Dark Matter Annihilation Effects On The High Redshift Intergalactic Medium

(Araya and Padilla (2014), MNRAS 445, 850)

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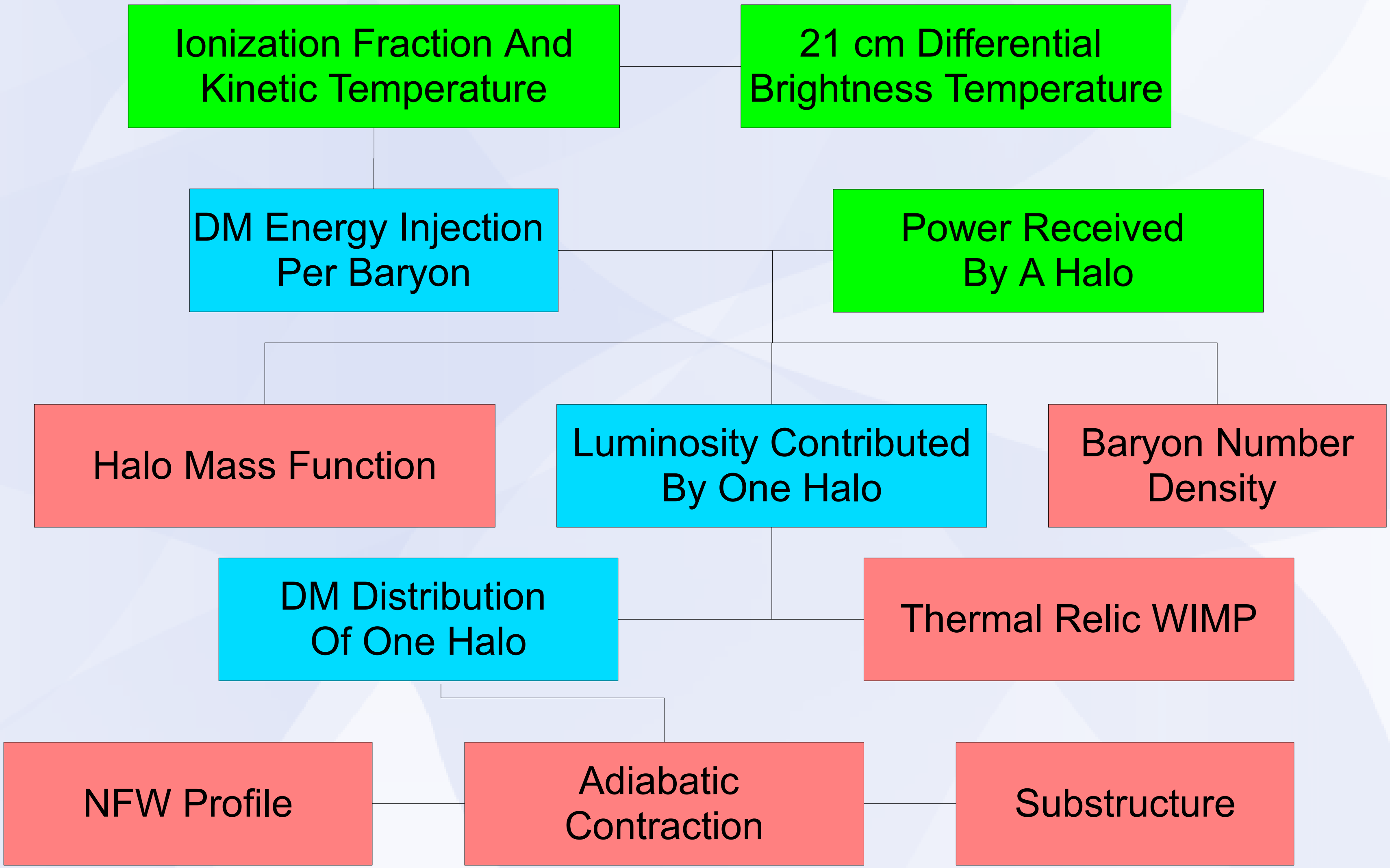
Contents

How Can DM Annihilation Affect The IGM?

- DM annihilation would inject extra energy to the baryonic component of the IGM.
- The IGM ionization fraction and temperature, are sensitive to the extra energy input on the baryons.
- The HI 21-cm line signal would be affected by the change in ionization fraction and temperature.
- If the energy output of DM is sufficient, it could affect the re-ionization process of the IGM and the feedback mechanisms in galaxy formation.
- This can allow to constrain DM models. E.g. 10GeV-1TeV thermal relic WIMP.

Computing The Effects Of DM Annihilation



What Is New In This Work?

- Other works include: Pierpaoli (2004), Mapelli et al. (2006), Ripamonti et al. (2007), Natarajan & Schwarz (2009), Cumberbatch et al. (2010), Valdés et al. (2007)...
- We consider the full hierarchy of DM clumpiness, accounting for the halo mass function, the presence of substructure and the density profile of a single (sub)-halo.
- We take a numerical approach when computing the halo mass function from the primordial power spectrum.
- For the substructure, we consider the exponential mass loss over time due to the relaxation of the mass distribution.

What Is New In This Work?

- We incorporate the modification of the density profile of a single (sub)-halo due to the adiabatic contraction that could be caused by the presence of a SMBH (for massive enough haloes).
- We also study the power received by a halo due to the DM annihilation energy output of the rest of the universe, obtained by computing the intensity of the corresponding radiation field.
- We discuss possible detectability windows for the 21cm signal.

The Thermal Relic WIMP

- A thermal relic WIMP is a Dark Matter particle that is massive (such that it was non-relativistic when it decoupled), weakly interacting, and whose creation and annihilation reactions where in thermal equilibrium in the early universe.
- Based on these characteristics alone, the annihilation cross-section can be estimated as (e.g., Kolb and Turner; 1990):

$$\langle \sigma v \rangle = \frac{4 \times 10^{-27}}{\Omega_{\chi,0} h^2} [\mathrm{cm}^3\, \mathrm{s}^{-1}].$$

- Two main candidates include the SUSY neutralino and the KK photon. (e.g., Hooper & Profumo (2007); Jungman, Kamionkowsky & Griest (1996)).

The DM Clustering

- We consider the ΛCDM cosmological model as given by Planck (arXiv:1303.5076).
- We compute the halo mass function numerically.
  - First we obtain $P_{DM}(k)$ by considering n_s=0.9624 and the BBKS transfer function (Bardeen et al., 1986)
  - Then we obtain $\boldsymbol{\sigma}^2(R)$ (Lacey and Cole, 1993; Mo & White, 1996) integrating $P_{DM}(k)$ with a top hat window function.
  - Finally, we compute $\nu = \frac{\delta_c(z)}{\sigma(R(M))}$ and the mass function using the Sheth et al. (2001) f(**ν**).

The DM Clustering

- For the substructure mass function, we use the form given by Giocoli et al. (2008):

$$\frac{\mathrm{d}N}{\mathrm{d}m} = \frac{N_0}{m} x^{-\alpha} \mathrm{e}^{-6.283x^3}, \quad x = \frac{m K^{-1}(z, M_\mathrm{h})}{\alpha M_\mathrm{h}}, \quad K(z, M_\mathrm{h}) = \exp\left[-\frac{\mathrm{LBT}(z_\mathrm{coll}(M_\mathrm{h})) - \mathrm{LBT}(z)}{\tau(z)}\right]$$

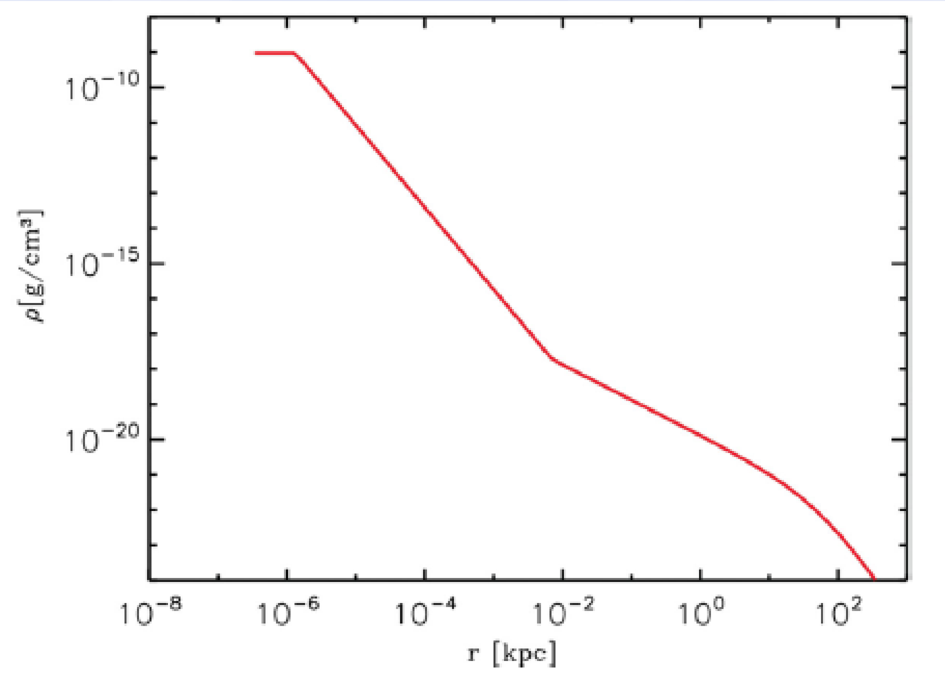
  - Exponential mass loss of the subhaloes due to relaxation of the mass distribution is accounted for.

- We consider a NFW (1997) DM density profile for both haloes and subhaloes. Average shape parameters are computed as functions of z and M.

- We also consider adiabatic contraction by a SMBH (Natarajan et al., 2008; Quinlan, Hernquist & Sigurdsson, 1995). The inner slope is modified:

The DM Clustering - DM Halo Profile

- An example of an adiabatically contracted profile:



$M_h = 5E13\ h^{-1}\ M_{sun}$
$z = 1.0$
$M_{BH} = 2.5E9\ h^{-1}\ M_{sun}$

$$\rho_{DM}(r) = \rho_{NFW}(r), r > r_{BH},$$

$$\rho_{DM}(r) = \rho_{NFW}(r_{BH}) \left(\frac{r}{r_{BH}}\right)^{-\gamma_{spike}}, r_{plateau} < r < r_{BH},$$

$$\rho_{DM}(r) = \frac{m_\chi}{t_{spike} < \sigma v >}, 4r_s < r < r_{plateau},$$

$$\rho_{DM}(r) = 0, r < 4r_s,$$

$$\gamma_{spike} = 2.\overline{33}.$$

The DM Annihilation Energy Output - Luminosity Of A Single Halo

- The energy generated per unit time in a DM halo is given by:

$$L_\chi = \frac{<\sigma v> c^2}{2m_\chi} \int_V \rho^2_{DM}(x,t) d^3x,$$

- This luminosity can be decomposed in the contribution of the main halo and the substructure:

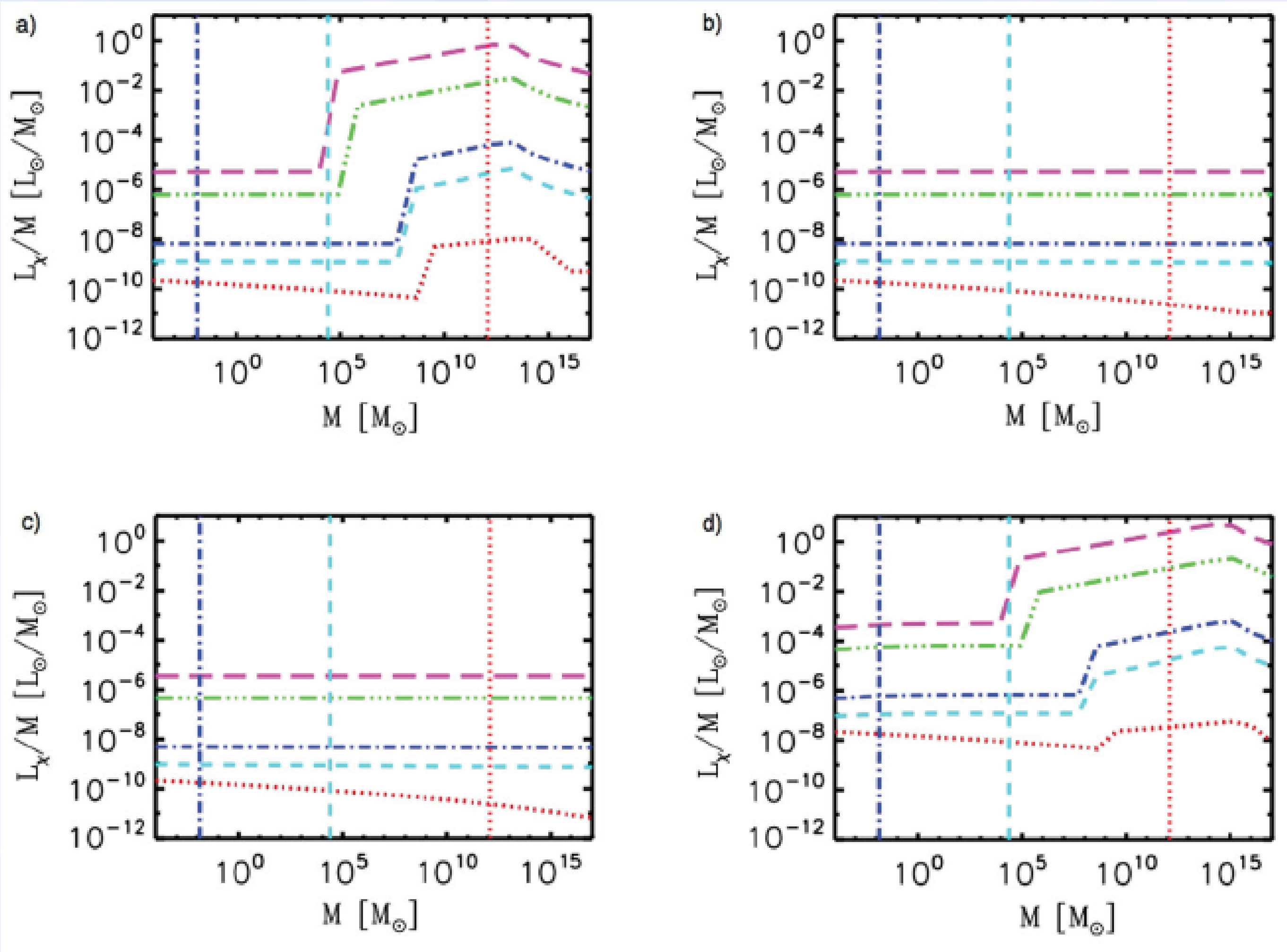
$$L_\chi = L_{\chi,main} + L_{\chi,subs},$$

- Given the density profile of DM halos and knowing the subhalo mass function, the total luminosity of a halo can be computed as:

$$L_{\chi,main} = L_\chi(M_{main}, z) = \frac{<\sigma v> c^2}{2m_\chi} \int_V \rho^2_{DM}(r, M_{main}, z) dV,$$

$$L_{\chi,subs} = L_{\chi,subs}(M_{main}, z) = \int_{m_{free}}^{M_{main}} \frac{dN}{dm} L_\chi(m, z) dm.$$

The DM Annihilation Energy Output - L/M Ratio for DM halos



a) Subs. + Ad. Cont. + M_{WIMP}= 1TeV

b) Subs. + M_{WIMP}= 1TeV

c) Pure NFW + M_{WIMP}= 1TeV

d) Sub. + Ad. Cont. + M_{WIMP}= 10GeV

z = 0

z = 5

z = 10

z = 50

z = 100

The DM Annihilation Energy Output - Global Energy Injection Rate Per Baryon

- The smooth energy injection rate per baryon can be written as:

$$\dot{E}_\chi^{\rm smooth} = \frac{1}{2}\frac{m_\chi}{n_{\rm b,0}} c^2 n_{\chi,0}^2 (1+z)^3 \langle \sigma v \rangle f_{\rm abs}(z)$$

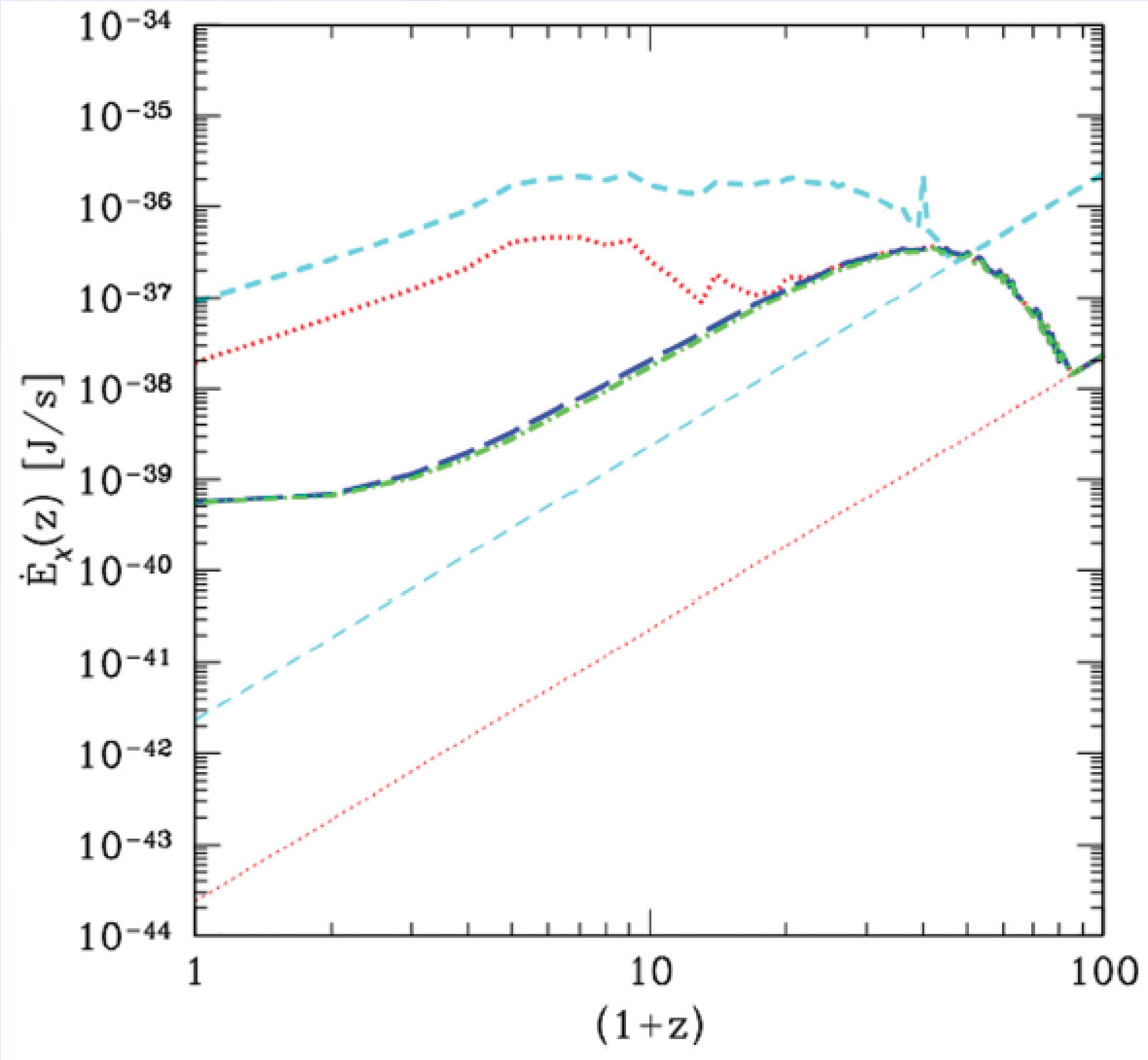
- The clumped energy injection rate per baryon is given by:

$$\epsilon_\chi^{\rm clumped}(z) = (1+z)^3 \int_{m_{\rm free}}^{\infty} L_\chi(M,z) \frac{{\rm d}n}{{\rm d}M}(M,z)\,{\rm d}M \qquad \dot{E}_\chi^{\rm clumped}(z) = \frac{\epsilon_\chi^{\rm clumped}(z)}{n_{\rm b}(z)}$$

- The corresponding clumpiness factor can thus be defined as:

$$C(z) = \frac{\dot{E}_\chi^{\rm clumped}(z)}{\dot{E}_\chi^{\rm smooth}(z)}$$

The DM Annihilation Energy Output - Global Energy Injection Rate Per Baryon



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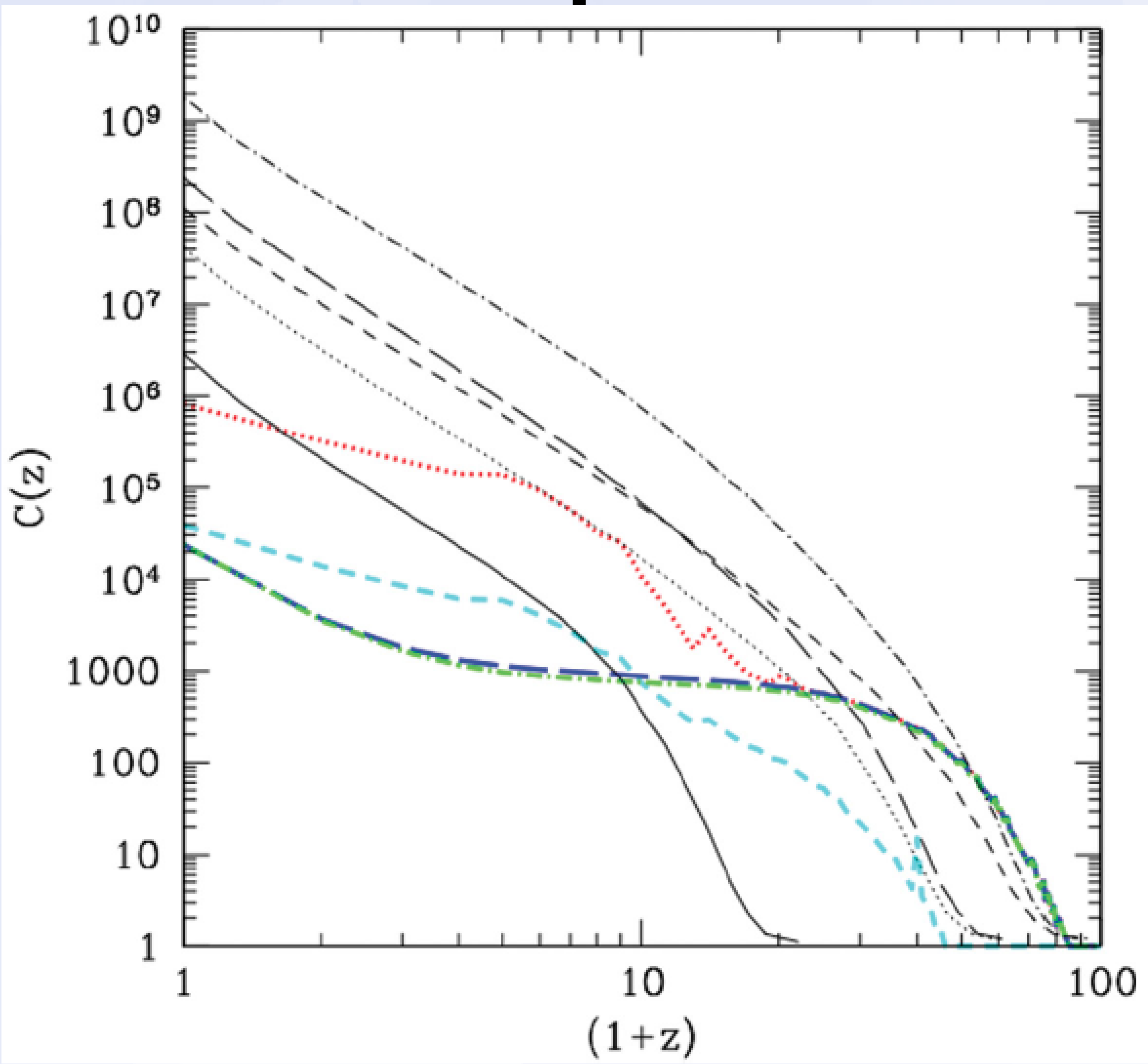
The DM Annihilation Energy Output - Clumpiness Factor



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Intensity Of The Radiation Field Due To DM Annihilations

- Following Haardt & Madau (1996), we solve the radiative transfer equation for the frequency integrated intensity of the radiation field due to DM annihilations. The solution considers the background cosmological expansion:

$$J(z_0) = \frac{1}{4\pi}\int_{z_0}^{\infty} \mathrm{d}z \frac{\mathrm{d}l}{\mathrm{d}z}\frac{(1+z_0)^4}{(1+z)^4}\epsilon_\chi(z)\mathrm{e}^{-\tau_{\mathrm{eff}}(z_0,z)} \qquad \frac{\mathrm{d}l}{\mathrm{d}z} = c\frac{\mathrm{dLBT}(z)}{\mathrm{d}z}$$

- The emissivity and optical depth are given by:

$$\epsilon_\chi(z) = \frac{1}{2}m_\chi c^2 n_{\chi,0}^2(1+z)^6\langle\sigma v\rangle C(z)$$

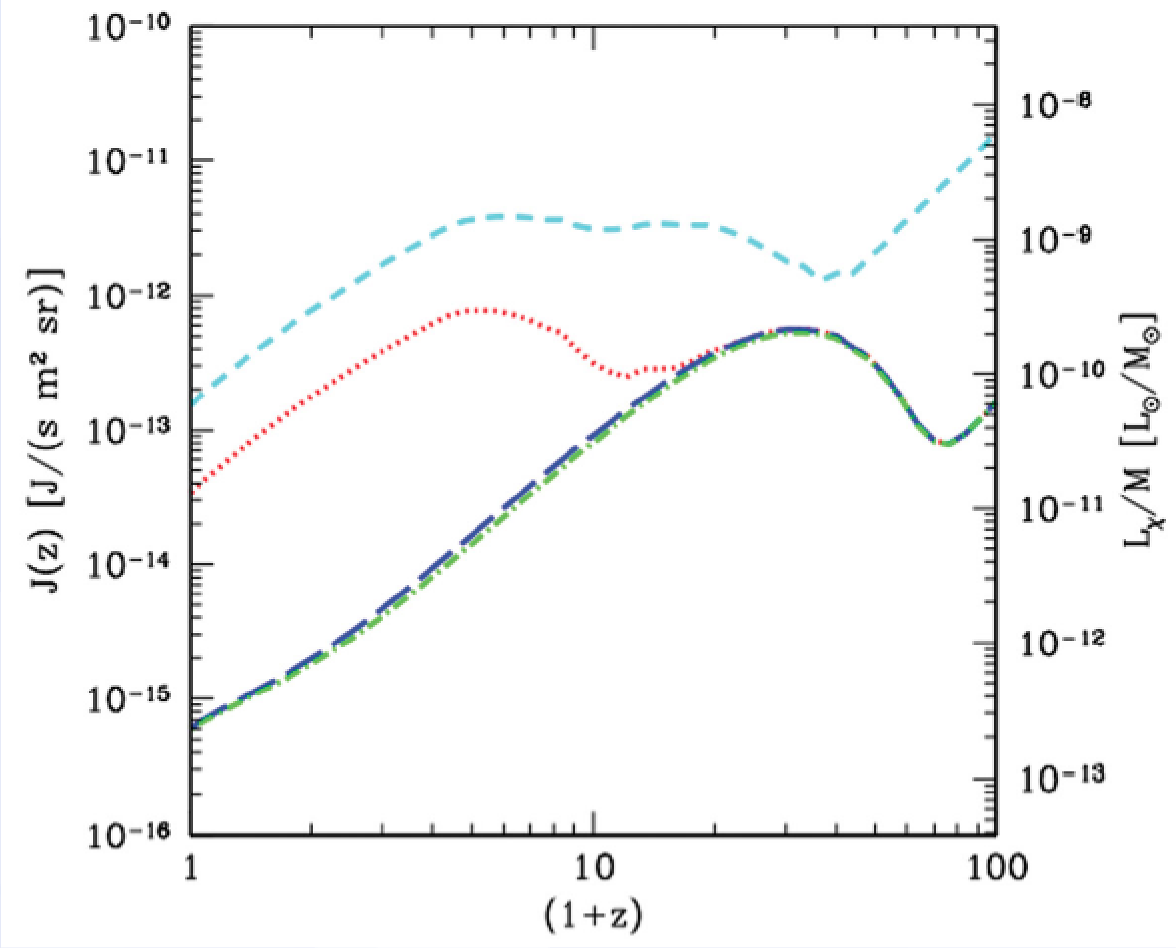
$$\tau_{\mathrm{eff}}(z_0,z) = \int_{m_{\mathrm{free}}}^{\infty}\int_{z_0}^{z}\mathrm{d}M\,\mathrm{d}z'\left(\frac{\mathrm{d}l}{\mathrm{d}z'}\right)\frac{\mathrm{d}n}{\mathrm{d}M}(M,z')(1+z')^3\sigma_{\mathrm{bary}}(M)$$

- The baryonic cross-section is computed as:

$$\sigma_{\mathrm{bary}}(M) = \sigma_{\mathrm{T}} f_{\mathrm{bary}}\left(\frac{M}{m_{\mathrm{p}}}\right)\left(1-\frac{Y_{\mathrm{p}}}{2}\right)$$

- The power received by a halo is given by: $L_\chi^{\mathrm{ext}} = 4\pi\sigma_{\mathrm{bary}}(M)J$

Intensity Of The Radiation Field Due To DM Annihilations



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Effects Of DM Annihilation On The IGM - The IGM Ionization Fraction

- With the DM annihilation energy injection per baryon, one can compute the evolution of the ionization fraction:

$$\frac{d\delta x_e}{dz} = \frac{-I_\chi(z)}{H(z)(1+z)} \qquad \delta x_e(z) = x_e(z) - x_e^{norad}(z)$$

  - $x_e^{no\text{-}rad}(z)$ is the standard ionization fraction in the absence of ionization sources.

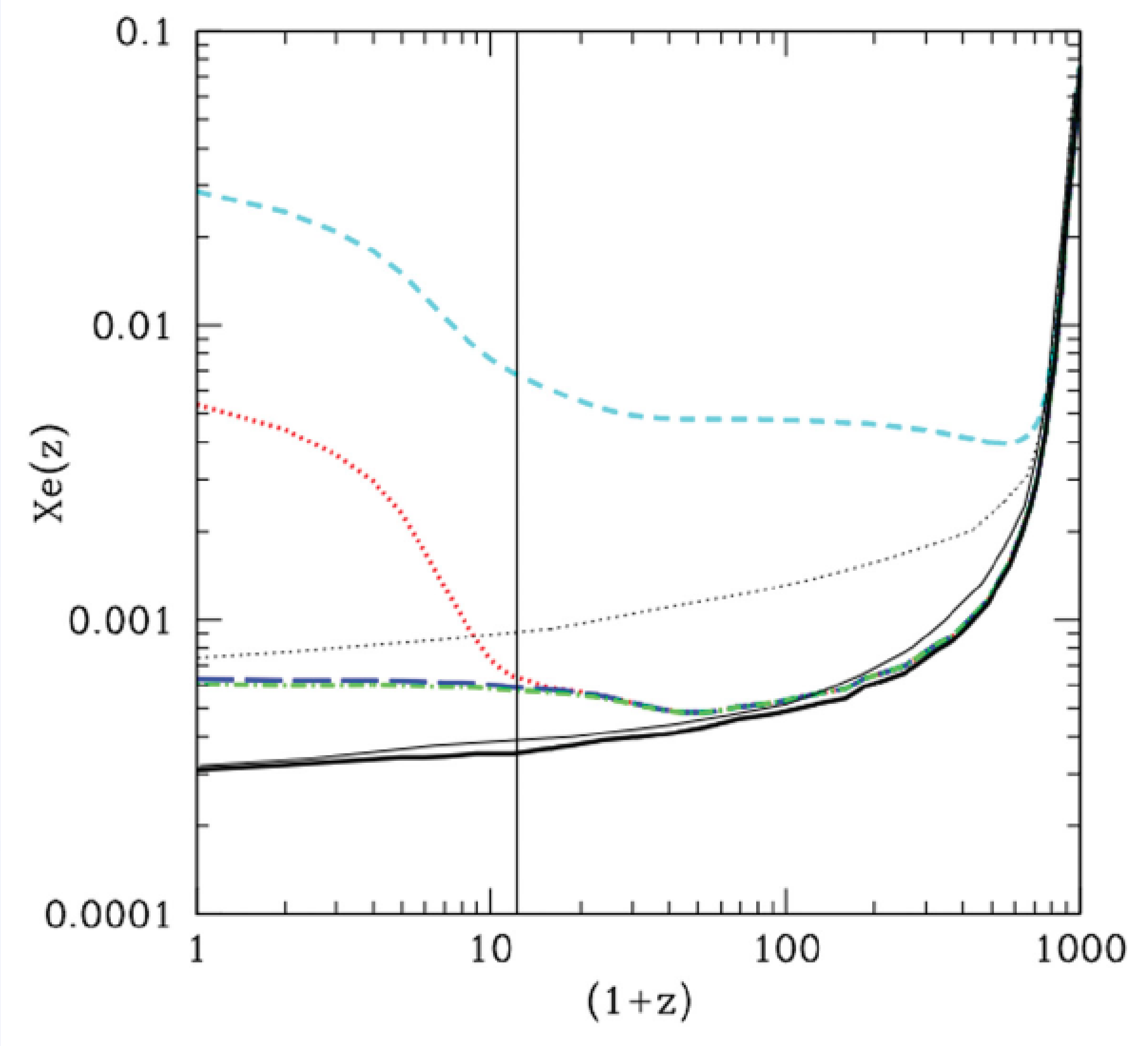
- The contribution of DM to the Ionization rate is given by:

$$I_\chi = \chi_i(z)\frac{\dot{E}_\chi}{E_0}$$

  - Where E_0 is the ionization energy of hydrogen and $\chi_i(z)$ is the ionization efficiency $(1-x_e)/3$.

- The initial condition corresponds to $\boldsymbol{\delta} x_e(z=1000)=0$ with $x_e(z=1000)\simeq 1$.

Effects Of DM Annihilation On The IGM - The IGM Ionization Fraction



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No DM annihilation energy injection

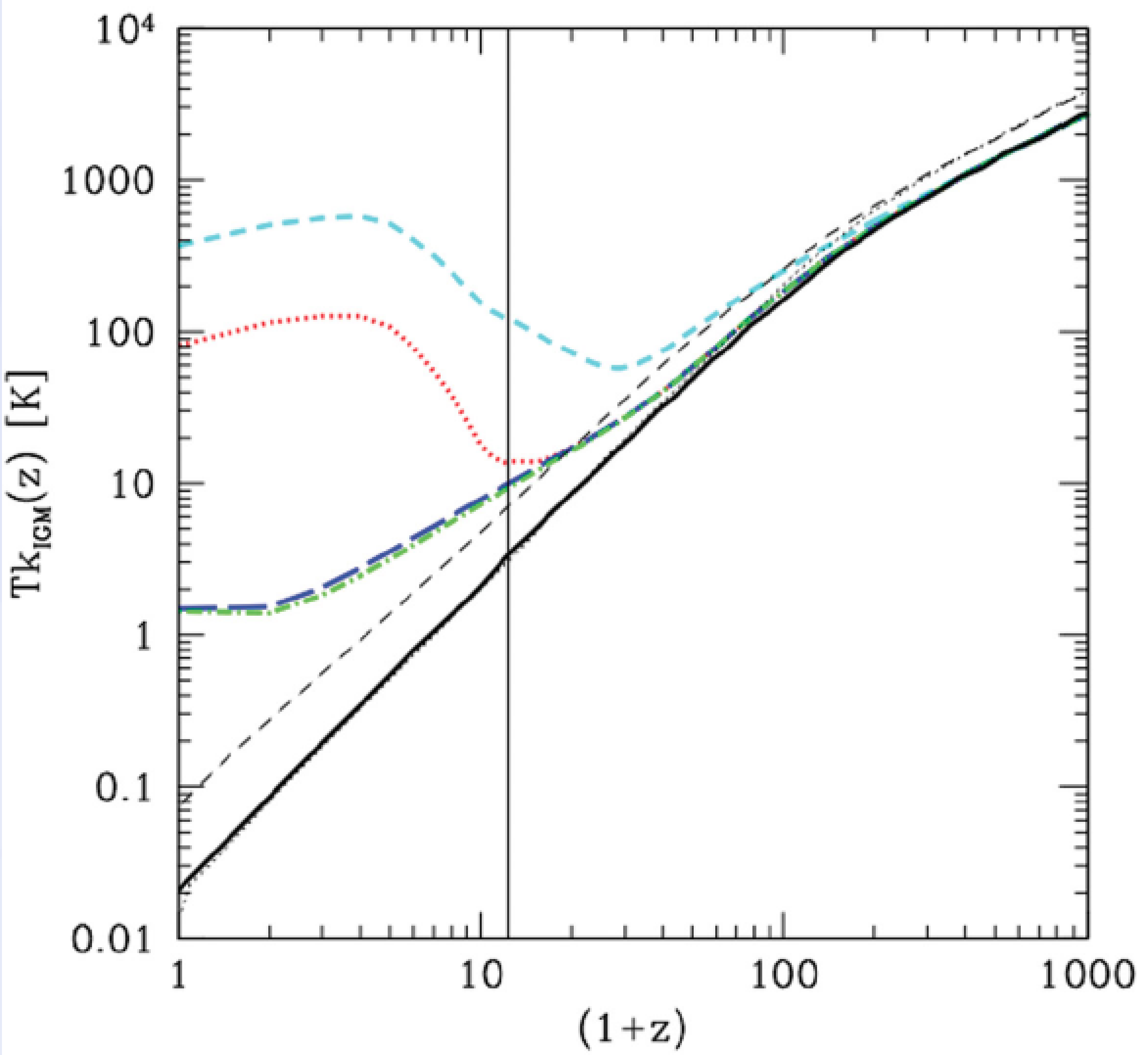
Effects Of DM Annihilation On The IGM - The IGM Kinetic Temperature

- With the DM annihilation energy injection per baryon, one can compute the evolution of the IGM kinetic temperature:

$$(1+z)\frac{dT_k}{dz} = 2T_k + \frac{l_\gamma x_e}{H(z)(1+Y+x_e)}(T_k - T_{CMB}) - \frac{2\chi_h \dot{E}_\chi}{3k_b H(z)(1+Y+x_e)}, \quad l_\gamma = \frac{(8\sigma_T a_R T_{CMB}^4)}{(3m_e c)}$$

- $\chi_h(z)$ is the ionization efficiency $(1+2x_e)/3$.
- The first term on the R.H.S. corresponds to the adiabatic cooling of the IGM.
- The second term corresponds to the heat exchange between the IGM and the CMB.
- The heating due to DM energy injection is given by the third term.
- The initial condition is given by the CMB temperature at z=1000.

Effects Of DM Annihilation On The IGM - The IGM Kinetic Temperature



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Effects Of DM Annihilation On The IGM - The 21 cm Signal

- IGM kinetic temperature, together with ionization fraction and DM energy injection, modify the global spin temperature of the IGM.

$$T_s = \frac{T_{CMB} + y_\alpha T_k + y_c T_k}{1 + y_\alpha + y_c},$$

- Two major processes couple Ts and Tk: Ly-alpha pumping (Wothuysen – Field effect) and spin exchange collisions.
- The W-F effect depends of the intensity of the Ly-alpha background due to collisional excitations and direct DM energy injection, The spin exchange collisions depend on the number densities of e^- and HI, ionization fraction and temperature.

Effects Of DM Annihilation On The IGM - The 21 cm Signal

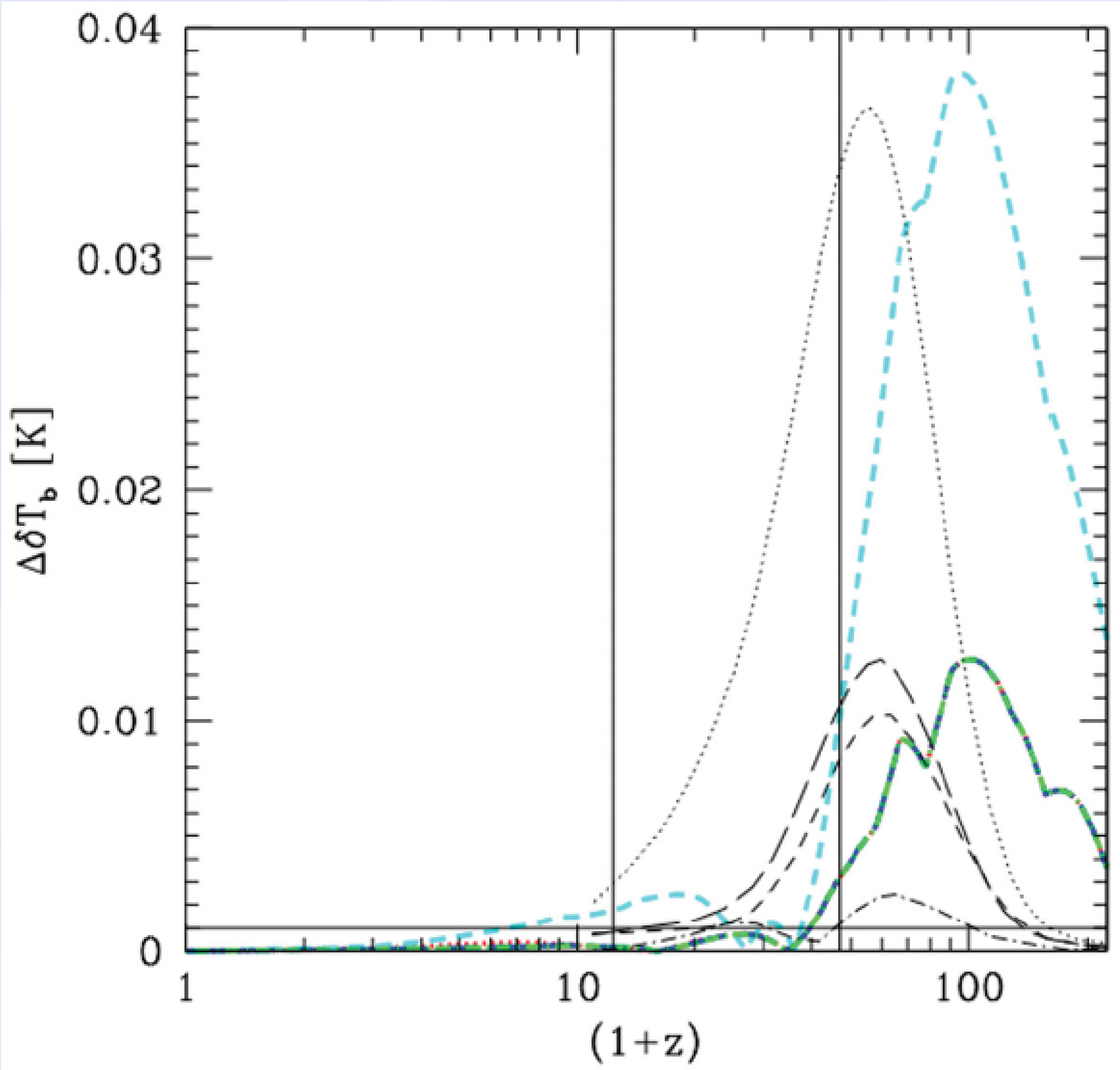
- Knowing the Ts, the differential brightness temperature is given by:

$$\delta T_b = \frac{T_s - T_{CMB}}{1+z}\tau(z), \qquad \tau(z) = \frac{3c^3 h A_{10}}{32\pi k_b \nu_0^2 T_s(z) H(z)} n_{HI}(z),$$

- τ(z) is the optical depth of the neutral IGM at 21(1+z) cm.
- This is a measurable quantity, and represents the difference in brightness between the CMB and the neutral hydrogen.
- Consider:

$$\Delta\delta T_b(z) = |\delta T_b(z) - \delta T_{b,0}(z)|,$$

Effects Of DM Annihilation On The IGM - The 21 cm Signal



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Limits (1mK sensitivity + 30MHz min frec. + PopIII stars) from Valdés et al. (2007) and Carilli (2008).

Conclusions

- Thermal relic WIMP (10GeV-1TeV) DM annihilation cannot re-ionize the universe, even with adiabatic contraction and maximal absorption fraction.
- It does not provide an alternative feedback mechanism for galaxy formation.
- 1TeV WIMPs would only have noticeable effects on the IGM at $z < 20$. Below $z \sim 10$, PopIII stars or early-BH's drive the IGM evolution so ignoring them is no longer allowed.
- At $z = 10$, a 10GeV WIMP could give Xe~8E-3 and Tk~200K. A 1TeV WIMP could give Xe~6E-4 and Tk~10K
- A 1TeV WIMP is unlikely to be detected in the (global) 21cm signal. A 10GeV WIMP could be detected in principle, but only at the ~3mK level in the frequency range of 55-120 MHz ($10 < z < 25$). Both could be detected in principle at frequencies < 40 MHz. According to Carilli (2008), this would require observations outside the ionosphere (e.g., from the moon).

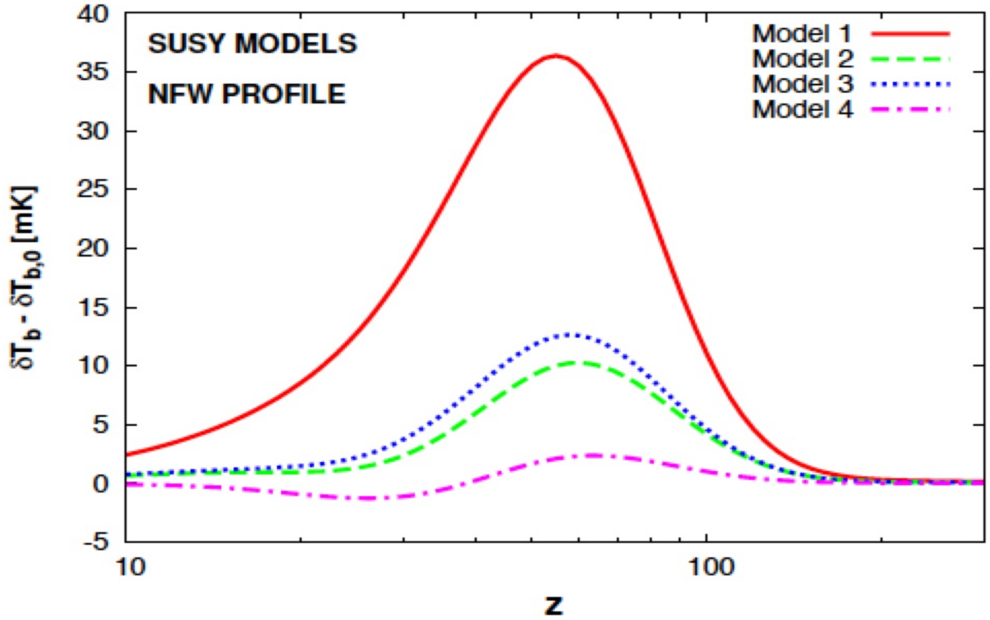
Important papers on DM annihilation effects on galaxy formation, the high-z IGM and the 21cm signal by other authors:

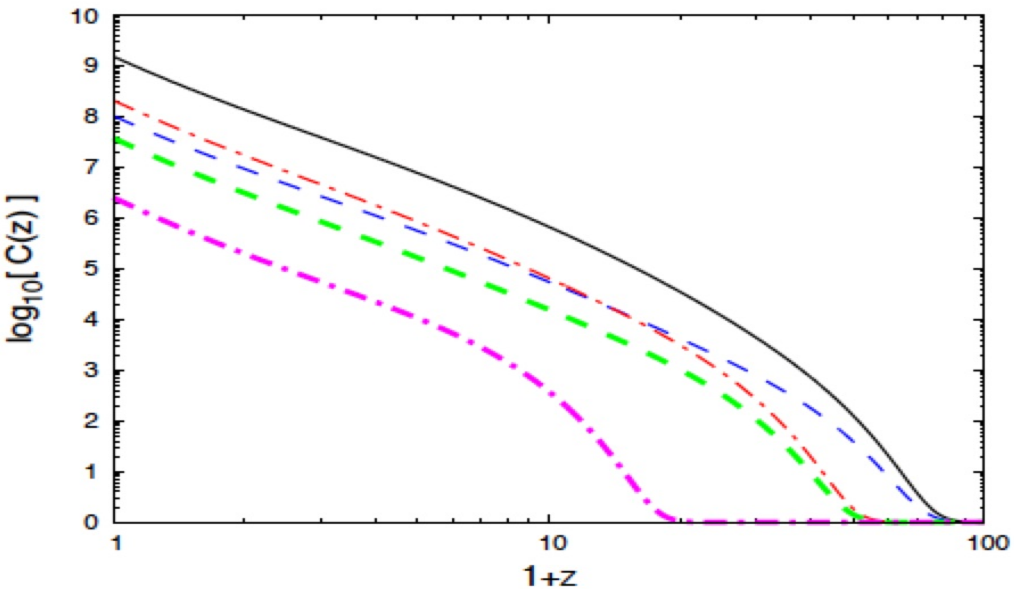
Galaxy Formation: Ascasibar (2006), Natarajan, Croton and Bertone (2008), etc...

High-z IGM and 21cm: Pierpaoli (2004), Mapelli, Ferrara & Pierpaoli (2006), Furlanetto, Oh and Pierpaoli (2006), Valdés et al. (2007), Ripamonti, Mapelli & Ferrara (2007), Chuzhoy (2008), Natarajan & Schwarz (2009), Cumberbatch, Lattanzi & Silk (2010), etc...

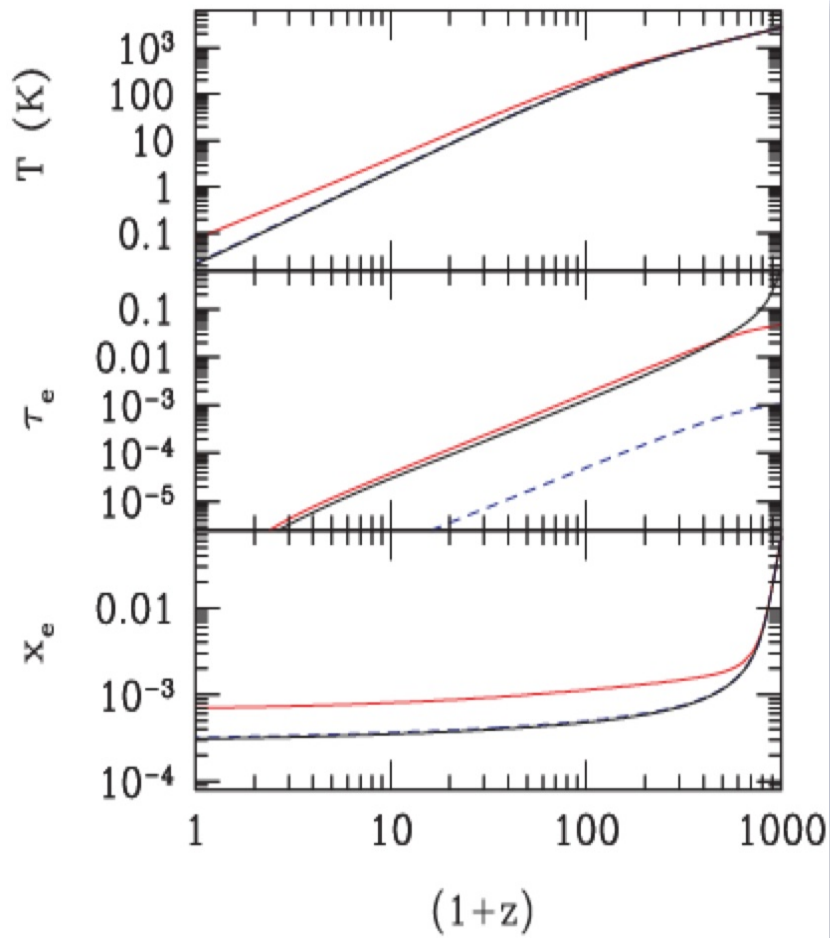
(Journal references given in the bibliography of MNRAS 445, 850)

THANK YOU FOR YOUR TIME





Cumberbatch, Lattanzi and Silk (2010)



Mapelli, Ferrara and Pierpaoli (2006)