The effect of early dark matter halos on reionization

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Outline -

1. Dark matter in the Universe.

    Luminosity of halos.

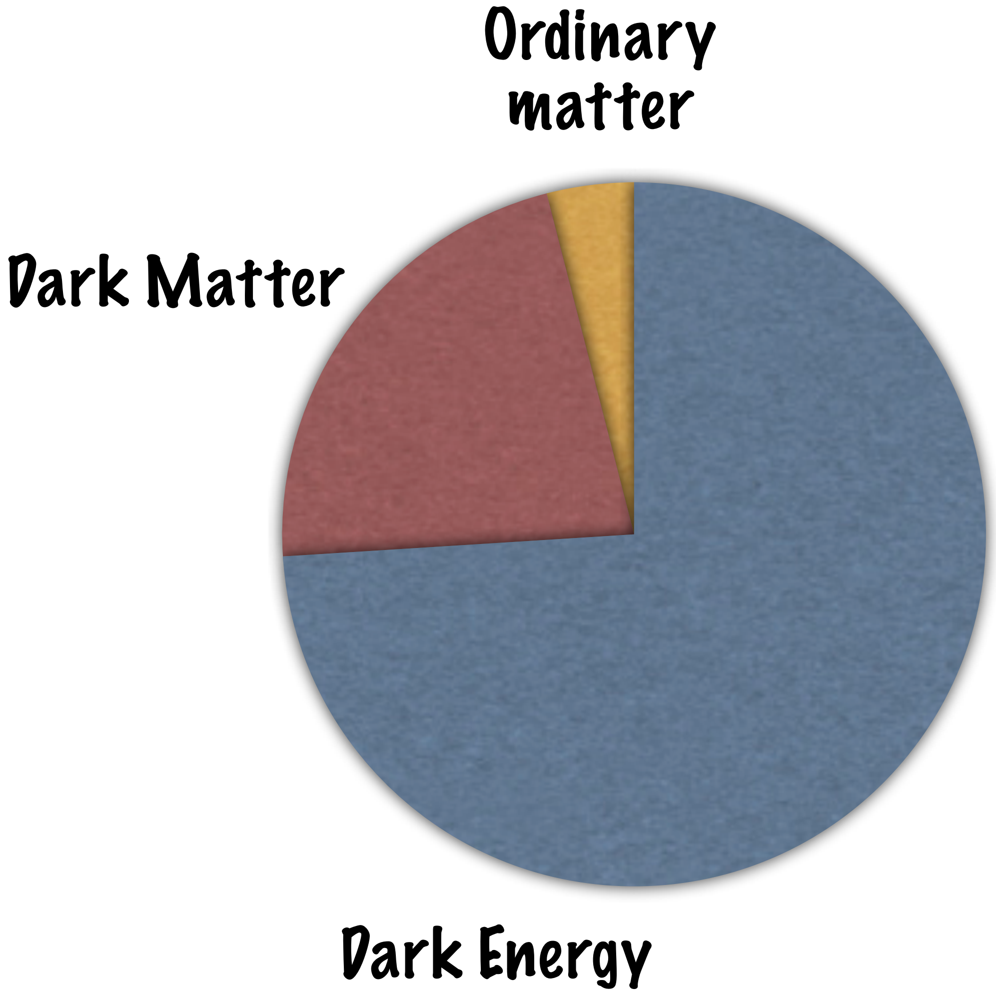
2. Effect on the IGM.

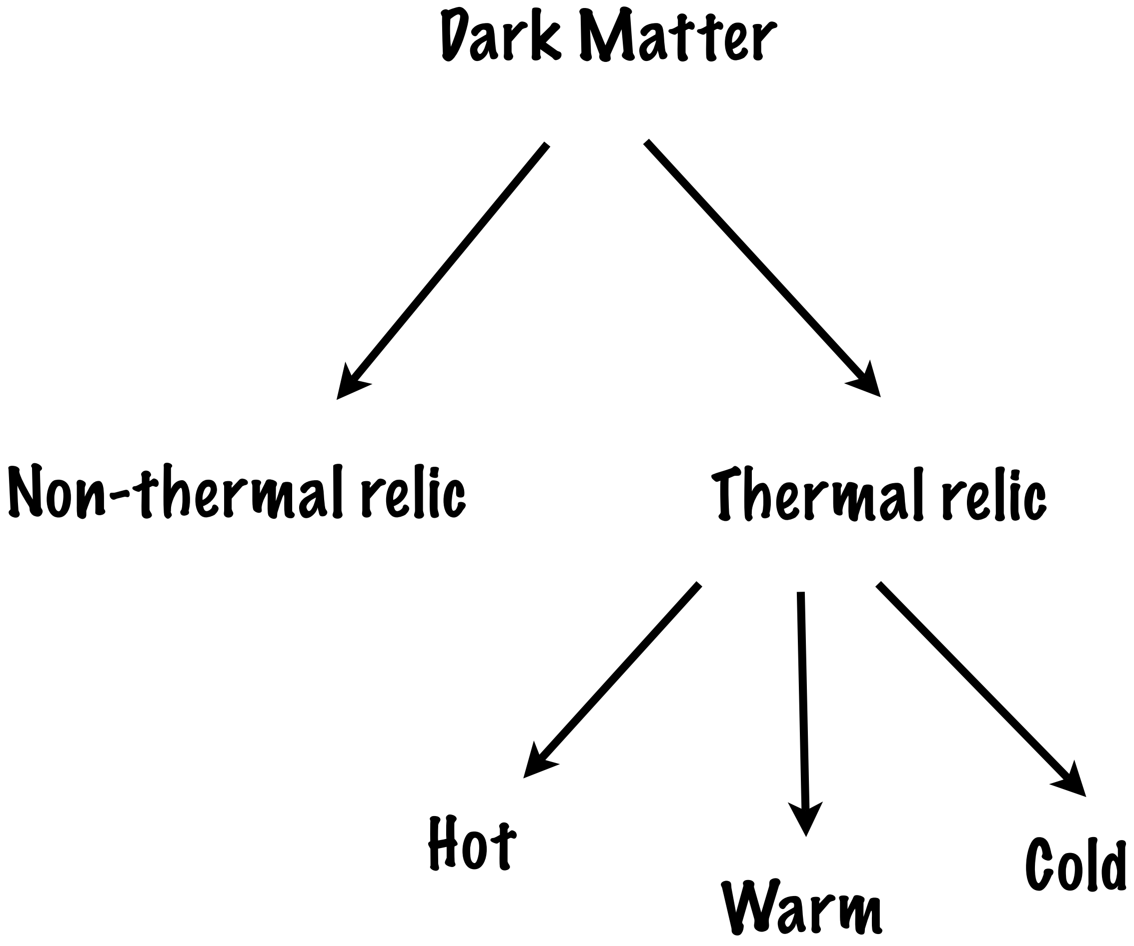
    can they reionize the Universe?

    (Furlanetto et al. '06; Mapelli et al. '06; Ripamonti et al. '07; Chuzhoy '08)

3. Contribution to the optical depth.

    constraints on particle and halo parameters.




Dark Matter

Non-thermal relic

Thermal relic

Hot

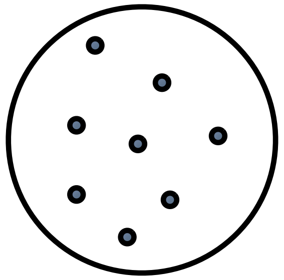
Warm

Cold

Most of the matter in our galaxy is dark

Dark matter searches : ADMX, DAMA, CDMS, Xenon, Edelweiss, Zeplin, EGRET, ...

Particle annihilation in clumps -



Probability of annihilation = $\langle \sigma_a v \rangle \, n_\chi \, \delta t$

Number of pairs = $\frac{1}{2} \, n_\chi \, \delta V$

Energy released per ann. = $\int dE_\gamma \, E_\gamma \, \frac{dN_\gamma}{dE_\gamma}$

$$\frac{dL}{dE_\gamma} = \frac{\langle \sigma_a v \rangle}{2} \, \frac{dN_\gamma}{dE_\gamma} \, E_\gamma \, \int dV \, \frac{\rho_\chi^2(r)}{m_\chi^2}$$

Energy spectrum of photons -

Let $x = E_\gamma / m_\chi$

$$\frac{dN_\gamma}{dx} = \frac{a e^{-bx}}{x^{1.5}}$$

$a = 0.9$

$b = 9.56$

(Bergström et al. '98; Feng et al. '01)

$$\frac{dL}{dx} = \frac{\langle \sigma_a v \rangle}{2 m_\chi} \frac{a\, e^{-bx}}{\sqrt{x}} 4\pi \int dr\, r^2 \rho^2(r) = \frac{a e^{-bx}}{\sqrt{x}} L_0$$

NFW $\rho(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}$

NFW like $\rho(r) = \frac{\rho_s}{(r/r_s)^\alpha (1+r/r_s)^\beta}$

Isothermal + core $\rho(r) = \frac{\rho_s}{(r/r_s)^2 + K}$

$$\rho(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}$$

r_{200} **:** $$\bar{\rho}(z_{\rm f}) = 200\,\rho_{\rm c}\,\Omega_{\rm m}\,(1+z_{\rm f})^3$$

$$\frac{4\pi r_{200}^3}{3}\,\bar{\rho}(z_f) = M(r_{200})$$

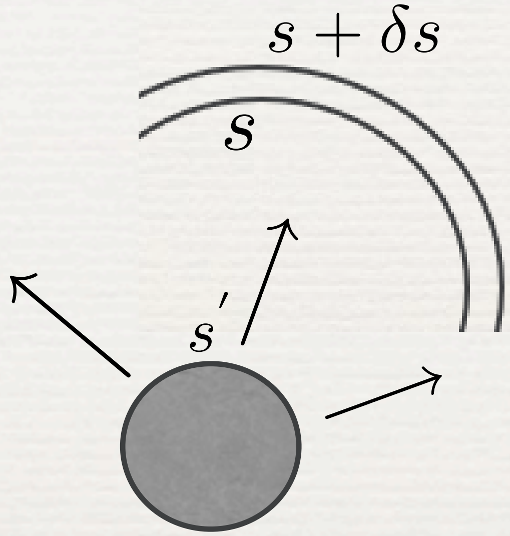
$$c_{200} = r_{200}/r_s$$

$$\begin{aligned} M_{\rm dm}(r_{200}) &= 4\pi\rho_{\rm s}r_{\rm s}^3\left[\ln(1+c_{200}) - \frac{c_{200}}{1+c_{200}}\right] \\ &= f_{\rm dm}\,M \\ &= \frac{4\pi}{3}r_{200}^3\,f_{\rm dm}\,\bar{\rho}(z_{\rm f}) \end{aligned}$$

$$f_{\rm dm} = \Omega_{\rm dm}/\Omega_{\rm m}$$

$$\rho_{\rm s} = \frac{f_{\rm dm}\,\bar{\rho}(z_{\rm f})}{3}\,\frac{c_{200}^3}{\ln(1+c_{200}) - \frac{c_{200}}{1+c_{200}}}$$

$$L_0 = L_0(M, c_{200})$$



n_b

σ

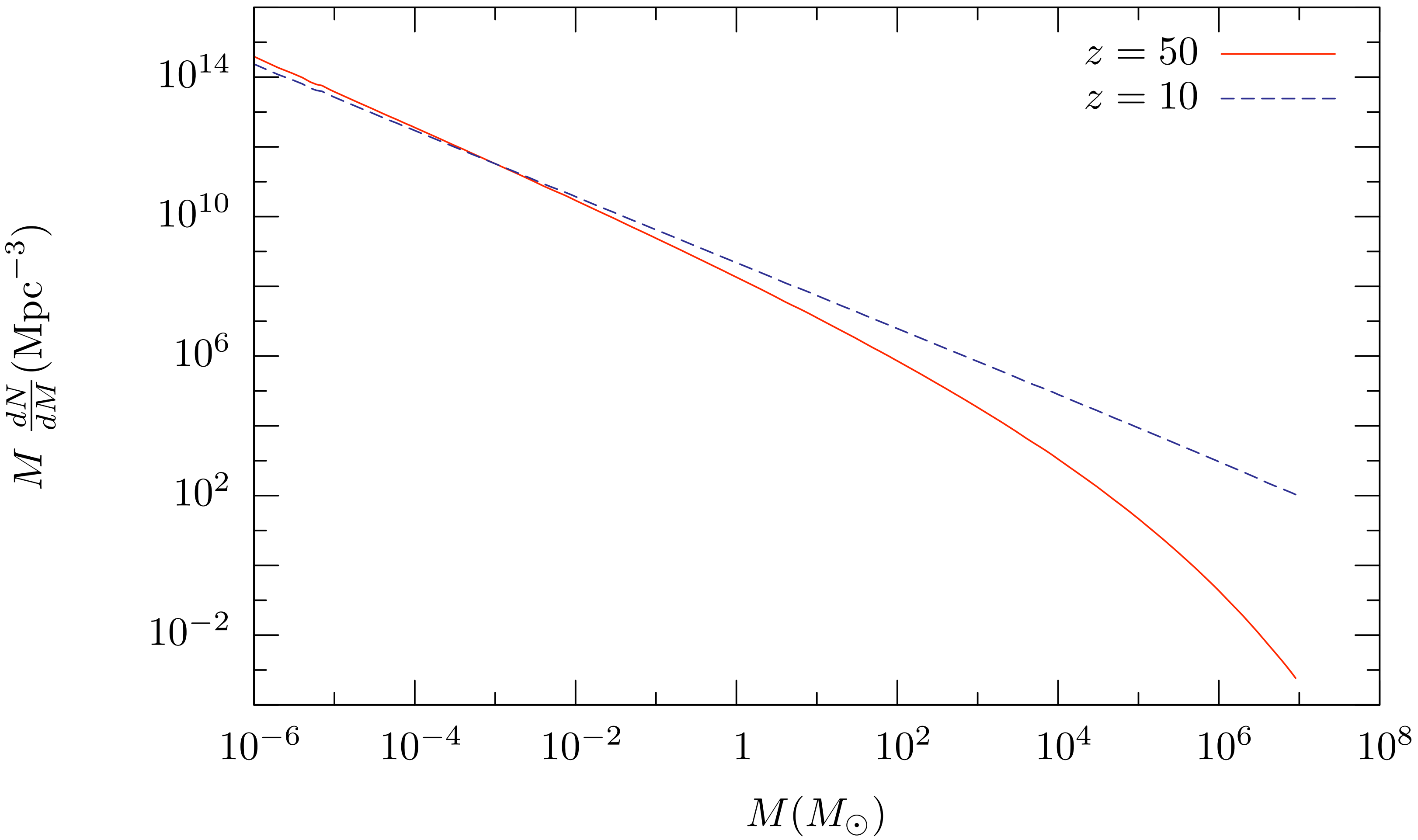
δs

$$p(s) = \frac{n_b(s)\sigma\delta s}{4\pi s^2 \delta s}$$

$$n_\gamma(s) = n_\gamma(s') \times \kappa(s';s)$$

$$\kappa(s';s) = \exp\left[-\int_{s'}^{s} ds\, n(s)\sigma\right]$$

How many halos ?



Num. ionizations per vol. per time at z =

$$\left[\frac{c\sigma_\mathrm{T} n_b}{H_0\sqrt{\Omega_m}}\right] \mu\,\eta\,[1 - x_\mathrm{ion}(z)]\;\frac{1}{\sqrt{1+z}} \qquad\qquad \times$$

$$\int_{z_\mathrm{F}}^{z} -dz'\,(1+z')^{-1/2} \quad \int_0^1 dx\,\frac{ae^{-bx}}{\sqrt{x}}\;\frac{\sigma(x)}{\sigma_\mathrm{T}}\,\kappa(z';z,x) \quad \int_{\mathrm{M_{min}}}^{\infty} dM\;\frac{dN}{dM}\;L_0(M)$$

$$x = E_\gamma/m_\chi \qquad\qquad \mu = \frac{0.76}{0.82}\,\frac{1}{13.6\,\mathrm{eV}} + \frac{0.06}{0.82}\,\frac{1}{24.6\,\mathrm{eV}}$$

Recombination:

$$\alpha_H = \frac{2.076 \times 10^{-11}\mathrm{cm}^3\mathrm{s}^{-1}}{\sqrt{T_K}}\,\Phi(T_K)$$

(L. Spitzer '48; H.Zanstra '54)

$$\Phi(T_K) \approx \sum_2^{n_{max}} \frac{1}{n}$$

$$n_{max} = \sqrt{\frac{1.58 \times 10^5}{T_K}}$$

$$\alpha_H \approx 3.746 \times 10^{-13}(T/\mathrm{eV})^{-0.724}$$

$$\alpha_{He} \approx 3.925 \times 10^{-13}\,(T/\mathrm{eV})^{-0.6353}$$

$$T \approx 8 \times 10^{-4}[(1+z)/61]^2\ \mathrm{eV}$$

$$R(z) = n_\mathrm{b}^2\, x_\mathrm{ion}^2 (1+z)^6 \left[\frac{0.76}{0.82}\,\alpha_\mathrm{H} + \frac{0.06}{0.82}\,\alpha_\mathrm{He}\right]$$

$$\begin{aligned} I(z) - R(z) &= n_b(1+z)^3 \frac{dx_{ion}}{dt} \\ &= -n_b H_0 \sqrt{\Omega_m}\, \frac{dx_{ion}}{dz}\, (1+z)^{11/2} \end{aligned}$$

$$\langle \sigma_{\rm a} v \rangle = 3 \times 10^{-26}\ {\rm cm^3\ s^{-1}}$$

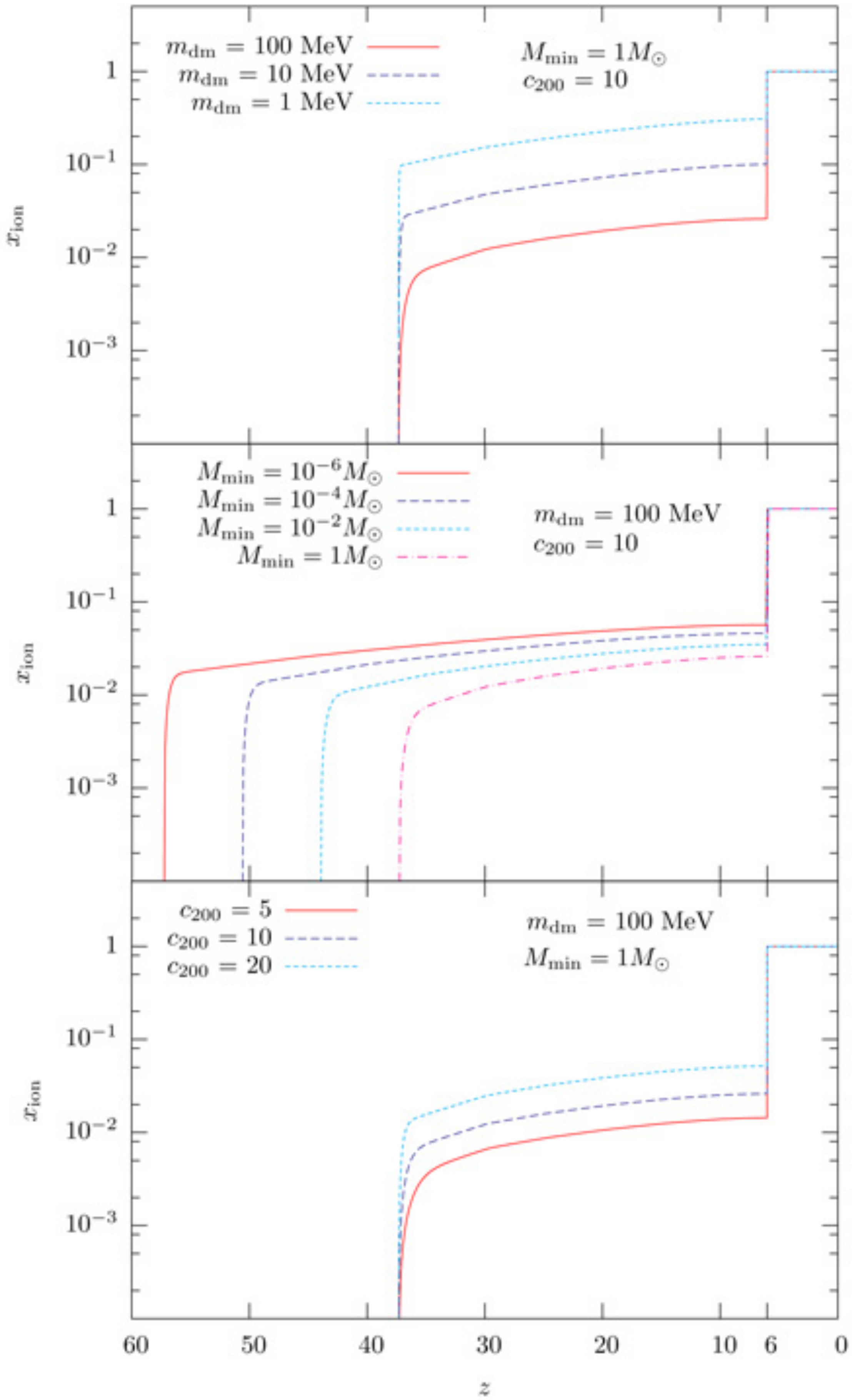
$x_{\rm ion}$ depends on -

1. Particle mass - MeV range.
2. Minimum halo mass.
3. Halo concentration parameter.

m_{dm}

M_{min}

c_{200}

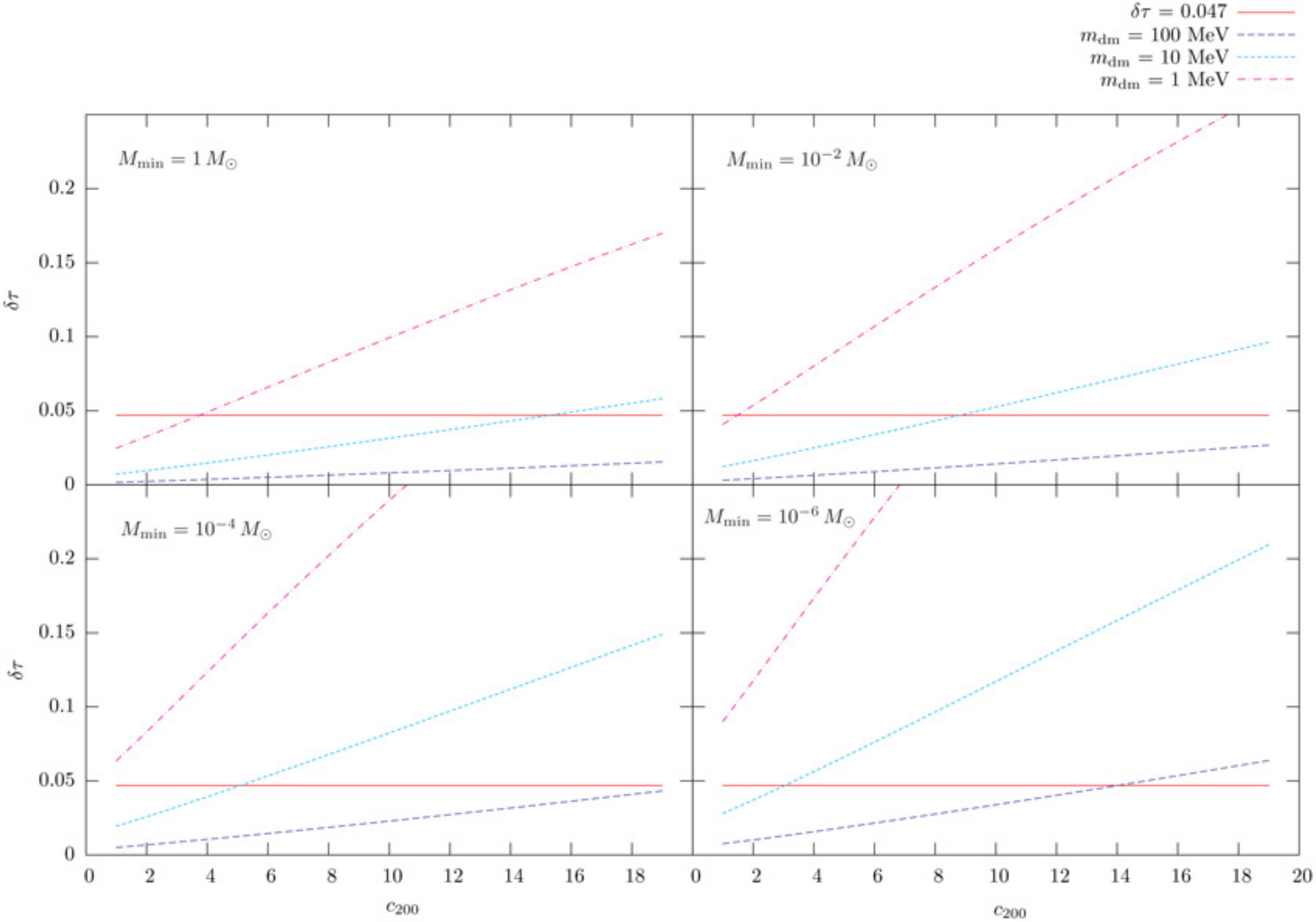


Optical depth $\tau = \int ds\, n_e(s)\, \sigma_T$

- No Gunn-Peterson trough in the spectrum of quasars at z < 6.
- H fully ionized at z = 6.
- He doubly ionized at z = 3.
- He singly ionized at z = 6.

$$\tau(z < 6) = 0.04$$

- But WMAP inferred $\tau = 0.087$!



$\delta\tau = 0.047$
$m_{\rm dm} = 100$ MeV
$m_{\rm dm} = 10$ MeV
$m_{\rm dm} = 1$ MeV
$M_{\rm min} = 1\, M_\odot$
$M_{\rm min} = 10^{-2}\, M_\odot$
$M_{\rm min} = 10^{-4}\, M_\odot$
$M_{\rm min} = 10^{-6}\, M_\odot$
$\delta\tau$
0
0.05
0.1
0.15
0.2
0
2
4
6
8
10
12
14
16
18
20
c_{200}

Conclusions:

1. Predicts a gradual reionization history.

2. H21 signal = 10's of mK at z=15

   (L. Chuzhoy '08)

3. Places an upper limit on the DM mass.

   Soft gamma ray background (K. Ahn, E. Komatsu, '05)

   Positron production (J.F. Beacom, N.F. Bell, G. Bertone, '05)

   $m_\chi \sim 20\ \mathrm{MeV}$

   May conflict with upper limit set by optical depth.

4. Pop. III star formation.

5. DM and stars.

   (Spolyar et al. '08; Freese et al. '08; Iocco et al. '08;
   Fairbairn et al. '08; Taoso et al. '08; Natarajan et al. '08)