Thermal Friction as a Solution to the Hubble and the Large-Scale Structure Tensions

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Based on 2204.09133

The Hubble Tension

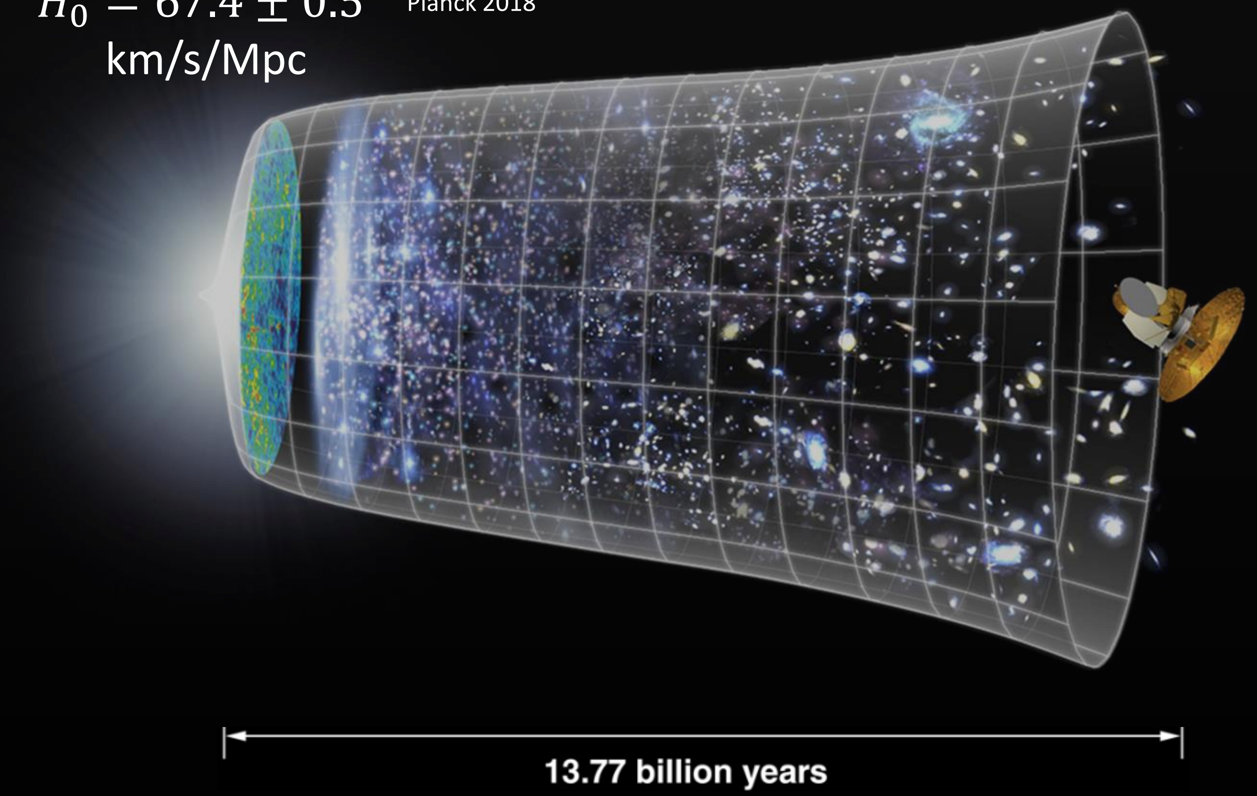
ΛCDM +
CMB measurement

$H_0 = 67.4 \pm 0.5$ km/s/Mpc Planck 2018

~ 5 σ

Direct
measurement

$H_0 = 73.3 \pm 1.0$ km/s/Mpc SH0ES 2022



The Large-Scale Structure Tension

ΛCDM +
CMB measurement

$S_8 = 0.82 \pm 0.01$ Planck 2018

~ 2 - 3 σ

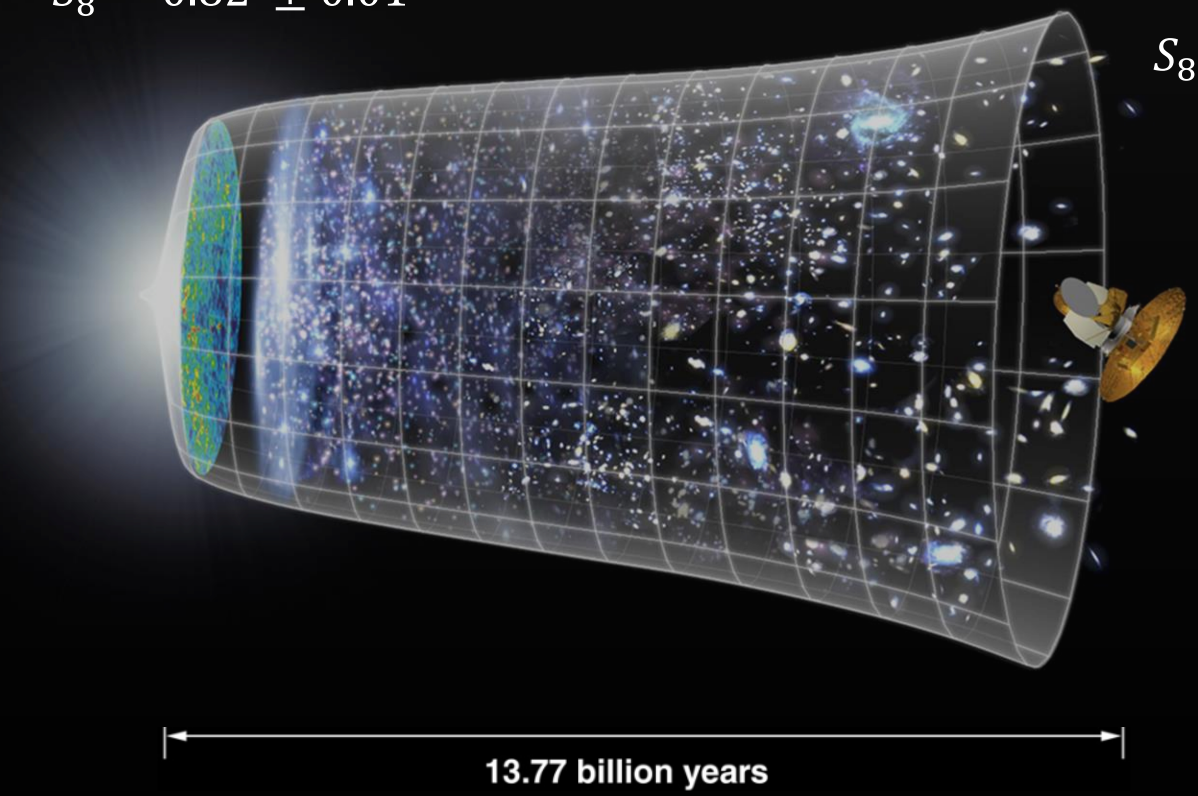
↔

Galaxy clustering
+ weak lensing
(DES Y1)

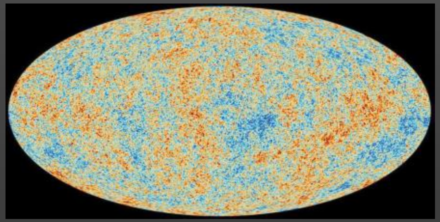
$S_8 = 0.77 \pm 0.02$ DES 2017

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

Amplitude of matter fluctuations

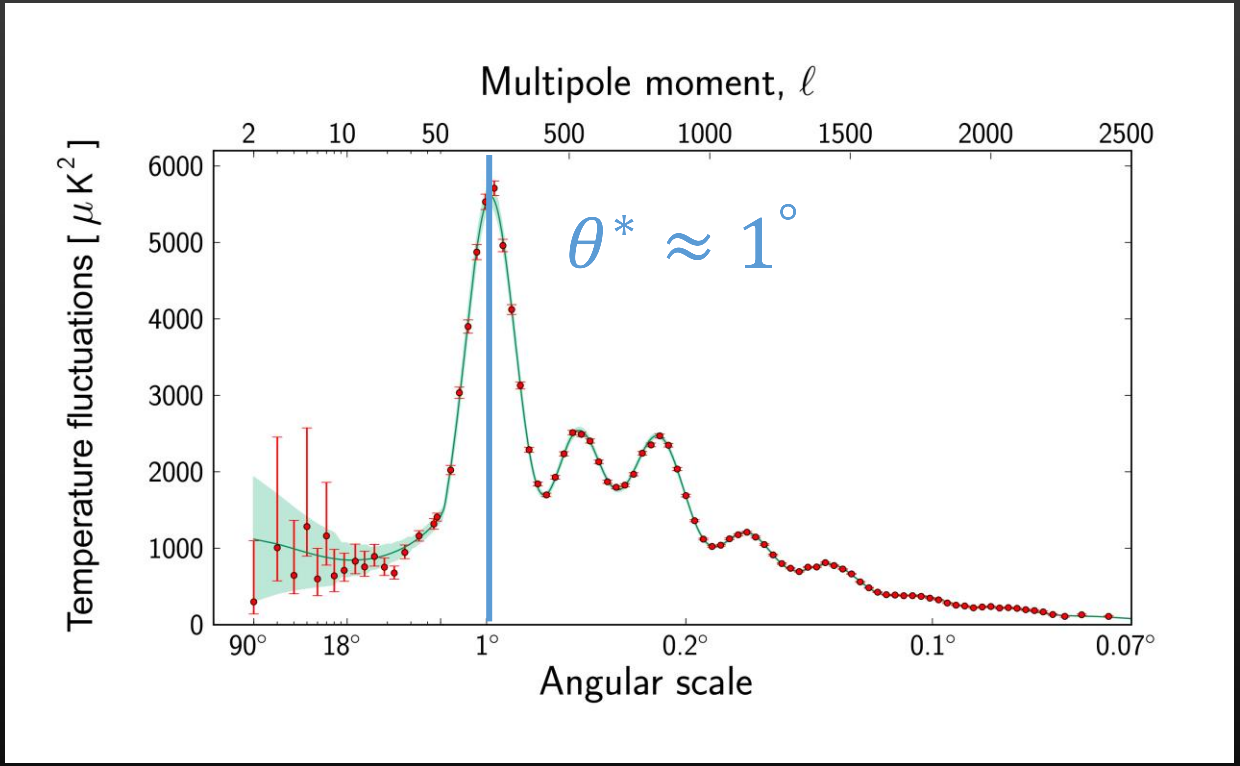


The Hubble Measurement with the CMB



$$\theta^* \propto r_s H_0$$

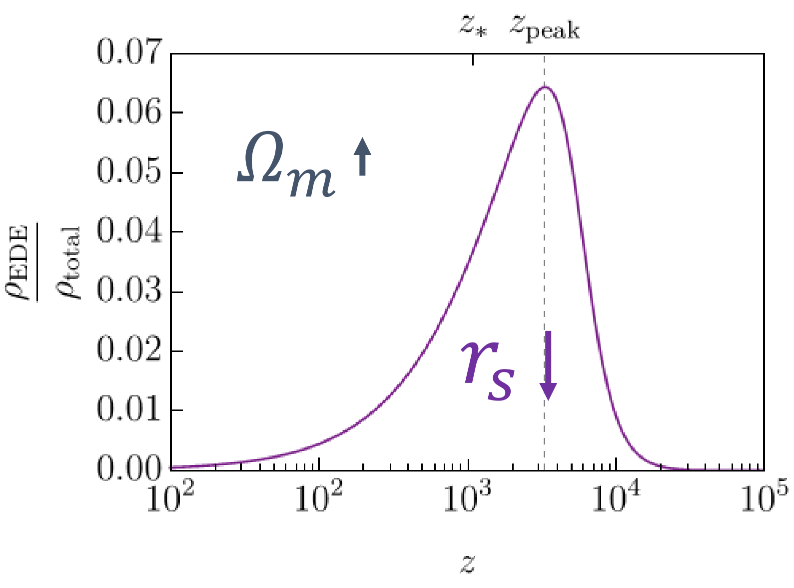
- r_s depends only on physics before formation of CMB
- Lowering r_s increases H_0



Planck 2018

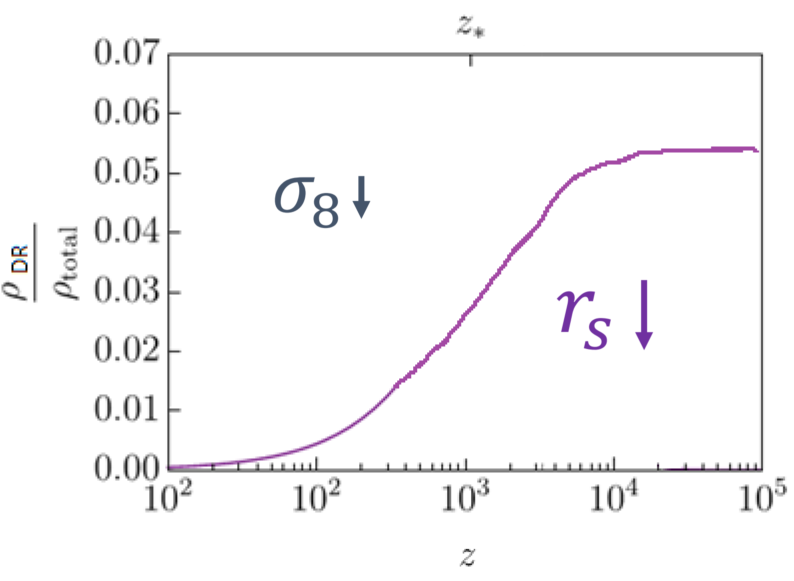
New physics that can lower the sound horizon

Early Dark Energy



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

Extra Radiation

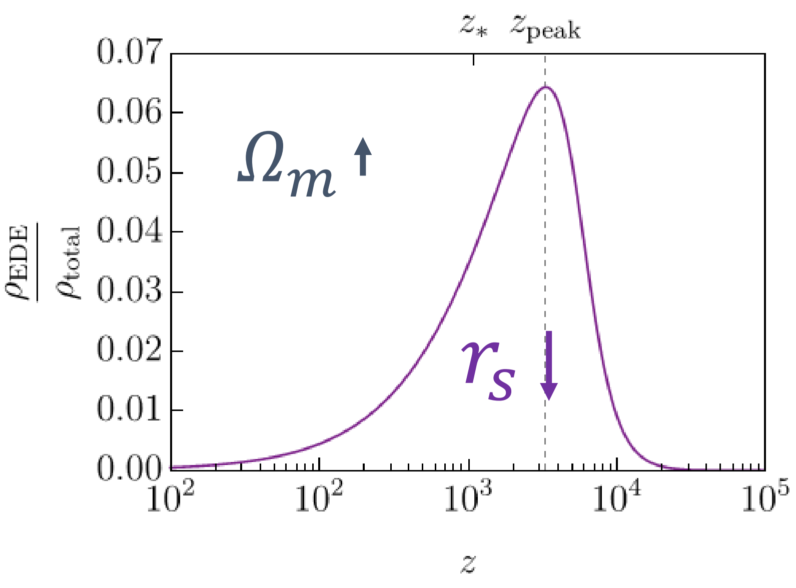


Maintains great fit to CMB
Resolves H0 but exacerbates LSS tension (Hill et. al., 2020, Ivanov et al. 2020)
Is fine-tuned

Worsens fit to CMB
Can ease LSS and Hubble tension

New physics that can lower the sound horizon

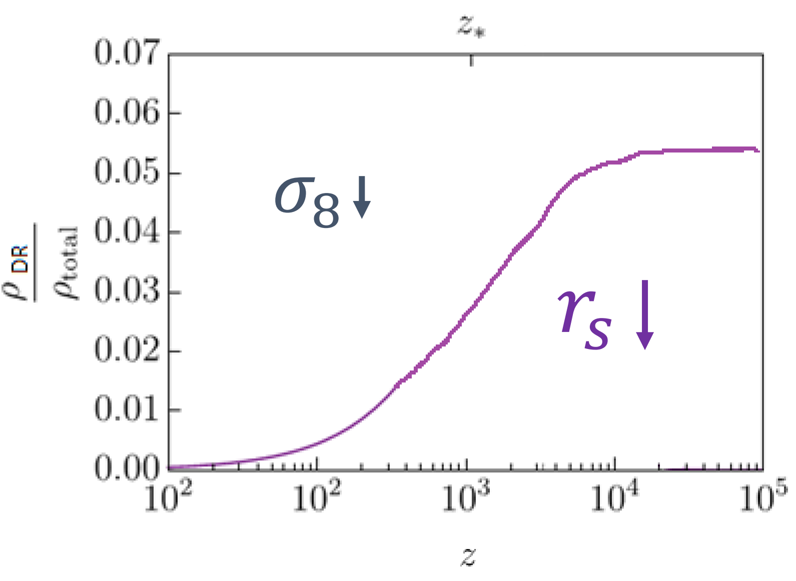
Early Dark Energy with thermal friction



combines

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

Extra Radiation

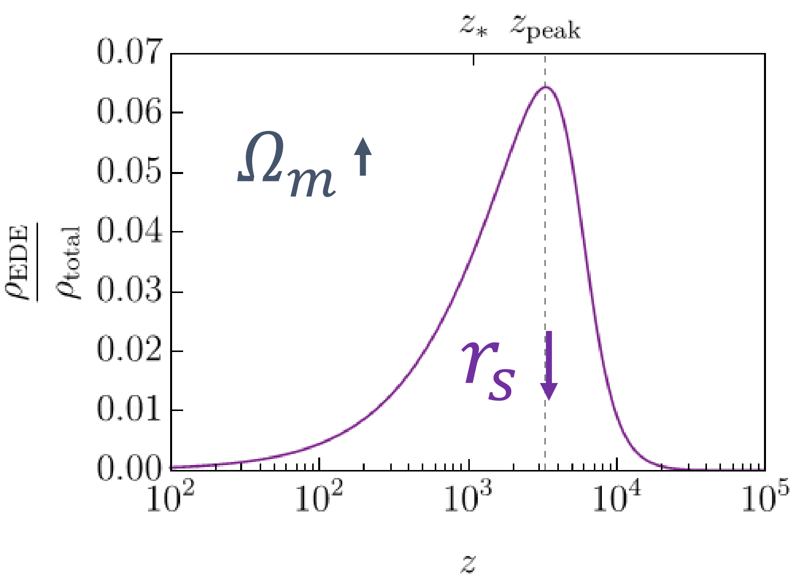


Maintains great fit to CMB
Resolves H0 but exacerbates LSS tension (Hill et. al., 2020, Ivanov et al. 2020)
~~Is fine tuned~~ (Berghaus, Karwal 2020)

Worsens fit to CMB
Can ease LSS and Hubble tension

New physics that can lower the sound horizon

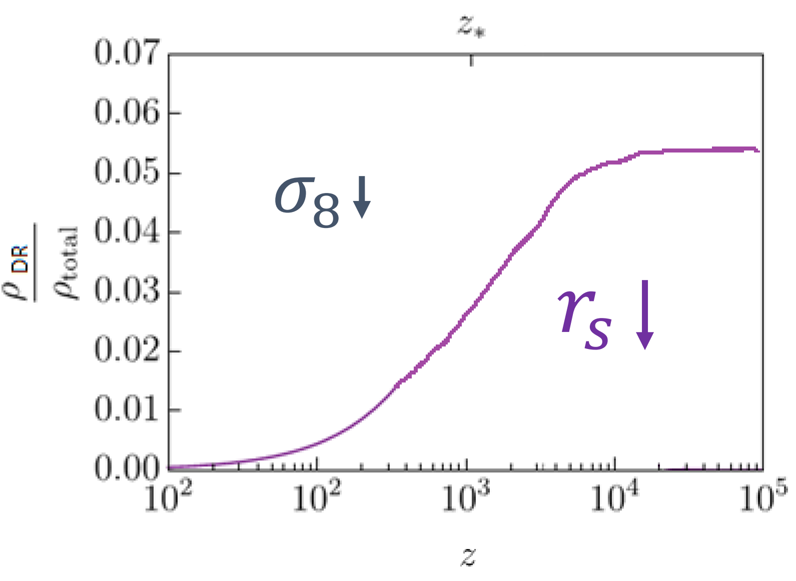
Early Dark Energy with thermal friction



combines

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

Extra Radiation



Maintains great fit to CMB ?

? Resolves H0 but exacerbates LSS tension (Hill et. al., 2020, Ivanov et al. 2020)

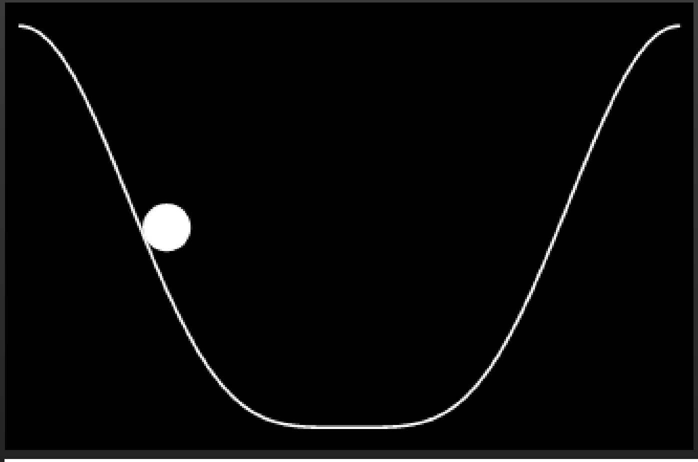
~~Is fine-tuned~~ (Berghaus, Karwal 2020)

Worsens fit to CMB

Can ease LSS and Hubble tension

?

Early Dark Energy



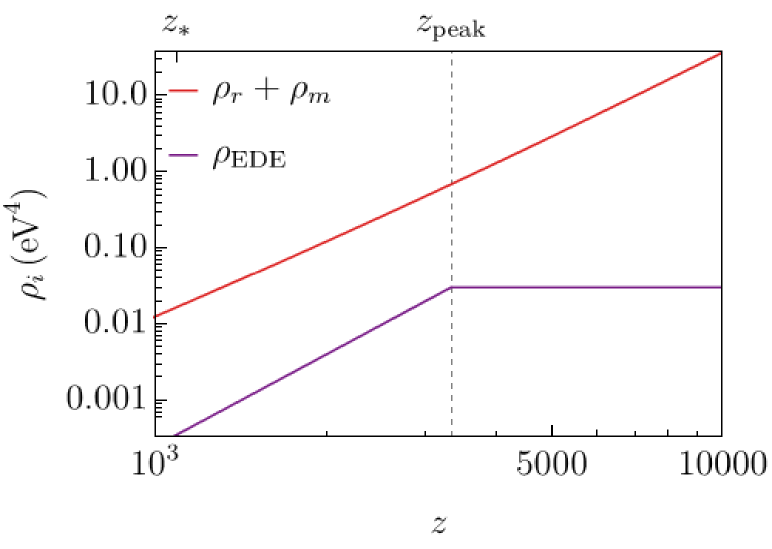
Frozen at early times by Hubble friction

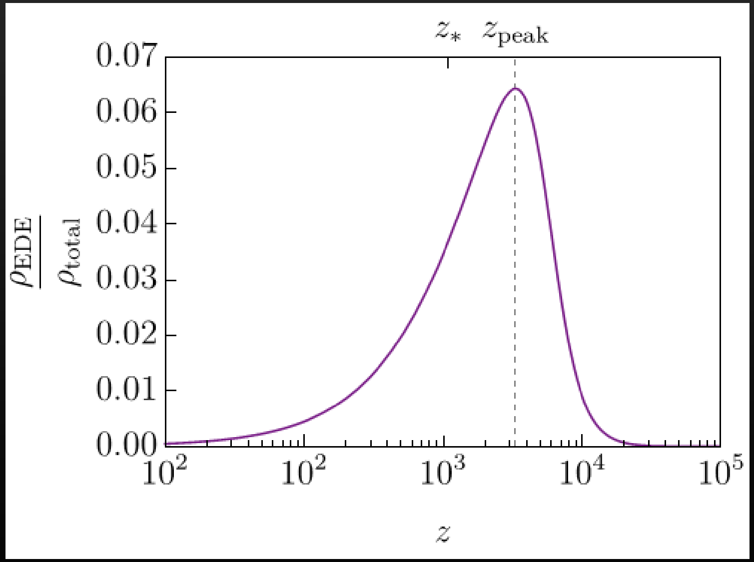
$$\ddot{\phi} + 3H\dot{\phi} + V' = 0$$

Dilutes away as radiation or faster when axion starts oscillating at critical redshift z_c

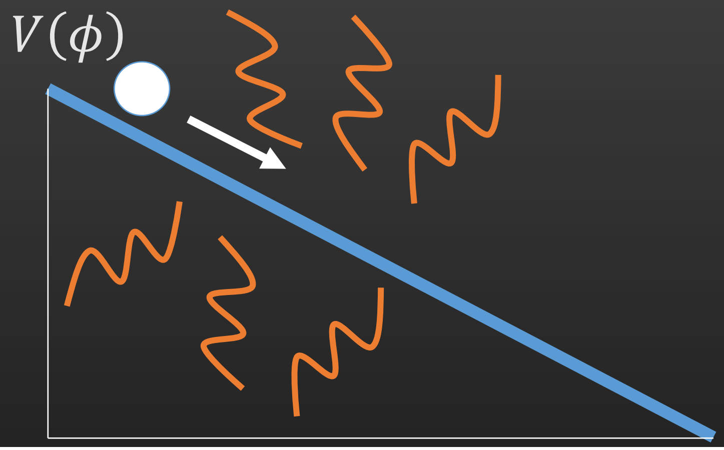
$$V \propto \left(1 - \cos\frac{\phi}{f}\right)^n$$

$$n \geq 2$$





Early Dark Energy with thermal friction

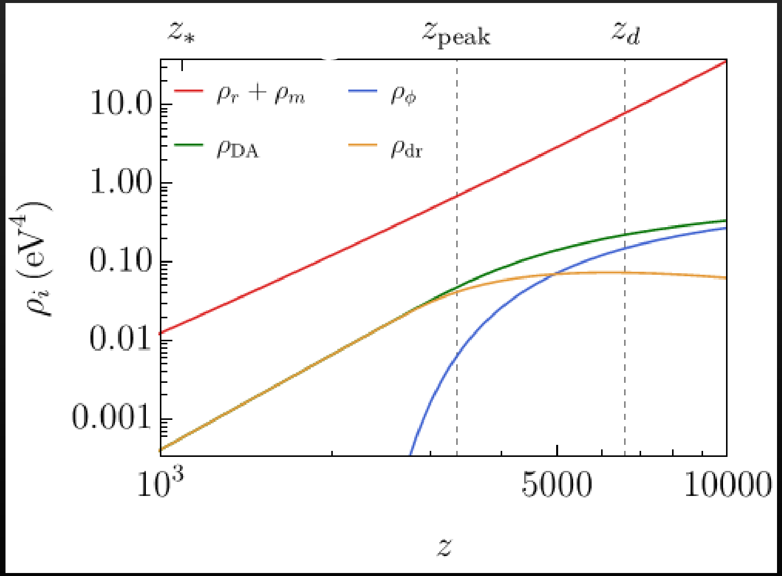


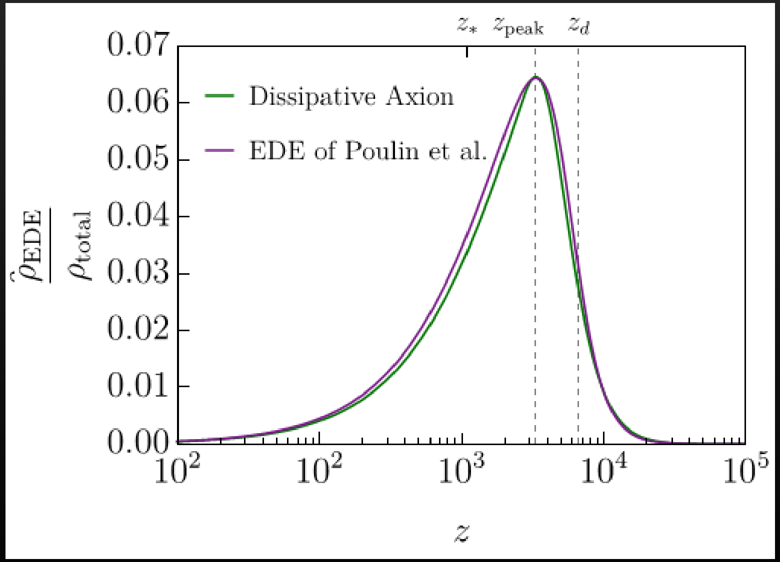
Frozen at early times by thermal friction

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

$$\dot{\rho}_{DR} + 4H\rho_{DR} = \Upsilon\dot{\phi}^{\,2}$$

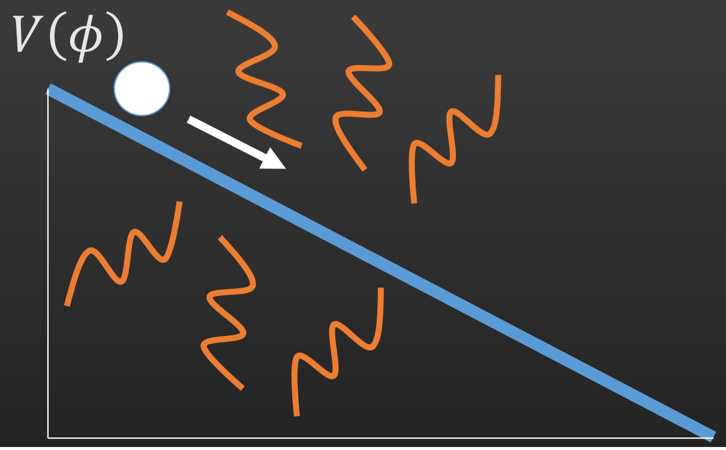
Overdamped at all time. Axion converts its energy into dark radiation at critical redshift z_c





Berghaus, Karwal 2019

Early Dark Energy with thermal friction



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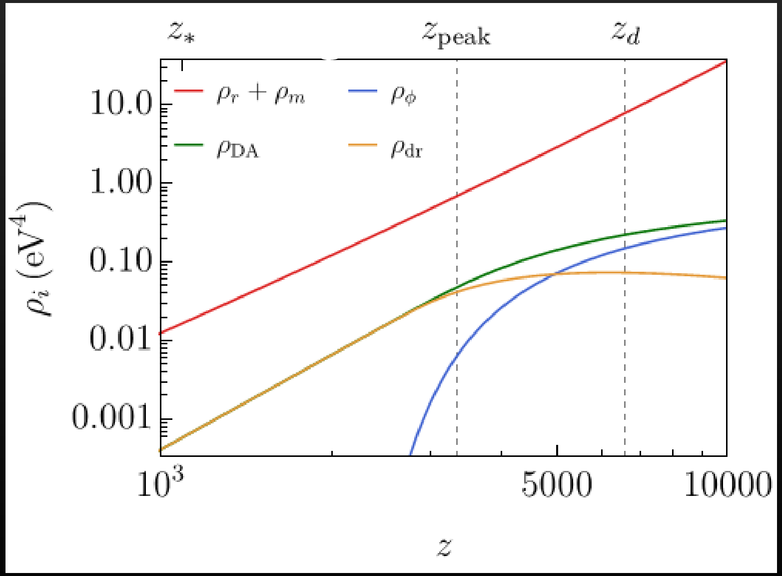
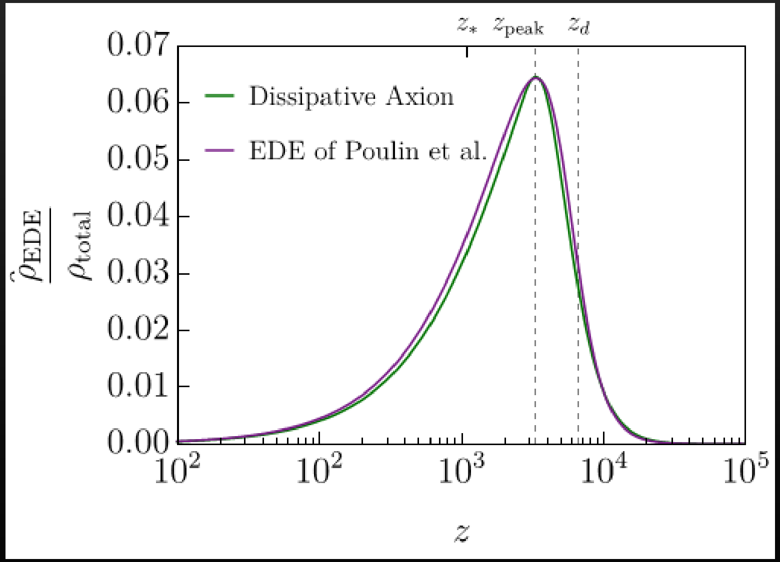
Overdamped at all time. Axion converts its energy into dark radiation at critical redshift z_c

Thermal friction generically arises for axions couplings to gauge fields

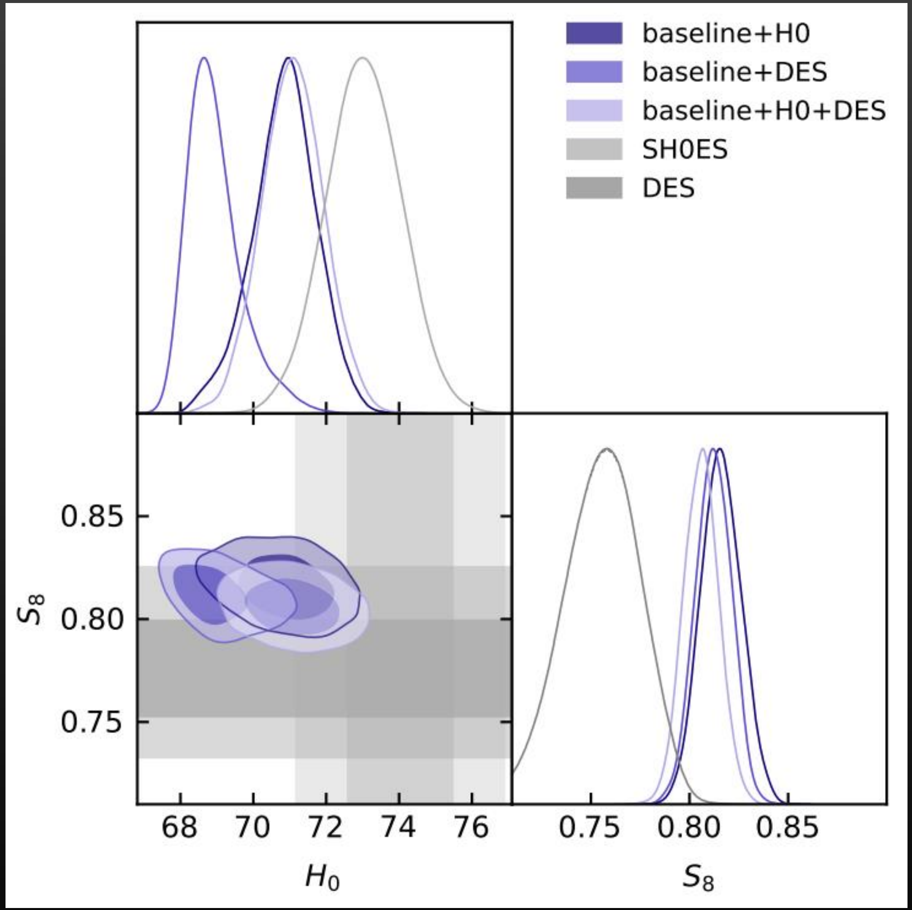
$$L_{\rm int} = -\phi \frac{\alpha}{16\pi f}\tilde{G}G$$





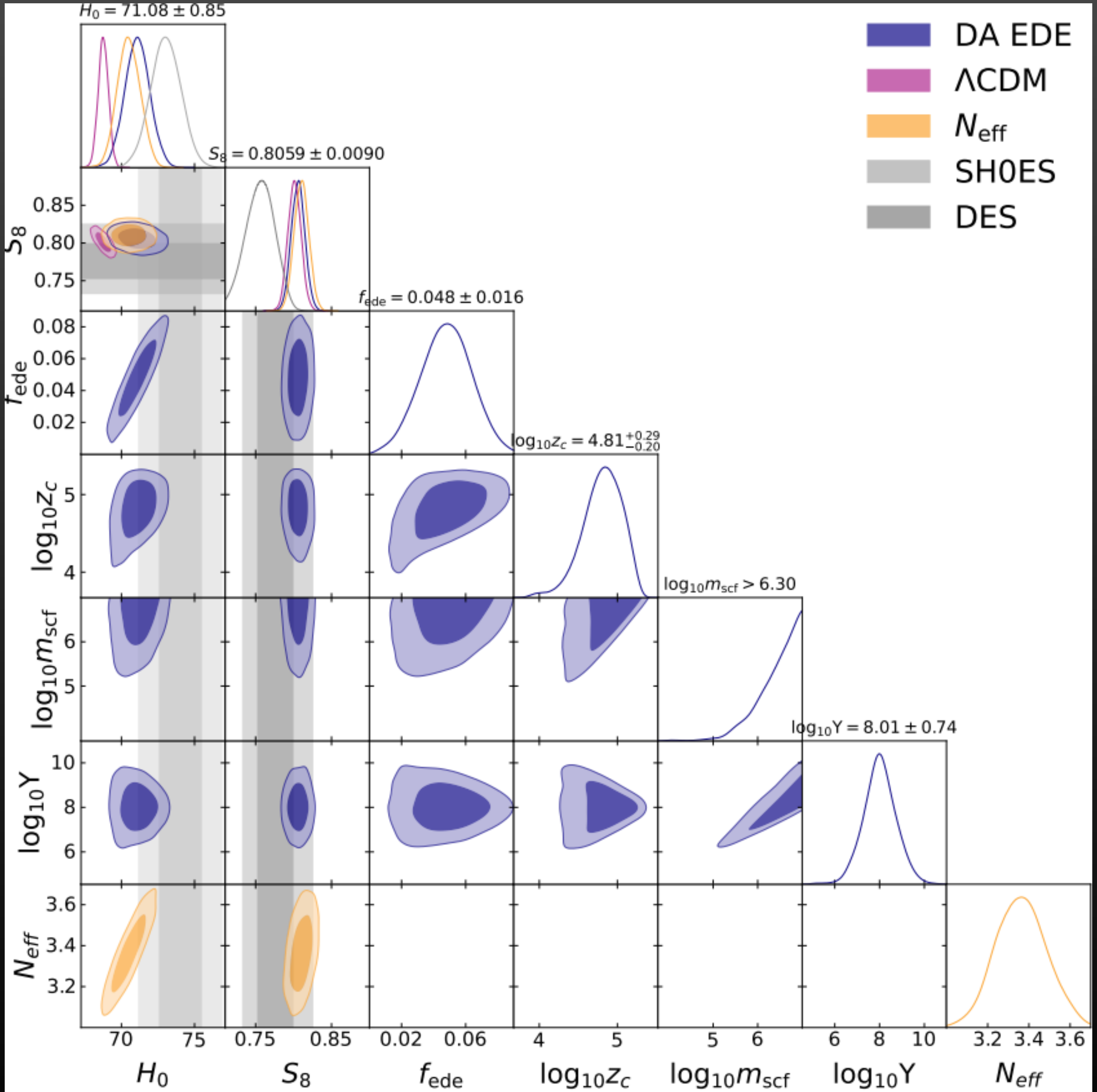
Berghaus, Karwal 2019

Results



Berghaus, Karwal 2022

Baseline + SH0ES + DES



Berghaus, Karwal 2022

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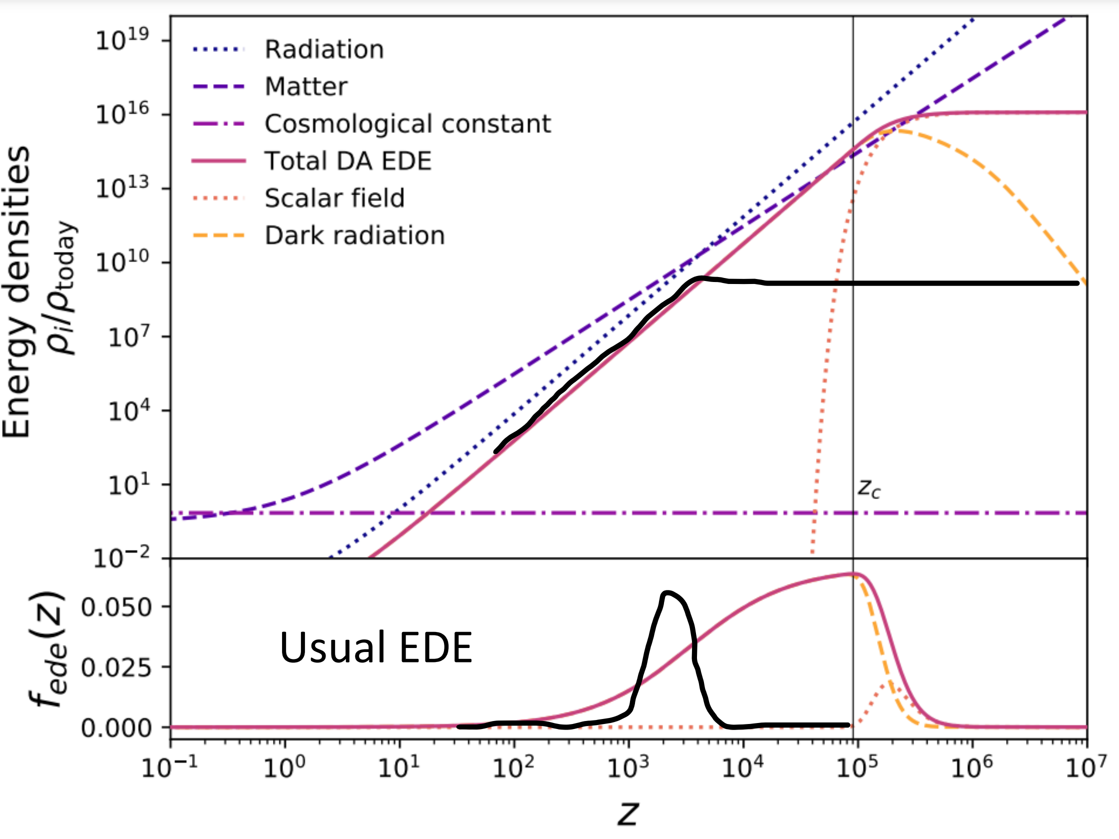
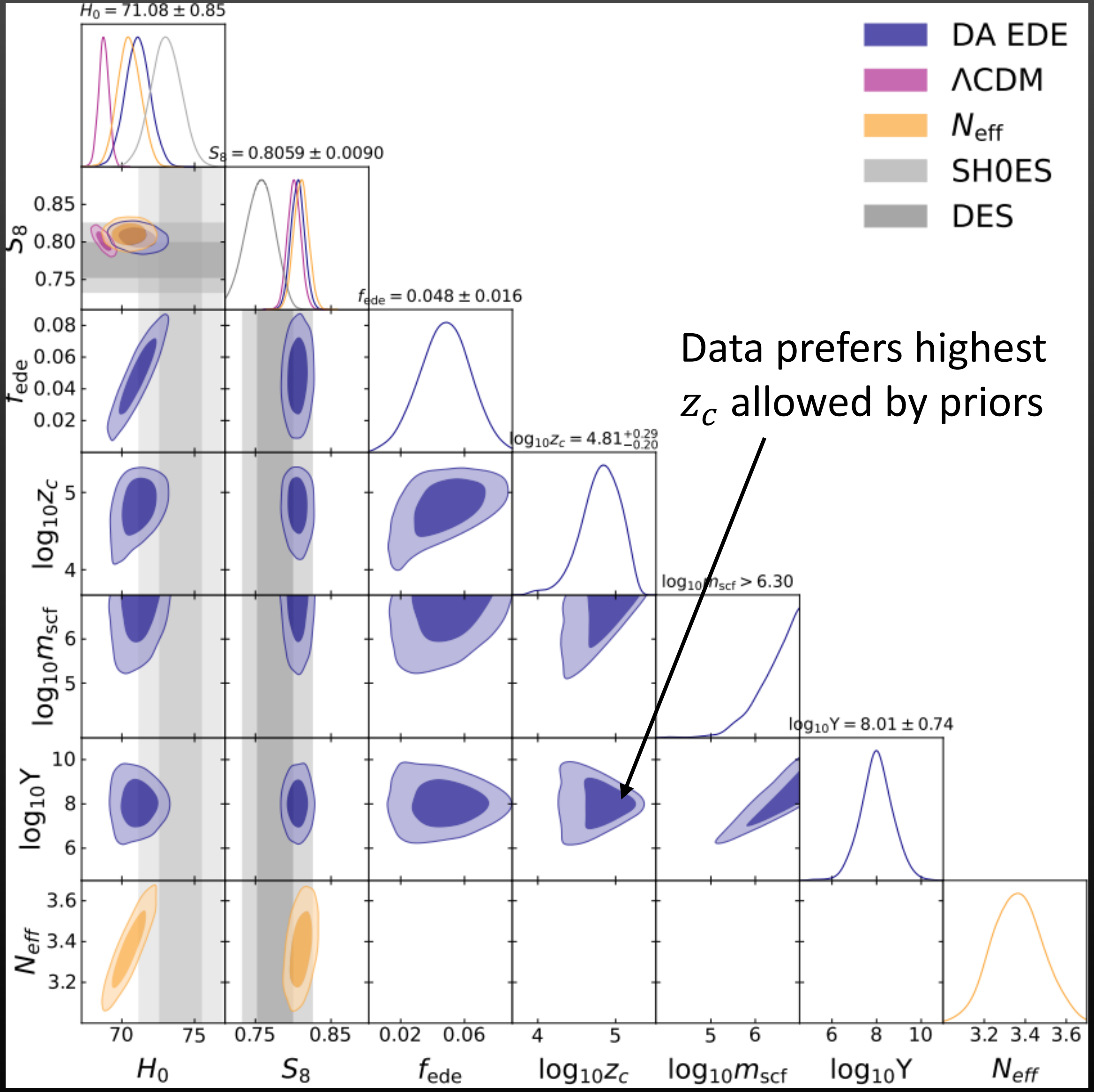


Berghaus, Karwal 2022



Data prefers highest z_c allowed by priors

Berghaus, Karwal 2022

Conclusions

- Thermal friction arises generically for rolling axions
- Thermal friction can resolve EDE fine-tuning at background level
- BUT data prefers thermal friction that asymptotes to extra radiation at high z_c
- Extra radiation eases the Hubble and the LSS tension but does not resolve it

Thank You

Back-up

Analysis

- thermal friction in CLASS: $V(\phi) = \frac{1}{2}m^2\phi^2$
- Effective parameters: $f_{ede}, z_c(m, \Upsilon), m$
- Data sets:
  - Planck 2018 CMB (TTTEEE) + lensing
  - BAO (BOSS DR12, SDSS Main Galaxy Sample, 6dFGS)
  - Pantheon Supernovae sample
  - SH0ES measurement $H_0 = 73.04 \pm 1.04$ km/s/Mpc
  - Dark Energy Survey Year 1 galaxy lensing and clustering

$\left.\begin{matrix} \text{Planck} \\ \text{BAO} \\ \text{Pantheon} \end{matrix}\right\}$ baseline

Why does data not prefer EDE thermal friction?

Answer must be in perturbations since background looks favorable

$$\delta\phi'' + 2aH\delta\phi' + \left(k^2 + a^2 V''(\phi)\right)\delta\phi = -\frac{h'\phi'}{2}$$

Regular EDE perturbations

$$\delta\phi'' + 2aH\delta\phi' + \left(k^2 + a^2 V''(\phi)\right)\delta\phi = -\frac{h'\phi'}{2} - a\Upsilon\delta\phi'$$

Axion perturbations with thermal friction

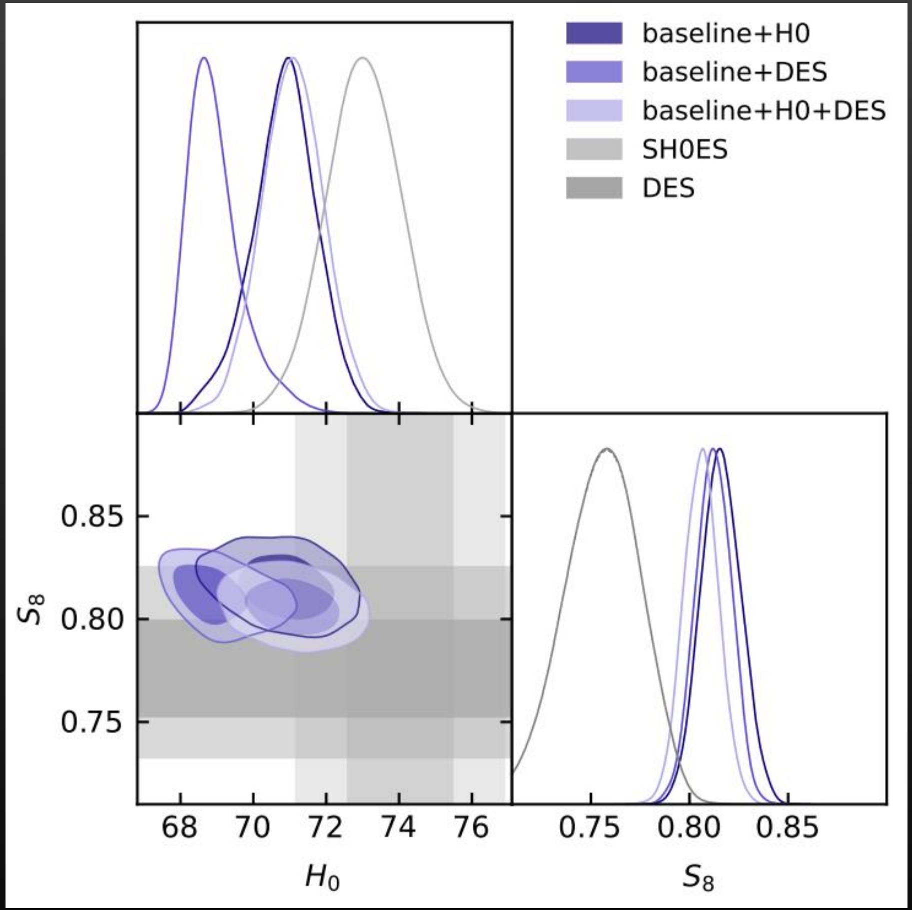
$$\delta'_{DR} = -\frac{2h'}{3} - \frac{4}{3}\theta_{DR} + \frac{2\Upsilon}{a\rho_{DR}}\delta\phi'\phi' - \frac{\boldsymbol{\Upsilon\phi'^2}}{\boldsymbol{a\rho_{DR}}}\boldsymbol{\delta_{DR}}$$

Dark radiation perturbations sourced by thermal friction

$$\delta_{DR} \equiv \frac{\delta\rho_{DR}}{\rho_{DR}} \qquad \theta_{DR} \equiv ik^j v_j$$

Sourcing of DR
smoothes anisotropies

Results



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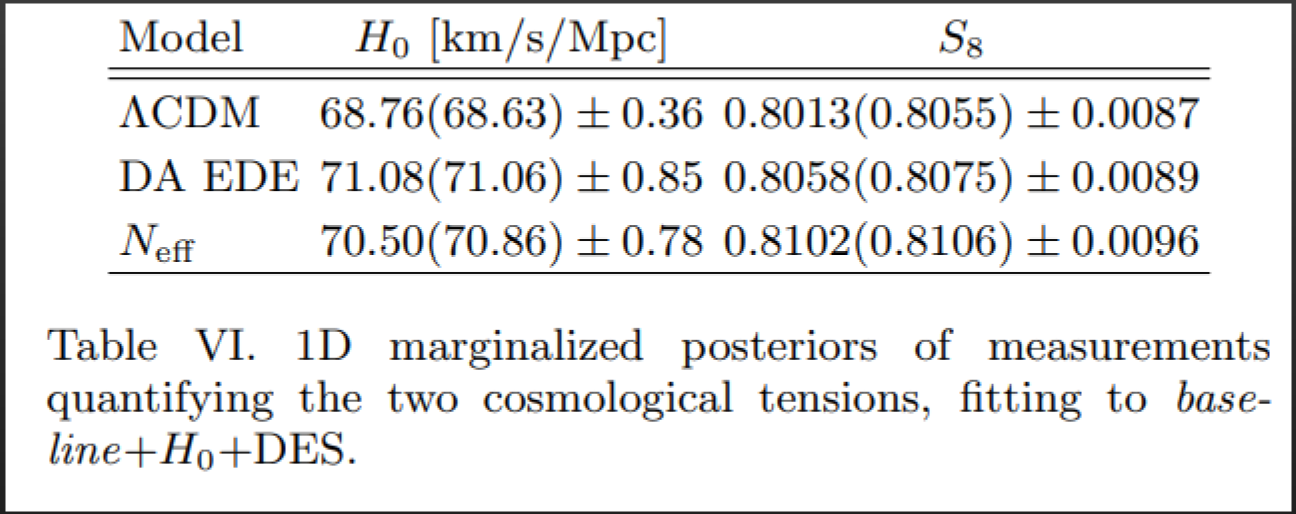
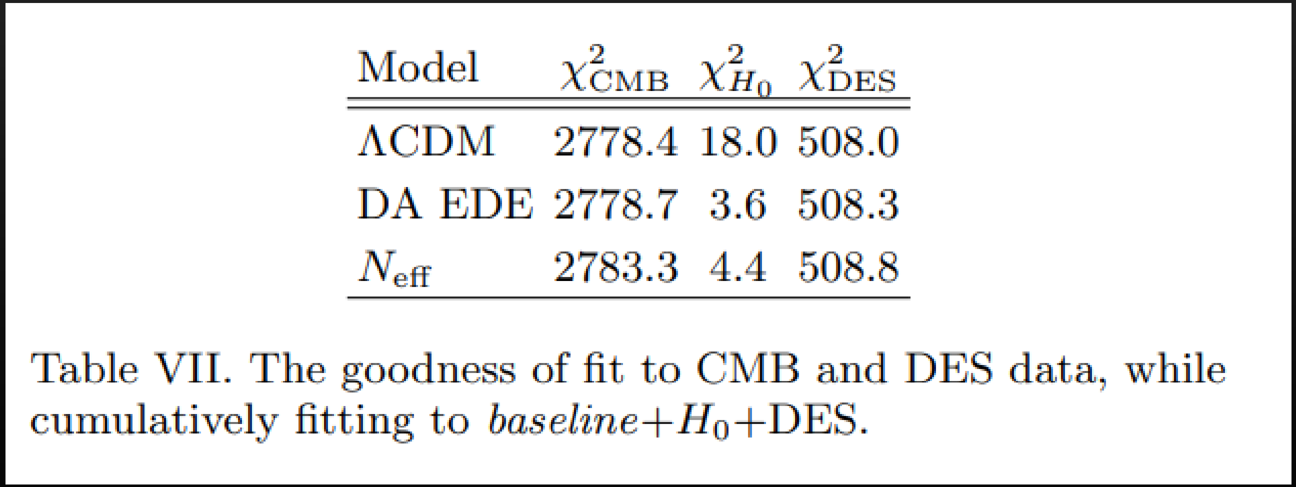


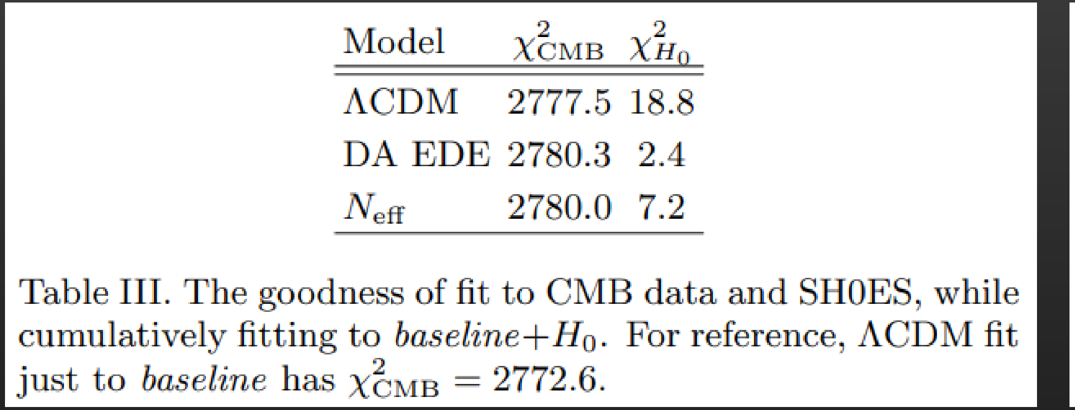
Model	H_0 [km/s/Mpc]	S_8
ΛCDM	$68.76(68.63) \pm 0.36$	$0.8013(0.8055) \pm 0.0087$
DA EDE	$71.08(71.06) \pm 0.85$	$0.8058(0.8075) \pm 0.0089$
N_{eff}	$70.50(70.86) \pm 0.78$	$0.8102(0.8106) \pm 0.0096$

Table VI. 1D marginalized posteriors of measurements quantifying the two cosmological tensions, fitting to *baseline*+H_0+DES.



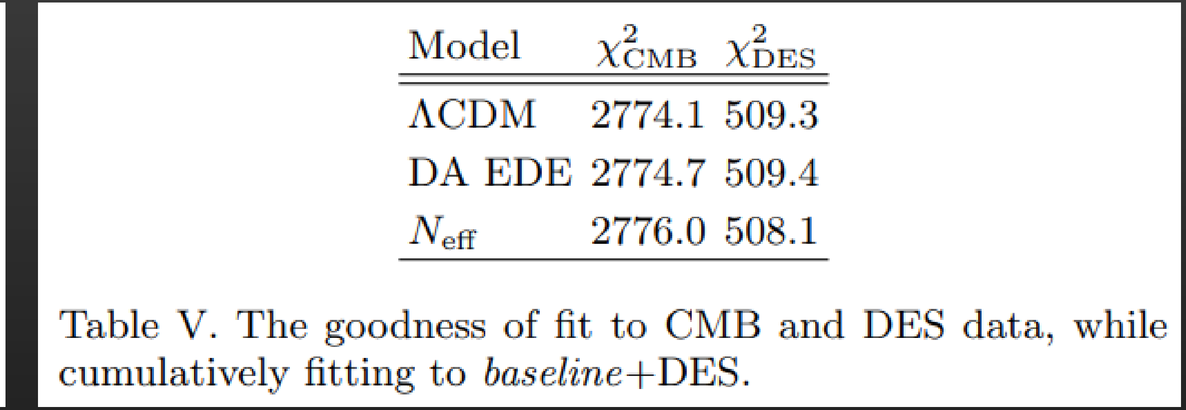
Model	χ^2_{CMB}	$\chi^2_{H_0}$	χ^2_{DES}
ΛCDM	2778.4	18.0	508.0
DA EDE	2778.7	3.6	508.3
N_{eff}	2783.3	4.4	508.8

Table VII. The goodness of fit to CMB and DES data, while cumulatively fitting to *baseline*+H_0+DES.



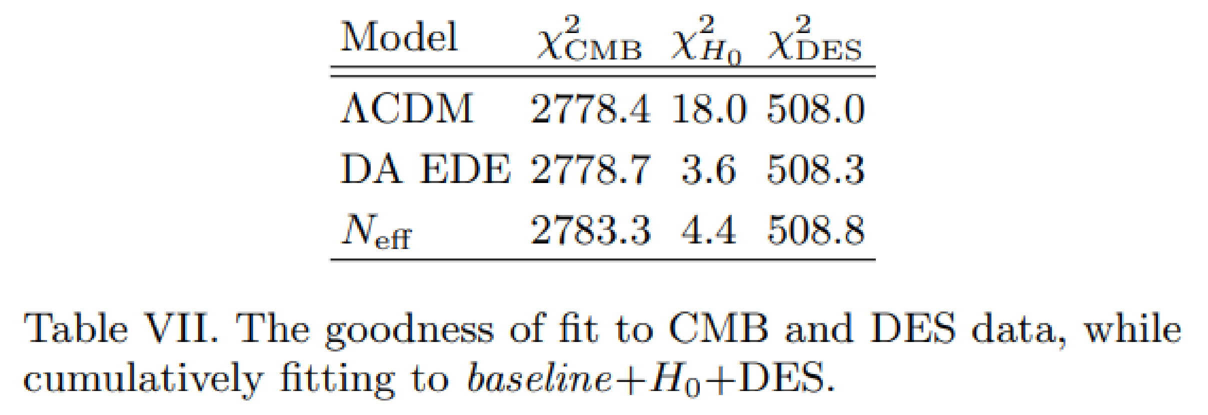
Model	$\chi^2_{\rm CMB}$	$\chi^2_{H_0}$
ΛCDM	2777.5	18.8
DA EDE	2780.3	2.4
$N_{\rm eff}$	2780.0	7.2

Table III. The goodness of fit to CMB data and SH0ES, while cumulatively fitting to *baseline*+H_0. For reference, ΛCDM fit just to *baseline* has $\chi^2_{\rm CMB} = 2772.6$.



Model	$\chi^2_{\rm CMB}$	$\chi^2_{\rm DES}$
ΛCDM	2774.1	509.3
DA EDE	2774.7	509.4
$N_{\rm eff}$	2776.0	508.1

Table V. The goodness of fit to CMB and DES data, while cumulatively fitting to *baseline*+DES.



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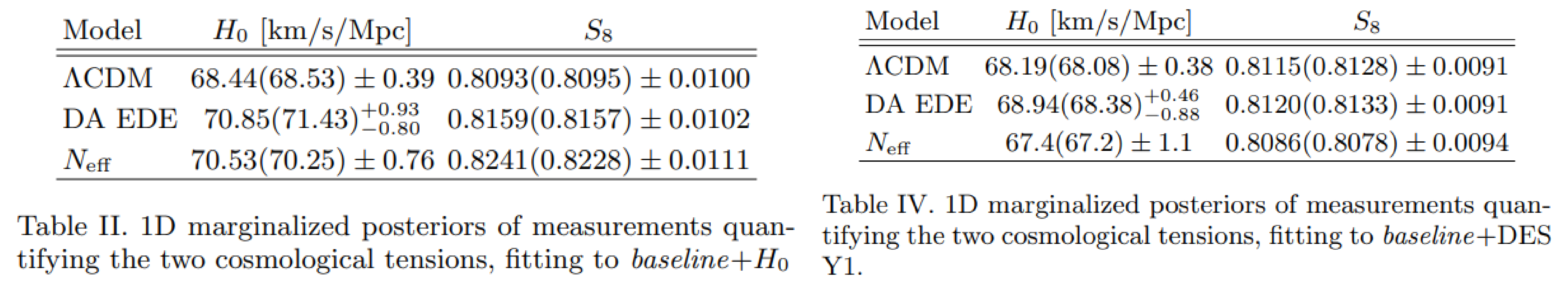

Model	H_0 [km/s/Mpc]	S_8
ΛCDM	$68.44(68.53) \pm 0.39$	$0.8093(0.8095) \pm 0.0100$
DA EDE	$70.85(71.43)^{+0.93}_{-0.80}$	$0.8159(0.8157) \pm 0.0102$
$N_{\rm eff}$	$70.53(70.25) \pm 0.76$	$0.8241(0.8228) \pm 0.0111$

Table II. 1D marginalized posteriors of measurements quantifying the two cosmological tensions, fitting to *baseline*+H_0

Model	H_0 [km/s/Mpc]	S_8
ΛCDM	$68.19(68.08) \pm 0.38$	$0.8115(0.8128) \pm 0.0091$
DA EDE	$68.94(68.38)^{+0.46}_{-0.88}$	$0.8120(0.8133) \pm 0.0091$
$N_{\rm eff}$	$67.4(67.2) \pm 1.1$	$0.8086(0.8078) \pm 0.0094$

Table IV. 1D marginalized posteriors of measurements quantifying the two cosmological tensions, fitting to *baseline*+DES Y1.

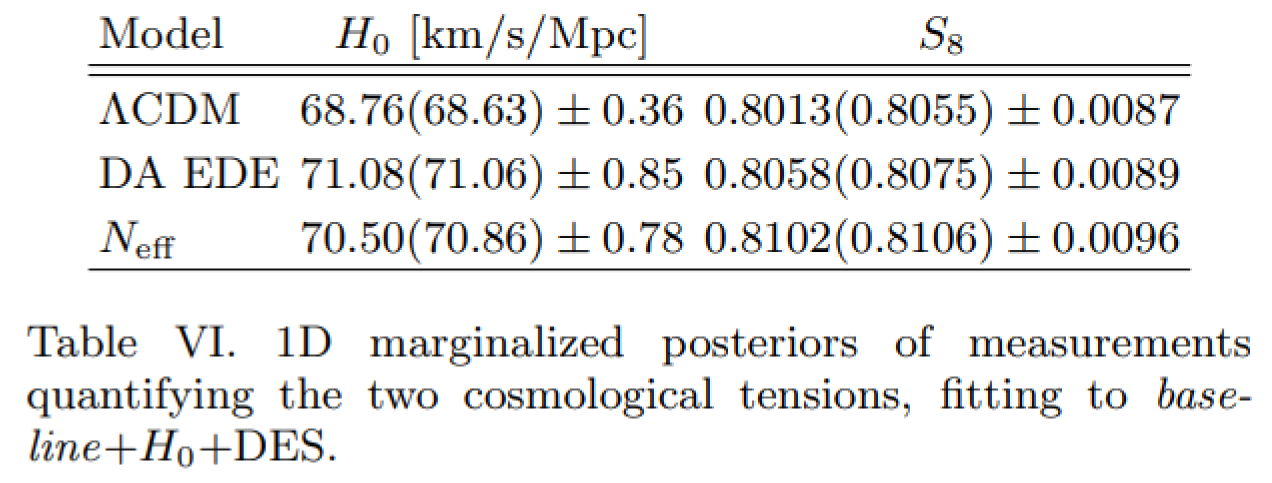

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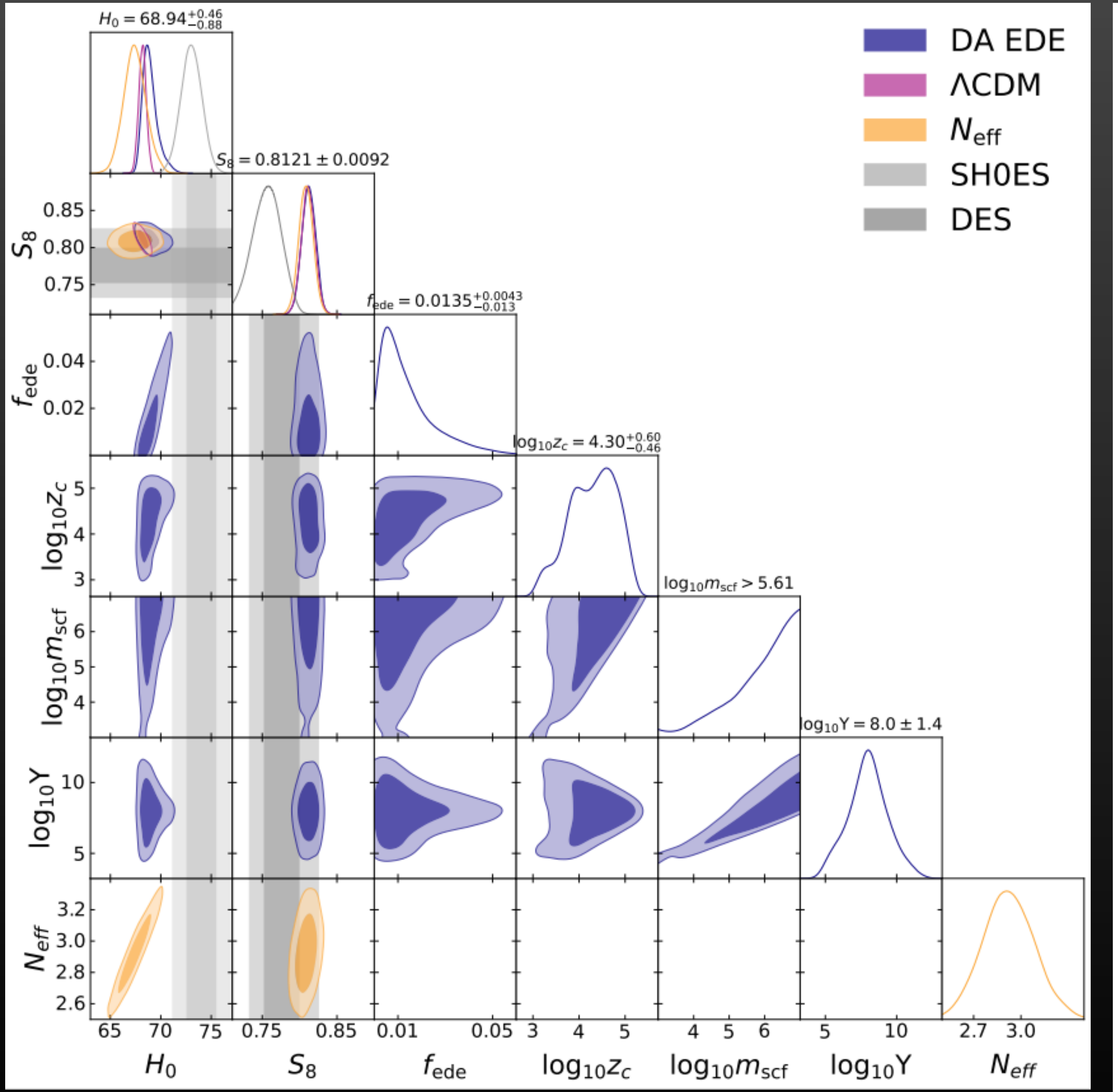
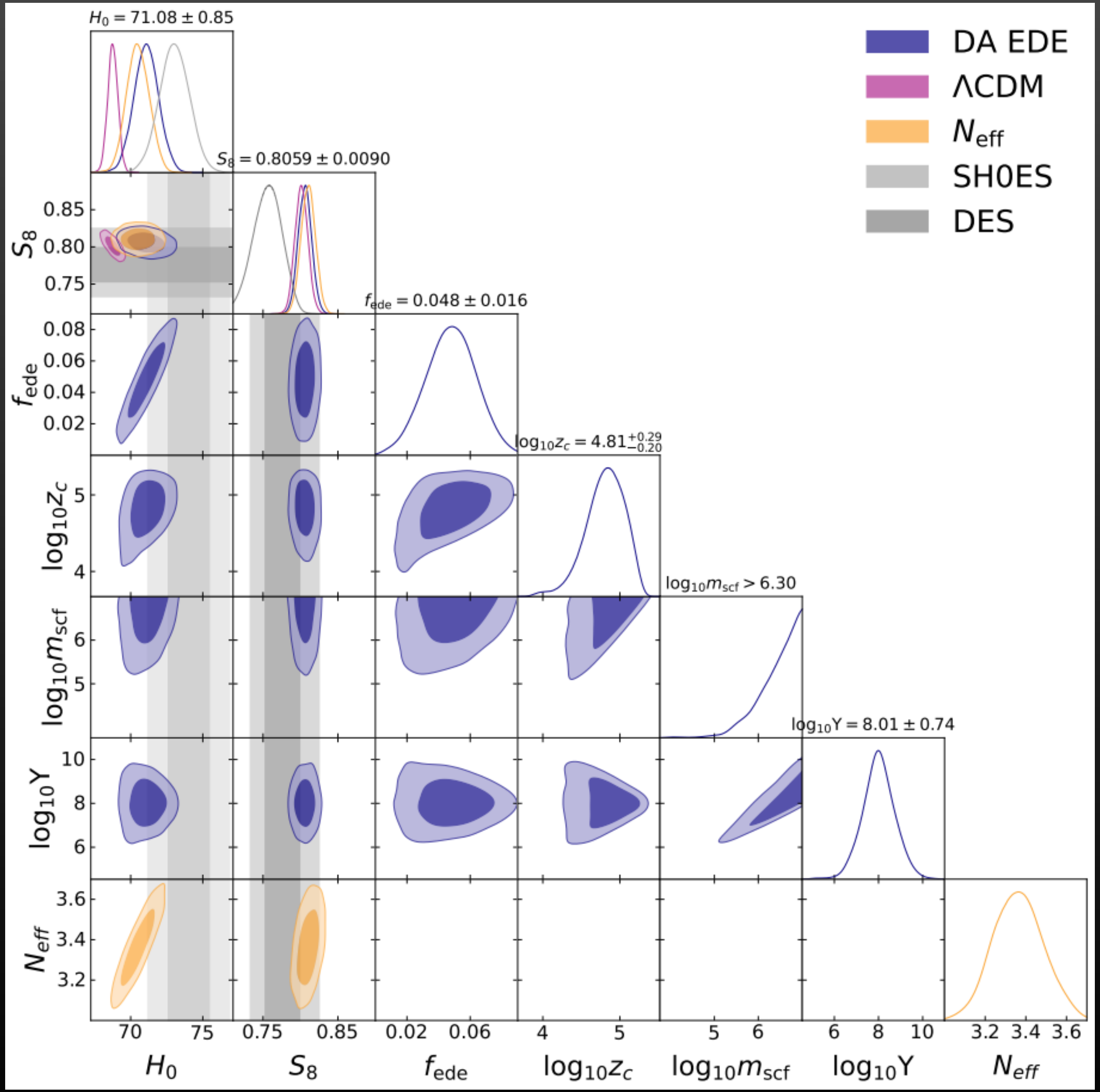
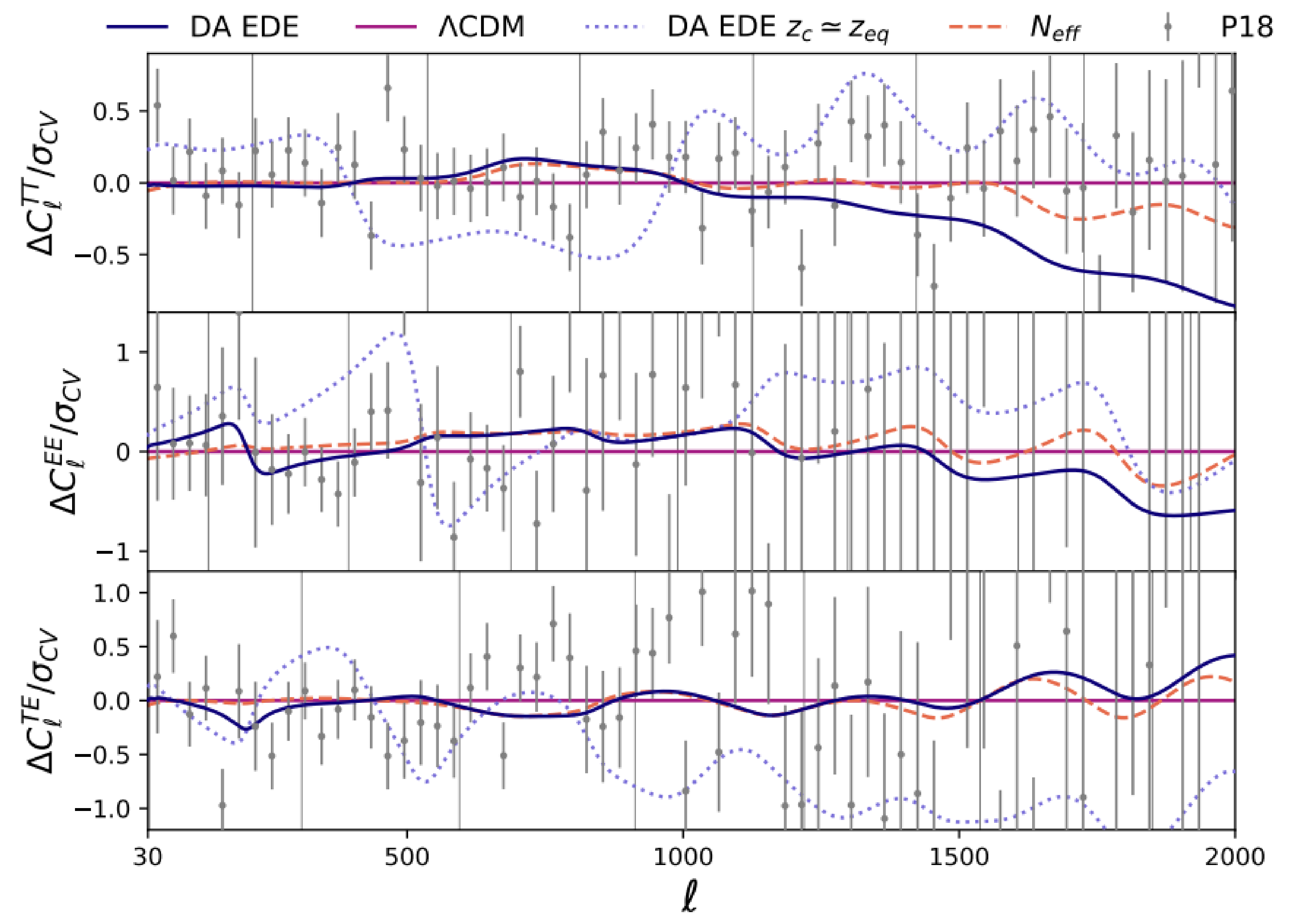
Table VI. 1D marginalized posteriors of measurements quantifying the two cosmological tensions, fitting to *baseline*+H_0+DES.

Baseline + DES

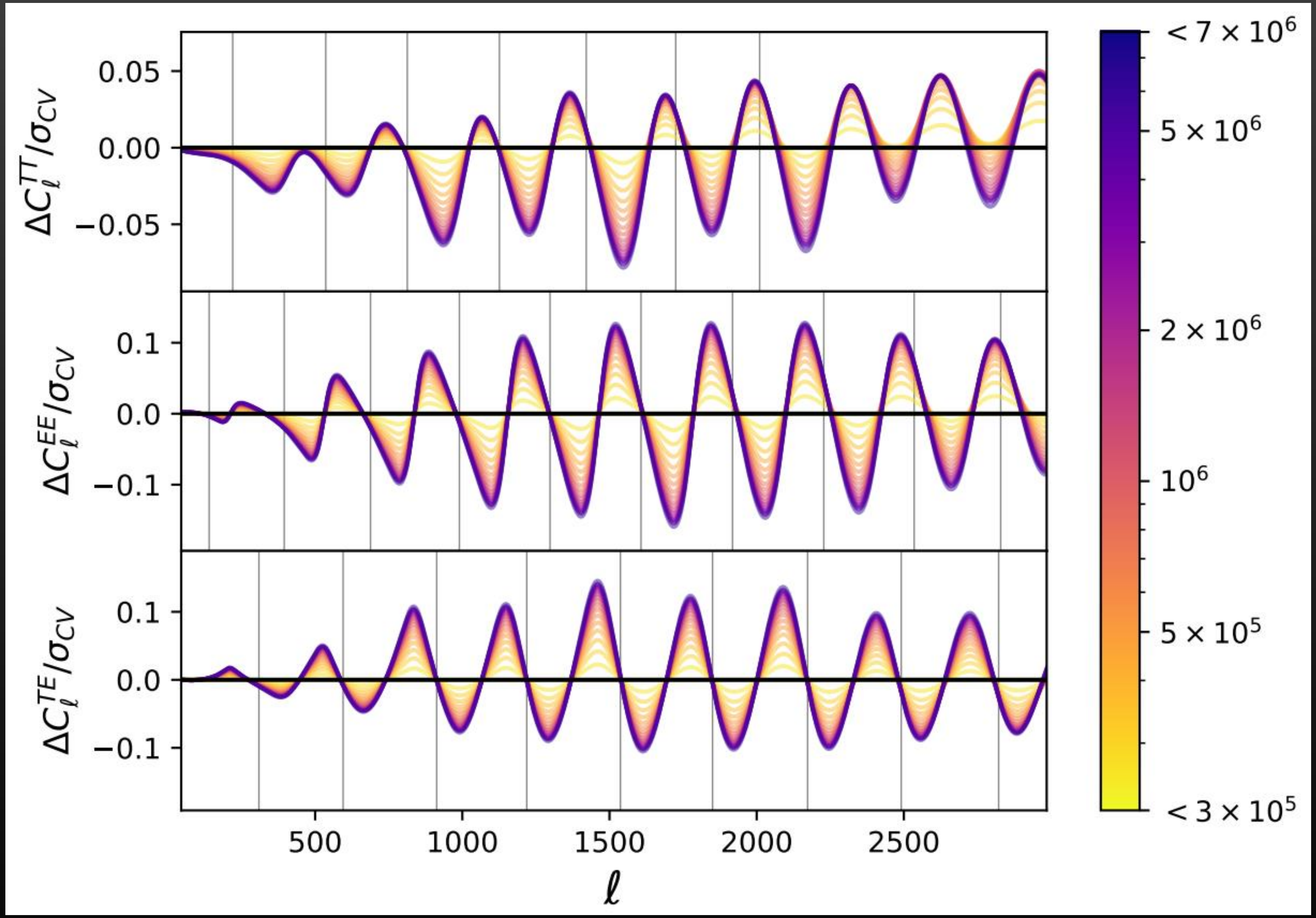


Baseline + DES + SH0ES




DA EDE
ΛCDM
DA EDE $z_c \simeq z_{eq}$
N_{eff}
P18
$\Delta C_\ell^{TT}/\sigma_{CV}$
0.5
0.0
−0.5
$\Delta C_\ell^{EE}/\sigma_{CV}$
1
0
−1
$\Delta C_\ell^{TE}/\sigma_{CV}$
1.0
0.5
0.0
−0.5
−1.0
30
500
1000
1500
2000
ℓ

Going to higher redshifts



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Data has sensitivity when $\frac{\Delta C_{el}^{XX}}{\sigma_{CV}} > 1$

Differences in predictions of the theory at larger z_c are not resolvable

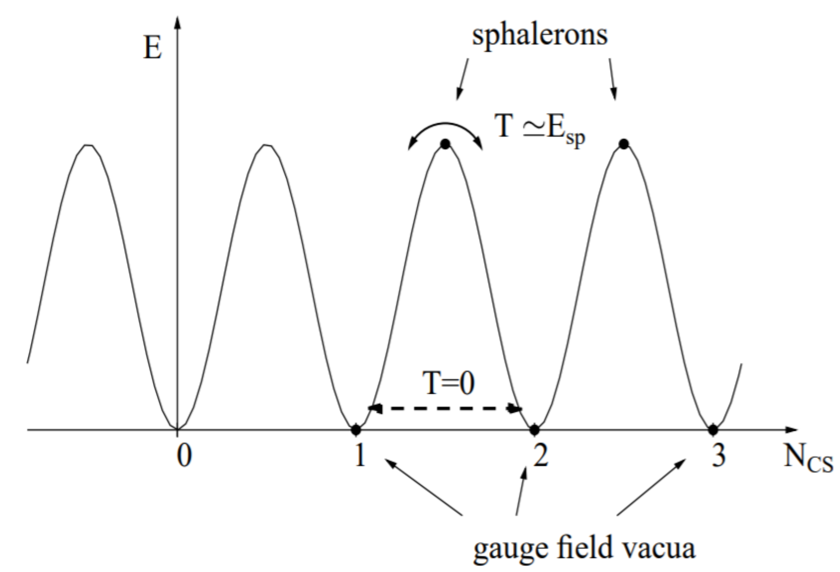
Thermal friction asymptotes to an extra-radiation solution

Dissipative Axion

$$\frac{\partial L}{\partial \phi} - \frac{d}{dt}\frac{\partial L}{\partial \dot{\phi}} = 0$$

- Couple scalar field to light degrees of freedom $L_{\text{int}} = -\phi \frac{\alpha}{16\pi f}\tilde{G}G$

$$\ddot{\phi} + 3H\dot{\phi} + V' = -\left\langle \frac{\alpha}{16\pi f}\tilde{G}G \right\rangle_{\text{non-eq}} (\phi)$$



$$\left\langle \frac{\alpha}{16\pi f}\tilde{G}G \right\rangle_{\text{non-eq}} (\phi) \approx \cancel{m_{th}^2}\phi + \Upsilon\dot{\phi} + O(\ddot{\phi})$$

Not allowed by symmetry

Dissipative Axion

$$\boxed{\partial_u K^u = \frac{\alpha}{16\pi f}\tilde{G}G}$$

$$\boxed{\frac{\partial L}{\partial \phi} - \frac{d}{dt}\frac{\partial L}{\partial \dot{\phi}} = 0}$$

- Couple scalar field to light degrees of freedom $L_{\text{int}} = -\phi\frac{\alpha}{16\pi f}\tilde{G}G = \dot{\phi}K^0$

$\sim \Delta N_{CS}$

$$\ddot{\phi} + 3H\dot{\phi} + V' = -\left\langle\frac{dK^0}{dt}\right\rangle_{\text{non-eq}}(\dot{\phi})$$

Nonzero $\langle\dot{\phi}\rangle$ gives linear potential to K^0