

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

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Based on Phys. Rev. D **106**, 023516 [arXiv:2203.07440]

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*Théorie, Univers et Gravitation - 05/10/2022*

# The $S_8$ tension

A tension within the  $\Lambda$ CDM model

## $S_8$ parameter

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

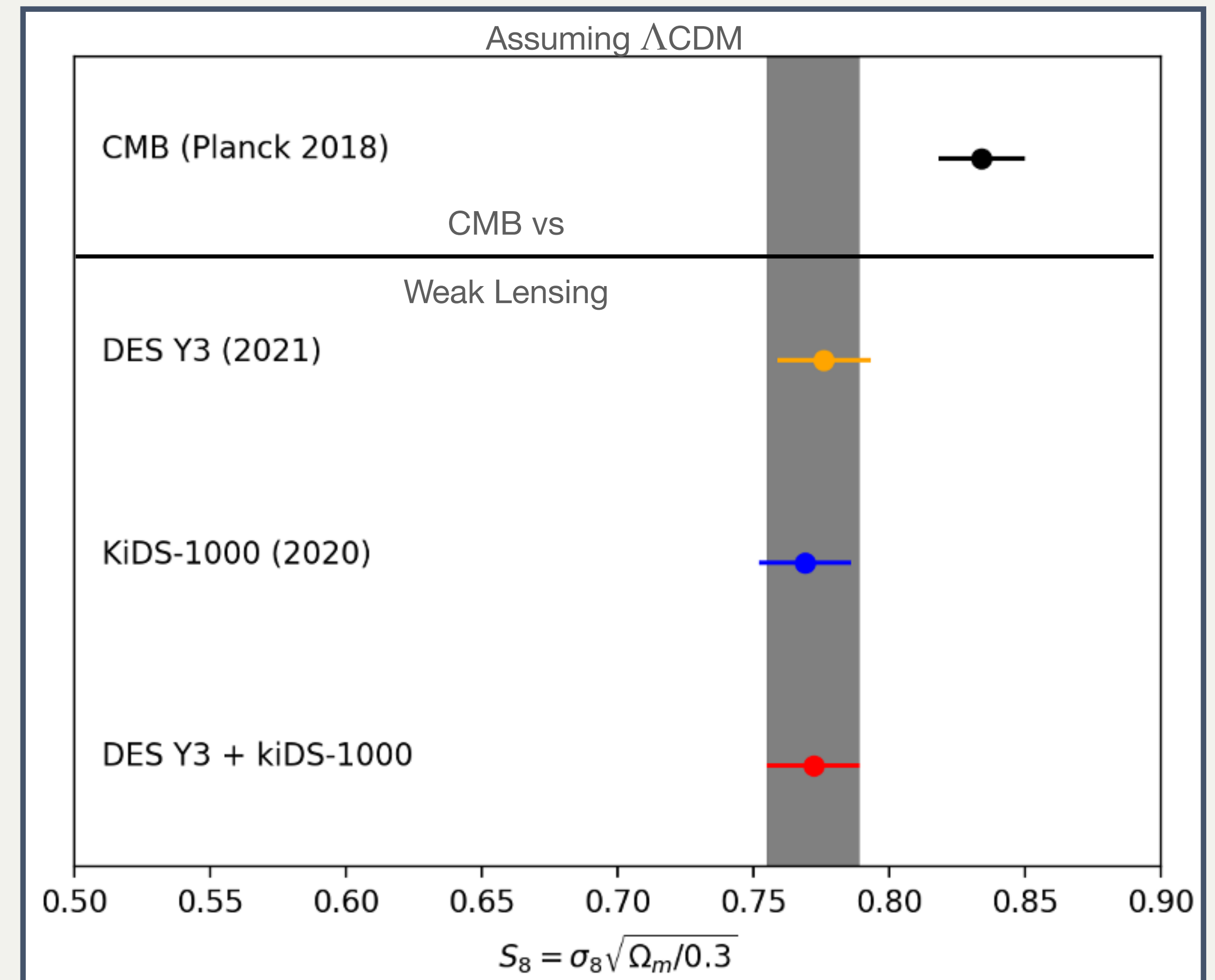
where:

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

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

→  $W_R$  is a « Window function »:

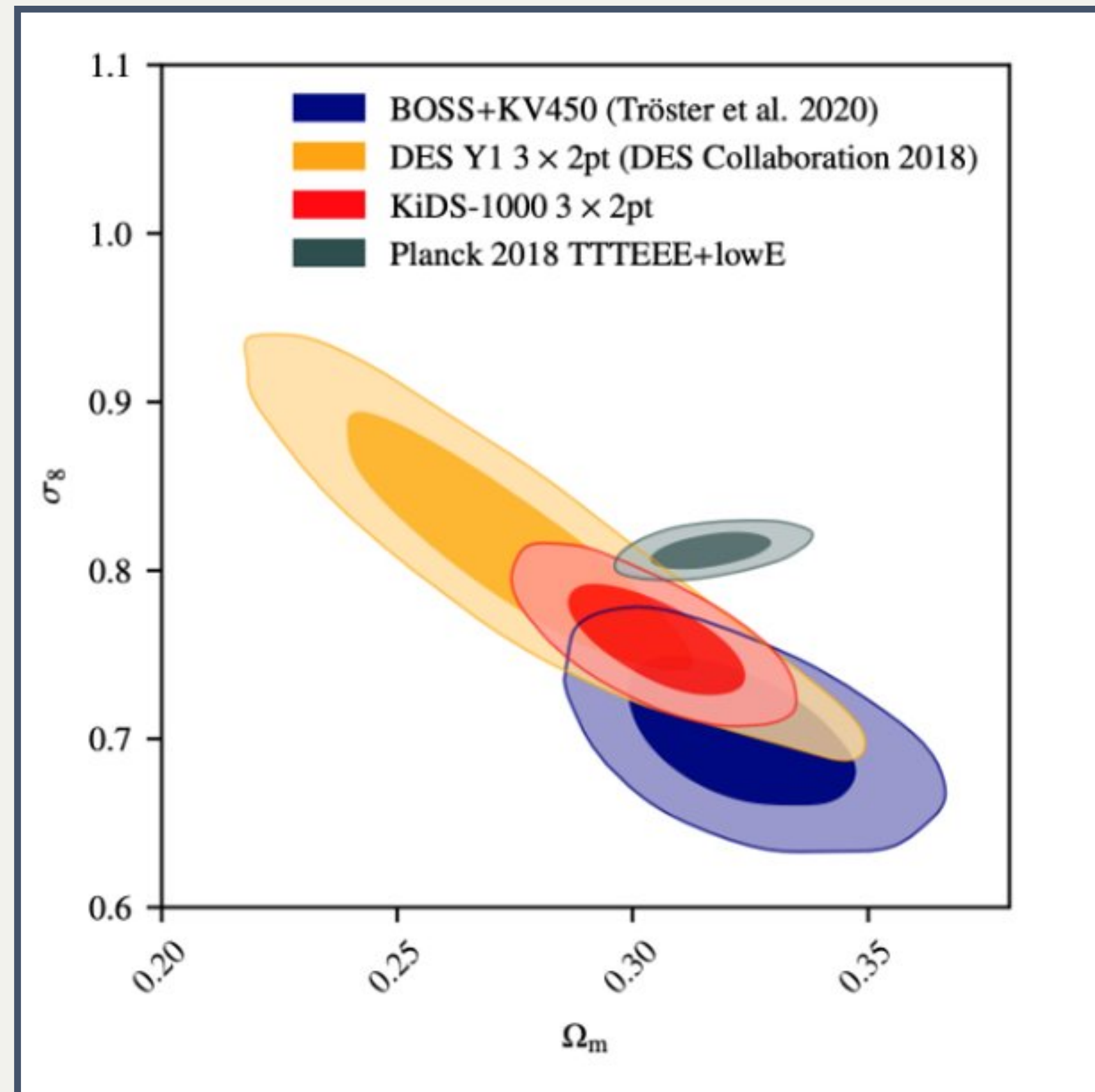
$$W_R = \frac{1}{4/3\pi R^3} \text{ for } r \leq R$$
$$W_R = 0 \text{ for } r > R$$



# The $\sigma_8$ tension and the matter power spectrum

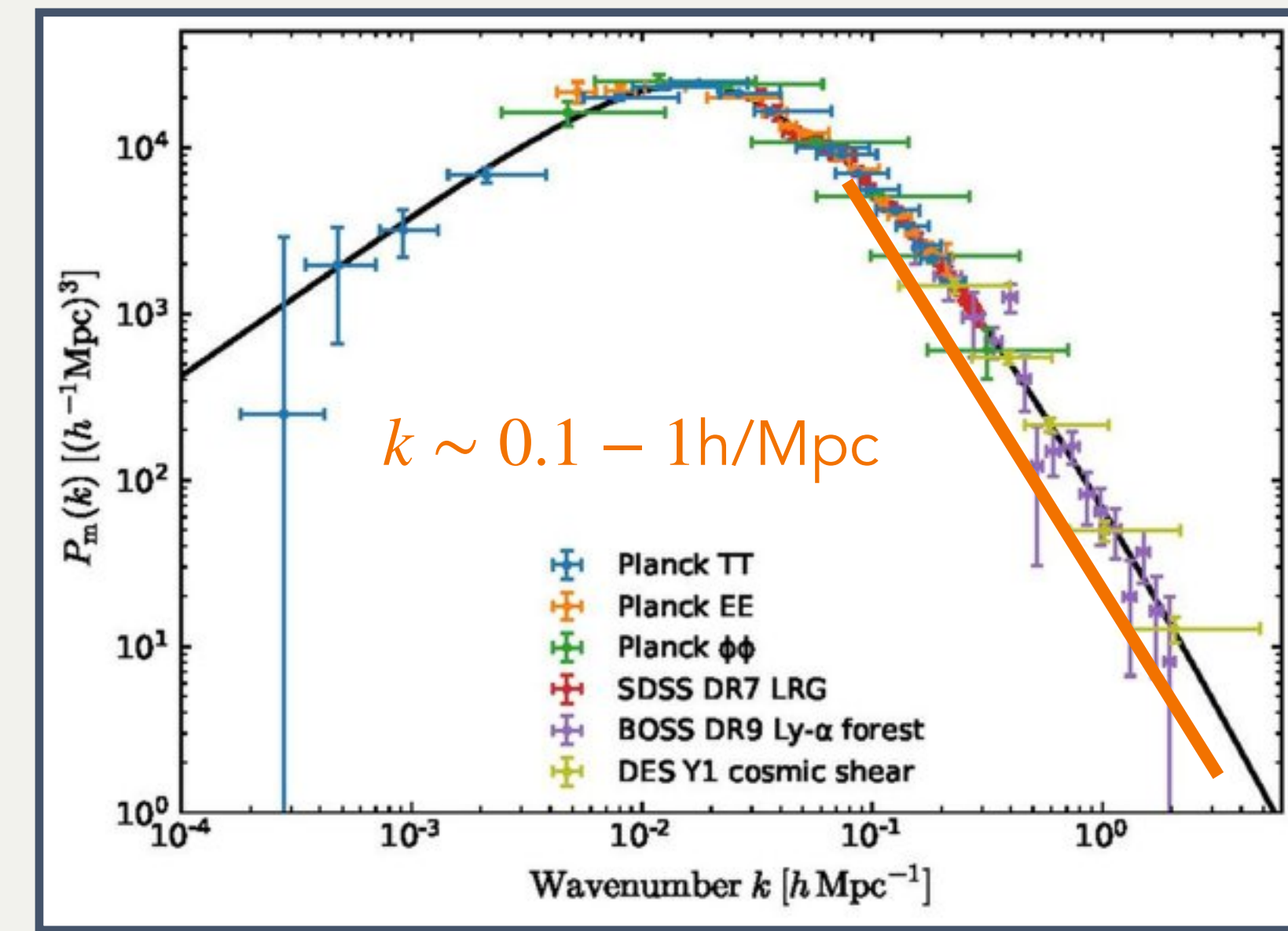
*A tension within the  $\Lambda$ CDM model*

Combining Galaxy Weak Lensing and clustering: the 3x2 statistics



$\sigma_8$  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

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

Lack of precision

[Kaiser '87]

$b_1$ : 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:

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



$$\begin{aligned} P_g(k, \mu) = & Z_1(\mu)^2 P_{11}(k) + 2Z_1(\mu) P_{11}(k) \left( c_{\text{ct}} \frac{k^2}{k_M^2} + c_{r,1} \mu^2 \frac{k^2}{k_M^2} + c_{r,2} \mu^4 \frac{k^2}{k_M^2} \right) \\ & + 2 \int \frac{d^3q}{(2\pi)^3} Z_2(\mathbf{q}, \mathbf{k} - \mathbf{q}, \mu) P_{11}(|\mathbf{k} - \mathbf{q}|) P_{11}(q) + 6Z_1(\mu) P_{11}(k) \int \frac{d^3q}{(2\pi)^3} Z_3(\mathbf{q}, -\mathbf{q}, \mathbf{k}, \mu) P_{11}(q) \\ & + \frac{1}{\bar{n}_g} \left( c_{\epsilon,0} + c_{\epsilon,1} \frac{k^2}{k_M^2} + c_{\epsilon,2} f \mu^2 \frac{k^2}{k_M^2} \right), \end{aligned}$$

[Perko et al. '16]

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

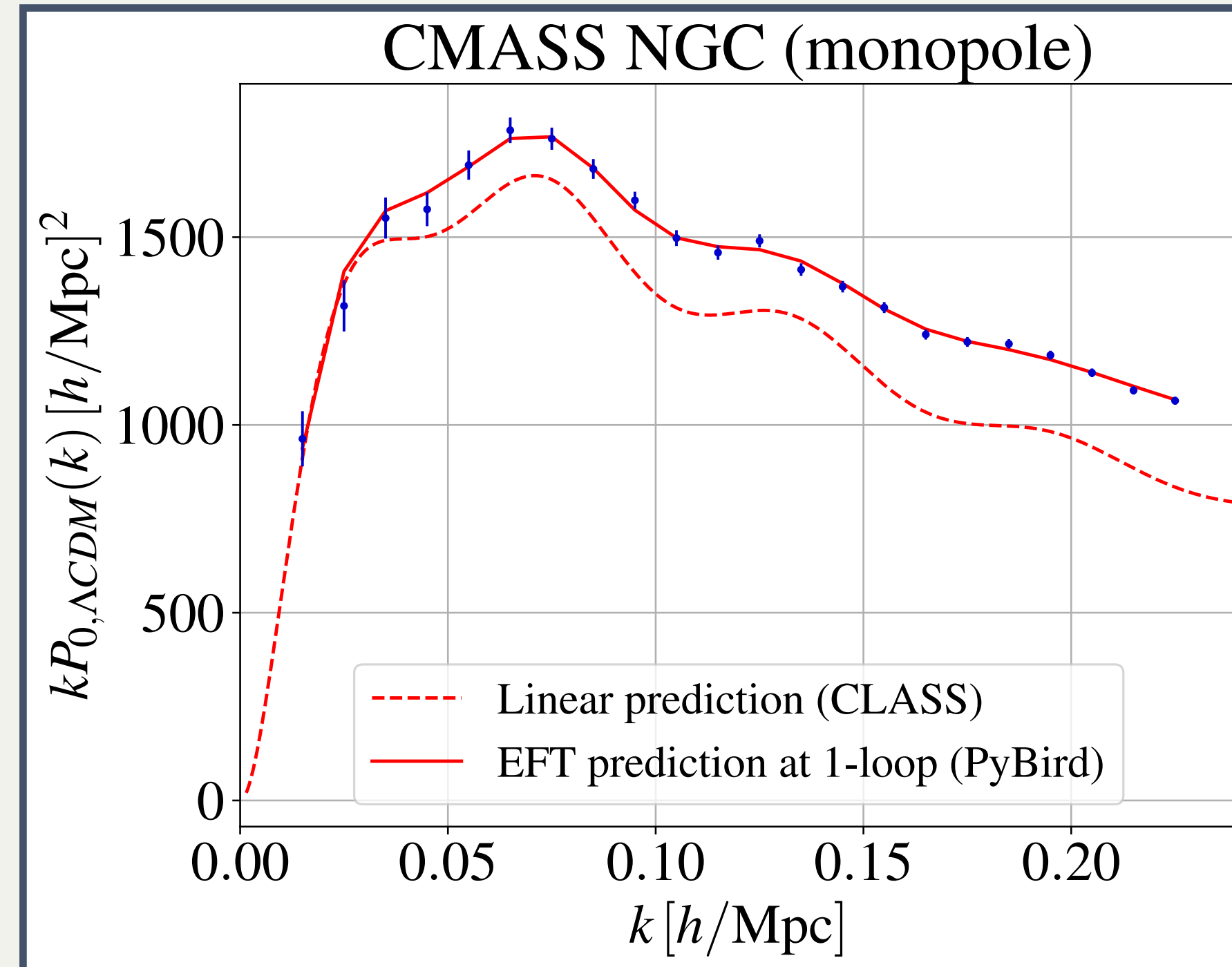
# The effective field theory of large-scale structures (EFTofLSS)

BOSS data

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

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

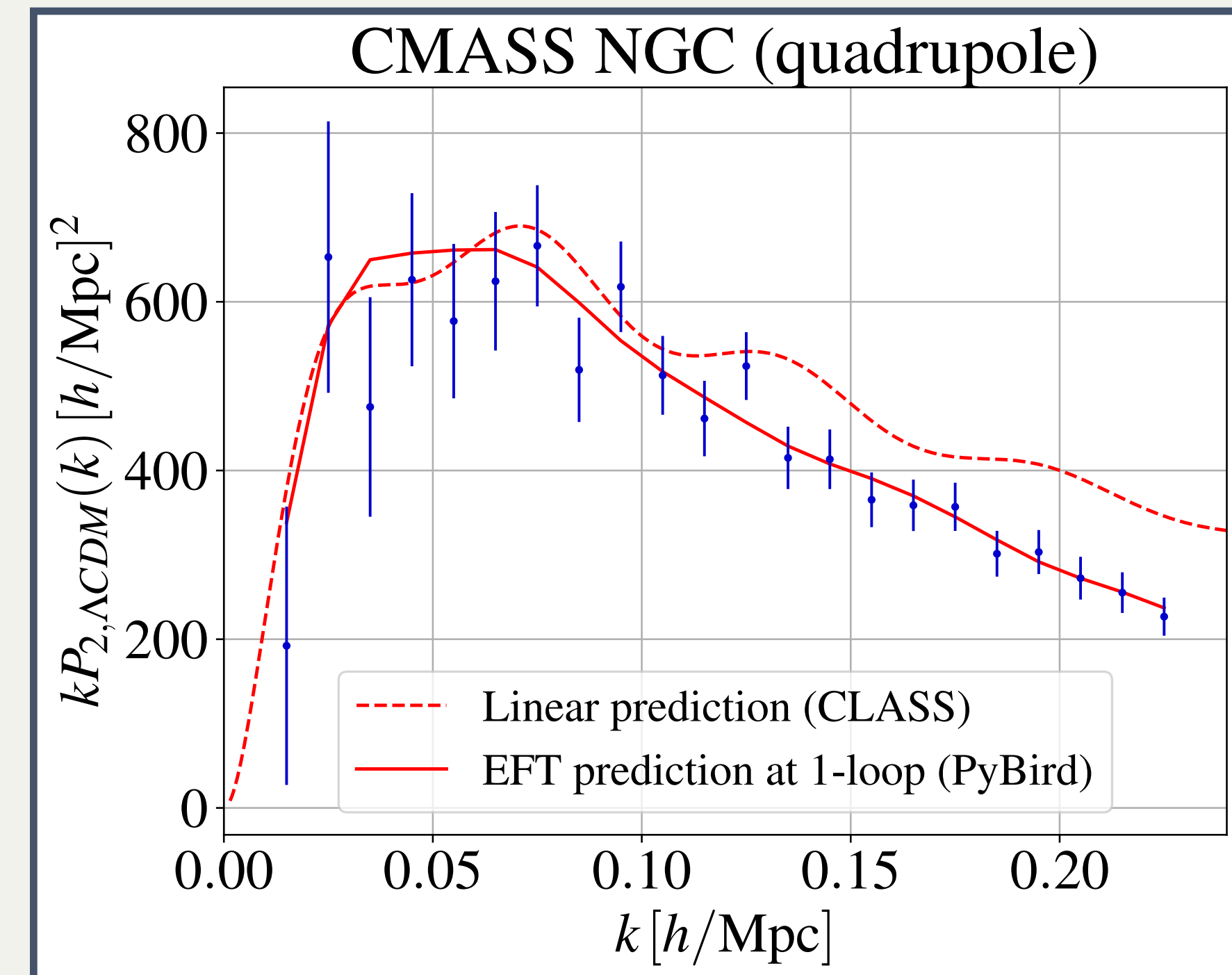
→ two main contributions to  $P_g(z, k, \mu)$  are the **monopole** ( $\ell = 0$ ) and the **quadrupole** ( $\ell = 2$ ).



[Colas et al. '19, Zhang et al. '21]

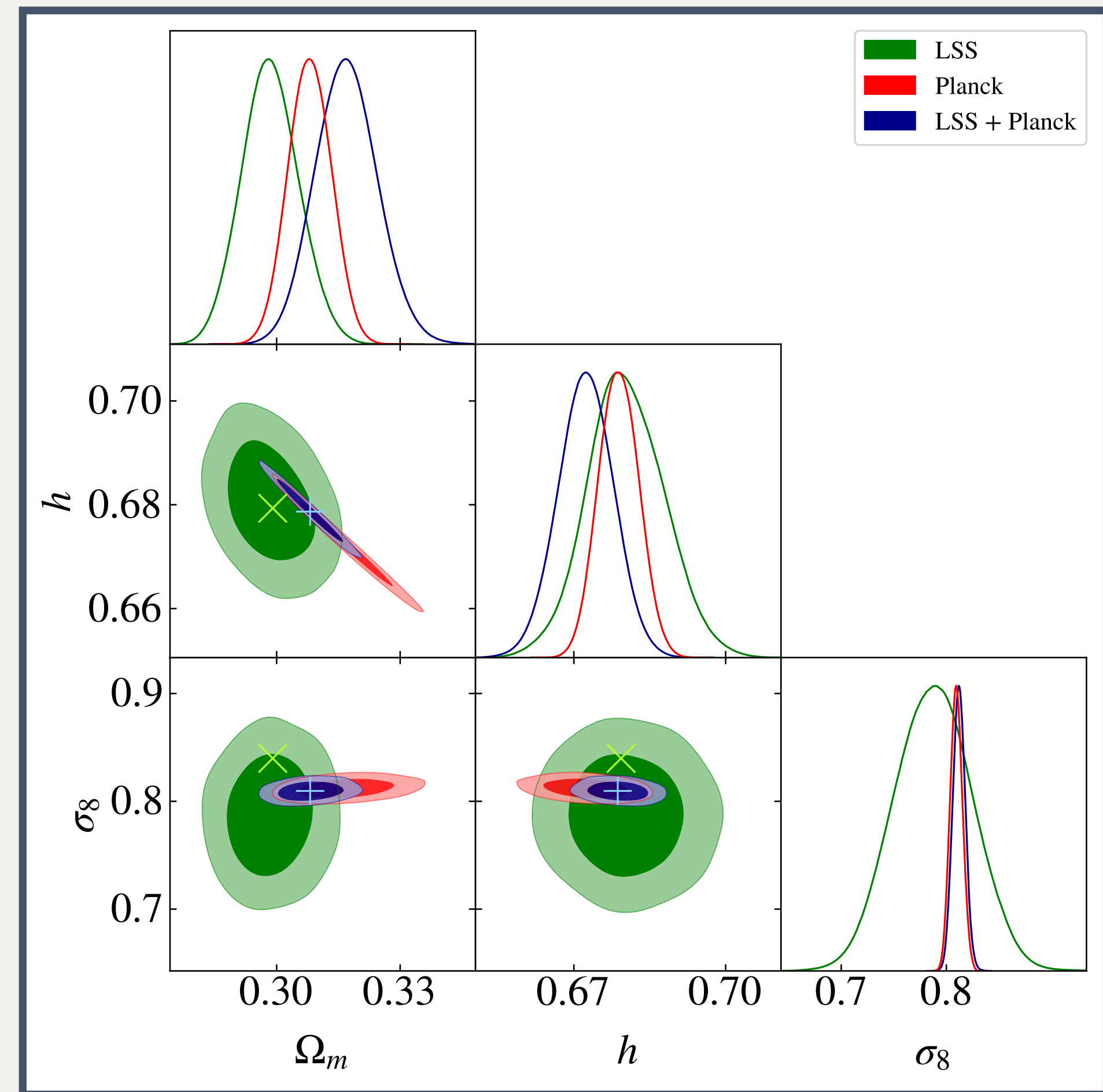
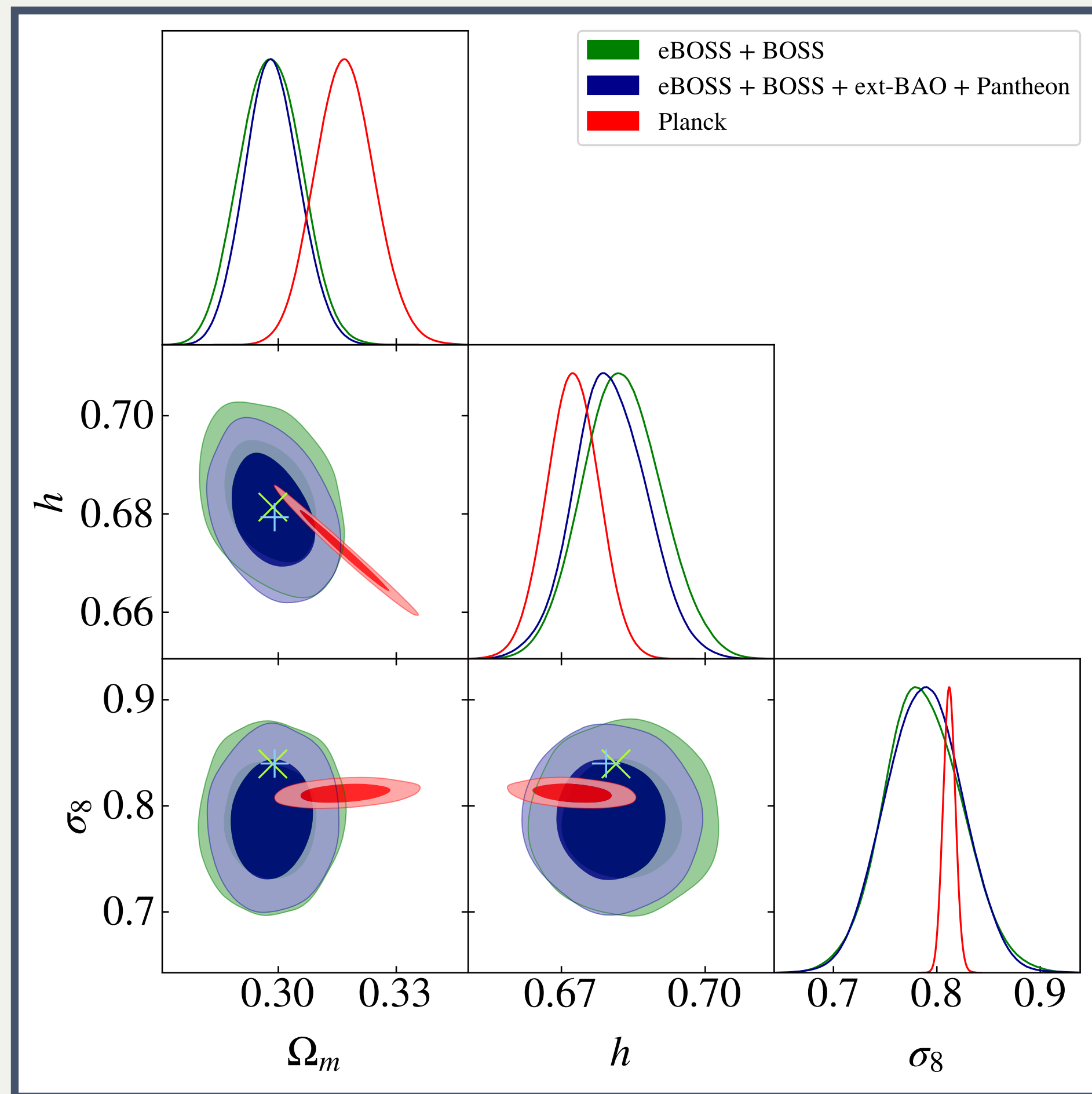
See also [TS et al. '22, arXiv:2208.05929]

Made with PyBird: [github.com/pierrexyz/pybird](https://github.com/pierrexyz/pybird)



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

*LSS data vs Planck*



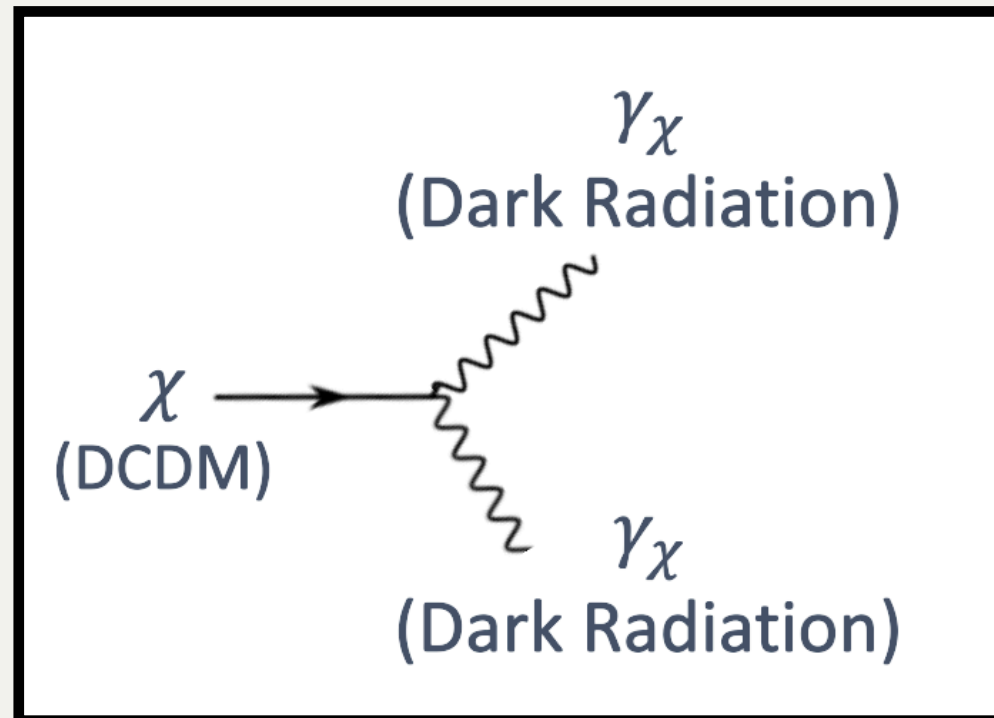
# The $\Lambda$ CDM $\rightarrow$ DR model

Presentation of the model

## The model

$\rightarrow$  **Extension** of the  $\Lambda$ CDM model.

$\rightarrow$  **Decay process** :

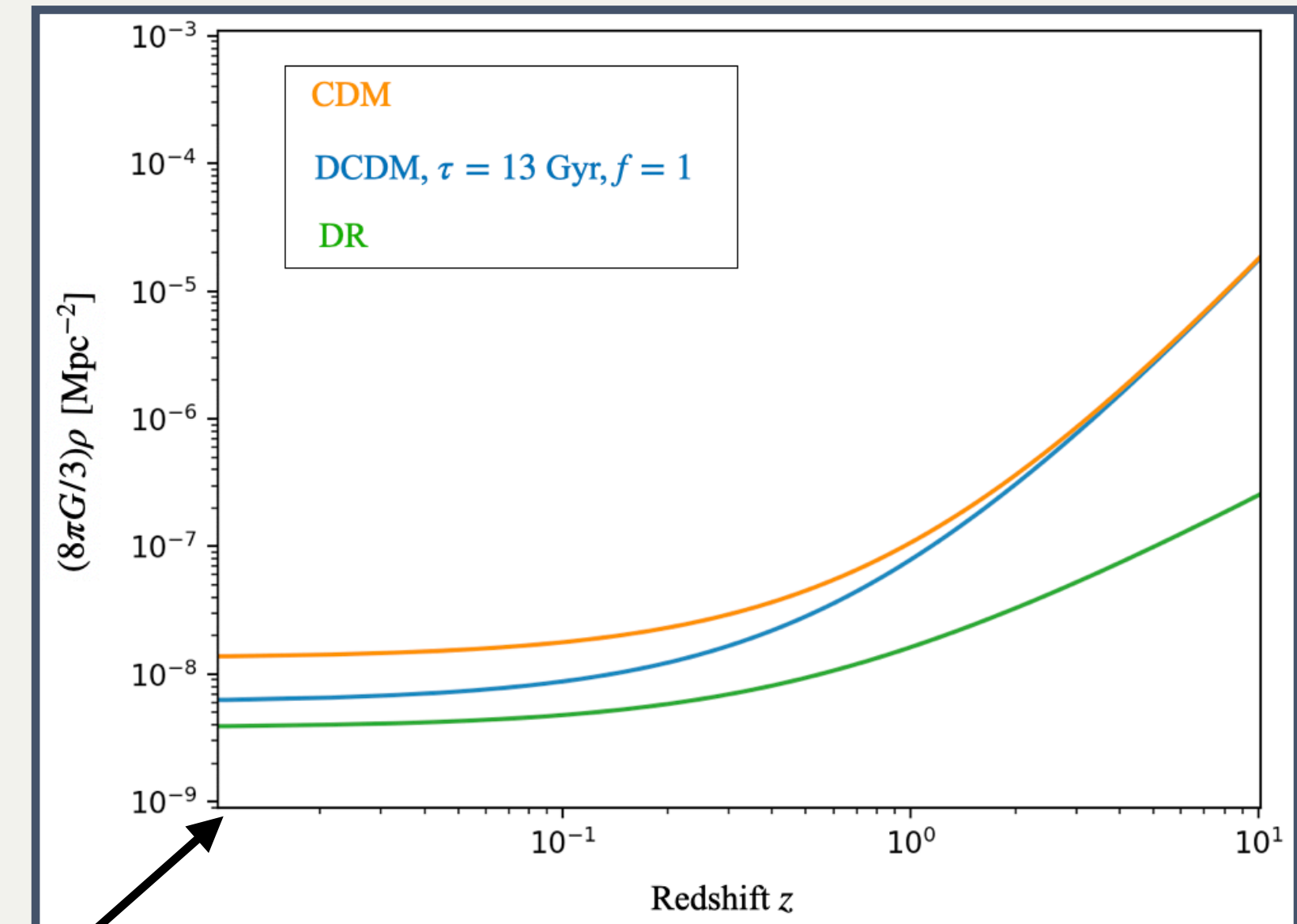


$\rightarrow$  DCDM  $\sim$   $\Lambda$ CDM + 2 parameters:

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

$$\begin{aligned}\dot{\bar{\rho}}_{\text{dcdm}} + 3\mathcal{H}\bar{\rho}_{\text{dcdm}} &= -a\Gamma\bar{\rho}_{\text{dcdm}} \\ \dot{\bar{\rho}}_{\text{dr}} + 4\mathcal{H}\bar{\rho}_{\text{dr}} &= a\Gamma\bar{\rho}_{\text{dcdm}}\end{aligned}$$



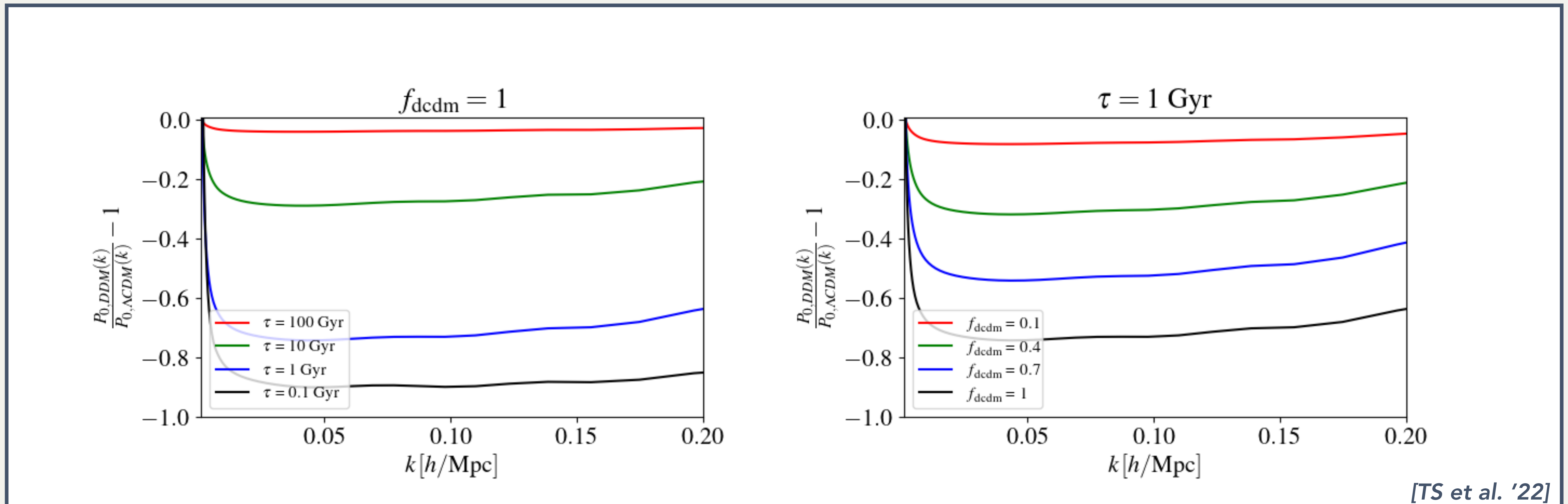
Today



# The $\Lambda$ CDM $\rightarrow$ DR model

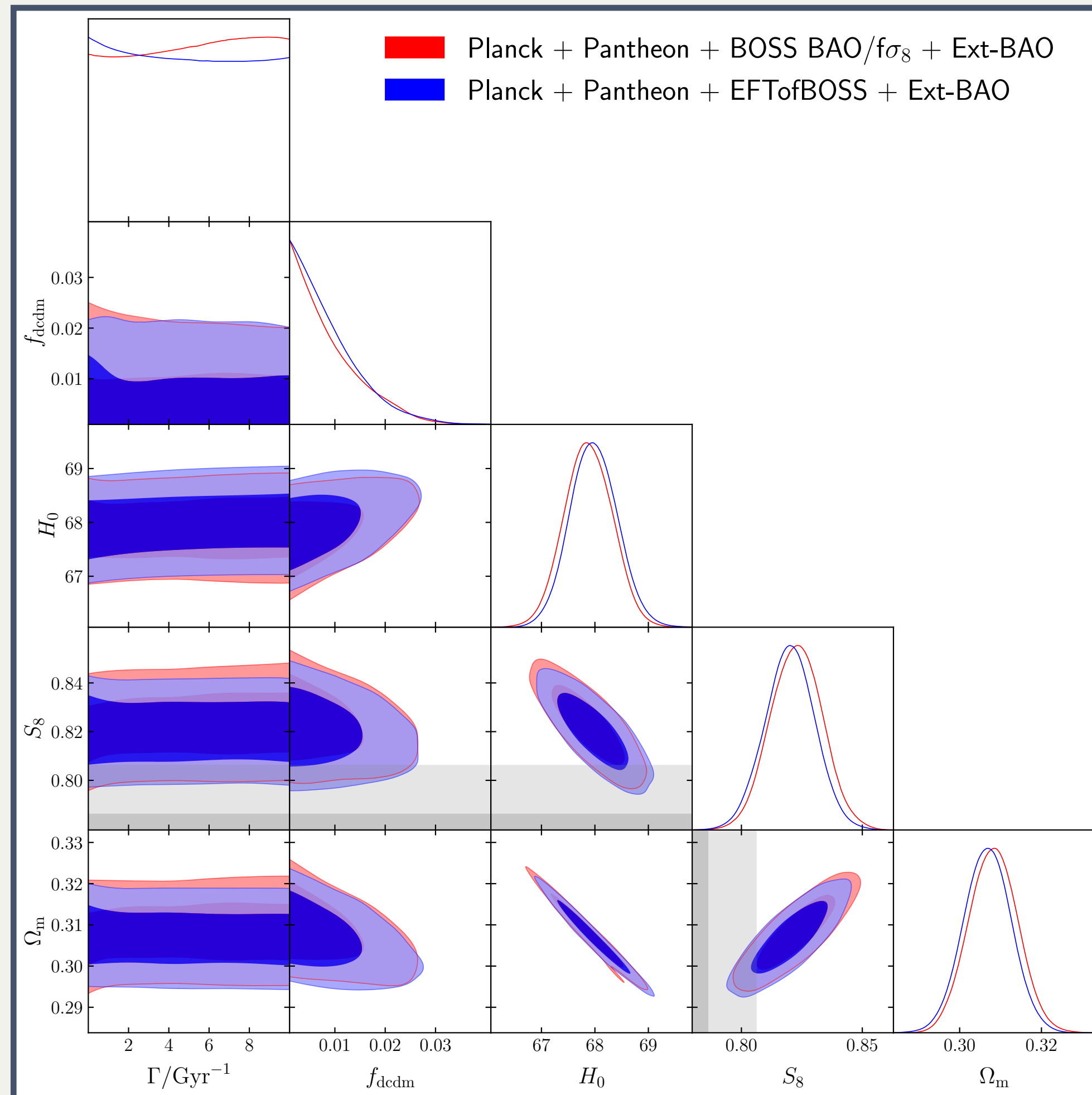
Results: galaxy power spectrum

- $\rightarrow$  At level of perturbations in the synchronous gauge co-moving with  $\Lambda$ CDM:  $\Lambda$ CDM perturbations are unchanged! We consider homogeneous decays.
- $\rightarrow$  The effect is dominated by the decrease of  $\Omega_m$  at the **background** (effect of daughter radiation is minor).



# The $\Lambda$ CDM $\rightarrow$ DR model

Results: constraints



[TS et al. '22]

## 3 main results

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

1. We derive the most up-to-date constraints
  - $\tau > 250.0 \text{ Gyr}$  for  $f = 1$
  - $f < 0.0216$  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

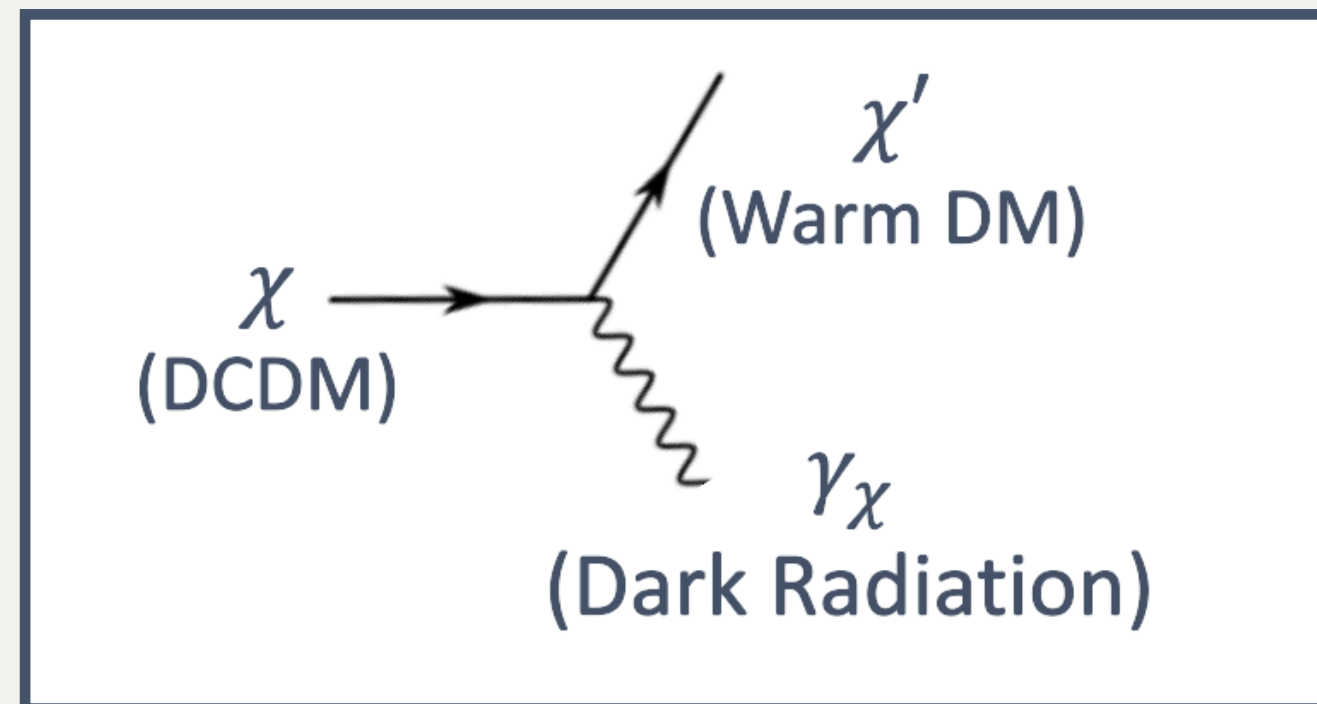
# The DCDM → WDM+DR model

Presentation of the model

## The model

→ **Extension** of the  $\Lambda$ CDM model.

→ **Decay process** :



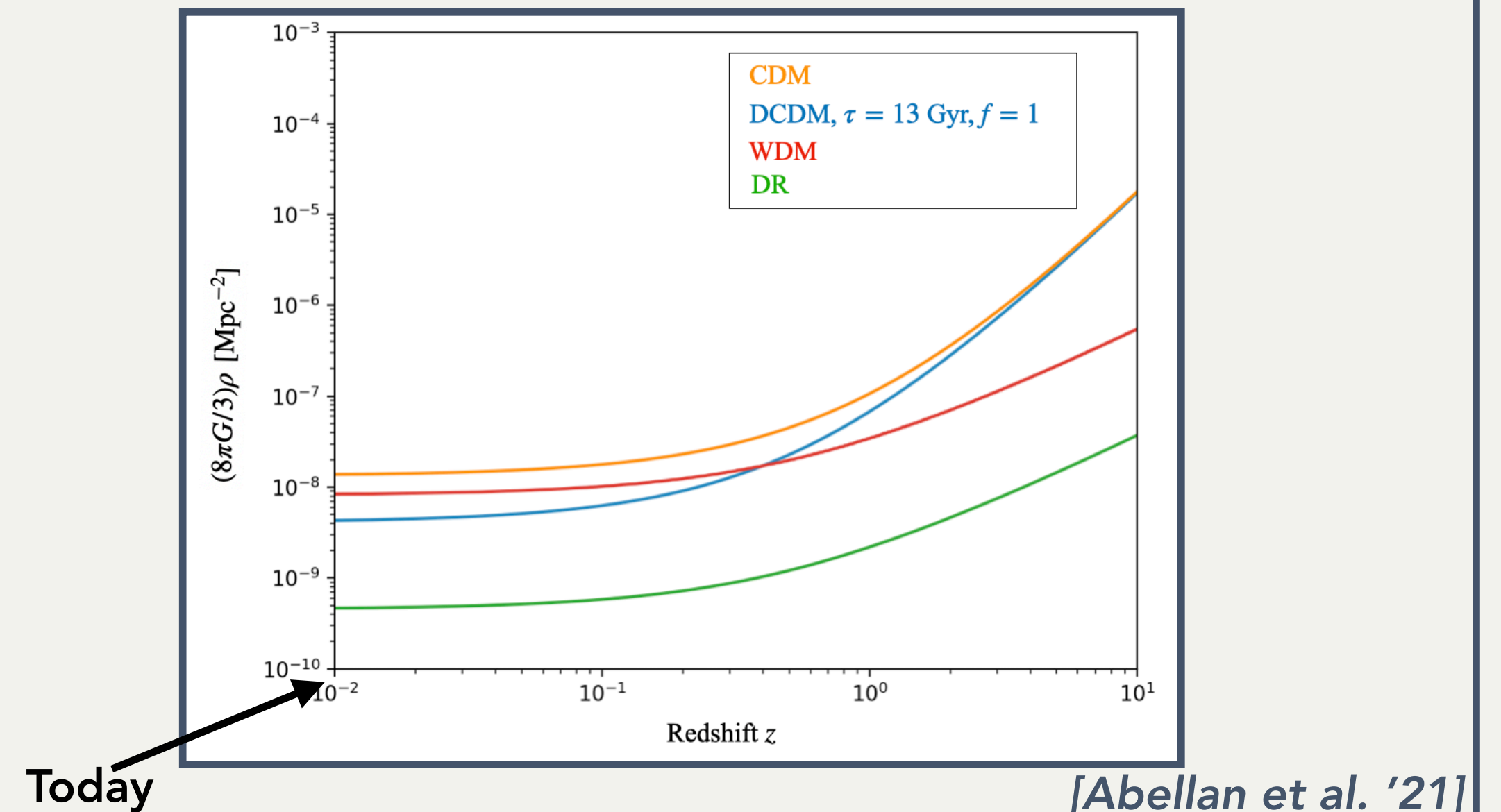
→ DCDM  $\sim \Lambda$ CDM + 2 parameters:

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

## Evolution of the energy densities

$$\begin{aligned} \dot{\bar{\rho}}_{\text{dcdm}} + 3\mathcal{H}\bar{\rho}_{\text{dcdm}} &= -a\Gamma\bar{\rho}_{\text{dcdm}} \\ \dot{\bar{\rho}}_{\text{dr}} + 4\mathcal{H}\bar{\rho}_{\text{dr}} &= \varepsilon\Gamma a\bar{\rho}_{\text{dcdm}} \\ \dot{\bar{\rho}}_{\text{wdm}} + 3(1+w)\mathcal{H}\bar{\rho}_{\text{wdm}} &= (1-\varepsilon)a\Gamma\bar{\rho}_{\text{dcdm}} \end{aligned}$$

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



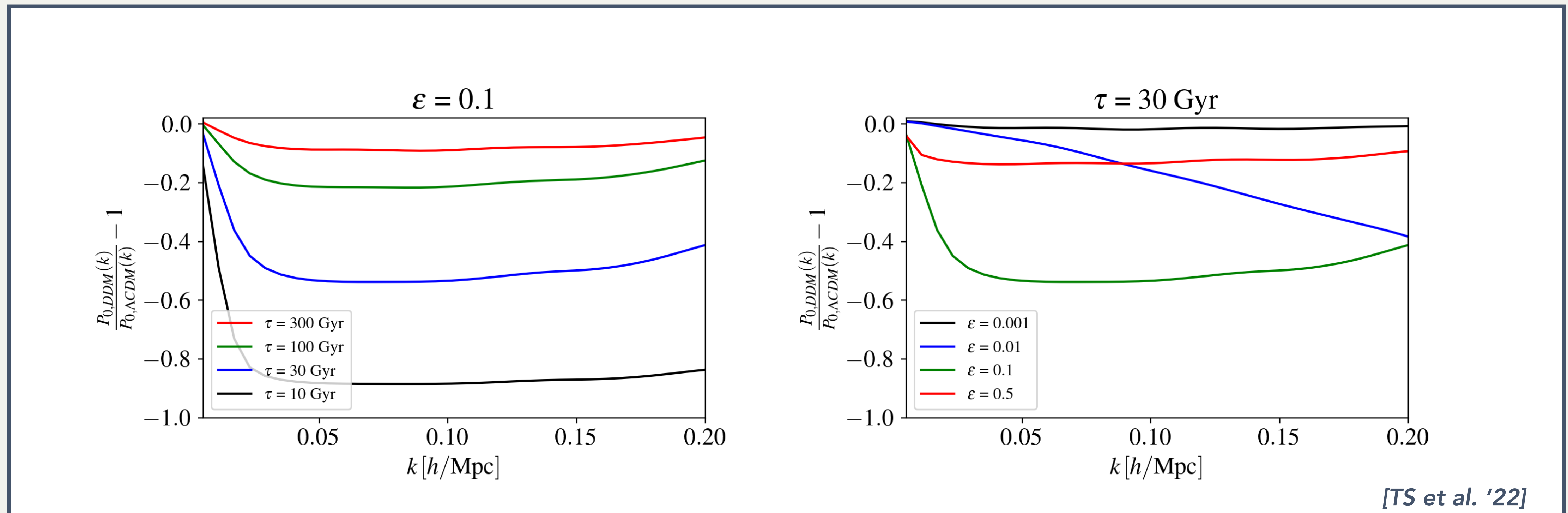
# The $\Lambda$ CDM $\rightarrow$ WDM+DR model

Results: galaxy power spectrum

$\rightarrow$  The effect **is not** dominated by a background effect

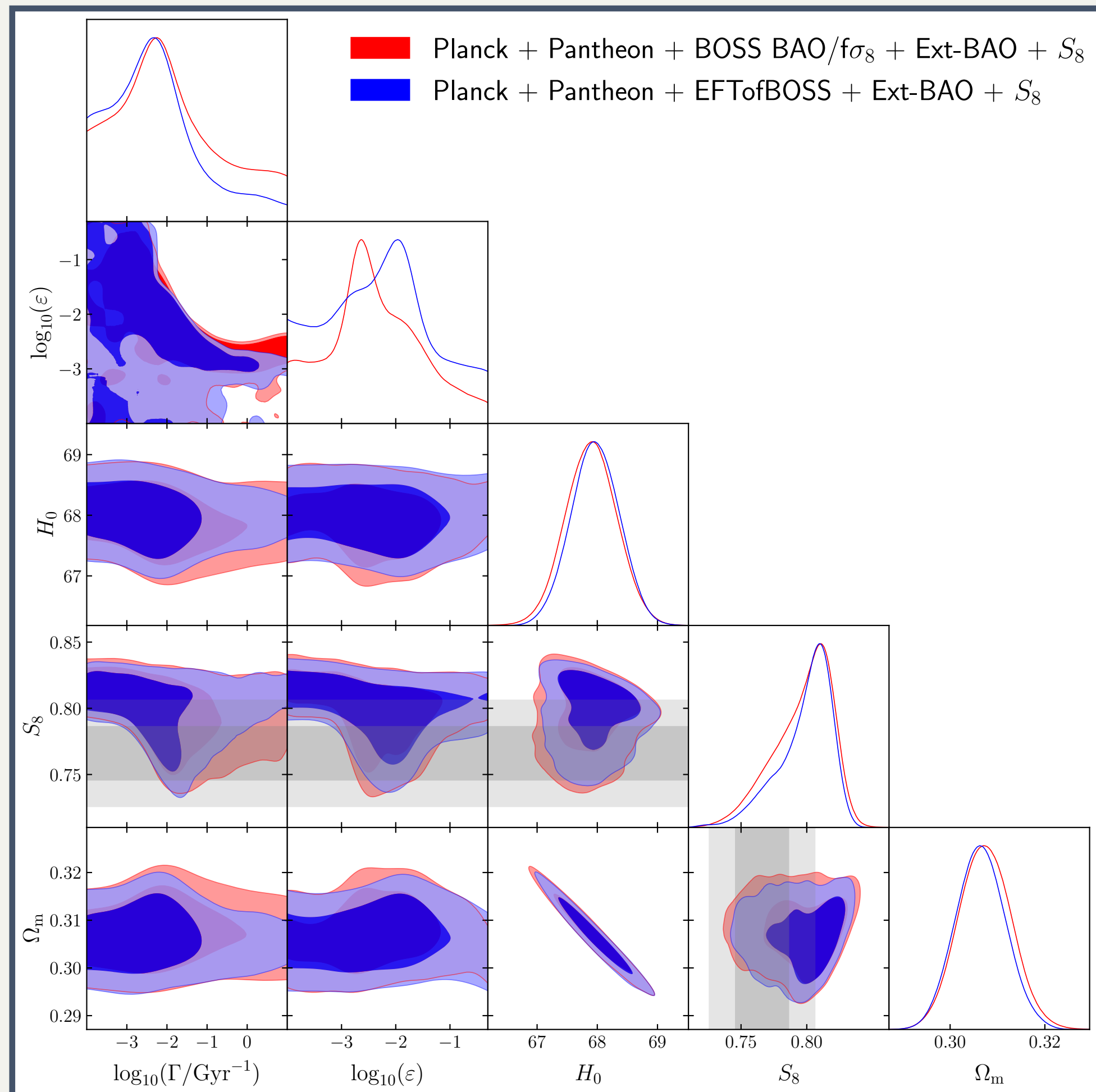
$\rightarrow$  WDM perturbed continuity equation :

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



# The $\Lambda$ CDM $\rightarrow$ WDM+DR model

Results: constraints



[TS et al. '22]

## 3 main results

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

1. This model **could resolve** the  $S_8$  tension!
2. The EFTofBOSS data **improve the constraints** on  $\tau$ :

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

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

3. It changes the **bestfit**:

$$\tau = 43 \text{ Gyr} \rightarrow \tau = 120 \text{ Gyr}$$

$$\epsilon = 0.6\% \rightarrow \epsilon = 1.2\%$$

# Conclusions and Perspectives

## Main results

→ EFTofLSS applied to BOSS (and eBOSS) data can have **constraining power** on alternative models to  $\Lambda$ CDM.

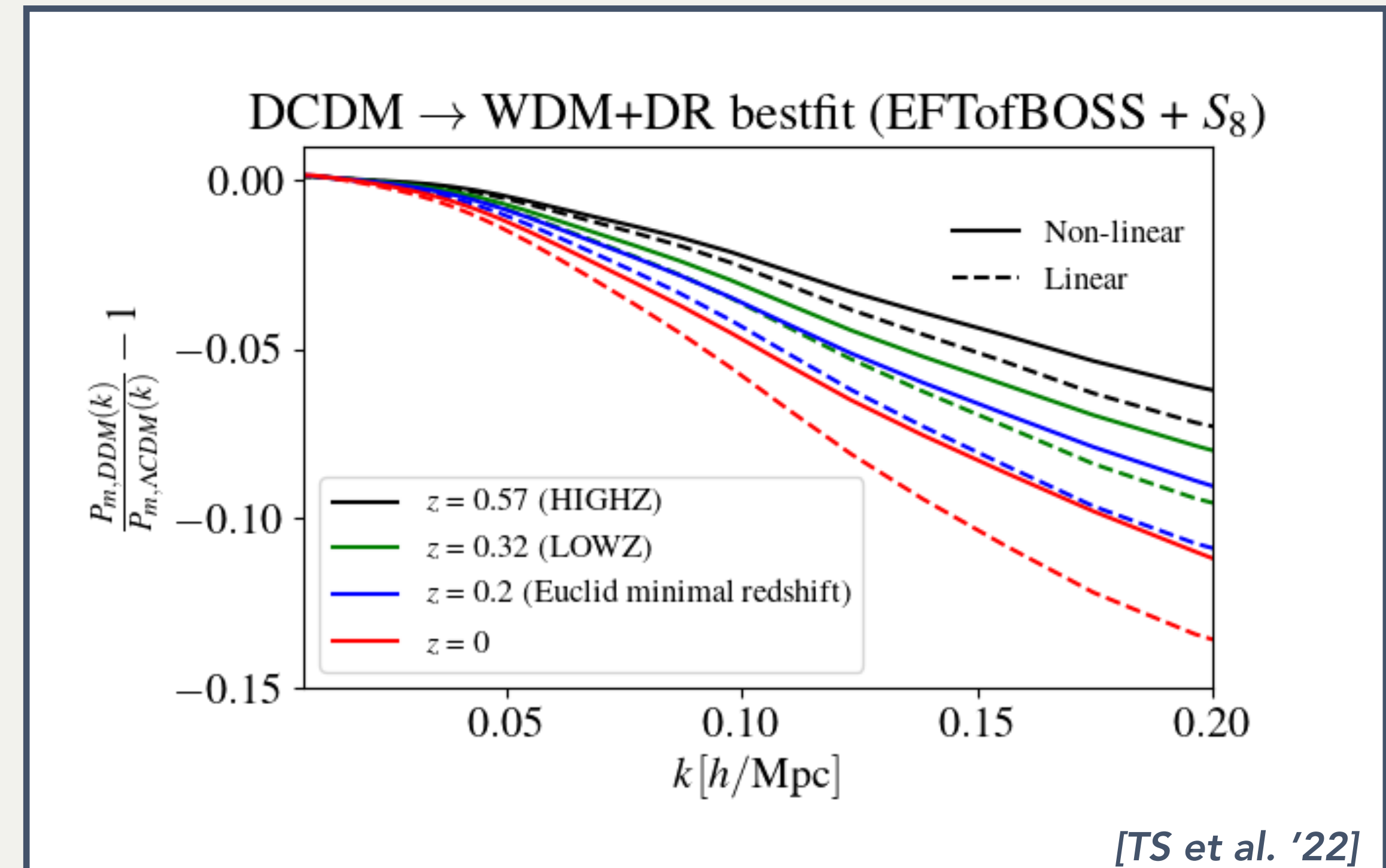
*See also [TS et al. '22, arXiv:2208.05930]*

→ We derive strong constraints on DCDM  $\rightarrow$  DR model:

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

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

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



The suppression increase with the redshift  $\rightarrow$  It will be interesting to have data at small redshift

# Thanks for your attention

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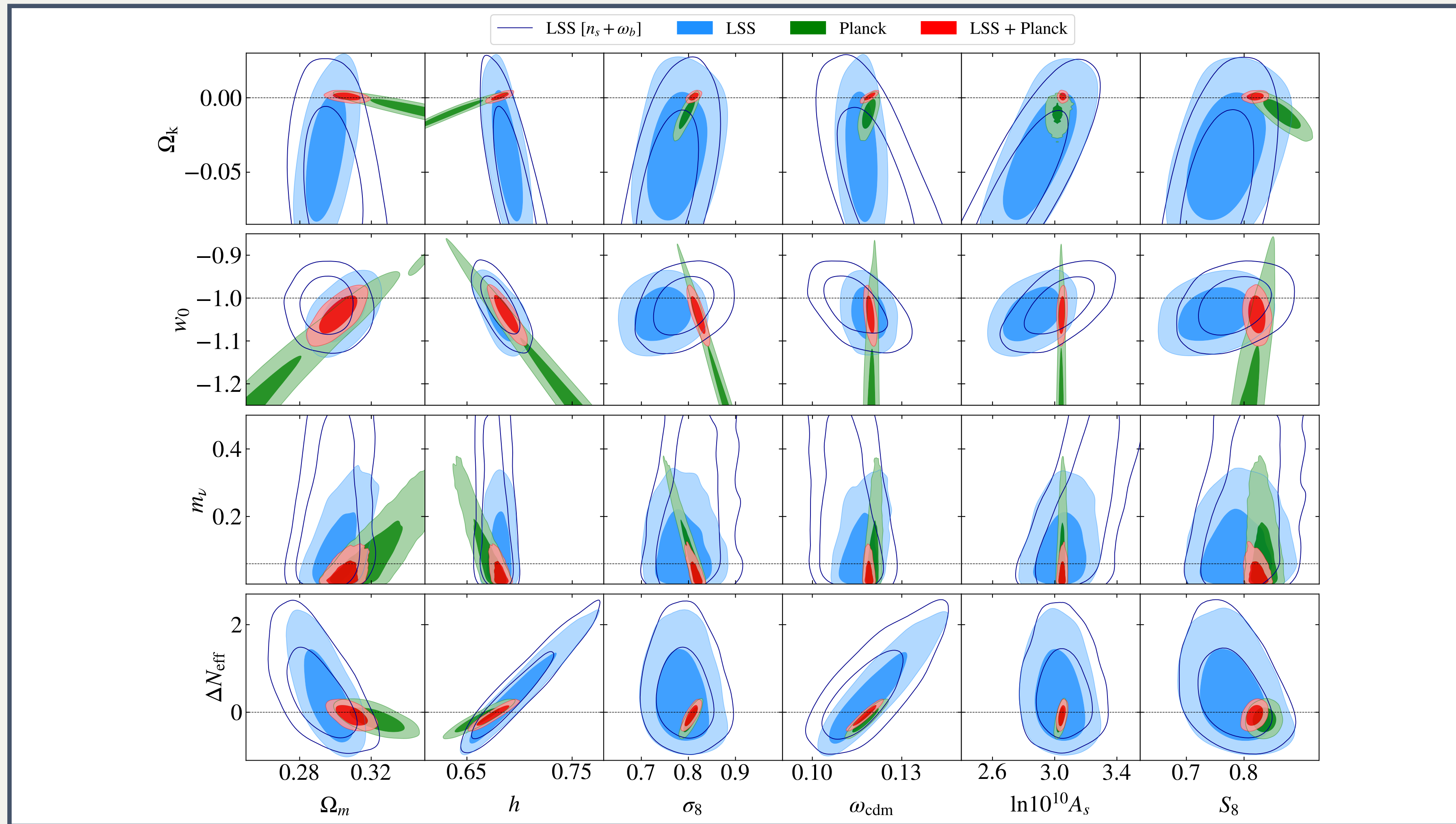


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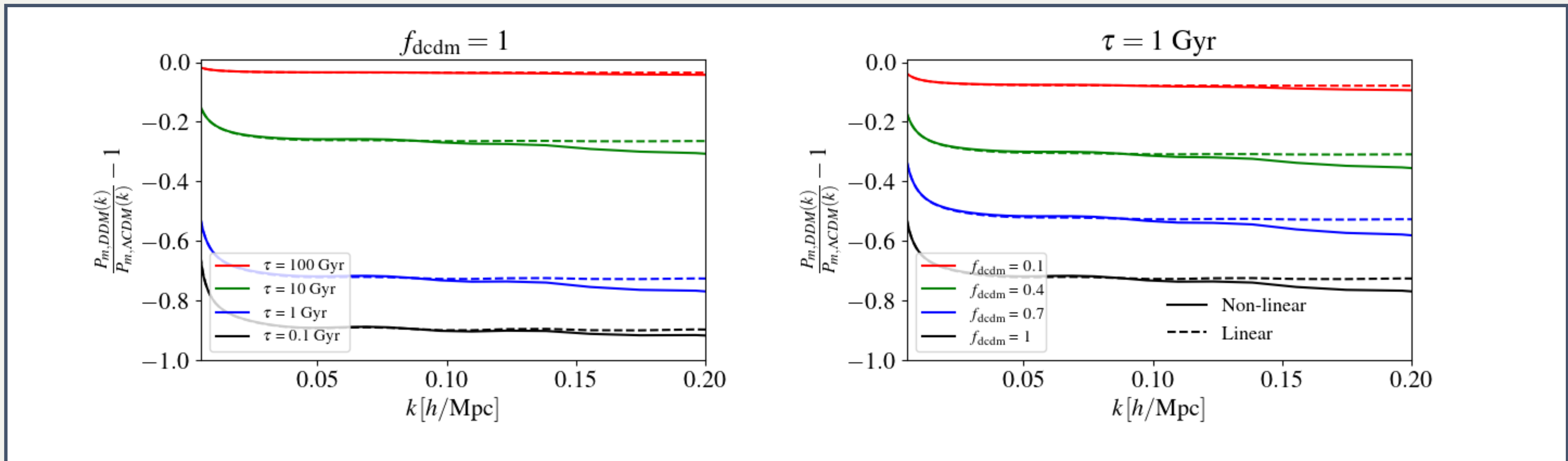
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# Backup I: Extensions to $\Lambda$ CDM

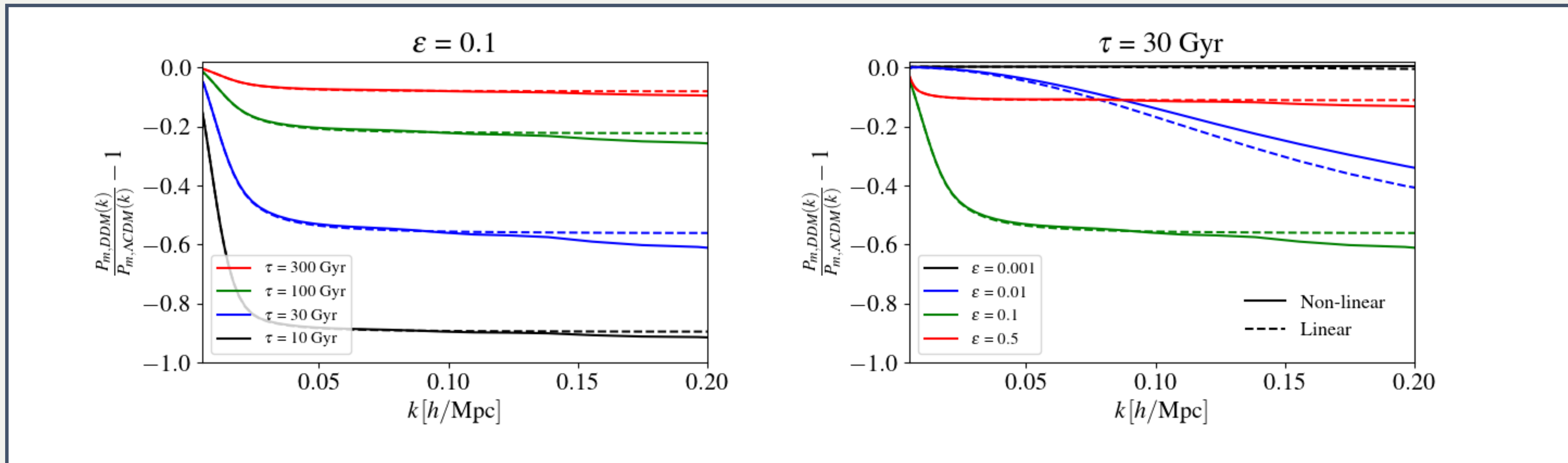




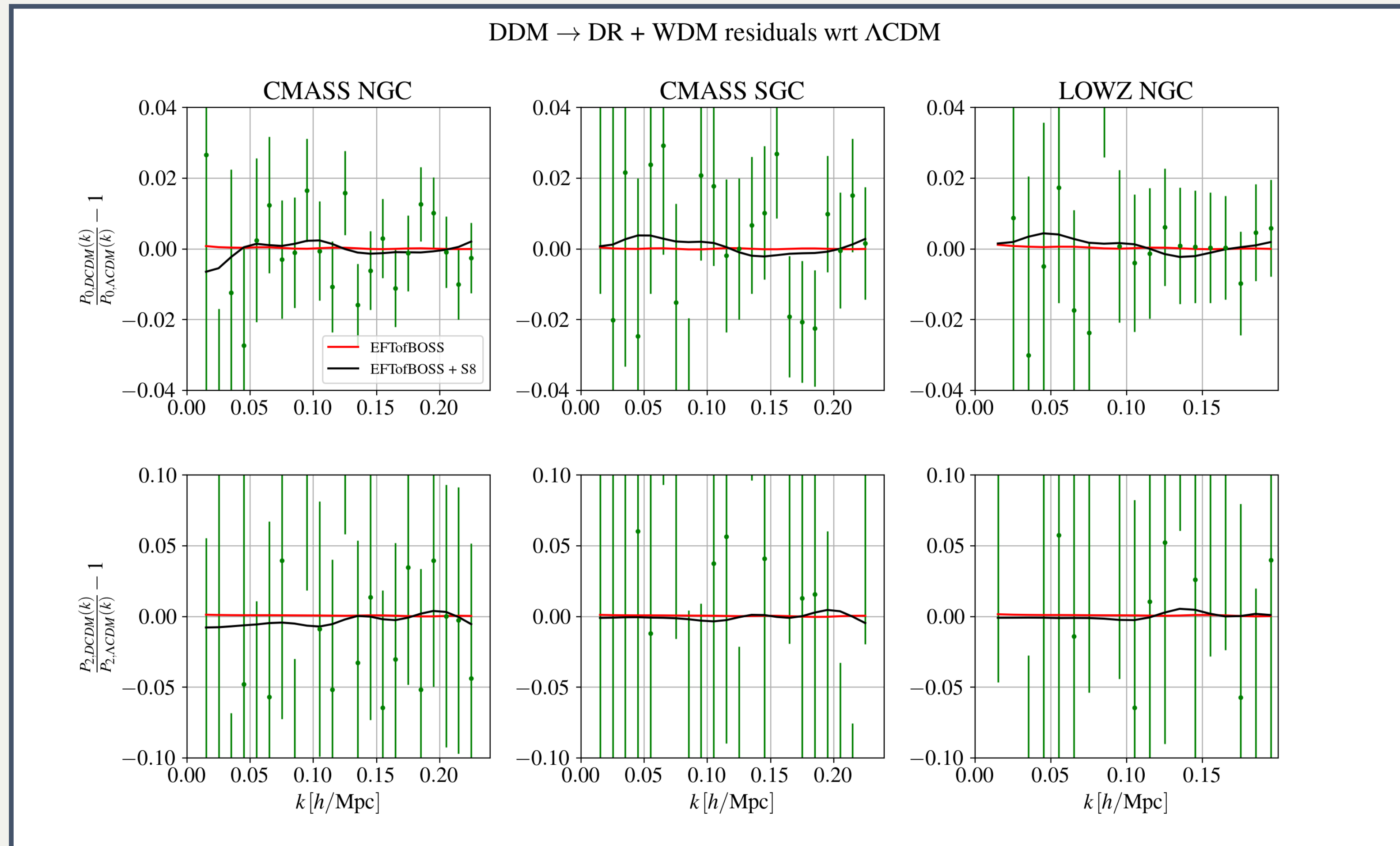
# Backup II: $\Lambda$ CDM $\rightarrow$ DR matter power spectrum



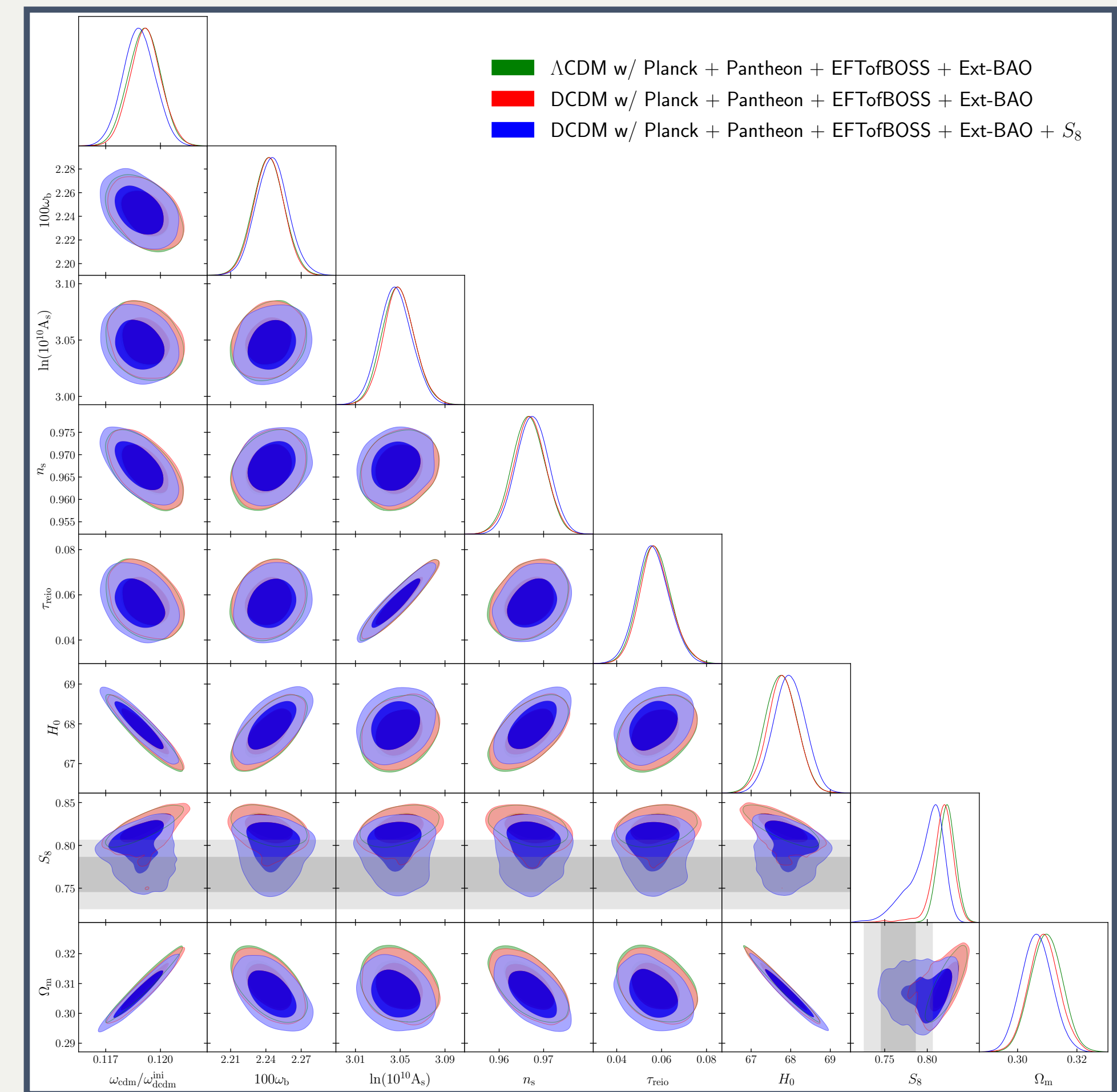
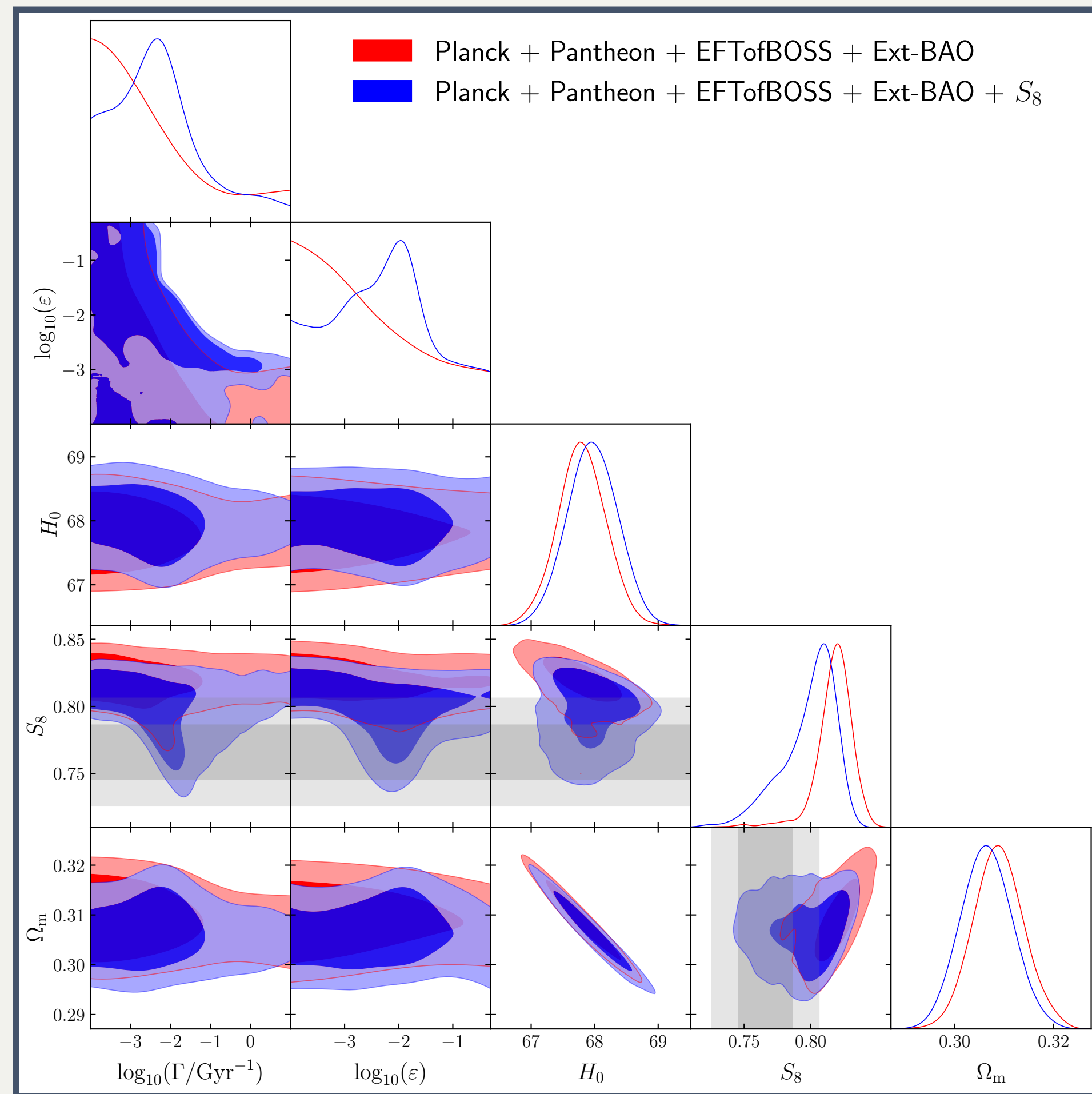
# Backup III: $\Lambda$ CDM $\rightarrow$ WDM+DR matter power spectrum



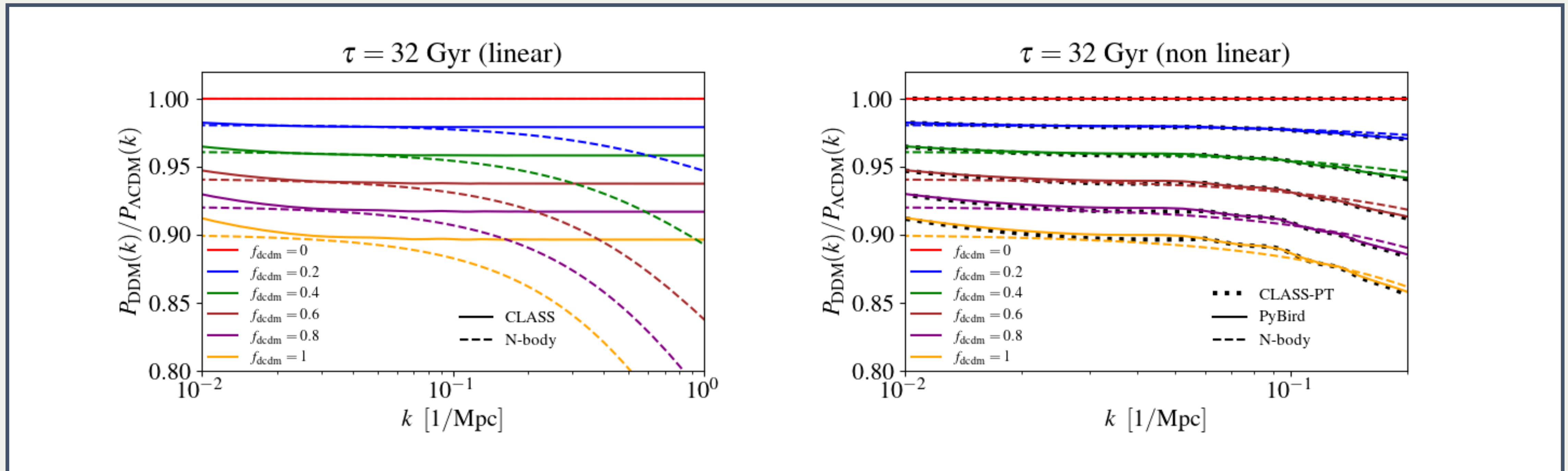
# Backup IV: $\Lambda$ CDM $\rightarrow$ WDM+DR bestfit power spectrum



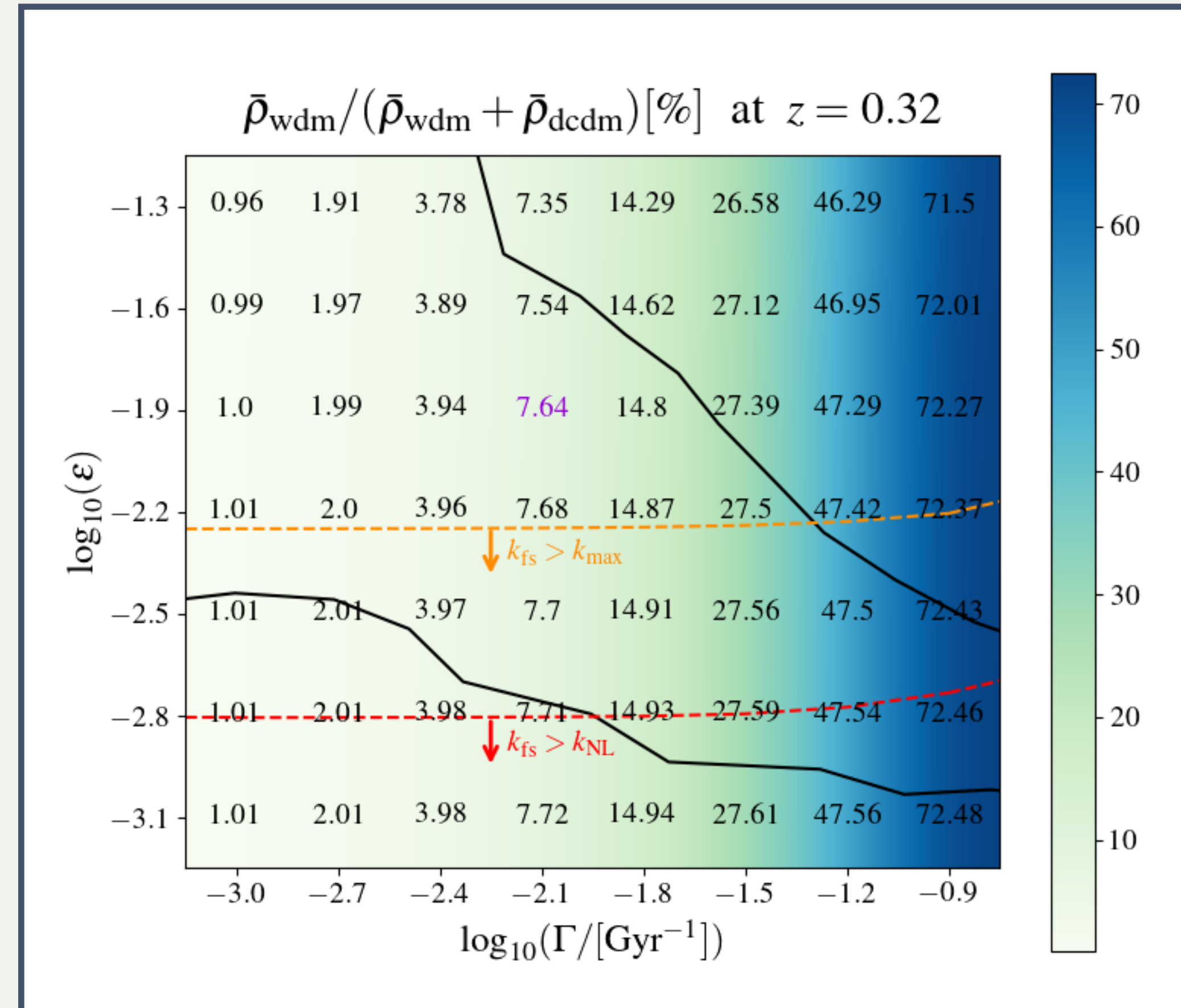
# Backup V: the $\Lambda$ CDM $\rightarrow$ WDM+DR model and the $S_8$ tension



# Backup VI: EFTofLSS vs N-body simulations (DCDM $\rightarrow$ DR model)



# Backup VII: validity of the EFTofLSS for the $\Lambda$ CDM $\rightarrow$ WDM+DR model



# Backup VIII: EFTofLSS parameters

$$\begin{aligned}
 P(k, \mu) &= Z_1(\mu)^2 P_{11}(k) \\
 &+ 2 \int \frac{d^3 q}{(2\pi)^3} Z_2(\mathbf{q}, \mathbf{k} - \mathbf{q}, \mu)^2 P_{11}(|\mathbf{k} - \mathbf{q}|) P_{11}(q) + 6 Z_1(\mu) P_{11}(k) \int \frac{d^3 q}{(2\pi)^3} Z_3(\mathbf{q}, -\mathbf{q}, \mathbf{k}, \mu) P_{11}(q) \\
 &+ 2 Z_1(\mu) P_{11}(k) \left( c_{ct} \frac{k^2}{k_M^2} + c_{r,1} \mu \frac{k^2}{k_M^2} + c_{r,2} \mu^2 \frac{k^2}{k_M^2} \right) + \frac{1}{\bar{n}_g} \left( c_{\epsilon,0} + c_{\epsilon,1} \frac{k^2}{k_M^2} + c_{\epsilon,2} f \mu^2 \frac{k^2}{k_M^2} \right), \quad (10)
 \end{aligned}$$


with


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

with

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

## 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.