How Will We Determine The Reionization History of the Universe?

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What were the sources of reionization?

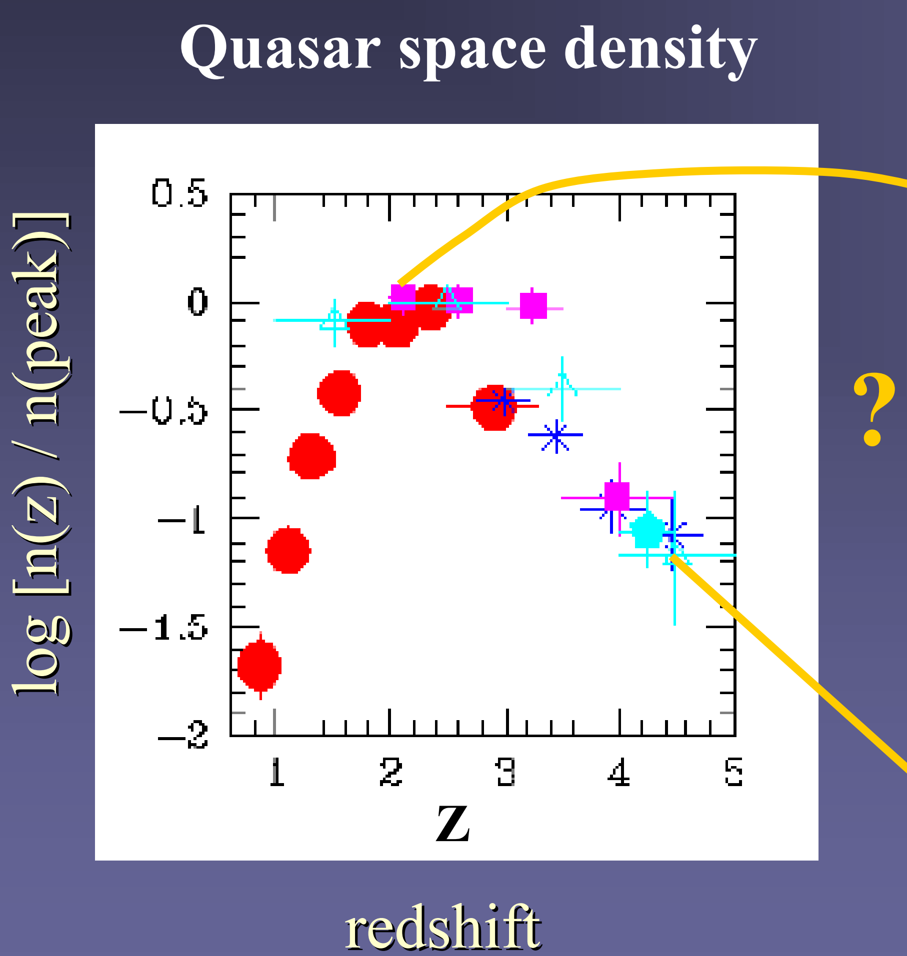
- **Not a stringent energetic requirement**
  - 13.6 eV (chemical) vs >MeV (nuclear or gravitational)

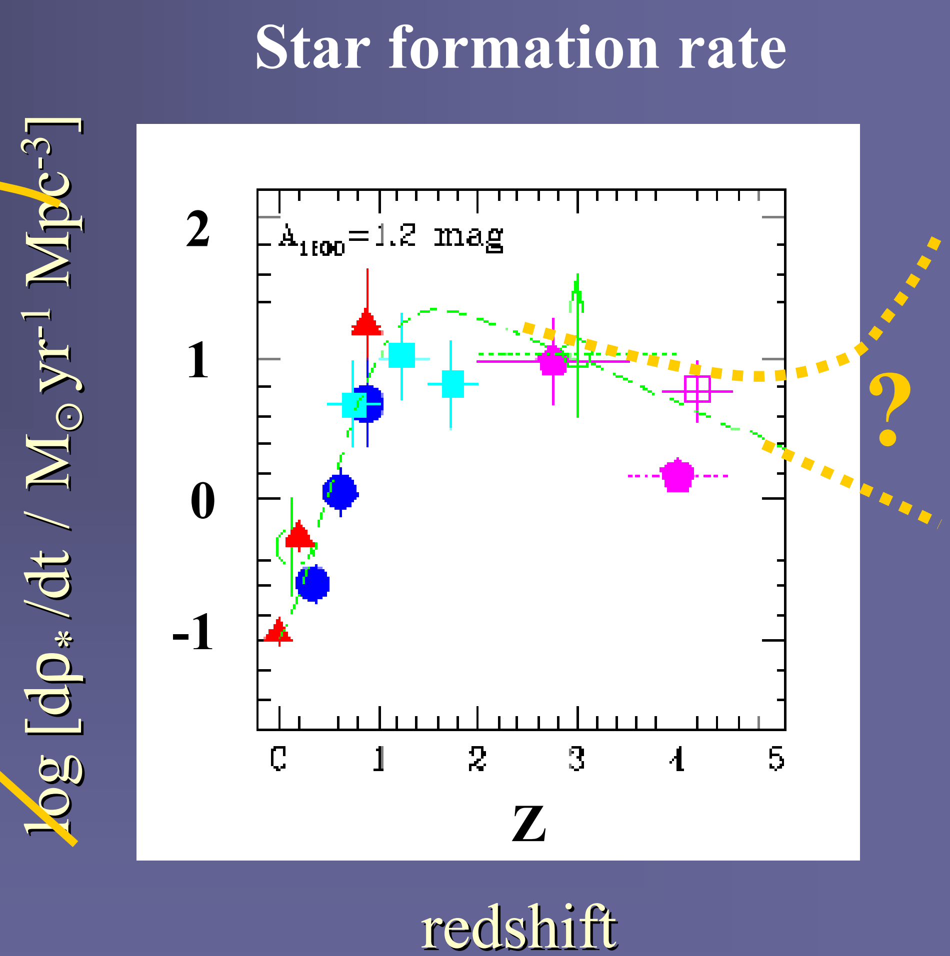
- **Non-linear structures are present early in most cosmologies**(*)
  - 2-3σ peaks above Jeans scale collapse at z=20-30

- **Photo-ionization natural candidate**
  - consistent with Lyman α forest at lower z
  - stars vs quasars
  - something more exotic - decaying particles with suitable τ, m

(*) **Interesting exceptions**

Extra Stars or Quasars are Needed





(Haiman, Abel & Madau 2001)

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 K	x	20
• H_2 cooling	$10^5\ M_\odot$	$T_{vir}=10^2$ K	TYPE II	17
• HI cooling	$10^8\ M_\odot$	$T_{vir}=10^4$ K	TYPE Ia	9
• Photo-heating	$10^{10}\ M_\odot$	$T_{vir}=10^5$ K	TYPE Ib	5

(Haiman & Holder 2003)

2σ 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 ~ 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 ~10 in number of ionizing photons/baryon
  - harder spectra up to hard X-rays
  - effects topology, IGM heating, H_2 chemistry
  - connections to quasars and remnant holes

    [especially z~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_2 chemistry (positive and negative)
  - metals enhance cooling
  - depends strongly on IMF

- **GLOBAL**
  - H_2 chemistry (positive and negative **TYPE II**)
  - photo-evaporation (**TYPE II**)
  - photo-heating (**TYPE Ia**)
  - global dispersion of metals (pop III $\rightarrow$ pop II)
  - mechanical (SN blast waves)

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First Global Feedback

Soft UV background:

this background inevitable and it destroys molecules

⊖

H_2 dissociated by 11.2-13.6 eV photons:

$$H_2+\gamma \rightarrow H_2^{(*)} \rightarrow H+H+\gamma'$$

Soft X-ray background:

this background from quasars promotes molecule formation

⊕

~ 1 keV photons promote free electrons → more H_2

$$H+\gamma \rightarrow H^{+}+\underline{e^{-}}+\gamma'$$

↓

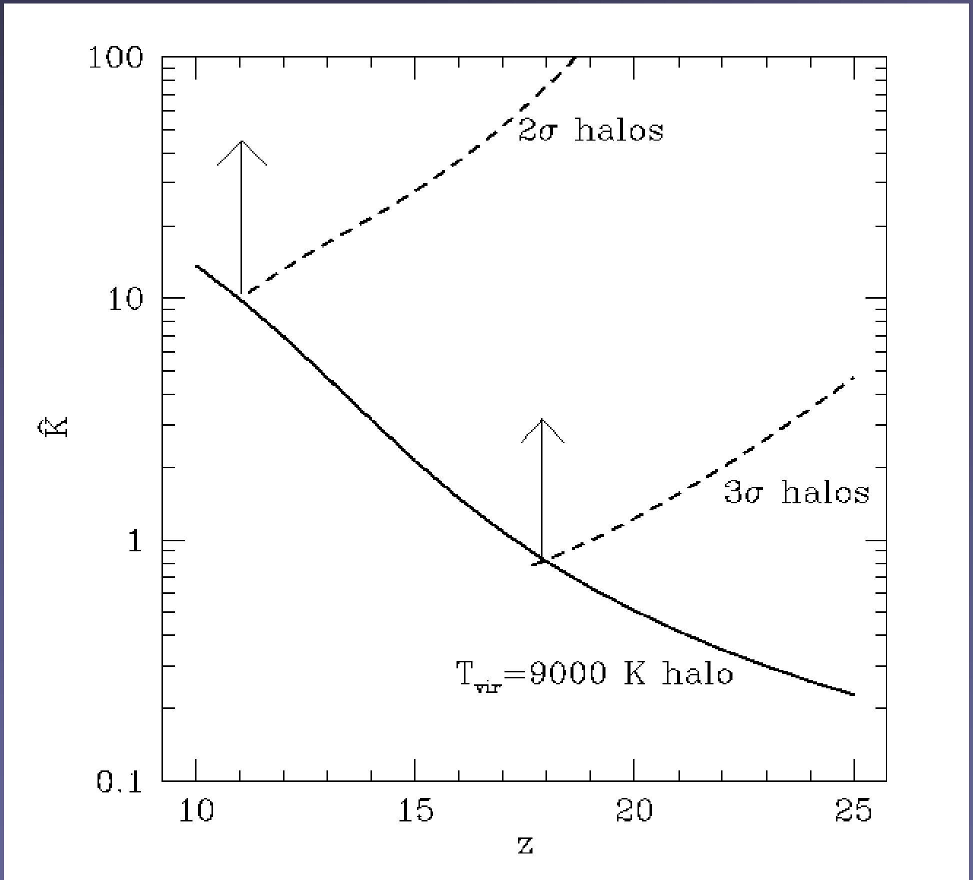
$$H + \underline{e^{-}} \rightarrow H^{-} + \gamma$$

$$H^{-} + H \rightarrow H_2 + e^{-}$$

Haiman, Abel & Rees (2000)

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 ~300 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

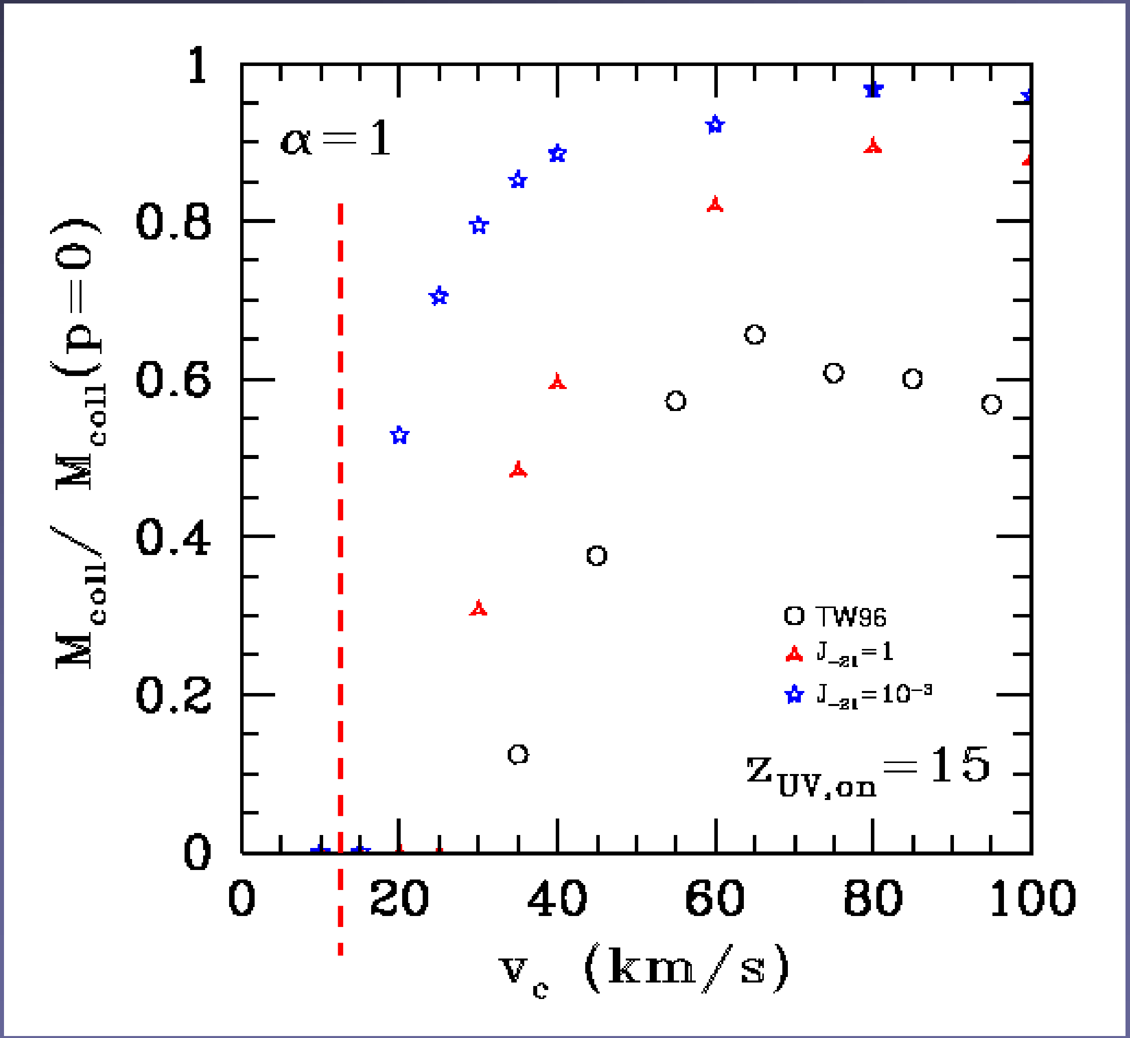
- **Photo-ionization heating**
  - suppresses gas infall into shallow (Type Ia) potential wells
  - significant for low-redshift dwarf galaxies (Efstathiou 1992)
  - critical circular velocity v(circ) ~ 50 km/s (Thoul & Weinberg1996)

- **Such a feedback would be important for reionization**
  - delays percolation until z~6-7, when ~ 50 km/s halos appear
  - could give natural e.s. opacity tail, increasing τ to » 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)

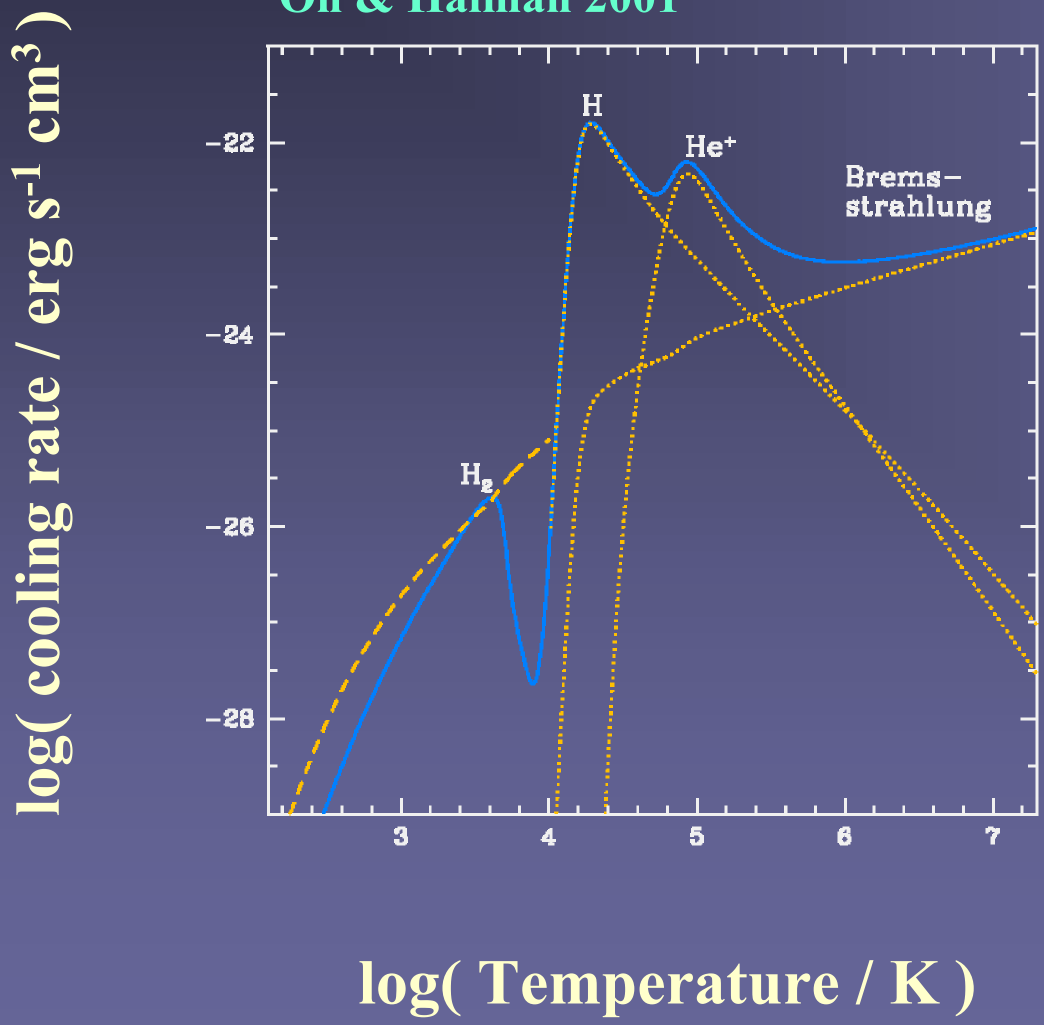
redshift z=2:
Vcirc = 50 km/s

redshift=12:
Vcirc = 15 km/s

Feedback largely eliminated at hi z

What happens in Type I halos?

Oh & Haiman 2001



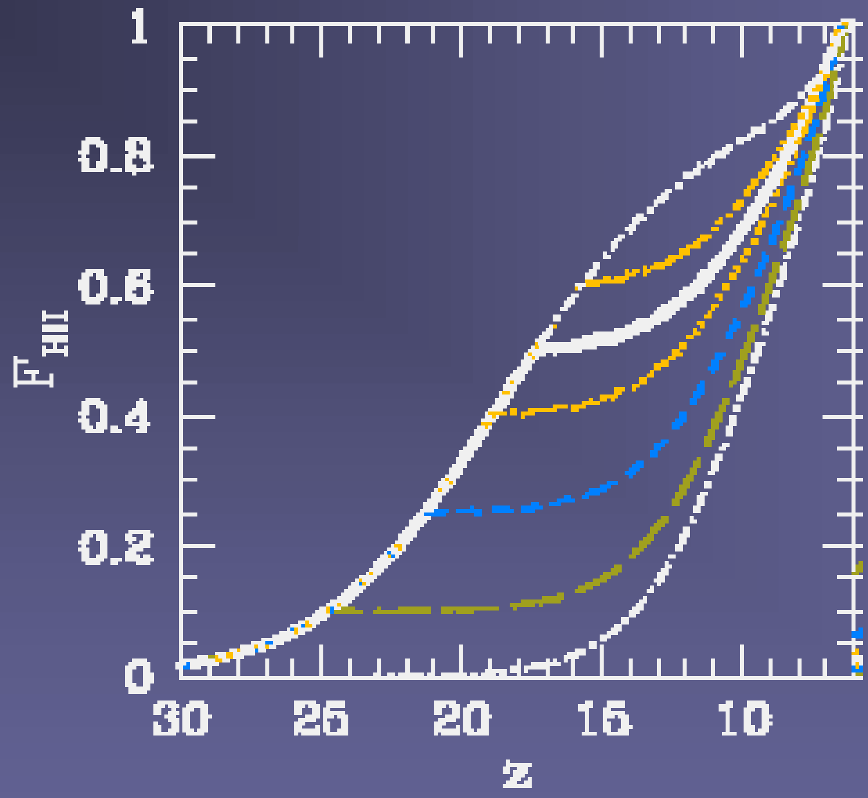
Key: gas cools faster than it recombines, leaving extra electrons

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

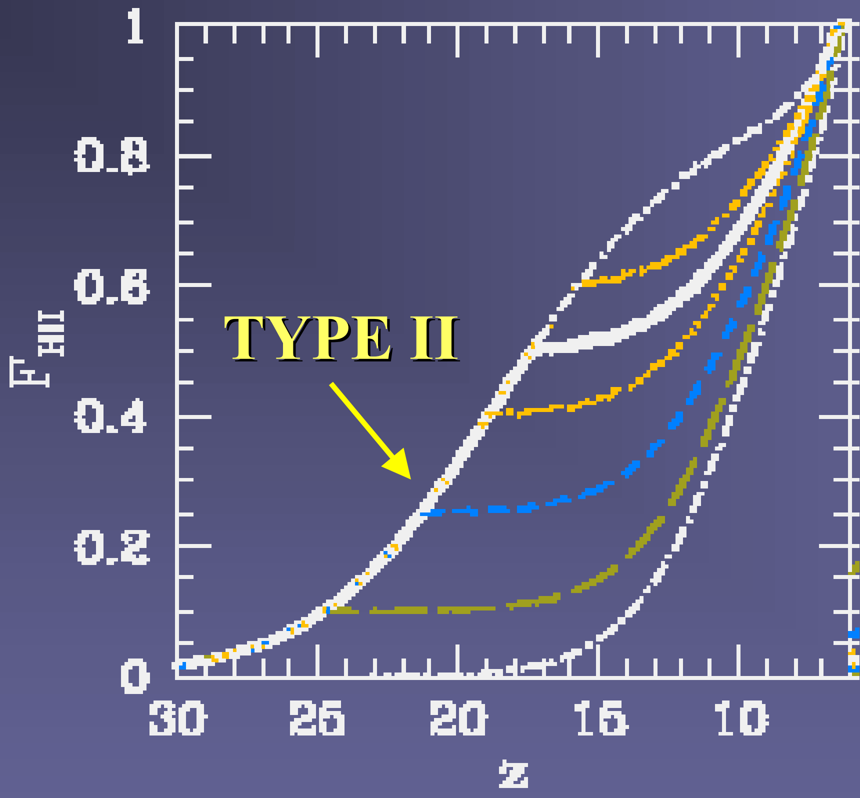


(Haiman & Holder 2003)

(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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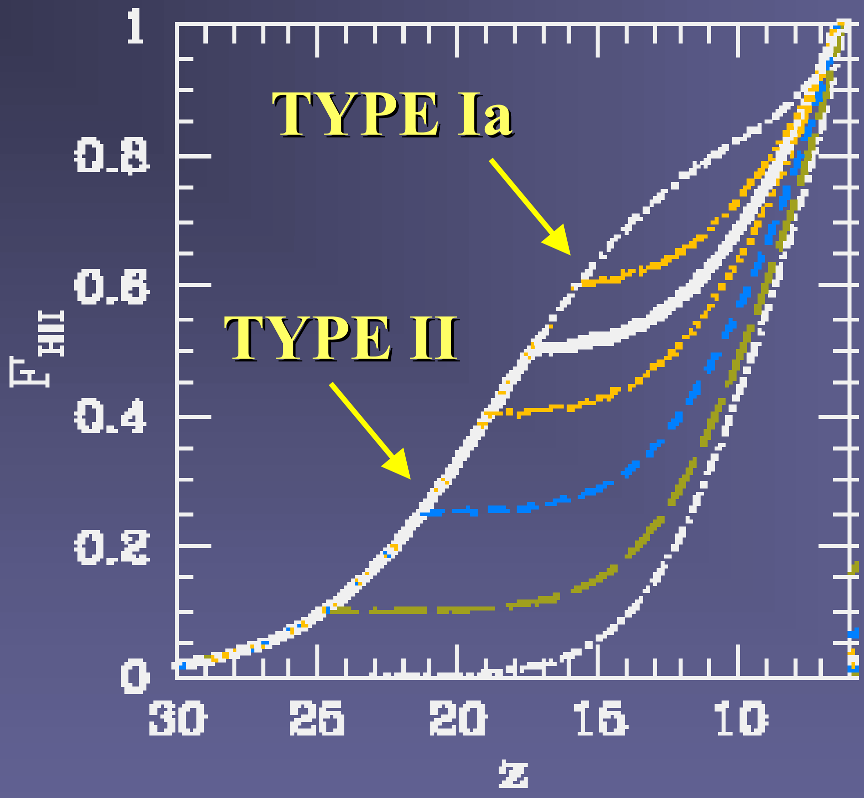

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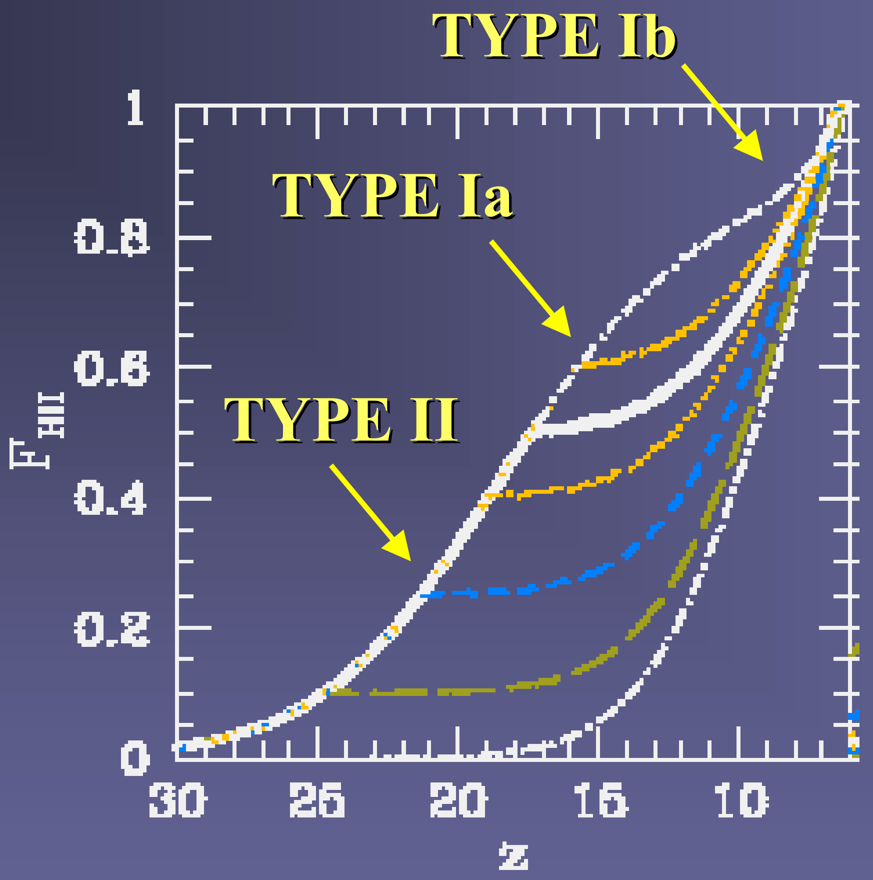

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Reionization History

- 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 ?

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“Percolation” is occurring at z~6-7

looking for hydrogen (HI)

- **Spectra of z~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)

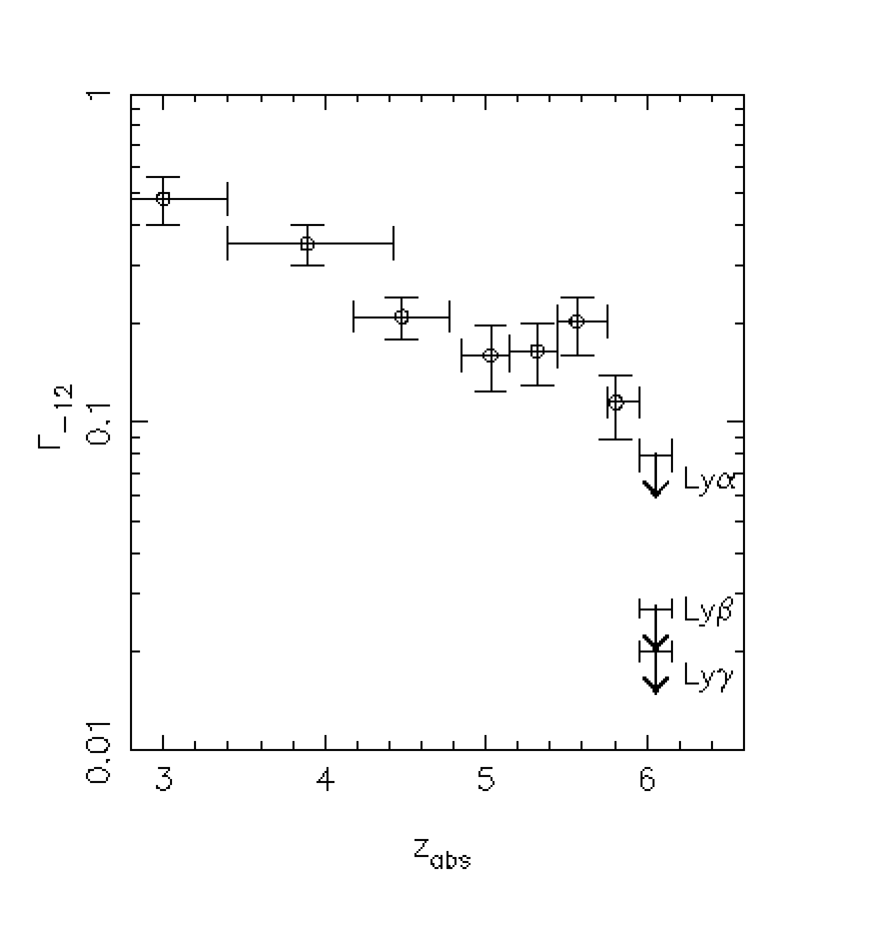
- **IGM Temperature**

  - IGM inferred to be warm from z~6 Lyman α 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} s^{-1})



redshift

Fan et al. 2002

cf.:

Lidz et al. 2002

Cen & McDonald 2002

Gnedin 2002

Songaila & Cowie 2002

Lyα emitters as a probe of reionization

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

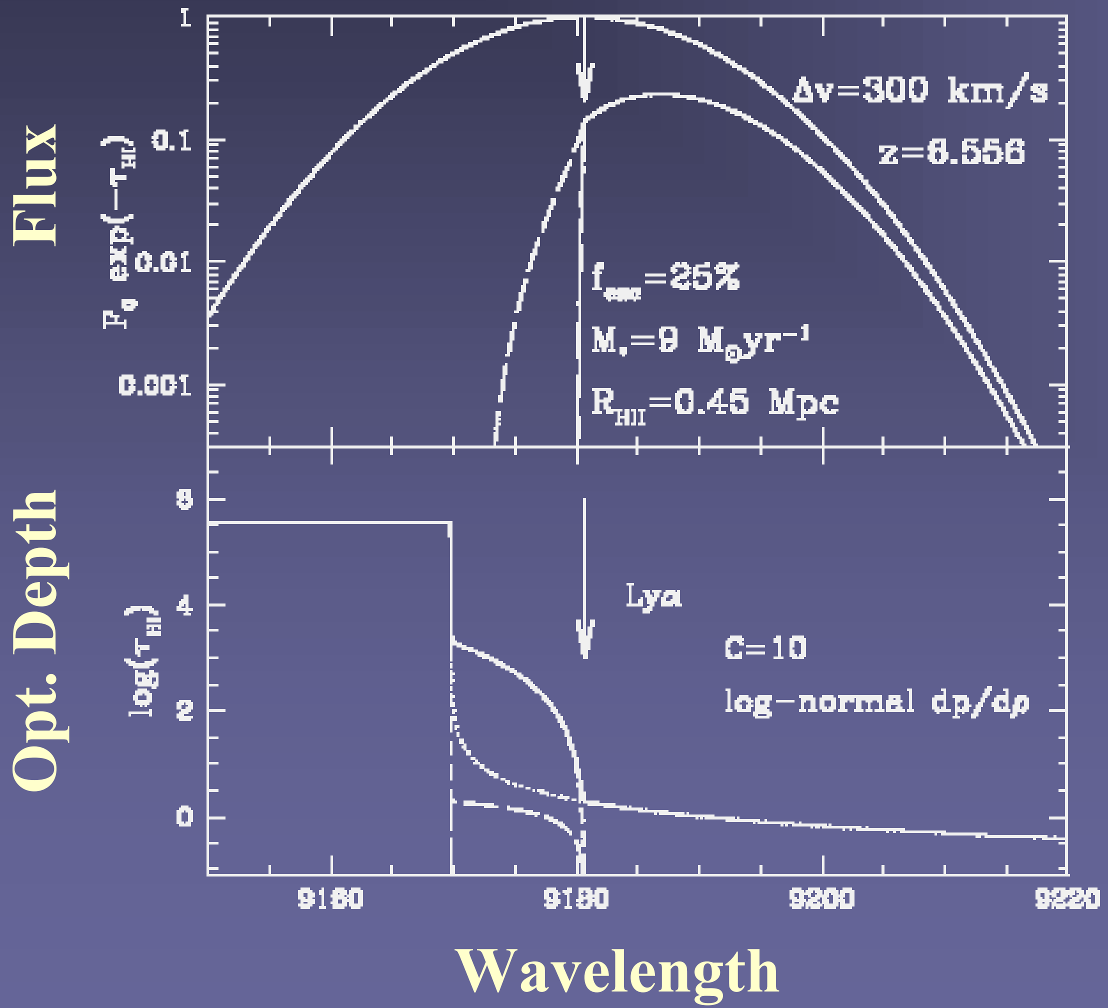
- **Lyman α emission line shape correlates with SFR.**
  Lower SFR should imply: Haiman 2002; Haiman & Cen 2003
  Madau & Rees 2000; Miralda-Escude & Rees
  - Line / continuum lower
  - Line more asymmetric
  - Apparent peak shifts to red (relative to other lines)
  - Line narrower

- **Luminosity function** Haiman & Spaans 1999
  - develops faint-end cutoff at $L(\mathrm{Ly}\alpha) \sim 10^{42}$ erg s^{-1}

- **Other characteristics (?)** Haiman & Cen 2003
  - FWHM not a monotonic function of $L(\mathrm{Ly}\alpha)$

Lyα emitters as a probe of reionization

Haiman 2002, ApJL



Hu et al (2002):

Ly alpha emitting
Galaxy discovered
at z=6.56:
Faint: SFR ~ 10 $M_\odot$/yr
(ionized region ~2 Mpc)

Reionization at z>6.6?

Not necessarily…source could be embedded in fully neutral IGM

Statistical inferences should be possible for a large Lyα sample (Rhoads, Malhotra et al)

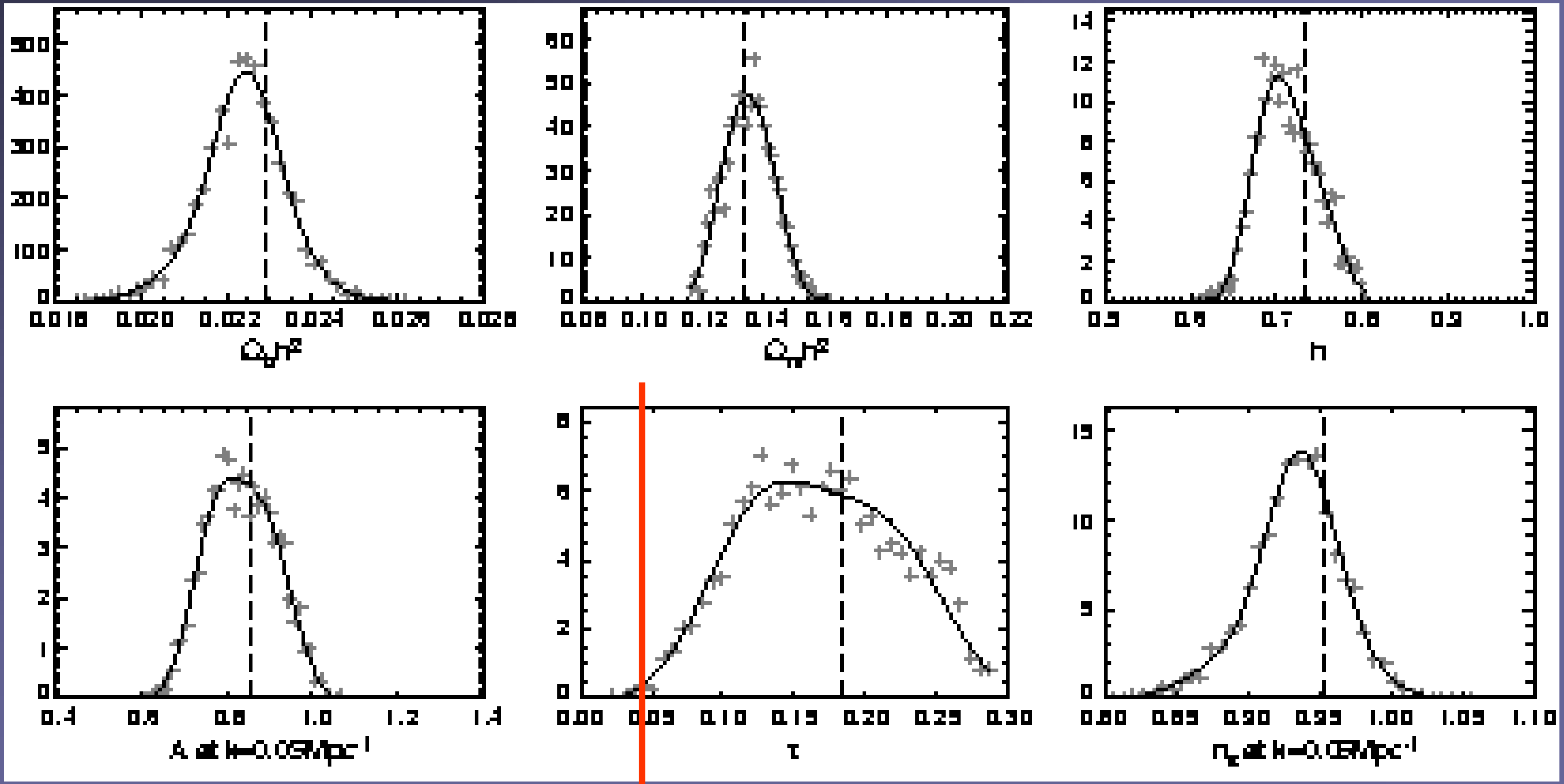
Electron Footprints on the CMB

- **CMB anisotropies**
  - damping of temperature anisotropy (geometrical, $l \gtrsim 10$) } τ
  - boosts large-angle polarization anisotropy ($l \lesssim 10$)
  - small scale SZ effects (Doppler, $l \gtrsim 3000$; Santos et al. 2003) } τ, 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

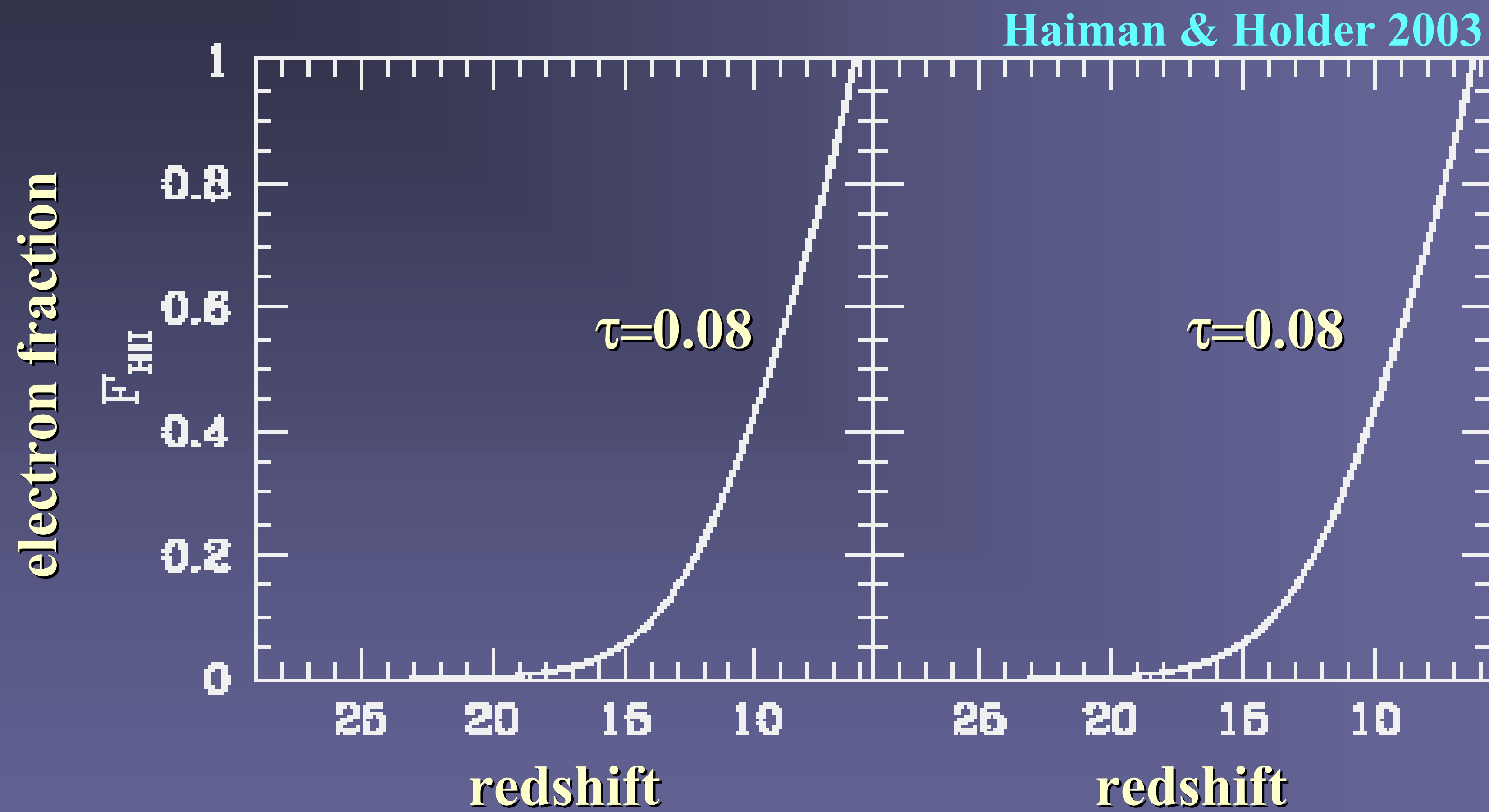
[marginalized errors from TE correlation]



(Spergel et al. 2003)

Z(reion)=6 ↔ τ=0.04

Reionization History



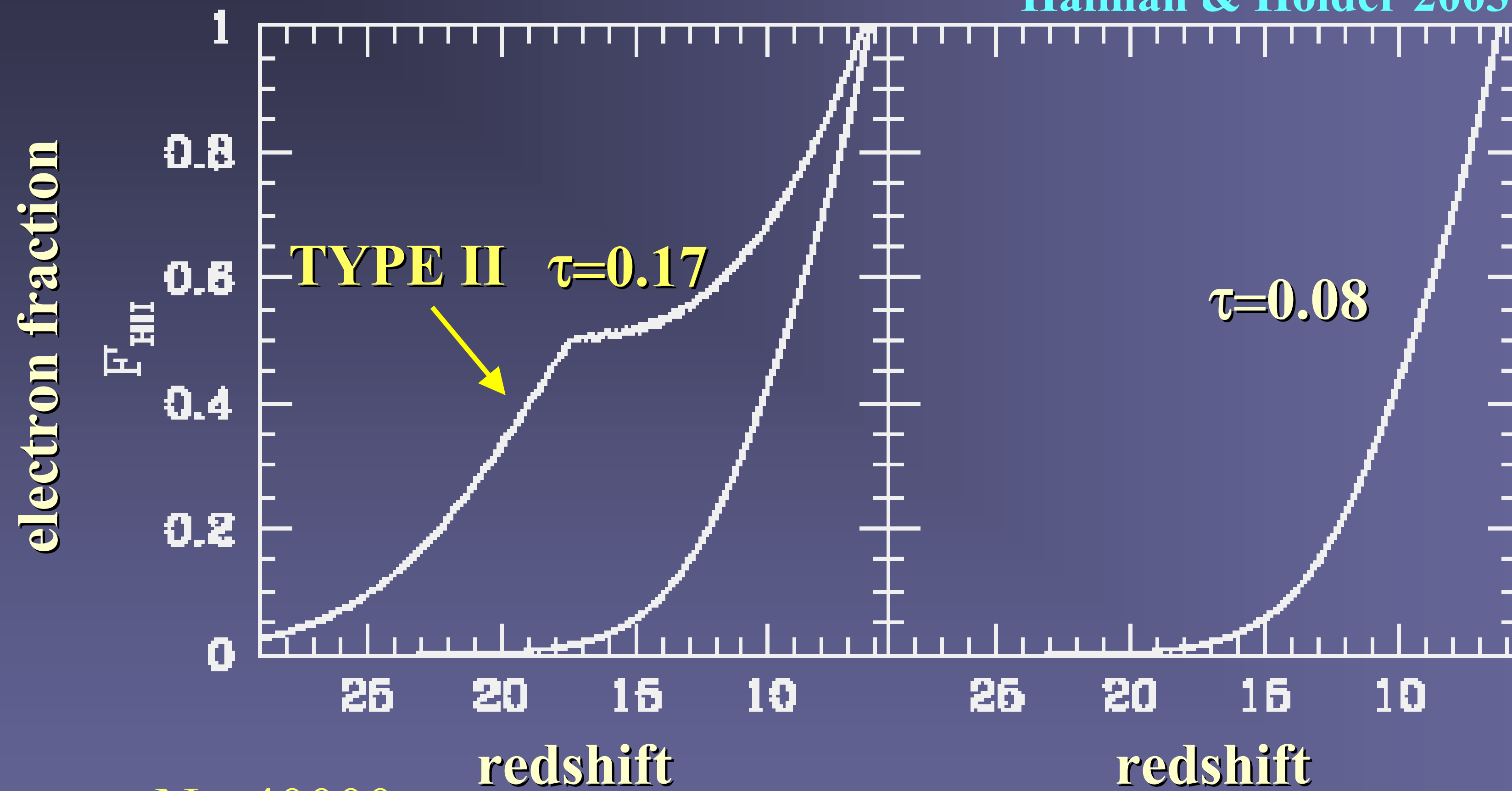
$N_\gamma=4000$
$f_*=20\%$
$f_{esc}=10\%$
$C=10$

$\epsilon \equiv N_\gamma f_* f_{esc}/C=8$

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

Reionization History

Haiman & Holder 2003



N_γ=40000

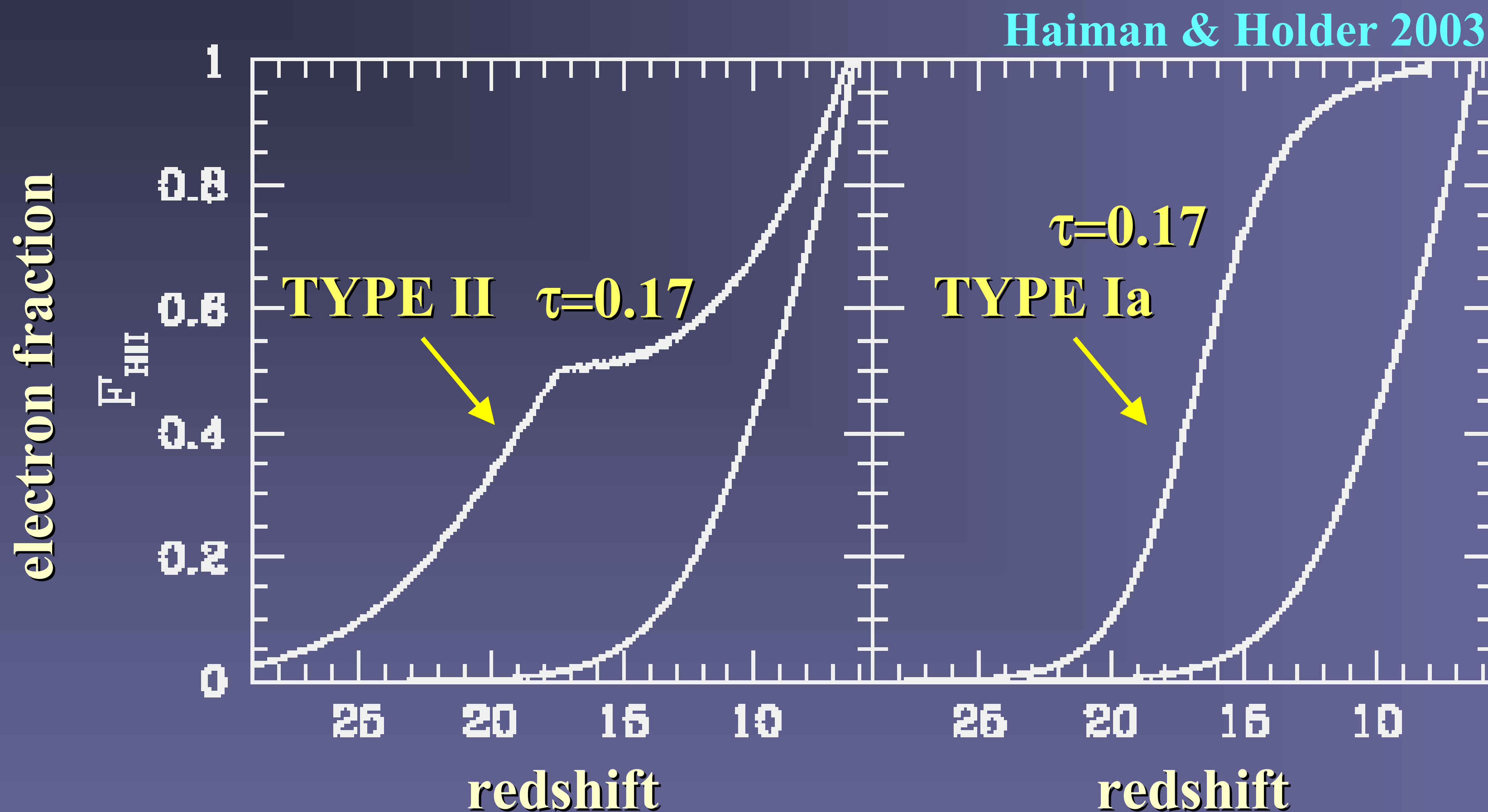
f_*=0.005

f_{esc}=100%

C=10

ε=20

Reionization History



N_γ=40000
f_*=0.005
f_{esc}=100%
C=10

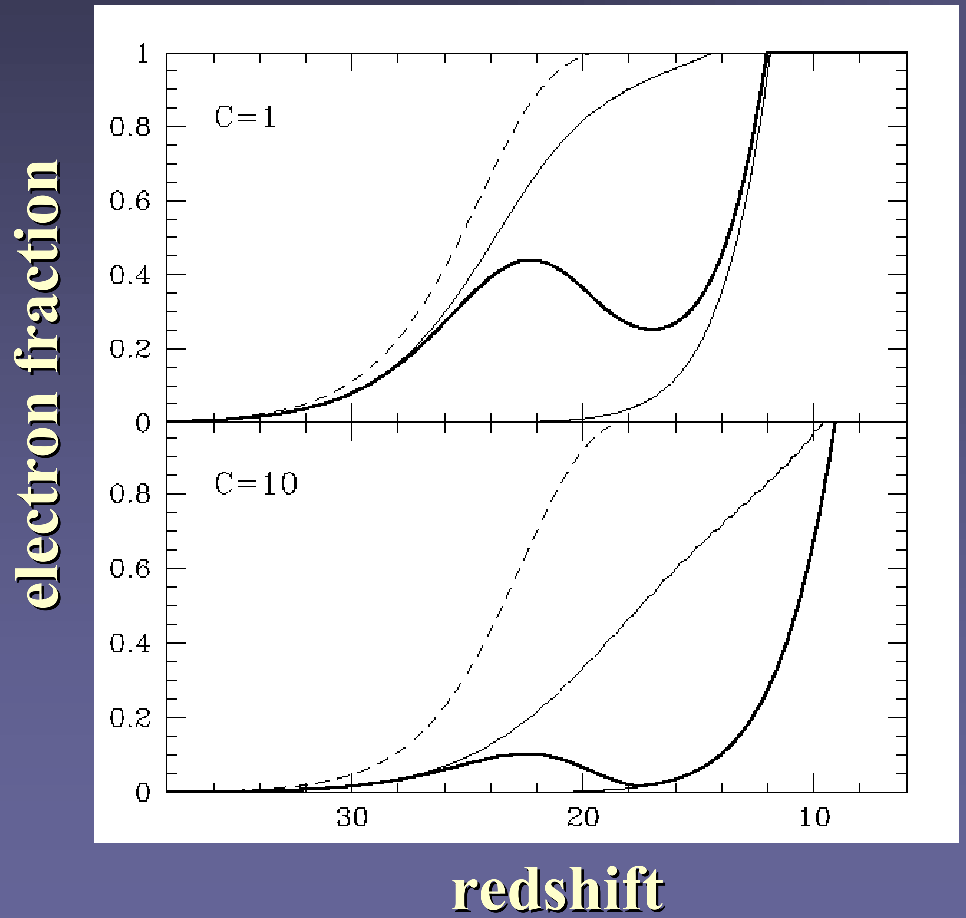
ε=20

ε=480

N_γ=40000
f_*=20%
f_{esc}=10%
C=2

Reionization Excluding Fossil HII Regions

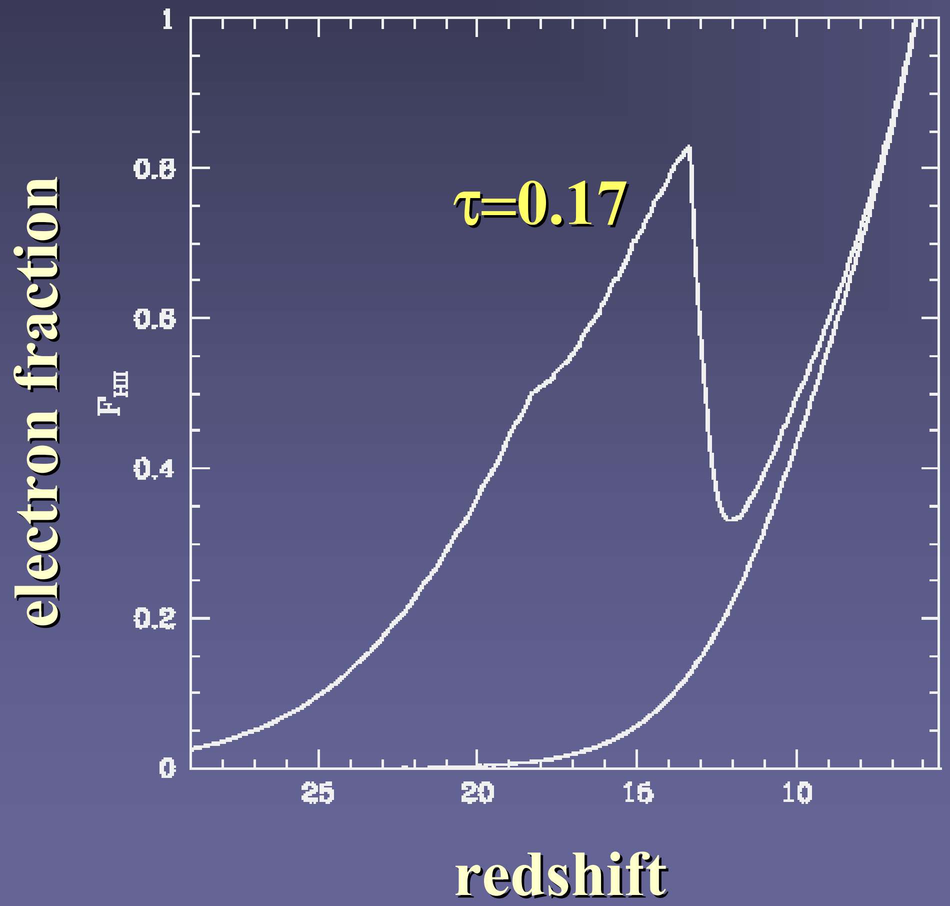
Oh & Haiman 2003



Contribution from Type II Halos τ=0.07

Reionization History

Haiman & Holder 2003



Sudden Transition from a Metal Free to a Normal Stellar Population

Wyithe & Loeb 2002
Cen 2002

ε=8 for z<14

ε=160 for z>14

WMAP implications

no 'crisis'

- **Complex reionization history required by WMAP + SDSS**
  - significant activity at high redshift ("3σ" result)

    either : metal-free stars, mini-quasars with x60 "boost" in Type Ia

    or : H_2 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 (~3? keV), Mixed DM (?) (Barkana, Haiman, Ostriker)
  - Running Index (requires x 50 boost and H_2 formation)

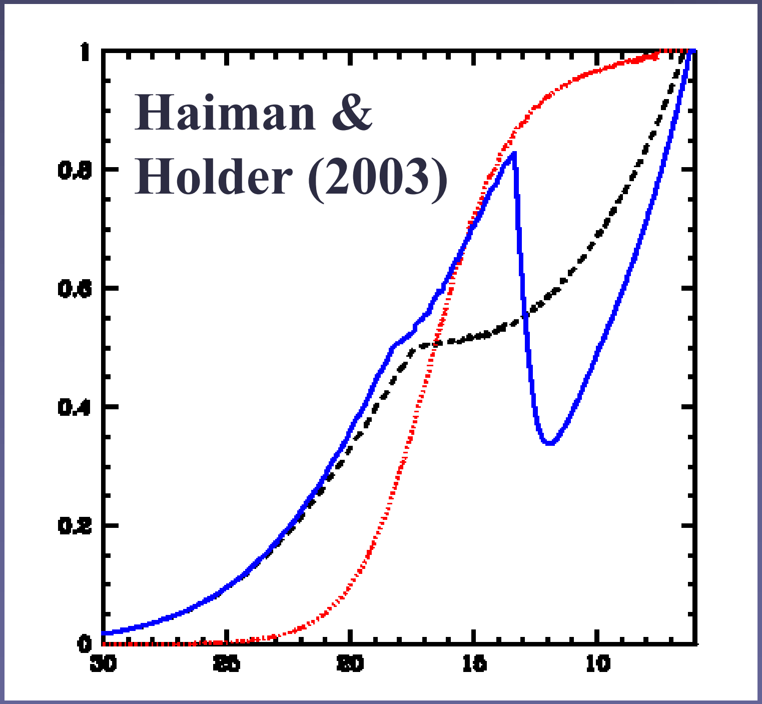
    or x 3000 boost (Haiman & Holder 2003)
- **Future promise**
  - WMAP is sensitive only to τ (total electron column)
  - But if $\tau \gtrsim 0.1$, then future EE/TE can distinguish $x_e(z)$

    (Kaplinghat et al. 2002 ; Holder et al. 2003; Santos et al. 2003)

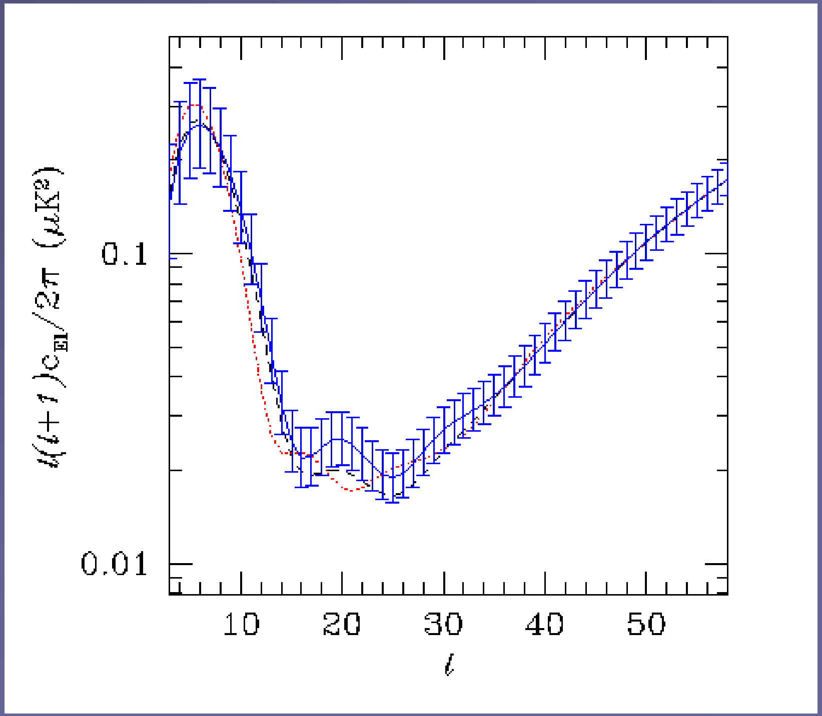
Future: Large Angle Polarization Spectrum

- Three reionization histories with same **τ=0.16**
- Different polarization power spectra; breaks **τ-σ_8** degeneracy
  >4σ in cosmic variance limit, >3σ for Planck
- Can induce bias in τ measurement ($\Delta\tau$ up to **~0.01**)

X_e



Redshift

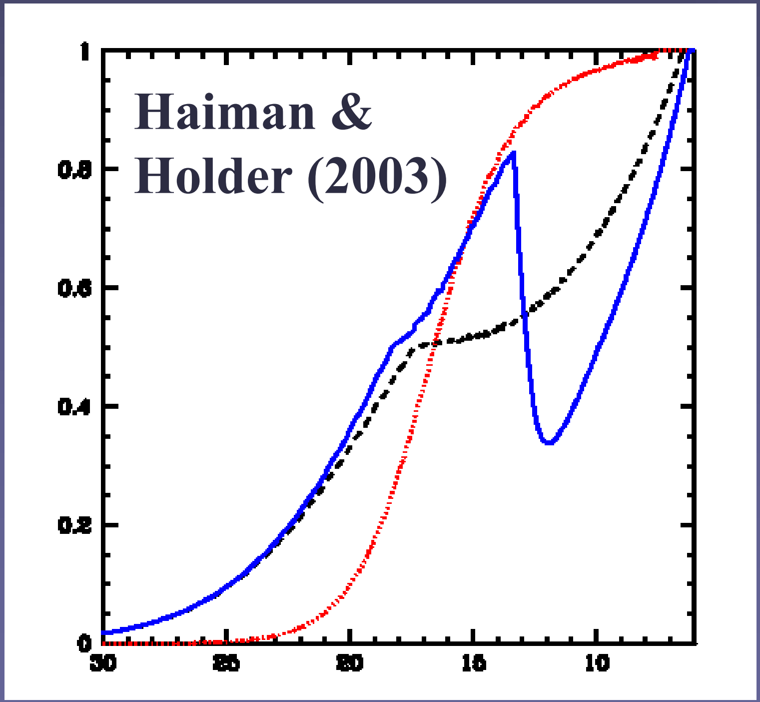


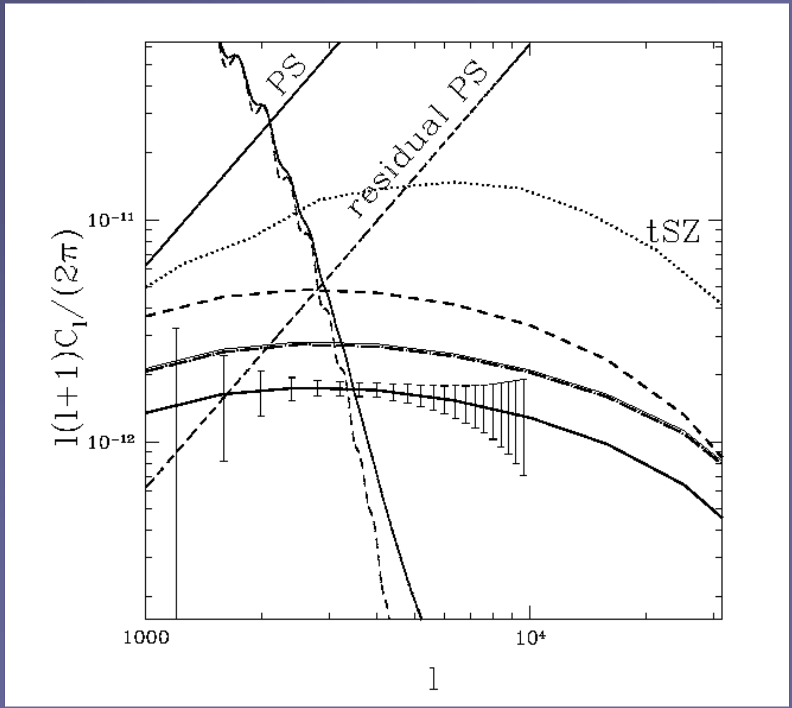
Future: Small-Angle Temperature Spectrum

- Three reionization histories with same **τ=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 $\propto$ τ×bias^2**)

Santos et al. 2003

x_e





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: 2x $10^8 M_\odot$ halo at z=14 (3σ peak)
  - SNe, GRB afterglows….

- **Line Emission**

  - Can provide information on spectral hardness
  - Hydrogen Lyman and Balmer α lines (Oh 1999)
  - Helium lines at 1640, 4686, 3203Å
    to z=10 for $1M_\odot$/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. Lyα 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~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~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 **$\tau \sim 3\times10^8$ 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 ($\sim10^{-25}$) mixing angle
  many ($\sim10^6$) ionizations per relativistic electron

Fate of ~100 MeV electron at z=20

- **Inverse Compton scattering with CMB photons**

  $\tau_{cool} \sim 6\times10^4$ yr $(M_e/100\ \mathrm{MeV})^{-1}\ [(1+z)/21]^{-4}$

- **CMB photons up-scattered to high energies:**

  13.6 eV < E_γ < 900 eV $[(1+z)/21]^{-4}$ for
  20 $[(1+z)/21]^{-1/2}$ **eV < M_e < 180 MeV**

- **Newly established (UV-X-ray) background**

  direct photo-ionization (UV) or
  collisional ionization by ~ keV photoelectrons

- **Effects on CMB spectrum:** just below (μ+y) detectability

Le Fin