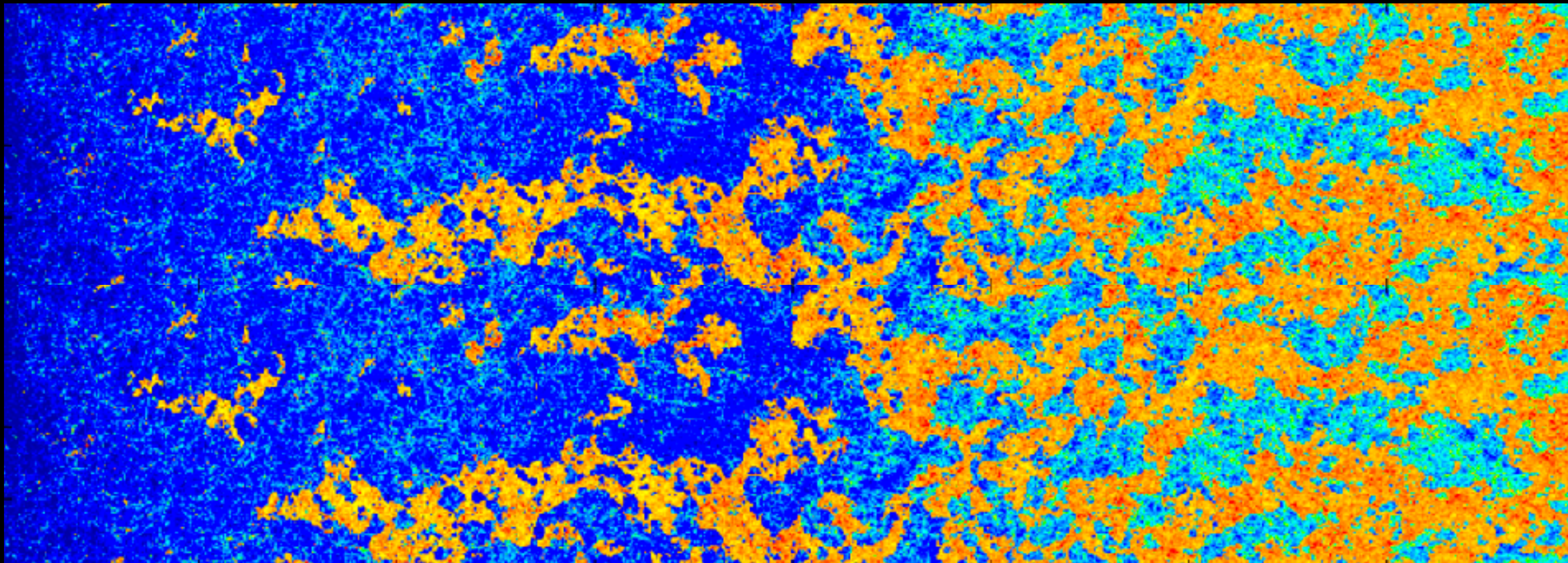
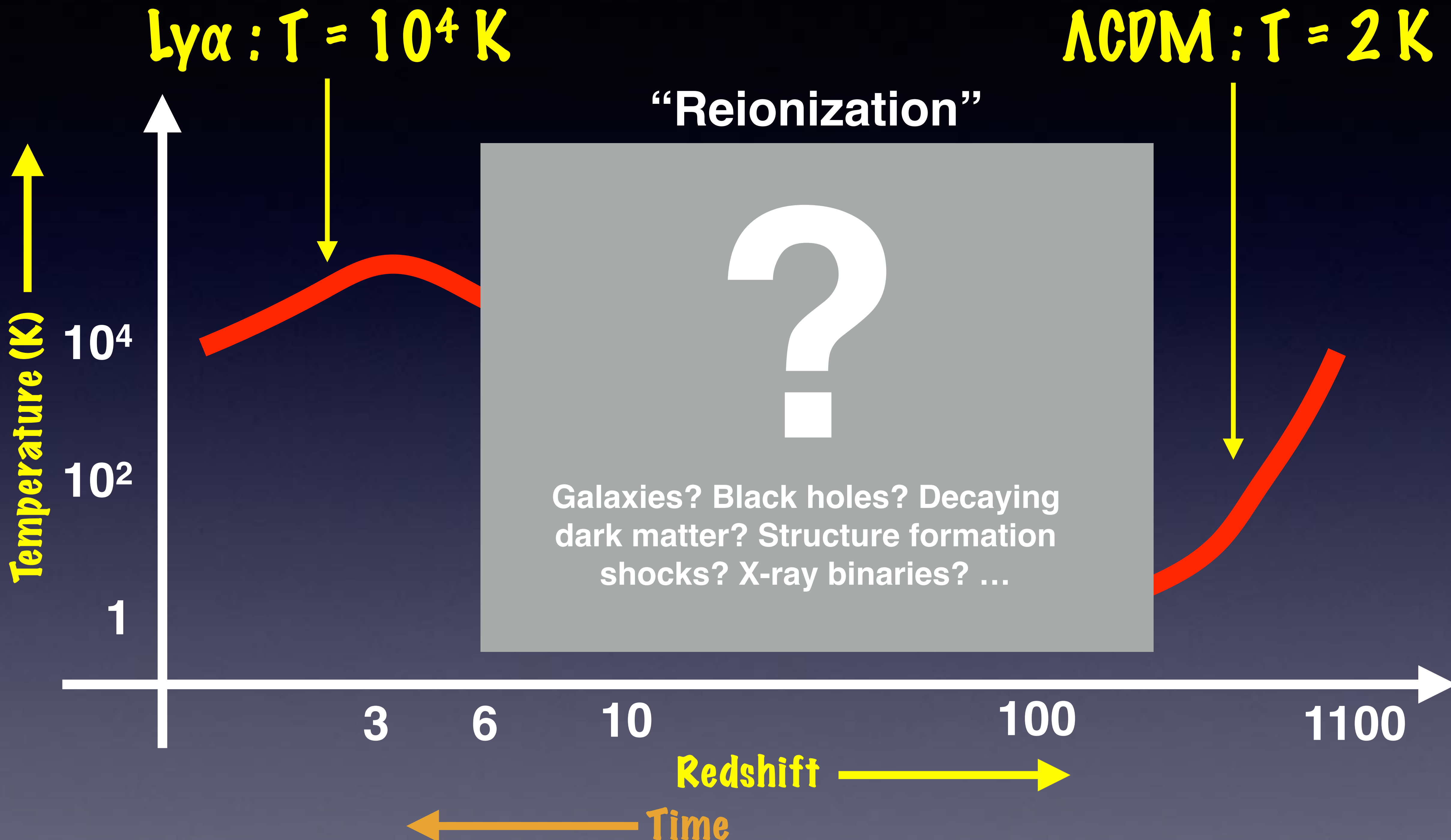


Preparing for 21 cm Cosmology: Building Accurate Models for Upcoming Data

Girish Kulkarni – IoA Cambridge – 22 February 2017

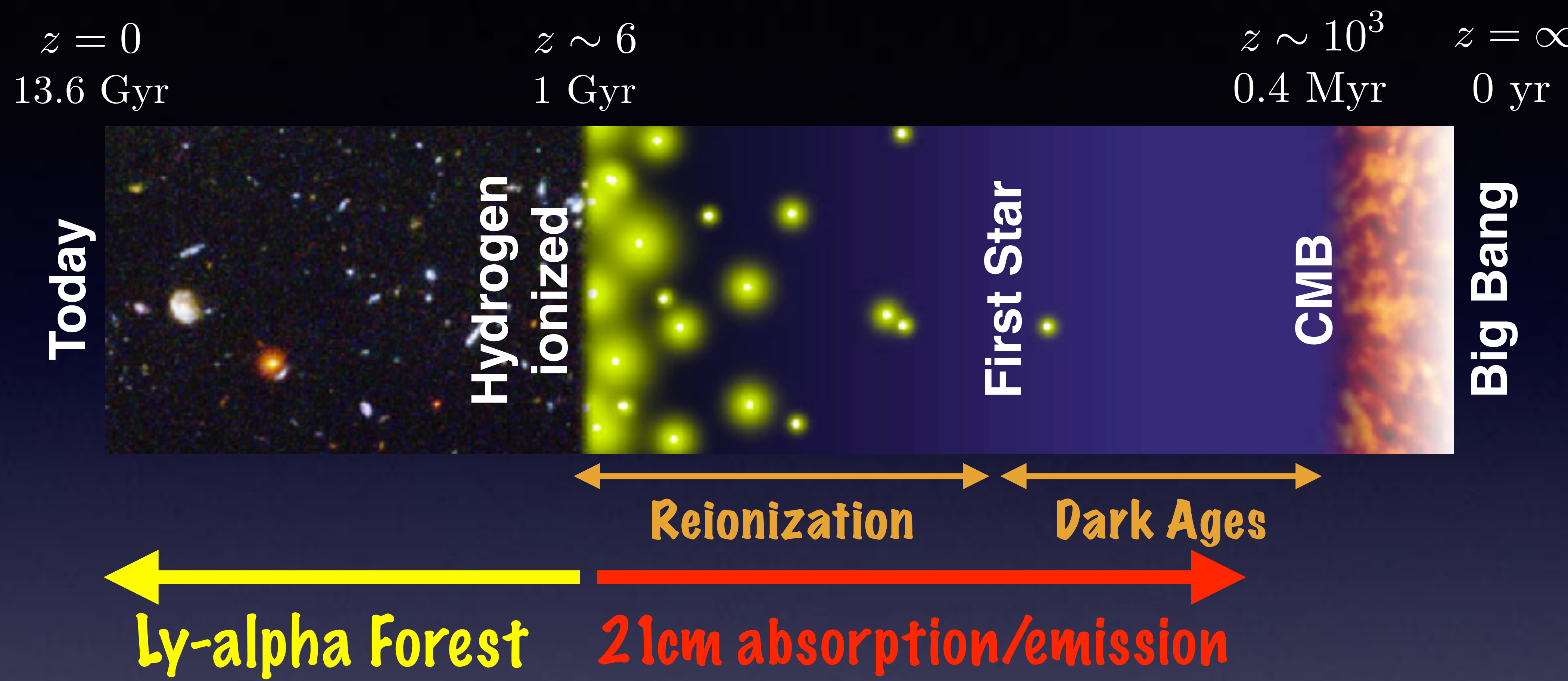
with Tirthankar Roy Choudhury (NCRA), Martin Haehnelt (Cambridge), Joe Hennawi (UC Santa Barbara), Avi Loeb (Harvard), Ewald Puchwein (Cambridge), Gábor Worseck (Heidelberg)

Epoch of Reionization



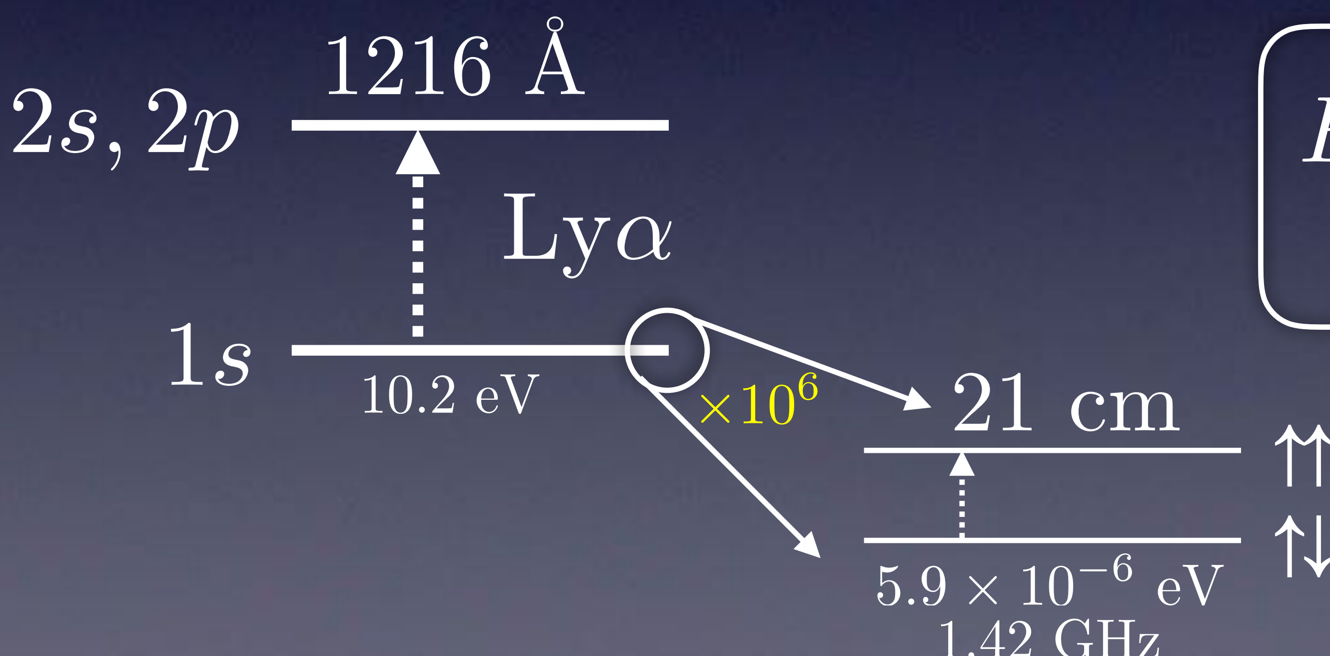
This talk: galaxy and quasar dominated reionization

How can we observe reionization?



- Lyα forest probes only post-reionization IGM because Lyα line saturates
- CMB, Lyβ forest, metal lines, quasar proximity zones, Lyα emission, but all limited in some way
- 21 cm probes all of reionization and does not suffer from these issues

21 cm: another probe into high redshift IGM

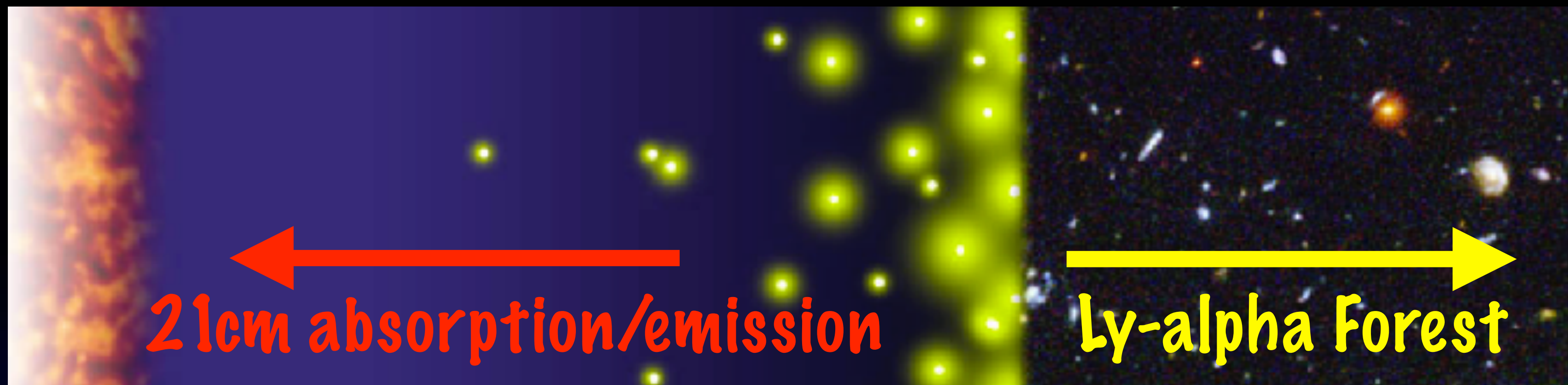


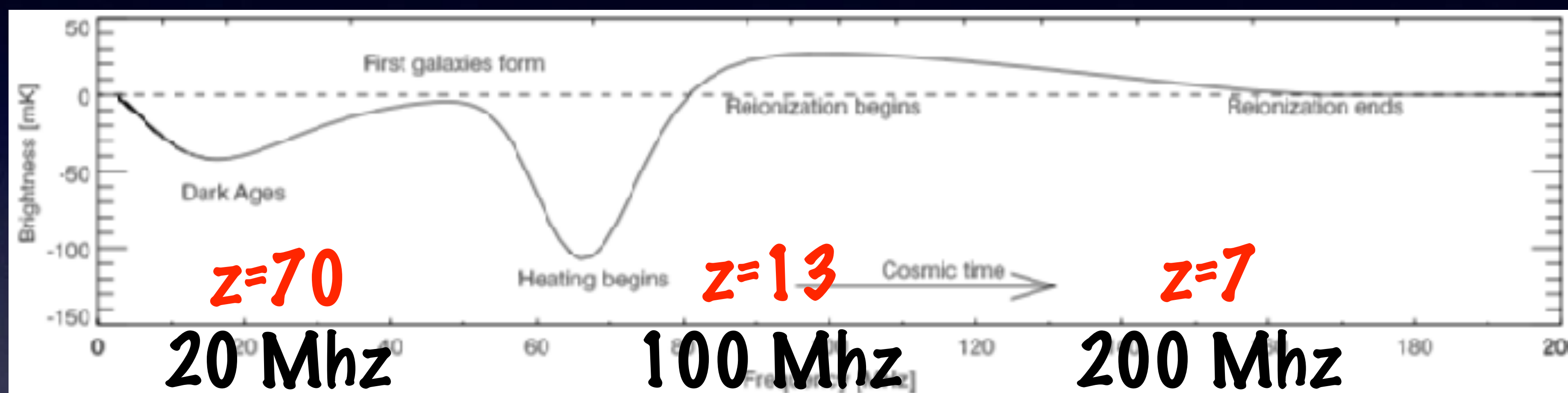
$$F_{\rm obs} = \underbrace{F_{\rm s}(1 - e^{-\tau})}_{\text{Emission}} + \underbrace{F_{\rm int} e^{-\tau}}_{\text{CMB}}$$

$$\tau \sim \int dl \cdot n \cdot \sigma \leftarrow \text{thermal state}$$

21 cm emission or absorption can open up the whole cosmic baryonic history to observations: EDGES, LOFAR, PAPER (Current) – SARAS, MWA, SKA (Upcoming)

21cm as a cosmic probe





$\delta T_b\,[\mathrm{mK}]$

Pritchard and Loeb 2012

$I_\nu c^2/2k_B\nu^2$

CMB/AGN/GRB

$$T_b(\nu) = T_S(1 - e^{-\tau_\nu}) + T_R(\nu)e^{-\tau_\nu}$$

"Spin Temp."

$\delta T_b = 22\mathrm{mK}\, x_{\mathrm{HI}}\Delta_{\mathrm{gas}}$ at z ~ 7

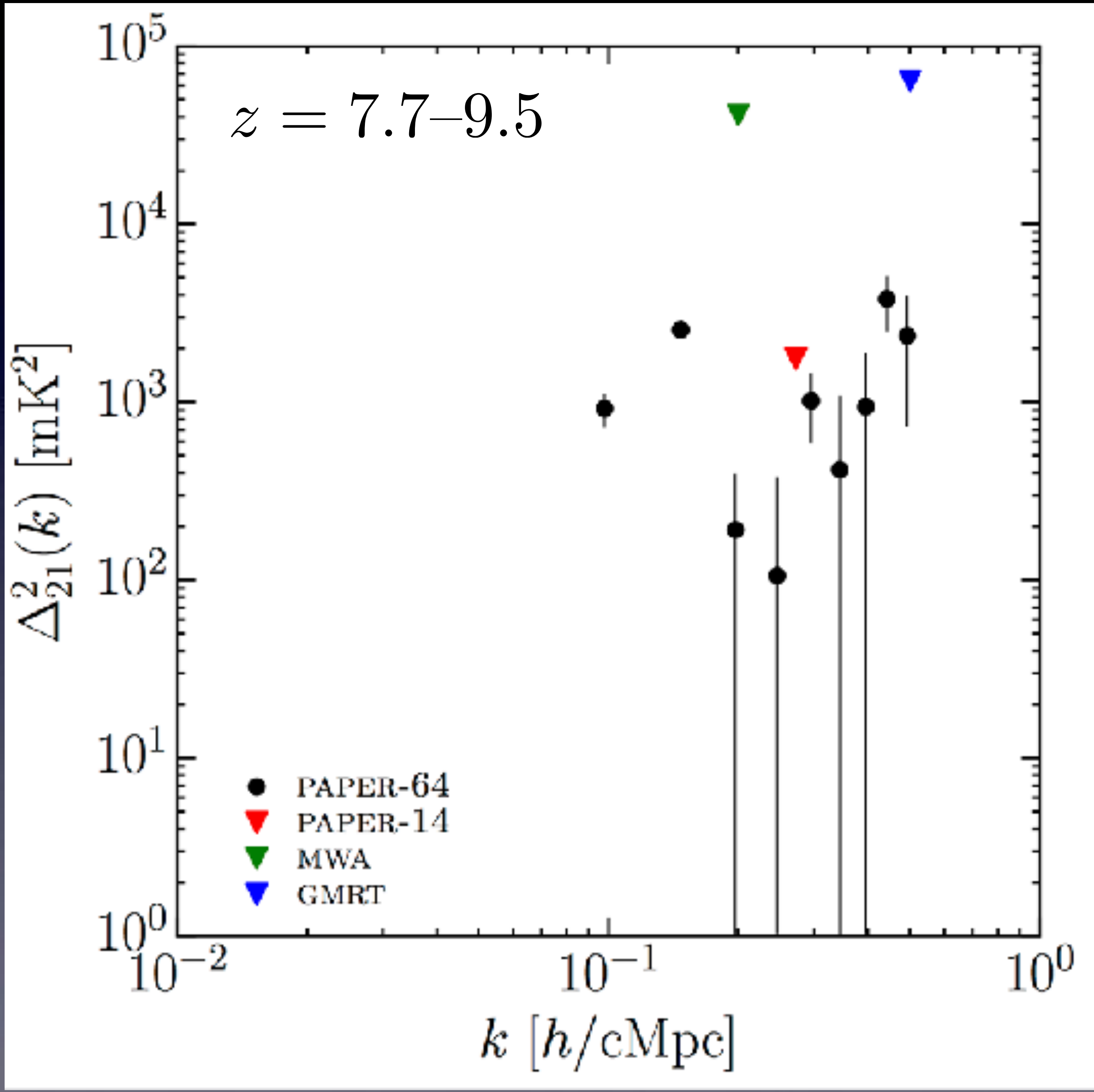
Theorist’s job:

- Improve intuition by modelling
- Create physics retrieval pipelines

Many ongoing and upcoming experiments

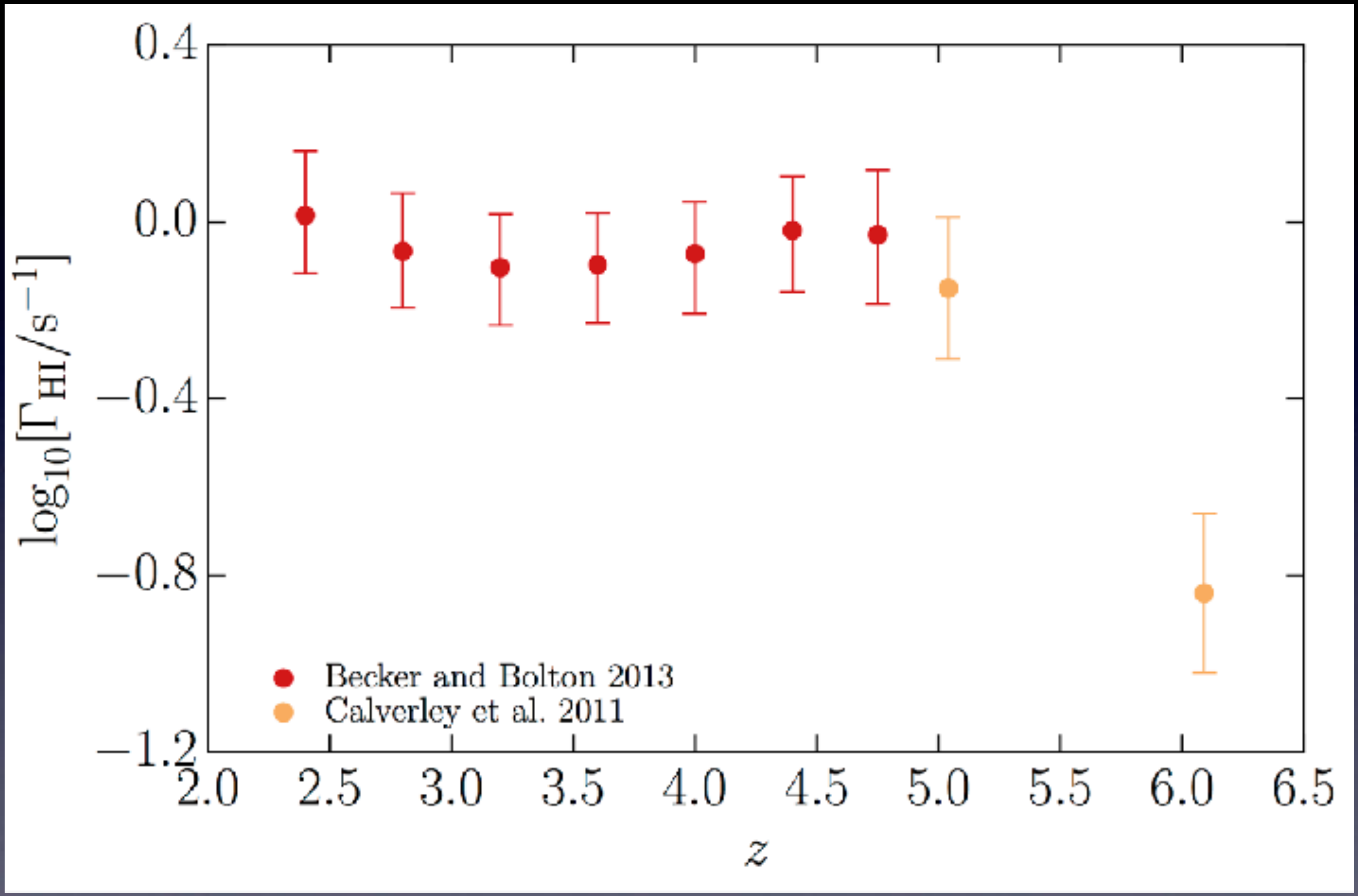
21 cm power spectrum

- First-generation experiments aim to measure power spectrum using interferometry
- Practical advantage: helps in separating signal on sky and in frequency (time)



PAPER collaboration: Ali et al. 2015

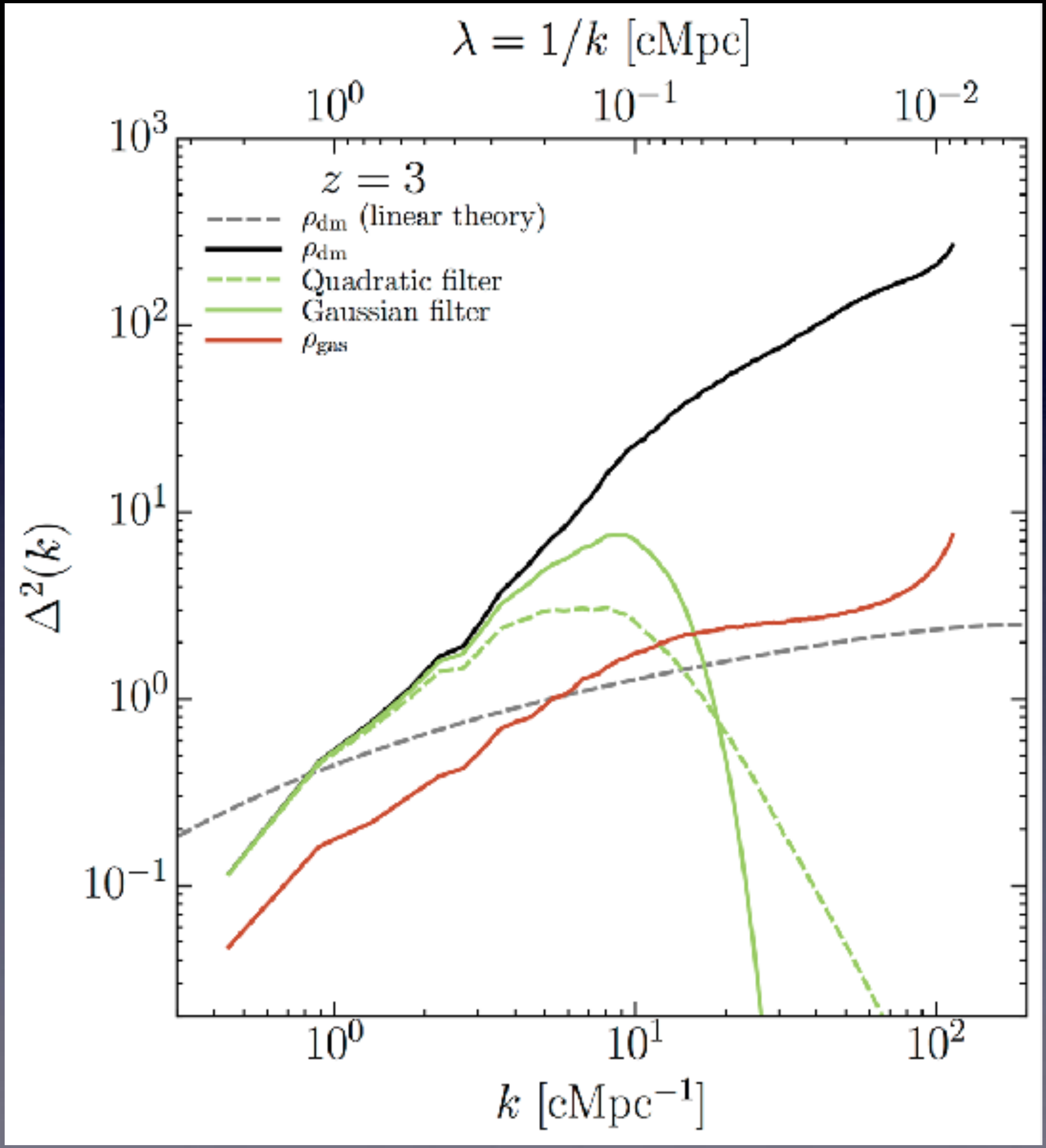
What makes predictions difficult?



Reionization is **photon-starved**: should have 1–3 photons per baryon at z ~ 6 (Bolton and Haehnelt 2007) while maintaining **consistency with CMB**

What makes predictions difficult?

- Gas expected to have rich small-scale structure, at least down to the Jeans scale.
- This acts as a sink for ionisation photons
- But importantly, small-scale structure can **self-shield** and become 21cm bright.
- This **can affect large-scale power**, but are missed by simulations



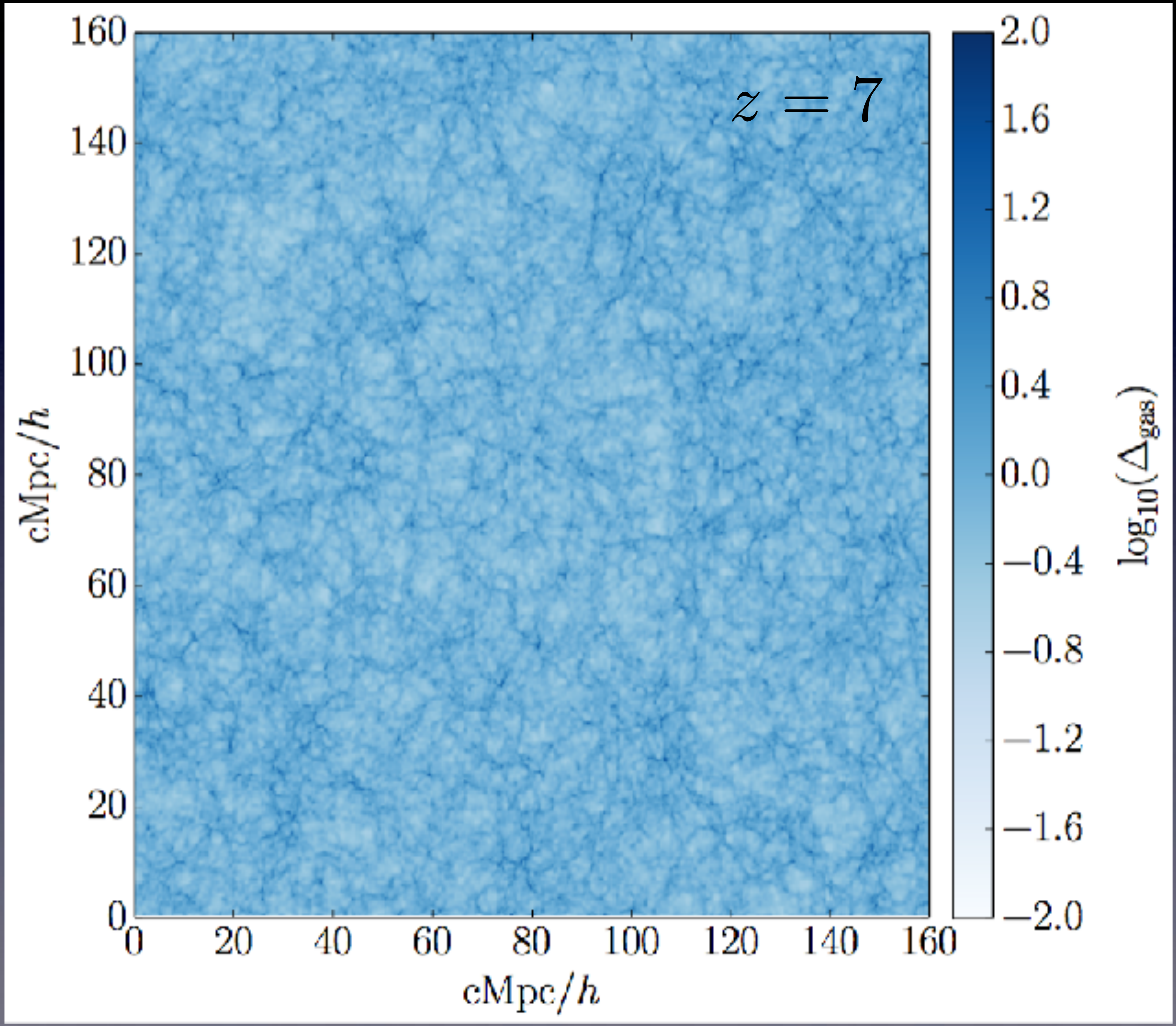
Kulkarni et al. 2015

Goal: Set up high dynamic range models that are calibrated to CMB and Lyα data

Need cosmological simulation with radiative transfer

Step 1: 'Sherwood' cosmological simulations

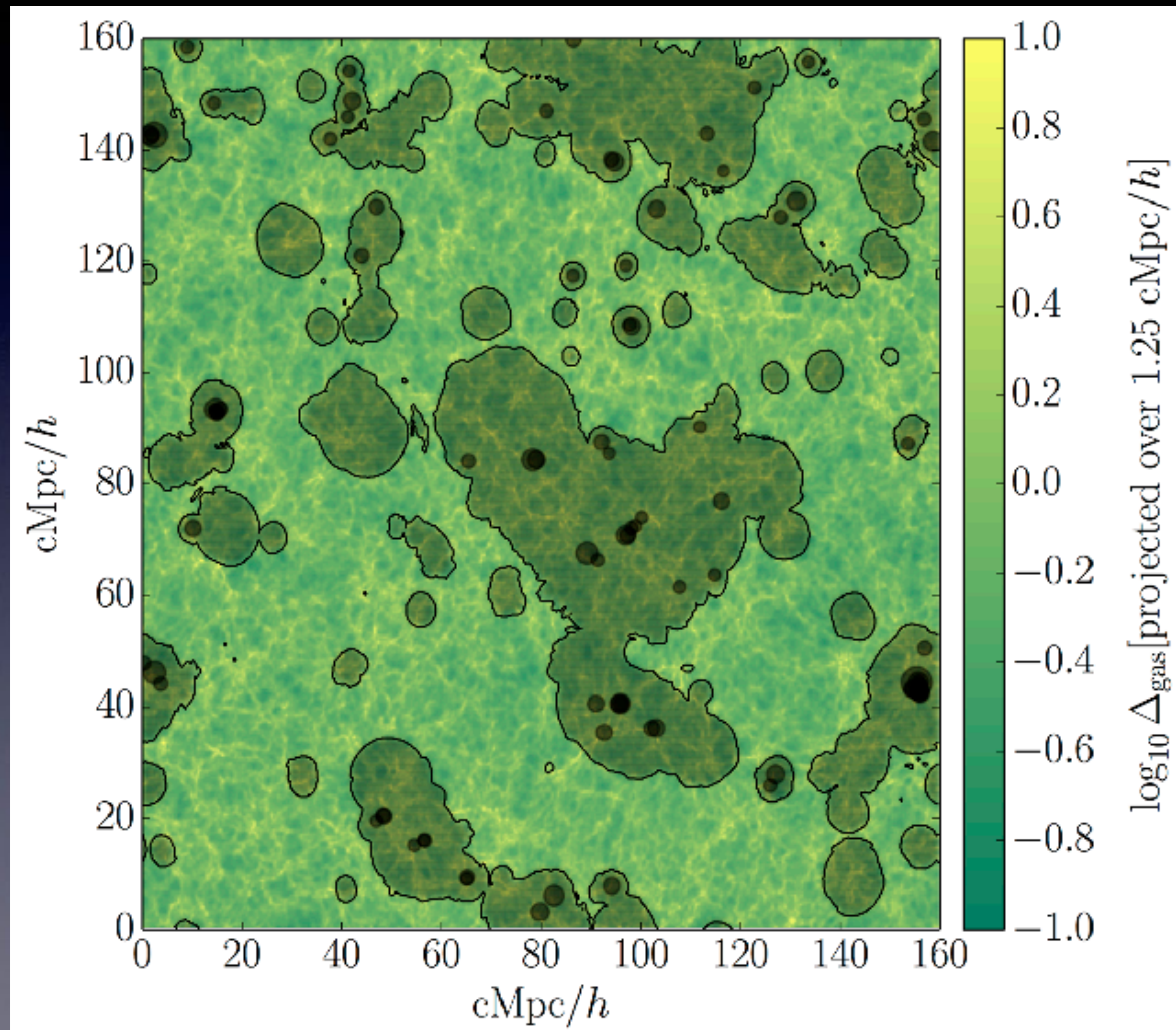
- P-Gadget-3: 2048^3 gas particles in a 160 Mpc/h box (Bolton et al. 2016)
- Mass resolution is ~4×10^6 $M_\odot$.
- Mean inter-particle separation is ~53 comoving kpc.



Kulkarni et al. 2016

Step 2: Excursion set radiative transfer

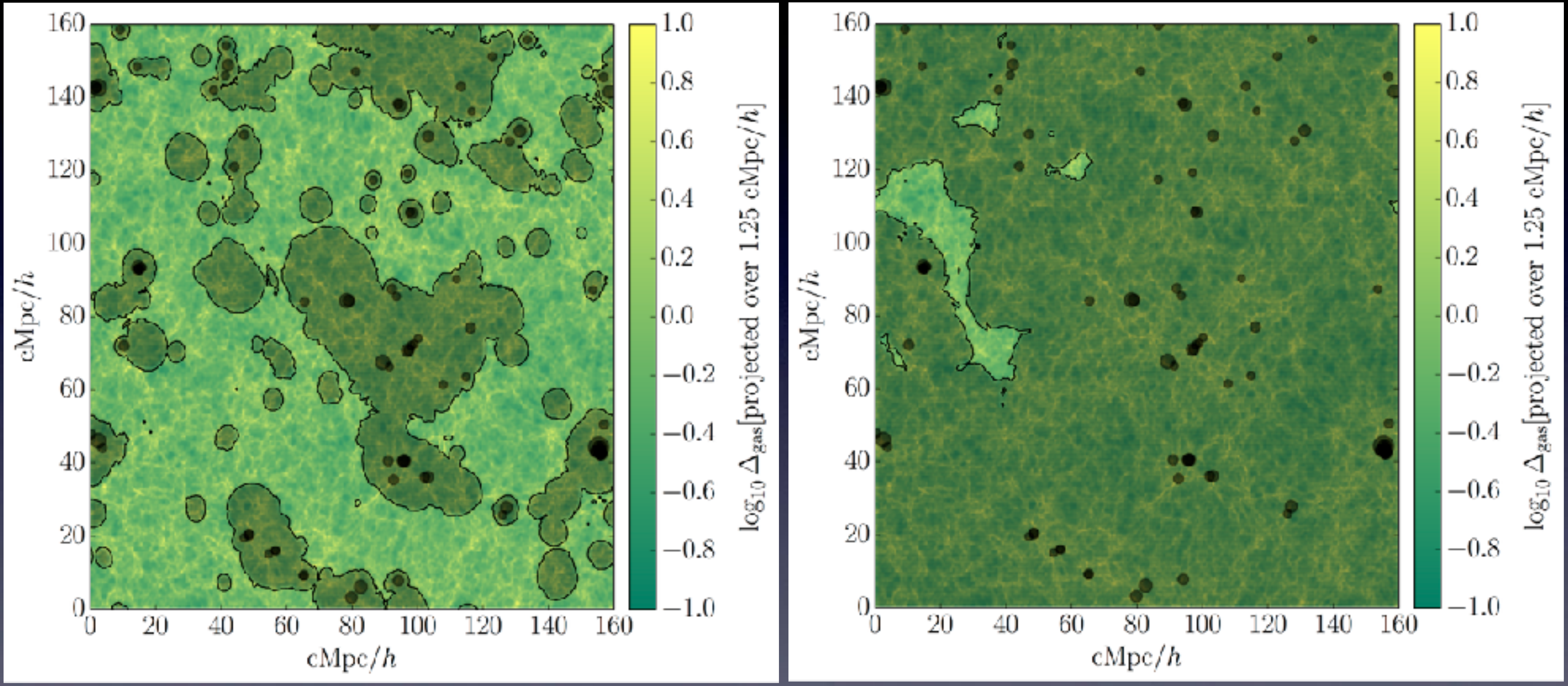
- For "radiative transfer," use excursion set method on the gas distribution (Furlanetto et al. 2004)
- A point is ionised if **sources/sinks > 1** in a sphere centred on it
- Gives large scale morphology (Majumdar et al. 2014) but still misses self-shielding



Kulkarni et al. 2016

Excursion threshold sets ionisation fraction

Kulkarni et al. 2016

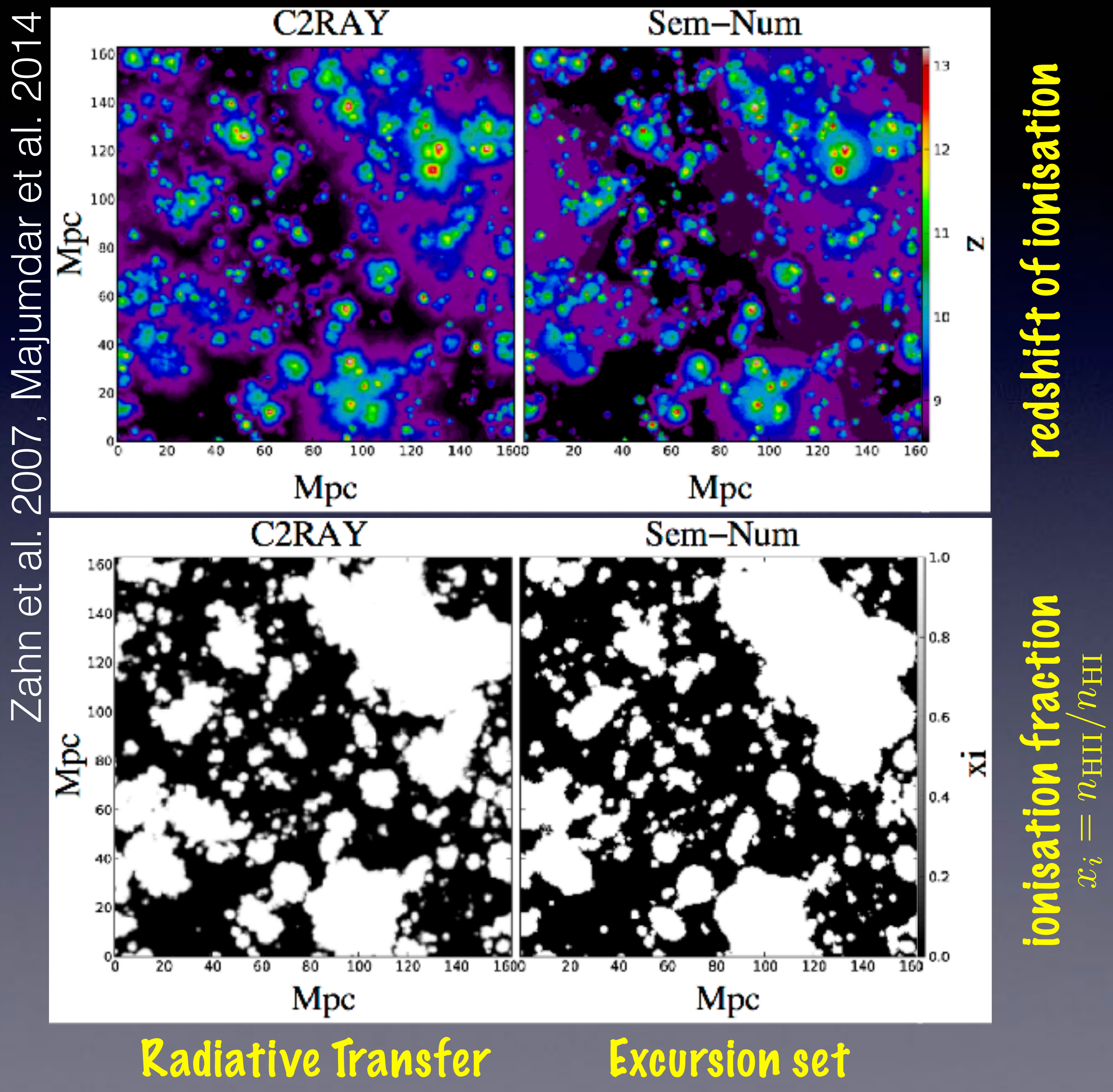


$\zeta_{\rm eff} = 0.5, Q_V = 0.31$

$\zeta_{\rm eff} = 1, Q_V = 0.94$

$$\zeta_{\rm eff}\, f(\mathbf{x}, R) \geq 1 \qquad f \propto \rho_m(R)^{-1} \int_{M_{\rm min}}^{\infty} dM\, \left.\frac{dN}{dM}\right|_R N_\gamma(M)$$

Does excursion set really work?



Step 3: Calibrate to a given reionization history

$$\frac{\partial I_\nu}{\partial t} + \frac{c}{a(t)}\hat{n}\cdot\nabla_x I_\nu - H(t)\nu\frac{\partial I_\nu}{\partial \nu} + 3H(t)I_\nu = -c\kappa_\nu I_\nu + \frac{c}{4\pi}\epsilon_\nu$$

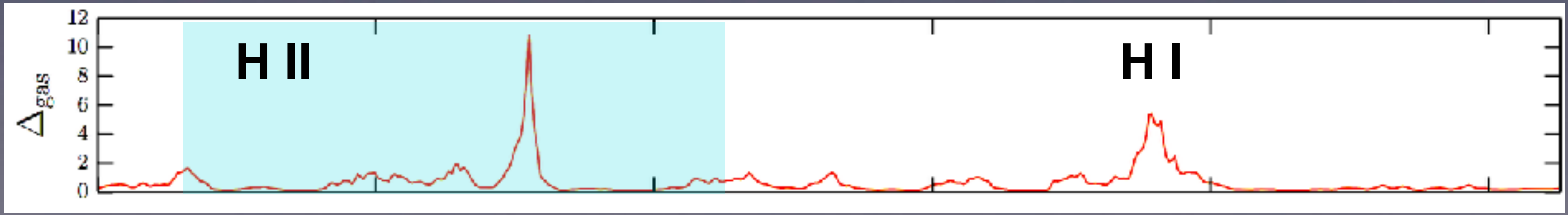
↓

Angle average + Local absorption + Ionisation Equilibrium

↓

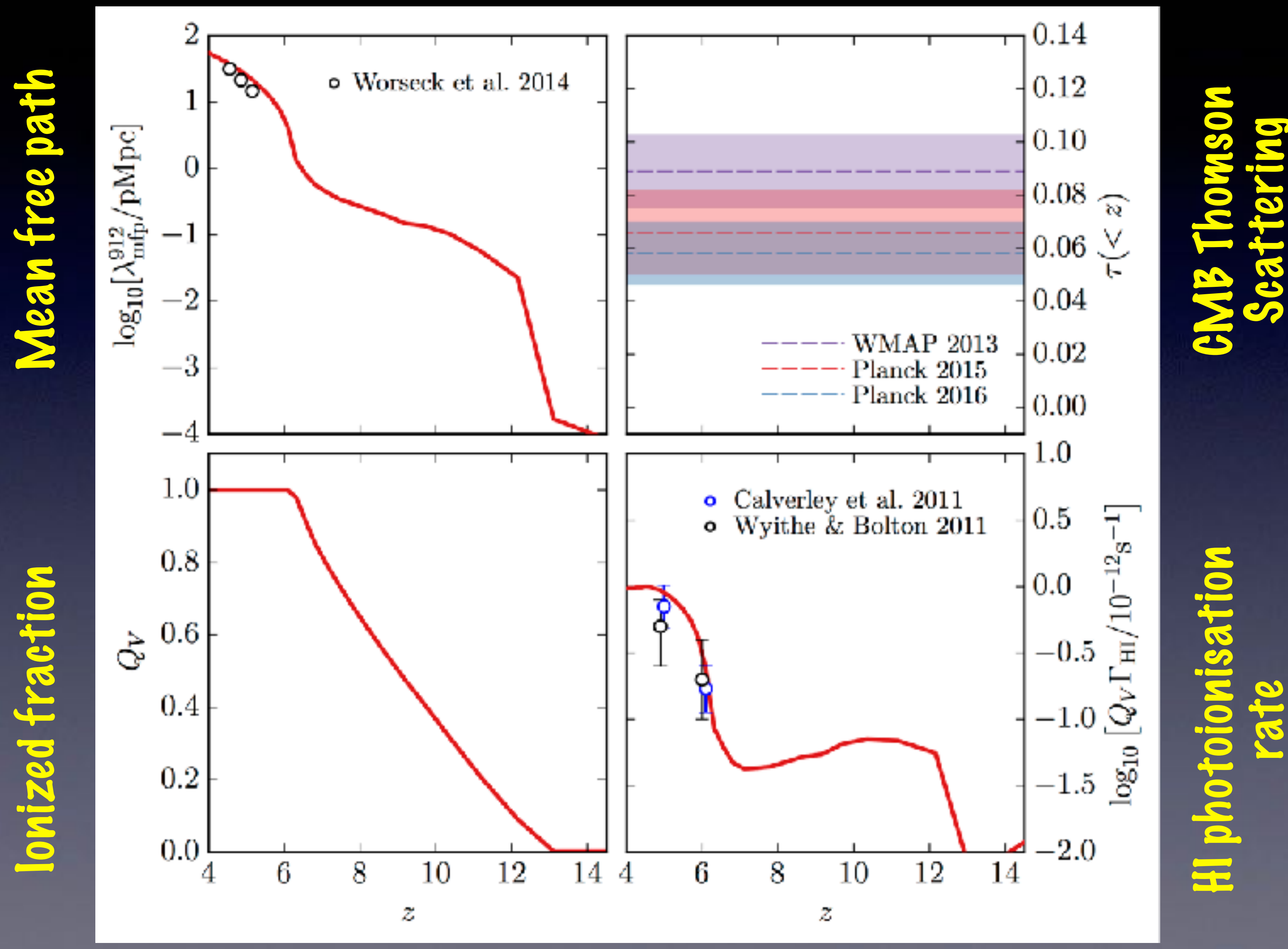
$$\frac{dQ}{dt} = \frac{\dot{n}_{\rm ion}}{n_H} - \frac{Q_M}{t_{\rm rec}}$$

For a given self-shielding criterion, solve global reionization evolution for photo-ionization rate



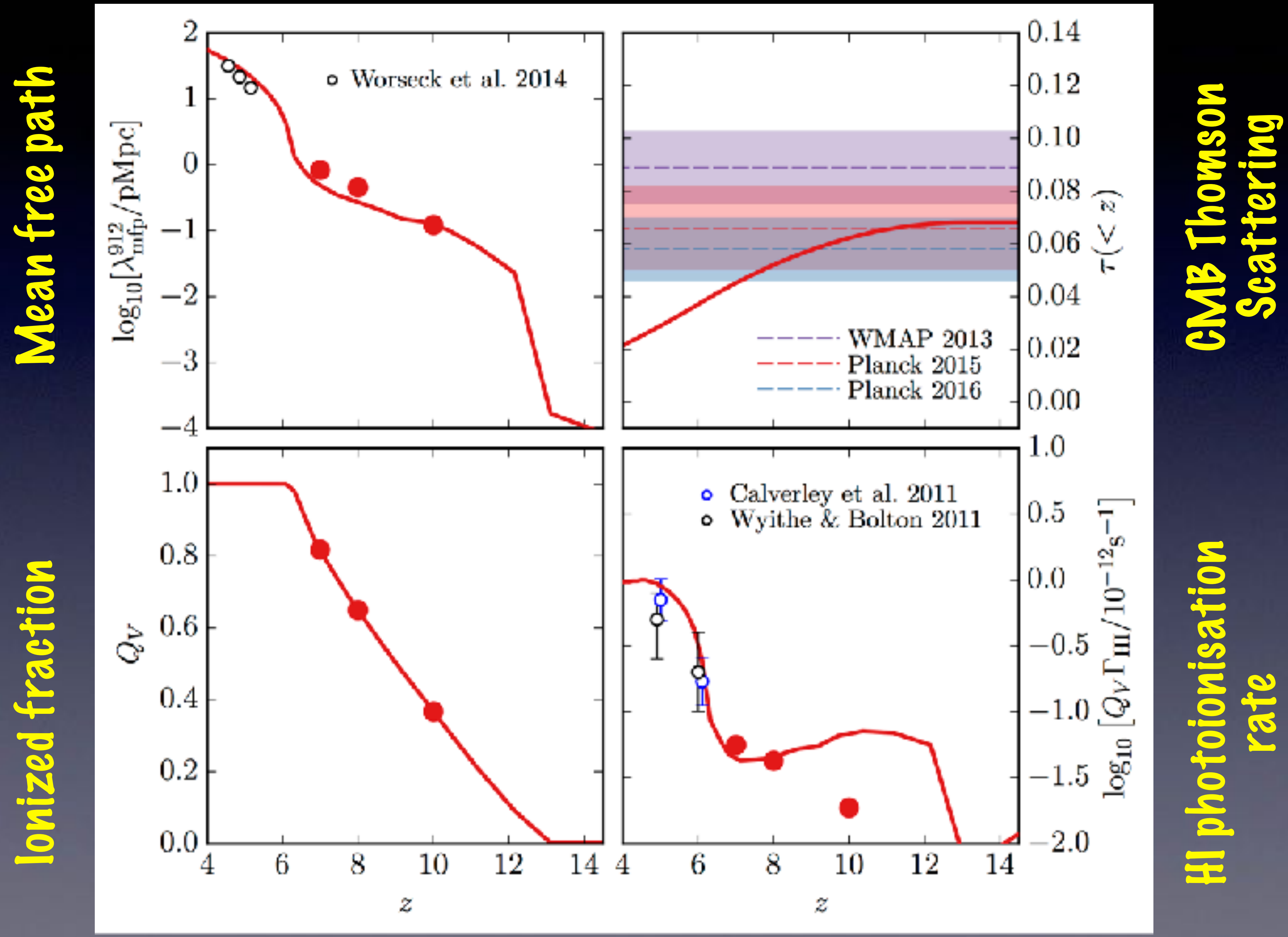
Kulkarni et al. 2016

Get consistent radiative transfer



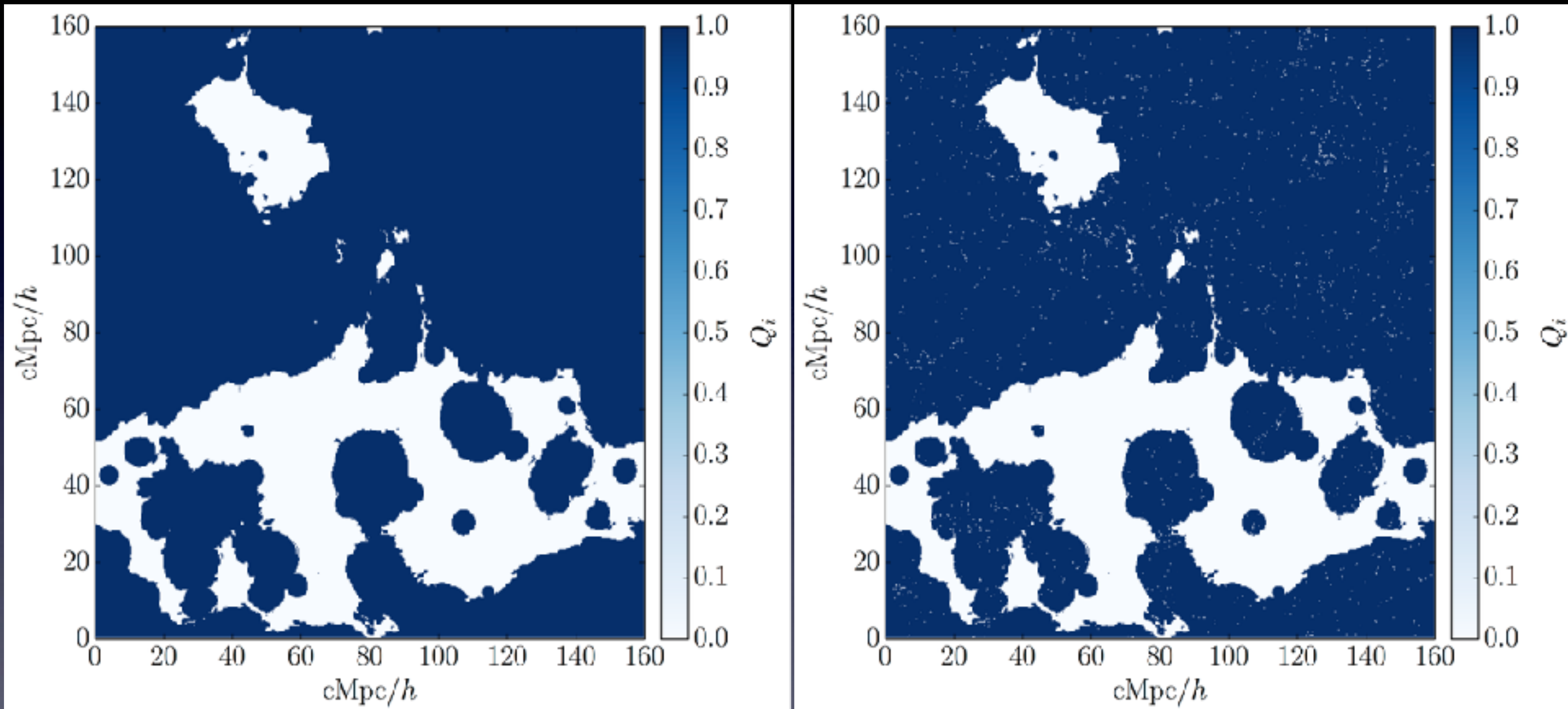
Haardt and Madau 2012, Kulkarni et al. 2016

Get consistent radiative transfer



Haardt and Madau 2012, Kulkarni et al. 2016

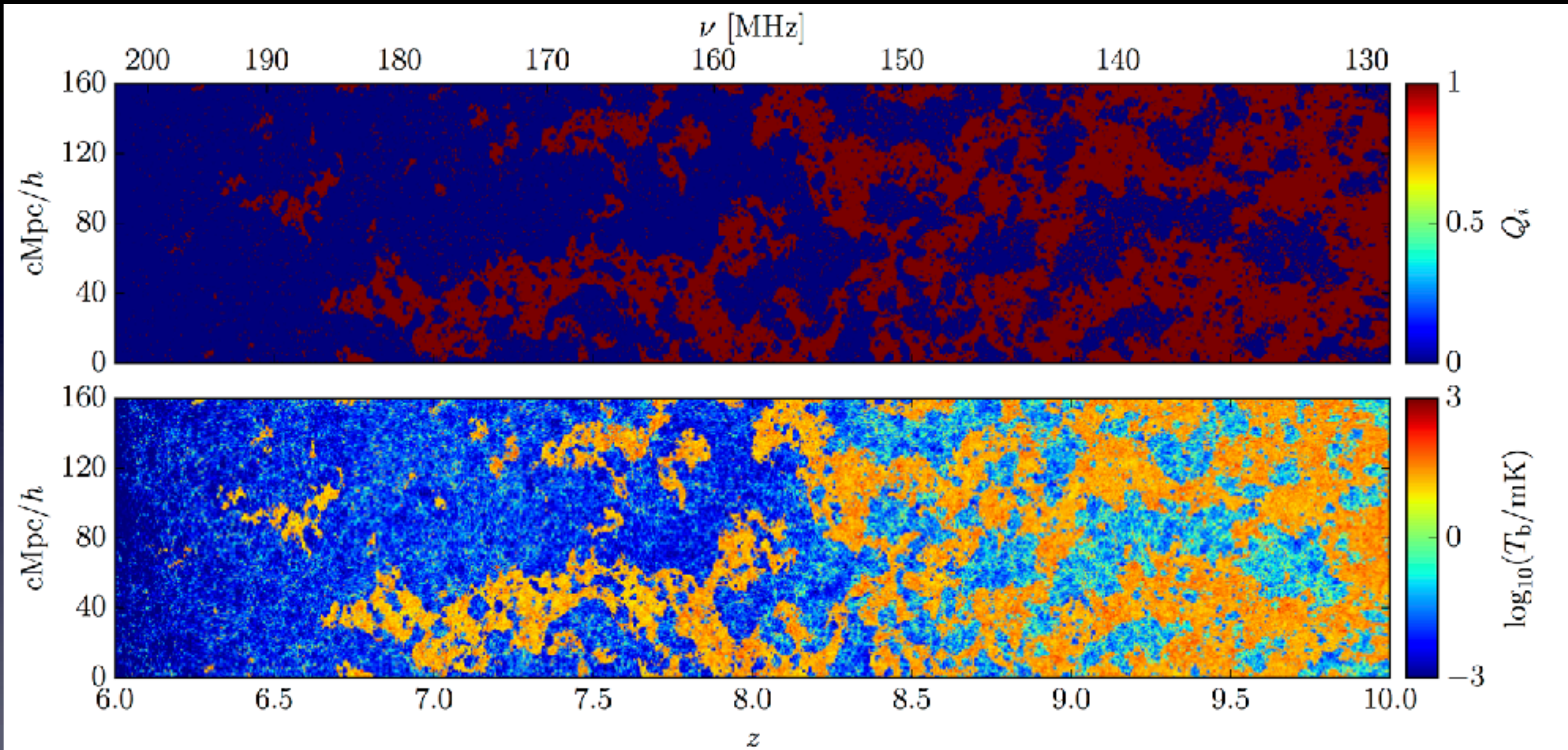
Self-shielded regions are now resolved



Kulkarni et al. 2016

Self-shielding reduces ionisation fraction in ionised regions.

Derive 21 cm brightness temperature

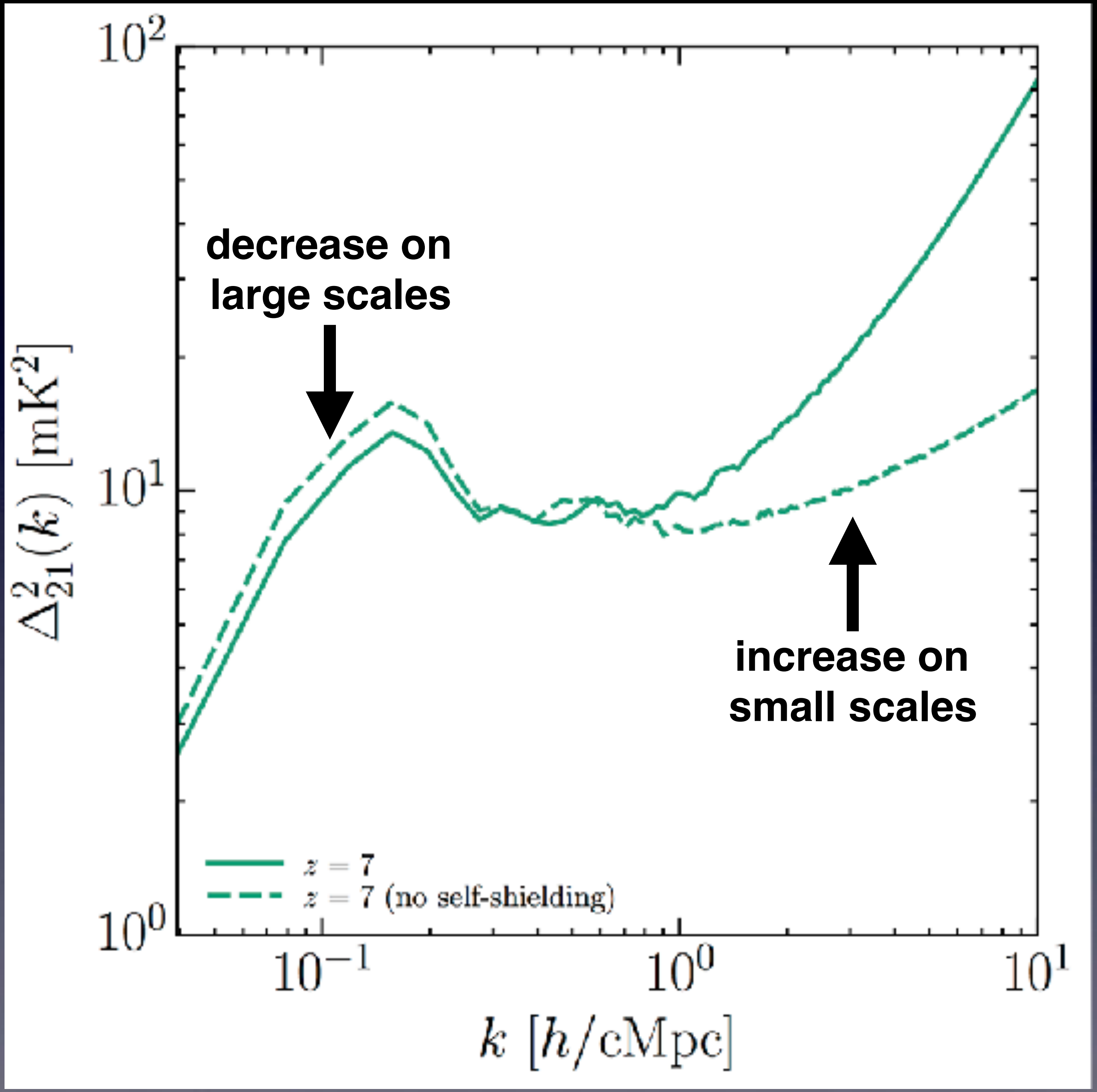


Kulkarni et al. 2016

$$\delta T_b = 22\mathrm{mK}\, x_{\mathrm{HI}} \Delta_{\mathrm{gas}}$$

21cm-bright self-shielded regions are now resolved in HII bubbles

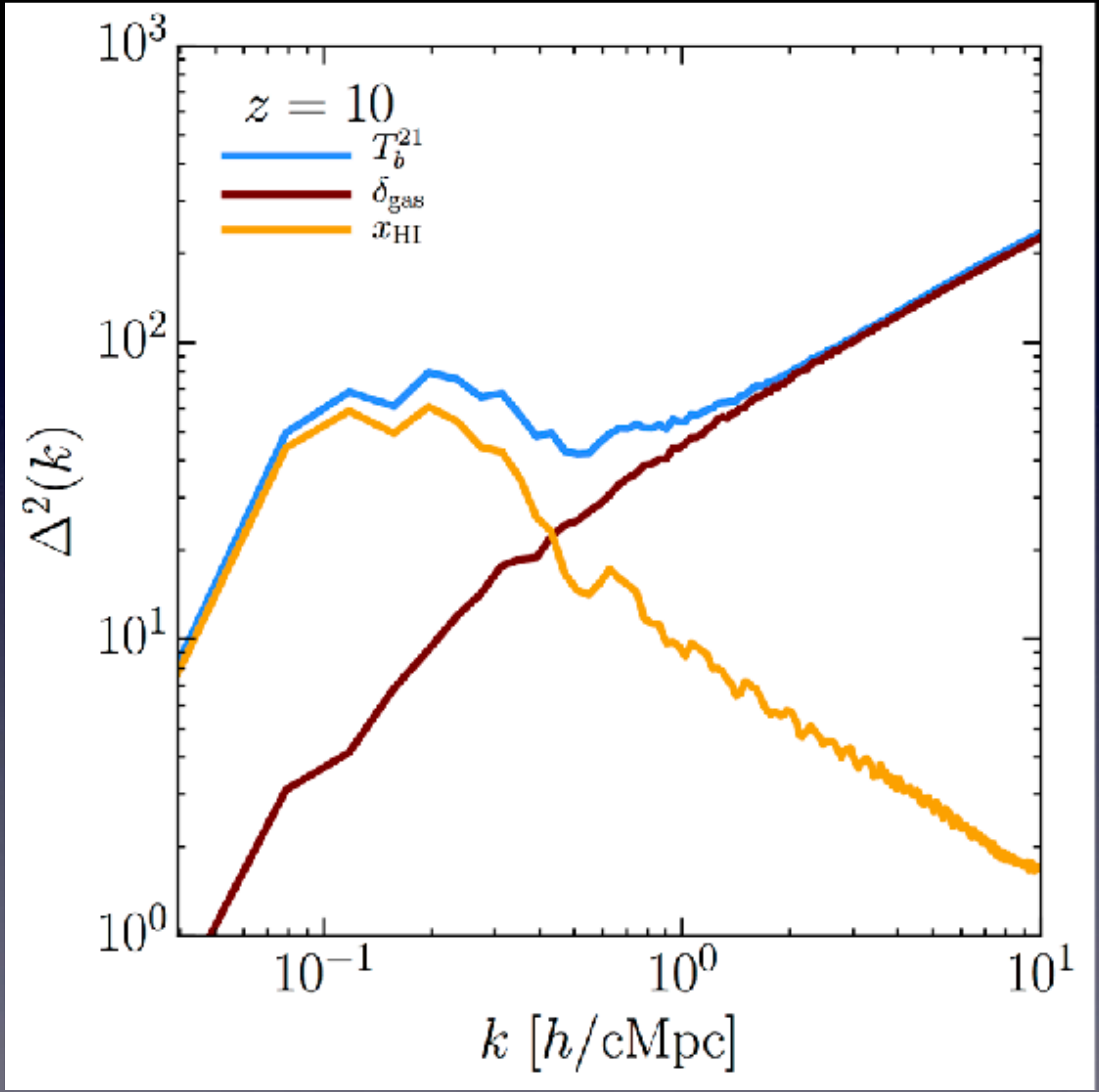
Can now predict 21 cm power spectrum



Kulkarni et al. 2016

$$\Delta^2_{21}(k) = \frac{k^3}{2\pi^2} \cdot \frac{\langle \widetilde{T_b}^2(k) \rangle}{V_{\rm box}}$$

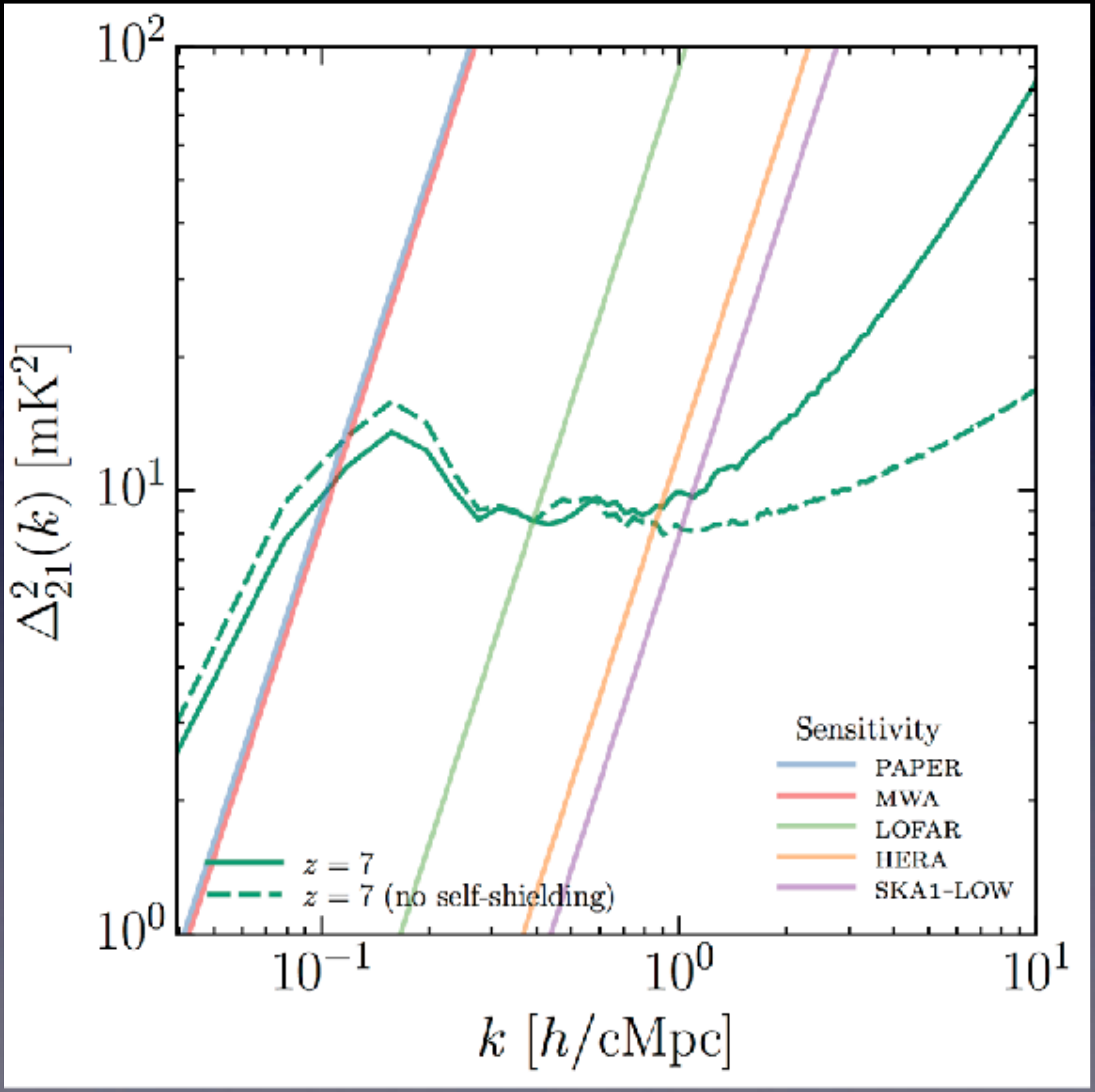
21 cm depends on sources and matter



Kulkarni et al. 2016

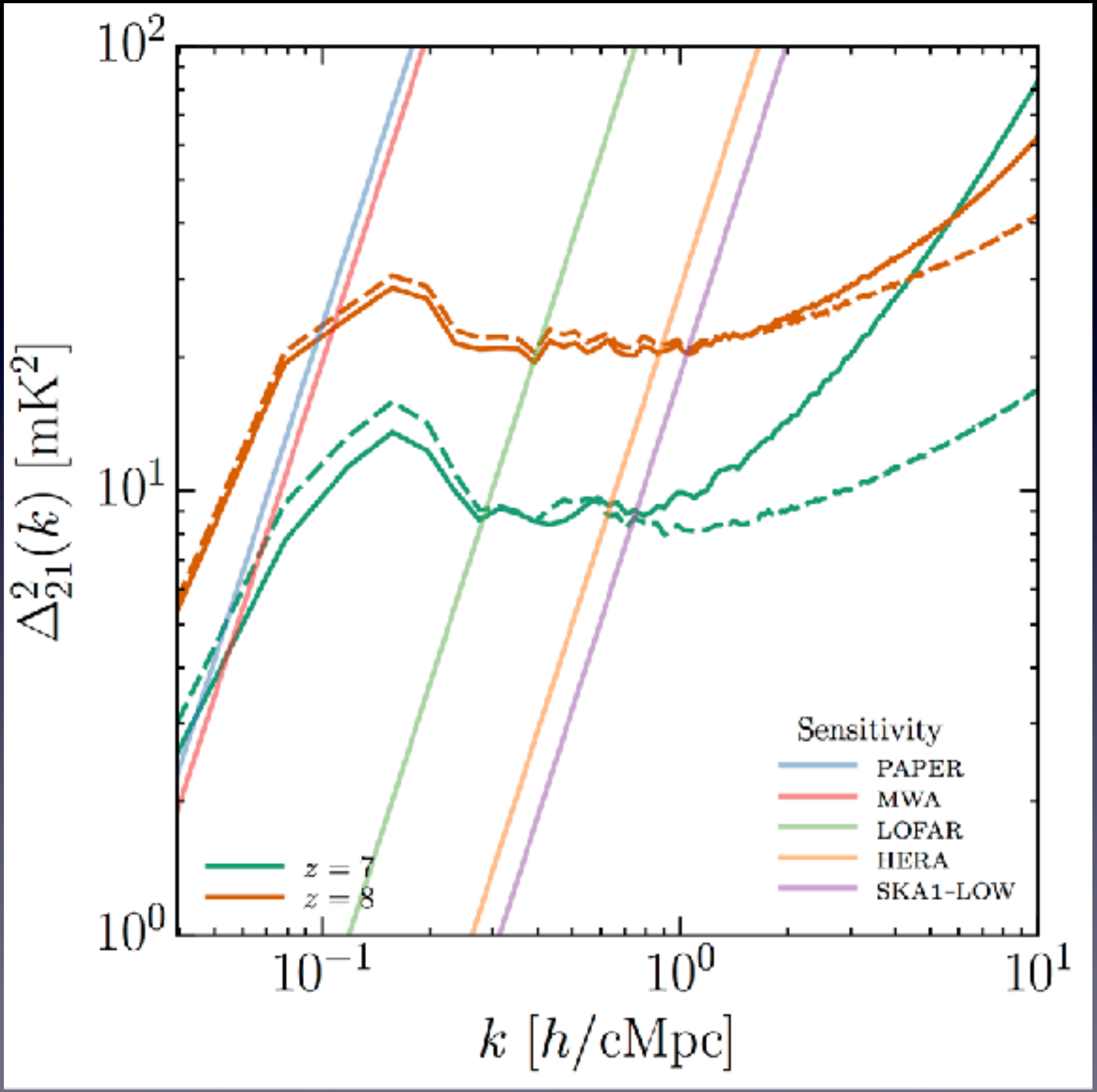
$$\Delta^2_{21}(k) = b_\delta \Delta^2_\delta(k) + b_x \Delta^2_{x_{\rm HI}}(k) + \text{cross-correlations}$$

Detectable for post-LOFAR experiments



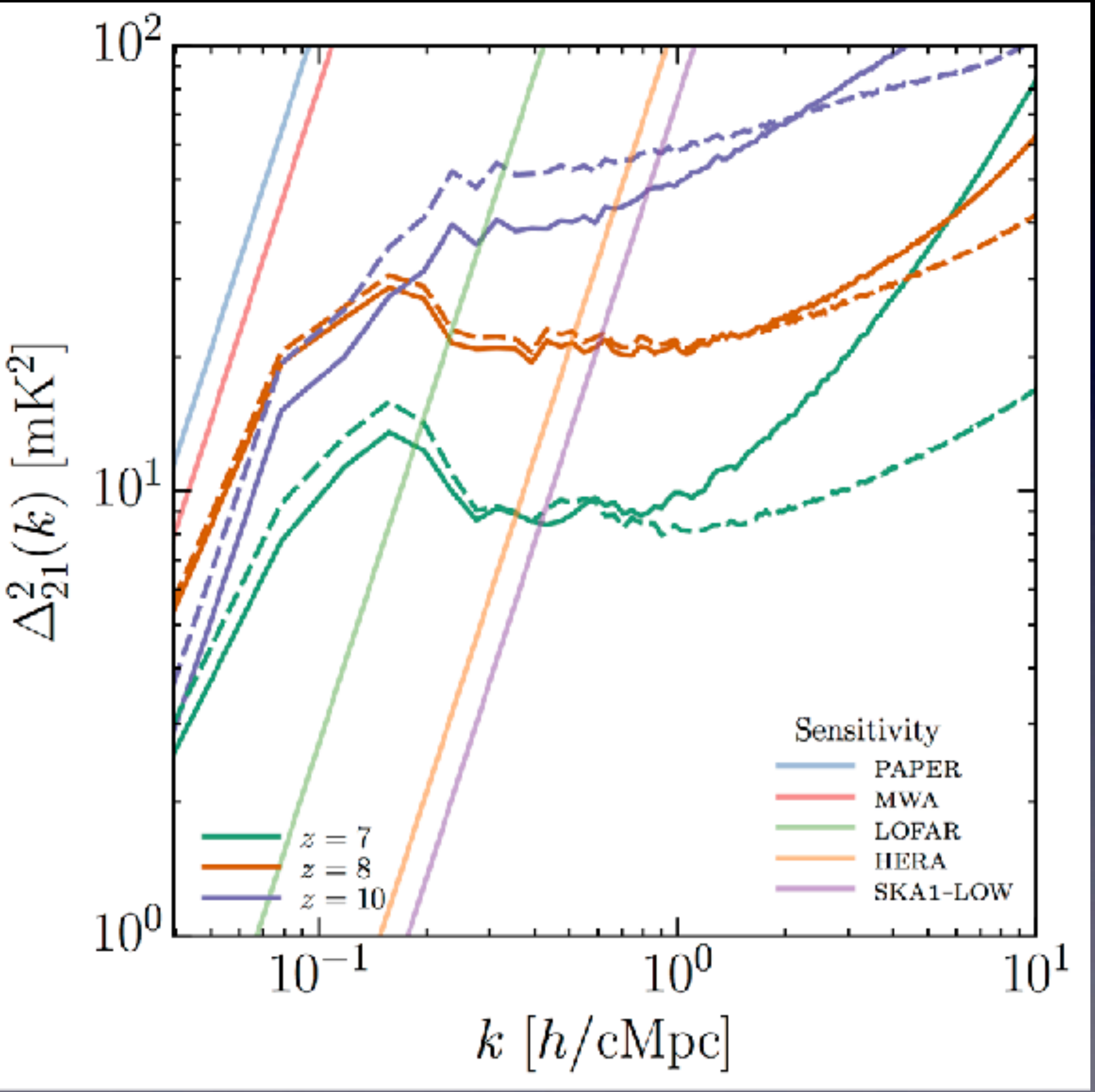
Kulkarni et al. 2016

Reionization model decides evolution



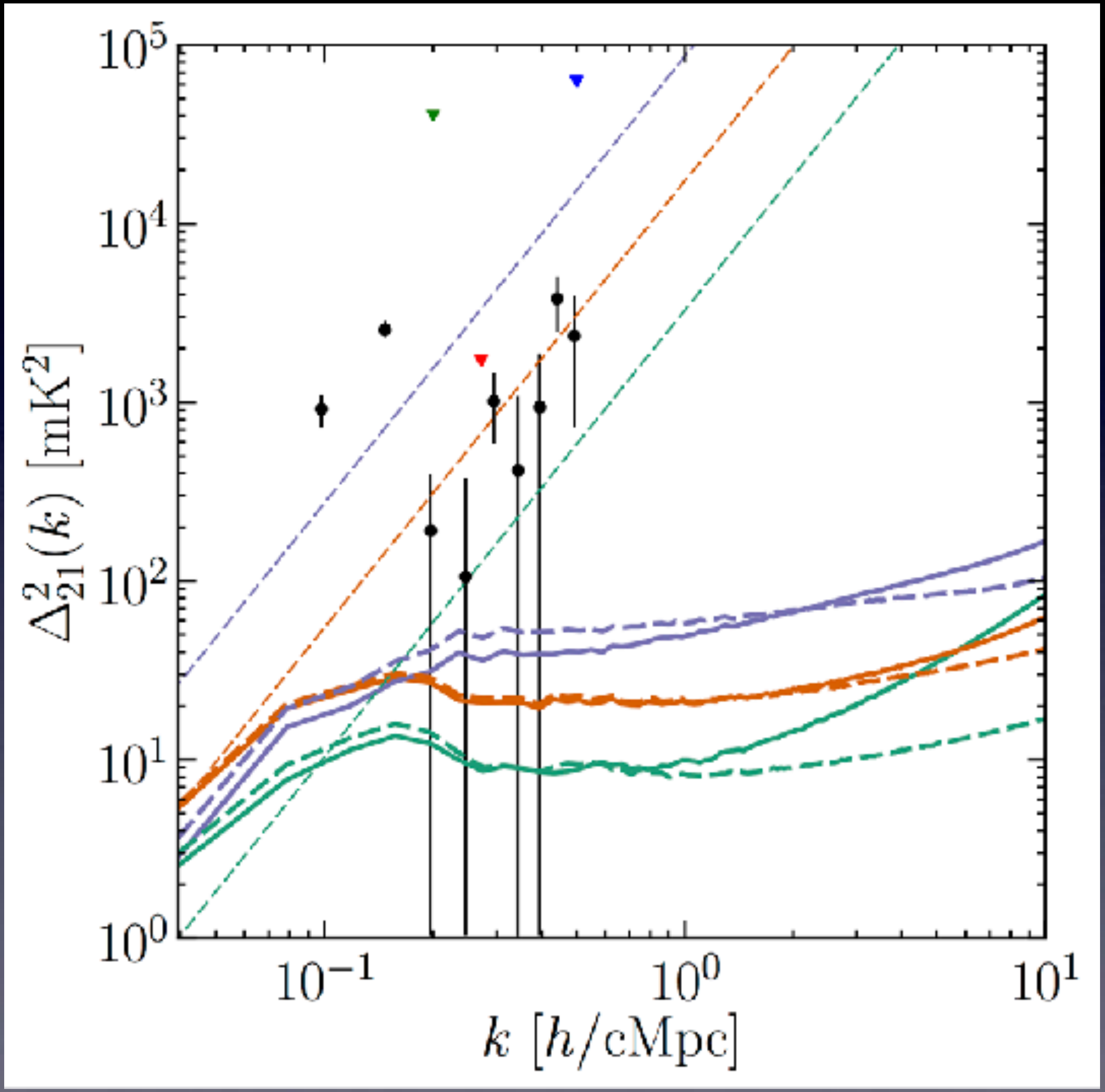
Kulkarni et al. 2016

Reionization model decides evolution



Kulkarni et al. 2016

Can now compare with current data

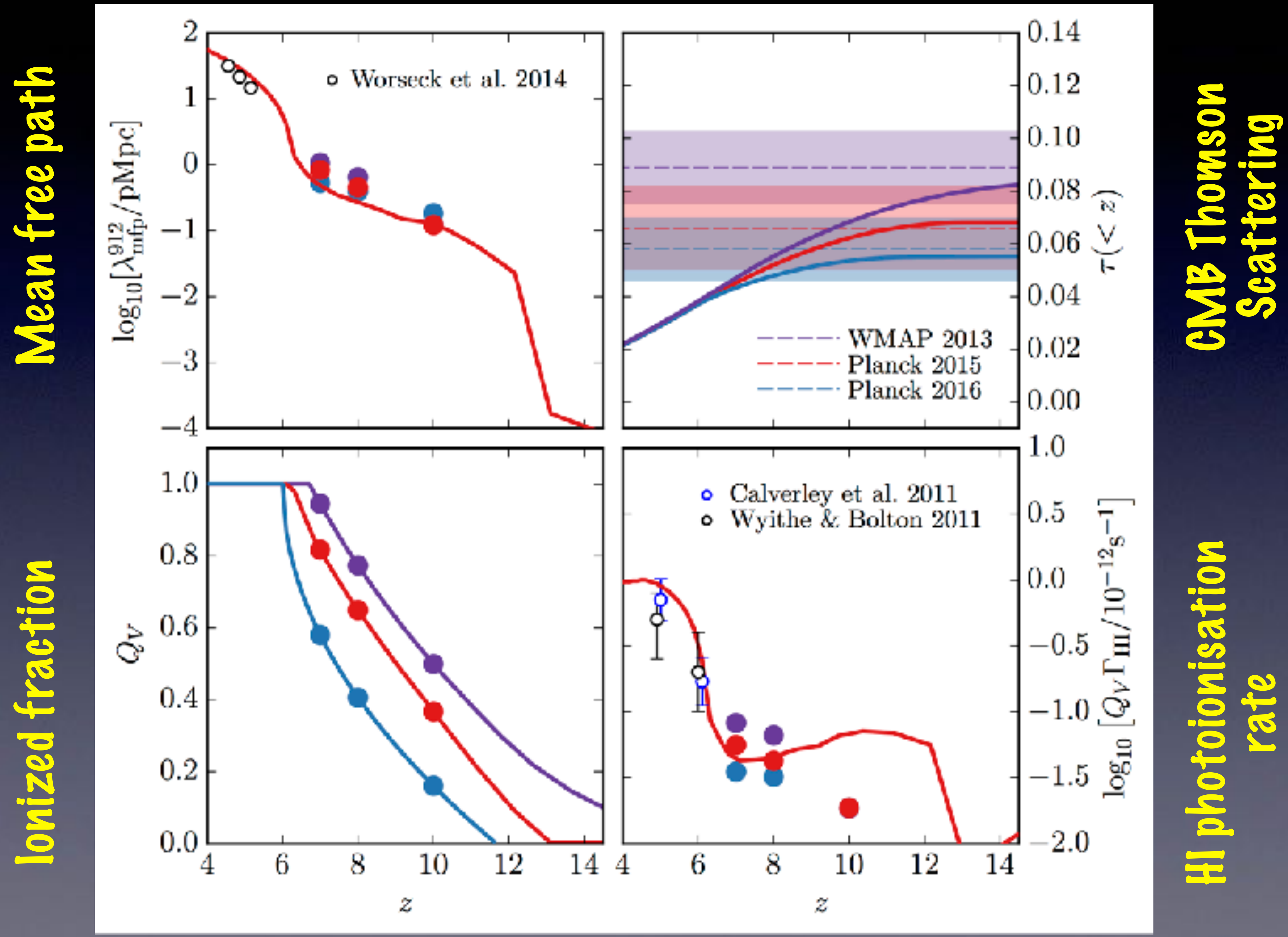


Kulkarni et al. 2016

RMS within a factor of few of sensitivities already reached by experiments

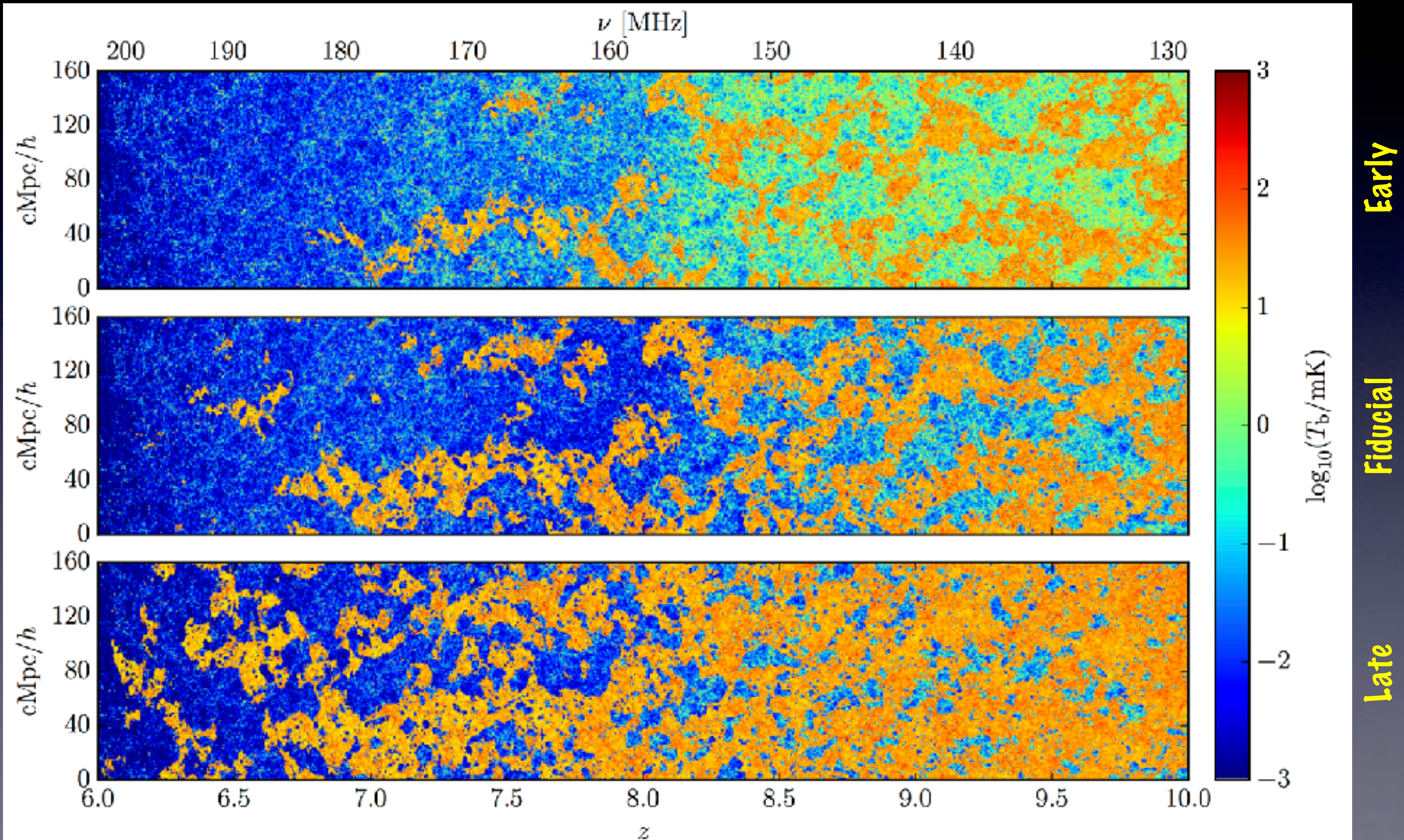
Consider different reionization histories

Kulkarni et al. 2016



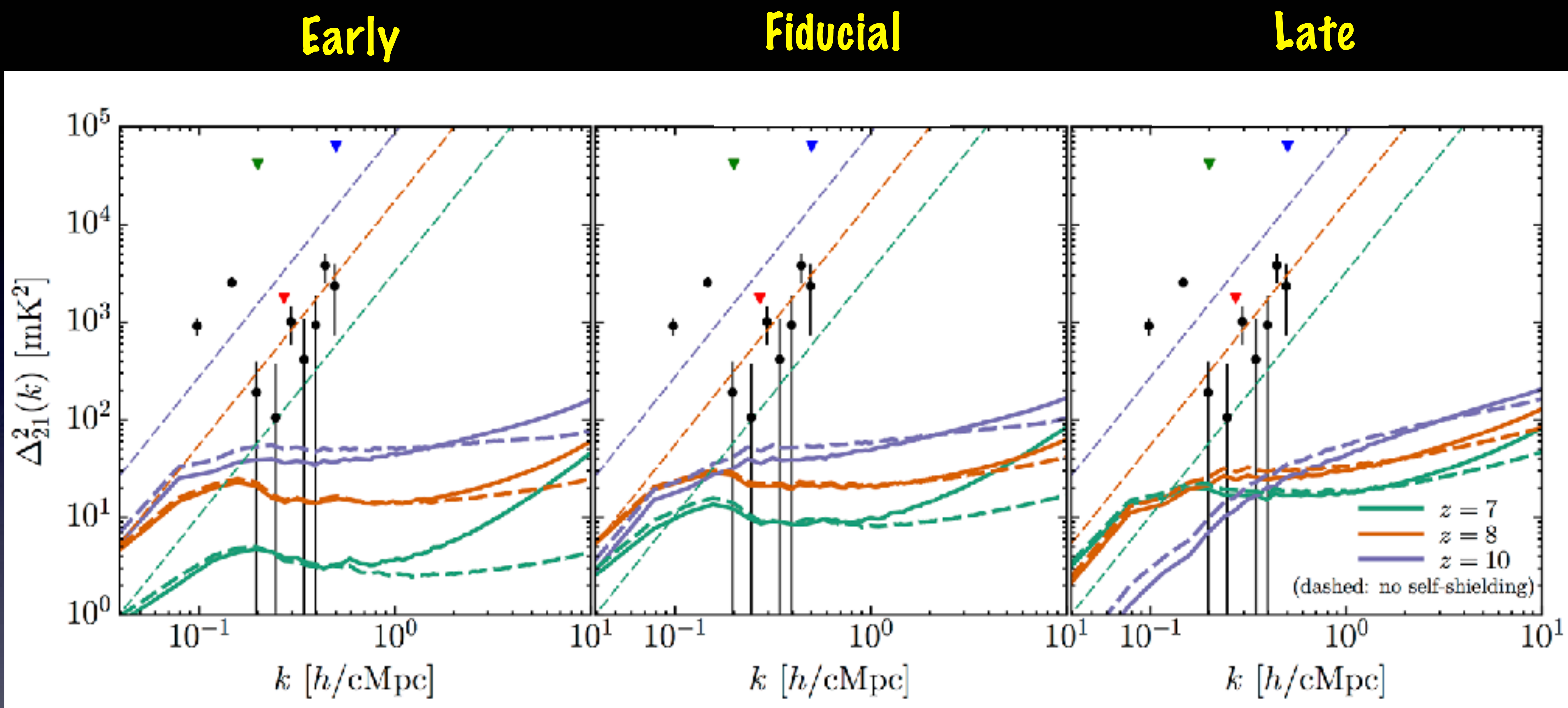
"Early", "Fiducial", and "Late".

These models delay or advance reionization



Kulkarni et al. 2016

Effect on the power spectrum

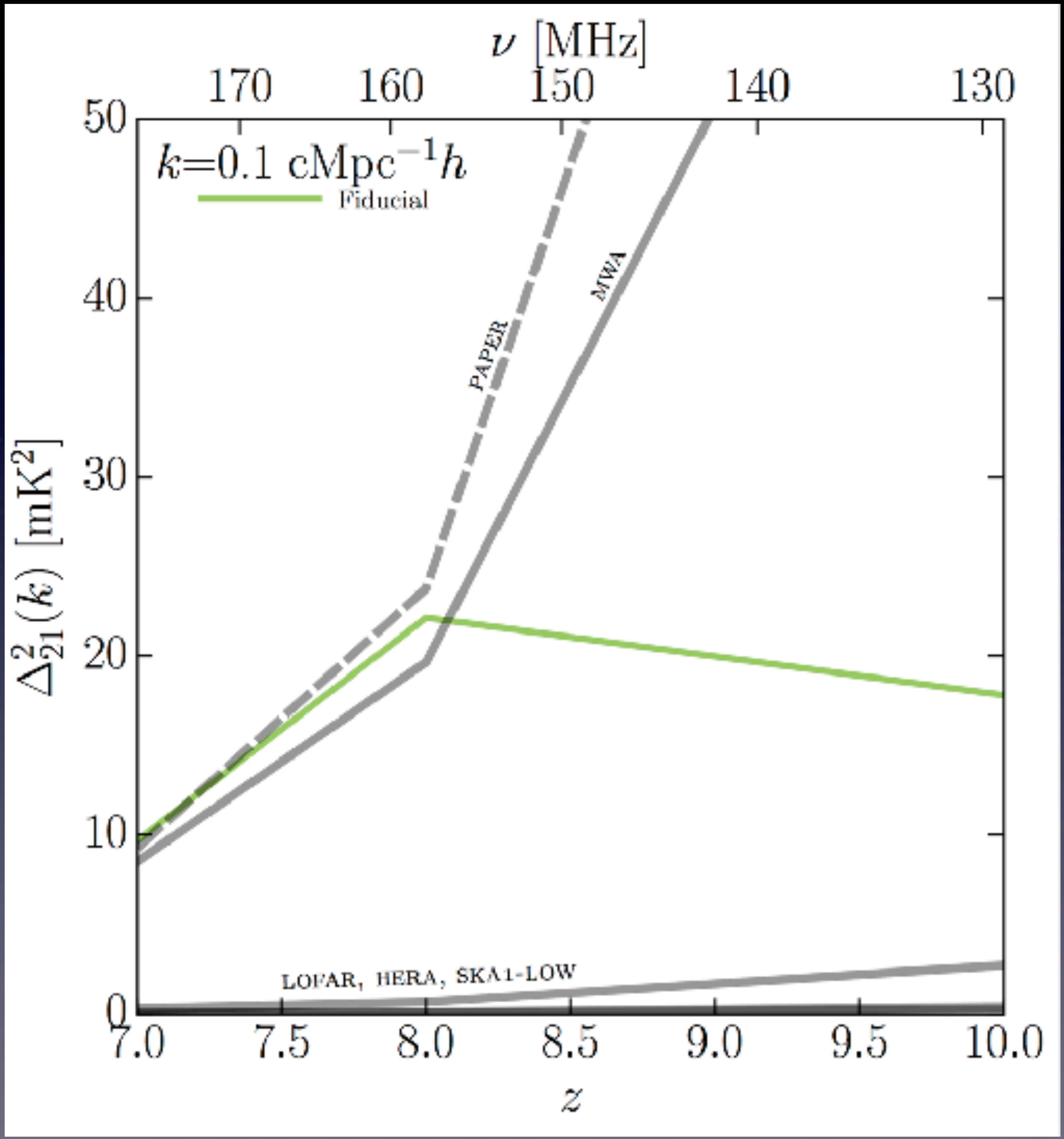


Kulkarni et al. 2016

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

Source clustering fixes large-scale power at large scales. **Matter clustering** fixes small-scale power. Reionization astrophysics decides how the two mix.

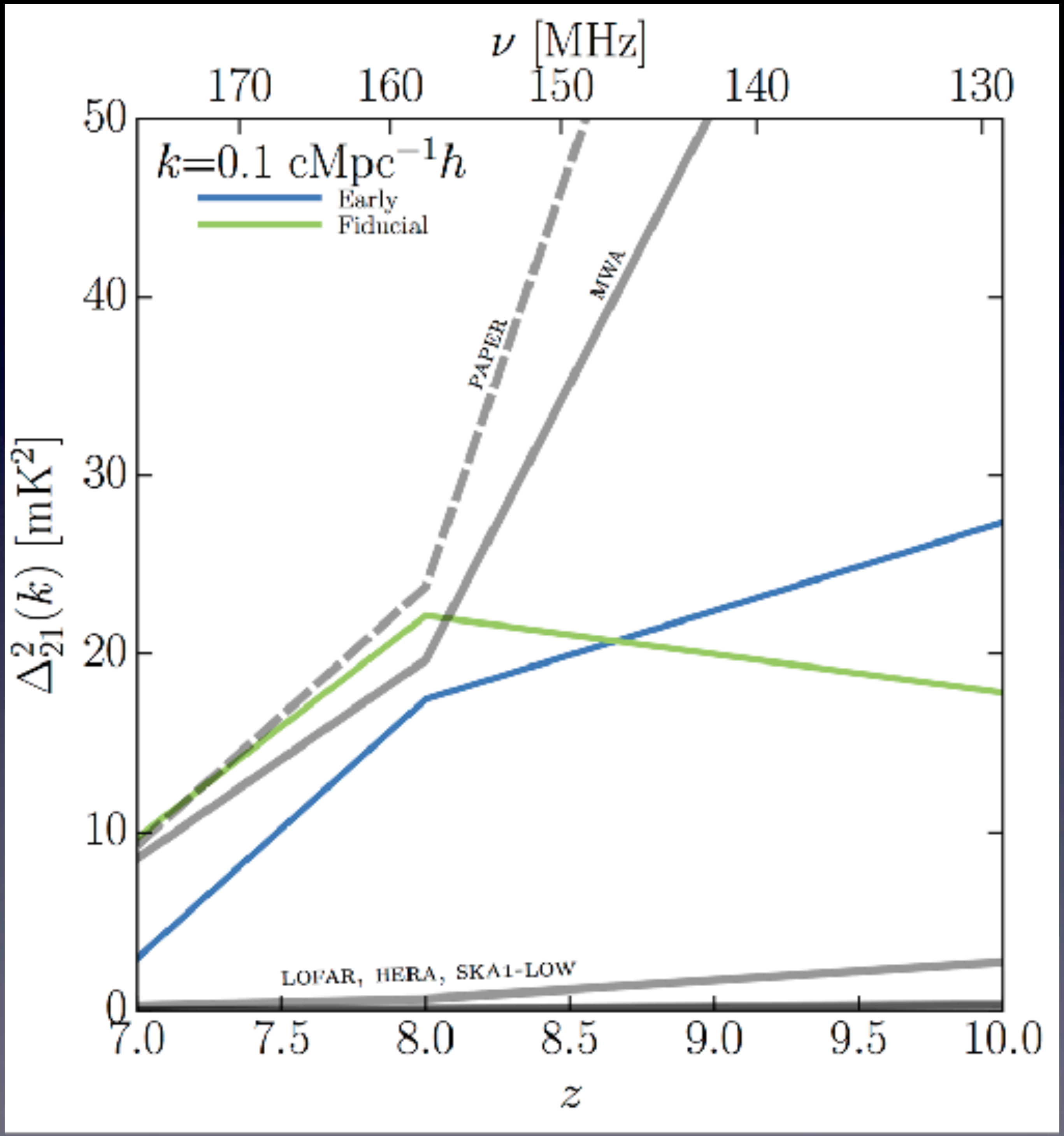
Evolution of large scale power



Kulkarni et al. 2016

Large-scale power peaks at reionization mid-point

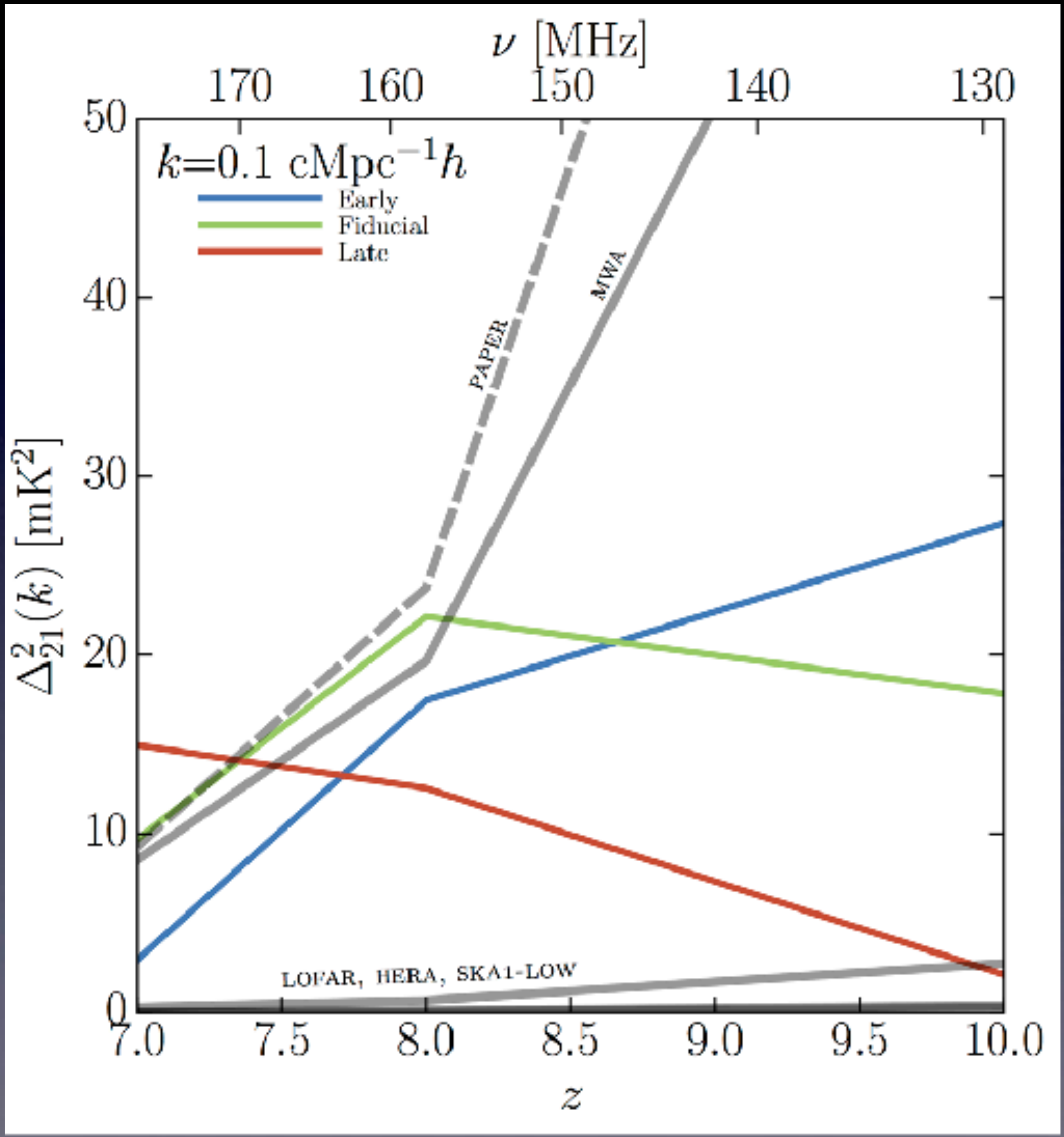
Evolution of large scale power



Kulkarni et al. 2016

Large-scale power peaks at reionization mid-point

Unique cosmological signature in large scale power?

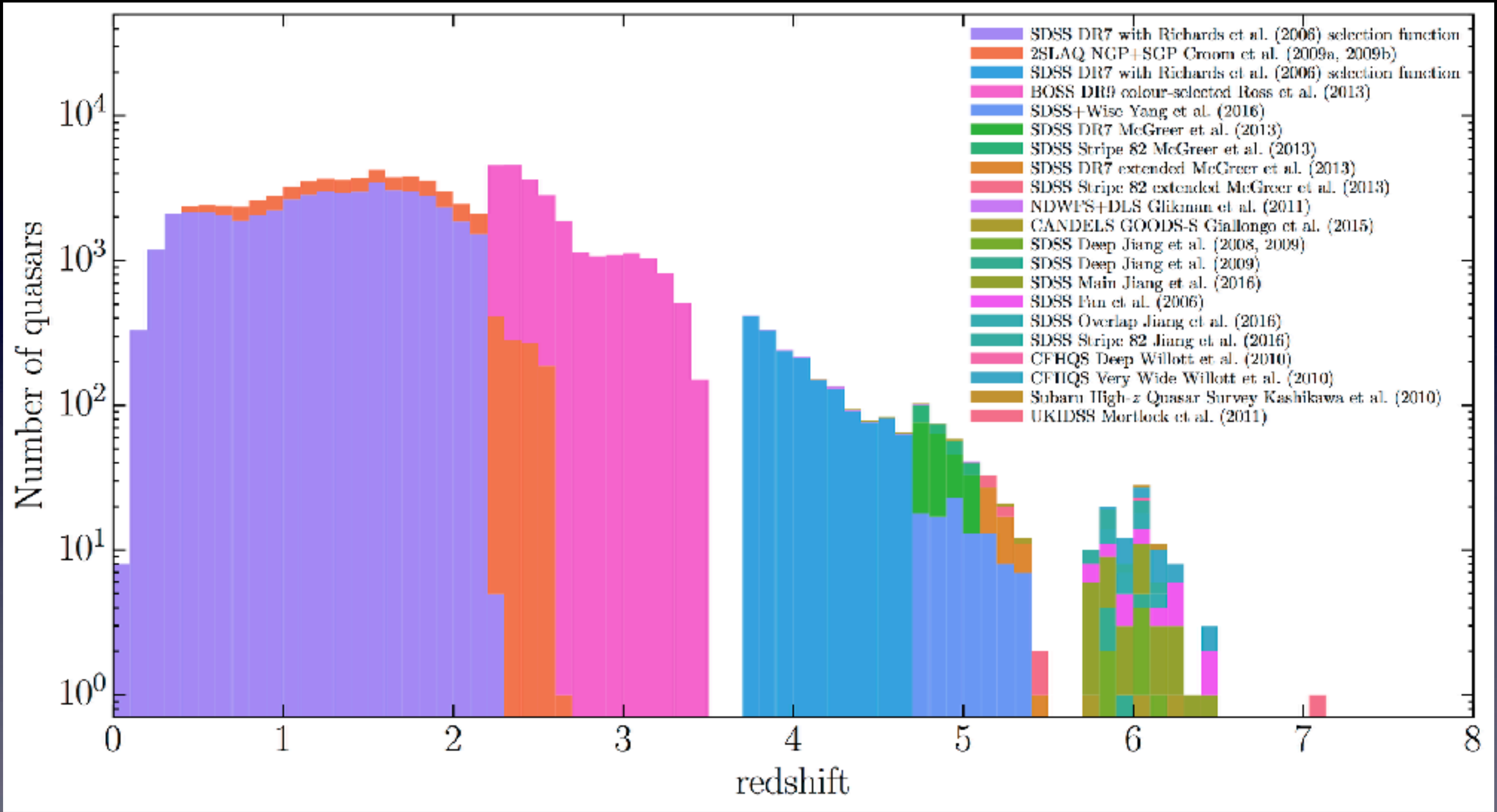


Kulkarni et al. 2016

Large-scale power peaks at reionization mid-point

21 cm signal in AGN-dominated reionization scenarios

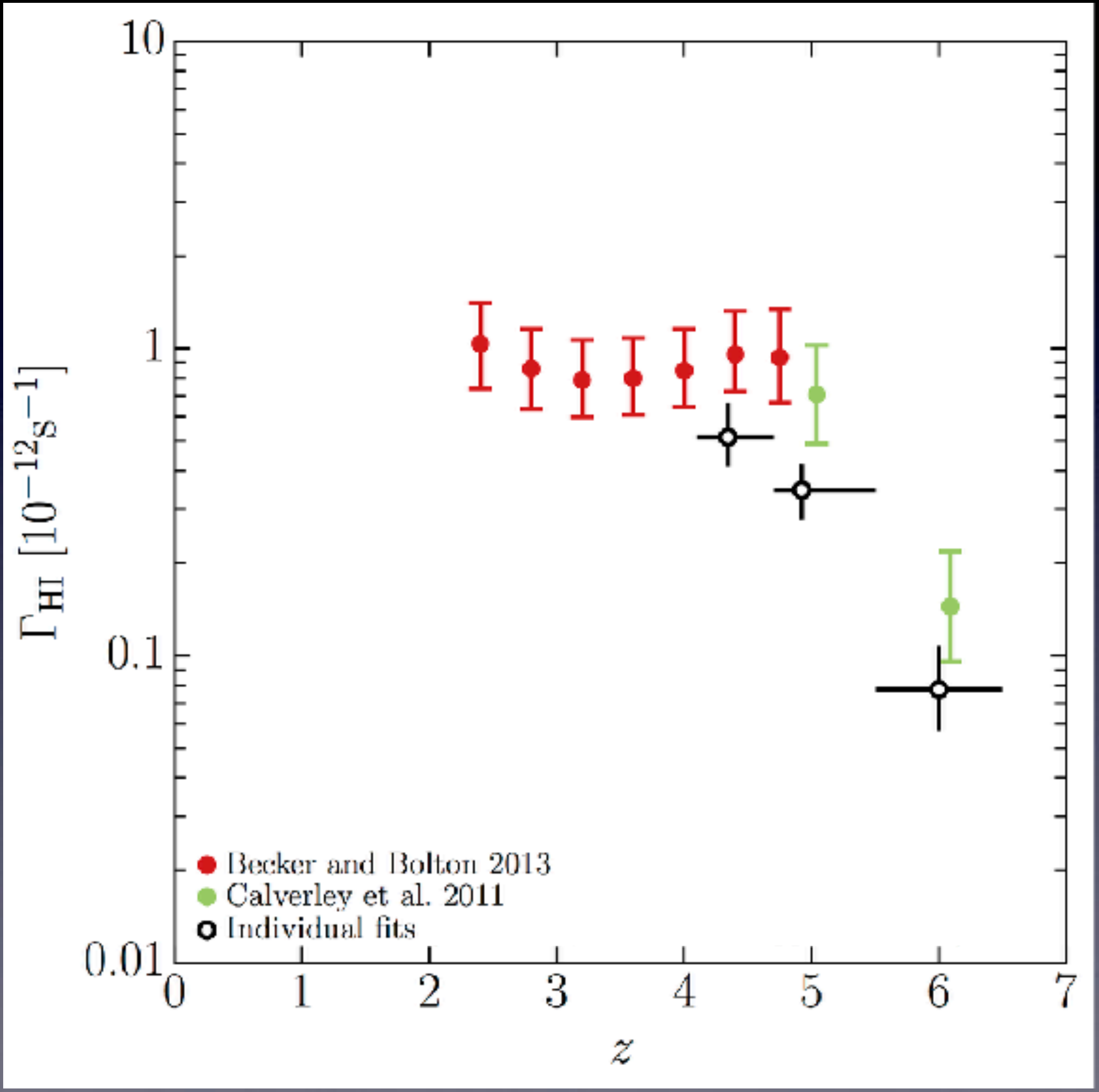
Prepare largest homogeneous quasar dataset



Kulkarni et al. *in prep*

84566 quasars with spectroscopic redshifts and completeness estimates

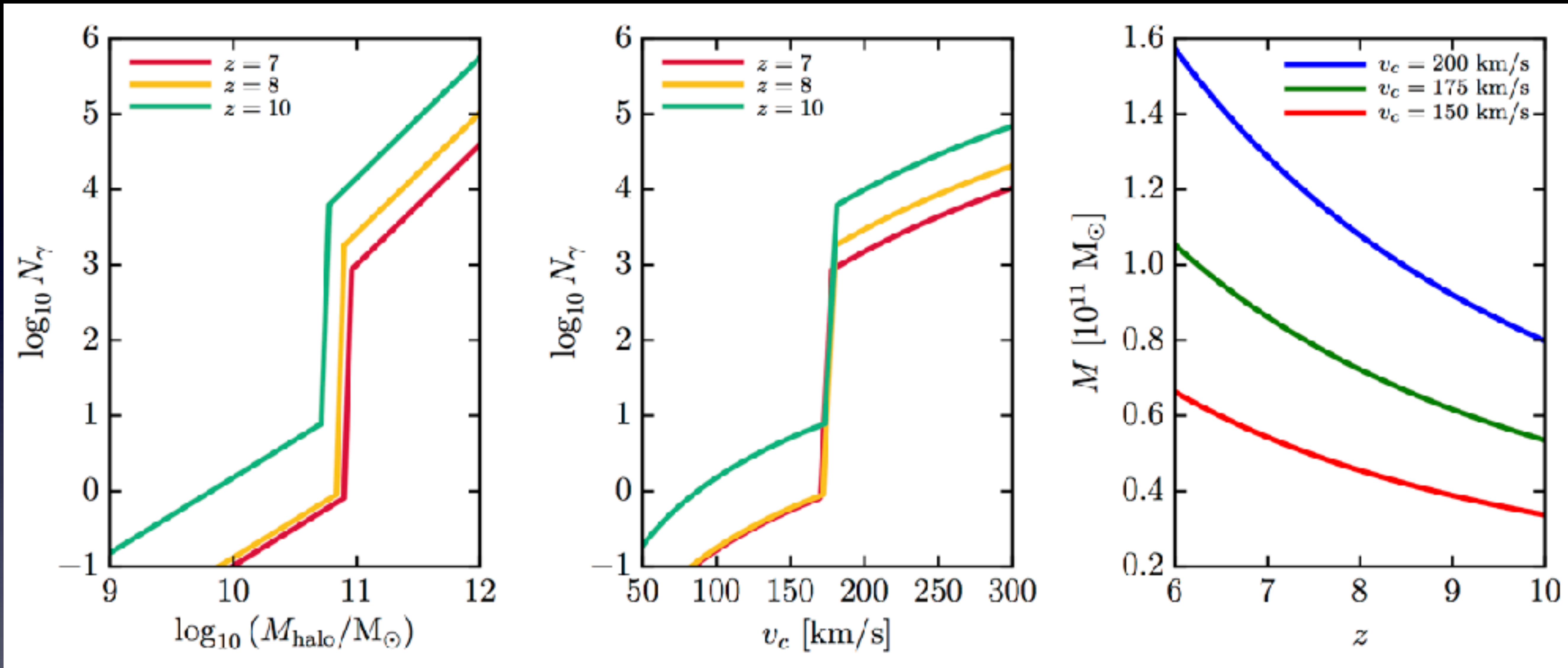
Quasar contribution to hydrogen ionization



Kulkarni et al. *in prep*

Quasars contribute 50–100% LyC photons at z = 4–6!

Need plausible model for high-z quasars

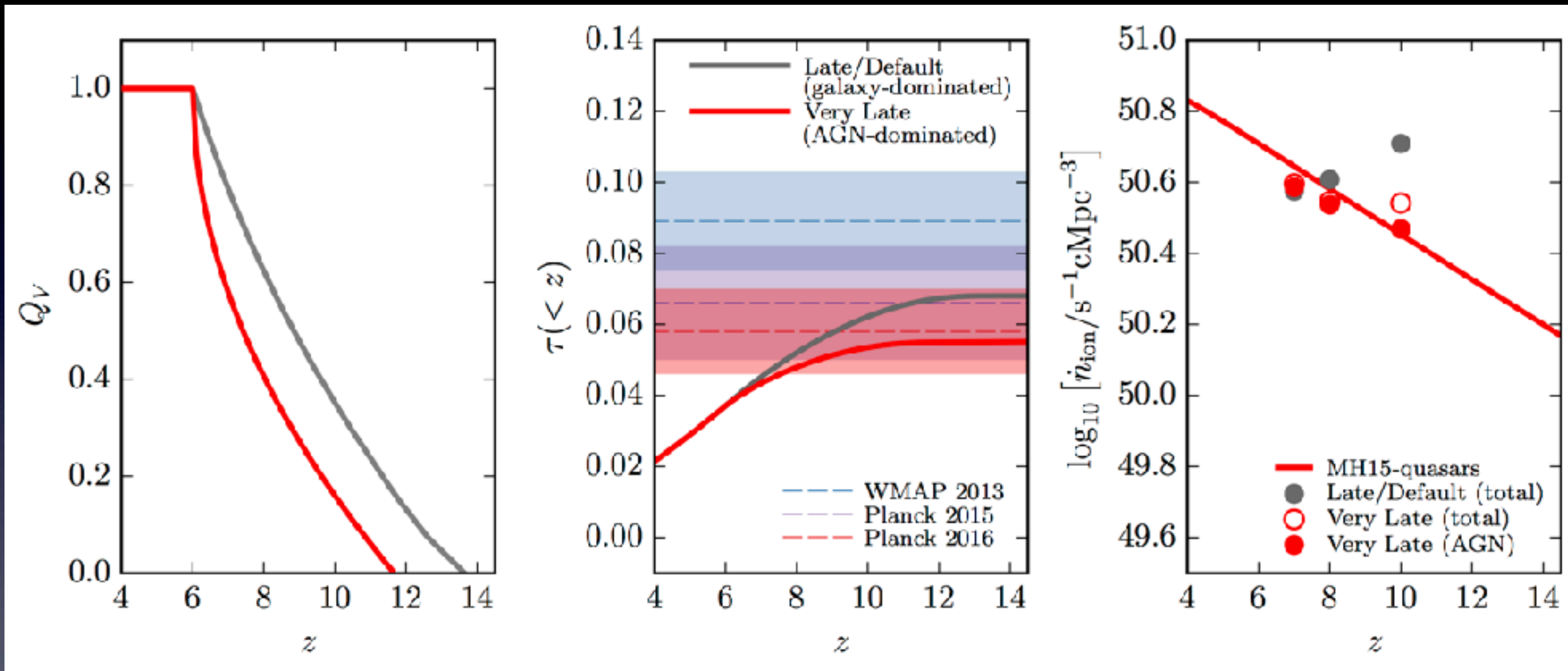


Kulkarni et al. 2017

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

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

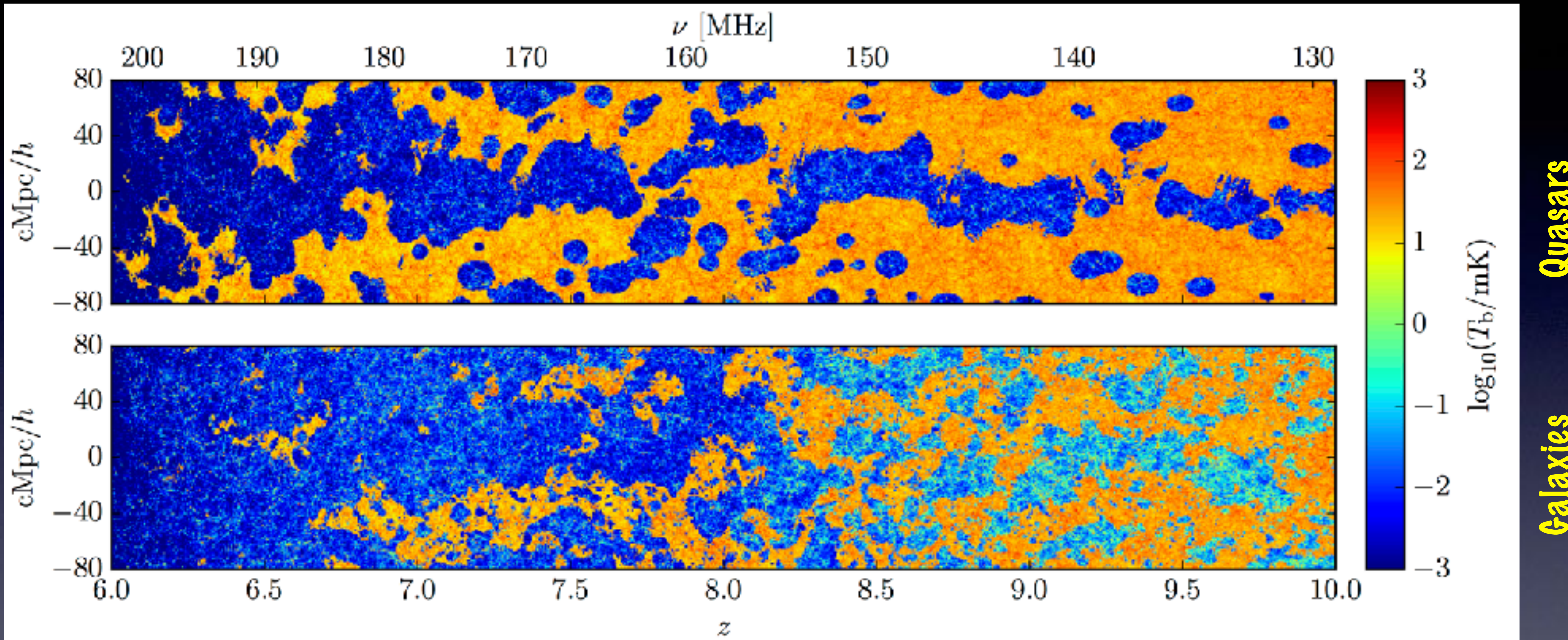
Calibrate to an AGN-dominated model



Kulkarni et al. 2017

Reionization history is close to the Very Late model.

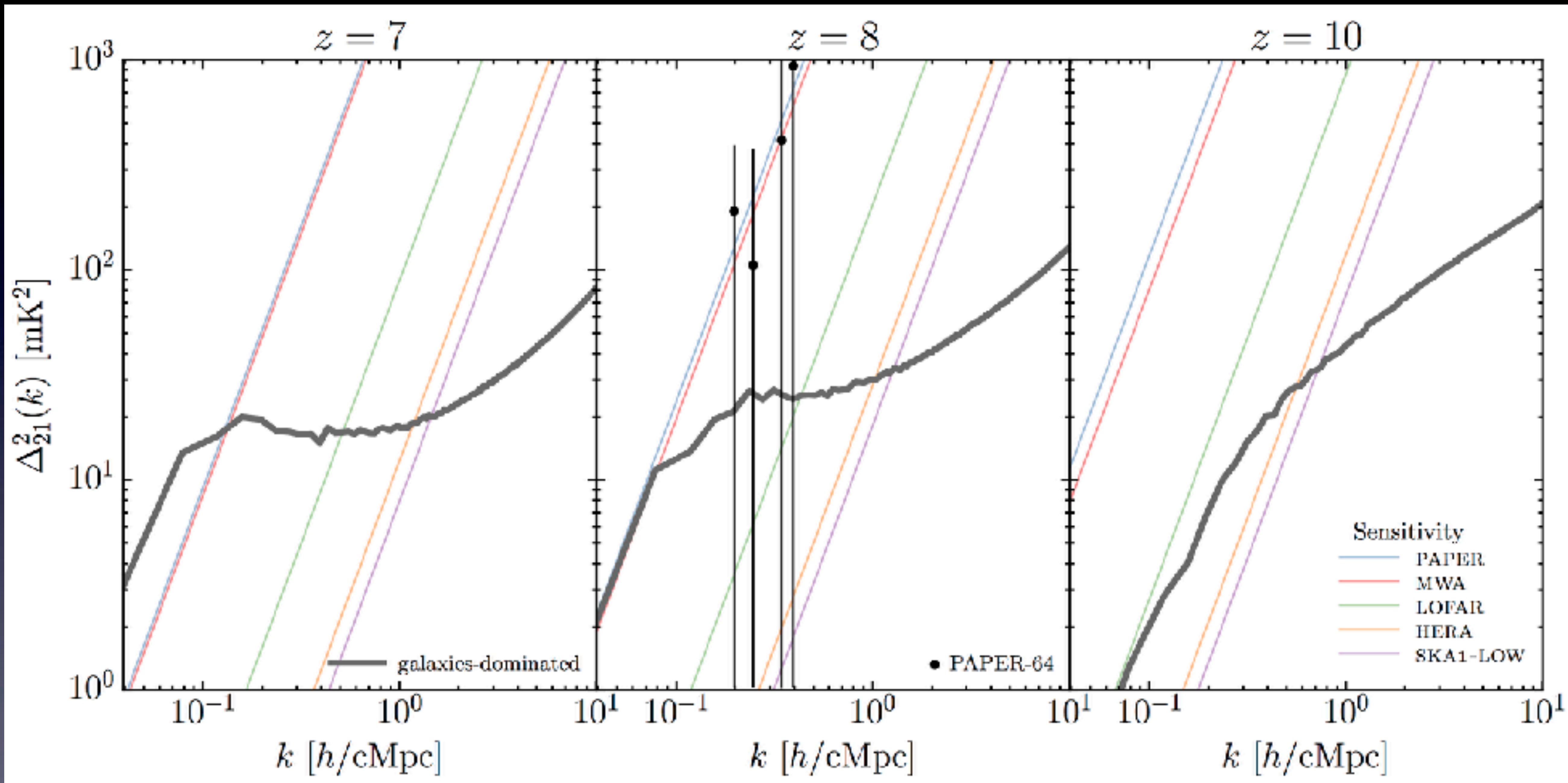
Reionization by Quasars?



Kulkarni and Loeb 2012; Kulkarni et al. 2017

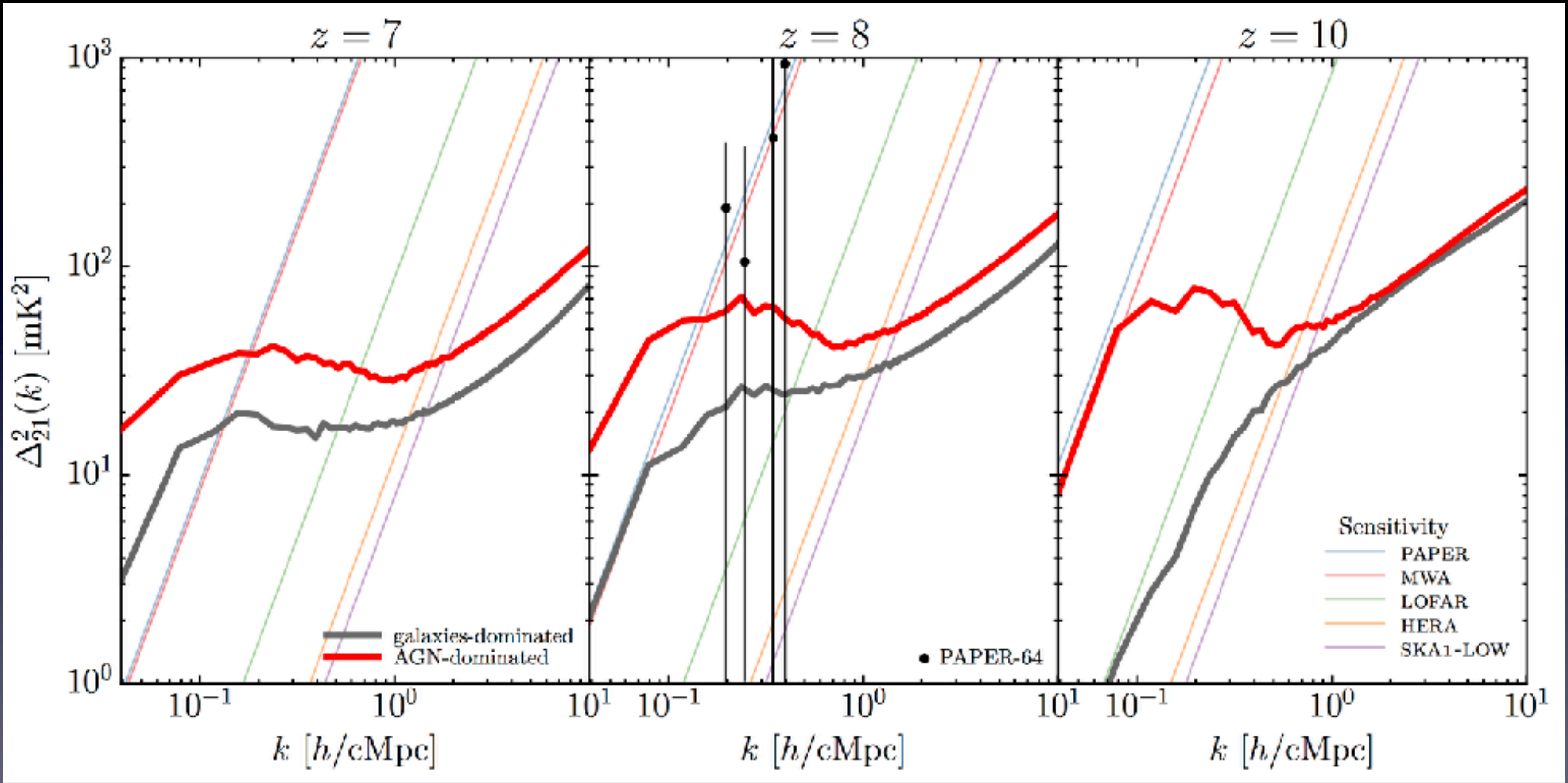
- 21 cm distribution dominated by large bubbles.
- Reionization happens later but ionised regions are now ~10 cMpc in size

Compare with the galaxies-dominated case



Kulkarni et al. 2017

Factor of 5–10 increase in power

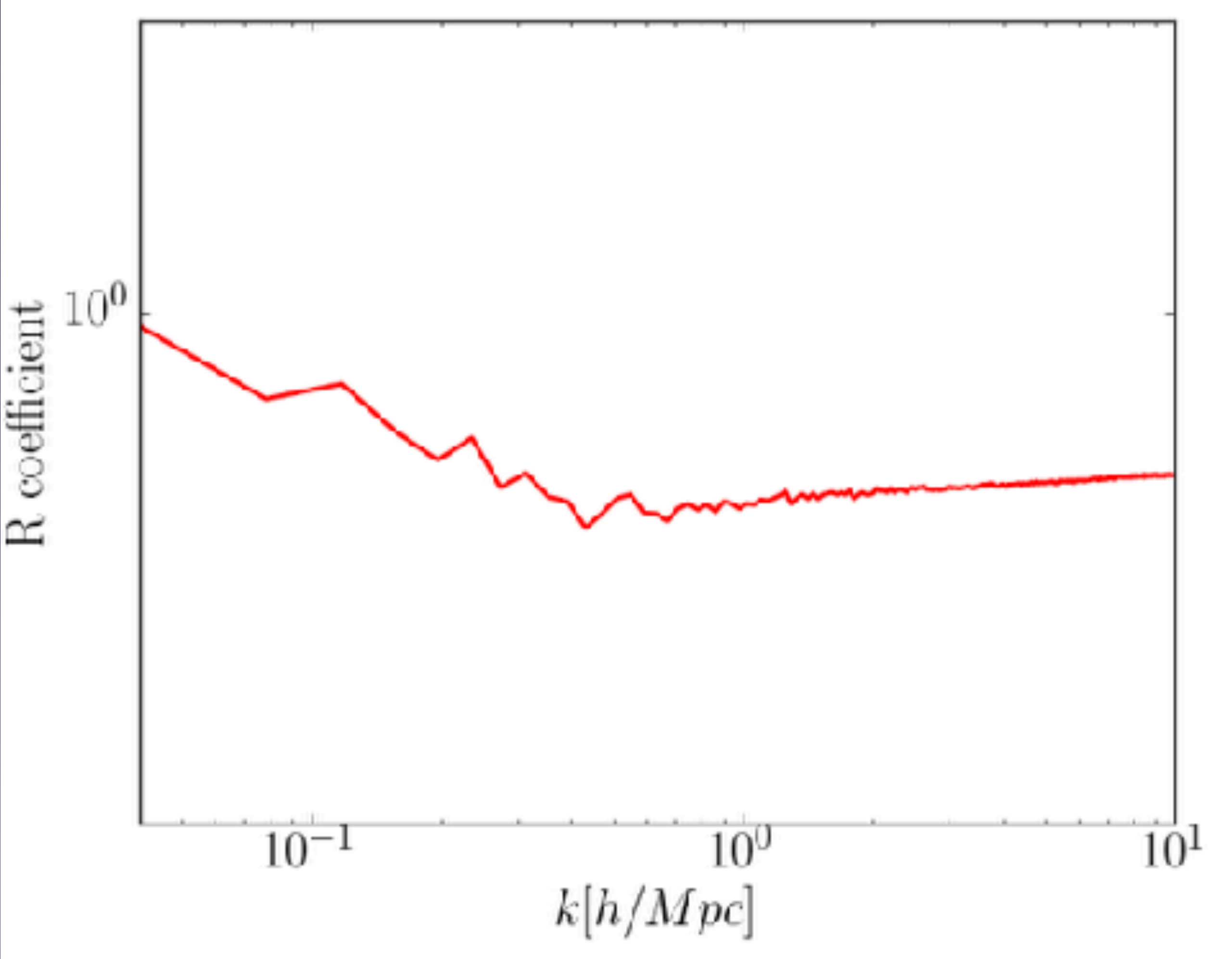


Kulkarni et al. 2017

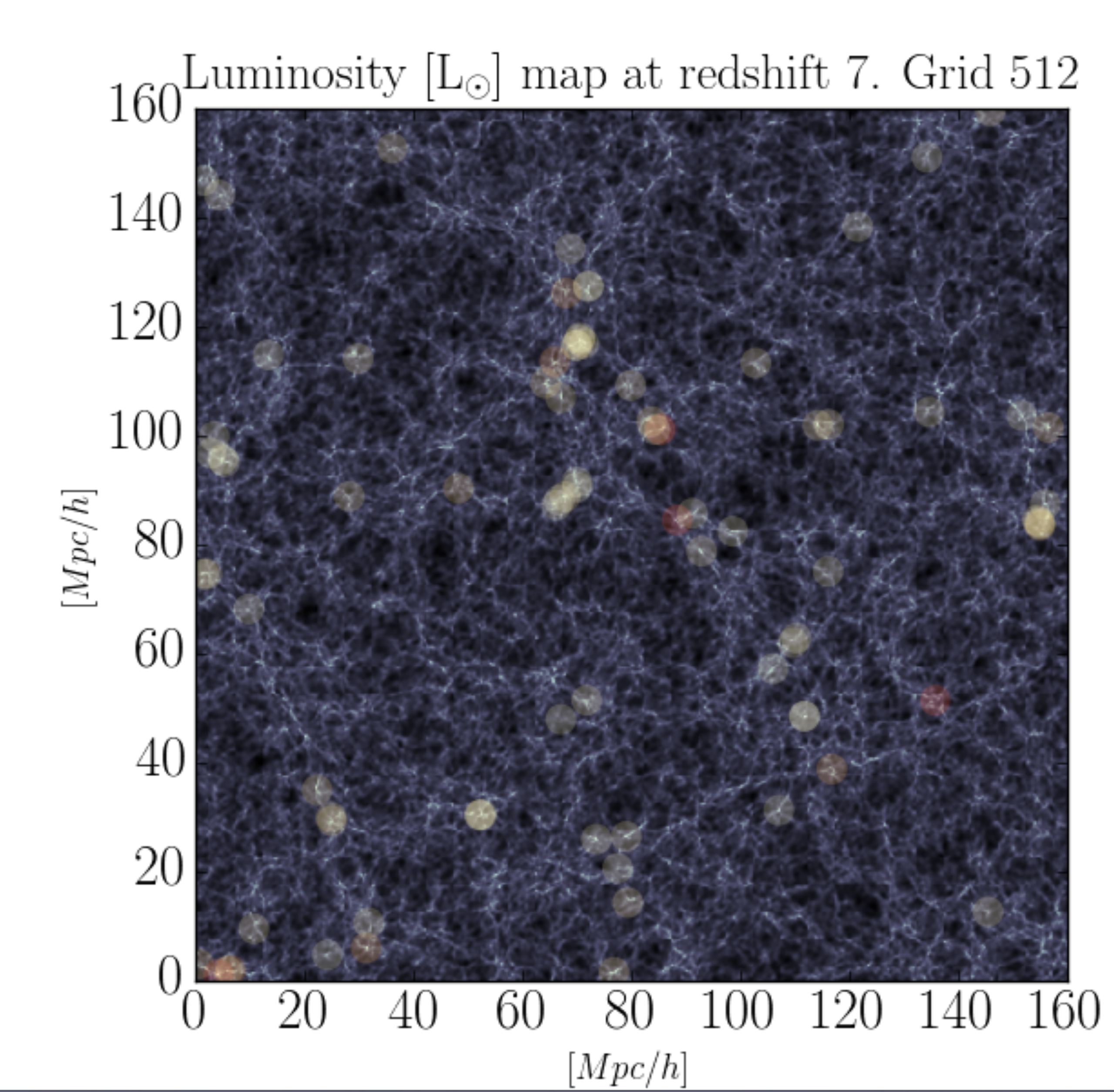
Peak power is only factor of ~2 smaller than current data. Potential source of constraint on high-z quasars.

Intensity mapping of the high-z universe

Dumitru, Kulkarni



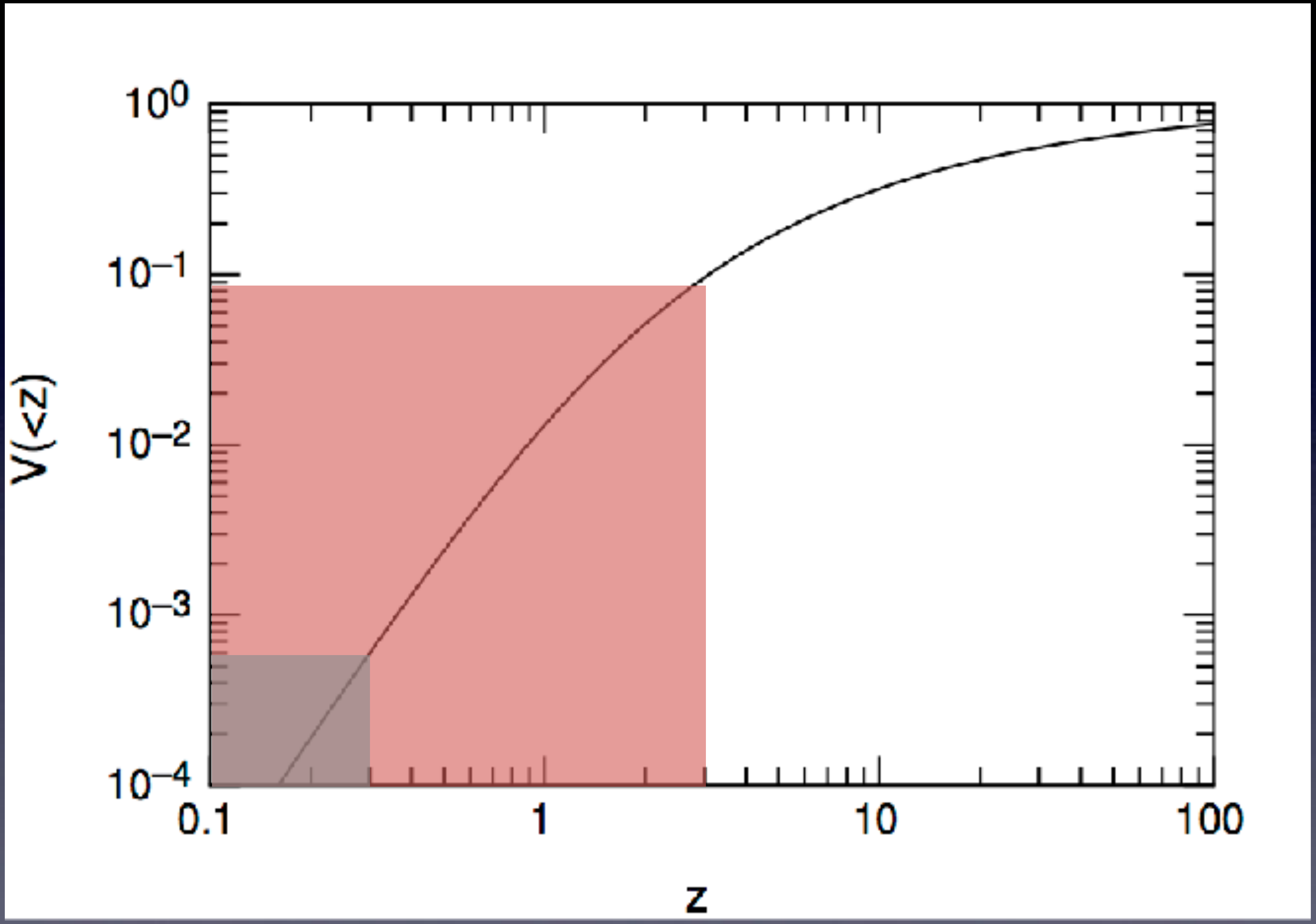
CO-CII cross-correlation



CO luminosity "map"

Intensity mapping the high-z universe and cross-correlating these maps with 21 cm will help retrieve more information

Cosmology with Intensity Mapping



Loeb and Wyithe 2008, Pritchard and Loeb 2012

21 cm IM will increase the observable volume of the Universe, which reduces errors ($\sigma \propto V_{\rm eff}^{-1/2}$). This helps BAO and dark energy science.

Conclusions

- We are producing highest-dynamic-range simulations of the 21 cm signal from the epoch of reionization
- Presented method to calibrate photon budget in high resolution simulations to Lyα and CMB data
- **Large scale 21 cm power** is ~10 mK^2, within reach of post-LOFAR experiments
- **Quasar-dominated reionization** histories have higher 21 cm power by factor of 5–10 (>50 mK^2).