Present constraints on cosmic reionization

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Pune

Workshop on the Epoch of Reionization
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19 July 2016

Studying the epoch of reionization

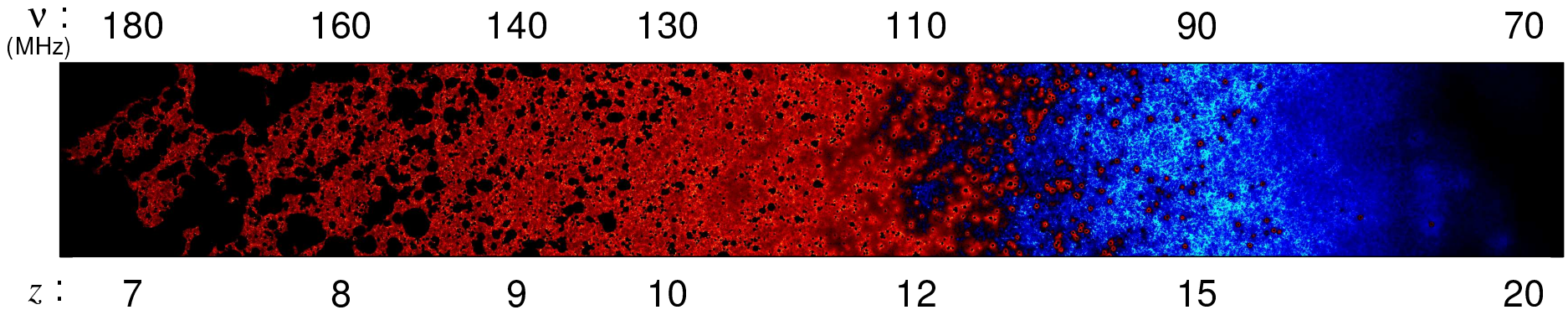
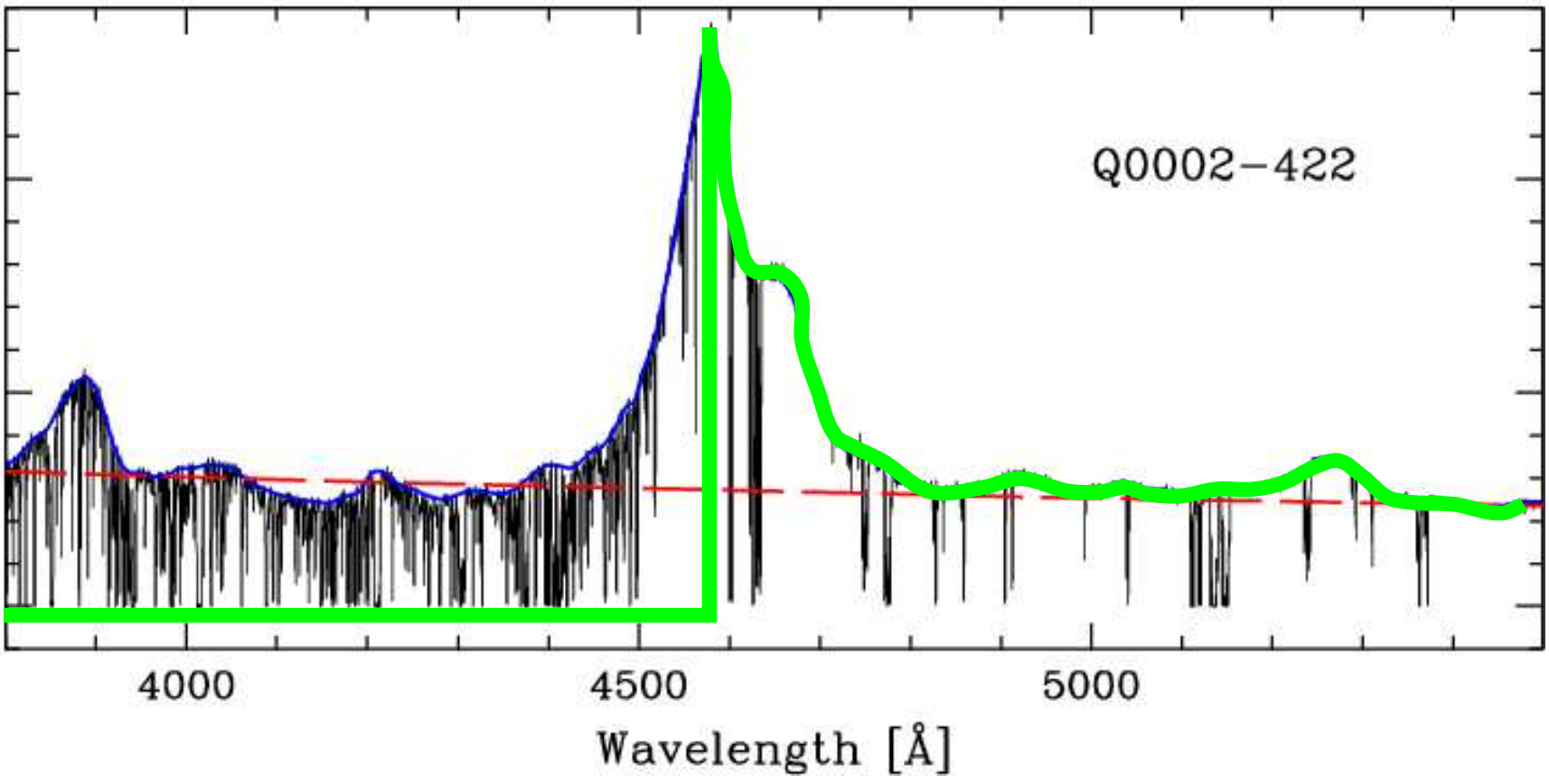


Figure courtesy Raghunath Ghara

- universe getting ionized by the first stars
- aim is to study the neutral hydrogen fraction $x_{\rm HI}(\mathbf{x}, z)$ as it decreases from ~ 1 to ~ 0
- get insights on the nature of the first stars

Evidence for reionization: quasar absorption spect

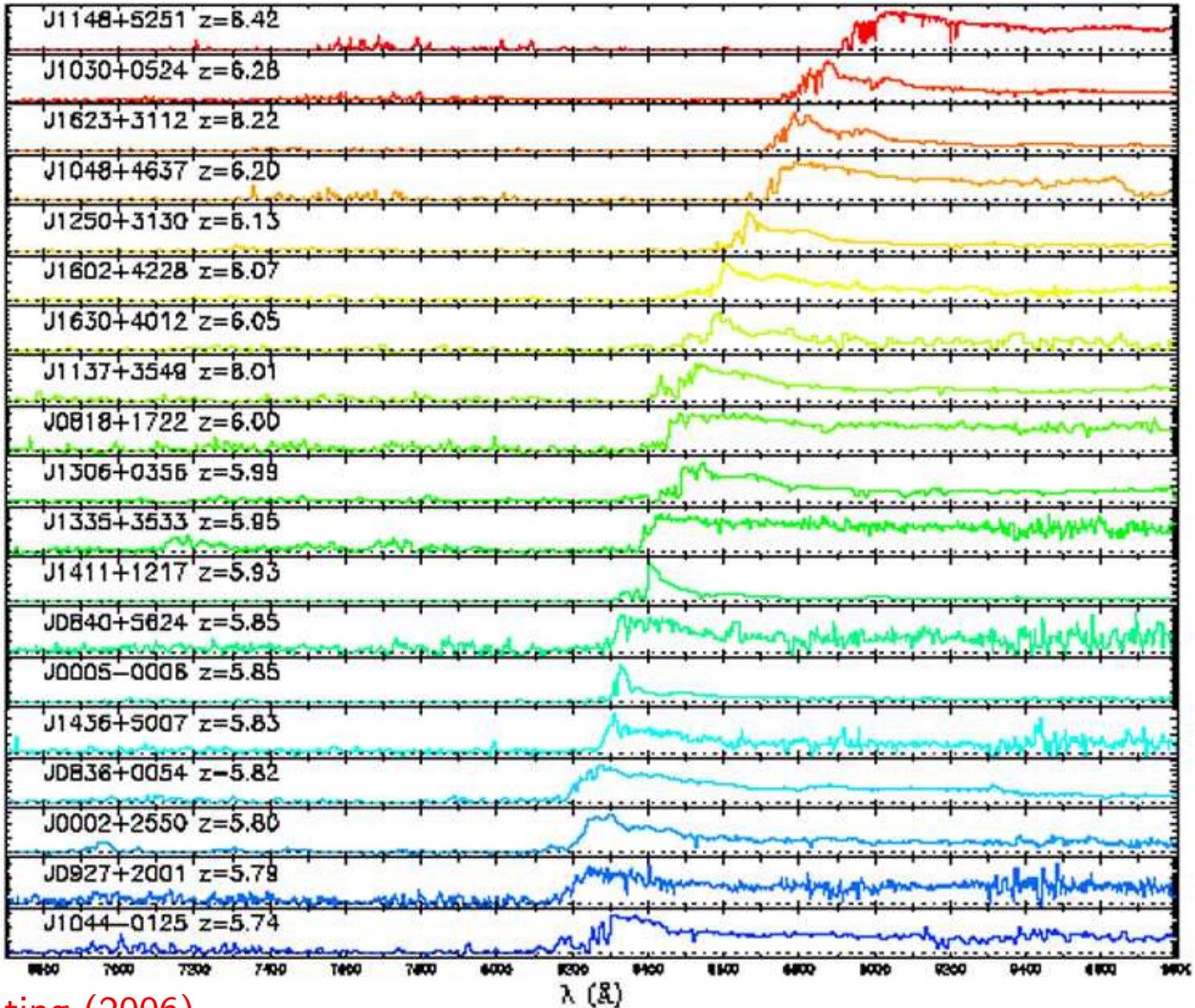


Observed flux $\sim$ Unabsorbed flux $\times$ exp $\left(-10^5\ x_{\rm HI}\right)$, where $x_{\rm HI} = \rho_{\rm HI}/\rho_H$.

The fact that there is non-zero flux implies that $x_{\rm HI} \lesssim 10^{-5}$

The conclusion holds till $z \sim 5.5$

Quasar absorption spectra at $z \gtrsim 6$

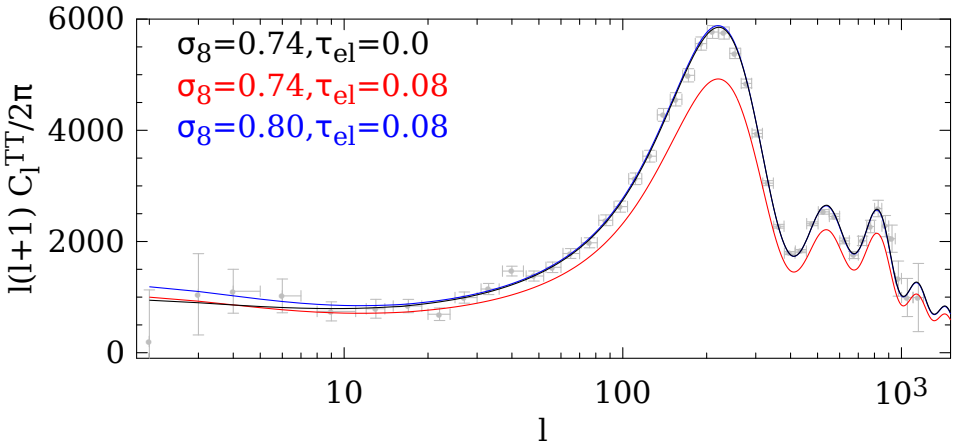


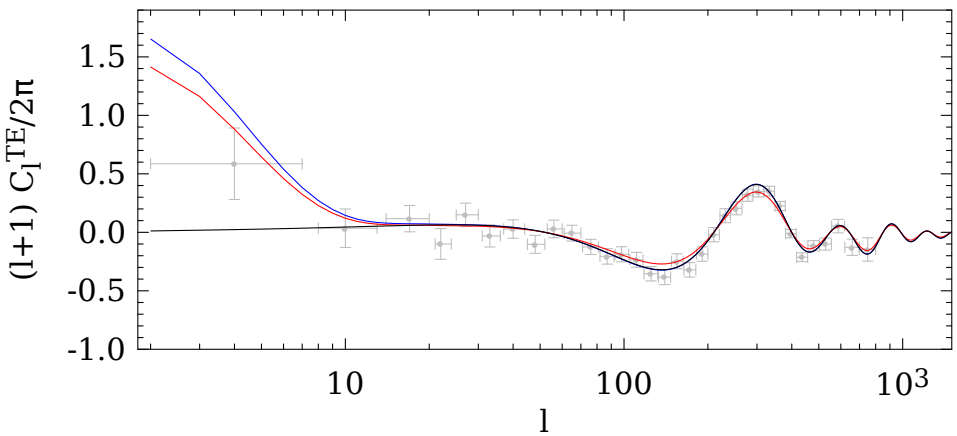
Fan, Carilli & Keating (2006)

$$F_{\rm obs} = F_{\rm cont}\ {\rm e}^{-\tau_{\rm GP}}, \quad \tau_{\rm GP} \sim \left(\frac{x_{\rm HI}}{10^{-5}}\right)$$

Probing reionization using CMBR

- CMBR photons scatter off free electrons. Current constraints on reionization come from





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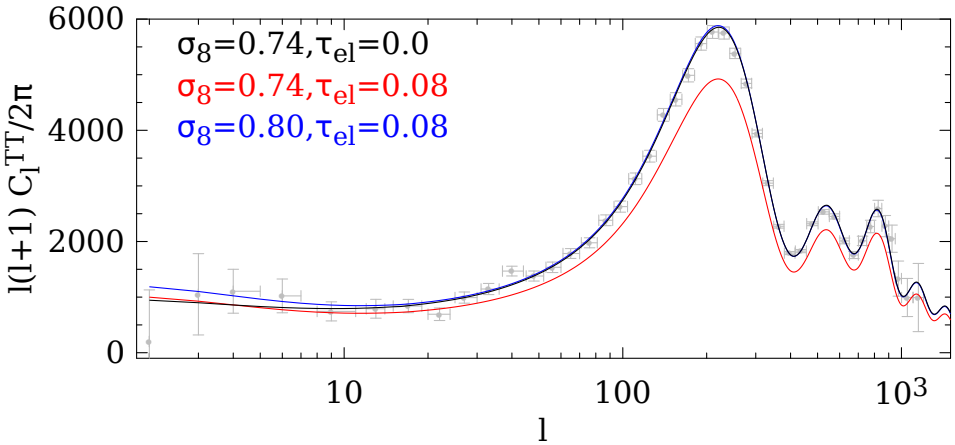

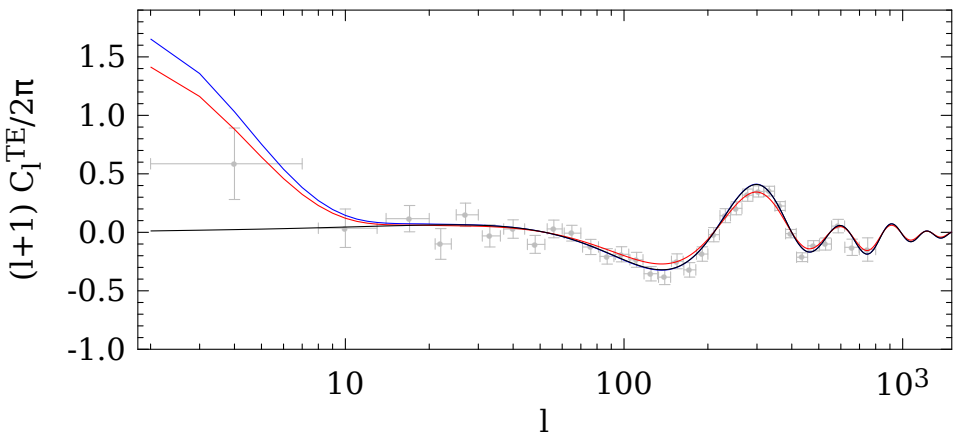

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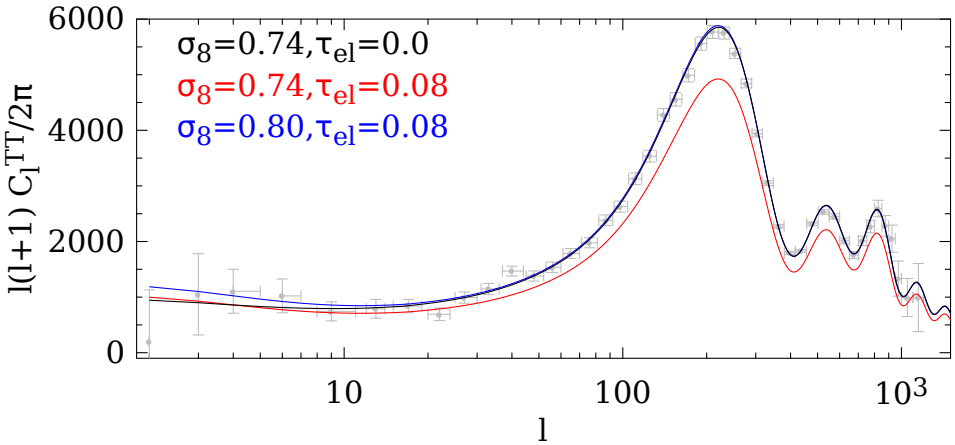
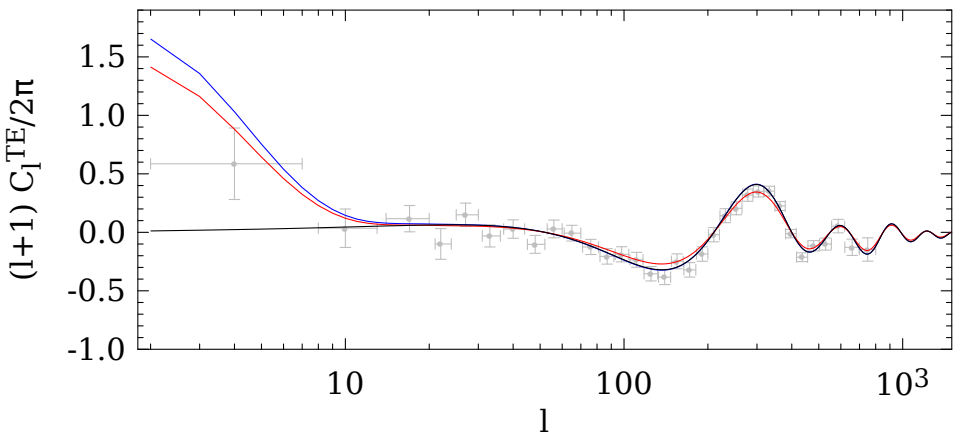
    (effect is degenerate with amplitude of density power spectrum)





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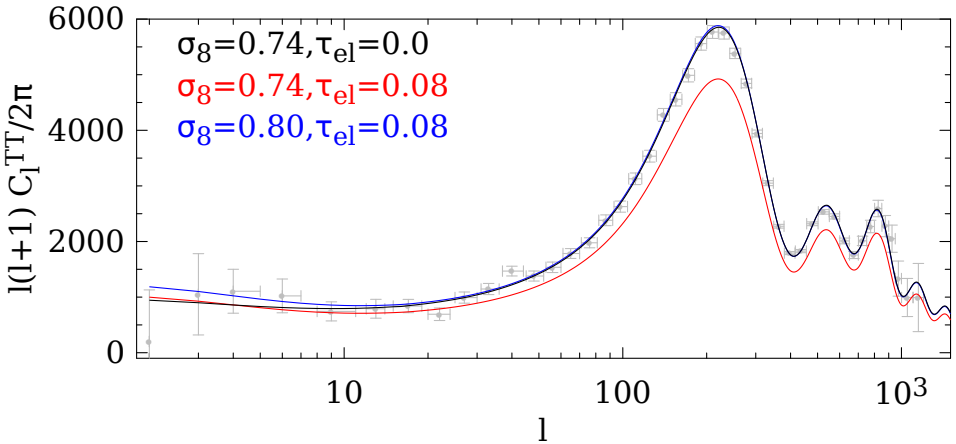

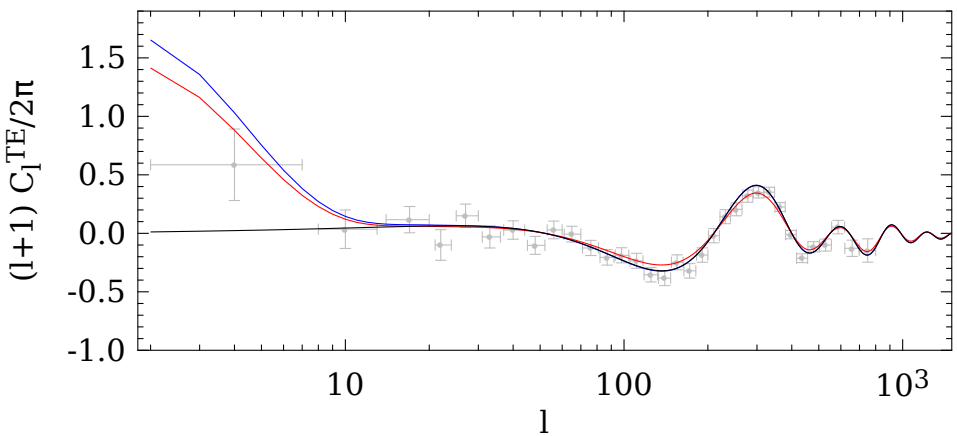

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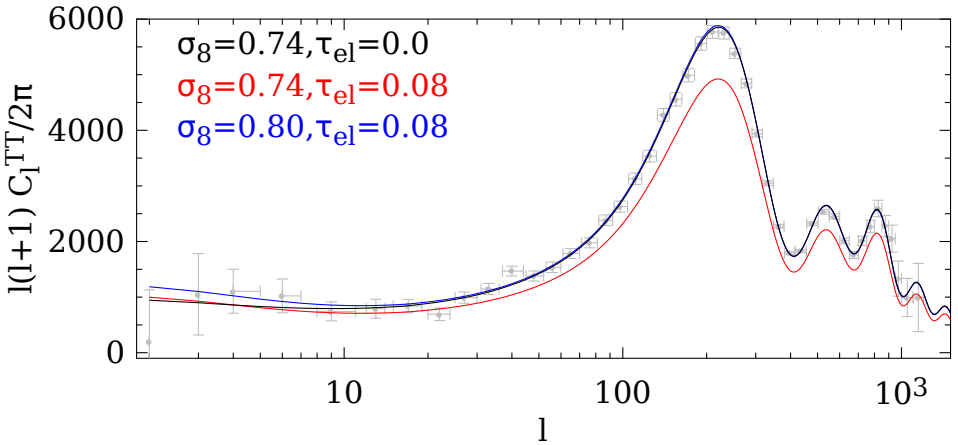
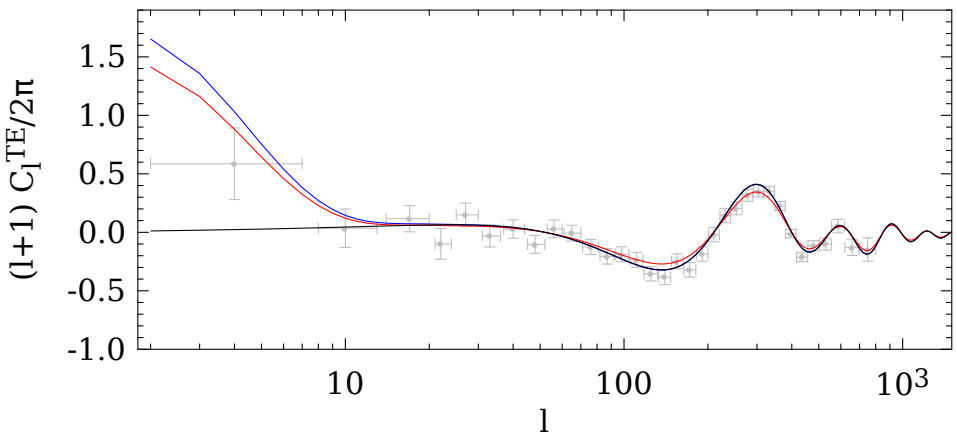
- The measured quantity in CMBR observations is the optical depth due to Thomson scattering off **free electrons**:

$$\tau_{\rm el} = \sigma_T c \int_{t_{\rm LSS}}^{t_0} {\rm d}t \; n_e \; (1+z)^3$$

Provided by reionization





Thomson scattering $\tau_{\rm el}$ from CMBR

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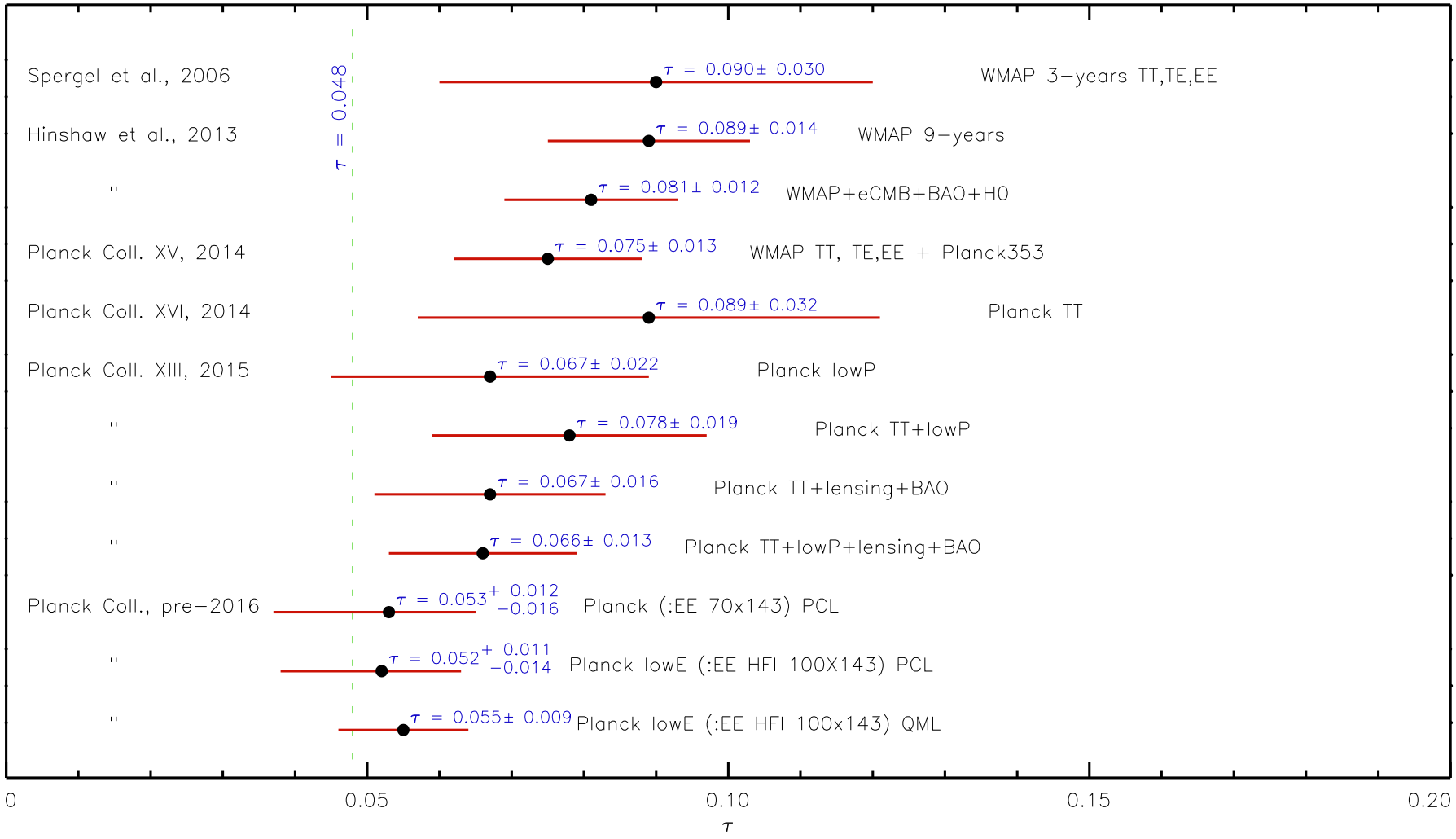
Planck Collaboration (2016)



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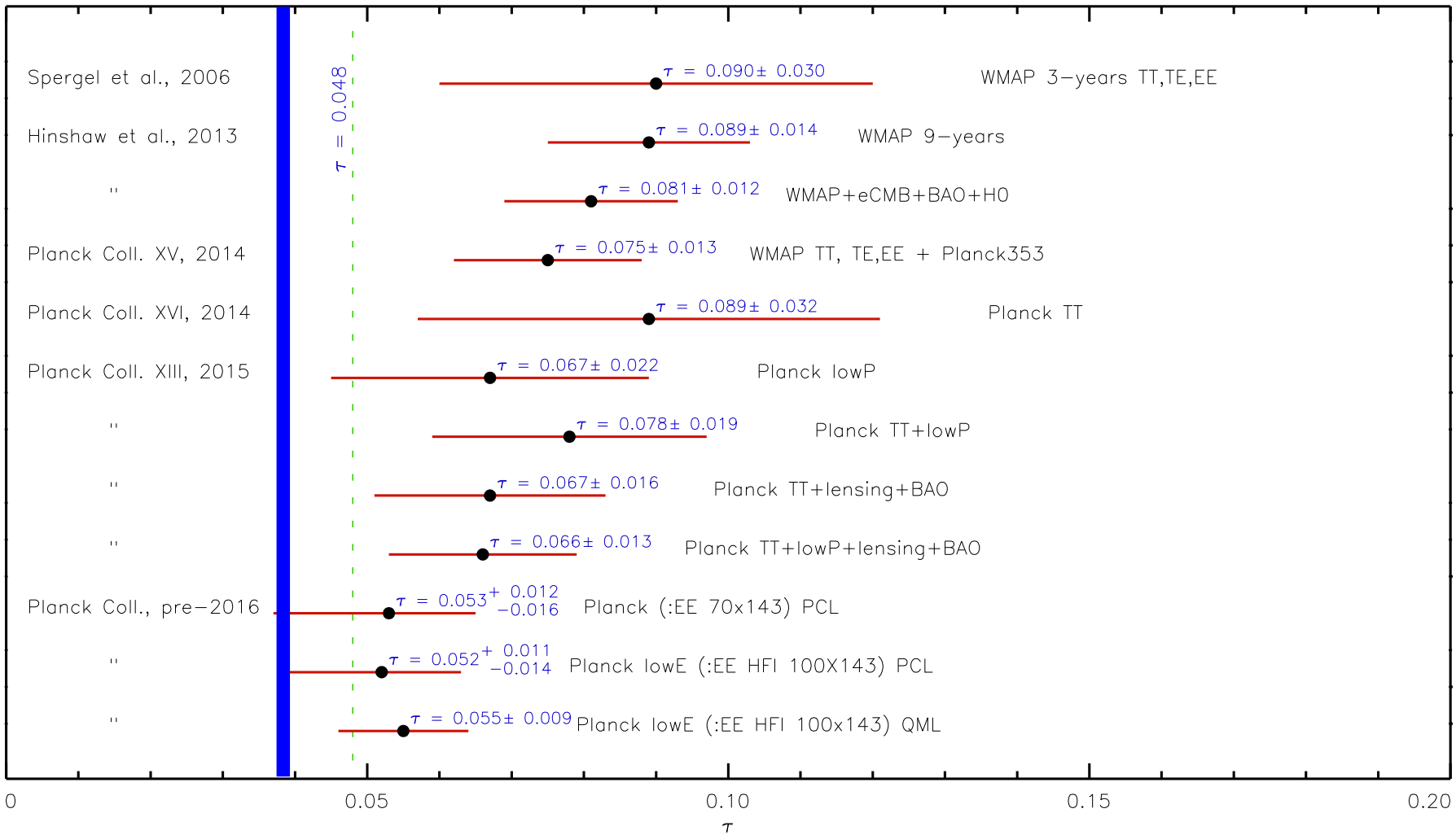

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  - Quasar absorption spectra imply that "redshift of reionization" is $z \sim 6$. No, they only imply that $x_{\rm HI} \gtrsim 10^{-4}$ at $z \sim 6$!

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  - reionization should start early enough to give a sufficiently high $\tau_{\rm el}$
  - reionization must end before $z \sim 6$
  - the model should produce the right number of photons such that $x_{\rm HI} \gtrsim 10^{-4}$ at $z \sim 6$

Analytical models: basic formalism

Choudhury & Ferrara (2005, 2006)

- Average the radiative transfer equation over large volumes $\Longrightarrow$ evolution of volume filling factor of ionized regions

$$\frac{\mathrm{d}Q_{\mathrm{HII}}}{\mathrm{d}t} = \frac{\dot{n}_{\gamma}}{n_H} - Q_{\mathrm{HII}} \mathcal{C}_{\mathrm{HII}} \frac{n_e}{a^3} \alpha_R(T)$$

  can be extended to account for density-dependent reionization
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- Supplemented by temperature and species evolution equations

Analytical models: sources

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- Assumption: reionization driven primarily by galaxies. Photon production rate:

$$\dot{n}_\gamma = N_{\mathrm{ion}} \left(\frac{\Omega_b}{\Omega_m}\right) \frac{\mathrm{d}f_{\mathrm{coll}}}{\mathrm{d}t}$$

Number of ionizing photons in the IGM per baryons

Collapse rate of dark matter haloes

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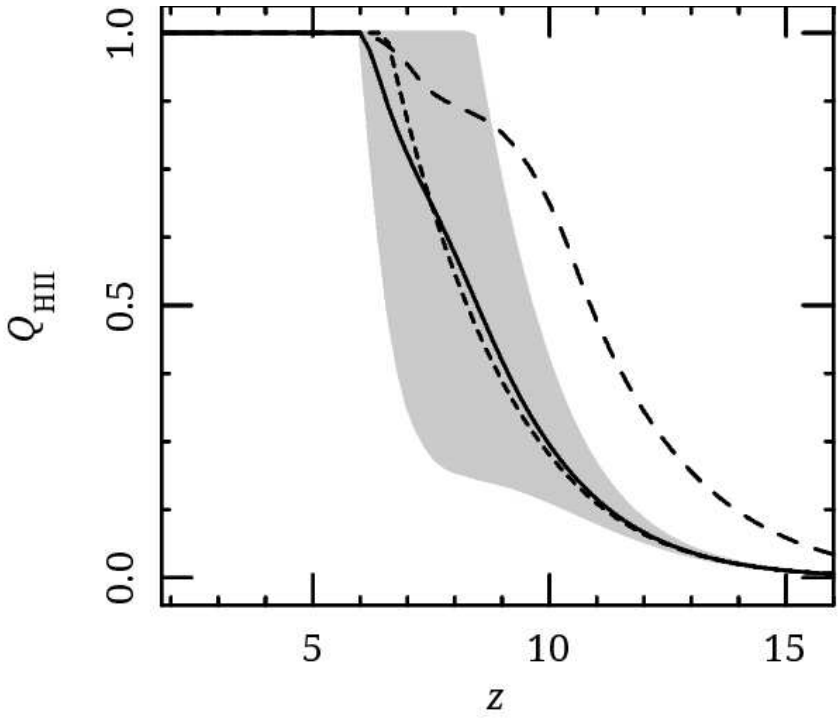
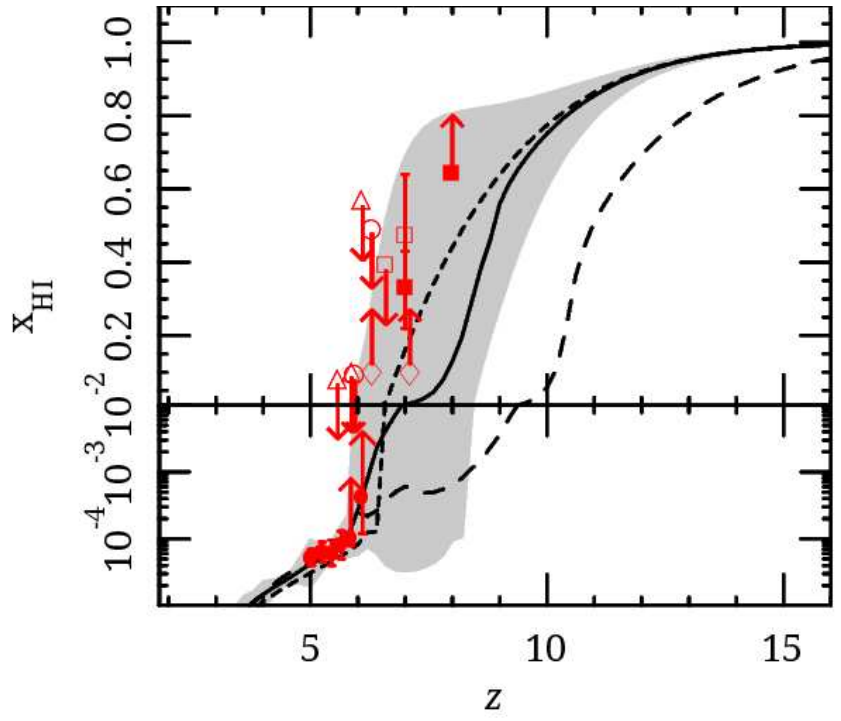
- Predict observables, e.g., $\tau_{\rm el}$ (or C_ℓ), photoionization rate (or mean transmitted flux), ...
- full MCMC analysis accounting for $N_{\rm ion}(z)$ and other free parameters

Data constrained models





Mitra, **Choudhury** & Ferrara (2015)

Constraints based on

- Planck15 data on $\tau_{\rm el}$
- quasar absorption line measurements at $z \lesssim 6$ (either $\Gamma_{\rm HI}$ or $\langle \tau_{\rm eff} \rangle$)
- prior on $x_{\rm HI}$ at $z \sim 5.5 - 6$ based on "dark pixel" fraction
  McGreer, Mesinger & D'Odorico (2015)

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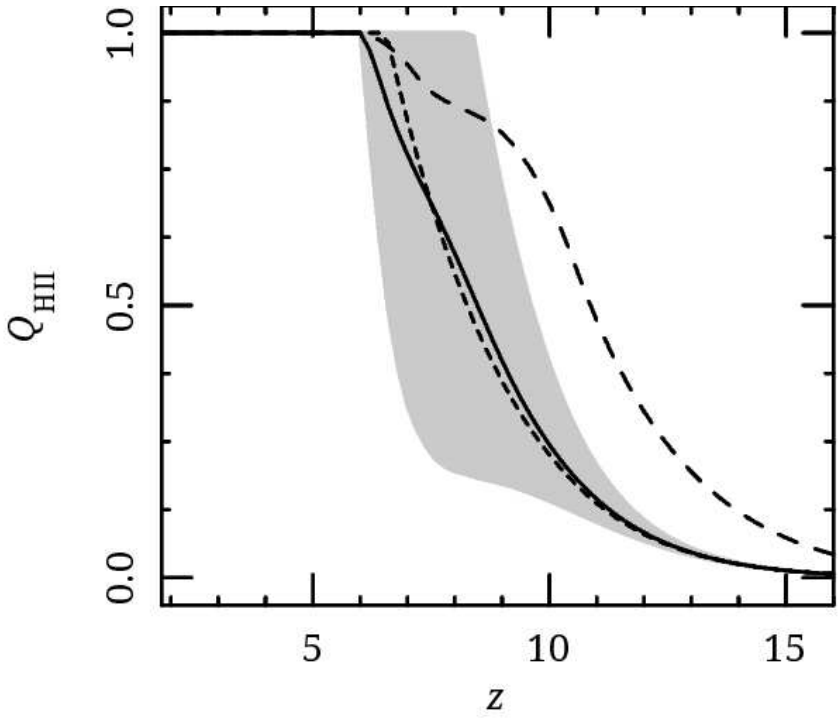
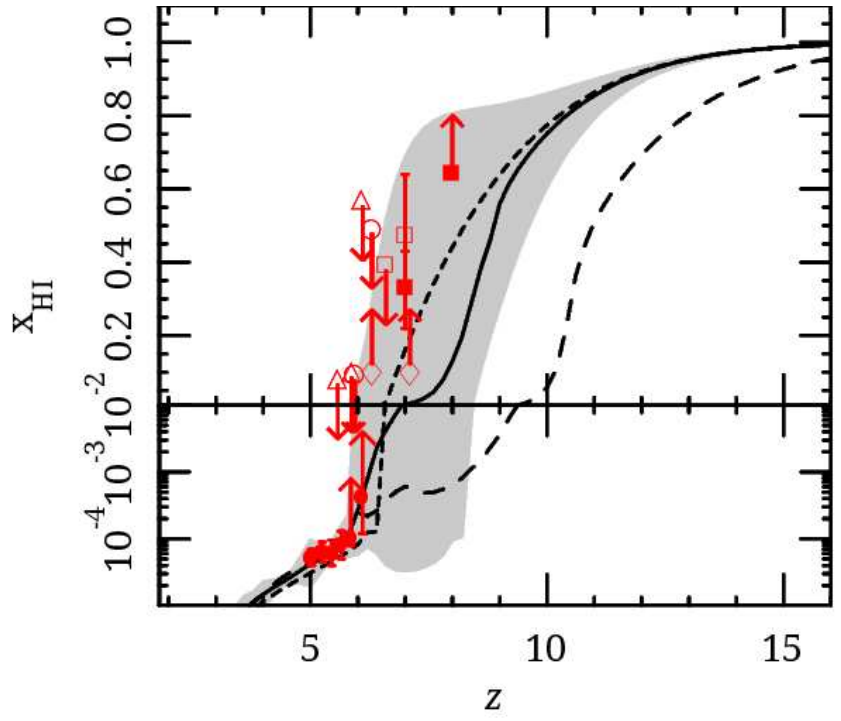
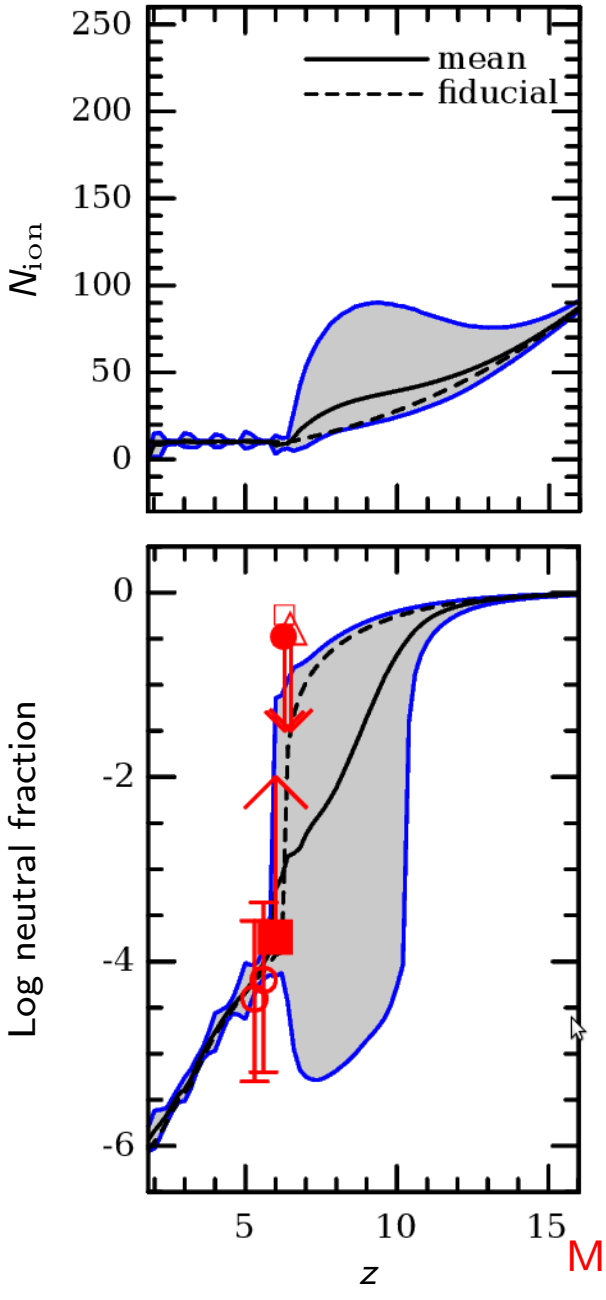




Mitra, **Choudhury** & Ferrara (2015)

- reionization starts at $z \sim 12 - 15$
- 50% ionized at $z \sim 6 - 10$
- large uncertainties at $7 \lesssim z \lesssim 10$

Constraints on reionization history: Planck (2015)



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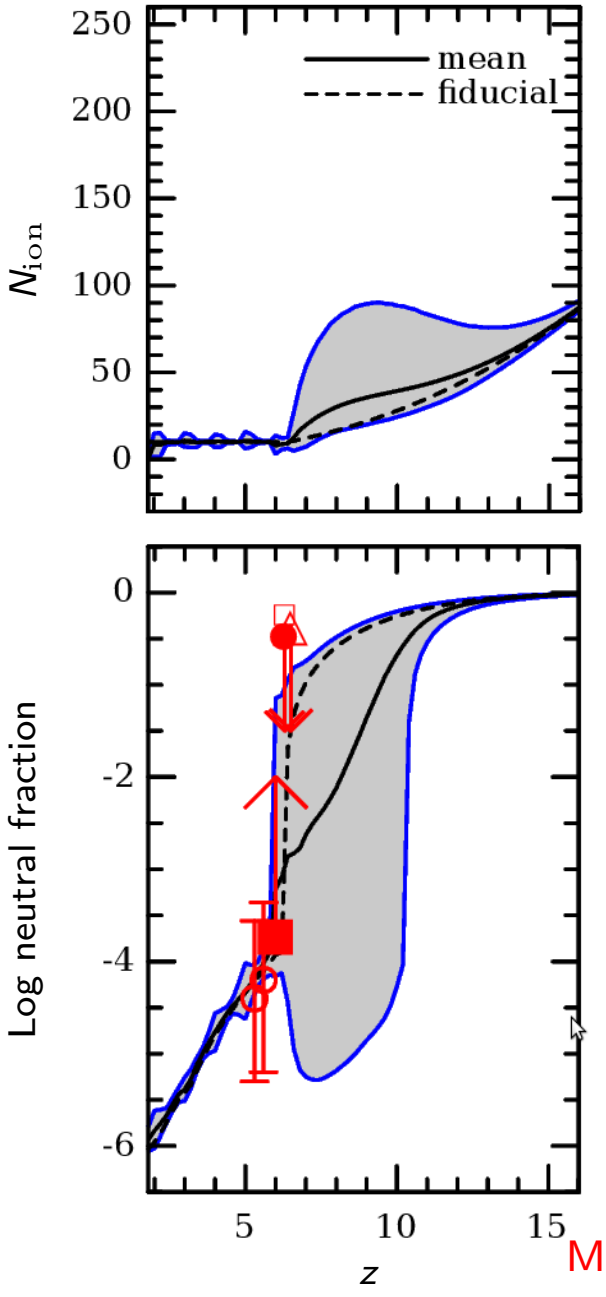

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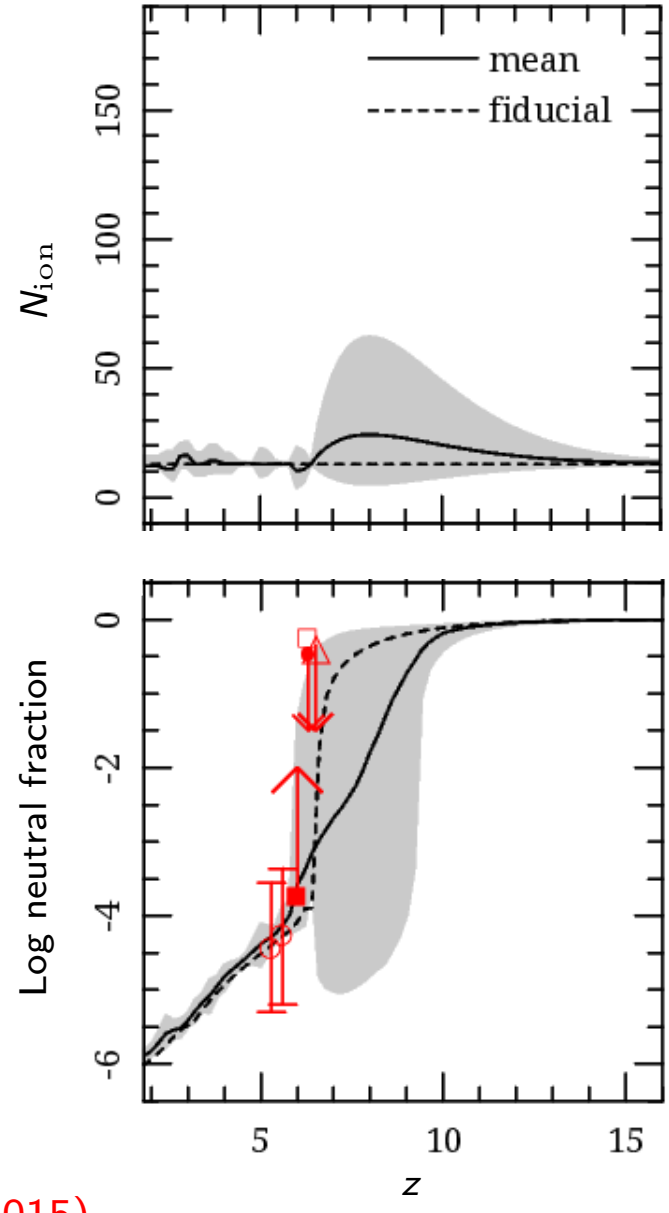

Mitra, **Choudhury** & Ferrara (2015)

How to constrain reionization at $z \gtrsim 7$?

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- Galaxy luminosity function: uncertain escape fraction
- Quasar absorption spectra (damping wings/near zones)
- IGM temperature
- Lyman-α emitters (number density, also clustering)
- Future: 21 cm experiments

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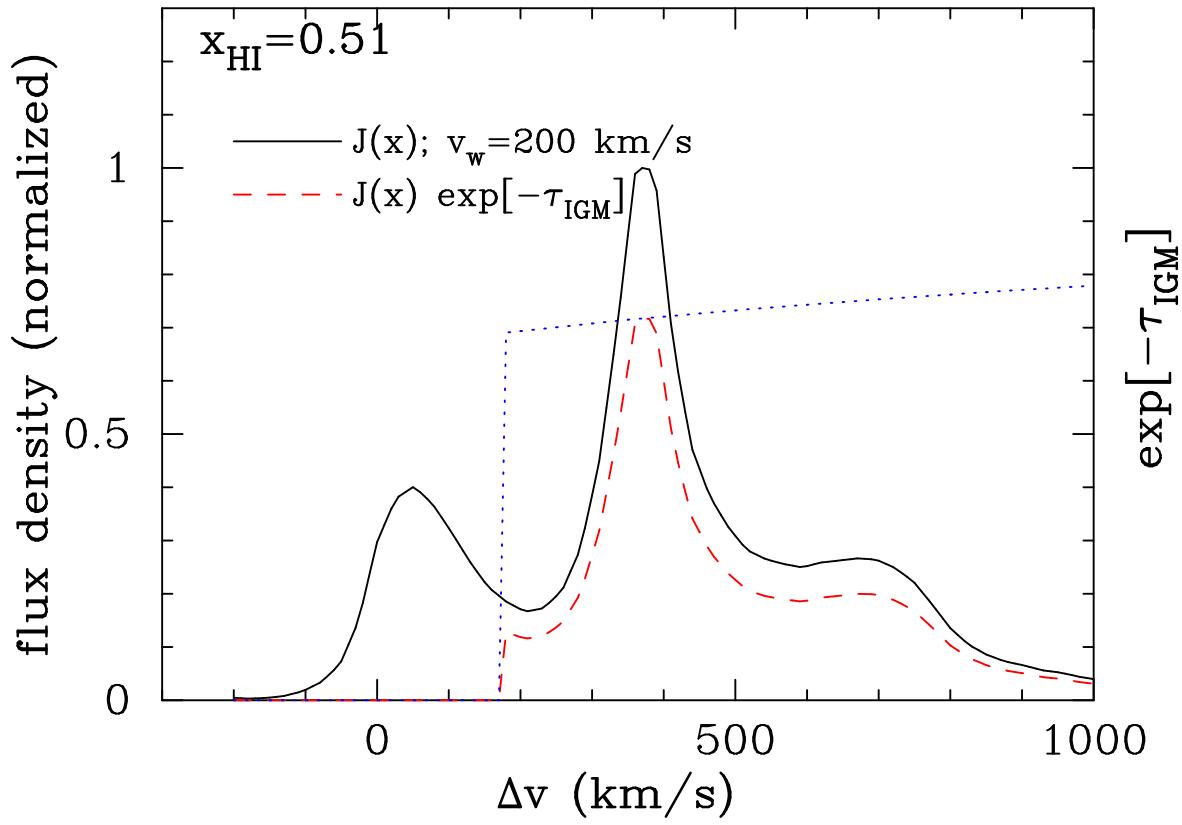
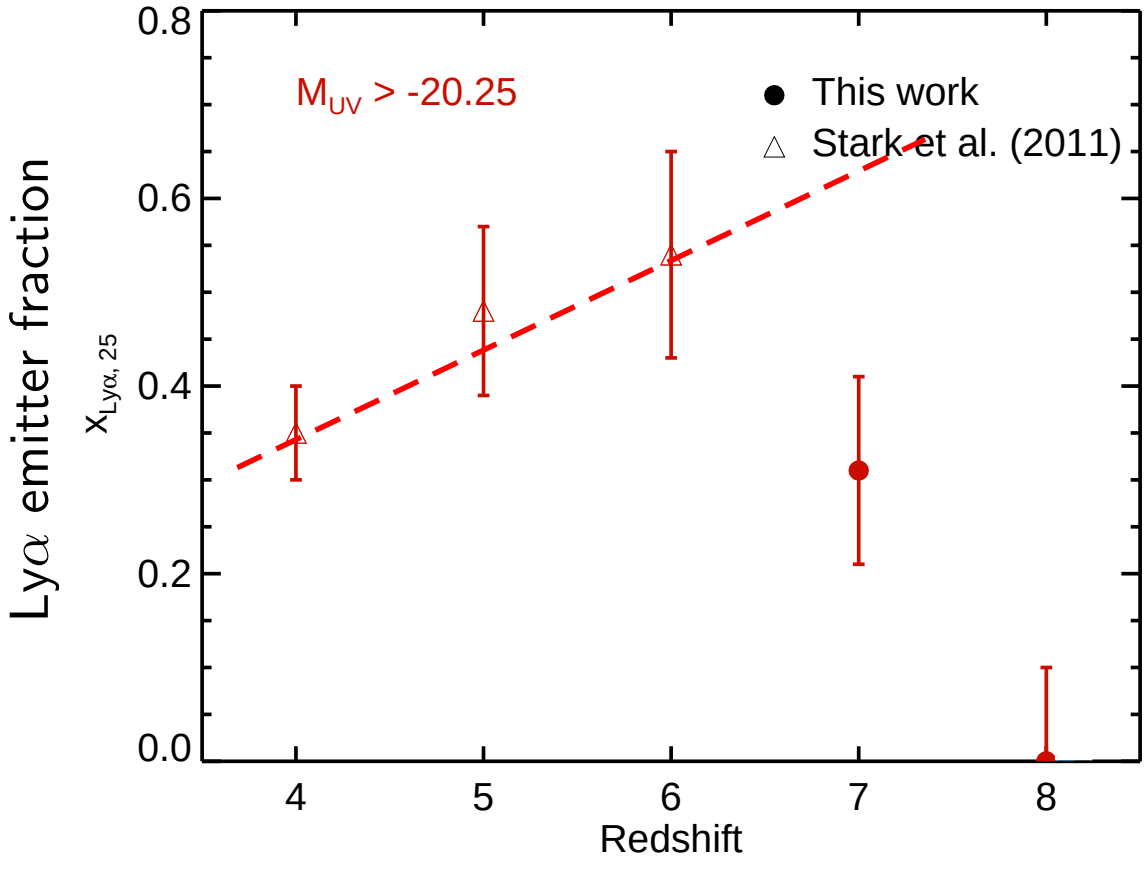
Lyα emitters and reionization



Dijkstra, Mesinger & Wyithe (2011)

Fraction of galaxies having Lyα emission



Schenker et al (2014)

"Sharp change" in behaviour at $z > 6$.

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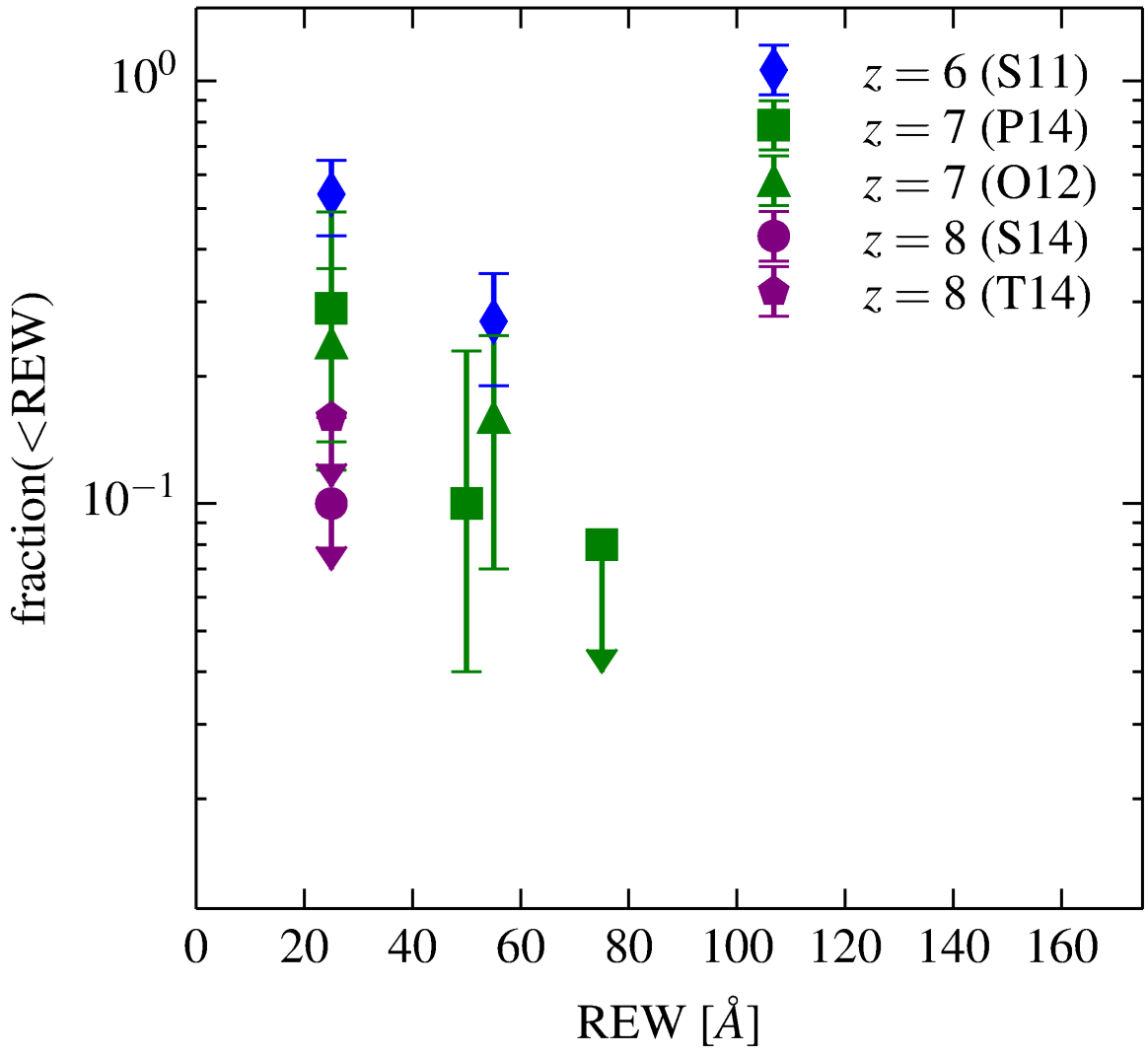

Uncertainties and challenges

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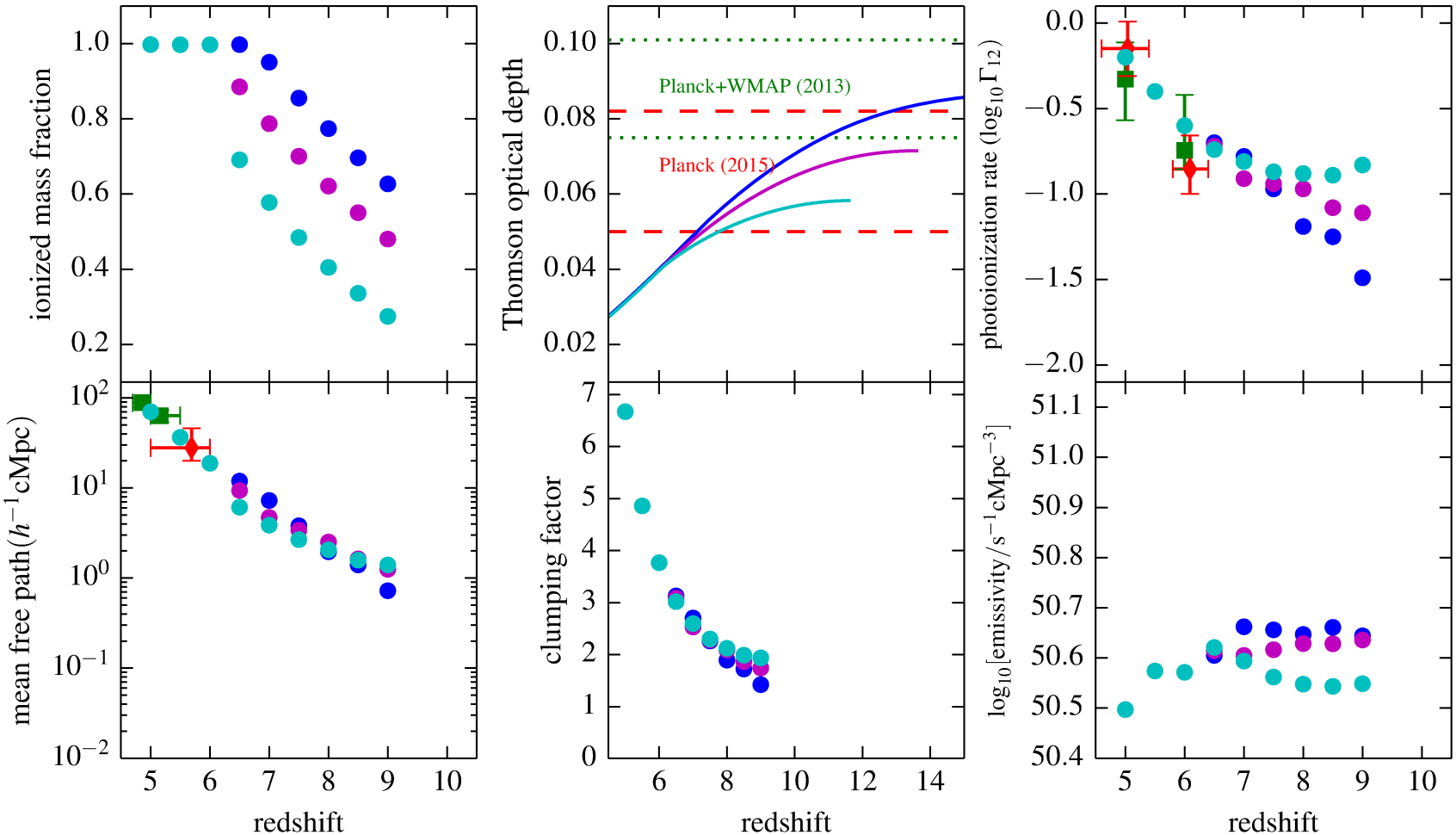
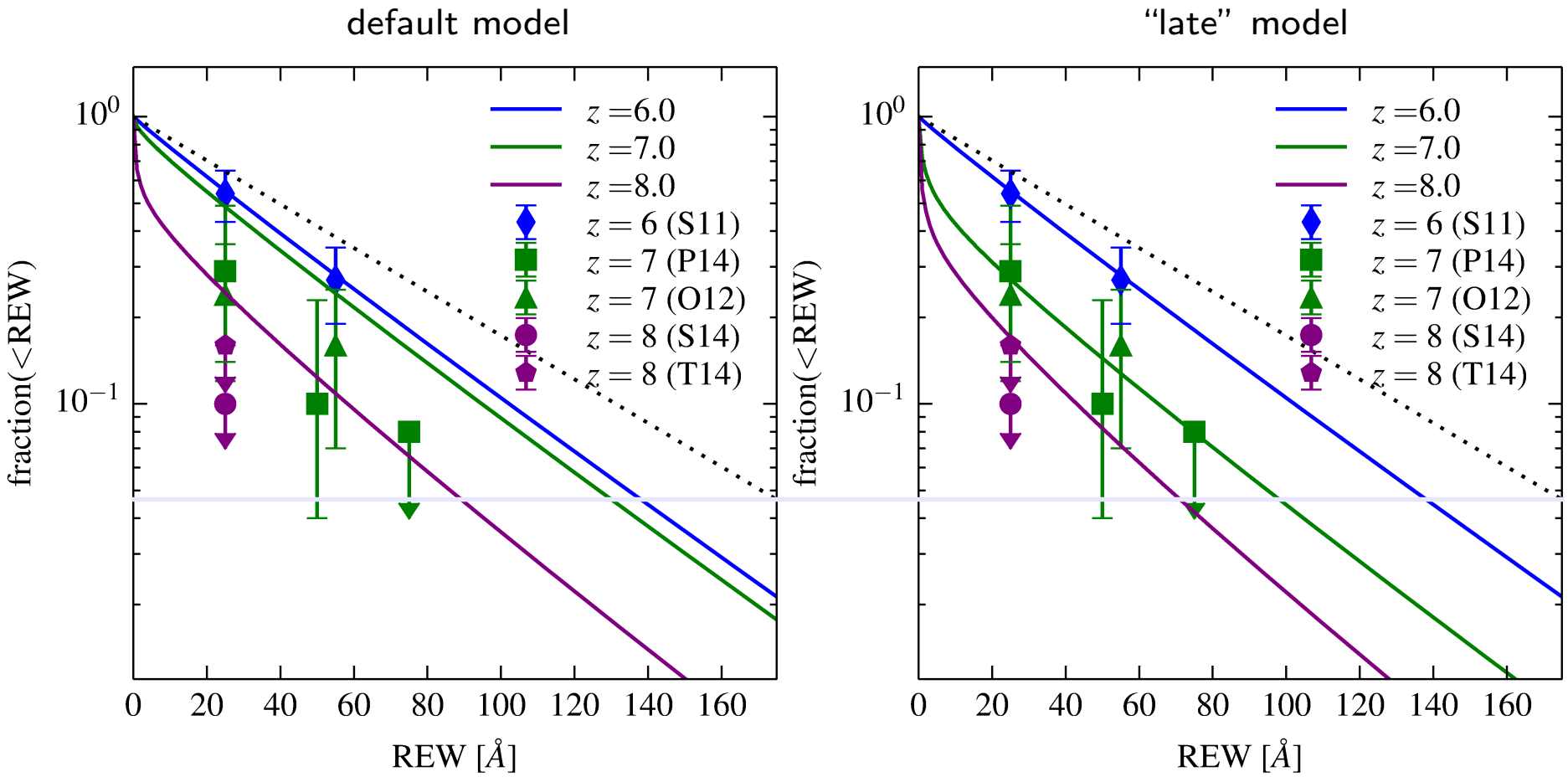
- decrease in the space density of Lyα emitters at $z > 6$.
- intrinsic, or damping wing of the surrounding neutral medium?
- modelling challenges: reionization topology, optically thick (super-) Lyman-limit systems
- use high (effective) dynamic range numerical simulations
  Choudhury, Puchwein, Haehnelt & Bolton (2015), Mesinger et al (2015), Kakiichi et al (2015)

Calibrating the reionization simulations



- Early ($\tau = 0.084$)
- Late ($\tau = 0.068$)
- Very Late ($\tau = 0.055$)

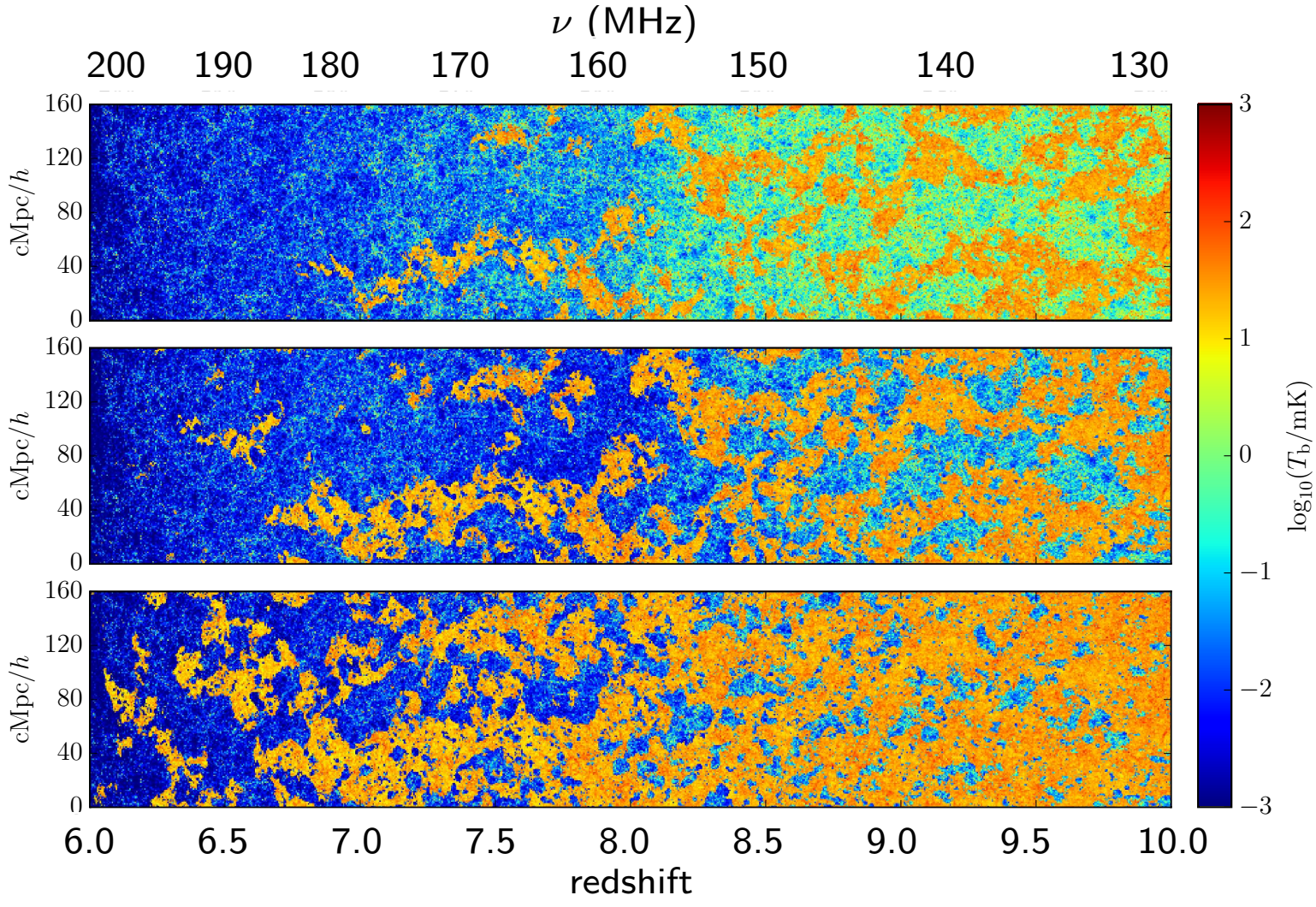
Matching the data



"late" reionization seems to explain the decrease in Lyα visibility consistent with other studies

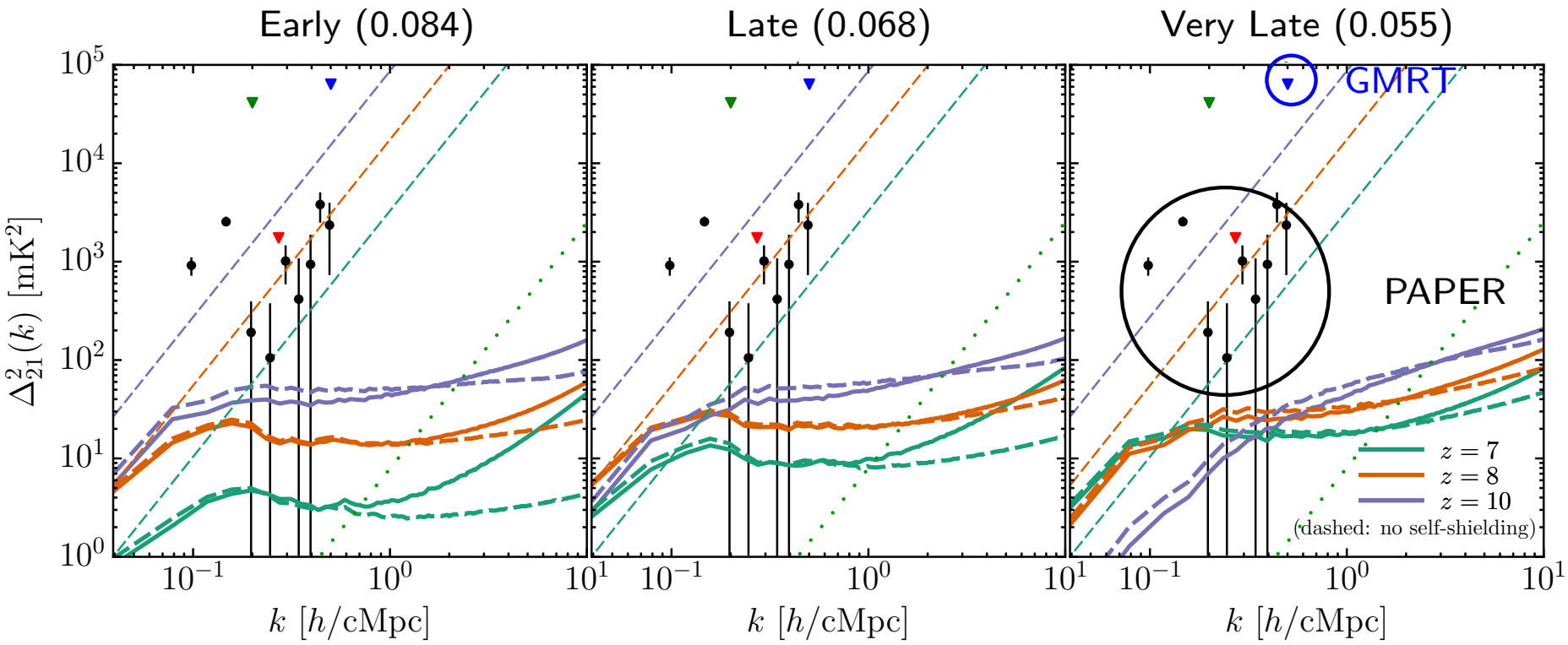
Choudhury, Puchwein, Haehnelt & Bolton (2015)

21 cm maps



Kulkarni, **Choudhury**, Puchwein & Haehnelt (2016)

21 cm power spectra



$z = 7$

$z = 8$

$z = 10$

Kulkarni, **Choudhury**, Puchwein & Haehnelt (2016)

Summary

- Good progress in modelling the reionization, possible to construct models consistent with available data
- Uncertainties at $z \gtrsim 7$, the Lyα emitters could put some constraints
- Future lies in the 21 cm experiments
- Currently operating telescopes (e.g., LOFAR) may be able to detect the statistical signal, else have to wait till the SKA1-low

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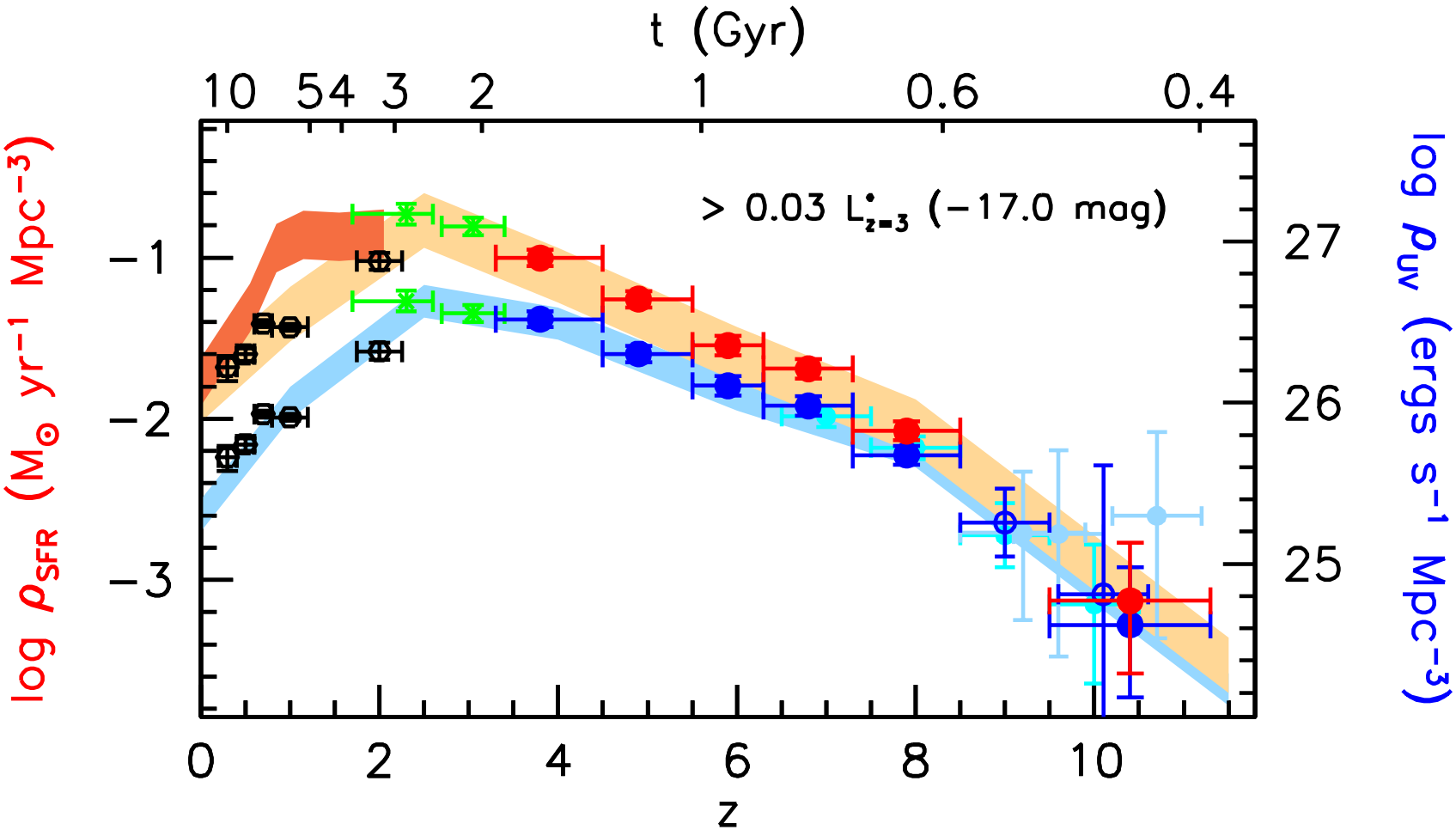
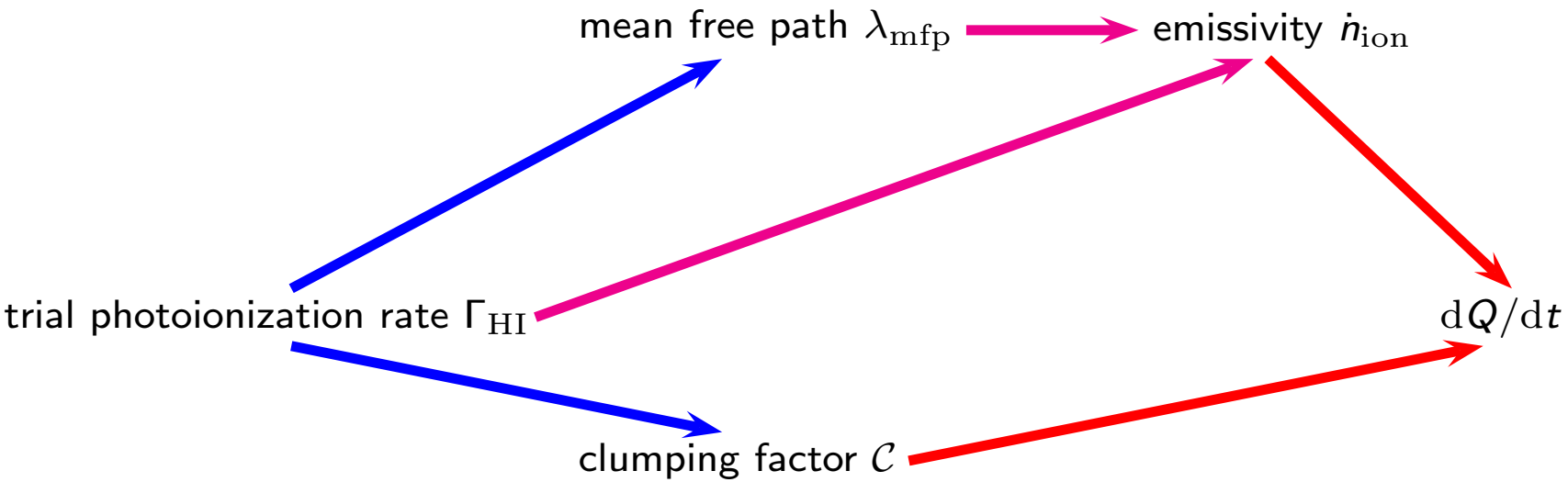
Thank you

UV luminosity function at $z > 6$



Self-consistent reionization from simulations

Assume $Q(z)$ to be given. Choose a z:



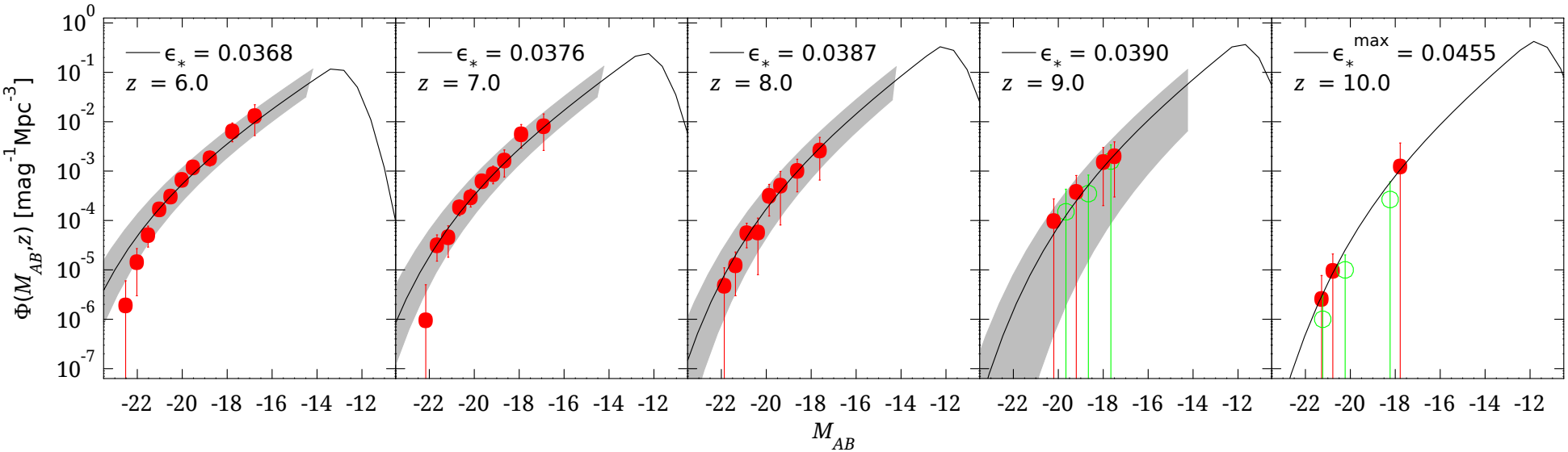
ionization field, self-shielding

invert $\Gamma_{\rm HI} \propto \dot{n}_{\rm ion}\ \lambda_{\rm mfp}$

solve $\mathrm{d}Q/\mathrm{d}t = \dot{n}_{\rm ion}/n_H - \mathcal{C} n_H \alpha_{\rm rec}$

Galaxy luminosity function

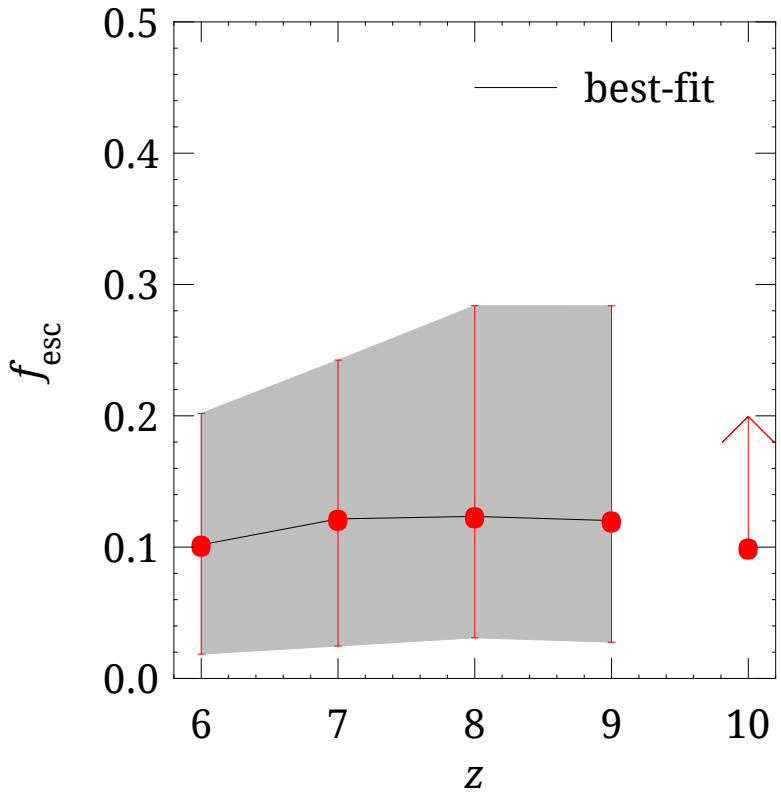
$$N_{\rm ion} = f_{\rm esc}\ \epsilon_*\ \times \text{ number of photons per baryons in stars}$$



Mitra, **Choudhury** & Ferrara (2015)

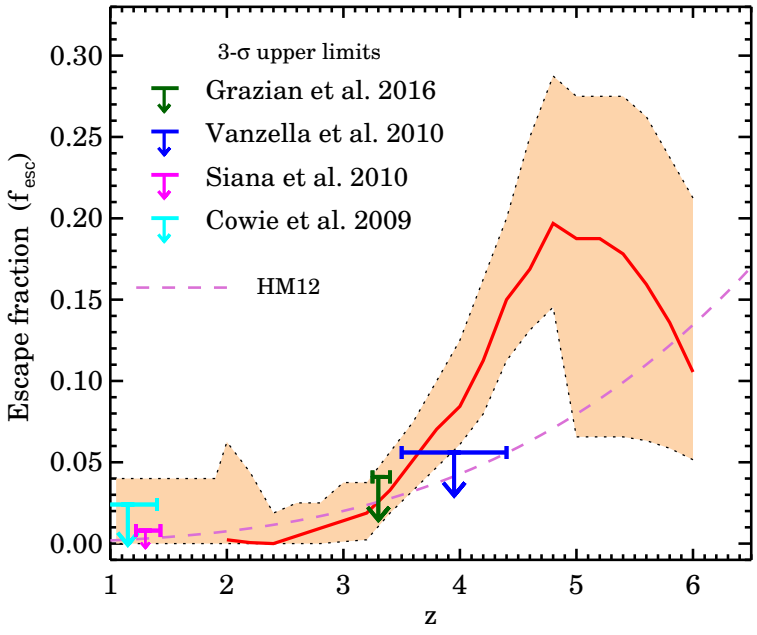
Constraints on $f_{\rm esc}$

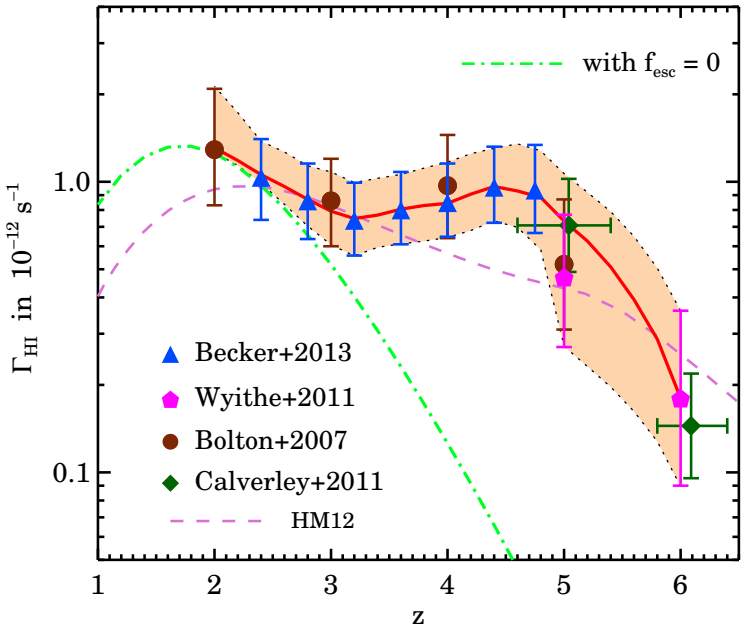
$N_{\rm ion} = f_{\rm esc}\ \epsilon_*\ \times$ number of photons per baryons in stars

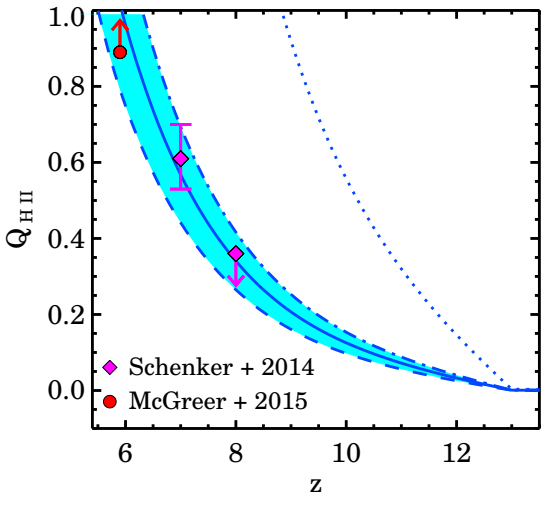


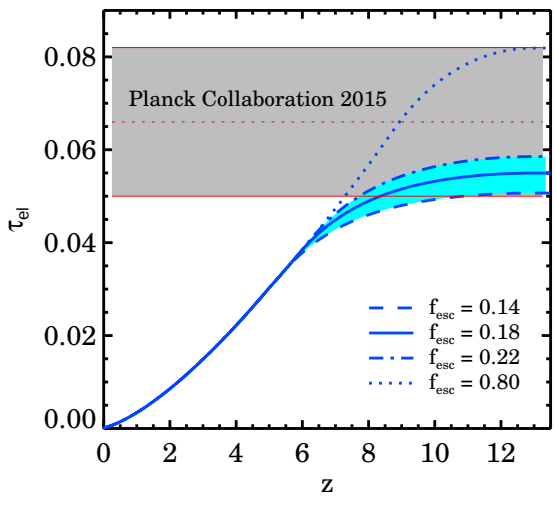
Mitra, **Choudhury** & Ferrara (2015)

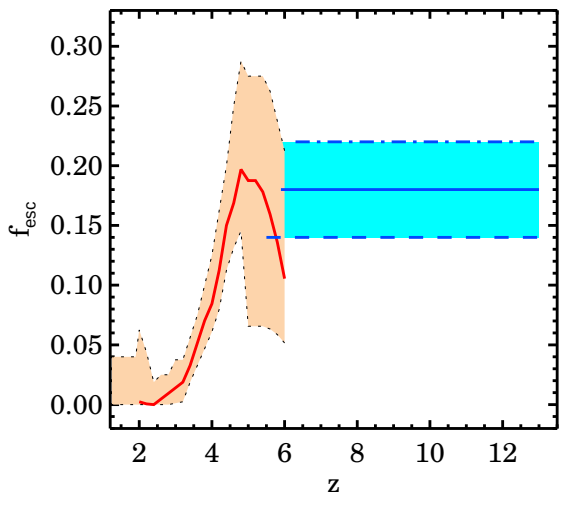
$f_{\rm esc}$ at lower redshifts





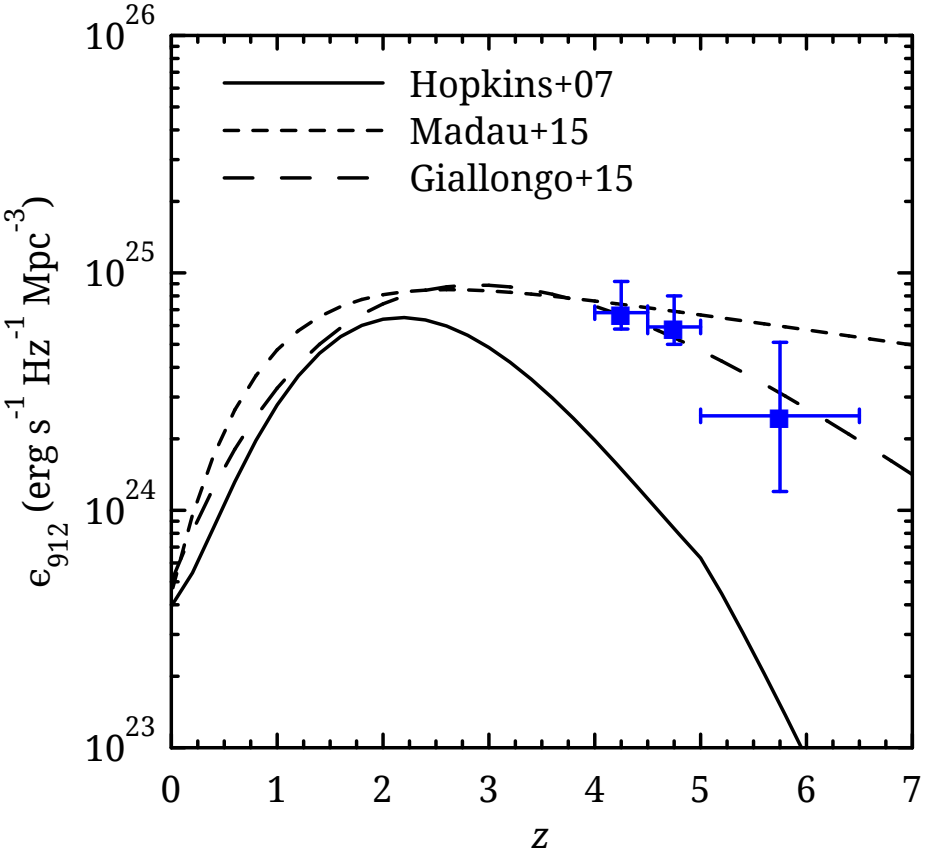






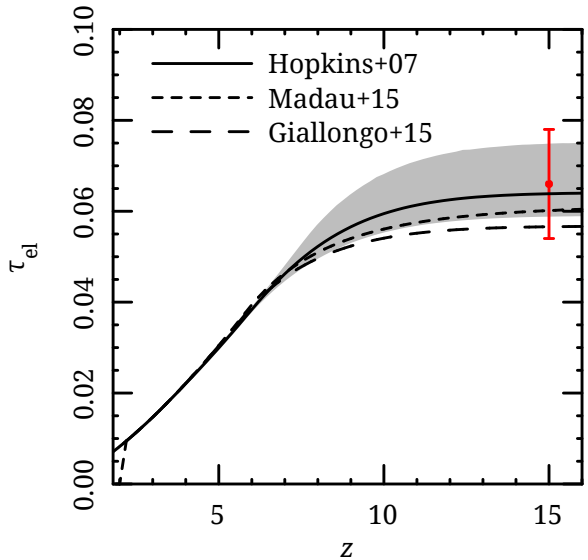
Khaire, Srianand, **Choudhury** & Gaikwad (2016)

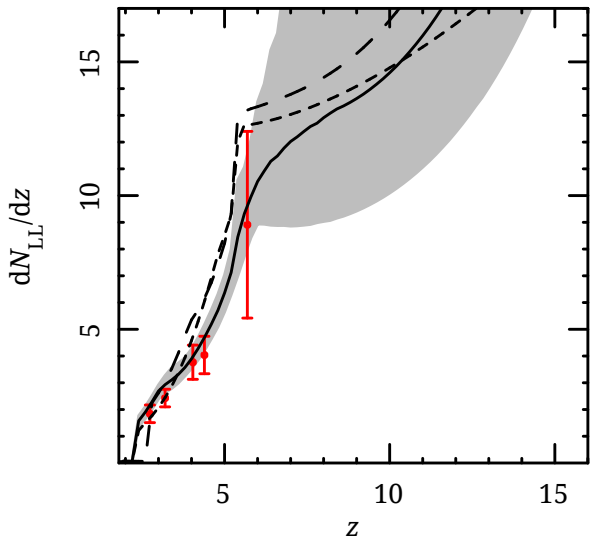
Reionization driven by quasars?

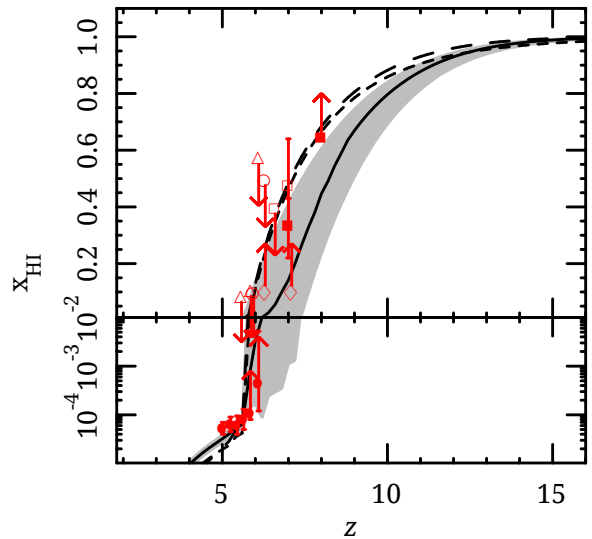


- $\sim$ 22 faint quasar candidates detected through multi-wavelength observations
  Giallongo et al (2015)
- leads to higher number of ionizing photons contributed by quasars

Constraints on the galaxy contribution







Parameters	best-fit with 2-σ errors		
	H07	MH15	G15
$\epsilon_{\rm II} \times 10^3$	$6.53^{+0.65}_{-0.98}$	< 0.04	$4.77^{+0.16}_{-0.34}$
$f_{\rm esc}$	$\sim 0.16^{+0.016}_{-0.024}$	< 0.001	$0.12^{+0.004}_{-0.009}$
$\tau_{\rm el}$	$0.064^{+0.014}_{-0.005}$	$0.061^{+0.002}_{-0.001}$	$0.057^{+0.001}_{-0.001}$

- what about helium reionization?