Thermal Friction as a Solution to the Hubble Tension

Kim V. Berghaus,

California Institute of Technology

based on

Phys. Rev. D 101, 083537 (2020) (1911.06281)

Phys. Rev. D 107, 103515 (2023) (2204.09133)

With Tanvi Karwal, KICP U Chicago

The Hubble Tension

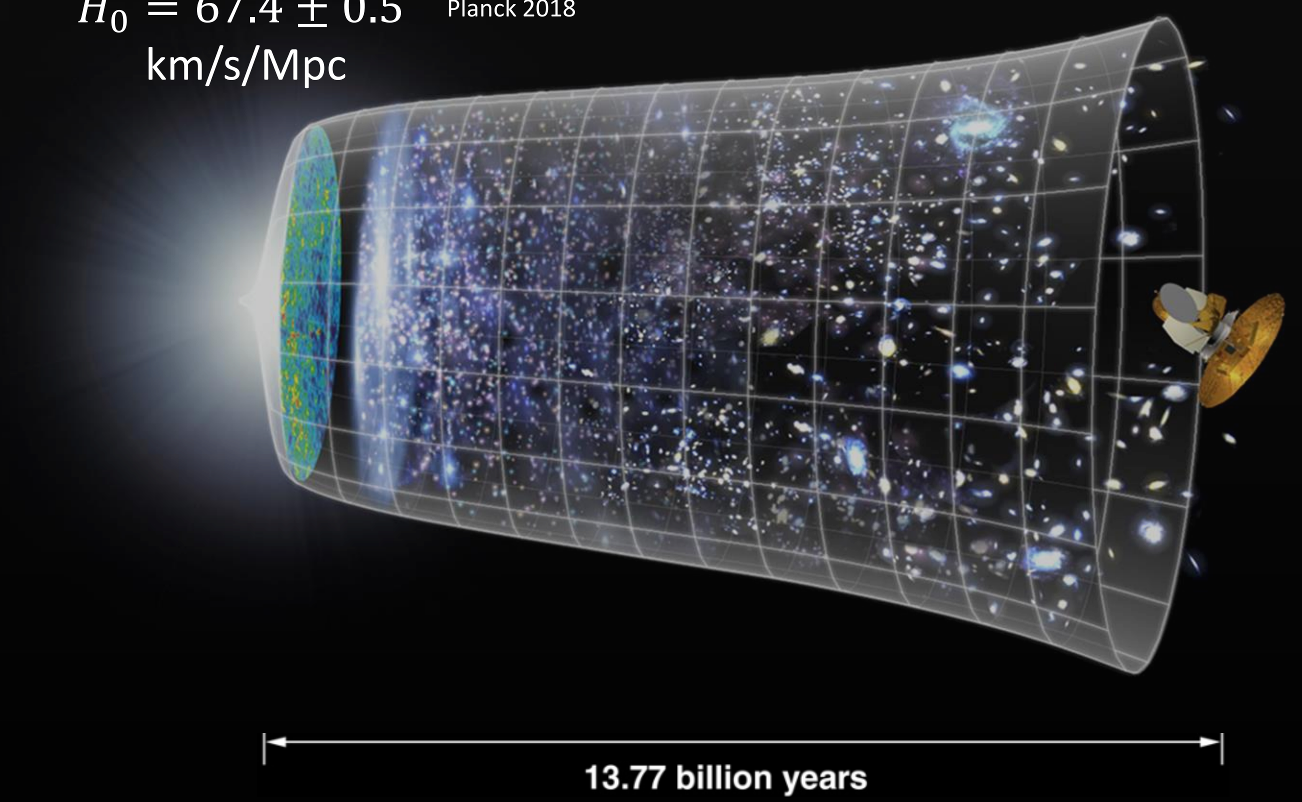
ΛCDM +
CMB measurement

$H_0 = 67.4 \pm 0.5$ 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

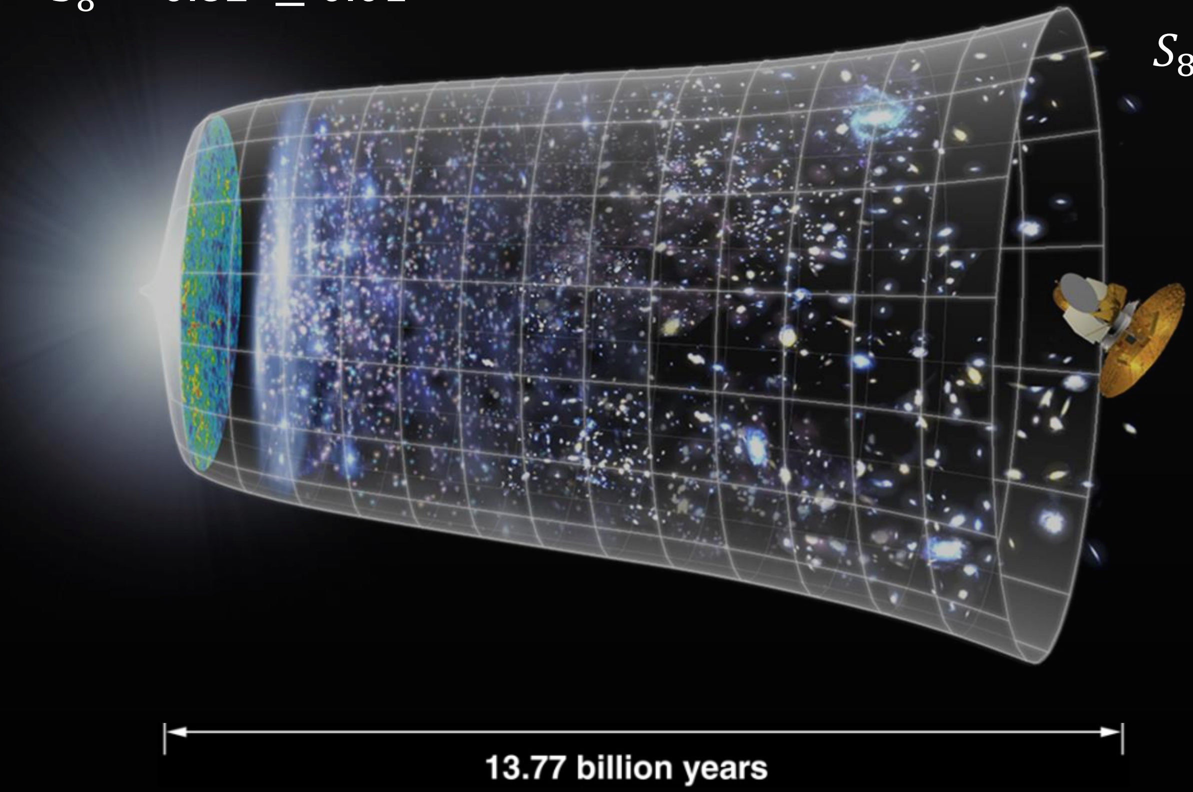
~ 2 - 3 σ

Galaxy clustering
+ weak lensing
(DES Y1)

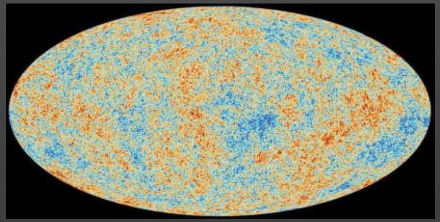
$S_8 = 0.77 \pm 0.02$ DES 2017

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

Amplitude of matter fluctuations

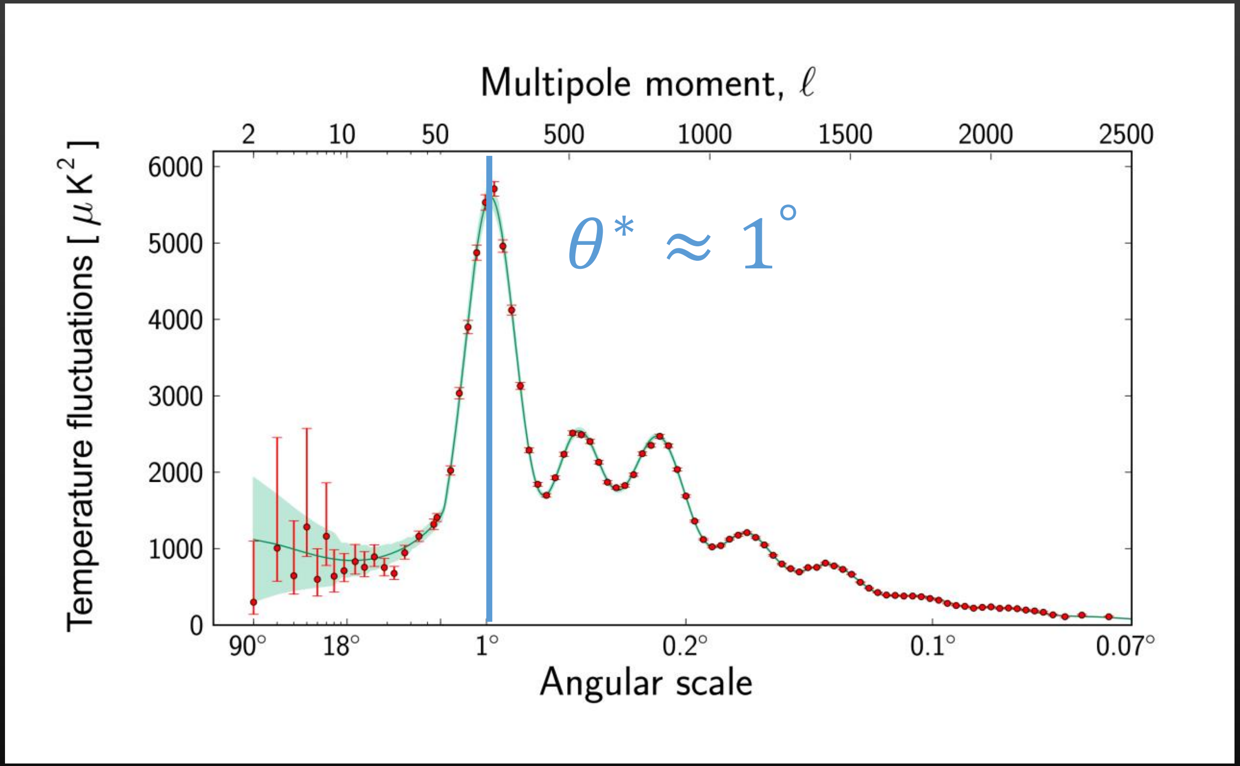


The Hubble Measurement with the CMB



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

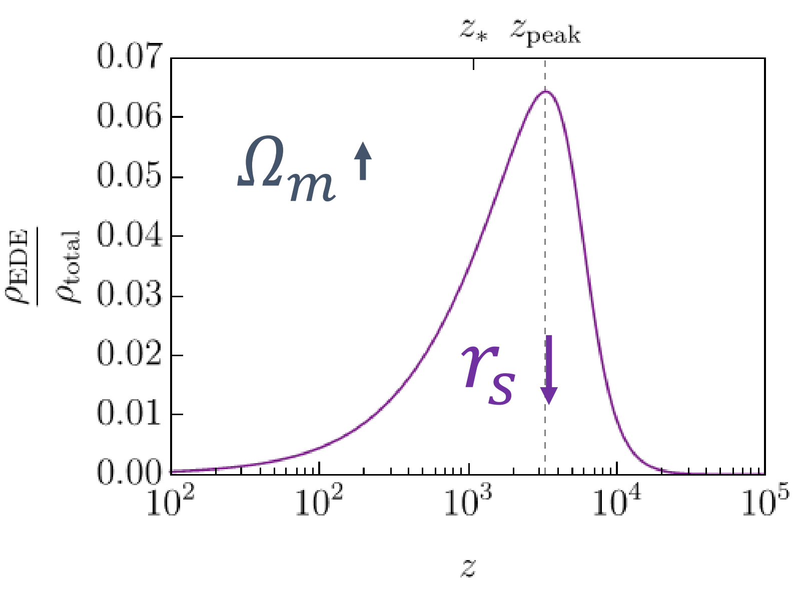
- r_s depends only on physics before formation of CMB
- Lowering r_s increases H_0



Planck 2018

New physics that can lower the sound horizon

Early Dark Energy



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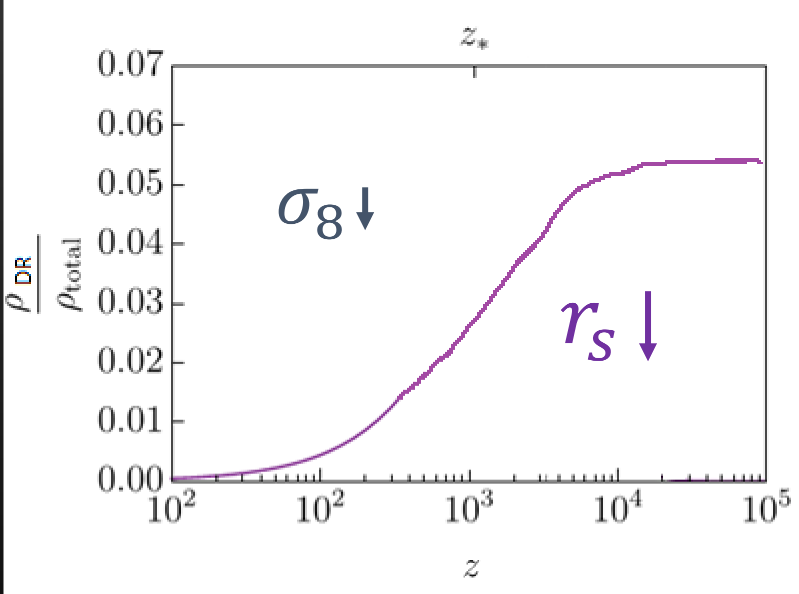
Extra Radiation

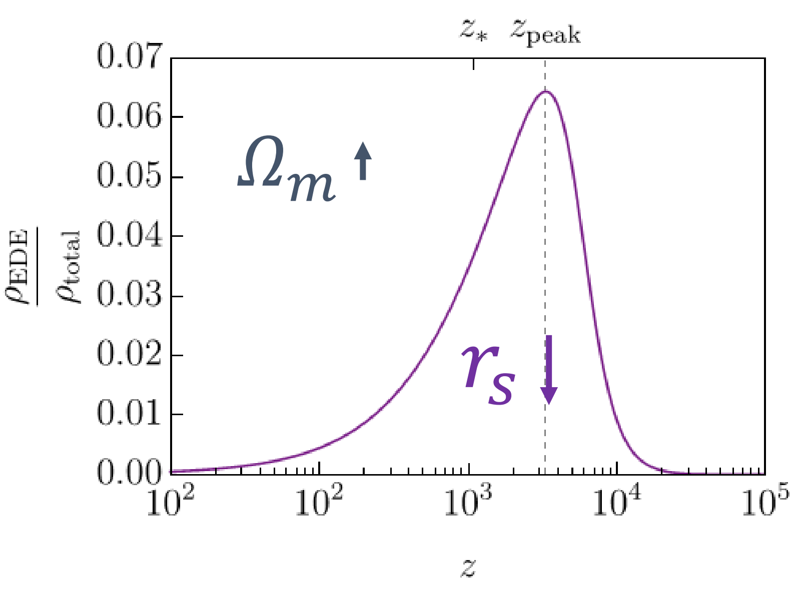


Maintains great fit to CMB
Resolves H0 but exacerbates LSS tension (Hill et. al., 2020, Ivanov et al. 2020)
Is fine-tuned

Worsens fit to CMB
Can ease LSS and Hubble tension

New physics that can lower the sound horizon

Early Dark Energy with thermal friction



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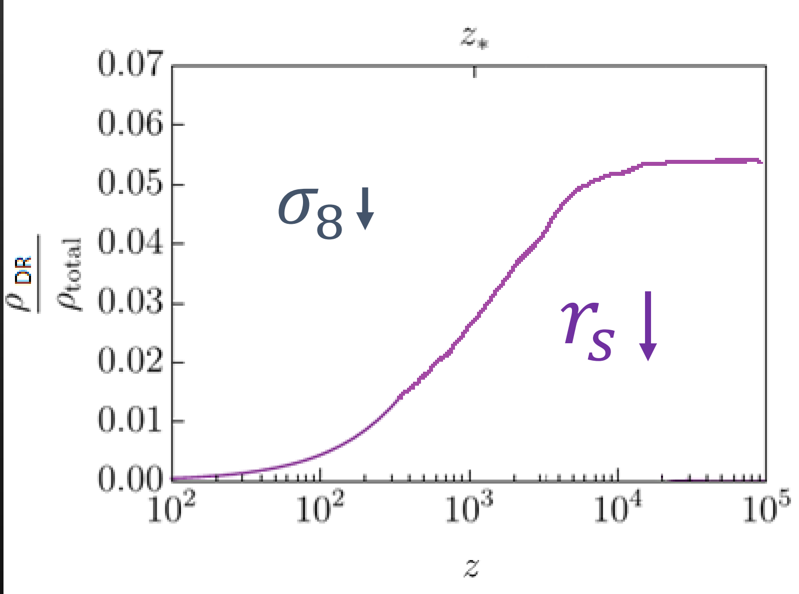

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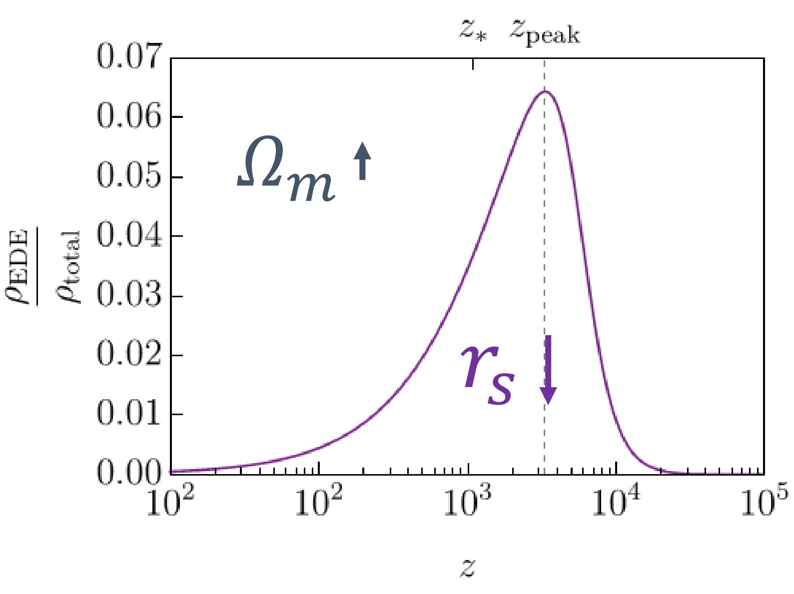

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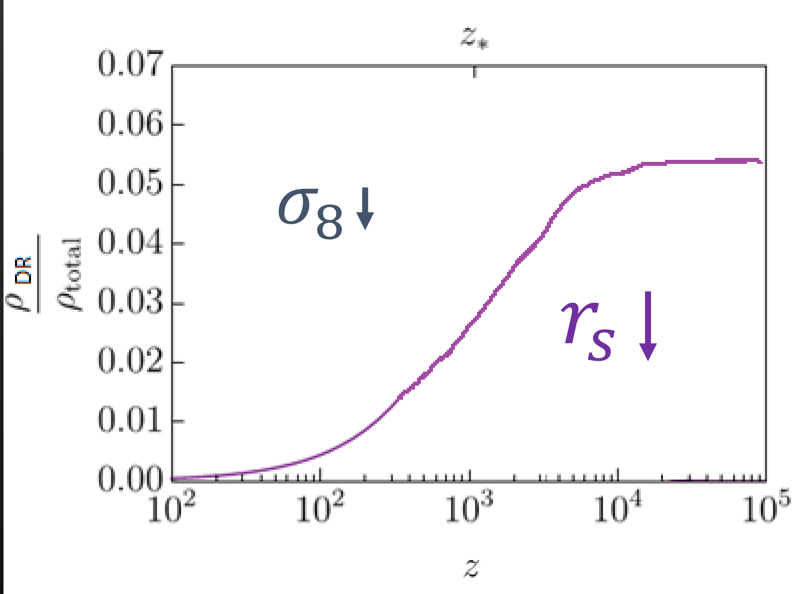

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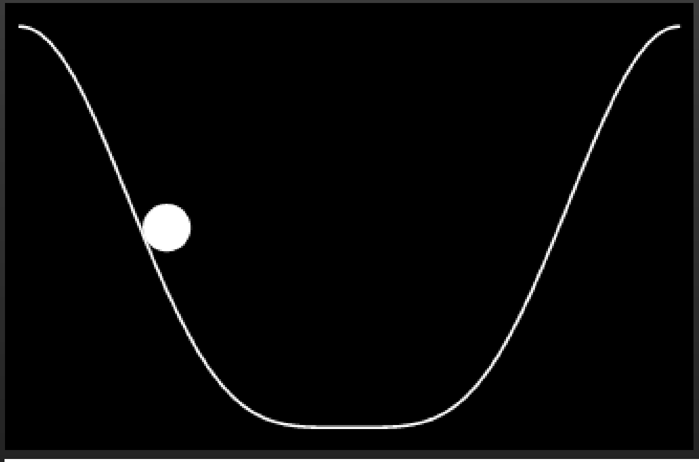


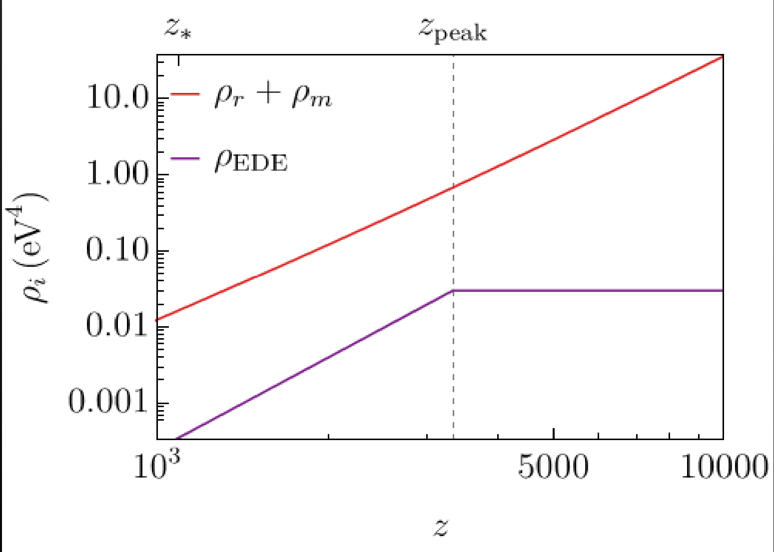
Frozen at early times by Hubble friction

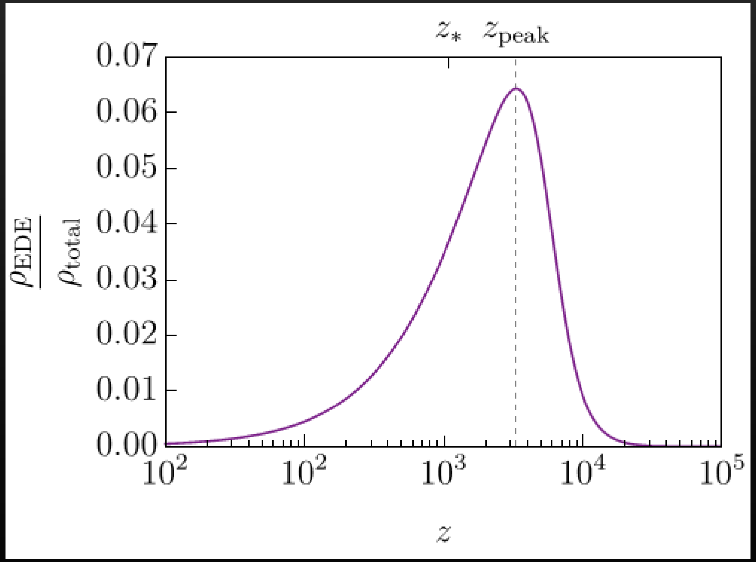
$$\ddot{\phi} + 3H\dot{\phi} + V' = 0$$

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

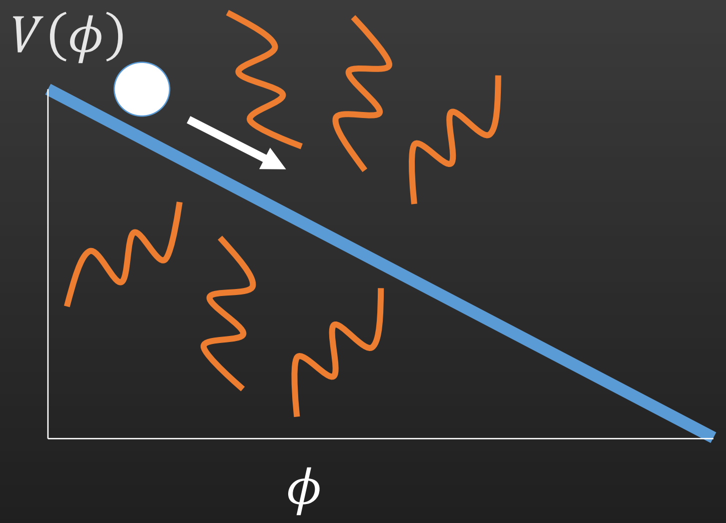
$$V \propto \left(1 - \cos\frac{\phi}{f}\right)^n$$

$$n \geq 2$$





Early Dark Energy with thermal friction



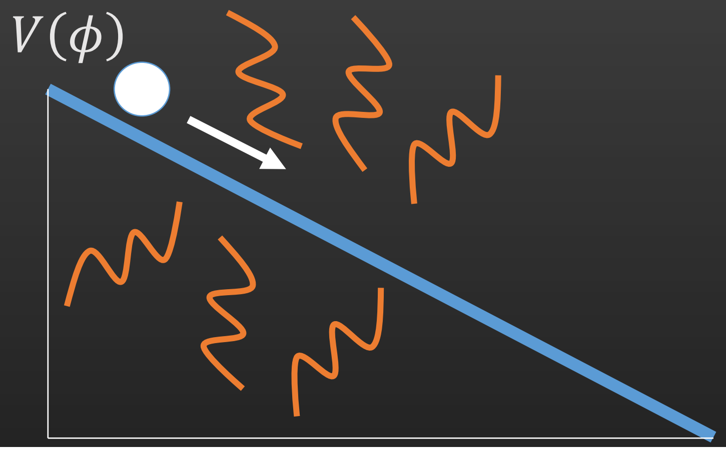
Frozen at early times by thermal friction

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

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

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

Early Dark Energy with thermal friction



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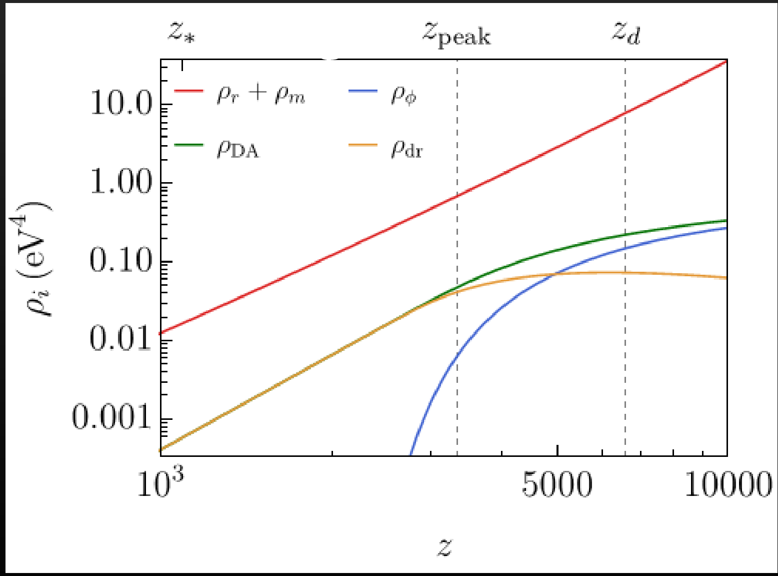
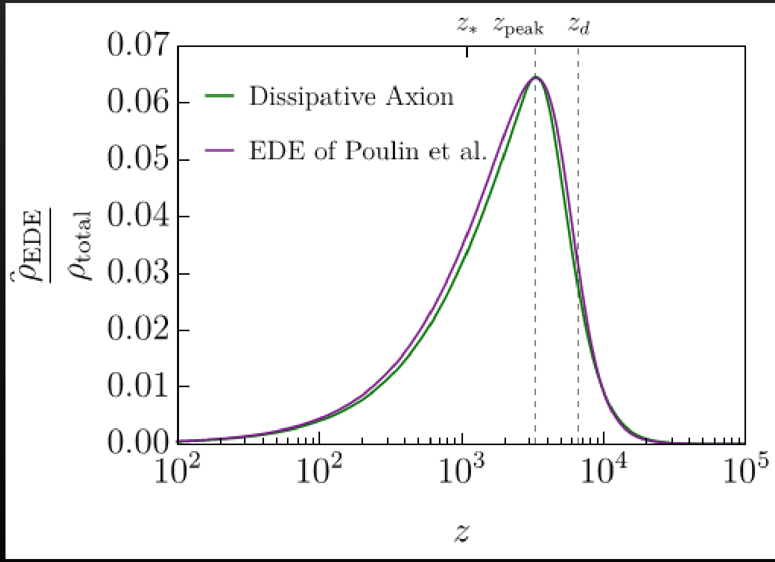
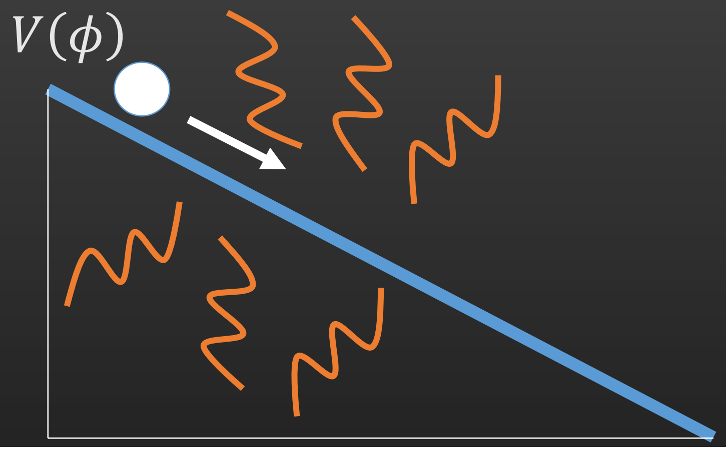




Berghaus, Karwal 2019

Early Dark Energy with thermal friction



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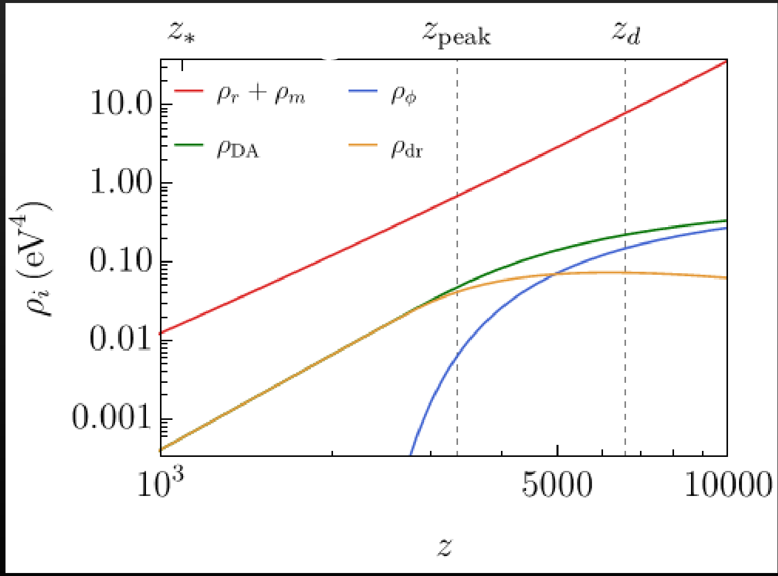
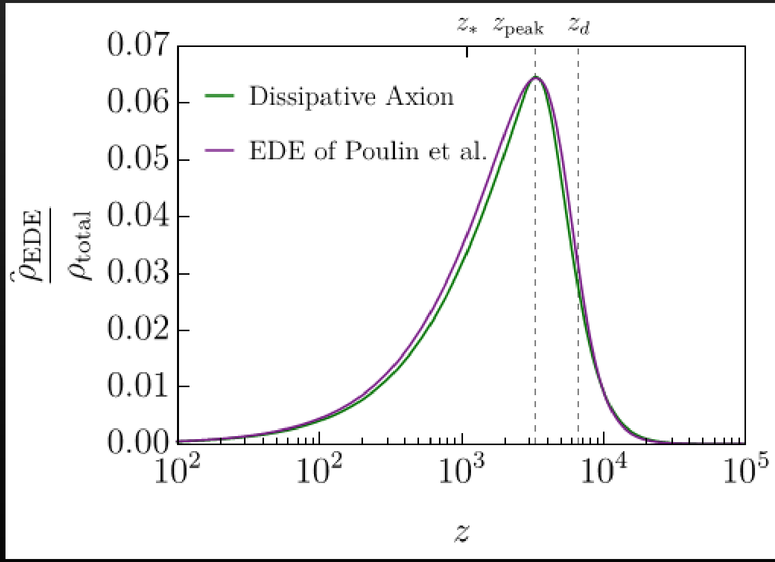
Overdamped at all time. Axion converts its energy into dark radiation at critical redshift z_c

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

Analysis

- Put thermal friction into CLASS: $V(\phi) = \frac{1}{2} m^2 \phi^2$
- Effective parameters: f_{ede}

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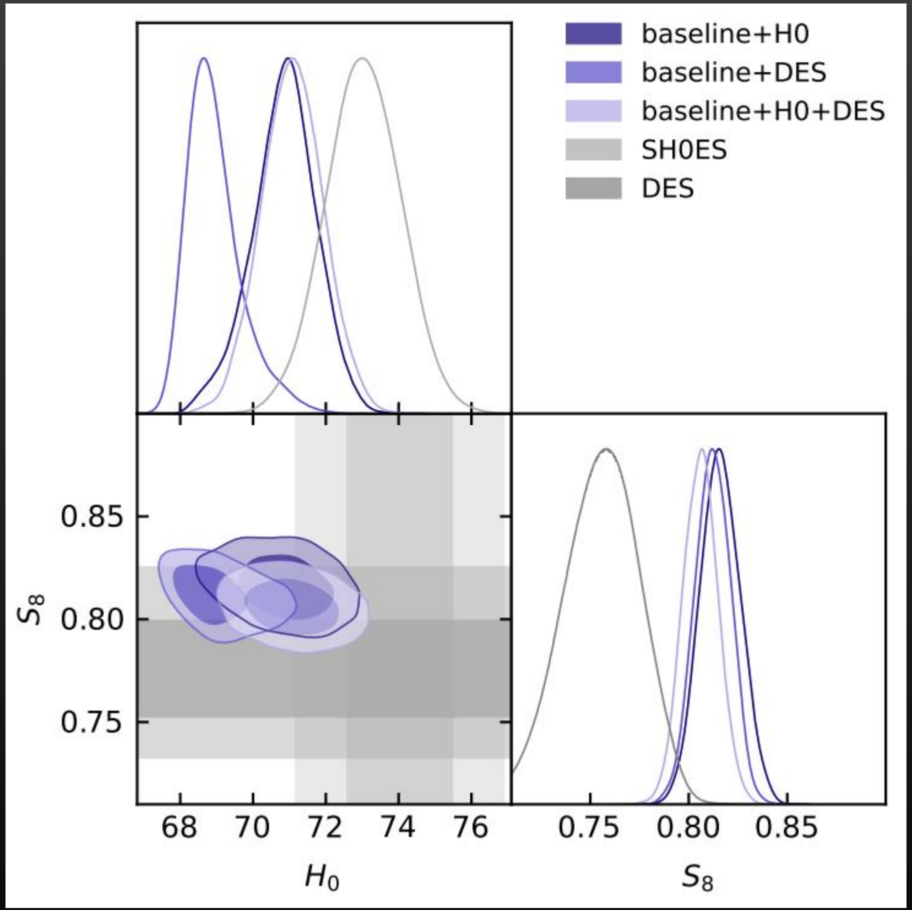
Analysis

- Put thermal friction 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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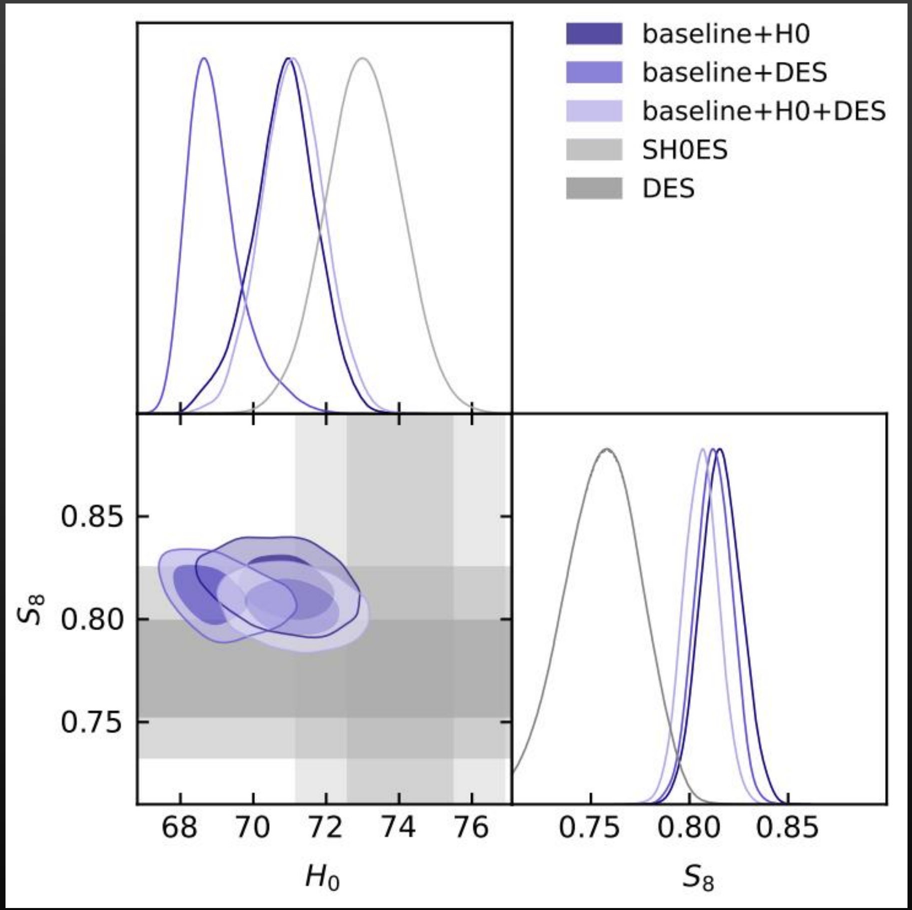


Berghaus, Karwal 2022

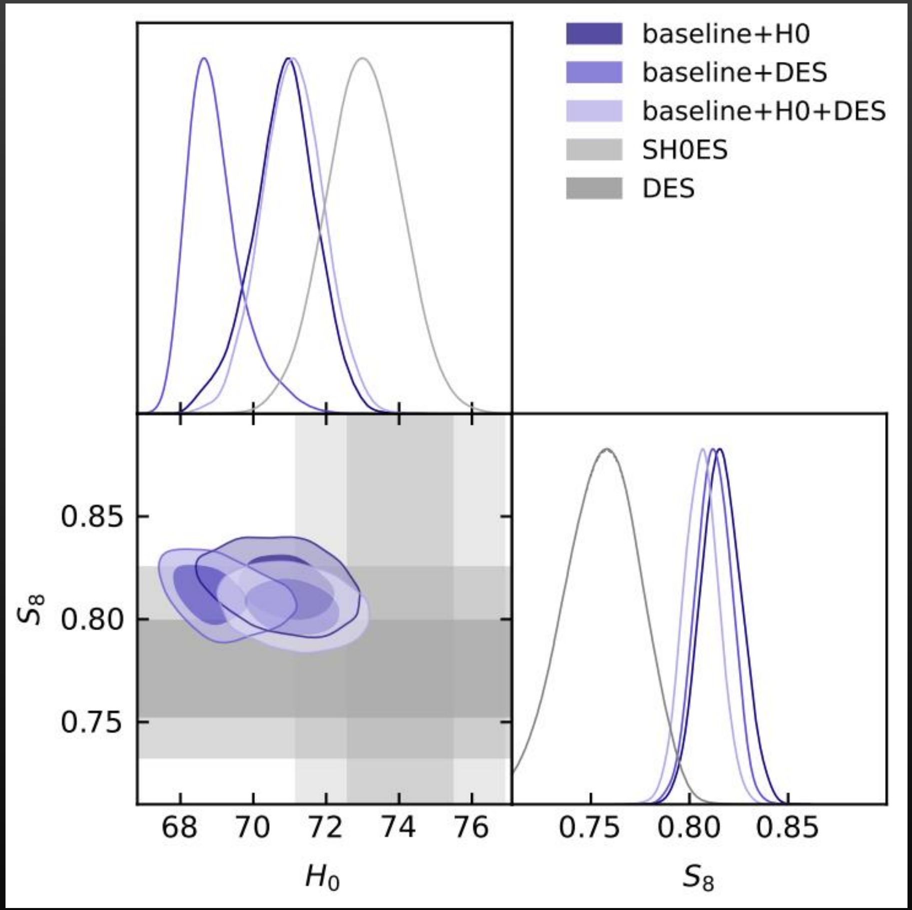
Model	H_0 [km/s/Mpc]	S_8
ΛCDM	$68.76(68.63) \pm 0.36$	$0.8013(0.8055) \pm 0.0087$
DA EDE	$71.08(71.06) \pm 0.85$	$0.8058(0.8075) \pm 0.0089$
$N_{\rm eff}$	$70.50(70.86) \pm 0.78$	$0.8102(0.8106) \pm 0.0096$

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



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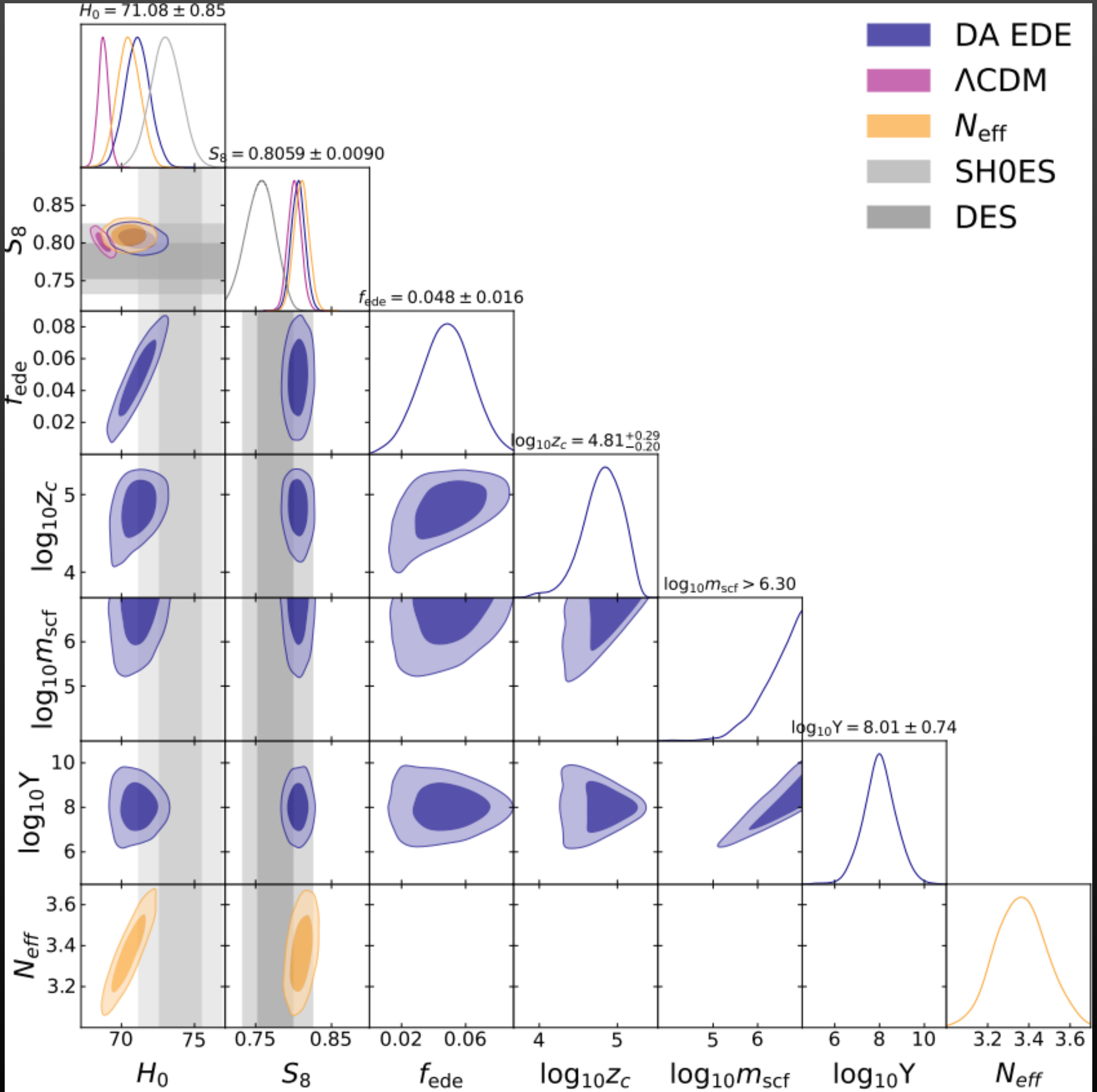
Baseline + SH0ES + DES



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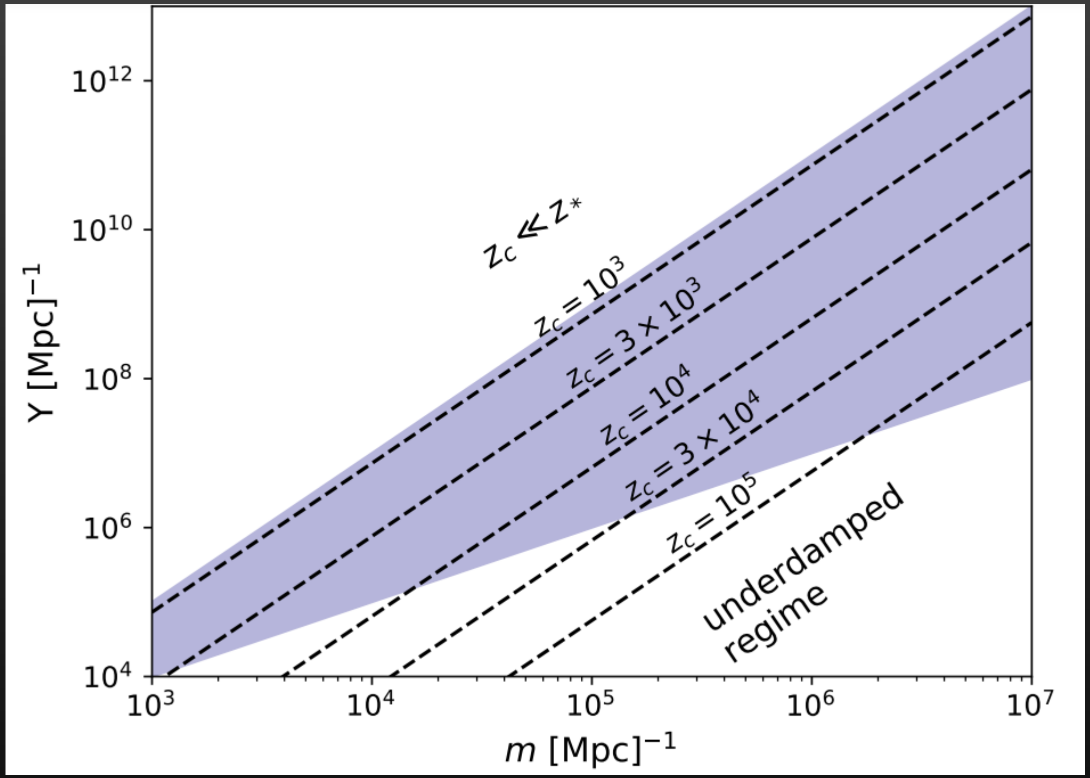

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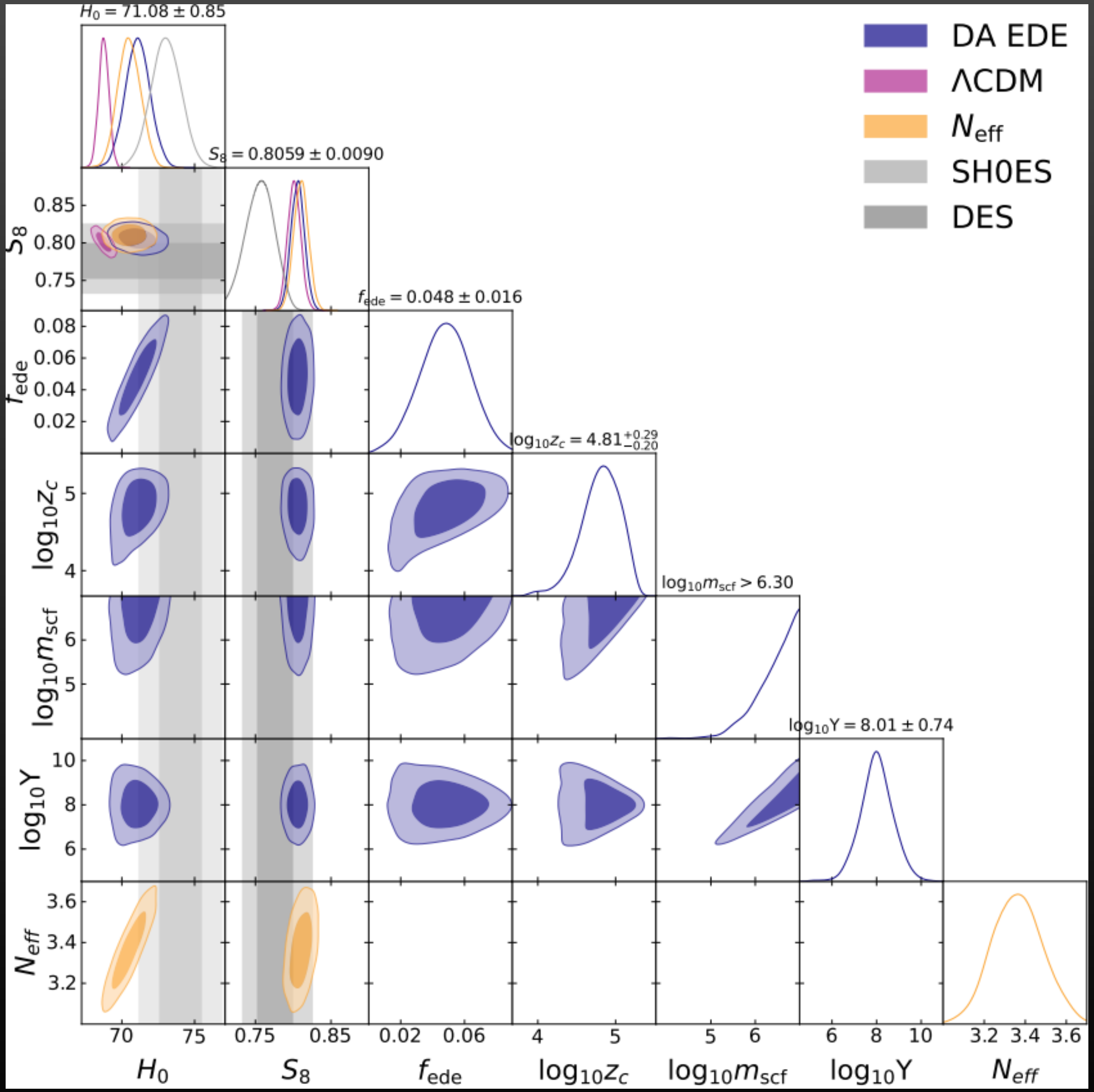

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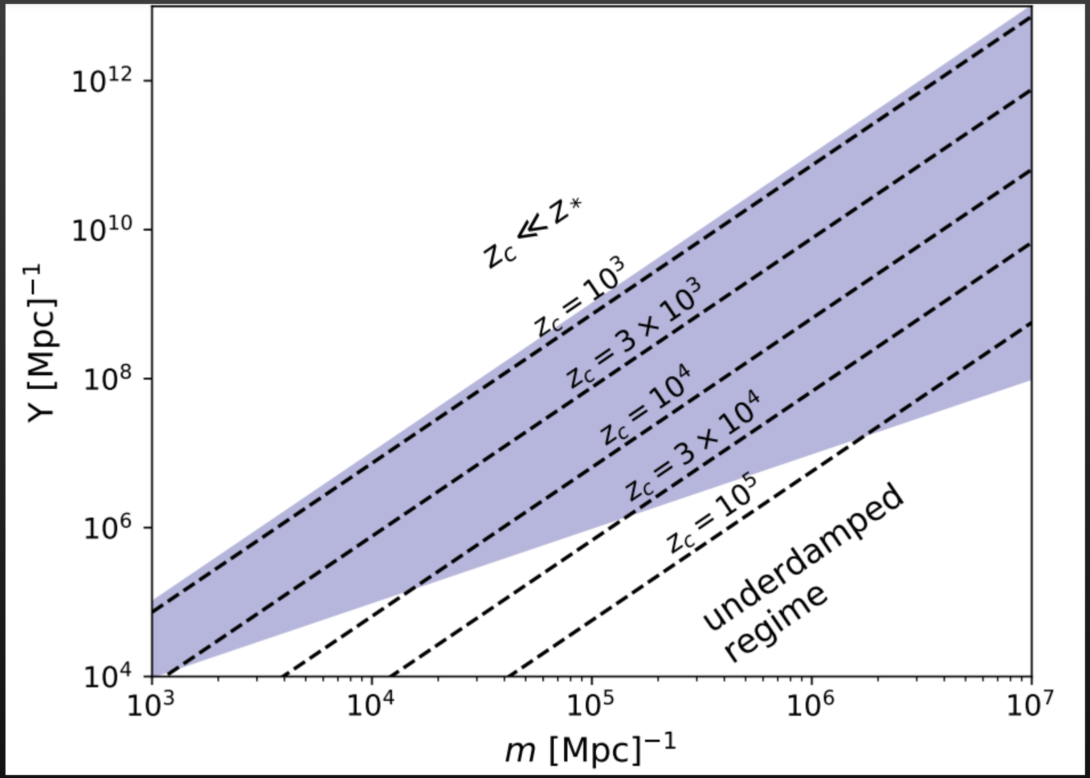

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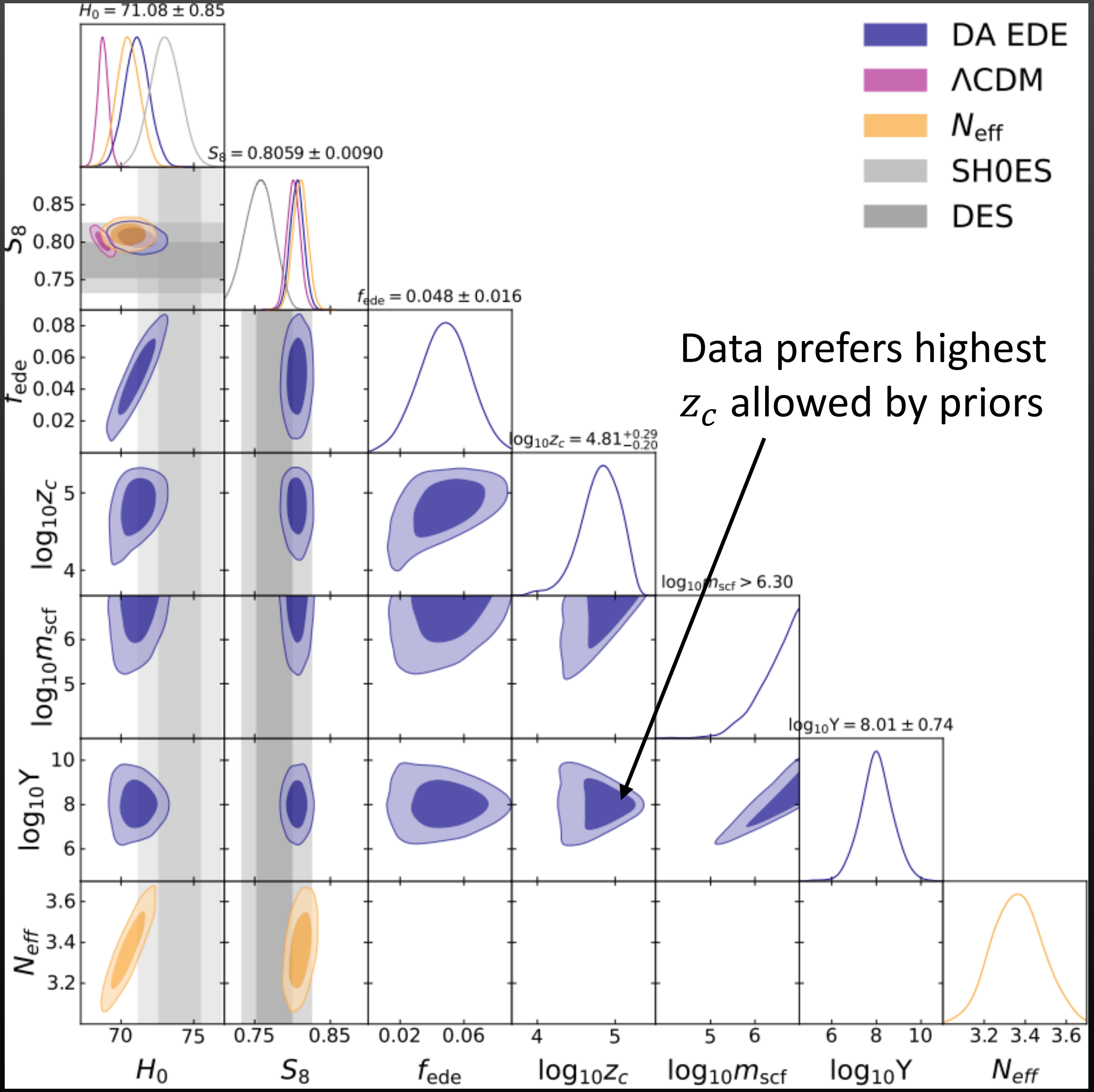

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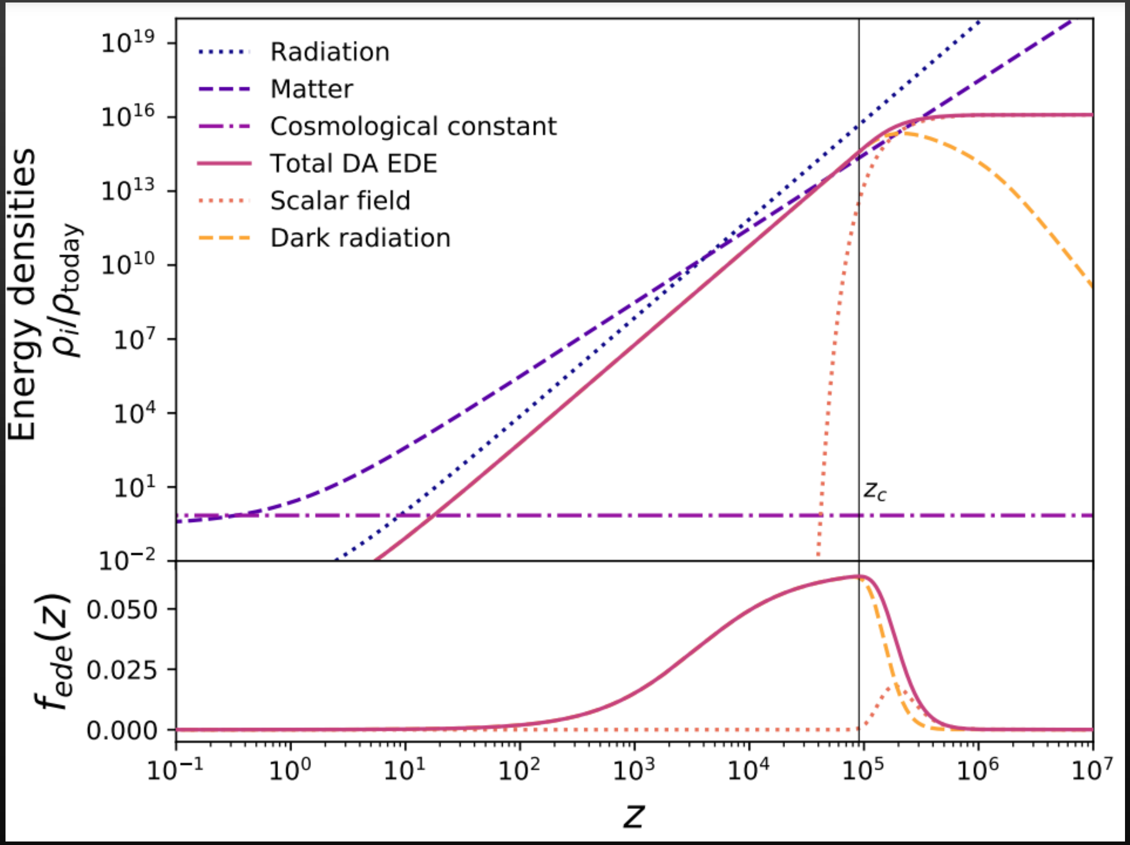

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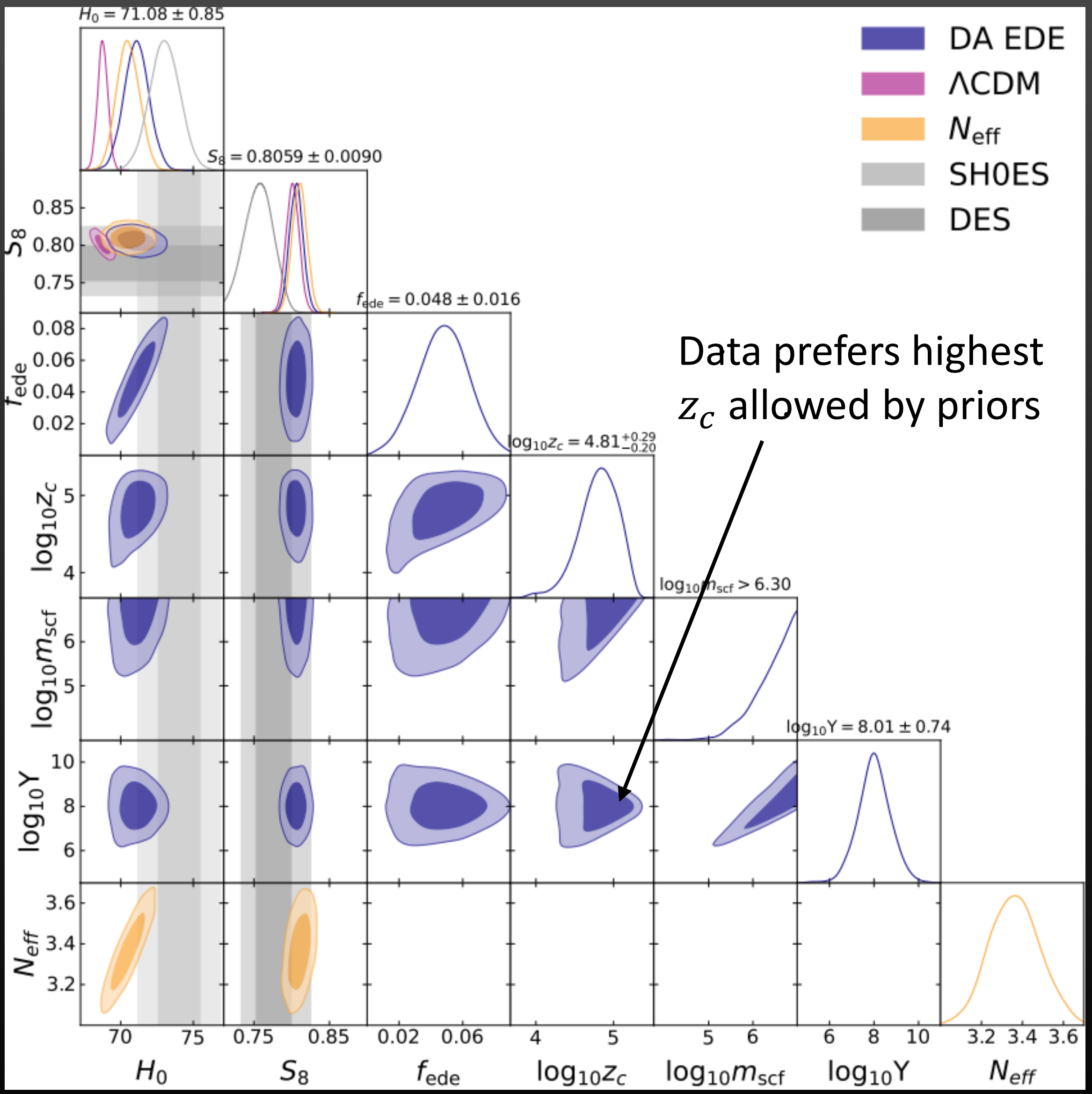

Data prefers highest z_c allowed by priors

Berghaus, Karwal 2022

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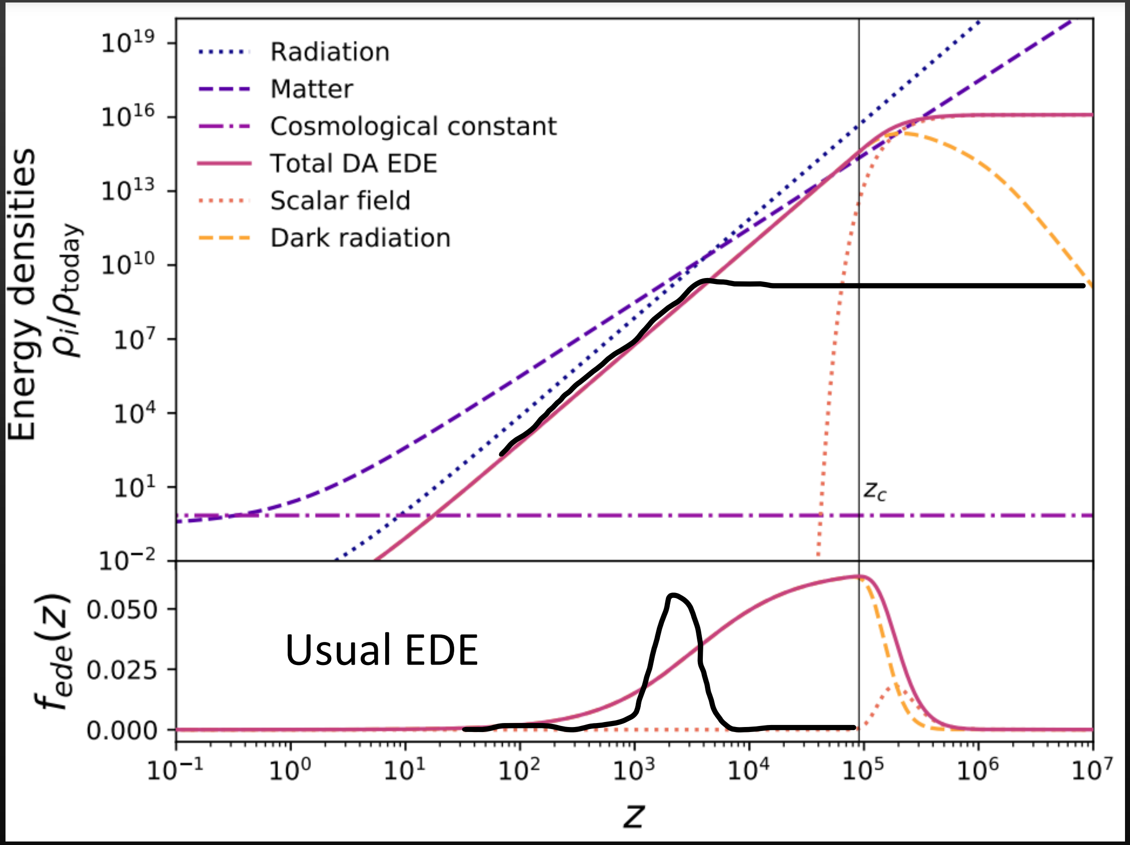

Berghaus, Karwal 2022

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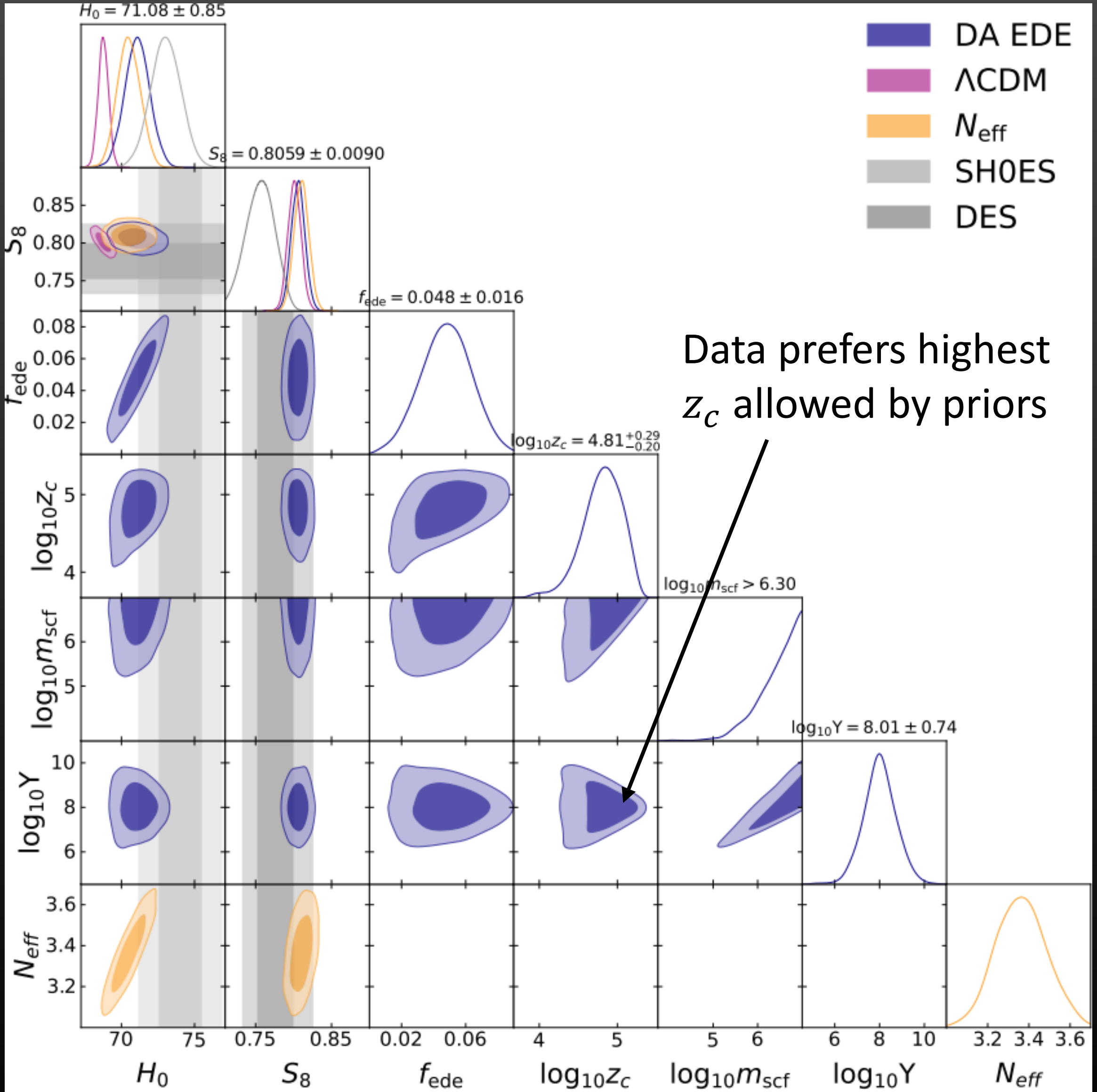

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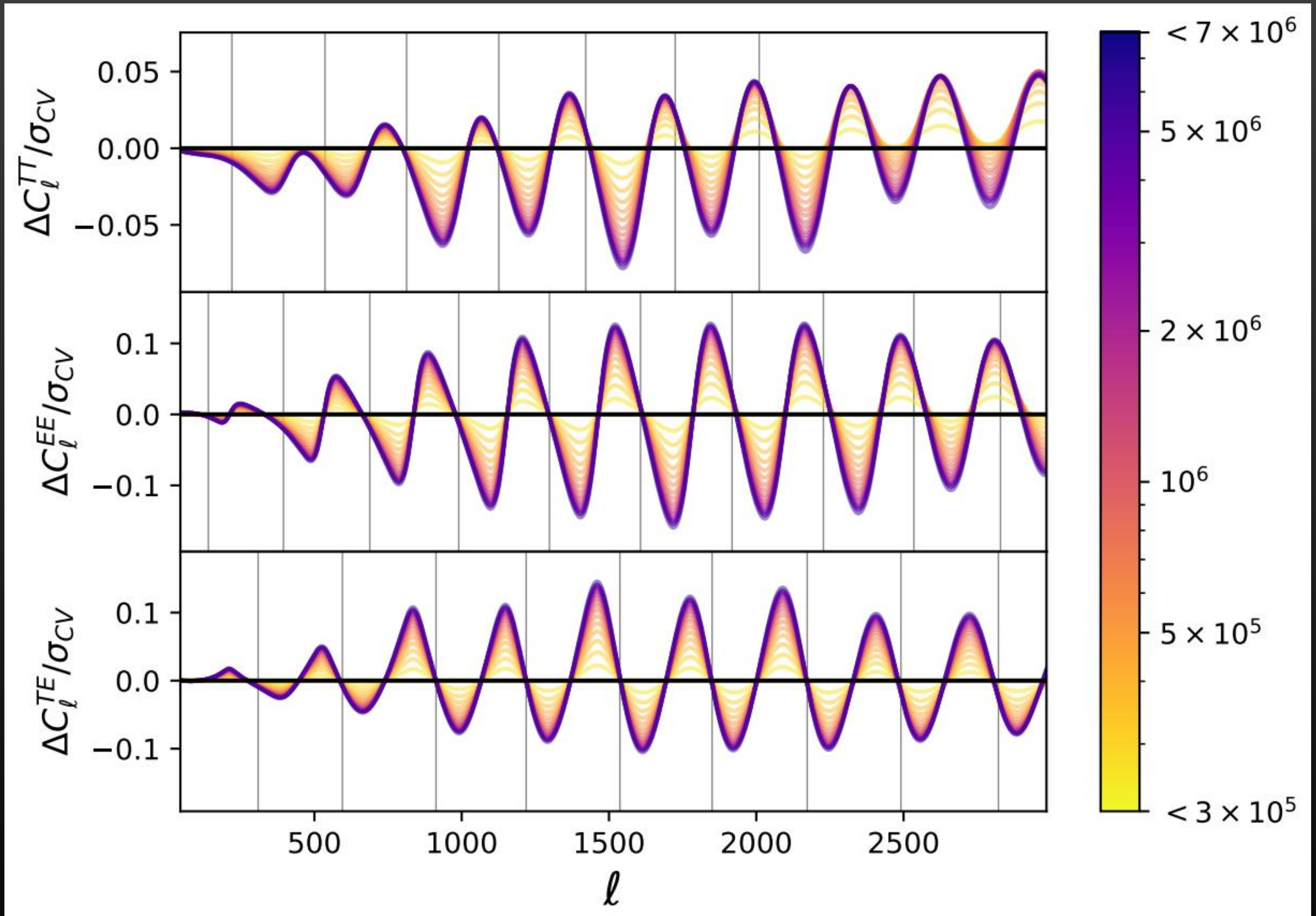
Going to higher redshifts



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

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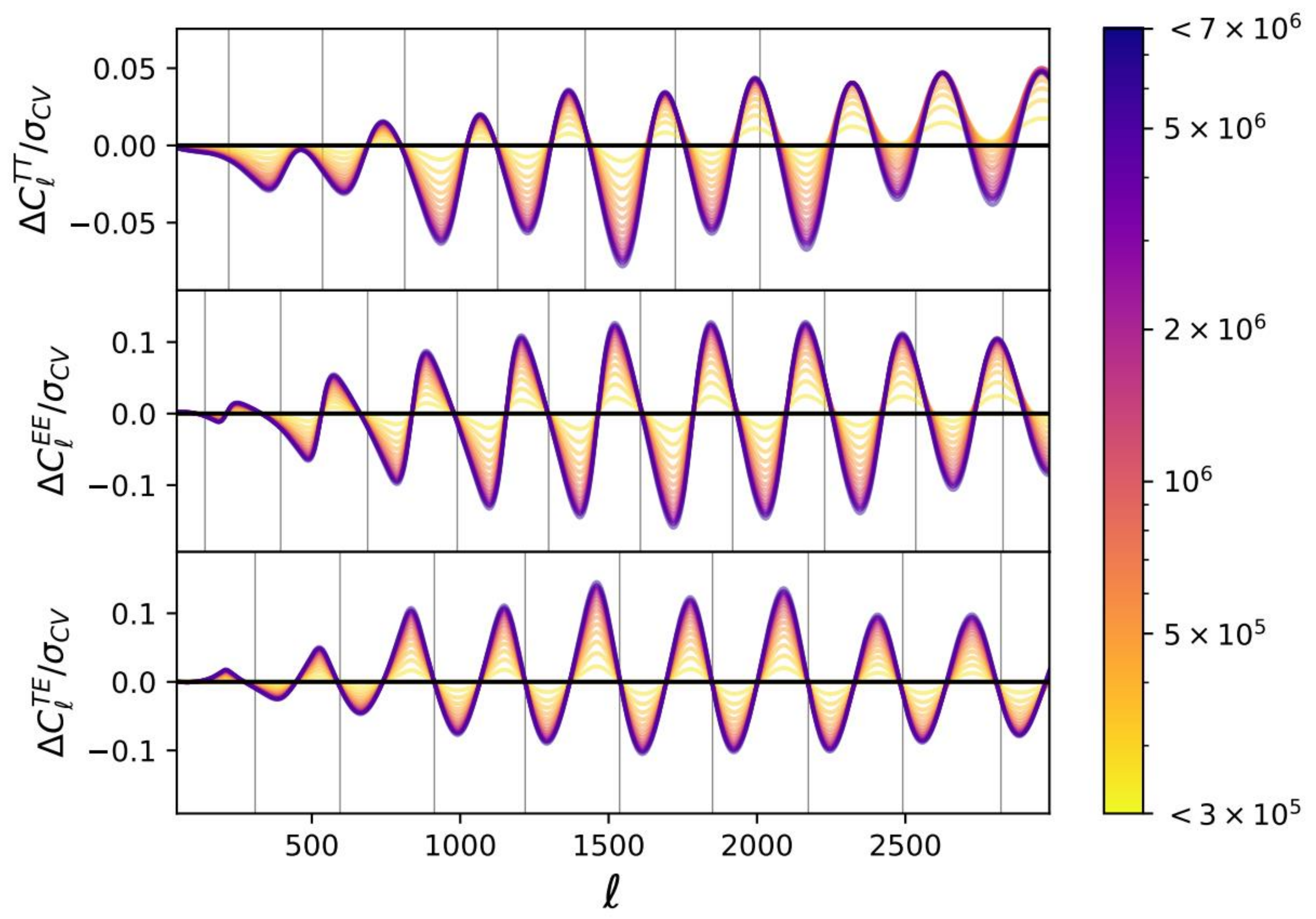

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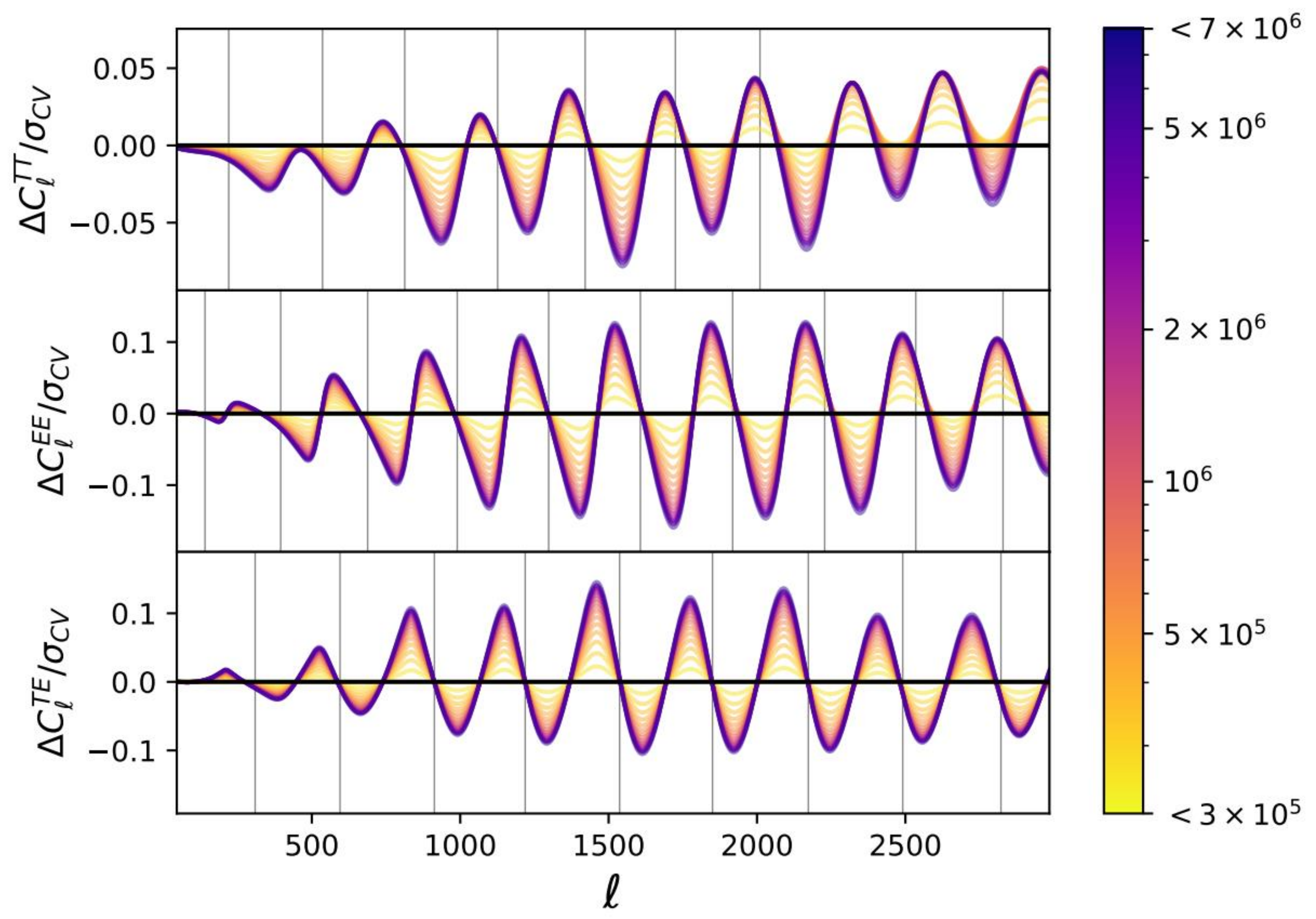

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Thermal friction asymptotes to an extra-radiation solution

Why does data not prefer EDE thermal friction?

Answer must be in perturbations since background looks favorable

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

Regular EDE perturbations

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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

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

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If injection occurs early the axion decays away completely. Only radiation left without friction terms.

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

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

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Sourcing of DR smoothes anisotropies

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- Data has no sensitivity to step-like transitions at redshifts $\mathrm{z} > 10^5$
- Data disfavors new physics with smoothed anisotropies

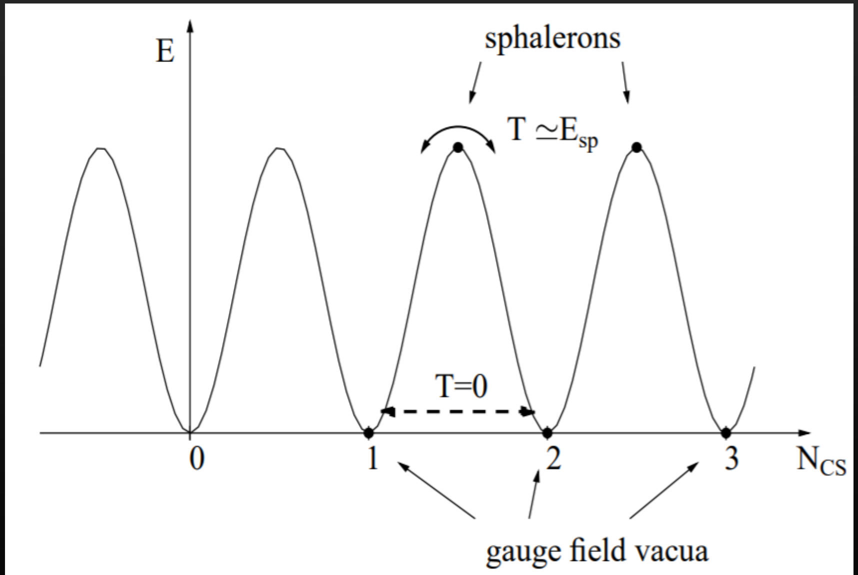
Thank You

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