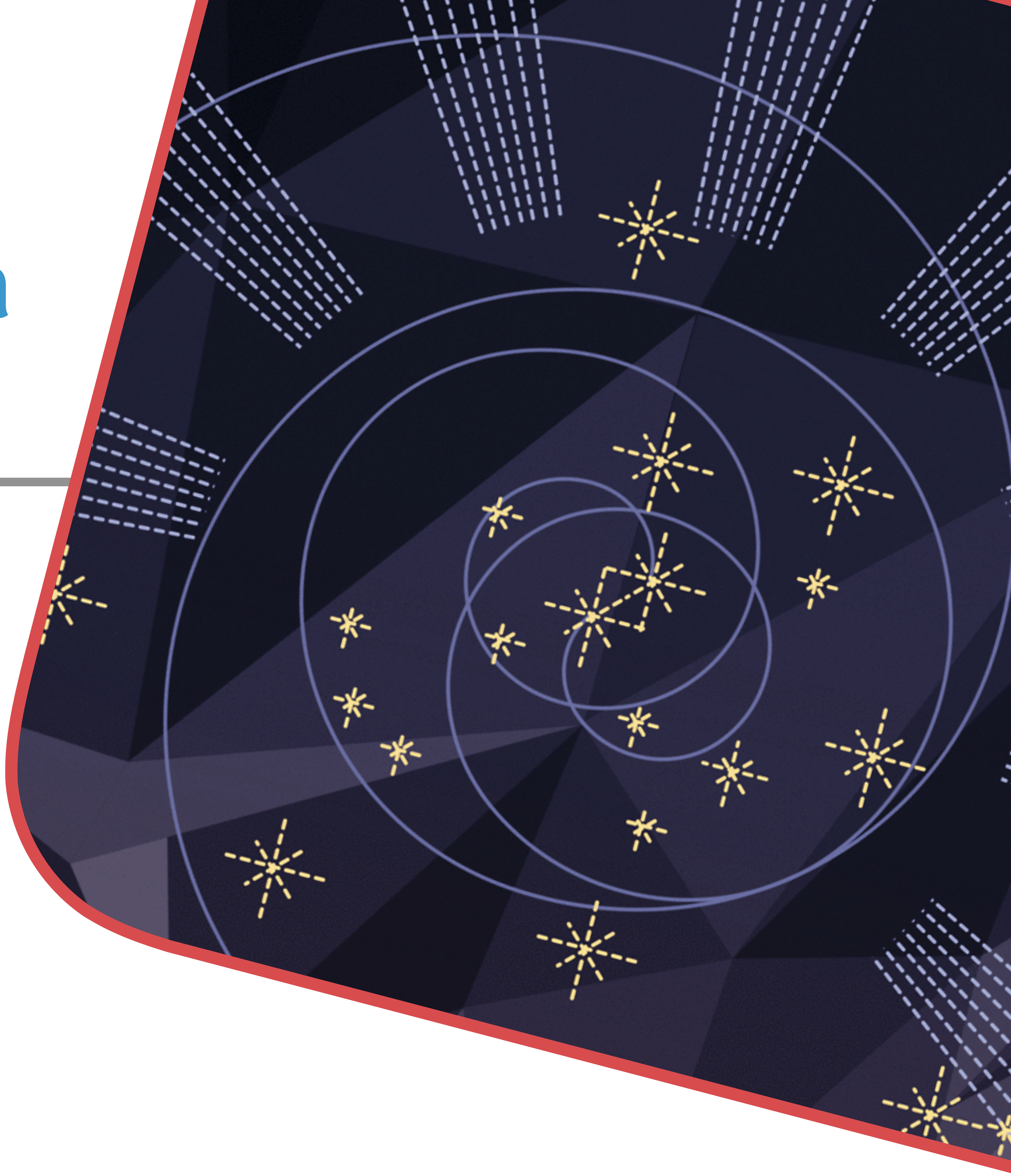
Implications of the S_8 tension for decaying dark matter

Guillermo Franco Abellán
w/ R. Murgia, V. Poulin, PRD 104 (2021)
w/ R. Murgia, V. Poulin, J. Lavalle, PRD 105 (2022)



What is needed to explain low S_8 values ?

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

$$\sigma_8^2 = \int P_m(k, z=0) W_R^2(k) d\ln k$$

- **Ω_m should be left unchanged** (well constrained by SNIa & galaxy clustering)

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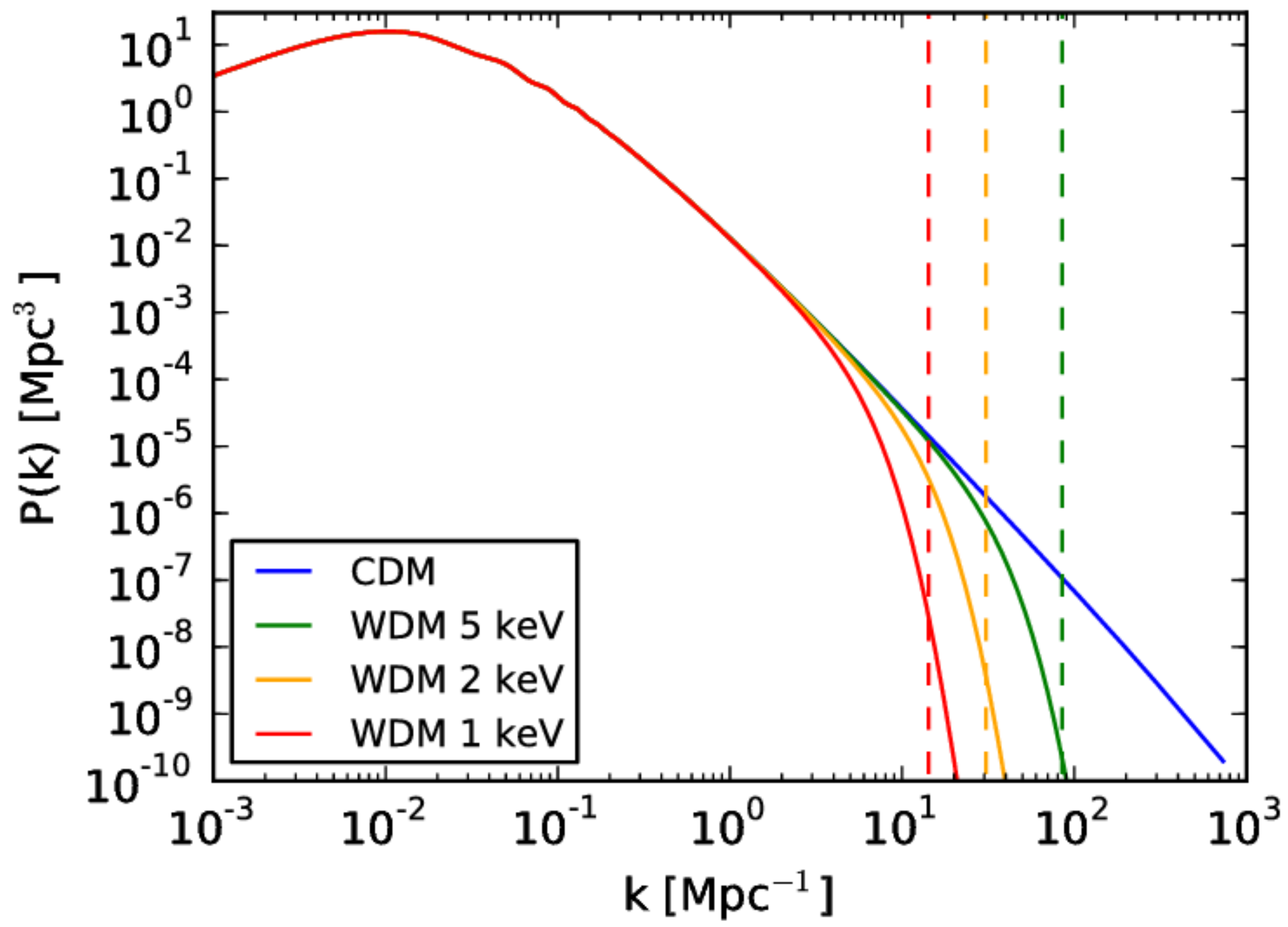
Ex: Warm dark matter



Very constrained by Ly-α !
[Iršič+ 17]

Decaying Dark Matter (DDM)

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Model-dependent, strongly constrained $\Gamma^{-1} \gtrsim 10^{7} - 10^{10}\ t_U$

[Blanco+ 18]

2 **To dark radiation**

Model-independent, less constrained $\Gamma^{-1} \gtrsim 10\ t_U$

[Nygaard+ 20]

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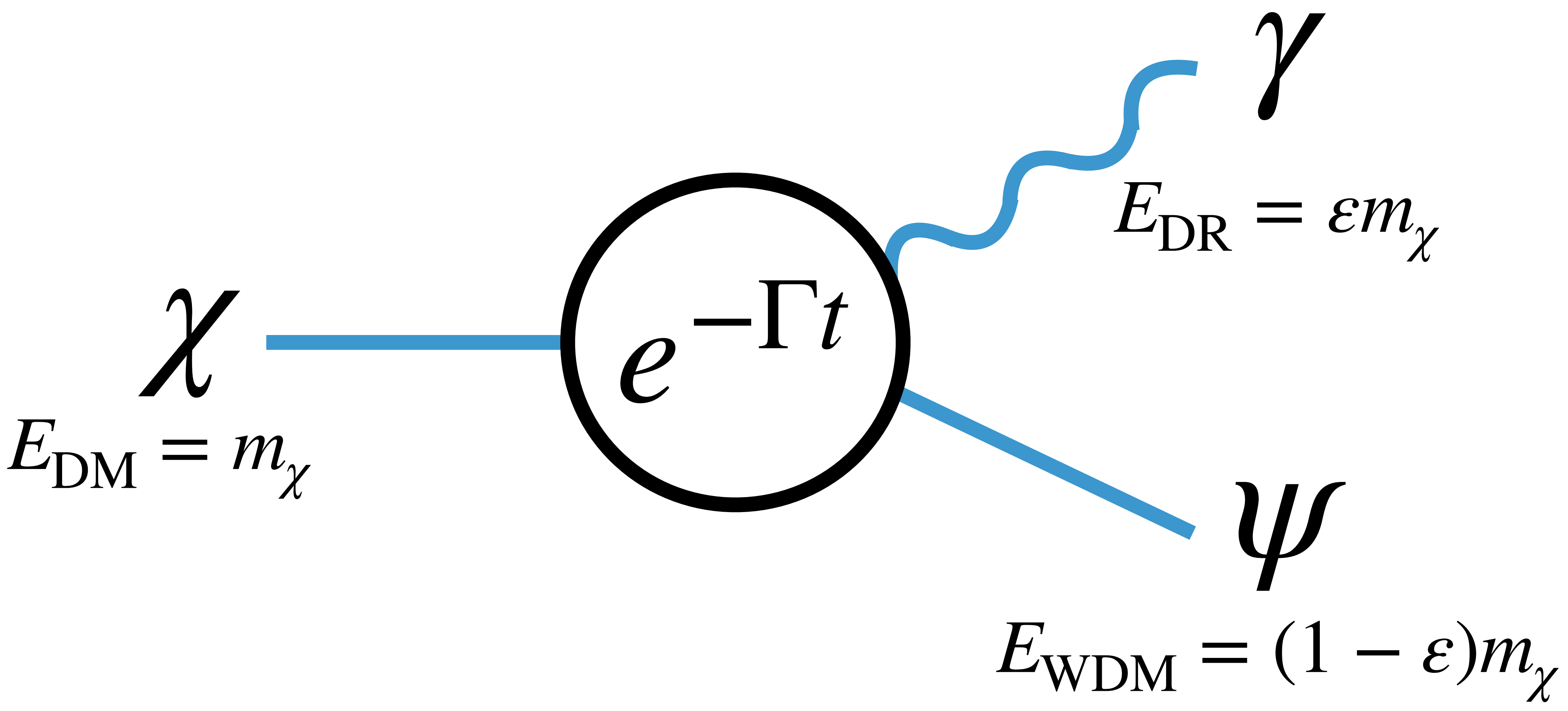
What about massive products?

DDM with massive decay products

We explore DM decays to
massless (Dark Radiation) and
massive (Warm Dark Matter) particles



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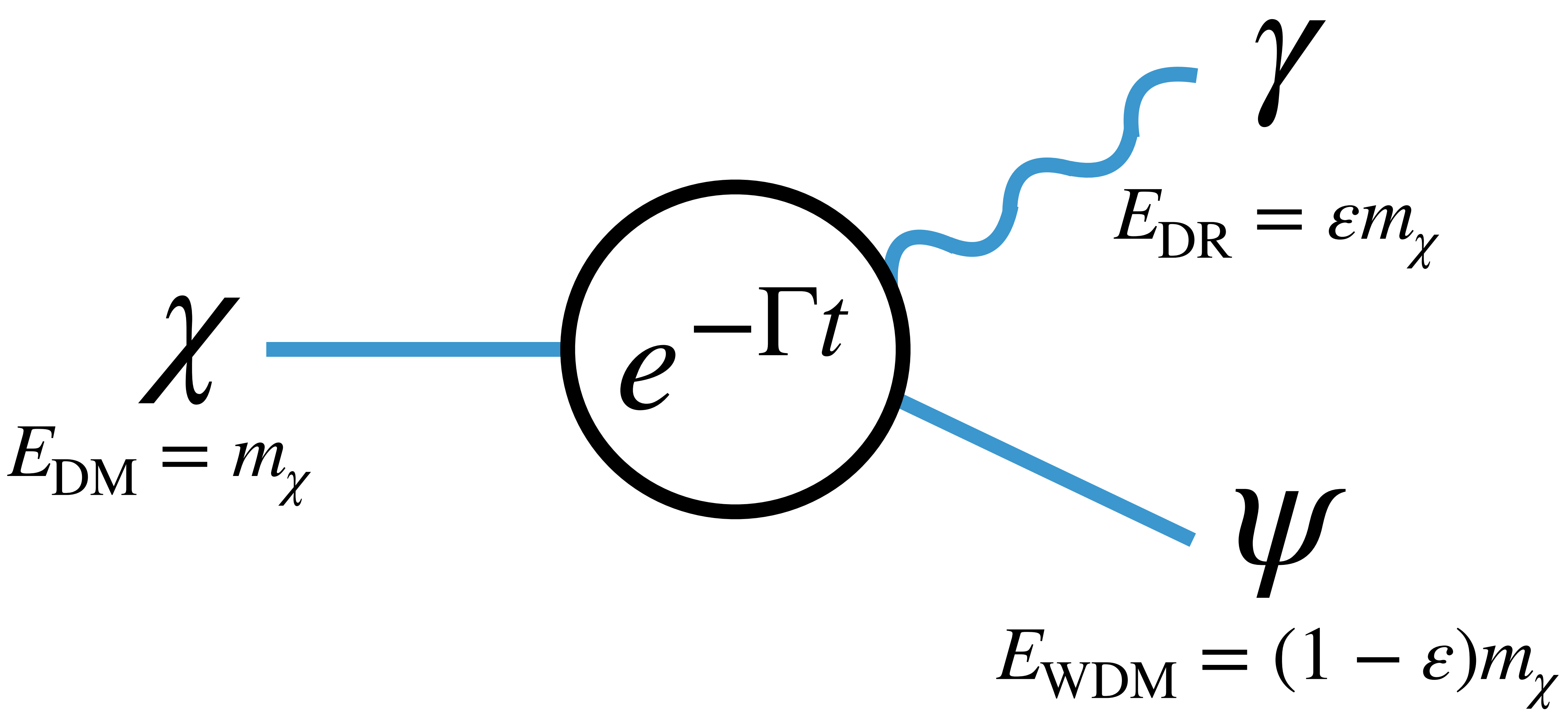

2 extra parameters:

Decay rate Γ

DR energy fraction ε

$$\varepsilon = \frac{1}{2}\left(1 - \frac{m_\psi^2}{m_\chi^2}\right) \begin{cases} = 0 & (\Lambda\mathrm{CDM}) \\ = 1/2 & (\mathrm{DM} \to \mathrm{DR}) \end{cases}$$

GOAL

Perform a parameter scan by including **full treatment of linear perts.**, in order to assess the impact on the **S_8 tension**

Evolution of DDM perturbations

- Track δ_i, θ_i **and** σ_i for i= dm, dr, idm

- Boltzmann hierarchy of eqs., dictate evolution of **p.s.d. multipoles** $\delta f_\ell(q, k, \tau)$

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- Boltzmann hierarchy of eqs., dictate evolution of
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  - For DM and DR, momentum d.o.f. are integrated out

  - For **WDM**, need to follow full evolution in phase space
    Computationally prohibitive, $\mathcal{O}(10^8)$ ODEs to solve!

New fluid equations for the WDM species

- **Based on previous approximation for massive neutrinos**

[Lesgourgues+ 11]

$$\delta'_{\rm wdm} = -3aH(c^2_{\rm syn} - w)\delta_{\rm wdm} - (1+w)\left(\theta_{\rm wdm} + \frac{h'}{2}\right) + a\Gamma(1-\varepsilon)\frac{\bar{\rho}_{\rm dm}}{\bar{\rho}_{\rm wdm}}(\delta_{\rm dm} - \delta_{\rm wdm})$$

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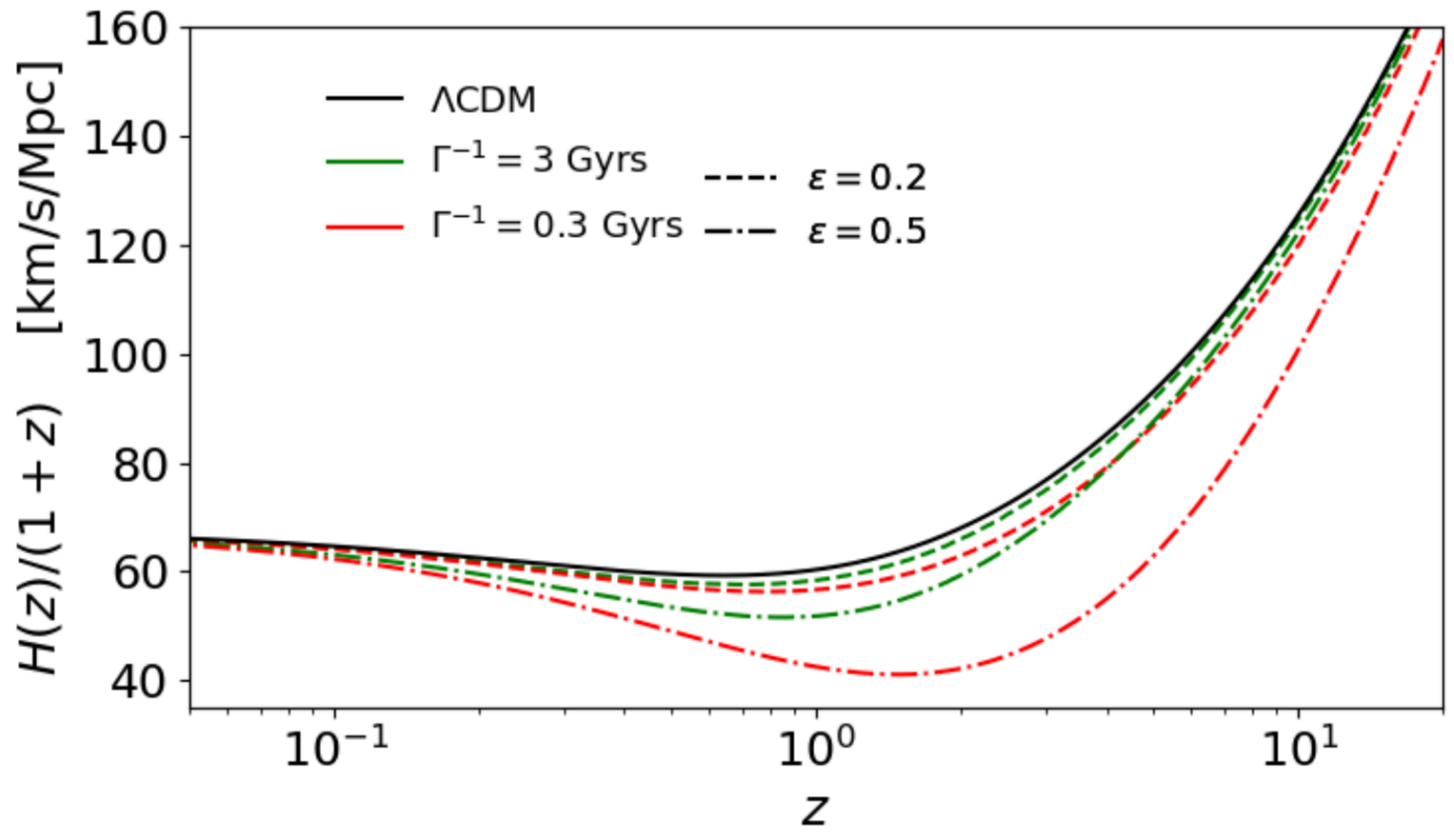
CPU time reduced from ~ 1 day to ~ 1 minute !!

H(z) more affected by the **DR**:

$\Gamma \uparrow \quad \varepsilon \uparrow$



Impact on background

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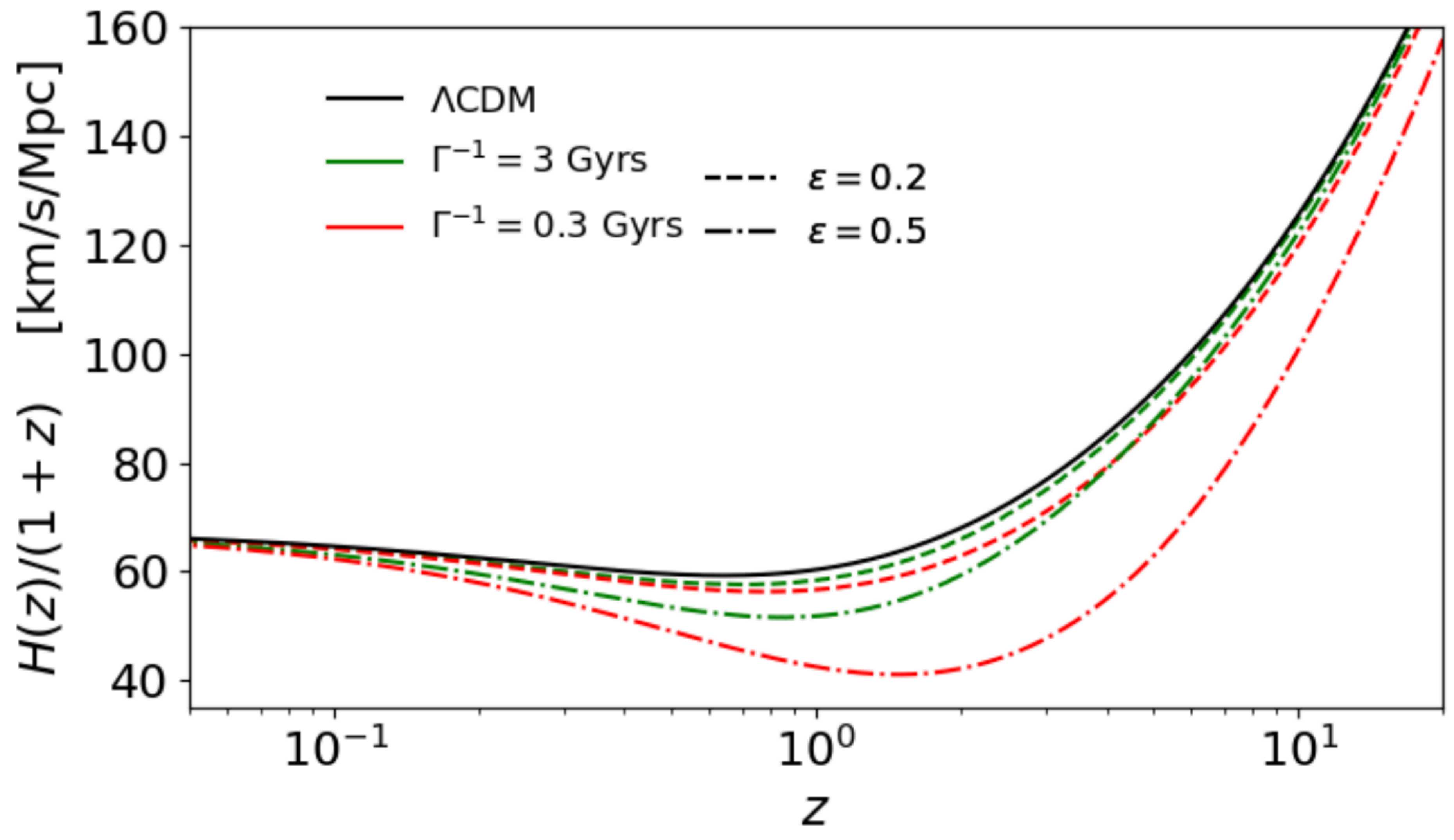
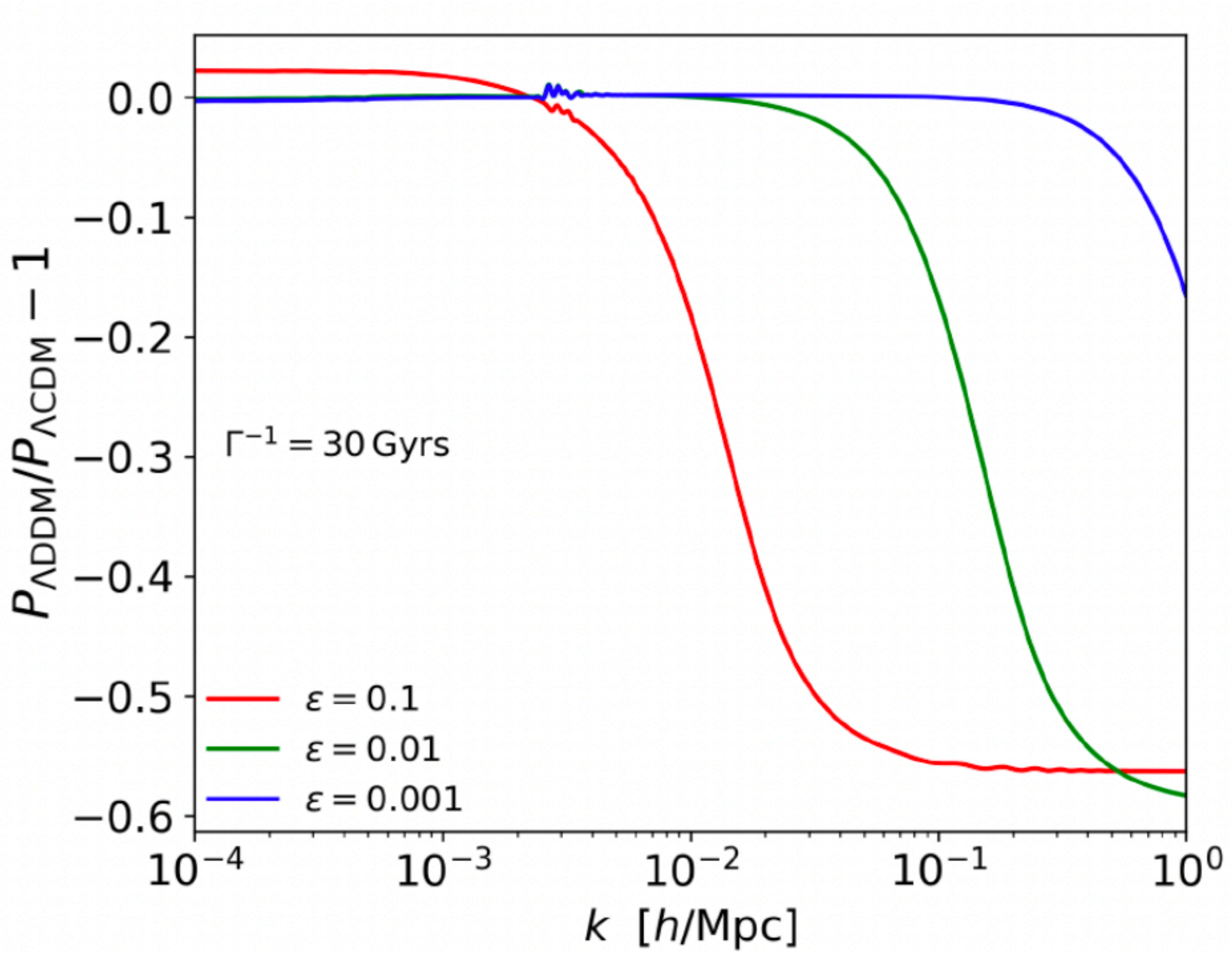


Impact on background

Impact on perturbations

P(k) more affected by the **WDM** (suppression at $k > k_{fs}$):

$\Gamma\uparrow \quad \varepsilon\downarrow$



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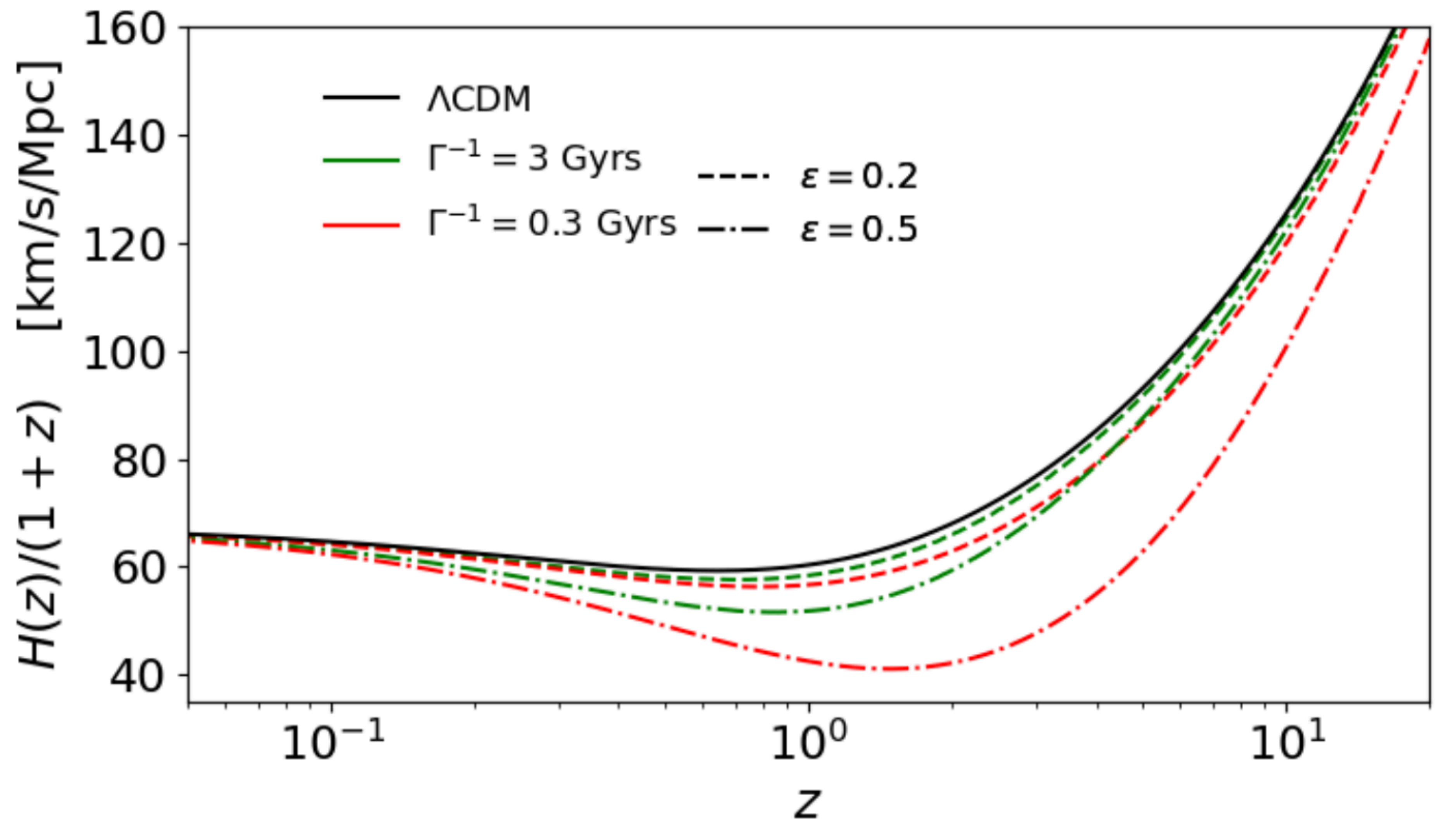

With large Γ and small ε, we can achieve a **P(k) suppression** while leaving **H(z) unaffected**

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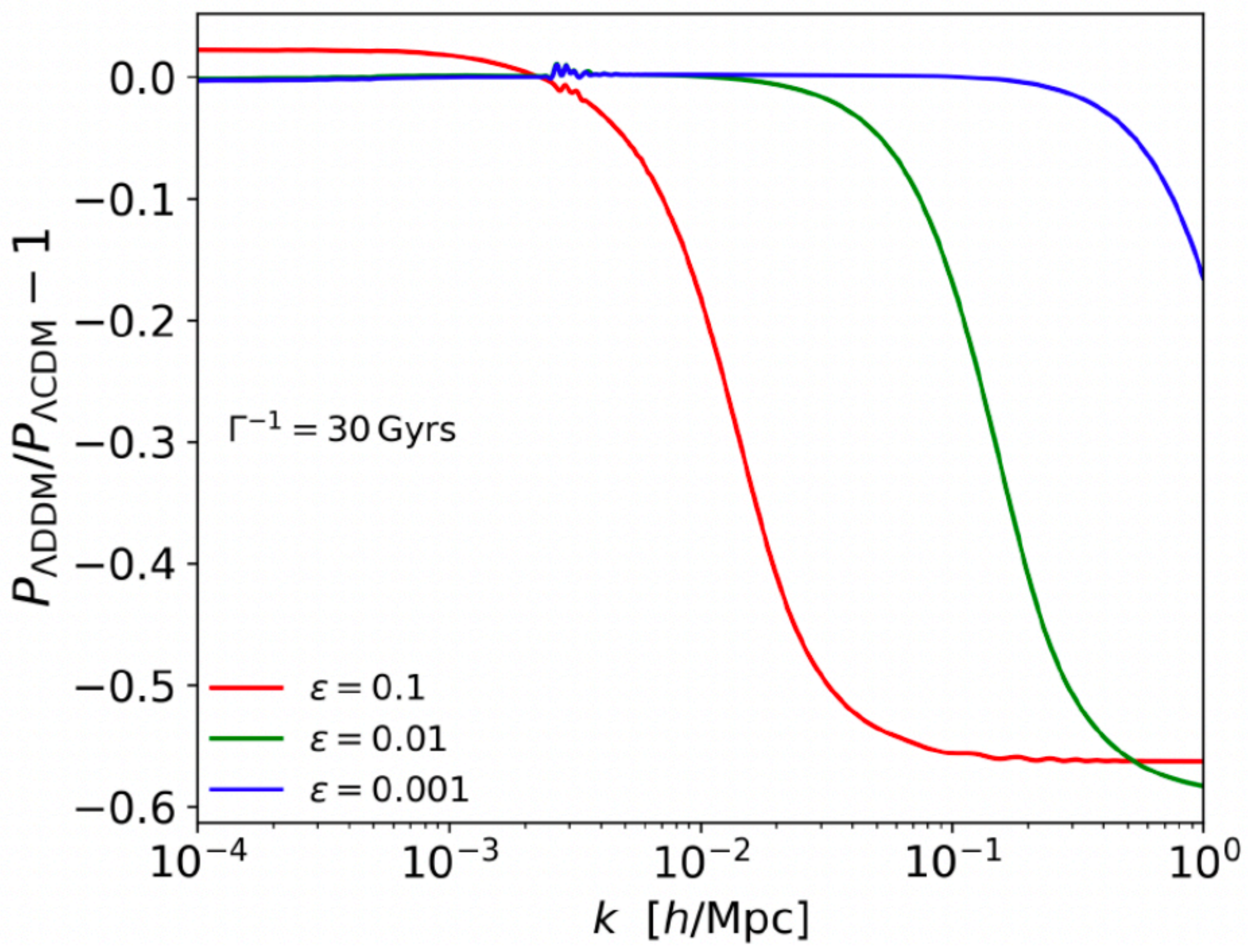

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this would require to run many expensive ΛDDM simulations

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this would require to run many expensive ΛDDM simulations

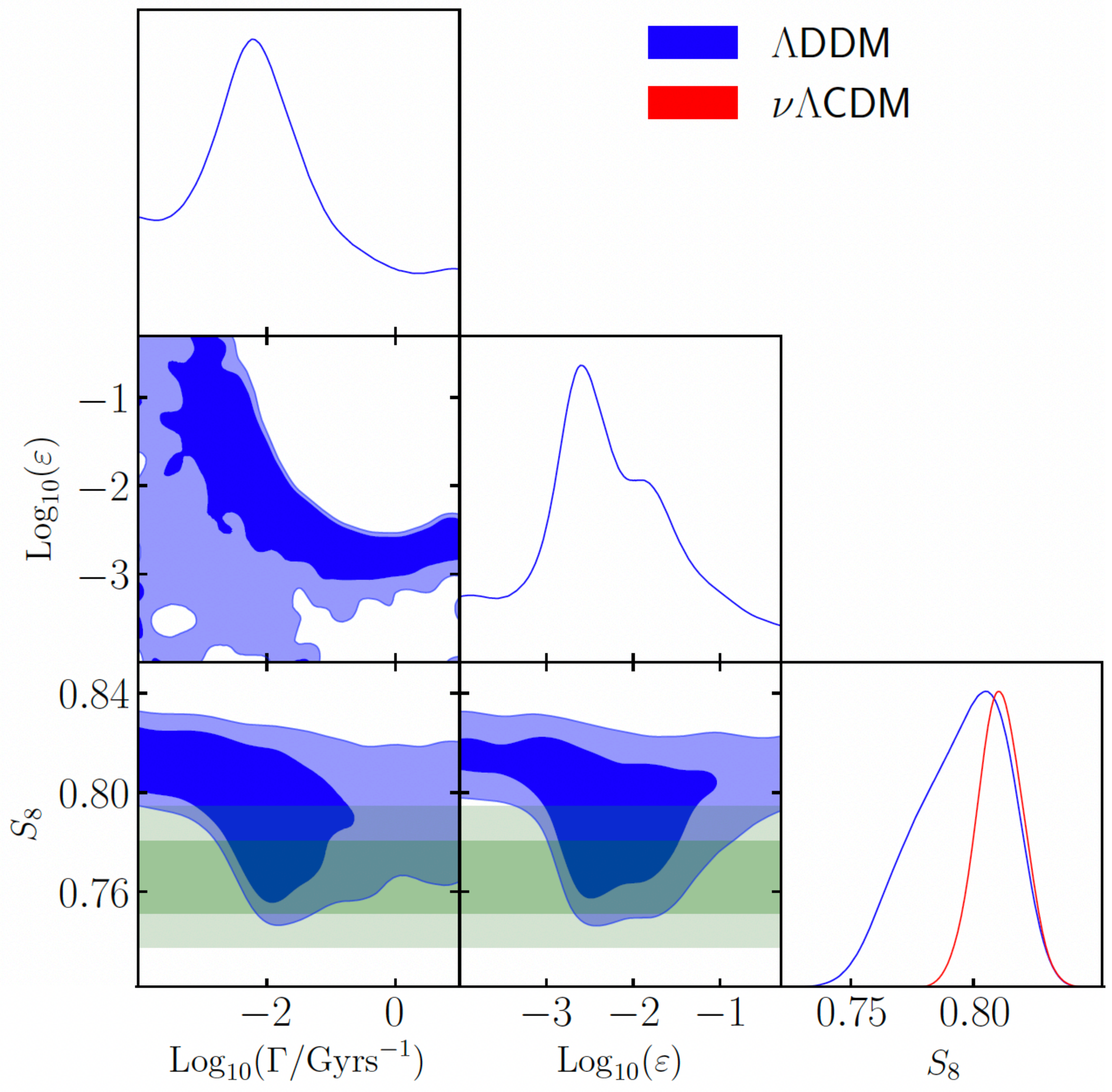
Use a **S_8 prior** instead (very simplistic, but should be seen as a **minimal test**)

✓

Explaining the S_8 tension

- Reconstructed S_8 values are in **excellent agreement** with WL data

Planck18 + BAO + SNIa
+ S_8 (KiDS+BOSS+2dfLenS):



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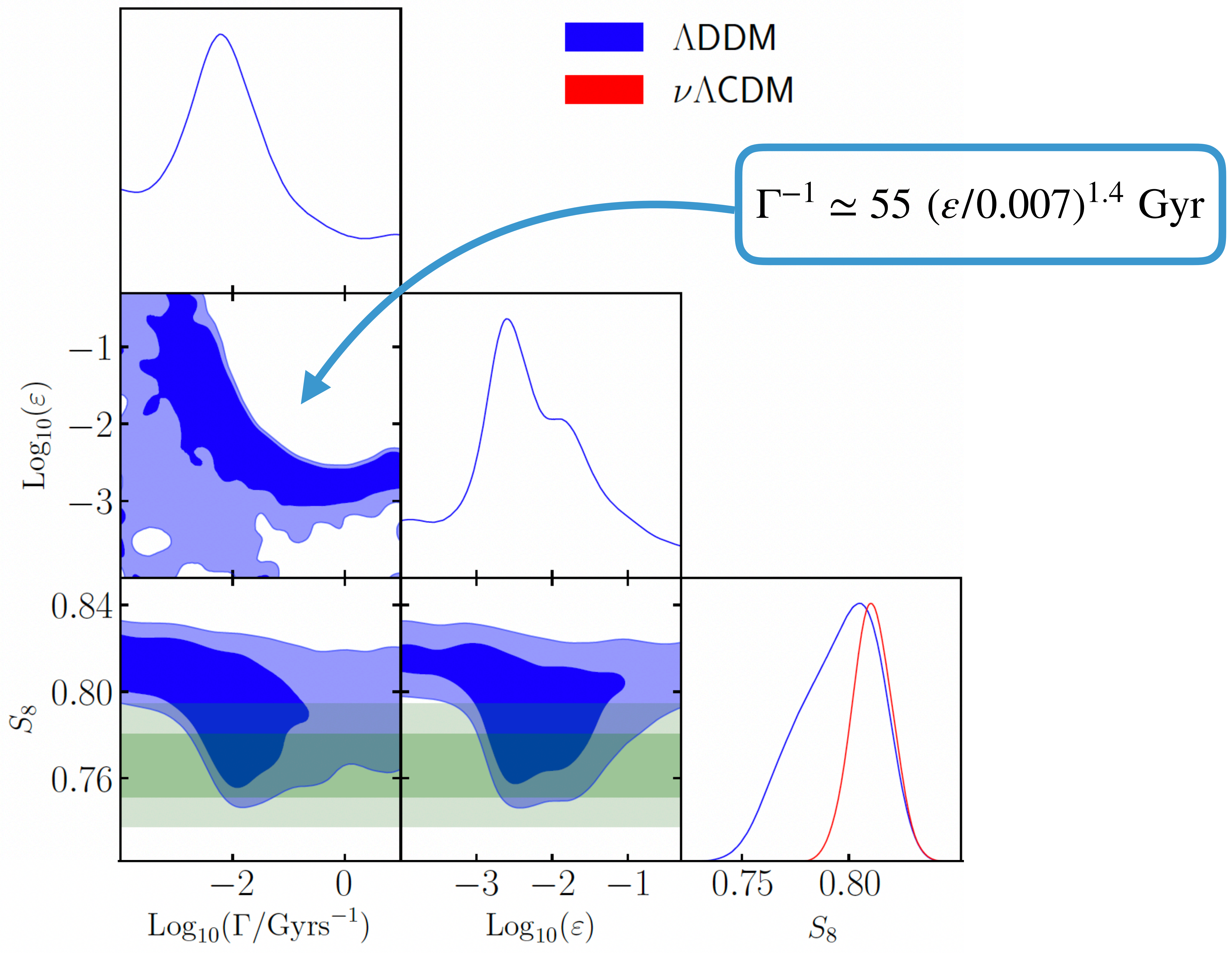

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	νΛCDM	ΛDDM
$\chi^2_{\rm CMB}$	1015.9	1015.2
$\chi^2_{S_8}$	5.64	0.002

→ $\Delta\chi^2_{\rm min} = -5.5$

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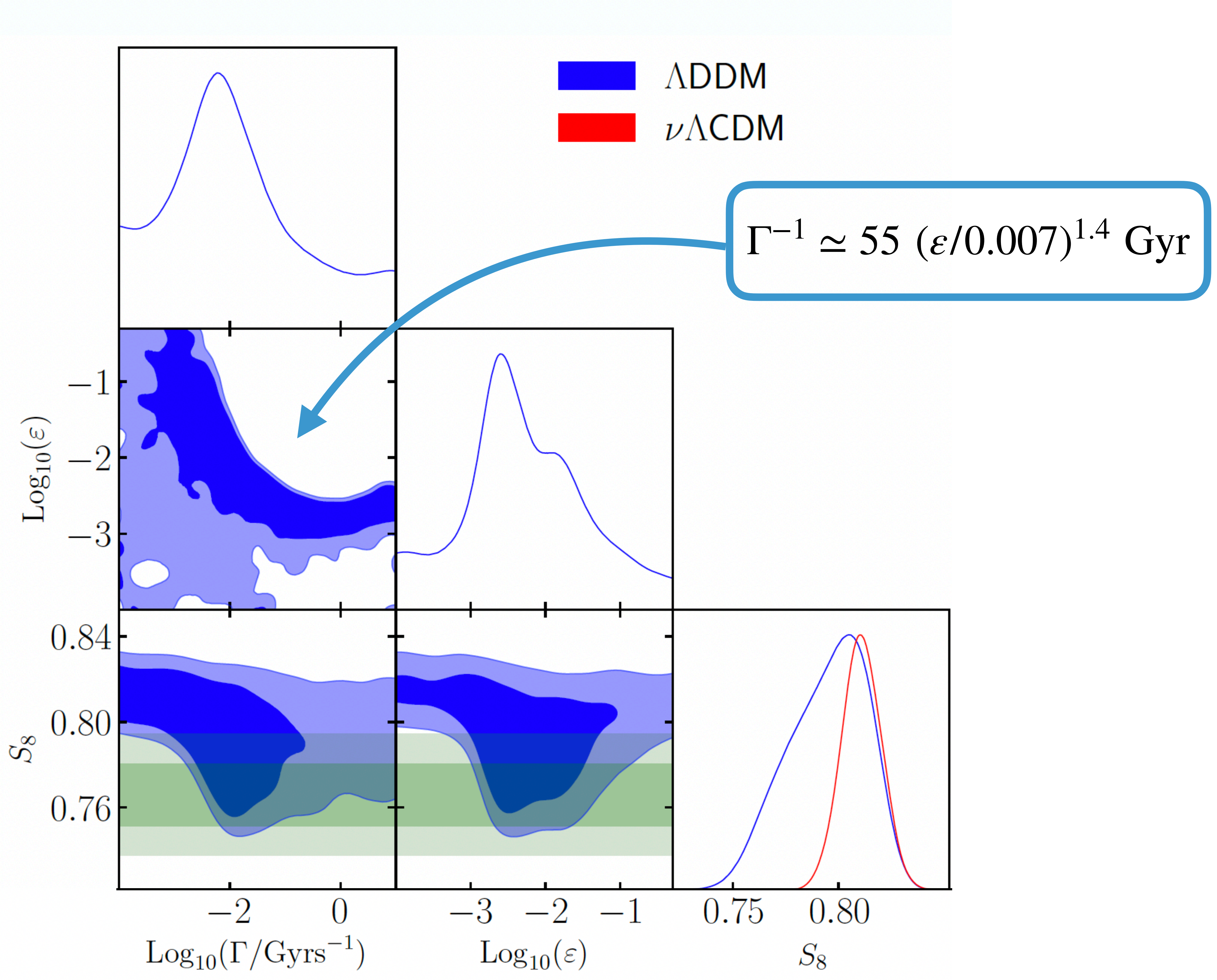
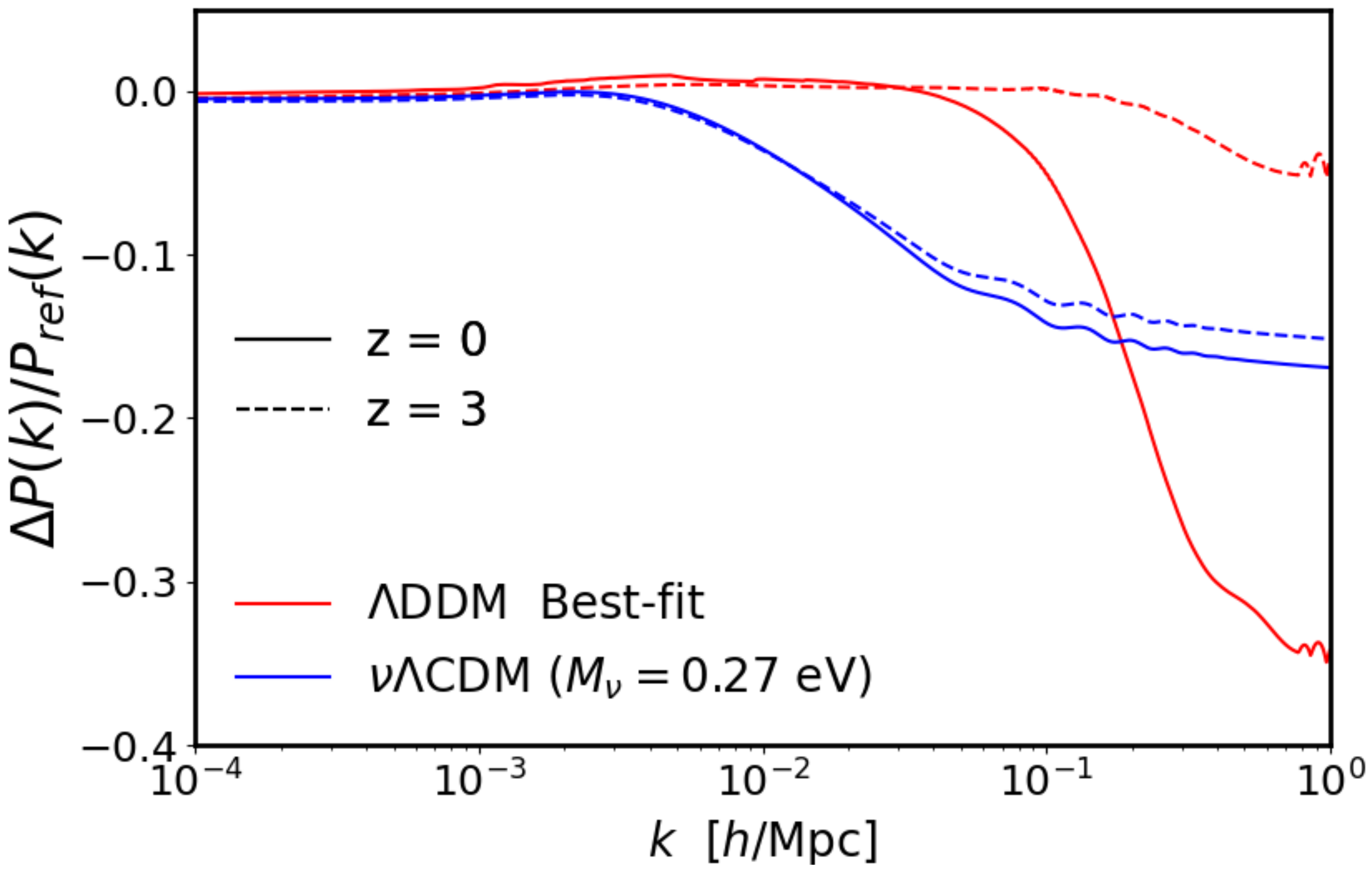


Why does the DDM model provide a better fit?



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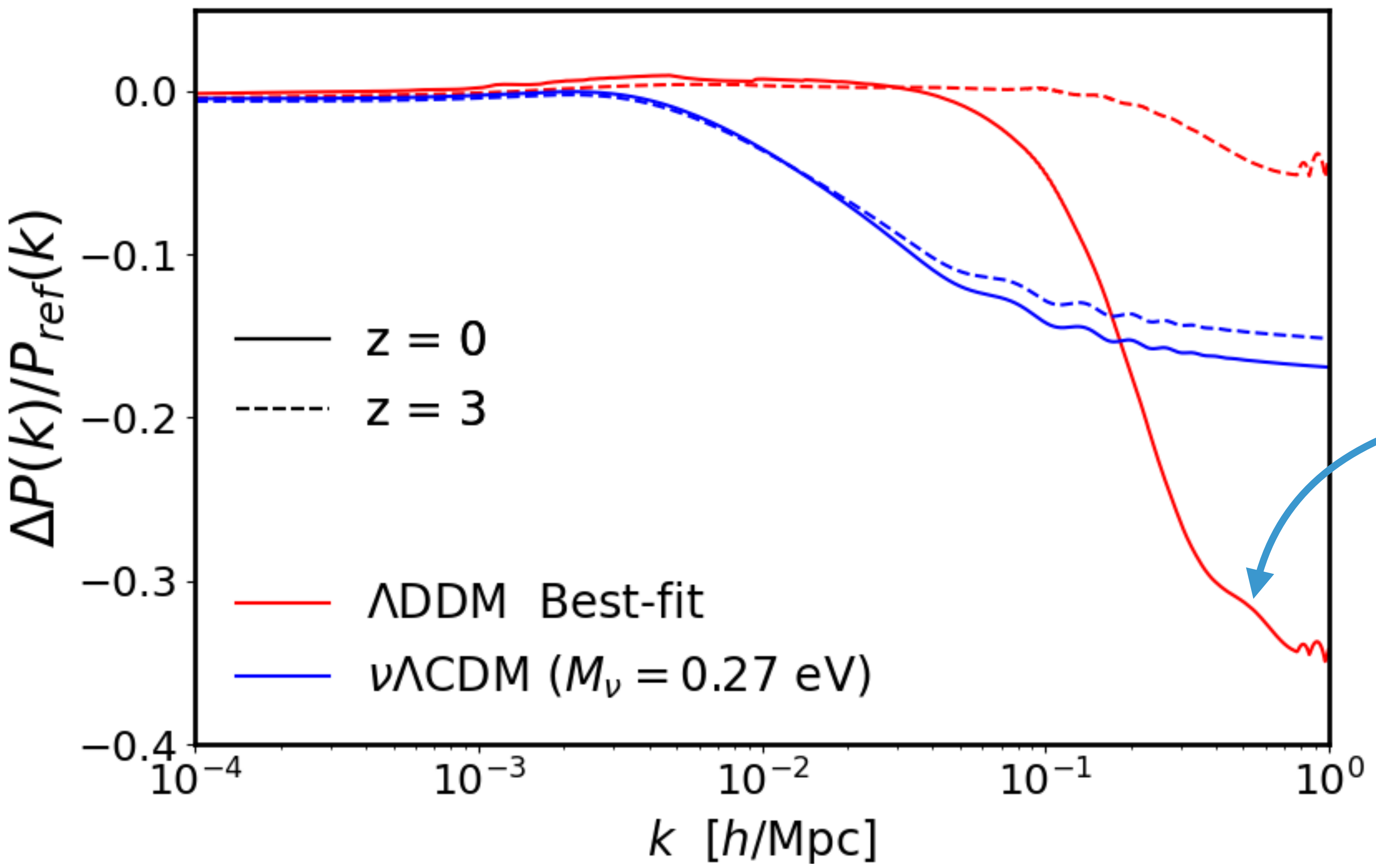

Suppression mainly affecting **non-linear** scales

(see A. Amon's talk)

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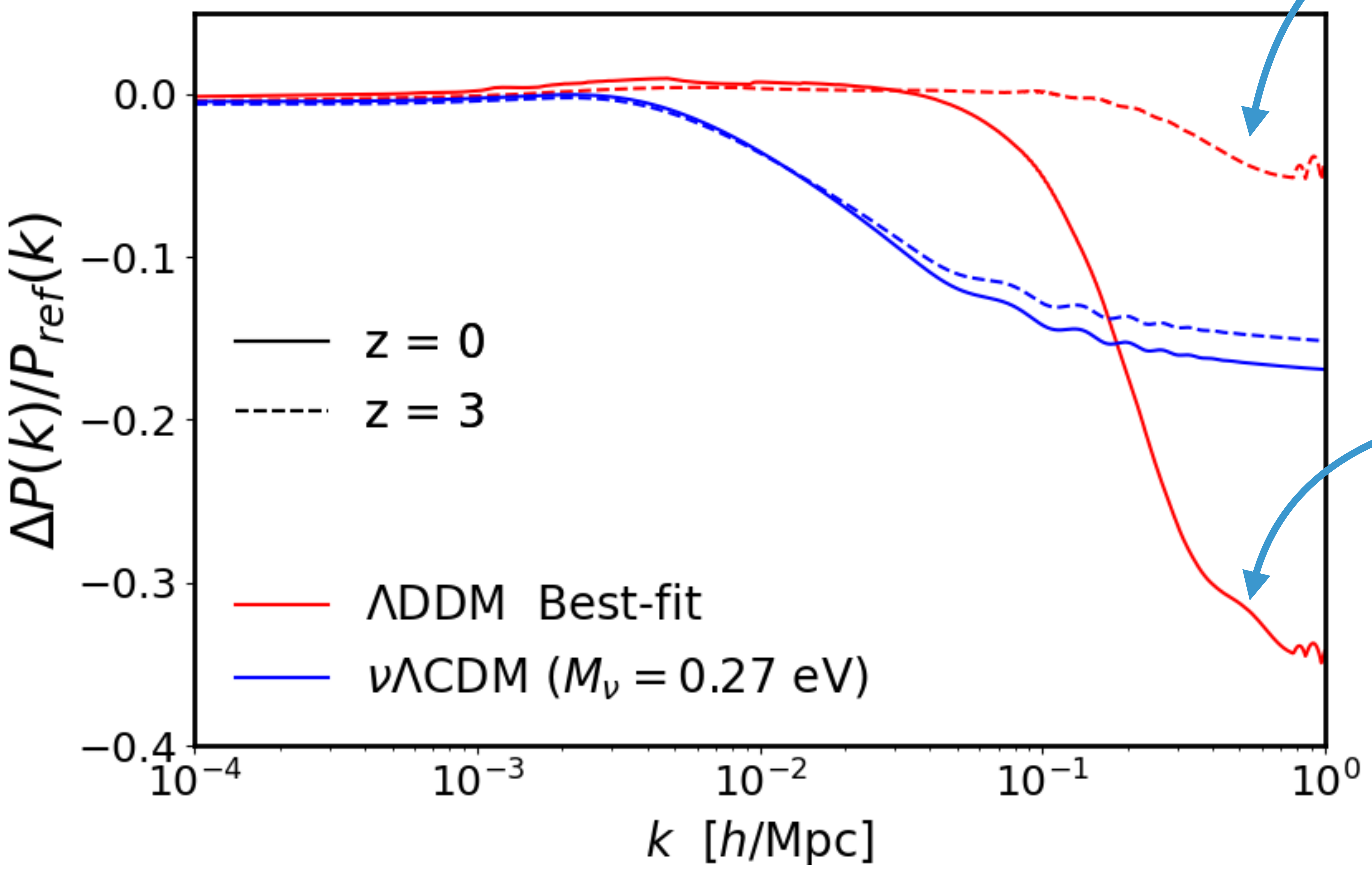

Lower suppression in the **past**

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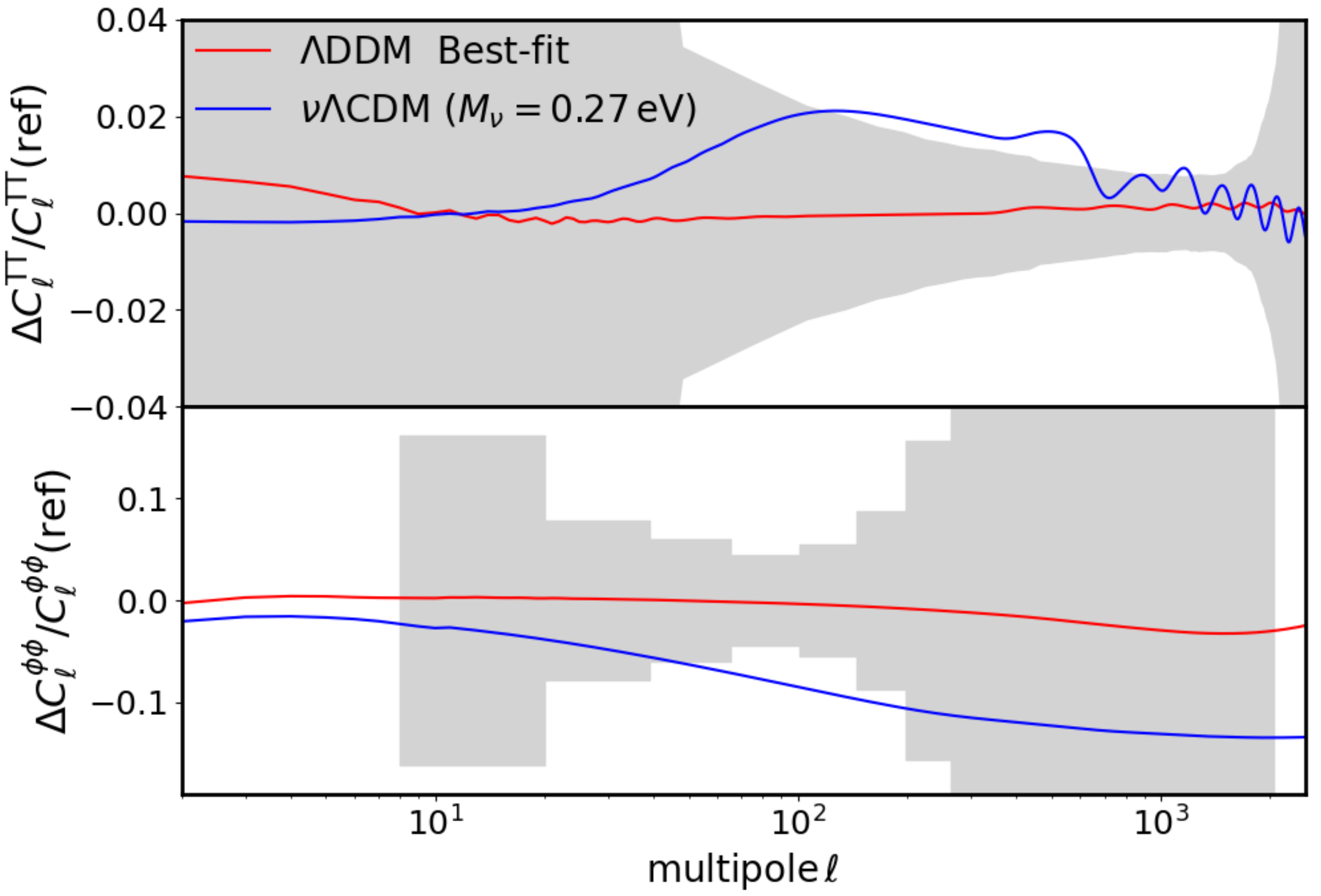
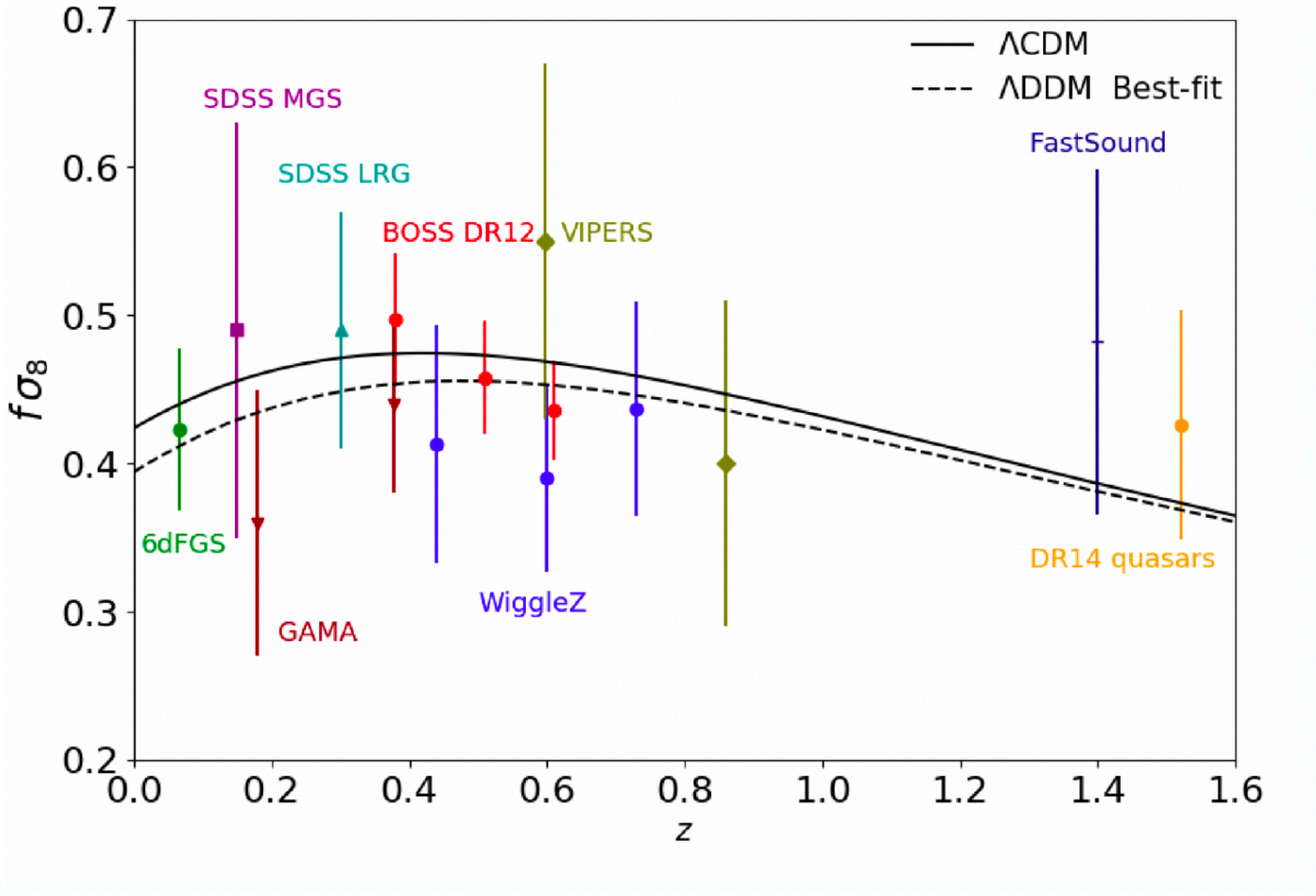
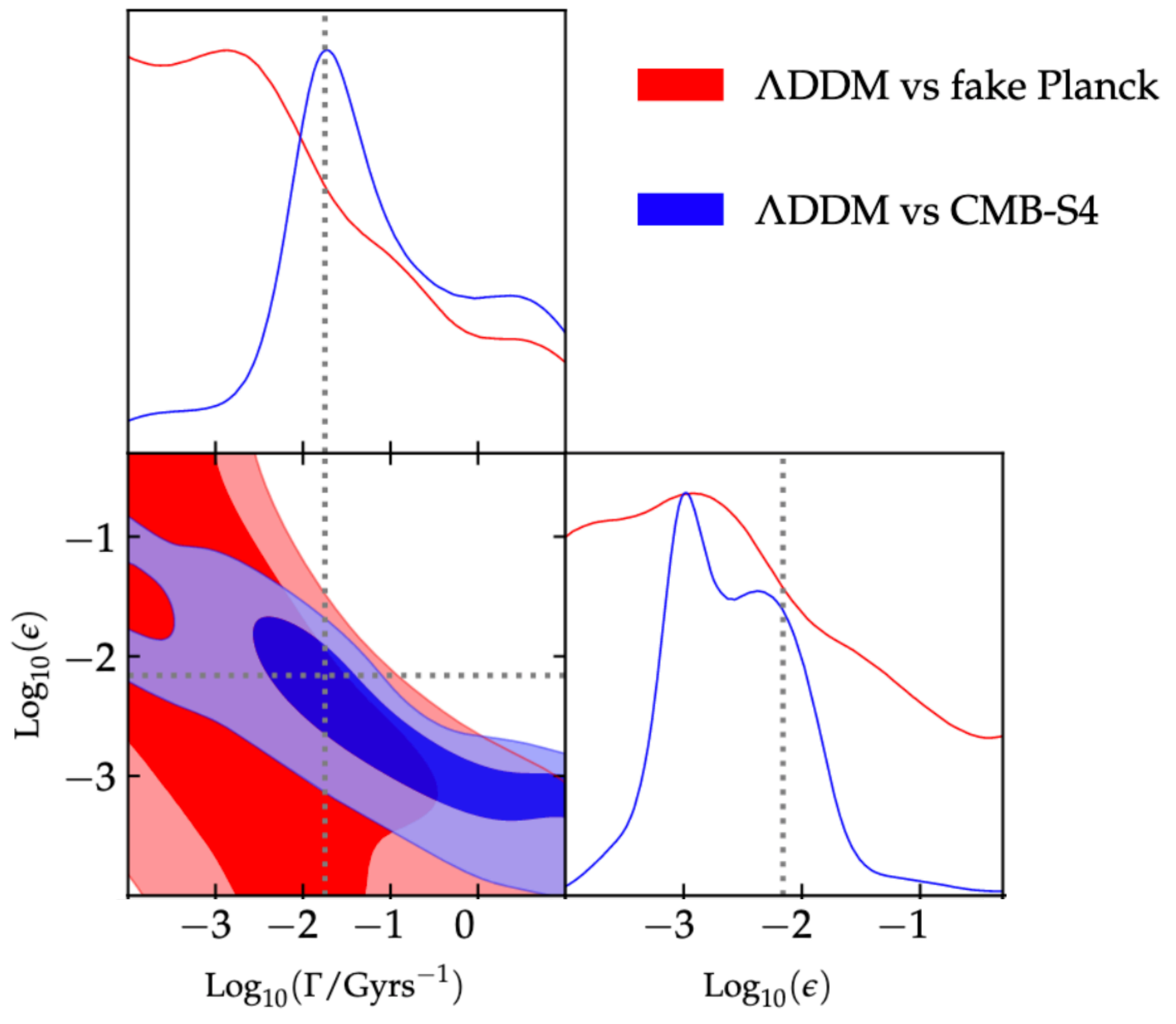


Time-dependence of DDM suppression allows for a better fit to CMB data

Prospects for DDM

- **Future** accurate **$f\sigma_8$ and CMB** data will be able to capture DDM signature





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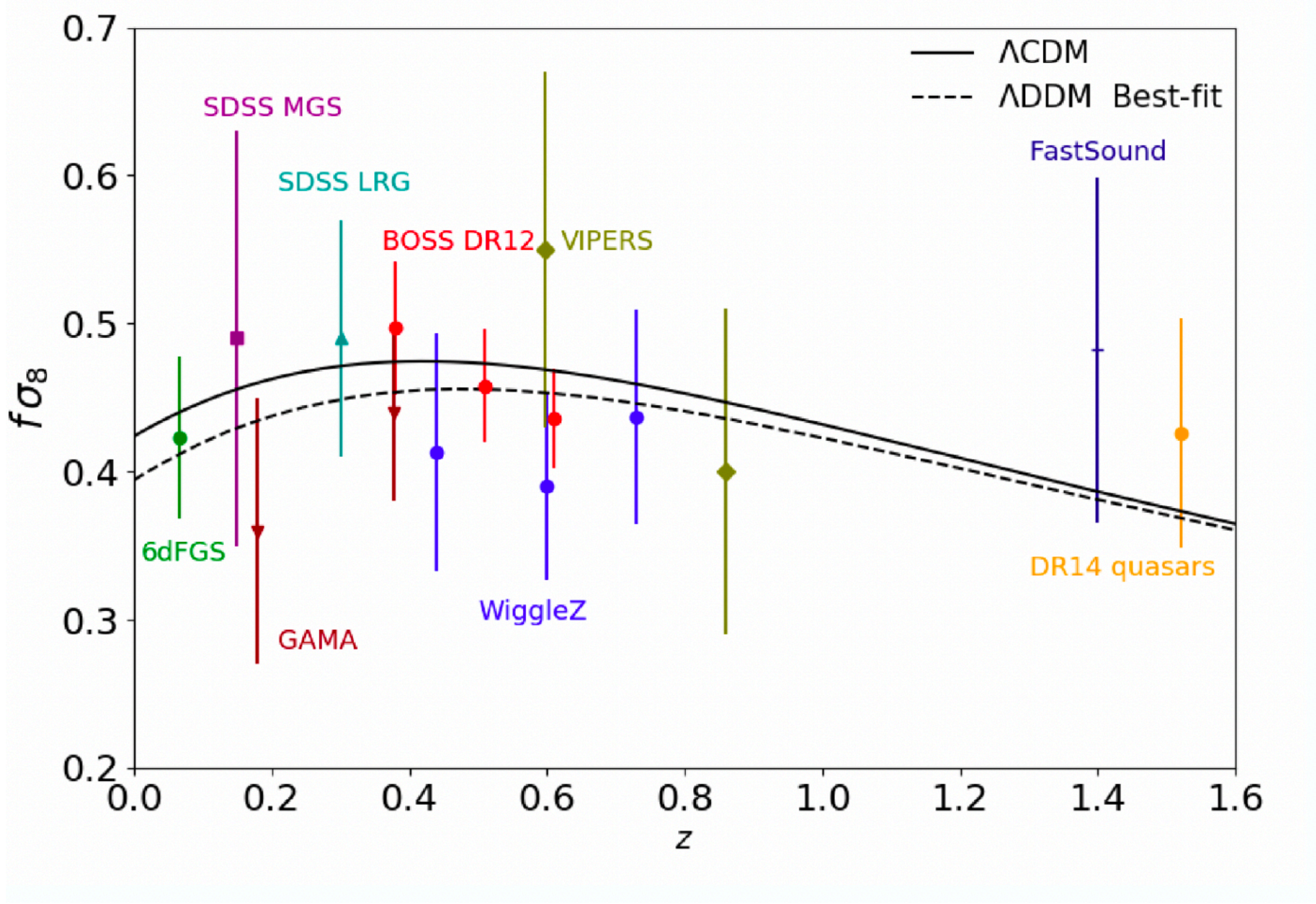

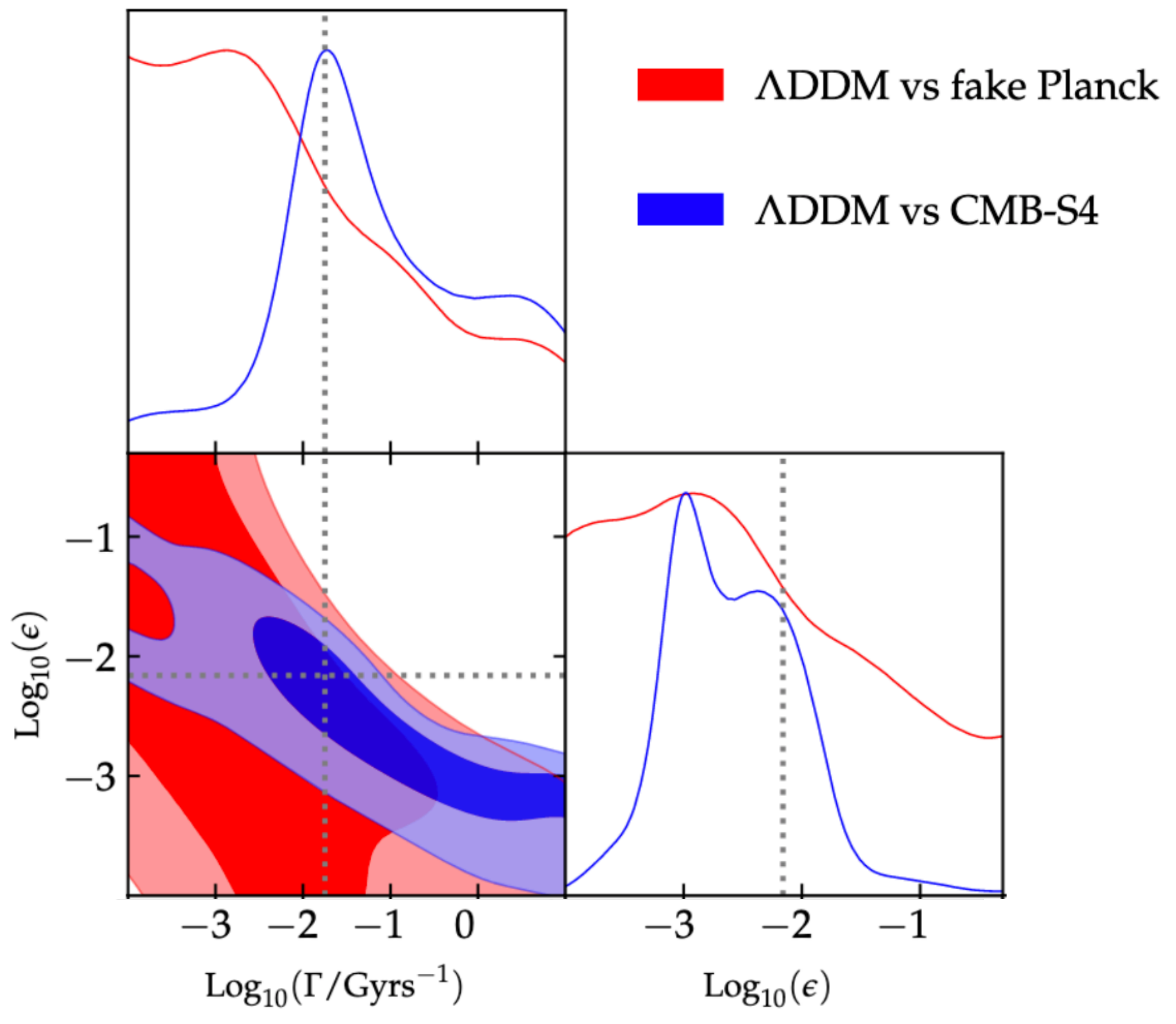

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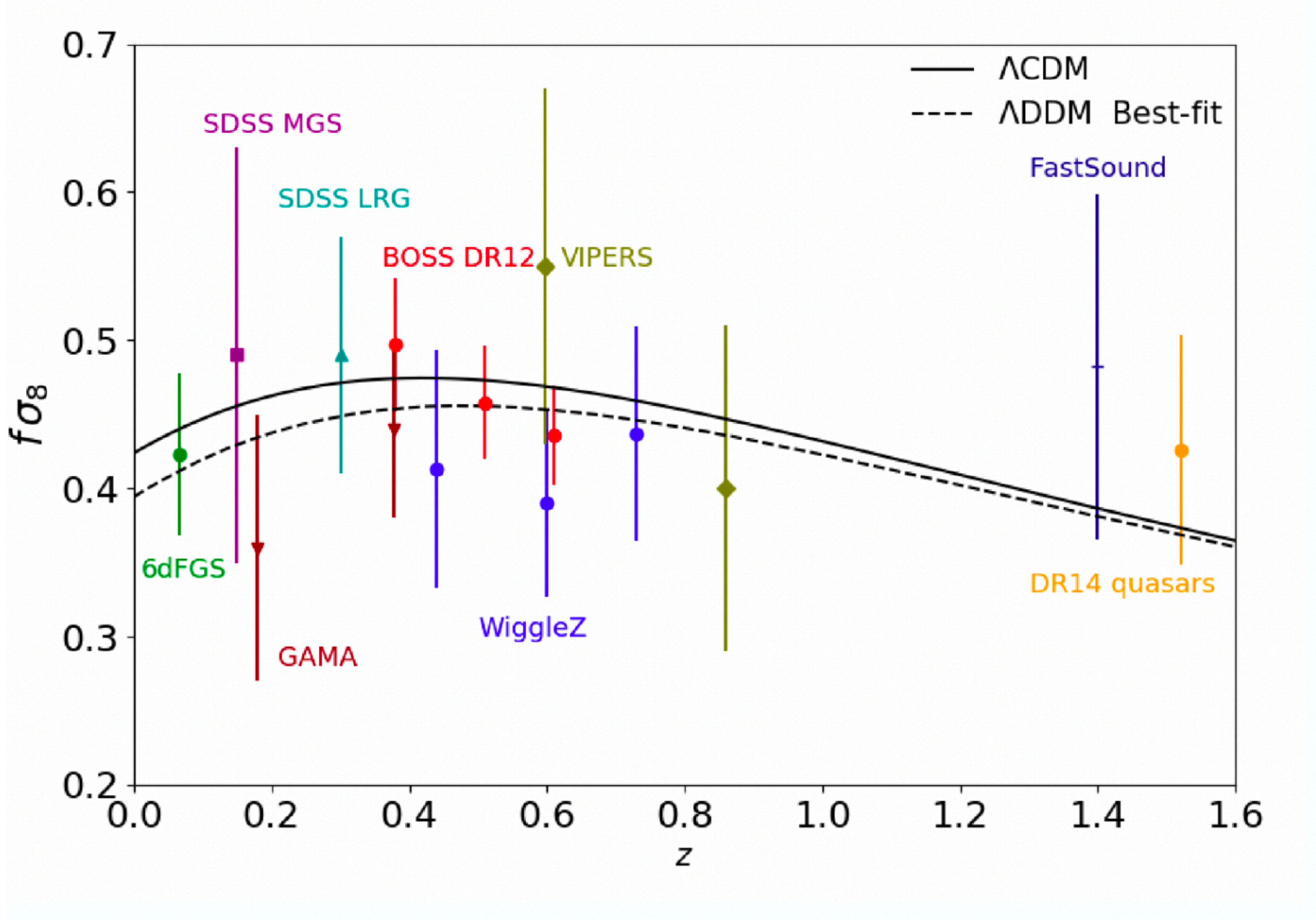
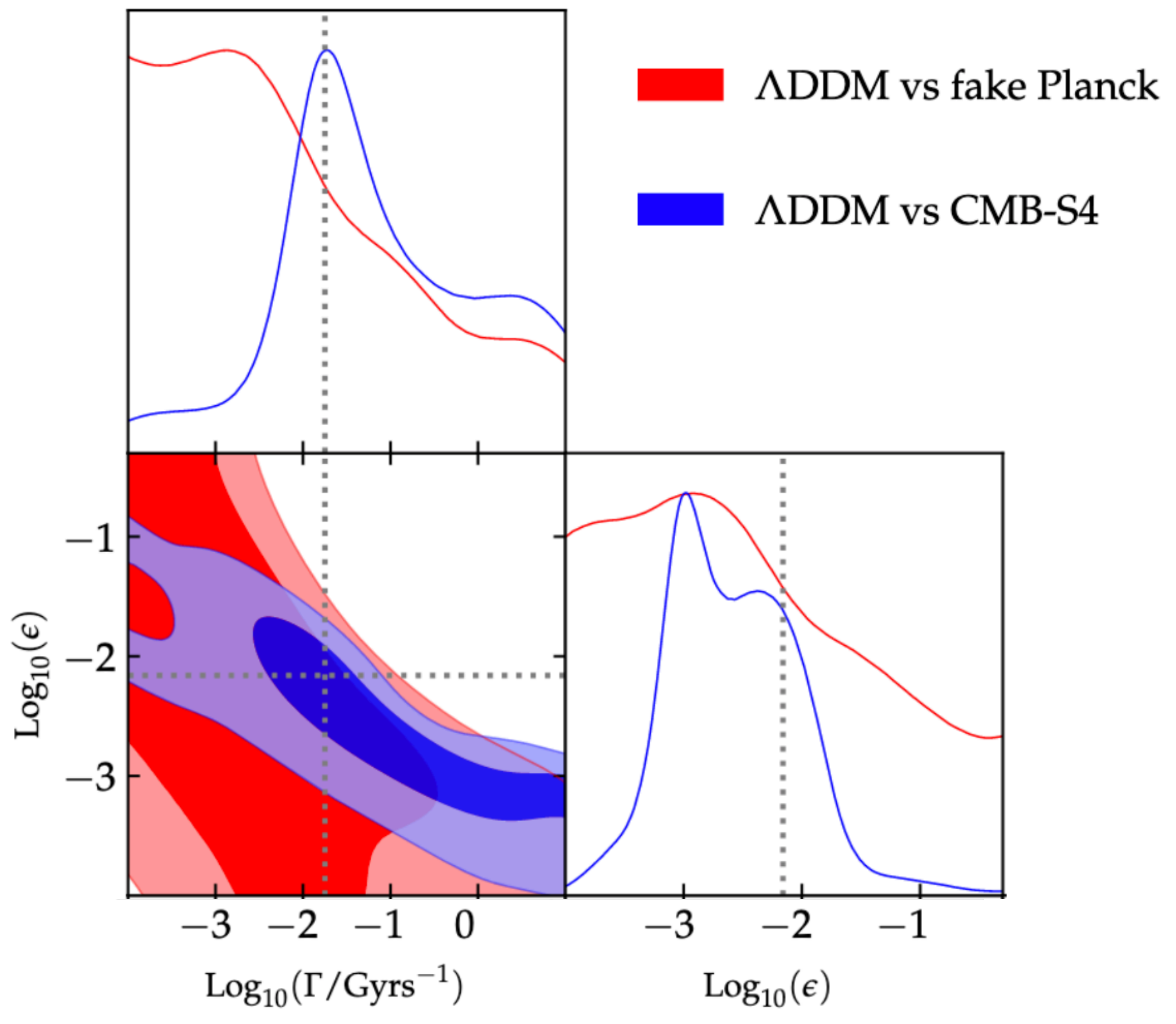
- Mildly non-linear analysis using the **EFTofBOSS** data already **improves constraints** on lifetime

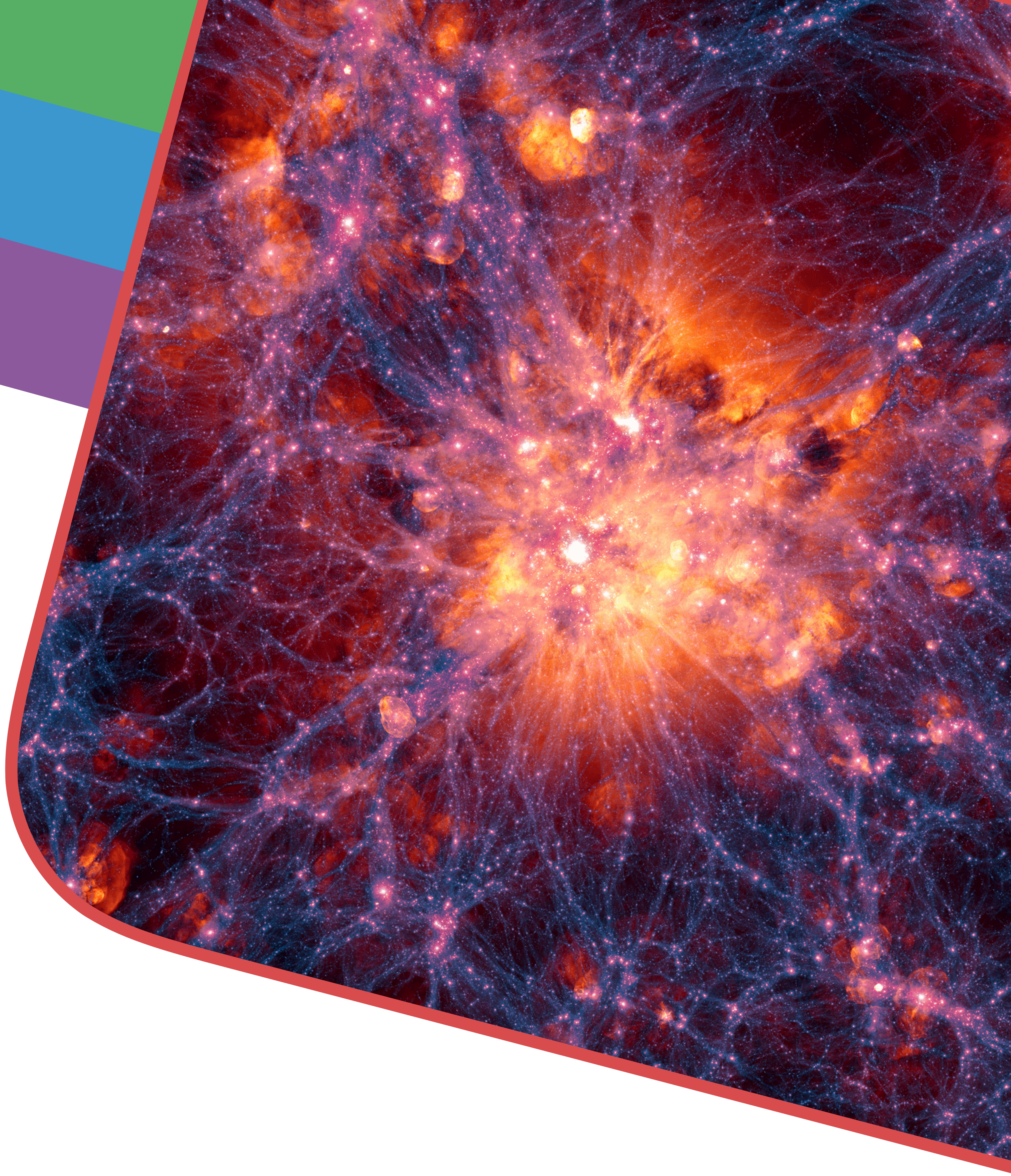
[Simon+ 22]





Conclusions

- First thorough cosmological analysis of this 2-body DM decay scenario by including a **full treatment of perturbations**



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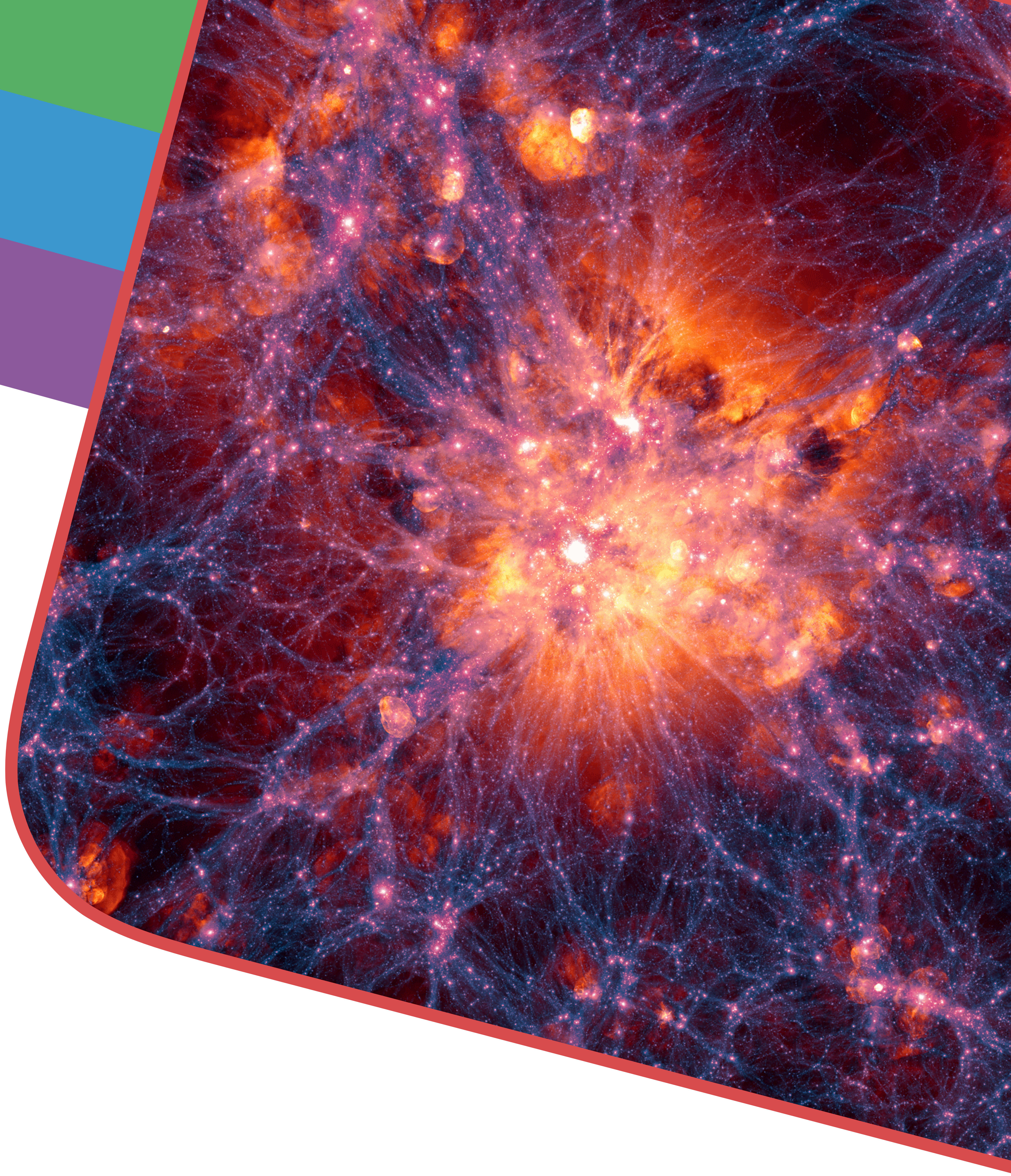

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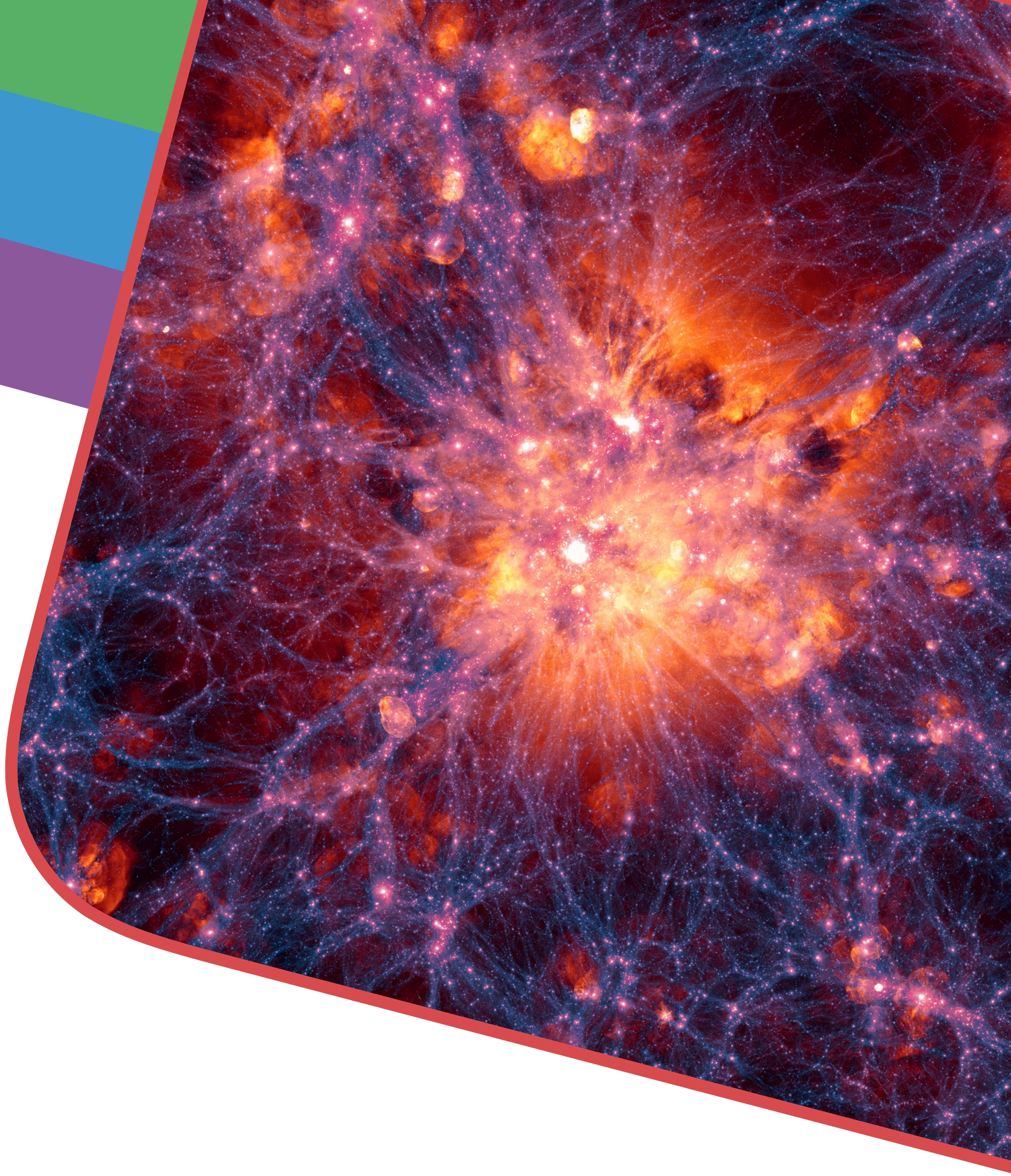
- It can successfully explain the **S_8 anomaly** while providing a good fit to CMB, BAO and SNIa data
- Future accurate **growth factor and CMB** data will be able to further test this scenario



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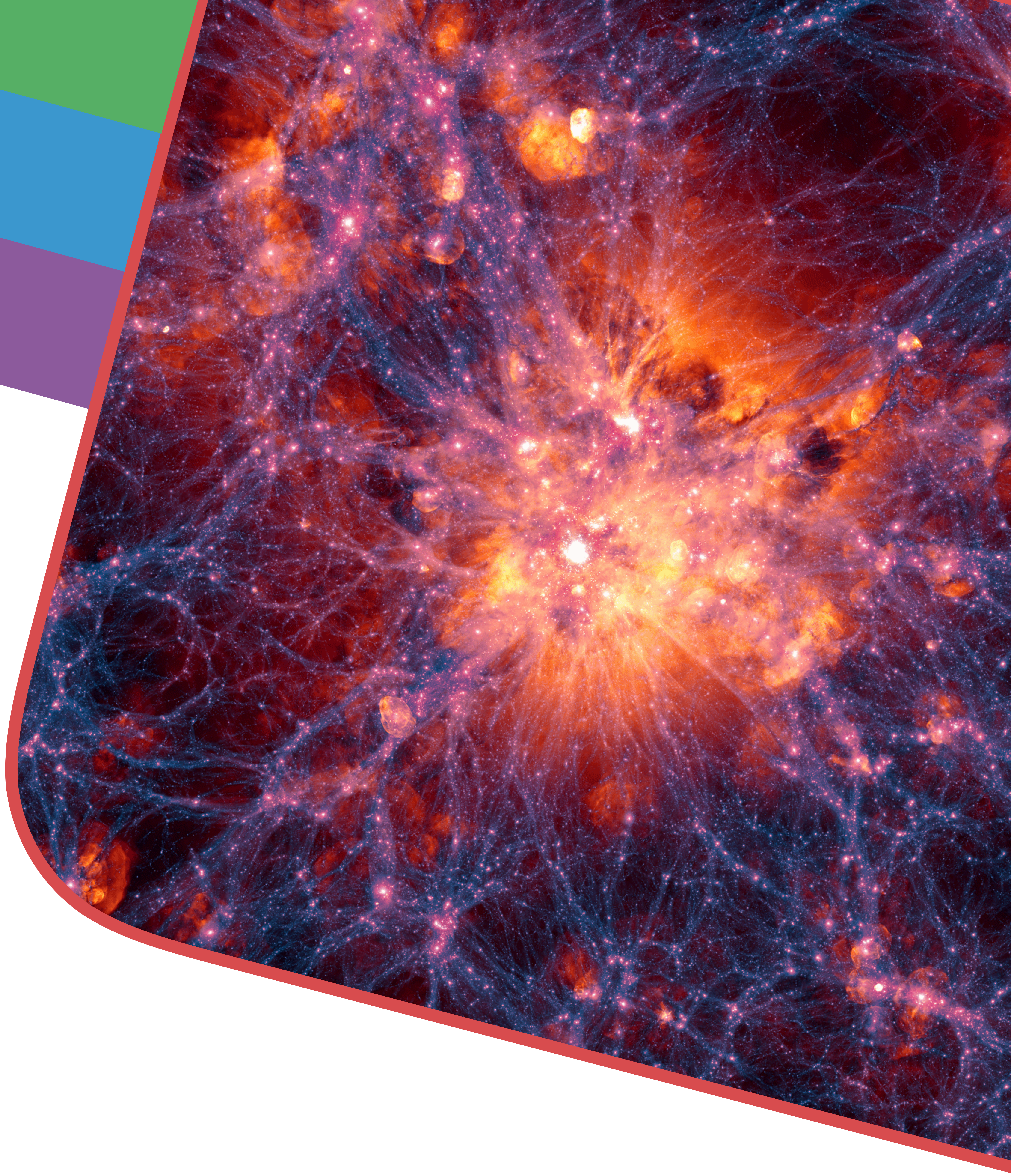

THANKS FOR YOUR ATTENTION

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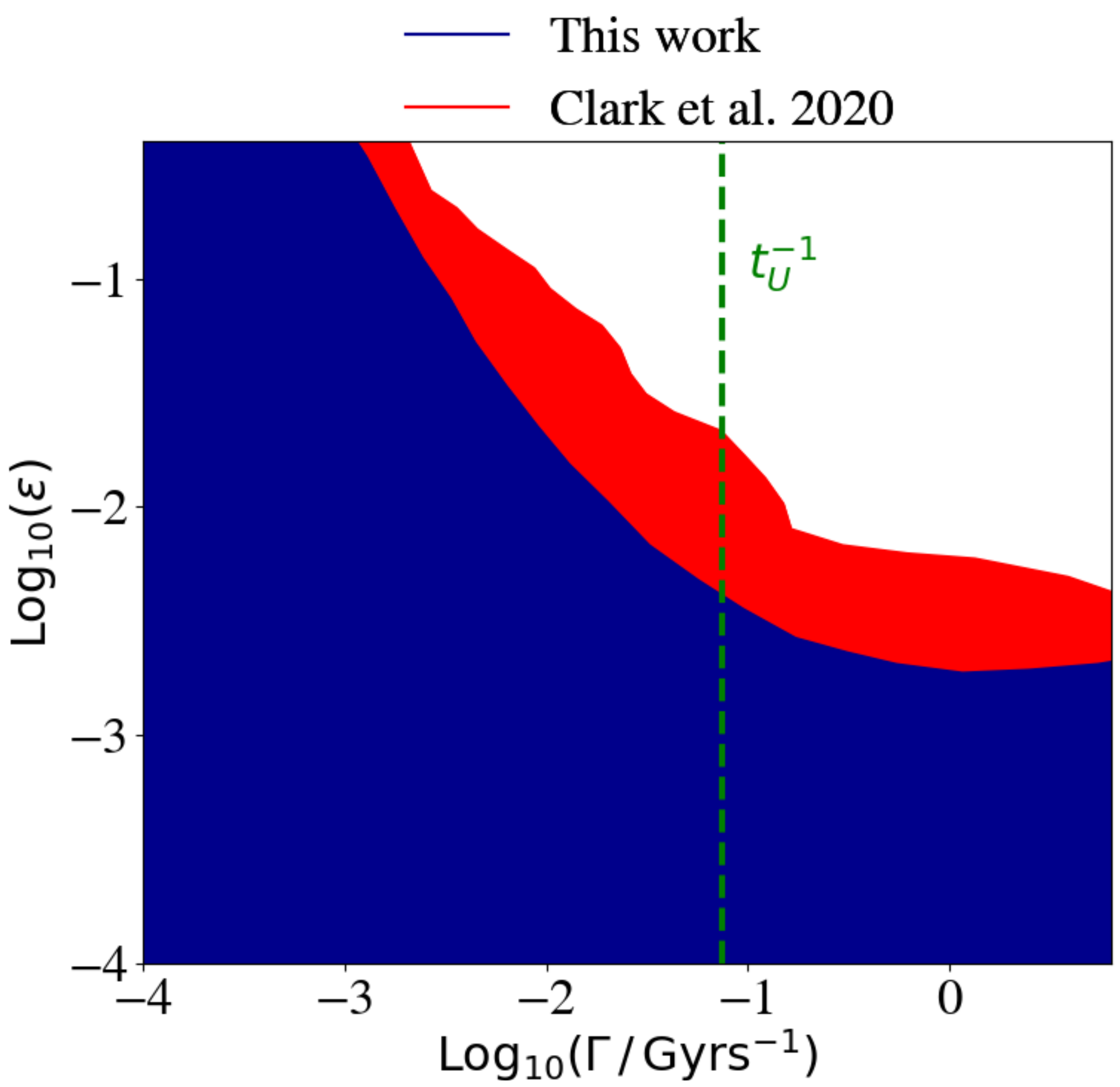
BACK-UP

General constraints

Planck18 + BAO + SNIa:



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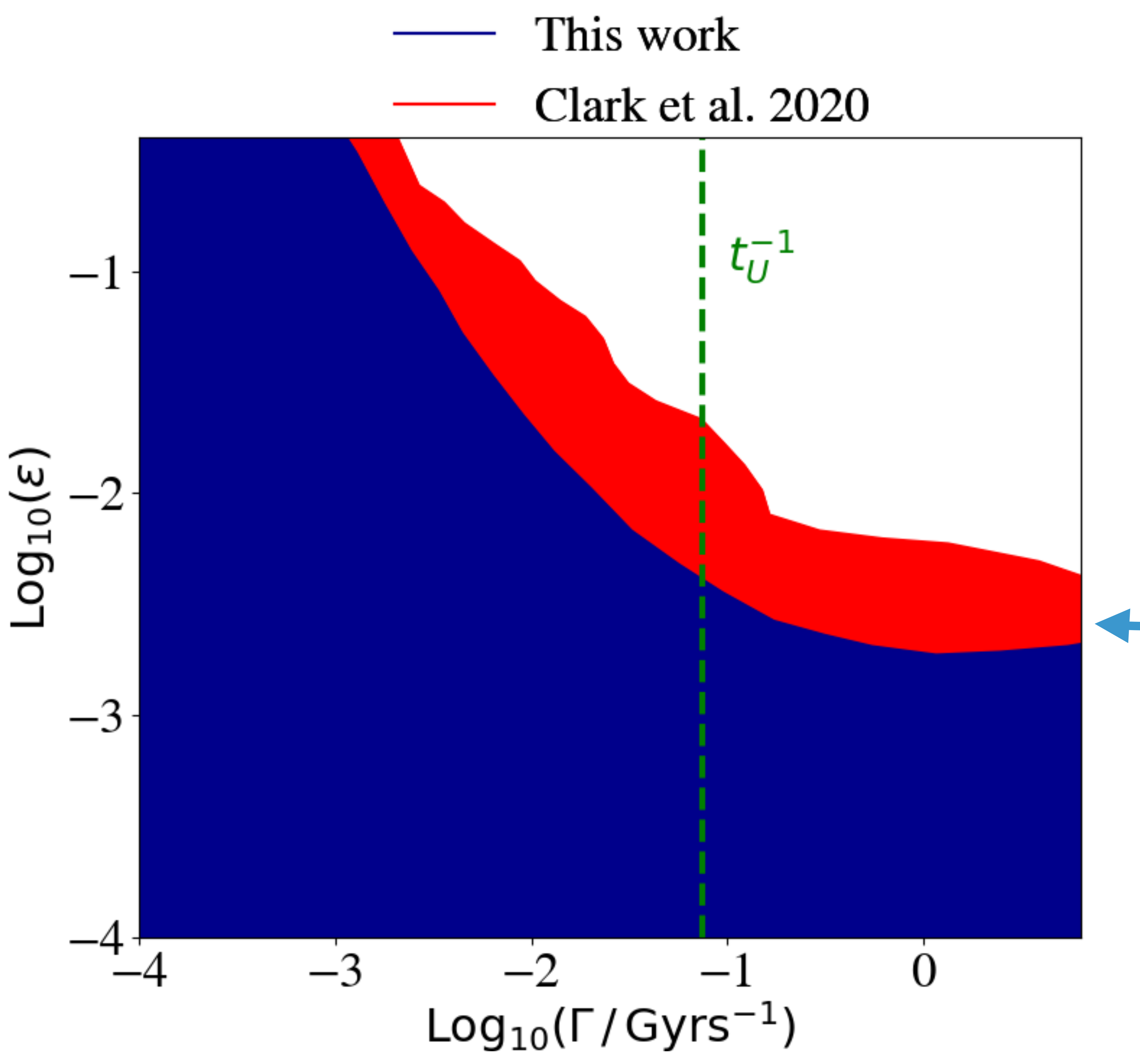

Constraints up to **1 order of magnitude stronger** than former works due to the **inclusion of WDM perts.**

Interesting implications

Model building

Why ε << 1/2, i.e. $m_{wdm} \sim m_{dm}$?

Ex: Supergravity

[Choi+ 21]

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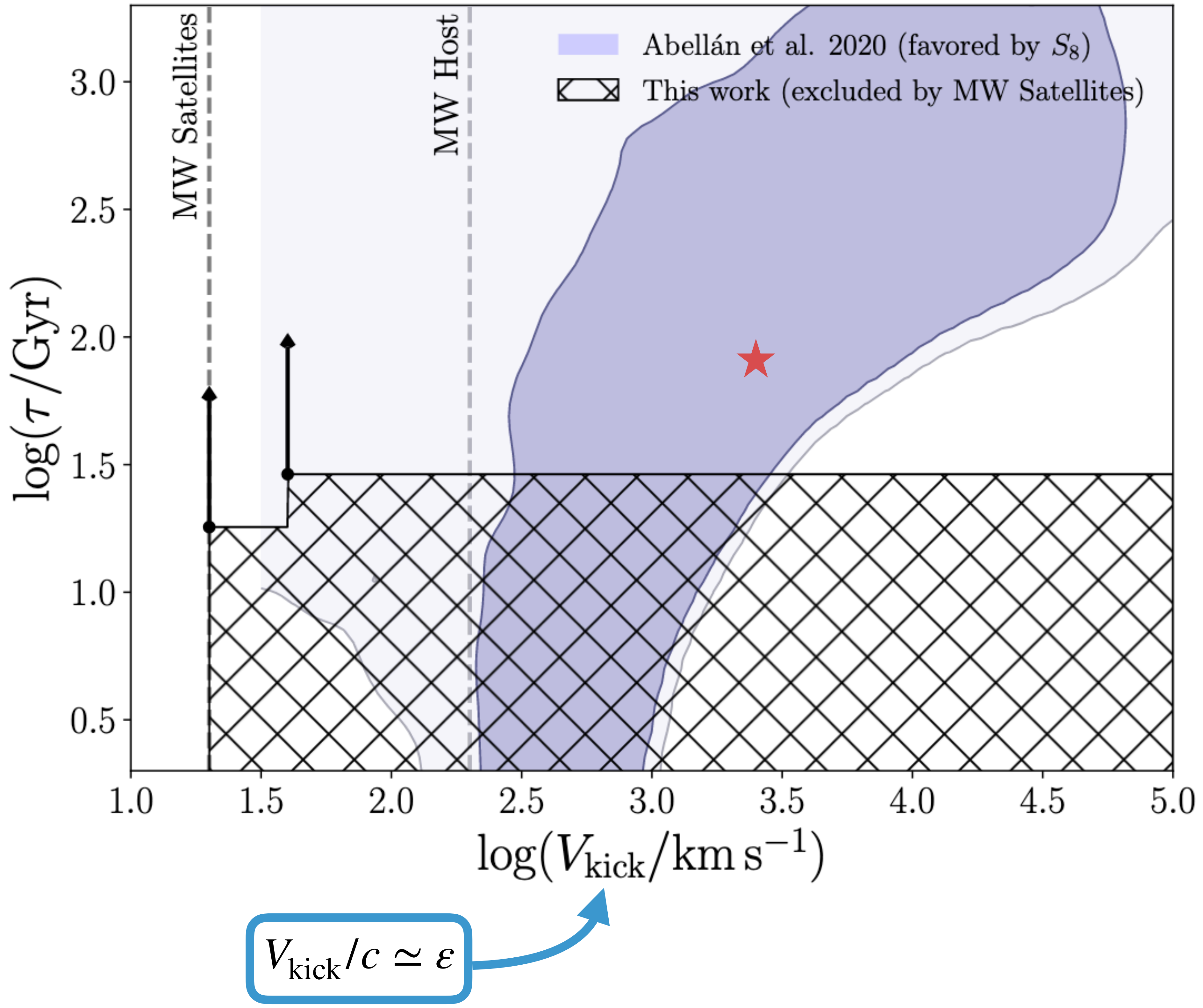
Small scales

Reduction in the abundance of **subhalos**, can be constrained by observations of **MW satellites**

[DES 22]



The full Boltzmann hierarchy

$$f(q,k,\mu,\tau) = \bar{f}(q,\tau) + \delta f(q,k,\mu,\tau)$$

Expand δf in multipoles. The Boltzmann eq. leads to the following **hierarchy** (in **synchronous** gauge comoving with the mother)

$$\frac{\partial}{\partial\tau}(\delta f_0) = -\frac{\mathbf{q}k}{\mathbf{aE}}\delta f_1 + q\frac{\partial\bar{f}}{\partial q}\frac{\dot{h}}{6} + \frac{\Gamma\bar{N}_{\rm dm}(\tau)}{4\pi q^3 H}\delta(\tau-\tau_q)\delta_{\rm dm},$$

$$\frac{\partial}{\partial\tau}(\delta f_1) = \frac{\mathbf{q}k}{3\mathbf{aE}}\left[\delta f_0 - 2\delta f_2\right],$$

$$\frac{\partial}{\partial\tau}(\delta f_2) = \frac{\mathbf{q}k}{5\mathbf{aE}}\left[2\delta f_1 - 3\delta f_3\right] - q\frac{\partial\bar{f}}{\partial q}\frac{(\dot{h}+6\dot{\eta})}{15},$$

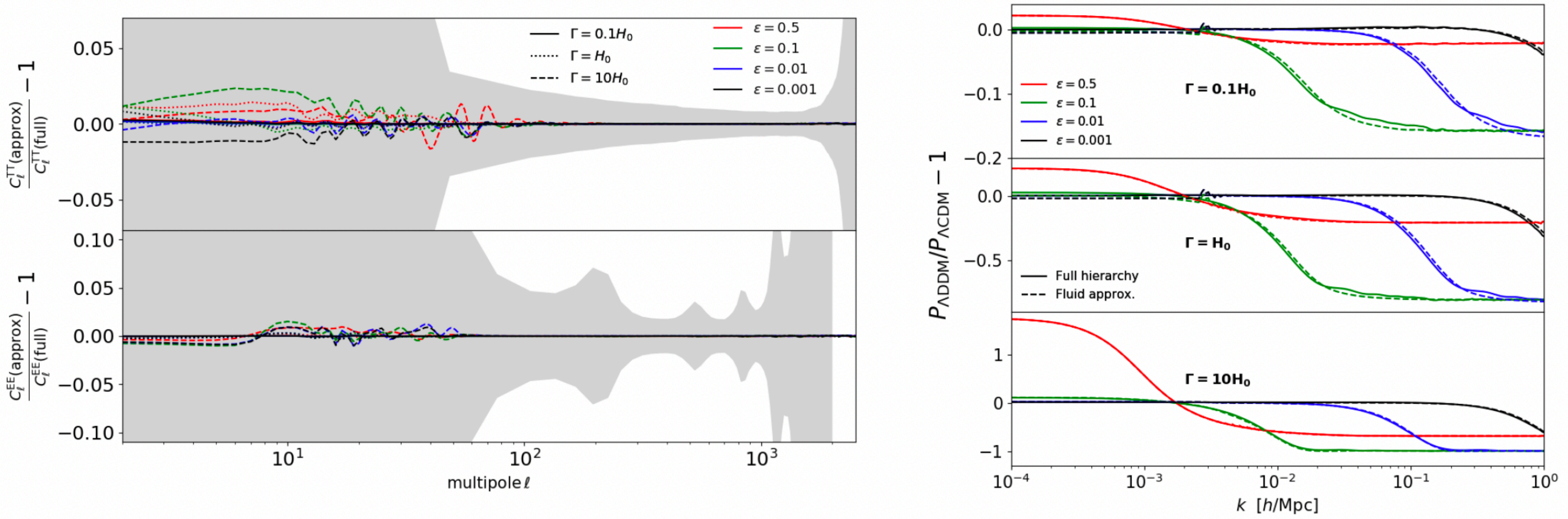
$$\frac{\partial}{\partial\tau}(\delta f_\ell) = \frac{\mathbf{q}k}{(2\ell+1)\mathbf{aE}}\left[\ell\delta f_{\ell-1} - (\ell+1)\delta f_{\ell+1}\right] \qquad (\text{for } \ell \geq 3)\,.$$

where $q = a(\tau_q)p_{\rm max}$. In the relat. limit $\mathbf{q/aE = 1}$, so one can take

$F_\ell \equiv \frac{4\pi}{\rho_c}\int dq\; q^3\delta f_\ell$ and **integrate out the dependency on q**

Checking the accuracy of the WDM fluid approx.

We compare the full Boltzmann hierarchy calculation with the WDM fluid approx.

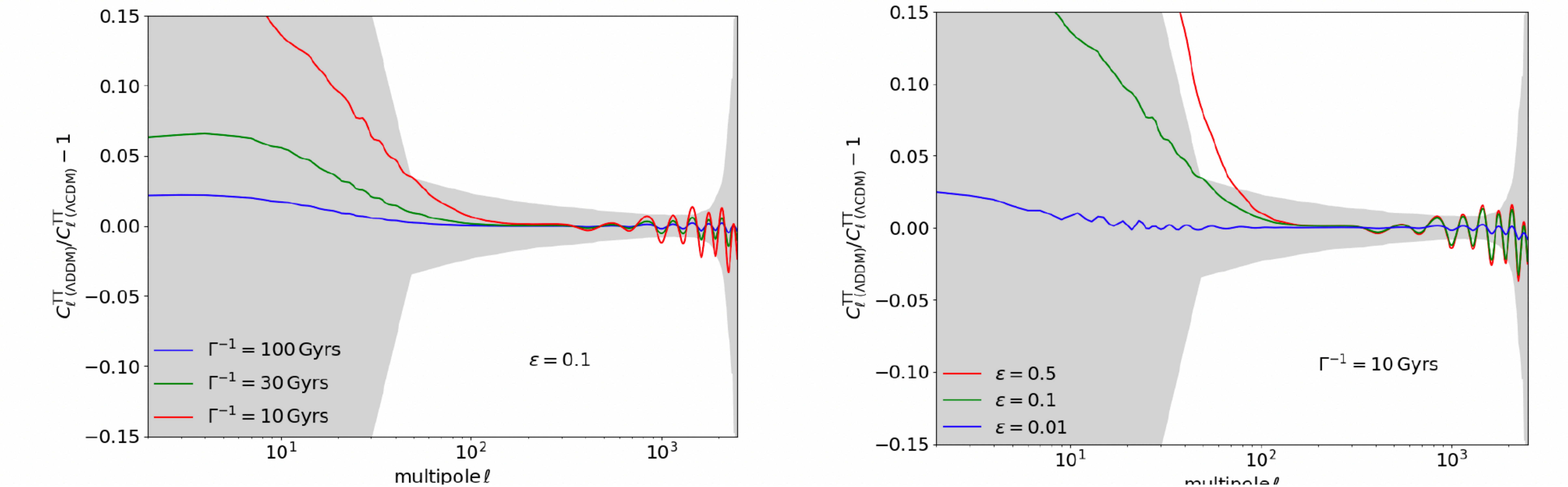


The max. error on S_8 is ~0.65 %, smaller than the ~1.8 % error of the measurement from BOSS+KiDS+2dfLenS

Impact of DDM on the CMB temperature spectrum

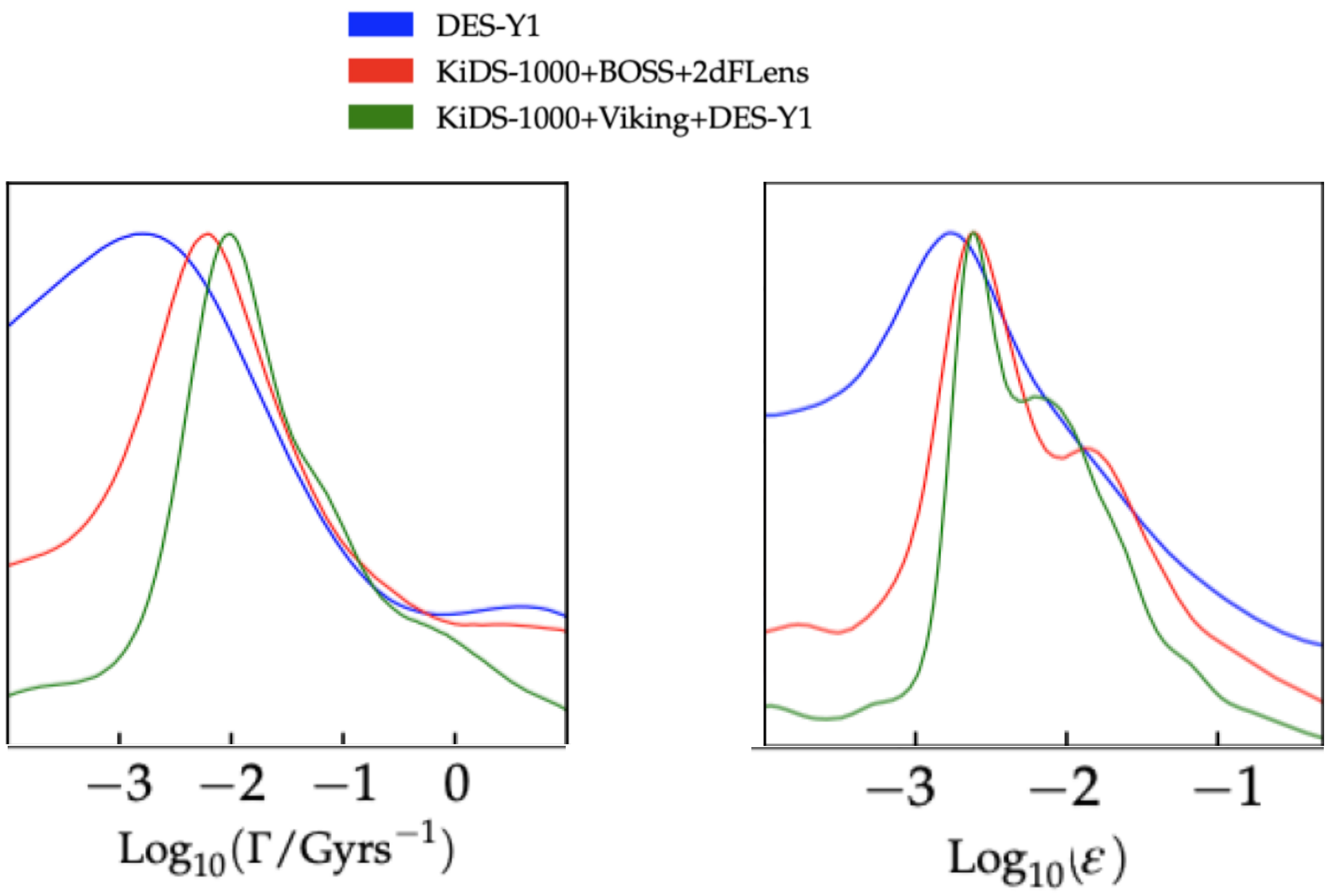
Low-ℓ : **enhanced** Late Integrated Sachs Wolfe (**LISW**) effect

High-ℓ : **suppressed** lensing (higher contrast between peaks)

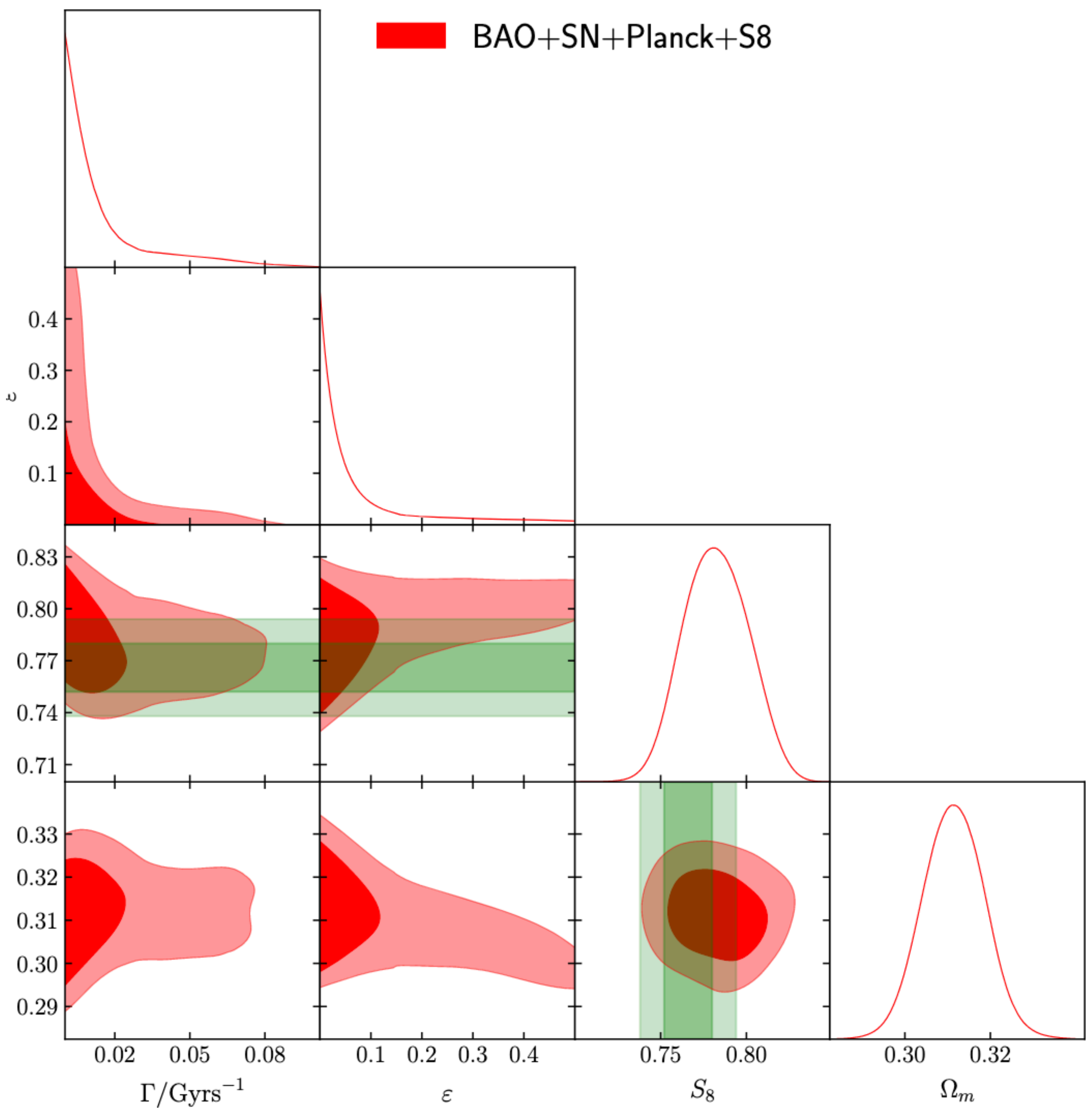


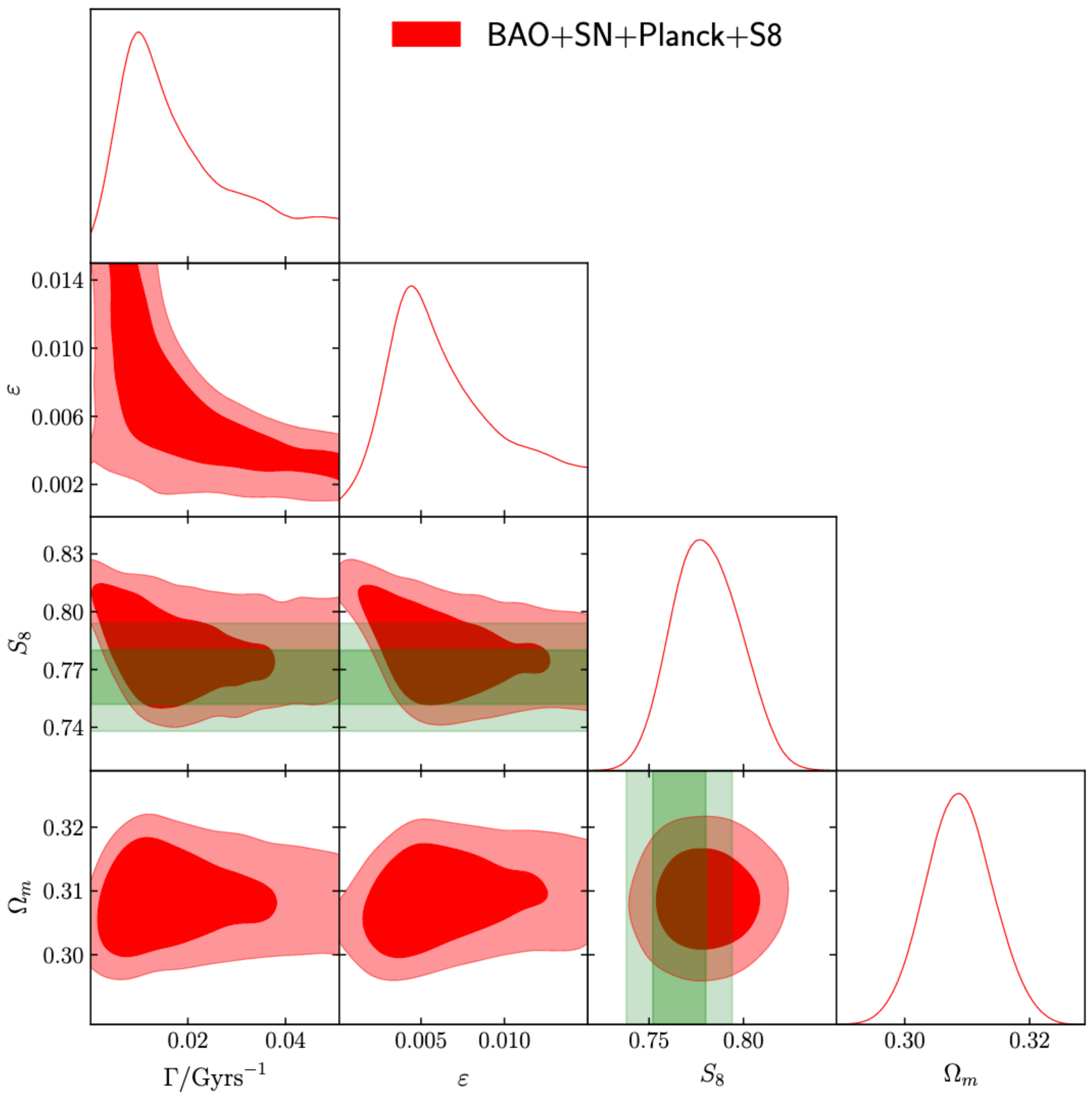
DDM resolution to the S_8 tension

The level of detection depends on the level of tension with ΛCDM

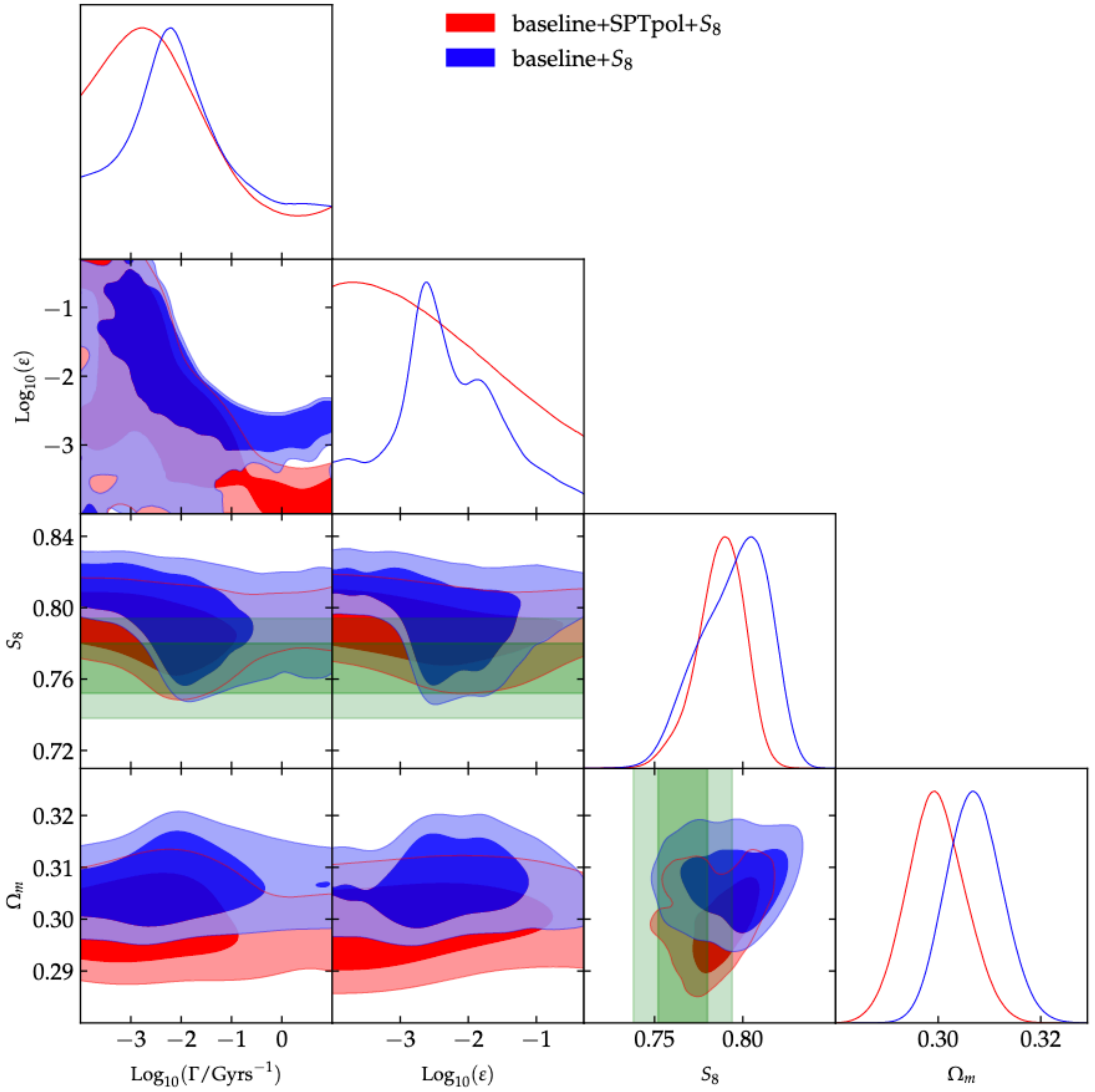


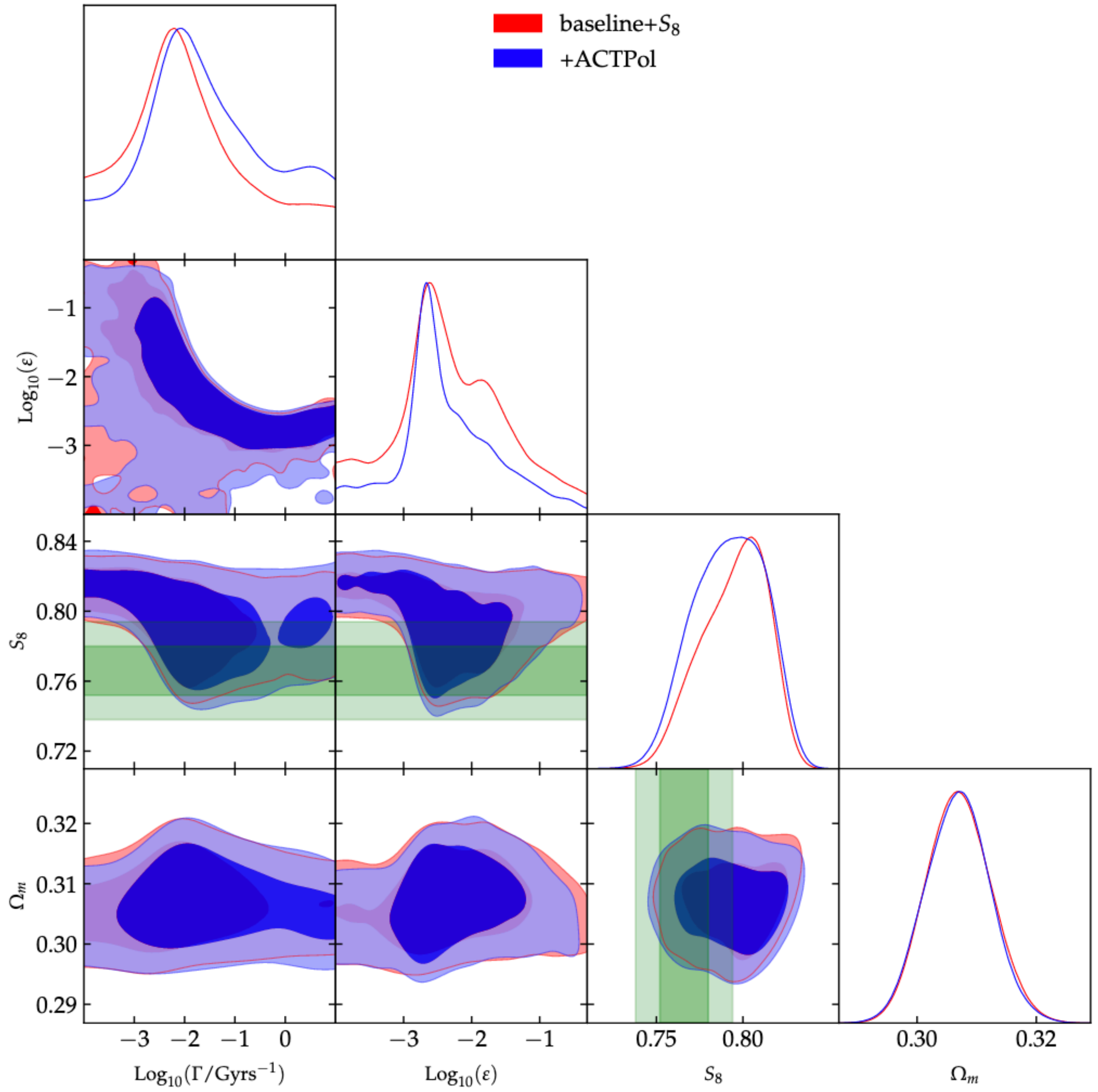
DDM results with linear priors





DDM results with SPTPol and ACT datasets





DDM results marginalizing over lensing information