WMAP Implications for Reionization

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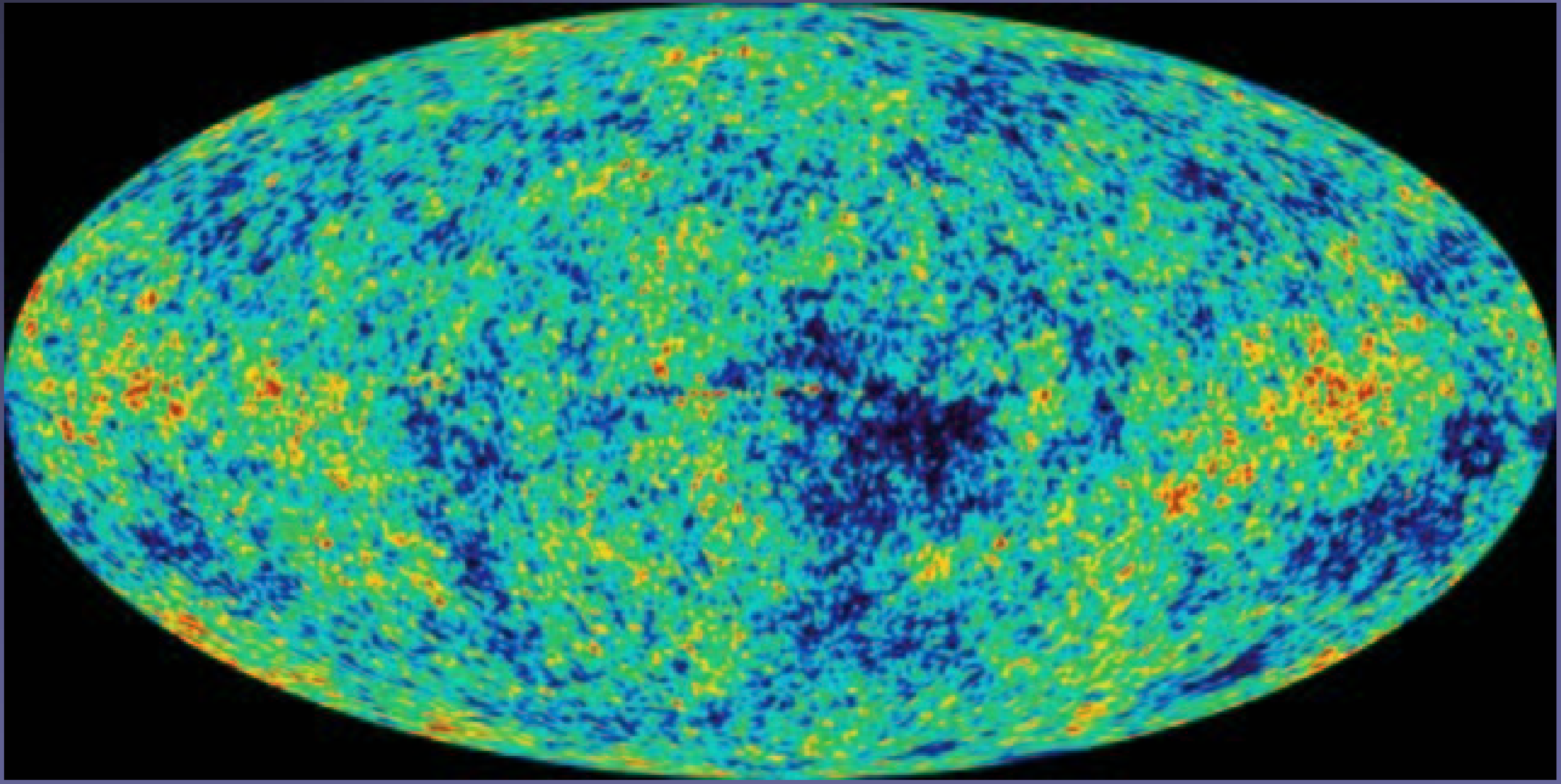
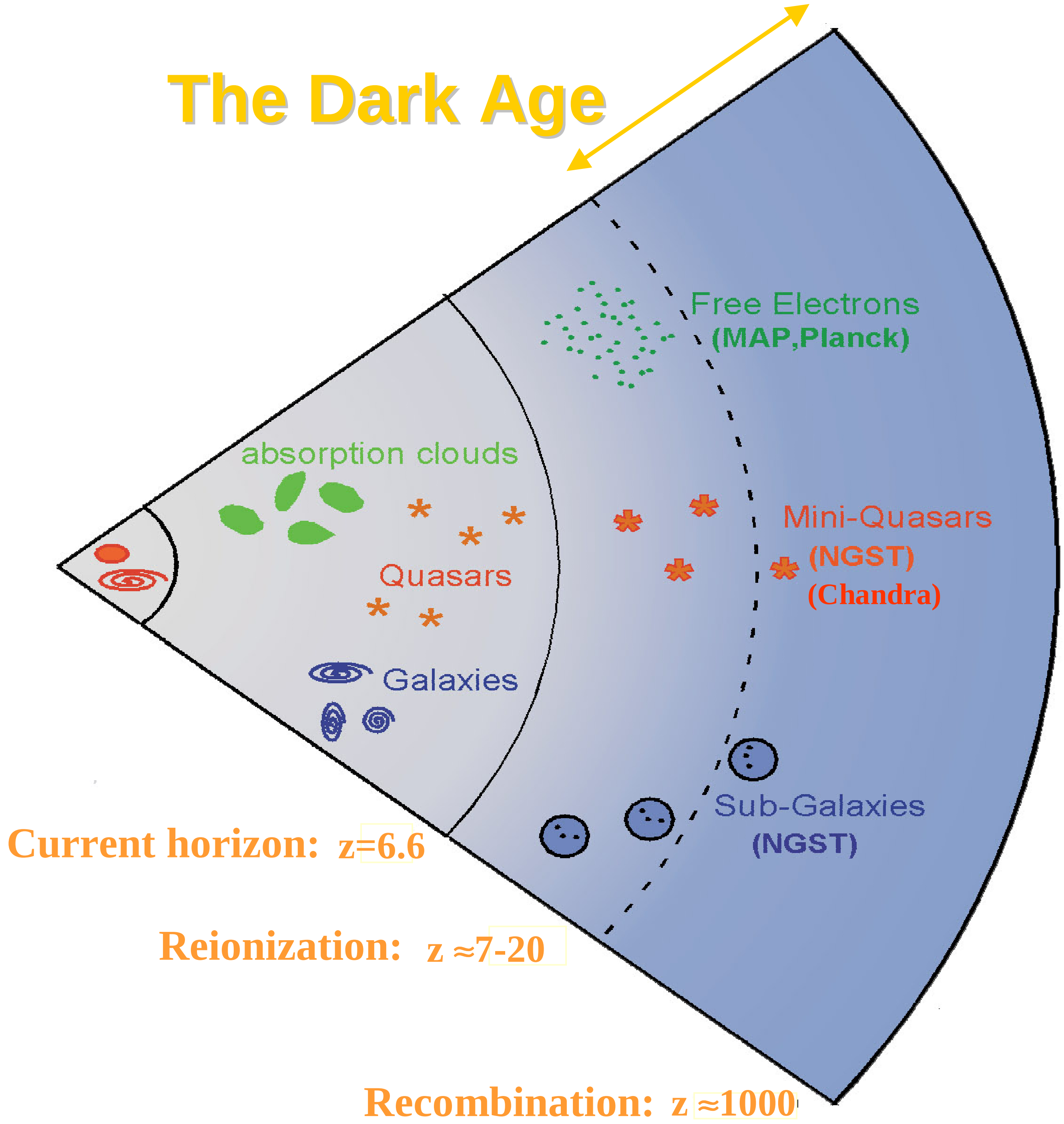
The Cosmic Microwave Background (CMB)

As seen by the Wilkinson Microwave Anisotropy Probe (WMAP)



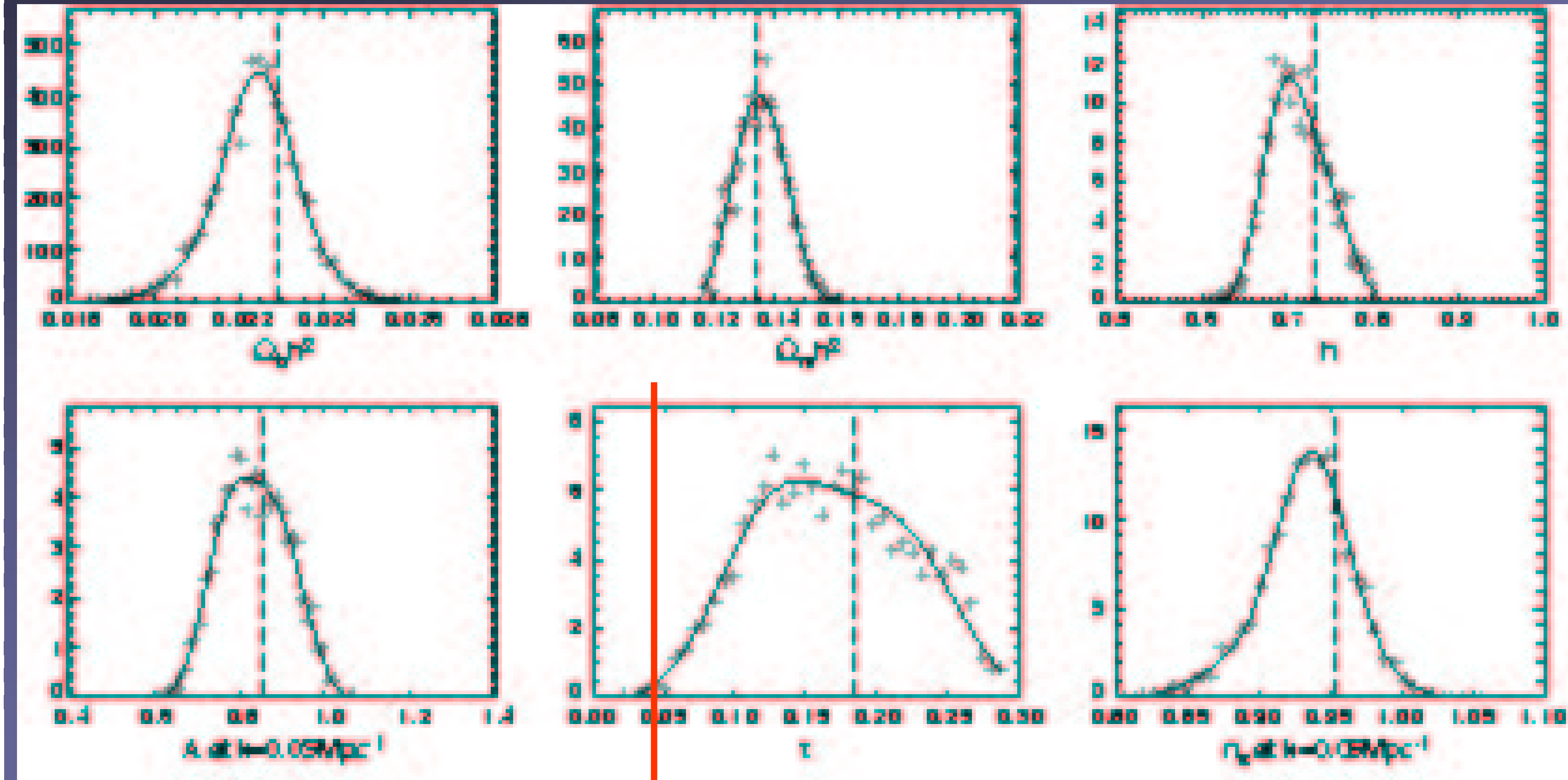
First results were announced February 14, 2003



The Dark Age
Free Electrons
(MAP,Planck)
absorption clouds
Mini-Quasars
(NGST)
(Chandra)
Quasars
Galaxies
Sub-Galaxies
(NGST)
Current horizon: z=6.6
Reionization: z ≈7-20
Recombination: z ≈1000

Looking for Electrons with WMAP

[marginalized errors from TE correlation]



(Spergel et al. 2003)

Z(reion)=6 ↔ τ=0.04

Outline of Talk

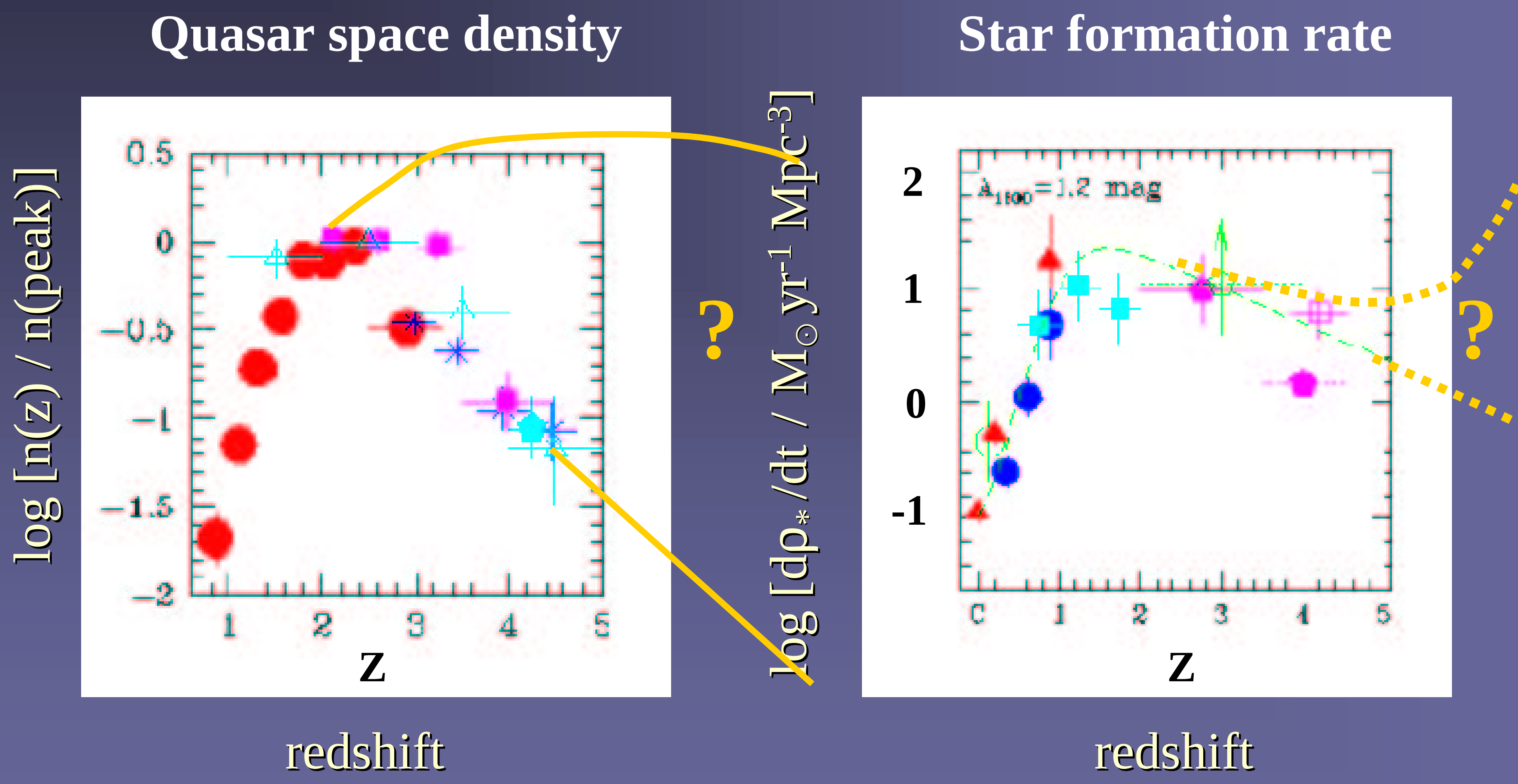
1. Theoretical Modeling of Reionization
   – what were the sources?
   – what are the key feedback processes?
2. Observational Signatures
   – distribution of neutral hydrogen
   – distribution of free electrons

What were the sources of reionization?

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

Relevant Halo Mass Scales

(masses at redshift z=10)

• Jeans Mass	$10^4\,M_\odot$	T_{vir}=20 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	$10^{10}\,M_\odot$	$T_{vir}=2\times10^5$ K	TYPE Ib	5

2σ peak redshifts

(Haiman & Holder 2003)

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

  } ε

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

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)

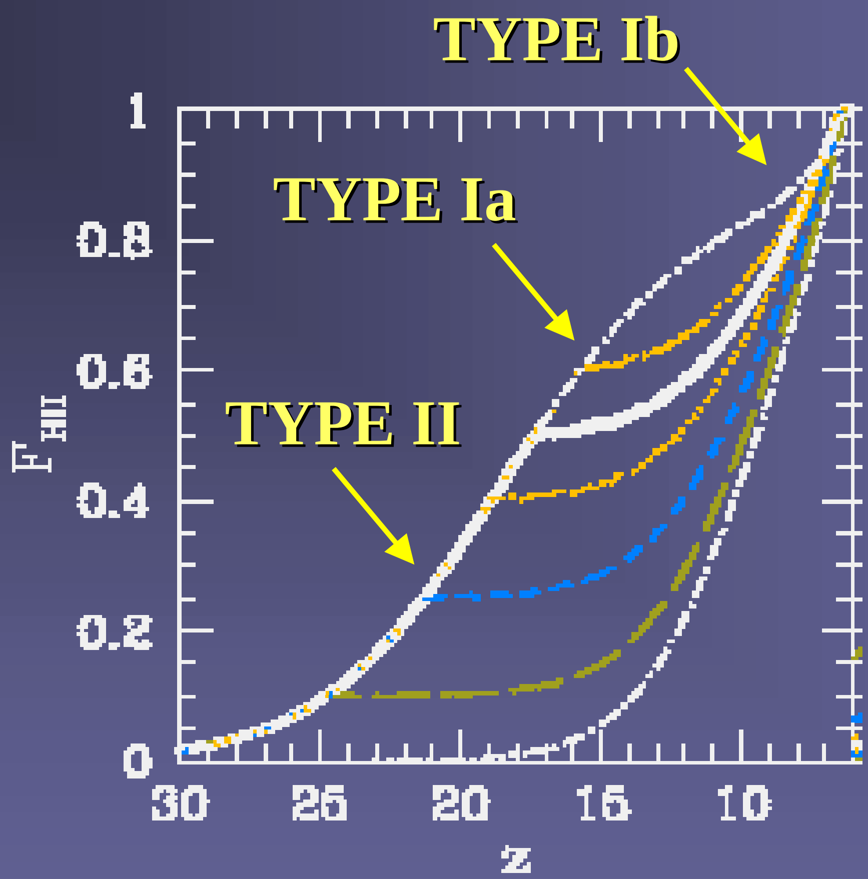
Second Global Feedback

PHOTO-IONIZATION HEATING:

- IGM temperature raised to $\gtrsim 10^4$K
- Gas in-fall suppressed in halos with velocity dispersion $\sigma \lesssim 50$ km/s
- [or: Jeans mass increased…]

0D: Efstathiou 1992
1D: Thoul & Weinberg 1995
3D: Navarro & Steinmetz 1997

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

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“Percolation” is occurring at z~6-7

looking for hydrogen

- **Spectra of z~6 quasars in Sloan Digital Sky Survey**

  - Gunn-Peterson troughs at $z > 6$
  - Compared to HI opacity in $5.5 \lesssim z \lesssim 6$ sources

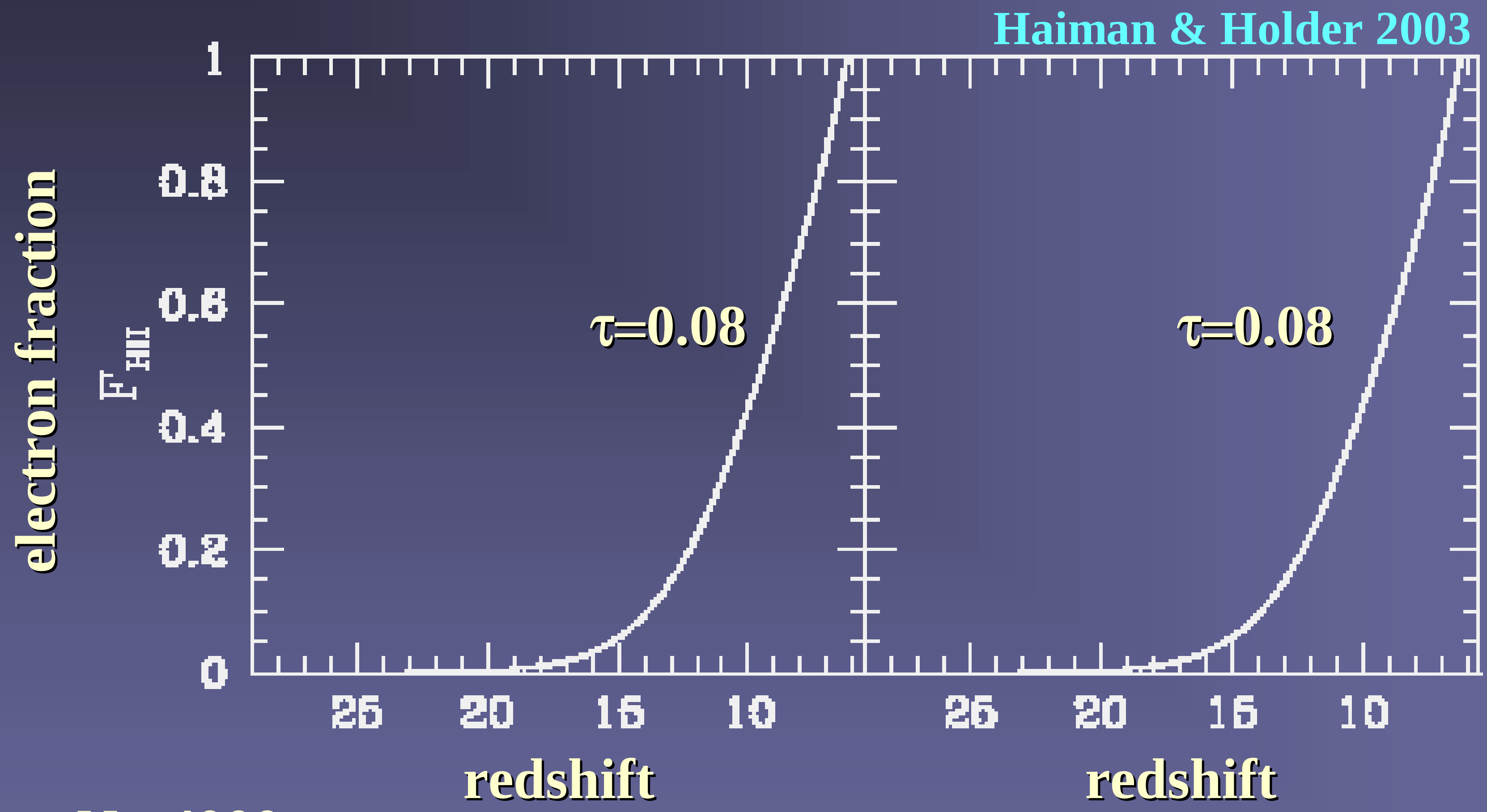
    (Becker et al. 2001; Fan et al. 2002, Songaila & Cowie 2002)

- **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)

Reionization History

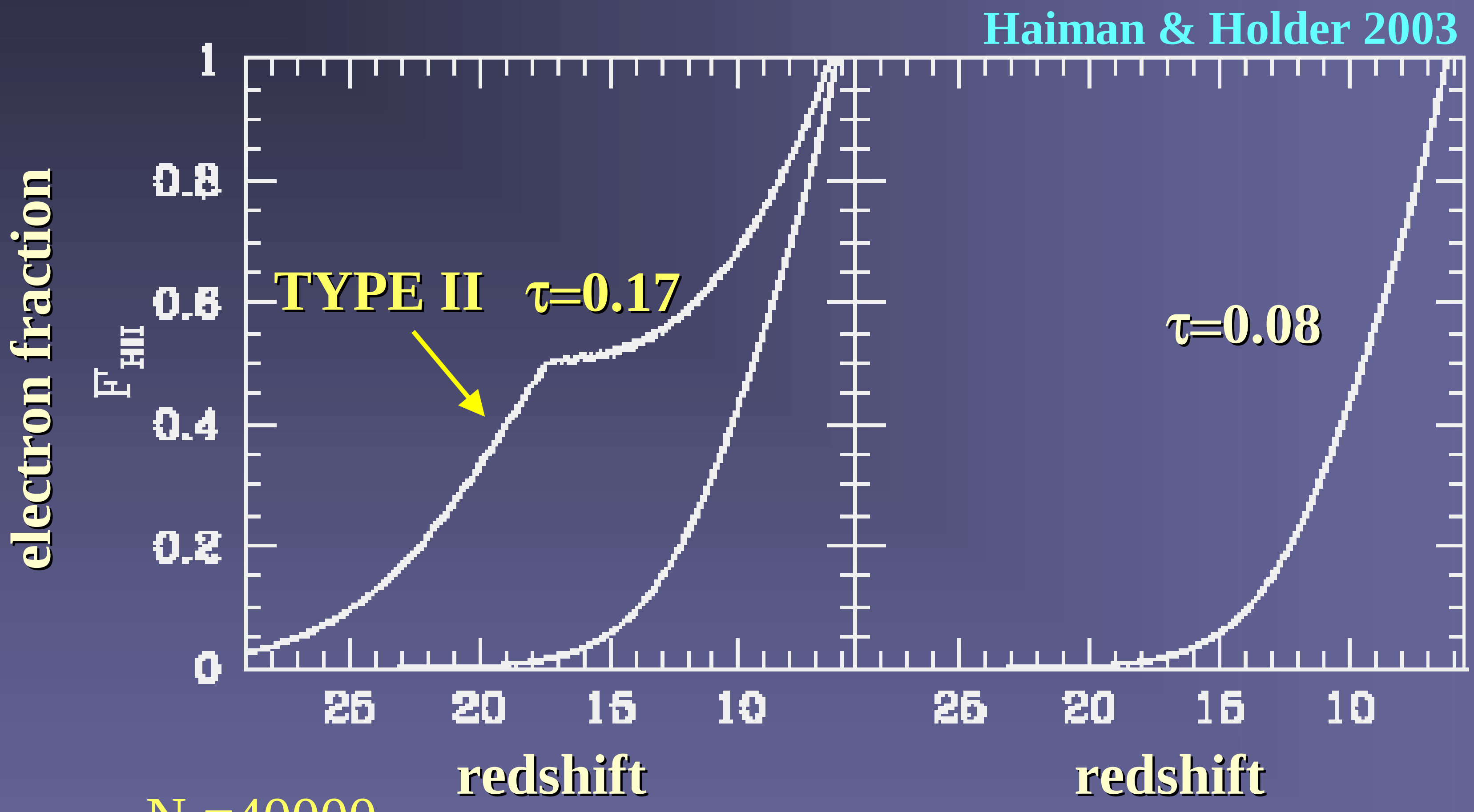


$N_\gamma=4000$
$f_*=20\%$
$f_{esc}=10\%$
$C=10$

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

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

Reionization History



N_γ=40000

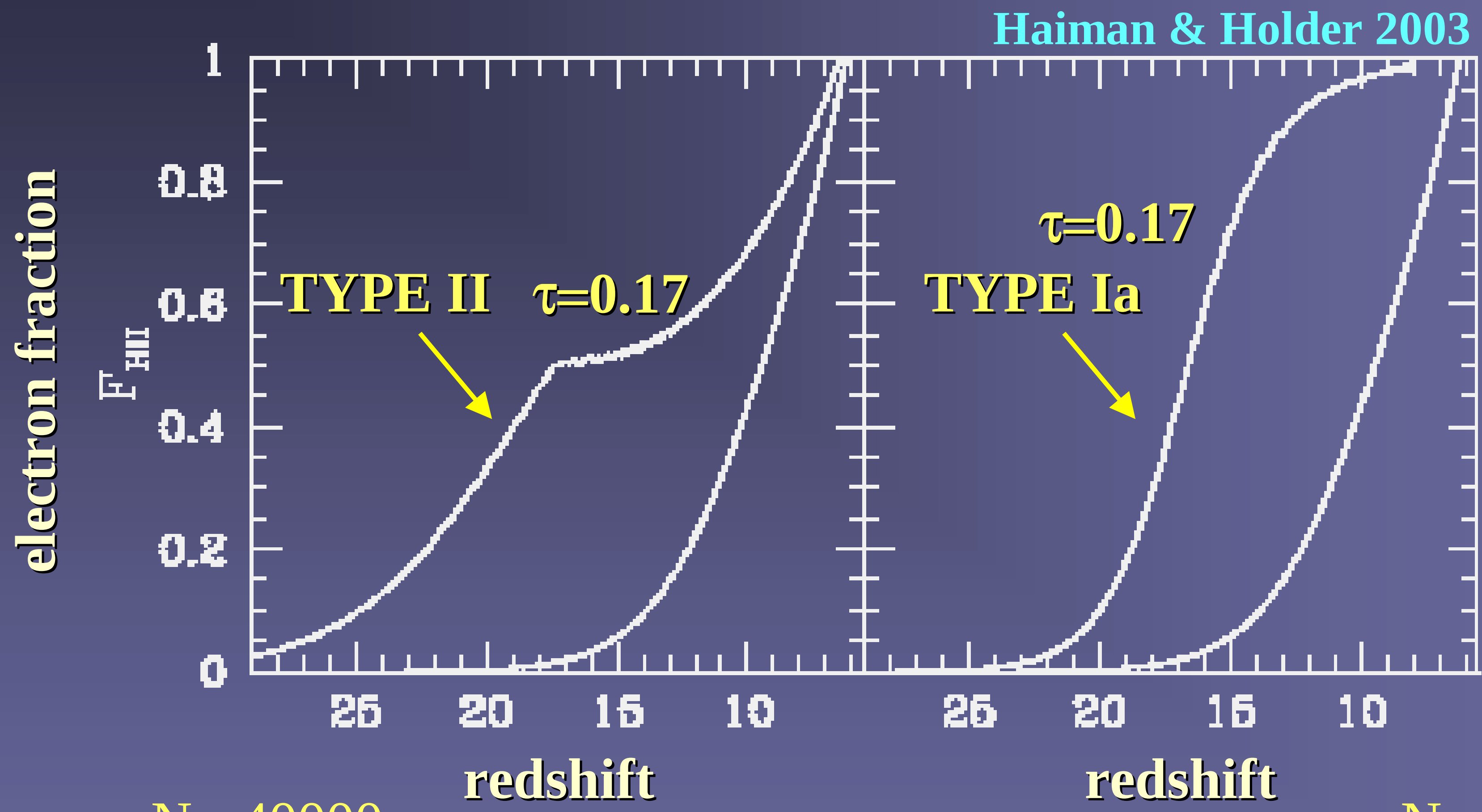
f_*=0.005

f_{esc}=100%

C=10

ε=20

Reionization History



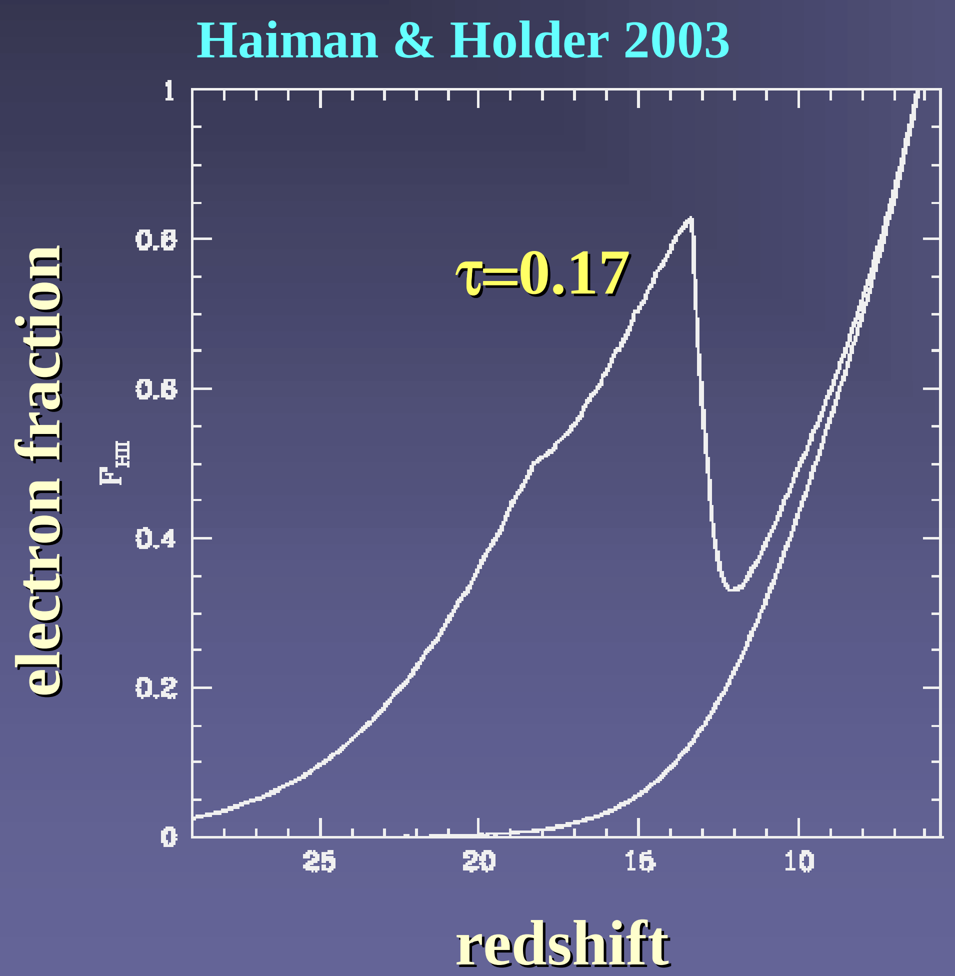
N_γ=40000
f_*=0.005
f_{esc}=100%
C=10

ε=20

ε=480

N_γ=40000
f_*=20%
f_{esc}=10%
C=3

Reionization History



Sudden Transition from a Metal Free to a Normal Stellar Population

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

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

Wyithe & Loeb 2002
Cen 2002

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
    (poster by Glover)
  - 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)

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)

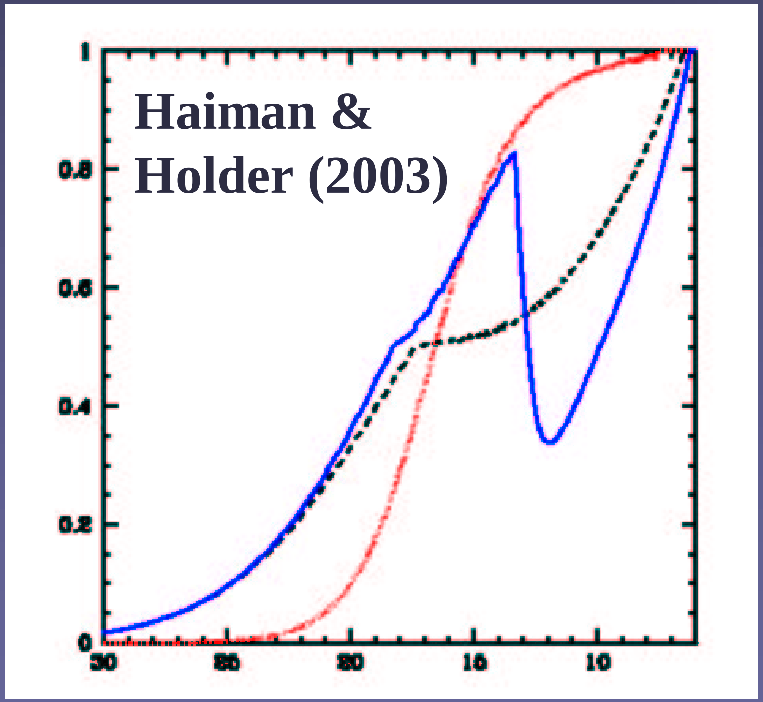
    or x 3000 boost (Haiman & Holder 2003)
- **Future promise**
  - WMAP is sensitive only to τ (total electron column)
  - But if $\tau \gtrsim 0.1$, then future EE/TE can distinguish $x_e(z)$

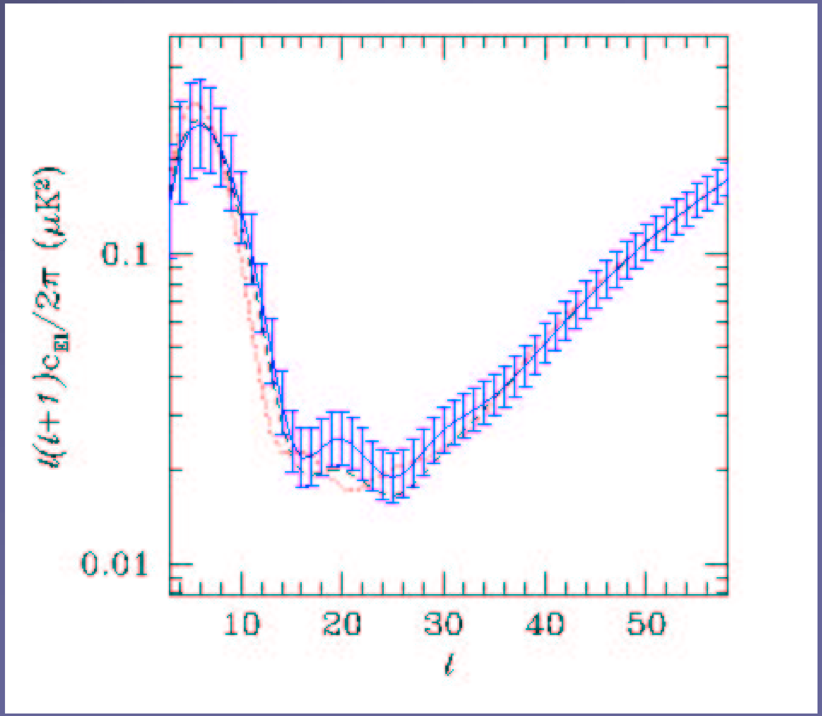
    (Kaplinghat et al. 2002 ; Holder et al. 2003; Santos et al. 2003)

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





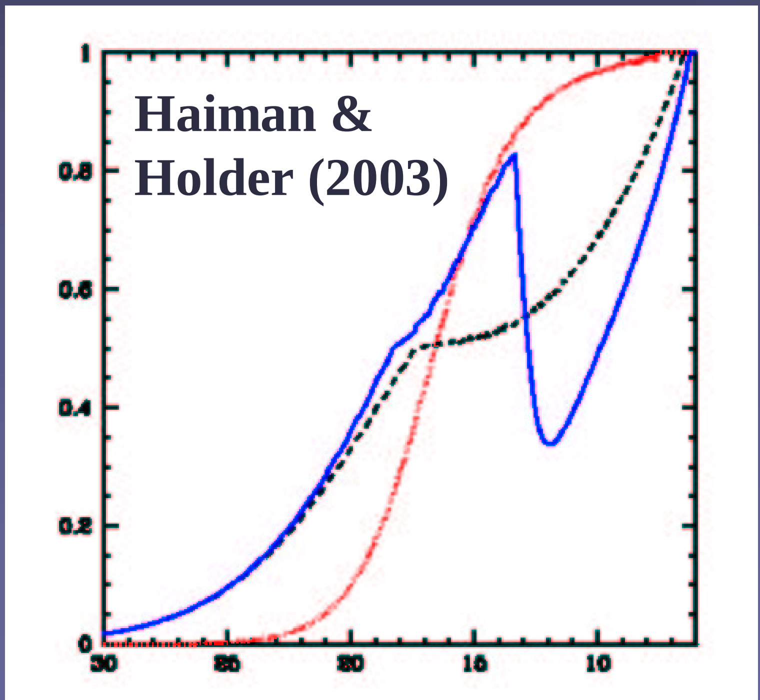
Redshift

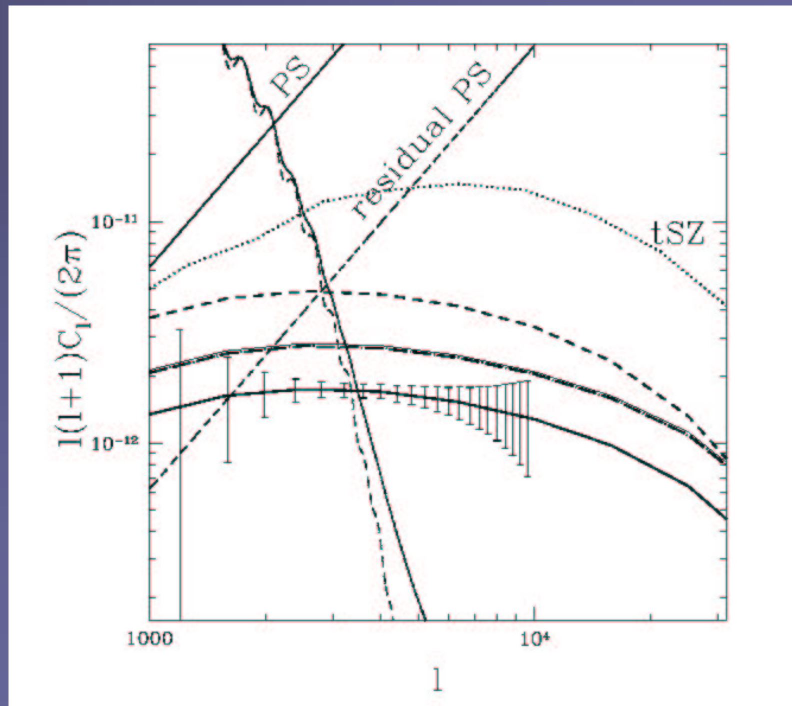
Future: Small-Angle Temperature Spectrum

- 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

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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_ν < 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** $(M_e/100 \text{ MeV})^{-1} [(1+z)/21]^{-4}$

- **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 $(\mu+y)$ detectability

Conclusion

1. LCDM cosmogony naturally accommodates reionization
2. Different populations to satisfy both SDSS QSO + WMAP
3. Either H_2 formation or significant (x60) boost in efficiency
4. Future CMB observations will probe reionization history

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5. Lyα Emitters and 21cm will probe neutral hydrogen
6. *JWST* will make direct detections to z=10 and beyond