21CMMC: an MCMC framework for the astrophysics of reionisation

Bradley Greig

In collaboration with A. Mesinger (SNS)

SCUOLA NORMALE SUPERIORE

European Research Council

ICTP, Trieste, May 13th 2015

Epoch of reionisation

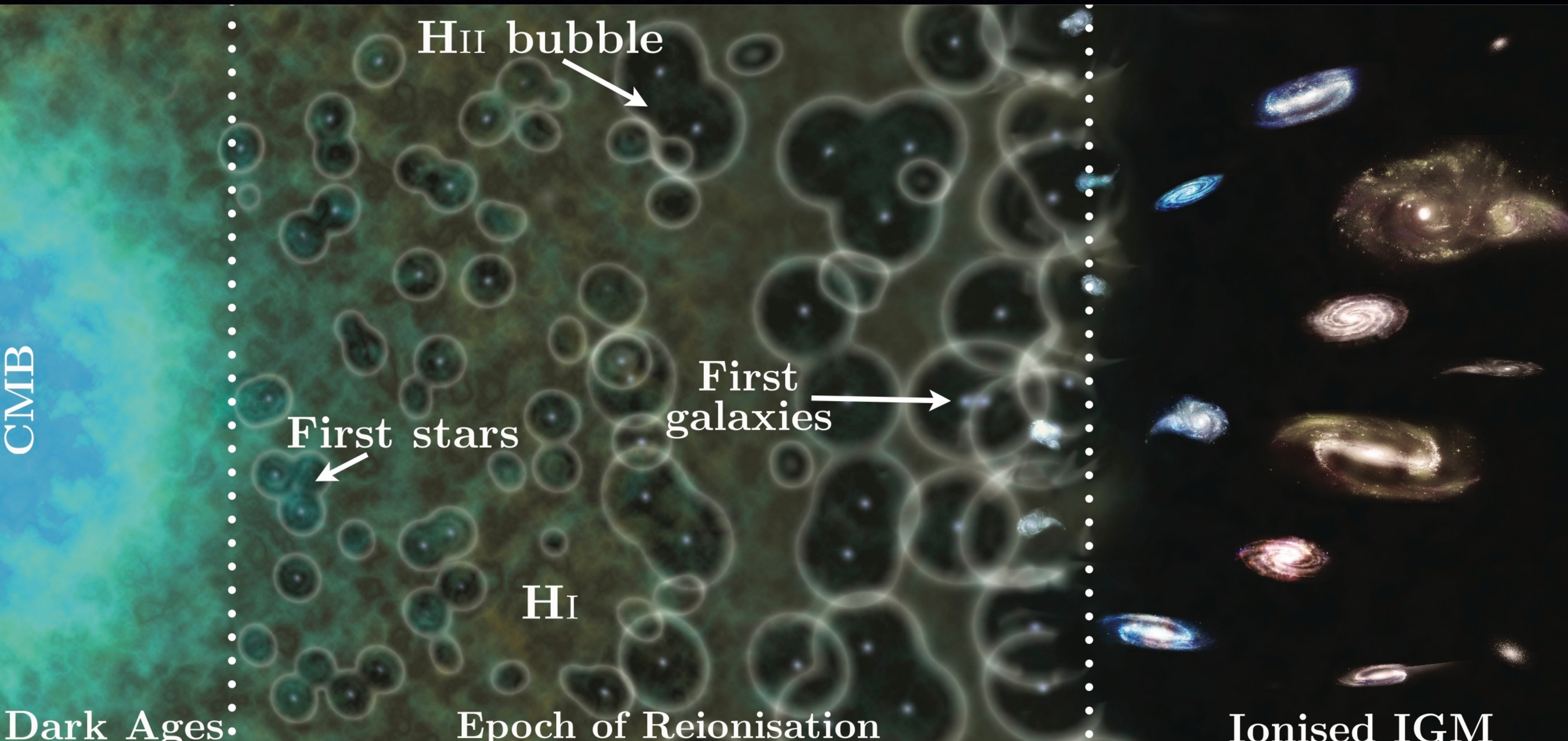
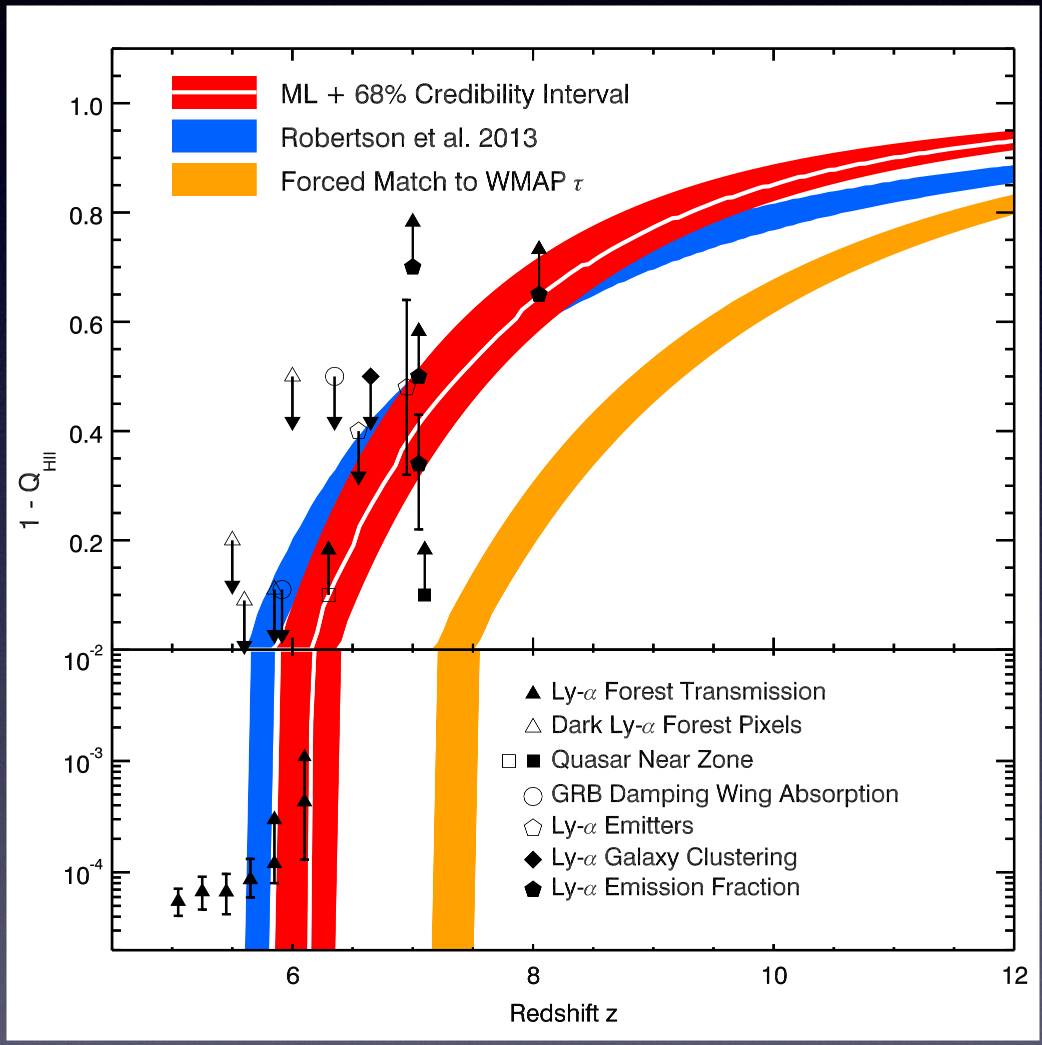


Image Credit: NASA/CXC/M.Weiss

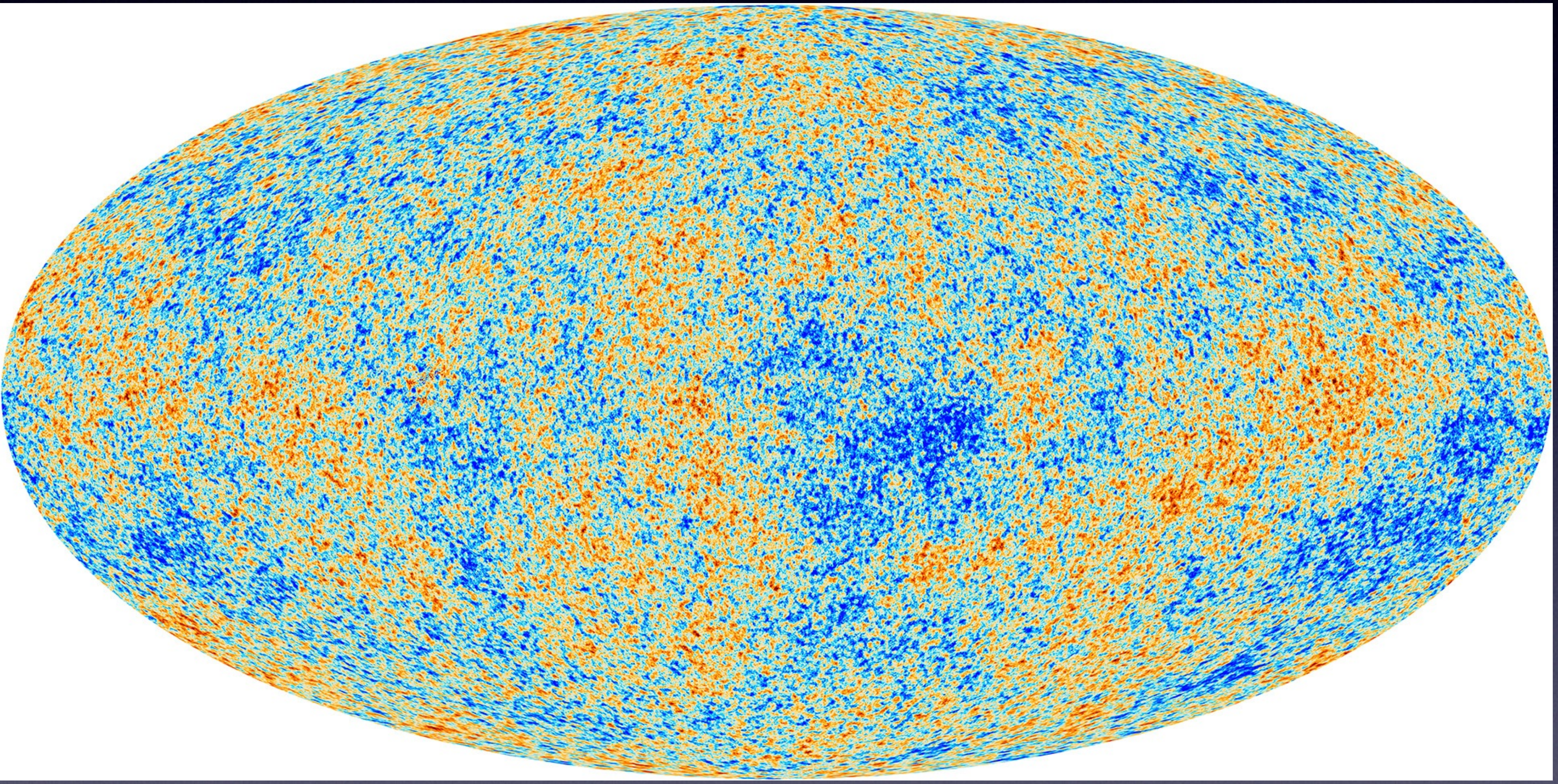
But what can we learn about reionsation?

- **Current constraints:**
  - Integral constraints from the CMB (Planck)
  - Measurements on the IGM neutral fraction at z ~ 6
- **Current and future 21 cm experiments:**
  - LOFAR, PAPER, MWA
  - SKA, HERA
- **What will these actually provide?**
- **How do we interpret the data?**



Robertson et al. (2015)

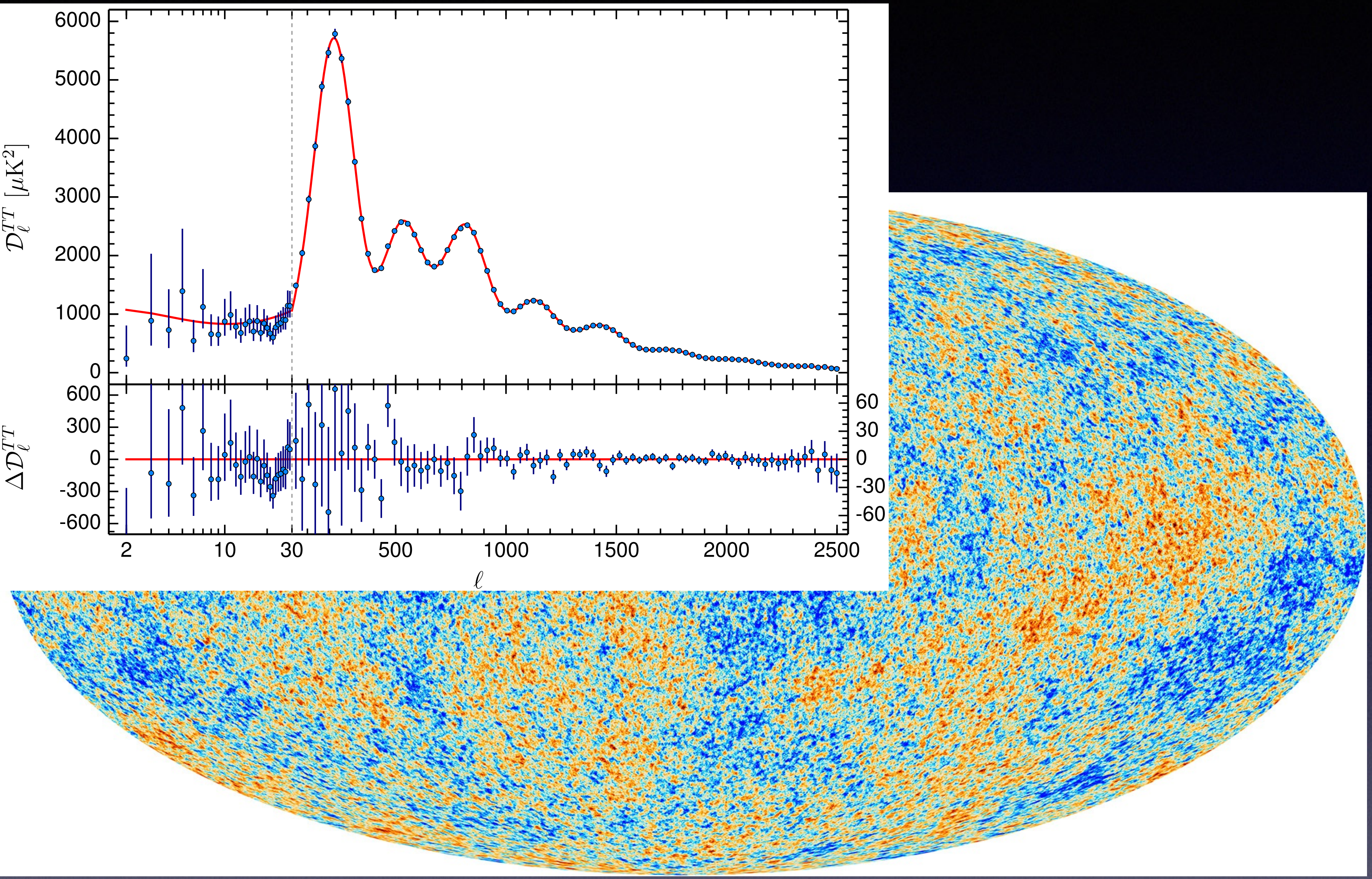
Statistical approach for the CMB



Planck collaboration (2015)

- Temperature fluctuations in the CMB are sensitive to the underlying physics of the ΛCDM model

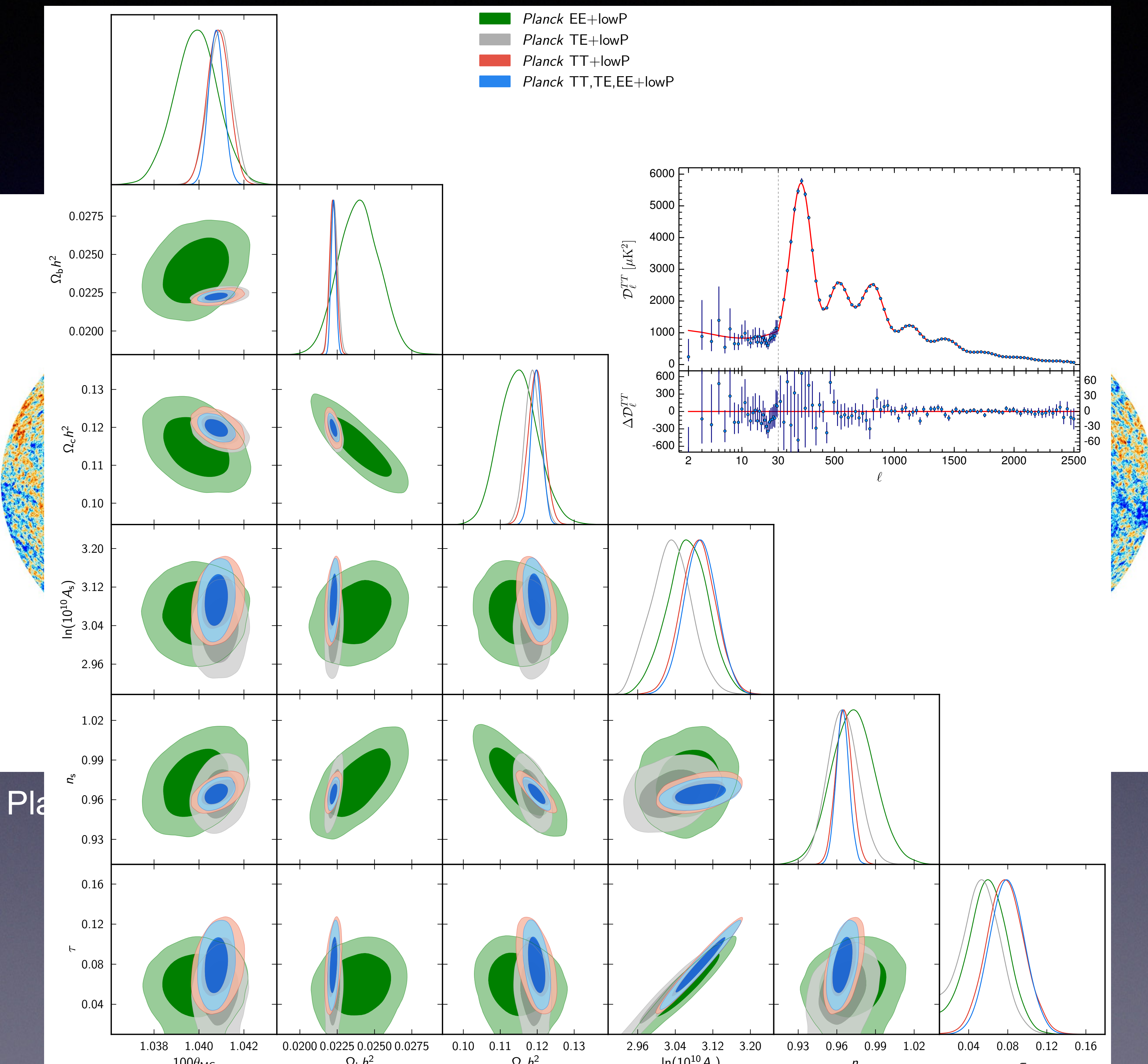
Statistical approach for the CMB



Planck collaboration (2015)

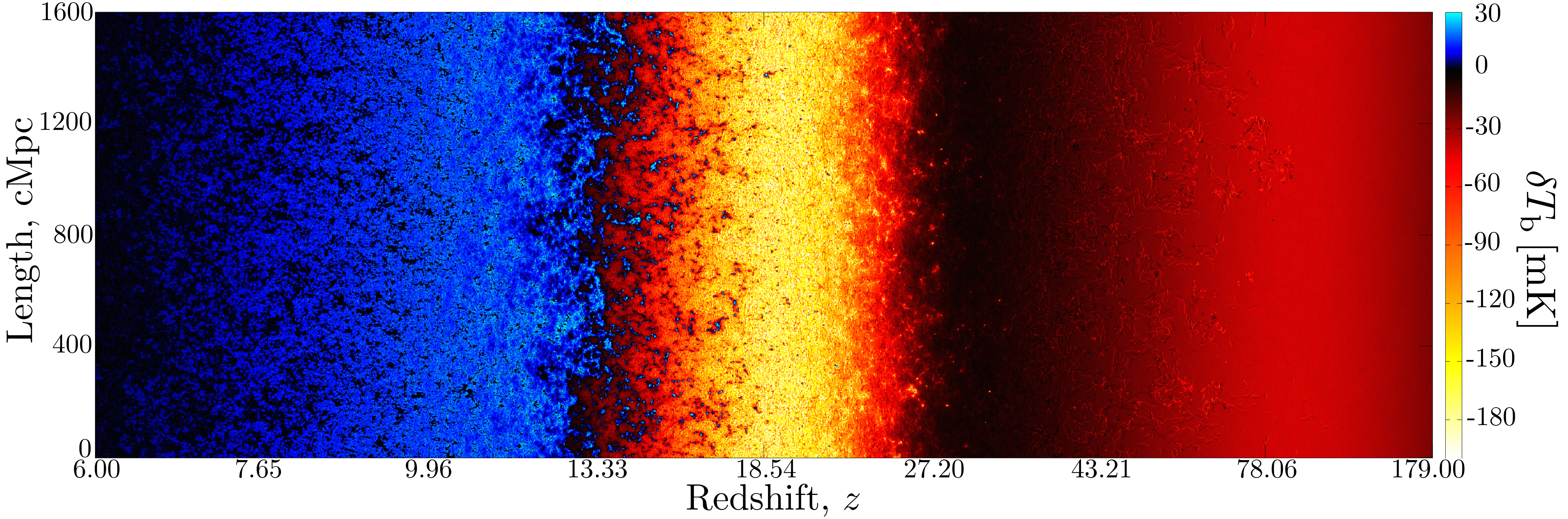
- Temperature fluctuations in the CMB are sensitive to the underlying physics of the ΛCDM model
- Exquisite data enables precise estimates of the signal statistics

Statistical approach for the CMB



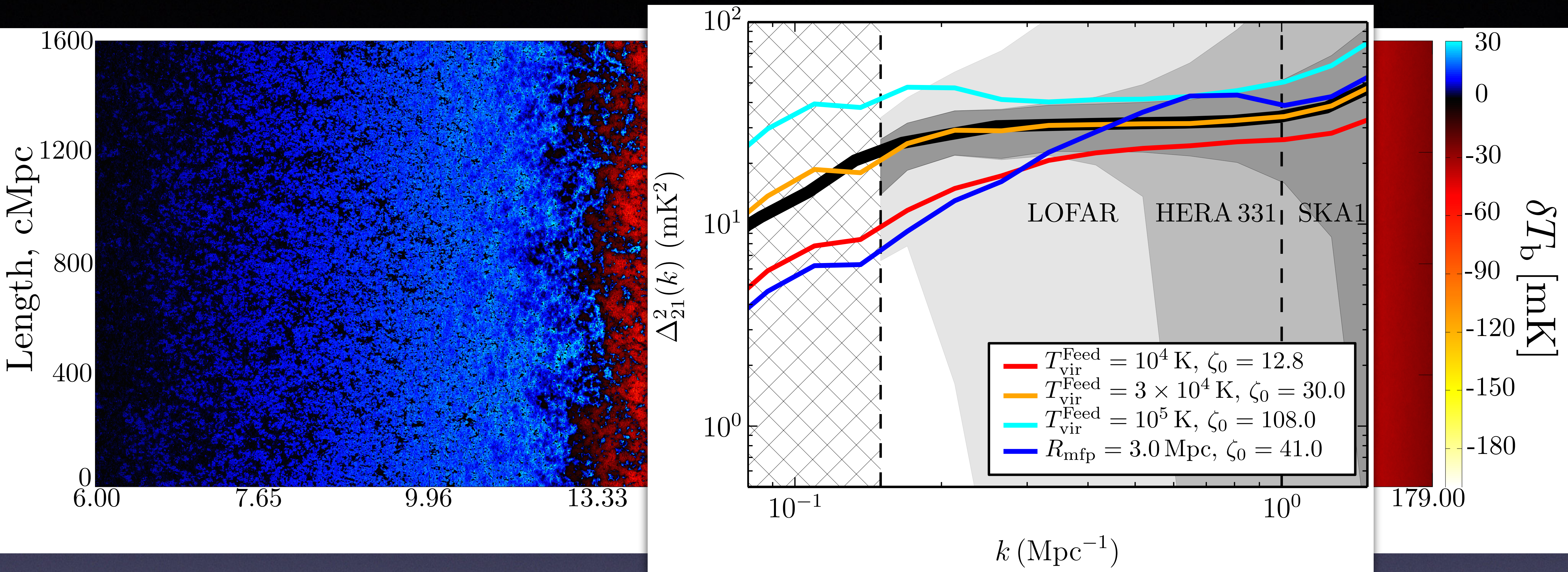
- Temperature fluctuations in the CMB are sensitive to the underlying physics of the ΛCDM model
- Exquisite data enables precise estimates of the signal statistics
- Through Bayesian sampling can recover constraints on the underlying cosmology

What about for 21 cm?



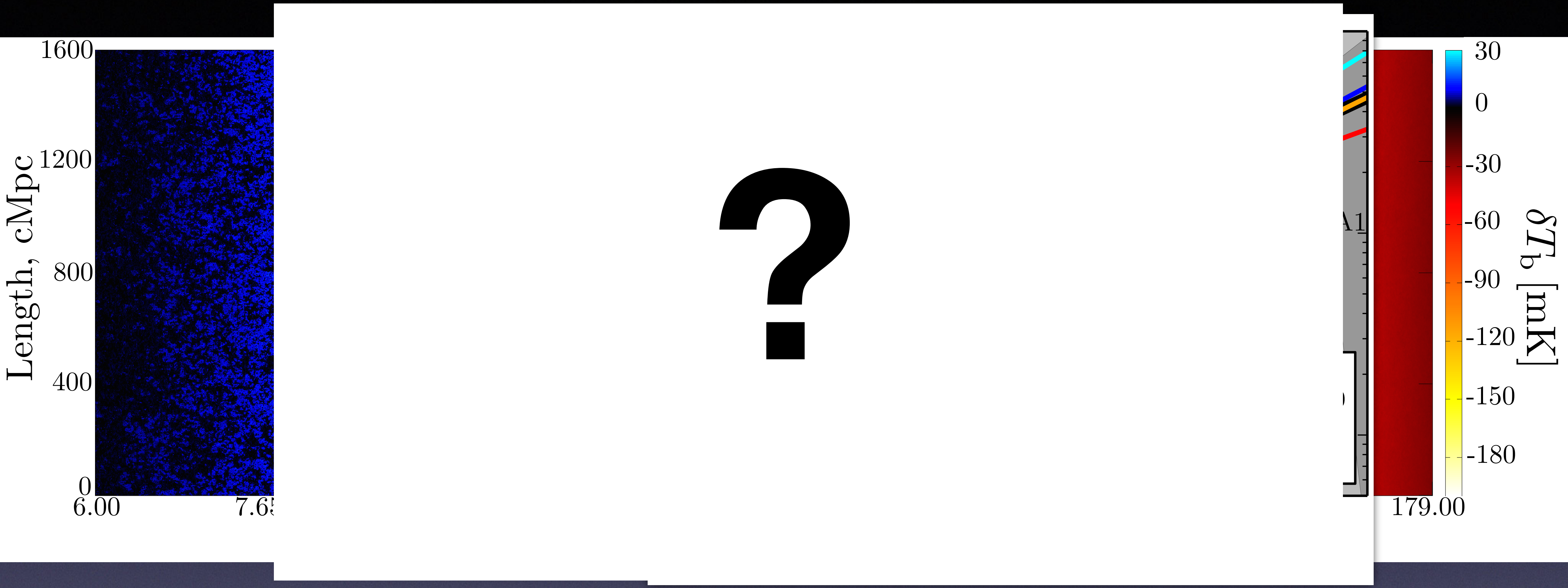
- Simulated light-cone of the expected 21 cm brightness temperature fluctuations
- Sensitive to reionisation astrophysics
  - Mean free path of IGM, ionising efficiency, IMF, escape fraction, …

What about for 21 cm?



- Simulated light-cone of the expected 21 cm brightness temperature fluctuations
- Sensitive to reionisation astrophysics
- Straightforward to recover statistics of the 21 cm (e.g PS)

What about for 21 cm?

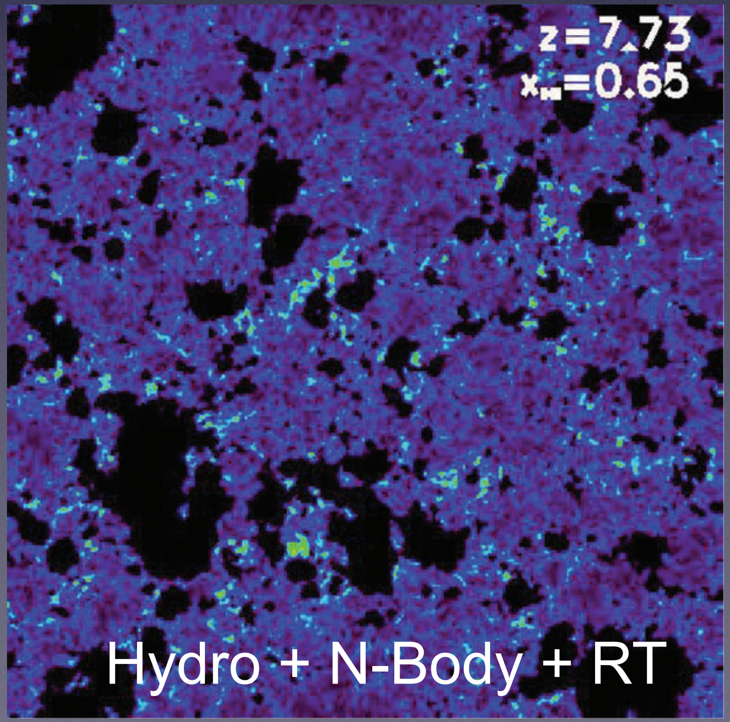


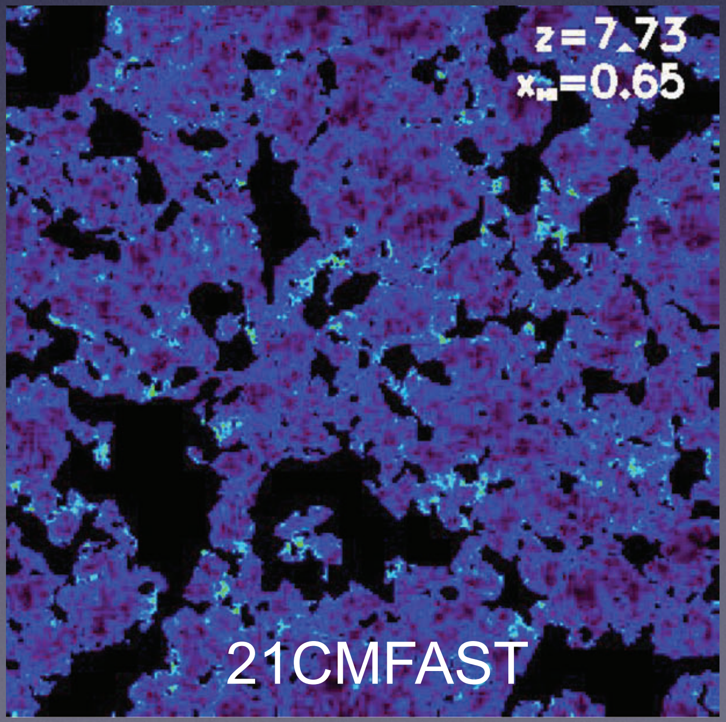
- Simulated light-cone of the expected 21 cm brightness temperature fluctuations
- Sensitive to reionisation astrophysics
- Straightforward to recover statistics of the 21 cm (e.g PS)
- Infer reionisation astrophysics in a Bayesian framework?

21CMMC

- Massively parallel MCMC driver for the EoR simulation code 21CMFAST
- 21CMFAST provides:
  - full 3D EoR simulations at a fraction of the computing cost of RT simulations
  - preserves the 3D structure of reionisation (superior to analytic models of EoR)
- Uses a modified version of the Python module CosmoHammer (Akeret et al. 2013) using the EMCEE sampler (Foreman-Mackey et al. 2013)
- Recovers astrophysical parameter constraints from any model of the EoR for any statistical measure of the 21 cm signal

~ few days on 1536 cores





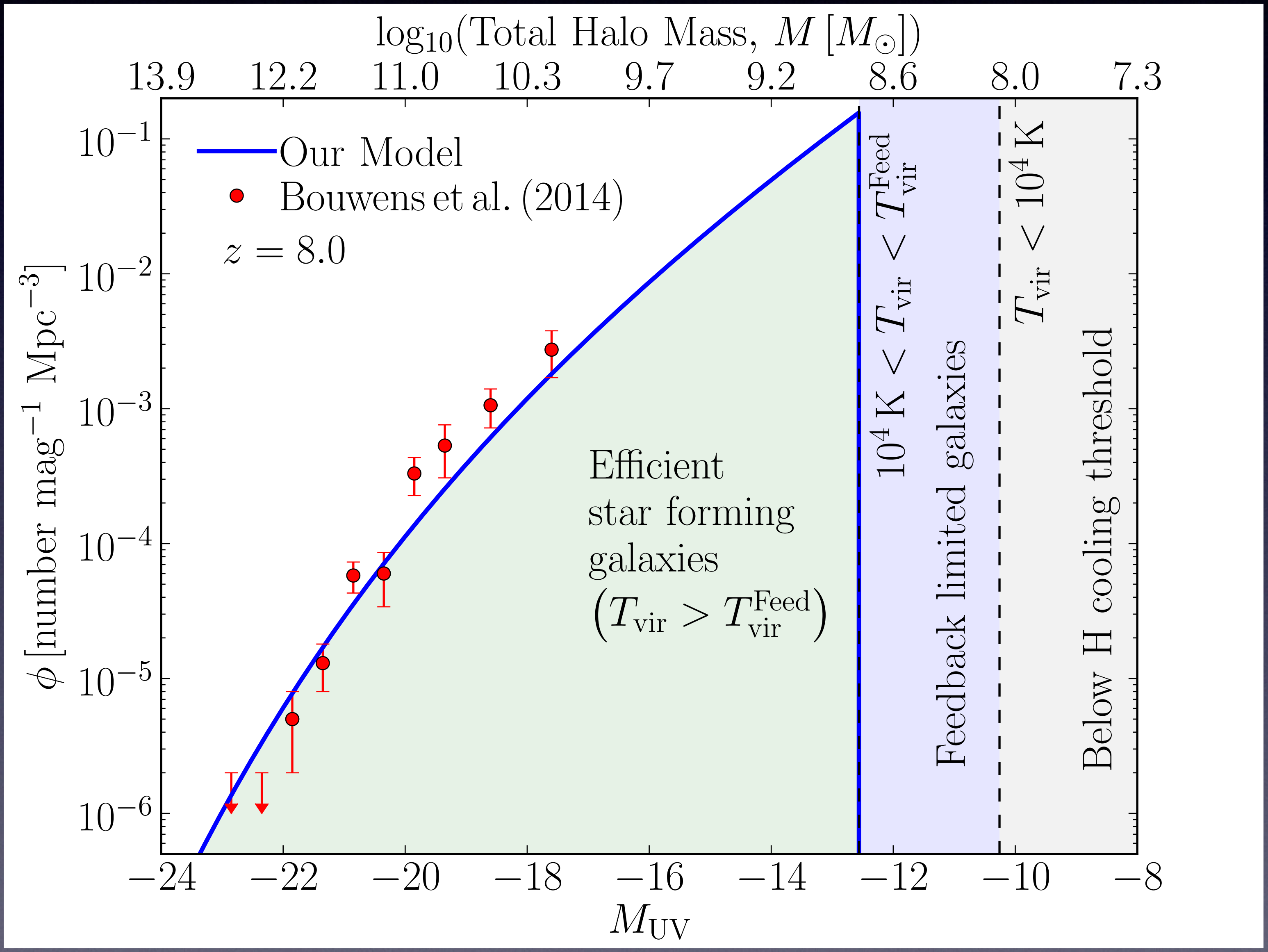
~ few minutes on a single core

L = 100 h^{-1} Mpc

Resolution = 768^3

Mesinger et al. (2007)

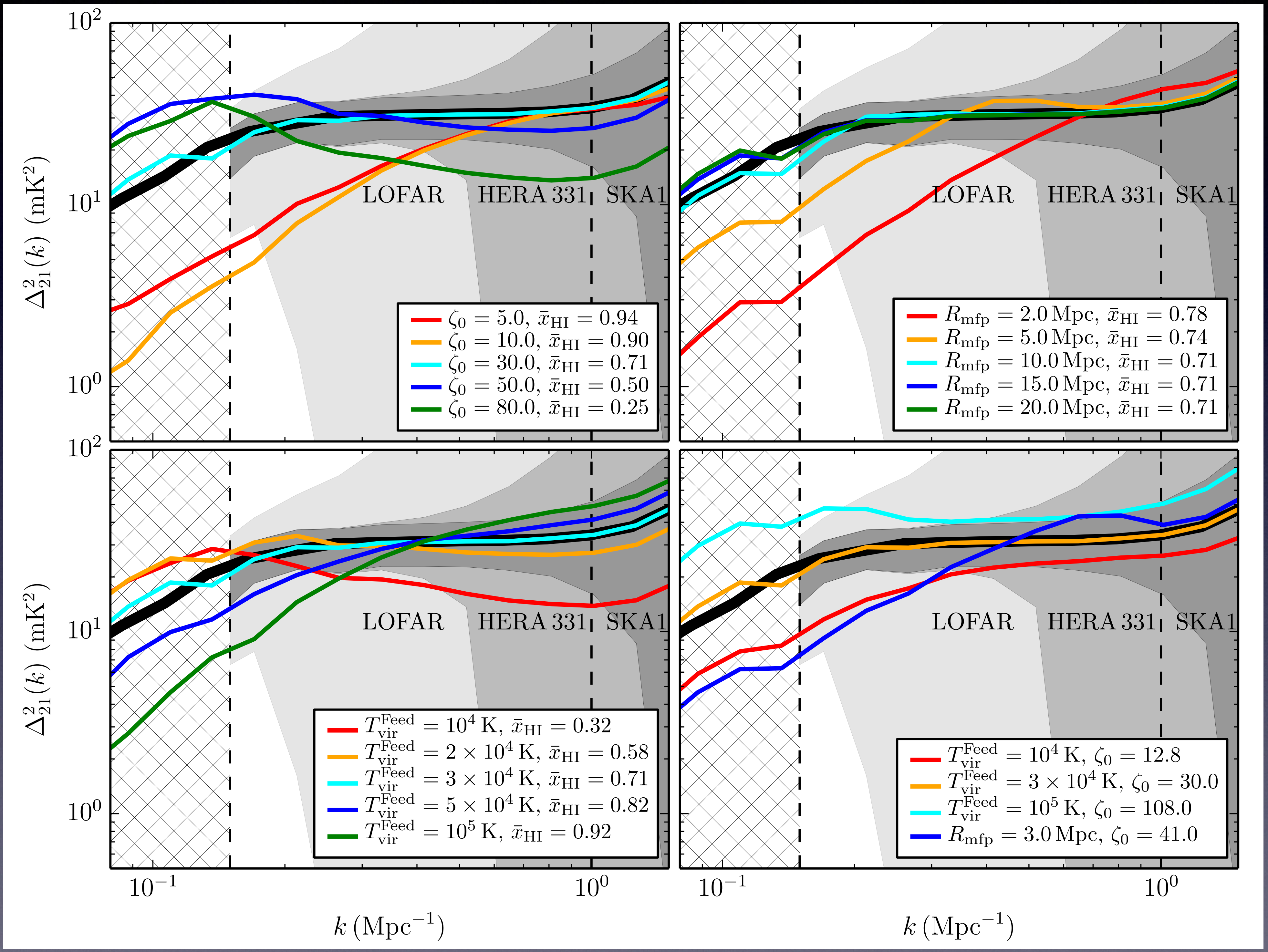
Modelling the EoR within 21CMMC



BG & Mesinger (2015)

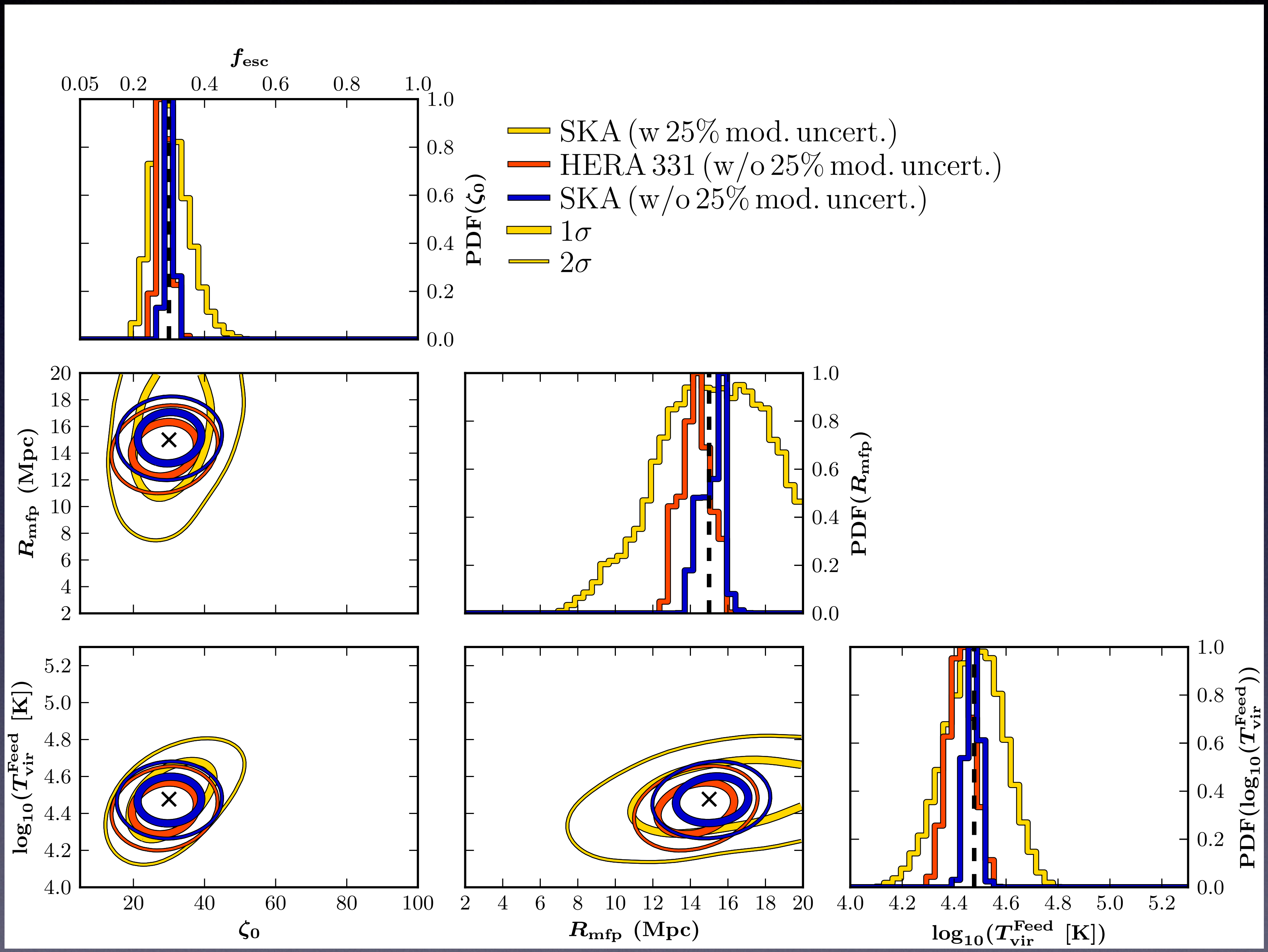
- Assumes a single population of ionising galaxies
- Consider a simple, 3 parameter empirical model for EoR
  - ζ_0: Constant ionising efficiency
  - $R_{\rm mfp}$: Mean free path
  - $T_{\rm vir}^{\rm Feed}$: Minimum mass threshold for star-forming haloes

Characterising the EoR



BG & Mesinger (2015)

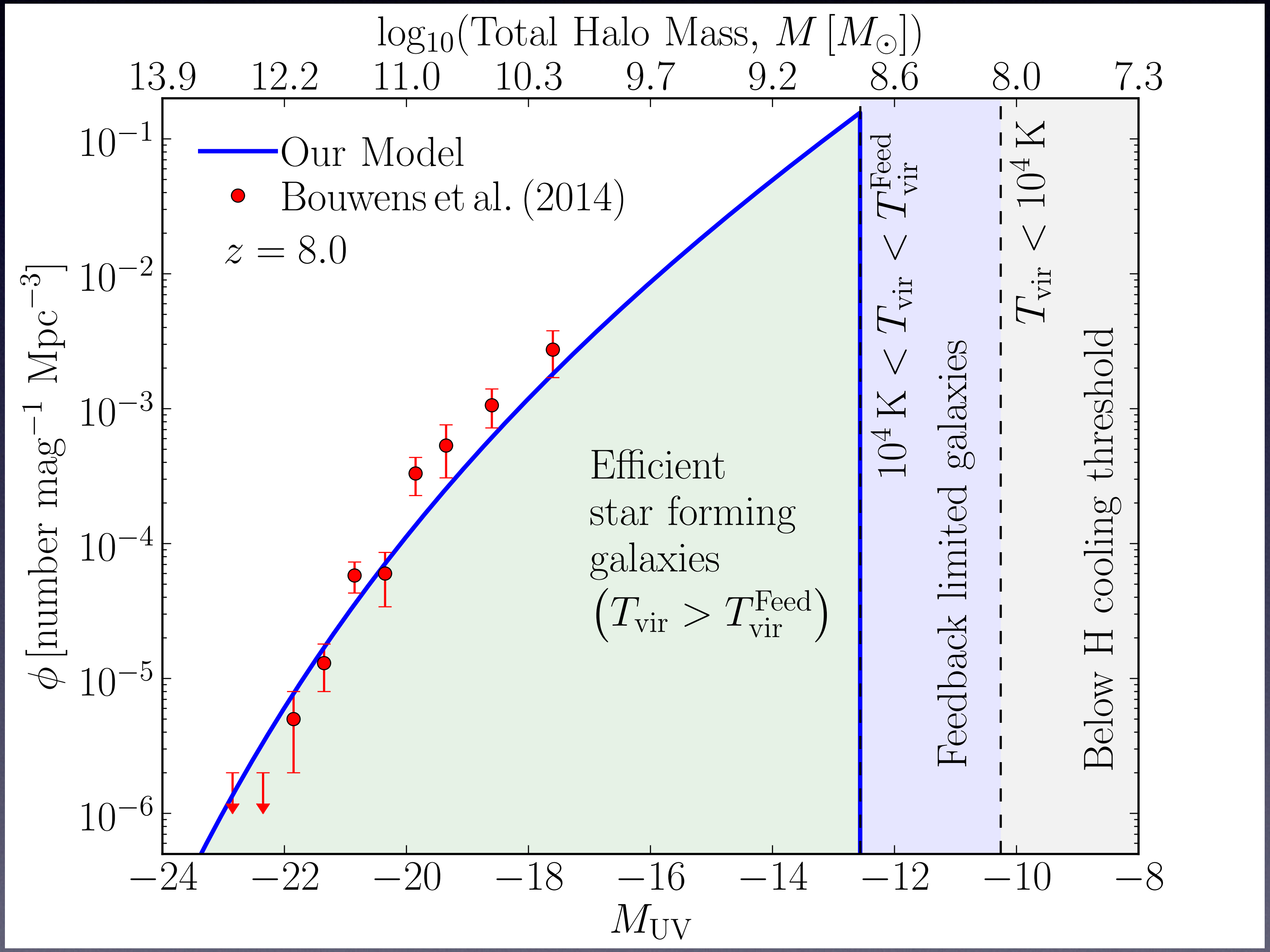
Constraints from a mock 21 cm observation



BG & Mesinger (2015)

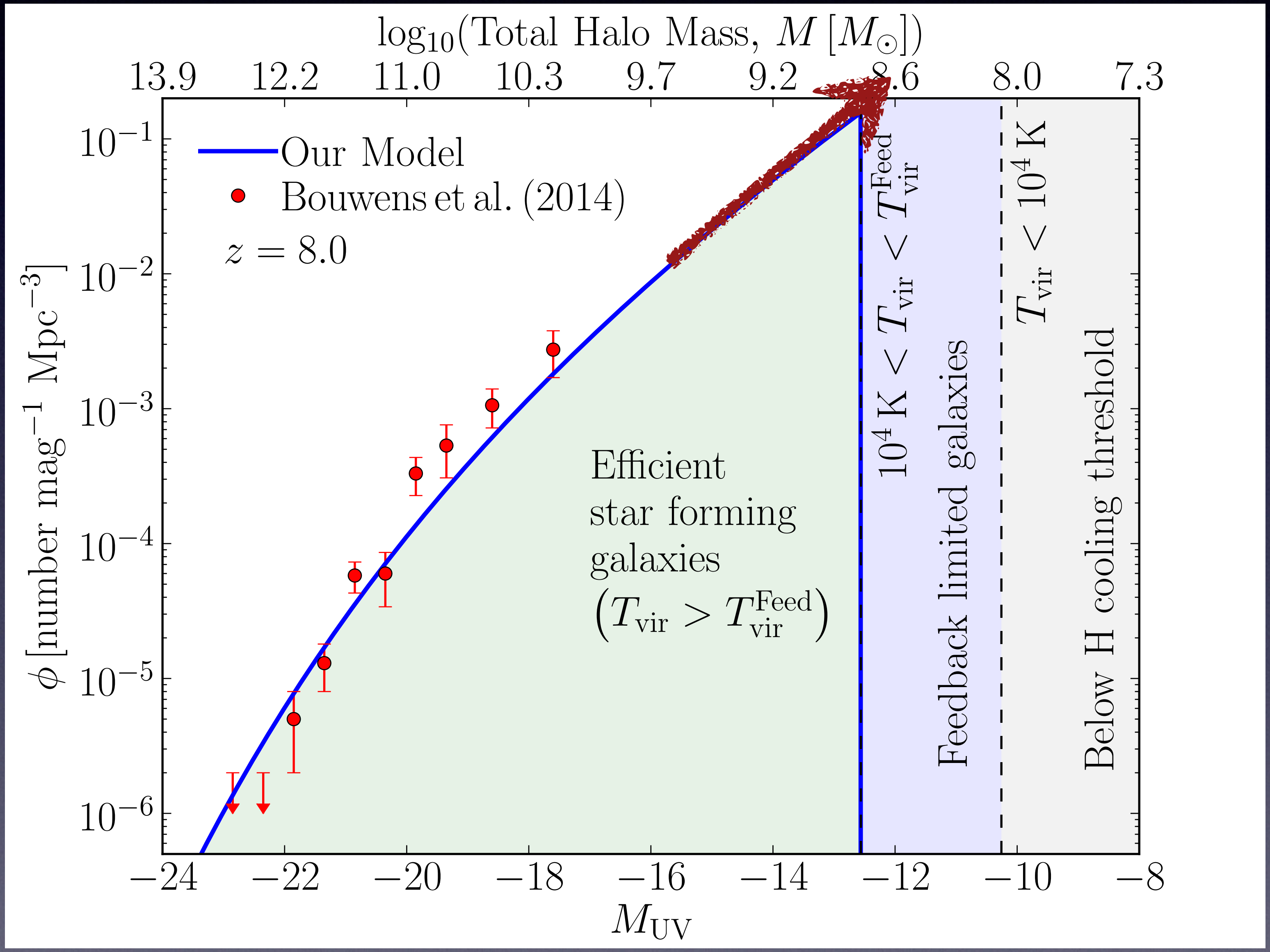
- Combining 3 coeval cubes at z = 8, 9 and 10
- 250 Mpc box
- 1000hr on sky integration
- 25% modelling uncertainty
  - approximations in simulations

Generalised model of reionisation



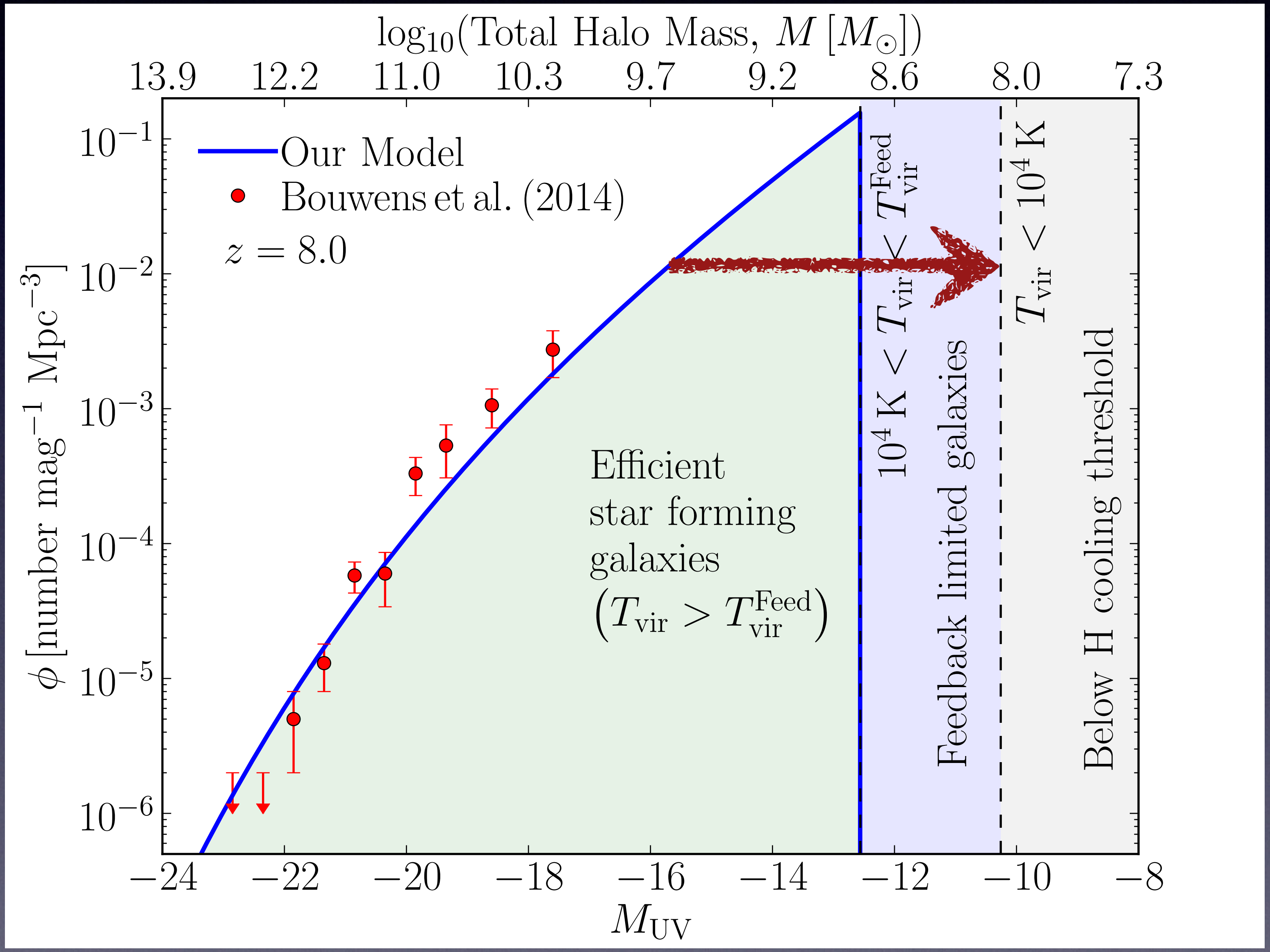
BG & Mesinger (2015)

Behaviour of the UV LF faint end



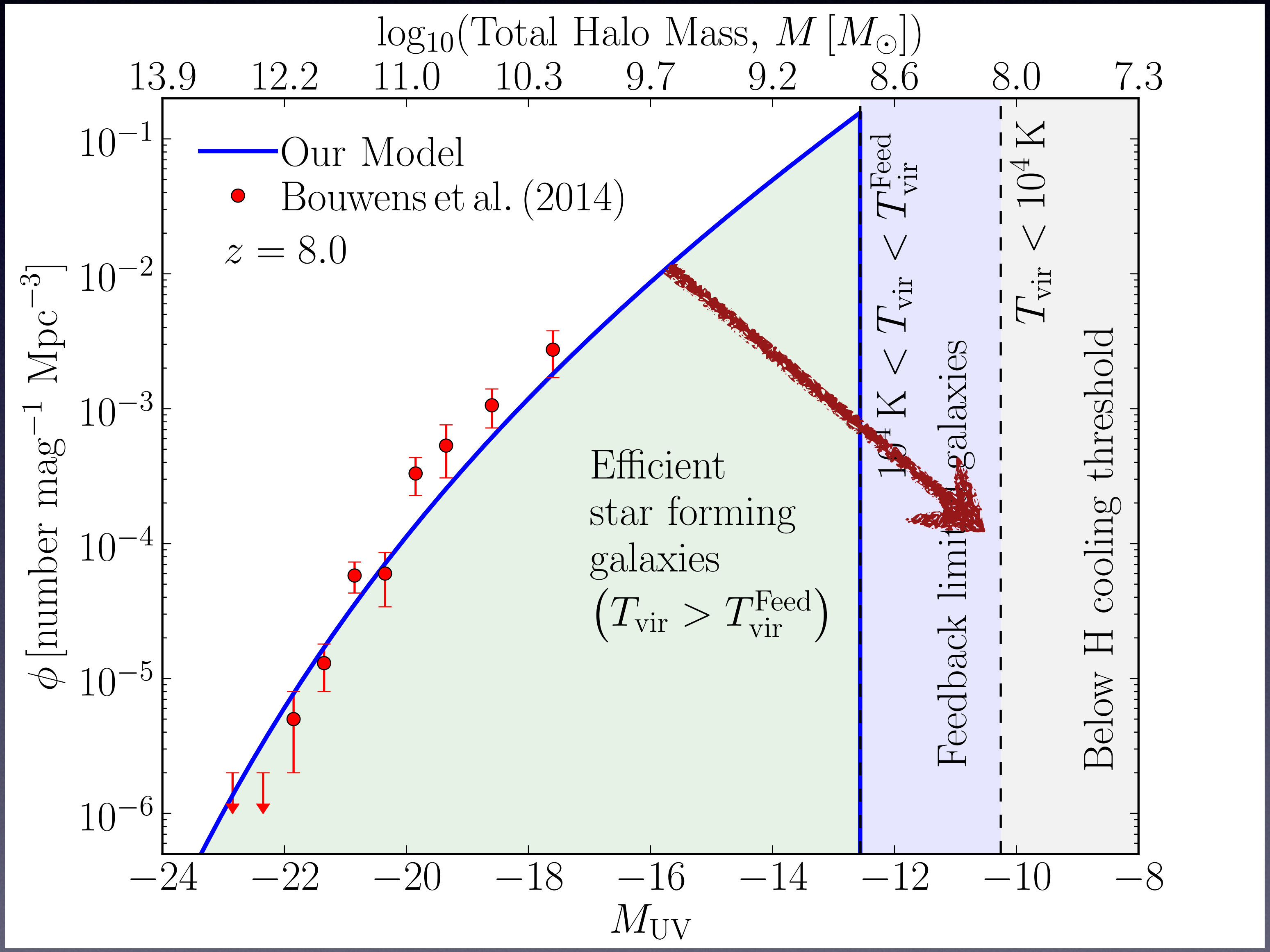
BG & Mesinger (2015)

Behaviour of the UV LF faint end



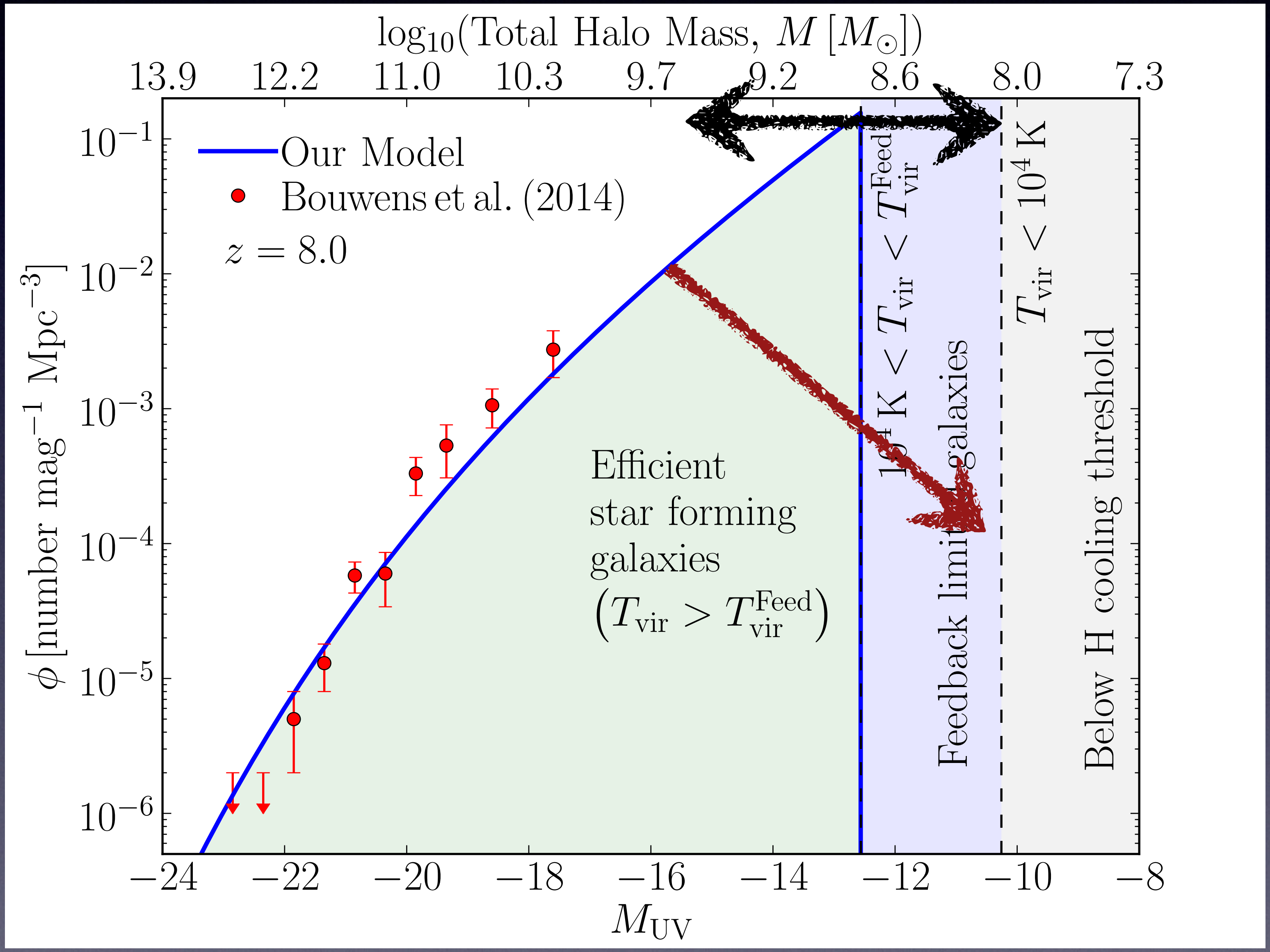
BG & Mesinger (2015)

Behaviour of the UV LF faint end



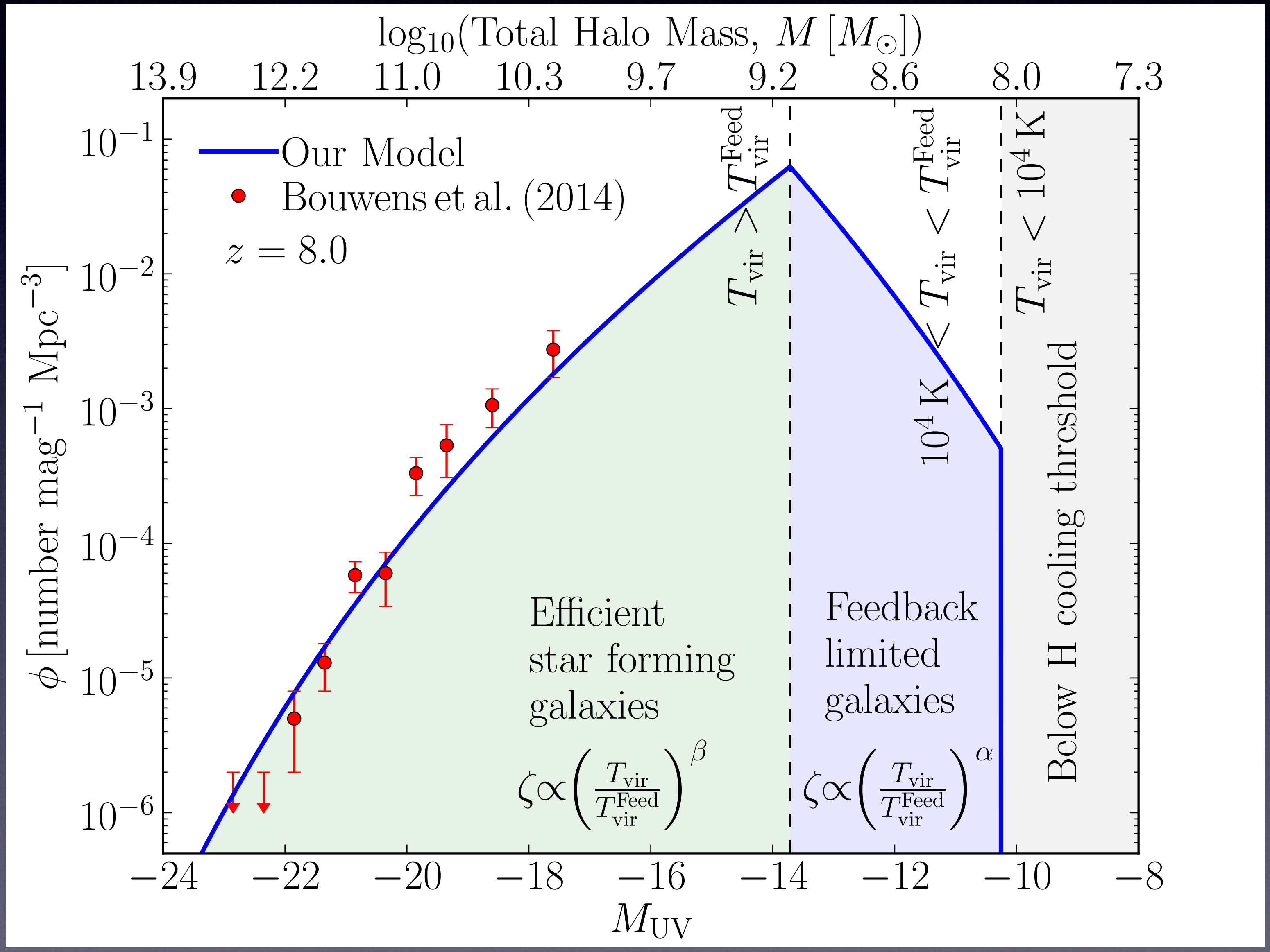
BG & Mesinger (2015)

Behaviour of the UV LF faint end



BG & Mesinger (2015)

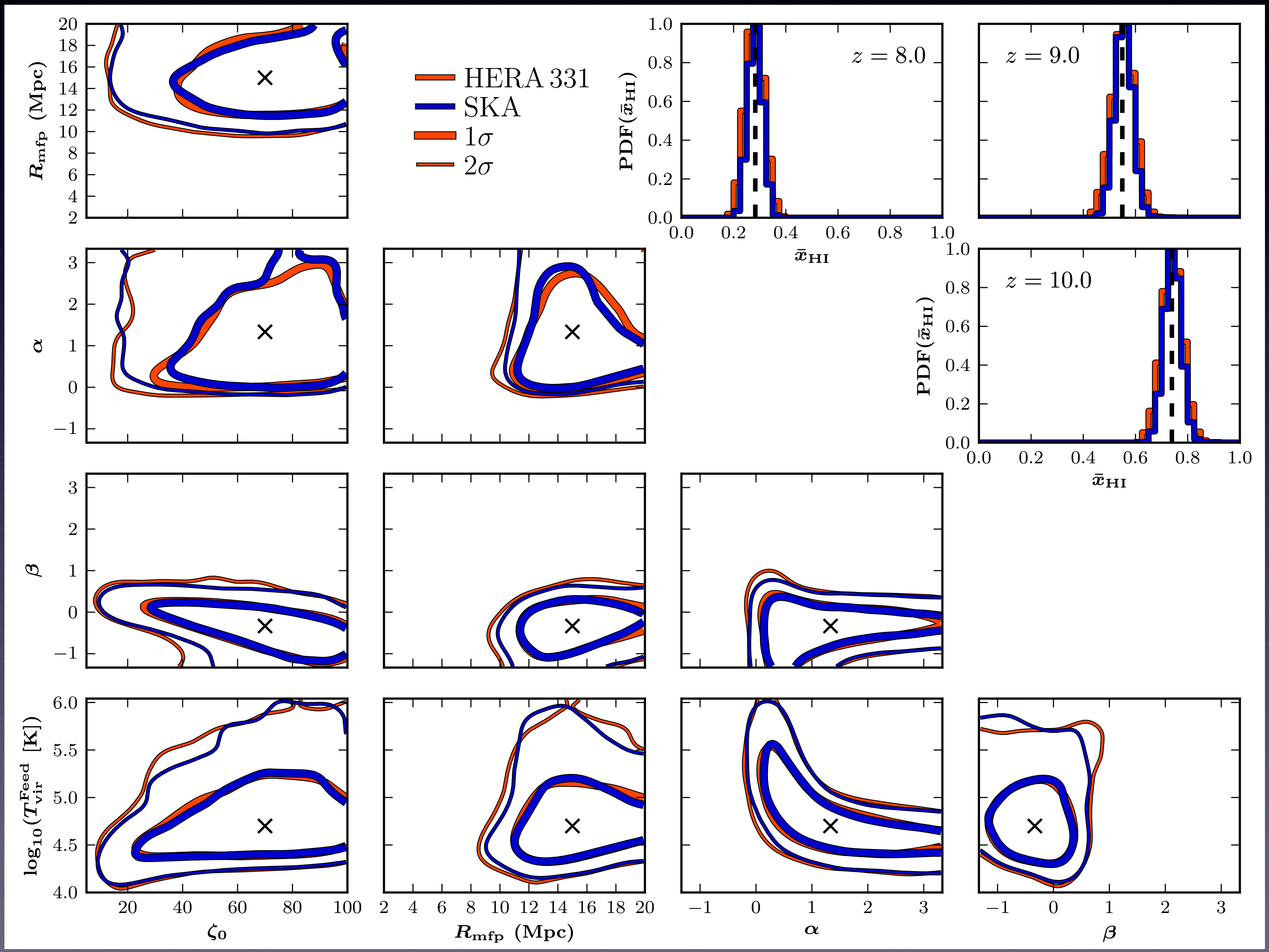
Generalised model of reionisation



BG & Mesinger (2015)

- Assumes two populations of ionising galaxies
- A 5 parameter empirical model
  - ζ_0: Normalisation of ionising efficiency
  - $R_{\rm mfp}$: Mean free path
  - $T_{\rm vir}^{\rm Feed}$: Minimum mass threshold for star-forming haloes
  - α: ionising efficiency feedback regulated slope
  - β: ionising efficiency star-forming slope

Constraints from a mock 21 cm observation

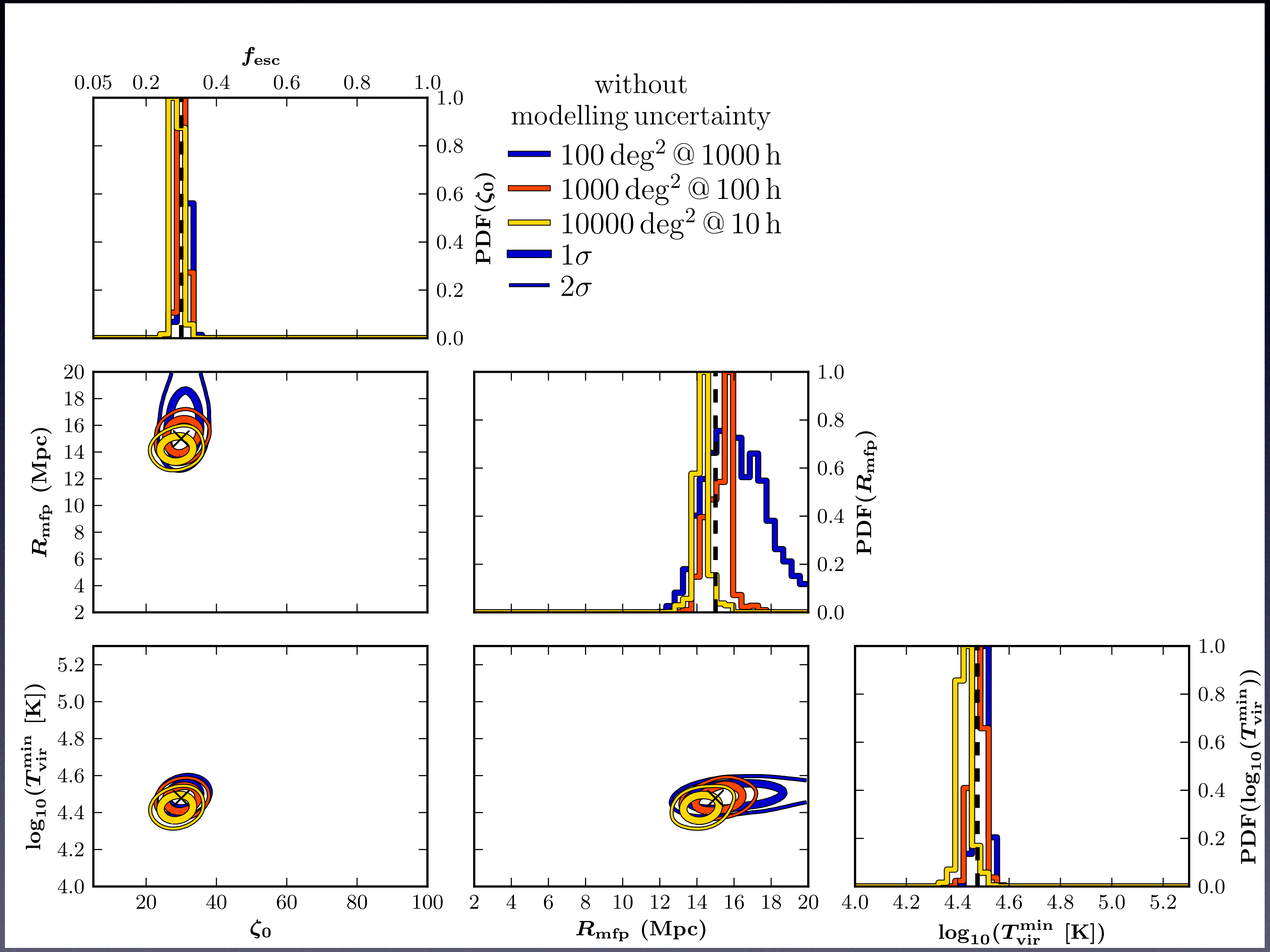


BG & Mesinger (2015)

- Combining 3 coeval cubes at z = 8, 9 and 10
- 250 Mpc box
- 1000hr on sky integration

Other applications?

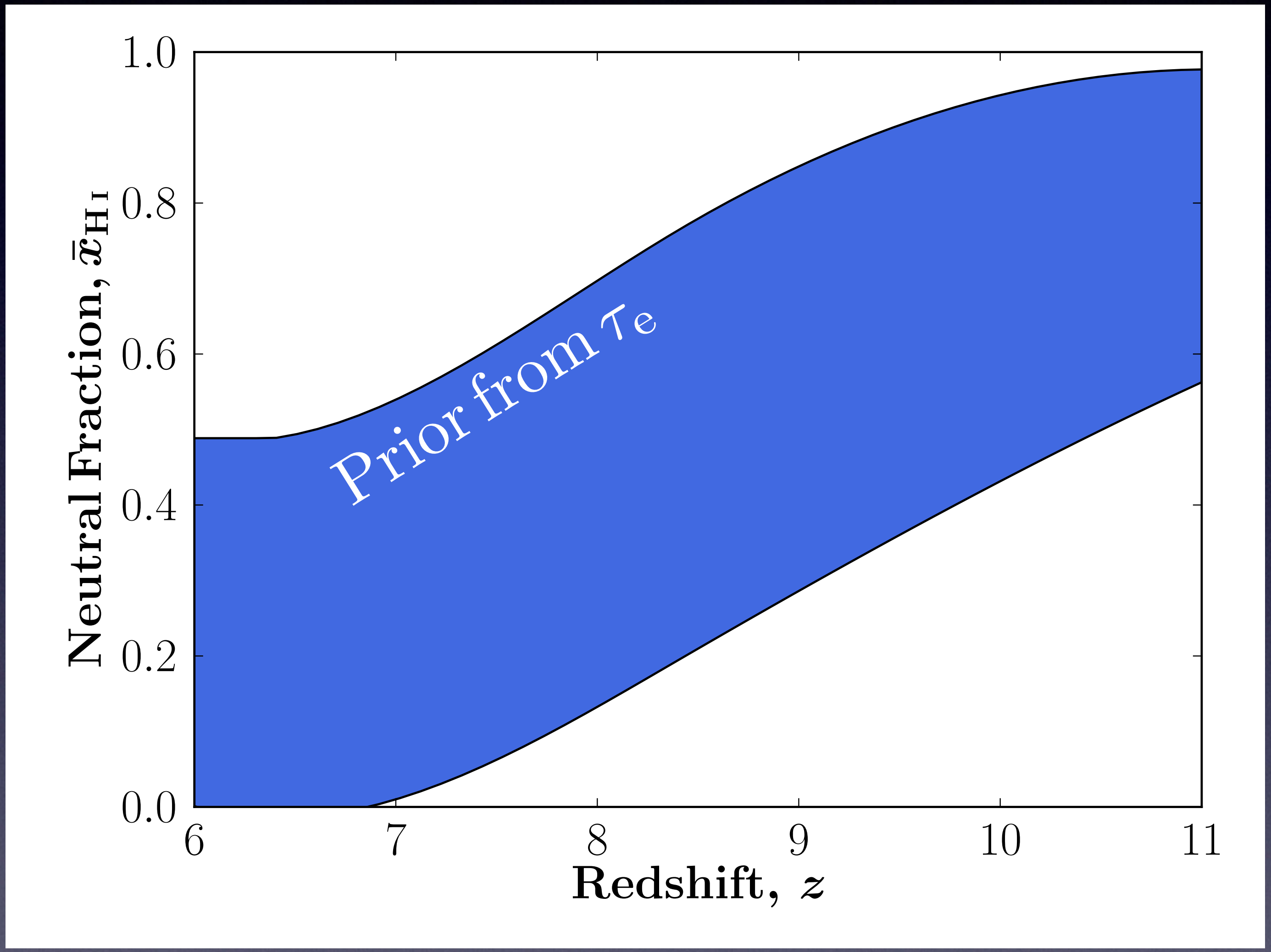
Optimisation studies for SKA1-Low



BG, Mesinger & Koopmans, in prep.

- What is the optimal observing strategy for recovery of EoR astrophysical parameters from the 21 cm PS?
- Consider three strategies
  - 100 sq. deg @ 1000 hr
  - 1000 sq. deg @ 100 hr
  - 10000 sq. deg @ 10 hr
- Trade-off between thermal noise and sample variance

Interpreting existing observations



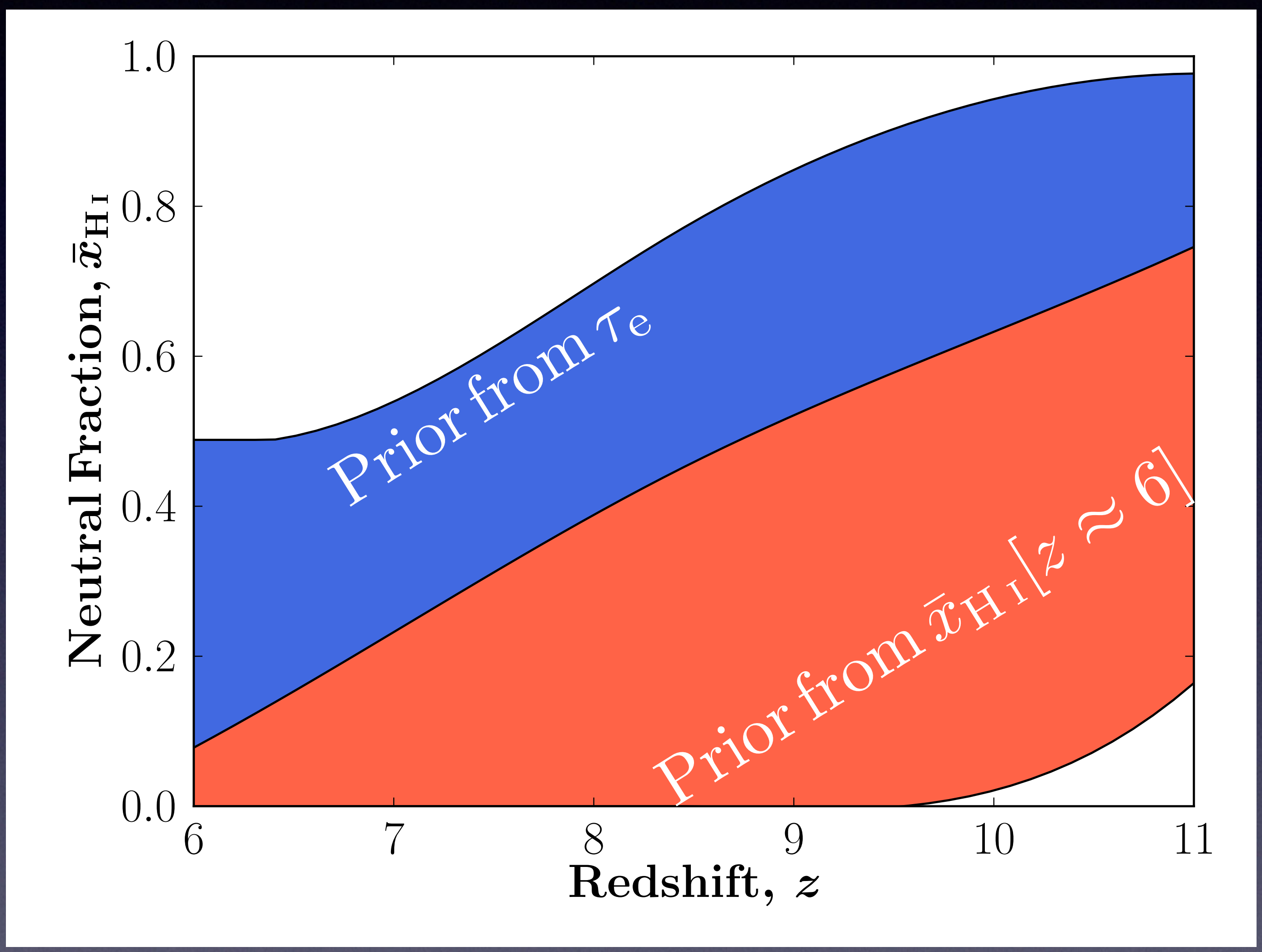
BG & Mesinger, in prep.

- To what extent can existing observations constrain reionisation?
- For example, consider the reionisation history of our 3 parameter EoR model
- First, consider Planck (favours delayed reionisation)

$$\tau_e = 0.066 \pm 0.016 \, (1\sigma)$$

- Previous approaches: Choudhury & Ferrara (2005), Barkana (2009), Mesinger et al., Zahn et al., Harker et al., Morandi & Barkana (2012), Mesinger et al. (2013), Patil et al., Pober et al. (2014)
- We MCMC sample full 3D simulations

Interpreting existing observations



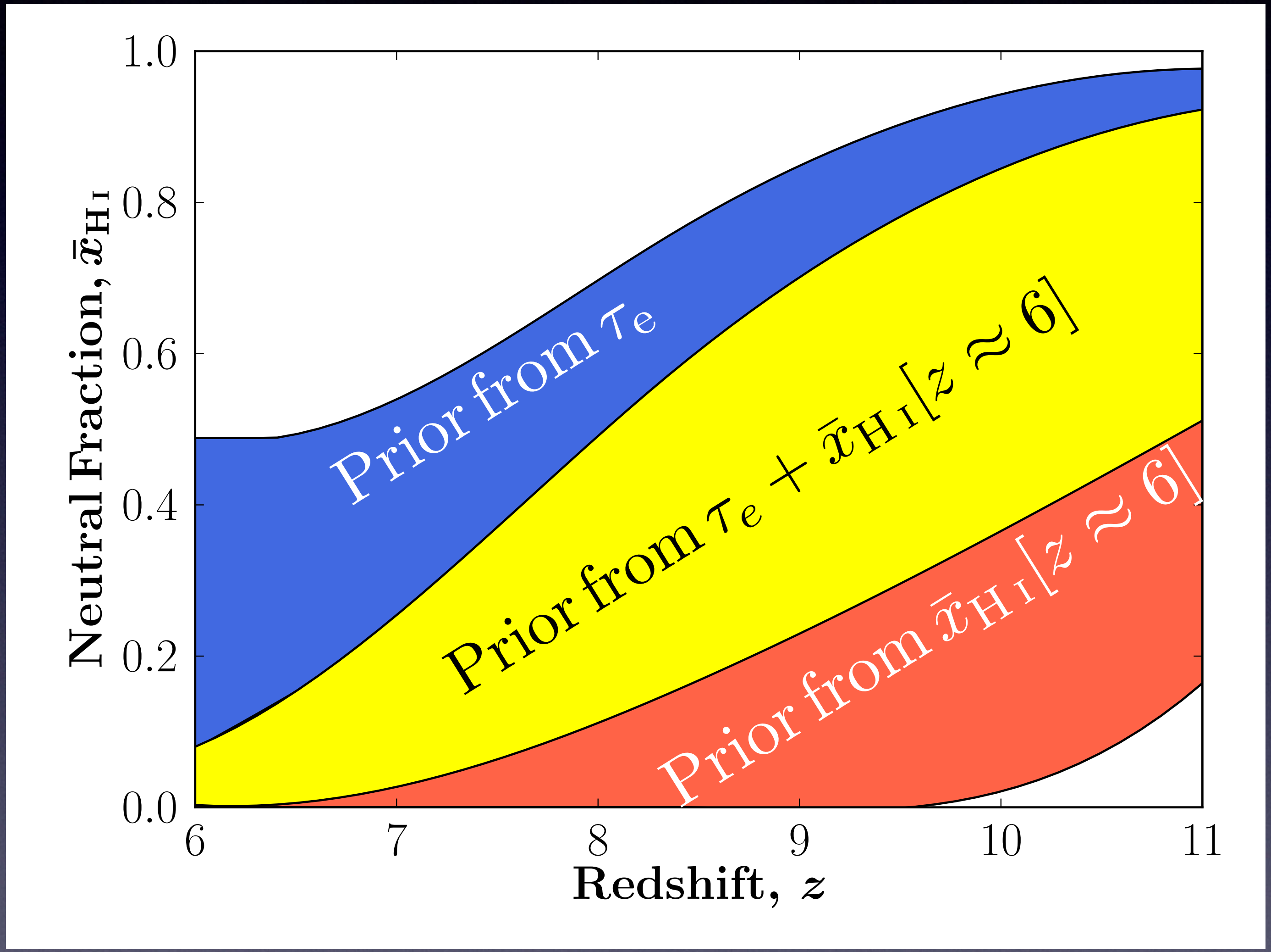
BG & Mesinger, in prep.

- To what extent can existing observations constrain reionisation?
- For example, consider the reionisation history of our 3 parameter EoR model
- McGreer et al. (2015) priors on tail-end of reionisation (prefers earlier reionisation)

$\bar{x}_{\mathrm{H\,I}} \leq 0.06 + 0.05\,(1\sigma)$ at z = 5.9

- Previous approaches:
Choudhury & Ferrara (2005), Barkana (2009), Mesinger et al., Zahn et al., Harker et al., Morandi & Barkana (2012), Mesinger et al. (2013), Patil et al., Pober et al. (2014)
- We MCMC sample full 3D simulations

Interpreting existing observations



BG & Mesinger, in prep.

- To what extent can existing observations constrain reionisation?
- For example, consider the reionisation history of our 3 parameter EoR model
- Combined constraints provide significantly tighter constraints on the EoR
- What about further constraints? (e.g. LAEs, Lyα forest, GRBs, kSZ etc.)

- Previous approaches:
  Choudhury & Ferrara (2005), Barkana (2009), Mesinger et al., Zahn et al., Harker et al., Morandi & Barkana (2012), Mesinger et al. (2013), Patil et al., Pober et al. (2014)
- We MCMC sample full 3D simulations

Other Applications of 21CMMC?

- Inferring the IGM temperature from PAPER-64 (BG, Mesinger & Pober, in prep.)
- Alternative statistics of the 21 cm signal
- Optimising foreground cleaning algorithms
- 21 cm imaging
- Investigating synergies with other observational probes
- And many more

Conclusions

- We have introduced the EoR MCMC analysis tool 21CMMC
- First MCMC code to sample full 3D simulations of the EoR
- Provides astrophysical parameter constraints on any EoR model, recovered from any statistical measure of the 21 cm signal
- Broad applicability to an extensive range of topics for exploring the astrophysics of reionisation
- Will be publicly available by the end of the year