

Probing Reionization and Early Structure

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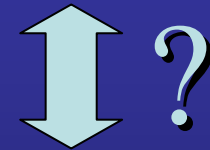
The reionization epoch is an important milestone in the Universe's evolution, providing a wealth of information about the physical processes and astrophysical objects dominating the early Universe.

Two recent, seemingly conflicting clues:

- SDSS quasars at $z > 6$
(e.g. Fan et al. 2004)



$x_{\text{HI}}(z \sim 6) > 10^{-3}$
reionization ends by $z \sim 6$?



- WMAP $\tau_e \sim 0.17 \pm 0.04$
(Kogut 2003; Spergel et al. 2003)



$x_{\text{HI}}(z \sim 15) \ll 1$
significant reionization by $z \sim 15-20$?

More data and more probes are needed!

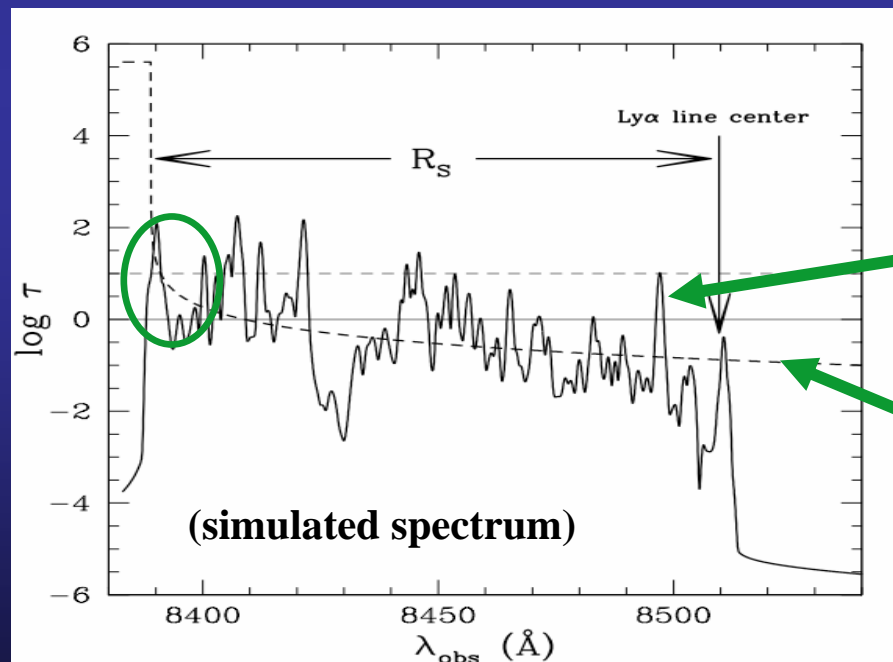
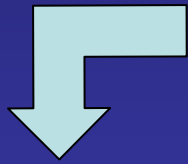
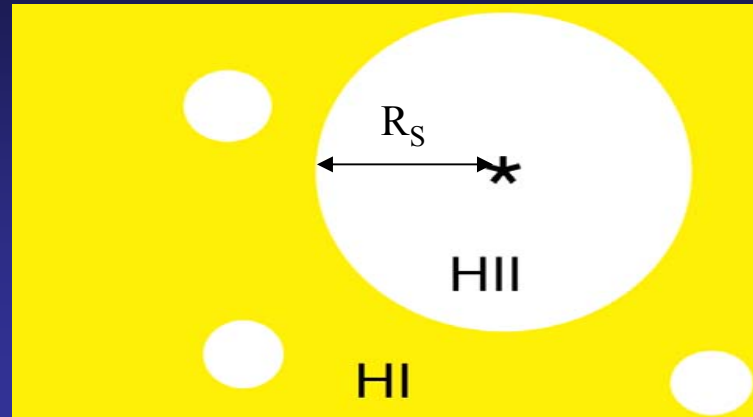


Mini-Conclusions

- Universe (or large part of it) is significantly neutral at $z \sim 6.2$
- High- z SNe rates could detect reionization and feedback effects out to $z_{\text{re}} \sim 13$
- High- z GRBs + *Swift* could provide valuable information about density fluctuations on small-scales

Cosmological Strömgren Spheres

e.g. Cen & Haiman 2000;
Madau & Rees 2000



Two contributions to
the Ly α optical depth,

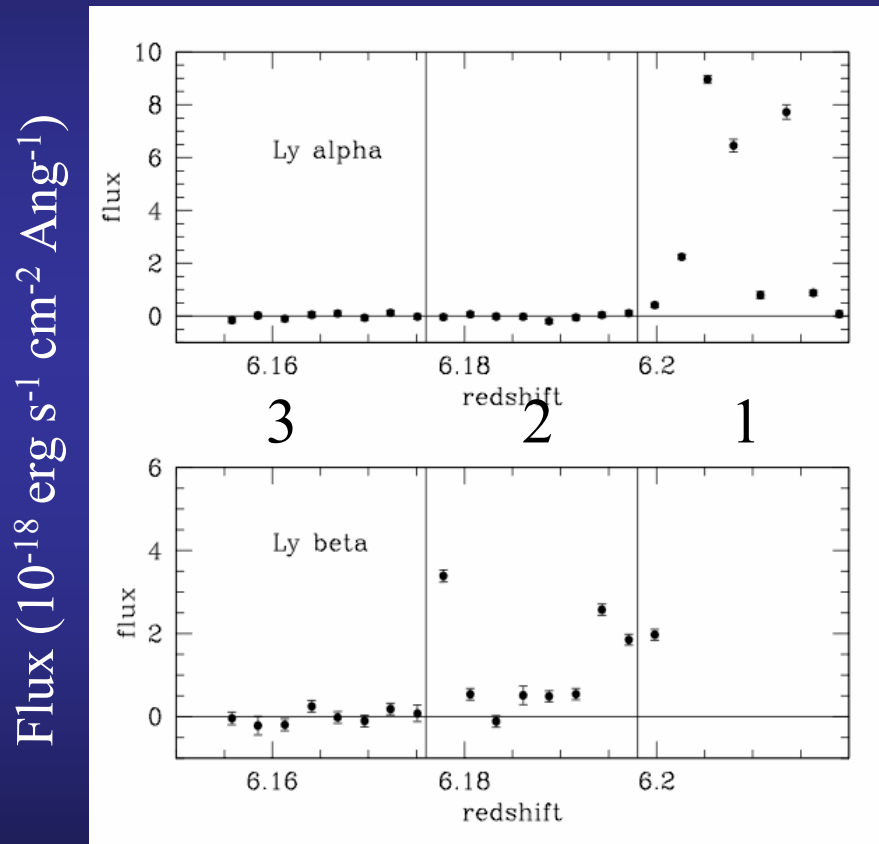
$$\tau_{\alpha} = \tau_R + \tau_D$$

τ_R - resonance optical depth
(not sensitive to x_{HI} or R_S)

τ_D - damping wing optical depth
(very sensitive to x_{HI} and R_S)

Case of SDSS J1030+0524, $z=6.28$

spectrum from White et al. (2003)



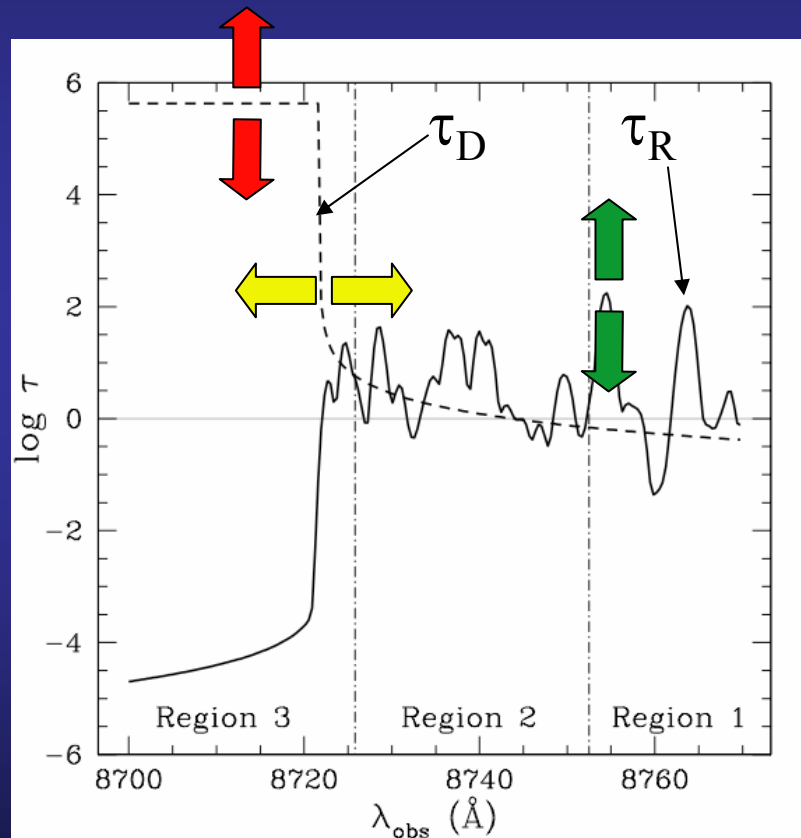
Extended dynamical range provided by $\text{Ly}\alpha$ and $\text{Ly}\beta$ regions of the spectrum:

- Region 1: $\tau_{\alpha} < 6$
- Region 2: $6 < \tau_{\alpha} < 11$
- Region 3: $\tau_{\alpha} > 11$

Z

Case of SDSS J1030+0524, $z=6.28$

Model gross observed features with hydro simulation (Cen et al. 2004)



Parameters:

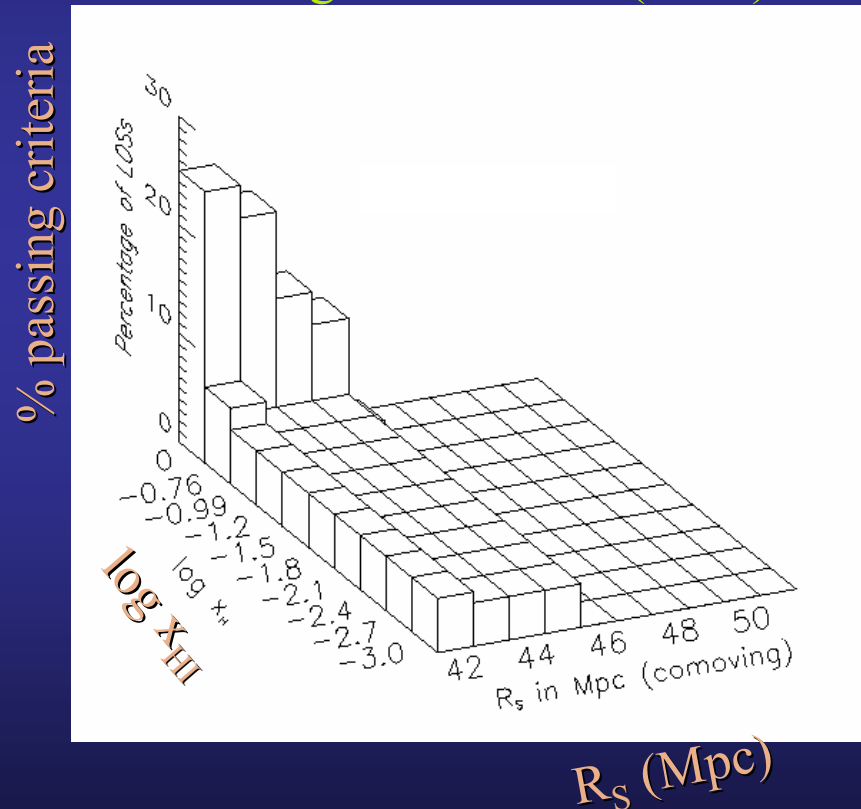
- IGM neutral fraction, x_{HI}
- Strömngren sphere radius, R_S
- QSO's ionizing luminosity, L_ν

Allow at most 2 “faulty” pixels
in each region

Constraints from SDSS J1030+0524, $z=6.28$

Procedure yields simultaneous constraints on all 3 parameters:

Mesinger & Haiman (2004)



- IGM neutral fraction:
 $x_{\text{HI}} > 0.2$
- Strömgen sphere radius:
 $R_S = 6.0 \pm 0.2 \text{ Mpc (proper)}$
- Ionizing luminosity:
 $\dot{N}_{ph} = (5.2 \pm 2.5) \times 10^{56} \text{ s}^{-1}$

Implications of SDSS J1030+0524 Analysis

- First detection of the boundary of a cosmological HII region
- Universe is significantly neutral at $z=6.2$
 - Directly from our analysis: $x_{\text{HI}} > 0.2$
 - From small HII bubble size ($R_S \sim 6$ proper Mpc) (Wyithe & Loeb 2004)
- Ionizing luminosity is a factor of $\sim 2-10$ lower than expected (Elvis et al. 1994; Telfer et al. 2002), strengthening arguments against quasar-dominated reionization (e.g. Dijkstra et al. 2004)
- Can compliment more detailed spectral analysis (e.g. Mesinger et al. 2004)
- Can be used to study ionization topology
- Sharpness of boundary
 - $\langle E_{\text{ph}} \rangle \leq 230$ eV
 - Can directly constrain the UV + X-ray emission

SNe as Probes of Reionization: Motivation

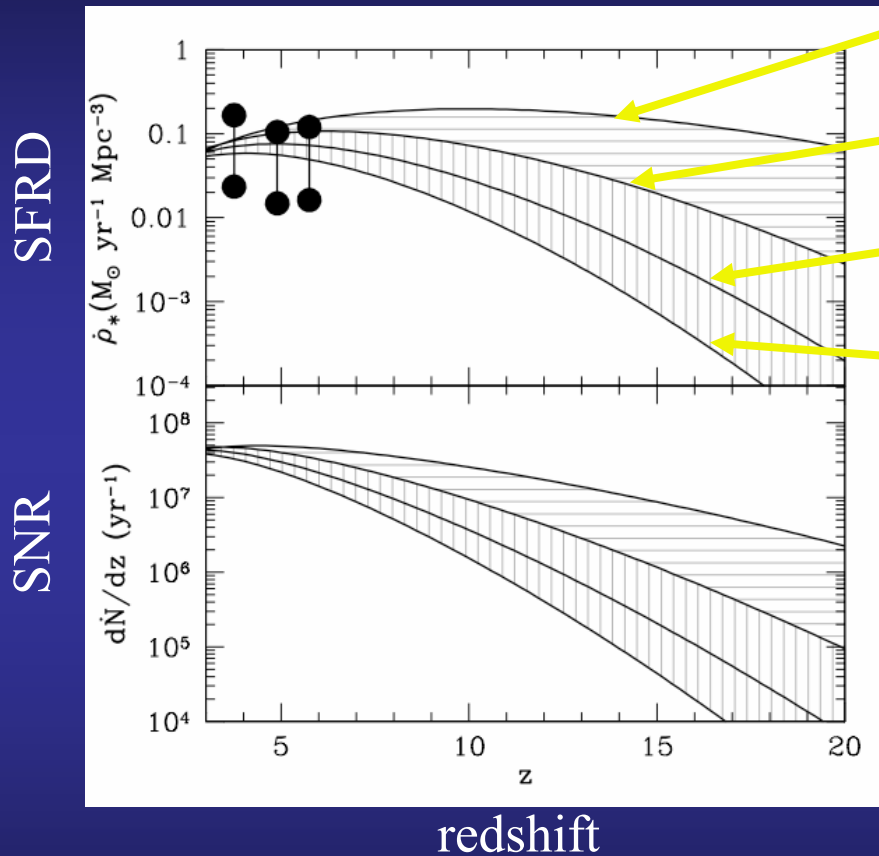
- Reionization is expected to be evidenced with a drop in the SFR (e.g. Efstathiou 1992; Thoul & Weinberg 1996)
- Location, size, and width of drop are all uncertain

Possibilities for Detection:

- non-monotonic evolution of IGM opacity (Cen & McDonald 2002)
 - > to improve low S/N, more deep, high-resolution QSO spectra needed
- high-z ‘Lilly-Madau’ diagram (Barkana & Loeb 2000)
 - > affected galaxies are faint and dangerously close to detection threshold
- high-z GRBs with *Swift*; stay tuned! (Mesinger, Perna & Haiman 2005)
 - > too rare for high S/N
- high-z SNe?
 - > brighter... more numerous...

Intrinsic SNe Rates

Mesinger, Johnson & Haiman (2005)



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

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

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

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

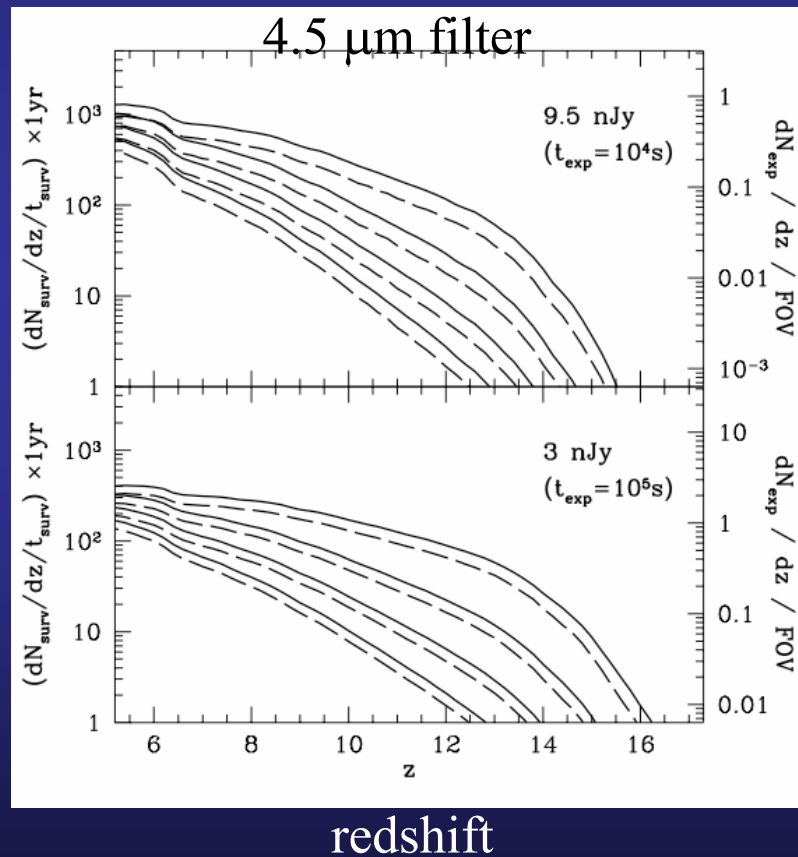
Assume:

- SFR traces formation of dark matter halos
- $\epsilon_* = 0.1$
- Salpeter IMF

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

Expected SNRs Observed with *JWST*

Mesinger, Johnson & Haiman (2005)



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)

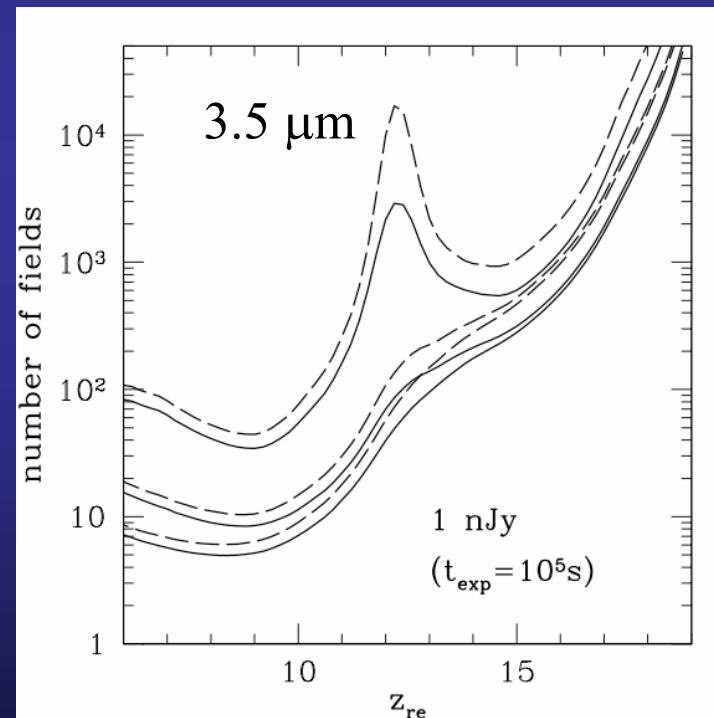
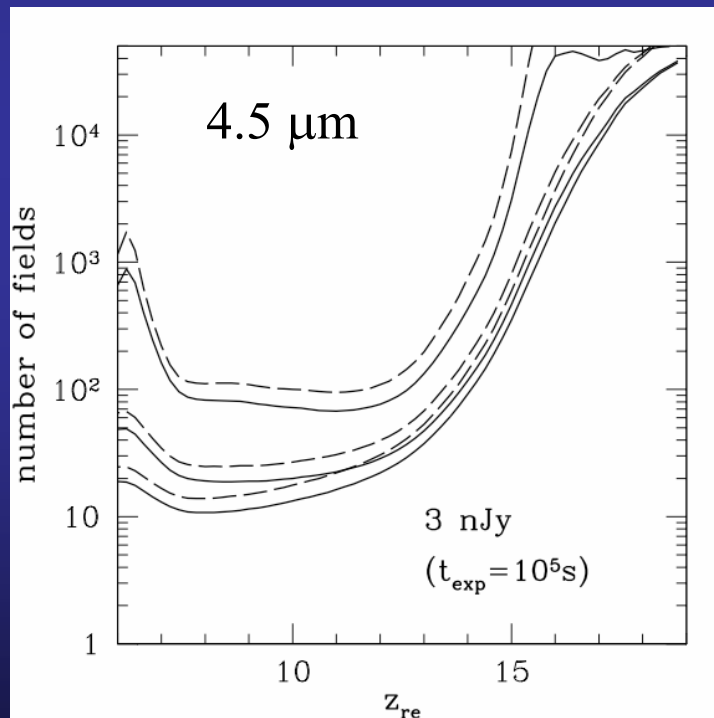
Assumed *JWST* properties:

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

Detecting the Reionization Signal

- Poisson S/N
- $\Delta z_{\text{re}} = 1$
- $S/N > 3$

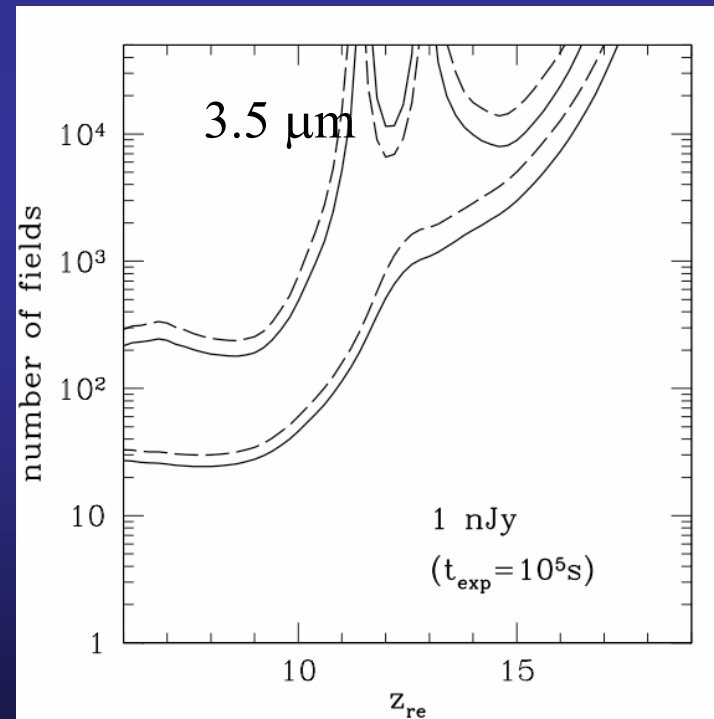
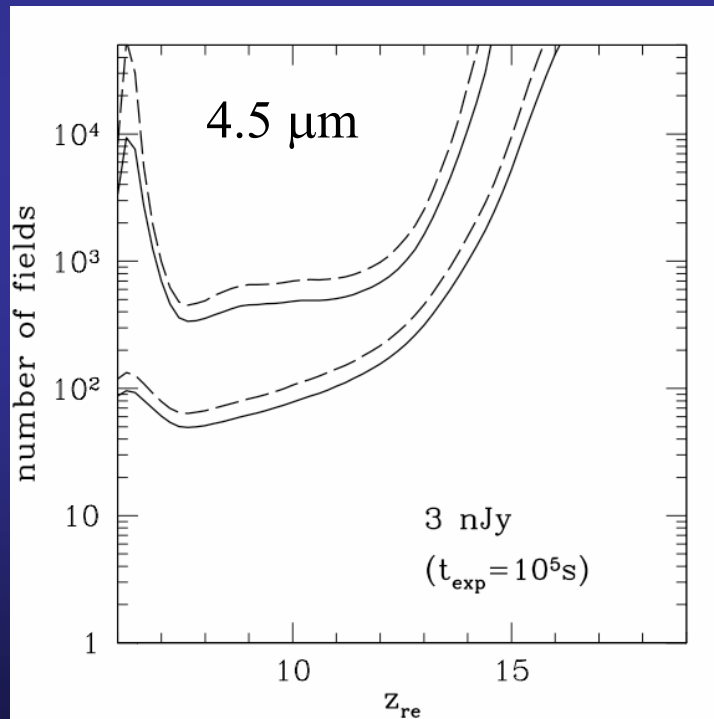
$$T_{\text{vir}} > 300 \text{ K} \Rightarrow ?$$



Detecting the Reionization Signal

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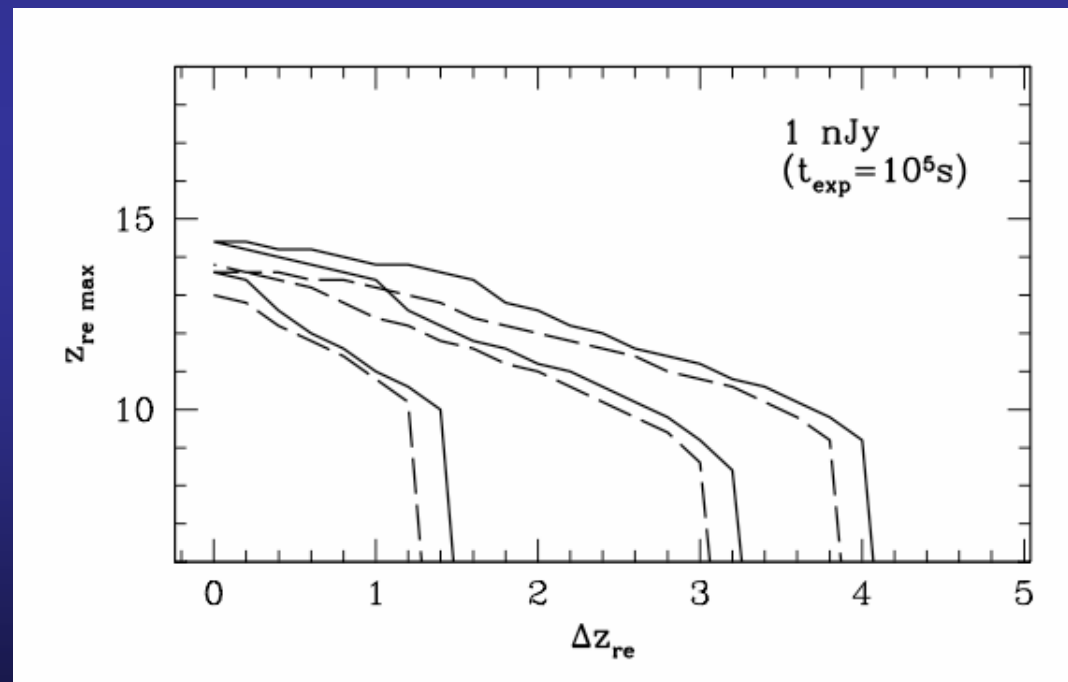
$$T_{\text{vir}} > 10^4 \text{ K} \Rightarrow ?$$



Varying Δz_{re}

- $S/N > 3$
- ~ 100 repeated images
- $T_{\text{vir}} > 300 \text{ K} \Rightarrow ?$

Mesinger, Johnson & Haiman (2005)



Summary of High-z SNe Results

- 4 - 24 SNe per ~ 10 arcmin² field at $z \geq 5$ at the detection threshold of 3 nJy (obtainable with a 10^5 s exposure in the 4.5 μ m band)
- 1 year survey can yield thousands of SNe per unit redshift at $z \sim 6$
- SNe rates can be used to detect reionization out to $z_{\text{re}} \sim 13$
- Provide valuable information about reionization feedback
- Main results should be valid as long as SNe properties evolve slower than Δz_{re}

Why Care About Small-Scales?

Hierarchical structure formation: small \rightarrow **BIG**

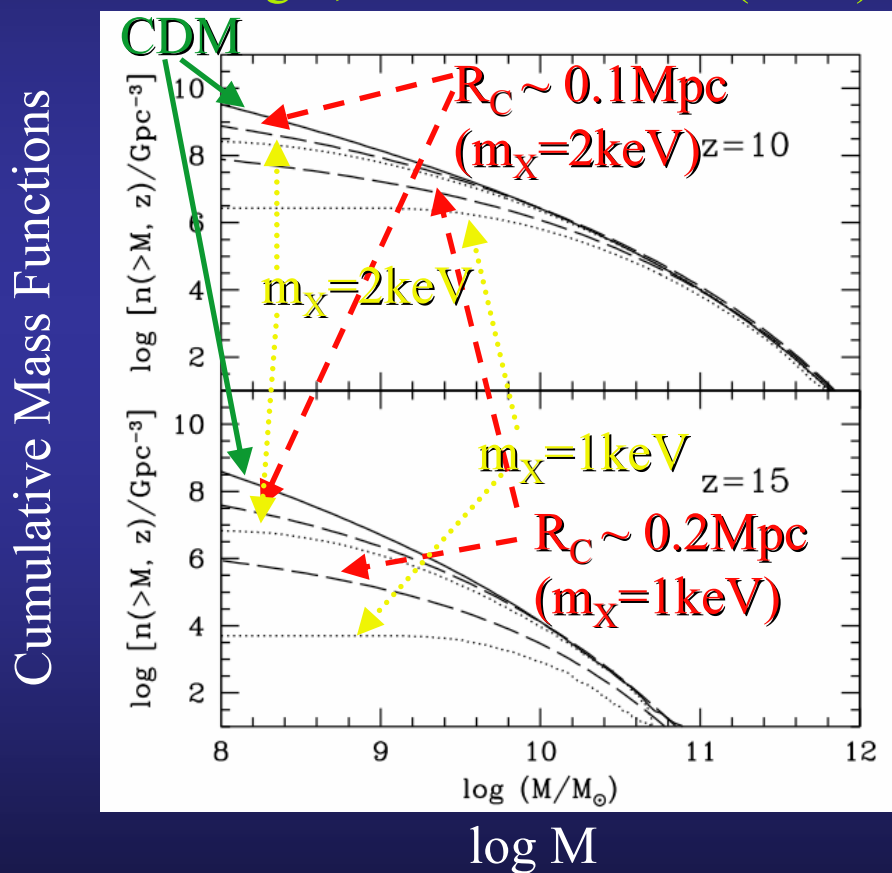
- WMAP early reionization \rightarrow considerable power on small-scales?
- Λ CDM \rightarrow already too much power on small-scales?
 - Dwarf galaxies in voids
 - Cuspy halos
 - Angular momentum problem
 - Too many satellite galaxies

 Answer: Baryonic feedback? Modify Λ CDM? (e.g. WDM)

High- z universe provides a unique window
onto early structures!

Mass Functions

Mesinger, Perna & Haiman (2005)



Two added effects:

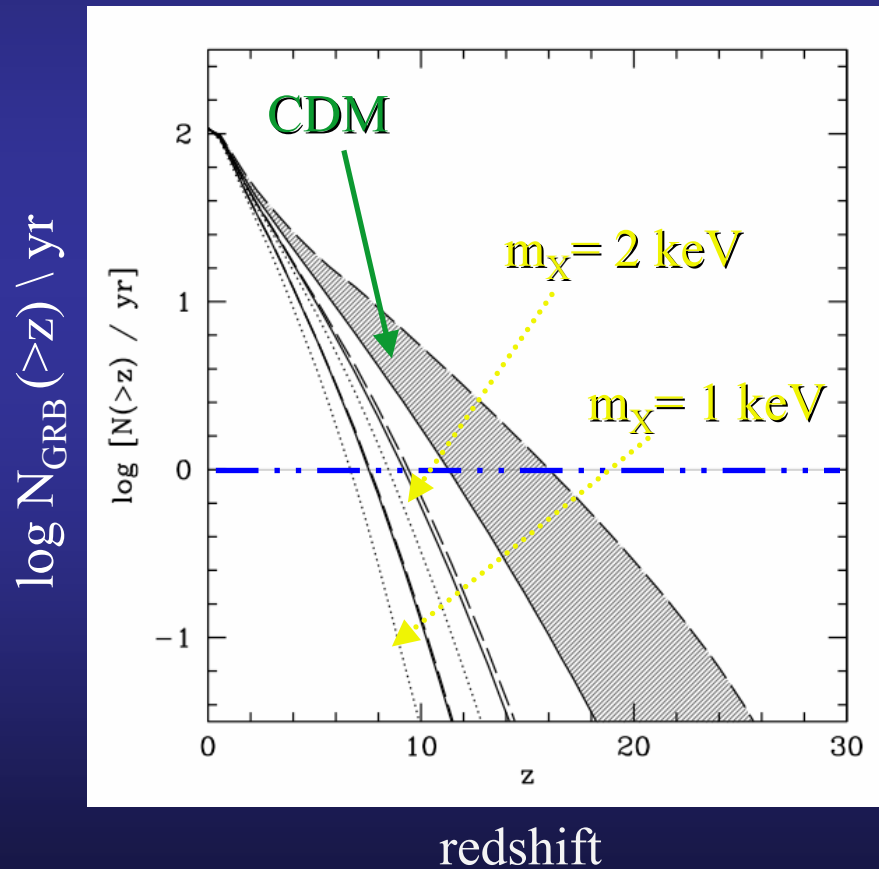
1. Exponential power spectrum cut-off on scales $< R_C$
2. Effective pressure of WDM modifies $\delta_C(M, z)$ (in addition to 1.)

Differences are more noticeable at higher redshifts!

Expected *Swift* GRB Rate

- GRBs trace structure formation
- rates normalized to *BATSE*

Mesinger, Perna & Haiman (2005)



a single GRB at $z > 8$
would improve current
constraints on m_X !

intrinsic GRB evolution
unlikely to mimic
exponential suppression

Summary of High-z GRB Results

- High-z universe is a great place to study the intrinsic power spectrum on small-scales
- A *Swift* detection of a single GRB at $z > 10$ or 10 GRBs at $z > 5$ would rule out $m_X < 2$ keV
- A *Swift* detection of a single GRB at $z > 12$ provides an upper limit on the running of the spectral index, $\alpha > -0.05$
- Analysis is valid for any models with a sharp suppression of small-scale power (e.g. Kamionkowski & Sigurdson 2005)

Concluding Conclusions

- The cosmological proximity effect can offer a wealth of information about the environments of high- z sources
 - SDSS J1030+0524: $x_{\text{HI}} > 0.2$; $R_S \sim 6$ proper Mpc; $\dot{N}_{ph} \sim 5.2 \times 10^{56} \text{ s}^{-1}$
 - Mapping ionization topology; QSO X-ray contribution; and more!
 - Future: Detailed pixel-to-pixel analysis of all existing high- z sources
- SNe rates can be used to detect reionization and provide valuable information about reionization feedback out to $z_{\text{re}} \sim 13$
- The high- z universe is a great test bed for small-scale power
 - A detection of a single GRB at $z > 8$ would improve current constraints on m_X

The End
Kraj
Vége
Le Fin
Einde
Hasof
La Fine
Vanakkam
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