Constraining Decaying Dark Matter with the Effective Field Theory of Large-Scale Structures

Théo SIMON

Based on arXiv:2203.07440

With Guillermo F. Abellan, Peizhi Du, Vivian Poulin and Yuhsin Tsai

theo.simon@umontpellier.fr

Rencontres de Blois - 24/05/2022

The S_8 tension

A tension within the ΛCDM model

S_8 parameter

$$S_8 = \sigma_8\sqrt{\Omega_m/0.3}$$

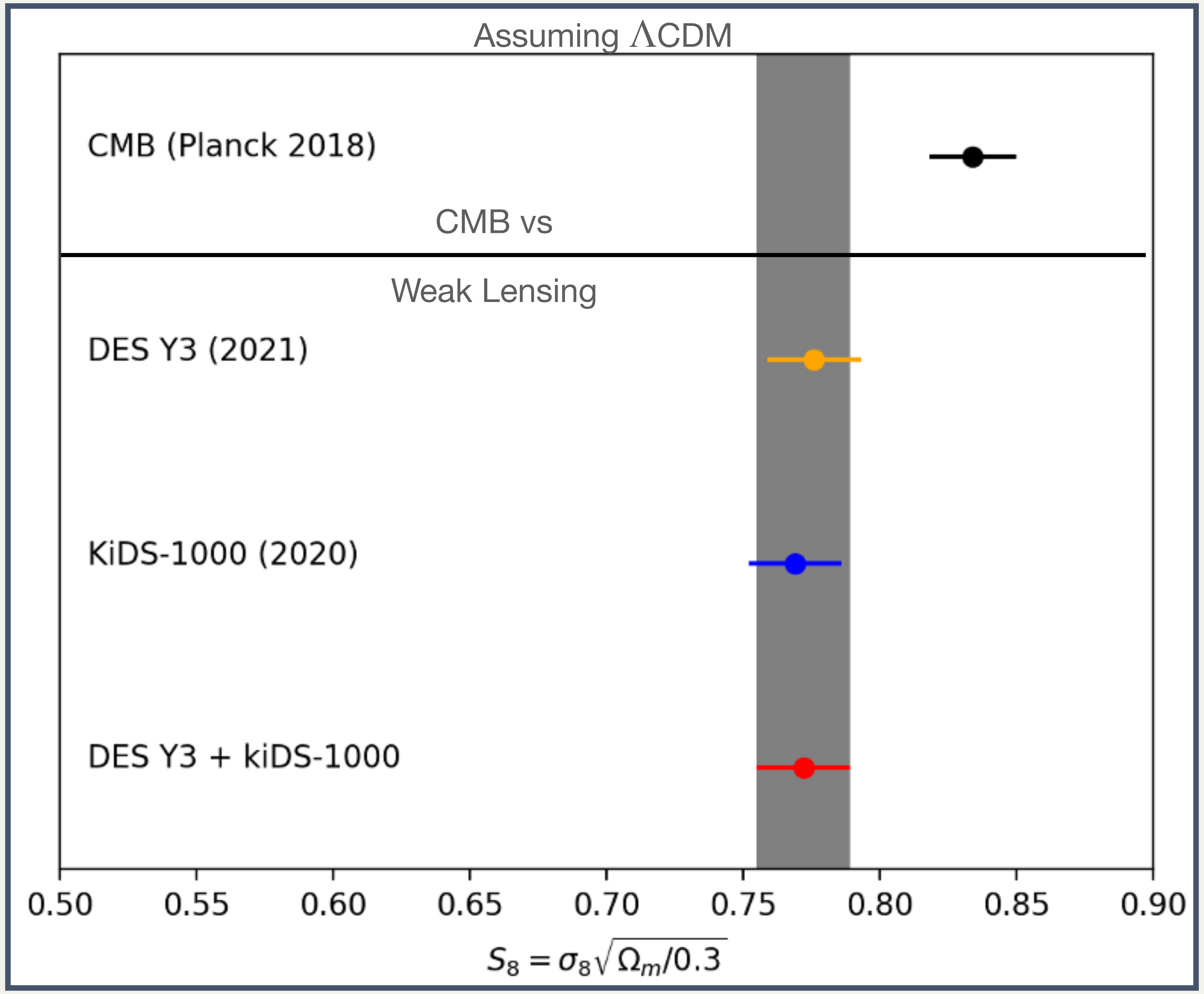
where:

$$\sigma_8^2 = \int \frac{k^3}{2\pi^2} P_m(k) W_8^2(k) d\ln(k)$$

→ $P_m(k)$ is the matter power spectrum

→ W_R is a « Window function »:

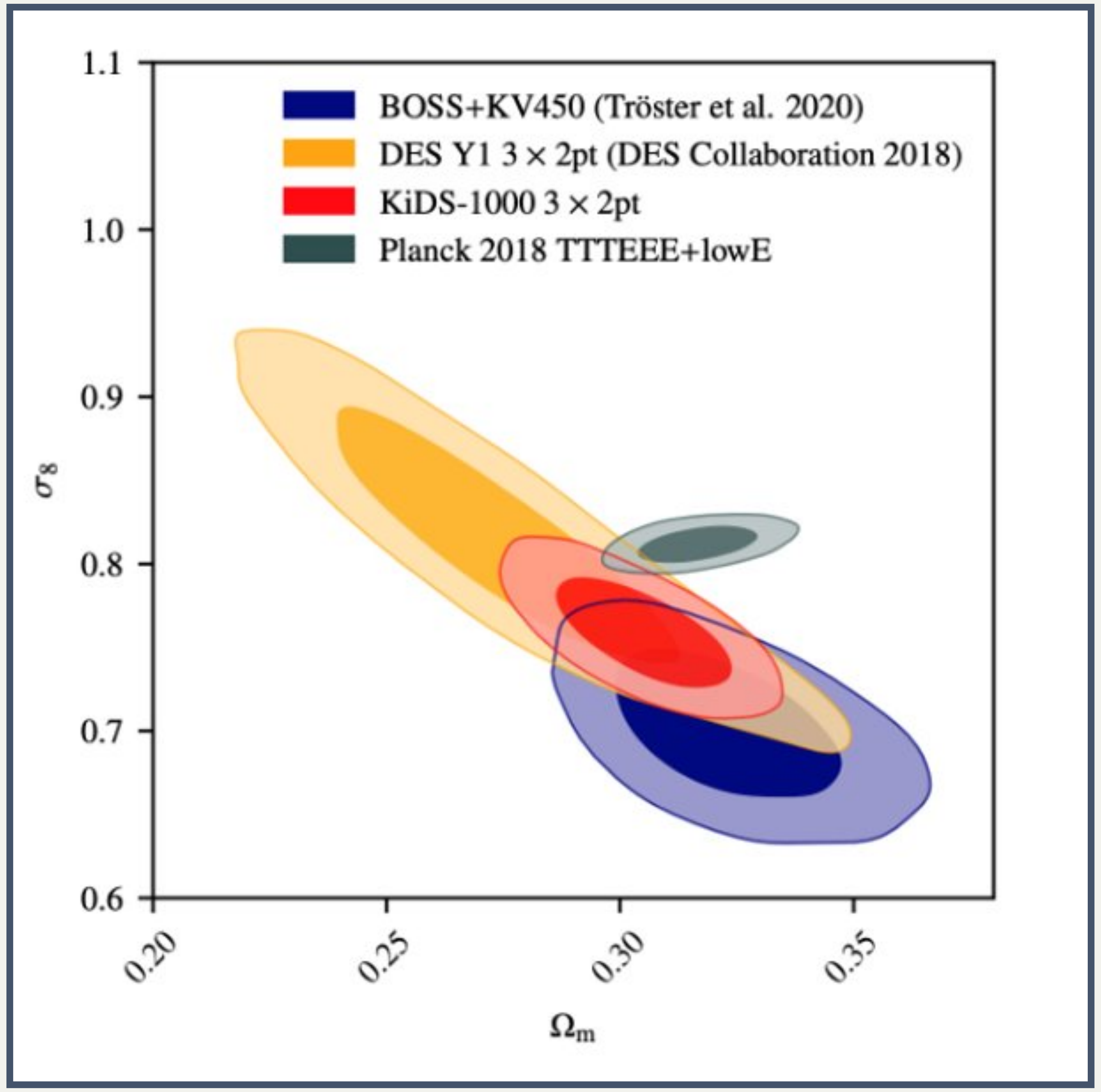
$$W_R = \frac{1}{4/3\pi R^3} \text{ for } r \leq R$$
$$W_R = 0 \text{ for } r > R$$



The S_8 tension and the matter power spectrum

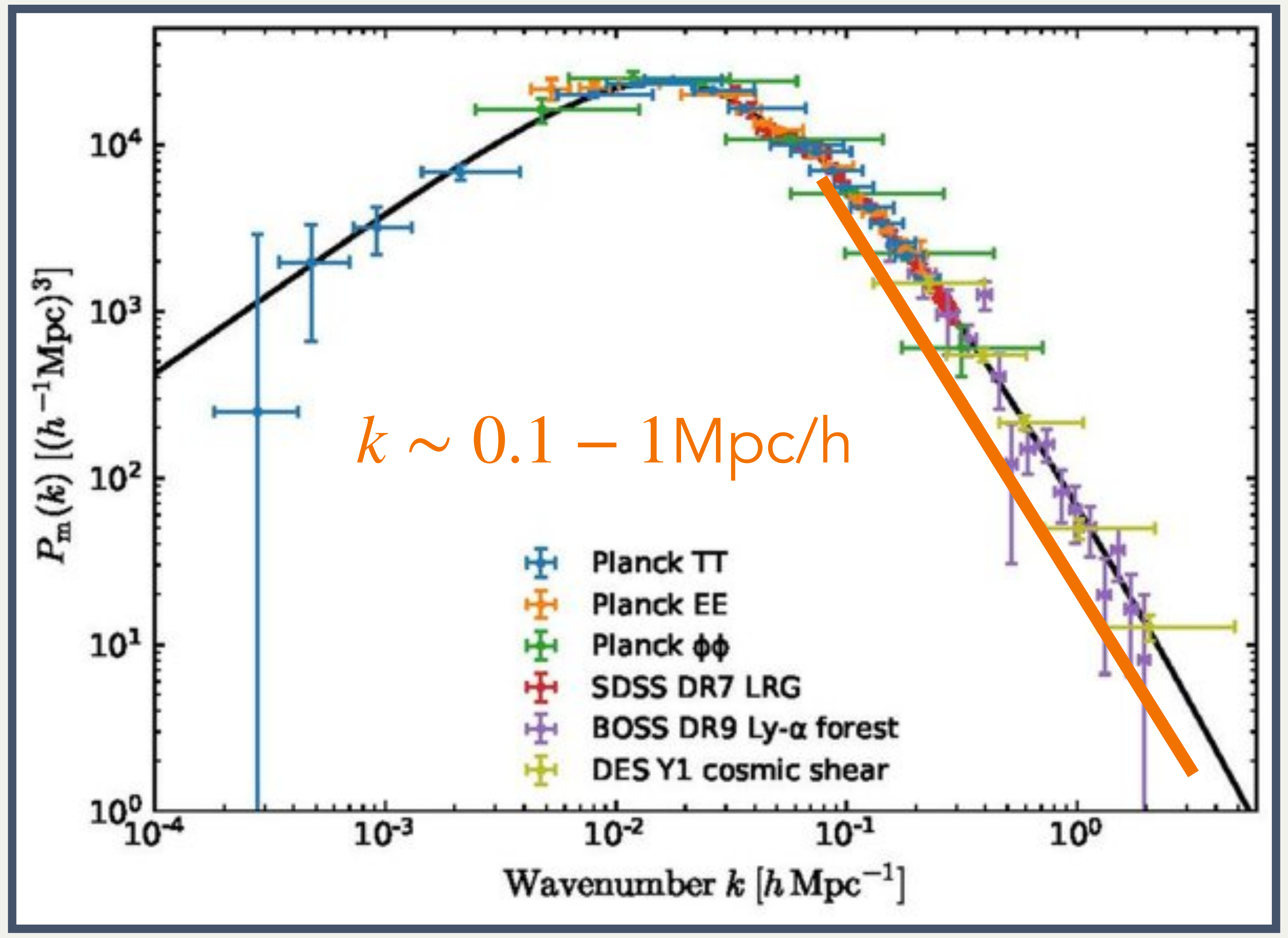
A tension within the ΛCDM model

Combining Galaxy Weak Lensing and clustering: the 3×2 statistics



σ_8 tension

$$\sigma_8 = \sqrt{\int \frac{k^3}{2\pi^2} P_m(k) W_8^2(k) d\ln(k)}$$



How to decrease power? Warm Dark Matter (excluded by Lyman alpha), Interacting Dark Matter… and decaying dark matter!

The effective field theory of large-scale structures (EFTofLSS)

Motivations

To constrain a model (through an MCMC), I focus on two main observables:

1. **CMB** → CMB power spectra: C_l^{TT}, C_l^{EE}, C_l^{TE}, etc.
2. **LSS** → the galaxy power spectrum: $P_g(z, k, \mu)$

In the **linear perturbation theory**, there is two popular ways to use LSS data :

1. Extract information with the full galaxy power spectrum

Lack of precision

$$P_g(z, k, \mu) \simeq \left[b_1(z) + f\mu^2\right]^2 P_m(z, k)$$

Kaiser 1987

b_1: bias parameter, f: growth factor and $\mu = \hat{z} \cdot \hat{k}$

2. Redshift Space Distortion (RSD) information : $f\sigma_8$.

Lack of information

The effective field theory of large-scale structures (EFTofLSS)

Motivations

The galaxy power spectrum in the framework of the EFTofLSS:

$$P_g(k,\mu) \simeq \left[b_1 + f\mu^2\right]^2 P_m(k) = Z_1(\mu)^2 P_m(k)$$

$$\Downarrow$$

$$P_g(k,\mu) = Z_1(\mu)^2 P_{11}(k) + 2Z_1(\mu) P_{11}(k)\left(c_{\rm ct}\frac{k^2}{k_{\rm M}^2} + c_{r,1}\mu^2\frac{k^2}{k_{\rm M}^2} + c_{r,2}\mu^4\frac{k^2}{k_{\rm M}^2}\right)$$
$$+ 2\int \frac{d^3q}{(2\pi)^3} Z_2(\boldsymbol{q}, \boldsymbol{k}-\boldsymbol{q}, \mu)^2 P_{11}(|\boldsymbol{k}-\boldsymbol{q}|) P_{11}(q) + 6Z_1(\mu) P_{11}(k) \int \frac{d^3q}{(2\pi)^3} Z_3(\boldsymbol{q}, -\boldsymbol{q}, \boldsymbol{k}, \mu) P_{11}(q)$$
$$+ \frac{1}{\bar{n}_g}\left(c_{\epsilon,0} + c_{\epsilon,1}\frac{k^2}{k_{\rm M}^2} + c_{\epsilon,2} f\mu^2 \frac{k^2}{k_{\rm M}^2}\right),$$

Perko et al. (2016)

$P_g(k,\mu)$ can be determined directly from $P_{11}(k) = P_m(k)$

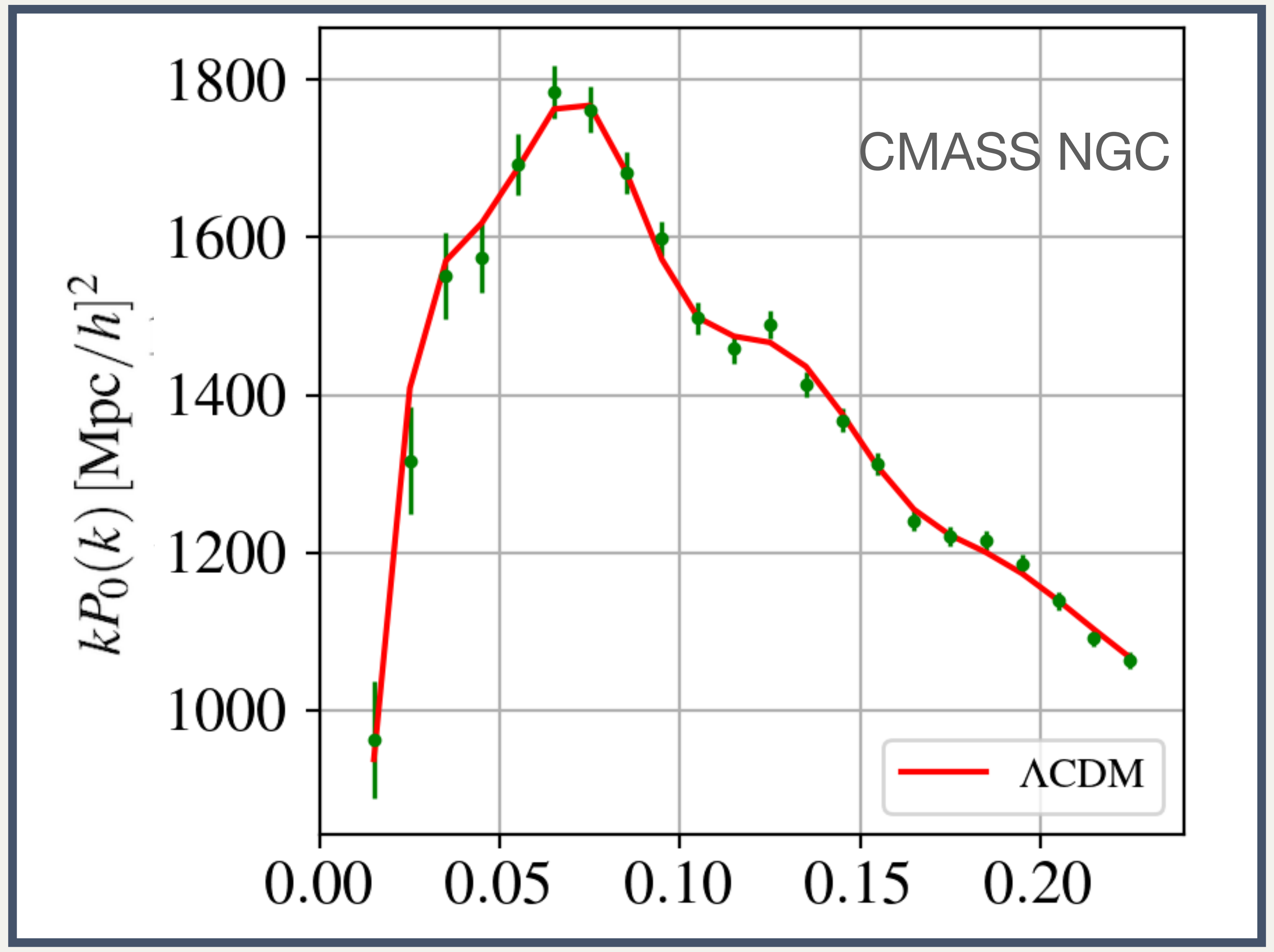
The effective field theory of large-scale structures (EFTofLSS)

BOSS data

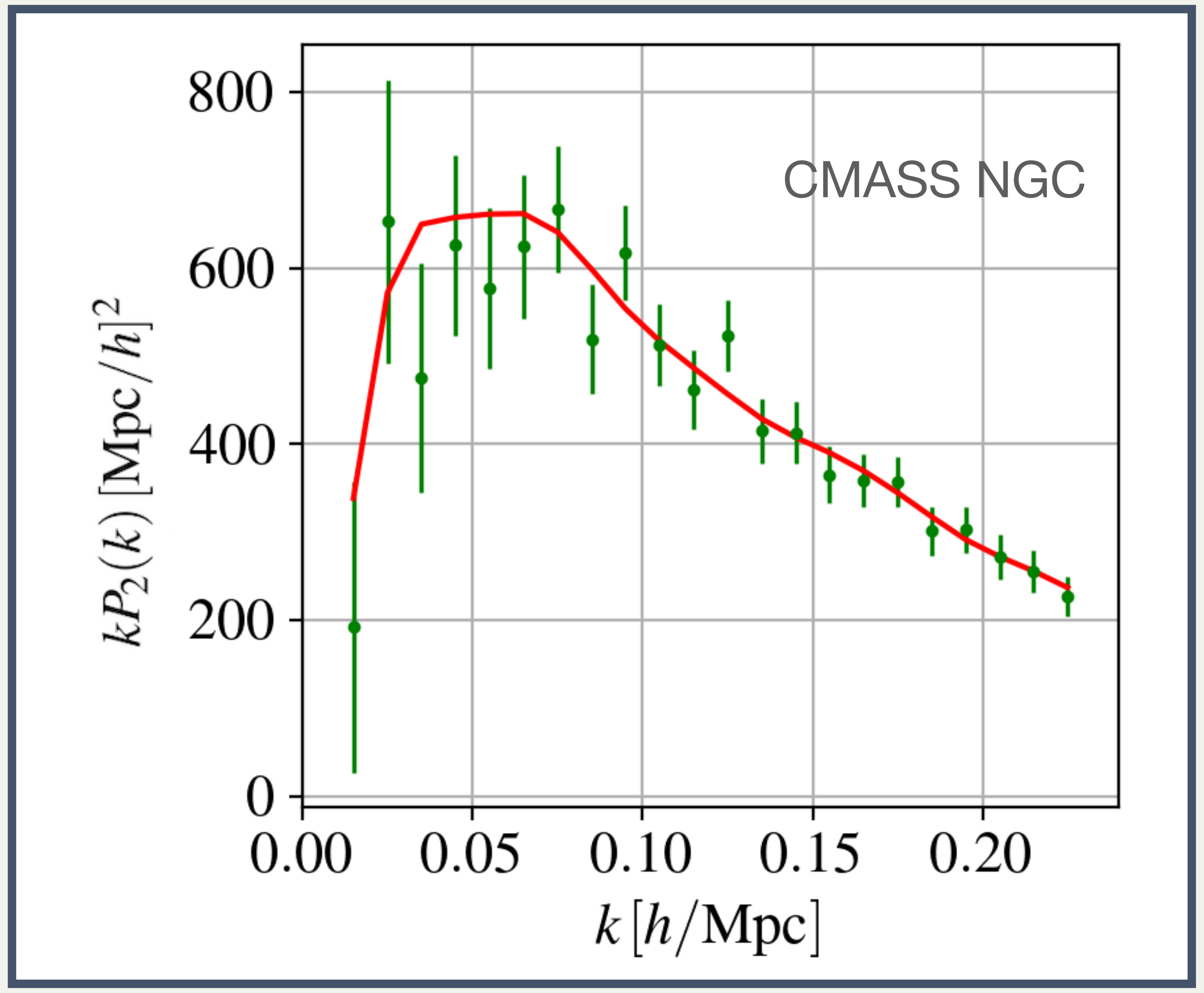
Multipoles of the galaxy power spectrum, obtained through a **Legendre** polynomials ($\mathscr{L}_\ell$) decomposition:

$$P_g(z,k,\mu) = \sum_{\ell \text{ even}} \mathscr{L}_\ell(\mu) P_\ell(z,k)$$

→ two main contributions to $P_g(z,k,\mu)$ are the **monopole** ($\ell = 0$) and the **quadrupole** ($\ell = 2$).



Made with PyBird: github.com/pierrexyz/pybird



We use 3 sky-cuts from BOSSDR12 at z =0.3 and 0.6.

arXiv:2203.07440, arXiv:2110.07539

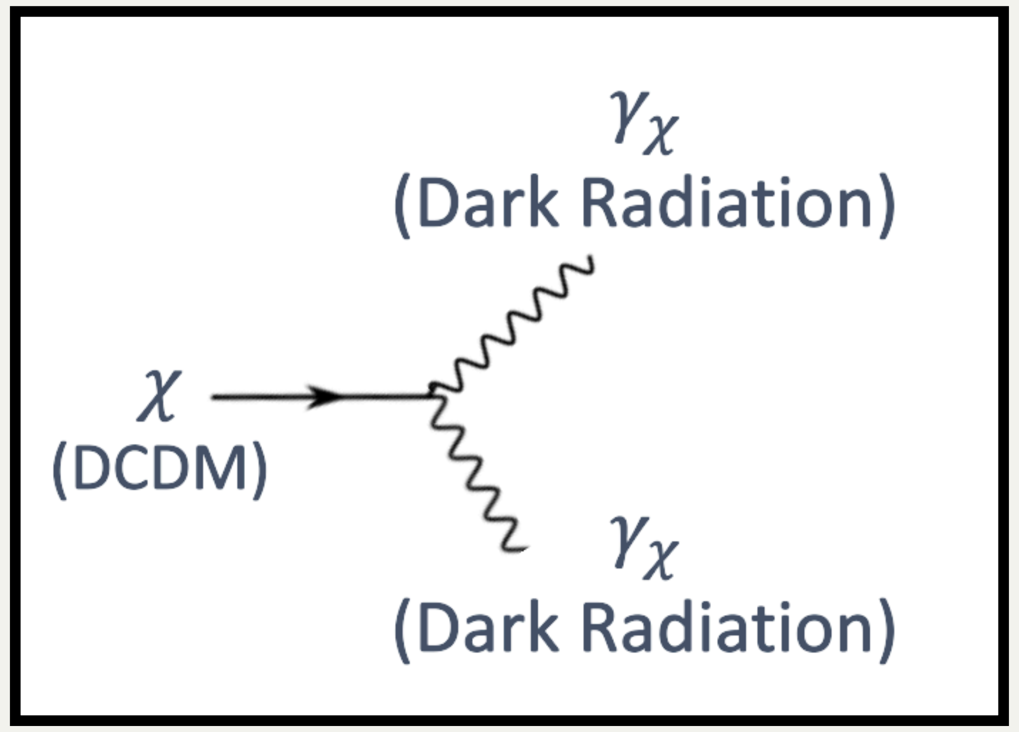
The DCDM → DR model

Presentation of the model

The model

→ **Extension** to the ΛCDM model.

→ **Decay process** :

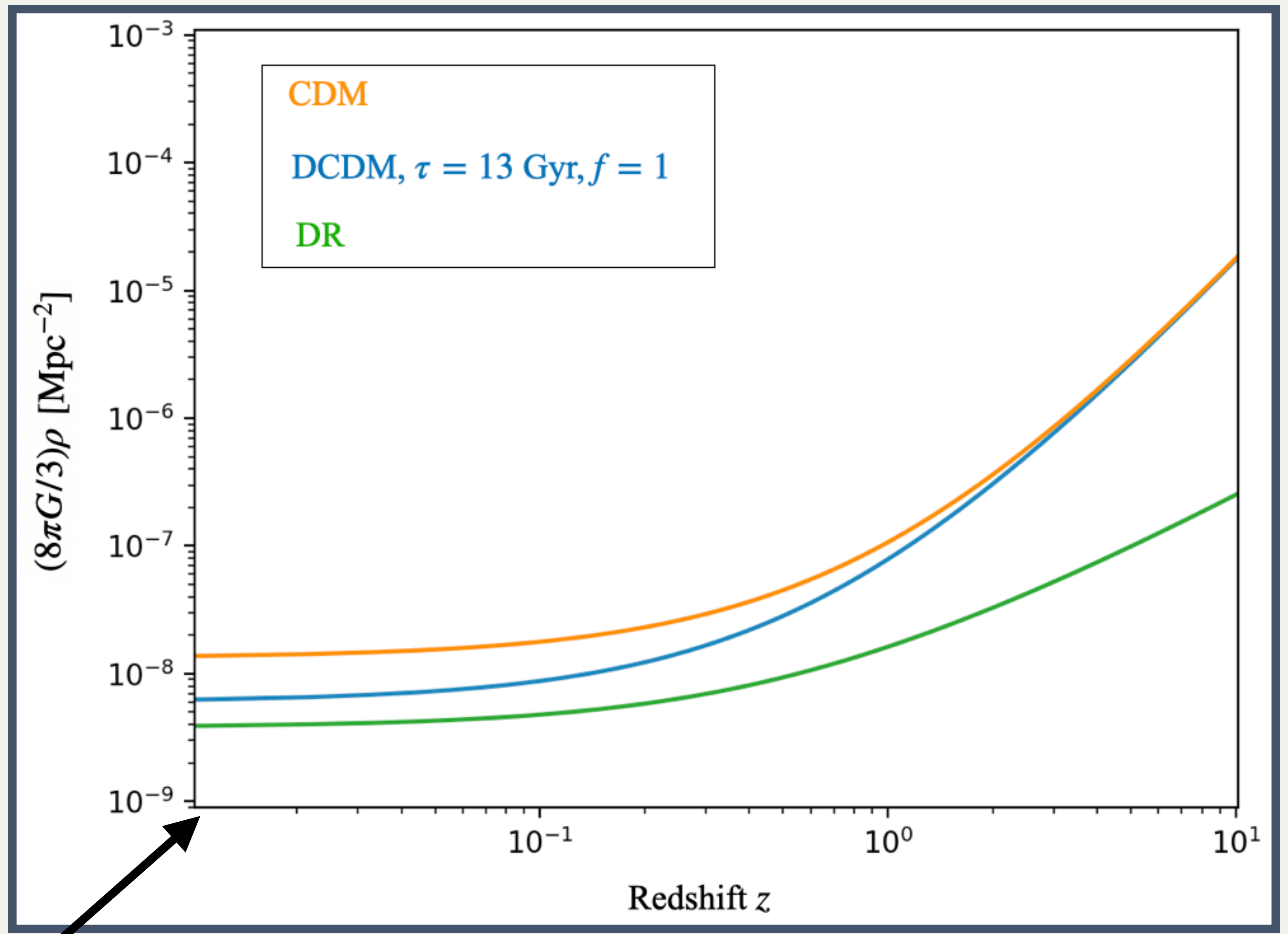


→ DCDM ~ ΛCDM + 2 parameters:

1. $\tau = \Gamma^{-1}$: **half-life** of the dark matter mother particle (DCDM)
2. f: **fraction** of the total CDM called DCDM is converted into Dark Radiation

Evolution of the energy densities

$$\dot{\bar{\rho}}_{\rm dcdm} + 3\mathscr{H}\bar{\rho}_{\rm dcdm} = -a\Gamma\bar{\rho}_{\rm dcdm}$$
$$\dot{\bar{\rho}}_{\rm dr} + 4\mathscr{H}\bar{\rho}_{\rm dr} = a\Gamma\bar{\rho}_{\rm dcdm}$$



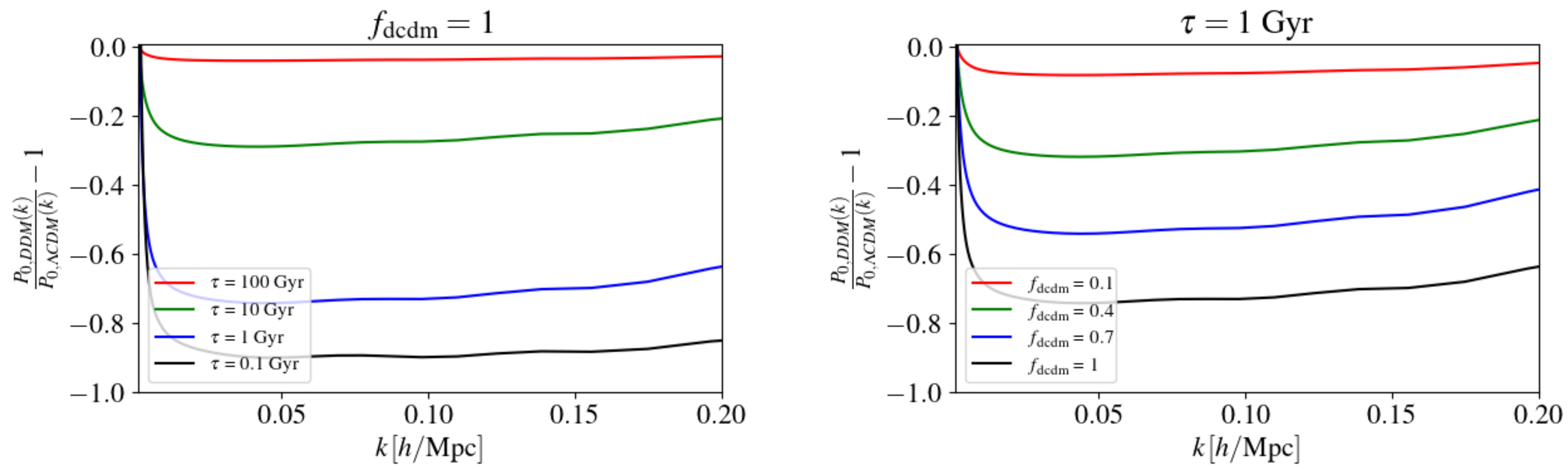
Today

The DCDM → DR model

Results: galaxy power spectrum

→ At level of perturbations in the synchronous gauge co-moving with DCDM: DCDM perturbations are unchanged! We consider homogeneous decays.

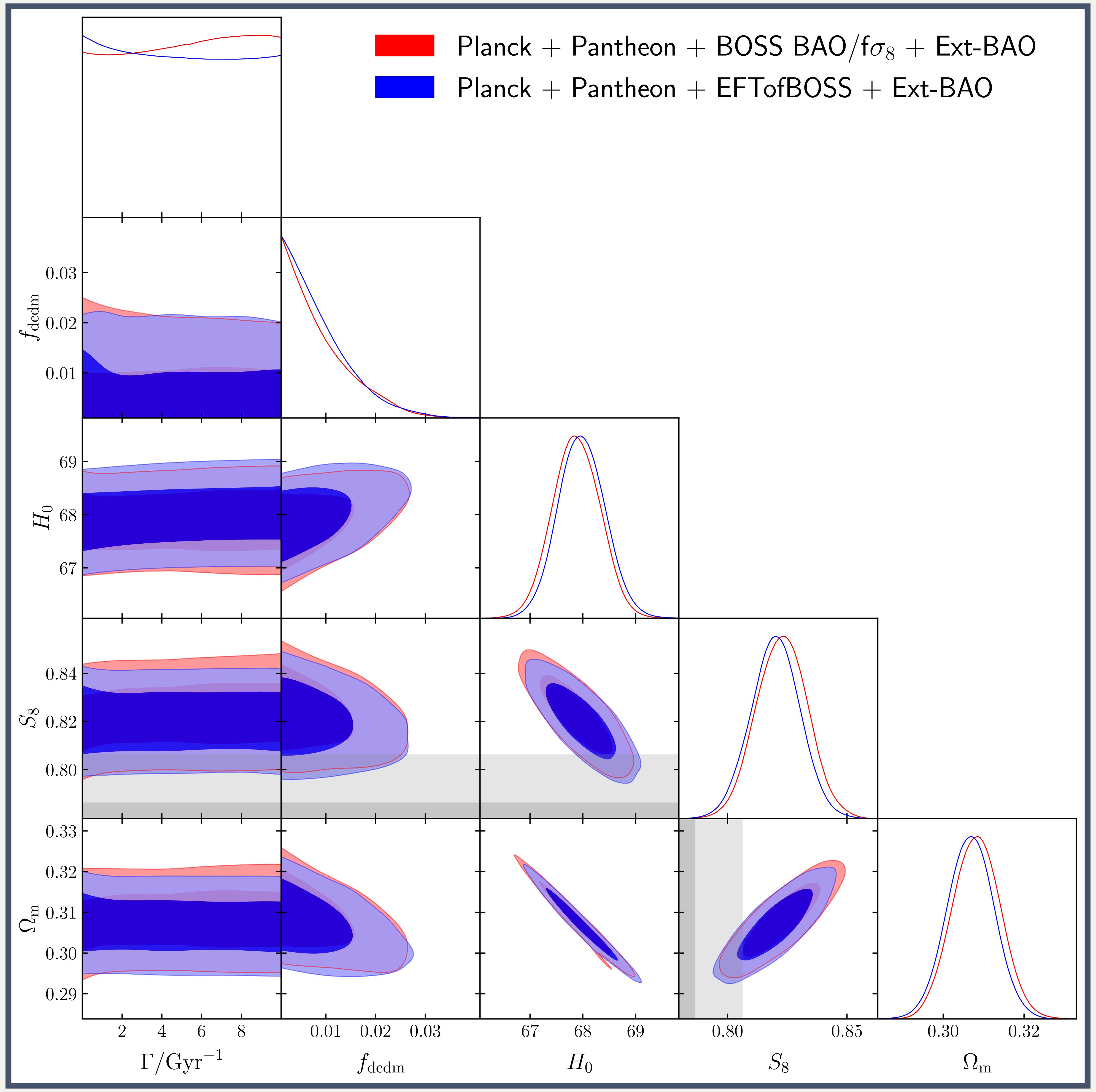
→ The effect is dominated by the decrease of Ω_m at the **background** (effect of daughter radiation is minor).



TS et al. 2022

The DCDM → DR model

Results: constraints



3 main results

Planck+Pantheon+BAO/$f\sigma_8$ or EFTofBOSS

1. We derive the most up-to-date constraints

$$\tau > 250.0 \text{ Gyr} \quad \text{for } f = 1$$
$$f < 0.0216 \quad \text{for } \tau < t_u$$

2. EFTofLSS does not improve the constraints over BAO/$f\sigma_8$

3. This model **does not resolve** the S_8 tension

TS et al. 2022, arXiv:2203.07440

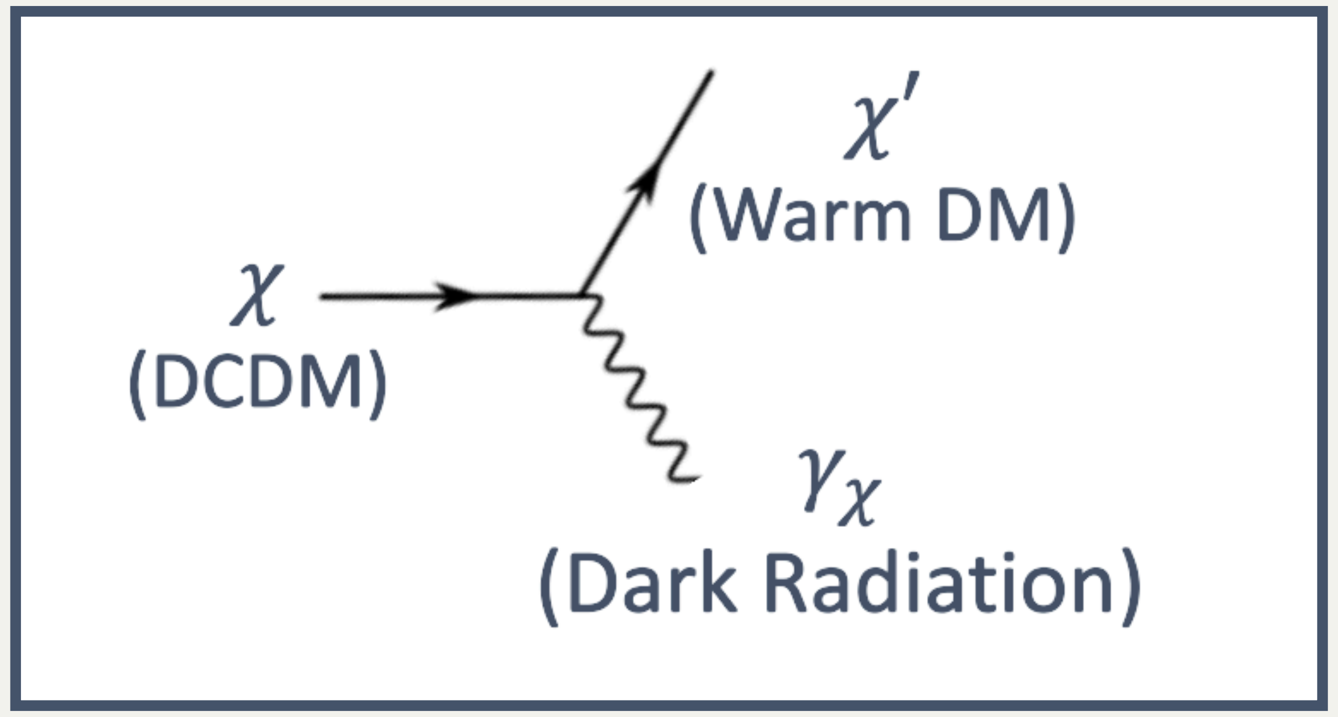
The DCDM → WDM+DR model

Presentation of the model

The model

→ **Extension** to the ΛCDM model.

→ **Decay process** :



→ DCDM ~ ΛCDM + 2 parameters:

1. $\tau = \Gamma^{-1}$: **half-life** of the dark matter mother particle (DCDM)
2. ε: **fraction** of the rest mass energy of the DCDM converted into Dark Radiation

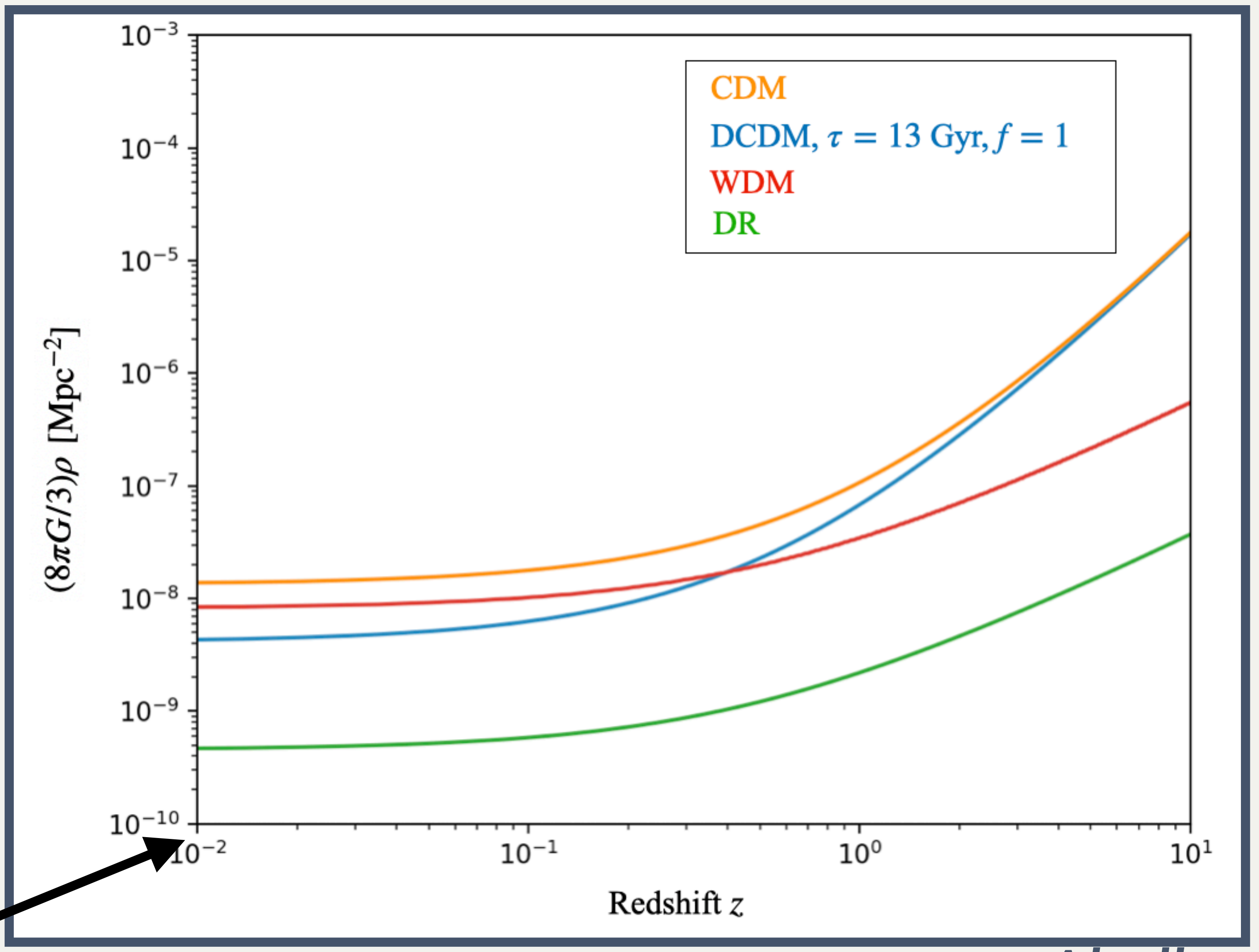
Evolution of the energy densities

$$\dot{\bar{\rho}}_{\rm dcdm} + 3\mathscr{H}\bar{\rho}_{\rm dcdm} = -a\Gamma\bar{\rho}_{\rm dcdm}$$

$$\dot{\bar{\rho}}_{\rm dr} + 4\mathscr{H}\bar{\rho}_{\rm dr} = \varepsilon\Gamma a\bar{\rho}_{\rm dcdm}$$

$$\dot{\bar{\rho}}_{\rm wdm} + 3(1+w)\mathscr{H}\bar{\rho}_{\rm wdm} = (1-\varepsilon)a\Gamma\bar{\rho}_{\rm dcdm}$$

with $w = \bar{P}_{\rm wdm}/\bar{\rho}_{\rm wdm}$



Today

Abellan et al. (2021)

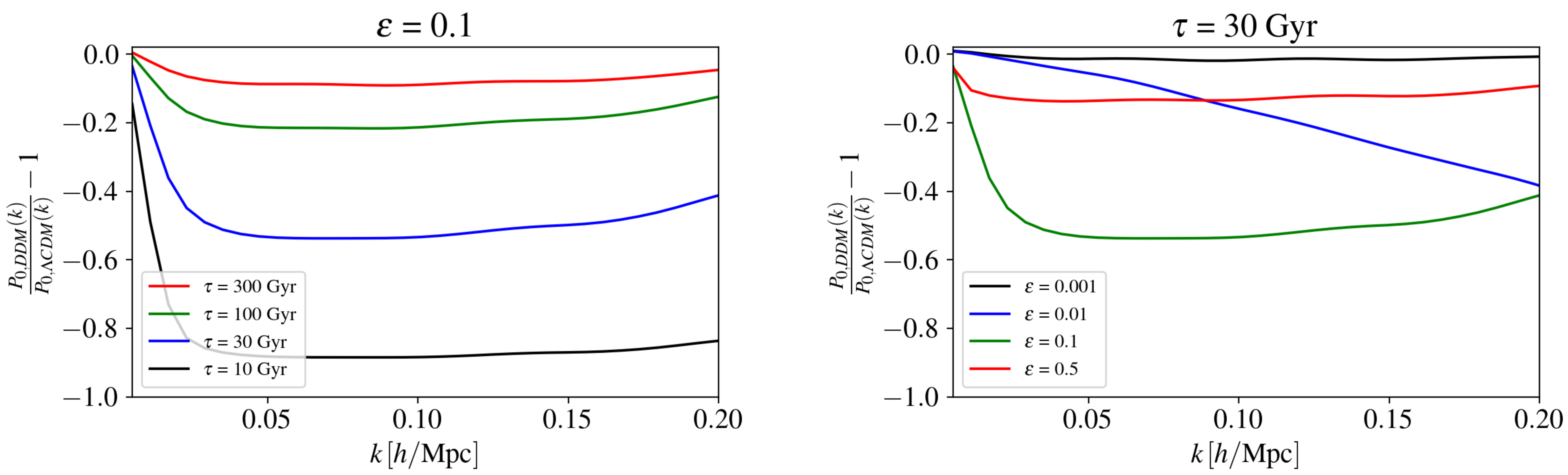
The DCDM → WDM+DR model

Results: galaxy power spectrum

→ The effet **is not** dominated by a background effect

→ WDM perturbed continuity equation :

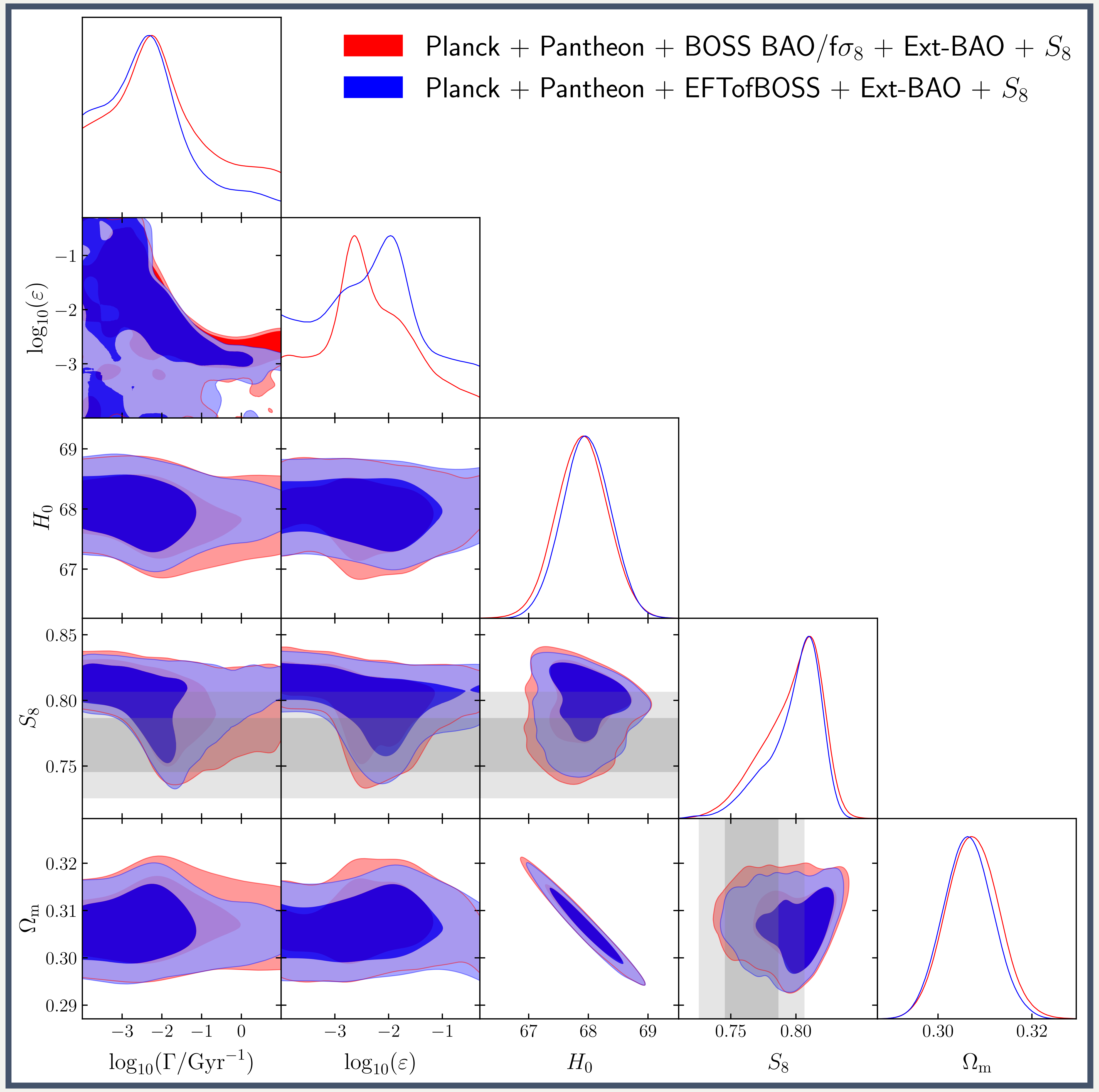
$$\dot{\delta}_{\rm wdm} = -3\mathscr{H}(c_s^2 - \omega)\delta_{\rm wdm} - (1+\omega)\left(\theta_{\rm wdm} + \frac{\dot{h}}{2}\right) + (1-\varepsilon)a\Gamma\frac{\bar{\rho}_{\rm dcdm}}{\bar{\rho}_{\rm wdm}}(\delta_{\rm dcdm} - \delta_{\rm wdm})$$



TS et al. 2022, arXiv:2203.07440

The DCDM → WDM+DR model

Results: constraints



TS et al. 2022, arXiv:2203.07440

3 main results

Planck+Pantheon+BAO/$f\sigma_8$ or EFTofBOSS

1. This model **could resolve** the S_8 tension!

   2.8σ for ΛCDM → 1.5σ for DCDM →WDM+DR

2. The EFTofBOSS data **improve the constraints** on τ:

   $1.61 < \log_{10}(\tau/\mathrm{Gyr}) < 3.71$ *with* EFTofBOSS

   $1.31 < \log_{10}(\tau/\mathrm{Gyr}) < 3.82$ *without* EFTofBOSS

3. It changes the **bestfit**:

   $\tau = 43$ Gyr → $\tau = 120$ Gyr

   $\varepsilon = 0.6\,\%$ → $\varepsilon = 1.2\,\%$

Conclusions and Perspectives

Main results

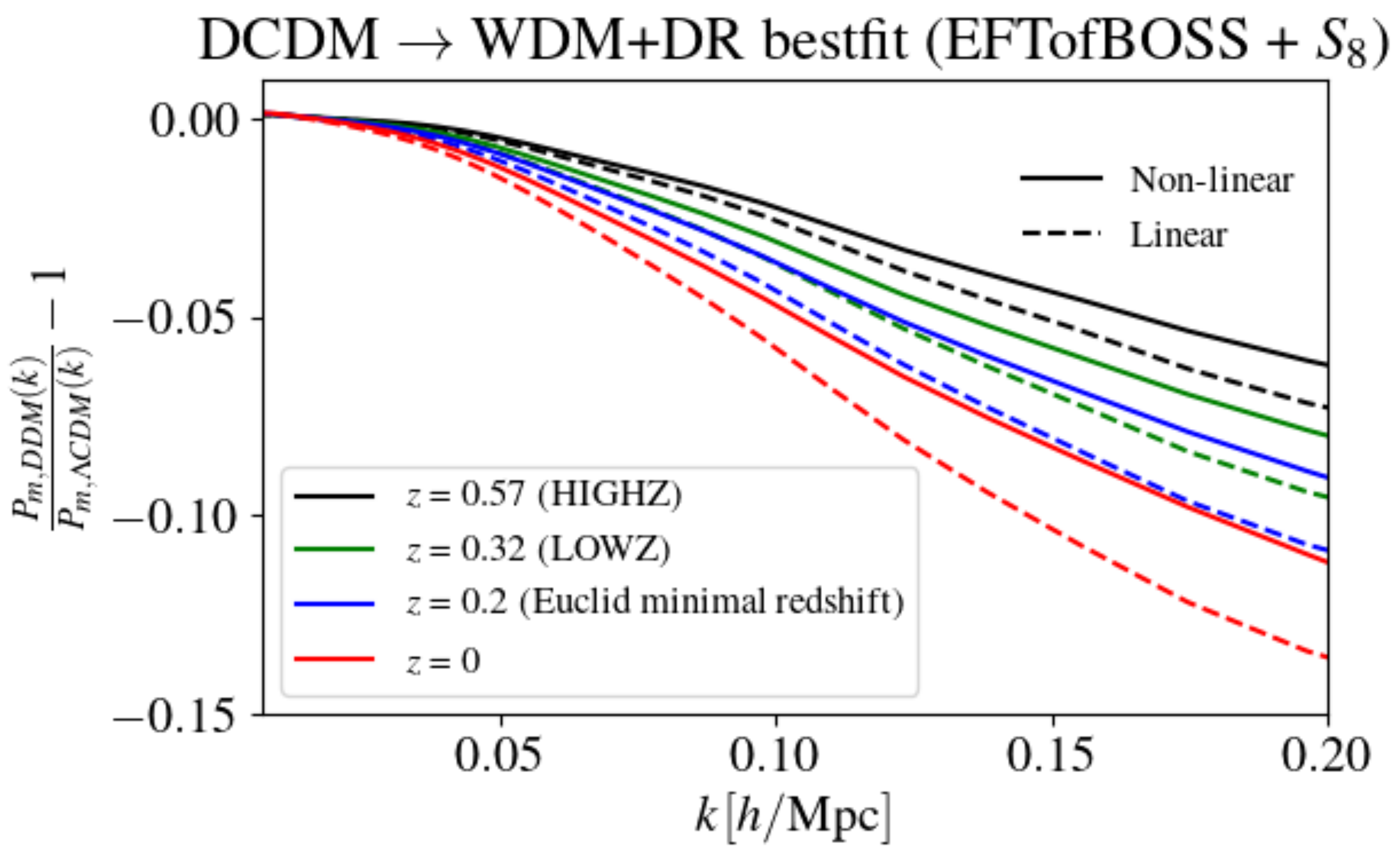
→ EFTofLSS can have **constraining power** on alternative models to ΛCDM.

→ We derive strong constraints on DCDM → DR model:

$$f < 0.0216$$
$$\tau > 250.0 \text{ Gyr}$$

→ The DCDM → WDM+DR model resolve the S8 tension and could be probed further with next generation LSS surveys:

$$\tau = 120 \text{ Gyr} \;\&\; \varepsilon = 1.2\,\%$$



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Thanks for your attention

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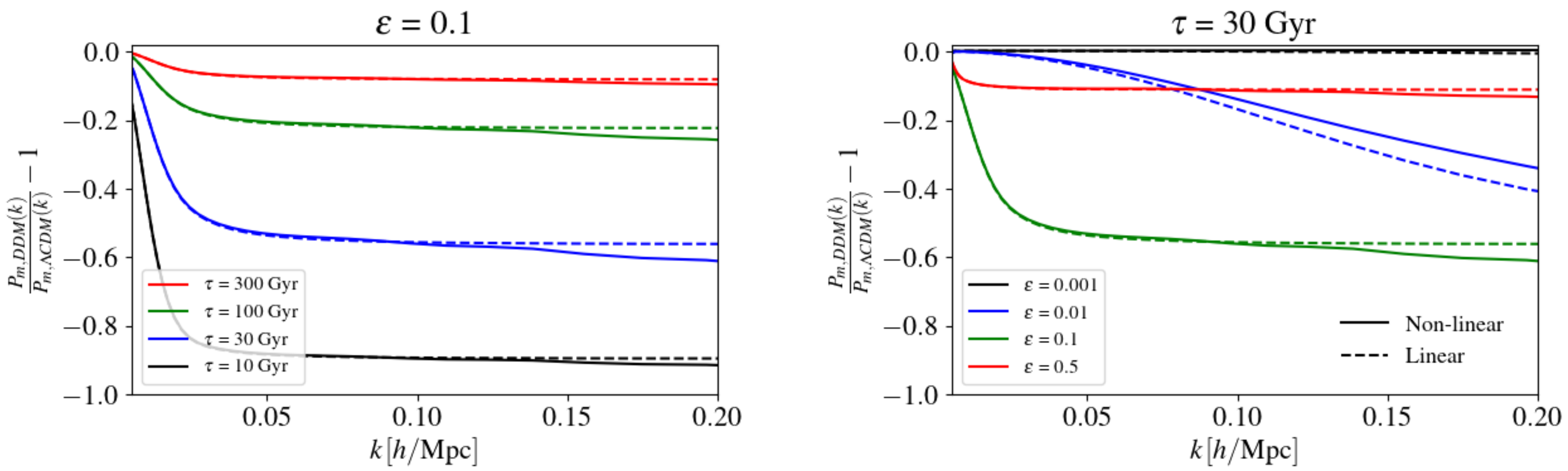
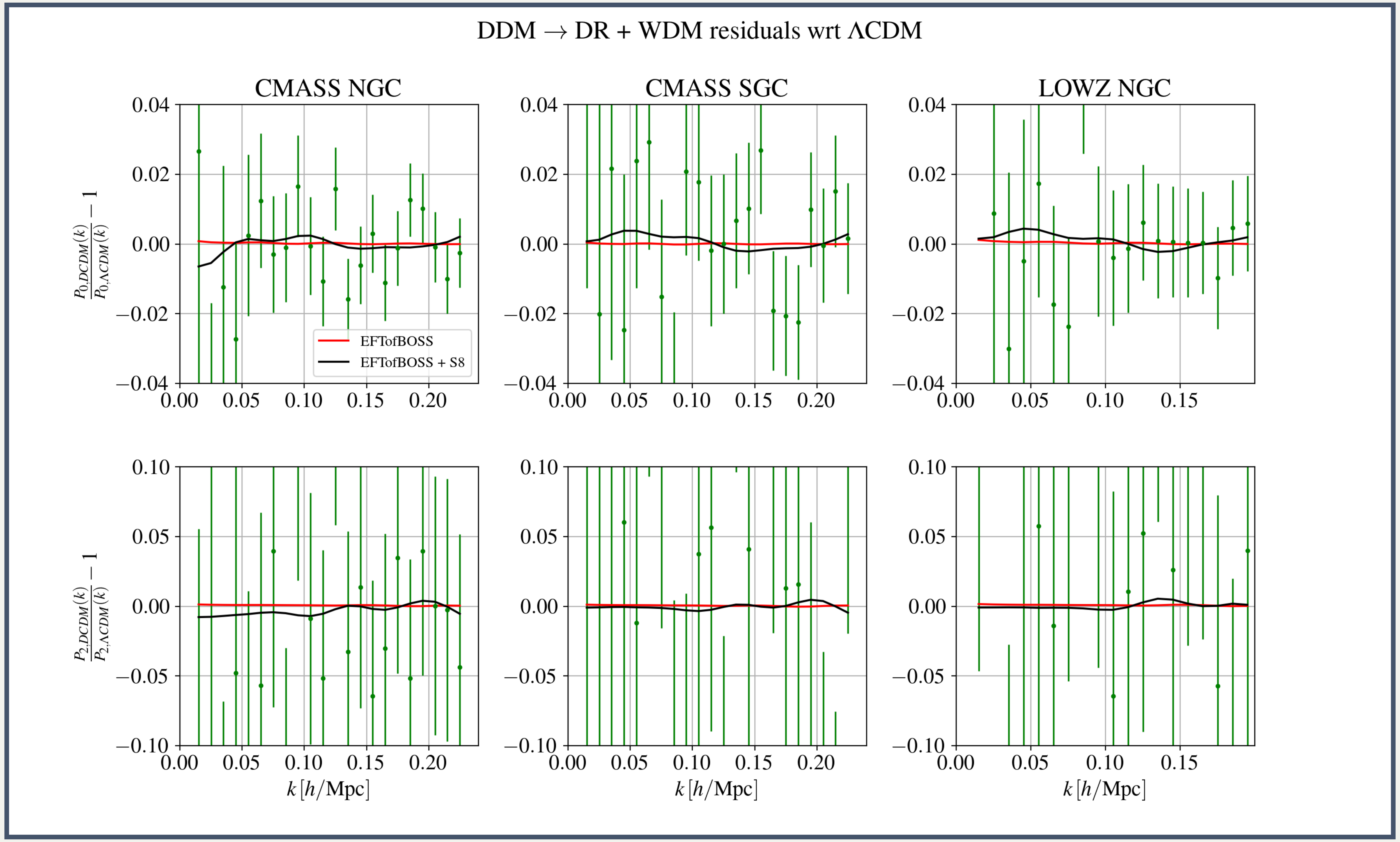
Backup I: DCDM → DR matter power spectrum

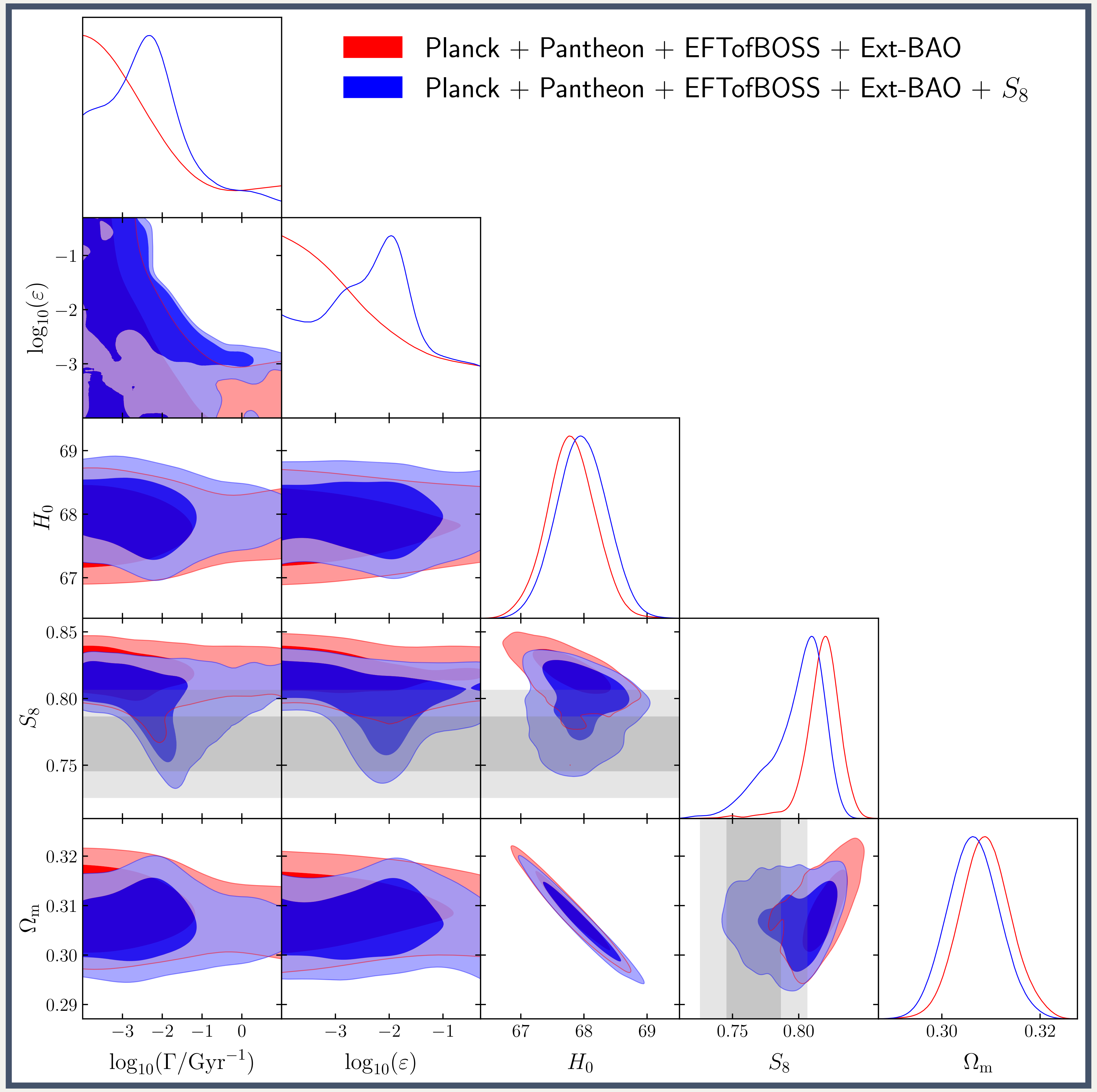
Backup II: DCDM → WDM+DR matter power spectrum

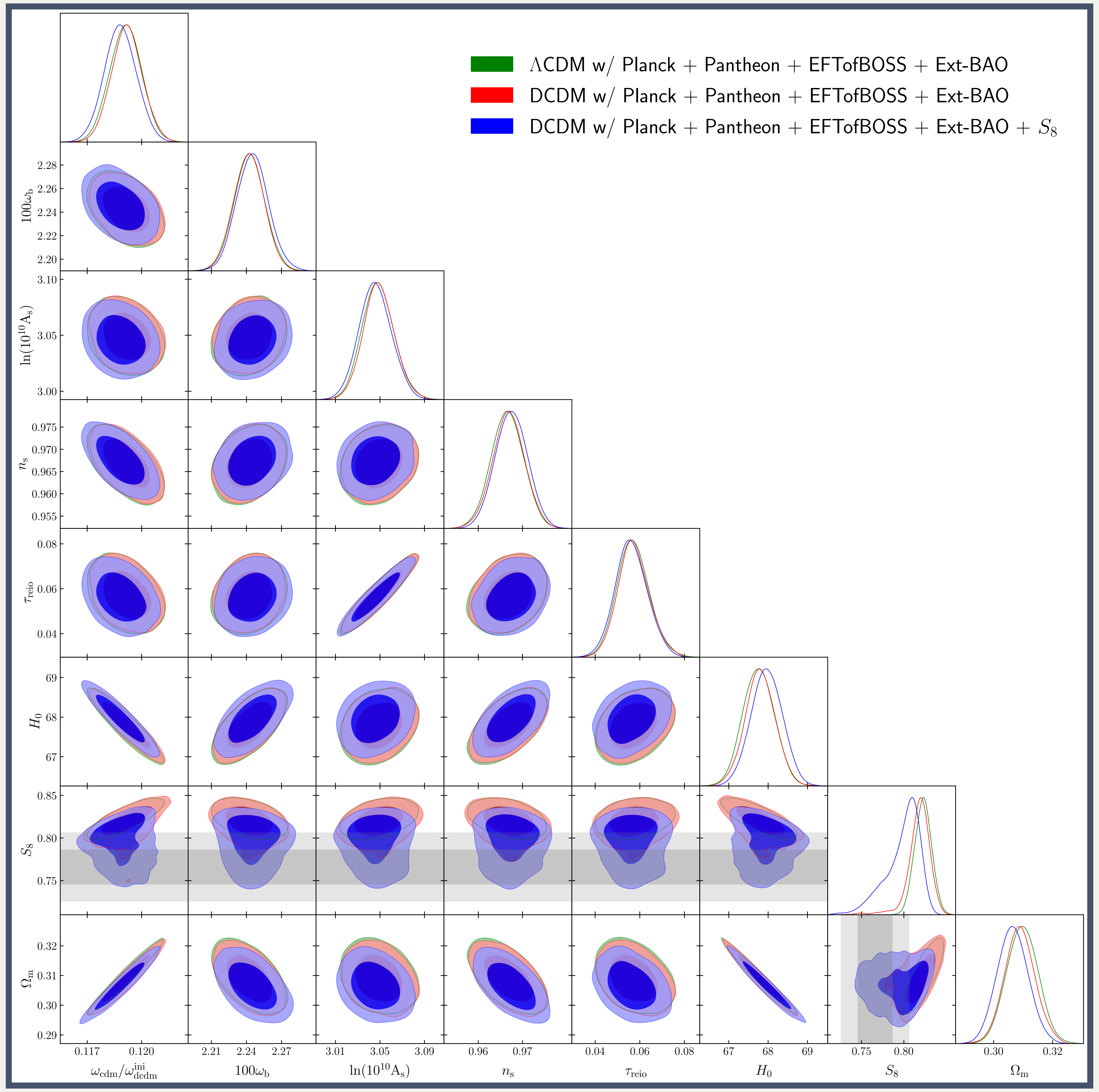


Backup III: DCDM → WDM+DR bestfit power spectrum

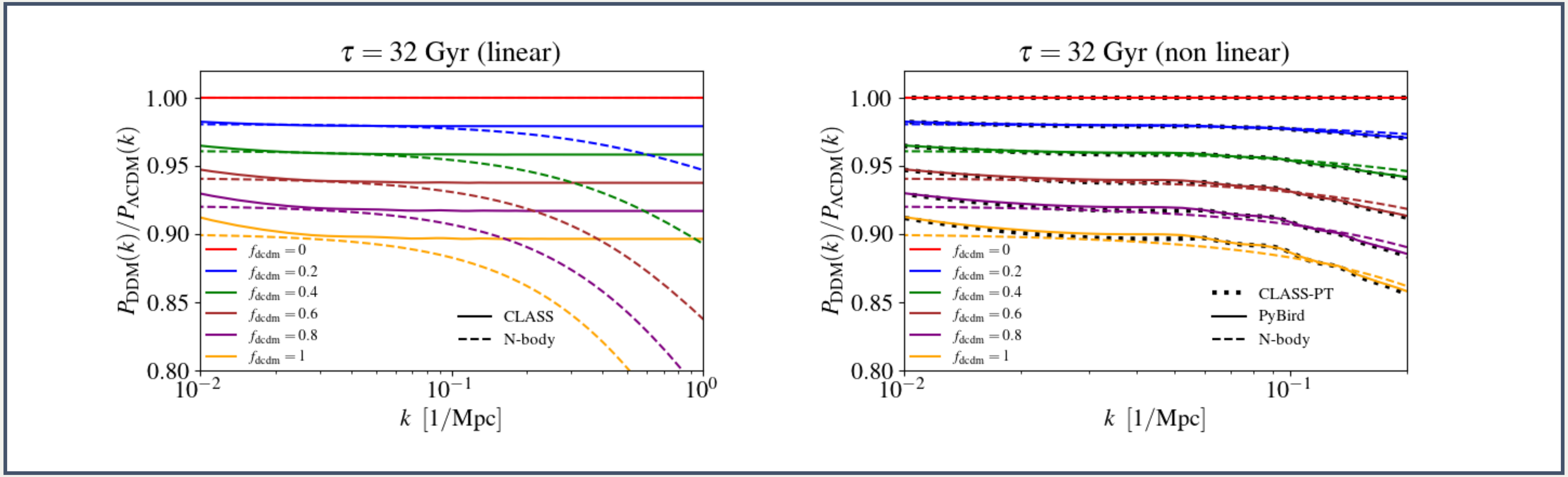


Backup IV: the DCDM → WDM+DR model and the S_8 tension

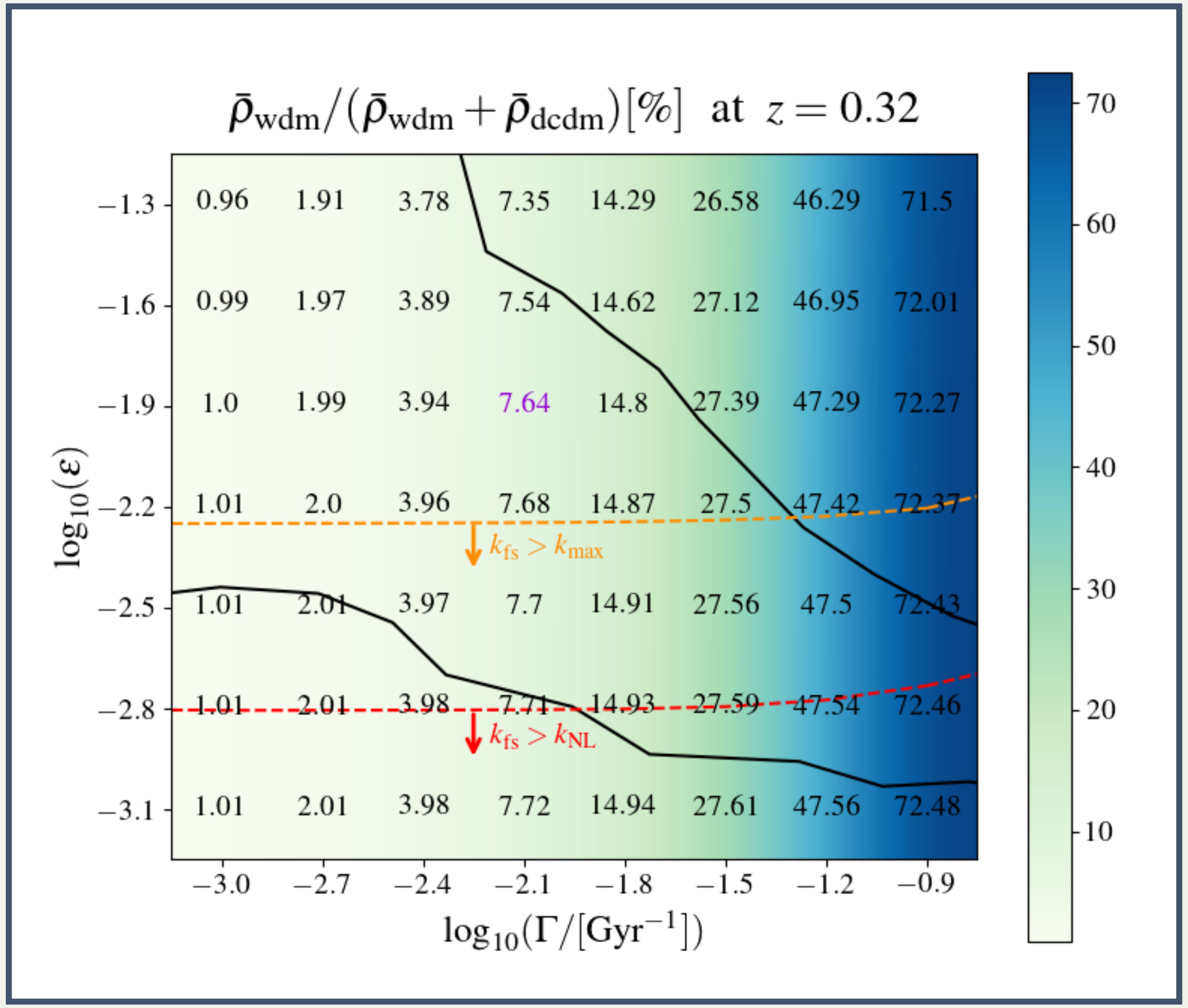


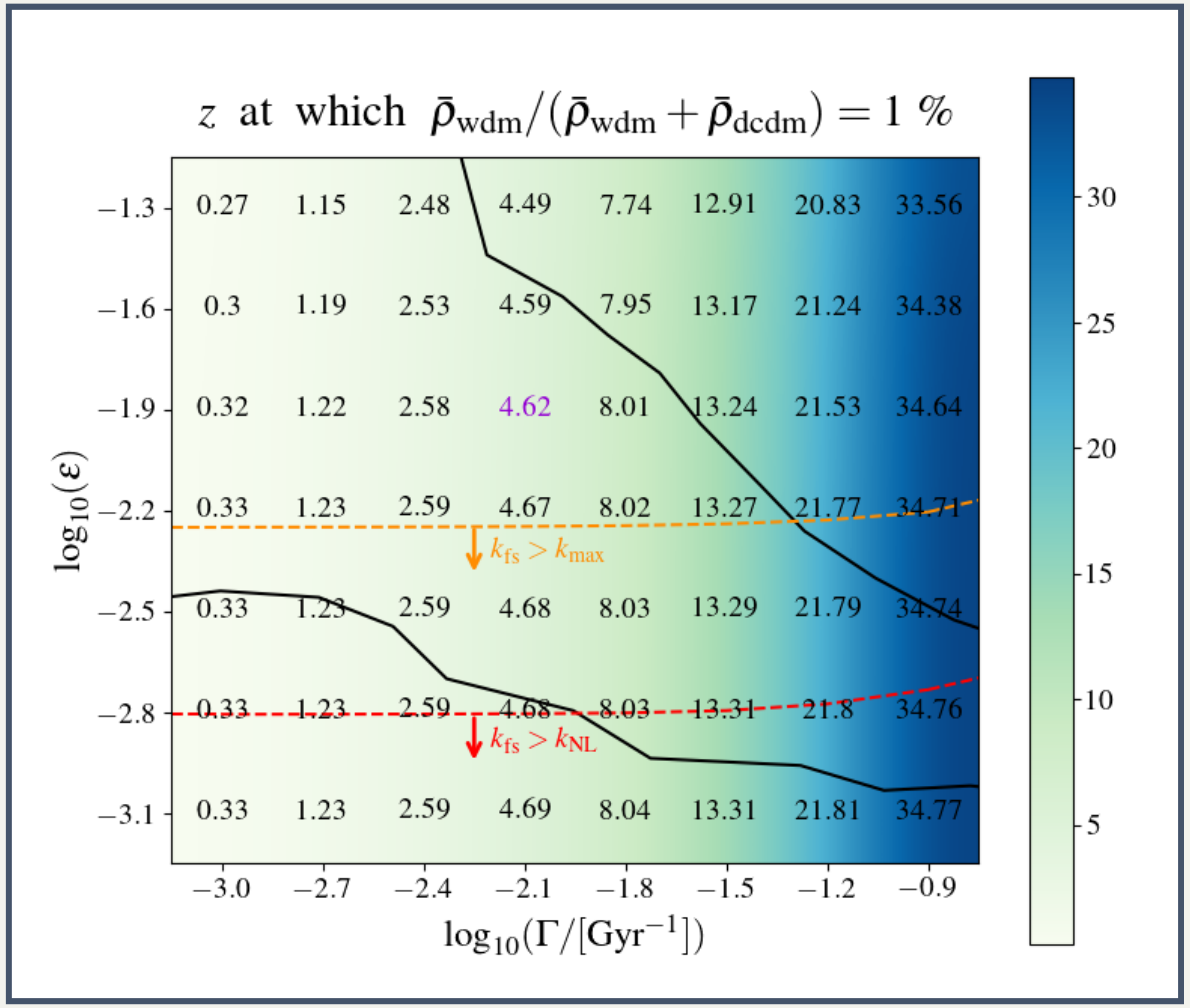


Backup V: EFTofLSS vs N-body simulations (DCDM → DR model)



Backup VI: validity of the EFTofLSS for the DCDM → WDM+DR model





Backup VII: EFTofLSS parameters

$$P(k,\mu) = Z_1(\mu)^2 P_{11}(k)$$
$$+ 2\int \frac{d^3q}{(2\pi)^3} Z_2(\mathbf{q},\mathbf{k}-\mathbf{q},\mu)^2 P_{11}(|\mathbf{k}-\mathbf{q}|)P_{11}(q) + 6Z_1(\mu)P_{11}(k)\int \frac{d^3q}{(2\pi)^3} Z_3(\mathbf{q},-\mathbf{q},\mathbf{k},\mu)P_{11}(q)$$
$$+ 2Z_1(\mu)P_{11}(k)\left(c_{\rm ct}\frac{k^2}{k_{\rm M}^2} + c_{r,1}\mu^2\frac{k^2}{k_{\rm M}^2} + c_{r,2}\mu^4\frac{k^2}{k_{\rm M}^2}\right) + \frac{1}{\bar{n}_g}\left(c_{\epsilon,0} + c_{\epsilon,1}\frac{k^2}{k_{\rm M}^2} + c_{\epsilon,2}f\mu^2\frac{k^2}{k_{\rm M}^2}\right), \qquad (10)$$

with

$$Z_1(\mathbf{q}_1) = K_1(\mathbf{q}_1) + f\mu_1^2 G_1(\mathbf{q}_1) = b_1 + f\mu_1^2,$$
$$Z_2(\mathbf{q}_1,\mathbf{q}_2,\mu) = K_2(\mathbf{q}_1,\mathbf{q}_2) + f\mu_{12}^2 G_2(\mathbf{q}_1,\mathbf{q}_2) + \frac{1}{2}f\mu q\left(\frac{\mu_2}{q_2}G_1(\mathbf{q}_2)Z_1(\mathbf{q}_1) + \text{perm.}\right),$$
$$Z_3(\mathbf{q}_1,\mathbf{q}_2,\mathbf{q}_3,\mu) = K_3(\mathbf{q}_1,\mathbf{q}_2,\mathbf{q}_3) + f\mu_{123}^2 G_3(\mathbf{q}_1,\mathbf{q}_2,\mathbf{q}_3)$$
$$+ \frac{1}{3}f\mu q\left(\frac{\mu_3}{q_3}G_1(\mathbf{q}_3)Z_2(\mathbf{q}_1,\mathbf{q}_2,\mu_{123}) + \frac{\mu_{23}}{q_{23}}G_2(\mathbf{q}_2,\mathbf{q}_3)Z_1(\mathbf{q}_1) + \text{cyc.}\right),$$

with

$$K_1 = b_1,$$
$$K_2(\mathbf{q}_1,\mathbf{q}_2) = b_1\frac{\mathbf{q}_1\cdot\mathbf{q}_2}{q_1^2} + b_2\left(F_2(\mathbf{q}_1,\mathbf{q}_2) - \frac{\mathbf{q}_1\cdot\mathbf{q}_2}{q_1^2}\right) + b_4 + \text{perm.},$$
$$K_3(k,q) = \frac{b_1}{504k^3q^3}\left(-38k^5q + 48k^3q^3 - 18kq^5 + 9(k^2-q^2)^3\log\left[\frac{k-q}{k+q}\right]\right)$$
$$+ \frac{b_3}{756k^3q^5}\left(2kq(k^2+q^2)(3k^4 - 14k^2q^2 + 3q^4) + 3(k^2-q^2)^4\log\left[\frac{k-q}{k+q}\right]\right)$$

10 parameters

4 parameters b_i ($i = 1,2,3,4$) to describe the **galaxy bias** which arises from the one-loop contributions.

3 parameters corresponding to **counterterms** (c_{ct} linear combination of a higher derivative bias and the dark matter sound speed, while $c_{r,1}$ and $c_{r,2}$ are the redshift-space counterterms).

3 parameters which describe **stochastic** terms.