Cosmological constraints on decaying Dark Matter

Vivian Poulin

LAPTh and RWTH Aachen University

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

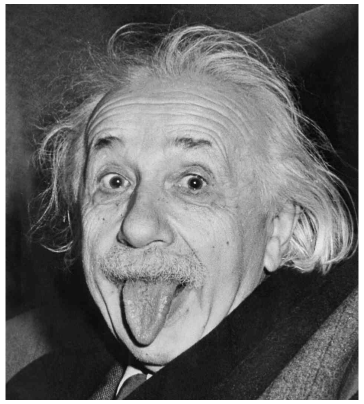
VP & Serpico PRL 114 (2015) no.9, 091101
VP & Serpico PRD 91 103007 (2015) no.10
VP, Serpico & Lesgourgues JCAP 1512 (2015) no.12 041
VP, Serpico & Lesgourgues ArXiv:1610.10051

RWTH AACHEN UNIVERSITY

Enigmass Meeting
09/12/2016

LAPTh

ΛCDM is a big success !



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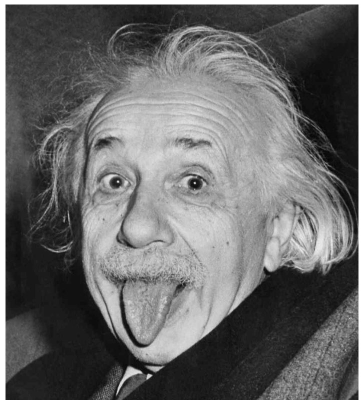
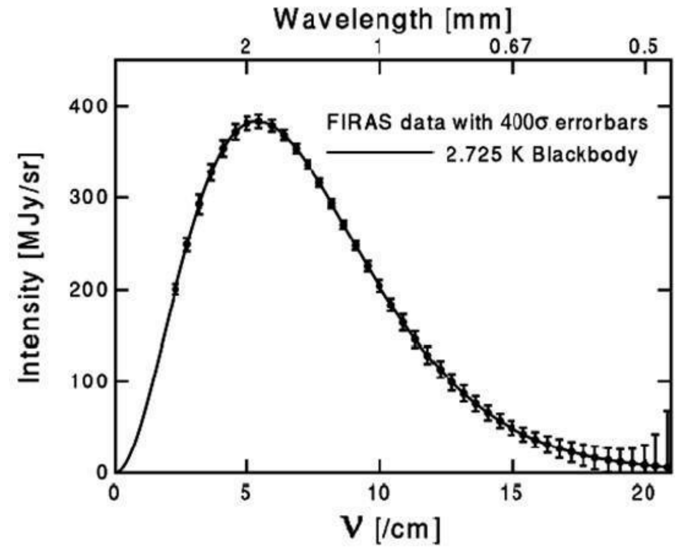
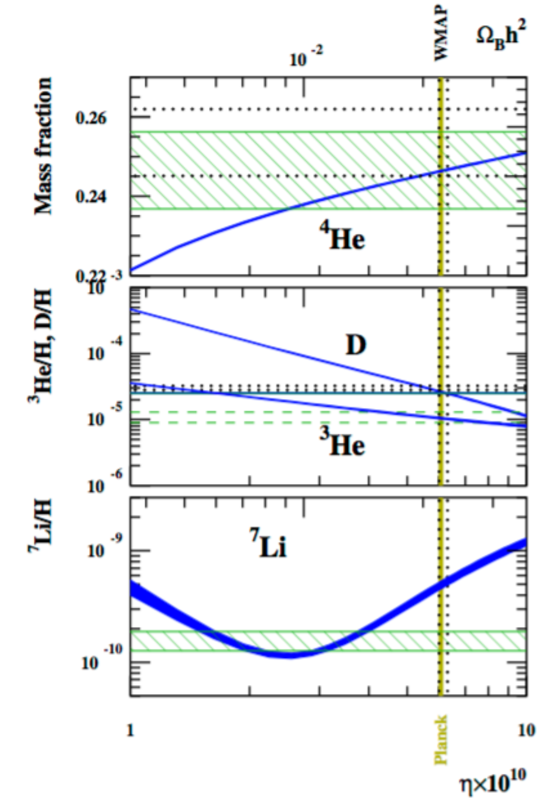


Homogeneous →



CMB blackbody distribution

Firas [astro-ph/9605054]



Big Bang Nucleosynthesis

Coc & Vengioni 2015

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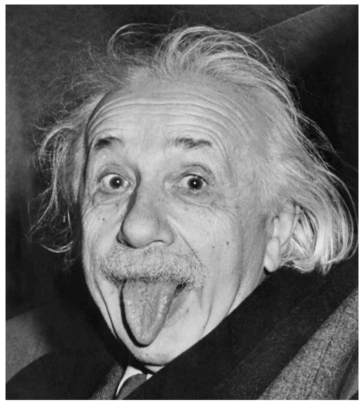

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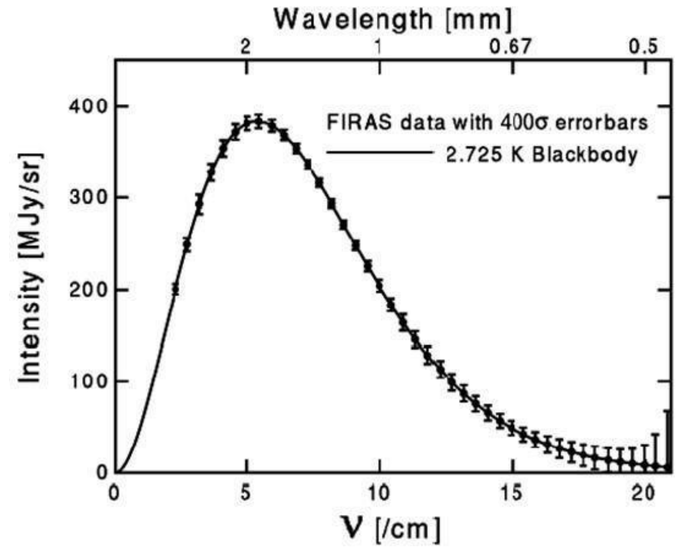

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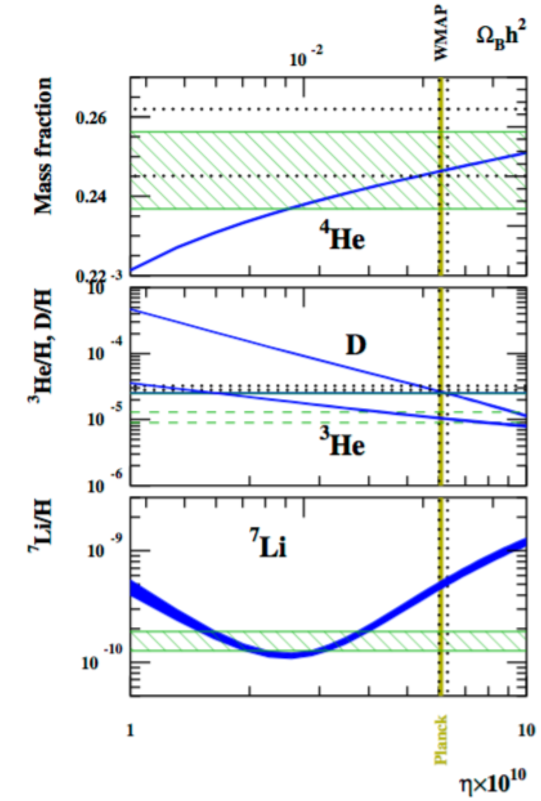

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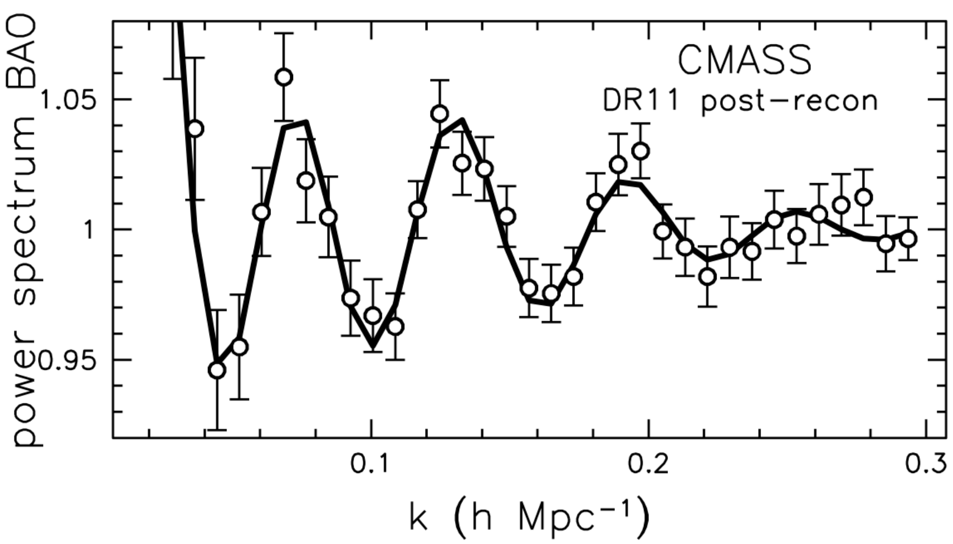
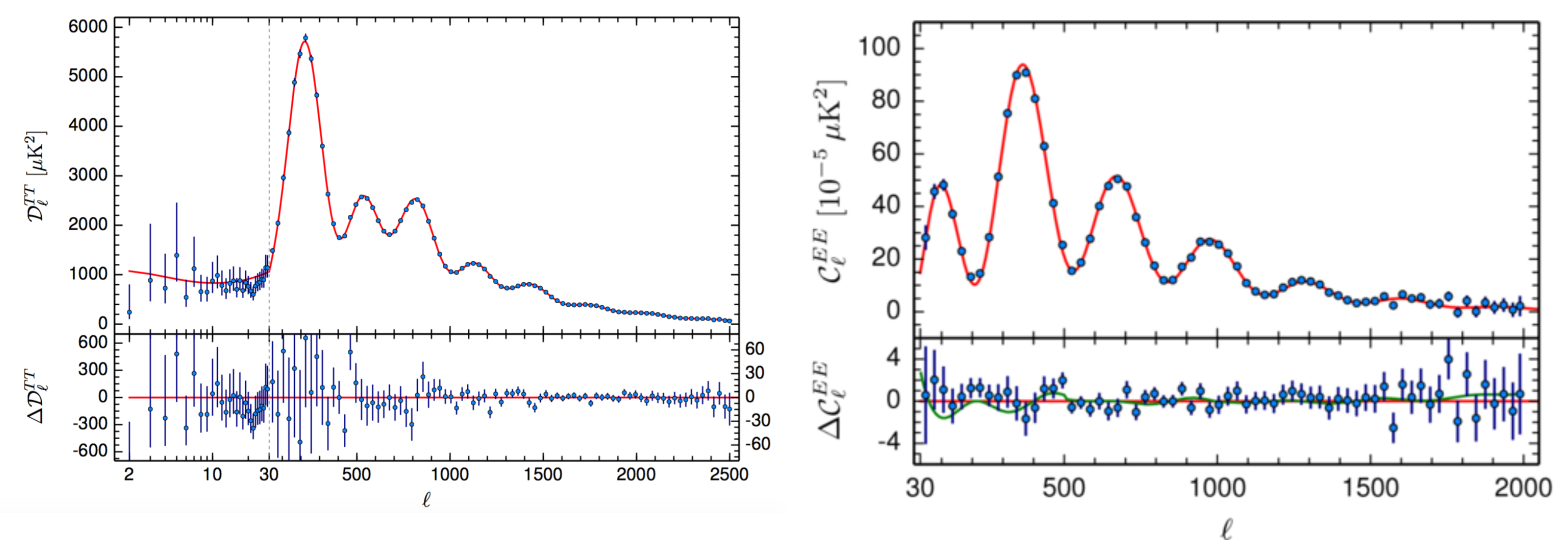
Perturbed



P(k) and BAO measurements

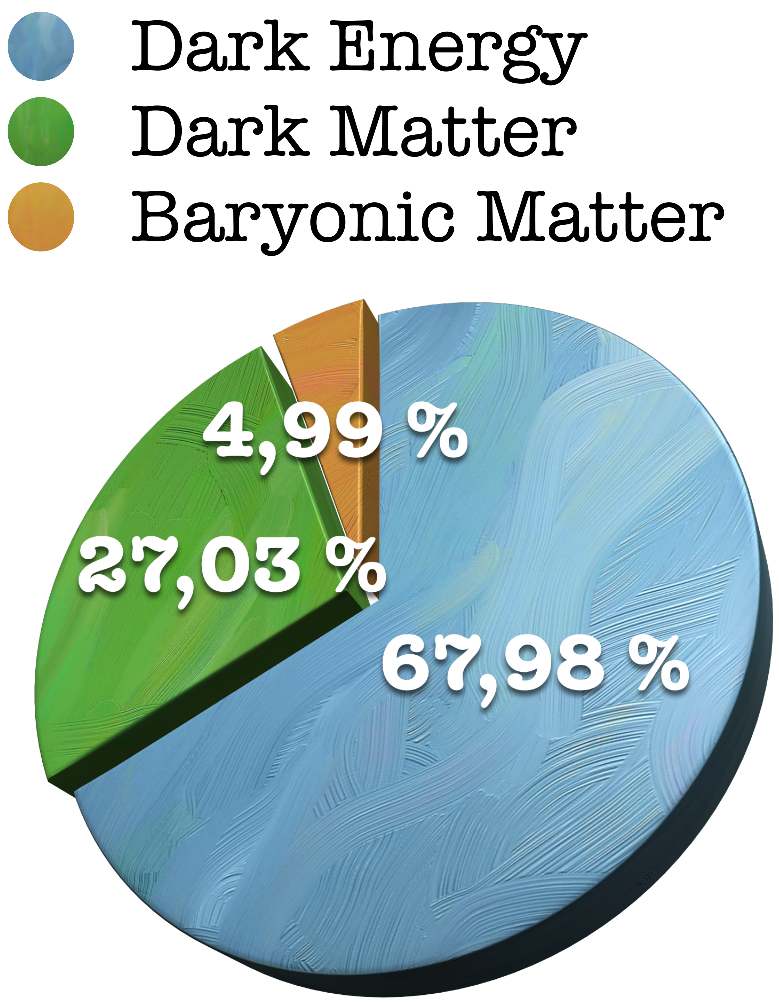
Andersen et al. 2012 [arXiv:1203.6594]



CMB power spectra

Planck 2015 [arXiv:1502.01589]

Most of the universe composition is unknown !

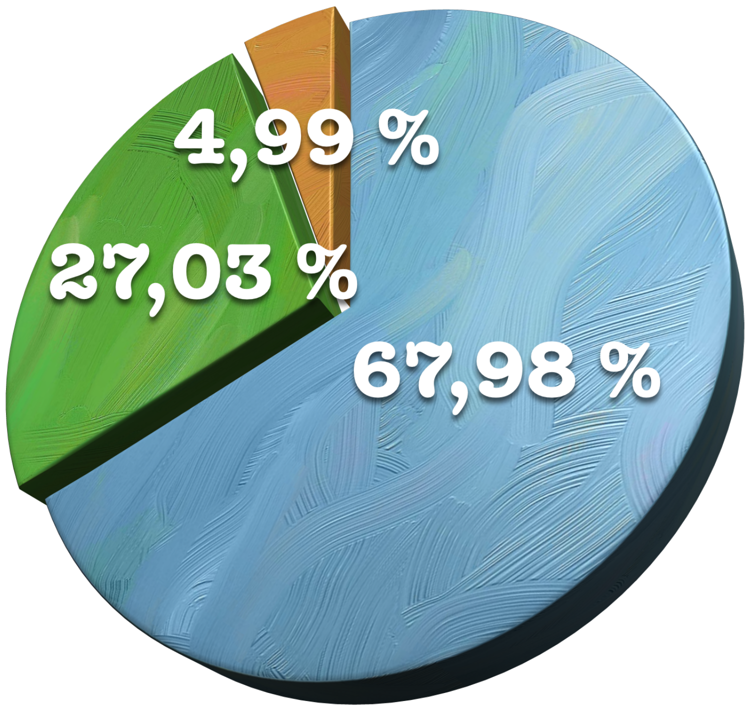


Dark Matter :
Stable, Only gravitational interaction

Planck 2016 [arXiv:1605.02985]

Most of the universe composition is unknown !

- Dark Energy
- Dark Matter
- Baryonic Matter



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**What happens if one tries to this picture ?
e.g adding electromagnetic decaying particles**

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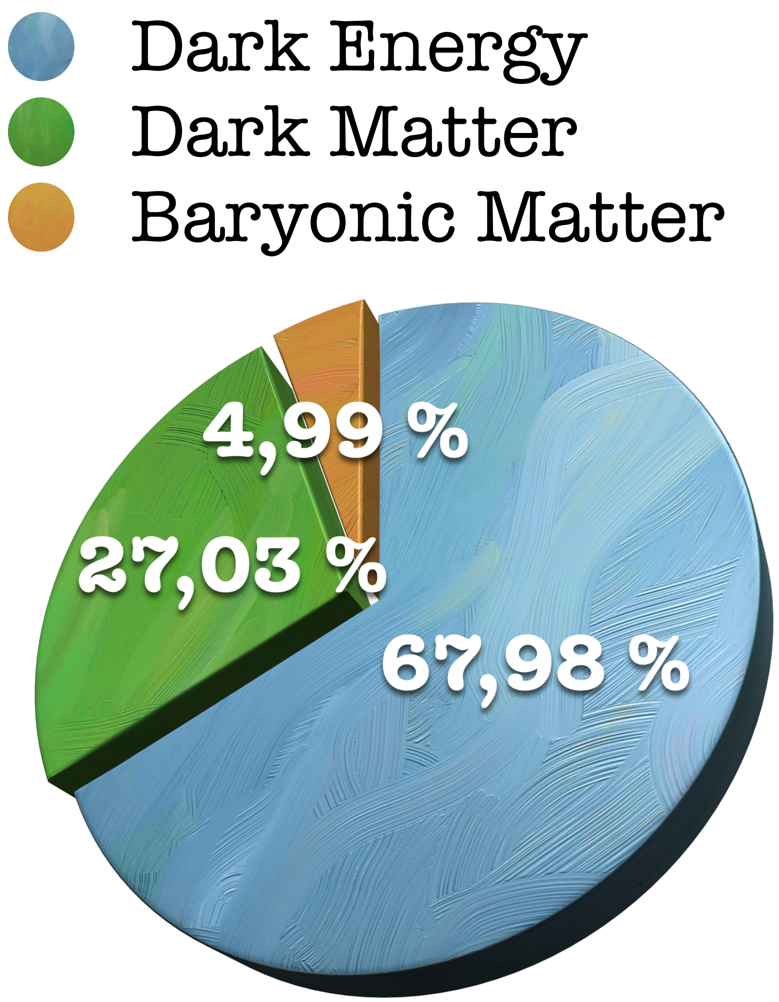

Dark Matter :
Stable, Only gravitational interaction

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What happens if one tries to this picture ?
e.g adding electromagnetic decaying particles

One could spoil (or improve !?) each of these observables !!

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 ?

Models	Observables

A Journey in Wonderland of particle physics

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Electromagnetic decay products

A Journey in Wonderland of particle physics

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Electromagnetic decay products

Purely gravitational impact of the decay

The typical electromagnetic decay of an exotic particle

χ

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

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

<u>What happens to the decay products ?</u>

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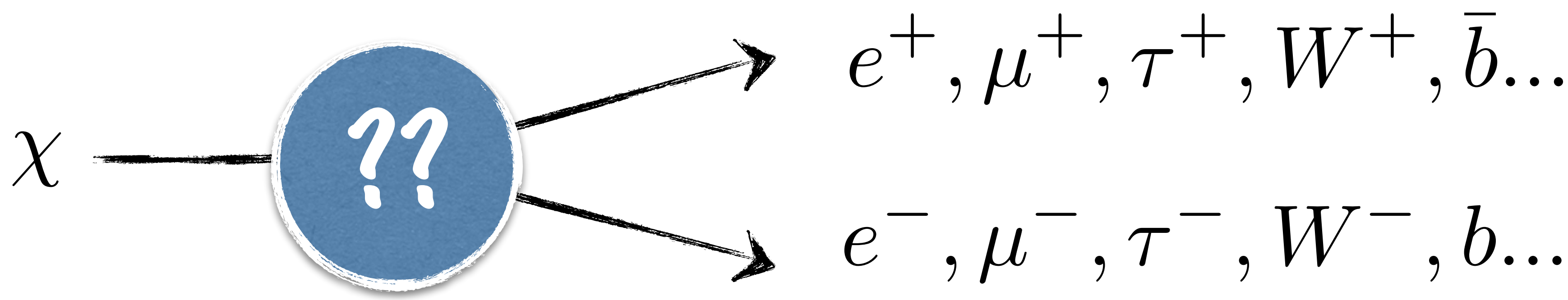

What happens to the decay products ?

e.g. Jedamzik
PRD D74 (2006) 103509

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

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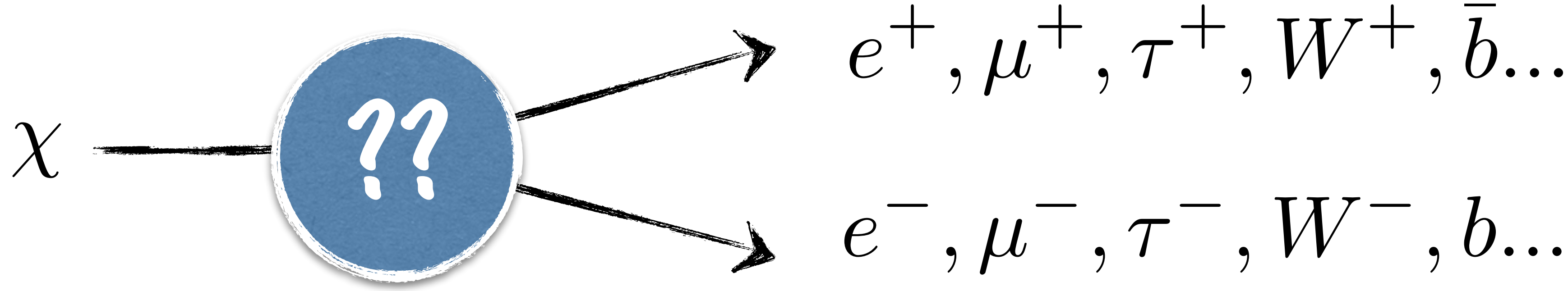

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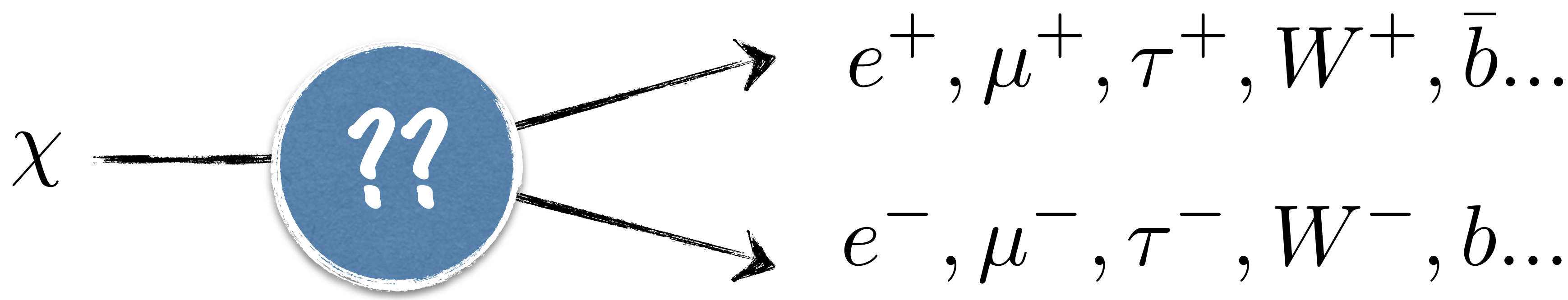

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- They lose their energy through interaction with CMB

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

spectral distortions

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

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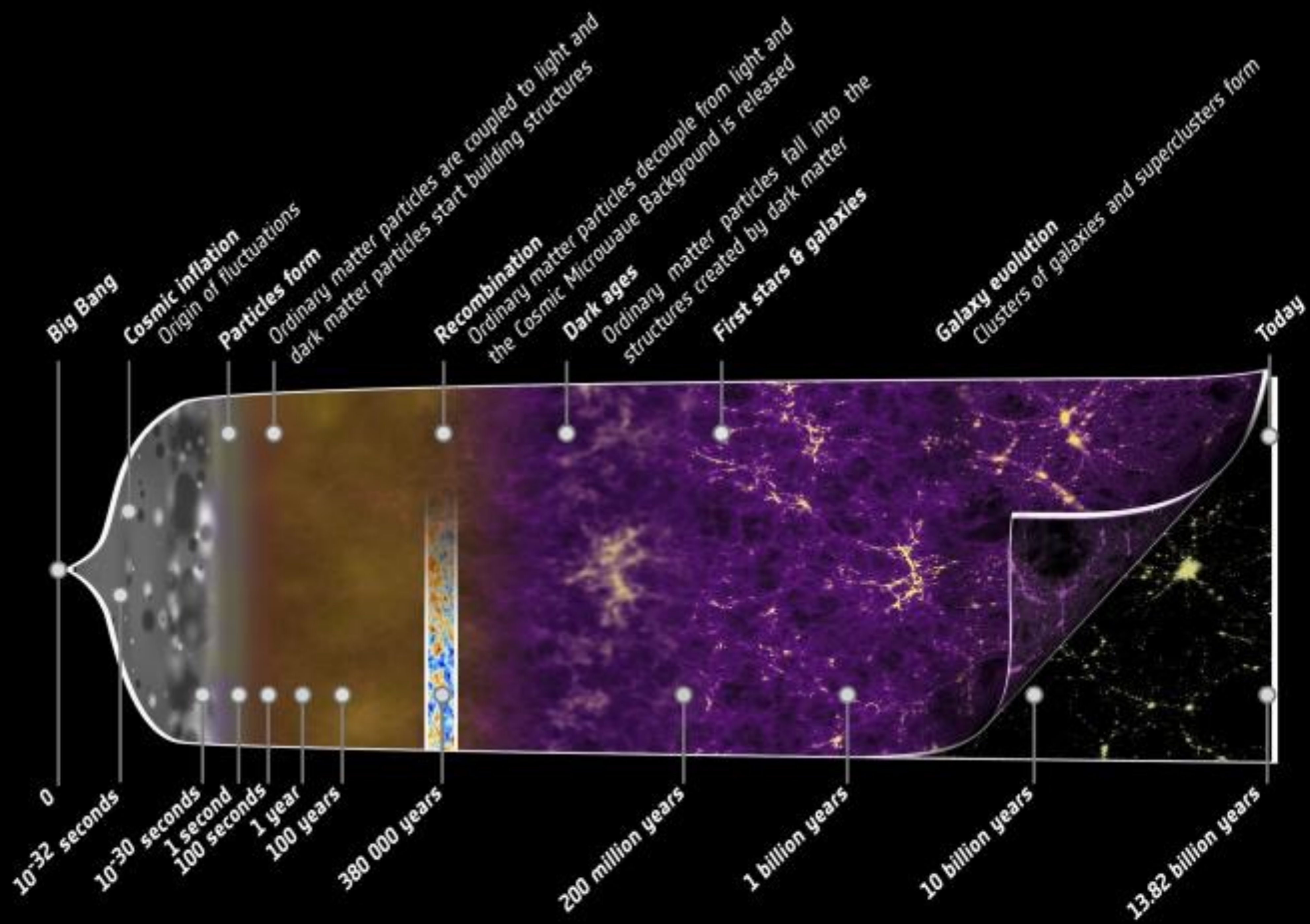
$$e\gamma_{\rm CMB} \rightarrow e\gamma \qquad \gamma\gamma_{\rm CMB} \rightarrow \gamma\gamma \qquad \gamma\gamma_{\rm CMB} \rightarrow e^+e^-$$

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

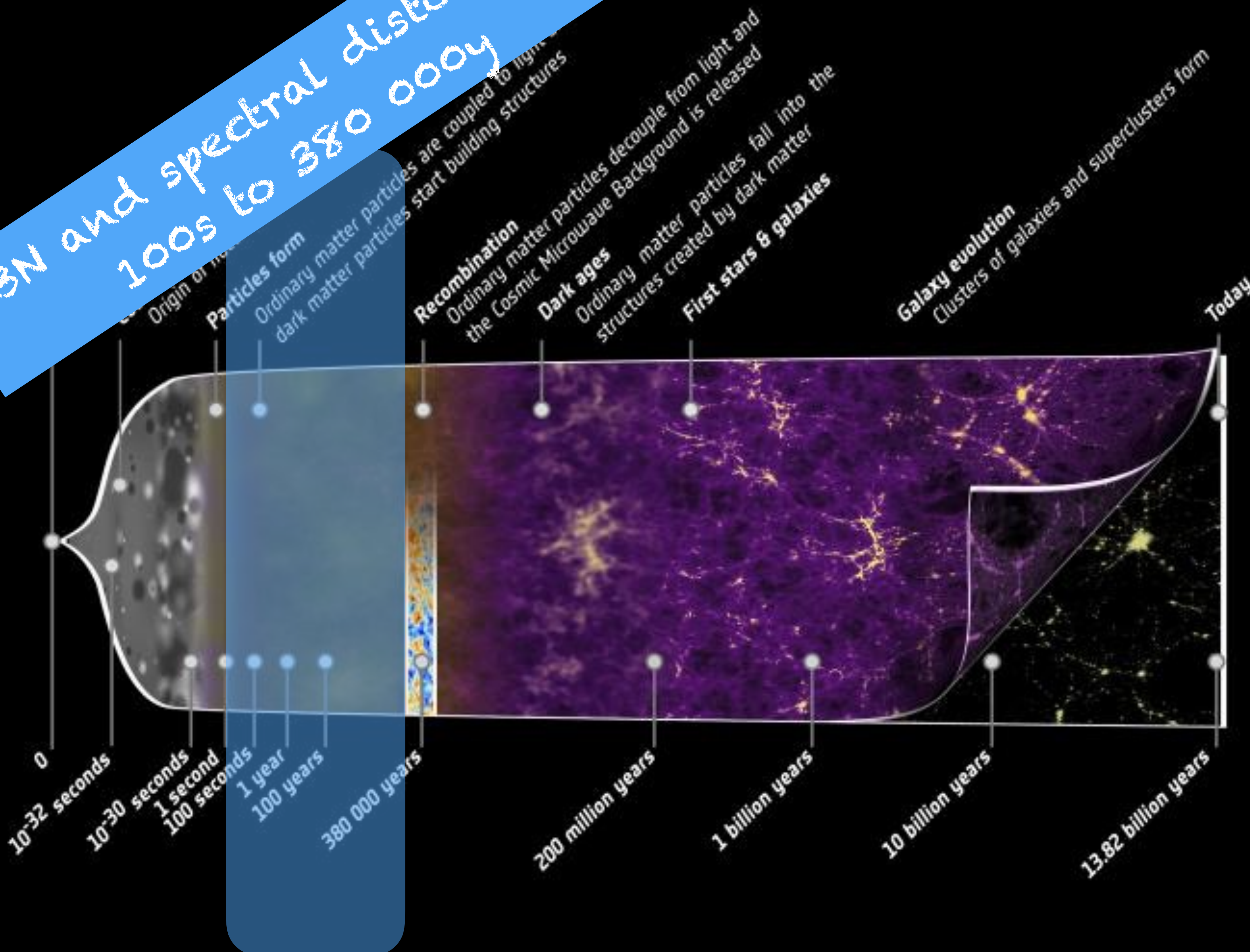
spectral distortions

BBN, CMB anisotropies



Cosmology can constrain many different lifetimes !

BBN and spectral distortions
100s to 380 000y



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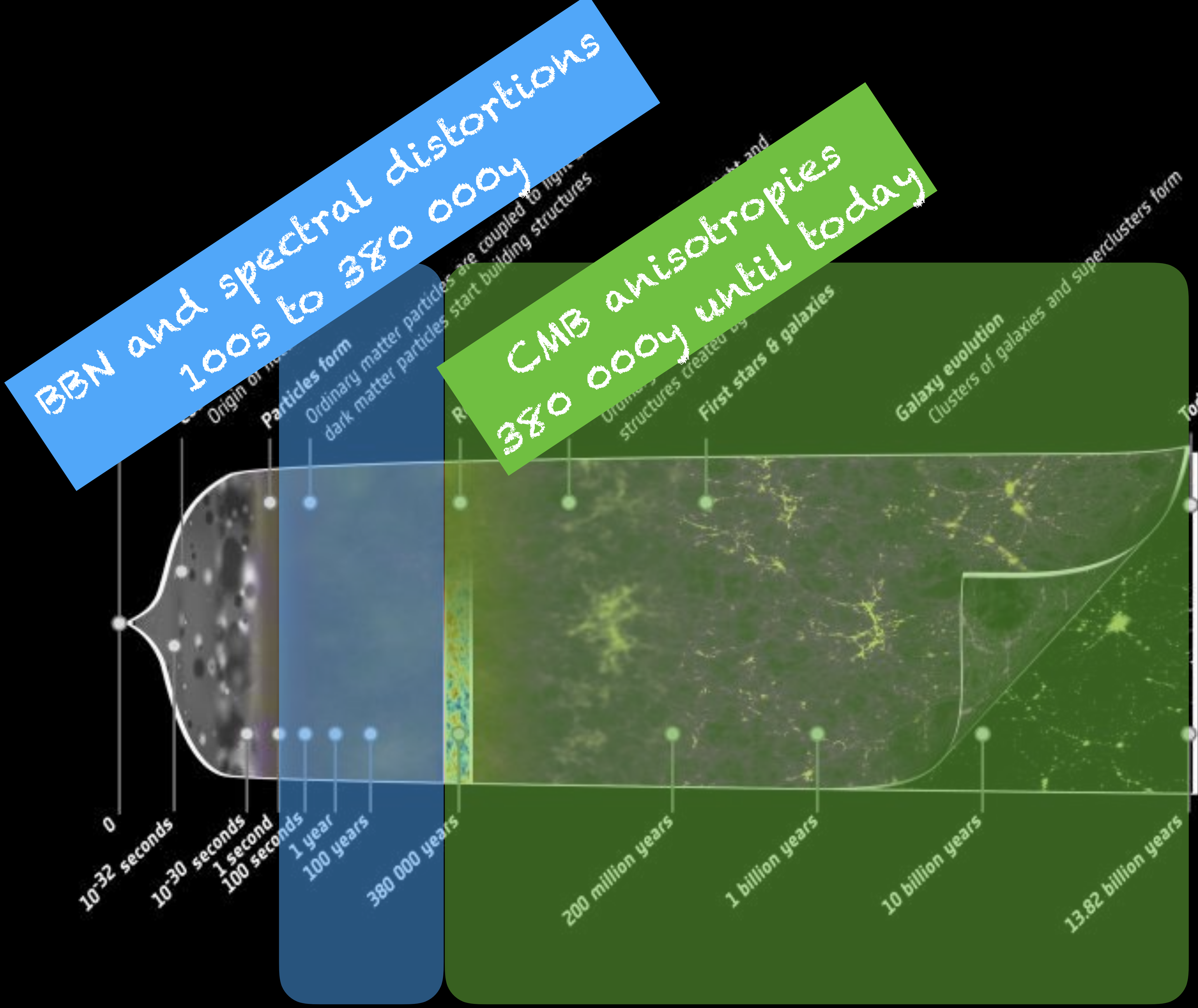

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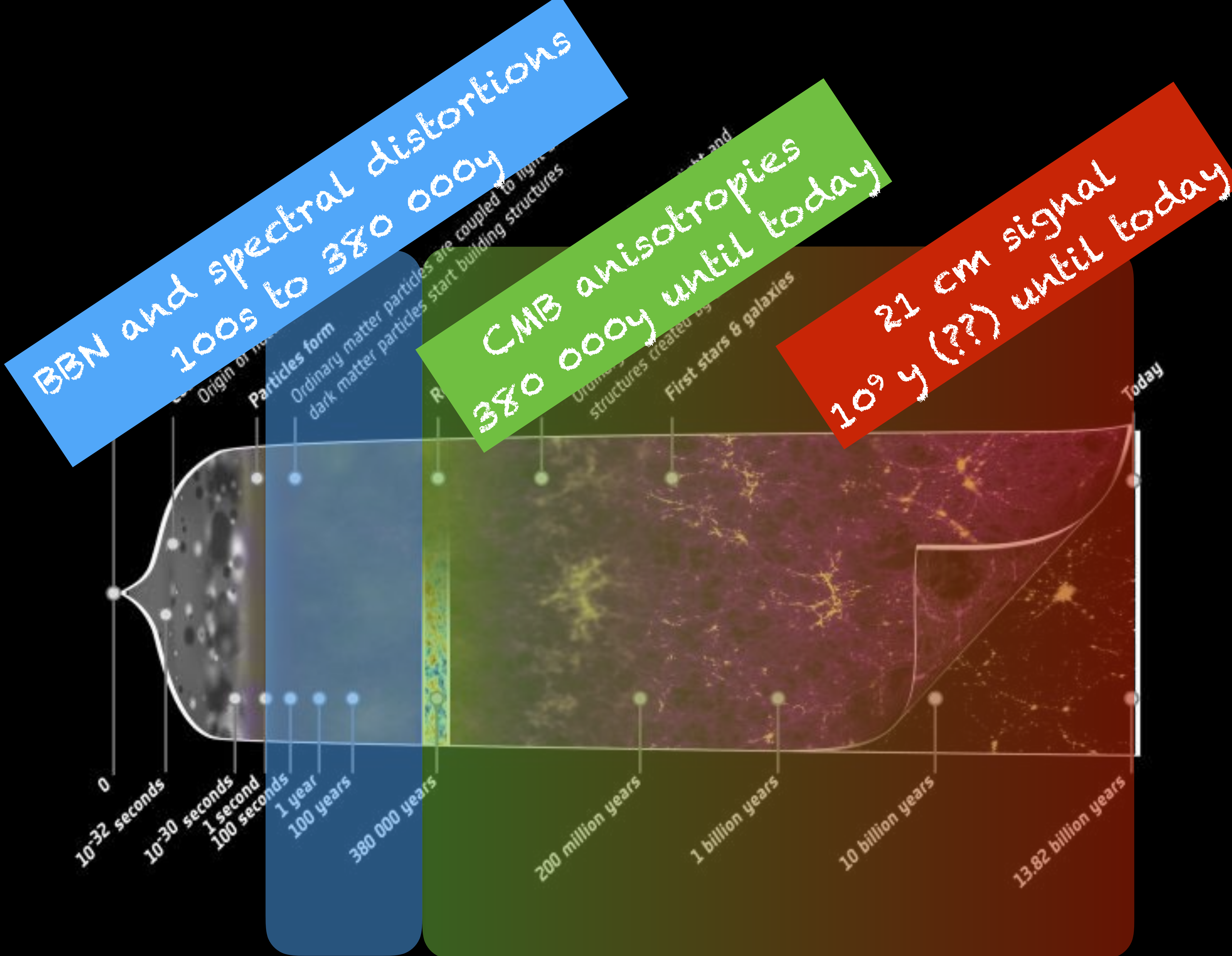

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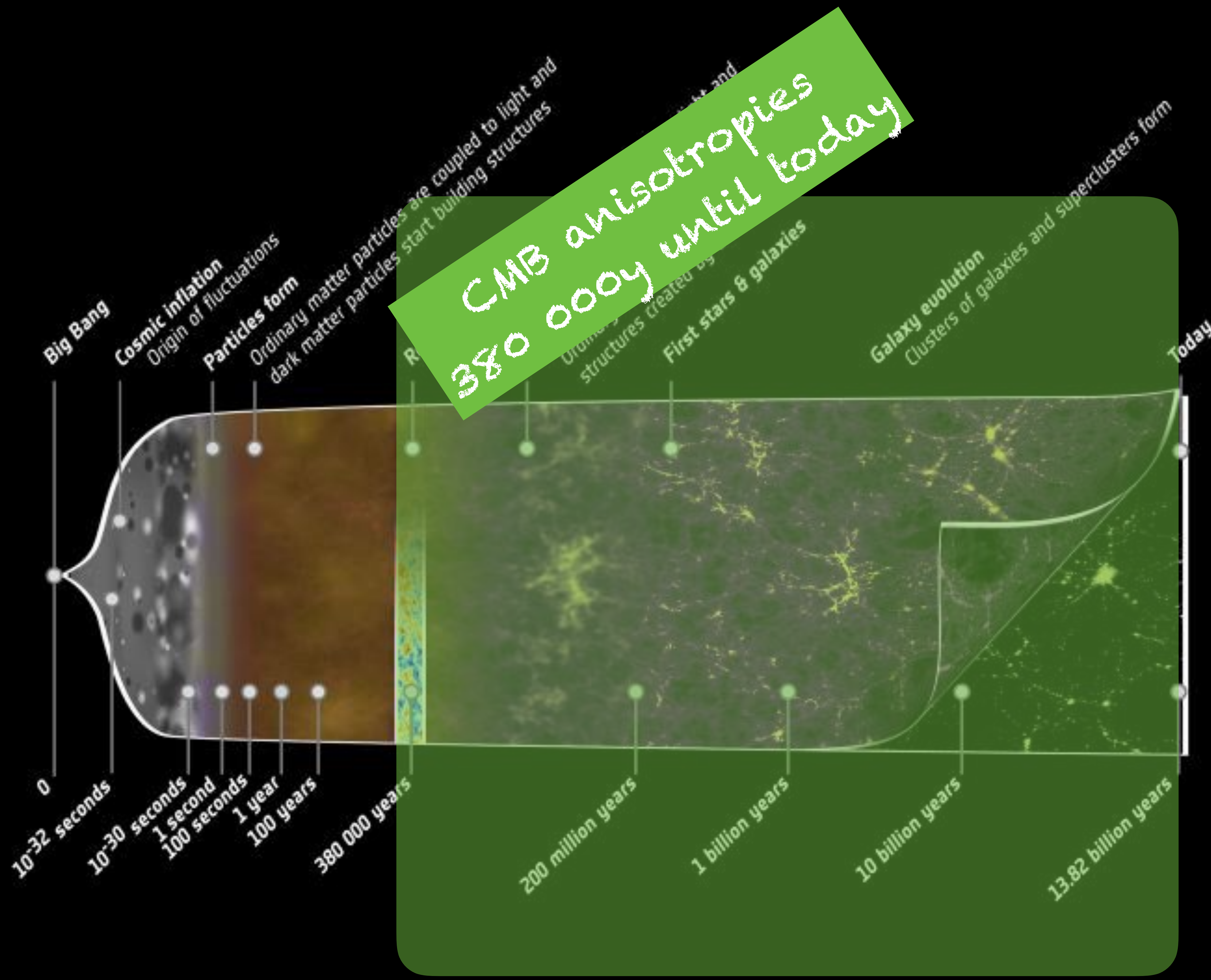
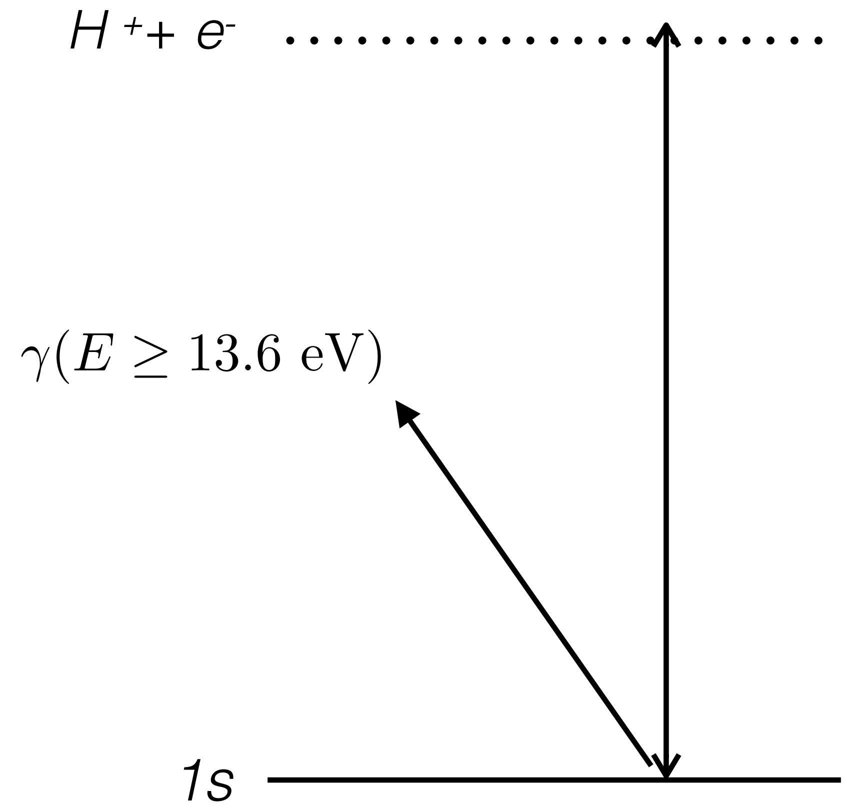


CMB anisotropies
380 000y until today
Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and
dark matter particles start building structures
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
0
10-32 seconds
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

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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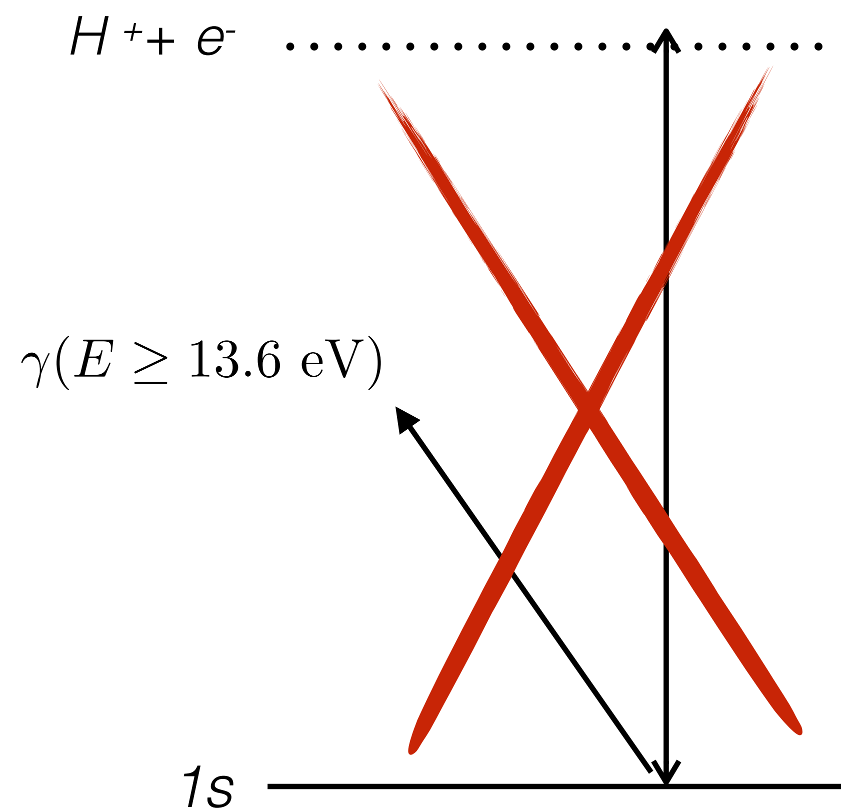

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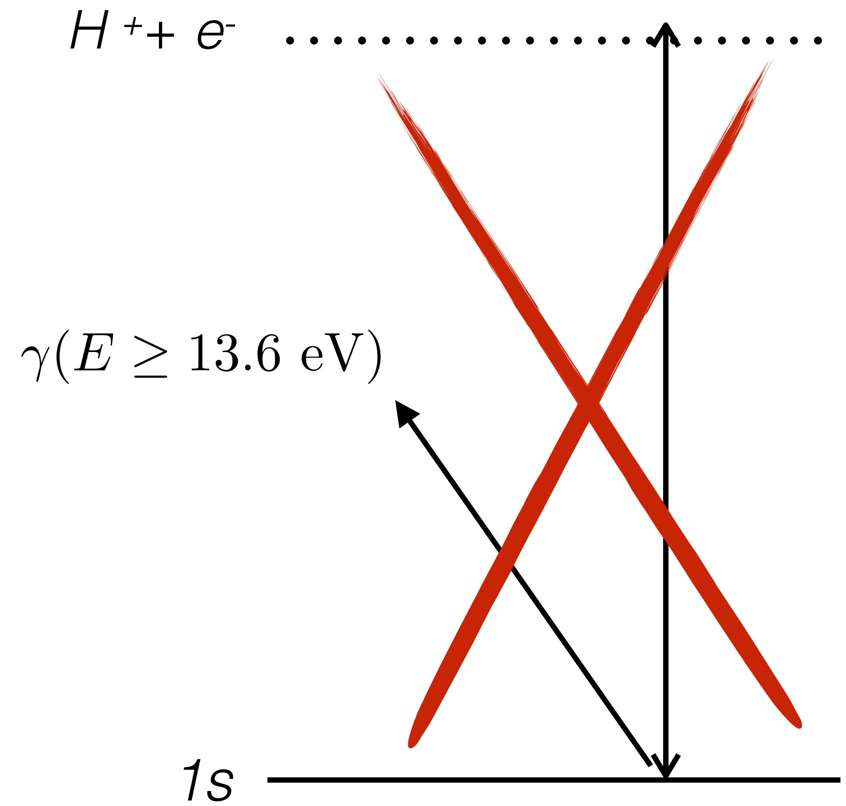
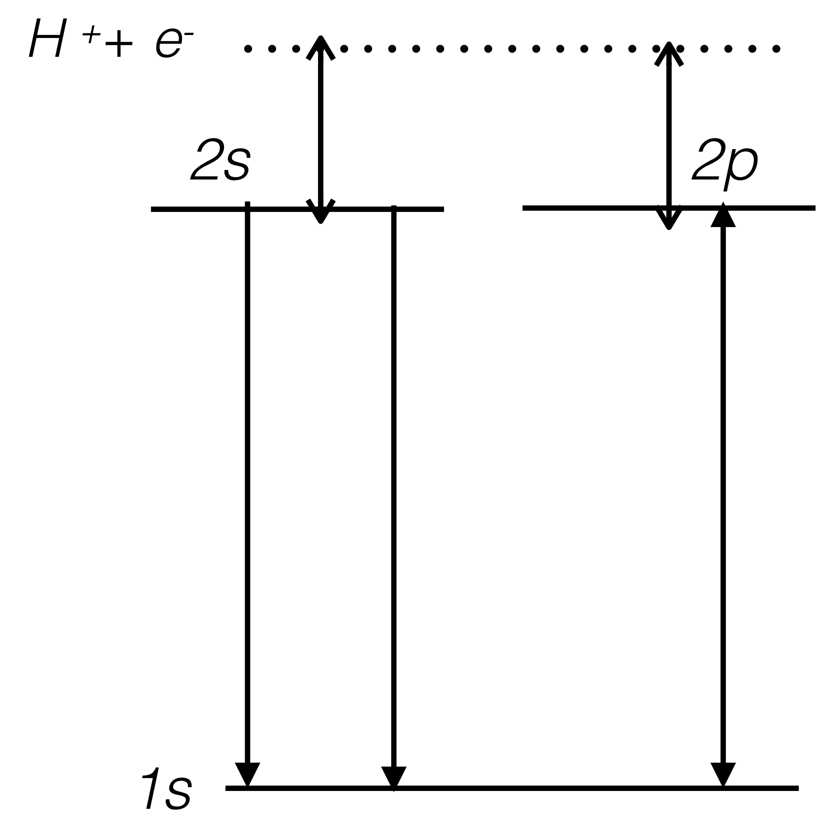


The « three-levels atom »

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

followed by

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

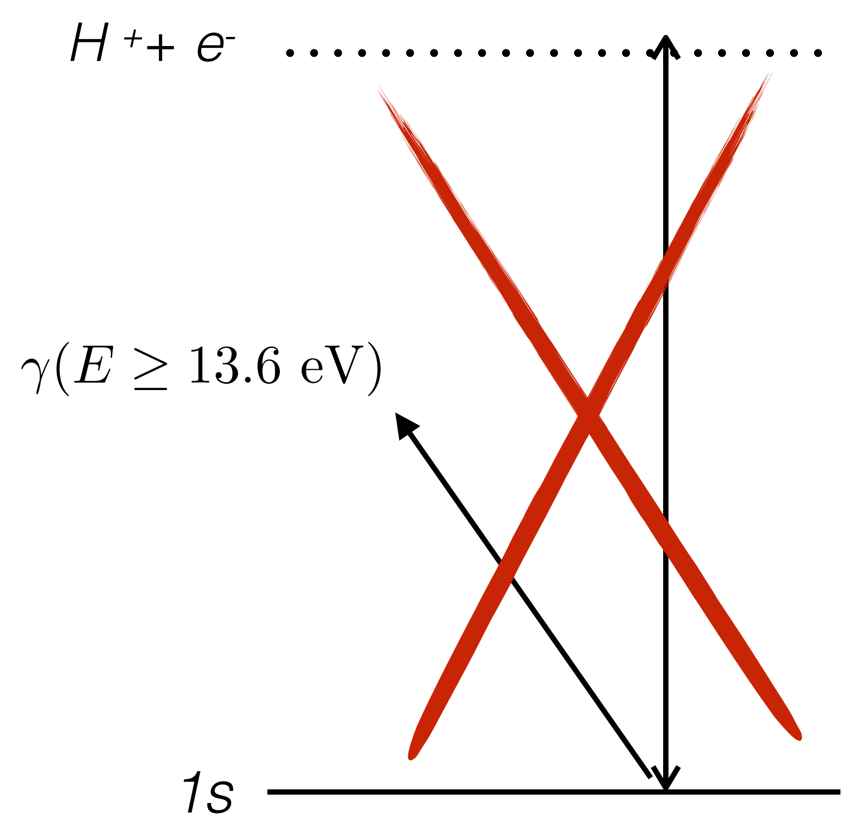


Rec… a nutshell

Peebles « case-b » recombination

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

…eads to the « saha » equation at equilibrium



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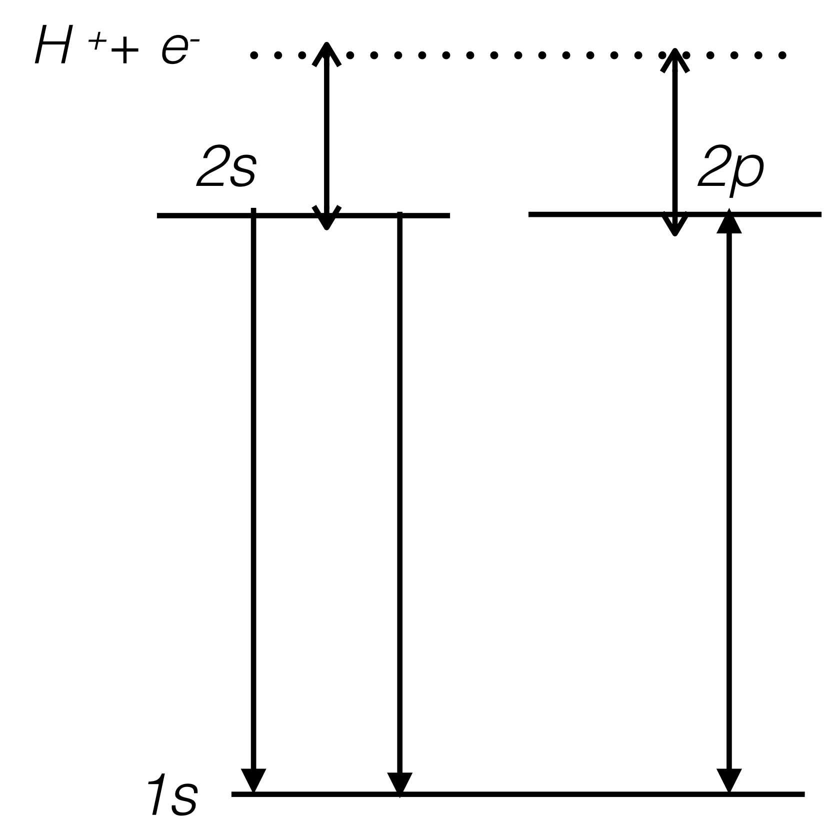
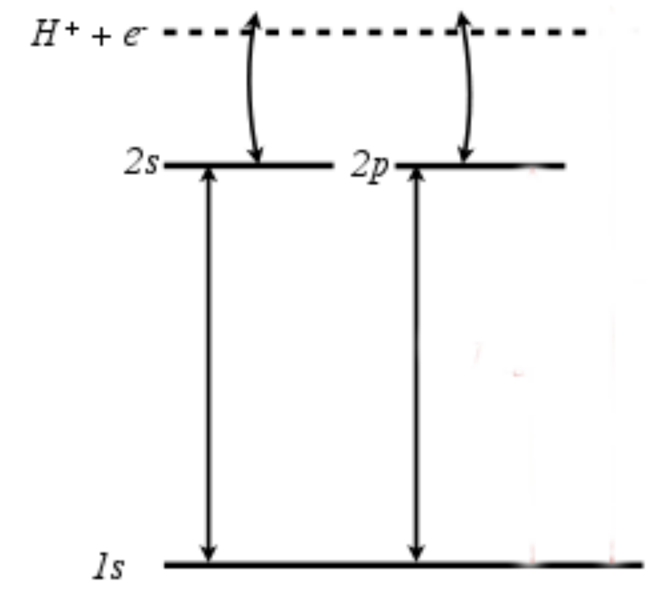


Evolution equations for x_e : the free electron fraction and T_m : the matter temperature

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

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



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

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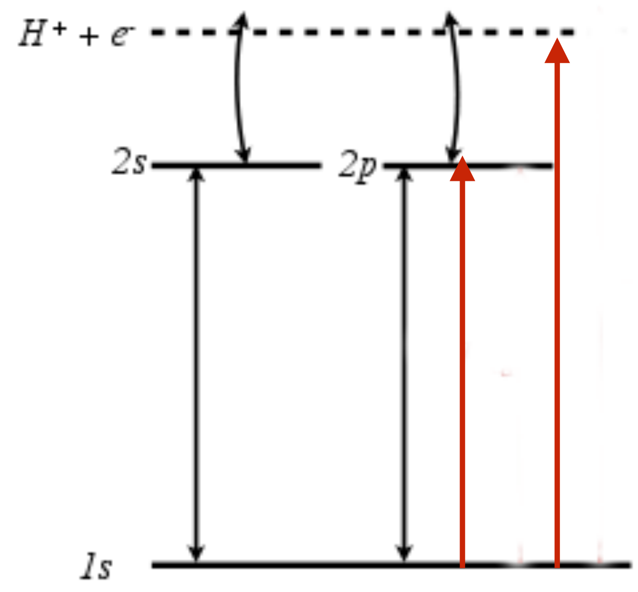

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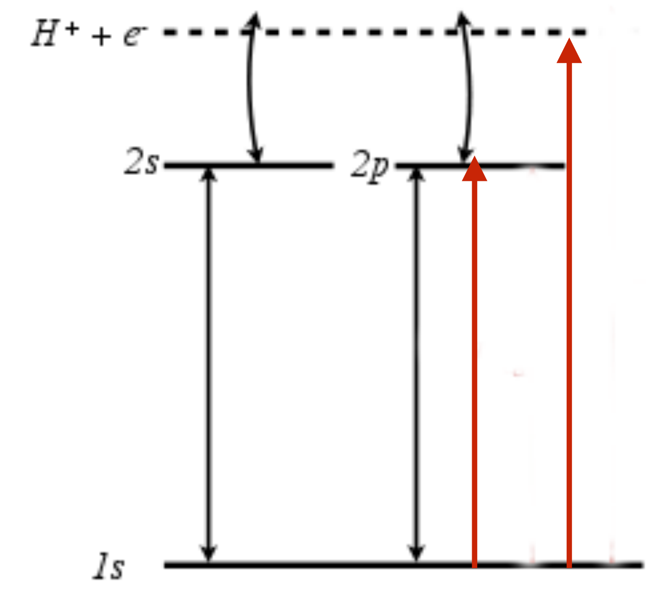

$$I_X(z) = I_{X_i}(z) + I_{X_\alpha}(z)$$

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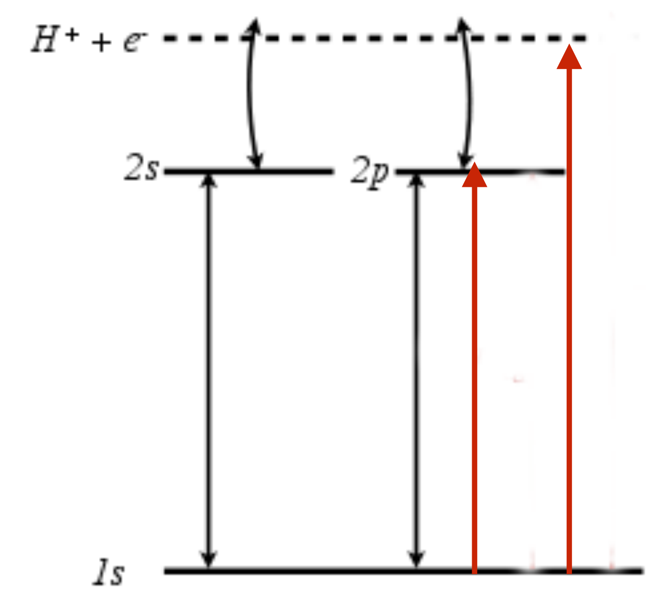
The energy deposited by the decay



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

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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. [arXiv:arXiv:0906.1197]

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

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

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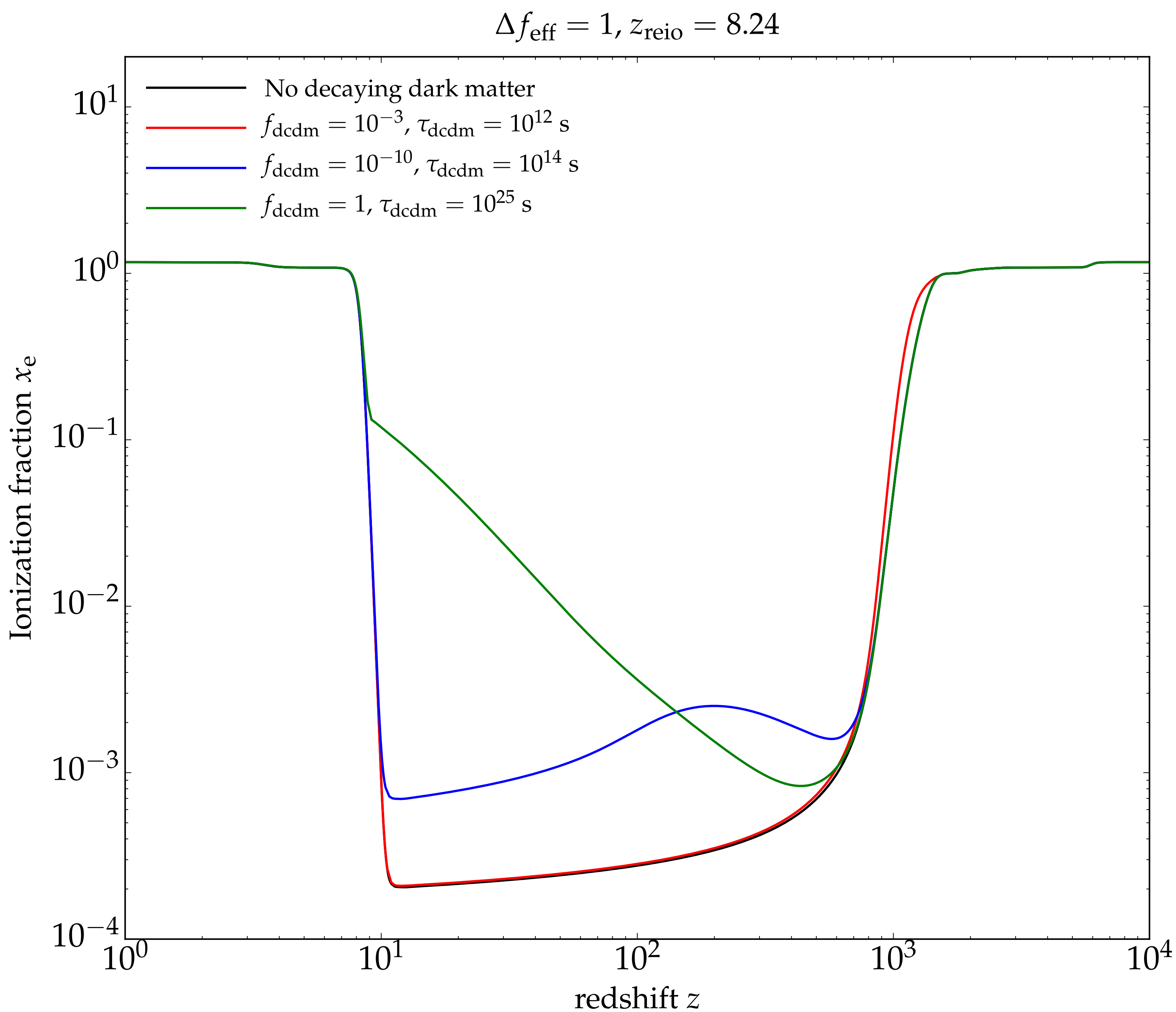
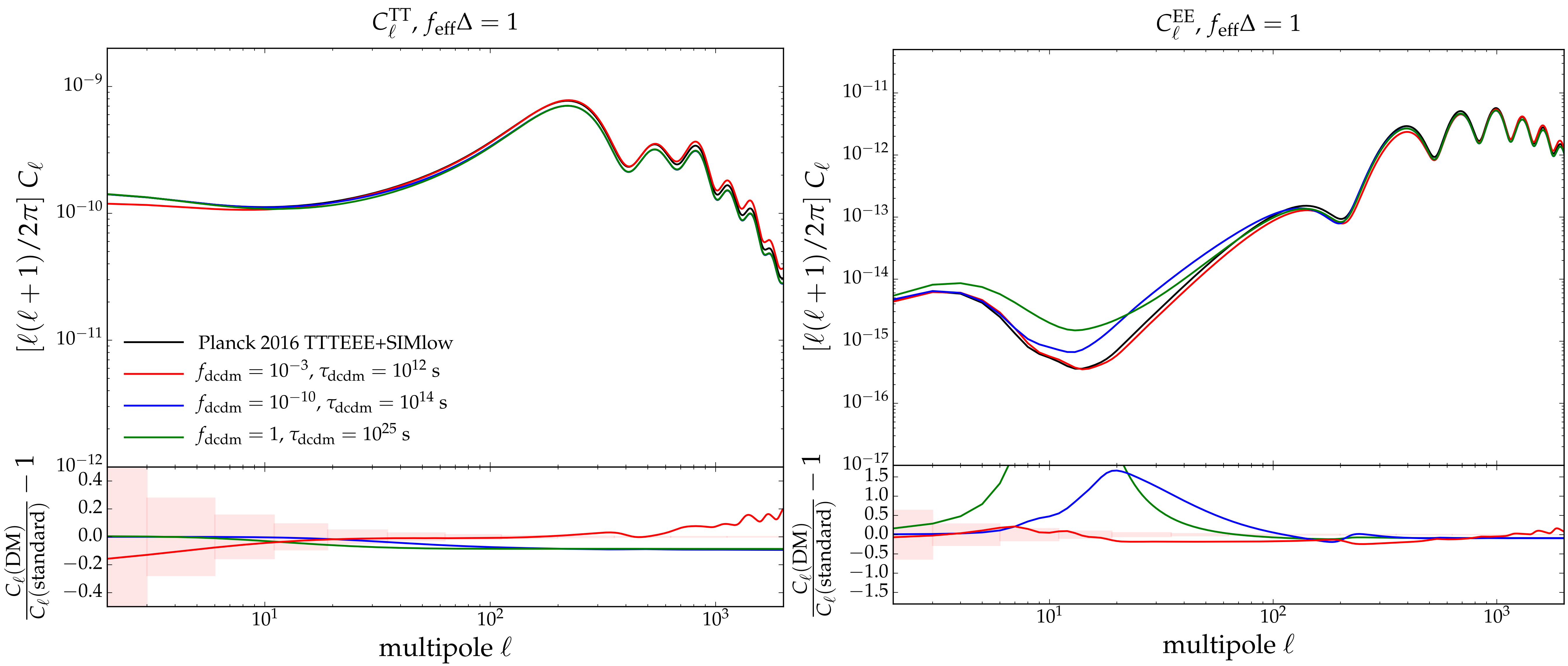
In practice, it depends on details of the particle physics and injection history.

The free electron fraction carries information on the time / amount of energy injection !



Many lifetime dependent effects on the CMB power spectra !

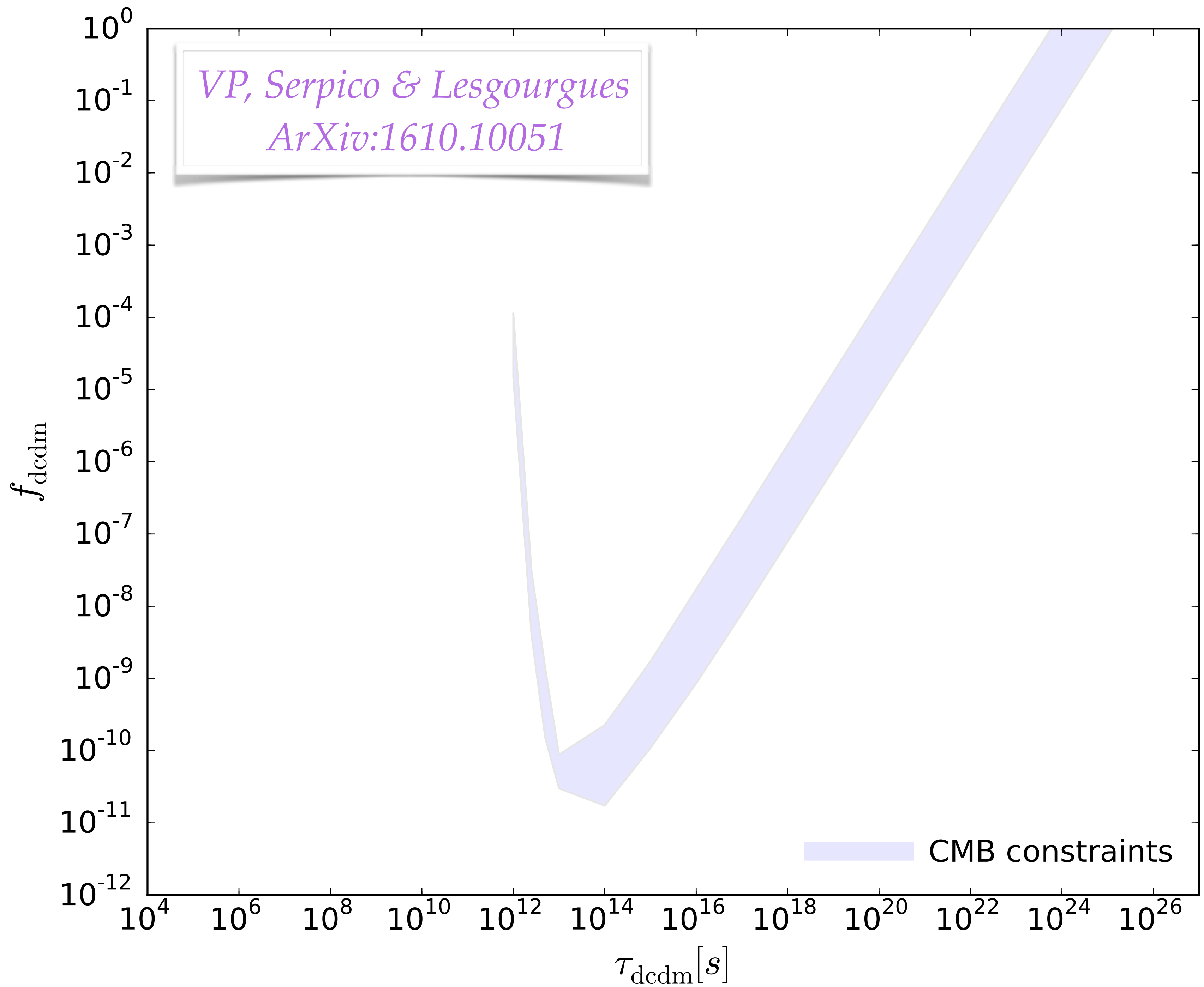


computed with CLASS by J. Lesgourgues, http://class-code.net

- Long lifetime : looks like reionization.
- Short lifetime: can have very peculiar behavior!

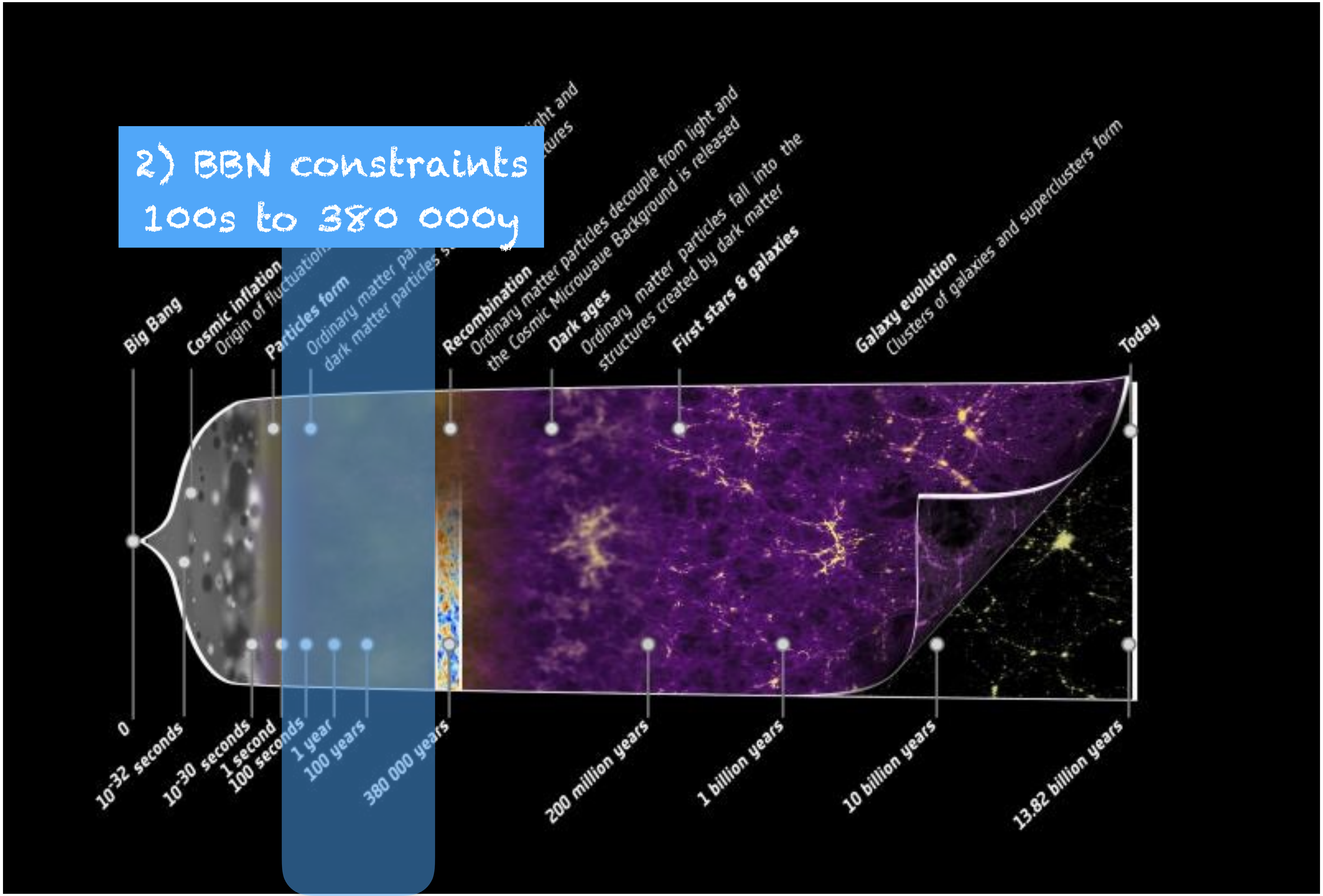
  => CMB anisotropy studies have a handle on the time / amount of energy injection.

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



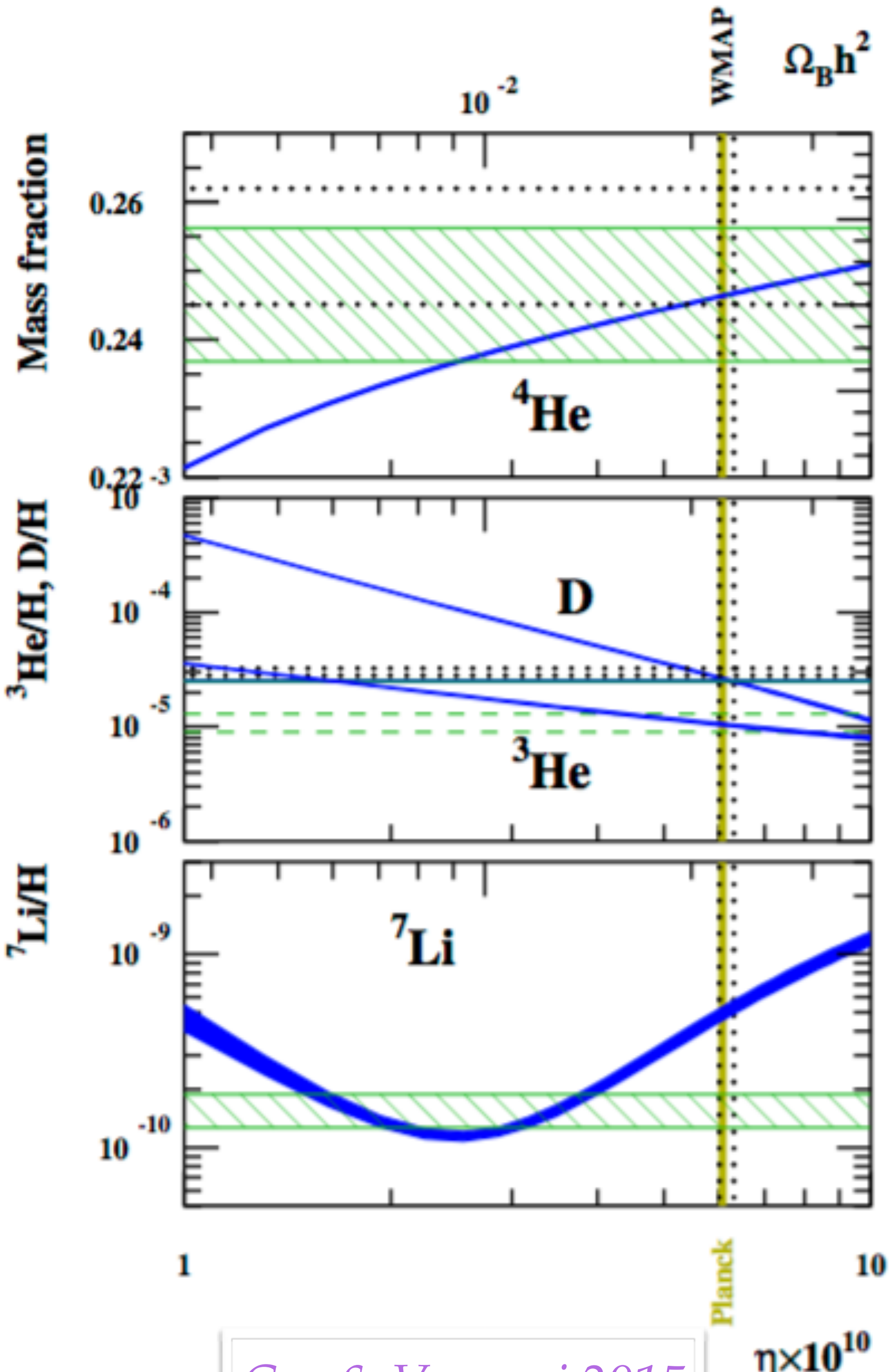
- Blue band : reflects difference between energy deposition efficiency.
- Results are reliable for mχ in [10^{3},10^{12}] eV whatever decay channel !

2) BBN constraints
100s to 380 000y



The light element abundances

BBN happened few min after BB



Coc & Vengoni 2015

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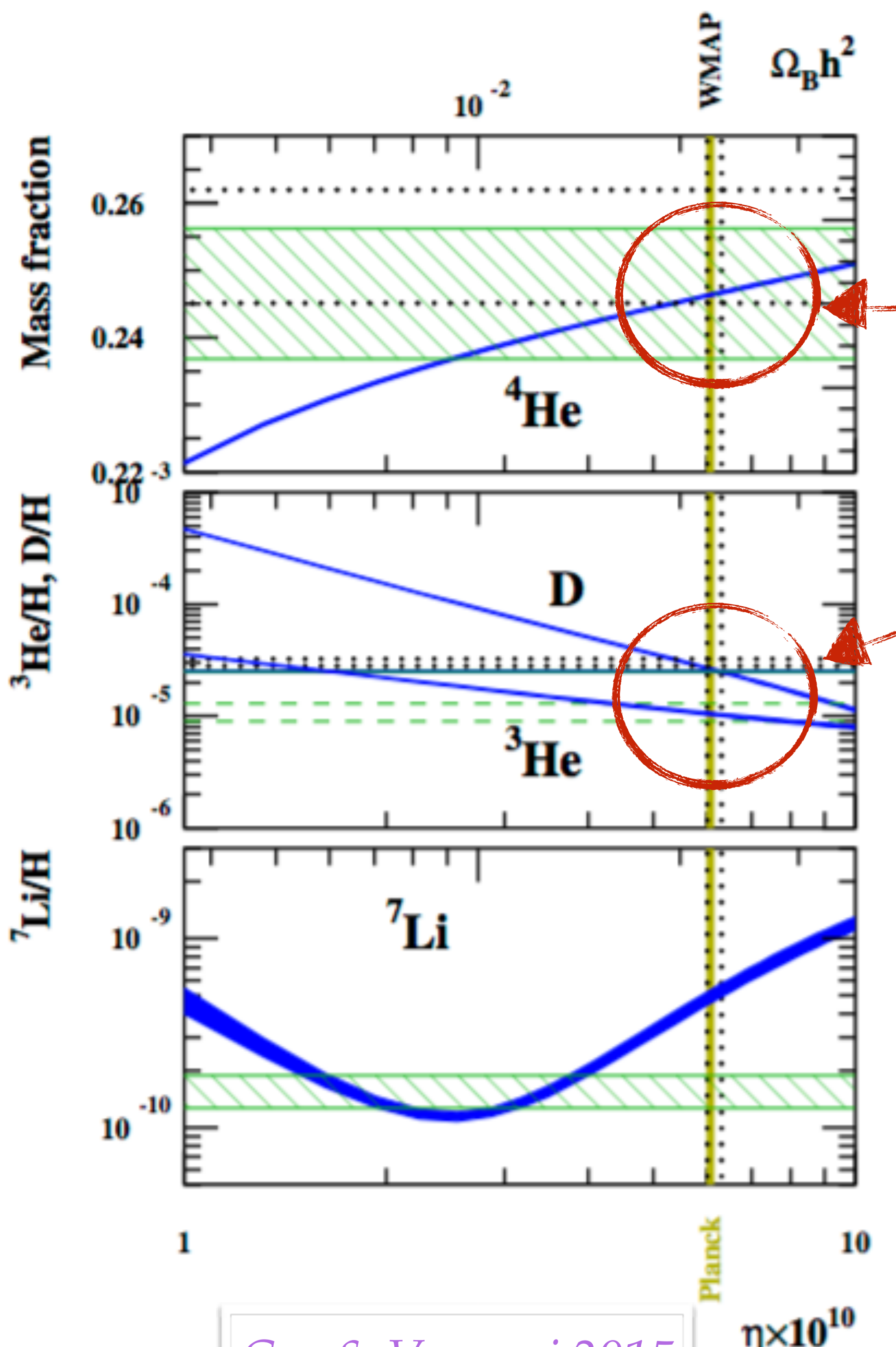

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For 3 nuclei :

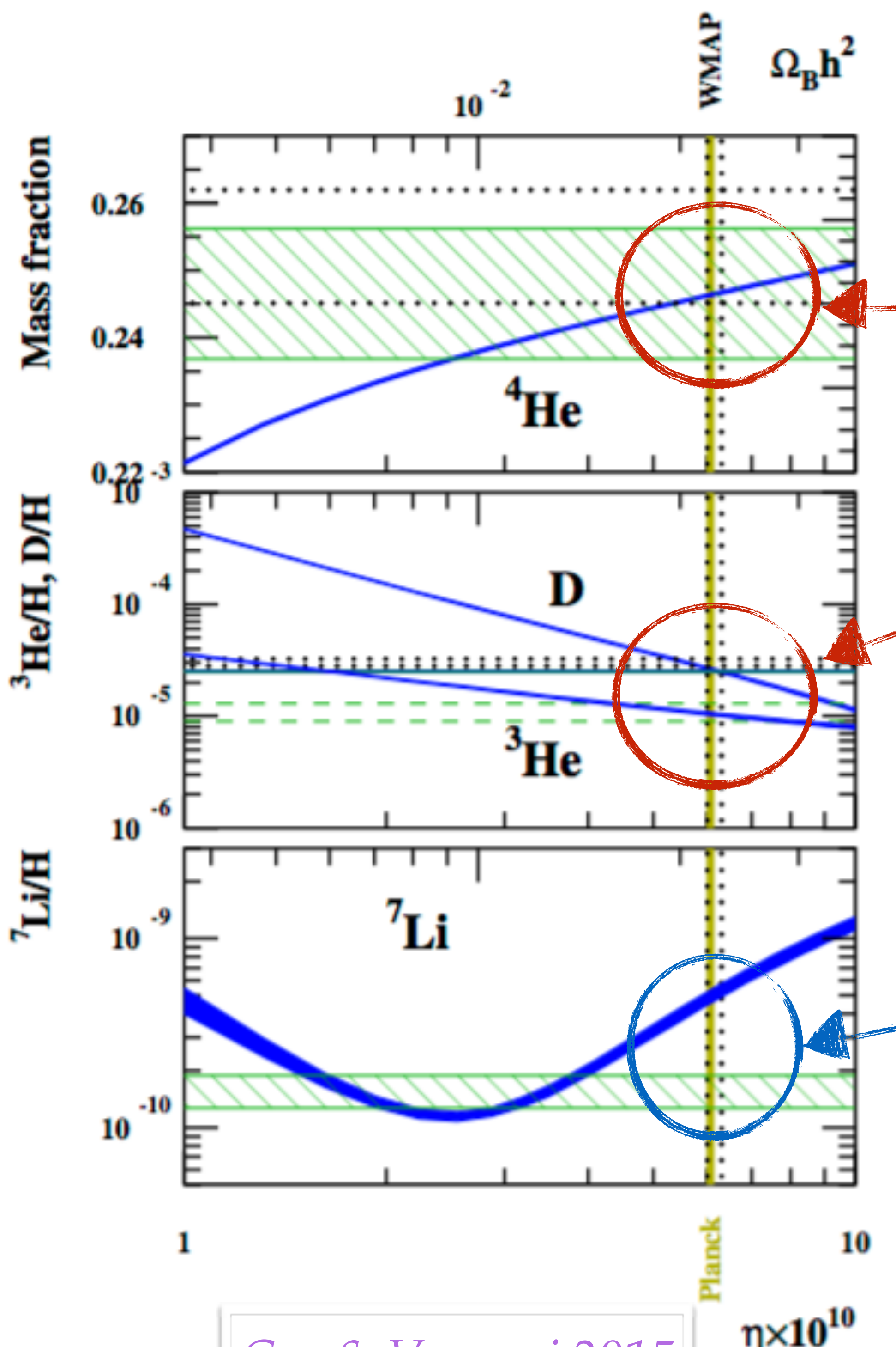
Strong observational constraints

$$Y_p > 0.2368$$

$$2.56\times10^{-5} < {}^2\mathrm{H/H} < 3.48\times10^{-5}$$

$$^3\mathrm{He/H} < 1.5\times10^{-5}$$

The light element abundances



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The Lithium problem :

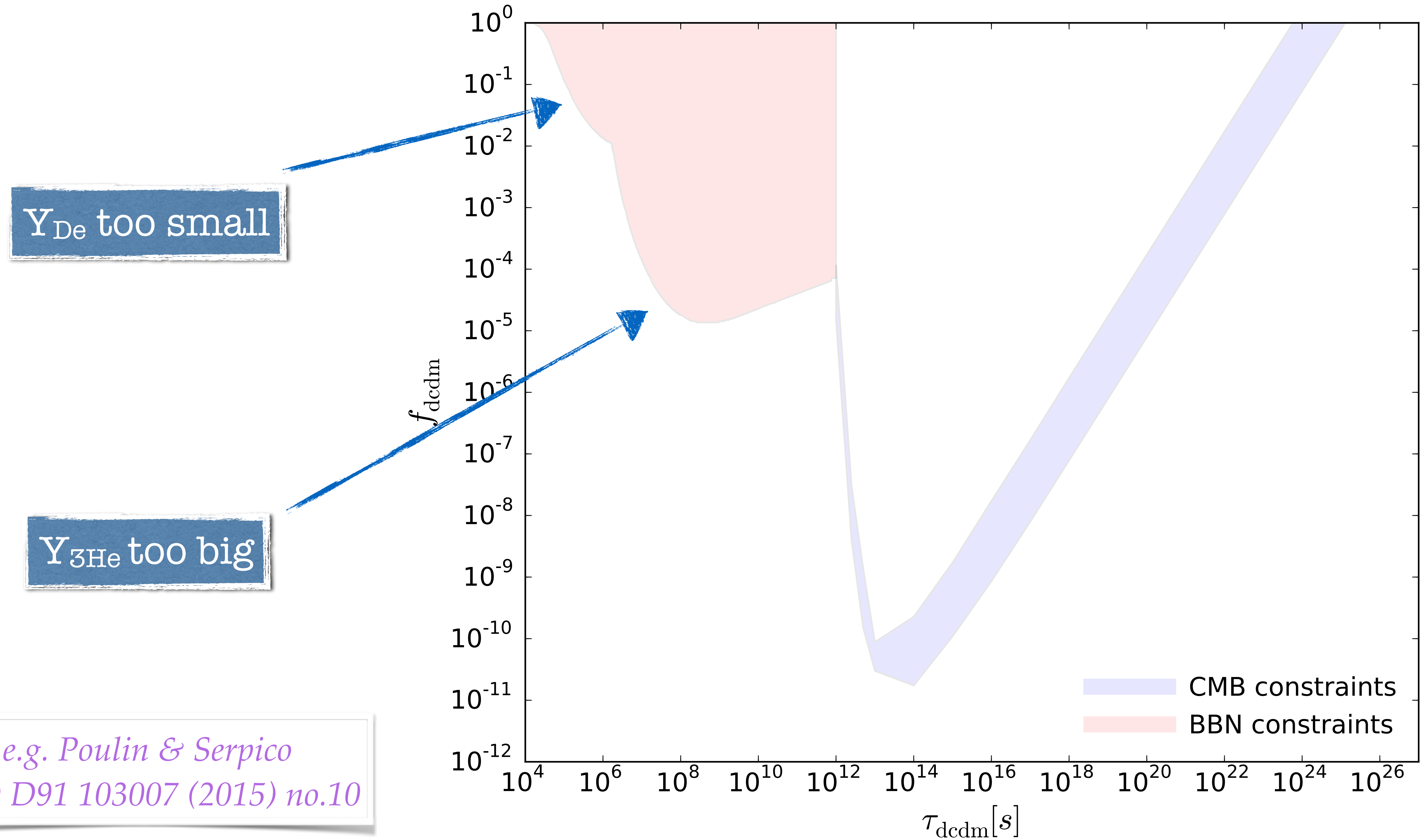
Overprediction of the ^{7}Li abundance

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

ignored today !

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

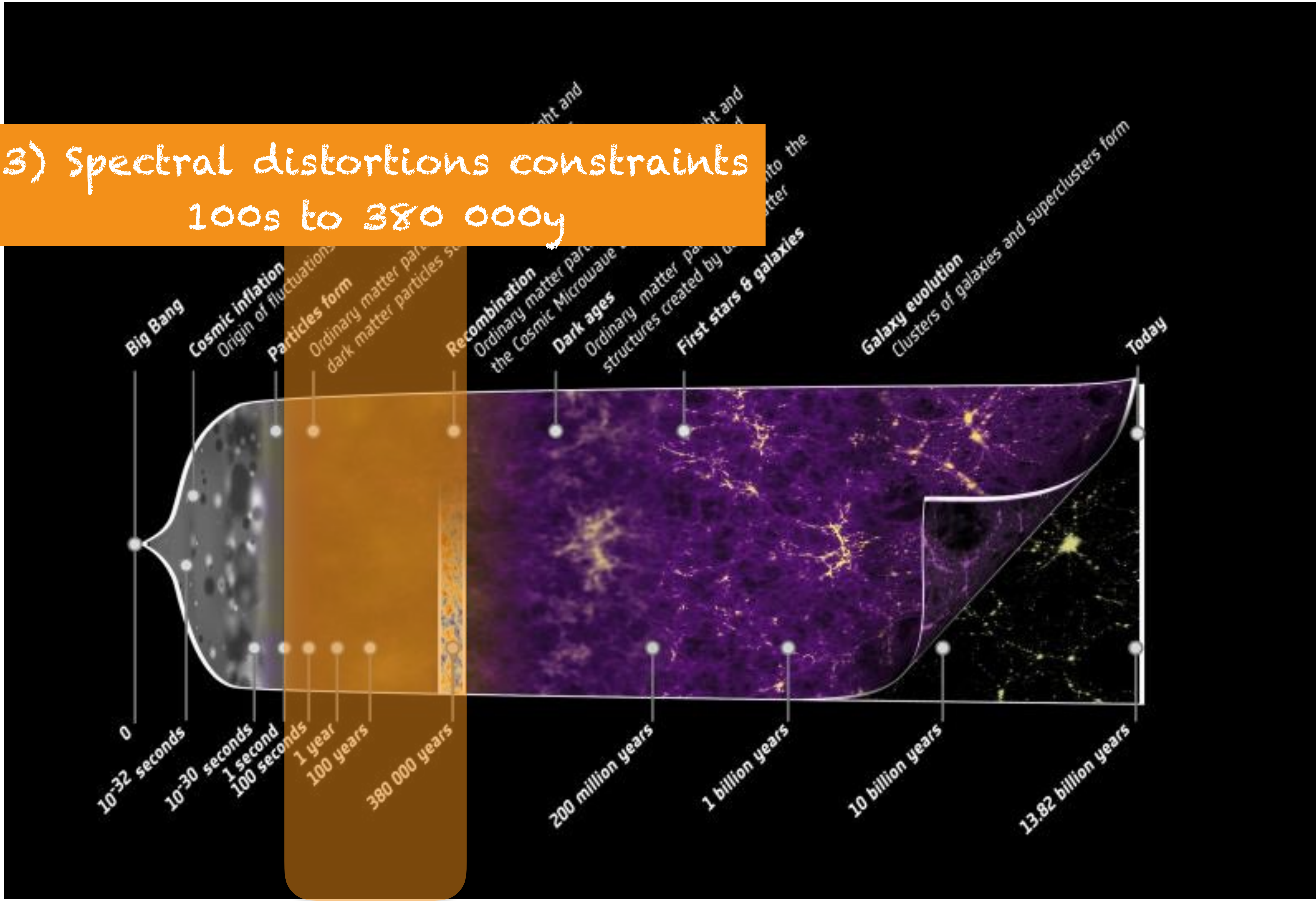
BBN very powerful at constraining $\tau = [10^4, 10^{12}]$s



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

⇨ Those bounds are very conservative !

3) Spectral distortions constraints
100s to 380 000y



μ and y spectral distortions

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

Following injection of photons/electrons, scattering processes should thermalize the distribution.
If those processes go out of equilibrium, in full generality:

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

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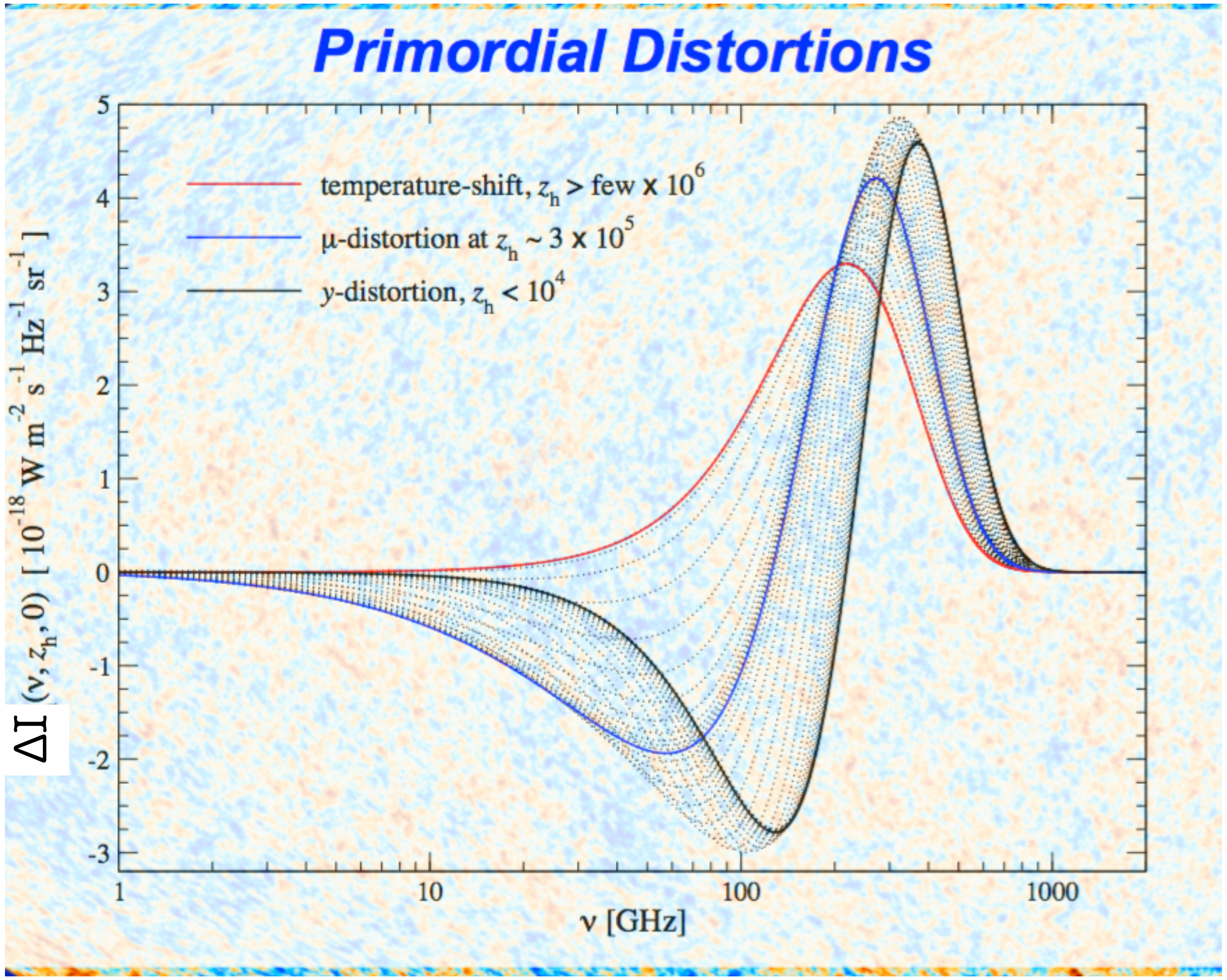


μ = creation of a chemical potential

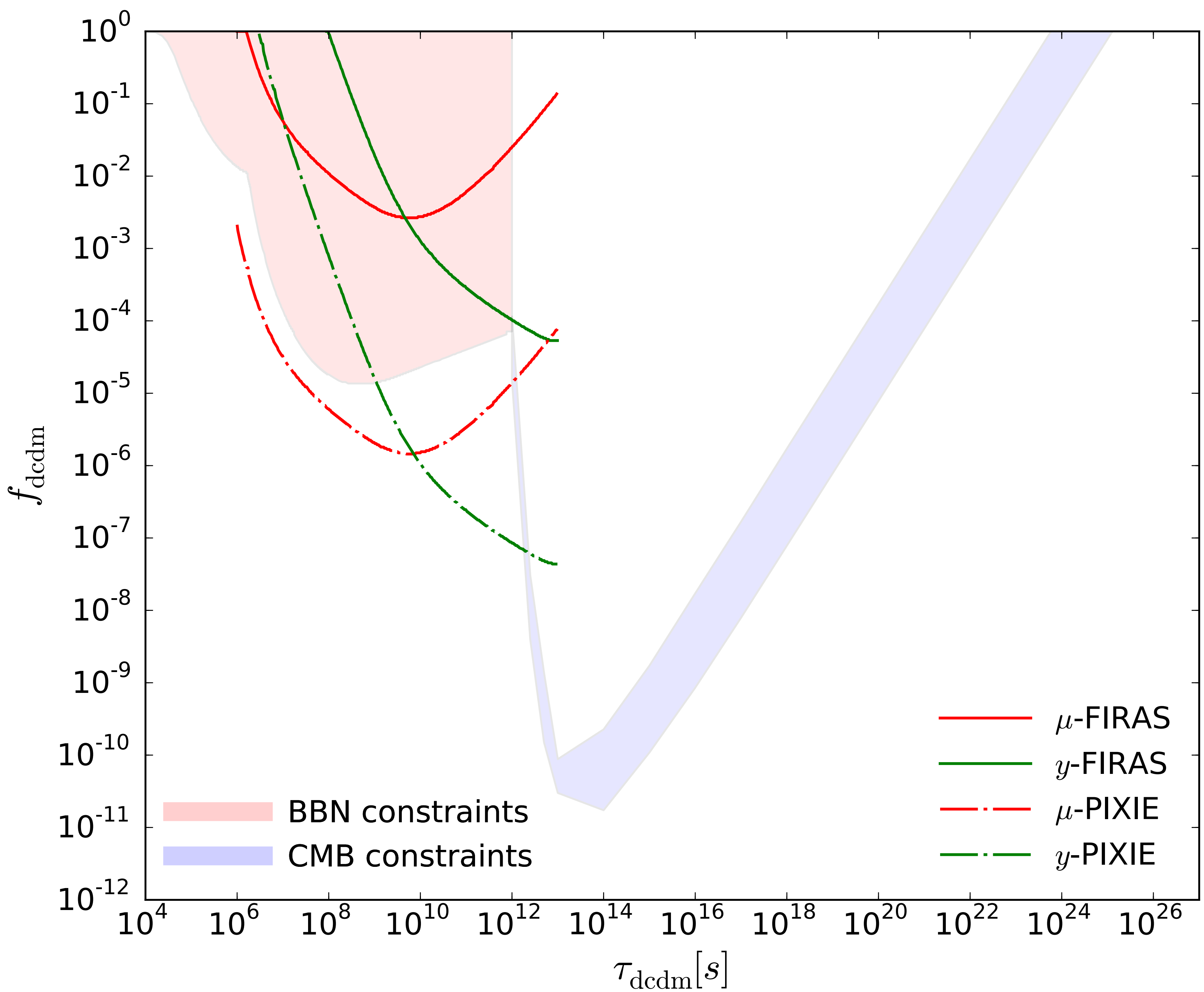
y = compton heating (or cooling!) of the CMB gas

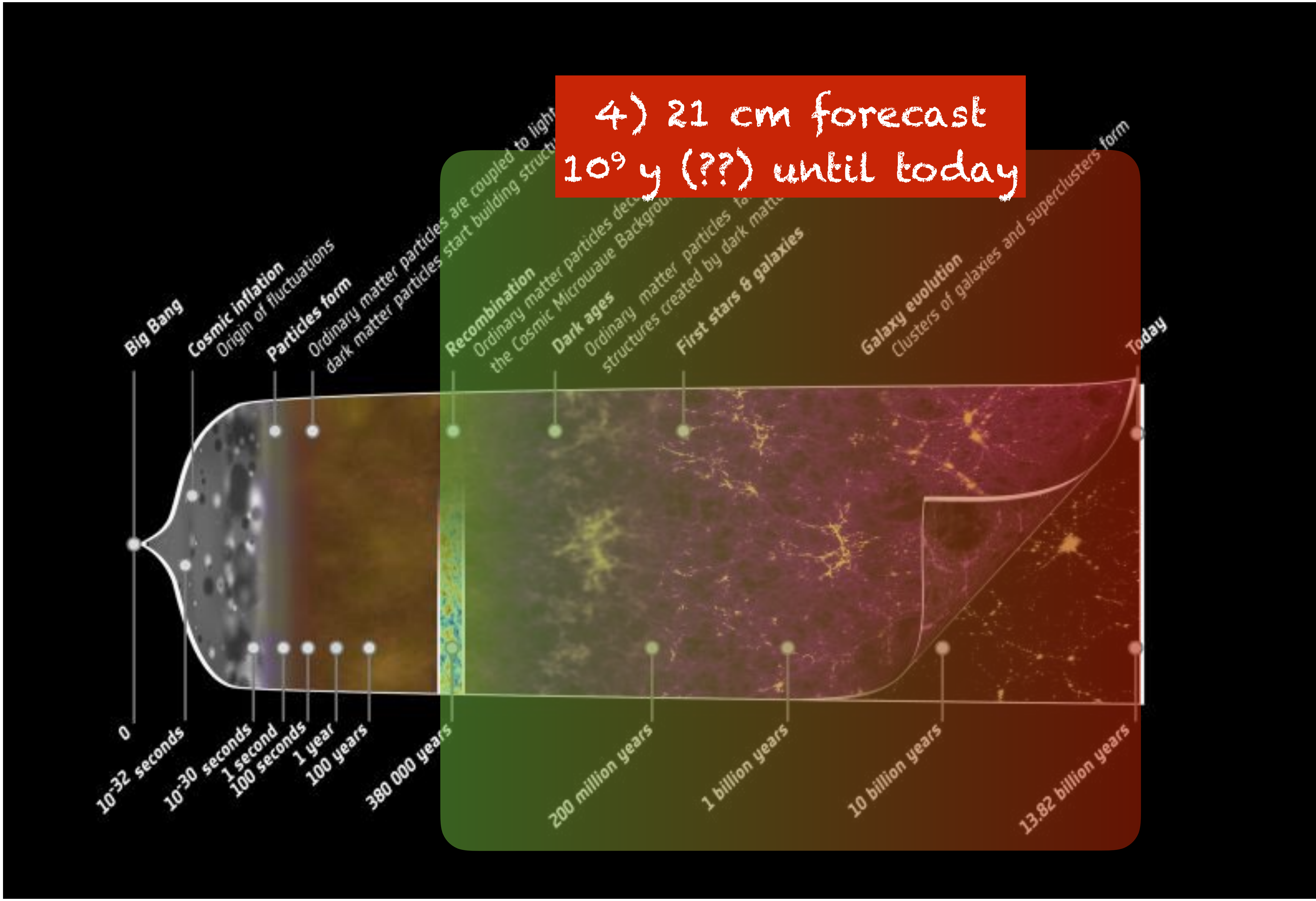
Intermediate distortions probe the time dependance of the energy injection history

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

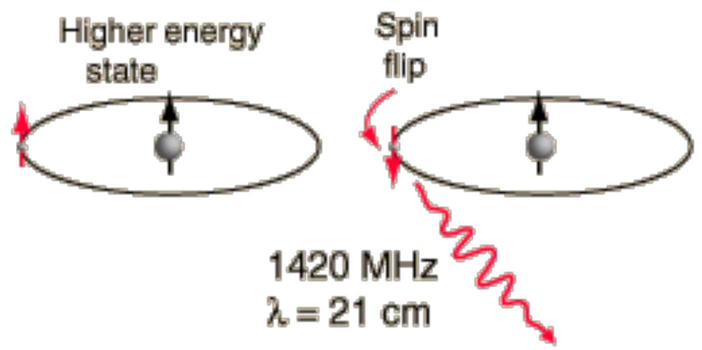
CMB vs BBN vs spectral distortions

Cosmology can constrain a very broad range of lifetime !!




4) 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



- 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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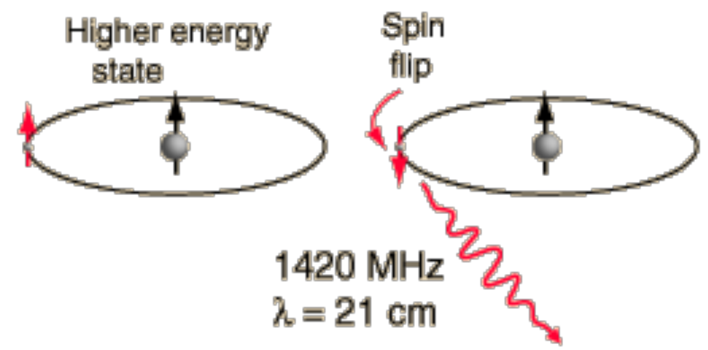

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Exc. = Des-exc.

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

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

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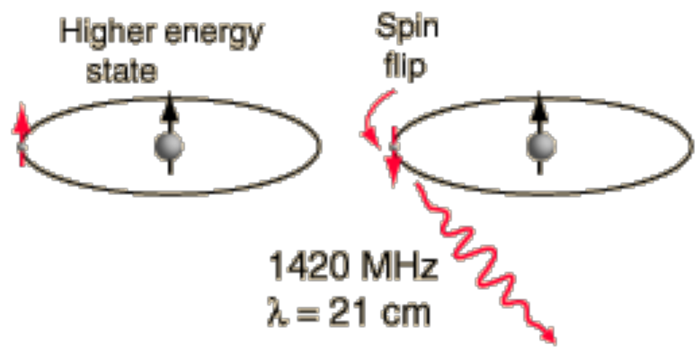

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Compare patch of the sky with/without hydrogen clouds:

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

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

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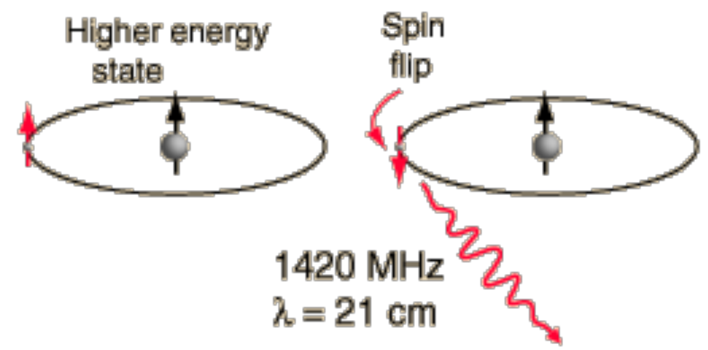

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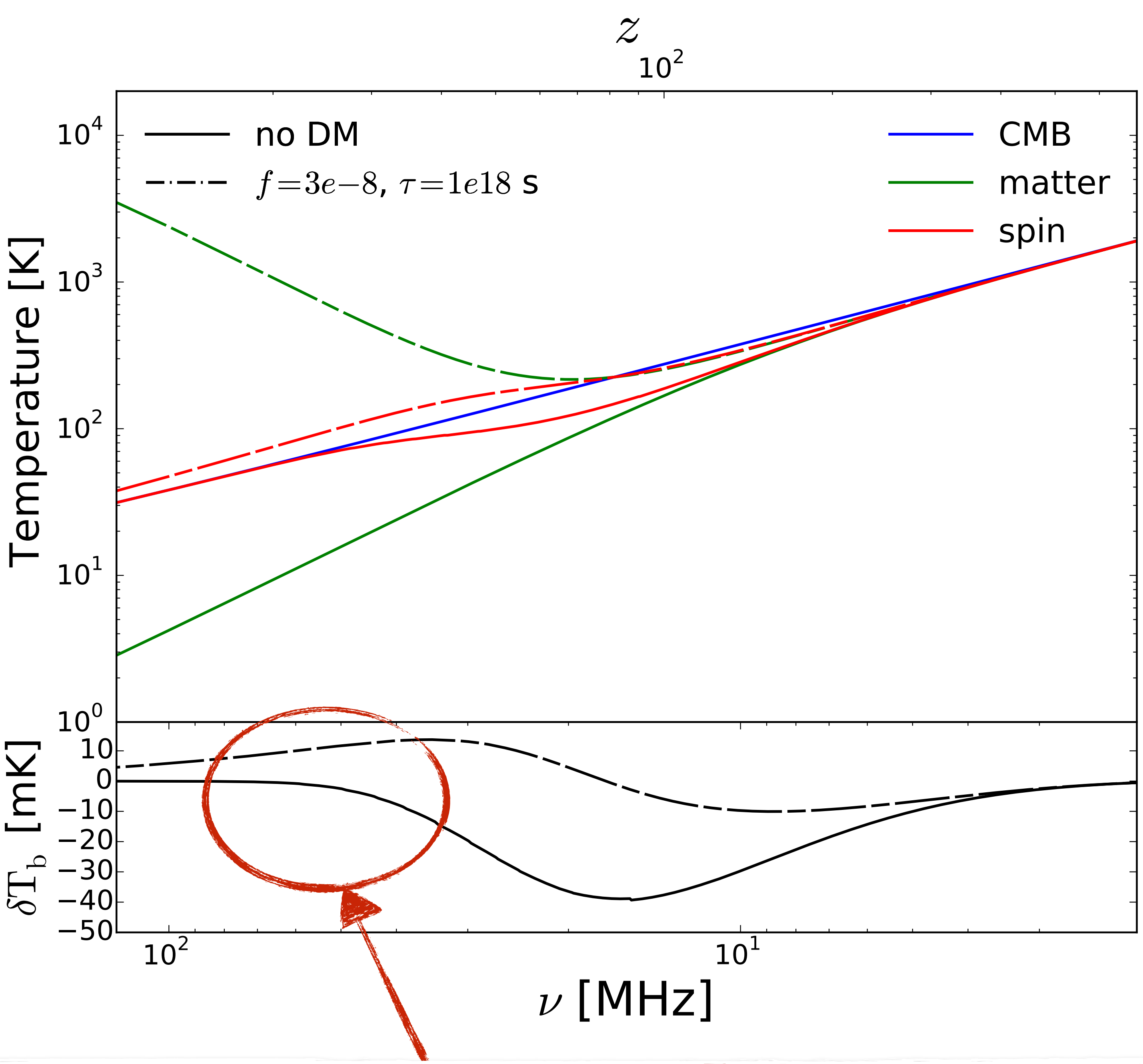
Difficulty = Huge astrophysical uncertainty, one trick :
SKA will be able to measure δT_b = 5-10 mK up to z= 20/25 (ν = 60 MHz)

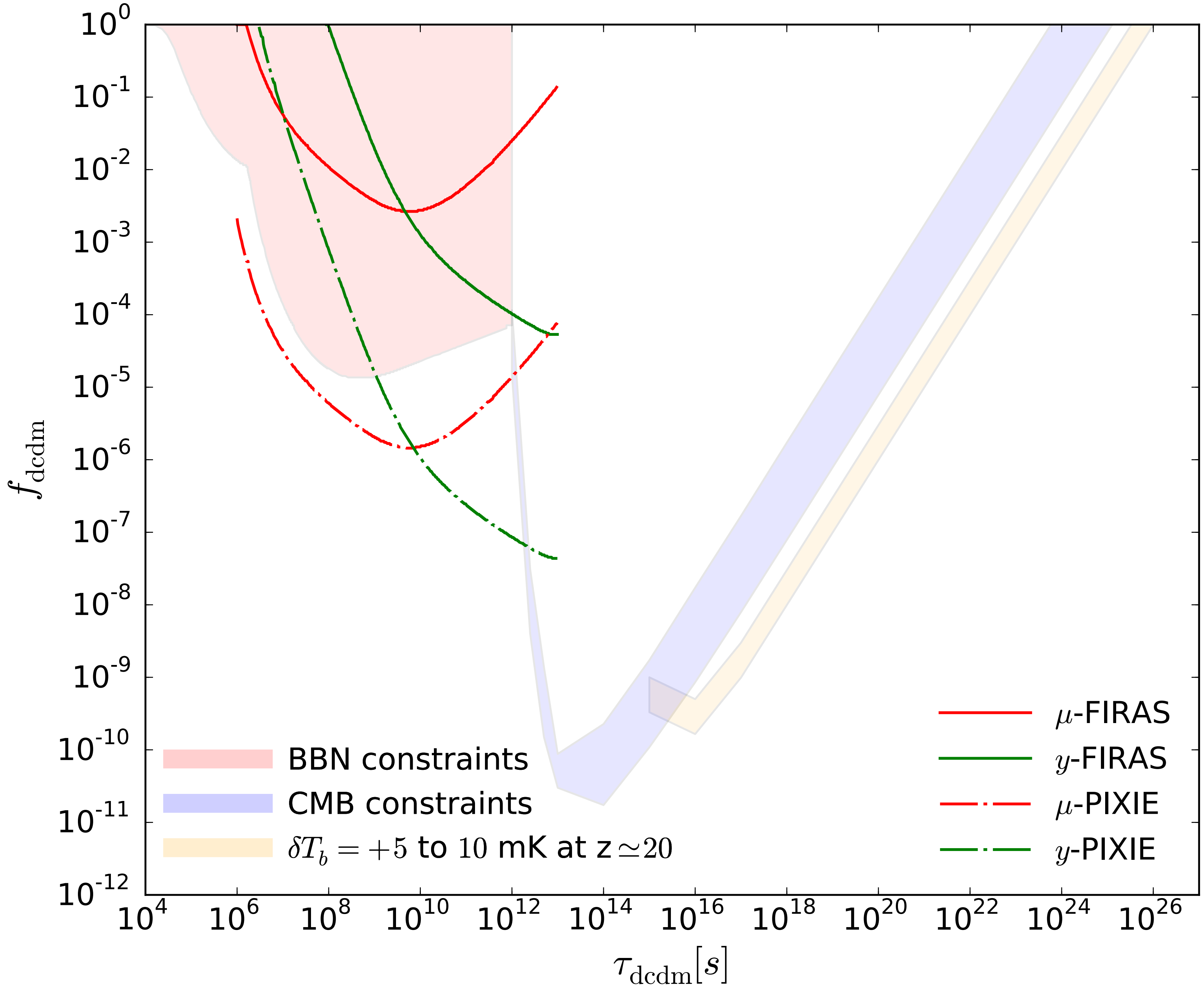
We neglect stars : valid until z ≈ 15, still in the SKA range !



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.

- 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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- Some hope : the dark ages, when no stars were there.

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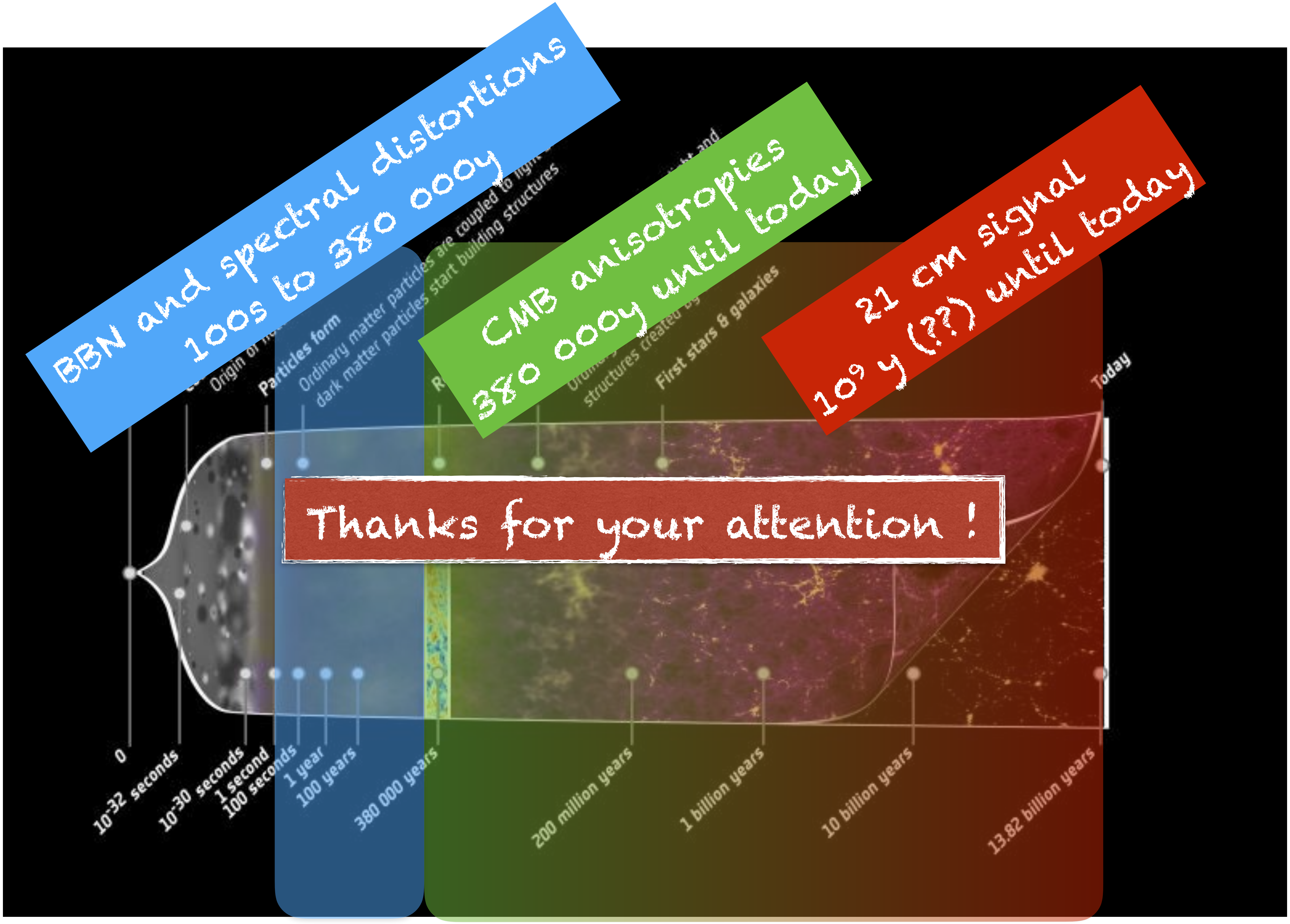
Stay tuned ! Many results to come !


BBN and spectral distortions
100s to 380 000y
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380 000y until today
21 cm signal
10⁹ y (??) until today
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First stars & galaxies
Today
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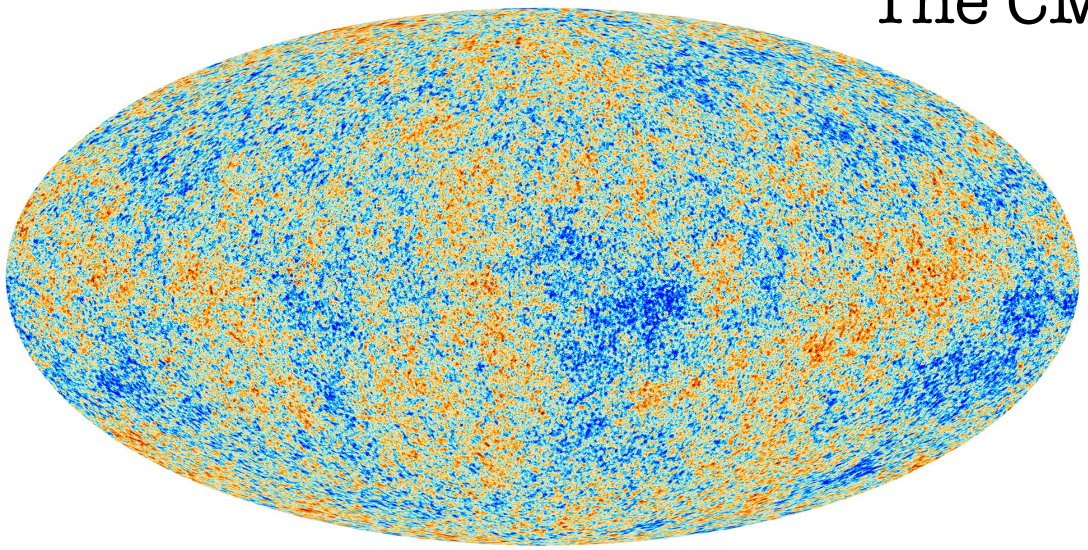
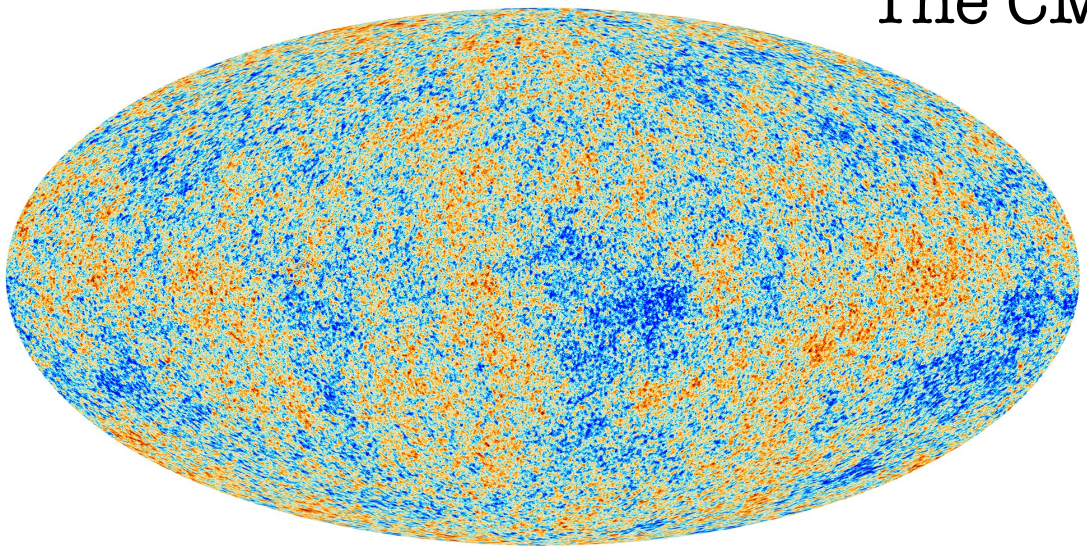
Backup slides



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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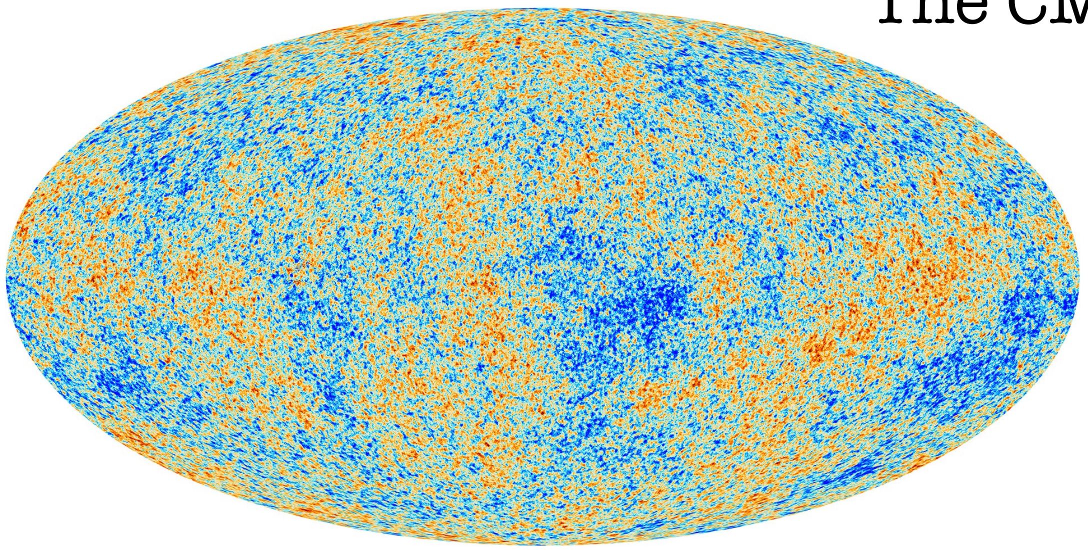

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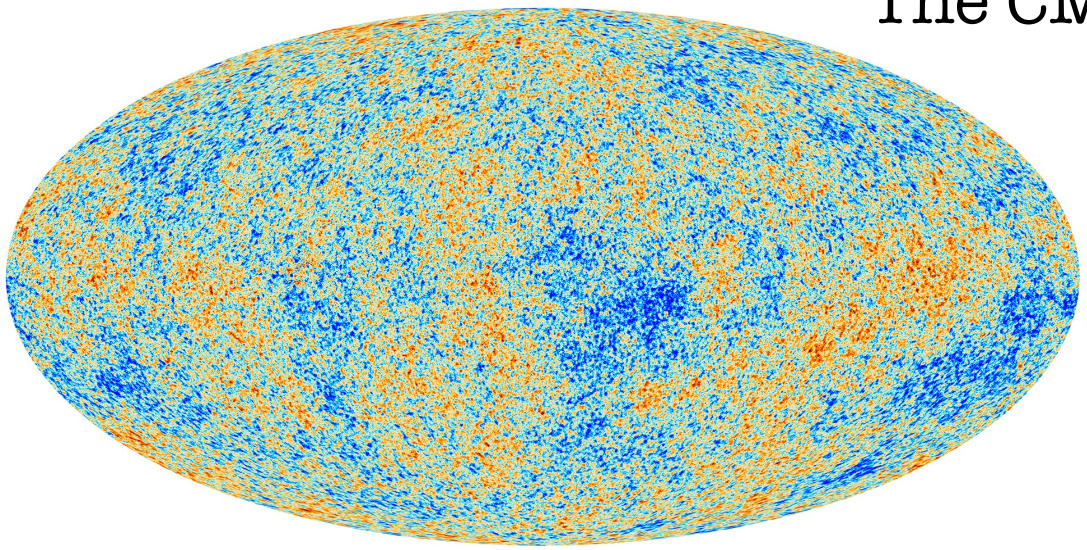

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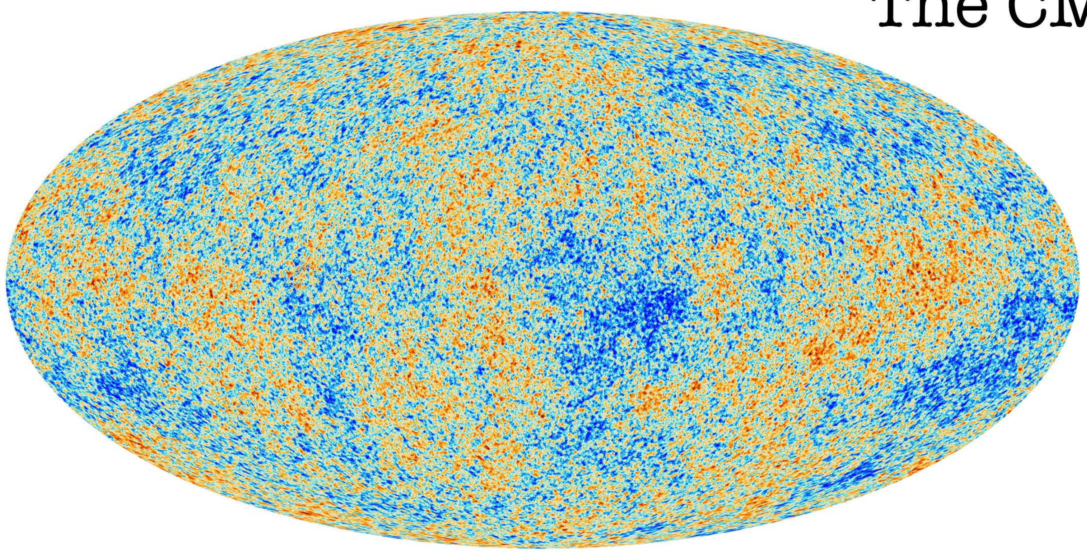

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Only 2 moments of interest : $\langle\Theta(\vec{n})\rangle = 0$ $\quad \langle\Theta(\vec{n_1})\Theta(\vec{n_2})\rangle \neq 0$

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SHI

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It represents the variance of the distribution for a given scale $\ell = \pi/\theta$
(in real space, you can relate it to the amplitude of fluctuations in a given box size)

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

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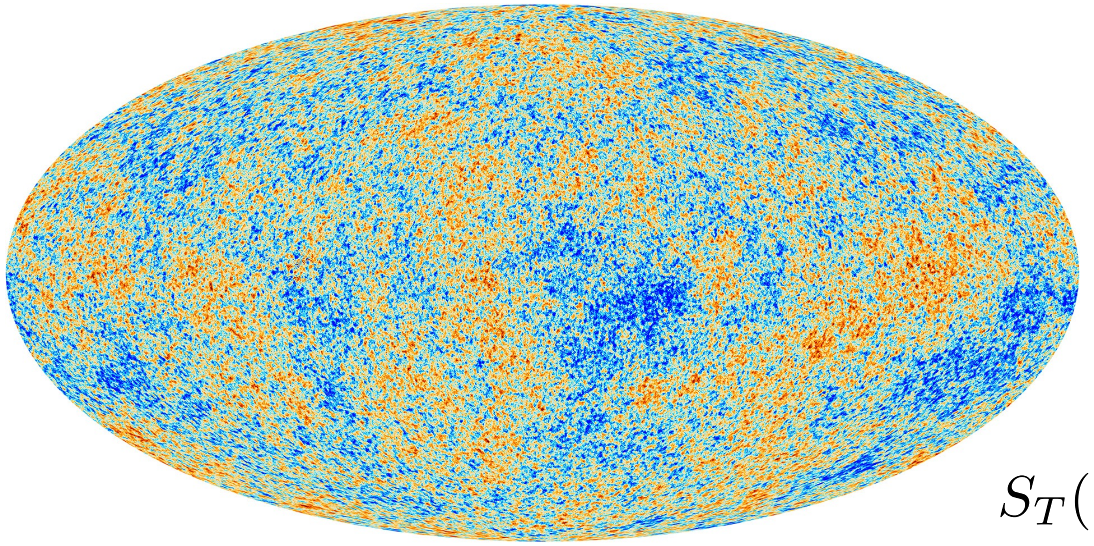
DM interacts only gravitationally in the standard Cosmology
=> Constraints can be derived



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

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

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

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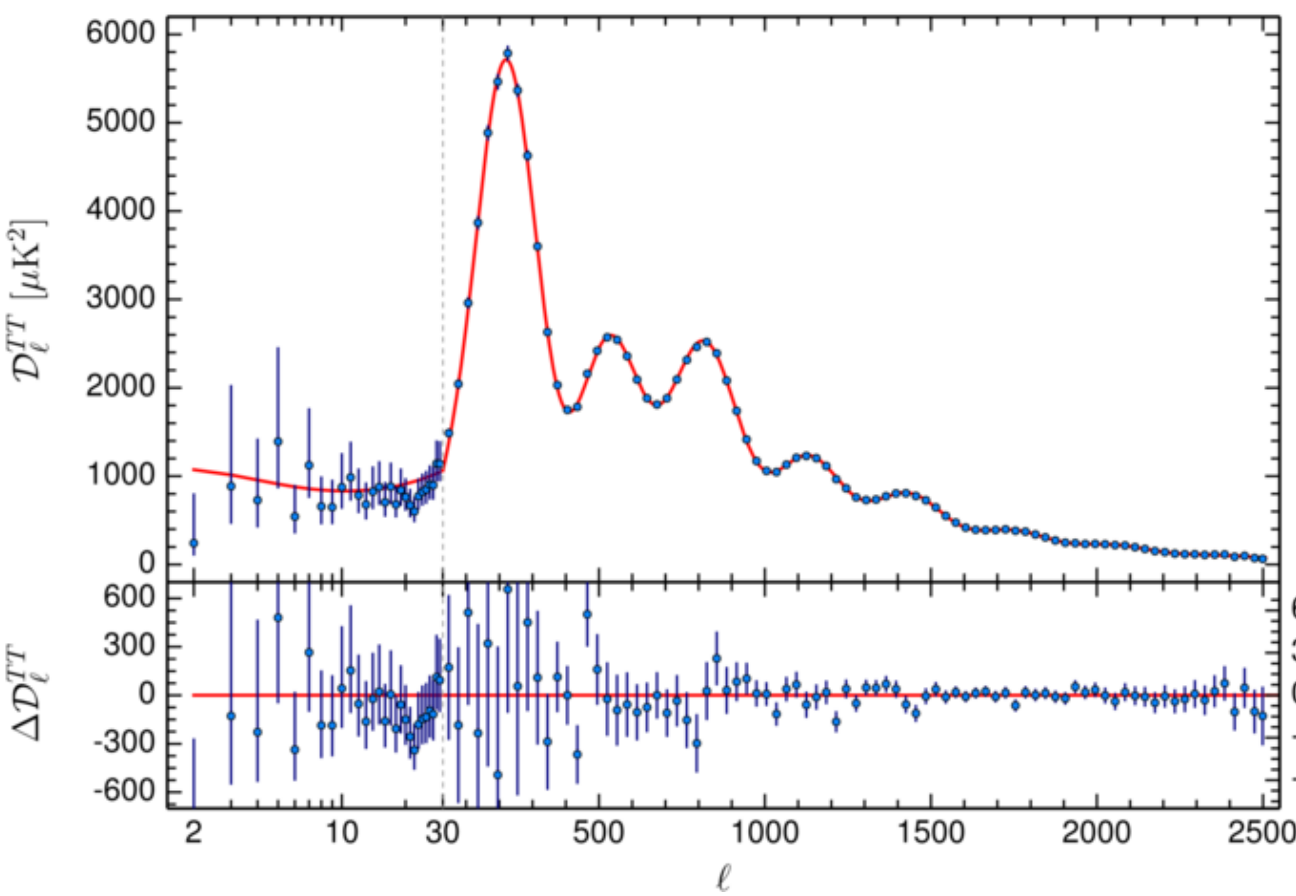

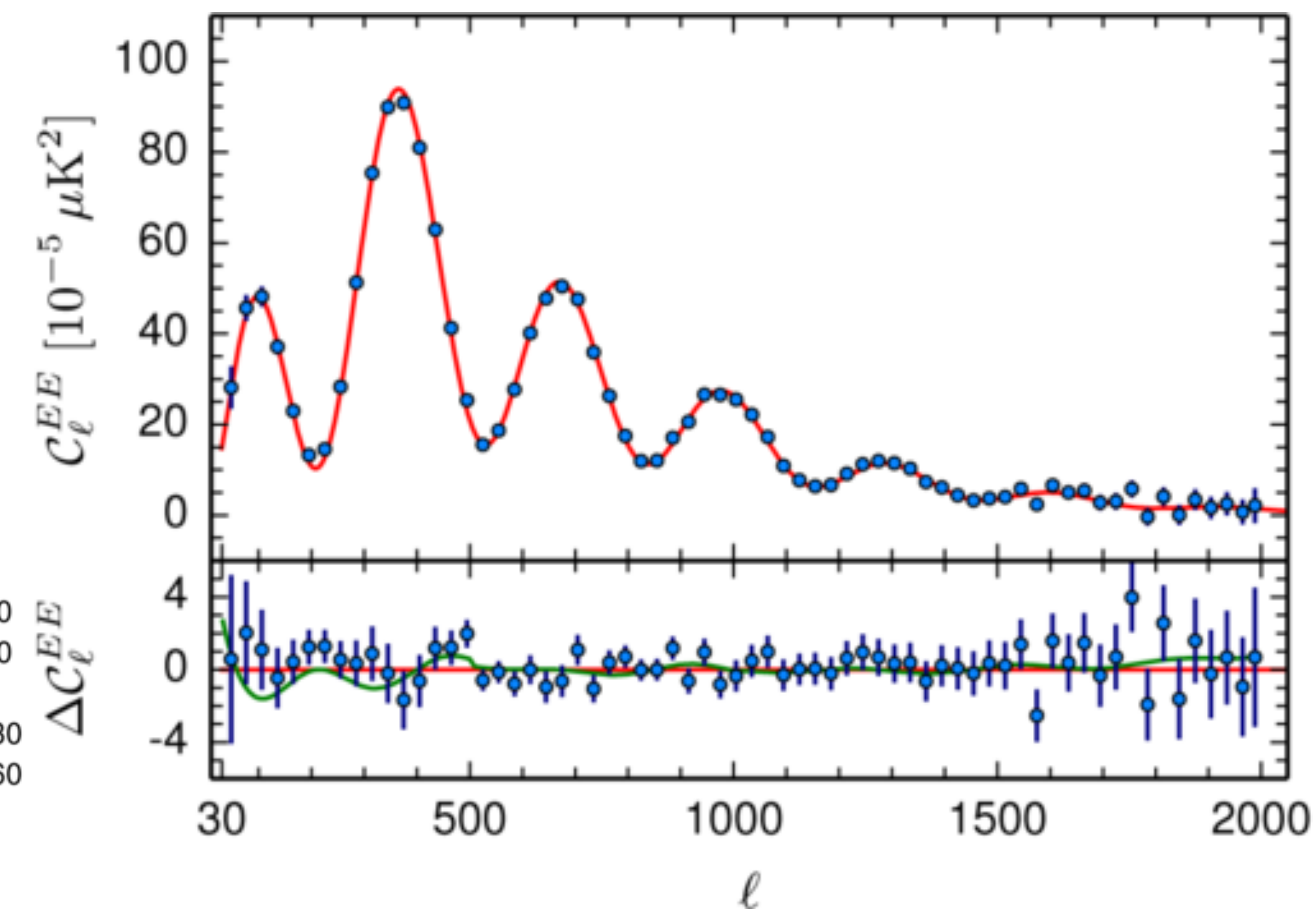

μ and y spectral distortions

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

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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$$\mu \equiv 1.401 \left[\frac{\Delta\rho_\gamma}{\rho_\gamma}\right]_\mu \simeq 1.4 \int \mathcal{J}_{\rm bb}\mathcal{J}_\mu \frac{1}{\rho_\gamma}\left(\frac{dE}{dt}\bigg|_\gamma\right)dt,$$

$$y \equiv \frac{1}{4}\left[\frac{\Delta\rho_\gamma}{\rho_\gamma}\right]_y \simeq \frac{1}{4}\int \mathcal{J}_{\rm bb}\mathcal{J}_y \frac{1}{\rho_\gamma}\left(\frac{dE}{dt}\bigg|_\gamma\right)dt$$

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

compton heating (or cooling!) of the CMB gas

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

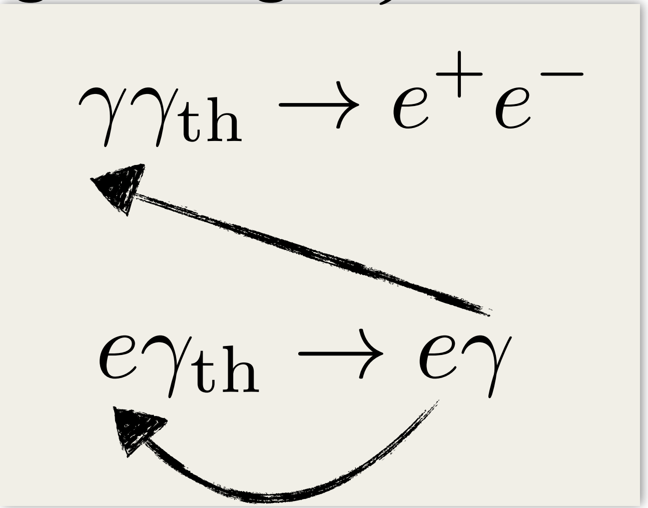
Visibility functions related to the range of efficiency of typical processes:

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

Electromagnetic Cascade in a nutshell

We want to describe electromagnetic energy injection in a plasma of photons (very few e+e-, nuclei) : what is the resulting metastable distribution of photons ?

Basic processes are (at high energies)



Particle multiplication and energy redistribution
=> Electromagnetic cascade !

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$$e\gamma_{\rm th} \to e\gamma$$

Particle multiplication and energy redistribution
=> Electromagnetic cascade !

The first process has a threshold, below it

$$\gamma\gamma_{\rm th} \to \gamma\gamma$$

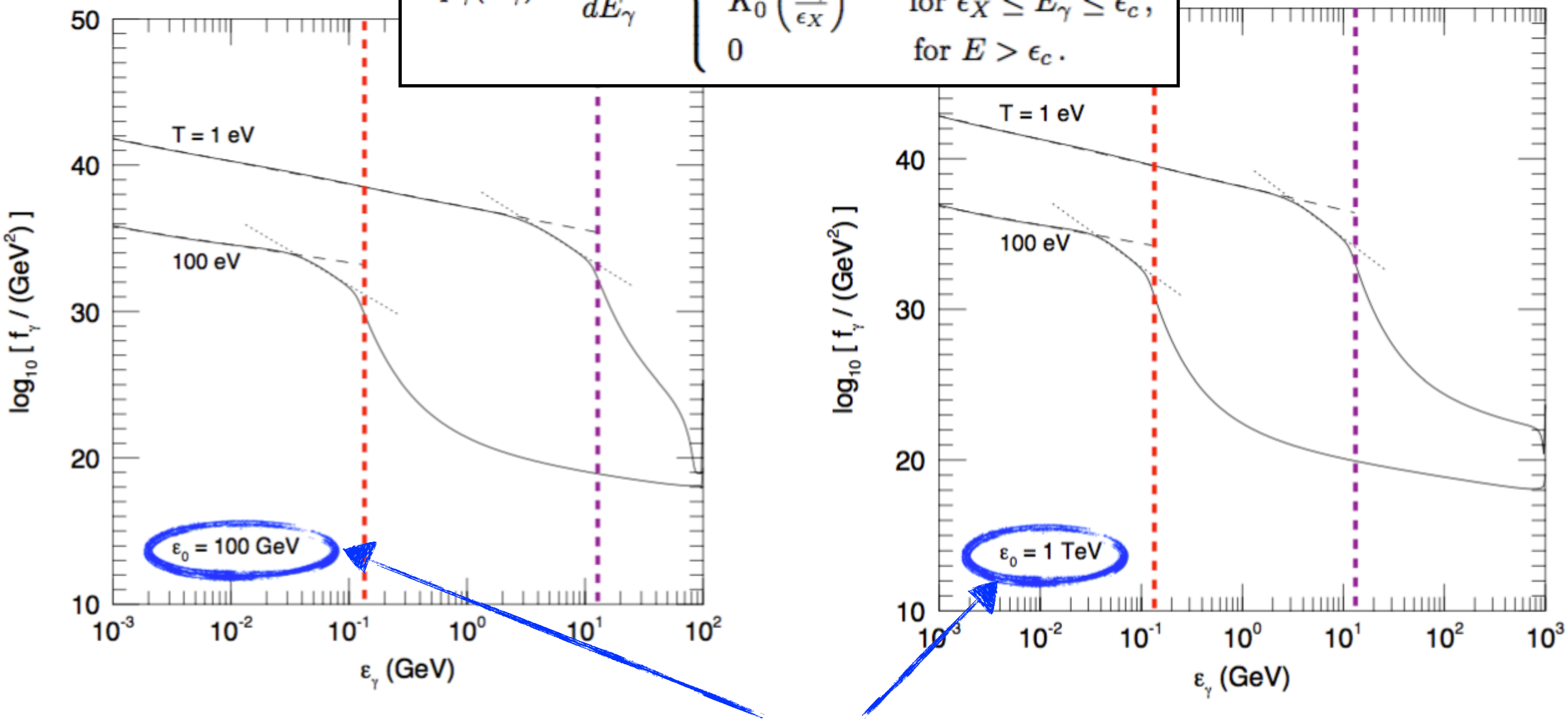
and eventually (very low rates)

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

Kawasaki & Moroi, ApJ 452,506 (1995)

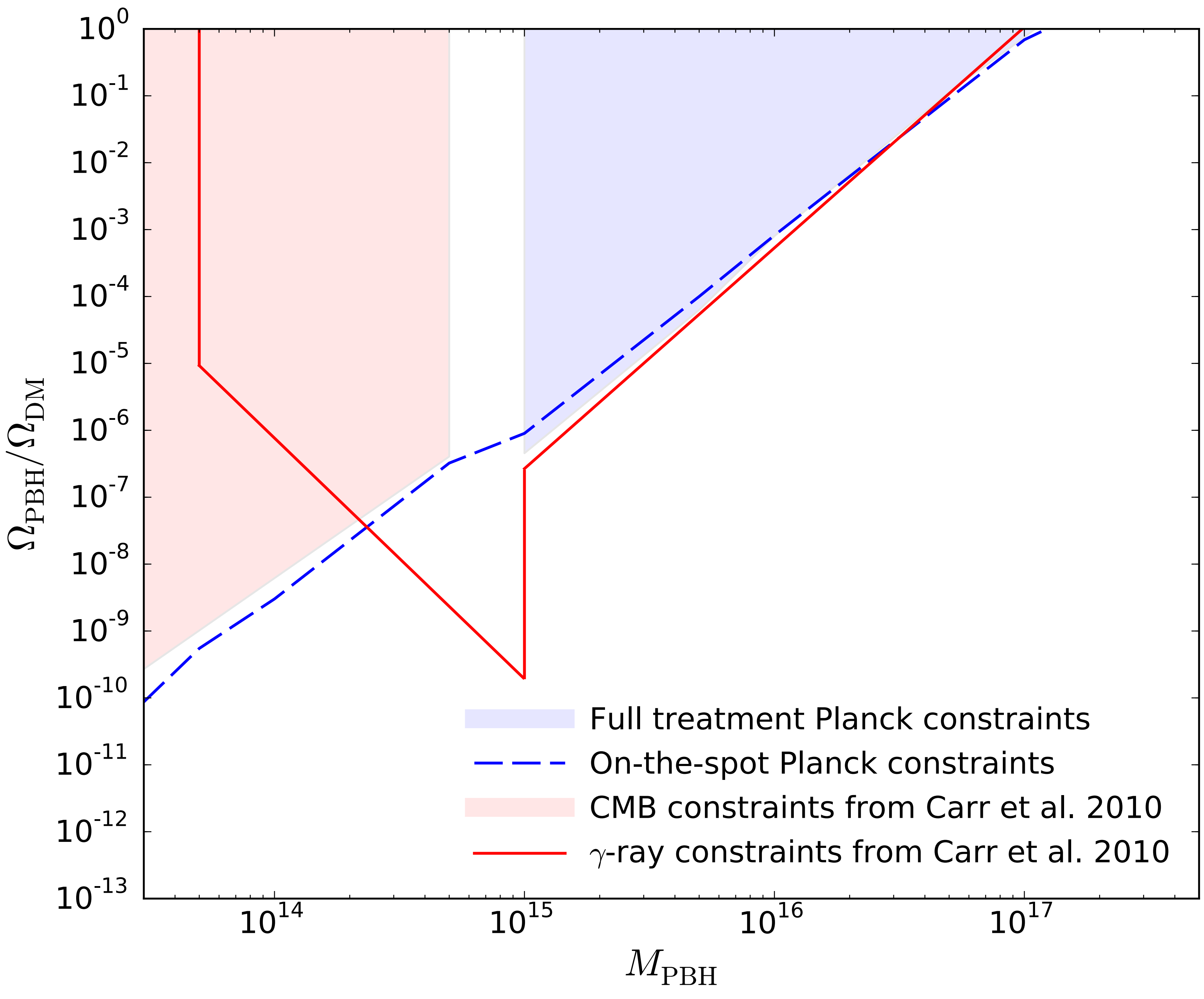
This has been shown to lead to a universal spectrum

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



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

Constraints on evaporating PBH



Constraints on sterile neutrinos