Cosmological anomalies shedding light on the dark sector

Guillermo Franco Abellán
Laboratoire Univers et Particules de Montpellier

Based on:

arXiv:2102.12498 (PRD in press)

arXiv:2008.09615 (PRD in press)

arXiv:2009.10733 PRD 103 (2020)

arXiv:2107.10291, submitted to Physics Reports

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II. The H_0 tension vs. Early Dark Energy

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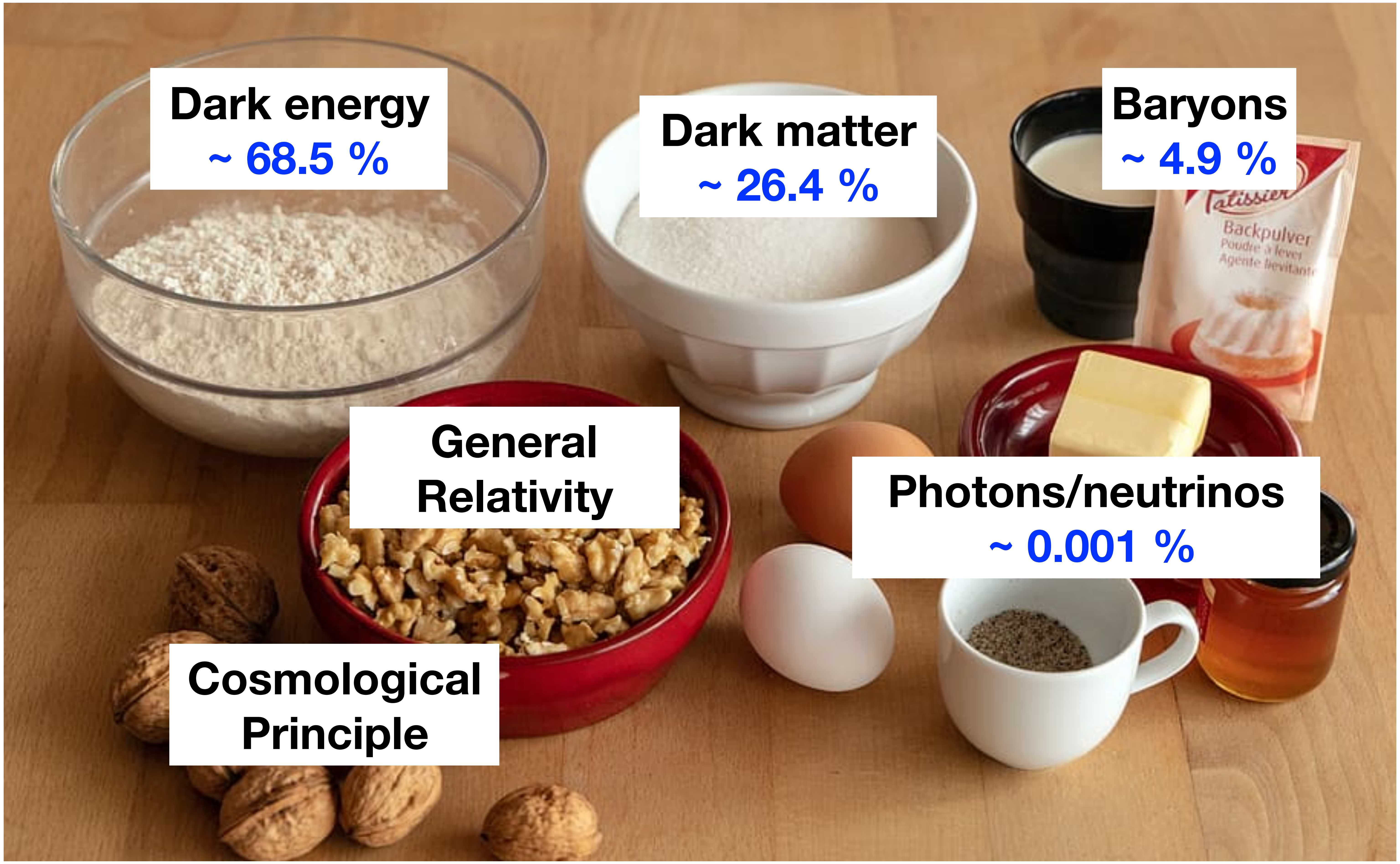
I. Cosmic concordance and discordance

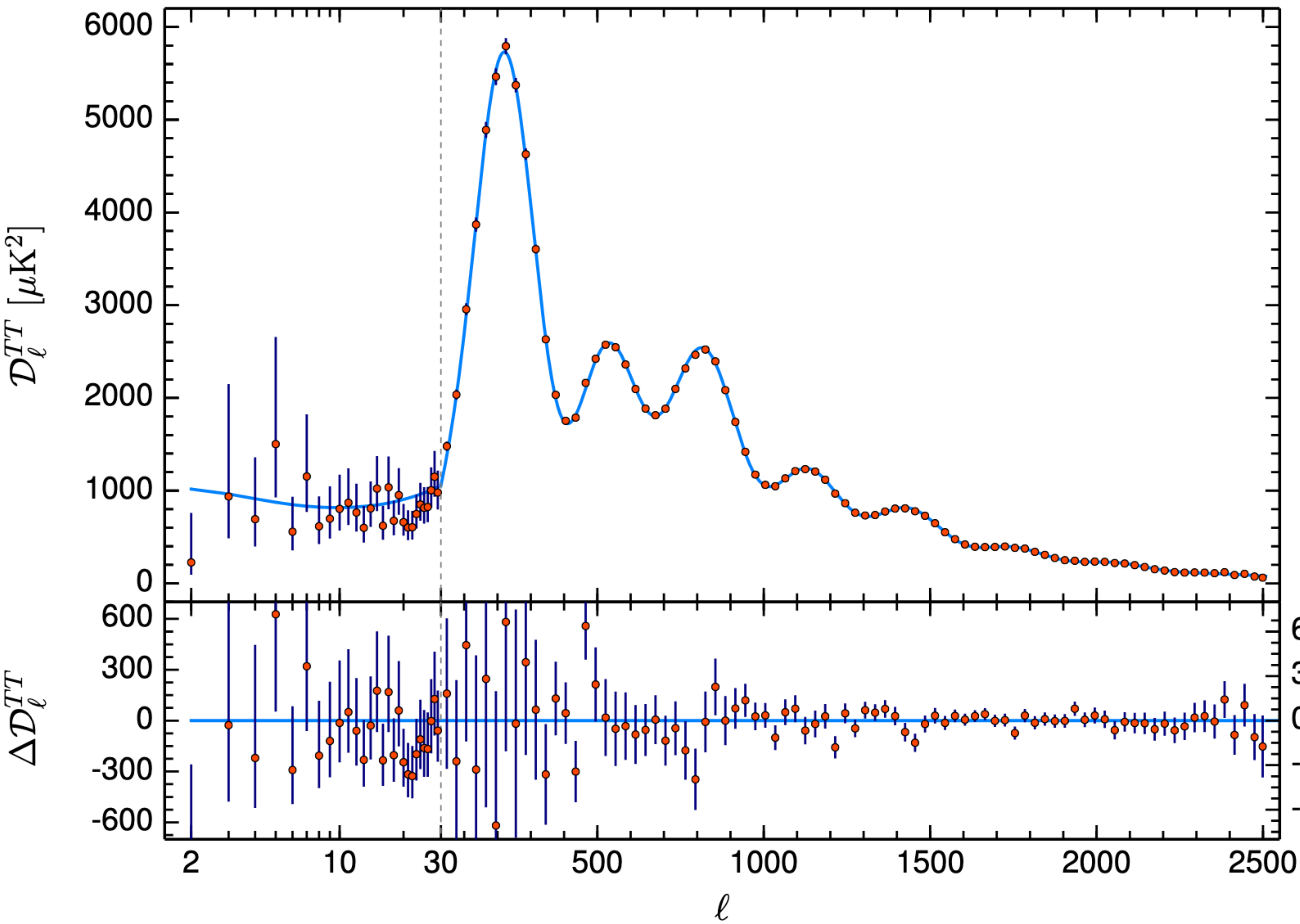
Cosmic recipe



ΛCDM model fully specified by $\left\{\Omega_c,\ \Omega_b,\ H_0,\ A_s,\ n_s,\ \tau_{reio}\right\}$

The era of precision cosmology

ΛCDM gives excellent fit to CMB anisotropy spectra



Planck 2018, 1807.06209

The era of precision cosmology

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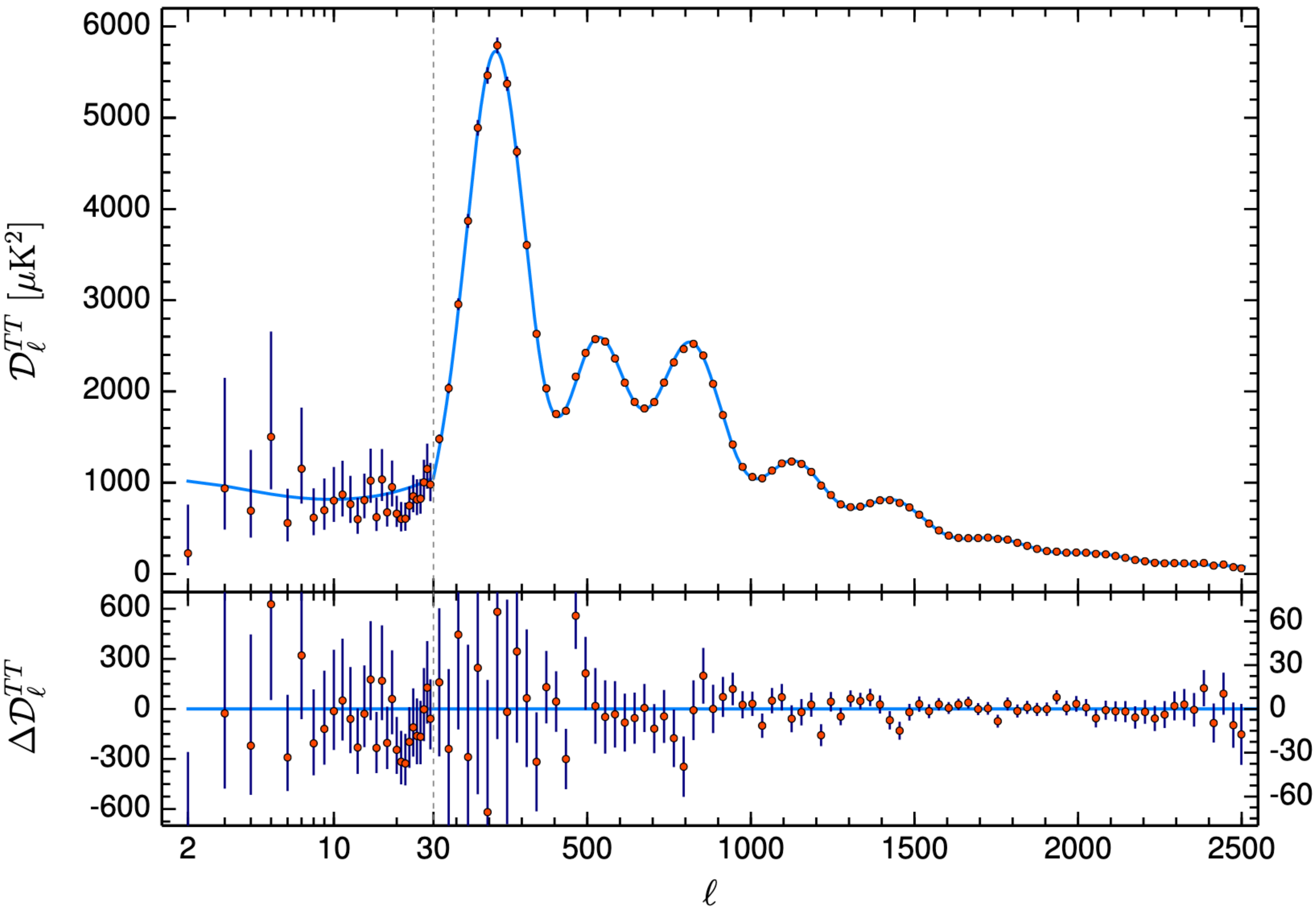

Planck 2018, 1807.06209

Also explains:

- Baryon acoustic oscillations,
- Supernovae Ia,
- Light element abundances,
- Large Scale Structure, etc

Challenges to the ΛCDM paradigm

1. What is dark matter? And dark energy?

- Are they made of **particles**?
- Are they made of **single species**?
- How are they **produced**?
- What is their **lifetime**?
- And their **mass**?

Challenges to the ΛCDM paradigm

2. Several discrepancies emerged in recent years

- S_8 with weak-lensing data
  KiDS-1000 2007.15632

- H_0 with local measurements
  Riess++ 2012.08534

Challenges to the ΛCDM paradigm

2. Several discrepancies emerged in recent years

- S_8 with weak-lensing data
  KiDS-1000 2007.15632

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Unaccounted systematics?

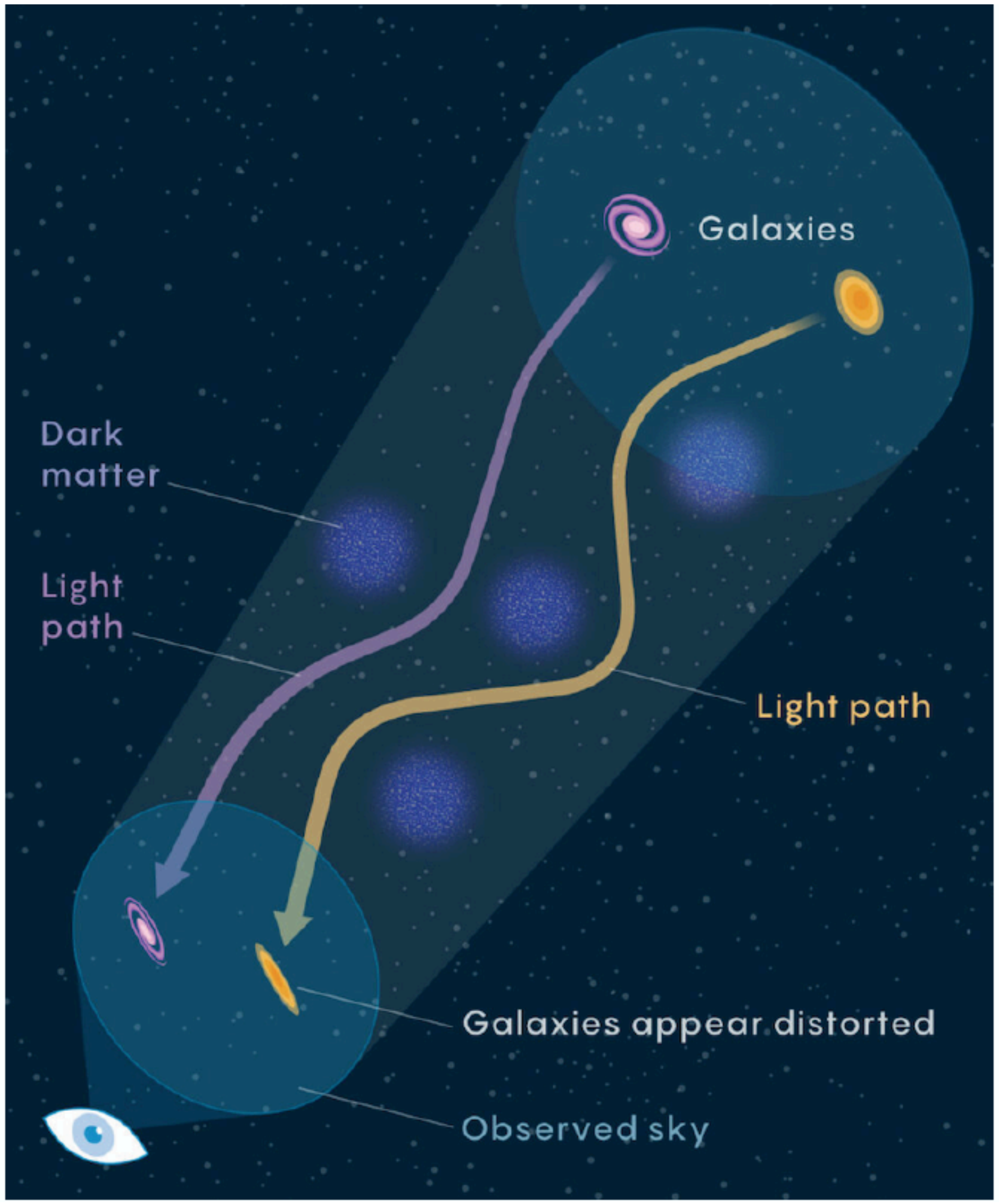
- Less exotic explanation ✅
- Difficult to account for all discrepancies ❌

Physics beyond ΛCDM?

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

The S_8 tension

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



where $\sigma_8 = \int \mathrm{P_m(k, z=0)W_R^2(k)dlnk}$

KiDS+BOSS+2dfLenS*:

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

Planck (*under ΛCDM*):

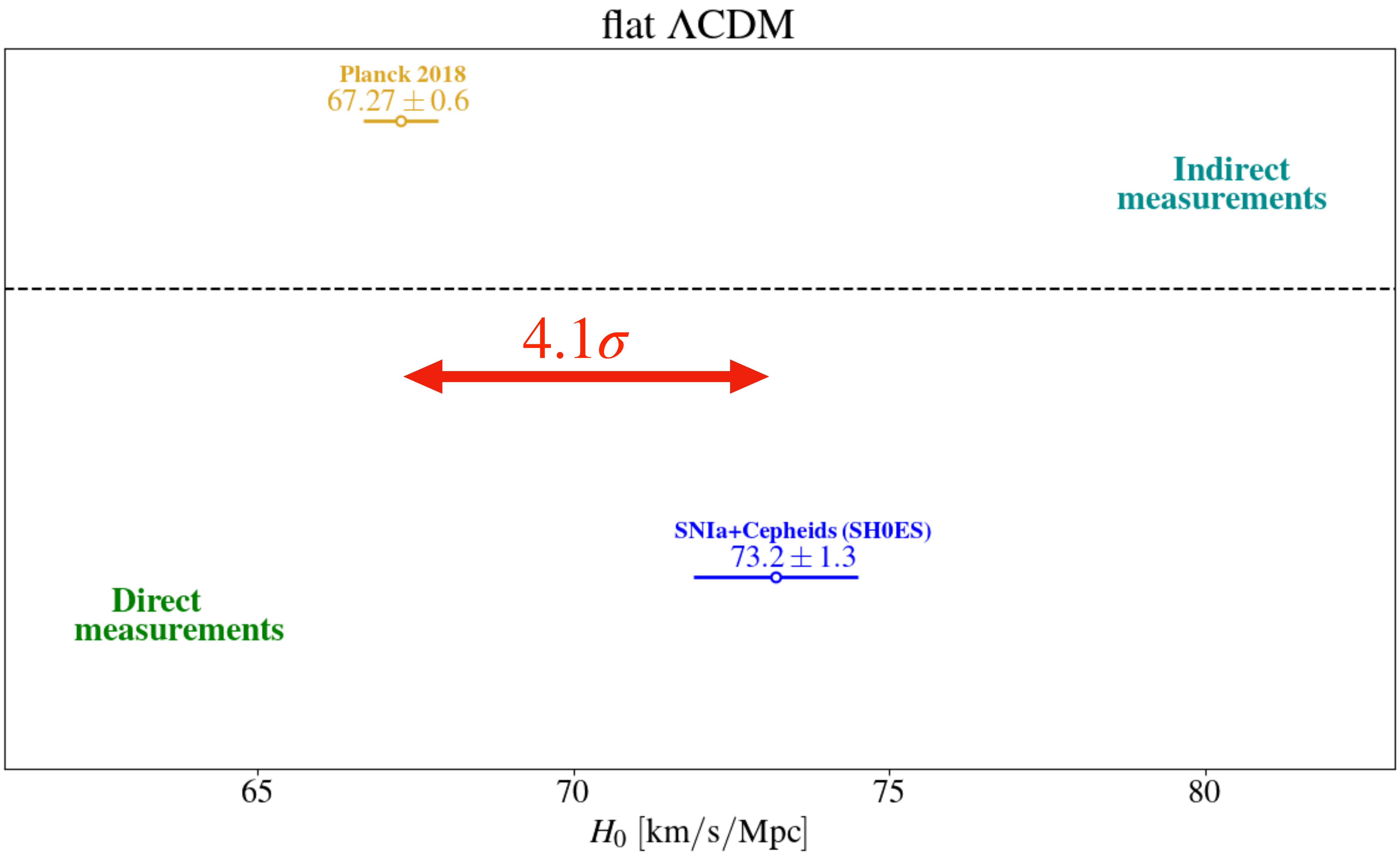
$$S_8 = 0.830 \pm 0.013$$

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

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

The H_0 tension

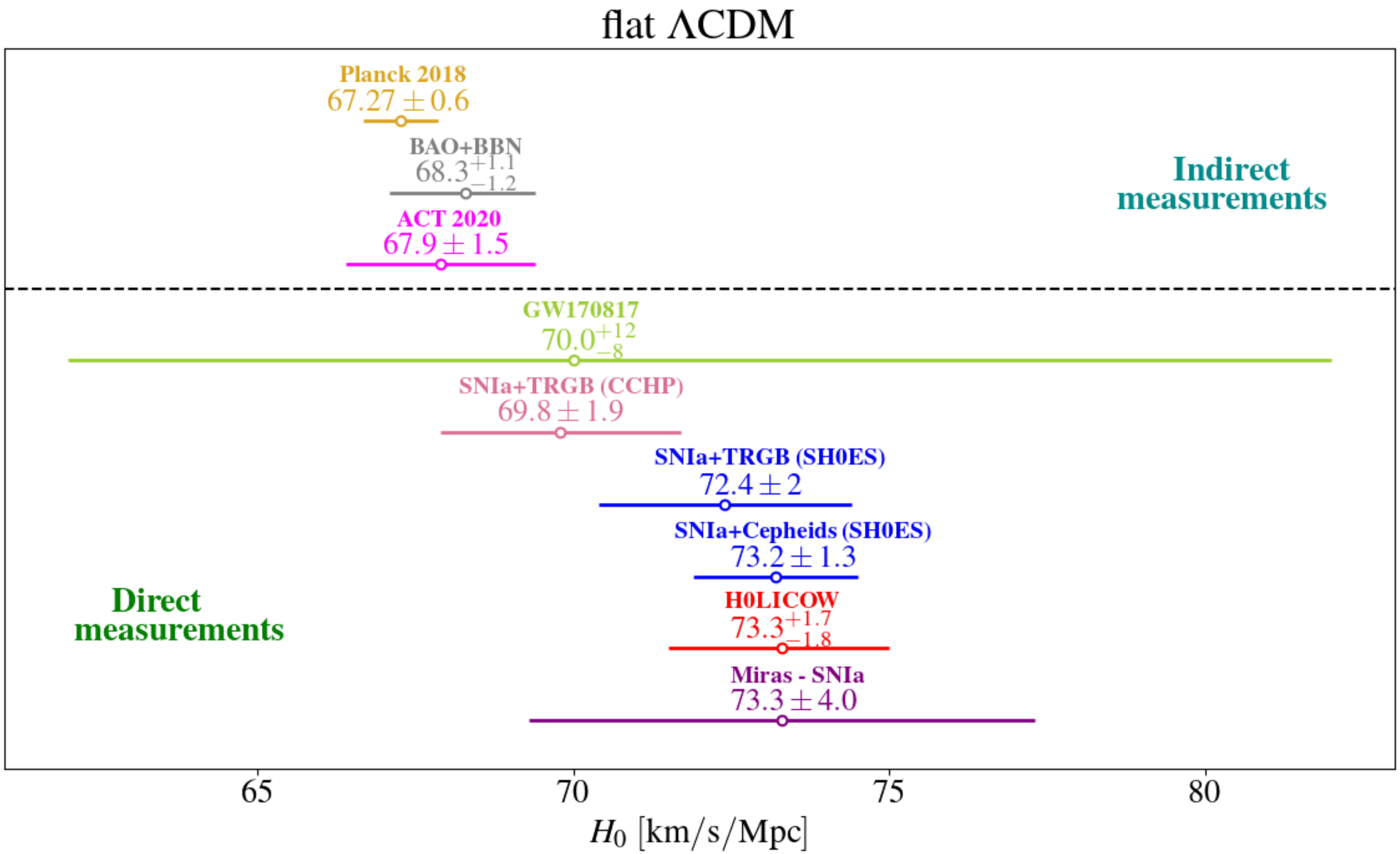
Planck (*under ΛCDM*) and SH0ES measurements are in **4.1σ tension**



The H_0 tension

Planck (*under ΛCDM*) and SH0ES measurements are in **4.1σ tension**

High- and low-redshift probes are typically discrepant



How does SH0ES determine H_0?

$$v = H_0 D$$

From spectrometry

$$1 + z = \frac{\lambda_{obs}}{\lambda_{emit}}$$

Distance to some standard candle, e.g. supernovae Ia

$$\text{Flux} = \frac{\text{L}}{4\pi \text{D}_\text{L}^2}$$

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$$\mathrm{Flux} = \frac{\mathrm{L}}{4\pi \mathrm{D_L^2}}$$

Focus on small z*, for which distances are approx. model-independent

$$D_L = (1+z)\int_0^z \frac{c\,dz'}{H(z')} \xrightarrow{z\ll1} czH_0^{-1} \simeq vH_0^{-1}$$

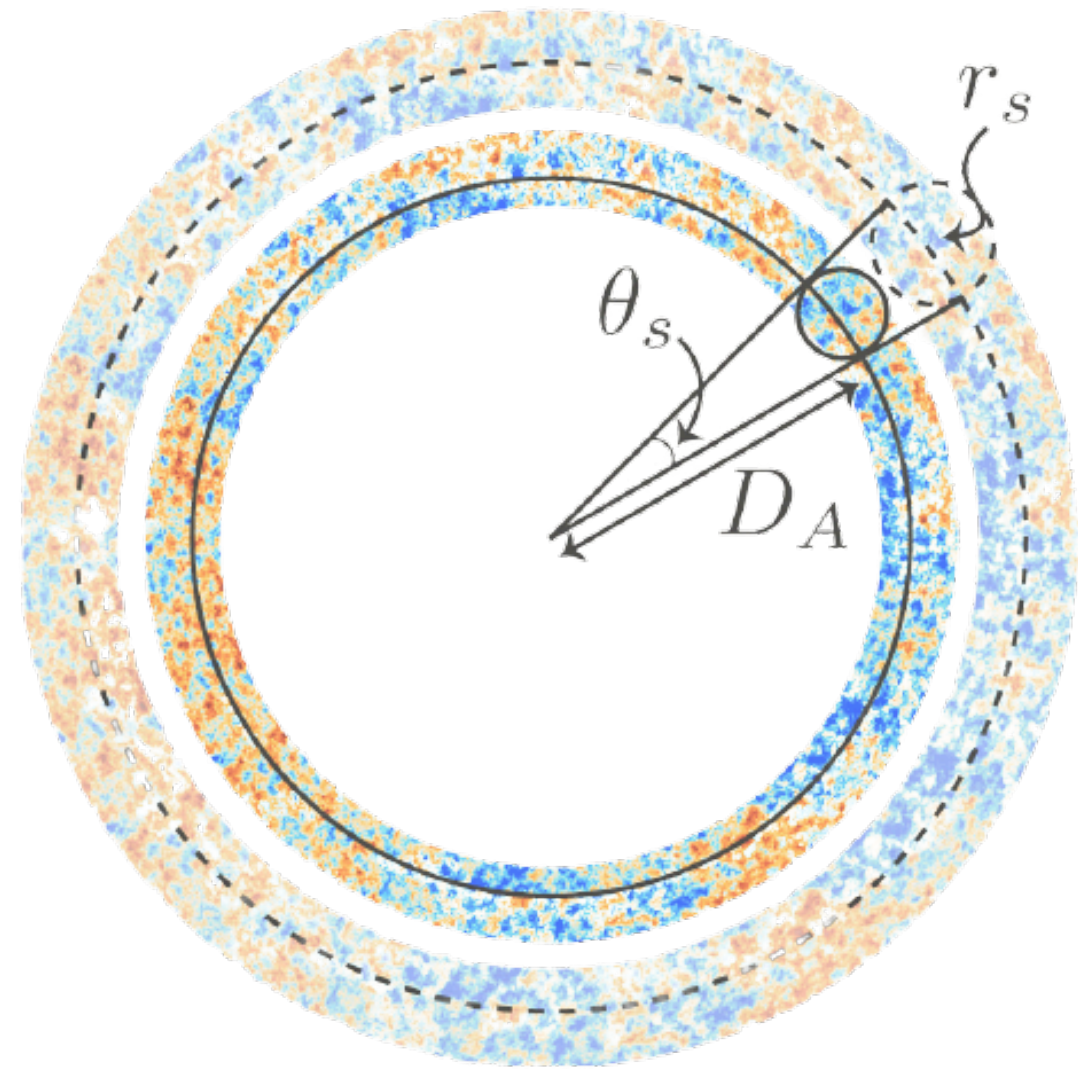
$$\text{where } \mathrm{H^2(z)} = \frac{8\pi \mathrm{G}}{3}\sum_{\mathrm{i}} \rho_{\mathrm{i}}(\mathrm{z})$$

*But not too small, to make sure peculiar velocities are negligible

How does Planck determine H_0?

Angular size of the sound horizon is measured at the 0.04 % precision

$$\theta_s = \frac{r_s(z_{\rm rec})}{D_A(z_{\rm rec})} = \frac{\int_0^{\tau_{\rm rec}} c_s(\tau)d\tau}{\int_{\tau_{\rm rec}}^{\tau_0} c\,d\tau}$$



T. Smith

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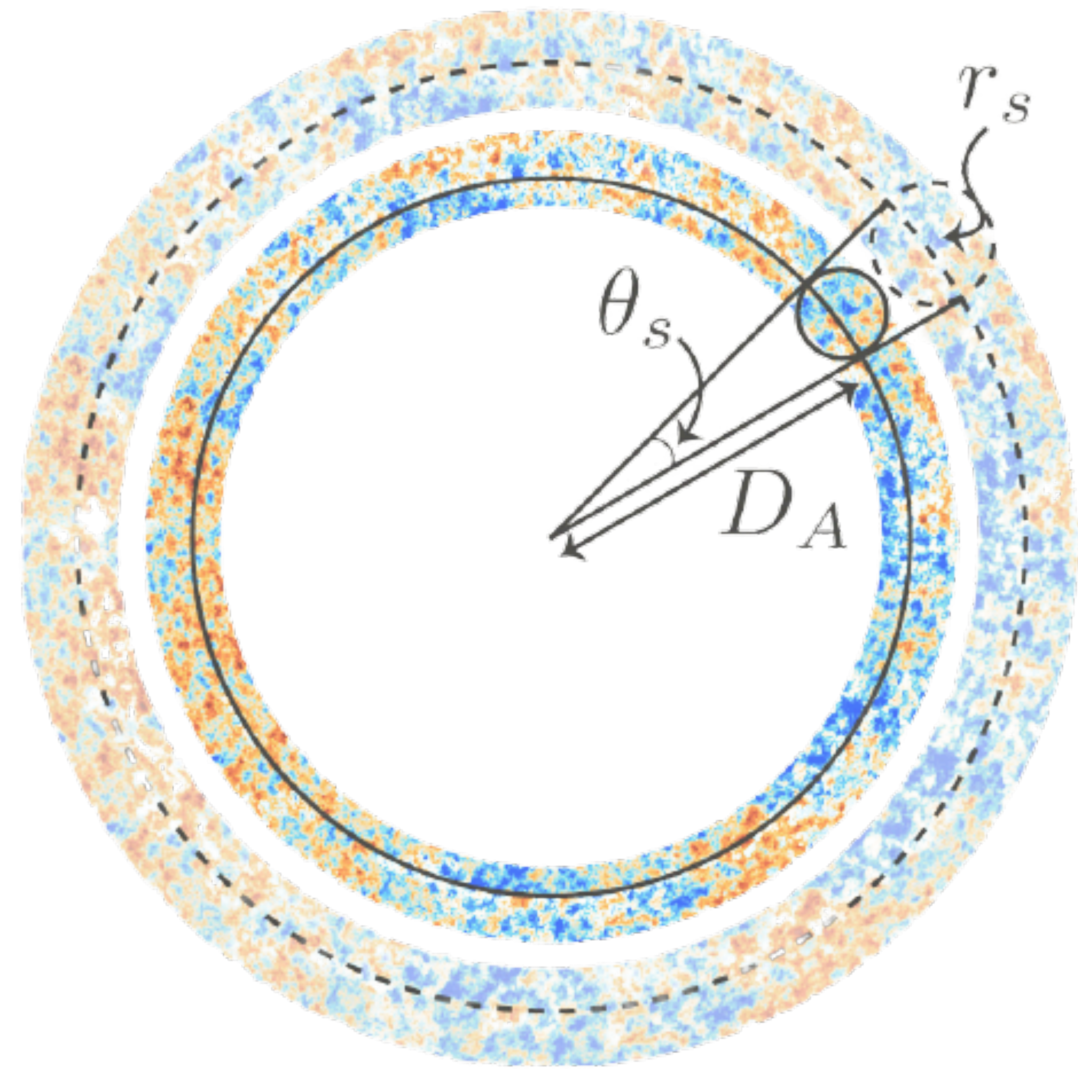
with $D_A \propto 1/H_0 = 1/\sqrt{\rho_{\rm tot}(0)}$



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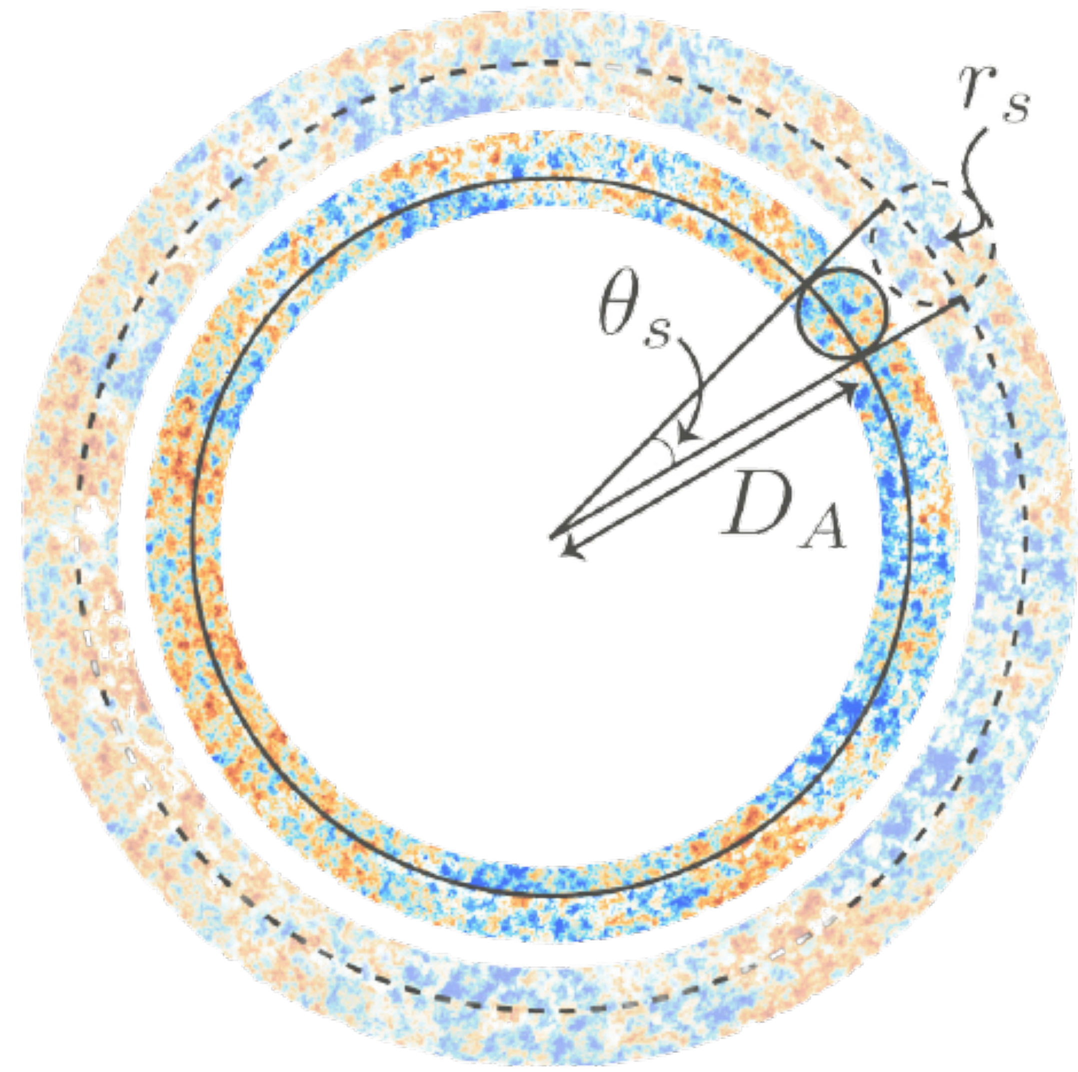

T. Smith

Early-time solutions

Decrease $r_s(z_{\rm rec})$ at fixed θ_s to decrease $D_A(z_{\rm rec})$ and increase H_0

Ex : $\Delta N_{\rm eff} > 0$

Late-time solutions

$r_s(z_{\rm rec})$ and $D_A(z_{\rm rec})$ are fixed, but $D_A(z < z_{\rm rec})$ is changed to allow higher H_0

Ex : $w < -1$

What is needed to resolve the H_0 tension?

- Late-time solutions appear to be almost excluded by BAO and SNIa data

  Poulin++ 1803.02474

- For early-time solutions, one seems to require a 7 % decrease in $r_s(z_*)$

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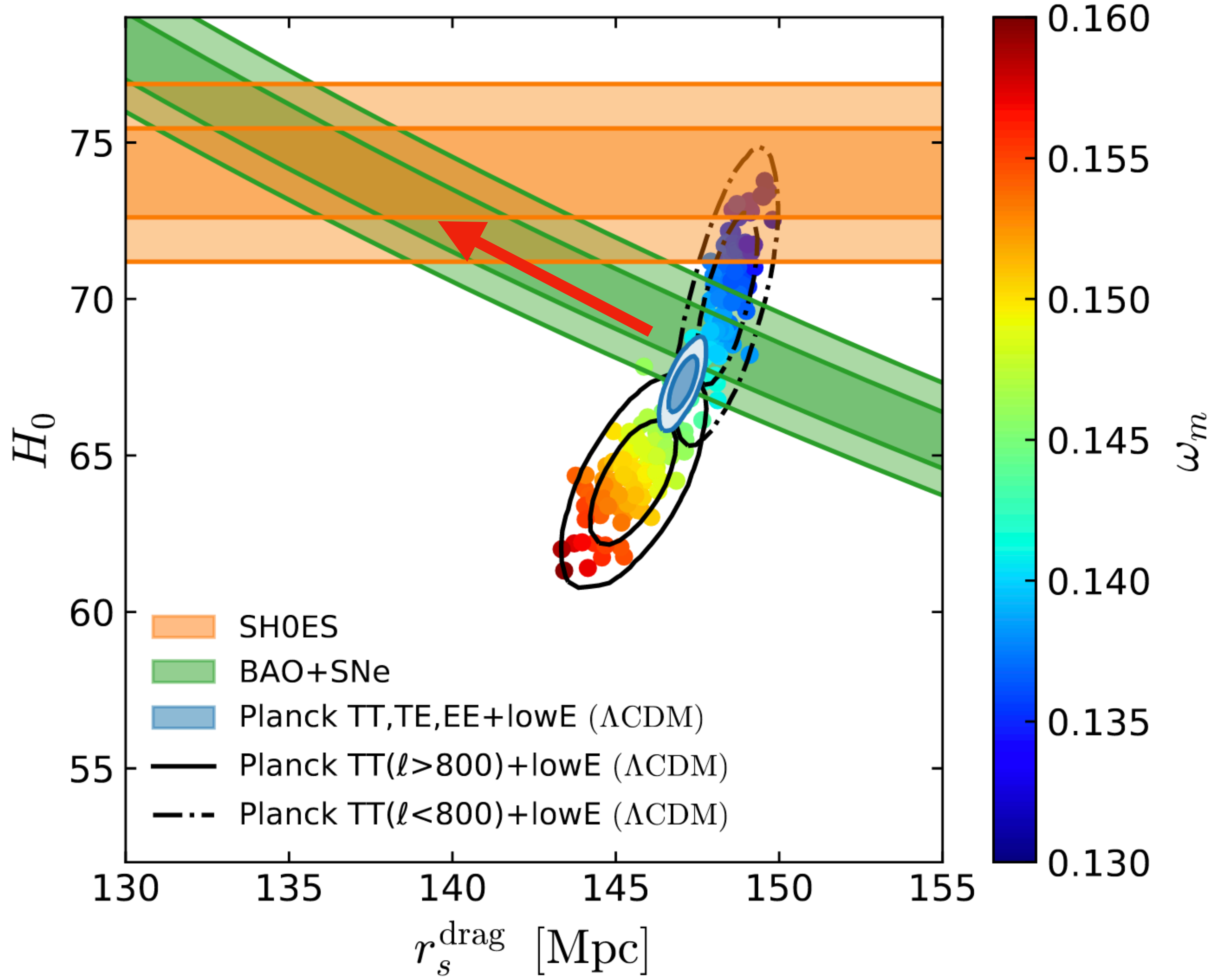


Knox & Millea 1908.03663

Given r_s, obtain D_A using BAO data

$$\theta_d(z)^{\perp} = \frac{r_s(z_{\rm drag})}{D_A(z)}, \quad \theta_d(z)^{\parallel} = r_s(z_{\rm drag})H(z)$$

↓

$$D_L(z) = D_A(z)(1+z)^2$$

↓

Obtain H_0 from calibration of SNIa

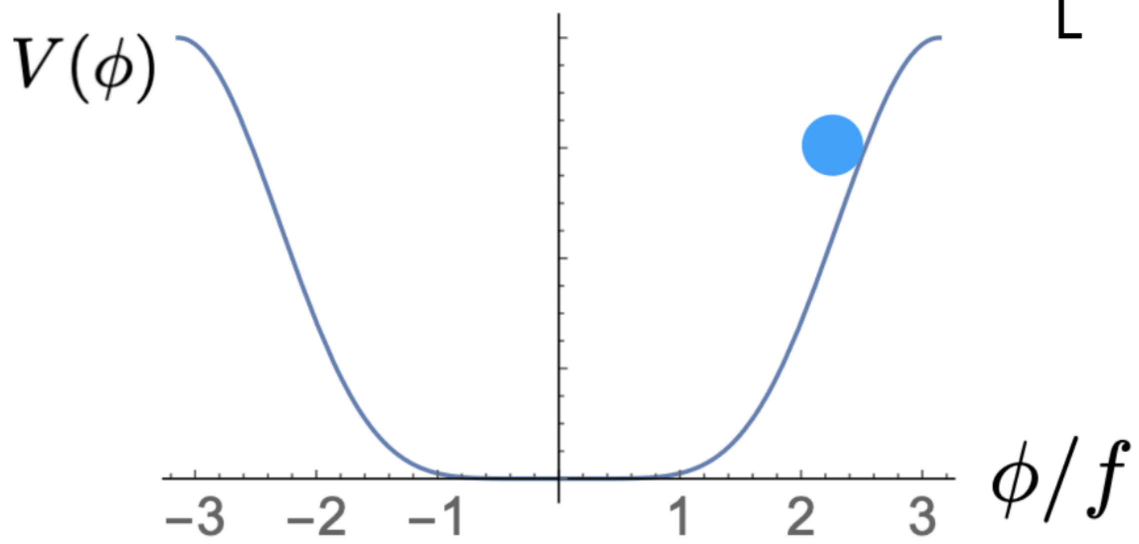
$$m(z) = 5{\rm Log}_{10}{\rm D_L(z)} + {\rm const}$$

II. The H_0 tension vs. Early Dark Energy

In collaboration with Riccardo Murgia and Vivian Poulin

Early Dark Energy

$$V(\phi) \propto \left[1 - \cos\left(\frac{\phi}{f}\right)\right]^3$$



Scalar field initially frozen, then dilutes away equal or faster than radiation

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$$

+ perturbed linear eqs.

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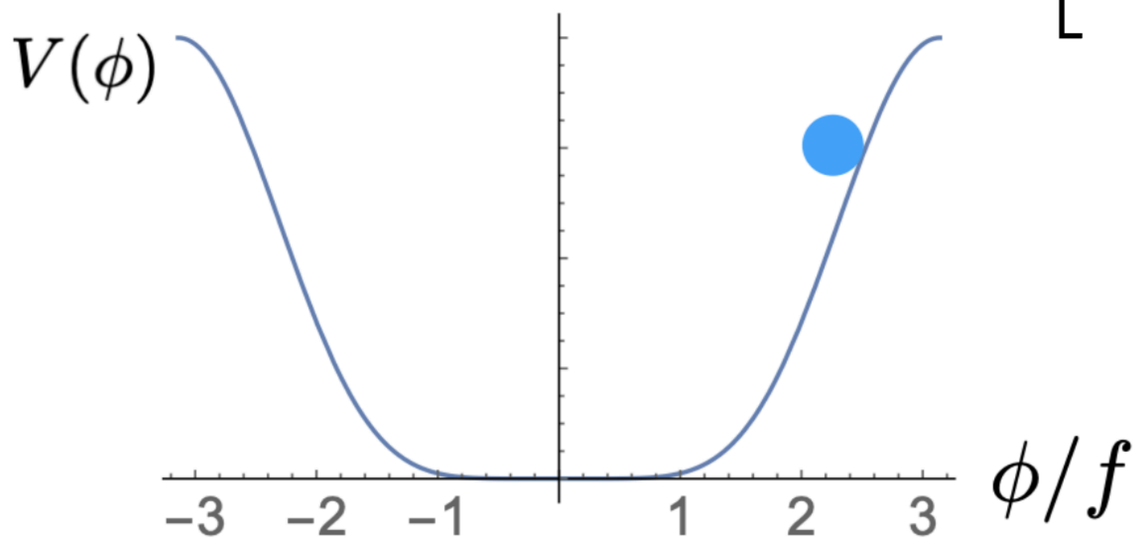

Scalar field initially frozen, then dilutes away equal or faster than radiation

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$$

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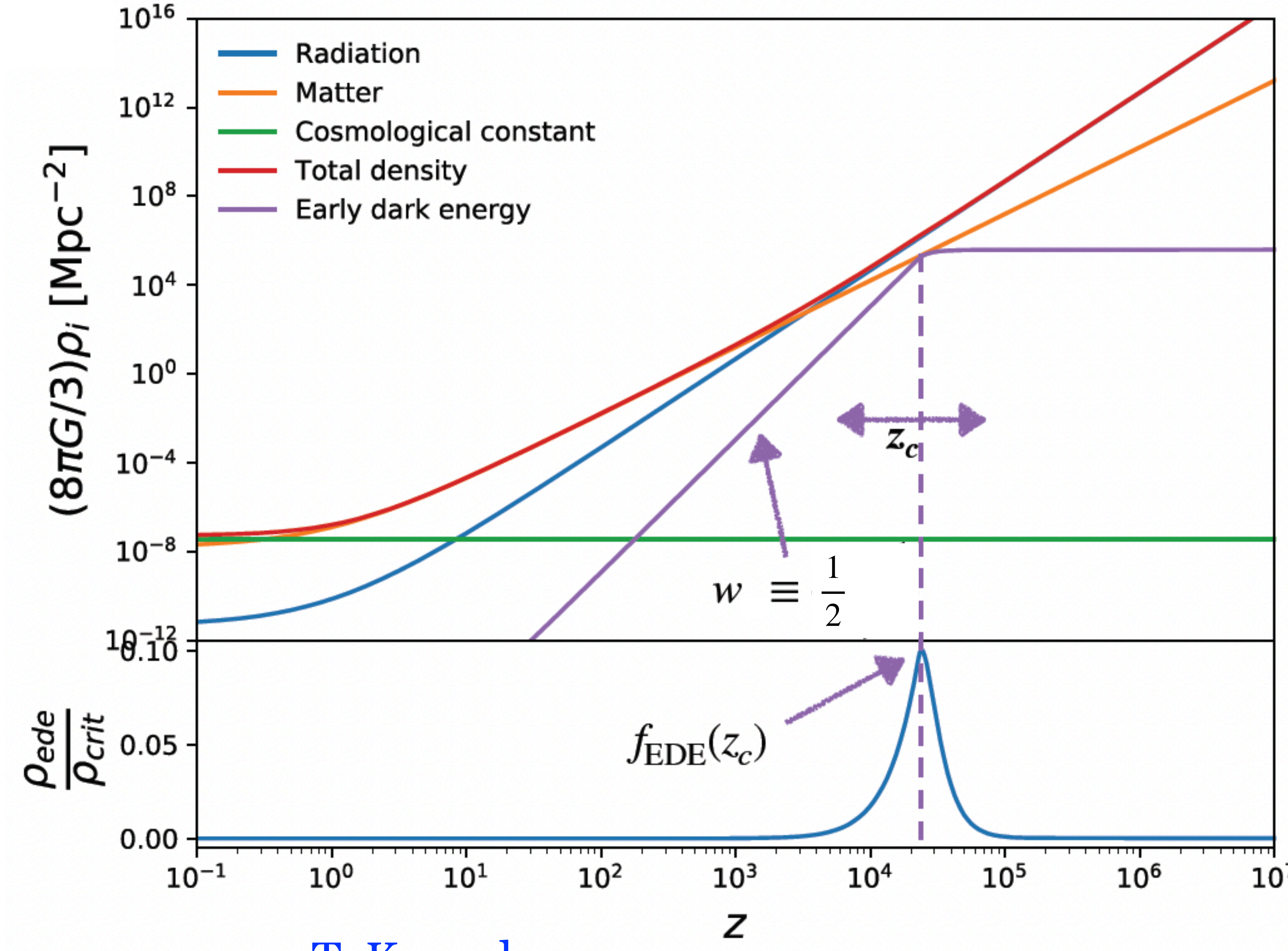
3 parameter EDE model (3pEDE):

$$\{f_{\rm EDE}(z_c),\ z_c,\ \phi_i\}$$

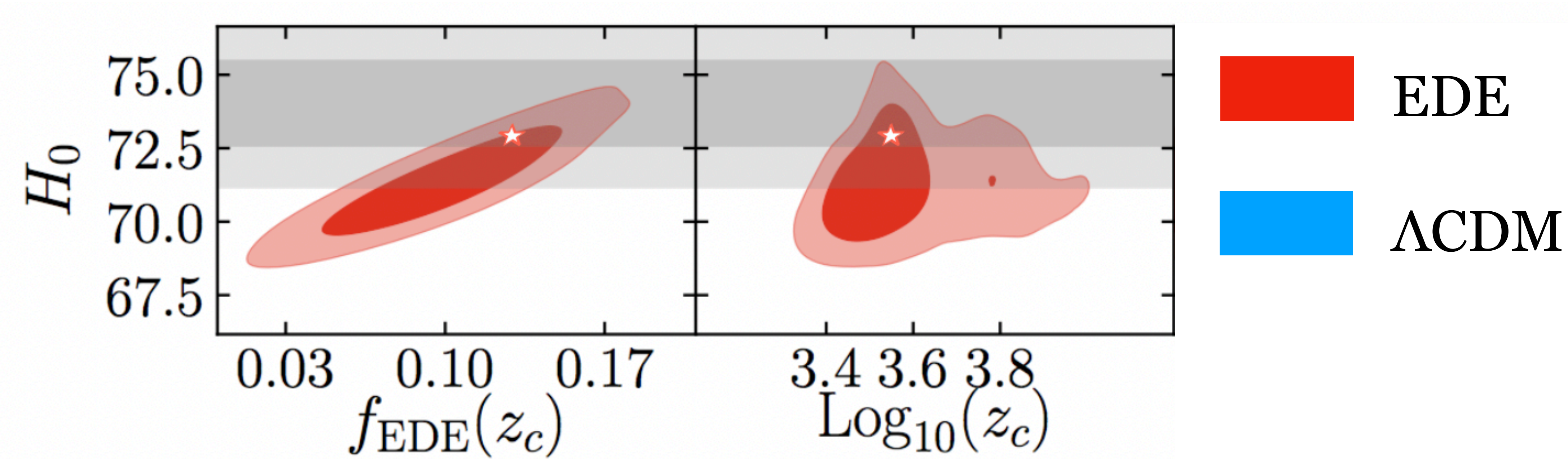


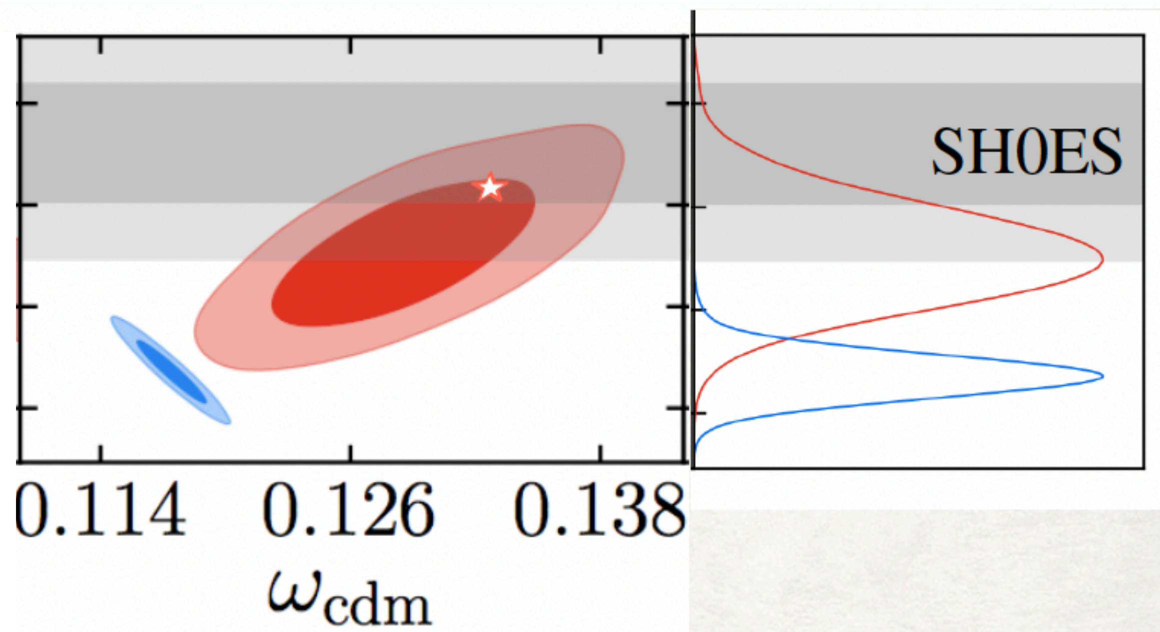
T. Karwal

Early Dark Energy

Early Dark Energy can resolve the H_0 tension if $f_{EDE}(z_c) \sim 10\,\%$ for $z_c \sim z_{eq}$

Planck+ BAO+ SNIa+ SH0ES analysis





Poulin++ 1811.04083 Smith++ 1908.06995

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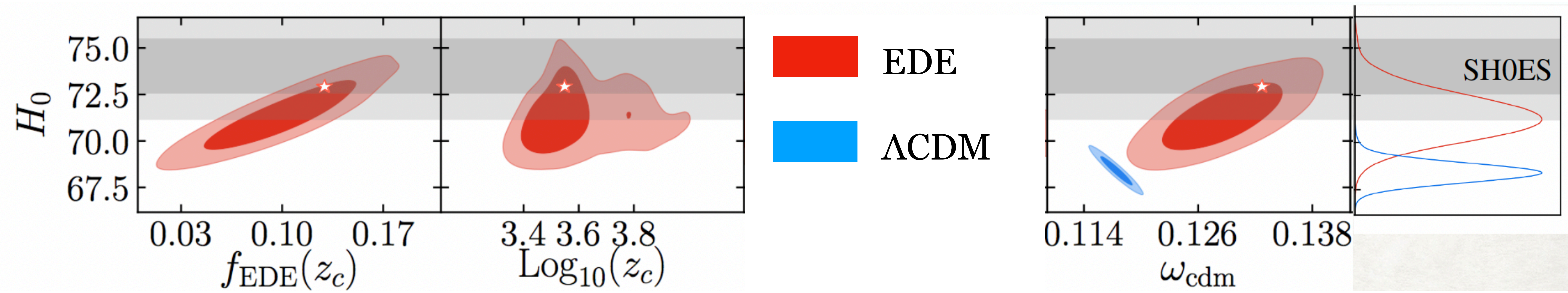


Poulin++ 1811.04083 Smith++ 1908.06995

Some caveats

1. *Very fine tuned?*

⟶ Proposed connexions of EDE with neutrino sector and present DE

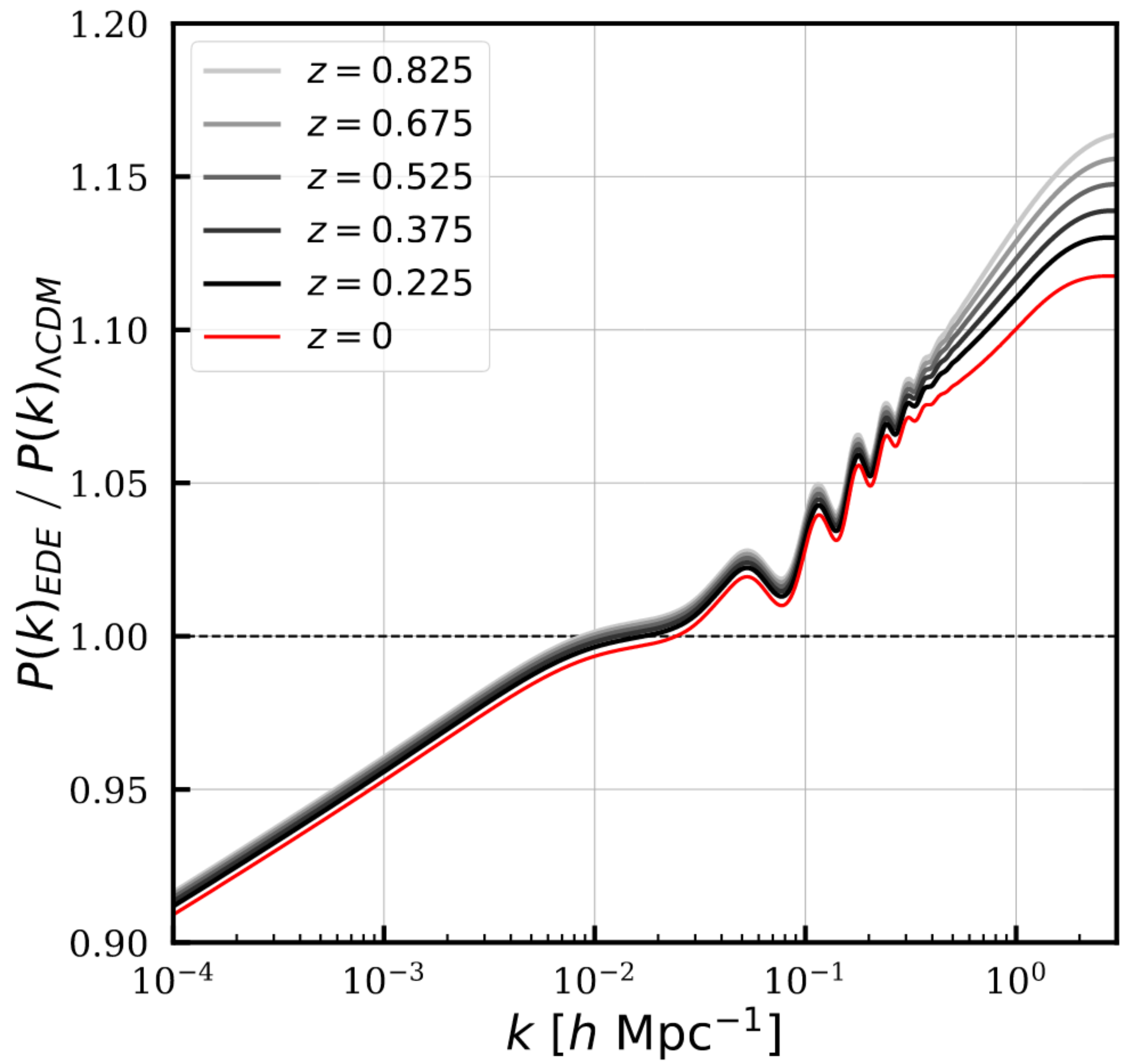
Sakstein++ 1911.11760 Freese++ 2102.13655

2. Increased value of $\omega_{\rm cdm} = \Omega_{\rm cdm} h^2$, *increases value of S_8*

Jedamzik++ 2010.04158.

Is EDE solution ruled out?

EDE solution increases power at small k (*with a corresponding increase in* S_8), rising mild tension with Large Scale Structure (LSS) data



Hill++ 2003.07355

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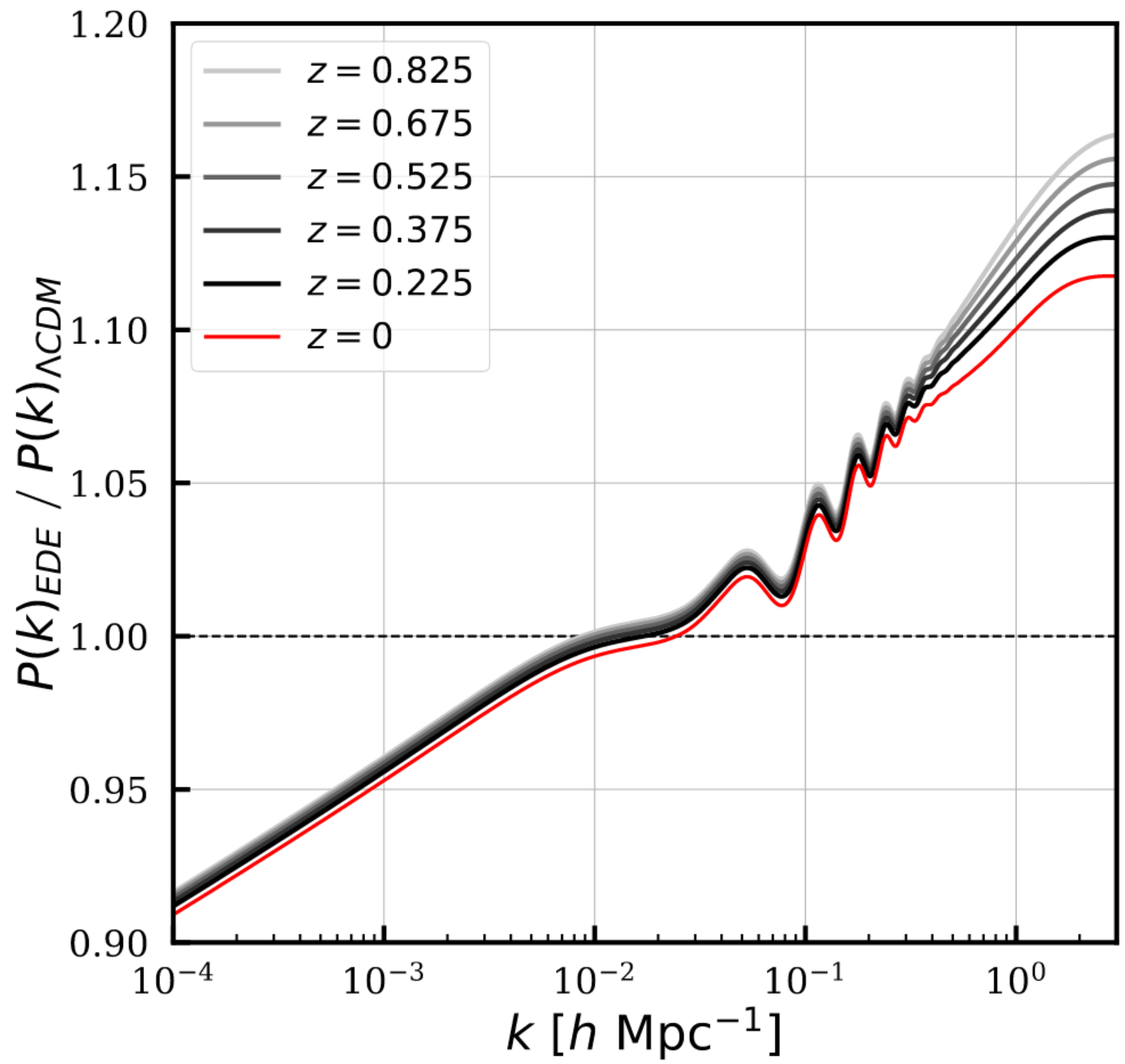
When LSS data is added to analysis, EDE detection is reduced from 3σ to 2σ

In addition, EDE is not detected from Planck data alone

D'amico++ 2006.12420
Ivanov++ 2006.11235



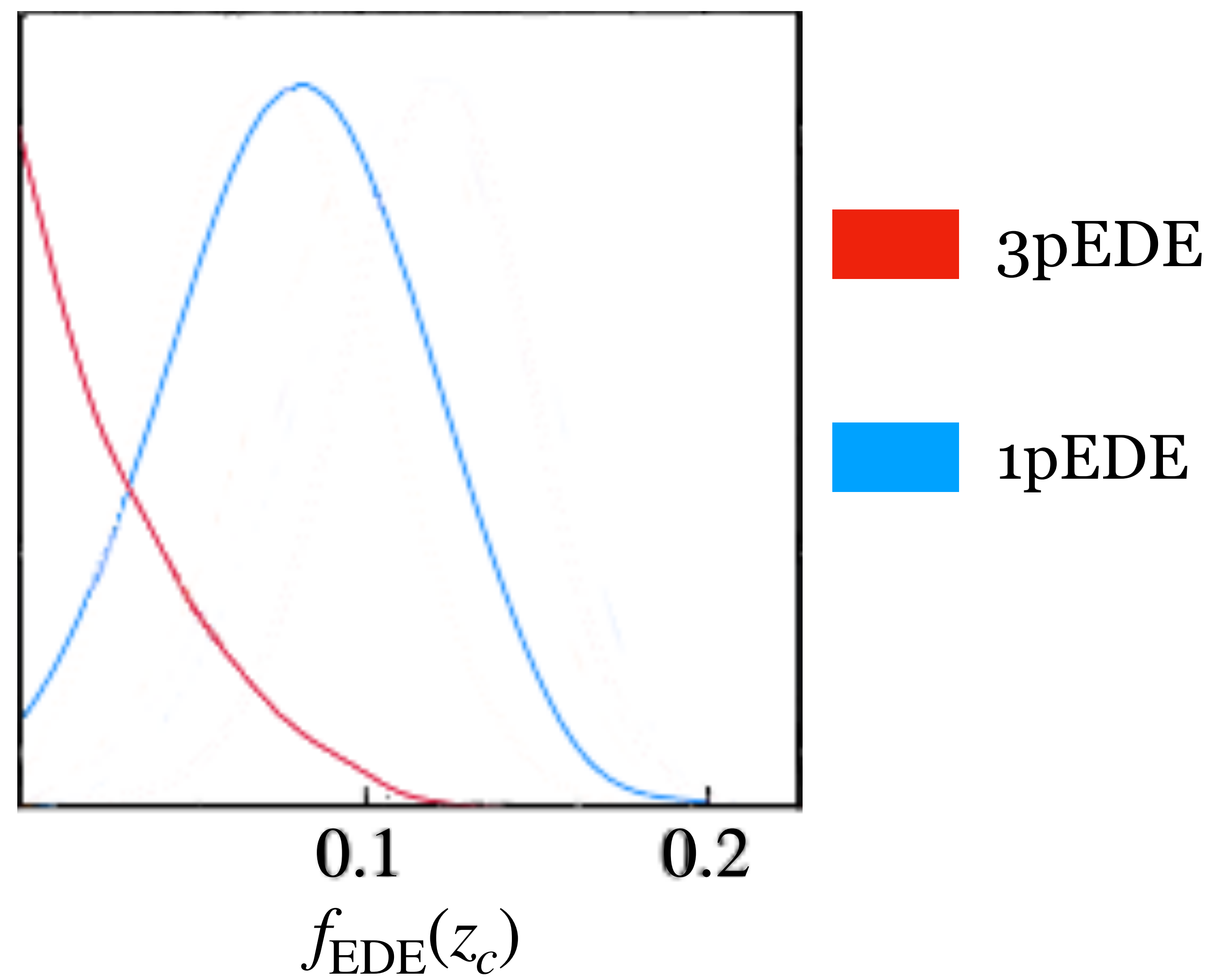
Hill++ 2003.07355

Answer: no, EDE solution is still robust

1. Why EDE is not detected from Planck alone?

χ^2 degeneracy in Planck between ΛCDM and EDE :
For $f_{\rm EDE} \lesssim 4\,\%$, parameters z_c and $\phi_{\rm i}$ become irrelevant,
so posteriors are naturally weighted towards ΛCDM

Planck 2018



Murgia, GFA, Poulin 2107.10291

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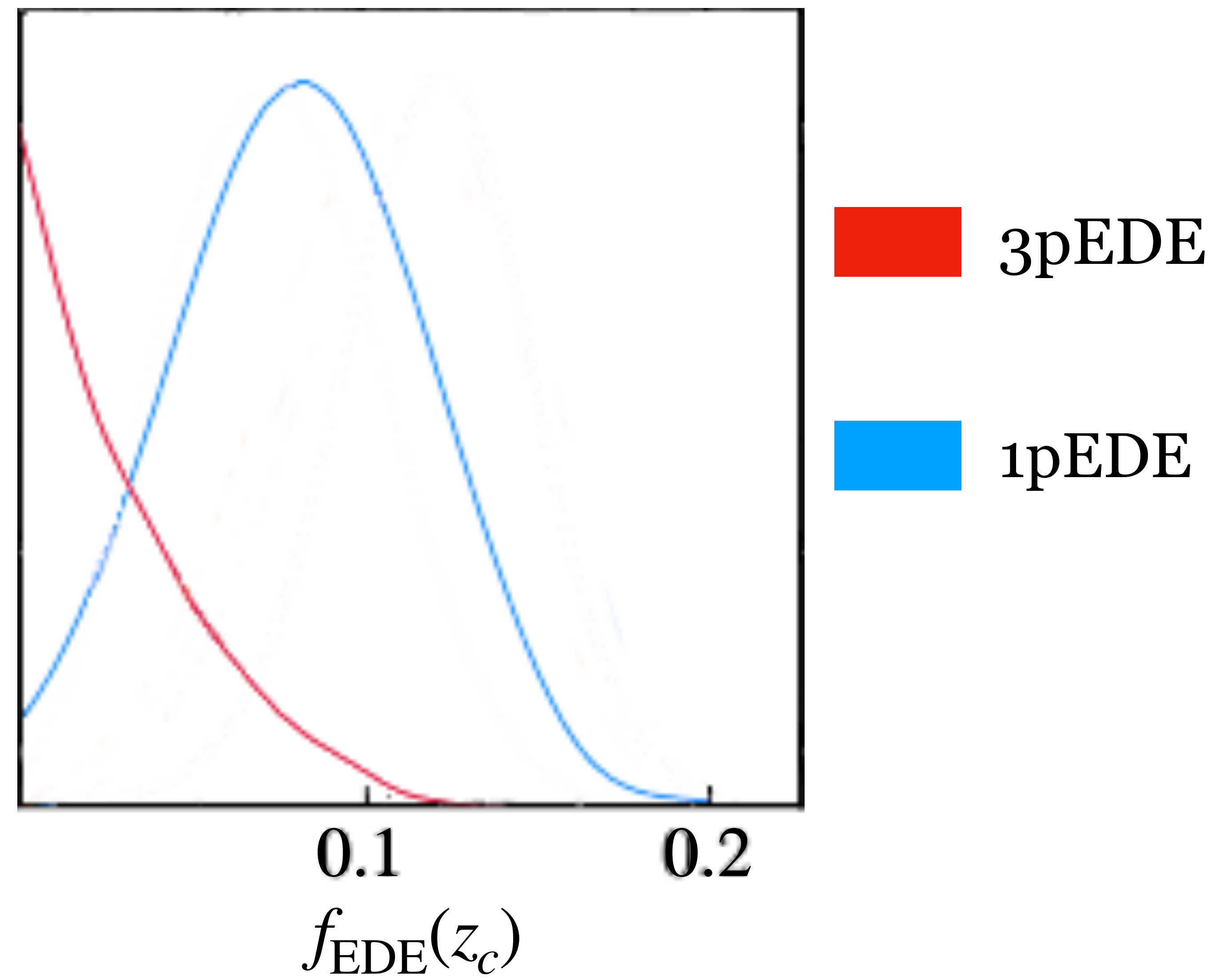
For $f_{\rm EDE} \lesssim 4\,\%$, parameters z_c and $\phi_{\rm i}$ become irrelevant,
so posteriors are naturally weighted towards ΛCDM

To avoid this Bayesian volume effect, consider a
1 parameter EDE model (1pEDE):
Fix z_c and ϕ_i and let f_{EDE} free to vary

Planck 2018



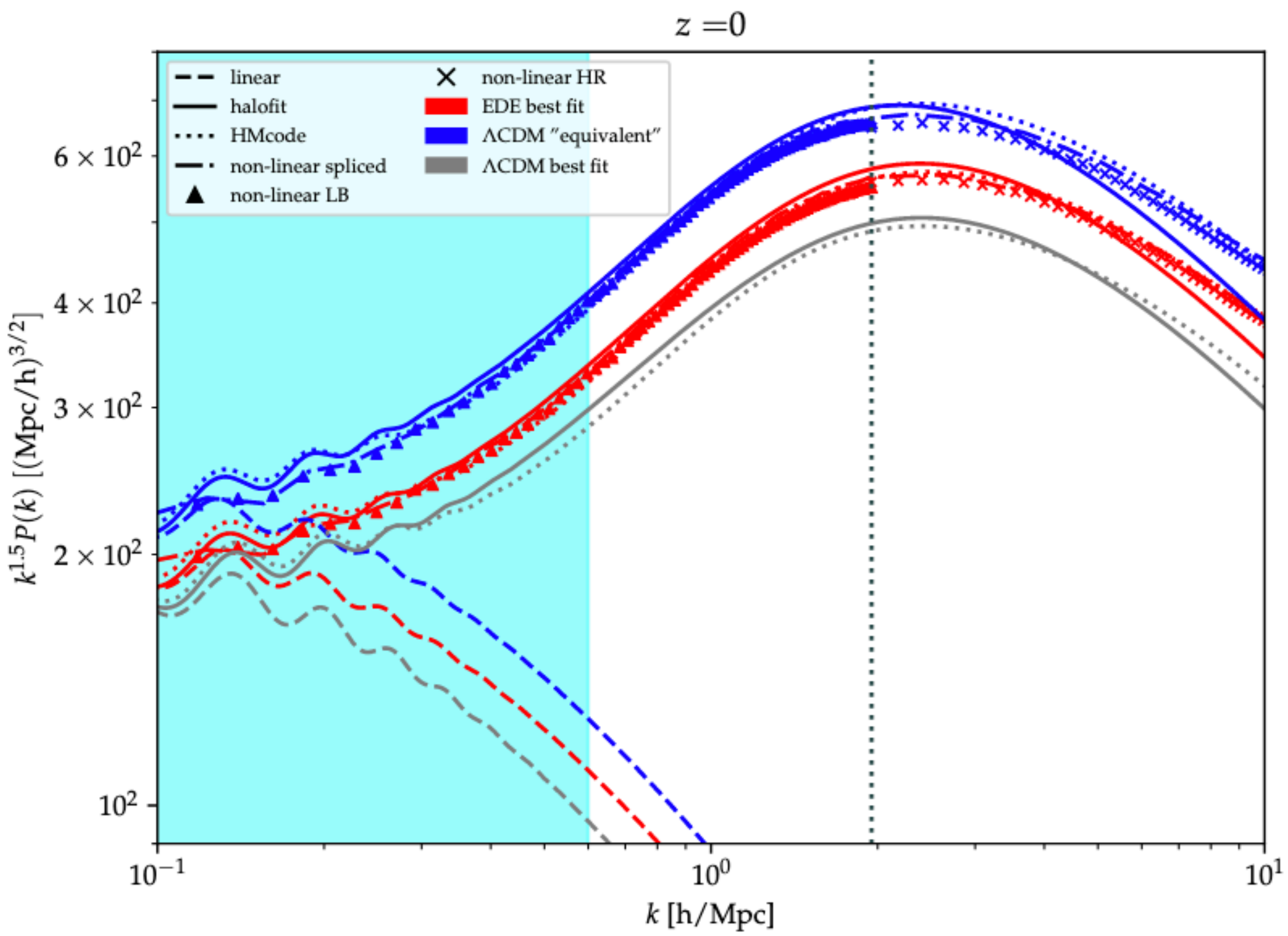
Within 1pEDE, we get a 2σ detection of EDE from *Planck data alone*

$$f_{\rm EDE} = 0.08 \pm 0.04 \qquad H_0 = 70 \pm 1.5 \ \text{km/s/Mpc}$$

Murgia, GFA, Poulin 2107.10291

Answer: no, EDE solution is still robust

2. Is LSS data constraining enough to rule out EDE?



EDE non-linear P(k)* from halofit agrees well with results from N-body simulations

*Intrinsic effect of EDE is a power suppression, but the shift of the ΛCDM params. leads to an enhancement

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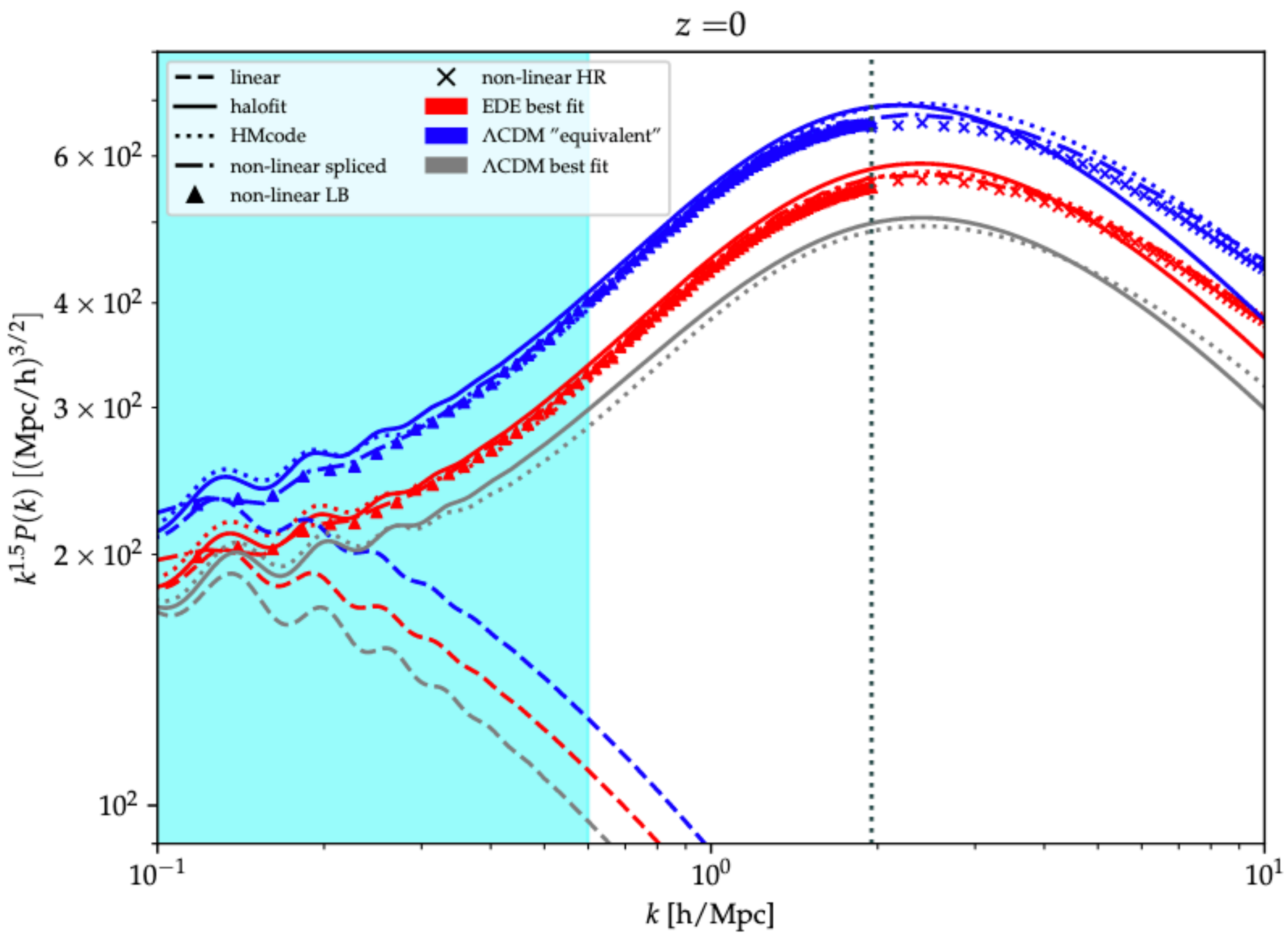

EDE non-linear P(k)* from halofit agrees well with results from N-body simulations

1pEDE tested against Planck+BAO+SNIa+SH0Es and WL data from KiDS/Viking+DES: S_8 tension persists, but fit is not significantly degraded wrt ΛCDM, and solution to the H_0 tension survives

Murgia, GFA, Poulin 2107.10291

$$f_{\rm EDE} = 0.09^{+0.03}_{-0.02} \qquad H_0 = 71.3 \pm 0.9 \ \text{km/s/Mpc}$$

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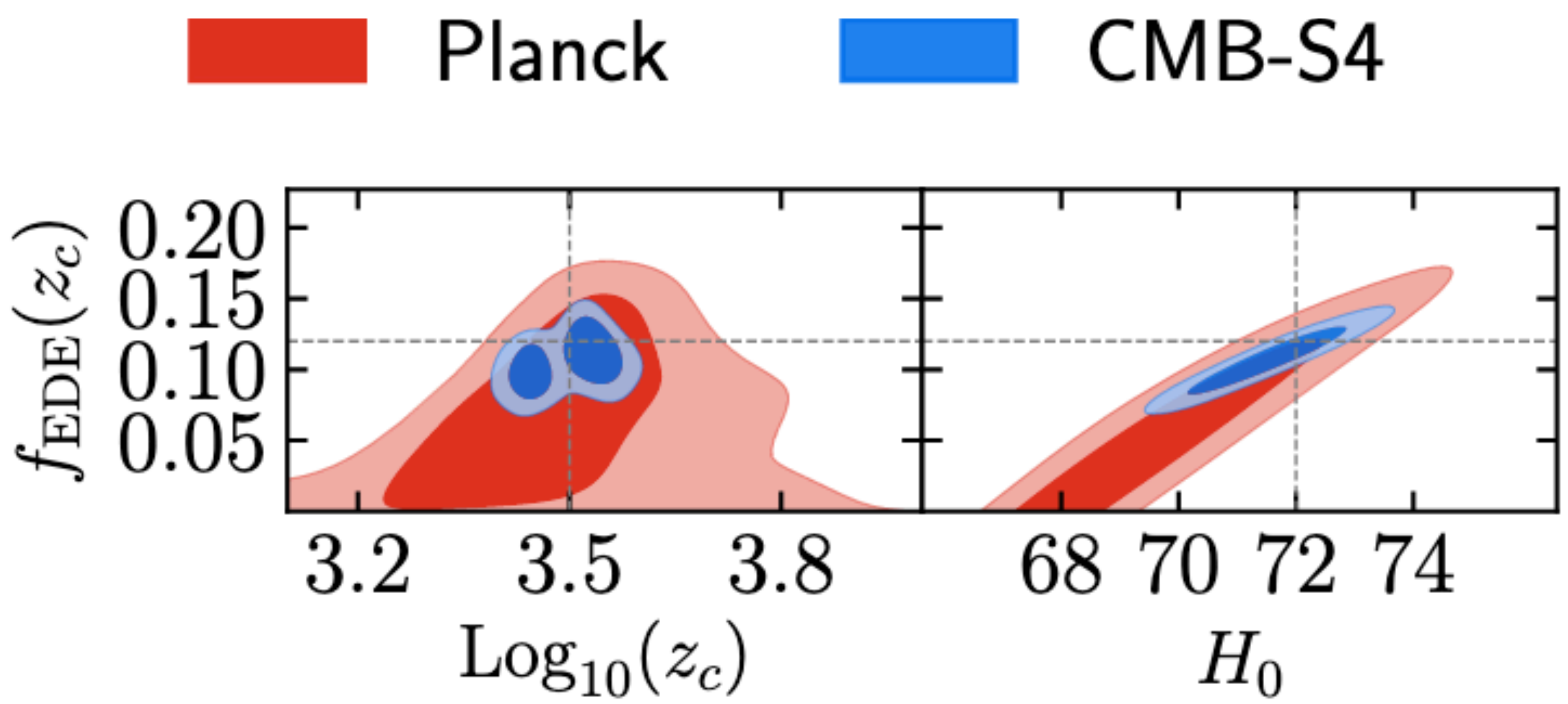
Prospects for Early Dark Energy

Future CMB experiments (i.e. CMB-S4) will be able to unambiguously detect EDE



Smith++ 1908.06995

Other current CMB experiments like ACT are already showing a 3σ detection of EDE!

Hill++ 2109.04451

Poulin++ 2109.06229

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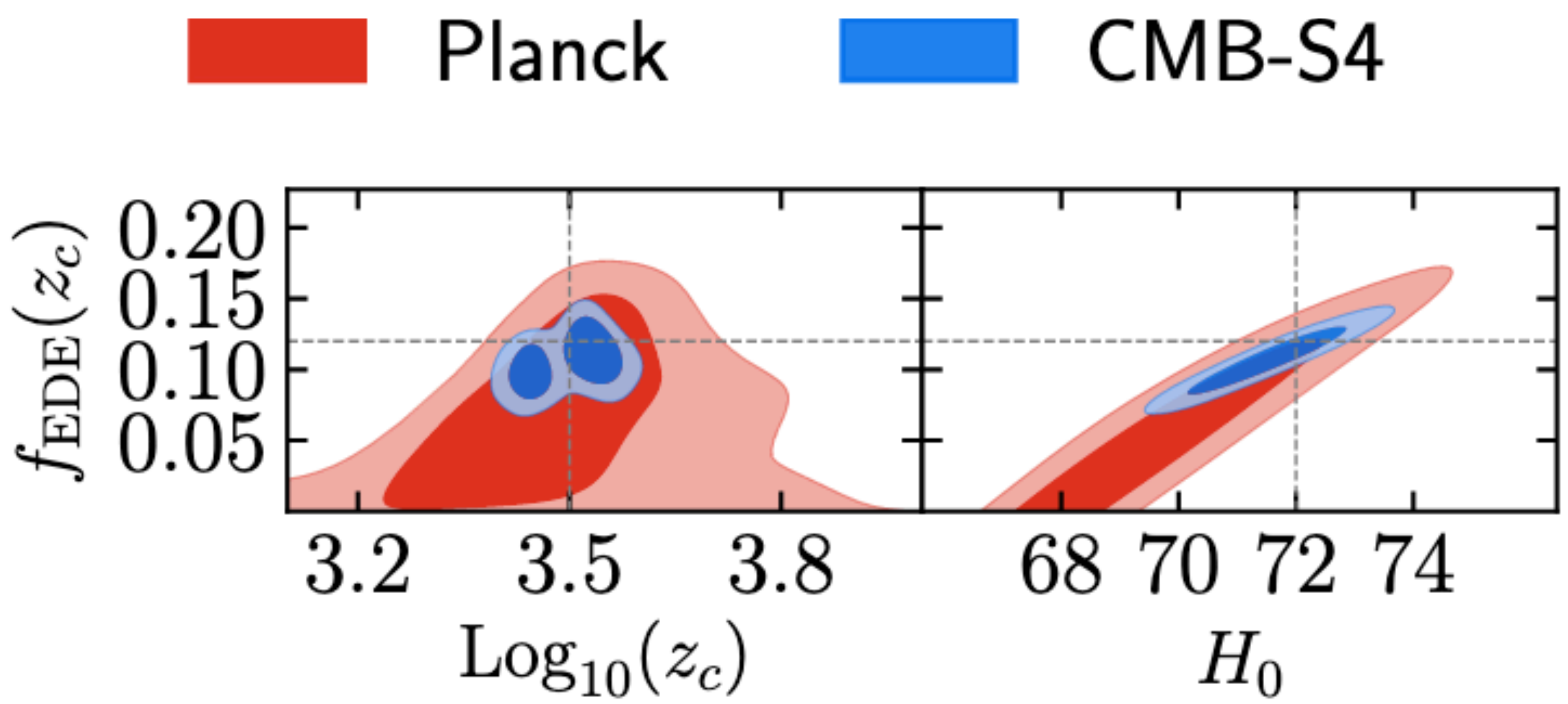


Smith++ 1908.06995

Other current CMB experiments like ACT are already showing a 3σ detection of EDE!

Hill++ 2109.04451

Poulin++ 2109.06229

Is there any model that could explain the S_8 anomaly?

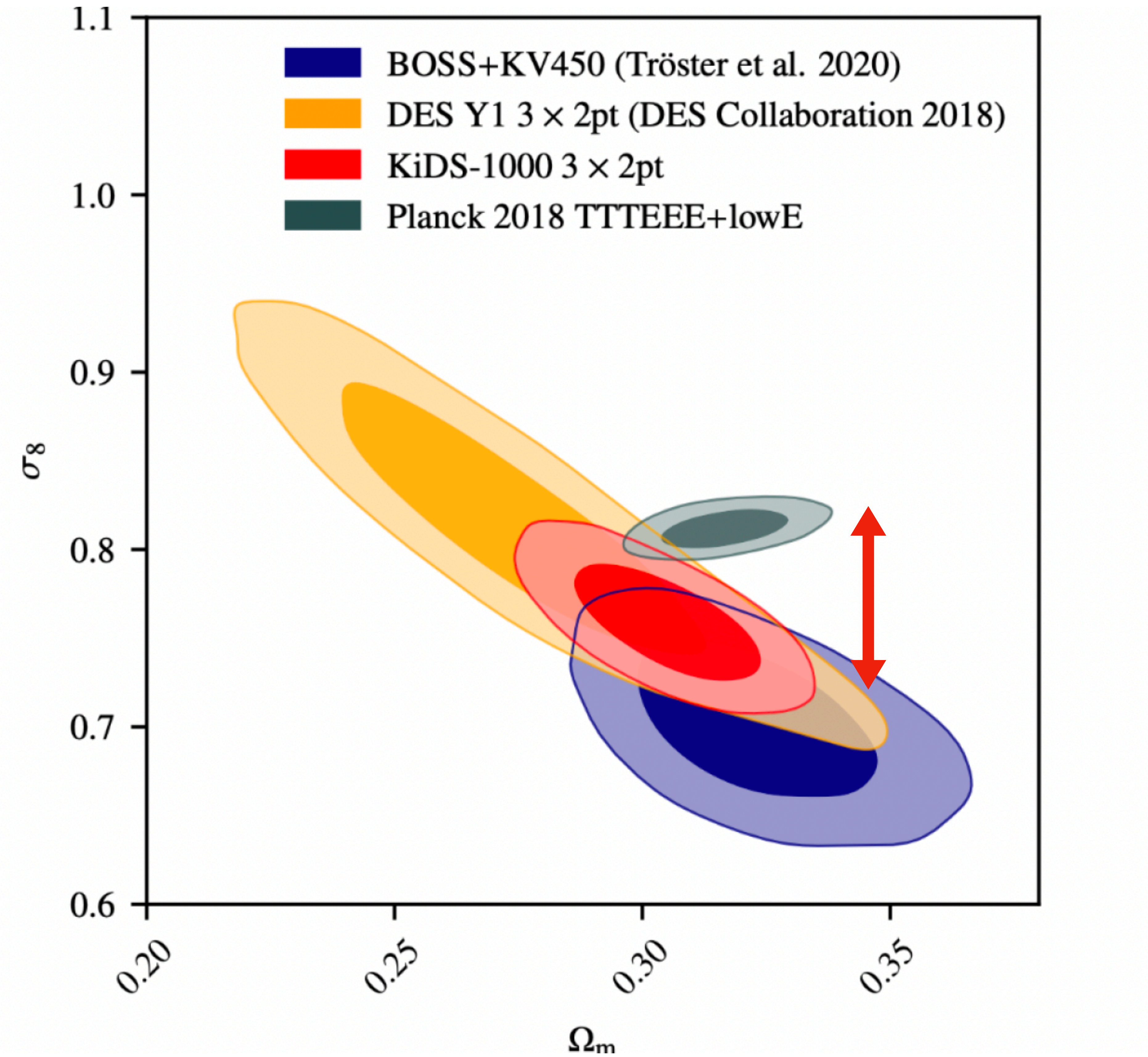
III. The S_8 tension vs. Decaying Dark Matter

In collaboration with Riccardo Murgia, Vivian Poulin and Julien Lavalle

What is needed to resolve the S_8 tension?

Di Valentino++ 2008.11285

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



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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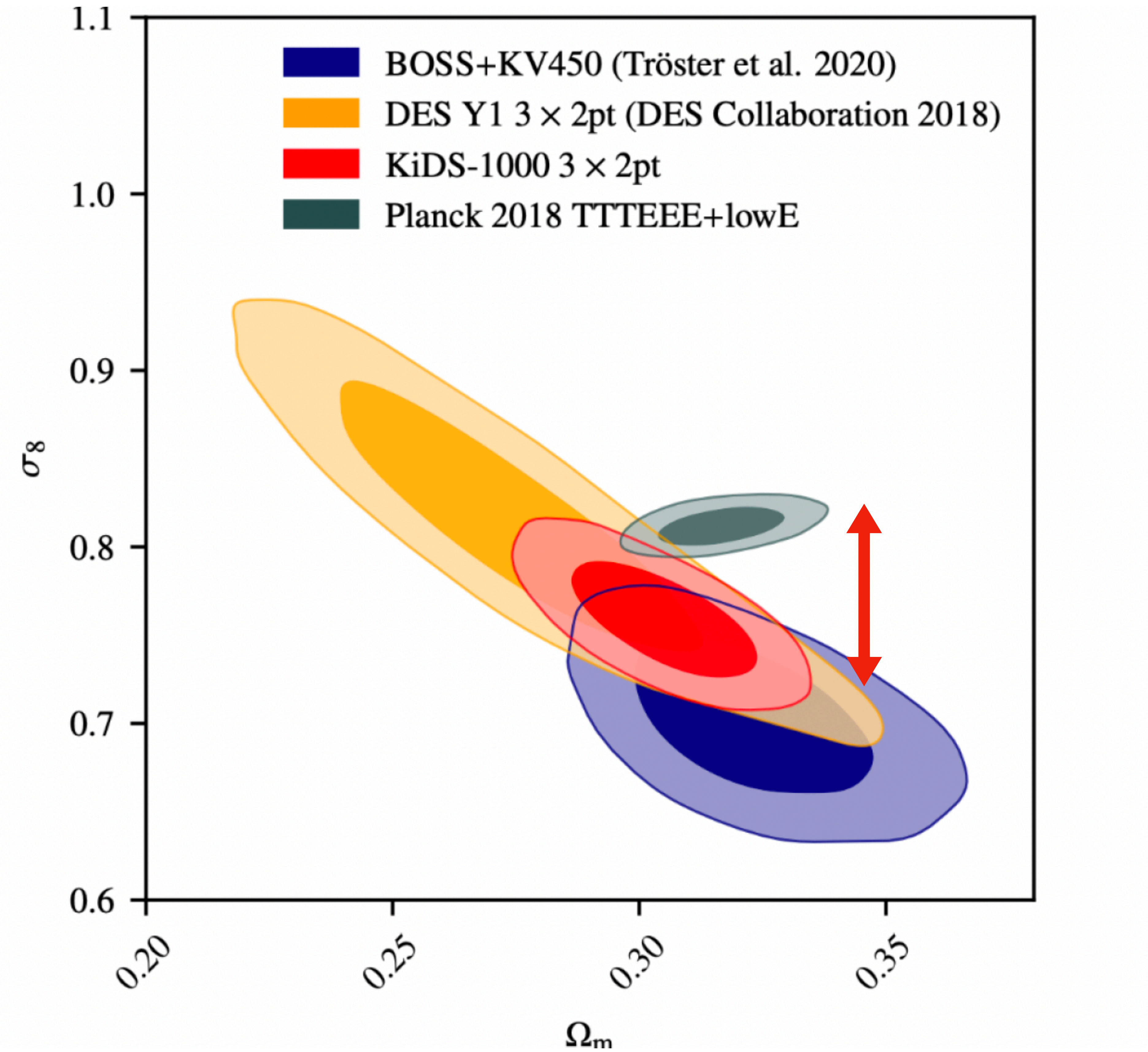
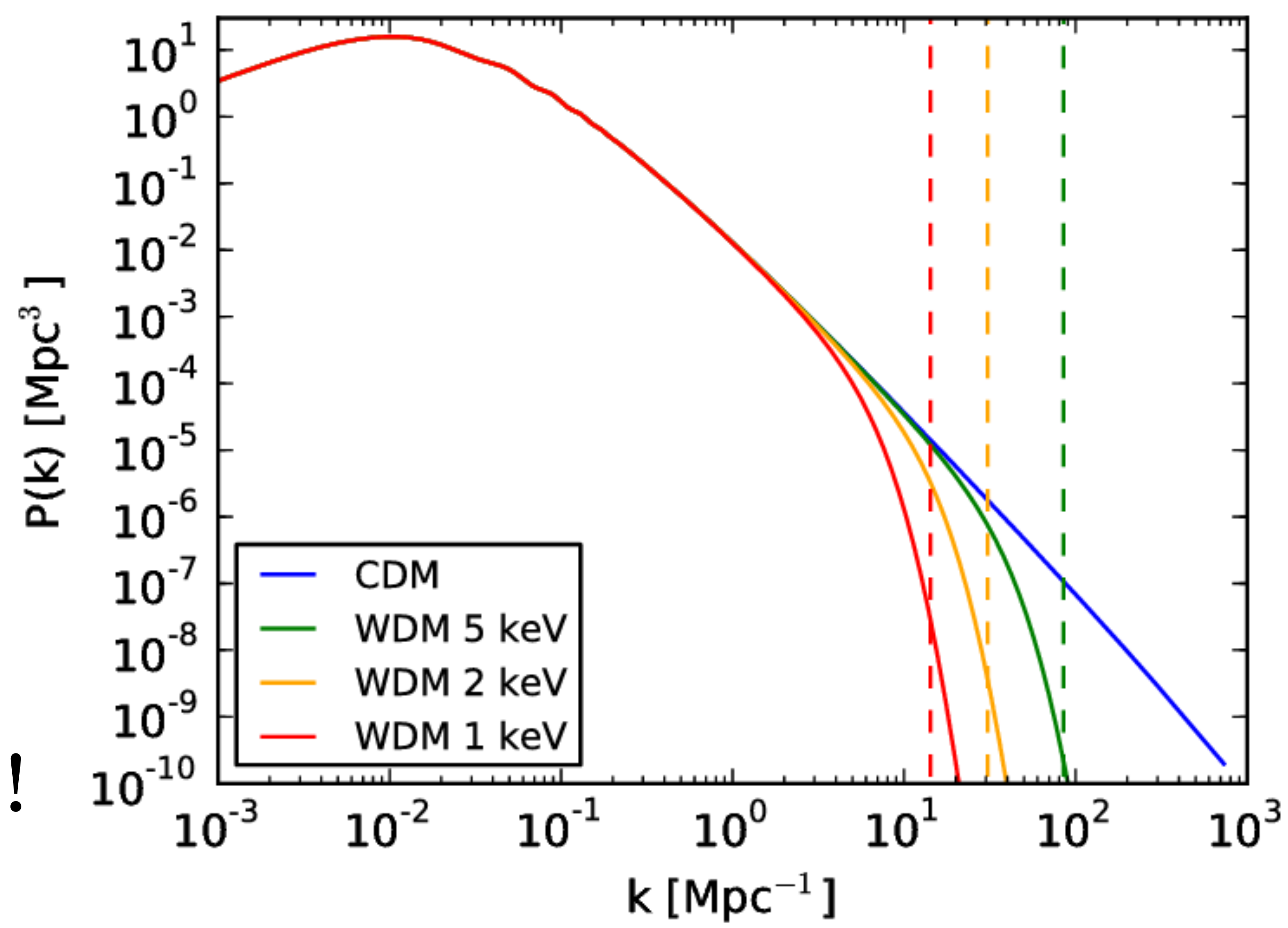


Ω_m should be left unchanged

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

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

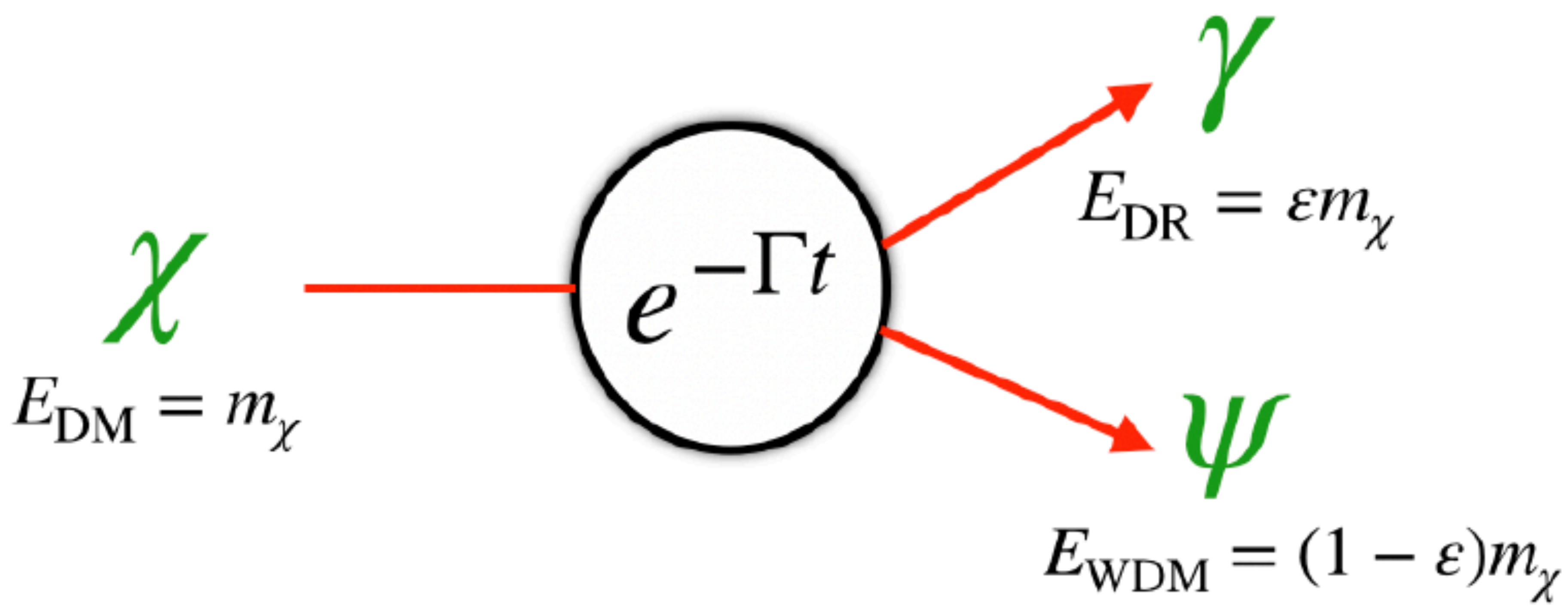


Ex: Warm Dark Matter

Very constrained by many probes!

2-body Dark Matter decay

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



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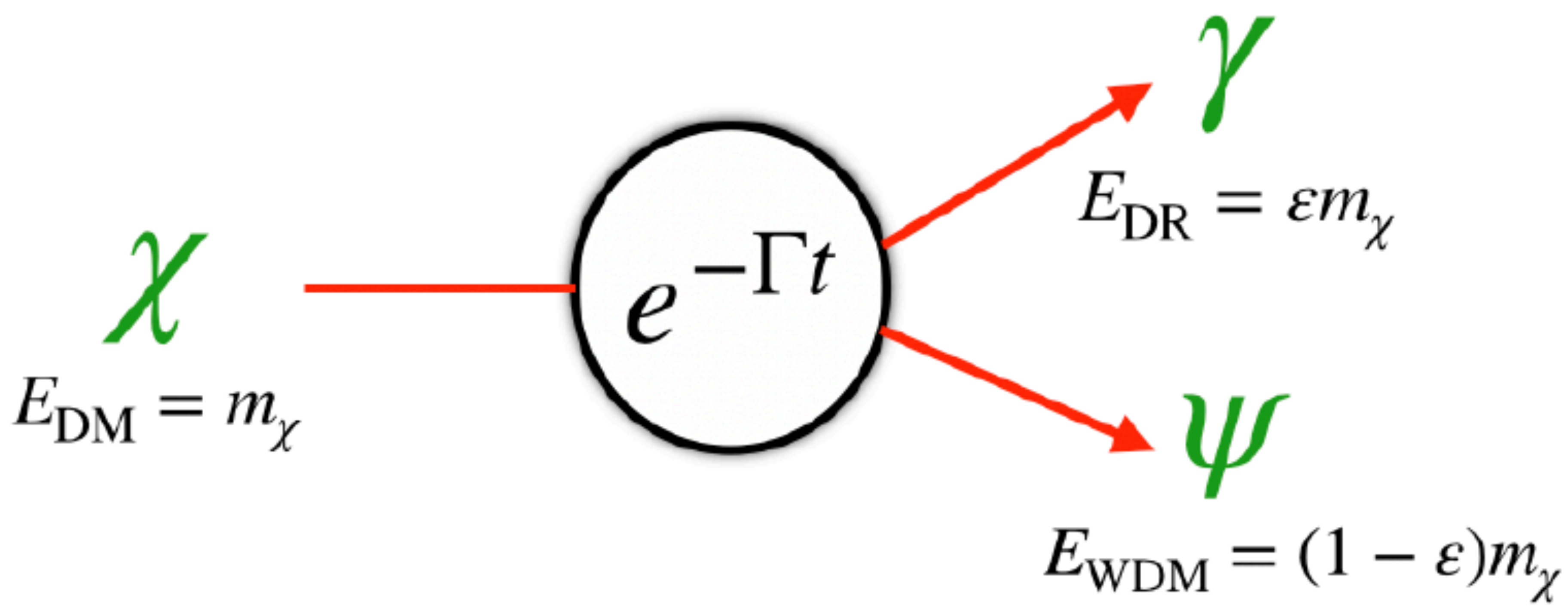

The model is fully specified by:

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

2-body Dark Matter decay

Aoyama++ 1402.2972	→	Full treatment of perts.	No parameter scan
Vattis++ 1903.06220	→	Resolution to H_0 tension ?	No perturbations
Haridasu++ 2004.07709	→	SNIa+BAO rule out solution	No perturbations
Clark++ 2006.03678	→	CMB rule out solution	No perturbations

2-body Dark Matter decay

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

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Clark++ 2006.03678 → CMB rule out solution

(Vattis++, Haridasu++, Clark++: No perturbations)

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 $\rm i = dm, dr, wdm$

- 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

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

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

*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

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

*Implemented in modified version of public Boltzmann solver CLASS

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Lesgourgues & Tram, 1104.2935

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

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

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

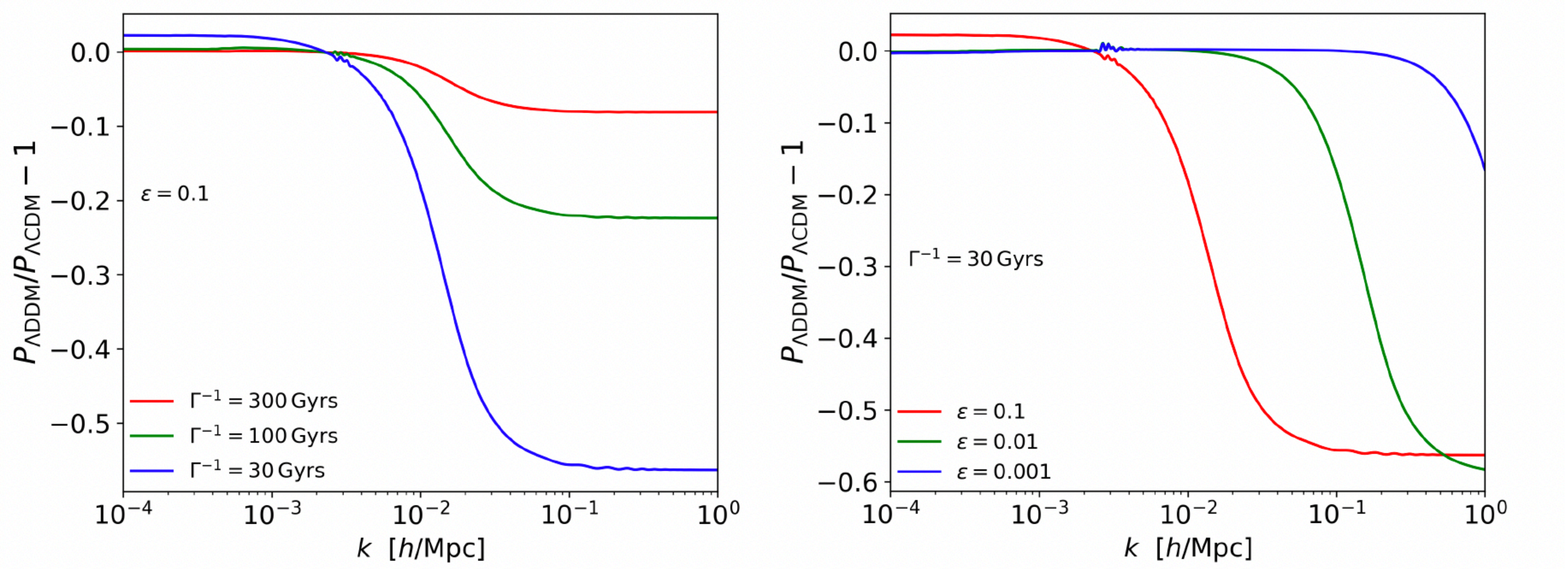
$$c^2_{\rm syn}(k,\tau) = c_a^2(\tau)\left[1 + (1-2\varepsilon)T(k/k_{\rm fs})\right]$$

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

*Implemented in modified version of public Boltzmann solver CLASS

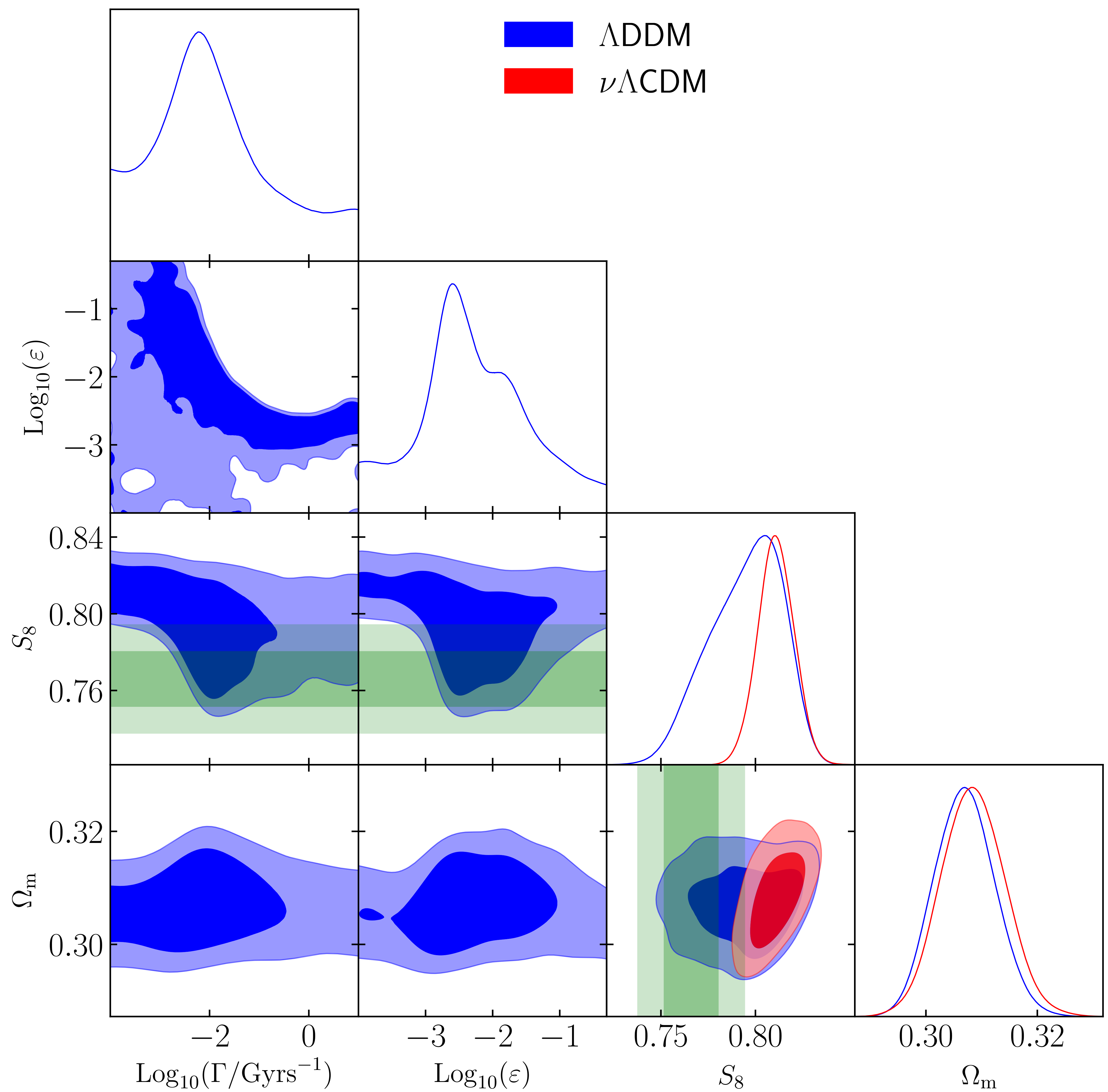
Impact of decaying DM on the matter spectrum

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



GFA, Murgia, Poulin 2008.09615

Resolution to the S_8 tension



GFA, Murgia, Poulin 2102.12498

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

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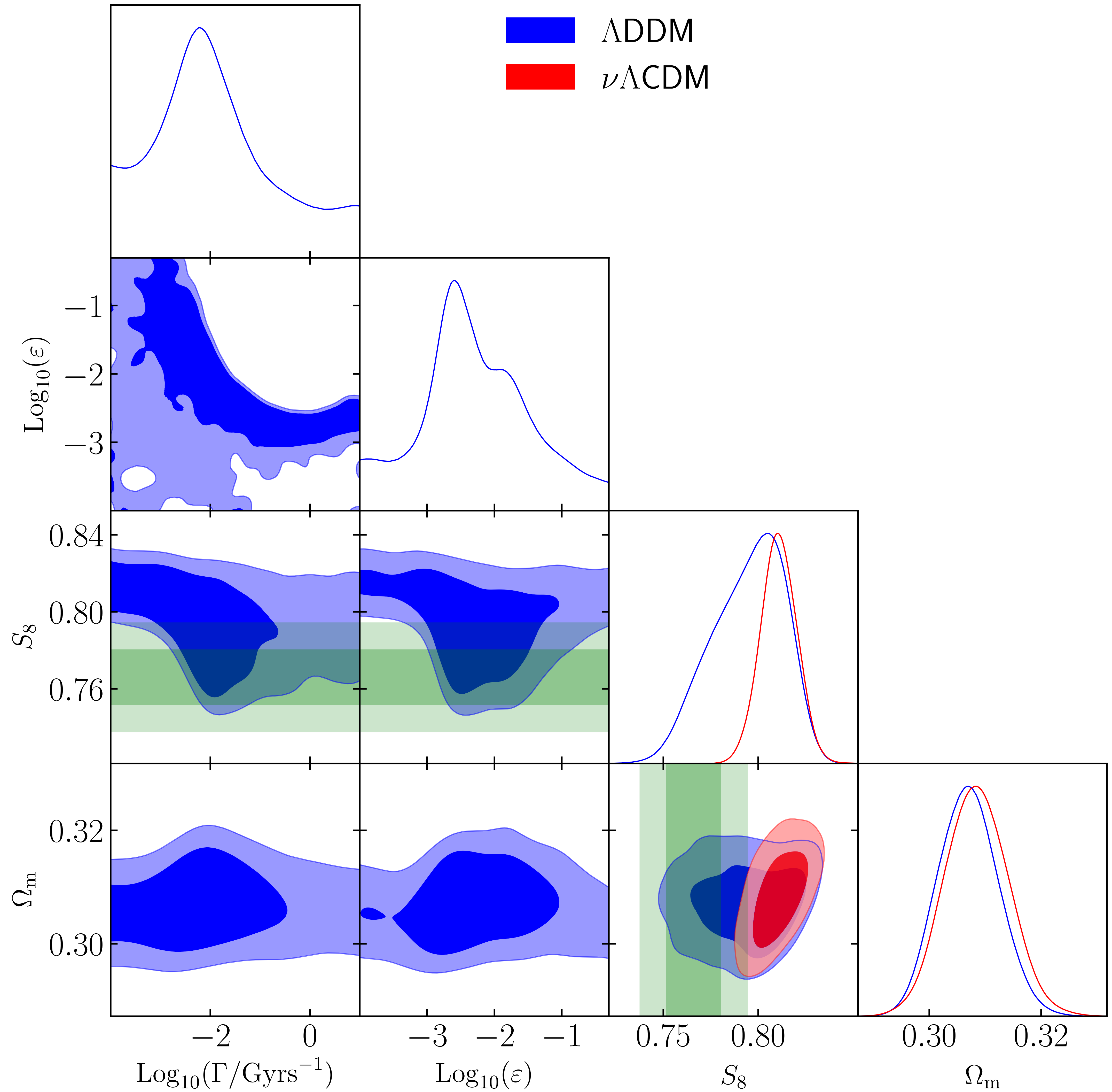


GFA, Murgia, Poulin 2102.12498

- 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!

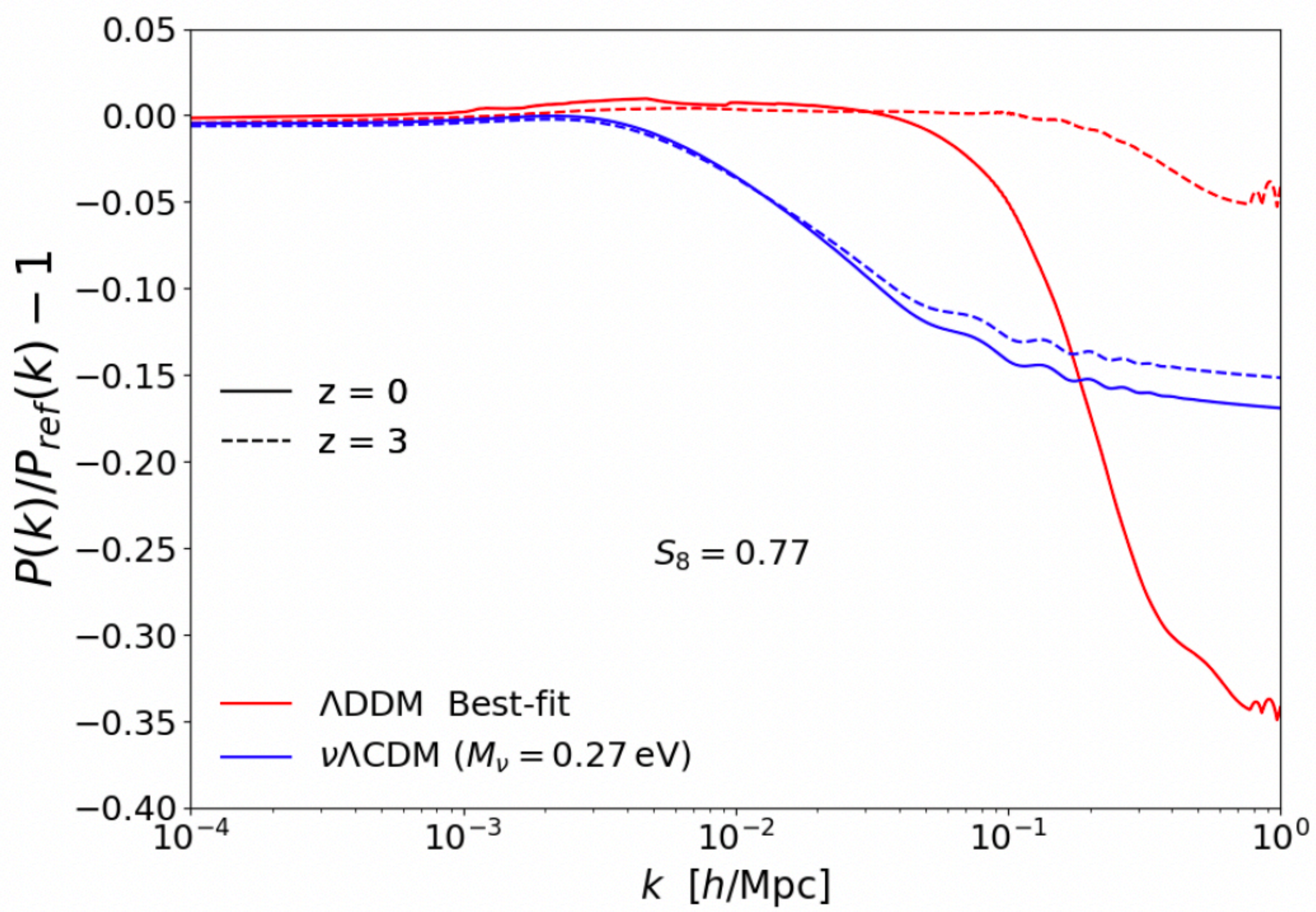
	$\nu\Lambda$CDM	ΛDDM
$\chi^2_{\rm CMB}$	1015.9	1015.2
$\chi^2_{S_8}$	5.64	0.002

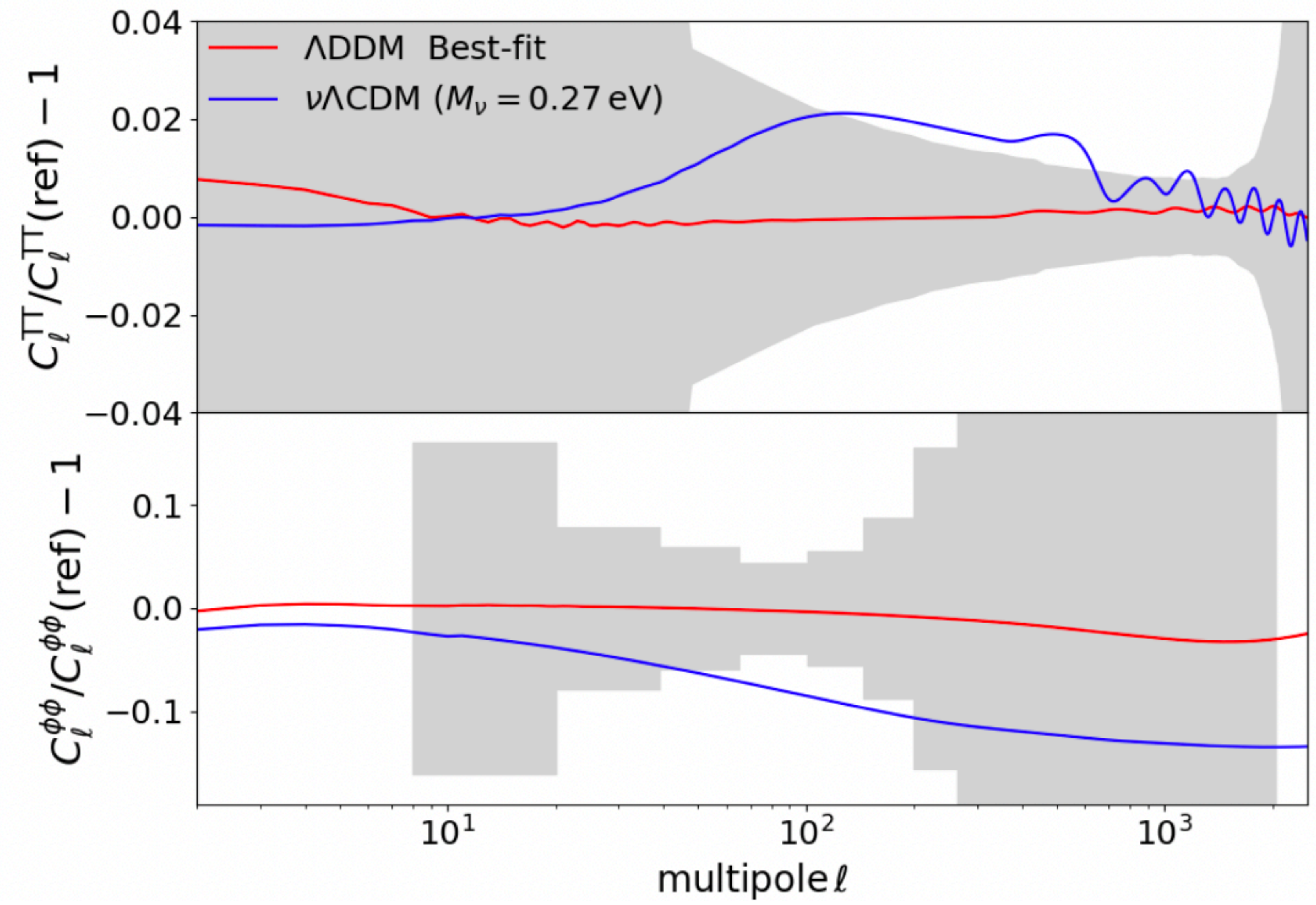
$$\longrightarrow \Delta\chi^2_{\rm min} \simeq -5.5$$

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

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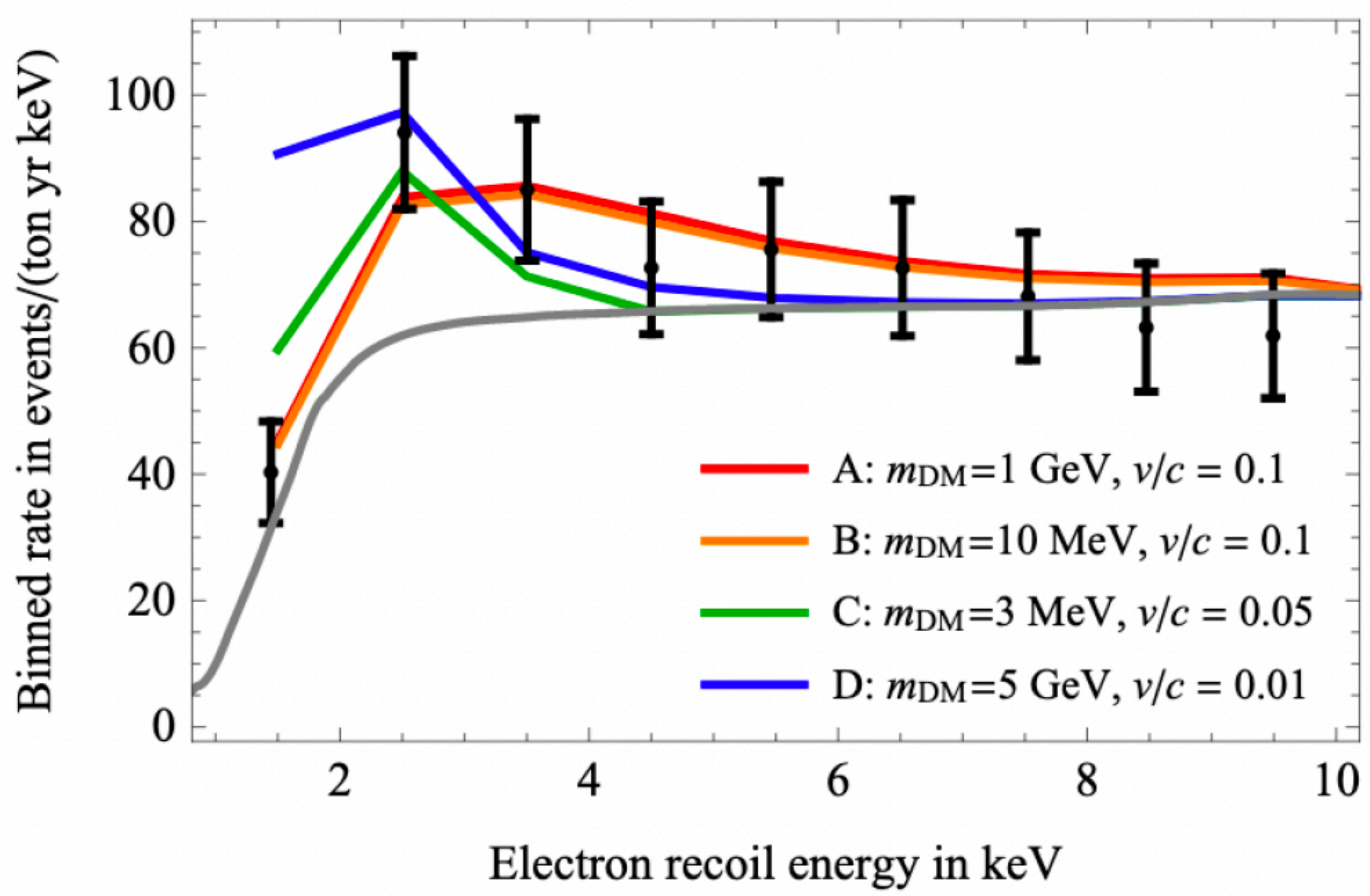
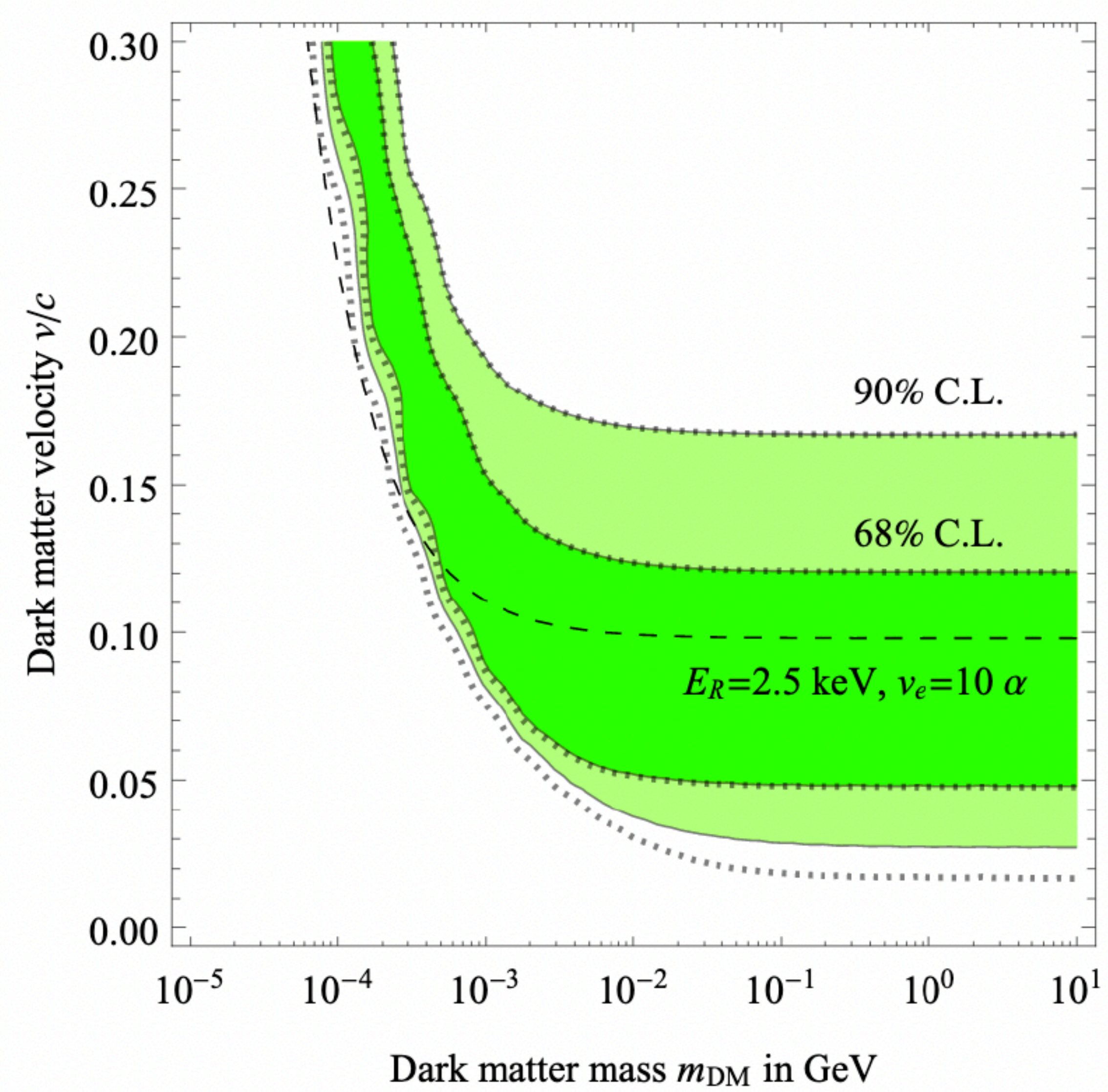
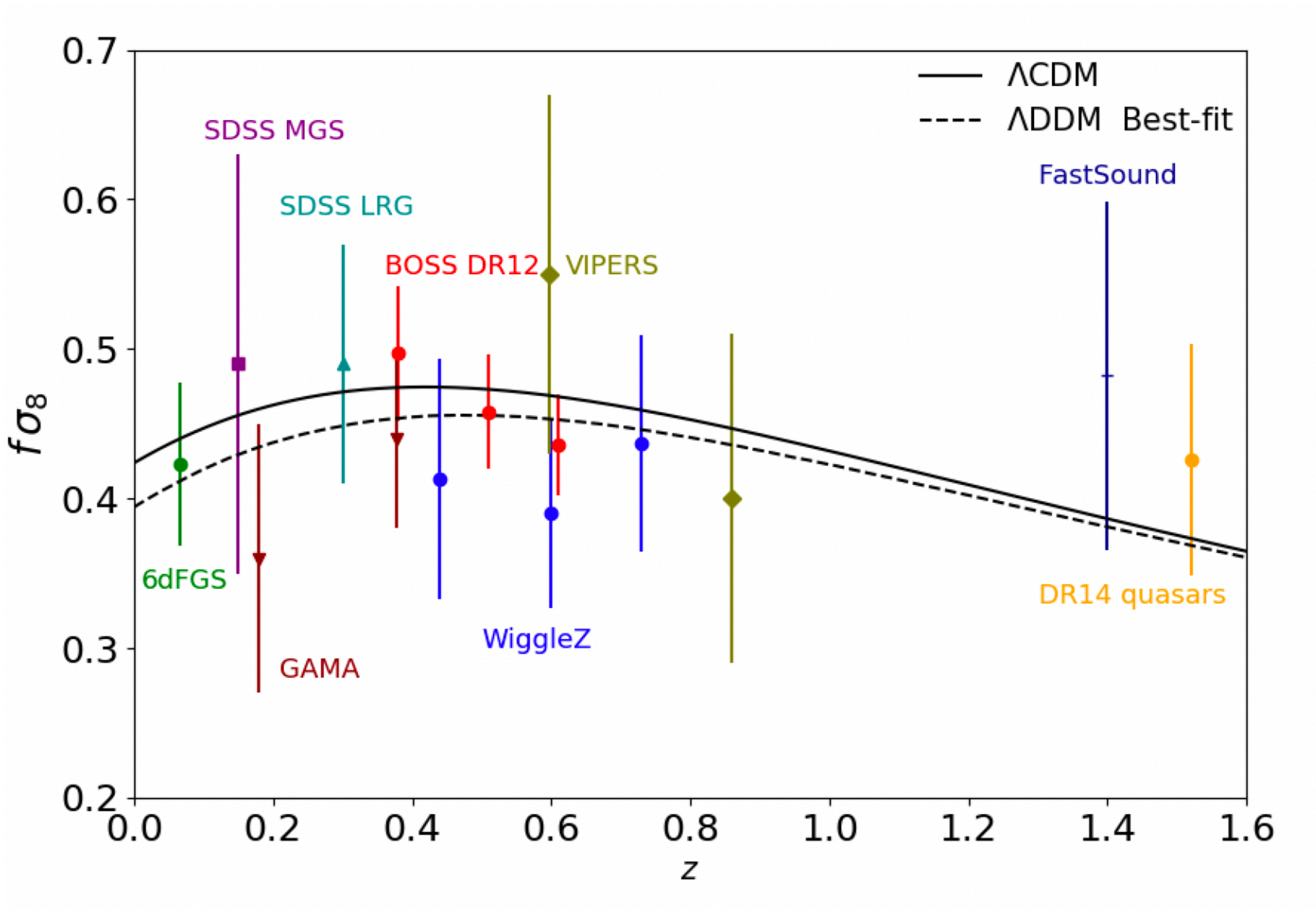
- Xenon-1T excess: It could be explained by a fast DM component, such as the WDM, with $v/c \simeq \varepsilon$ Kannike++ 2006.10735





Prospects for the 2-body DM decay

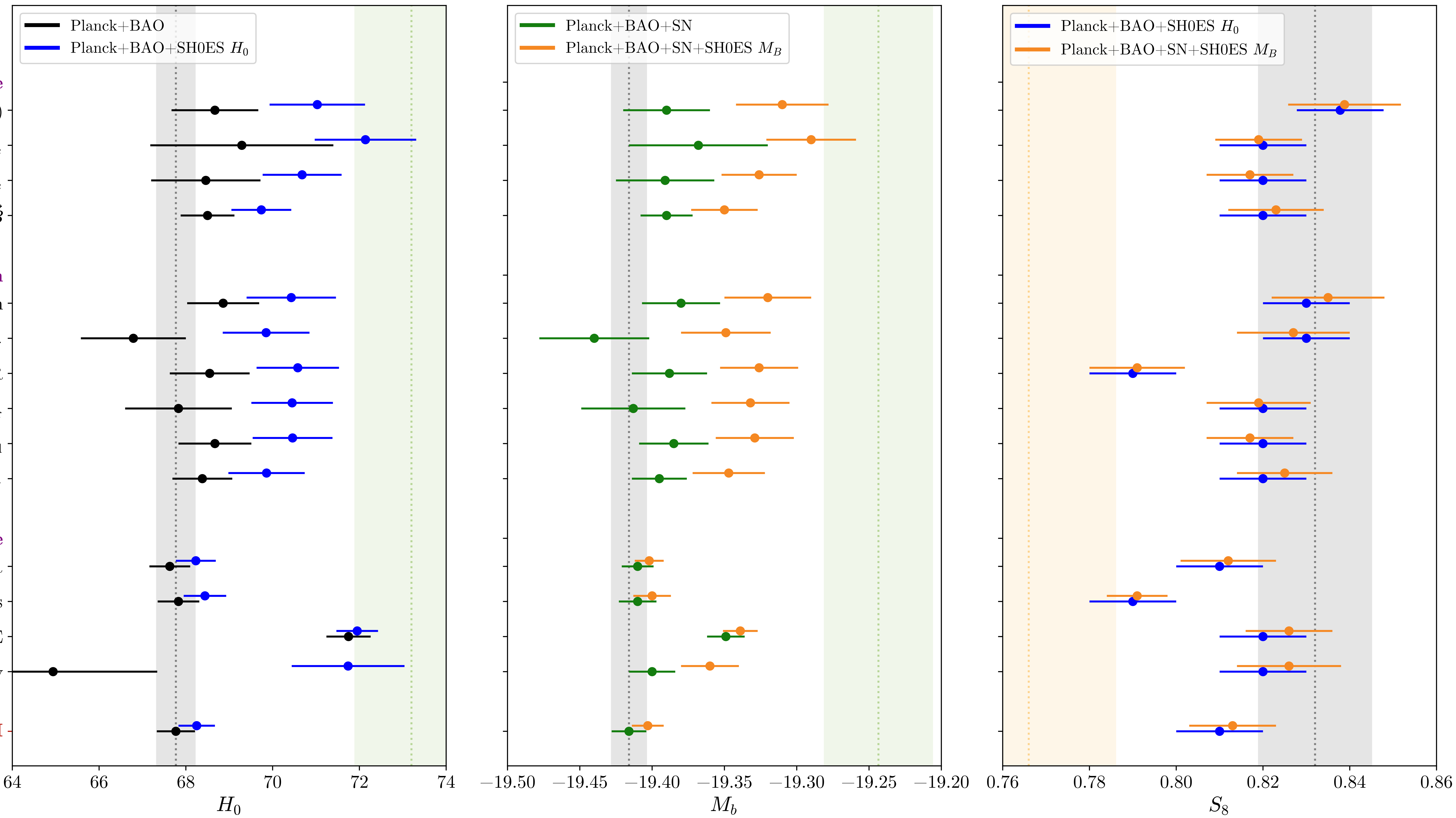


Accurate measurements of $f\sigma_8$ at $0 \lesssim z \lesssim 1$ will further test the 2-body decay

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

Addendum: The H_0 Olympics

Goal: Take a representative sample of proposed solutions, and quantify the relative success of each using certain metrics and a wide array of data



16 different models considered, including EDE and DM → DR +WDM

Schöneberg, GFA, Pérez, Witte, Poulin, Lesgourgues 2107.10291

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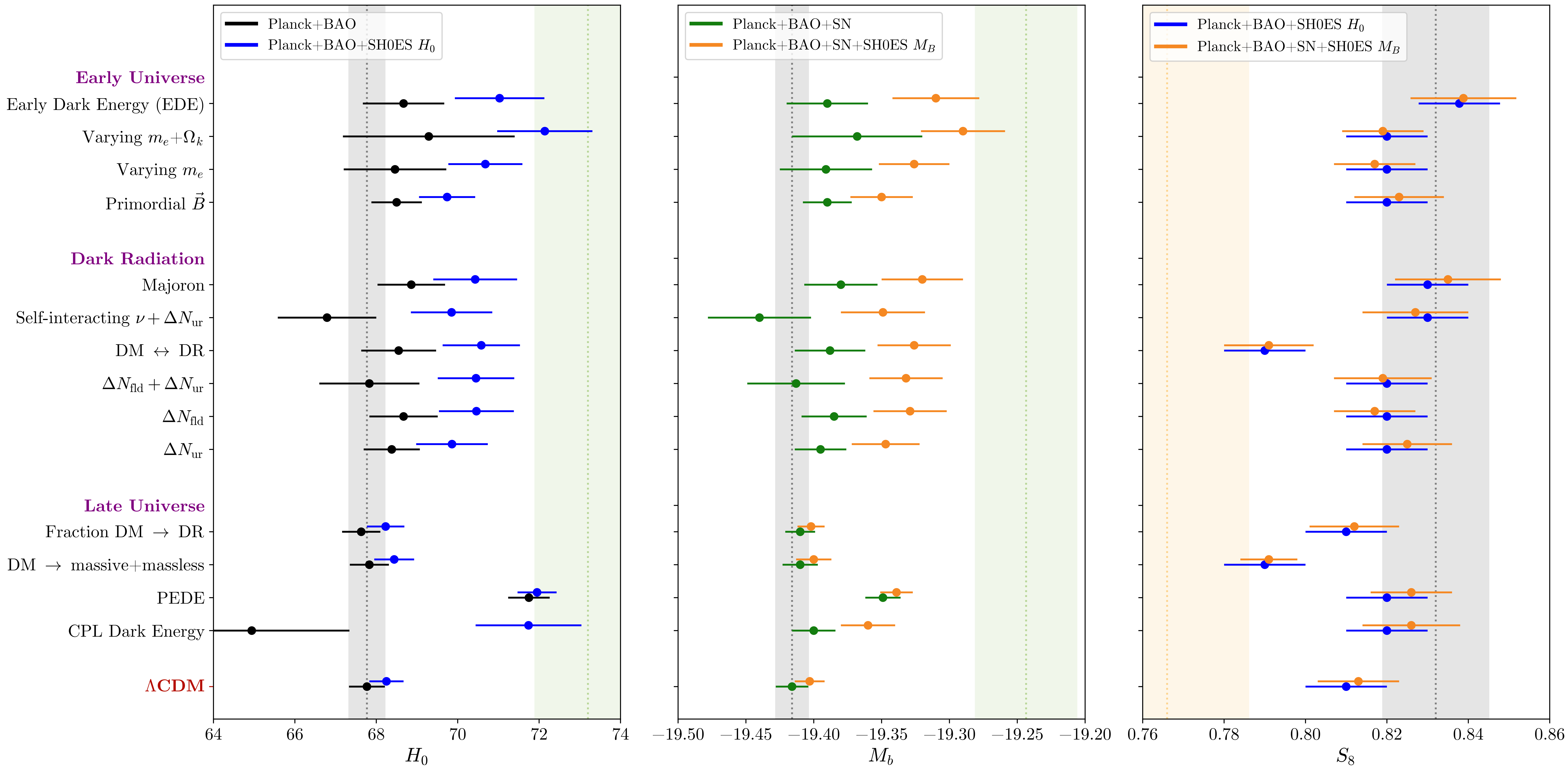

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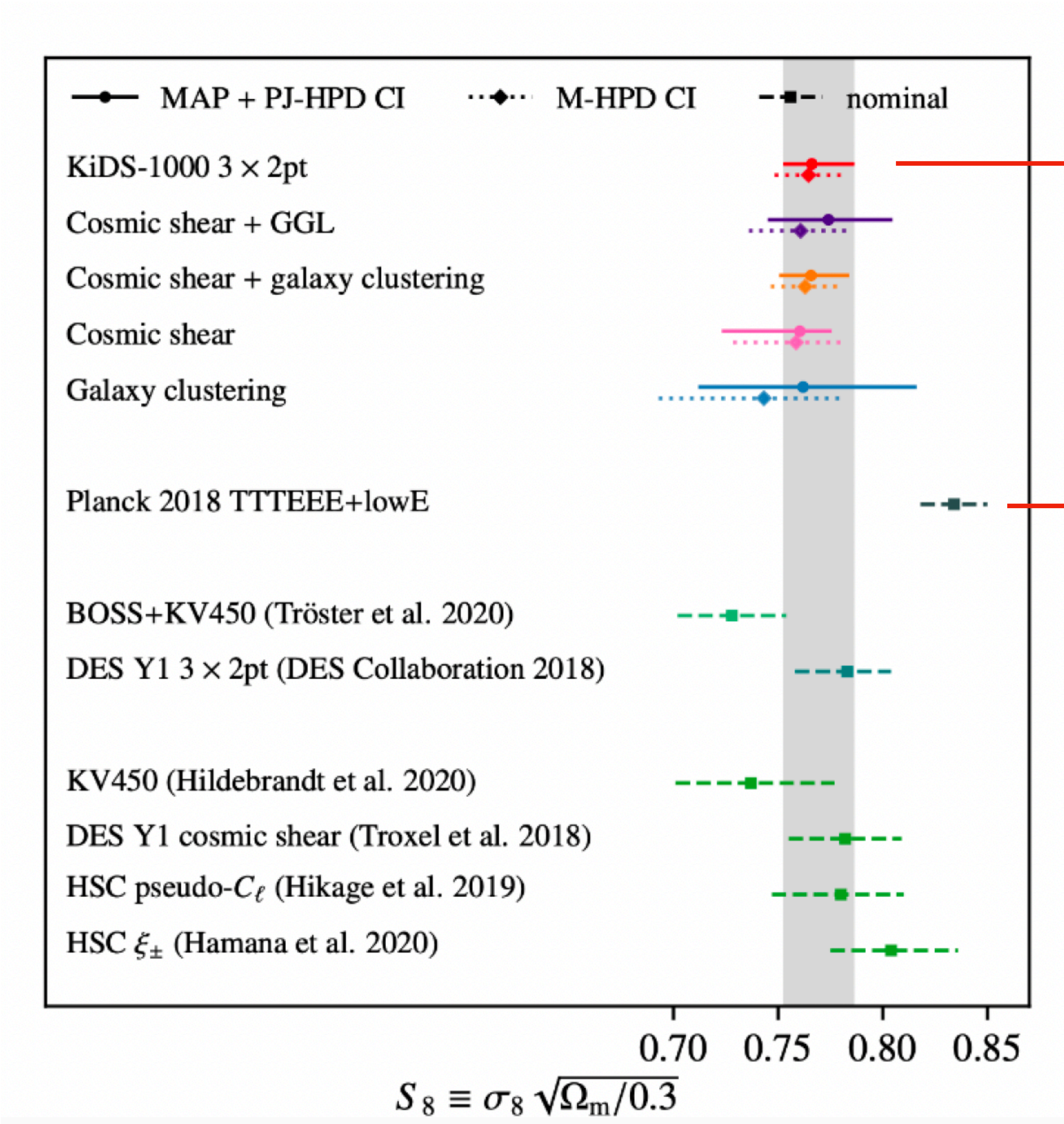
Clark++ 2110.09562

We might be on the verge of the discovery of a rich dark sector!

BACK-UP SLIDES

The S_8 tension



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

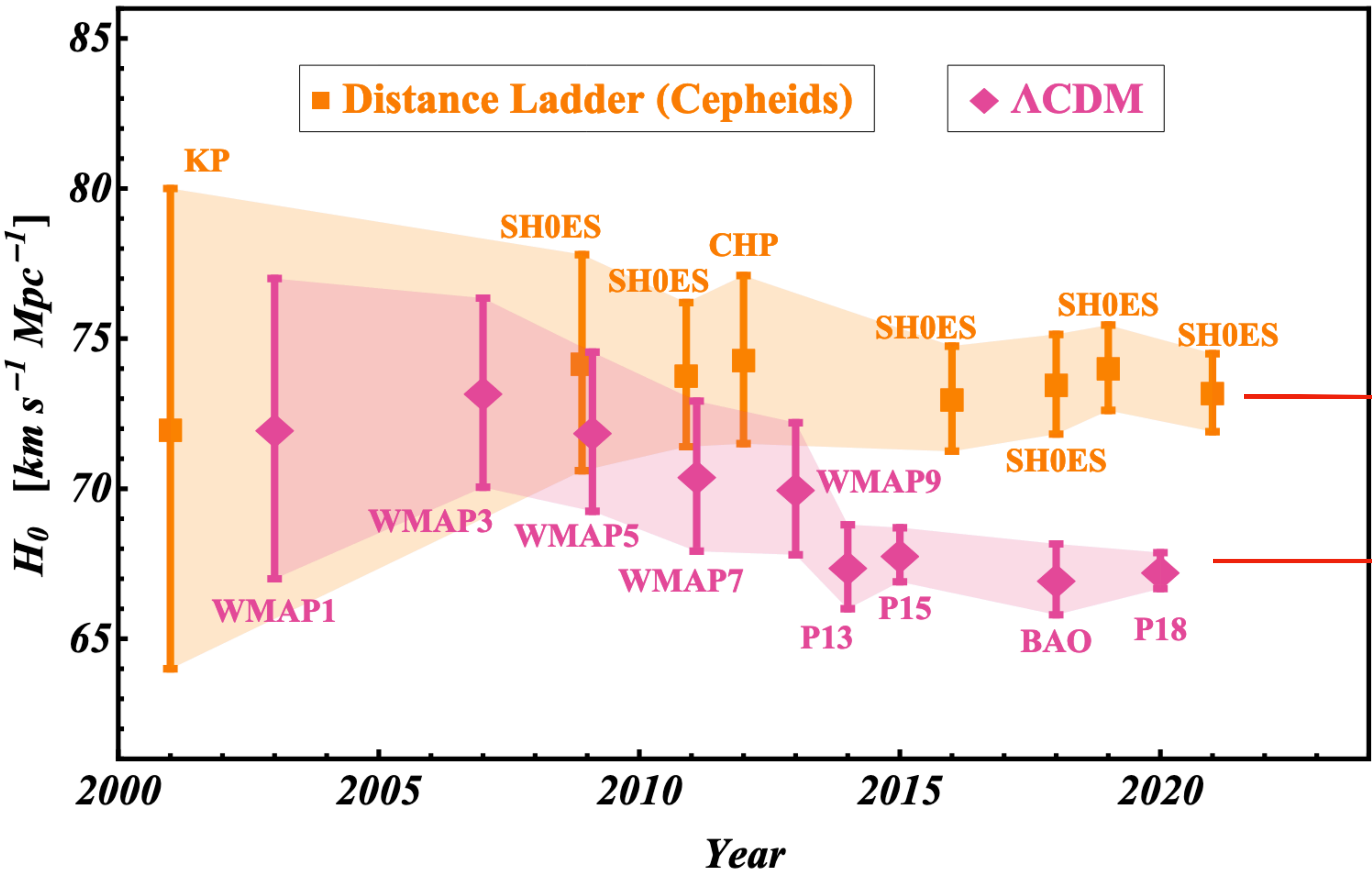
$$S_8 = 0.830 \pm 0.013$$

$$\Longrightarrow \sim 3\sigma \text{ tension}$$

Di Valentino++ 2008.11285

The H_0 tension

Predominantly driven by the Planck and SH0ES collaborations



$$H_0 = 73.2 \pm 1.3^*$$

$$H_0 = 67.27 \pm 0.6$$

$$\Longrightarrow \quad 4.1\sigma \text{ tension}$$

Perivolaropoulos&Skara 2105.05208

*Units of km/s/Mpc are always assumed

Decaying dark matter

- Dark matter (DM) is assumed to be perfectly stable in ΛCDM

Can we test this hypothesis?

- DM Decays to SM particles ⟶ very constrained

  From $\mathbf{e.m.}$ $\mathbf{impact}$ on CMB : $\Gamma^{-1} \gtrsim 10^8$ Gyr   Poulin++ 1610.10051

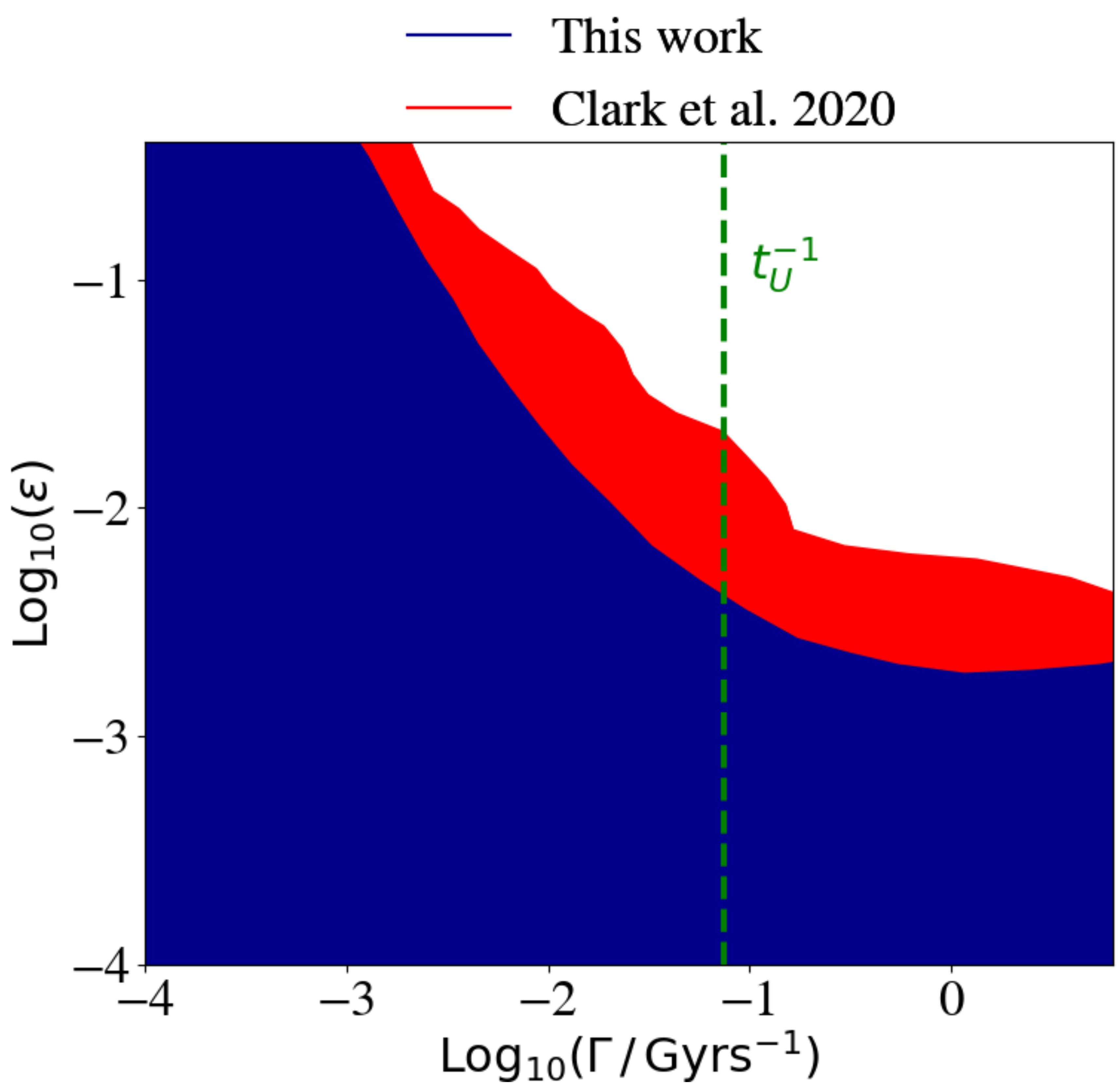
- DM decays to **massless** Dark Radiation ⟶ less constrained, but more model-independent

  From $\mathbf{grav.}$ $\mathbf{impact}$ on CMB : $\Gamma^{-1} \gtrsim 10^2$ Gyr   Audren++ 1407.2418
  Poulin++ 1606.02073

- What about massive products?

General constraints on the 2-body DM decay

Planck+BAO+SNIa analysis



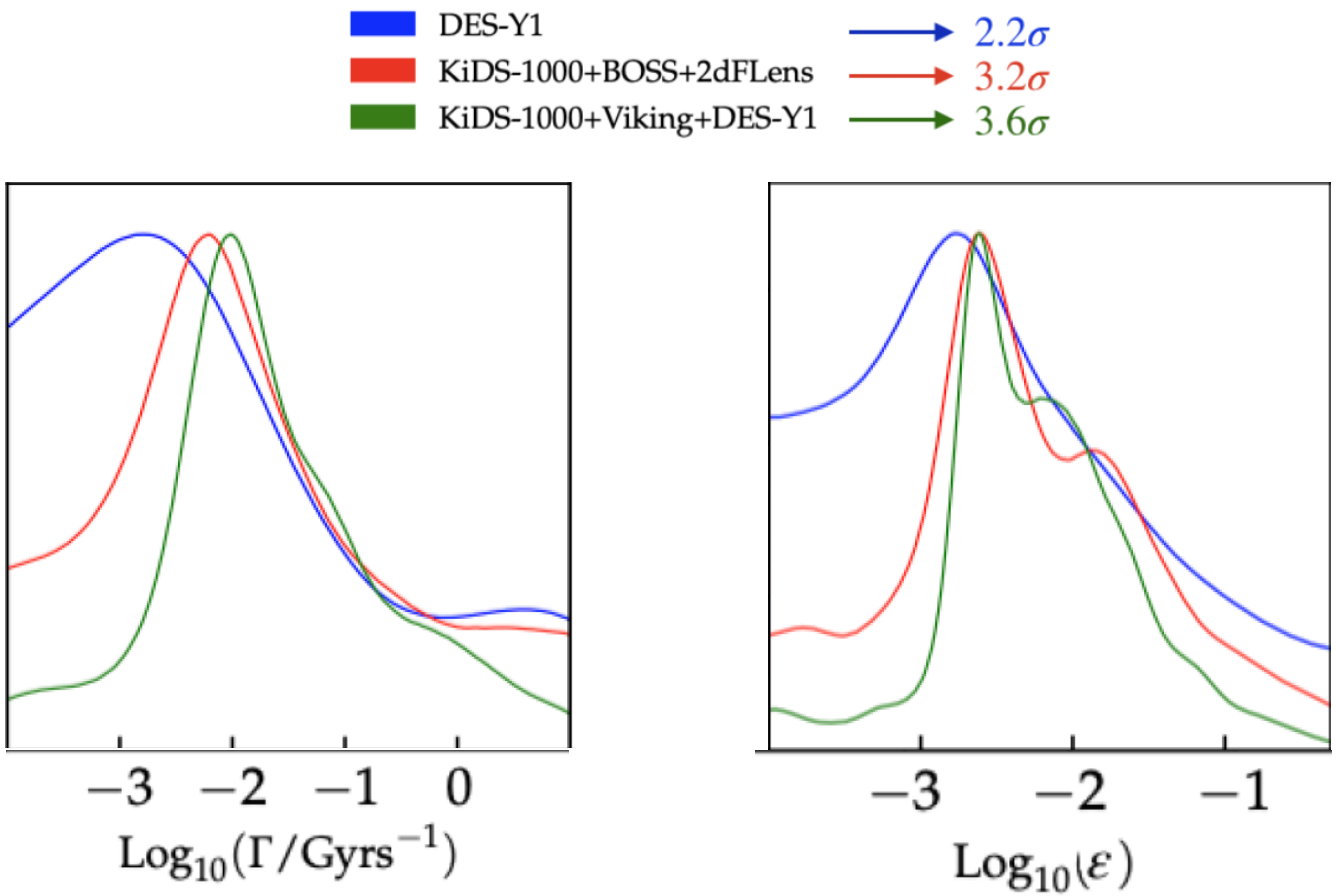
Strong negative correlation between ε and Γ

Constraints up to 1 order of magnitude stronger than previous literature

GFA, Murgia, Poulin 2008.09615

Resolution to the S_8 tension

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



GFA, Murgia, Poulin 2008.09615

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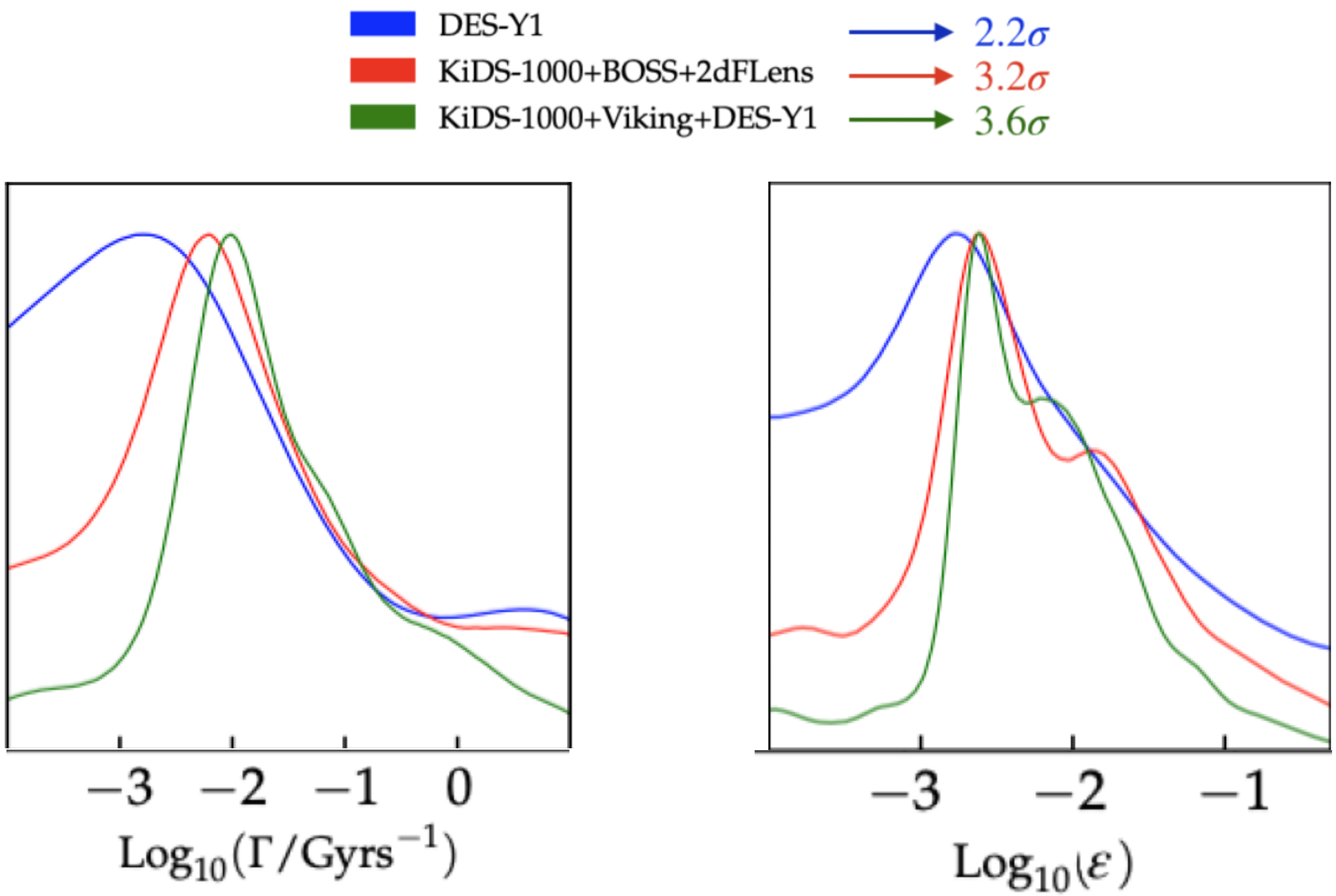

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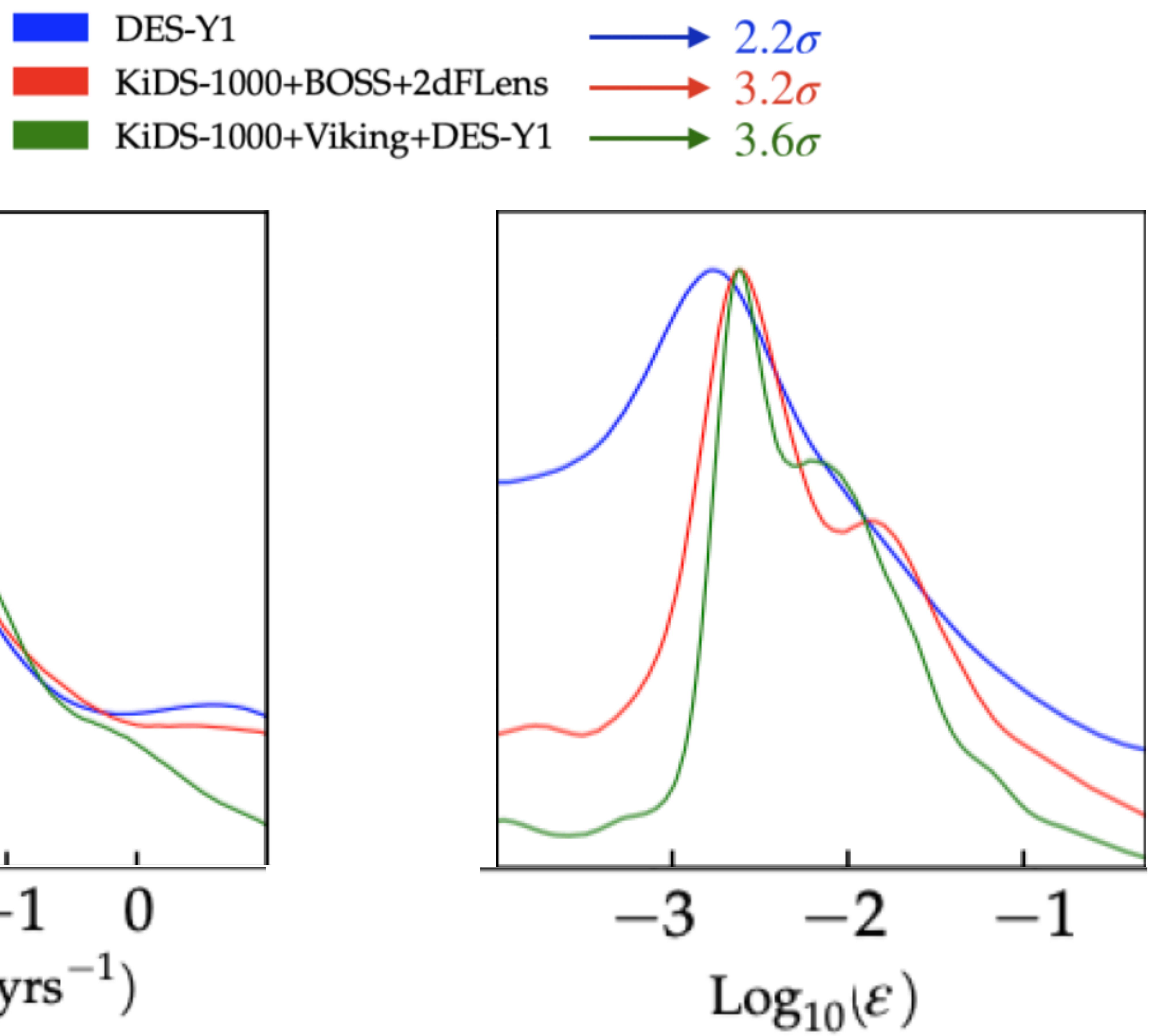

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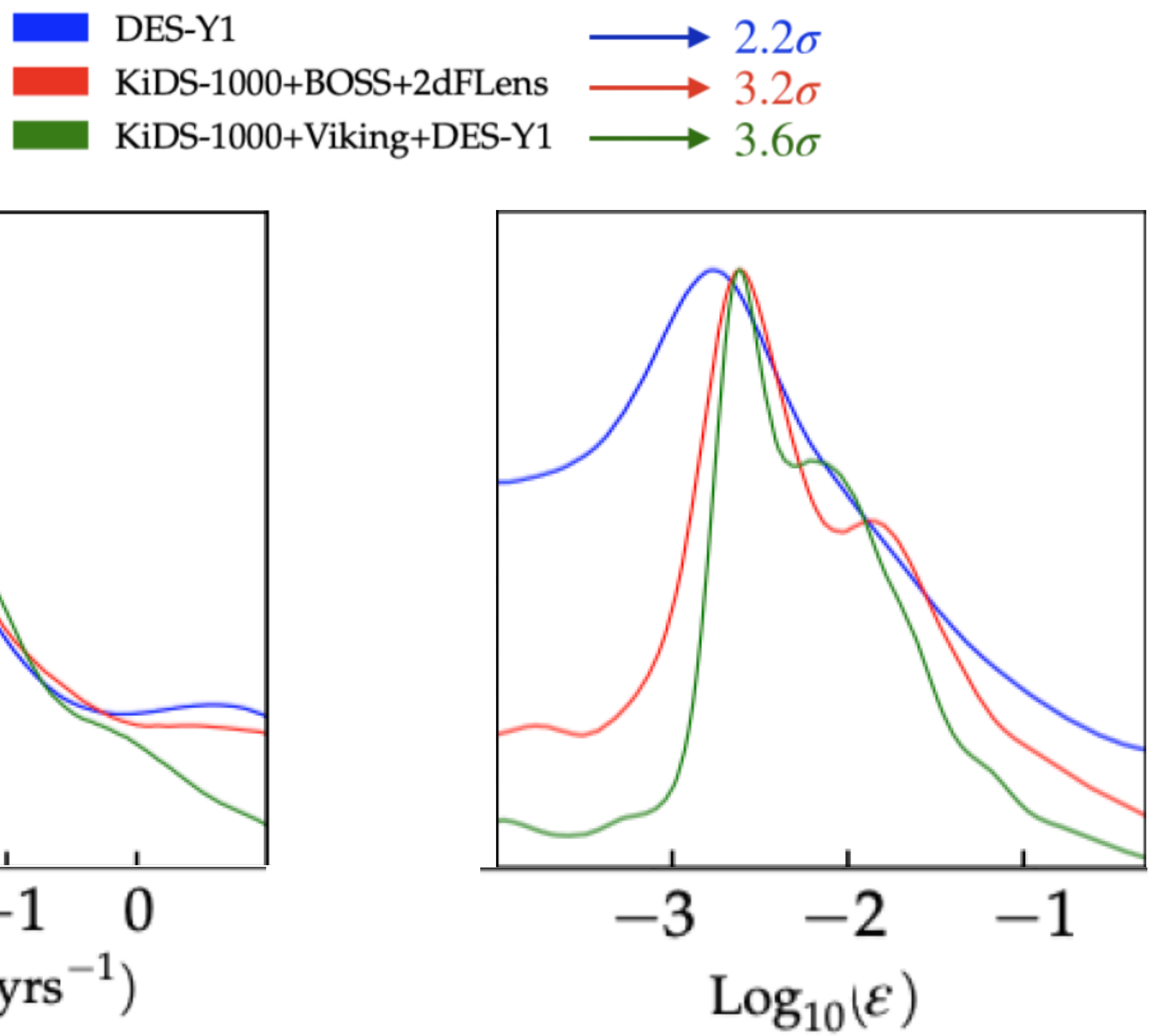

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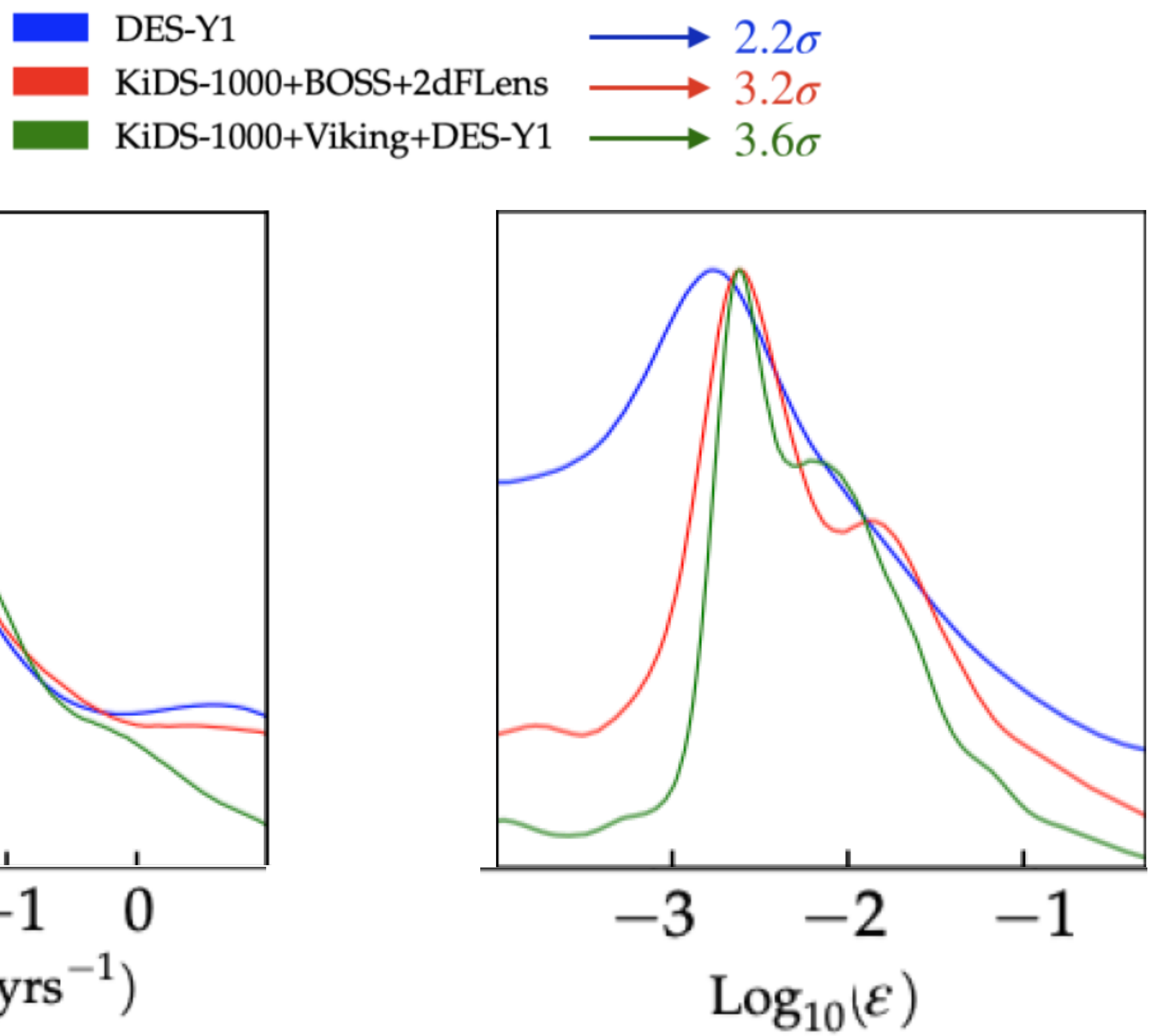

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