Warm Dark Matter and the End of the Cosmological Dark Ages

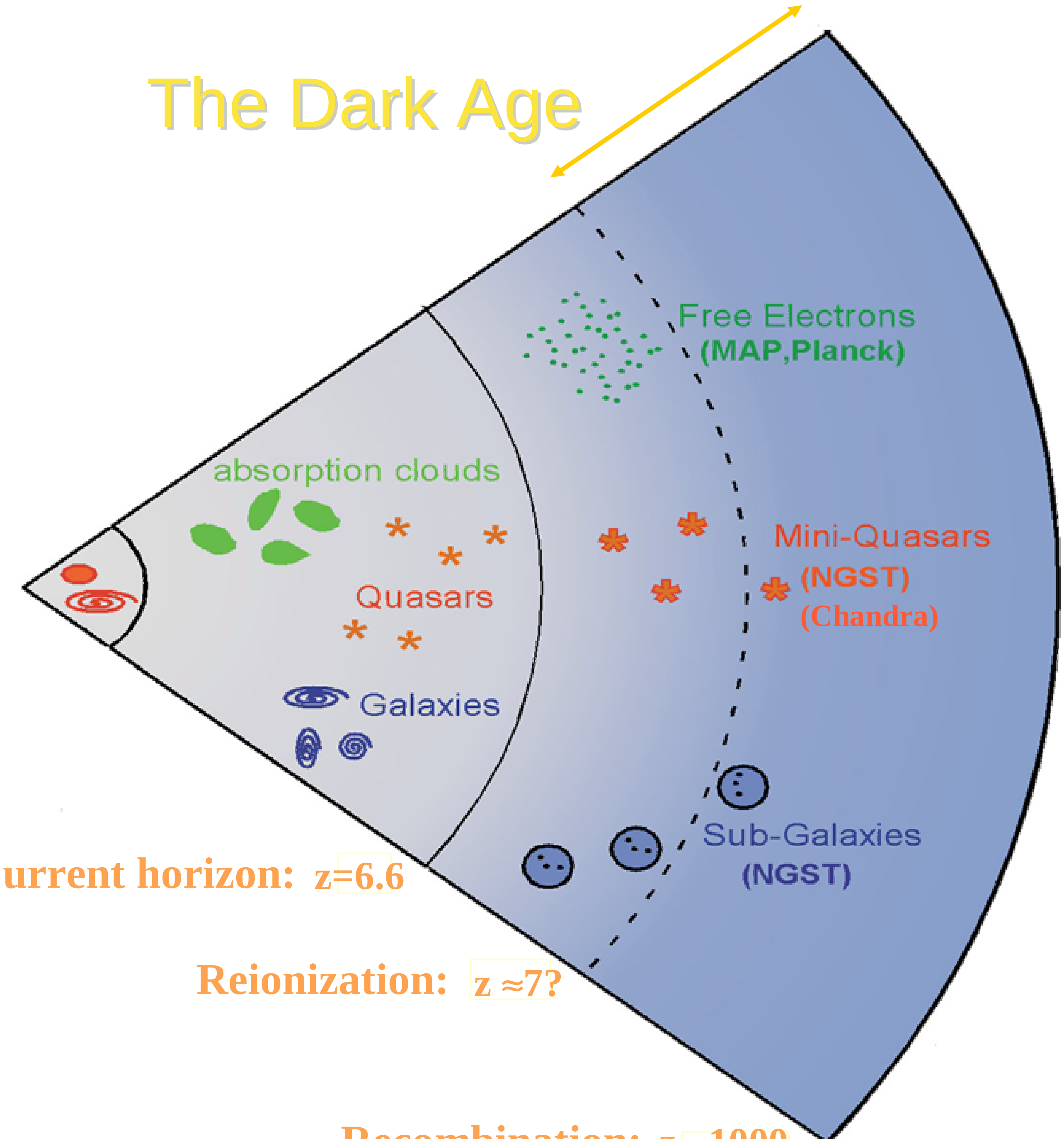
Zoltán Haiman

Princeton University
Columbia University

Collaborators: Rennan Barkana, Jerry Ostriker, Renyue Cen
Manoj Kaplinghat, Lloyd Knox, Gil Holder

Neutrino News, Fermilab, Oct 17-19, 2002

The Dark Age

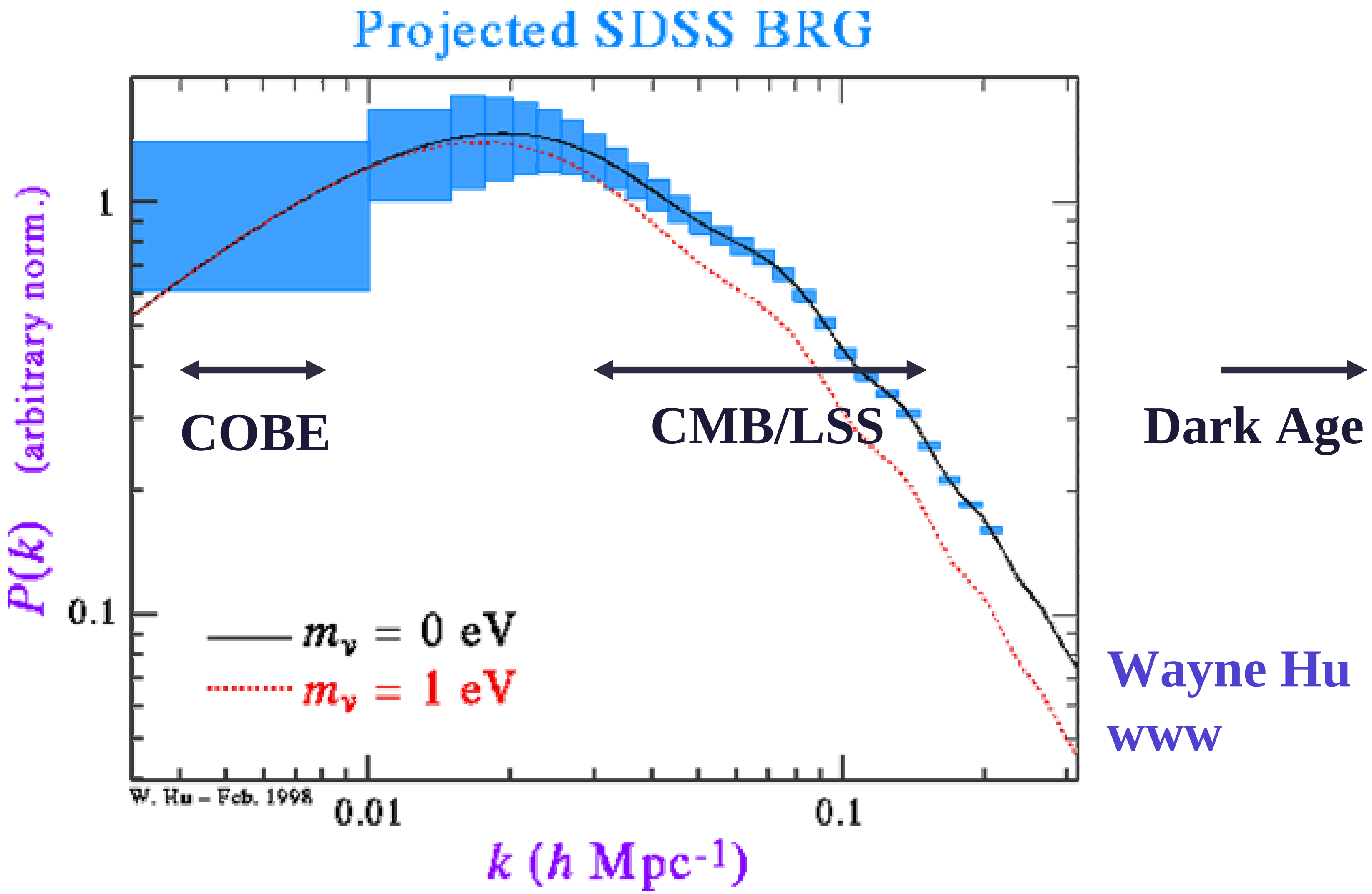


Current horizon: z=6.6

Reionization: z ≈7?

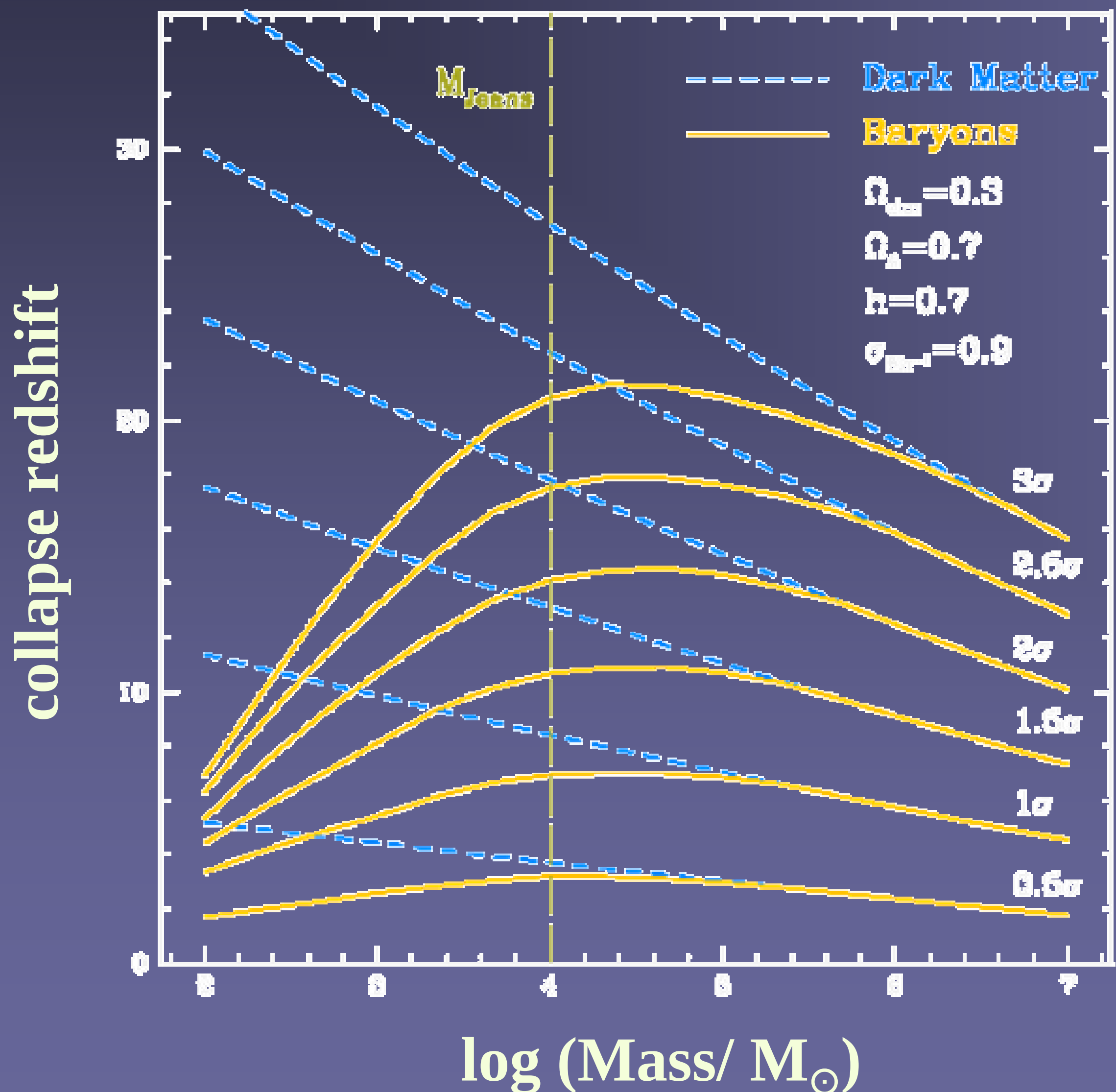
Recombination: z ≈1000

Power Spectrum



Wayne Hu
www

Nonlinear CDM Condensations



Smallest scales condense first

Jeans mass:
~10^4 $M_\odot$

Z. Haiman
PhD Thesis (1998)

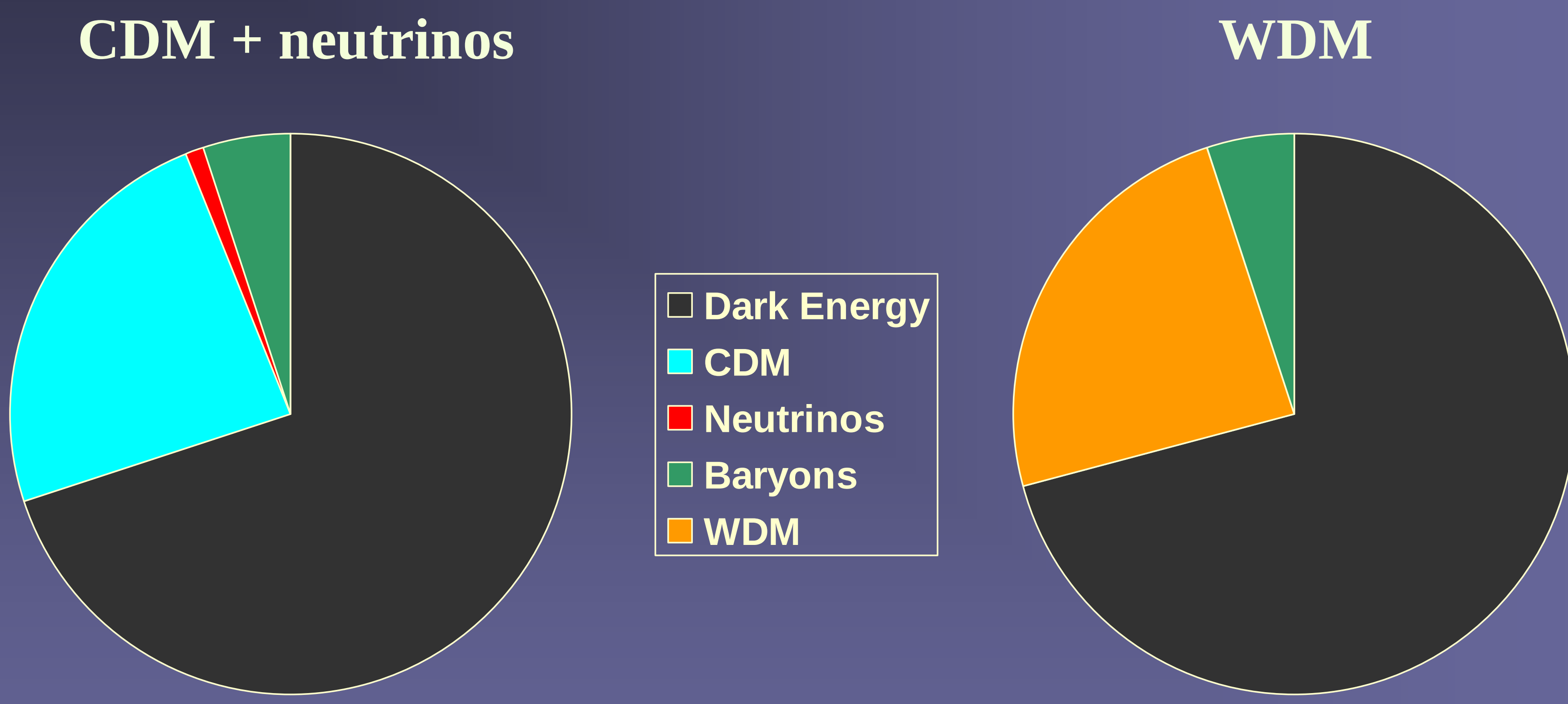
The Dark Age

- Theory: High Redshift Universe = test bed of power spectrum P(k) on ~0.1 Mpc scales
  - CDM predicts nonlinear condensations by z~15-20

- Observations: Currently limited to z~6 but hints to higher z
  - Metals in Lyα forest
  - Reionization

The Future: Multi-wavelength science

- X-rays: CXO ✓
- Microwave: MAP/Planck (2002/2007)
- Infrared: LAMA/NGST (2007/2009)
- (sub)mm: LMT/ALMA (2004/?)
- Radio: GMRT,LoFAr, SKA (✓/2004/?)


CDM + neutrinos
WDM
Dark Energy
CDM
Neutrinos
Baryons
WDM

Probing Small Scale Power

- Directly: By mere existence of objects at $z \gtrsim \mathbf{6}$
  - record holder galaxy z=6.56
  - record holder quasar z=6.28
- Indirectly: signatures of high-redshift objects
  - Reionization
  - (metal enrichment?)

High Redshift Objects

- Quasars:
  - z=6.28 -27.7 mag (→M_{bh} =4x10^9 M□)
    1200 deg^2 (~10 Gpc^3 Fan et al. 2001)
  - z=5.50 -22.7 mag (→M_{bh} =4x10^7 M□)
    74 $amin^2$ (~10^5 Mpc^3 Stern et al. 2000)

- Lyα emitters:
  - z=6.56 (SFR =10 M□ yr^{-1})
    0.46 $amin^2$ (~10^3 Mpc^3 Hu et al. 2001)
  - z=5.58 (SFR =0.5 M□ yr^{-1})
    100 $asec^2$ (~10 Mpc^3 Ellis et al. 2000)

Abundance of CDM halos

Dependence on cosmological parameters

(Semi-)analytic (Press & Schechter 1974; Sheth, Mo & Tormen 2001)

$$\frac{dn}{dM} = -\sqrt{\frac{2}{\pi}}\frac{\rho_0}{M}\left(\frac{\delta_{crit}}{g_z\sigma_M{}^2}\frac{d\sigma_M}{dM}\right)\exp\left\{-\frac{\delta_{crit}{}^2}{2[g_z\sigma_M)]^2}\right\}$$

Hubble volume simulation (Jenkins et al. 2001) ~20% accuracy

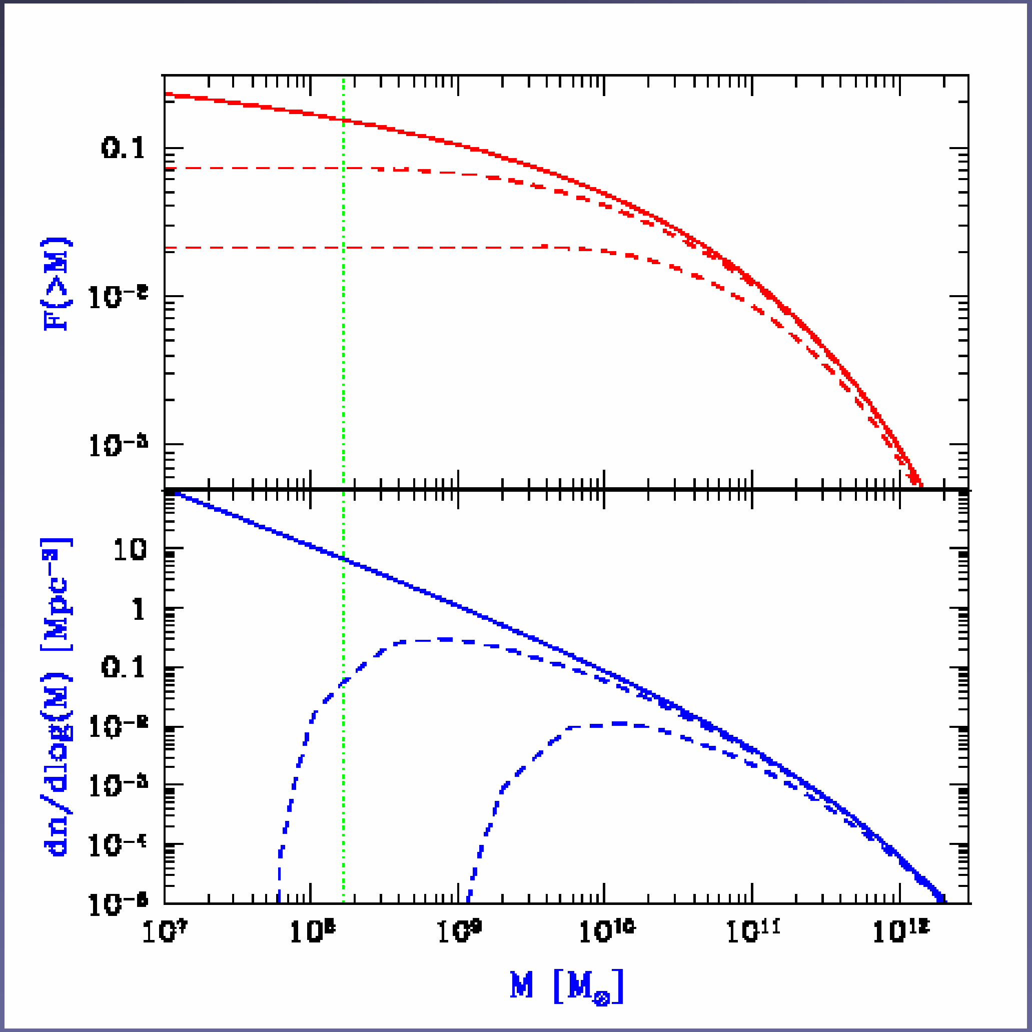
$$\frac{dn}{dM} = -0.315\frac{\rho_0}{M}\left(\frac{1}{\sigma_M}\frac{d\sigma_M}{dM}\right)\exp\left\{-[0.61-\log(g_z\sigma_M)]^{3.8}\right\}$$

overall normalization $(\propto \Omega_M h^2)$

power spectrum $(M \propto \Omega_M h^2 r^3)$

growth function

CDM Halo Mass Function



Redshift z=6

Sheth & Tormen (1999)

High Redshift Objects

CDM halos

- quasars:
  - z=6.28 -27.7 mag ($\rightarrow M_{bh} = 4\times10^{9} M_{\odot}$) **$M_{halo} = 2\times10^{13} M_{\odot}$**
    1200 deg^2 ($\sim$10 Gpc^3 Fan et al. 2001)
  - z=5.50 -22.7 mag ($\rightarrow M_{bh} = 4\times10^{7} M_{\odot}$) **$M_{halo} = 4\times10^{12} M_{\odot}$**
    74 $amin^2$ ($\sim10^5$ Mpc^3 Stern et al. 2000)

- Lyα emitters:
  - z=6.56 (SFR = 10 $M_{\odot}\ yr^{-1}$) **$M_{halo} = 3\times10^{11} M_{\odot}$**
    0.46 $amin^2$ ($\sim10^3$ Mpc^3 Hu et al. 2001)
  - z=5.58 (SFR = 0.5 $M_{\odot}\ yr^{-1}$) **$M_{halo} = 2\times10^{10} M_{\odot}$**
    100 $asec^2$ ($\sim$10 Mpc^3 Ellis et al. 2000)

CDM “works”
(□ enough halos of reasonable size)*

What about WDM?

* but only “marginally” if timescale to grow BH is ~Salpeter time

What is WDM?

Decouples while relativistic and in thermal equilibrium

Spin ½ Fermion [Example: sterile neutrino]

Invoked as an alternative to HDM **(Peebles 1982; Olive & Turner 1982 Bond, Szalay & Turner 1982 Pagels & Primack 1982; Colombi et al. 1996)**

Resurrected to solve small-scale crisis(?) of CDM

(Colín, Avila-Reese & Valenzuela; Hogan & Dalcanton; White & Croft Sommer-Larsen & Dolgov; Sellwood Bode, Ostriker & Turok)

Basic Properties of WDM

- **"X-particle" of mass** $m_X \sim 1 \;\; \text{keV}$

  $\sim 10 \;\; \text{eV}$ **HDM**

  $\sim 1 \;\; \text{GeV}$ **CDM**

- **Abundance from DM density at z=0** $m_X n_X \propto \Omega h^2$

- **Abundance from Fermi-Dirac distribution at z=0**

$$v_{\text{rms}}(z) = 0.44 \left(\frac{1+z}{10}\right) \left(\frac{\Omega h^2}{0.15}\right)^{1/3} \left(\frac{g_X}{1.5}\right)^{-1/3} \left(\frac{m_X}{1\text{keV}}\right)^{-4/3} \text{km/s}$$

The lighter, the hotter.

[**NB:** $g_{\text{dec}} = 766 \left(\frac{\Omega h^2}{0.15}\right)^{-1} \left(\frac{g_X}{1.5}\right) \left(\frac{m_X}{1\text{keV}}\right)$ **cf 106.75 of standard model**]

What does WDM do ?

1. Free Streaming: sharp damping of P(k) on scales below

$$R_S \approx 0.31 \left(\frac{\Omega_X}{0.3}\right)^{0.15} \left(\frac{h}{0.65}\right)^{1.3} \left(\frac{m_X}{1\mathrm{keV}}\right)^{-1.15} \quad h^{-1}\mathrm{Mpc}$$

2. Collapse Dynamics: acts like pressure with "Jeans scale"

$$\lambda_J \approx \frac{(1+z)v_{\mathrm{rms}}}{\sqrt{\mathrm{G}\rho}} = 0.1 \left(\frac{\Omega h^2}{0.15}\right)^{-1/6} \left(\frac{1+z}{10^3}\right)^{1/2} \left(\frac{g_X}{1.5}\right) \left(\frac{m_X}{1\mathrm{keV}}\right)^{-4/3} \quad \mathrm{Mpc}$$

Irrelevant in local universe, but important for reionization:

$\Rightarrow \quad M_J \approx 2\times 10^8 M_\odot$ **bigger than usual gas Jeans**

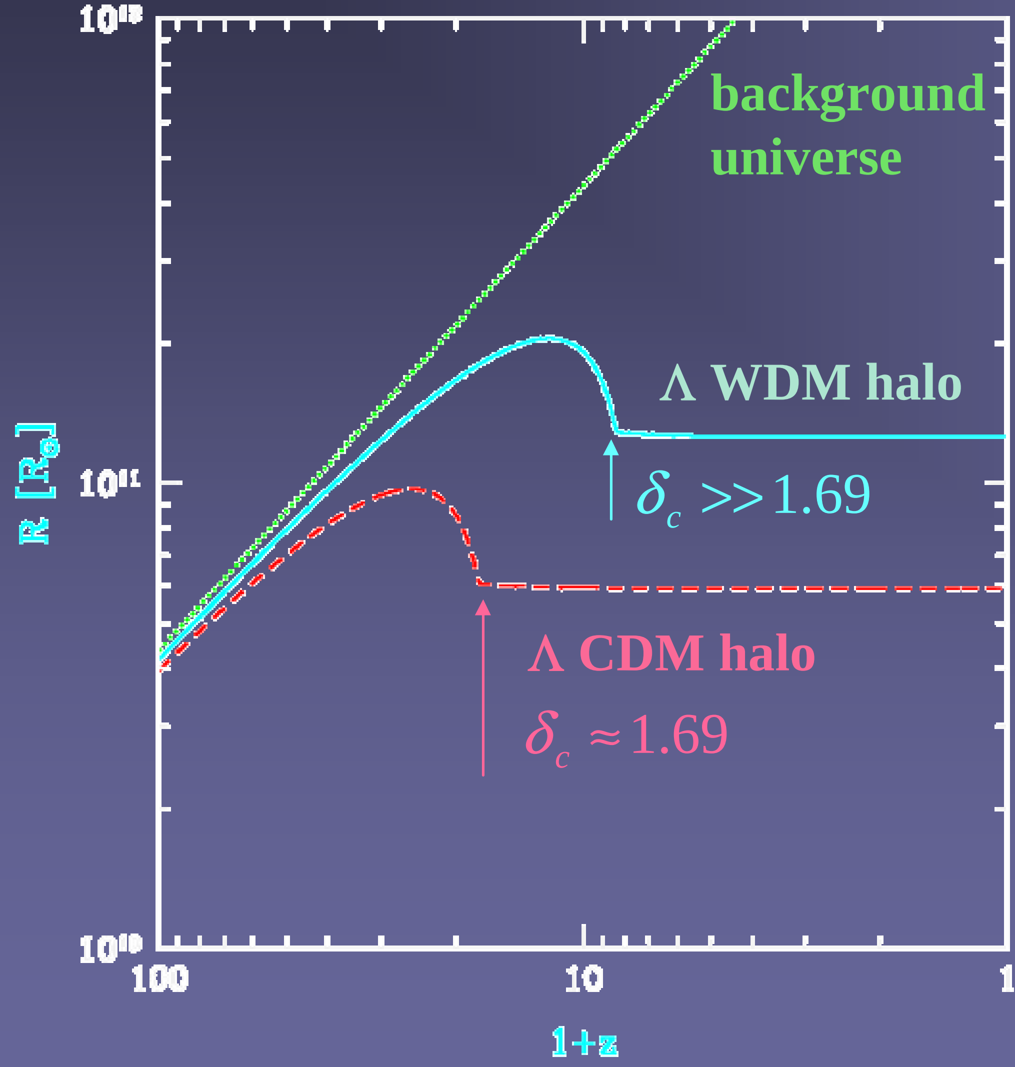
WDM Halo Mass Function

Two complications relative to CDM universe:

- transfer function modified (see C.P. Ma, N. Turok)

- linear over-density threshold $\delta_{crit} = \delta_{crit}(z,M) \neq 1.69$

Simulation of Halo Collapse



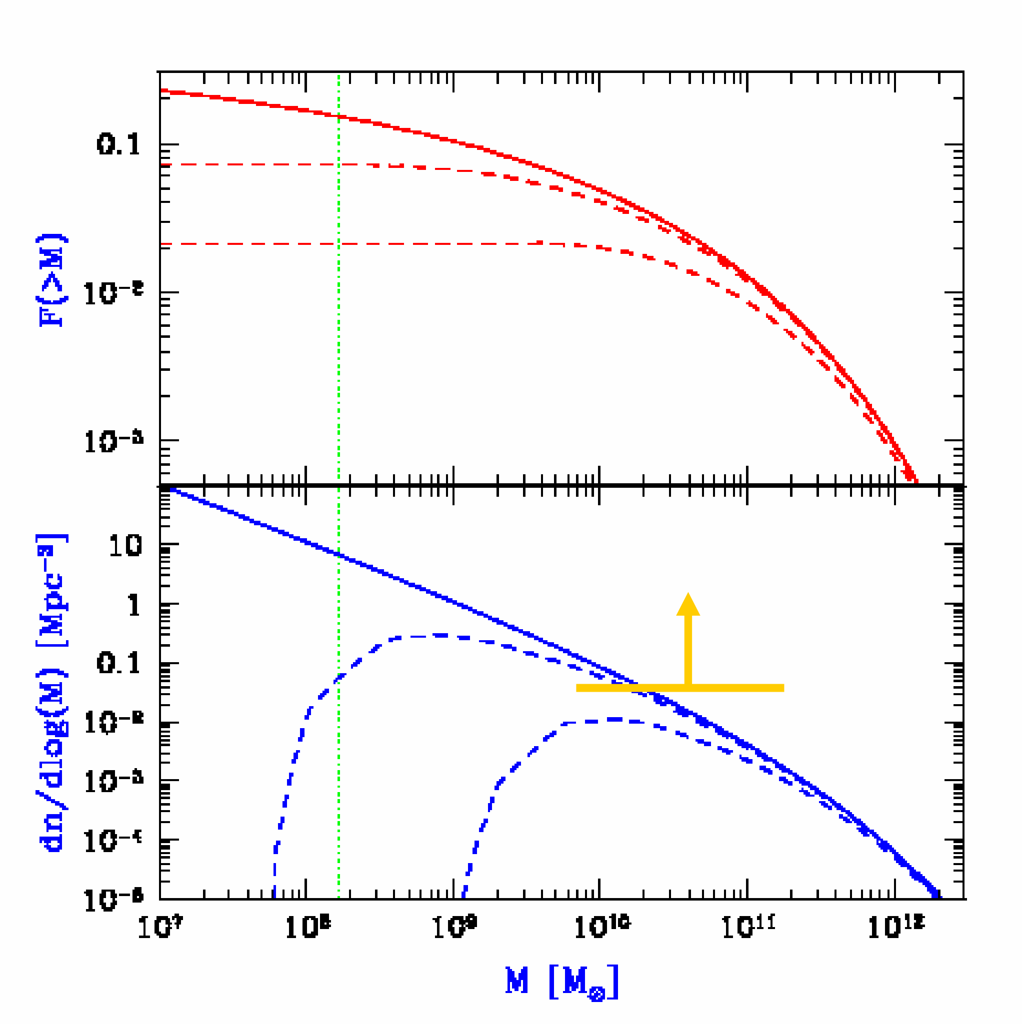
1D Lagrangian Hydrodynamics code

ΛWDM vs ΛCDM

$m_X = 1$ keV

$M_{\rm halo} = 2\times10^8$ M☉

WDM Halo Mass Function



Redshift z=6

Sheth & Tormen Formula

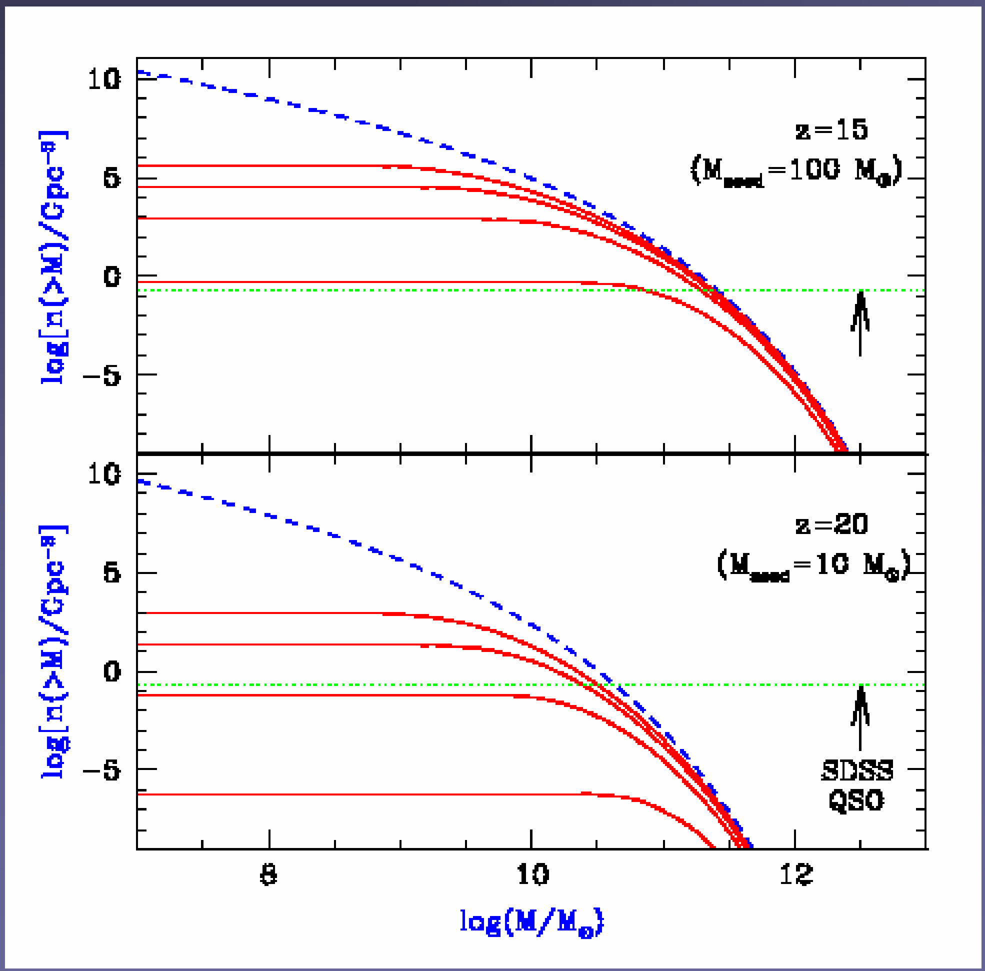
m_x=1.5 keV

m_x=0.75 keV

Faint z=5.6 Lyα emitters: $m_X \gtrsim 1$ keV

High Redshift Quasars

Two additional assumptions:



(1) Eddington luminosity:

$M_{bh} = 4 \times 10^9 M_\odot$

(2) Eddington Accretion:

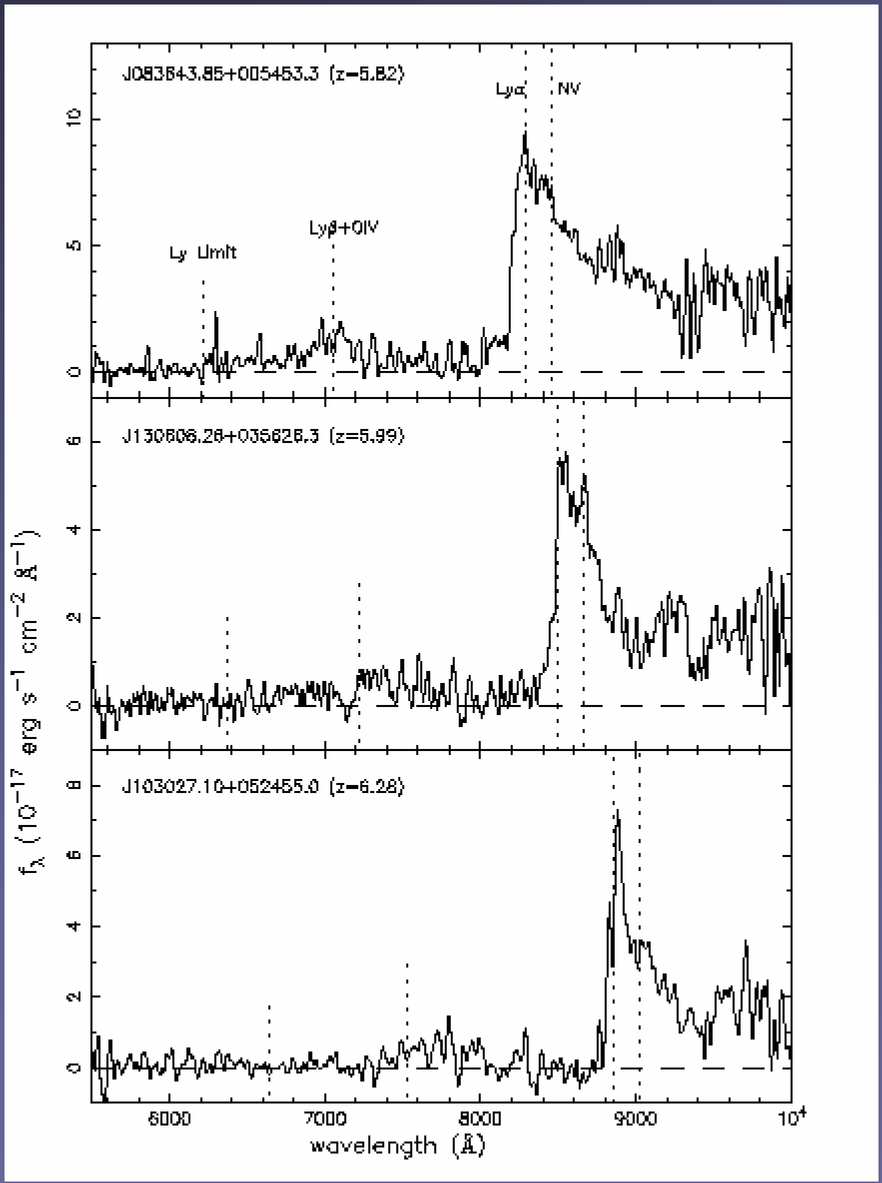
$t_{qso} = 4 \times 10^7 \ \ln(M_{bh}/M_{seed})$ yr

Redshift z=15, 20

m_x=0.5-1.25 keV

High=z QSOS:
$m_X \gtrsim 0.5$ keV

Constraints from Reionization



need sufficient number of ionizing photons by z≈6 to eliminate “GP trough”:

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

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

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

Fan et al. 2002

Modeling Reionization

- WDM Halo Mass Function ✓

- Astrophysics:

  - Ionizing Photon Sources: Stars (or Quasars)

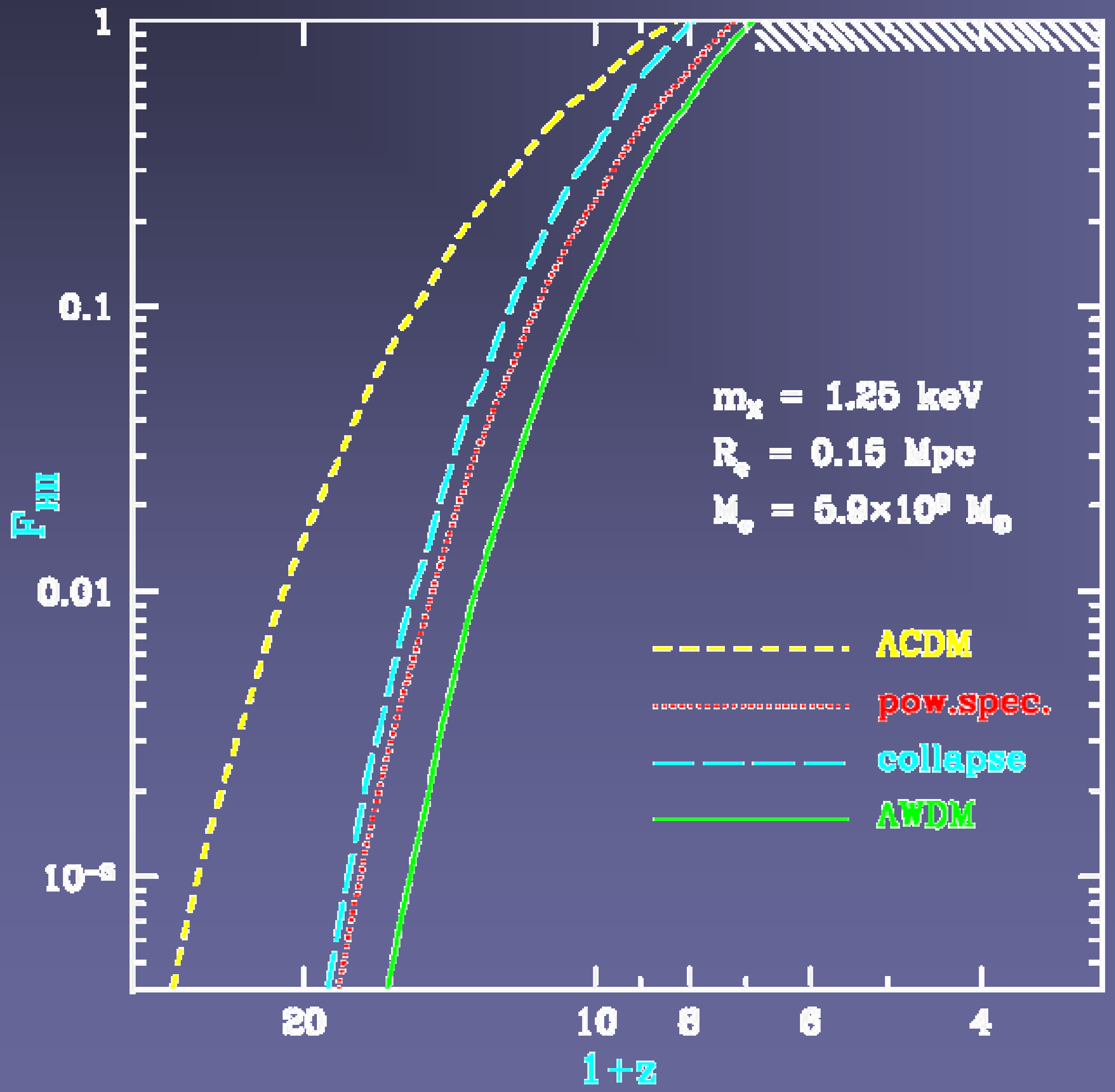
    Star-formation efficiency, IMF, escape fraction, threshold

    (10 %) (Scalo 1998) (10%) (T_{vir}=10^4 K)

  - Intergalactic Medium

    Clumping: $C \equiv \langle\rho^2\rangle/\langle\rho\rangle^2 \approx 10$ (Gnedin & Ostriker simulation)

Ionized Fraction



Reionization by redshift z=6:

$m_X \gtrsim$ 1.2 keV

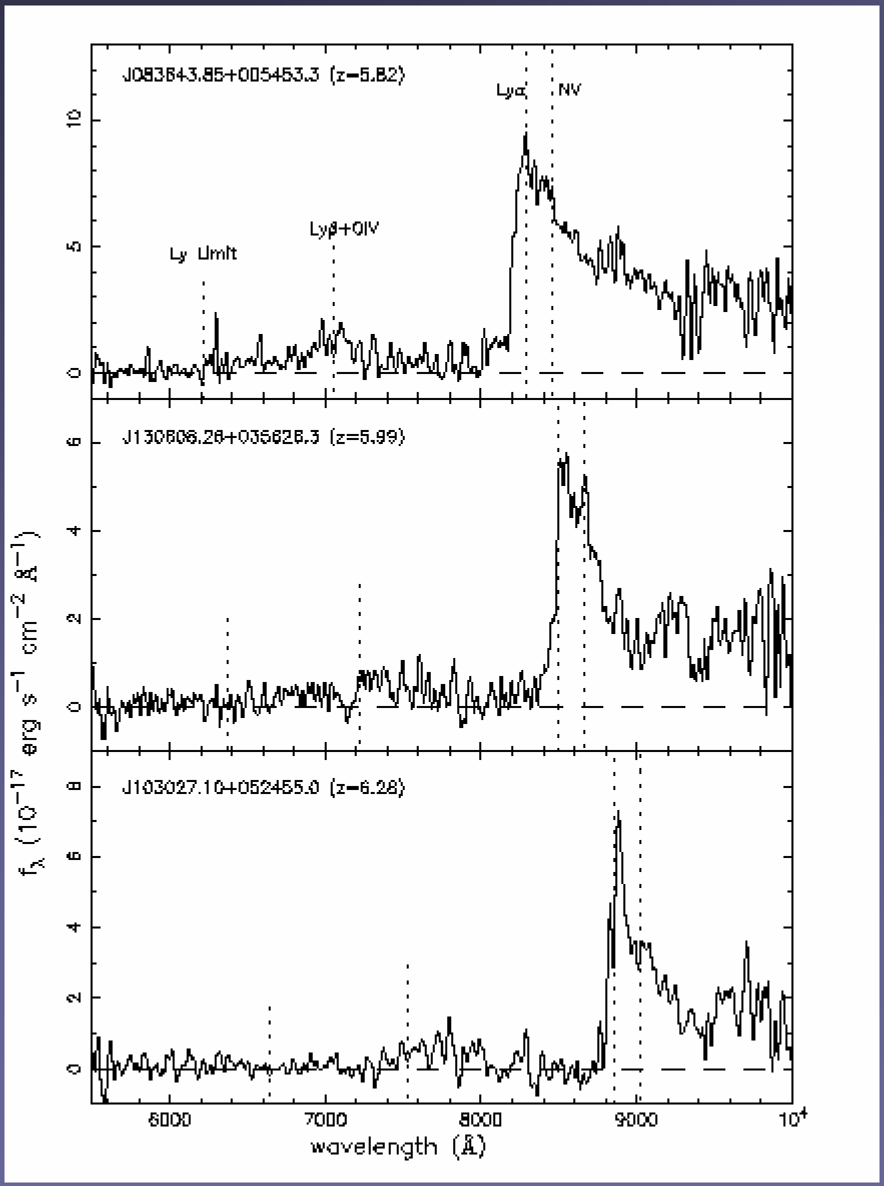
Constraints from Dark Ages:

1. Warm Dark Matter particle mass $m_X \gtrsim 1$ keV.

2. Can be improved significantly by pushing to higher z.

3. When was the universe reionized ??

Reionization at z~6?



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

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

Gunn-Peterson trough:

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

Fan et al. 2002

Implications of z=6.3 quasar:

- **Intriguing increase of neutral fraction from $z = 5.5 \rightarrow 6.3$**

- but -

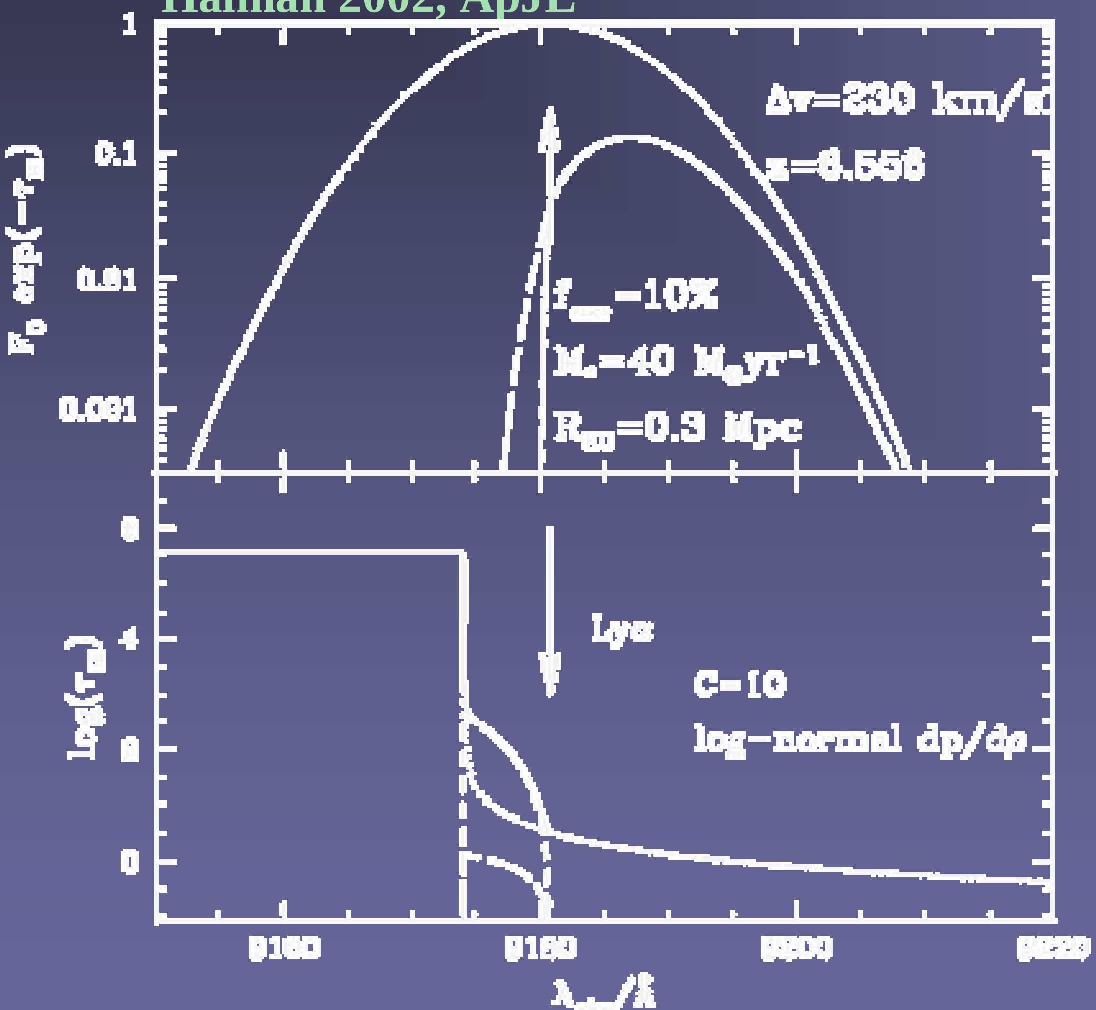
- **We cannot rule out z□6 from (hydrogen) GP trough alone.**

⟶ **Crucial to have alternative probes of neutral hydrogen density in the IGM:**

1. **Shapes of Lyα profiles** **(Z.H. 2002 ApJL)**
2. **Large angle CMB polarization** **(Kaplinghat et al. 2002)**
3. **21 cm of neutral HI** **(Gnedin et al. 2002)**
4. **Metal line "GP troughs"** **(Oh 2002)**

Lyα emitters as a probe of reionization

Haiman 2002, ApJL



Flux

Opt. Depth

Wavelength

Hu et al (2002):

Ly alpha emitting Galaxy discovered at z=6.56.

Faint: SFR ~ 10 $M_\odot$/yr (ionized region only 2 Mpc)

Reionization at z>6.6?

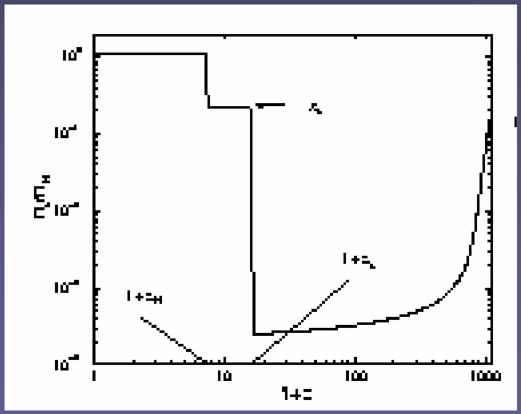
No… source could be embedded in fully neutral IGM

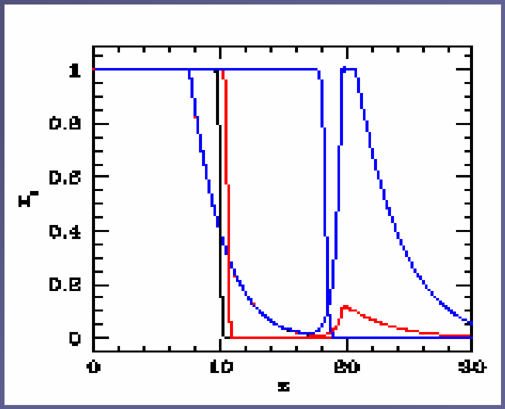
CMB polarization: probe of reionization

Kaplinghat et al., astro-ph/0207591 (ApJ, in press)

Consider two alternative reionization histories:

- **A. long period of partial ionization with $\langle x_H \rangle \sim 10^{-3}$**
- **B. ‘double’ reionization**





Are these distinguishable from sharp reionization at z=6.3?

1. **MAP ?**
2. **Planck ?**
3. **Cosmic variance limited experiment?**

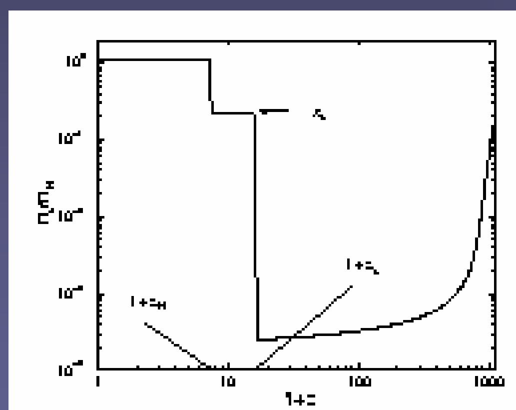
CMB polarization: probe of reionization

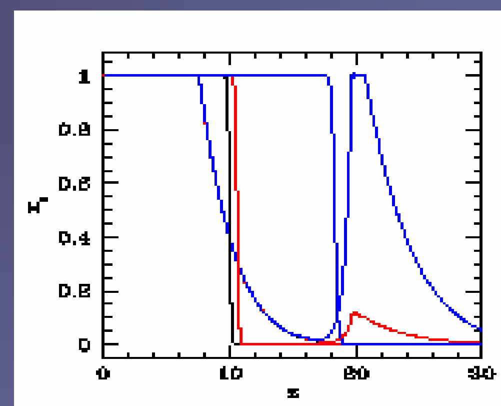
Kaplinghat et al., astro-ph/0207591 (ApJ, in press)

Consider two alternative reionization histories:

A. long period of partial ionization with $\langle x_H \rangle \sim 10^{-3}$

B. 'double' reionization





Are these distinguishable from sharp reionization at z=6.3?

1. **MAP ? (A) with z $\gtrsim$13 (B) difficult**
2. **Planck ? (A) with z $\gtrsim$8 (B) if full bump**
3. **Cosmic variance limited experiment? ✓(A,B)**

Conclusions

1. High redshift universe is a test bed of small-scale P(k), and hence of models such as Warm Dark Matter.

2. $m_X \gtrsim 1$ keV follows from mere existence of $z \sim 6$ objects.
   $m_X \gtrsim 1.2$ keV from reionization by $z \gtrsim 6$ (better, but less direct).

3. Significant improvements by going to higher redshift: reionization can be studied by Lyα line profiles and by CMB polarization.

The End