales

1. What are the implications for 21 cm?

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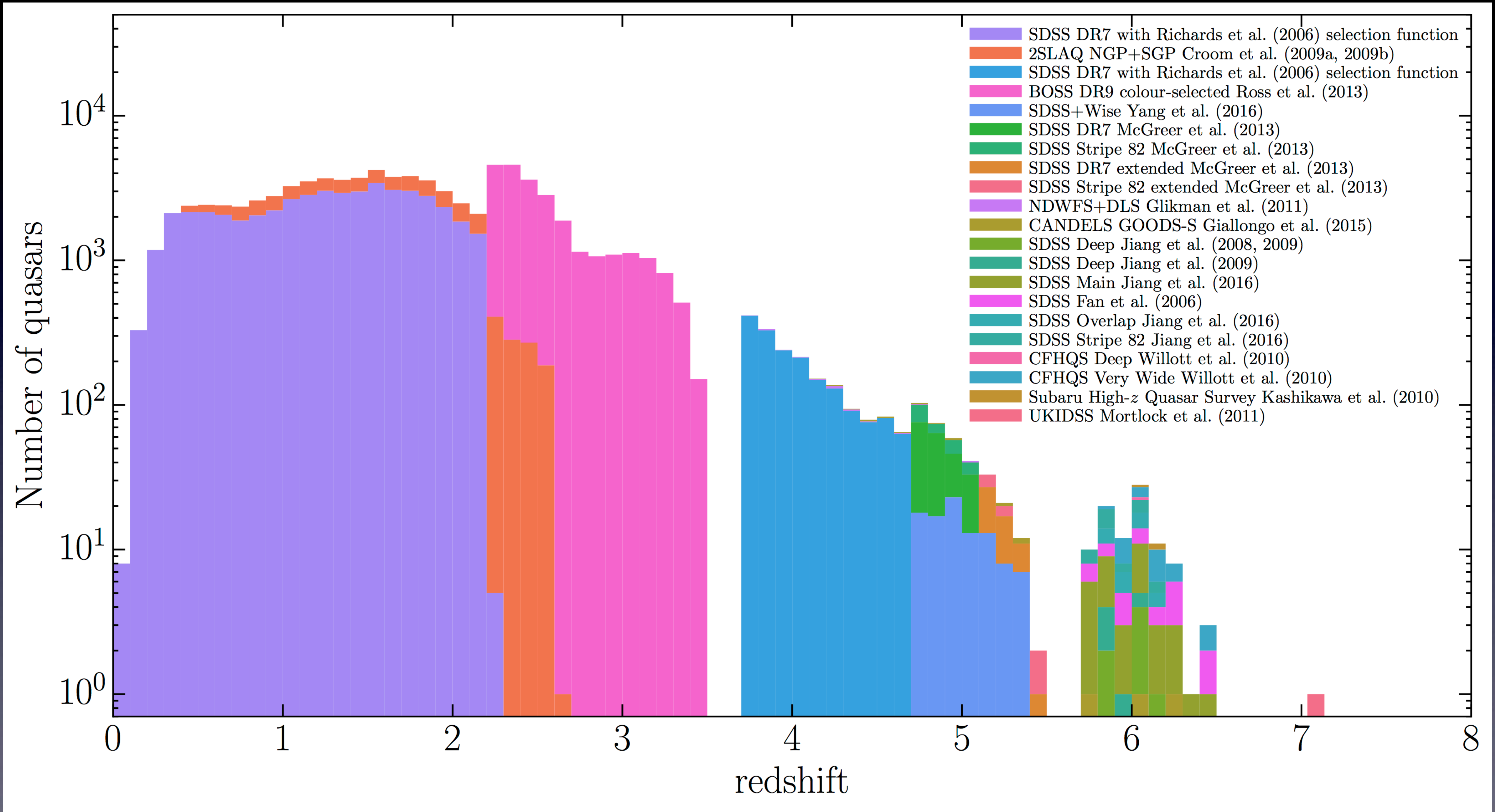
For and Against AGN-dominated Reionization

- Steep faint-end slope of quasar luminosity function (Giallongo et al. 2015)
- Lyα opacity fluctuations (Chardin et al. 2015; Bosman talk)
- Shallow bright-end slope of z ~ 7 galaxy luminosity function (Bowler et al. 2015, Bradley et al. 2014) and hard spectra (Stark et al. 2017)
- LyC escape from faint galaxies at high z unknown

- He II reionization and IGM temperature (D'Aloisio et al. 2016; Garaldi talk)
- Abundance of C IV absorption systems (Finlator et al. 2016)
- AGN X-ray luminosity function (Ricci et al. 2017)
- LyC escape fraction < 100% for AGN? (Micheva et al. 2017)

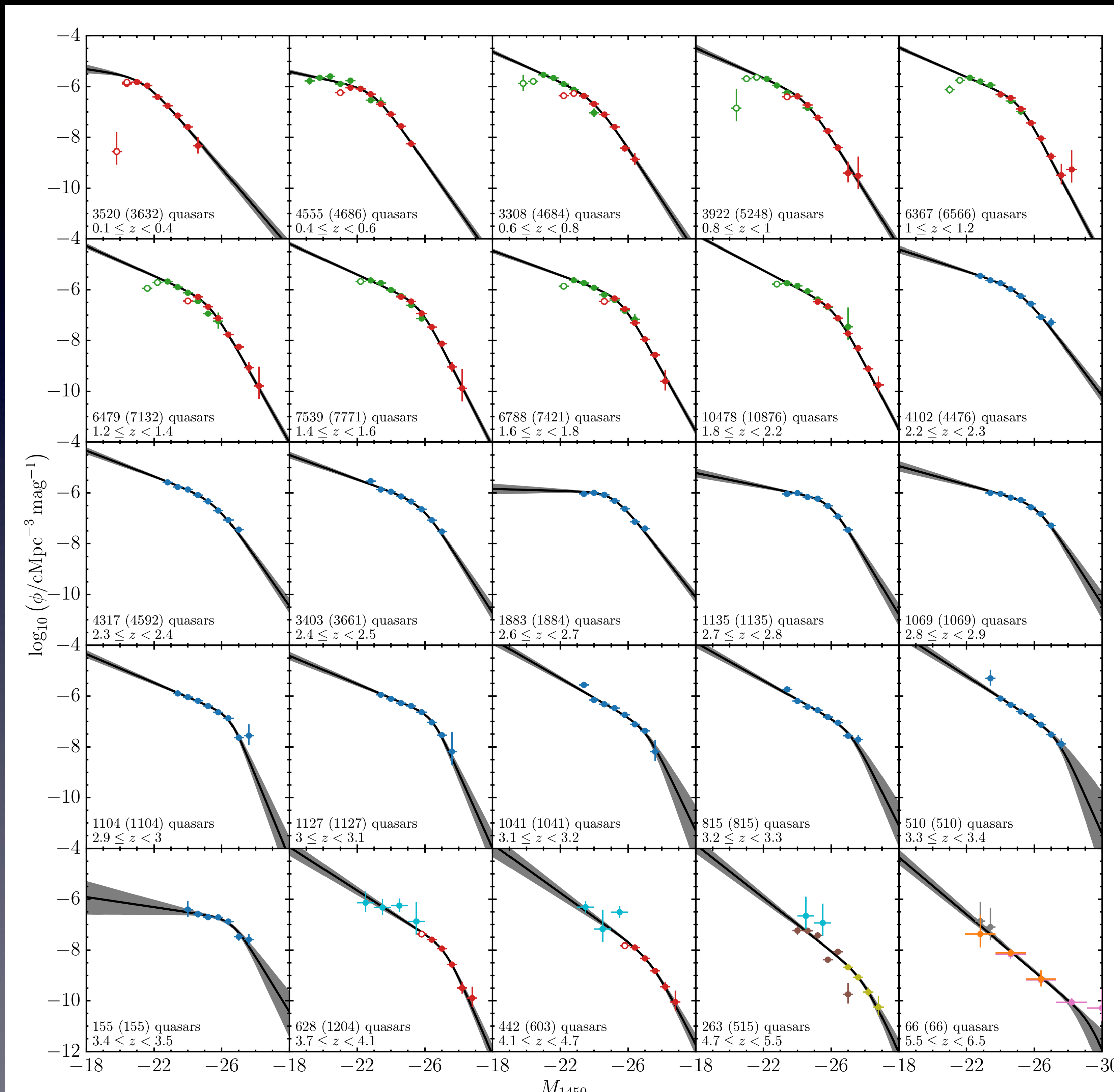
Prepare largest homogeneous quasar dataset



Kulkarni et al. *in prep*

84,566 quasars with spectroscopic redshifts and completeness estimates

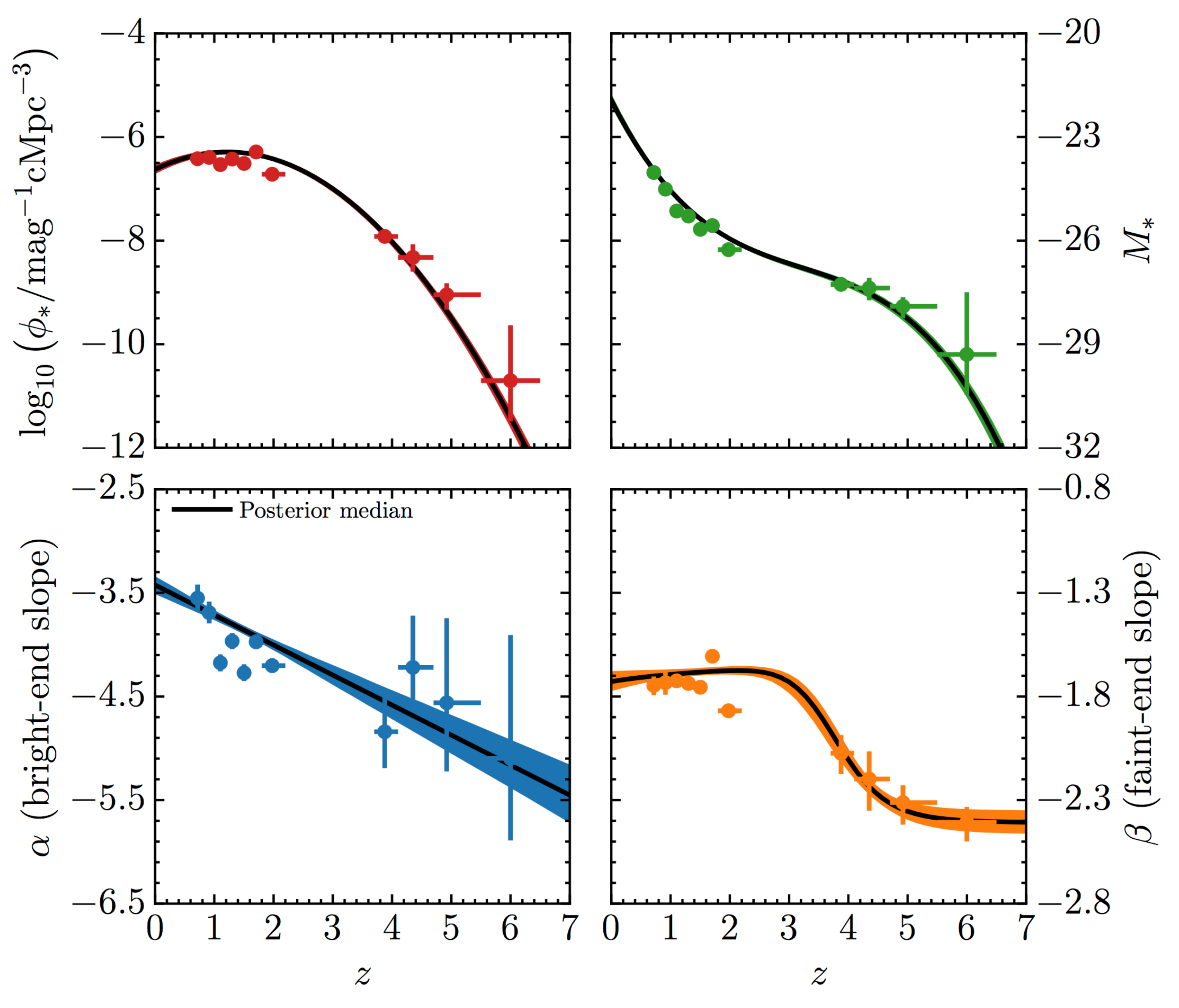
Reassessment of the Quasar Luminosity Function



Kulkarni et al. *in prep*

- Parameter variation in small z bins points to severe systematic errors in surveys
- Luminosity function is double power law at all redshifts
- Giallongo quasars somewhat more abundant than the spectroscopic sample

Quasar luminosity function evolution



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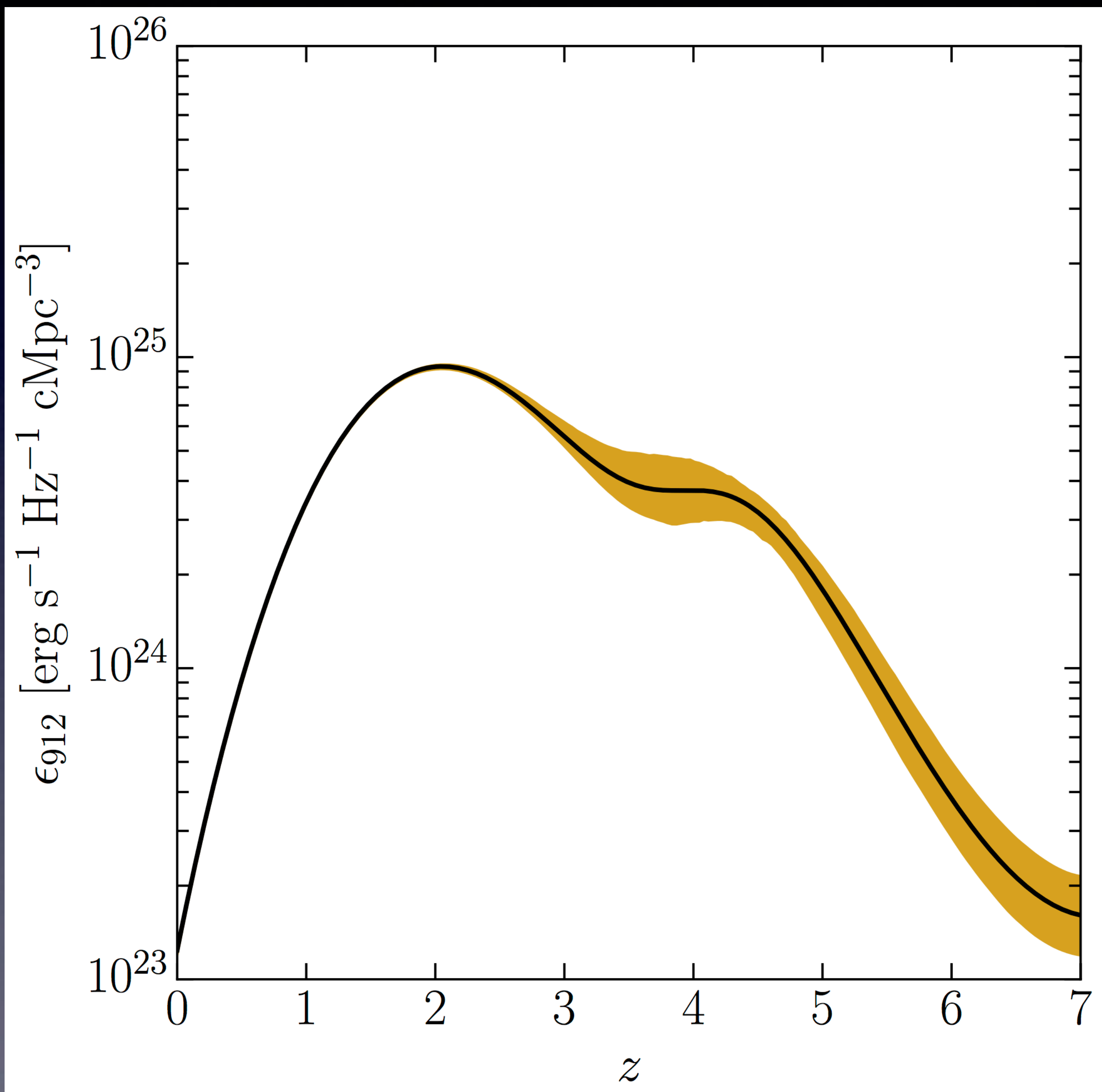
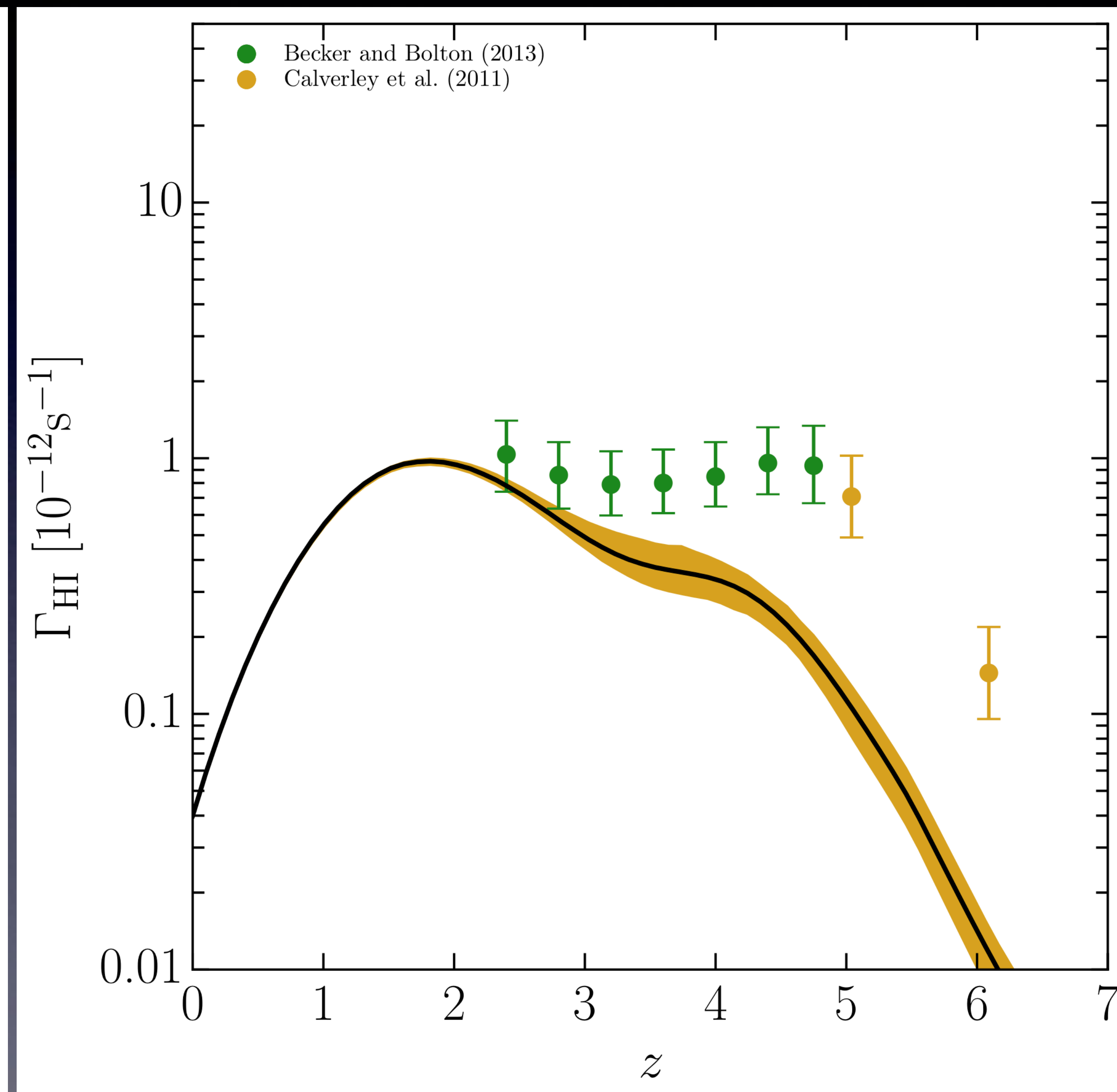
15-parameter flexible double power law describes data very well. Faint-end slope steepens rapidly at z ~ 4.

Quasar contribution sub-dominant

Ionizing Emissivity



Photoionization Rate

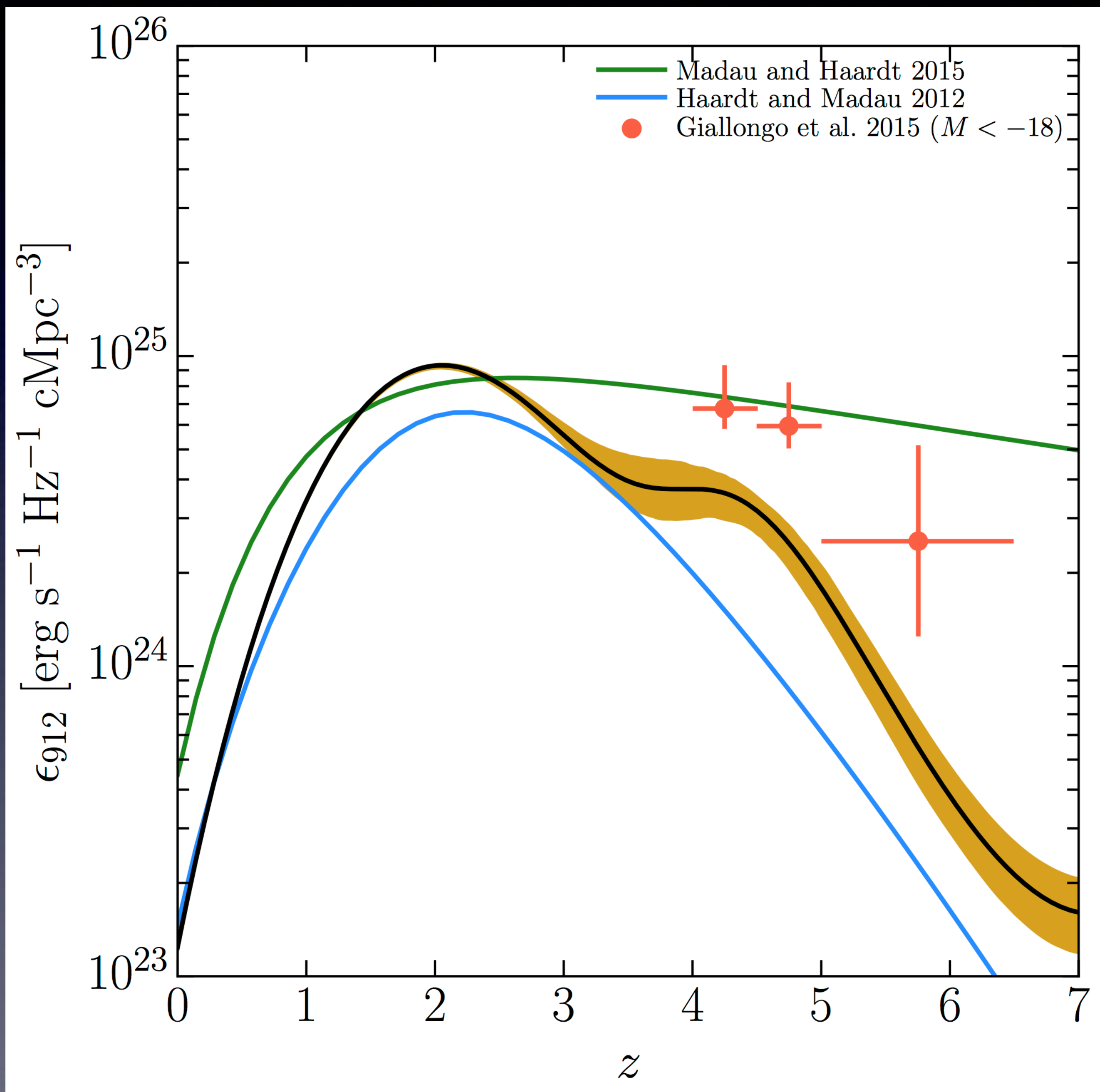


Kulkarni et al. *in prep*

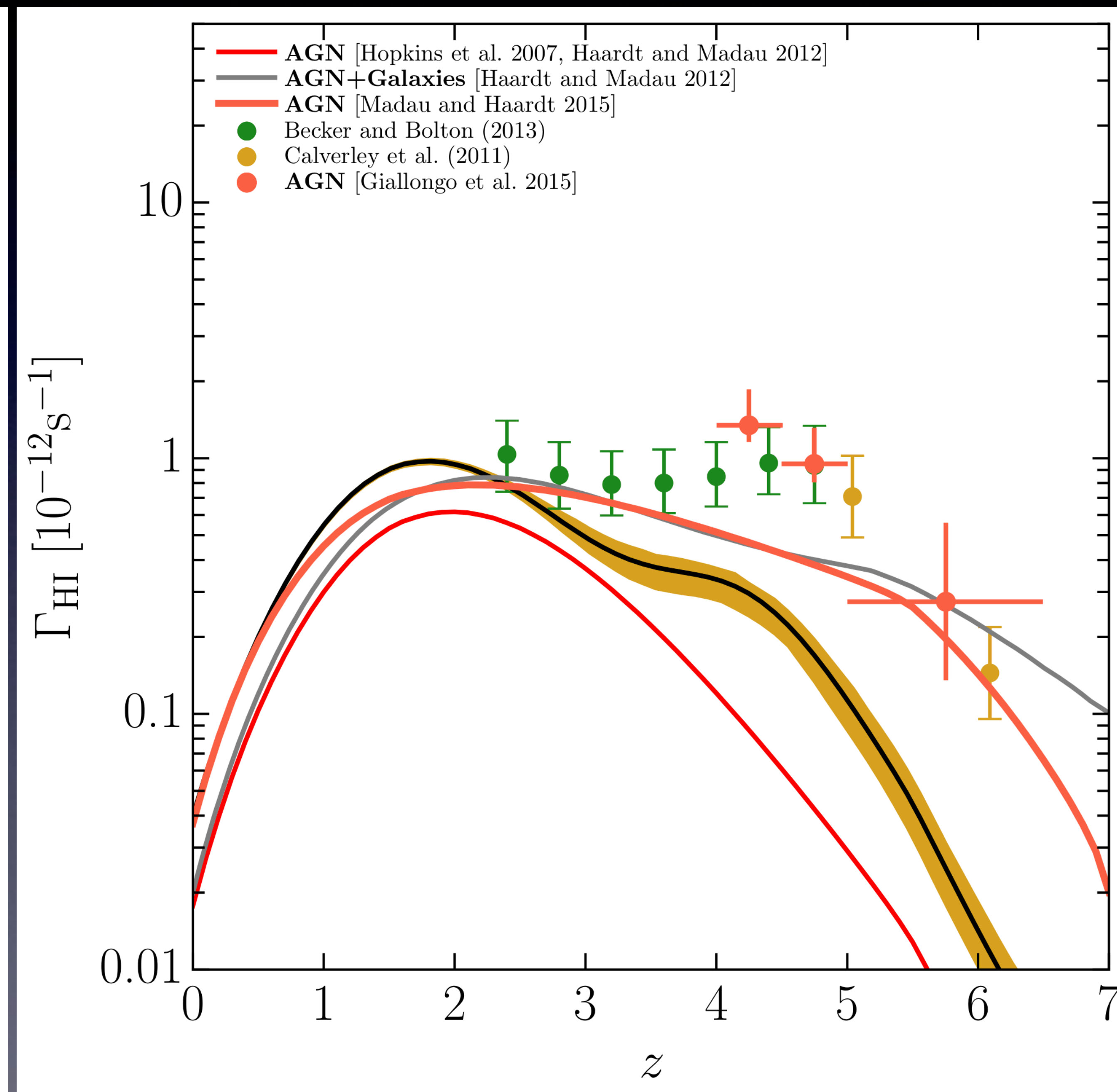
Preliminary result: quasar contribution to UV background less than the Giallongo inference

Quasar contribution sub-dominant

Ionizing Emissivity



Photoionization Rate



Kulkarni et al. *in prep*

Preliminary result: quasar contribution could still be non-negligible

Conclusions

- Quasars **increase large-scale 21 cm power**
- Quasar-dominated reionization histories will be the **first to be constrained** by 21 cm power spectrum measurements
- Quasar UV luminosity function **severely systematics-limited**
- New consistent analysis finds **sub-dominant but non-negligible** contribution of quasars