

# How will we determine the reionization history of the universe?: introduction to session 2

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# How Will We Determine The Reionization History of the Universe?



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Columbia University



# What were the sources of reionization?

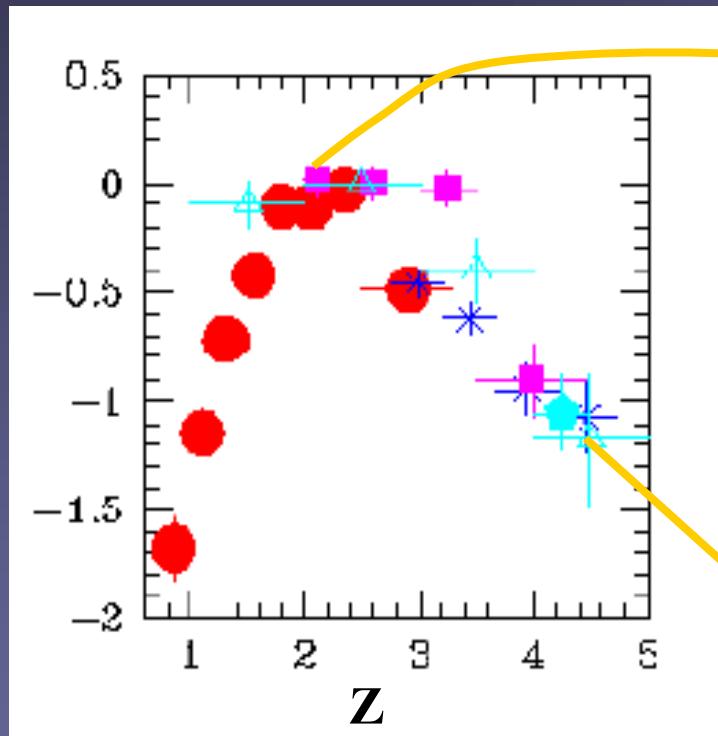
- Not a stringent energetic requirement
  - 13.6 eV (chemical) vs >MeV (nuclear or gravitational)
- Non-linear structures are present early in most cosmologies<sup>(\*)</sup>
  - 2-3 $\sigma$  peaks above Jeans scale collapse at z=20-30
- Photo-ionization natural candidate
  - consistent with Lyman  $\alpha$  forest at lower z
  - stars vs quasars
  - something more exotic - decaying particles with suitable  $\tau, m$

<sup>(\*)</sup> Interesting exceptions

# Extra Stars or Quasars are Needed

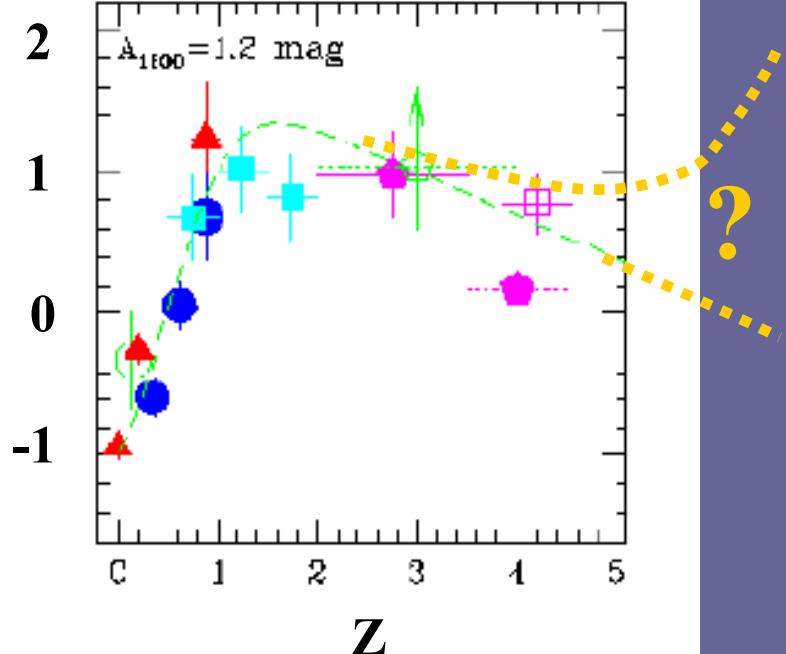
Quasar space density

$\log [n(z) / n(\text{peak})]$



redshift

Star formation rate



redshift

# Outline of Talk

1. Theoretical Issues of Reionization
  - what were the sources?
  - what are the key feedback processes?
2. Observational Signatures
  - distribution of neutral hydrogen
  - distribution of free electrons

# Relevant Halo Mass Scales

(masses at redshift z~10)

• Jeans Mass	$10^4 M_{\odot}$	$T_{vir}=10 \text{ K}$	x	20
• H <sub>2</sub> cooling	$10^5 M_{\odot}$	$T_{vir}=10^2 \text{ K}$	TYPE II	17
• HI cooling	$10^8 M_{\odot}$	$T_{vir}=10^4 \text{ K}$	TYPE Ia	9
• Photo-heating	$10^{10} M_{\odot}$	$T_{vir}=10^5 \text{ K}$	TYPE Ib	5

(Haiman & Holder 2003)

↑  
2 $\sigma$  peak  
redshifts

# What forms in these early halos?

- **STARS: FIRST GENERATION METAL FREE**
  - massive stars with harder spectra
  - boost in ionizing photon rate by a factor of  $\sim 20$
  - return to “normal” stellar pops at  $Z \gtrsim 10^{-4} Z_{\odot}$   
(Tumlinson & Shull 2001 ; Bromm, Kudritzki & Loeb 2001; Schaerer 2002)
- **SEED BLACK HOLES: PERHAPS MASSIVE ( $\sim 10^6 M_{\odot}$ )**
  - boost by  $\sim 10$  in number of ionizing photons/baryon
  - harder spectra up to hard X-rays
  - effects topology, IGM heating, H<sub>2</sub> chemistry
  - connections to quasars and remnant holes  
[especially  $z \sim 6$  super-massive BHs; also gravity waves]

(Oh; Venkatesan & Shull; Haiman, Abel & Rees; Haiman & Menou)

# Feedback Processes

- INTERNAL TO SOURCES

- UV flux unbinds gas
- supernova expels gas, sweeps up shells
- H<sub>2</sub> chemistry (positive and negative)
- metals enhance cooling
- depends strongly on IMF

- GLOBAL

- H<sub>2</sub> chemistry (positive and negative **TYPE II**)
- photo-evaporation (**TYPE II**)
- photo-heating (**TYPE Ia**)
- global dispersion of metals (pop III → pop II)
- mechanical (SN blast waves)

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}  $\epsilon$

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# First Global Feedback

Soft UV background:

this background inevitable  
and it destroys molecules

⊖

H<sub>2</sub> dissociated by 11.2-13.6 eV  
photons:



Soft X-ray background:

this background from quasars  
promotes molecule formation

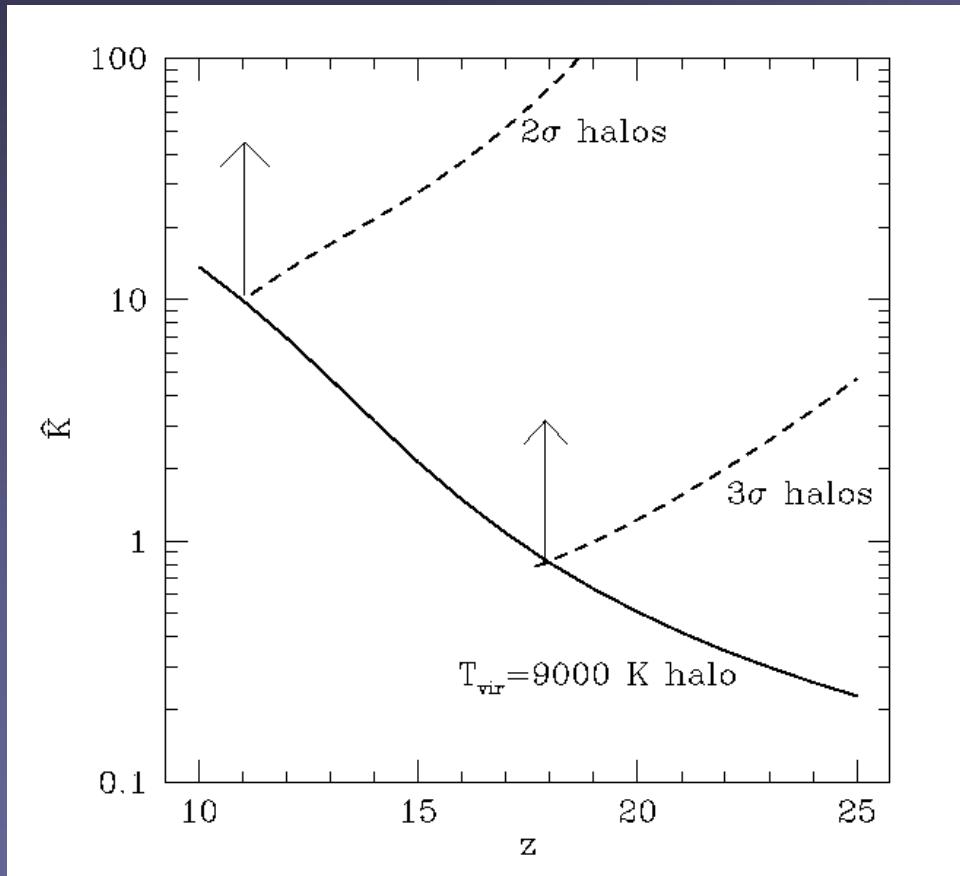
⊕

~ 1 keV photons promote  
free electrons → more H<sub>2</sub>



# Entropy Floor in Fossil HII Regions

Oh & Haiman 2003 (astro-ph/0307135)



First HII regions quickly recombine as source turns off

Fossil HII regions cool by Compton scattering to  $\sim 300 \text{ K}$

Fossil HII regions remain on high adiabat – this gas can no longer contract in Type II halos

Strongly limits importance of Type II halos for reionization

cf.: Ricotti, Gnedin & Shull (2002)

# Photo-ionization feedback at high redshift

- **Photo-ionization heating**

- suppresses gas infall into shallow (Type Ia) potential wells
- significant for low-redshift dwarf galaxies (Efstathiou 1992)
- critical circular velocity  $v(\text{circ}) \sim 50 \text{ km/s}$  (Thoul & Weinberg 1996)

- **Such a feedback would be important for reionization**

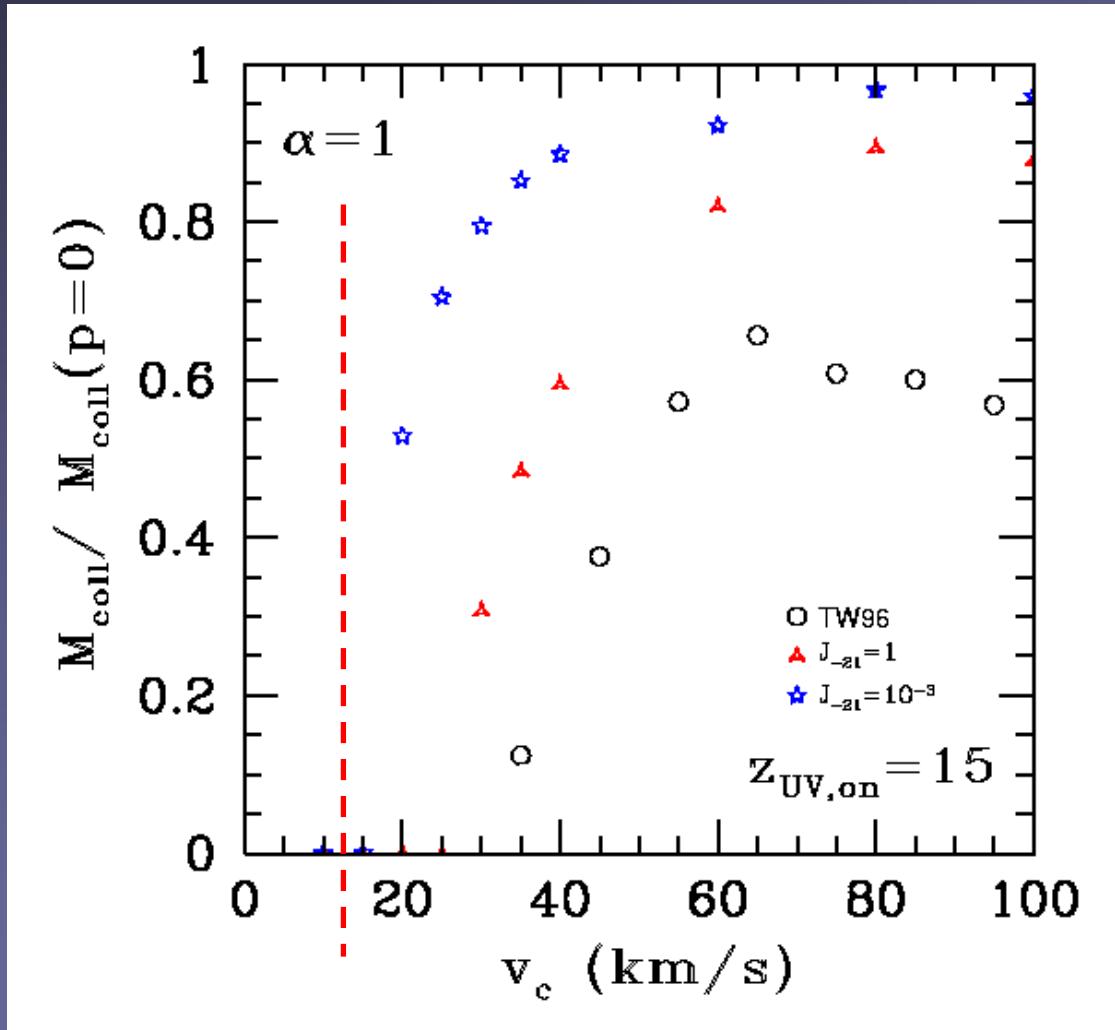
- delays percolation until  $z \sim 6-7$ , when  $\sim 50 \text{ km/s}$  halos appear
- could give natural e.s. opacity tail, increasing  $\tau$  to  $\gg 0.04$

- **However, feedback should be less important at high-z**

- shorter cooling times
- lower amplitude of background flux  $J$
- background absent until late stages of collapse
- self-shielding

# Photo-ionization feedback

(Dijkstra, Haiman, Rees & Weinberg 2003)



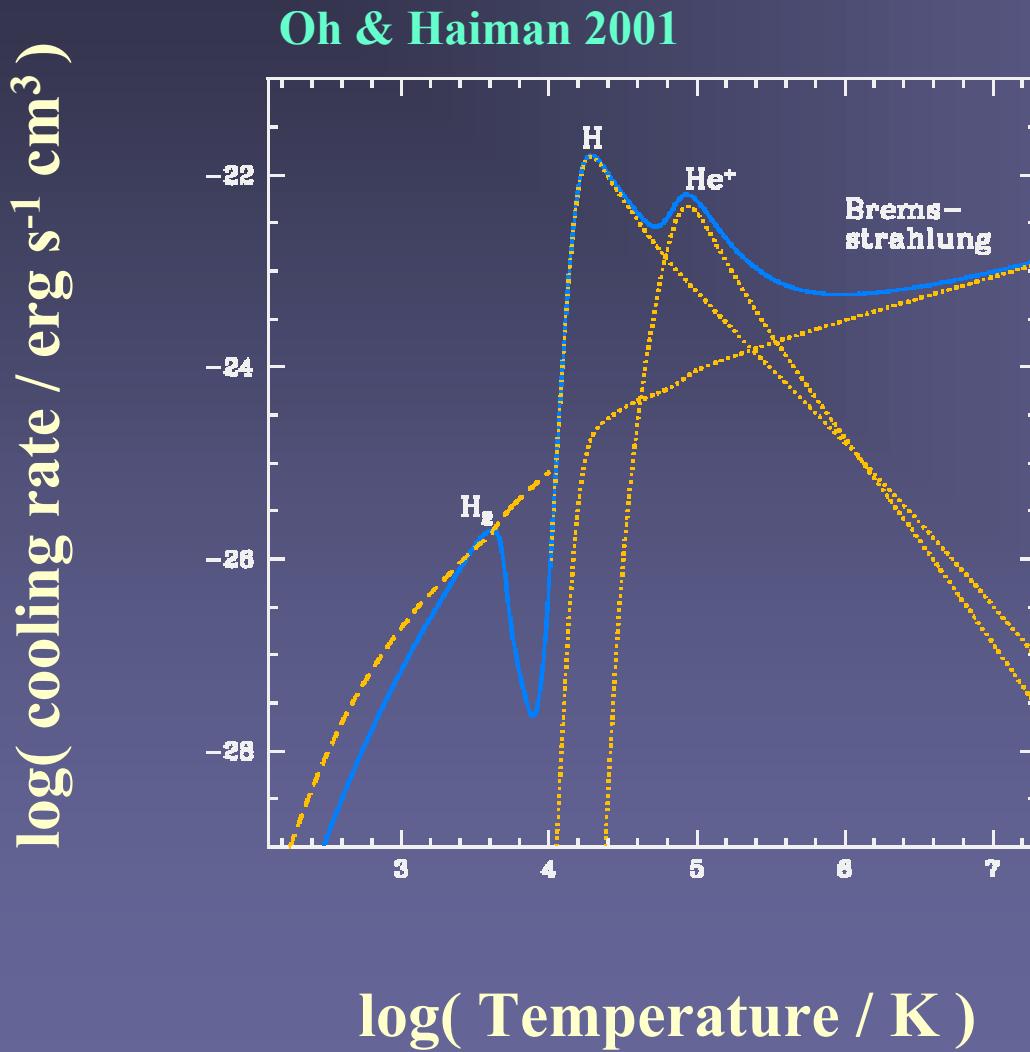
Infall suppression  
in 1-D hydro runs  
(Thoul & Weinberg 1996)

redshift  $z=2$ :  
 $V_{\text{circ}} = 50$  km/s

redshift=12:  
 $V_{\text{circ}} = 15$  km/s

Feedback largely  
eliminated at hi z

# What happens in Type I halos?



Key: gas cools faster than it recombines, leaving extra electrons

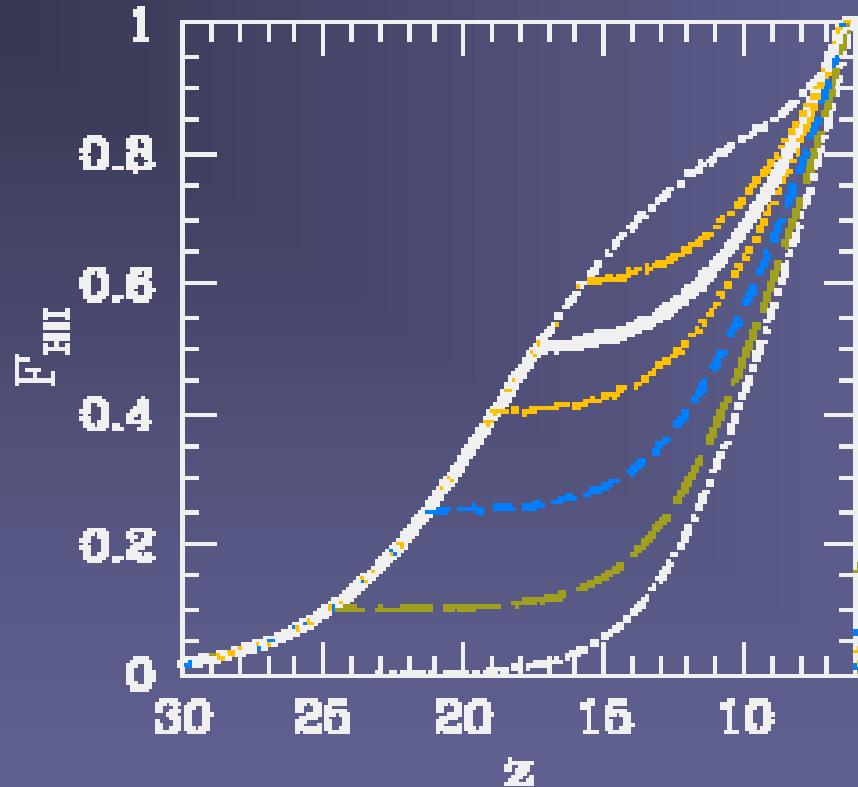
Shapiro & Kang (1987)  
Hellsten & Lin (1997)



universal ratio of  
 $n(H_2)/n(H) \sim 10^{-3}$

independent of  
density, temperature,  
background flux

# Reionization History

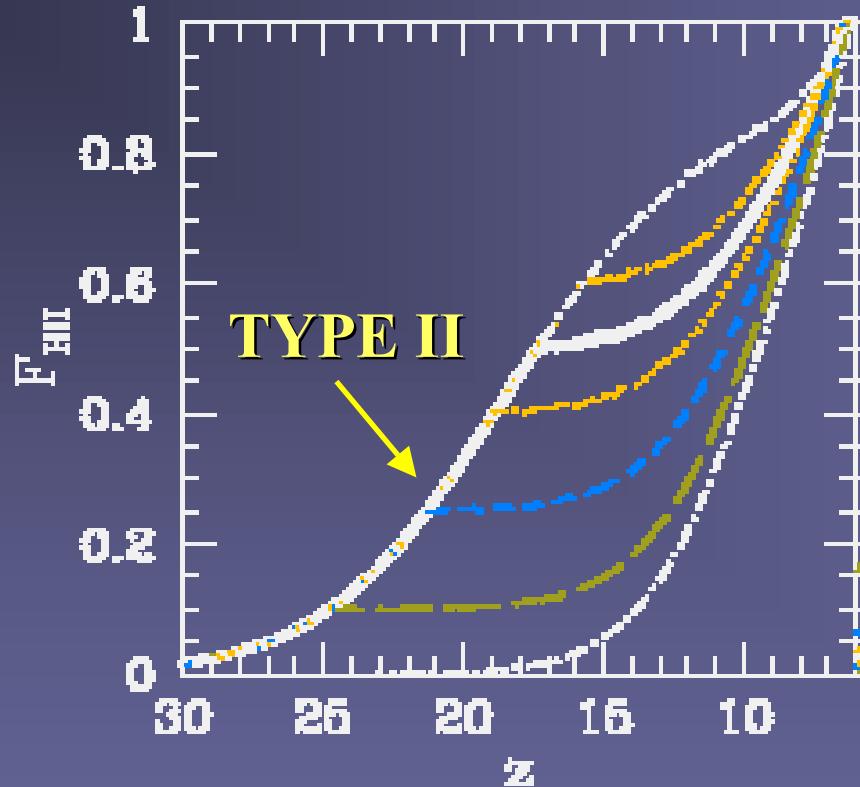


(Haiman & Holder 2003)

(Wyithe & Loeb; Ciardi et al; Somerville et al.;  
Fukugita & Kawasaki; Cen; Sokasian et al.; Chiu et al.)

N(astro-ph)~10

# Reionization History



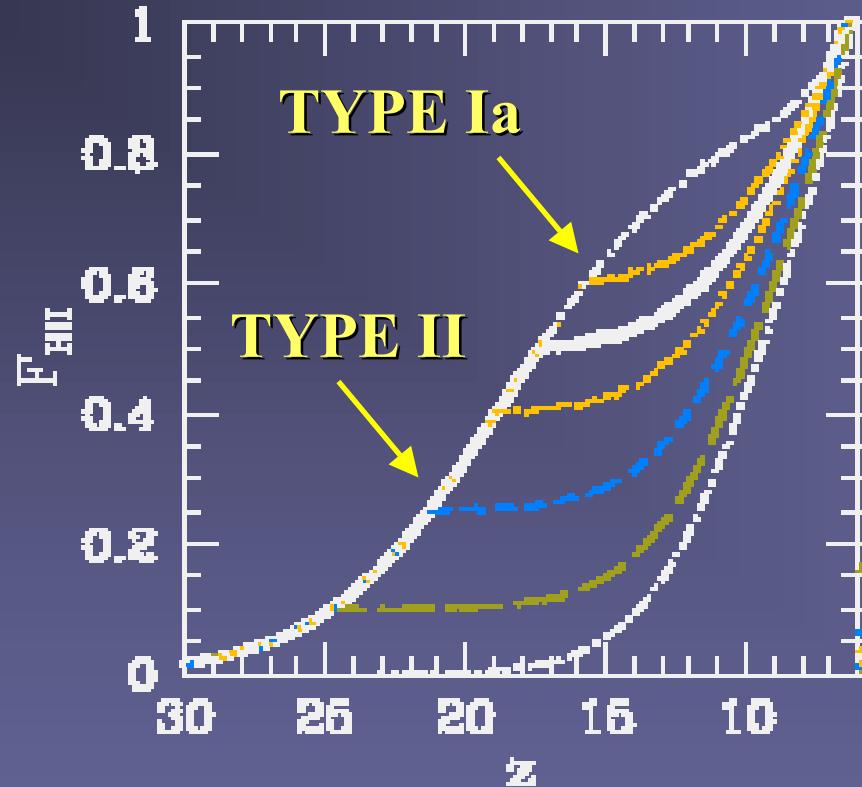
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N(astro-ph)~10

# Reionization History

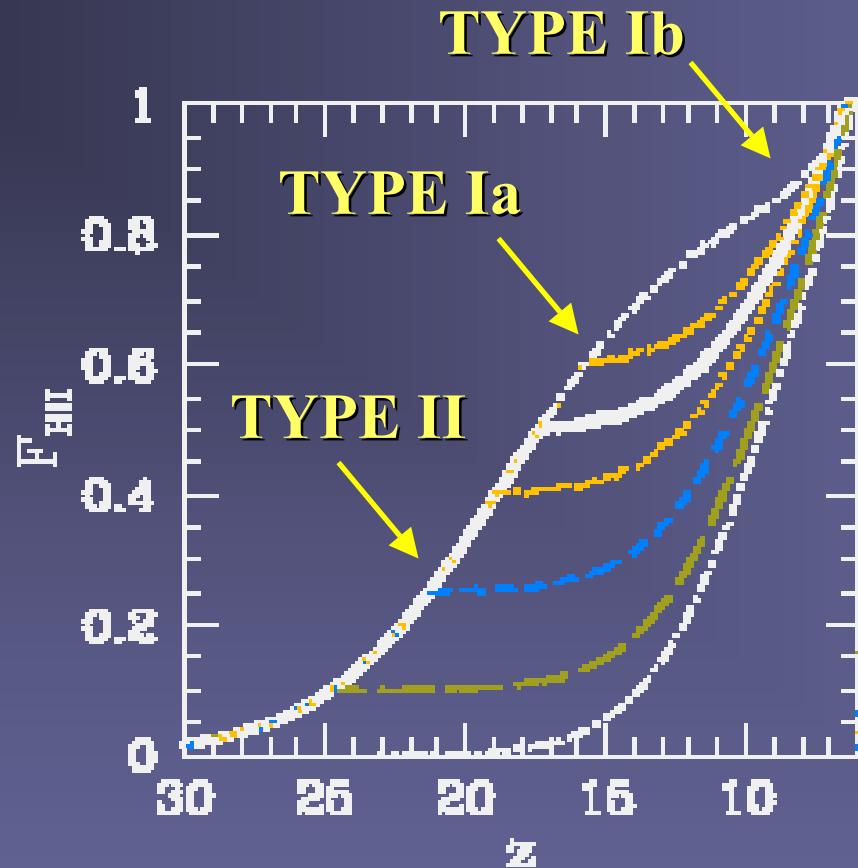


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# Reionization History



(Haiman & Holder 2003)

(Wyithe & Loeb; Ciardi et al; Somerville et al.;  
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N(astro-ph)~10

# Reionization History

- $Xe(z)$  is likely to have features arising from feedback processes.
- Are these features observable?
- How can we distinguish a neutral fraction  $\langle x_H \rangle = 1$  from  $\langle x_H \rangle = 10^{-3}$  at  $z=6$  ?

# Outline of Talk

1. Theoretical Issues of Reionization
  - what were the sources?
  - what are the key feedback processes?

# “Percolation” is occurring at $z \sim 6\text{-}7$

looking for hydrogen (HI)

- Spectra of  $z \sim 6$  quasars in SDSS

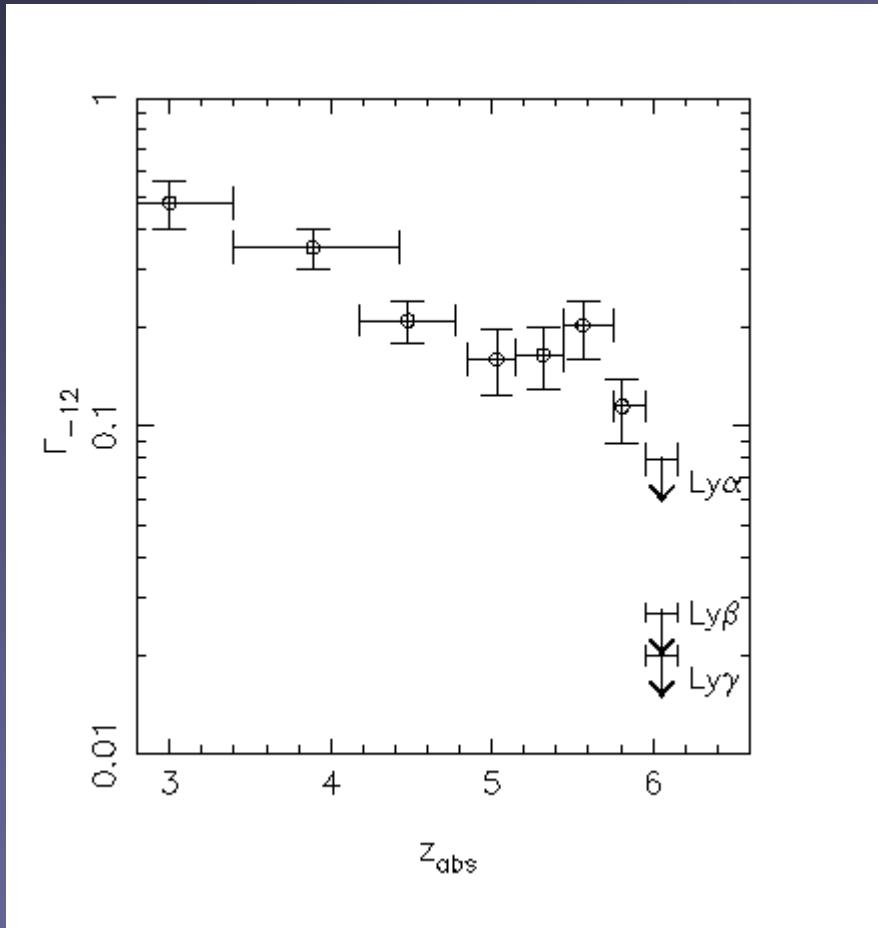
- Gunn-Peterson troughs at  $z > 6$
- Compared to HI opacity in  $5.5 \lesssim z \lesssim 6$  sources  
(Becker et al. 2001; Fan et al. 2002, Songaila & Cowie 2002)

- IGM Temperature

- IGM inferred to be warm from  $z \sim 6$  Lyman  $\alpha$  forest
- It would be too cold for single early reionization  
(Hui & Haiman 2003; Zaldarriaga et al. 1997; Theuns et al. 2002)

# Evolution of the Ionizing Background

Ionizing background ( $10^{-12} \text{ s}^{-1}$ )



redshift

Fan et al. 2002

cf.:

Lidz et al. 2002

Cen & McDonald 2002

Gnedin 2002

Songaila & Cowie 2002

# **Ly $\alpha$ emitters as a probe of reionization**

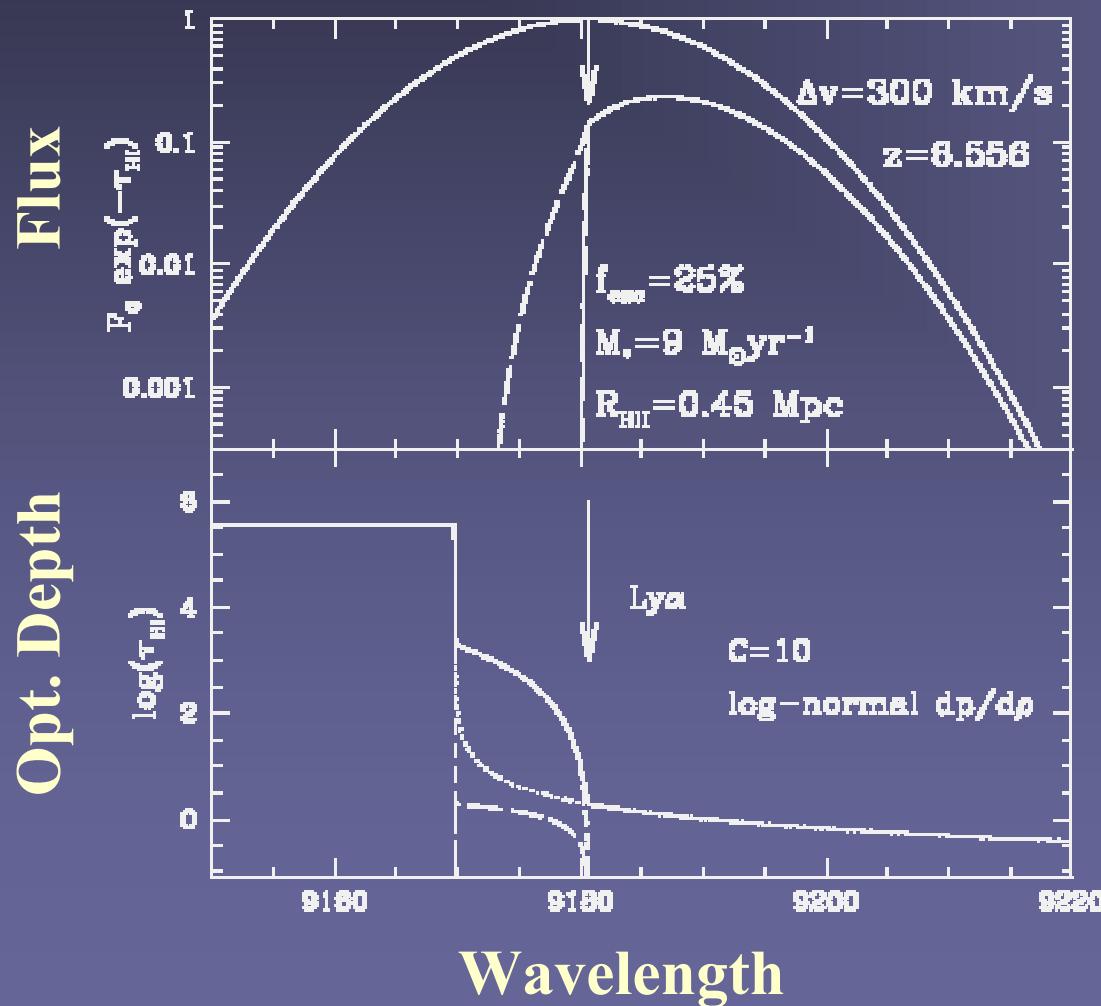
Can we distinguish  $\langle x_H \rangle = 1$  from  $\langle x_H \rangle = 10^{-3}$  ?

- Lyman  $\alpha$  emission line shape correlates with SFR.  
Lower SFR should imply: Haiman 2002; Haiman & Cen 2003  
Madau & Rees 2000; Miralda-Escude & Rees
  - Line / continuum lower
  - Line more asymmetric
  - Apparent peak shifts to red (relative to other lines)
  - Line narrower
- Luminosity function Haiman & Spaans 1999
  - develops faint-end cutoff at  $L(Ly\alpha) \sim 10^{42}$  erg s $^{-1}$
- Other characteristics (?) Haiman & Cen 2003
  - FWHM not a monotonic function of  $L(Ly\alpha)$

# Ly $\alpha$ emitters as a probe of reionization

Hu et al (2002):

Haiman 2002, ApJL



Ly alpha emitting  
Galaxy discovered  
at  $z=6.56$ :

Faint:  $SFR \sim 10 M_\odot/\text{yr}$   
(ionized region  $\sim 2 \text{ Mpc}$ )

Reionization at  $z > 6.6$ ?

Not necessarily... source  
could be embedded in  
fully neutral IGM

Statistical inferences  
should be possible for  
a large Ly $\alpha$  sample  
(Rhoads, Malhotra et al)

# Electron Footprints on the CMB

- **CMB anisotropies**

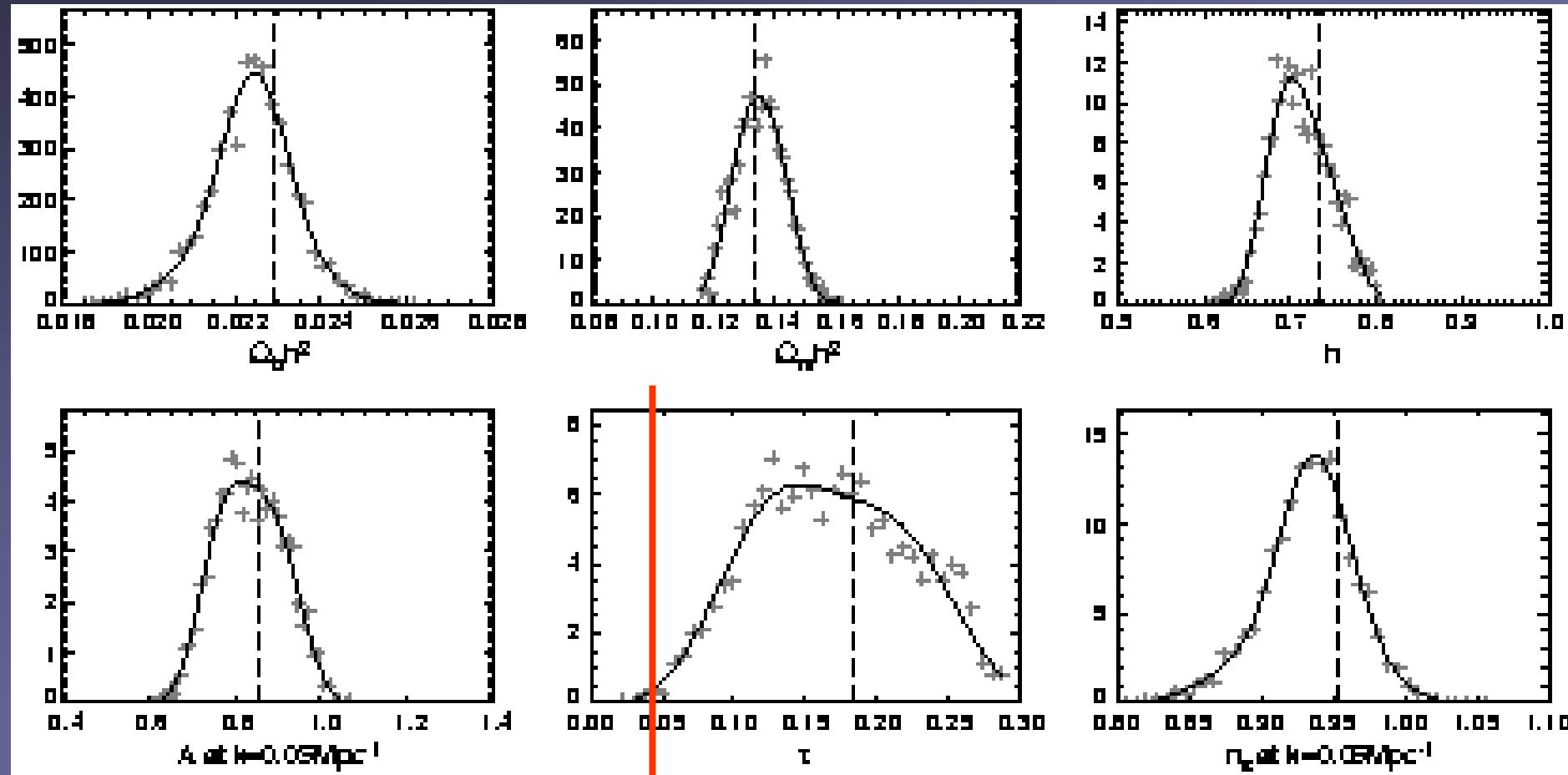
- damping of temperature anisotropy (geometrical,  $l \gtrsim 10$ ) } $\tau$
- boosts large-angle polarization anisotropy ( $l \lesssim 10$ )
- small scale SZ effects (Doppler,  $l \gtrsim 3000$ ; Santos et al. 2003) } $\tau, b$   
(energy,  $l \gtrsim 1000$ ; Oh et al. 2003)

- **Distortions of mean spectrum**

- Compton heating:  $y = 1/4 \Delta u/u \sim 10^{-5}$   
if  $10^{-4}$  of baryons in BHs, with 1% into heating
- dust scattering with  $0.3 M_\odot$  dust per SN:  $y \sim 10^{-5}$   
(Loeb & Haiman 1997)
- measurable with improved FIRAS/COBE limits  
(Fixsen & Mather 2002)

# Electron Scattering in WMAP data

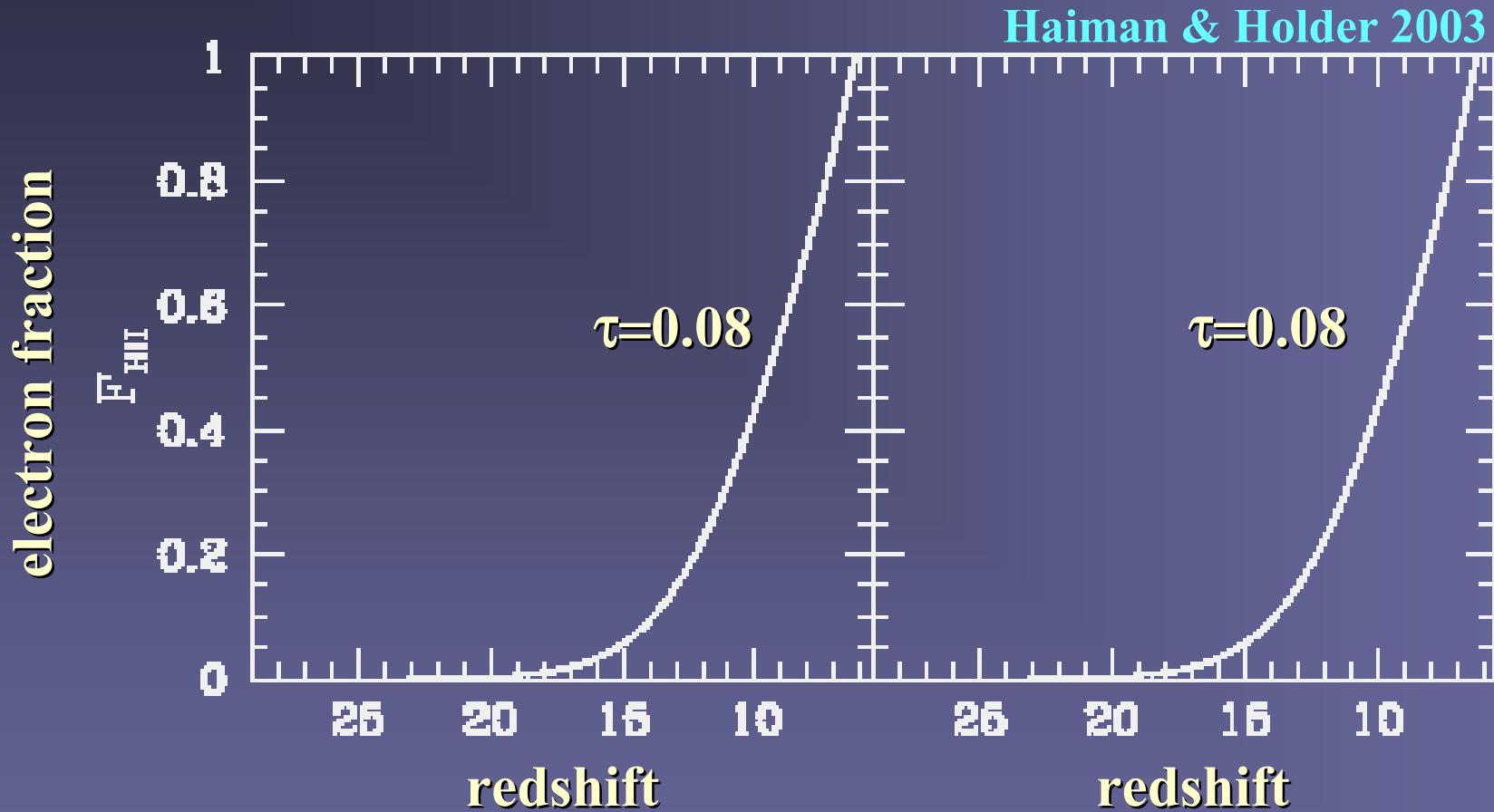
[marginalized errors from TE correlation]



(Spergel et al. 2003)

$Z(\text{reion})=6 \leftrightarrow \tau=0.04$

# Reionization History



$$N_\gamma = 4000$$

$$f^* = 20\%$$

$$f_{\text{esc}} = 10\%$$

$$C = 10$$

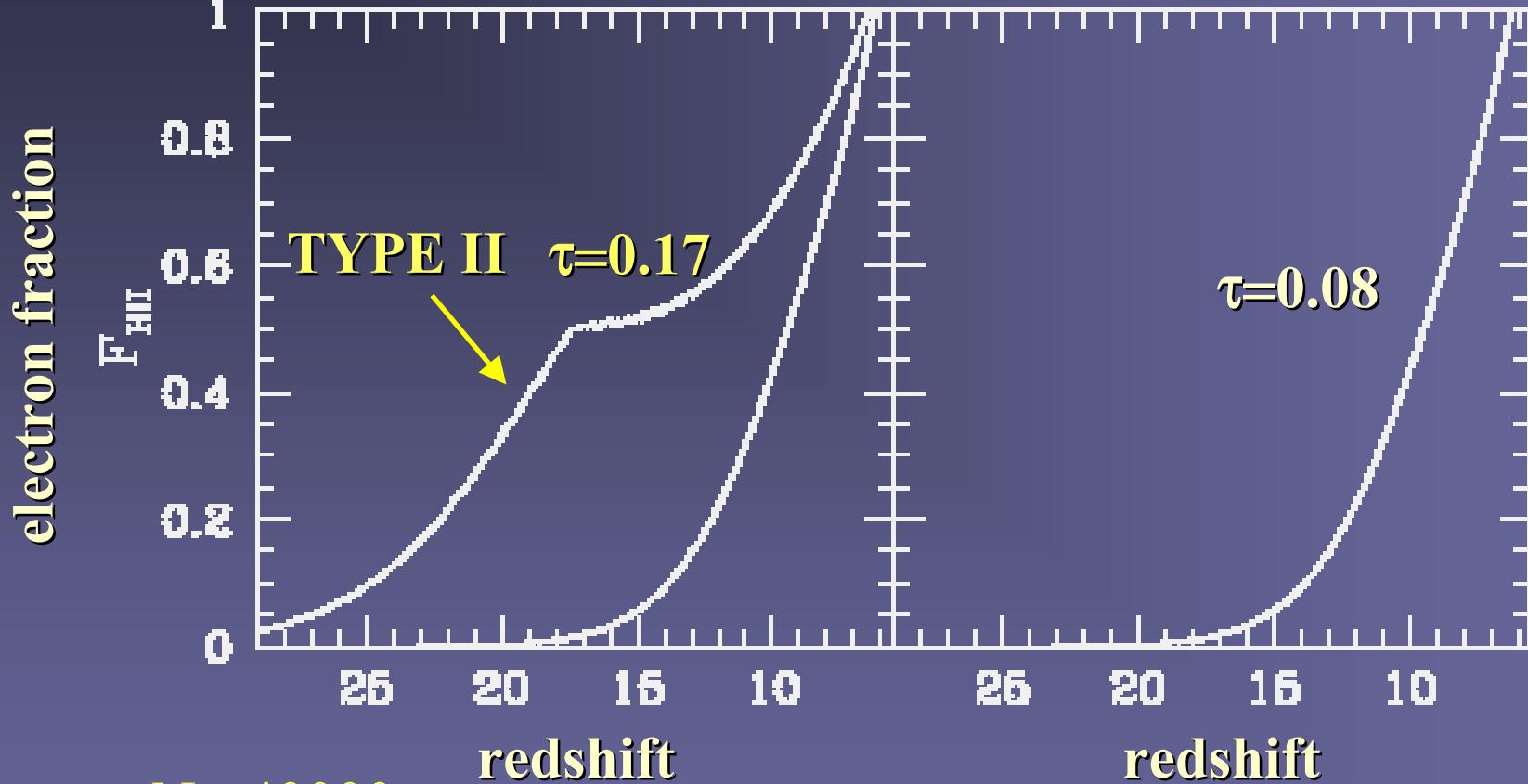


$$\varepsilon \equiv N_\gamma f^* f_{\text{esc}} / C = 8$$

Wyithe & Loeb; Ciardi et al.  
Somerville et al.; Sokasian et al.  
Fukugita & Kawasaki; Cen

# Reionization History

Haiman & Holder 2003



$$N_\gamma = 40000$$

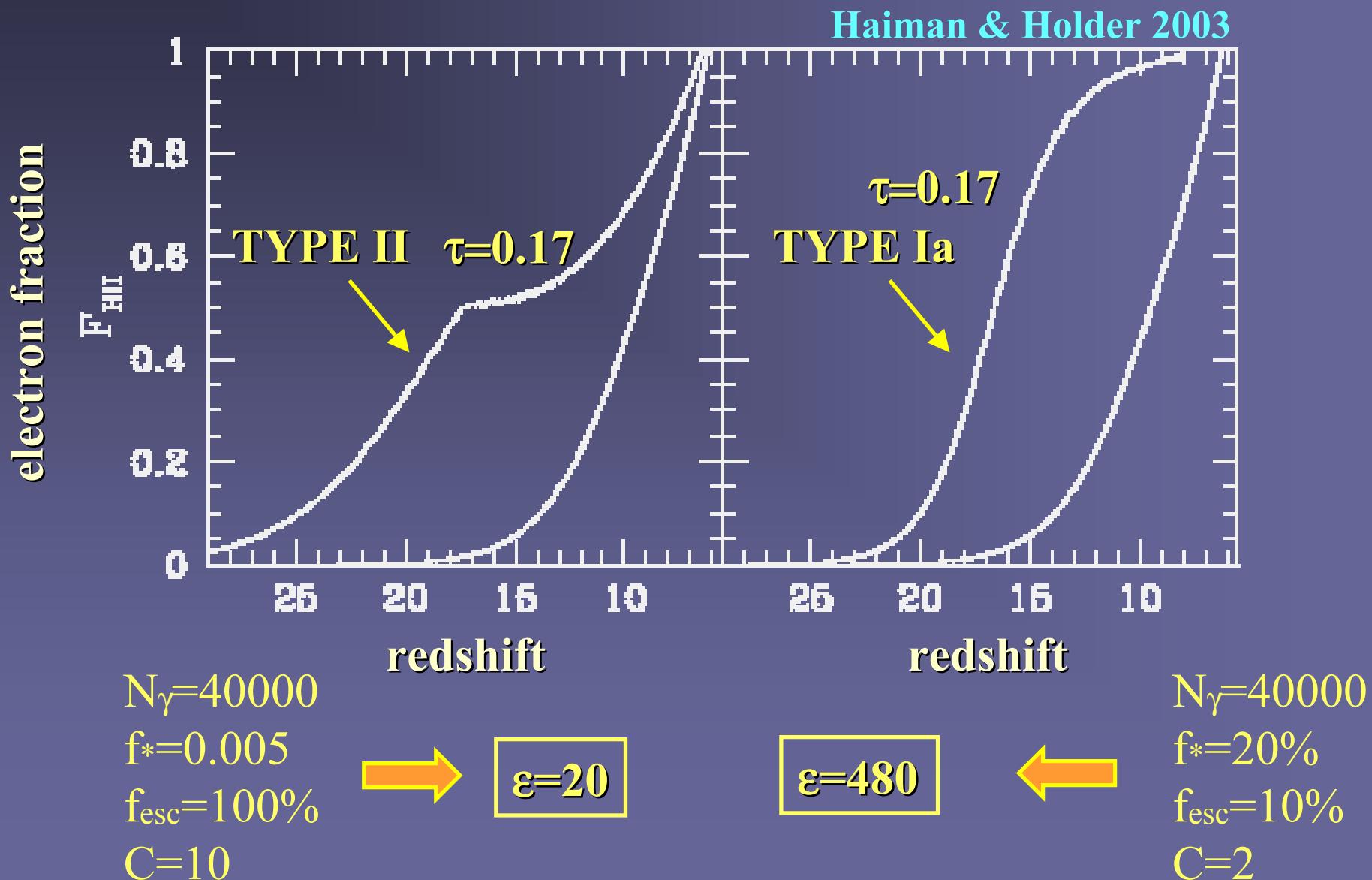
$$f_* = 0.005$$

$$f_{\text{esc}} = 100\%$$

$$C = 10$$

→  $\boxed{\varepsilon = 20}$

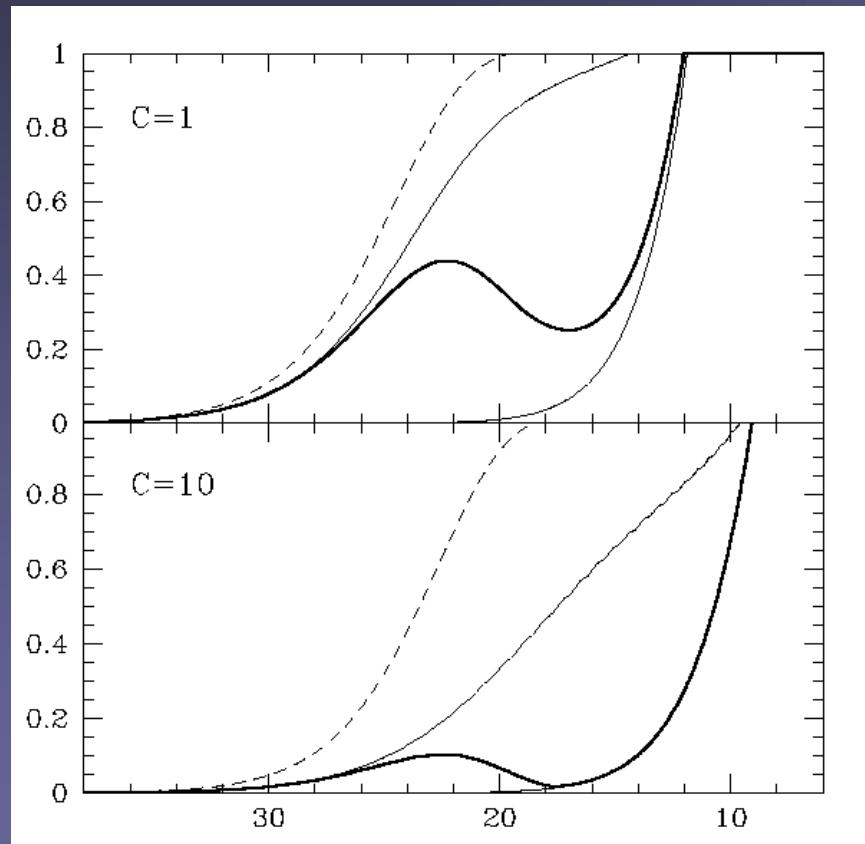
# Reionization History



# Reionization Excluding Fossil HII Regions

Oh & Haiman 2003

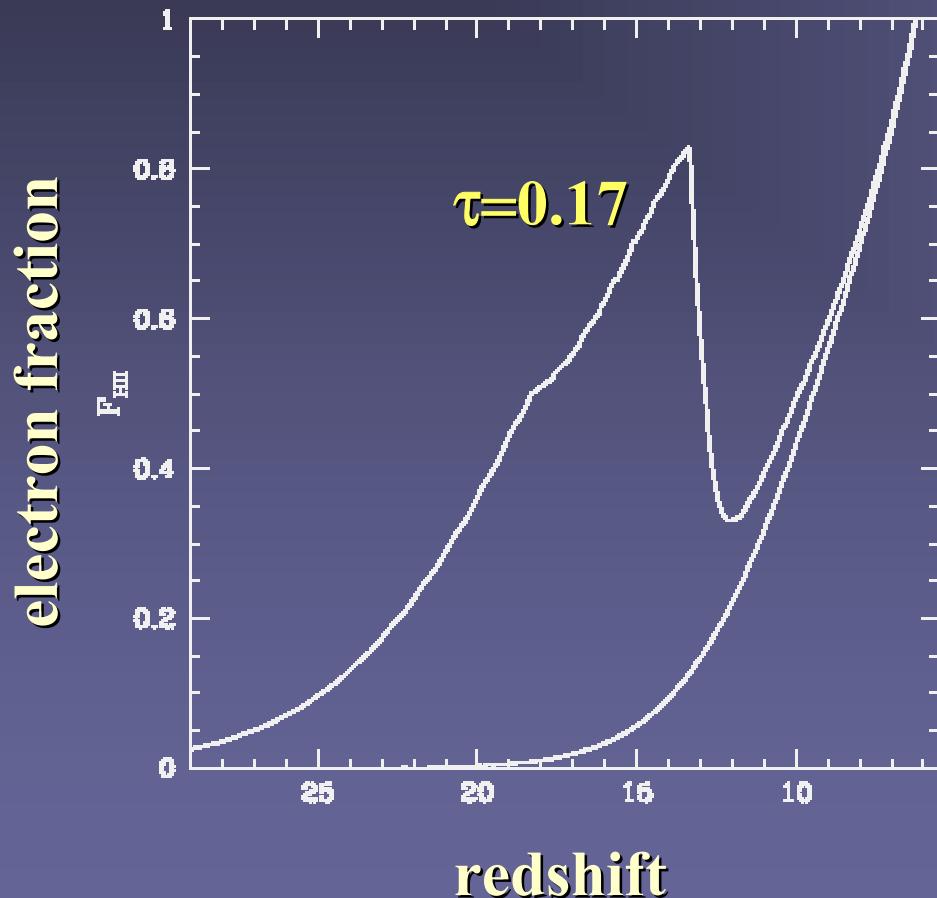
electron fraction



Contribution from Type II  
Halos  $\tau=0.07$

# Reionization History

Haiman & Holder 2003



Sudden Transition from  
a Metal Free to a Normal  
Stellar Population

Wyithe & Loeb 2002  
Cen 2002

$\varepsilon=8$  for  $z<14$

$\varepsilon=160$  for  $z>14$

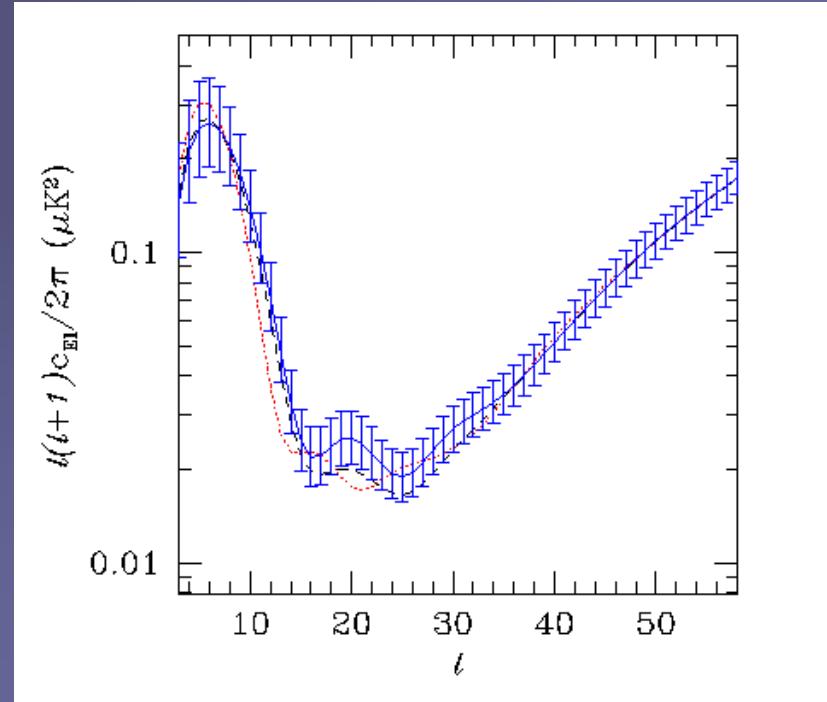
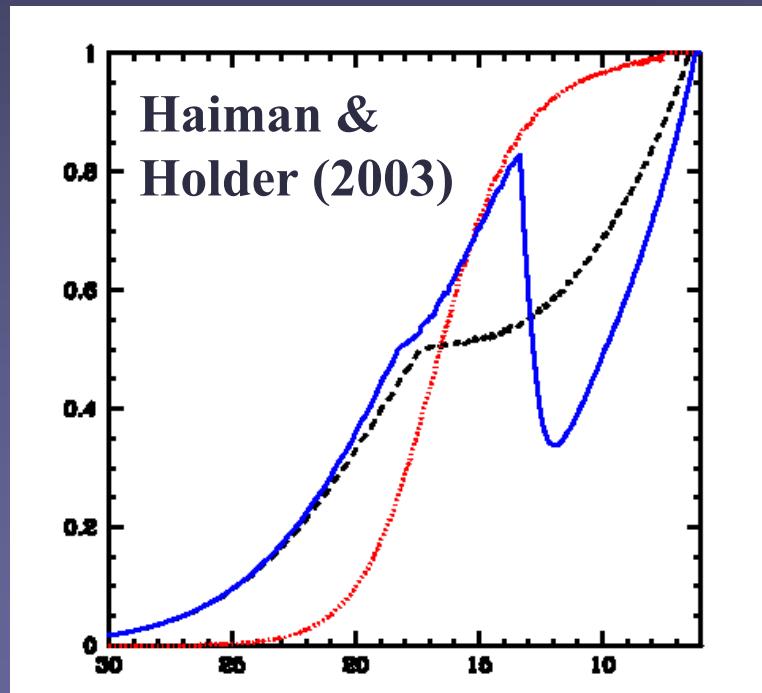
# WMAP implications

no ‘crisis’

- Complex reionization history required by WMAP + SDSS
  - significant activity at high redshift (“ $3\sigma$ ” result)  
either : metal-free stars, mini-quasars with x60 “boost” in Type Ia  
or : H<sub>2</sub> molecules form efficiently in Type II halos  
(Haiman & Holder 2003)
- Some cosmogonies can be ruled out
  - dark age = test-bed of small-scale P(k)
  - WDM ( $\sim 3?$  keV), Mixed DM (?) (Barkana, Haiman, Ostriker)
  - Running Index (requires x 50 boost and H<sub>2</sub> formation)  
or x 3000 boost (Haiman & Holder 2003)
- Future promise
  - WMAP is sensitive only to  $\tau$  (total electron column)
  - But if  $\tau \gtrsim 0.1$ , then future EE/TE can distinguish x<sub>e</sub>(z)  
(Kaplinghat et al. 2002 ; Holder et al. 2003; Santos et al. 2003)

# Future: Large Angle Polarization Spectrum

- Three reionization histories with same  $\tau=0.16$
- Different polarization power spectra; breaks  $\tau-\sigma_8$  degeneracy  
 $>4\sigma$  in cosmic variance limit,  $>3\sigma$  for Planck
- Can induce bias in  $\tau$  measurement ( $\Delta\tau$  up to  $\sim 0.01$ )

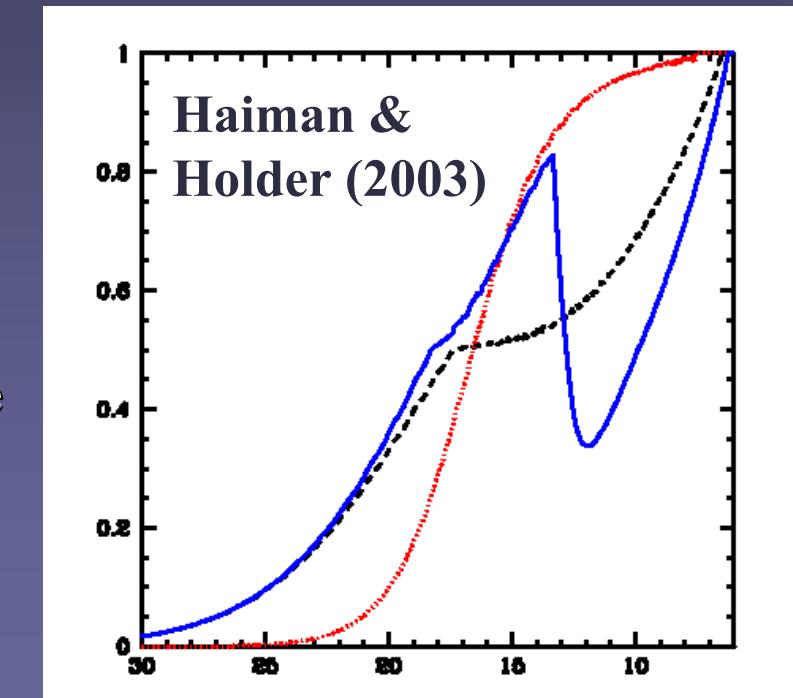


Redshift

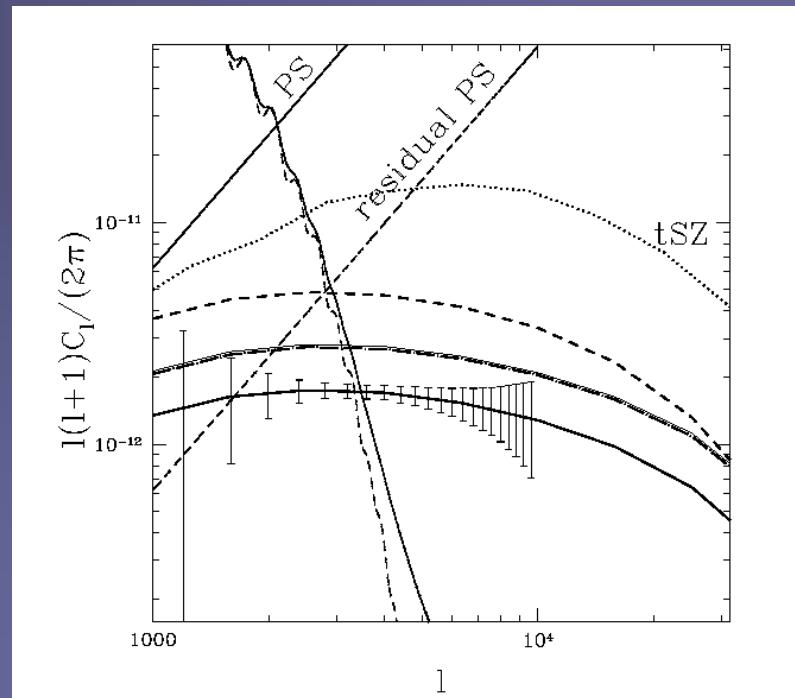
# Future: Small-Angle Temperature Spectrum

- Three reionization histories with same  $\tau=0.16$
- Patchiness (not the density fluctuations) dominates signal
- Measurable at  $10^3 \lesssim l \lesssim 10^4$  with ACT, SPT
- Provides information on effective bias (signal  $\propto \tau \times \text{bias}^2$ )

Santos et al. 2003



Redshift



$l$

# Direct Detections by JWST

[to be built by NGST]

- Continuum

- globular cluster or  $10^5 M_\odot$  mini-quasar BH to z=10
- JWST Deep Field:  $2 \times 10^8 M_\odot$  halo at z=14 (3 $\sigma$  peak)
- SNe, GRB afterglows....

- Line Emission

- Can provide information on spectral hardness
- Hydrogen Lyman and Balmer  $\alpha$  lines (Oh 1999)
- Helium lines at 1640, 4686, 3203Å  
to z=10 for  $1 M_\odot/\text{yr}$  starburst or  $10^5 M_\odot$  mini-quasar BH  
(Oh, Haiman & Rees 2001; Tumlinson & Shull 2001)

# Conclusions

1. LCDM cosmogony naturally accommodates reionization
2. Several different stages due to different source populations
3. Future CMB observations will probe reionization history
4. Ly $\alpha$  Emitters and GRBs will probe neutral hydrogen

# Alternative scenario at high redshift

- **Reionization by decaying particles**
  - light neutrinos as hot dark matter
  - decays directly into UV photons

(Sciama 1982; Adams, Sarkar & Sciama 1998)
- **Astrophysical limits**
  - Big bang nucleosynthesis, photon decoupling, SN cooling
  - CMB spectrum
  - Gamma ray background
- **Heavy sterile neutrino with  $M \sim 200$  MeV** (Hansen & Haiman 2003)
  - minimal extension of the standard model
  - interacts with one of the active neutrinos
  - c.f. light sterile neutrino (WDM,  $M \sim 1$  keV)

# Decay of Heavy Sterile Neutrinos

- Dominant decay channel for  $140 < M_\nu < 500$  MeV:

$$\nu_s \rightarrow e^- + \pi_+$$

- Relativistic decay electrons have:

mass  $M_e = (M_\nu - 1)/2$  or  $0 < M_e < 180$  MeV

decay time  $\tau \sim 3 \times 10^8$  yr /  $[M_{e\pi} (M_{e\pi}^2 - 1) (\sin^2 \theta / 10^{-25})]$

abundance  $n_s / n_H \sim 10^{-6} M_{e\pi} (\sin^2 \theta / 10^{-25})$

- As a result, we need:

small ( $\sim 10^{-25}$ ) mixing angle

many ( $\sim 10^6$ ) ionizations per relativistic electron

# Fate of ~100 MeV electron at z=20

- Inverse Compton scattering with CMB photons

$$\tau_{\text{cool}} \sim 6 \times 10^4 \text{ yr} \quad (M_e/100 \text{ MeV})^{-1} \quad [(1+z)/21]^{-4}$$

- CMB photons up-scattered to high energies:

$$13.6 \text{ eV} < E_\gamma < 900 \text{ eV} \quad [(1+z)/21]^{-4} \quad \text{for}$$

$$20 \quad [(1+z)/21]^{-1/2} \text{ eV} < M_e < 180 \text{ MeV}$$

- Newly established (UV-X-ray) background

direct photo-ionization (UV) or  
collisional ionization by  $\sim$  keV photoelectrons

- Effects on CMB spectrum: just below ( $\mu+y$ ) detectability

**Le Fin**