Warm Early Dark Energy

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Based on 2204.09133 with Tanvi Karwal

Content

1. Cosmic Tensions
2. Possible Solutions
3. Warm Early Dark Energy
4. Results
5. Conclusions

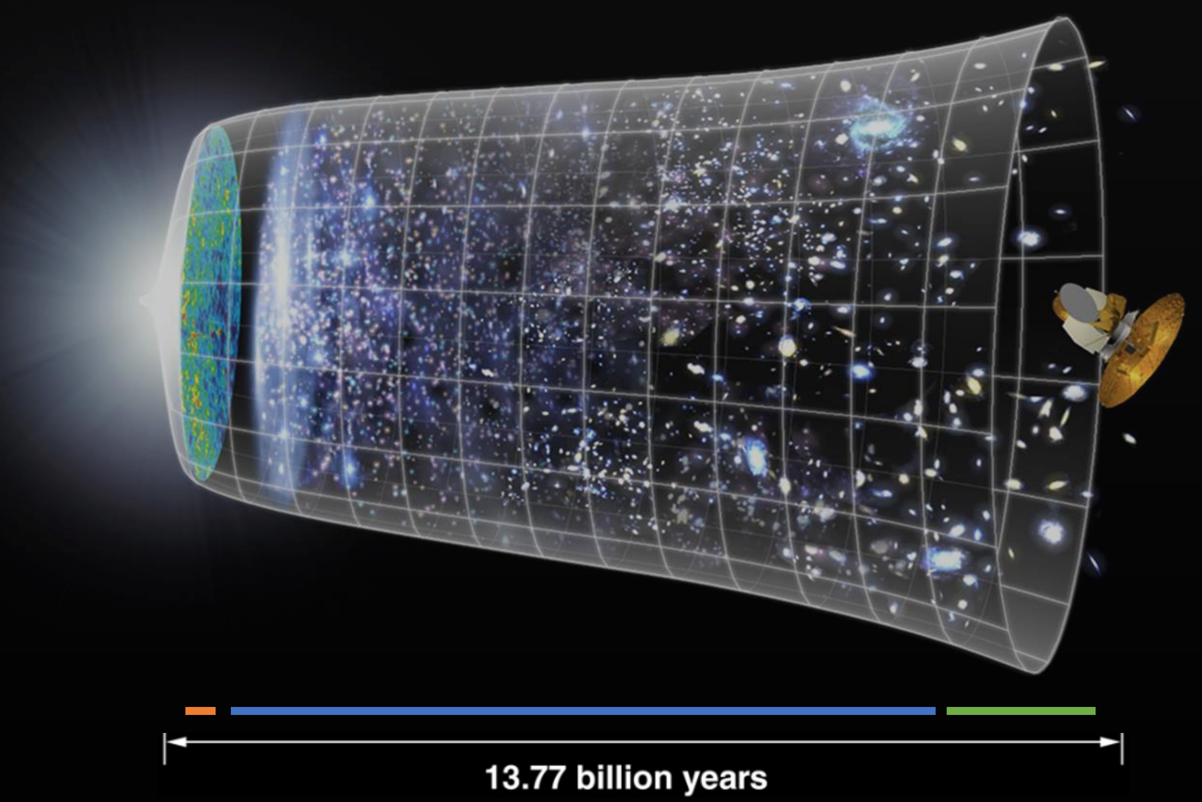
The ΛCDM model of Cosmology

Energy content

Matter $\propto a^{-3}$

Radiation $\propto a^{-4}$

$\Lambda \propto a^{0}$



The Hubble Tension

Energy content

Matter $\propto a^{-3}$

Radiation $\propto a^{-4}$

$\Lambda \propto a^{0}$

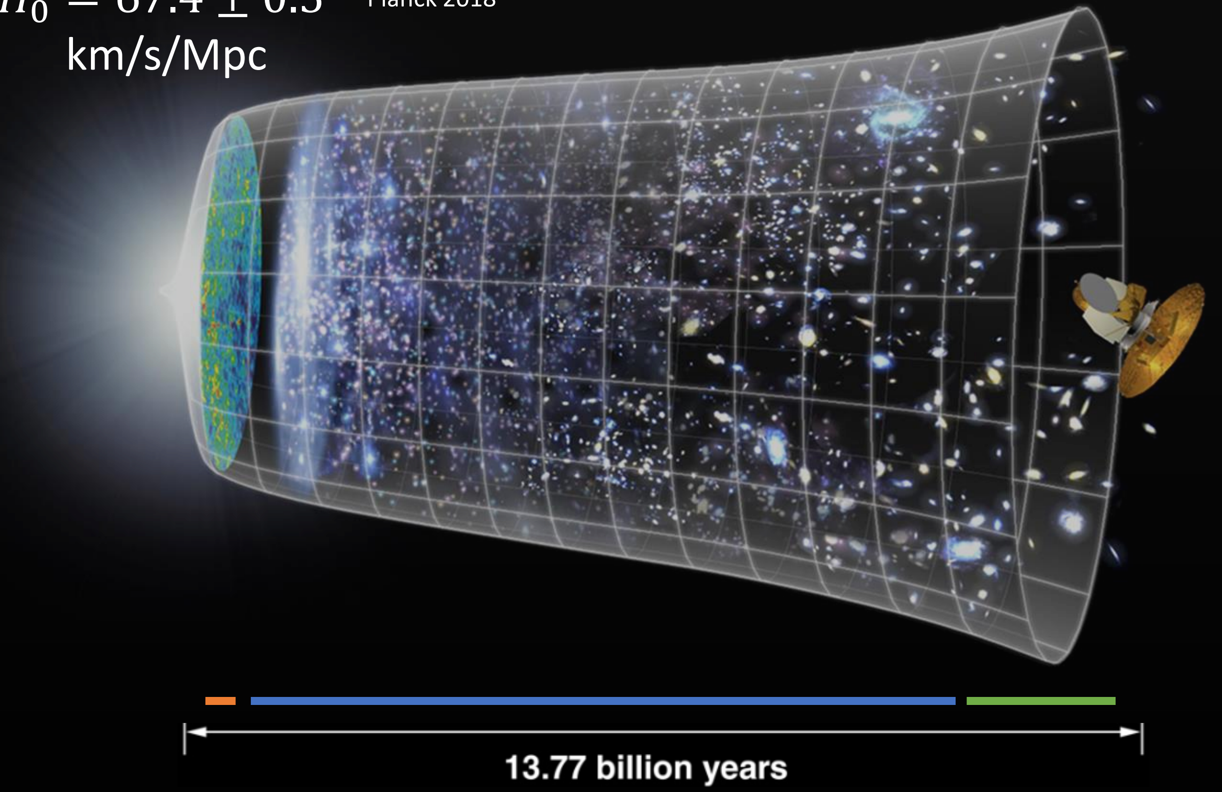
ΛCDM +
CMB measurement

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

~ 5 σ

Direct measurement

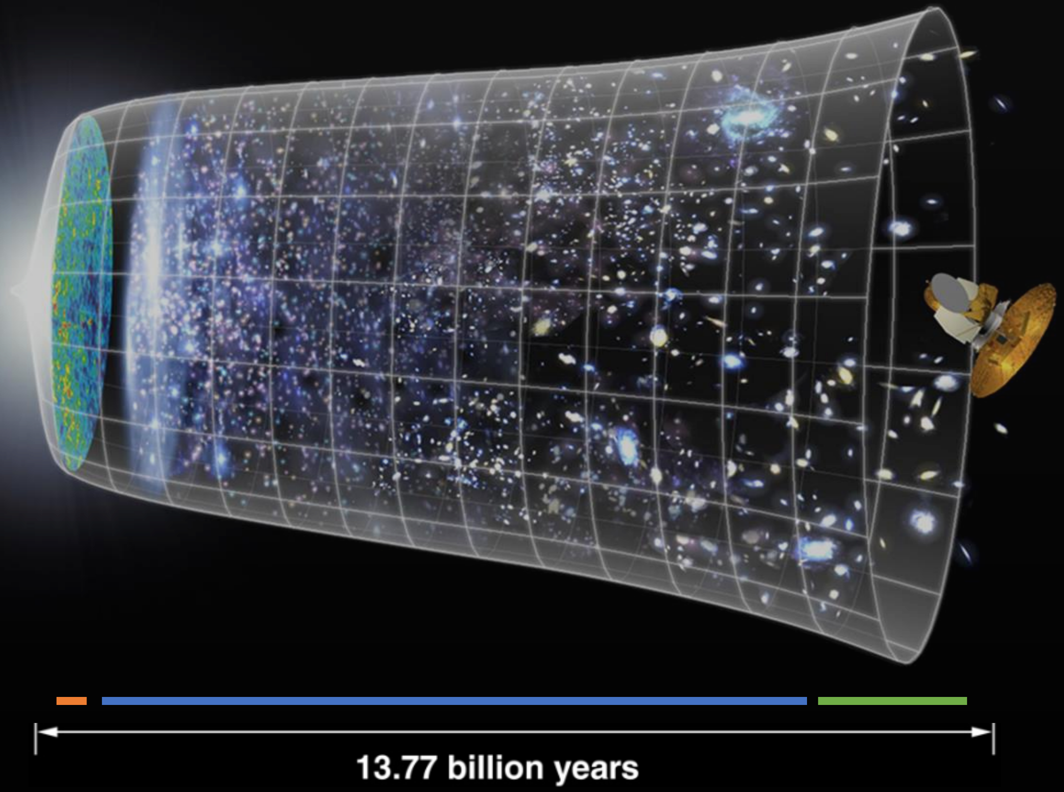
$H_0 = 73.3 \pm 1.0$ km/s/Mpc SH0ES 2022



The Large-Scale Structure Tension

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

Amplitude of matter fluctuations



The Large-Scale Structure Tension

ΛCDM +
CMB measurement

$S_8 = 0.82 \pm 0.01$ Planck 2018

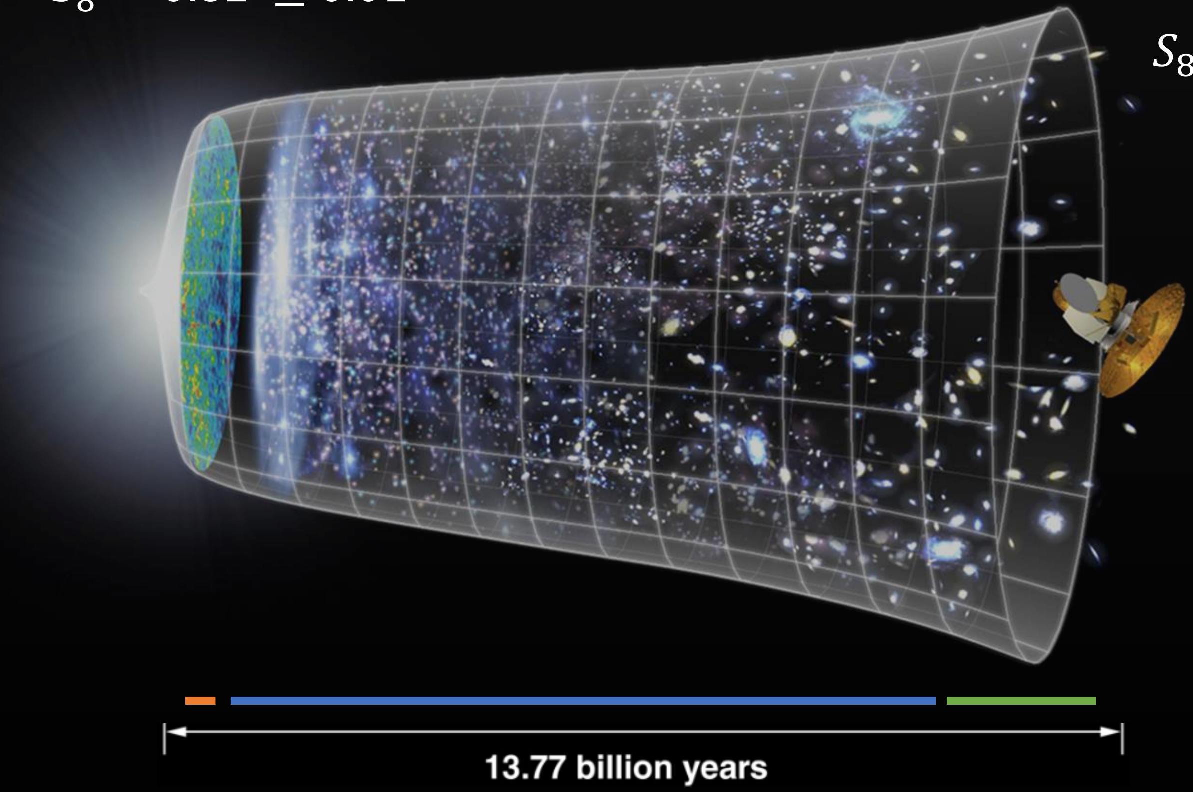
~ 2 - 3 σ

Galaxy clustering
+ weak lensing
(DES Y1)

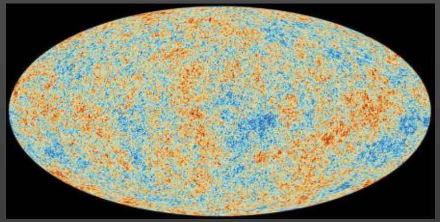
$S_8 = 0.77 \pm 0.02$ DES 2017

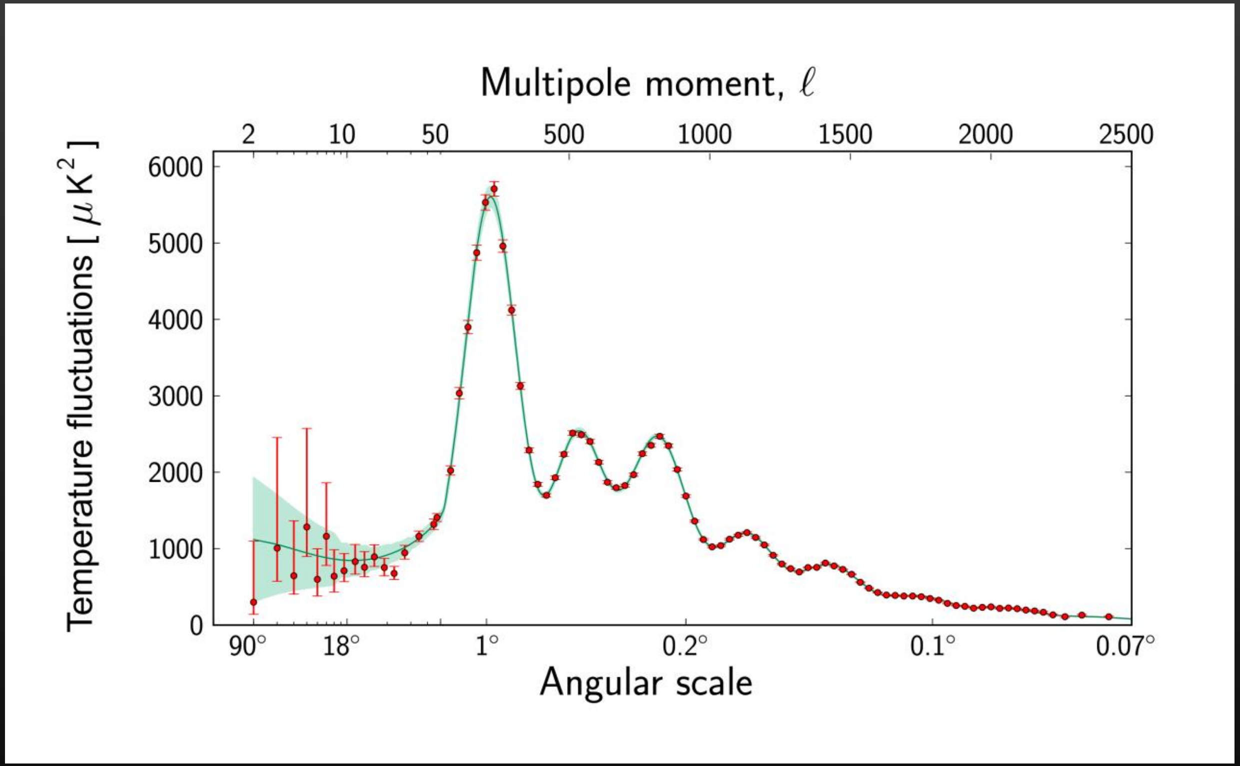
$$S_8 = \sigma_8 \sqrt{\frac{\Omega_m}{0.3}}$$

Amplitude of matter fluctuations



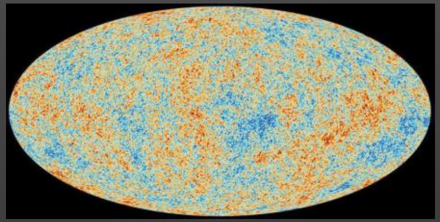
The Hubble Measurement with the CMB



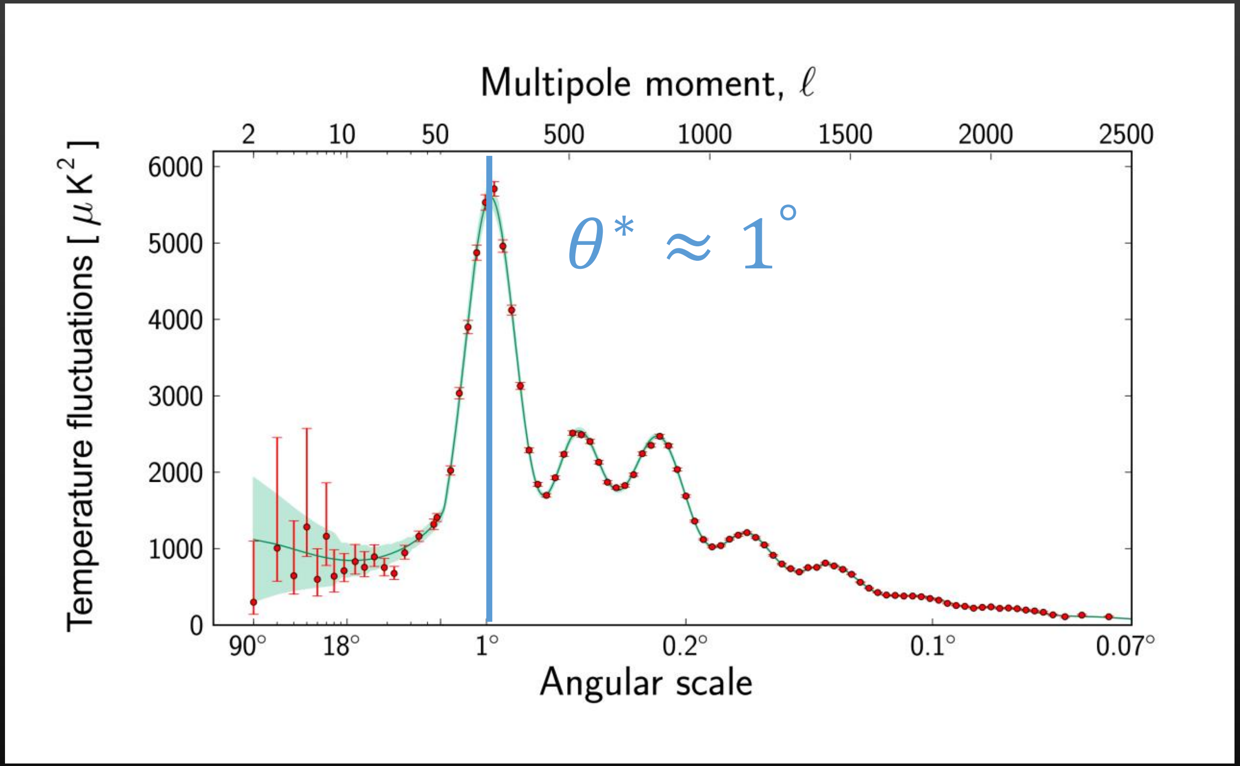


Planck 2018

The Hubble Measurement with the CMB



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



Planck 2018

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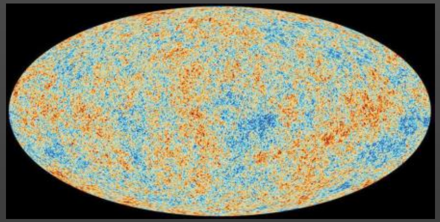
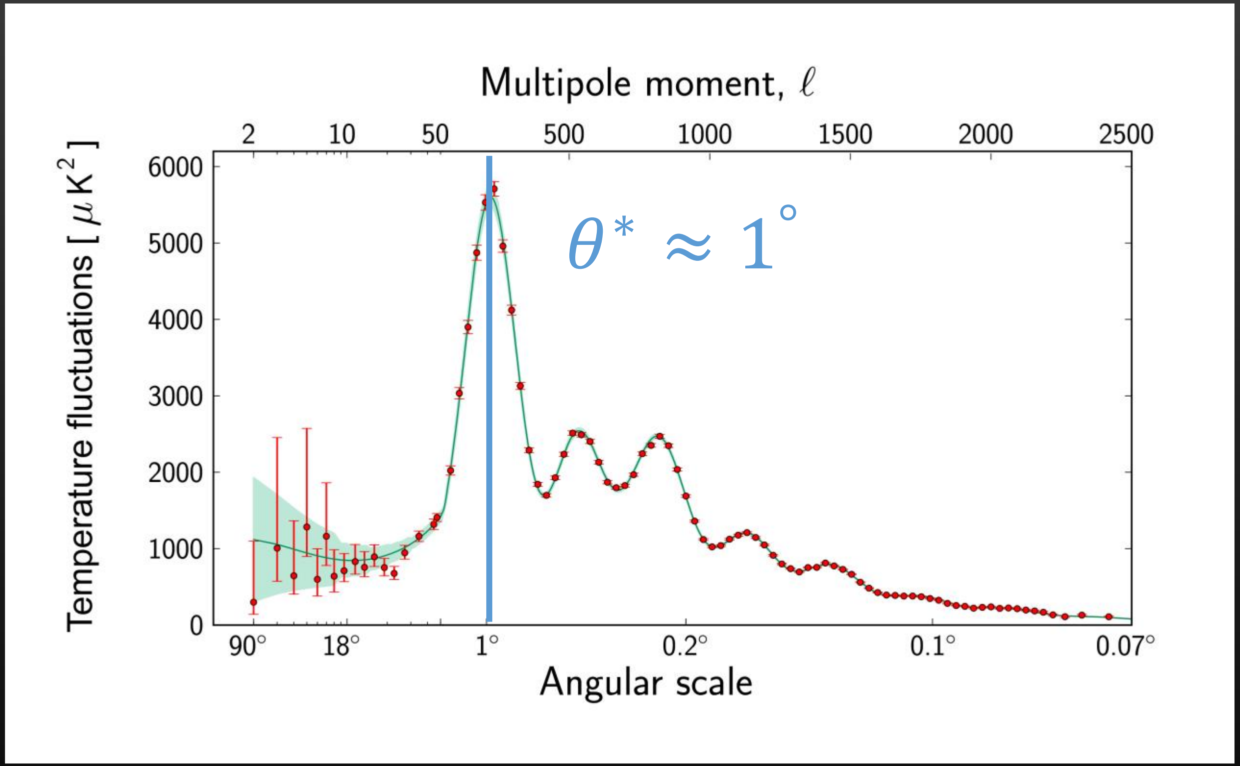


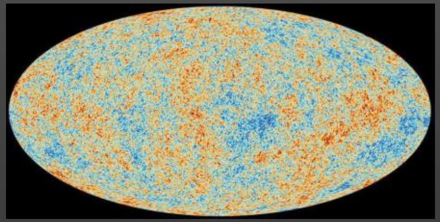
$$\theta^* \propto r_s H_0$$

- r_s depends only on physics before formation of CMB



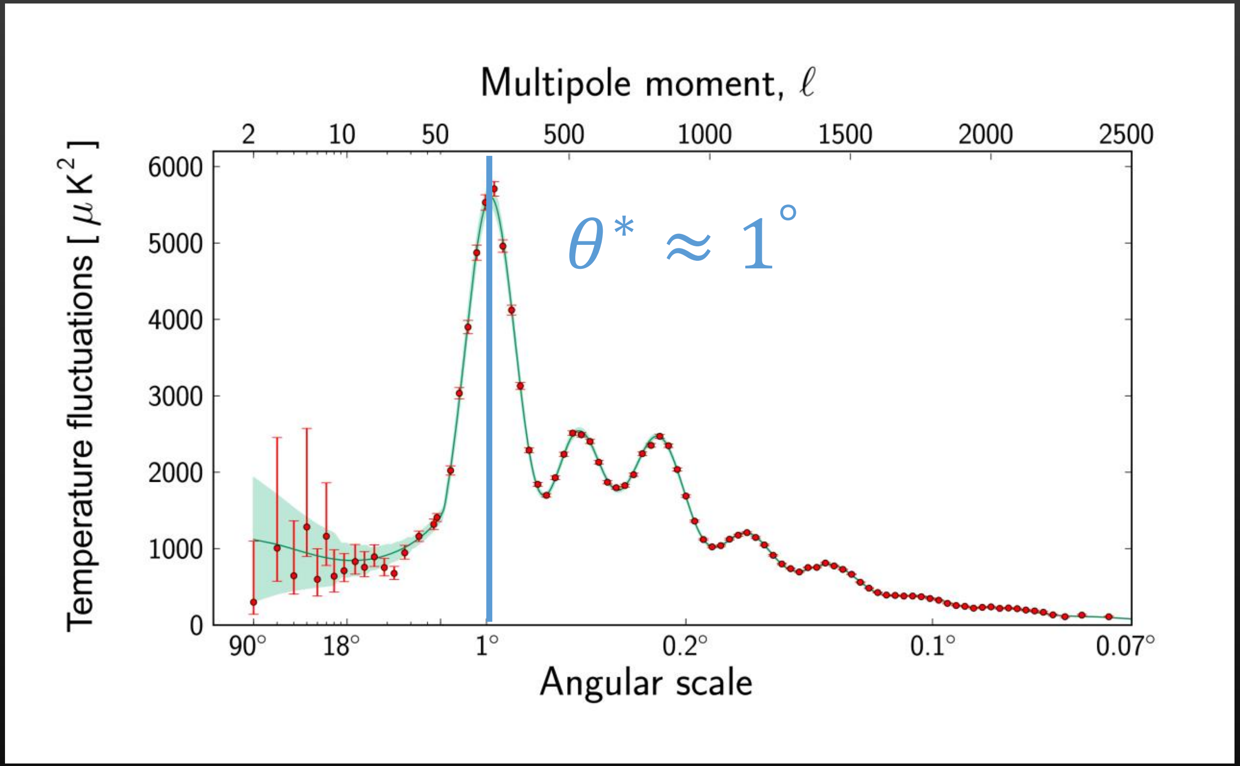
Planck 2018

The Hubble Measurement with the CMB



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

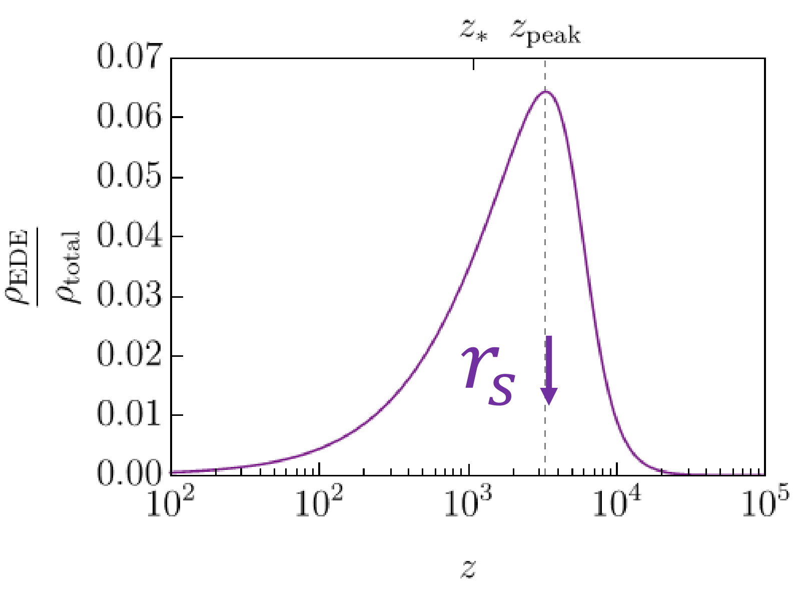
- r_s depends only on physics before formation of CMB
- Lowering r_s increases H_0



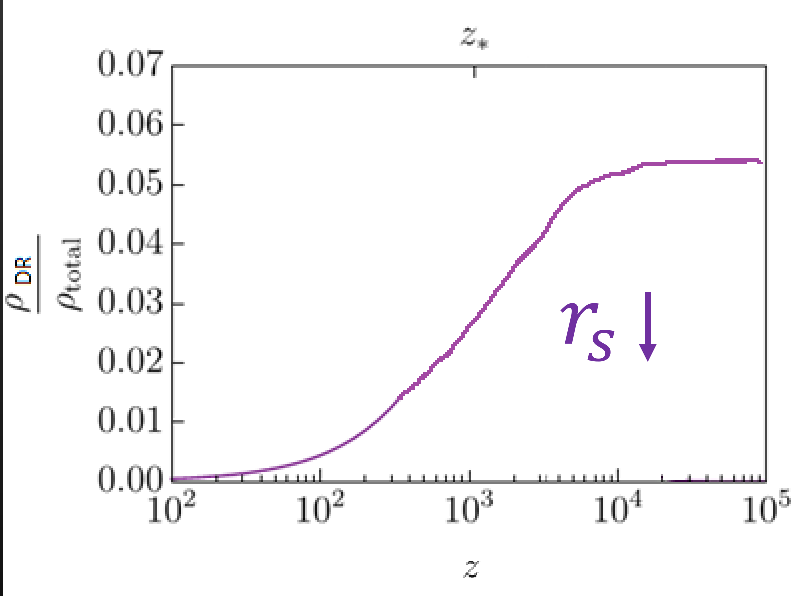
Planck 2018

New physics that can lower r_s

Early Dark Energy



Extra Radiation



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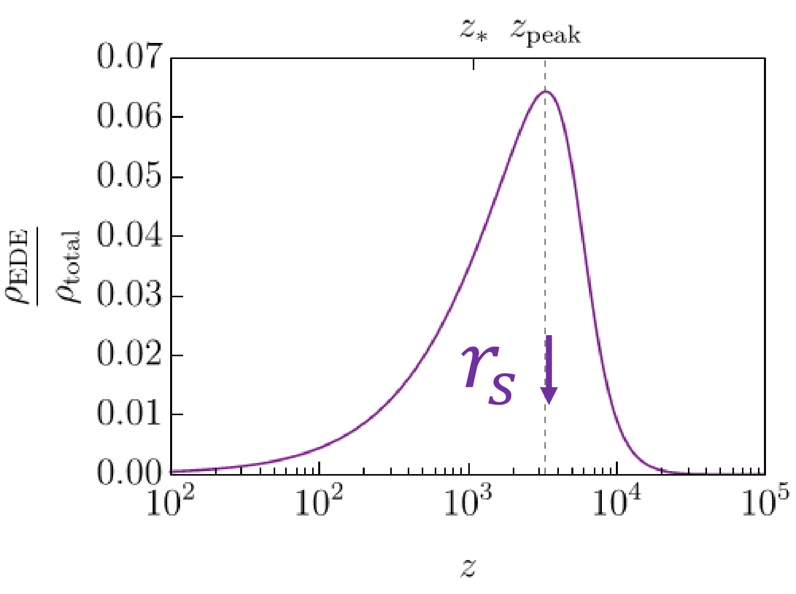

Maintains great fit to CMB

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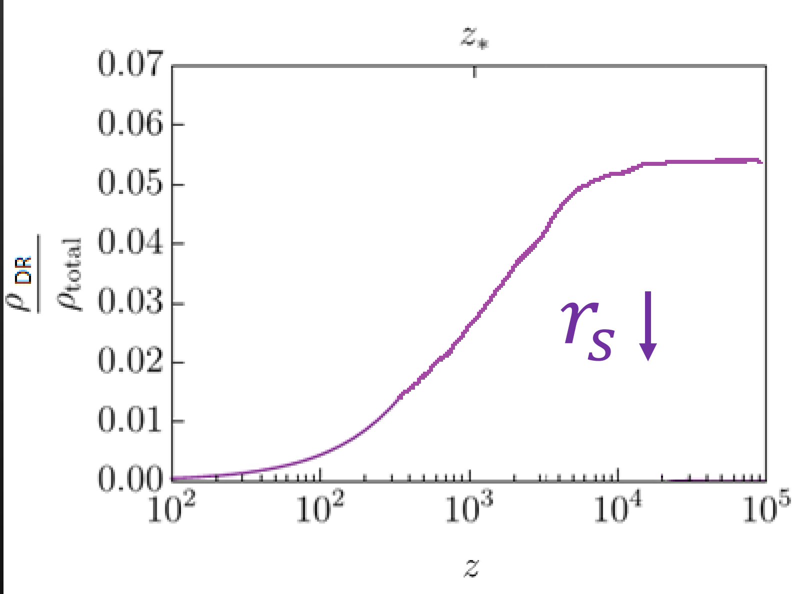
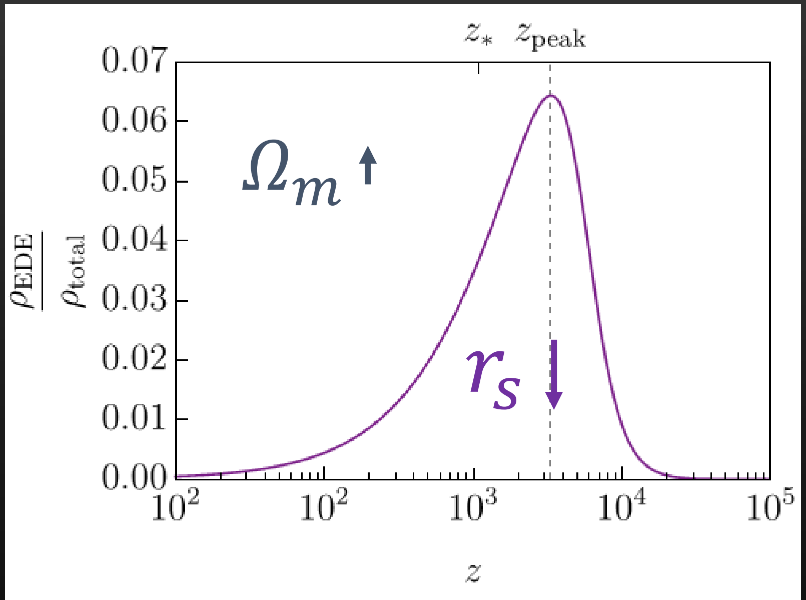


Worsens fit to CMB

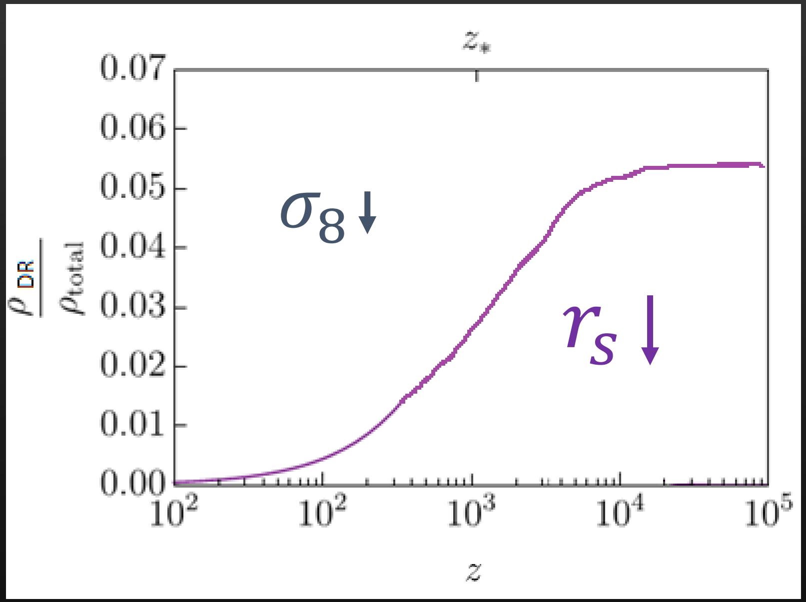
New physics that can lower r_s

Early Dark Energy



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

Extra Radiation

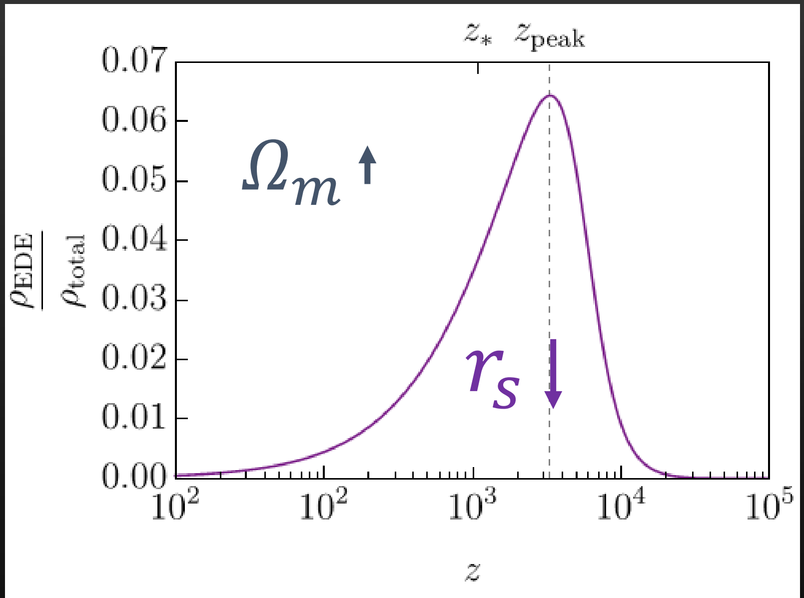


Maintains great fit to CMB
Resolves H0 but exasterbates LSS tension (Hill et. al., 2020, Ivanov et al. 2020)

Worsens fit to CMB
Can ease LSS and Hubble tension

New physics that can lower r_s

Early Dark Energy



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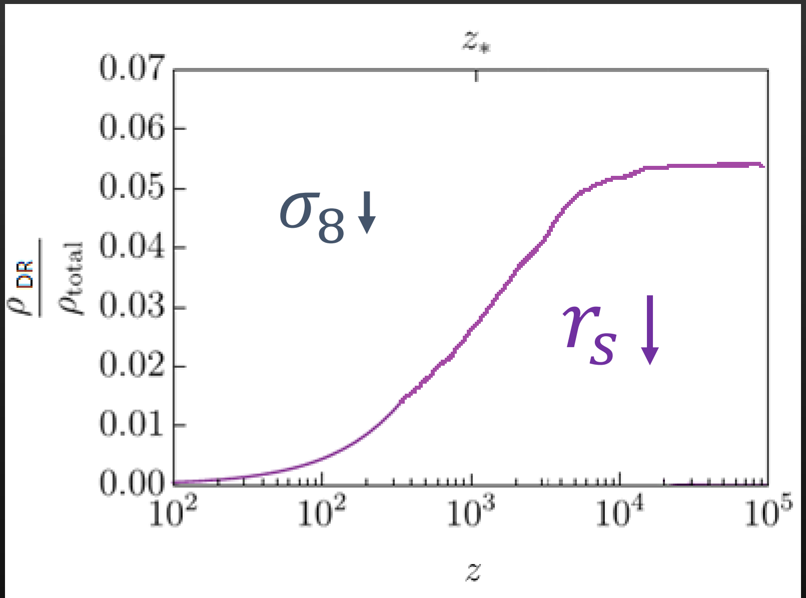

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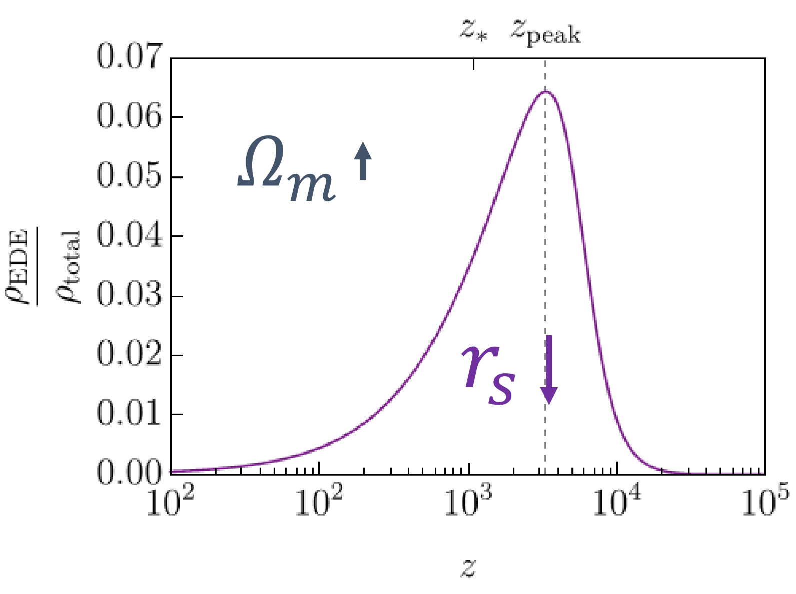
Resolves H0 but exasterbates LSS tension (Hill et. al., 2020, Ivanov et al. 2020)
Relies on fine-tuned scalar field potentials

Worsens fit to CMB
Can ease LSS and Hubble tension

New physics that can lower r_s

Warm Early Dark Energy with thermal friction



Maintains great fit to CMB

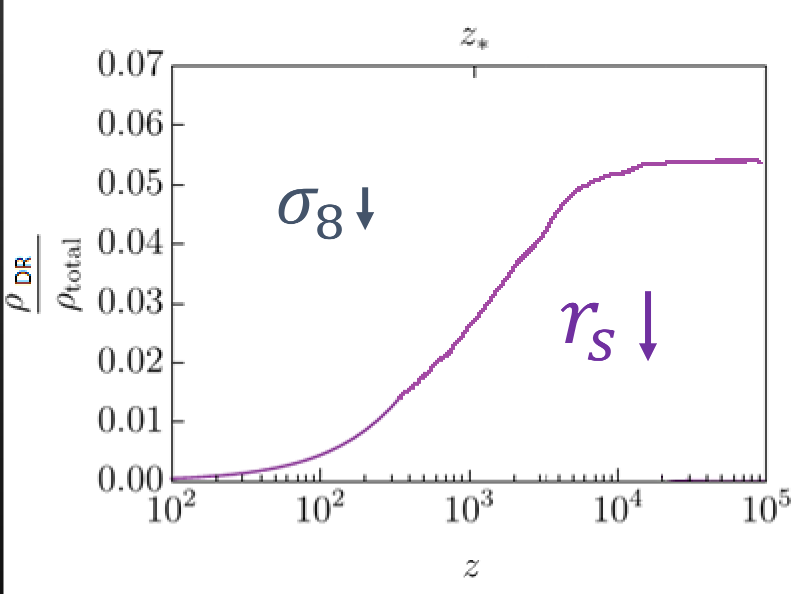
Resolves H0 but exasterbates LSS tension (Hill et. al., 2020, Ivanov et al. 2020)

~~Relies on fine-tuned scalar field potentials~~ (Berghaus, Karwal 2020)

combines

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

Extra Radiation



Worsens fit to CMB

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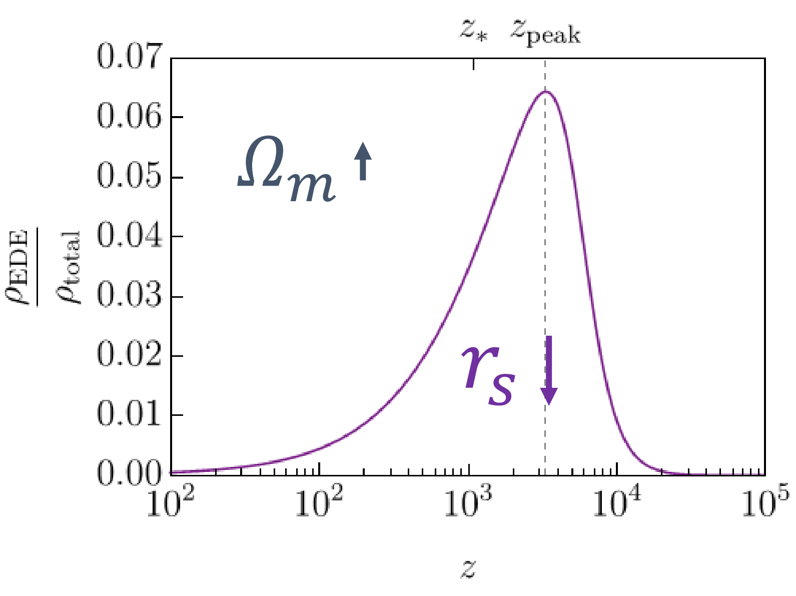

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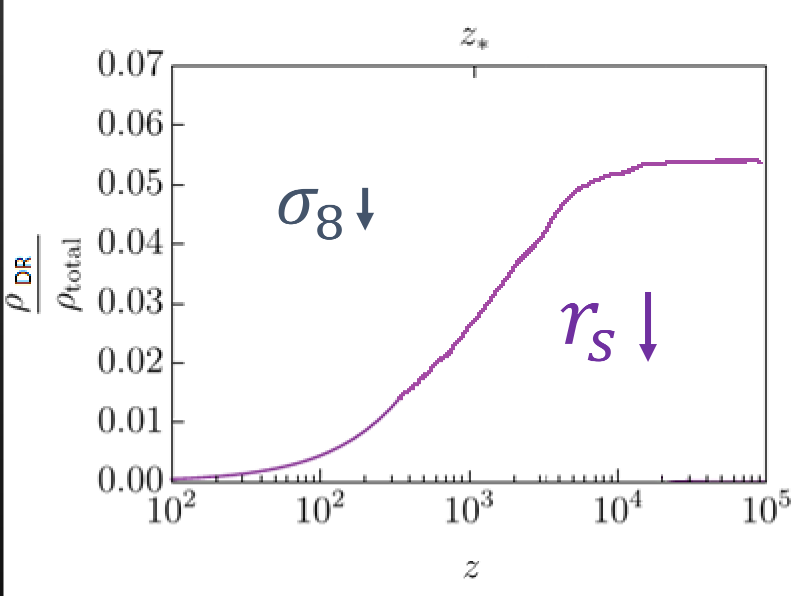
Extra Radiation



Maintains great fit to CMB ?

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

~~Relies on fine-tuned scalar field potentials~~ (Berghaus, Karwal 2020)

Worsens fit to CMB

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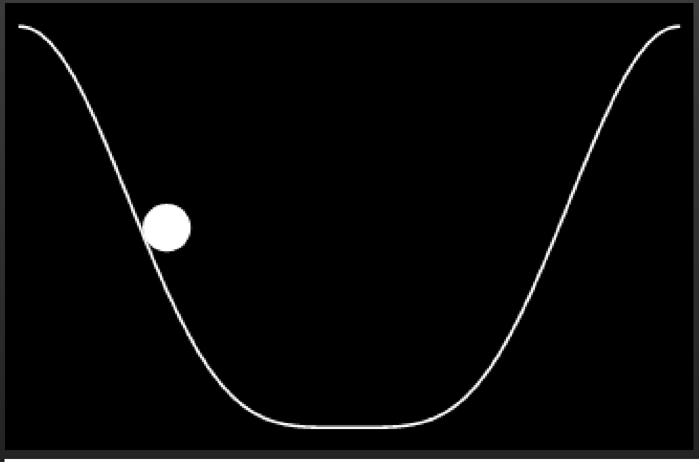
?

Early Dark Energy



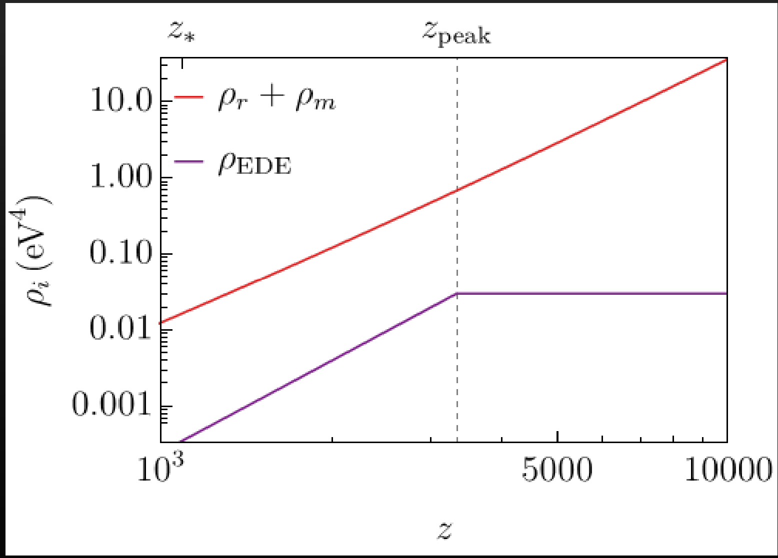
Frozen at early times by Hubble friction

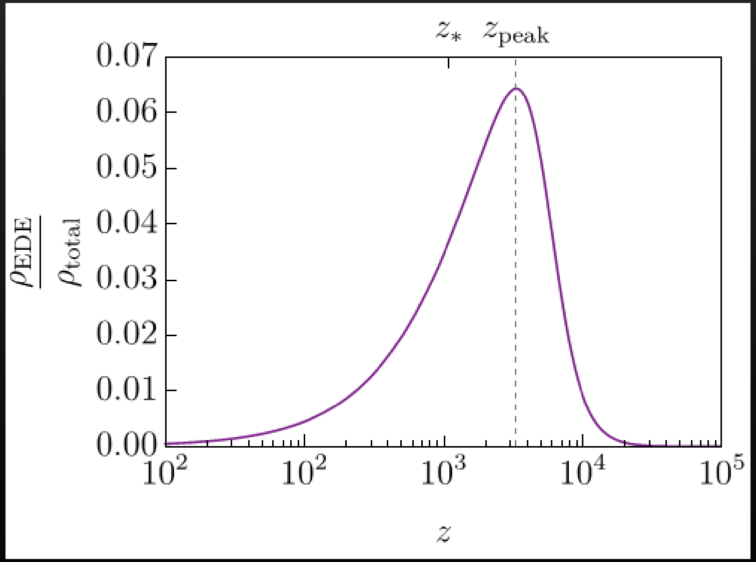
$$\ddot{\phi} + 3H\dot{\phi} + V' = 0$$

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

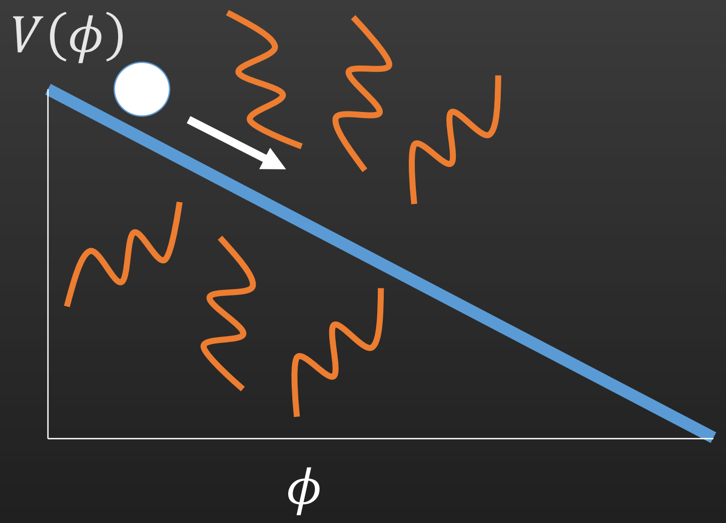
$$V \propto \left(1 - \cos\frac{\phi}{f}\right)^n$$

$$n \geq 2$$





Warm Early Dark Energy



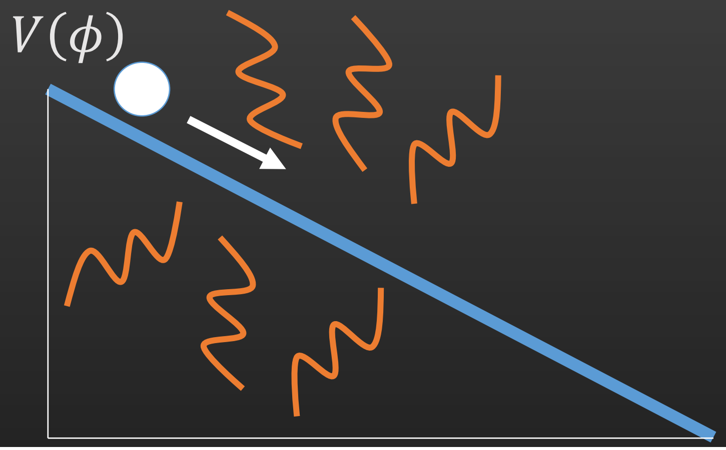
Frozen at early times by thermal friction

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

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

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

Warm Early Dark Energy



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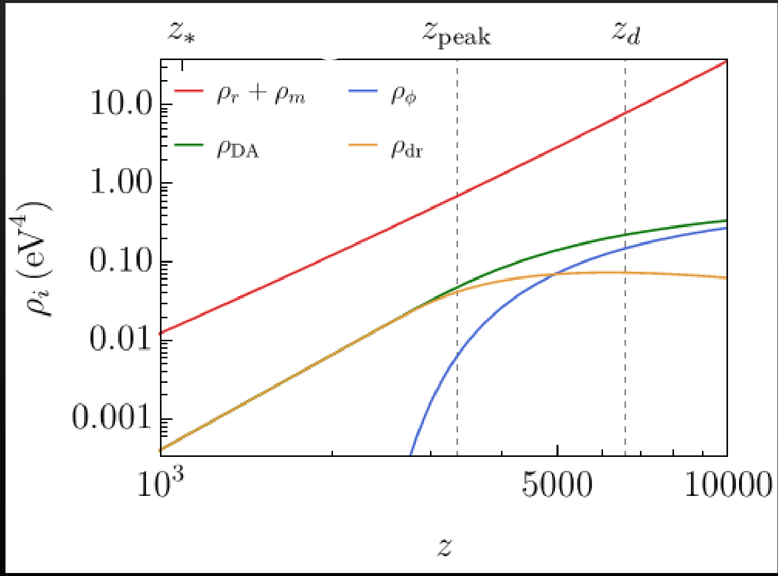
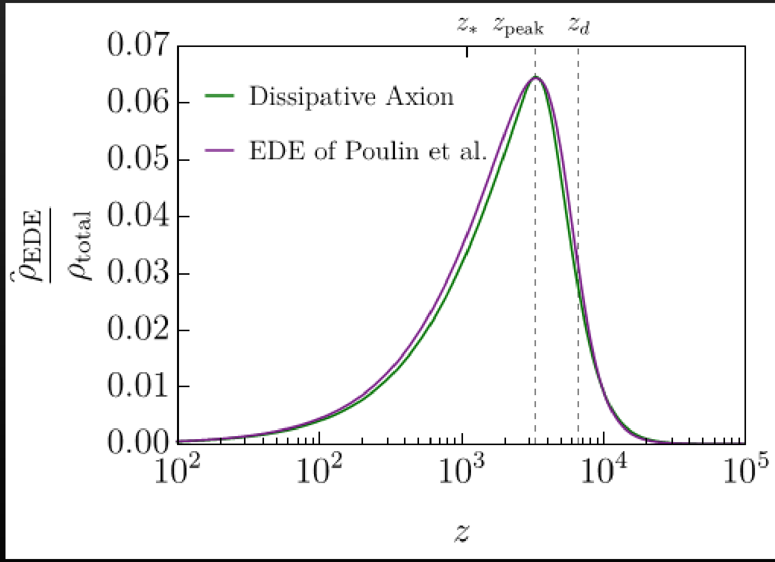
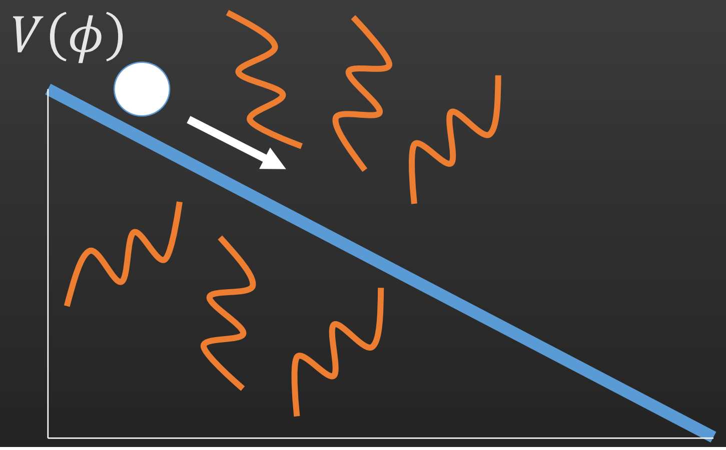




Berghaus, Karwal 2019

Warm Early Dark Energy



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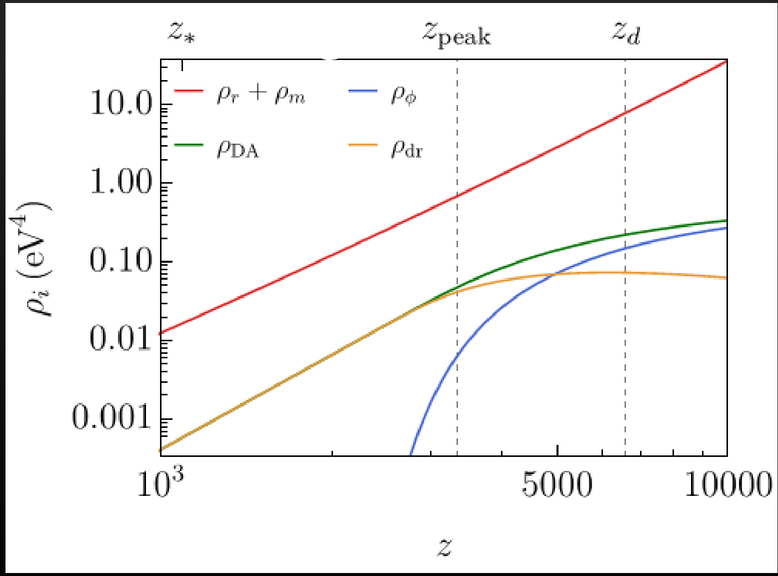
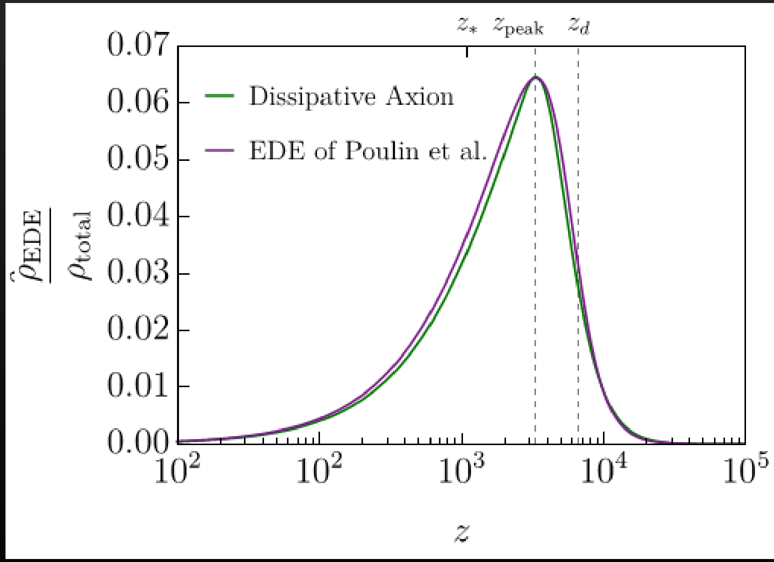
Thermal friction generically arises for axions couplings to gauge fields

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

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





Berghaus, Karwal 2019

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

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

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

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Not allowed by symmetry

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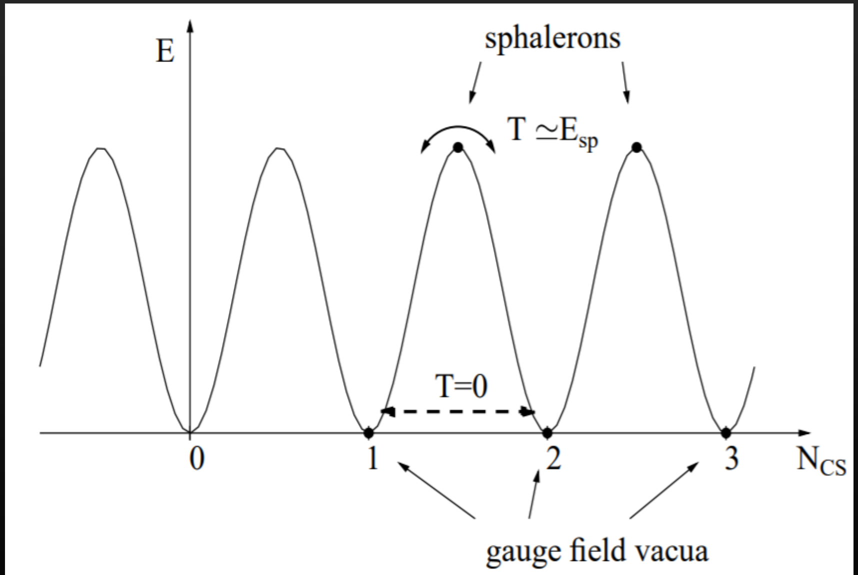

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Not allowed by symmetry

Dissipative Axion

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

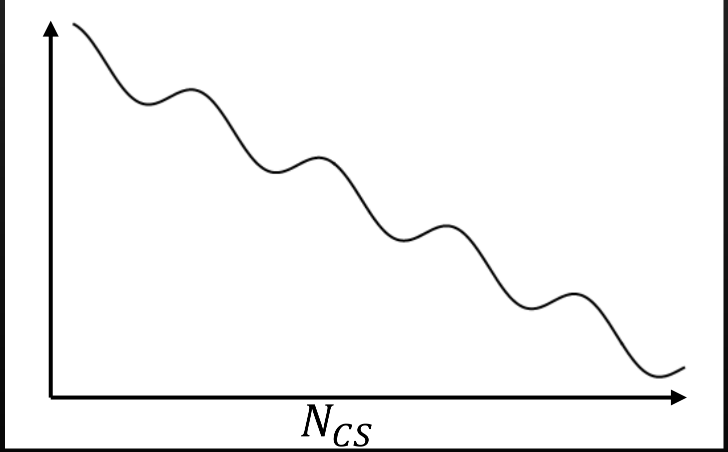
$$\frac{\partial L}{\partial \phi} - \frac{d}{dt}\frac{\partial L}{\partial \dot{\phi}} = 0$$

- 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



Analysis

- Put Warm Early Dark Energy into CLASS: $V(\phi) = \frac{1}{2} m^2 \phi^2$
- Effective parameters: $f_{ede}, z_c(m, \Upsilon), m$

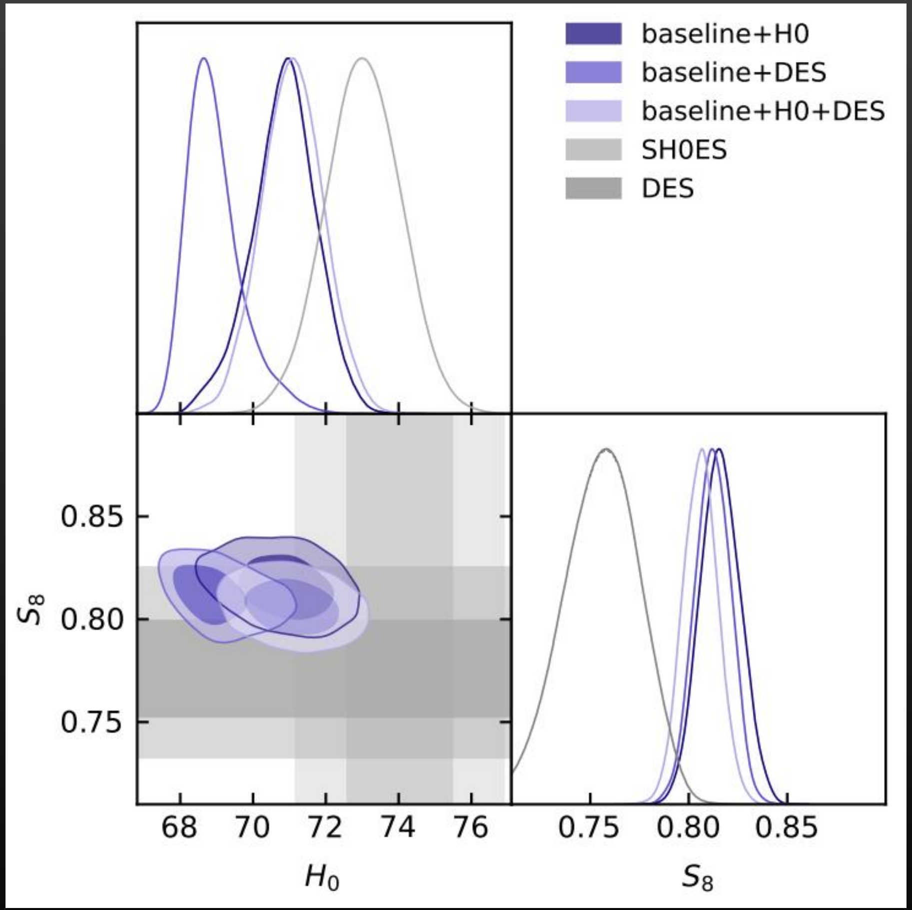
Analysis

- Put Warm Early Dark Energy into 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

  baseline

  - SH0ES measurement $H_0 = 73.04 \pm 1.04$ km/s/Mpc
  - Dark Energy Survey Year 1 galaxy lensing and clustering

Results



Berghaus, Karwal 2022

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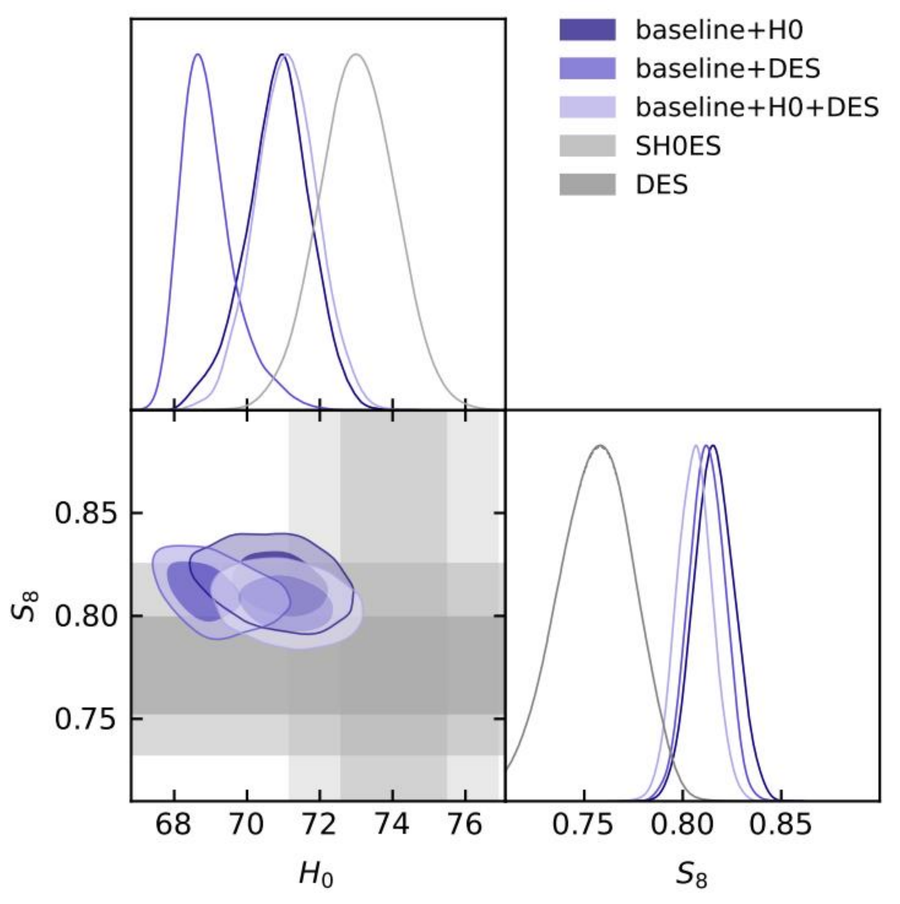


Berghaus, Karwal 2022

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	$71.08(71.06) \pm 0.85$	$0.8058(0.8075) \pm 0.0089$
$N_{\rm eff}$	$70.50(70.86) \pm 0.78$	$0.8102(0.8106) \pm 0.0096$

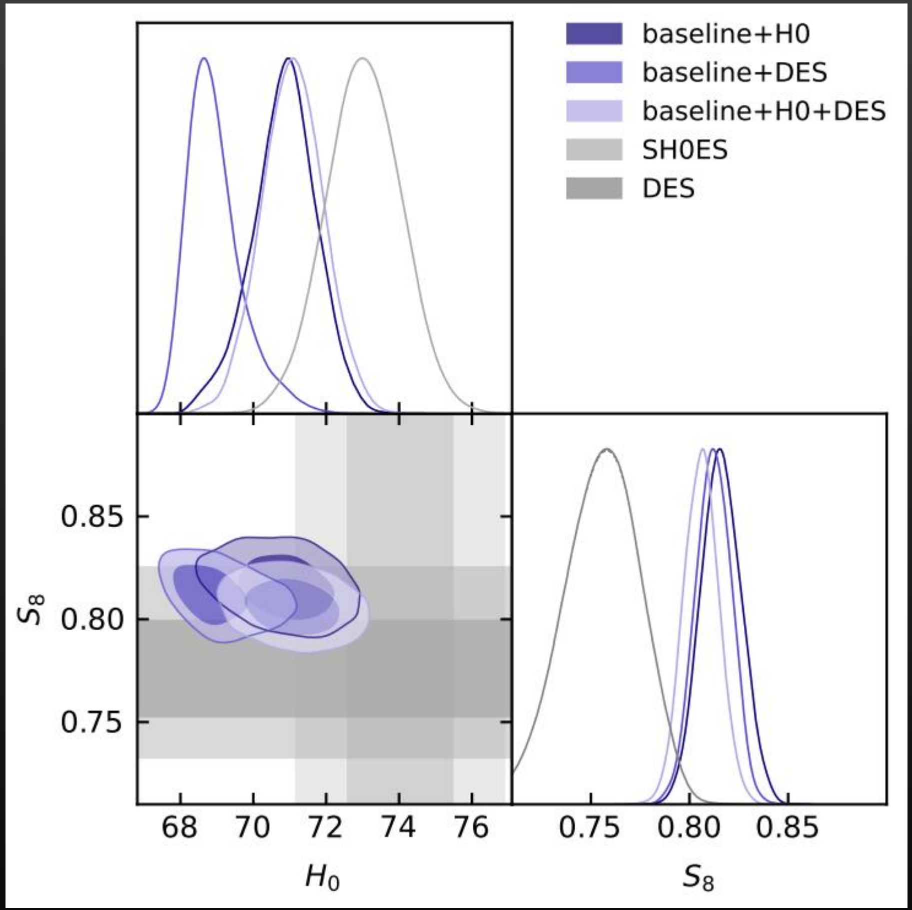
Table VI. 1D marginalized posteriors of measurements quantifying the two cosmological tensions, fitting to *baseline*+H_0+DES.

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

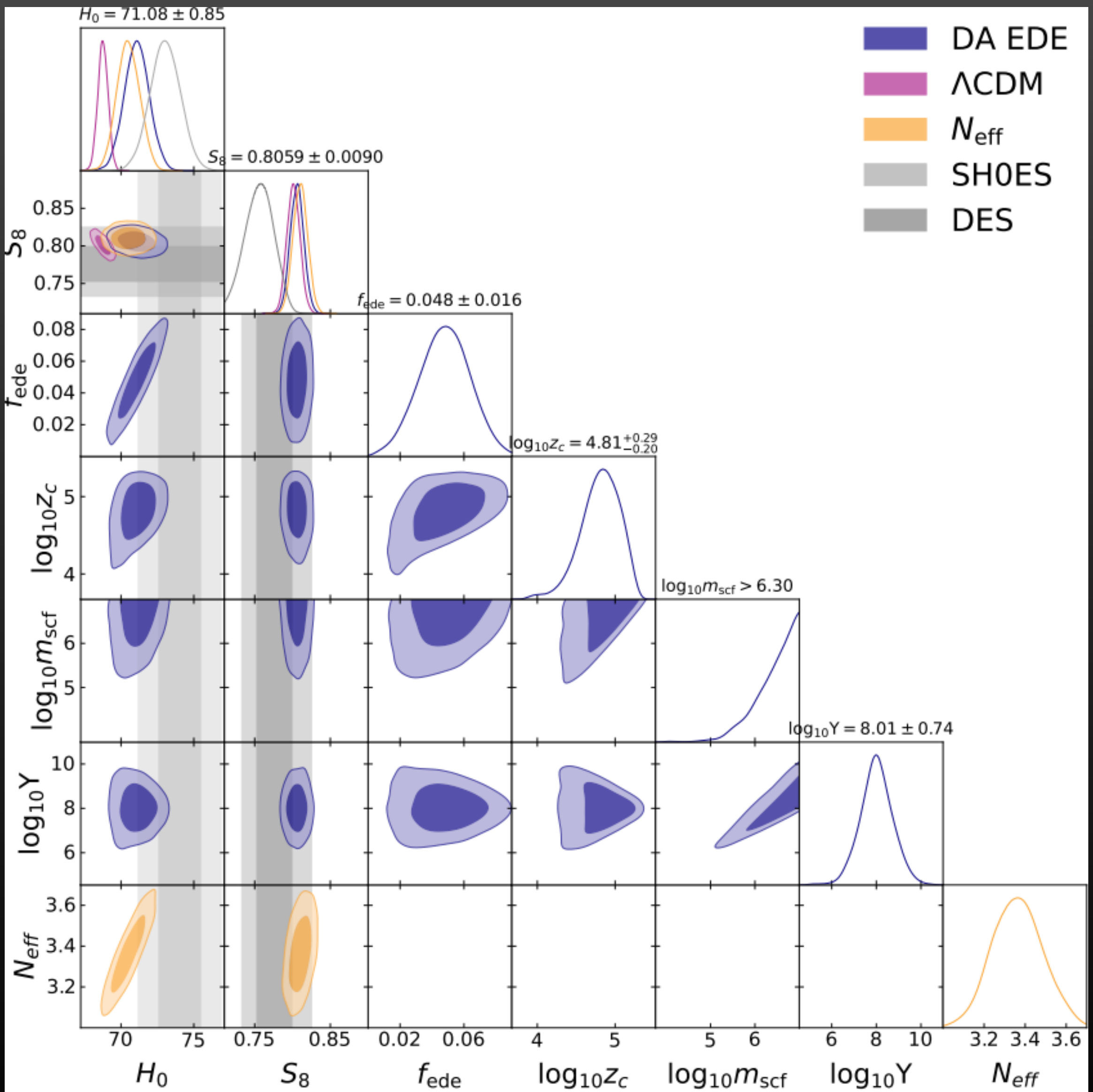
Table VII. The goodness of fit to CMB and DES data, while cumulatively fitting to *baseline*+H_0+DES.

Results

Baseline + SH0ES + DES



Berghaus, Karwal 2022



Berghaus, Karwal 2022

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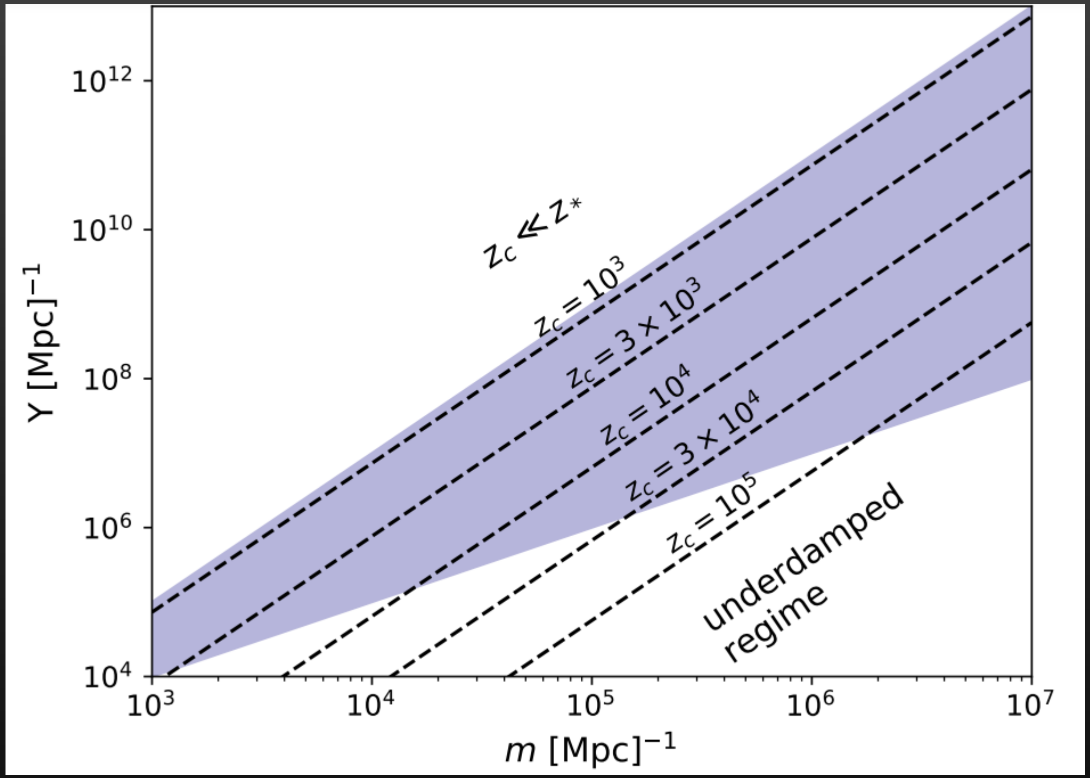

Berghaus, Karwal 2022

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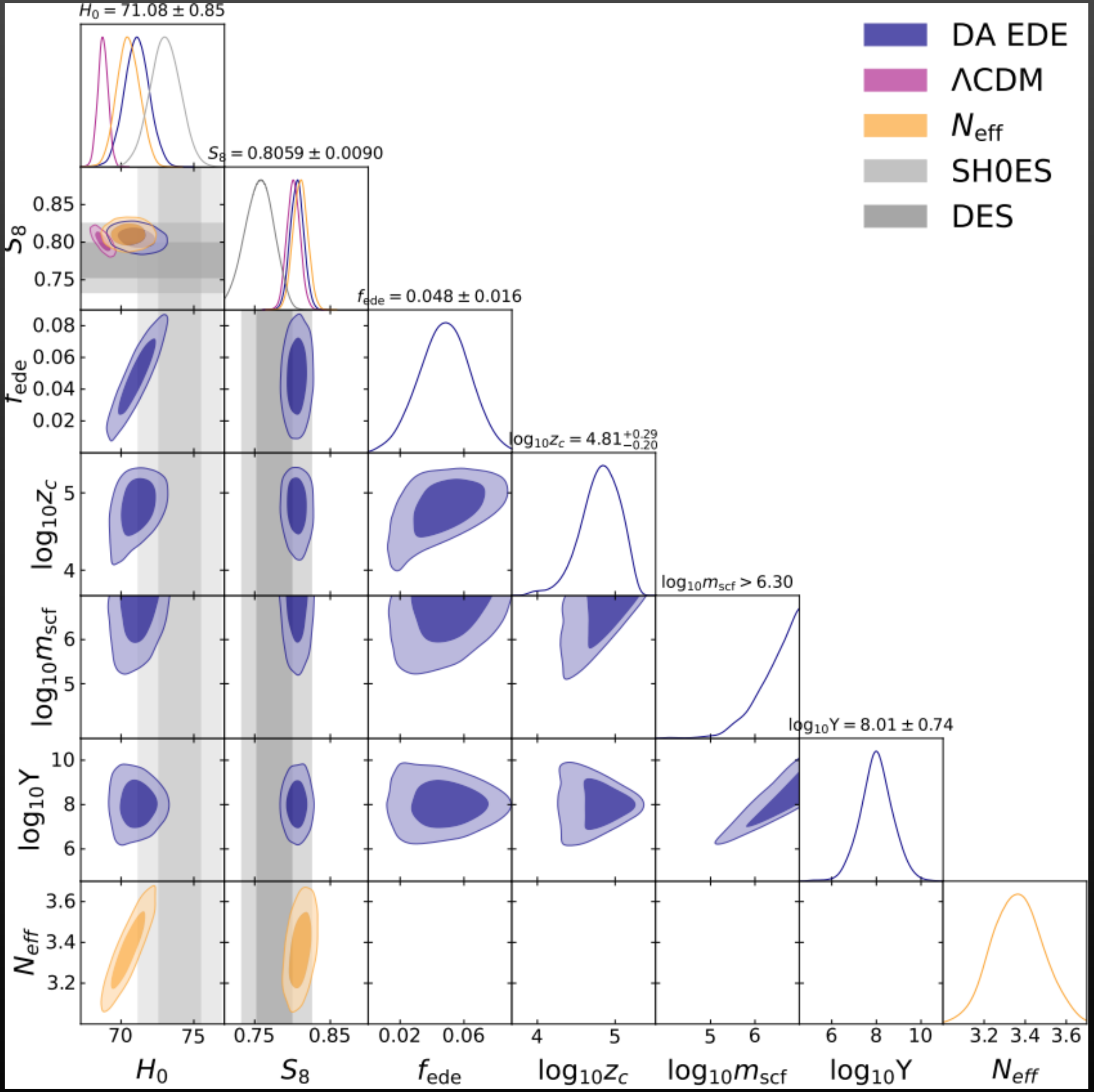

Berghaus, Karwal 2022

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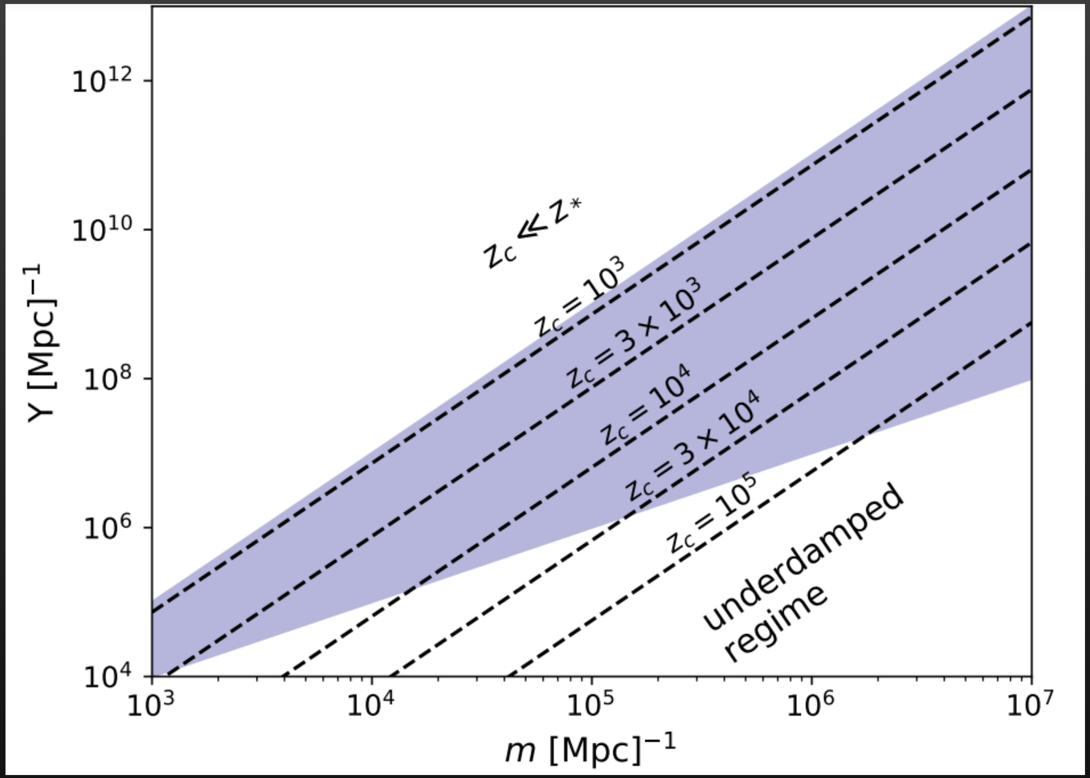

Berghaus, Karwal 2022

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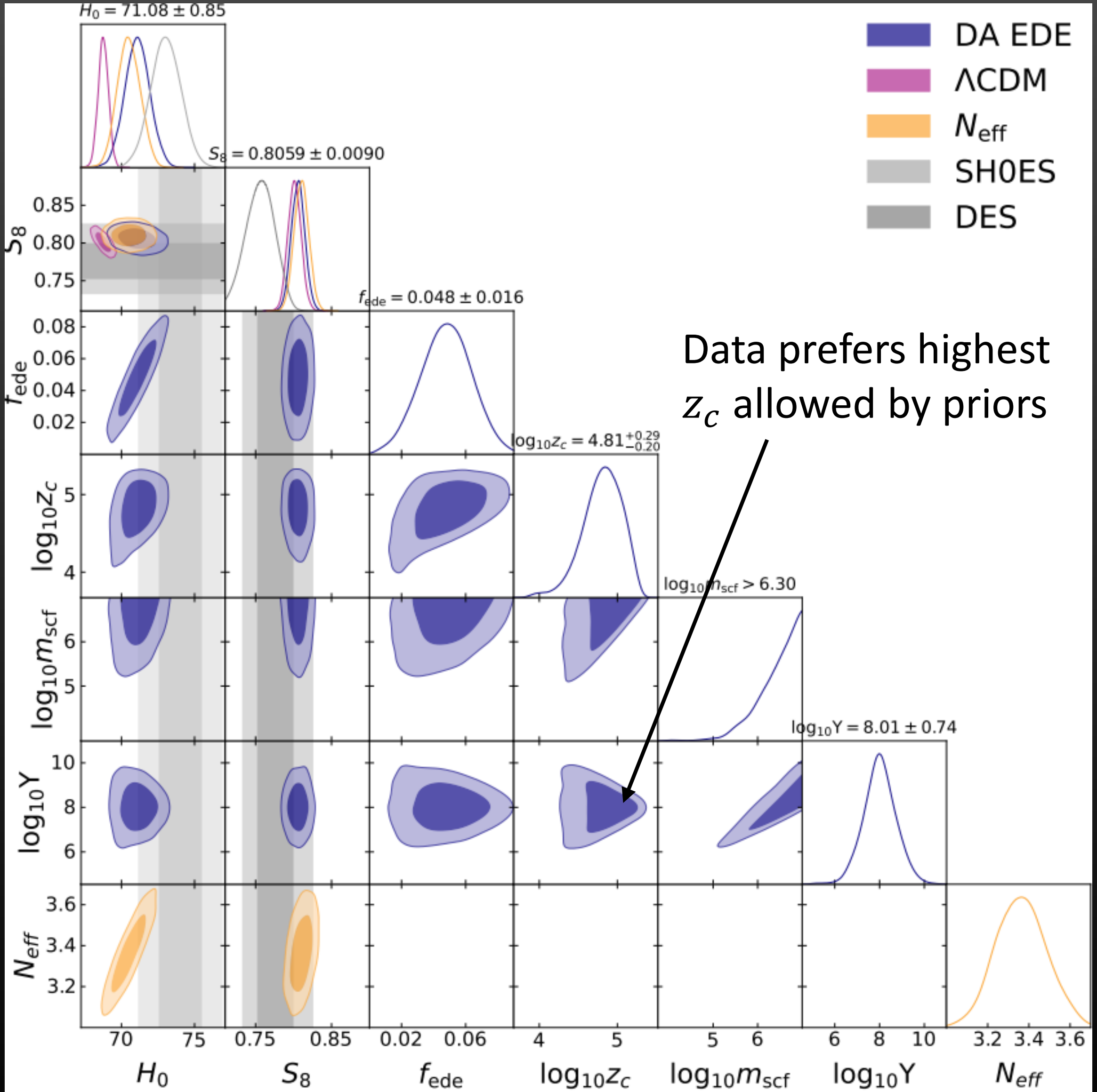

Berghaus, Karwal 2022

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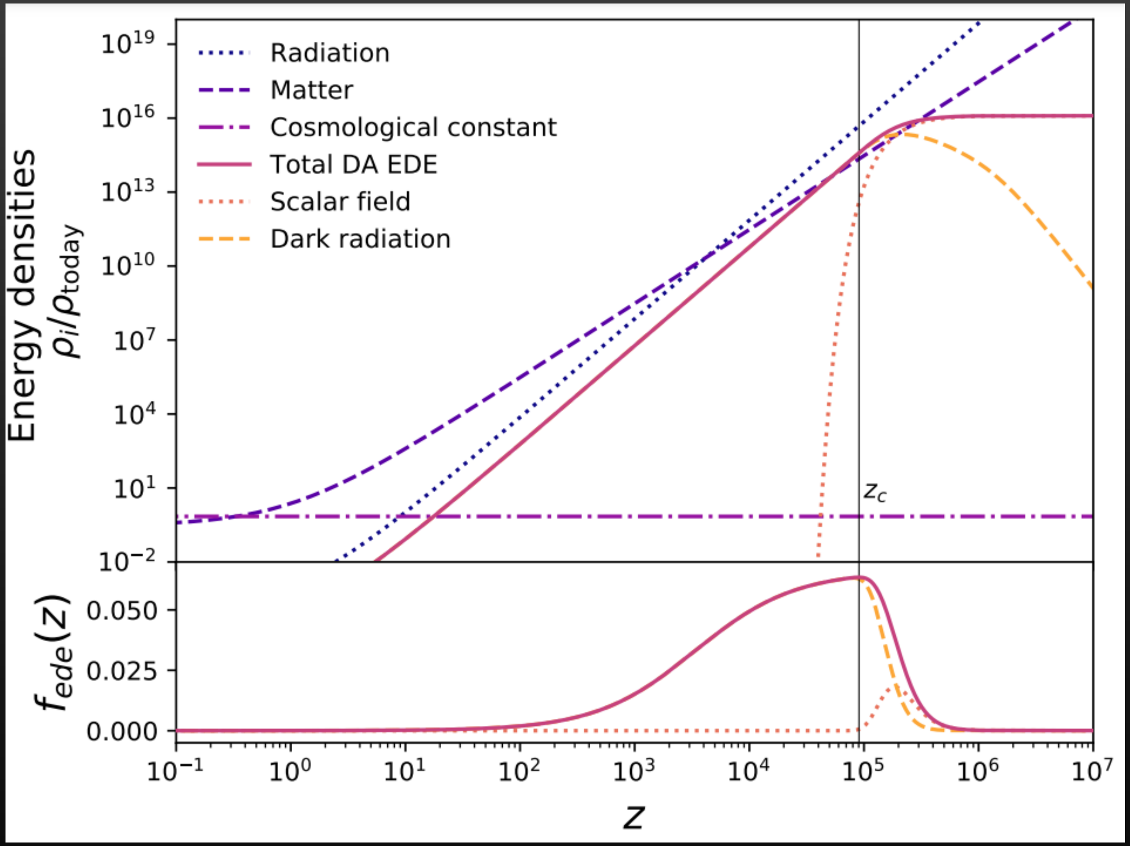

Berghaus, Karwal 2022

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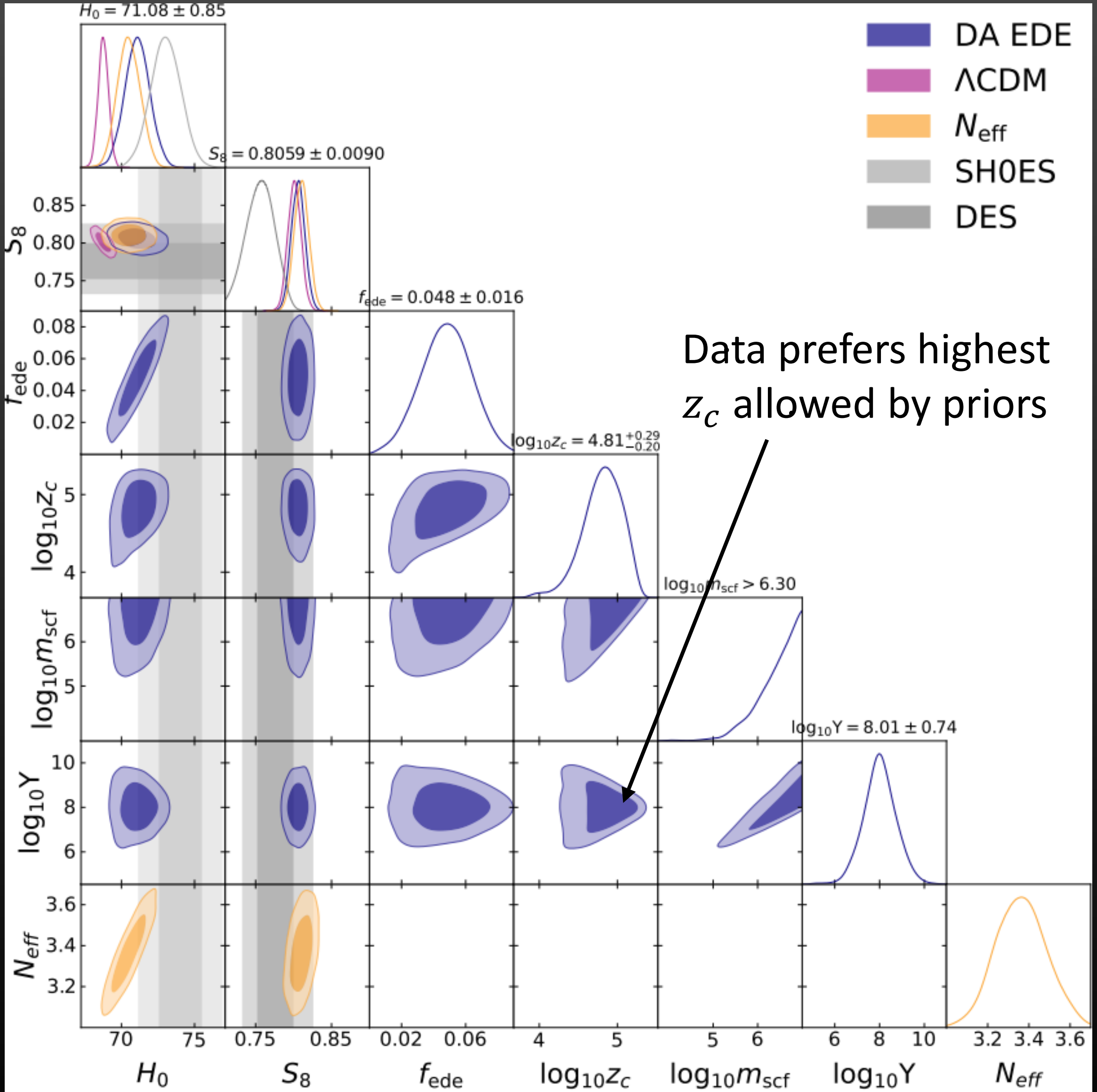

Berghaus, Karwal 2022

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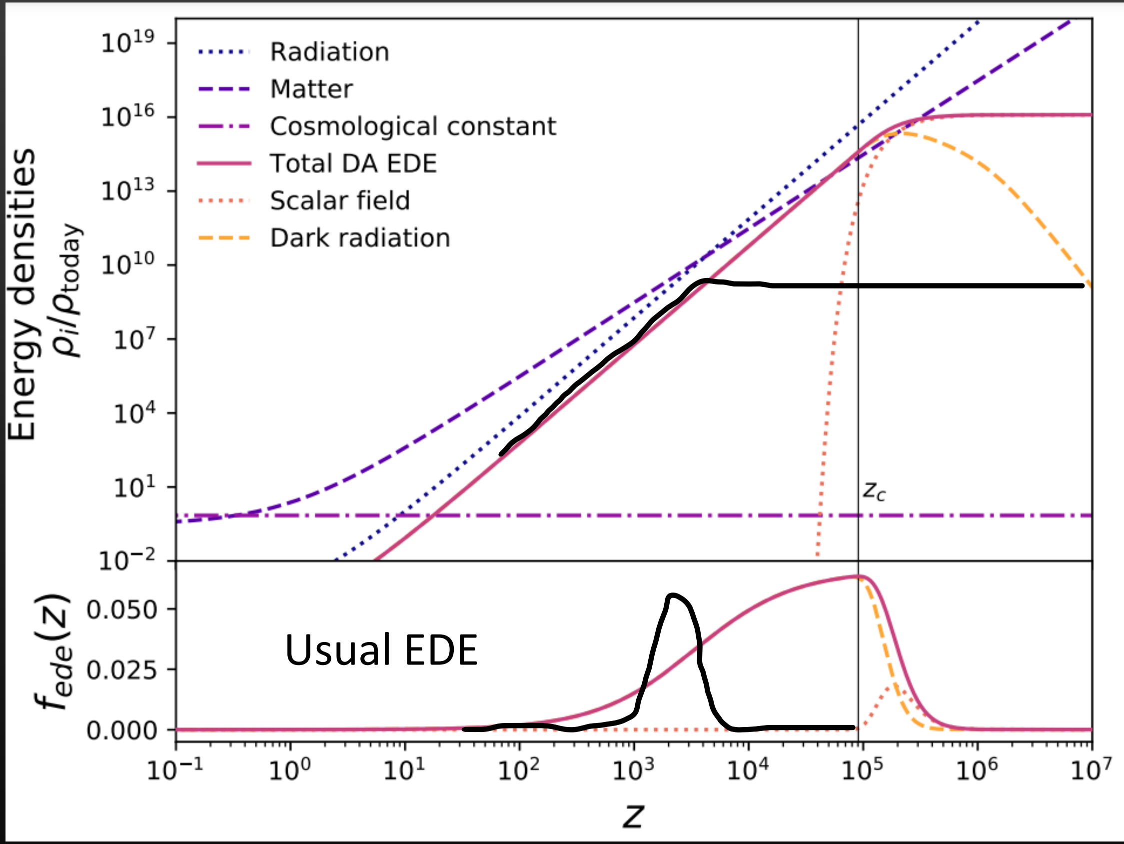
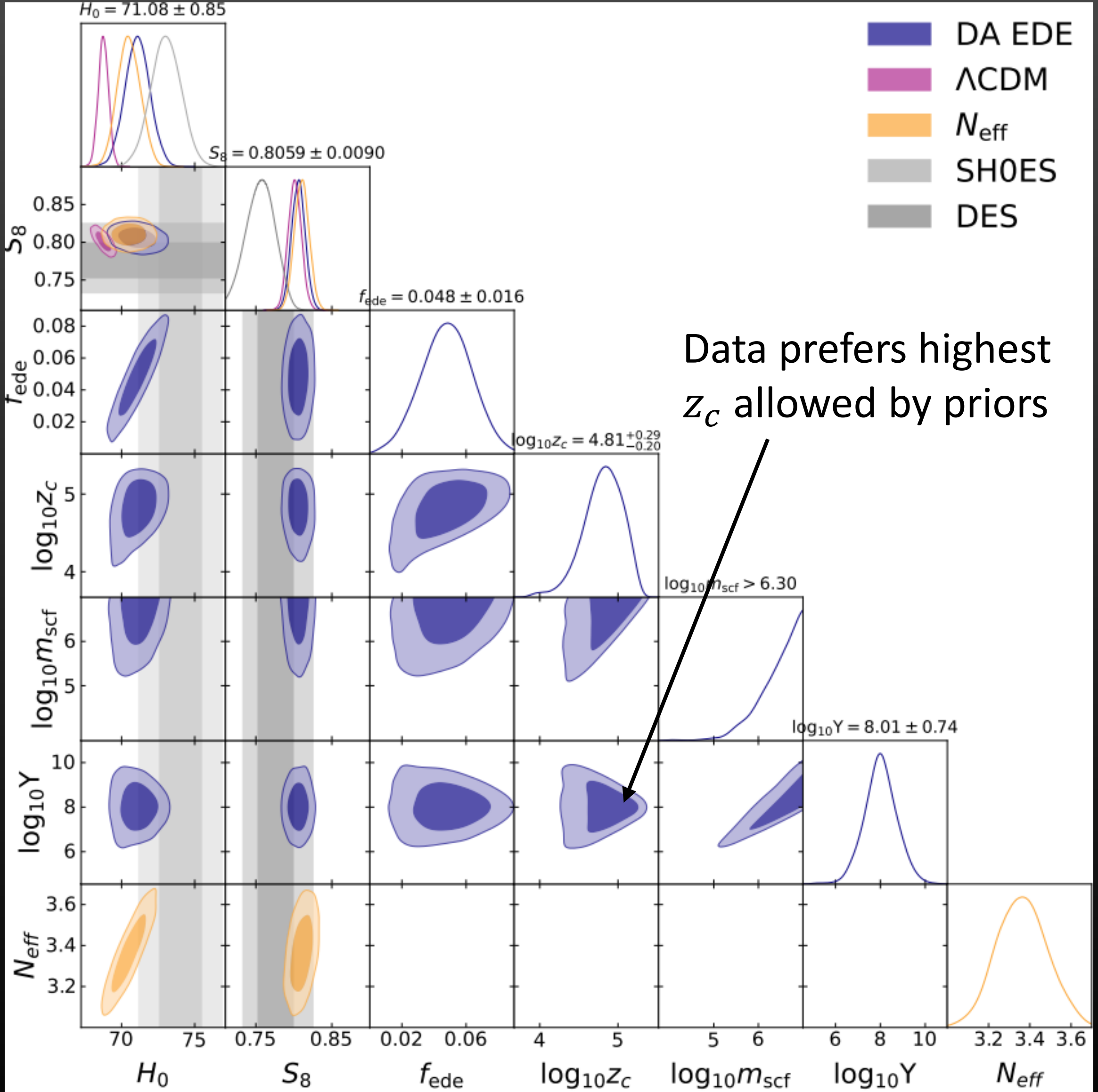


Berghaus, Karwal 2022

Baseline + SH0ES



Data prefers highest z_c allowed by priors

Berghaus, Karwal 2022

Why does data not prefer **Warm** EDE?

Answer must be in perturbations since background looks favorable

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

Regular EDE perturbations

Why does data not prefer Warm EDE?

Answer must be in perturbations since background looks favorable

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Regular EDE perturbations

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Warm EDE 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 warm EDE

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Sourcing of DR smoothes anisotropies

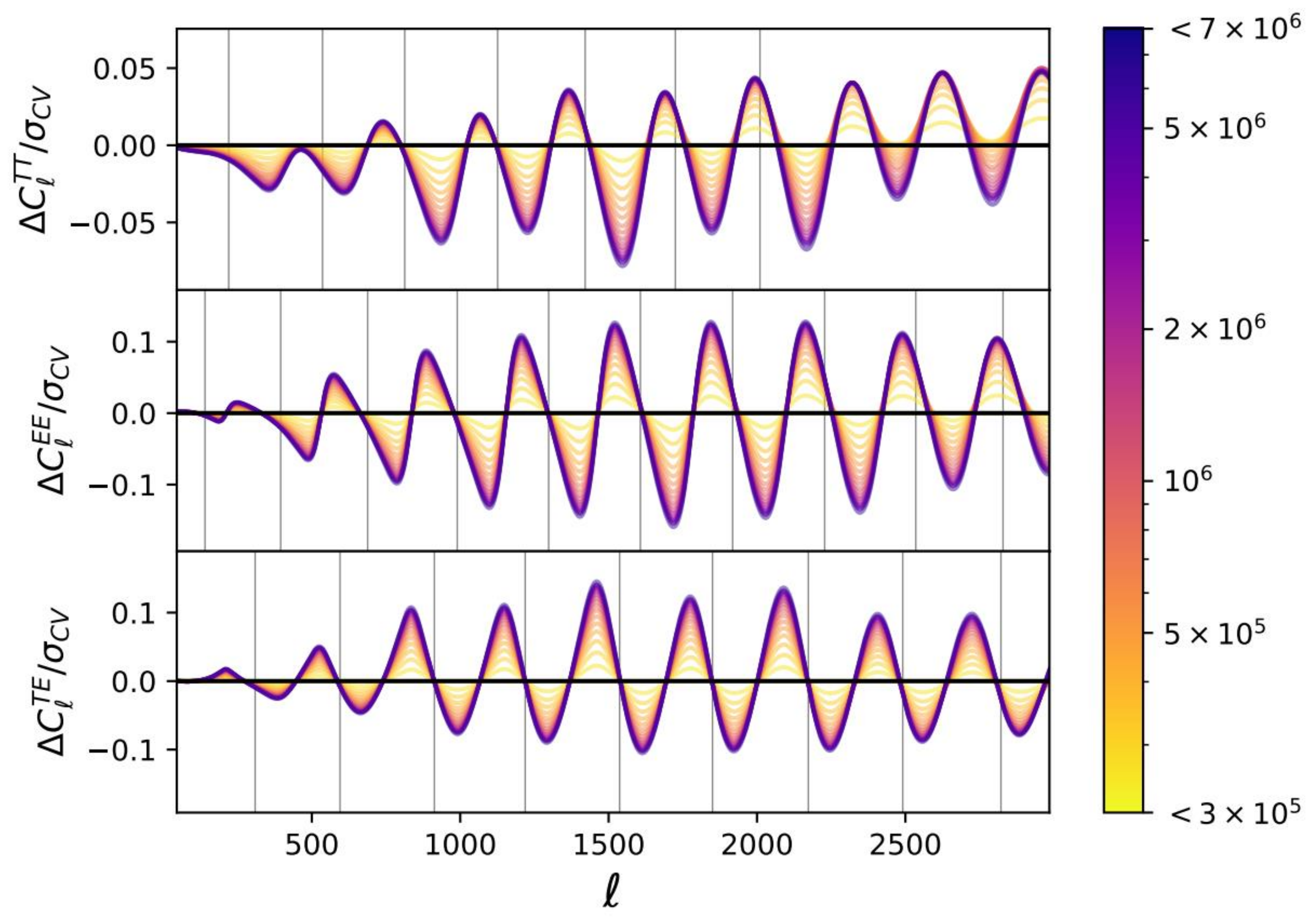
If injection occurs around $z_c \sim z_{eq}$ then $\delta\phi \ll \delta\rho_{DR}$ shortly after z_c.

Conclusions

- Thermal friction arises generically for rolling axions giving rise to Warm EDE
- Warm EDE resolves EDE fine-tuning at background level
- But Warm Early Dark Energy is not preferred by data
- Solution asymptotes to extra radiation at high z_c
- Extra radiation eases the Hubble and the LSS tension but does not resolve it
- Data loses sensitivity to step-like transitions at redshifts $\mathrm{z} > 10^5$
- Data disfavors new physics with smoothed anisotropies

Thank You

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

Back-up

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.

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	$71.08(71.06) \pm 0.85$	$0.8058(0.8075) \pm 0.0089$
$N_{\rm eff}$	$70.50(70.86) \pm 0.78$	$0.8102(0.8106) \pm 0.0096$

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

Model	$\chi^2_{\rm CMB}$	$\chi^2_{H_0}$
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 $\chi^2_{\rm CMB} = 2772.6$.

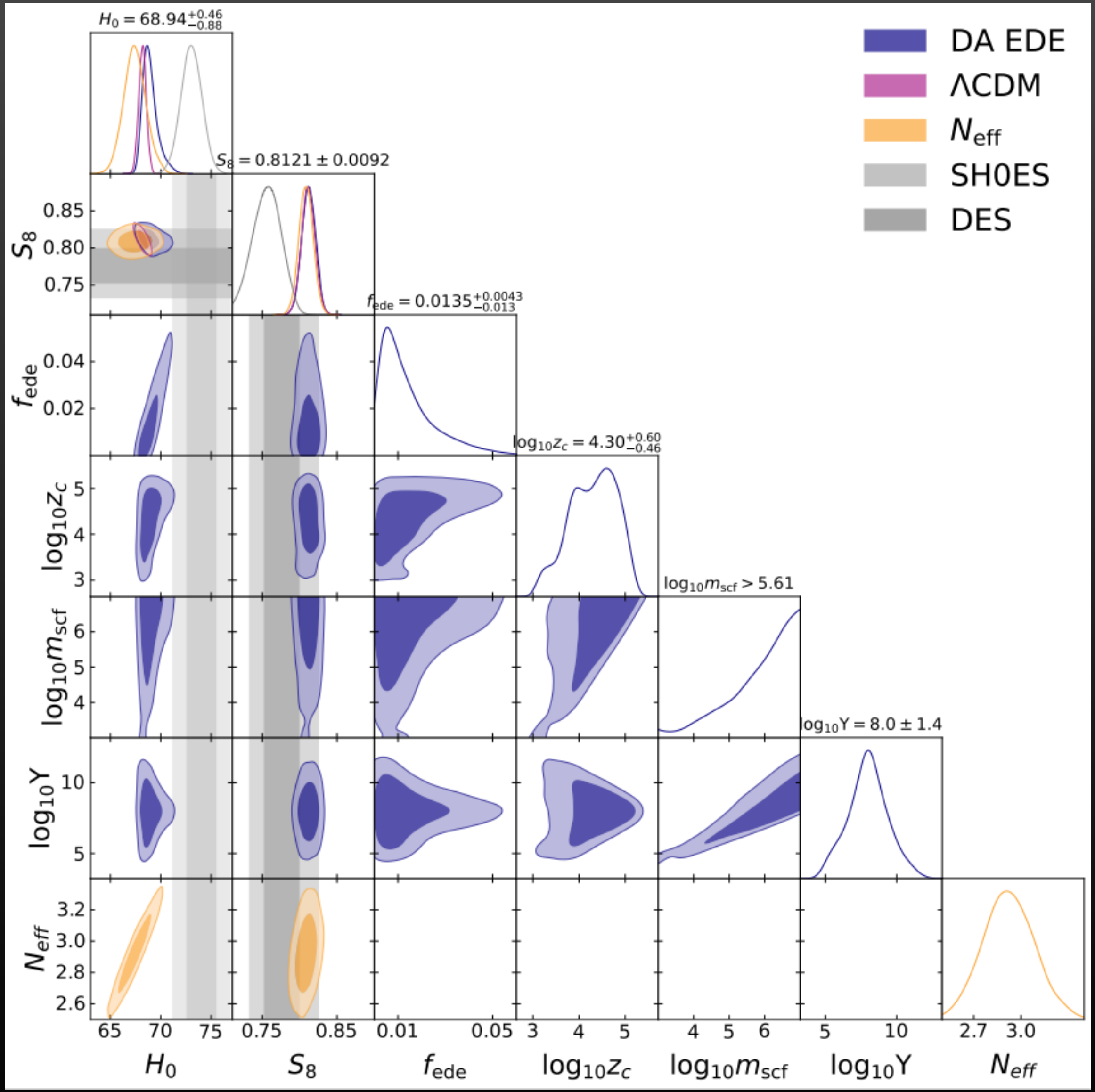
Model	$\chi^2_{\rm CMB}$	$\chi^2_{\rm DES}$
ΛCDM	2774.1	509.3
DA EDE	2774.7	509.4
$N_{\rm eff}$	2776.0	508.1

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

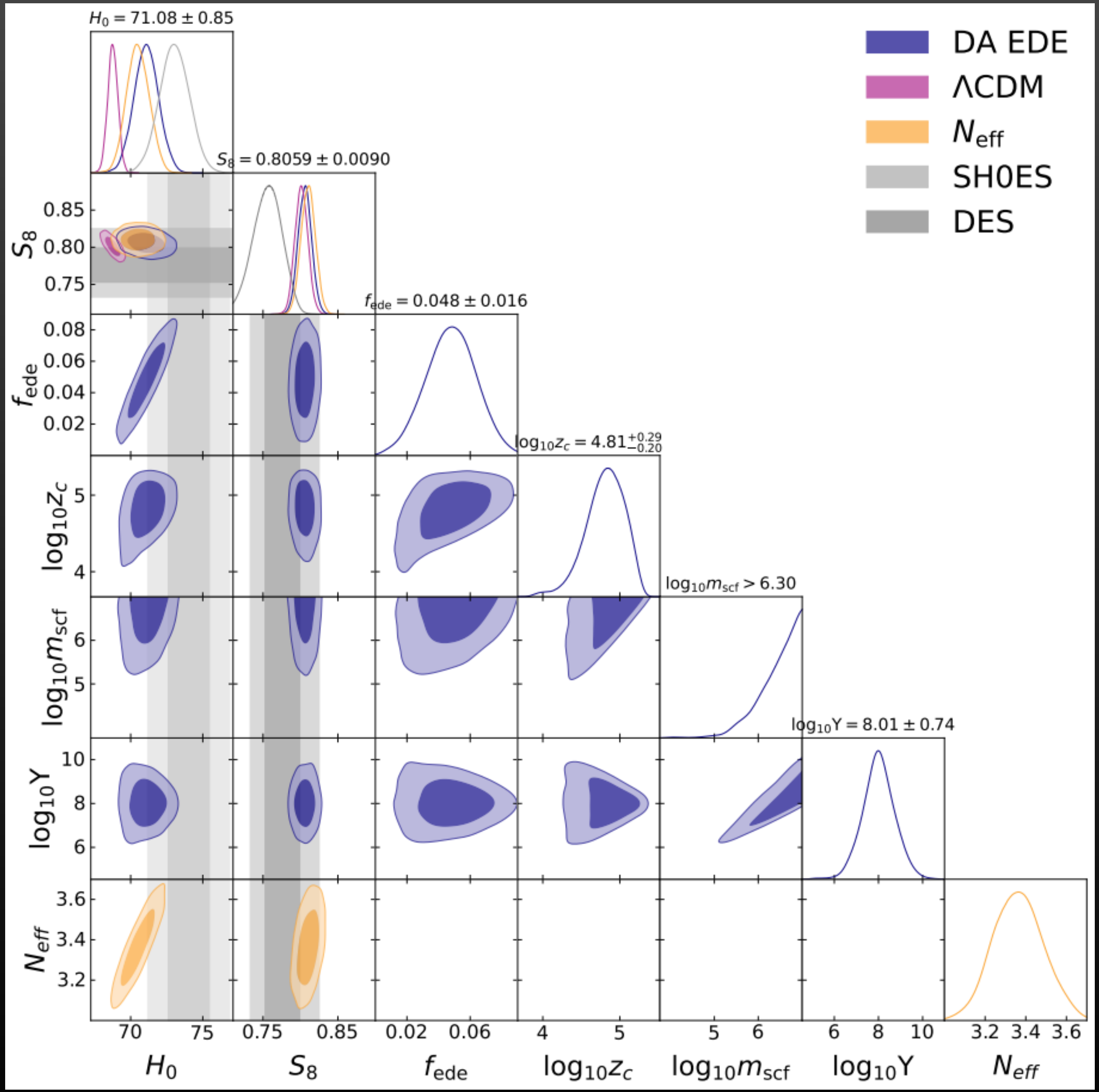
Model	$\chi^2_{\rm CMB}$	$\chi^2_{H_0}$	$\chi^2_{\rm DES}$
ΛCDM	2778.4	18.0	508.0
DA EDE	2778.7	3.6	508.3
$N_{\rm eff}$	2783.3	4.4	508.8

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

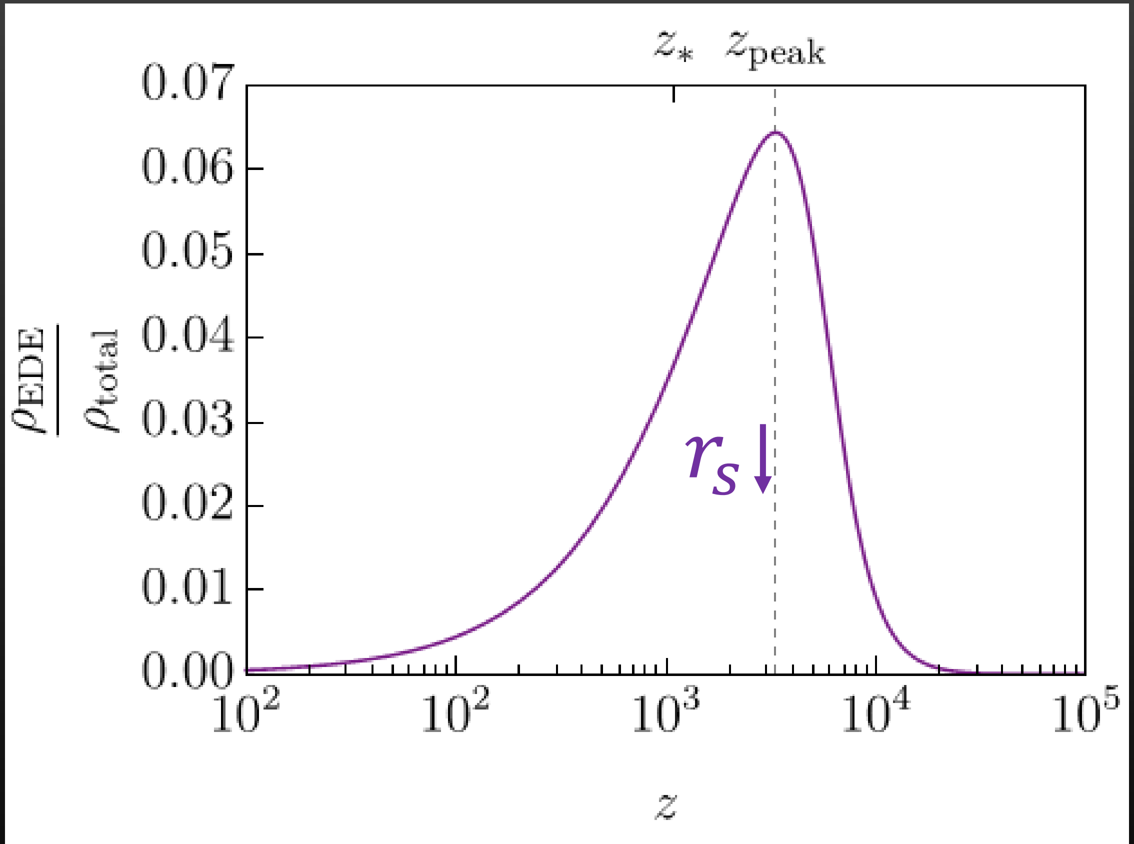
Baseline + DES

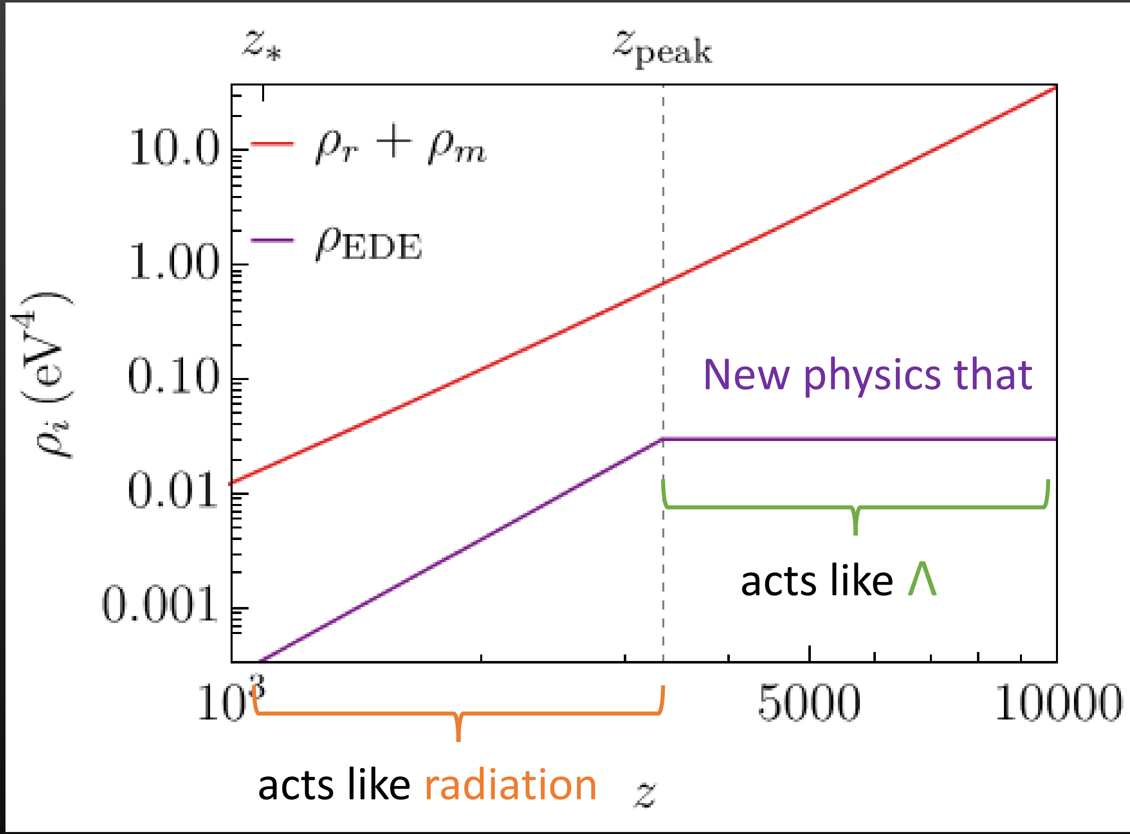


Baseline + DES + SH0ES

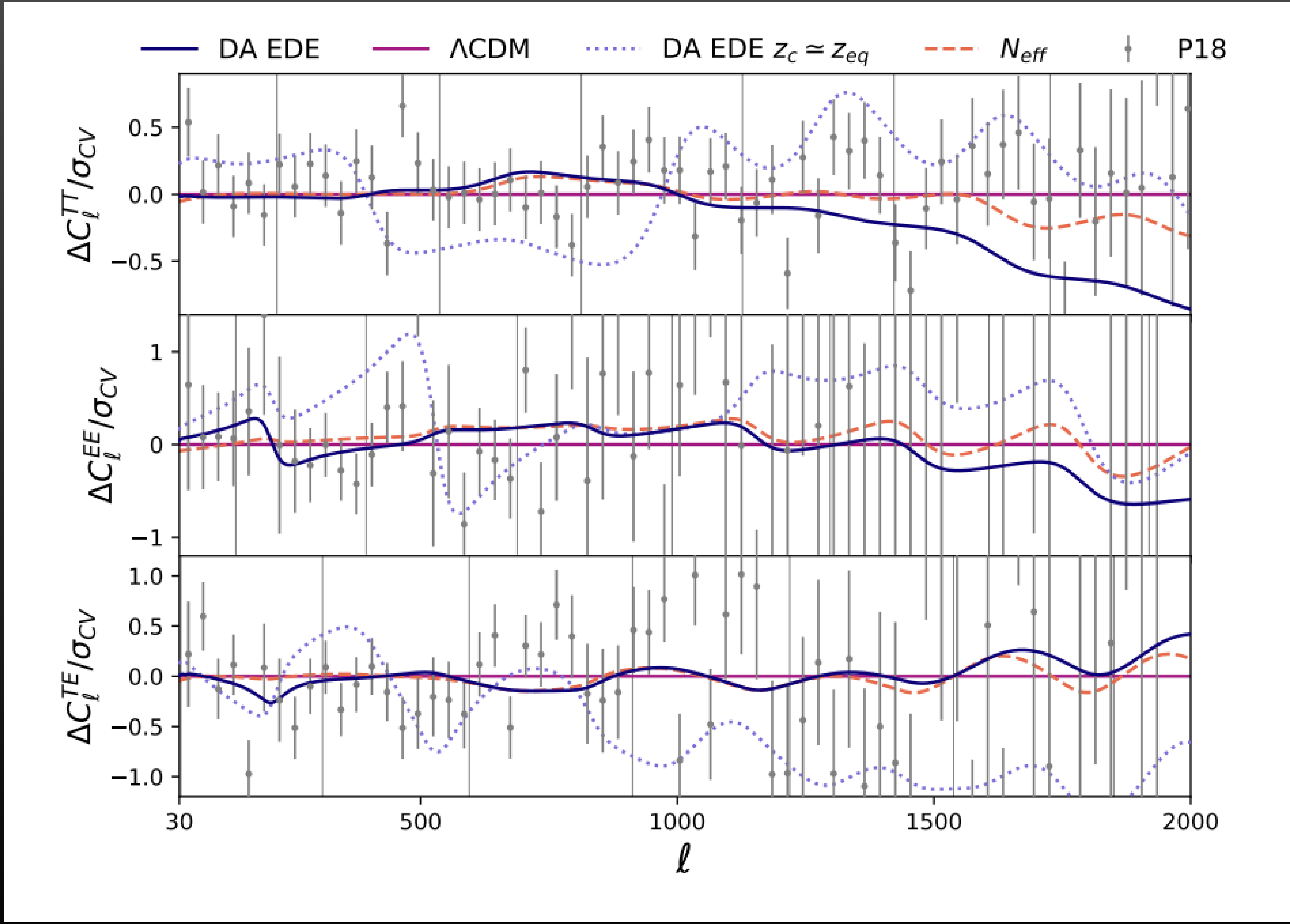


New physics that can lower the sound horizon





Phenomenological early dark energy solution to Hubble tension by Poulin et. al. (2019)


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