# Cosmological signature of (e.m.) decaying Dark Matter


Vivian Poulin
LAPTh, Annecy, France and RWTH, Aachen, Germany

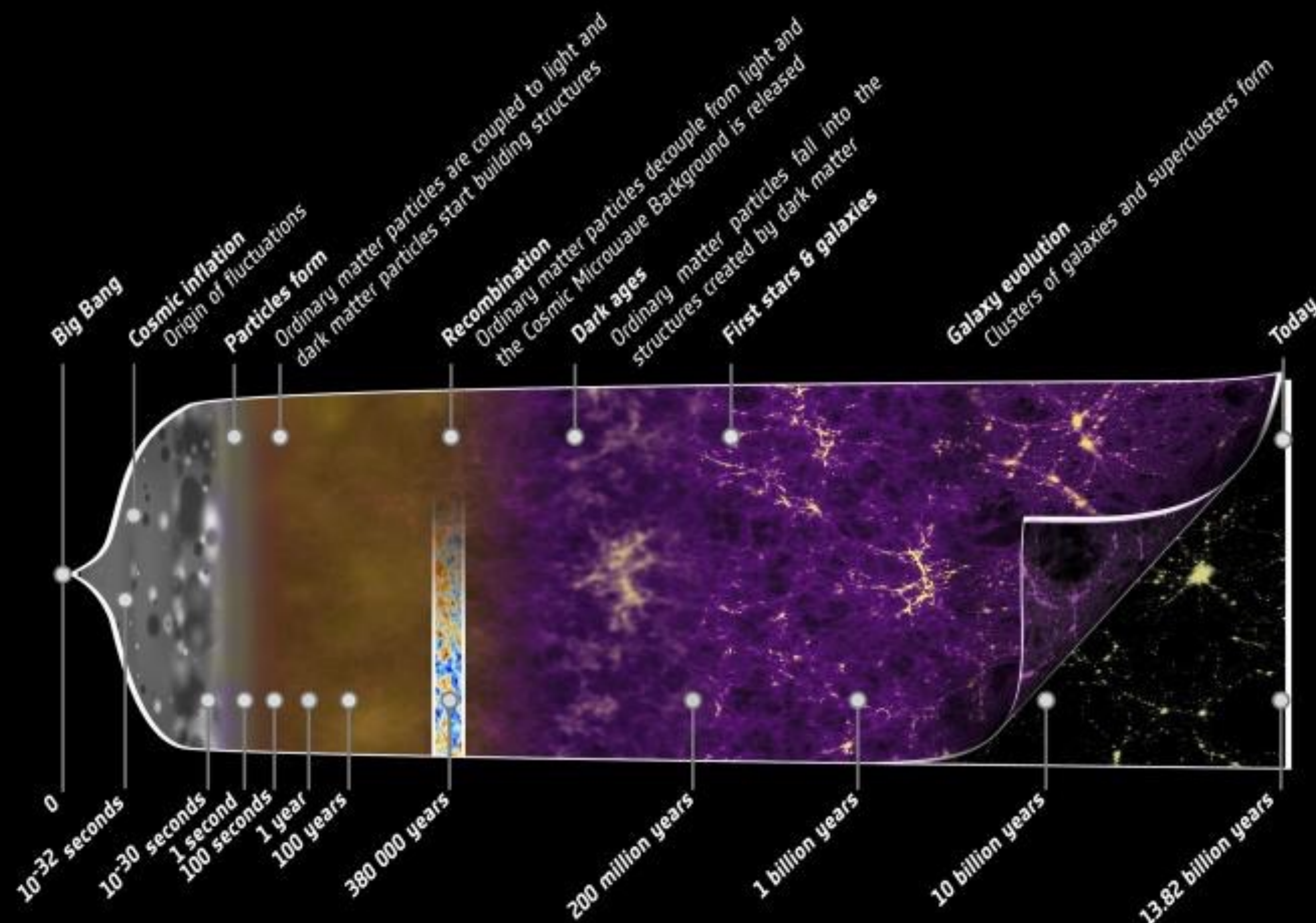
In collaboration with
Julien Lesgourgues (RWTH, Aachen)
and Pasquale D. Serpico (LAPTh, Annecy)


*mainly : VP, Serpico & Lesgourgues JCAP 1703 (2017) no.03, 043*
*see also : VP & Serpico PRL 114 (2015) no.9, 091101*
*VP & Serpico PRD 91 103007 (2015) no.10*
*VP, Serpico & Lesgourgues JCAP 1512 (2015) no.12 041*

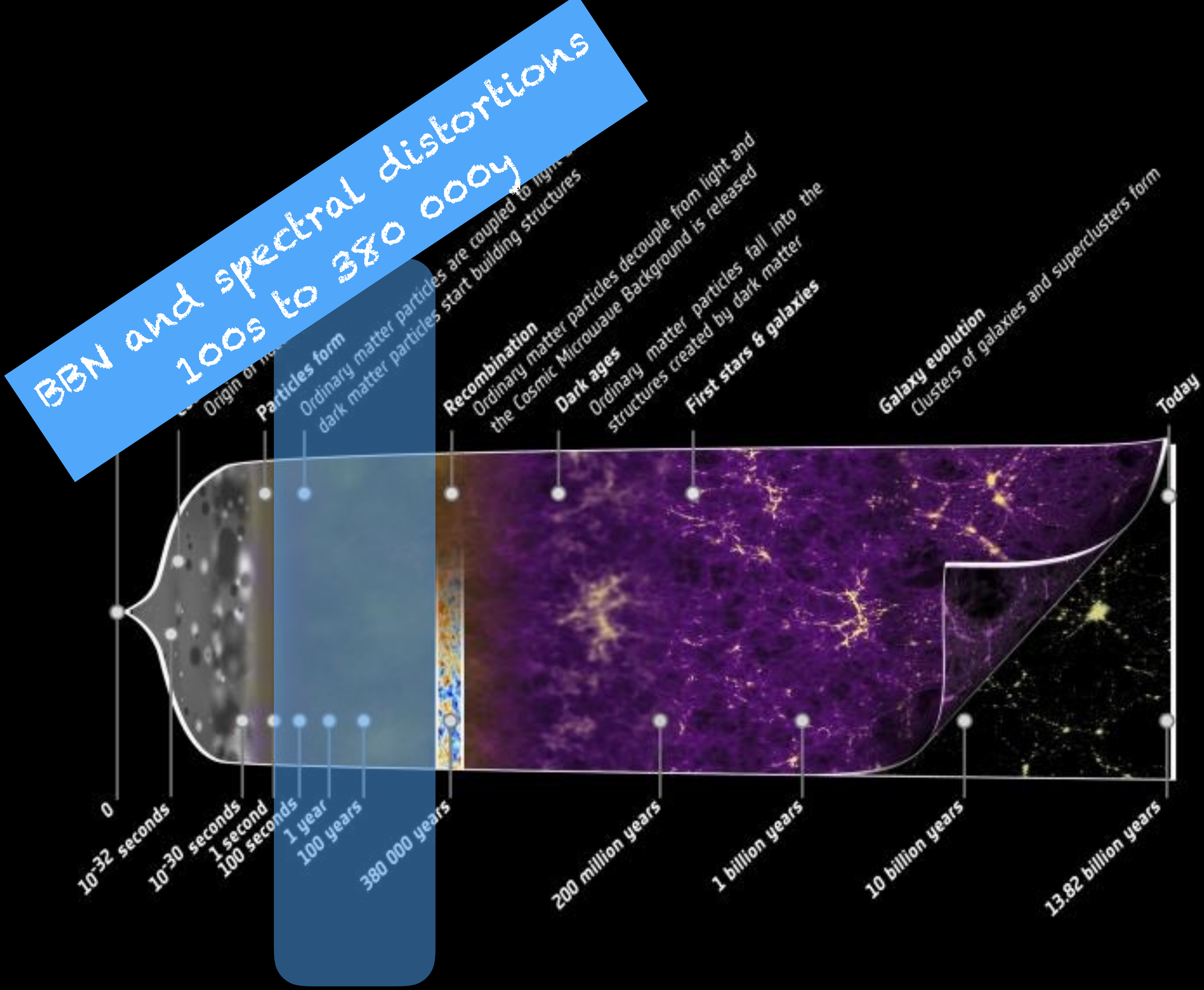
RWTH AACHEN UNIVERSITY

PONT, Avignon
27/04/2017

LAPTh




Our Universe is a great particle physics laboratory !

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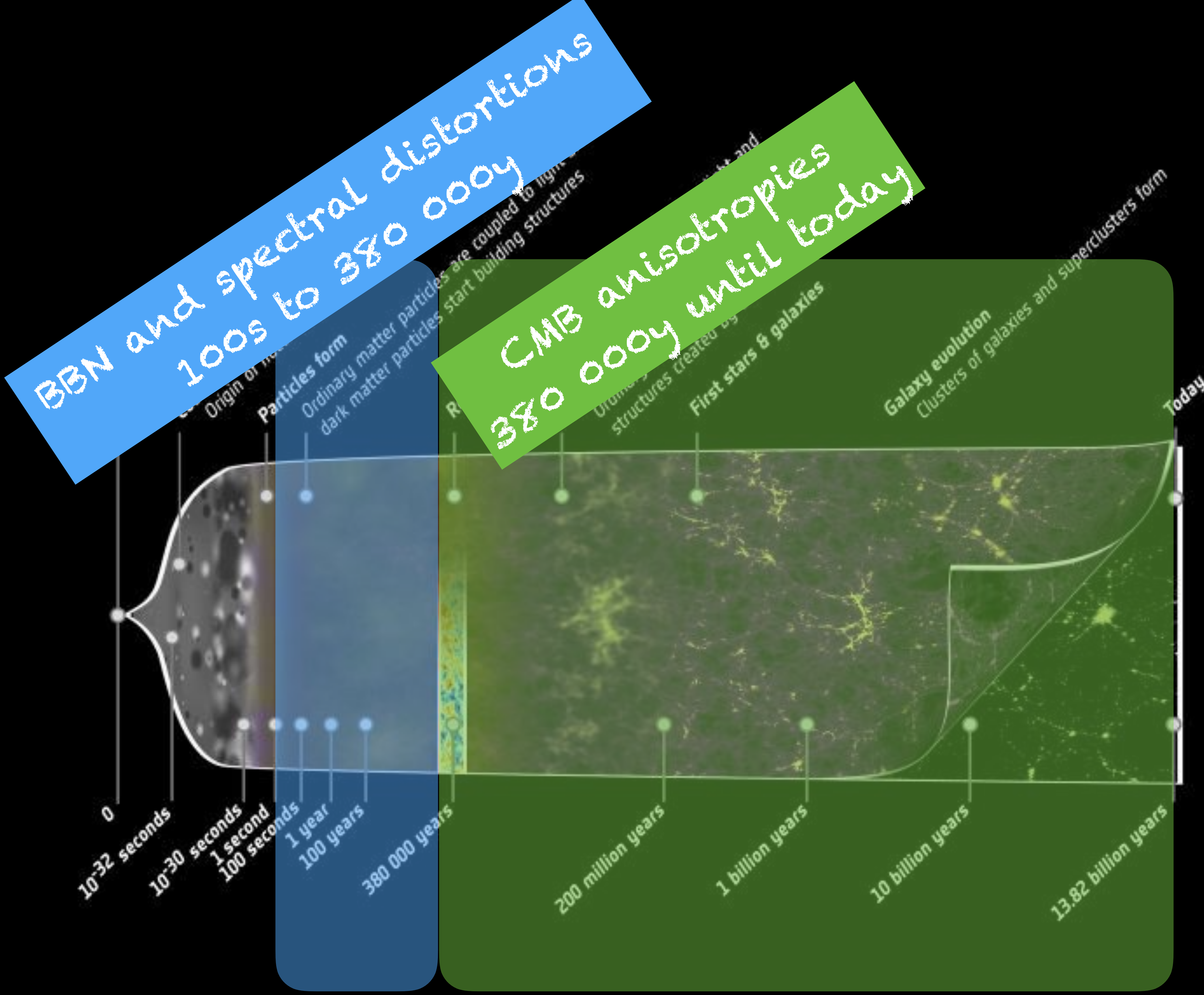


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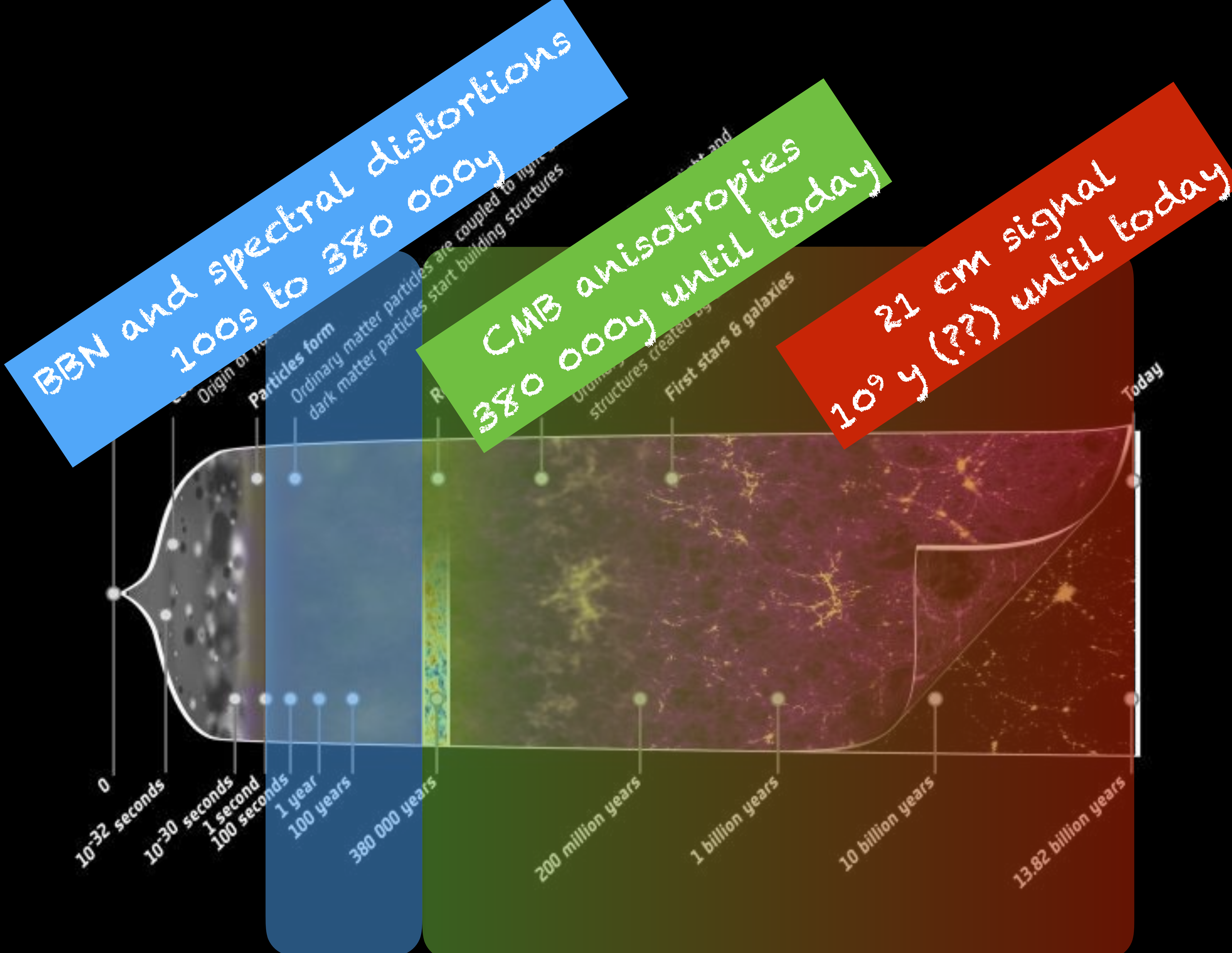


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# A Journey in Wonderland of particle physics

*see e.g.*
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**Q.** : What models are concerned by these constraints ?

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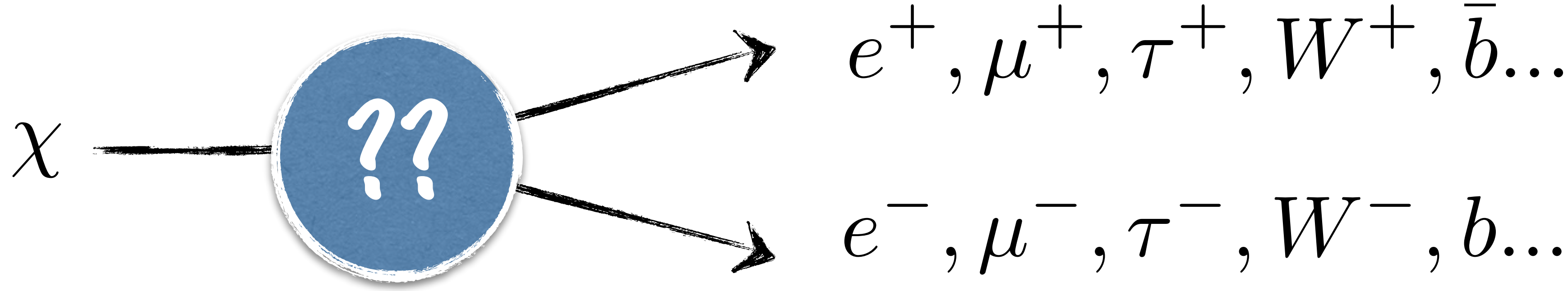
## The typical electromagnetic decay of an exotic particle

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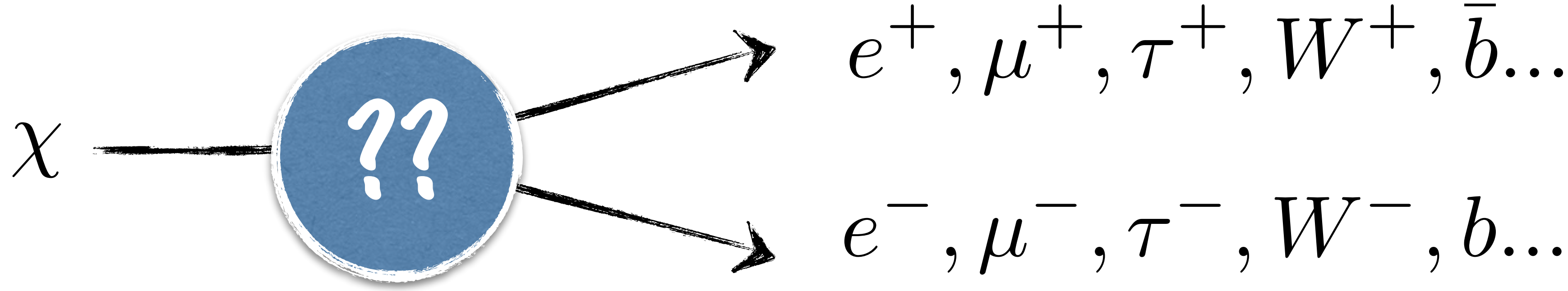


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One Caveat : We restrict ourself to lifetime > 1000 s.
=> We can neglect hadronic products!
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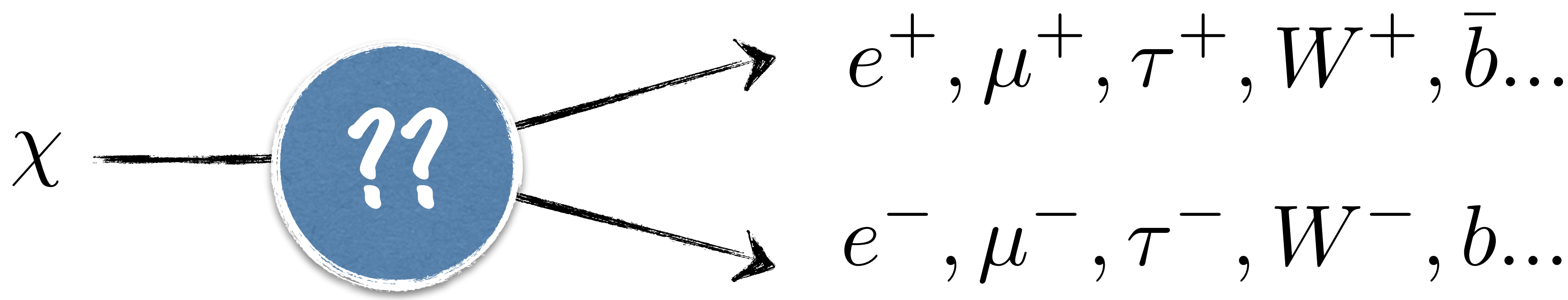


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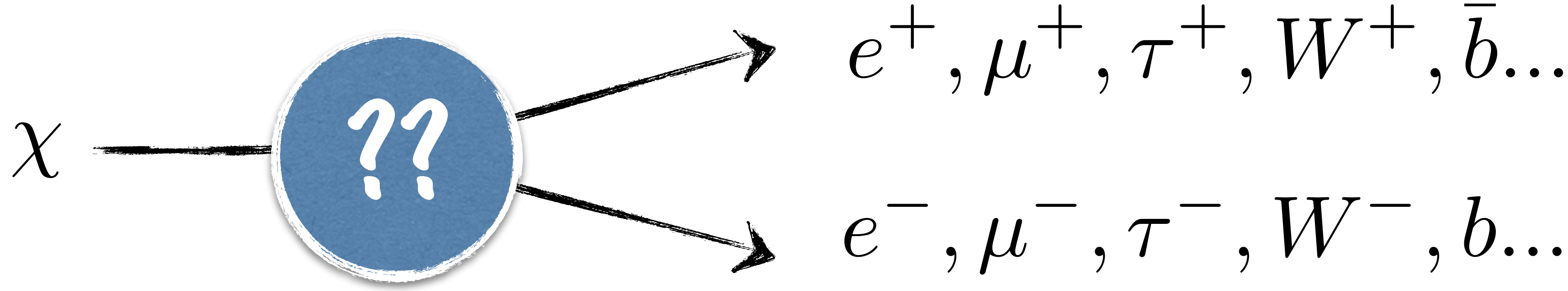


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$$\gamma\gamma_{\rm CMB} \to e^+e^- \qquad e\gamma_{\rm CMB} \to e\gamma \qquad \gamma\gamma_{\rm CMB} \to \gamma\gamma$$

spectral distortions

# The typical electromagnetic decay of an exotic particle


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

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

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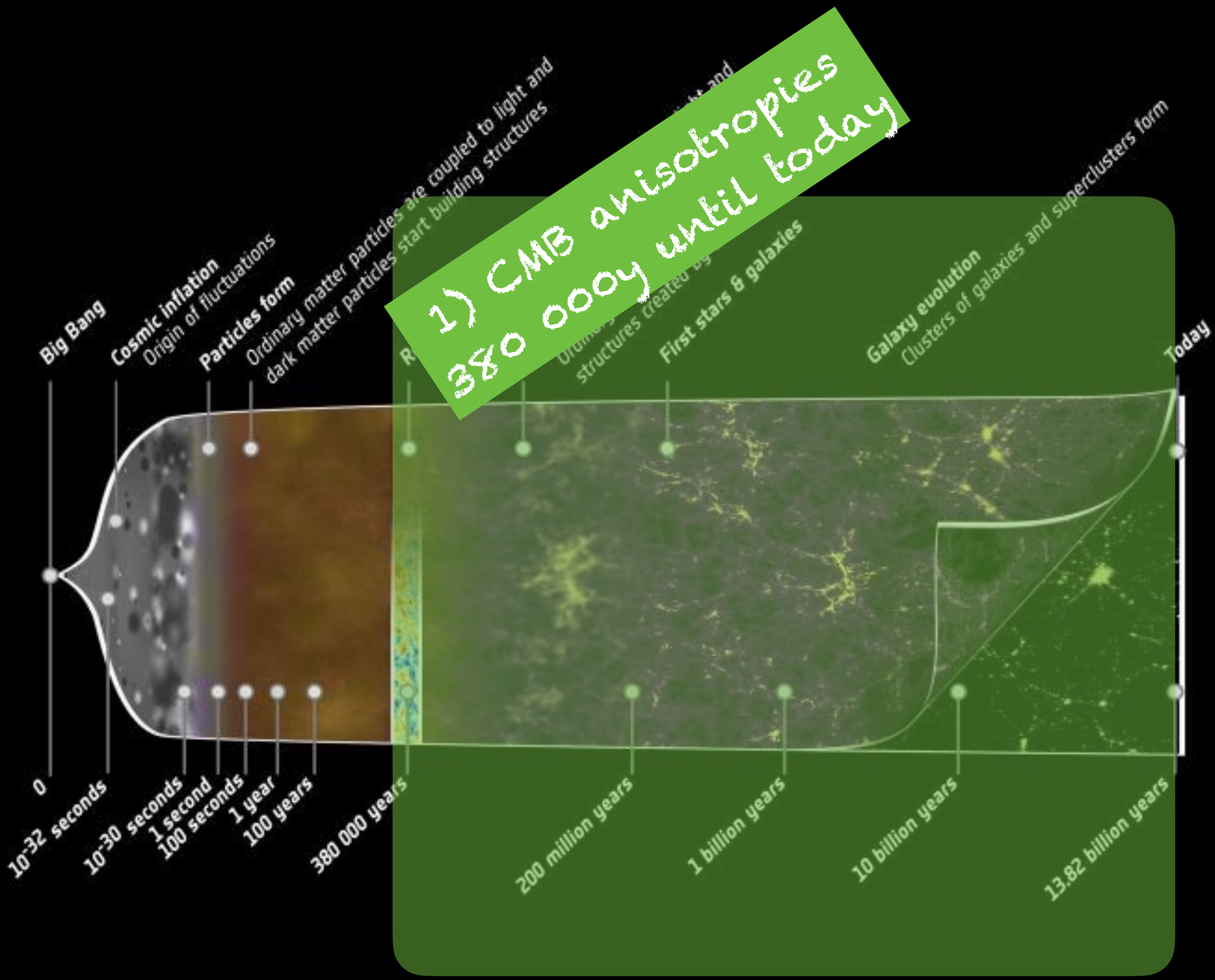
$$\gamma\gamma_{\rm CMB} \rightarrow e^+e^- \qquad e\gamma_{\rm CMB} \rightarrow e\gamma \qquad \gamma\gamma_{\rm CMB} \rightarrow \gamma\gamma$$

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

spectral distortions

BBN, CMB anisotropies


1) CMB anisotropies
380 000y until today
Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and
dark matter particles start building structures
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

# From perturbations to spectrum of temperature anisotropies

*see e.g. textbook « The Cosmic Microwave Background » by R. Durrer; « Cosmology » By Weinberg.*
*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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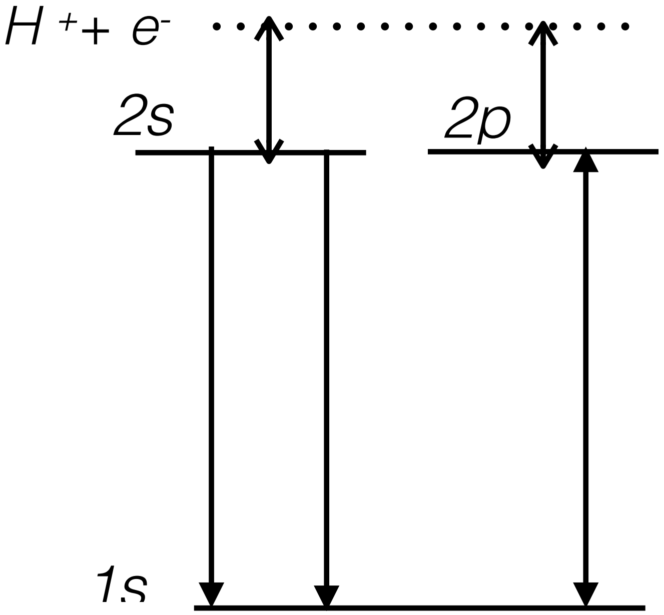
non e.m. decay : modify $\phi$' and $\psi$'

# 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*
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*and references therein*

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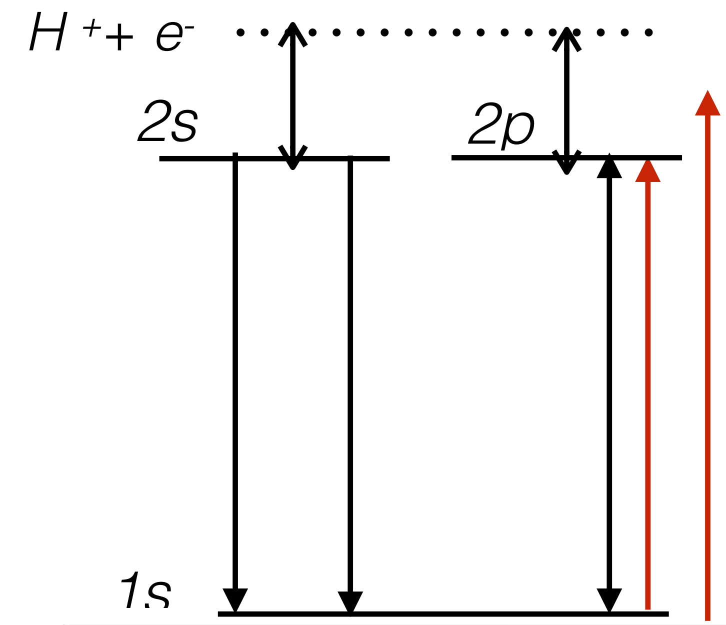


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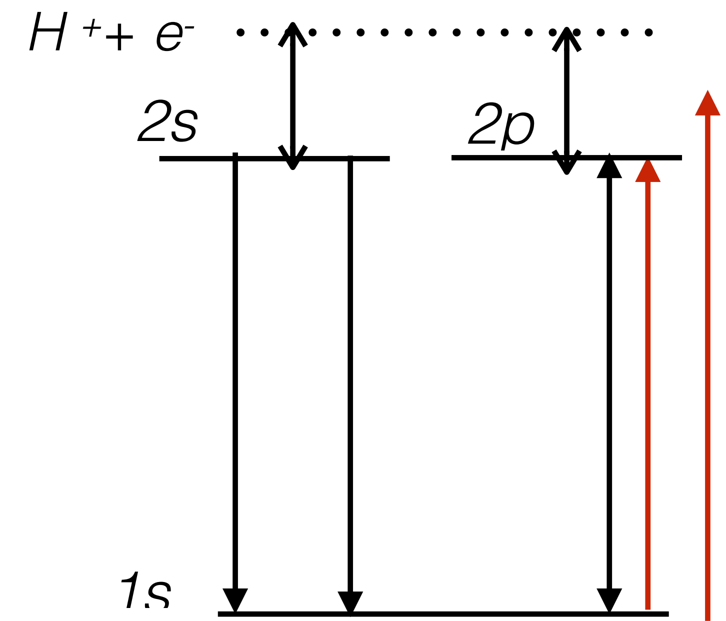


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$$I_X(z) \text{ and } K_h(z) \propto \left.\frac{dE}{dV\,dt}\right|_{\rm dep,c}$$

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

- 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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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*

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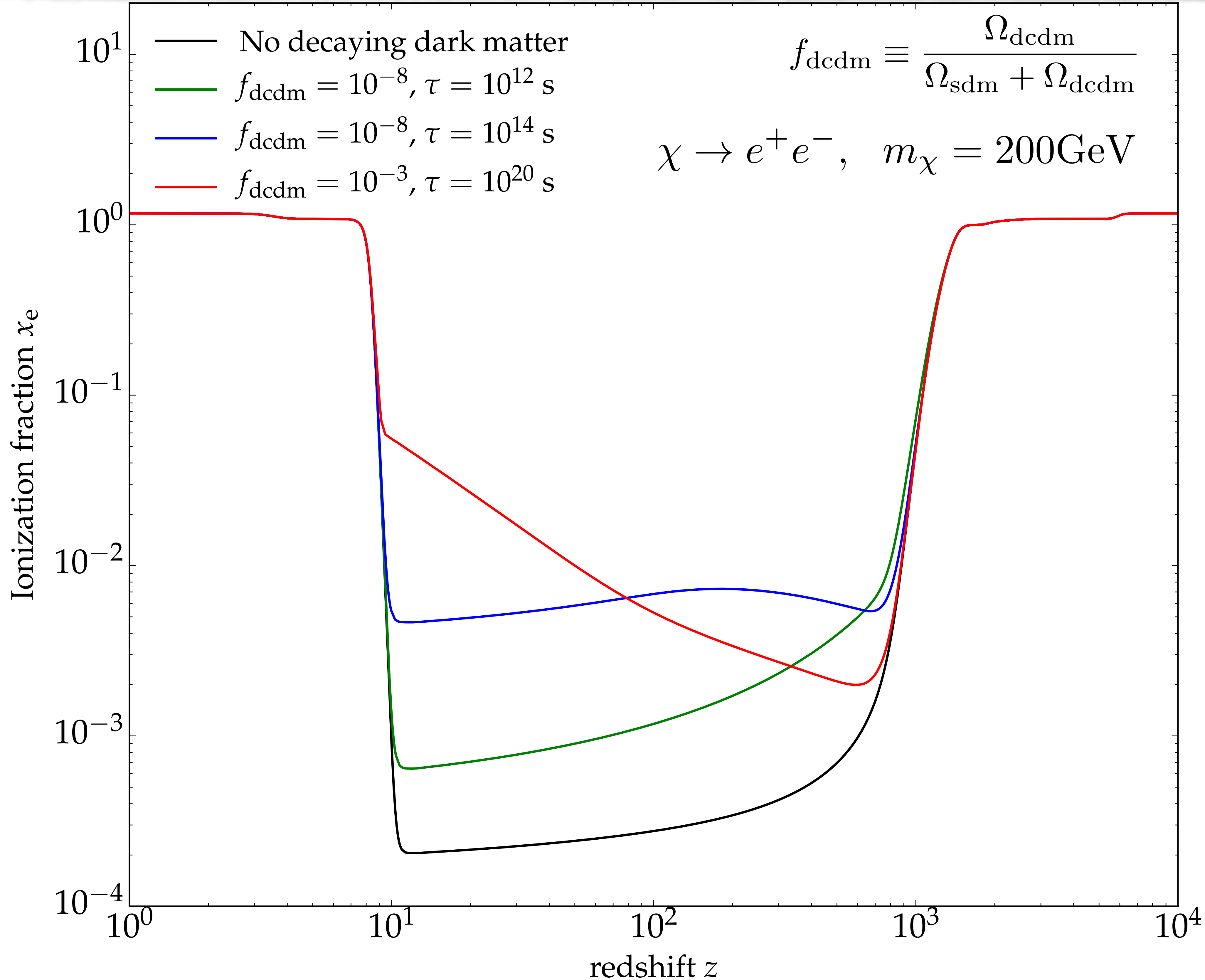
$f_c(z, x_e)$ is the key quantity, it encodes:

- 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’

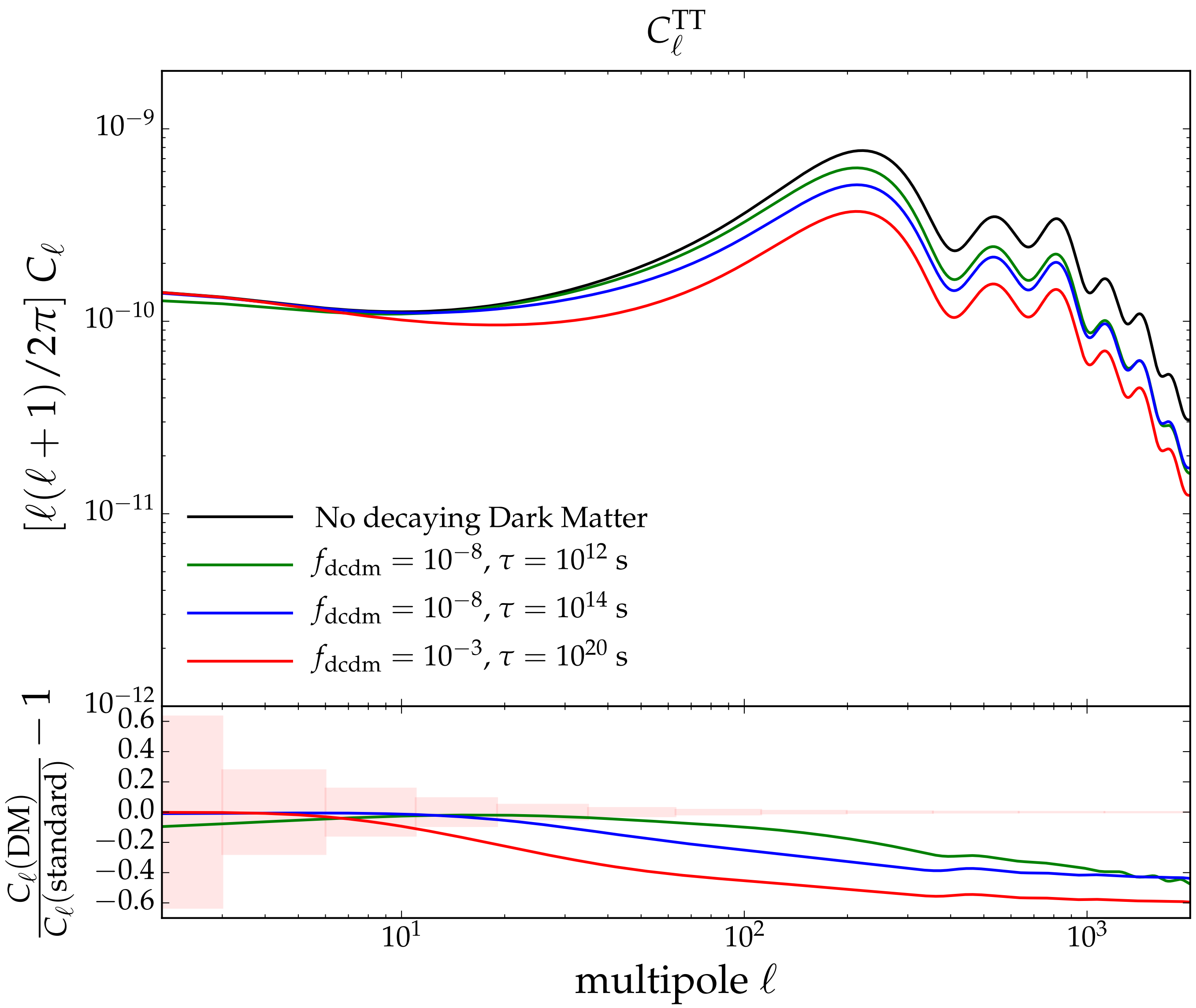
In practice, it depends on details of the particle physics and injection history.

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

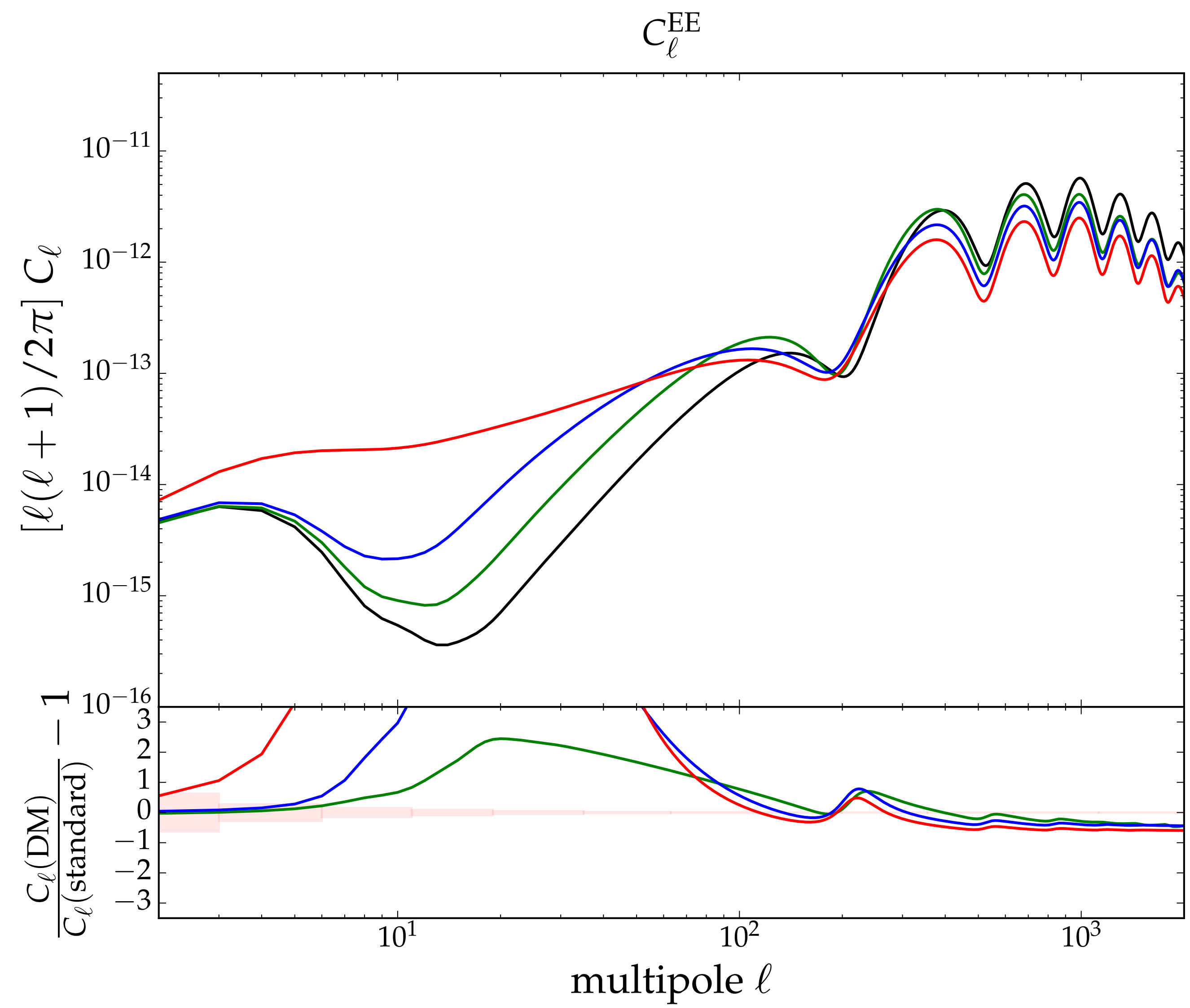


## Many lifetime dependent effects on the CMB power spectra !

### temperature anisotropies

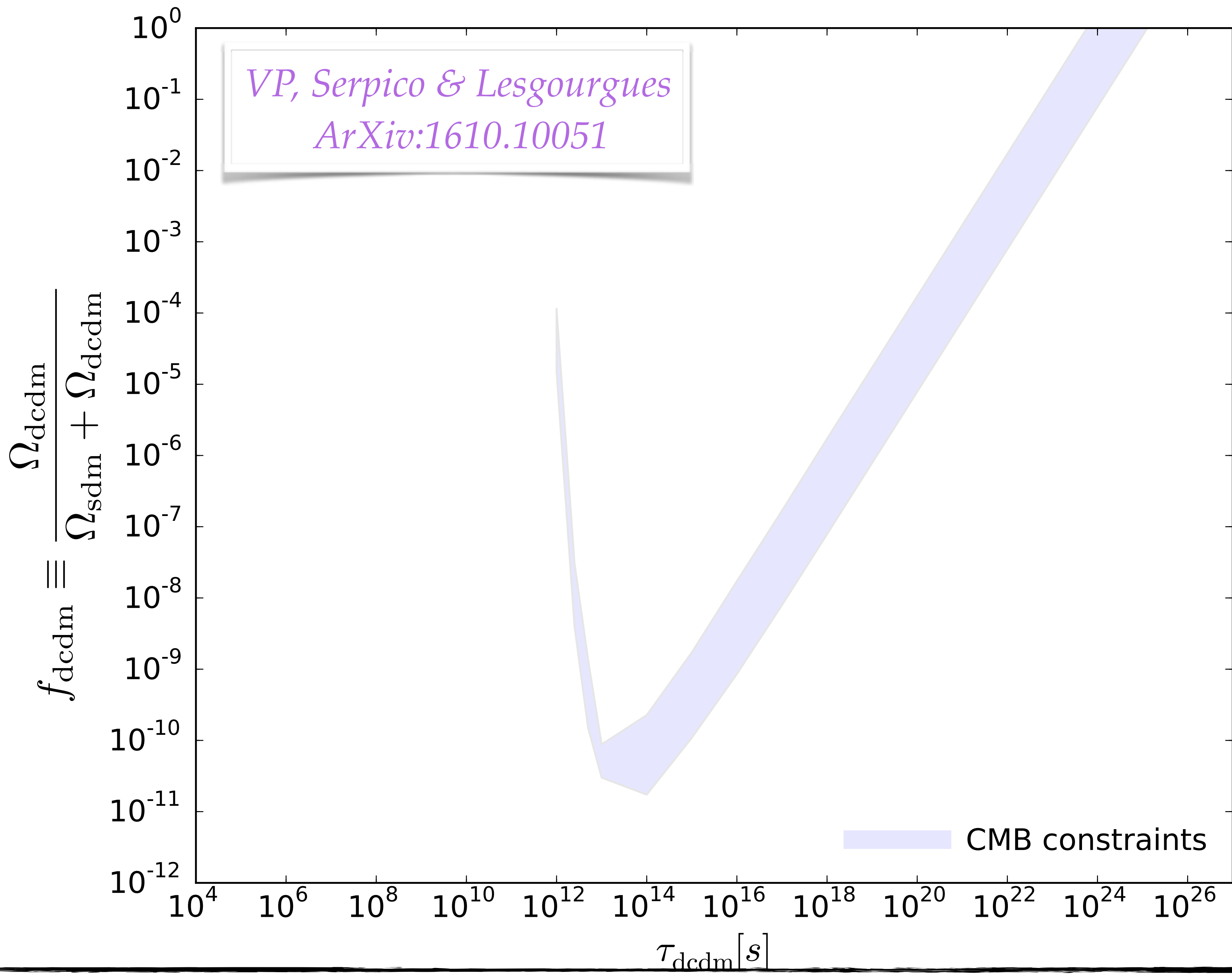



### polarization anisotropies



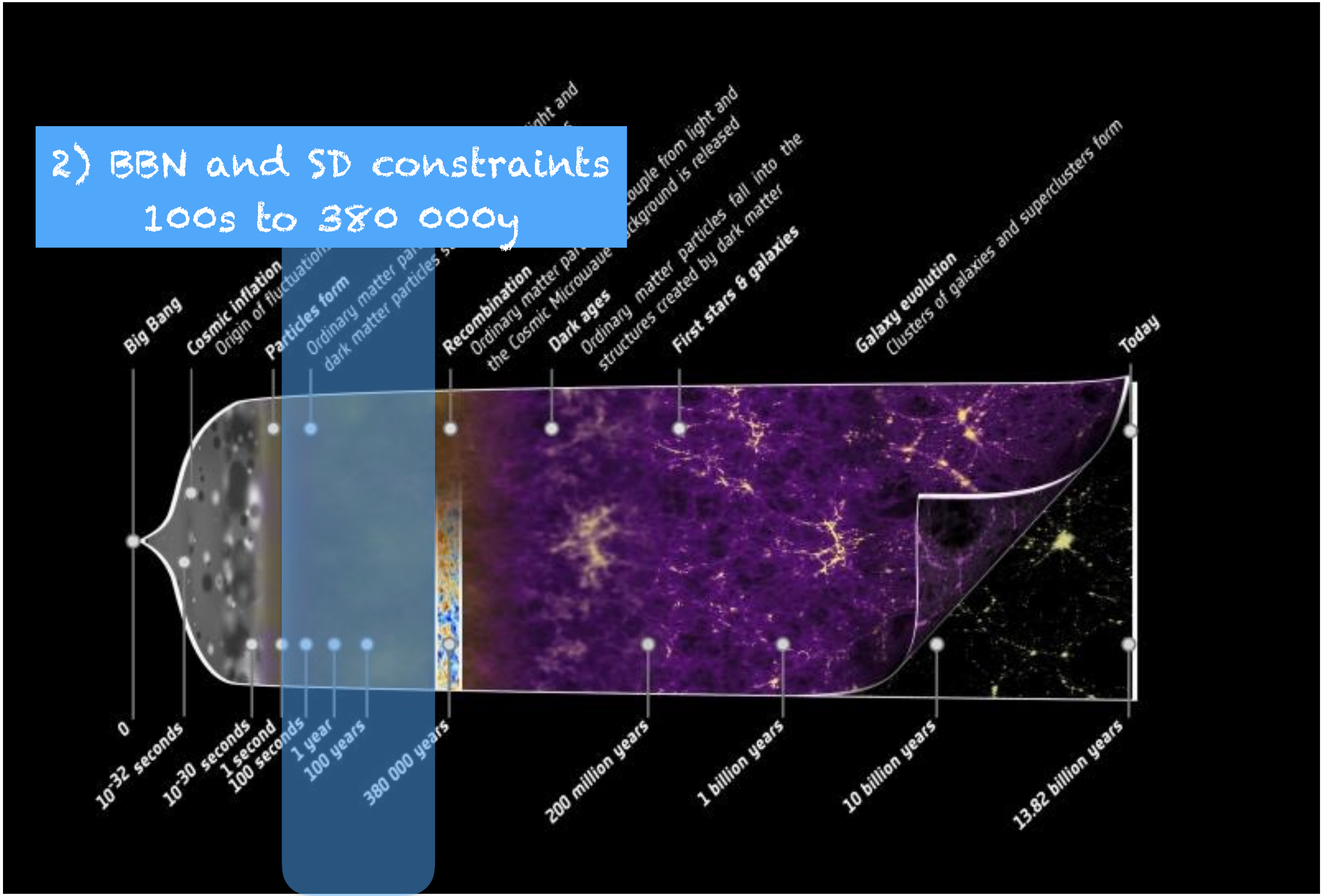

- Long lifetime : looks like early reionization, i.e. increase of $\kappa_{\rm reio}$ leads to step-like suppression above l = 10 and bigger reionization bump.
- Short lifetime: can have very peculiar behaviour! Larger damping tail, shifted/broaden reionization bump and suppress LISW.

# CMB anisotropies very powerful at constraining τ = [10^12,10^25]s




*see also Slatyer&Wu PRD (2017) no.2, 023010*

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


2) BBN and SD constraints
100s to 380 000y
Big Bang
Cosmic inflation
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
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380 000 years
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1 billion years
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13.82 billion years

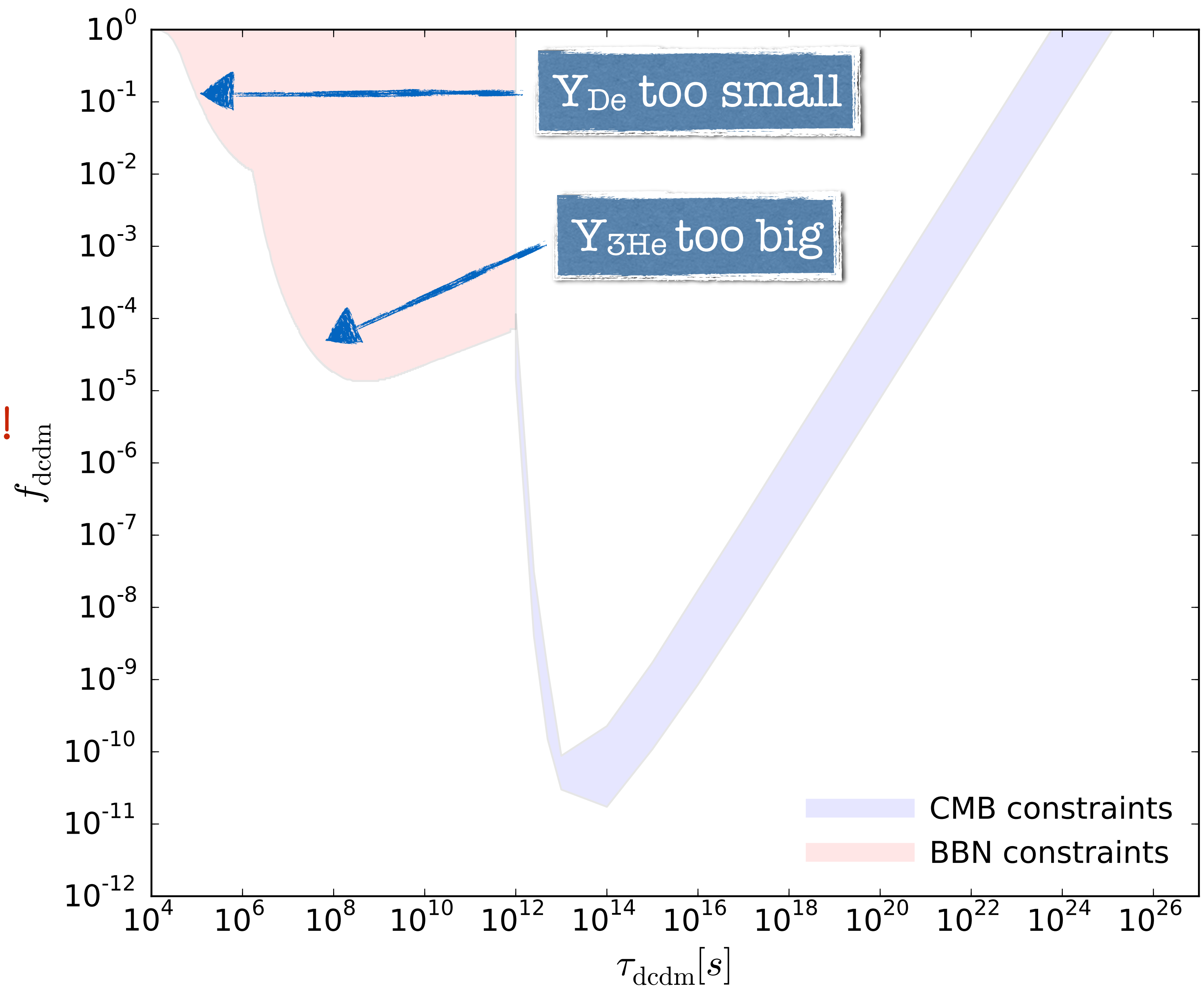
# BBN very powerful at constraining $\tau = [10^4, 10^{12}]$s

Injected high energy particles initiate an E.M. Cascade :

Same idea as before but now $\Gamma_{scat} >> \Gamma_{hubble}$ ! (valid until recombination)

Those bounds are universal !!

*Kawasaki & Moroi, ApJ 452,506 (1995)*



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For MeV-GeV energy injection, bounds can be much stronger.

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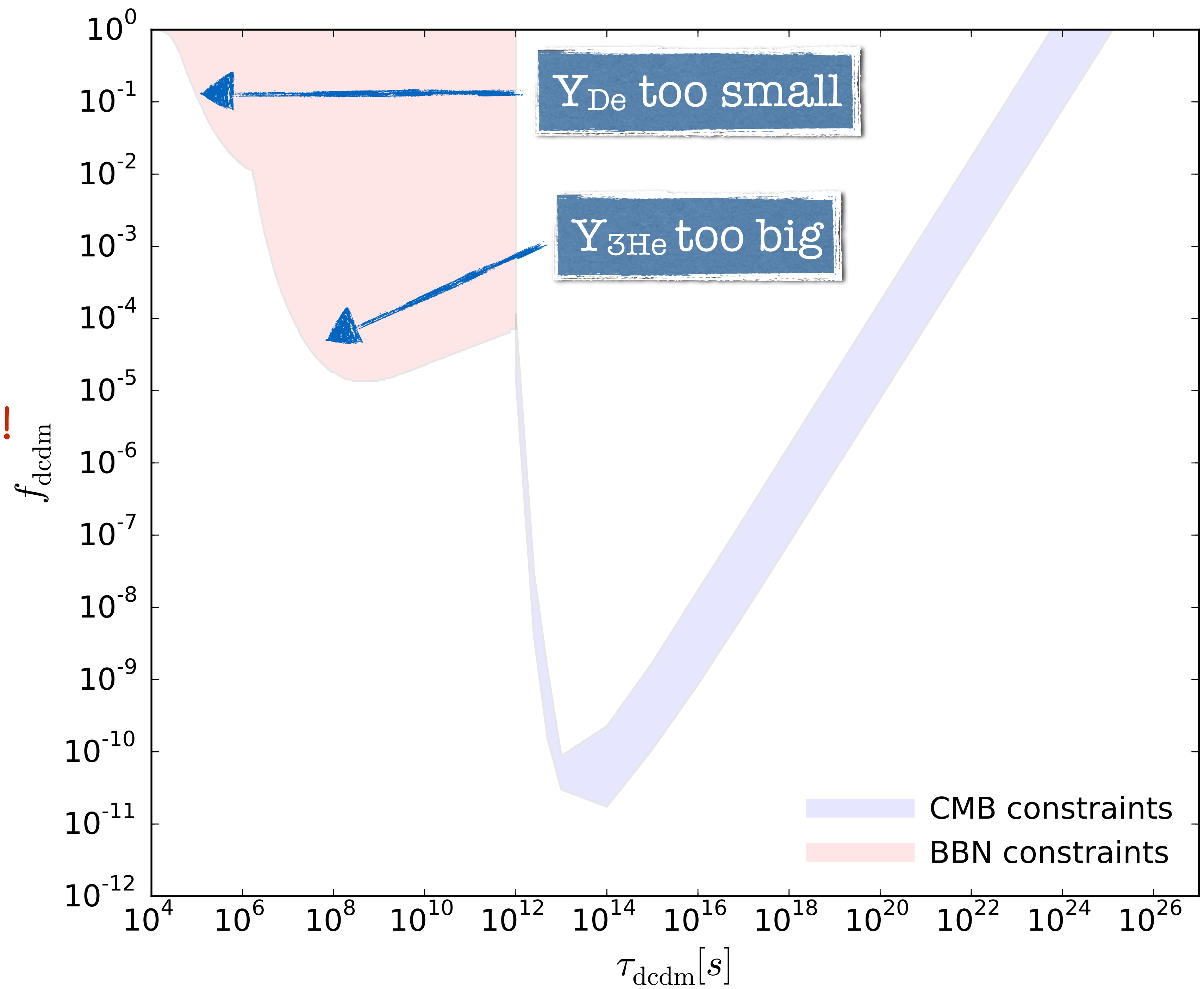

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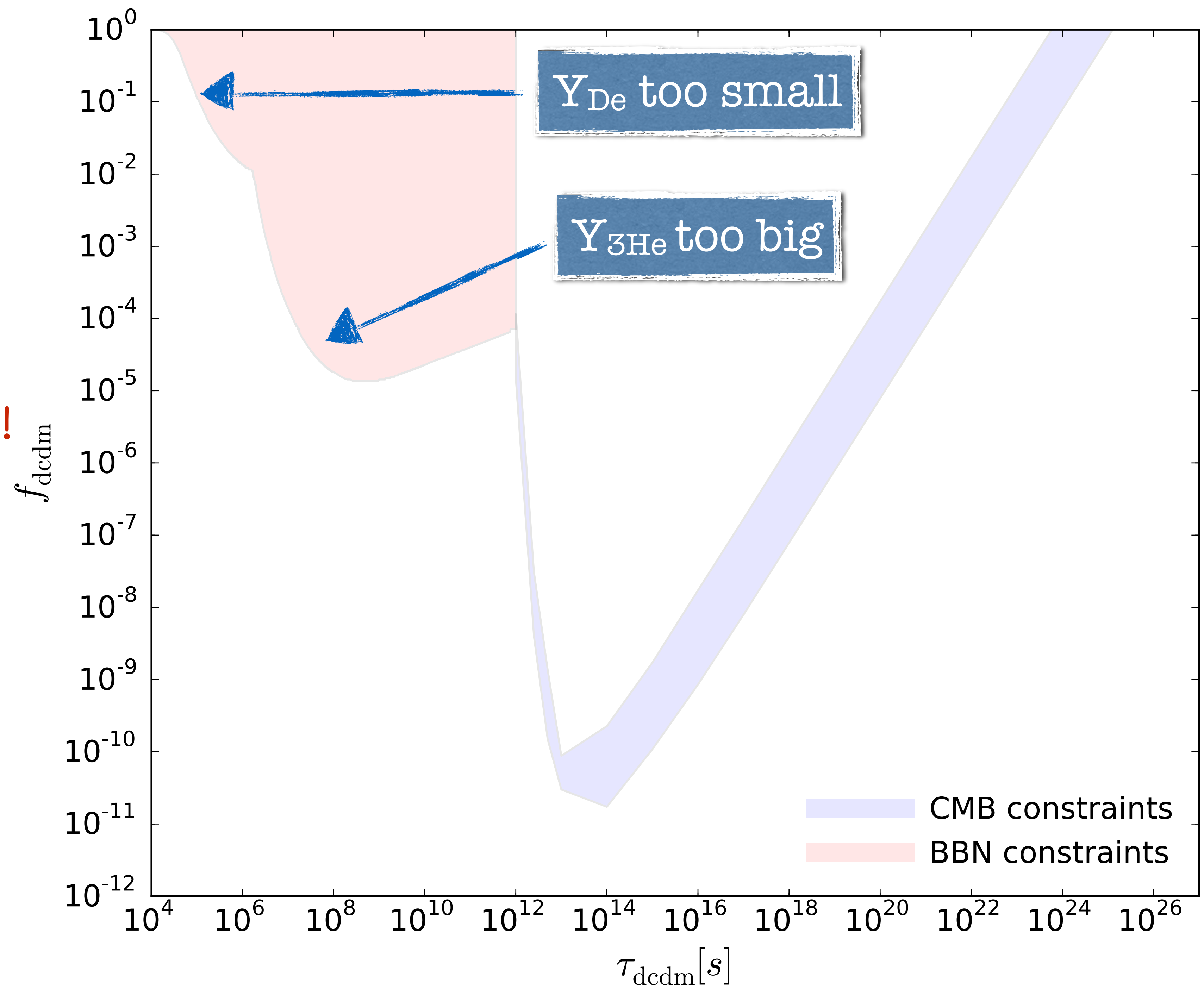



⇨ Those bounds are very conservative !

# CMB vs BBN vs spectral distortions

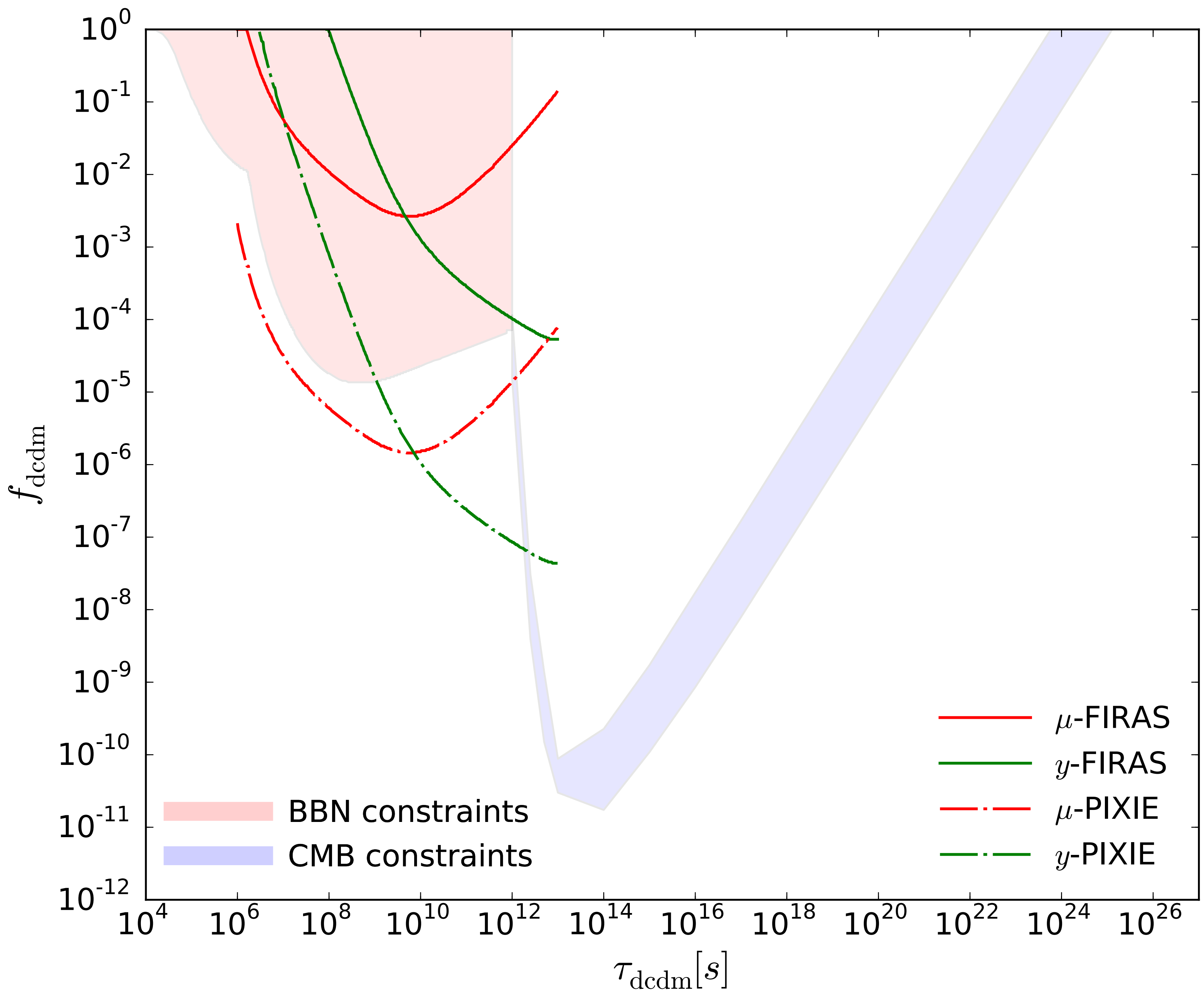
Double Compton / Bremsstrahlung off

μ = creation of a chemical potential

Compton Scattering off

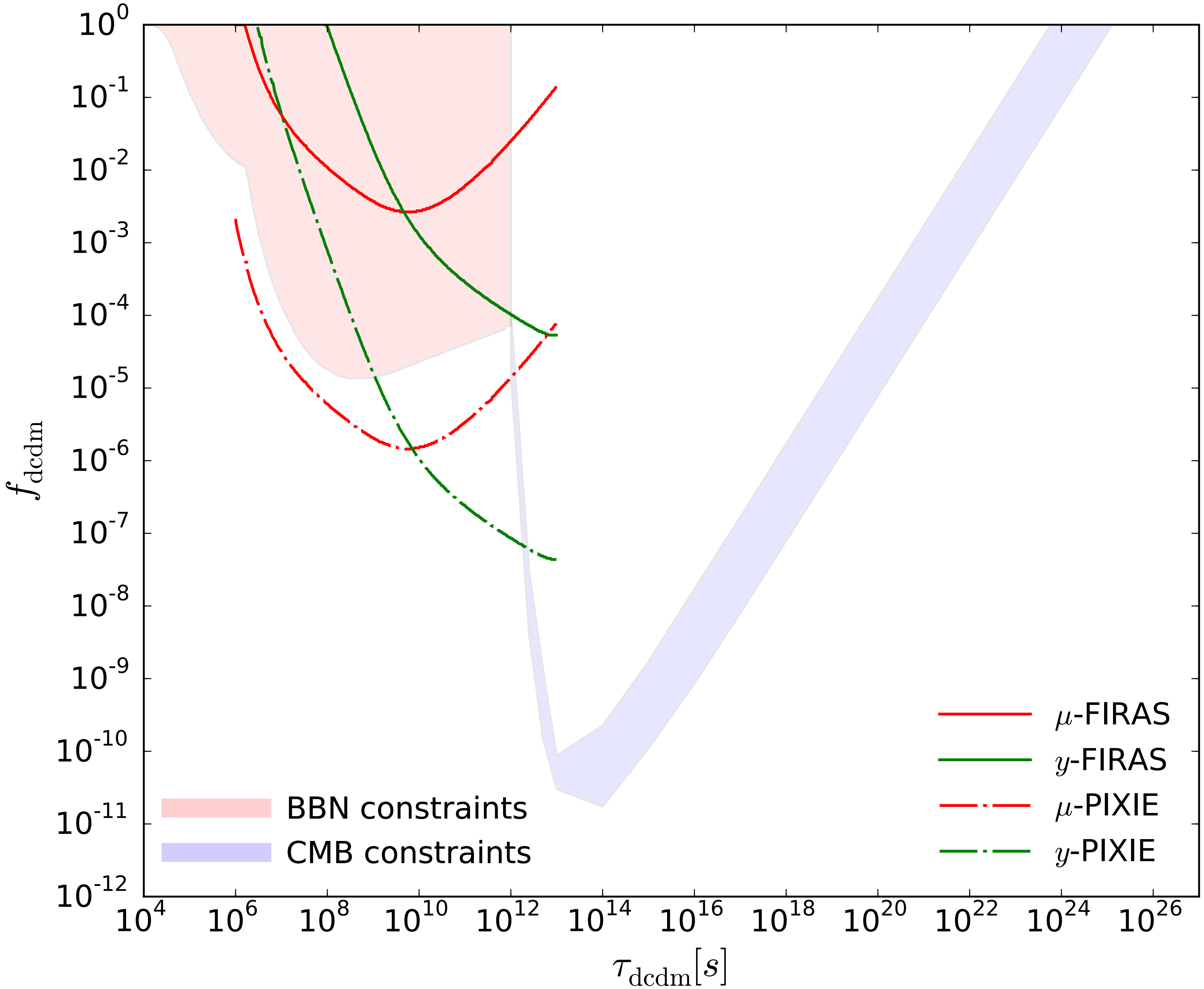
y = Compton heating (or cooling!) of the CMB gas

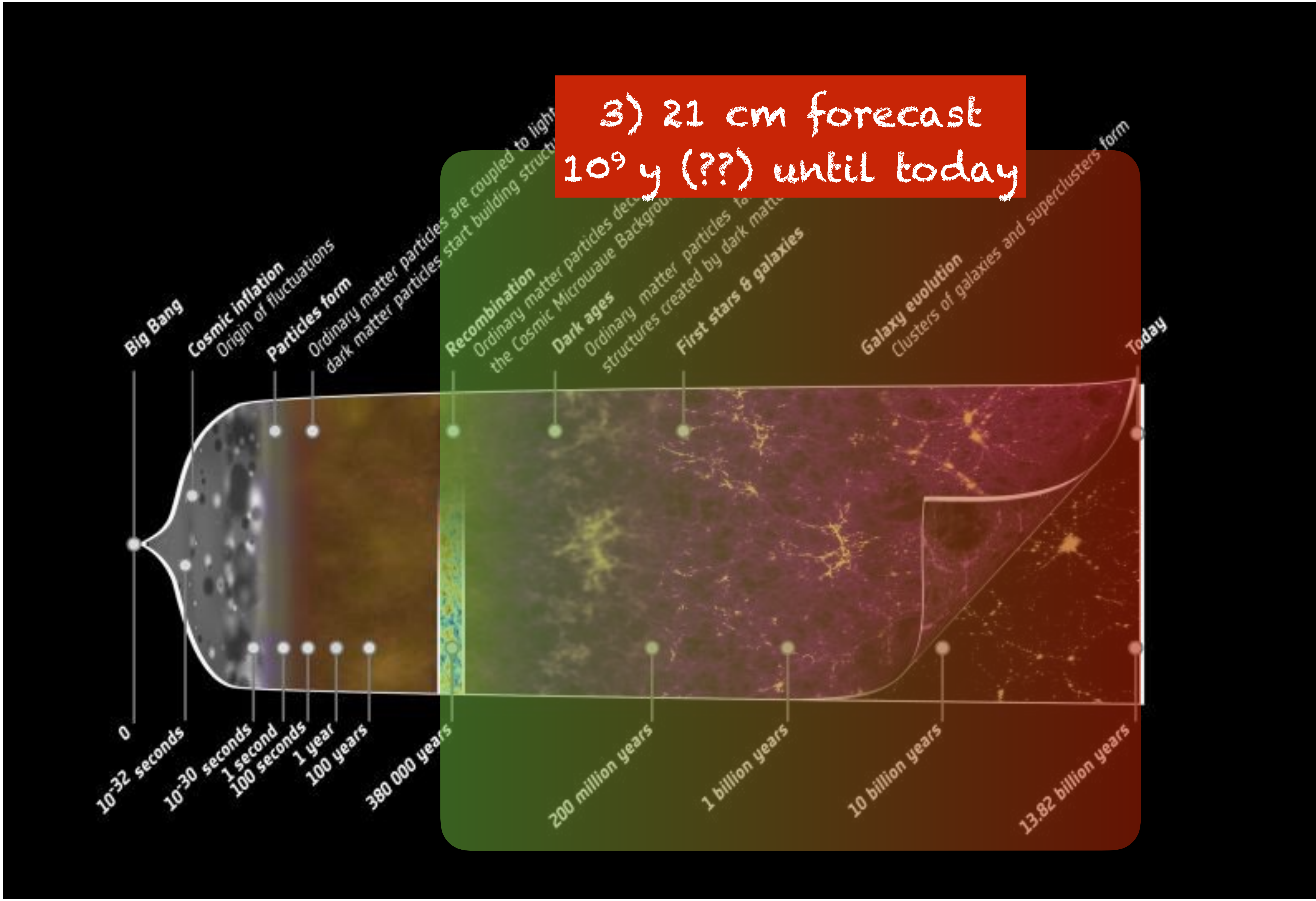
*Review: Chluba & Sunyaev [arXiv:1109.6552]*



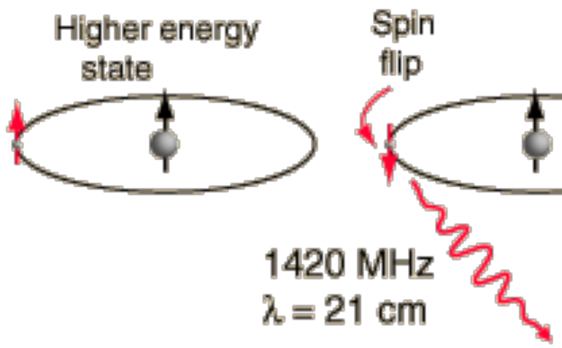

Current constraints from **FIRAS** on the μ and y parameters are worst than BBN. This will (might) change in the future with **PIXIE** !

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




3) 21 cm forecast
$10^9$ 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

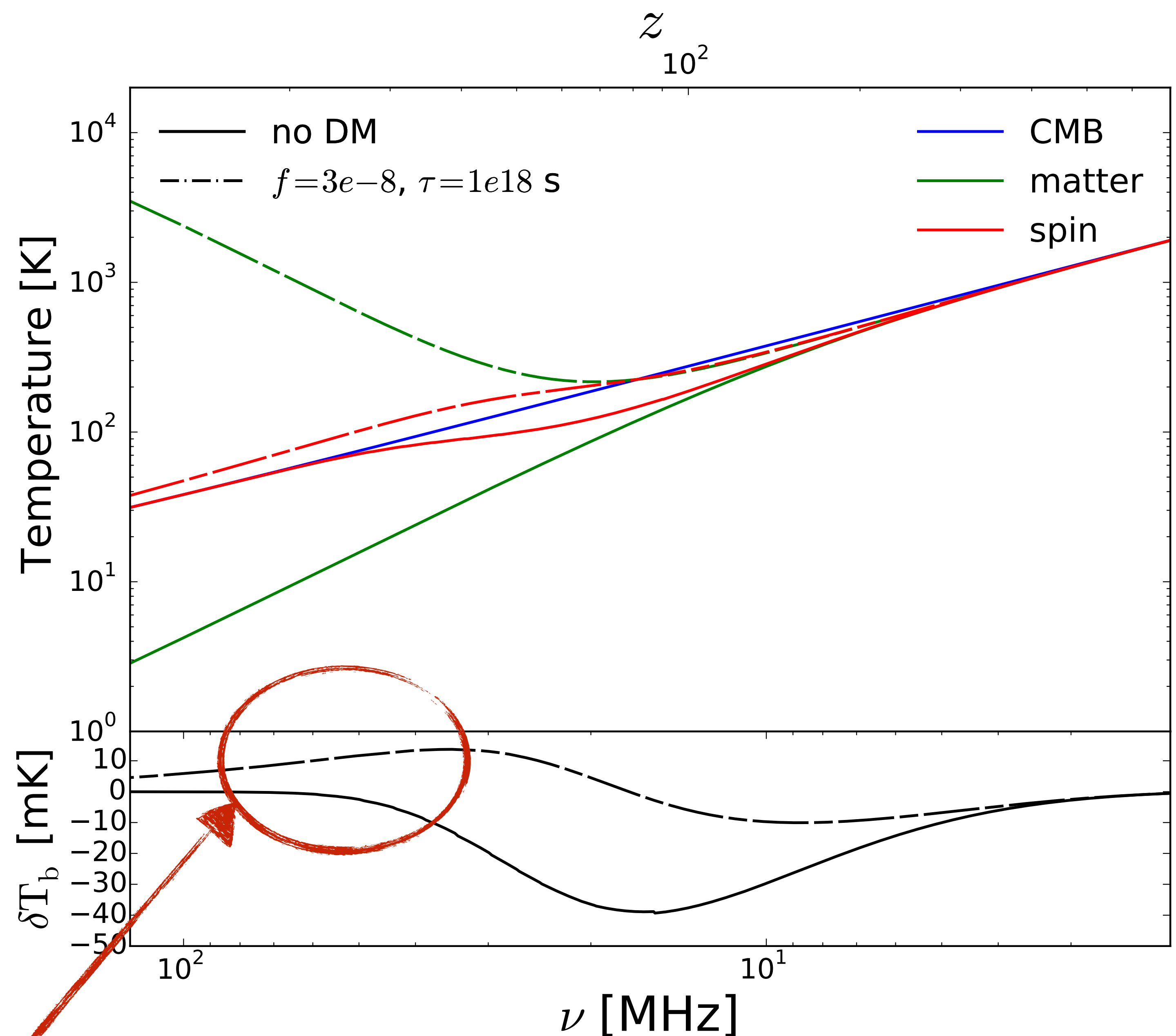



$$\delta T_b(\nu) = \frac{T_s - T_{\rm CMB}}{1+z}\left(1 - \exp(-\tau_{\nu 21})\right)$$

At low-z, large uncertainty due to star formation leads to pessimistic results.

*Lopez-Honorez et al.*
*JCAP 1608 (2016) no.08, 004*

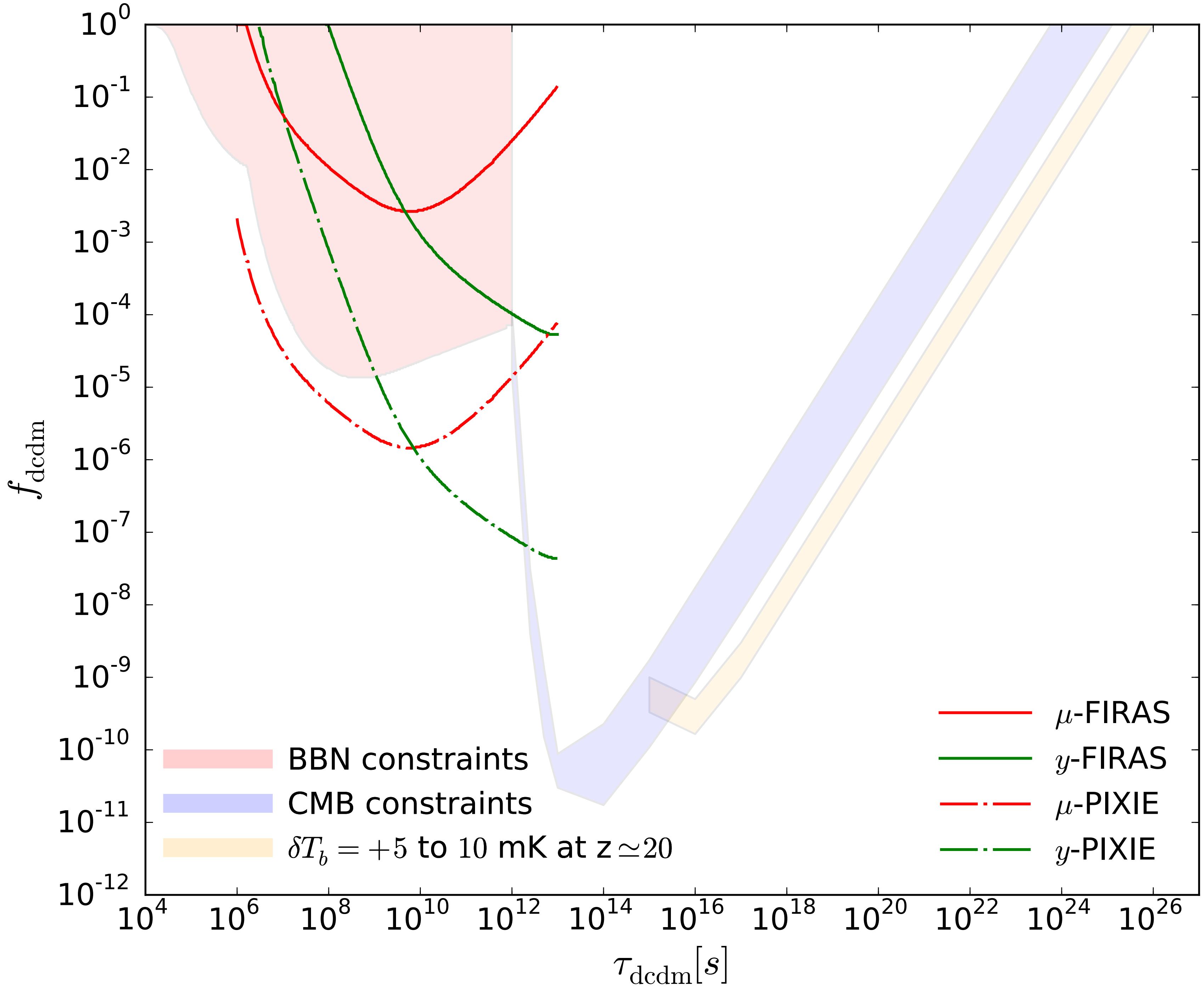
We neglect stars : valid until z = 20.
=> SKA will measure $\delta T_b$ = 5-10 mK
up to z= 20/25 (ν = 60 MHz) !




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.

- Bounds are competitive with diffuse gamma-ray background ones.
- Combination of BBN /spectral distortions / CMB allow constraining more than 20 orders of magnitude in lifetime, and 10 orders of magnitude in abundances.
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Next Step : 21 cm and reionization ! Many experiments are launched (e.g. SKA, HERA).

- First result quite pessimistic given the huge astrophysical uncertainties.
- Some hope : the dark ages, when no stars were there.

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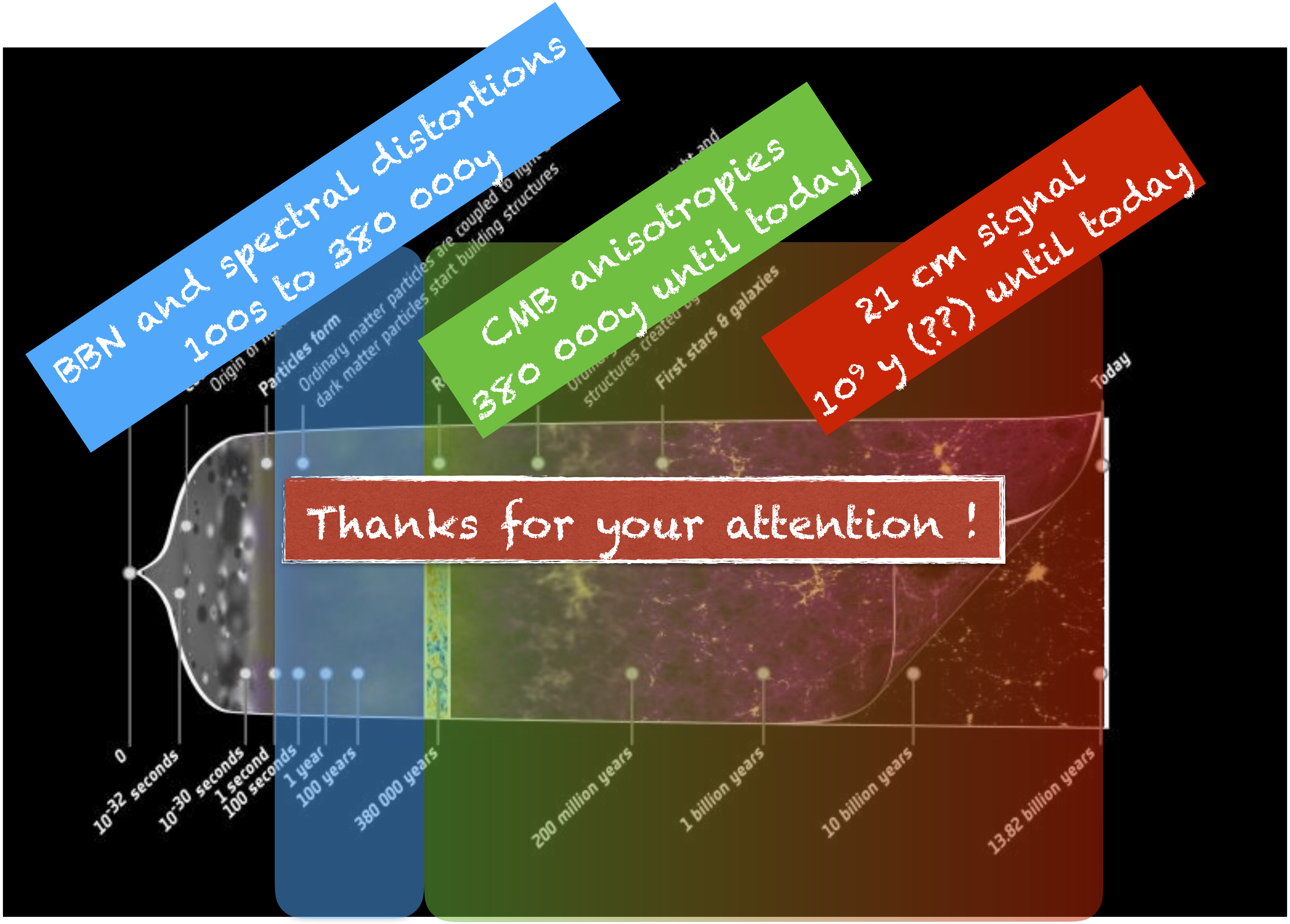
**Stay tuned ! Many results to come !**


BBN and spectral distortions
100s to 380 000y
CMB anisotropies
380 000y until today
21 cm signal
10⁹ y (??) until today
Particles form
First stars & galaxies
Today
Thanks for your attention !
0
10-32 seconds
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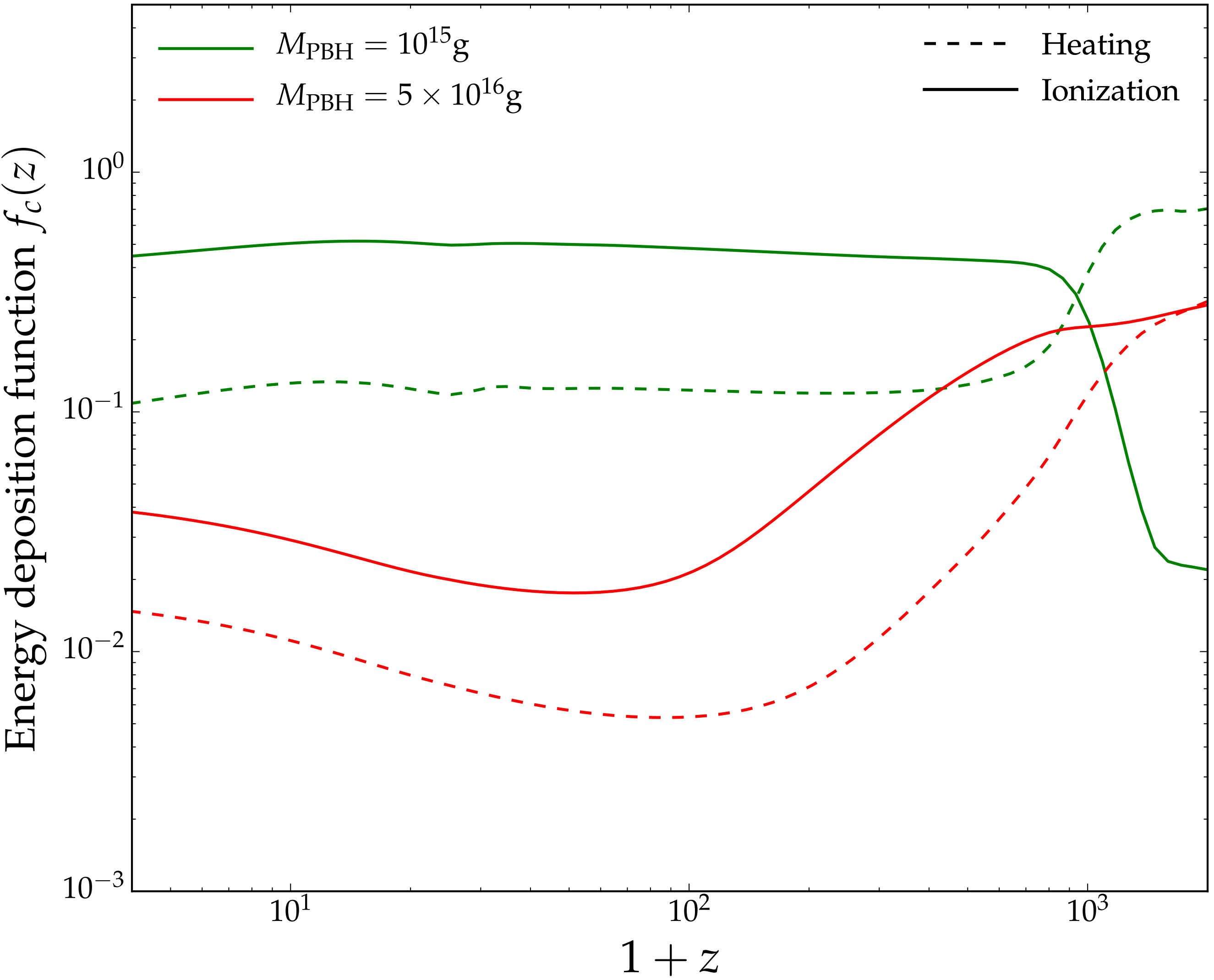
# Backup slides

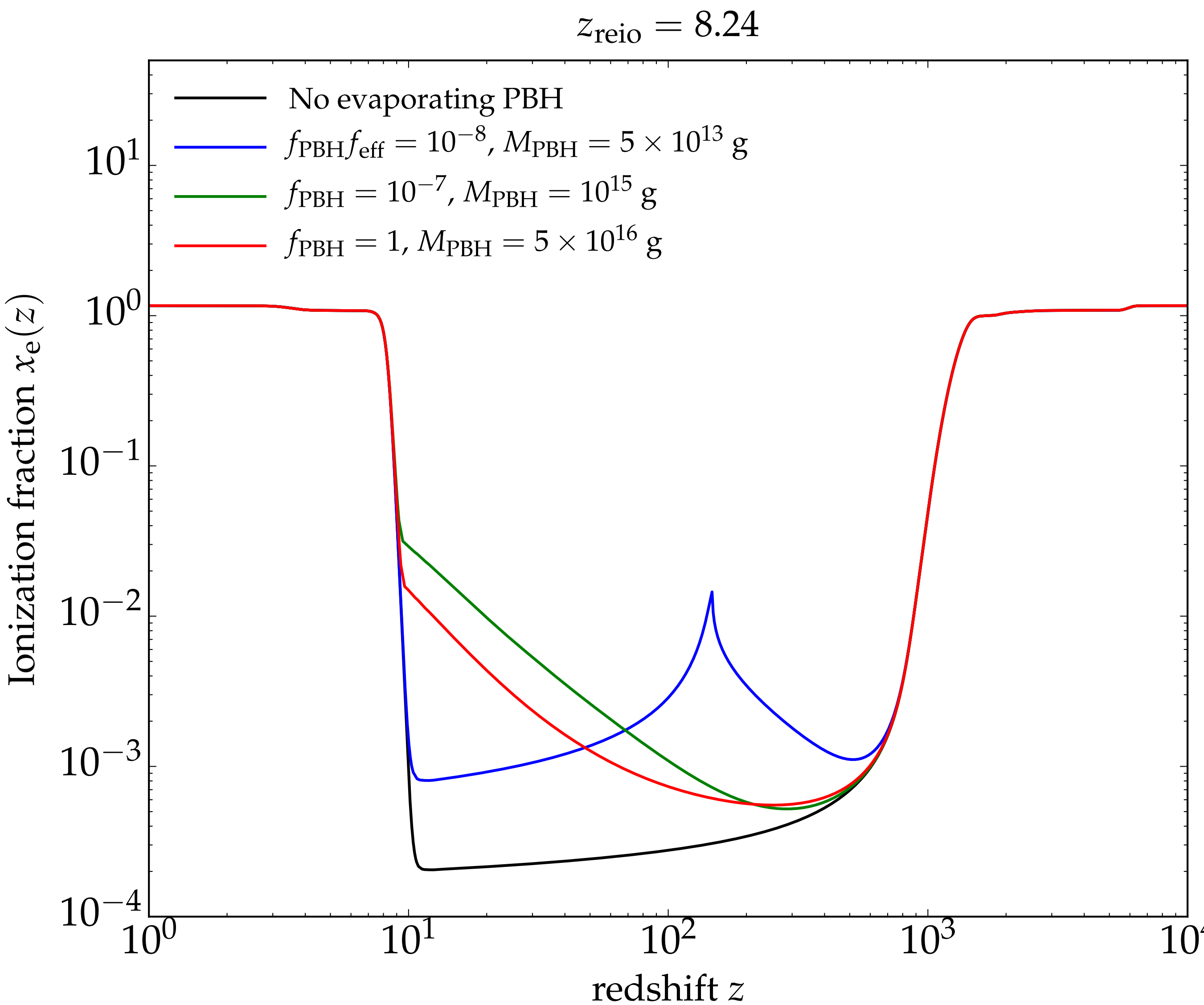
# Constraints on evaporating PBH (1)

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

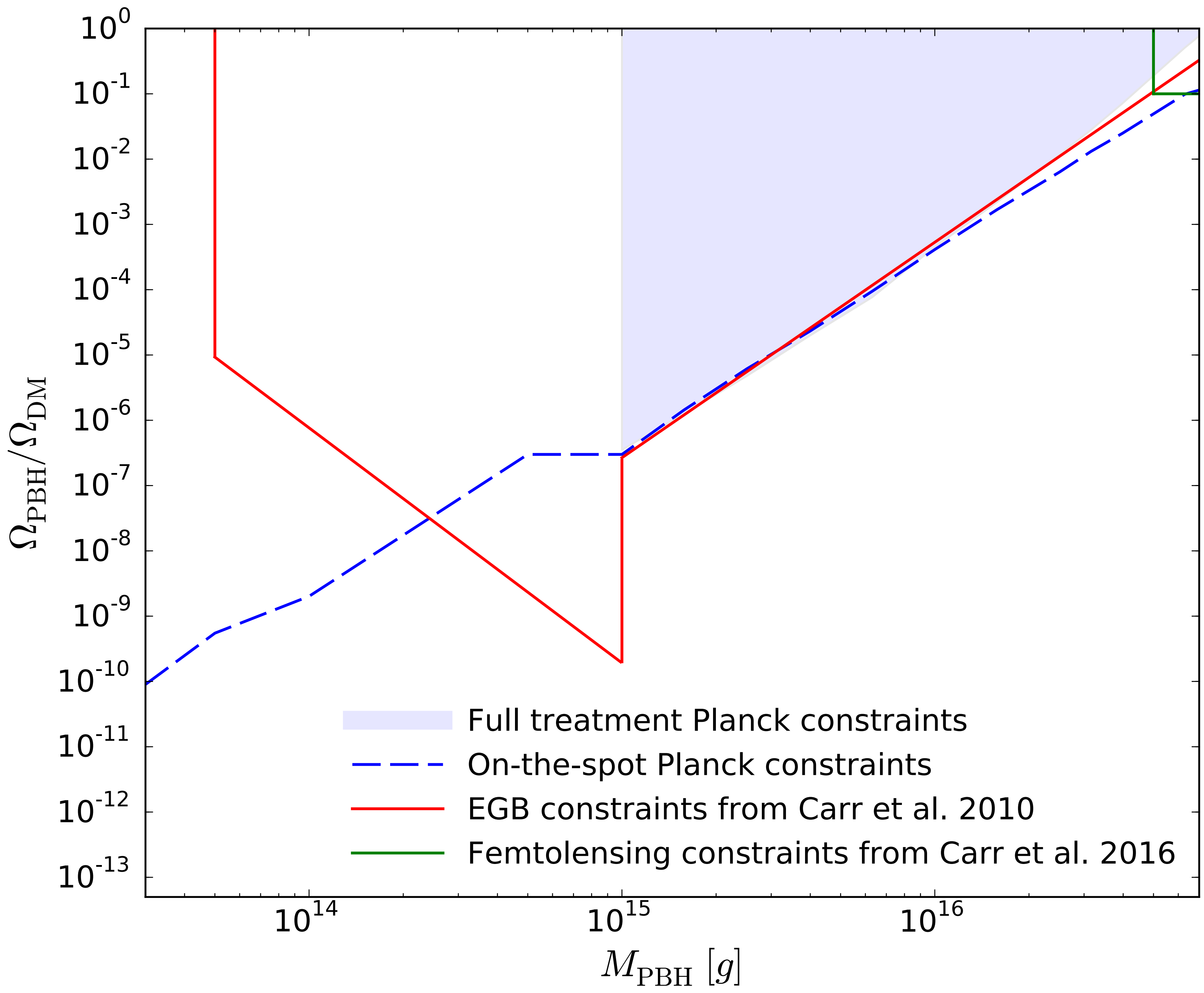
$$T_{\rm BH} = \frac{1}{8\pi G M} \simeq 1.06\left(\frac{10^{10}{\rm g}}{M}\right)\ {\rm TeV}$$

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



# Constraints on evaporating PBH (2)

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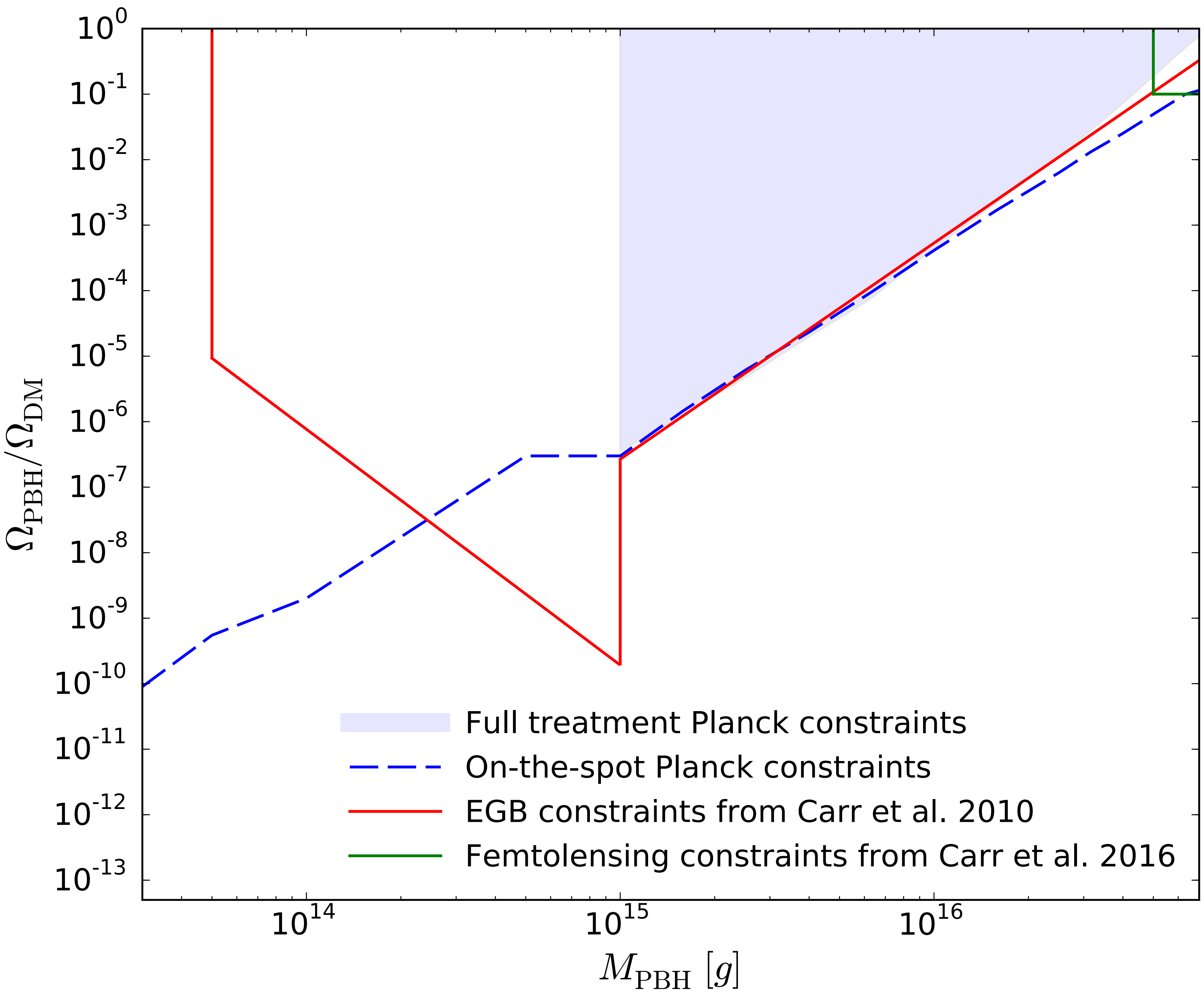
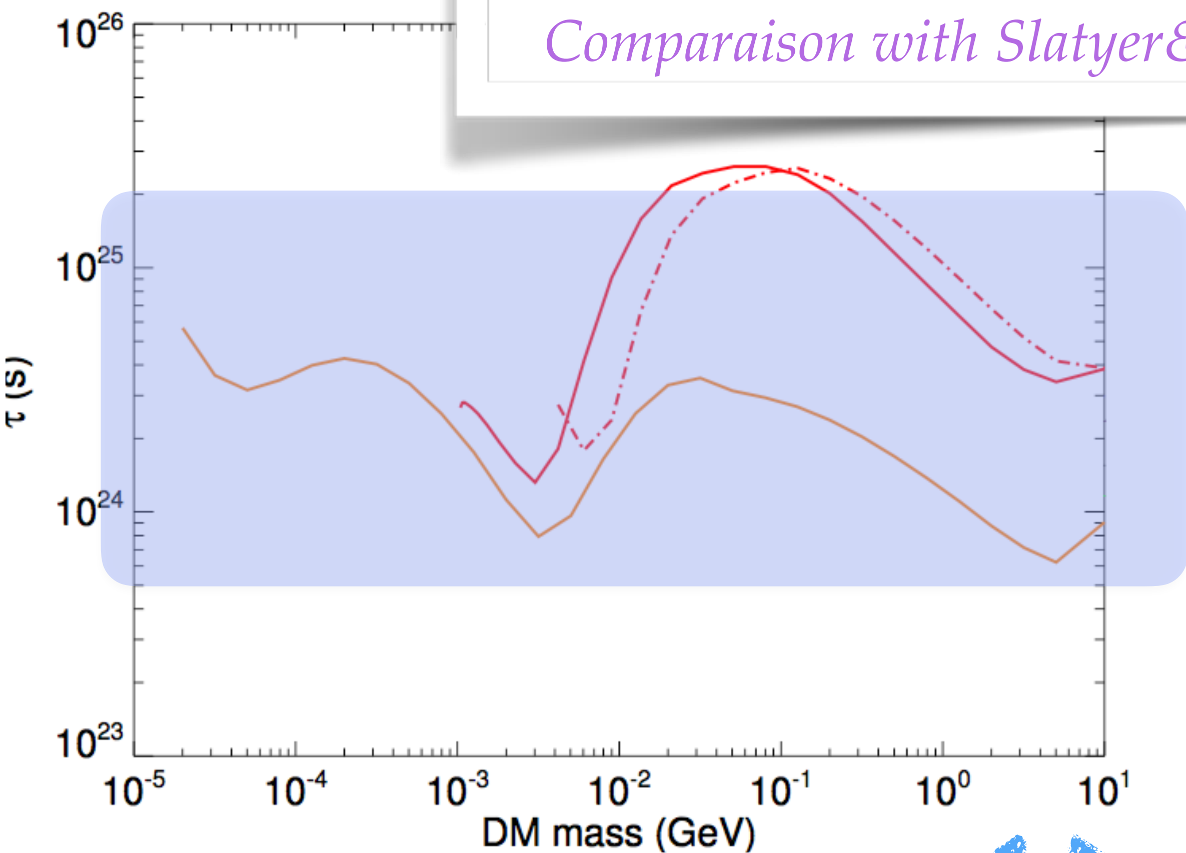
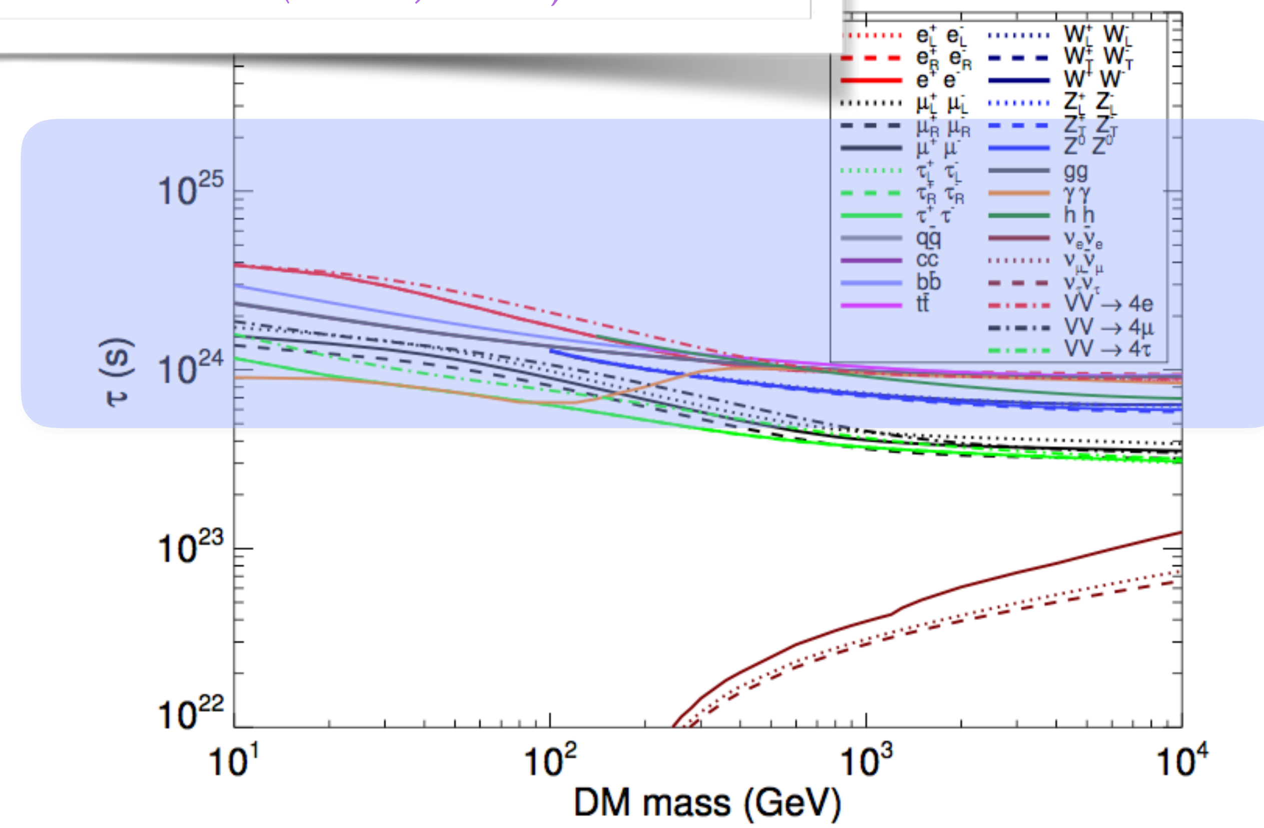
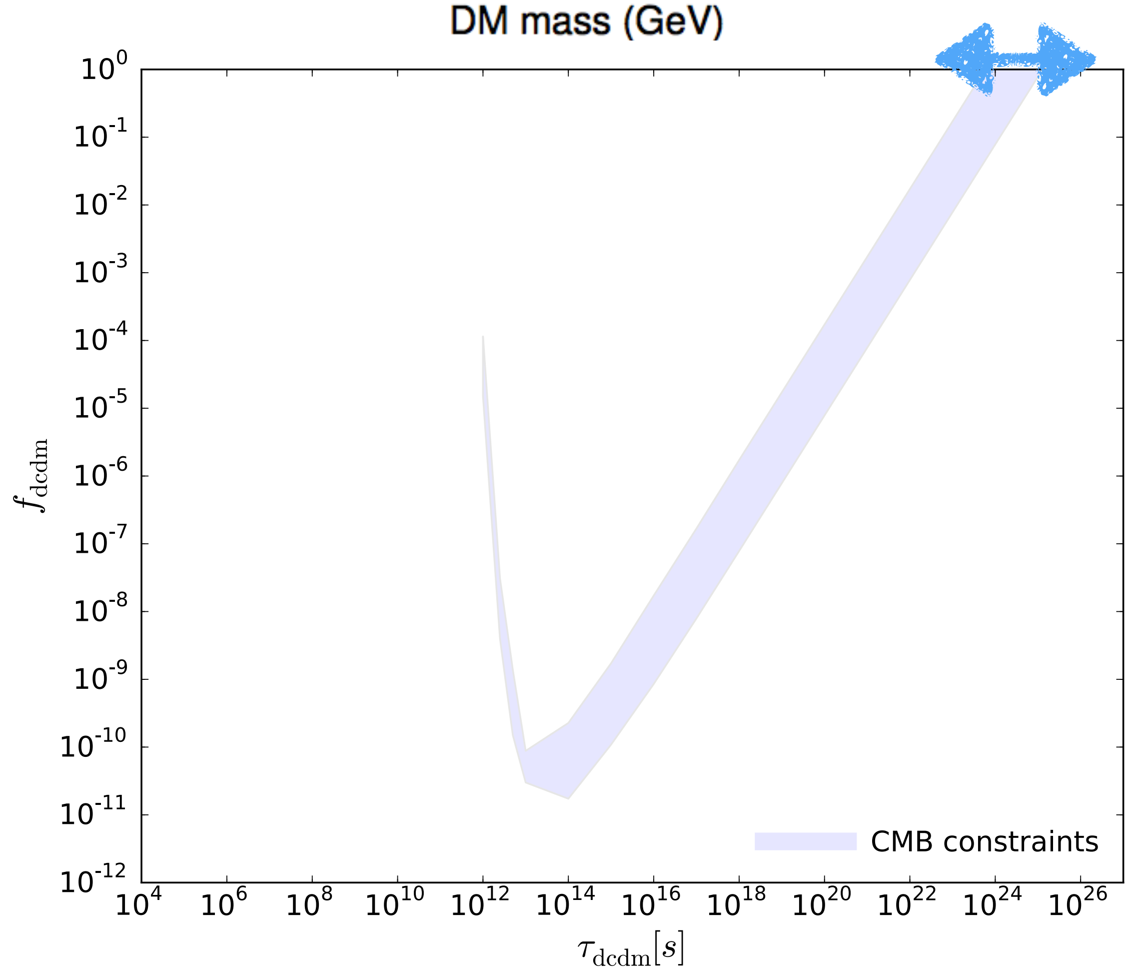



CMB dominates at low masses and is very competitive until $3*10^{16}$g !

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



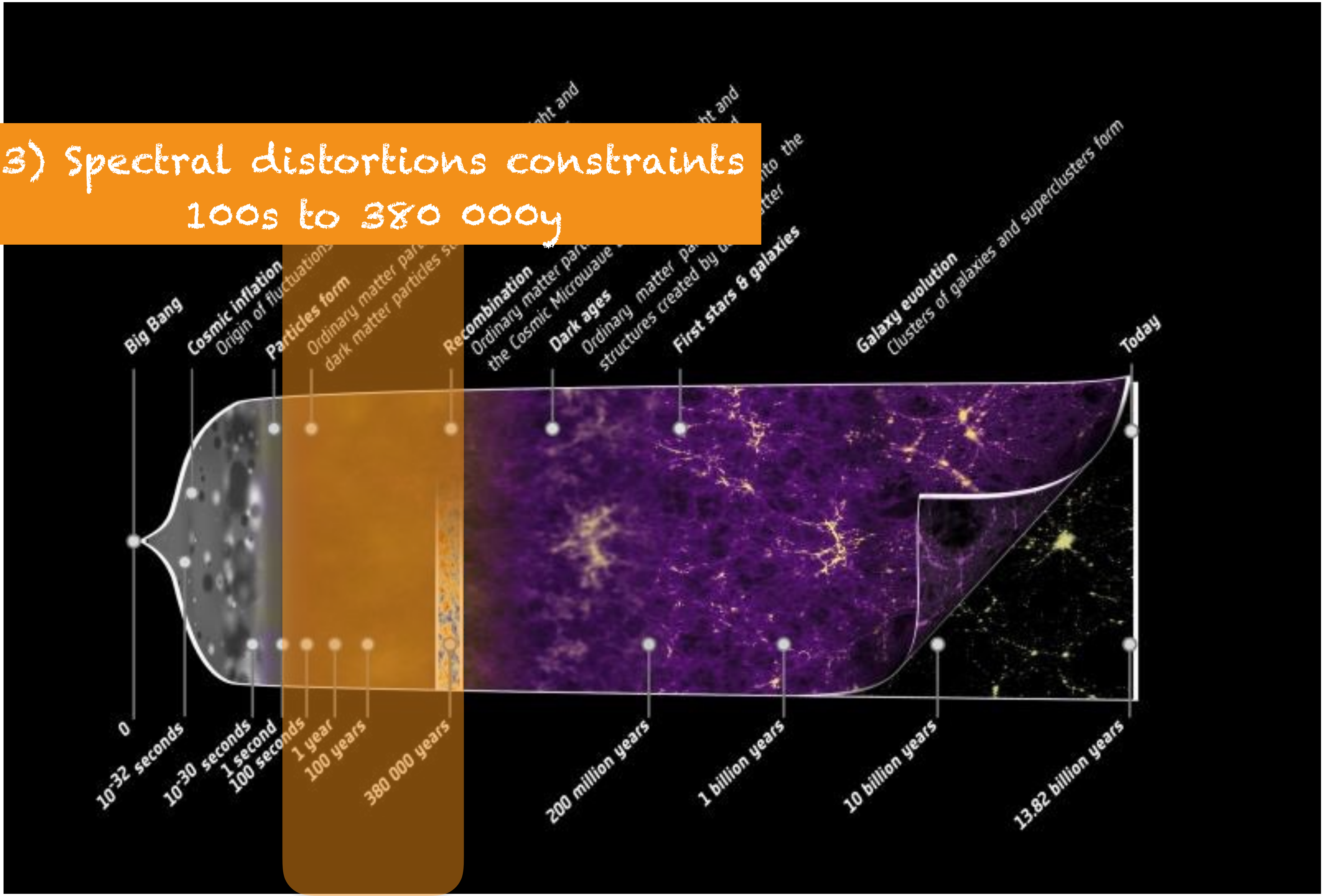




- « Proof of principle »:

All decay channels and masses are contained in the uncertainty band, except neutrinos.

- Models with invisible decay products should typically rescale bound by the corresponding e.m. BR

3) Spectral distortions constraints
100s to 380 000y



# μ and y spectral distortions

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

Most important processes to thermalize any energy injection are Bremsstrahlung, Compton and Double-Compton scattering.
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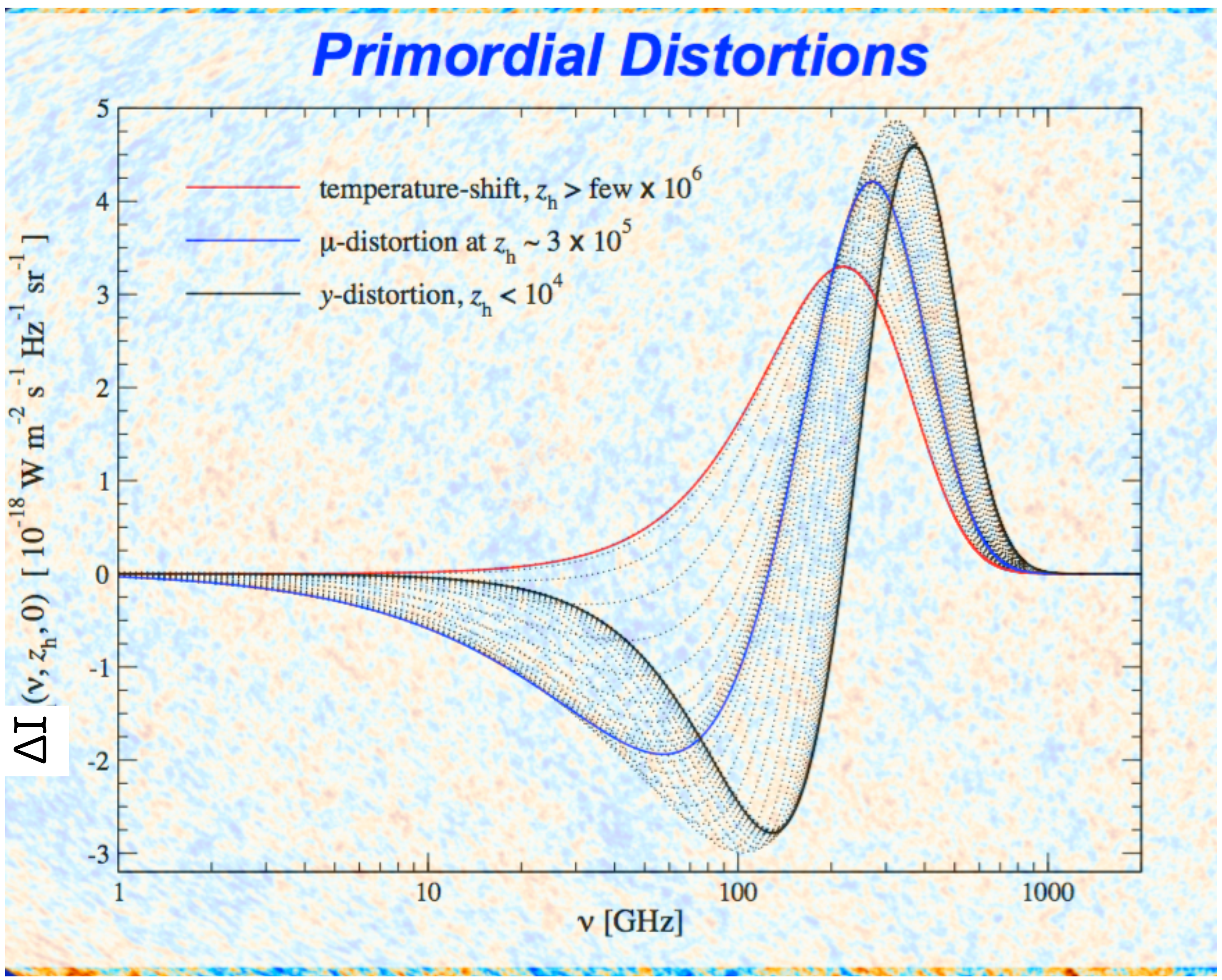


µ = creation of a chemical potential

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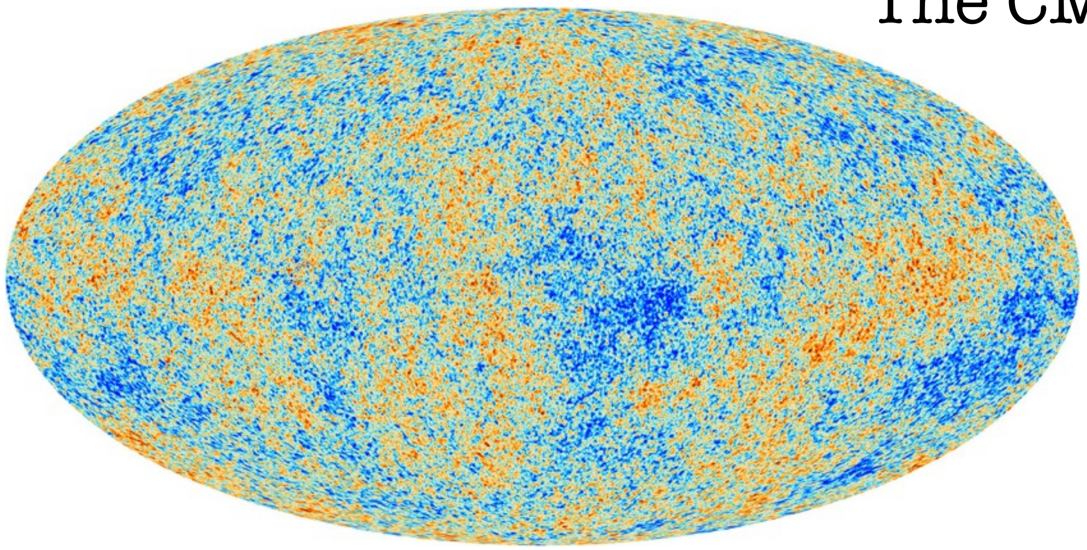
Intermediate distortions probe the time dependance of the energy injection history

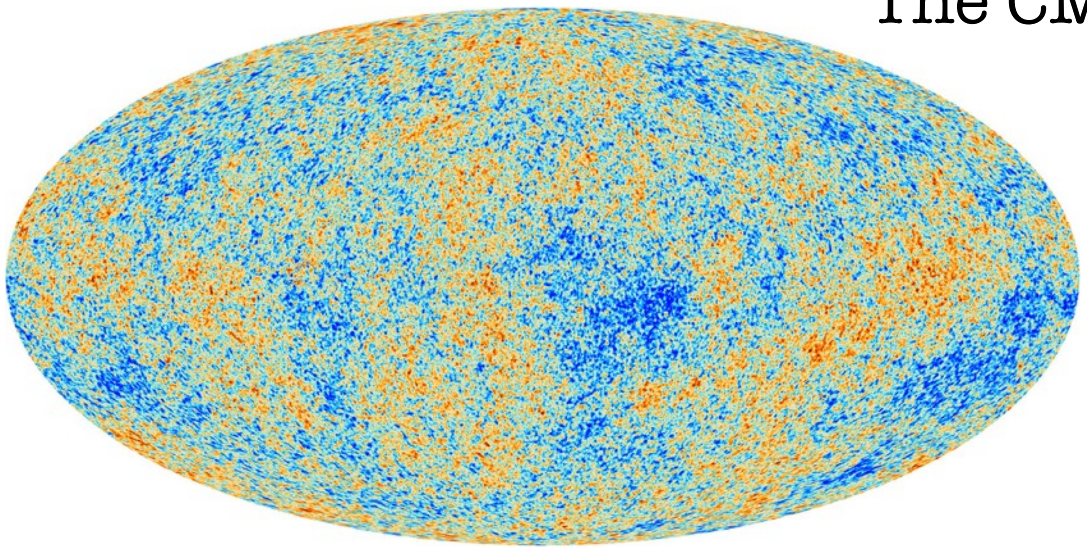
*credit: Jens Chluba, « Ecole de Gif », 2014*



The CMB is the most perfect black body in the Universe, it is very homogeneous and isotropic.

T = 2.72548 +/- 0.00057 K

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



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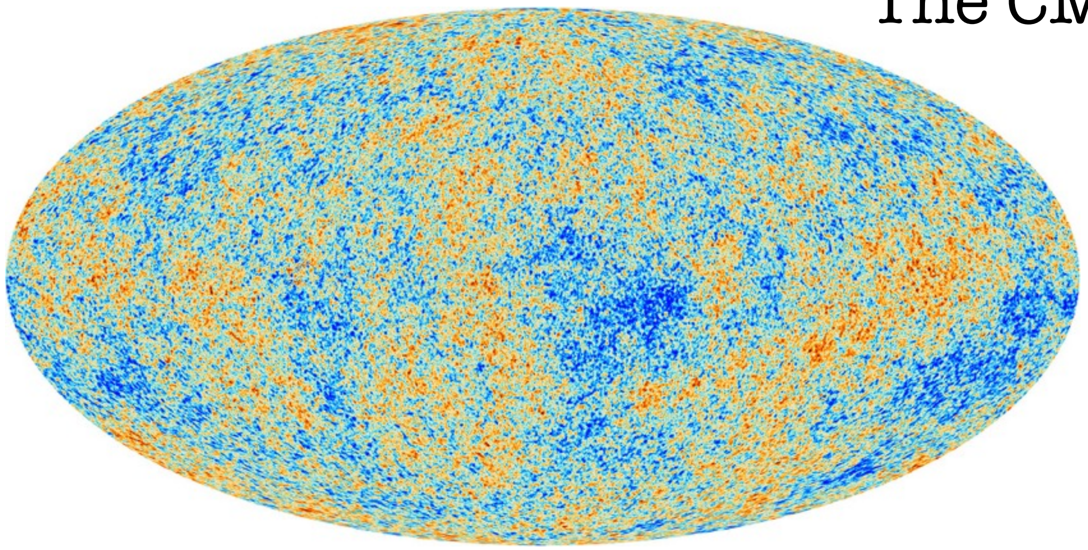

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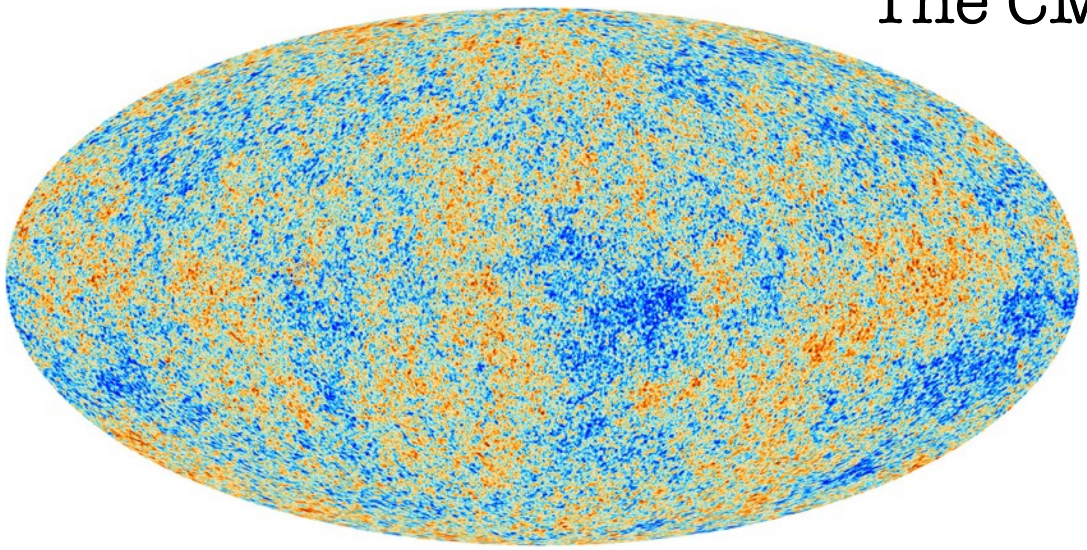

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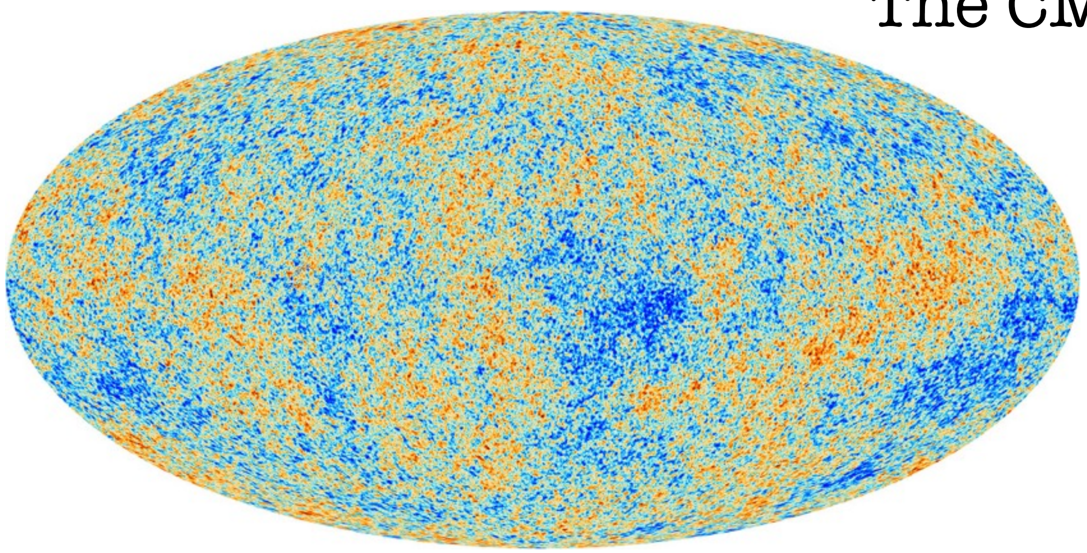

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Only 2 moments of interest : $\langle\Theta(\vec{n})\rangle = 0$ $\qquad$ $\langle\Theta(\vec{n_1})\Theta(\vec{n_2})\rangle \neq 0$

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

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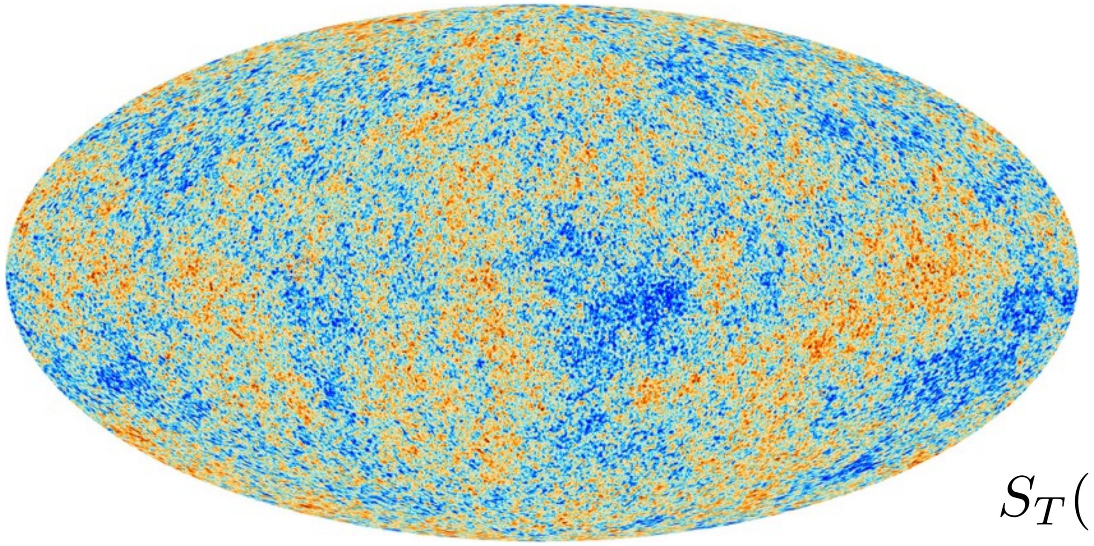
**DM interacts only gravitationally in the standard Cosmology**
**=> Constraints can be derived**

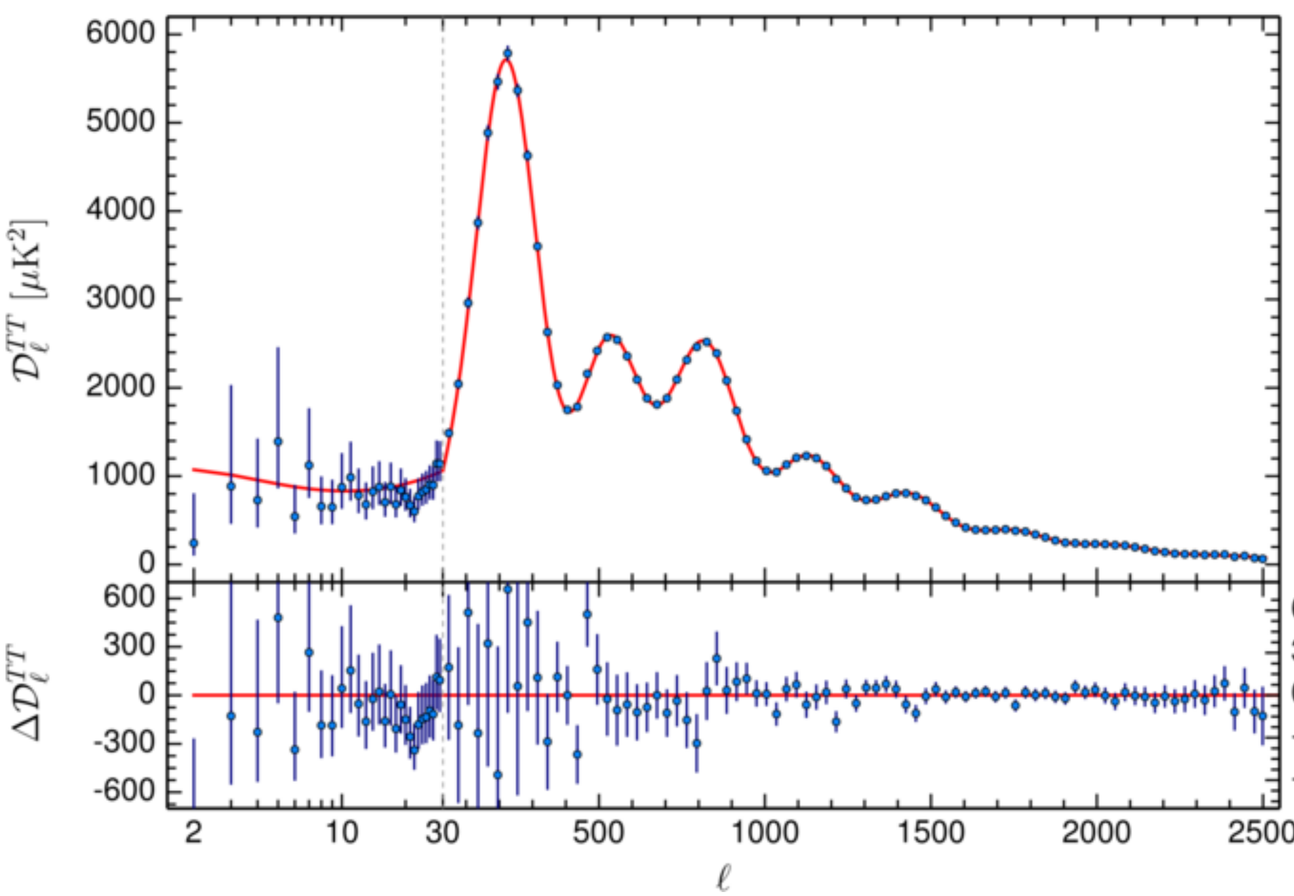


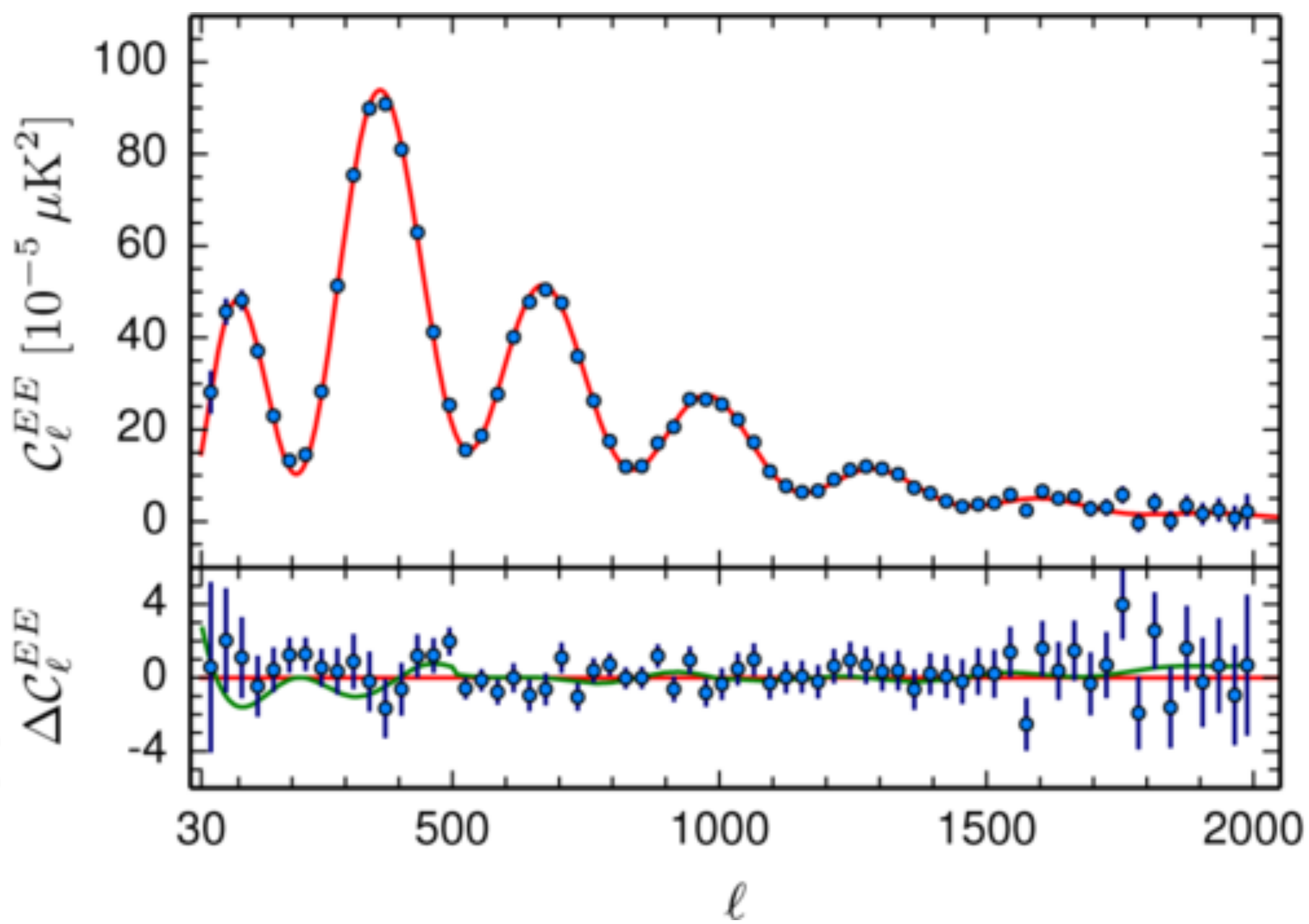
$$C_\ell = \int \frac{dk}{k} \mathcal{P}_{\mathcal{R}}(k) [\Theta_\ell(\tau_0, k)]^2$$

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

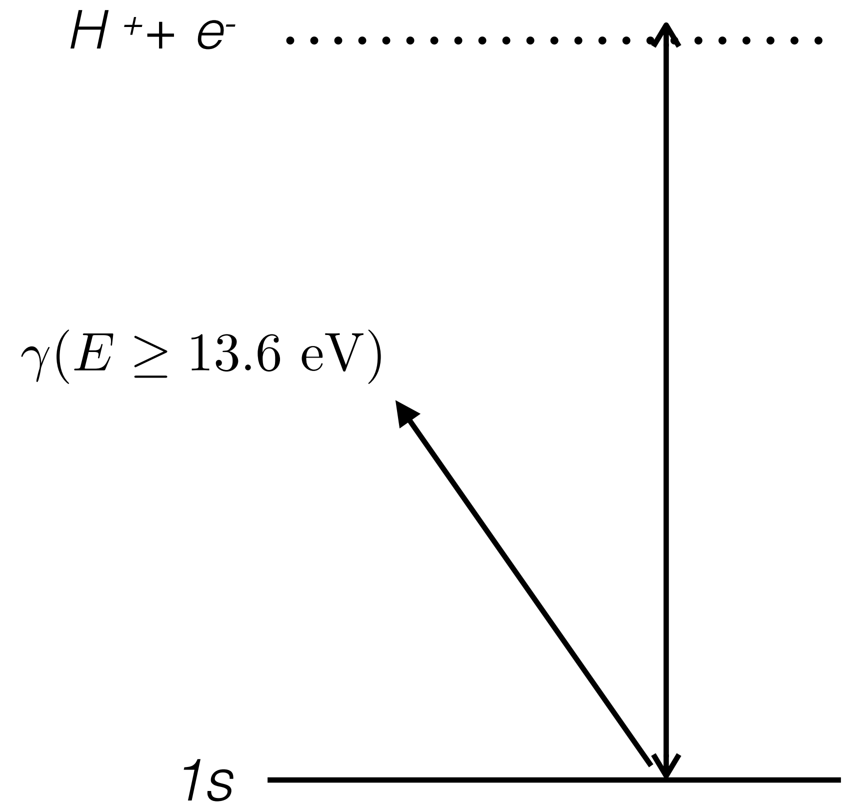
$$S_T(k,\tau) \equiv \underbrace{g(\Theta_0 + \psi)}_{\text{SW}} + \underbrace{(gk^{-2}\theta_B)'}_{\text{Doppler}} + \underbrace{e^{-\kappa}(\phi' + \psi')}_{\text{ISW}} + \text{polarisation}$$

6 free parameters to be « fitted » : $\{\omega_b,\ \omega_{cdm},\ h,\ A_s,\ n_s, z_{reio}\}$



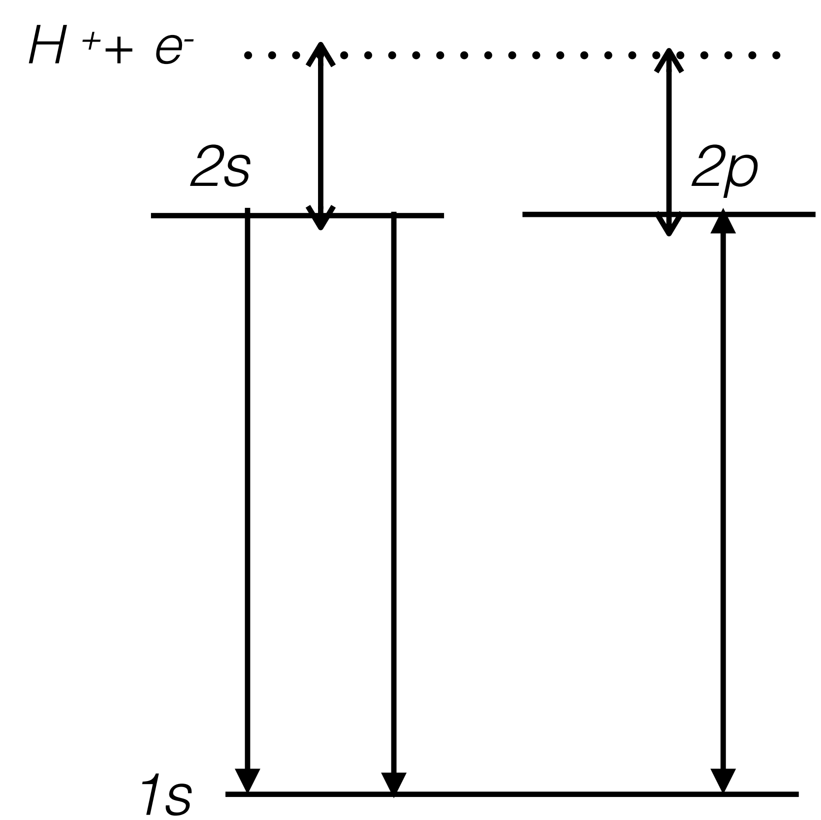



## Recombination in a nutshell




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

leads to the « saha » equation at equilibrium

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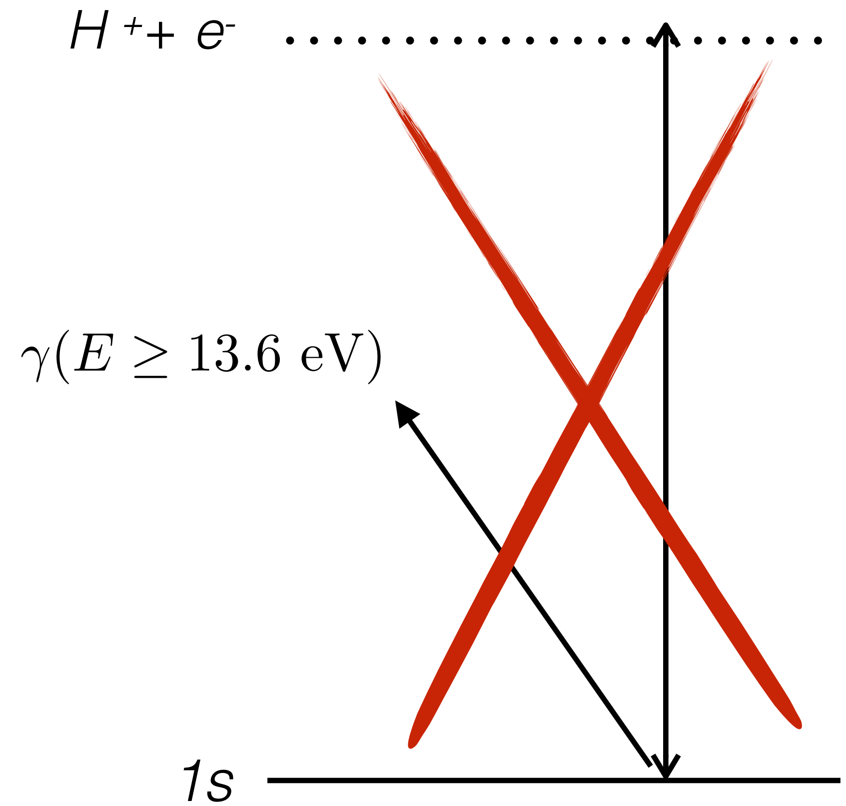


### The « three-levels atom »

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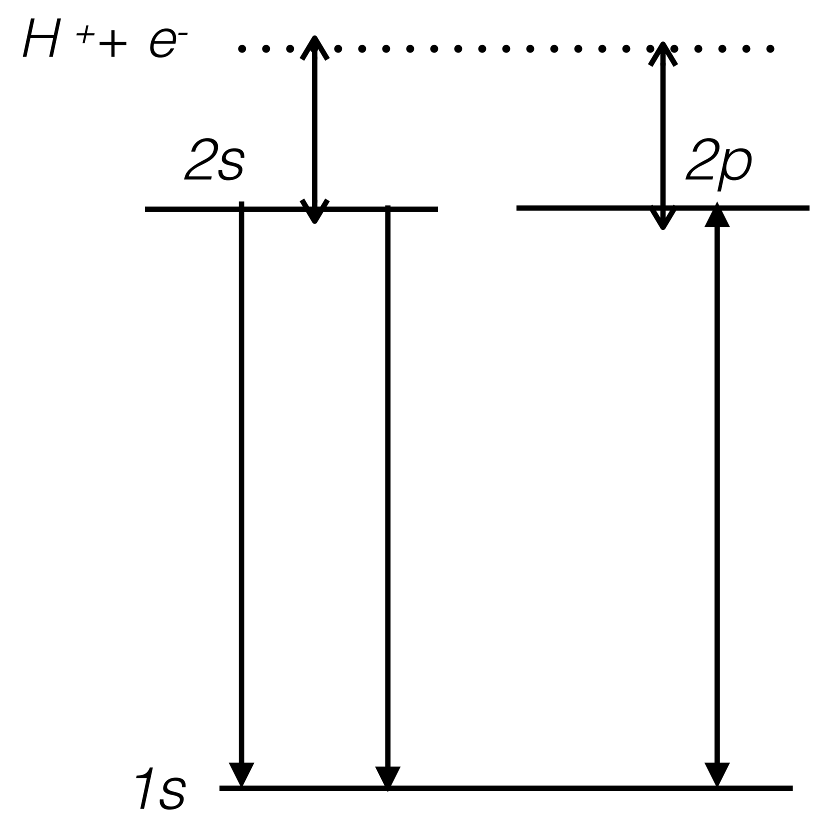

## Rec… a nutshell

Peebles « case-b » recombination

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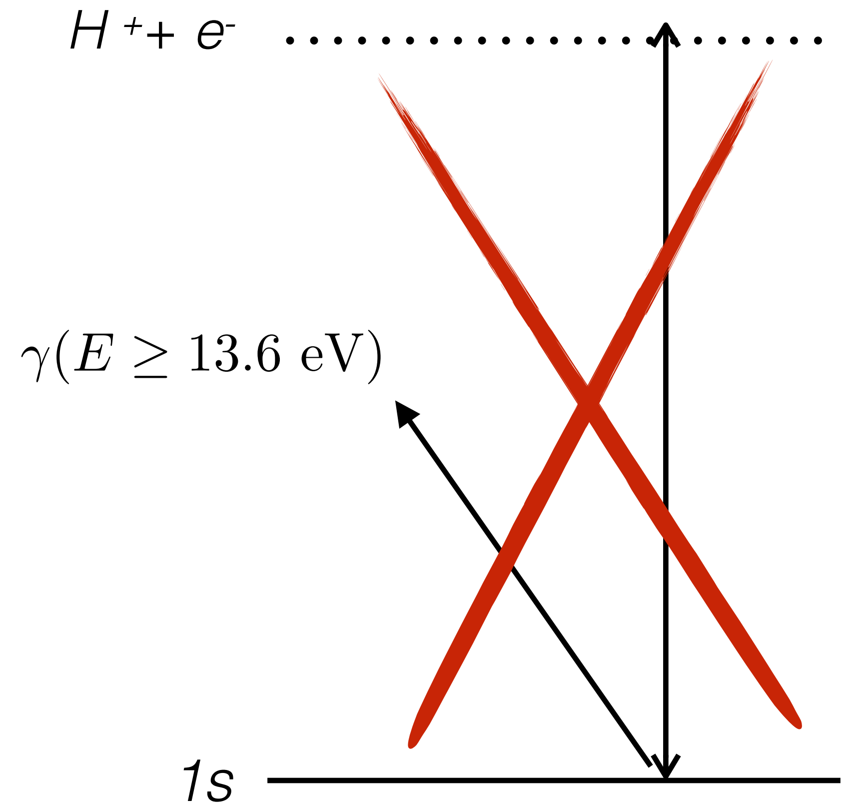


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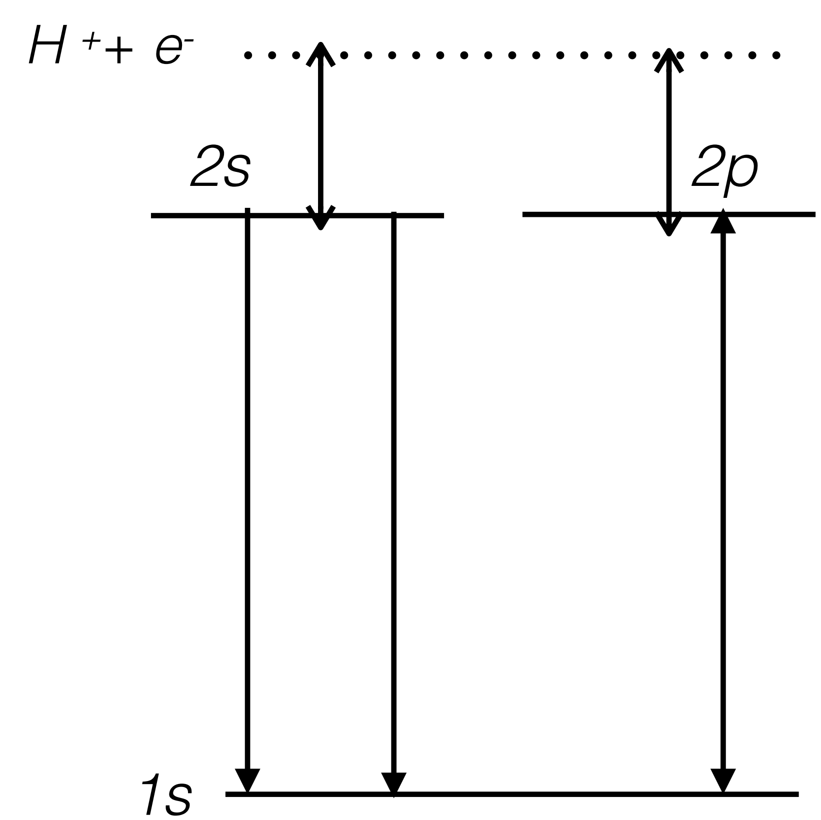

# μ and y spectral distortions

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

Scattering processes should thermalize the injected photons, but if those processes go out of equilibrium

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

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

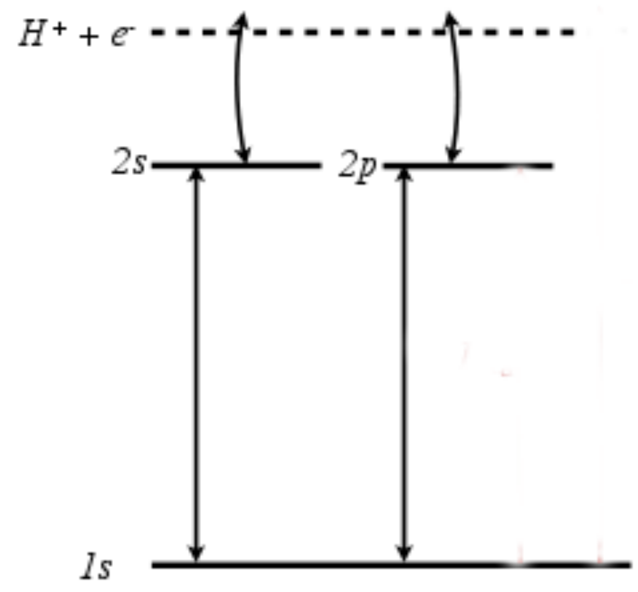
- Compton scattering for Comptonization-y
- Double Compton and Bremsstrahlung for μ-distortion

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

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

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

$$I_x(z) \text{ and } K_h(z) \propto \left.\frac{dE}{dV dt}\right|_{\rm dep,c}$$




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

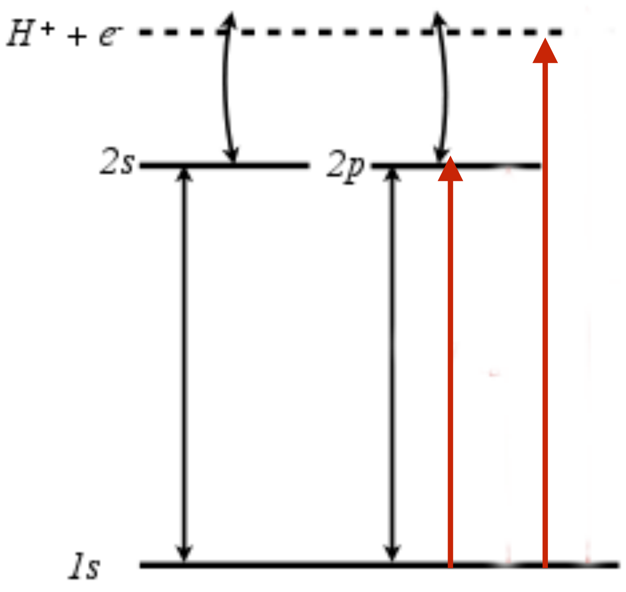
- The energy deposition rate by the decay per unit volume in each channel: ionization, excitation, heating
- Depending on z and $x_e$, the plasma can be very inefficient at absorbing energy !
- In full generality, very complicated to compute, need MC simulations.

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

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

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

$$I_x(z) \text{ and } K_h(z) \propto \left.\frac{dE}{dV\,dt}\right|_{\rm dep,c}$$

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

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

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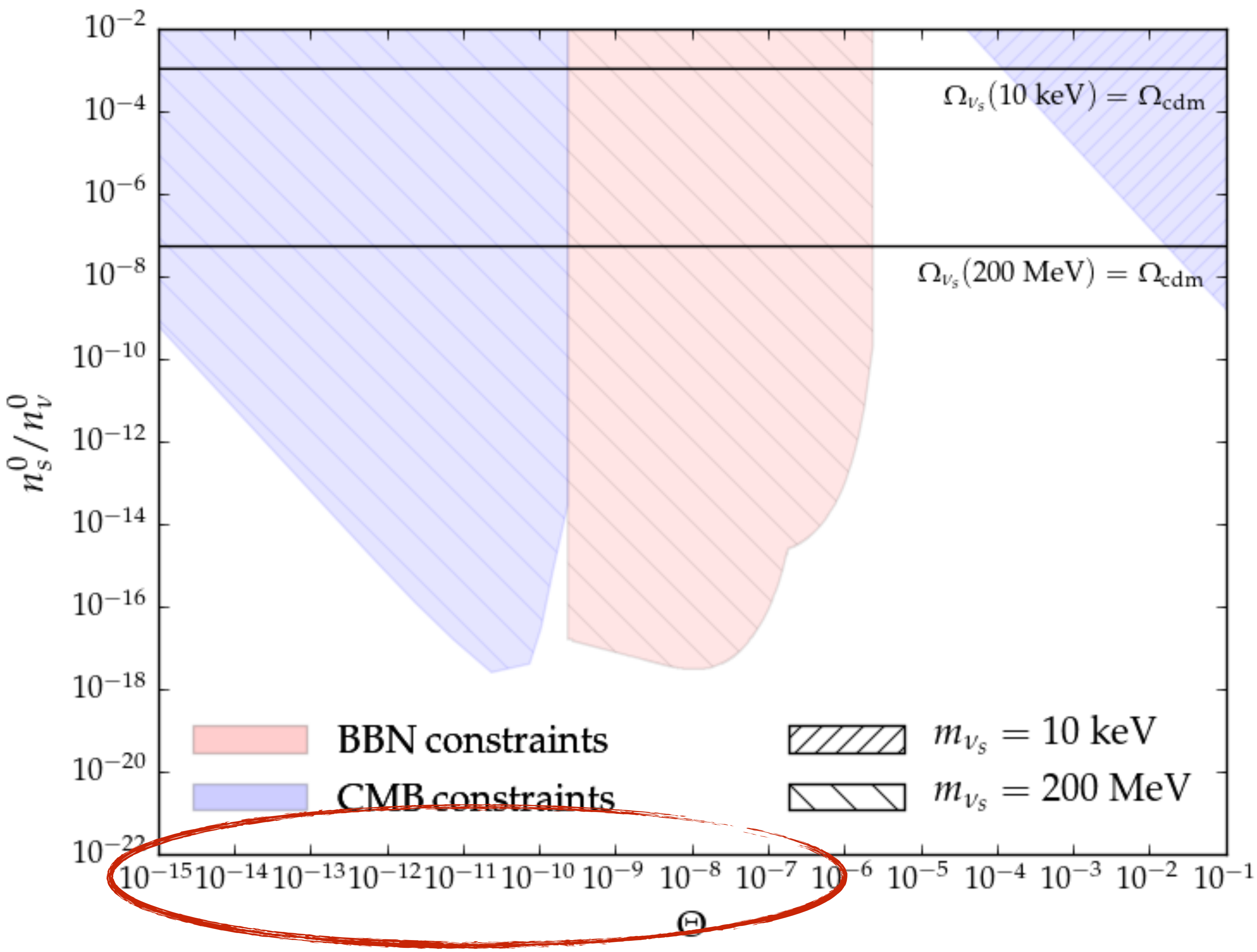

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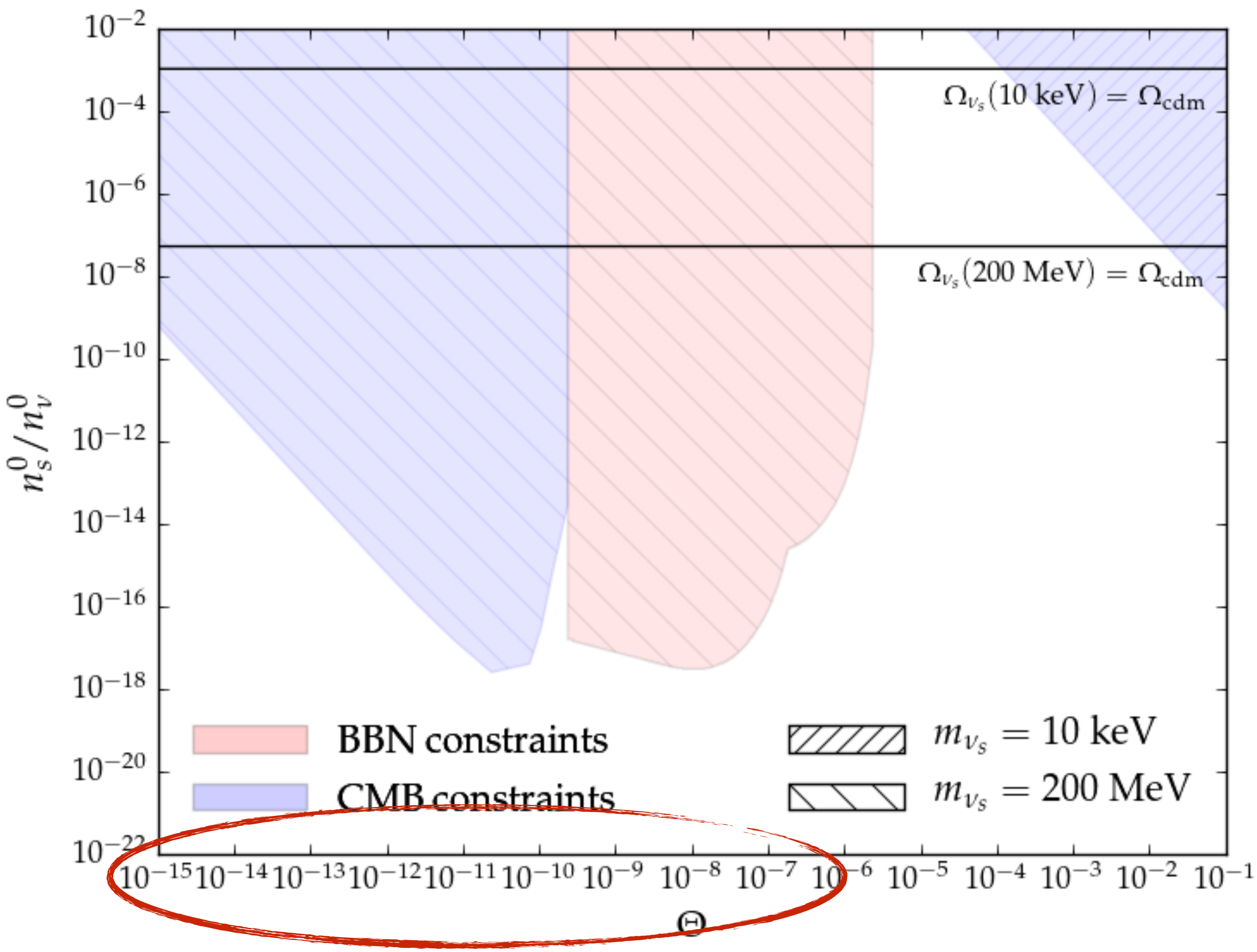
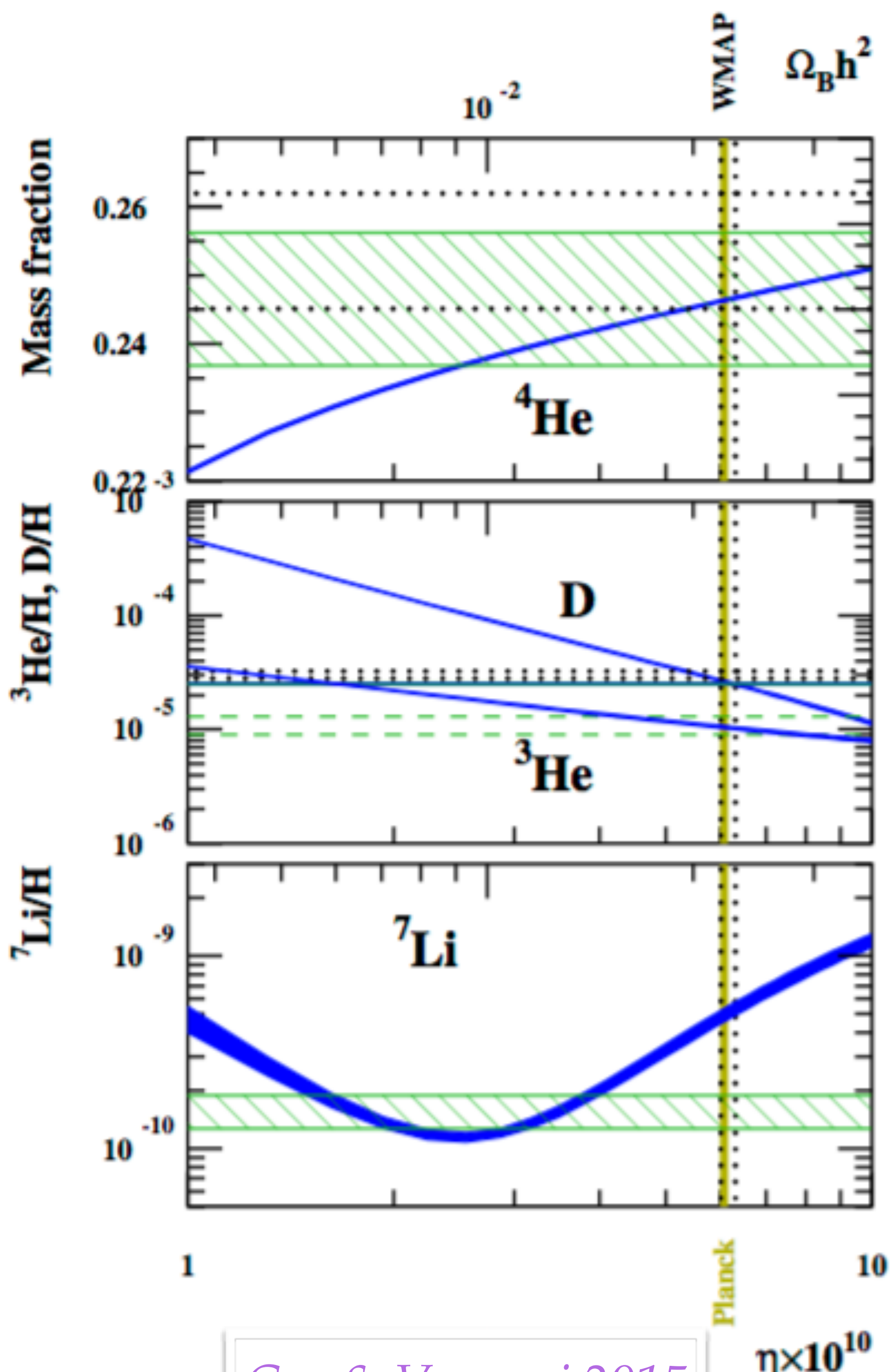



- Cosmology is mostly sensitive to sterile neutrinos more weakly coupled than those evolve in see-saw mechanism;
- Still, it is interesting since masses and mixing of the right-handed neutrinos are not constrained by fundamental physics arguments !
- KeV-scale neutrinos are usually better constrained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

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

# The light element abundances

BBN happened few s / min after BB when $T \approx$ KeV- MeV




Coc & Vengoni 2015

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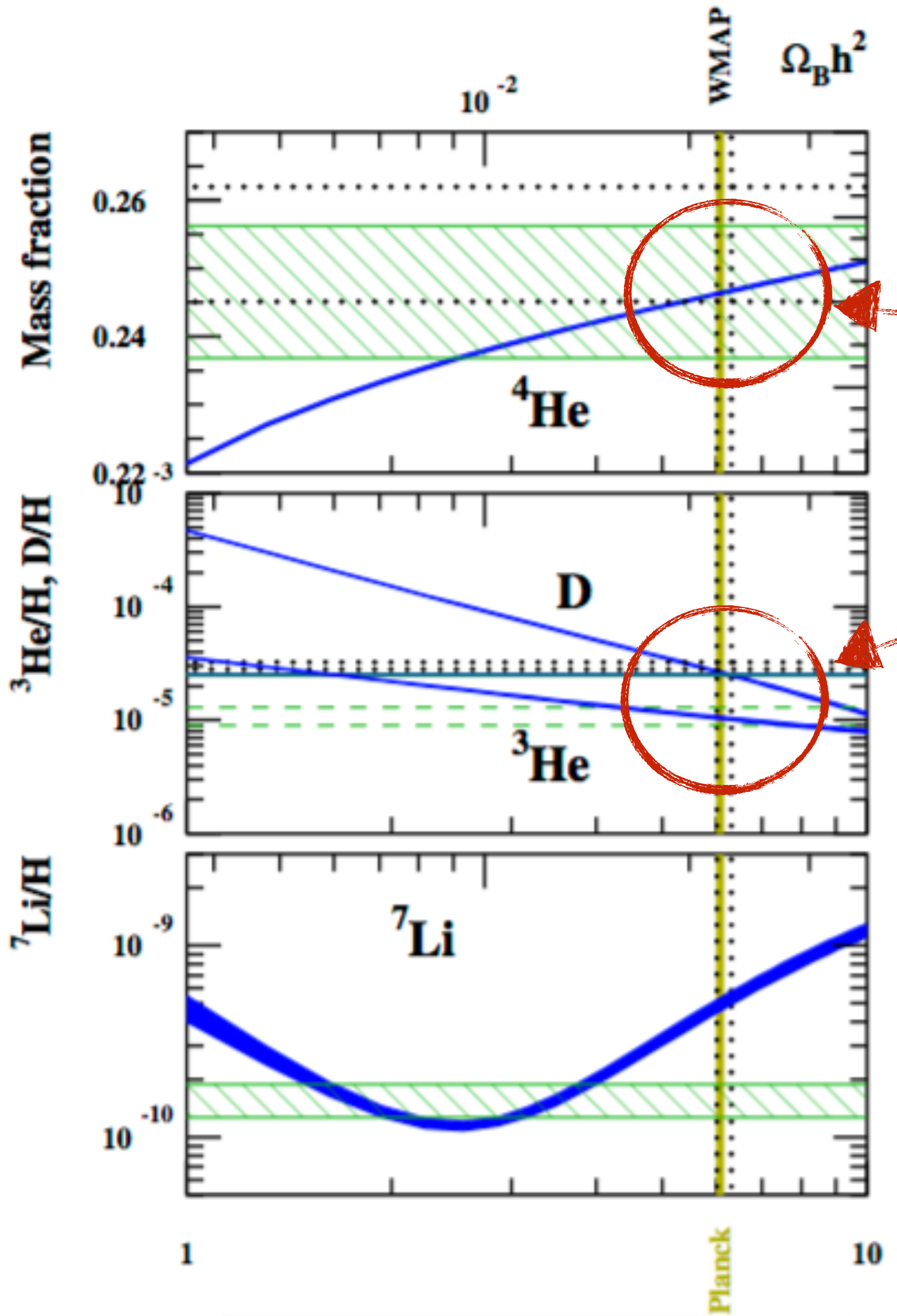


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For 3 nuclei :

Strong observational constraints

$$Y_p > 0.2368$$

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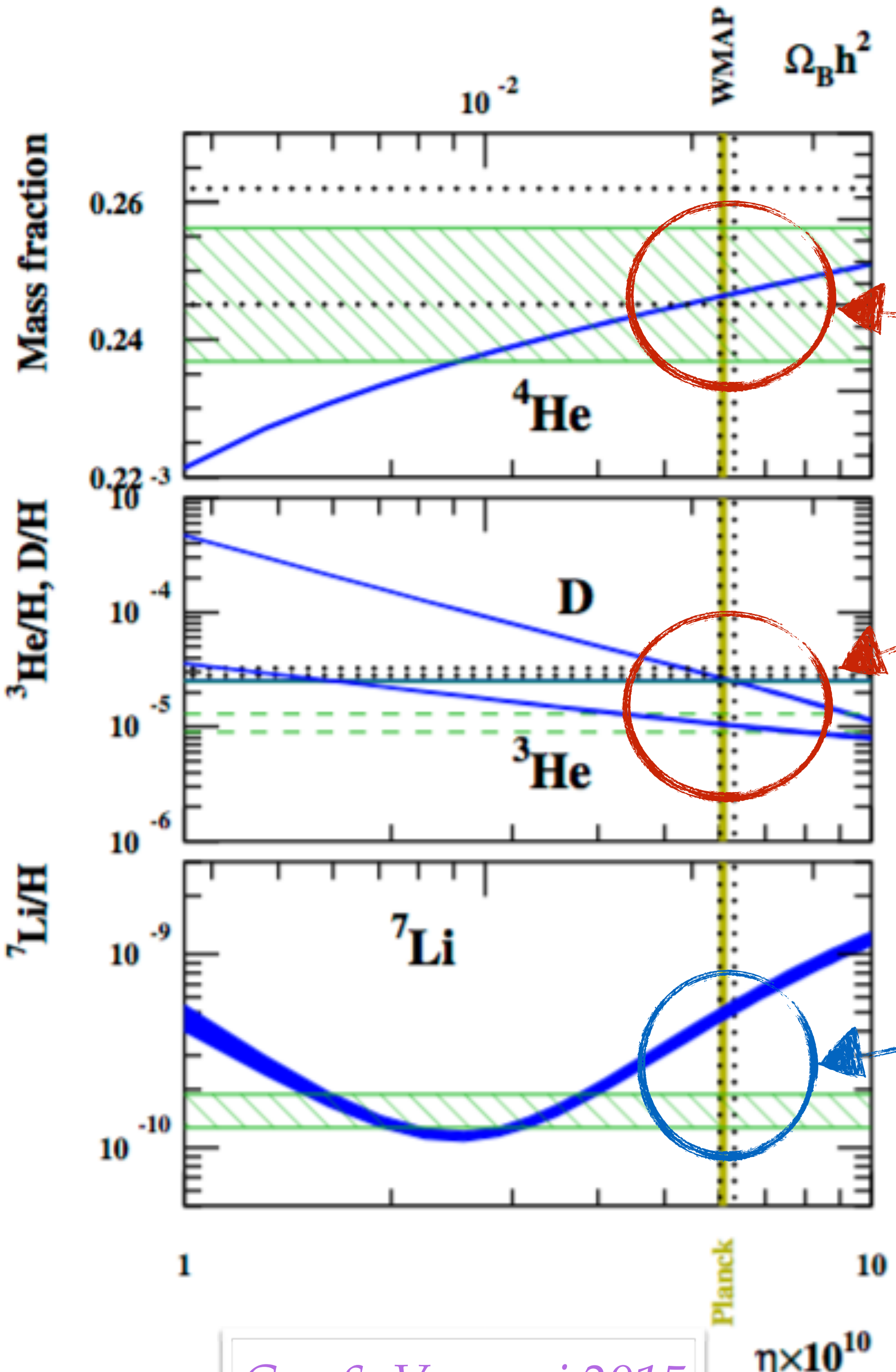


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## The Lithium problem :

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 $n_\gamma >> n_b$

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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)

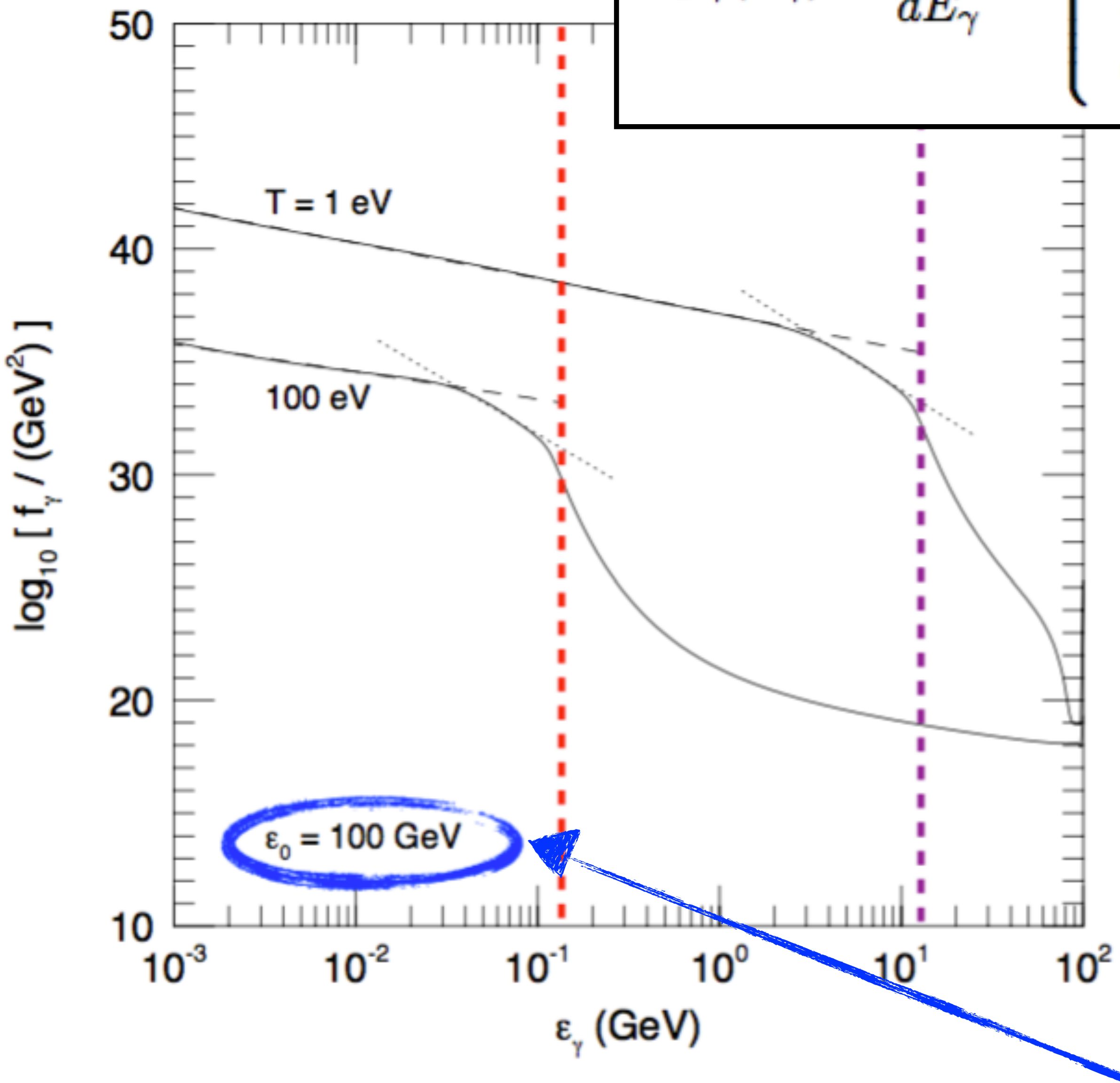
$$\gamma N \to eN \qquad \gamma e_{\rm th} \to \gamma e$$

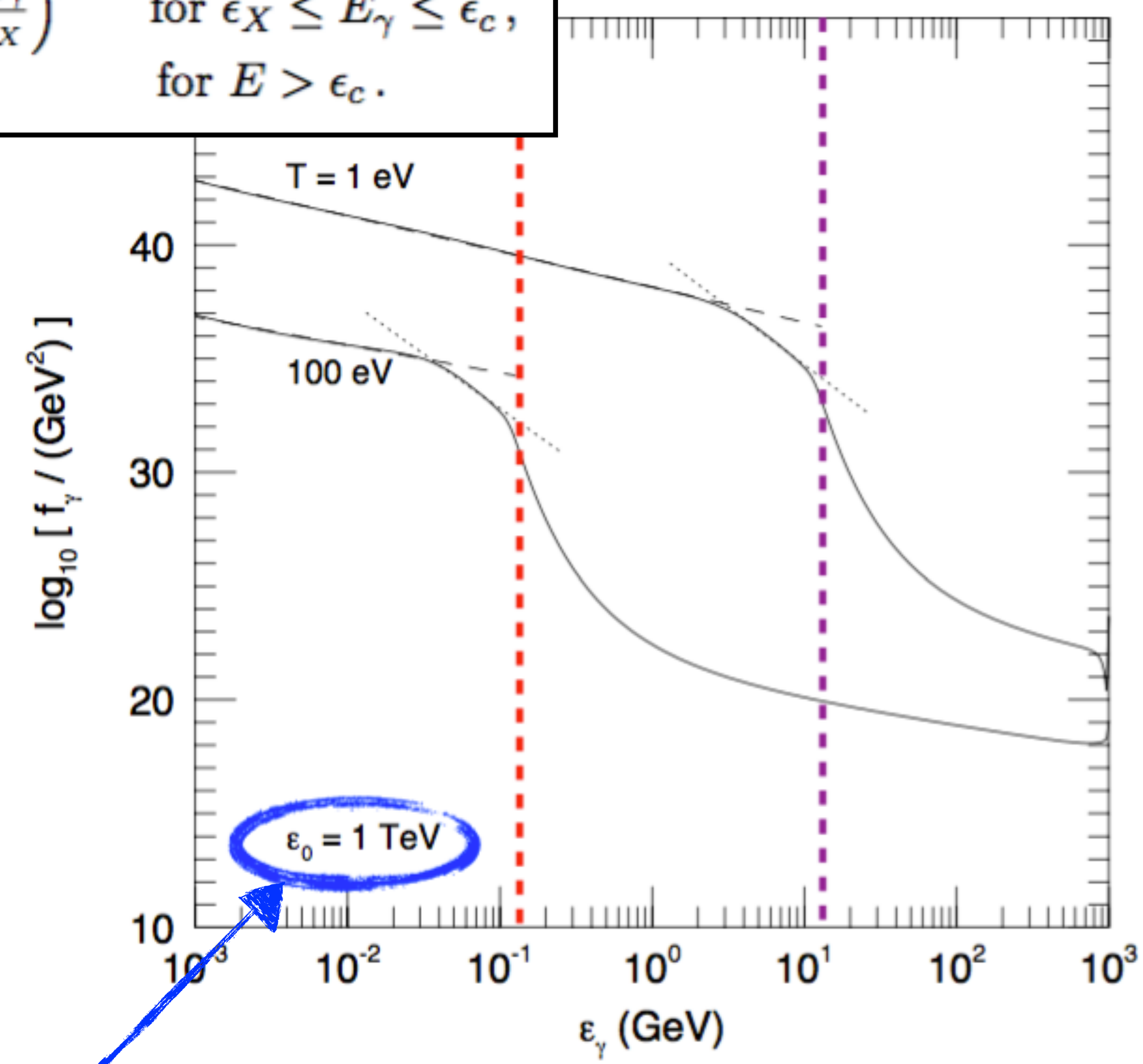
Particle multiplication and energy redistribution
=> Electromagnetic cascade !

*Kawasaki & Moroi, ApJ 452,506 (1995)*

This has been shown to lead to a universal spectrum

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




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

# 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 :
$E_{\rm threshold}(Be) = 1.58$ 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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$$f_\gamma^{\rm S}(E_\gamma) = \frac{\mathcal{S}(E_\gamma, t)}{\Gamma_\gamma(E_\gamma, t)}$$

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

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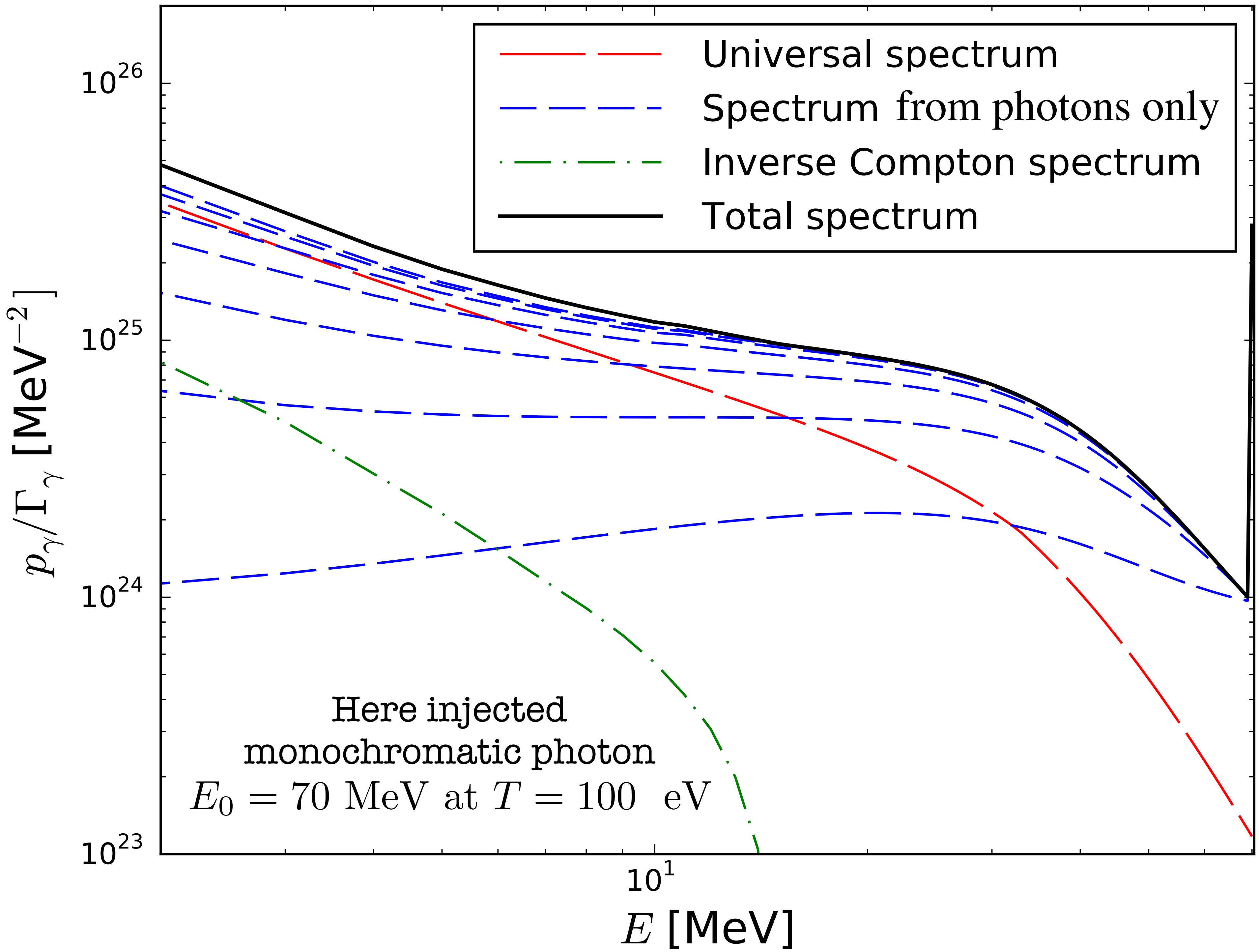
Typical results for a given energy and a given temperature of the thermal bath



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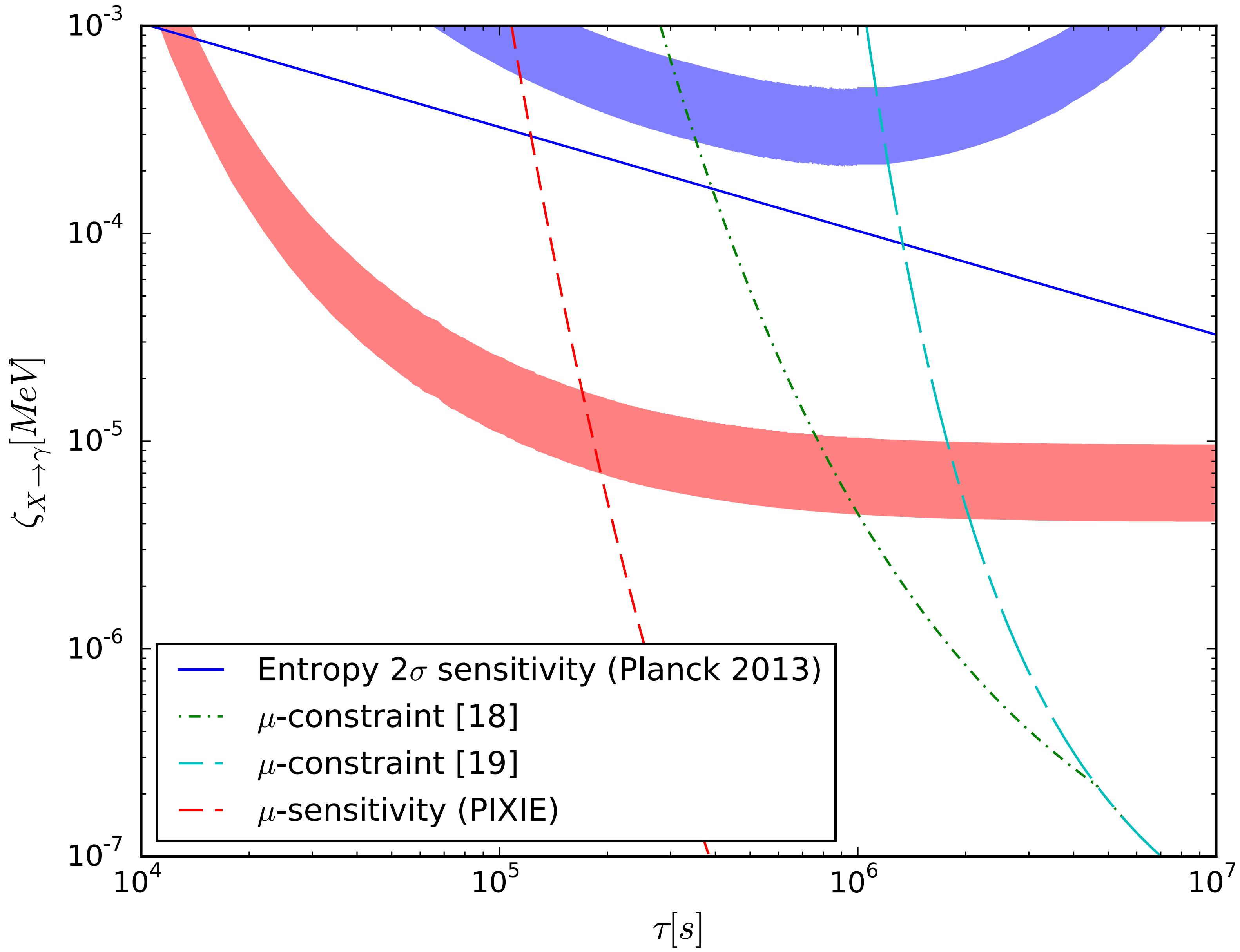

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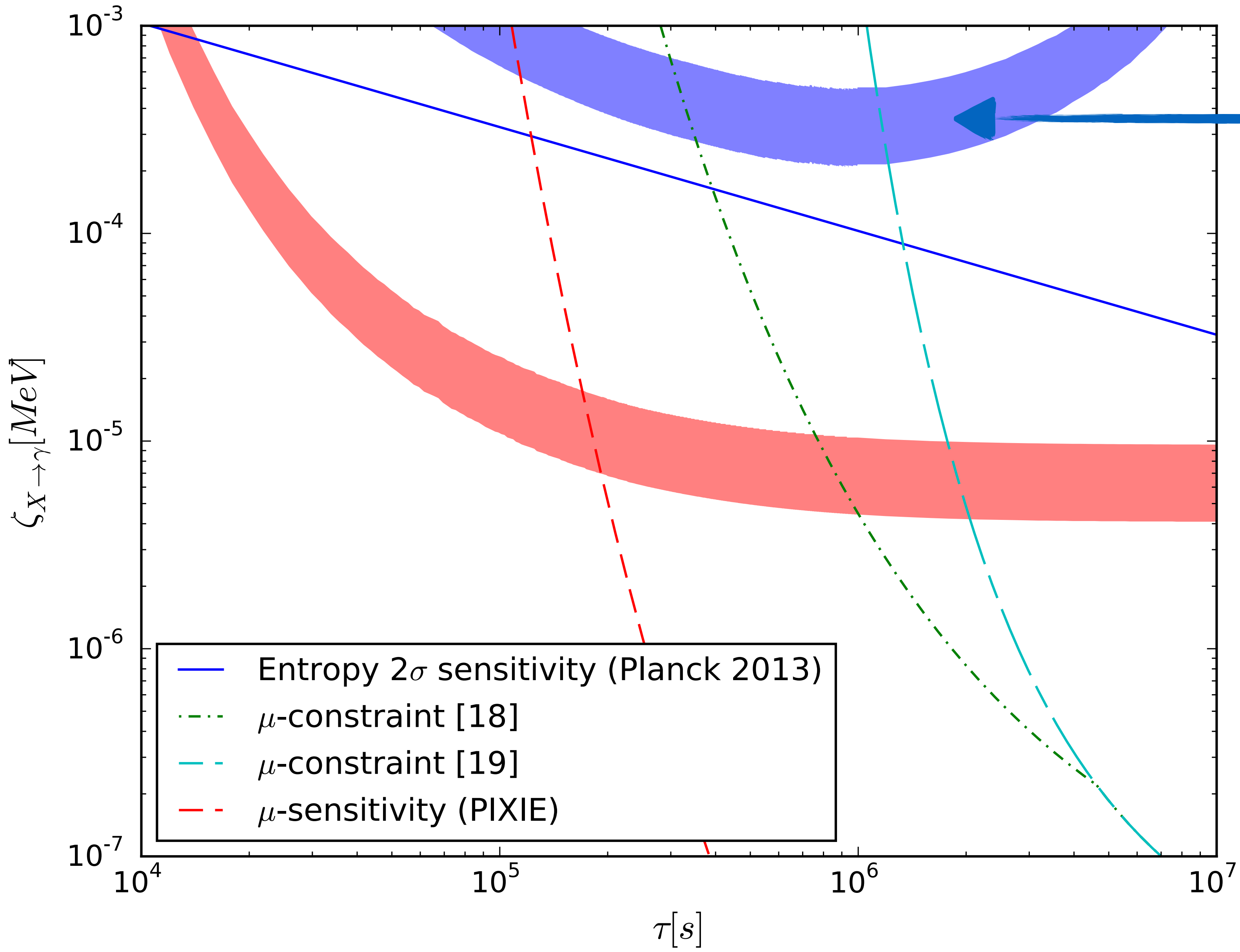


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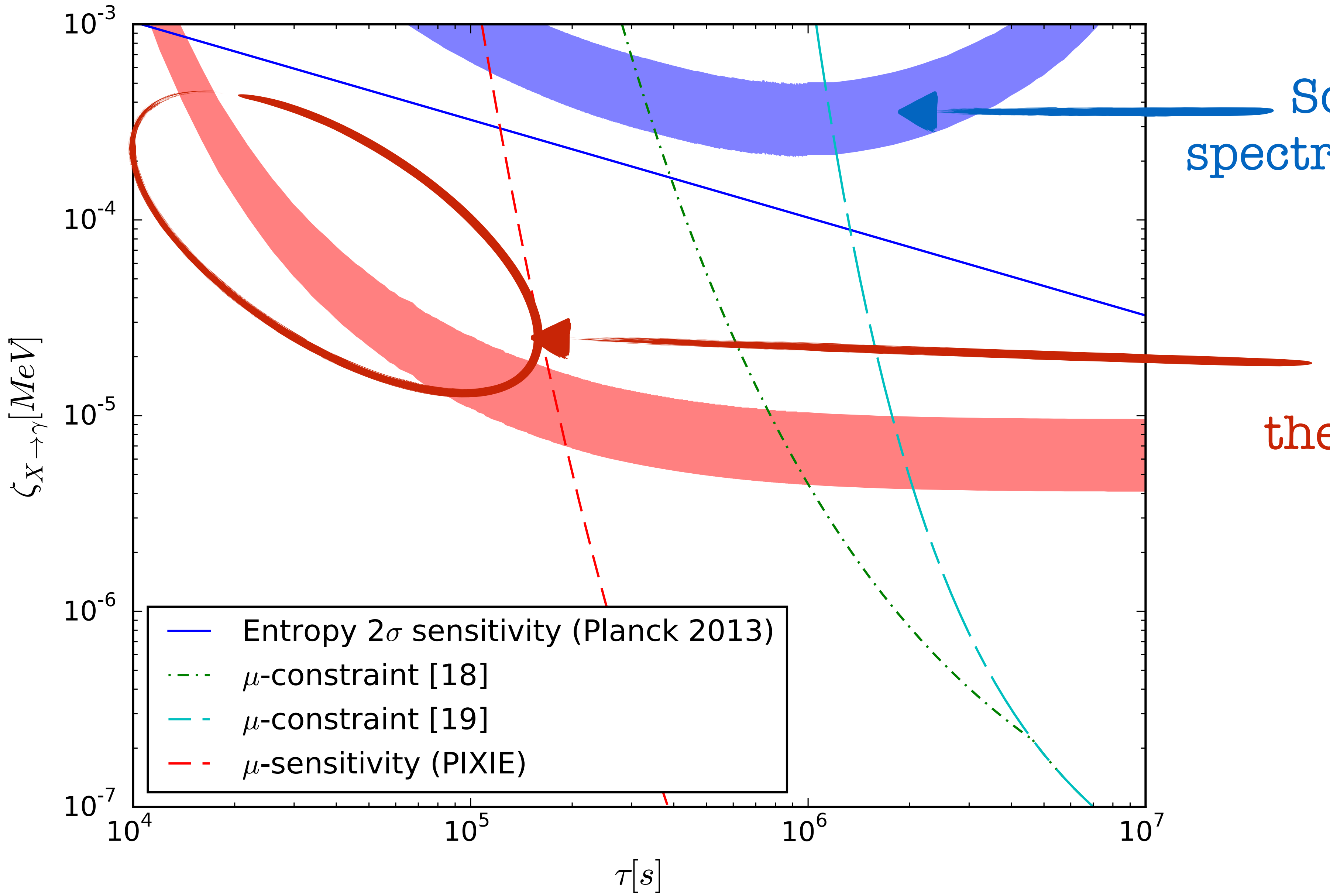


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Our solution : there's a living region !

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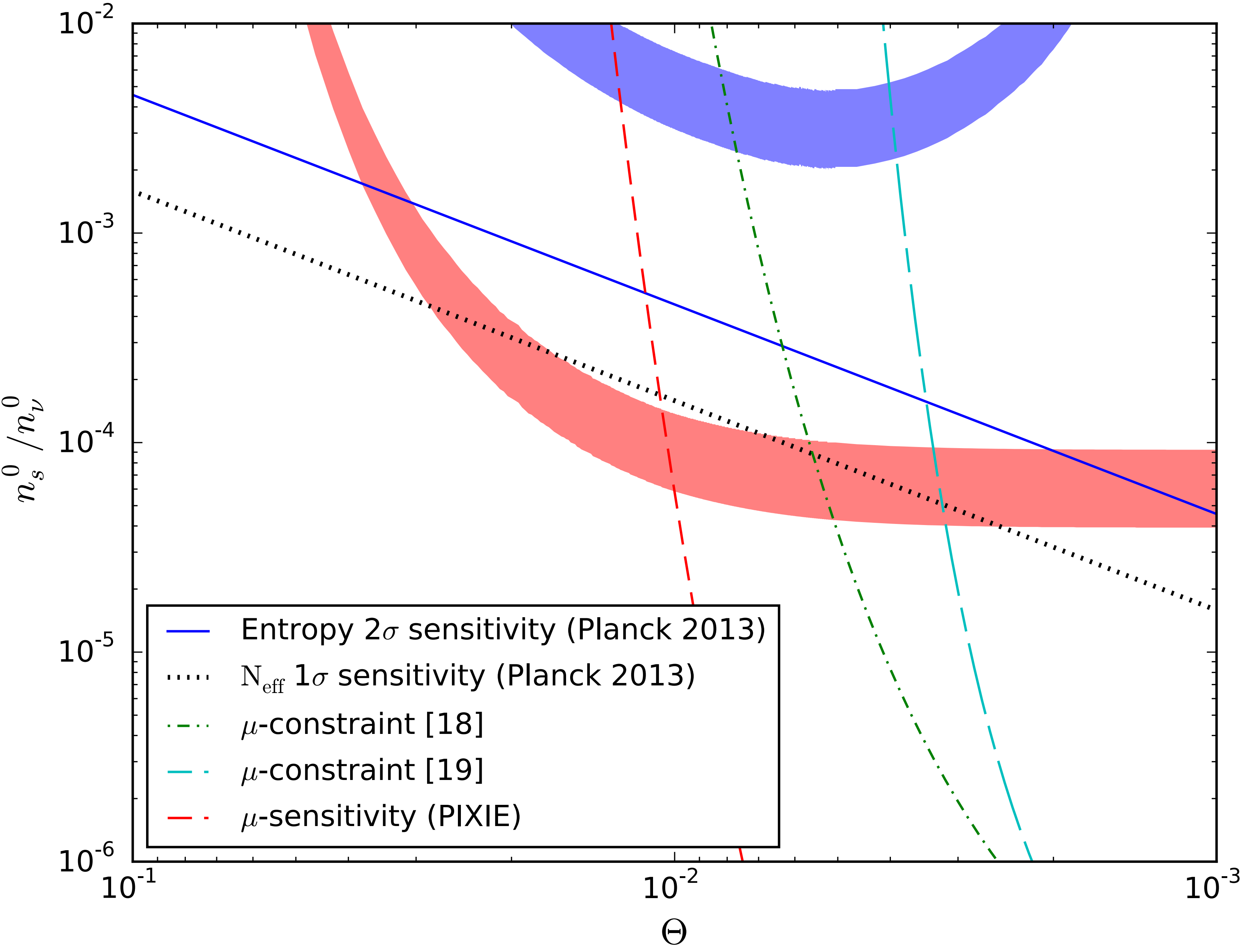
*H. Ishida et al. PRD 90, 8, 083519 (2014)*



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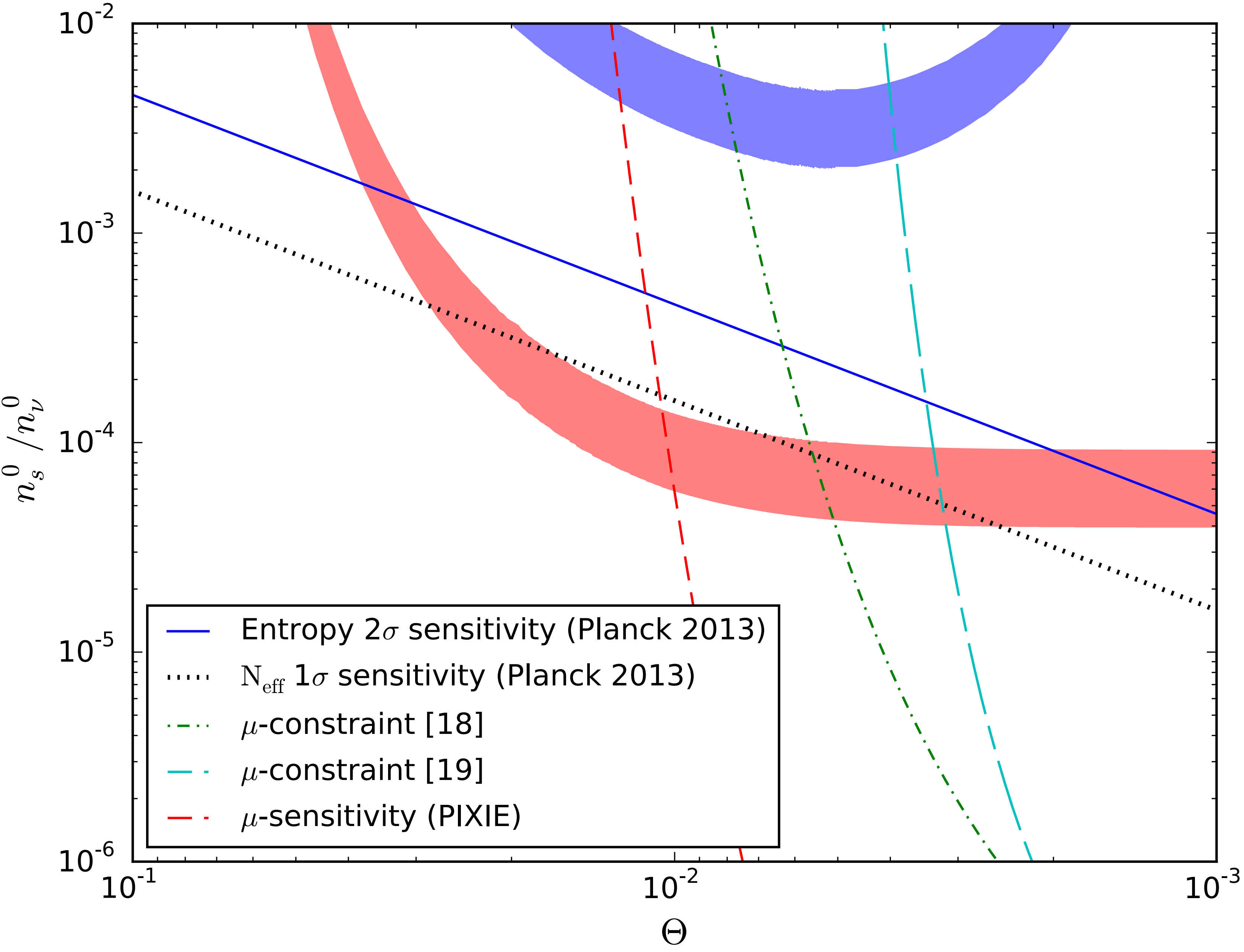


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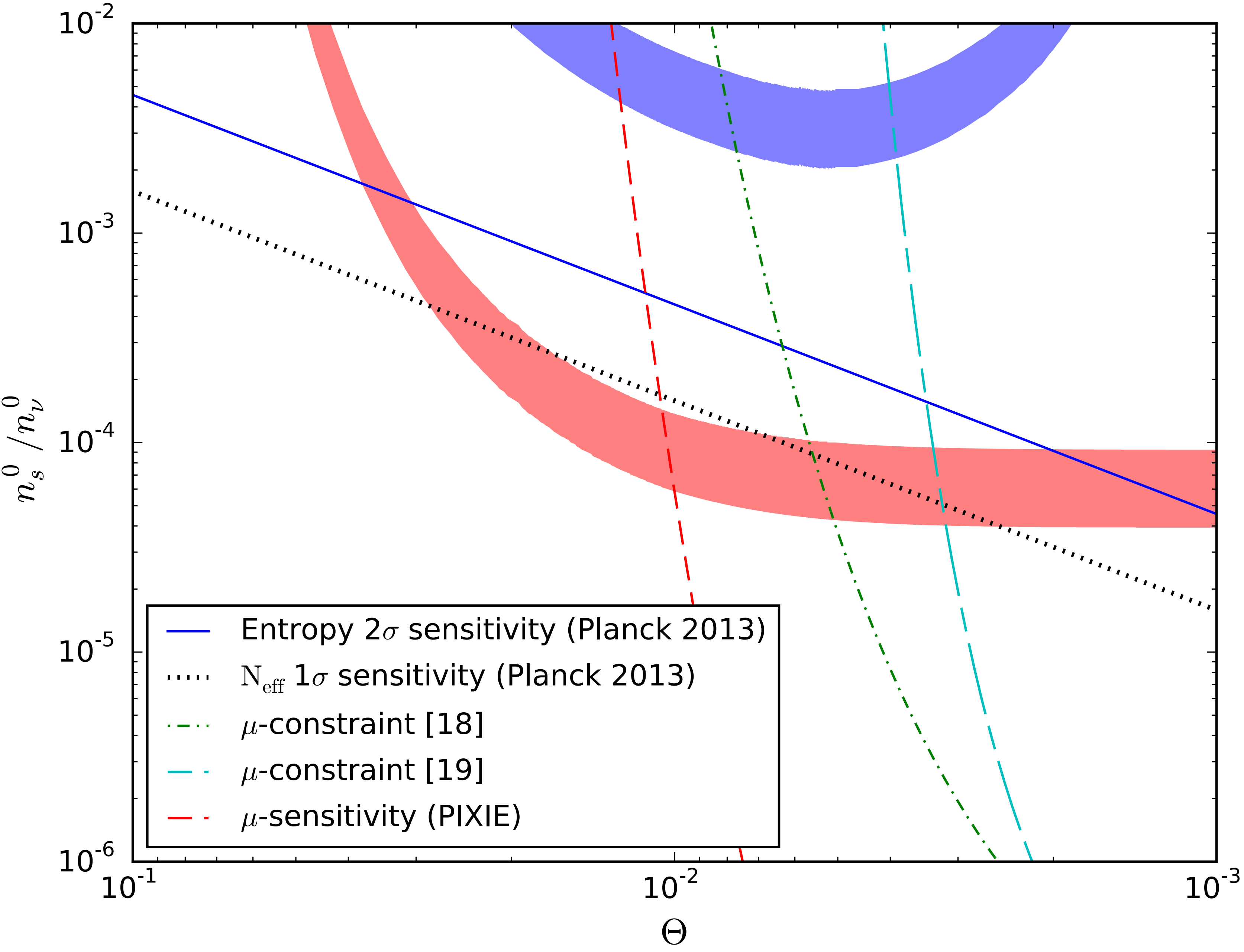


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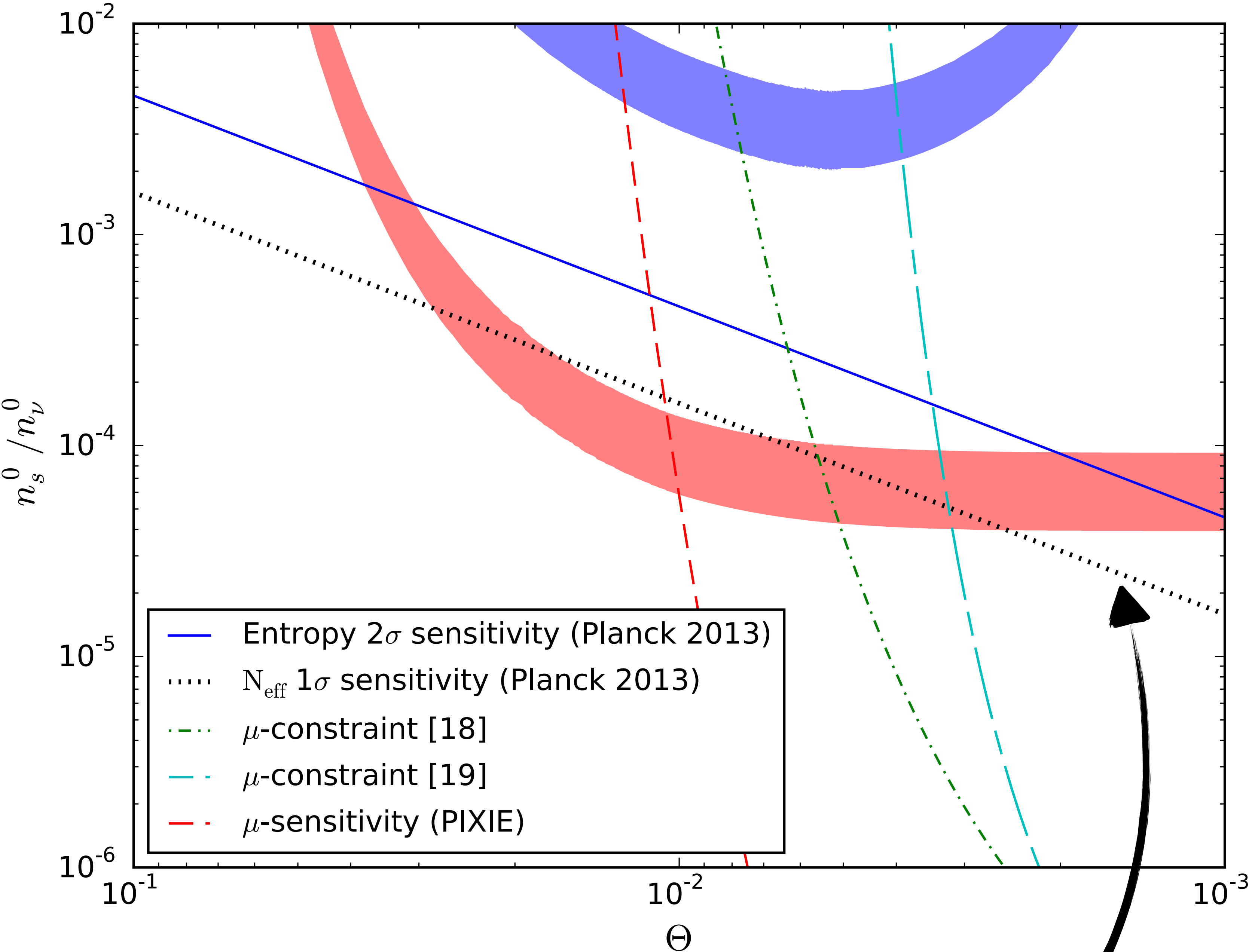


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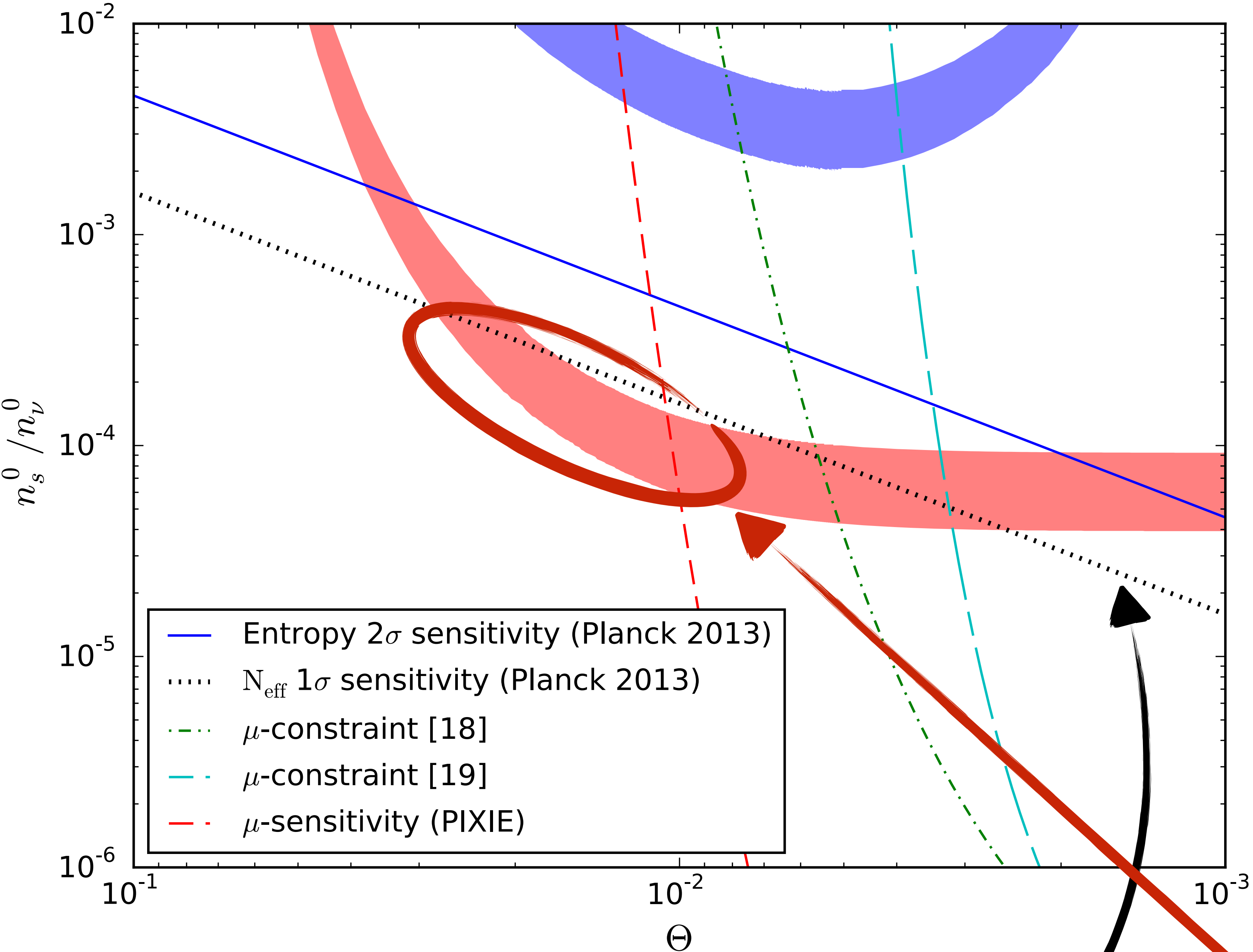


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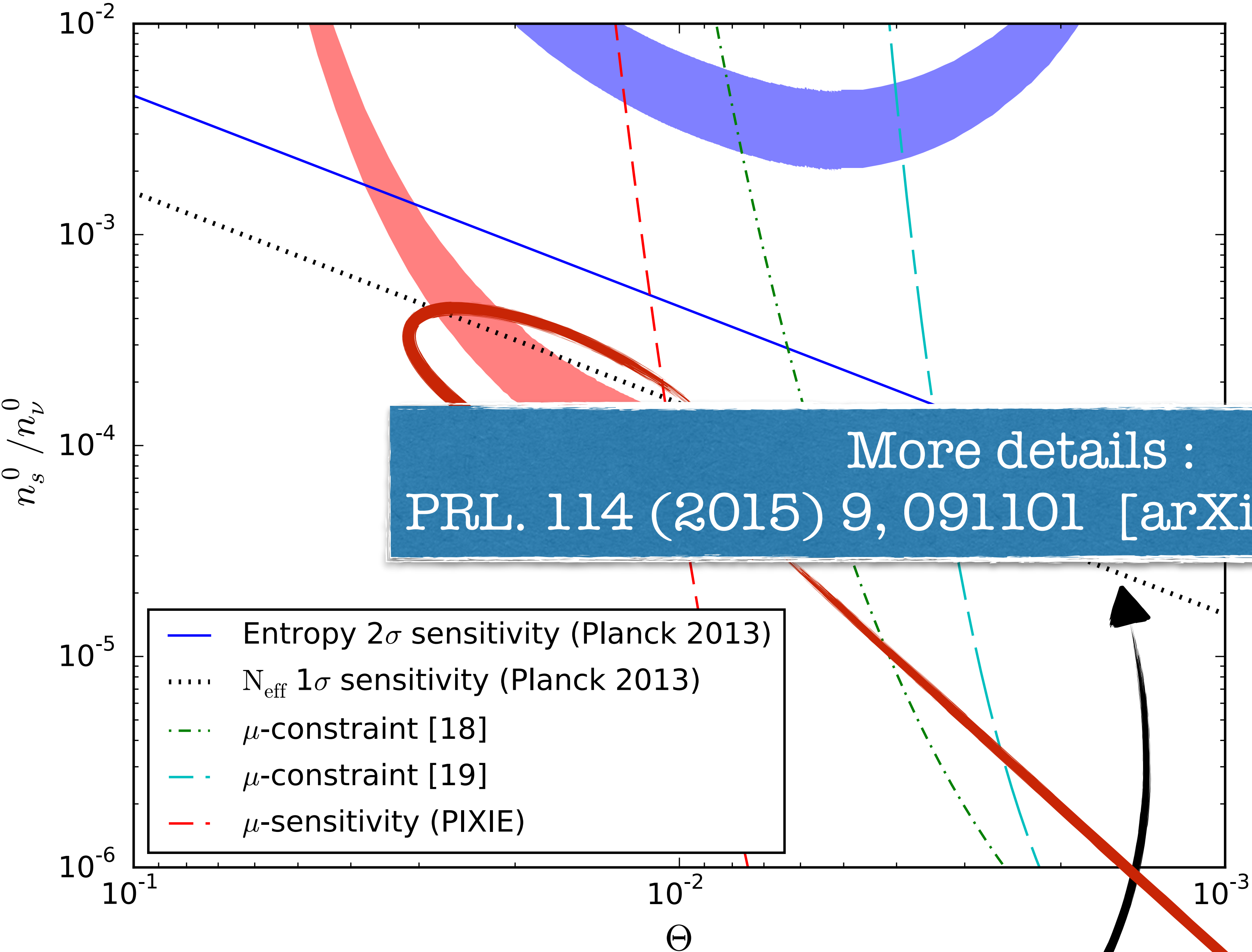


More details :
PRL. 114 (2015) 9, 091101 [arXiv:1502.01250]

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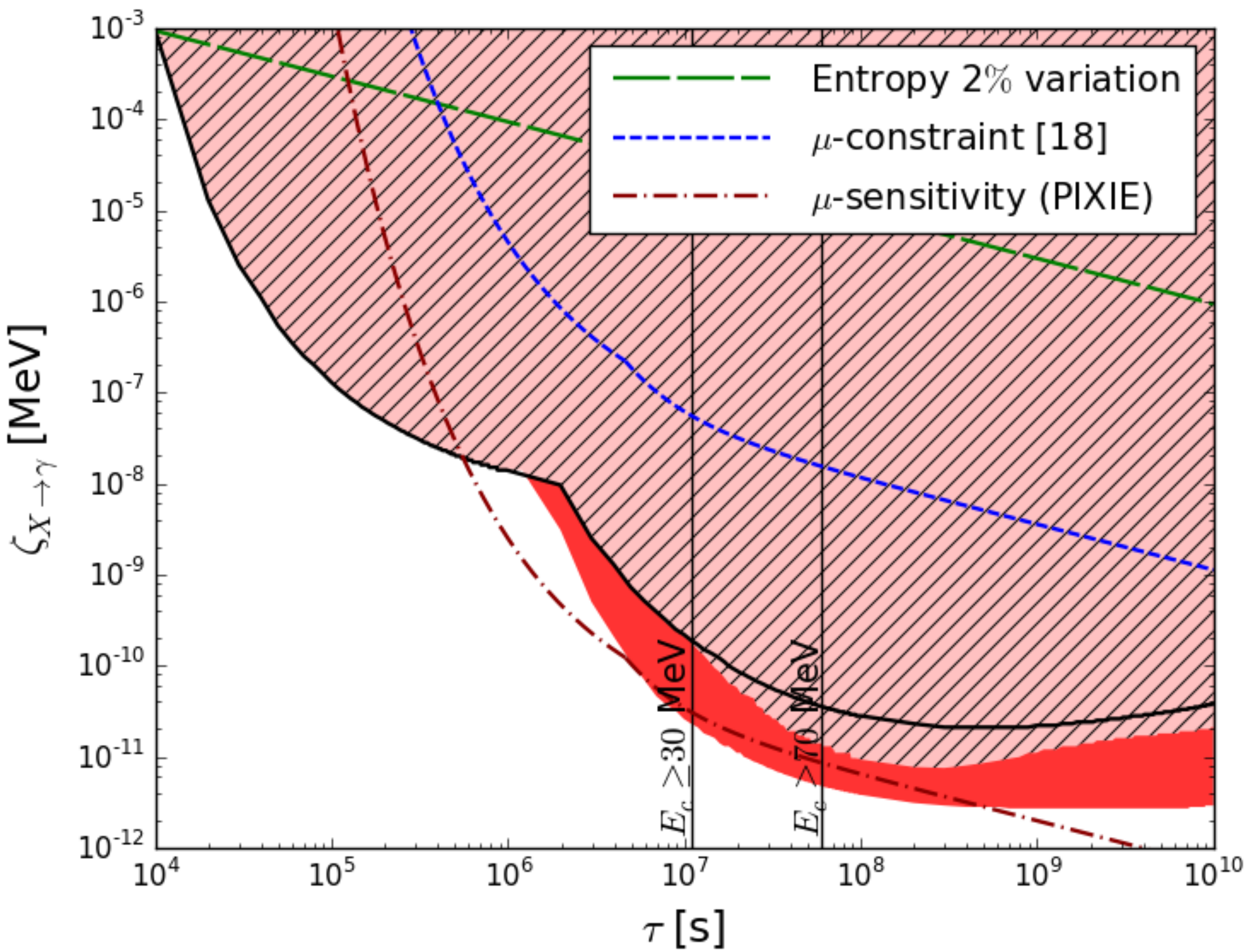


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*VP & Serpico PRD. 91 (2015) 10, 103007*

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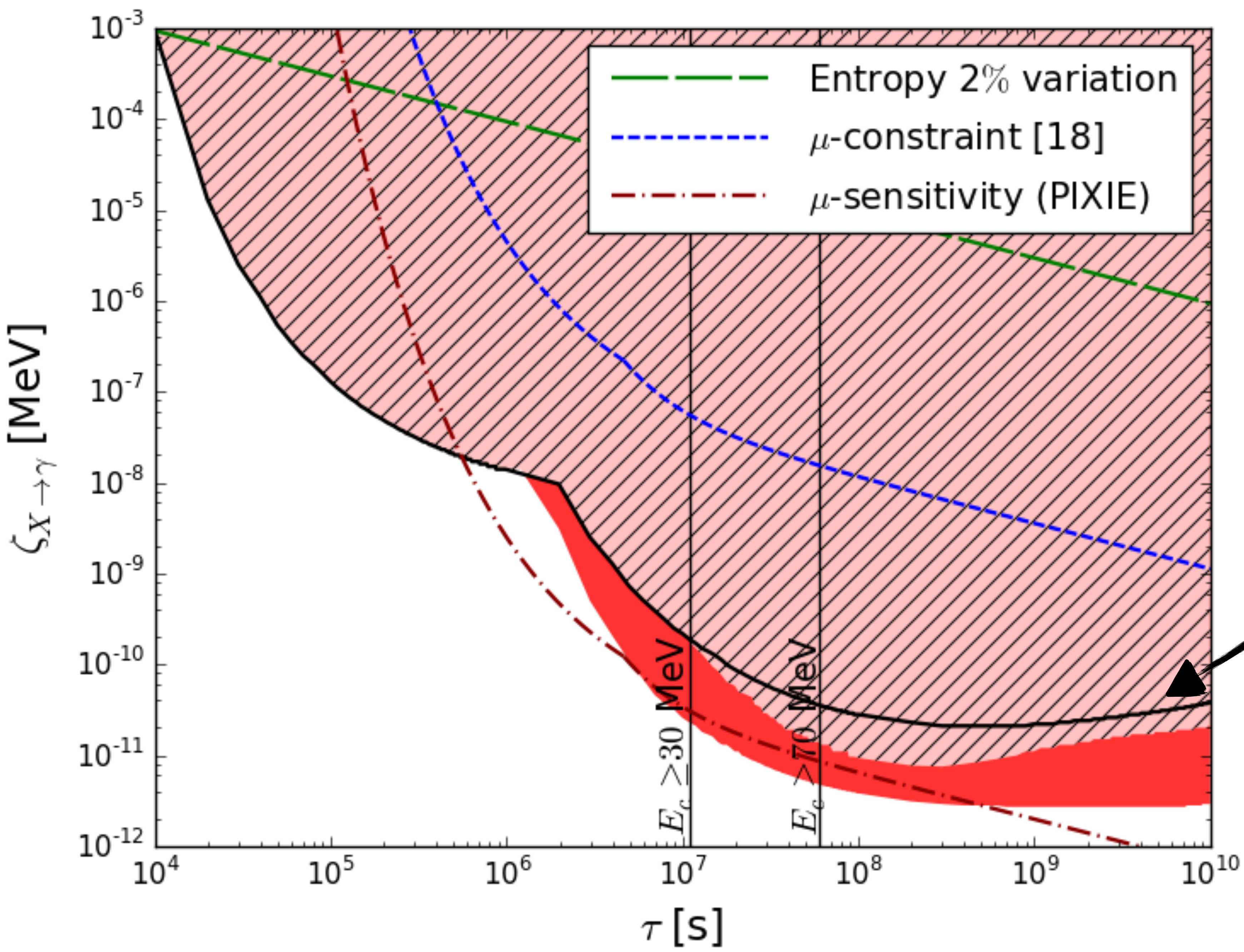


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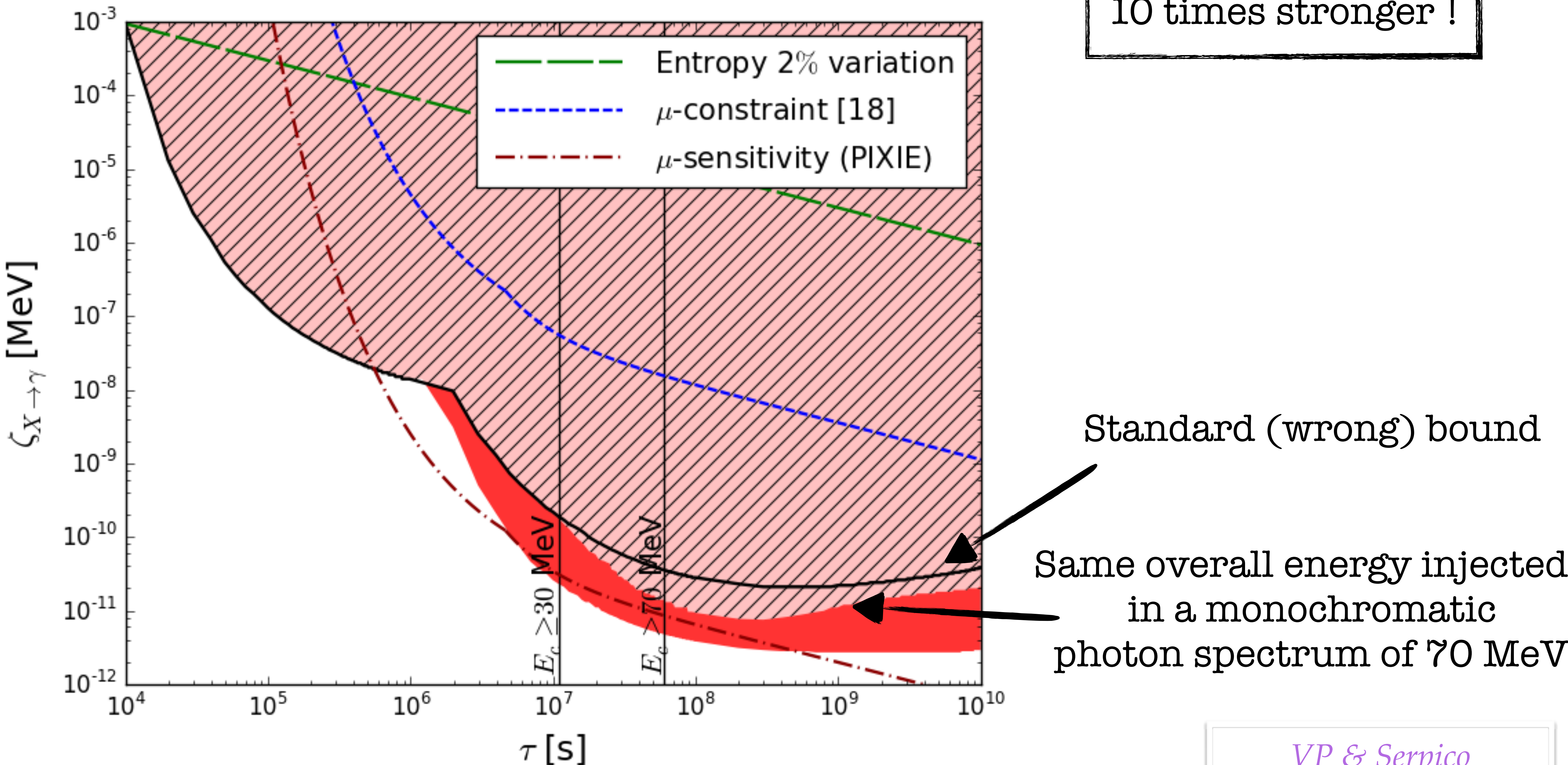


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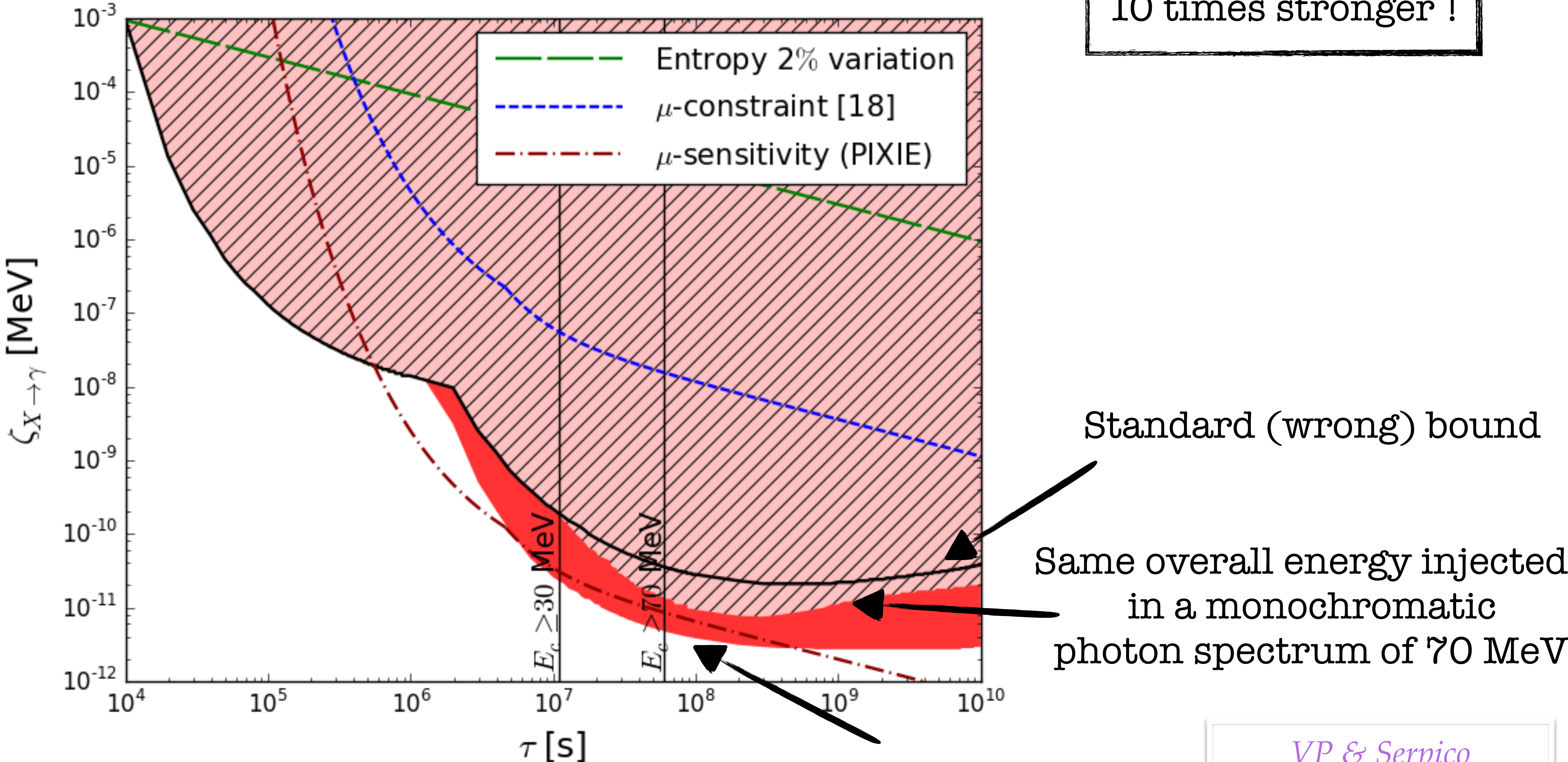


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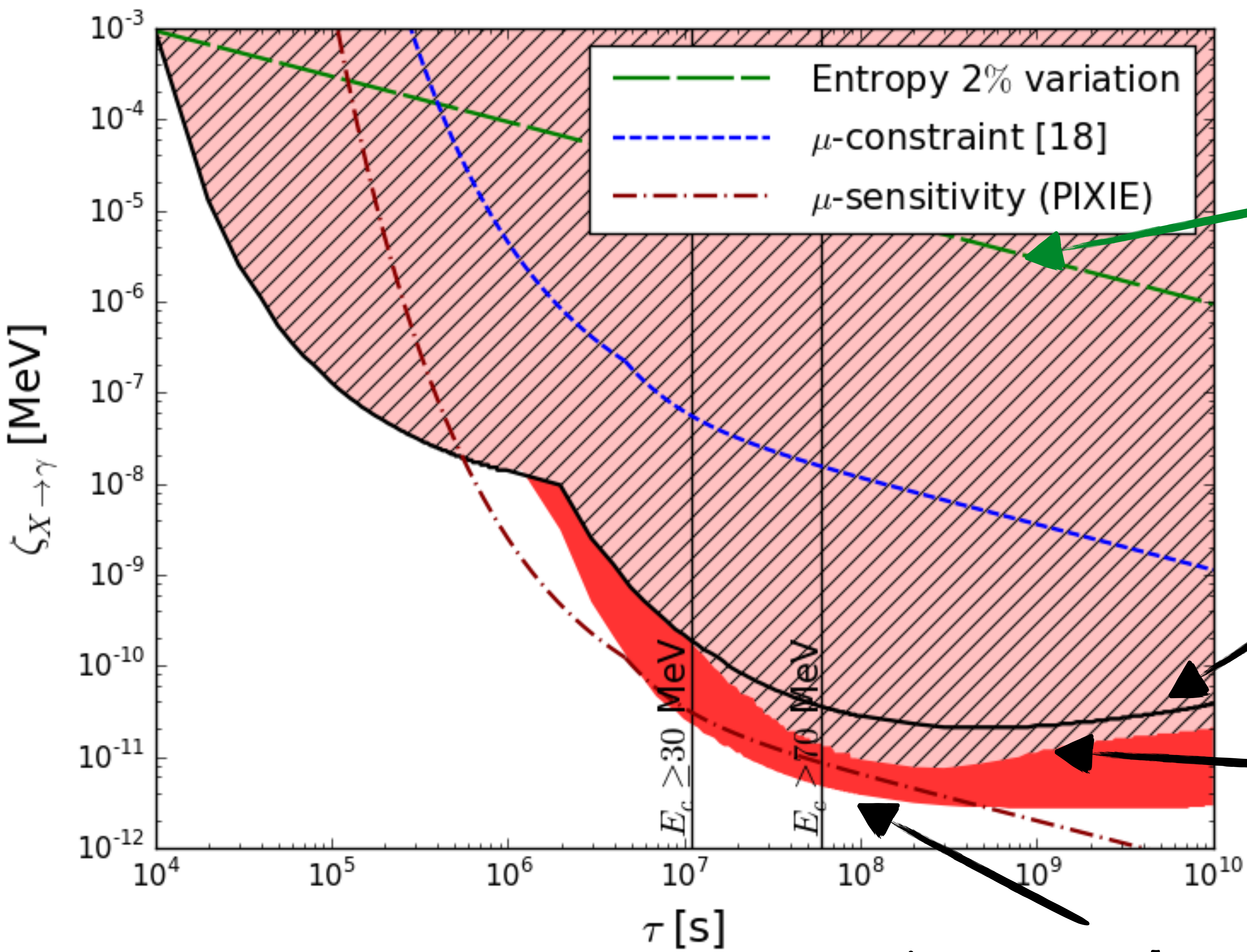


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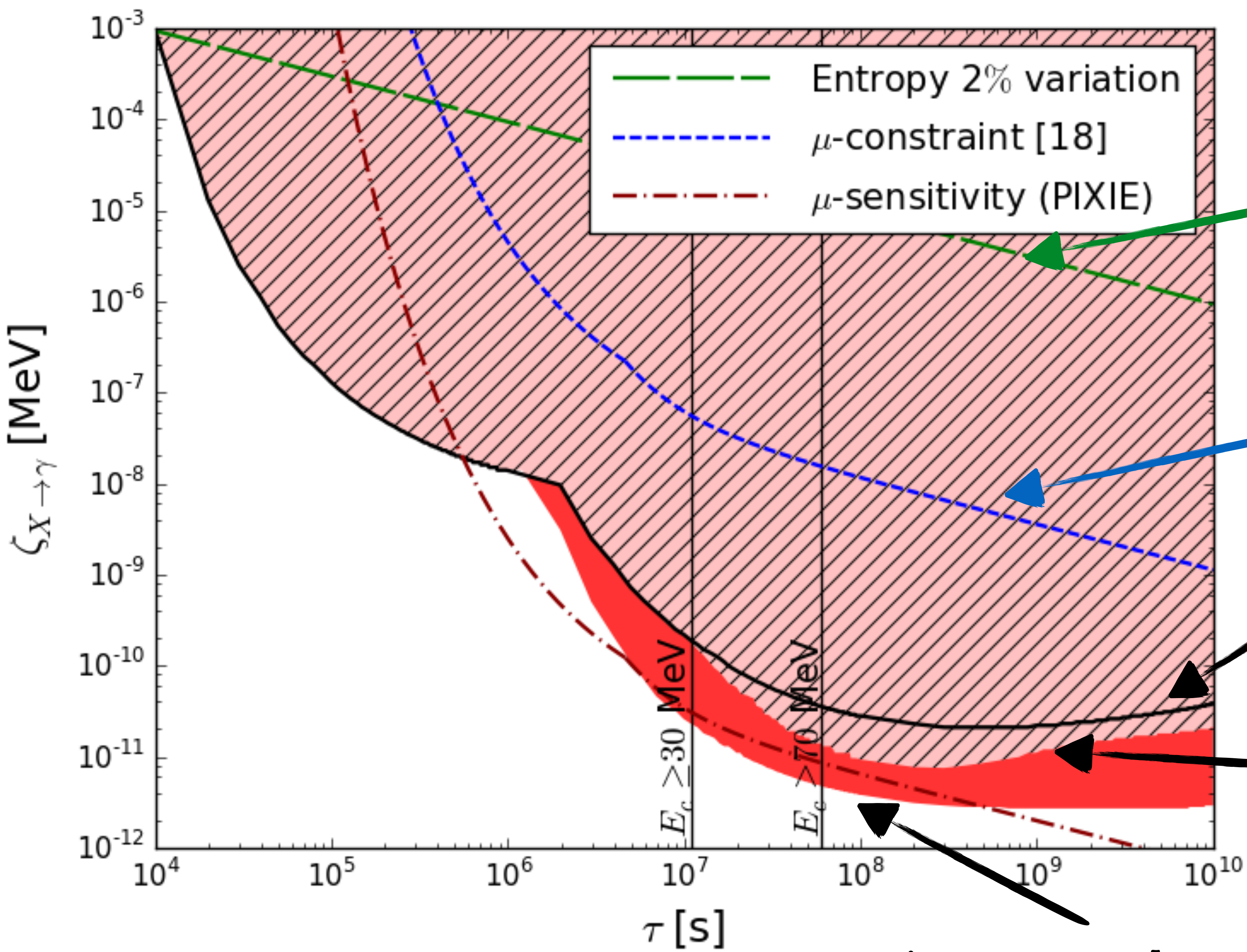


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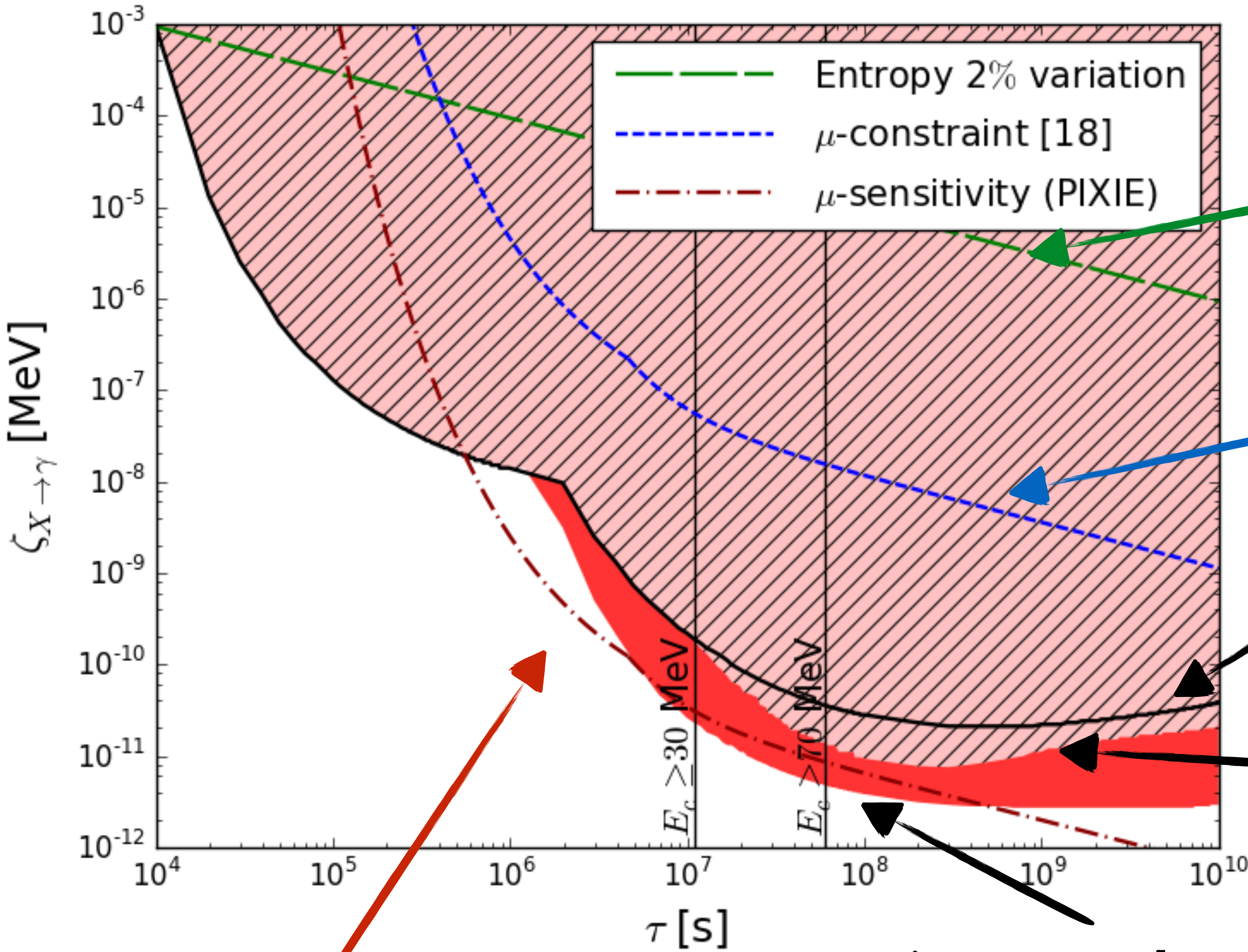


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Forecast CMB distortion sensitivity of PIXIE

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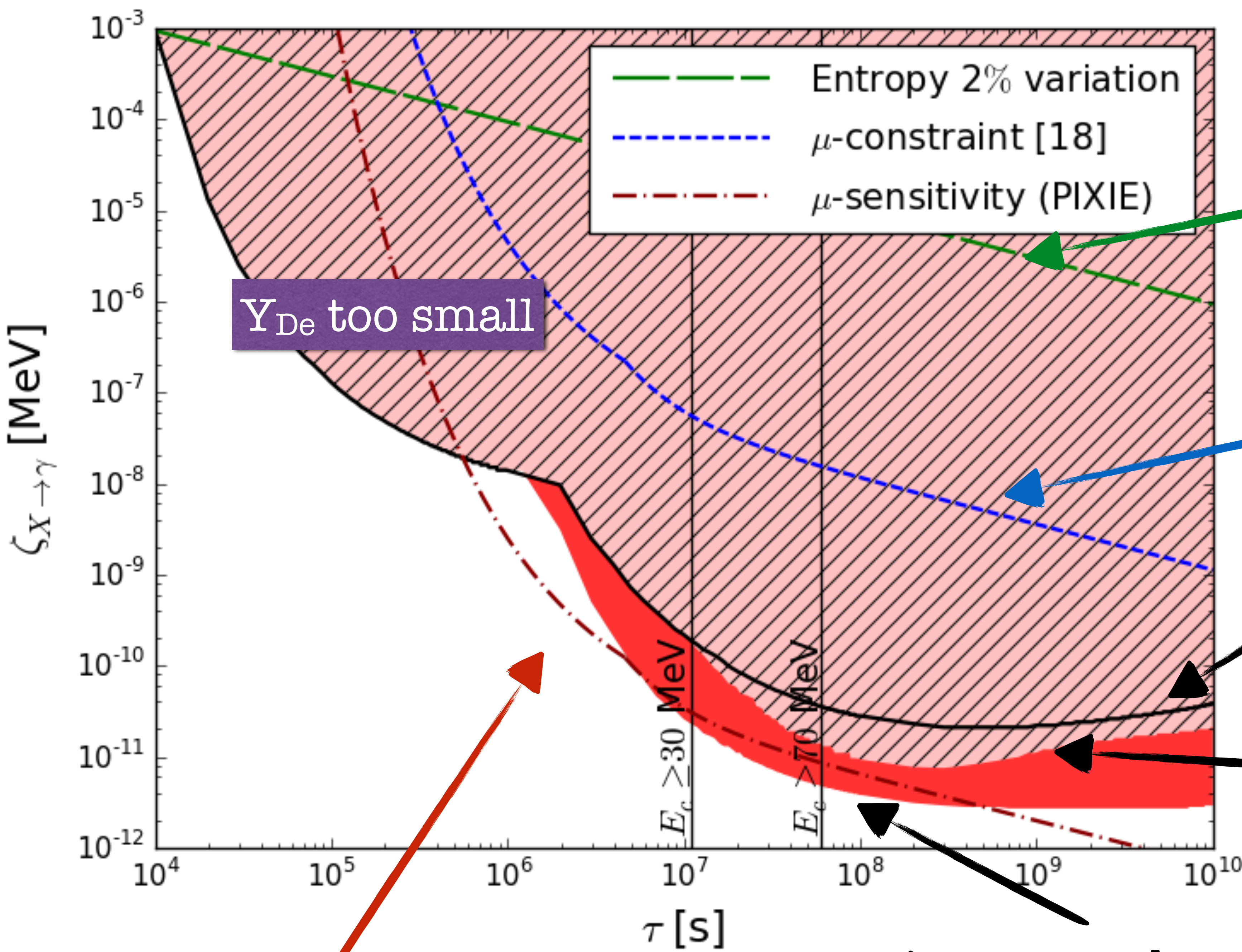


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Standard (wrong) bound

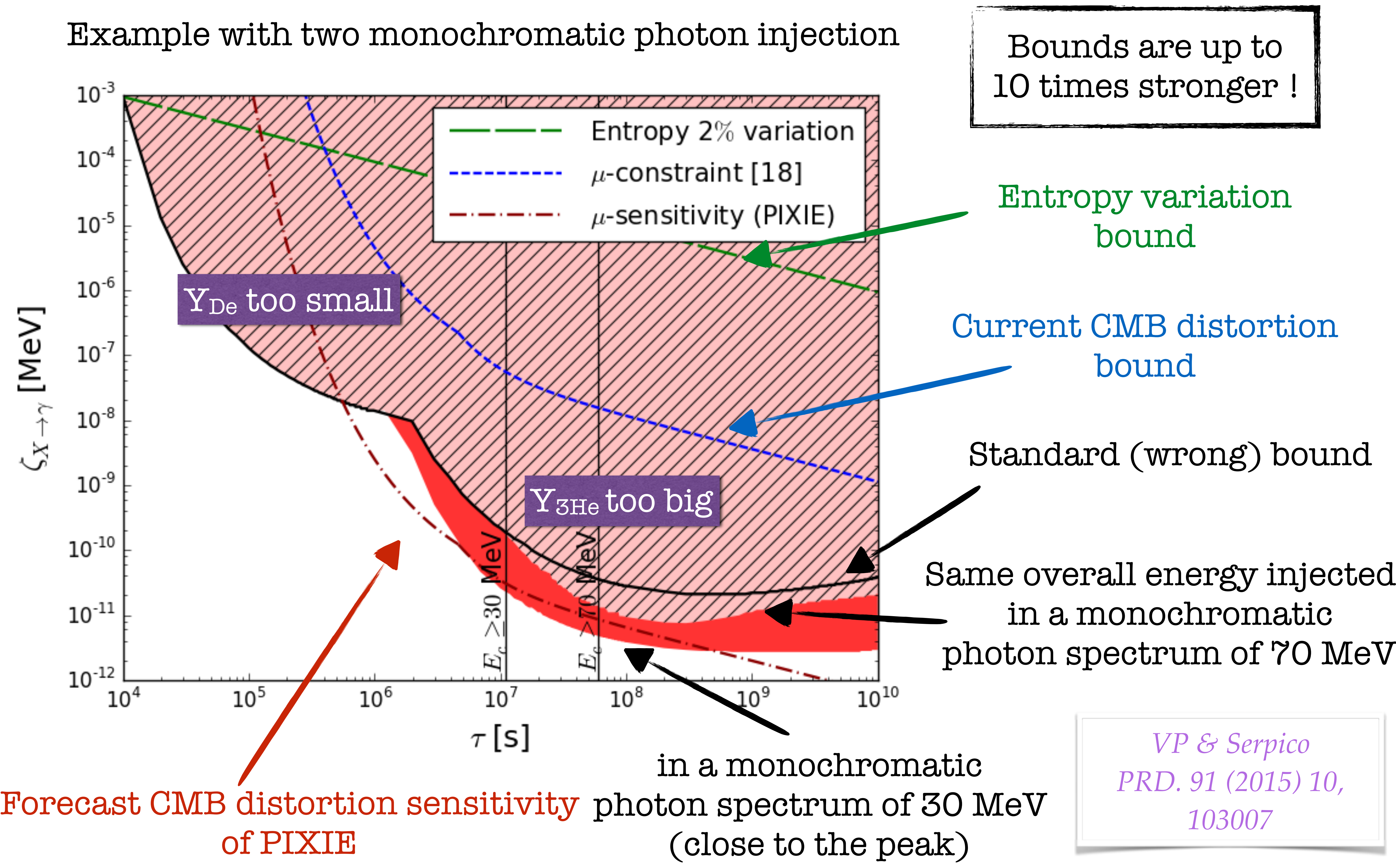
Same overall energy injected in a monochromatic photon spectrum of 70 MeV

in a monochromatic photon spectrum of 30 MeV (close to the peak)

Forecast CMB distortion sensitivity of PIXIE

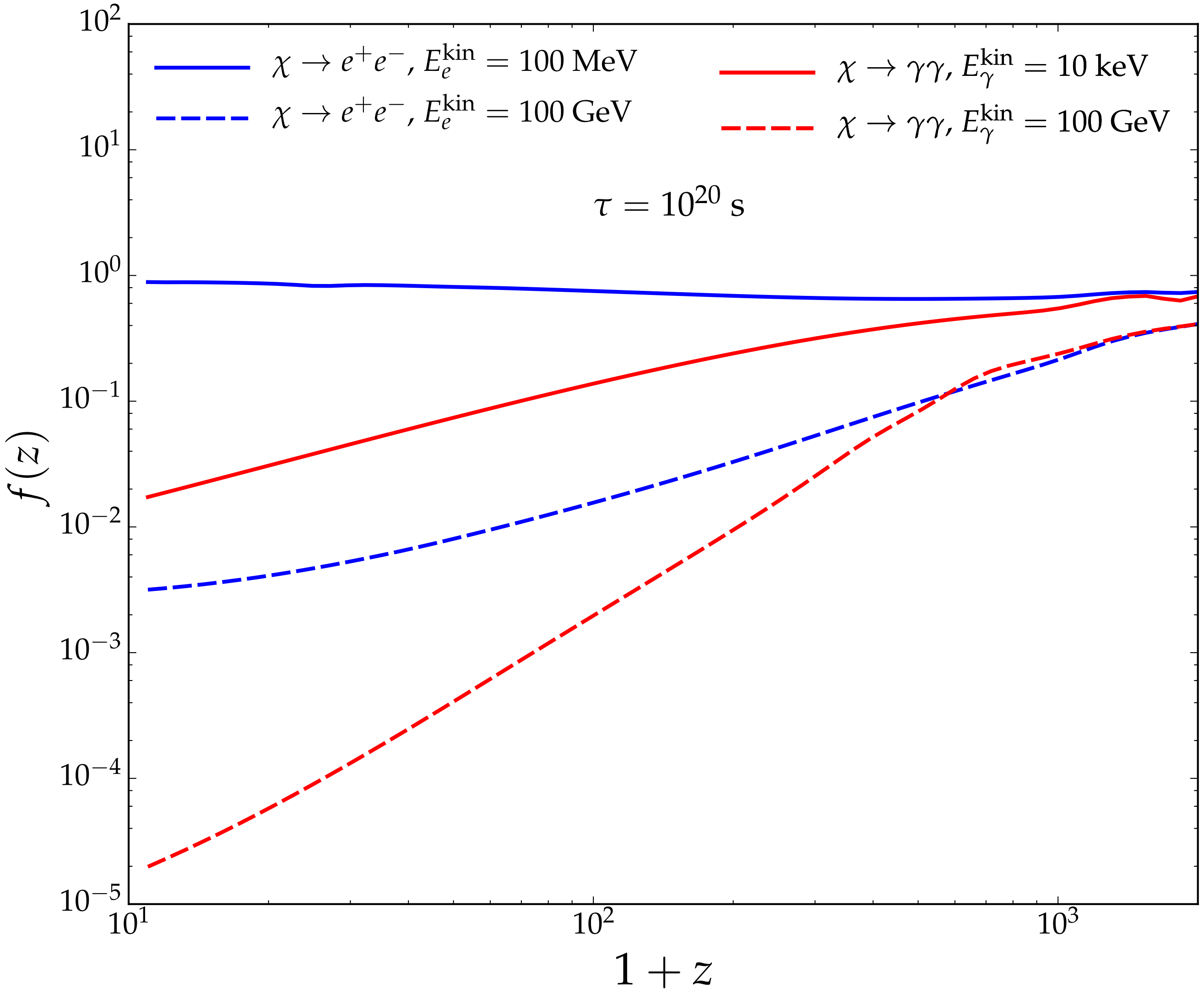
*VP & Serpico PRD. 91 (2015) 10, 103007*

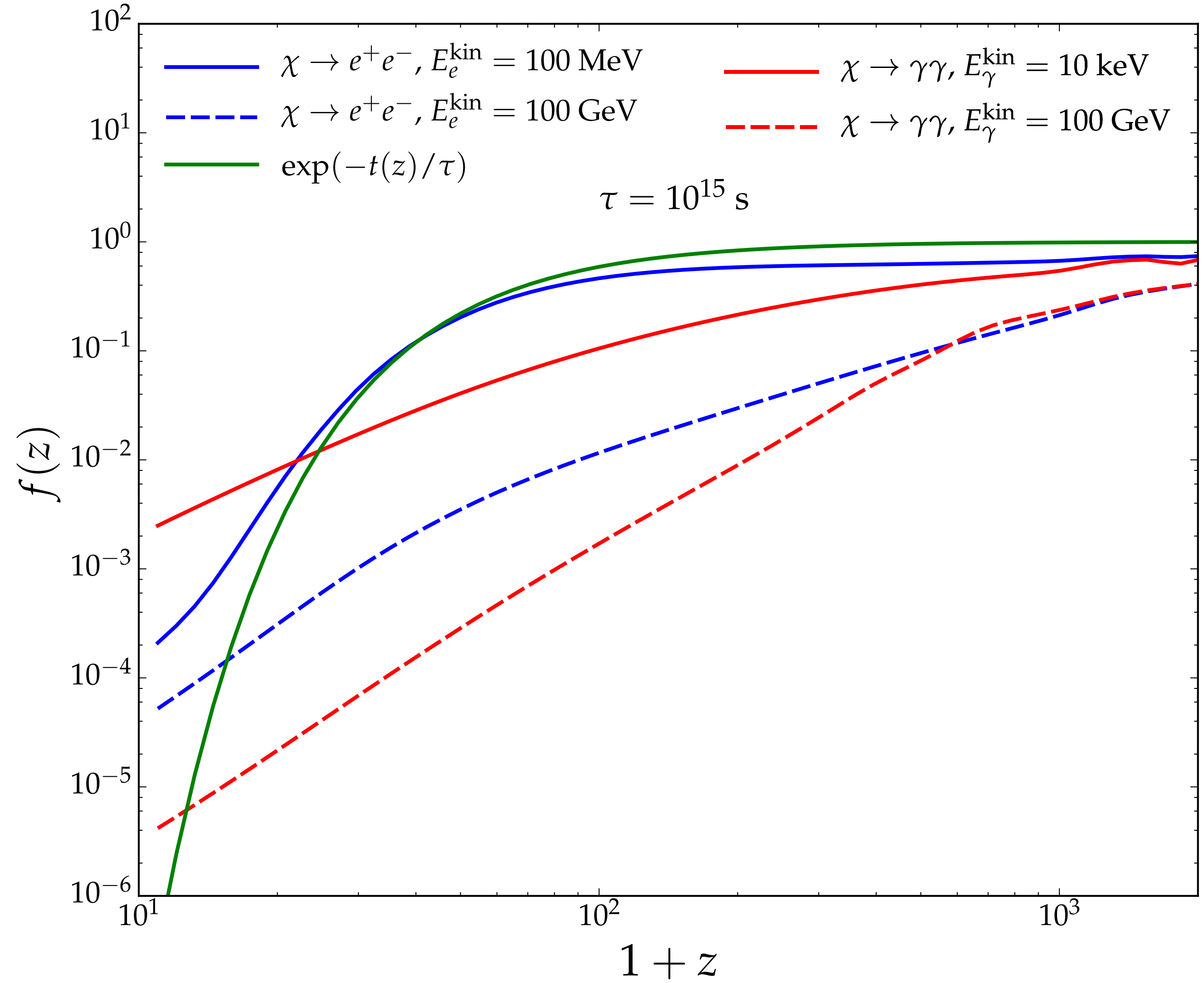
Example with two monochromatic photon injection




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

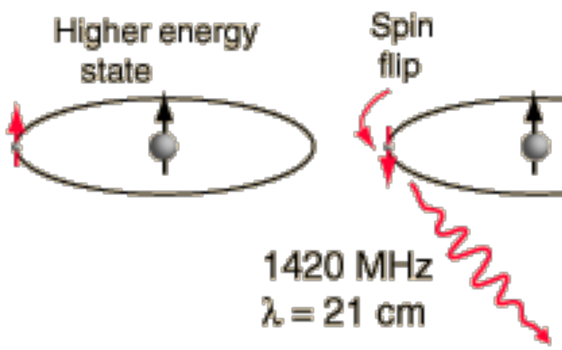
# examples of energy deposition efficiency function




- Here, the deposition efficiency is summed over all channels : It represents the efficiency of the plasma at absorbing energy.
- It typically depends on the lifetime, particle energy and nature!

# The next-generation experiment : 21cm with SKA

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- Very sensitive probes of the Epoch of Reionization (EoR)
- Key quantities : Spin temperature and differential brightness temperature

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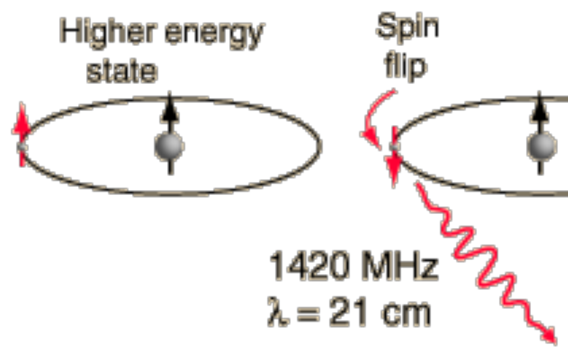


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$$\frac{n_1}{n_0} = 3e^{-E_{10}/k_B T_S}$$

⇒ Exc. = Des-exc.

$$T_S^{-1} = \frac{T_{\rm CMB}^{-1} + x_c T_K^{-1} + x_\alpha T_c^{-1}}{1 + x_c + x_\alpha}$$

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

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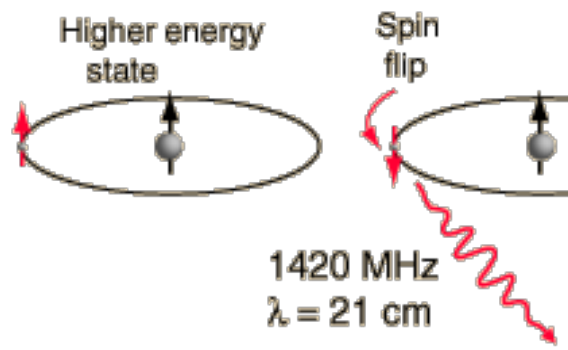


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scattering with CMB — collision within the gas — interaction with UV from stars

Compare patch of the sky with/without hydrogen clouds:

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

*see e.g. Furlanetto et al. [astro-ph/0608032]*

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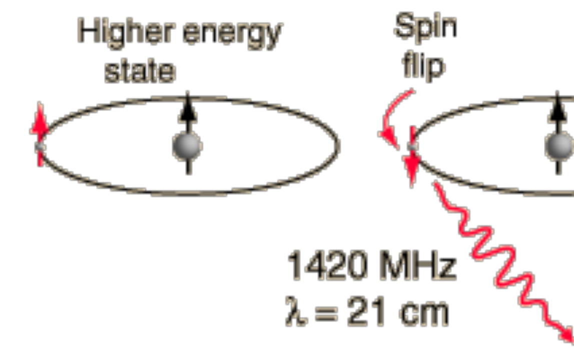


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Difficulty = Huge astrophysical uncertainty, one trick :
SKA will be able to measure $\delta T_b$ = 5-10 mK up to z= 20/25 (ν = 60 MHz)