Constraining **decaying dark matter** with the **effective field theory** of **large-scale structures**

Guillermo Franco Abellán

Based on:

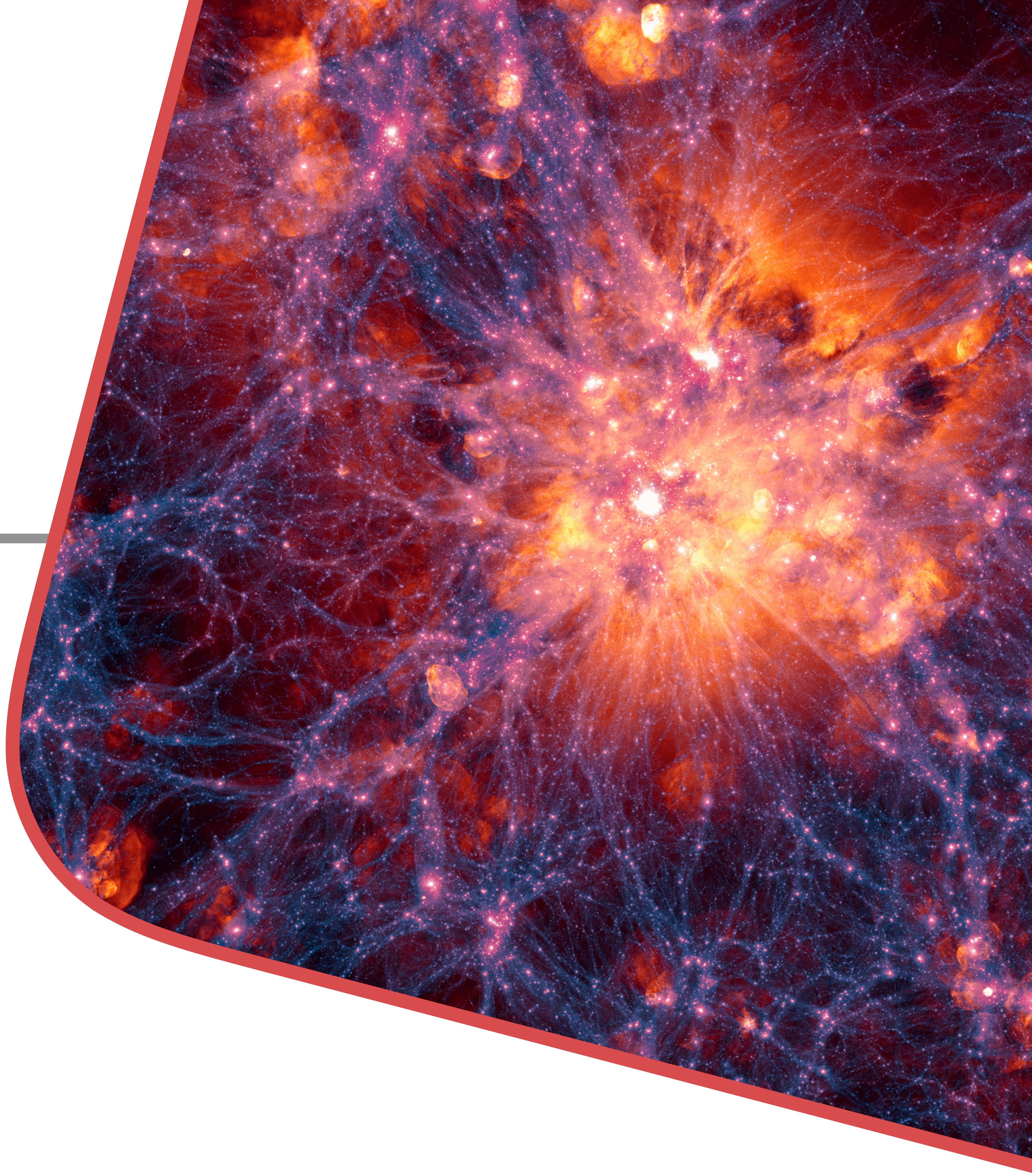
PRD 106 (2022), [arXiv:2203.07440]

PRD 104 (2021), [arXiv:2102.1249]

PRD 105 (2022), [arXiv:2008.09615]

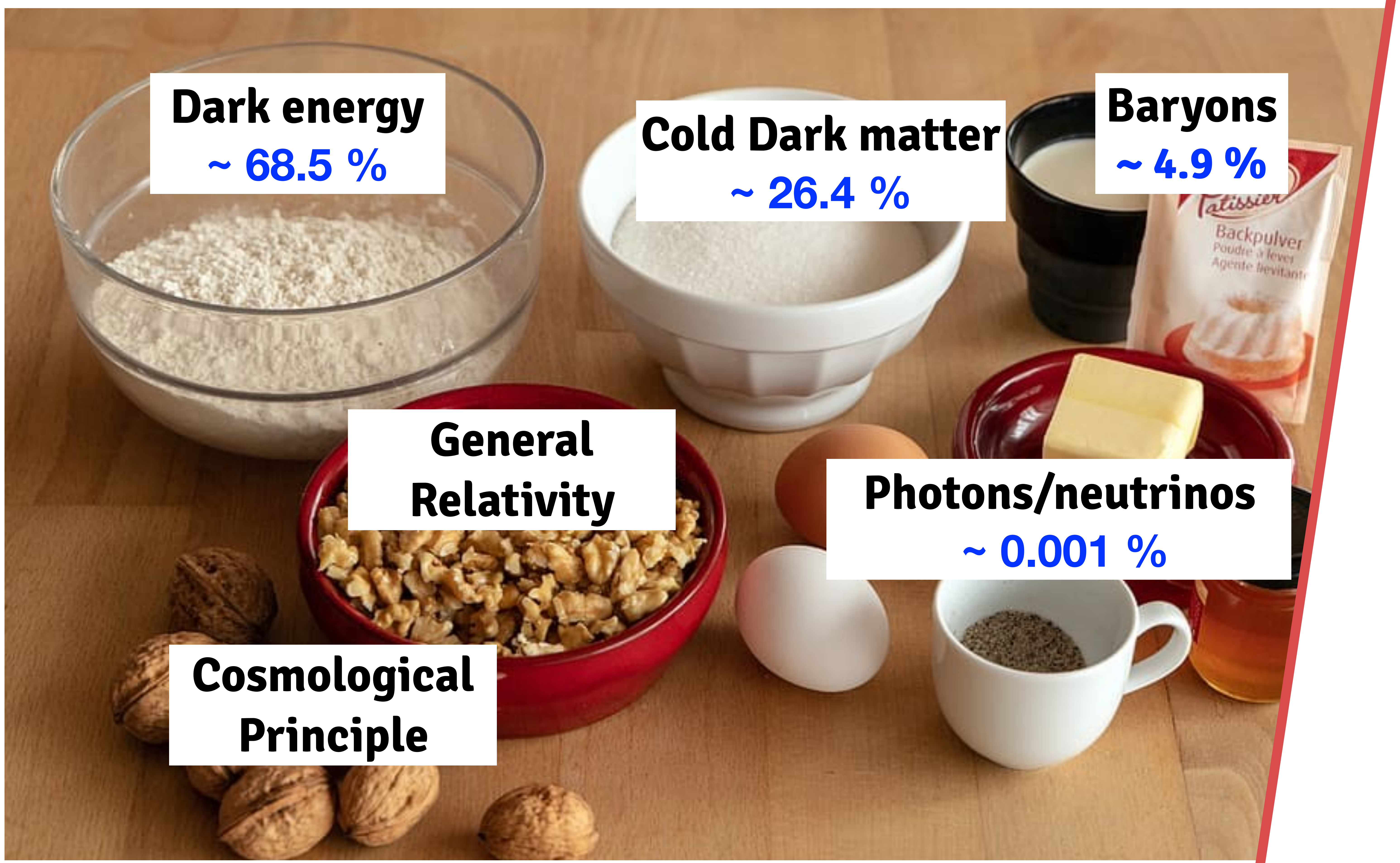
with T. Simon, V. Poulin, P. Du, Y. Tsai, R. Murgia, J. Lavalle

IAC - 24/03/2023



GRAPPA
GRavitation AstroParticle Physics Amsterdam

Concordance ΛCDM model of cosmology:



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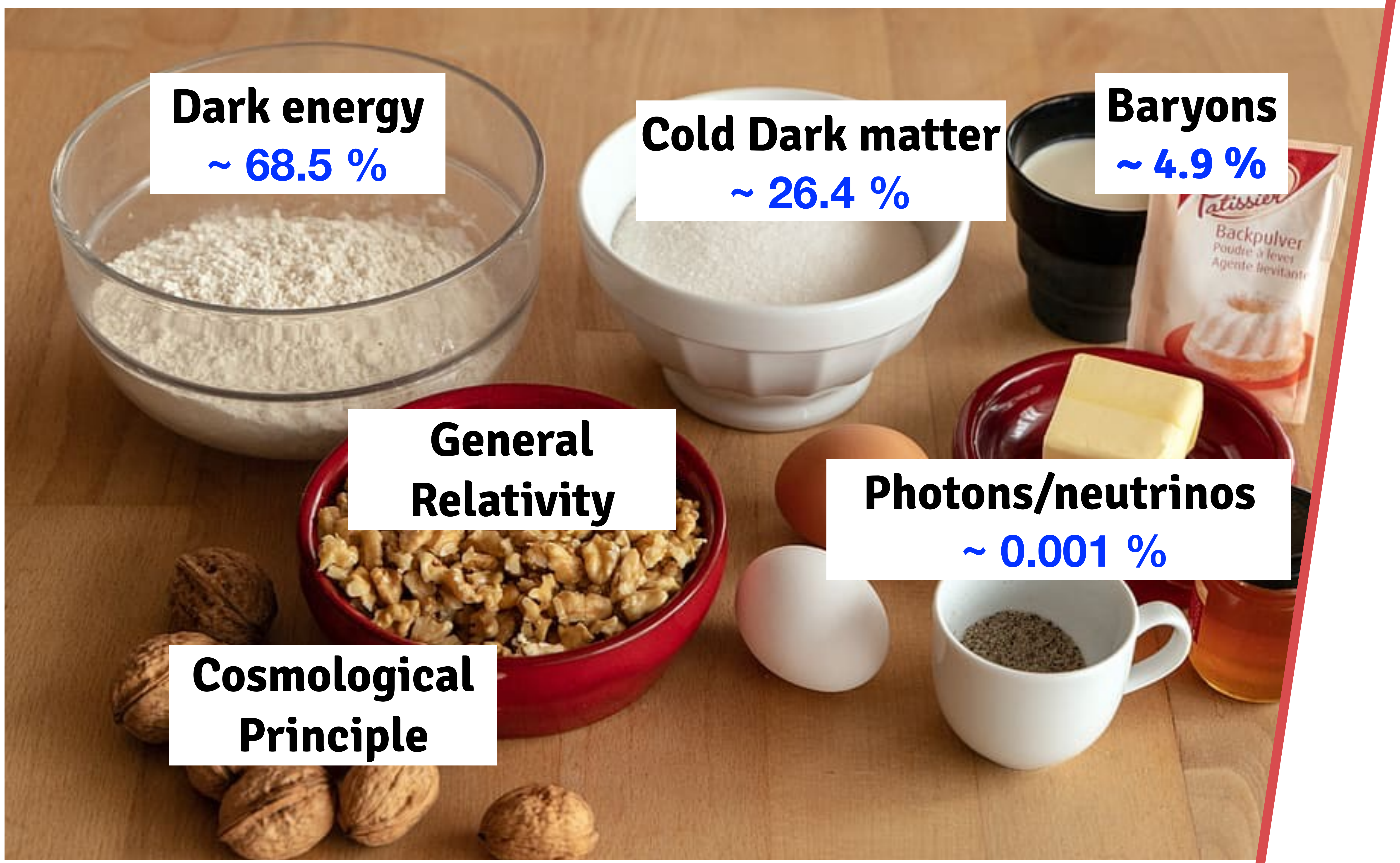


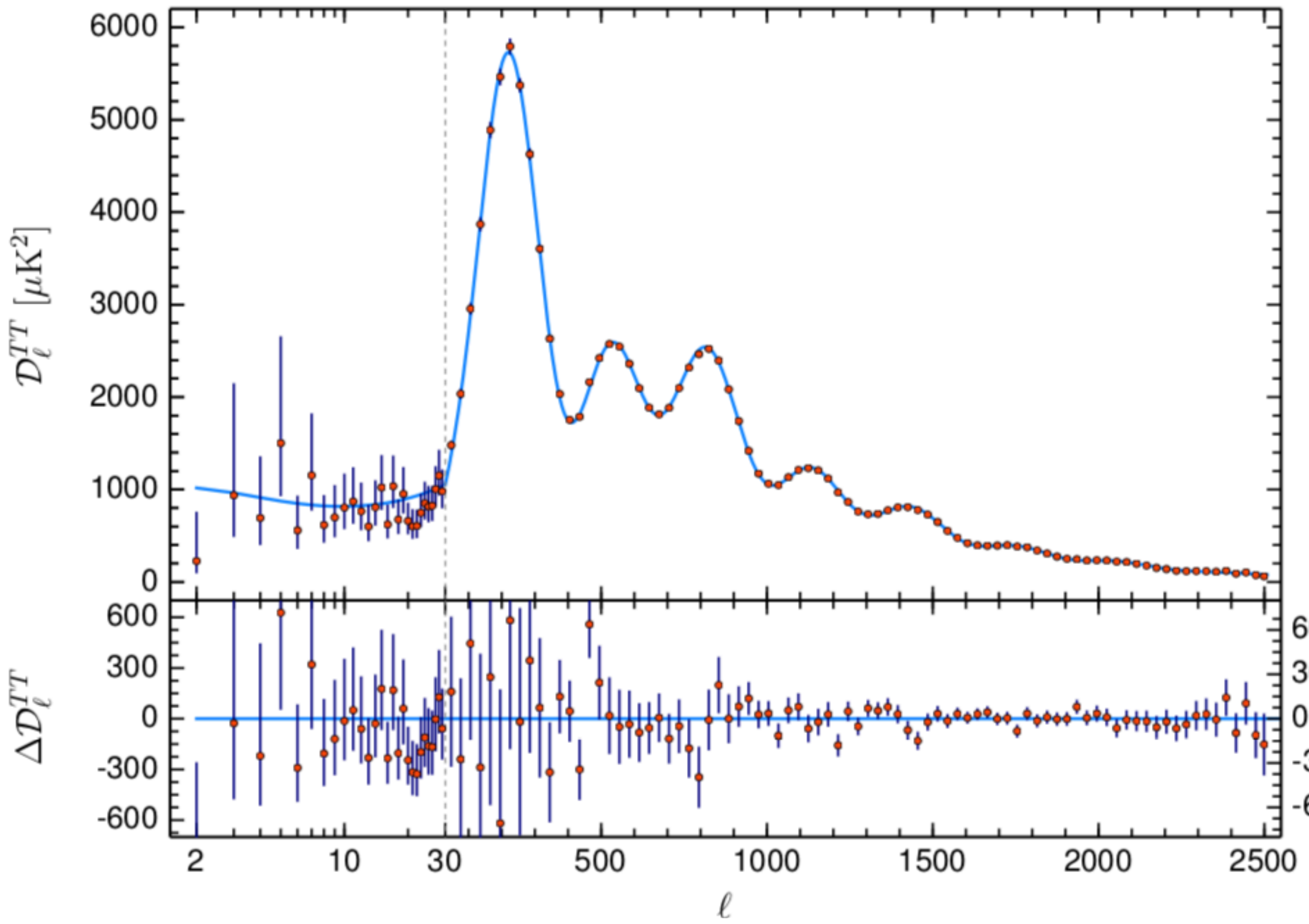
Only 6 free parameters:

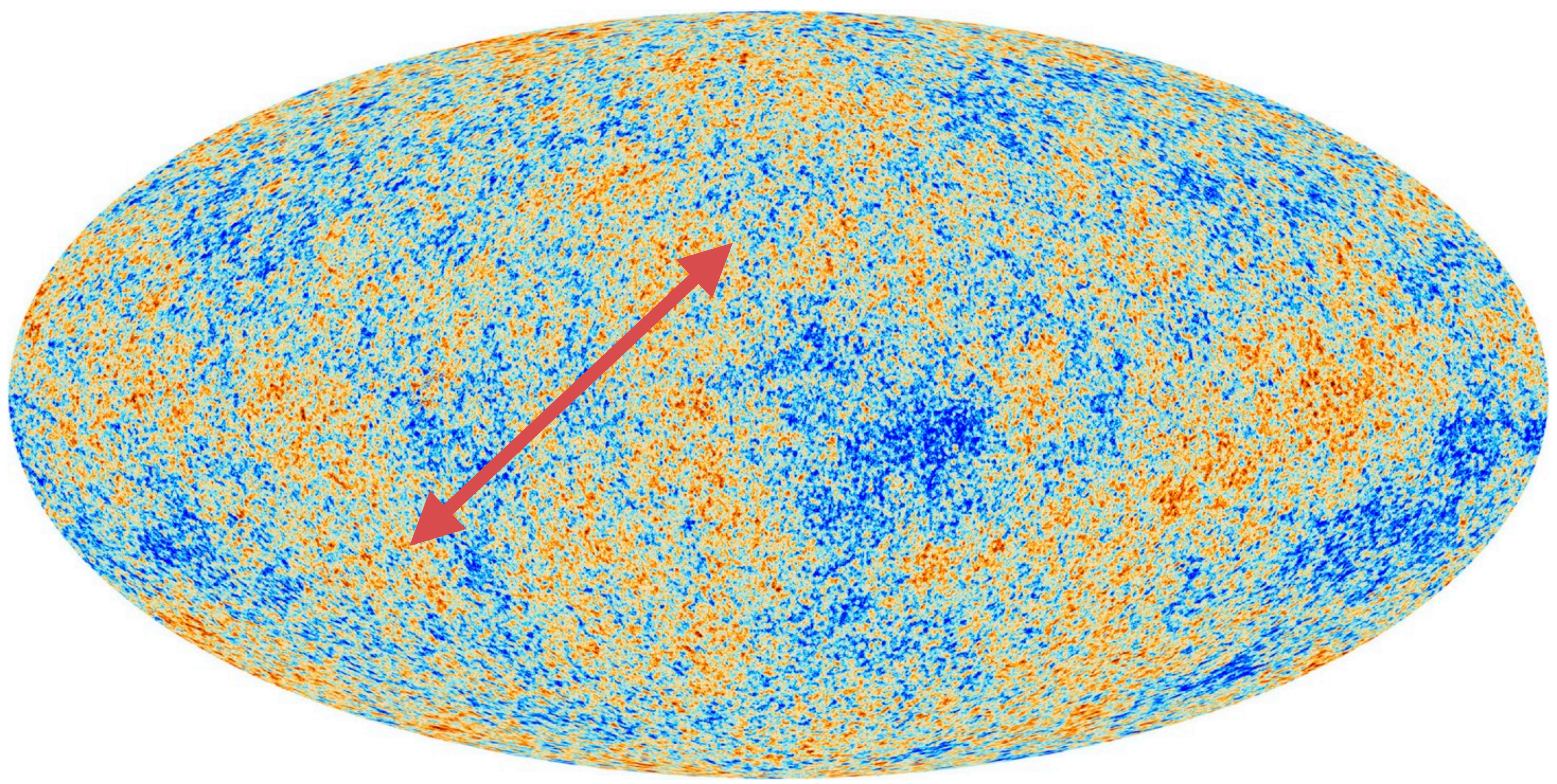
ω_c ω_b H_0

A_s n_s τ_{reio}

Excellent agreement with a wide variety of observations

CMB anisotropy spectra





$$C_\ell^{\mathrm{TT}} \sim \left\langle \left(\frac{\delta T}{T} \right)^2 \right\rangle \qquad \ell \sim \frac{1}{\theta}$$

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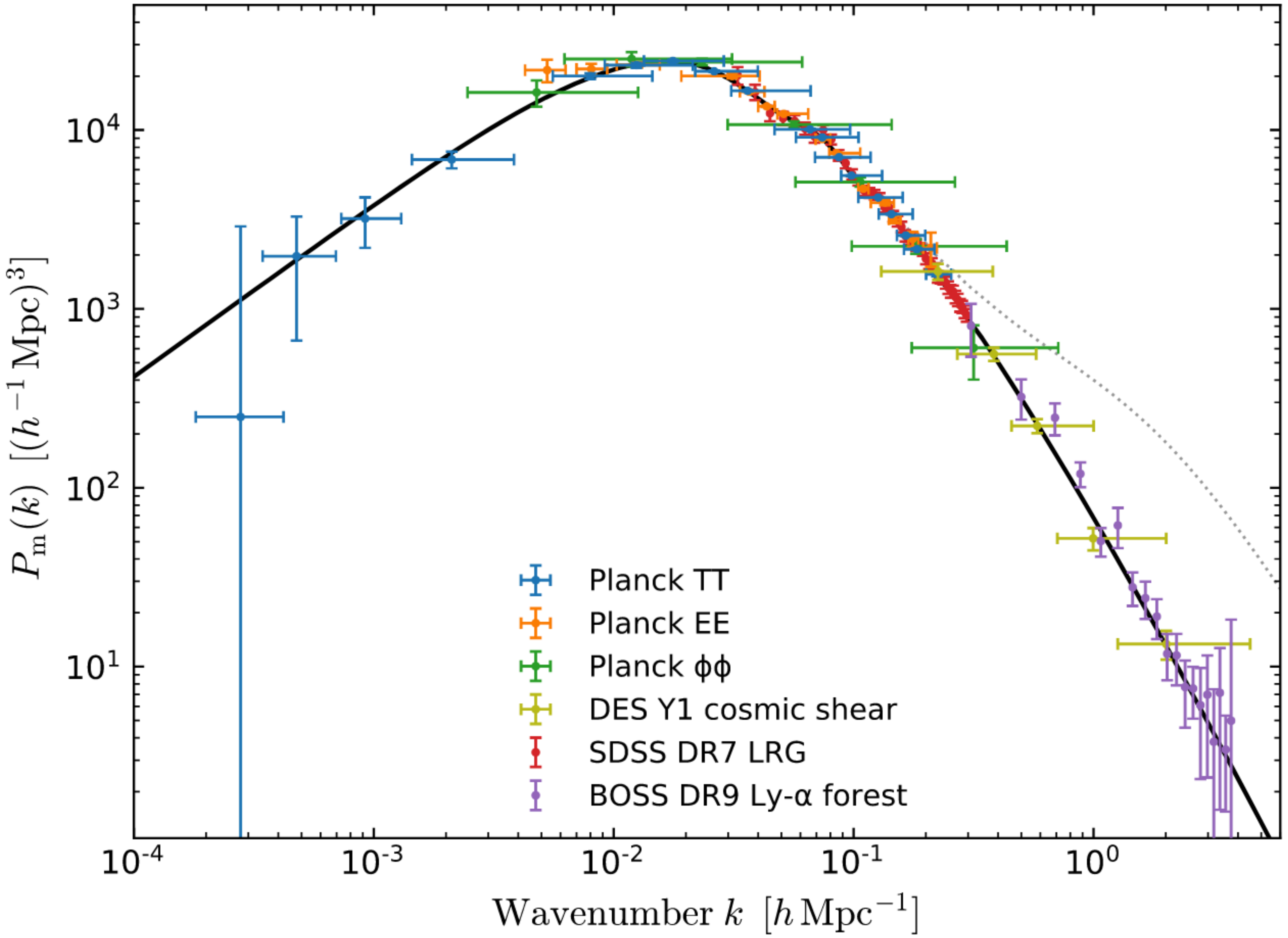
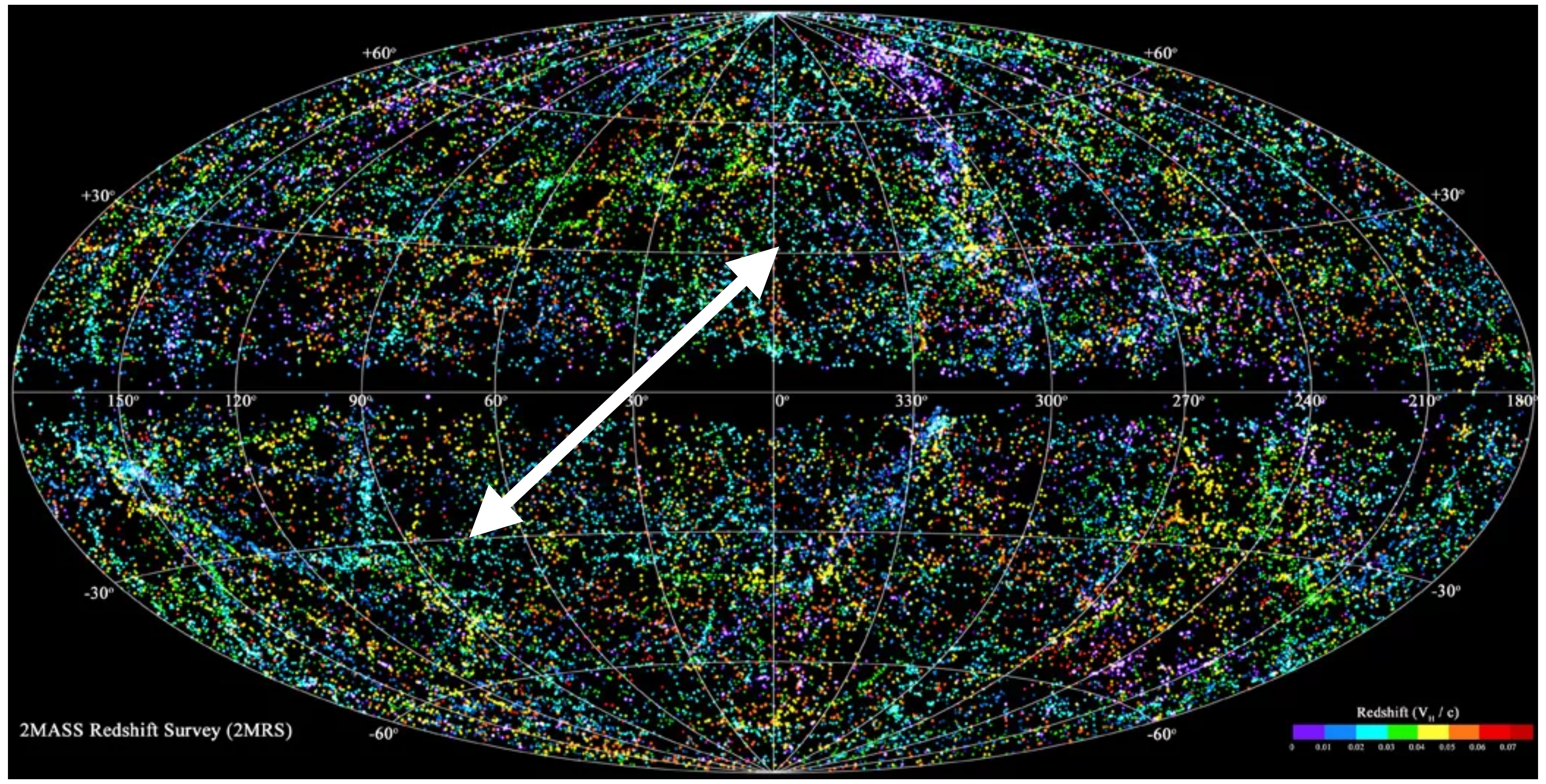
Matter power spectrum

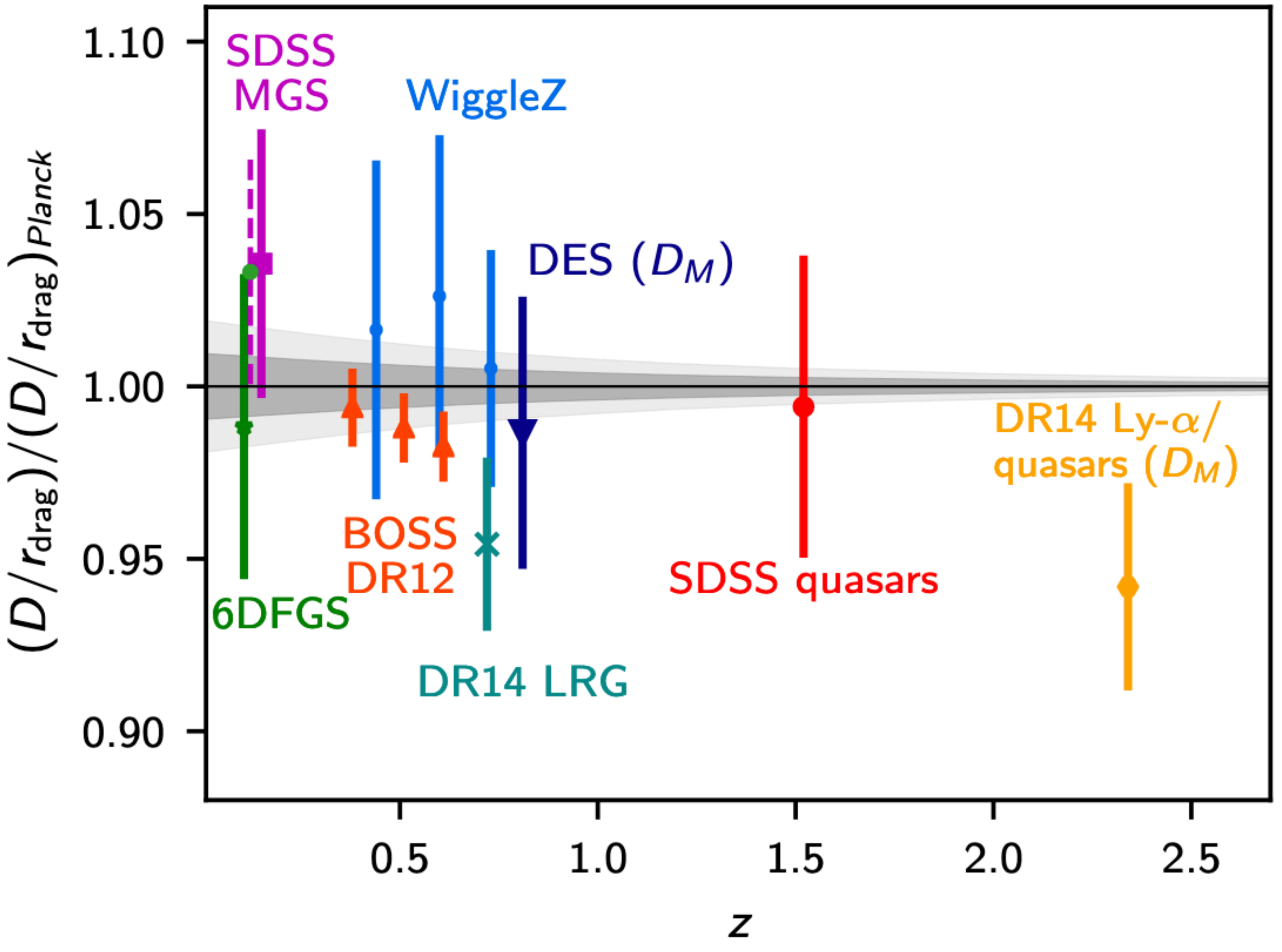




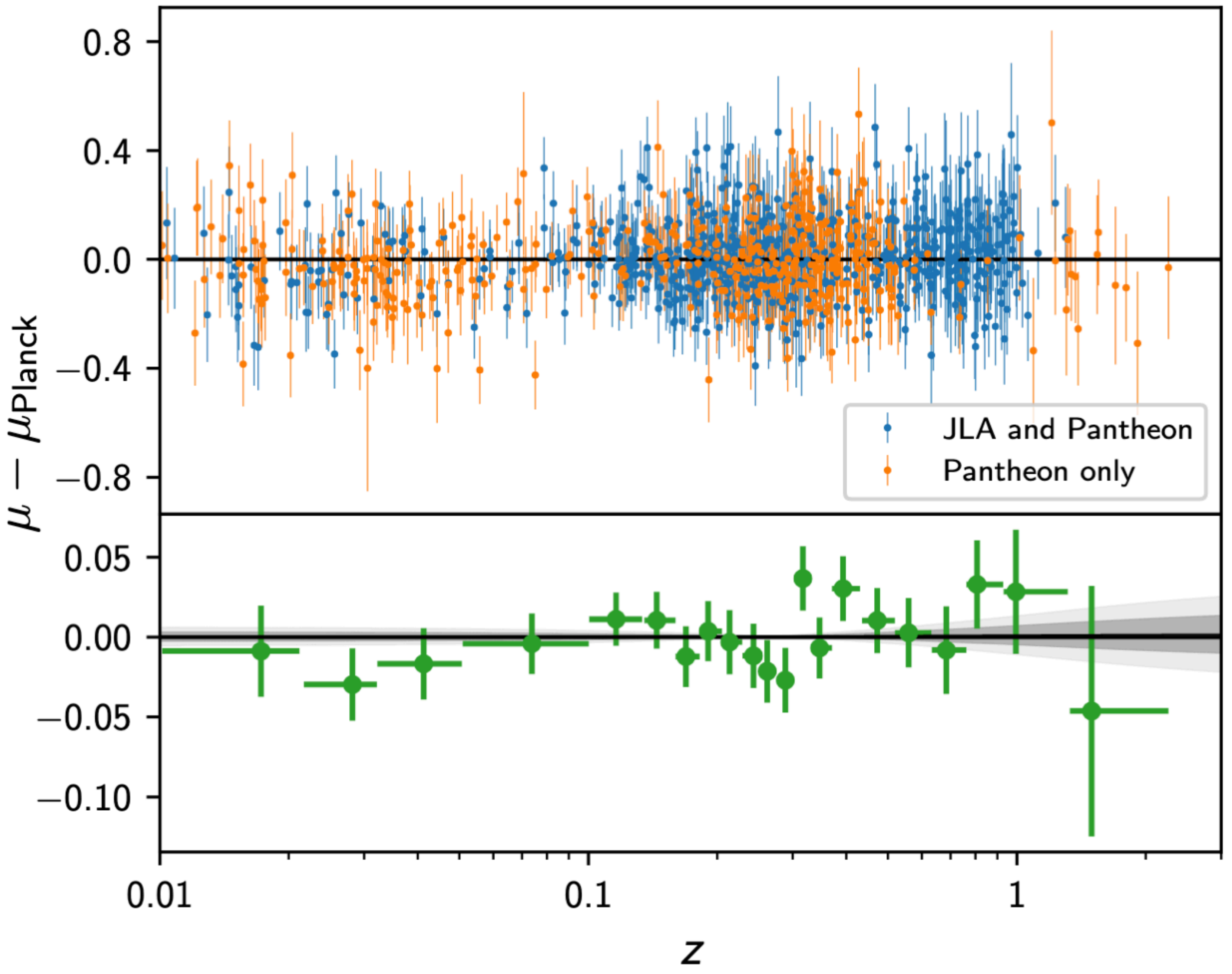
$$P(k) \sim \left\langle \left(\frac{\delta\rho}{\rho} \right)^2 \right\rangle \qquad k = \frac{2\pi}{\lambda}$$

Excellent agreement with a wide variety of observations

Baryon acoustic oscillations (BAO)

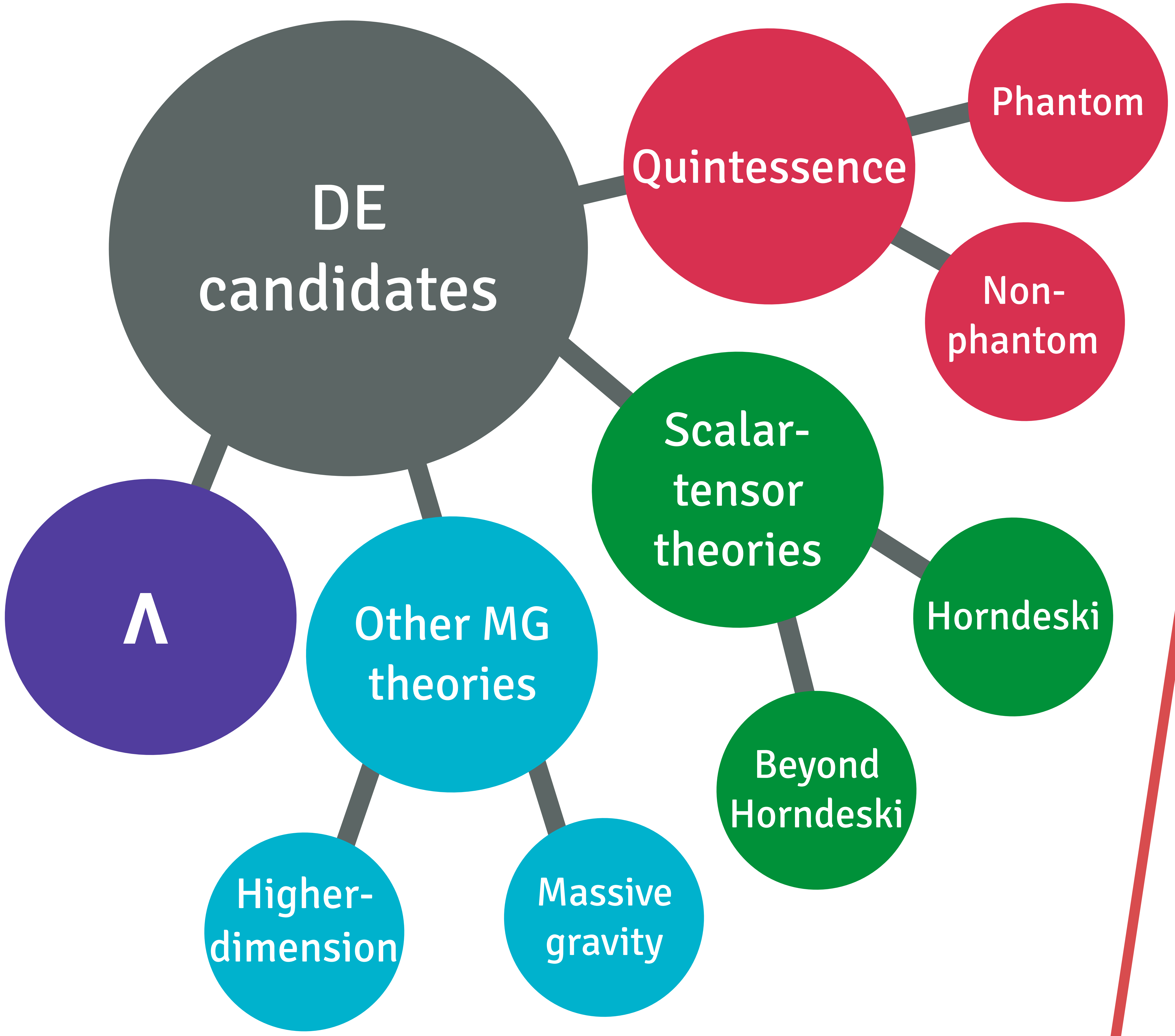


Supernovae Ia (SNIa)

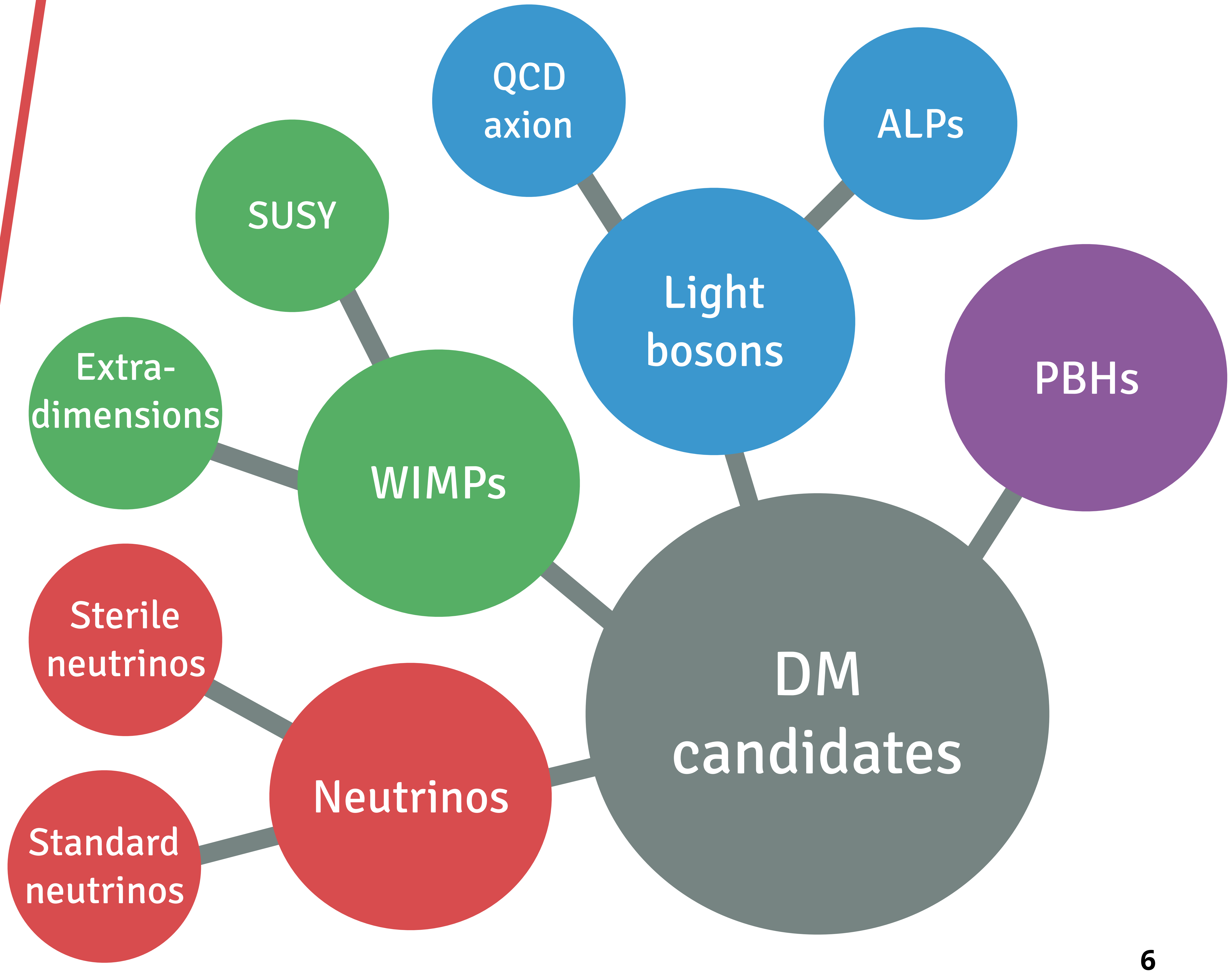


$$H(z)$$

$$D(z) \propto \int_0^z \frac{dz'}{H(z')}$$



However, the nature of the **dark sector** remains a **mystery**



In addition, several **discrepancies have emerged** in recent years

- H_0 tension (5σ)

  [Riess+ 21] [Planck 18]

- S_8 tension ($2\text{-}3\sigma$)

  [KiDS 20] [DES 21] [Planck 18]

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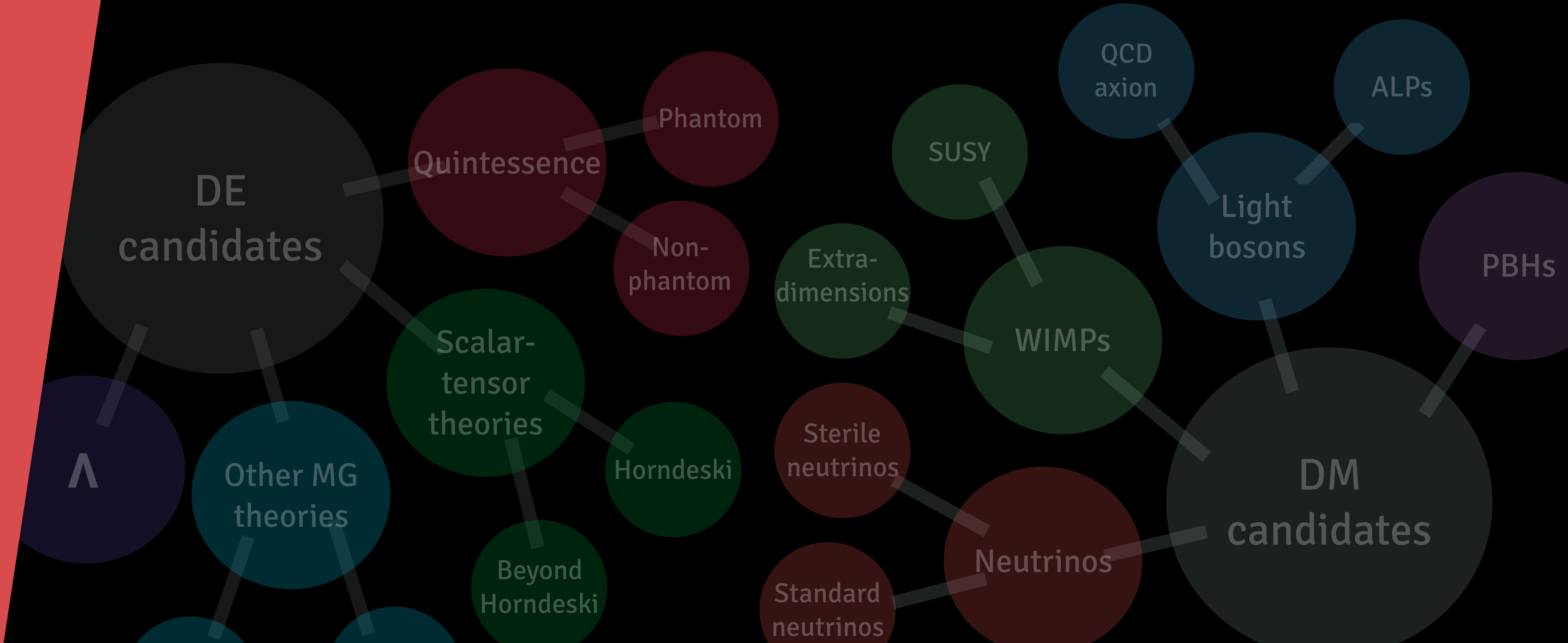
Systematics?

New physics?

Cosmic tensions could **shed some light** on the mysterious dark sector



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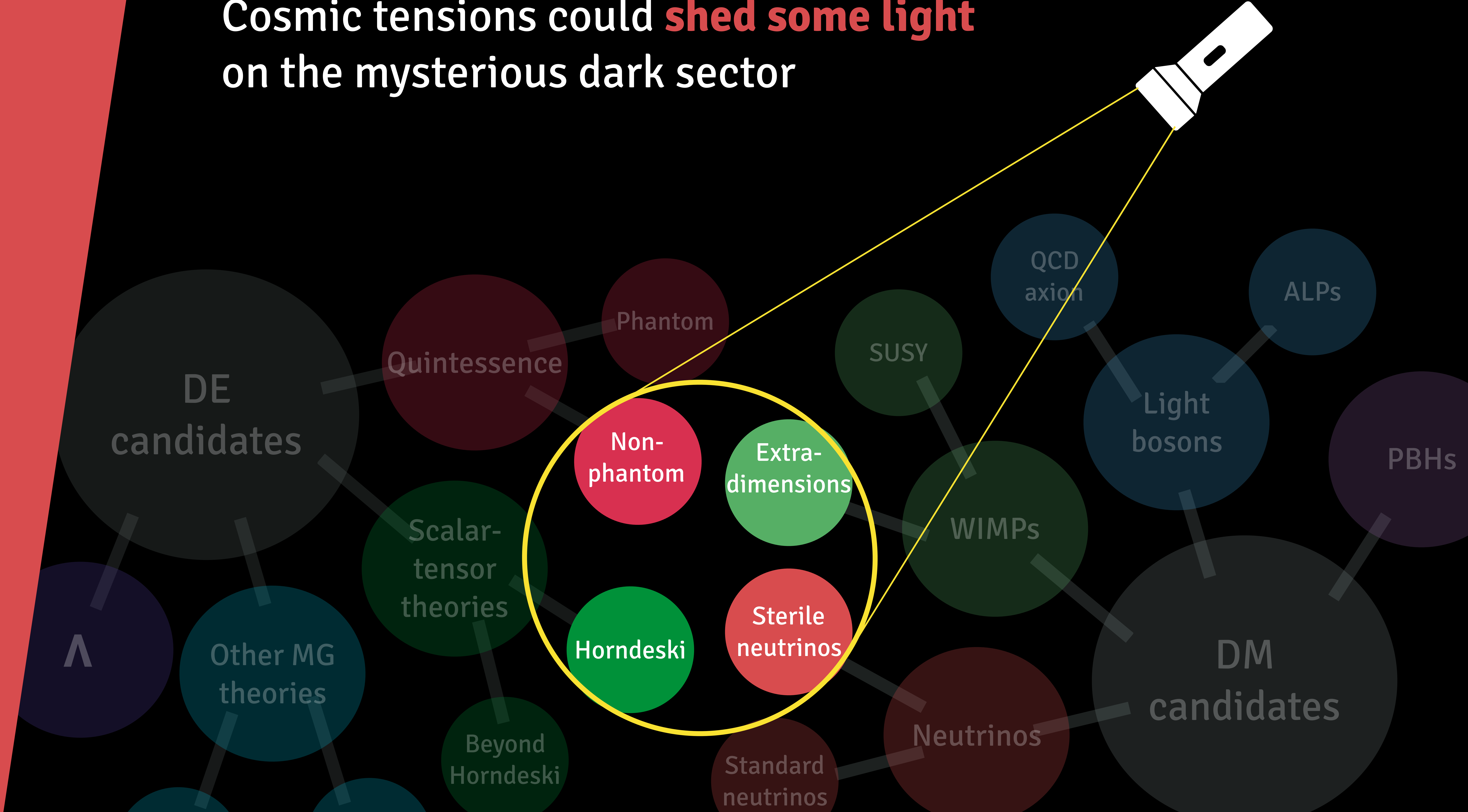


Part I:

DDM AND THE S_8 TENSION

Part II:

INTRODUCTION TO THE EFTofLSS

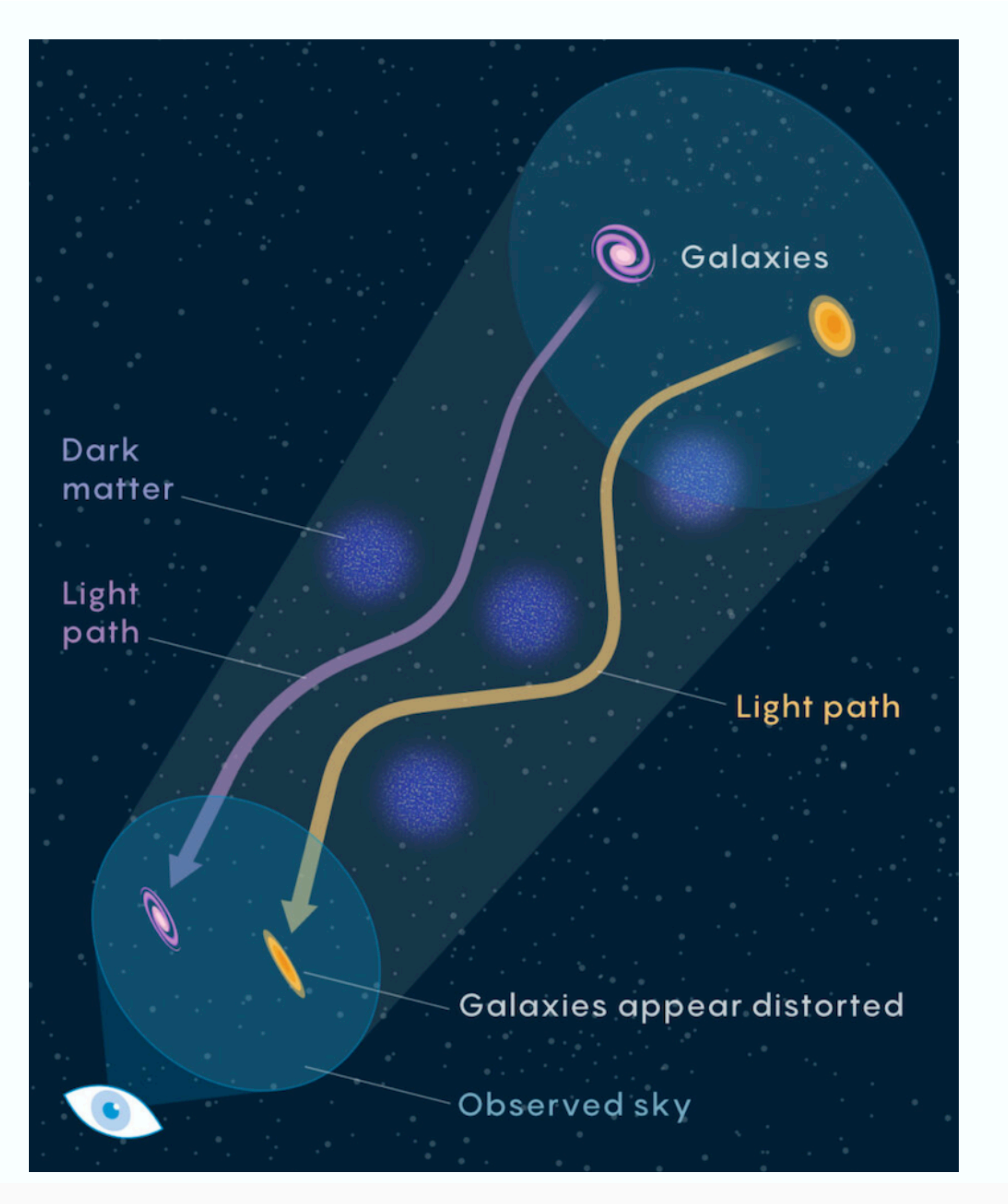
Part III:

CONSTRAINTS ON DDM FROM EFTofLSS

Part I:

DDM AND THE S_8 TENSION

The S_8 tension in a nutshell



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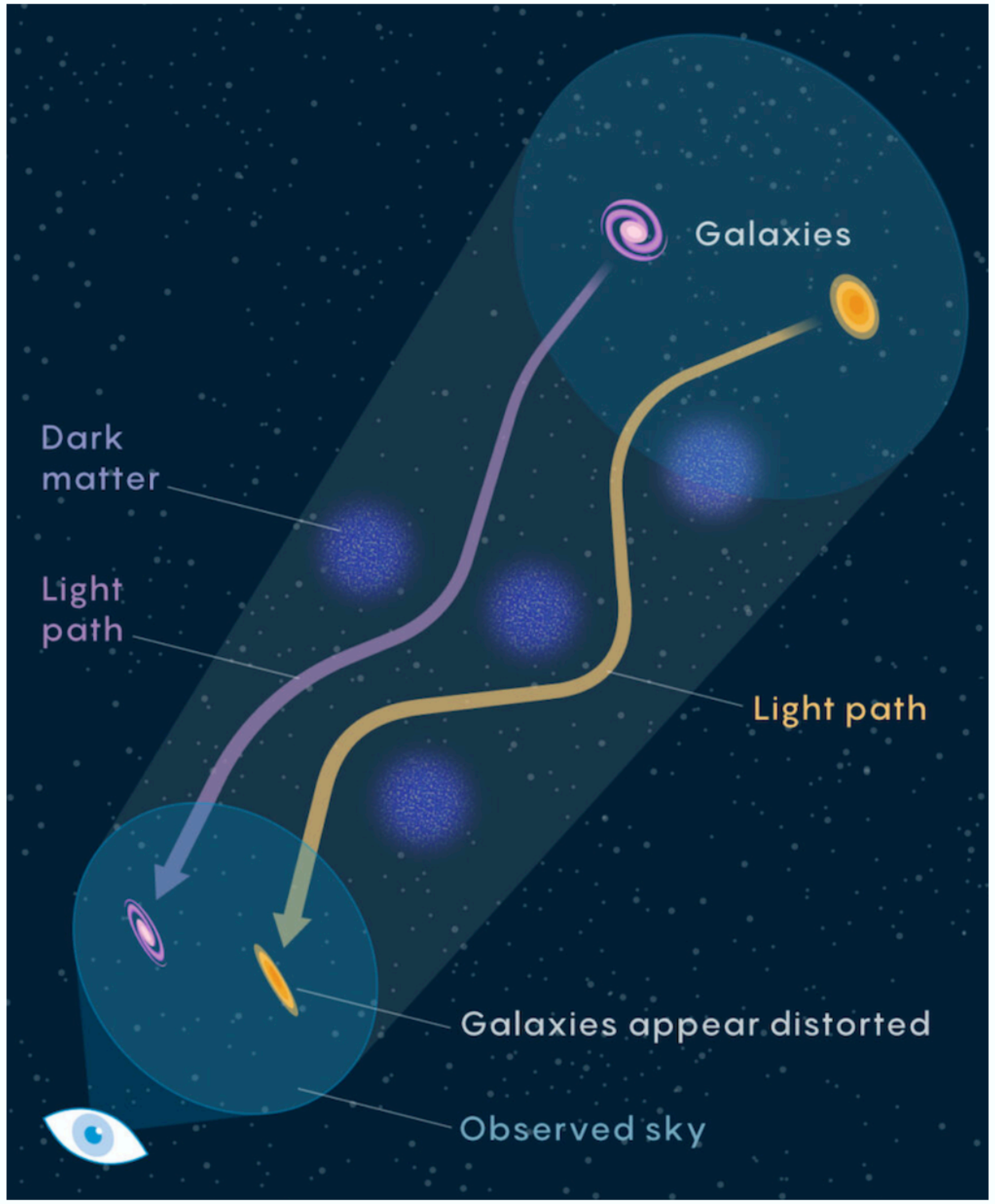

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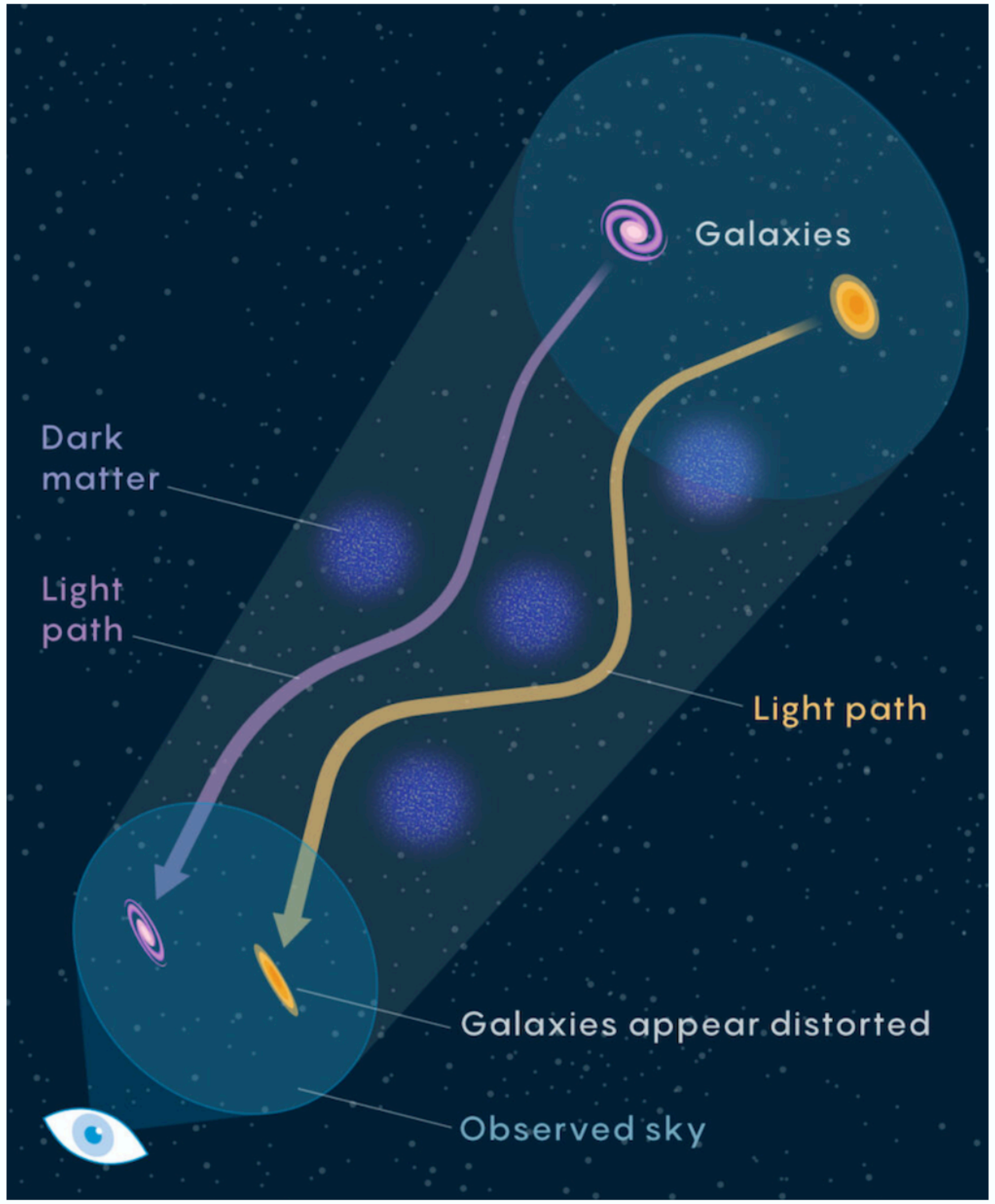

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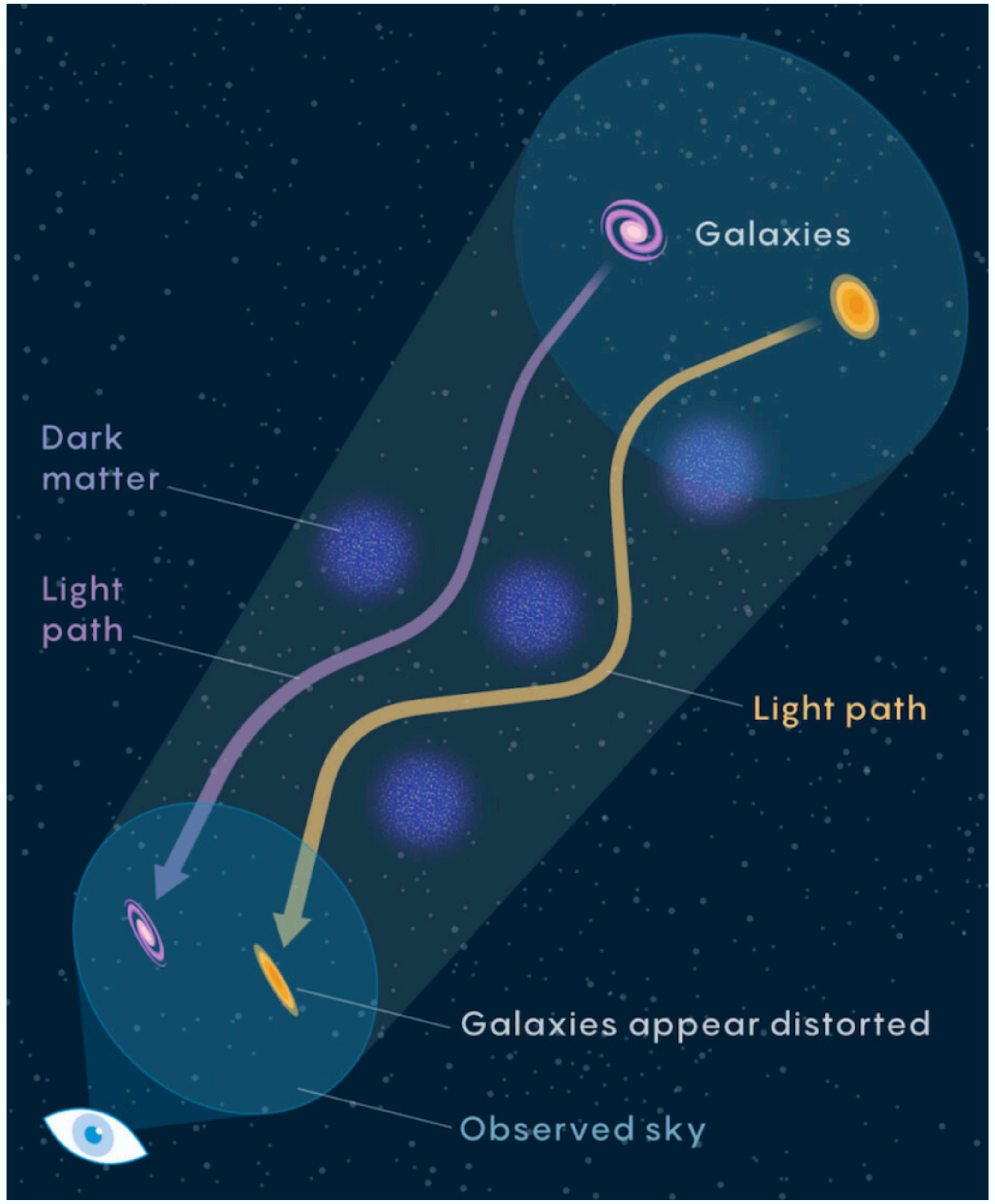

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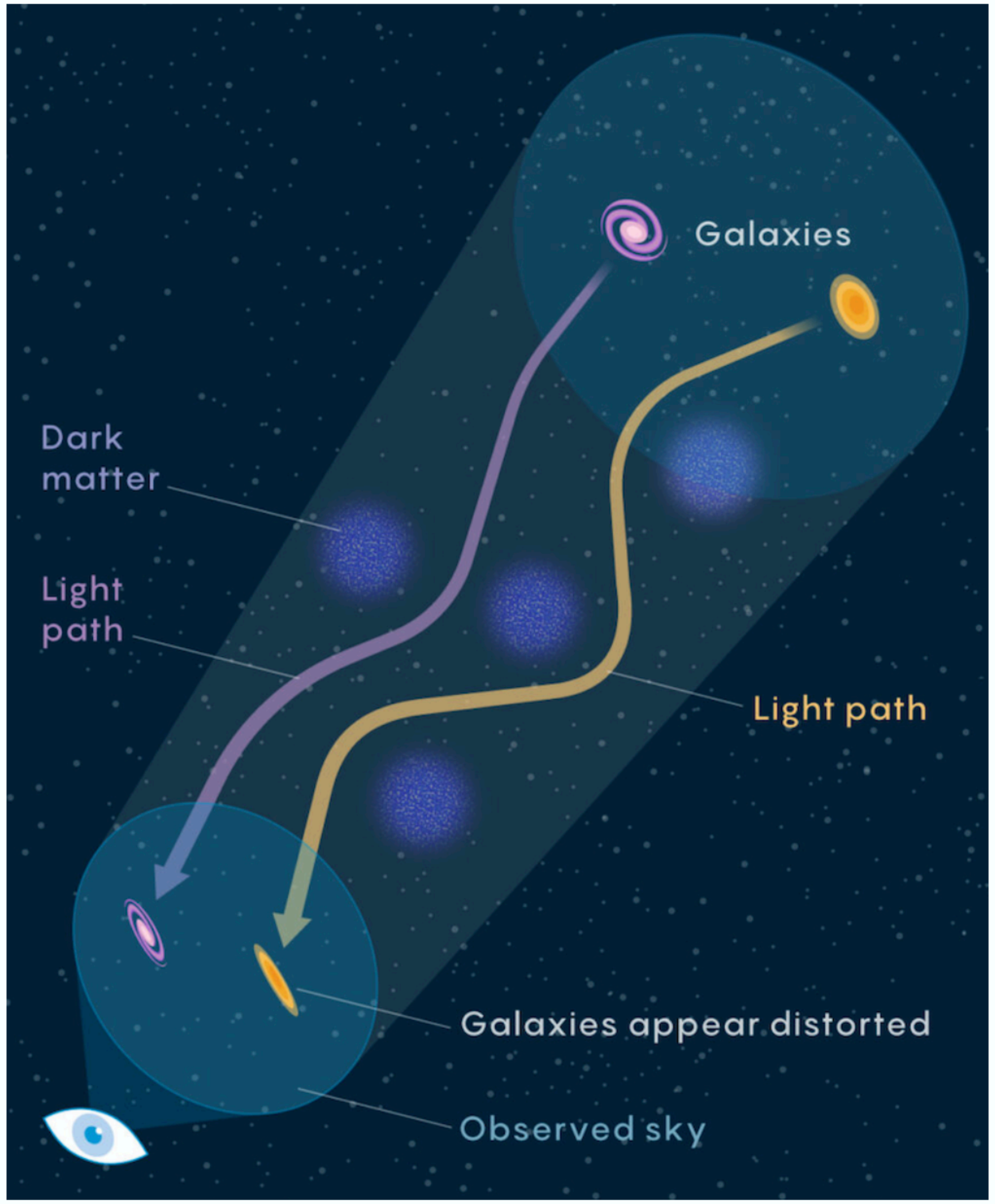

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Other weak-lensing surveys and LSS probes see also tension at 2-3σ level

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

$$\sigma_8^2 = \int P_m(k, z=0)W_8^2(k)d\ln k$$

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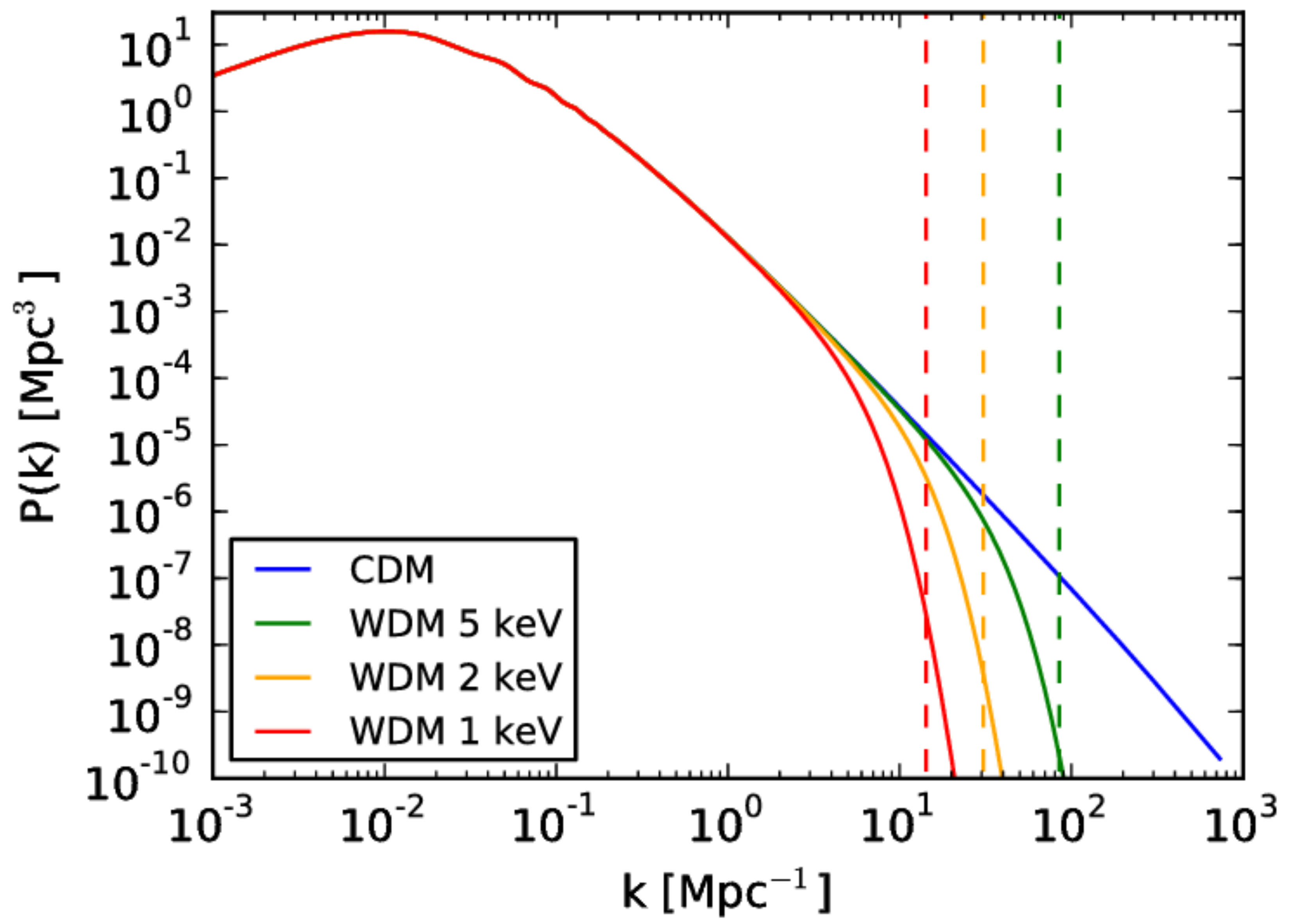
Ex: Warm dark matter (WDM)



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

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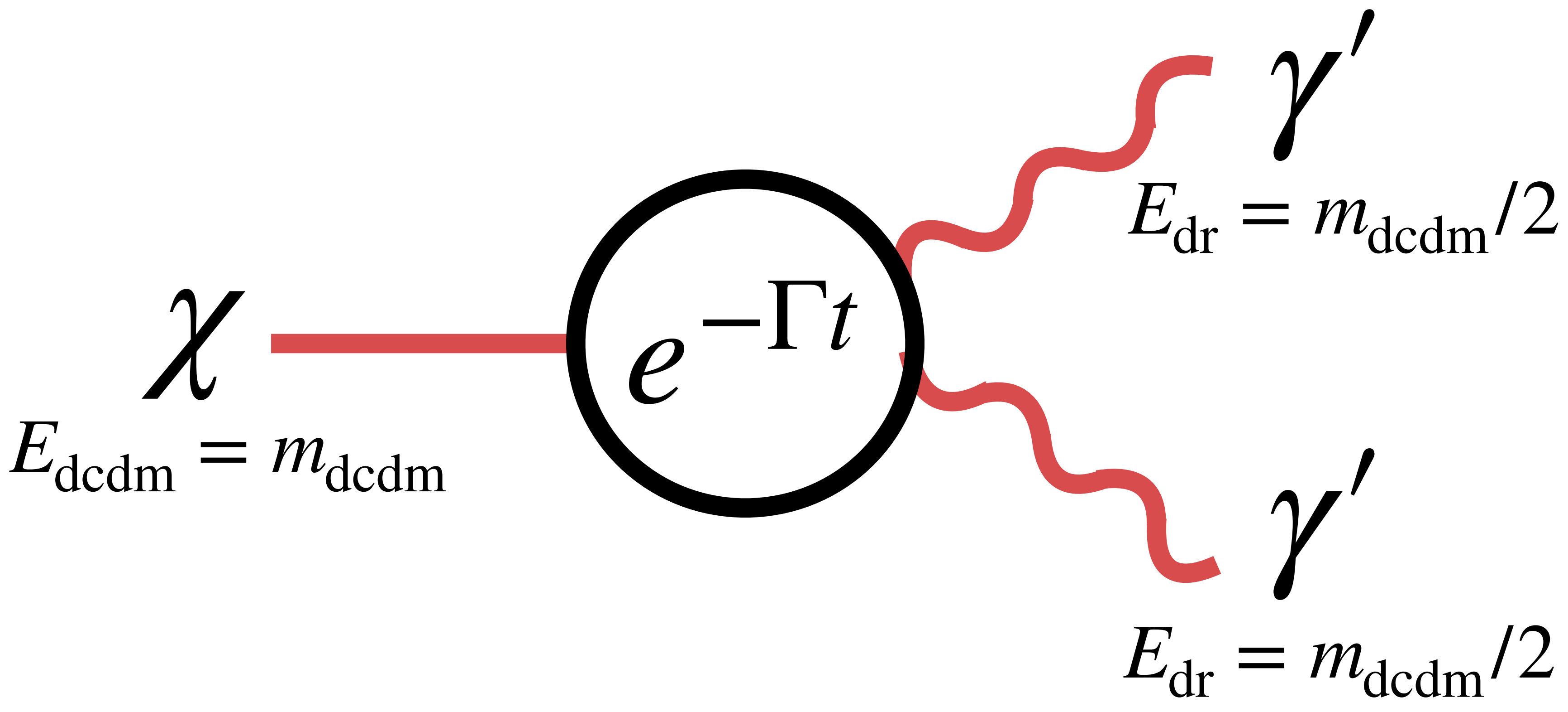
Fraction of CDM decaying to DR



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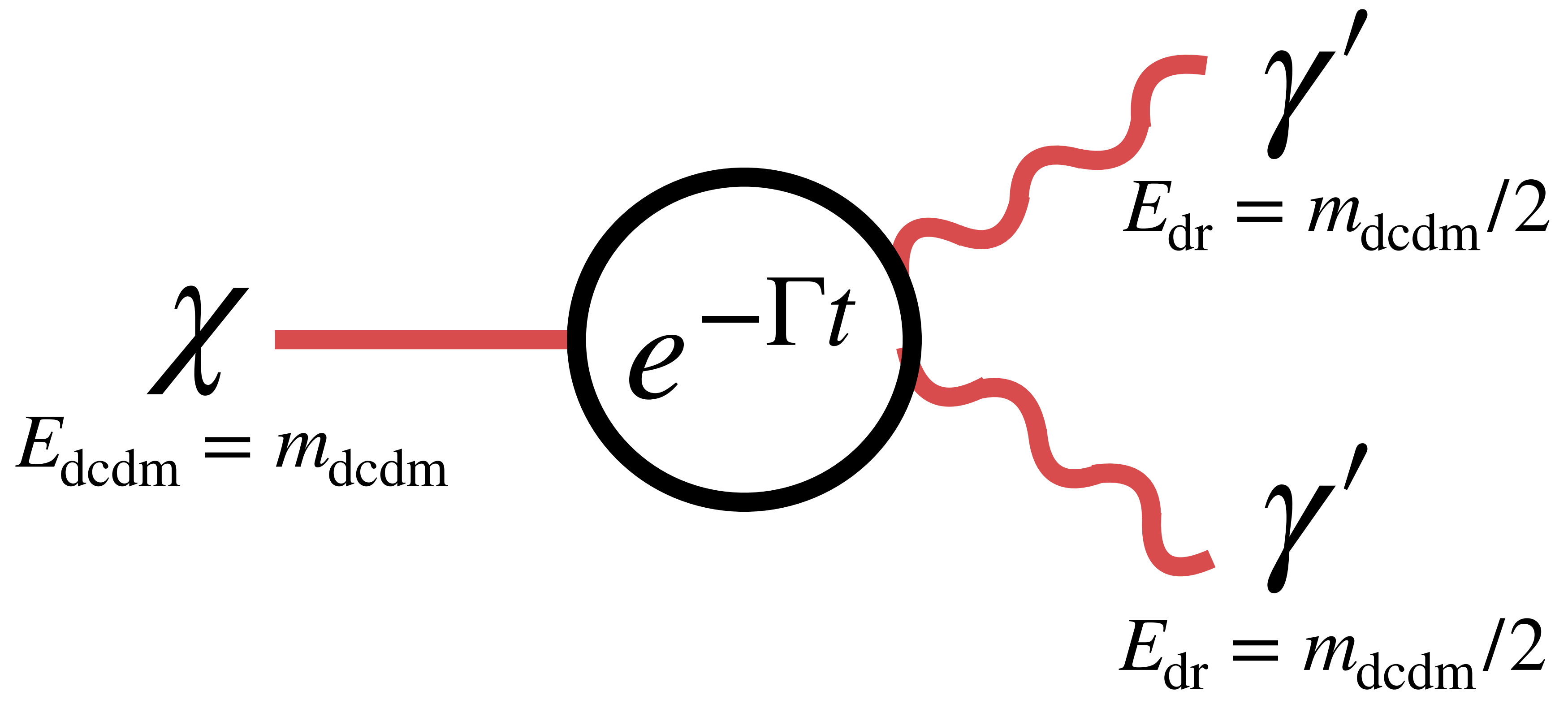

Decay rate Γ

DCDM fraction $f_{\rm dcdm}$

$$f_{\rm dcdm} \equiv \frac{\Omega_{\rm dcdm}^{\rm ini}}{\Omega_{\rm dcdm}^{\rm ini} + \Omega_{\rm cdm}} \in [0,\ 1]$$

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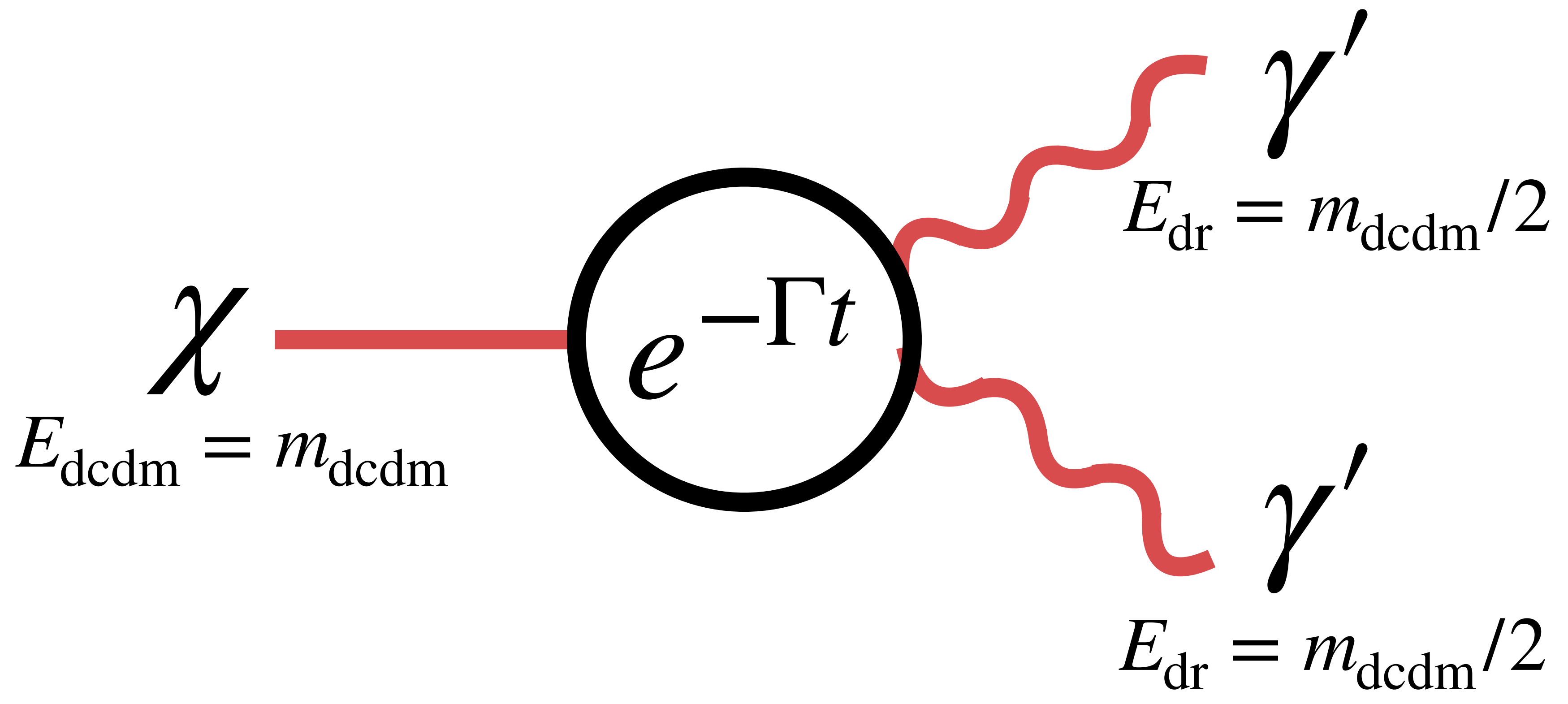

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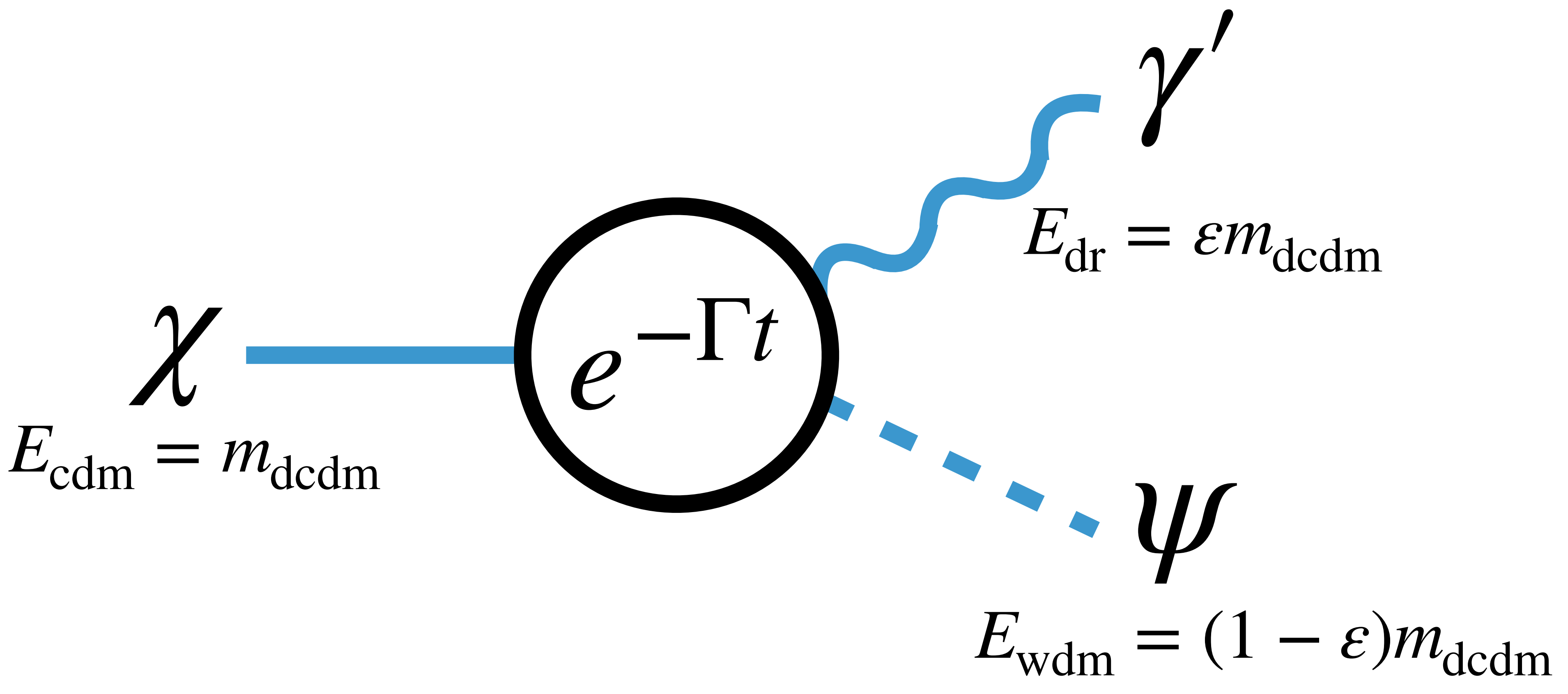

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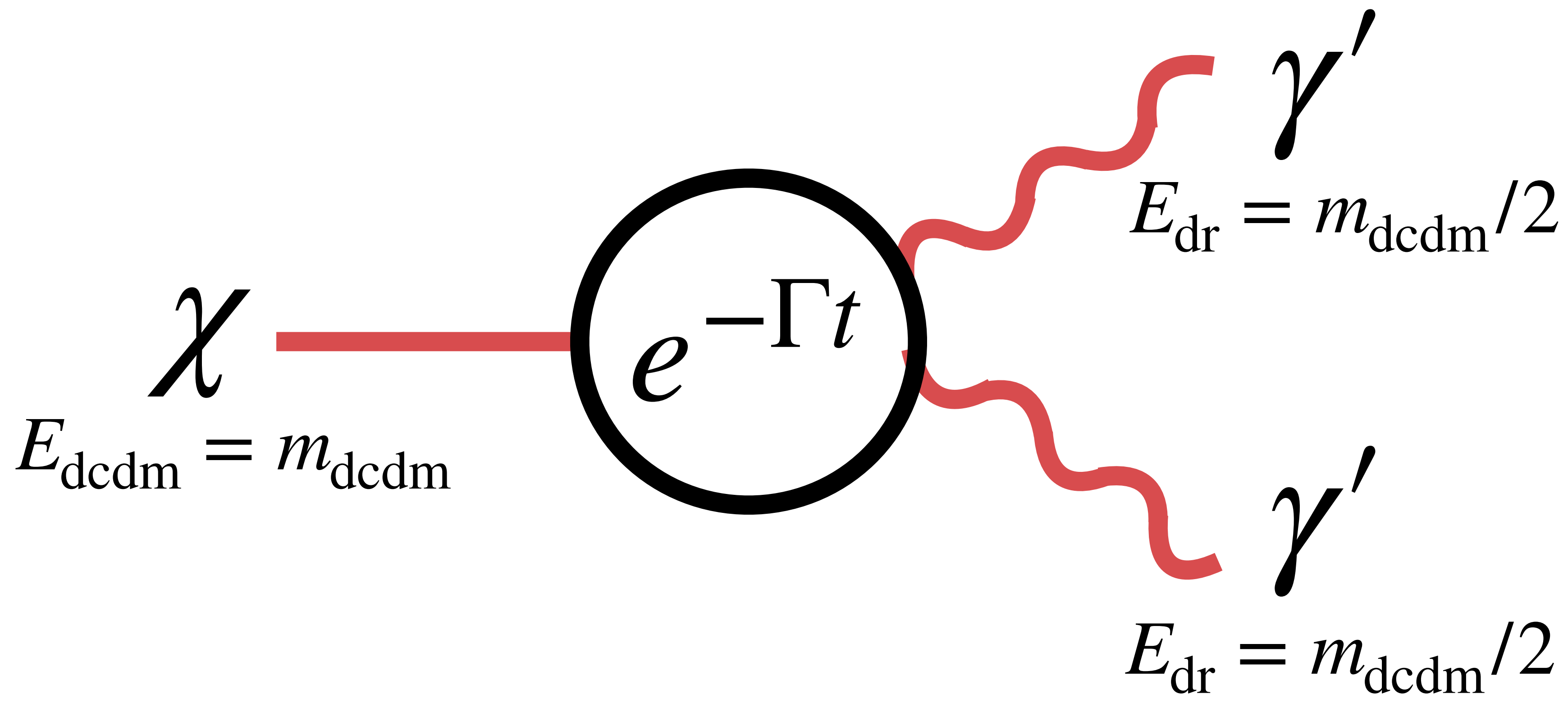

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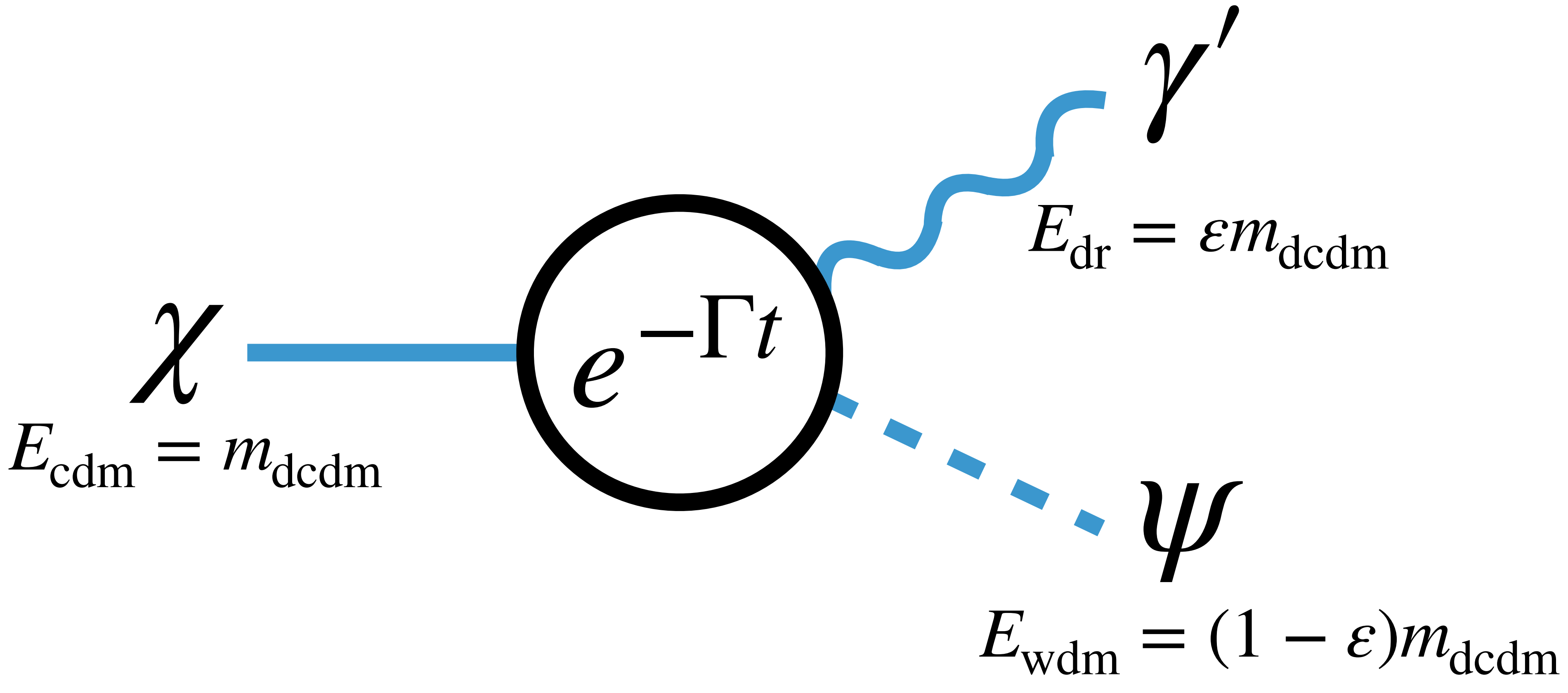

Decay rate Γ

DR energy fraction ε

$$\varepsilon = \frac{1}{2}\left(1 - \frac{m^2_{\rm wdm}}{m^2_{\rm dcdm}}\right) \in [0, 1/2]$$

Fraction of CDM decaying to DR

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

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WDM is time consuming.
New fluid approx. allowed to **reduce CPU time** from ~ 1 day to ~ 1 minute **[Abellán+ 21]**

What's the impact on cosmological observables?

Expansion history H(z)

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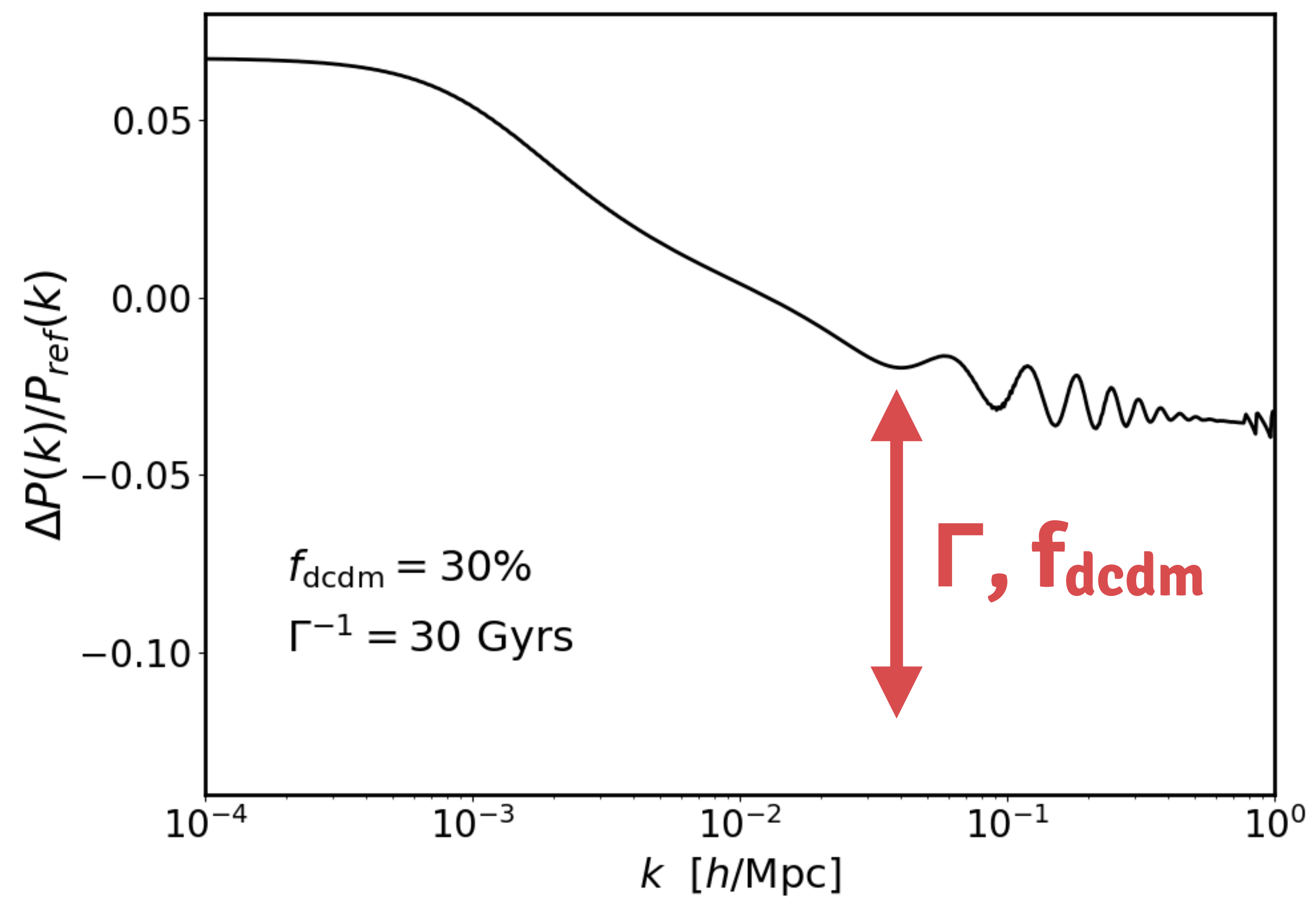
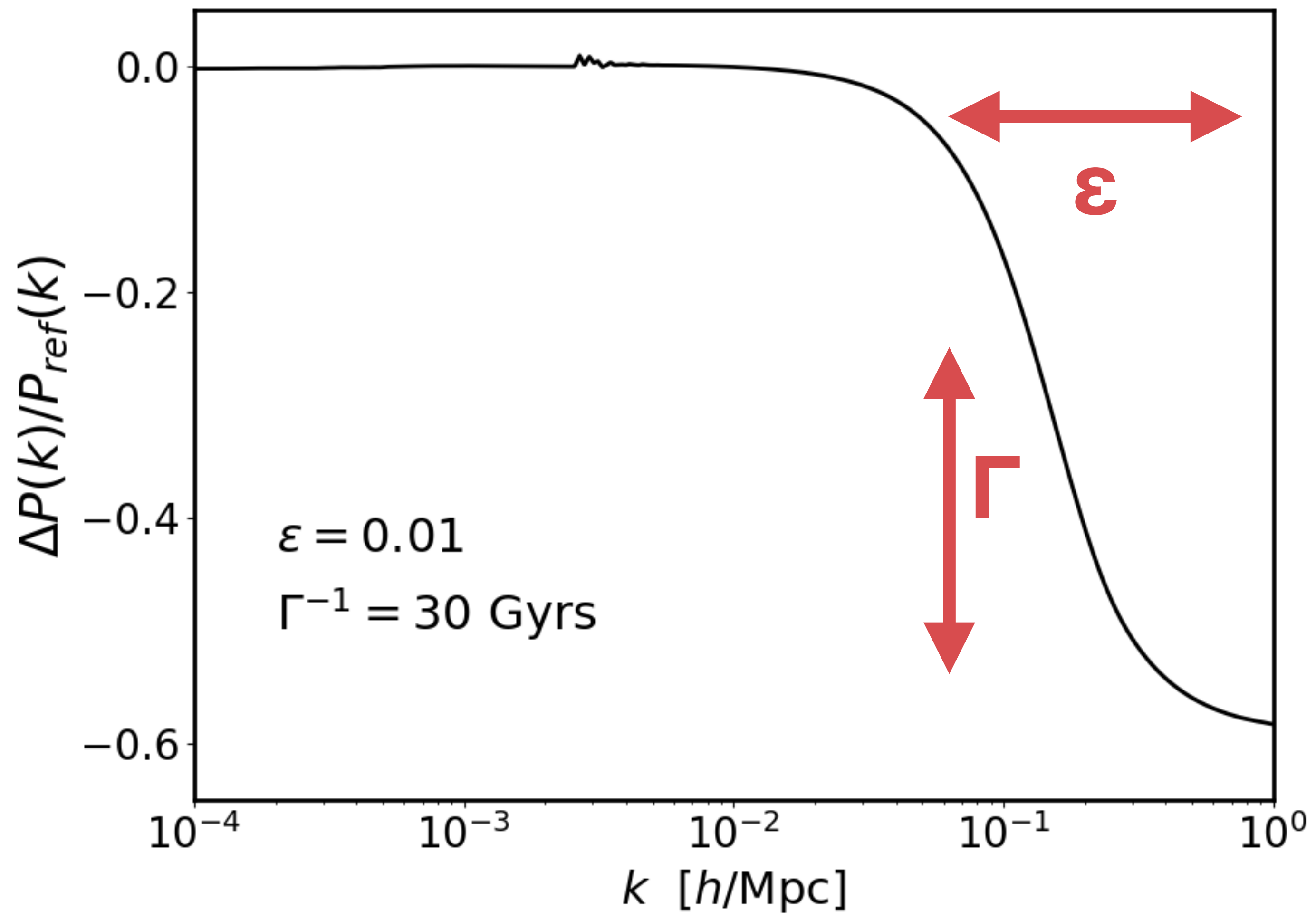
Linear matter power spectrum $P_m(k)$

CDM → DR shifts position of the peak



CDM → DR+WDM suppresses power at k > k_{fs}



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- What about the CDM → DR+WDM model?

CDM → DR+WDM solves the S_8 tension

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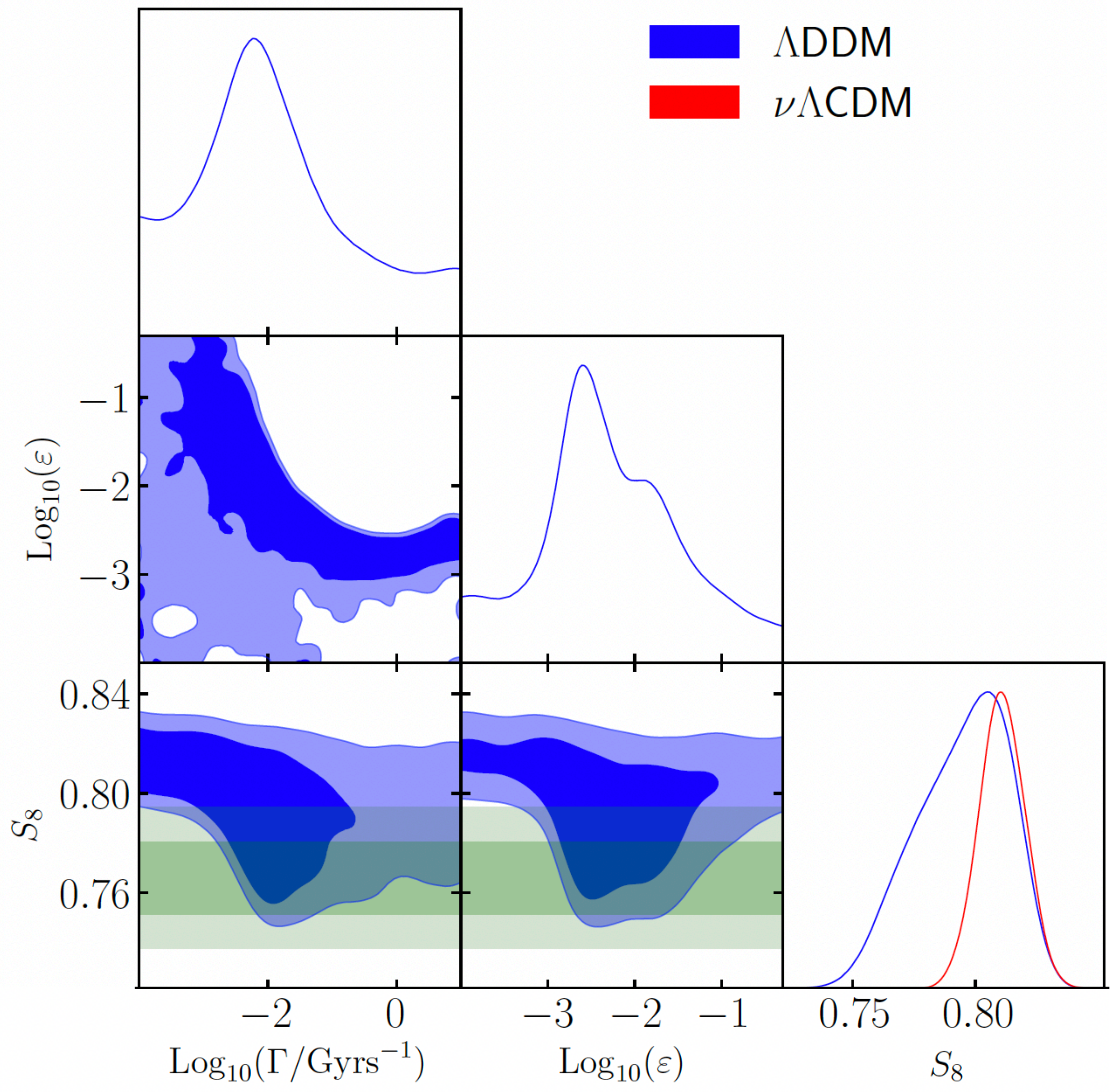
Planck18 + BAO + SNIa
+S_8 prior (KiDS+BOSS+2dfLenS):



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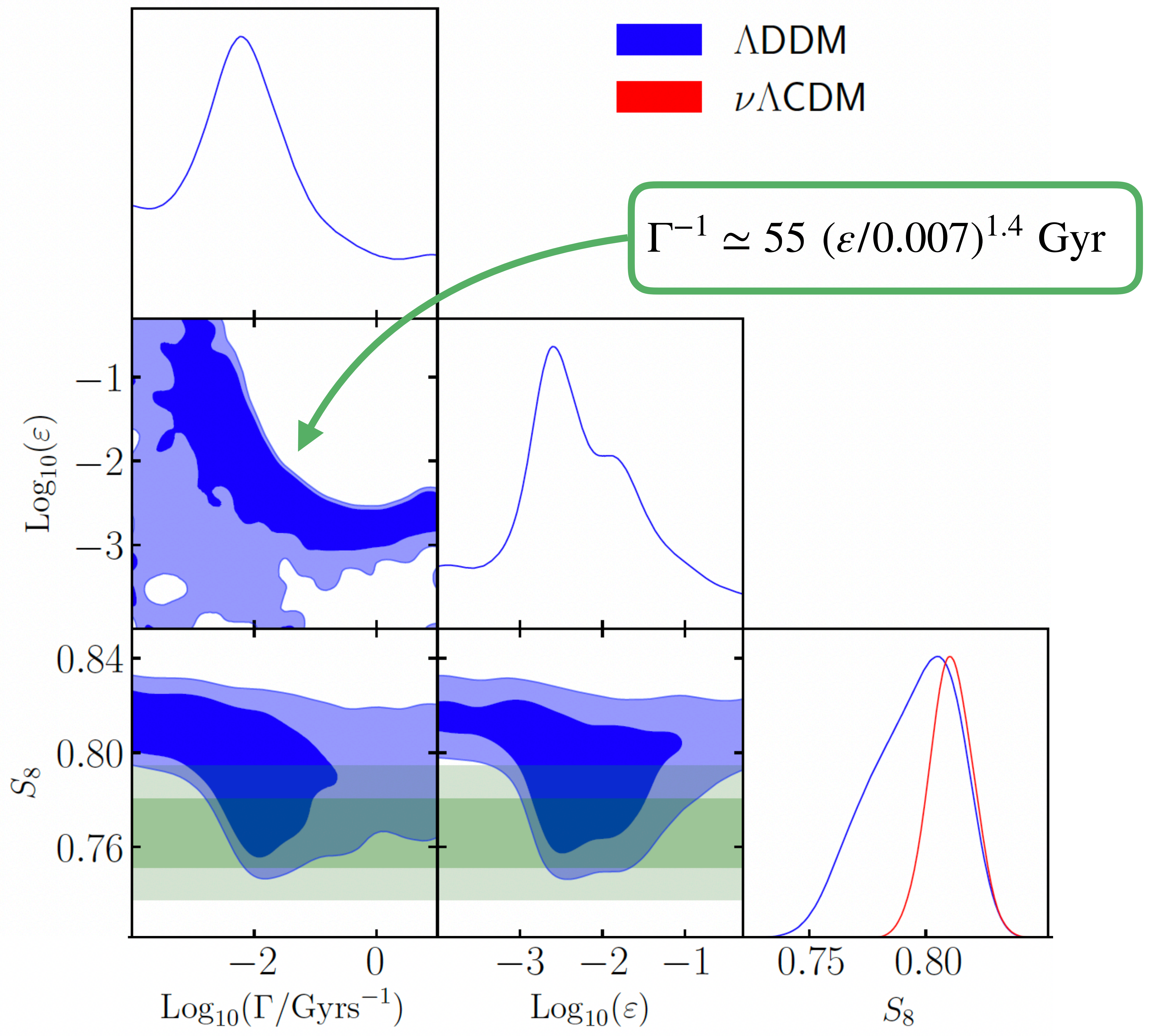

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- Can we test this with other probes?

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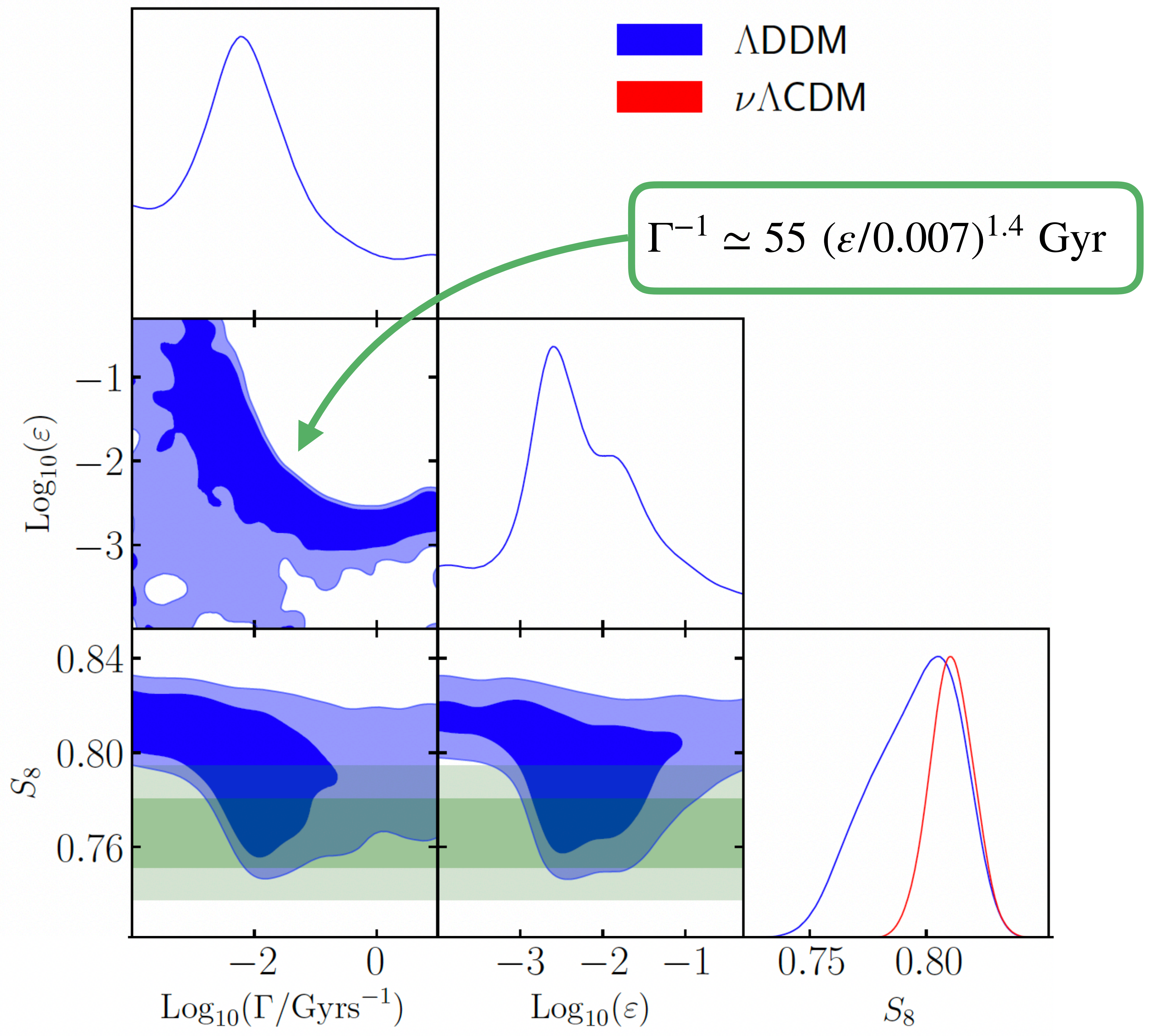

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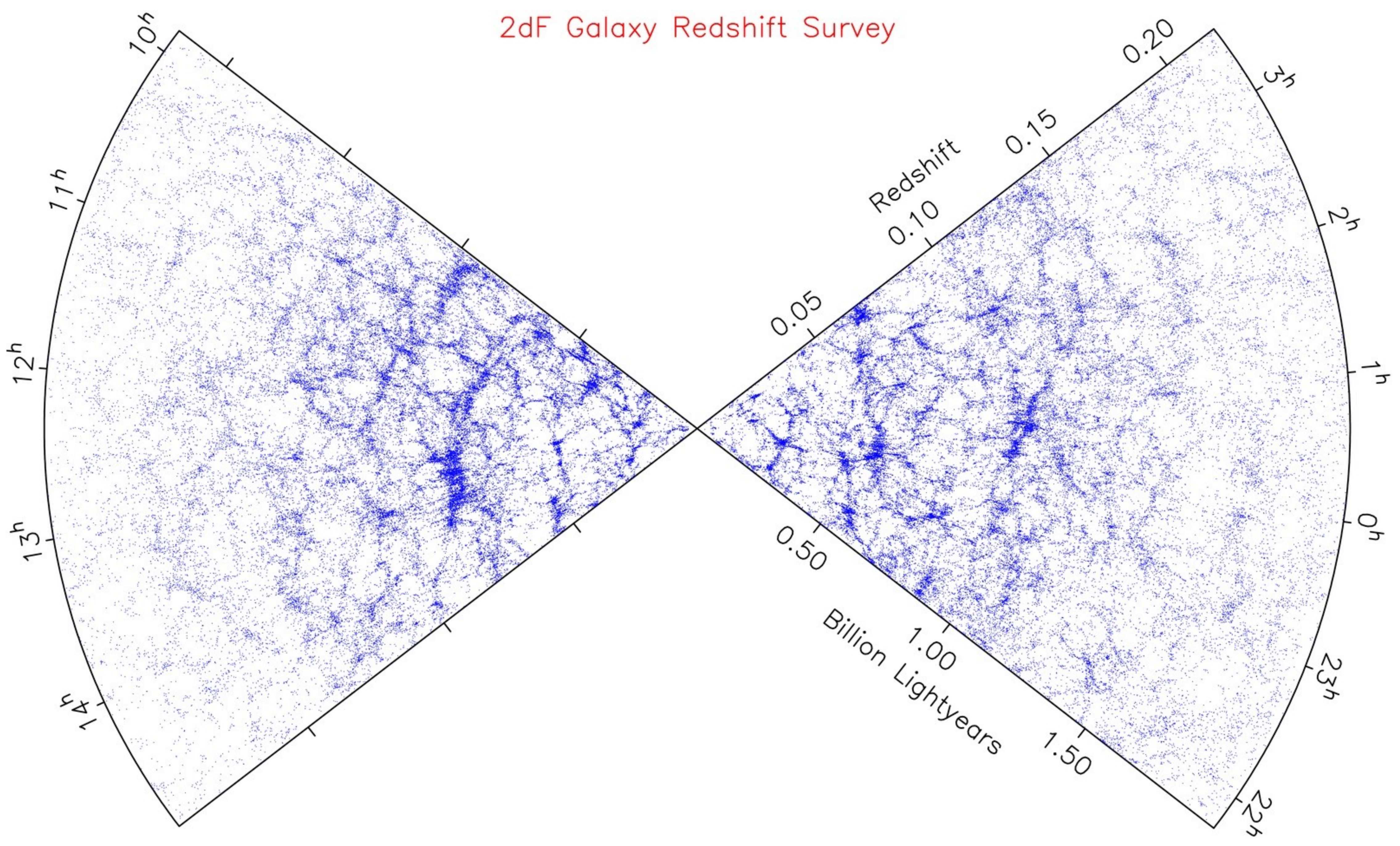
Part II:

INTRODUCTION TO THE EFTofLSS

We would like to analyze the **clustering of galaxies** on the largest scales



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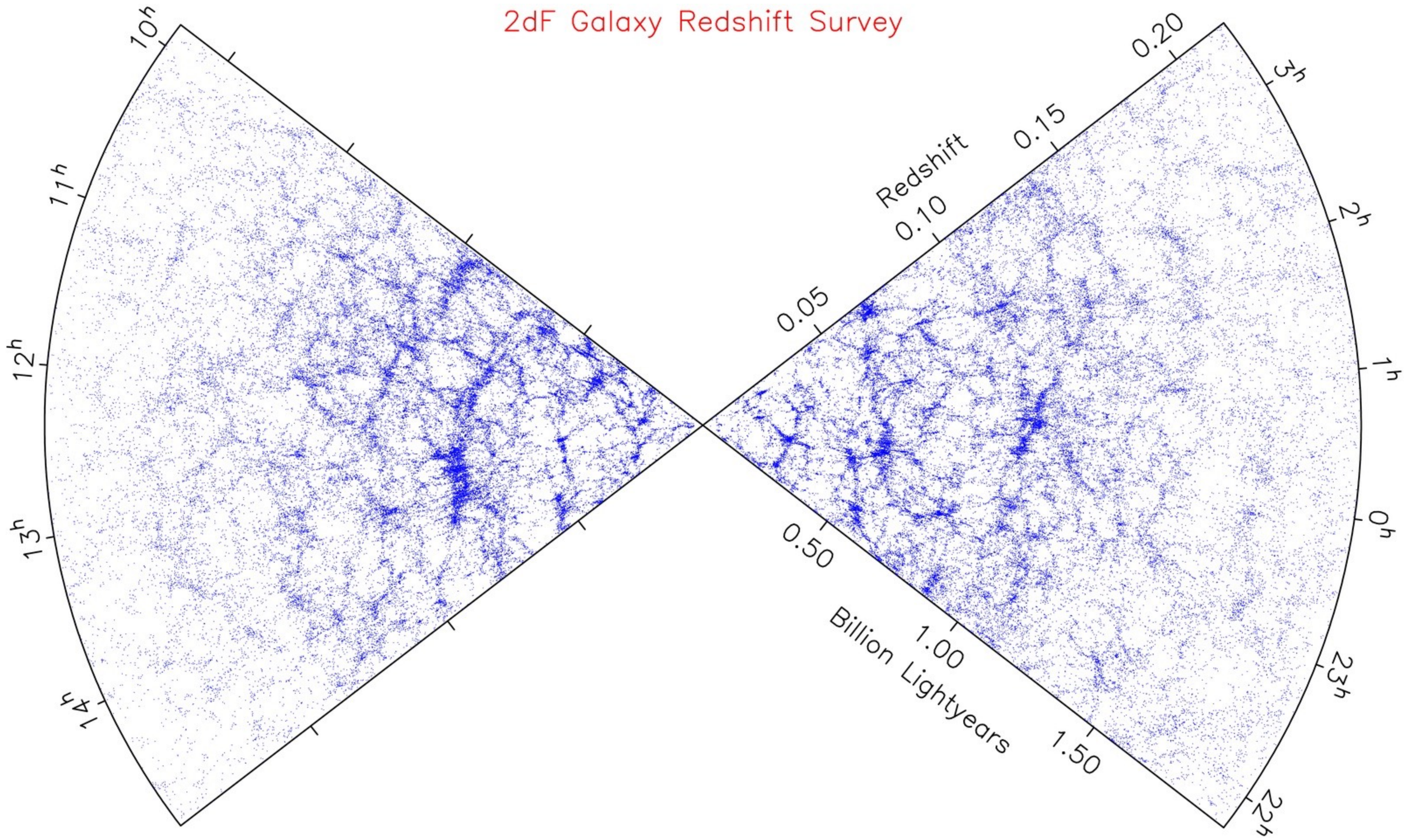

Unfortunately, we **cannot rely on linear theory** anymore

$$\partial_\tau \delta + \partial_i[(1+\delta)v^i] = 0$$

$$\partial_\tau v^i + aHv^i + \partial^i\Phi + v^j\partial_j v^i = -\frac{1}{a\rho}\partial_j\tau^{ij}$$

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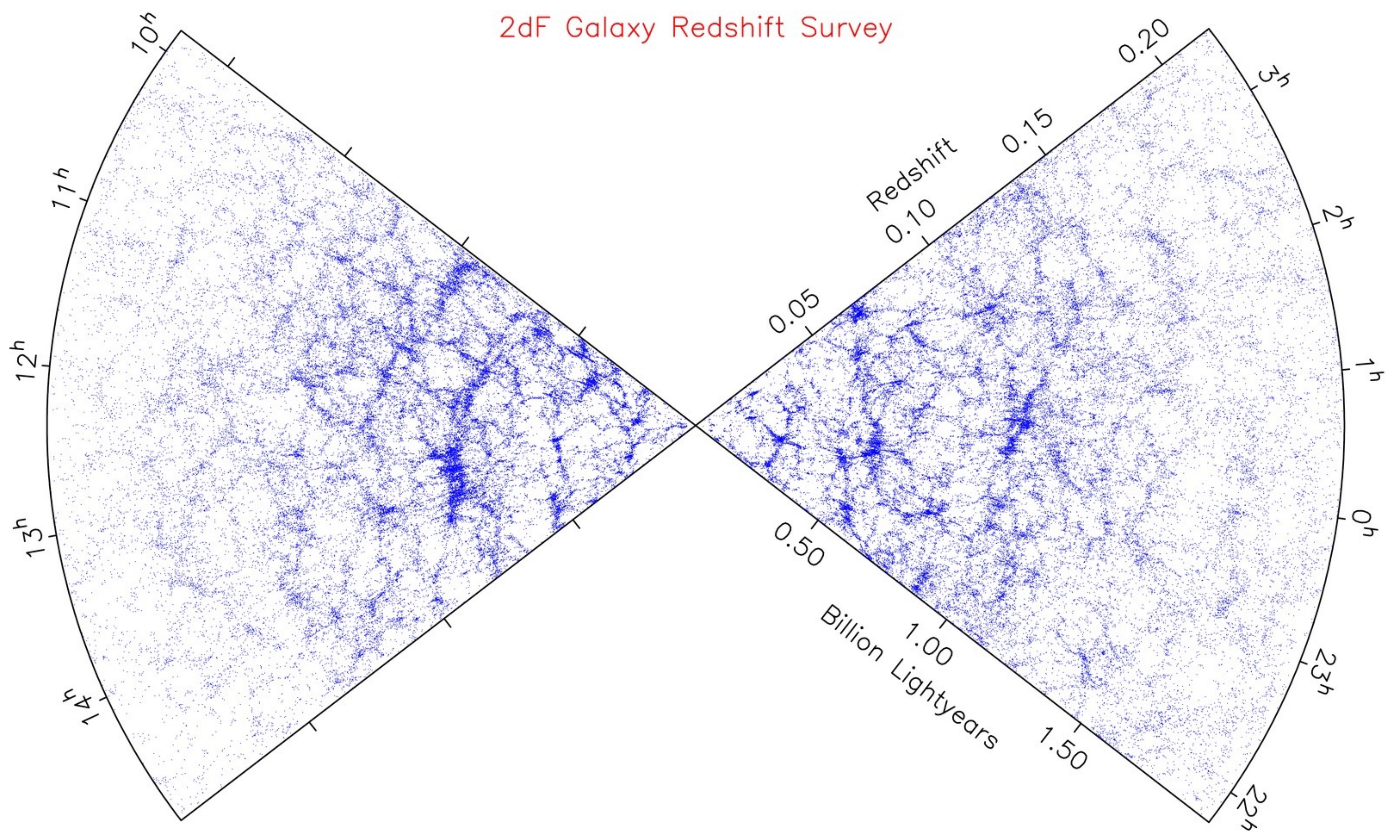

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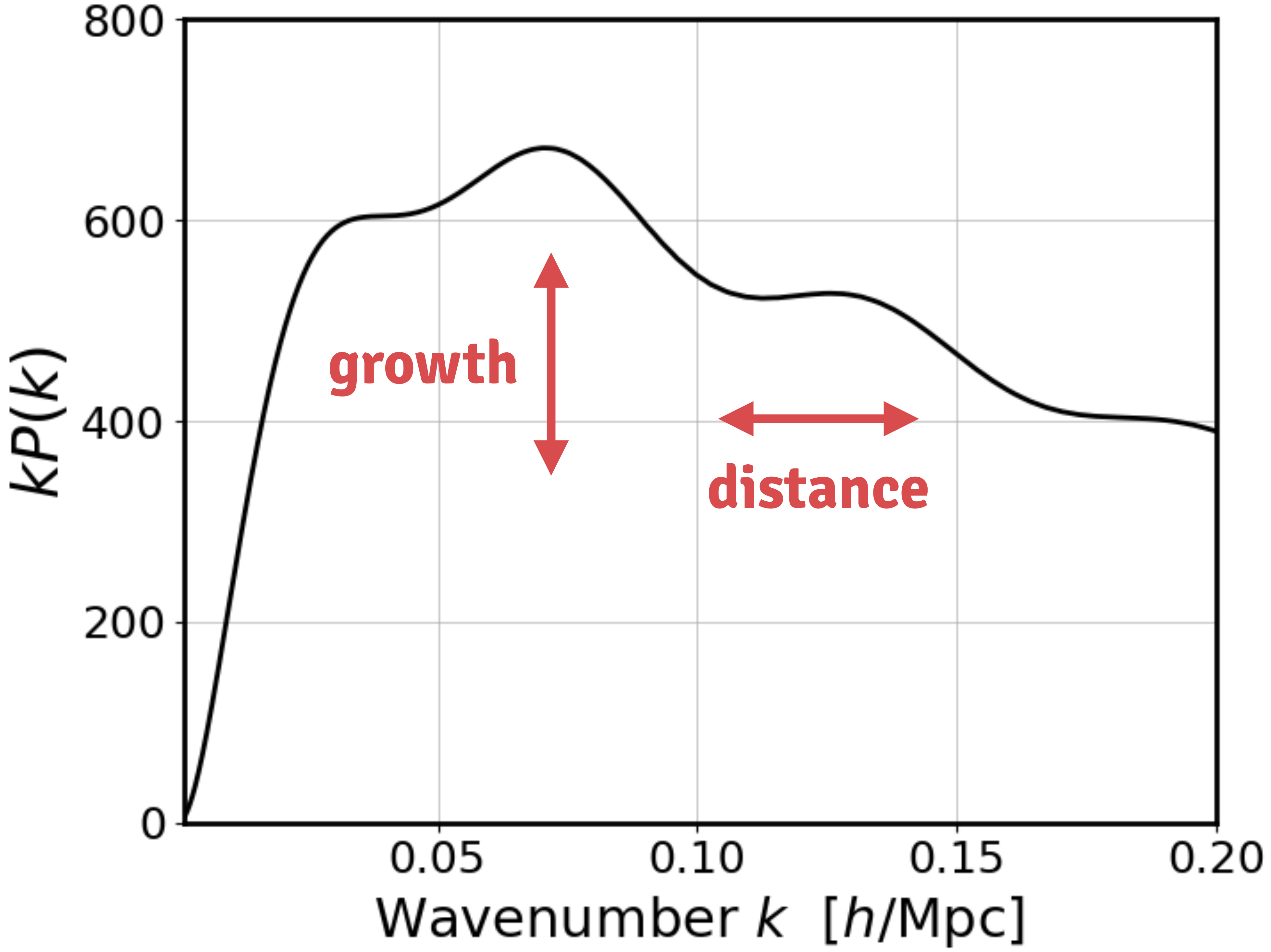

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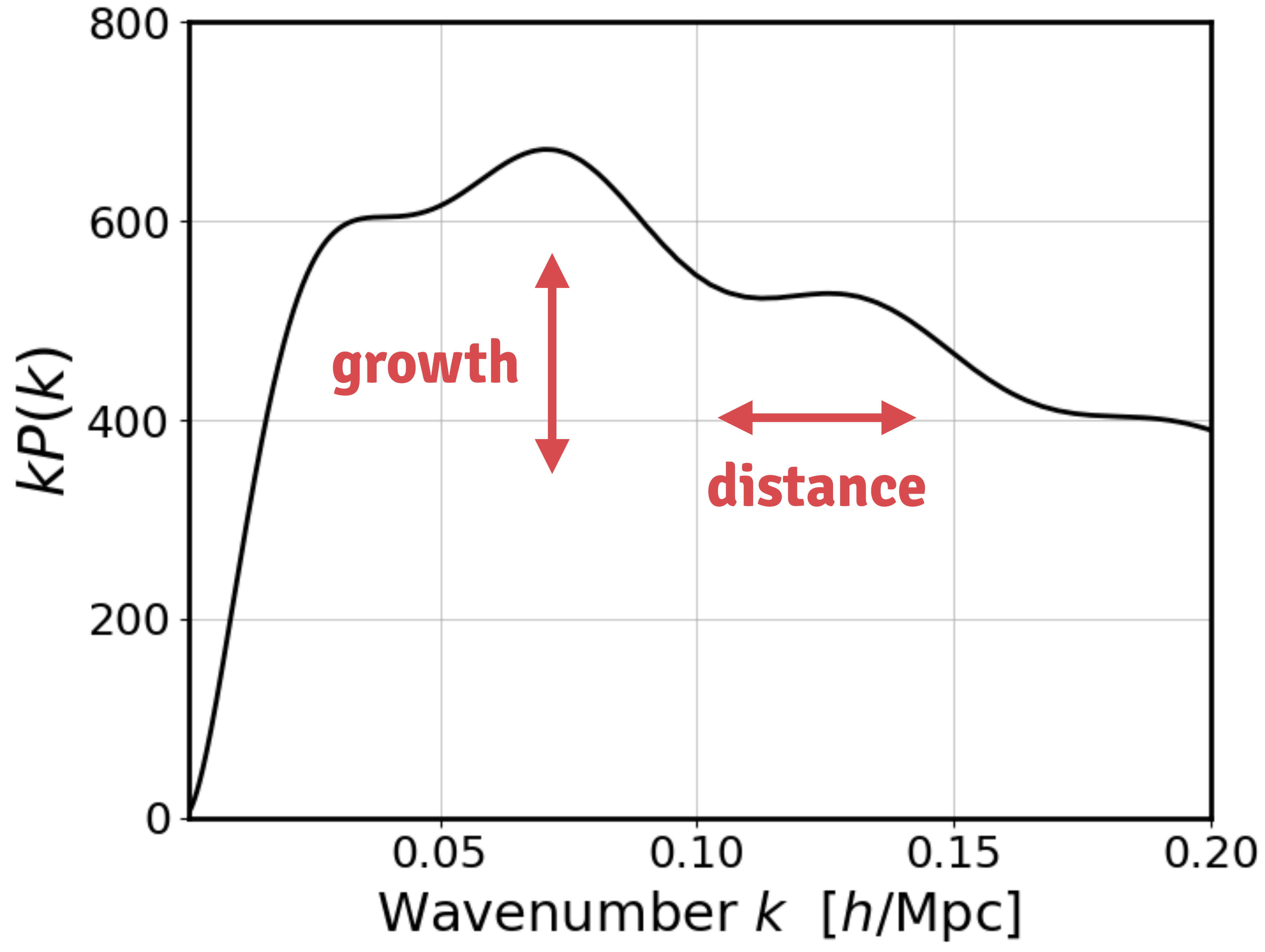
fσ₈/BAO tests

$$\frac{f\sigma_8(z)}{(f\sigma_8(z))_{\rm fid}} \quad \frac{H(z)}{H(z)_{\rm fid}} \quad \frac{D_A(z)}{D_A(z)_{\rm fid}}$$



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- Can we use the **full shape** information?

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- ✓ Good for matter clustering
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Effective Field Theory

- ✗ Limited range of scales (based on perturbation theory)
- ✓ More insight into data
- ✓ Fast & accurate predictions
- ✓ Marg. over uncertainties (free parameters that capture small-scale physics)

Two important ingredients

Galaxy bias

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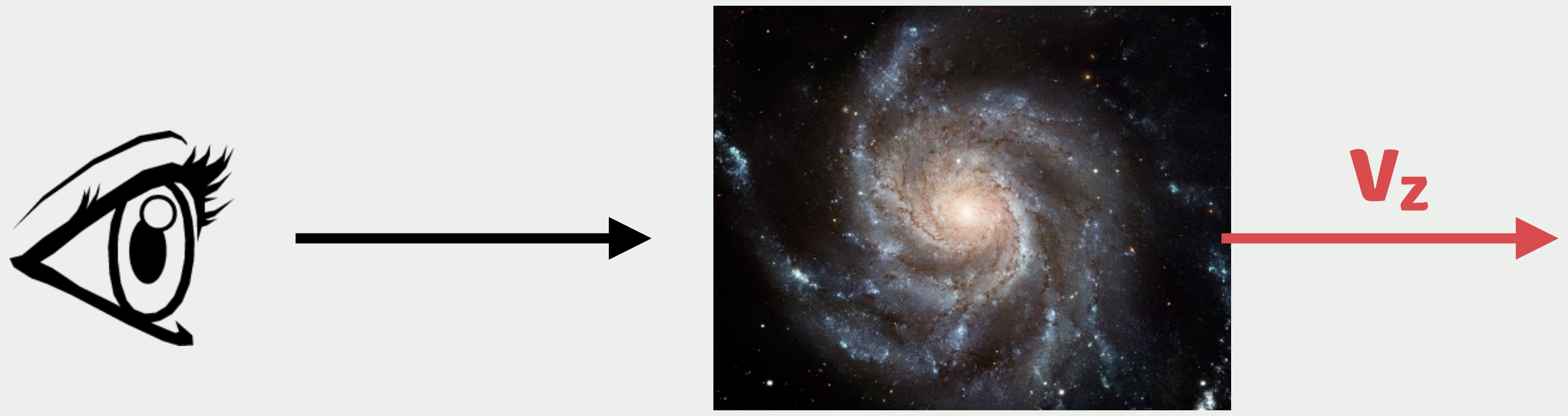

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Redshift Space Distortions

$$z = Hr + v_z$$

Galaxy spectra are anisotropic

$$P(\mu, k) \text{ with } \mu \equiv \hat{\mathrm{k}} \cdot \hat{\mathrm{z}}$$

Expand in Legendre multipoles

$$P_\ell(k) = \frac{2\ell + 1}{2} \int_{-1}^{1} L_\ell(\mu) P(\mu, k) d\mu$$

$\ell = 0$ (monopole), $\ell = 2$ (quadrupole), ...

EFTofLSS approach:

[Baumann, Nicolis, Senatore, Zaldarriaga 10]

$$P_\ell(k) = P_\ell^{\mathrm{tree}}(k) + P_\ell^{\mathrm{one-loop}}(k) + P_\ell^{\mathrm{counterterms}}(k) + P_\ell^{\mathrm{stochastic}}(k)$$

Linear theory (Kaiser model) $\propto P_{\mathrm{linear}}(k)$

Perturbation theory $\propto k^2 P_{\mathrm{linear}}(k)$

Ultraviolet counterterms $\propto k^2 P_{\mathrm{linear}}(k)$

Stochastic

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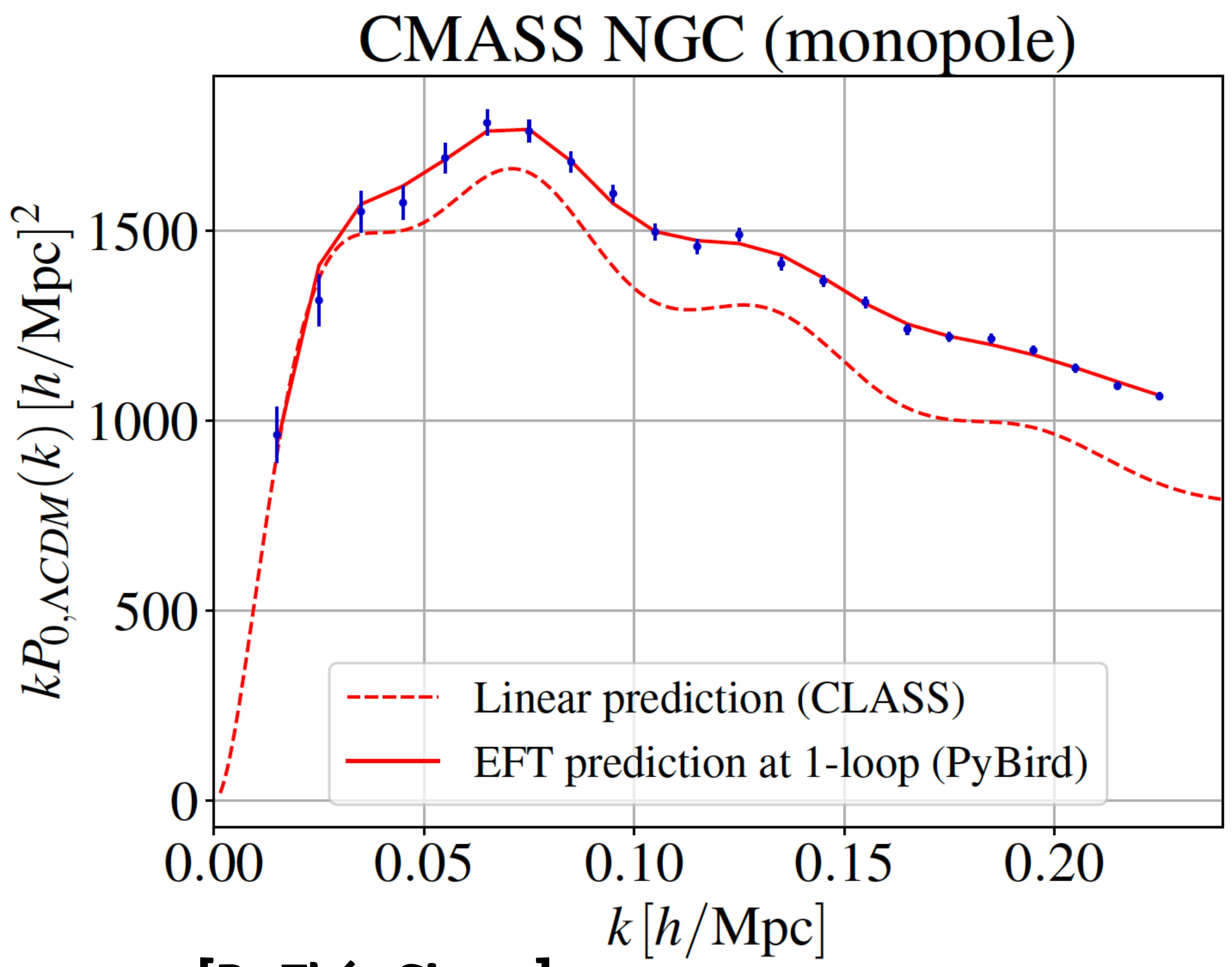
- P_ℓ^{tree}: Linear theory (Kaiser model) $\propto P_{\text{linear}}(k)$
- $P_\ell^{\text{one-loop}}$: Perturbation theory $\propto k^2 P_{\text{linear}}(k)$
- $P_\ell^{\text{counterterms}}$: Ultraviolet counterterms $\propto k^2 P_{\text{linear}}(k)$
- $P_\ell^{\text{stochastic}}$: Stochastic

Two main codes:

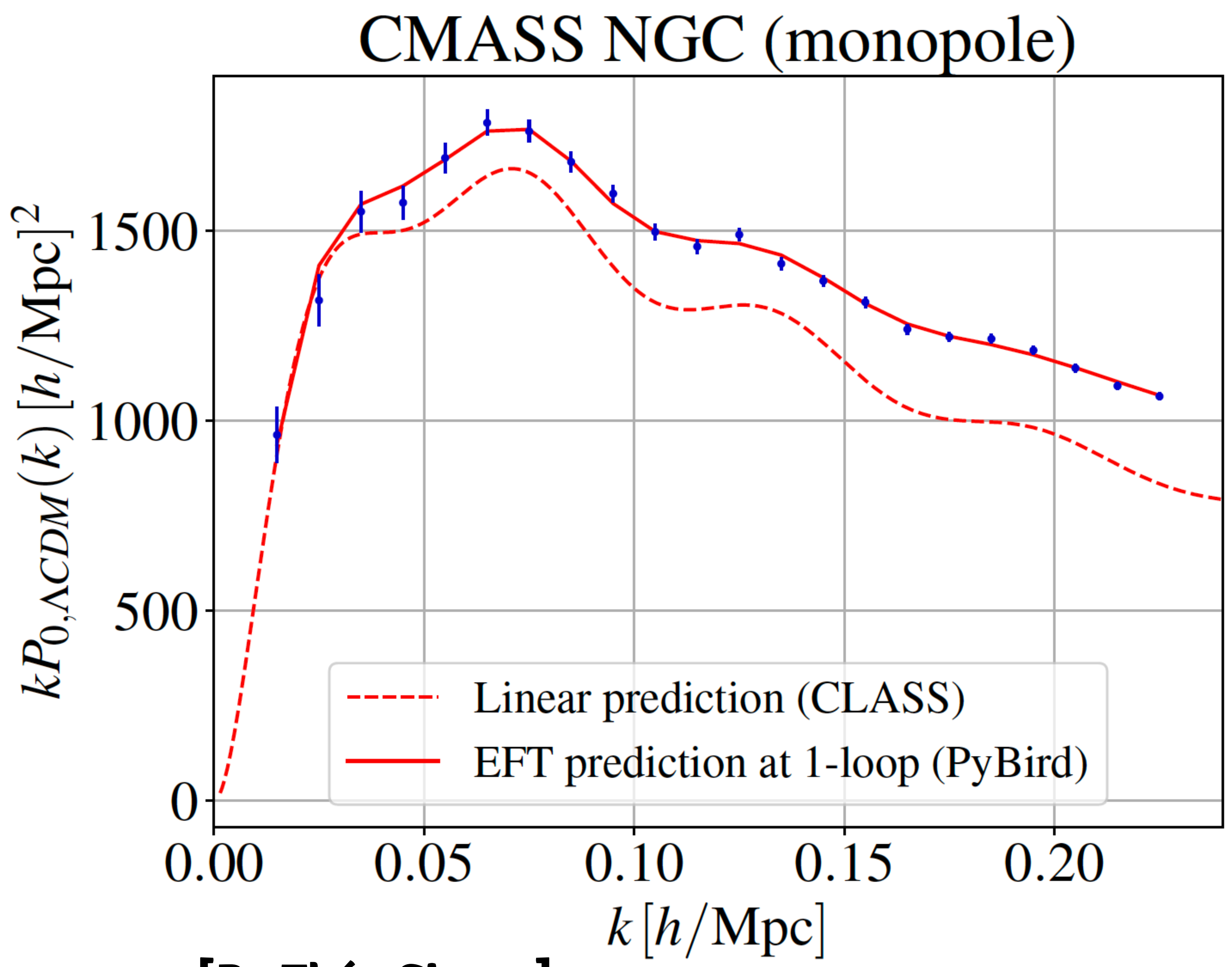
- **CLASS-PT** [Ivanov, Chudaykin, Philcox, Simonovic 20]
- **PyBird** [Zhang, D'Amico, Senatore 20]

The success of EFTofLSS



[By Théo Simon]

- The EFTofLSS has been successfully applied to BOSS data



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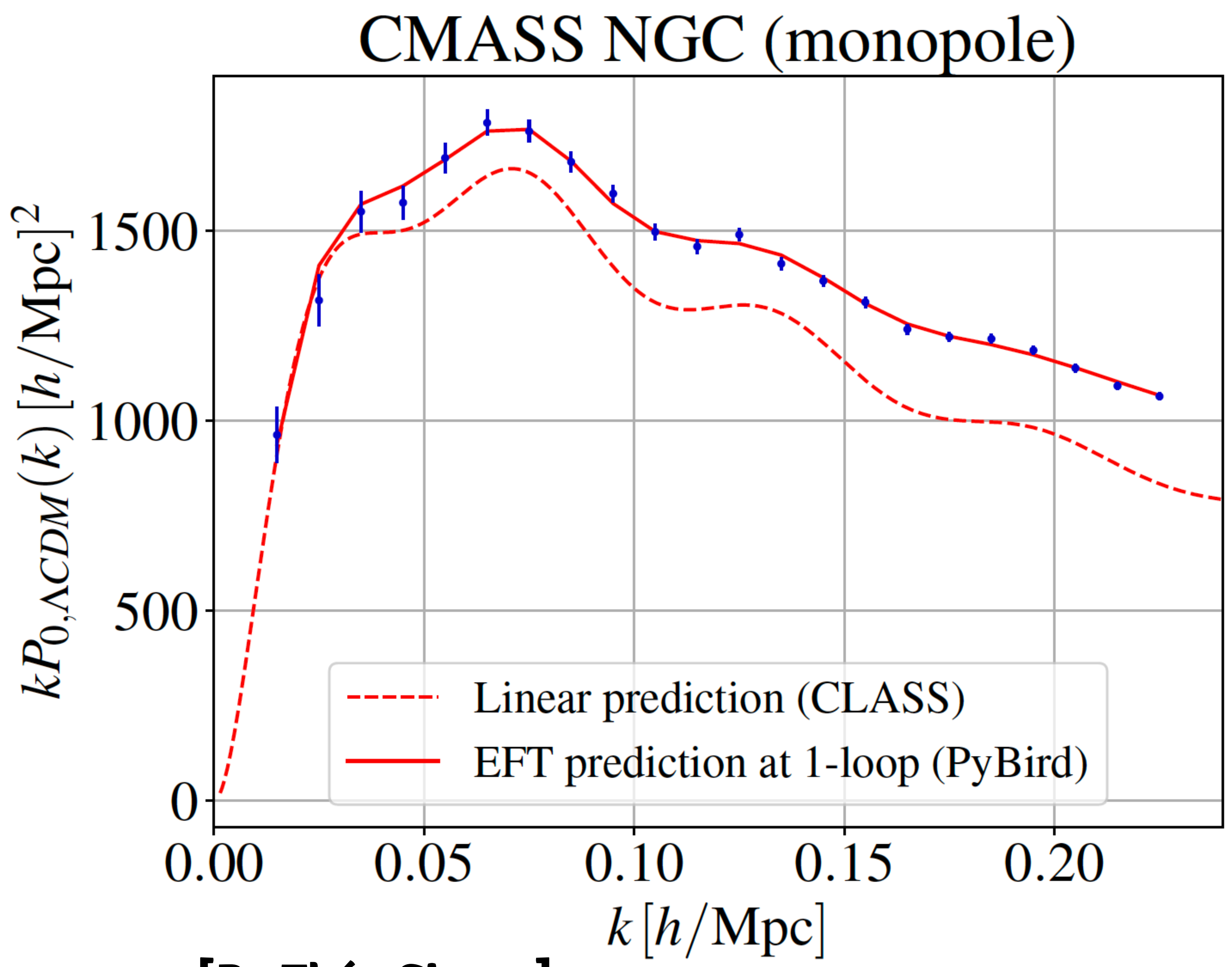
Constraints on H_0 and Ω_m competitive with Planck!

[Colas+ 19] [D'Amico+ 19]



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The success of EFTofLSS

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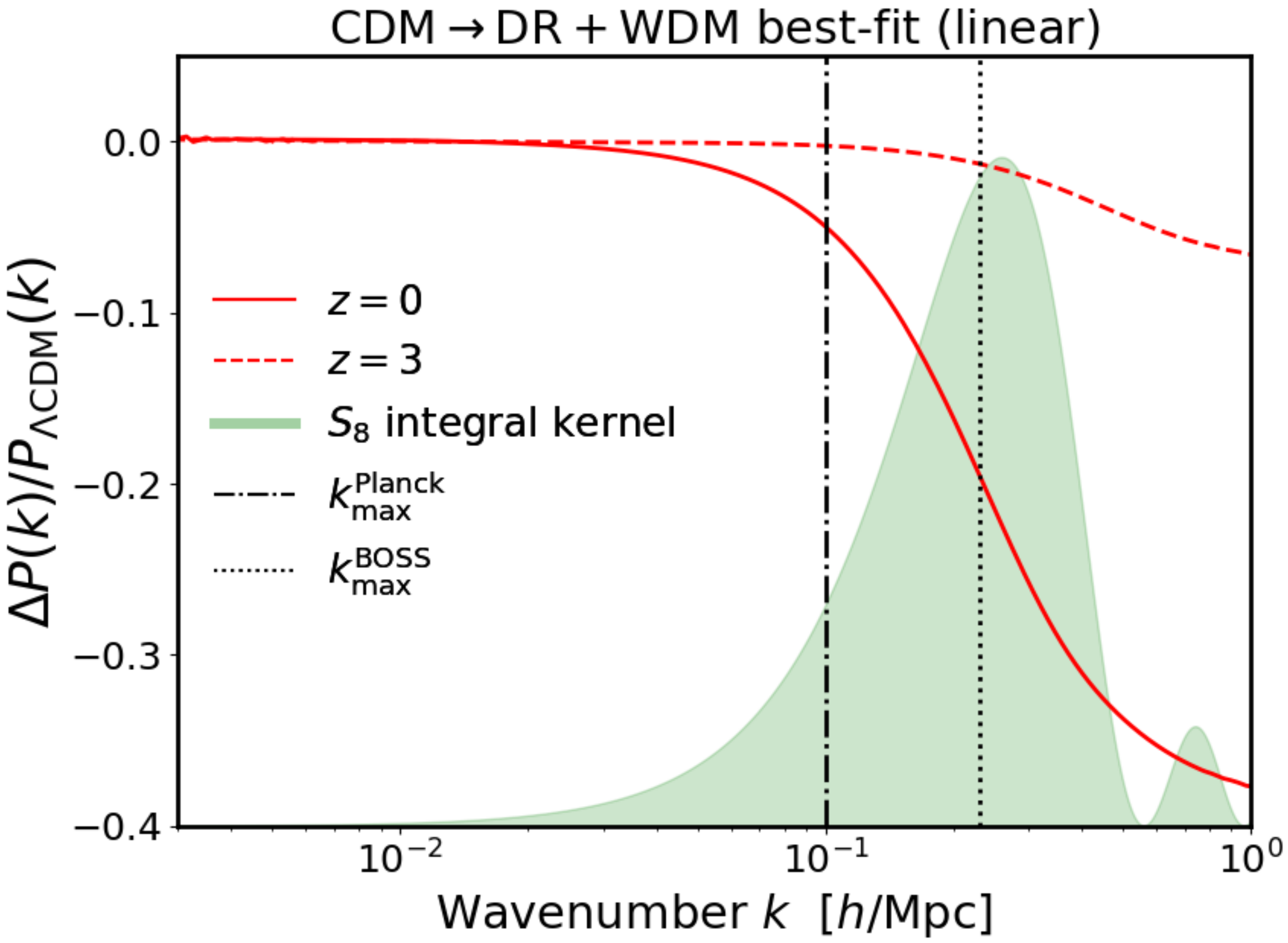
  [Colas+ 19] **[D'Amico+ 19]**

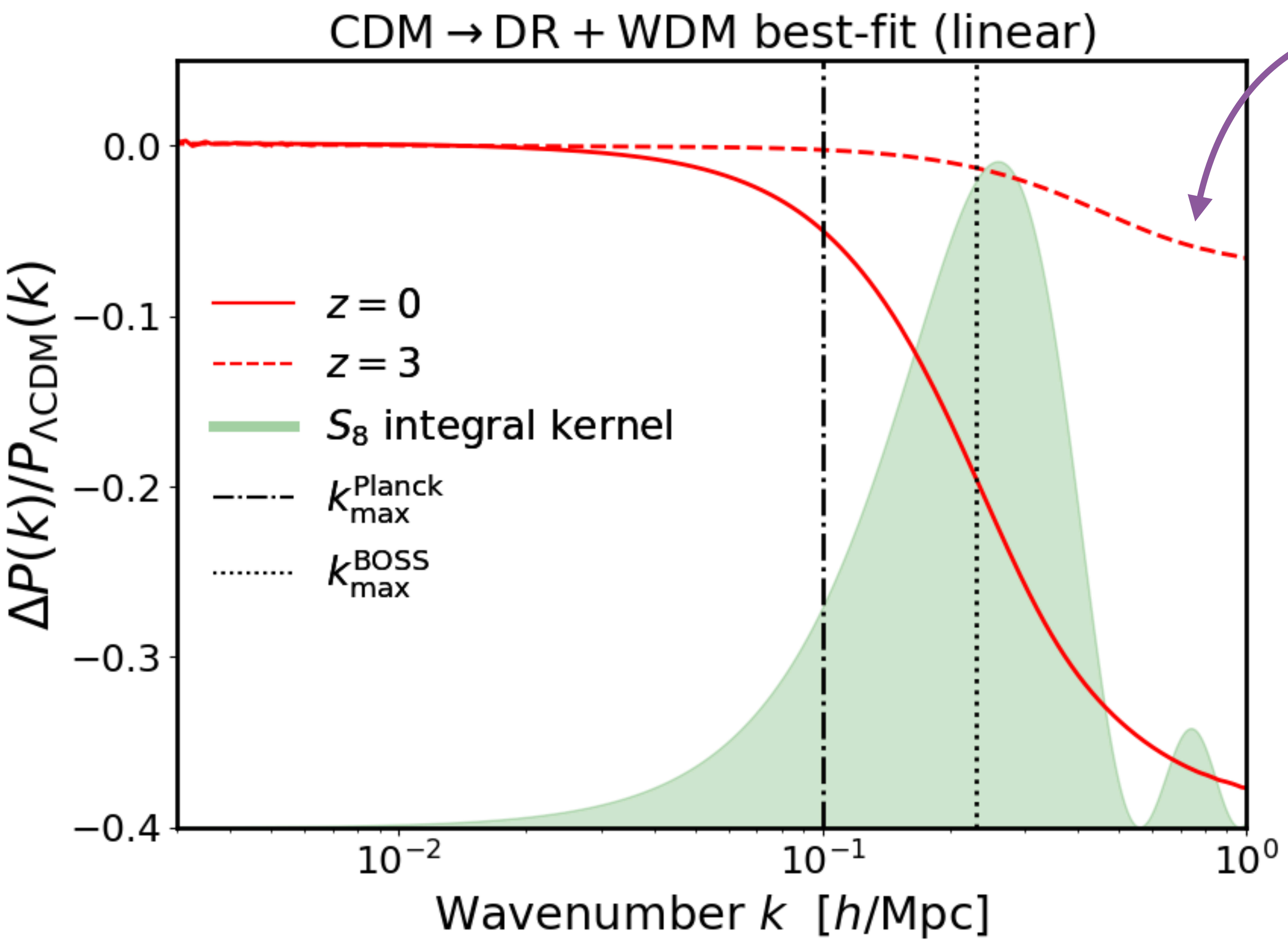
- Can we use this to test DDM?

Part III:

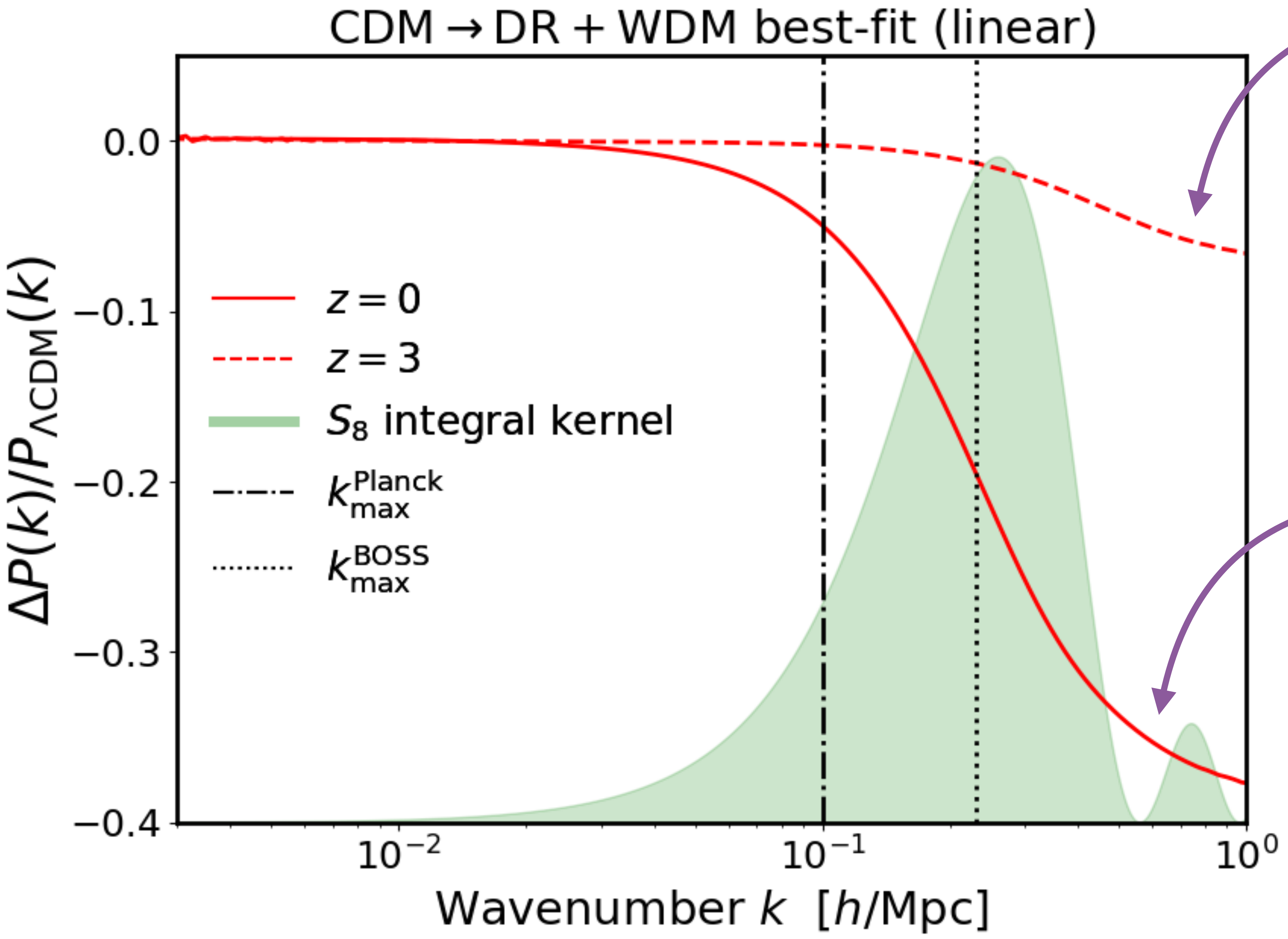
CONSTRAINTS ON DDM FROM EFTofLSS



CDM → DR + WDM best-fit (linear)
0.0
−0.1
−0.2
−0.3
−0.4
$\Delta P(k)/P_{\Lambda\mathrm{CDM}}(k)$
$z=0$
$z=3$
S_8 integral kernel
$k_{\mathrm{max}}^{\mathrm{Planck}}$
$k_{\mathrm{max}}^{\mathrm{BOSS}}$
10^{-2}
10^{-1}
10^{0}
Wavenumber k [h/Mpc]



Lower suppression in the **past**



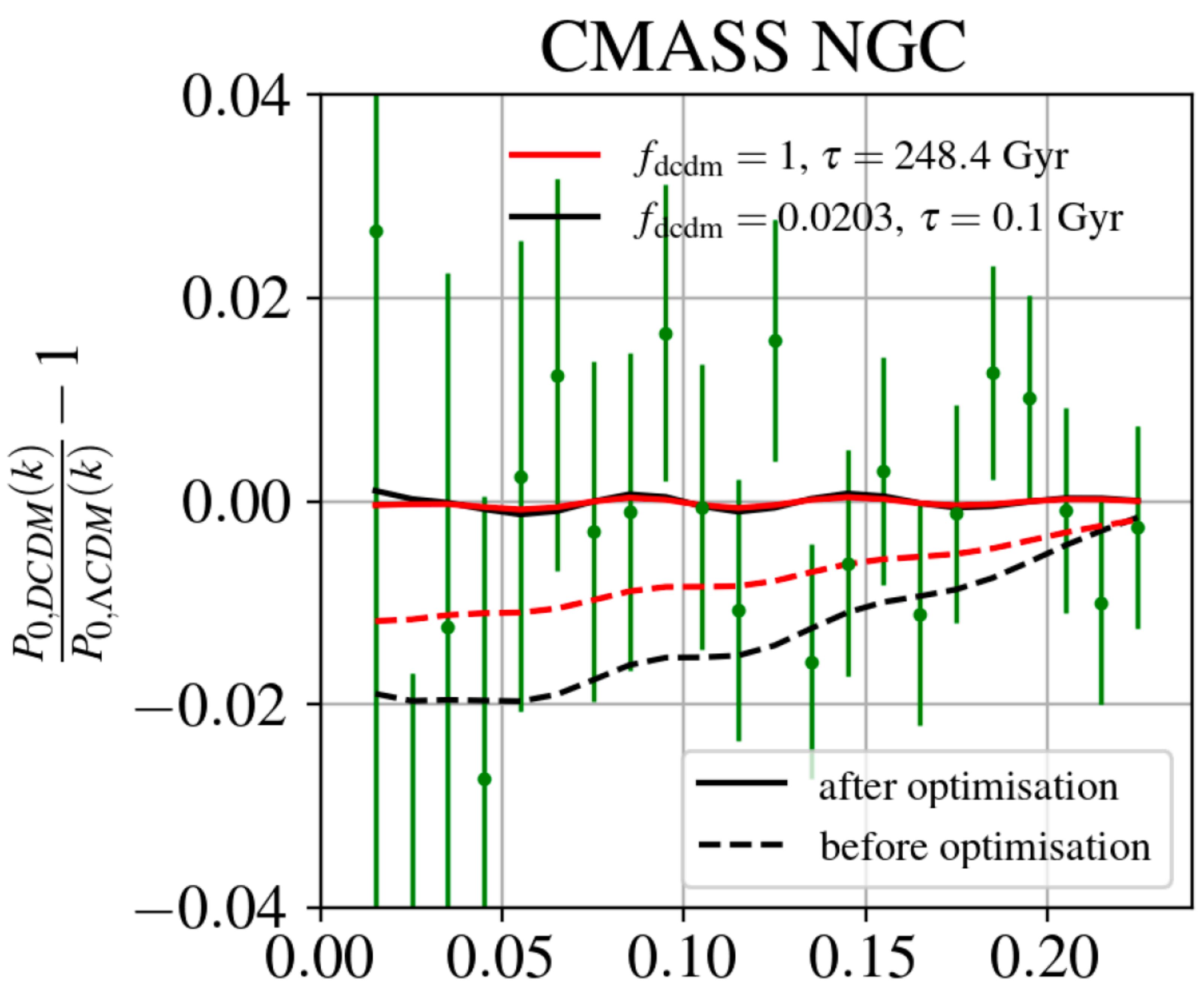
Lower suppression in the **past**

Suppression affects **scales** probed by **BOSS** galaxy data

- Test CDM → DR and CDM → DR + WDM w/ our modified **CLASS** version + **PyBird**

- Test CDM → DR and CDM → DR + WDM w/ our modified `CLASS` version + `PyBird`

- **Beware of nuisance EFT** parameters! Can be **degenerate** with effects of DDM



[Simon, Abellán+ 22]

- Test CDM → DR and CDM → DR + WDM w/ our modified **CLASS** version + **PyBird**

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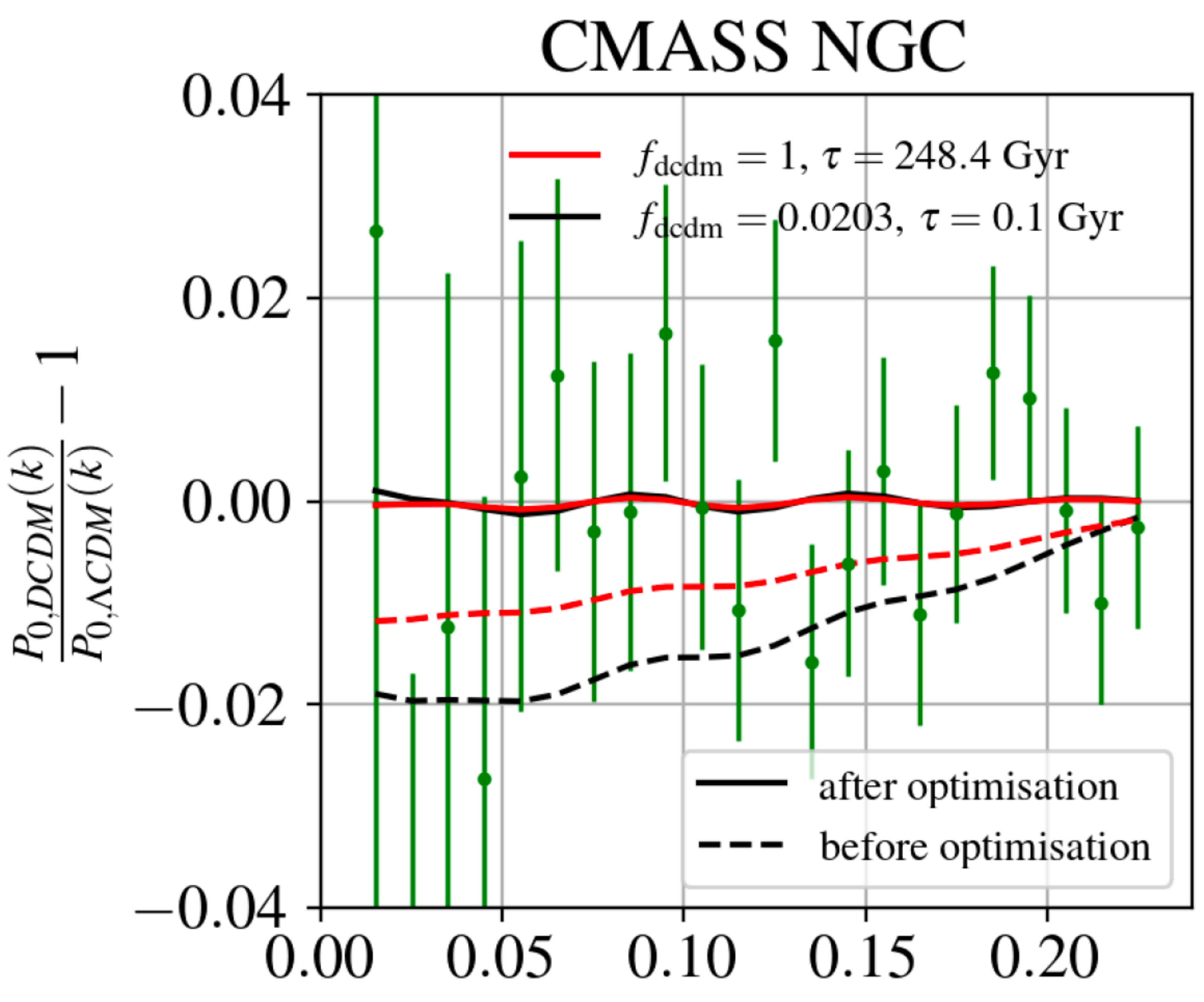
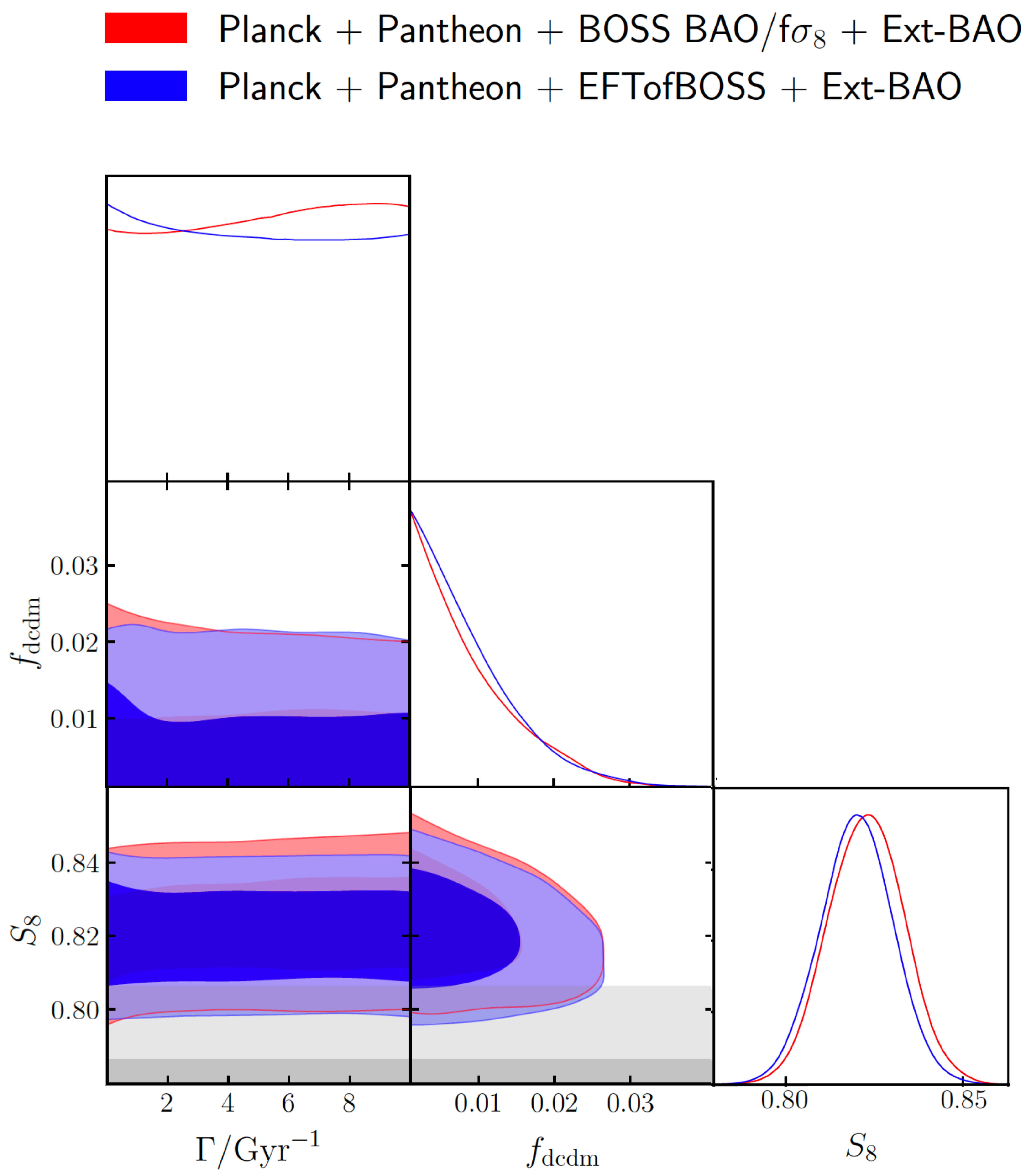
- Compare results with and without EFT



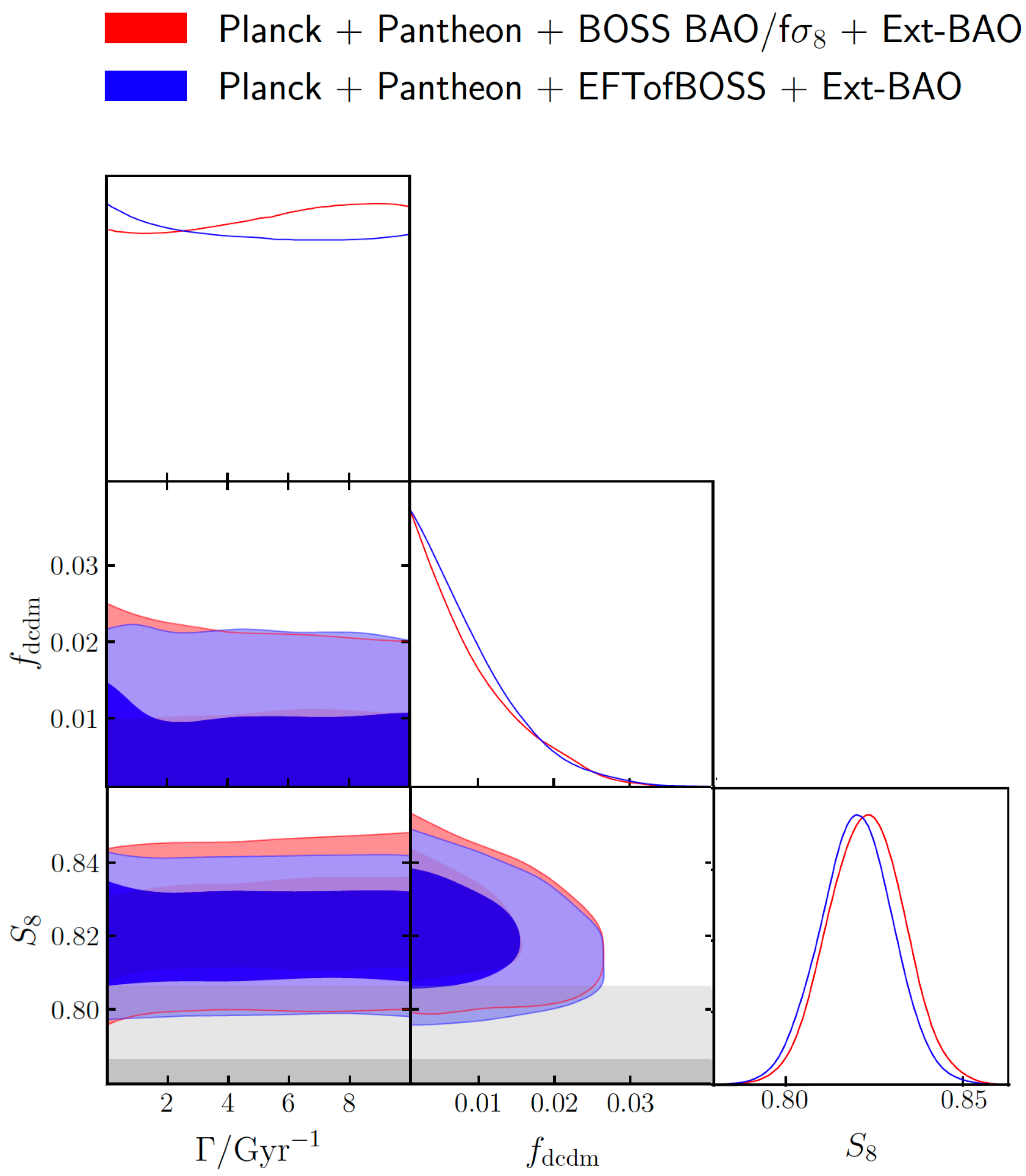
[Simon, Abellán+ 22]

Results for CDM → DR



[Simon, Abellán+ 22]

- EFTofBOSS doesn’t improve the constraints significantly



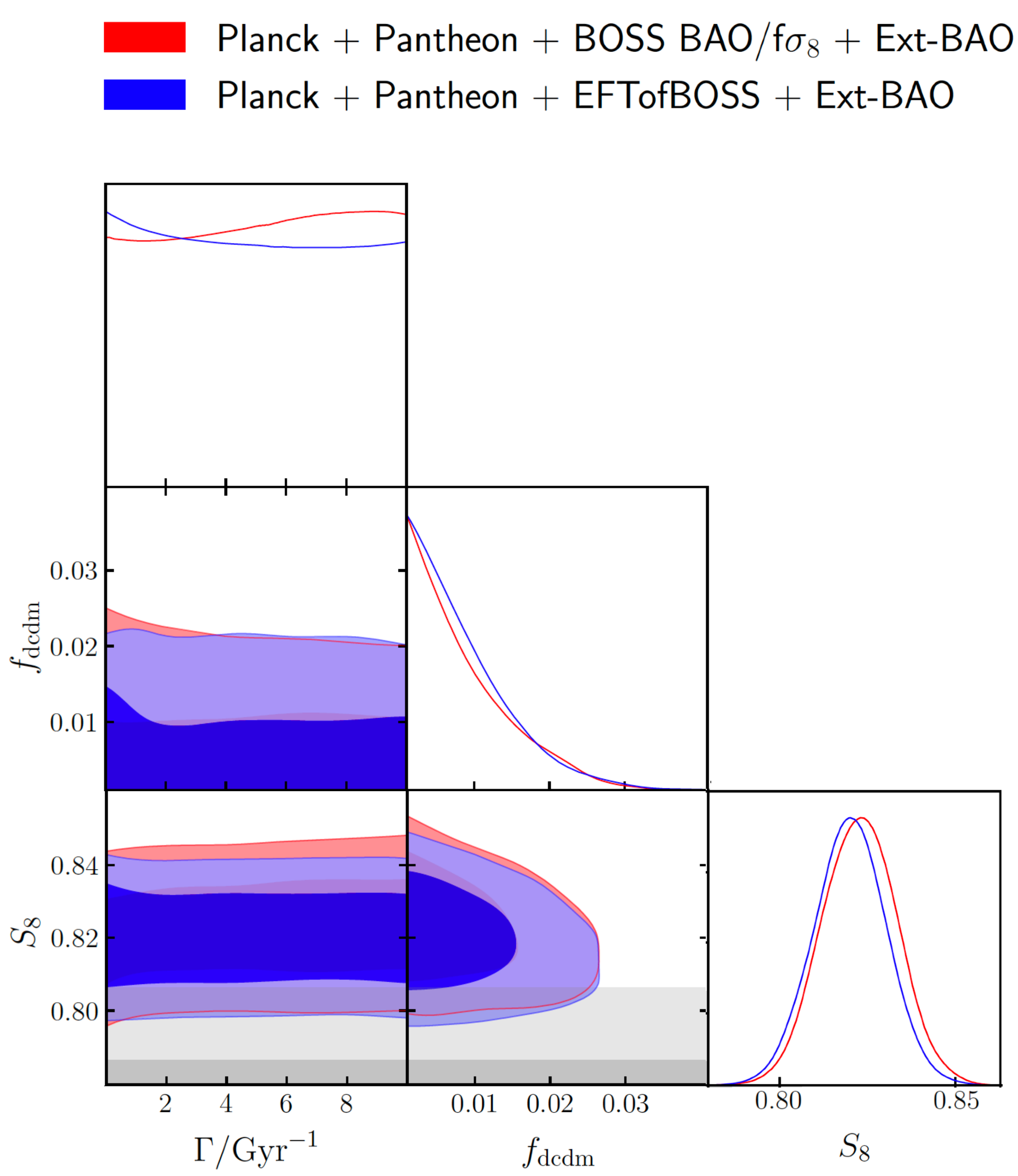
[Simon, Abellán+ 22]

Results for CDM → DR

- EFTofBOSS doesn't improve the constraints significantly
- **Most up-to-date** constraints

$$\tau > 250 \text{ Gyr} \quad \text{for} \quad f_{\rm dcdm} = 1$$

$$f_{\rm dcdm} < 2.16\,\% \quad \text{for} \quad \tau < t_U$$



[Simon, Abellán+ 22]

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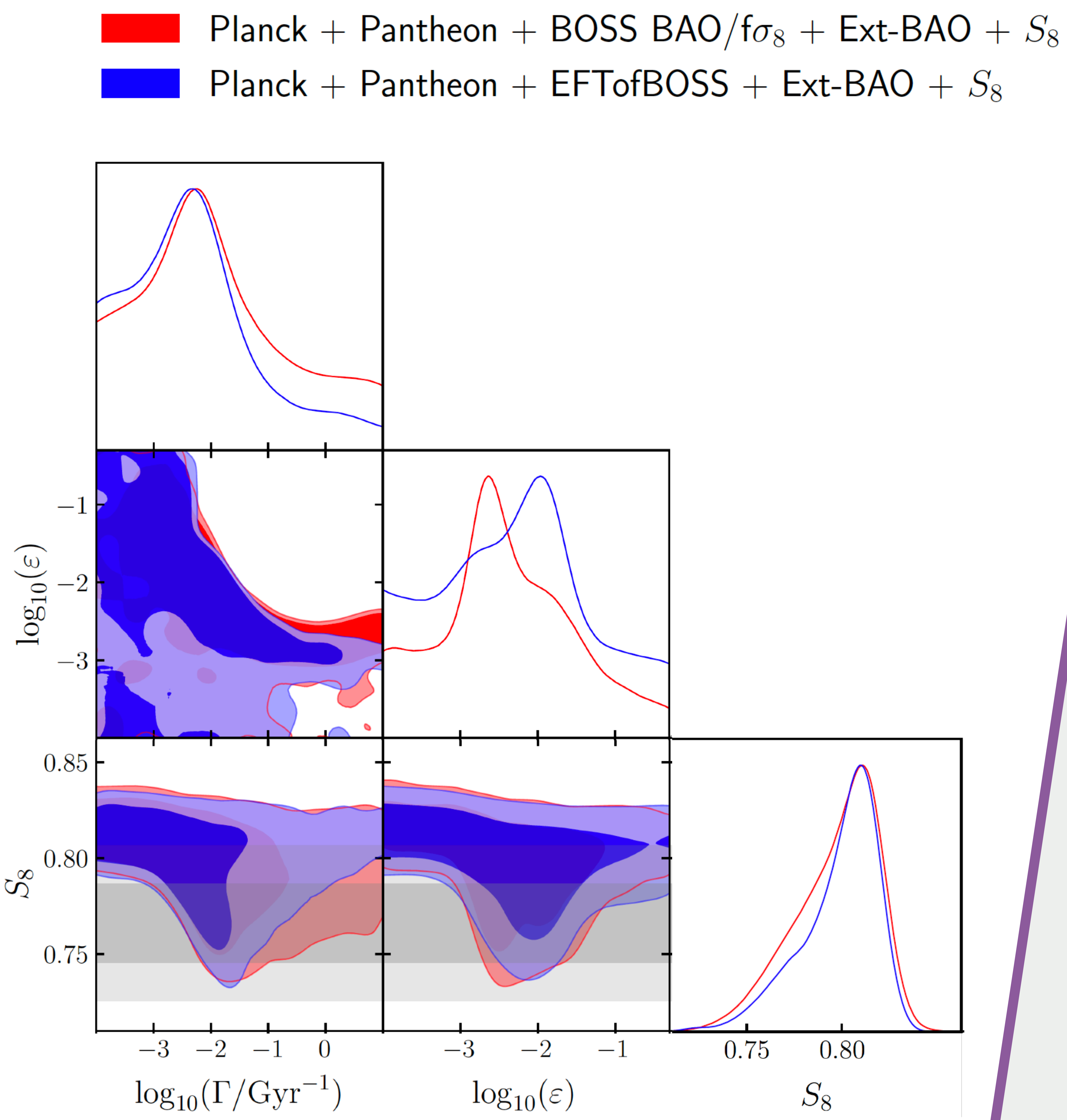
- We confirm that this model does **not resolve** the S_8 tension

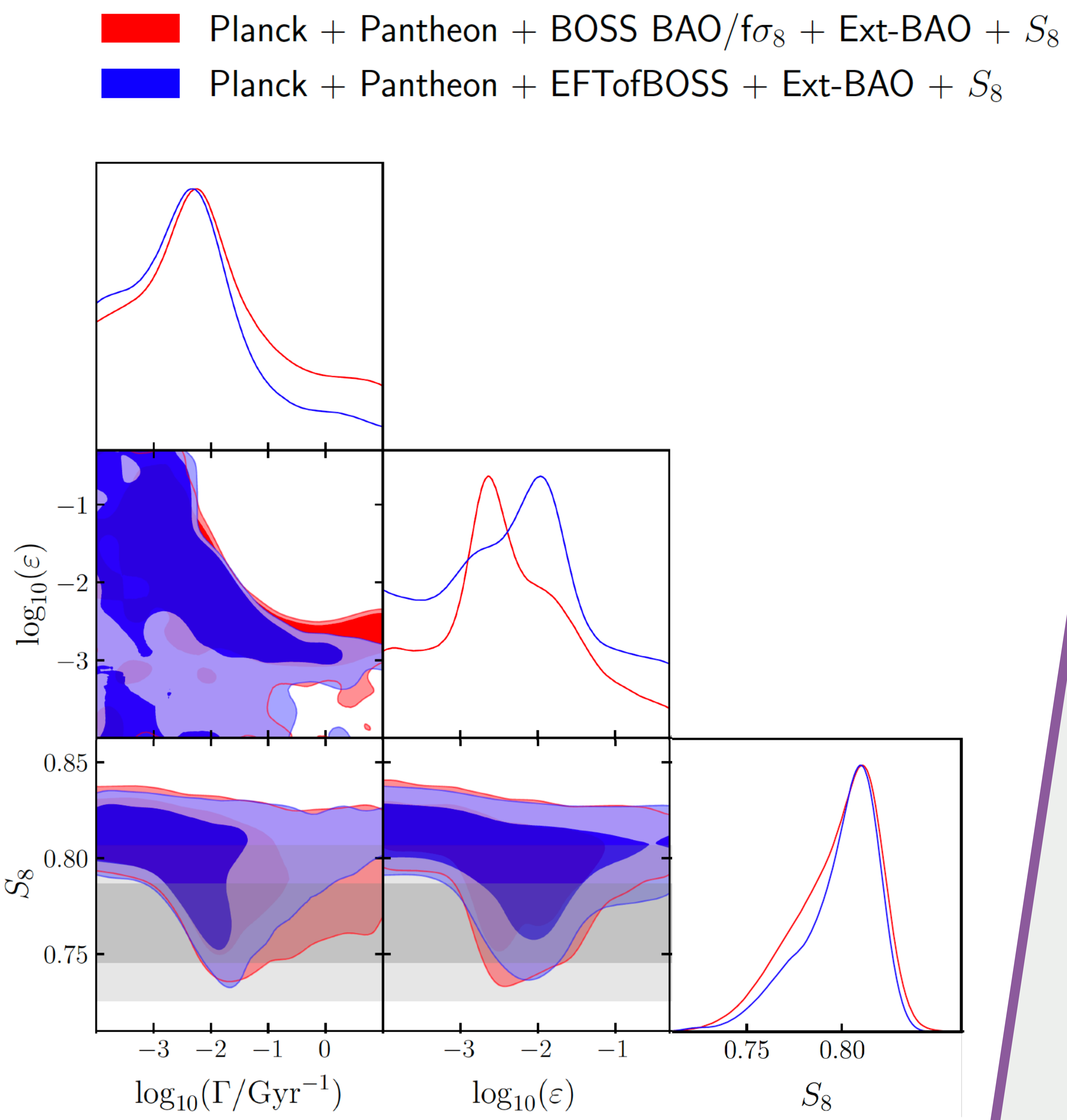


[Simon, Abellán+ 22]

Results for CDM → DR + WDM

- This model can **still resolve** the S_8 tension

Results for CDM → DR + WDM

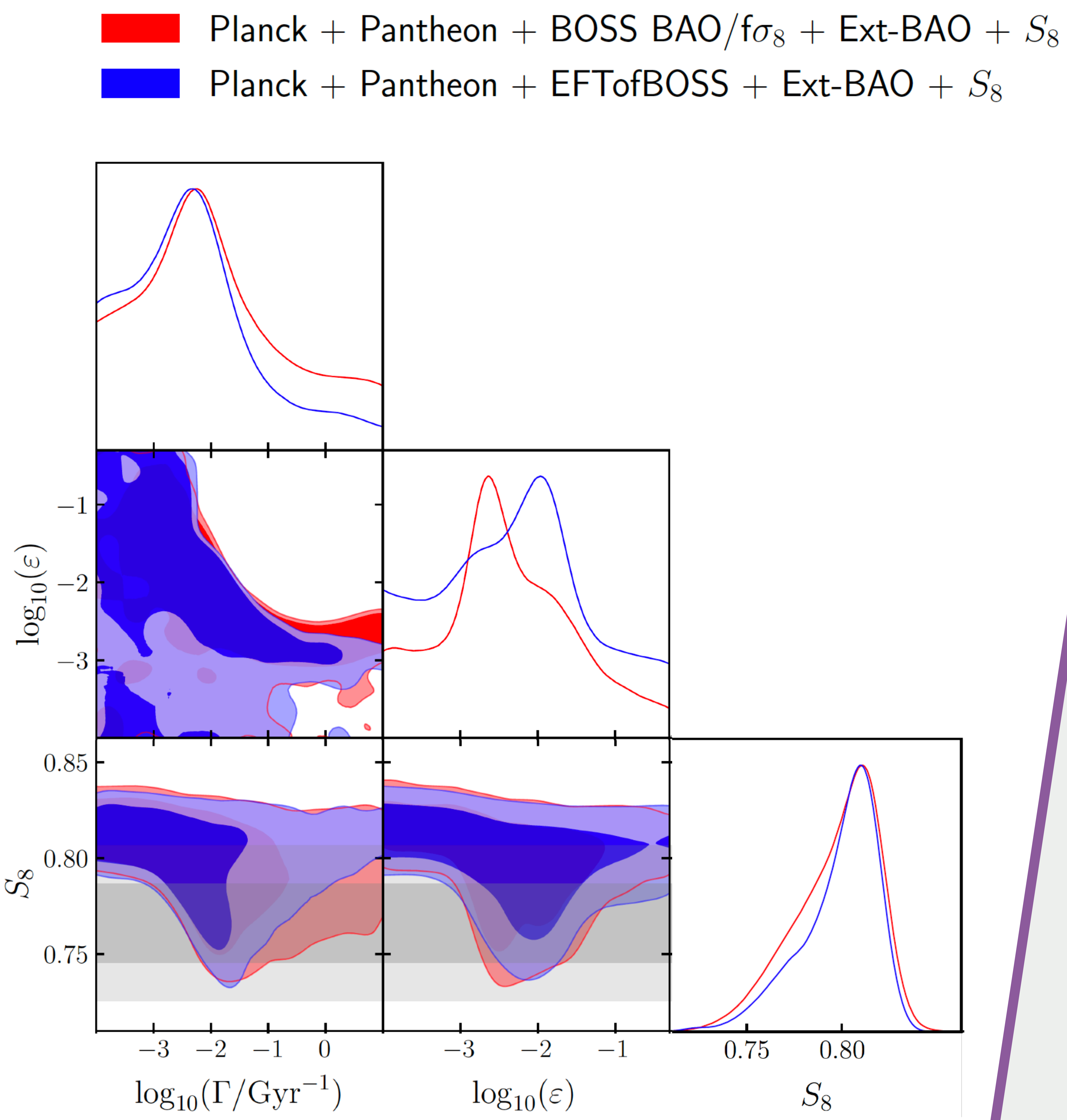


[Simon, Abellán+ 22]

- This model can **still resolve** the S_8 tension
- EFTofBOSS **improves constraints** on the lifetime

$$1.3 < \log_{10}(\tau/\mathrm{Gyr}) < 3.8 \text{ without EFT}$$

$$1.6 < \log_{10}(\tau/\mathrm{Gyr}) < 3.7 \text{ with EFT}$$



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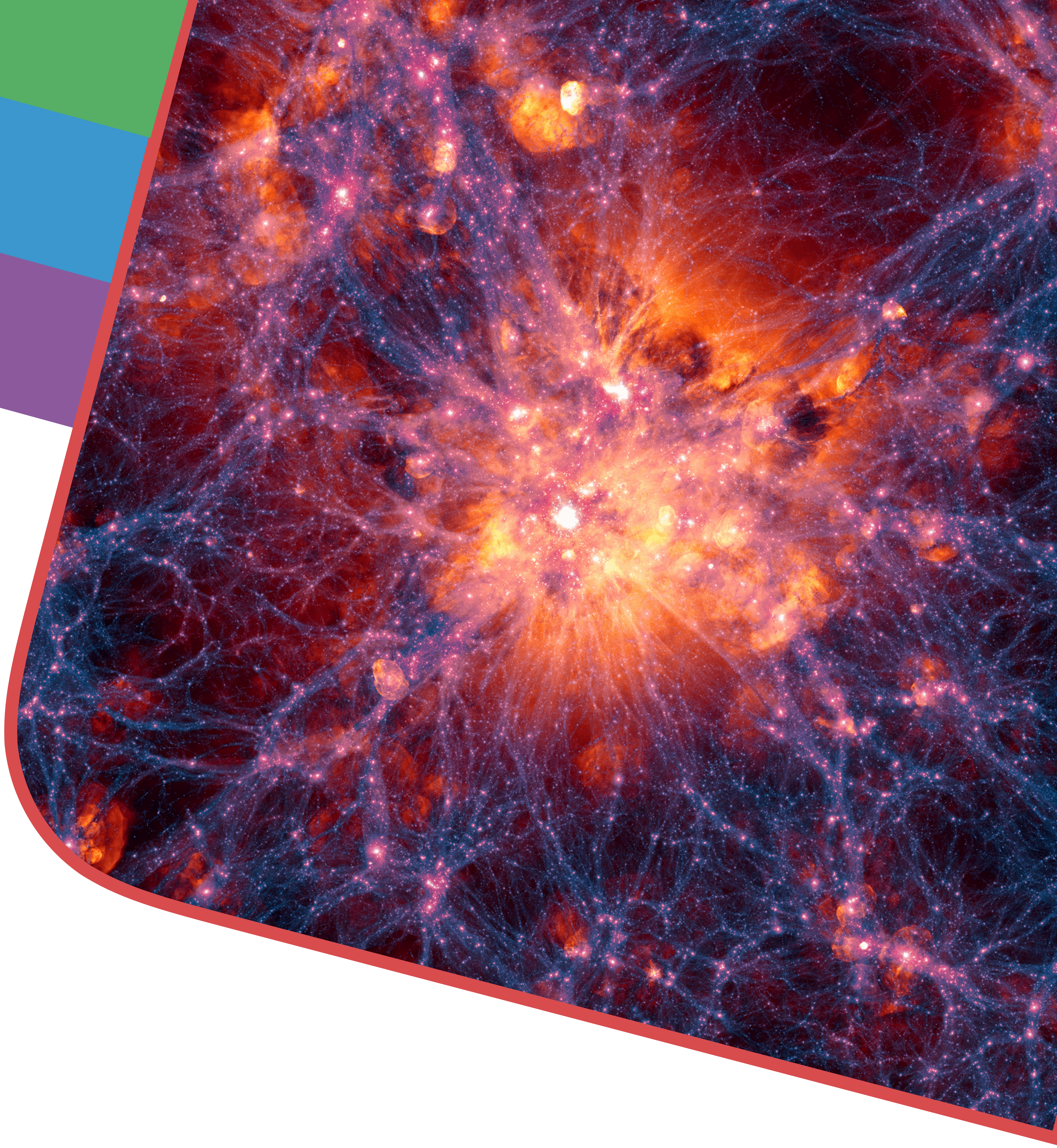
- It changes the best-fit

$$\tau = 55 \text{ Gyr} \longrightarrow \tau = 120 \text{ Gyr}$$

$$\varepsilon = 0.7\,\% \longrightarrow \varepsilon = 1.2\,\%$$

Conclusions

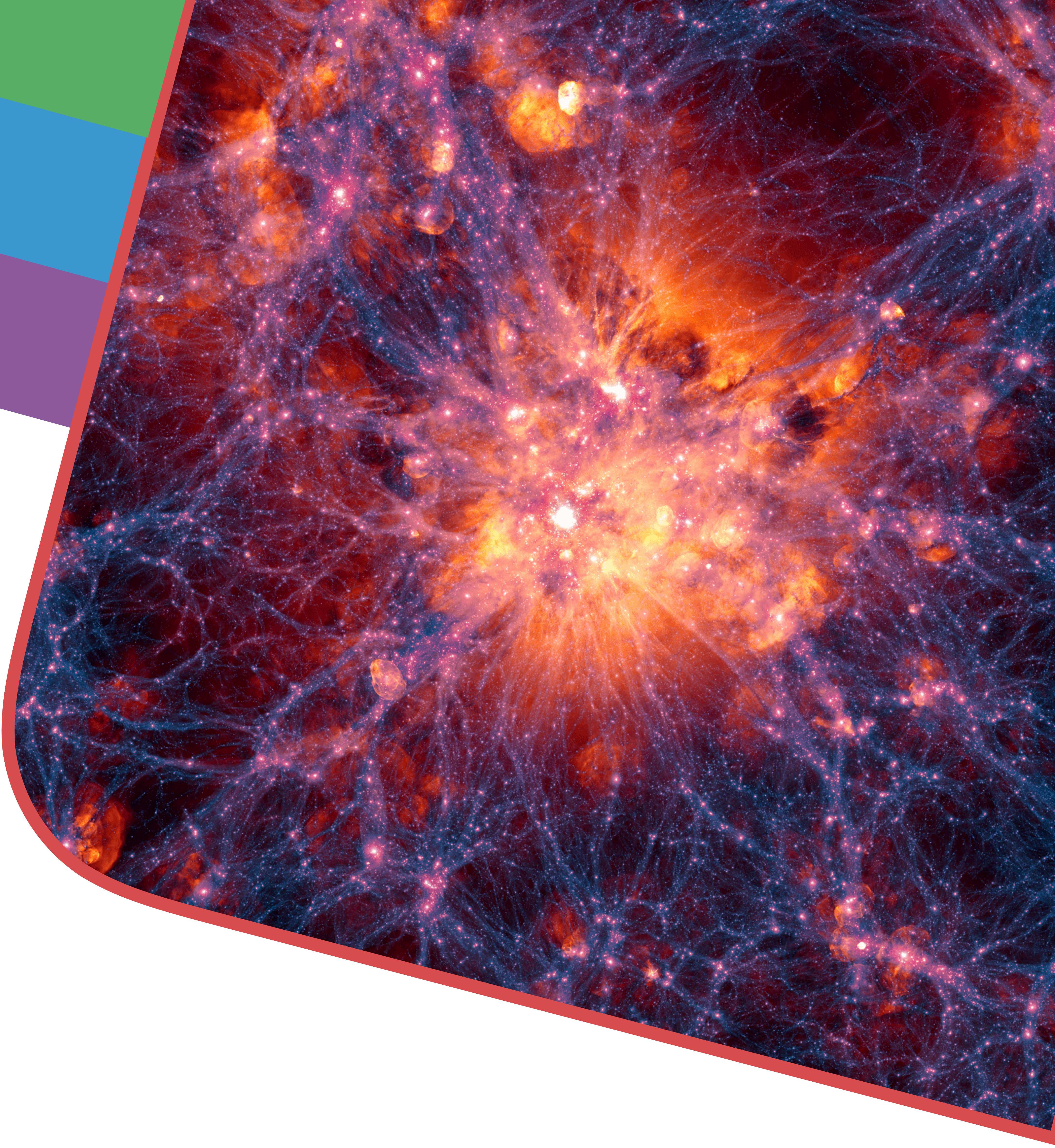
- **EFTofLSS** applied to BOSS data can have **constraining power** on ΛCDM extensions



Conclusions

- **EFTofLSS** applied to BOSS data can have **constraining power** on ΛCDM extensions

- We derived **most up-to-date** constraints on two **DDM** scenarios, which are relevant for **model building** and the **S_8 tension**

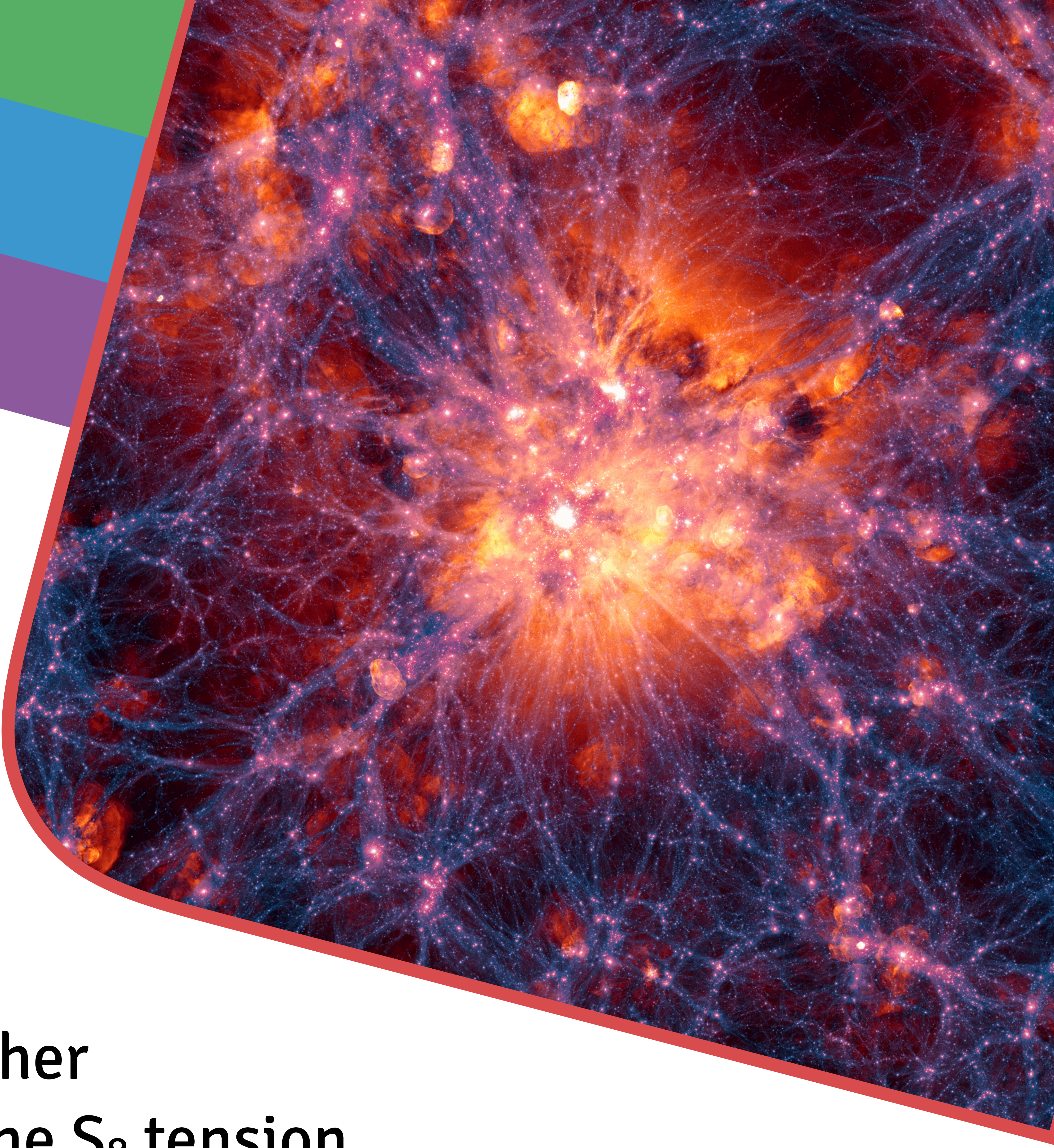


Conclusions

- **EFTofLSS** applied to BOSS data can have **constraining power** on ΛCDM extensions

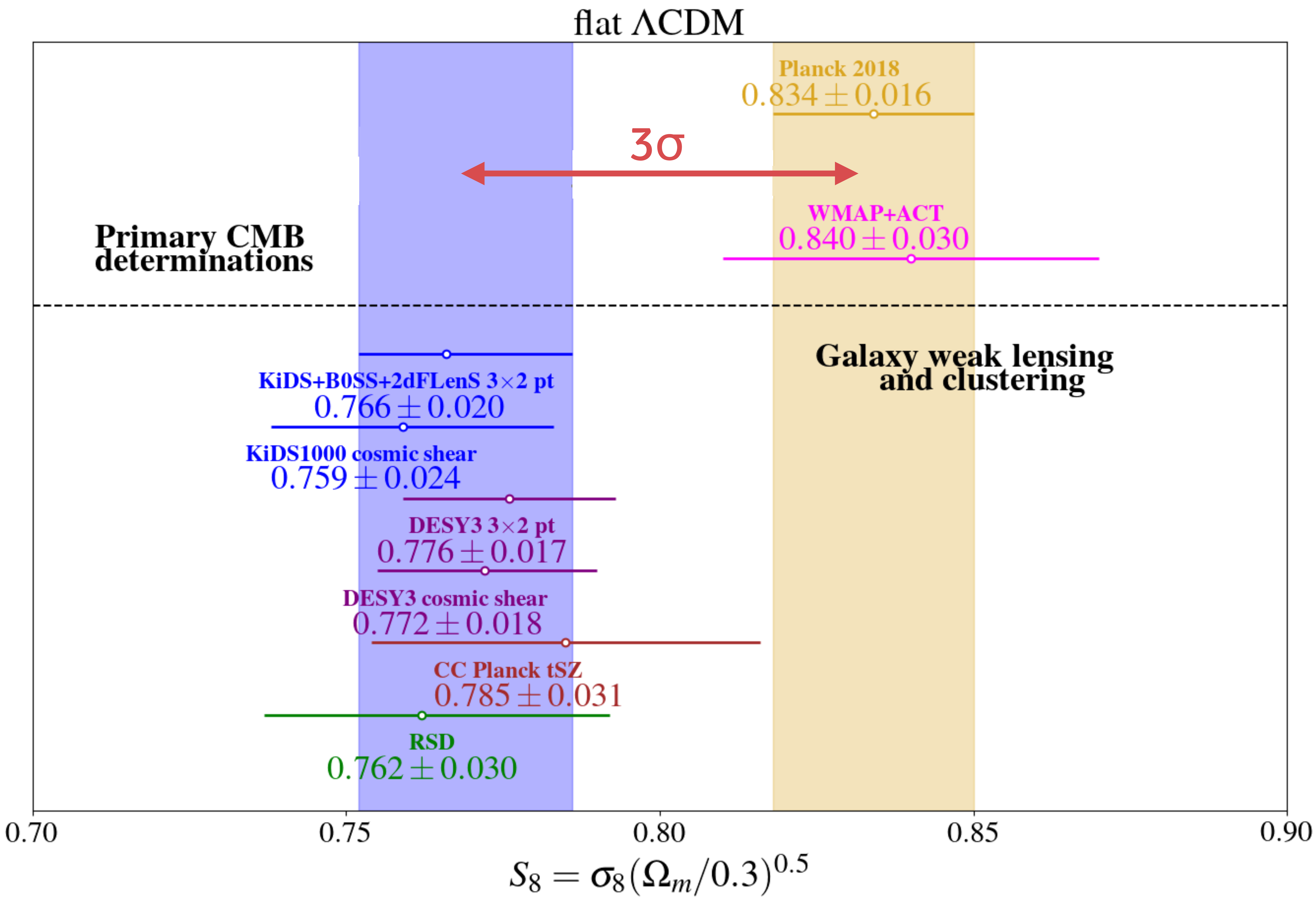
- We derived **most up-to-date** constraints on two **DDM** scenarios, which are relevant for **model building** and the **S_8 tension**

- **Future LSS** data (at small z) **will probe** further the **CDM → DR + WDM** model that solves the S_8 tension



BACK-UP

A closer look at the S_8 tension



Evolution of DDM perturbations

- Track $\boldsymbol{\delta_i}$, $\boldsymbol{\theta_i}$ **and** $\boldsymbol{\sigma_i}$ for i= CDM, DR, WDM

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

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

$$\theta'_{\rm wdm} = -aH(1-3c_a^2)\theta_{\rm wdm} + \frac{c_{\rm syn}^2}{1+w}k^2\delta_{\rm wdm} - k^2\sigma_{\rm wdm} - a\Gamma(1-\varepsilon)\frac{\bar{\rho}_{\rm dm}}{\bar{\rho}_{\rm wdm}}\frac{1+c_a^2}{1+w}\theta_{\rm wdm}$$

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

Other LSS probes to test CDM → DR + WDM

- **Reduction** in the abundance of **subhalos**, can be constrained by observations of **MW satellites** [DES 22]

- Model well compatible with **Lyman-α forest data**, given time-dependence of power suppression [Fuss, Garny 22]

- Can also be probed by looking at **abundance of clusters** detected with the **Sunyaev Zel'dovich** effect [Tanimura+ 23]

EFTofLSS parameters

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

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

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

4 parameters to describe **galaxy bias**

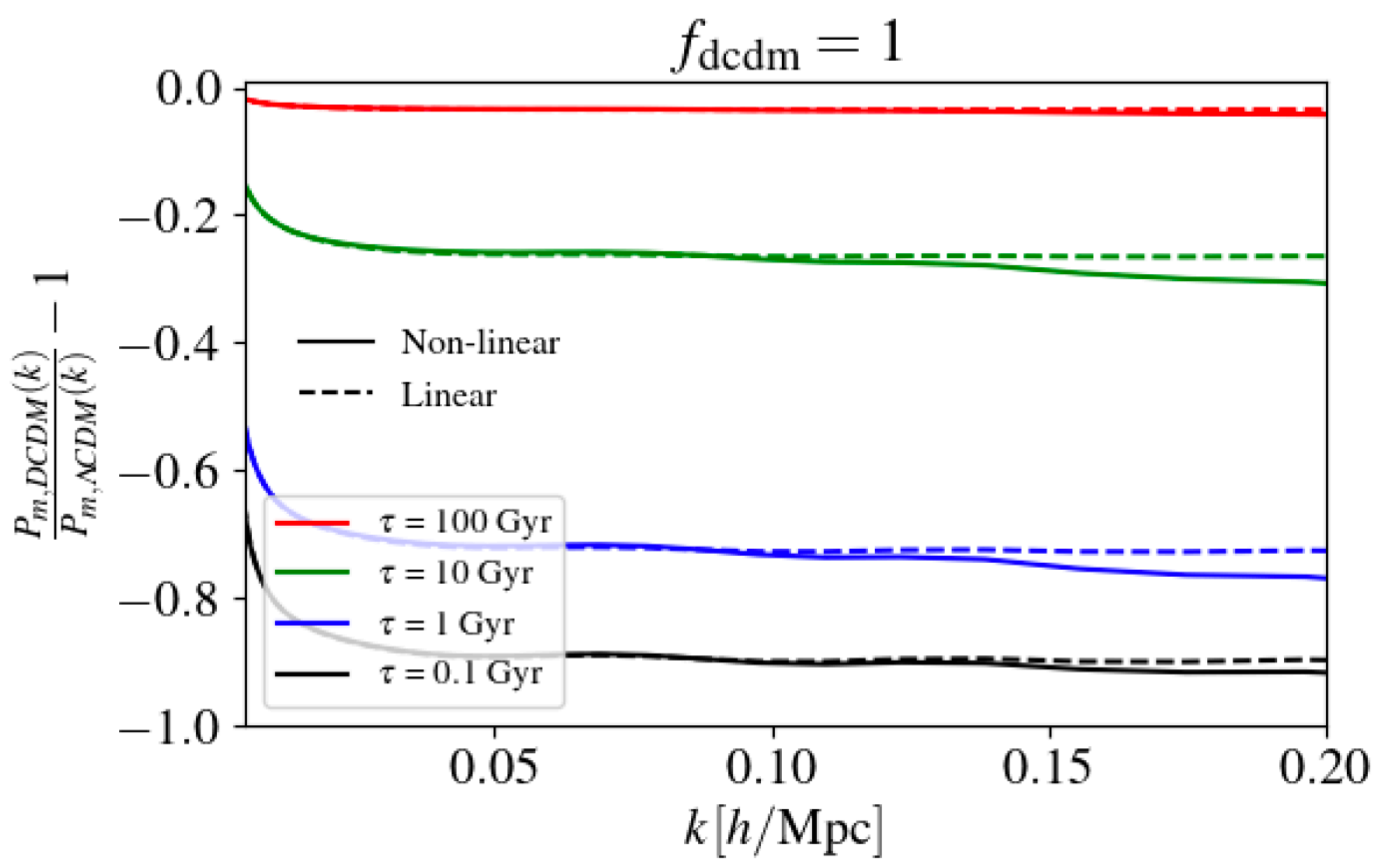
3 parameters to describe **counterterms**

3 parameters to describe **stochastic terms**

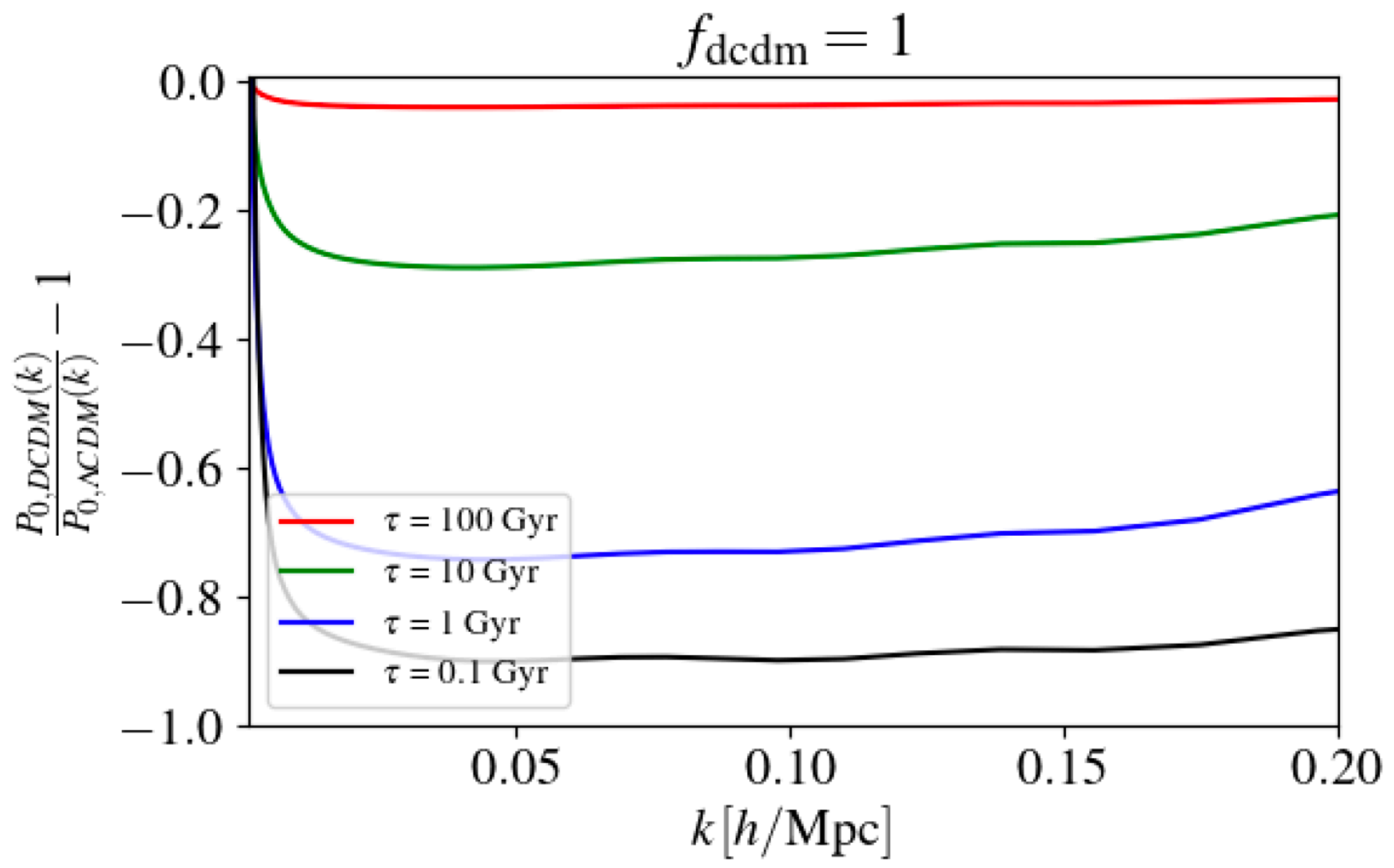
10 parameters in total,
but 8 are analytically marginalized

Matter and galaxy power spectra for CDM → DR

Matter power spectrum



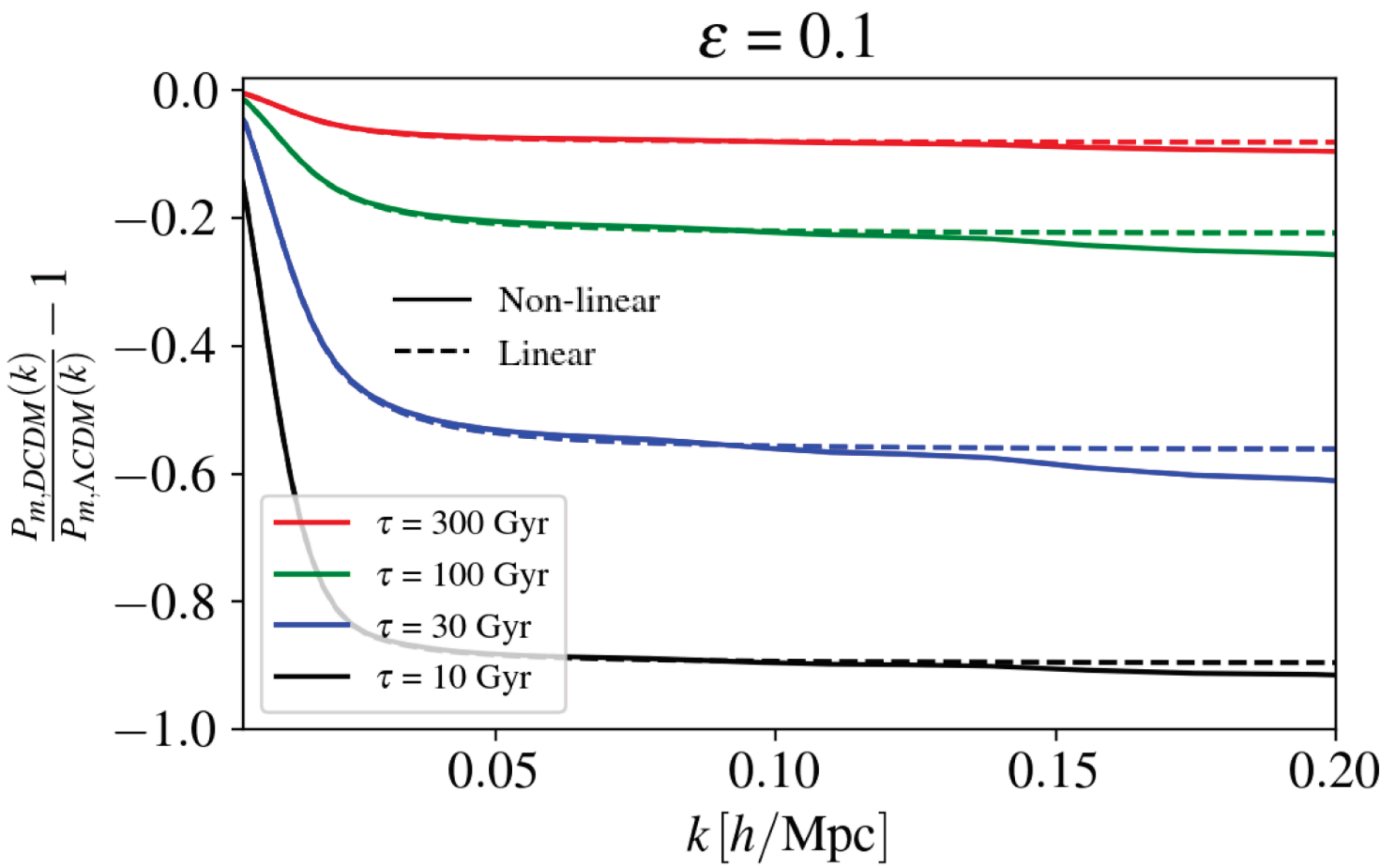
Galaxy spectrum (monopole)



[Simon, Abellán+ 22]

Matter and galaxy power spectra for CDM → DR + WDM

Matter power spectrum



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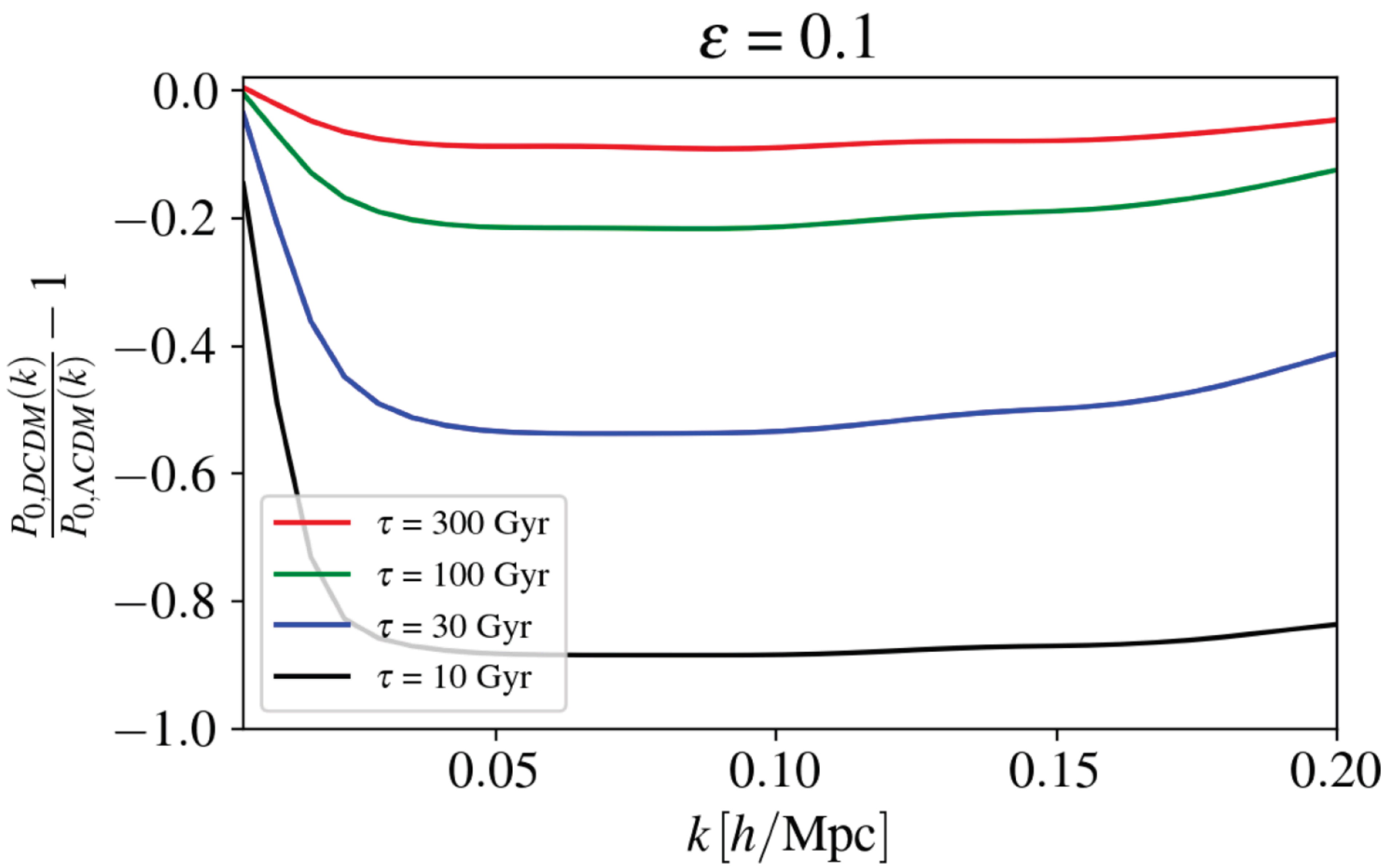
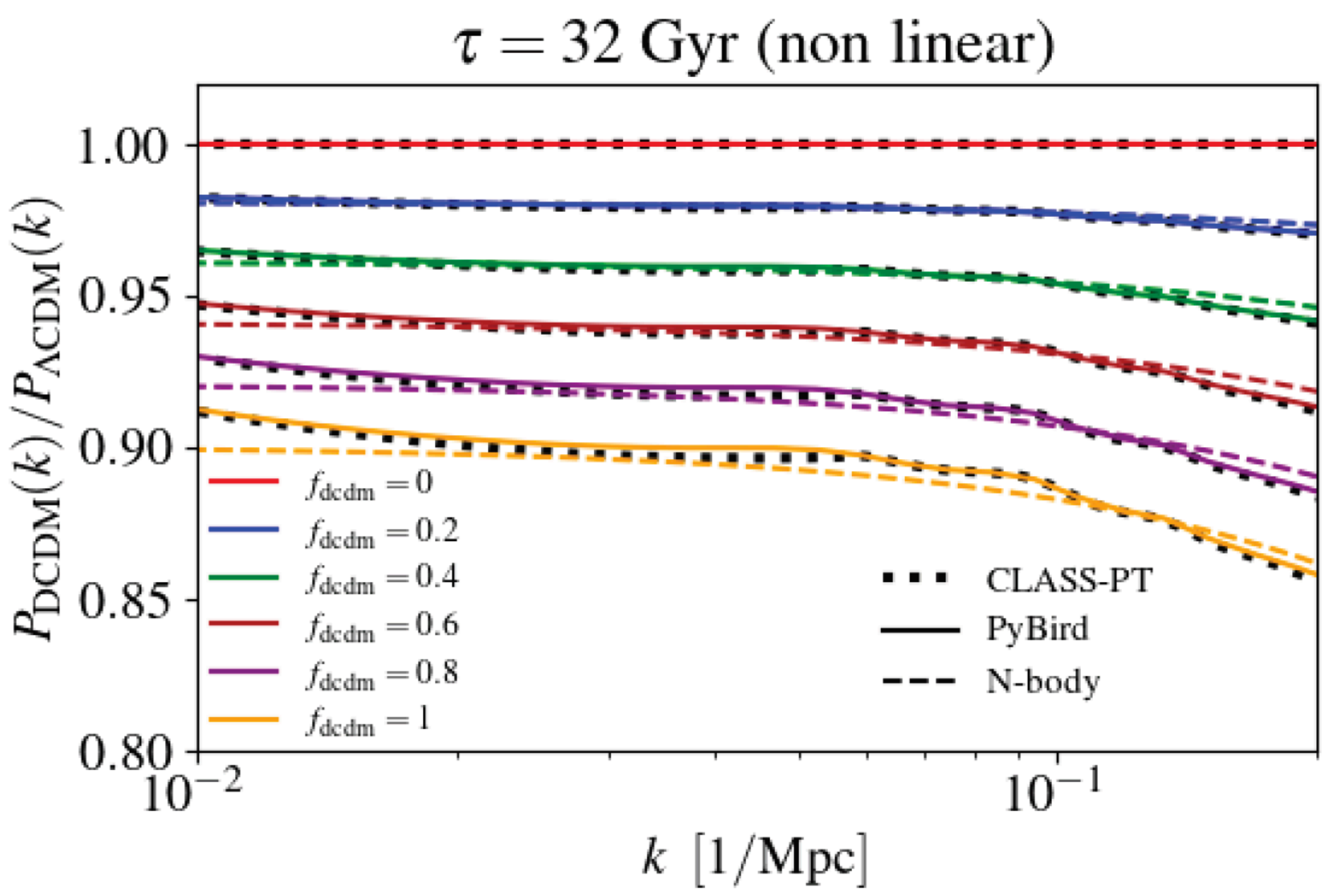


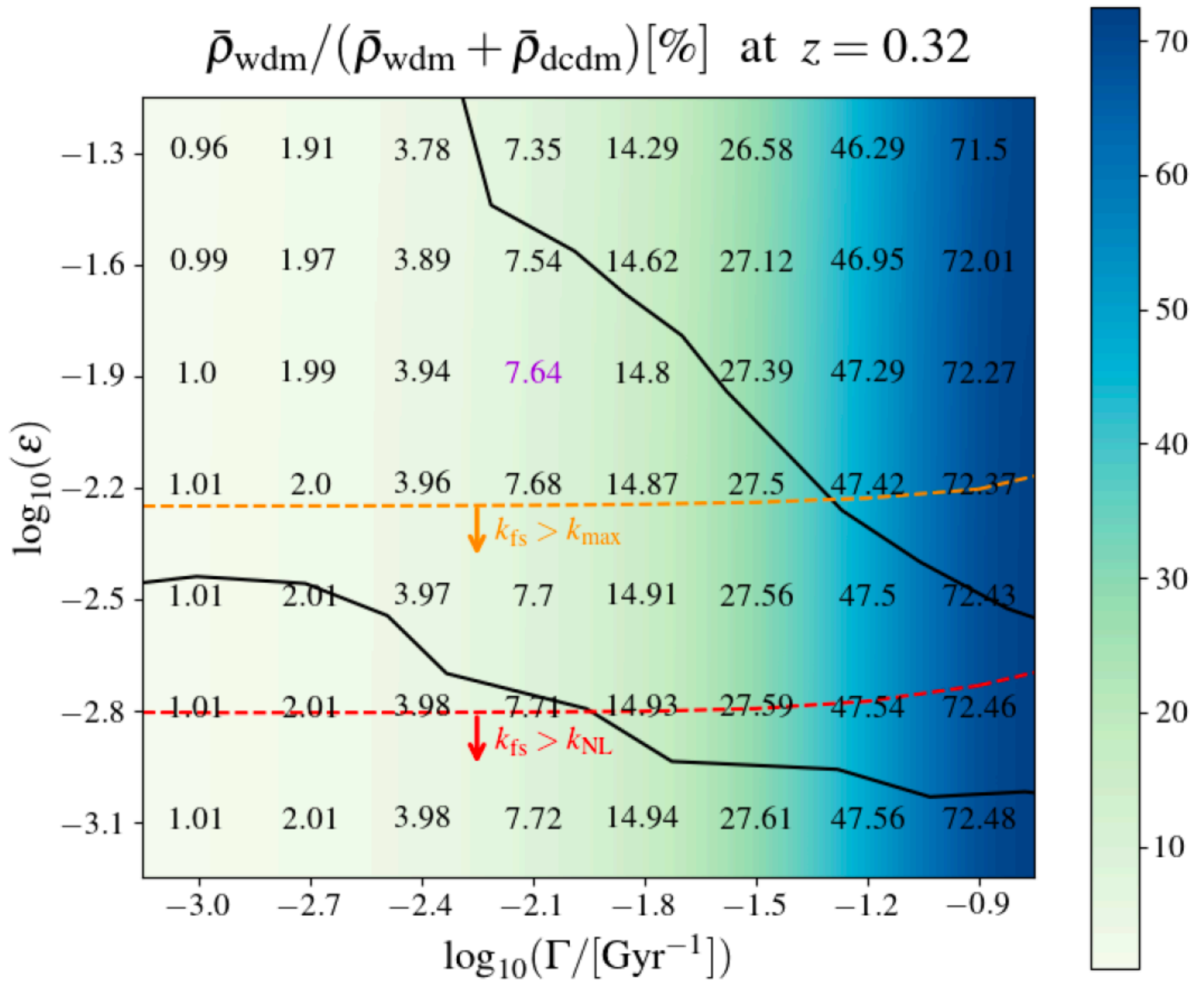
[Simon, Abellán+ 22]

Checking validity of EFTofLSS applied to DDM

CDM → DR



CDM → DR + WDM



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