Decaying dark matter: cosmological constraints and implications for the S_8 tension

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Based on:

arXiv:2102.12498 (PRD in press)

arXiv:2008.09615 (PRD in press)

with Riccardo Murgia, Vivian Poulin and Julien Lavalle

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Tensions in cosmology

With the era of precision cosmology, several discrepancies have emerged

- S_8 with weak-lensing data
  KiDS-1000 2007.15632

- H_0 with local measurements
  Riess++ 2012.08534

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- Less exotic explanation ✅
- Difficult to account for all discrepancies ❌

Physics beyond ΛCDM?

- Reveal properties about the dark sector ✅
- Very challenging ❌

Tensions in cosmology

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- S_8 with weak-lensing data → This talk
  KiDS-1000 2007.15632
- H_0 with local measurements → My previous works:
  Riess++ 2012.08534
  Murgia, GFA, Poulin 2009.10733
  Schöneberg, GFA++ 2107.10291

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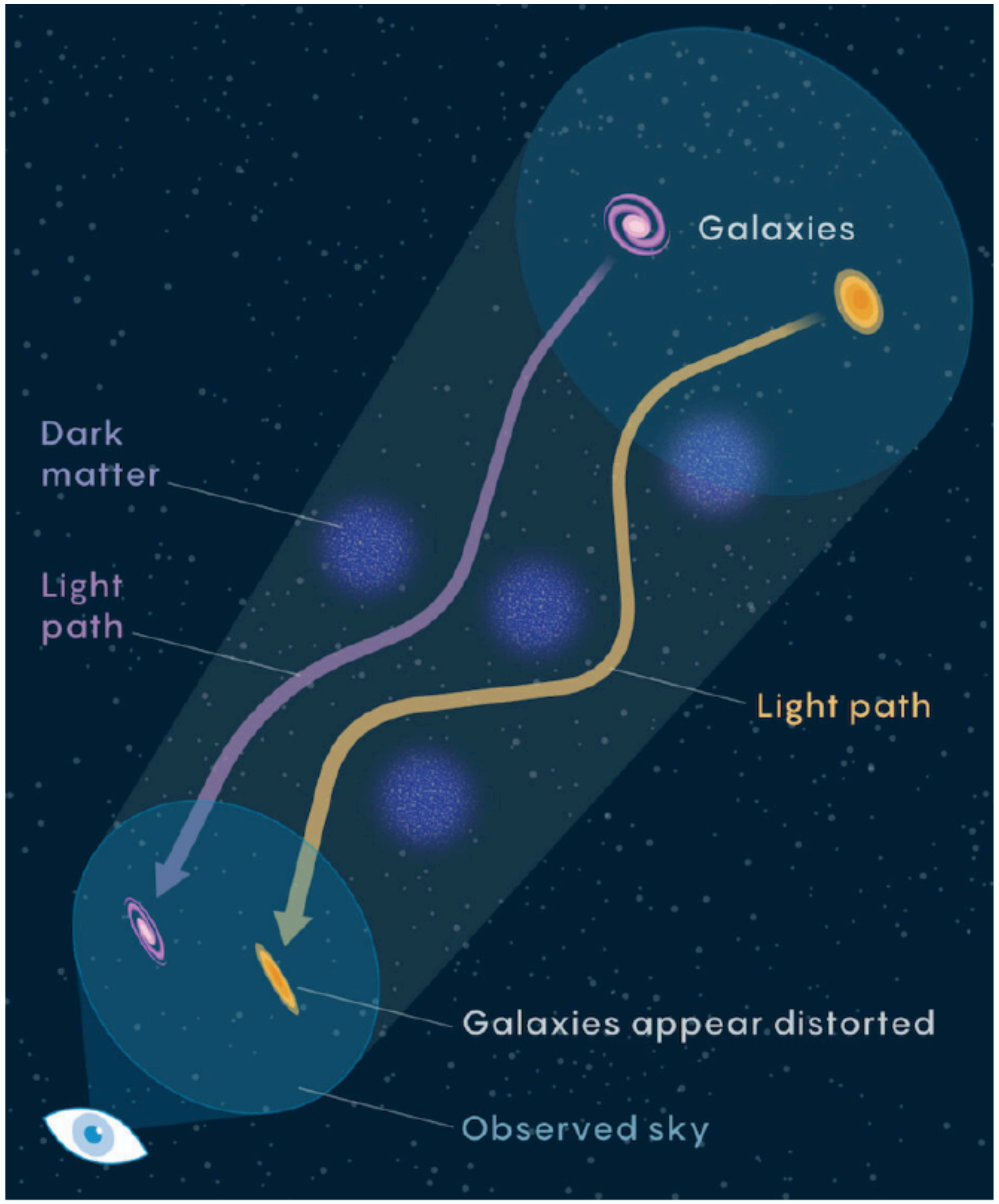
The S_8 tension

Weak-lensing surveys are mainly sensible to $S_8 \equiv \sigma_8\sqrt{\Omega_m/0.3}$



KiDS+BOSS+2dfLenS*:

$$S_8 = 0.766^{+0.020}_{-0.014}$$

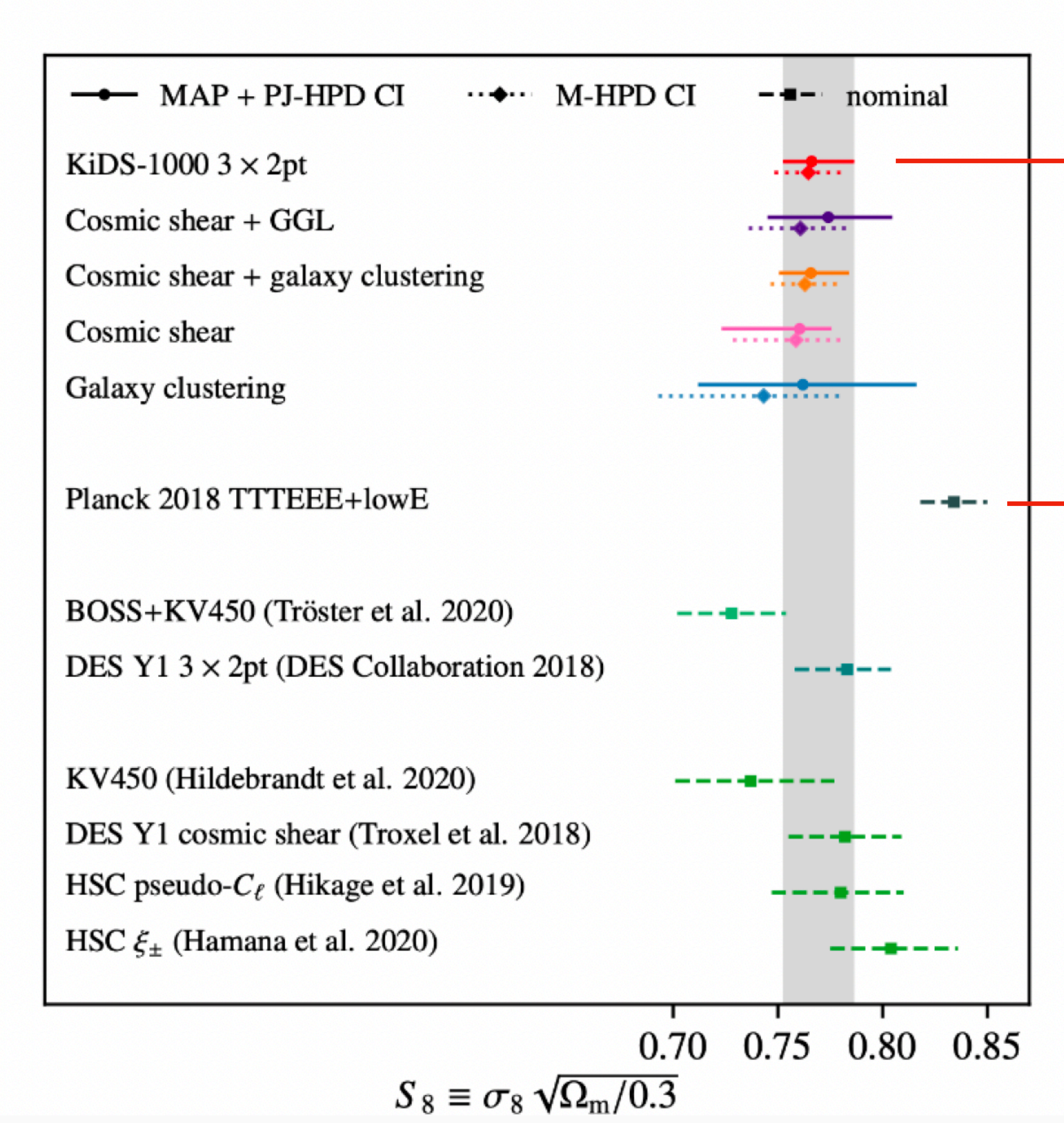
Planck (*under ΛCDM*):

$$S_8 = 0.830 \pm 0.013$$

$\rightarrow$ $\sim \mathbf{2-3}\boldsymbol{\sigma}$ tension

*Other surveys such as DES, CFHTLens or HSC yield similar results

The S_8 tension



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Di Valentino++ 2008.11285

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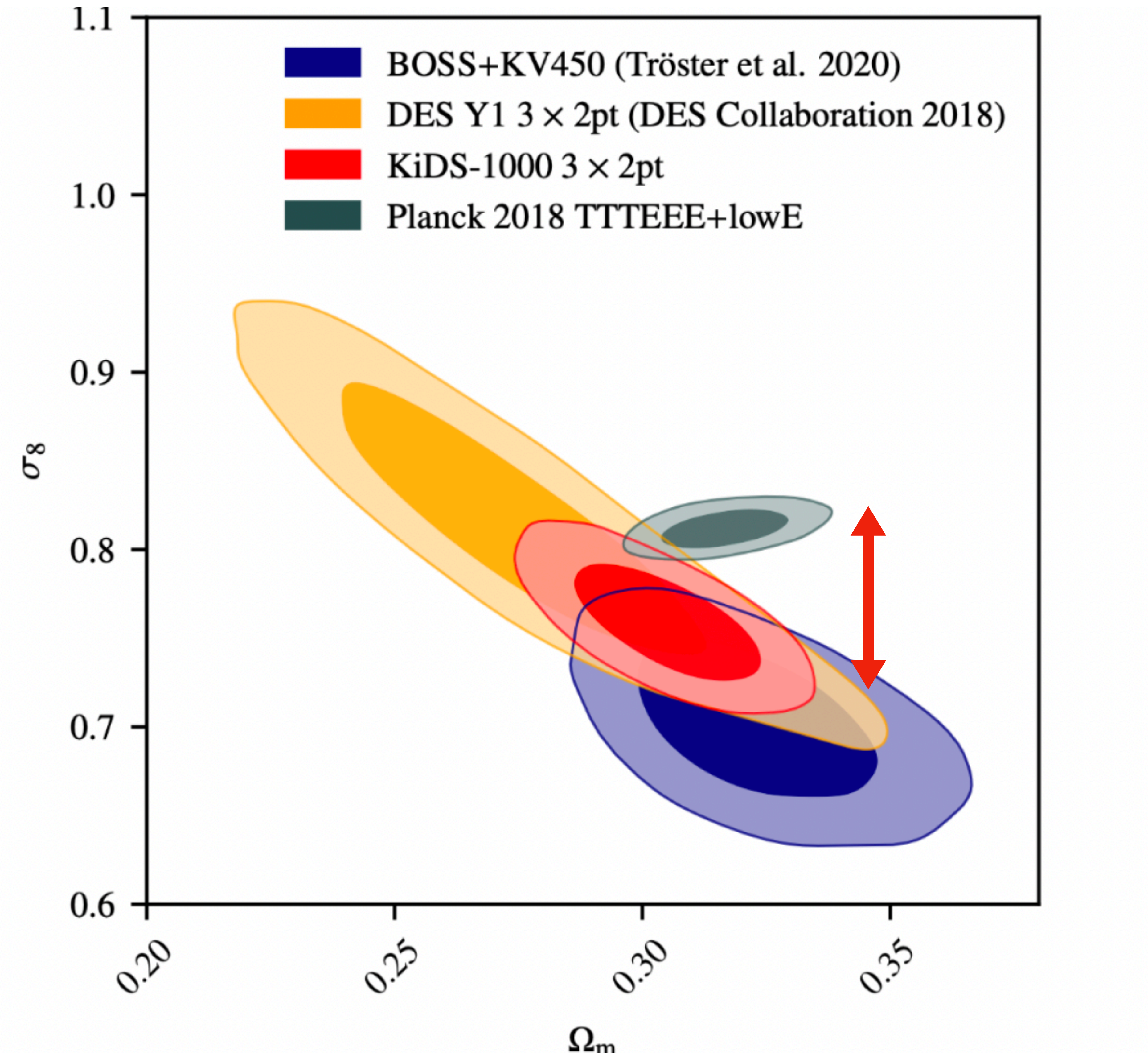

Ω_m should be left unchanged

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

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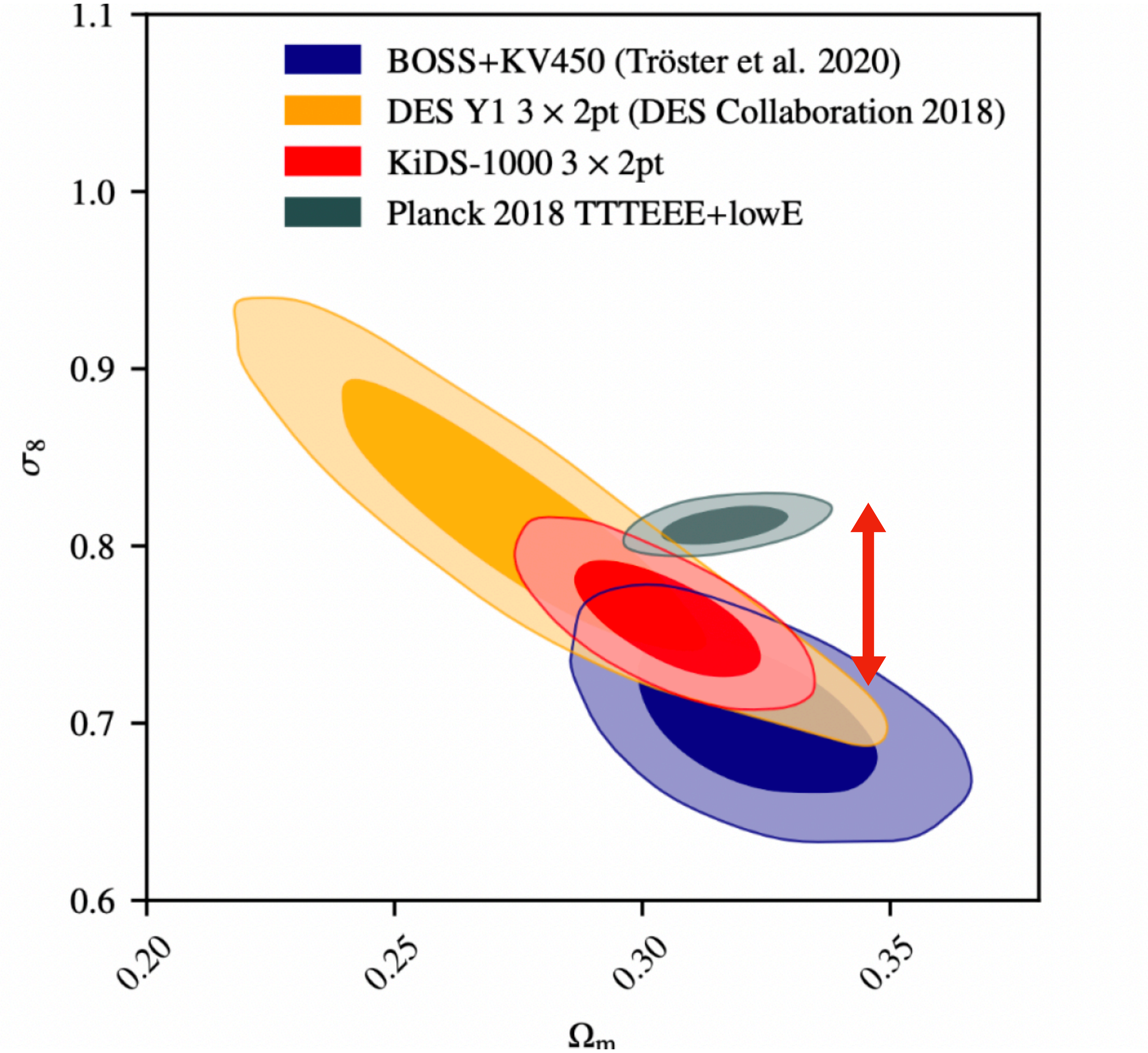

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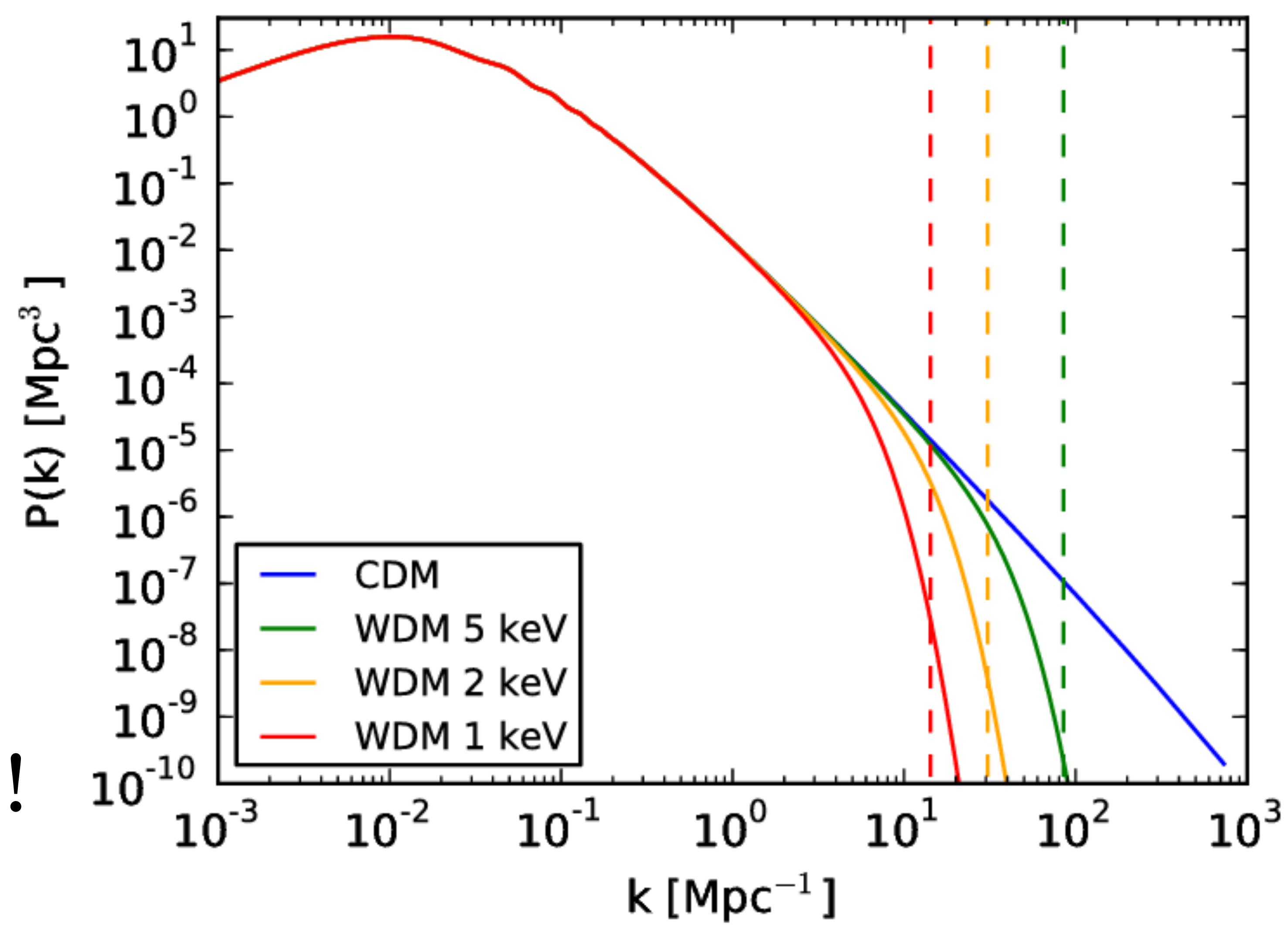
↓

Need to suppress power at scales $k \sim 0.1 - 1\ h/\mathrm{Mpc}$

Ex: Warm Dark Matter

Very constrained by many probes!



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Can we test this hypothesis?

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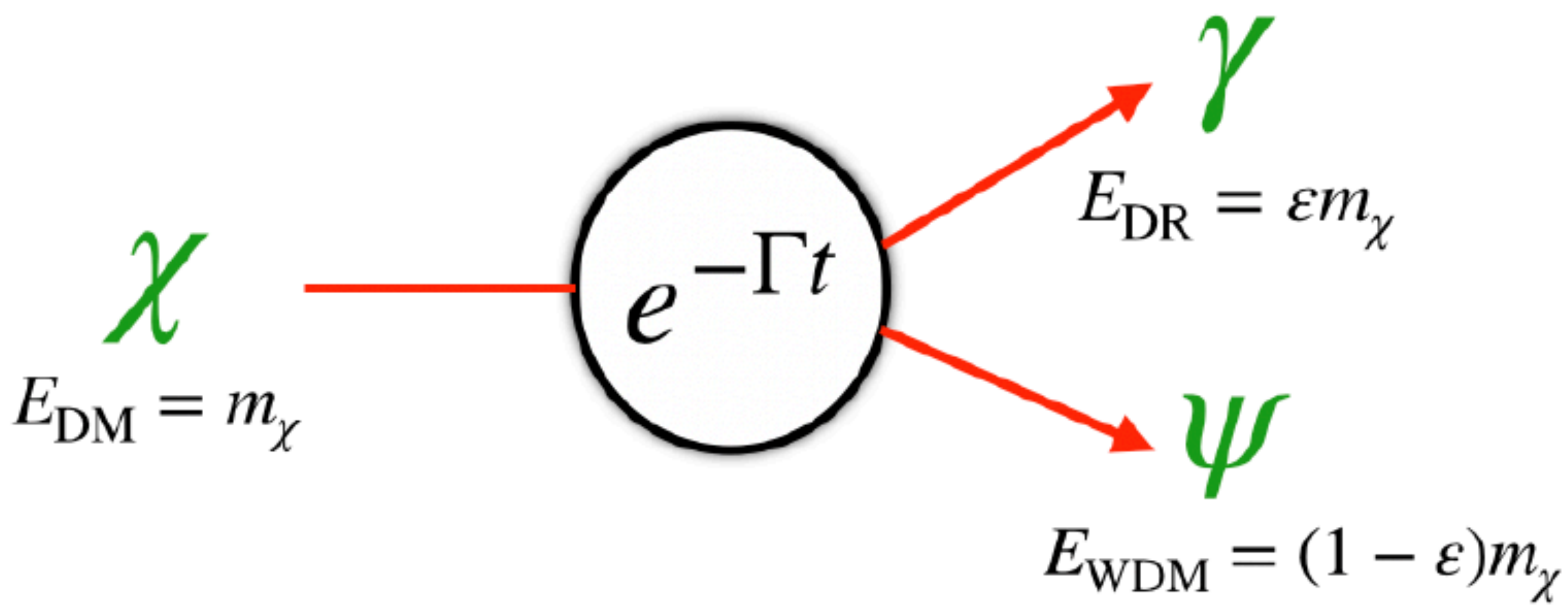
- What about massive products?

2-body Dark Matter decay

We explore DM decays to massless (Dark Radiation) and massive (Warm Dark Matter) particles, $\chi(\mathrm{DM}) \rightarrow \gamma(\mathrm{DR}) + \psi(\mathrm{WDM})$



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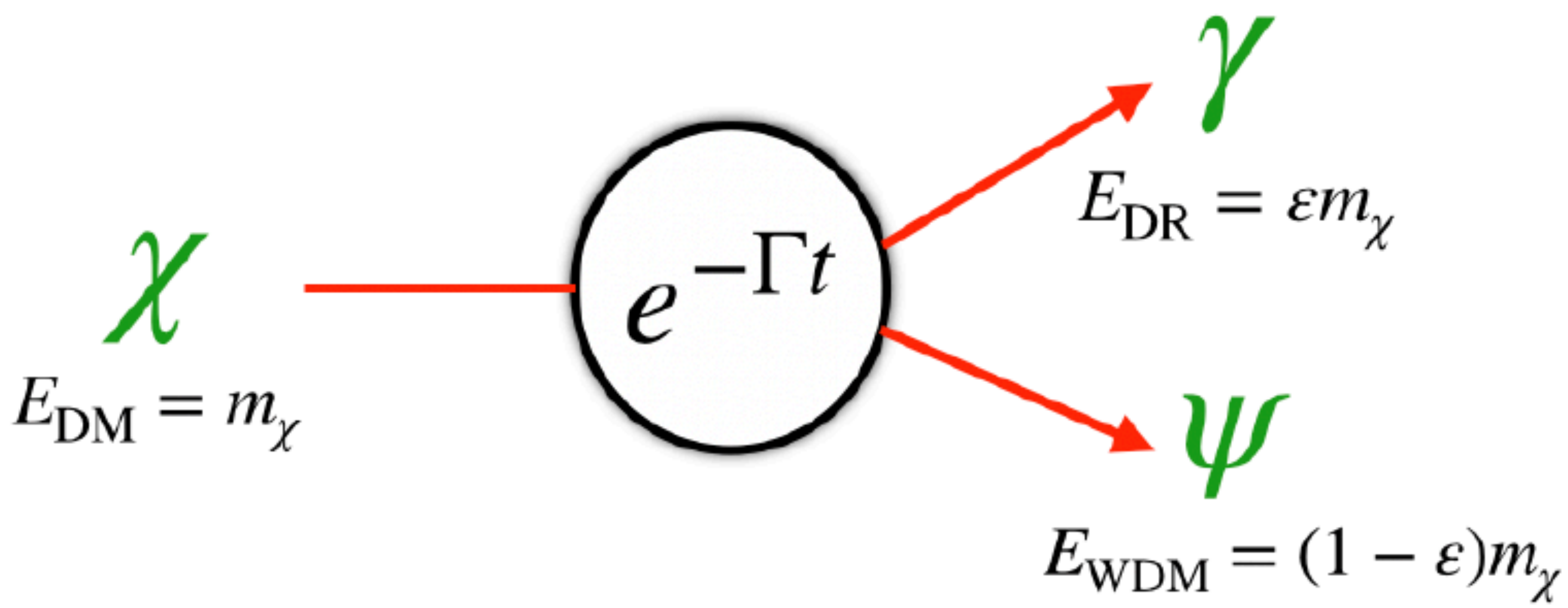

The model is fully specified by:

$$\{\Gamma,\ \varepsilon\} \quad \text{where} \quad \varepsilon = \frac{1}{2}\left(1 - \frac{\mathbf{m}_\psi^2}{\mathbf{m}_\chi^2}\right) \begin{cases} = \mathbf{0} \text{ for } \Lambda\mathrm{CDM} \\ = \mathbf{1/2} \text{ for DM} \to \mathrm{DR} \end{cases}$$

2-body Dark Matter decay

Aoyama++ 1402.2972 → Full treatment of perts. — No parameter scan

Vattis++ 1903.06220 → Resolution to H_0 tension ?

Haridasu++ 2004.07709 → SNIa+BAO rule out solution

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Our goal: Perform parameter scan by including full treatment of linear perts, in order to assess the impact on the S_8 tension

Evolution of perturbations: full treatment

- Effects on $P_m(k)$ and C_ℓ ? Track linear perts. for the particles species involved in the decay: δ_i, θ_i and $\sigma_{\rm i}$ for $\rm i = dm, dr, wdm$

Evolution of perturbations: full treatment

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- Boltzmann hierarchy of eqs. Dictate the evolution of the p.s.d. multipoles $\Delta f_\ell(q, k, \tau)$

✦ DM and DR treatments are easy, momentum d.o.f. are integrated out

✦ For WDM, one needs to follow the evolution of the full p.s.d.
Computationally expensive ⟶ $\mathcal{O}(10^8)$ ODEs to solve!

Evolution of perturbations: fluid equations

New fluid eqs.*, based on previous approximation for massive neutrinos

Lesgourgues & Tram, 1104.2935

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

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*Implemented in modified version of public Boltzmann solver CLASS

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where

$$c_a^2(\tau) = w\left(5 - \frac{\mathfrak{p}_{\rm wdm}}{\bar{P}_{\rm wdm}} - \frac{\bar{\rho}_{\rm dm}}{\bar{\rho}_{\rm wdm}}\frac{\Gamma}{3wH}\frac{\varepsilon^2}{1-\varepsilon}\right)\left[3(1+w) - \frac{\bar{\rho}_{\rm dm}}{\bar{\rho}_{\rm wdm}}\frac{\Gamma}{H}(1-\varepsilon)\right]^{-1}$$

and

$$c^2_{\rm syn}(k,\tau) = c_a^2(\tau)\left[1 + (1-2\varepsilon)T(k/k_{\rm fs})\right]$$

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

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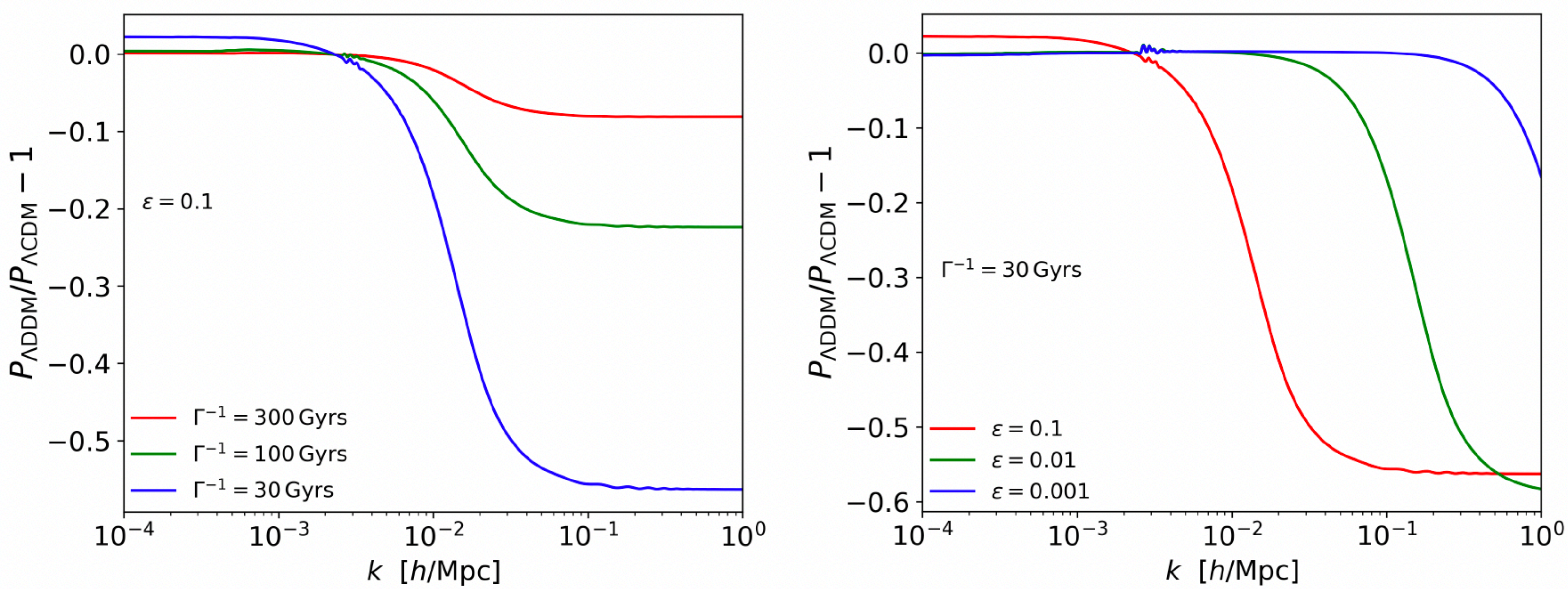
Impact of decaying DM on the matter spectrum

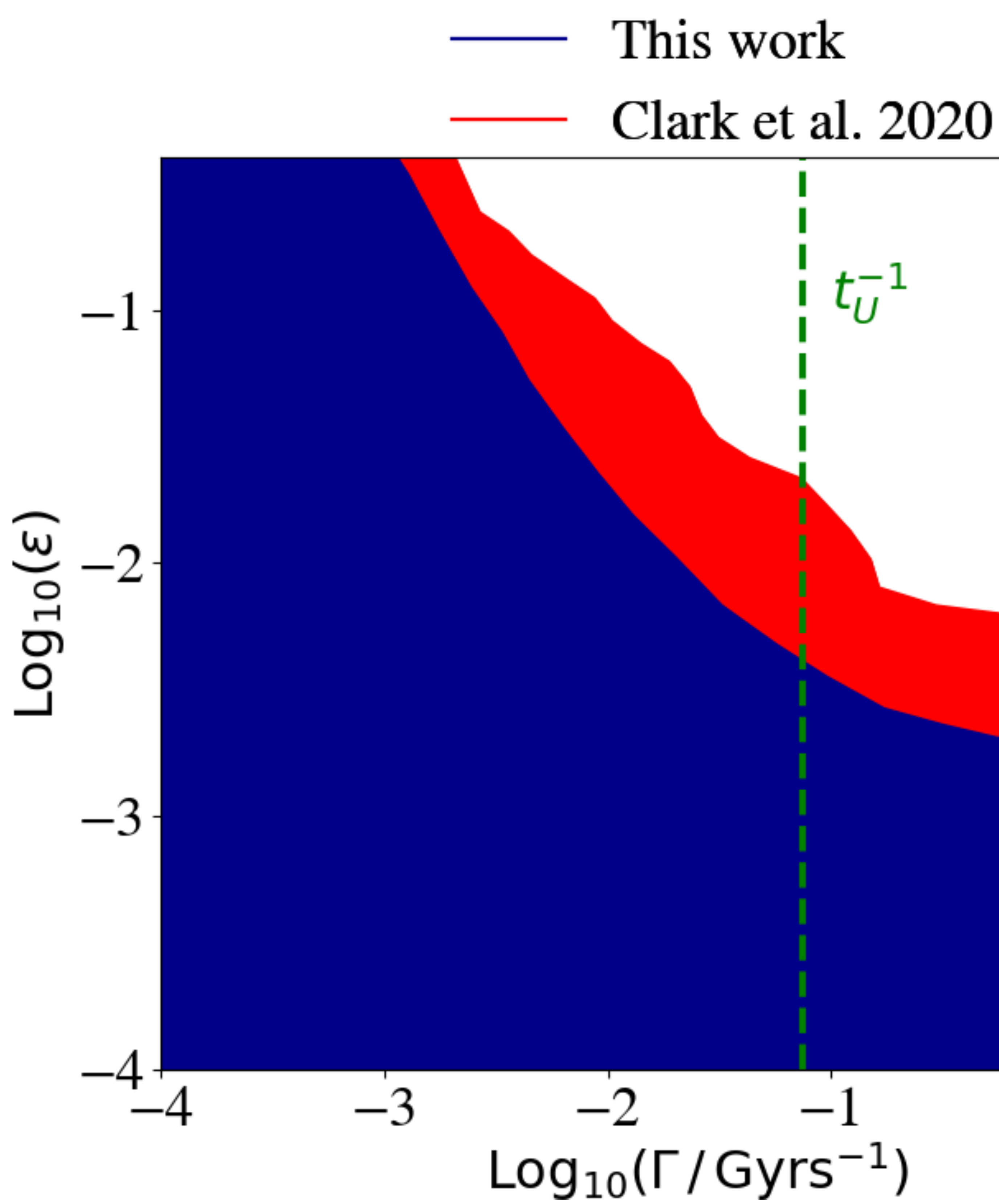
The WDM daughter leads to a power suppression in $P_m(k)$ at small scales $k > k_{fs}$, where $k_{fs} \sim aH/c_a$



GFA, Murgia, Poulin 2008.09615

General constraints on the 2-body DM decay

Planck+BAO+SNIa analysis



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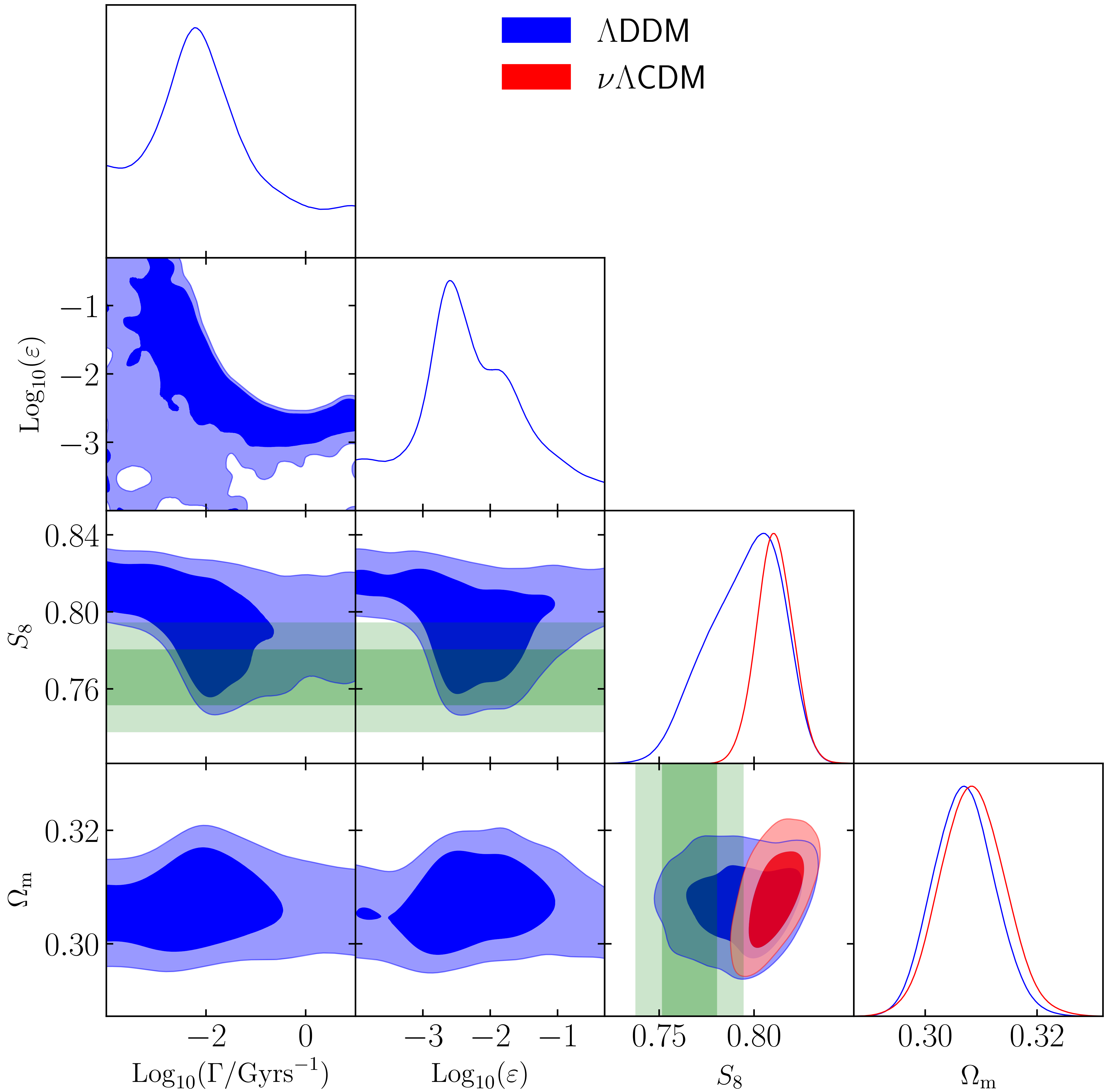
Strong negative correlation between ϵ and Γ

Constraints up to 1 order of magnitude stronger than previous literature

Explaining the S_8 tension



- MCMC analysis using Planck+BAO+SNIa+prior on S_8 from KIDS+BOSS+2dfLenS

GFA, Murgia, Poulin 2102.12498

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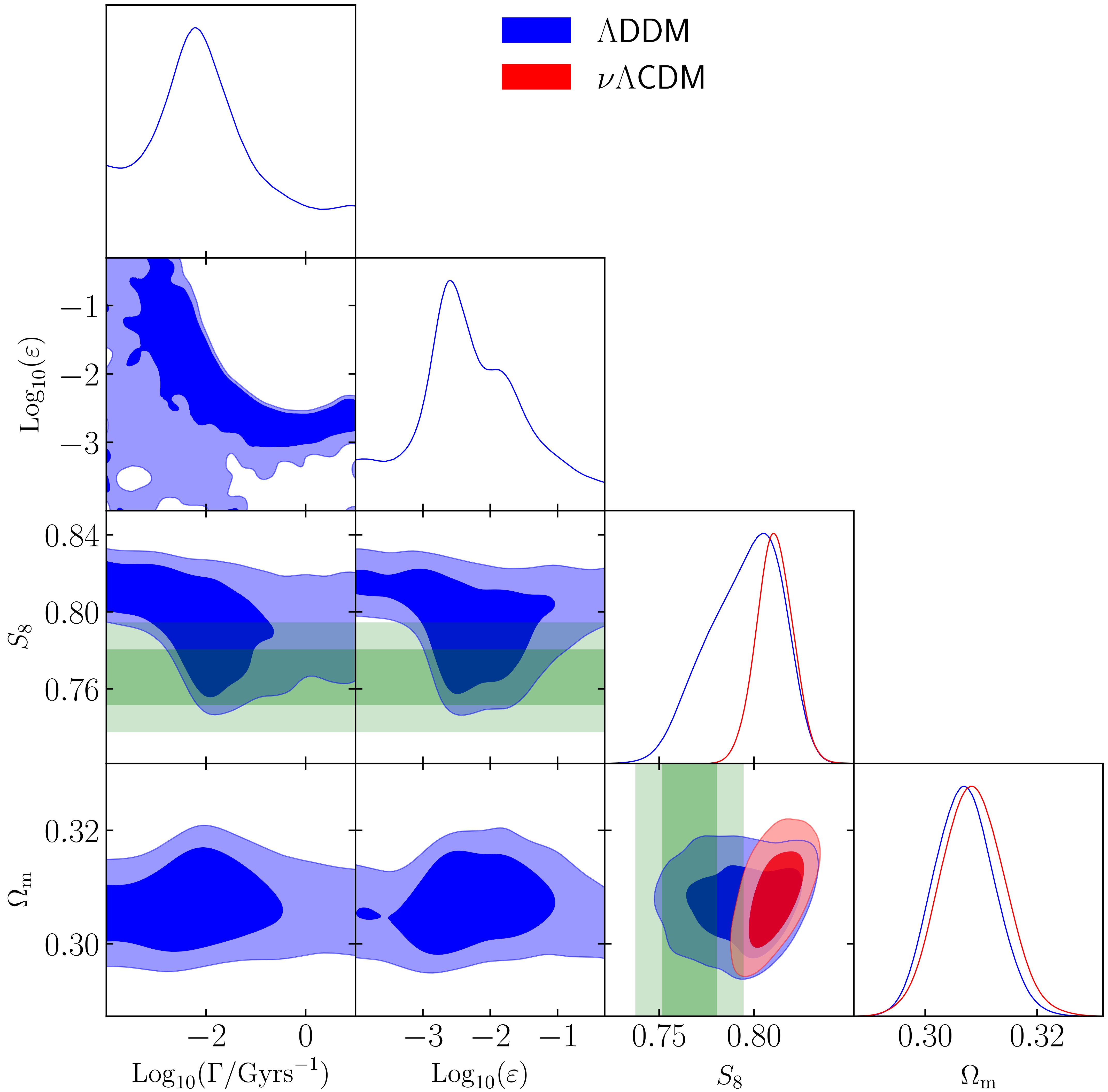

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- MCMC analysis using Planck+BAO+SNIa+prior on S_8 from KIDS+BOSS+2dfLenS

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

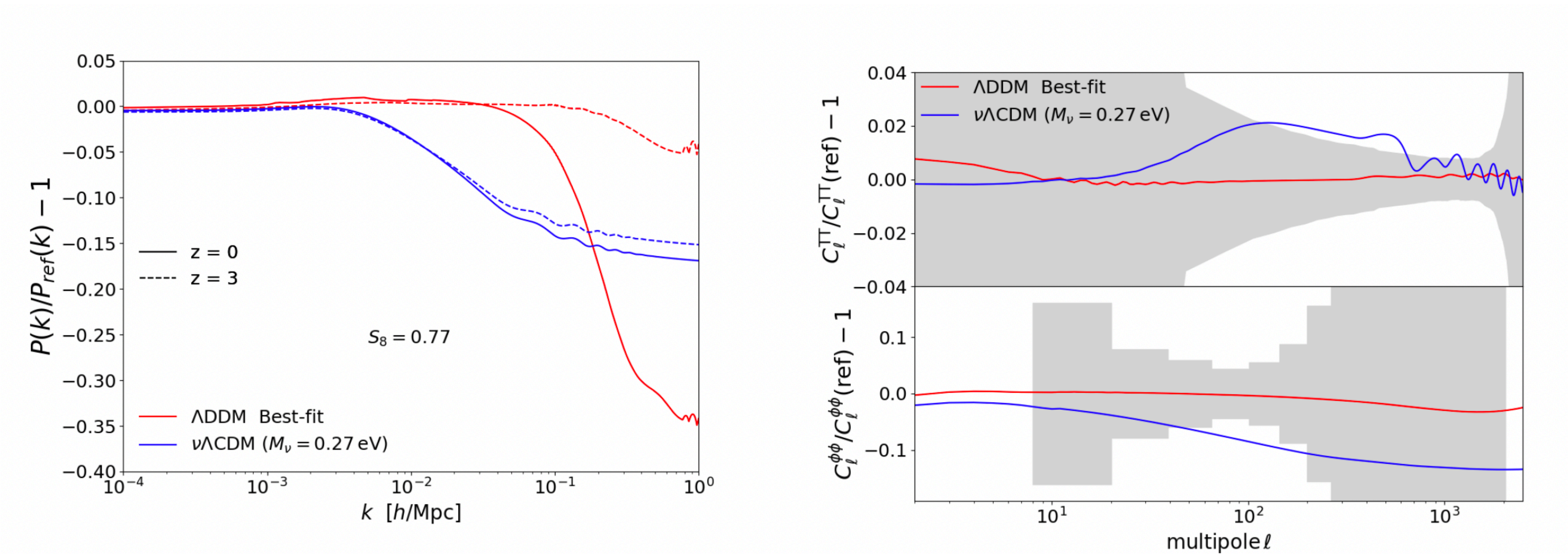
	$\nu\Lambda$CDM	ΛDDM
$\chi^2_{\rm CMB}$	1015.9	1015.2
$\chi^2_{S_8}$	5.64	0.002

$$\longrightarrow \Delta\chi^2_{\rm min} \simeq -5.5$$

$$\Gamma^{-1} \simeq 55\ (\varepsilon/0.007)^{1.4}\ \text{Gyr}$$

Why does the 2-body DM decay work better than massive neutrinos?

The 2-body decay gives a better fit thanks to the time-dependence of the power suppression and the cut-off scale



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Interesting implications

- Model building: Why $\varepsilon \ll 1/2$, i.e. $m_{wdm} \sim m_{dm}$?
  Ex : Supergravity Choi&Yanagida 2104.02958

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- Small-scale crisis of ΛCDM: Reduction in the abundance of subhalos and their concentrations Wang++ 1406.0527

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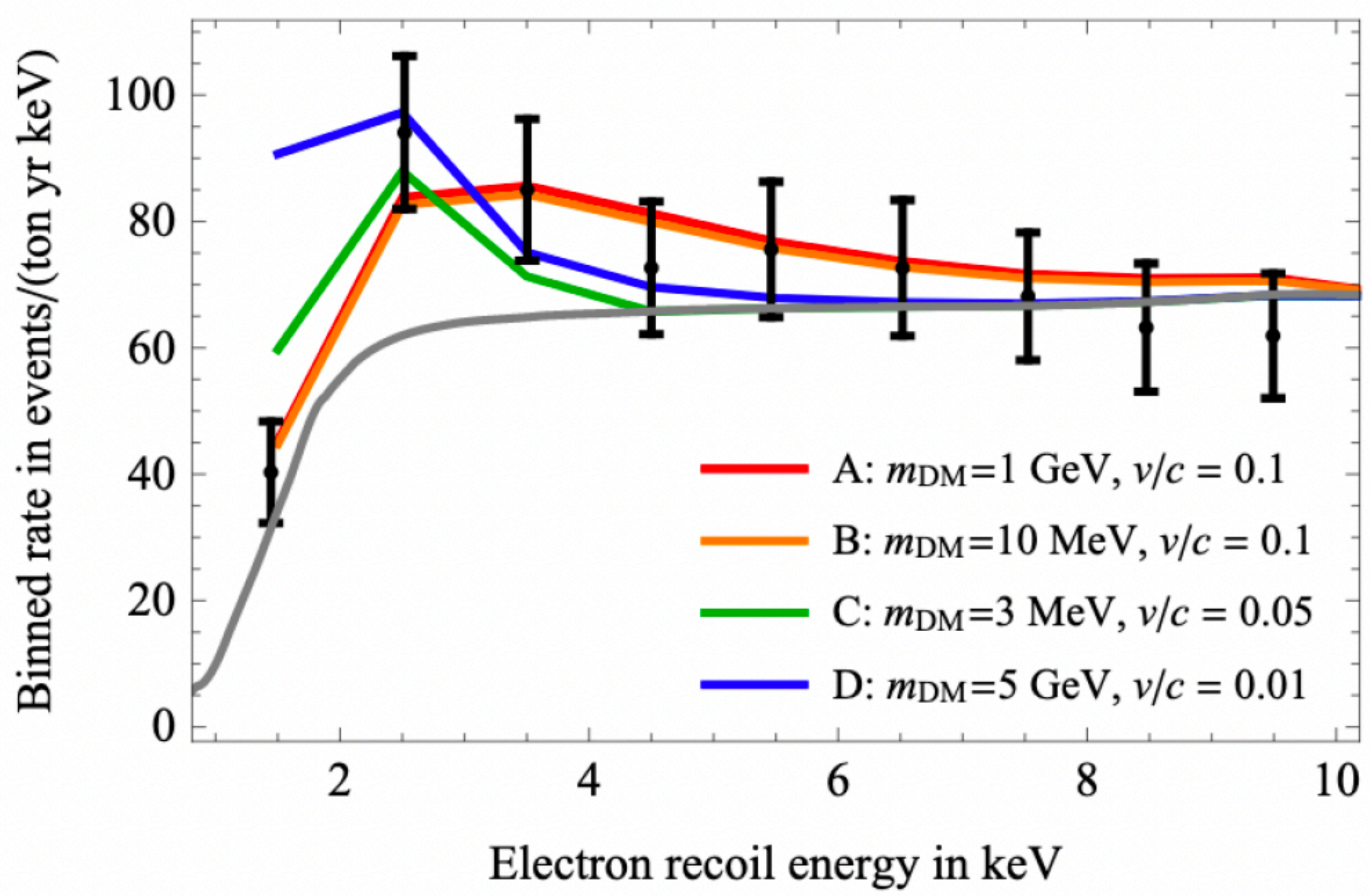
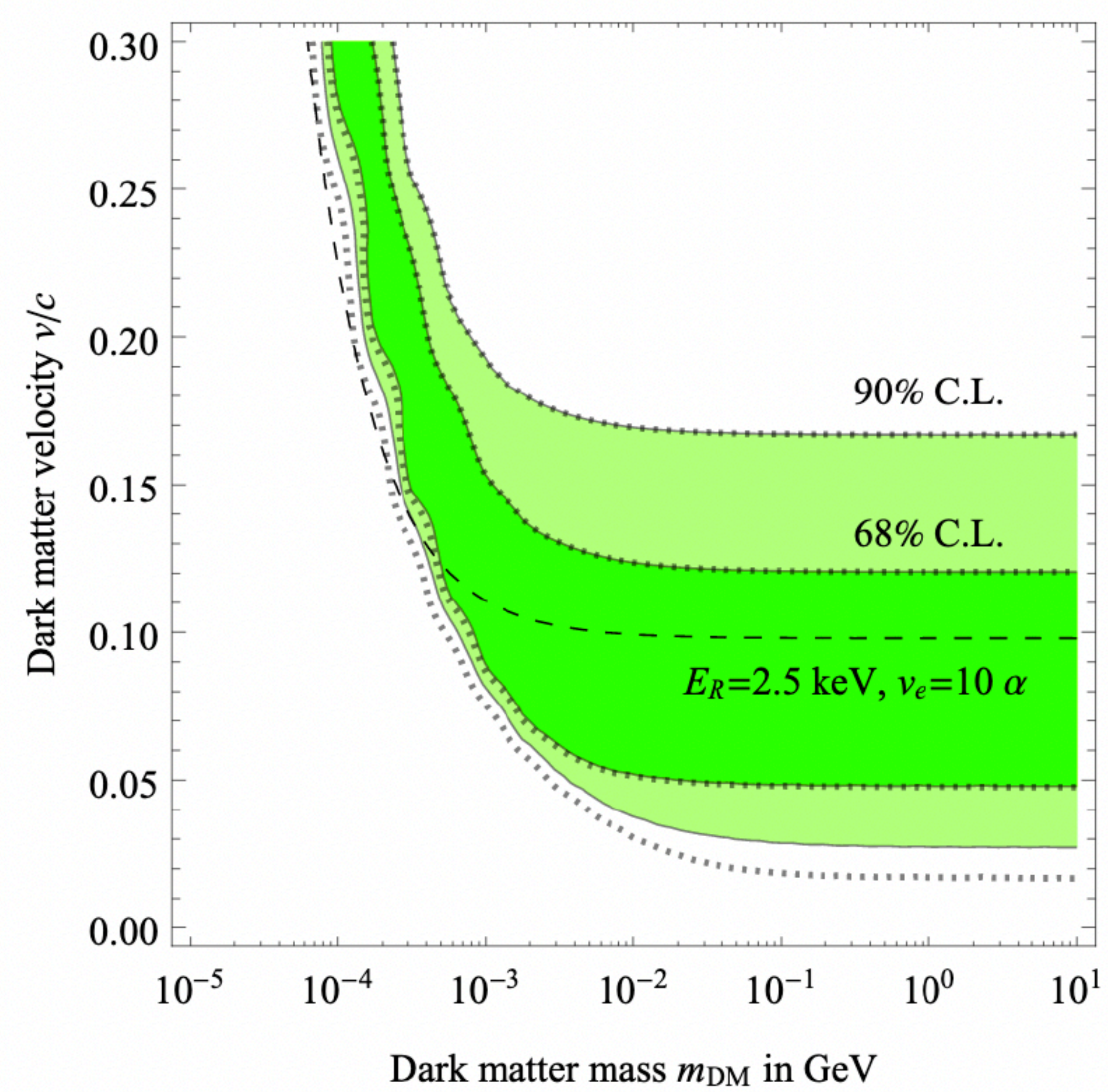
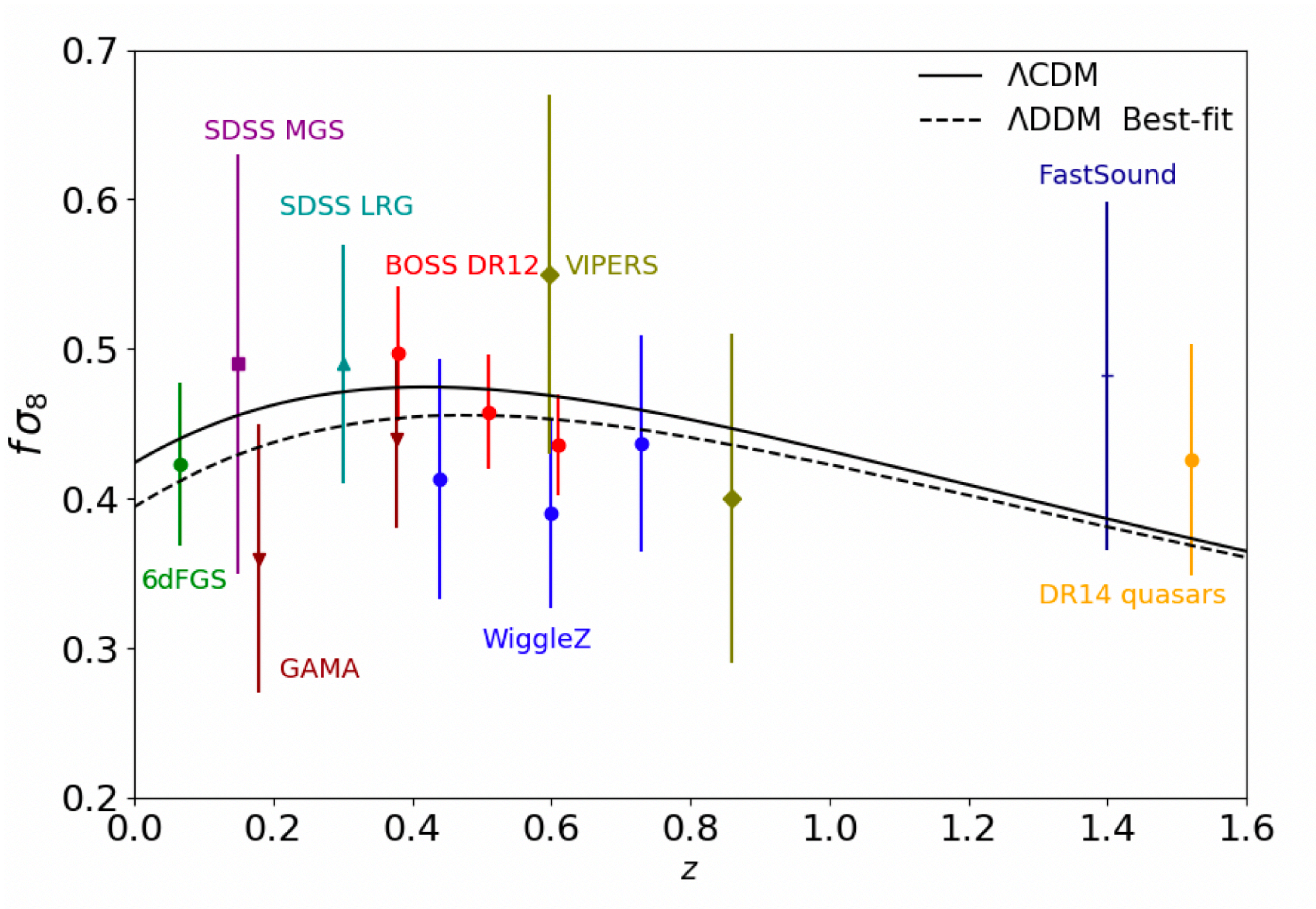
- Small-scale crisis of ΛCDM: Reduction in the abundance of subhalos and their concentrations Wang++ 1406.0527

- Xenon-1T excess: It could be explained by a fast DM component, such as the WDM, with $v/c \simeq \varepsilon$ Kannike++ 2006.10735





Prospects for the 2-body DM decay



Accurate measurements of $f\sigma_8$ at $0 \lesssim z \lesssim 1$ will further test the 2-body decay

Next goal: Predict non-linear matter power spectrum (using either N-body simulations or EFT of LSS)

Conclusions

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Conclusions

- First thorough cosmological analysis of the 2-body DM decay scenario and strongest model-independent constraints up to date
- It can explain the S_8 anomaly (as opposed to massive neutrinos), but if fails at resolving the H_0 tension
- It could have interesting implications for model building, the small-scale crisis, and the recent Xenon-1T excess
- Future growth factor measurements can further test this scenario

BACK-UP SLIDES

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*)

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

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

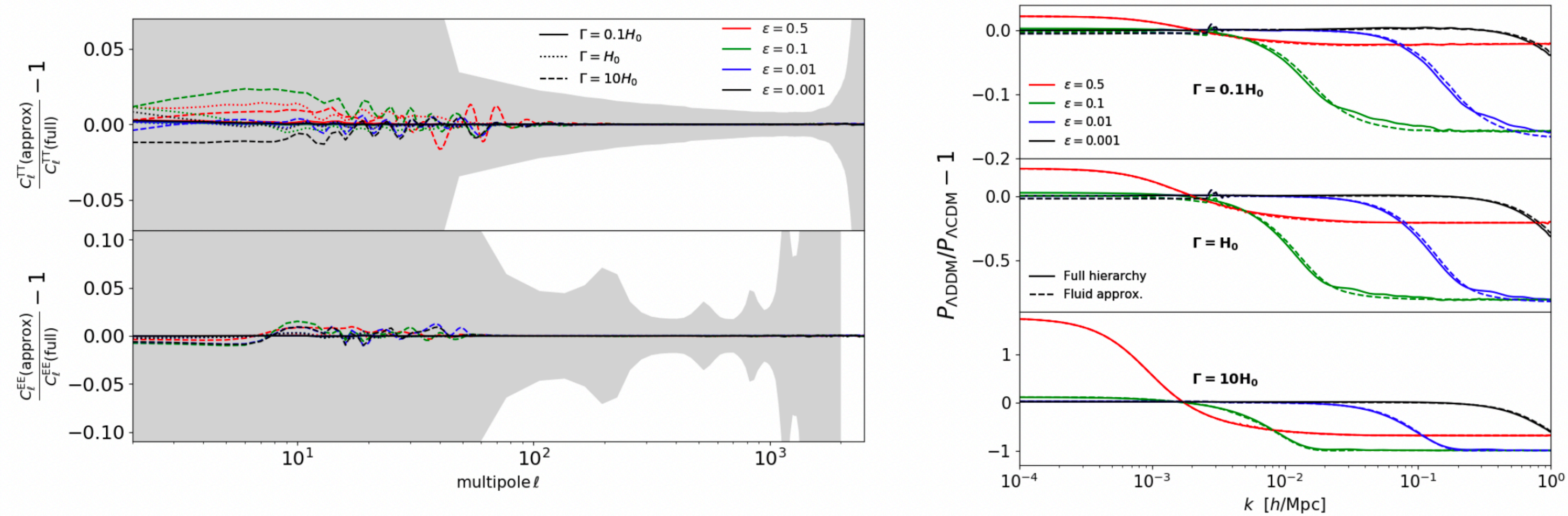
$$\frac{\partial}{\partial\tau}\left(\delta f_2\right) = \frac{\mathbf{q}k}{5\mathbf{aE}}\left[2\delta f_1 - 3\delta f_3\right] - q\frac{\partial\bar{f}}{\partial q}\frac{(\dot{h}+6\dot{\eta})}{15},$$

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

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.

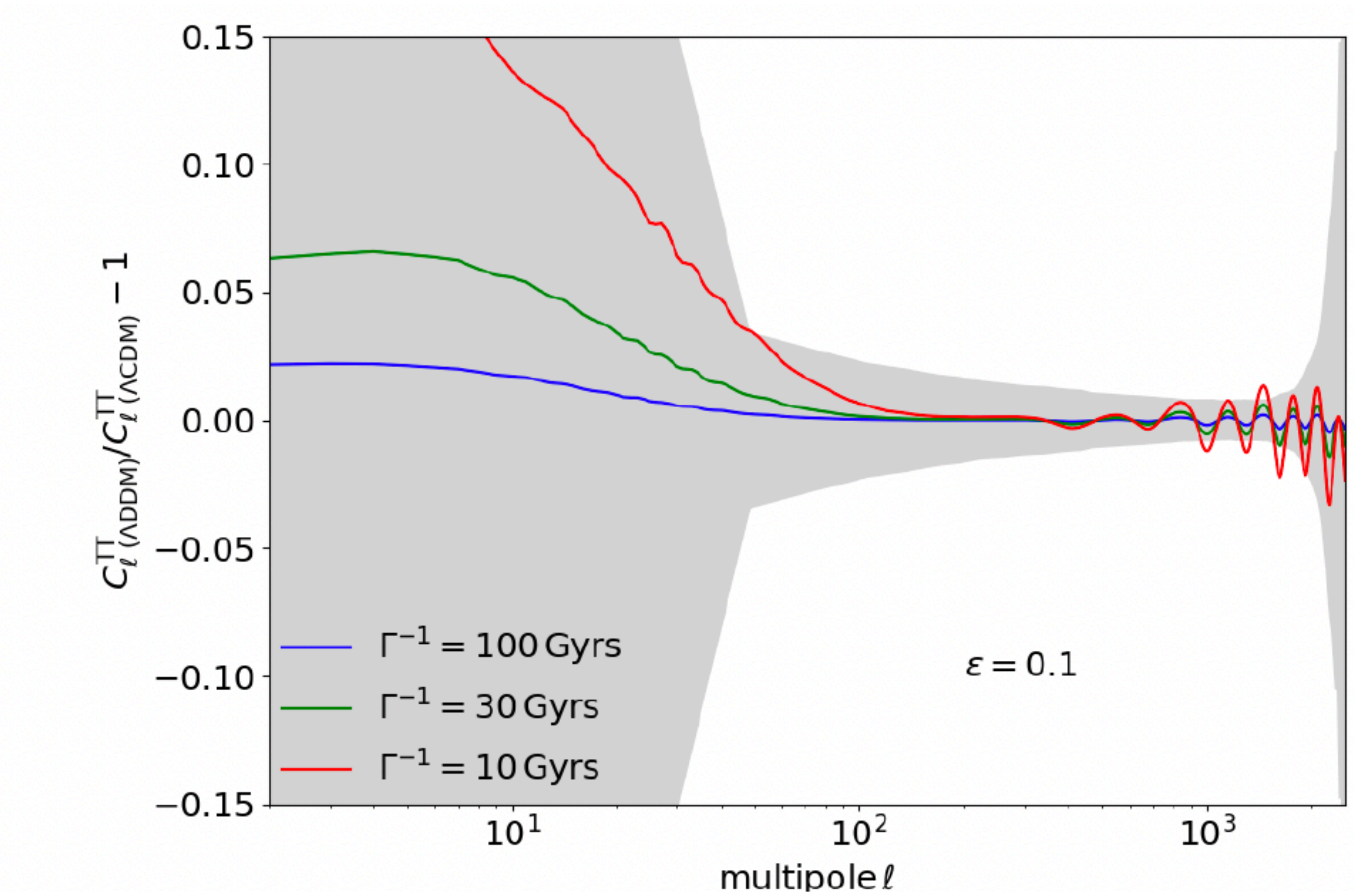


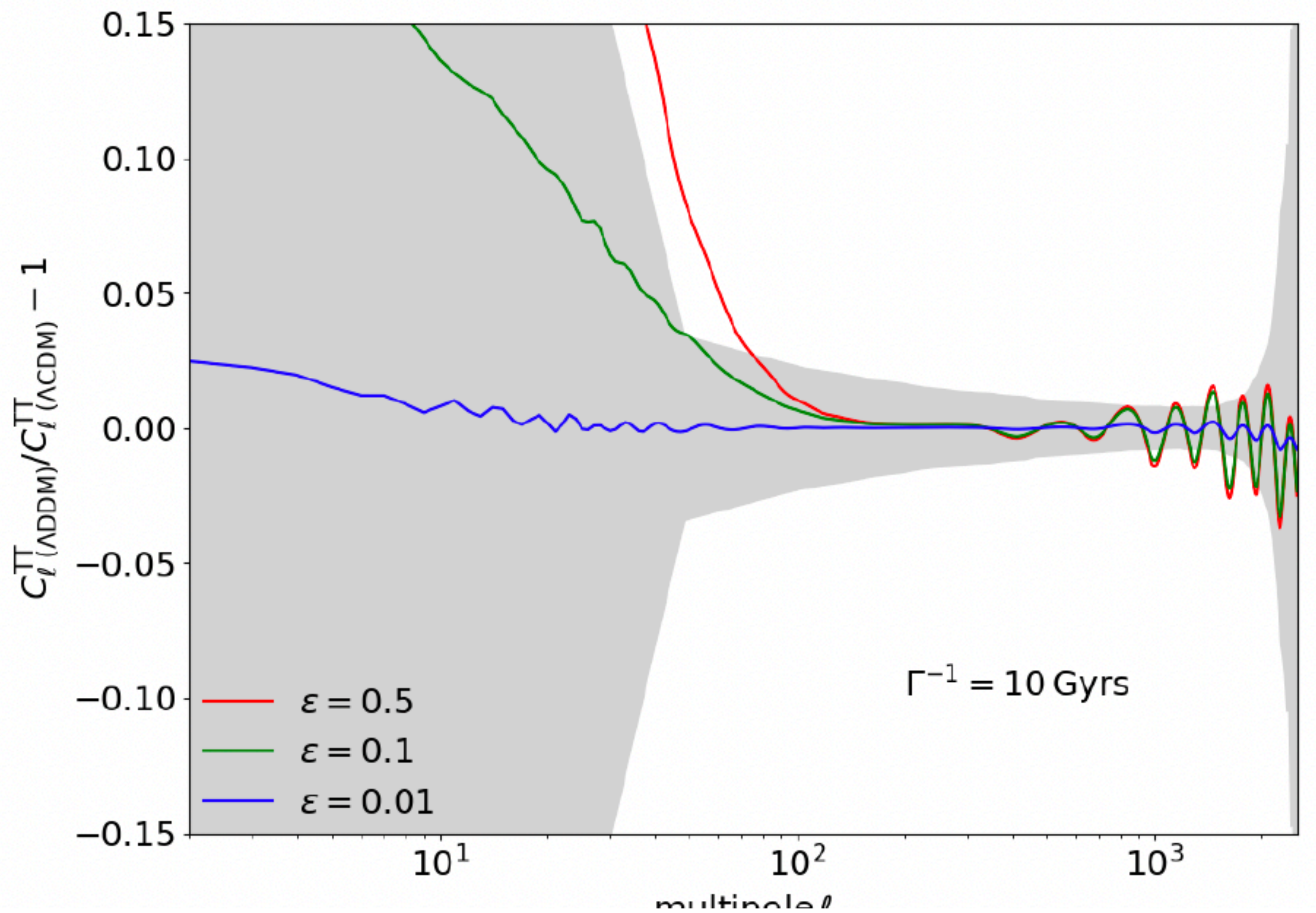
The max. error on S_8 is ~0.65 %, smaller than the ~1.8 % error of the measurement from BOSS+KiDS+2dfLenS

Impact on the CMB temperature spectrum

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

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





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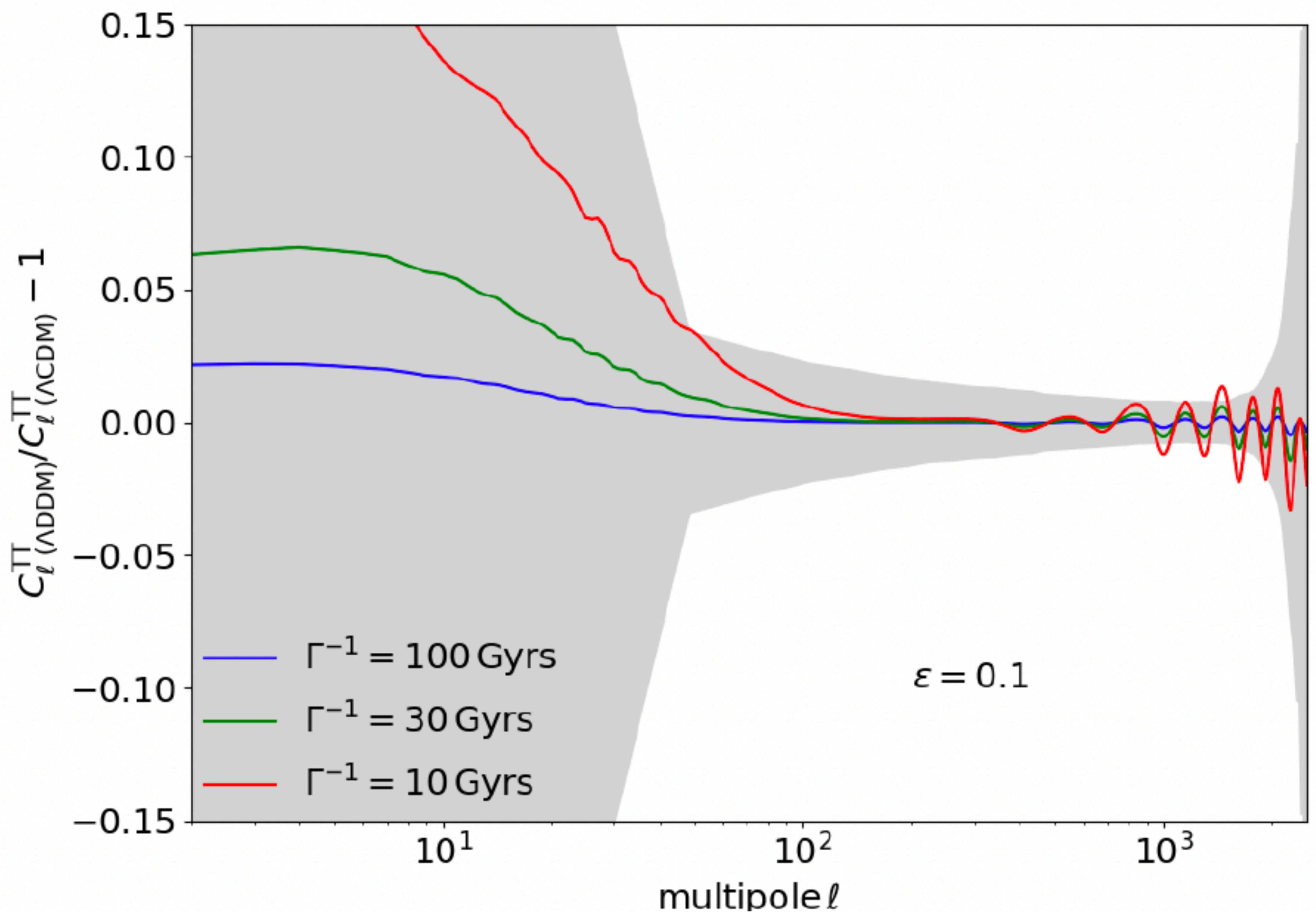

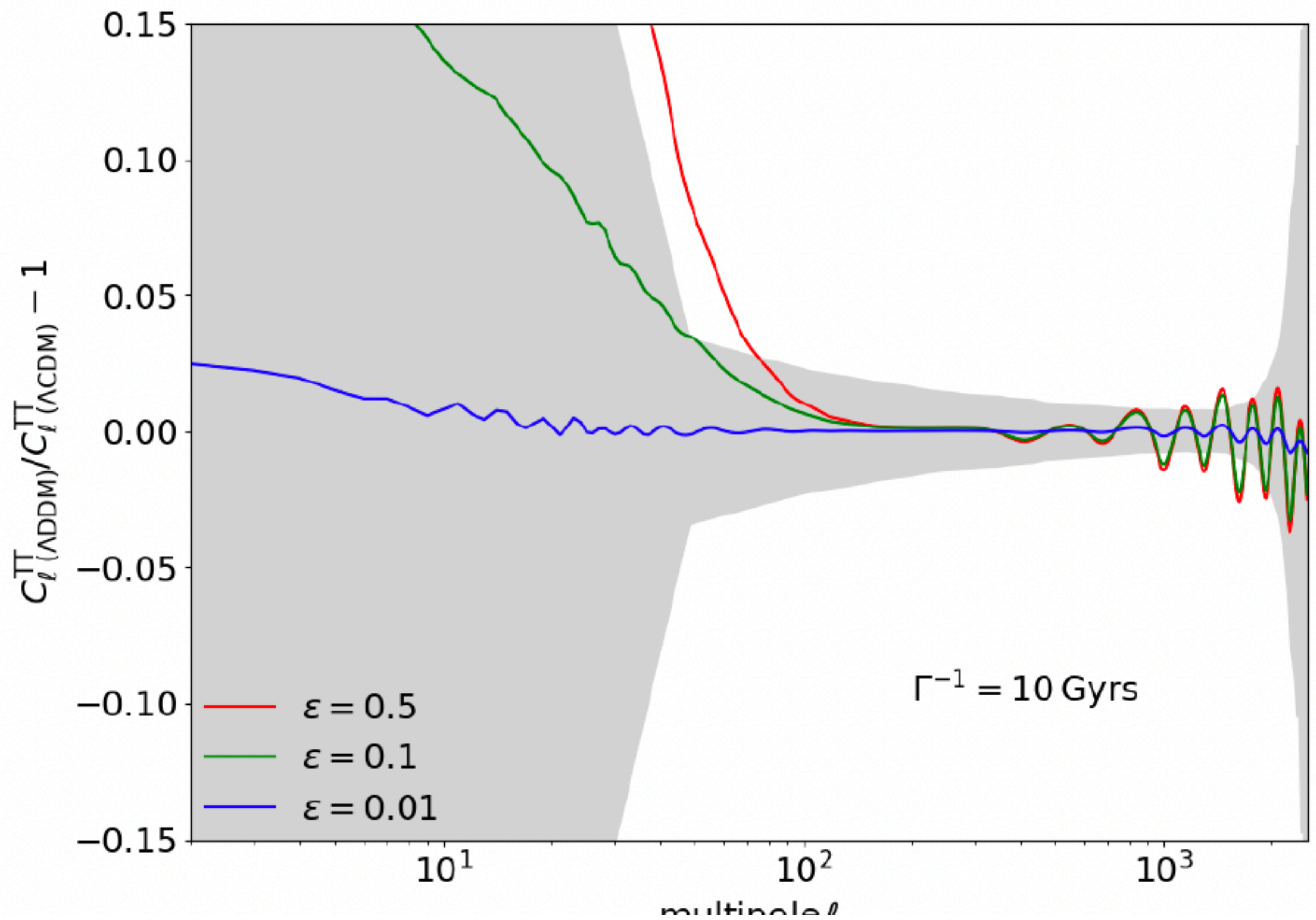

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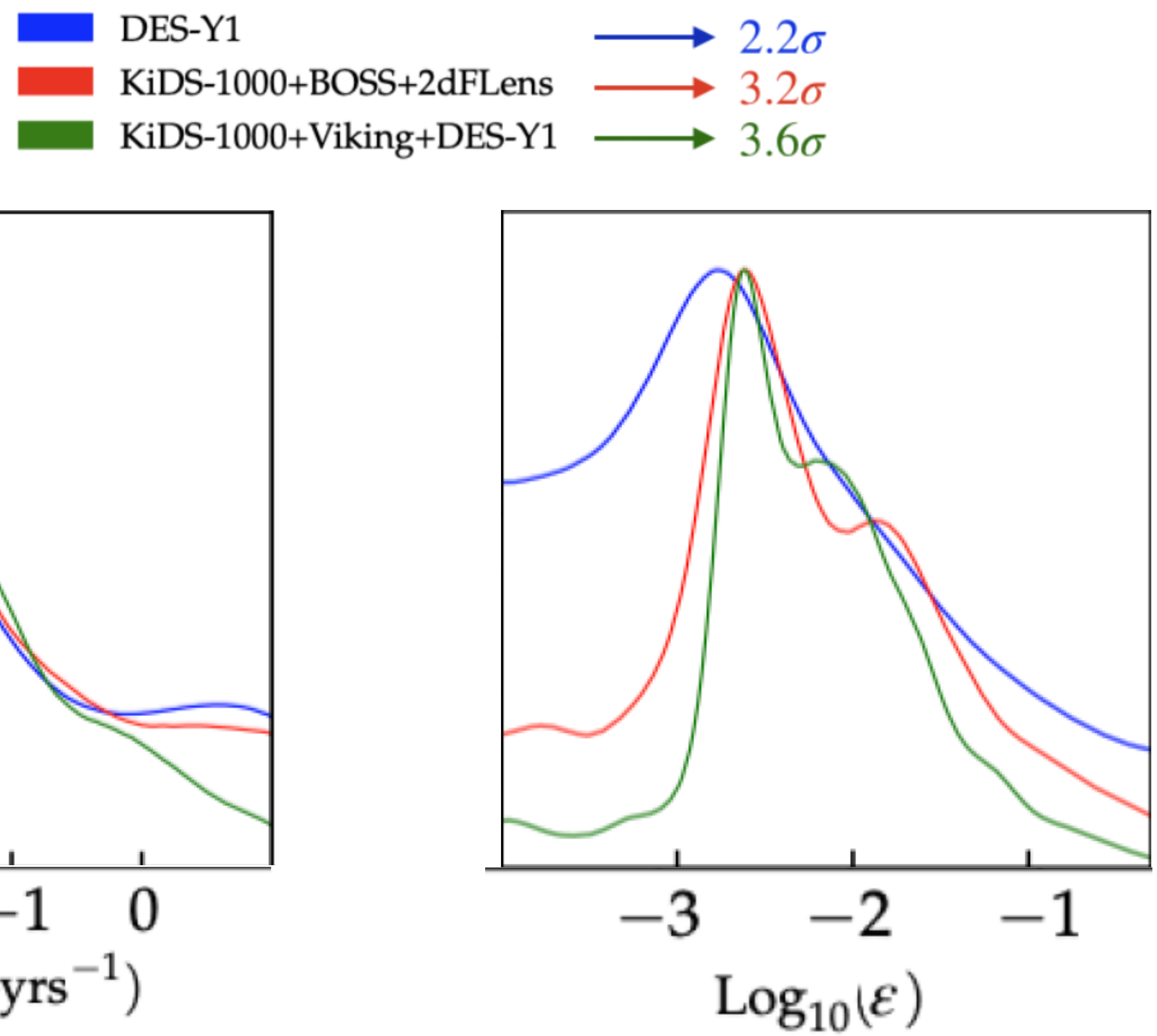
Resolution to the S_8 tension

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



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