Constraining reionization using 21 cm experiments in combination with CMB and Lyman alpha forest data

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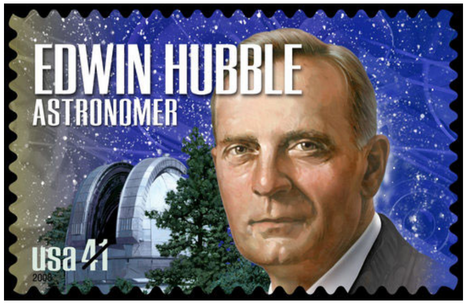
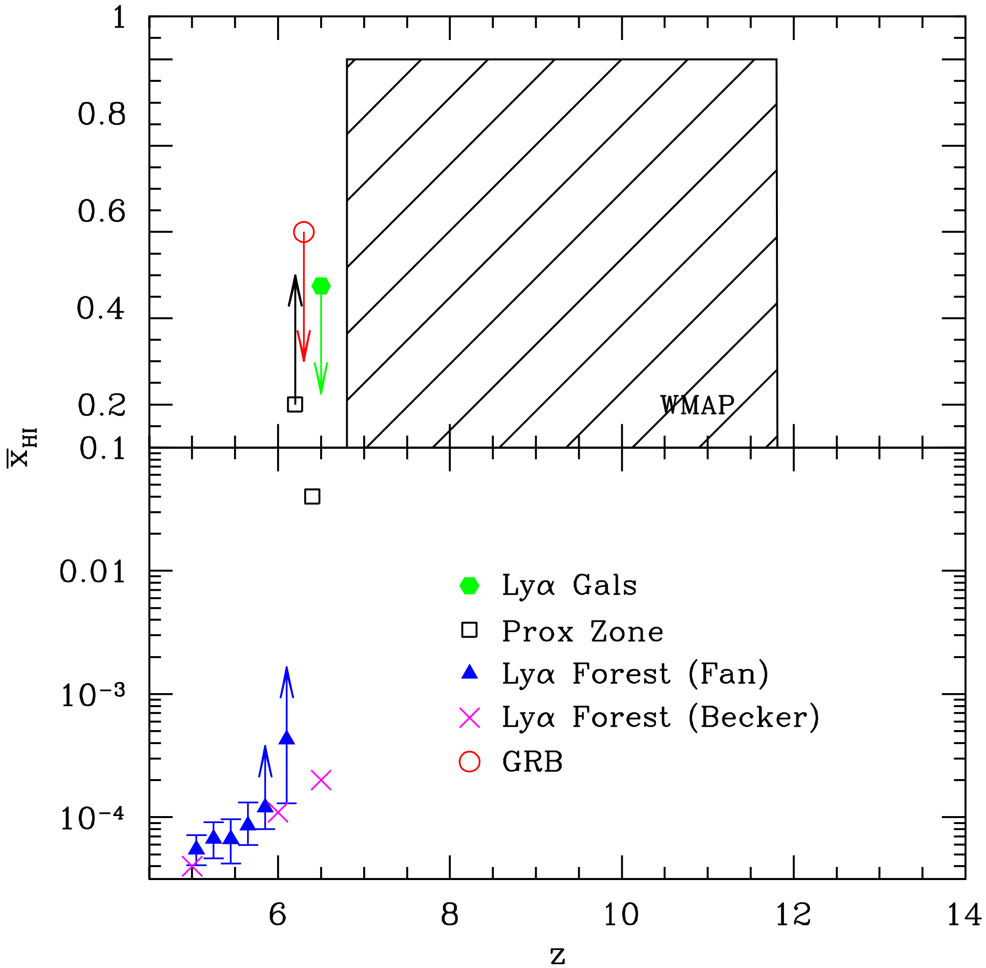


Overview



Furlanetto, Oh, Briggs 2006

1. Observations constraining reionization
2. Modeling reionization
3. Inferring the ionization history
4. Implications for 21 cm experiments

Given current observations what bounds can we place on the reionization history?

Bayesian Inference

Use data {D} to constrain parameters {w} of model {M}

$$\boxed{p(w|D,M) = \frac{p(D|w,M)p(w|M)}{p(D|M)},}$$

Use model+parameters to infer ionization history

$$\boxed{p(x_i|M) = \int \mathrm{d}w\, p(w|D,M)\delta[x_i(w|M) - x_i]}$$

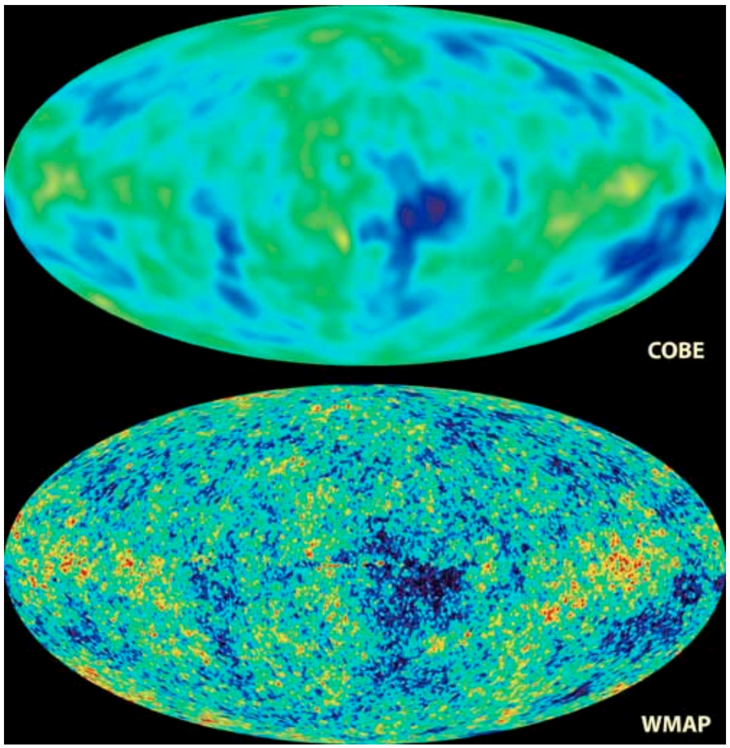
Use inferred ionization history to make predictions
for 21 cm experiments

Observational Constraints

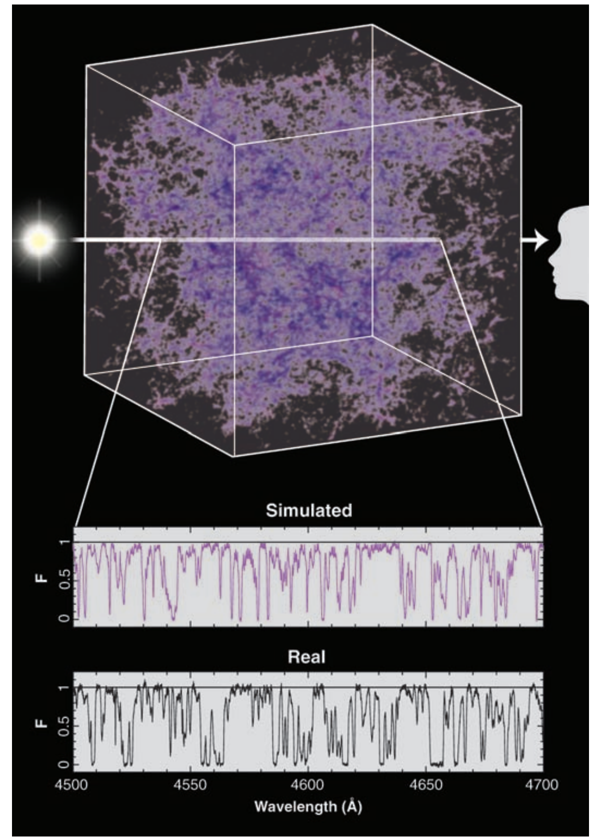
- CMB
- Lyman alpha forest
- IGM temperature
- IGM metallicity
- Galaxy counts
- LAE clustering
- GRB
- 21 cm experiments
- ...

Observations

CMB



Lyman alpha forest



Relatively well understood measurements

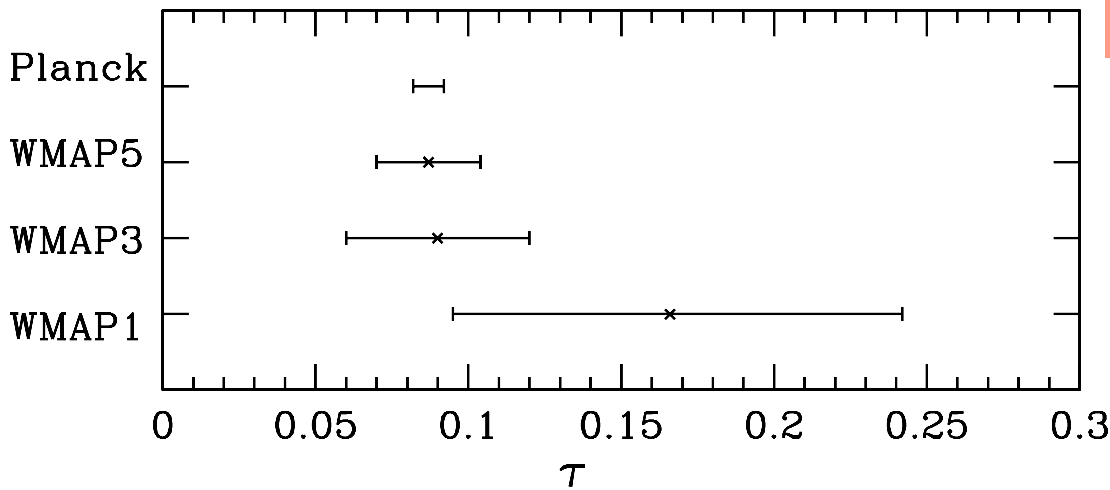
CMB optical depth

$$\tau_{\rm CMB} = \int_0^{z_{\rm CMB}} {\rm d}z \, \frac{{\rm d}t}{{\rm d}z} x_e(z) n_H(z) \sigma_T .$$

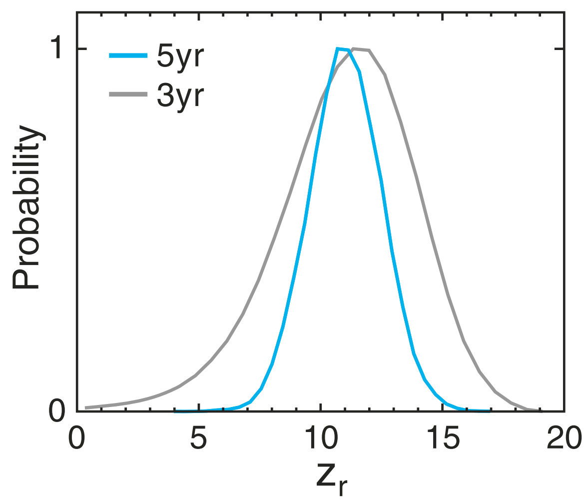
$$\sigma_\tau^{\rm Planck} = 0.005$$ Tegmark+ 2000

$$\tau_{\rm CMB} = 0.087 \pm 0.017$$

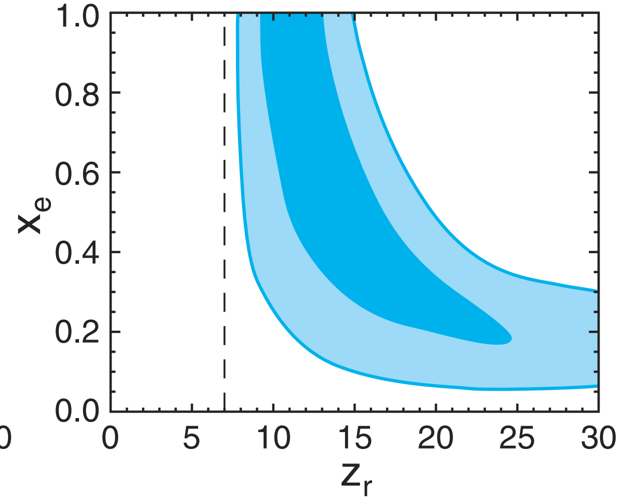
Dunkley+ 2009



Instantaneous



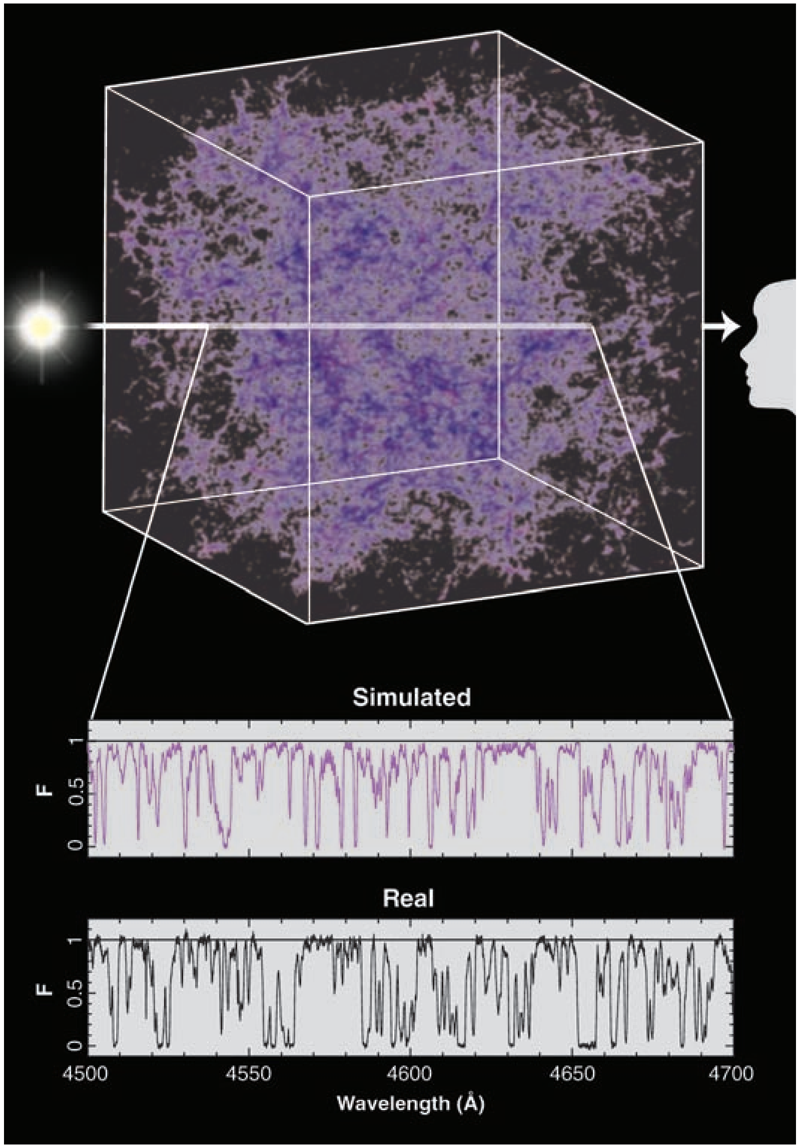
Step function



$$x_e(z) = \begin{cases} 1 & z \leq 7 \\ x_e & 7 < z \leq z_r \\ 0 & z > z_r \end{cases}$$

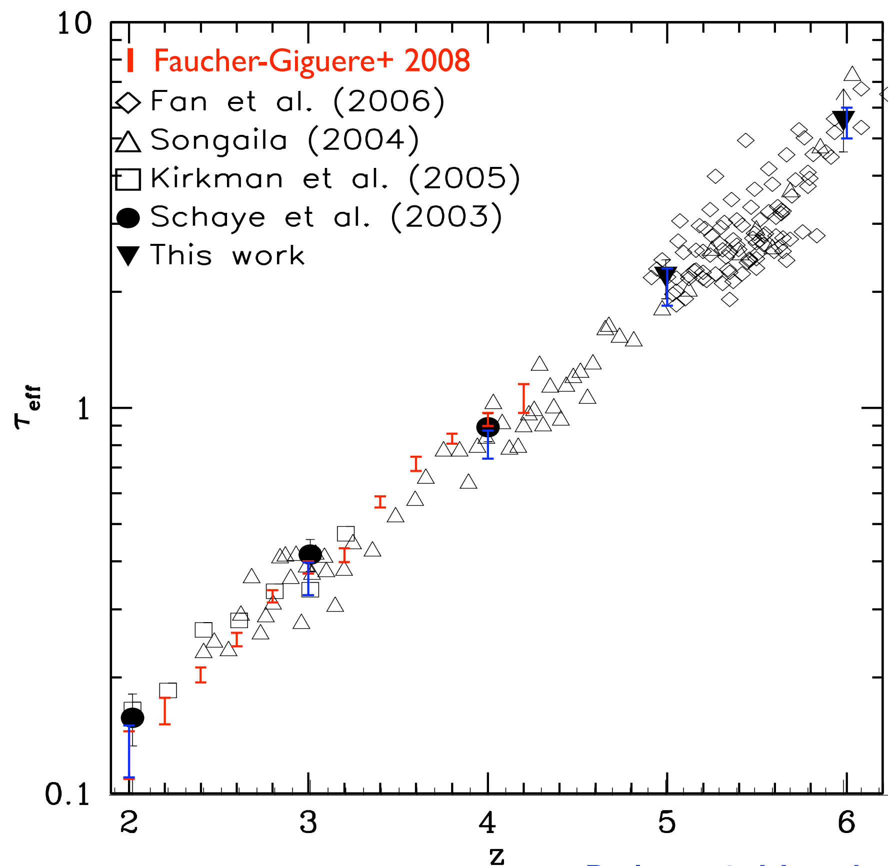
Dunkley+ 2009 $z_r = 11 \pm 1.4$

Lyman alpha forest



Faucher-Giguere+ 2008

$$\tau_{\rm eff} \equiv -\log[\langle F\rangle(z)],$$



Bolton & Haenhelt '07

Connecting Lya forest to CMB

1. Convert mean transmittance to ionizing background
2. Connect ionizing background to sources
3. Use source prescription to calculate ionization history
4. Use ionization history to calculate CMB optical depth

$$\tau_{\rm eff} \longrightarrow \Gamma_{-12} \longrightarrow \dot{N}_{ion} \longrightarrow Q_i \longleftarrow \tau_{\rm CMB}$$

Use Lya forest to constrain evolution of sources

Fluctuating Gunn-Peterson approximation $\boxed{\tau_{\rm eff} \rightarrow \Gamma_{-12}} \rightarrow \dot{N}_{ion}$

Effective optical depth

$$\tau_{\rm eff} \equiv -\log[\langle F\rangle(z)],$$

Mean Transmittance

$$\langle F\rangle(z) = \int_0^\infty {\rm d}\Delta\, P(\Delta; z)\exp(-\tau).$$

Miralda-Escude+ 2000

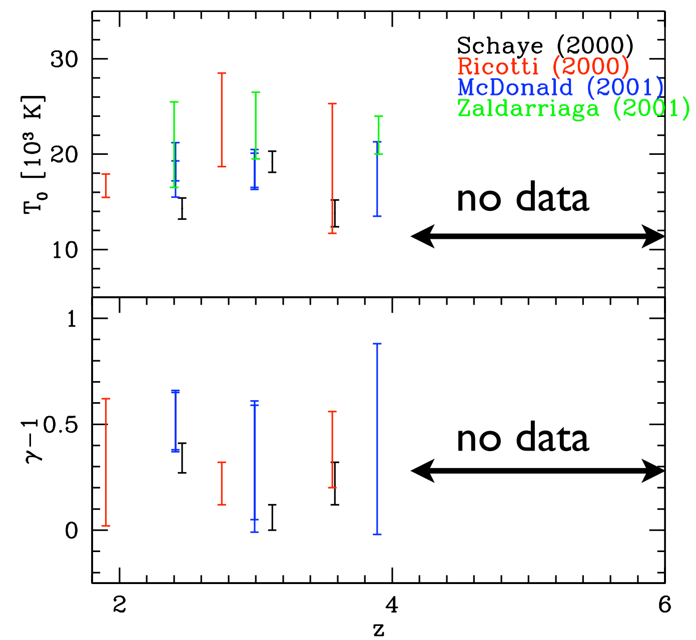
Lya optical depth

$$\tau = \frac{\pi e^2 f_{\rm Ly\alpha}}{m_e \nu_{\rm Ly\alpha}} \frac{1}{H(z)} \frac{R(T) n_{\rm HII} n_e}{\Gamma}.$$

Density-Temperature relation

$$T = T_0 \Delta^\beta$$

$$\Delta = 1 + \delta.$$



Relating Gamma to sources

$\tau_{\rm eff} \longrightarrow \boxed{\Gamma_{-12} \longrightarrow \dot{N}_{ion}}$

$$\boxed{\dot{N}_{\rm ion} = 10^{51.2}\,\Gamma_{-12}\,\underbrace{\left(\frac{\alpha_S}{3}\right)^{-1}\left(\frac{\alpha_S+3(2-\gamma)}{6}\right)}_{\text{Source spectrum}} \times \underbrace{\left(\frac{\lambda_{\rm mfp}(\nu_0)}{40\,{\rm Mpc}}\right)^{-1}\left(\frac{1+z}{7}\right)^{-2}}_{\text{Properties of absorbing systems}}\,{\rm s}^{-1}\,{\rm Mpc}^{-3}.}$$

Source spectrum: hard or soft?

Distribution of absorbing systems processes radiation from sources

$$f(\tau) \sim \tau^{-\gamma}$$

Misawa+ 2007

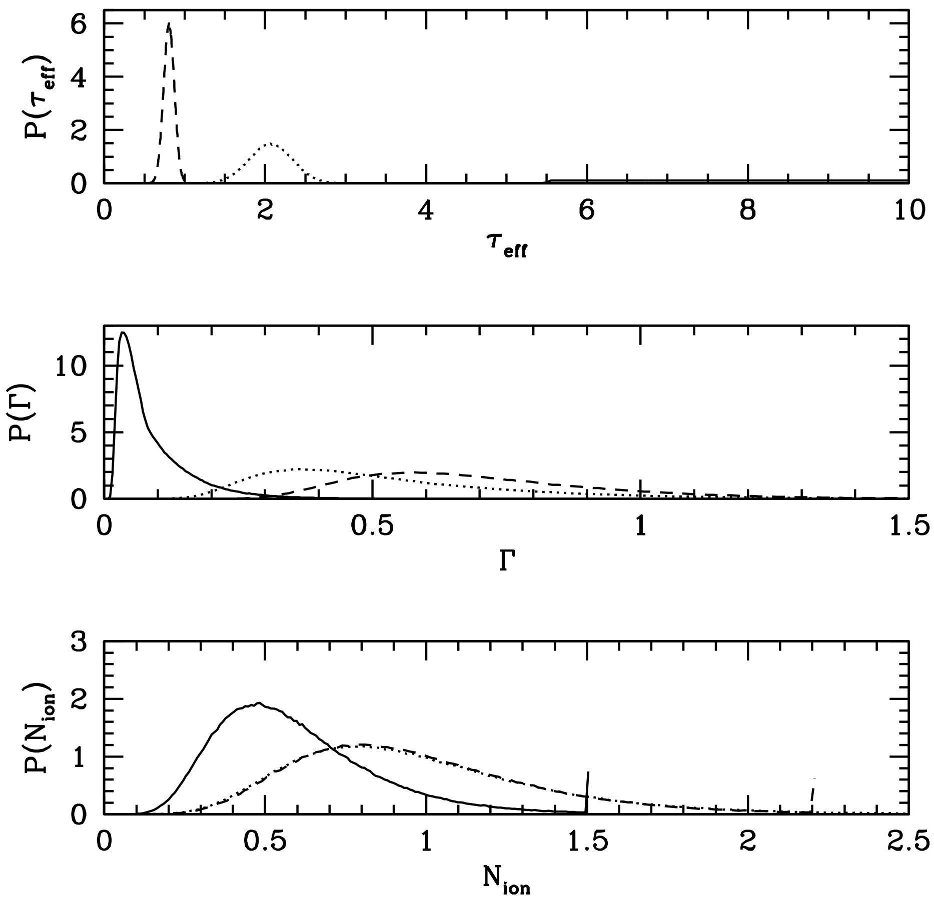
Mean free path from spacing between LLS

$$\lambda_{\rm LLS} = \frac{cH^{-1}}{(1+z)}\left(\frac{{\rm d}N_{\rm LLS}}{{\rm d}z}\right)^{-1}$$

Storrie-Lombardi 1994

Many uncertainties arising from poorly constrained IGM properties at z≥4

Constraints on N_{ion}



Randomly sample parameters to build up distribution of Gamma and N_{ion}

Parameter	$\bar{x}$ ($x_{\rm low}$)	σ_x ($x_{\rm high}$)	prior
T_0	0.5×10^4K	3.0×10^4K	uniform
β	0	0.6	uniform
α_S	1	3	uniform
γ	1	3	uniform
κ	1	0.2	gaussian
σ_8	0.8	0.05	gaussian
Ω_m	0.3	0.04	gaussian
Ω_b	0.046	0.0005	gaussian
h	0.7	0.04	gaussian

Redshift	$\tau_{\rm eff}$	Γ_{-12}	$\dot{N}_{\rm ion}$
4	0.805 ± 0.067	$0.57^{+0.35\,(+0.71)}_{-0.10\,(-0.22)}$	$0.80^{+0.53\,(+1.1)}_{-0.19\,(-0.40)}$
5	2.07 ± 0.27	$0.36^{+0.39\,(+0.83)}_{-0.06\,(-0.16)}$	$0.80^{+0.53\,(+1.2)}_{-0.21\,(-0.42)}$
6	$5.5 - 15$	$0.03^{+0.11\,(+0.25)}_{-0.002\,(-0.02)}$	$0.48^{+0.34\,(+0.75)}_{-0.12\,(-0.25)}$

Consistent with:
Faucher-Giguere+ 2008
Bolton & Haenhelt 2007

Ionization history

Filling fraction of ionized regions

$$\frac{\mathrm{d}Q_{\rm HII}}{\mathrm{d}t} = \boxed{\frac{\dot{N}_{\rm ion}}{n_H(0)}} - Q_{\rm HII}\boxed{C_{\rm HII}}n_H(0)(1+z)^3\alpha_A(T).$$

Source emissivity

$$\dot{N}_{\rm ion}(z) = \zeta(z)n_H(0)\frac{\mathrm{d}f_{\rm coll}(z)}{\mathrm{d}t},$$

Clumping

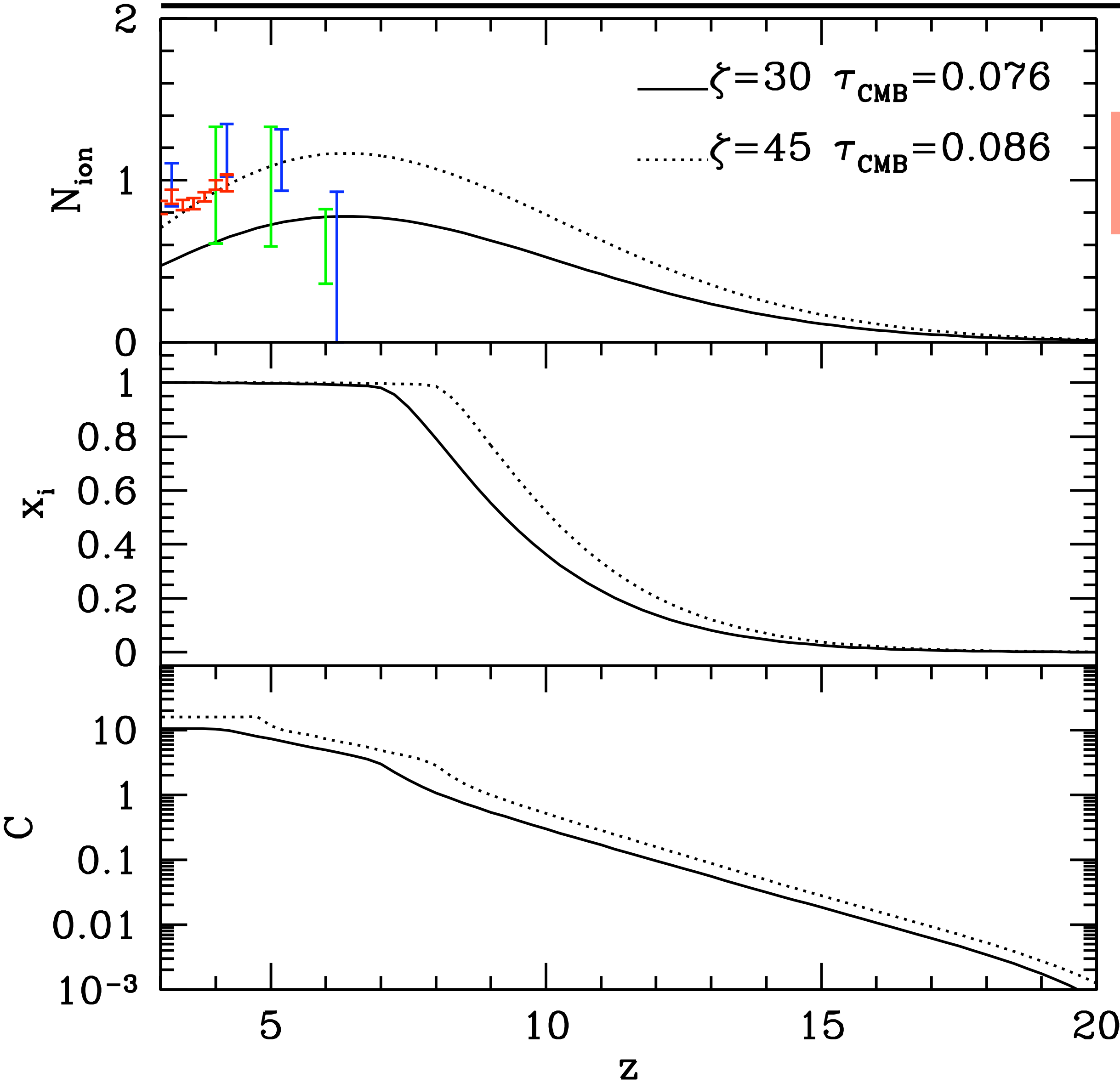
$$C \equiv \langle n_{\rm HII}^2\rangle/\langle n_{\rm HII}\rangle^2.$$

$$R = R_u\int^{\Delta_i}\mathrm{d}\Delta P_V(\Delta)\Delta^2 \equiv CR_u.$$

Before overlap Δ_i set by bubble size

Miralde-Escude+ 2000
Furlanetto & Oh 2005

Model properties



constant zeta

$$\dot{N}_{\rm ion}(z) = \zeta(\cancel{z}) n_H(0) \frac{{\rm d}f_{\rm coll}(z)}{{\rm d}t},$$

Slight tension between Lya forest and CMB

Error bars from:
Pritchard+ 2009
Faucher-Gauguere+ 2008
Bolton & Haenhelt 2007

Parametrizations of Ndot

Need to explore different parametrizations of Nion
...try two

via source emissivity

$$\dot{N}_{\rm ion}(z) = \zeta(z) n_H(0) \frac{{\rm d}f_{\rm coll}(z)}{{\rm d}t},$$

$$\zeta(z) = \zeta_0 + \frac{(\zeta_1 - \zeta_0)}{2}\left[\tanh\left(\frac{z - z_0}{\Delta z}\right) + 1\right]$$

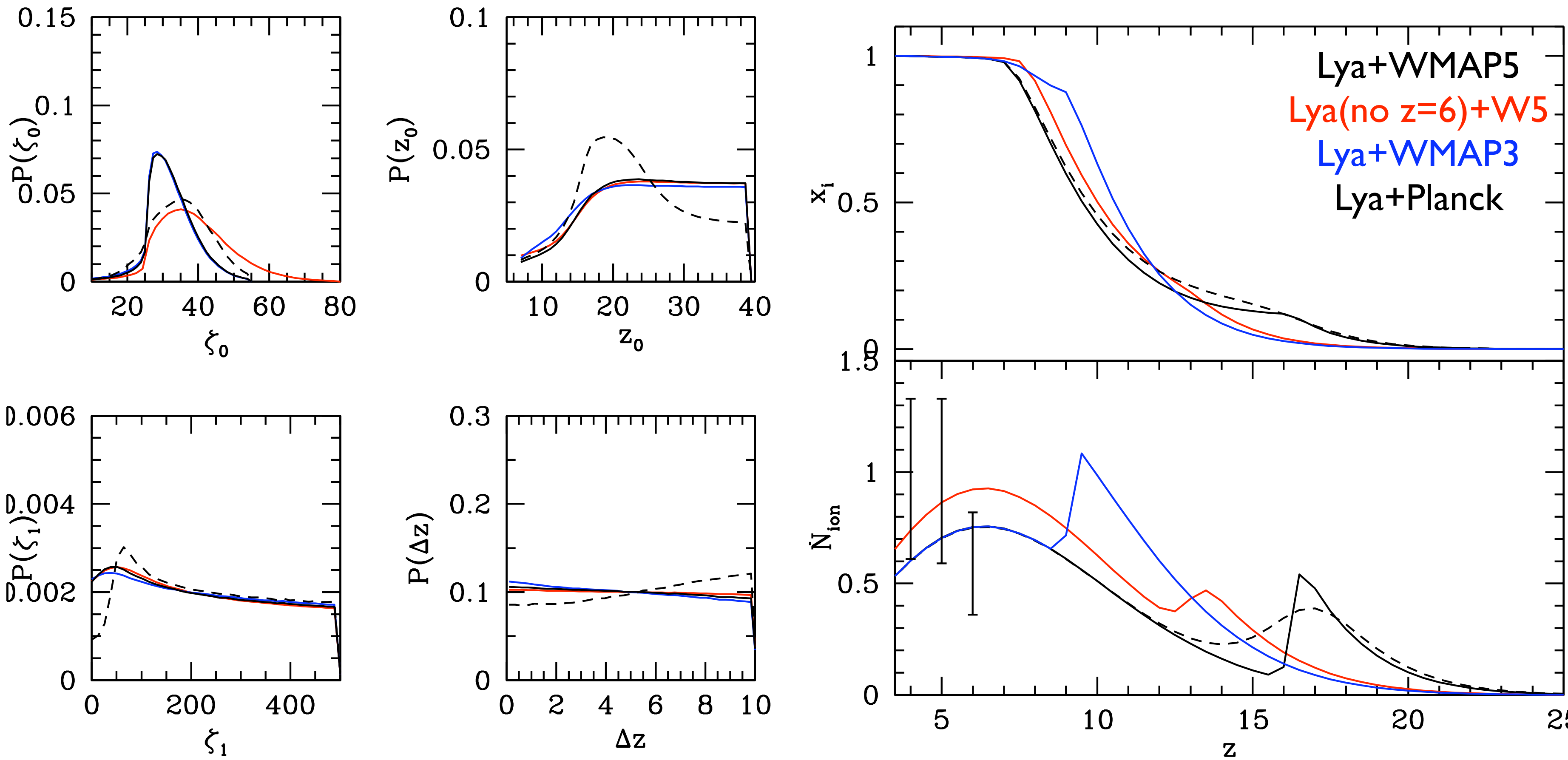
Directly

$$\dot{N}_{\rm ion} = N_0 A_{\rm ion}[1 + N_1(z - z_0) + N_2(z - z_0)^2 + N_3(z - z_0)^3] \times \Theta(z - z_{\rm max}), \quad (5)$$

If very different parametrizations give same physical predictions may be robust

Zeta model

$$\zeta(z) = \zeta_0 + \frac{(\zeta_1 - \zeta_0)}{2}\left[\tanh\left(\frac{z - z_0}{\Delta z}\right) + 1\right]$$

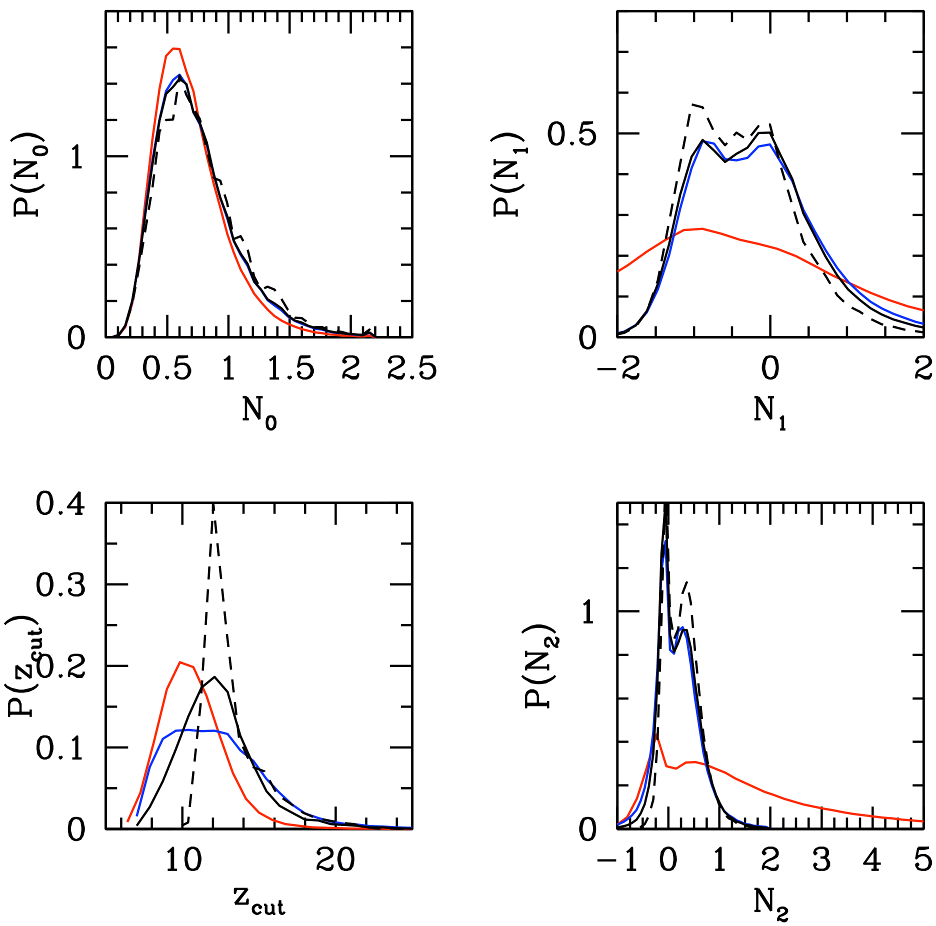


model parameters

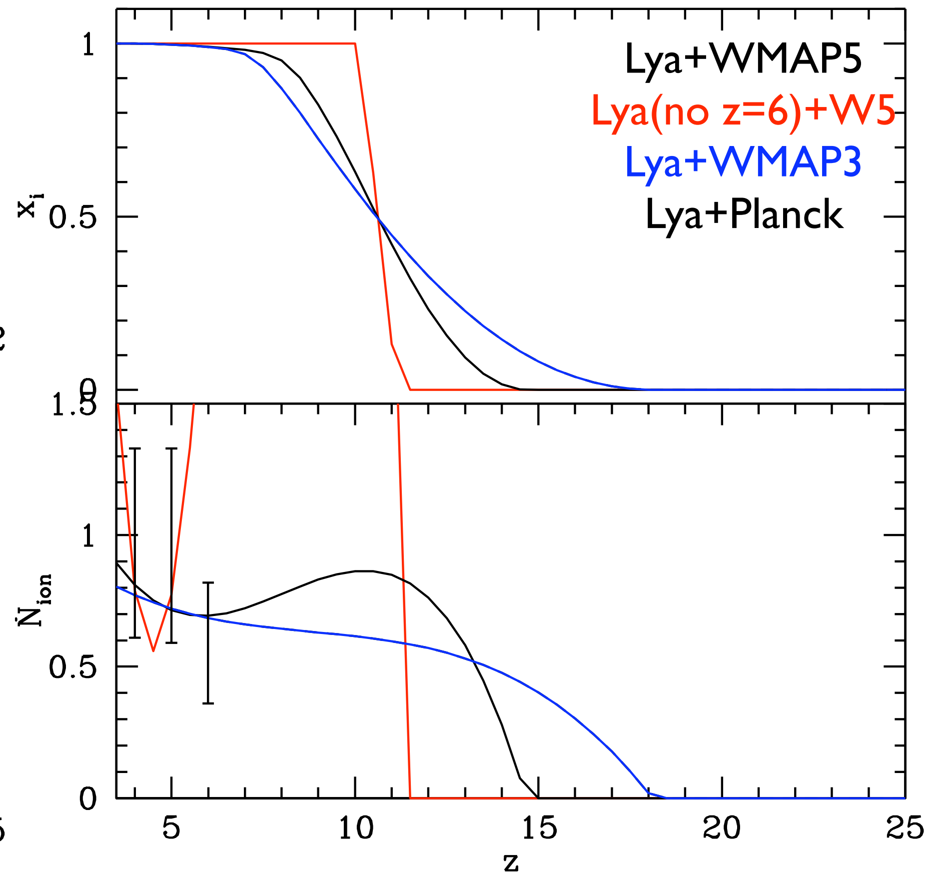
best fitting history

Nion model

$$\dot{N}_{\rm ion} = N_0 A_{\rm ion}[1 + N_1(z - z_0) + N_2(z - z_0)^2 + N_3(z - z_0)^3] \times \Theta(z - z_{\rm max}), \quad (5)$$



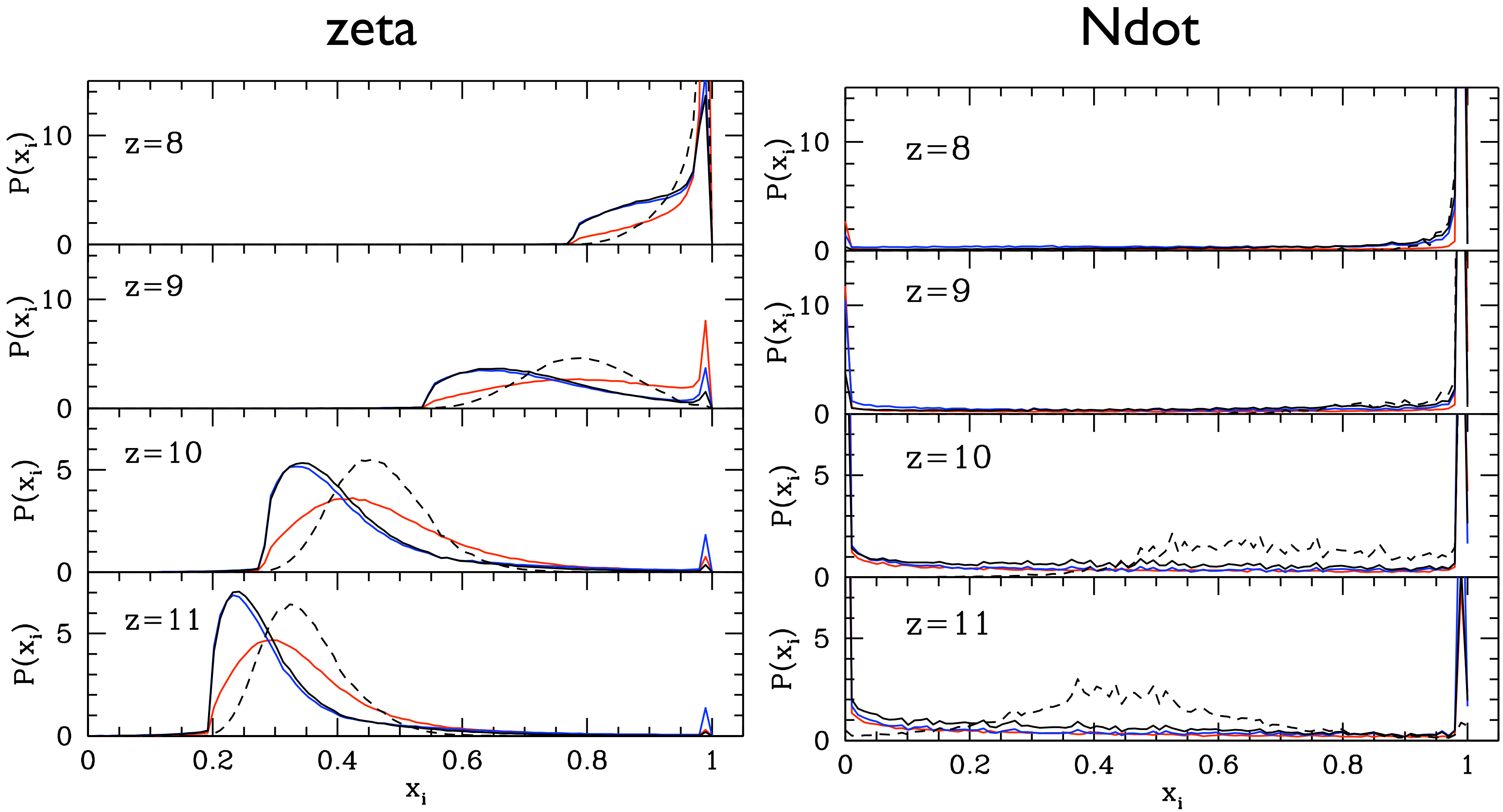
model parameters



best fitting history

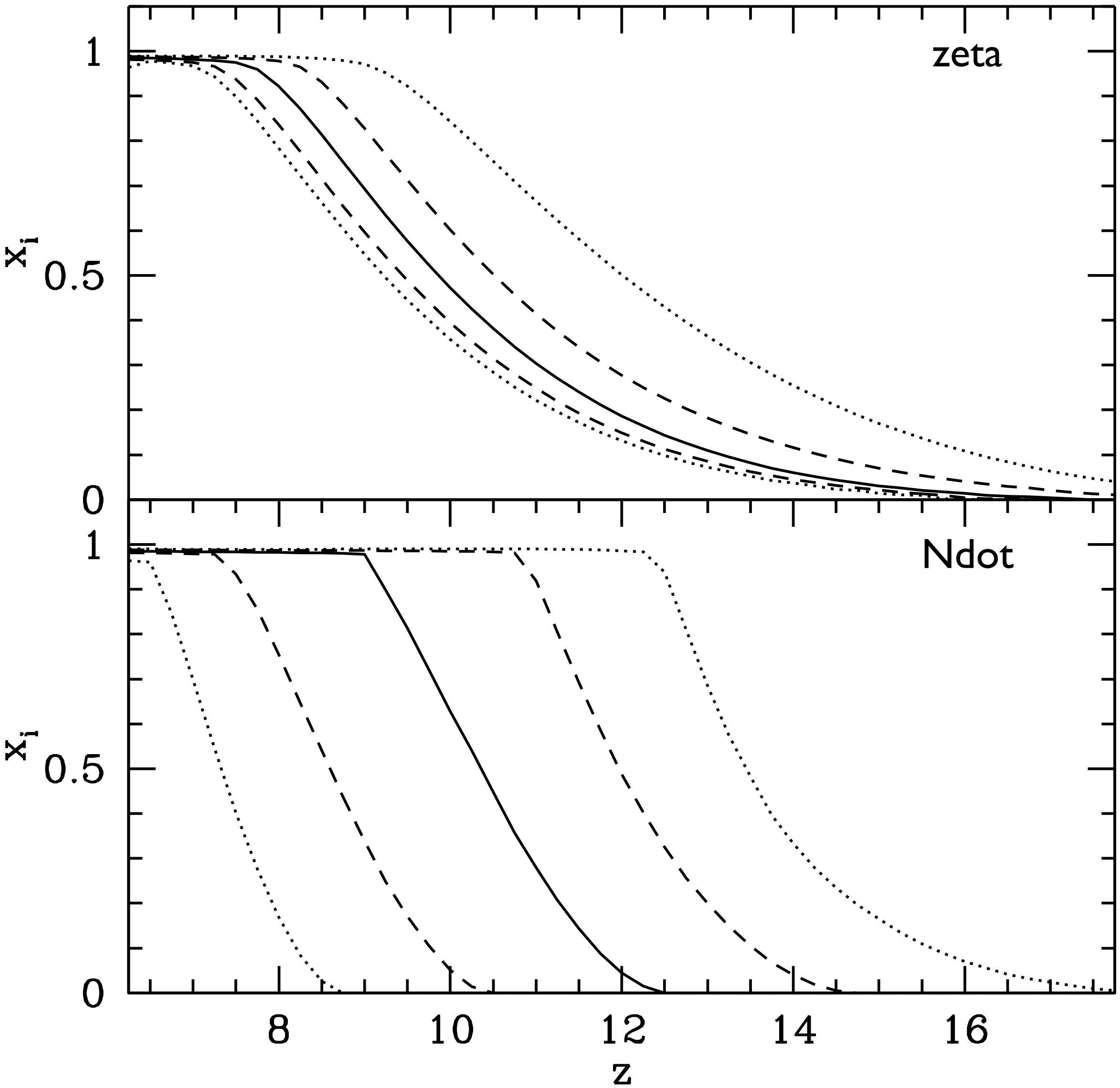
Distribution of x_i

$$p(x_i|M) = \int \mathrm{d}w\, p(w|D,M)\delta[x_i(w|M) - x_i]$$



Marginalise over the model parameters to infer the ionization fraction at a given redshift

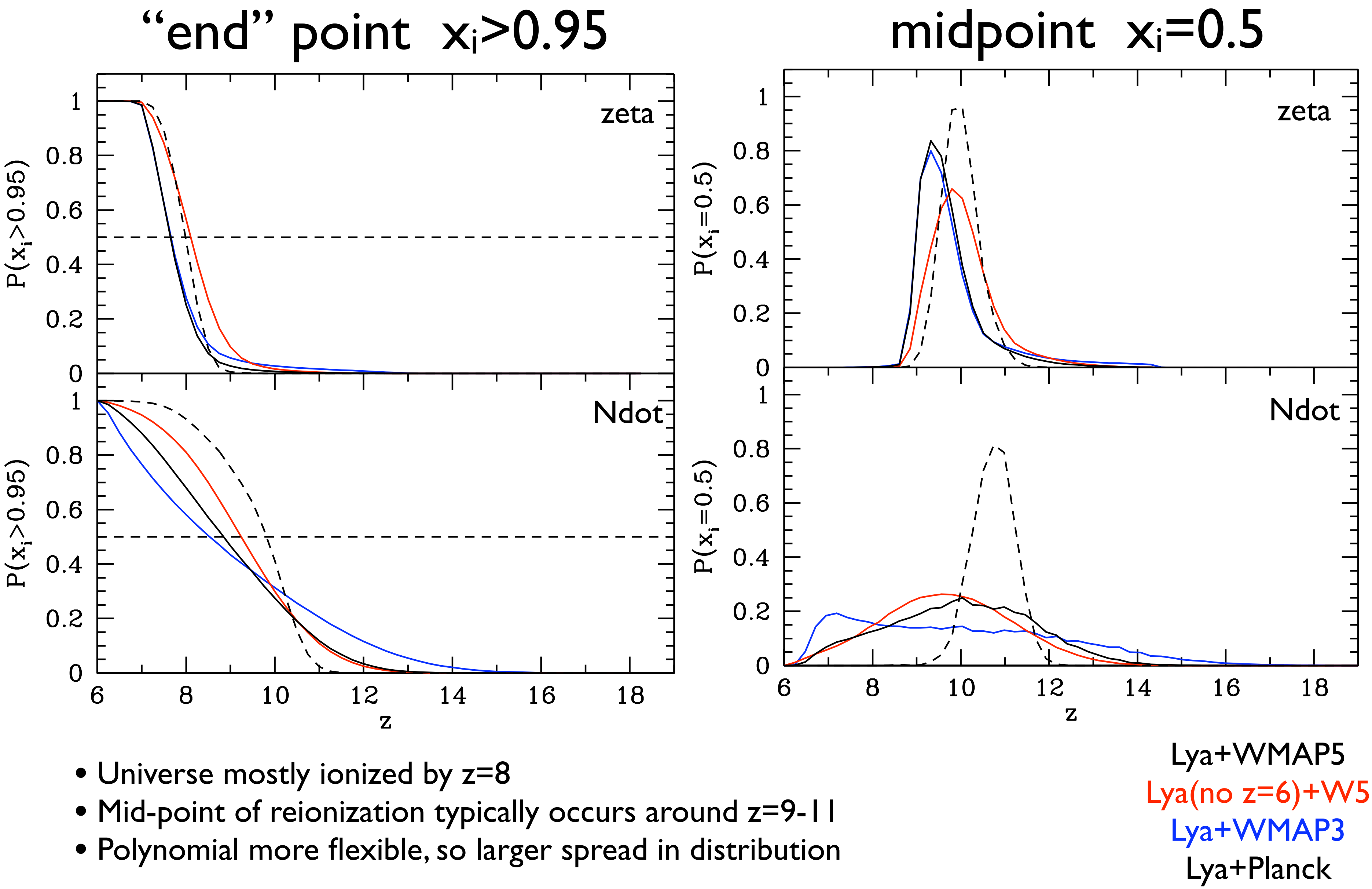
Ionization history



Contours from cumulative probability distribution (not 1 & 2 sigma errors and not best fit)

More restrictive parametrization gives tighter bounds on allowed histories

Milestones of reionization



- Universe mostly ionized by z=8
- Mid-point of reionization typically occurs around z=9-11
- Polynomial more flexible, so larger spread in distribution

Mapping x_i to 21 cm fluctuations

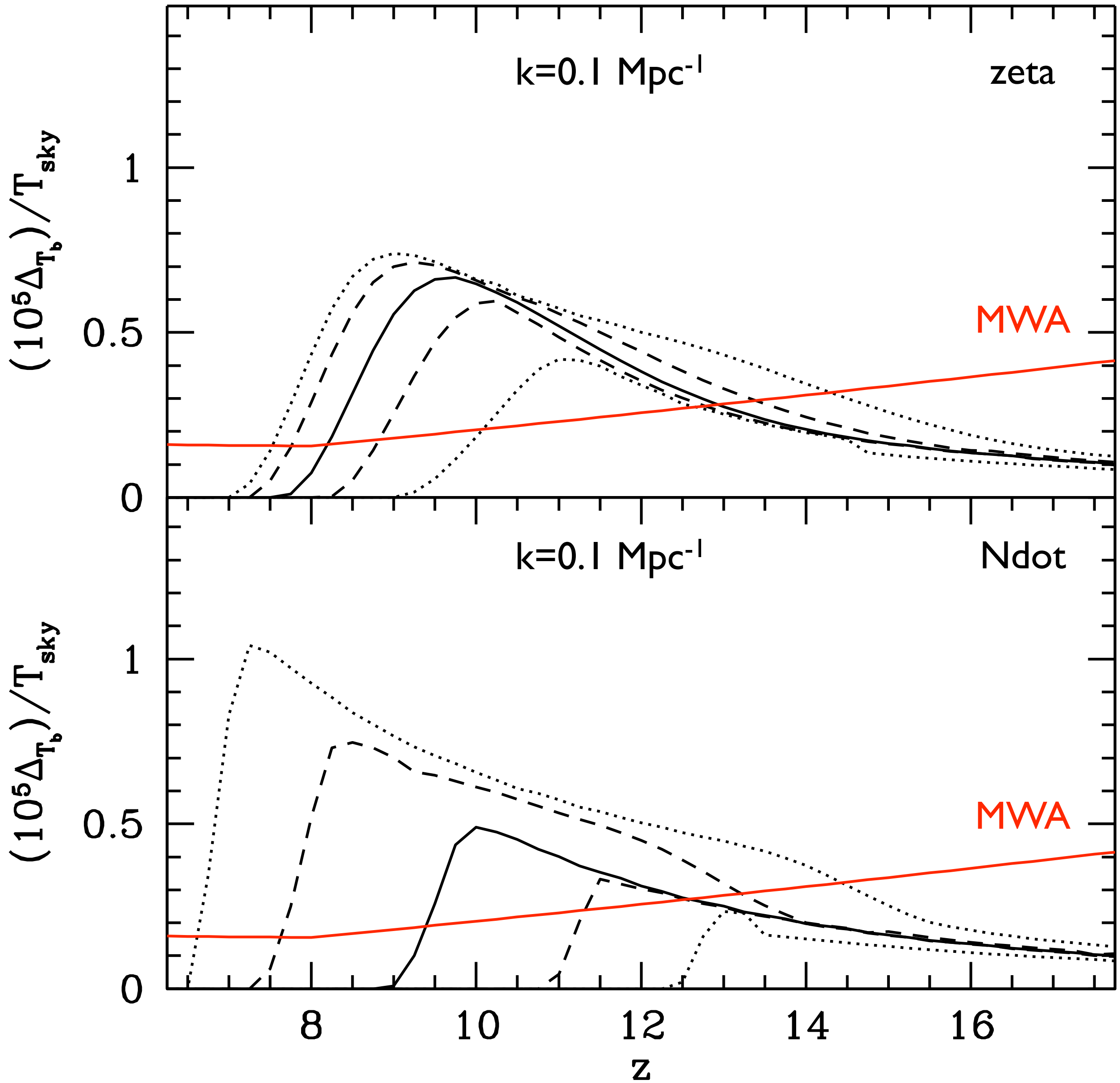
$$\boxed{x_i \longrightarrow P_{xx} \longrightarrow \bar{T}_b^2 P_{T_b}}$$

Use FZH04 bubble model to map x_i to amplitude of 21 cm fluctuations

Assume T_S saturated so that $T_b \approx 27 x_{\rm HI} \left(\frac{1+z}{10} \right)^{1/2} \, {\rm mK}.$

(probably not good at z> 10, but
very uncertain)

21 cm fluctuations



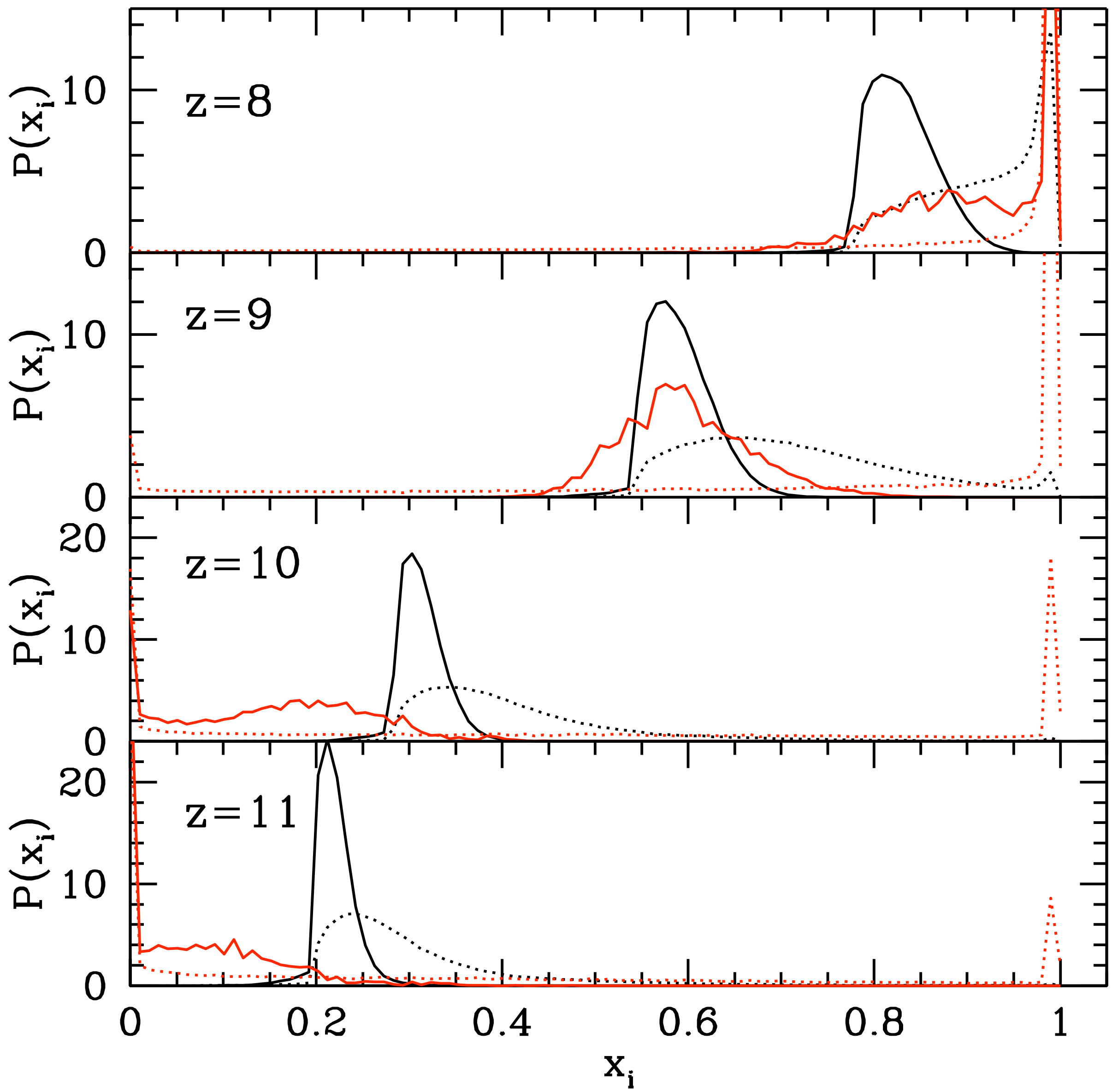
Contours from cumulative probability distribution (not 1 & 2 sigma errors and not best fit)

$$\Delta_{T_b} = \sqrt{\frac{k^3 P_{T_b}}{2\pi^2}}$$

Sky temperature taken to be $T_{\rm sky} \approx 180(\nu/180{\rm MHz})^{-2.6}$ K.

MWA sensitivity curve assumes 2000 hrs on two fields. Collecting area capped at z=8.

What do you gain?



Add 21 cm data point
$x_i(z=9)=0.5\pm0.05$

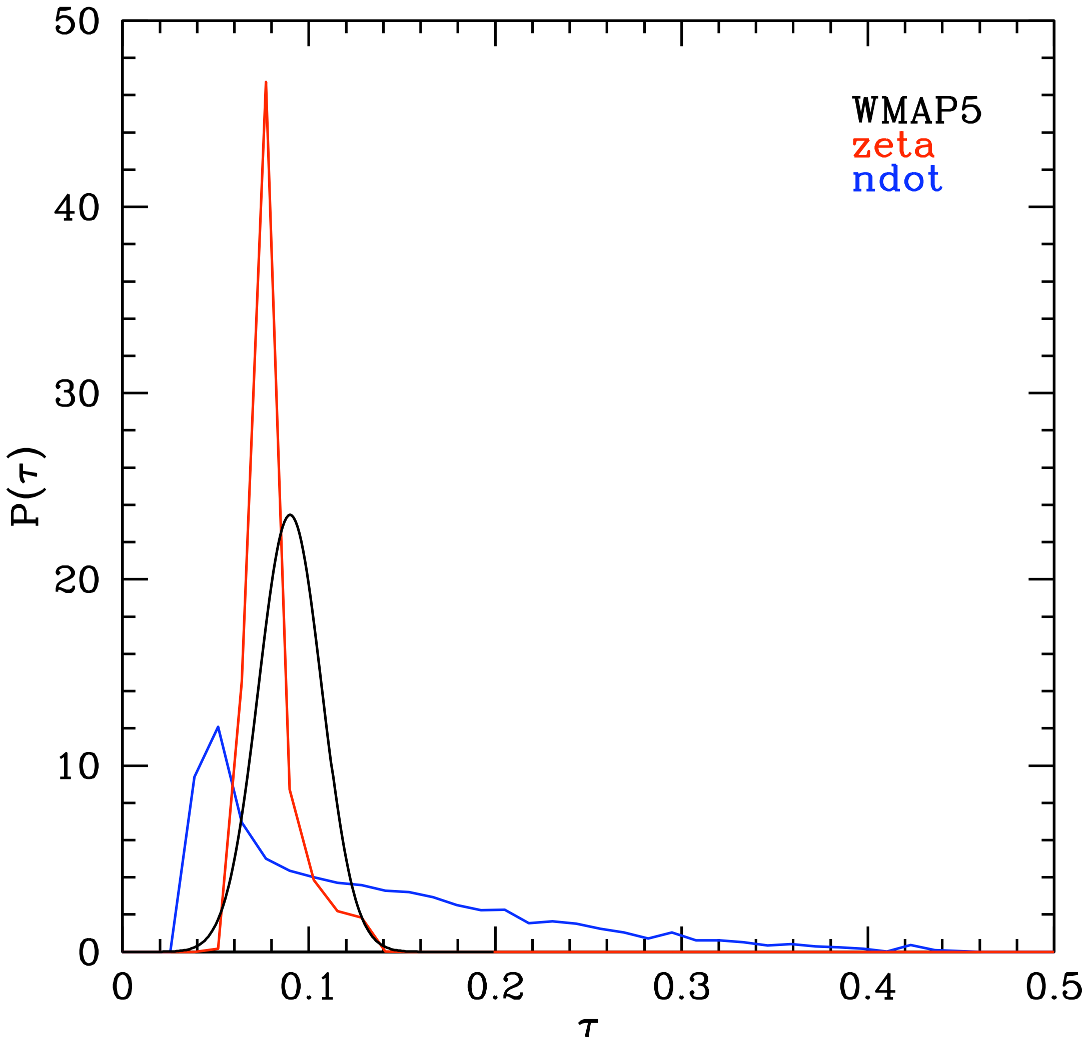
Tightens distributions significantly

zeta **ndot**

dotted=Lya+CMB
solid=Lya+CMB+21cm

Measure tau?

Can imagine measuring CMB optical depth with 21 cm experiments



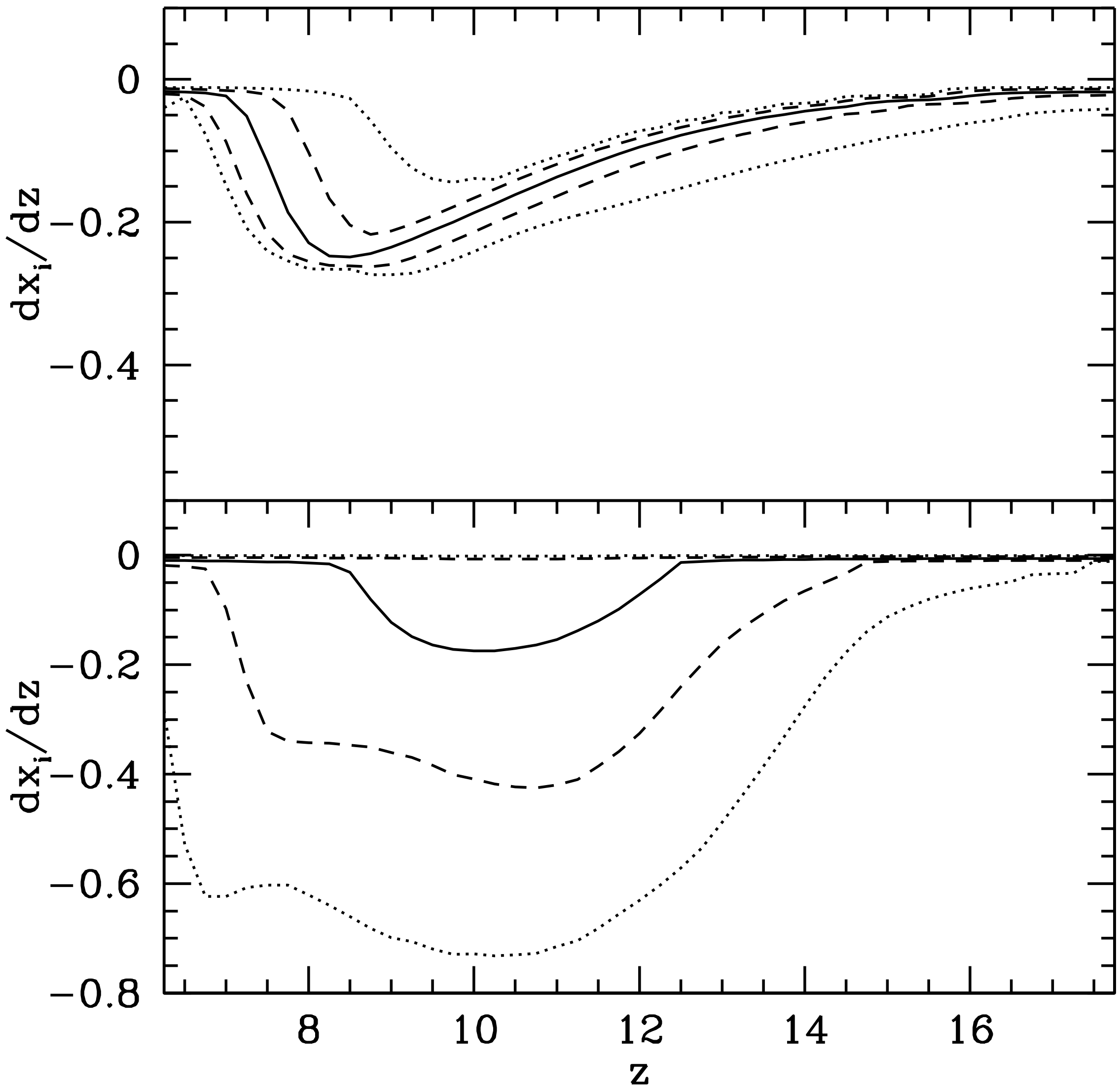
21 cm measurements in two bins

$$x_i(z=7) > 0.8$$

$$x_i(z=9) = 0.5 \pm 0.05$$

With enough data might constrain tau at interesting level

Global T_b experiments



Same exercise leads to distribution of dx_i/dz

Potentially useful for guiding global experiments e.g. EDGES

Bowman+ 2008

Mapping to sensitivity not totally straightforward

Caveats

- Ignored covariances between data sets and cosmological parameters
- Ignored spin temperature variation (but may well be important at these redshifts)
- Lya forest model approximate
- Could include more data: high-z galaxies, DLA, IGM temperature, etc.

Conclusions

- Despite uncertainties interesting to take analytical reionization models and perform inference exercise - Quantify our ignorance
- Two different parametrizations agree that
  - Reionization likely complete by z=8
  - Mid point of reionization probably in range z=9-11
- Adding 21 cm measurements will improve things
- Framework easily extended to include other observations