The First Stars and Black Holes and their Contribution to Reionization

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Reionization History: Two Recent Clues

- Early milestone in structure formation
- Conspicuous effect of the 1st generation of light sources

WMAP:
baryons significantly ionized already at z~15-20

SDSS quasars:
baryons mostly neutral at z~6-7

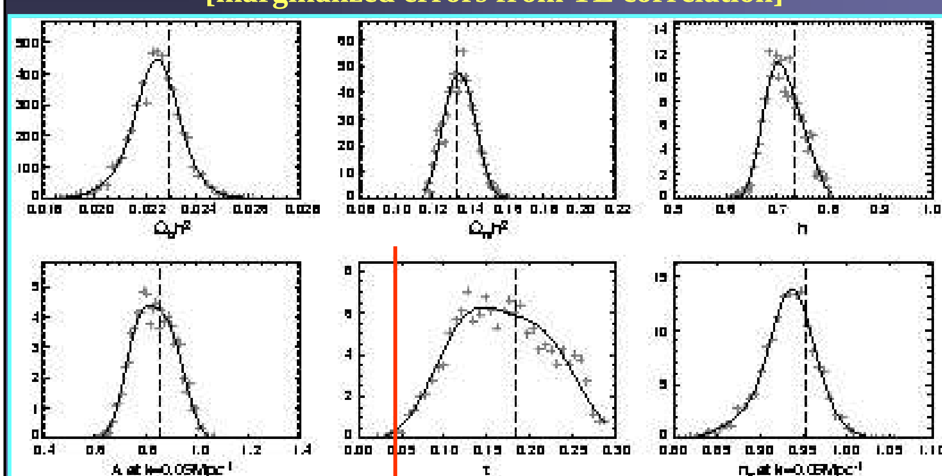
- Reionization history extended and complex
- What role did early stars and BHs play?

Outline of Talk

1. Observational Summary
   – neutral hydrogen (quasar spectra)
   – free electrons (imprints on CMB)
2. Physics of Reionization
   – what were the sources ?
   – what are the key physical processes?
3. The Future Probes

Electron Scattering in WMAP data

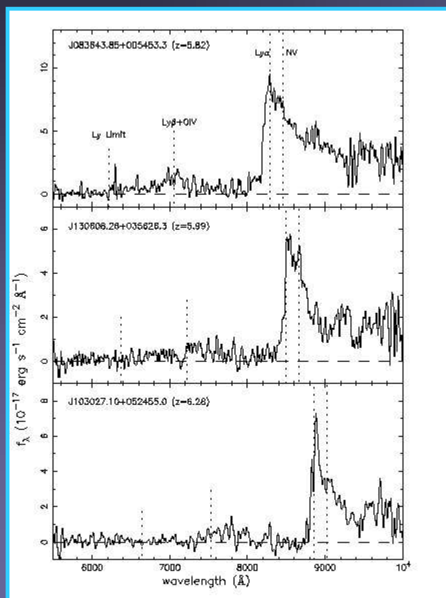
[marginalized errors from TE correlation]



(Spergel et al. 2003)

Z(reion)=6 ↔ τ(e)=0.04
Z(reion)=17 ↔ τ(e)=0.17

Distant Quasars: Reionization at z~6?



Fan et al. 2002

$\langle x_H \rangle \approx 10^{-4}$ z=5.82

$\langle x_H \rangle \approx 2\times10^{-4}$ z=5.99

Gunn-Peterson trough:

$\langle x_H \rangle$ □ 10^{-3}	z=6.28

"Percolation" is occurring at z~6-7?

1. IGM Temperature

- IGM inferred to be warm from z~4 Lyman α forest
- It would be too cold for single early reionization

(Hui & Haiman 2003; Zaldarriaga et al. 1997; Theuns et al. 2002)

2. Redshift-Evolution of Ionizing Background (τ_α *vs* z)

- Gunn-Peterson troughs at z > 6
- Compared to HI opacity in 5.5 □ z □ 6 sources

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

3. Boundary of Strömgren Sphere (τ_α *vs* λ)

- Sharp transition ~100Å away from Lyman α line
- Requires presence of a GP damping wing

(Mesinger & Haiman 2004)

1. Thermal Memory of IGM

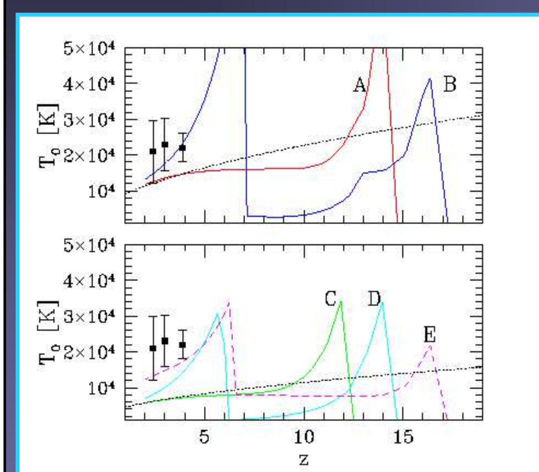
(Hui & Haiman 2003)

- **IGM temperature evolution**
  - determined by photo-ionization heating vs adiabatic cooling
  - heating during first ionization event 'boosts' temperature
  - residual heating determines asymptotic temperature $T{\sim}10^4$K

- **Thermal state of IGM at z<4**
  - does not remember ionization history at z>10
  - has 'short term' memory of z<10 events:
    higher reionization redshift implies lower temperature

- **IGM temperature measured at z=3-4**
  - $T{\sim}2{\times}10^4$K, about twice the asymptote value
    (Schaye et al. 2000; Zaldarriaga et al. 2001)

Thermal state of IGM: evidence for z_r □ 10



(Hui & Haiman 2003; Theuns et al. 2002)

Compute Temp. Evolution
- assume hard spectrum
  ($F_\nu \propto \nu^{1.5}$)

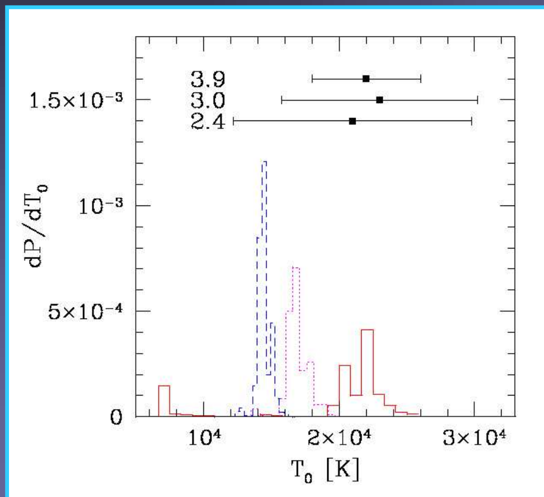
- A,B: He doubly ionized
- C,D: He singly ionized
- E: 2^{nd} He ionization

- requires large changes
  in the ionized fractions
  at low redshift (z<10)

Caveat/Question:
- can known QSOs do it
  by HeII→HeIII ionization

Temperature distribution

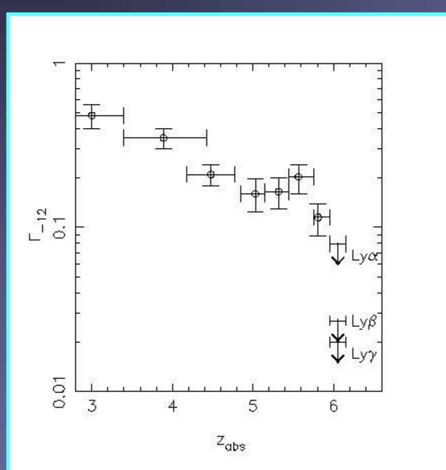
Hui & Haiman 2003



- temperature **distribution** contains information on reionization history
- results in large scatter in temperatures, as each fluid element is ionized at a different redshift
- scatter diminishes with time

2. Evolution of the Ionizing Background

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



redshift

Rapid evolution between 5.5 □ z □ 6

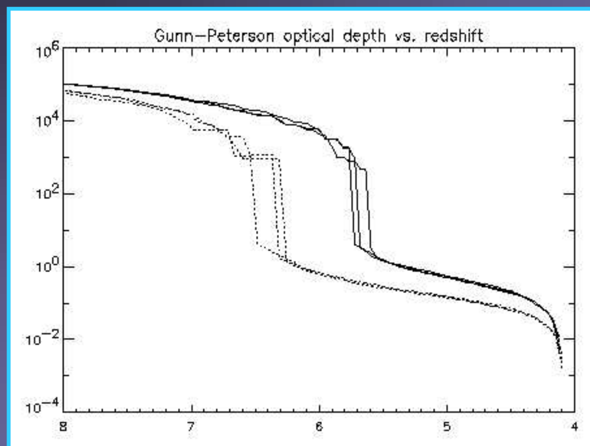
Fan et al. 2002
Lidz et al. 2002
Cen & McDonald 2002
Gnedin 2002

cf.:
Songaila & Cowie 2002
Songaila 2004

Cosmological Simulations

can follow (1) topology and (2) decrease in the neutral fraction

Gun-Peterson opacity



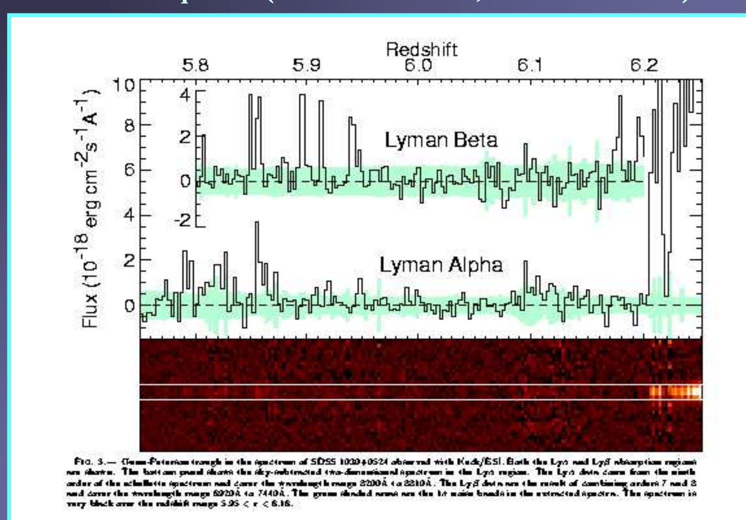
Redshift

Razoumov et al. 2001
Gnedin; Sokasian et al.
Ciardi et al. ; Cen et al.

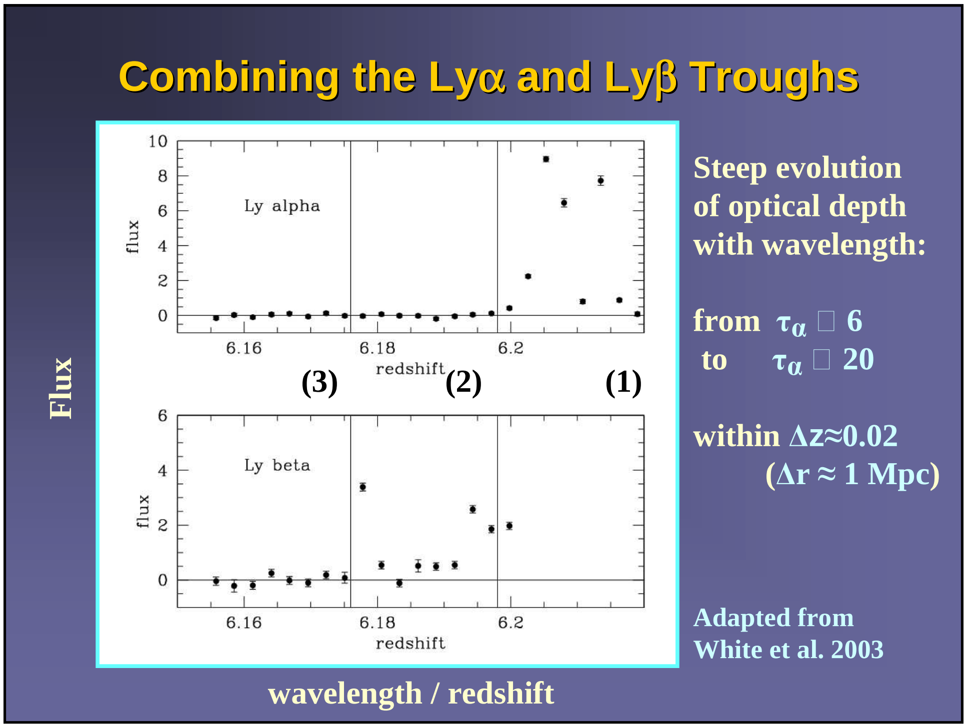
3. Combining the Lyα and Lyβ Troughs

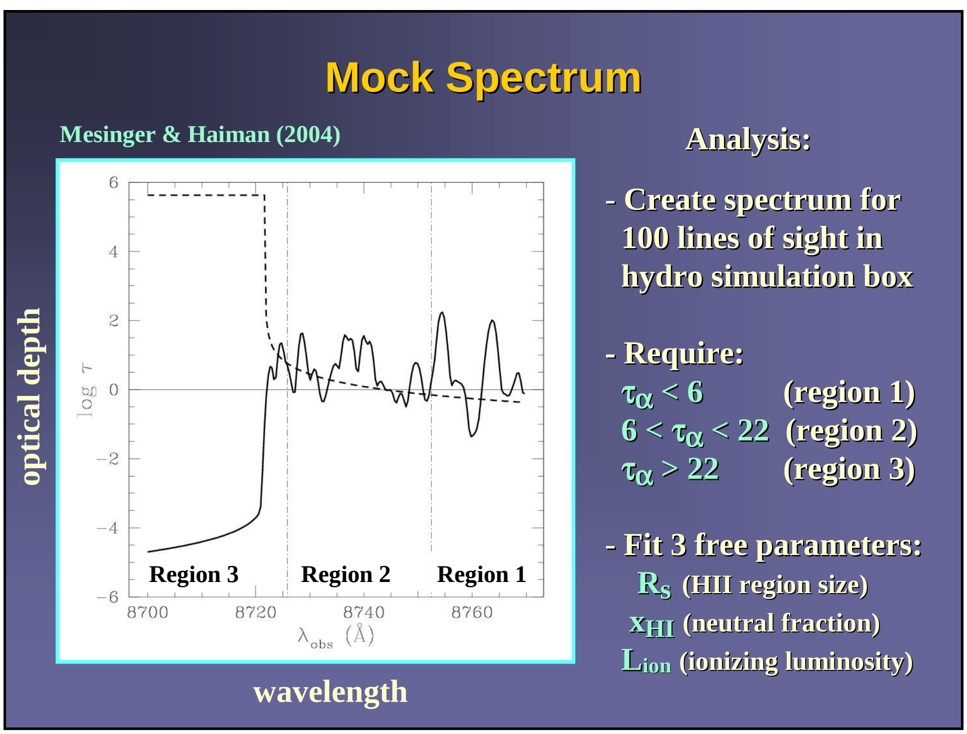
z=6.28 quasar (Becker et al. 2001; White et al. 2003)

Flux



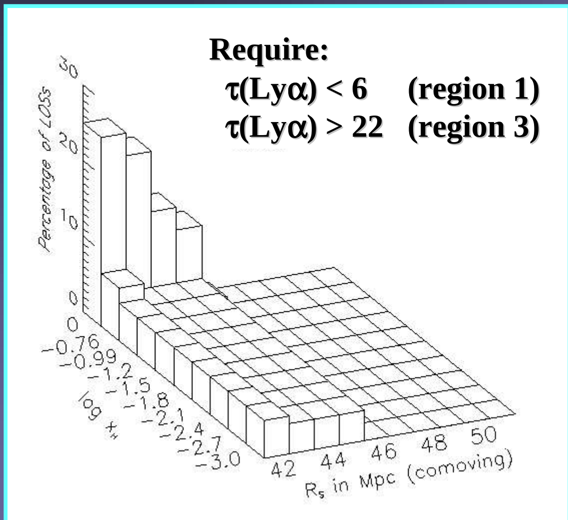
wavelength / redshift


Combining the Lyα and Lyβ Troughs
Ly alpha
Ly beta
flux
redshift
(3)
(2)
(1)
Flux
wavelength / redshift
Steep evolution of optical depth with wavelength:
from τ_α □ 6
to τ_α □ 20
within Δz≈0.02
(Δr ≈ 1 Mpc)
Adapted from White et al. 2003


Mock Spectrum
Mesinger & Haiman (2004)
log τ
λ_{obs} (Å)
Region 3
Region 2
Region 1
optical depth
wavelength
Analysis:
- Create spectrum for 100 lines of sight in hydro simulation box
- Require:
$\tau_\alpha < 6$ (region 1)
$6 < \tau_\alpha < 22$ (region 2)
$\tau_\alpha > 22$ (region 3)
- Fit 3 free parameters:
R_S (HII region size)
x_{HI} (neutral fraction)
L_{ion} (ionizing luminosity)

Detection of a Cosmic Strömgren Sphere

Mesinger & Haiman (2004)



$R_S = 6 \pm 0.3$ Mpc
$0.2 \leq X_{HI} < 1$
$L_{ion} = (0.2\text{-}0.6) \times 10^{57} s^{-1}$

Implications:

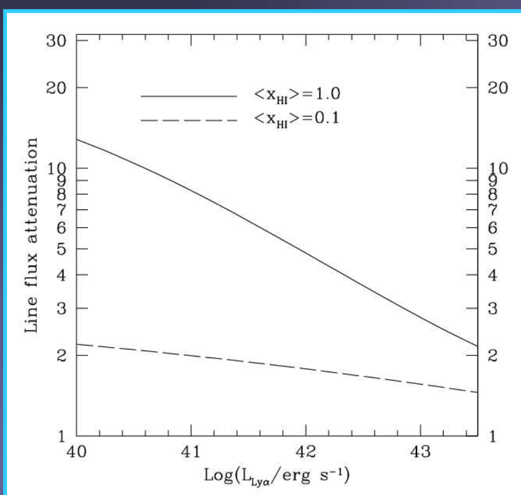
- IGM nearly neutral
  Mesinger & Haiman (2004)
  Wyithe & Loeb (2004)

- method to find ionization topology

- constrain spectrum $\langle E_{ion} \rangle < 0.2$ keV

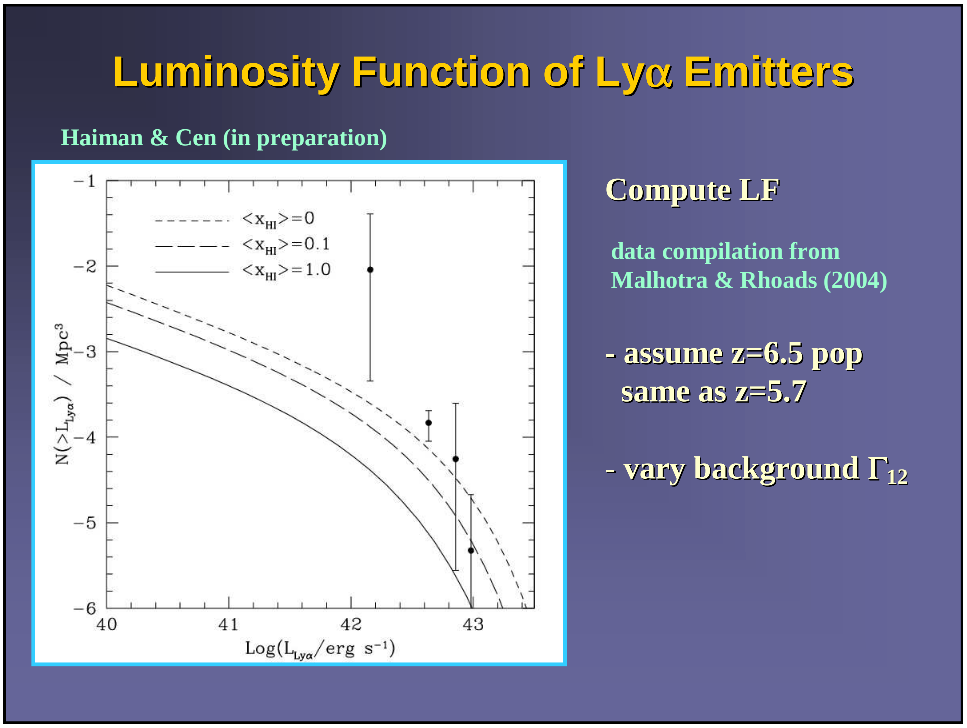
Luminosity Function of Lyα Emitters

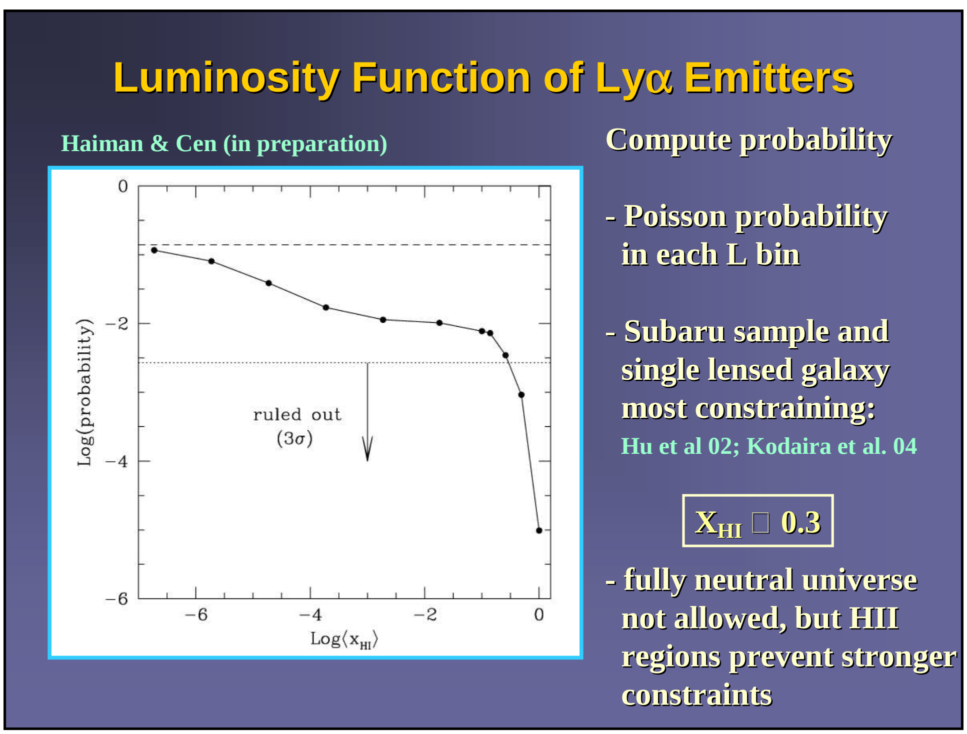
Haiman & Cen (in preparation)

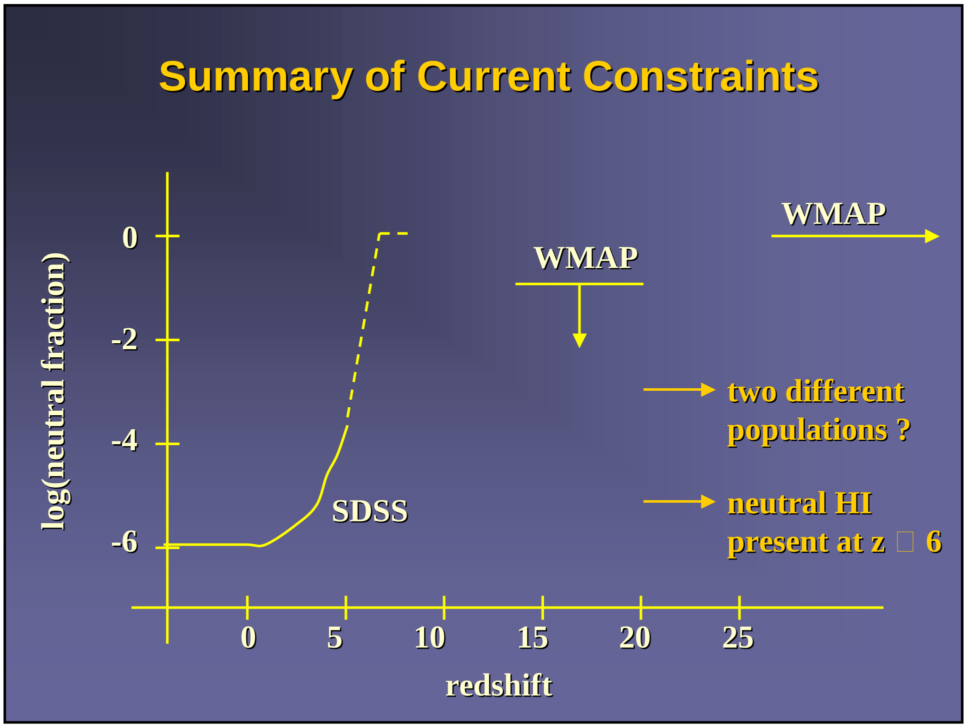


Compute line attenuation

- $t = 10^8$ yrs
- f(esc)=100%
- log-normal density PDF
- C=10
- Kennicut SFR vs L(Lyα)
- line width Δv=300 km/s


Luminosity Function of Lyα Emitters
Haiman & Cen (in preparation)
$\langle x_{HI} \rangle = 0$
$\langle x_{HI} \rangle = 0.1$
$\langle x_{HI} \rangle = 1.0$
$N(>L_{Ly\alpha})$ / Mpc^3
$\log(L_{Ly\alpha}/\mathrm{erg\ s^{-1}})$
Compute LF
data compilation from
Malhotra & Rhoads (2004)
- assume z=6.5 pop
same as z=5.7
- vary background Γ_{12}


Luminosity Function of Lyα Emitters
Haiman & Cen (in preparation)
Log(probability)
$\log\langle x_{HI} \rangle$
ruled out
(3σ)
Compute probability
- Poisson probability
in each L bin
- Subaru sample and
single lensed galaxy
most constraining:
Hu et al 02; Kodaira et al. 04
X_{HI} □ 0.3
- fully neutral universe
not allowed, but HII
regions prevent stronger
constraints



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Dark Matter Halo Hierarchy

(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

2σ peak redshifts

(Haiman & Holder 2003)

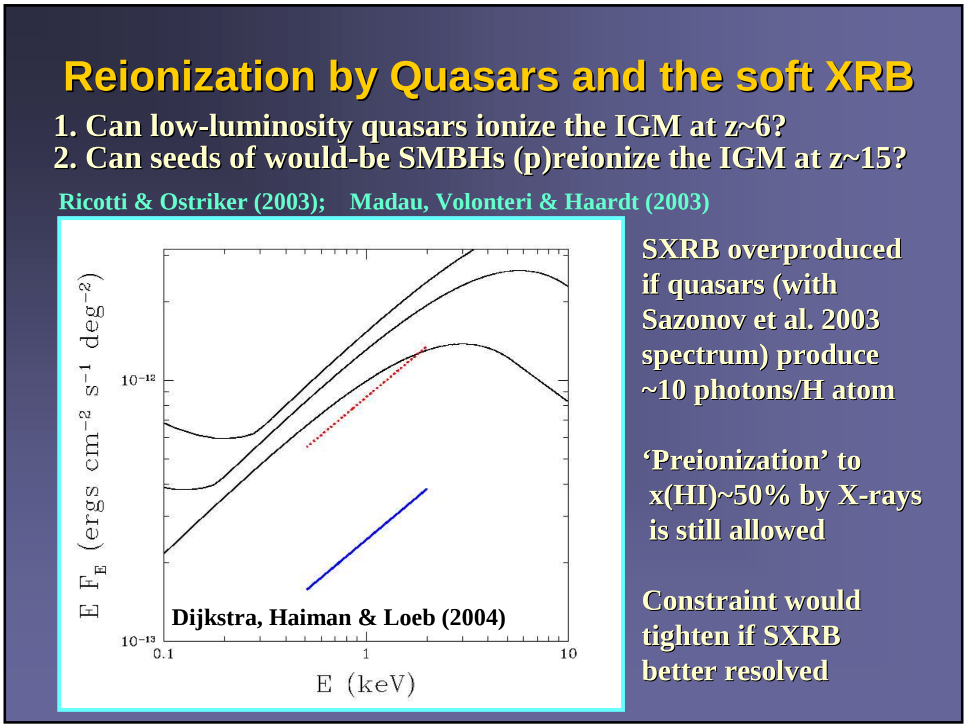
What forms in the early halos?

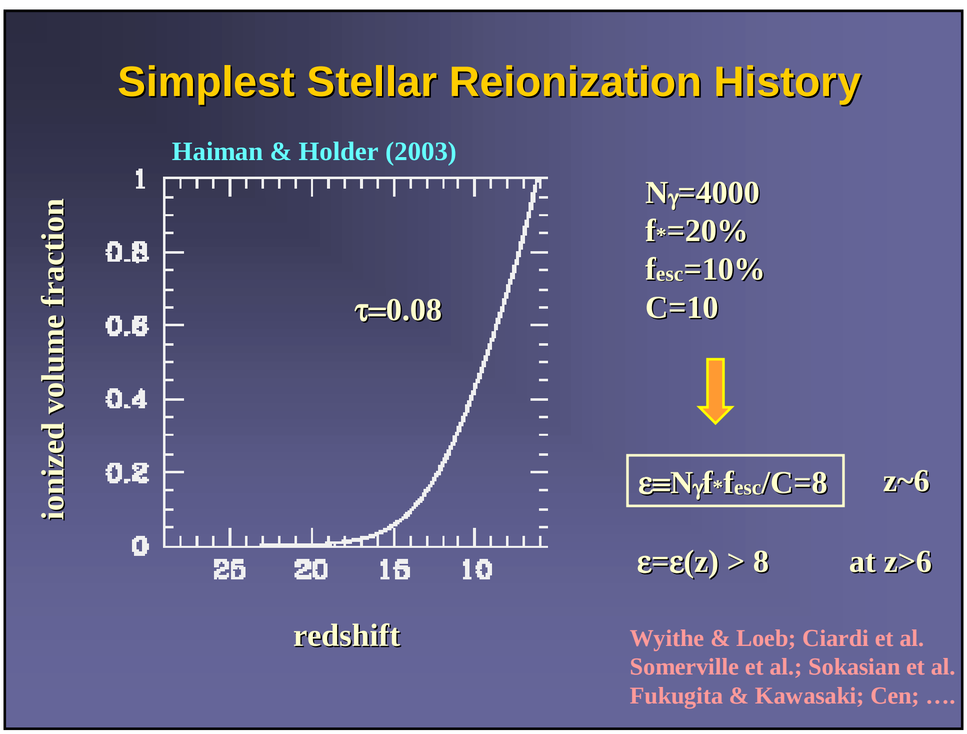
- **STARS: FIRST GENERATION METAL FREE**
  - massive stars with harder spectra
  - boost in ionizing photon rate by a factor of ~ 20
  - return to "normal" stellar pops at Z□$10^{-4} Z_\odot$

  (Tumlinson & Shull 2001 ; Bromm, Kudritzki & Loeb 2001; Schaerer 2002)

- **SEED BLACK HOLES:**
  - 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)


Reionization by Quasars and the soft XRB
1. Can low-luminosity quasars ionize the IGM at z~6?
2. Can seeds of would-be SMBHs (p)reionize the IGM at z~15?
Ricotti & Ostriker (2003); Madau, Volonteri & Haardt (2003)
E F_E (ergs cm^-2 s^-1 deg^-2)
10^-12
10^-13
0.1
1
10
E (keV)
Dijkstra, Haiman & Loeb (2004)
SXRB overproduced if quasars (with Sazonov et al. 2003 spectrum) produce ~10 photons/H atom
'Preionization' to x(HI)~50% by X-rays is still allowed
Constraint would tighten if SXRB better resolved

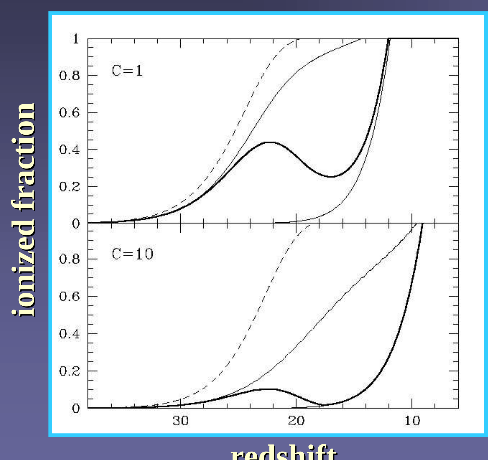

Simplest Stellar Reionization History
Haiman & Holder (2003)
ionized volume fraction
1
0.8
0.6
0.4
0.2
0
25
20
15
10
redshift
τ=0.08
Nγ=4000
f*=20%
fesc=10%
C=10
ε≡Nγf*fesc/C=8
z~6
ε=ε(z) > 8
at z>6
Wyithe & Loeb; Ciardi et al.
Somerville et al.; Sokasian et al.
Fukugita & Kawasaki; Cen; ….

Feedback at high redshift

- **H_2 molecule feedback**
  - Type II halos can initially form H_2 and cool
  - H_2 abundance suppressed (SUV)
  - Destructive feedback too effective? (Oh & Haiman 2003)
- **Photo-heating feedback**
  - 10–50 km/s halos suppressed in HII zones (Thoul & Weinberg1996)
  - could naturally delay 'percolation' (Haiman & Holder 2003)
  - Feedback does not work at high-z ? (Dijkstra et al. 2004)
- **Metal-pollution feedback** (Cen 03, Wyithe & Loeb 03)
  - sudden switch from pop III to pop II
  - pollution local and too prompt?

Reionization Excluding Fossil HII Regions

Oh & Haiman 2003



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

Limits H2 formation and role of Type II halos for reionization

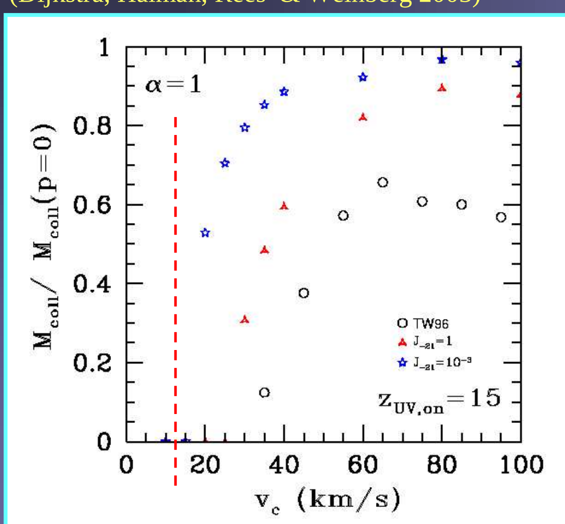
Contribution from Type II halos limited to τ=0.07
Type II halos "suicidal"

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 turns out unimportant at z□6**
  - self-shielding
  - shorter cooling times
  - lower amplitude of background flux J
  - background absent until late stage of collapse

Photo-ionization feedback

(Dijkstra, Haiman, Rees & Weinberg 2003)



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

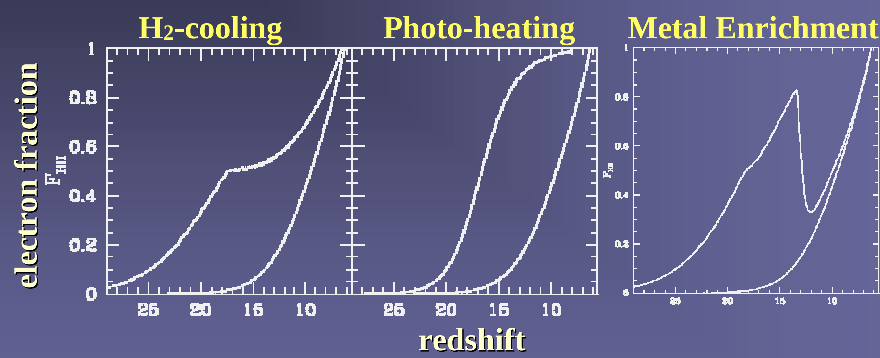
redshift z=2:
Vcirc = 50 km/s

redshift=12:
Vcirc = 15 km/s

Feedback largely eliminated at hi z

Reionization History with Feedback

Haiman & Holder 2003

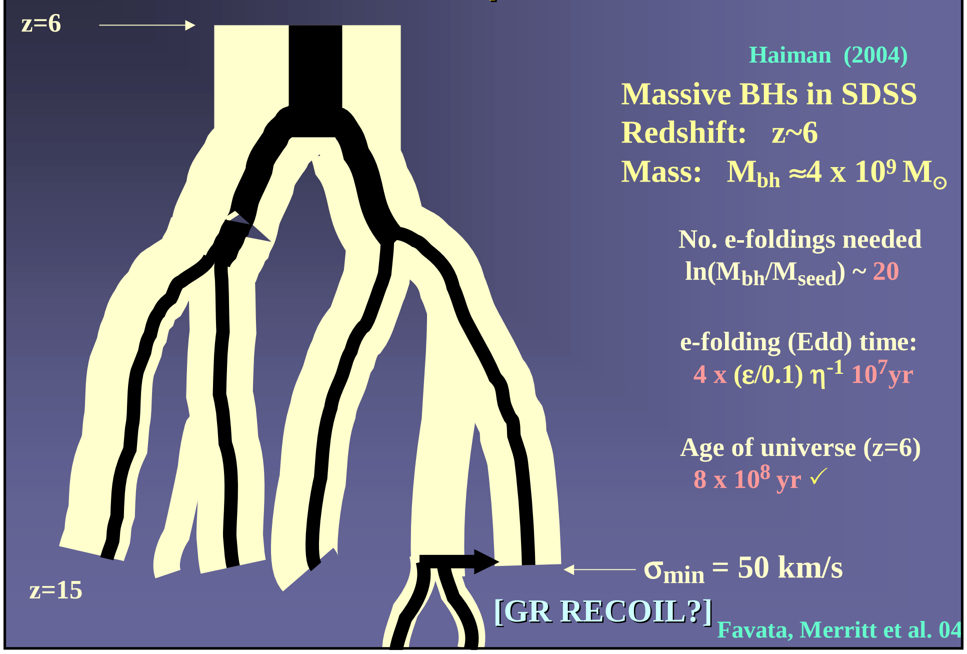


ε=20	ε=480	ε=160
×2	×60	×20

Different Sources at High Redshift

- **Pre-ionization by early BHs**
  - X-rays partially ionize IGM (Oh; Venkatesan & Shull)
  - early seed BHs sufficient (Ricotti & Ostriker 2004 Madau et al. 2004)
  - Soft X-ray background?
- **Decaying particles?**
  - sterile neutrinos with m~100 MeV (Hansen & Haiman 2003)
  - neutrino → electron → X-ray photon
  - Narrow m range allowed by CMB (Chen & Kamionkowski 2003 Pierpaoli 2003)

Growth of a Supermassive BH



Haiman (2004)

Massive BHs in SDSS
Redshift: z~6
Mass: $M_{bh} \approx 4 \times 10^9 M_\odot$

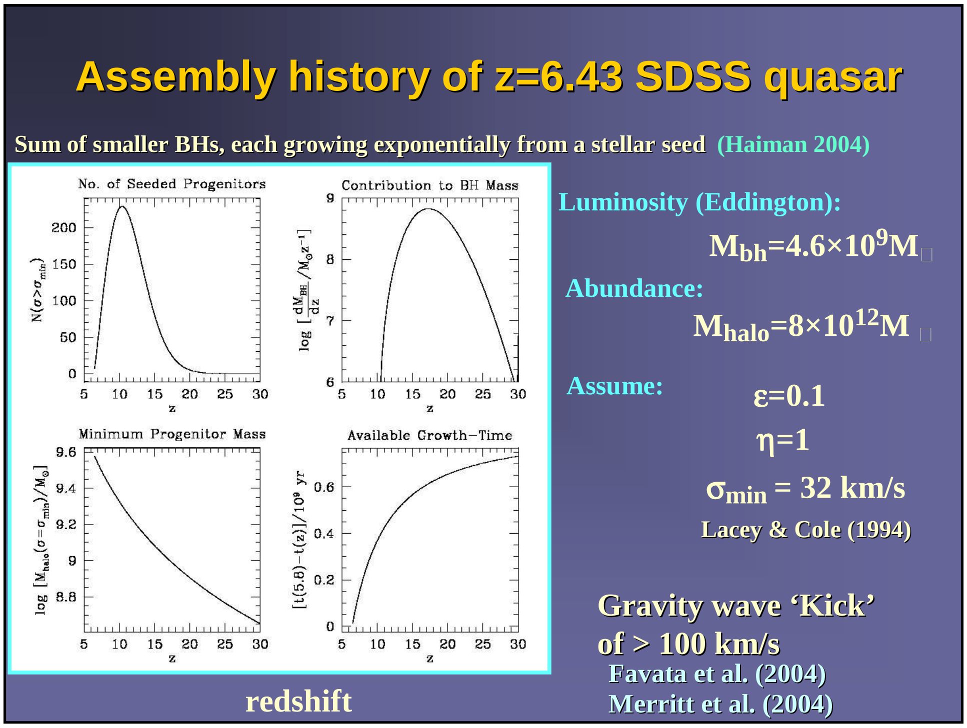
No. e-foldings needed
$\ln(M_{bh}/M_{seed}) \sim 20$

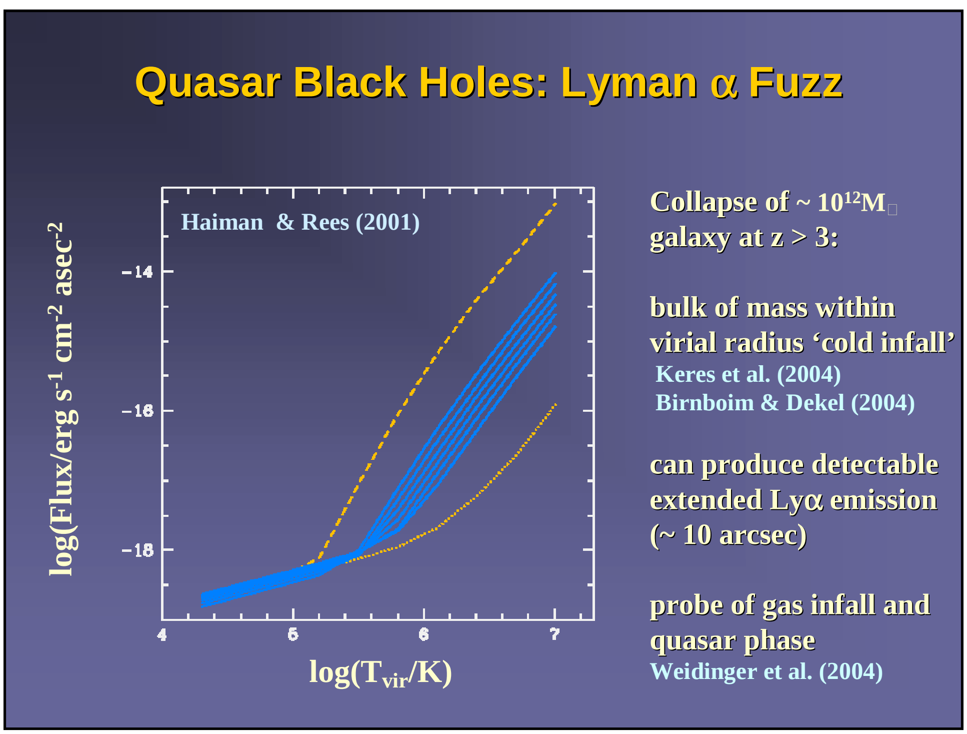
e-folding (Edd) time:
$4 \times (\epsilon/0.1)\, \eta^{-1}\, 10^7$yr

Age of universe (z=6)
8×10^8 yr ✓

Gravitational Lensing of SDSS QSOs

- **Detection of High-Magnification Lensing:**
  - for spherical lens, high μ produces multiple images
  - No 2nd image on HST images of 4 high-z QSOs to 0.3” resolution (Richards et al. 2004)
- **Magnification without Multiple Images** (Keeton, Kuhlen & Haiman 2004)
  - ellipticity and/or shear can give high μ
  - average over realistic e, γ distributions
  - dwarfs (NFW), galaxies (SIS), clusters (NFW)
- **Fraction of Lens Systems without 2nd Image**
  - single image: 5-10% (mostly NFW)
  - 2nd image too faint or unresolved: 24-1% (mostly SIS)


Assembly history of z=6.43 SDSS quasar
Sum of smaller BHs, each growing exponentially from a stellar seed (Haiman 2004)
No. of Seeded Progenitors
Contribution to BH Mass
Minimum Progenitor Mass
Available Growth–Time
redshift
Luminosity (Eddington):
$M_{bh}=4.6\times10^9 M_\odot$
Abundance:
$M_{halo}=8\times10^{12} M_\odot$
Assume:
$\epsilon=0.1$
$\eta=1$
σ_{min} = 32 km/s
Lacey & Cole (1994)
Gravity wave 'Kick'
of > 100 km/s
Favata et al. (2004)
Merritt et al. (2004)


Quasar Black Holes: Lyman α Fuzz
Haiman & Rees (2001)
log(Flux/erg s^{-1} cm^{-2} asec^{-2}
log(T_{vir}/K)
Collapse of ~ $10^{12} M_\odot$
galaxy at z > 3:
bulk of mass within
virial radius 'cold infall'
Keres et al. (2004)
Birnboim & Dekel (2004)
can produce detectable
extended Lyα emission
(~ 10 arcsec)
probe of gas infall and
quasar phase
Weidinger et al. (2004)

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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 ?**

Future Probes of Neutral Hydrogen

- **Lyman α spectra** **(in lieu of a GRB afterglow…)**
  - Systematic effects of IGM on spectral shape
  - Abundance / luminosity function towards high z

  Mesinger, Haiman & Cen 2004; Rhoads & Malhotra 2002
  Hu et al 2002; Haiman 2002

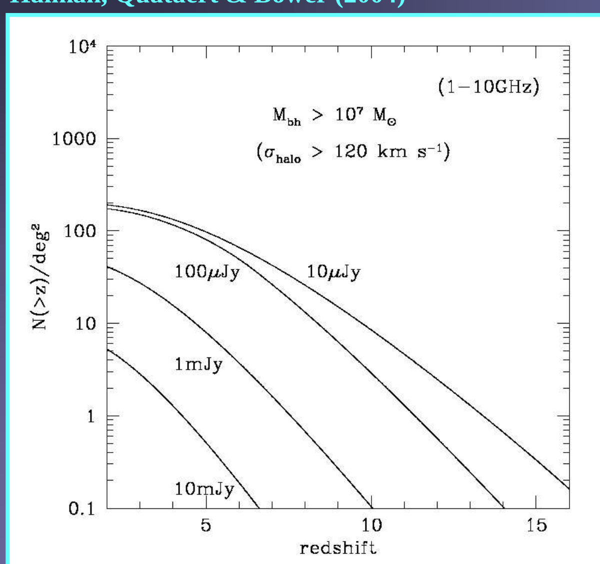
- **Redshifted 21cm signatures**

  Spin temperature can be decoupled from CMB temperature
  - tomography (map/spectra) Madau et al. 1997; Iliev et al. 2002; Ciardi & Madau 2003; Chen & Miralda-Escude 2003
  - radio "Gunn-Peterson trough" (small τ) Shaver et al. 1999
  - radio "Lyα forest" Furlanetto & Loeb 2002; Carilli et al. 2002

- **Metal Tracers**
  - OI has τ ~ 1 if $Z \sim 10^{-3} Z_{\odot}$ Oh 2002
  - other metals (fine structure transitions) Sunyaev et al. 2004

Direct Detections in Radio

Haiman, Quataert & Bower (2004)



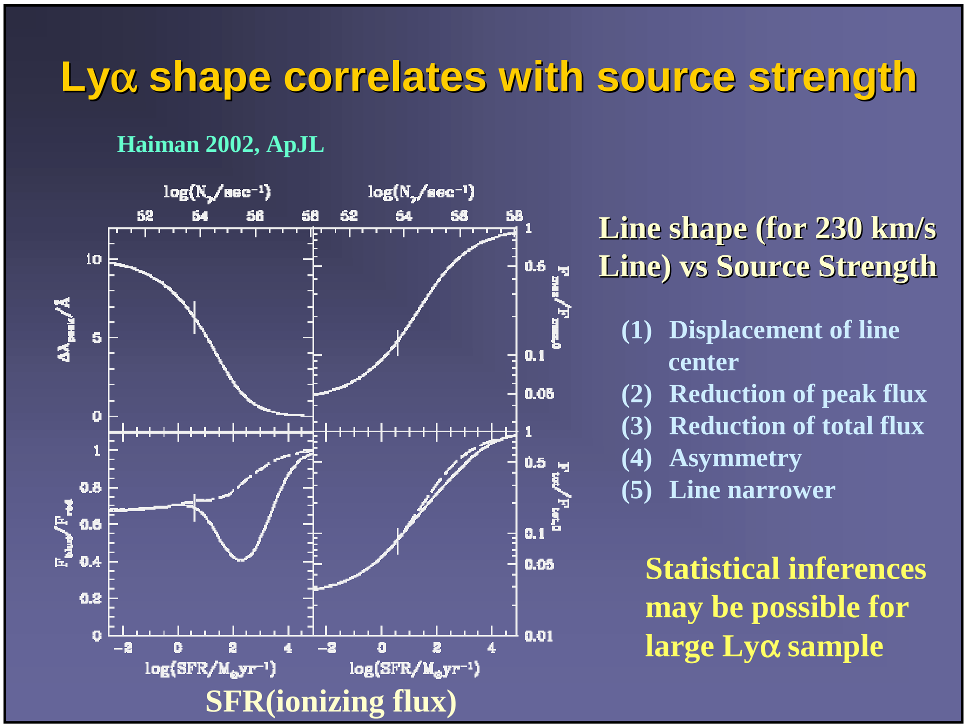
Model assumes

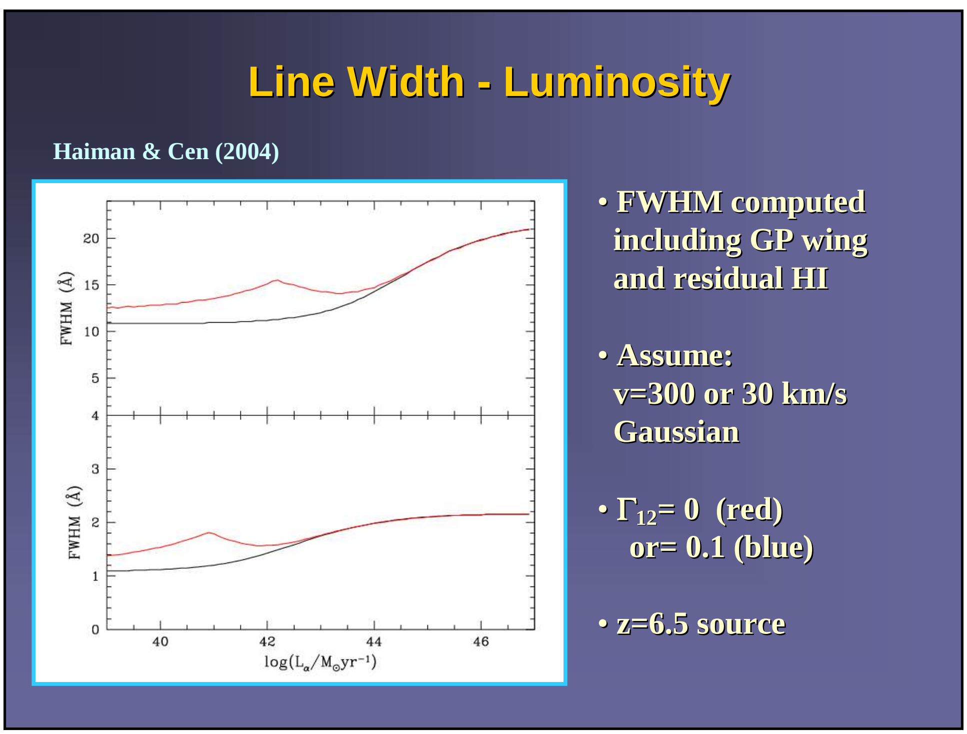
$M_{bh} \propto M_{halo}^{5/3}(1+z)$ (feedback; Silk & Rees 1998)

RL distribution from FIRST-SDSS sample (Ivezic et al. 2003)

Duty cycle of 2×10^{7}yr

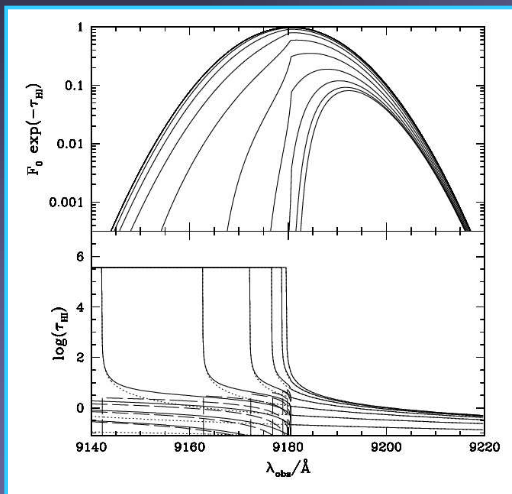
Minimum BH mass $M_{bh} > 10^{7} M_{\odot}$


Lyα shape correlates with source strength
Haiman 2002, ApJL
log(Nγ/sec⁻¹)
52 54 56 58
log(SFR/M⊙yr⁻¹)
SFR(ionizing flux)
Line shape (for 230 km/s Line) vs Source Strength
(1) Displacement of line center
(2) Reduction of peak flux
(3) Reduction of total flux
(4) Asymmetry
(5) Line narrower
Statistical inferences may be possible for large Lyα sample


Line Width - Luminosity
Haiman & Cen (2004)
FWHM (Å)
log(Lα/M⊙yr⁻¹)
• FWHM computed including GP wing and residual HI
• Assume: v=300 or 30 km/s Gaussian
• Γ12= 0 (red) or= 0.1 (blue)
• z=6.5 source

Line Shapes - Luminosity

Haiman & Cen (2004)

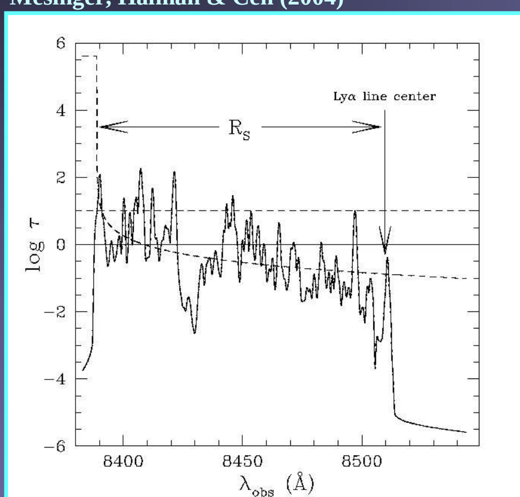


- 39<log L(Lyα)<45
- Γ_{12}= 0
- z = 6.5

Transition from residual HII to GP wing domination around log L(Lyα) ~ 42.5

Inferring the Neutral Fraction

Mesinger, Haiman & Cen (2004)

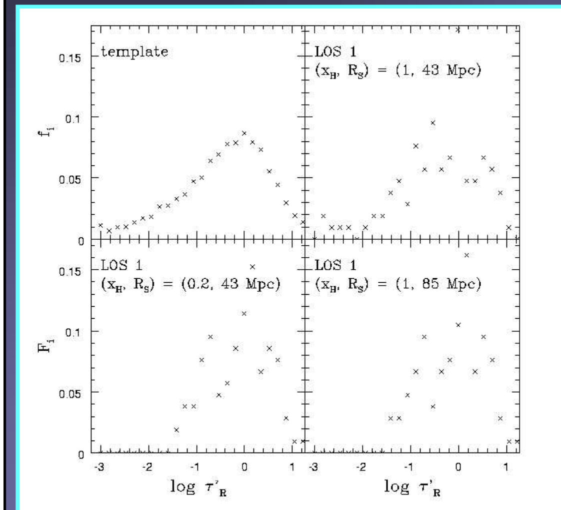


- Mock spectrum from a hydro simulation
- Assume:
  x(HI) = 1
  Rs = 40 Mpc
- Recover x and R from spectrum

Assumes
1) source template
2) IGM density field

Inferring the Neutral Fraction

Mesinger, Haiman & Cen 2004



- **Top left: template for density distribution**
- **Top: Reconstruction with correct (x, R)**
- **Bottom: Reconstruction with incorrect (x, R)**

x=1 vs 10^{-2} statistically distinguishable with 10-30 bright quasars (incl. template uncertainty)

Electron Footprints on the CMB

- **CMB anisotropies**
  - damping of temperature anisotropy (geometrical, *l* □ 10)
  - boosts large-angle polarization anisotropy (l □ 10)

  }τ(z)
  - small scale SZ effects (Doppler, *l* □ 3000; Santos et al. 2003)

    (energy, *l* □ 1000; Oh et al. 2003)

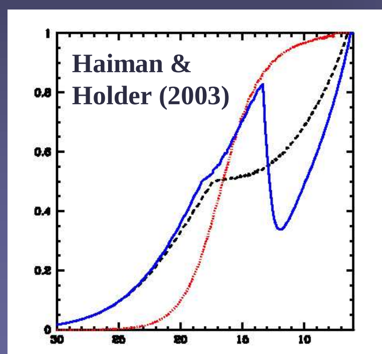
  }τ, b
- **Distortions of mean spectrum**
  - Compton heating: y=1/4 Δu/u ~ 10^{-5}
  - measurable with improved FIRAS/COBE limits

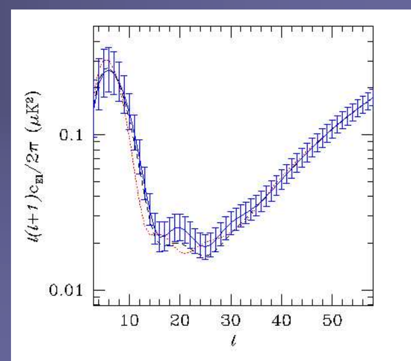
  (Fixsen & Mather 2002)

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





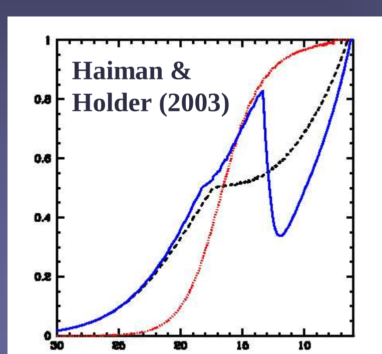
Redshift

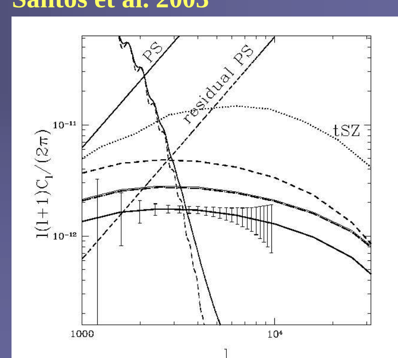
Small-Angle Temperature Spectrum

- Three reionization histories with same **τ=0.16**
- Patchiness (not the density fluctuations) dominates signal
- Measurable at **10^3 □ l □ 10^4** with ACT, SPT
- Provides information on effective bias (**signal ∝ τ×bias^2**)

Santos et al. 2003

X_e





Redshift ***l***

Conclusions

1. ΛCDM "explains" reionization, but WMAP+SDSS a puzzle
2. Different ionization stages due to different source pops
   - high-z population (BHs?), followed by normal one (stars)
3. Future CMB observations will probe free electrons
   (***evolution*** with redshift + ***topology*** at z=10-30)
4. Lyα spectra and 21cm studies will probe neutral hydrogen
   (***evolution*** with redshift + ***topology*** at z=6-10)

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