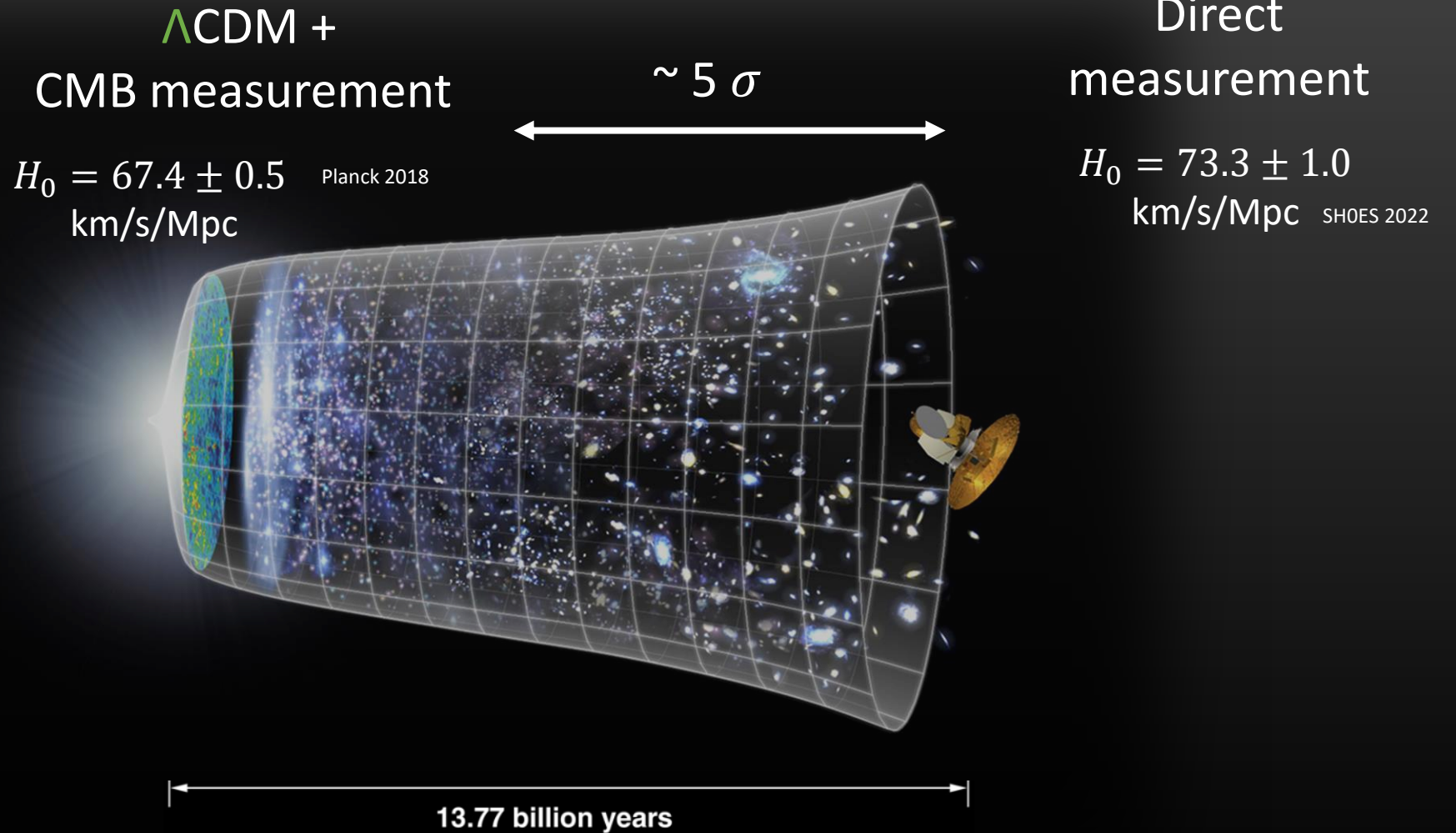


Can Thermal Friction Thaw the Hubble Tension?

Kim V. Berghaus, YITP Stony Brook

Based on 2204.09133

The Hubble Tension



The Large-Scale Structure Tension

Λ CDM +
CMB measurement

$$S_8 = 0.82 \pm 0.01 \text{ Planck 2018}$$

$\sim 2 - 3 \sigma$

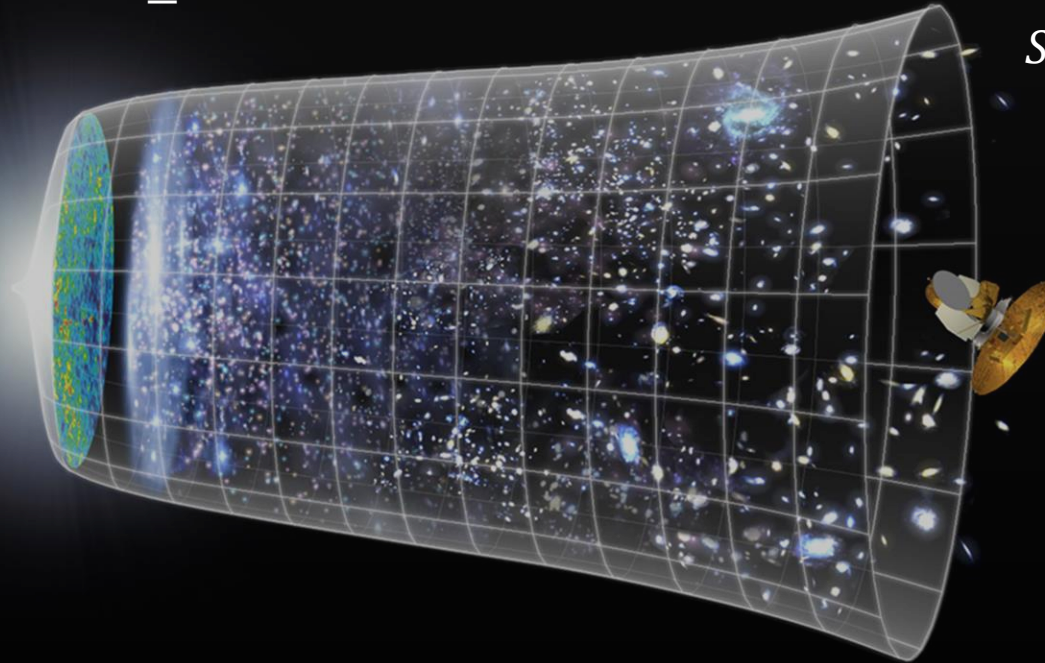


Galaxy clustering
+ weak lensing
(DES Y1)

$$S_8 = 0.77 \pm 0.02 \text{ DES 2017}$$

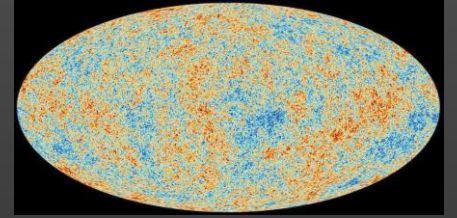
$$S_8 = \sigma_8 \sqrt{\frac{\Omega_m}{0.3}}$$

Amplitude of matter
fluctuations



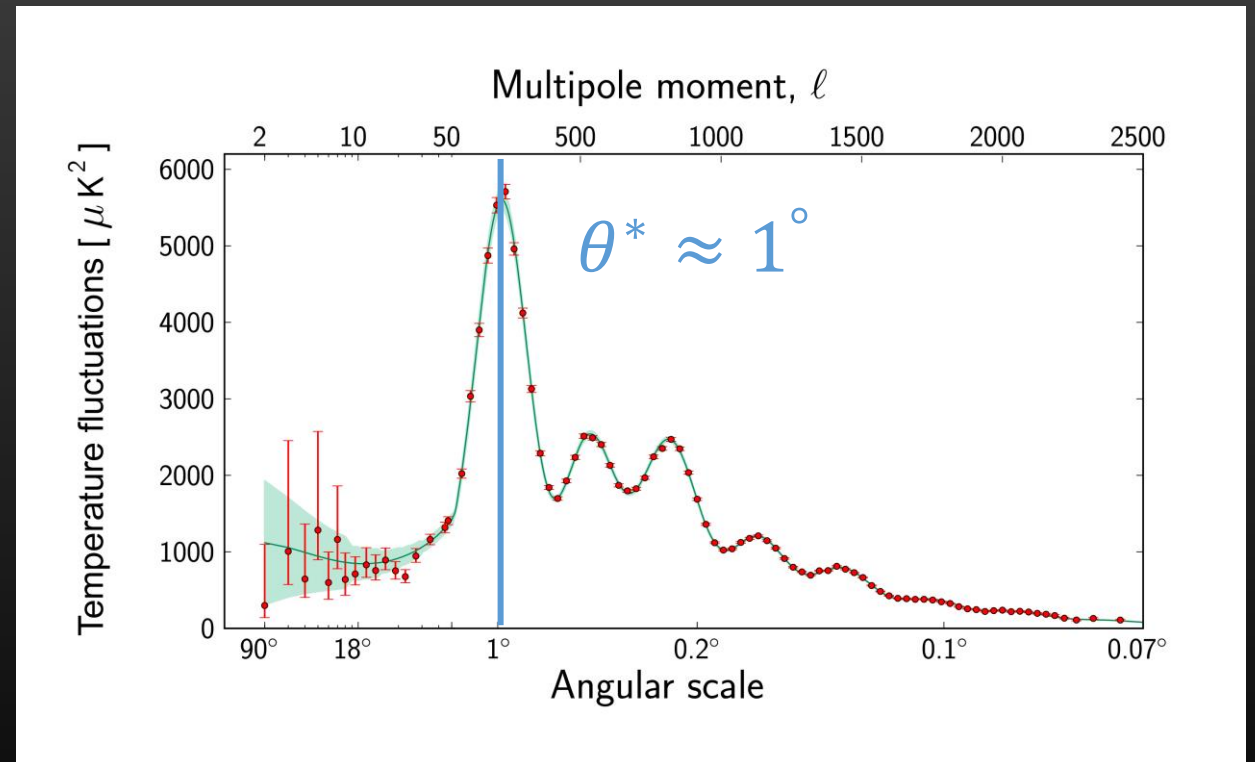
13.77 billion years

The Hubble Measurement with the CMB



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

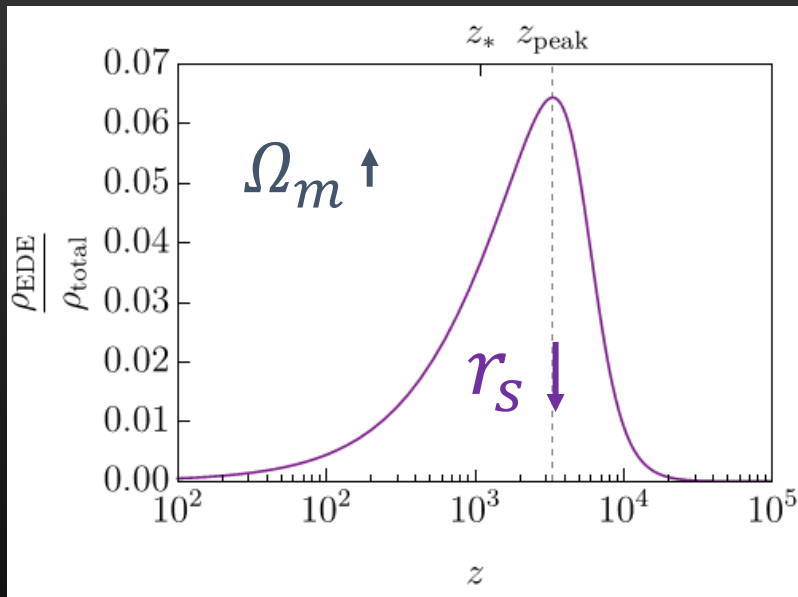
- r_s depends only on physics before formation of CMB
- Lowering r_s increases H_0



Planck 2018

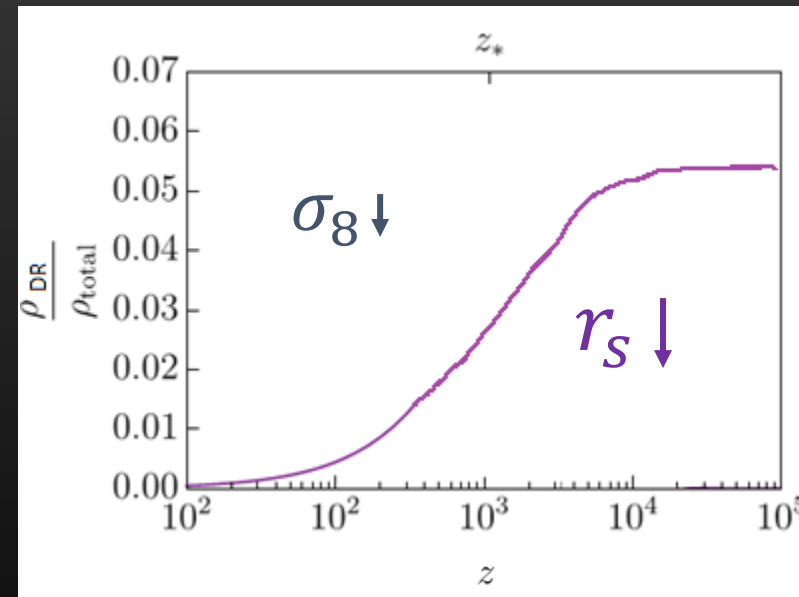
New physics that can lower the sound horizon

Early Dark Energy



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

Extra Radiation



Maintains great fit to CMB

Resolves H_0 but exacerbates LSS tension (Hill et. al., 2020, Ivanov et al. 2020)

Is fine-tuned

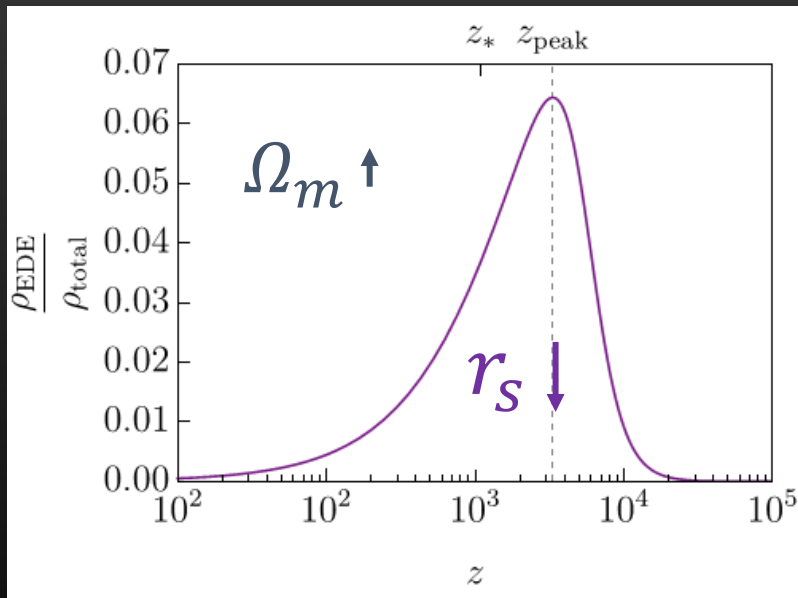
Worsens fit to CMB

Can ease LSS and Hubble tension

New physics that can lower the sound horizon

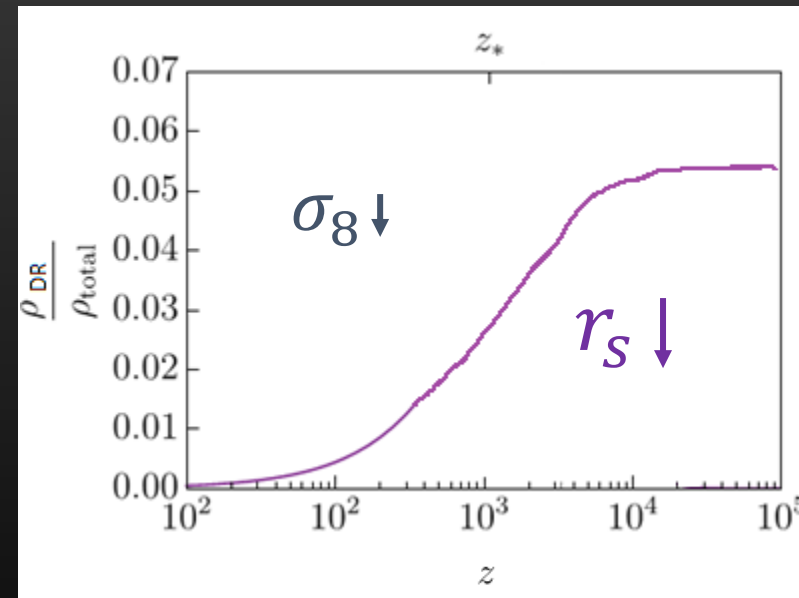
Early Dark Energy with **thermal friction**

Extra Radiation



combines

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



Maintains great fit to CMB

Resolves H_0 but exacerbates LSS tension (Hill et. al., 2020, Ivanov et al. 2020)

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

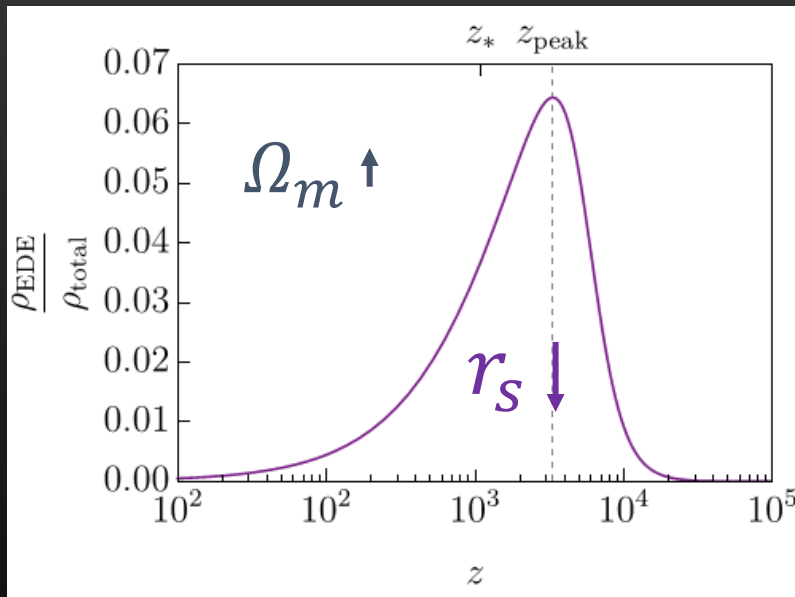
Worsens fit to CMB

Can ease LSS and Hubble tension

New physics that can lower the sound horizon

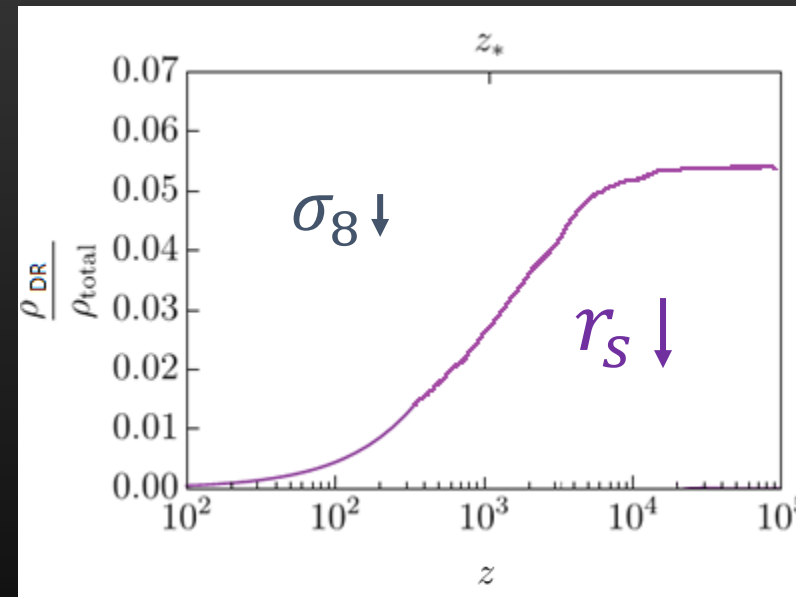
Early Dark Energy with **thermal friction**

Extra Radiation



combines

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



Maintains great fit to CMB ?

? Resolves H_0 but exacerbates LSS tension (Hill et. al., 2020, Ivanov et al. 2020)

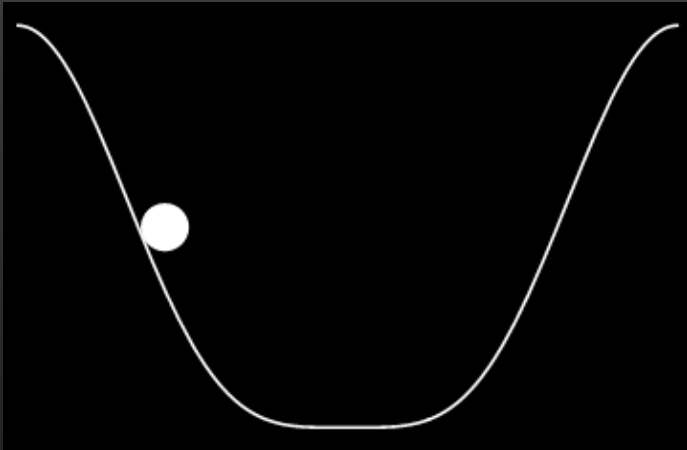
~~Is fine tuned~~ (Berghaus, Karwal 2020)

Worsens fit to CMB

Can ease LSS and Hubble tension

?

Early Dark Energy



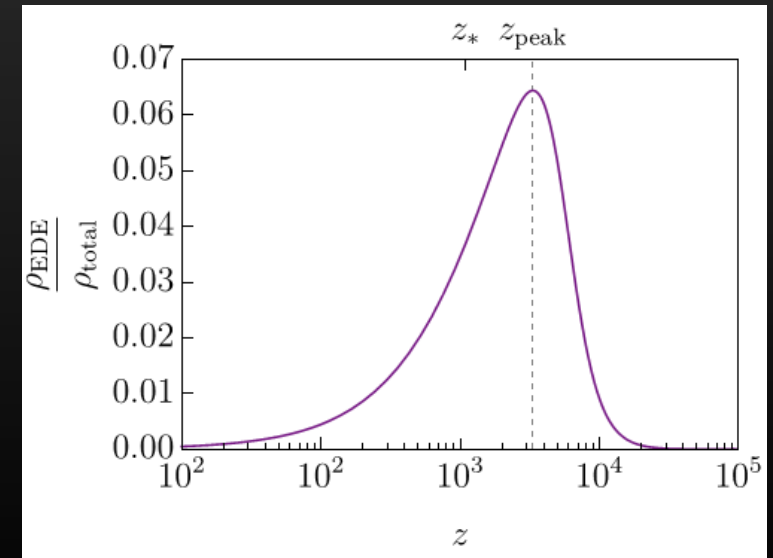
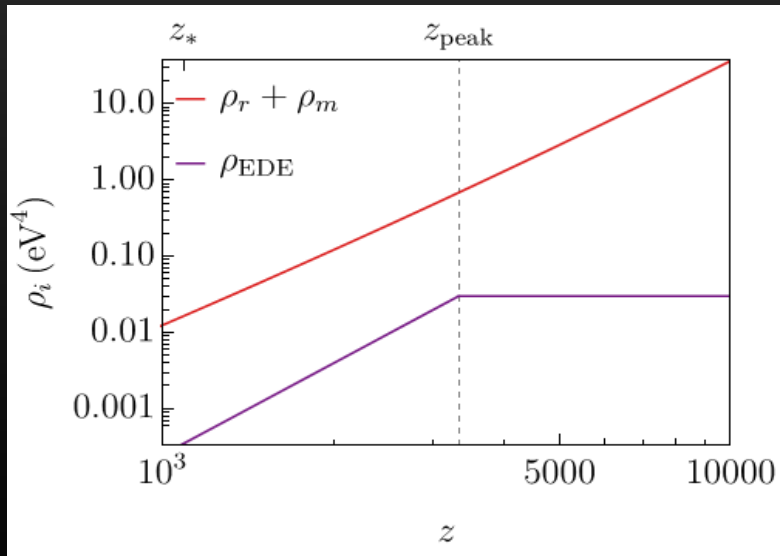
Frozen at early times by Hubble friction

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

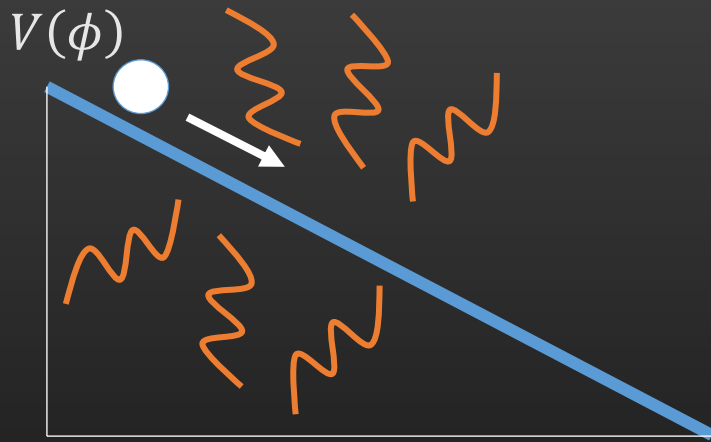
Dilutes away as radiation or faster when axion starts oscillating at critical redshift z_c

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

$$n \geq 2$$



Early Dark Energy with **thermal friction**

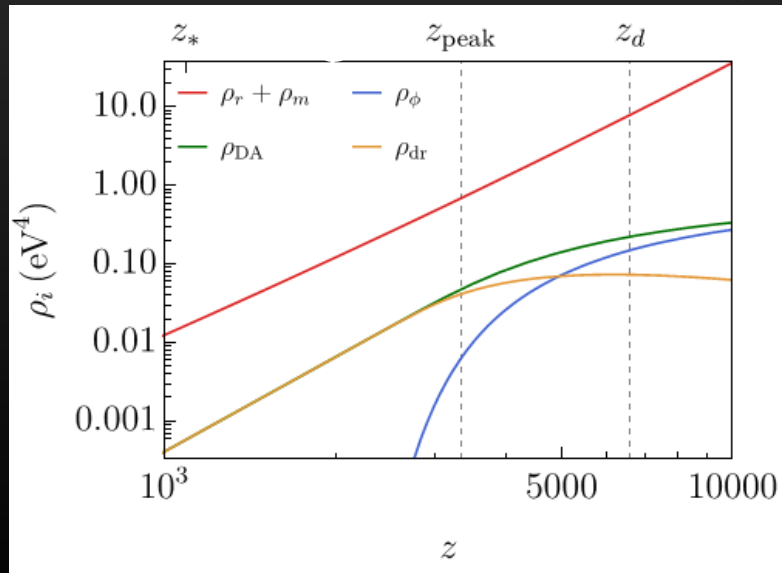


Frozen at early times by **thermal friction**

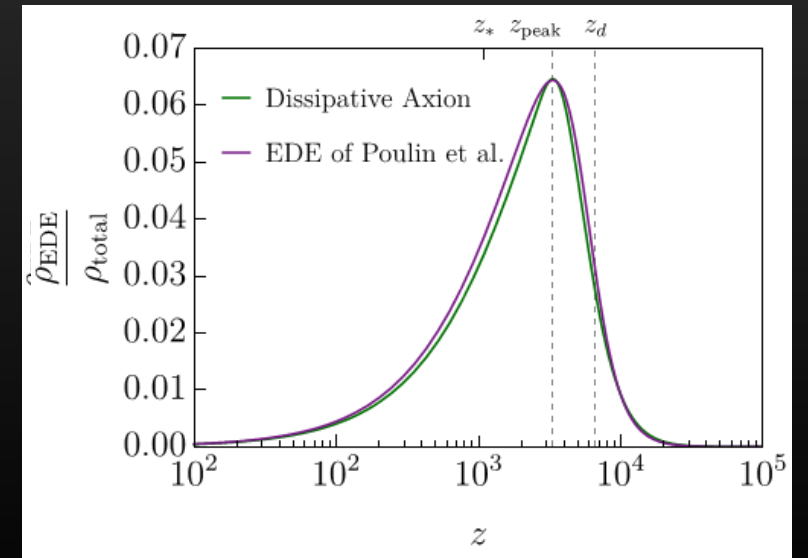
$$\ddot{\phi} + (3H + \Upsilon)\dot{\phi} + V' = 0$$

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

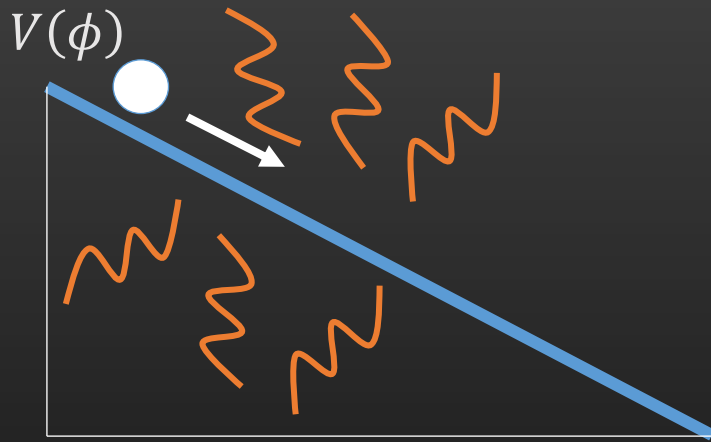
Overdamped at all time. Axion converts its energy into dark radiation at critical redshift z_c



$$\phi(z) \approx \phi_0 e^{-\frac{m^2}{\Upsilon H(z)}}$$



Early Dark Energy with **thermal friction**



Frozen at early times by **thermal friction**

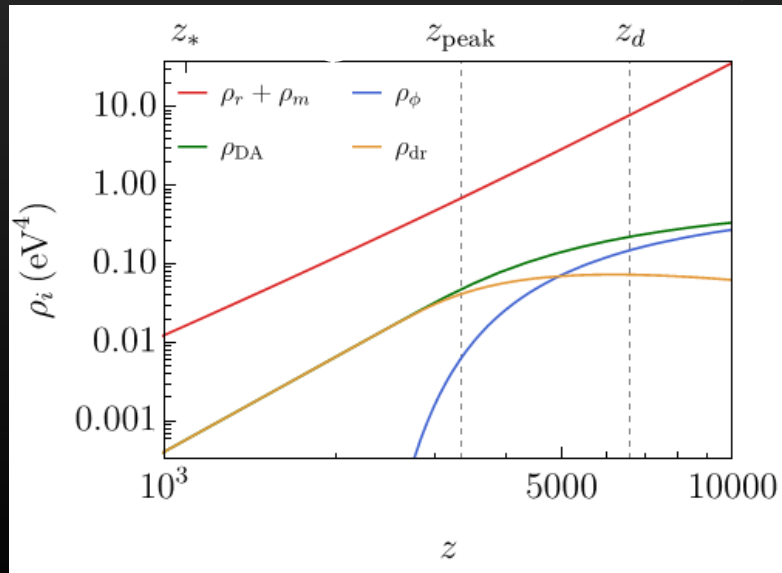
$$\ddot{\phi} + (3H + \Upsilon)\dot{\phi} + V' = 0$$

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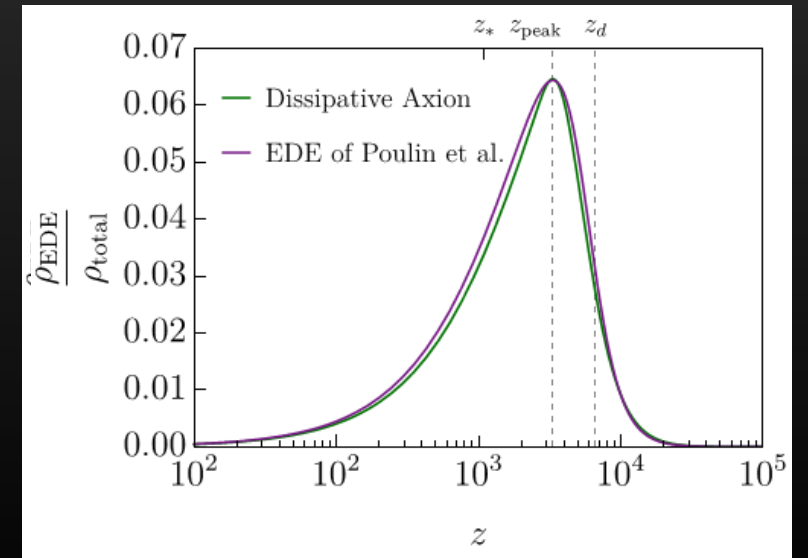
Overdamped at all time. Axion converts its energy into dark radiation at critical redshift z_c

Thermal friction generically arises for axions couplings to gauge fields

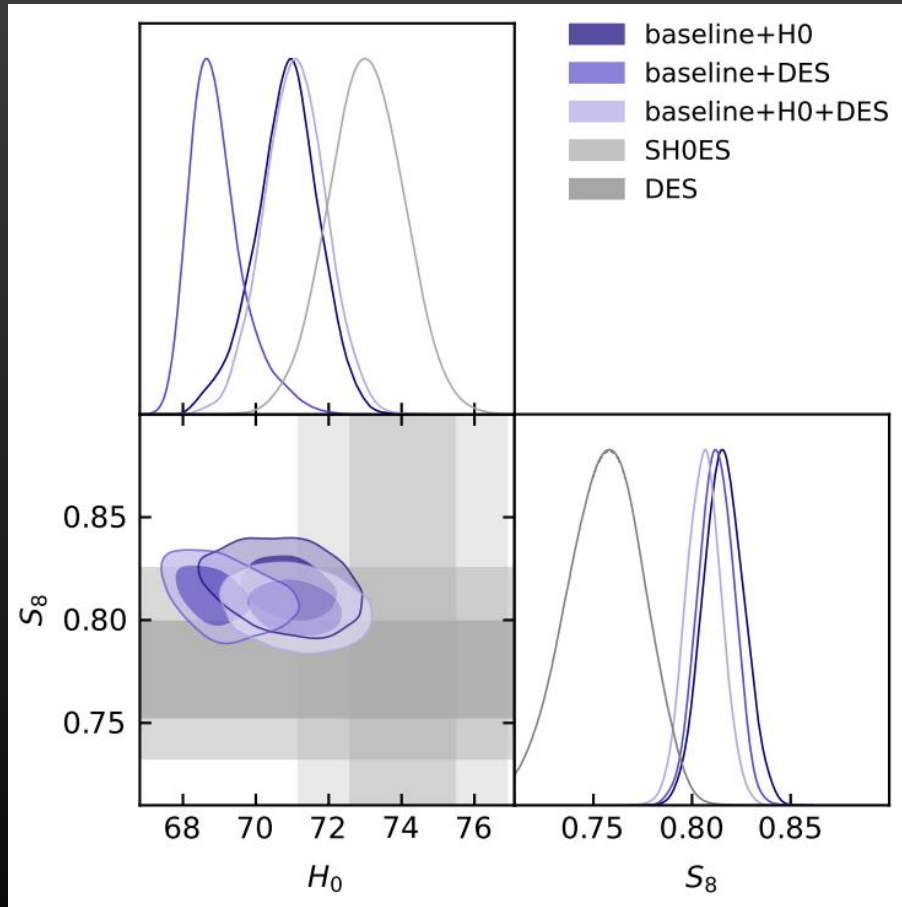
$$L_{\text{int}} = -\phi \frac{\alpha}{16\pi f} \tilde{G}G$$



$$\phi(z) \approx \phi_0 e^{-\frac{m^2}{\Upsilon H(z)}}$$

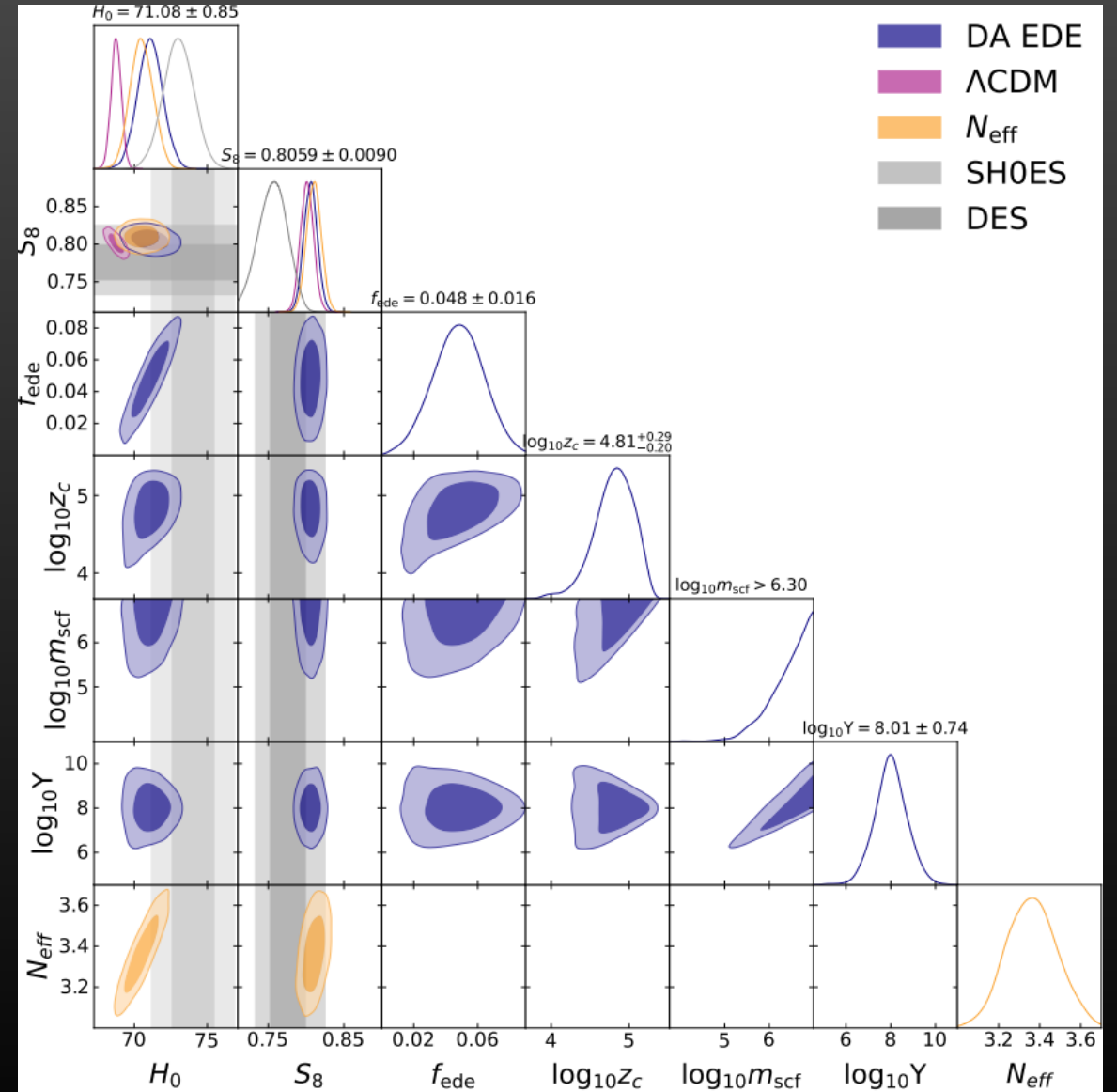


Results



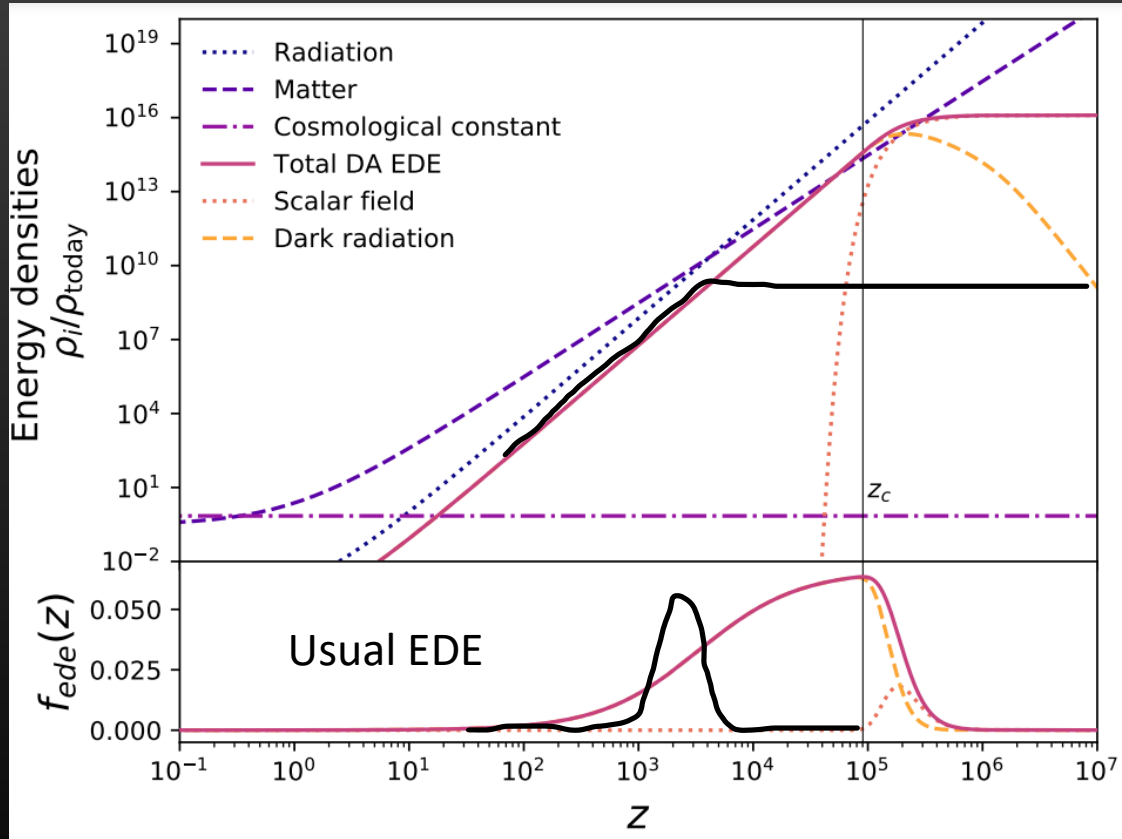
Berghaus, Karwal 2022

Baseline + SH0ES + DES



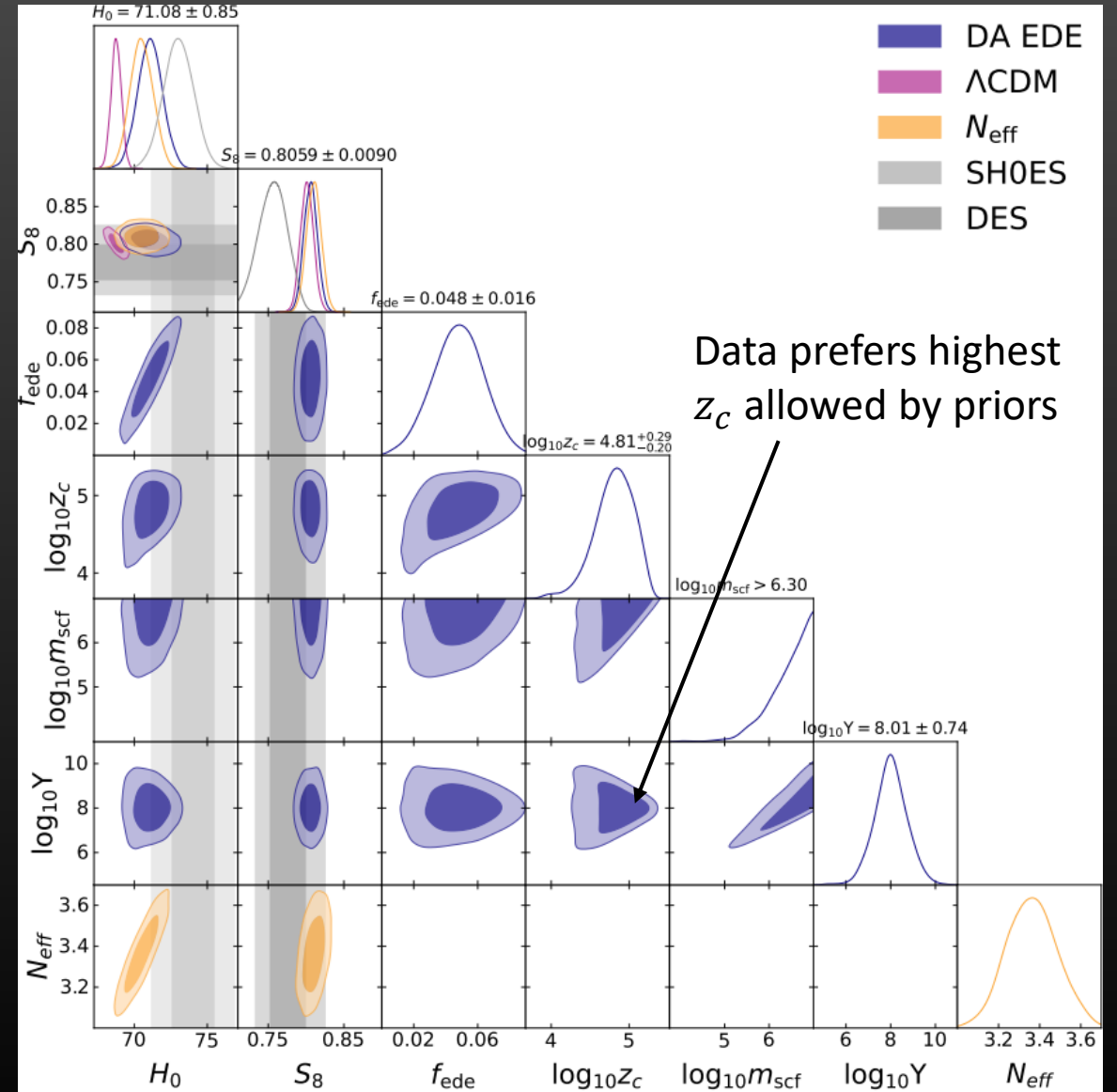
Berghaus, Karwal 2022

Results



Berghaus, Karwal 2022

Baseline + SHOES + DES



Data prefers highest z_c allowed by priors

Berghaus, Karwal 2022

Why does data not prefer EDE thermal friction?

Answer must be in perturbations since background looks favorable

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

Regular EDE perturbations

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

Axion perturbations with thermal friction

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

Dark radiation perturbations sourced by thermal friction

$$\delta_{DR} \equiv \frac{\delta\rho_{DR}}{\rho_{DR}}$$

$$\theta_{DR} \equiv ik^j v_j$$

Sourcing of DR
smoothes anisotropies

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

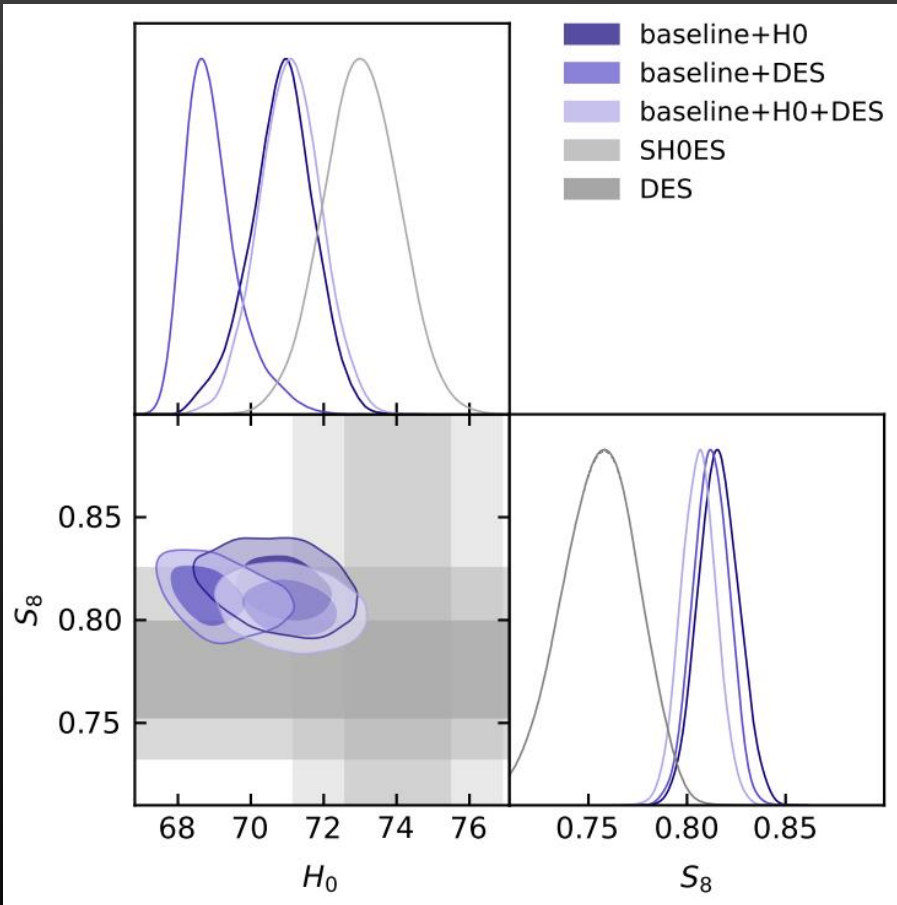
Thank You

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
 - SHOES measurement $H_0 = 73.04 \pm 1.04$ km/s/Mpc
 - Dark Energy Survey Year 1 galaxy lensing and clustering
- } baseline

Results



Berghaus, Karwal 2022

Model	H_0 [km/s/Mpc]	S_8
Λ CDM	$68.76(68.63) \pm 0.36$	$0.8013(0.8055) \pm 0.0087$
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+H₀+DES*.

Model	χ^2_{CMB}	$\chi^2_{H_0}$	χ^2_{DES}
Λ CDM	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+H₀+DES*.

Model	χ^2_{CMB}	$\chi^2_{H_0}$
Λ CDM	2777.5	18.8
DA EDE	2780.3	2.4
N_{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, Λ CDM fit just to *baseline* has $\chi^2_{\text{CMB}} = 2772.6$.

Model	χ^2_{CMB}	χ^2_{DES}
Λ CDM	2774.1	509.3
DA EDE	2774.7	509.4
N_{eff}	2776.0	508.1

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

Model	χ^2_{CMB}	$\chi^2_{H_0}$	χ^2_{DES}
Λ CDM	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	H_0 [km/s/Mpc]	S_8
Λ CDM	$68.44(68.53) \pm 0.39$	$0.8093(0.8095) \pm 0.0100$
DA EDE	$70.85(71.43)_{-0.80}^{+0.93}$	$0.8159(0.8157) \pm 0.0102$
N_{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

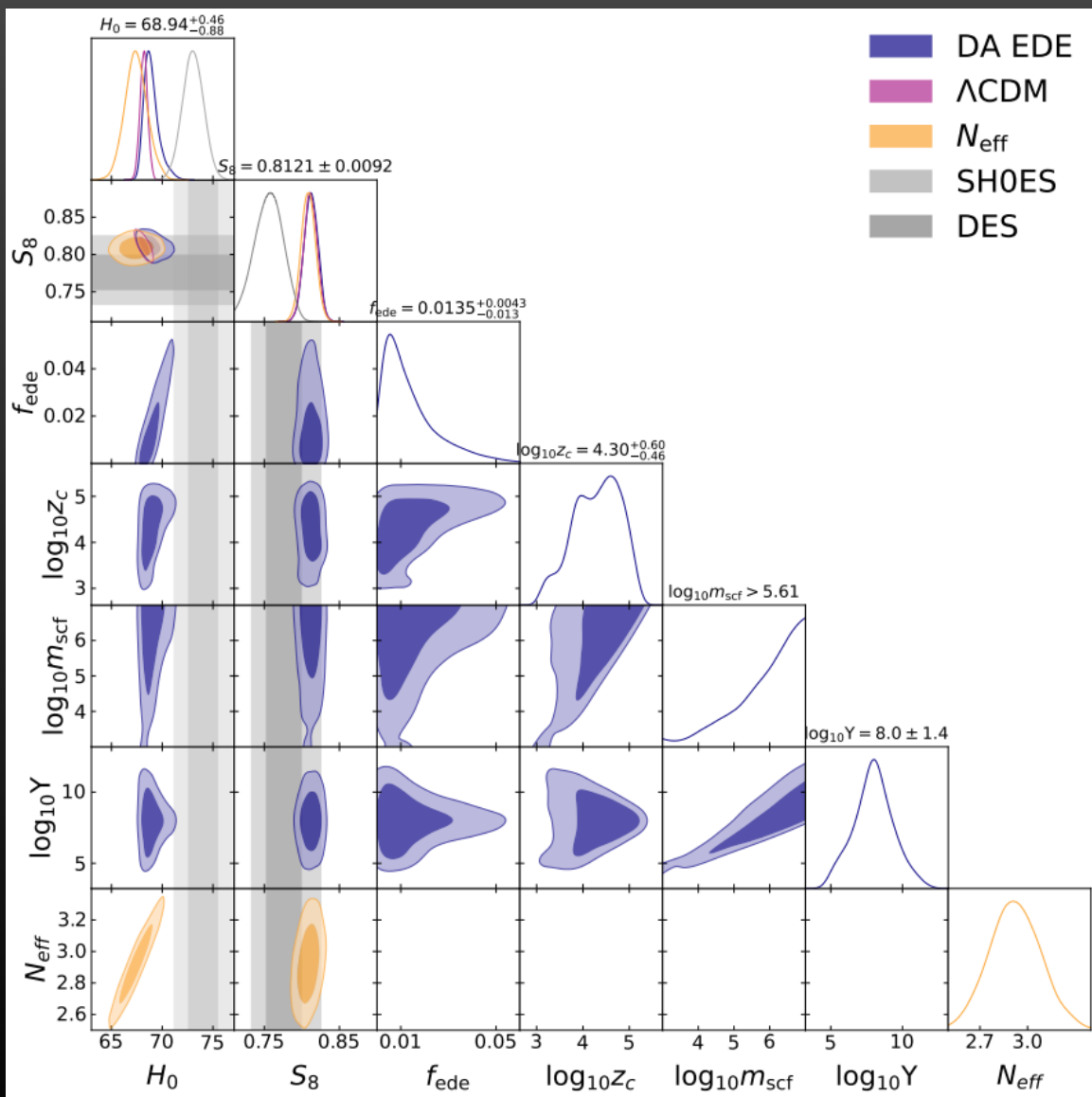
Model	H_0 [km/s/Mpc]	S_8
Λ CDM	$68.19(68.08) \pm 0.38$	$0.8115(0.8128) \pm 0.0091$
DA EDE	$68.94(68.38)_{-0.88}^{+0.46}$	$0.8120(0.8133) \pm 0.0091$
N_{eff}	$67.4(67.2) \pm 1.1$	$0.8086(0.8078) \pm 0.0094$

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

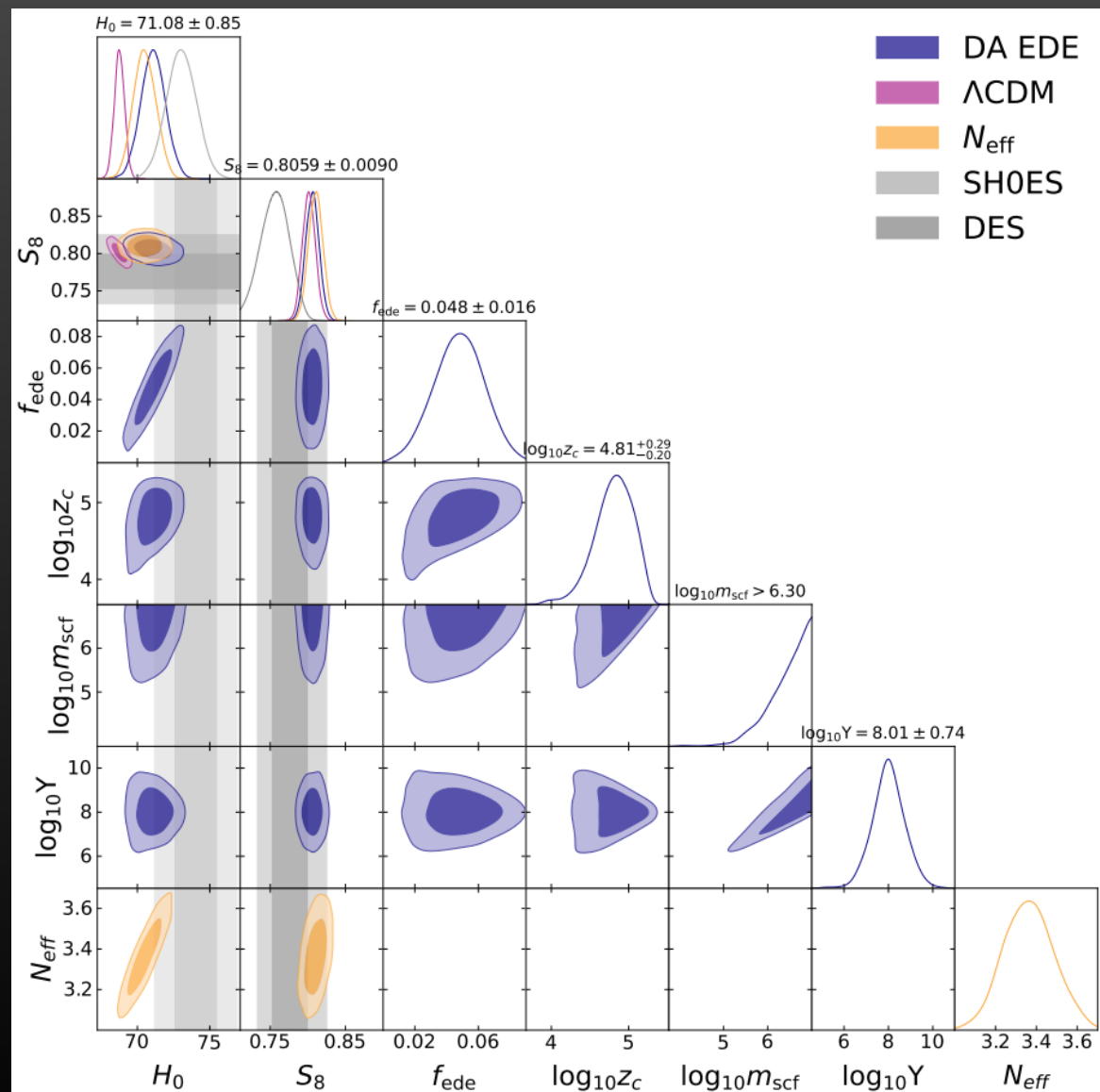
Model	H_0 [km/s/Mpc]	S_8
Λ CDM	$68.76(68.63) \pm 0.36$	$0.8013(0.8055) \pm 0.0087$
DA EDE	$71.08(71.06) \pm 0.85$	$0.8058(0.8075) \pm 0.0089$
N_{eff}	$70.50(70.86) \pm 0.78$	$0.8102(0.8106) \pm 0.0096$

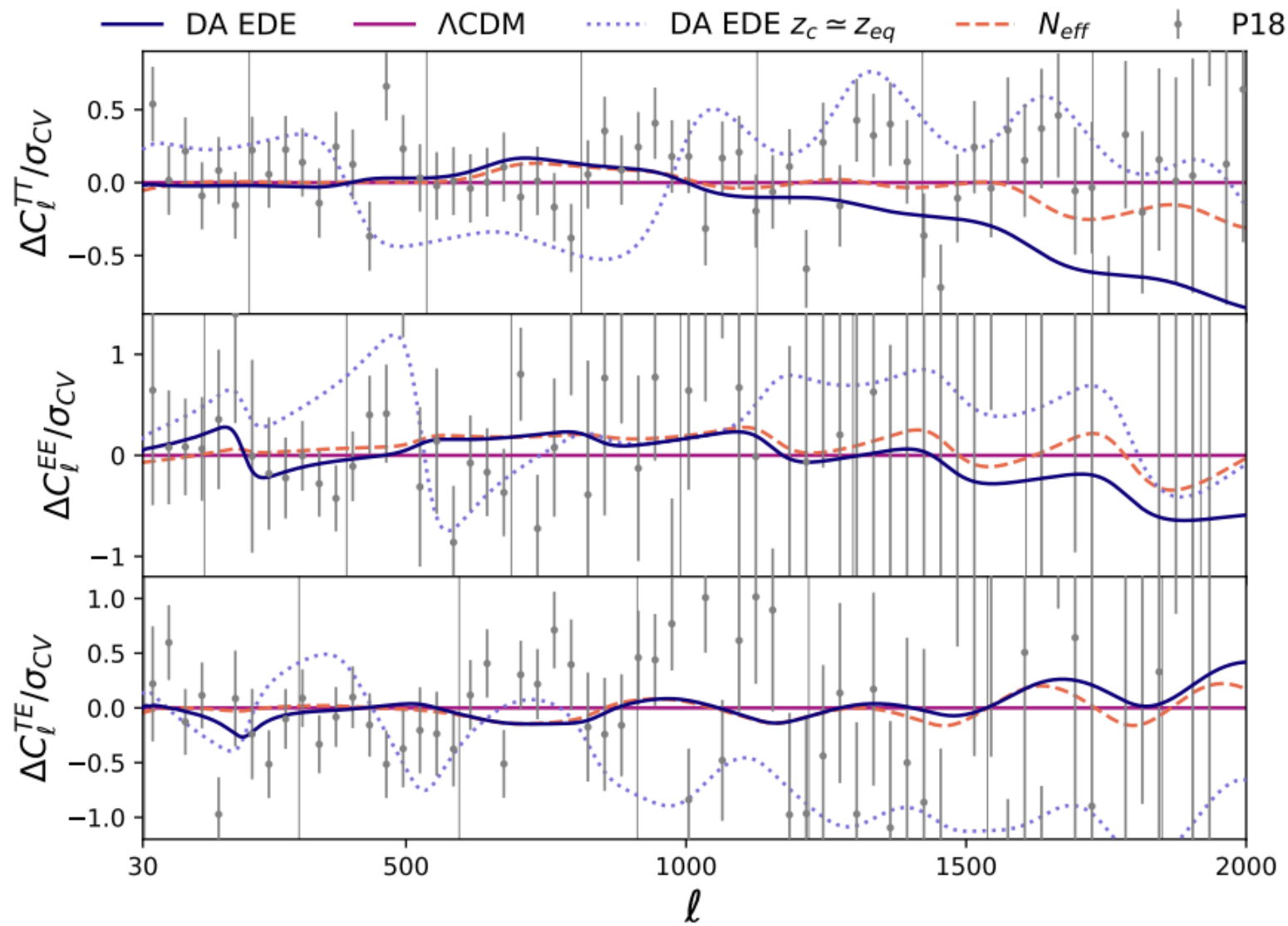
Table VI. 1D marginalized posteriors of measurements quantifying the two cosmological tensions, fitting to *baseline*+ H_0 +DES.

Baseline + DES

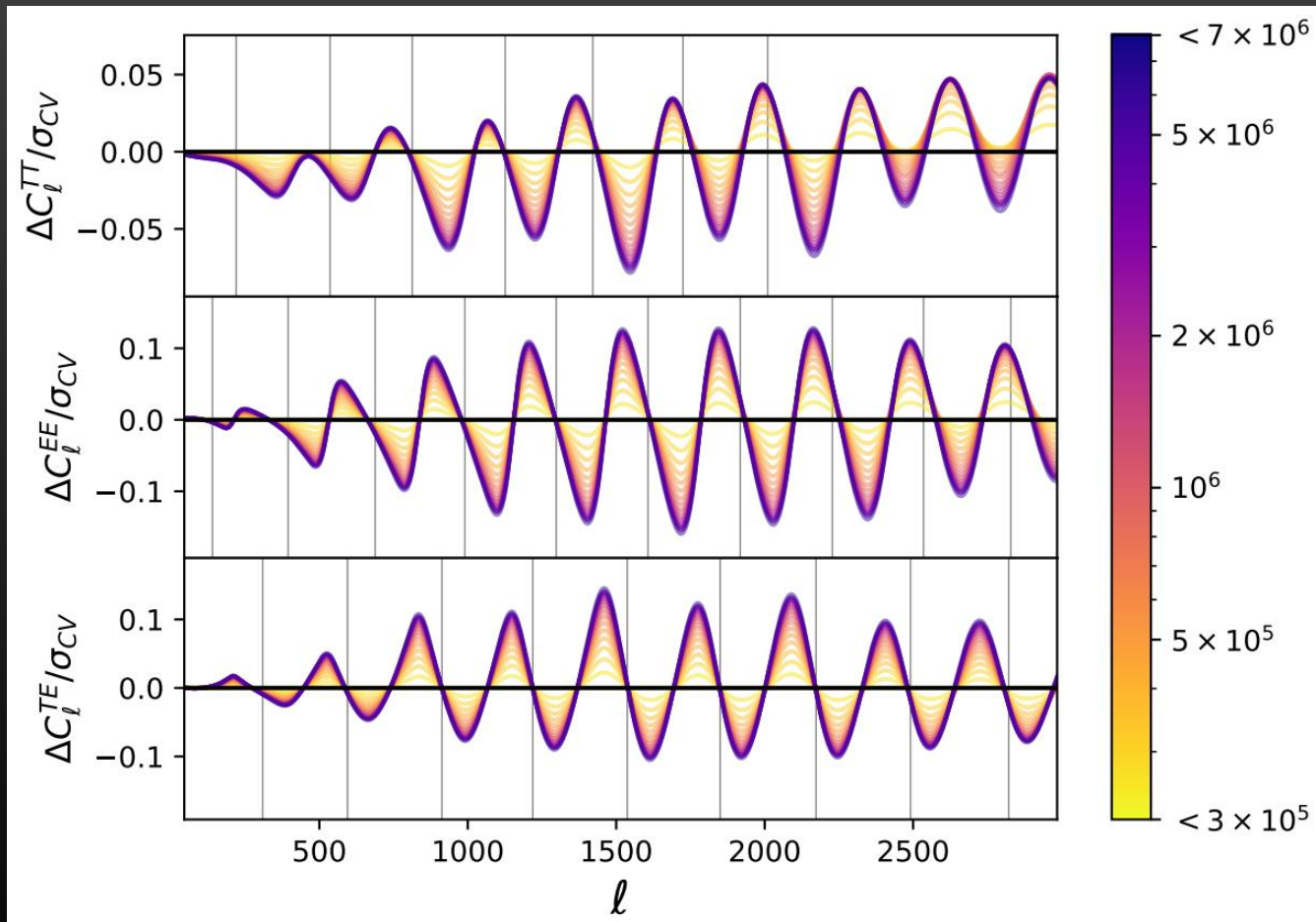


Baseline + DES + SHOES





Going to higher redshifts



Berghaus, Karwal 2022

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

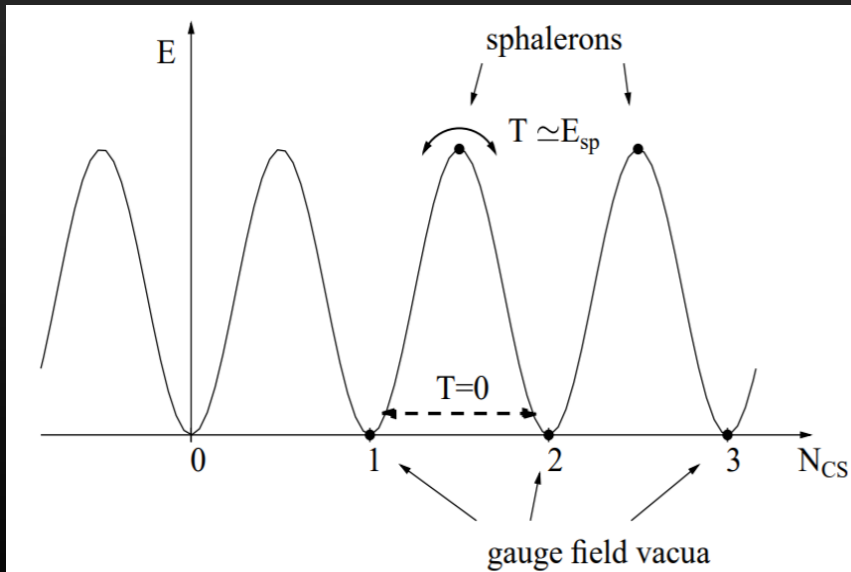
Thermal friction asymptotes to an extra-radiation solution

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

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



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

Not allowed by symmetry

Dissipative Axion

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

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

- 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

