Disentangling cosmic distance tensions with early and late dark energy

Tanisha Jhaveri

with
Tanvi Karwal, Tom Crawford, Wayne Hu, Ali Rida Khalife, Lennart Balkenhol, Fei Ge

This talk

- Cosmic distance tensions
  - CMB+BAO+SN and phantom dark energy
  - Disentangling CMB+BAO and BAO+SN
  - H_0 tension
- Addressing these tensions
  - Early time: CMB+BAO(+H_0) and early dark energy
  - Late time: BAO+SN and thawing quintessence

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- Addressing these tensions
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Three probes of the expansion history of the universe

Cosmic background microwave
(CMB)
z ~ 1100

Baryon acoustic
oscillations
(BAO)
z ~ 1

Supernovae
(SN)
z ~ 0.1-1

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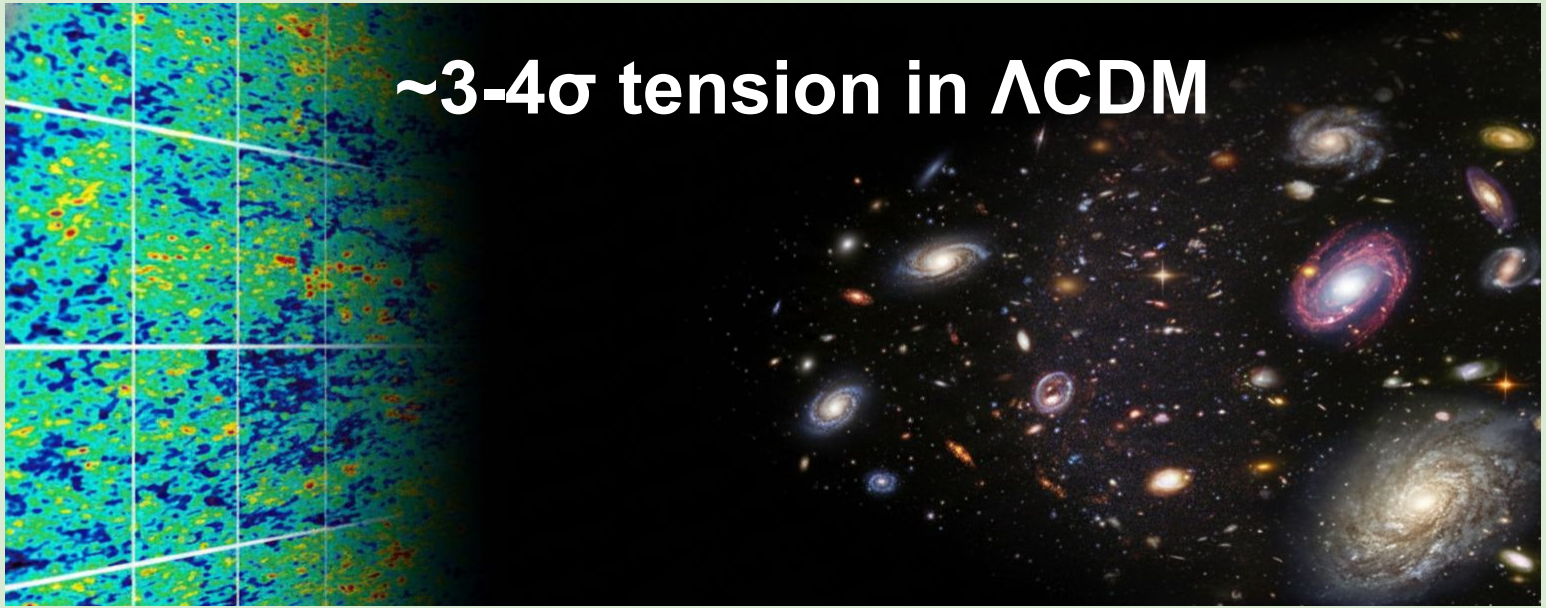
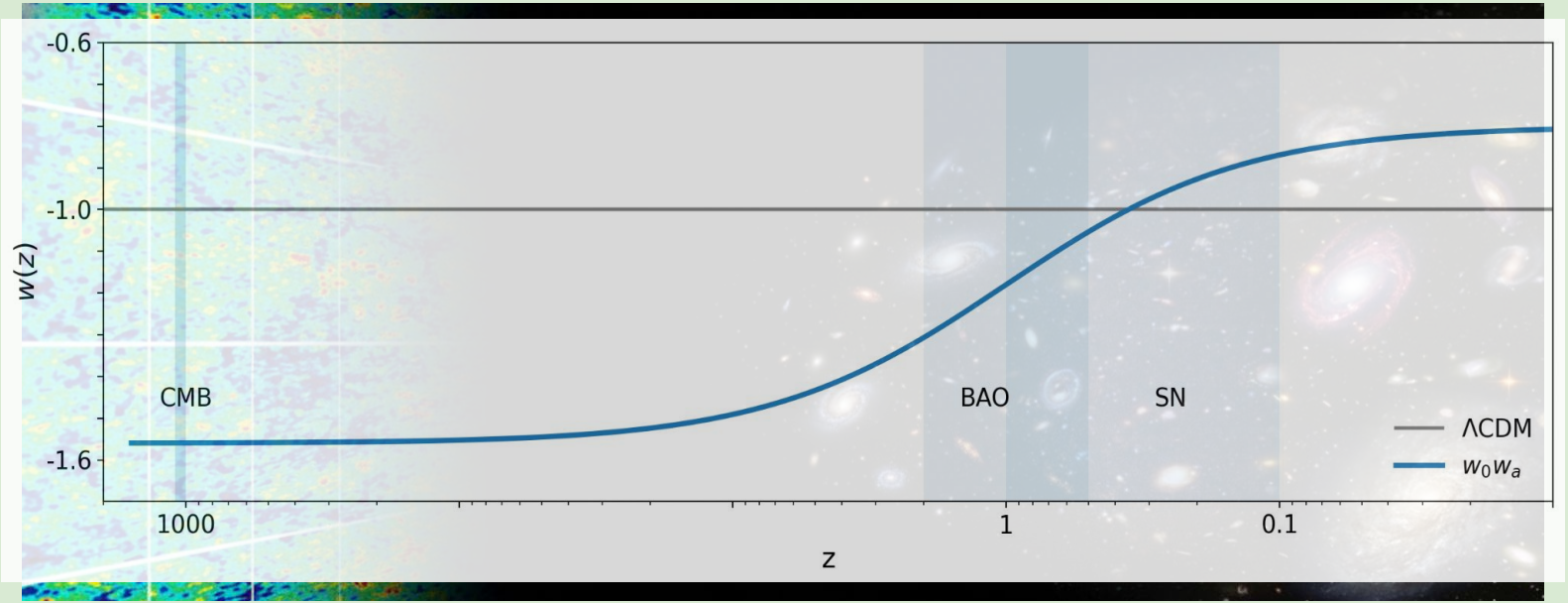


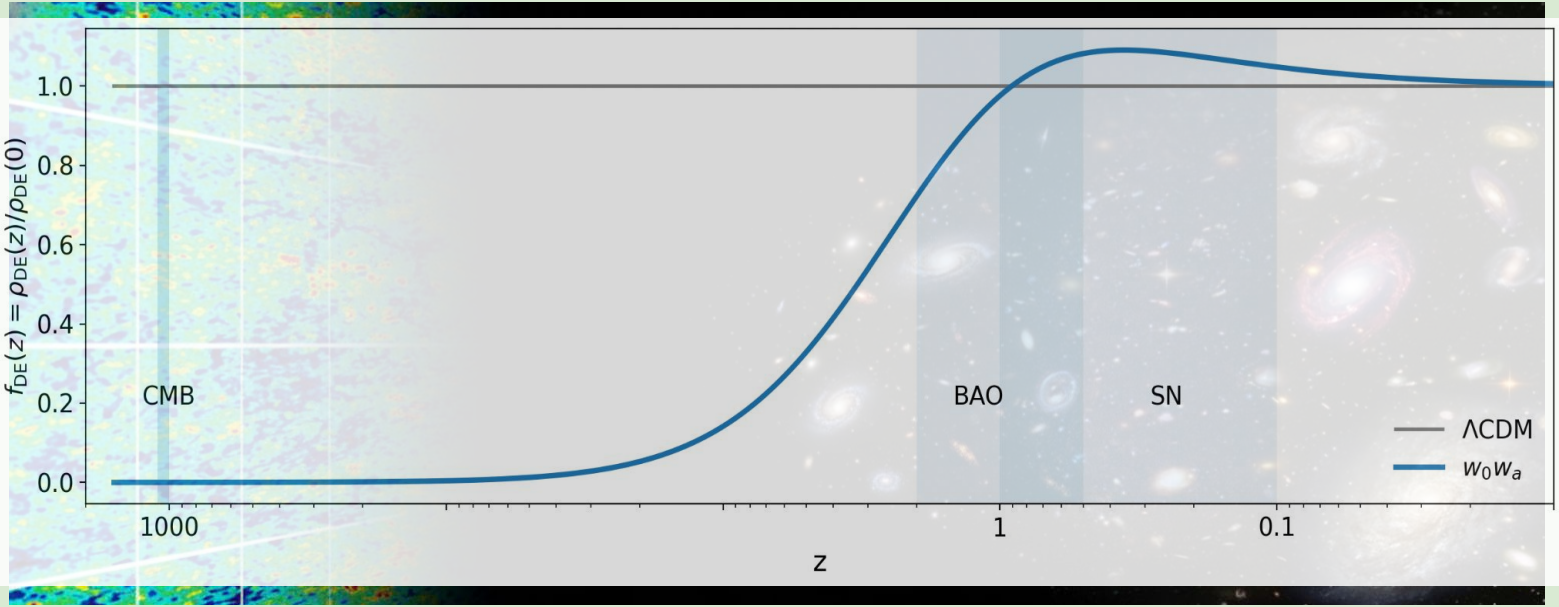
Can be interpreted as a preference for phantom DE

CPL parametrization:

$$w(z) = w_0 + w_a \, z/(1+z)$$



Energy density of DE appears to grow over time



Energy density of DE appears to grow over time

CMB+BAO tension is about high redshift distances

CMB

z ~ 1100

BAO

z ~ 1

BAO+SN tension is about low redshift distances

BAO SN

z ~ 1 z ~ 0.1-1

Disentangle the tensions

CMB

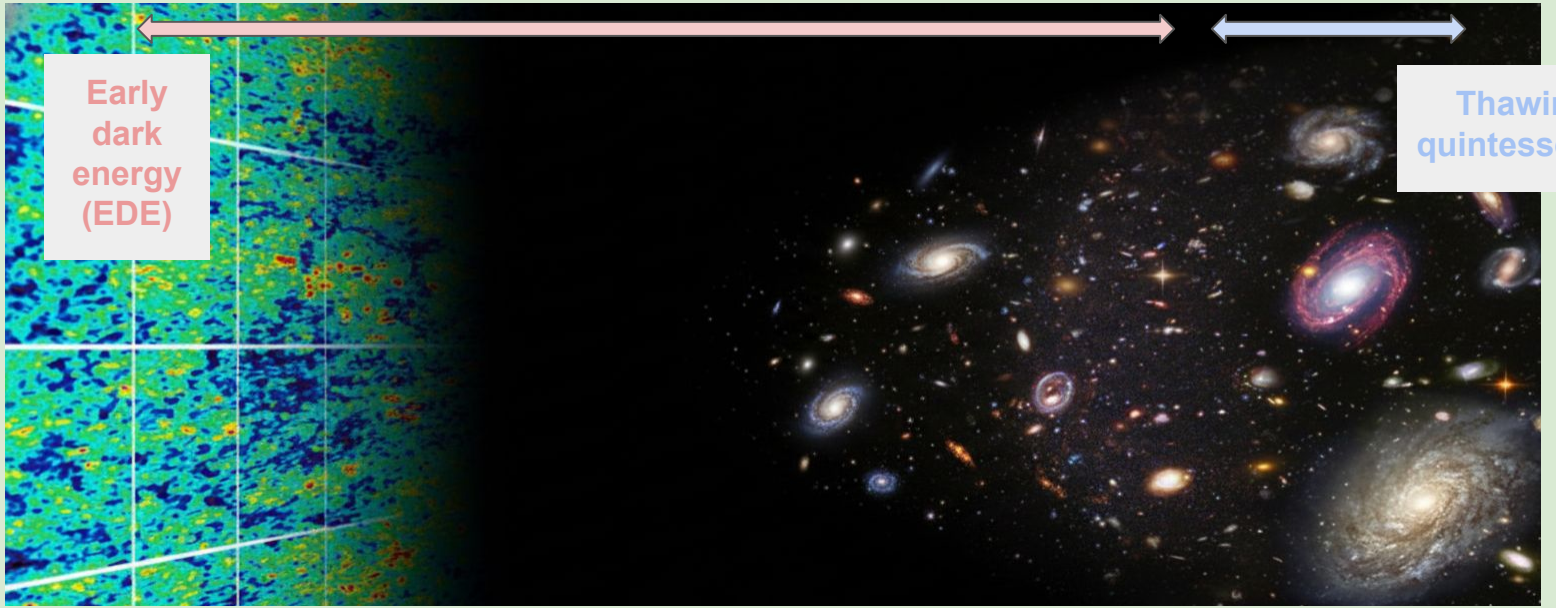
z ~ 1100

BAO

z ~ 1

SN

z ~ 0.1-1

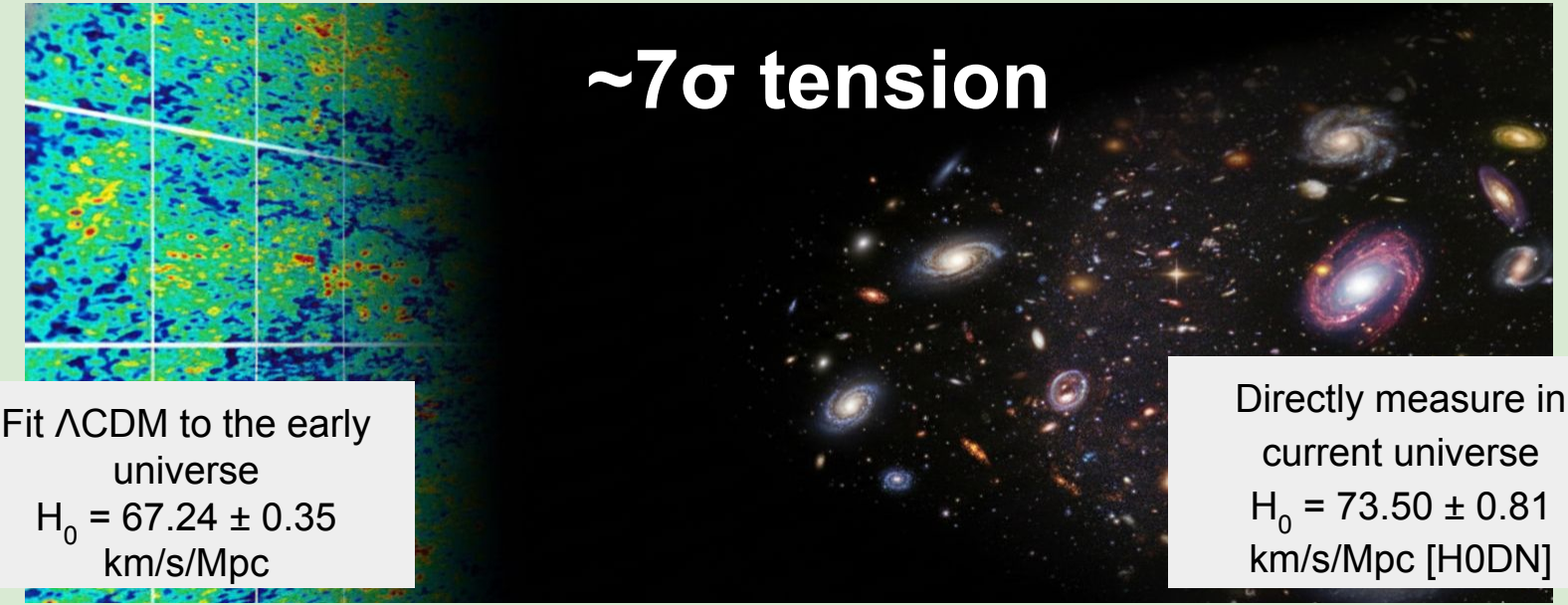


EDE: potential resolution to the Hubble tension

Fit ΛCDM to the early universe
H_0 = 67.24 ± 0.35 km/s/Mpc

Directly measure in current universe
H_0 = 73.50 ± 0.81 km/s/Mpc [H0DN]

EDE: potential resolution to the Hubble tension



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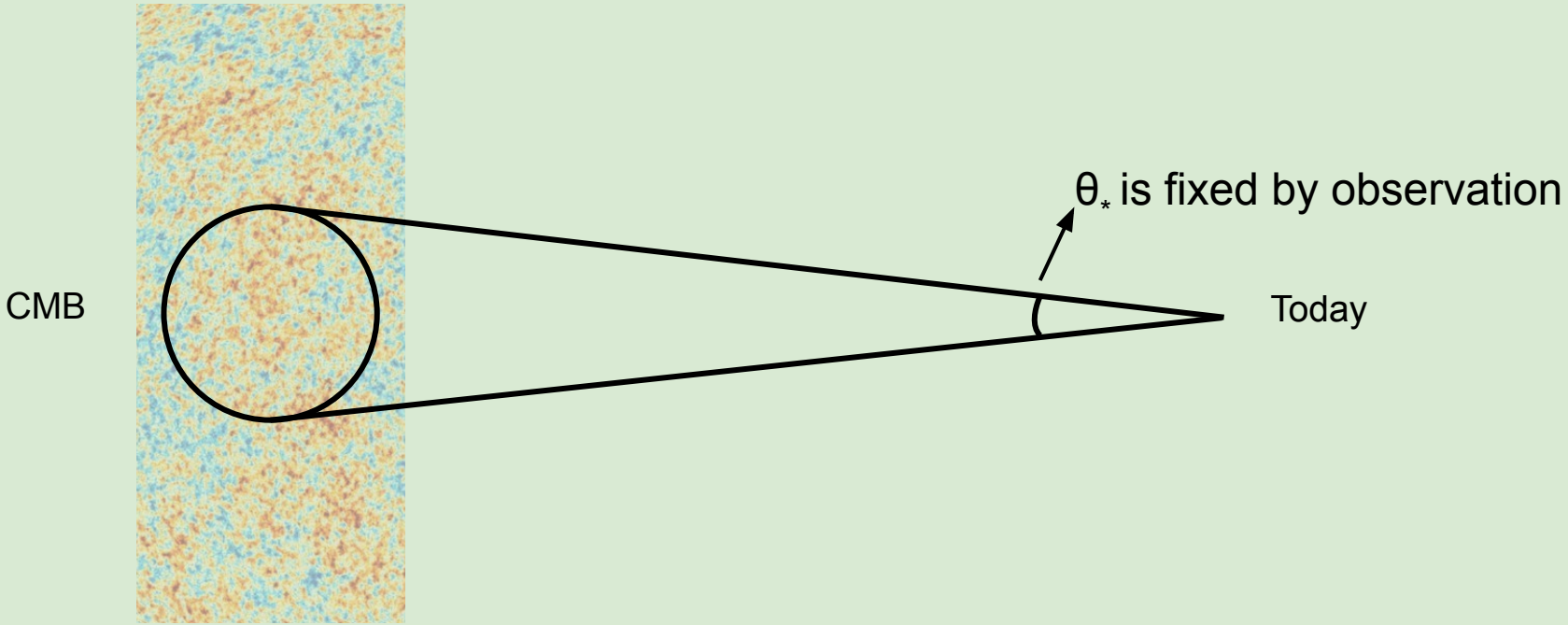
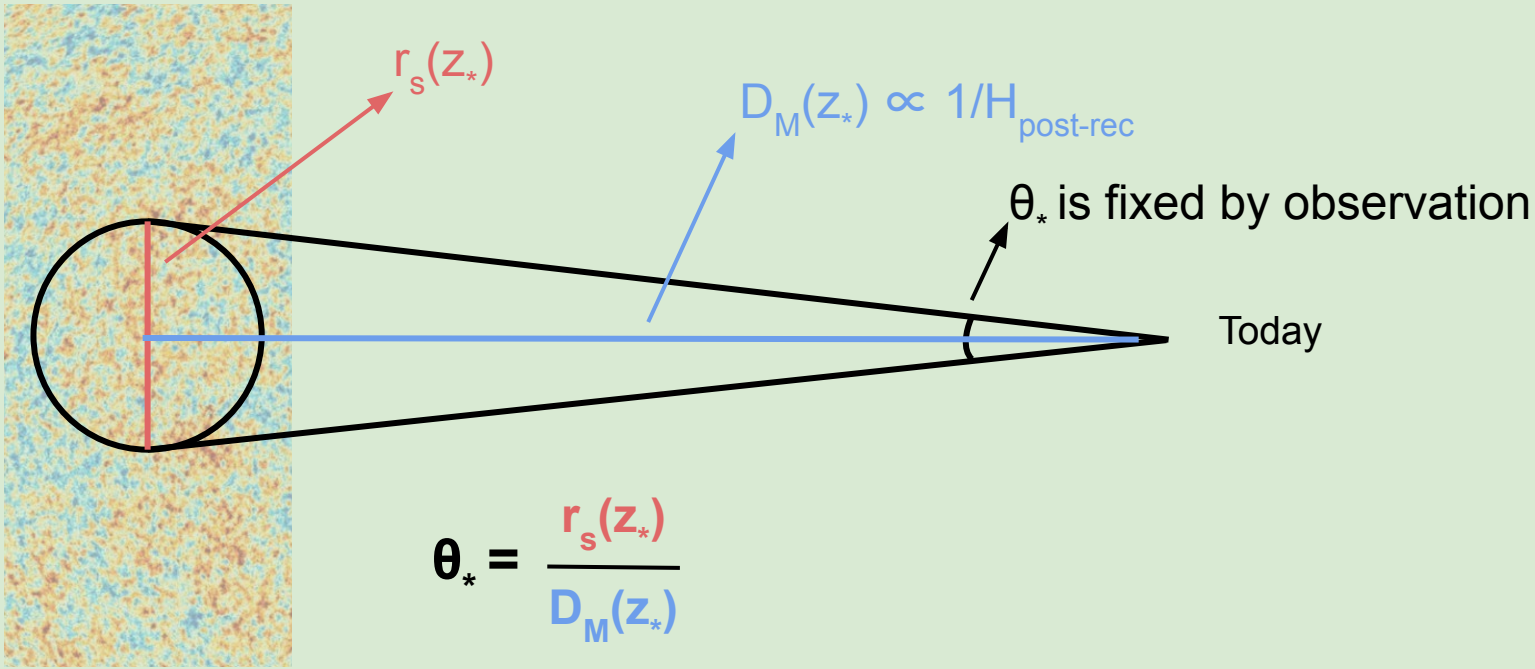
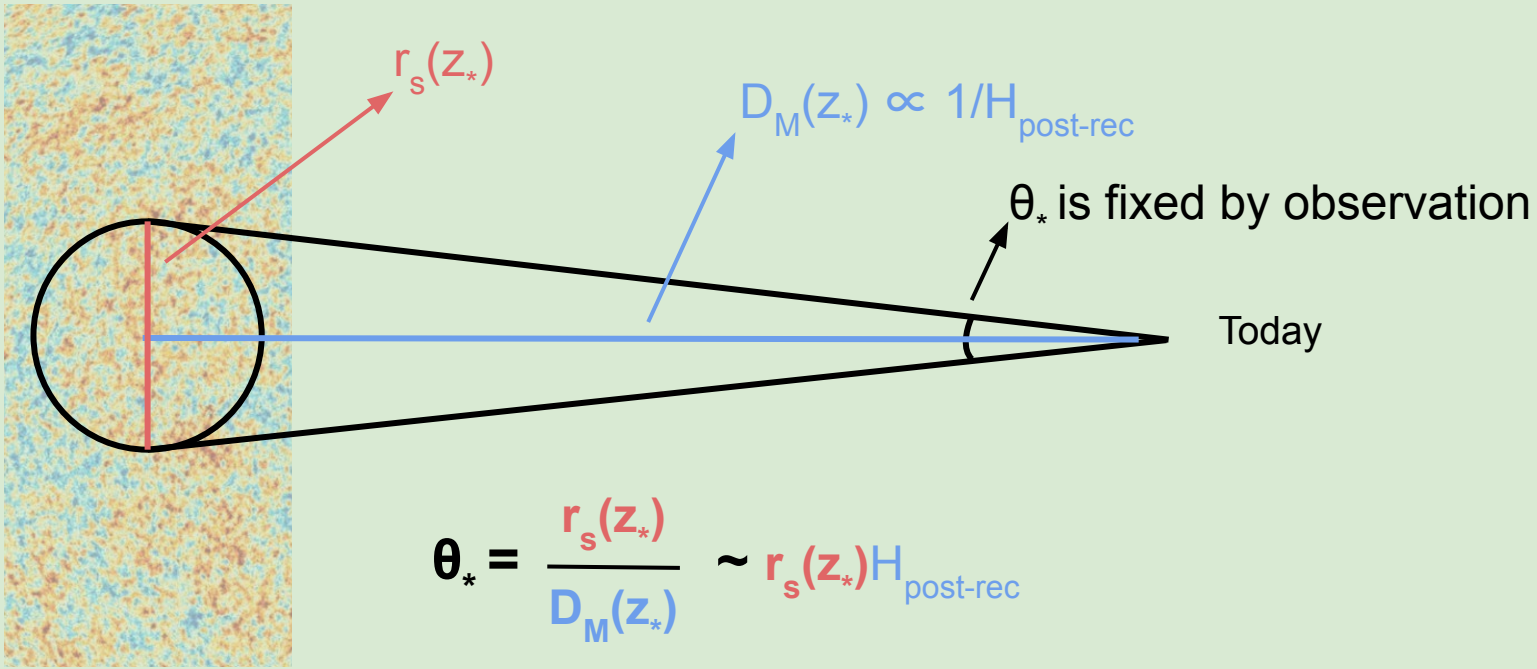
CMB primer



CMB primer

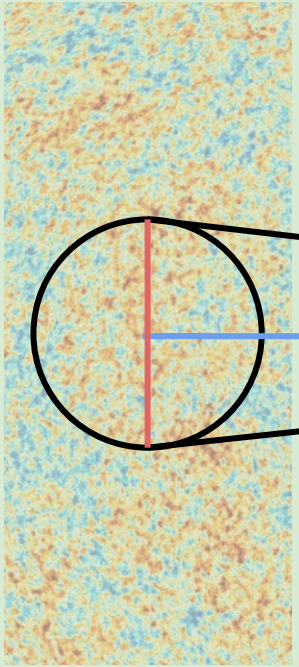

$r_s(z_*)$
$D_M(z_*) \propto 1/H_{post\text{-}rec}$
θ_* is fixed by observation
CMB
Today
$\theta_* = \frac{r_s(z_*)}{D_M(z_*)}$

CMB primer



$$\theta_* = \frac{r_s(z_*)}{D_M(z_*)} \sim r_s(z_*) H_{\text{post-rec}}$$

CMB primer



CMB

θ_* is fixed by observation

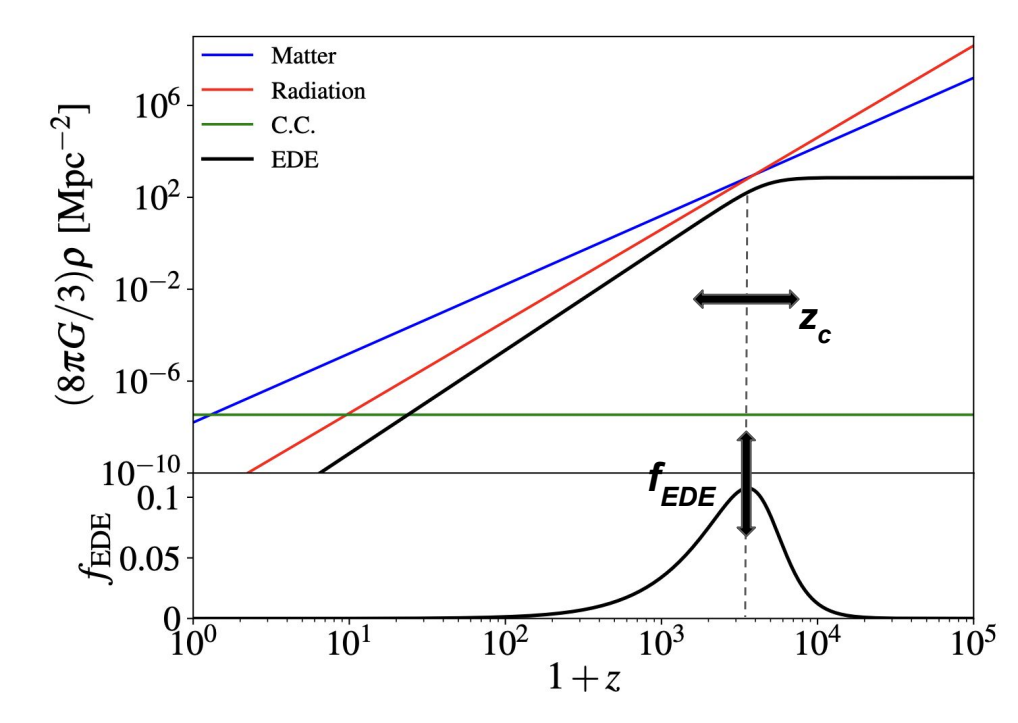
Today

$$\theta_* = \frac{r_s(z_*)}{D_M(z_*)} \sim r_s(z_*)H_{\text{post-rec}}$$

EDE reduces $r_s(z_*)$

Which increases inferred H_0

Early dark energy



EDE model parameters

f_{EDE} → how much EDE
z_c → when it appears
ϕ_i → initial value of scalar field

Figure from Poulin et al, 2023

Disentangle the tensions

CMB

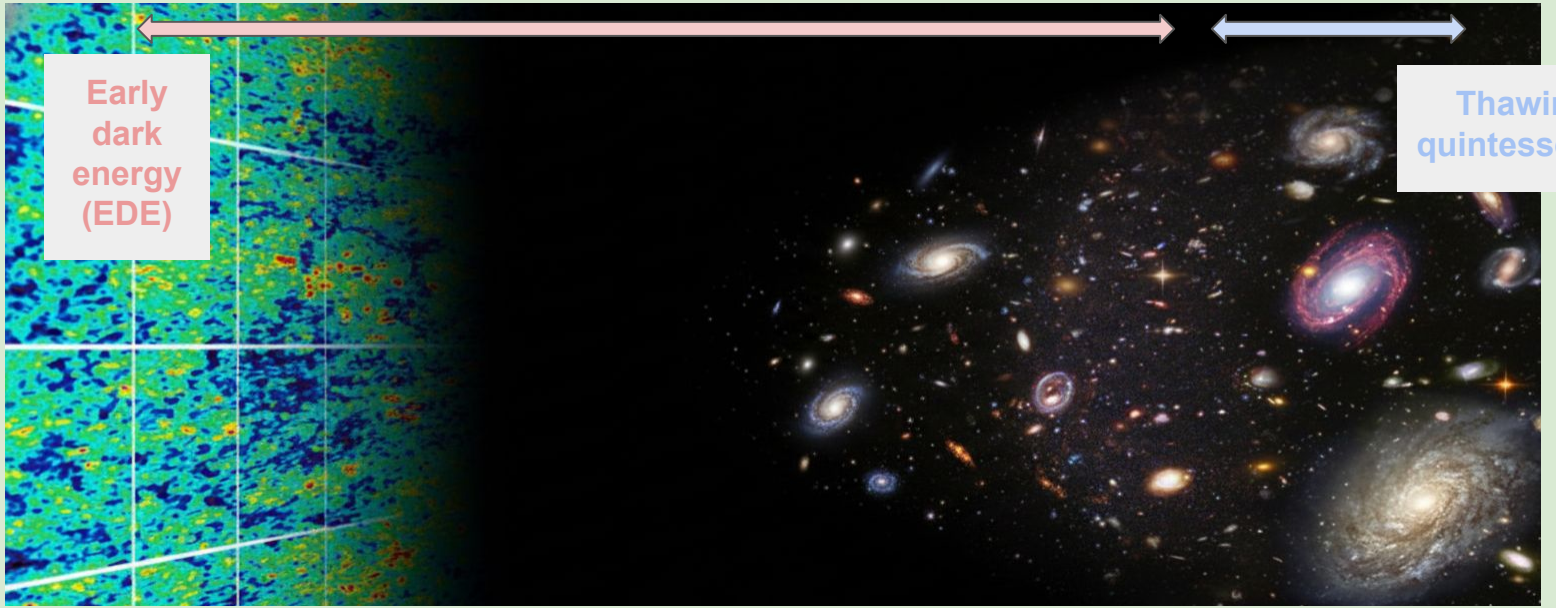
z ~ 1100

BAO

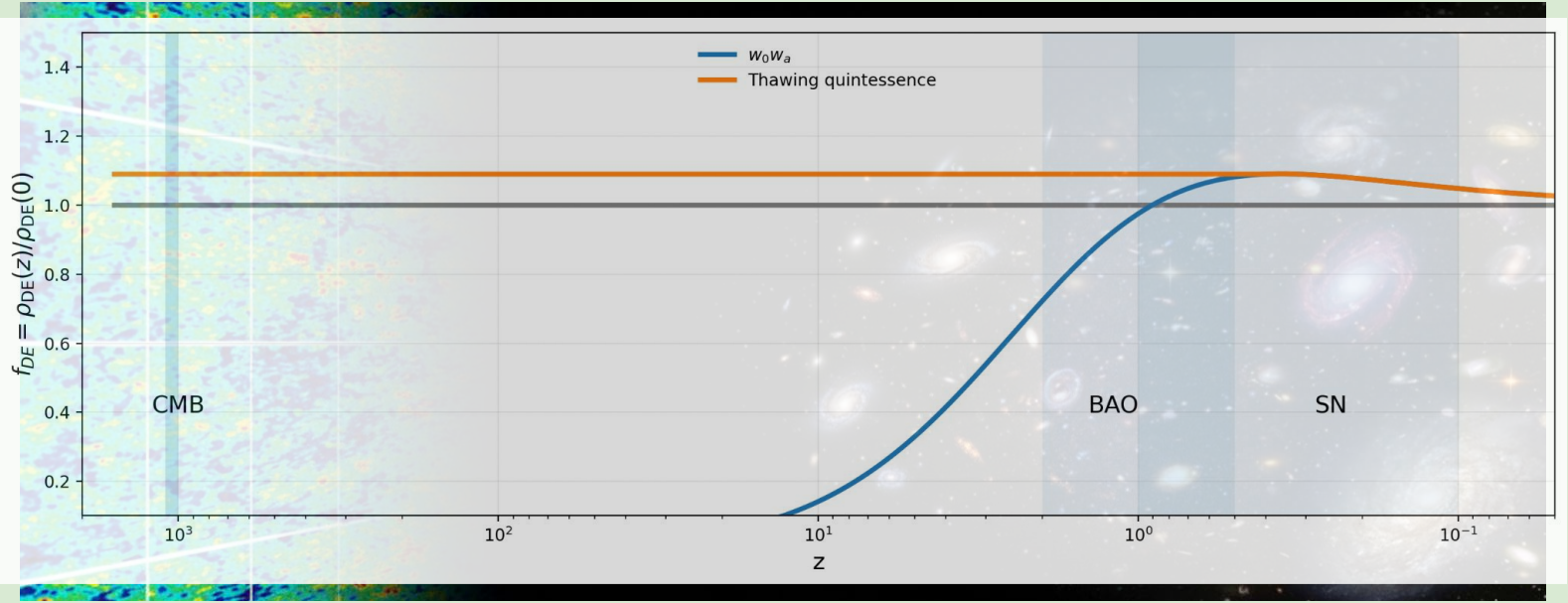
z ~ 1

SN

z ~ 0.1-1

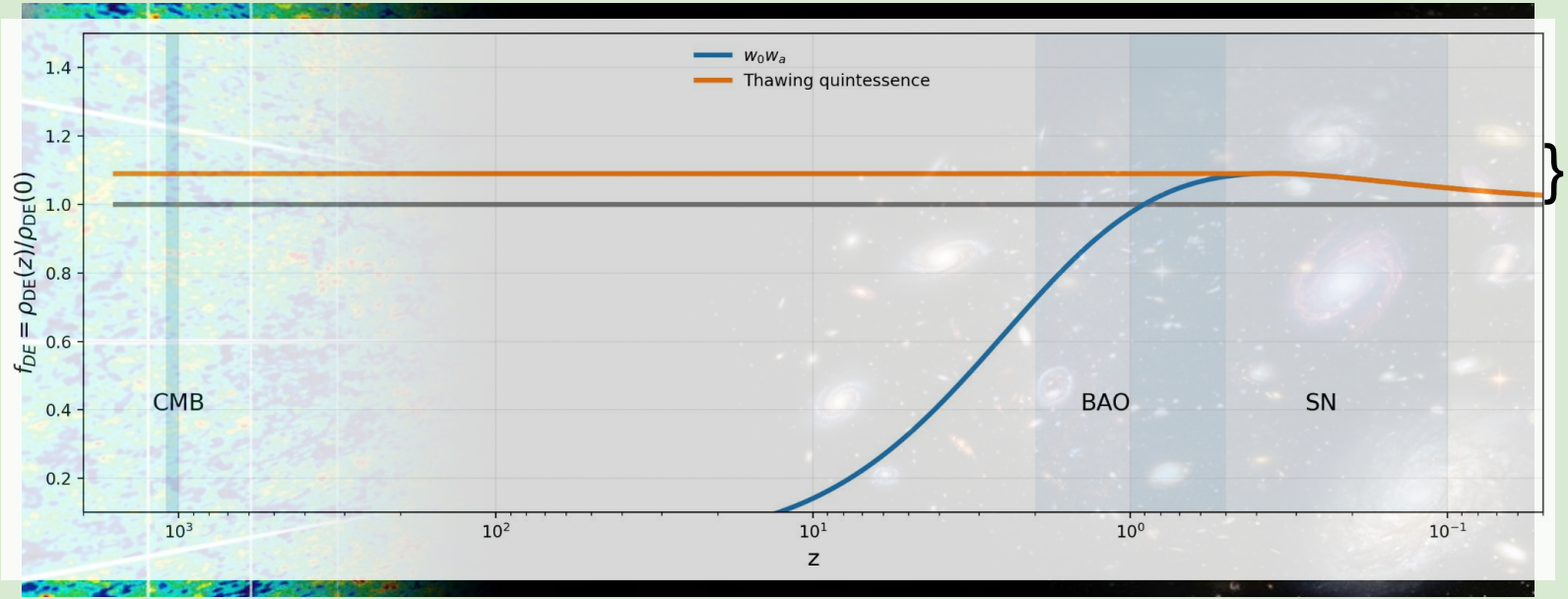


Thawing quintessence models start “frozen” at constant ρ and then “thaw”



Thawing quintessence models start “frozen” at constant ρ and then “thaw”

Deviation from Λ given by one free parameter w_0



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  - Disentangling CMB+BAO and BAO+SN
  - H_0 tension
- **Addressing these tensions**
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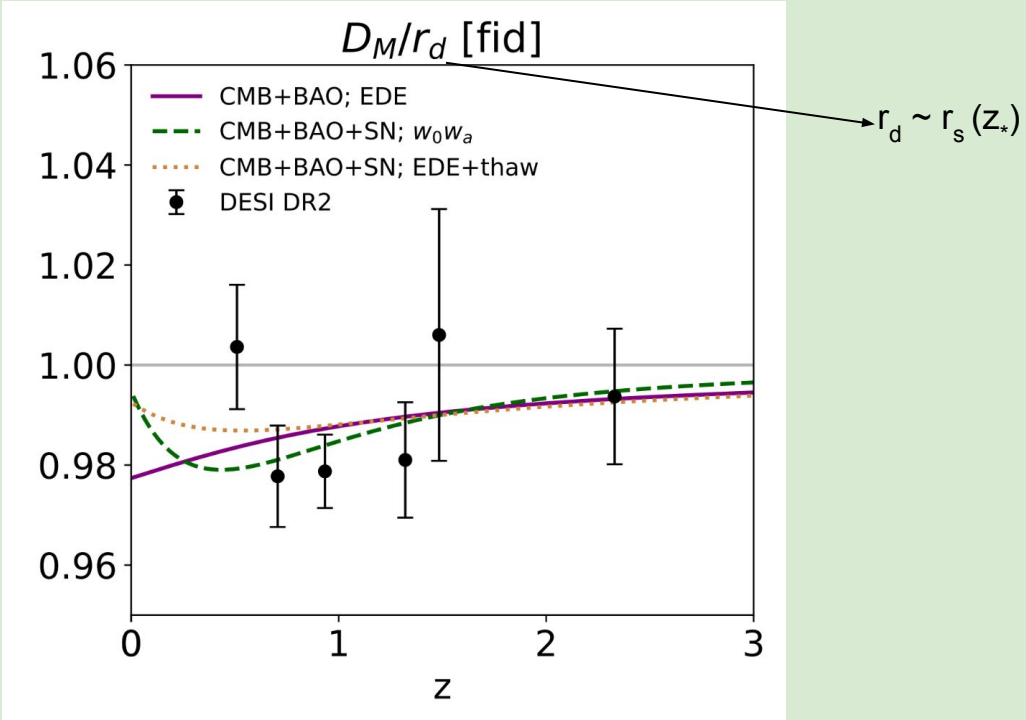
  - **Late time: BAO+SN and thawing quintessence**

BAO measure distances relative to the sound horizon

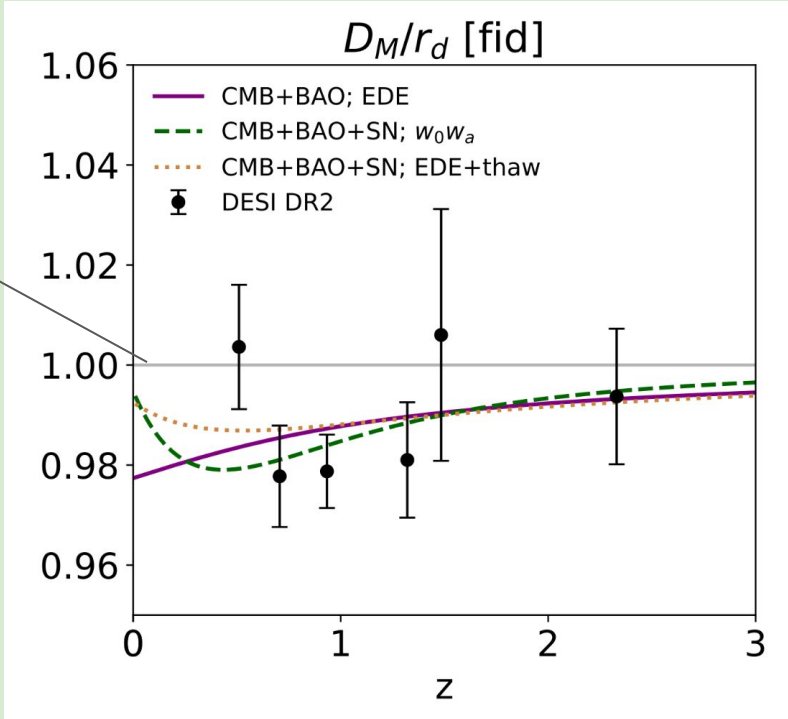


CMB+BAO tension

CMB = Planck + ACT DR6 + SPT3G (incl. lensing)

BAO = DESI DR2

Fid. LCDM model



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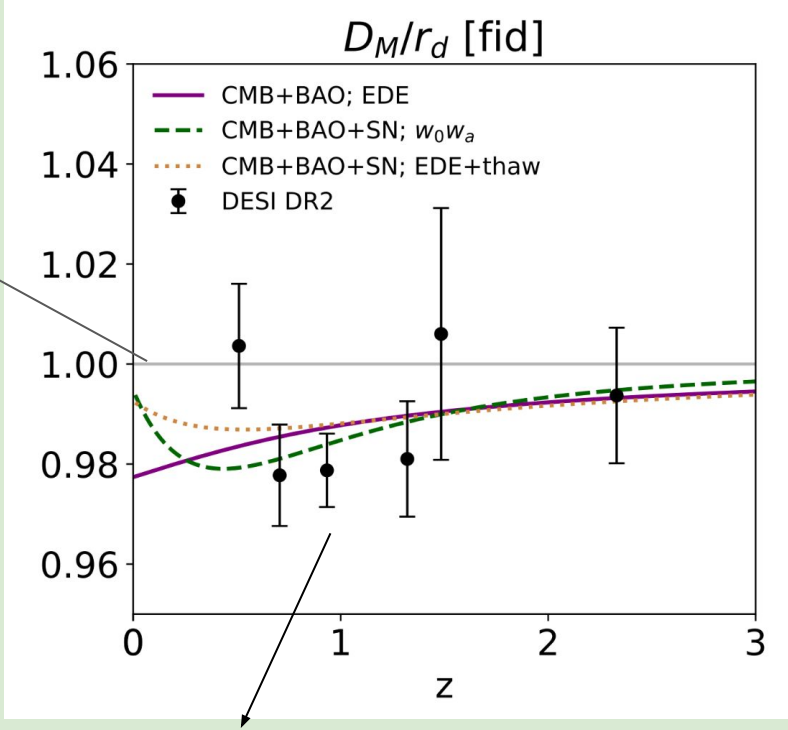

BAO data 1-2% lower D_M/r_d

CMB+BAO tension

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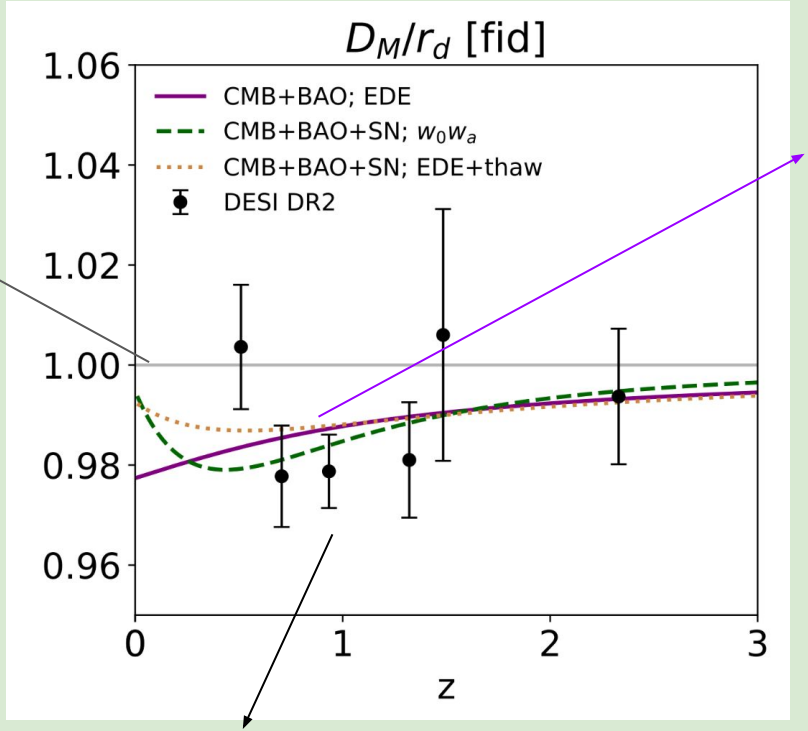


EDE lowers D_M/r_d

BAO data 1-2% lower D_M/r_d

EDE reduces both the CMB+BAO and Hubble tensions

For CMB+BAO data:

$$\chi^2_{\text{EDE}} - \chi^2_{\text{LCDM}} = -9.4$$

LCDM

$H_0 = 68.16$

EDE

$H_0 = 70.87$

EDE reduces both the CMB+BAO and Hubble tensions

For CMB+BAO data:

[Note that this does not include H_0 data]

$$\chi^2_{EDE} - \chi^2_{LCDM} = -9.4$$

LCDM

$H_0 = 68.16$

EDE

$H_0 = 70.87$

$7.1\sigma \rightarrow 2.1\sigma$

Disentangle the tensions

CMB

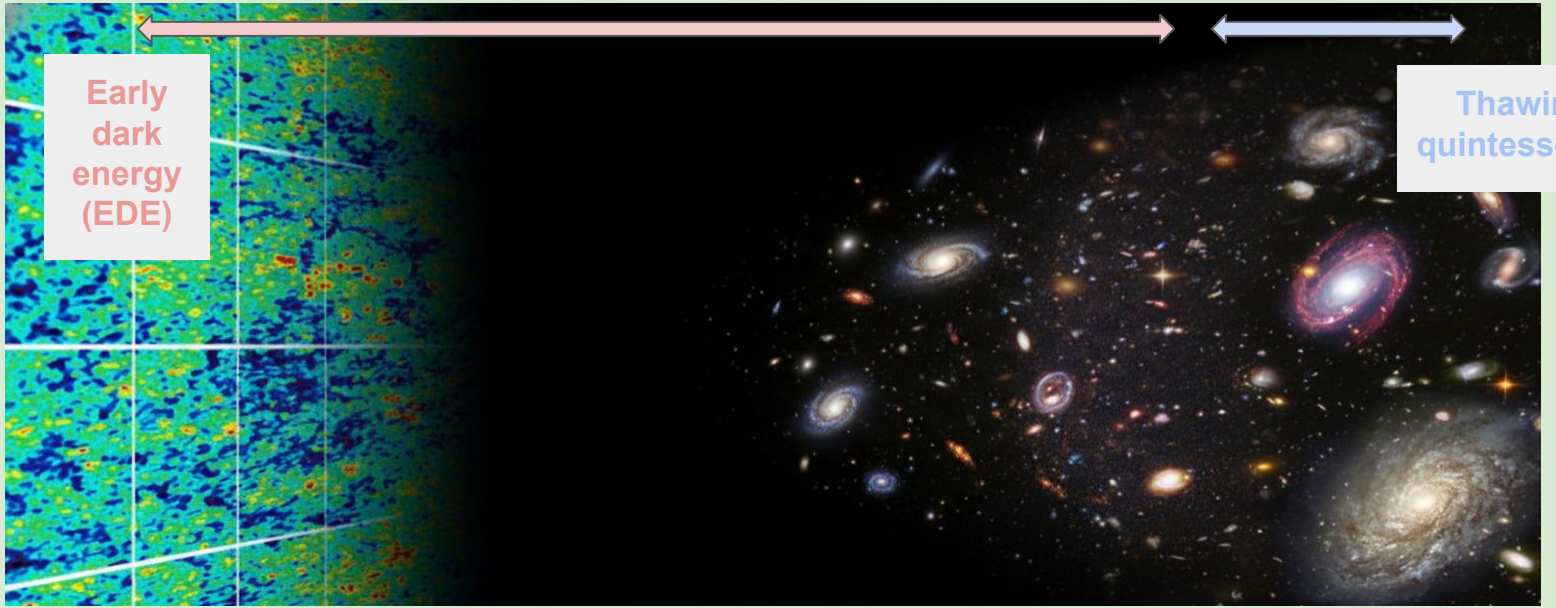
z ~ 1100

BAO

z ~ 1

SN

z ~ 0.1-1



What about SN?

1) Does adding SN data disfavor the EDE solution to the CMB+BAO(+H_0) tension?

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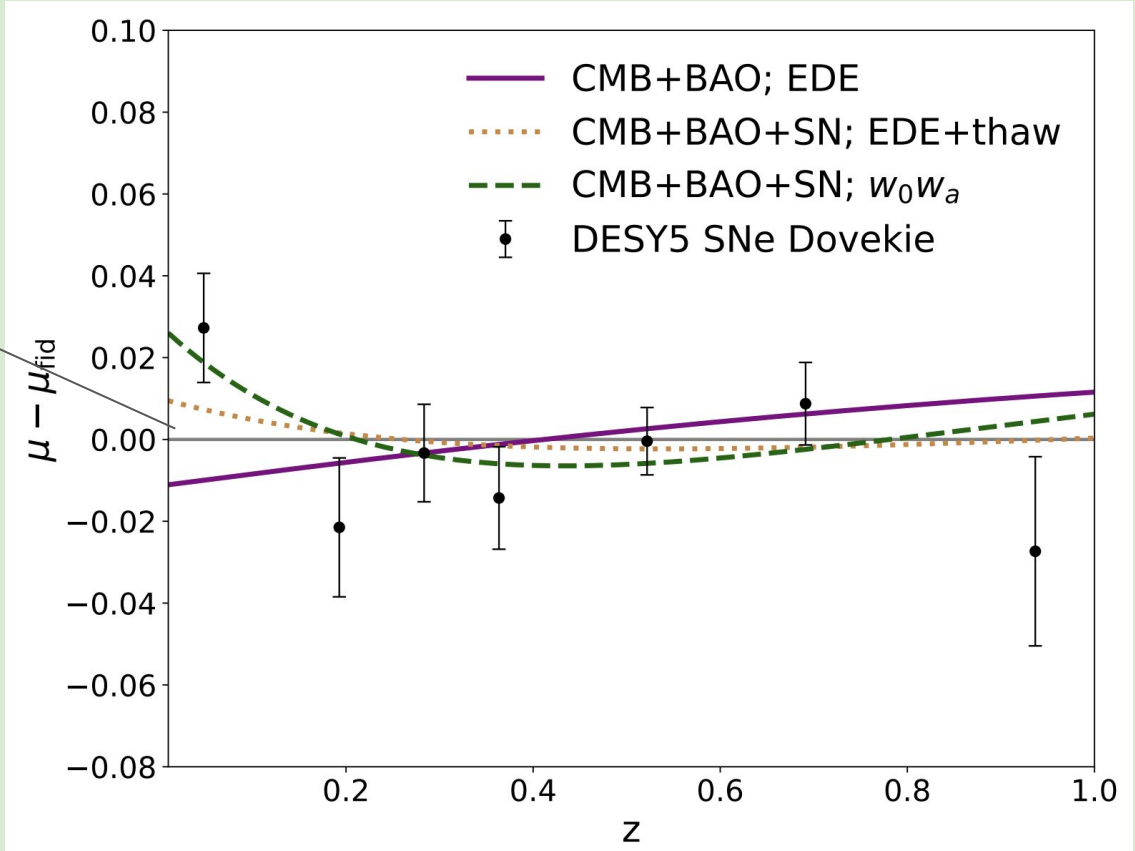
1) Does adding SN data disfavor the EDE solution to the CMB+BAO(+H_0) tension?

2) Can we treat the tension with SN separately with thawing quintessence? Can it still resolve H_0 tension?

CMB+BAO+SN tension

SN = DESY5 Dovekie

Fid. LCDM model



CMB+BAO+SN tension

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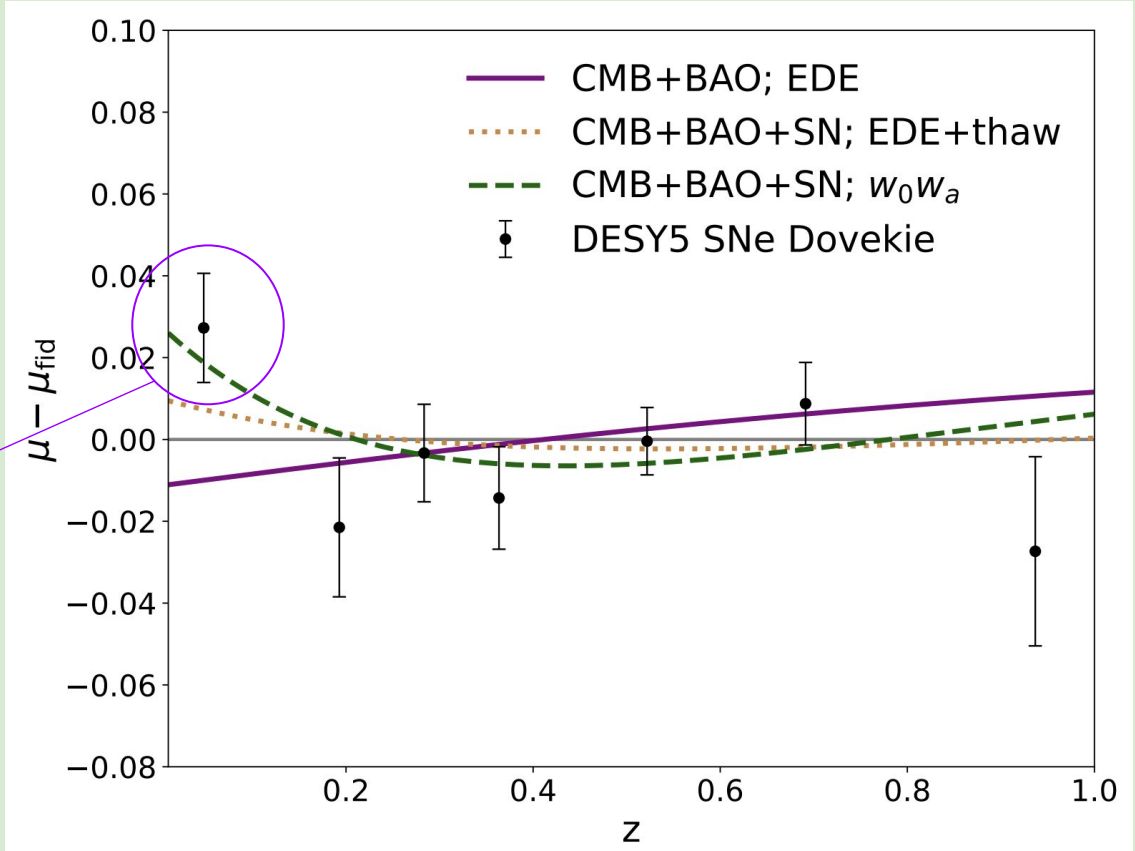
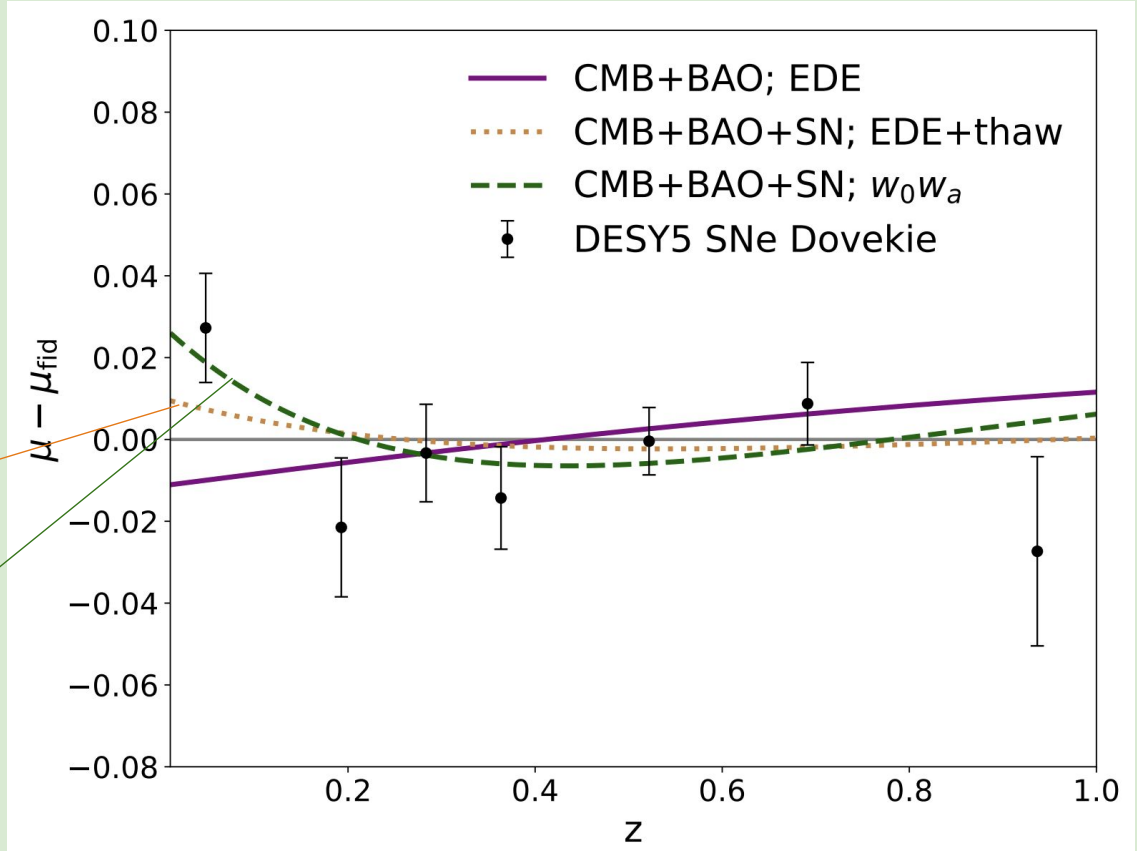


z ~ 0.1 bin not a good fit to CMB+BAO (EDE)

CMB+BAO+SN tension

SN = DESY5 Dovekie



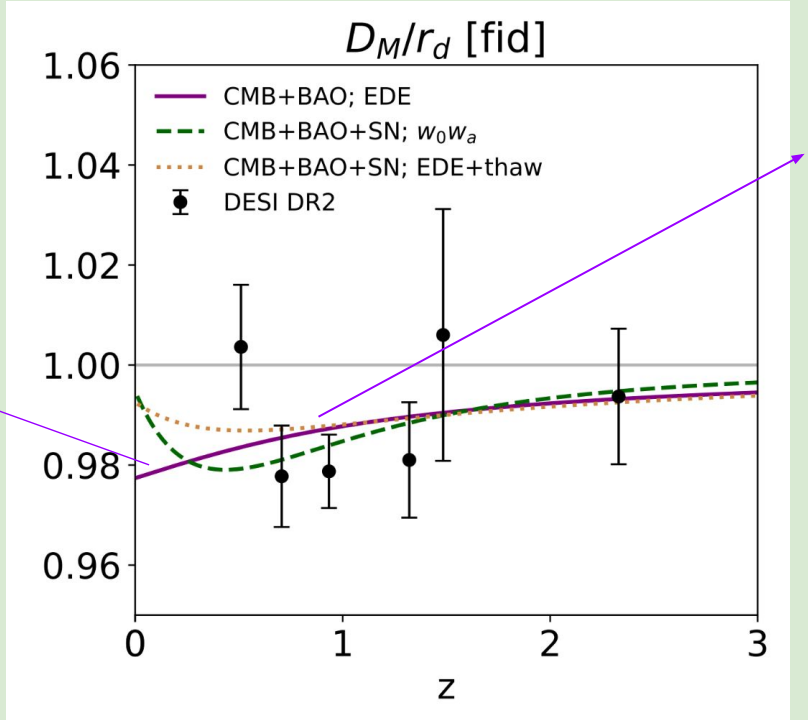
EDE+thaw matches SN data better

similar to w_0w_a

BAO data

CMB = Planck + ACT DR6 + SPT3G (incl. lensing)

BAO = DESI DR2



EDE lowers D_M/r_d

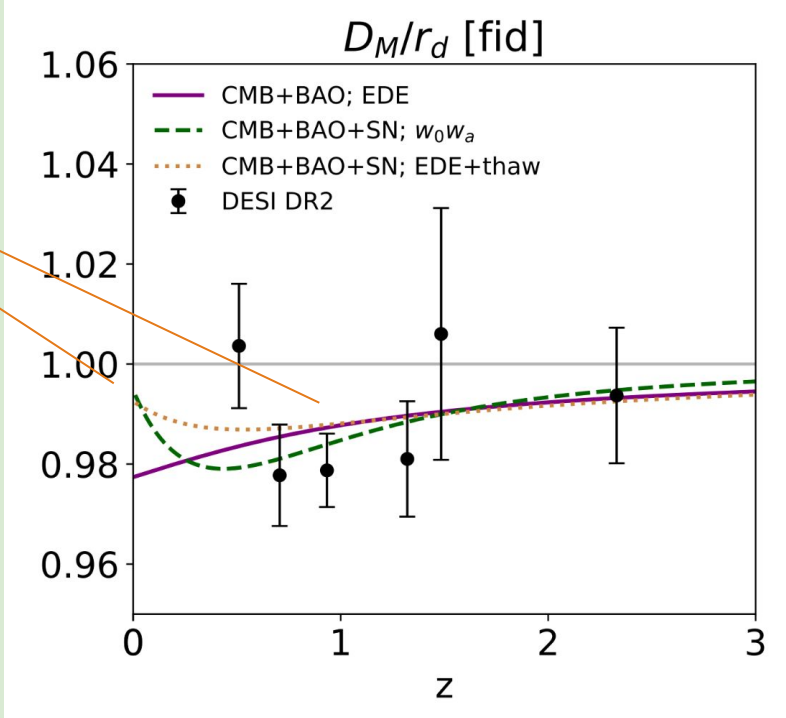
…but SN don't like this

BAO data

CMB = Planck + ACT DR6 + SPT3G (incl. lensing)

BAO = DESI DR2

EDE + thaw attempts both



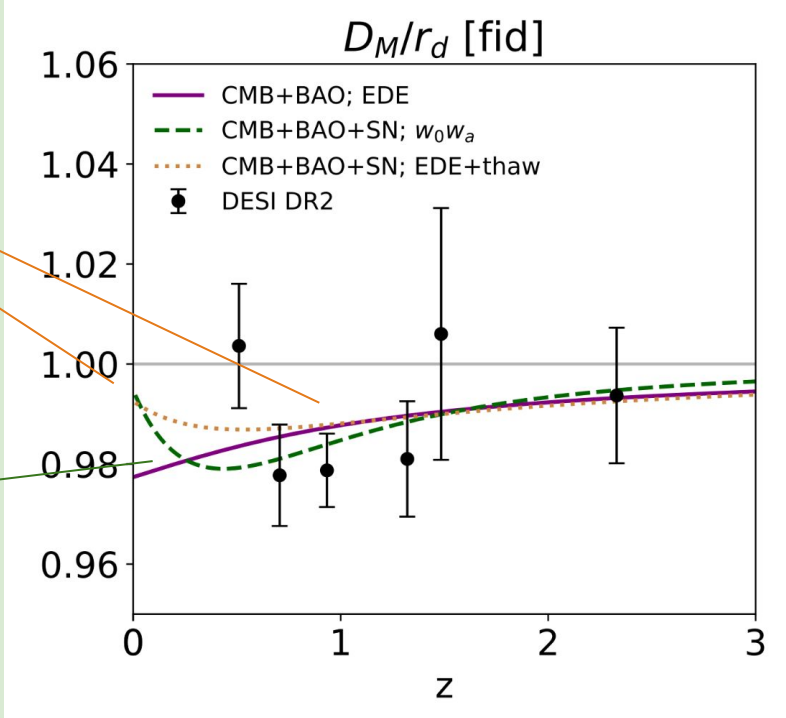
BAO data

CMB = Planck + ACT DR6 + SPT3G (incl. lensing)

BAO = DESI DR2

EDE + thaw attempts both

similar to w_0w_a, but without phantom



EDE preference remains for CMB+BAO+SN data

SN = DESY5 Dovekie

$$\chi^2_{\text{EDE}} - \chi^2_{\text{LCDM}} = -8.5$$

LCDM

$H_0 = 68.07$

EDE

$H_0 = 70.49$

But EDE alone cannot solve CMB+BAO+SN tension

SN = DESY5 Dovekie

$$\chi^2_{\text{EDE}} - \chi^2_{\text{LCDM}} = -8.5$$

$\Delta\chi^2_{\text{EDE-LCDM}}$ breakdown by experiment

Model	$\Delta\chi^2_{\text{CMB}}$	$\Delta\chi^2_{\text{BAO}}$	$\Delta\chi^2_{\text{SN}}$
EDE	-7.3	-1.9	0.78

EDE+thaw can reduce the CMB+BAO+SN tension

$$\chi^2_{\text{EDE}} - \chi^2_{\Lambda\text{CDM}} = -8.5$$

$\Delta\chi^2$ breakdown by experiment

Model	$\Delta\chi^2_{\text{CMB}}$	$\Delta\chi^2_{\text{BAO}}$	$\Delta\chi^2_{\text{SN}}$
EDE	-7.3	-1.9	0.78
EDE+thaw	-5.0	-3.7	-3.9

$$\chi^2_{\text{EDE+thaw}} - \chi^2_{\Lambda\text{CDM}} = -12.6$$

EDE+thaw performs comparably well to w_0w_a

EDE+thaw

$\chi^2_{\text{EDE+thaw}} - \chi^2_{\text{LCDM}} = -12.6$

$H_0 = 69.90$

w_0w_a

$\chi^2_{\text{w0wa}} - \chi^2_{\text{LCDM}} = -15.8$

$H_0 = 67.43$

$H_0 = 68.07$ (LCDM)

EDE+thaw performs comparably well to w_0w_a

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w_0w_a

$\chi^2_{\text{w0wa}} - \chi^2_{\text{LCDM}} = -15.8$

$H_0 = 67.43$

$H_0 = 68.07$ (LCDM)

Preference for phantom dark energy is significantly driven by lowest redshift SN bin

	CMB + BAO + SN	CMB + BAO + SN (z>0.1)
$\chi^2_{\text{w0wa}} - \chi^2_{\text{LCDM}}$	-15.8	-8.0

SN = DESY5 Dovekie

Without the lowest redshift SN bin, EDE preference returns to that of CMB+BAO

	CMB + BAO + SN	**CMB + BAO + SN (z>0.1)**
$\chi^2_{\text{w0wa}} - \chi^2_{\text{LCDM}}$	-15.8	-8.0
$\chi^2_{\text{EDE}} - \chi^2_{\text{LCDM}}$	-8.5	-9.4

Same preference as CMB+BAO

SN = DESY5 Dovekie

Without the lowest redshift SN bin, you don't need thawing quintessence

	CMB + BAO + SN	CMB + BAO + SN (z>0.1)
$\chi^2_{\text{w0wa}} - \chi^2_{\text{LCDM}}$	-15.8	-8.0
$\chi^2_{\text{EDE}} - \chi^2_{\text{LCDM}}$	-8.5	-9.4
$\chi^2_{\text{EDE+thaw}} - \chi^2_{\text{LCDM}}$	-12.6	-9.4

Same preference as CMB+BAO

SN = DESY5 Dovekie

Results

1. EDE can reduce CMB+BAO(+H_0) tension
2. EDE cannot restore consistency between CMB+BAO+SN
3. EDE+thaw offers a reasonable alternative to w_0w_a since it:
   a. performs comparably well
   b. does not require phantom crossing
   c. reduces H_0 tension

CMB+BAO (early-time) and BAO+SN (late-time) sides can be treated independently instead of jointly with phantom dark energy

arXiv: 2604.08530

More work on the CMB+BAO tension & τ

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More work on the CMB+BAO tension & τ

Backup

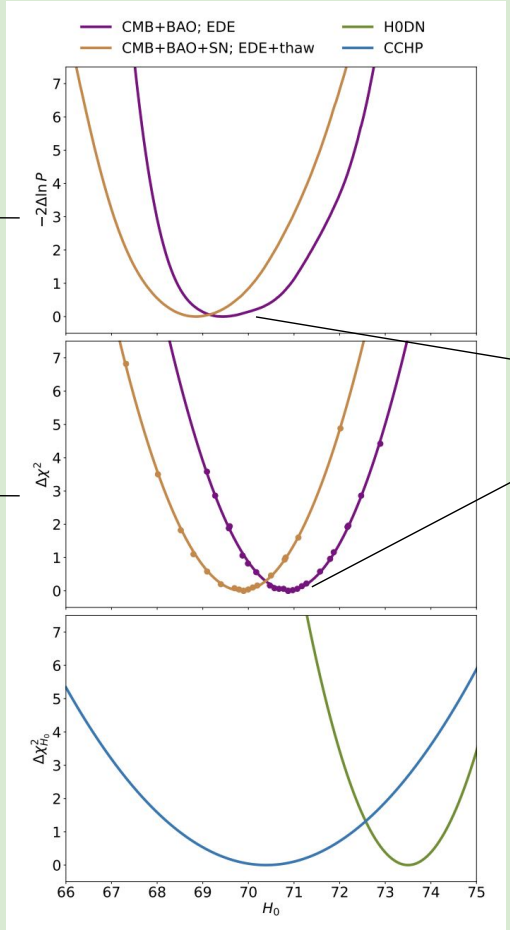
H0 tension resolution

H_0 tension

Posterior

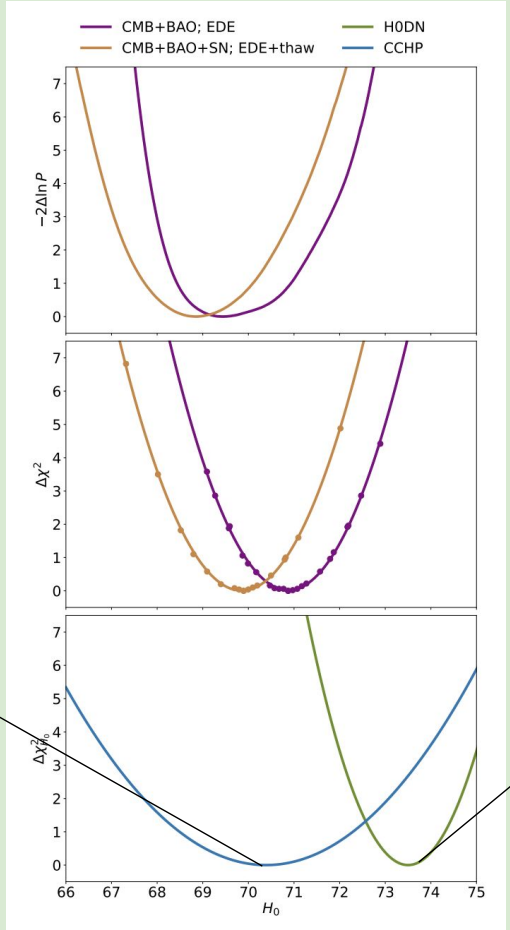
Profile

i.e., for each value of H_0, minimize chi2 over all other parameters



Posterior biased towards low H_0 (low f_{EDE}) → prior volume effect

H_0 tension



CCHP (1.6σ)

CMB+BAO (EDE): 0.2σ

CMB+BAO+SN (EDE+thaw): 0.2σ

H0DN (7.1σ)

CMB+BAO (EDE): 2.1σ

CMB+BAO+SN (EDE+thaw): 2.9σ

Chi2 tables

CMB+BAO: full table

CMB + BAO									
Model	$\Delta\chi^2$	$\Delta\chi^2_{\rm CMB}$	$\Delta\chi^2_{\rm BAO}$	r_d [Mpc]	$f_{\rm EDE}$	H_0	S_8	Ω_m	$D_M(0.8)/r_d$
Fid. ΛCDM	16.9	-5.9	22.8	147.00	0	67.15	0.84	0.318	19.59
ΛCDM	0	0	0	147.54	0	68.16	0.82	0.303	19.37
EDE	-9.4	-7.4	-1.9	142.51	0.09	70.87	0.83	0.300	19.32

CMB+BAO+SN: full table

CMB + BAO + SN											
Model	$\Delta\chi^2$	$\Delta\chi^2_{\rm CMB}$	$\Delta\chi^2_{\rm BAO}$	$\Delta\chi^2_{\rm SN}$	$f_{\rm EDE}$	H_0	S_8	w_0	w_a	$H_0 r_d$	$D_M(0.8)/r_d$
Fid. ΛCDM	14.3	-5.1	21.7	-2.3	0	67.15	0.84	-1	0	9871	19.59
ΛCDM	0	0	0	0	0	68.07	0.82	-1	0	10042	19.39
EDE	-8.5	-7.3	-1.9	0.78	0.08	70.49	0.83	-1	0	10077	19.35
thaw	-2.5	1.8	-0.6	-3.6	-	67.27	0.82	-0.94	-0.09	9927	19.40
EDE+thaw	-12.6	-5.0	-3.7	-3.9	0.10	69.90	0.84	-0.93	-0.11	9945	19.34
$w_0 w_a$	-15.8	-6.5	-4.4	-4.8	0	67.43	0.83	-0.80	-0.76	9923	19.24

Alternate SN datasets

CMB + BAO + SN ($z > 0.1$)											
Model	$\Delta\chi^2$	$\Delta\chi^2_{\rm CMB}$	$\Delta\chi^2_{\rm BAO}$	$\Delta\chi^2_{\rm SN}$	$f_{\rm EDE}$	H_0	S_8	w_0	w_a	$H_0 r_d$	$D_M(0.8)/r_d$
Fid. ΛCDM	17.2	-6.1	22.9	0.4	0	67.15	0.84	-1	0	9871	19.59
ΛCDM	0	0	0	0	0	68.17	0.82	-1	0	10058	19.37
EDE	-9.4	-7.5	-2.0	0.07	0.09	70.89	0.83	-1	0	10101	19.32
EDE+thaw	-9.4	-7.8	-1.6	0.06	0.09	71.01	0.83	-1.01	0.002	10117	19.32
$w_0 w_a$	-8.0	-7.2	-2.9	2.1	0	67.83	0.83	-0.85	-0.62	9986	19.25

CMB + BAO + SN (DESY5)											
Model	$\Delta\chi^2$	$\Delta\chi^2_{\rm CMB}$	$\Delta\chi^2_{\rm BAO}$	$\Delta\chi^2_{\rm SN}$	$f_{\rm EDE}$	H_0	S_8	w_0	w_a	$H_0 r_d$	$D_M(0.8)/r_d$
Fid. ΛCDM	12.7	-4.2	20.7	-3.8	0	67.15	0.84	-1	0	9871	19.59
ΛCDM	0	0	0	0	0	68.01	0.82	-1	0	10028	19.40
EDE	-8.0	-7.0	-2.1	1.1	0.08	70.35	0.83	-1	0	10062	19.37
EDE+thaw	-17.3	-3.3	-4.6	-9.4	0.10	69.32	0.84	-0.89	-0.17	9854	19.36
$w_0 w_a$	-22.7	-5.7	-6.5	-10.5	0	66.82	0.84	-0.75	-0.88	9834	19.25

CMB + BAO + SN (Pantheon+)											
Model	$\Delta\chi^2$	$\Delta\chi^2_{\rm CMB}$	$\Delta\chi^2_{\rm BAO}$	$\Delta\chi^2_{\rm SN}$	$f_{\rm EDE}$	H_0	S_8	w_0	w_a	$H_0 r_d$	$D_M(0.8)/r_d$
Fid. ΛCDM	14.8	-5.3	22.0	-1.9	0	67.15	0.84	-1	0	9871	19.59
ΛCDM	0	0	0	0	0	68.09	0.82	-1	0	10045	19.38
EDE	-8.7	-7.4	-2.0	0.7	0.08	70.50	0.83	-1	0	10082	19.34
EDE+thaw	-11.7	-5.5	-3.2	-3.0	0.09	69.93	0.84	-0.94	-0.095	9952	19.35
$w_0 w_a$	-13.1	-6.3	-4.2	-2.5	0	67.56	0.83	-0.83	-0.66	9945	19.26

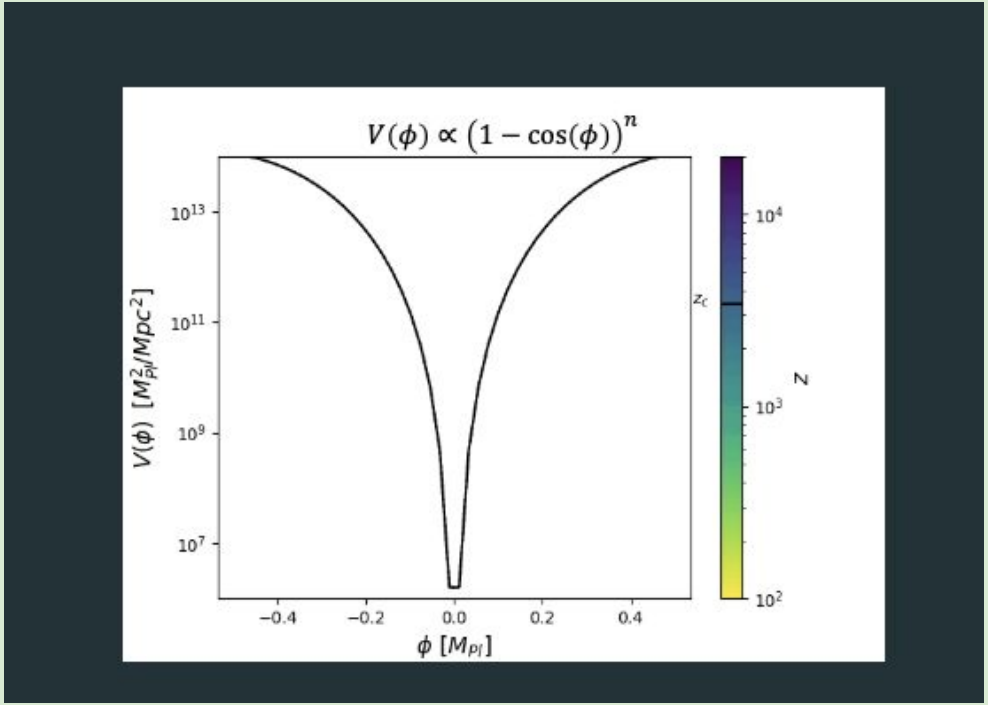
CMB+BAO+SN (z>0.1)

Model	$\Delta\chi^2_{CMB}$	$\Delta\chi^2_{BAO}$	$\Delta\chi^2_{SN}$
EDE	-7.5	-2.0	0.07
EDE+thaw	-7.8	-1.6	0.06
w_0w_a	-7.2	-2.9	2.1

EDE+thaw: bestfit $w_0 = -1$, $w_a = 0$ → consistent with cosmological constant

EDE model

Ultralight axion inspired EDE (n = 3)



Ultralight axion inspired EDE (n = 3)

$\phi_i = \theta_i f_\phi$

m_ϕ = mass of the axion

f_ϕ = decay constant of the axion

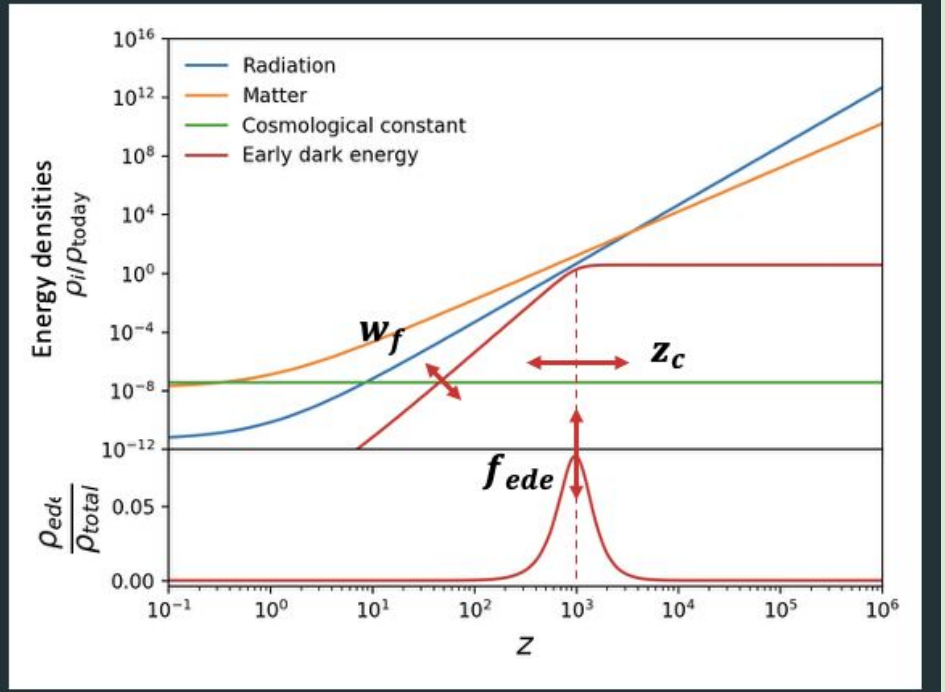
$$V(\phi) = m_\phi^2 f_\phi^2 [1 - \cos(\phi / f_\phi)]^3$$

Ultralight axion inspired EDE

Additional energy component that increases the pre-CMB expansion rate

- Λ-like behaviour initially
- Then dilutes faster than matter at w_f
- Localised peak in $f_{ede} = \frac{\rho_{ede}}{\rho_{total}}$ at z_c

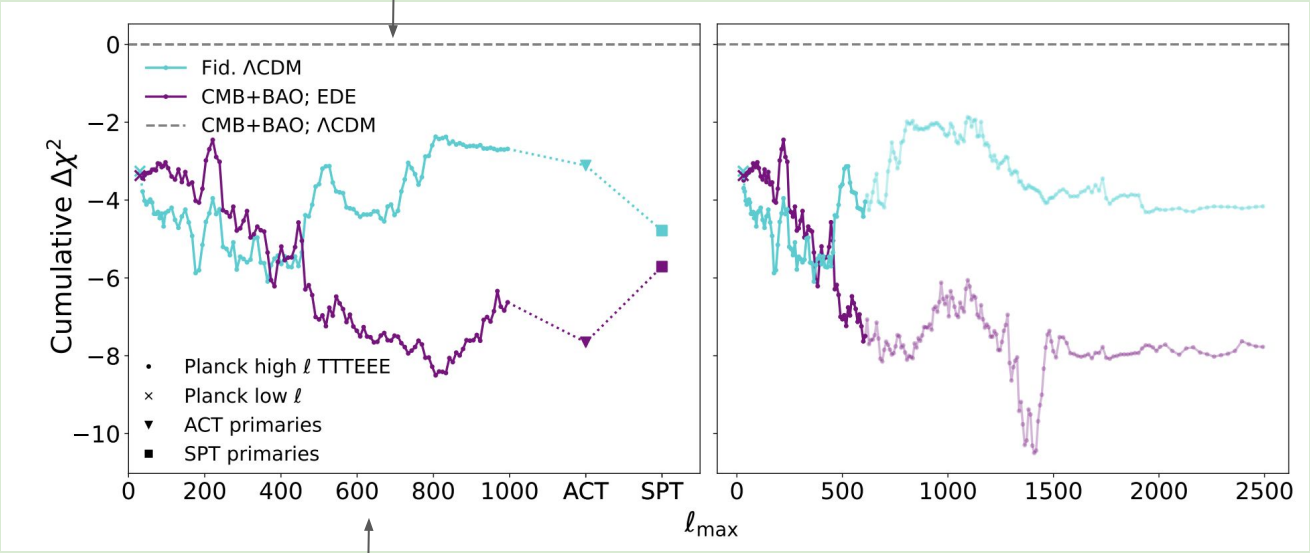
f_{ede} - how much EDE
z_c - when EDE appears
w_f - how fast is disappears



EDE fitting the CMB

Breaking down χ^2 contribution with l for different experiments and models

Improvement relative to CMB + BAO (LCDM)

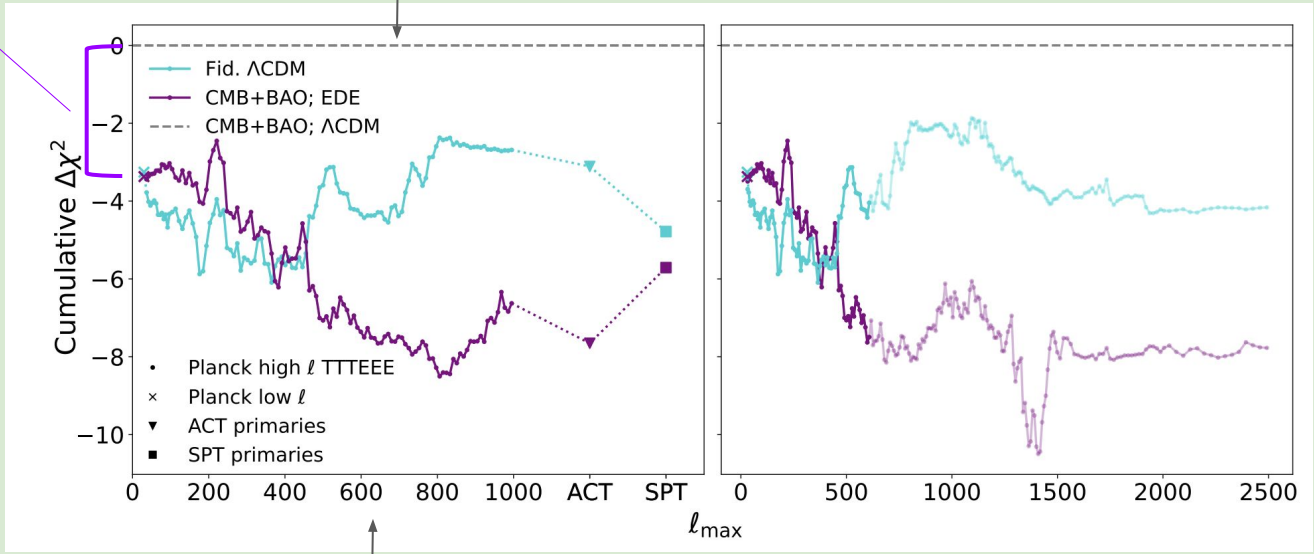


depending on the multipole range included for the data

Breaking down $\Delta\chi^2$ contribution with l for different experiments and models

Improvement relative to CMB + BAO (LCDM)

Planck low l TT and EE



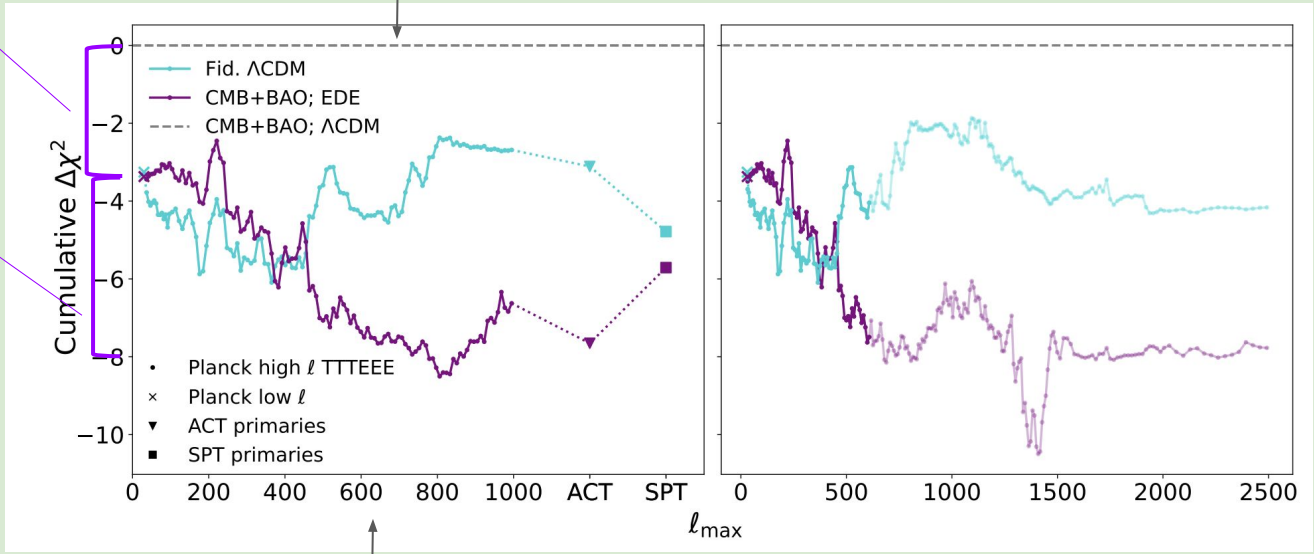
depending on the multipole range included for the data

Breaking down χ^2 contribution with l for different experiments and models

Improvement relative to CMB + BAO (LCDM)

Planck low l TT and EE

Planck high l TTTEEE



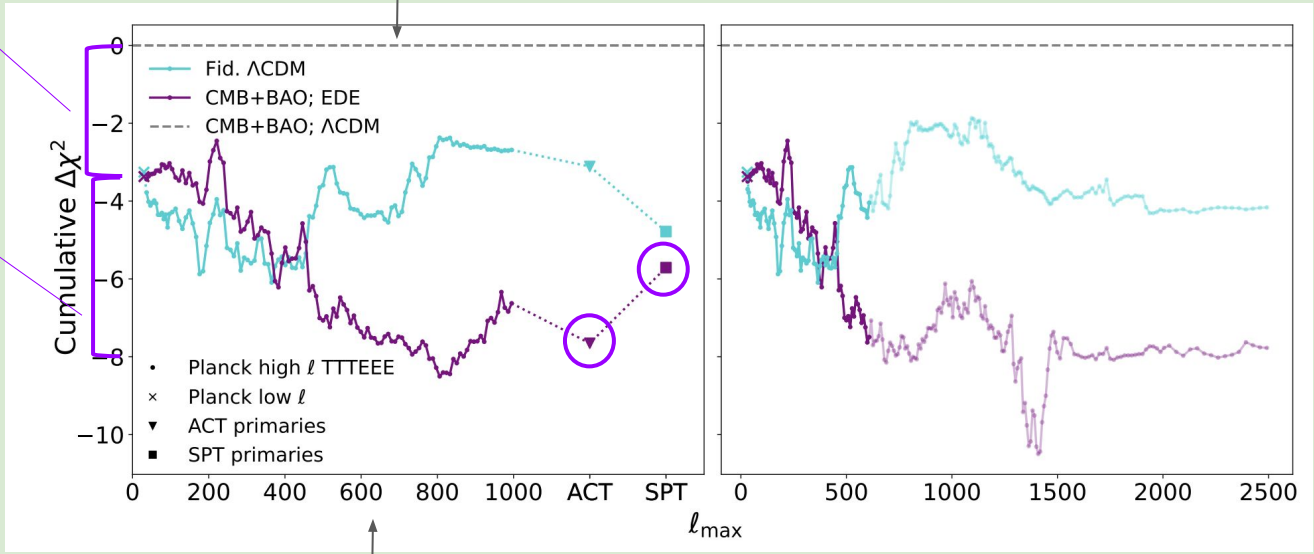
depending on the multipole range included for the data

Breaking down χ^2 contribution with l for different experiments and models

Improvement relative to CMB + BAO (LCDM)

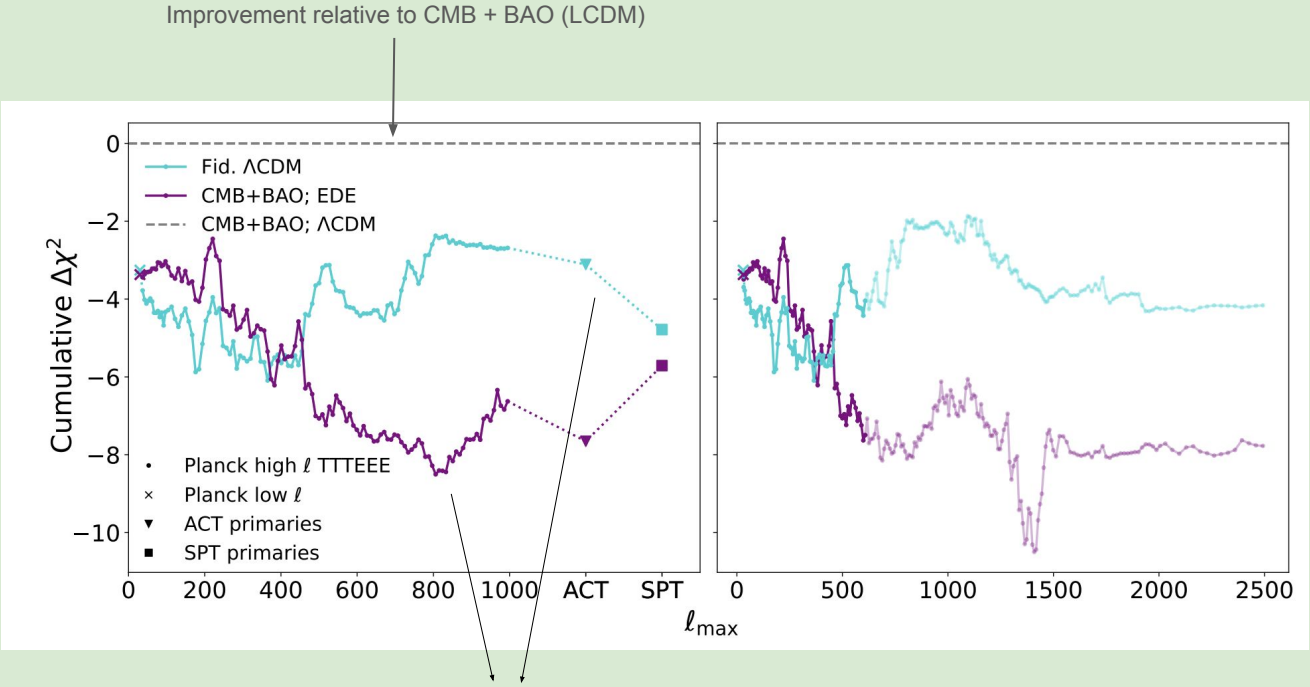
Planck low l TT and EE

Planck high l TTTEEE



depending on the multipole range included for the data

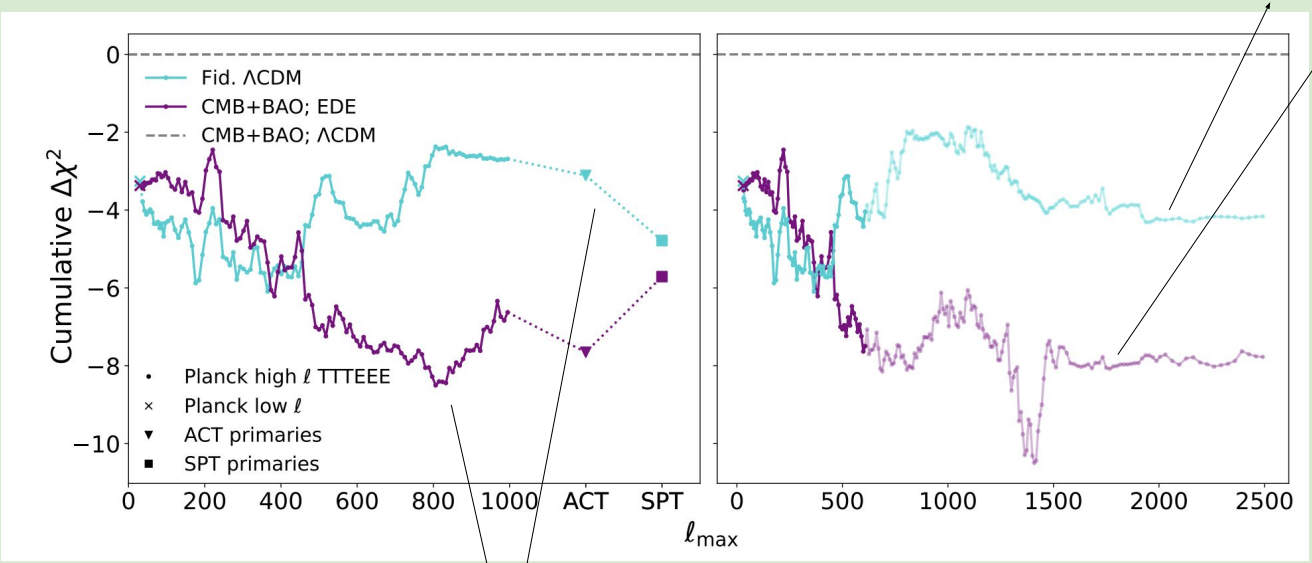
Breaking down $\Delta\chi^2$ contribution with l for different experiments and models



CMB+BAO (EDE) fits CMB primary data better than even Fid. LCDM (which is *optimized to* CMB primaries + lensing)

Breaking down $\Delta\chi^2$ contribution with l for different experiments and models

Planck high l TTTEEE *above range included in analysis* prefer EDE over Fid. LCDM



CMB+BAO (EDE) fits CMB primary data better than even Fid. LCDM (which is *optimized to* CMB primaries + lensing)

Phantom DE

Aside: Why is it tricky to find a physically-motivated model?

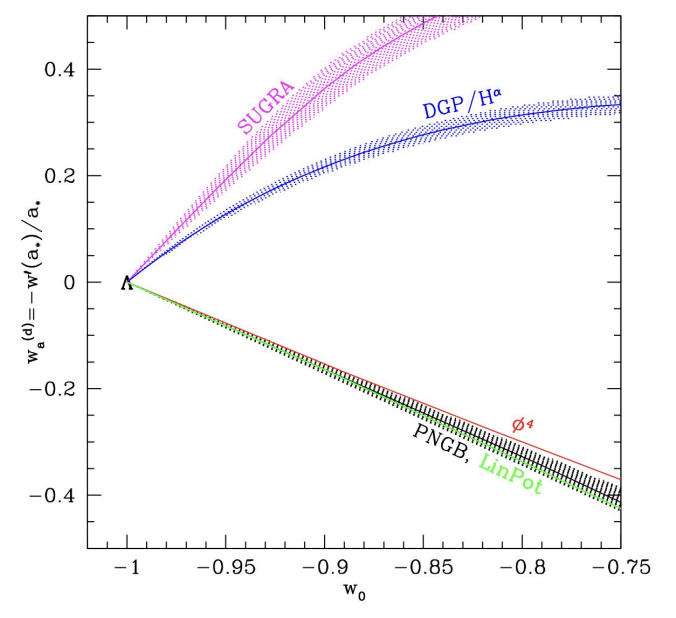
- For a canonical scalar field in GR, w ≥ -1

$$w = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)} \geq -1 \longrightarrow \dot{\phi}^2 > 0$$

1. *Modify gravity*
   - (Non-minimally) couple scalar field to gravity to allow phantom crossing
2. *Dark sector interactions*
   - If DE and DM interact but we assume they don't, it can appear that w_{DE} crosses below -1

Calibrated thawing quintessence

- Thawing quintessence DE models have no phantom physics
- Their observational impact can be mimicked by

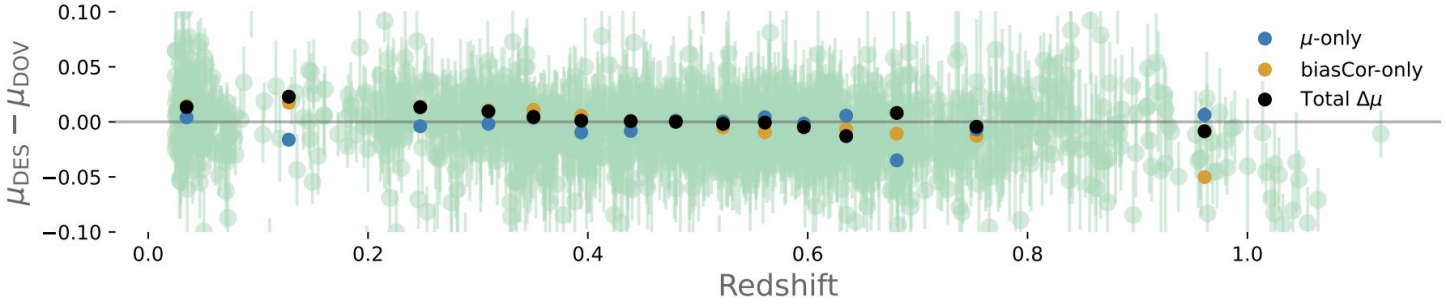


$w_a = -1.58(1+w_0)$

one free parameter

[arXiv: 0808.0189]

Dovekie



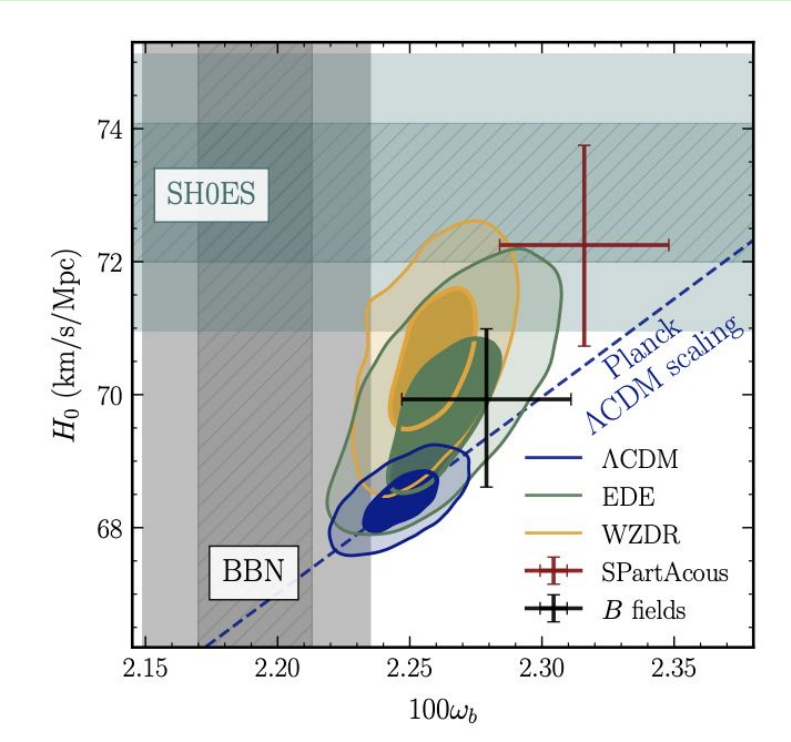
(b) The difference between the DES-SN5YR published distances and DES-Dovekie distances. The error-weighted average $\Delta\mu$ in black includes shift in μ *and* the change in bias-correction. We show the un-bias-corrected μ averages in blue, and the bias-correction component alone in orange.

Figure 3. The DES-Dovekie Hubble Diagram, and the change in inferred, bias-corrected μ values between DES-SN5YR and this work.

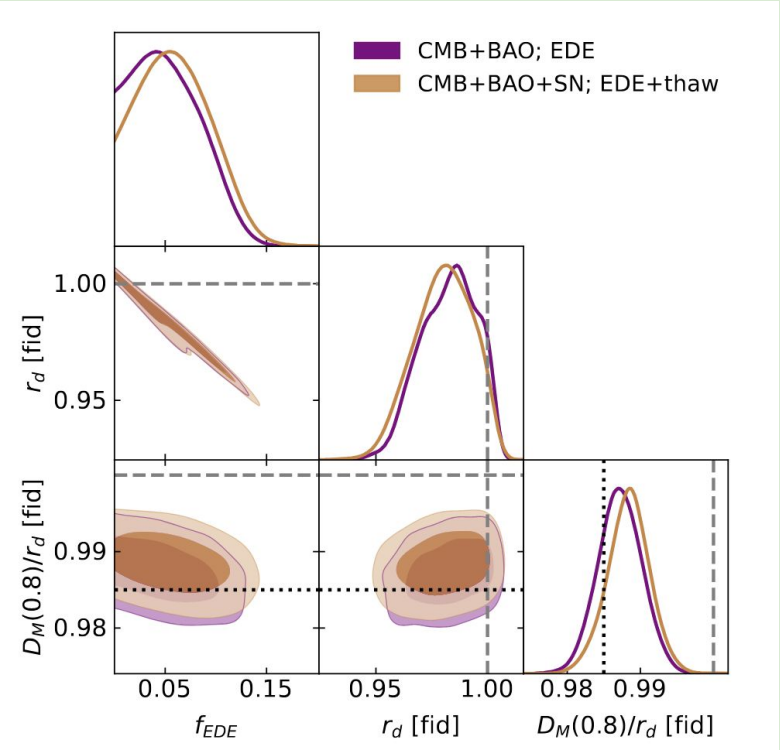
Misc

BBN

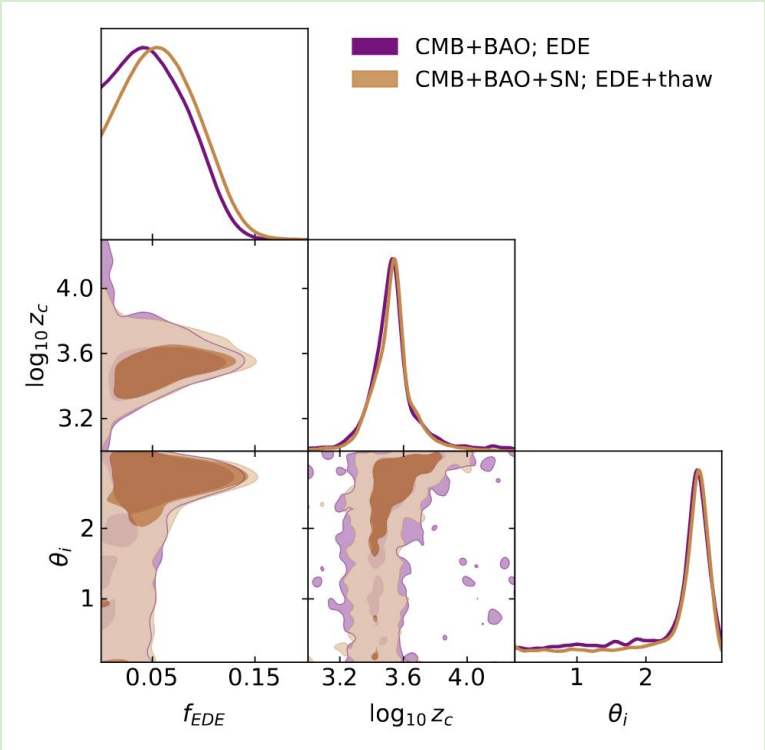
https://arxiv.org/pdf/2604.05095v1



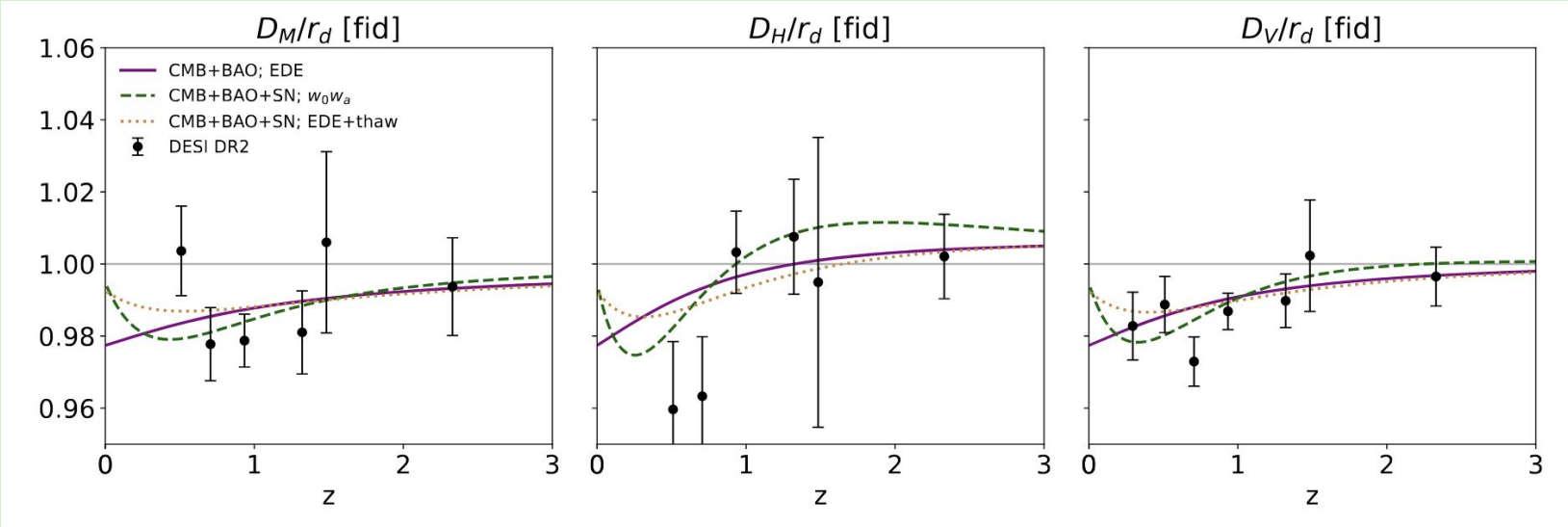
DM/rd, rd, fEDE


CMB+BAO; EDE
CMB+BAO+SN; EDE+thaw
1.00
0.95
r_d [fid]
0.99
0.98
$D_M(0.8)/r_d$ [fid]
0.05
0.15
f_{EDE}
0.95
1.00
r_d [fid]
0.98
0.99
$D_M(0.8)/r_d$ [fid]

EDE model posteriors



All BAO data


D_M/r_d [fid]
D_H/r_d [fid]
D_V/r_d [fid]
CMB+BAO; EDE
CMB+BAO+SN; w_0w_a
CMB+BAO+SN; EDE+thaw
DESI DR2
1.06
1.04
1.02
1.00
0.98
0.96
0
1
2
3
z

Tau/CMB+BAO tension

CMB+BAO separate from CMB+SN