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

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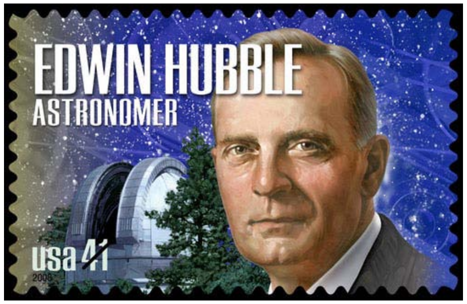
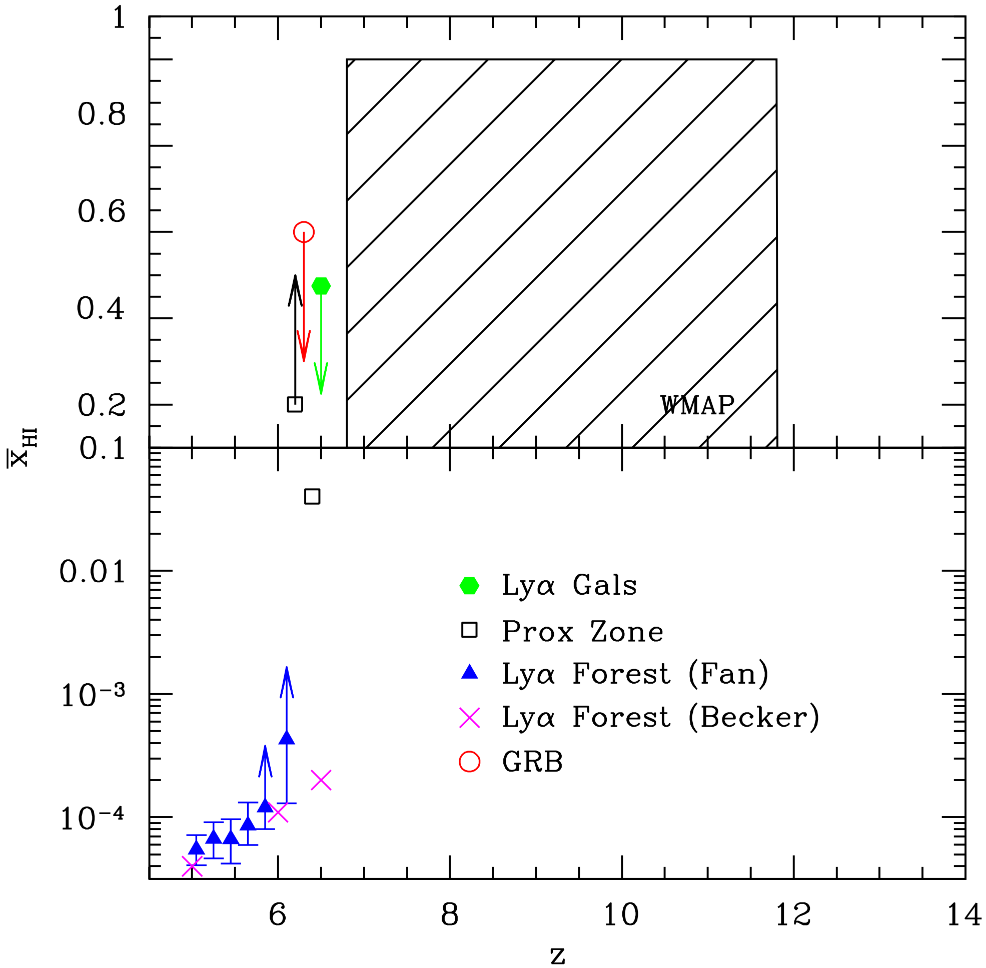
Aspen
2010



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}

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

Use model+parameters to infer ionization history

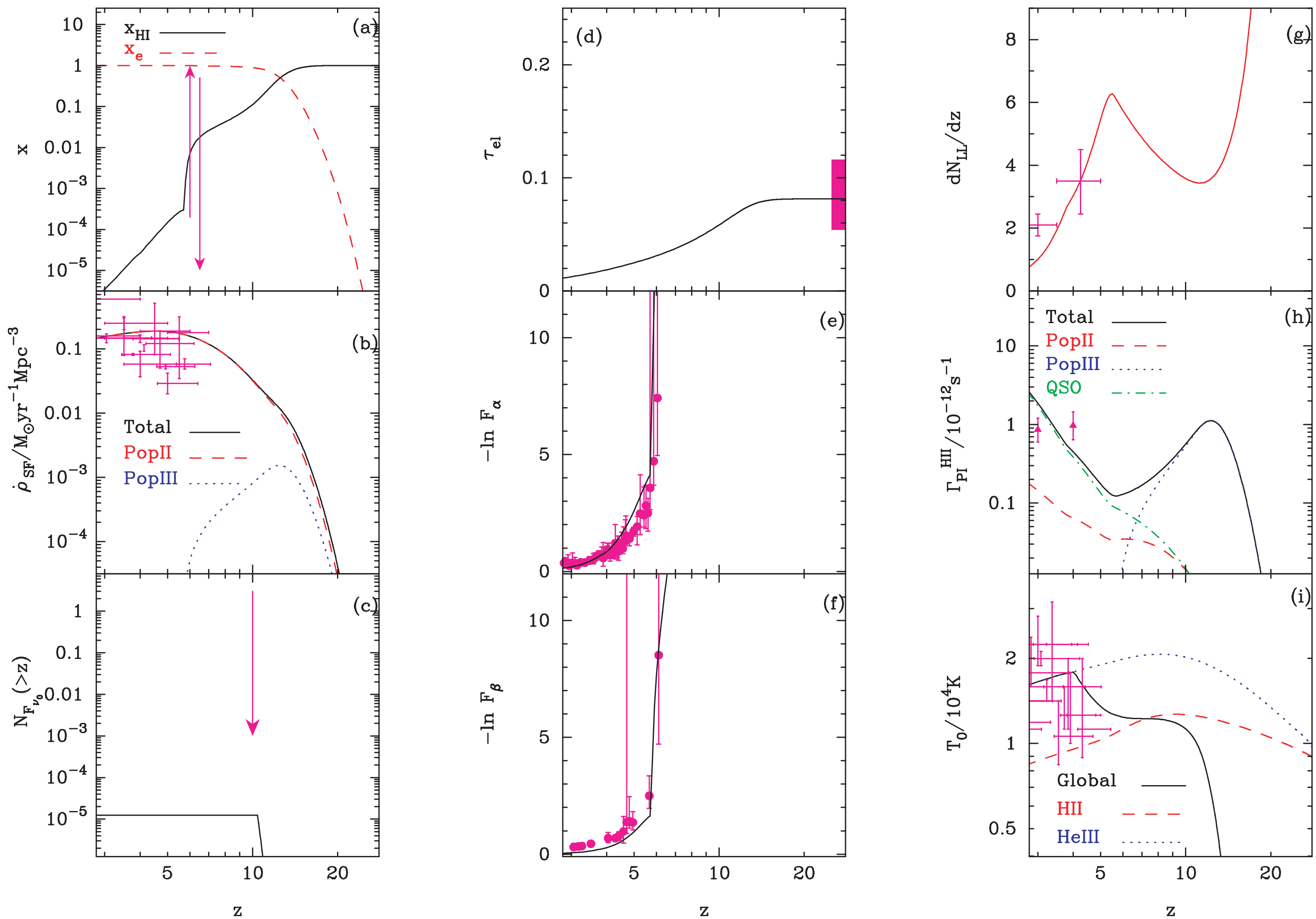
$$p(x_i|M) = \int \mathrm{d}w\, p(w|D,M)\delta[x_i(w|M) - x_i]$$

Use inferred ionization history to make predictions
for 21 cm experiments

Observational Constraints?

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

Self-consistent reionization modeling

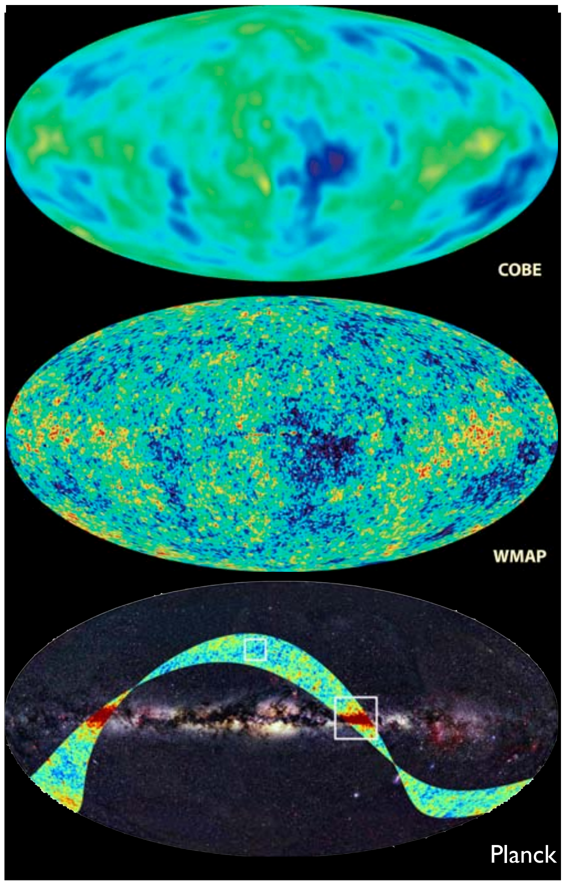


Throw all observations at detailed model and make predictions

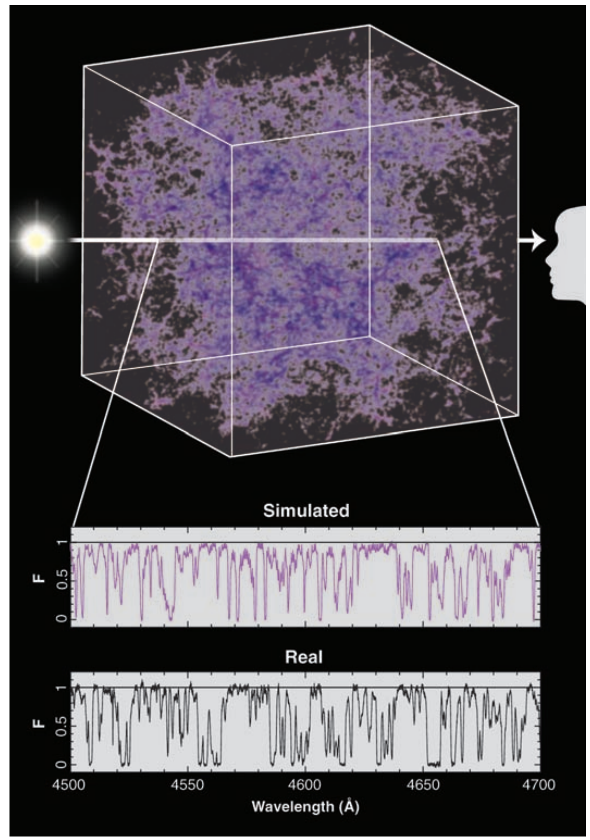
Choudhury & Ferrara 2008

Observations

CMB



Lyman alpha forest



Here focus on CMB & Ly alpha forest
and stay agnostic about sources

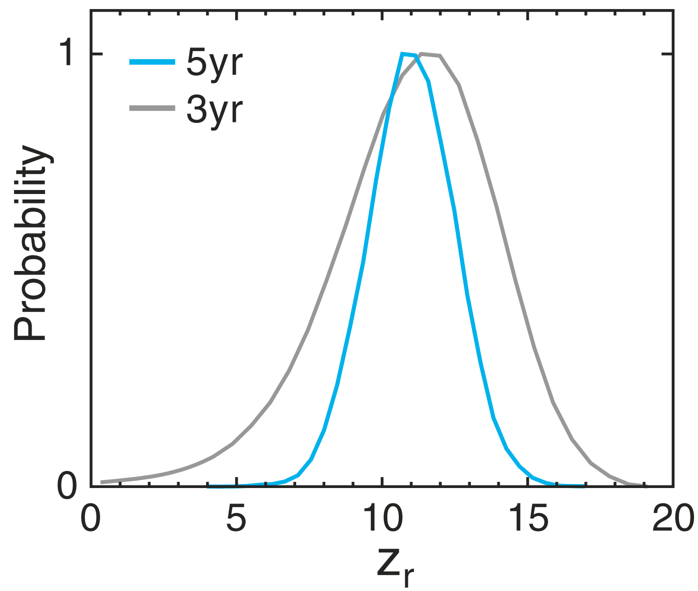
CMB optical depth

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

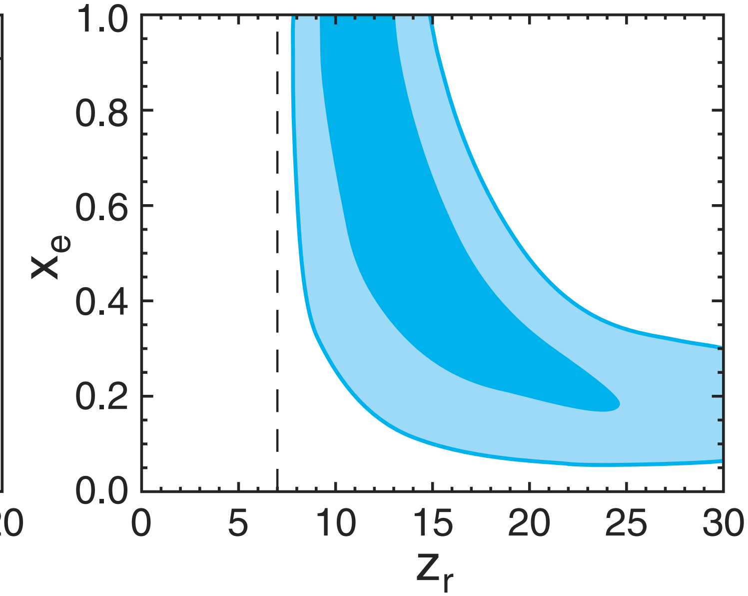
$\tau_{\rm CMB} = 0.087 \pm 0.017$ Dunkley+ 2009

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

Instantaneous



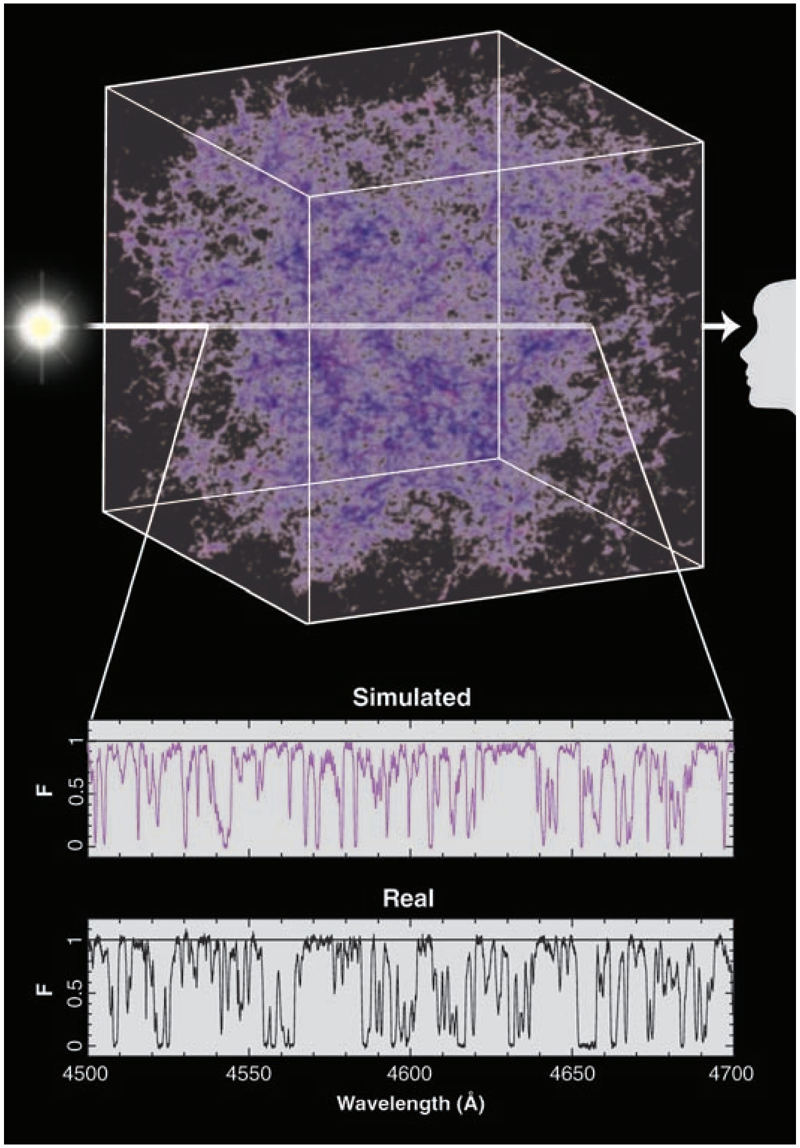
Step function



Dunkley+ 2009

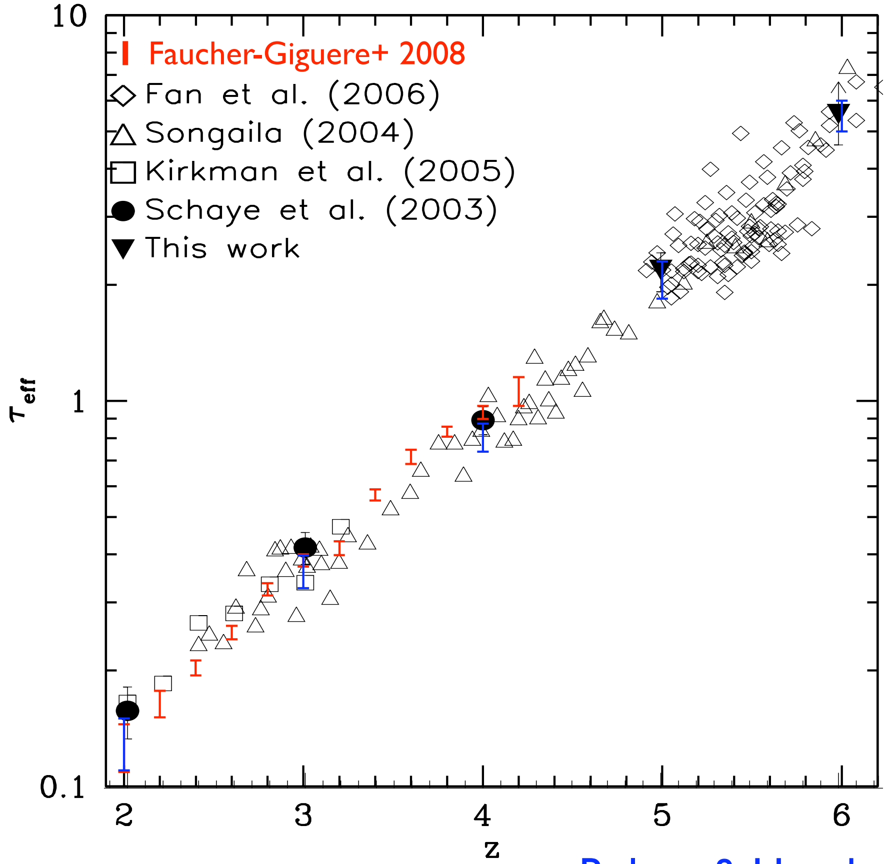
$z_r = 11 \pm 1.4$

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

$$\boxed{\tau_{\rm eff} \rightarrow \Gamma_{-12} \rightarrow \dot{N}_{ion} \rightarrow Q_i \leftarrow \tau_{\rm CMB}}$$

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

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

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 pdf reasonable match to simulations at important densities

Miralda-Escude+ 2000
Bolton & Becker 2008

Density-temperature relation taken as power law
- parameters and scatter about this form highly uncertain
- no temperature measurements at z>4 (but see Bolton+ 2009)
- helium reionization important at lower redshifts

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

Relating Gamma to sources

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

ionizing photons

ionizing backgnd

Source spectrum

absorbing systems

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

Source spectrum: hard or soft?

α_S~1 PopIII — Bromm+2001

α_S~3 PopII — Leitherer+1999

Distribution of absorbing systems processes radiation from sources

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

Misawa+ 2007

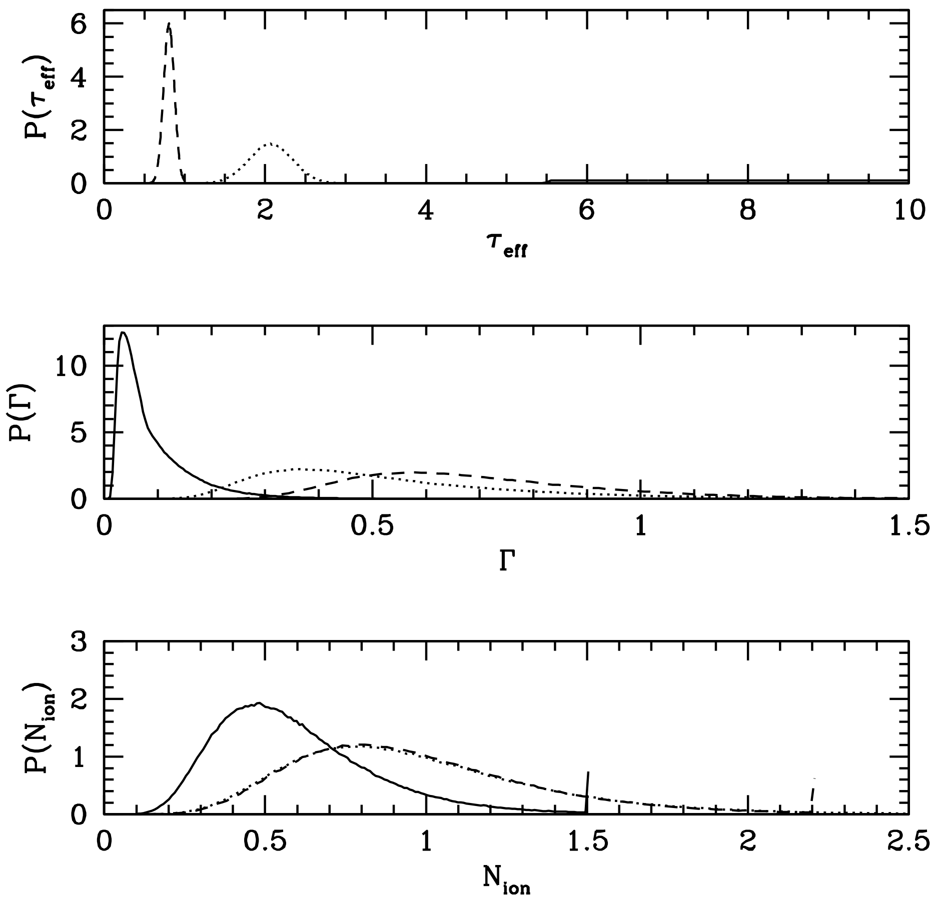
Mean free path from spacing between LLS

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

Storrie-Lombardi 1994

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

Constraints on N_{ion}



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	$5.5 - 15$	$0.03^{+0.11\,(+0.25)}_{-0.002\,(-0.02)}$	$0.48^{+0.34\,(+0.75)}_{-0.12\,(-0.25)}$

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

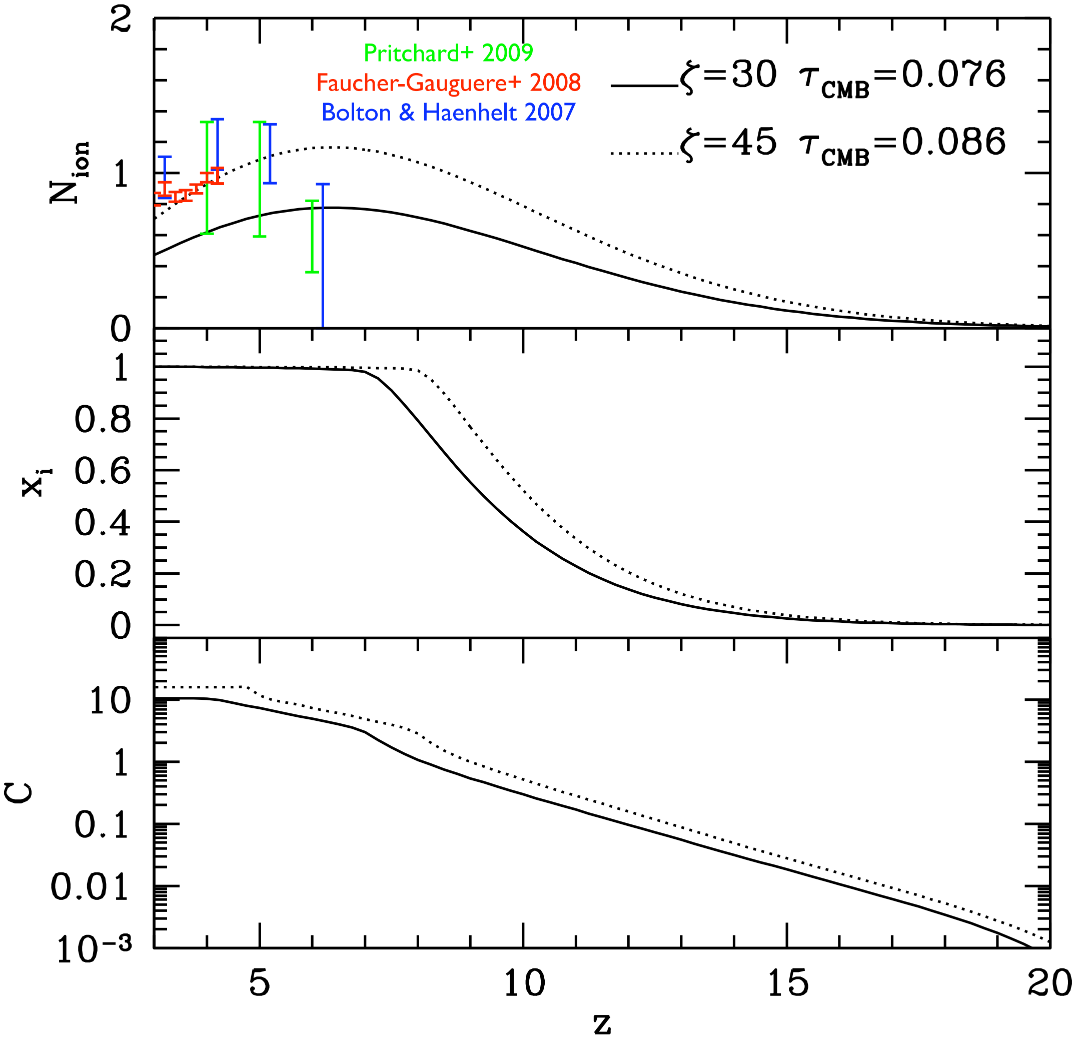
Parameter	$\bar{x}$ ($x_{\rm low}$)	σ_x ($x_{\rm high}$)	prior
T_0	0.5×10^4K	3.0×10^4K	uniform
β	0	0.6	uniform
α_S	1	3	uniform
γ	1	3	uniform
κ	1	0.2	gaussian
σ_8	0.8	0.05	gaussian
Ω_m	0.3	0.04	gaussian
Ω_b	0.046	0.0005	gaussian
h	0.7	0.04	gaussian

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

Model properties

Filling fraction of ionized regions

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



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

Clumping set assuming IGM ionized up to density threshold set by HII region size

Miralde-Escude+ 2000

Furlanetto & Oh 2005

Parametrizations of Ndot

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

via source emissivity

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

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

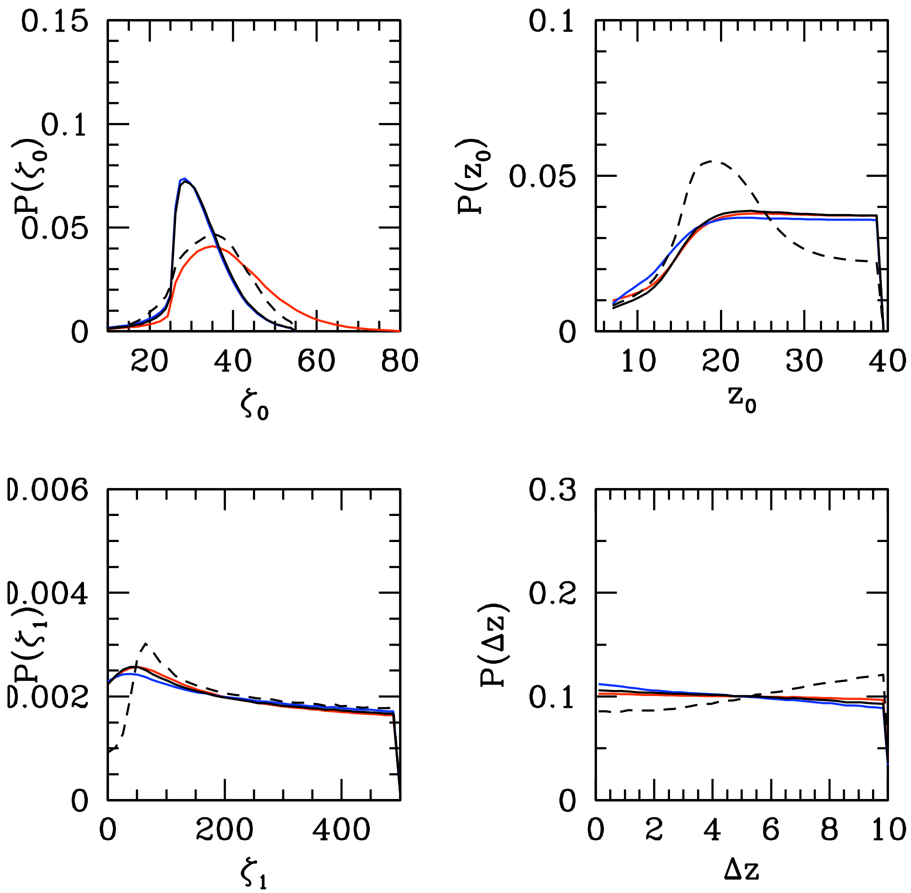
polynomial

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

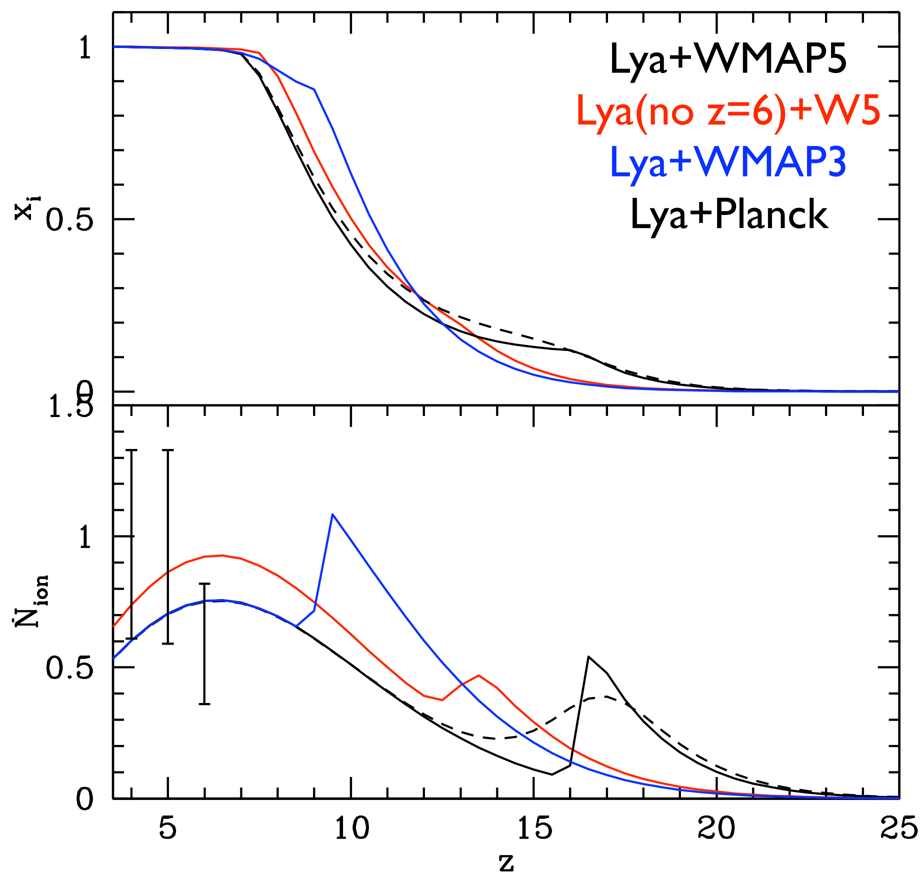
If very different parametrizations give same physical predictions may be robust

Step model

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



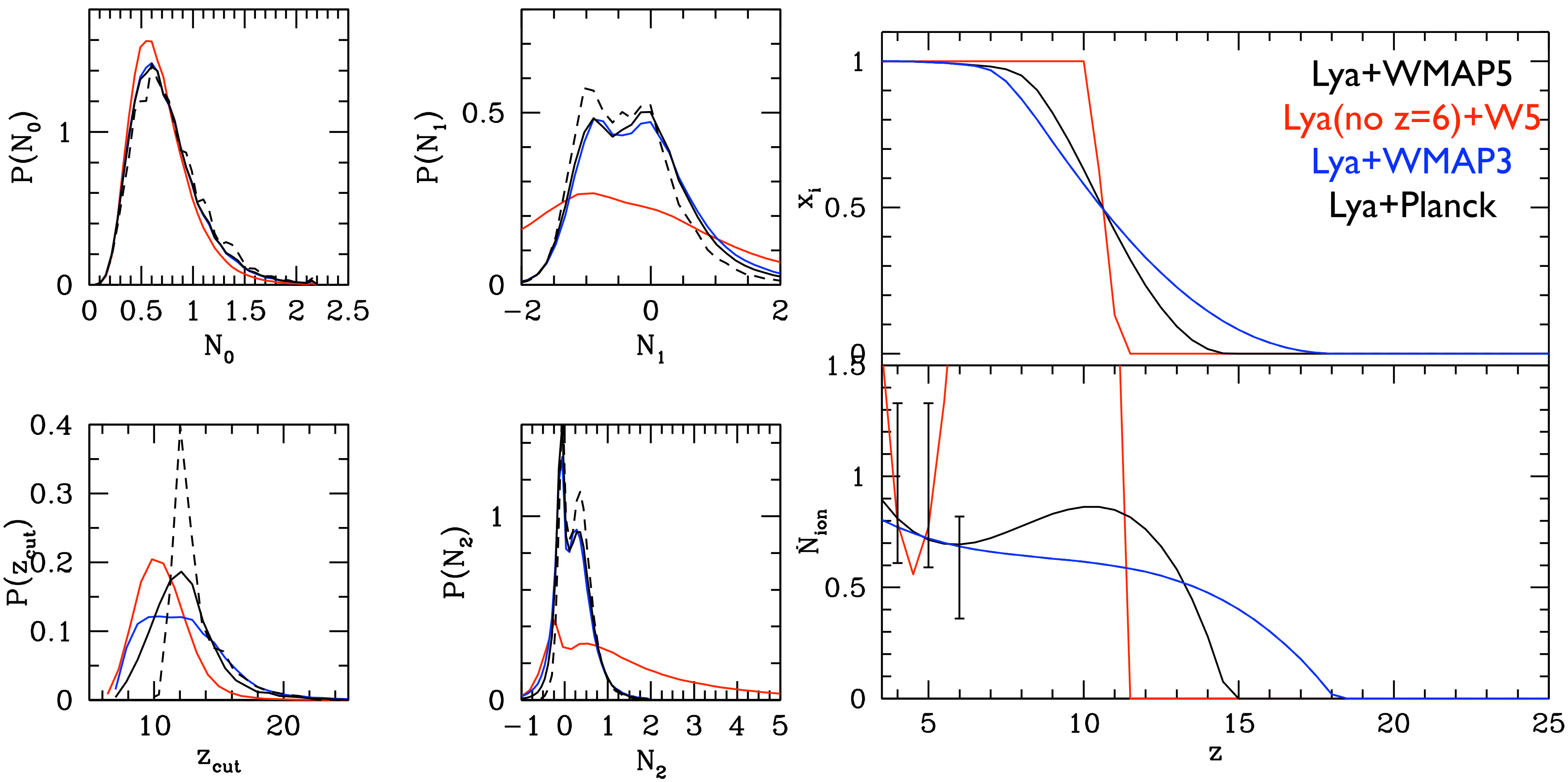
model parameters



best fitting history

Polynomial model

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



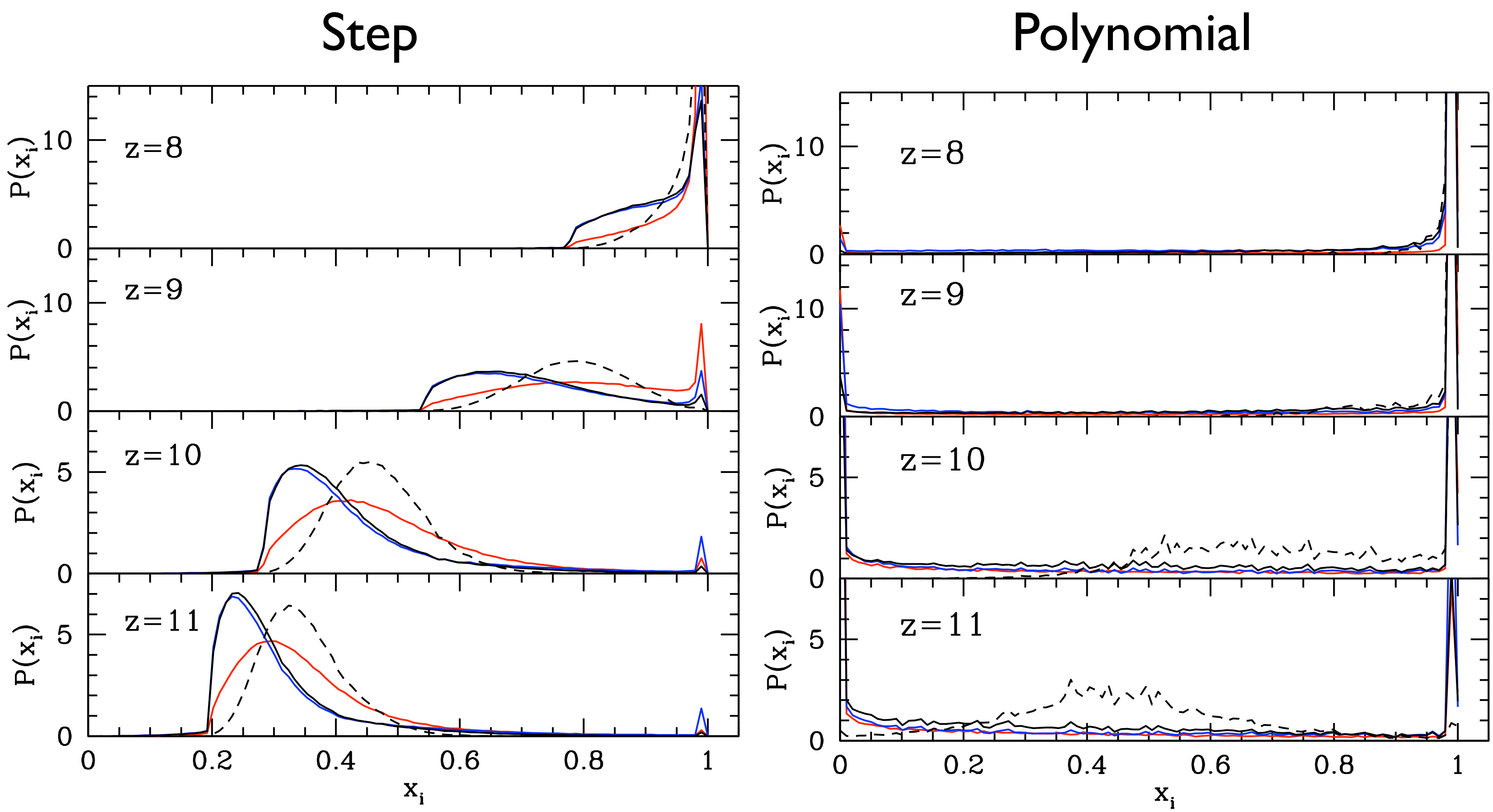
model parameters

best fitting history

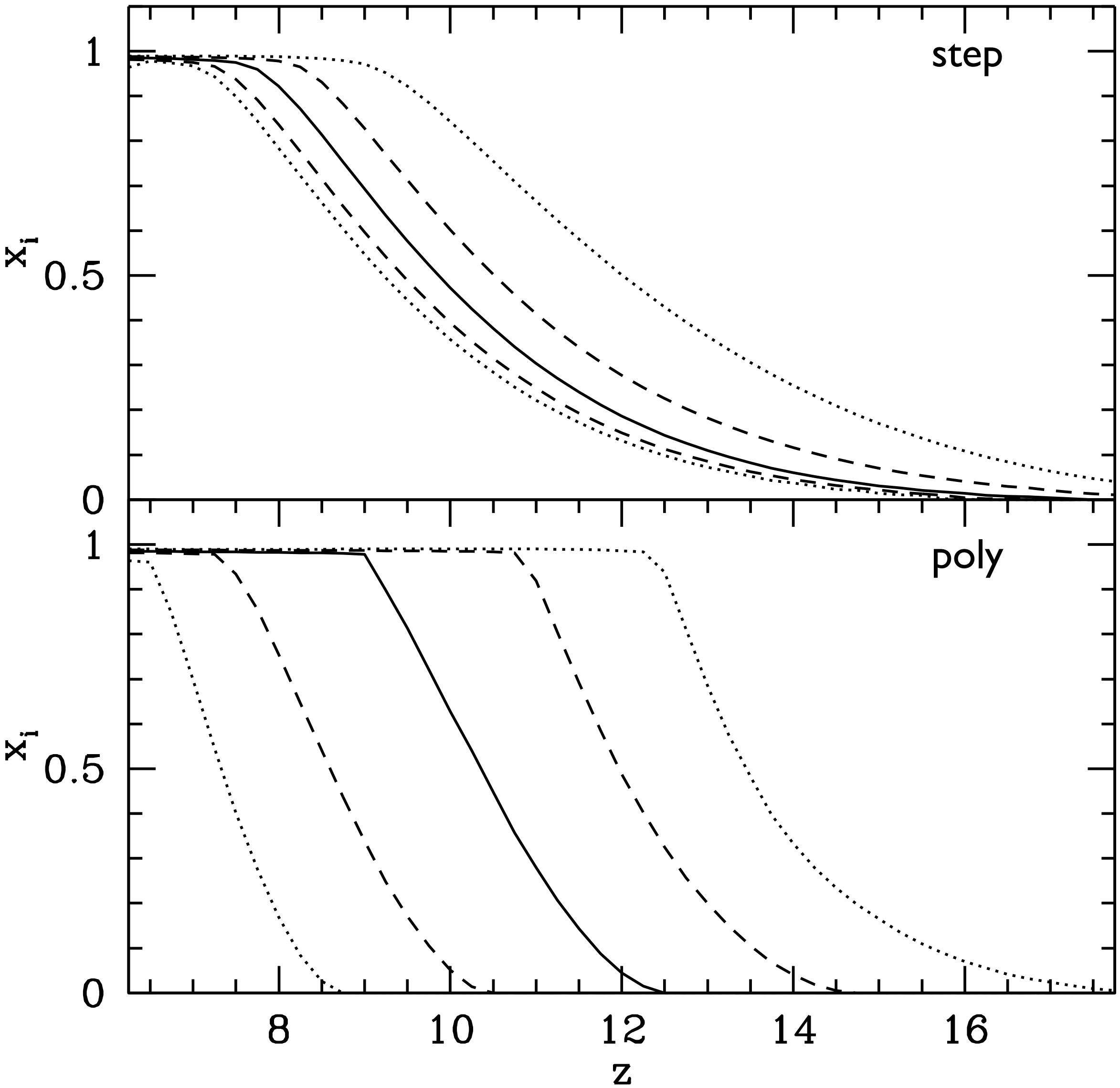
Distribution of x_i

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

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



Ionization history

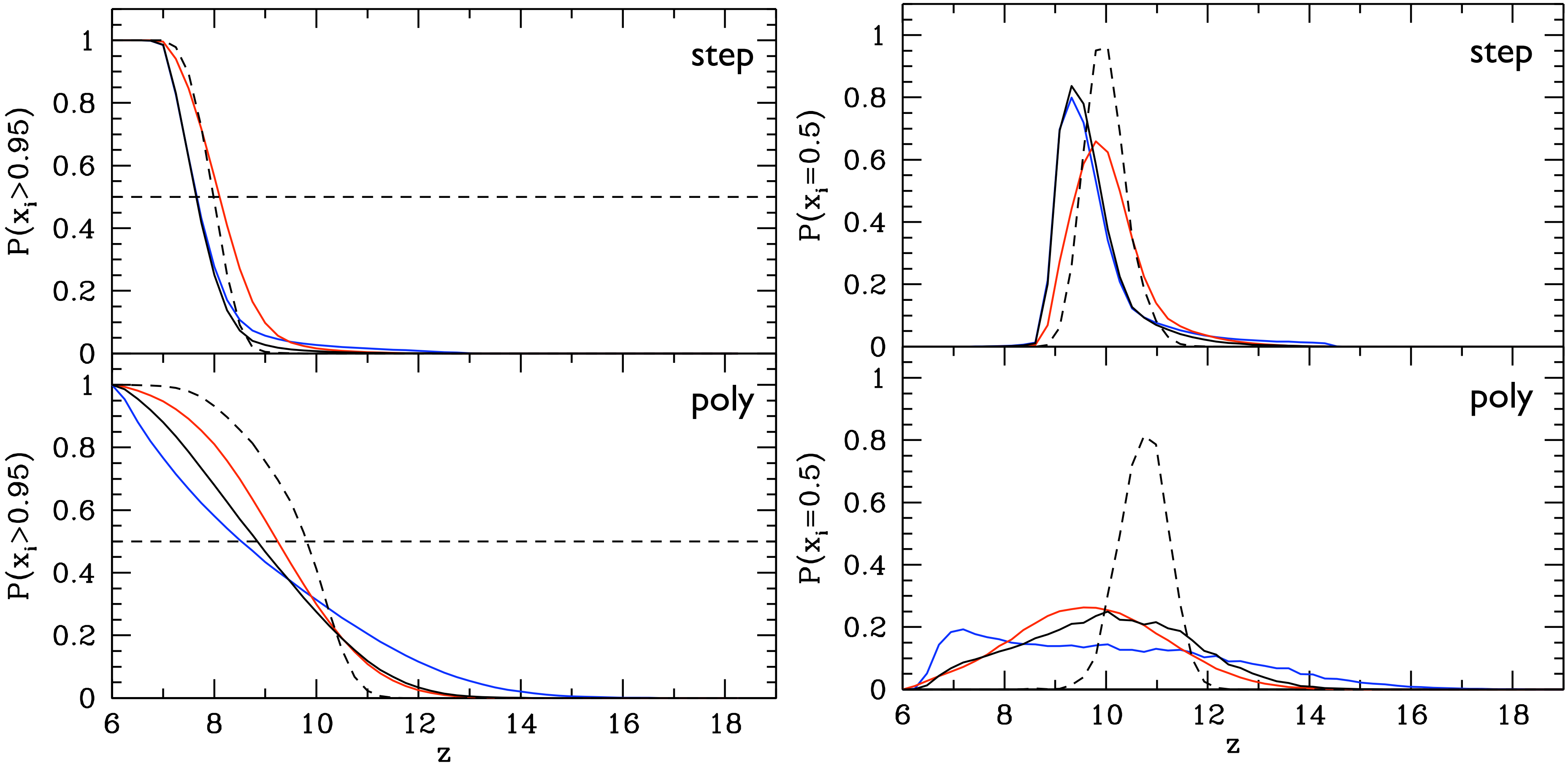


Contours from cumulative probability distribution (not 1 & 2 sigma errors and not best fit)

More restrictive parametrization gives tighter bounds on allowed histories

Milestones of reionization

"end" point $x_i>0.95$ — midpoint $x_i=0.5$



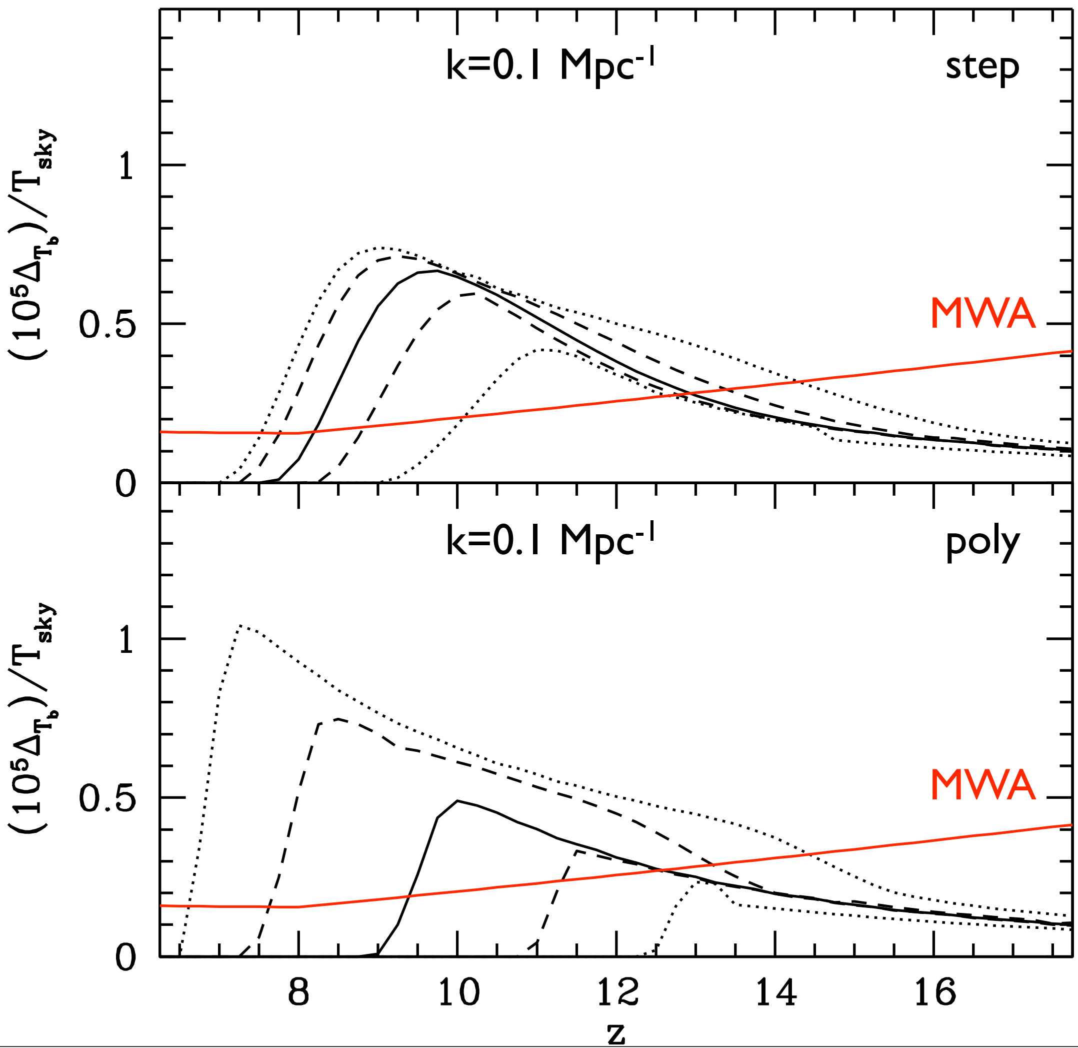
- Universe mostly ionized by z=8
- Mid-point of reionization typically occurs around z=9-11
- Polynomial more flexible, so larger spread in distribution

Lya+WMAP5
Lya(no z=6)+W5
Lya+WMAP3
Lya+Planck

21 cm fluctuations

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

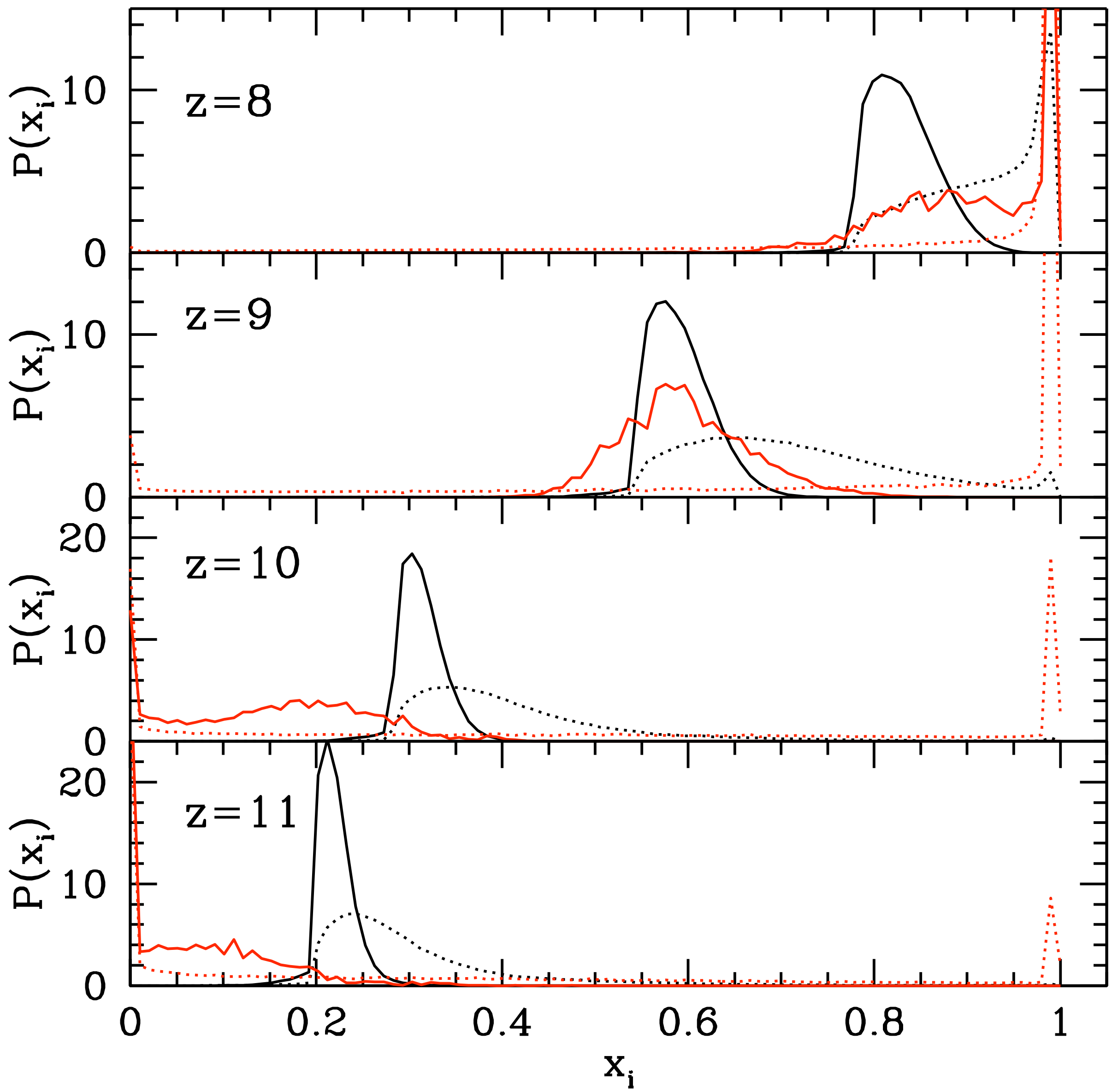
Use FZH04 bubble model to map x_i to amplitude of 21 cm fluctuations Furlanetto+ 2004



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

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

What do you gain?



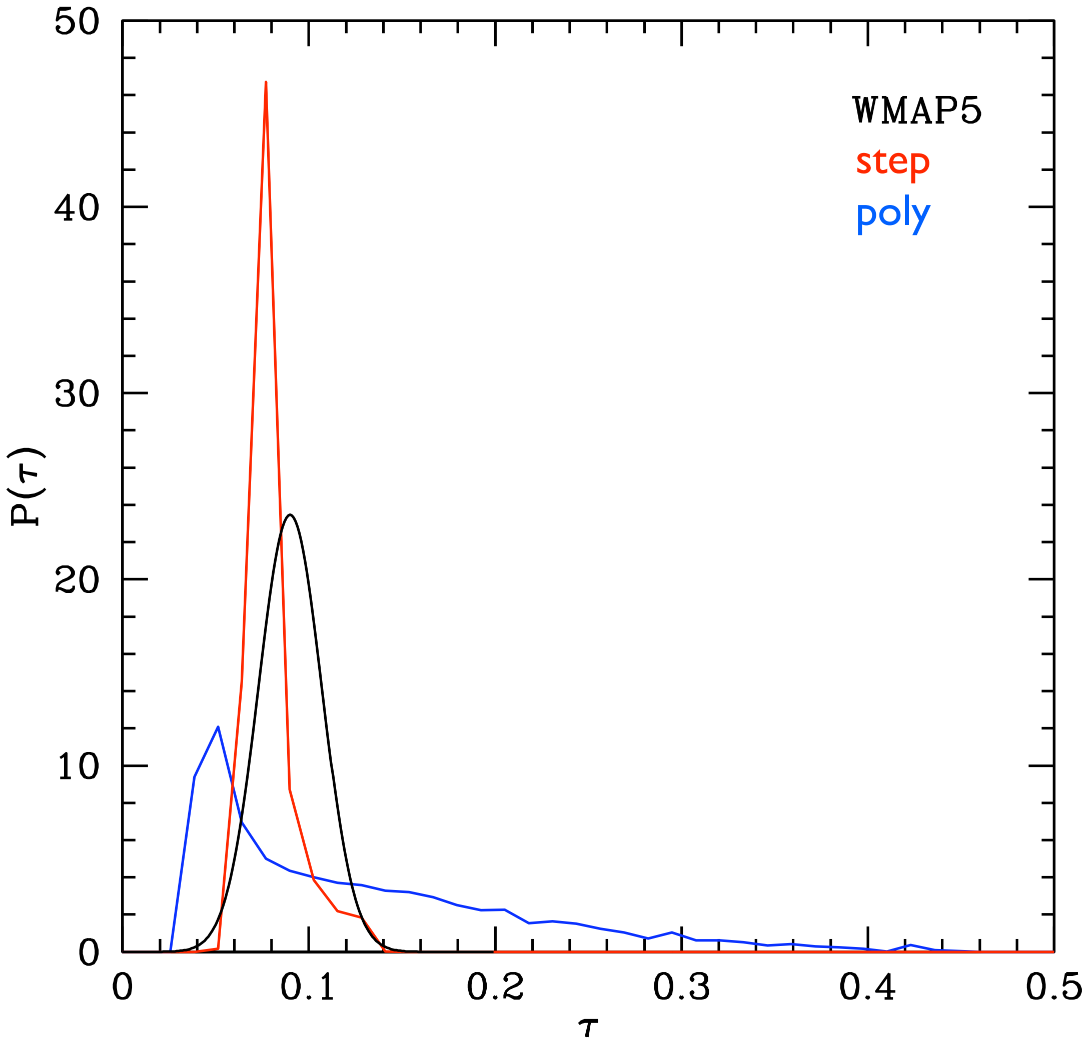
Add 21 cm data point
$x_i(z=9)=0.5\pm0.05$

Tightens distributions significantly

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

Measure tau?

Can imagine constraining CMB optical depth with astrophysical measurements of reionization



Lyman alpha forest +
21 cm measurements in two bins

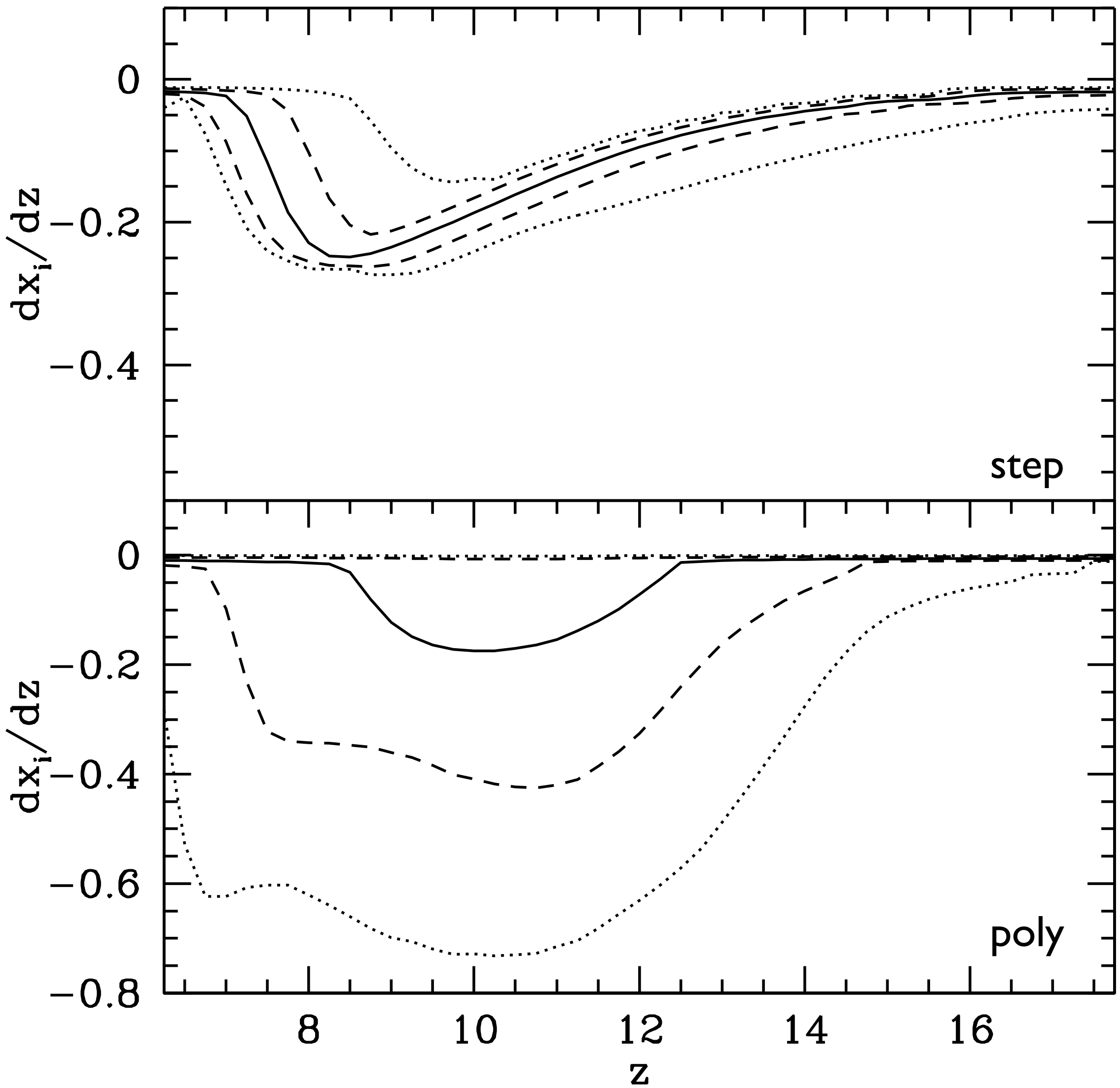
$$x_i(z=7) > 0.8$$

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

With enough data might constrain tau at interesting level

break CMB degeneracies

Global T_b experiments



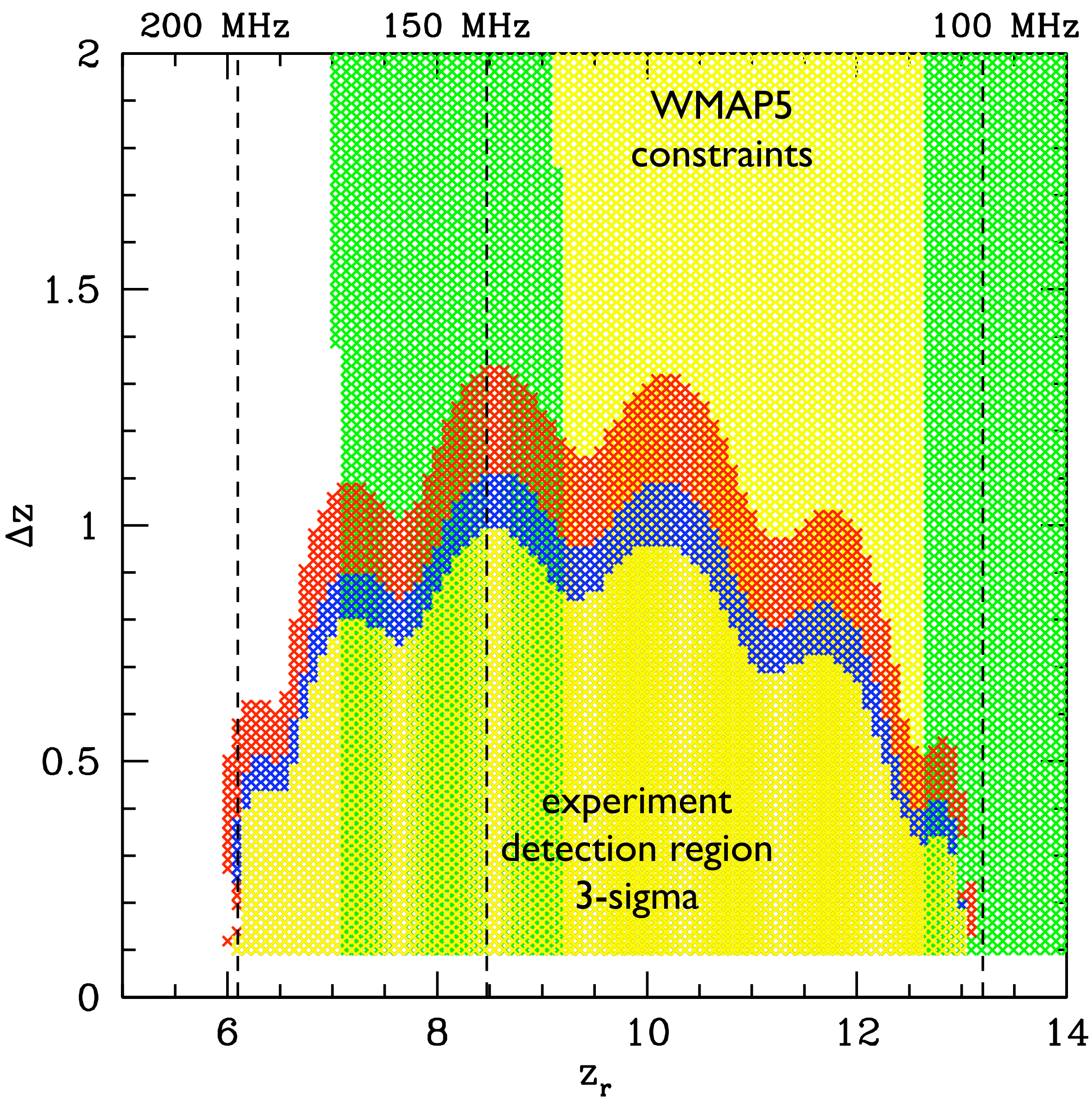
Same exercise leads to distribution of dx_i/dz

Extended histories $\Delta z>2$ preferred

Potentially useful for comparing with global experiments e.g. EDGES

Bowman+ 2008

Global 21 cm experiments



$$T_{\rm sky} = T_{\rm fg} + T_{21}$$

$$\log T_{\rm fg} = \log T_0 + \sum_{n=1}^{N_{\rm poly}} a_n \log(\nu/\nu_0)^n$$

$$T_{21}(z) = \frac{T_b}{2}\left[\tanh\left(\frac{z-z_r}{\Delta z}\right)+1\right]$$

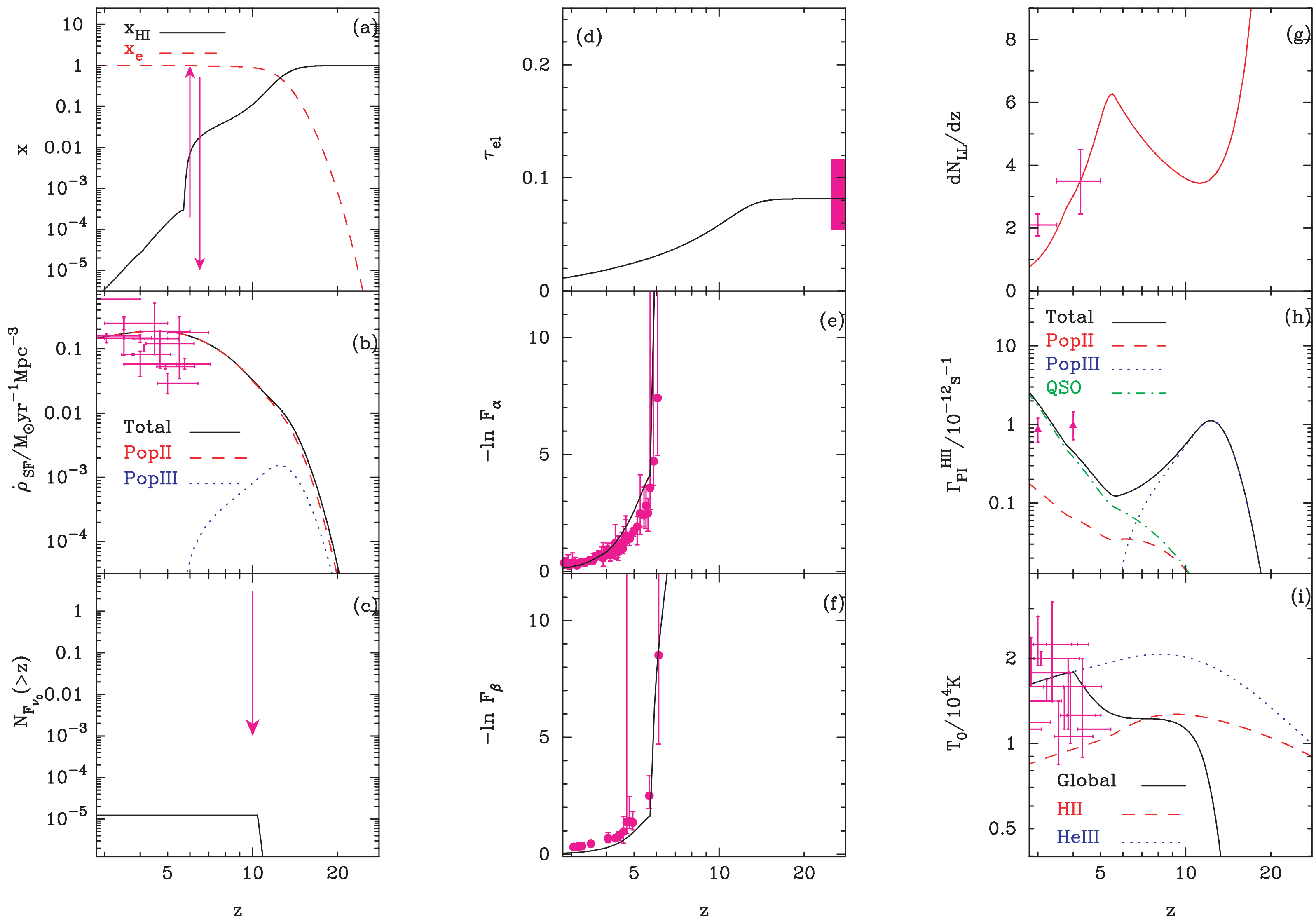
Npoly=6 integrating for 500 hr

Global experiments could begin to probe interesting region

Conclusions

- Despite uncertainties interesting to take analytical reionization models and perform inference exercise - Quantify our ignorance
- Strong priors on sources can be misleading
- Two very different parametrizations agree that
  - Reionization likely complete by z=8
  - Mid point of reionization probably in range z=9-11
- Framework easily extended to include other observations - especially high-z galaxies

Self-consistent reionization modeling



Throw all observations at detailed model and make predictions

Choudhury & Ferrara 2008