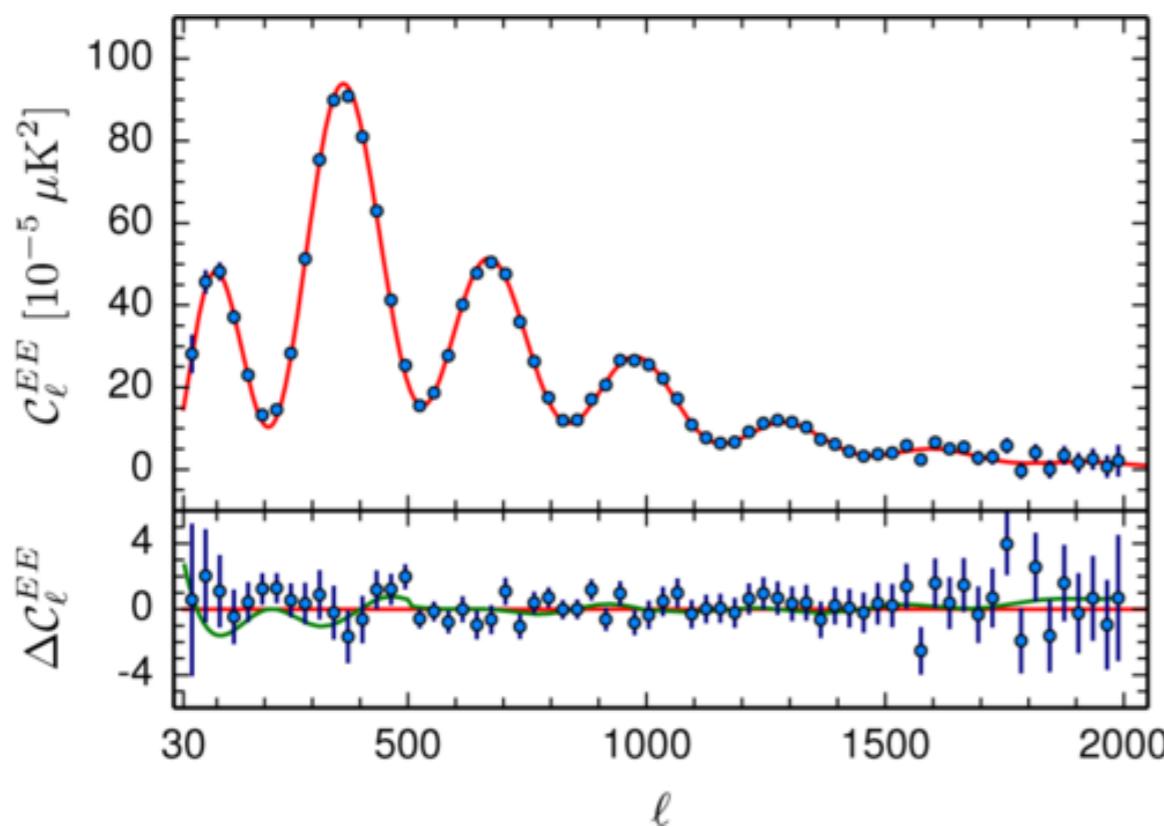
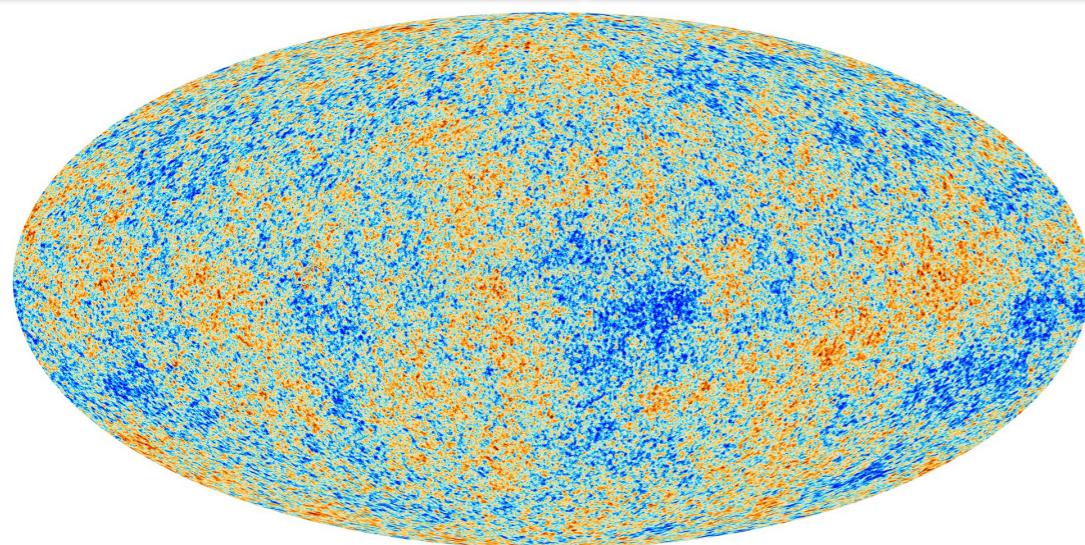


Constraints on Dark Matter annihilations from the CMB : The impact of halo formation

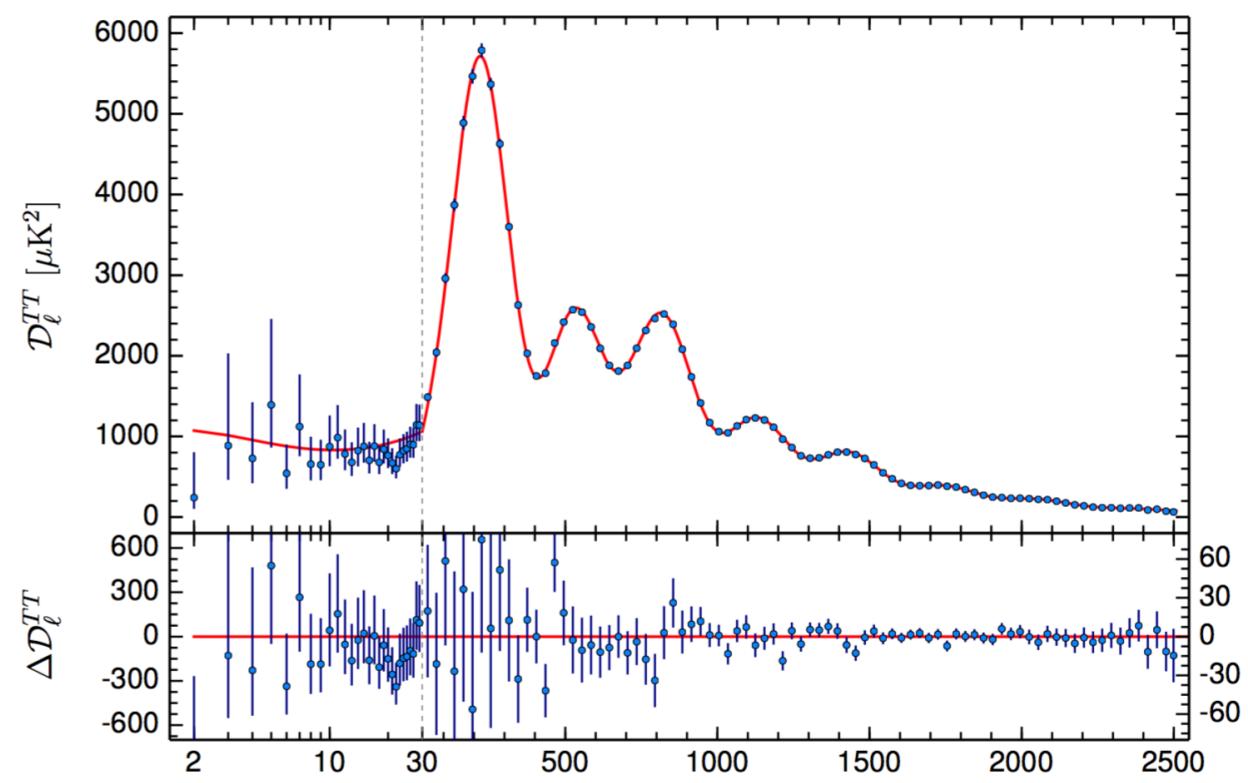
Vivian Poulin
LAPTh and RWTH Aachen University

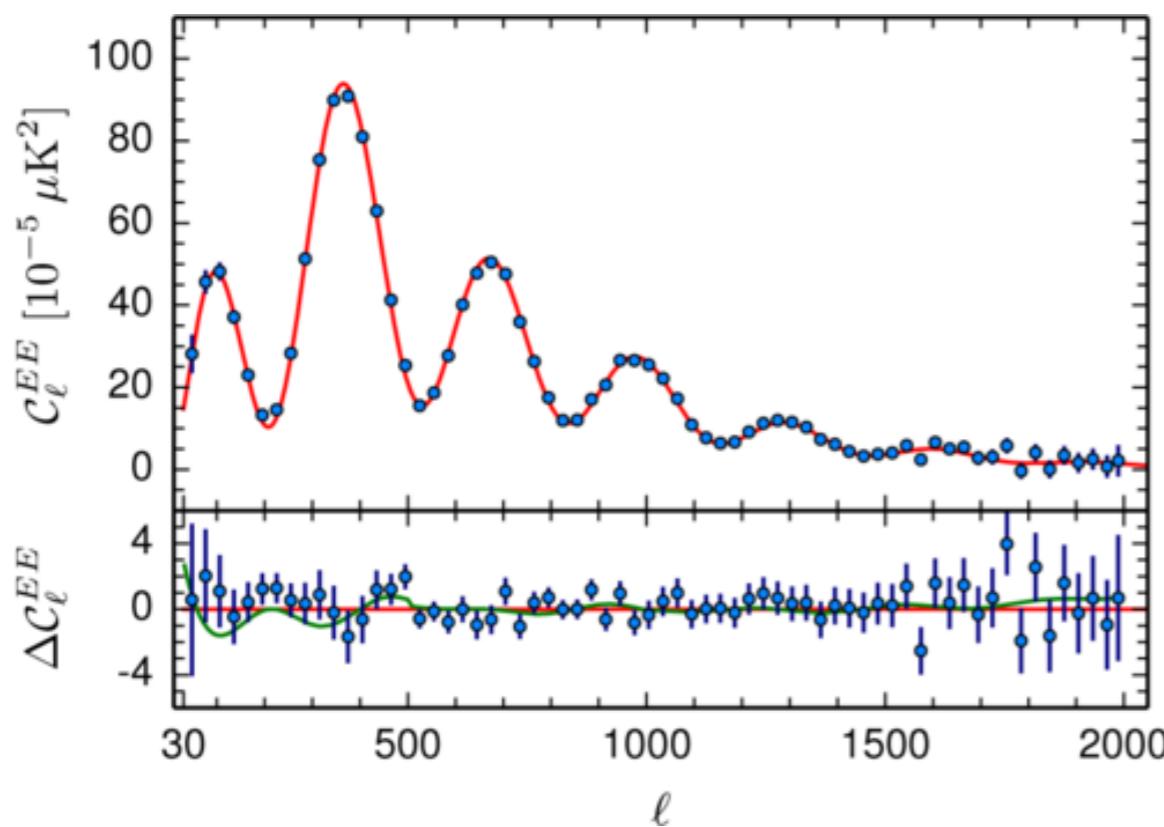
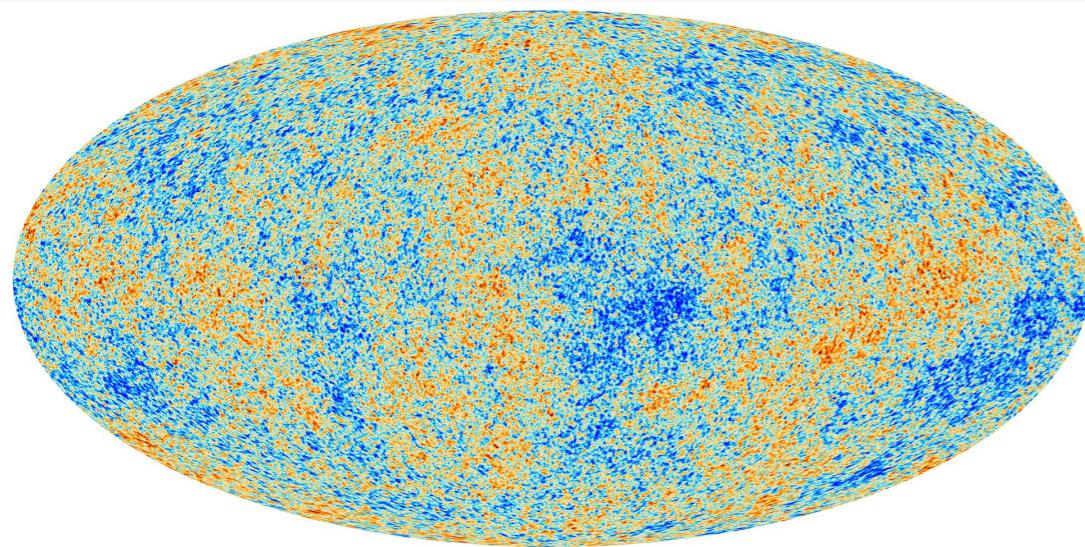
Talk based on
Poulin et al., JCAP 1512 (2015) 12, 041
In collaboration with
P. Serpico (LAPTh) and J. Lesgourgues (RWTH)



CMB as measured by Planck

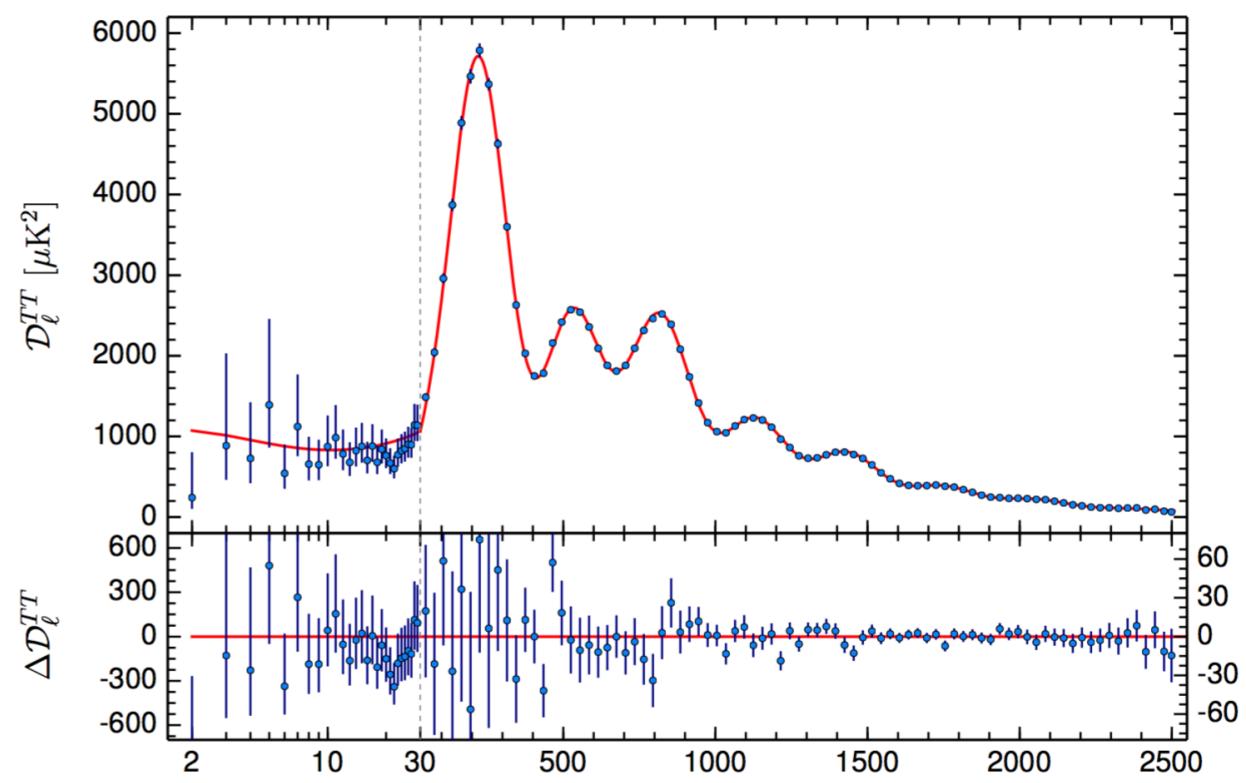
Planck 2015 [[arXiv:1502.01589](https://arxiv.org/abs/1502.01589)]





CMB as measured by Planck

Planck 2015 [arXiv:1502.01589]



TT power spectrum

DM interacts only gravitationally in the standard Cosmology
=> Constraints can be derived

DM annihilations in the smooth background distribution
is a very well documented subject

About 30 papers in 12 years :

a non-exhaustive sample

- X.-L. Chen and M. Kamionkowski, Phys.Rev., vol. D70, p. 043502, 2004.
- S. Galli, F. Iocco, G. Bertone, and A. Melchiorri, Phys.Rev., vol. D80, p. 023505, 2009.
- C. Evoli, M. Valdes, and A. Ferrara, PoS, vol. CRF2010, p. 036, 2010.
- D. P. Finkbeiner, S. Galli, T. Lin, and T. R. Slatyer, Phys.Rev., vol. D85, p. 043522, 2012.
- T. R. Slatyer, Phys.Rev., vol. D87, no. 12, p. 123513, 2013.
- S. Galli, T. R. Slatyer, M. Valdes, and F. Iocco, Phys.Rev., vol. D88, p. 063502, 2013.
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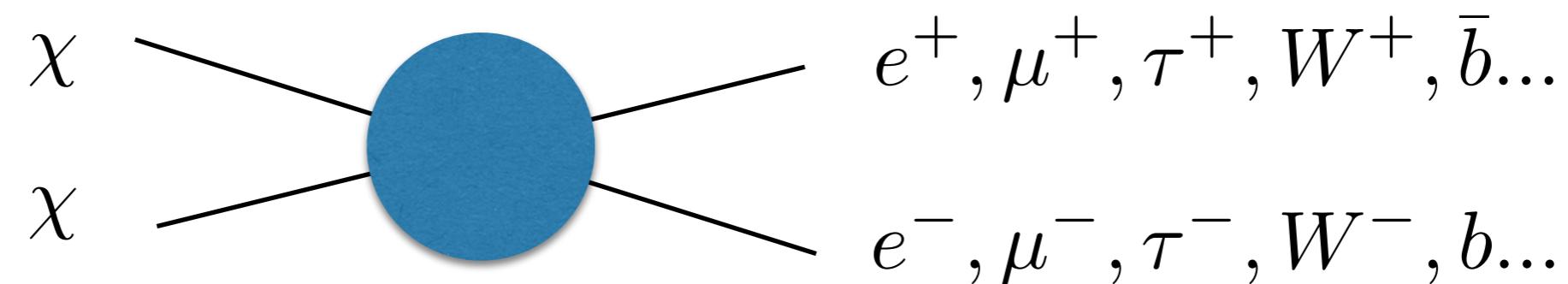
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- ...

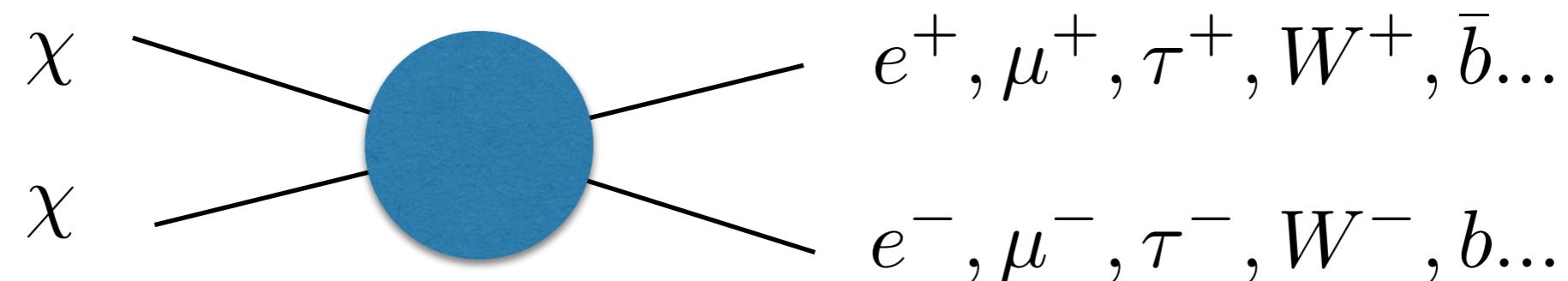
DM annihilations in halos are
less studied, with authors reaching different conclusions

About 10 papers in 7 years :

- A. V. Belikov and D. Hooper, Phys.Rev., vol. D80, p. 035007, 2009.
- M. Cirelli, F. Iocco, and P. Panci, JCAP, vol. 0910, p. 009, 2009.
- A. Natarajan and D. J. Schwarz, Phys.Rev., vol. D81, p. 123510, 2010.
- G. Giesen, J. Lesgourgues, B. Audren, and Y. Ali-Haimoud, JCAP, vol. 1212, p. 008, 2012.
- L. Lopez-Honorez, O. Mena, S. Palomares-Ruiz, and A. C. Vincent, JCAP, vol. 1307, p. 046, 2013.
- ...



What happen to the annihilation products ?



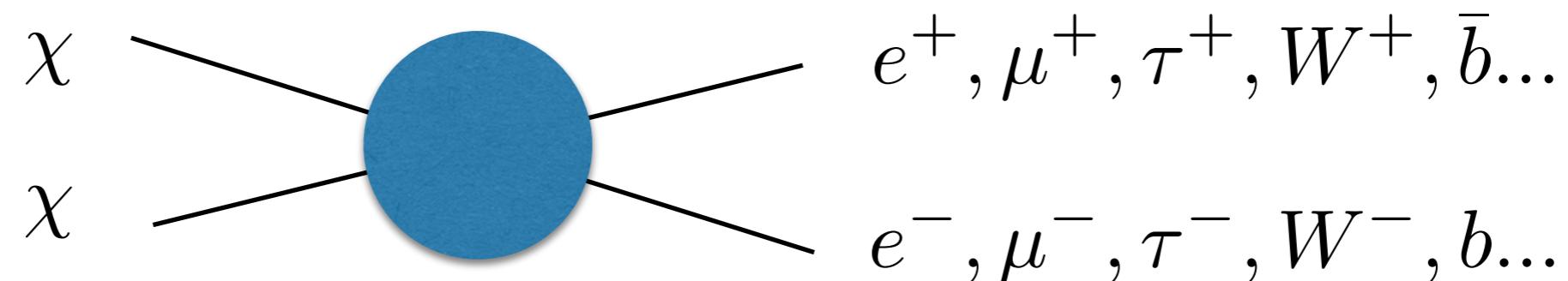
What happen to the annihilation products ?

Only e^\pm, γ interact with the intergalactic medium (IGM) and CMB. They can :

- i) Lose their energy through interaction with CMB and redshifting

$$e\gamma_{\text{CMB}} \rightarrow e\gamma \quad \gamma\gamma_{\text{CMB}} \rightarrow \gamma\gamma \quad \gamma\gamma_{\text{CMB}} \rightarrow e^+e^- ;$$

- ii) ionize, excite or heat the IGM.



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Main impact of DM annihilations :
modification of the recombination

Peebles "case-b"
recombination

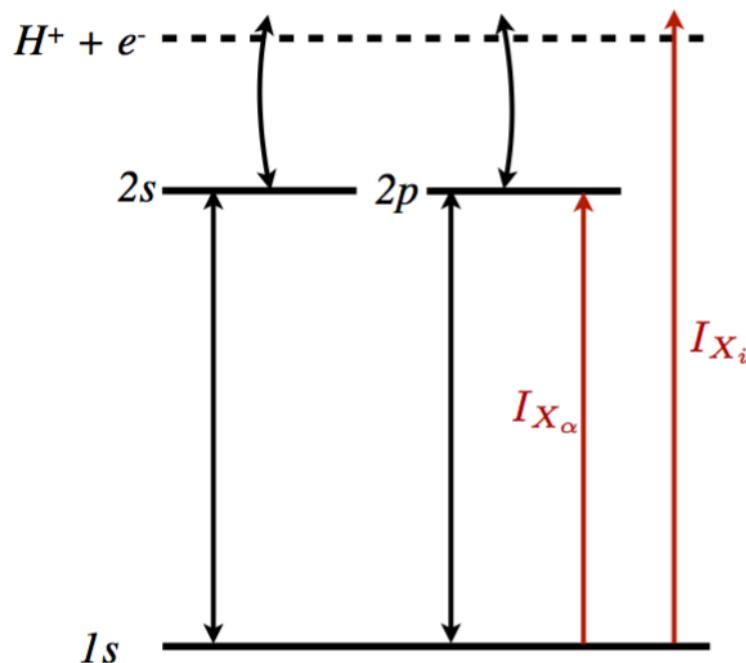
$$\frac{dx_e}{dz} = \frac{1}{(1+z)H(z)} [R_s(z) - I_s(z) - I_X(z)]$$

$$x_e \equiv \frac{n_e}{n_H}$$

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$$I_X(z) = I_{X_i}(z) + I_{X_\alpha}(z)$$

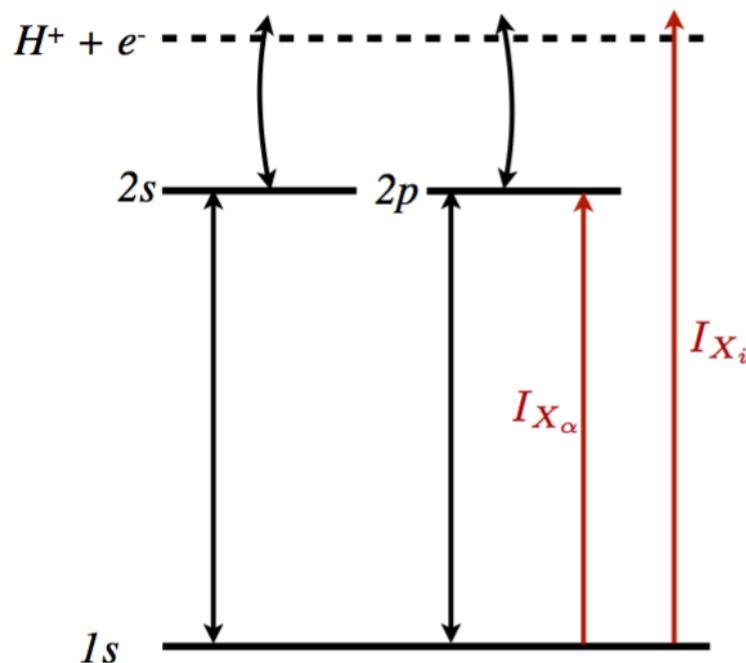
$$I_{X_i}(z) = \frac{\chi_i(z)}{n_H(z)E_i} \left. \frac{dE}{dVdt} \right|_{\text{dep}}$$

$$I_{X_\alpha}(z) = \frac{(1-C)\chi_\alpha(z)}{n_H(z)E_\alpha} \left. \frac{dE}{dVdt} \right|_{\text{dep}}$$

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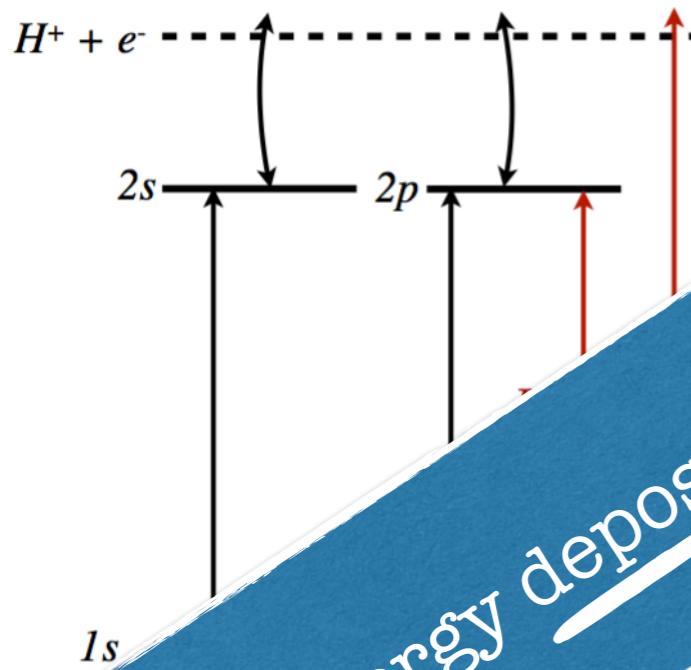
$$\frac{dT_M}{dz} = \frac{1}{1+z} \left[2T_M + \gamma(T_M - T_{\text{CMB}}) + K_h \right]$$

$$K_h = - \frac{2\chi_h(z)}{H(z)3k_b n_H(z)(1+f_{He}+x_e)} \left. \frac{dE}{dVdt} \right|_{\text{dep}}$$

Peebles "case-b"
recombination

$$\frac{dx_e}{dz} = \frac{1}{(1+z)H(z)} [R_s(z) - I_s(z) - I_X(z)]$$

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The energy deposited by the DM

$$I(z) = I_{X_i}(z) + I_{X_\alpha}(z)$$

$$I_{X_i}(z) = \frac{\chi_i(z)}{n_H(z)E_i} \left. \frac{dE}{dVdt} \right|_{\text{dep}}$$

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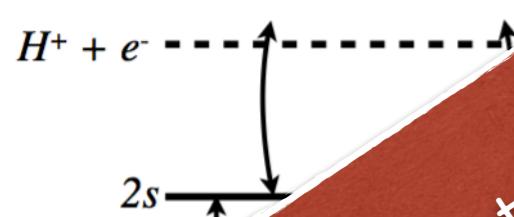
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The energy repartition functions

The energy deposited by the DM

$$I_s(z) = I_{X_i}(z) + I_{X_\alpha}(z)$$

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$$\left. \frac{dE}{dVdt} \right|_{\text{inj}}(z) = \left(n_{\text{pairs}} = \kappa \frac{n_{\text{DM}}}{2} \right) \cdot \left(P_{\text{ann}} = \langle \sigma_{\text{ann}} v \rangle n_{\text{DM}} \right) \cdot \left(E_{\text{ann}} = 2m_{\text{DM}}c^2 \right)$$

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number density
of pairs

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number density
of pairs

×

annihilation probability

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energy released
per annihilation

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×

annihilation probability

×

energy released
per annihilation

In the smooth background :

$$\frac{dE}{dVdt} \Big|_{\text{inj,smooth}}(z) = \kappa \rho_c^2 c^2 \Omega_{\text{DM}}^2 (1+z)^6 \frac{\langle \sigma_{\text{ann}} v \rangle}{m_{\text{DM}}}$$

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number density
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\times annihilation probability

\times energy released
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In the smooth background :

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Typical parameterization through the $f(z)$ functions :

$$\frac{dE}{dVdt} \Big|_{\text{dep}}(z) = f(z) \frac{dE}{dVdt} \Big|_{\text{inj}}(z)$$

In practice, for annihilations in the smooth background, it has been found that the CMB is only sensitive to

$$p_{\text{ann}} \equiv f_{\text{eff}} \frac{\langle \sigma_{\text{ann}} v \rangle}{m_{\text{DM}}} \quad \text{where} \quad f_{\text{eff}} \equiv f(z = 600) .$$

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Hence, we usually write

$$\left. \frac{dE}{dVdt} \right|_{\text{dep}} (z) = p_{\text{ann}} \cdot \kappa \rho_c^2 c^2 \Omega_{\text{DM}}^2 (1 + z)^6$$

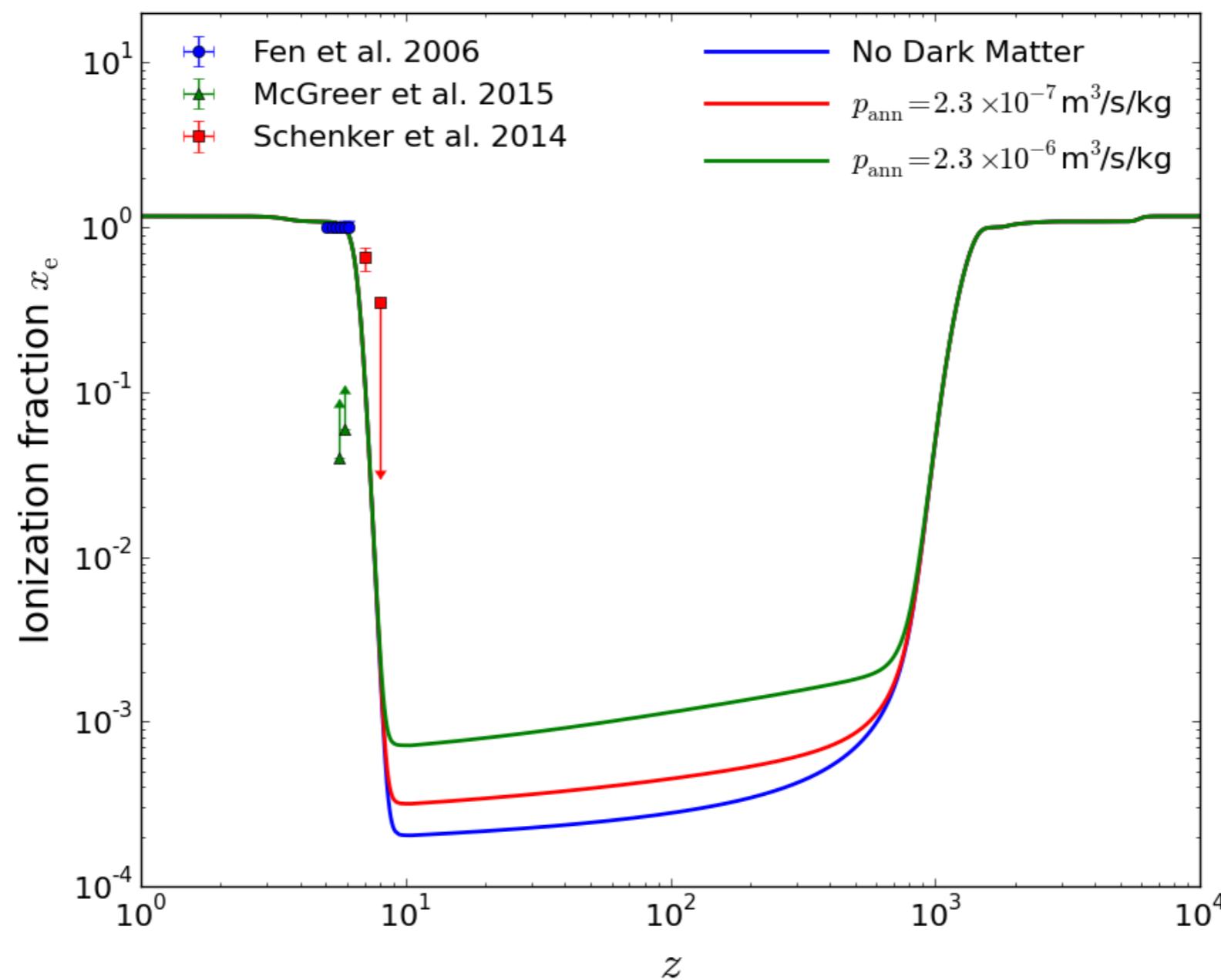
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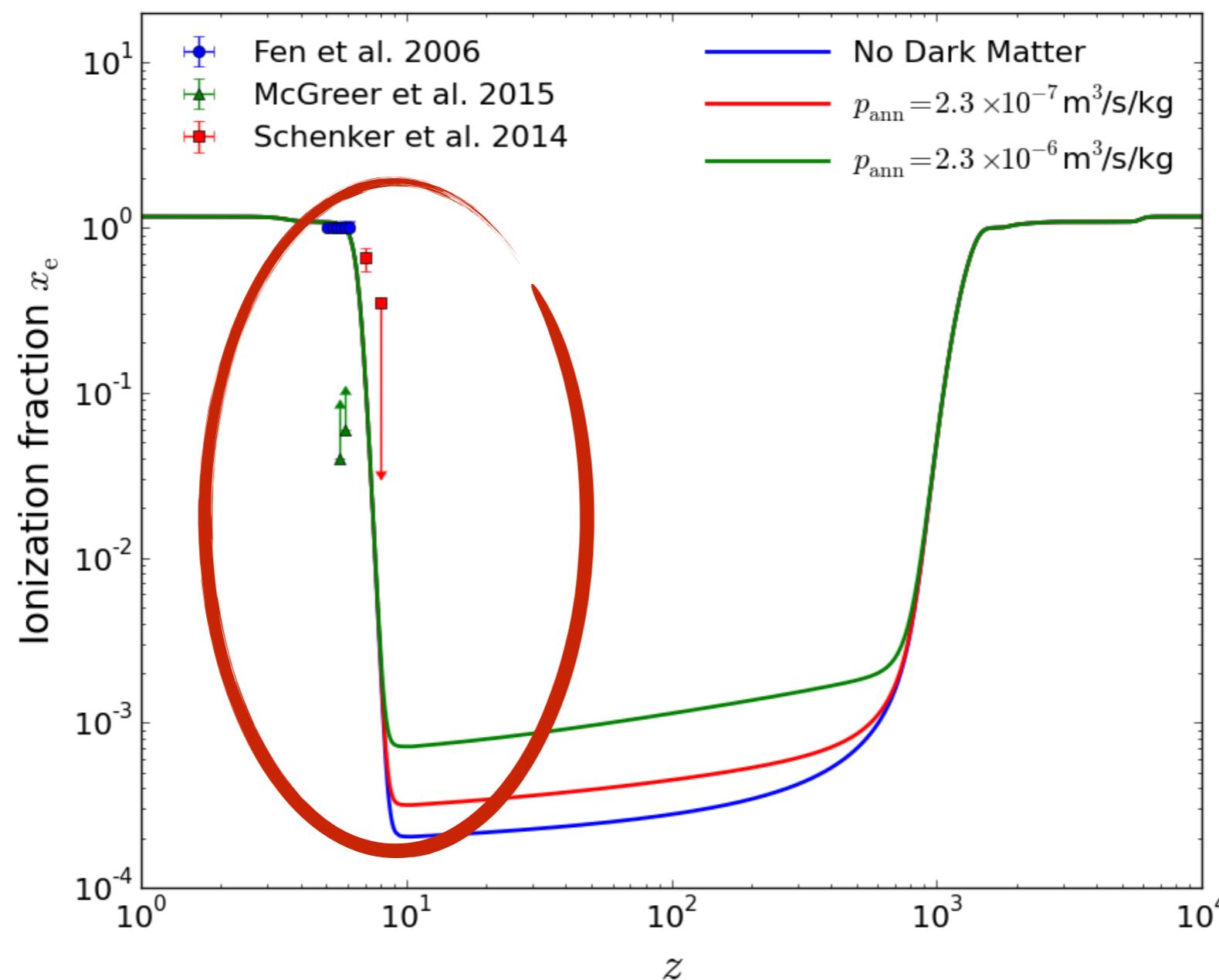
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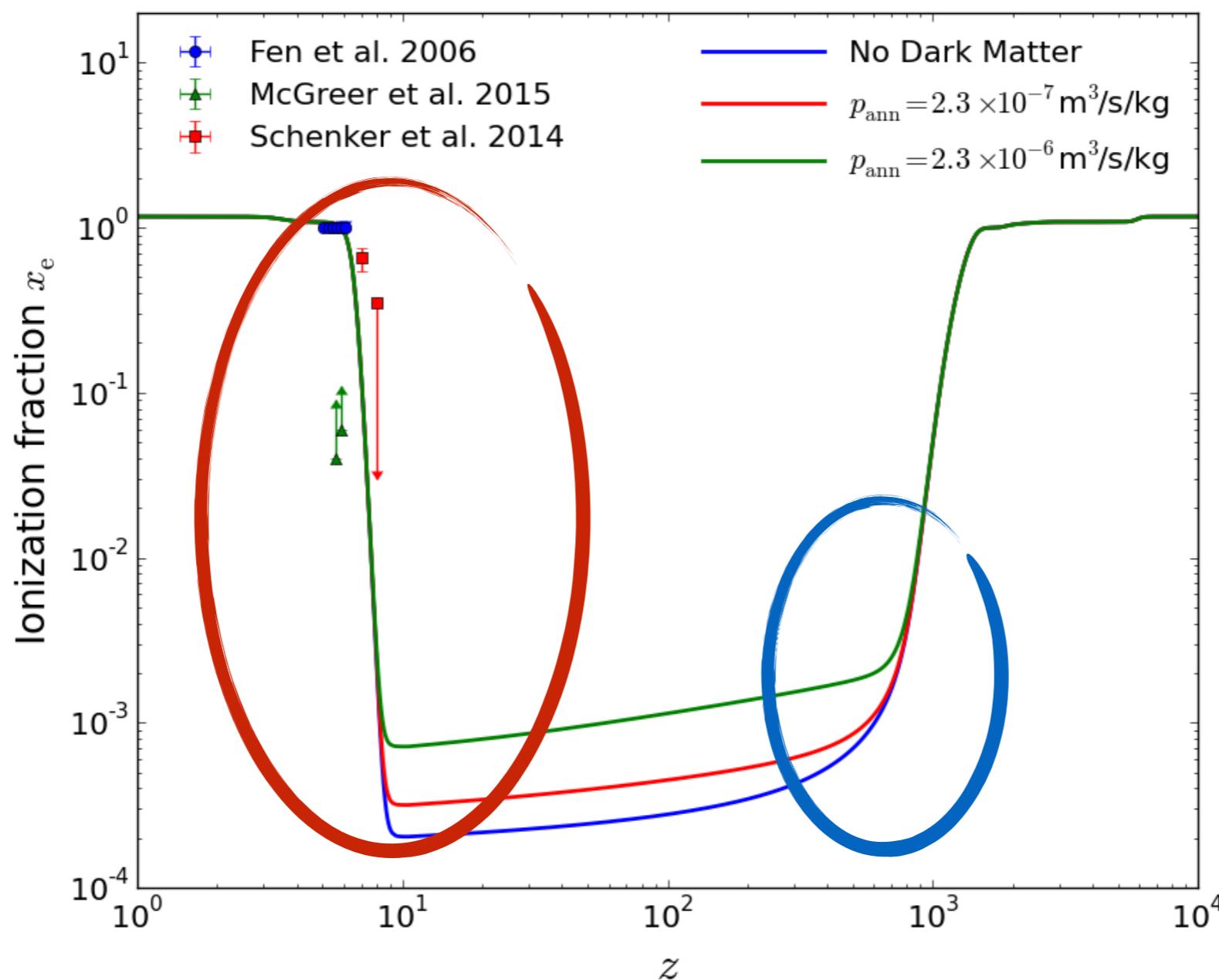
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This is the quantity really constrained by CMB power spectra analysis !





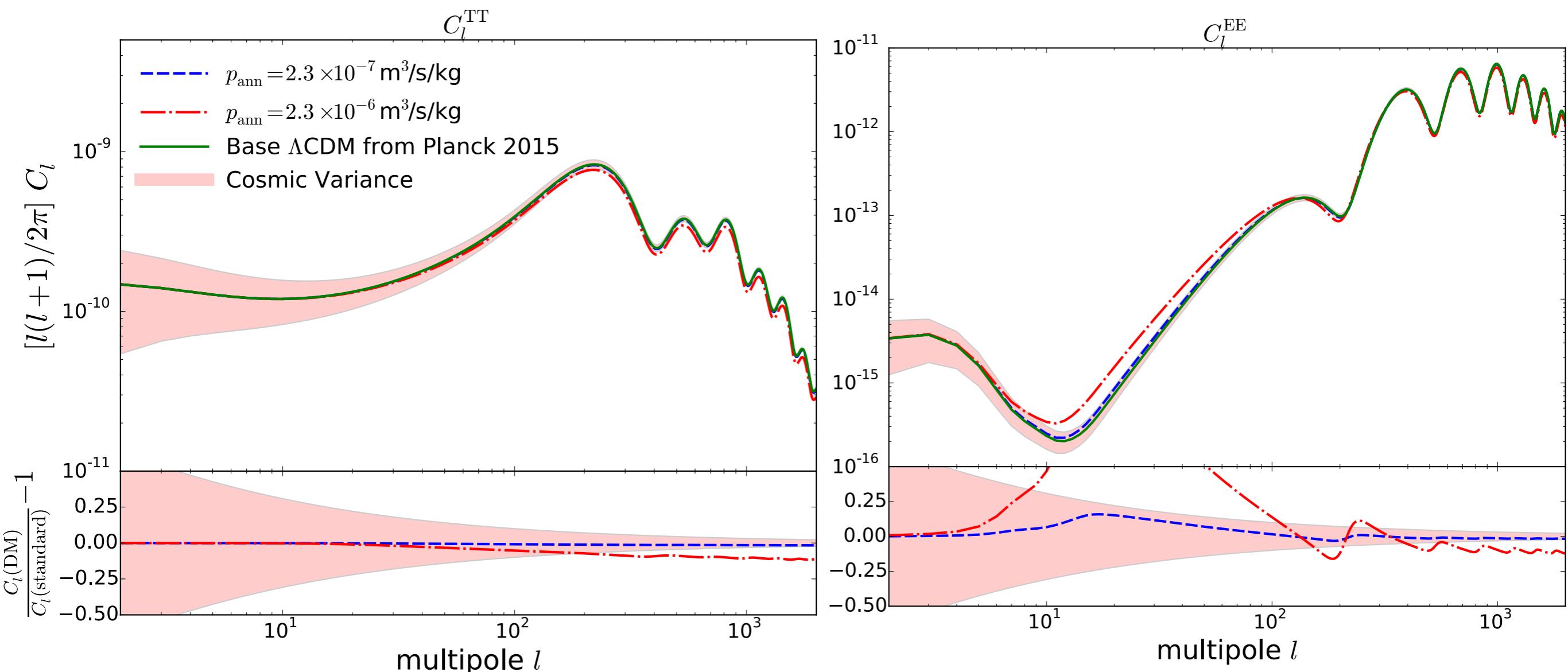
Reionization : put by hand !
Mostly due to star formation.
Still to understand.



Reionization : put by hand !
 Mostly due to star formation.
 Still to understand.

DM annihilations delay the recombination
 and enforce the free electron fraction
 to freeze-out ($z=600$) at higher values.

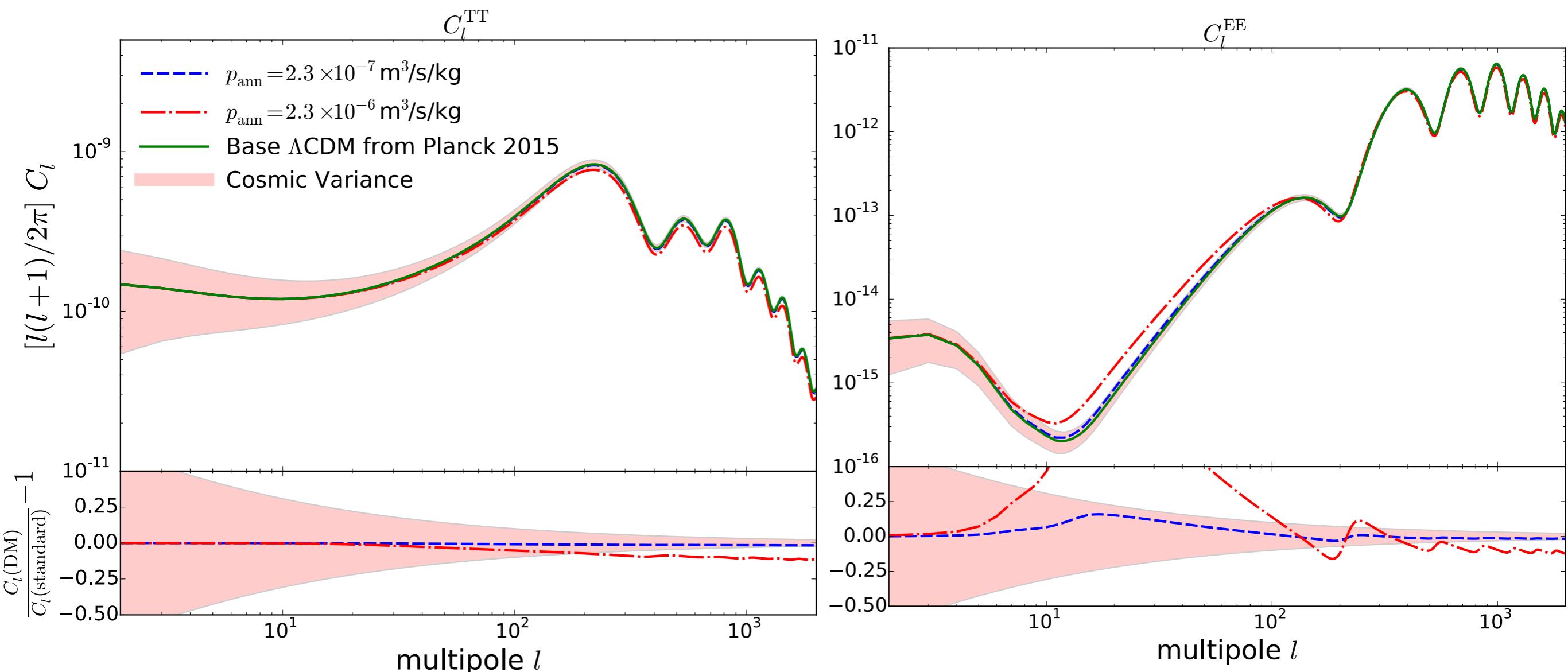
Modification of the ionisation fraction will in turn affect the CMB power spectra through CMB scattering with free electrons.



Recombination delay implies :

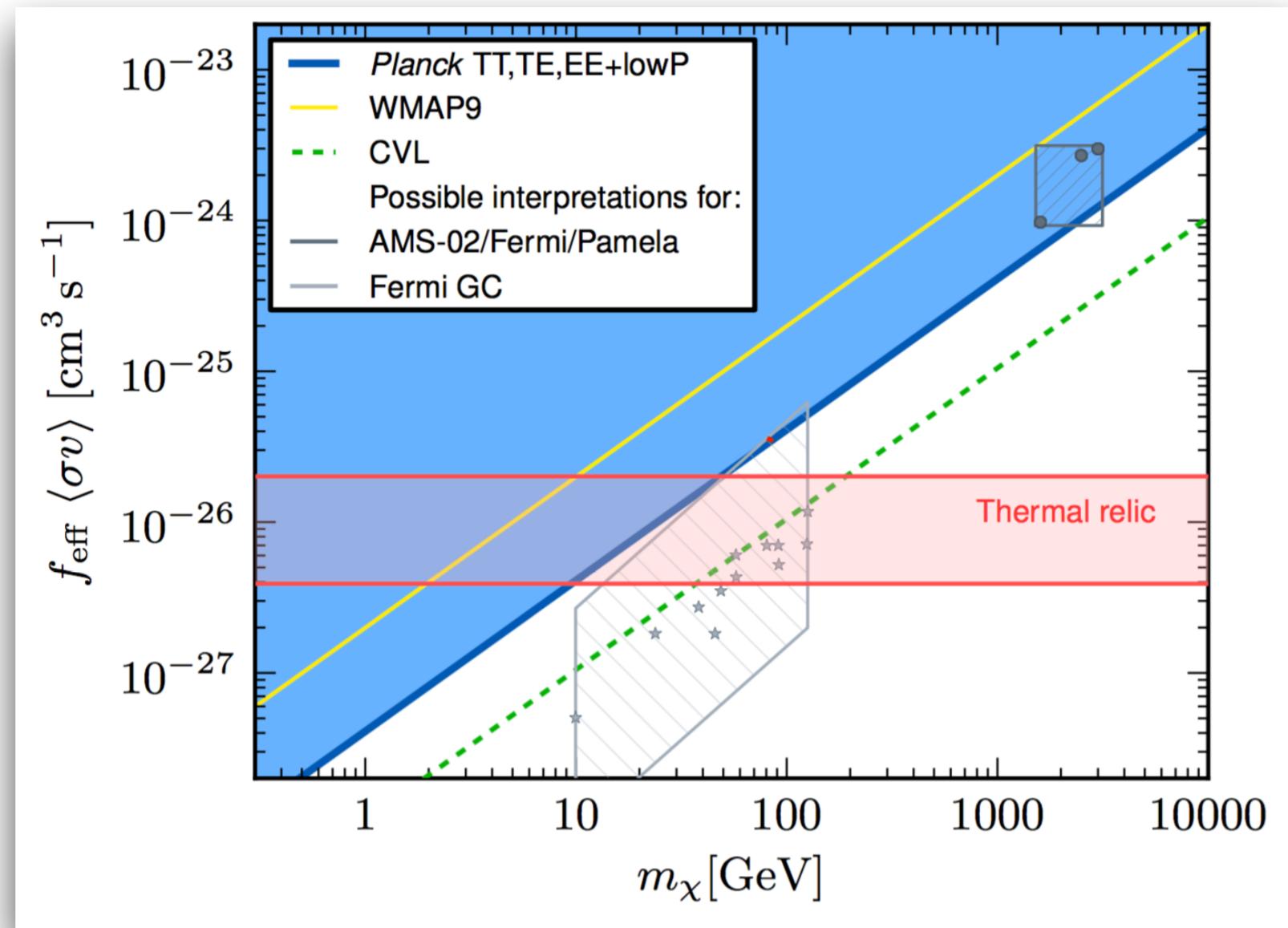
- 1) Shift of the peaks
- 2) More diffusion damping

Modification of the ionisation fraction will in turn affect the CMB power spectra through CMB scattering with free electrons.



More scattering implies :

- 1) Suppression of power on all scales with $\ell > 200$
- 2) Regeneration of power in the polarization spectrum



$$p_{\text{ann}} \equiv f_{\text{eff}} \frac{\langle \sigma_{\text{ann}} v \rangle}{m_{\text{DM}}} < 3.4 \times 10^{-28} \text{ cm}^3 \text{ s}^{-1} \text{ GeV}^{-1}$$

TT, TE, EE + lowP + lensing

Planck 2015 [[arXiv:1502.01589](https://arxiv.org/abs/1502.01589)]

Results obtained from annihilation in the smooth background only
Is it possible to improve over it by taking into account Dark Matter halo formation?

As time goes by, virialized structures of DM starts to form,
the so-called « DM halos ».

Universe globally homogeneous

$$\langle \rho \rangle^2|_{\text{smooth}} = \langle \rho \rangle^2|_{\text{smooth+halos}}$$

however

$$\langle \rho^2 \rangle|_{\text{smooth}} \leq \langle \rho^2 \rangle|_{\text{smooth+halos}}$$

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It is the last quantity that enters the energy injection from DM !

=> More energy injected => Better constraints.

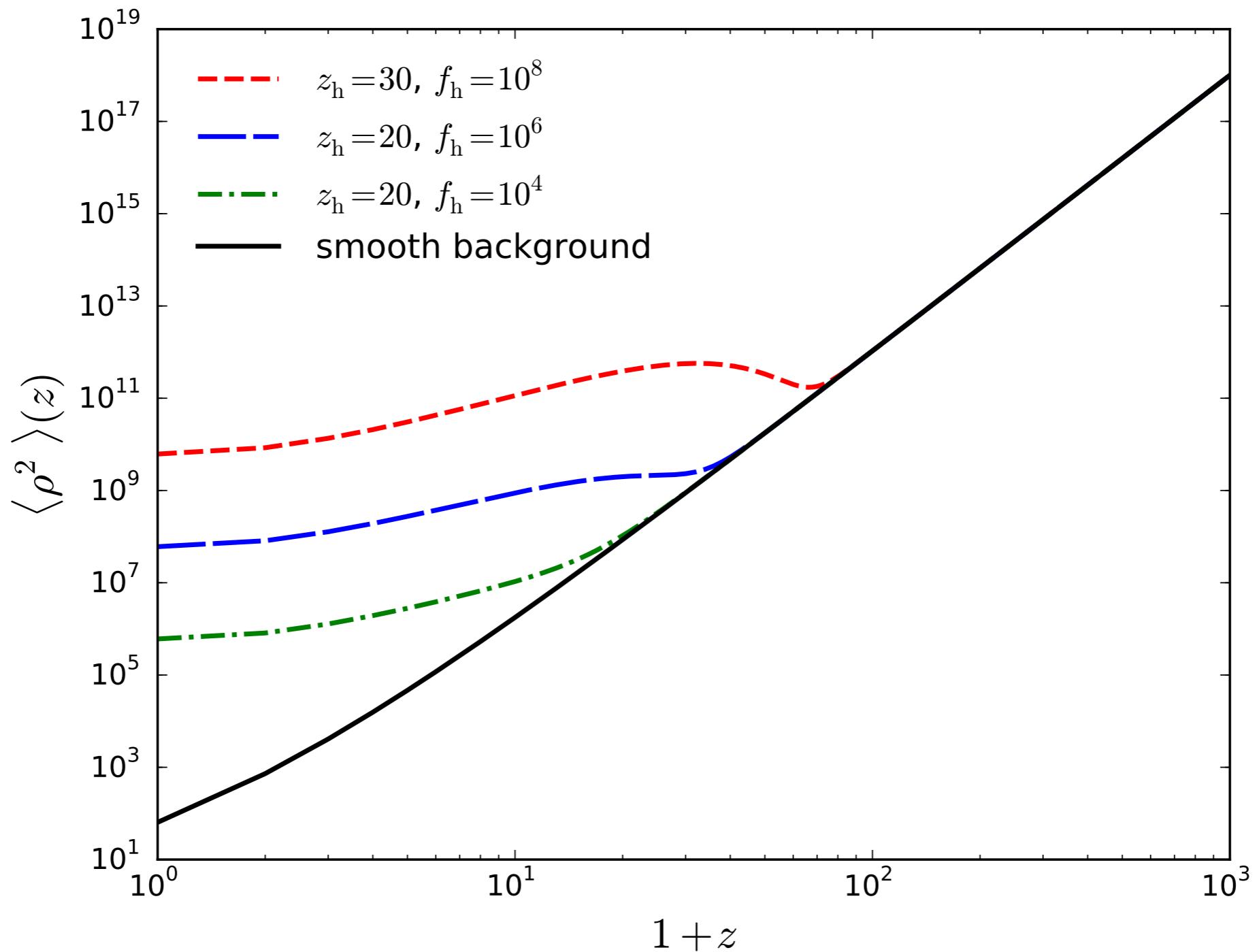
But, is it very so easy ? unfortunately, no !

Useful parameterization

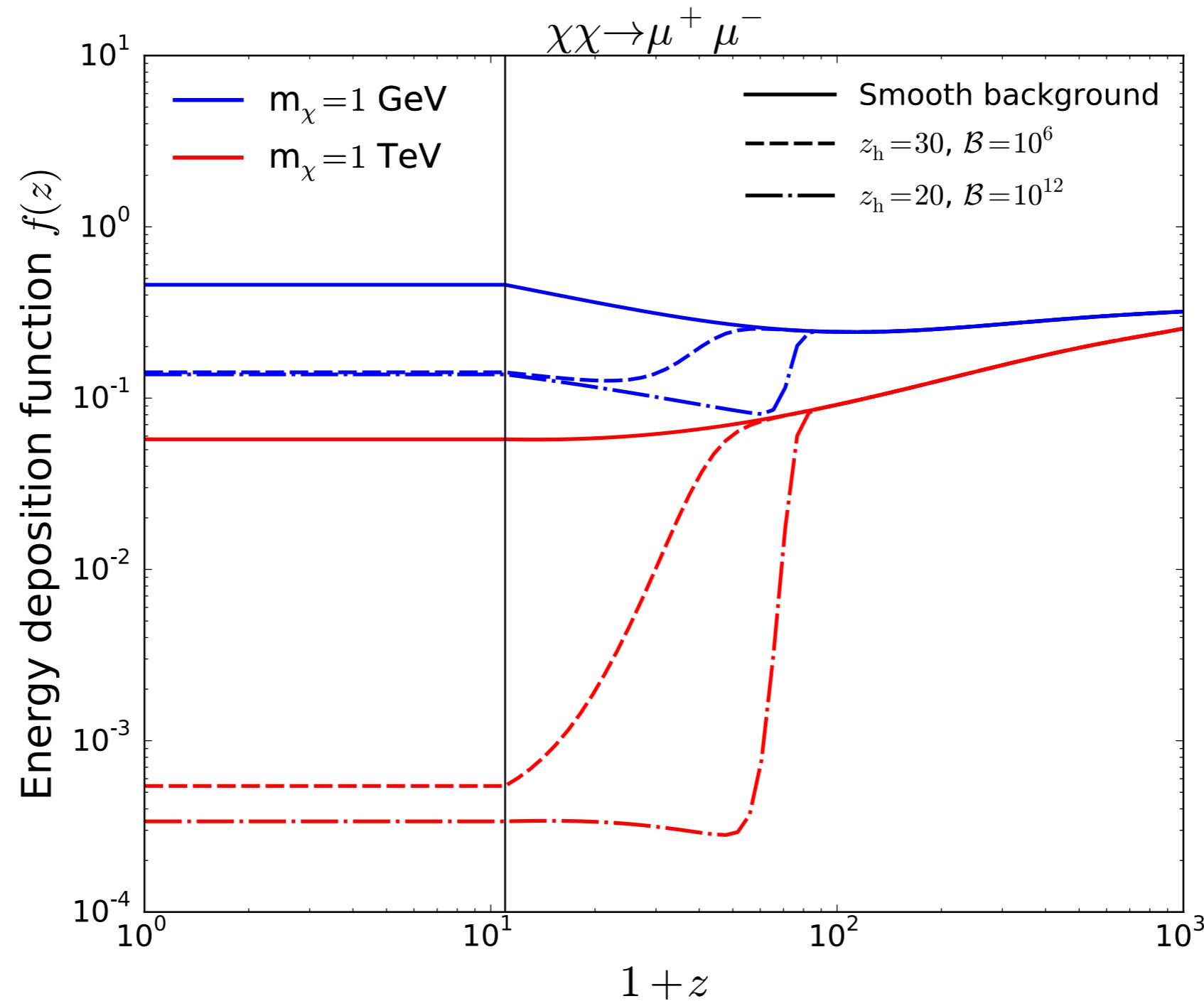
$$\langle \rho^2 \rangle(z) = (1 + \mathcal{B}(z)) \langle \rho^2 \rangle$$

In the « Press-schechter formalism »

$$\mathcal{B}(z) = \frac{f_h}{(1+z)^3} \operatorname{erfc} \left(\frac{1+z}{1+z_h} \right)$$



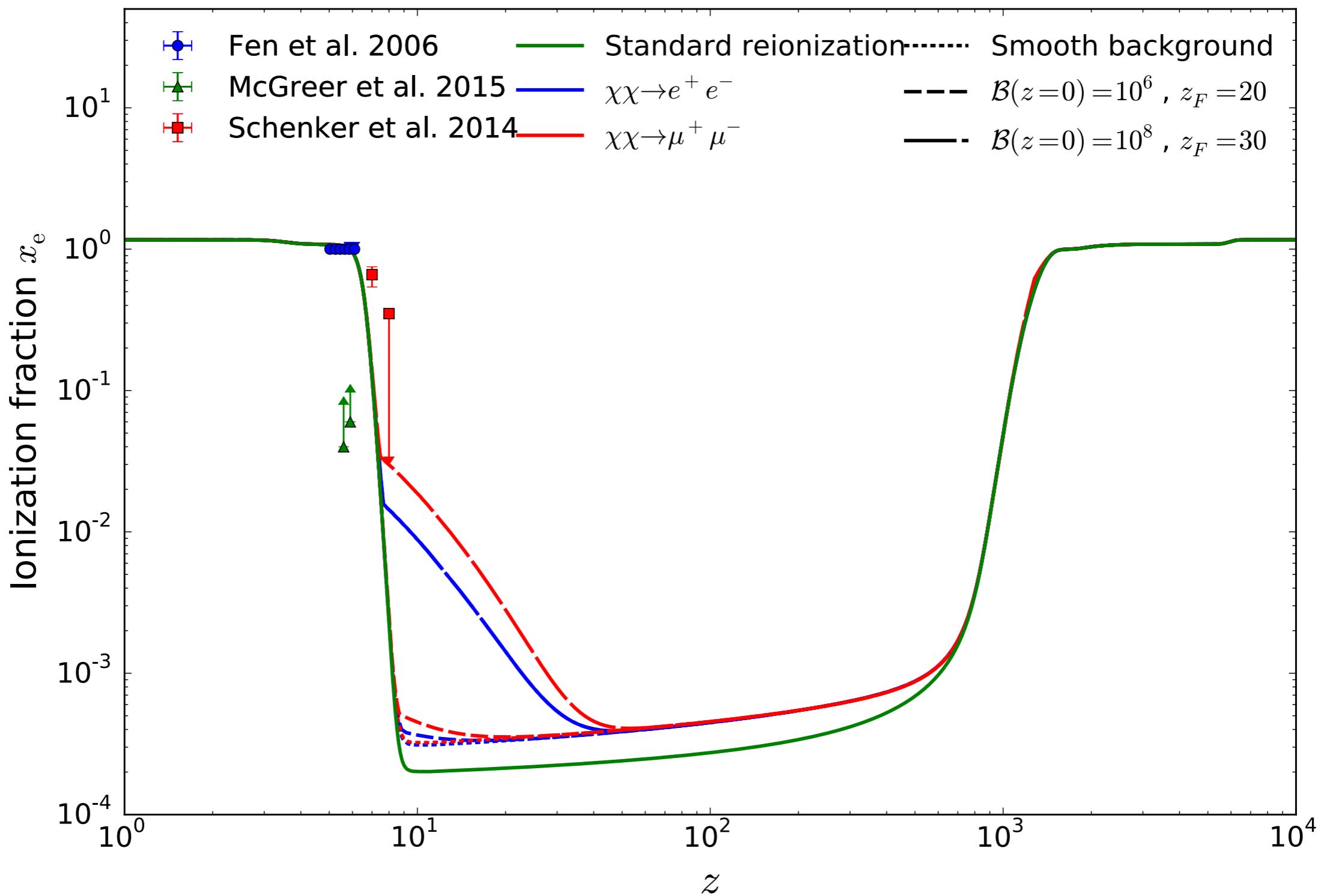
We need to recompute the $f(z)$ functions !



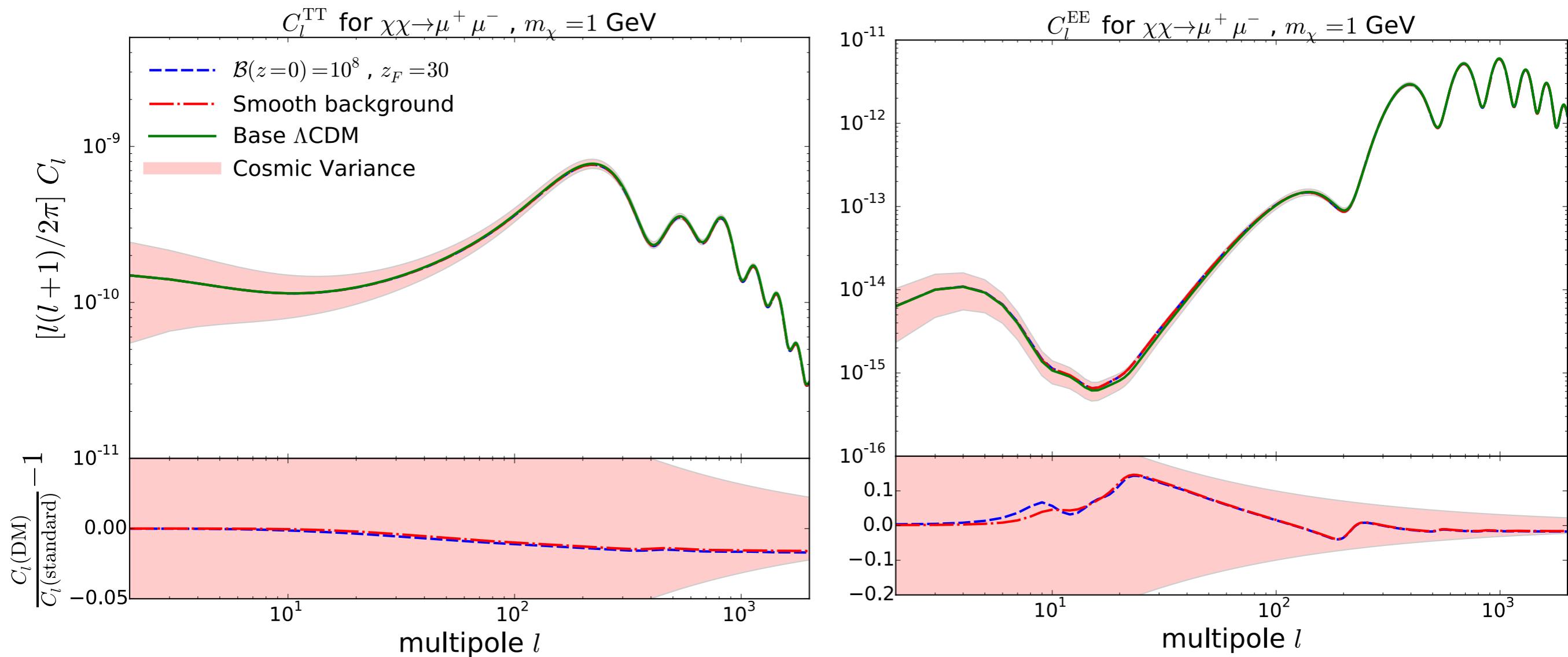
$f(z)$ decreases but it will be multiply by $(1 + \mathcal{B}(z))$

see also [arXiv:1303.5094]

Impact of halos is similar to reionization



Impact of « standard halos » not distinguishable by the CMB



at low l : Effect well below cosmic variance.

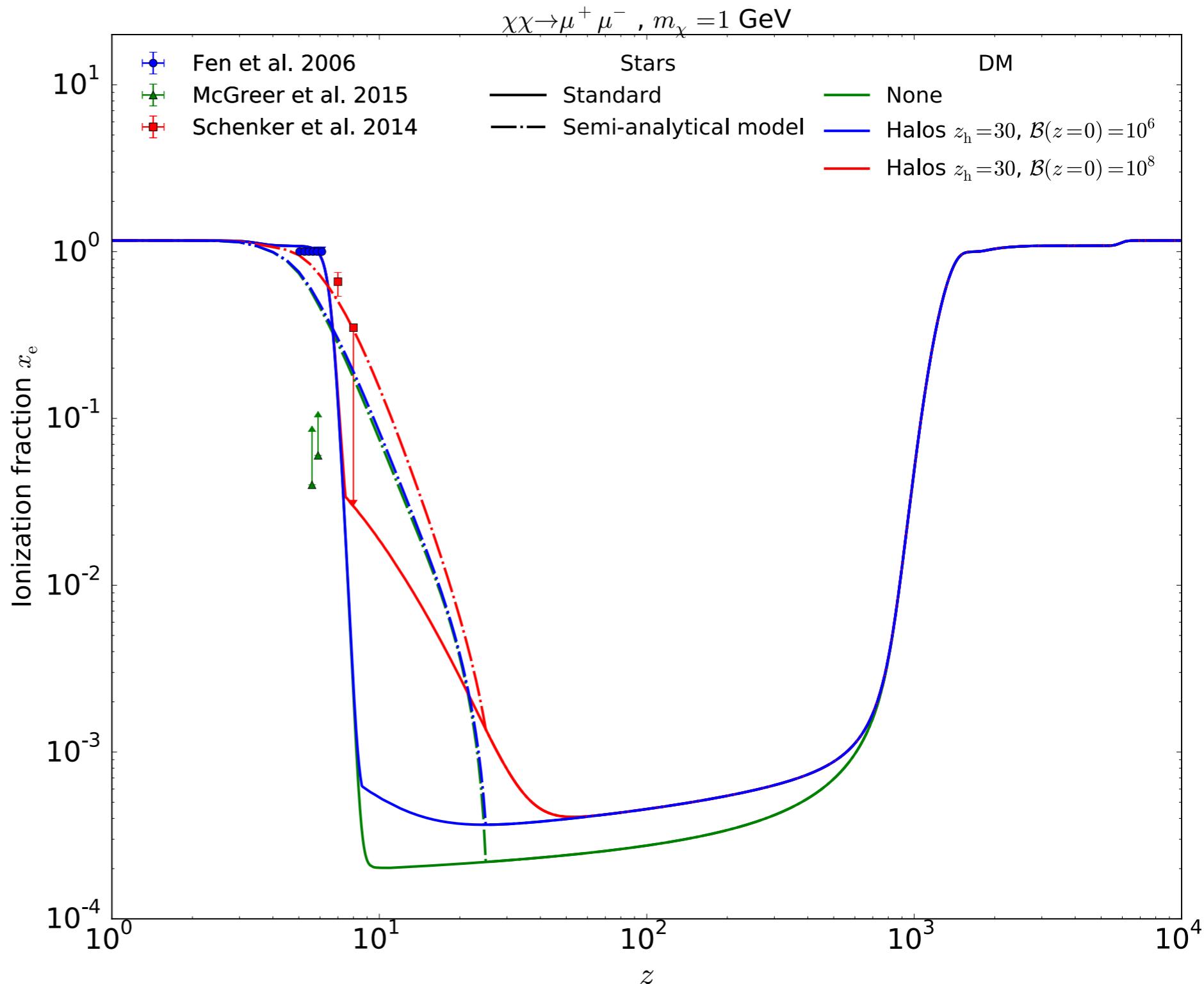
at high l : not distinguishable from background annihilations.

[\[arXiv:1508.01370\]](https://arxiv.org/abs/1508.01370)

UV sources in
star-forming galaxies
reionize the IGM

Standard :
tanh parameterization
centered on « z_{reio} »

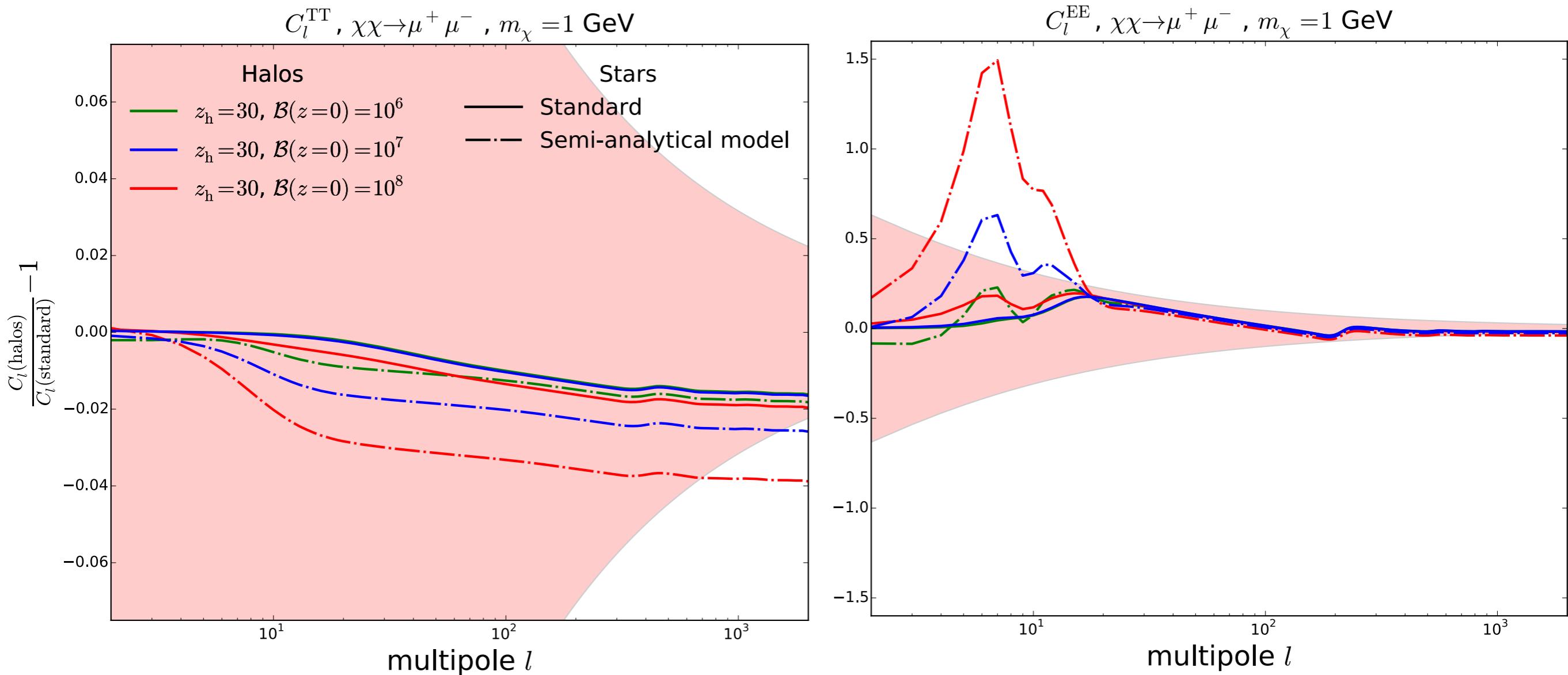
Semi analytical-model :
add a source term
prop. to
the star formation rate,
itself prop. to
UV luminosity.



$$\frac{1}{E} \frac{dE}{dVdt} \Big|_{\text{dep}} = A_* f_{\text{esc}} \xi_{\text{ion}} \rho_{\text{SFR}}(z) (1+z)^3$$

see also [arXiv:1502.02024]

Two different treatments of star reionization will lead to different conclusions !



A more realistic treatment might indicate that impact of halos is non-negligible.
Caveat : Only for « big halos », disfavored by numerical simulations.

In a nutshell :

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From annihilations in the smooth background only, Planck

- improved bounds on $\langle \sigma v \rangle$ up to **1 order of magnitude**;
- ruled out thermal relics **below 10 GeV** whatever annihilation channels;
- ruled out Fermi/Pamela/AMS DM candidates.

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From annihilations in the smooth background only, Planck

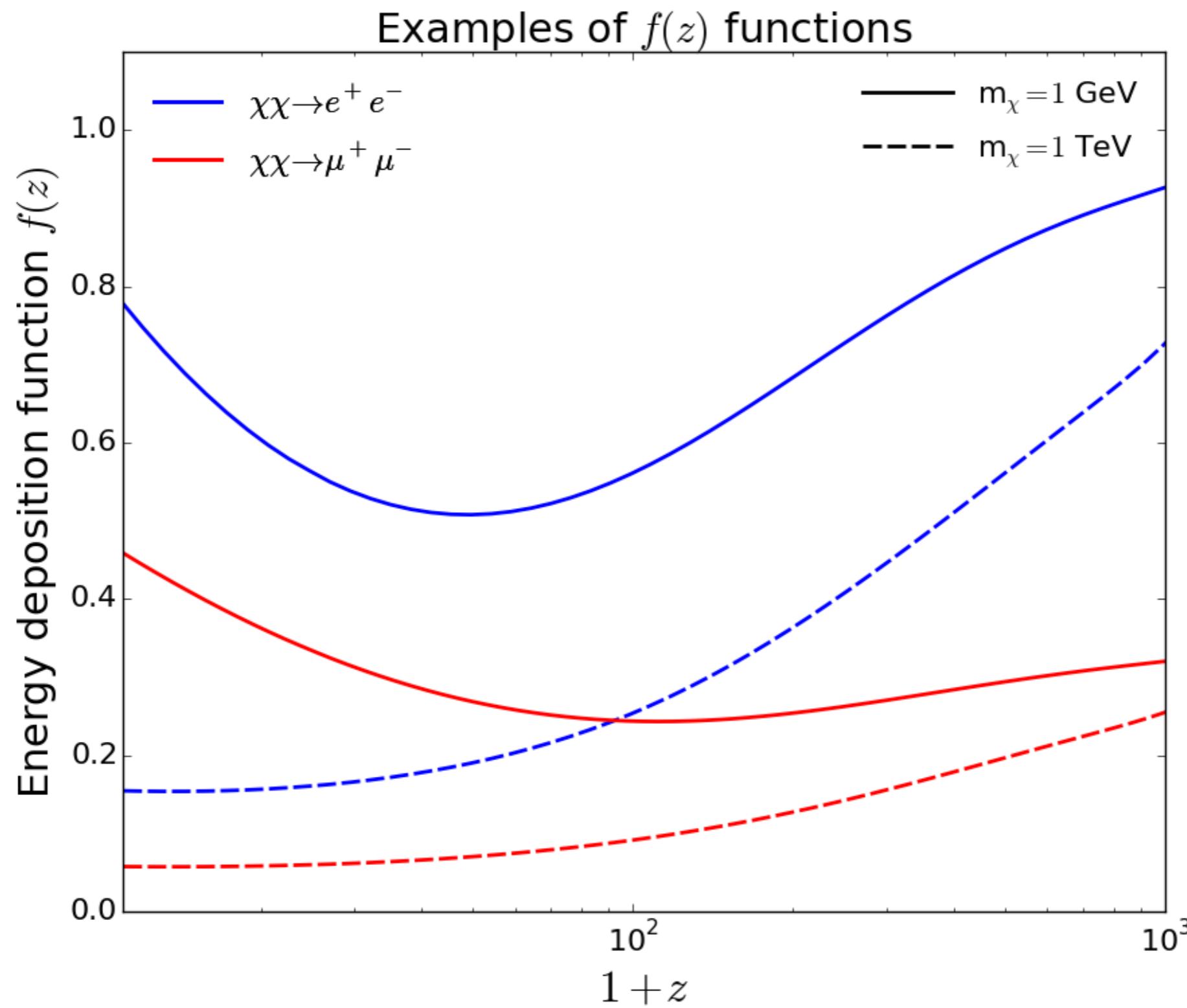
- improved bounds on $\langle \sigma v \rangle$ up to **1 order of magnitude**;
- ruled out thermal relics **below 10 GeV** whatever annihilation channels;
- ruled out Fermi/Pamela/AMS DM candidates.

From annihilations of standard DM models in halos :

- impact on CMB power spectra depends on reionization modeling :
 - **too small** to improve bounds for the standard parameterization;
 - **non-negligible** for « big halos » in a more realistic modelization of stars.
- Interesting consequences on the **IGM temperature and 21cm signal**.

Thanks for your attention !

Backup slides



Increased optical depth to reionisation

$$\tau_{\text{reio}} \equiv c\sigma_T \int_0^{z_{\text{reio}}} n_H(z) x_e(z) \frac{dt}{dz} dz$$

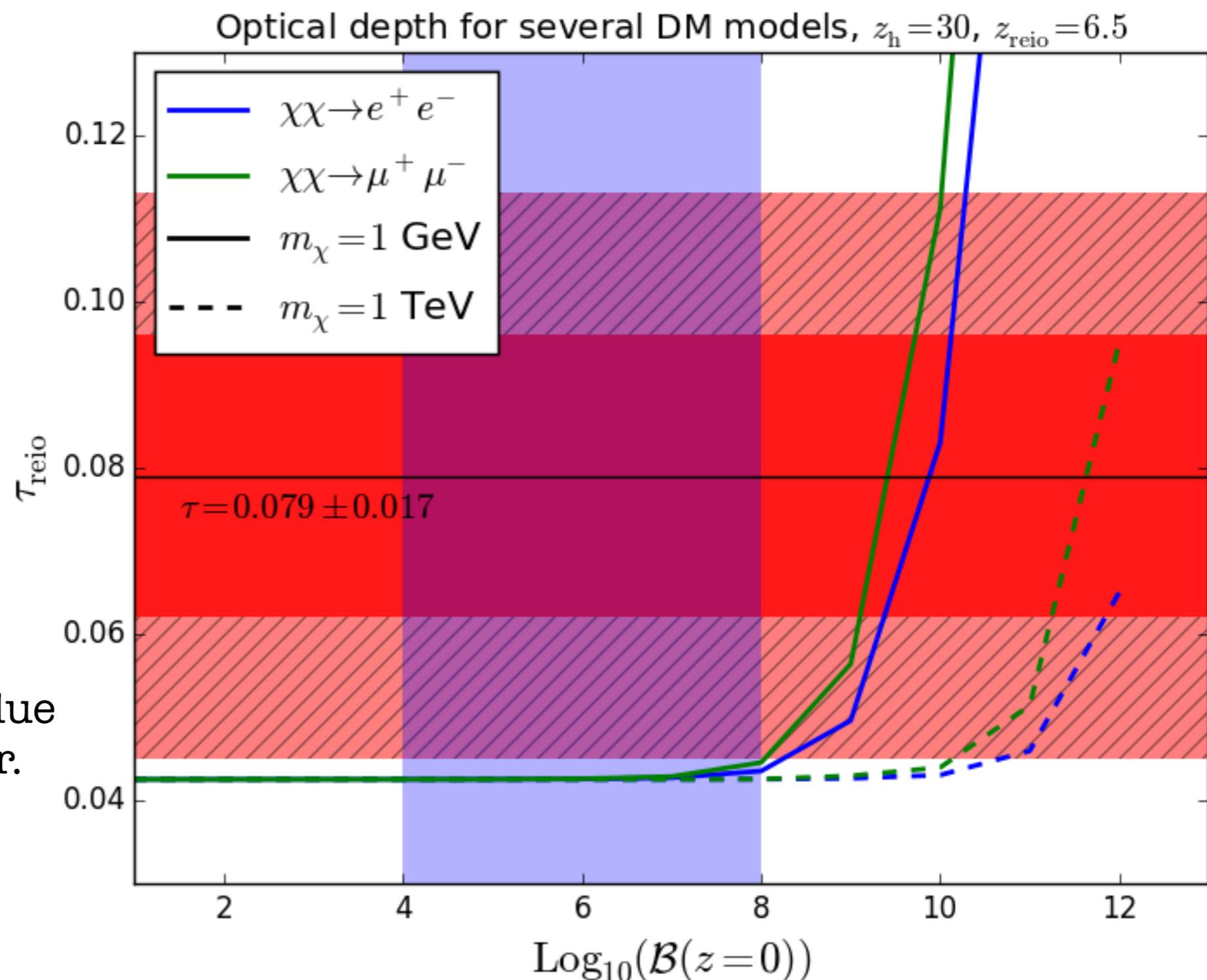
We set « p_{ann} » to
the maximum allowed value
and vary the boost factor.

Increased optical depth to reionisation

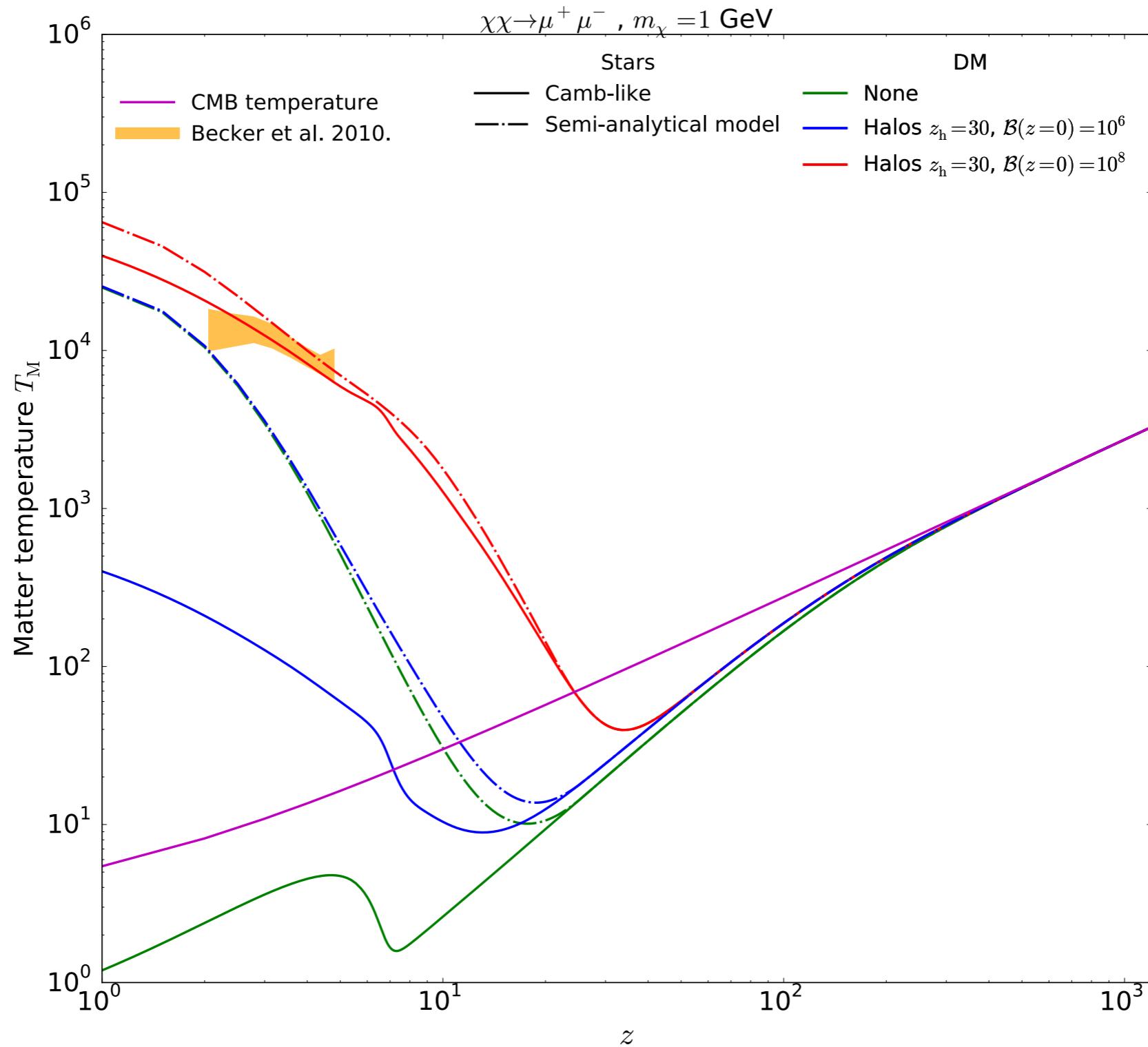
$$\tau_{\text{reio}} \equiv c\sigma_T \int_0^{z_{\text{reio}}} n_H(z) x_e(z) \frac{dt}{dz} dz$$

This effect had been invoked to solve a discrepancy between « Gunn Peterson Trough » and CMB measurements of τ_{reio} .

We set « p_{ann} » to the maximum allowed value and vary the boost factor.



Measurements of the IGM temperature and 21 cm signal will improve our knowledge on DM properties.



see e.g. [arXiv:astro-ph/0310473], [arXiv:0911.1125], [arXiv:1306.0563]

Old approach « physically » motivated :

χ_i and χ_α are proportional to the number of **neutral atoms** (« the targets »)

$$\chi_\alpha = \chi_i = (1 - x_e)/3 \Rightarrow \chi_h = (1 + 2x_e)/3$$

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New approach = monte carlo study :

Starting from one electron of a few KeV,
how does it share its energy between ionisation, excitation and heating?

see e.g. [[arXiv:astro-ph/0310473](#)], [[arXiv:0911.1125](#)], [[arXiv:1306.0563](#)]

Old approach « physically » motivated :

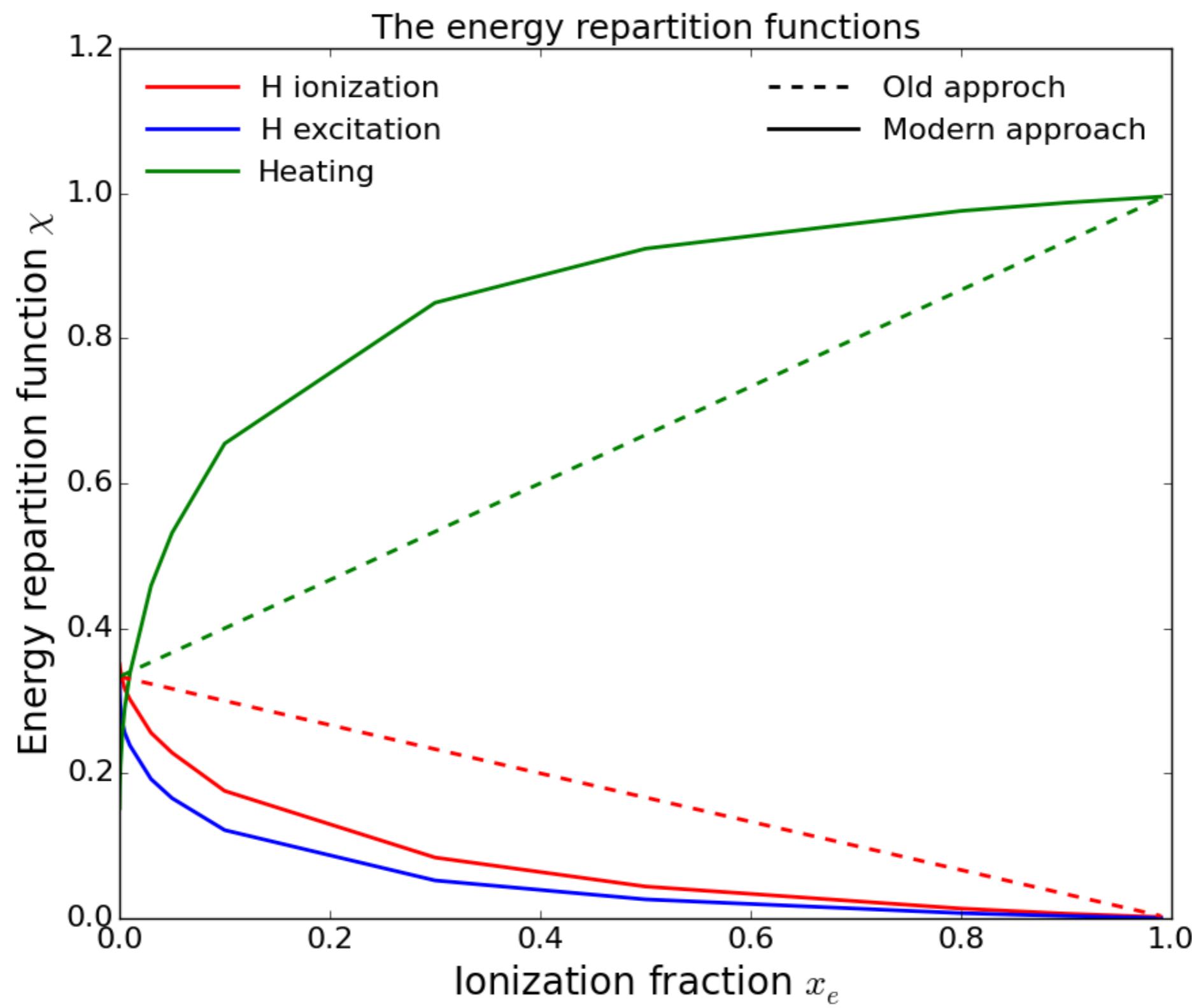
χ_i and χ_α are proportional to the number of **neutral atoms** (« the targets »)

$$\chi_\alpha = \chi_i = (1 - x_e)/3 \Rightarrow \chi_h = (1 + 2x_e)/3$$

New approach = monte carlo study :

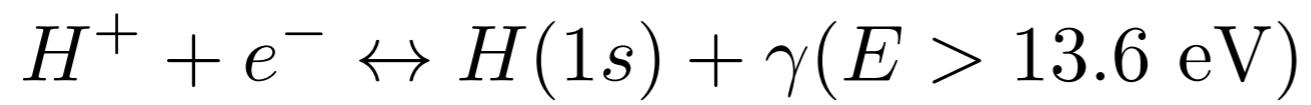
Starting from one electron of a few KeV,
how does it share its energy between ionisation, excitation and heating?

Results show important differences with previous picture.

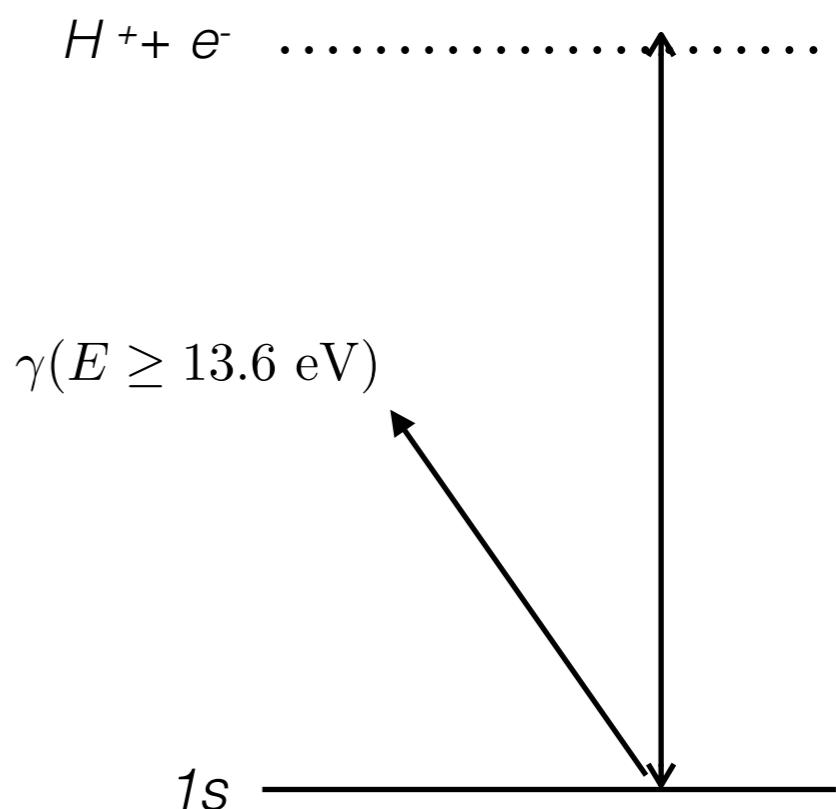


[arXiv:1306.0563]

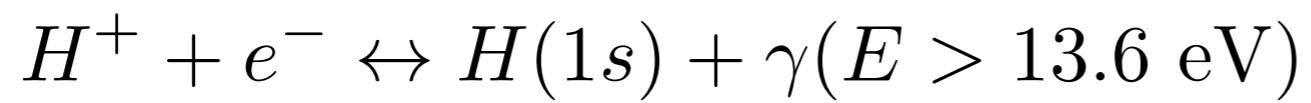
Recombination in a nutshell



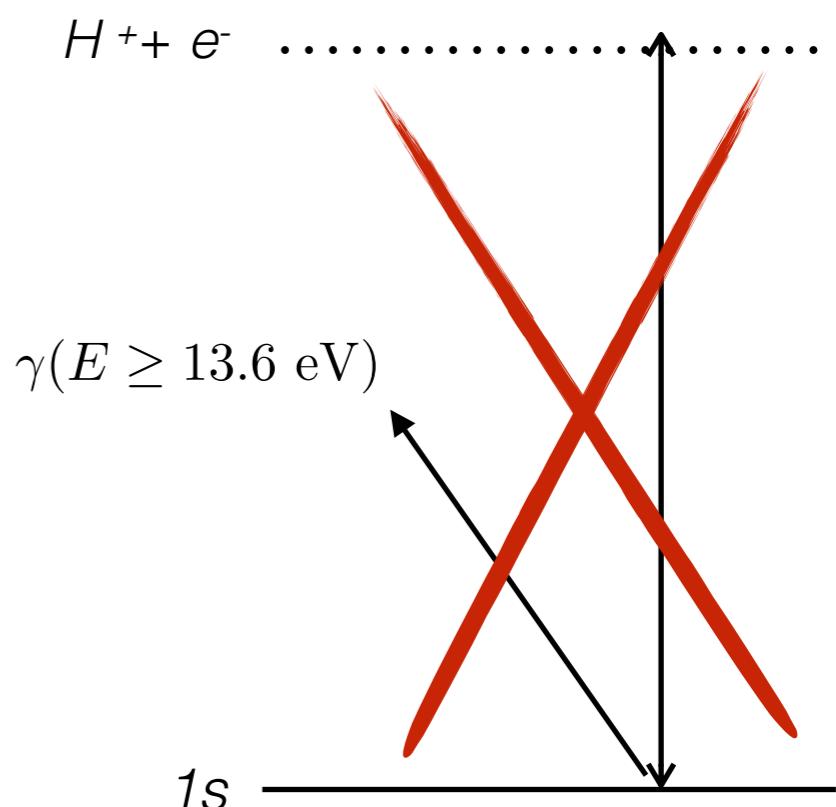
leads to the « saha » equation at equilibrium



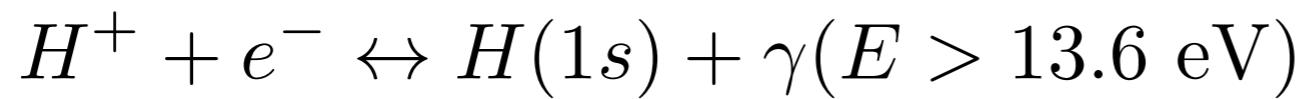
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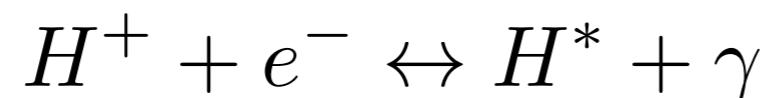


Recombination in a nutshell

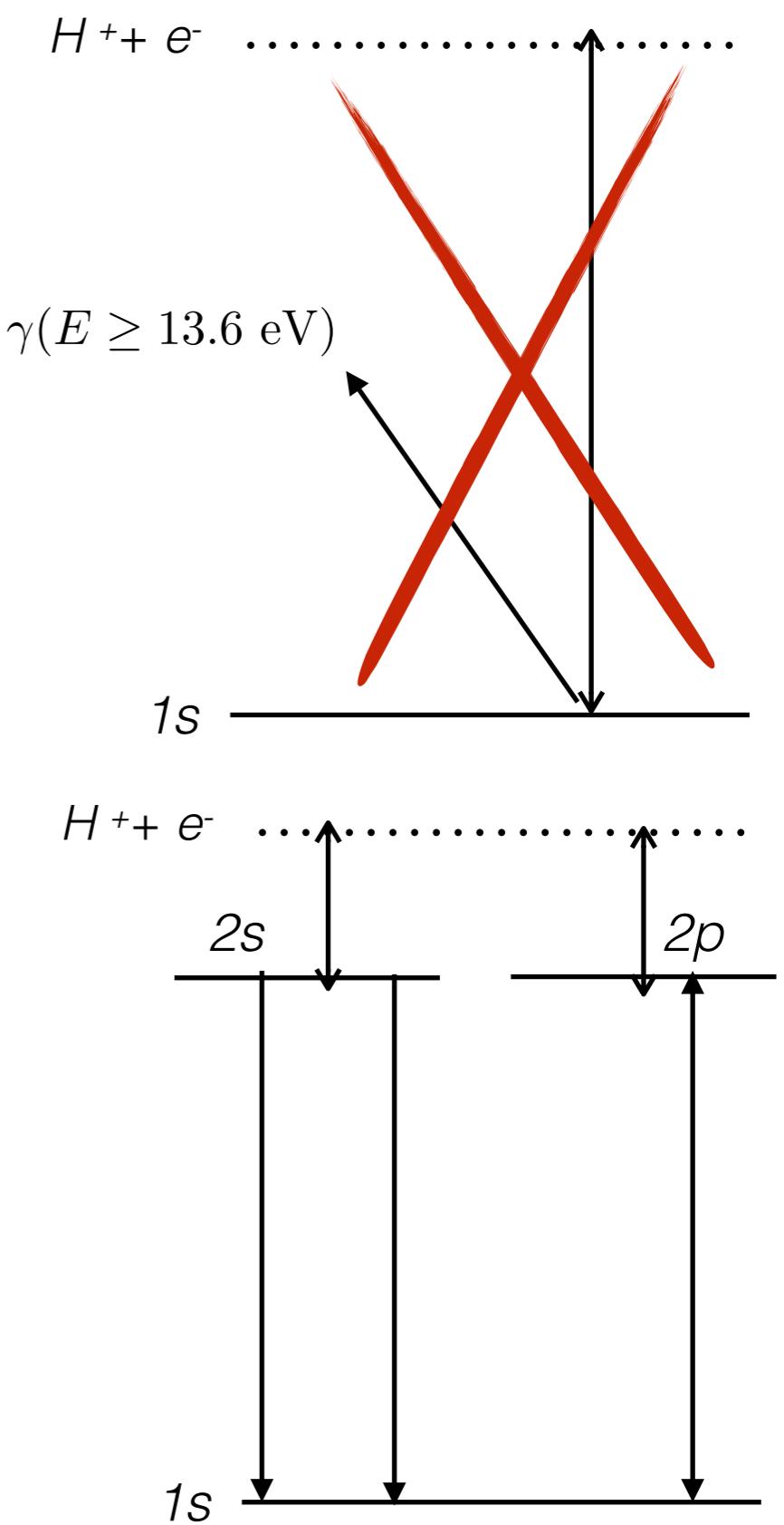
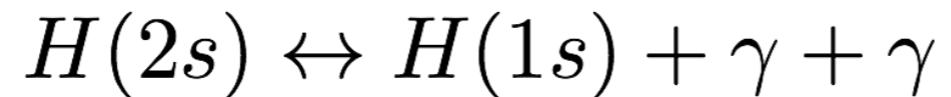


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The « three-levels atom »



followed by



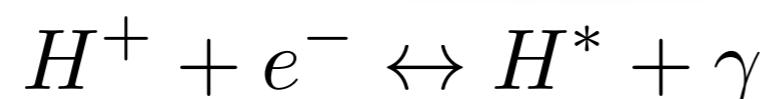
Recombination in a nutshell

Peebles "case-b"
recombination

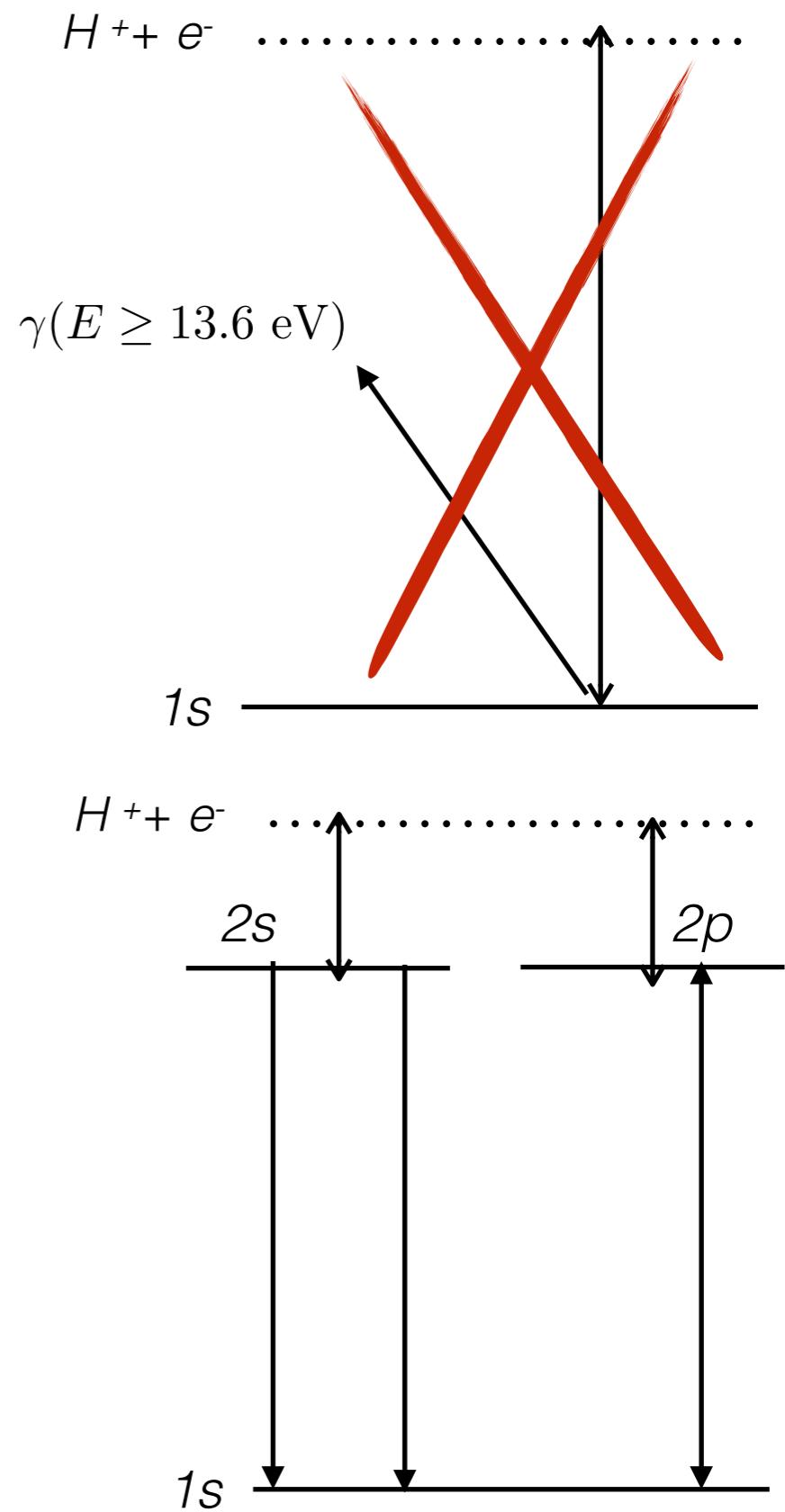
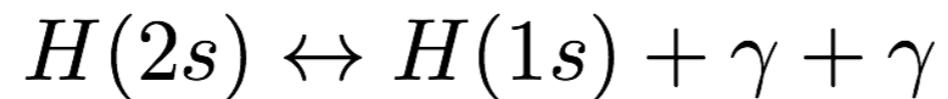
$$e^- \leftrightarrow H(1s) + \gamma (E > 13.6 \text{ eV})$$

leads to the "saha" equation at equilibrium

The "three-levels atom"



followed by



Parameterization :

$$\langle \rho^2 \rangle(z) = (1 + \mathcal{B}(z)) \langle \rho^2 \rangle$$

$$\mathcal{B}(z) = \frac{1}{\rho_c^2 \Omega_{\text{DM}}} (1+z)^3 \int_{M_{\min}}^{\infty} dM \frac{dn}{dM}(z) \left(\int_0^{r_{200}} dr 4\pi r^2 \rho_h^2(r) \right)$$

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Underlying, there's a universality hypothesis :
 whatever the mass, matter inside halos is distributed in the same way.

CMB spans **several order of magnitudes** in redshift!

For what matters, we introduce a simple parameterization :

$$\mathcal{B}(z) = \frac{f_h}{(1+z)^3} \operatorname{erfc}\left(\frac{1+z}{1+z_h}\right)$$

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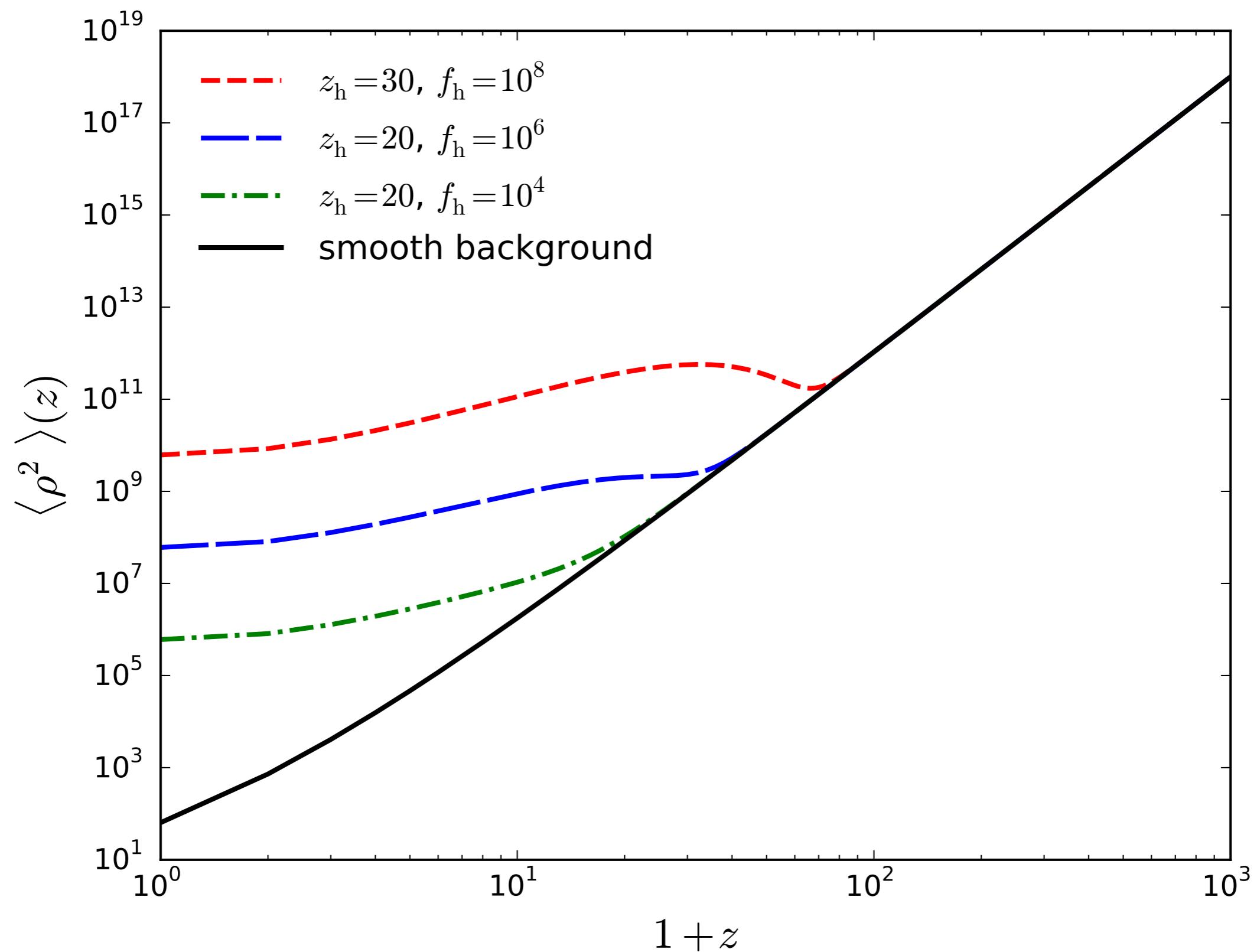
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z_h is the **characteristic redshift** at which halos starts to play a role.

Typically, $z_h \simeq \frac{1}{2} z_F$ with $z_F \in [40, 60]$.



We need to recompute the $f(z)$ functions !

$$\frac{dE}{dVdt} \Big|_{\text{dep, smooth+halos}} = f(z) \frac{dE}{dVdt} \Big|_{\text{inj, smooth+halos}}$$

$$f(z) = \frac{\int d \ln(1+z') \frac{(1+z')^3}{H(z')} (1 + \mathcal{B}(z')) \sum_\ell \int T^{(\ell)}(z', z, E) E \frac{dN}{dE} \Big|_{\text{inj}}^{(\ell)} dE}{\frac{(1+z)^3}{H(z)} (1 + \mathcal{B}(z)) \sum_\ell \int E \frac{dN}{dE} \Big|_{\text{inj}}^{(\ell)}}$$

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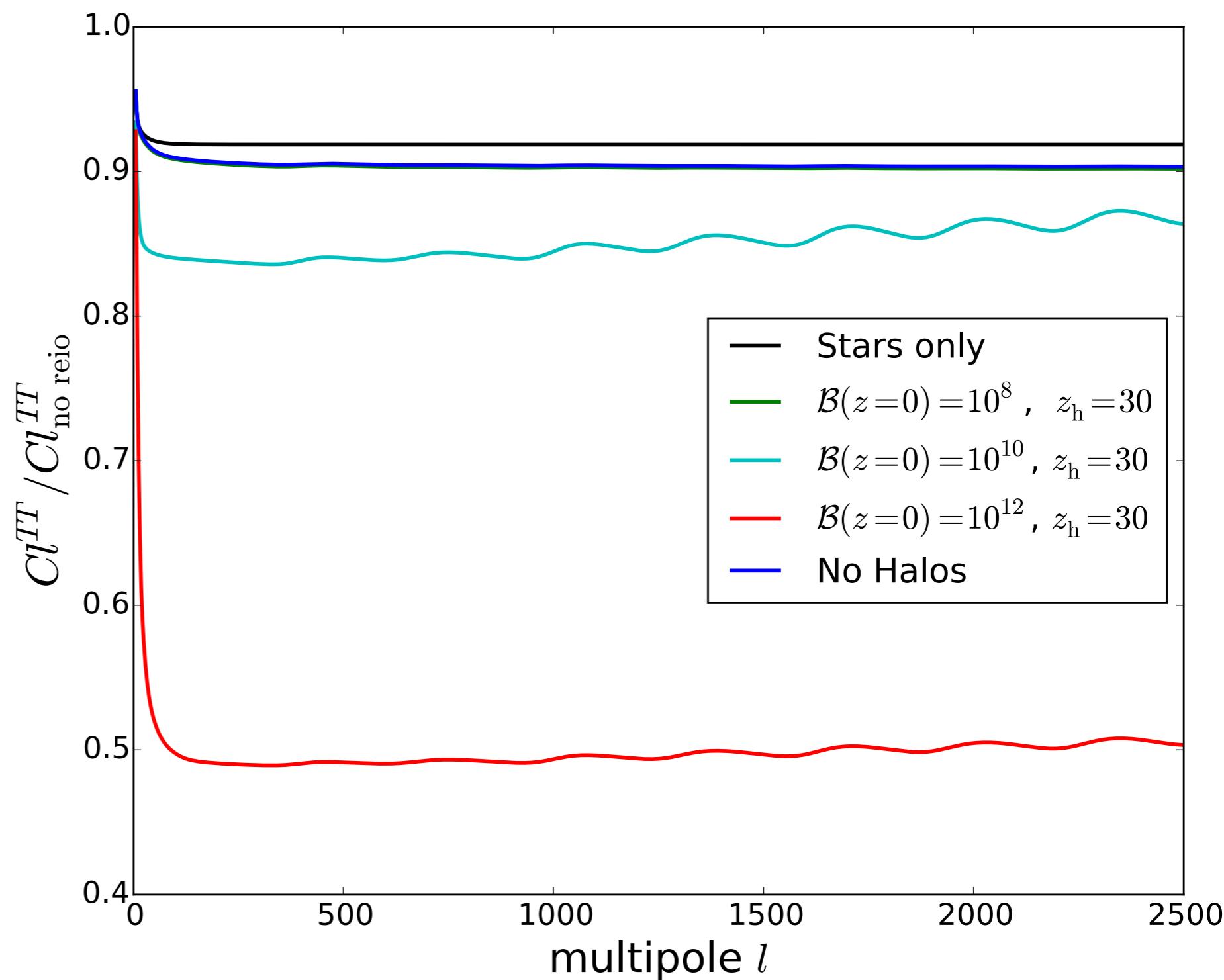
Same as before, but we convolute along z with the boost factor.

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optical depth
mainly through
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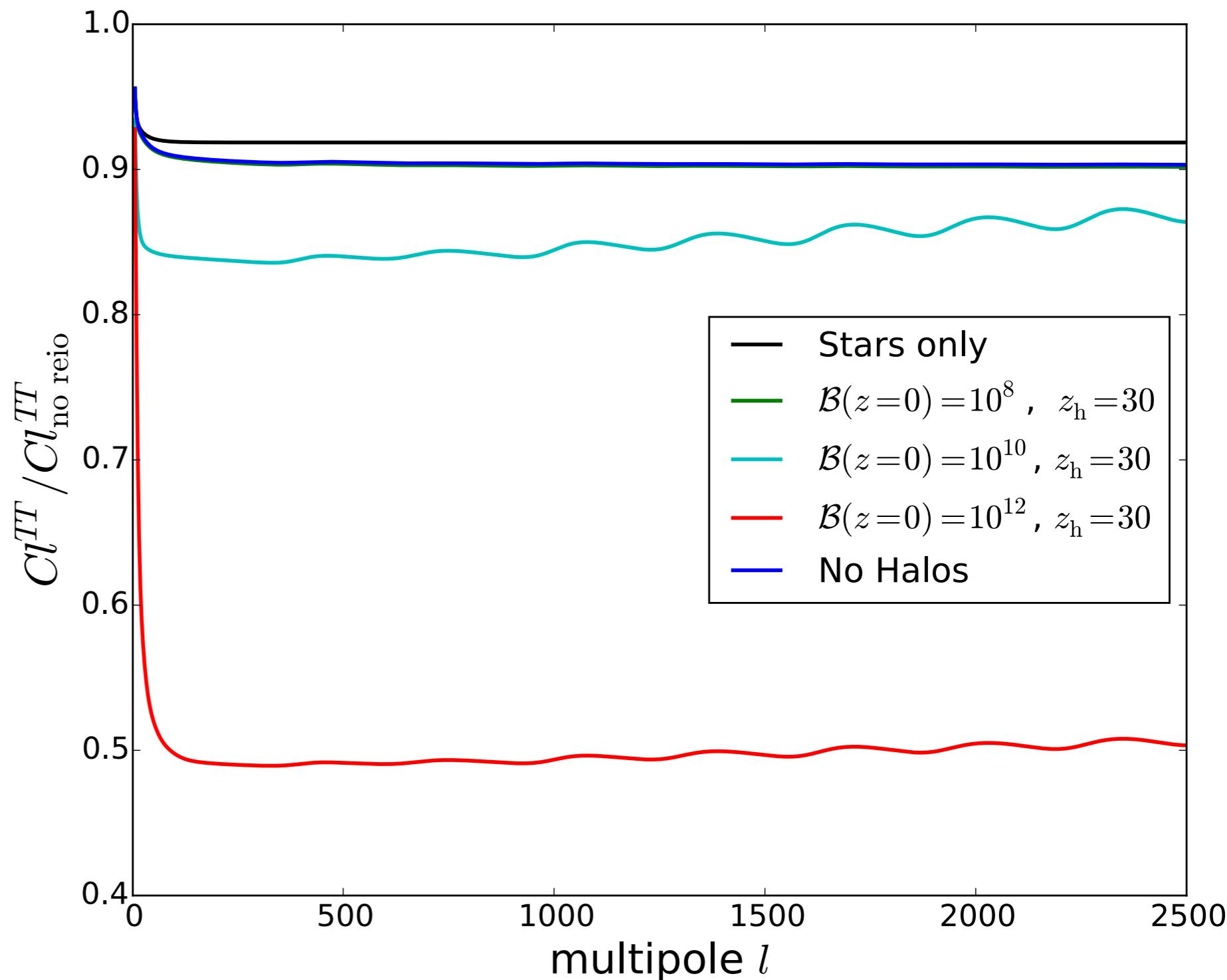


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By « chance »

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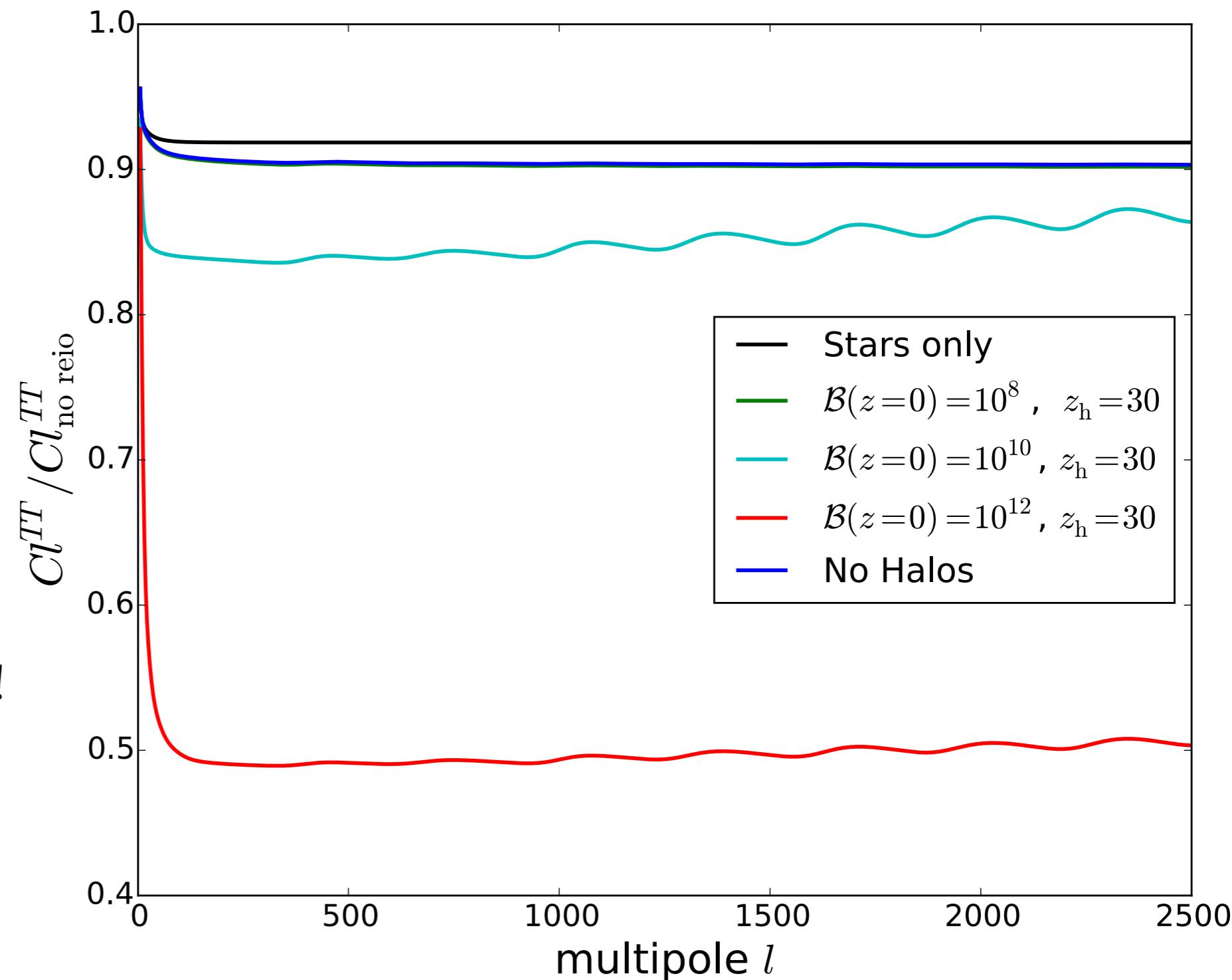


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In my cases, up to 10% differences.