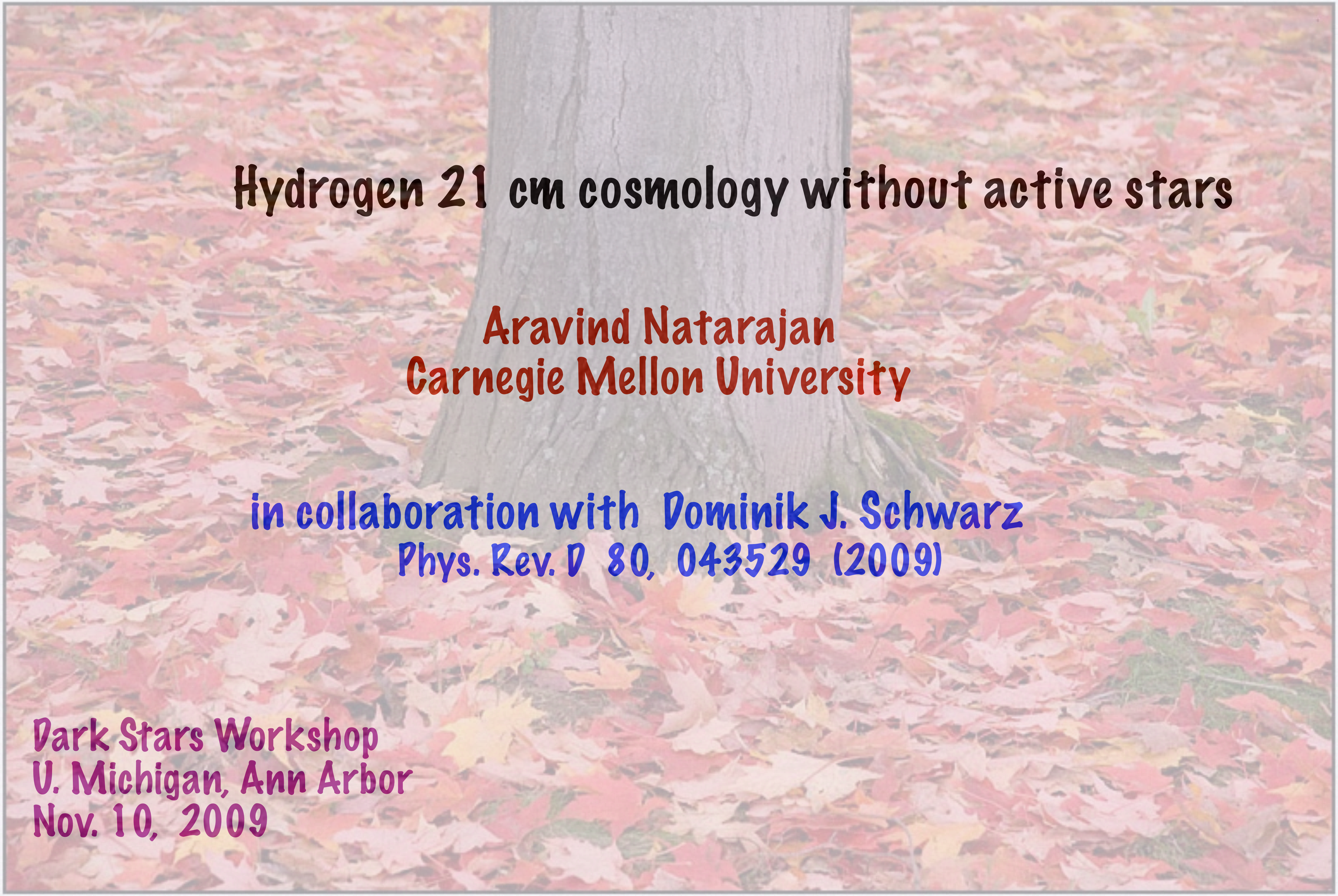

Hydrogen 21 cm cosmology without active stars

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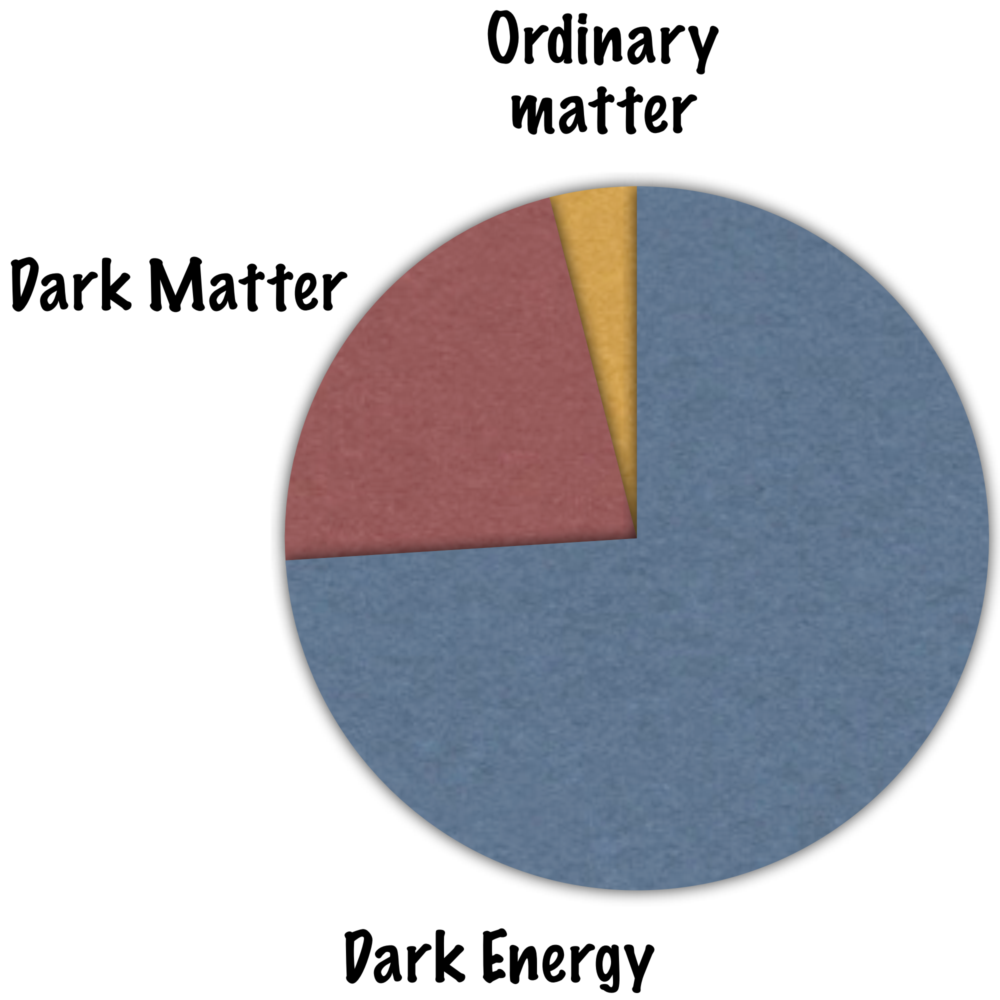
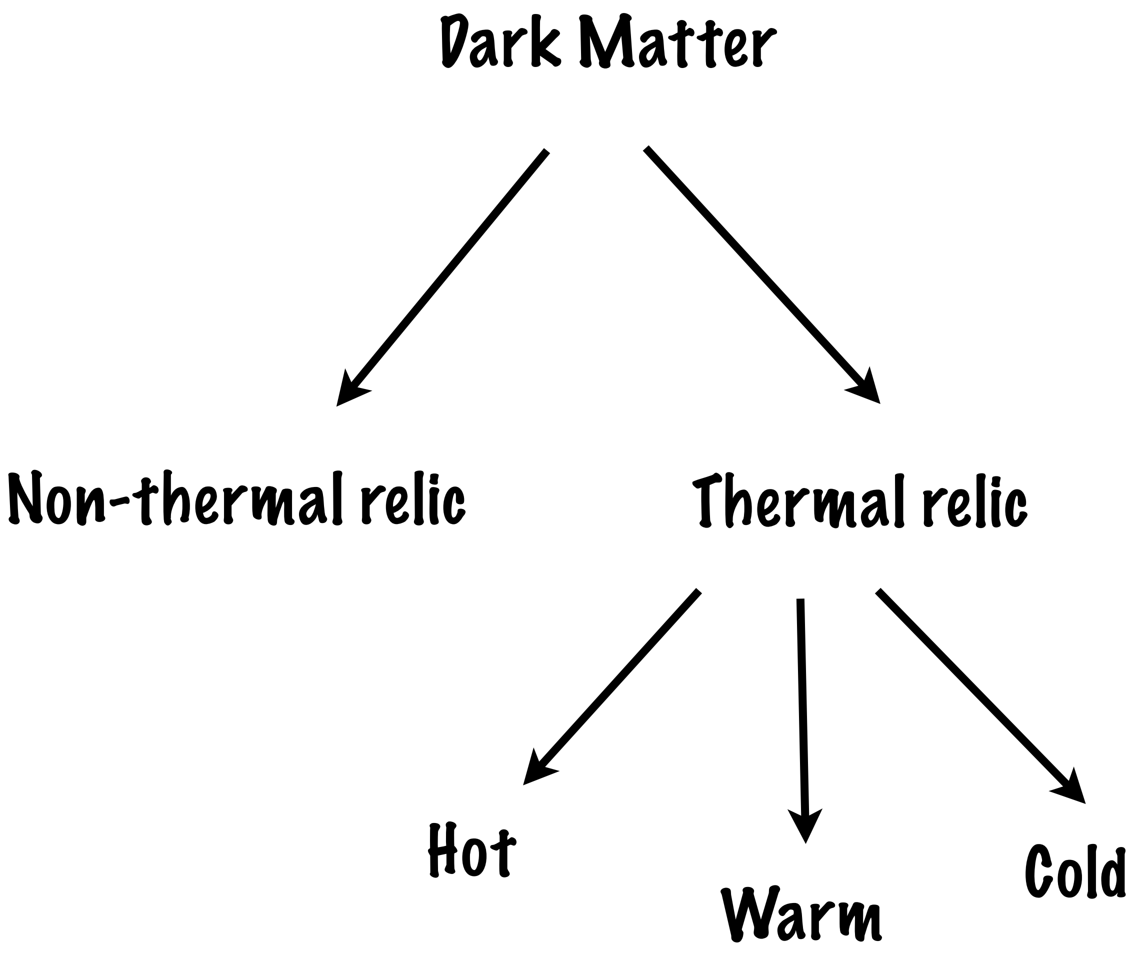
Phys. Rev. D 80, 043529 (2009)

Dark Stars Workshop
U. Michigan, Ann Arbor
Nov. 10, 2009




Dark Matter

Non-thermal relic

Thermal relic

Hot

Warm

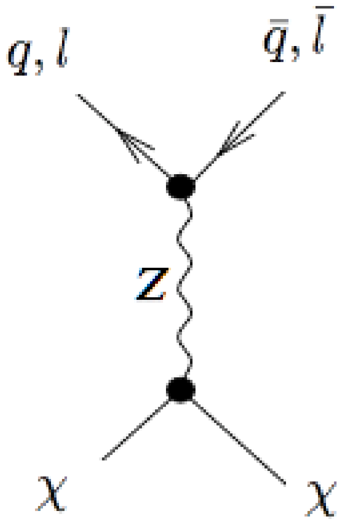
Cold

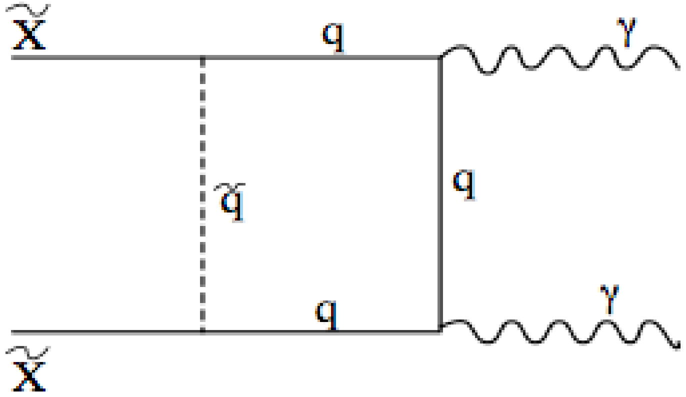
Most of the matter in the Universe is dark

SuSy Neutralino-

$$\tilde{\chi}^0 = g_1 \tilde{B} + g_2 \tilde{W}^3 + h_1 \tilde{H}_1 + h_2 \tilde{H}_2$$

$$|g_1|^2 + |g_2|^2 + |h_1|^2 + |h_2|^2 = 1$$

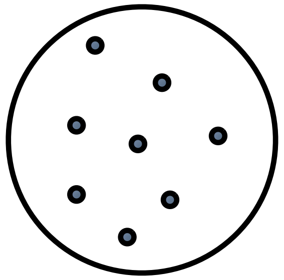




(See for ex, Jungman, Kamionkowski, Griest, '95)

Note: There exist other dark matter candidates!

Particle annihilation in clumps -



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

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

Energy released per annihilation = $2 \, m_\chi \, c^2$

$$\frac{dN_{\rm ann}}{dt dV} \propto \rho_\chi^2$$

Density Profile:

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

Einasto $$\rho(r) = \rho_0 \, \exp - A r^\alpha$$

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

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

$$\tfrac{4}{3}\,\pi r_{200}^3\,\bar{\rho}(z_\mathrm{f}) = M$$

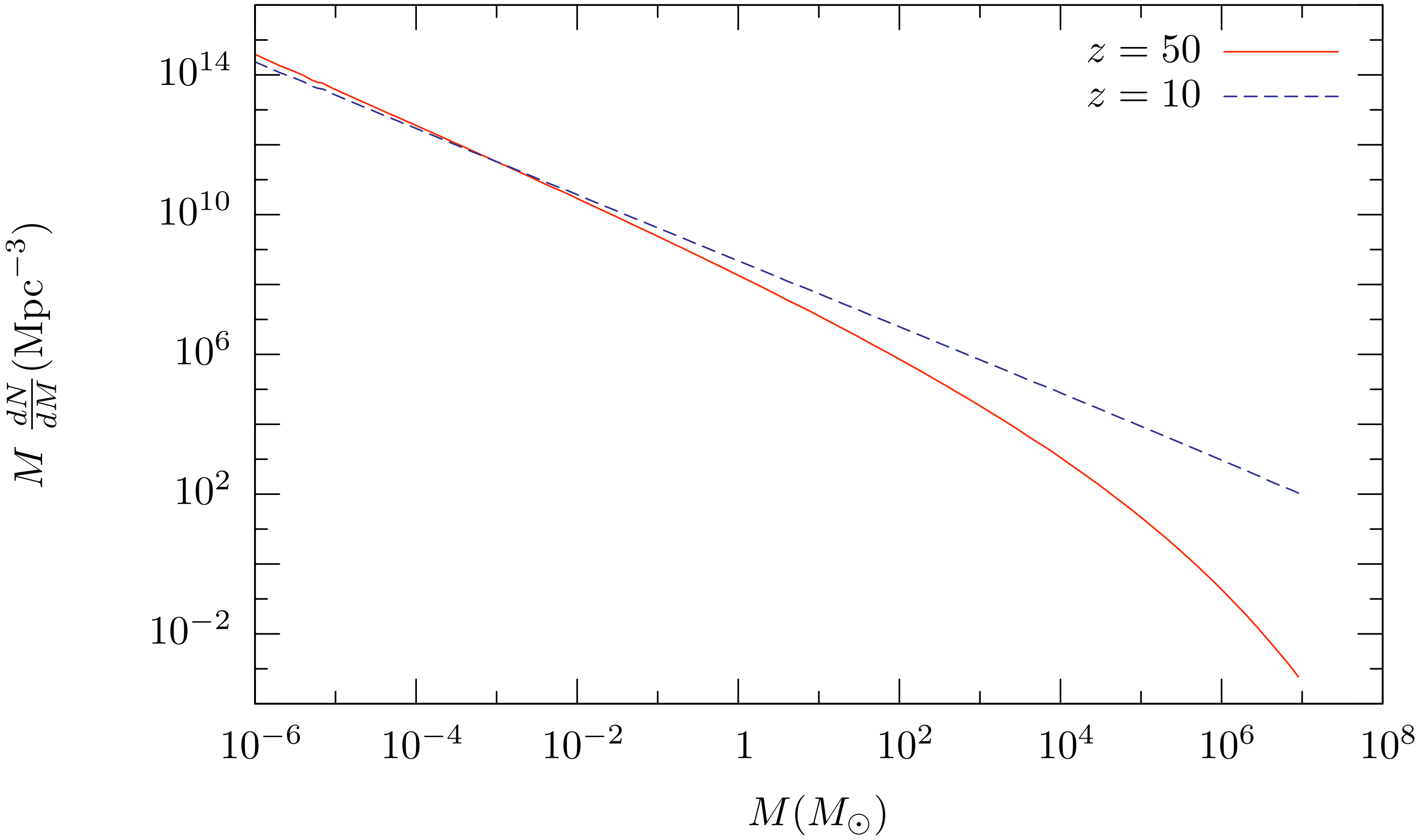
$$c_{200} = r_{200}/r_s$$

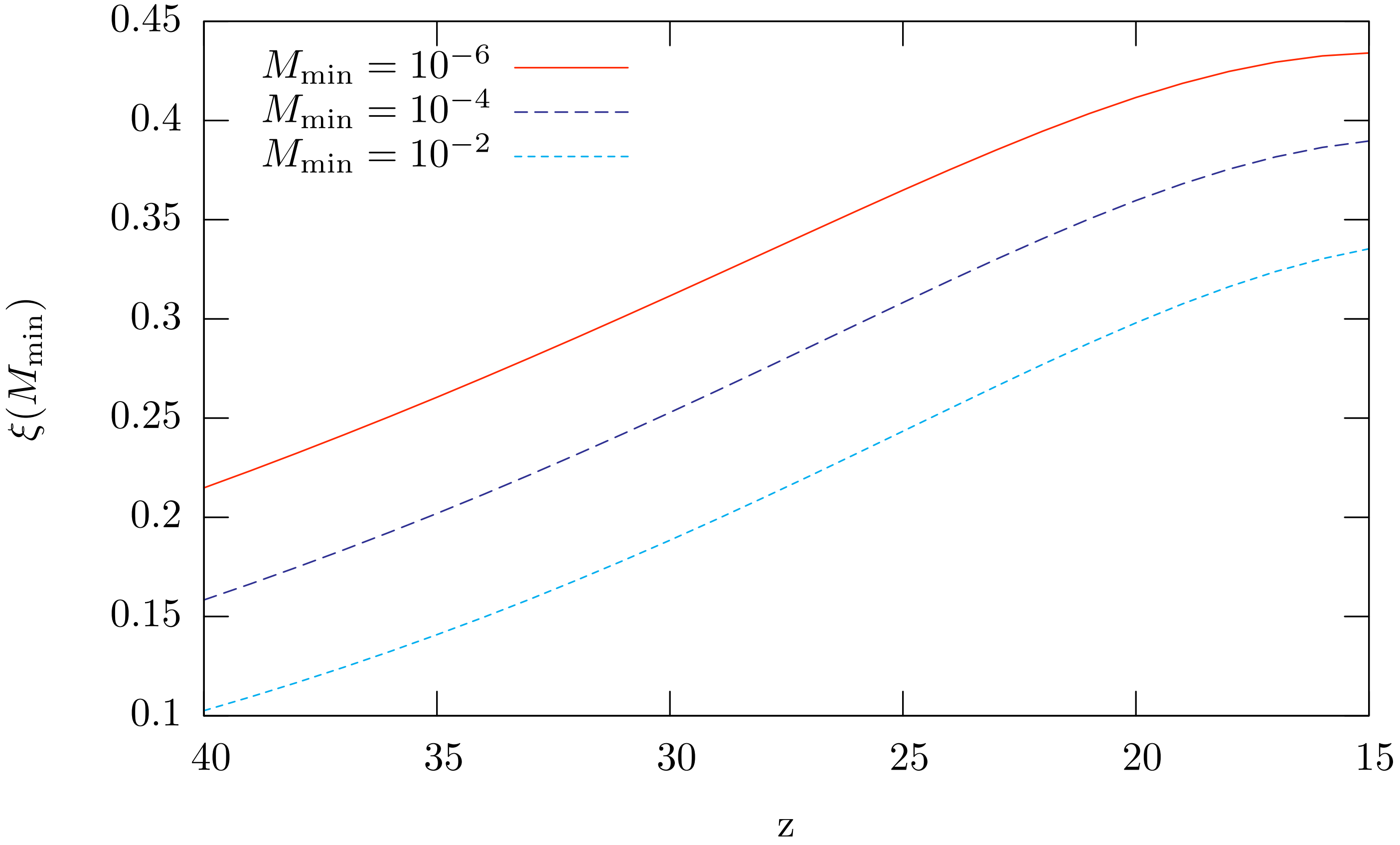
dwarf galaxies $c_{200} \sim 10$ (Maccio, Dutton, van den Bosch, '08)

small clumps $c_{200} \sim 3$ (Diemand, Moore, Stadel '05)

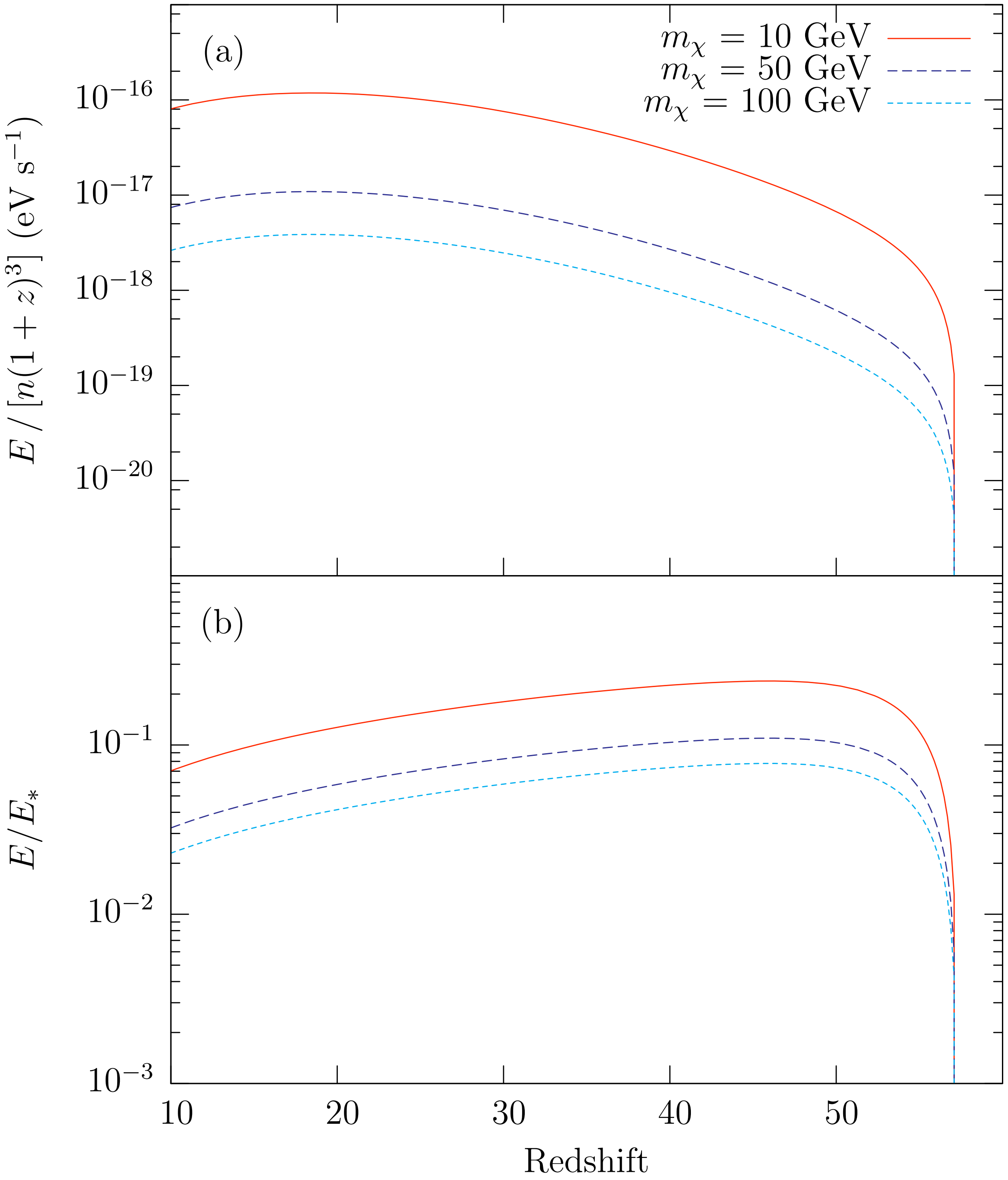
Thermal relic - $\langle \sigma_\mathrm{a} v \rangle \approx 3 \times 10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$

Number density of halos-





$$\frac{E(z)}{n(z)} = \int_{\infty}^{z} \frac{-dz'}{(1+z')H(z')} \left(\frac{1+z}{1+z'}\right)^{3} \left(\frac{dN_{\text{ann}}}{dt\,dV}\right)(z') \int_{E_1}^{E_2} dE'_{\gamma} E'_{\gamma} \frac{dN_{\gamma}}{dE'_{\gamma}}(E'_{\gamma})\, e^{-\kappa(z',z;E'_{\gamma})} \left[c\sigma(E'_{\gamma})\right]$$



$$\frac{E(z)}{n(z)} = \int_\infty^z \frac{-dz'}{(1+z')H(z')} \left(\frac{1+z}{1+z'}\right)^3 \left(\frac{dN_{\rm ann}}{dt\,dV}\right)(z') \int_{E_1}^{E_2} dE'_\gamma E'_\gamma \frac{dN_\gamma}{dE'_\gamma}(E'_\gamma)\, e^{-\kappa(z',z;E'_\gamma)}\, \left[c\sigma(E'_\gamma)\right]$$

$$(1+z)H(z)\frac{dx_{\rm ion}(z)}{dz} = -\mu\,[1-x_{\rm ion}(z))]\,\eta_{\rm ion}(z)\left[\frac{E(z)}{n(z)}\right] + n(z)x^2_{\rm ion}(z)\alpha(z)$$

$$(1+z)H(z)\frac{dT(z)}{dz} = 2T(z)H(z) - \frac{2\eta_{\rm heat}(z)}{3k_{\rm b}}\left[\frac{E(z)}{n(z)}\right] - \frac{x_{\rm ion}(z)\,\left[T_\gamma(z)-T(z)\right]}{t_{\rm c}(z)}$$

A. Natarajan and D.J. Schwarz '08; A. Natarajan and D.J. Schwarz '09;

D. Hooper and A. Belikov '09; Cirelli, Iocco, and Panci '09; Hutsi, Hektor, Raidal '09

- Ionization.

- Increase in gas temperature.

- Increase in LyA photons.

Many consequences for cosmology.

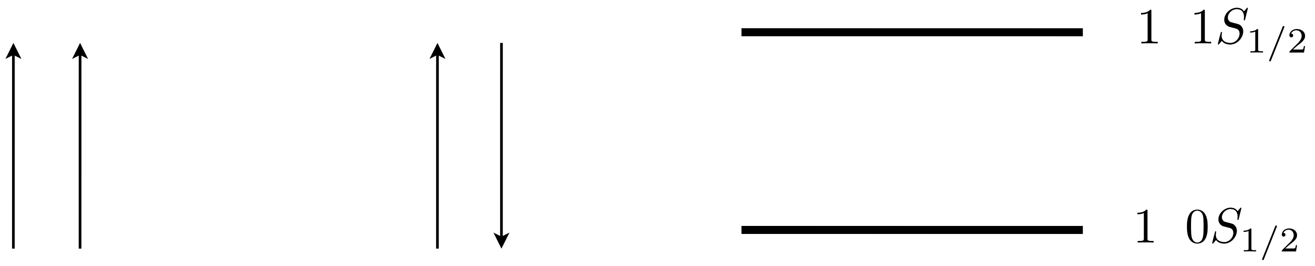
Hydrogen 21cm cosmology -

www.skatelescope.org
SETI Institute

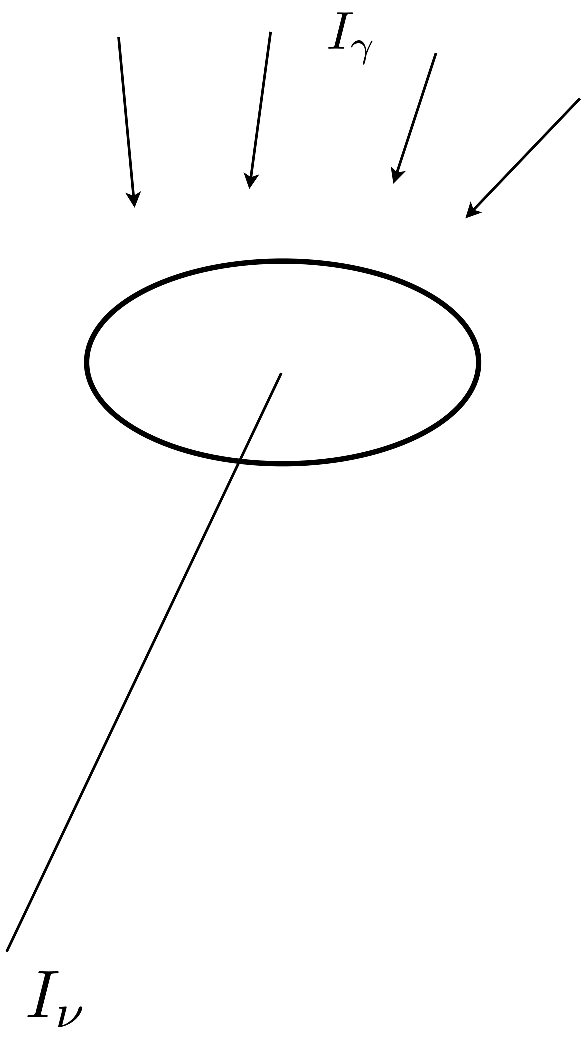
www.lofar.org
LOFAR Project

www.gmrt.ncra.tifr.res.in
GMRT

H21 cm spin flip transition:



$$\frac{n_1}{n_0} = \frac{g_1}{g_0}\, e^{-h\nu/kT_s}$$



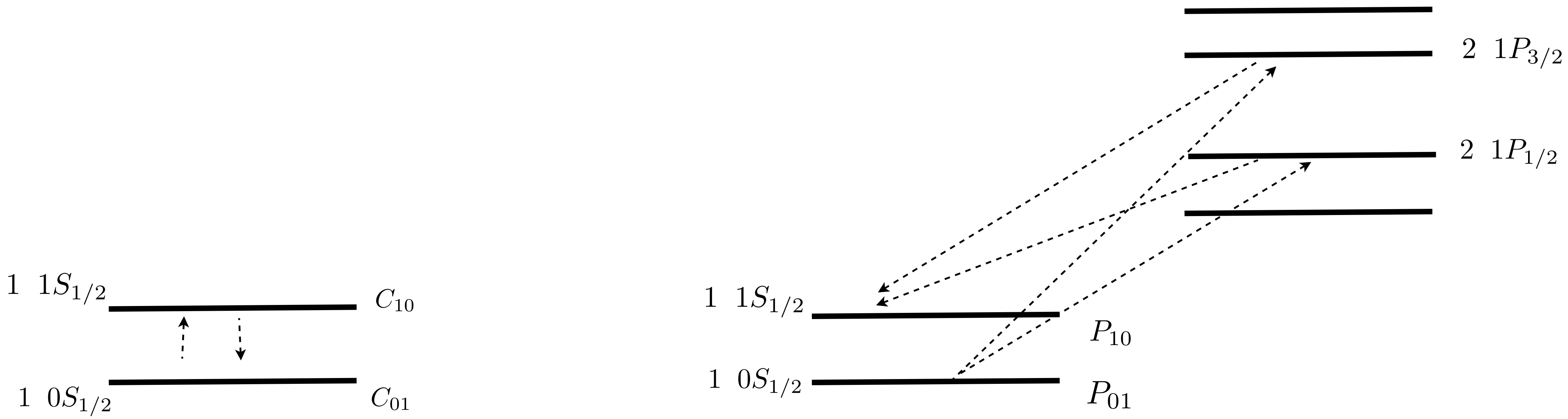
$$\frac{dI_\nu}{ds} = -\kappa_\nu I_\nu + j_\nu$$

$$I_\nu = I_\gamma e^{-\tau} + \int_0^\tau d\tau' \, e^{-\tau'} \frac{j_\nu}{\kappa_\nu} \qquad \tau = \int ds \, \kappa_\nu$$

Intensity (I) ⟶ **Temperature (T_R)**

$$T_{\rm b} = \frac{T_{\rm R} - T_\gamma}{1+z}$$

$$T_{\mathrm{b}} = 27\,\mathrm{mK}\ \sqrt{\frac{1+z}{10}}\,(1-x_{\mathrm{ion}})\,\frac{n}{n_0}\,\frac{\xi}{1+\xi}\,\left(1-\frac{T_\gamma}{T}\right)\left[\frac{H(z)/(1+z)}{dv_{||}/dr_{||}}\right]$$



$$\xi_{\mathrm{c}} = \frac{n(1+z)^3}{A_{10}}\,\frac{T_*}{T_{\gamma,0}(1+z)}\left[x_{\mathrm{ion}}\boldsymbol{\kappa}^{\mathrm{e}} + (1-x_{\mathrm{ion}})\boldsymbol{\kappa}^{\mathrm{H}}\right].$$

$$\xi_\alpha \approx 0.012\left(\frac{21}{1+z}\right)^{5/2}\left(\frac{E}{10^{-20}\ \mathrm{eV\,cm^{-3}\,s^{-1}}}\right).$$

(S. Furlanetto et al. '06)

$$\xi = \xi_{\mathrm{c}} + \xi_\alpha$$

The standard lore-

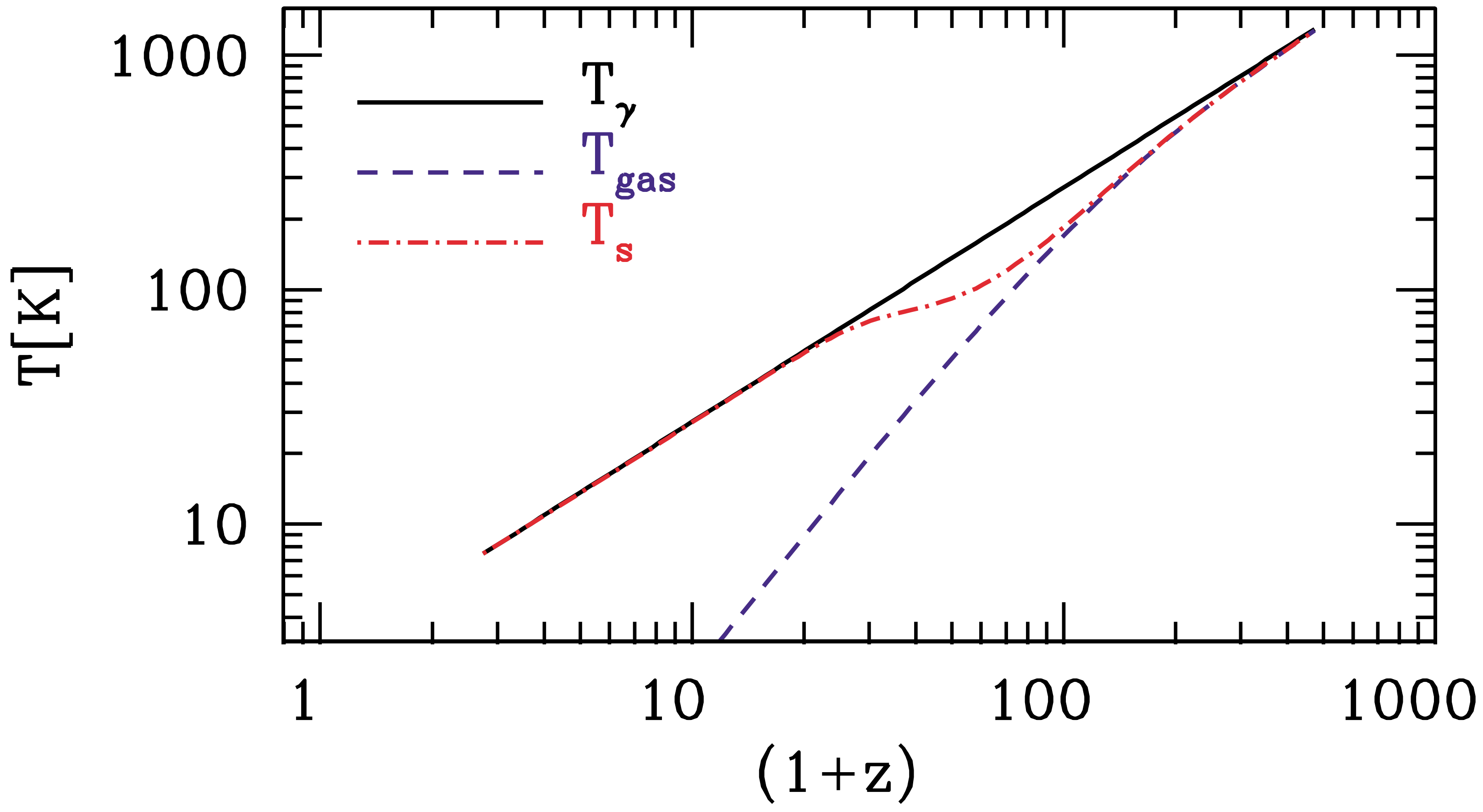


Fig. from Loeb and Zaldarriaga, PRL 92, 211301 (2004)

- At high redshifts $30 < z < 200$, the kinetic temperature of the gas is well coupled to the spin temperature.
- H21 only seen in absorption as T_gas < T_cmb.
- H21 not seen for $z < 30$ in the absence of stars.

Dark matter and H21cm transitions-

- Dark matter annihilation increases the gas temperature. This leads to more collisions between atoms, and hence more 21 cm transitions.

- Some energy goes into collisional excitations of gas atoms, resulting in Ly-A photons. The presence of a Ly-A background also increases the rate of transitions.

- Fluctuations in the 21cm temperature are sensitive to fluctuations in the gas density, the ionized fractions, and the temperature.

n

$T_{\mathrm{b}} \propto$ x_{ion}

T

$$
\begin{aligned}
1 - x_{\mathrm{ion}} &= 1 - x_{\mathrm{ion},0} - x_{\mathrm{ion},0}\delta_{\mathrm{x}} \\
n &= n_0 + n_0\delta_{\mathrm{n}} \\
1 - \frac{T_\gamma}{T} &= 1 - \frac{T_\gamma}{T_0} + \frac{T_\gamma}{T_0}\delta_{\mathrm{T}}
\end{aligned}
$$

$$\xi = \xi_0 + \left[\frac{\partial \xi_0}{\partial n} n_0 \delta_{\mathrm{n}} + \frac{\partial \xi_0}{\partial T} T_0 \delta_{\mathrm{T}} + \frac{\partial \xi_0}{\partial x_{\mathrm{ion}}} x_{\mathrm{ion},0} \delta_{\mathrm{x}}\right]$$

$$T_\mathrm{b} \propto \begin{matrix} n \\ \\ x_\mathrm{ion} \\ \\ T \end{matrix}$$

$$\begin{aligned} 1 - x_\mathrm{ion} &= 1 - x_\mathrm{ion,0} - x_\mathrm{ion,0}\delta_\mathrm{x} \\ n &= n_0 + n_0\delta_\mathrm{n} \\ 1 - \frac{T_\gamma}{T} &= 1 - \frac{T_\gamma}{T_0} + \frac{T_\gamma}{T_0}\delta_\mathrm{T} \\ \xi &= \xi_0 + \left[\frac{\partial \xi_0}{\partial n} n_0 \delta_\mathrm{n} + \frac{\partial \xi_0}{\partial T} T_0 \delta_\mathrm{T} + \frac{\partial \xi_0}{\partial x_\mathrm{ion}} x_\mathrm{ion,0}\delta_\mathrm{x}\right] \end{aligned}$$

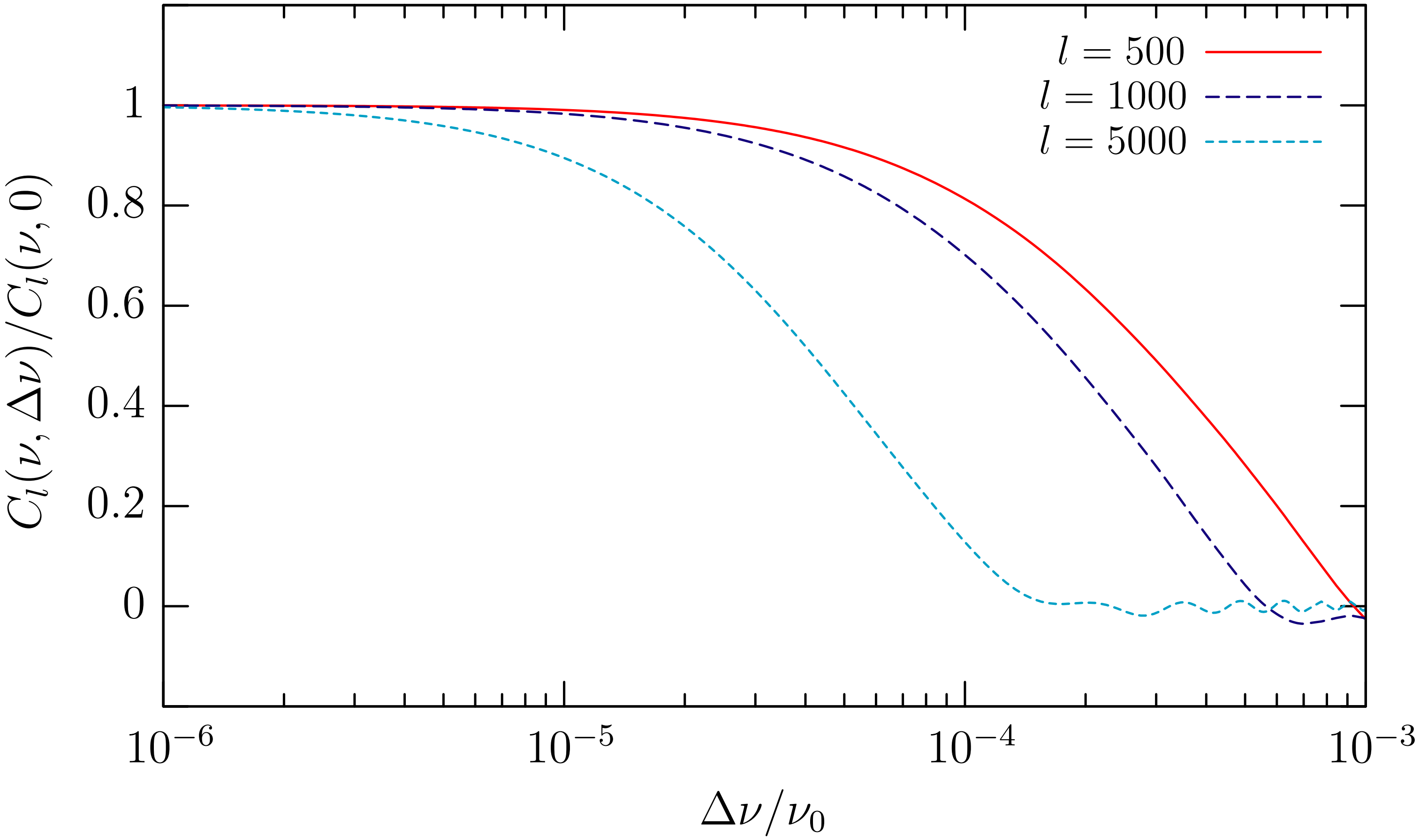
$$\delta_{21}(z, \hat{n}) = \sum_{l,m} a_{lm}(z) Y_{lm}(\hat{n})$$

$$C_l(\nu, \Delta\nu)\delta_{ll'}\delta_{mm'} = \langle a_{lm}(\nu) a^*_{l'm'}(\nu') \rangle$$

power spectrum-

$$\delta_{21}(z,\hat{n}) = \sum_{l,m} a_{lm}(z) Y_{lm}(\hat{n}),$$

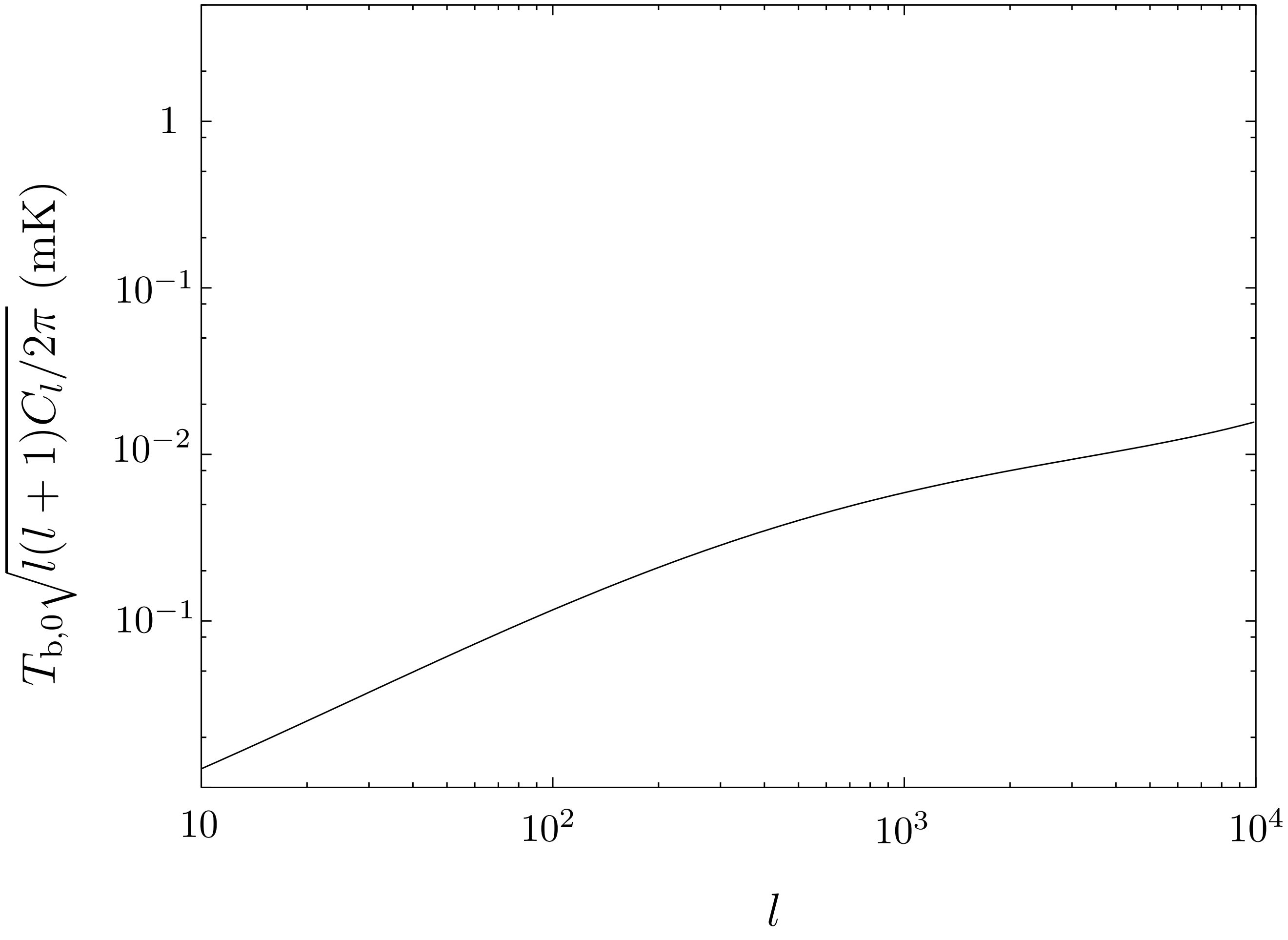
$$C_l(\nu,\Delta\nu)\delta_{ll'}\delta_{mm'} = \langle a_{lm}(\nu) a^*_{l'm'}(\nu')\rangle \qquad \nu = \frac{\nu_0}{1+z}$$



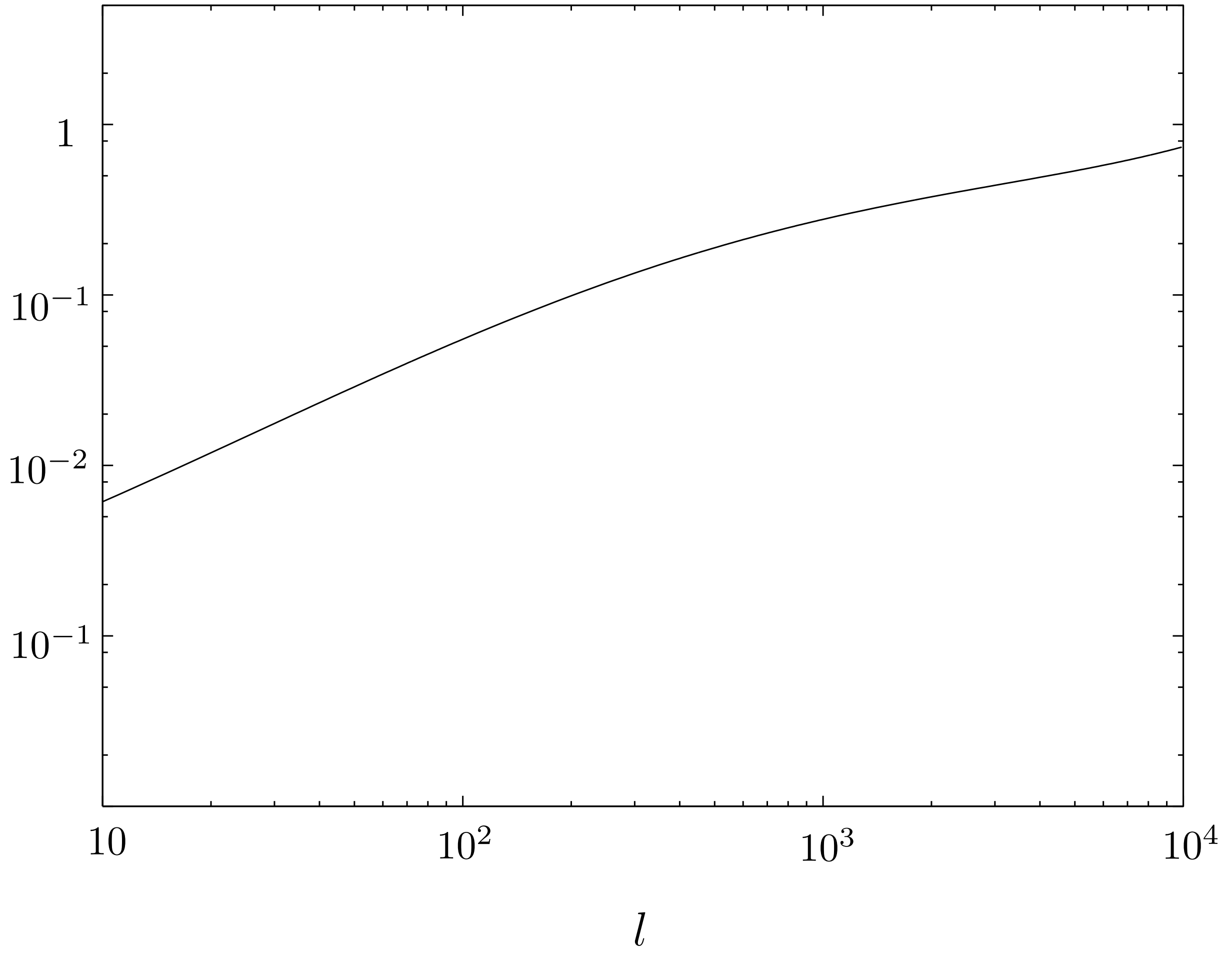
C_l measured at different redshifts

$$\nu = \frac{\nu_0}{1+z} \qquad \Delta\nu = 0$$

$$z = 15$$



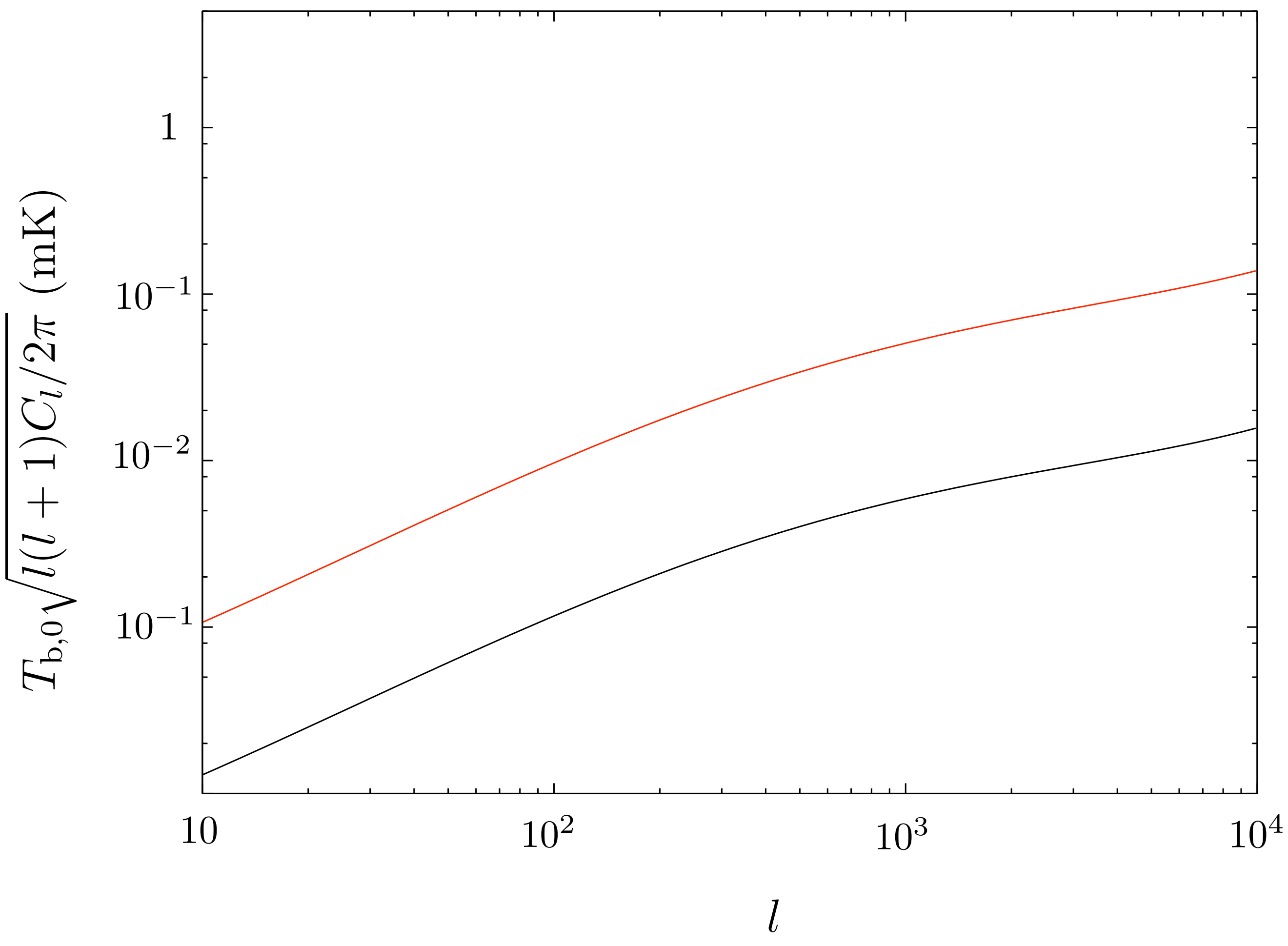
No DM heating



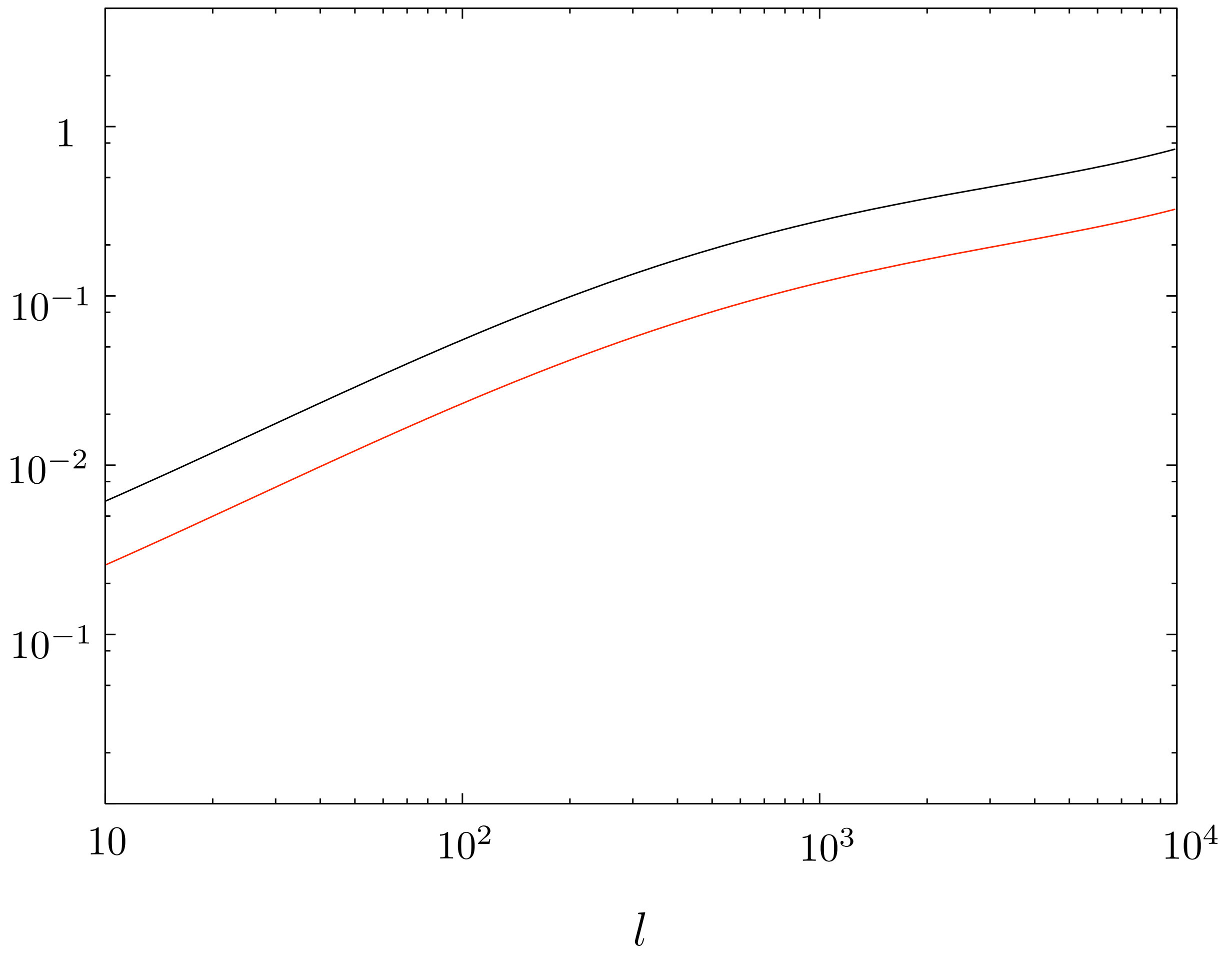
$m_\chi = 10$ GeV
$c_{200} = 5$

$$\nu = \frac{\nu_0}{1+z} \qquad \Delta\nu = 0$$

$$z = 15, 25$$



No DM heating

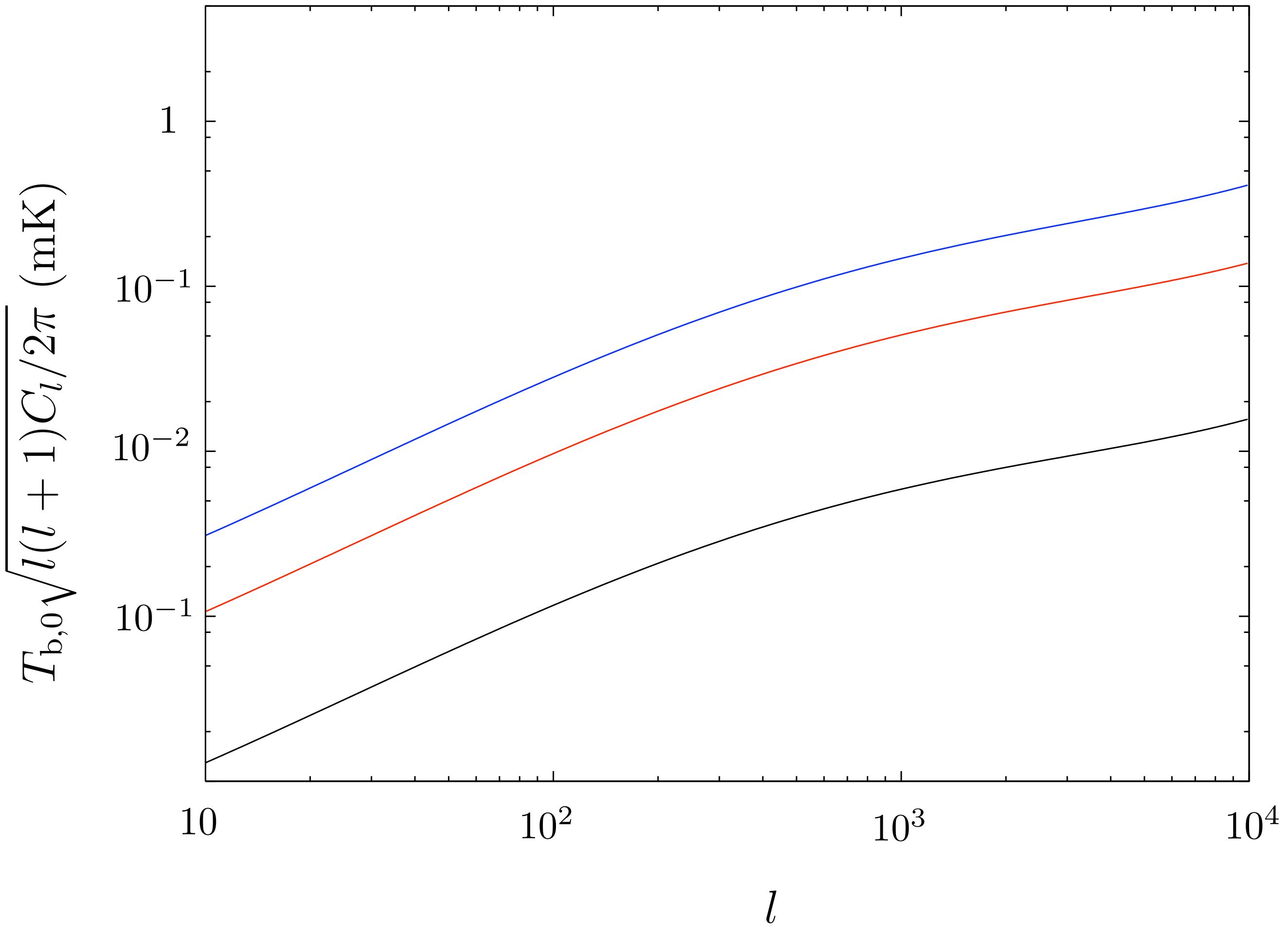


$m_\chi = 10$ GeV

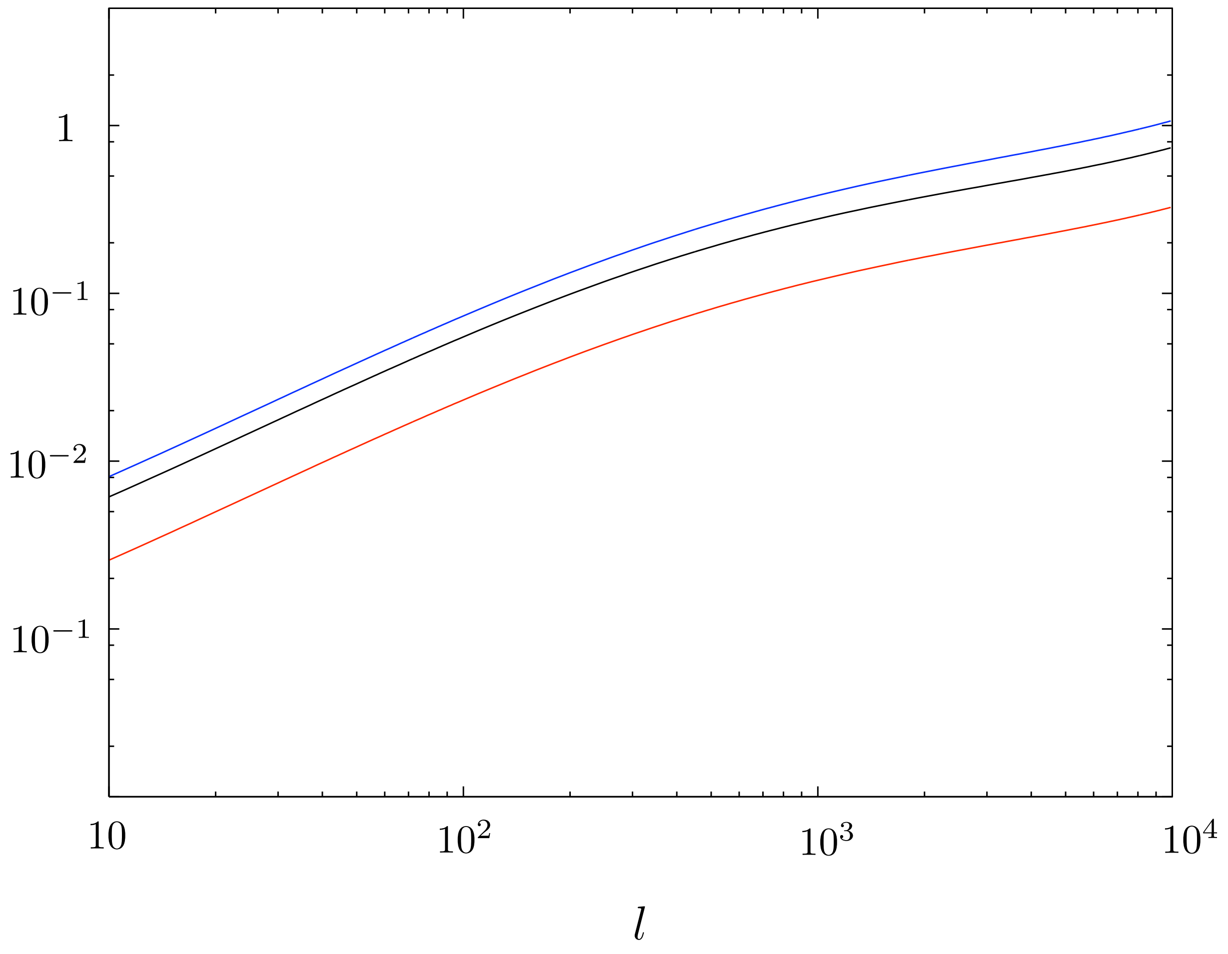
$c_{200} = 5$

$$\nu = \frac{\nu_0}{1+z} \qquad \Delta\nu = 0$$

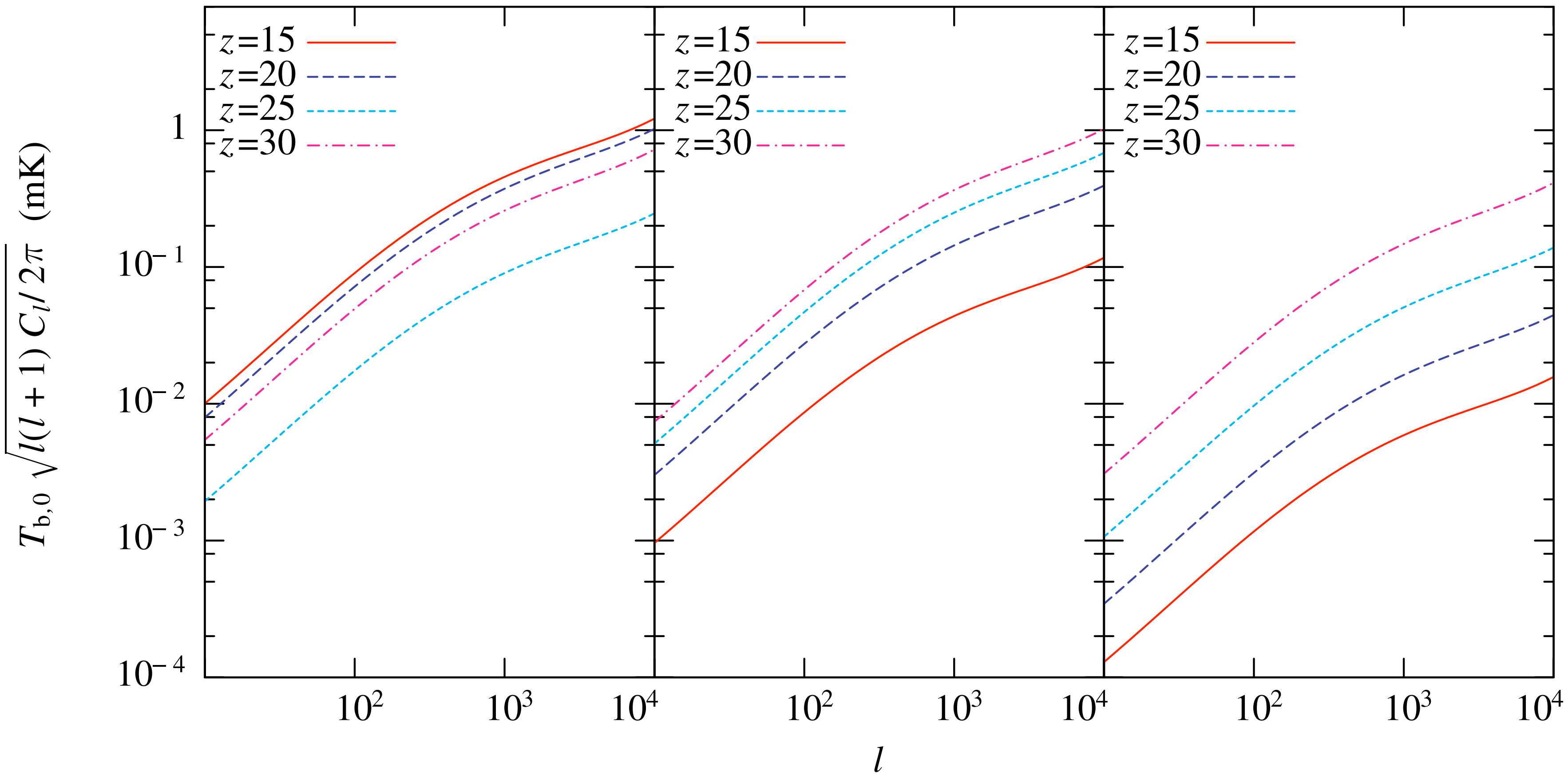
$z = 15, 25, 30$



No DM heating



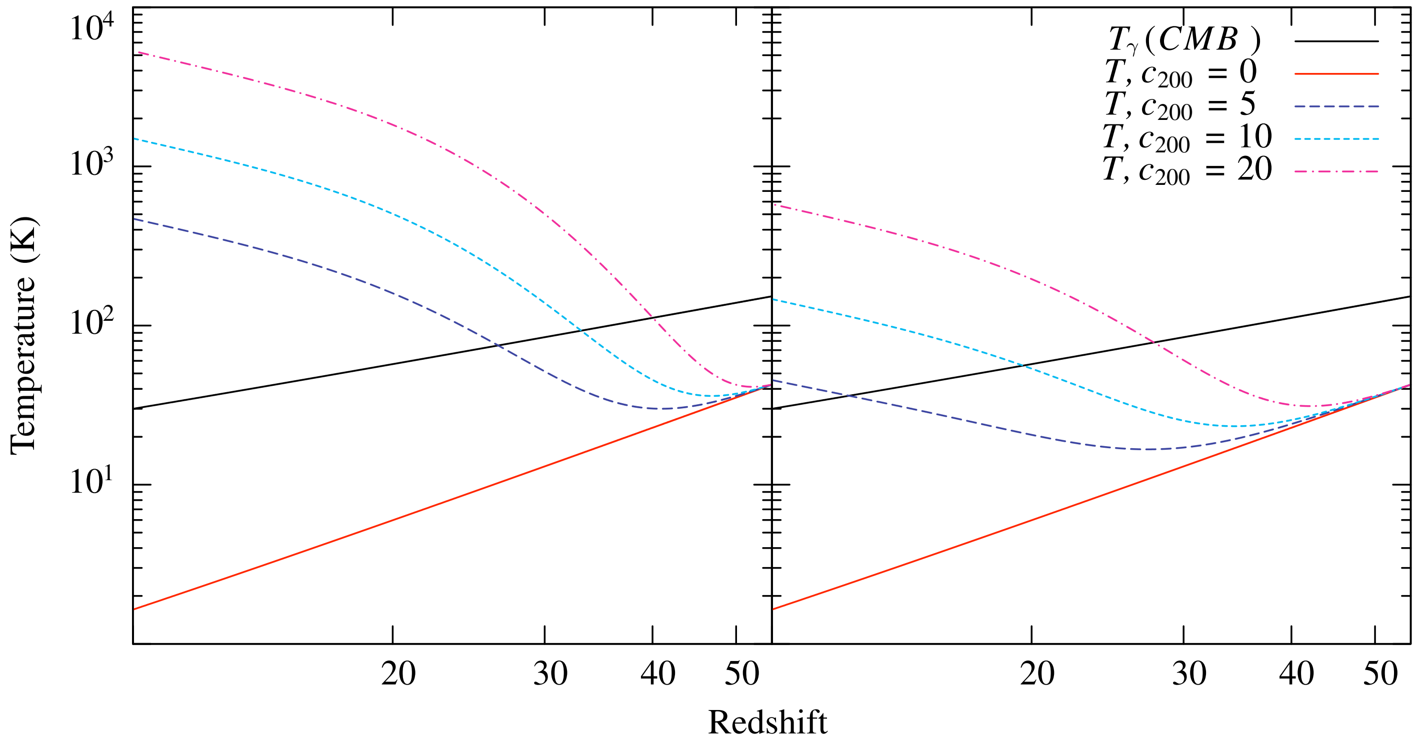
$m_\chi = 10$ GeV
$c_{200} = 5$



(a) $m_\chi = 10$ GeV
$c_{200} = 5$

(b) $m_\chi = 50$ GeV
$c_{200} = 5$

(c) No DM heating



(a) m = 10 GeV

(b) $m_\chi = 50$ GeV

Contamination by the first stars.

The first stars are massive, short lived, and form early.

$$R_{\mathrm{i}} \sim 3\ \mathrm{kpc},\ T_{\mathrm{core}} \sim 10^4\ \mathrm{K},\ R_{\mathrm{n}} \sim 8\ \mathrm{kpc},\ z_{\mathrm{f}} \sim 25$$

(X.Chen and J. Miralda Escude '08)

$$\langle T_{\mathrm{b}} \rangle_{\mathrm{star}} = \mathcal{N} \int d\Omega \int ds\, T_{\mathrm{b}}(s, \theta)$$

$$\langle T_{\mathrm{b}} \rangle = f\, \langle T_{\mathrm{b}} \rangle_{\mathrm{star}} + (1 - f)\, T_{\mathrm{other}}$$

$$f \sim 0.3$$

$$\langle T_{\mathrm{b}} \rangle_{\mathrm{star}} = 1.22\ \mathrm{mK}$$

Not numerous enough to heat the baryons.

Contamination by low-z astrophysical objects-

Pop. II stars, quasars, etc contribute at lower z.

(J. Pritchard and A. Loeb, '08)

$$T_{\rm b} \sim -2 \text{ mK at } z = 25$$

$$T_{\rm b} \sim -100 \text{ mK at } z = 17$$

$$T_{\rm b} > 0 \text{ mK at } z = 14 - 15$$

Very different prediction for z = 17.

Cannot distinguish between DM and standard sources for z < 15.

Conclusions:

- If the dark matter is made up of WIMPs, they will annihilate, releasing energy.
- The Hydrogen 21 cm radiation is sensitive to changes in the gas density, temperature, and ionization fraction.
- The power spectrum has a minimum at a certain redshift. By observing the power spectrum at different redshifts, it is possible to identify heating by dark matter / some exotic source.
- The minimum is not present in all dark matter models, but only those with favorable particle and/or halo properties.