Theoretical approaches to cosmic tensions

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KICP

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Based on work with: Kim Berghaus, Vivian Poulin, Tristan L. Smith, Marco Raveri, Lucas Secco, Omar Ramadan, Yashvi Patel, Thejs Brinckmann, Marc Kamionkowski, Bhuv Jain, Justin Khoury, Mark Trodden, Daniel Grin, Wayne Hu, Elisabeth Krause, Jeremy Sakstien, Vivian Miranda

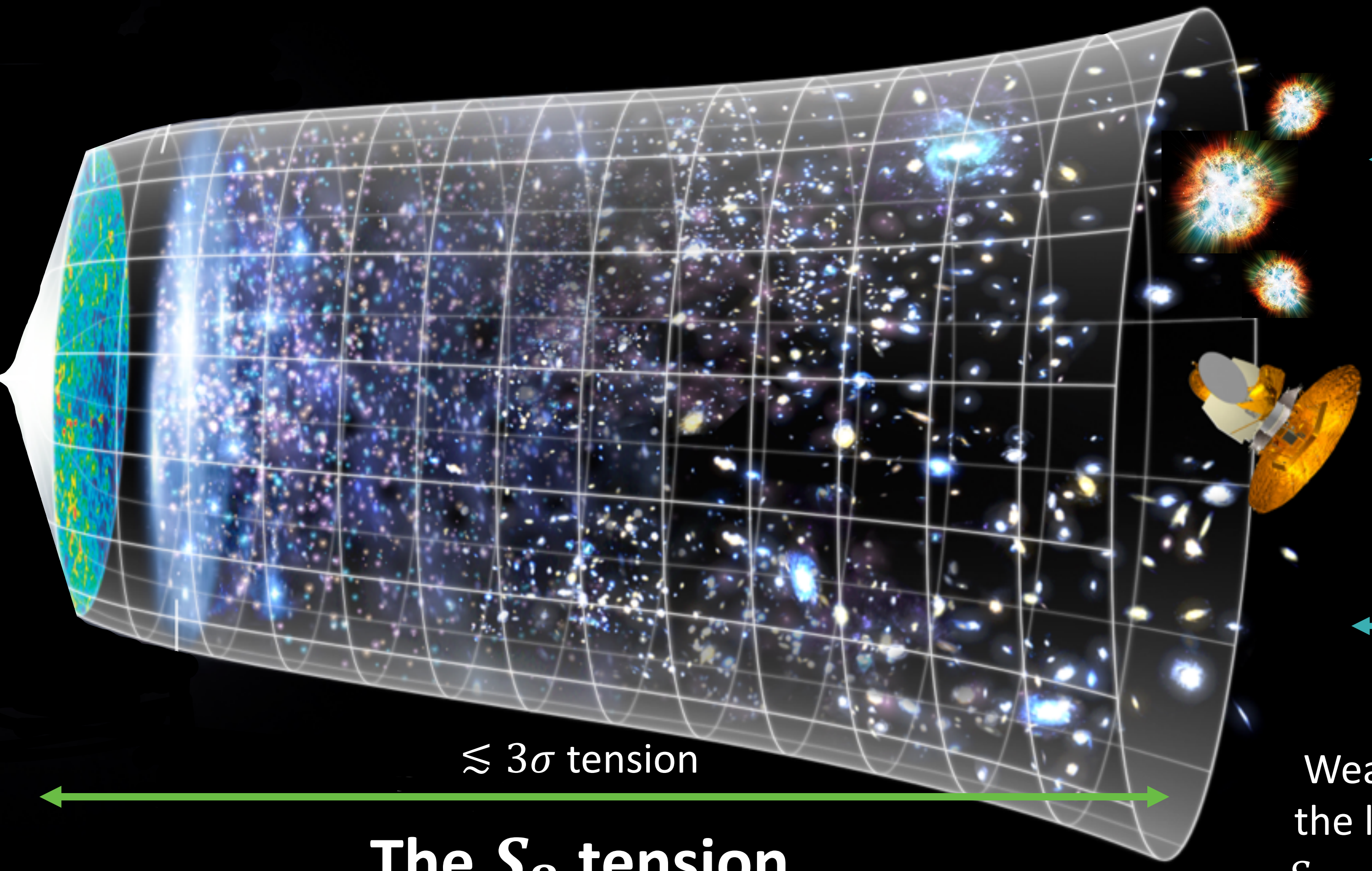
Fit ΛCDM to the CMB
$H_0 = 67.4 \pm 0.5$
km/s/Mpc

5.7σ tension

The Hubble tension

Cepheid distance ladder
$H_0 = 73.29 \pm 0.90$
km/s/Mpc

Cosmic microwave background
+
Cosmological assumptions



Late universe +
astro/cosmo assumptions

Fit ΛCDM to the CMB
$S_8 = 0.832 \pm 0.013$

$\lesssim 3\sigma$ tension

The S_8 tension

Weak lensing in the late universe
$S_8 = 0.759^{+0.024}_{-0.021}$

NASA/WMAP Science Team

Cosmic tensions, solutions and extensions

- Guidelines for a theoretical solution to H_0
- The Early Dark Energy solution(s)
- Challenges to EDE solutions
- Going beyond EDE

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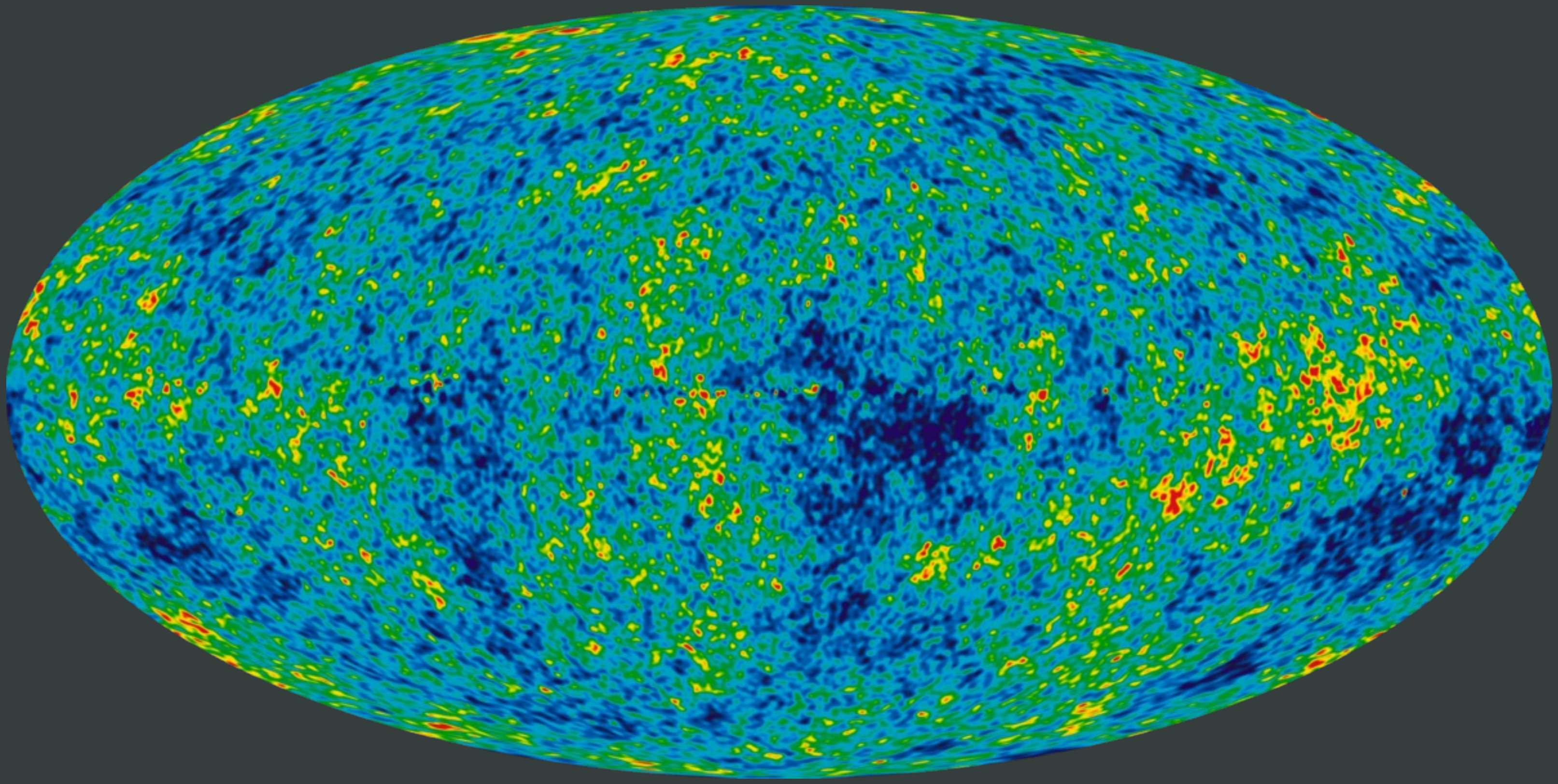
Theoretical guidelines

H_0 from the CMB

Density imprint produced by sound waves in the early universe



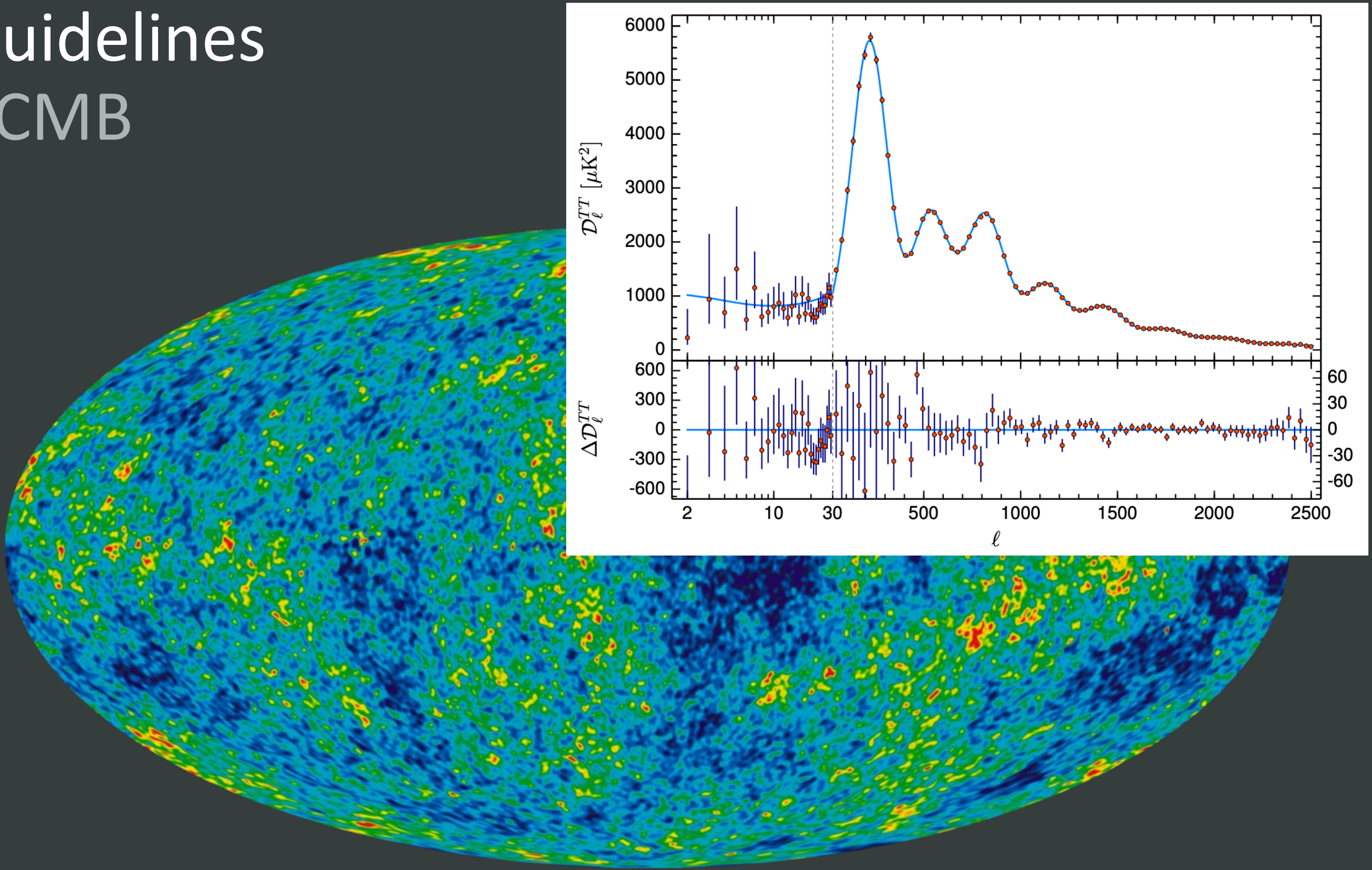
Source: WMAP

Theoretical guidelines
H_0 from the CMB

Density imprint produced by sound waves in the early universe

Maximum variation at $\theta_* \sim 1°$ scales

Farthest distance that sound waves travelled $\sim r_s$
The sound horizon

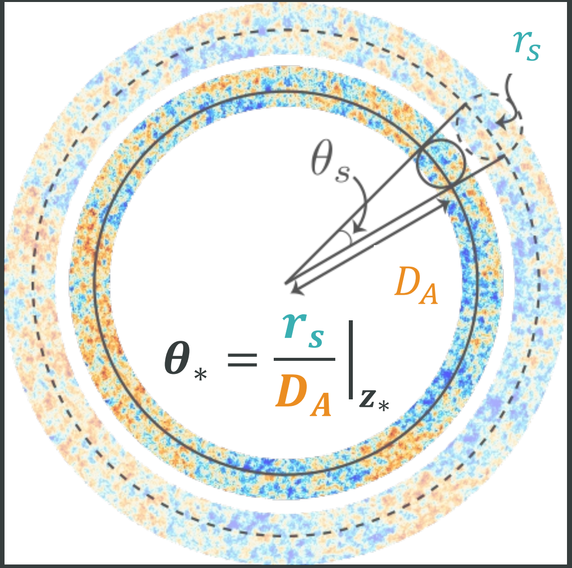


Planck 2018

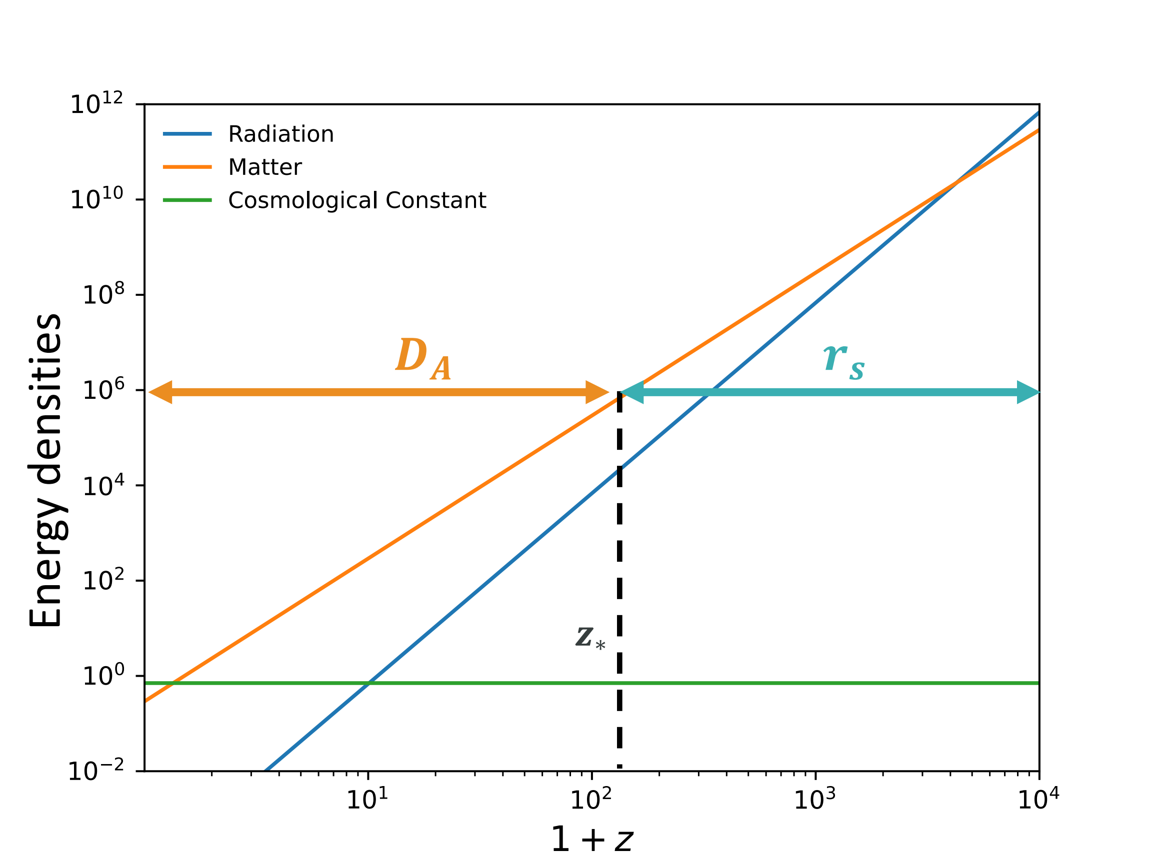
Source: WMAP

Theoretical guidelines
A model–dependent H_0

Precisely measured θ_* is an approximate proxy for CMB peak locations



Cartoon by Tristan L. Smith



$D_A \propto 1/H_{post}$

$r_s \propto 1/H_{pre}$

Both are fixed by ΛCDM

For precisely measured θ_*

$$\theta_* \sim \frac{r_s}{1/H_{post}} \sim r_s H_0$$

$$r_S \propto 1/H_0$$

In support of an early universe modification:
Karwal et al [1608.01309]
Planck [1807.06209]
Bernal et al [1607.05617]
Evslin et al [1711.01051]
Aylor et al [1811.00537]
Raveri et al [2002.11707]
…

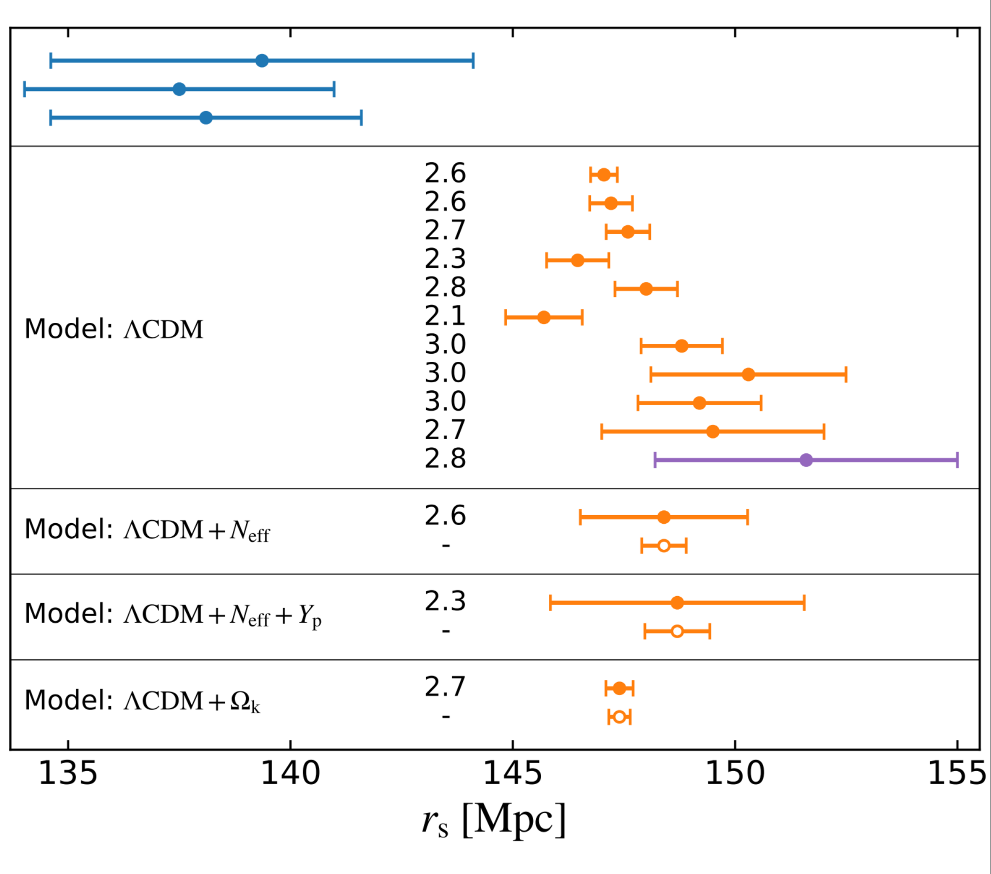
Theoretical guidelines

Hubble Tension ⟷ Sound Horizon Tension

Distance ladder and other late universe

CMB, early universe

No CMB data, early universe



Higher H_0 measured

Lower H_0 inferred

Lower H_0 inferred

Aylor et al [1811.00537]

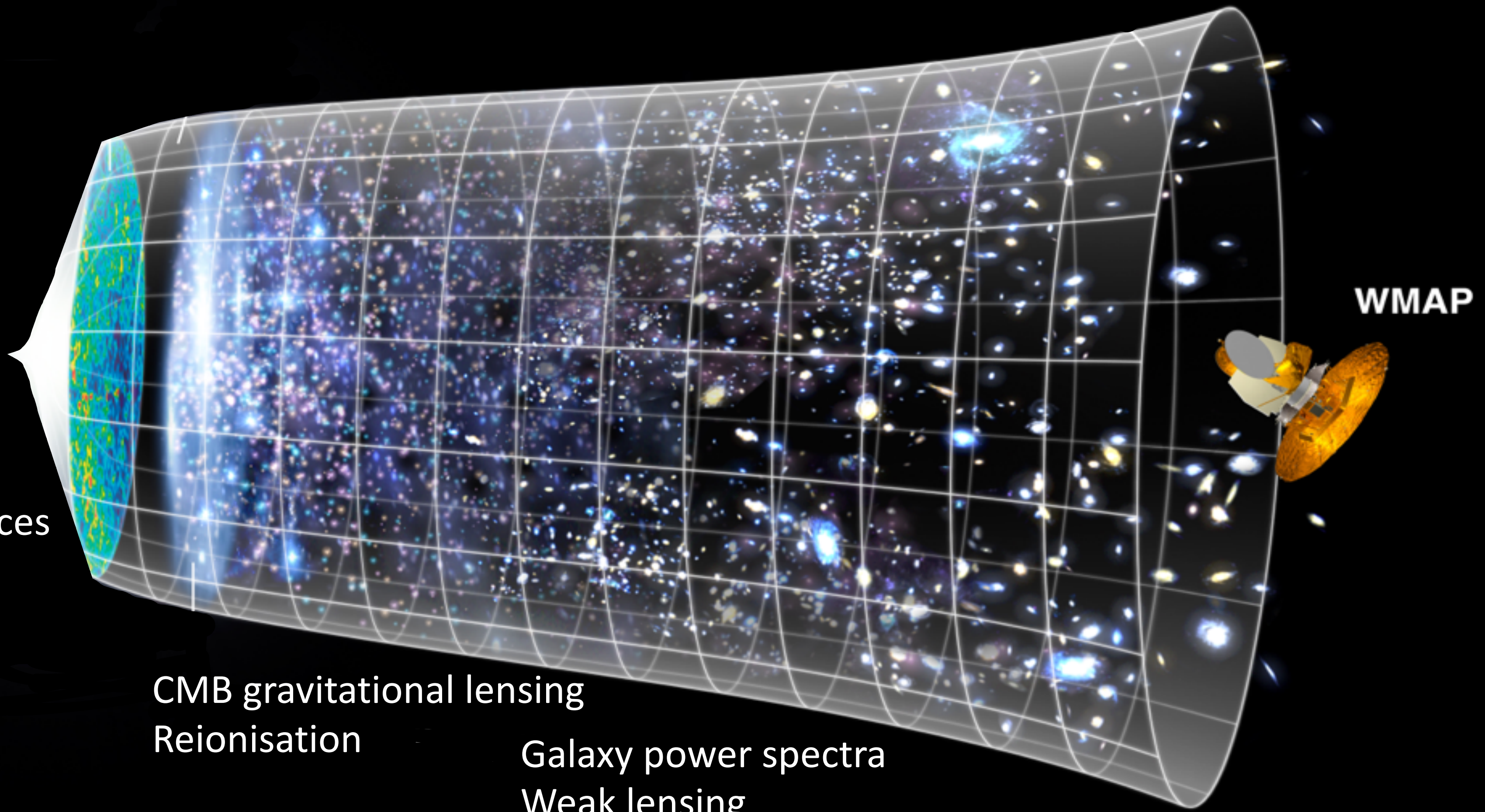
Theoretical guidelines

- Maintaining a good fit to the CMB requires $r_S \propto 1/H_0$.
  Decrease the sound horizon r_s to increase the predicted H_0.
  Because $r_s \propto 1/H_{pre}(z)$, new physics must be added before the CMB

- New physics must vanish post recombination ← Models that don't work or create new tensions

Theoretical guidelines

Leave late universe unchanged



CMB spectra
Light element abundances

CMB gravitational lensing
Reionisation

Galaxy power spectra
Weak lensing
Redshift space distortions
Supernovae

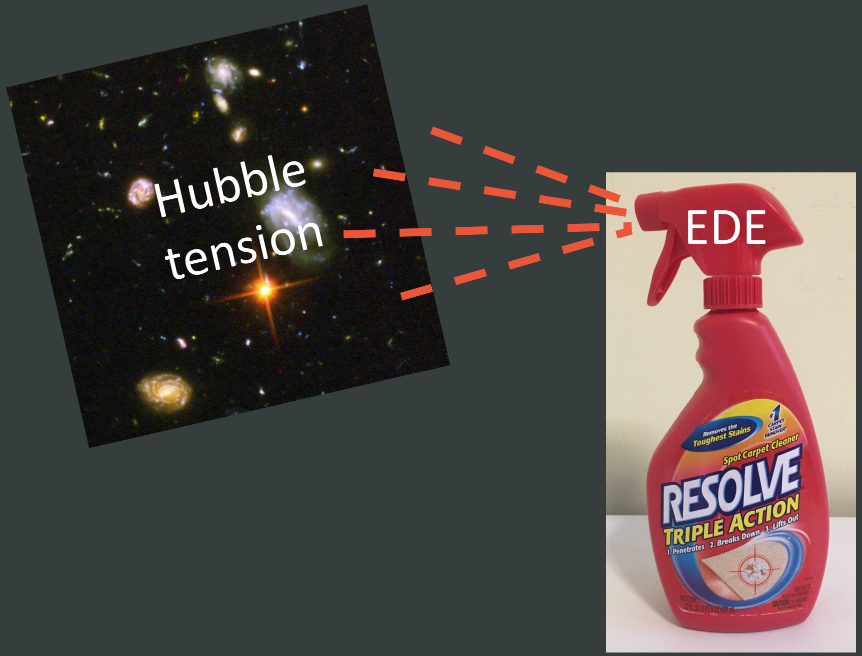
Distance ladder

Theoretical guidelines

- Maintaining a good fit to the CMB requires $r_S \propto 1/H_0$.
  Decrease the sound horizon r_s to increase the predicted H_0.
  Because $r_s \propto 1/H_{pre}(z)$, new physics must be added before the CMB
- New physics must vanish post recombination
  - Modifications to D_A introduce new tensions between CMB and BAO
  - Late-universe modifications to $w(z)$ are tightly constrained by supernovae
  - Very-late $H(z)$ modifications do not resolve the tension at $z \simeq 0.15$

Cosmic tensions, solutions and extensions

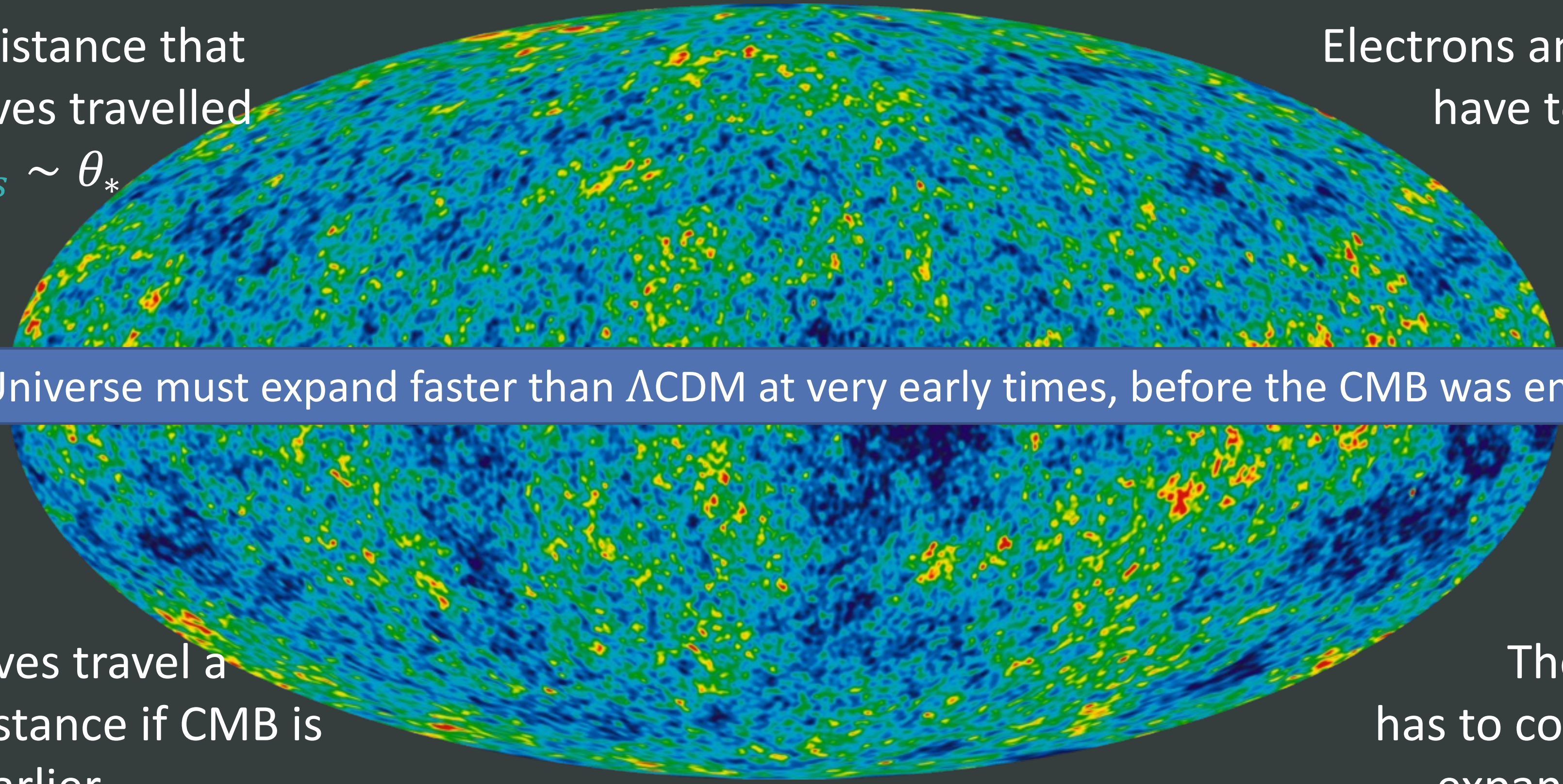
- Guidelines for a theoretical solution to H_0
- The Early Dark Energy solution(s)
- Challenges to EDE solutions
- Going beyond EDE



Early dark energy
Effect on cosmic microwave background

Farthest distance that sound waves travelled $\sim r_s \sim \theta_*$

Electrons and protons have to combine sooner



The Universe must expand faster than ΛCDM at very early times, before the CMB was emitted

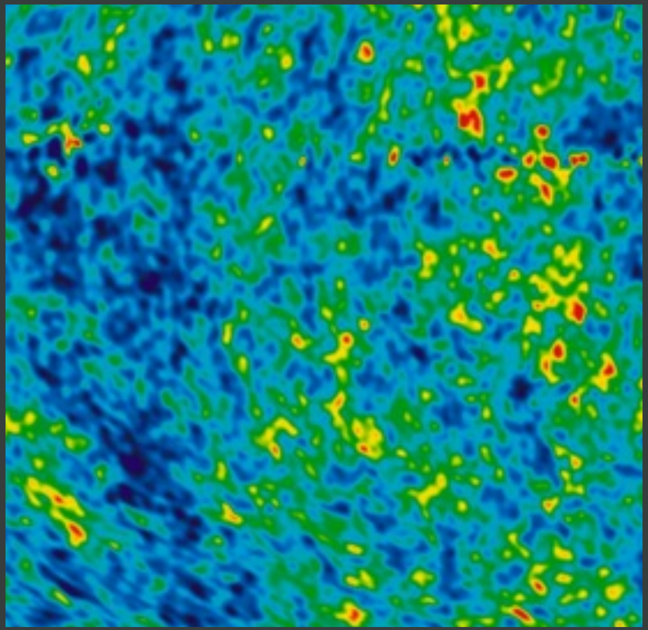
Sound waves travel a shorter distance if CMB is emitted earlier

The Universe has to cool through expansion faster

WMAP, NASA

Early dark energy

Effect on cosmic microwave background



Observed CMB

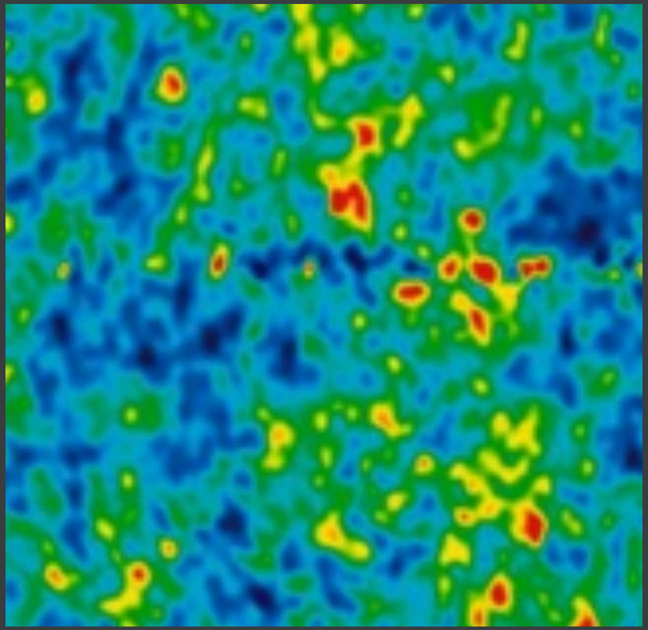
Increase

H_0

Add early dark energy

Decrease

r_s



Disagreement with observed CMB

Early dark energy
Phenomenology

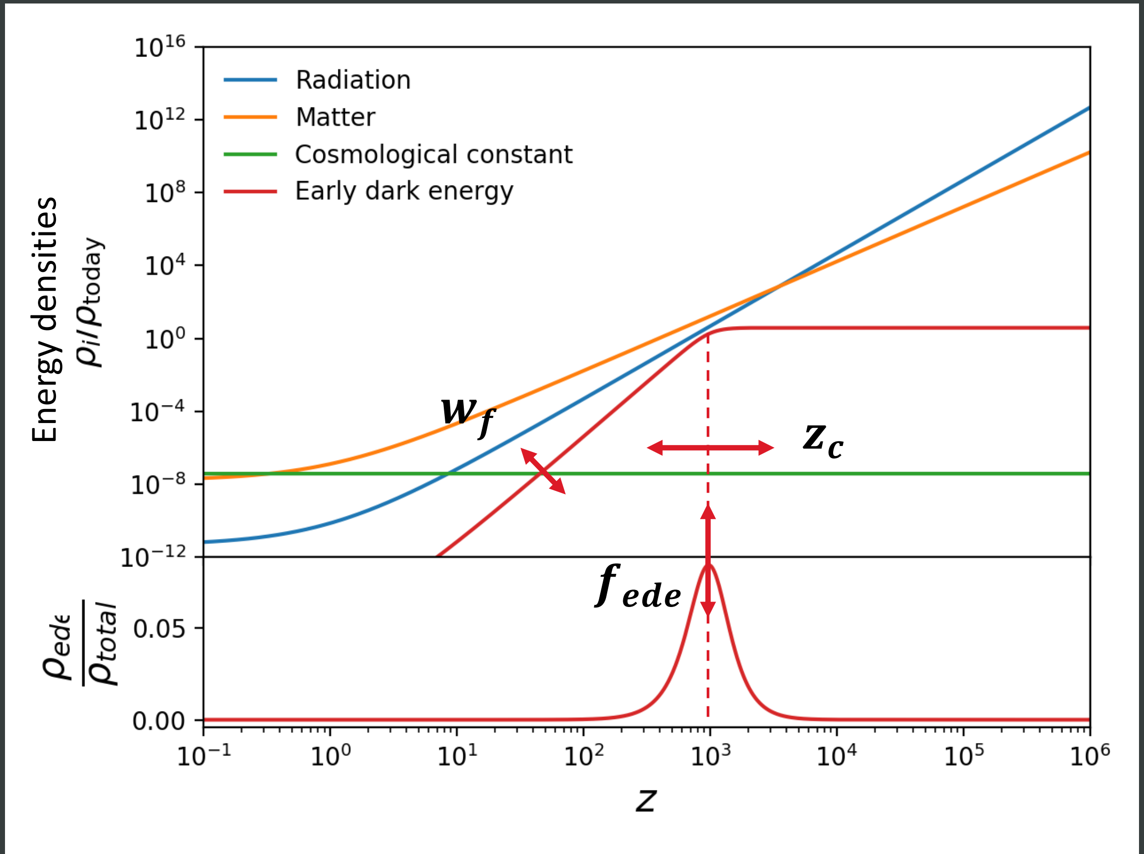
$$H^2 \sim \rho_{total}$$

Expansion rate ~ energy content

Additional energy component with the properties:

- 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



Theoretical guidelines

- ✓ Decrease the sound horizon r_s to increase the predicted H_0. Because $r_s \propto 1/H_{pre}(z)$, new physics must be added before the CMB
- ✓ New physics must vanish post recombination

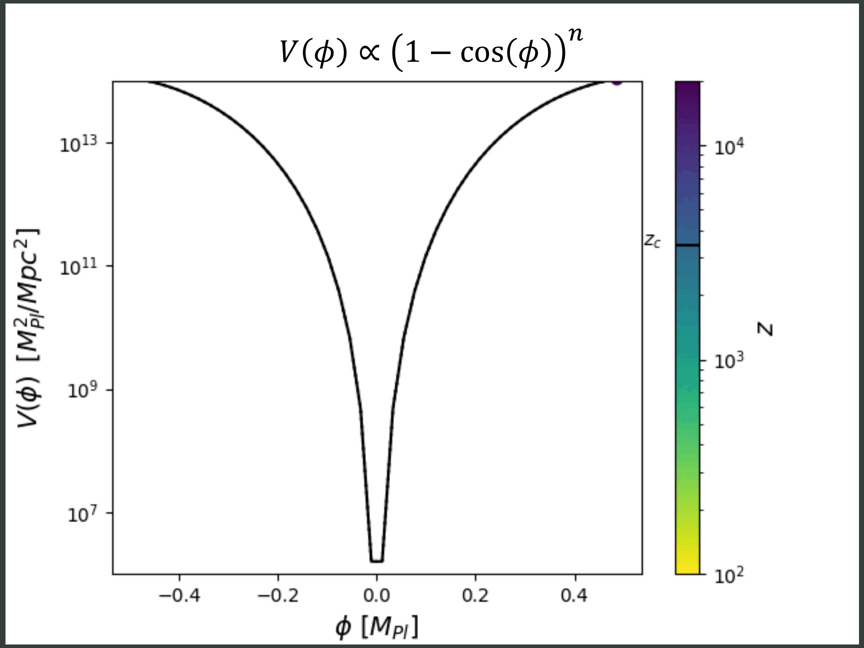
Early dark energy
Models

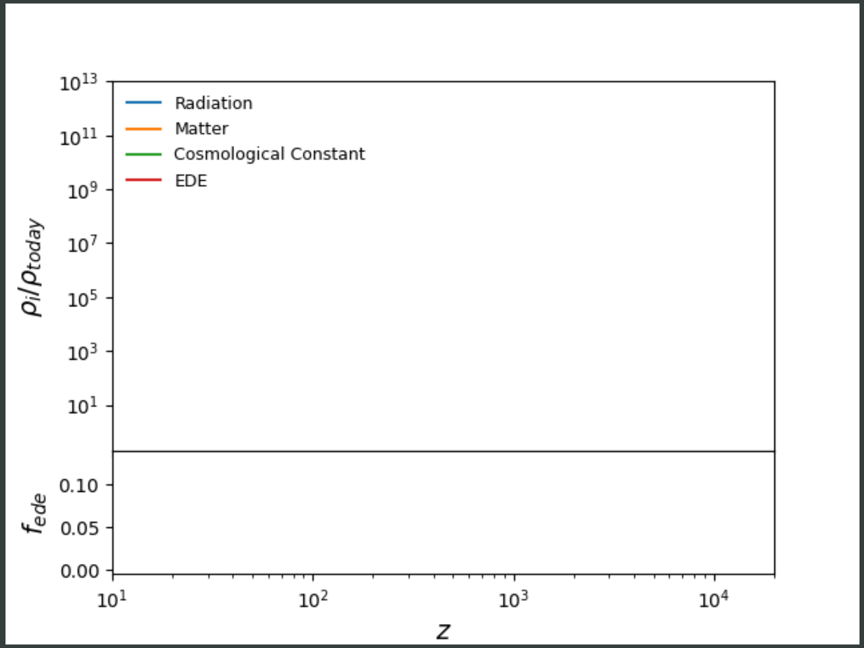
- Early Dark Energy, the Hubble Parameter, and the String Axiverse
  TK & Kamionkowski [1608.01309]
- Cosmological Implications of Ultralight Axionlike Fields
  Poulin, TK et al [1806.10608]
- Early Dark Energy Can Resolve The Hubble Tension
  Poulin, TK et al [1811.04083]
- Thermal Friction as a Solution to the Hubble Tension
  Berghaus & TK [1911.06281]
- Chameleon Early Dark Energy and the Hubble Tension
  TK, Raveri, Jain, Khoury, Trodden [2106.13290]
- Thermal Friction as a Solution to the Hubble and Large-Scale Structure Tensions
  Berghaus & TK [2204. 09133]
- An Attractive Proposal for Resolving the Hubble Tension: Dynamical Attractors that Unify Early and Late Dark Energy
  Ramadan, TK & Sakstein [2309.08082]

Non-comprehensive list:

- Rock 'n' Roll Solutions to the Hubble Tension. Agrawal et al [1904.01016]
- Axion-Dilaton Destabilization and the Hubble Tension. Alexander & McDonough [1904.08912]
- Acoustic Dark Energy: Potential Conversion of the Hubble Tension. Lin, Raveri, Hu [1905.12618]
- Oscillating scalar fields and the Hubble tension: a resolution with novel signatures. Smith, Poulin, Amin [1908.06995]
- New Early Dark Energy. Neidermann & Sloth [1910.10739]
- Early Dark Energy from Massive Neutrinos as a Natural Resolution of the Hubble Tension. Sakstein & Trodden [1911.11760]
- Unifying Inflation with Early and Late-time Dark Energy in F(R) Gravity. Nojiri et al [1912.13128]
- Is the Hubble tension a hint of AdS phase around recombination? Ye & Piao [2001.02451]
- Unified framework for early dark energy from α-attractors. Braglia et al [2005.14053]
- A novel early Dark Energy model. Garcia, Castaneda, Tejeiro [2009.07357]
- Neutrino-Assisted Early Dark Energy: Theory and Cosmology. Gonzalez et al [2011.09895]
- The Early Dark Sector, the Hubble Tension, and the Swampland. McDonough, .. Hill, Hu, et al [2112.09128]
- Effects of a Geometrically Realized Early Dark Energy Era on the Spectrum of Primordial Gravitational Waves, Oikonomou et al [2206.00721]
- Early dark energy and the screening mechanism, Sadjadi et al [2205.15693]
- Early Dark Energy from a Higher-dimensional Gauge Theory, Kojima et al [2205.13777]
- Unifying inflation with early and late dark energy with multiple fields: Spontaneously broken scale invariant two measures theory, Guendelman et al [2201.06470]
- Quintessential early dark energy, Sohail et al [2408.03229]
- …

Early dark energy
Ultra-light-axion-inspired scalar potential





Based on Poulin,.. TK, et al [arxiv:1806.10608]

Early dark energy
ULA-inspired scalar

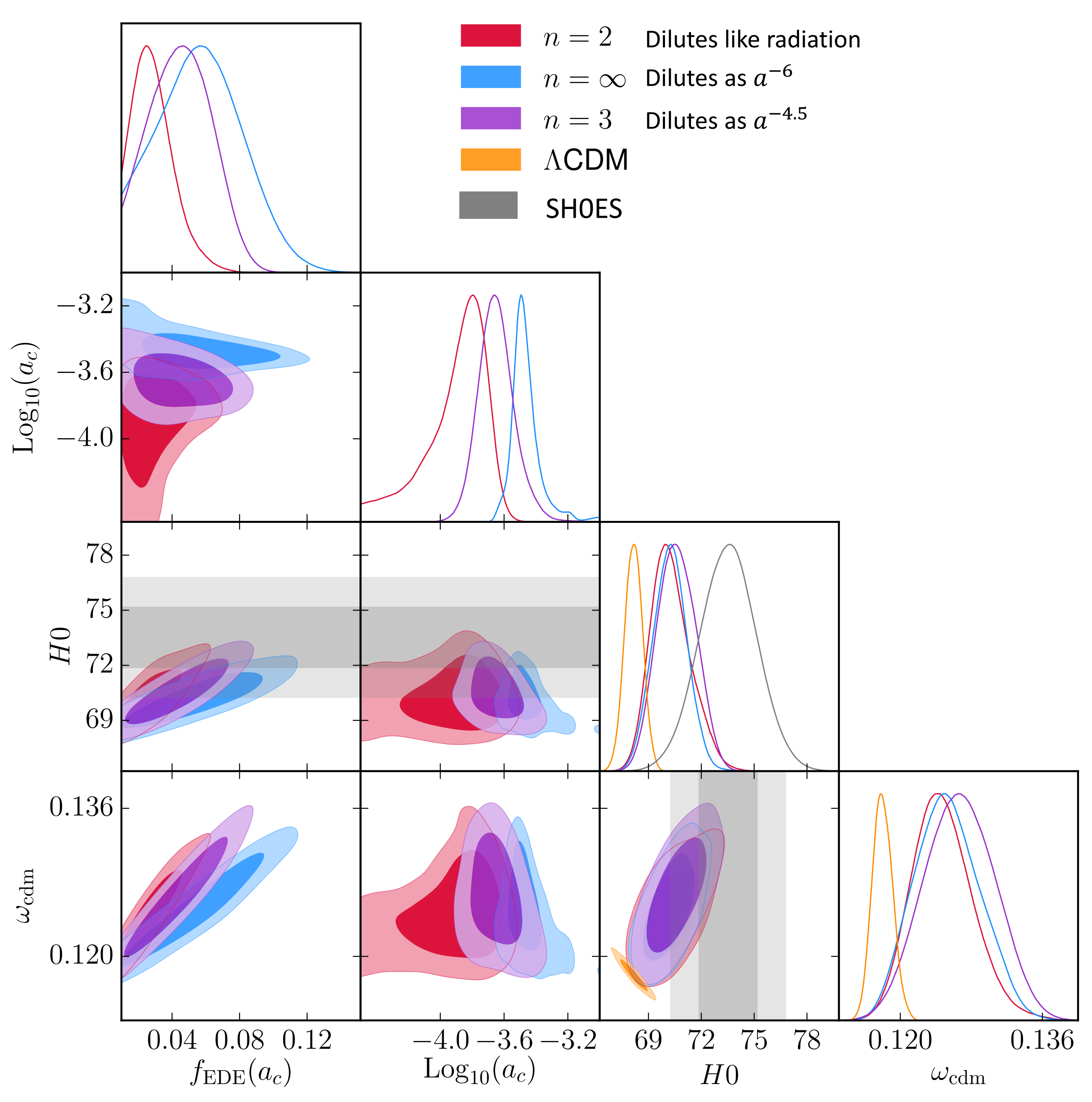
Fit to CMB+BAO+SNe+H0

- ω_{cdm} = amount of cold dark matter today

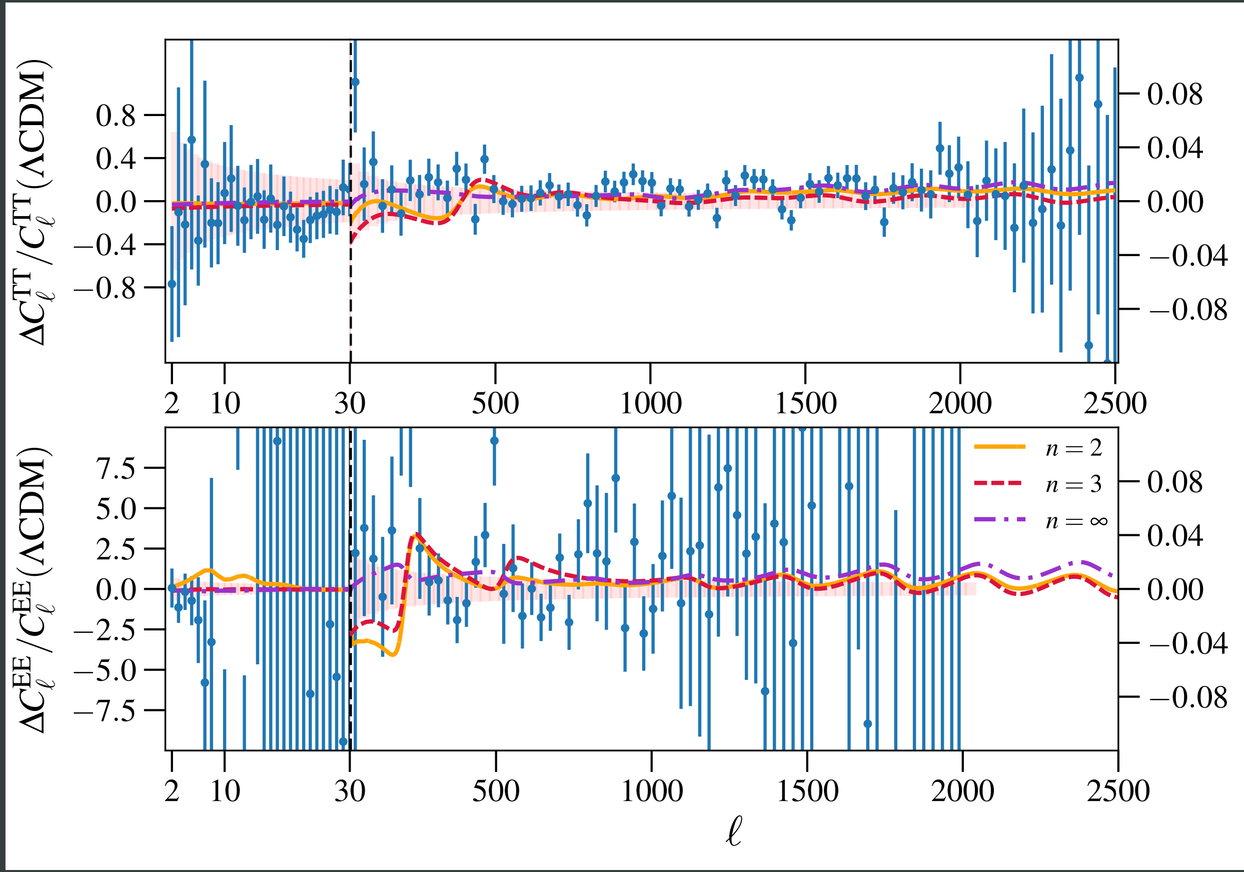
- $f_{ede}(a_c)$ = fractional energy density in the axion field at critical redshift $z_c \approx 1/a_c$
- $w_f = \frac{n-1}{n+1}$

We find an improved χ^2 for ΛCDM + EDE for combined datasets

Poulin,.. TK et al [1811.04083]



Early dark energy
Detection in the CMB



Poulin,.. TK et al [1811.04083]

Could detect EDE in cosmic-variance-limited, high-ell
CMB polarisation data

ACT and SPT have already had implications for EDE constraints

Smith et al [2309.03265]
Smith et al [2202.09379]
La Posta et al [2112.10754]
Hill et al [2109.04451]
Lin et al [2009.08974]
Chudaykin et al [2004.13046] and [2011.04682]

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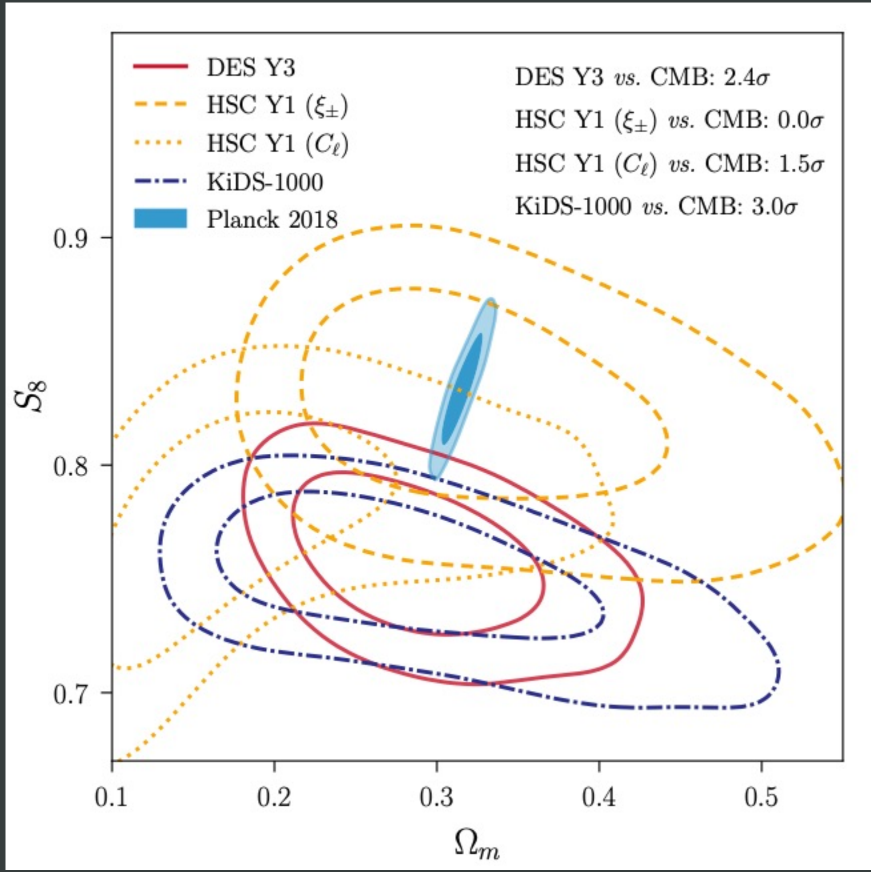
Challenges to EDE

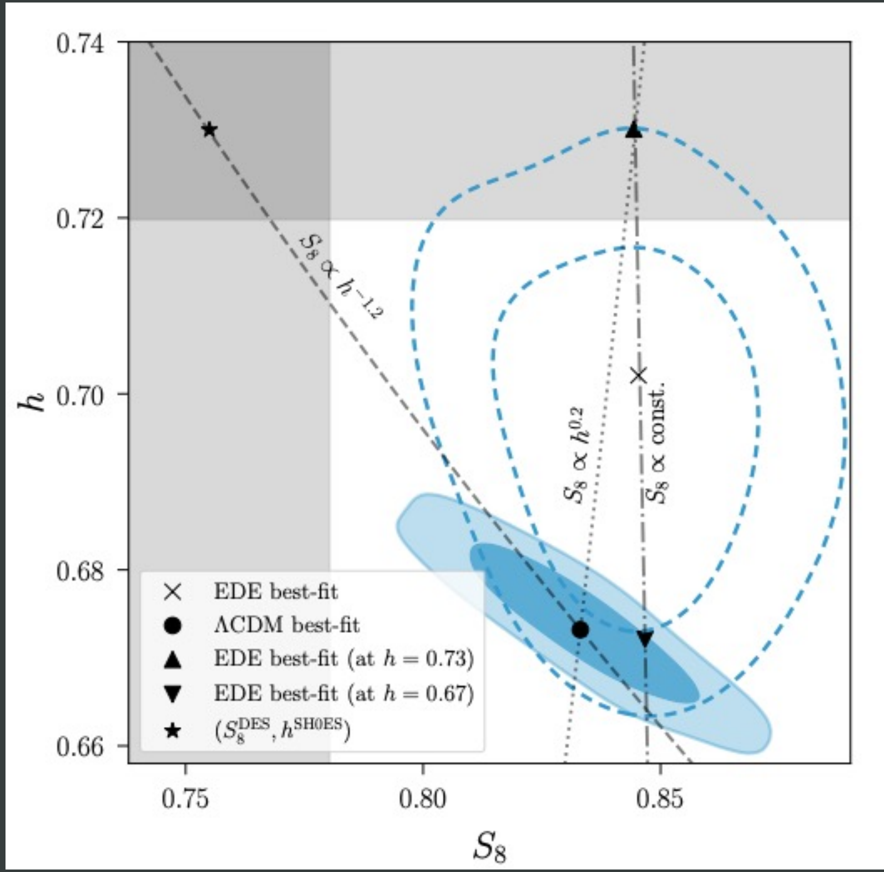
Weak-lensing S_8 tension

Amplitude σ_8 of matter density fluctuations

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



Impact of EDE on LSS tension



Secco, TK et al [2209.12997]

Challenges to EDE

Solutions and obstacles

- Resolves the Hubble tension
- Can arise from numerous theoretical scenarios
- Scalar field $V(\phi) \sim (1 - \cos\phi)^n$ does particularly well
- Improves the fit to cosmological data relative to ΛCDM

- Worsens the LSS tension
- Solution is fine-tuned in theoretical parameters – why matter-radiation equality?
- $V(\phi) \sim (1 - \cos\phi)^n$ is a very contrived potential
- Need to include local H_0 while fitting via Bayesian methods

Cosmic tensions, solutions and extensions

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Beyond EDE

EDE without SH_0ES priors

Alternate statistical frameworks

Bayesian inference

$$\mathcal{P}(\theta|d) = \frac{\Pi(\theta)\mathcal{L}(d|\theta)}{\mathcal{E}(d)}$$

Prior volume increases as $f_{ede} \to 0$

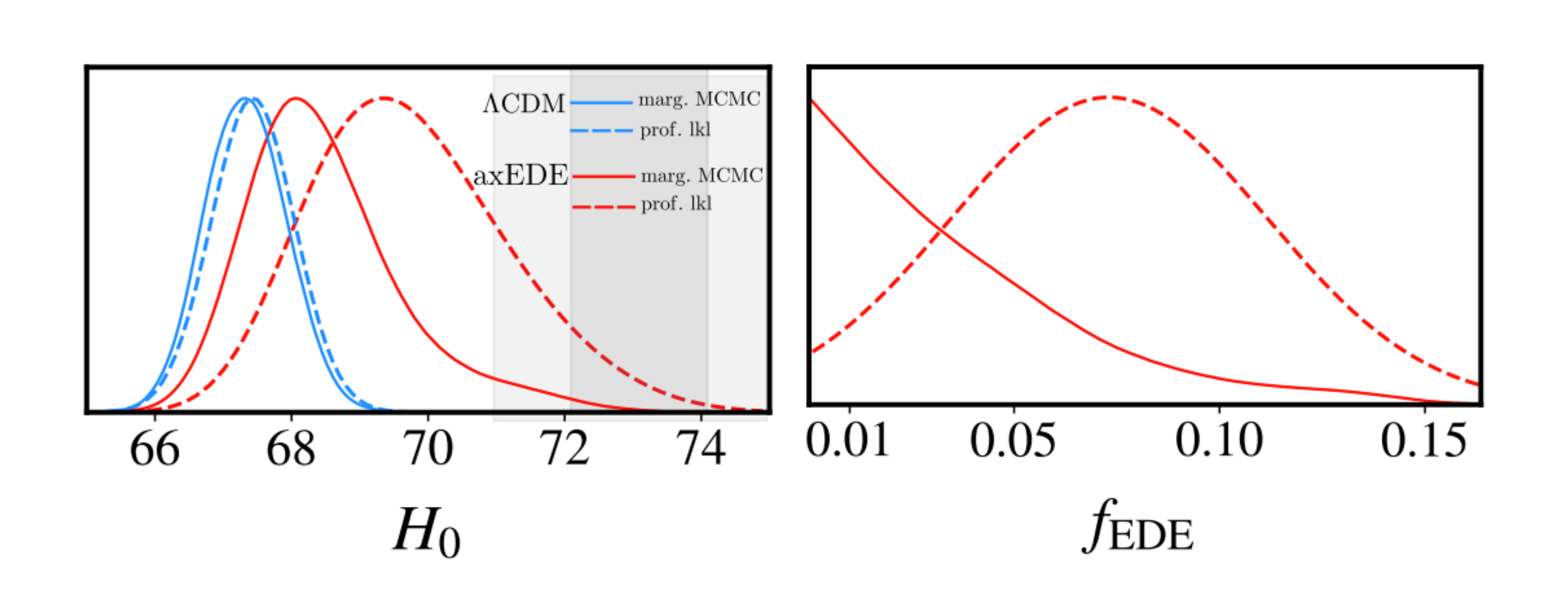
z_c and w_f become unconstrained

Profile likelihoods

No dependence on prior

$$\mathbb{P}(\theta_i) = \max \mathcal{L}(\boldsymbol{\theta}|\theta_i = \theta_i') \; \forall \, \theta_i'$$

Fit to CMB+BAO+SNe, no H_0 prior



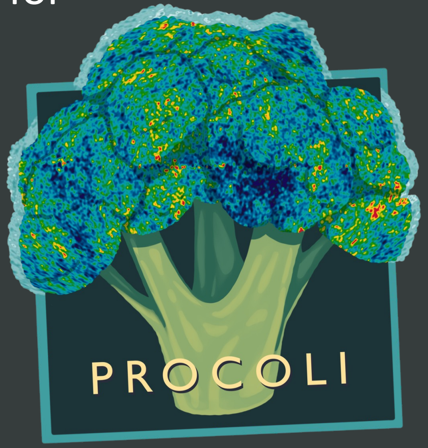
Poulin, Smith and TK [2302.09032]

Beyond EDE
Profile likelihoods

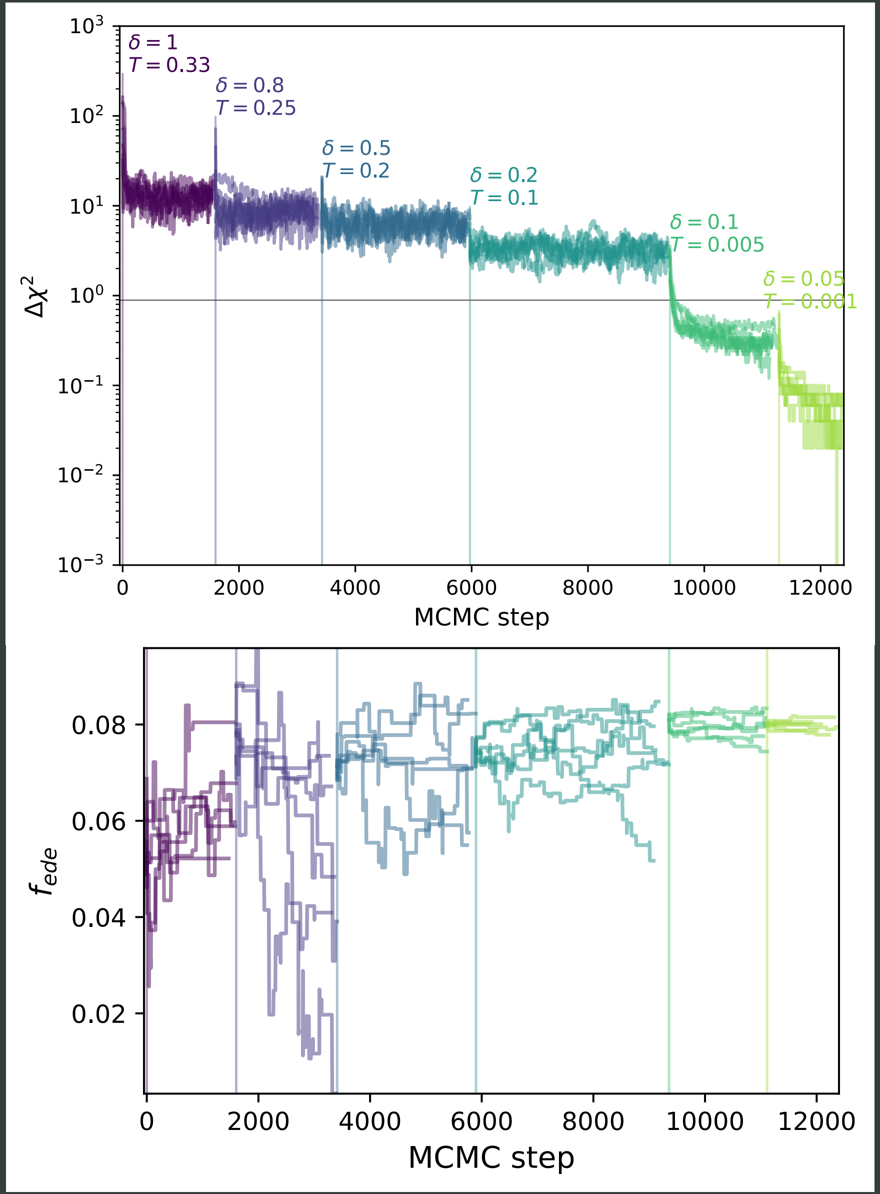
Profile likelihoods
No dependence on prior

$$\mathbb{P}(\theta_i) = \max \mathcal{L}(\boldsymbol{\theta}|\theta_i = \theta_i') \;\forall\; \theta_i'$$

With simulated-annealing optimization for high-dimensional parameter spaces

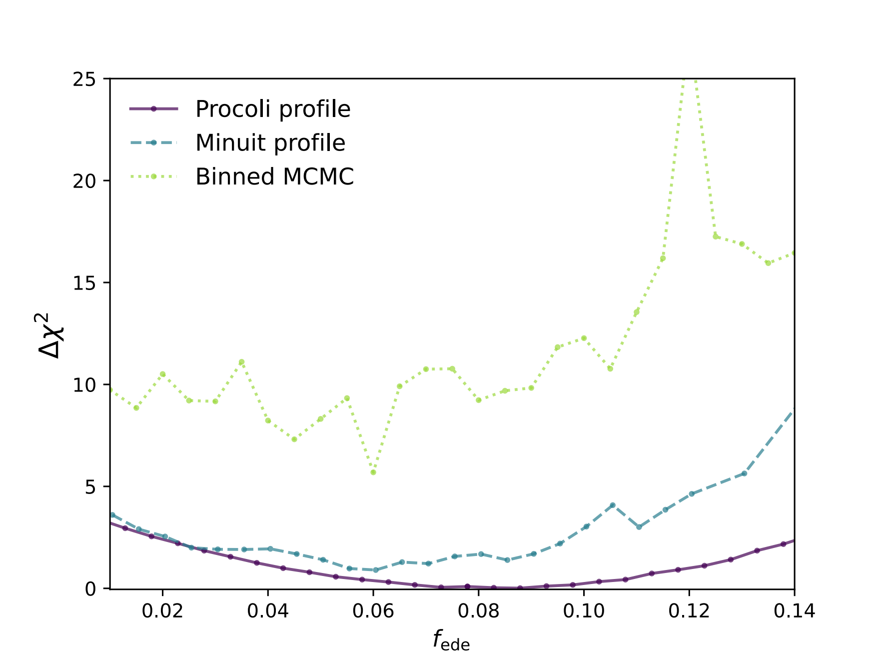


TK et al [2401.14225]

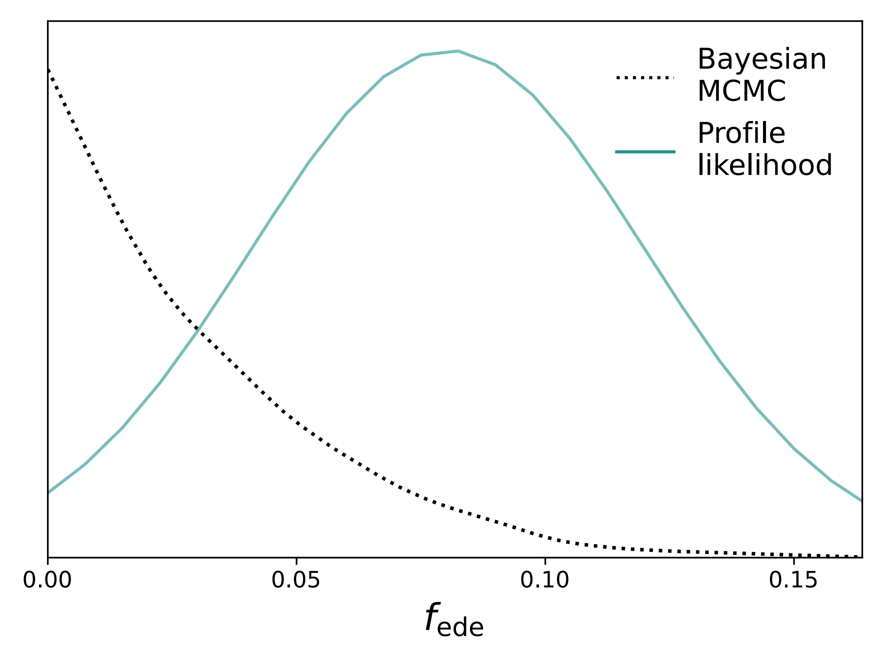


Beyond EDE
Profile likelihoods

Profile likelihood with simulated annealing
Profile likelihood without stochastic algorithm
Posterior profile



Additional insight into model that may be hidden by prior-dependent posteriors



TK et al [2401.14225]

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Beyond EDE
Chameleon EDE coupled to dark matter

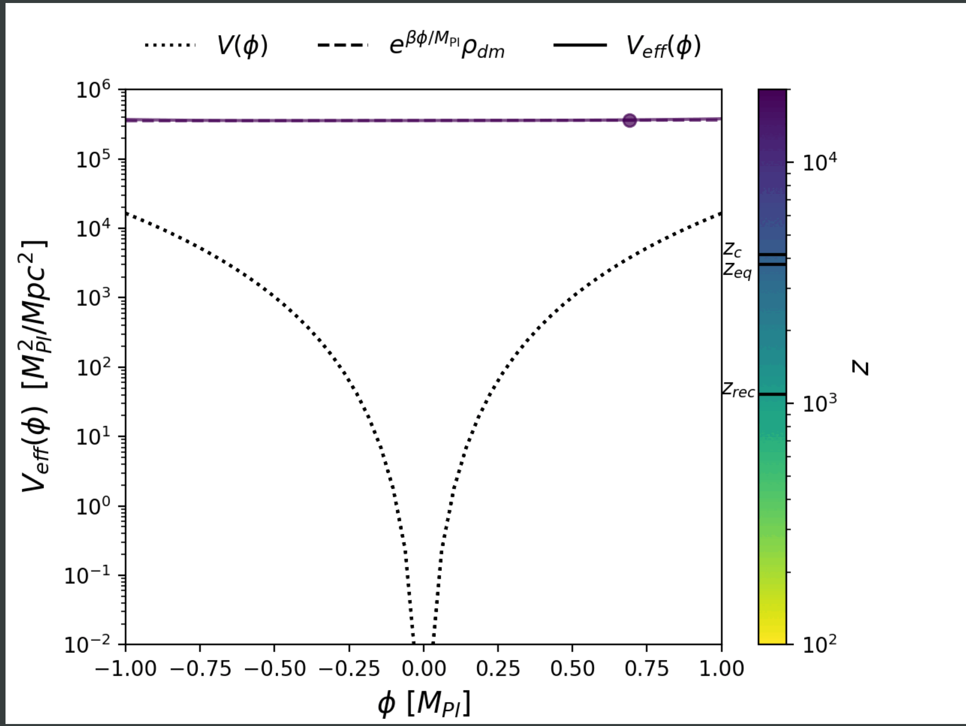
Conformally couple a scalar field to dark matter

$$\rho_{total} \mathrel{+}= \rho_{dm} A(\phi)$$

$$V_{eff}(\phi) = V(\phi) + \rho_{dm} A(\phi)$$

- Modifies DM evolution → S_8 ?
- Tie the redshift of EDE to z_{eq} through coupling $A(\phi)$

$V(\phi) \sim \phi^4 \quad A(\phi) \sim e^{\beta\phi}$



TK et al [2106.13290]

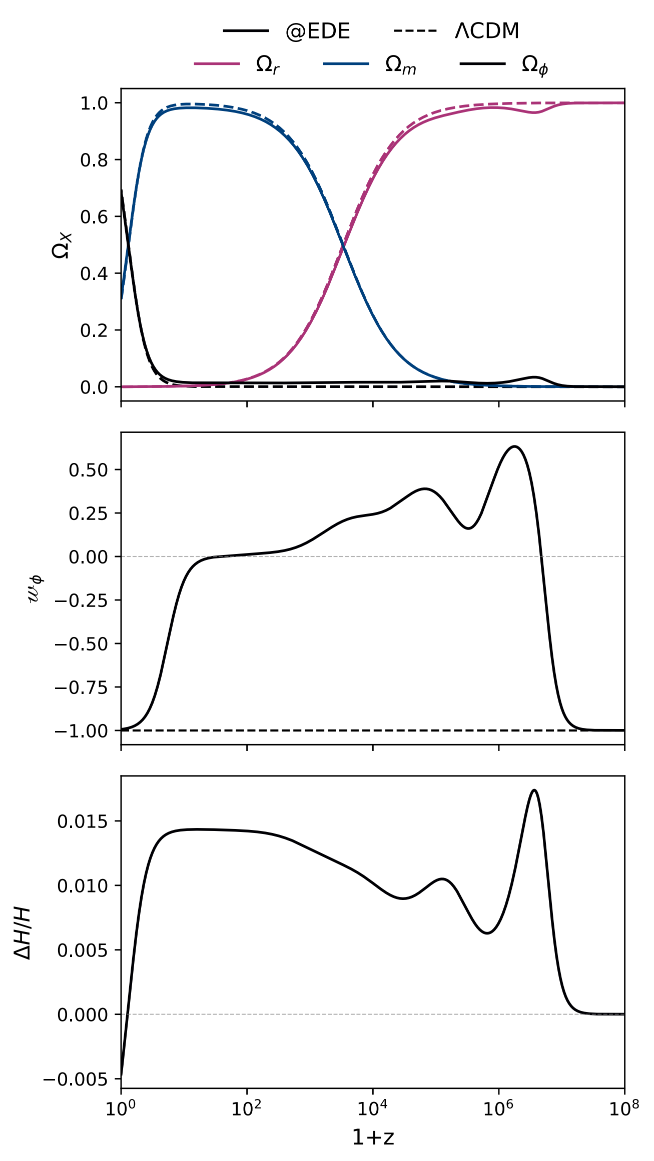
Beyond EDE

Attractive EDE coupled to dark energy

$$V(\phi) = V_\alpha e^{-\alpha\frac{\phi}{M_{Pl}}} + V_\beta e^{-\beta\frac{\phi}{M_{Pl}}}$$

For $\alpha > \beta$, early and late dark energy attractors

- EDE saddle point in the radiation era
- Transition to a matter saddle in the matter era
- Settle into dark energy attractor



Ramadan, TK et al [2309.08082]

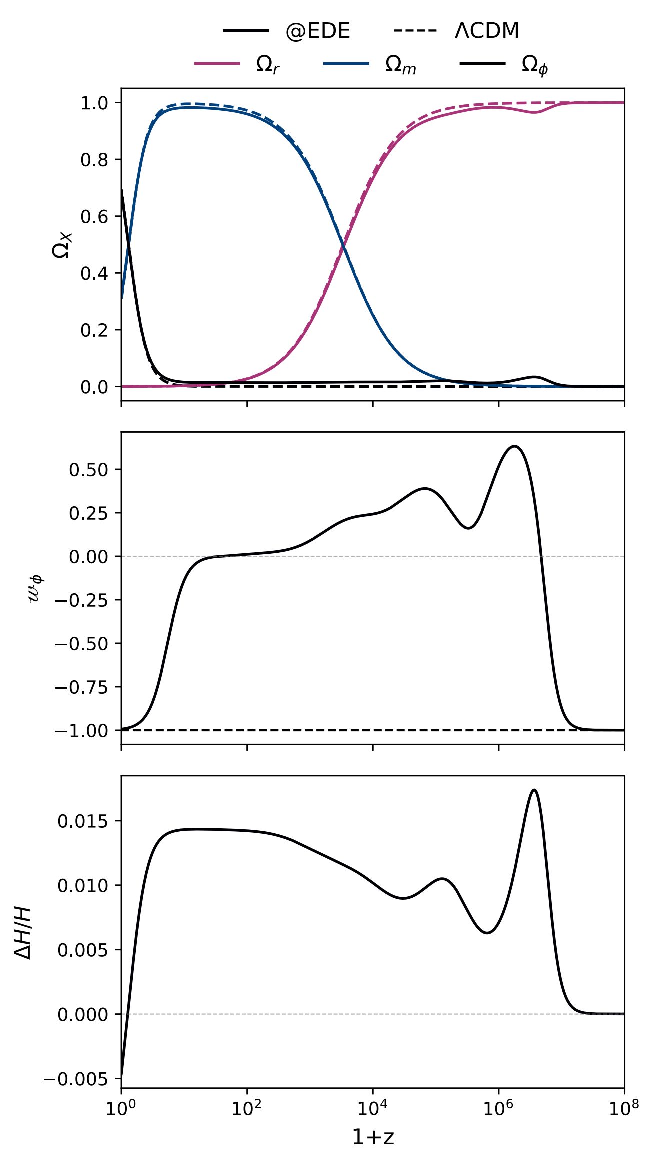
Beyond EDE
Attractive EDE coupled to dark energy

$$V(\phi) = V_\alpha e^{-\alpha\frac{\phi}{M_{Pl}}} + V_\beta e^{-\beta\frac{\phi}{M_{Pl}}}$$

Too much contribution from @EDE during the matter era strongly constrains this model, preventing a Hubble solution

- @EDE presence at early times increases the early ISW effect, requiring an increase in ω_c
- @EDE contribution post-recombination decreases D_A requiring a decreases in ω_c

Model-building guidance - minimise the contribution of @EDE during matter-domination



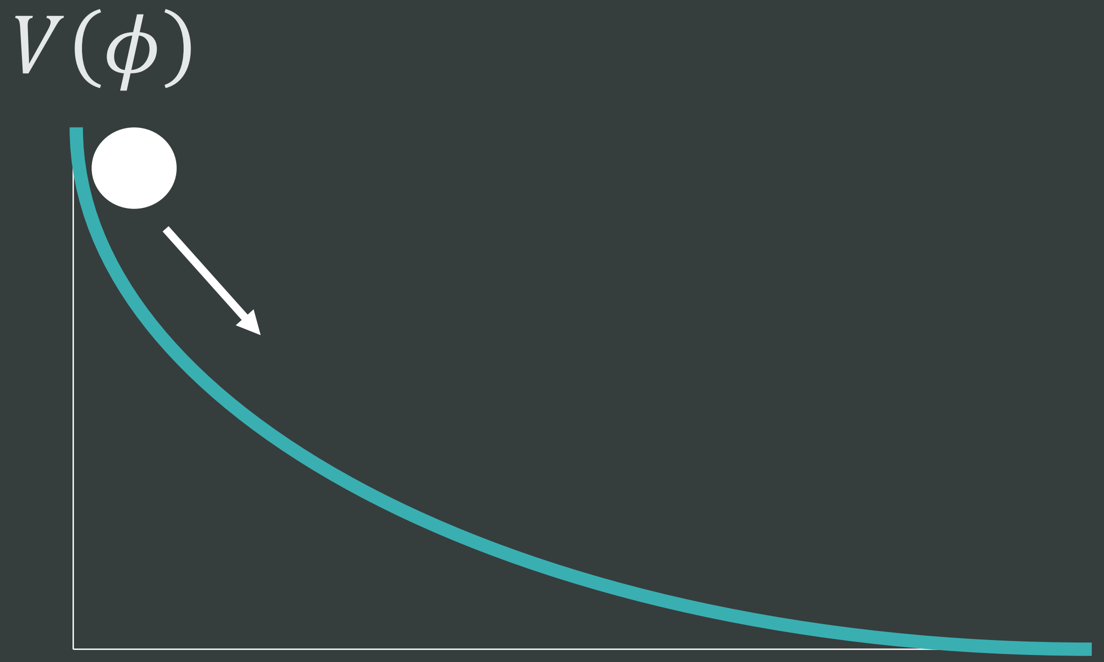
Ramadan, TK et al [2309.08082]

Beyond EDE
Dissipative axion EDE coupled to dark radiation

Uncoupled scalar experiences Hubble friction. Uncoupled DR dilutes as $(1+z)^4$

$$\ddot{\phi} + (3H)\,\dot{\phi} + V_{\phi} = 0$$

$$\dot{\rho}_{dr} = -4H\rho_{dr}$$



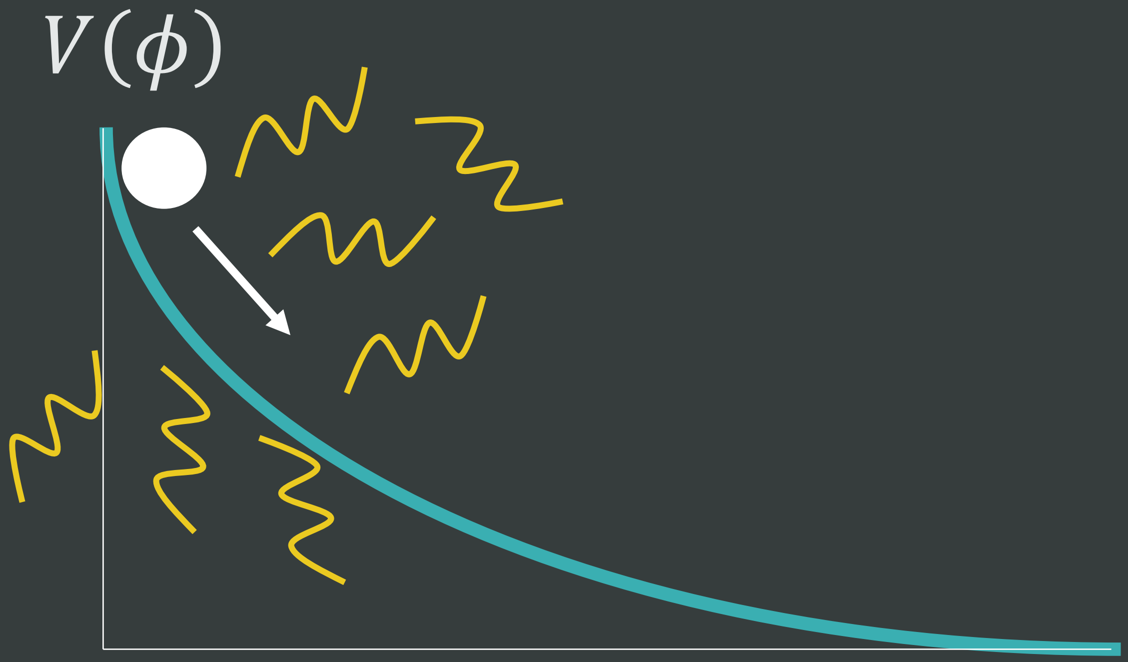
Berghaus & Karwal [1911.06281]

Beyond EDE
Dissipative axion EDE coupled to dark radiation

Scalar coupled to DR additionally experiences thermal friction

$$\ddot{\phi} + (3H + \Upsilon)\,\dot{\phi} + V_\phi = 0$$

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



Berghaus & Karwal [1911.06281]

Beyond EDE

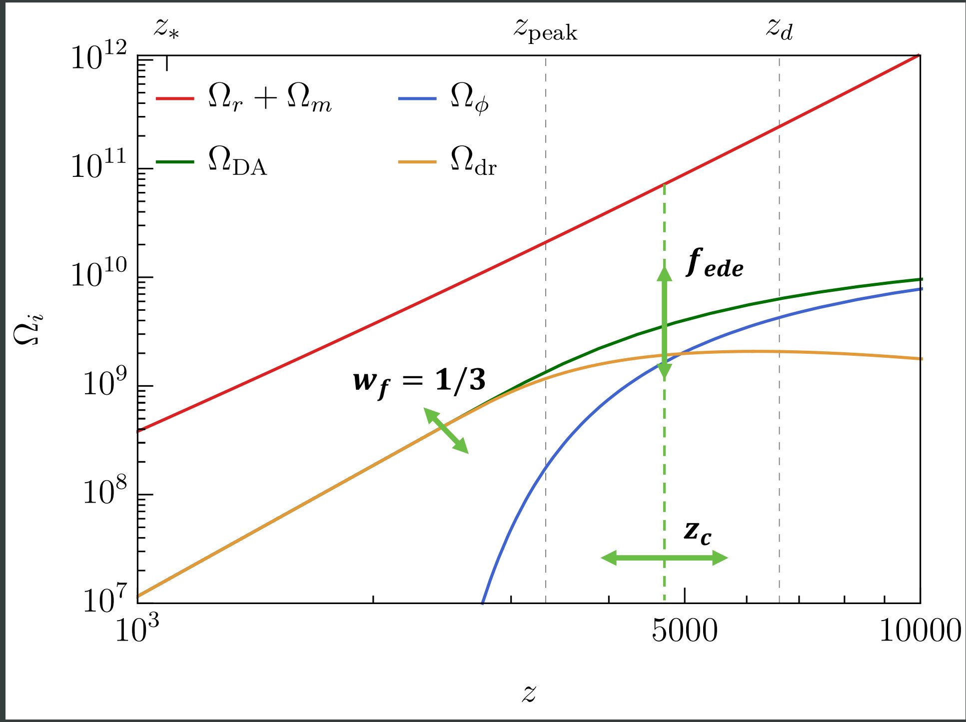
Dissipative axion EDE coupled to dark radiation

$$\ddot{\phi} + \left(3H + \Upsilon(T_{dr})\right) \dot{\phi} + V_\phi = 0$$

$$\dot{\rho}_{dr} = -4H\rho_{dr} + \Upsilon(T_{dr})\dot{\phi}^2$$

$$m, \phi_i \to f_{ede}$$
$$m, \Upsilon(\mathrm{T_{dr}}) \to z_c$$
$$w_f = 1/3$$

Robust to choice of $V(\phi)$



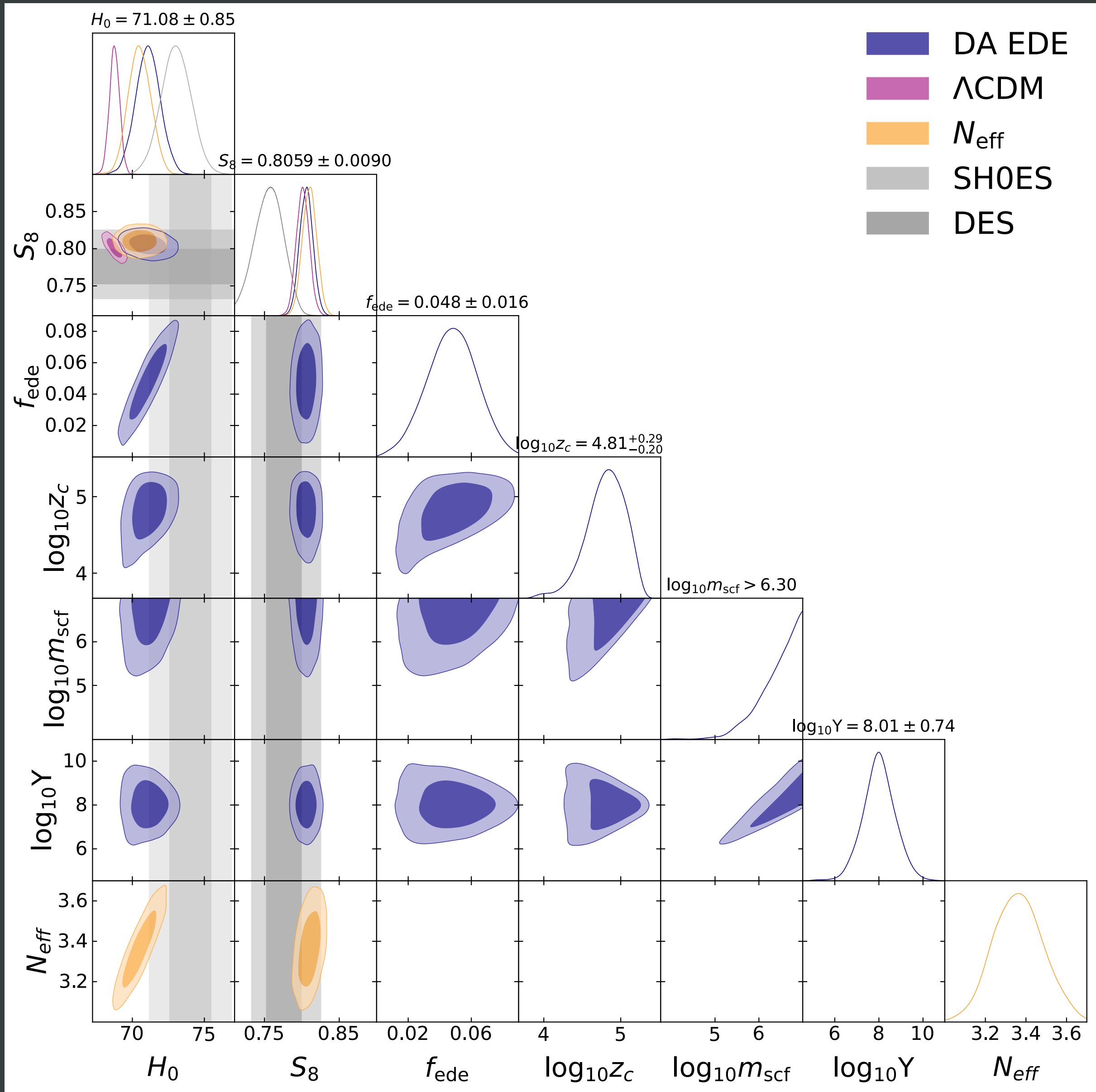
Berghaus & Karwal [1911.06281]

Beyond EDE
DA EDE coupled to DR

Fit to CMB+BAO+SNe+H0+DES

- Higher Hubble than ΛCDM and N_{eff}
- Similar S_8 to ΛCDM and N_{eff}
- Extra radiation preferred over EDE-like injection
- Similar fit to CMB as ΛCDM, but worse than ΛCDM fit to concordant data

Dissipative axion performs better than N_{eff} but suffers the same CMB constraints as other extra radiation



Berghaus & Karwal [2204.09133]

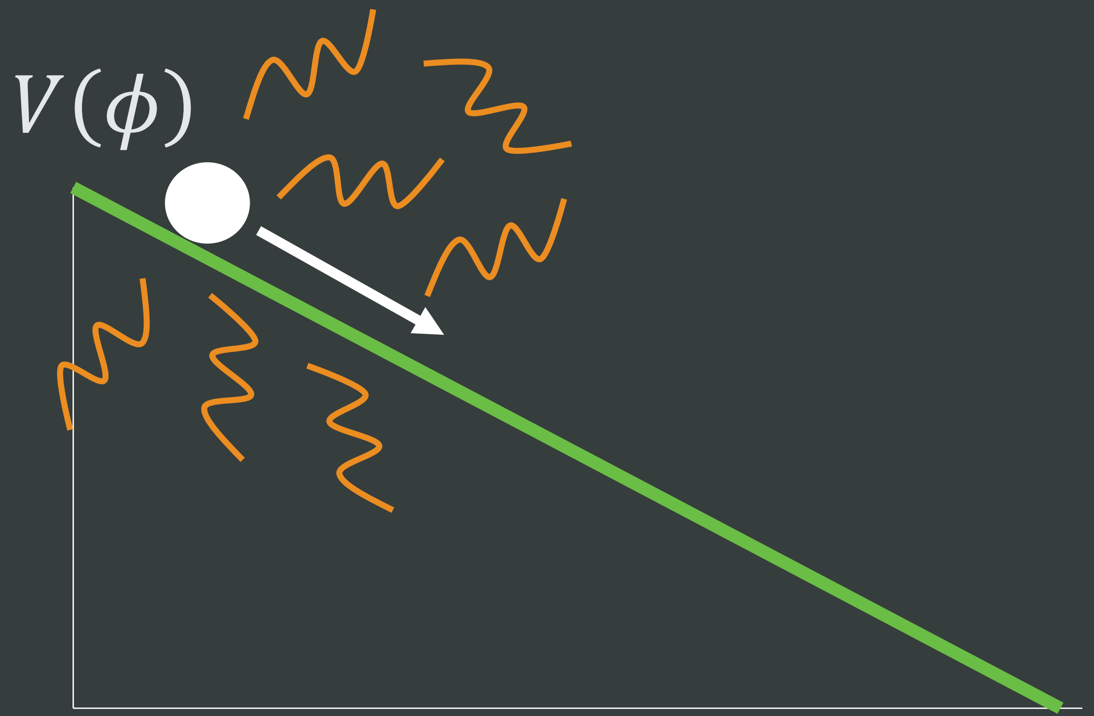
Beyond EDE
Dissipative axion as late dark energy

Scalar coupled to DR additionally experiences thermal friction

$$\ddot{\phi} + (3H + \Upsilon)\,\dot{\phi} + V_\phi = 0$$

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

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



Berghaus, Karwal et al [2311.08638]

Beyond EDE
Dark energy radiation

Current data:

Planck CMB + BAO + Pantheon SNe

$V(\phi) = C\phi$

$\Omega_{DER} \simeq 0.03$ at 2σ

$100 \times$ ΛCDM radiation $\Omega_\gamma \sim 10^{-4}$

$5000 \times \Delta N_{eff}$ radiation $\Omega_{N_{eff}} \sim 10^{-5}$

Future data:

SO CMB + BAO + Roman SNe

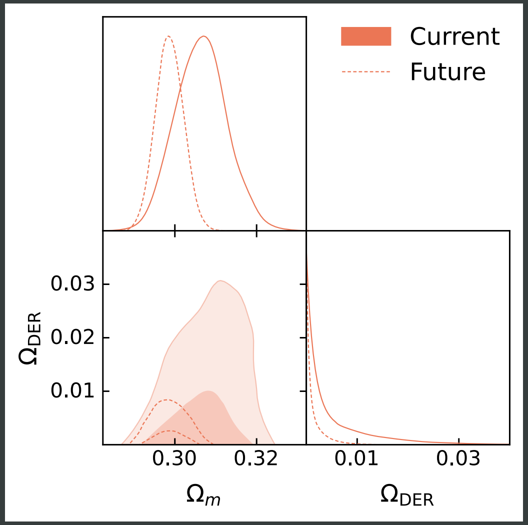
$\Omega_{DER} \simeq 1\%$ at 2σ

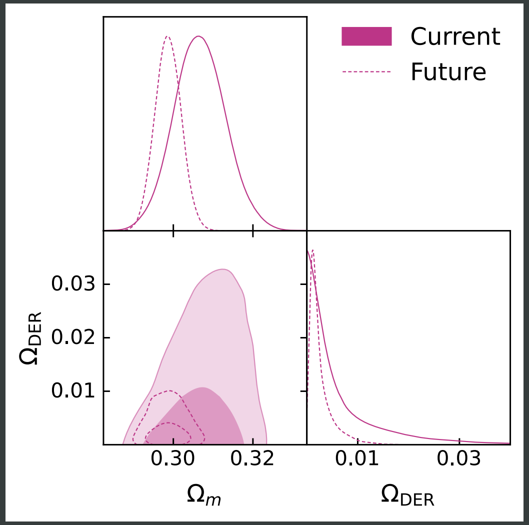
Recent DESI data:

CMB + DESI + Pan+

$\Omega_{DER} \simeq 0.03$ at 1σ with

Berghaus et al [2404.14341]





Minimal DER

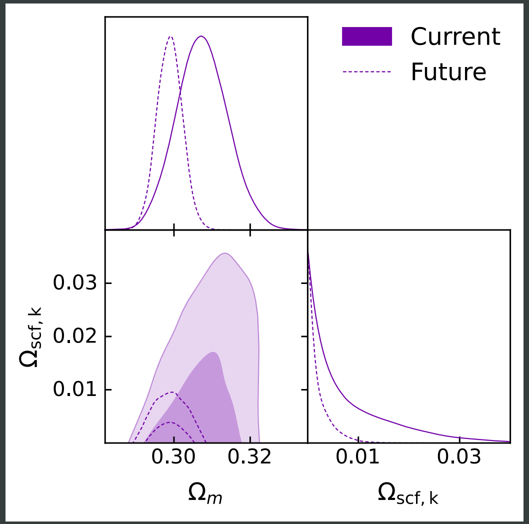
$\Upsilon \propto \rho_{DER}^{3/4}$

Toy DER

Υ = constant

Quintessence

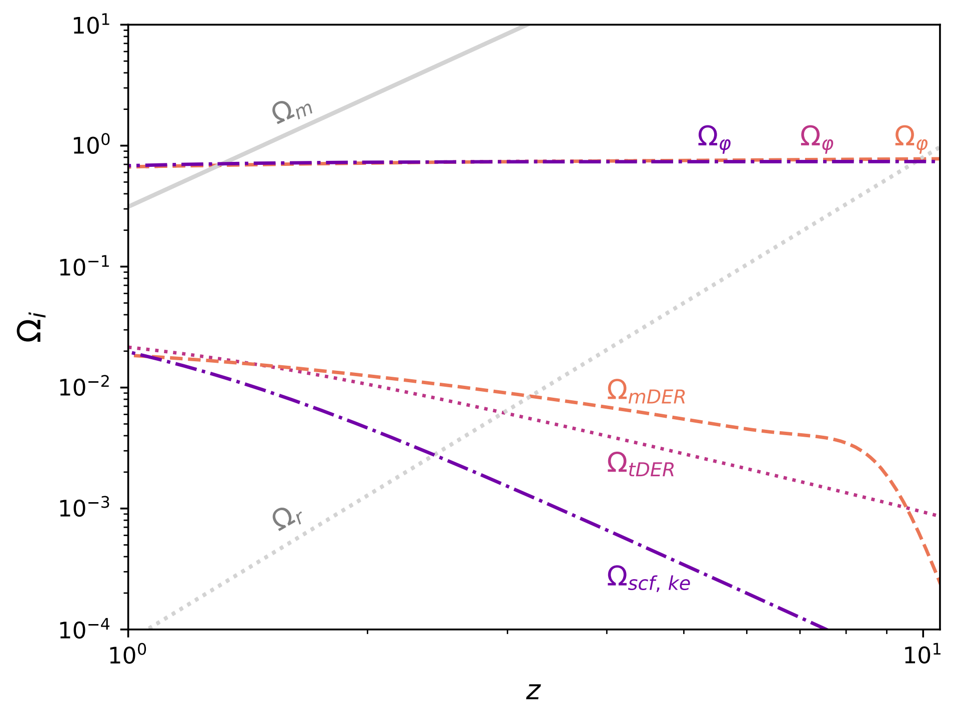
$\Upsilon = 0$



Berghaus, Karwal et al [2311.08638]

Beyond EDE
Dark energy radiation

ΛCDM
Minimal DER
Toy DER
Quintessence



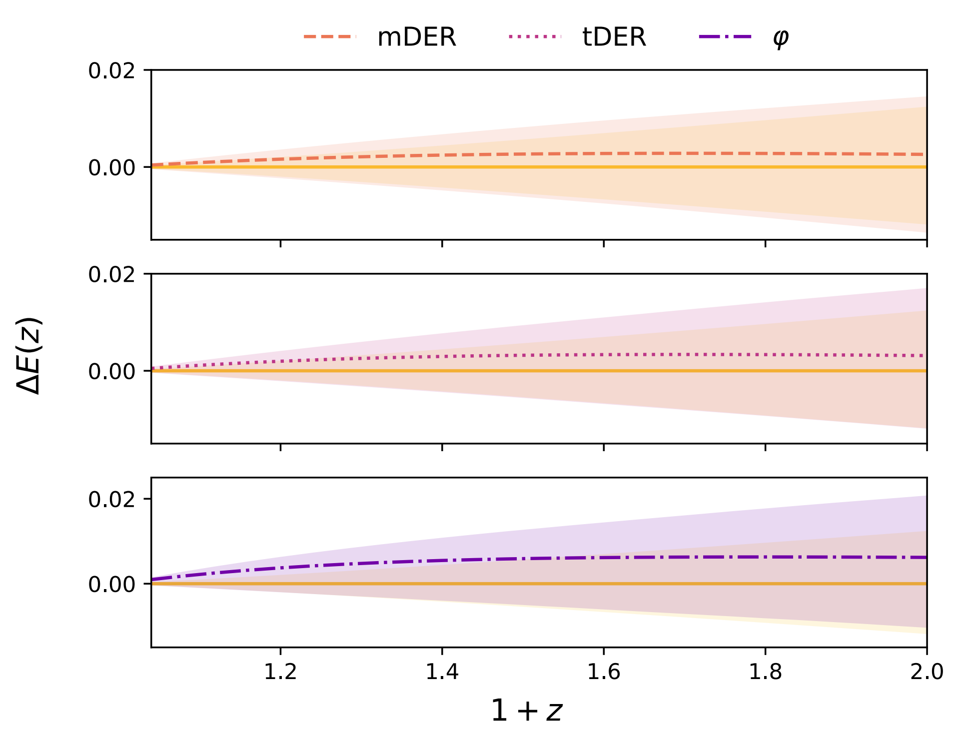
Berghaus, Karwal et al [2311.08638]

DER produced dynamically in the late universe evades early-universe DR bounds where $\Omega_{DER} \simeq 0$

Constraints are dominated by the impact of DER on the background expansion $H(z) = H_0\, E(z)$

Beyond EDE
Dark energy radiation

ΛCDM
Minimal DER
Toy DER
Quintessence



Berghaus, Karwal et al [2311.08638]

Neither current or future CMB and SNe data will able to distinguish these models in

$$E(z) = \frac{H(z)}{H_0}$$

or

$$w(z)$$

Beyond EDE

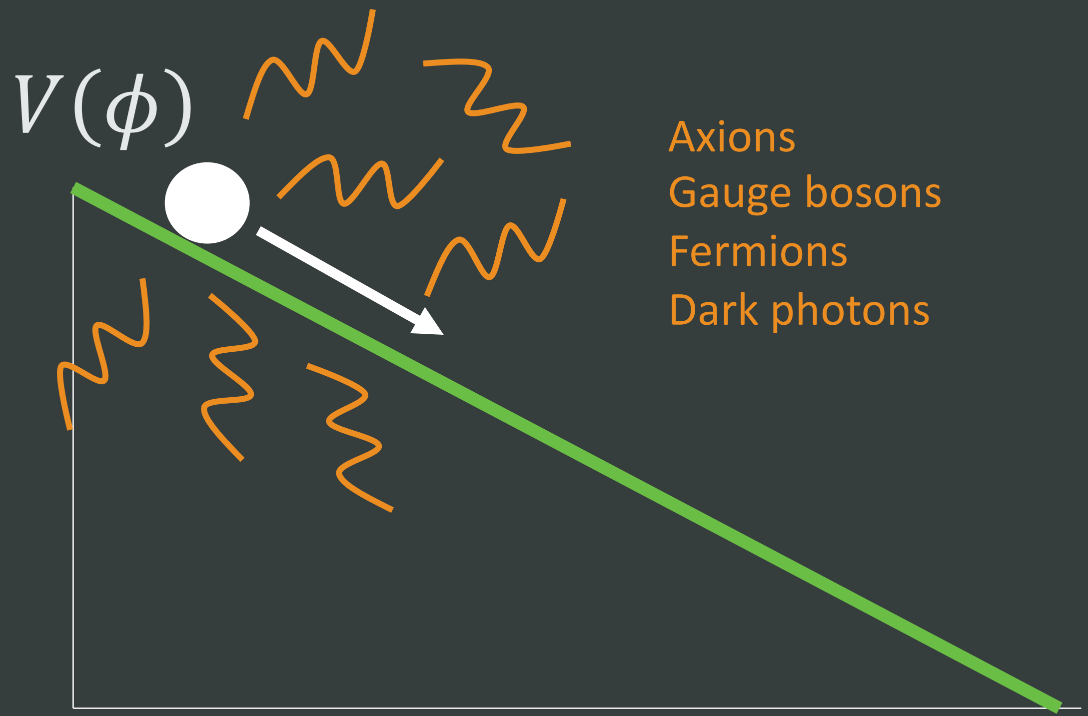
Dark energy radiation interacting with dark photons

Scalar coupled to DR additionally experiences thermal friction

$$\ddot{\phi} + (3H + \Upsilon)\,\dot{\phi} + V_\phi = 0$$

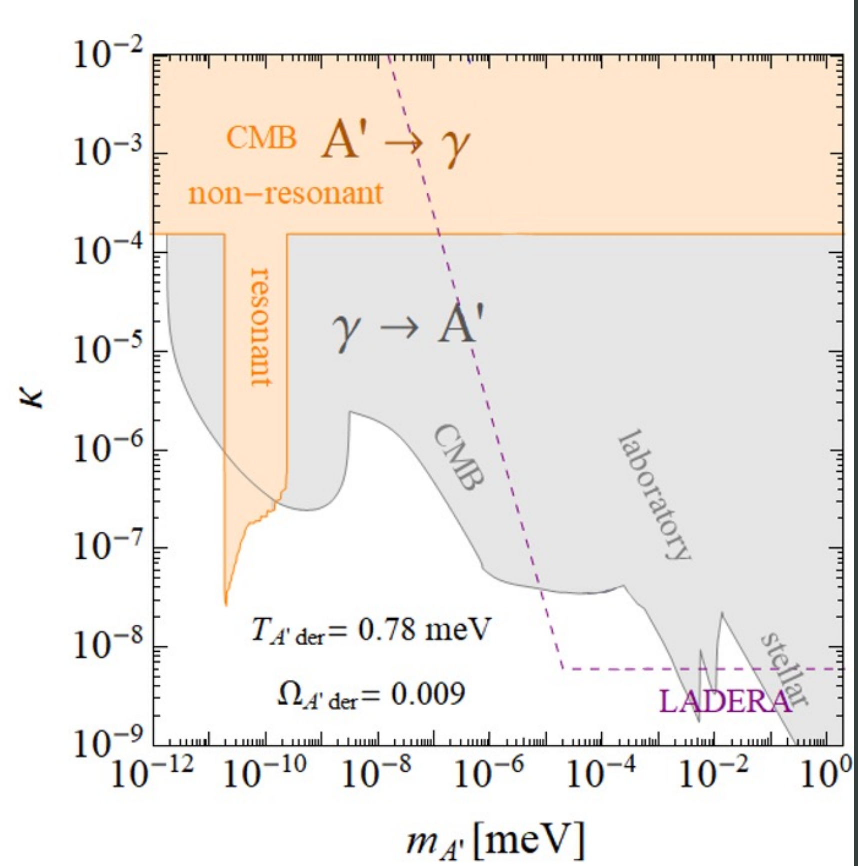
$$\dot{\rho}_{dr} = -4H\rho_{dr} + \Upsilon\dot{\phi}^2$$

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



Berghaus, Karwal et al [2311.08638]

Beyond EDE
Dark energy radiation interacting with dark photons



Berghaus, Karwal et al [2311.08638]

- Charge fermions ψ under dark U(1) A'_μ

$$g\psi \to A'\psi$$

- OR Couple axion ϕ to dark photon

$$L \supset \frac{\phi}{f}\tilde{F}_{\mu\nu}{}'F'^{\mu\nu}$$

- Then kinetically mix dark and SM photons

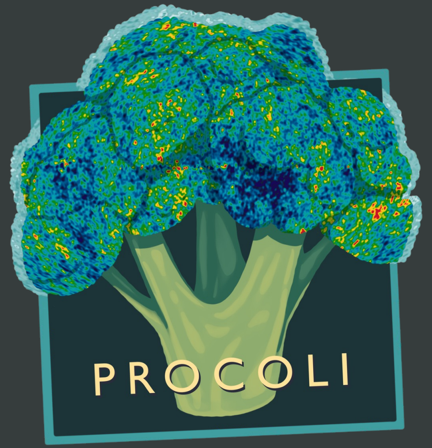
$$\frac{\kappa}{2}F_{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m^2_{A'}A'_\mu A^{\mu\prime}$$

FIRAS CMB spectral distortions

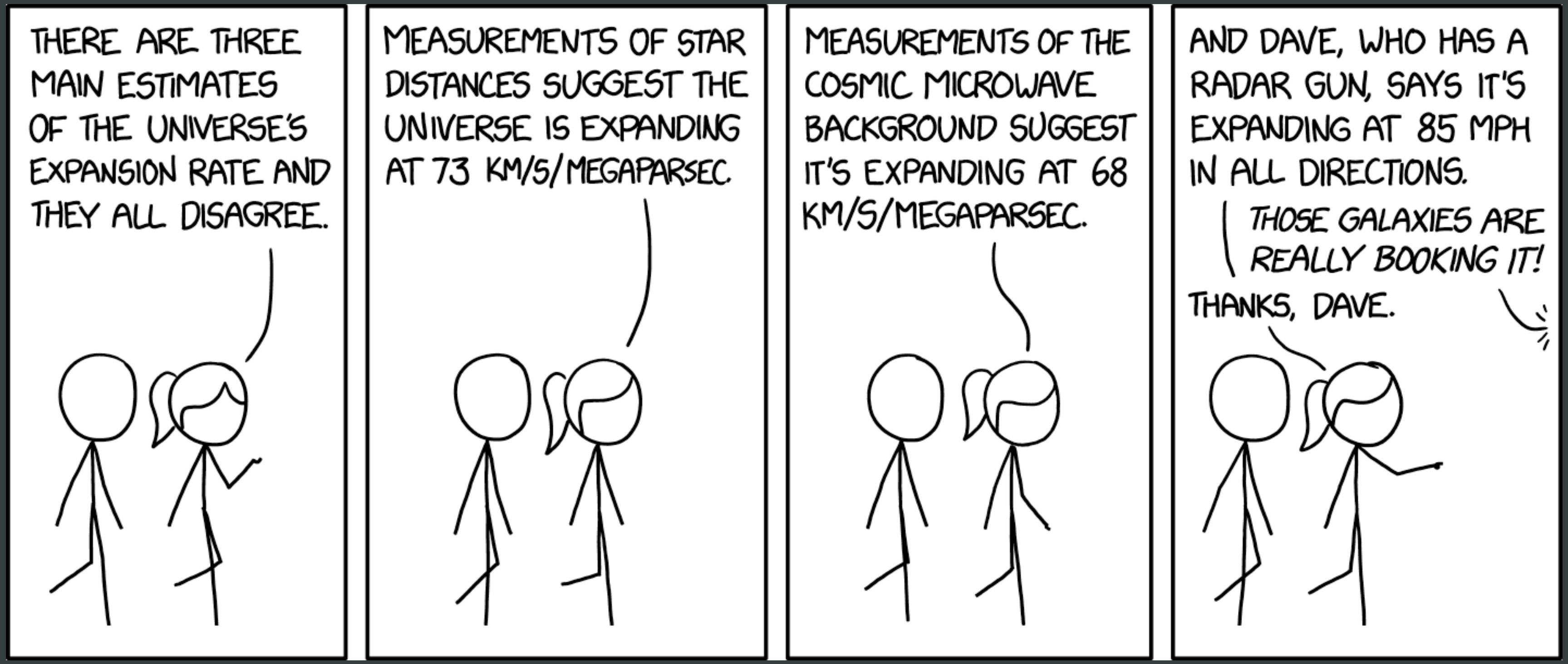
Other observational limits

Late Dark Energy Radiation (LADERA)

Cosmic tensions, solutions and extensions



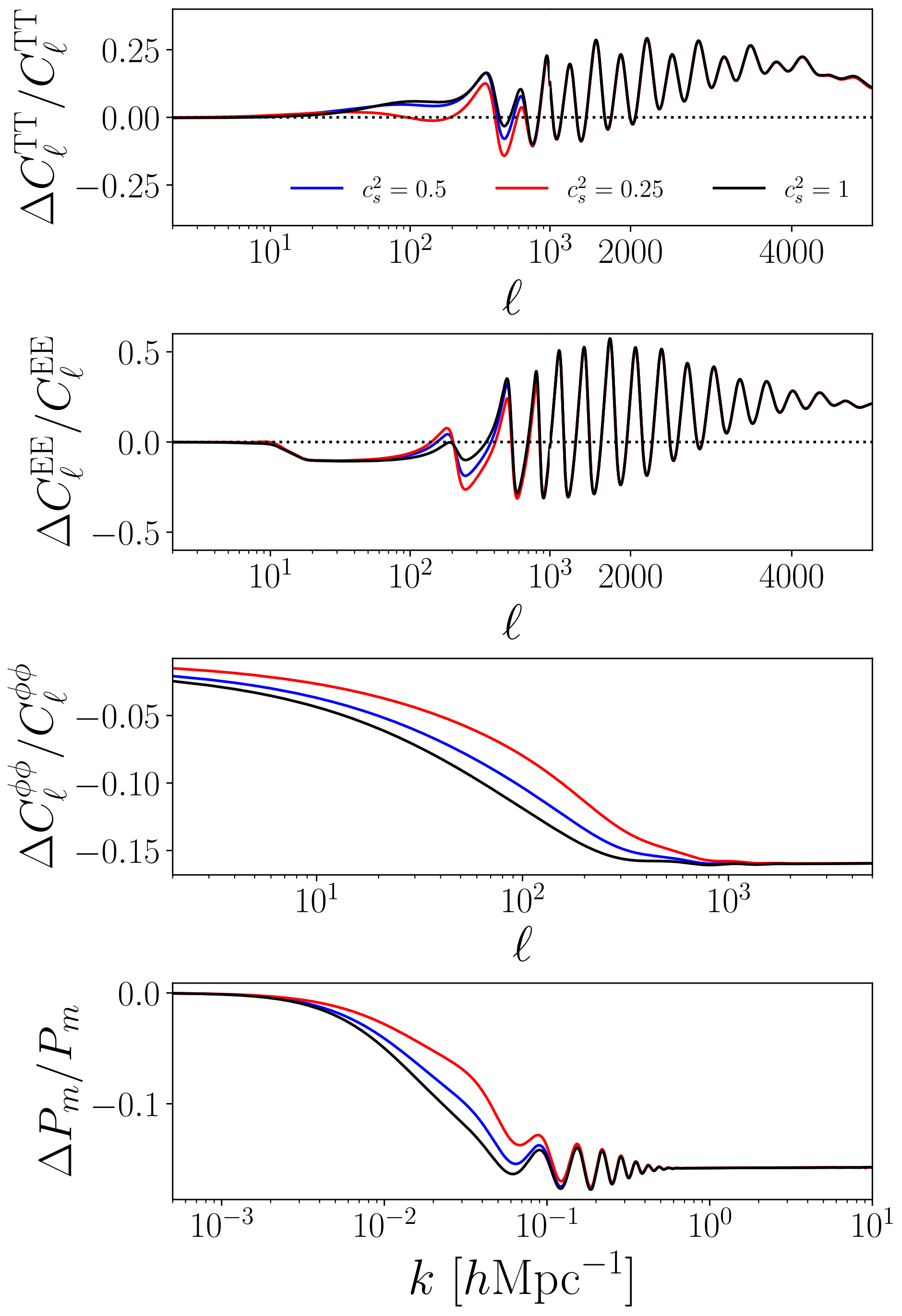
- Are the tensions real (CMB lensing sees no S_8 tension)? Do they point to new, undiscovered physics?
- Hubble tension requires a modification to the background universe, at early times
- Early dark energy can resolve the Hubble tension
  - Several fundamental models can form EDE, with details of the model dictating resolution of tension and fit to data
  - Current and future CMB data can detect and to some extent distinguish models
- Challenges to EDE include the LSS tension, a new coincidence problem, improving the fundamental model, prior volume effects
  - Model-building insight, using EDE avatars as a stepping stone – eg. interactions with dark matter, late dark energy or dark radiation
  - Profile likelihoods provide more insight into these models.
- Models are applicable to other eras of accelerated expansion – dark energy (DER) and inflation (See warm inflation papers by Berghaus)
  - Dark radiation dynamically produced in the late universe evades cosmic bounds on ever-present DR.
    Can be as large as $\Omega_{DER} \simeq 0.03 = 100\times\Omega_{rad}^{\Lambda CDM}$, with a temperature much higher than that of the CMB
- Inelegance: two independent solutions required for H_0 and LSS?
  - H_0 depends on background expansion
  - LSS depends on perturbation evolution


THERE ARE THREE MAIN ESTIMATES OF THE UNIVERSE'S EXPANSION RATE AND THEY ALL DISAGREE.
MEASUREMENTS OF STAR DISTANCES SUGGEST THE UNIVERSE IS EXPANDING AT 73 KM/S/MEGAPARSEC.
MEASUREMENTS OF THE COSMIC MICROWAVE BACKGROUND SUGGEST IT'S EXPANDING AT 68 KM/S/MEGAPARSEC.
AND DAVE, WHO HAS A RADAR GUN, SAYS IT'S EXPANDING AT 85 MPH IN ALL DIRECTIONS.
THOSE GALAXIES ARE REALLY BOOKING IT!
THANKS, DAVE.

XKCD 2516

Back-up Slides

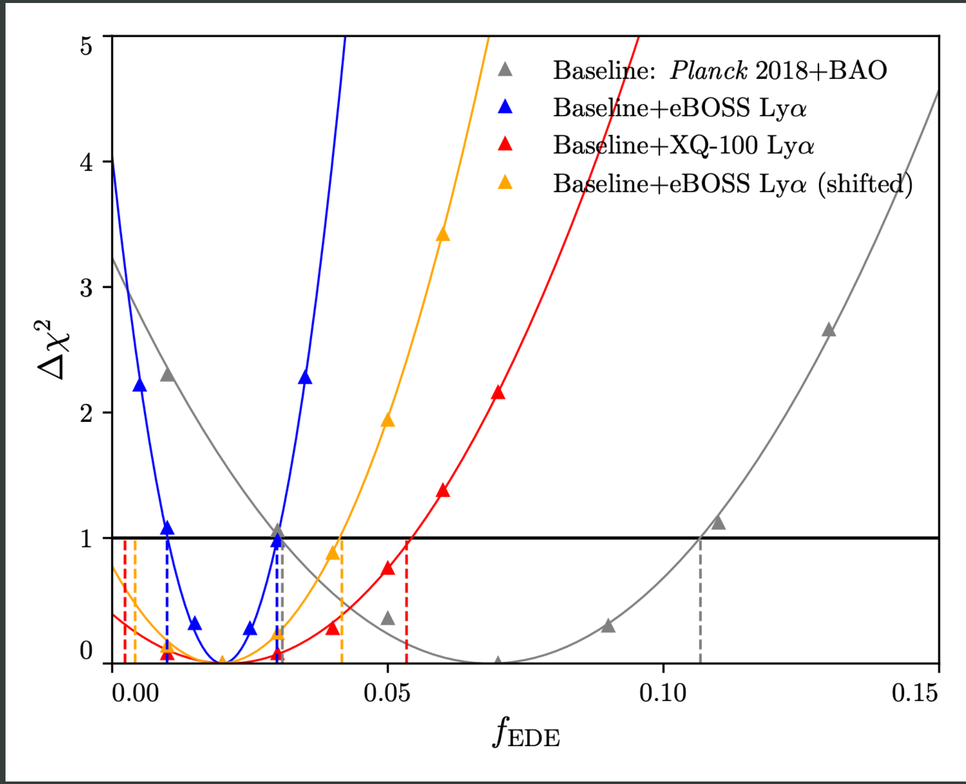
Differentiation in CMB data



Poulin, Smith and TK [2302.09032]

Lyman-α data is in tension with ΛCDM

- Measurements of the Lyman-α forest are in tension with ΛCDM
- Combining with data sets consistent with ΛCDM worsens χ^2 of both
- Lyman-α measurements shifted into consistency with ΛCDM strongly constrain EDE



Goldstein, Hill et al [2303.00746]