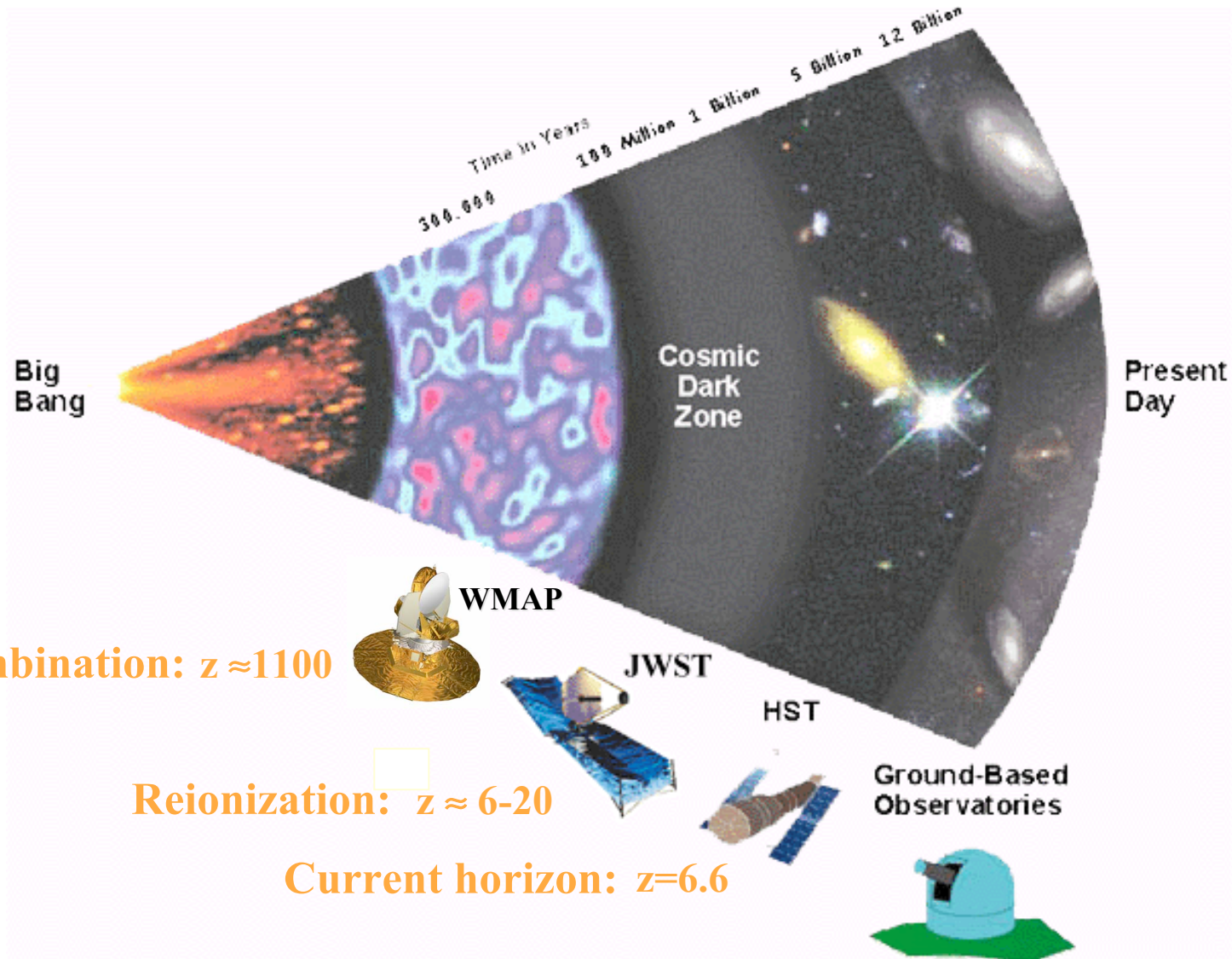


Observing the First Stars and Black Holes

Zoltán Haiman

Columbia University

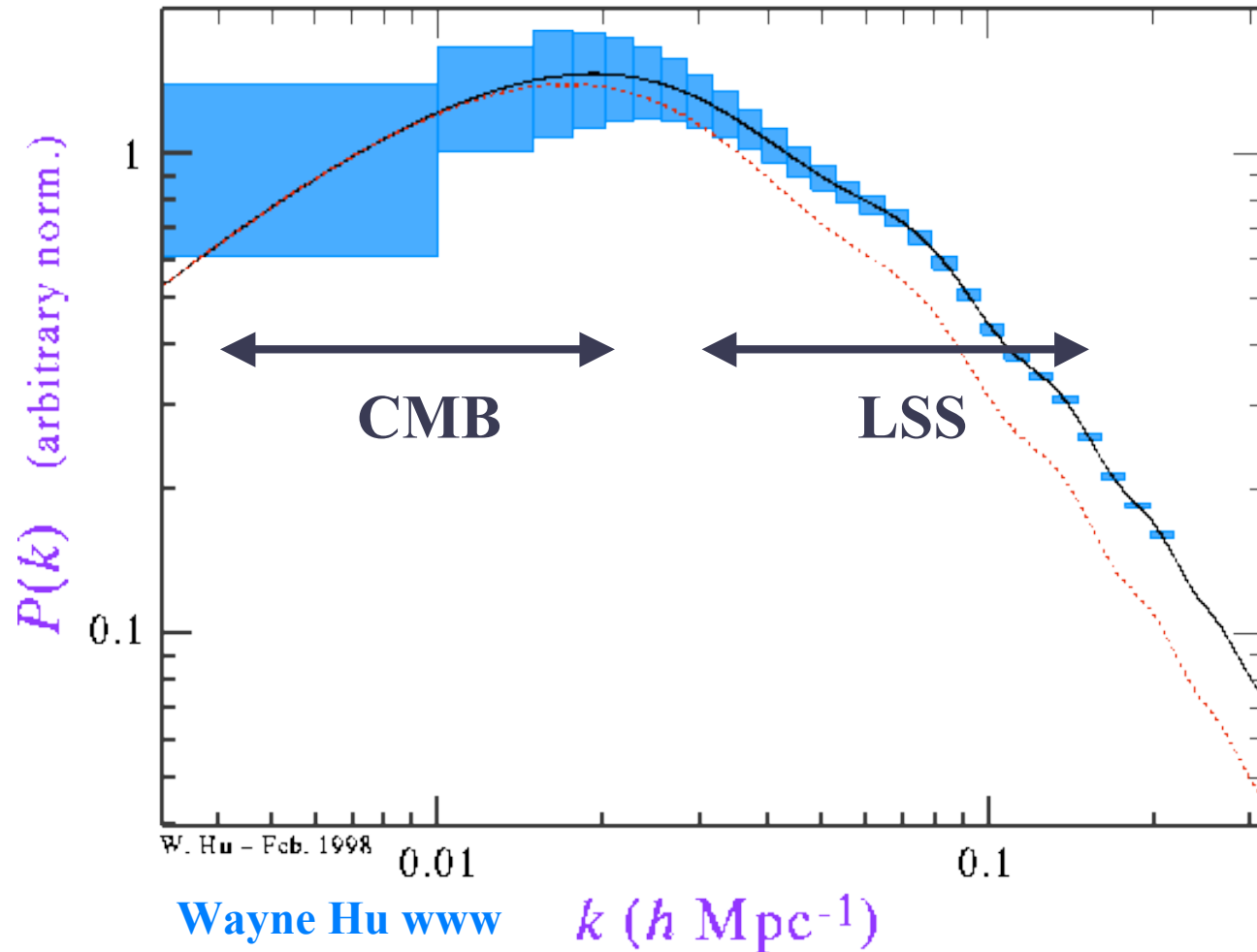
The Dark Age: Can we Close the Gap?



Outline of Talk

- How large were the first objects ? [4]
 - stellar clusters with $1 < N < 10^6$ stars ?
 - black holes with $10 M_{\odot} < M < 10^6 M_{\odot}$?
- Can future instruments reveal (feedback) processes? [11]
 - can we go deep enough in the LFs to see it directly ?
 - can we detect IGM ionization / metallicity (or lack of it: pop III ?)
- The first black holes [5]
 - can we clarify how they formed and evolved into quasars
 - finding high-z SMBHs with LISA (and their counterparts)
- Assembly of proto-galaxies: large-scale gas in-fall [5]
 - can we detect diffuse Lyman / Balmer emission ?
 - is cooling radiation detectable ?

Seed Fluctuations on Small Scales



extrapolation
by a factor of
about 100 in
linear scale

mass function
of DM halos
directly tested
in simulations at
 $z=20$; $M=10^5 M_{\odot}$

Yoshida et al. (2003)
Mesinger et al. (2006)

Stars and BHs in the first minihalos

- **STARS: METAL FREE, VIA H₂ COOLING**

- (a single?) massive star, with harder spectra
- boost in ionizing photon rate by a factor of ~ 20
- return to “normal” stellar pops at $Z \gtrsim 10^{-3.5} Z_{\odot}$

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

- **SEED BLACK HOLES: ($\sim 10^{2-6} M_{\odot}$)**

- remnants of massive (non-rotating) metal free stars
($25 M_{\odot} \lesssim M \lesssim 140 M_{\odot}$ and $M \gtrsim 260 M_{\odot}$ Heger et al 2001)
- boost by ~ 10 in number of ionizing photons/baryon
- harder spectra up to hard X-rays: smoother reionization
- must eventually evolve to quasars and remnant holes
(Oh; Venkatesan & Shull; Haiman, Abel & Rees; Haiman & Menou)

- **DETECTABLE ONLY INDIRECTLY**

- individual explosive remnants (SNe, GRBs, metal patterns)
- impact on IGM (reionization) and source pop. (feedback)

Gas in Collapsing DM Halos Exposed To:

- **EARLY COSMIC BACKGROUNDS:**

- soft UV (11-13.6 eV) photo-dissociates H₂
- soft X-rays (~1 keV) catalyze H₂ formation

- **UV FLUX OF NEARBY SOURCES (>13.6 eV):**

- photo-evaporation (minihalos with $\sigma < 10$ km/s)
- photo-dilution (halos with $10 \text{ km/s} < \sigma < 50$ km/s)

- **PAST ACTIVITY IN FOSSIL HII REGION:**

- gas retains heat (“entropy floor”)
- extra free electrons from incomplete recombination

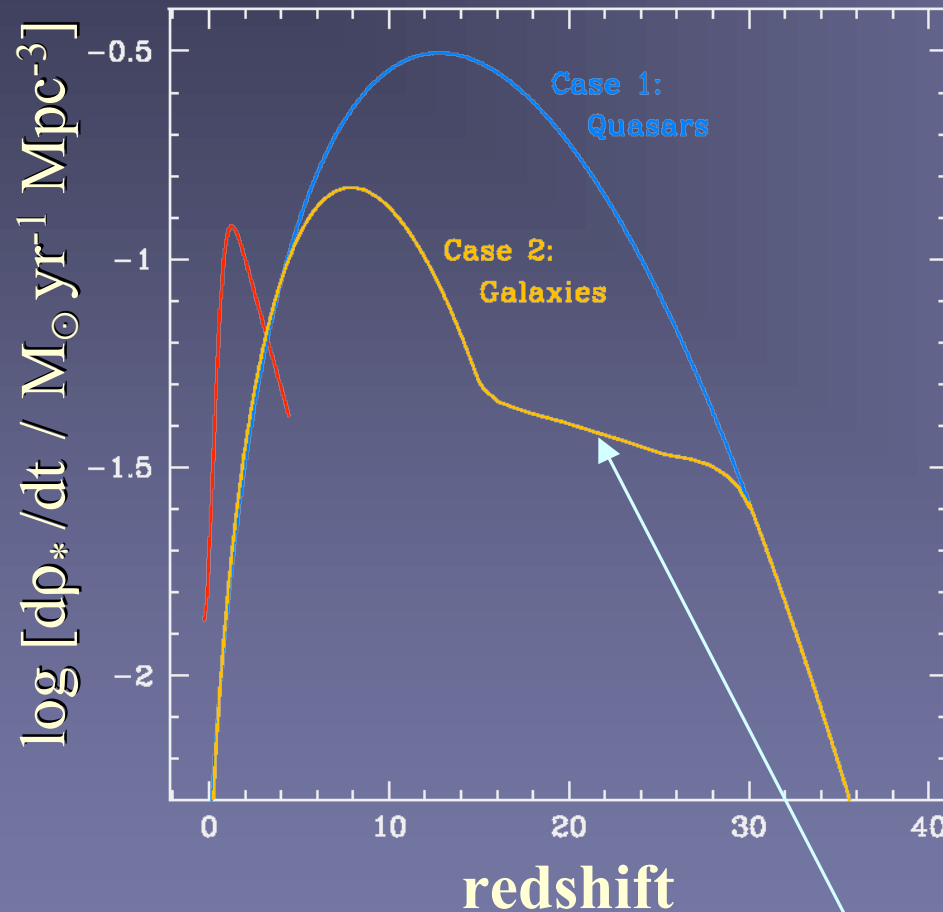
- **OTHER EFFECTS:**

- SN blast waves, metal pollution (pop III → pop II)
- internal feedback (metals, UV, SNe) inside minihalos

Do most minihalos fail to form stars or black holes?

SF/Reionization History Self-Regulates?

Haiman, Abel & Rees (2000)



Case 1 : No net feedback

reionization completed early
small halos
closely spaced
smooth
He/H close in time

Case 2 : Negative feedback

reionization completed later
larger halos,
farther spaced
more patchy
He/H farther in time

IF feedback regulates reionization history, then there will be a period with a robust 'steady state' solution for the star formation history - need to know $J_{\text{crit}}(M_{\text{halo}}, z)$

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Characteristic Halo Mass Scales

(masses at redshift $z=10$)

• Jeans Mass	$10^4 M_{\odot}$	$T_{\text{vir}}=20 \text{ K}$	$z=20$
• H₂ cooling	$10^5 M_{\odot}$	$T_{\text{vir}}=10^2 \text{ K}$	$z=17$
• HI cooling	$10^8 M_{\odot}$	$T_{\text{vir}}=10^4 \text{ K}$	$z=9$
• Photo-heating	$10^{10} M_{\odot}$	$T_{\text{vir}}=2 \times 10^5 \text{ K}$	$z=5$

JWST: $1 \text{ nJy} \rightarrow M_* \approx 10^7 M_{\odot}$ or $M_{\text{bh}} \approx 10^5 M_{\odot}$
(10^5 sec) (at $z=10$)

→ few sources / amin^2

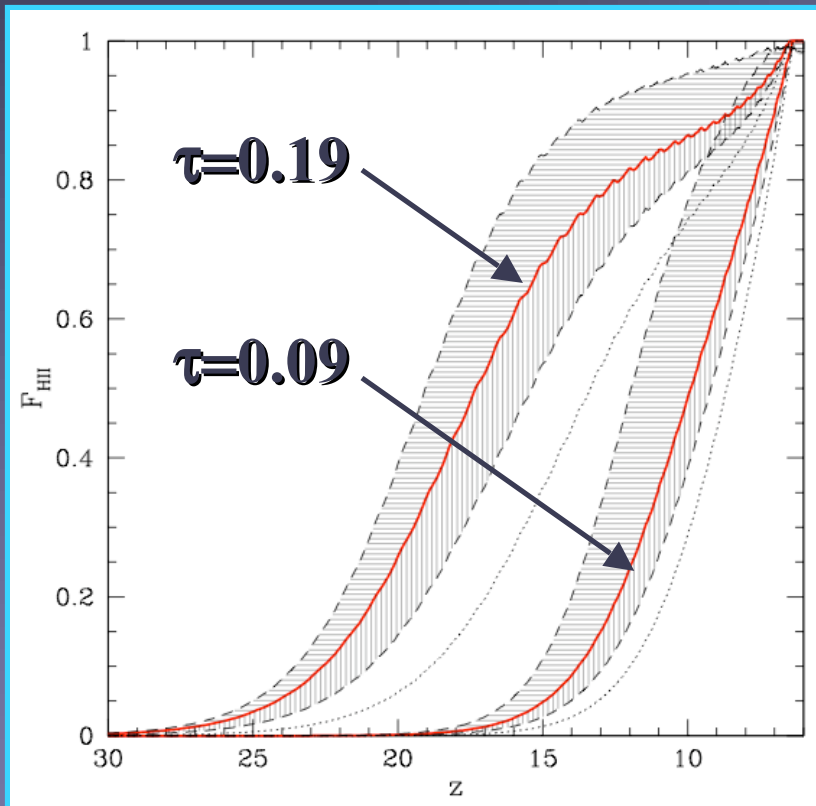
2 σ peak
collapse
redshifts



Evidence for Feedback from WMAP

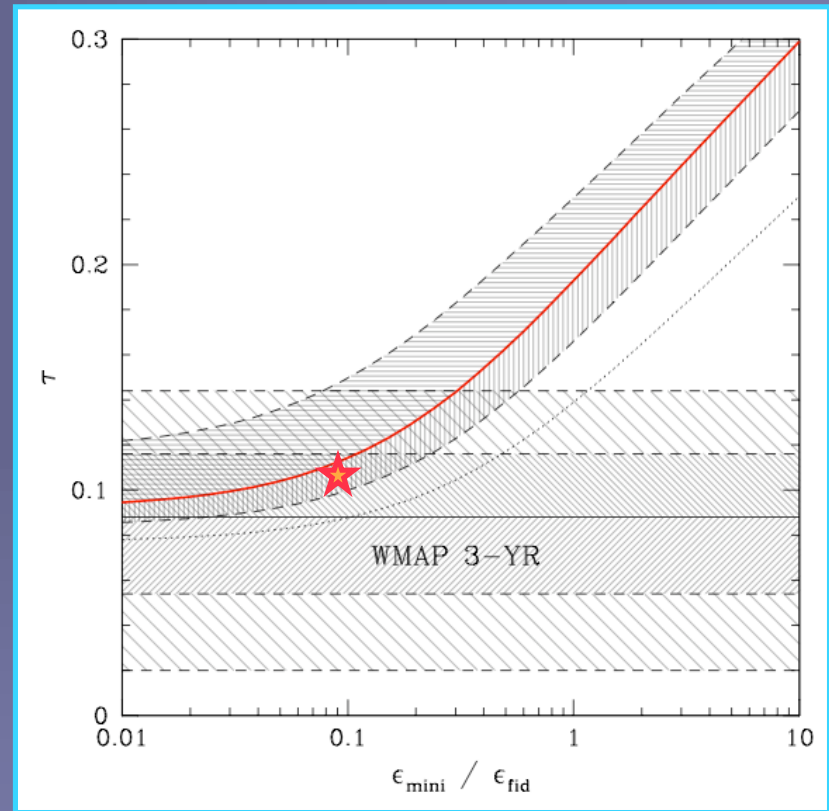
Haiman & Bryan (2006)

ionized volume fraction



redshift

Optical depth



efficiency

Minihalo contribution suppressed by a factor of ~ 10

How Will We Detect the Feedback ?

- **Reionization could be accompanied by a drop in the global star formation rate (low-mass halos are suppressed)**
size , location and sharpness of any drop is uncertain

Possibilities for Detection

- **Evolution of 21cm signal** (Furlanetto's talk)
 - mean brightness and fluctuations
- **Large-angle CMB polarization** (Kaplinghat et al. 2002, Holder & Haiman 03)
 - ionization history shape (3-4 σ differences)
- **Small-angle kSZ and tSZ power spectrum** (Santos et al. 03, Oh et al. 03)
 - Doppler / energy effects w/ACT, SPT
- **Tomography of Ly α emitters** (Xiaohui Fan's talk)
 - LF (compared to continuum) (Dijkstra et al. 2007)
 - systematic effect of IGM on line shape (ZH 02, Santos 04)

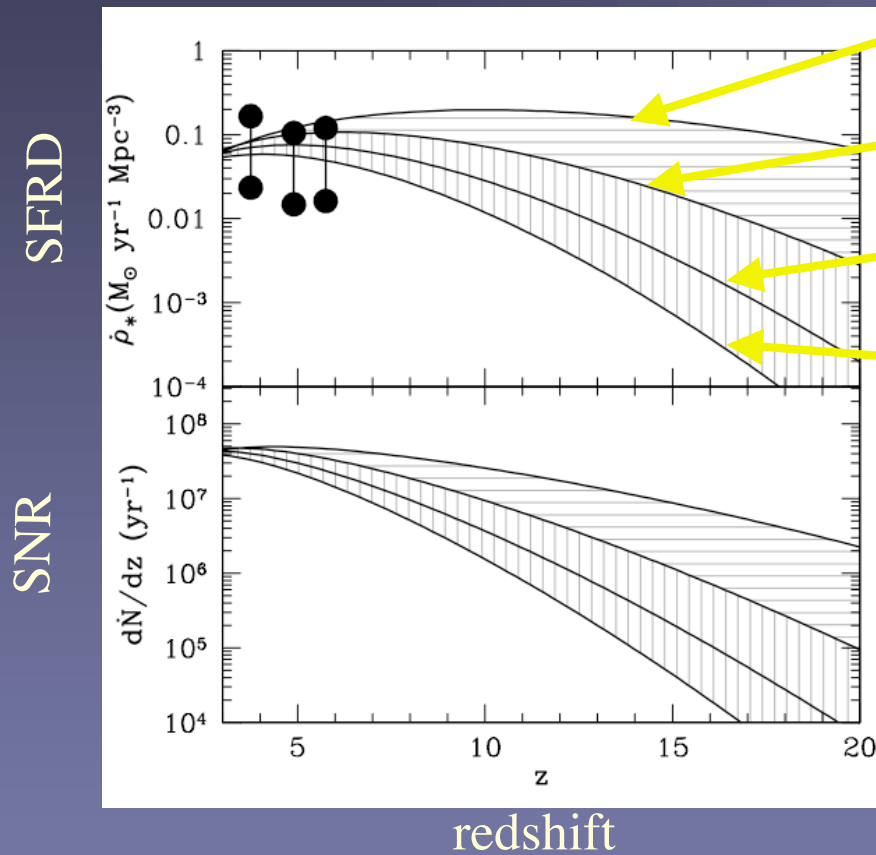
How Will We Detect the Feedback ?

More Possibilities for Detection

- **Non-monotonic Evolution of IGM opacity** (Cen & McDonald 2002)
 - improve S/N from $z > 5$ quasar spectra
- **Fluctuations in IGM opacity** (Wyithe & Loeb 2006)
 - need more sources, deeper spectra (aliasing, bias)
- **Direct detection in “Lilly-Madau diagram”** (Barkana & Loeb 2000)
 - possible only if small galaxies detectable by JWST
- **Trace global SFR with GRBs** (Mesinger, Haiman & Perna 2005)
 - $z > 5$ GRBs too rare to yield accurately trace SFR(z)
- **Trace global SFR with SNe** (Mesinger, Johnson & Haiman 2006)
 - SN brighter (detectable) and more numerous

SNe as tracers of high-z SFR

Mesinger, Johnson & Haiman (2006)



$T_{\text{vir}} > 300 \text{ K}$ ($v_{\text{circ}} > 3 \text{ km/s}$)

$T_{\text{vir}} > 10^4 \text{ K}$ ($v_{\text{circ}} > 17 \text{ km/s}$)

$T_{\text{vir}} > 4.5 \times 10^4 \text{ K}$ ($v_{\text{circ}} > 35 \text{ km/s}$)

$T_{\text{vir}} > 1.1 \times 10^5 \text{ K}$ ($v_{\text{circ}} > 55 \text{ km/s}$)

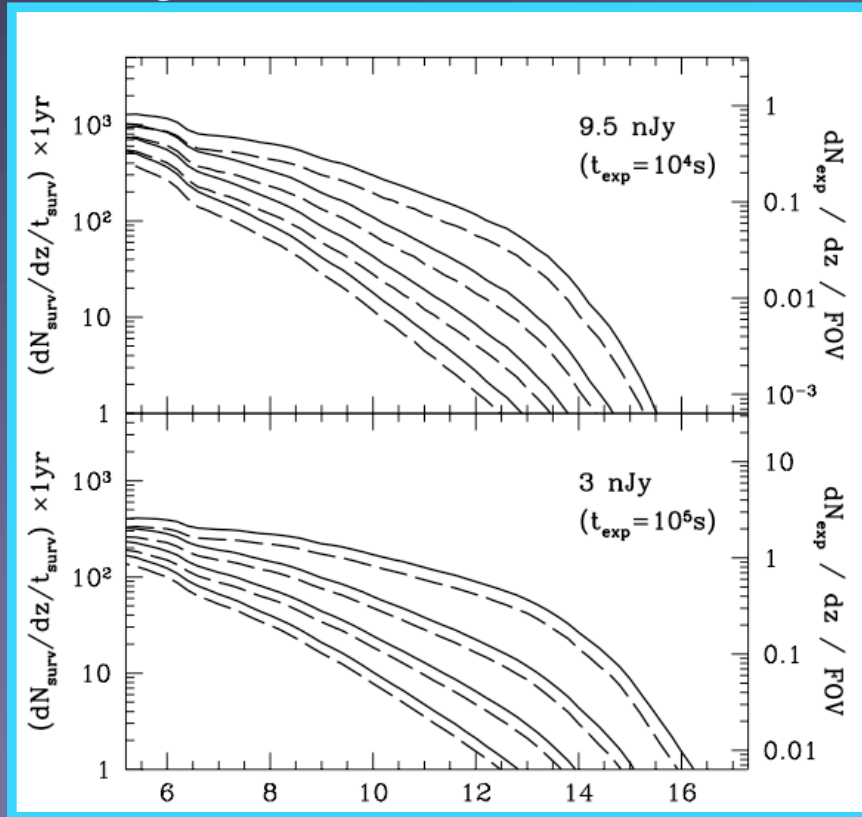
Assume:

- SFR traces formation of dark matter halos
- $\epsilon_* = 0.1$
- Salpeter IMF
($0.007 \text{ SNe}/M_\odot$)

points indicate results from GOODS
(Giavalisco et al. 2004)

Expected SN Rate Observed with JWST

Mesinger, Johnson & Haiman (2006)



redshift

4 - 24 SNe per ~ 10 arcmin² field
at $z \geq 5$ at flux threshold of 3 nJy

Assumed SNe properties:

- 1/2 of Type IIP; 1/2 of Type IIL
- Peak magnitude distributions (Richardson et al. 2002)
- Lightcurve shapes (Doggett & Branch 1985)
- Template spectrum (Baron et al. 2000)

Assumed JWST properties:

- FOV: $2.3' \times 4.6'$
- Simultaneous imaging in 2 filters
- Detection threshold of 3 nJy (10σ) in $4.5 \mu\text{m}$ band in 10^5 sec
- Detection threshold of 1 nJy (10σ) in $3.5 \mu\text{m}$ band in 10^5 sec

Metal Enrichment

1. When was significant fraction of IGM enriched?
2. When did metal-free star-formation end?

- First stars appear early ($z \sim 20-30$)
- Trace amount of metals modify stellar structure
- No metal-free stars detected in local universe

Metal-free stars a long-gone curiosity?

BUT

- Metal mixing efficiency: large vs small scales
- Micro-mixing timescale?
- Minihalos: reservoirs of metal-free gas?

(to $z \sim 5$; e.g. Cen & Wyithe 2006)

Diagnosing PopIII Stars: He 1640Å Line

[Assumption: escape fraction of ionizing photons small]

(Oh, Haiman & Rees; Tumlinson & Shull)

1. Mini-quasars:

$F_\nu \sim \nu^{-\alpha}$ with $\alpha=1-1.8$ (Elvis et al. 1994; Zheng 1998)

$$J = 25 \left(\frac{R}{1000} \right) \times \left(\frac{1+z}{10} \right)^{-1} \times \left(\frac{M_{\text{BH}}}{10^5 M_\odot} \right) \times \left(\frac{4^{-\alpha}}{0.25} \right) \times (1 - f_{\text{esc}}) \text{ nJy}$$

2. Metal-Free Starbursts:

$Q = N(>54.4\text{eV})/N(>13.6\text{eV})$ (Tumlinson & Shull 2000)

$$J = 11 \left(\frac{R}{1000} \right) \times \left(\frac{1+z}{10} \right)^{-1} \times \left(\frac{\text{SFR}}{1 M_\odot \text{yr}^{-1}} \right) \times \left(\frac{Q}{0.05} \right) \times (1 - f_{\text{esc}}) \text{ nJy}$$

1 Source per 2.3' x 4.6' observable with JWST to $z \sim 12$
(together with Balmer line; Oh 2002)

Metal-Free Stars Forming at $z = 3-4$?

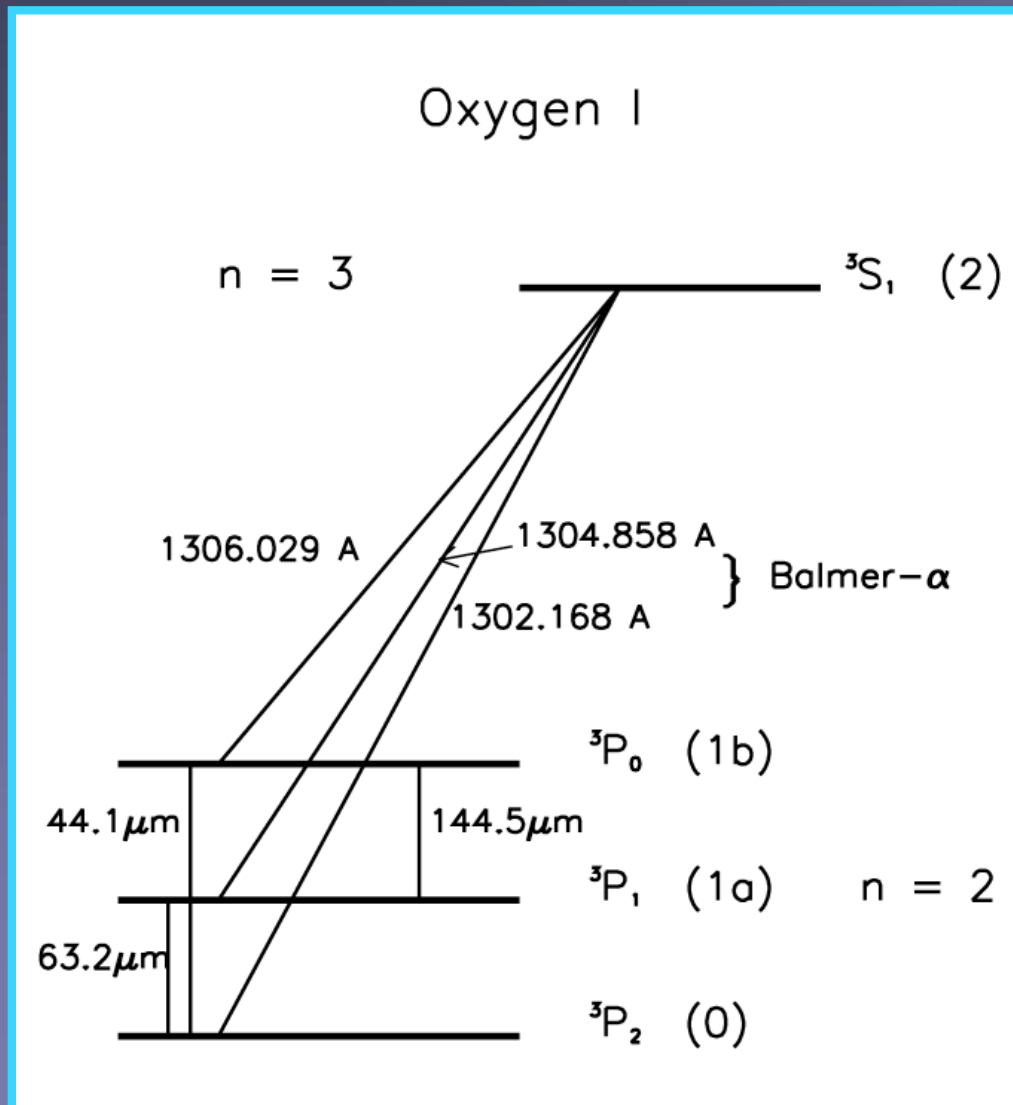
(Jimenez & Haiman 2006, Nature)

~10% stars massive, metal-free (added to normal Salpeter IMF)

- **Strong He1640 Emission Line From $z\sim 3$ LBG Composite**
 - Equivalent width 2\AA ; FWHM 1500\AA (Shapley et al. 2003)
 - Cannot be explained by normal Wolf-Rayet stars
- **Strong Hydrogen-Ionizing Continuum from $z\sim 3$ LBGs**
 - significant flux detected at $\lambda \leq 912\text{\AA}$ (Steidel et al. 2001, Shapley et al. 2006)
- **Strong Lyman α Emitters at $z\sim 4.5$**
 - EW distribution extends to $>1000\text{\AA}$ (Malhotra & Rhoads 2002)
- **Extended Lyman α Blobs at $z\sim 3$** (Matsuda et al. 2004)
 - 1/3 of the 35 candidates have too little (and blue) or no continuum

Global Metal Distribution: Oxygen Pumping

Hernandez-Monteagudo, Haiman, Jimenez & Verde (2007)



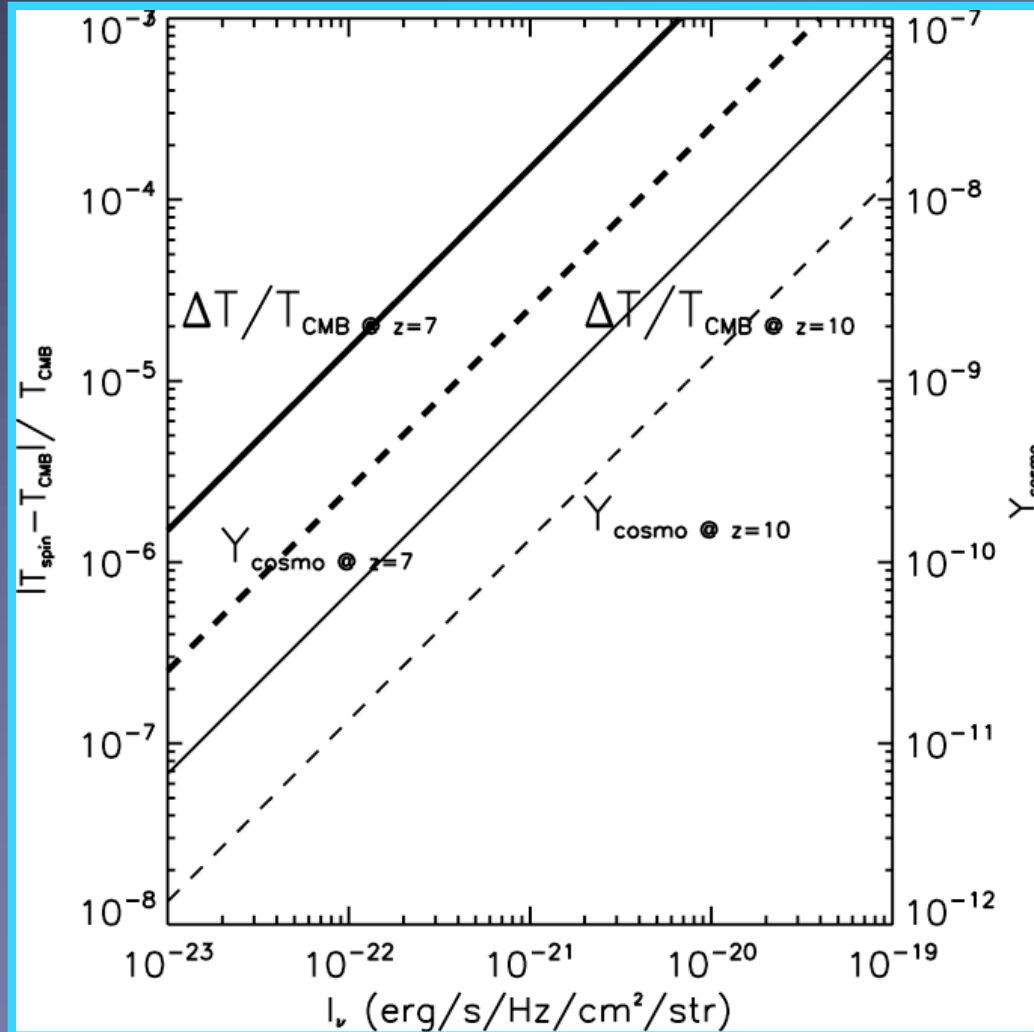
Can pumping analogous to Wouthuysen-Field process work for some metal line?

1. Abundant metal in right ionization state
2. Spin transition at detectable frequency, small A coeff
3. UV pumping at $\lambda > 1215 \text{\AA}$
4. Large enough SUVB flux

Direct probe of IGM metal pollution at early stages of reionization

Distortion of CMB Spectrum

Hernandez-Monteagudo, Haiman, Jimenez & Verde (2007a,b)



$y \approx 10^{-7}$ is produced if OI abundance is $\sim 10^{-2.5}$ solar at $z=7$, and $J(1300\text{\AA}) \sim 10$

$y \approx 10^{-7}$ achievable with state-of-the art technology and with improvements over FIRAS detector and design (?)

(Fixsen & Mather 2002)

\sim nK fluctuations on

\sim arcmin scales at

$\sim 700\text{GHz}$ detectable..?

Outline of Talk

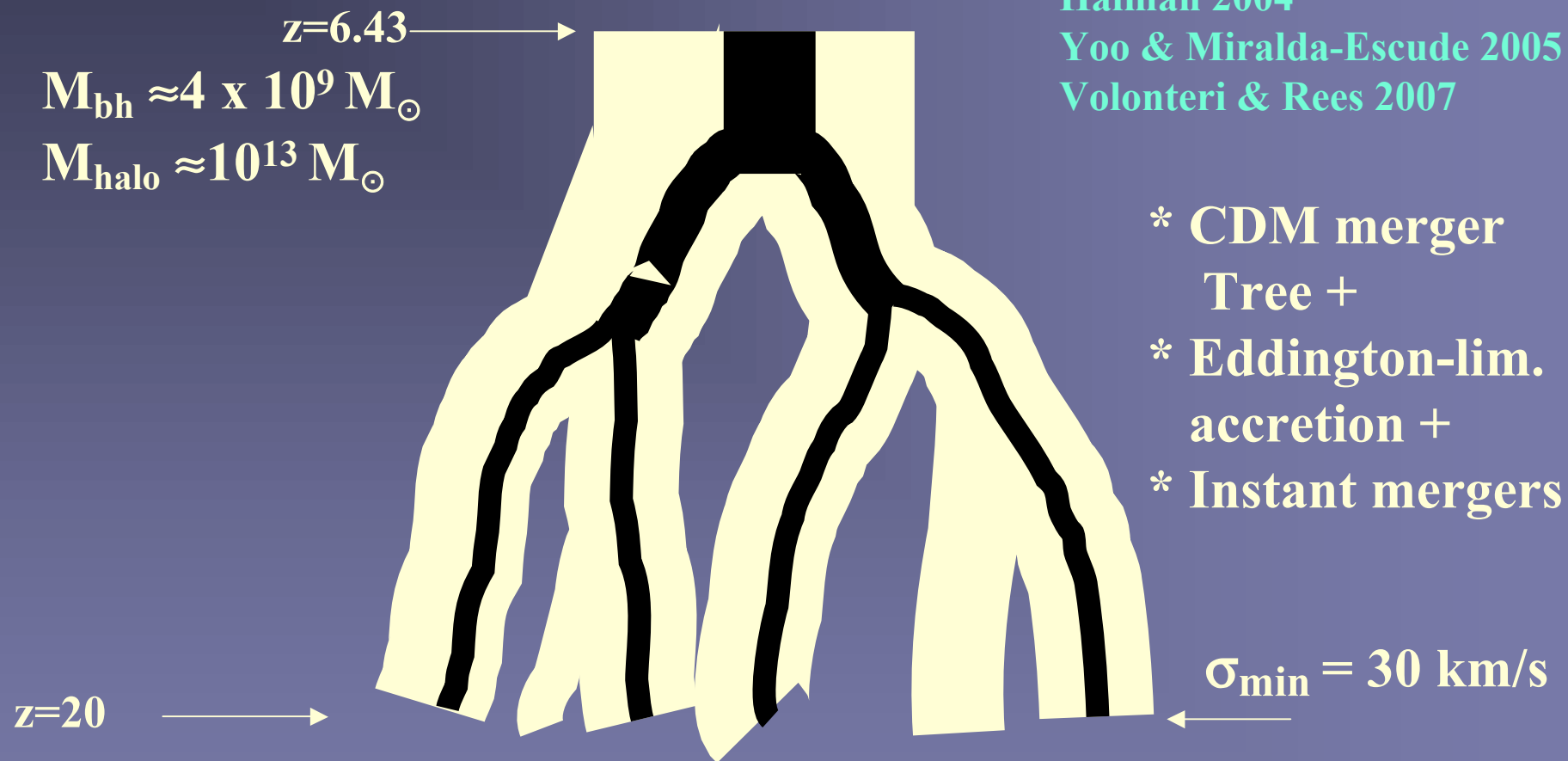
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Growth of High-z Supermassive BHs

Haiman 2004

Yoo & Miralda-Escude 2005

Volonteri & Rees 2007



1. Most of the BH mass from $z \sim 15$ seeds: must start early
2. Gravitational wave-induced kicks $> 100 \text{ km/s}$
3. A (modestly) super-Eddington accretion phase is required

Can gas in $T_{\text{vir}} > 10^4 \text{K}$ halos cool to $\sim 100 \text{K}$?

Similar to minihalos:

Rely on H_2 cooling and fragment on similar (few $100 M_{\odot}$) scales

Oh & Haiman (2002)

Main difference:

**contract to high densities
less susceptible to feedback**

**HD reduces temperature
and fragmentation scale?**

cf: direct SMBH formation

Volonteri & Rees 2005

Bromm & Loeb 2005

Begelman et al. 2006

(if there is no H_2)

Uehara & Inutsuka 2000

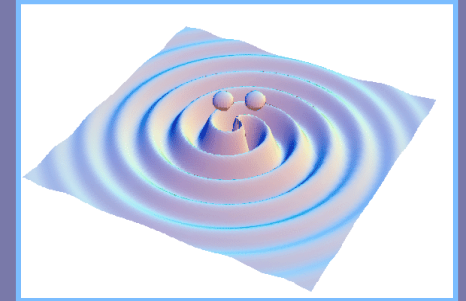
Machida et al. 2005

Johnson & Bromm 2005

Gravitational waves: LISA sensitive to $(10^5 - 10^7)/(1+z) M_{\odot}$

Gravitational Waves from BH mergers

- LISA can detect low-frequency gravitational waves from super-massive black hole binaries
 - sensitive to $(10^5-10^7)/(1+z) M_{\odot}$
- Can detect tens(?) of coalescing binaries / yr out to $z > 10$
- Cosmology: Gravity wave information alone yields $d_A(z)$
 - $f (df/dt)^{-1} \rightarrow$ automatic ‘standard siren’ (Schutz 1980)
 - limited to few % by weak-lensing fluctuations in $d_A(z)$
- Precise SMBH parameters (mass, spin, orbit)
 - can compute Eddington ratio as function of M, z , etc



Can we find an electromagnetic counterpart?

Identifying the EM Counterpart

AFTER THE MERGER IS COMPLETE:

(1) Is the GW event localized well enough in space so that error box contains a unique quasar ?

(Kocsis, Frei, Haiman & Menou 2005)

BEFORE AND DURING COALESCENCE:

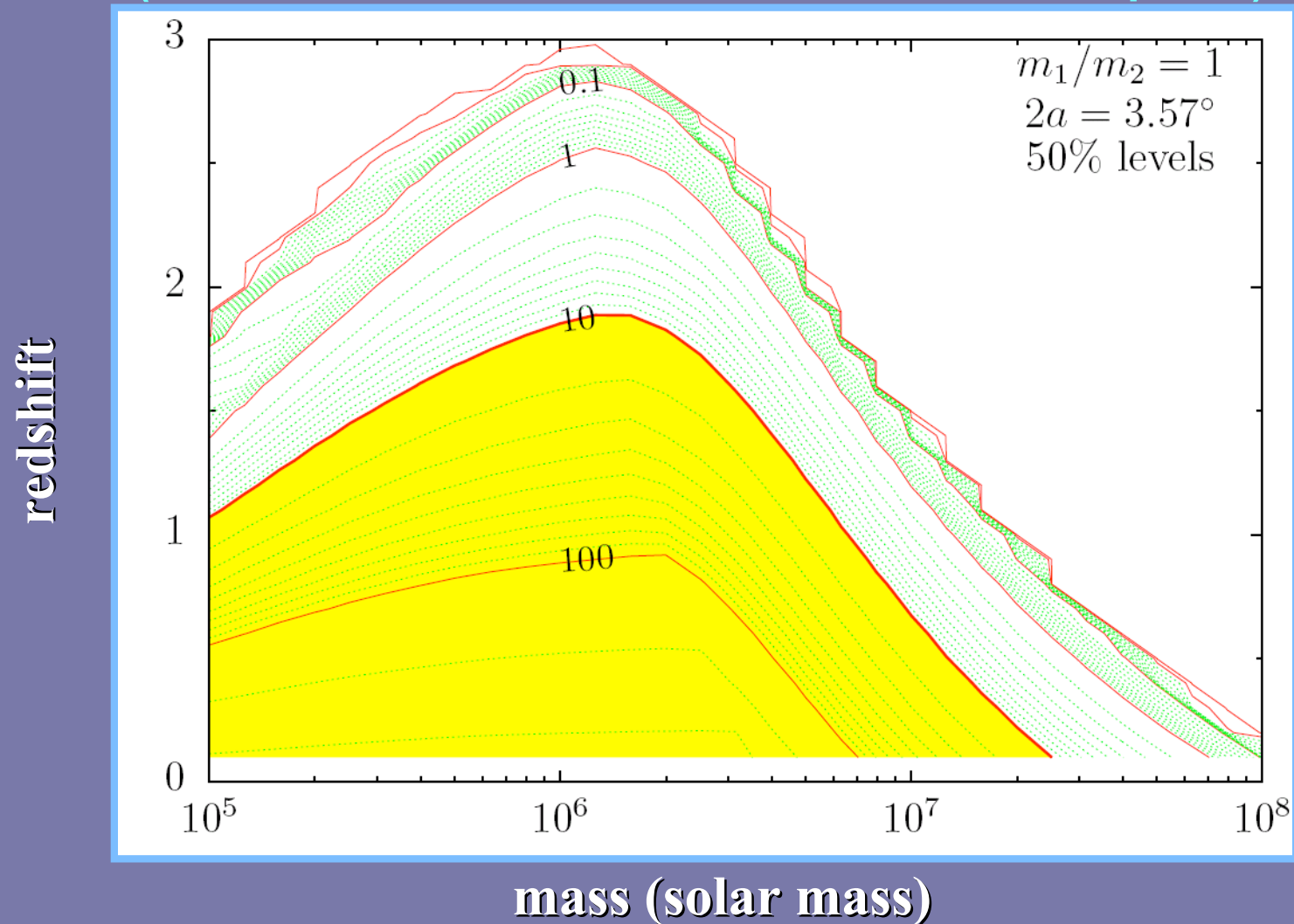
(2) Can real-time LISA data-stream localize the source well enough in advance, so that a world-wide variability search can be triggered with wide-field instruments?

(Kocsis, Haiman, Menou & Frei 2007, PRD in press)

How much advance notice from LISA?

Look-back time when sky position error shrinks down to $\sim 10 \text{ deg}^2$

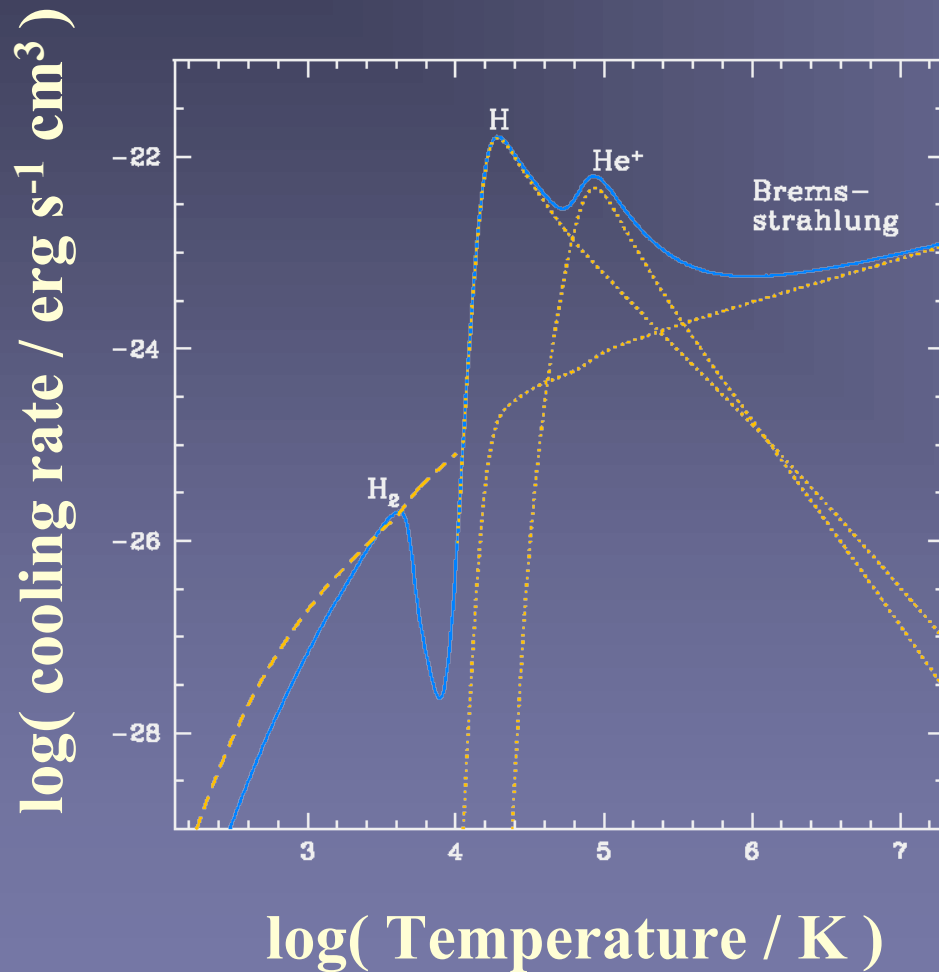
(Kocsis, Haiman, Menou & Frei 2007, PRD in press)



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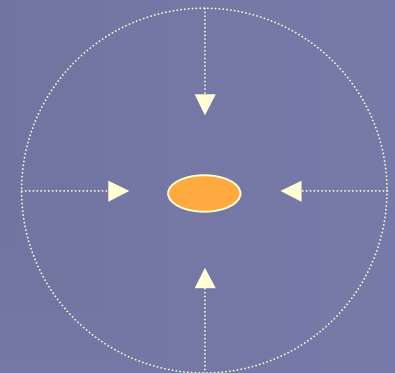
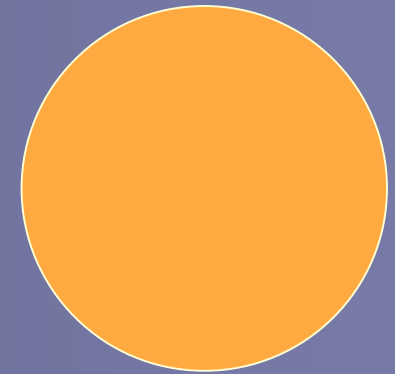
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Assembly of proto-galaxies: spatially extended gas infall ?



$$\lambda_s R_{\text{vir}} \sim \frac{R_{\text{vir}}}{10}$$

$\sim R_{\text{vir}}$



Can We Detect the Cooling Radiation?

1. How does cooling halo look like? (Haiman, Spaans & Quataert 2000)

“cooling flow” - extended Ly α “blob”

JWST limiting line flux at $3 < z < 8$:

mostly Ly α emission:

flux spread over R_{vir} :

$$F \geq 10^{-16} - 10^{-17} \text{ erg/s/cm}^2$$

$$v_{\text{circ}} \geq 150 \text{ km/s}$$

$$\Theta_{\text{vir}} \sim R_{\text{vir}} / d_A(z) \sim 5-10''$$

2. How many halos can we hope to detect ?

blind search in R=5 filter
(narrow filter can go deeper)

~1 halo per JWST field at $z=7$

~10 halos per field at $z=3$

3. What if a bright quasar turns on in a collapsing halo?

10-100 times brighter “fuzz” !

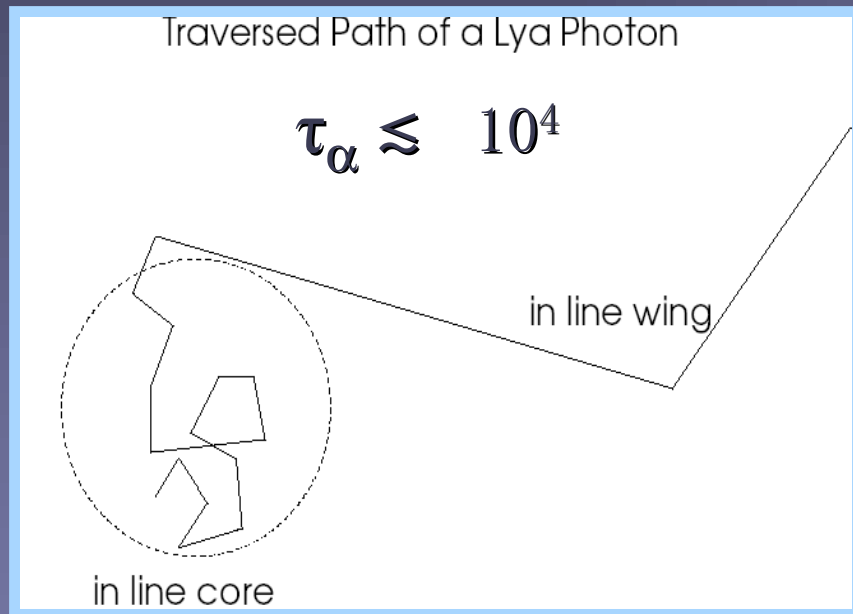
constrains galaxy formation

(Haiman & Rees 2001)

Ly α Transfer Basics

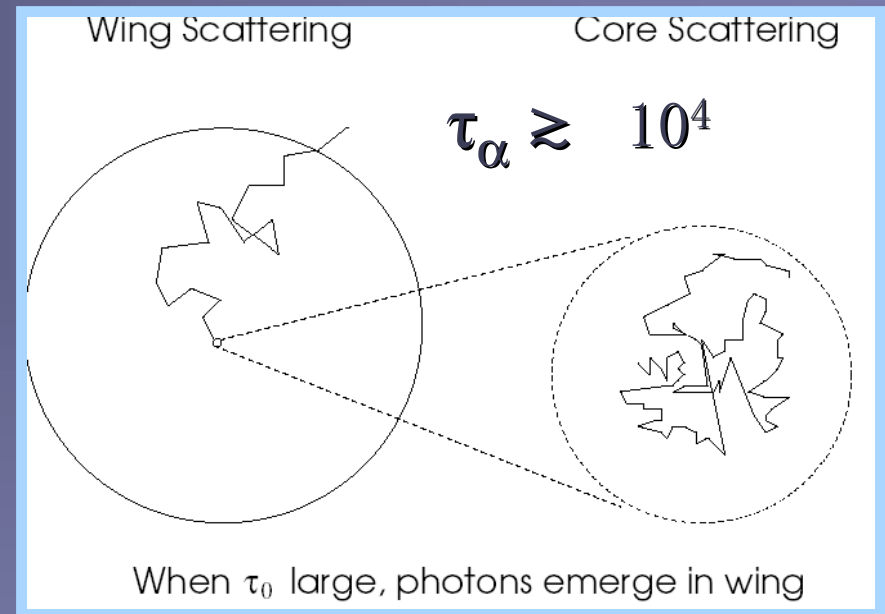
Challenge: interpretation of spatially resolved Ly α emission

Photons undergo random walk in space+frequency (Neufeld 1991)



Moderate optical depth:

photon escapes in wing
in single flight.



Extreme optical depth:

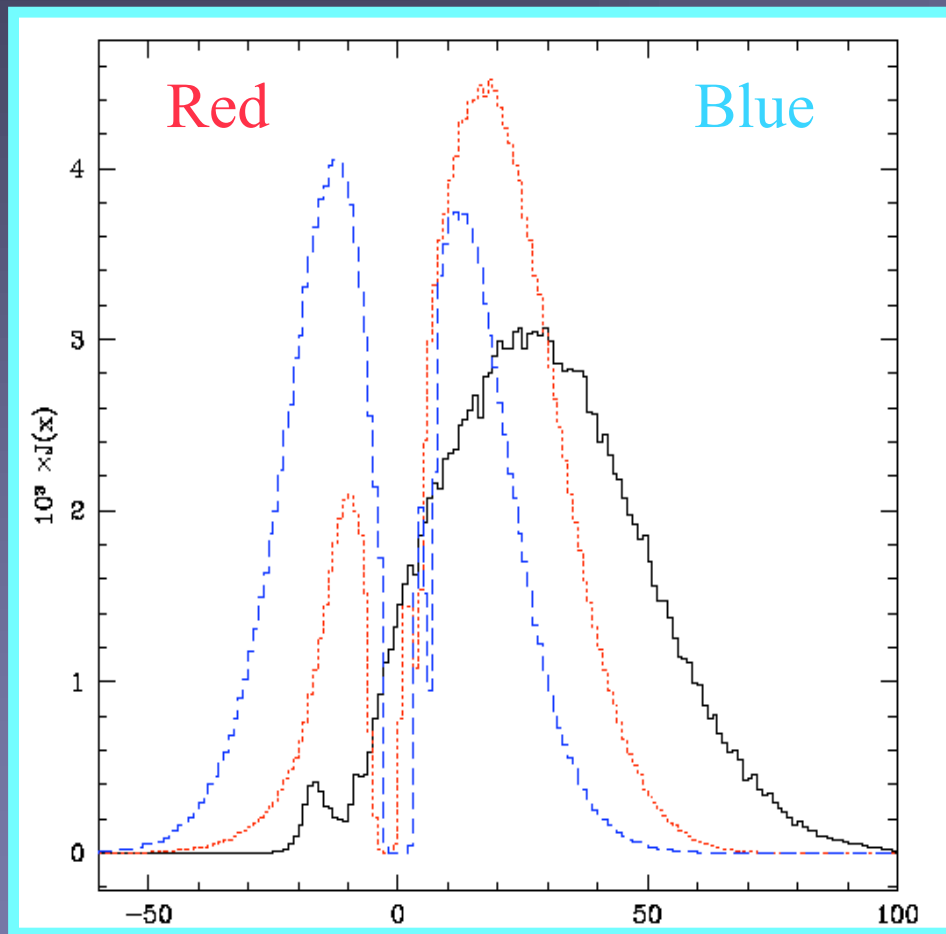
photon escapes in multi-
step "excursion".

Spectrum Emerging from Collapsing Sphere

Dijkstra, Haiman & Spaans (2006a,b)

650 km/s

-1300 km/s



$\Delta v/v_D$

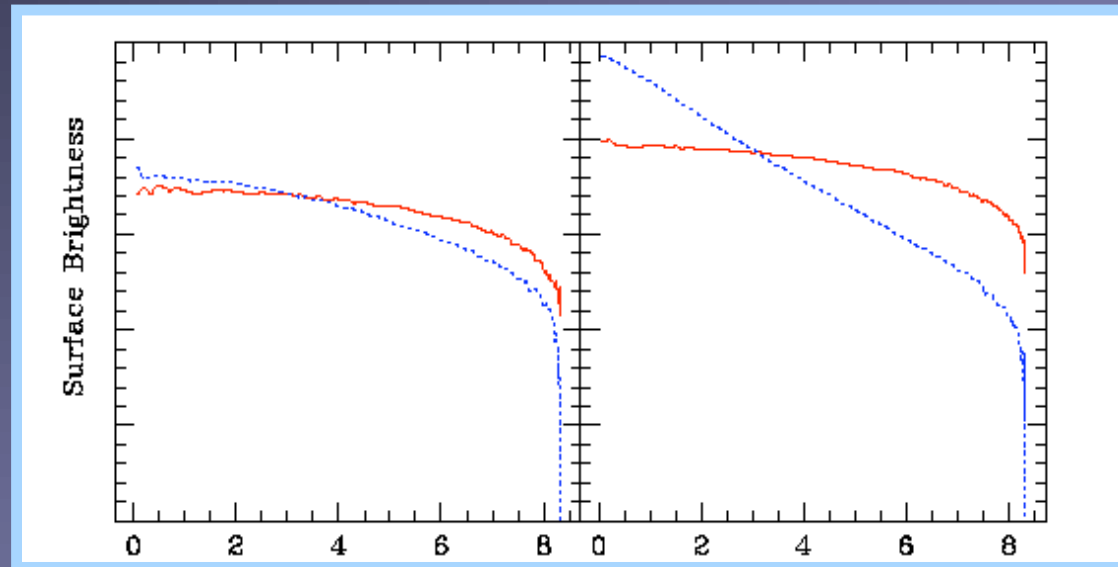
- Collapsing spherical toy model with Monte Carlo radiative transfer
- Ly α radiation emerges mainly blue-shifted
- IGM opacity makes it hard to detect at high z

Diagnostic of Gas Infall: Brightness Profile

shallow $v(r)$

steep $v(r)$

Surface
brightness
profile



radius (arcsec)

- Bluer photons come preferentially from central regions
- Surface brightness profiles flat (log. slope of -0.5)
- Scattering vs. Intrinsic effect distinguished using $H\alpha$

Conclusions

- First individual stars detectable via SN / GRB remnants
- Global feedback likely regulates SFR (WMAP evidence)
- Multiple ways to characterize feedback: e.g. JWST SNe
- Metal enrichment (PopIII→PopII) by He line (or PISN)
- Global metal enrichment hard to map out - OI pumping?
- Rapid SMBH growth in $T_{\text{vir}} > 10^4 \text{K}$ halos: $n(\text{H}_2)$, $n(\text{HD})$ key
- BH growth probed by GWs from LISA (EM counterparts?)
- Diffuse Ly α emission could probe high-z galaxy assembly