Cosmological signature of decaying Dark Matter

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LAPTh and RWTH Aachen University

In collaboration with

Julien Lesgourgues (RWTH, Aachen) and Pasquale D. Serpico (LAPTh, Annecy)

VP & Serpico PRL 114 (2015) no.9, 091101

VP & Serpico PRD 91 103007 (2015) no.10

VP, Serpico & Lesgourgues JCAP 1608 (2016) no.08, 036

VP, Serpico & Lesgourgues JCAP 1703 (2017) no.03, 043

RWTH AACHEN UNIVERSITY

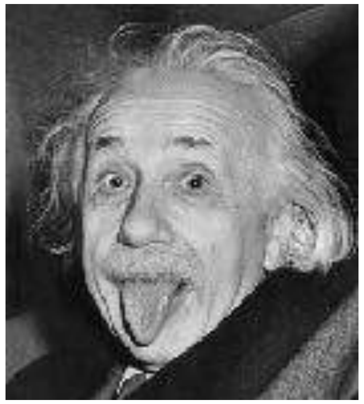
HIP, Helsinki

12.04.2017

LAPTh

ΛCDM is a big success !

From GR



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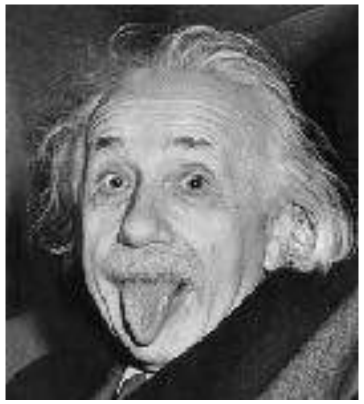
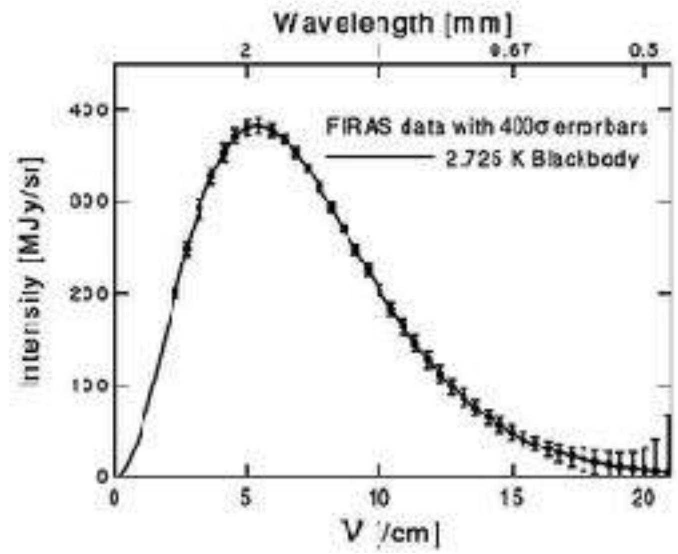
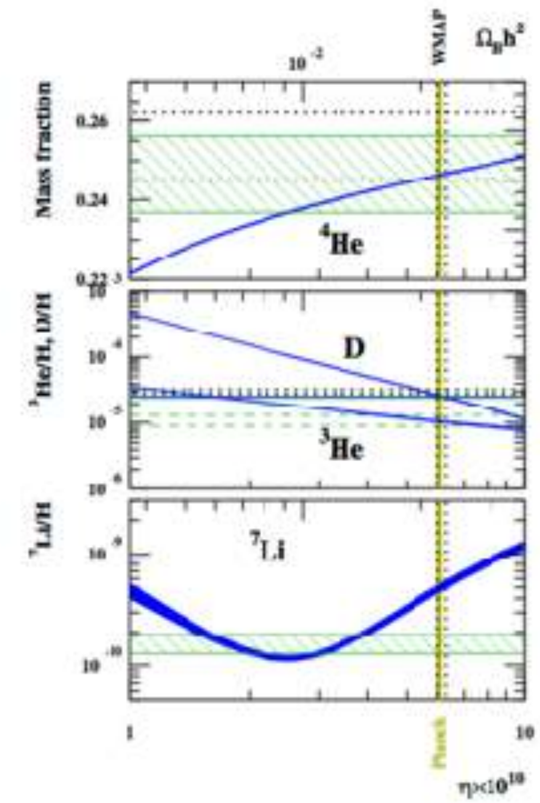


Homogeneous & isotropic



CMB blackbody distribution

Firas [astro-ph/9605054]



Big Bang Nucleosynthesis

Coc & Vengioni 2015

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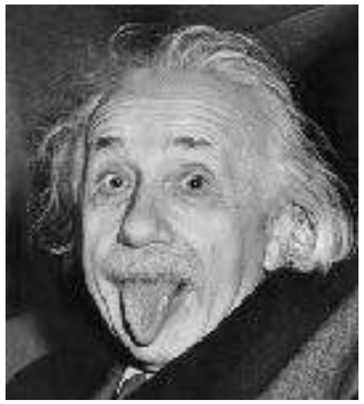

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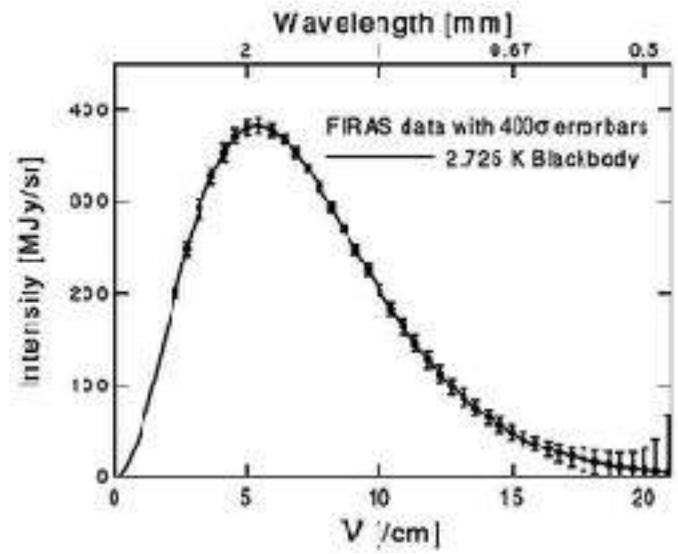

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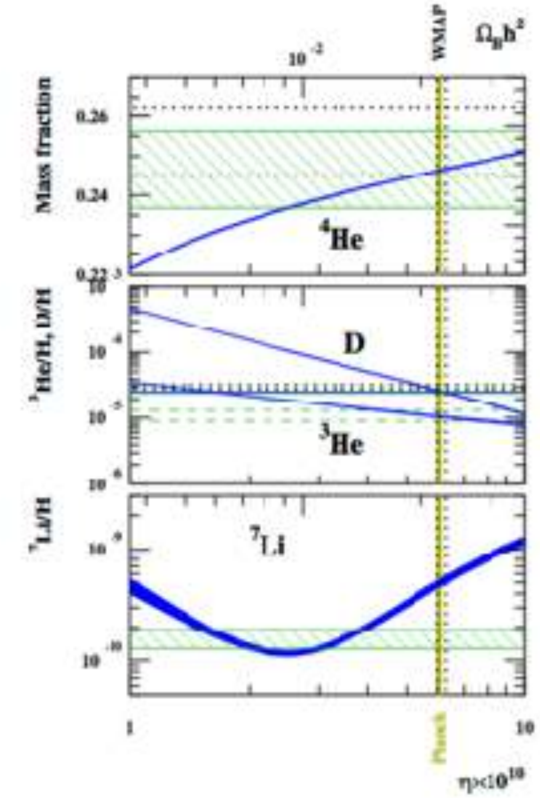

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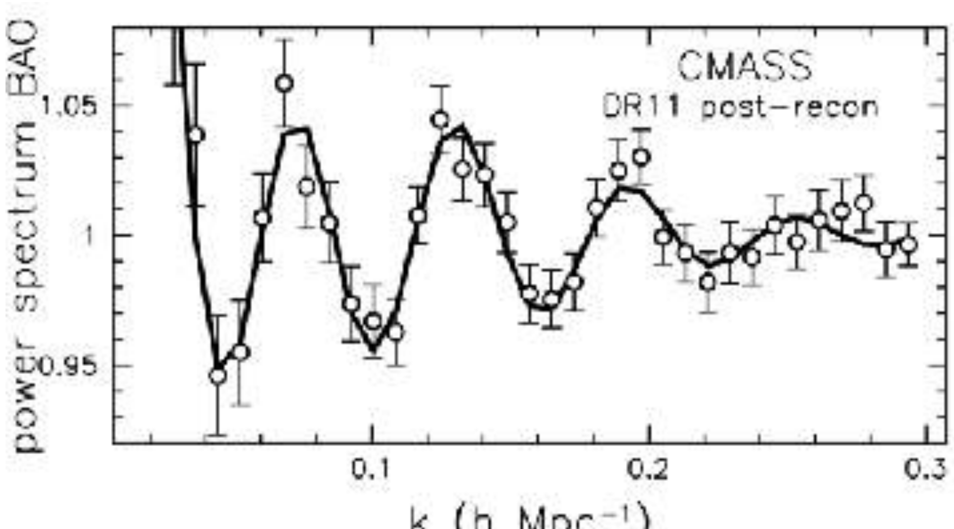
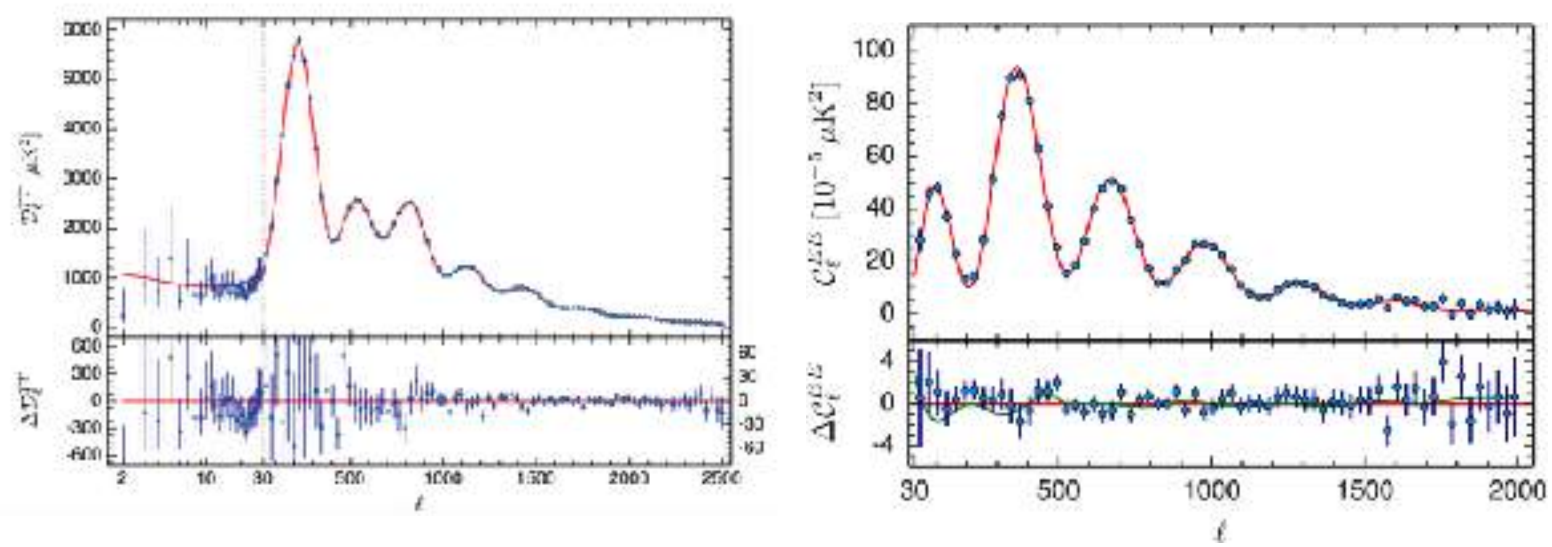
Perturbed



P(k) and BAO measurements

Andersen et al. 2012 [arXiv:1203.6594]

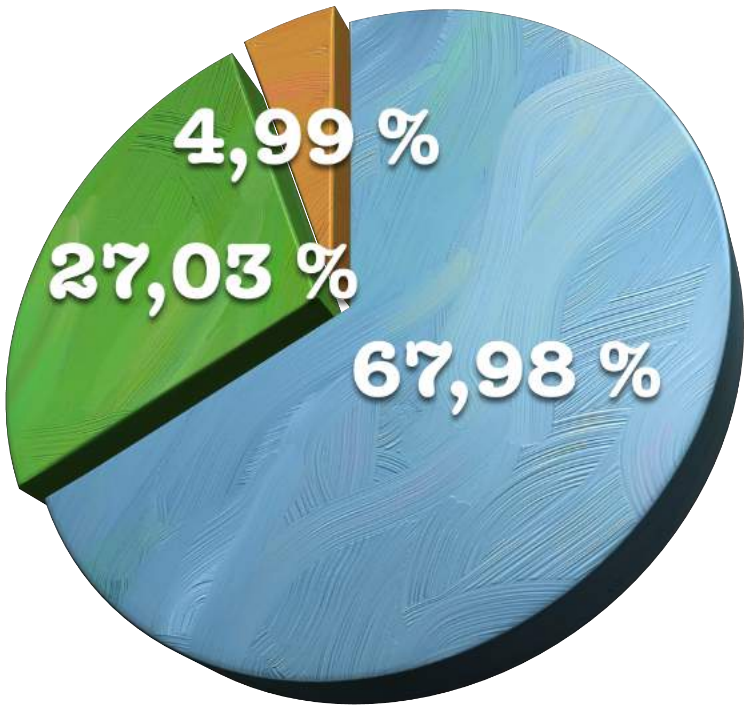


CMB power spectra

Planck 2015 [arXiv:1502.01589]

Most of the universe composition is unknown !

- Dark Energy
- Dark Matter
- Baryonic Matter



In the vanilla ΛCDM, Dark Matter is stable, only gravitational interaction

Planck 2016 [arXiv:1605.02985]

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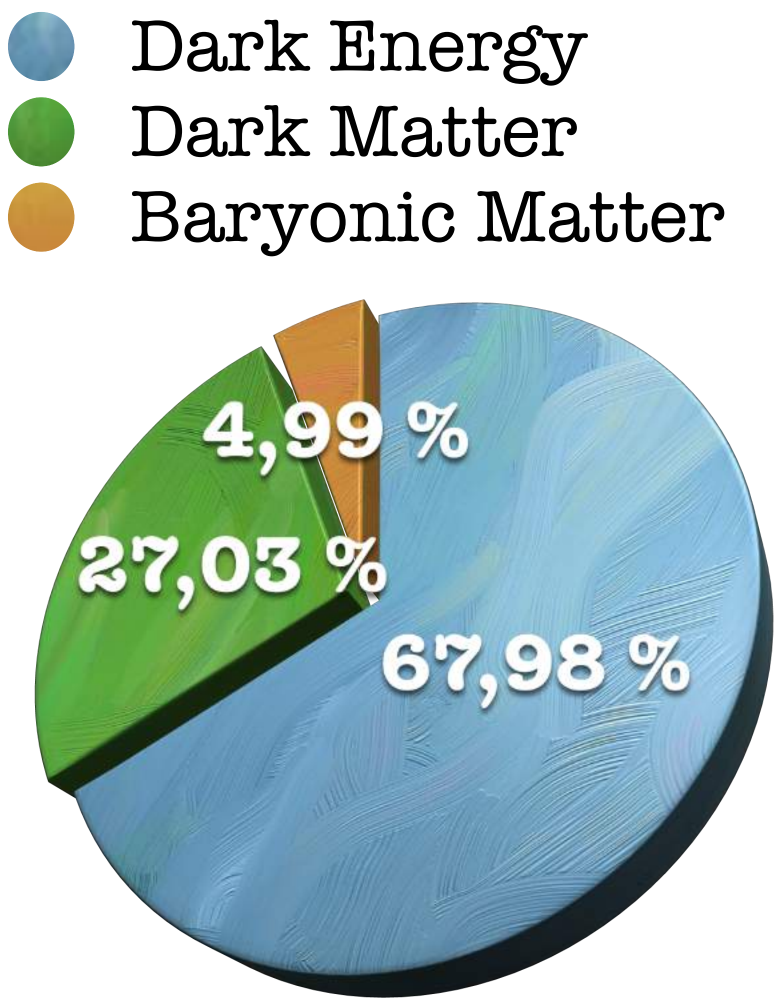

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Can we learn more on DM properties using cosmological data ? e.g. decay/annihilations rate ? SM Branching Ratio ? etc.

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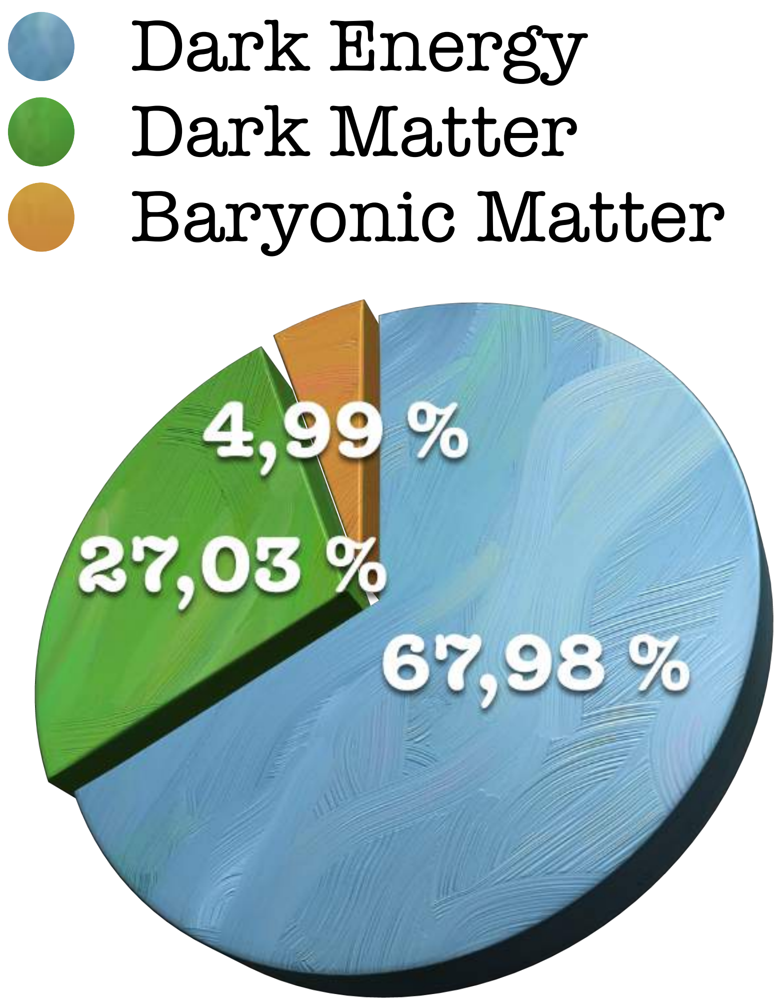

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Potentially yes !! But currently all we have are constraints ...

A Journey in Wonderland of particle physics

see e.g. [hep-ph/0404175], [arXiv:0810.0713], [arXiv:0912.5297], [arXiv:1602.04816]

Q. : What models are concerned by these constraints ?

A : Today, models with constant decay lifetime with or without e.m. channels open.

Models	Observables

A Journey in Wonderland of particle physics

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	• Spectral Distortions of the BB distribution
• Sterile neutrinos / Majoron	• CMB power spectra
• Primordial Black Holes	• Matter power spectrum

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Electromagnetic decay products

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Electromagnetic decay products

Purely gravitational impact of the decay

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	• Future: 21 cm ? ?

Electromagnetic decay products

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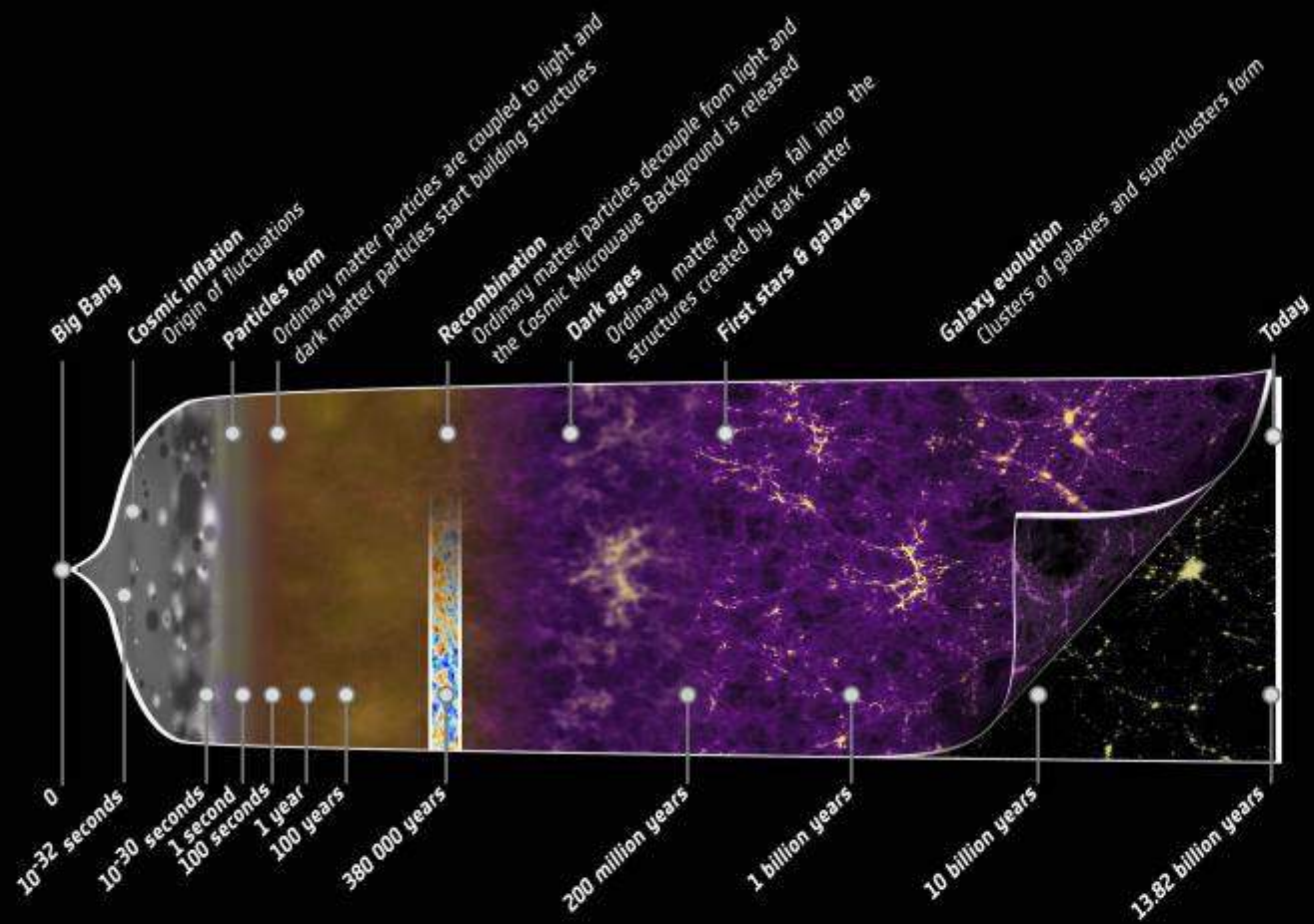
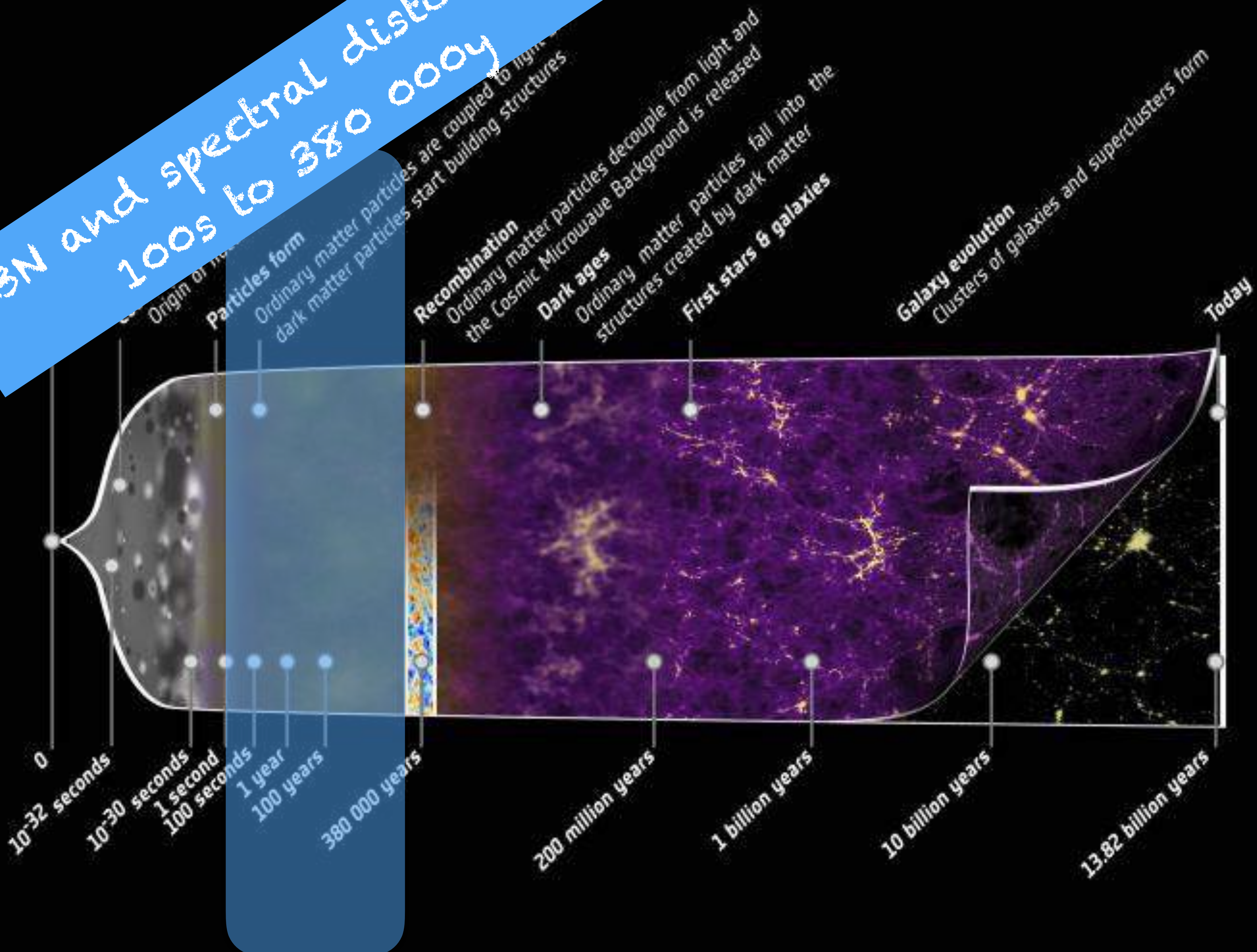


Our Universe is a great particle physics laboratory !

BBN and spectral distortions
100s to 380 000y



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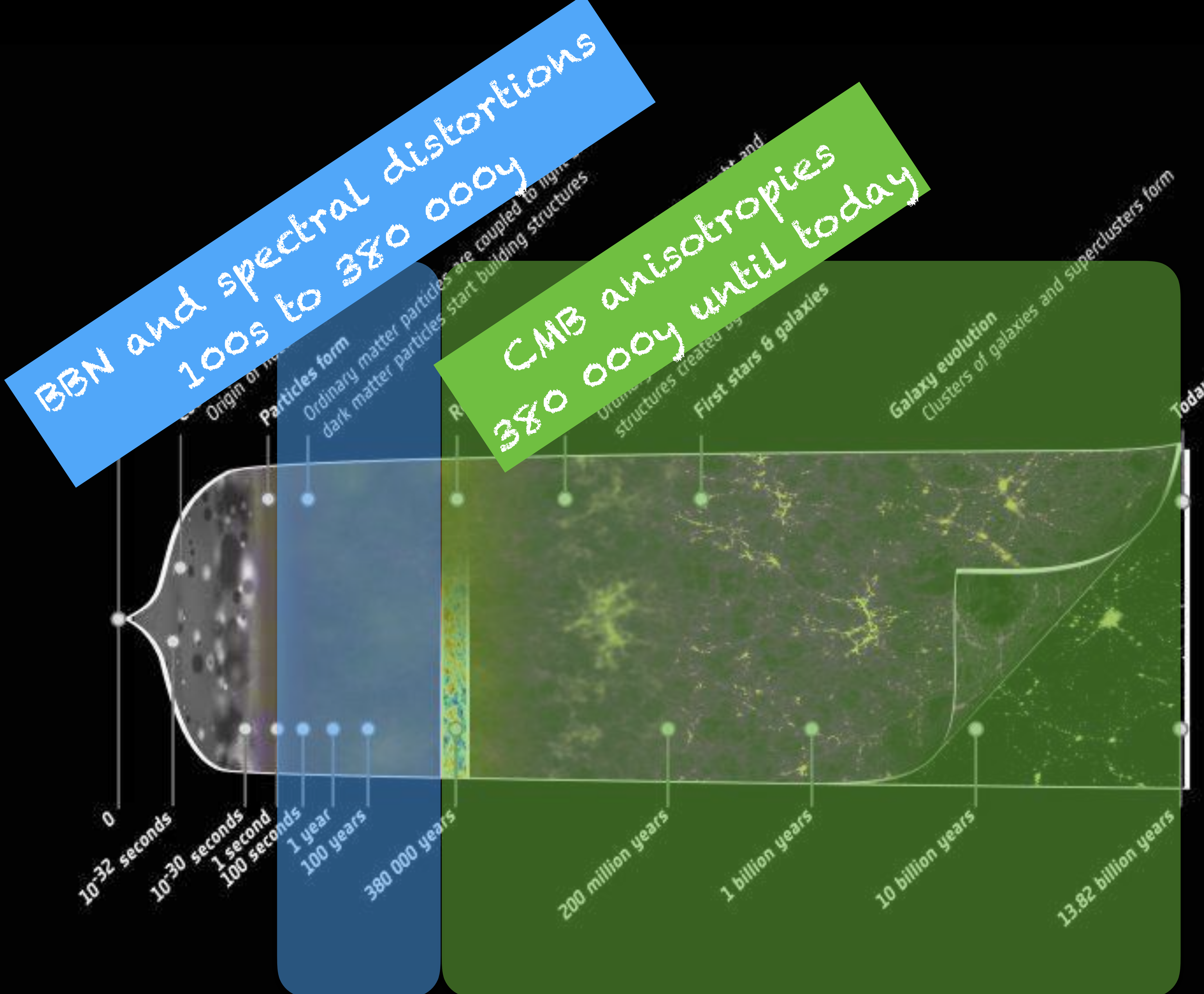

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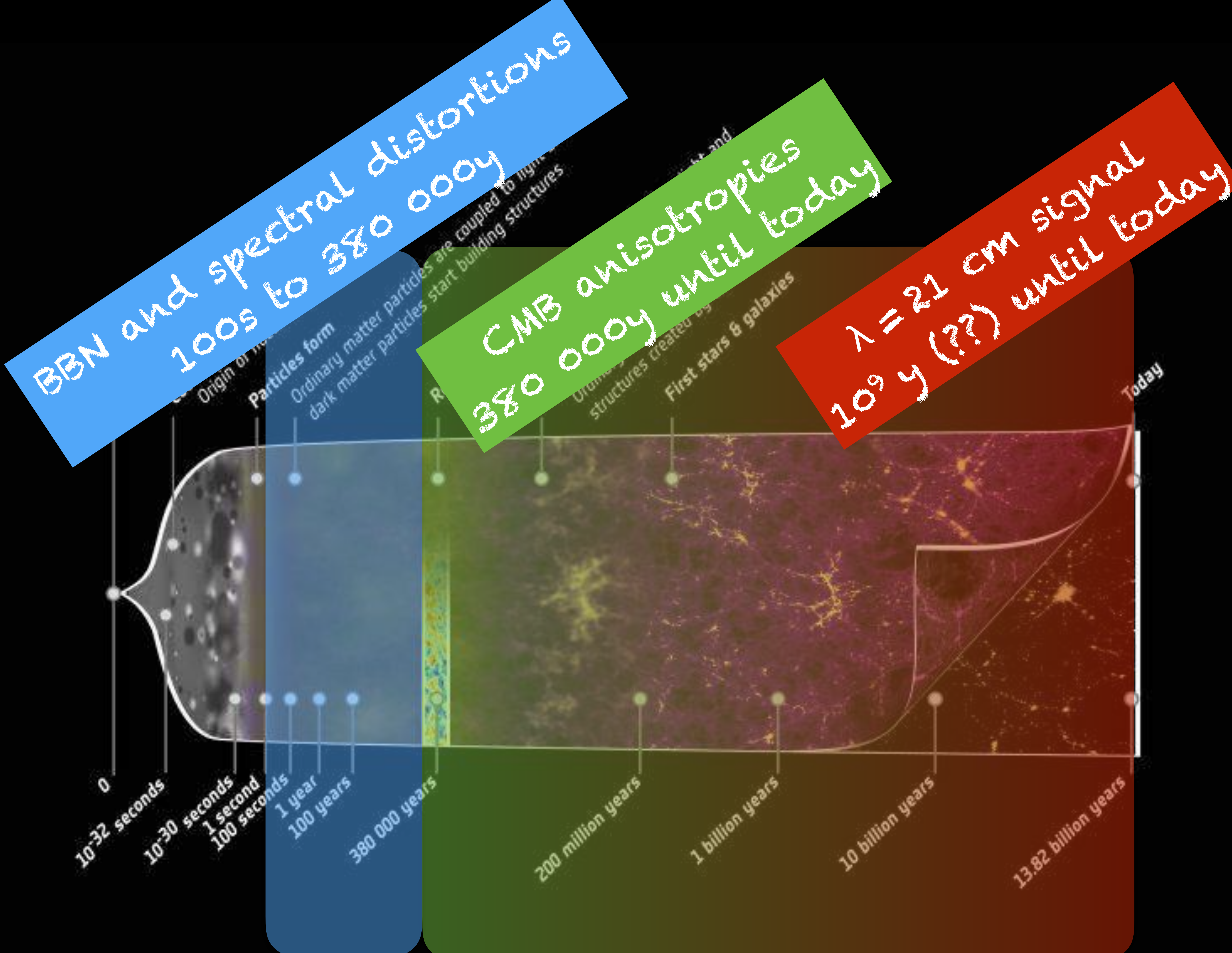

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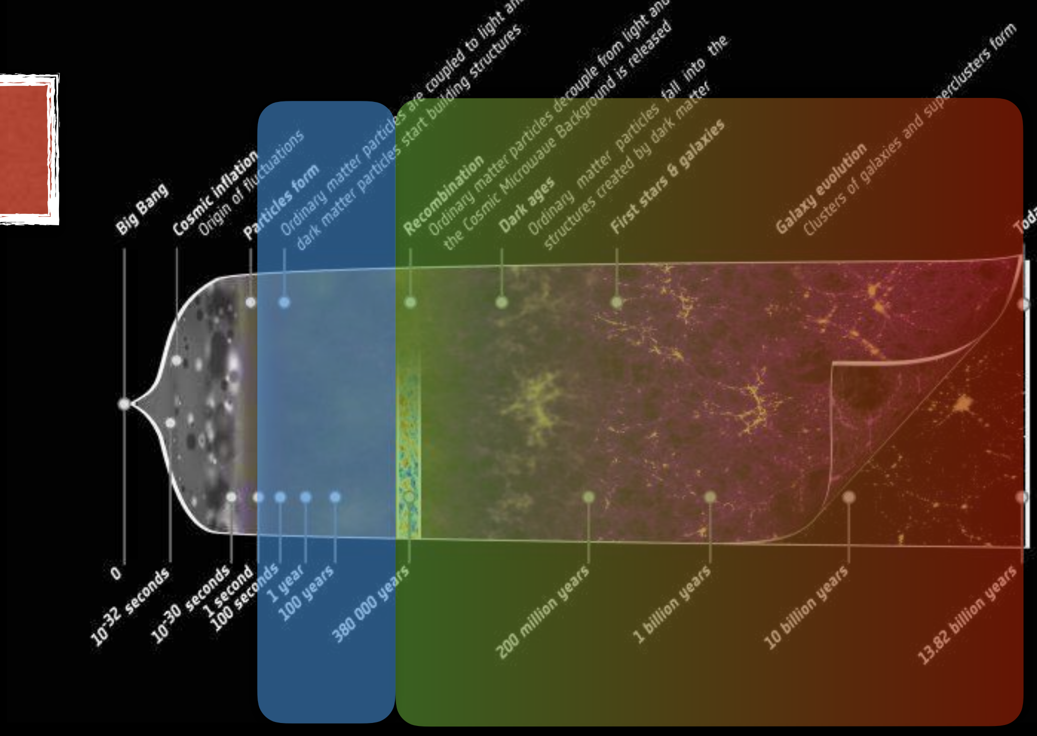
Table of contents



CMB anisotropies
380 000y until today

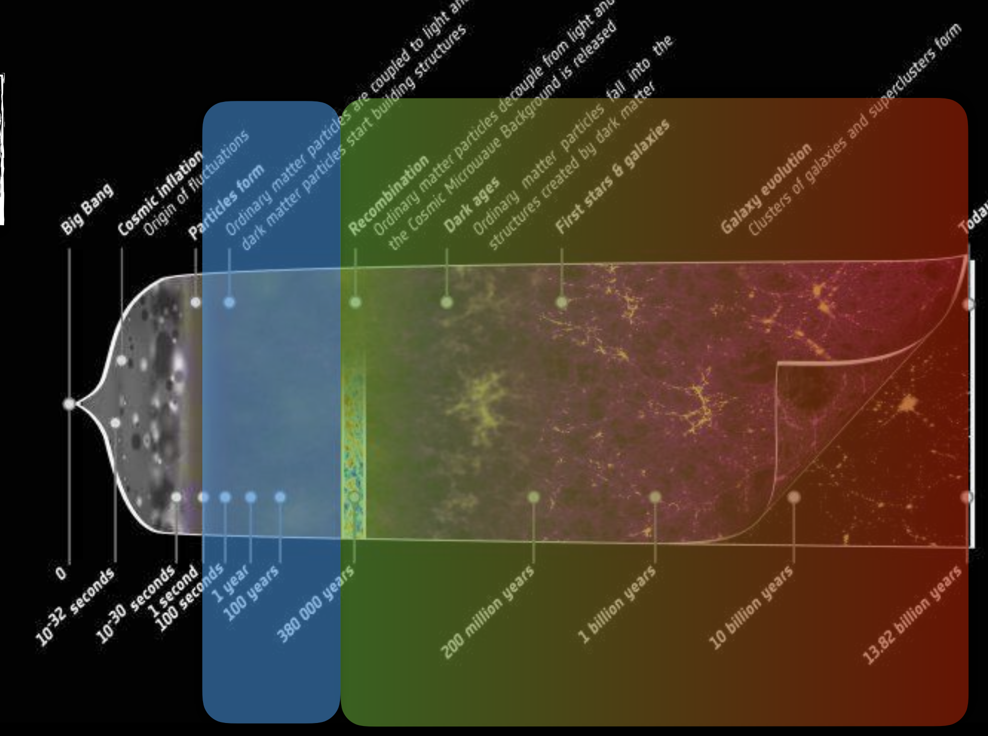
i) Decay into a Dark sector
ii) Electromagnetic decay

BBN and spectral distortions
100s to 380 000y

i) Non-thermal BBN
ii) Most important spectral distortions

21 cm signal
10^9 y (??) until today

Table of contents



CMB anisotropies
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→

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From perturbation to spectrum of temperature anisotropies

see e.g. textbook « The Cosmic Microwave Background » by R. Durrer; « Neutrino Cosmology » By Lesgourgues et al. or original papers Seljak & Zaldarriaga APJ. 469 (1996) 437-444; Kamionkowski et al. PRD55 (1997) 7368-7388

In the L.O.S formalism:
(Here, I only recall computation of Temp. anisotropies at 1st order, Newt. gauge)

$$C_\ell^{TT} = \int \frac{dk}{k}\mathcal{P}_{\mathcal{R}}(k)[\Theta_\ell(\tau_0,k)]^2$$

Temperature power spectrum

$$\Theta_\ell(\tau_0,k) = \int_\tau^{\tau_0} d\tau S_T(\tau,k) j_\ell(k(\tau_0-\tau))$$

Transfer function

$$S_T(k,\tau) \equiv \underbrace{g(\Theta_0+\psi)}_{\text{SW}} + \underbrace{(gk^{-2}\theta_B)'}_{\text{Doppler}} + \underbrace{e^{-\kappa}(\phi'+\psi')}_{\text{ISW}} + \text{polarisation}$$

Temperature source function

$$g(\tau) \equiv -\kappa' e^{-\kappa} \qquad \kappa(\tau) = \int_\tau^{\tau_0} d\tau \sigma_T a n_e x_e$$

Visibility function, optical depth

What could DM decay do to these functions?

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non e.m. decay : modify ϕ' and ψ'

I) Decay into a dark sector

Q: Why do we care ?

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« Because we can ! »

Interesting by itself to study gravitational impact of dark matter decay.

Modifications of Boltzmann equation : **Careful gauge choice**.

Study of **potential degeneracies** with other cosmological parameters.

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« Because we should ! »

Help to **constrain peculiar dark matter models.**
We here study models in which **a fraction of DM can decay into dark radiation** :
e.g. majoron, some SUSY scenarios ... or PBH (merger) as dark matter!

[arXiv:0812.4016], [arXiv:1407.2418], [arXiv:1501.07565], [arXiv:1603.05234]

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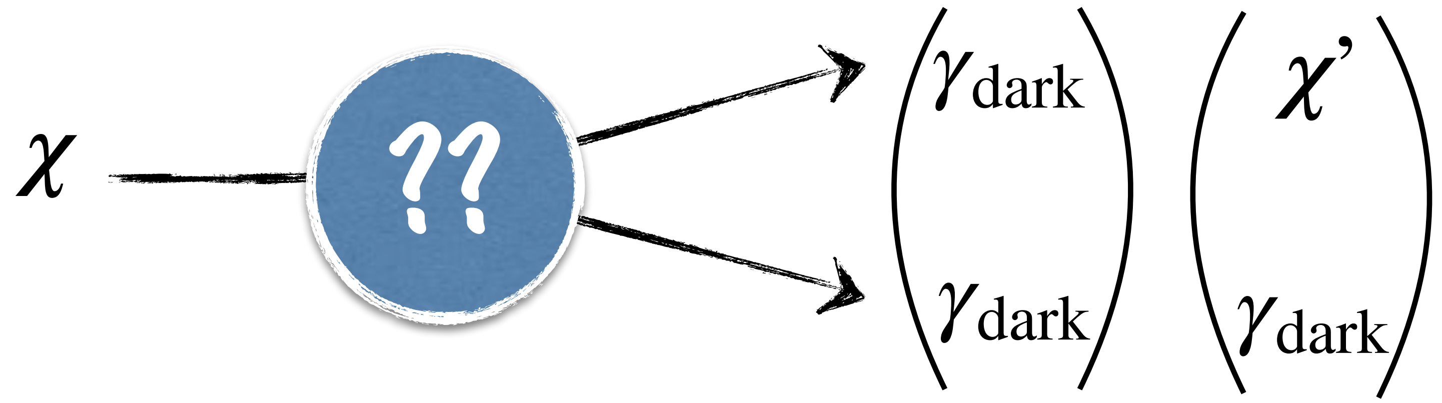
« Because we must ! »

Experiments show deviation from Planck-LCDM at low redshift for the quantities $(\sigma_8, \Omega_M, H_0)$ such models have been invoked to **solve these** (small) **discrepancies**.

[arXiv:1505.03644], [arXiv:1505.05511], [arXiv:1602.08121]

Welcome to DM decay 101

a **fraction** of the cdm can decay in such way



Background equations (e.g. from $T_{\mu\nu}$ covariant conservation).

$$\rho'_{\rm dcdm} = -3\frac{a'}{a}\rho_{\rm dcdm} - a\Gamma_{\rm dcdm}\rho_{\rm dcdm}$$

$$\rho'_{\rm dr} = -4\frac{a'}{a}\rho_{\rm dr} + a\Gamma_{\rm dcdm}\rho_{\rm dcdm}$$

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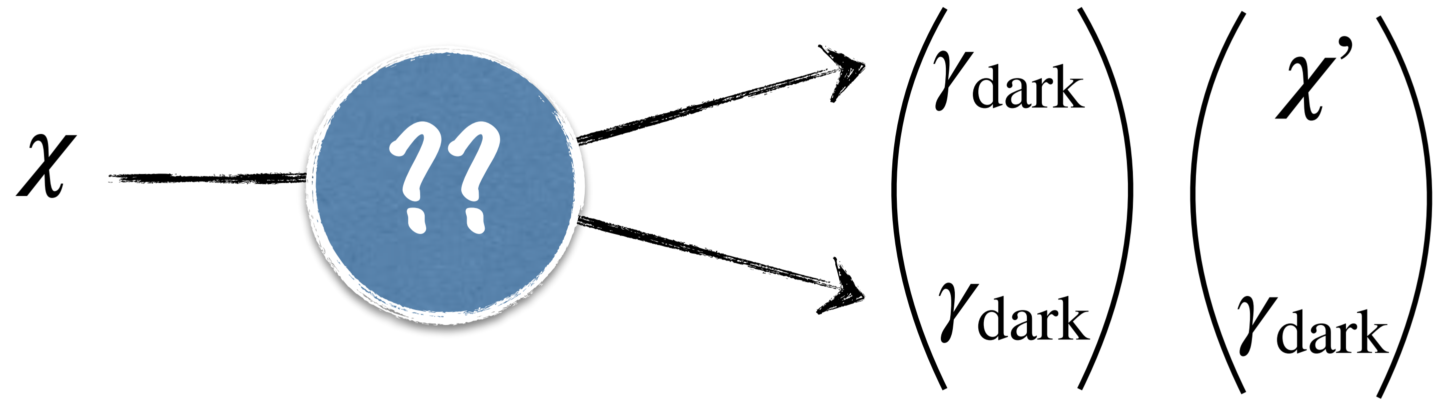

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Perturbation equations : beware of the gauge choice !!

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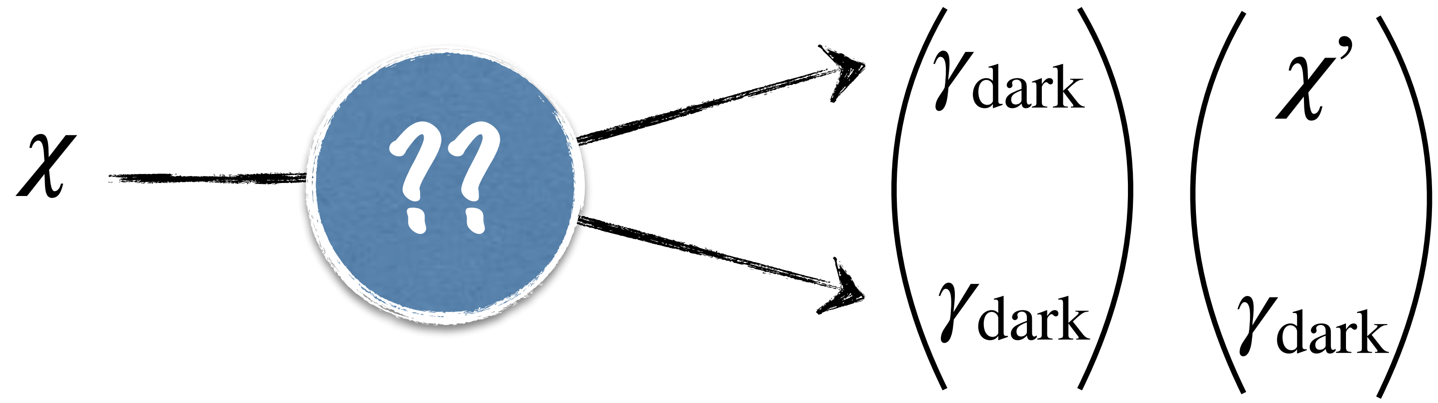

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Perturbation equations : beware of the gauge choice !!

The decay term takes a trivial form in the comoving-synchronous gauge in which the dark matter velocity divergence vanishes, but **only in this gauge** !

This point was missed in the only paper deriving bounds on the models we are dealing with. [astro-ph/0403164]

Perturbation equations in gauge invariant variables

Start with $\delta G^{\mu}_{\nu} = 8\pi G \delta T^{\mu}_{\nu}$ and $\mathcal{L}(\delta f) = \pm a\Gamma\delta f$

dark matter

$$\delta'_{dcdm} = -\theta_{dcdm} - \mathfrak{m}_{\rm cont} - a\Gamma\mathfrak{m}_{\psi}$$
$$\theta'_{dcdm} = -\mathcal{H}\theta_{dcdm} + k^2\mathfrak{m}_{\psi}$$

dark radiation

$$F'_{dr,0} = -kF_{dr,1} - \frac{4}{3}r_{dr}\mathfrak{m}_{\rm cont} + r'_{dr}(\delta_{dcdm} + \mathfrak{m}_{\psi}) \ ,$$
$$F'_{dr,1} = \frac{k}{3}F_{dr,0} - \frac{2k}{3}F_{dr,2} + \frac{4k}{3}r_{dr}\mathfrak{m}_{\psi} + \frac{r'_{dr}}{k}\theta_{dcdm} \ ,$$
$$F'_{dr,2} = \frac{2k}{5}F_{dr,1} - \frac{3k}{5}F_{dr,3} + \frac{8}{15}r_{dr}\mathfrak{m}_{\rm shear} \ ,$$
$$F'_{dr,l} = \frac{k}{2l+1}\left(lF_{dr,l-1} - (l+1)F_{dr,l+1}\right) \qquad l > 2.$$

	Synchr.	Newt.
$\mathfrak{m}_{\rm cont}$	$h'/2$	$-3\phi'$
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New terms in the DCDM models

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New terms in the DCDM models

+ Poisson and shear equation

$$k^2\phi + 3\frac{a'}{a}\left(\phi' + \frac{a'}{a}\psi\right) = -4\pi G\, a^2 \sum_i \delta\rho_i$$
$$k^2(\phi - \psi) = 12\pi G a^2 \sum_i (\bar{\rho}_i + \bar{p}_i)\sigma_i$$

	Synchr.	Newt.
$\mathfrak{m}_{\rm cont}$	$h'/2$	$-3\phi'$
$\mathfrak{m}_{\psi}$	0	ψ
$\mathfrak{m}_{\rm shear}$	$(h' + 6\eta')/2$	0

Impact on the CMB power spectra

using CLASS: http://class-code.net

$$(\theta_s, \omega_b, \omega_{\rm cdm}^{\rm ini}, z_{\rm reio}, A_s e^{-2\tau}, n_s)$$

set to best Planck 2015 TT,TE,EE+low-P

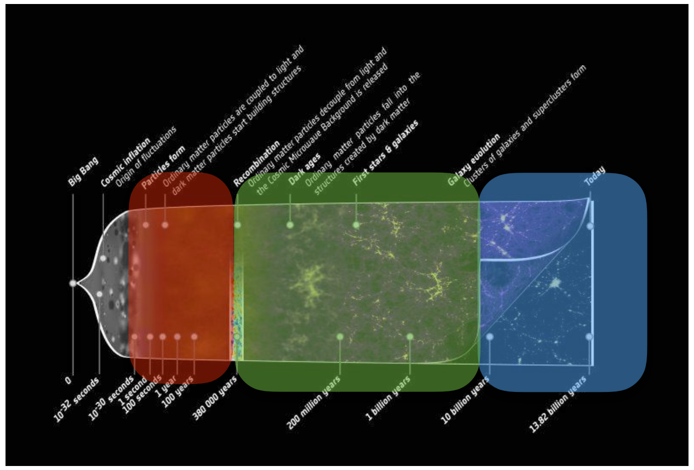
$$+\tau_{\rm dcdm}$$

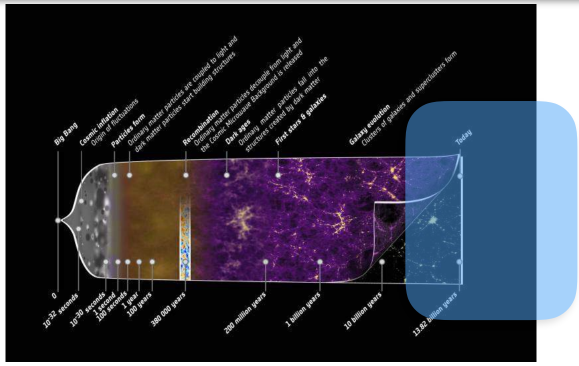
$$\omega_{\rm cdm}^{\rm ini} = \omega_{\rm cdm} + \omega_{\rm dcdm}^{\rm ini}$$

$$f_{\rm dcdm} = \frac{\omega_{\rm dcdm}^{\rm ini}}{\omega_{\rm cdm} + \omega_{\rm dcdm}^{\rm ini}}$$

Now consider 3 cases :

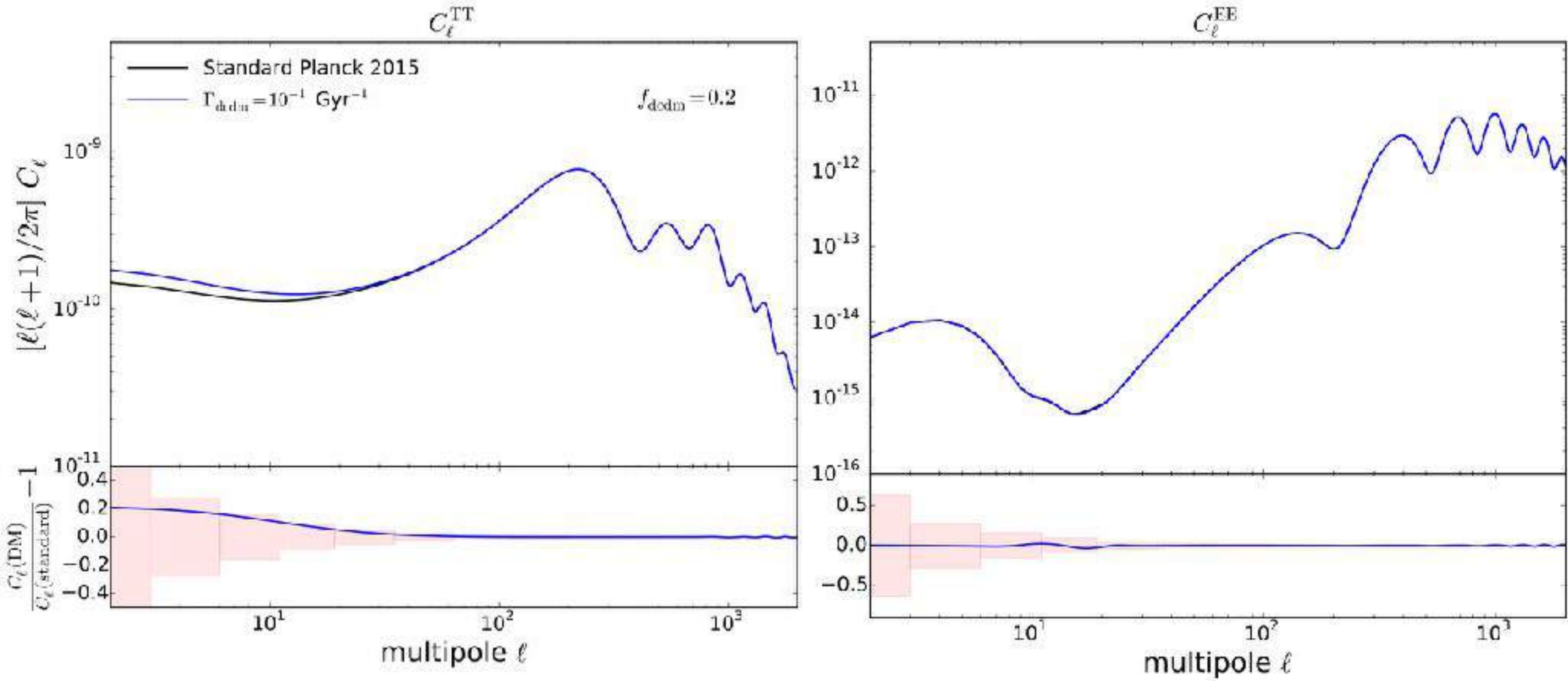
- decay **after** recombination / **after** matter-radiation eq.
- decay **before** recombination / **after** matter-radiation eq.
- decay **before** recombination/ **before** matter-radiation eq.





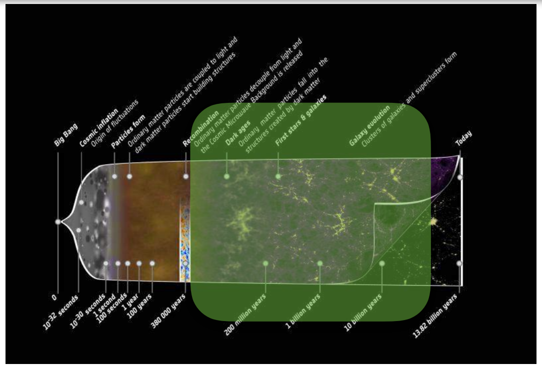
Impact on the CMB power spectra

Decay happens **well after recombination**

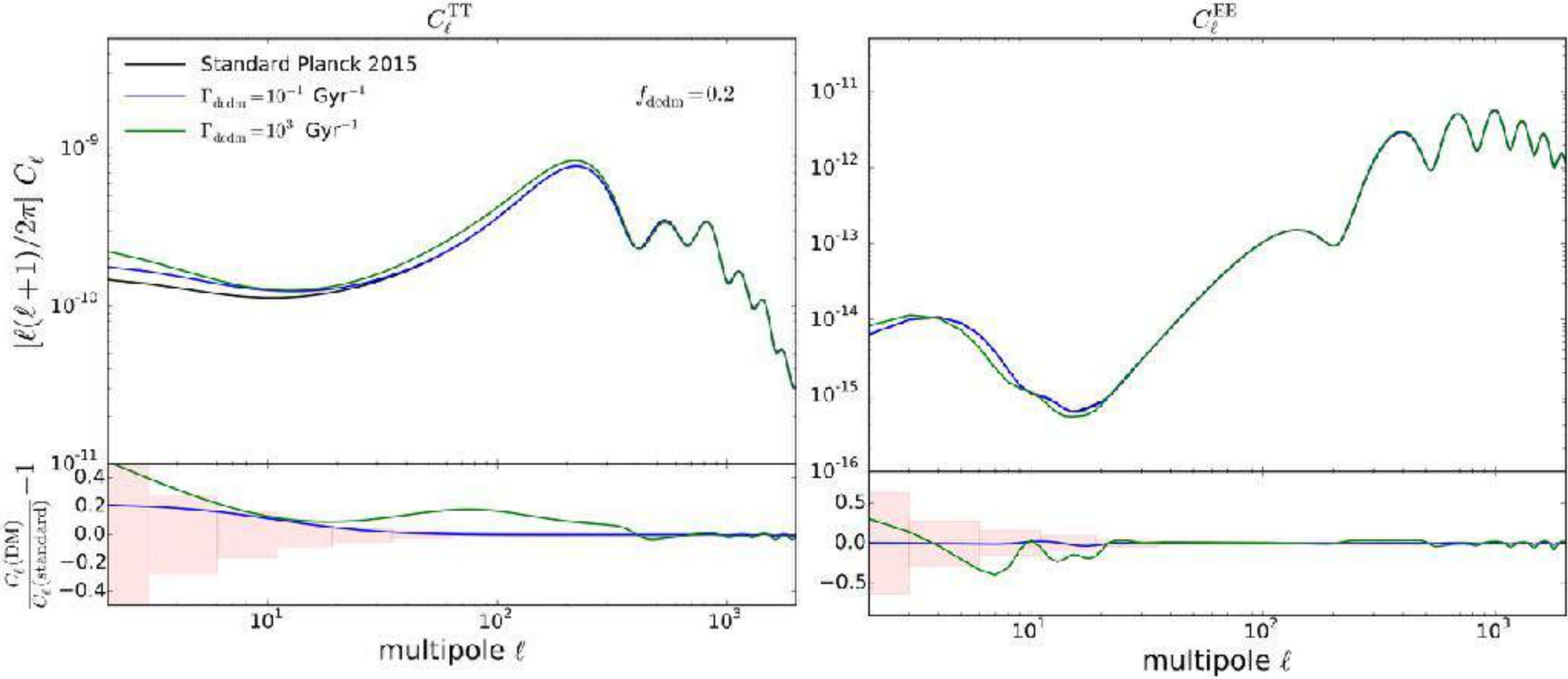


- $\theta_s \equiv r_s(\text{rec})/D_A(\text{rec})$: increase of Ω_Λ => well-known Late ISW effects in TT at low l
- modification of the background evolution => wiggles in EE

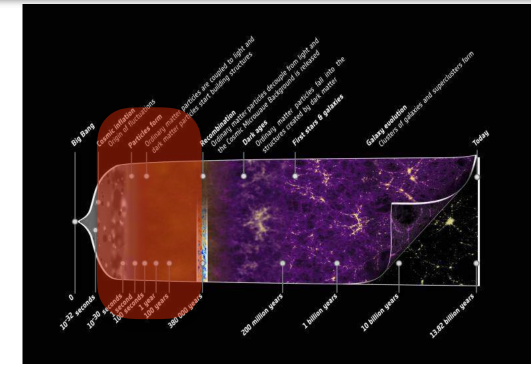
Impact on the CMB power spectra



Decay happens **around recombination**

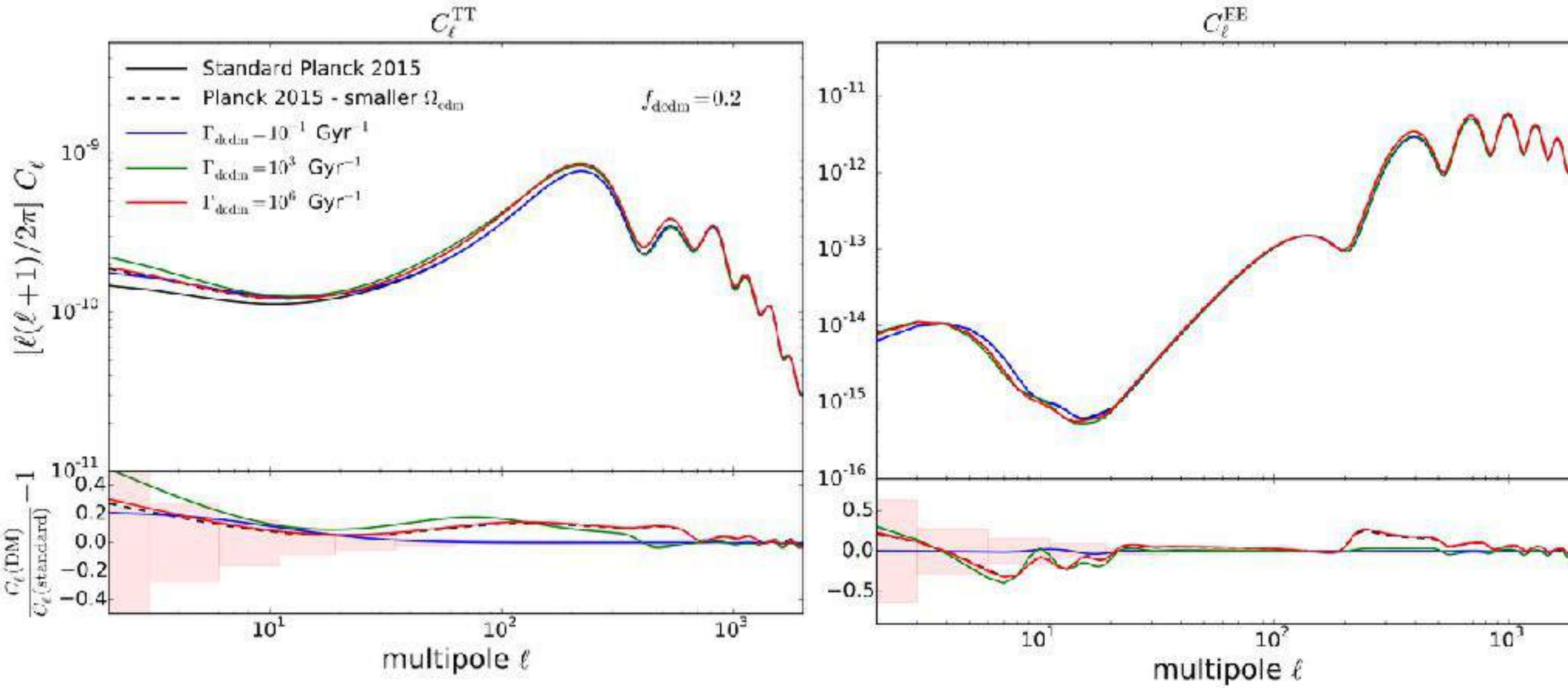


- l ∼100 : modification of EISW due to extra metric damping
- High-l : Wiggles due to lensing

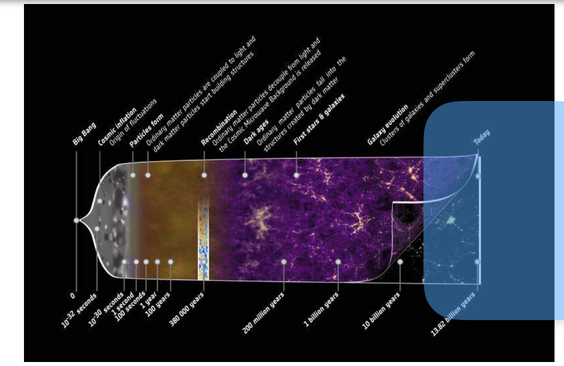


Impact on the CMB power spectra

Decay happens **before recombination**



- z_{eq} shifted towards later time ! Bigger EISW and SW terms (less friction)
- expected limiting case : less DM from the beginning

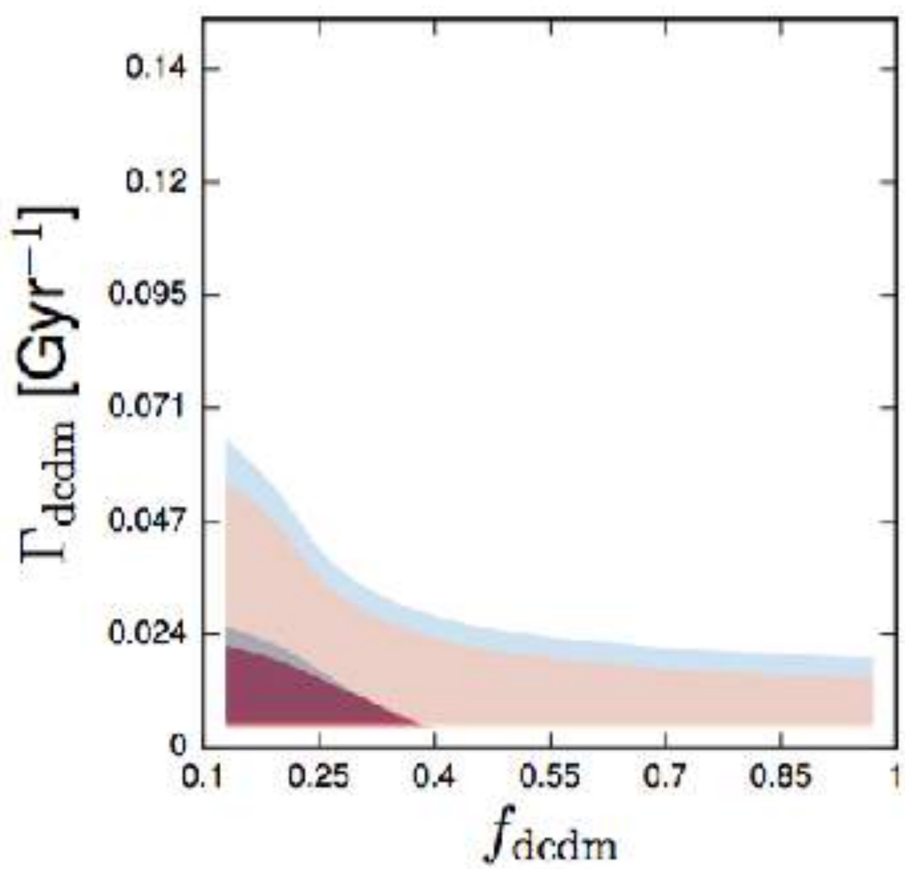


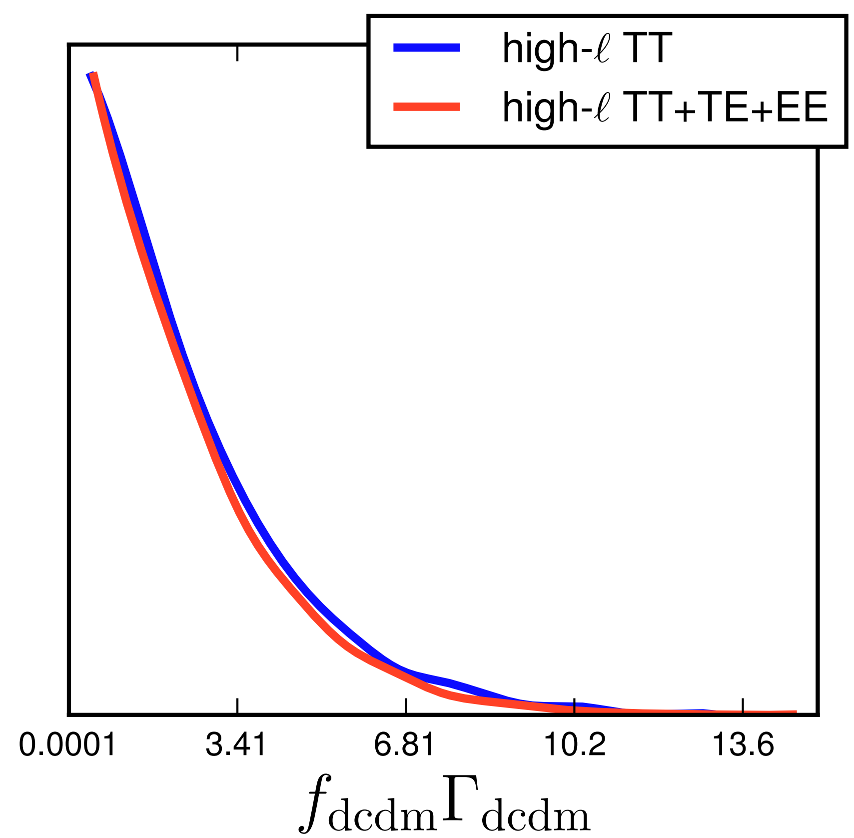
Constraints on $(\Gamma_{\rm dcdm}, f_{\rm dcdm})$ from the CMB only

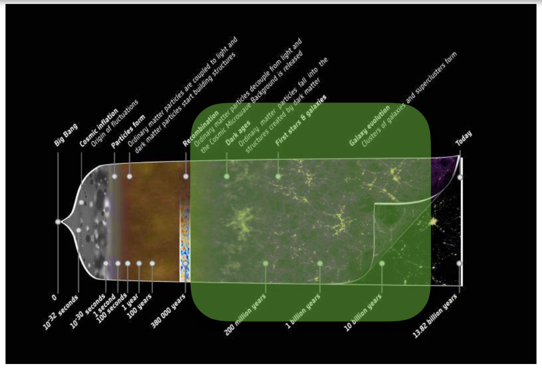
- long lifetime : what matters is (roughly) $f_{\rm dcdm} \cdot \Gamma_{\rm dcdm}$

$$\Omega_{\rm cdm,tot} \sim (1 - f_{\rm dcdm}\Gamma_{\rm dcdm}t)\Omega_{\rm cdm,tot} + \mathcal{O}((\Gamma_{\rm dcdm}t)^2)$$

$f_{\rm dcdm} \cdot \Gamma_{\rm dcdm} < 6.3 \times 10^{-3}\ {\rm Gyr}^{-1} \Leftrightarrow \tau \gtrsim f_{\rm dcdm} \times 160$ Gyr
(95%CL, Planck lowl, high-l TT+TE+EE, lensing)



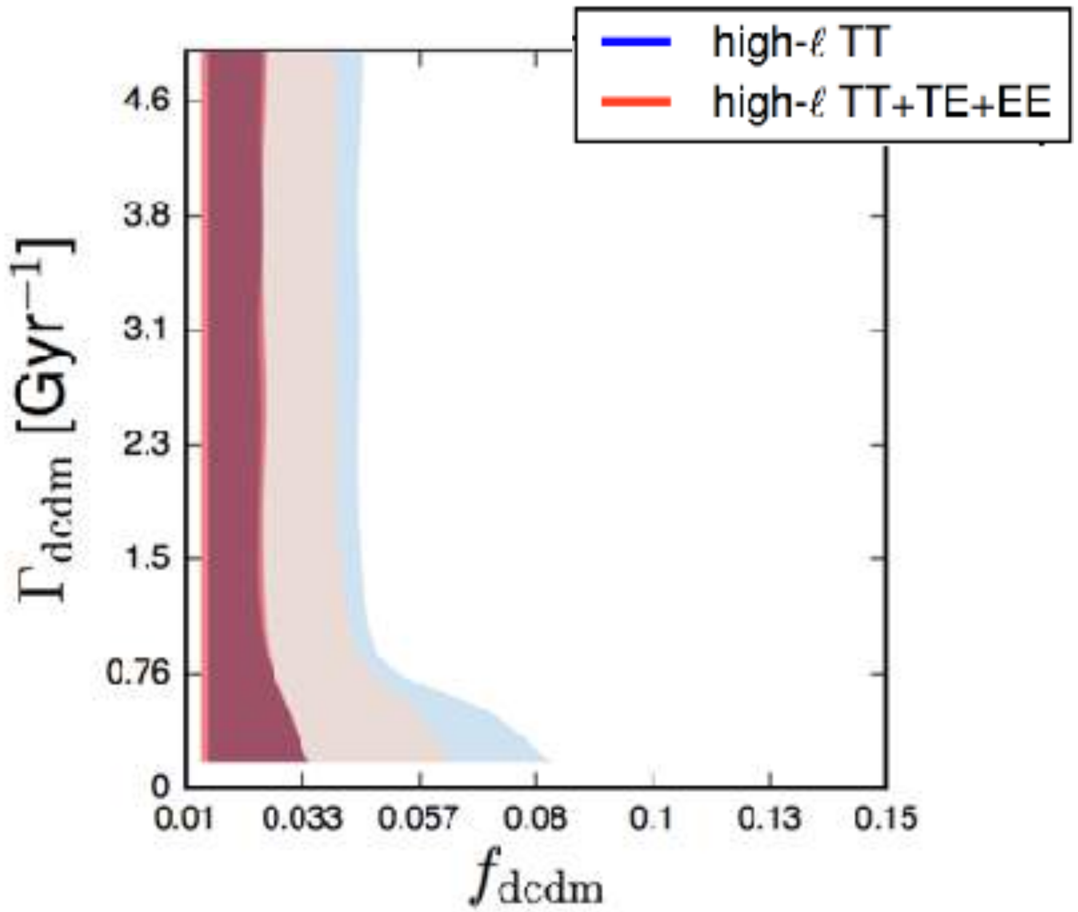




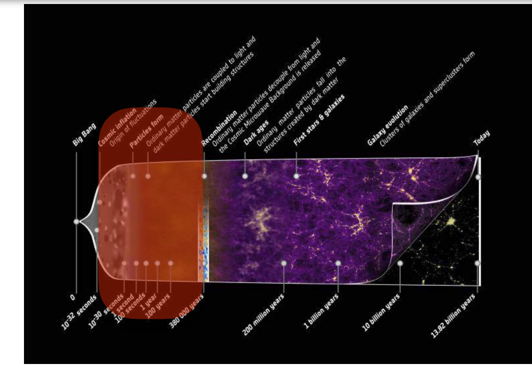
Constraints on $(\Gamma_{\rm dcdm}, f_{\rm dcdm})$ from the CMB only

- intermediate lifetime : as long as $\Gamma > 3H_0$ **all the DM has decayed**.

$f_{\rm dcdm} < 0.038$
(95%CL, Planck lowl, high-l TT+TE+EE, lensing)



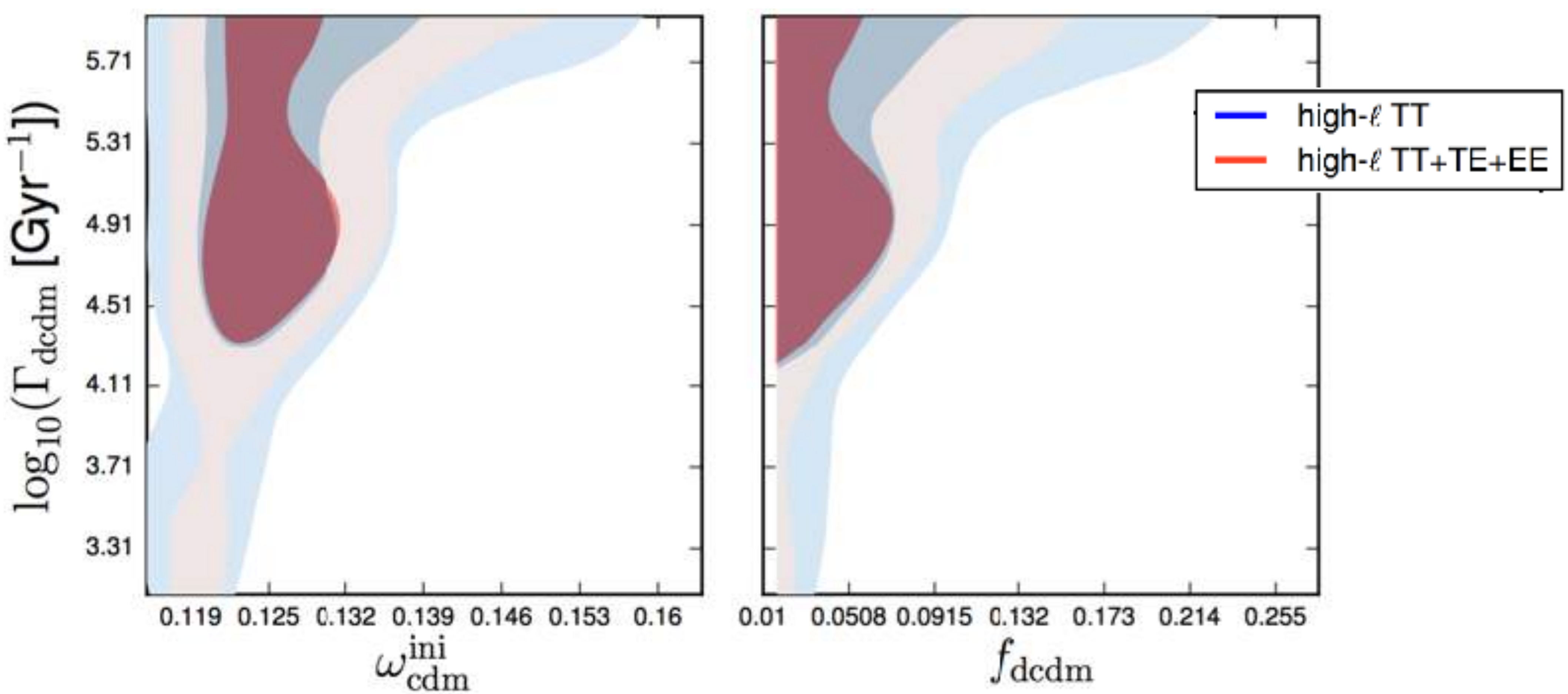
This is the fraction of DM that can « disappear » between matter-radiation equality and today.

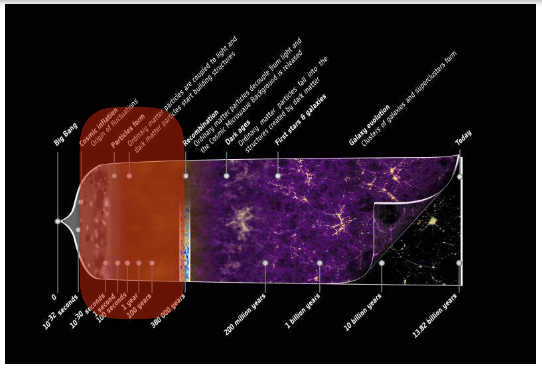


Constraints on $(\Gamma_{\rm dcdm}, f_{\rm dcdm})$ from the CMB only

- Short lifetime : the bound relaxes as $\omega_{\rm ini}^{\rm cdm}$ increases !

Decay happens **before recombination** and eventually before matter/radiation equality.





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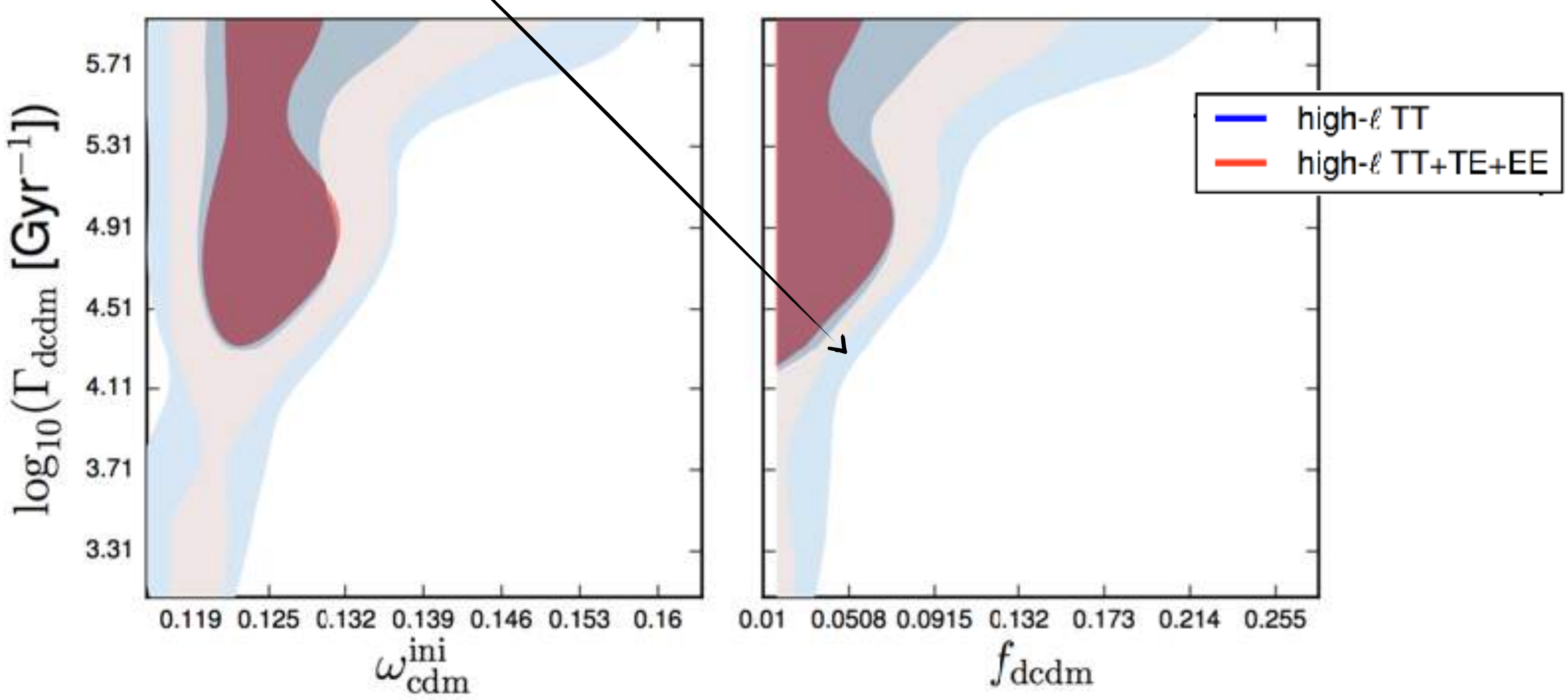
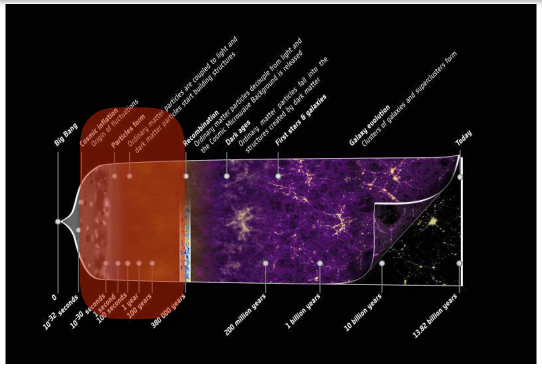
1[st] kink : Decay starts before z_{eq}





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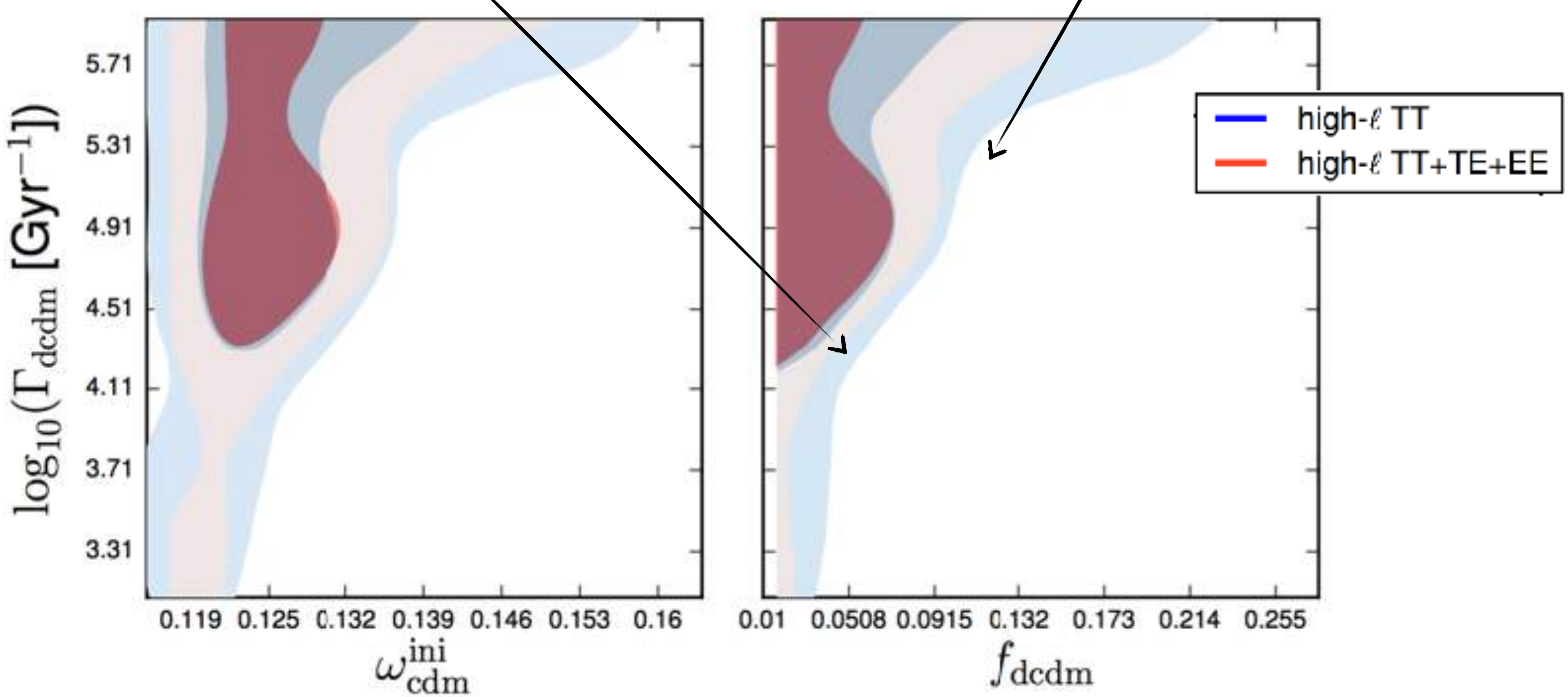
1 st kink : Decay starts before z_{eq}

2nd kink : Decay over by z_{eq}



Intermediate summary

Topic discussed today

- We have studied consequences of DM decays on a **much broader parameter space** than previously.
- We have derived the **strongest « gravitational » bounds to date** on the decaying fraction of DM as a function of the lifetime (and basically the only ones) : these bounds **always apply** (almost...) !

Intermediate summary

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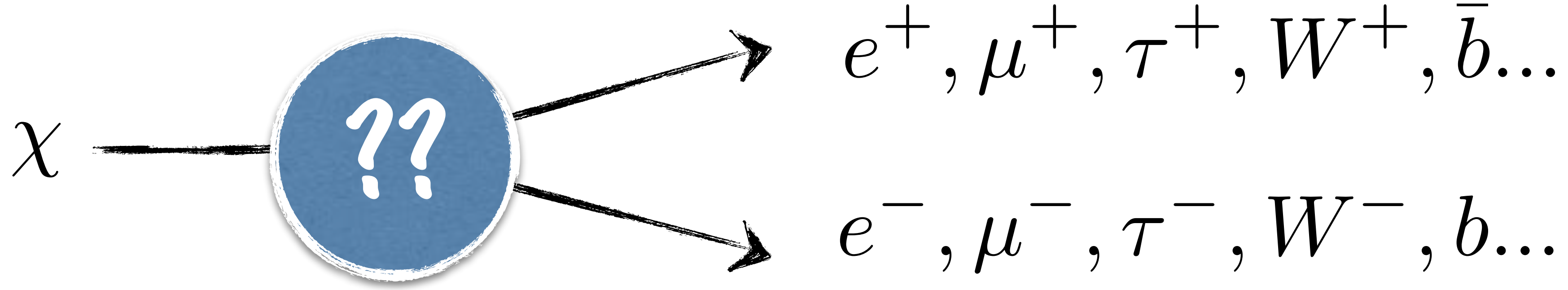
- We have derived the **strongest « gravitational » bounds to date** on the decaying fraction of DM as a function of the lifetime (and basically the only ones) : these bounds **always apply** (almost...) !

Not discussed but included in publication

- We have started to study **impact on non-linear matter power spectrum** : **Disagreement** between **halo fit** and the only available **N-body simulation** would need to be studied further.
- We **have not found any significant improvement** over LCDM to solve the $(\sigma_8, \Omega_M, H_0)$ discrepancies.
- Study of **potential degeneracy with neutrino mass** : It is there only for low neutrino mass (<0.6 eV) in the TT spectra, any information from **LSS breaks it**.

II) Electromagnetic decay



Q: What happens to the decay products ?

II) Electromagnetic decay

$$e^+, \mu^+, \tau^+, W^+, \bar{b}...$$

$$e^-, \mu^-, \tau^-, W^-, b...$$

Q: What happens to the decay products ?

One Caveat : We restrict ourself to lifetime > 1000 s.
=> We can neglect hadronic products!
Only BBN constraints (for very short lifetime) are sensitive.

e.g. Kawasaki et al.
PRD D71 (2005) 083502
Jedamzik
PRD D74 (2006) 103509

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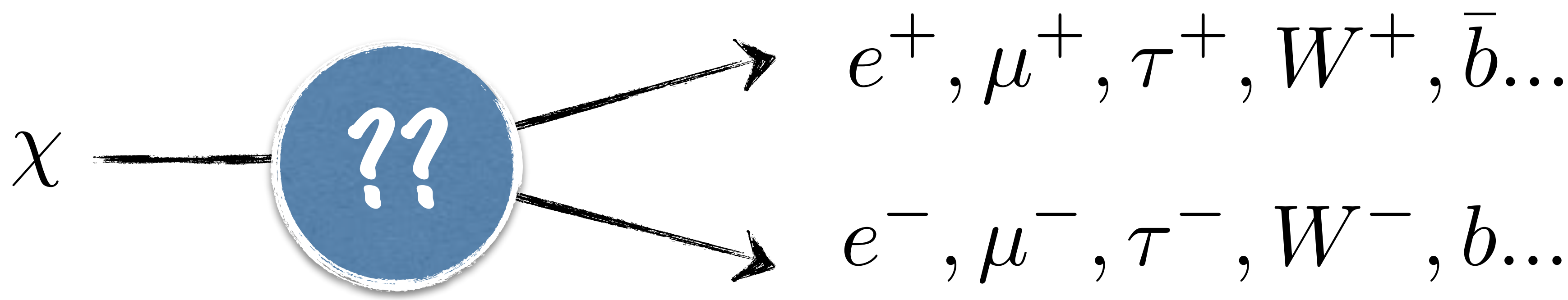

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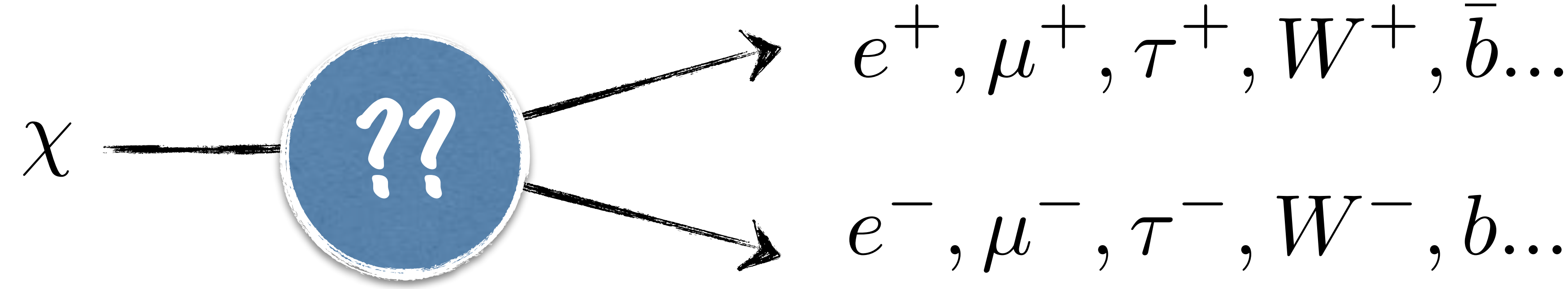

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$$e\gamma_{\rm CMB} \rightarrow e\gamma \qquad \gamma\gamma_{\rm CMB} \rightarrow \gamma\gamma \qquad \gamma\gamma_{\rm CMB} \rightarrow e^+e^-$$

Spectral distortions

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$$e\gamma_{\rm CMB} \to e\gamma \qquad \gamma\gamma_{\rm CMB} \to \gamma\gamma \qquad \gamma\gamma_{\rm CMB} \to e^+e^-$$

- They ionize, excite or heat the IGM… and break atoms !

Spectral distortions

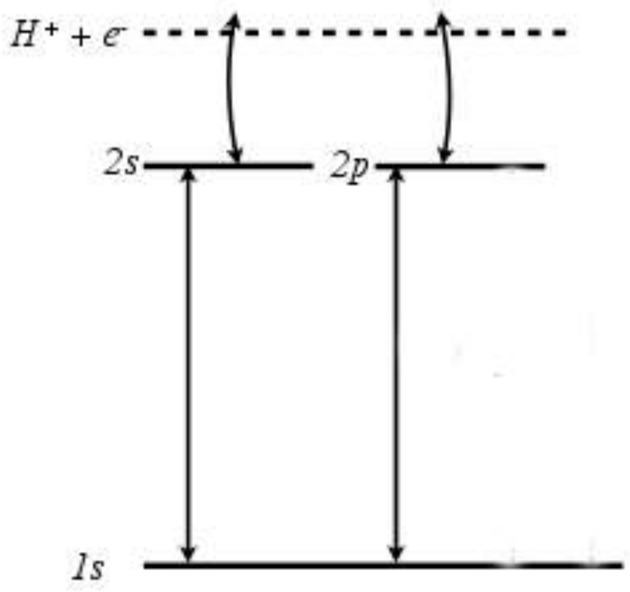
BBN, CMB anisotropies

Evolution equations for x_e : the free electron fraction and T_m : the matter temperature

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

$$\frac{dT_{\rm M}}{dz} = \frac{1}{1+z}\left[2T_{\rm M} + \gamma(T_{\rm M} - T_{\rm CMB})\right]$$

VP, Serpico & Lesgourgues ArXiv:1610.10051 and references therein



« The 3-level atom » by Peebles

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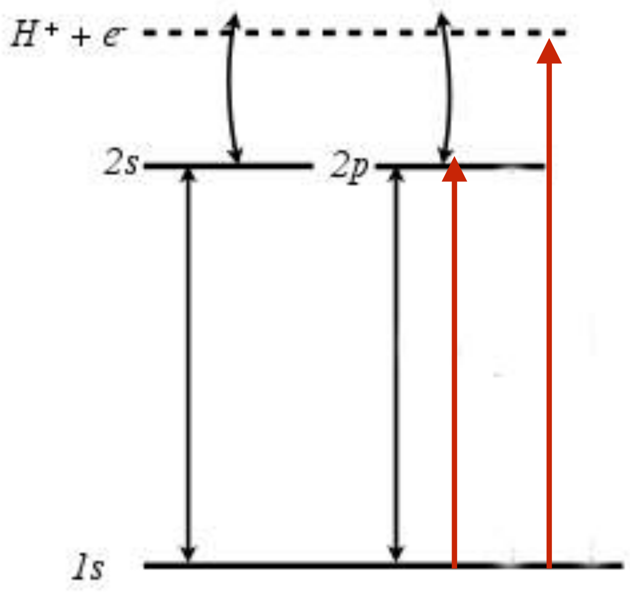

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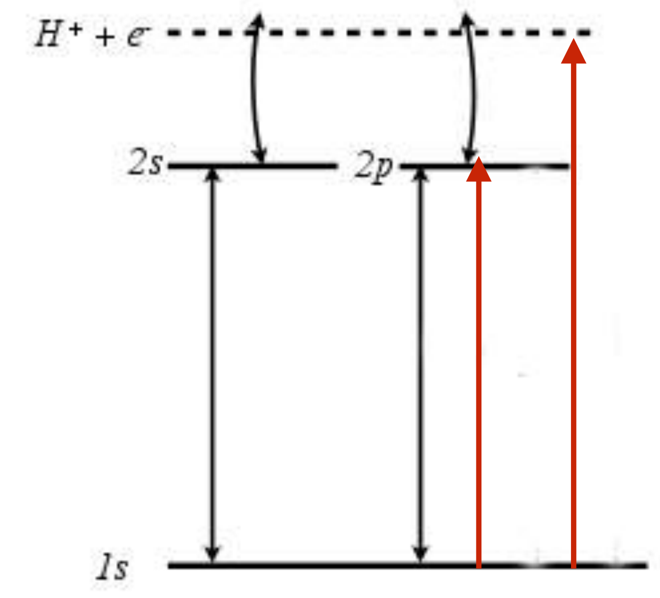

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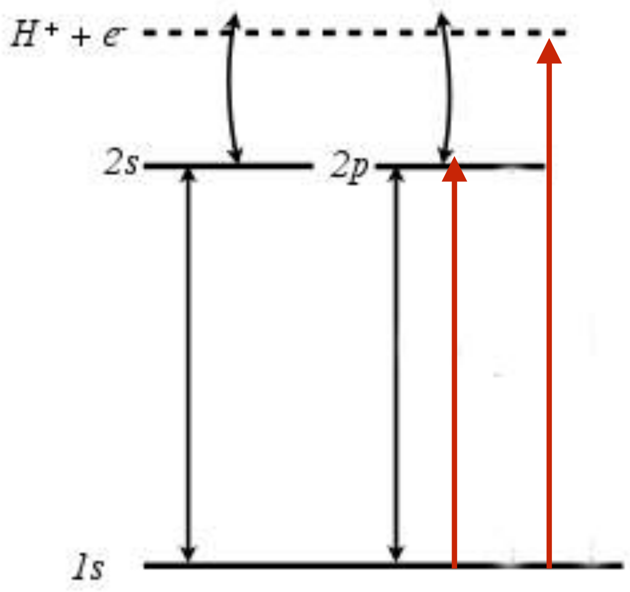

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« The 3-level atom » by Peebles

Key quantity $dE/dVdt|_{dep,c}$:

- The energy deposition rate by the decay per unit volume in each channel: ionization, excitation, heating.
- Depending on z and x_e, the plasma can be very inefficient at absorbing energy !

$$\left.\frac{dE}{dV\,dt}\right|_{\rm inj}(z) = (1+z)^3 f_{\rm dcdm}\rho_{\rm dm}c^2 \times \Delta_{\rm em} \times \frac{e^{-t/\tau}}{\tau}$$

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number density
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Typical parametrization through the $f_c(z,x_e)$ functions :

see e.g. Slatyer et al. PRD80 (2009) 043526 updated in PRD93 (2016) no.2, 023521

$$\left.\frac{dE}{dV\,dt}\right|_{\rm dep,c}(z) = f_c(z,x_e)\left.\frac{dE}{dV\,dt}\right|_{\rm inj}(z)$$

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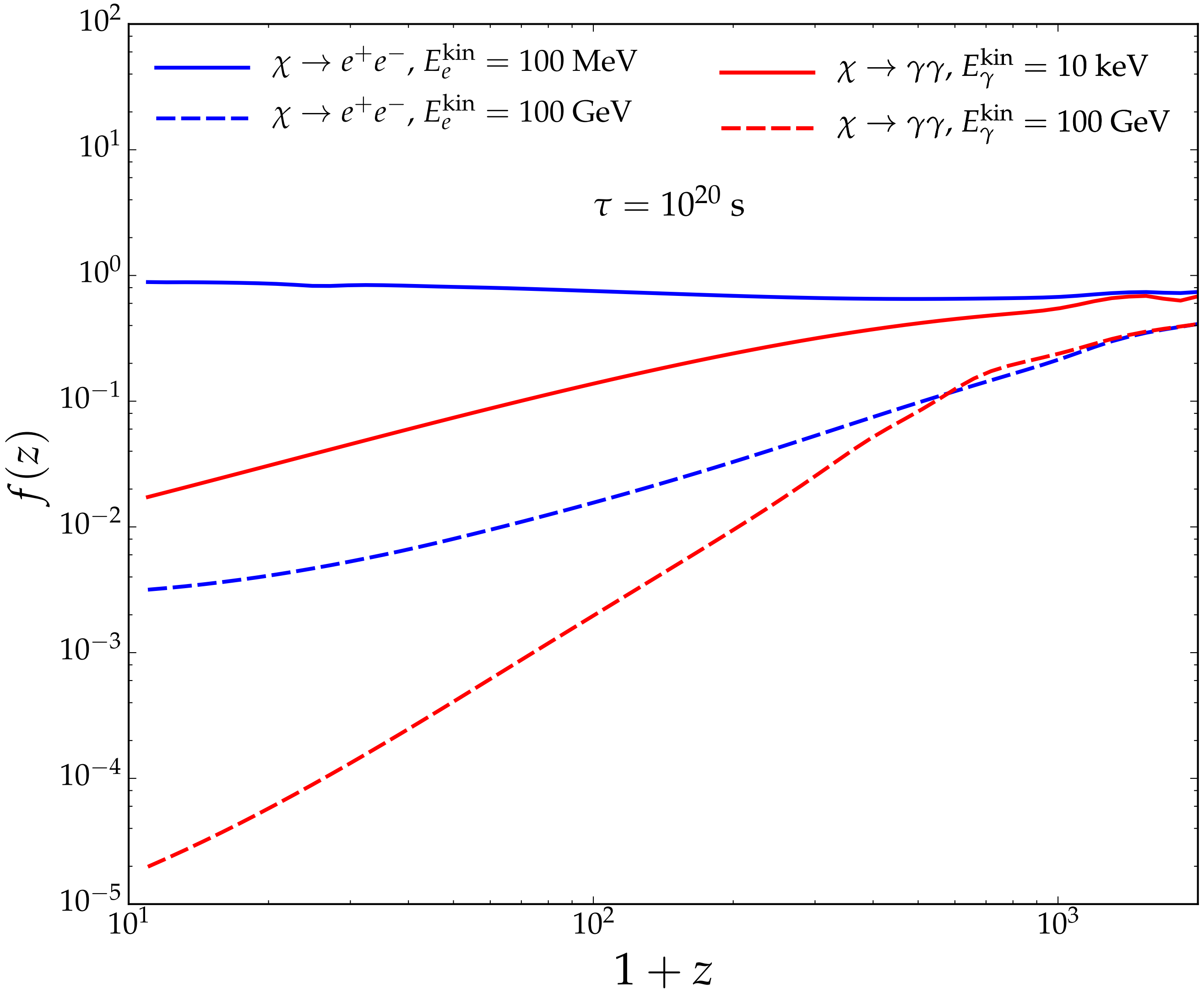
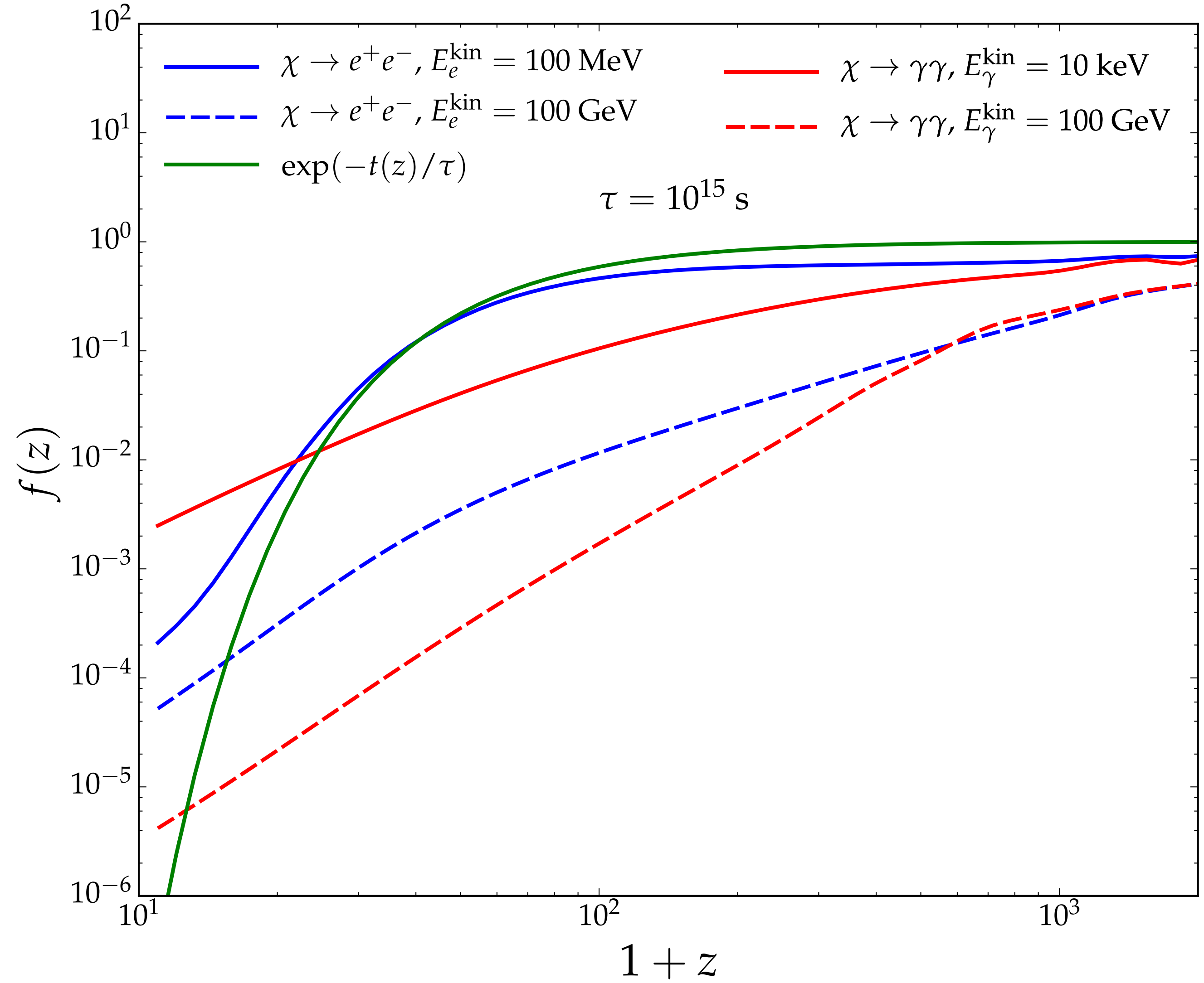
$f_c(z, x_e)$ is the key quantity, it encodes:

- What fraction of the injected energy is left to interact with the IGM
- How this is energy is distributed among each channel :'heat', 'ionization', 'excitation'

In practice, it depends on details of the particle physics and injection history.

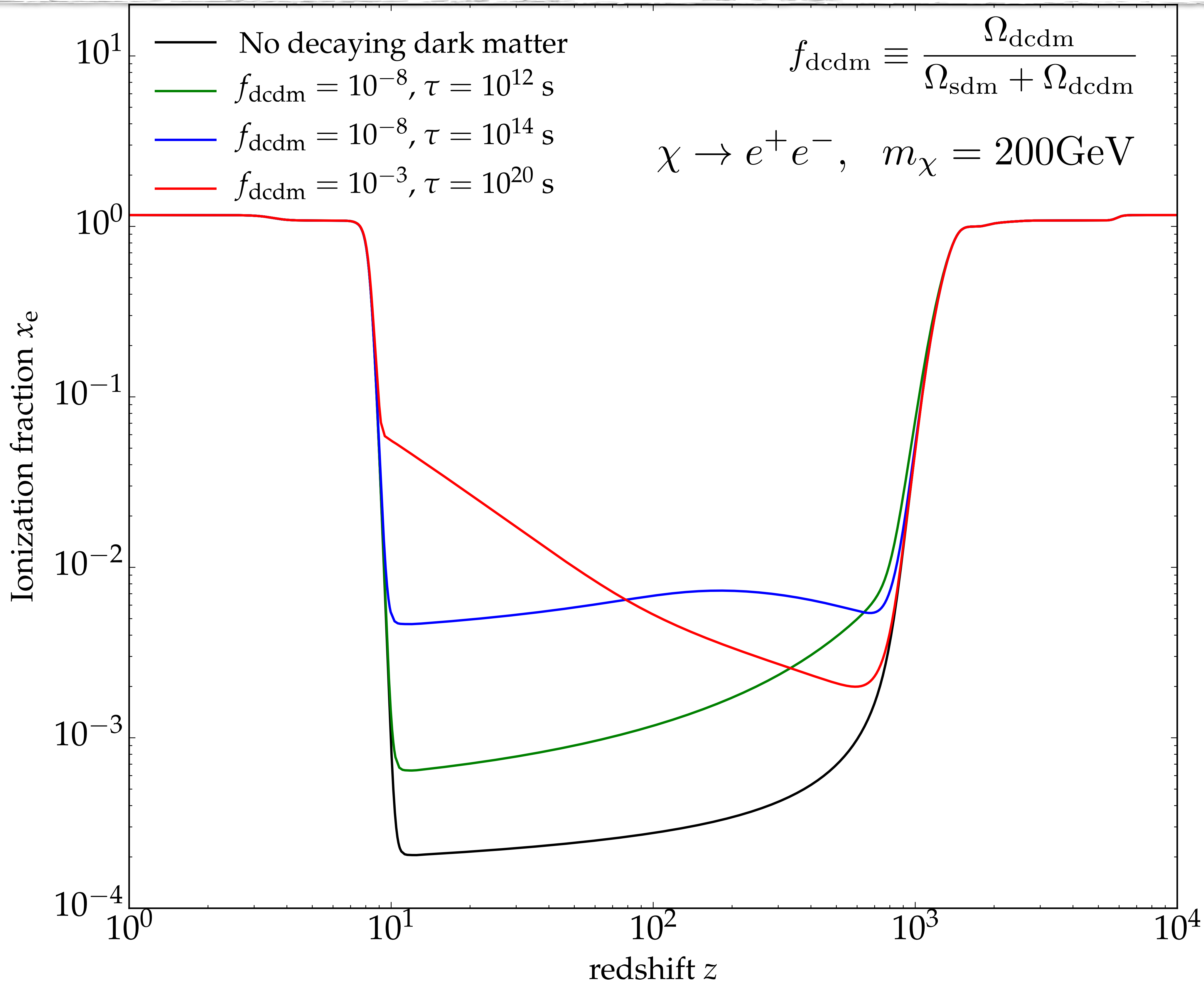
examples of energy deposition efficiency function





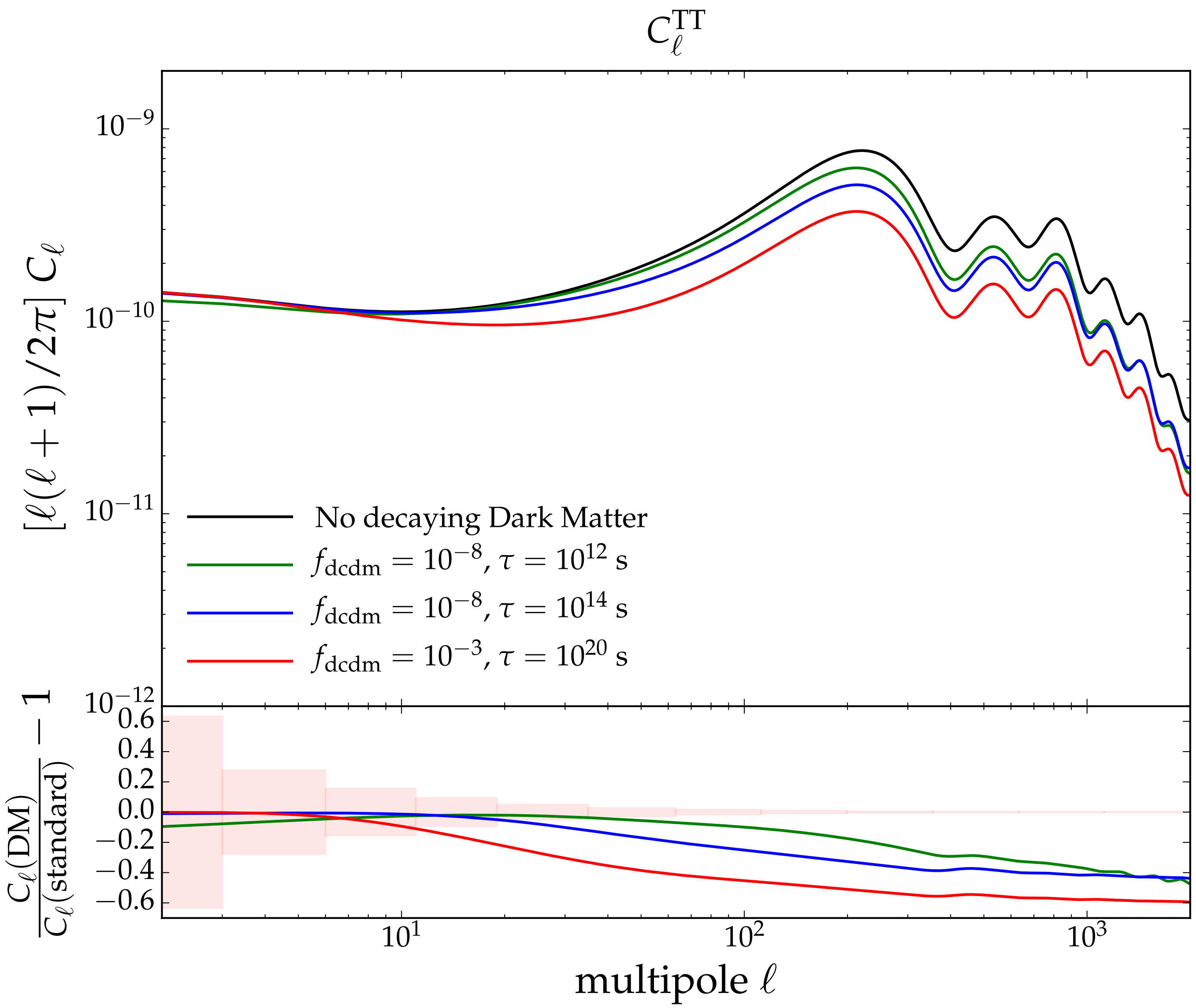
- Here, the deposition efficiency is summed over all channels.
- It typically depends on the lifetime, particle energy and nature!

x_e carries information on the time / amount of energy injection !

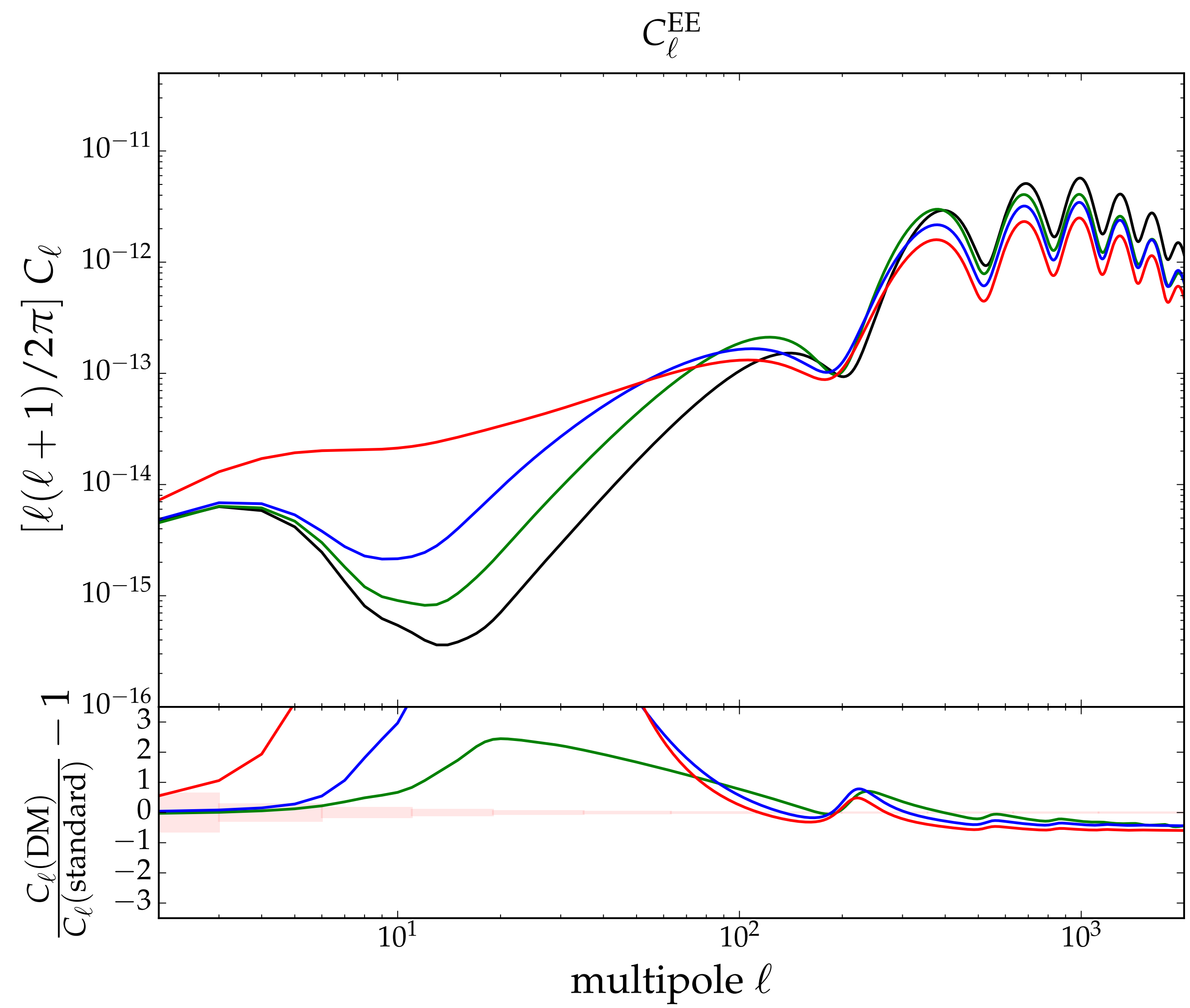


Many lifetime dependent effects on the CMB power spectra !

temperature anisotropies



polarization anisotropies



- Long lifetime : looks like early reionization, i.e. increase of τ_{reio} leads to step-like suppression above l = 10 and bigger reionization bump.

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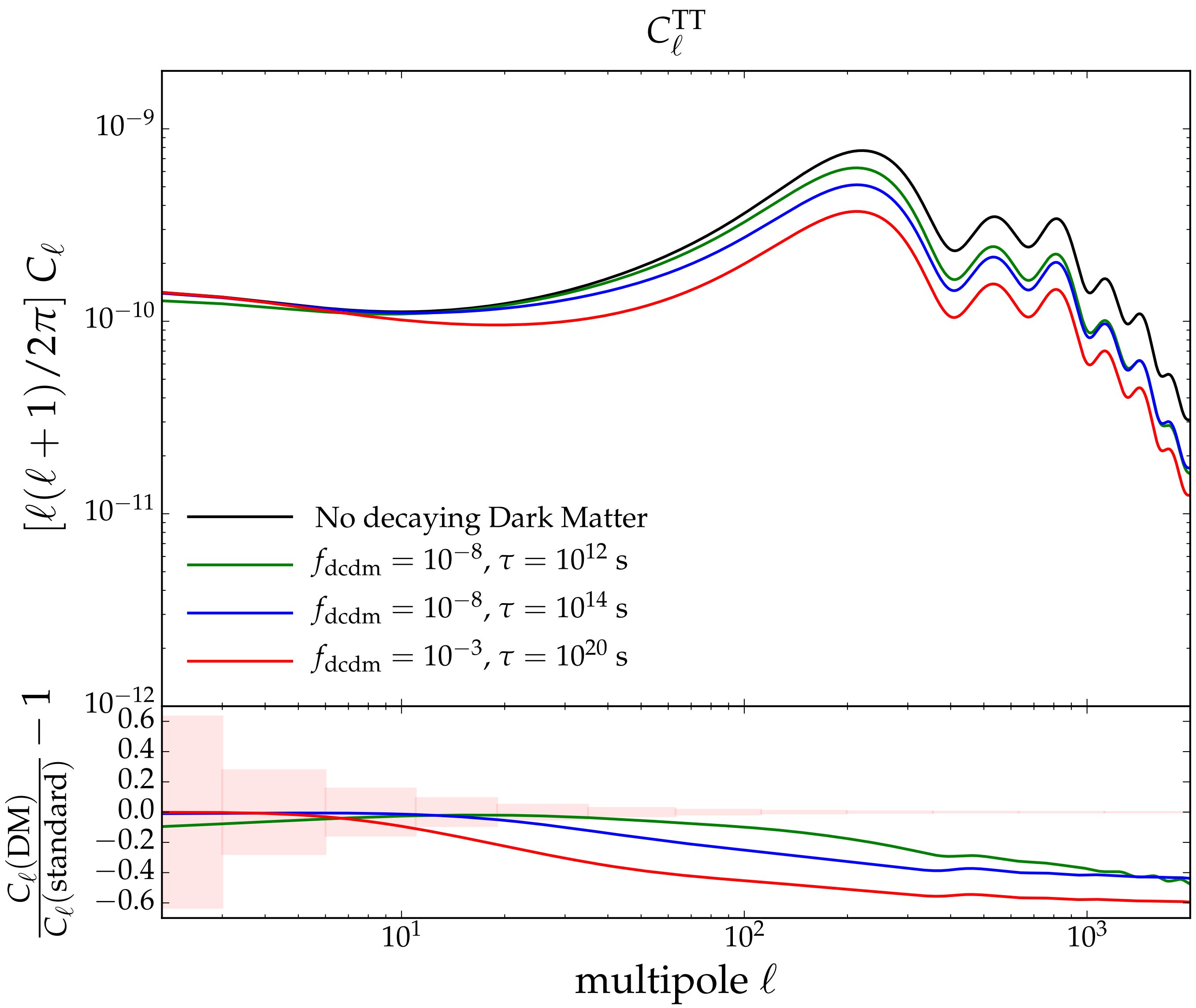

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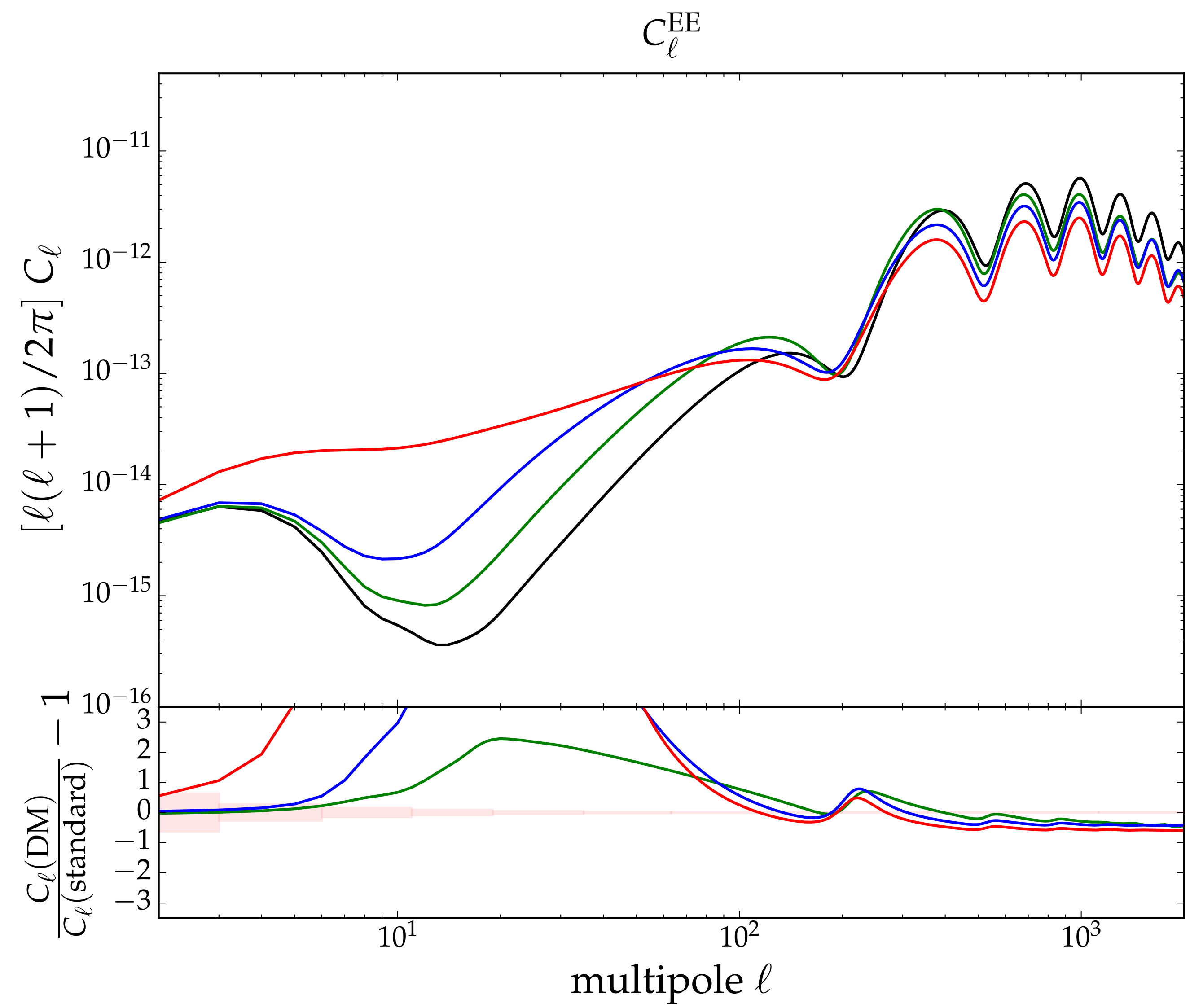
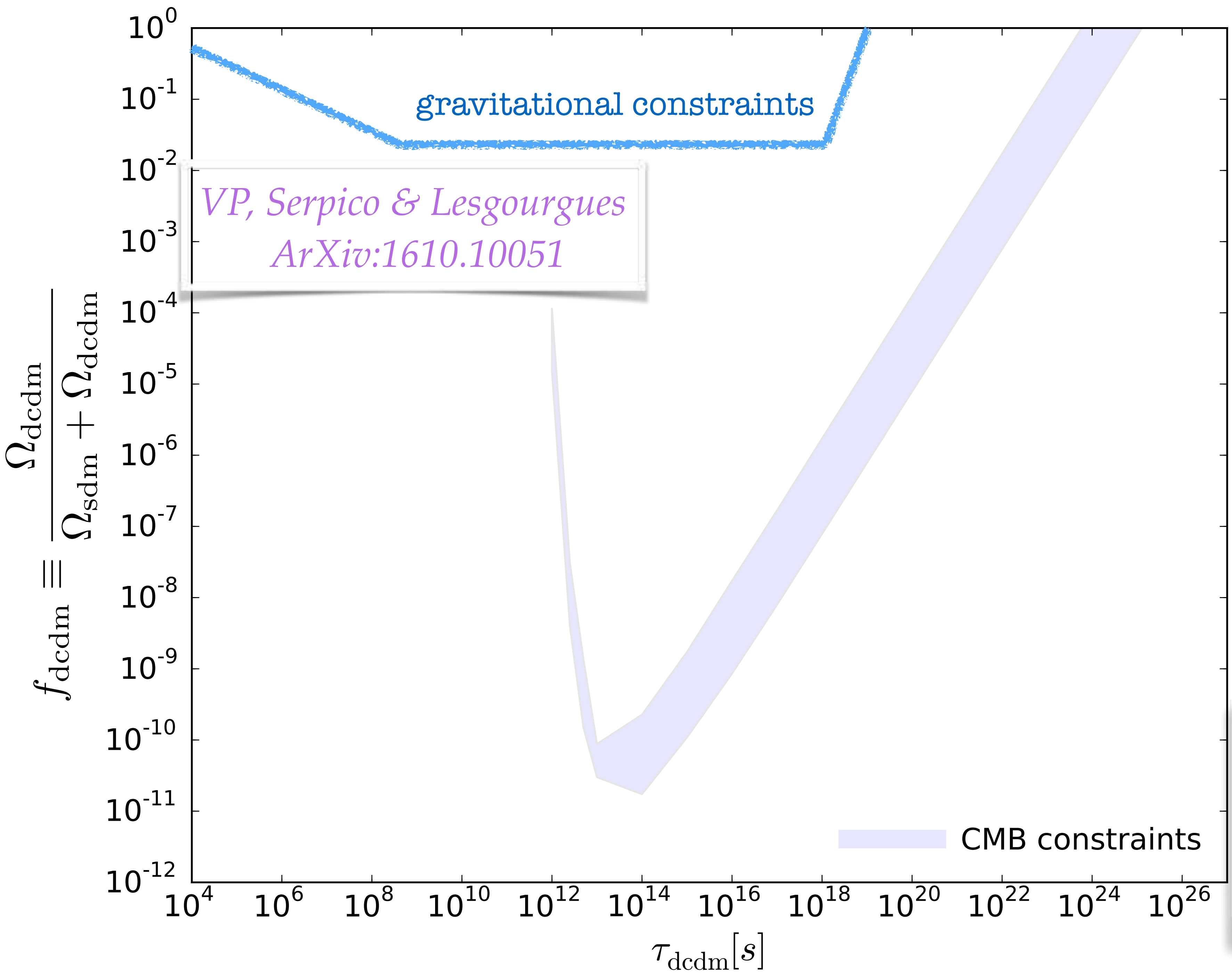


- Long lifetime : looks like early reionization, i.e. increase of τ_{reio} leads to step-like suppression above l = 10 and bigger reionization bump.
- Short lifetime: can have very peculiar behaviour! Larger damping tail, shifted/broaden reionization bump and suppress LISW.

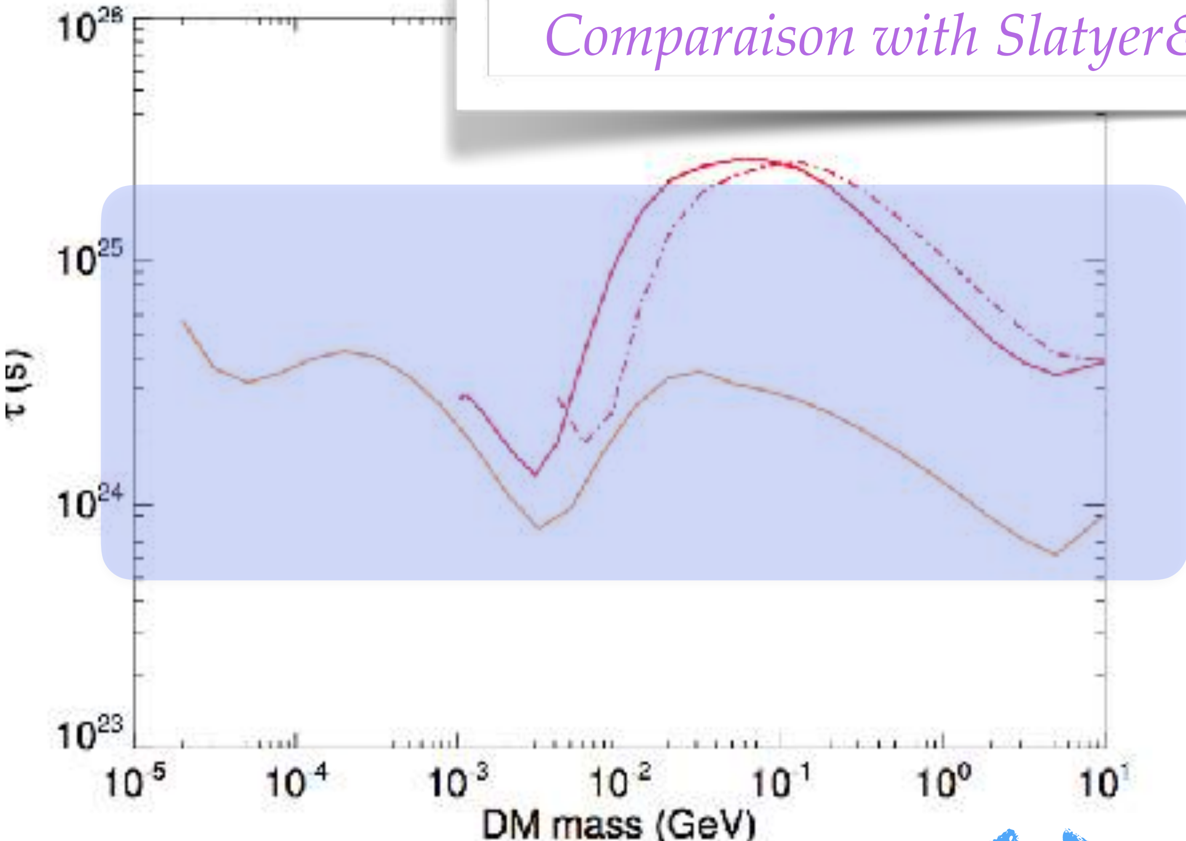
CMB anisotropies very powerful at constraining τ = [10^{12},10^{26}]s

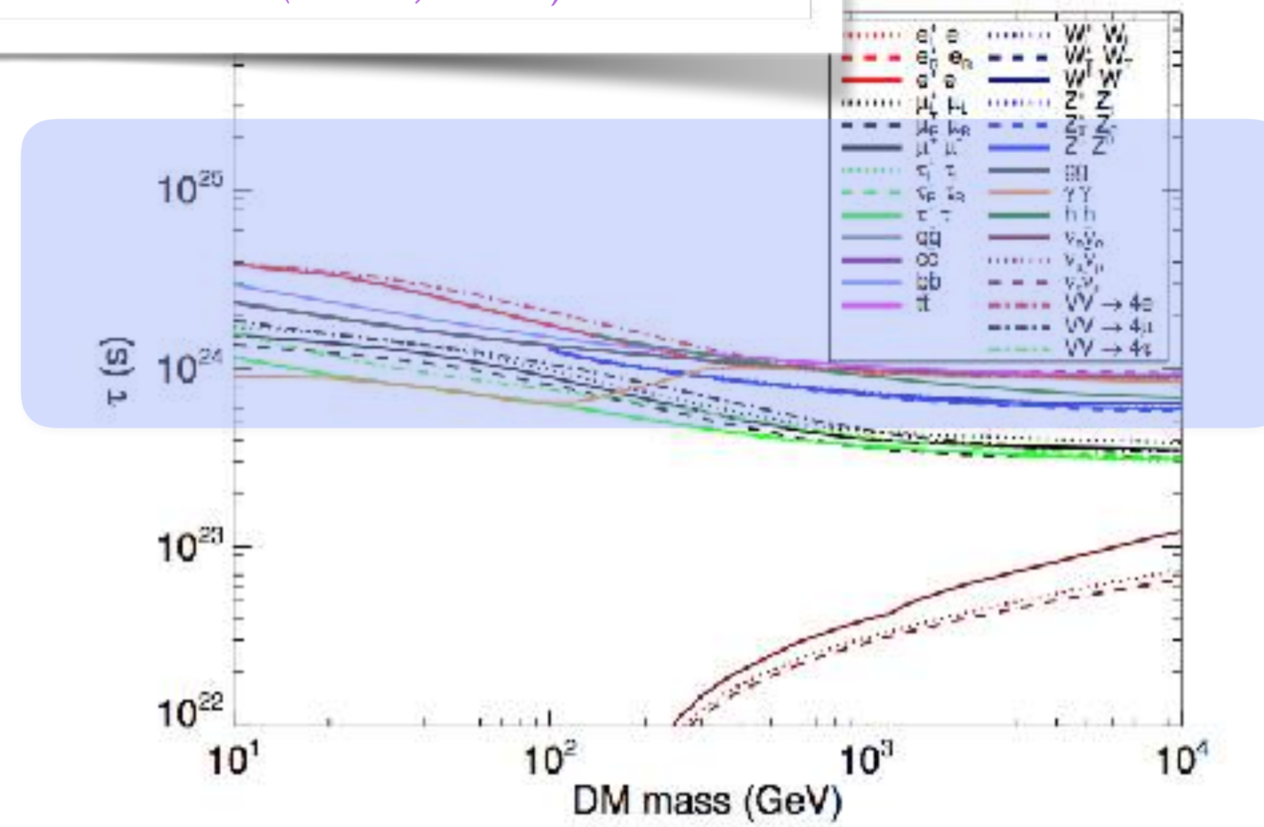


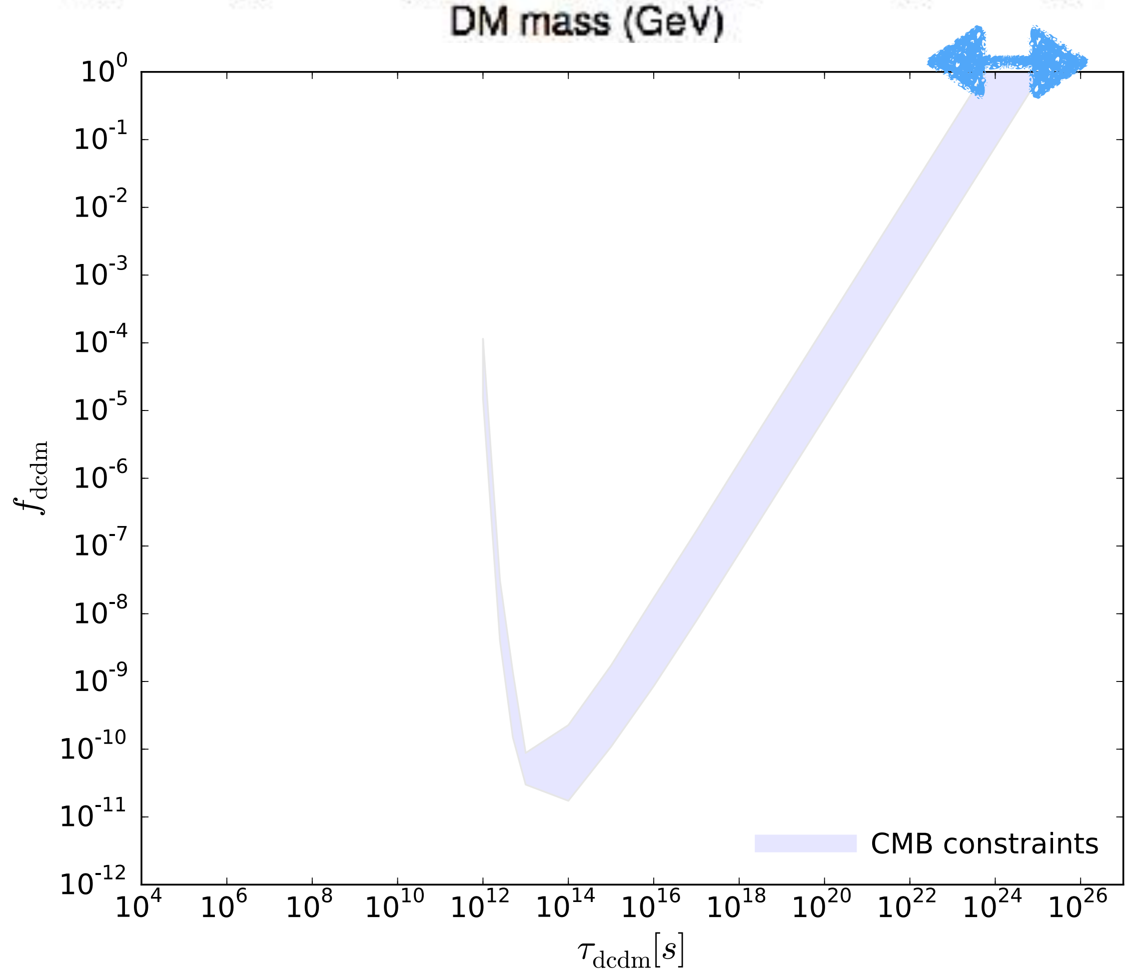
see also
Slatyer&Wu
arXiv:1610.06933

- Blue band : reflects difference between energy deposition efficiency.
- Results are reliable for mχ in [10^3,10^{12}] eV whatever decay channel !

Comparaison with Slatyer&Wu PRD 95 (2017) no.2, 023010







- Slatyer & Wu consider many possible « 2 body decay » final states and a wide range of mass.

- « Proof of principle »:
All decay channels and masses are roughly contained in the uncertainty band, except neutrinos.

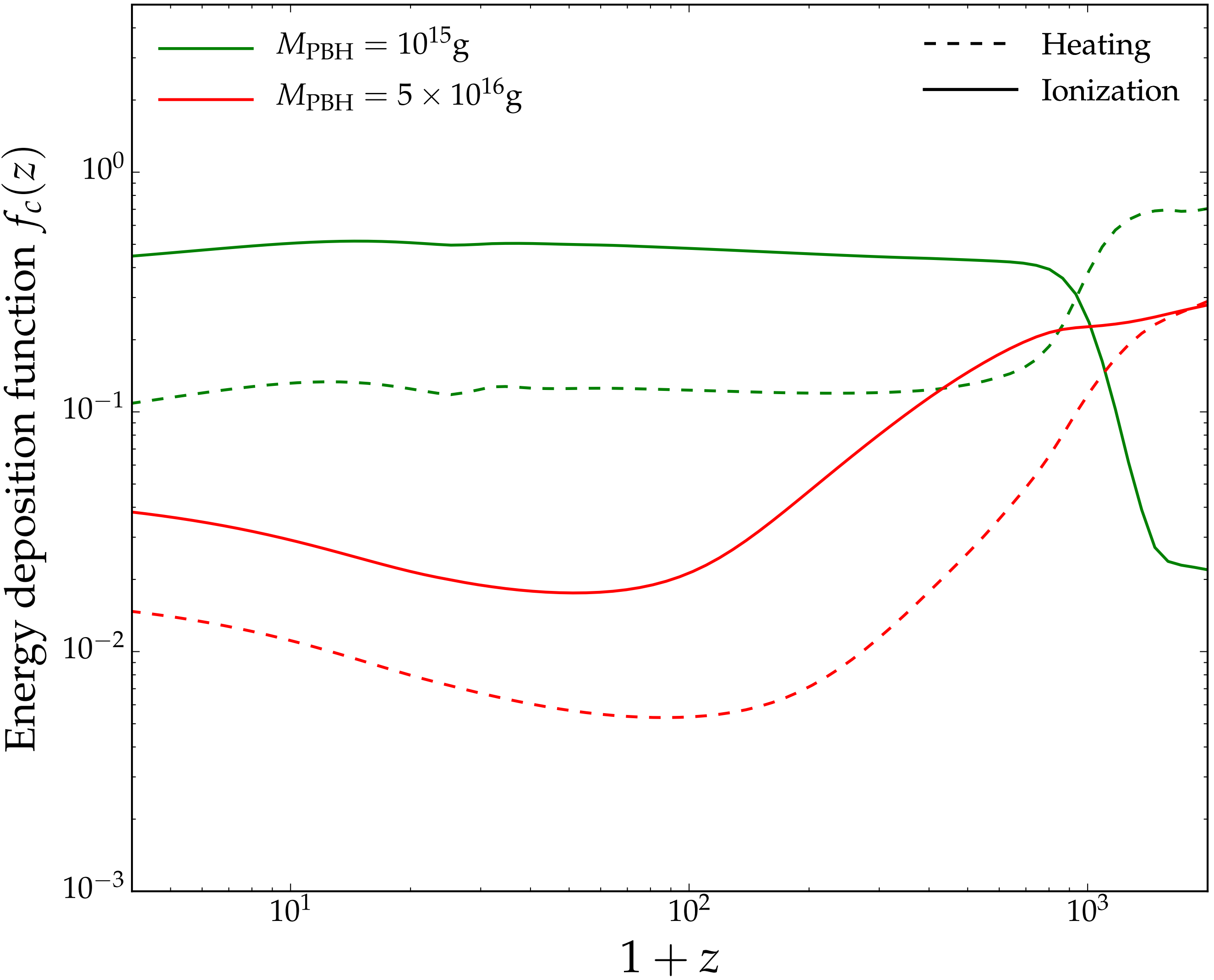
- For models with invisible decay products one should rescale bound by the e.m. BR

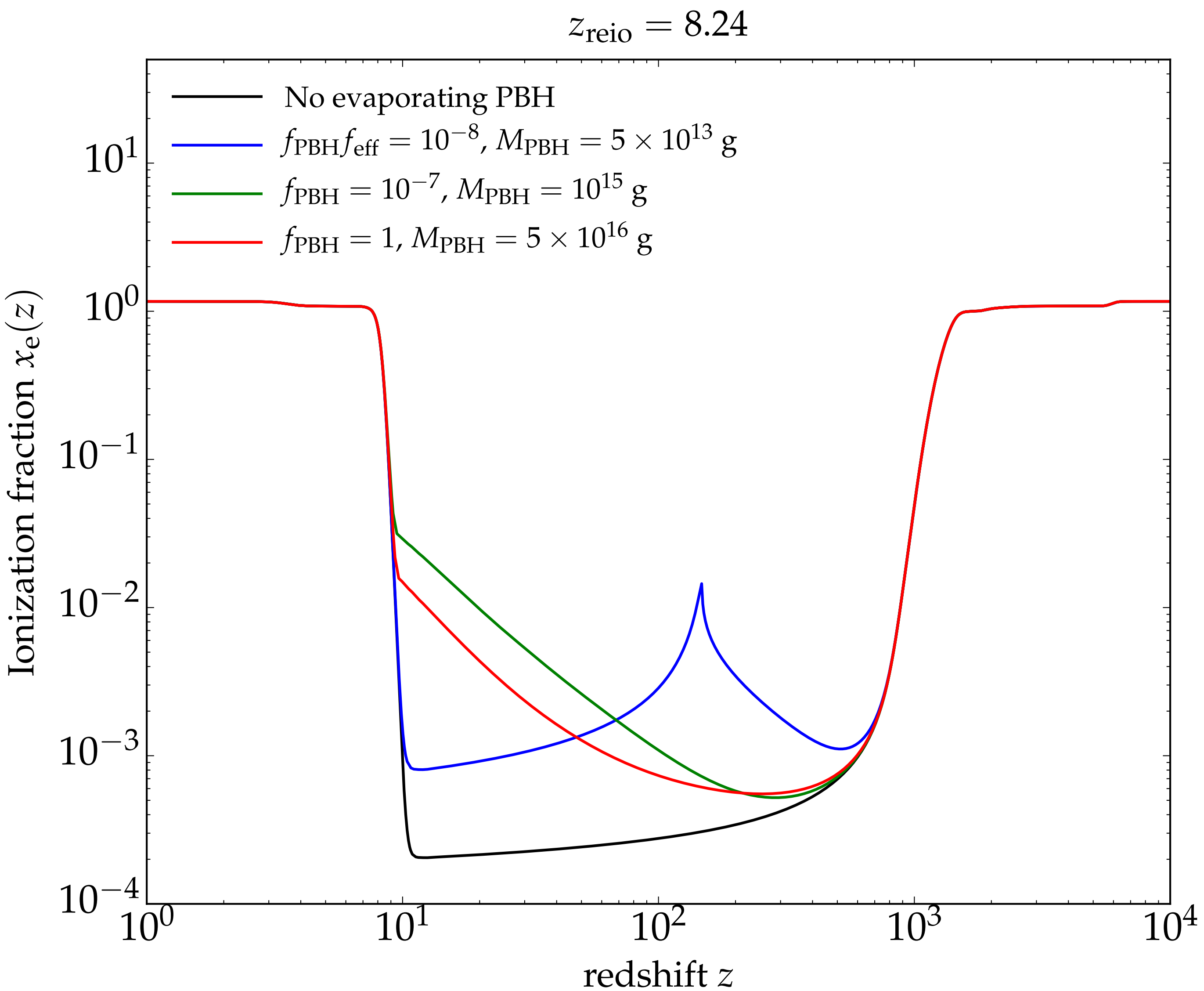
Constraints on evaporating PBH (1)

Hawking, Nature 248, 30 (1974), more details in Carr et al. PRD81 (2010) 104019

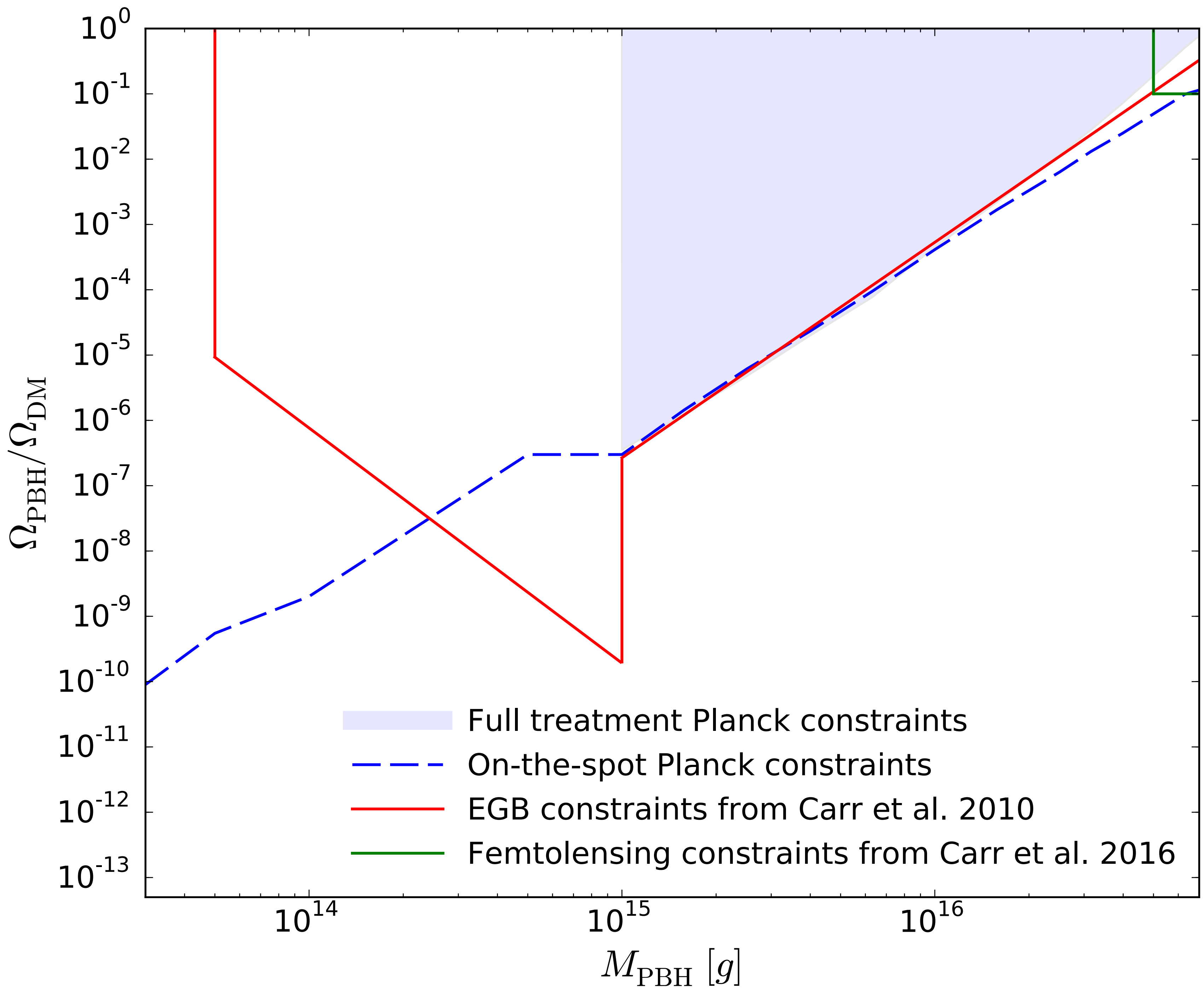
$$T_{\rm BH} = \frac{1}{8\pi G M} \simeq 1.06\left(\frac{10^{10}{\rm g}}{M}\right)\ {\rm TeV}$$

$$\Gamma^{-1}_{\rm PBH} \simeq 407\left(\frac{15.35}{\mathcal{F}(M)}\right)\left(\frac{M}{10^{10}{\rm g}}\right)^3\ {\rm s}$$





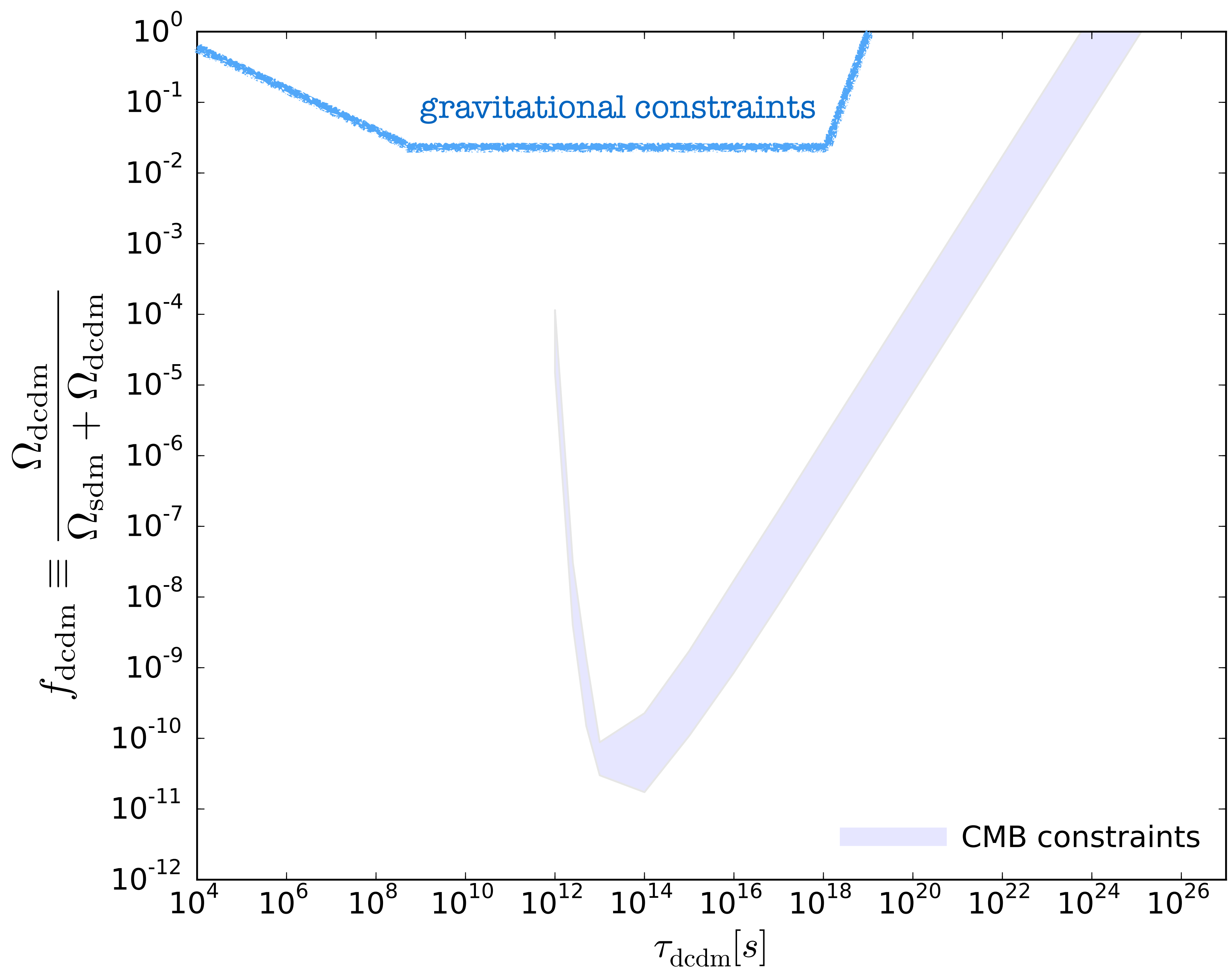
Constraints on evaporating PBH (2)

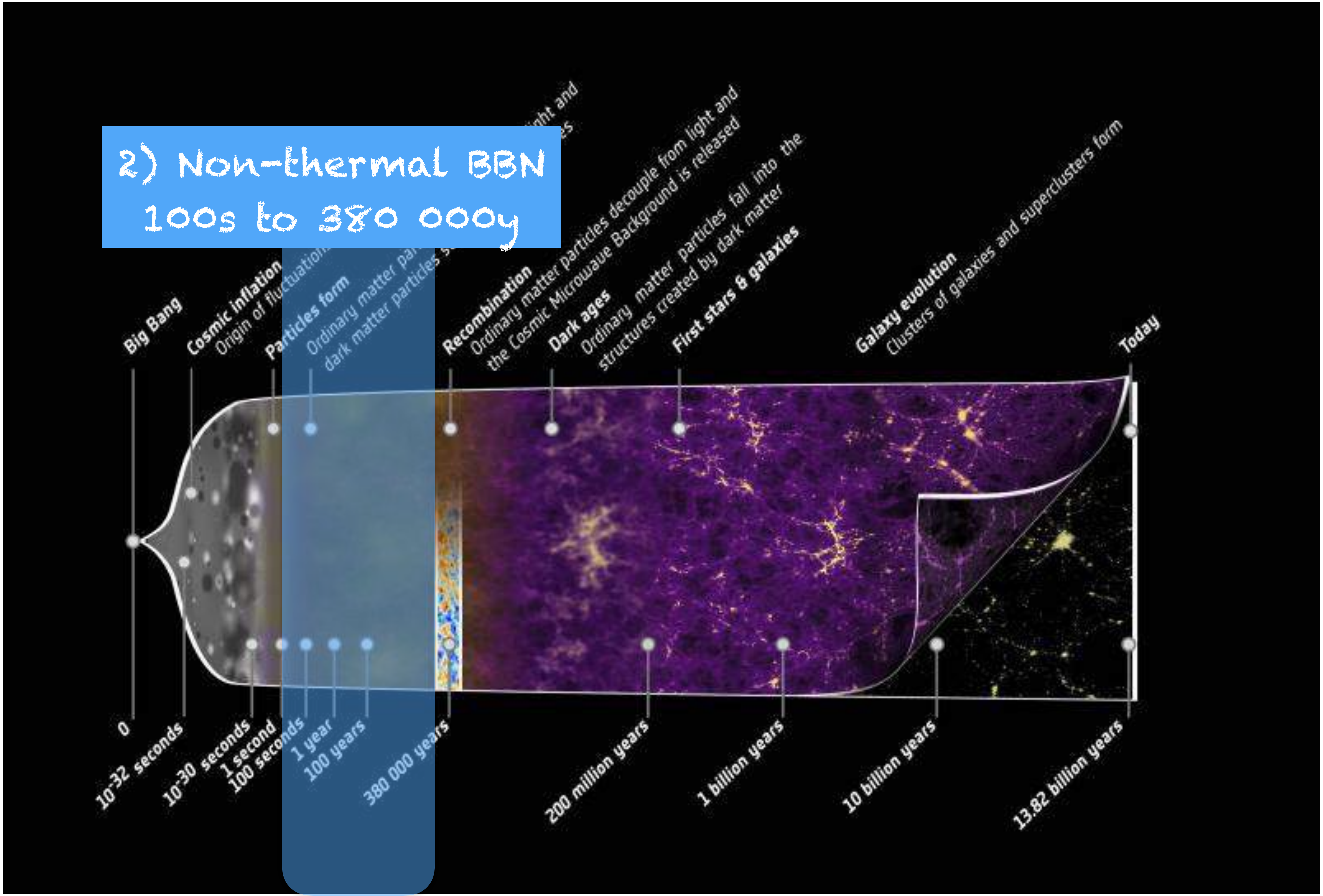


CMB dominates at low masses and is very competitive until $3 * 10^{16}$g !

VP, Serpico & Lesgourgues
ArXiv:1610.10051

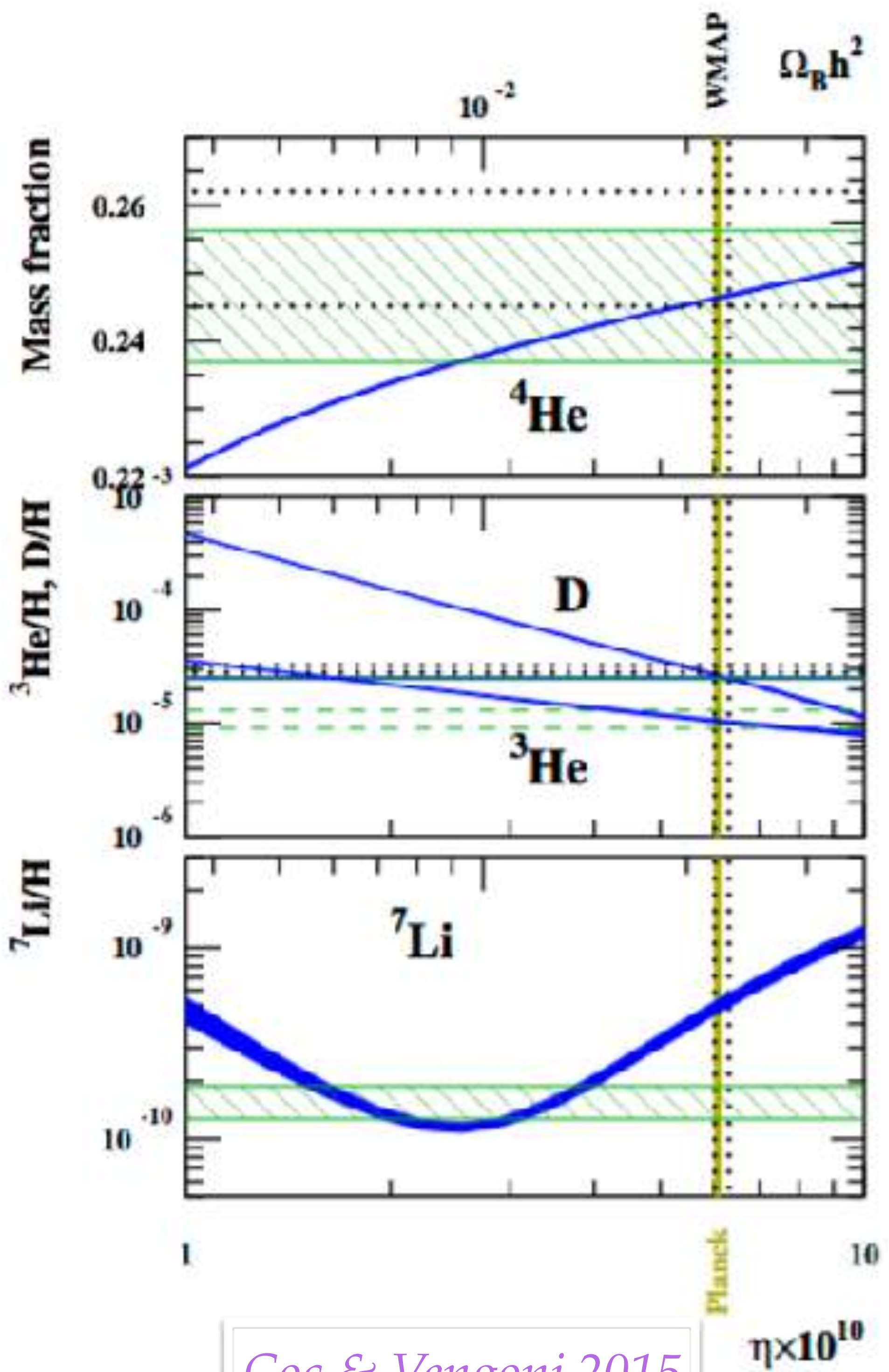
Can we do better at low lifetime ?




2) Non-thermal BBN
100s to 380 000y
Big Bang
Cosmic inflation
Particles form
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
0
10⁻³² seconds
10⁻³⁰ seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years

BBN in a nutshell

- It is the era of creation of light element in the U.
- It happened few s / min after BB when $T \approx \mathrm{MeV}$



Coc & Vengoni 2015

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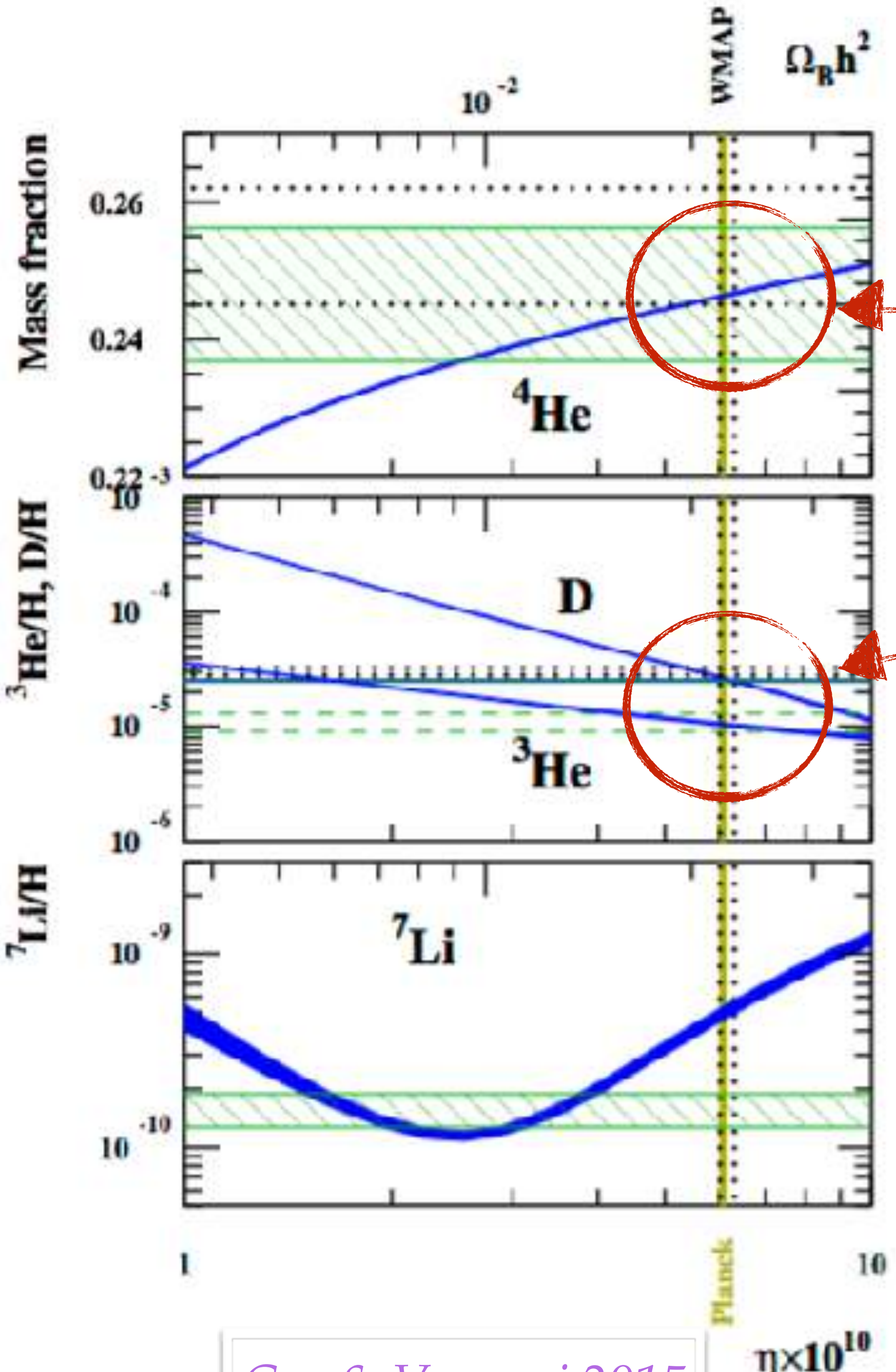

Coc & Vengoni 2015

For 3 nuclei :

Strong observational constraints

$$Y_p > 0.2368$$

$$2.56 \times 10^{-5} < {}^2\mathrm{H/H} < 3.48 \times 10^{-5}$$

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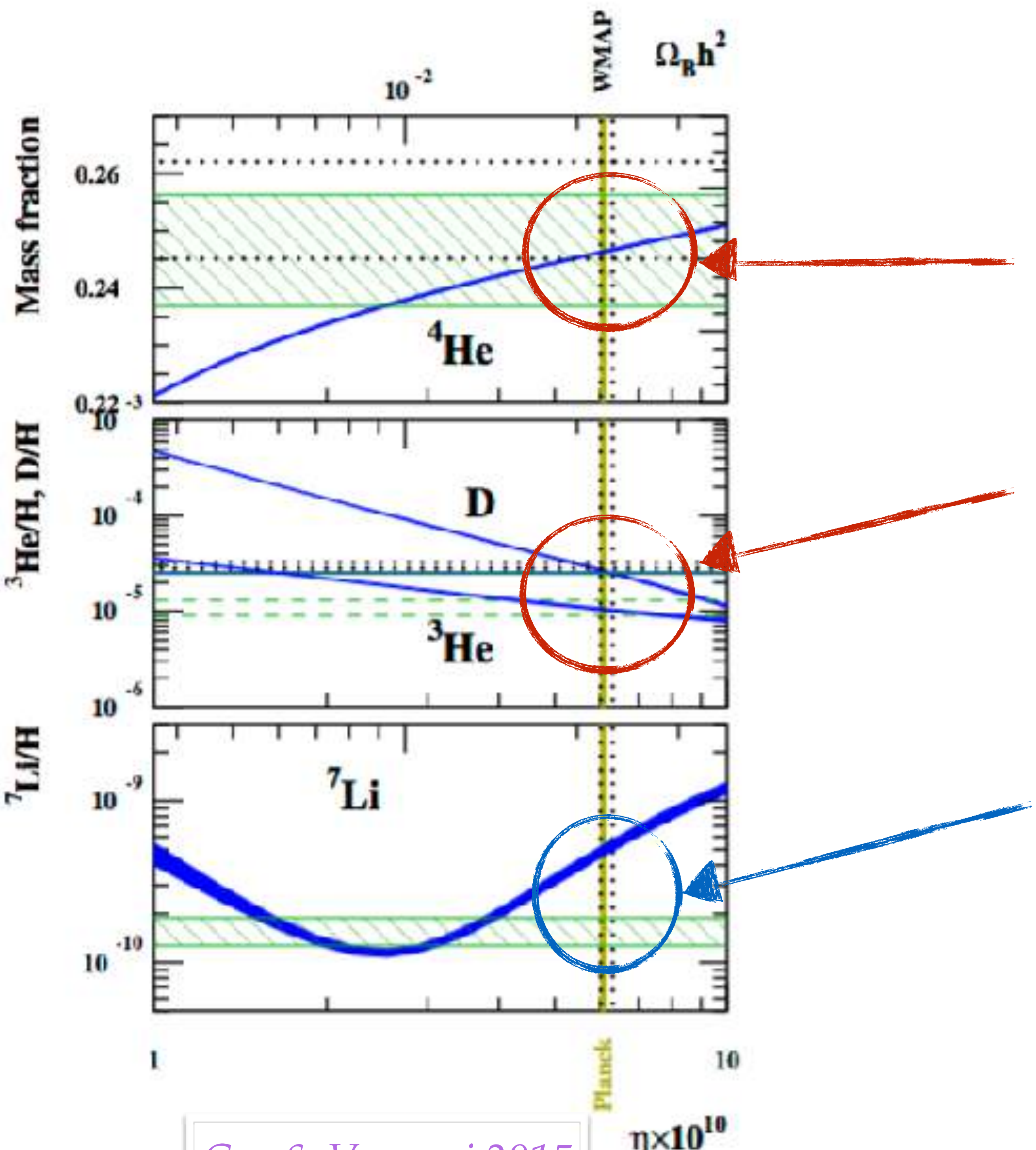

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The Lithium problem :

Overprediction of the ^{7}Li abundance

$$Y_{\mathrm{Li}}^{\mathrm{theo}} \simeq 3 \times Y_{\mathrm{Li}}^{\mathrm{obs}}$$

ignored today !

e.g. Poulin & Serpico
PRL 114 (2015) no.9, 091101

same « EM cascade » to compute … But much simpler

We inject electromagnetic energy in a plasma with $n_\gamma >> n_b$

Q : What is the resulting metastable distribution of photons ?

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Basic processes are (at high energies)

$$\gamma\gamma_{\rm th} \to e^+e^- \qquad e\gamma_{\rm th} \to e\gamma \qquad \gamma\gamma_{\rm th} \to \gamma\gamma$$

and eventually (very low rates)

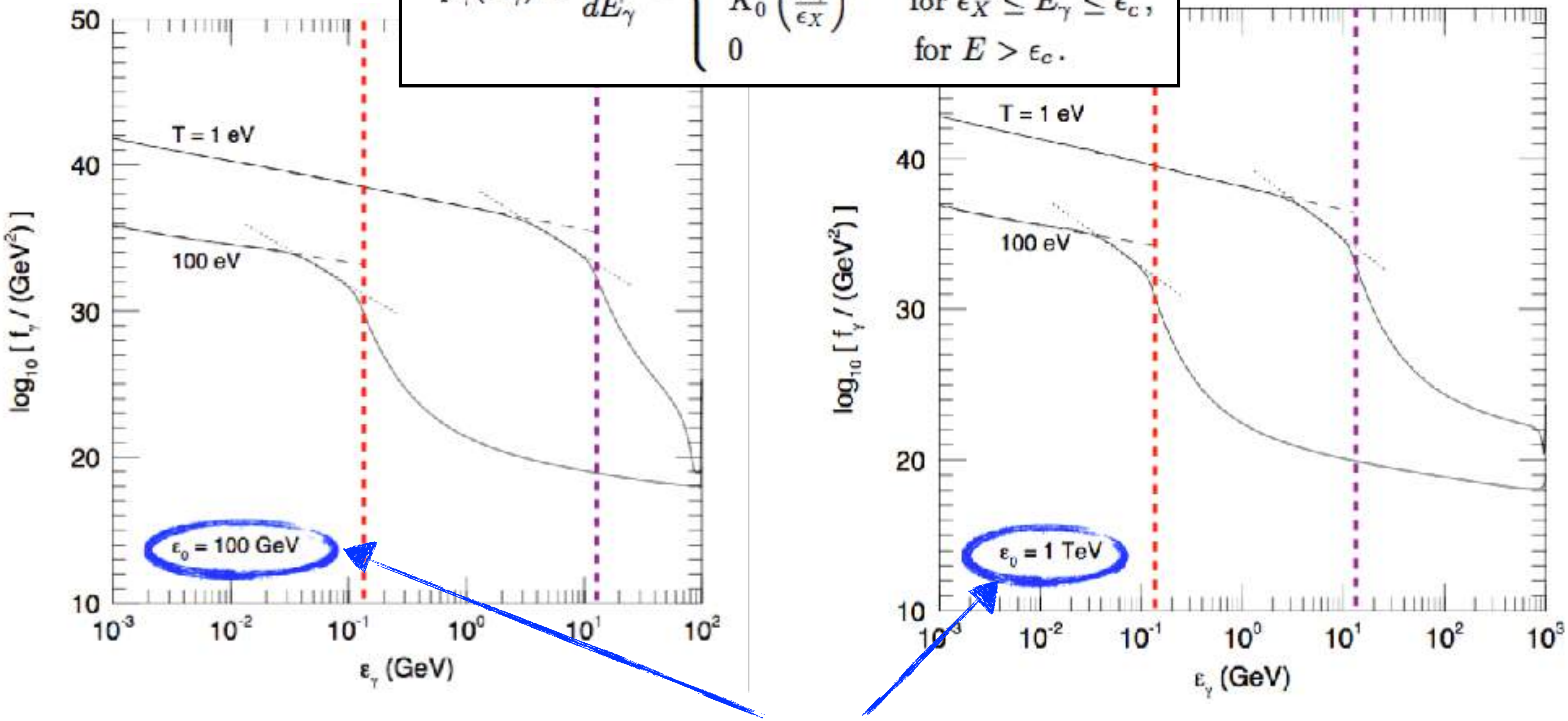
$$\gamma N \to e N \qquad \gamma e_{\rm th} \to \gamma e$$

Particle multiplication and energy redistribution
=> Electromagnetic cascade !

Kawasaki & Moroi, ApJ 452,506 (1995)

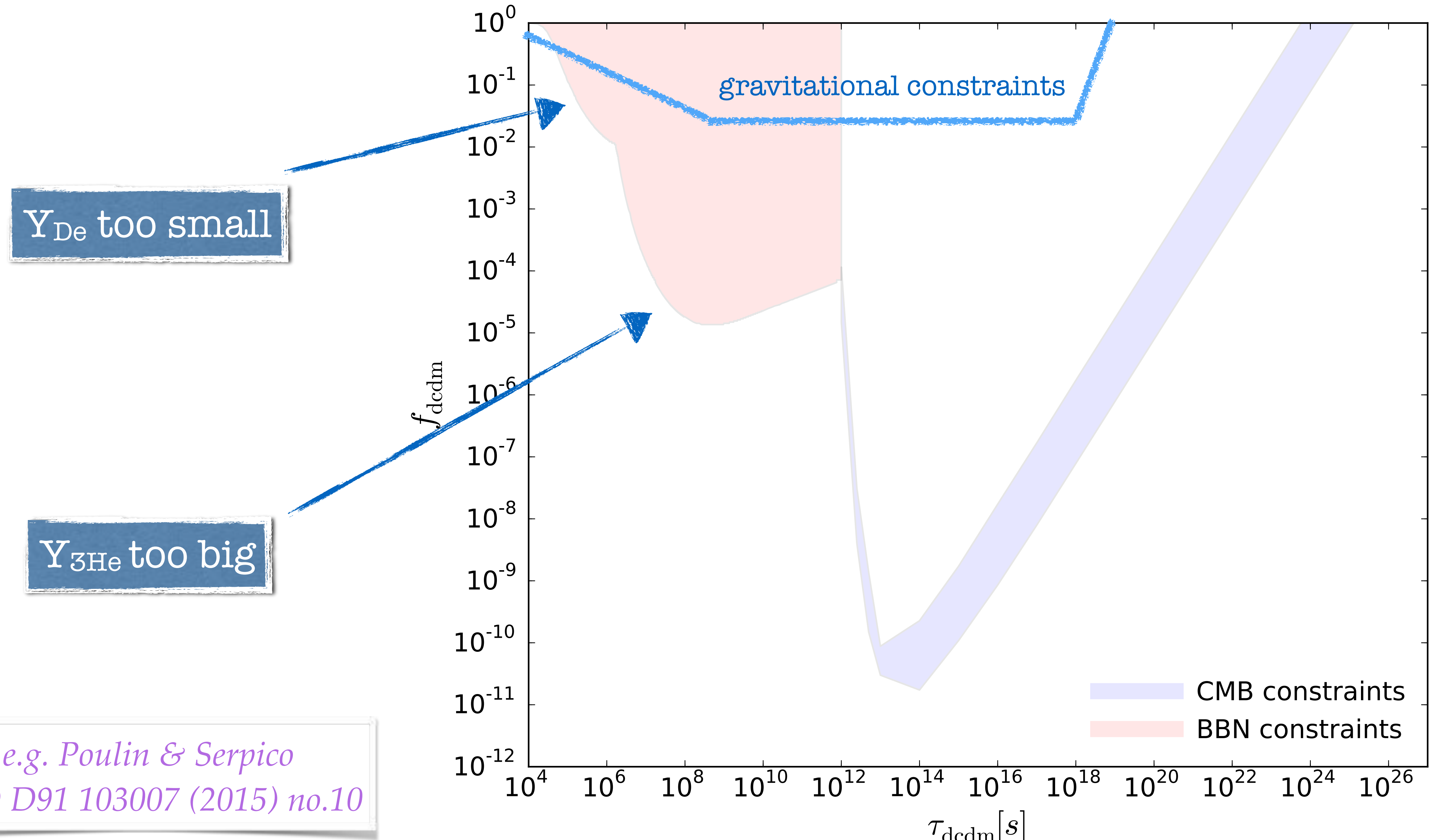
This has been shown to lead to a universal spectrum

$$p_\gamma(E_\gamma) = \frac{dN_\gamma}{dE_\gamma} = \begin{cases} K_0 \left(\frac{E_\gamma}{\epsilon_X}\right)^{-3/2} & \text{for } E_\gamma < \epsilon_X \,, \\ K_0 \left(\frac{E_\gamma}{\epsilon_X}\right)^{-2} & \text{for } \epsilon_X \le E_\gamma \le \epsilon_c \,, \\ 0 & \text{for } E > \epsilon_c \,. \end{cases}$$



- Shape independent of the energy / temperature of the bath: Only dictates the overall normalisation;
- Threshold due to pair production.

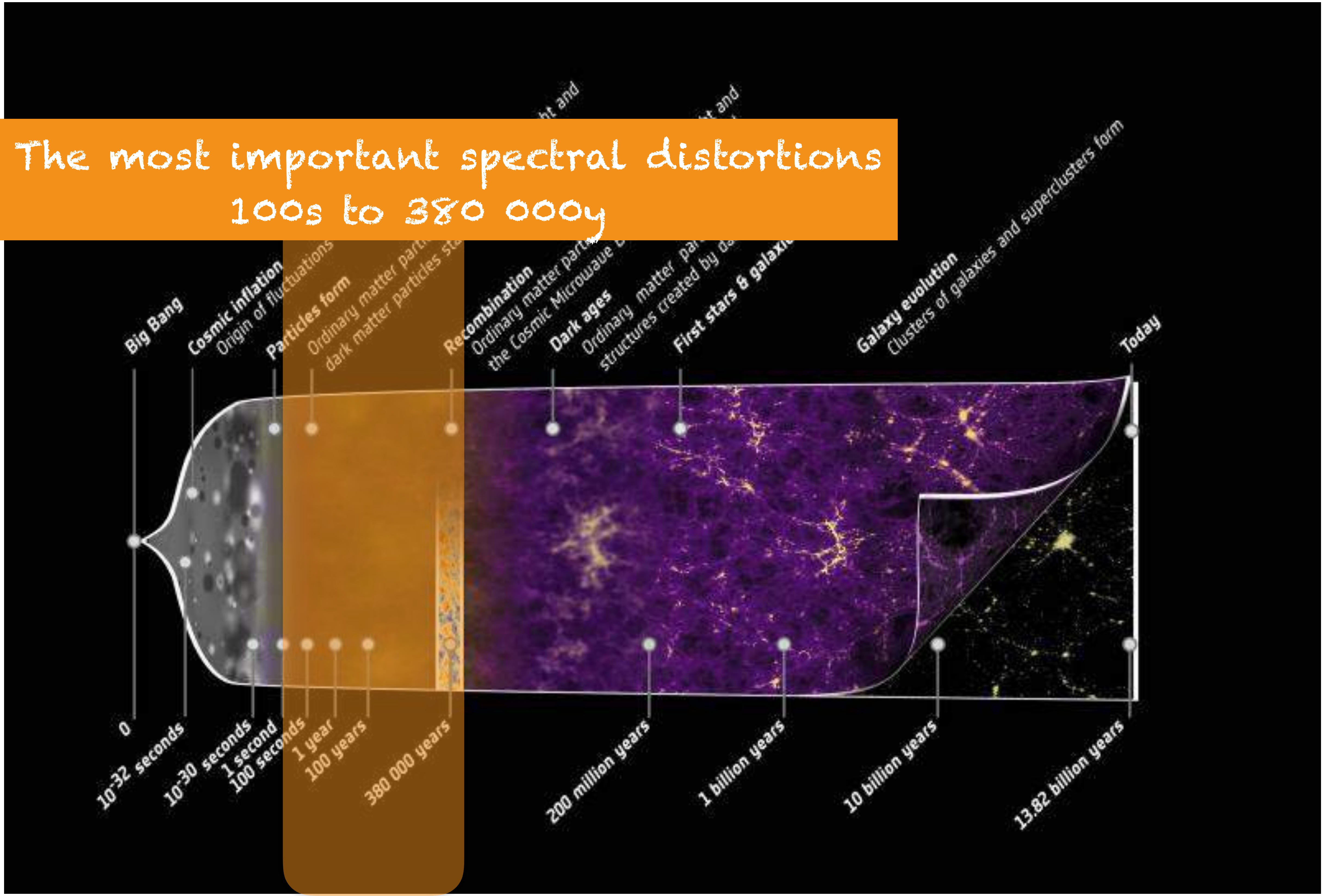
BBN very powerful at constraining τ = [10^4,10^{12}]s



e.g. Poulin & Serpico
PRD D91 103007 (2015) no.10

⇨ Those bounds are very conservative!
For MeV- GeV injection they can be up to 1 order of magnitude better.

3) The most important spectral distortions 100s to 380 000y



CMB spectral distortions

see e.g. Chluba & Sunyaev MNRAS. 419 (2012) 1294-1314

- Most important processes to thermalise any energy injection are Bremsstrahlung, Compton and Double-Compton scattering.
- If those processes go out of equilibrium, SD can occur.

$$\Delta I(\nu) = I_{\rm true}(\nu) - I_{\rm bb}(\nu)$$

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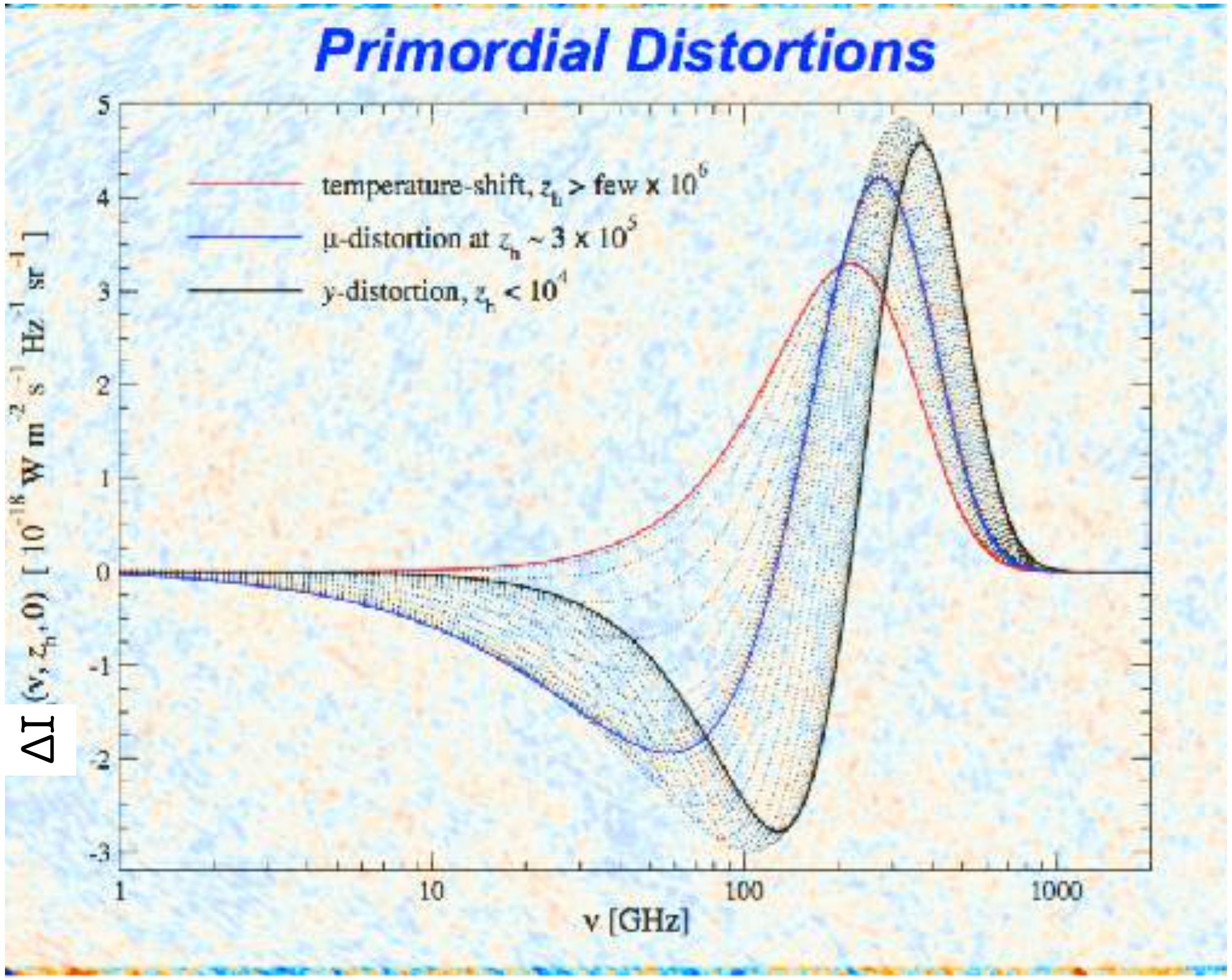


μ = creation of a chemical potential

y = compton heating (or cooling!) of the CMB photons

Intermediate distortions probe injection history, i.e. lifetime !

© Jens Chluba, « Ecole de Gif », 2014

CMB vs BBN vs spectral distortions

Cosmology can constrain a very broad range of lifetime !!

- From COBE-Firas :

$|\mu| \leq 9 \times 10^{-5}$

$|y| < 1.5 \times 10^{-5}$

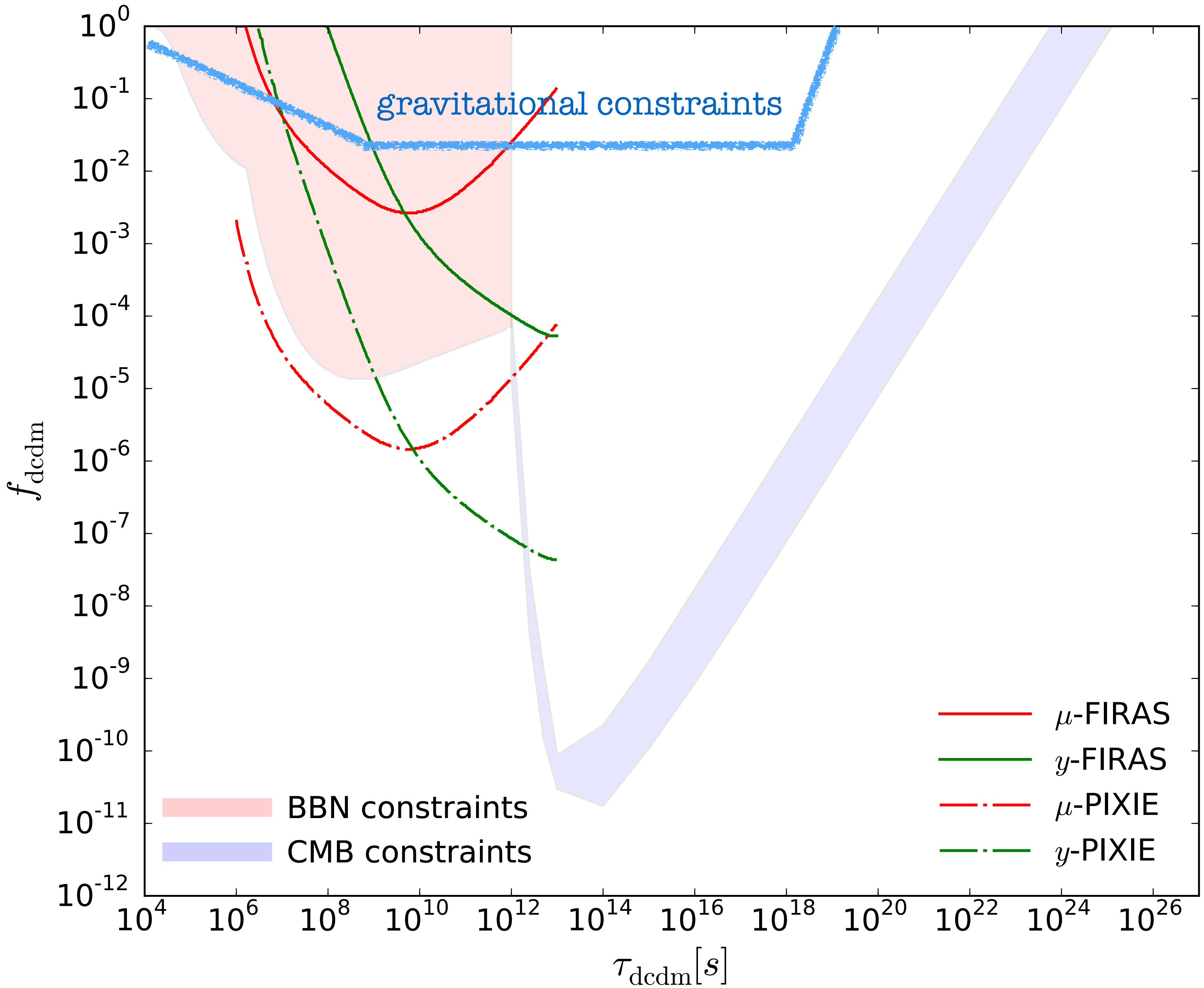
Fixsen et al. APJ. 473, 576 (1996)

- With Pixie :

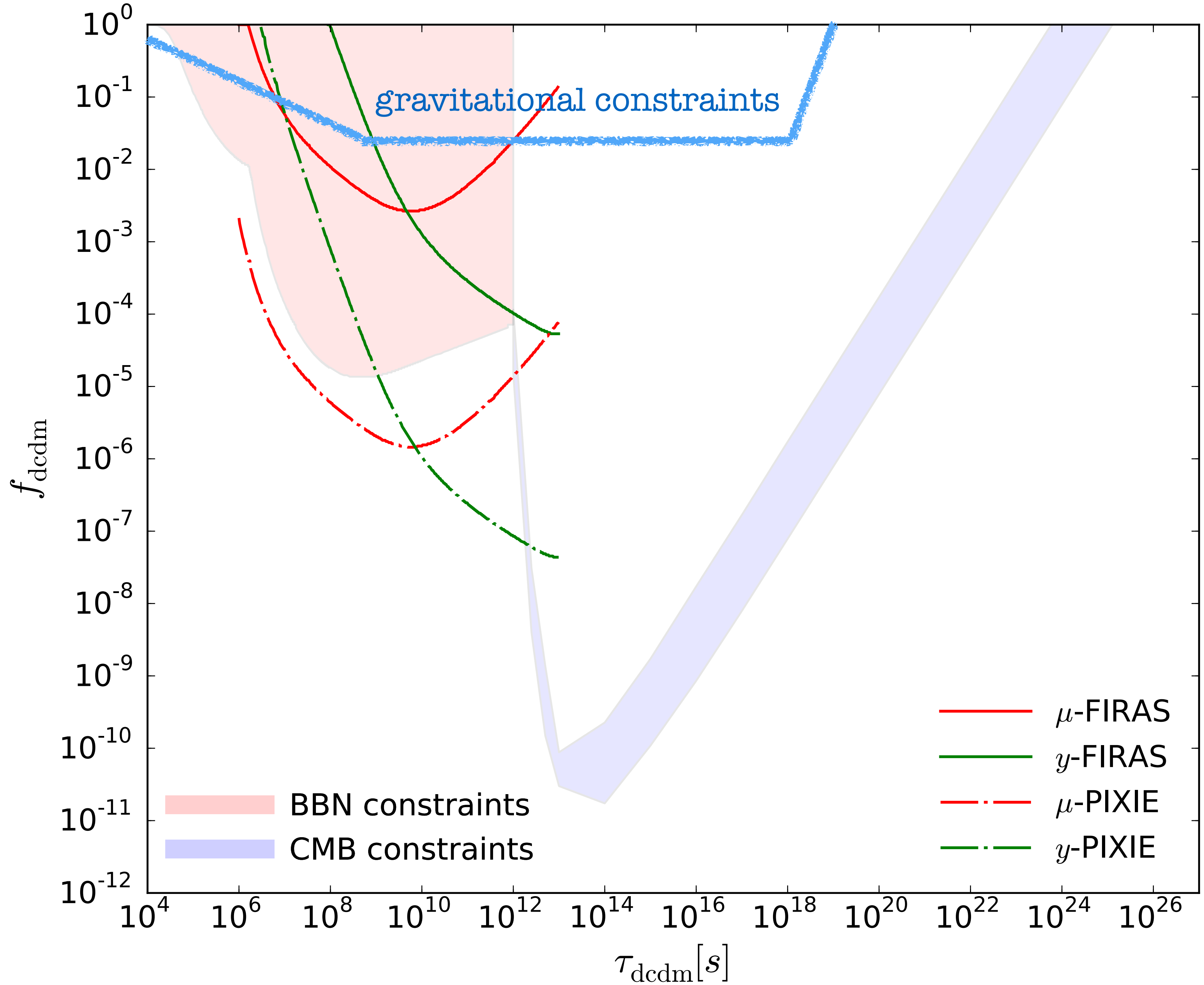
$|\mu| \sim 5 \times 10^{-8}$

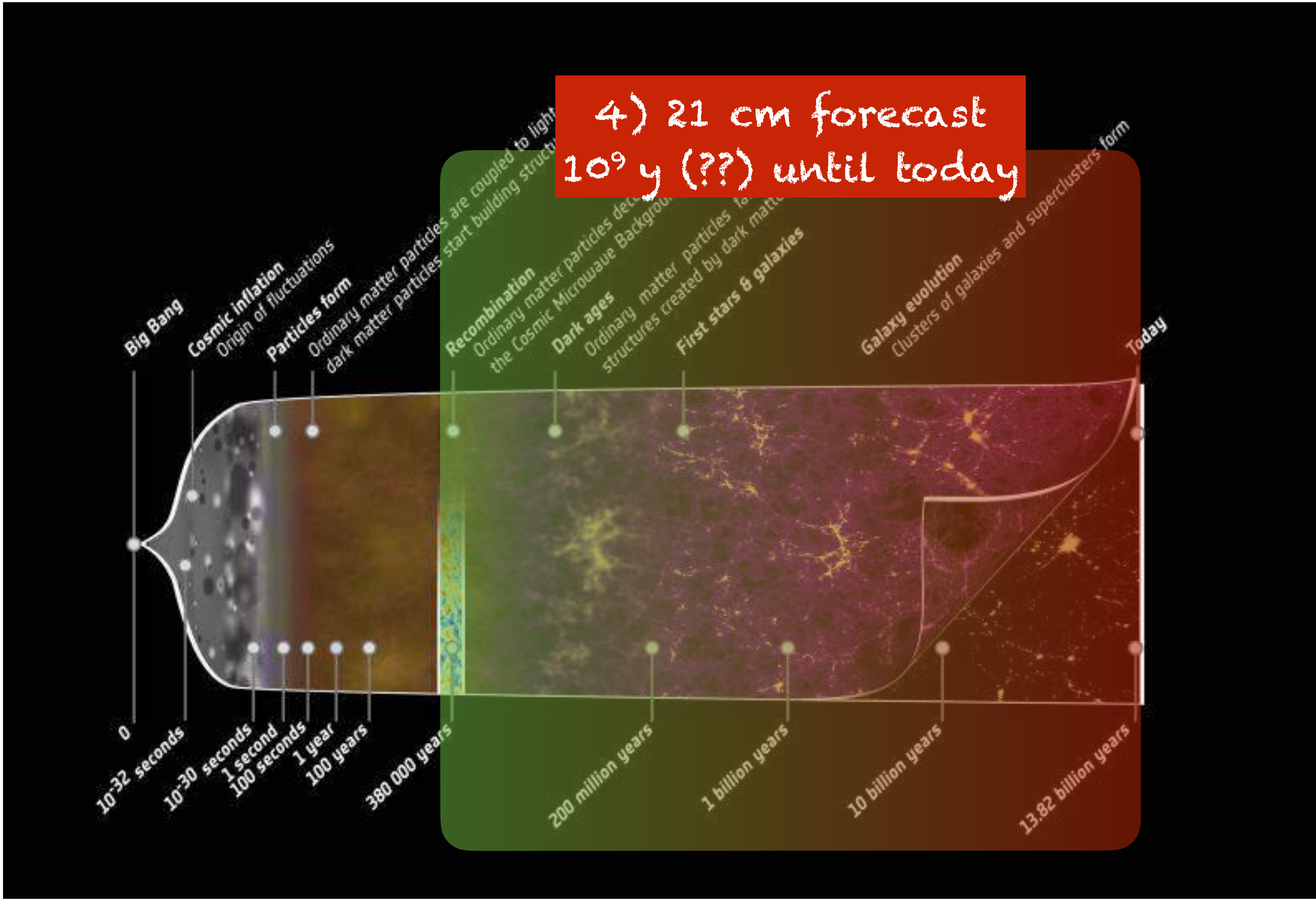
$|y| \sim 1 \times 10^{-8}$

Kogut et al., JCAP. 7, 025 (2011)

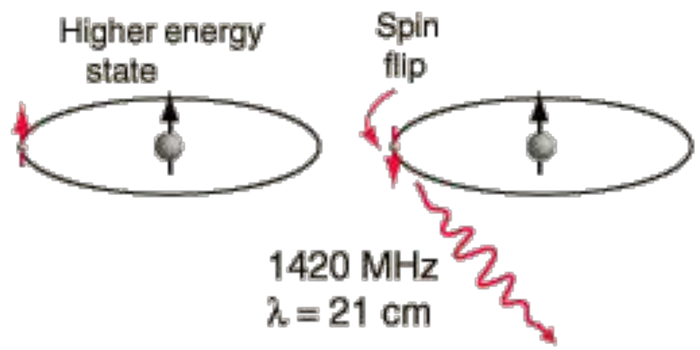


A fair « State of the art », what's next ?




4) 21 cm forecast
10⁹ y (??) until today
Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Recombination
Dark ages
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
0
10-32 seconds
10-30 seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years

The next-generation experiment : 21cm with SKA



- Hyperfine transition from neutral hydrogen
- Very sensitive probes of the Epoch of Reionization (EoR)
- Key quantities : Spin temperature and differential brightness temperature

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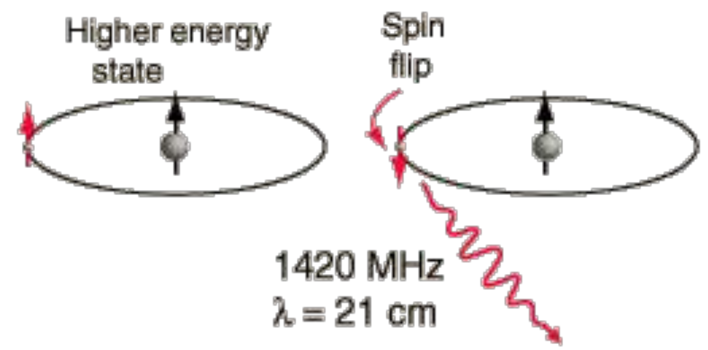

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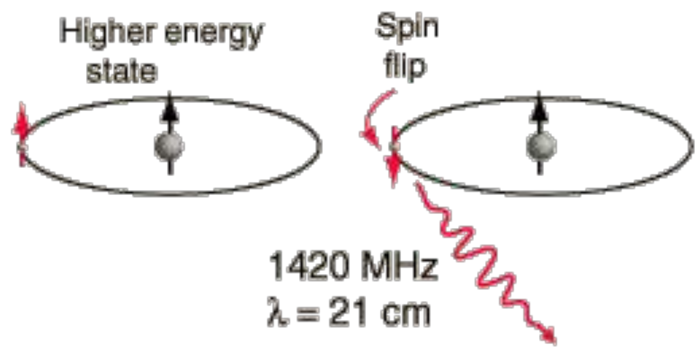

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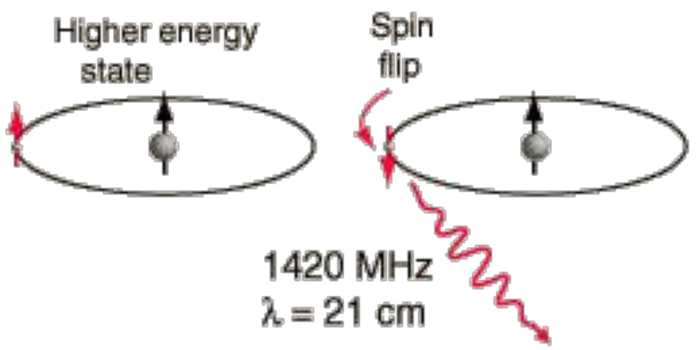

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scattering with CMB   collision within the gas

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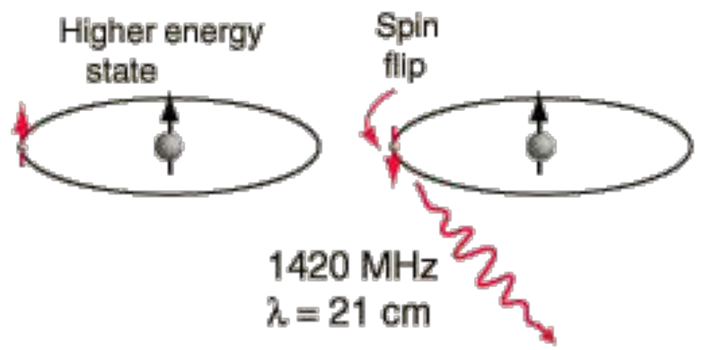

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scattering with CMB | collision within the gas | interaction with UV from stars

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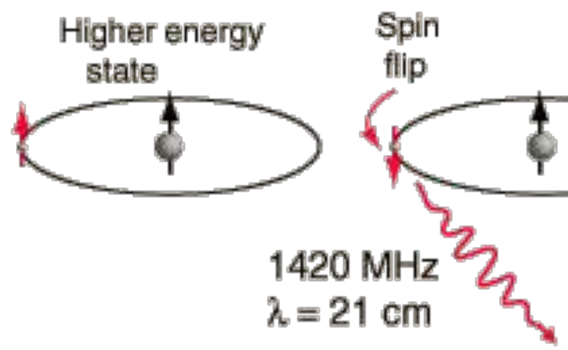

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scattering with CMB — collision within the gas — interaction with UV from stars

Compare patch of the sky with/without hydrogen clouds:

$$\delta T_b(\nu) = \frac{T_s - T_{\rm CMB}}{1+z}(1 - \exp(-\tau_{\nu 21}))$$

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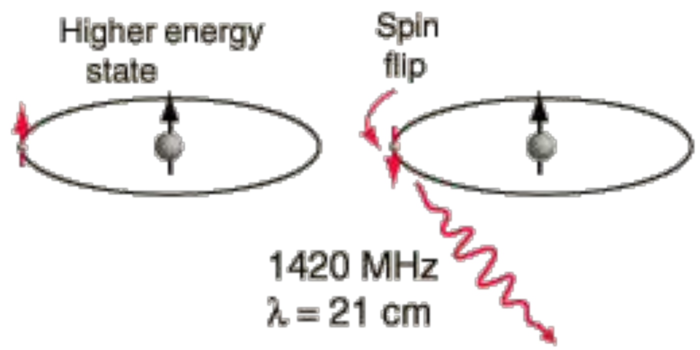

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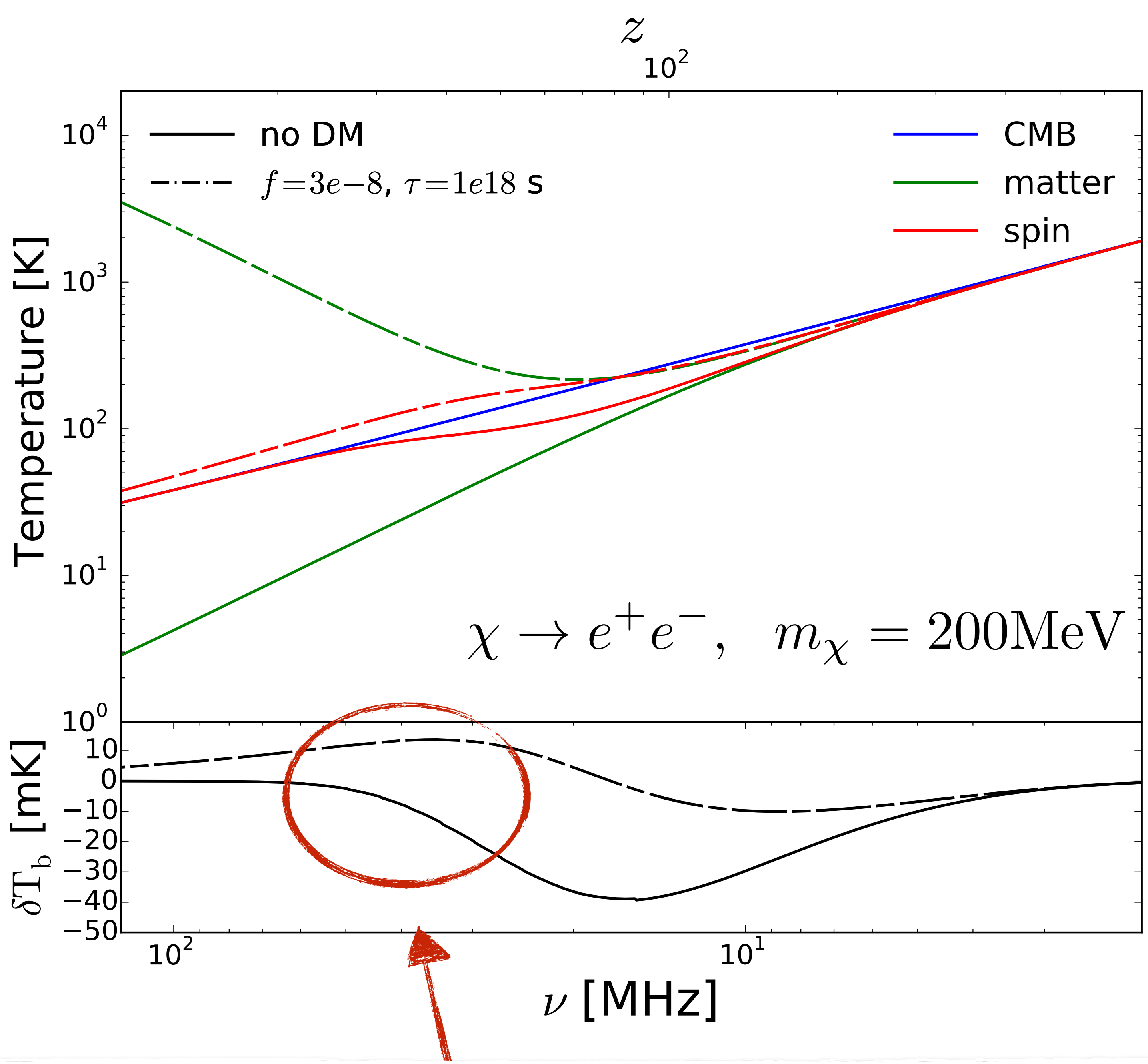
Difficulty = Huge astrophysical uncertainty below z ≈20, one trick :
SKA will be able to measure δT_b = 5-10 mK up to z= 25 (ν = 60 MHz)

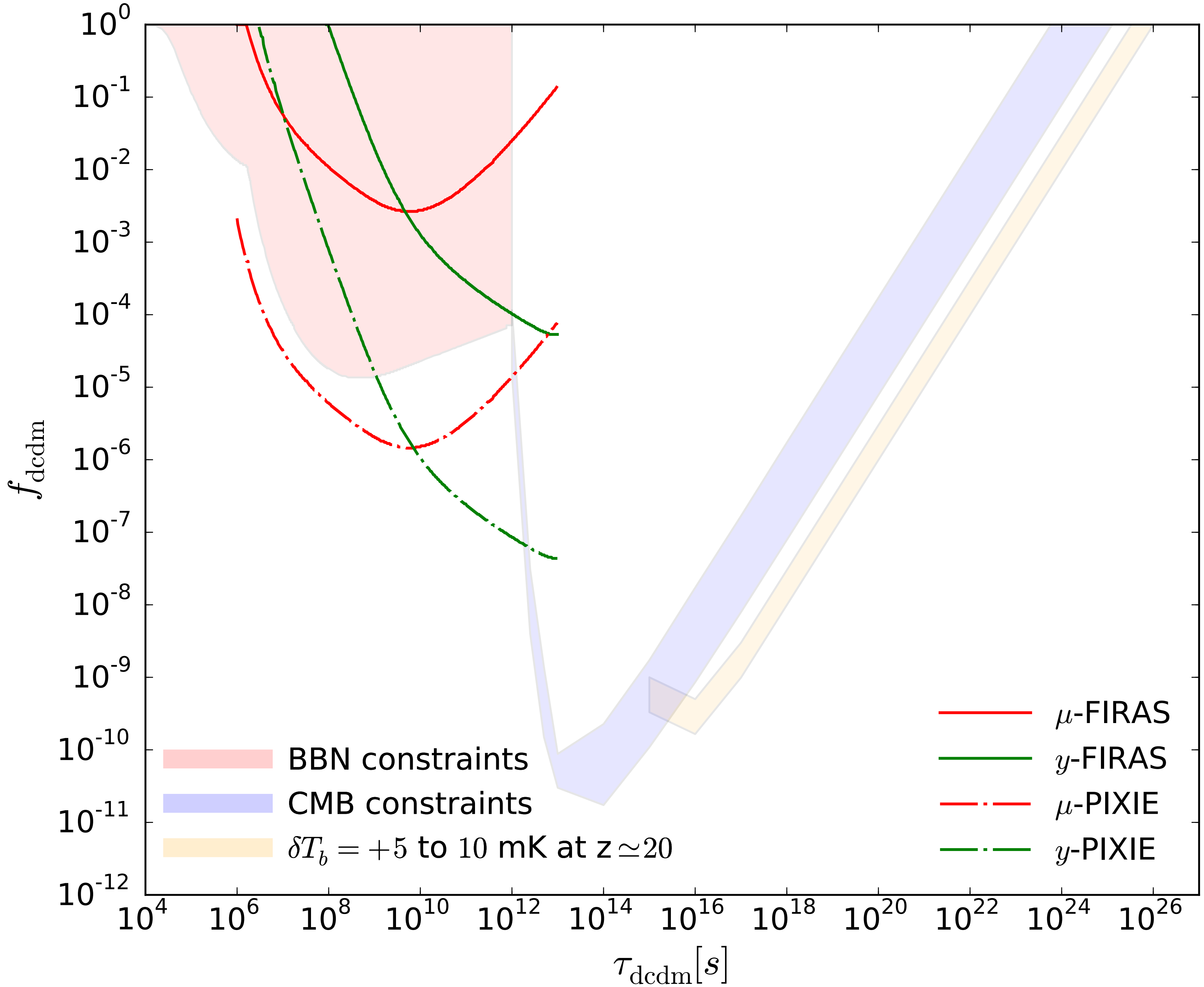
We neglect stars : valid until z ≈20, still in the SKA range !



Potential « smoking gun » signal from DM e.m. decay at the end (and during !) the dark ages

SKA could be better at detecting - or constraining - e.m. decay

Very crude treatment, for illustration only :
next step => add information from power spectrum analysis



Take-home message

Exotic particle decays (including DM) can be strongly constrained by Cosmology.

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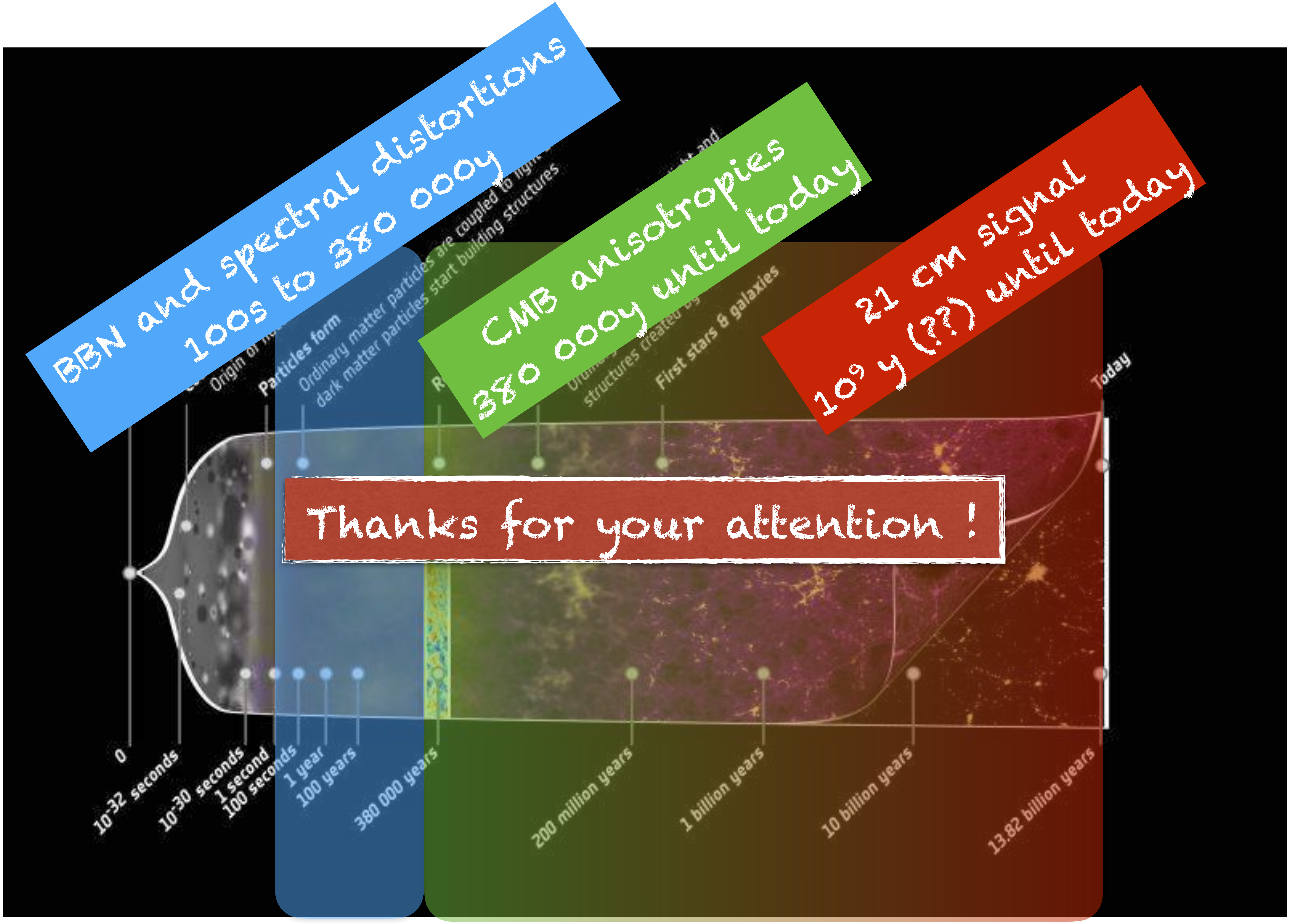
Stay tuned ! Many results to come !


BBN and spectral distortions
100s to 380 000y
CMB anisotropies
380 000y until today
21 cm signal
10^9 y (??) until today
Thanks for your attention !
Particles form
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Today
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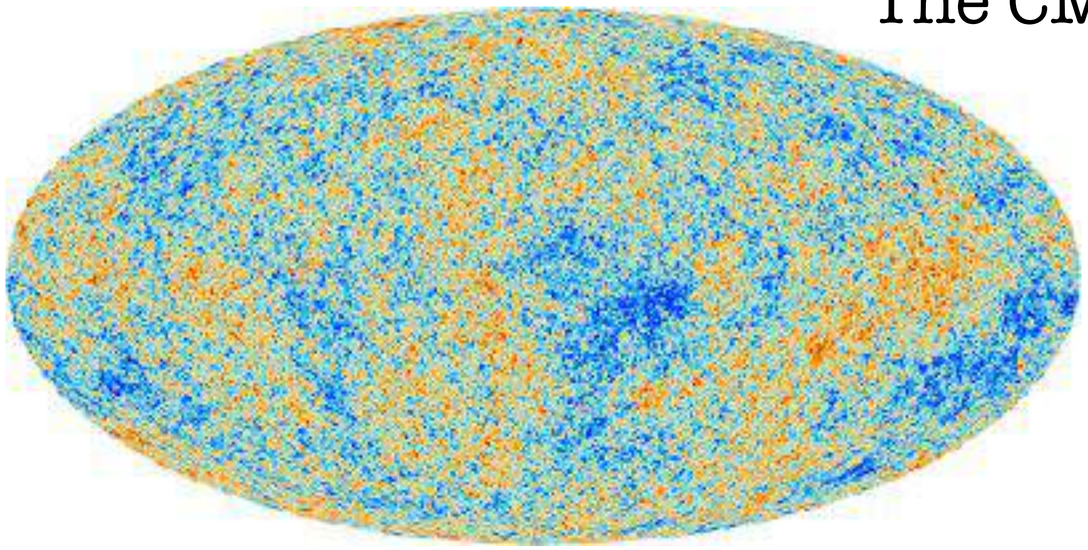
Backup slides



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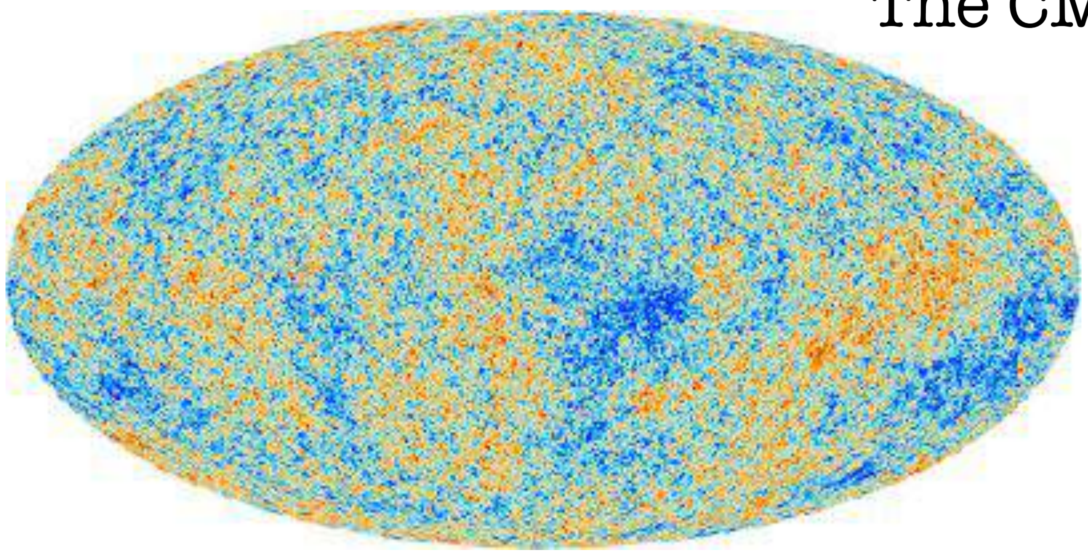
T = 2.72548 +/- 0.00057 K

Fluctuations $\mathcal{O}(10^{-5})$!



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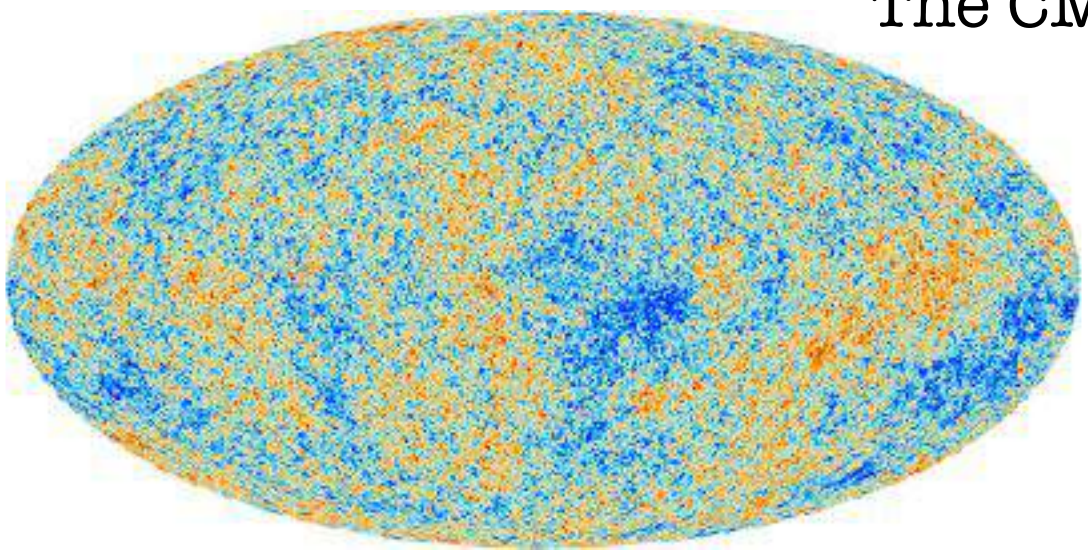

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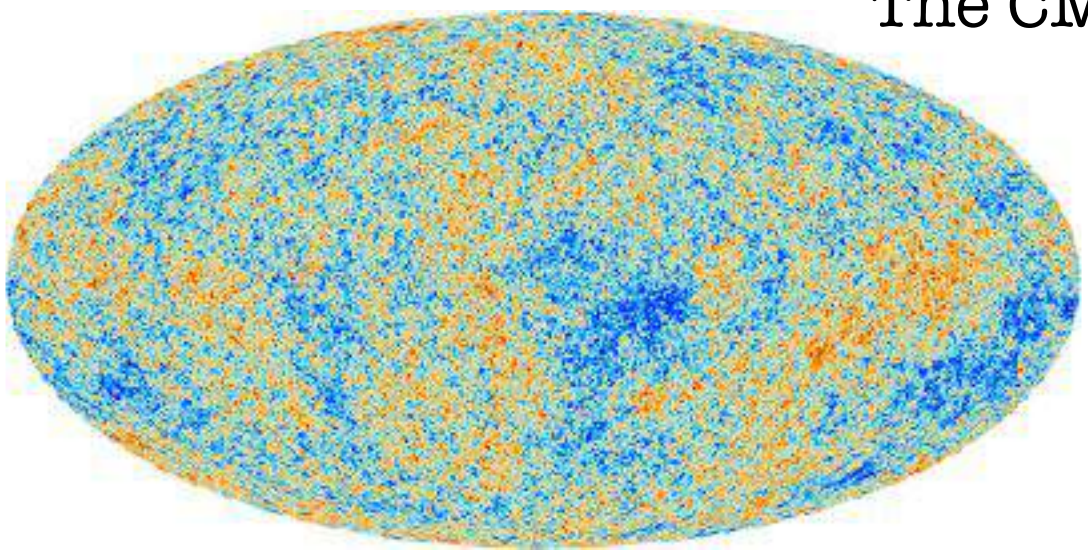

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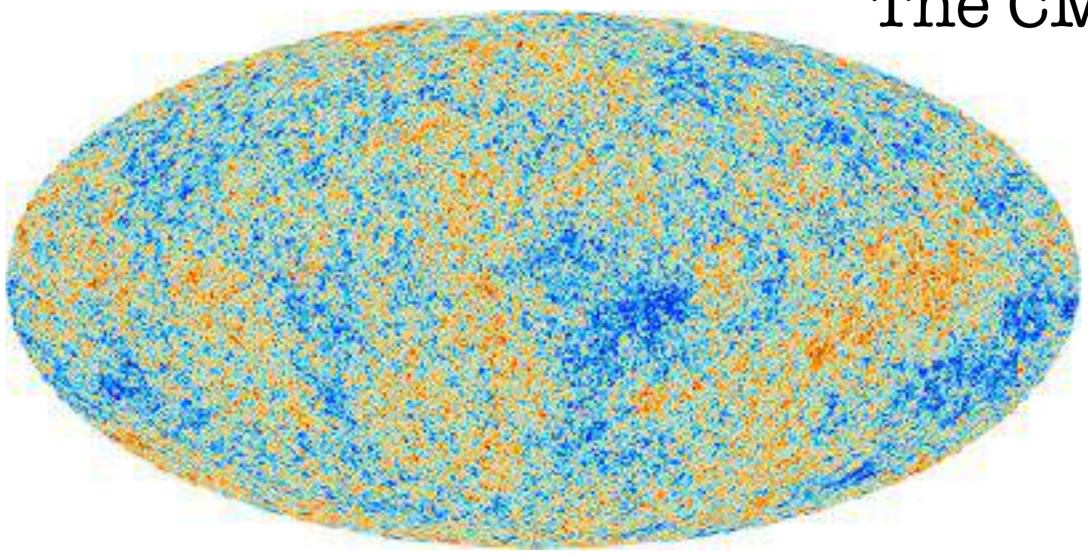

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Only 2 moments of interest : $$\langle\Theta(\vec{n})\rangle = 0 \qquad \langle\Theta(\vec{n_1})\Theta(\vec{n_2})\rangle \neq 0$$

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6 free parameters to fit : $\{\omega_b, \ \omega_{cdm}, \ h, \ A_s, \ n_s, z_{reio}\}$

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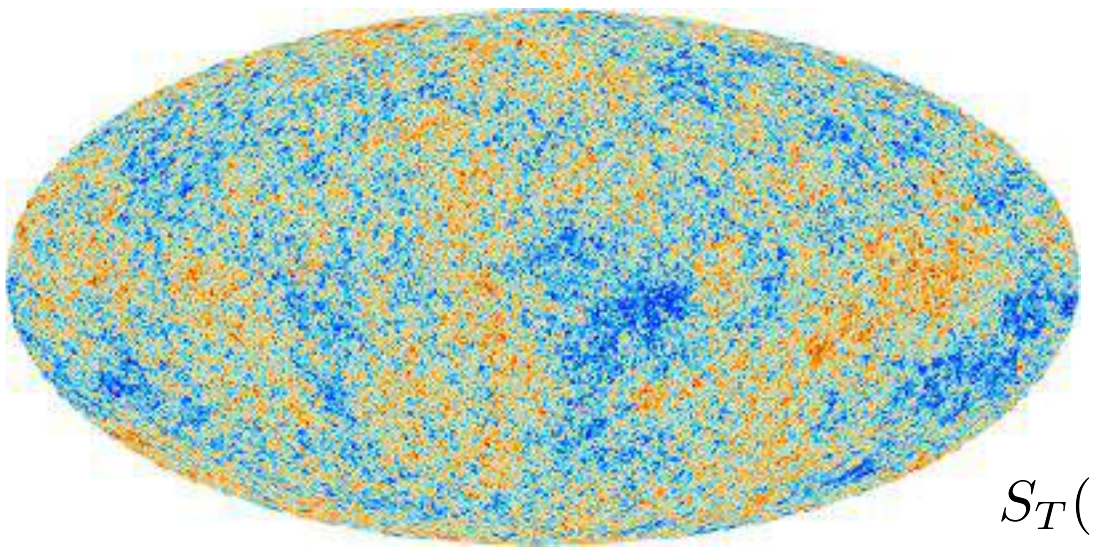
DM interacts only gravitationally in the standard Cosmology
=> Constraints can be derived



$$C_\ell = \int \frac{dk}{k} \mathcal{P}_\mathcal{R}(k)[\Theta_\ell(\tau_0, k)]^2$$

$$\Theta_\ell(\tau_0, k) = \int_\tau^{\tau_0} d\tau S_T(\tau, k) j_\ell(k(\tau_0 - \tau))$$

$$S_T(k,\tau) \equiv \underbrace{g(\Theta_0 + \psi)}_{\text{SW}} + \underbrace{(gk^{-2}\theta_B)'}_{\text{Doppler}} + \underbrace{e^{-\kappa}(\phi' + \psi')}_{\text{ISW}} + \text{polarisation}$$

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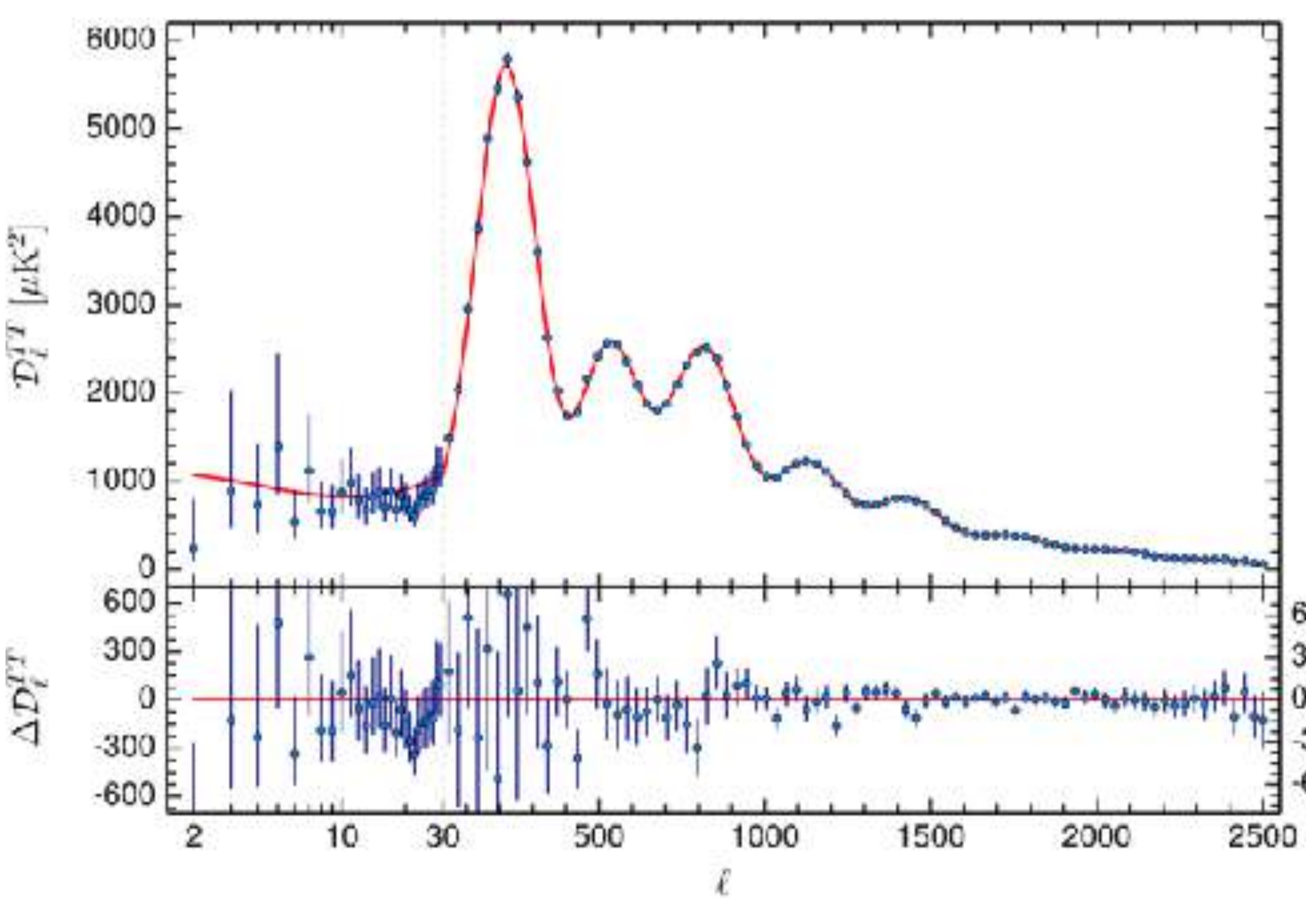

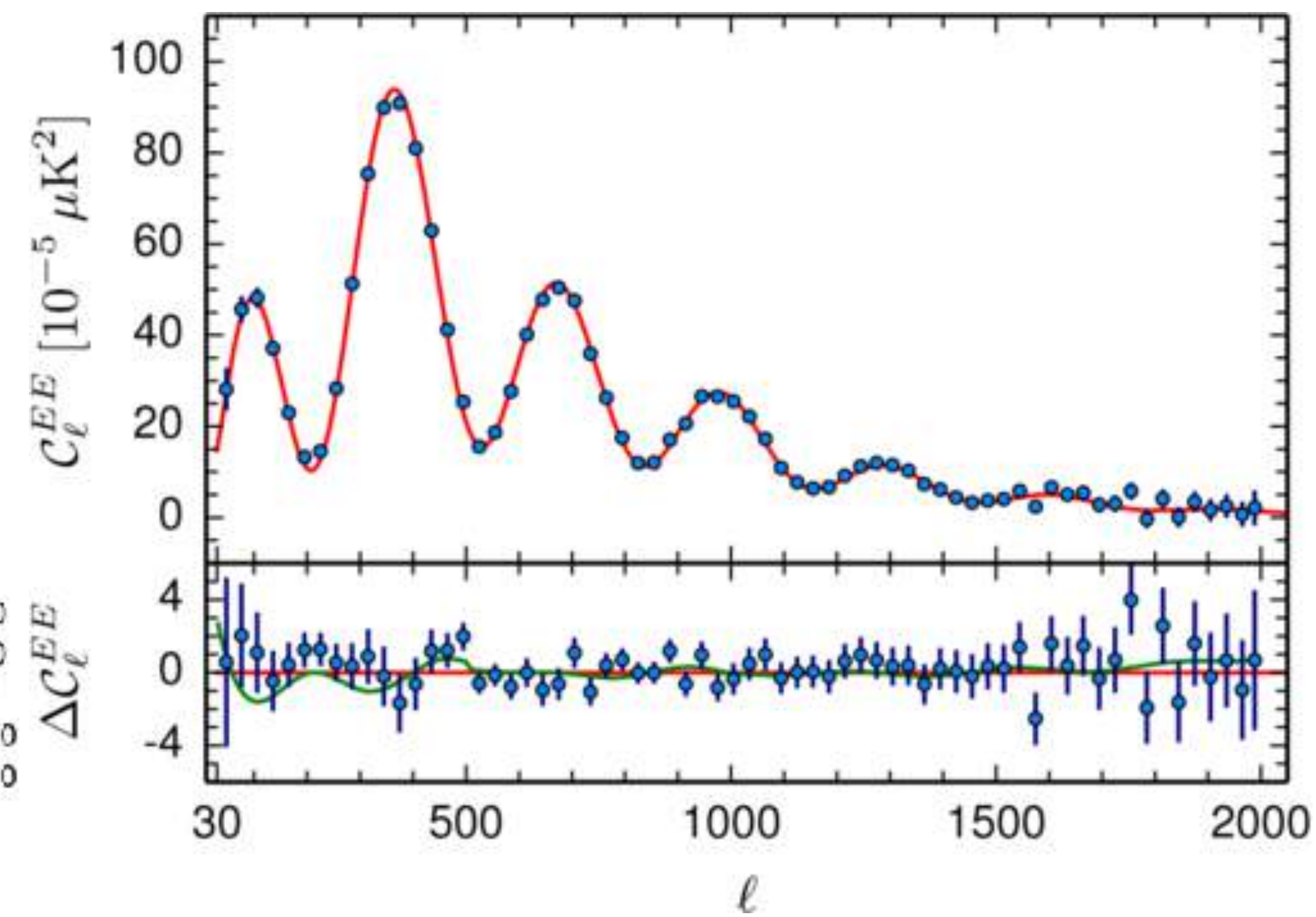

μ and y spectral distortions

see e.g. Chluba & Sunyaev [arXiv:1109.6552]

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In full generality: $\Delta I(\nu) = I_{\rm true}(\nu) - I_{\rm bb}(\nu)$ μ and y are (almost) eigenmodes in the PCA!

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creation of a chemical potential (more/less photons than a BB)

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$$\mathcal{J}_{\rm bb}(z) \approx \exp[-(z/z_\mu)^{5/2}], \quad \mathcal{J}_y(z) \approx \left[1 + \left(\frac{1+z}{6\times 10^4}\right)^{2.58}\right]^{-1}, \quad \mathcal{J}_\mu(z) \approx 1 - \mathcal{J}_y\,.$$

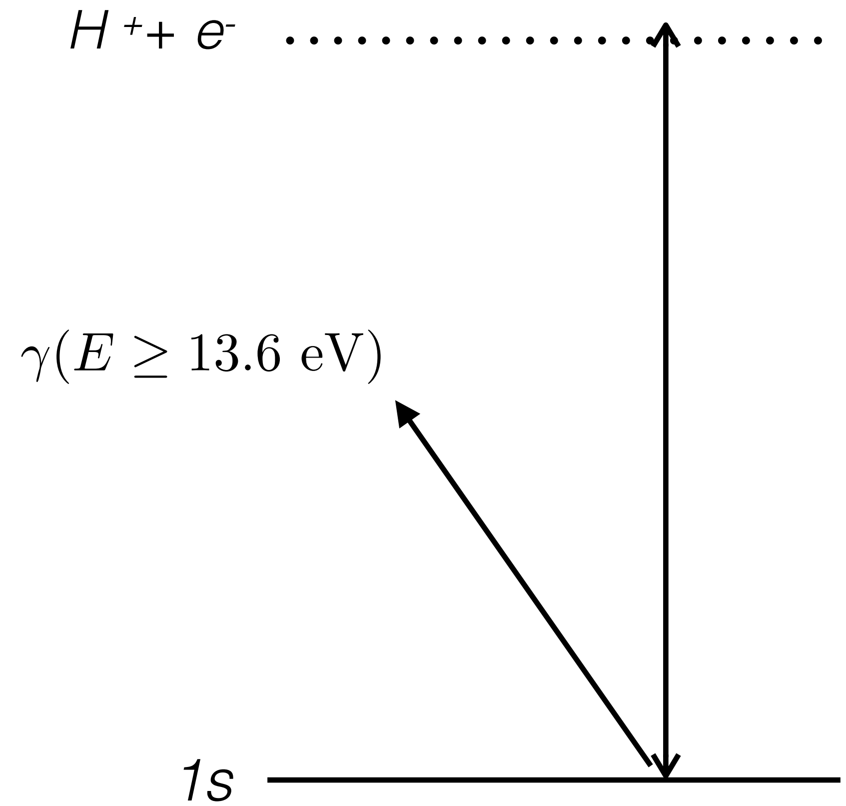
Visibility functions related to the range of efficiency of typical processes:

- Compton scattering for Comptonization-y
- Double Compton and Bremsstrahlung for µ-distortion

Recombination in a nutshell

- Era of the universe at which p and e+ recombine.
- About 380 000 y after the Big Bang at T ≈ eV

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



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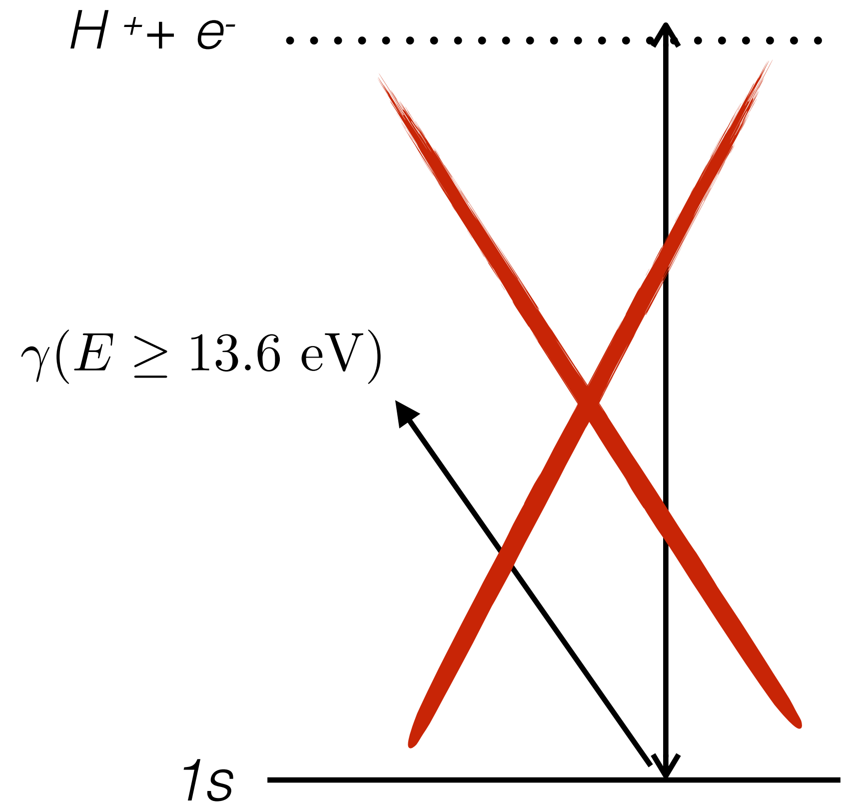
=> Wrong in Cosmology!



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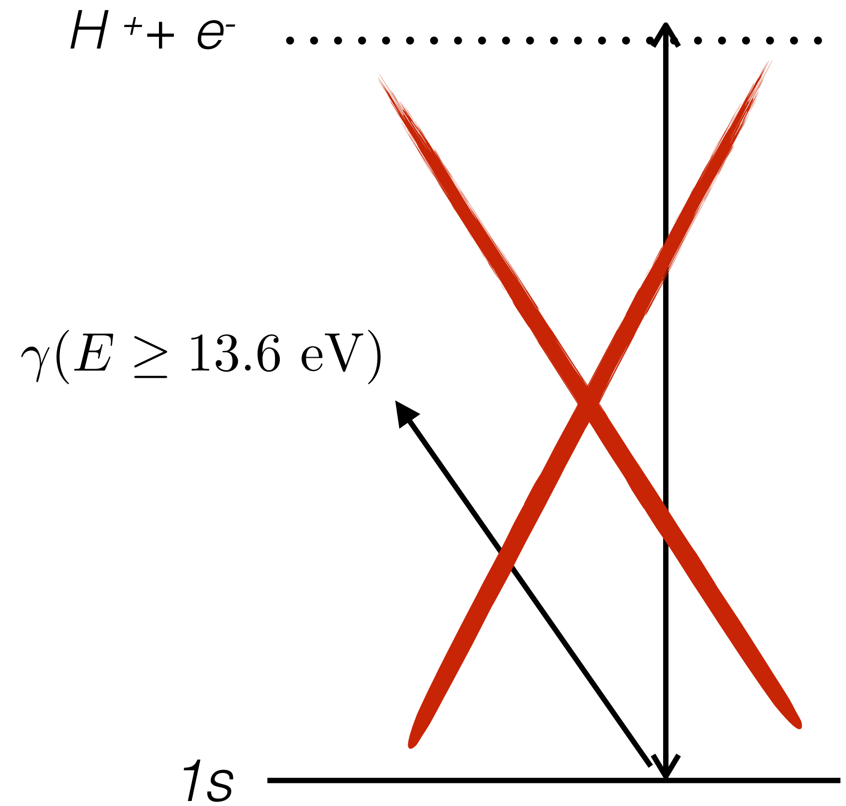

Toy model : The « three-levels atom » aka Peebles « case-b » recombination

$$H^+ + e^- \leftrightarrow H^* + \gamma$$

followed by

$$H(2p) \leftrightarrow H(1s) + \gamma$$
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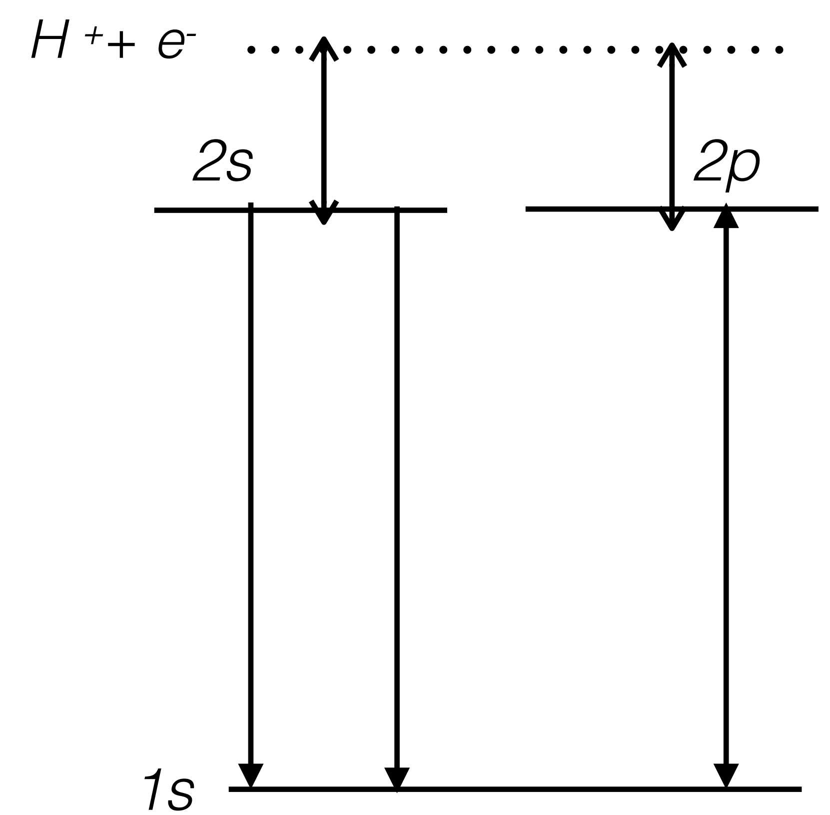

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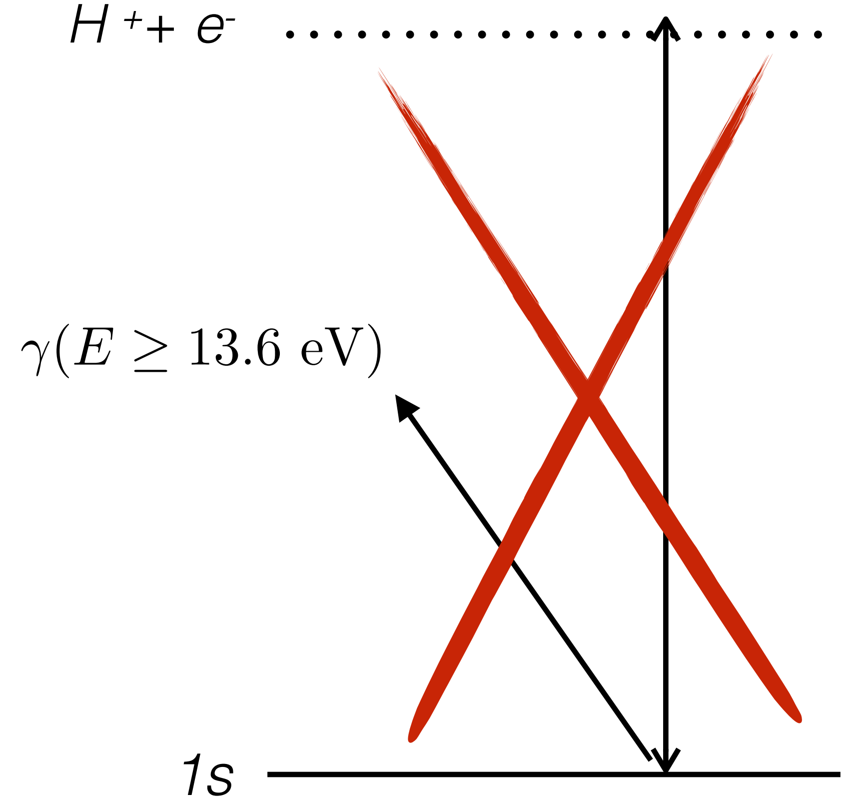

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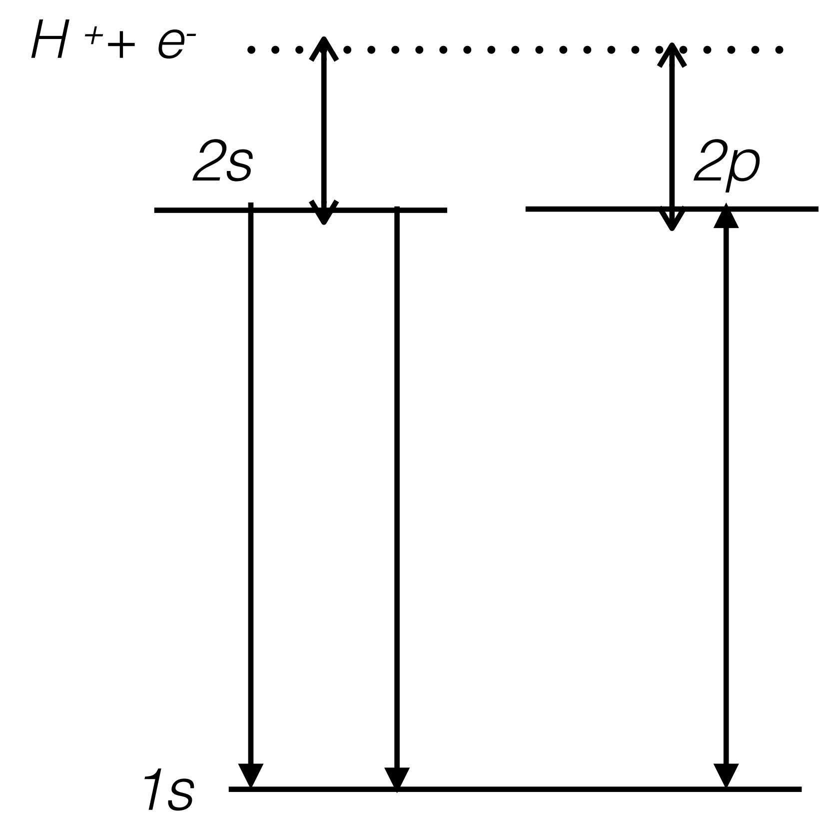
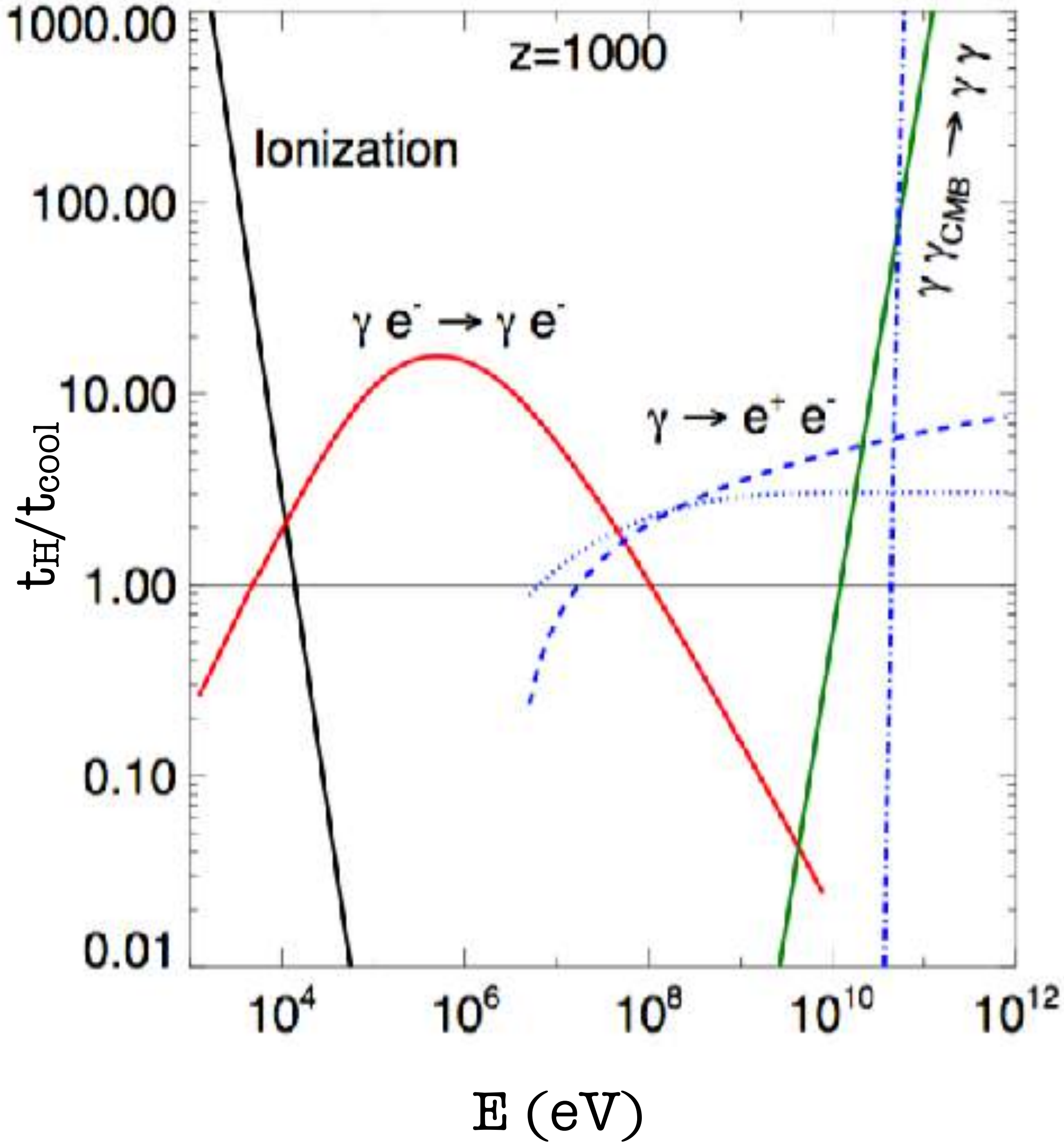
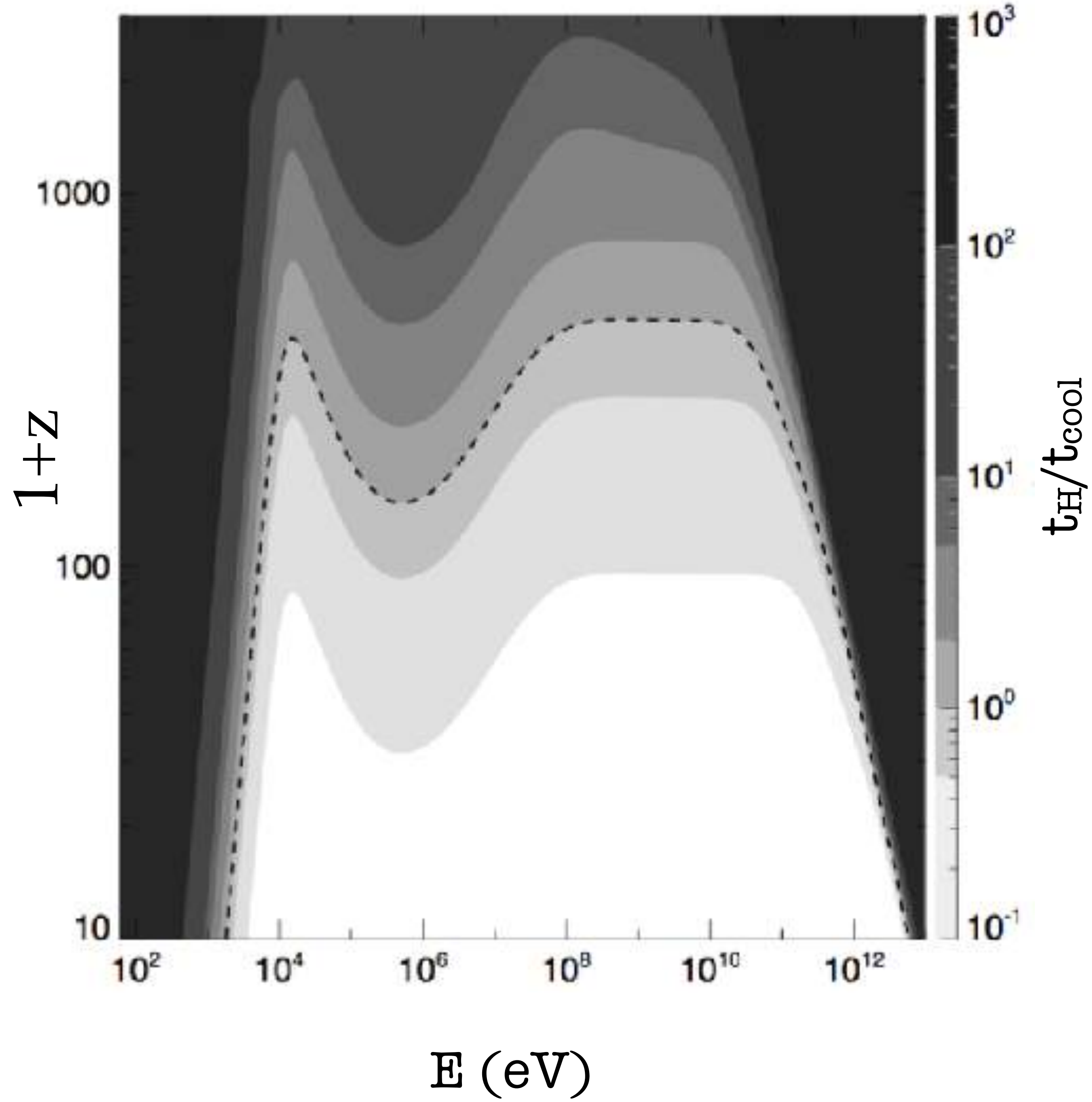
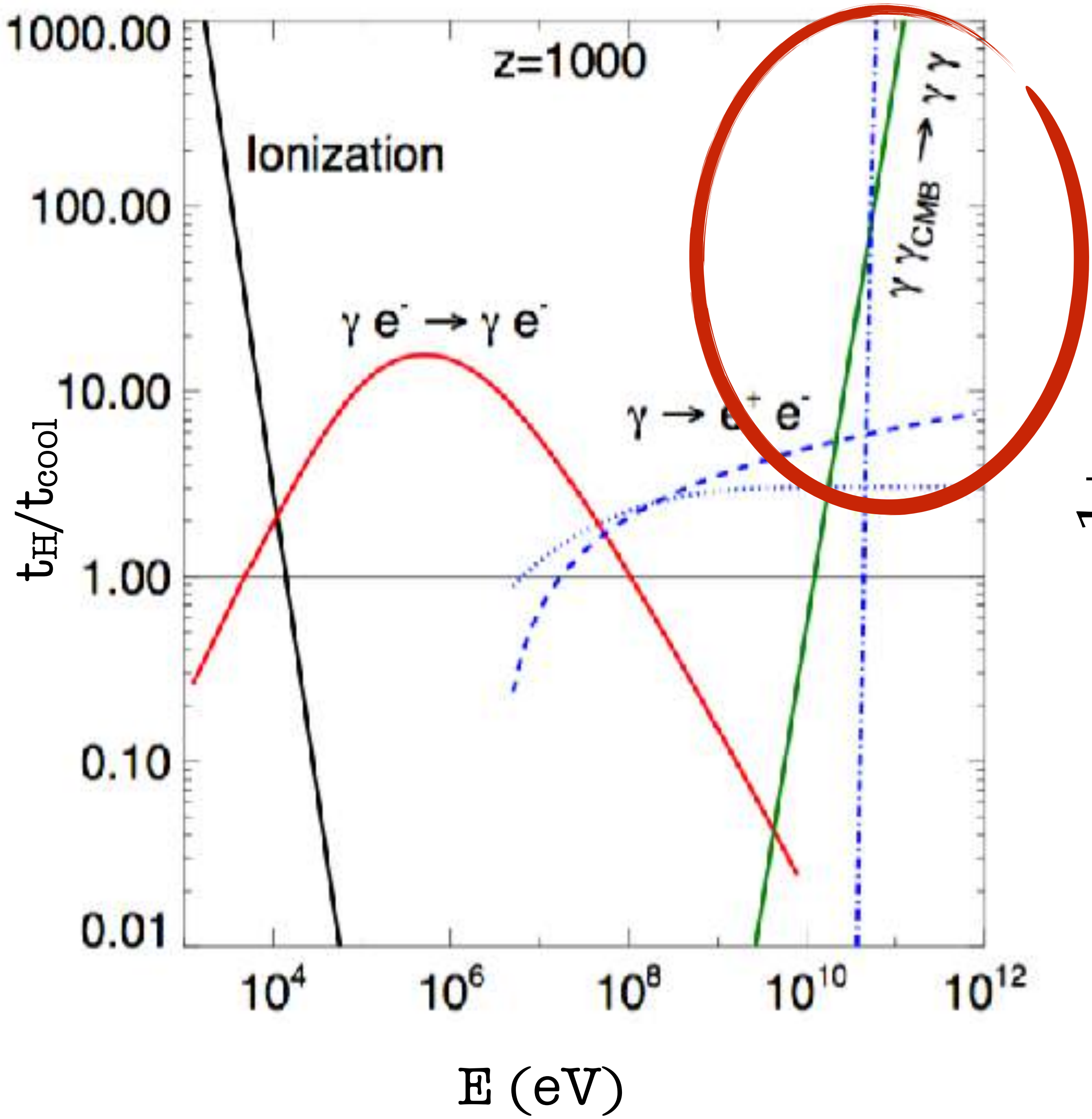


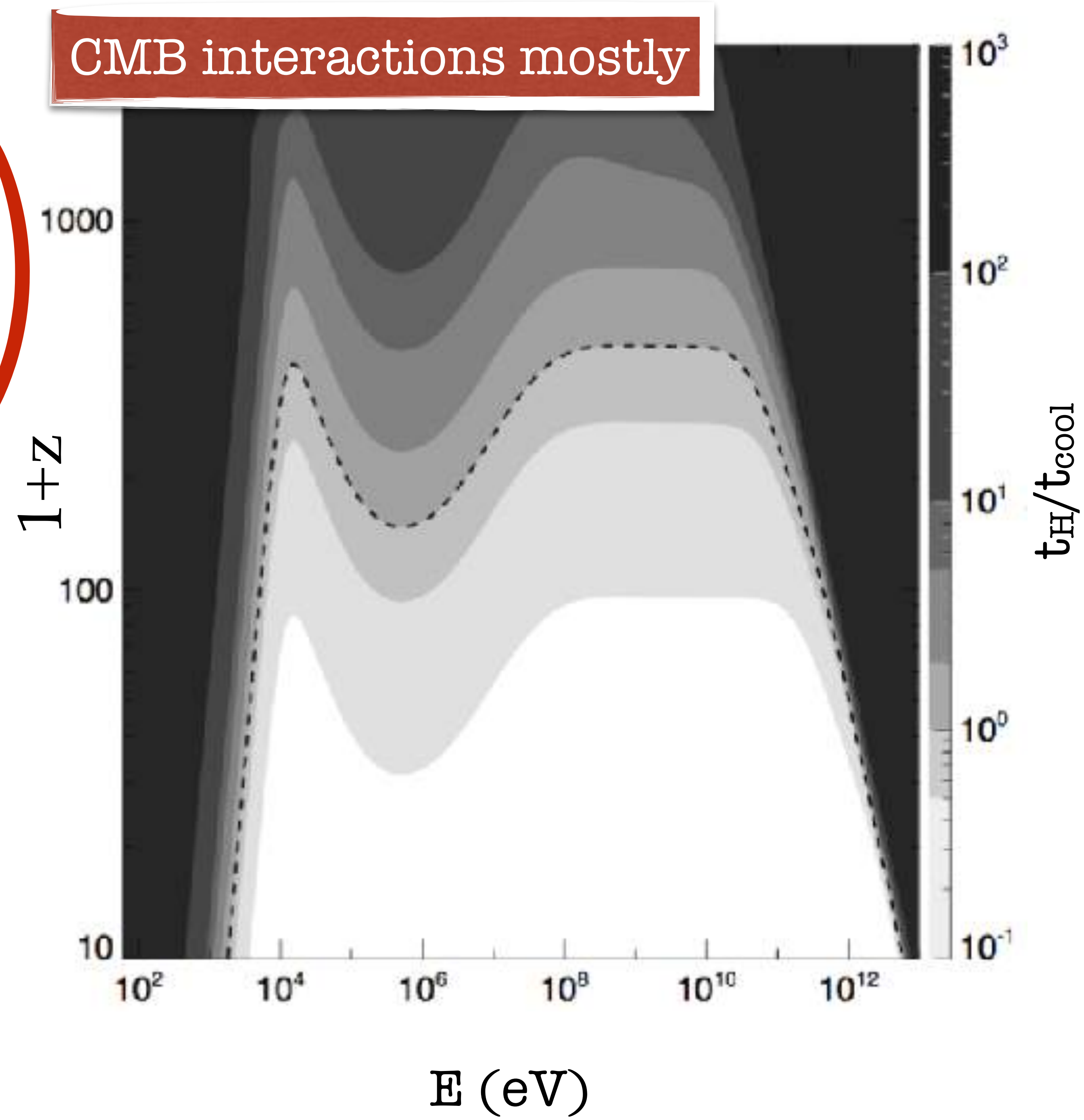
For cosmology, sub % precision is needed !
Thus, numerical codes have been developped:
e.g. **Recfast**, **Hyrec, CosmoRec**





from Slatyer et al. [arXiv:0906.1197]





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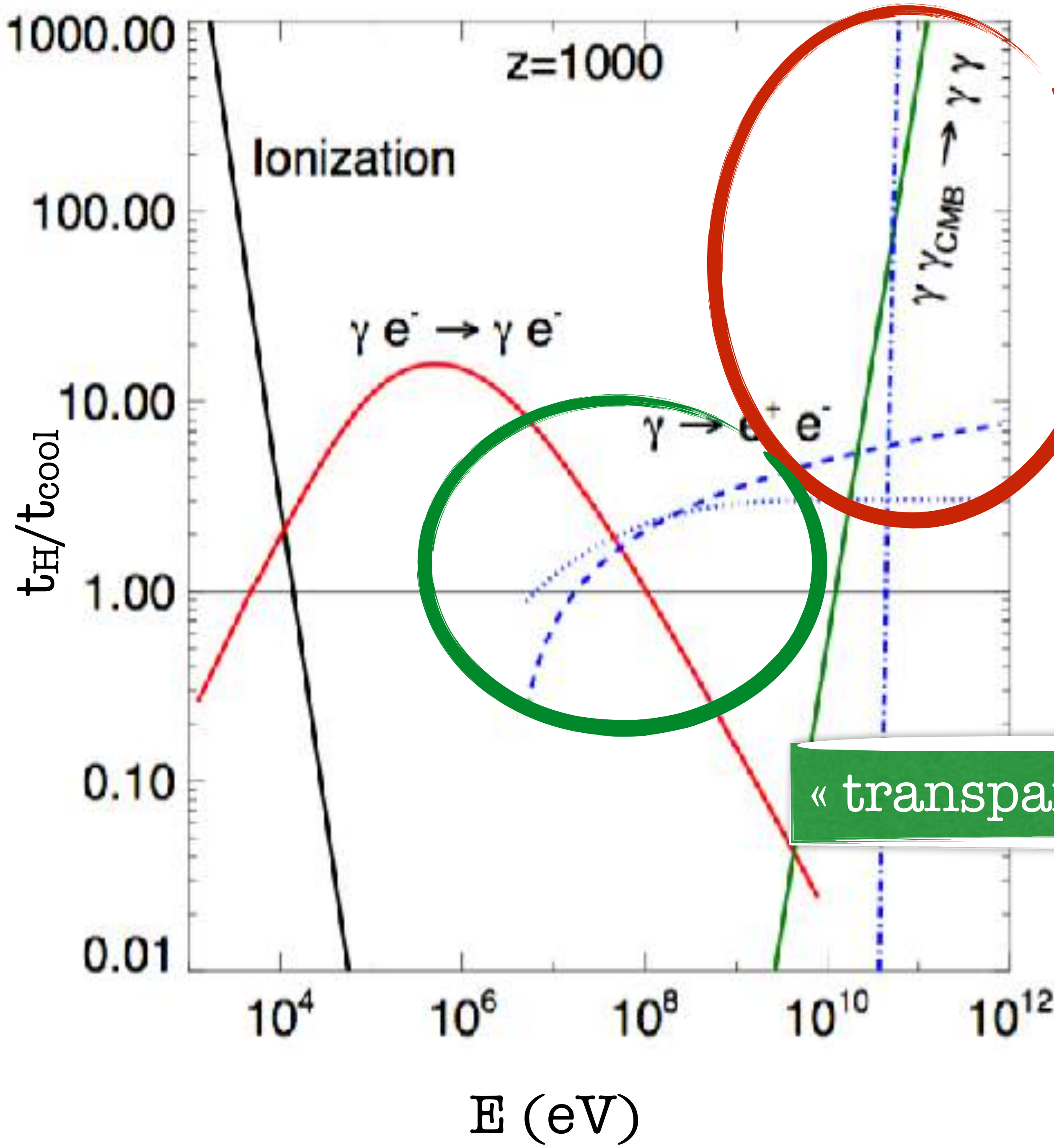

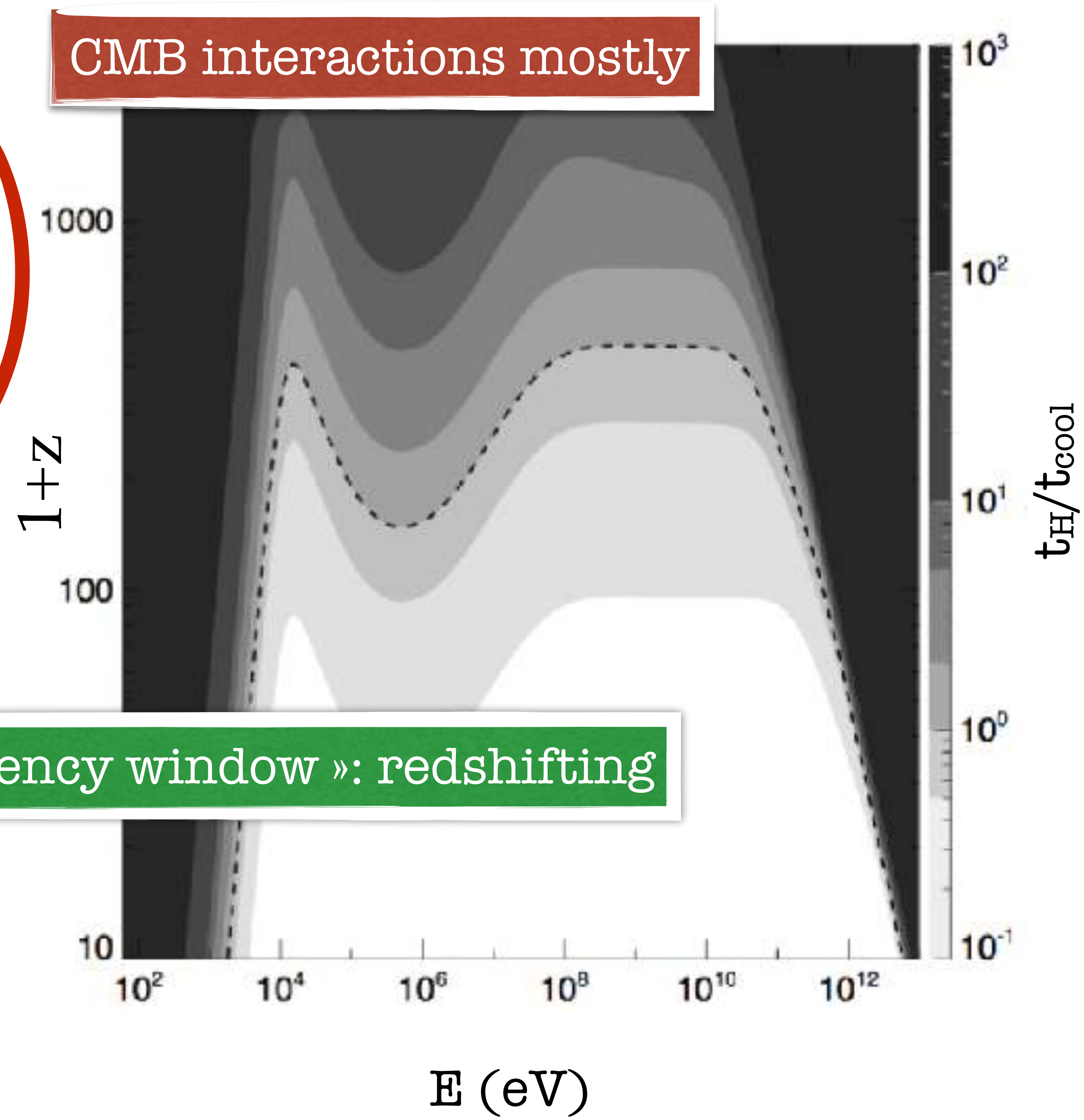

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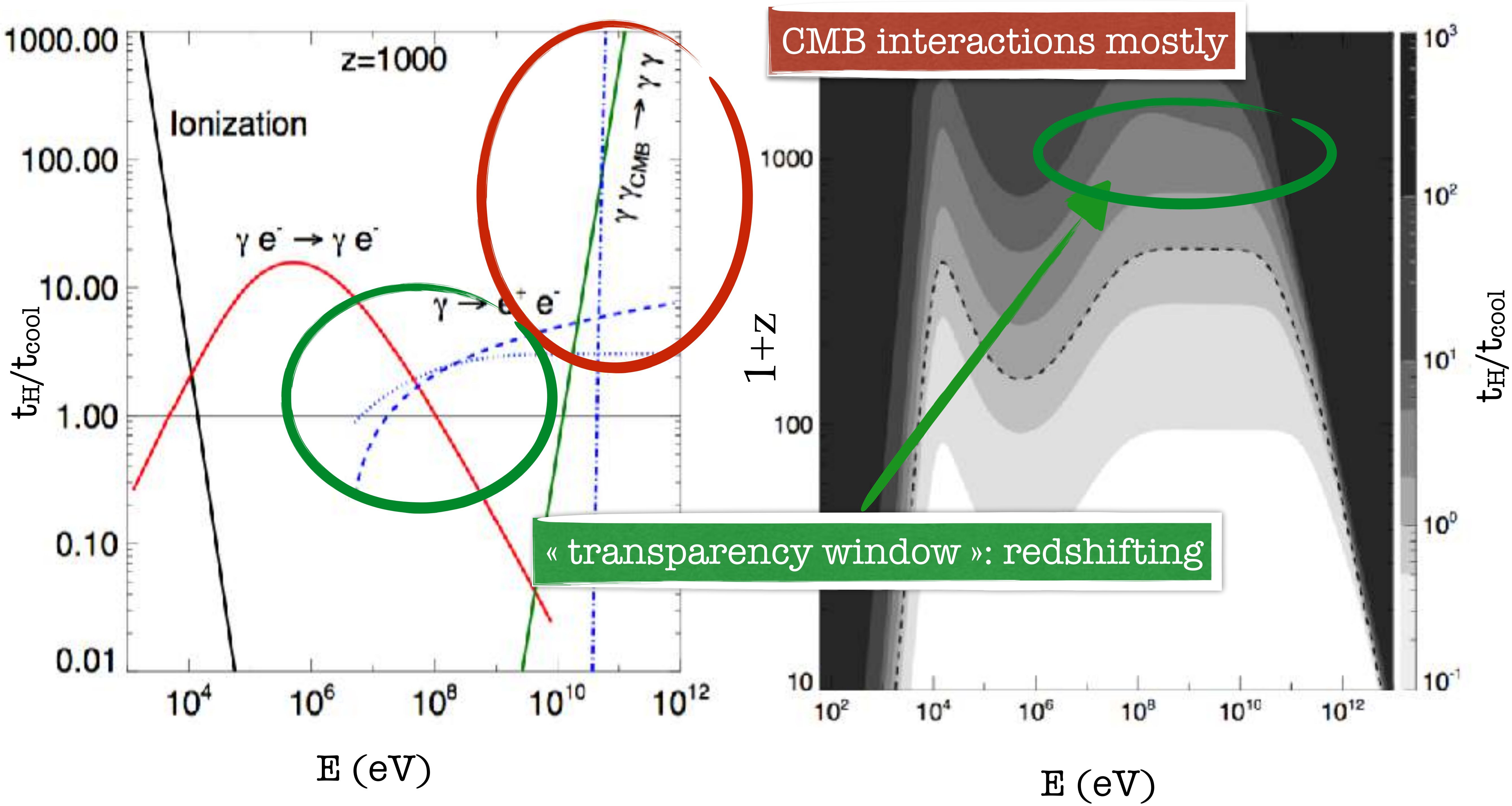

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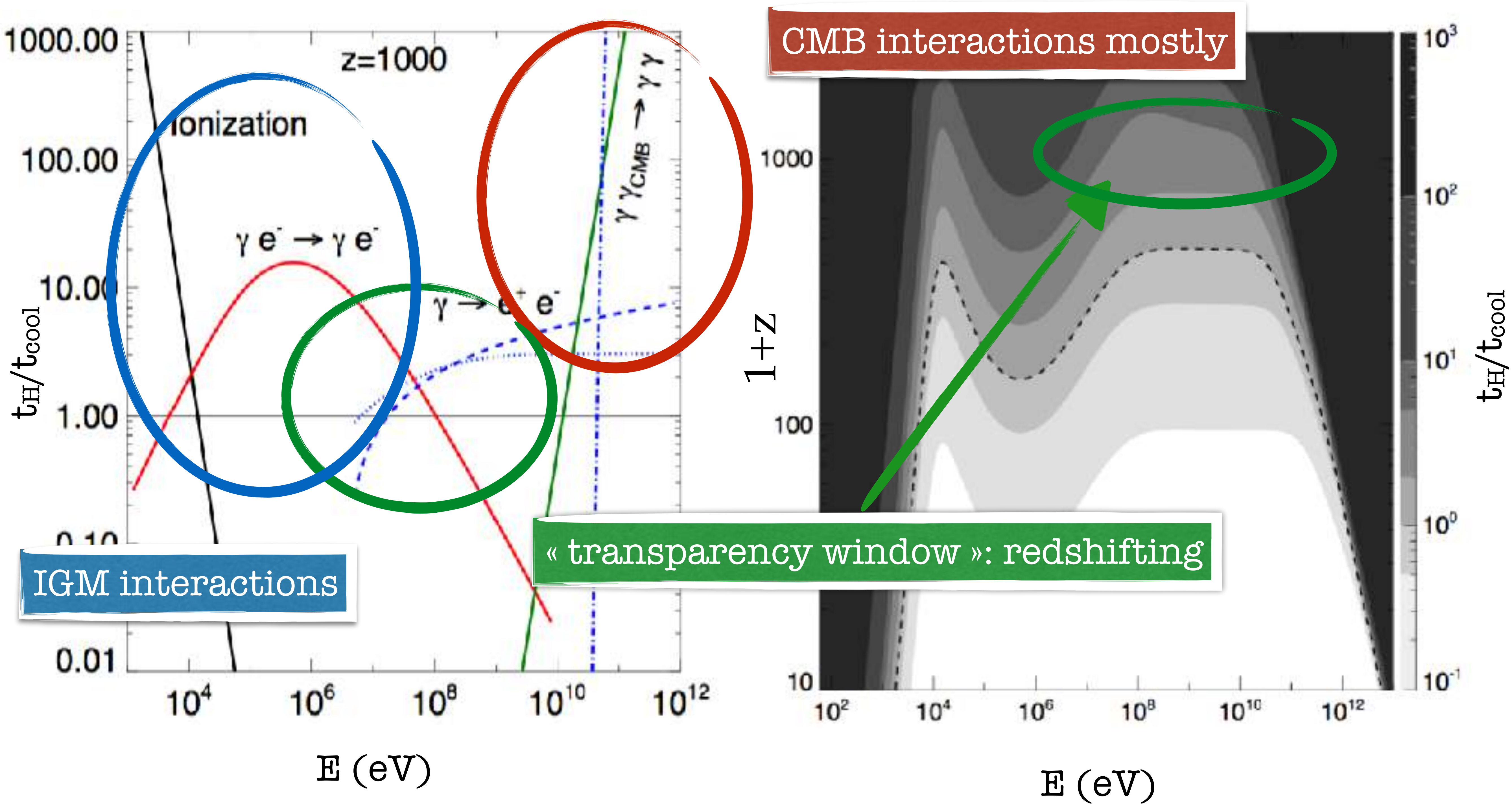

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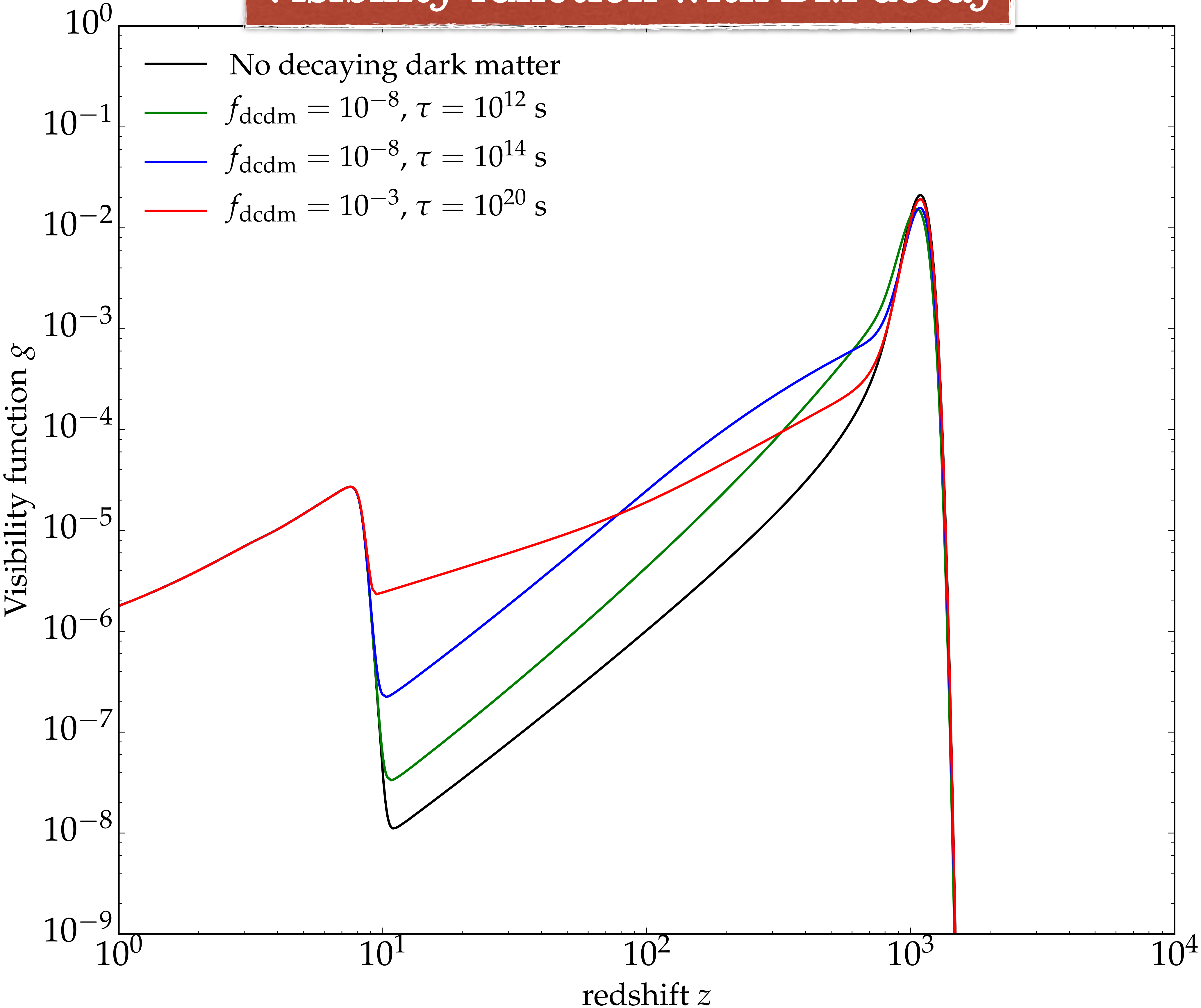
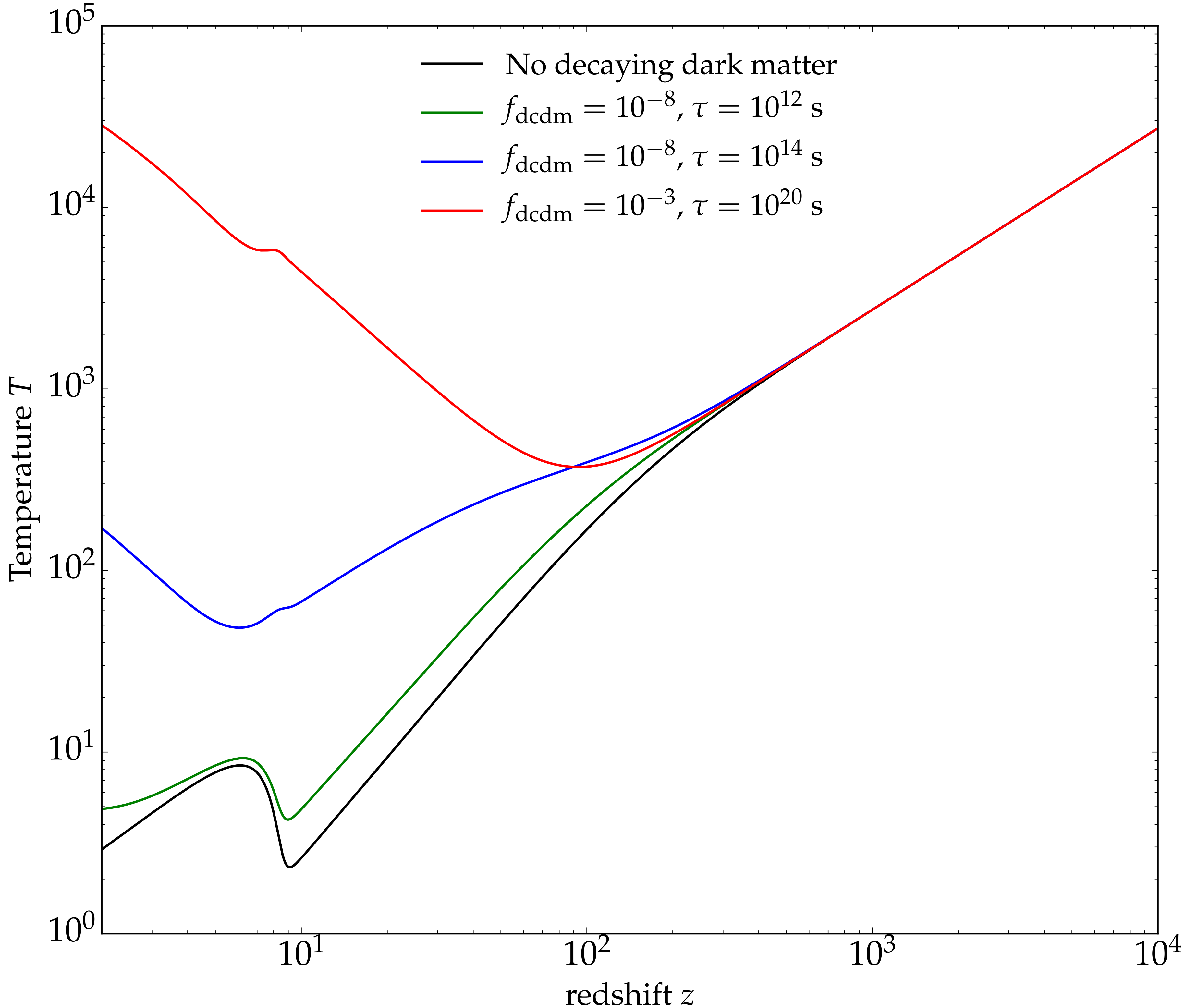
Visibility function with DM decay



IGM Temperature with DM decay

What about 21cm signal?



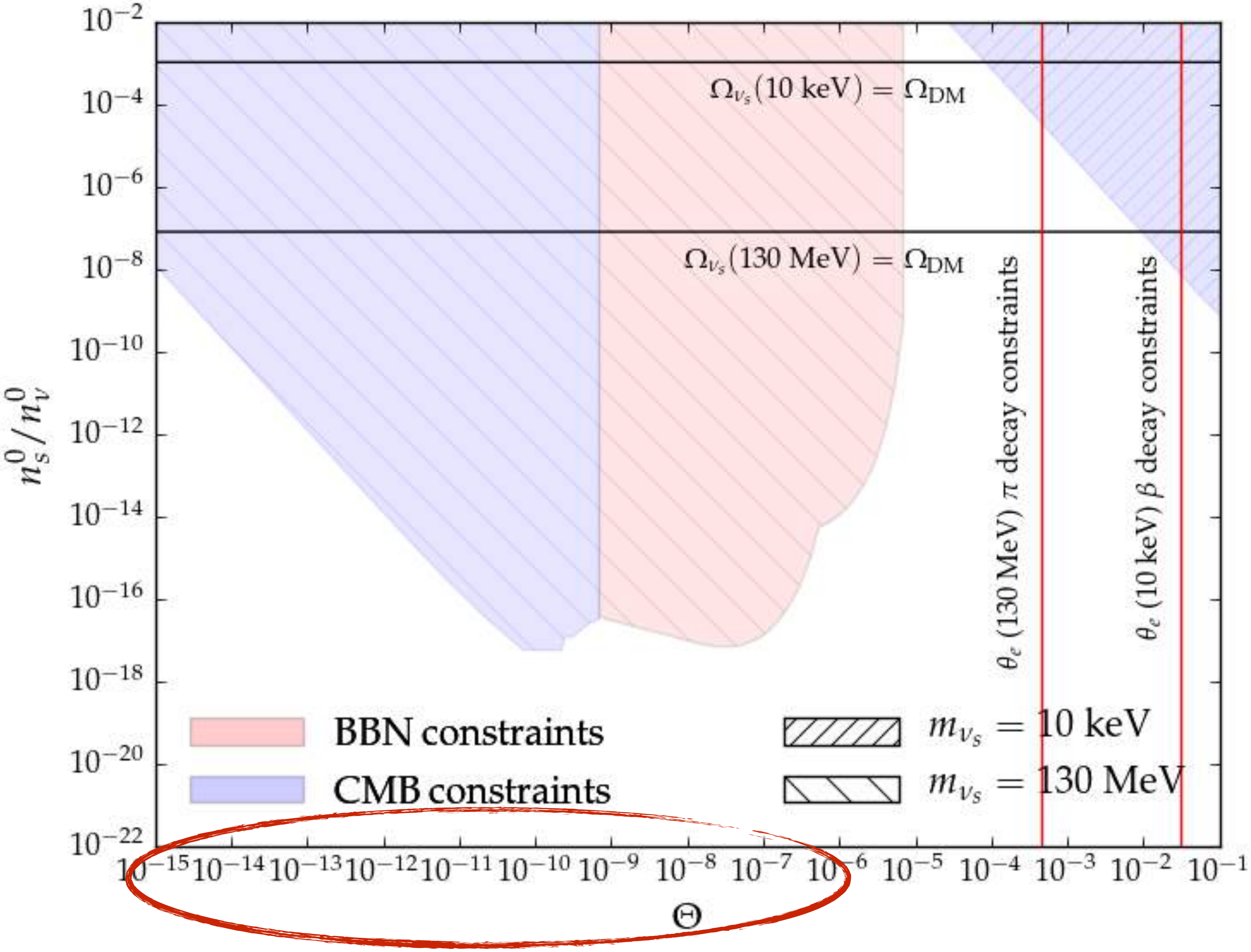
Constraints on keV-MeV scale majorana sterile neutrinos

e.g. Drewes et al. JCAP 1701(2017) 025

- Below 130MeV, main decay channels are :

$$\Gamma_{3\nu}^{-1} \simeq 3 \times 10^4 \mathrm{s} \left(\frac{\mathrm{MeV}}{\mathrm{M_s}}\right) \Theta^{-2} \qquad \Gamma_{\nu\gamma} \simeq 1.6\% \Gamma_{3\nu} \qquad \Gamma_{\nu e^+ e^-} \simeq \mathcal{O}(10\%) \Gamma_{3\nu}$$

- See saw requires typically, $\Theta^2 \gtrsim 10^{-5} M_{\mathrm{MeV}}^{-1}$ what do we learn then ?



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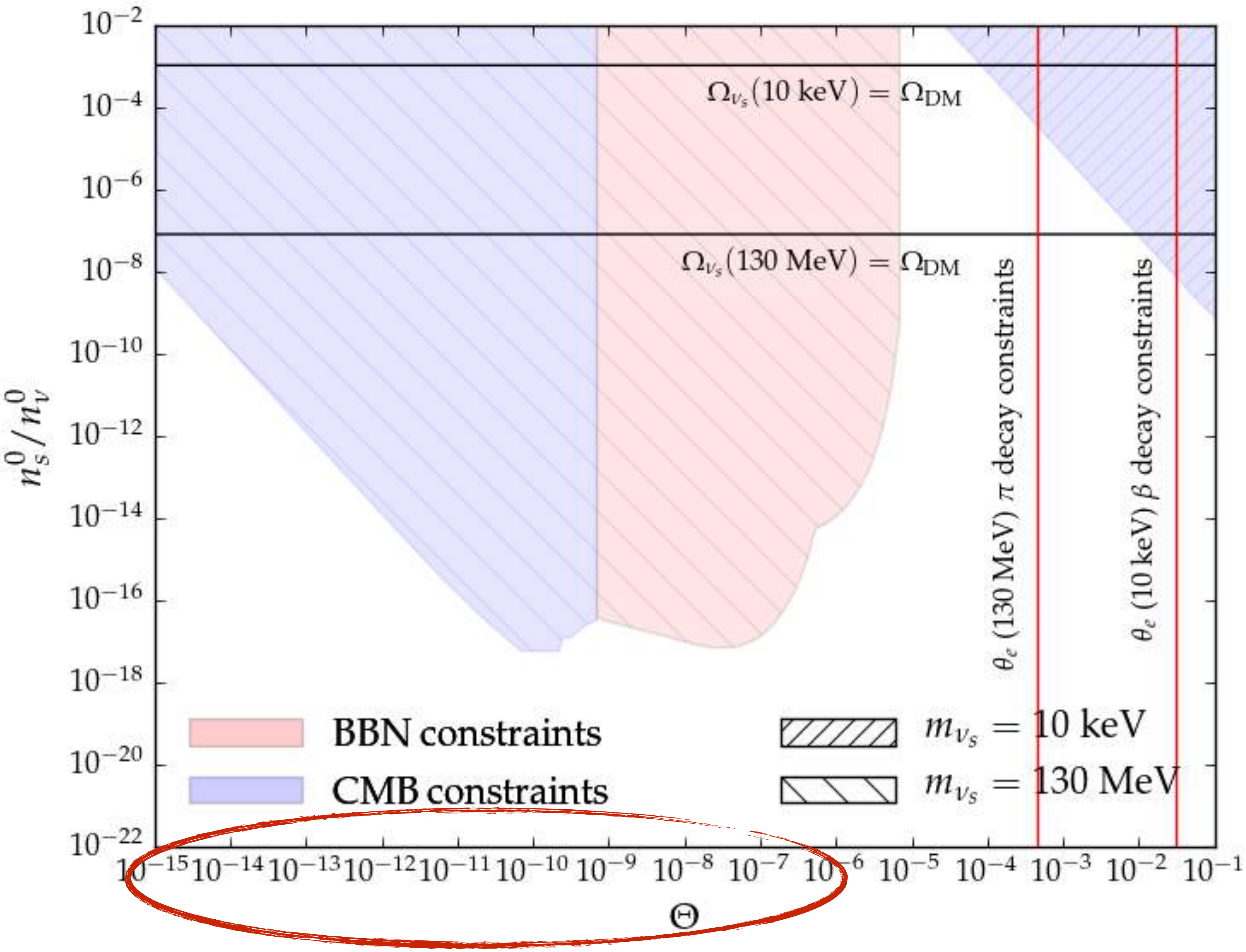

- Cosmology is mostly sensitive to sterile neutrinos more weakly coupled than those evolve in see-saw mechanism;
- Still, it is interesting since masses and mixing of the right-handed neutrinos are not constrained by fundamental physics arguments !
- KeV-scale neutrinos are usually better constrained by diffuse X-ray background

Boyarsky et al. MNRAS 370 (2006) 213–218

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

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number density
of pairs

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number density of pairs × annihilation probability × energy released per annihilation

In the smooth background :

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

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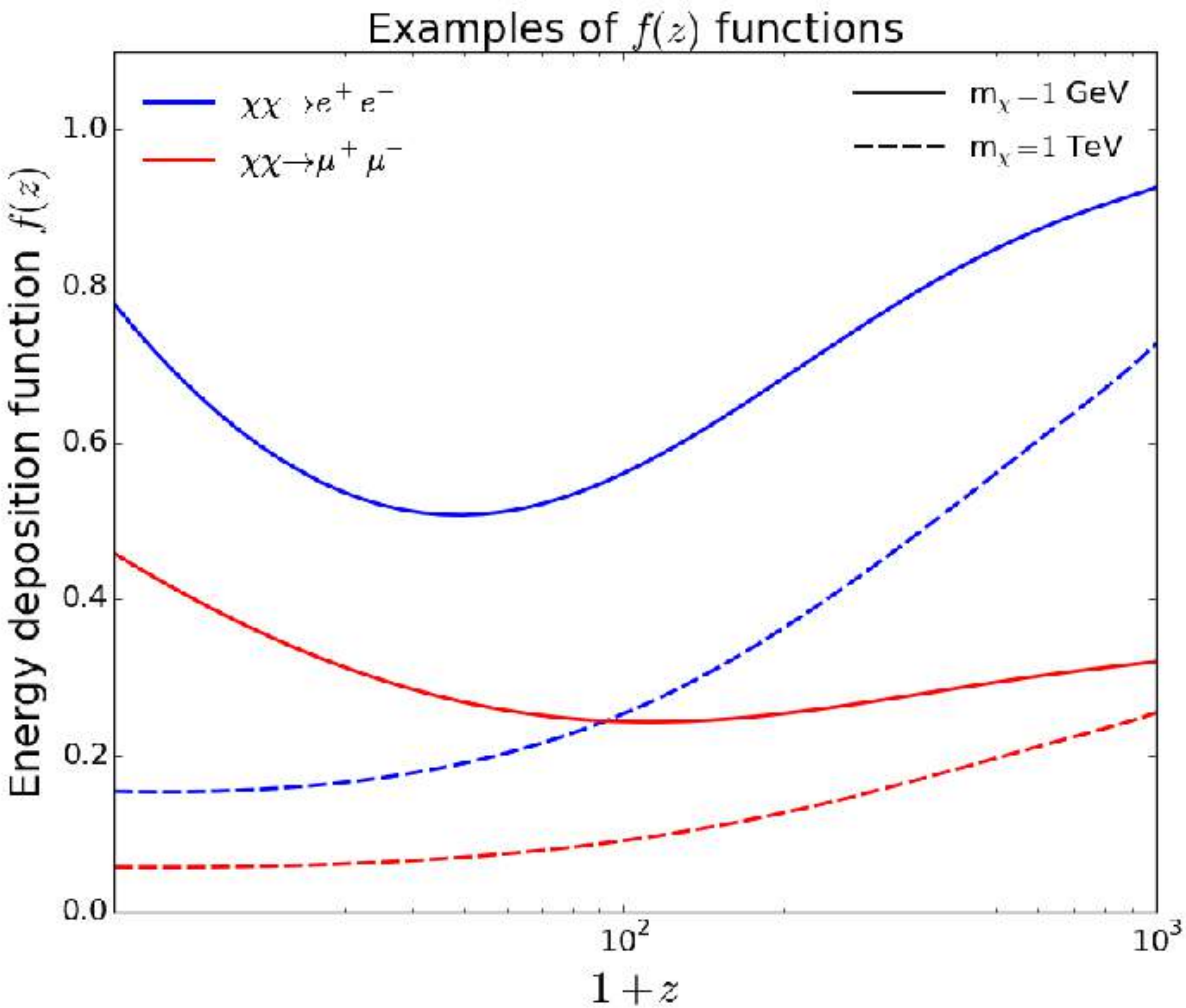
Typical parameterization through the $f(z)$ functions :

$$\left.\frac{dE}{dV\,dt}\right|_{\rm dep}(z) = f(z)\left.\frac{dE}{dV\,dt}\right|_{\rm inj}(z)$$


Examples of $f(z)$ functions
$\chi\chi\to e^+e^-$
$\chi\chi\to\mu^+\mu^-$
$m_\chi=1$ GeV
$m_\chi=1$ TeV
Energy deposition function $f(z)$
1.0
0.8
0.6
0.4
0.2
0.0
10^2
10^3
$1+z$

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

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

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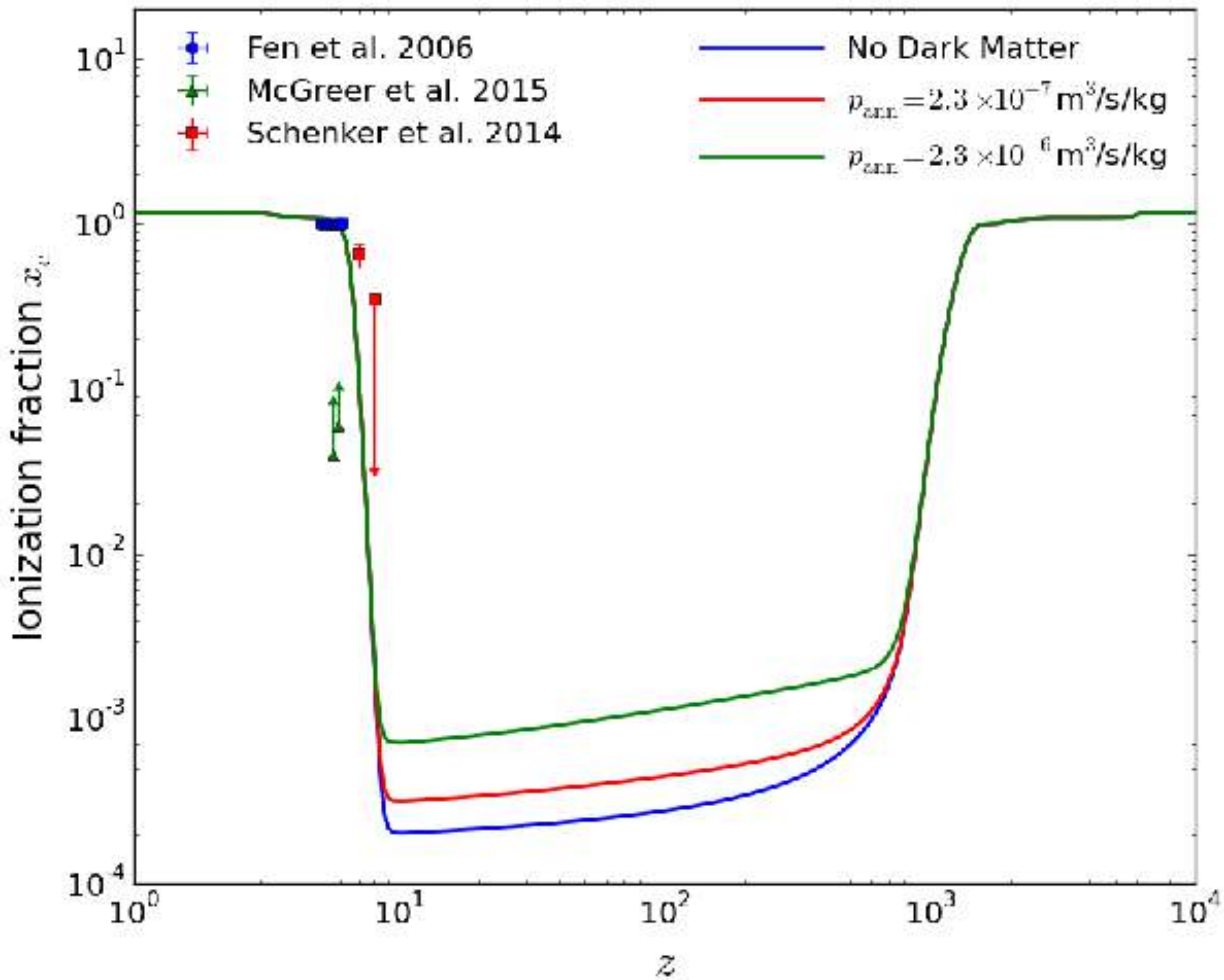
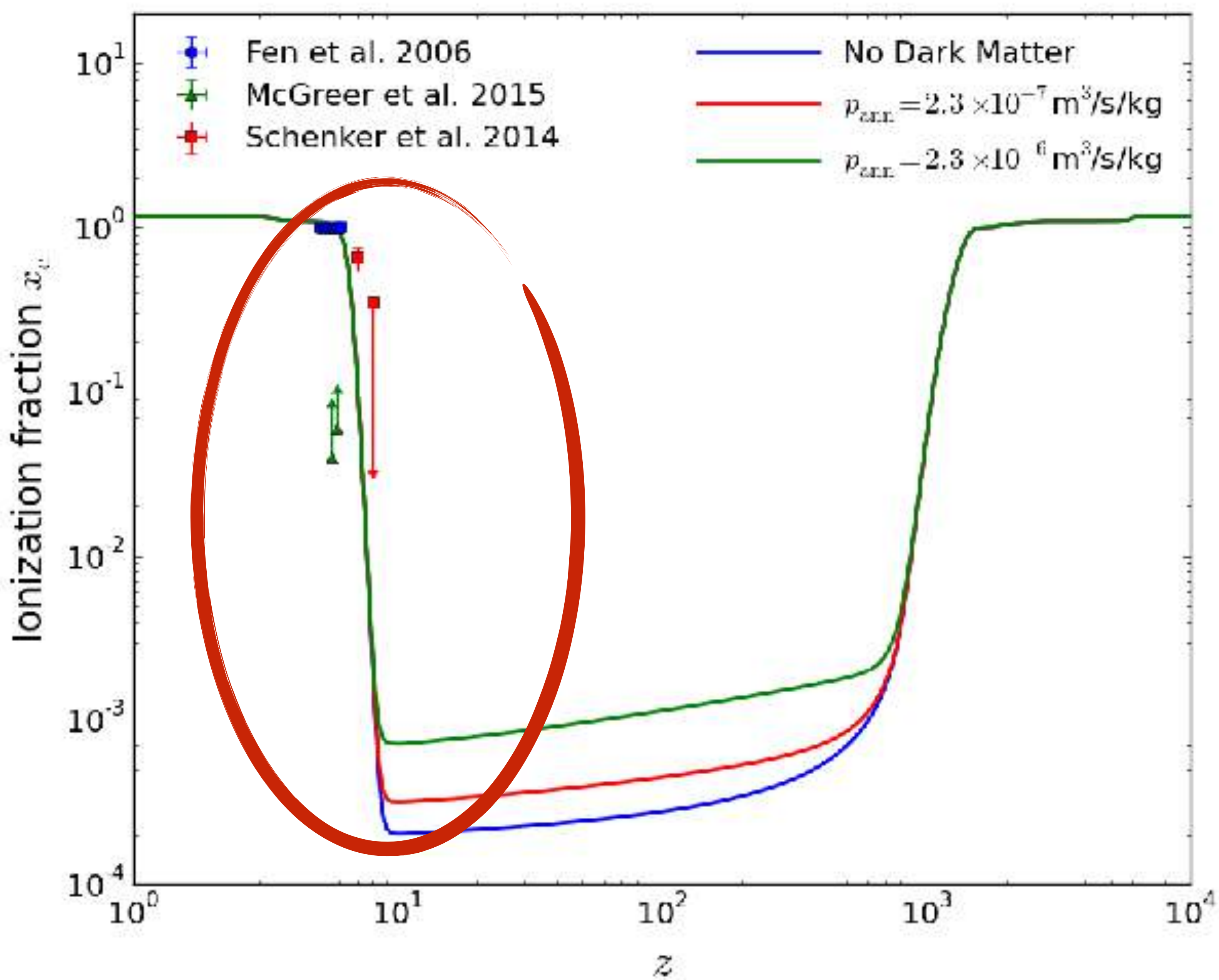
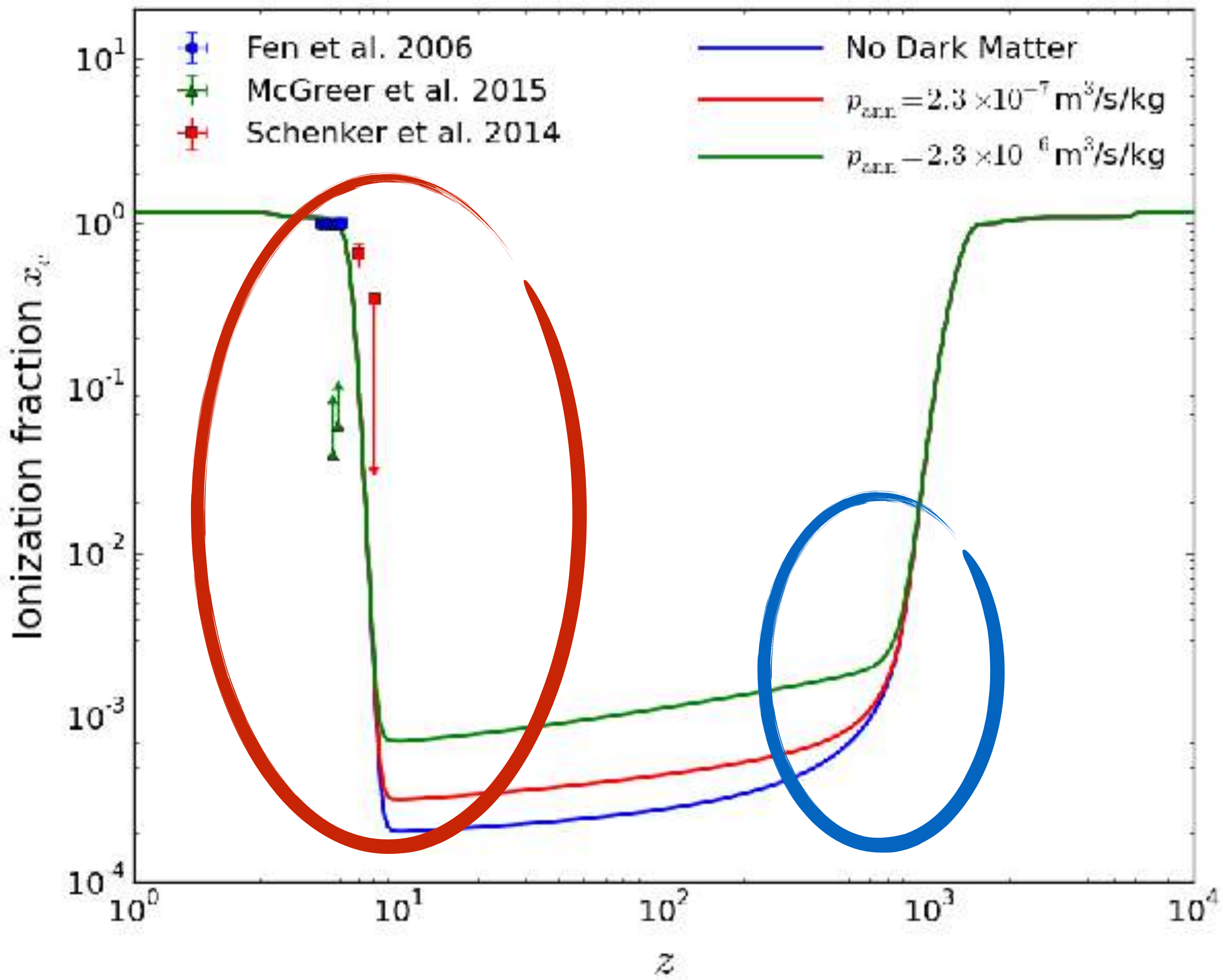
This is the quantity really constrained by CMB power spectra analysis !


Fen et al. 2006
McGreer et al. 2015
Schenker et al. 2014
No Dark Matter
$p_{ann} = 2.3 \times 10^{-7}$ m^3/s/kg
$p_{ann} = 2.3 \times 10^{-6}$ m^3/s/kg
Ionization fraction x_e
z
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^0
10^1
10^2
10^3
10^4



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



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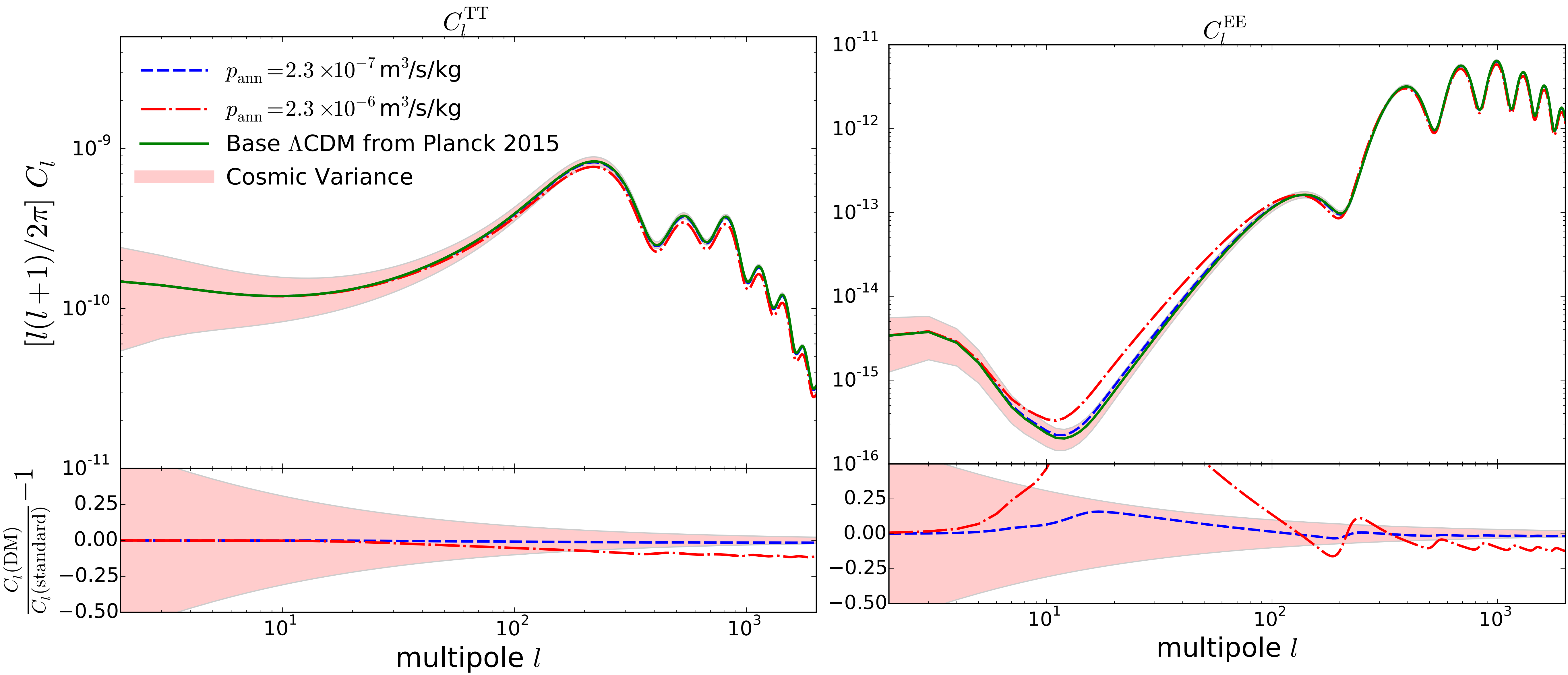
Mostly due to star formation.
Still to understand.

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

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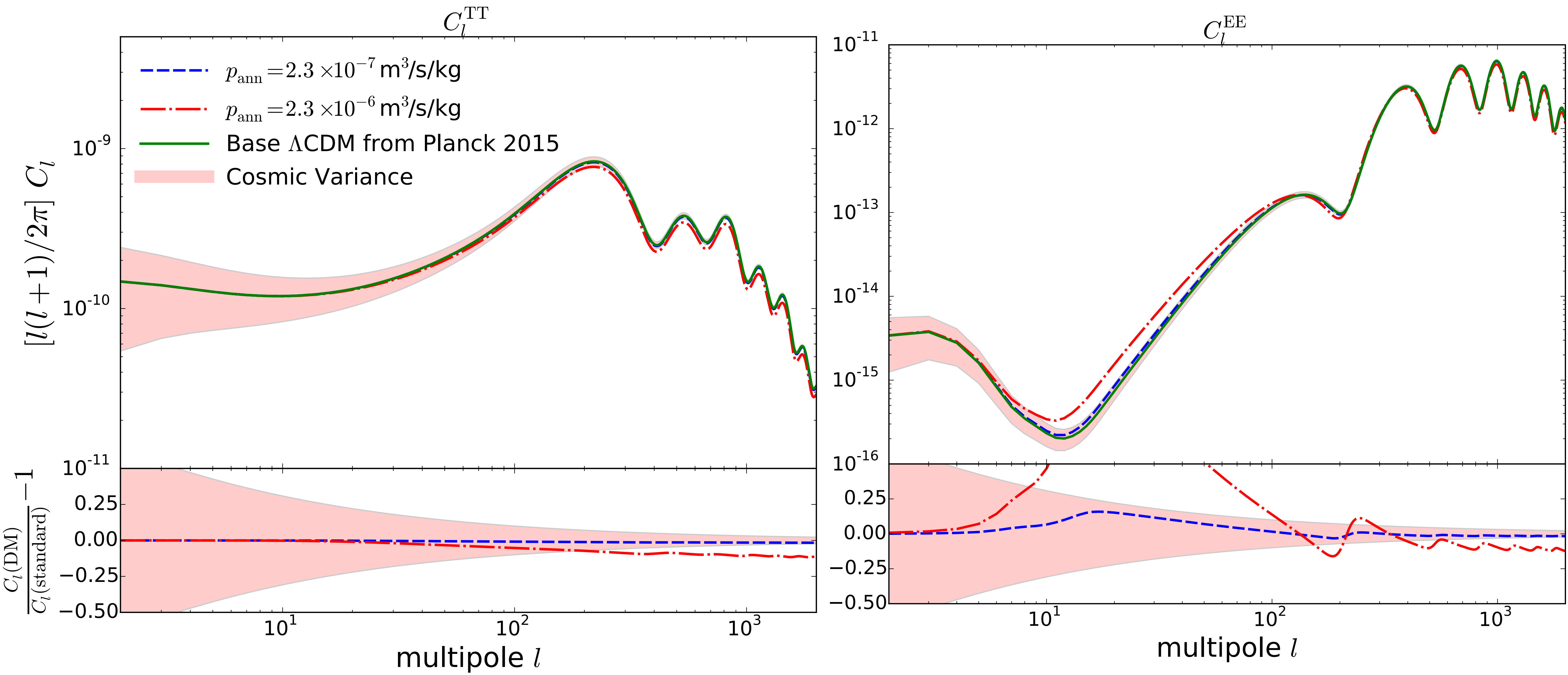
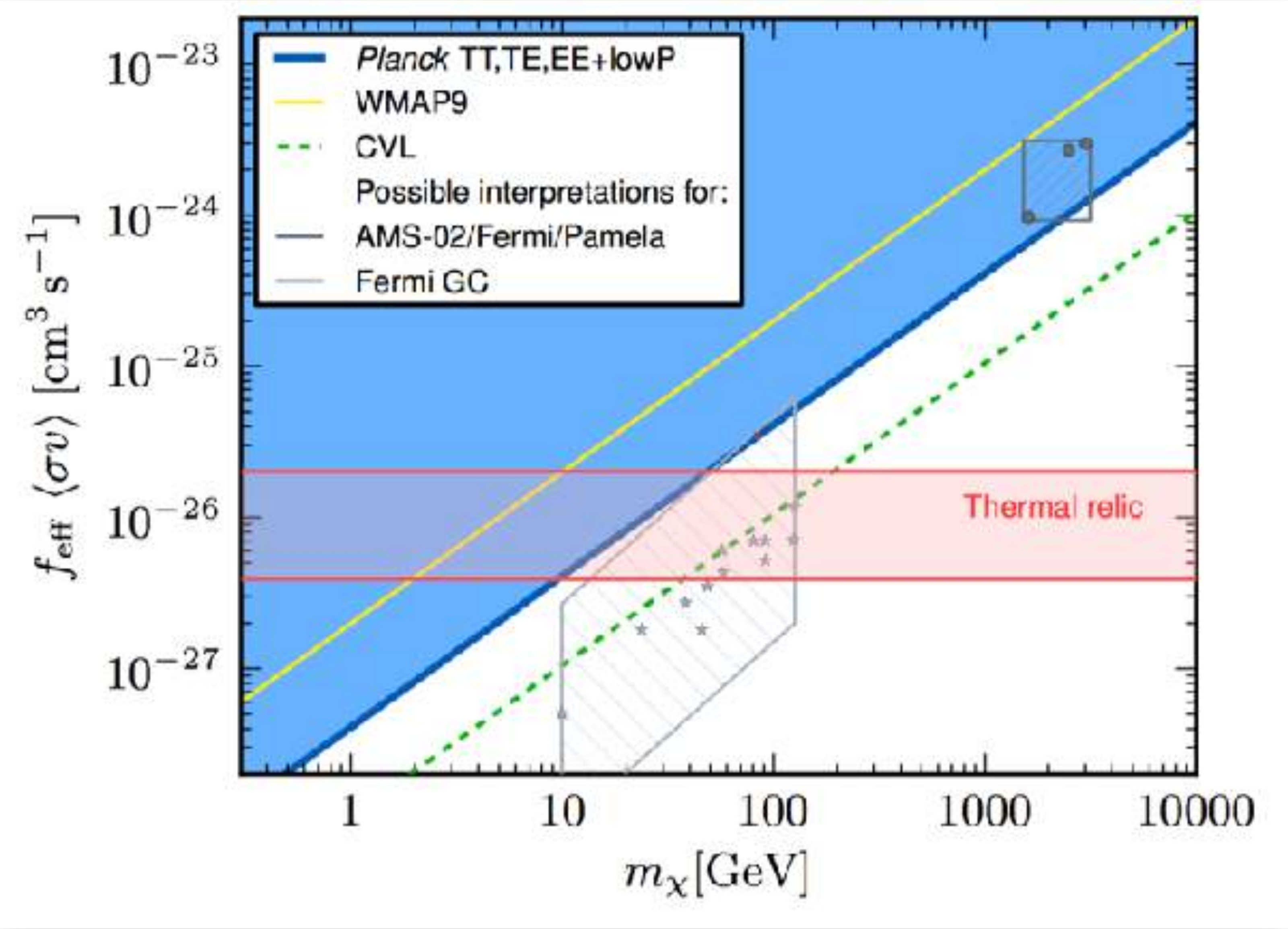


More scattering implies :

1) Suppression of power on all scales with $\ell > 200$

2) Regeneration of power in the polarization spectrum



$$p_{\rm ann} \equiv f_{\rm eff}\frac{\langle\sigma_{\rm ann}v\rangle}{m_{\rm DM}} < 3.4\times10^{-28}{\rm cm}^3{\rm s}^{-1}{\rm GeV}^{-1}$$

$$\text{TT, TE, EE + lowP + lensing}$$

Planck 2015 [arXiv: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?

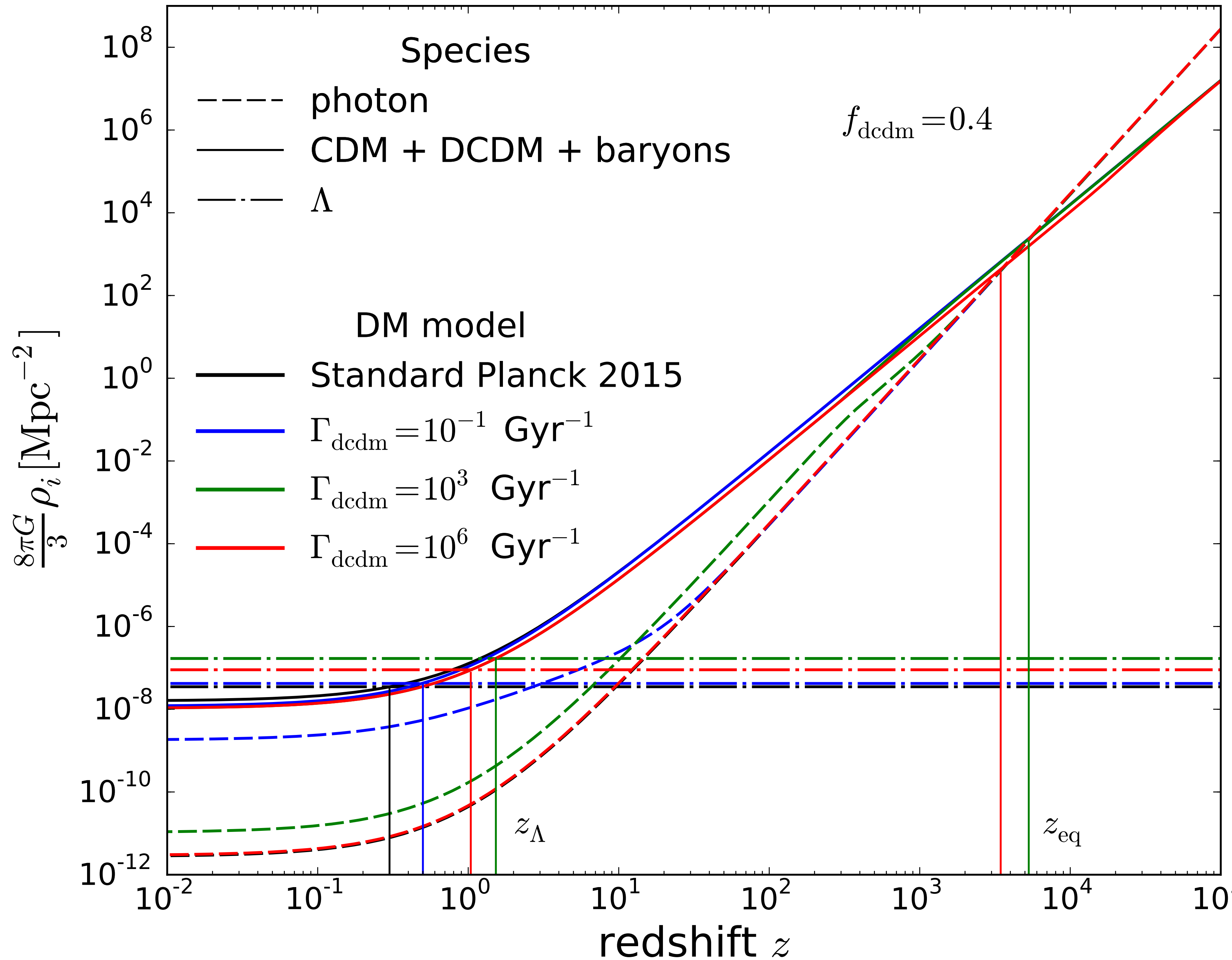
Evolution of background quantities

$$\theta_s = \frac{d_s(\text{rec})}{d_A(\text{rec})}$$

$$d_A(\text{rec}) = a\int_0^{z_{\text{rec}}} \frac{dz}{H(z)}$$

$$H(z) = \sqrt{\omega_m(1+z)^3 + \omega_\Lambda}$$

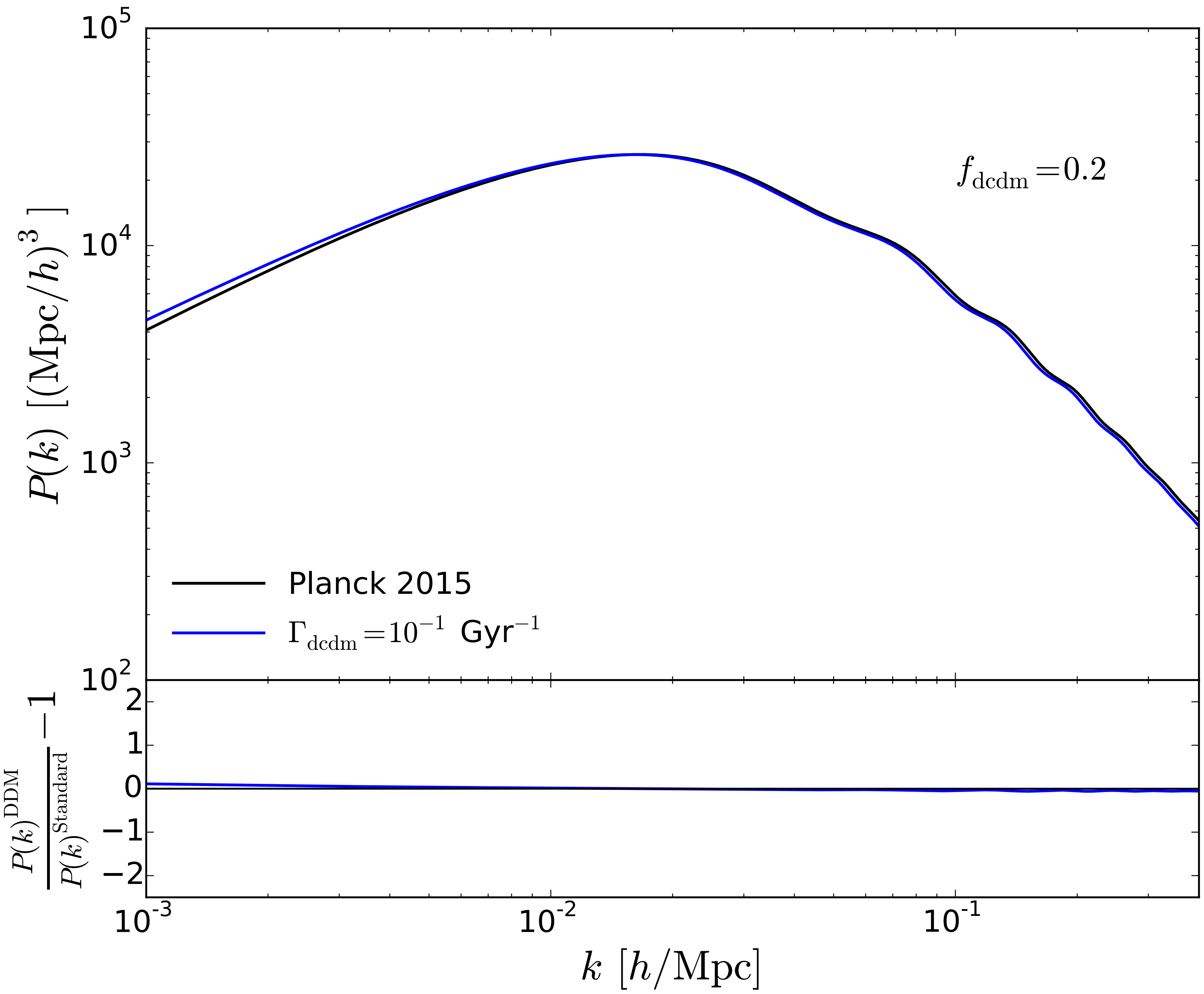
Fixing θ_s requires changing ω_Λ



Main impact:

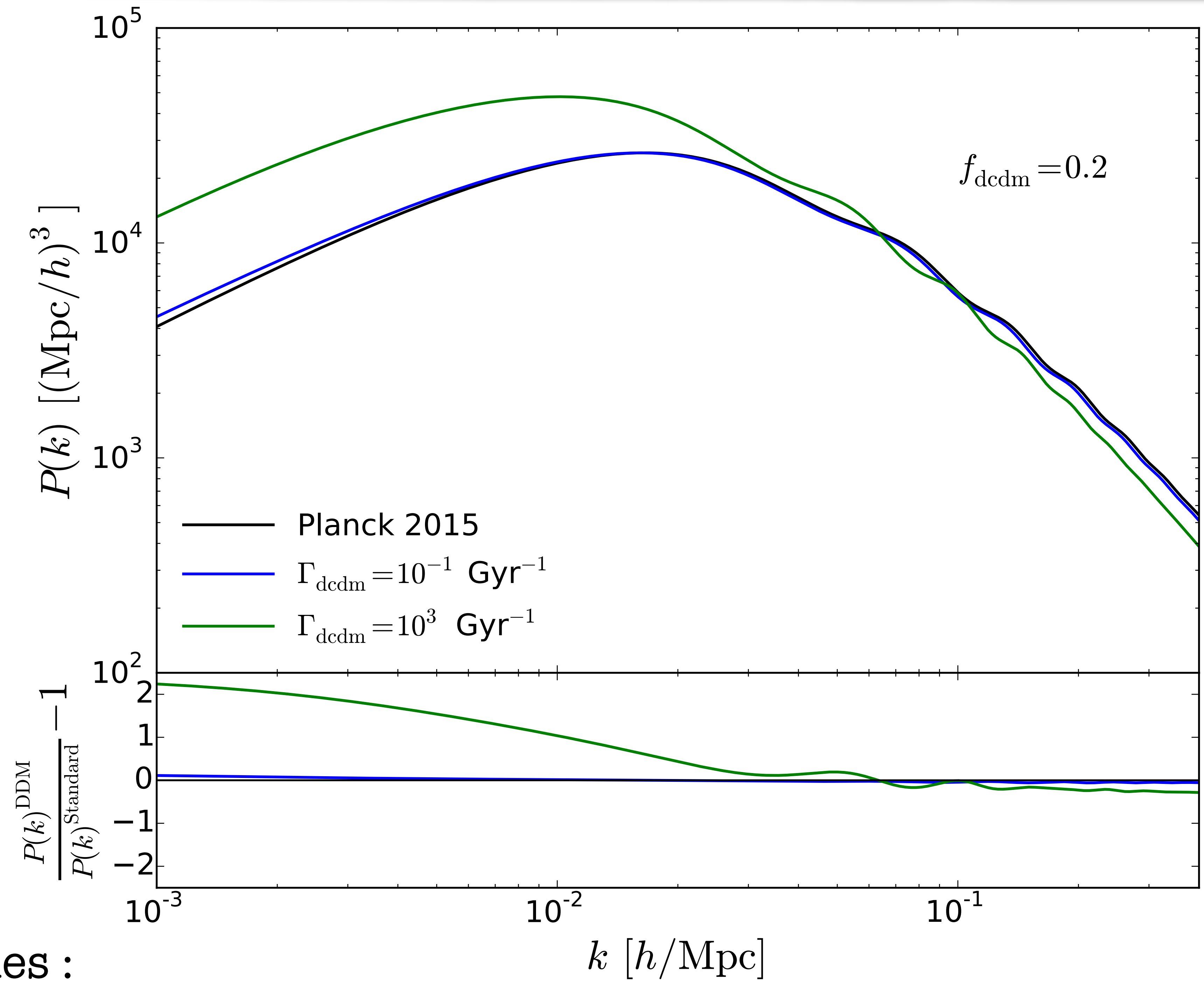
- Shifts of z_{eq}, z_Λ and extra metric damping => ISW modified
- Modification of CMB lensing

Impact on the (linear) matter power spectrum



- Slight (horizontal) shift of the peak because the ratio $k_{\rm eq}/a_0 H_0$, which sets the peak scale, is smaller.

Impact on the (linear) matter power spectrum

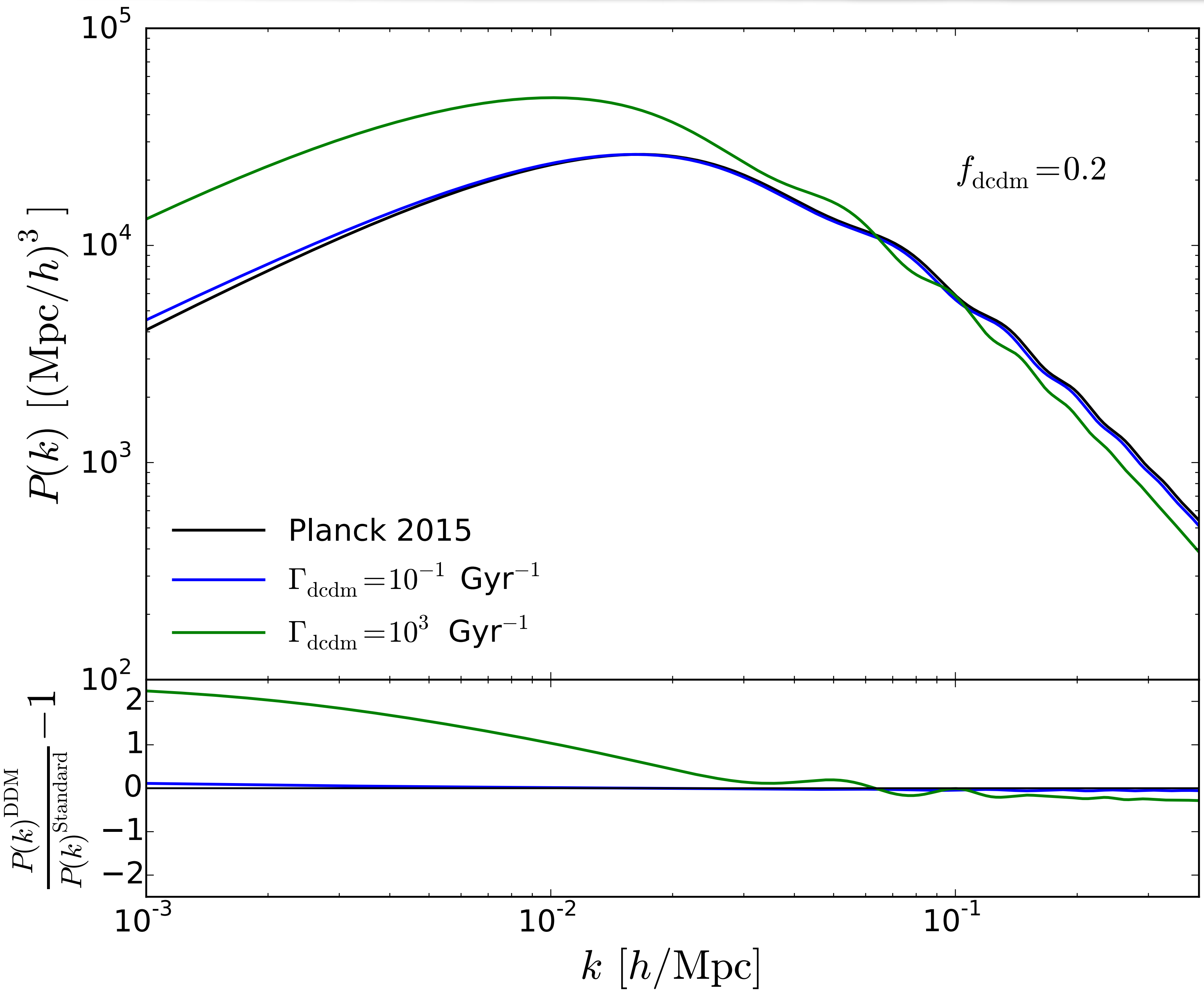


- On large scales :

$P(k) \propto (g(a_0,\Omega_m)/\Omega_m)^2$; $g(a_0,\Omega_m)$ suppression of growth rate during Λ domination

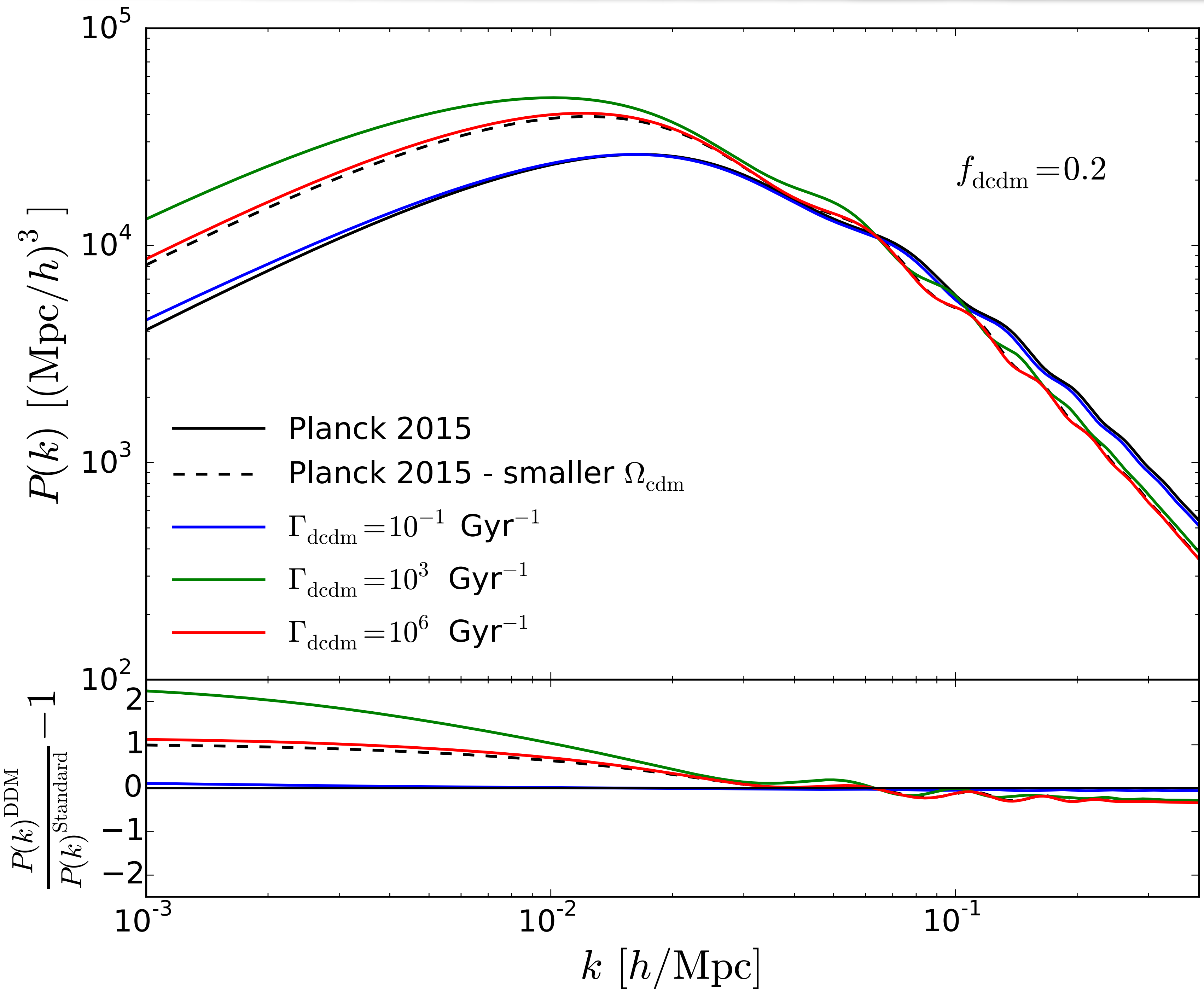
Ω_m decreases more than $g(a_0,\Omega_m)$ => Enhancement of $P(k)$ on large scales

Impact on the (linear) matter power spectrum



- On small scales : the ratio Ω_b/Ω_m start to change at early times
  => suppression of P(k) on small scales
  => shift of the BAO because of a different sound horizon at baryon drag.

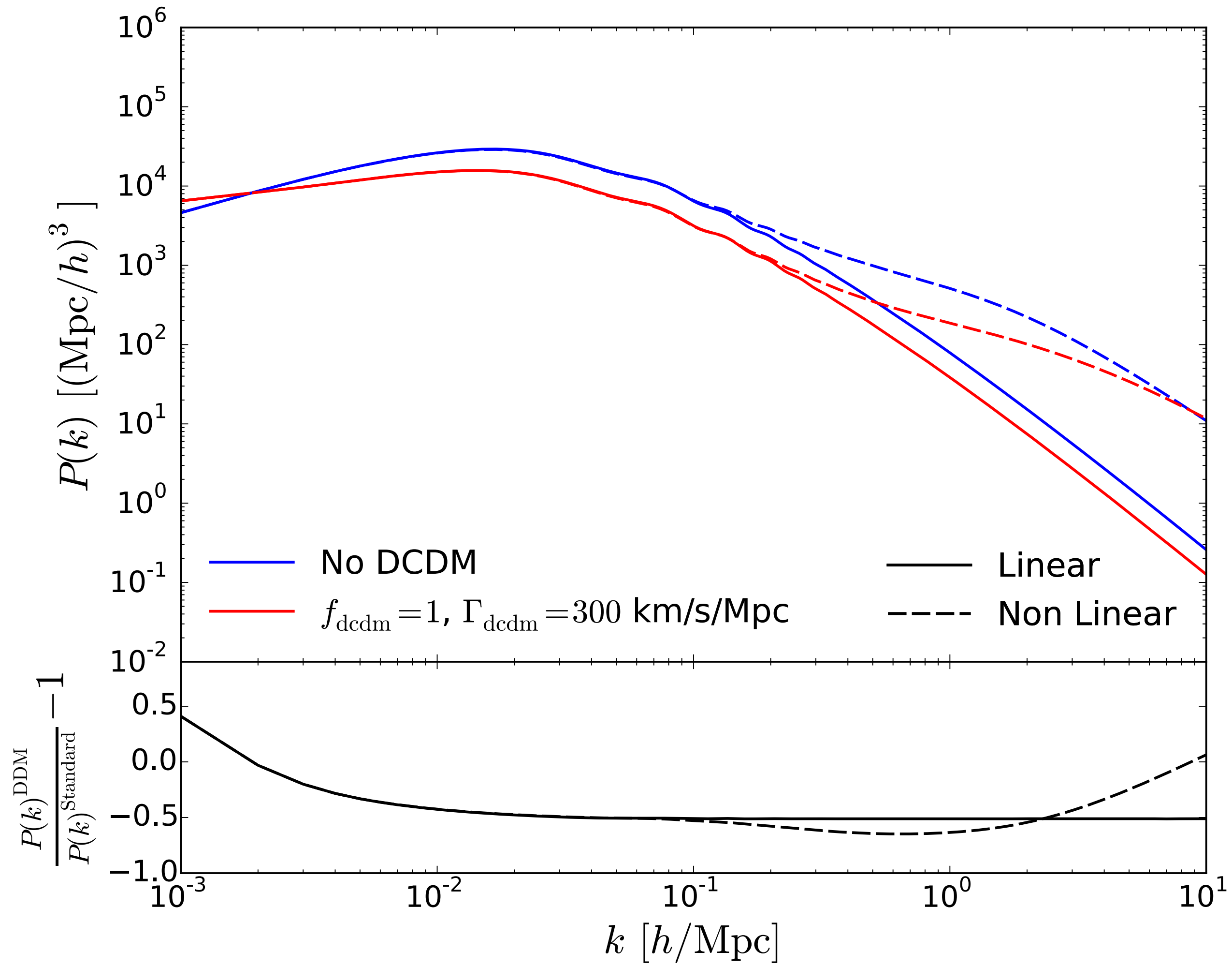
Impact on the (linear) matter power spectrum



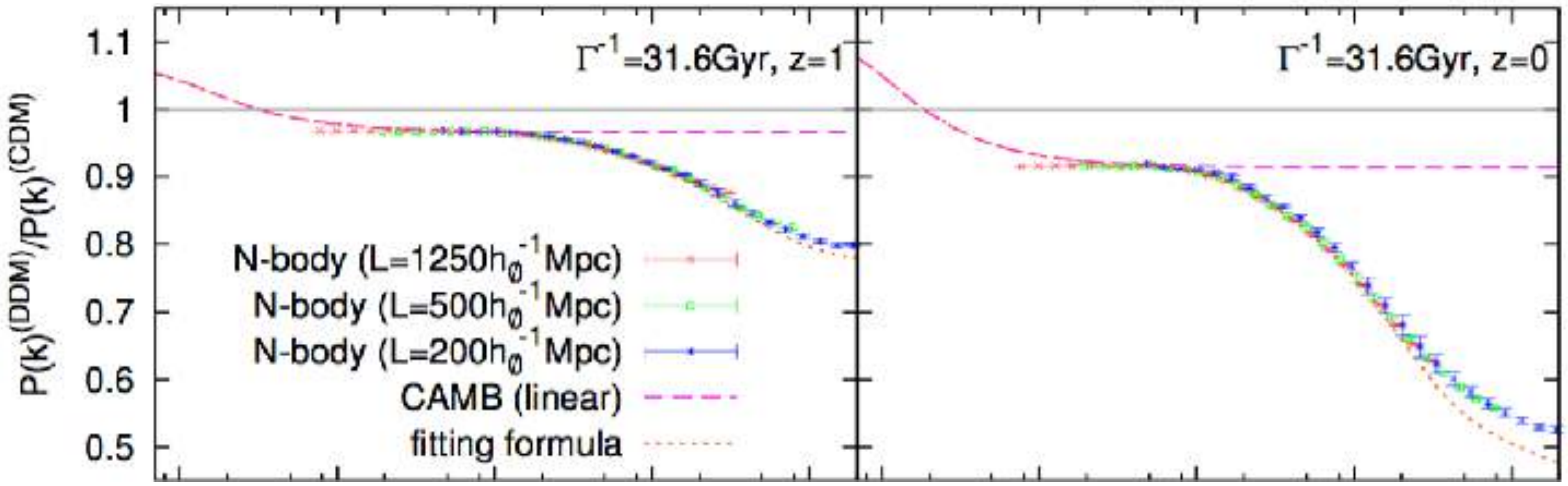
- $\theta_s \equiv r_s(\text{rec})/D_A(\text{rec})$: Shift of the sound horizon at rec. => Ω_m is less modified.
- Shift in the BAO scale increases.
- Expected limiting case : smaller $\Omega_{\rm cdm}$ from the beginning.

What about impact on non linear matter power spectrum?

To be studied further ...

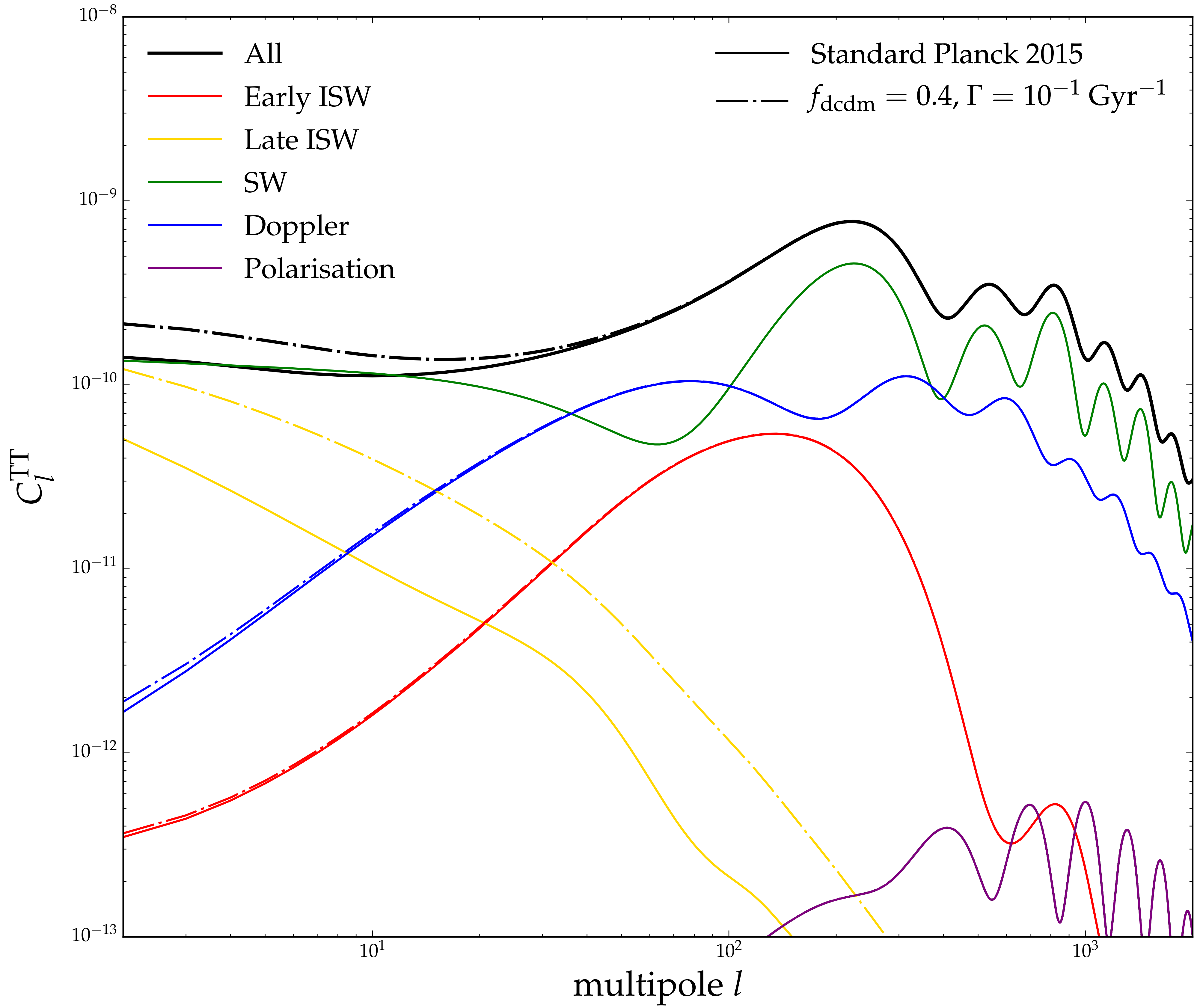


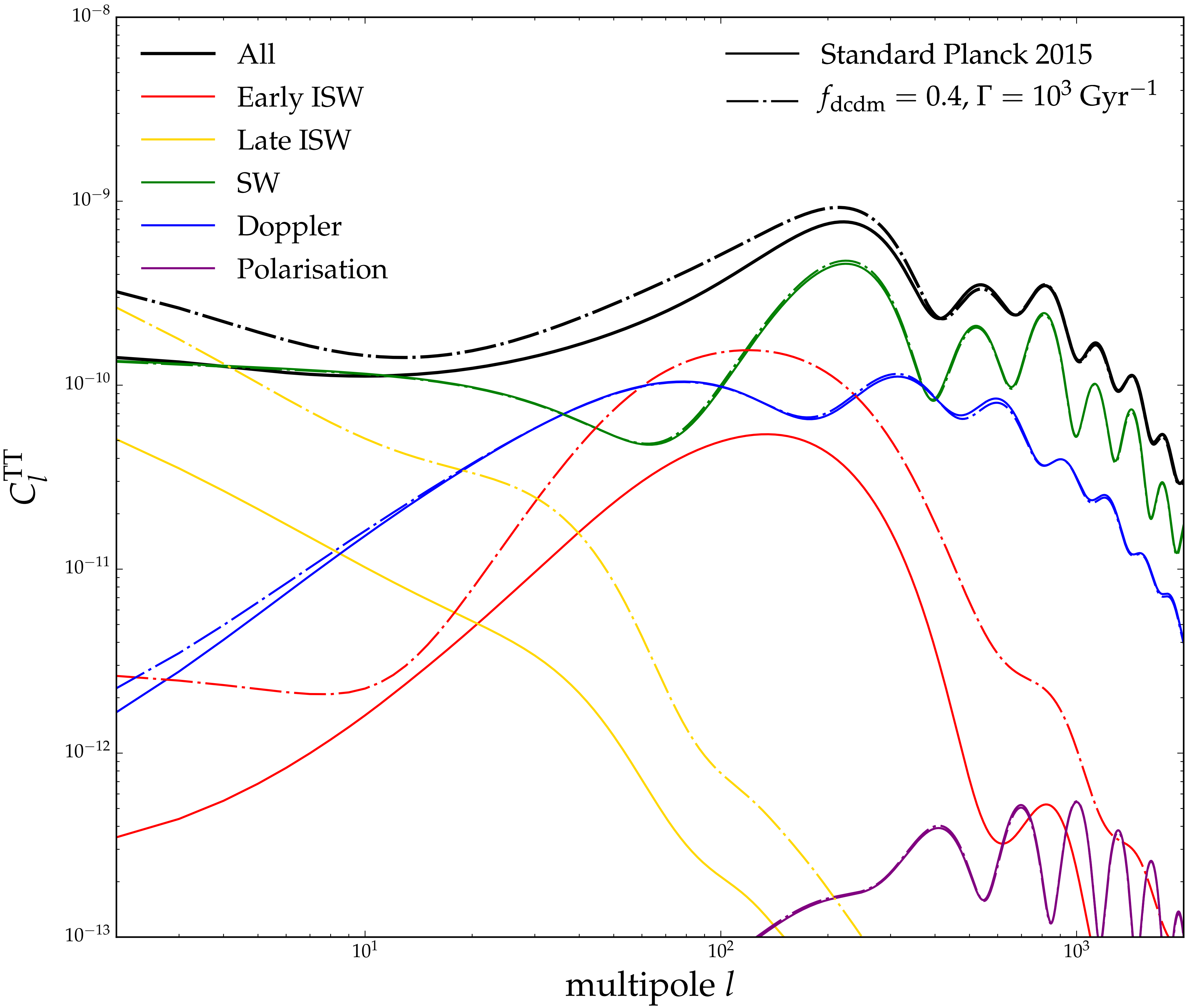
halofit result vs Nbody simulations



too small scales probed ?

[arXiv:1505.05511]


All
Early ISW
Late ISW
SW
Doppler
Polarisation
Standard Planck 2015
$f_{\rm dcdm} = 0.4, \Gamma = 10^{-1}$ Gyr^{-1}
$C_l^{\rm TT}$
multipole l
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{1}
10^{2}
10^{3}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Early ISW
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SW
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Standard Planck 2015
$f_{\rm dcdm} = 0.4, \Gamma = 10^3$ Gyr^{-1}
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10^1
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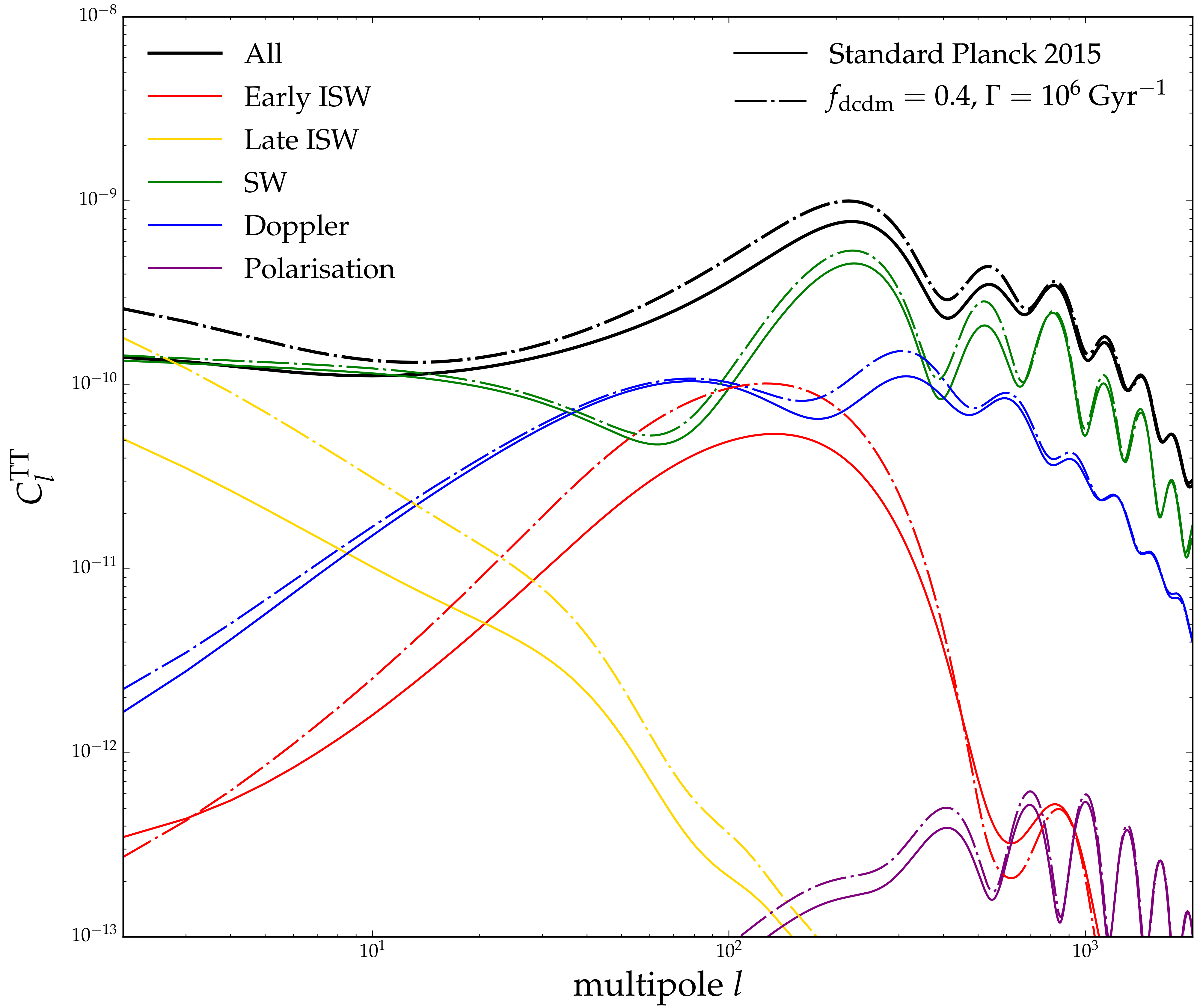
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SW
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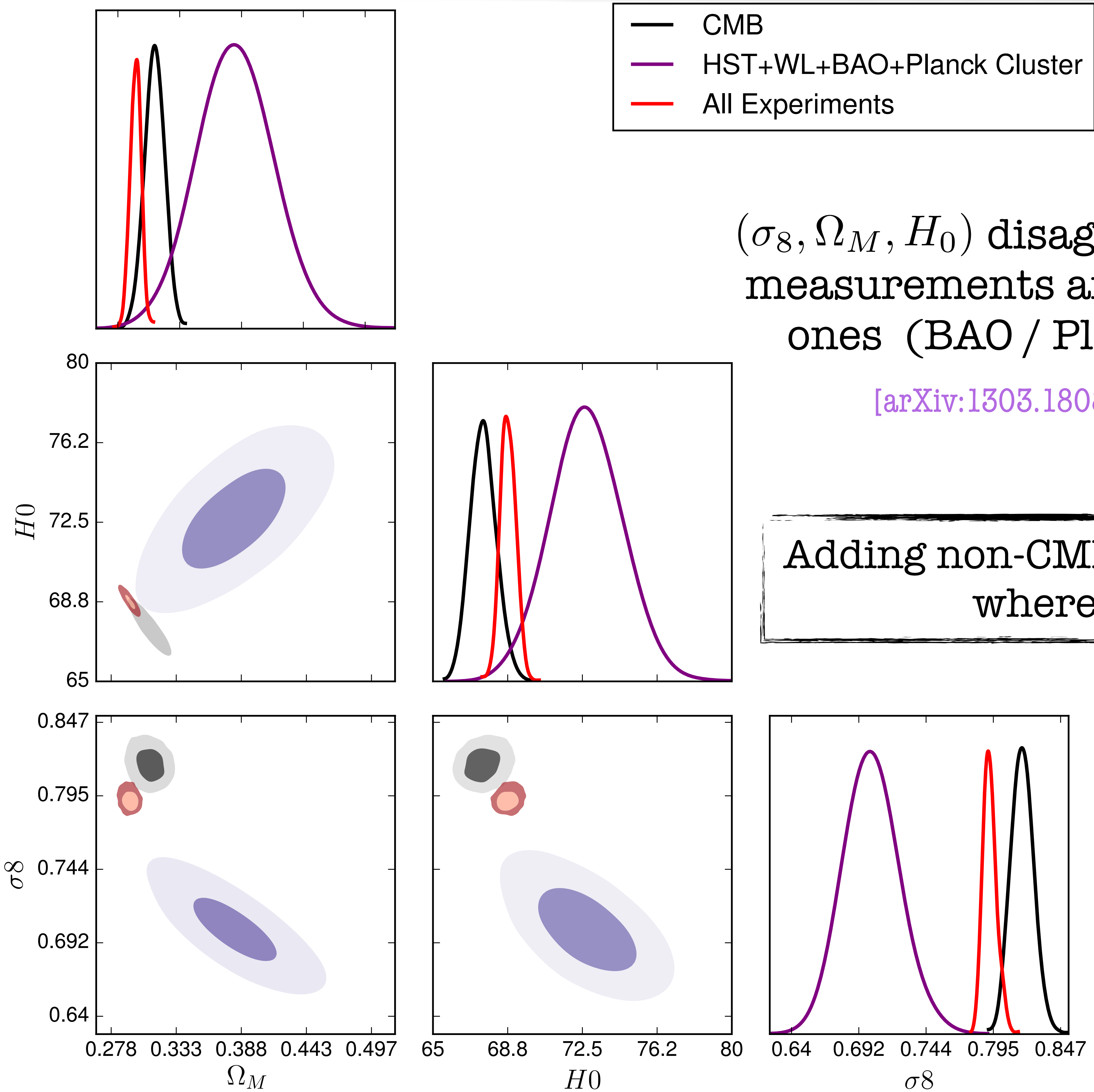
C_l^{TT}
multipole l
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^1
10^2
10^3

The low redshift measurement discrepancies



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$(\sigma_8, \Omega_M, H_0)$ disagrees at about 3σ between CMB measurements and combination of low redshifts ones (BAO / Planck Cluster / HST/ CHFT-σ_8)

[arXiv:1303.1808], [arXiv:1404.1801], [arXiv:1502.01597], [arXiv:1604.01424]

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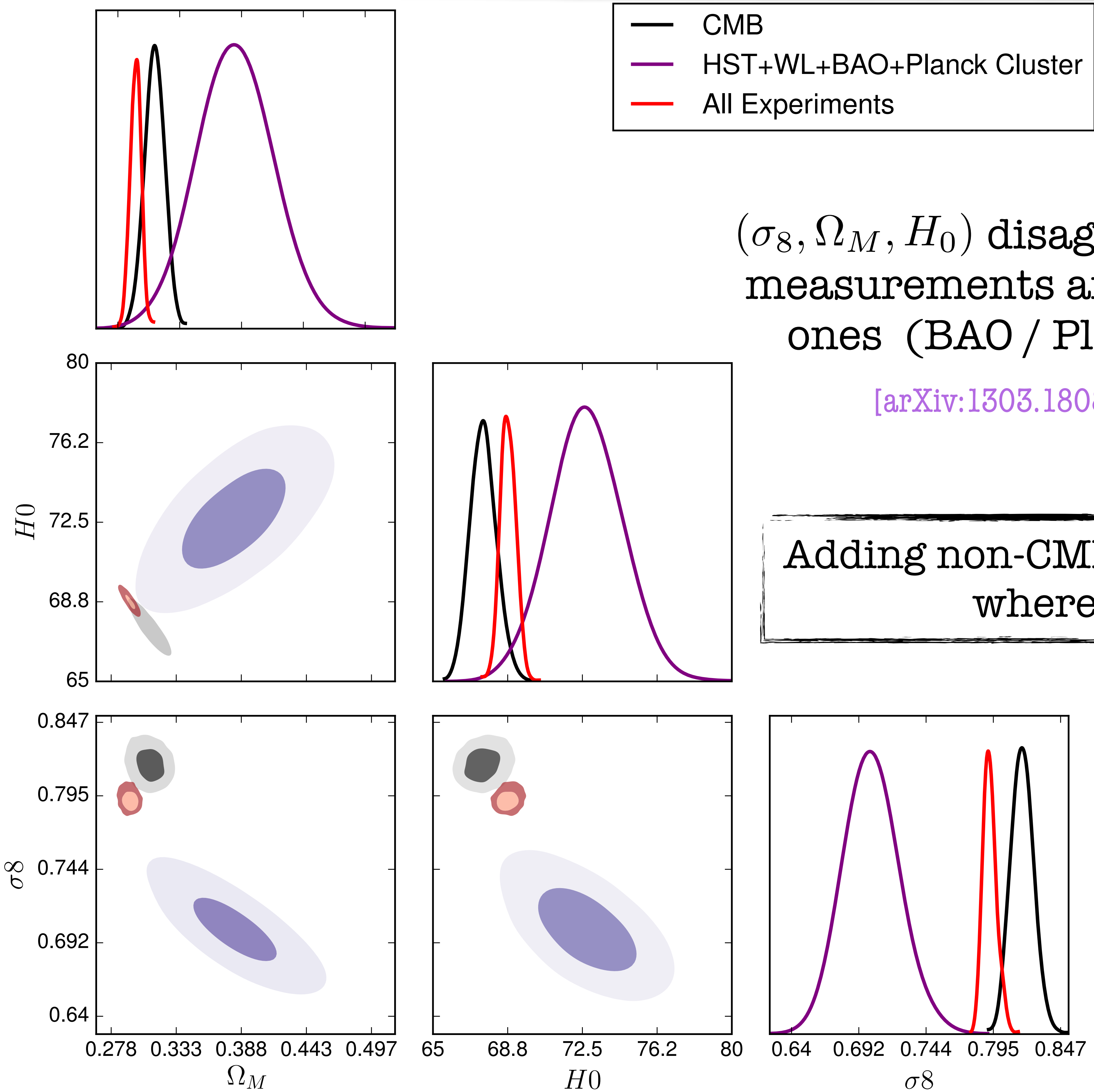

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Adding non-CMB datasets one expects $\Delta\chi^2 = 5$ whereas one gets $\Delta\chi^2 = 31.2$

It has been claimed that decaying DM could solve (loose) these discrepancies.

[arXiv:1402.2972], [arXiv:1411.1074], [arXiv:1505.03644],[arXiv:1505.05511], [arXiv:1602.08121]

Why this could work (in principle)

- as we have seen, since $\Omega_{\rm cdm}\searrow$, $h^2\nearrow$
- Similarly, cluster count and WL measures $\sigma_8\Omega_m^\alpha$, since $\Omega_{\rm cdm}\searrow$, $\sigma_8\nearrow$

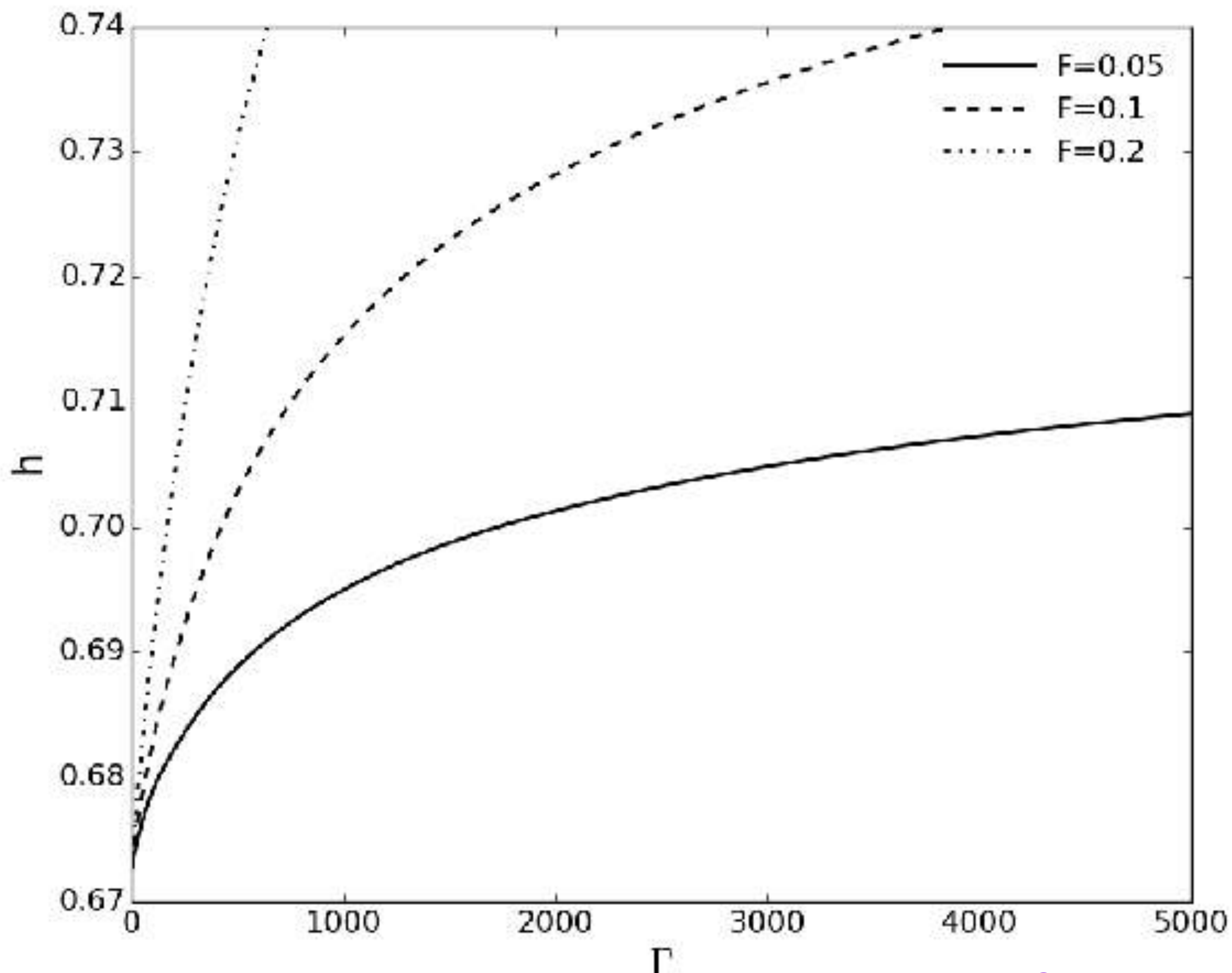
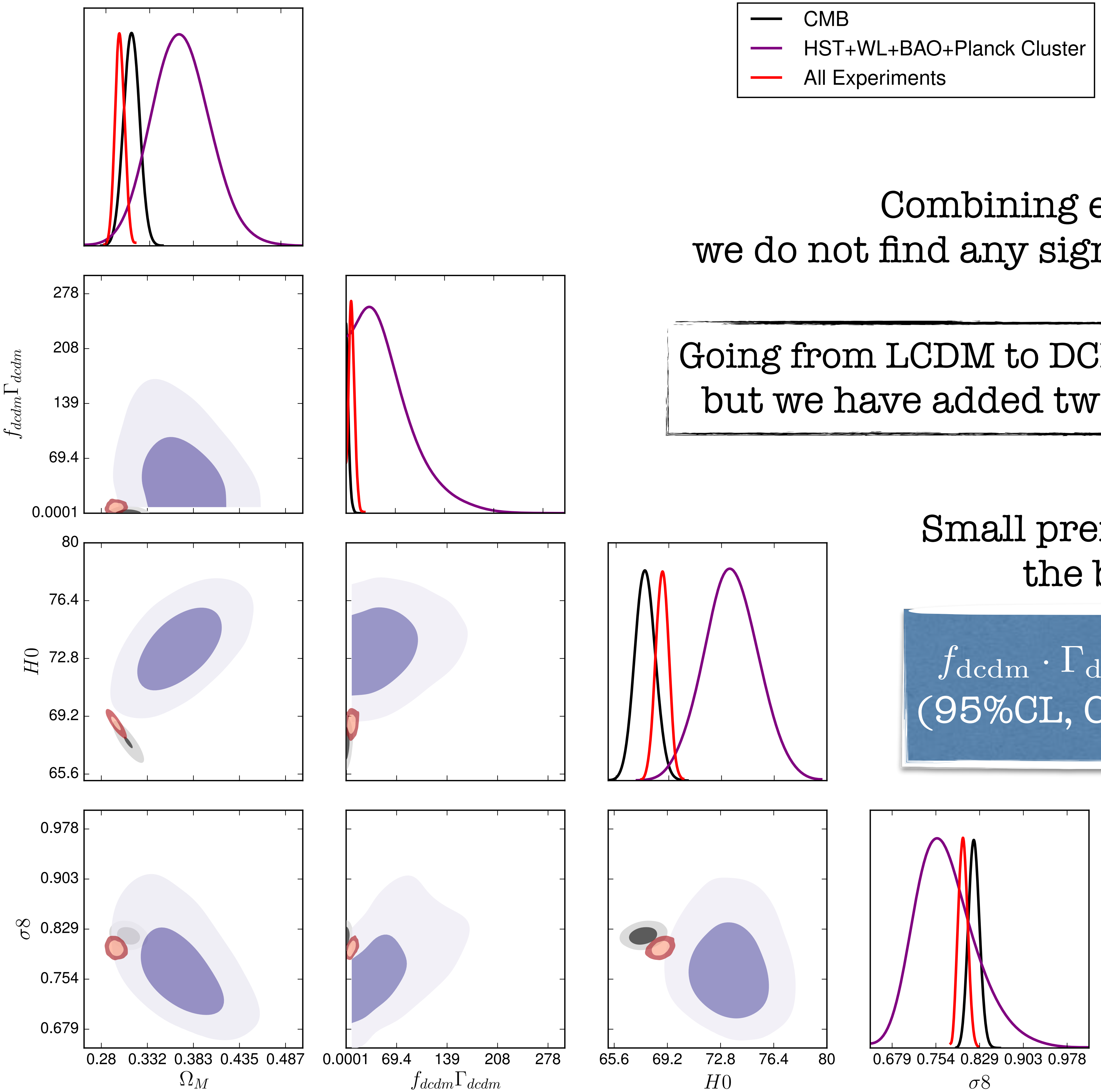


fig. originally from [arXiv:1505.03644]



Combining experiments,
we do not find any significative improvement

Going from LCDM to DCDM one gets $\Delta\chi^2$= -6.7
but we have added two new parameters ...

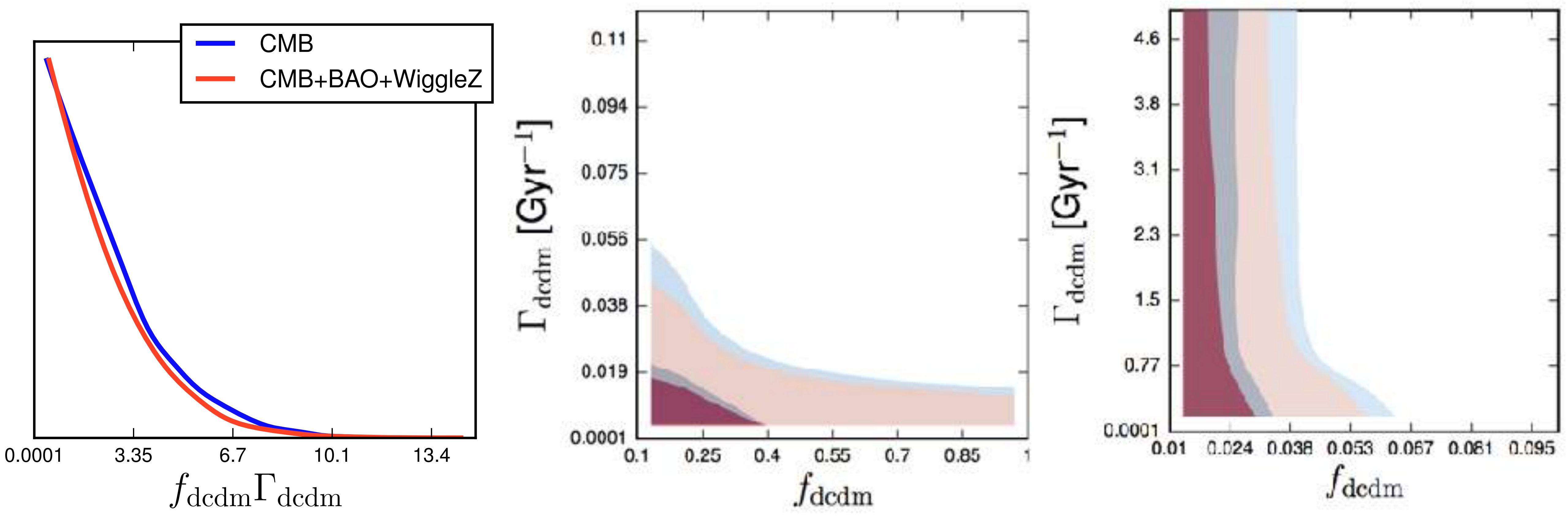
Small preferences for the dcdm :
the bounds relaxes to

$f_{\rm dcdm} \cdot \Gamma_{\rm dcdm} < 15.9 \times 10^{-3}$ Gyr^{-1}
(95%CL, CMB + BAO + WL + HST)

If you choose to ignore discrepant data
(Invoking e.g. some unknown systematics)

$f_{\rm dcdm} \cdot \Gamma_{\rm dcdm} < 5.8 \times 10^{-3}$ Gyr^{-1} (95%CL, CMB + BAO + Wiggle Z)

$f_{\rm dcdm} < 0.036$ (95%CL, CMB + BAO) for $\Gamma_{\rm dcdm} > 3\ H_0$



Non-Universal BBN bounds

Typically, after the end of standard BBN (5 keV) :

$$E_{\rm cutoff}(1\ {\rm keV}) \sim 12\ {\rm MeV} \qquad E_{\rm cutoff}(10\ {\rm eV}) \sim 1.2\ {\rm GeV}$$

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After « standard » BBN :
$E_{\rm threshold}(\rm Be) = 1.58$ MeV $< E_{\rm cutoff}$

If $E_{\rm threshold} < E_0 < E_{\rm cutoff}$
results in the literature are wrong !

Consider a photon injection and start by neglecting diffused electrons.
Remaining processes are :

$$\gamma\gamma_{\rm th} \to \gamma\gamma,\ \gamma e^{\pm}_{\rm th} \to \gamma e^{\pm},\ \gamma N \to N e^{\pm}$$

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$$\frac{\partial f_\gamma(E_\gamma)}{\partial t} = -\Gamma_\gamma(E_\gamma, T(t)) f_\gamma(E_\gamma, T(t)) + \mathcal{S}(E_\gamma, t)$$

whose stationary solution is

$$f_\gamma^{\rm S}(E_\gamma) = \frac{\mathcal{S}(E_\gamma, t)}{\Gamma_\gamma(E_\gamma, t)}$$

Hubble rate much smaller than
all particle physics interaction rate,
thus neglected

where for a decaying particle

$$\mathcal{S}(E_\gamma, t) = \frac{n_\gamma^0 \zeta_X (1+z(t))^3\, e^{-t/\tau_X}}{E_0 \tau_X} p_\gamma(E_\gamma, t)$$

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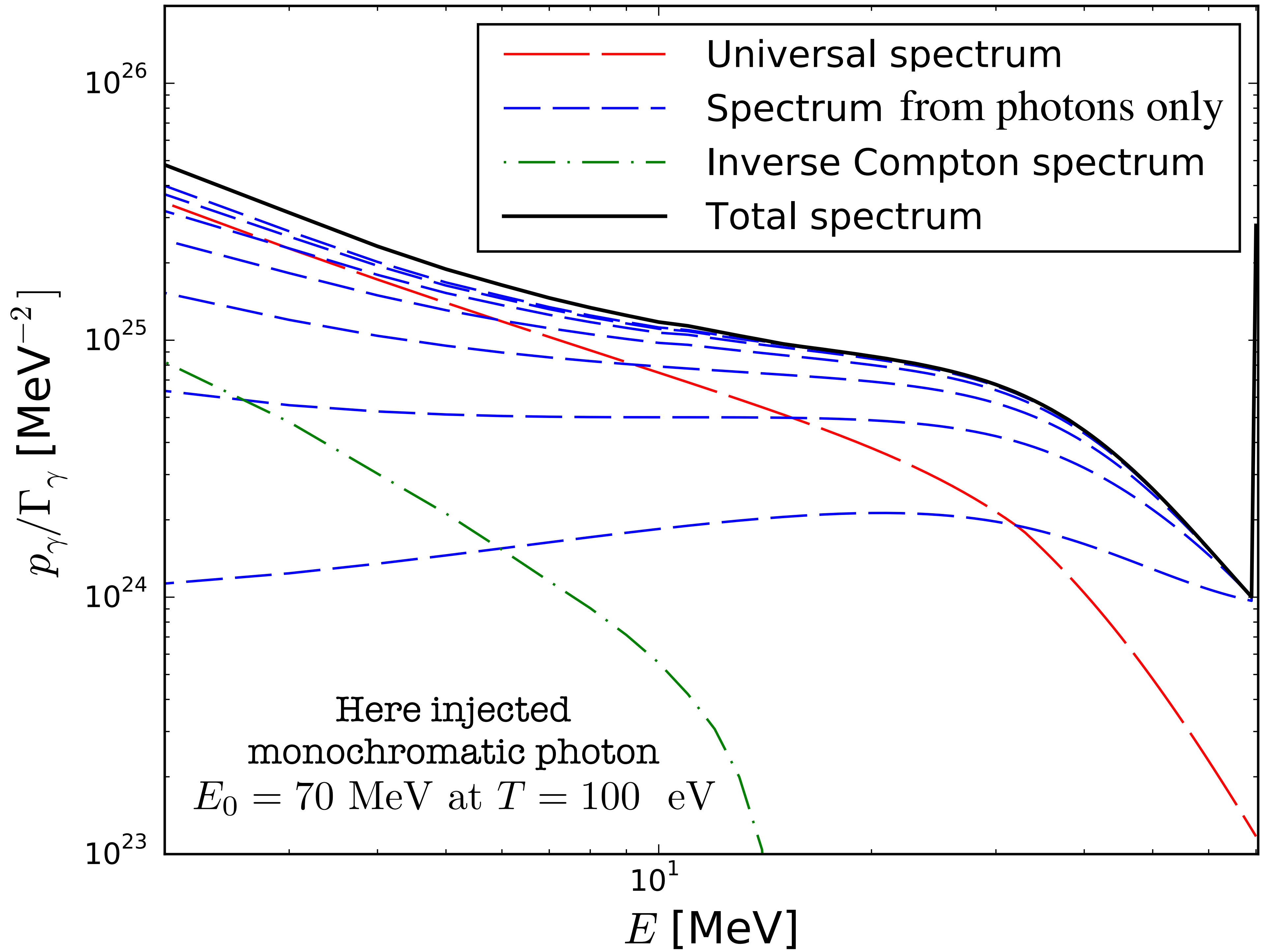
Typical results for a given energy and a given temperature of the thermal bath



Proof of principle solution :
monochromatic photon injection

In our case, it is possible to solve the lithium problem, while fulfilling other constraints.

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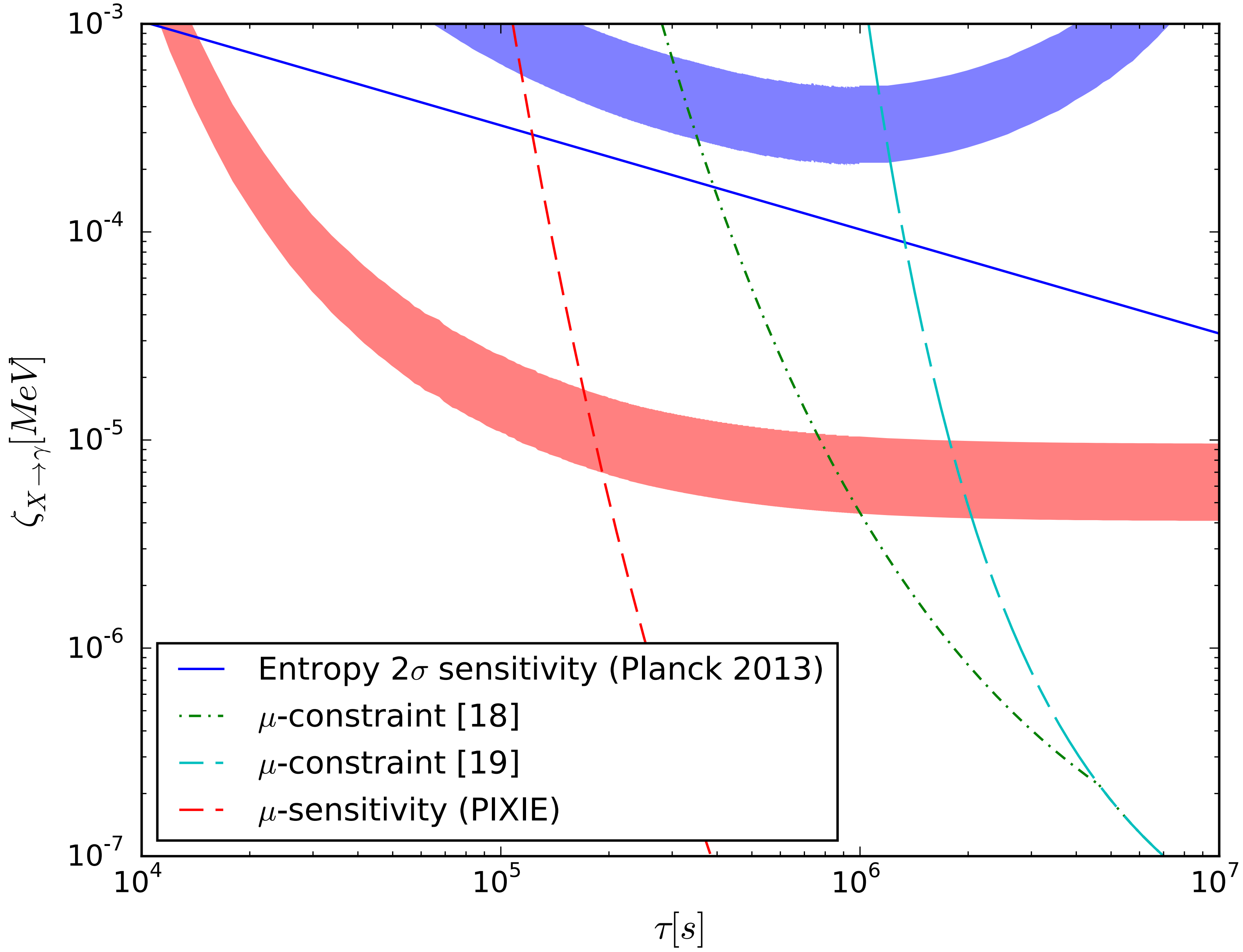

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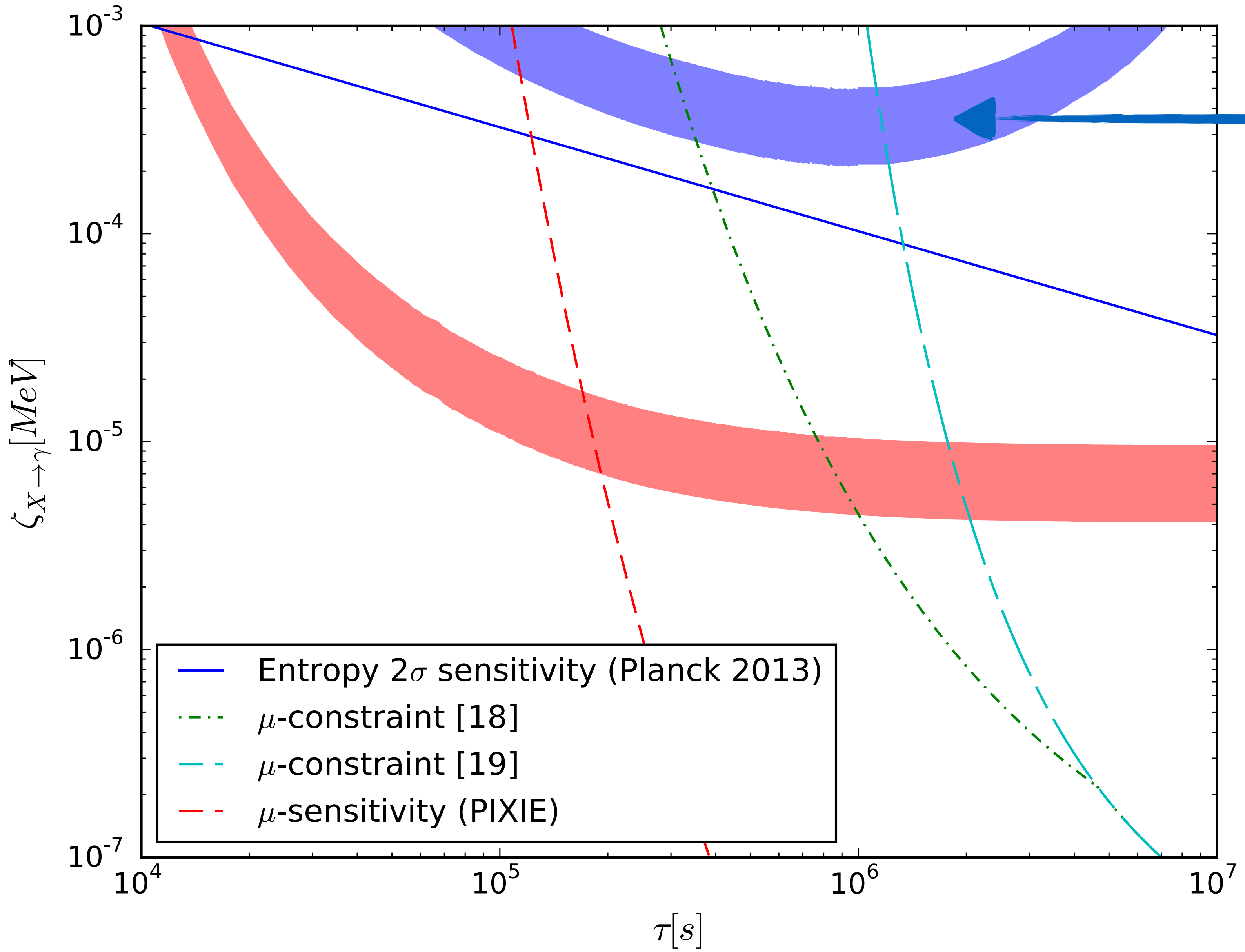

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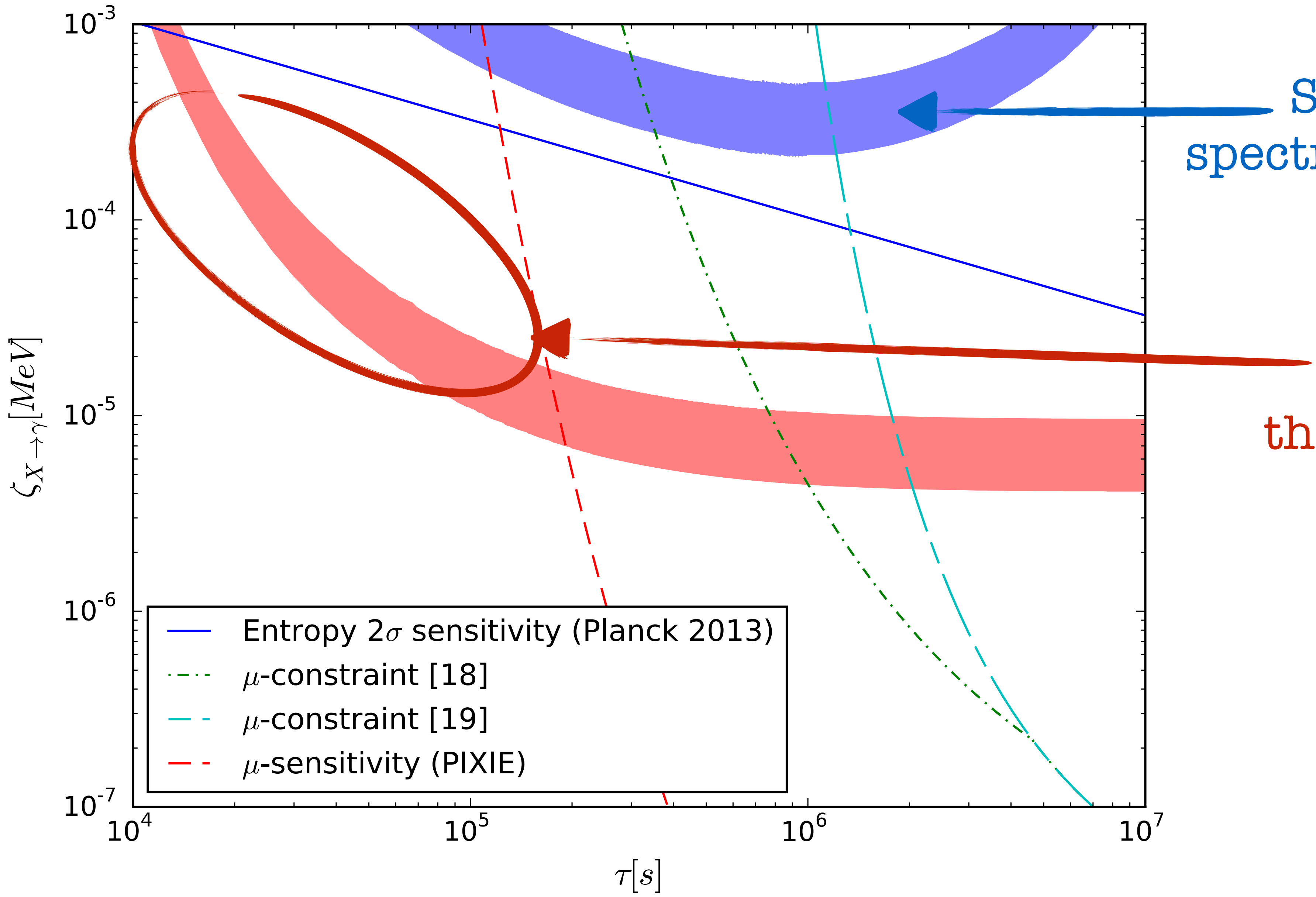

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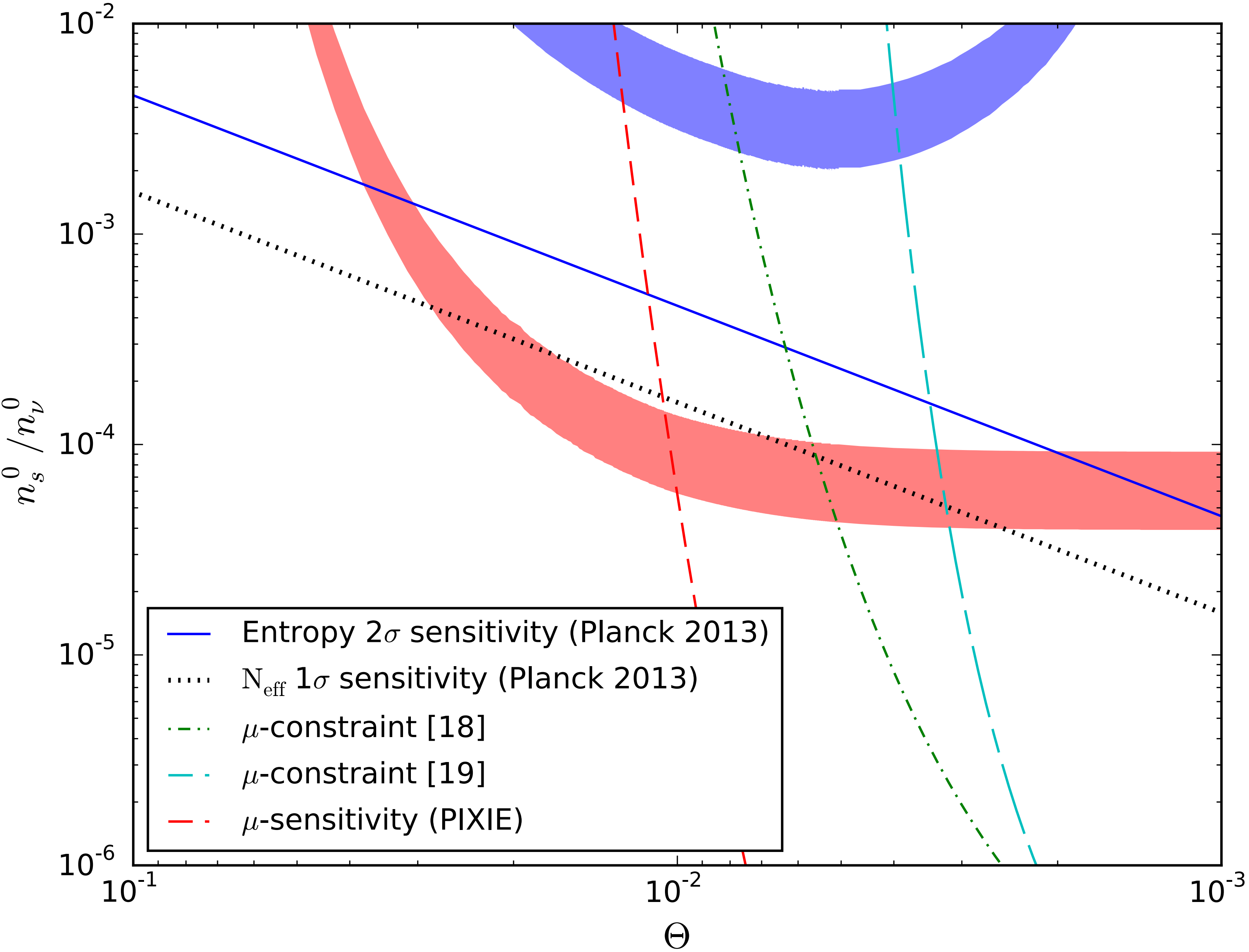
Our solution : there's a living region !

Try with a « real » model that was known to fail when using universal spectrum : the Sterile (majorana) Neutrino

H. Ishida et al.
PRD 90, 8, 083519 (2014)



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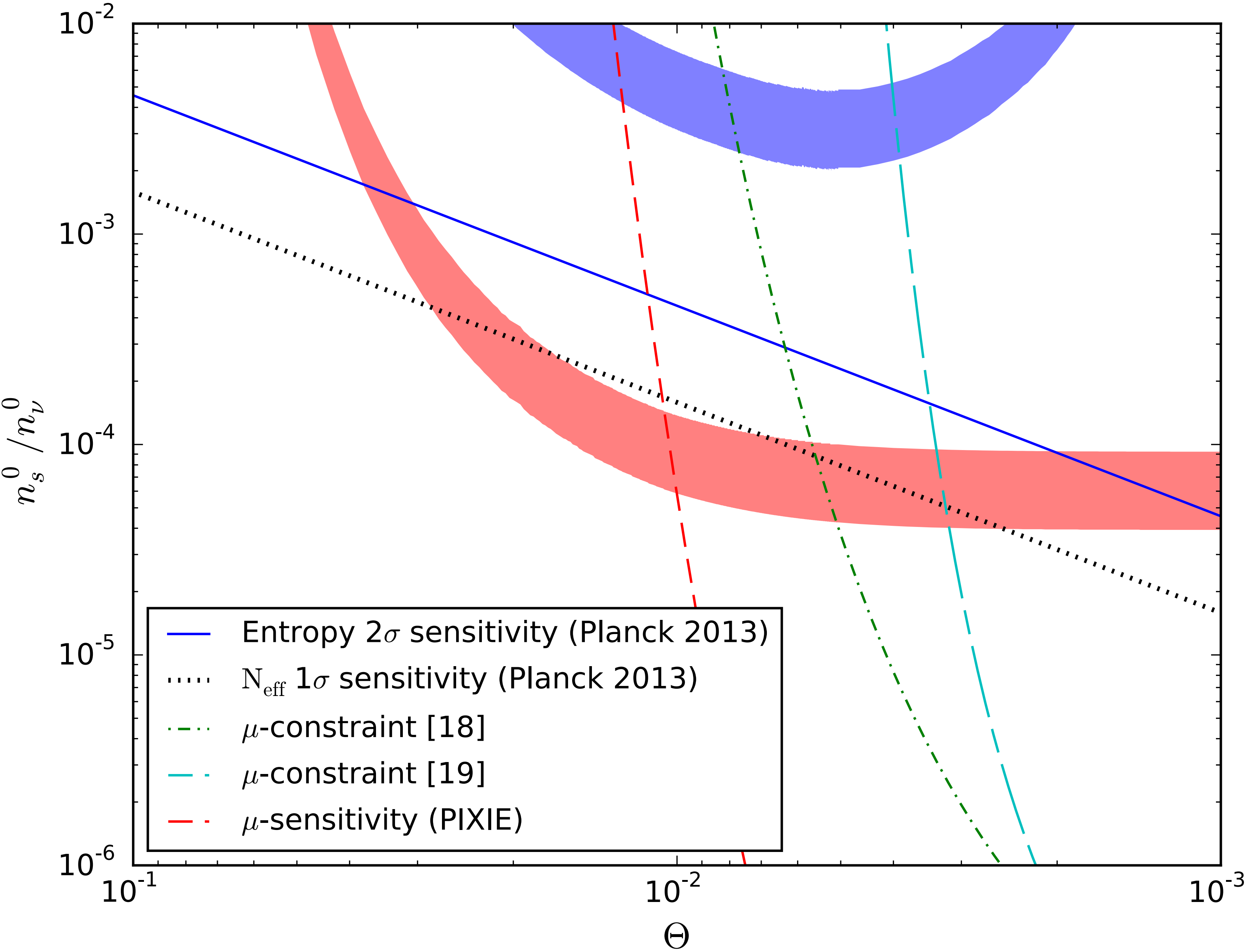

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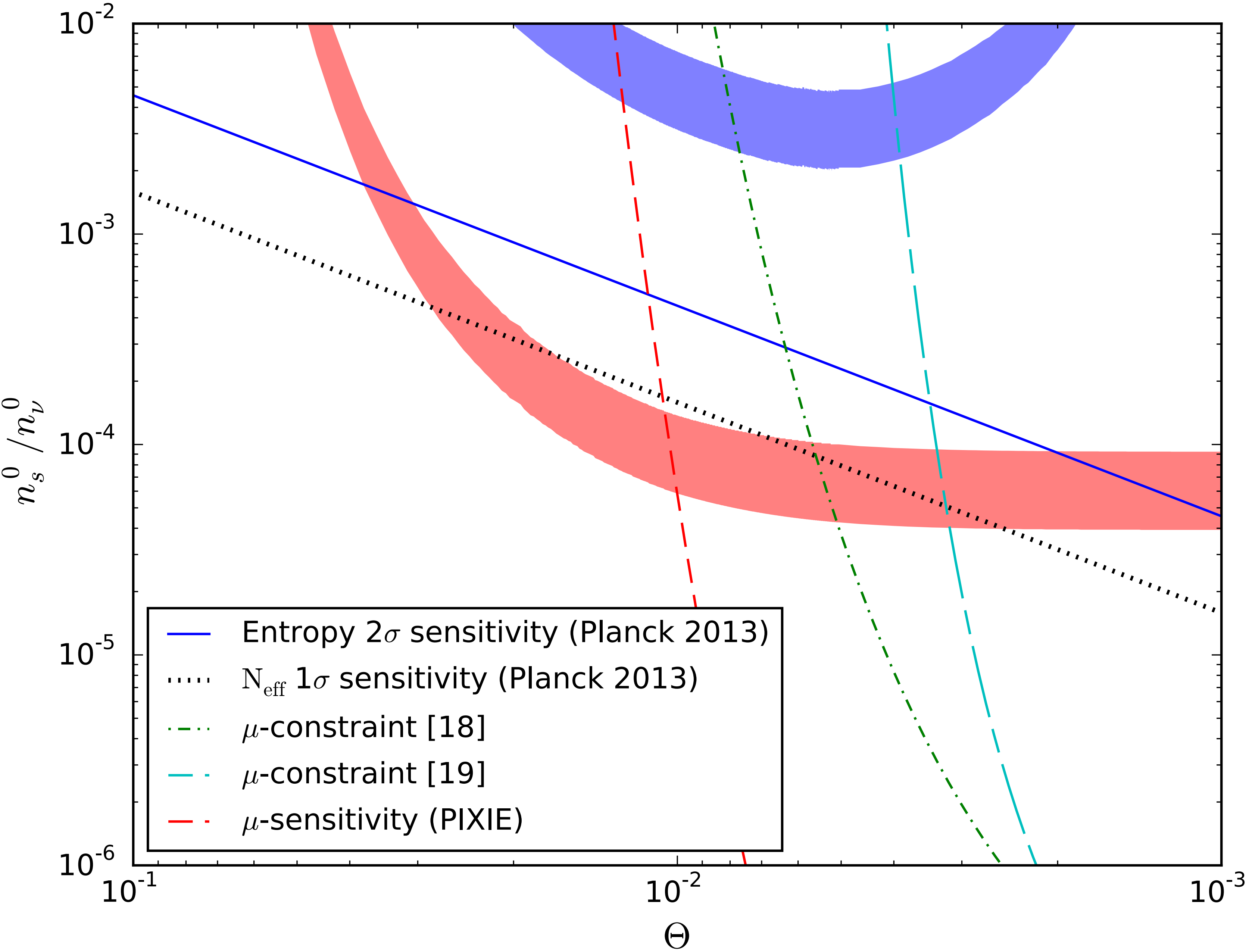

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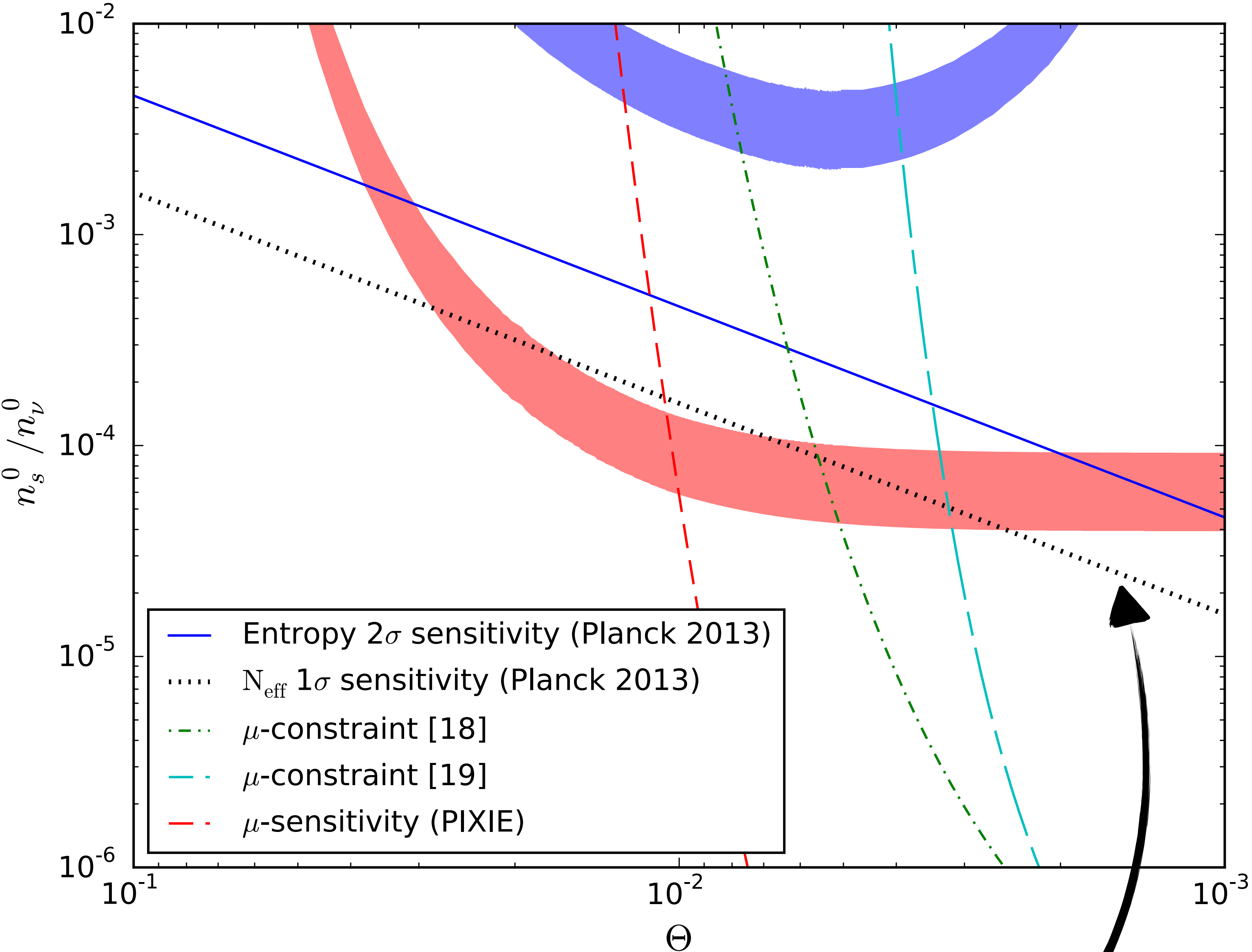

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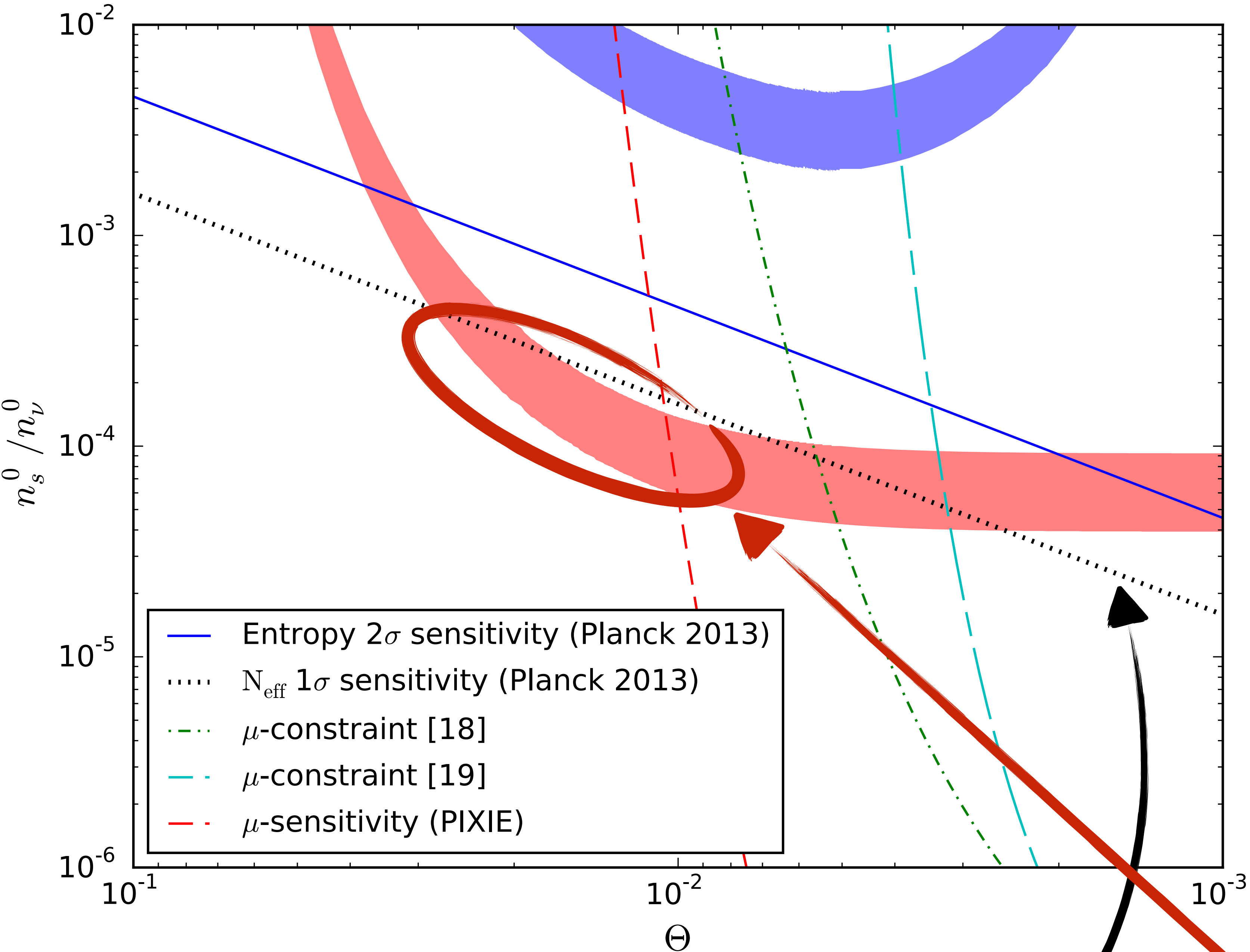

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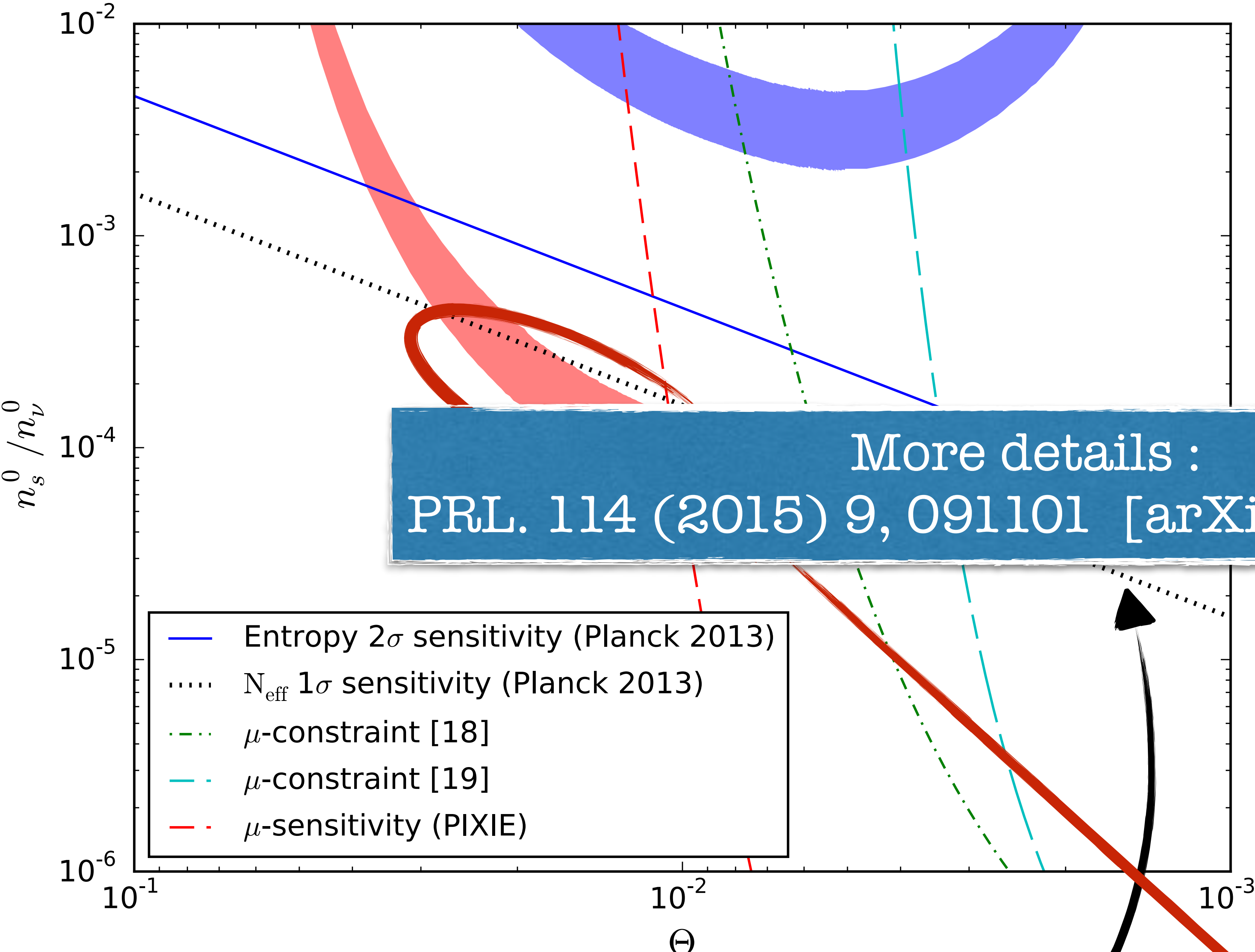

More details :
PRL. 114 (2015) 9, 091101 [arXiv:1502.01250]

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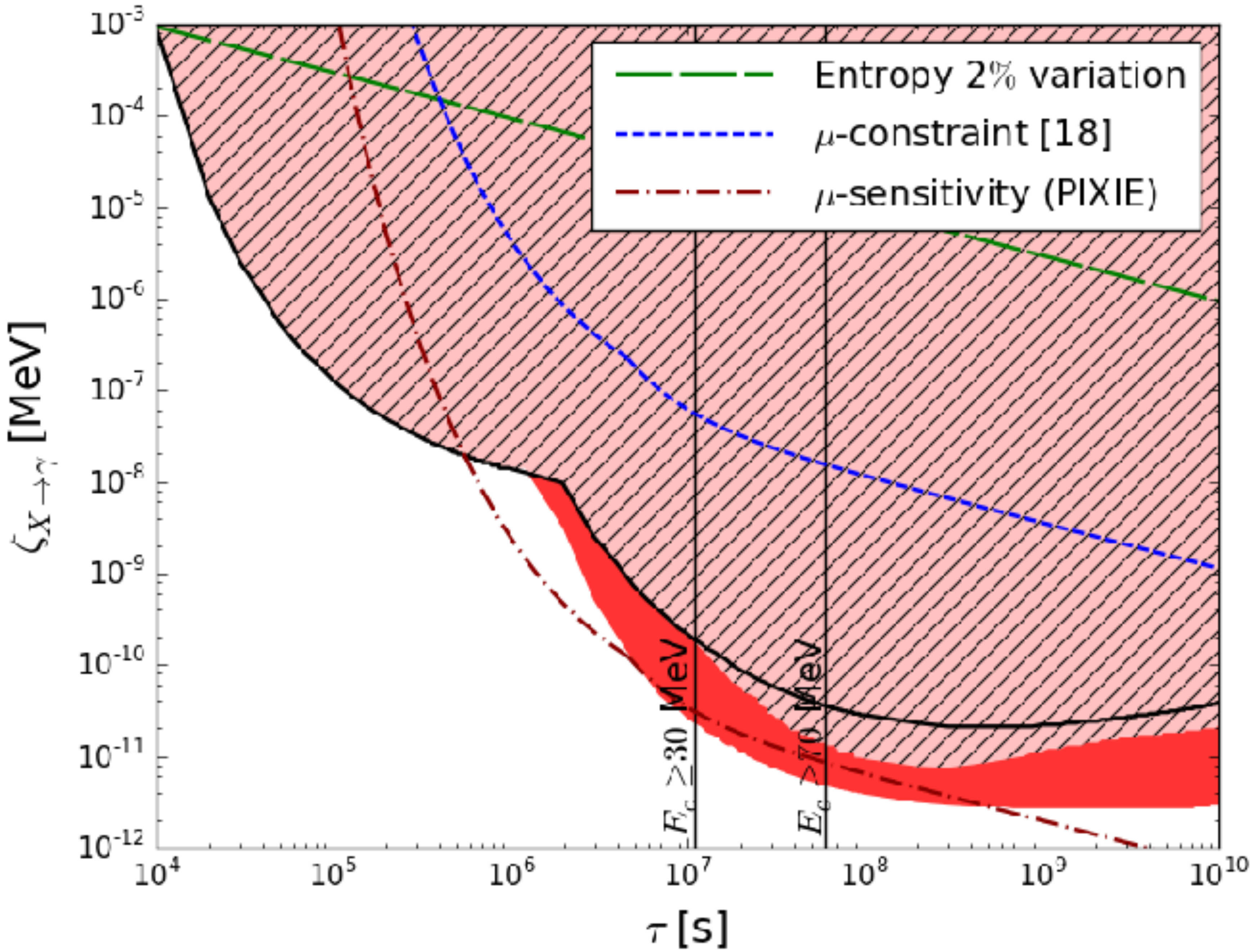

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VP & Serpico PRD. 91 (2015) 10, 103007

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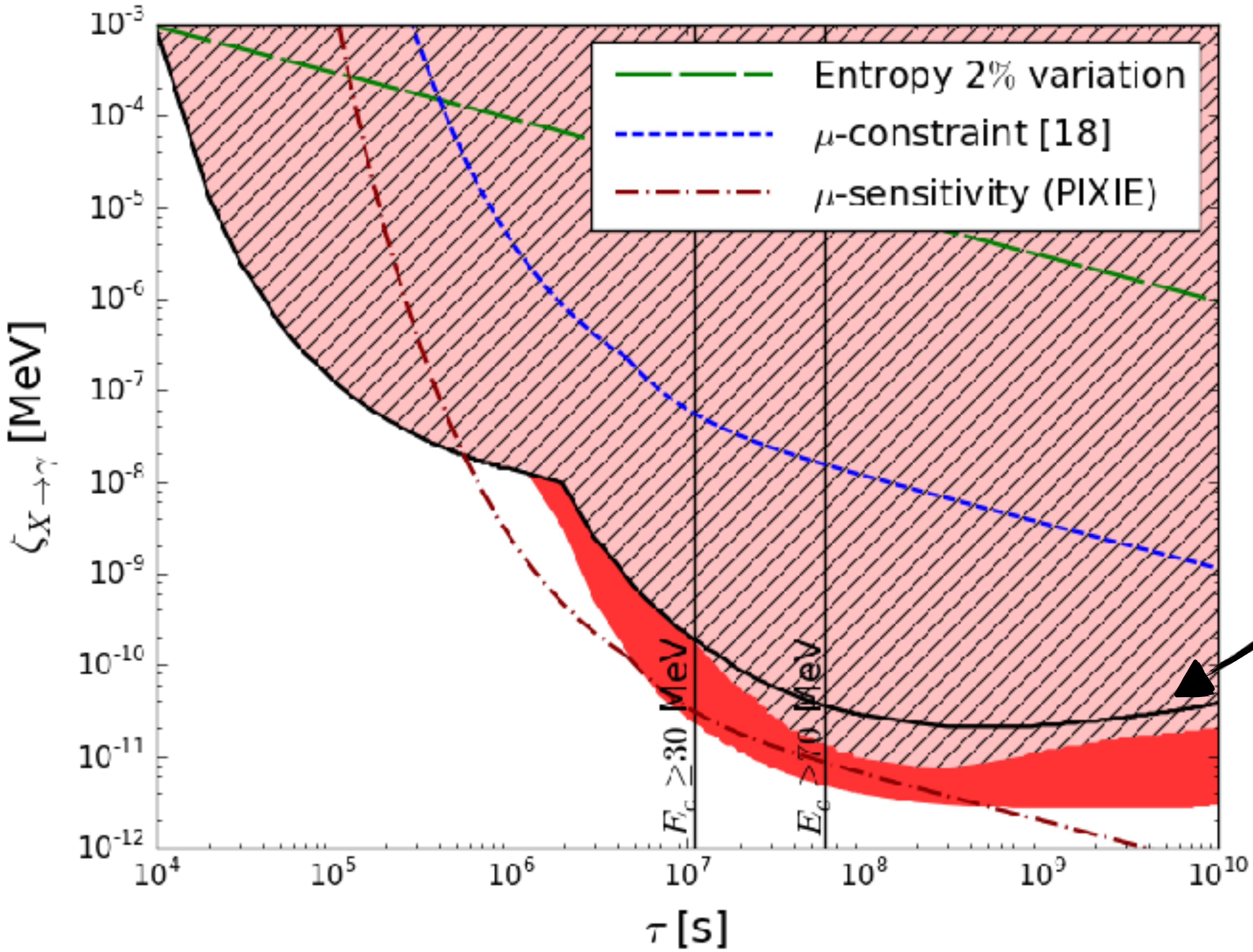

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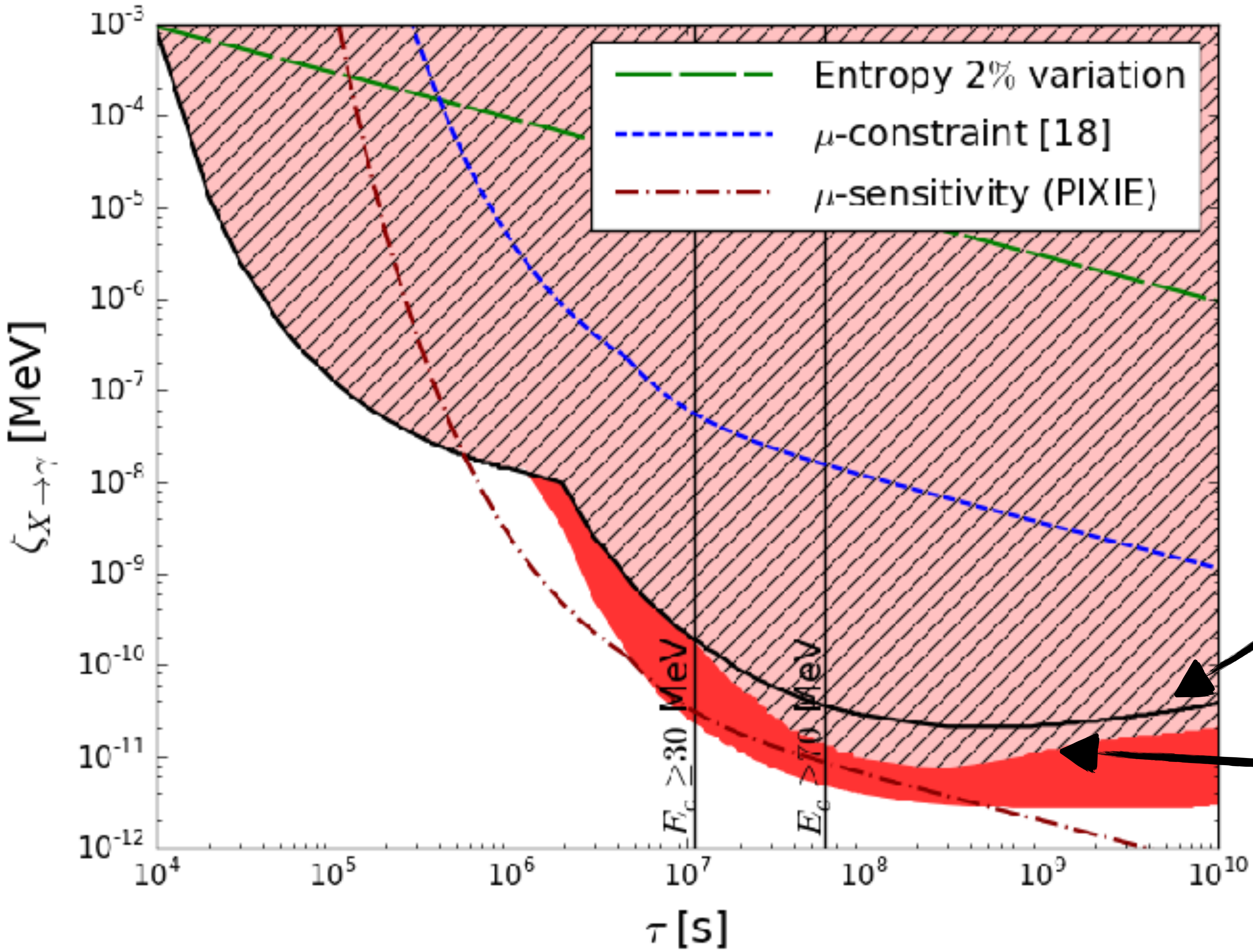

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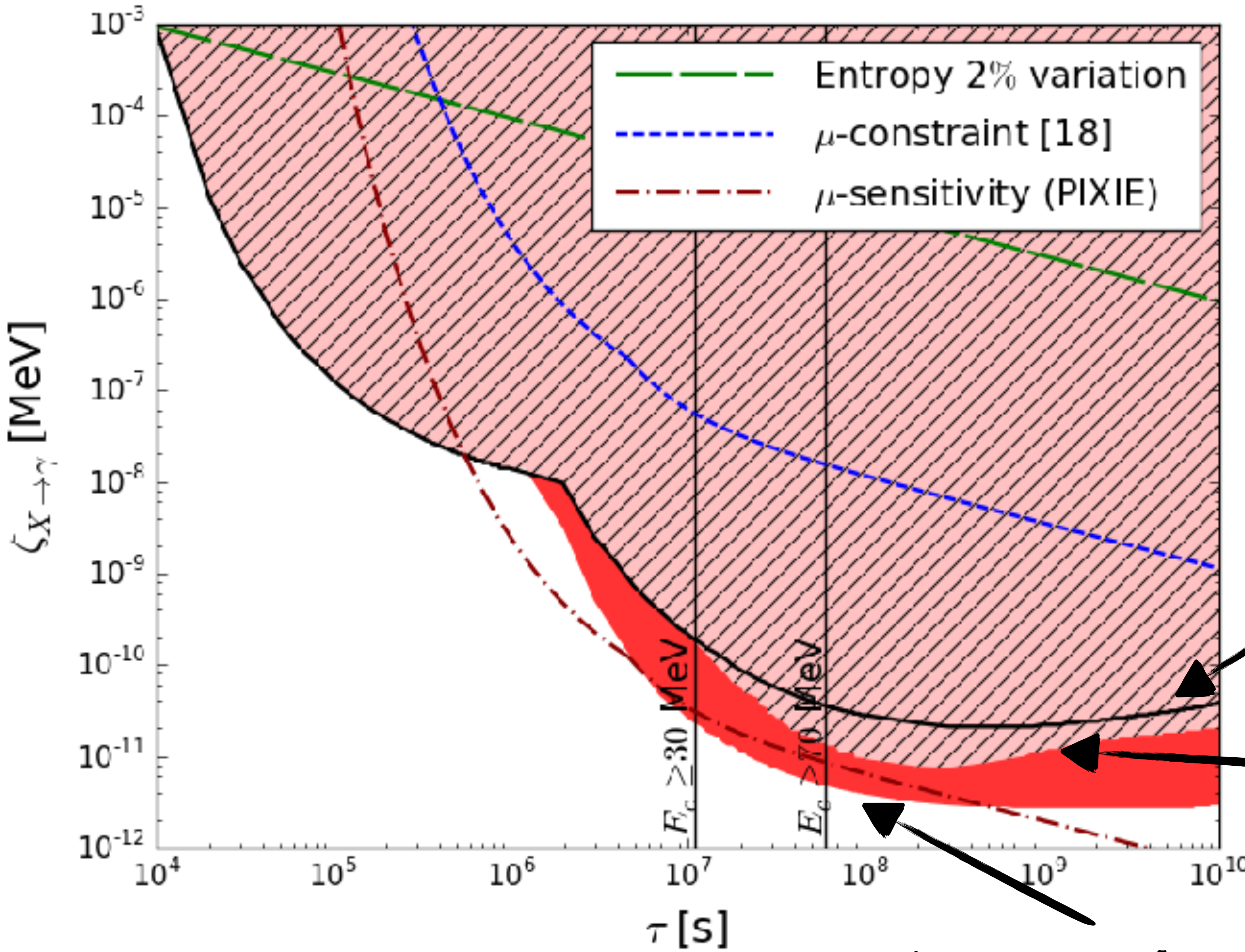

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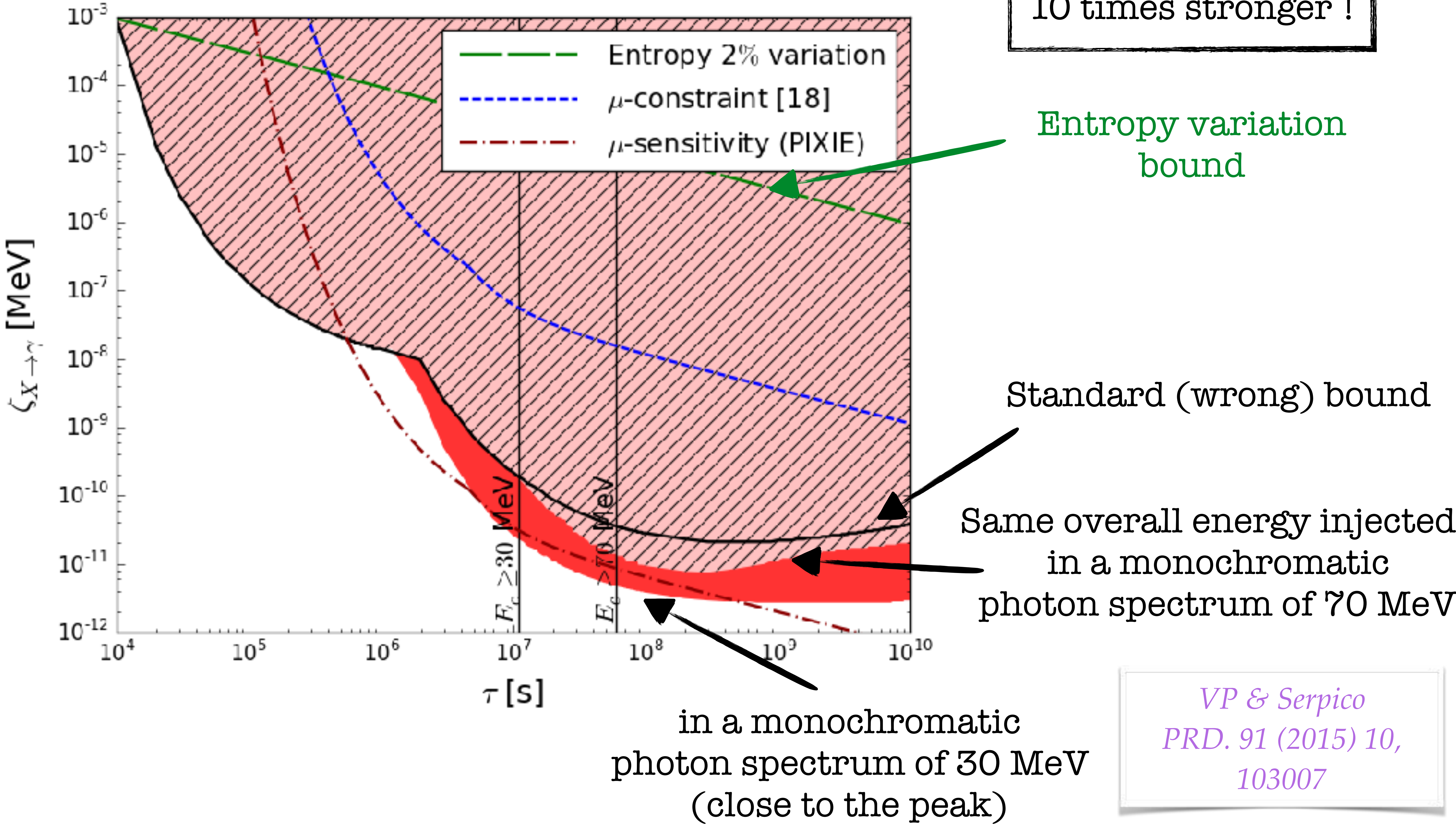

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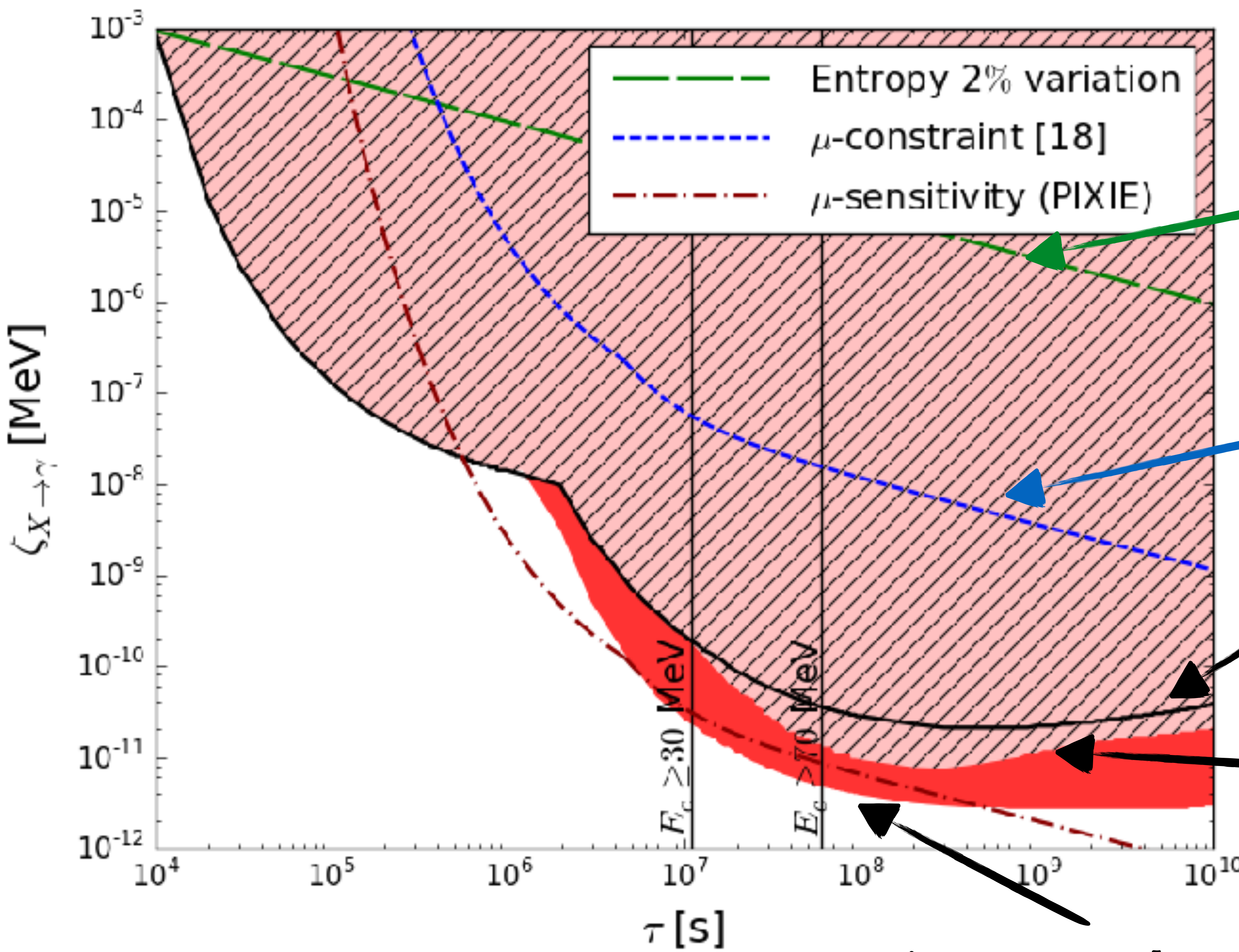

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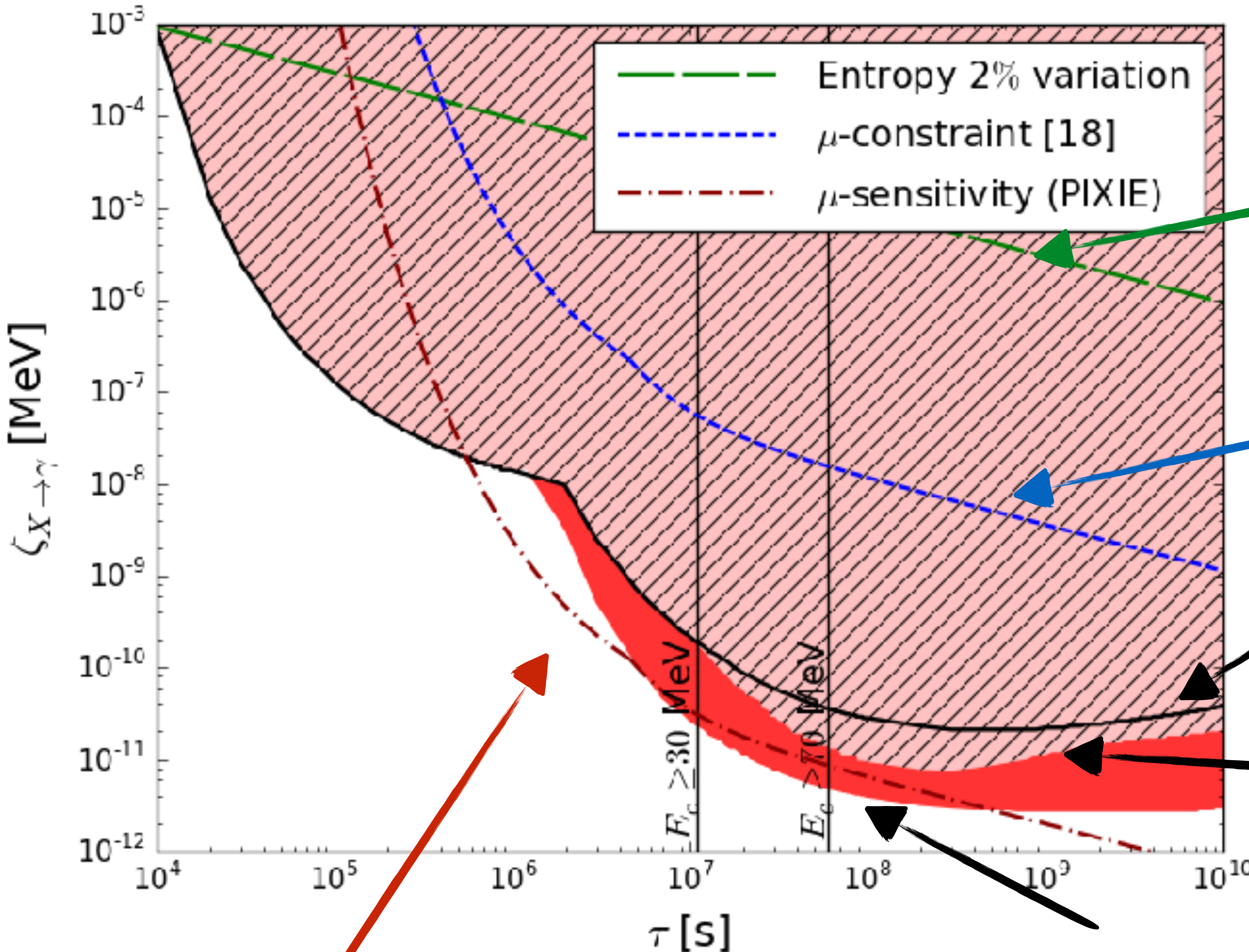

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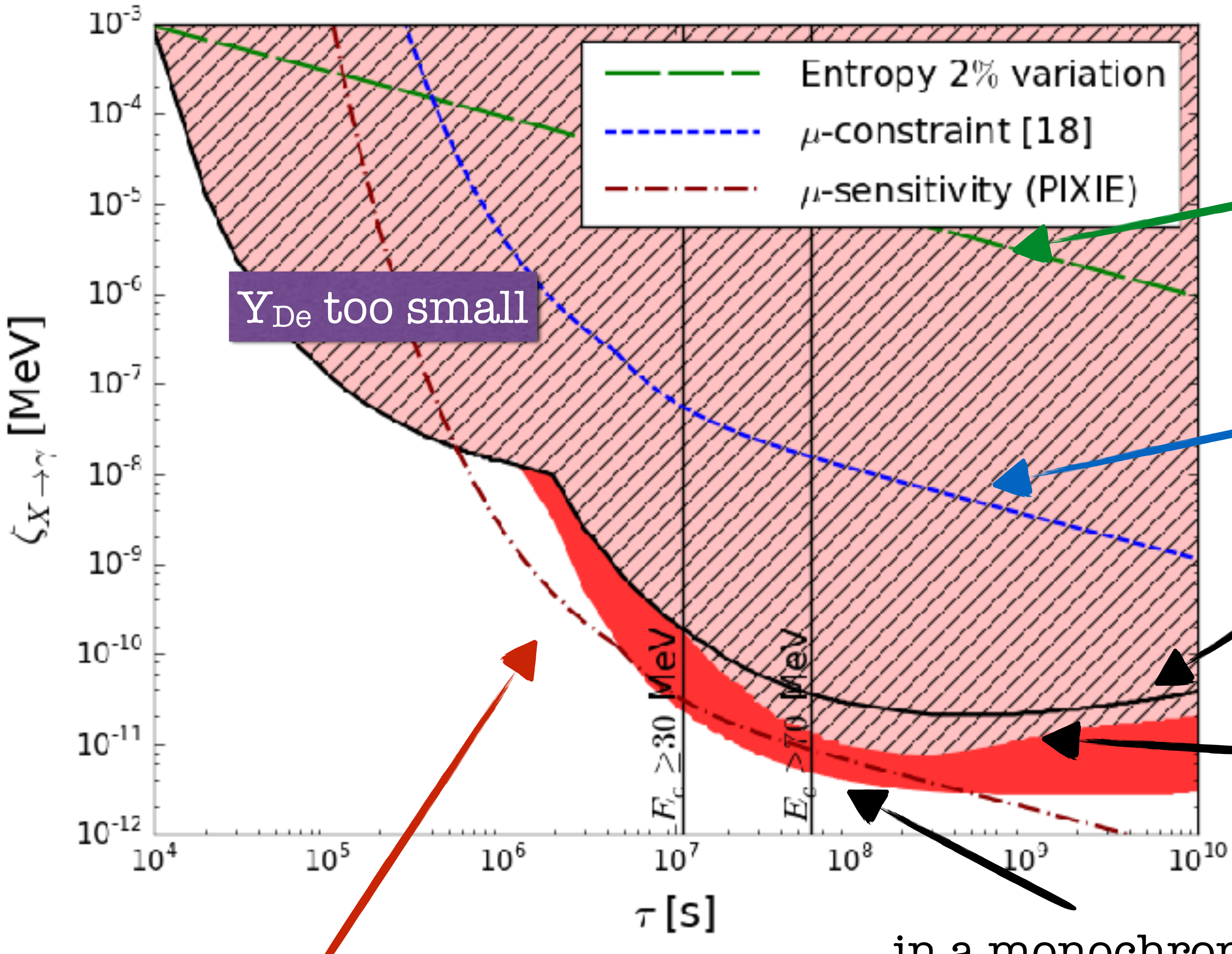

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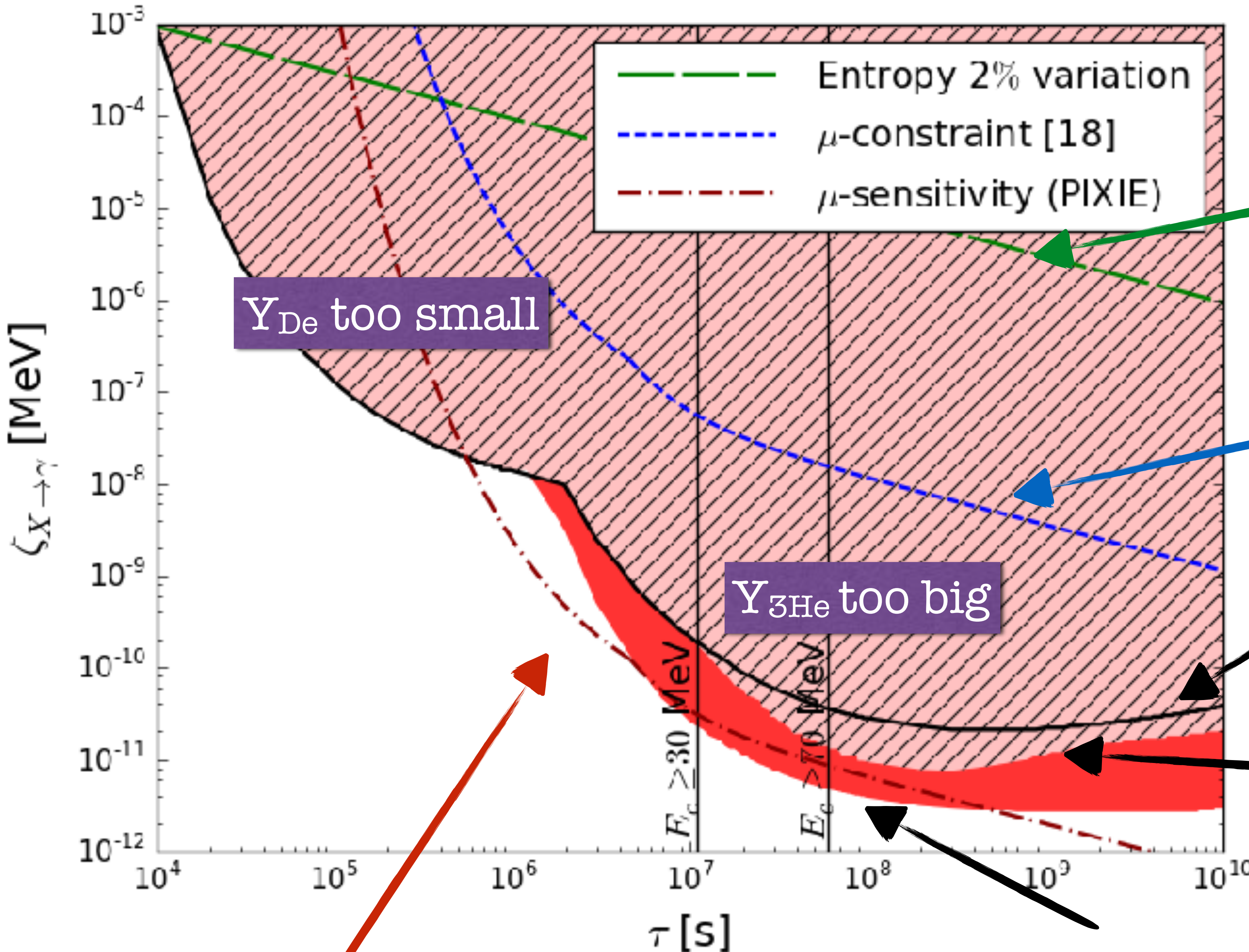

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