The H_0 and S_8 tensions necessitate early and late time changes to ΛCDM

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Based Upon:
arXiv: 2110.09562

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Introduction

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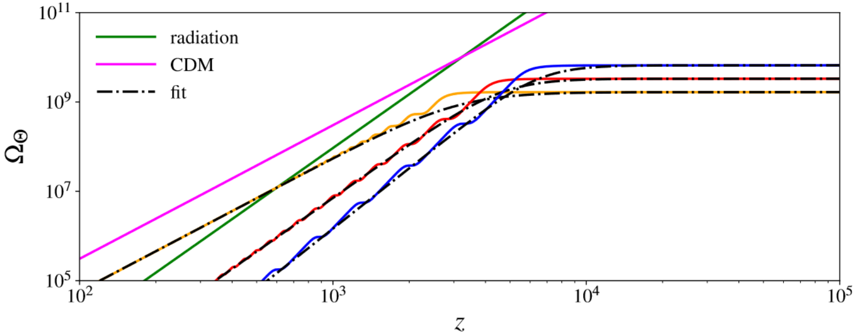
- The H_0 tension: Discrepancy between early and late time measurements of the Hubble Constant.
- S_8: While not to the same level, a discrepancy is forming between local measurements of the amount of structure in the Universe between our direct measurements and those inferred by other methods like CMB analysis.
- Attempts at resolving these differences have been met with minimal success.

- A subcomponent of the early Universe composed of dark energy that then undergoes a transition which causes it to dissipate.



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$$V(\phi) \propto (1 - \cos[\phi/f])^n$$

* arXiv: 1806.10608

Introduction: EDE

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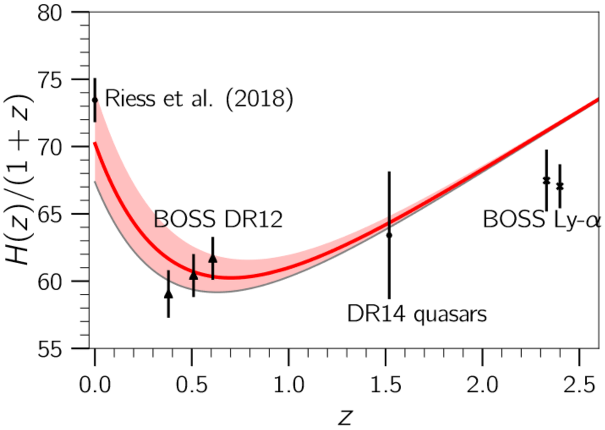
- The Bad: Results in an increase in structure formation turning a discrepancy into a tension in S_8.
- The Ugly: This is a general problem with most solutions that attempt to resolve the H_0 tension.

Introduction: Decaying Dark Matter (DDM)

- Dark matter decays into one massive and one massless daughter resulting in a shift in the budget equation.



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- The Ugly: The decrease to S_8 needs additional information to be selected.
  - This is not surprising considering the time period of both the measurements and the physics.
  - This is also true for many H_0 resolutions.

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- EDE increases H_0, but at the expense of also increasing S_8.
- DDM is unable to increase H_0, but it does have the capacity to influence S_8.
- Can a combination of the two yield produce an effect that individually, they are unable to achieve?

Implementation: EDE

- Equation of State

$$w_{\rm EDE} = w_0 + \frac{w_a}{2}\left\{1 - \tanh\left[\alpha \log_{10}(a_{\rm EDE}/a)\right]\right\}$$

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- Perturbations

$$\begin{aligned}\dot{\delta}_{\rm EDE} =& -(1 + w_{\rm EDE})\left(\theta_{\rm EDE} + \frac{\dot{h}}{2}\right) - 3(c_s^2 - w_{\rm EDE})\mathcal{H}\delta_{\rm EDE} \\ & - 9(1 + w_{\rm EDE})(c_s^2 - c_a^2)\mathcal{H}\frac{\theta_{\rm EDE}}{k^2} \\ \dot{\theta}_{\rm EDE} =& -(1 - 3c_s^2)\mathcal{H}\theta_{\rm EDE} + \frac{c_s^2 k^2}{1 + w_{\rm EDE}}\delta_{\rm EDE}\end{aligned}$$

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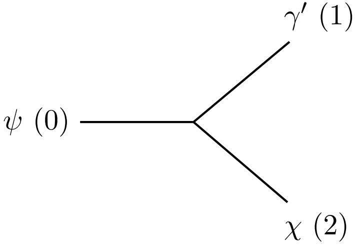
$$\dot{\theta}_{\rm EDE} = -\,(1 - 3c_s^2)\mathcal{H}\theta_{\rm EDE} + \frac{c_s^2 k^2}{1 + w_{\rm EDE}}\delta_{\rm EDE}$$

- Sound Speeds

$$c_a^2 = -2 - w_n \qquad c_s^2 = \frac{4a^2 w_n \overline{\omega}^2 + (1 - w_n)k^2}{4a^2\overline{\omega}^2 + (1 - w_n)k^2}$$
$$w_n = (n-1)/(n+1) \qquad \overline{\omega} = \overline{\omega}_0 a^{-3w_n}$$

Implementation: DDM



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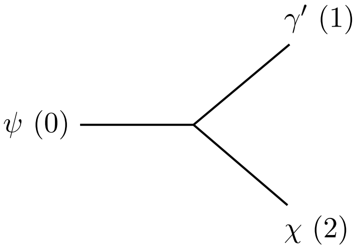

- Background Density Evolution

$$
\begin{aligned}
\dot{\bar{\rho}}_0 &= -3\mathcal{H}\bar{\rho}_0 - a\Gamma\bar{\rho}_0 \\
\dot{\bar{\rho}}_1 &= -4\mathcal{H}\bar{\rho}_1 + \epsilon a\Gamma\bar{\rho}_0 \\
\dot{\bar{\rho}}_2 &= -3(1+w_2)\mathcal{H}\bar{\rho}_2 + (1-\epsilon)a\Gamma\bar{\rho}_0
\end{aligned}
$$

- Parent

$$\dot{\delta}_0 = -\frac{\dot{h}}{2}$$

Implementation: DDM - Perturbations

- Parent

$$\dot{\delta}_0 = -\frac{\dot{h}}{2}$$

- Massless Daughter

$$\begin{aligned}
(\delta_1 \dot{r}_1) &= -\frac{4}{3} r_1 \theta_1 - \frac{2}{3} r_1 \dot{h} + \dot{r}_1 \delta_0 \\
\frac{4}{3k} (\theta_1 \dot{r}_1) &= \frac{k}{3} \delta_1 r_1 - \frac{4k}{3} r_1 \sigma_1 \\
2(\sigma_1 \dot{r}_1) &= \frac{8}{15} \theta_1 r_1 + \frac{4}{15} r_1 (\dot{h} + 6\dot{\eta}) + \text{h.o.}
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\end{aligned}$$

- Note that it is the same as the non decaying version apart from a non-zero $\dot{r}_1 \propto \Gamma$

Implementation: DDM - Perturbations

- Massive Daughter

$$\dot{\delta}_2 = -3\mathcal{H}(c_{sg}^2 - w_2)\delta_2 - (1+w_2)\left(\theta_2 + \frac{\dot{h}}{2}\right) + (1-\epsilon)a\Gamma\,\frac{\overline{\rho}_0}{\overline{\rho}_2}\,(\delta_0 - \delta_2)$$

$$\dot{\theta}_2 = -\mathcal{H}(1-3c_g^2)\theta_2 + \frac{c_{sg}^2}{1+w_2}k^2\delta_2 - k^2\sigma_2 - (1-\epsilon)a\Gamma\frac{1+c_g^2}{1+w_2}\frac{\overline{\rho}_0}{\overline{\rho}_2}\theta_2$$

$$c_{sg}^2 \equiv \delta P_2/\delta\rho_2 \qquad\qquad c_g^2 \equiv \dot{\overline{P}}_2/\dot{\overline{\rho}}_2$$

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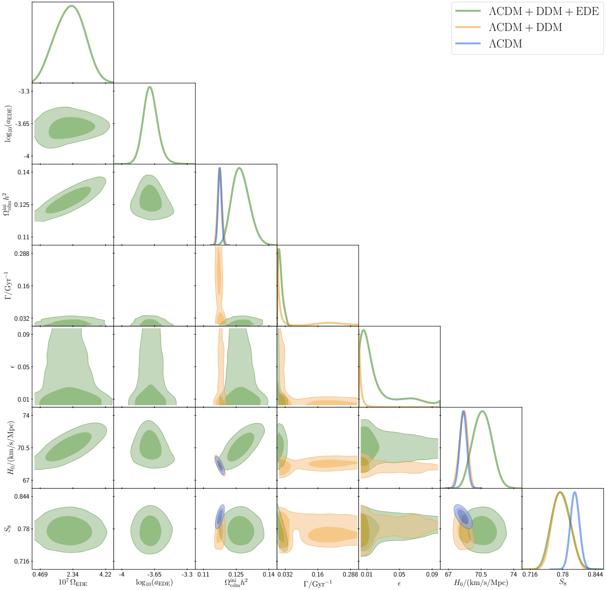
$$c_{sg}^2 \equiv \delta P_2/\delta\rho_2 \qquad\qquad c_g^2 \equiv \dot{\overline{P}}_2/\dot{\overline{\rho}}_2$$

- Once again, reduces to warm dark matter equation when $\Gamma = 0$.

Results: Model Comparison



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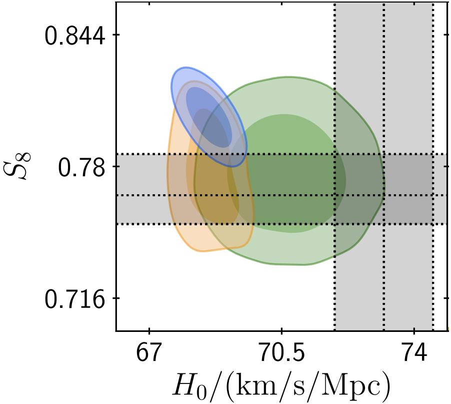
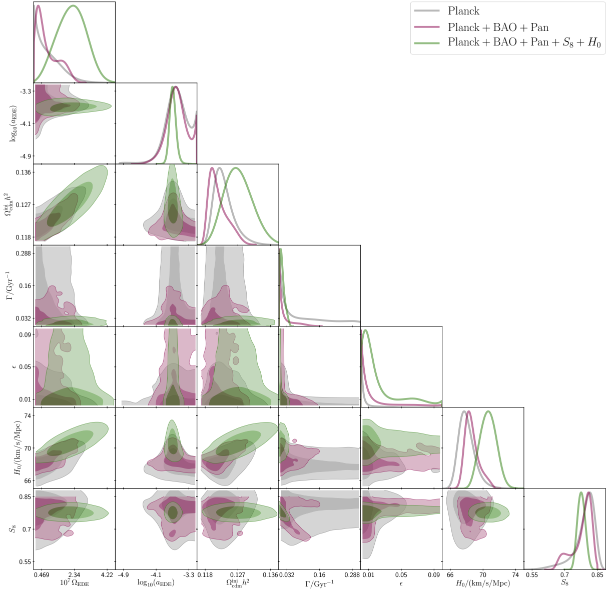


Results: Model Comparison - Figure Main Points

- (Note: not shown) While EDE does provide an increase to the preferred value of H_0, with large scale structure data included, this increase is greatly suppressed.
- DDM results in a reduction to S_8 without changing the matter densities much.
- Using EDE + DDM, both H_0 and S_8 discrepancies are reduced.
- The selection of the lower Γ region in EDE + DDM is a combined effect of increased matter to satisfy H_0, leads to a larger ϵ to satisfy S_8. With this combination, the lensing potential prefers lower Γ as it is more sensitive to changes in ϵ.

Results: Dataset Comparison



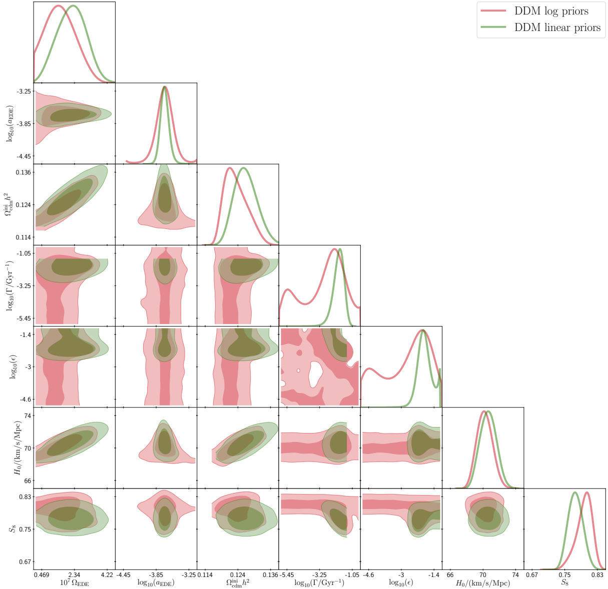
Results: Dataset Comparison - Figure Main Points

- Planck measurements alone do not constrain the model well as expected as EDE and DDM separately at best have a mild preference.

- BAO + Pantheon do not improve much. But, in S_8 - Γ two branches form representing the ΛCDM degenerate region, and a second branch with substantial decays.

- With the S_8 and H_0 priors, the lower branch is selected.

Results: Search Parameter Comparison



Results: Search Parameter Comparison - Figure Main Points

- In many works involving DDM, the DDM parameters are performed in log scale.
- Because the model is not preferred over the base model (ΛCDM), large degeneracies are produced.
- These degenerate regions are effected by the choice of prior and can mask features.

Summary

- The difficulty in resolving H_0 and S_8 may be an indicator that alteration need to be done at multiple cosmological periods.
- Individually, EDE and DDM are unable to resolve both tensions.
- However, together, their synergistic properties allow them to overcome their individual weaknesses and produce an overall improved result.
- This is just one example, and more work needs to be done on the strengths of multiple adjustments.

Thank You!

Supplemental: Model Comparison Table

Model	ΛCDM	ΛCDM + DDM	ΛCDM + EDE
Dataset	Planck + BAO + Pan + S_8 + H_0		
$100\ \Omega_b h^2$	$2.260^{+0.013}_{-0.013}$	$2.261^{+0.014}_{-0.014}$	$2.275^{+0.020}_{-0.020}$
$100\ \theta_s$	$1.04211^{+0.00029}_{-0.00028}$	$1.04211^{+0.00028}_{-0.00029}$	$1.04164^{+0.00039}_{-0.00036}$
$\ln(10^{10} A_s)$	$3.048^{+0.014}_{-0.015}$	$3.044^{+0.016}_{-0.018}$	$3.052^{+0.014}_{-0.015}$
n_s	$0.9716^{+0.0038}_{-0.0036}$	$0.9719^{+0.0039}_{-0.0039}$	$0.9794^{+0.0060}_{-0.0065}$
$\tau_{\rm reio}$	$0.0581^{+0.0071}_{-0.0078}$	$0.0567^{+0.0076}_{-0.0084}$	$0.0569^{+0.0068}_{-0.0079}$
$\Omega^{\rm ini}_{\rm cdm} h^2$	$0.11748^{+0.00080}_{-0.00083}$	$0.1175^{+0.0009}_{-0.0010}$	$0.1230^{+0.0029}_{-0.0036}$
$\Gamma/{\rm Gyr}^{-1}$	–	Unconstrained	–
ϵ	–	< 0.00476	–
$10^7 \Omega_{\rm EDE}$	–	–	$1.41^{+0.68}_{-0.81}$
$\log_{10}(a_{\rm EDE})$	–	–	$-3.68^{+0.10}_{-0.12}$
$H_0/({\rm km/s/Mpc})$	$68.58^{+0.38}_{-0.38}$	$68.60^{+0.46}_{-0.42}$	$70.18^{+0.87}_{-1.05}$
S_8	$0.8039^{+0.0090}_{-0.0092}$	$0.777^{+0.016}_{-0.019}$	$0.812^{+0.010}_{-0.011}$
m	28	30	30
AIC	3938.70	3935.32	3936.96
ΔAIC	–	-3.38	-1.74

Supplemental: Dataset Comparison Table

Model	ΛCDM + DDM + EDE		
Dataset	Planck + BAO + Pan + S_8 + H_0	Planck	Planck + BAO + Pan
$100\ \Omega_b h^2$	$2.275^{+0.020}_{-0.020}$	$2.239^{+0.018}_{-0.021}$	$2.251^{+0.015}_{-0.019}$
$100\ \theta_s$	$1.04138^{+0.00041}_{-0.00039}$	$1.04163^{+0.00039}_{-0.00033}$	$1.04177^{+0.00040}_{-0.00032}$
$\ln(10^{10} A_s)$	$3.064^{+0.015}_{-0.017}$	$3.053^{+0.016}_{-0.016}$	$3.052^{+0.013}_{-0.017}$
n_s	$0.9825^{+0.0063}_{-0.0066}$	$0.9679^{+0.0051}_{-0.0074}$	$0.9710^{+0.0042}_{-0.0068}$
$\tau_{\rm reio}$	$0.0594^{+0.0072}_{-0.0082}$	$0.0559^{+0.0076}_{-0.0081}$	$0.0570^{+0.0063}_{-0.0079}$
$\Omega^{\rm ini}_{\rm cdm} h^2$	$0.1273^{+0.0036}_{-0.0042}$	$0.1231^{+0.0016}_{-0.0035}$	$0.1217^{+0.0015}_{-0.0032}$
$\Gamma/{\rm Gyr}^{-1}$	< 0.0172	< 0.138	< 0.0256
ϵ	< 0.0160	< 0.00527	< 0.0184
$10^7 \Omega_{\rm EDE}$	$2.16^{+0.81}_{-0.87}$	< 1.09	< 1.00
$\log_{10}(a_{\rm EDE})$	$-3.691^{+0.064}_{-0.076}$	$-3.61^{+0.26}_{-0.28}$	$-3.61^{+0.24}_{-0.26}$
$H_0/({\rm km/s/Mpc})$	$70.64^{+0.96}_{-1.04}$	$68.00^{+0.67}_{-1.19}$	$68.61^{+0.54}_{-1.04}$
S_8	$0.776^{+0.017}_{-0.019}$	$0.792^{+0.060}_{-0.021}$	$0.780^{+0.056}_{-0.016}$
m	32	31	32
AIC	3931.98	2840.22	3926.72
ΔAIC	-6.72	—	—