Theoretical approaches to cosmic tensions

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Penn

Understanding cosmological observations, Benasque
31st July, 2023

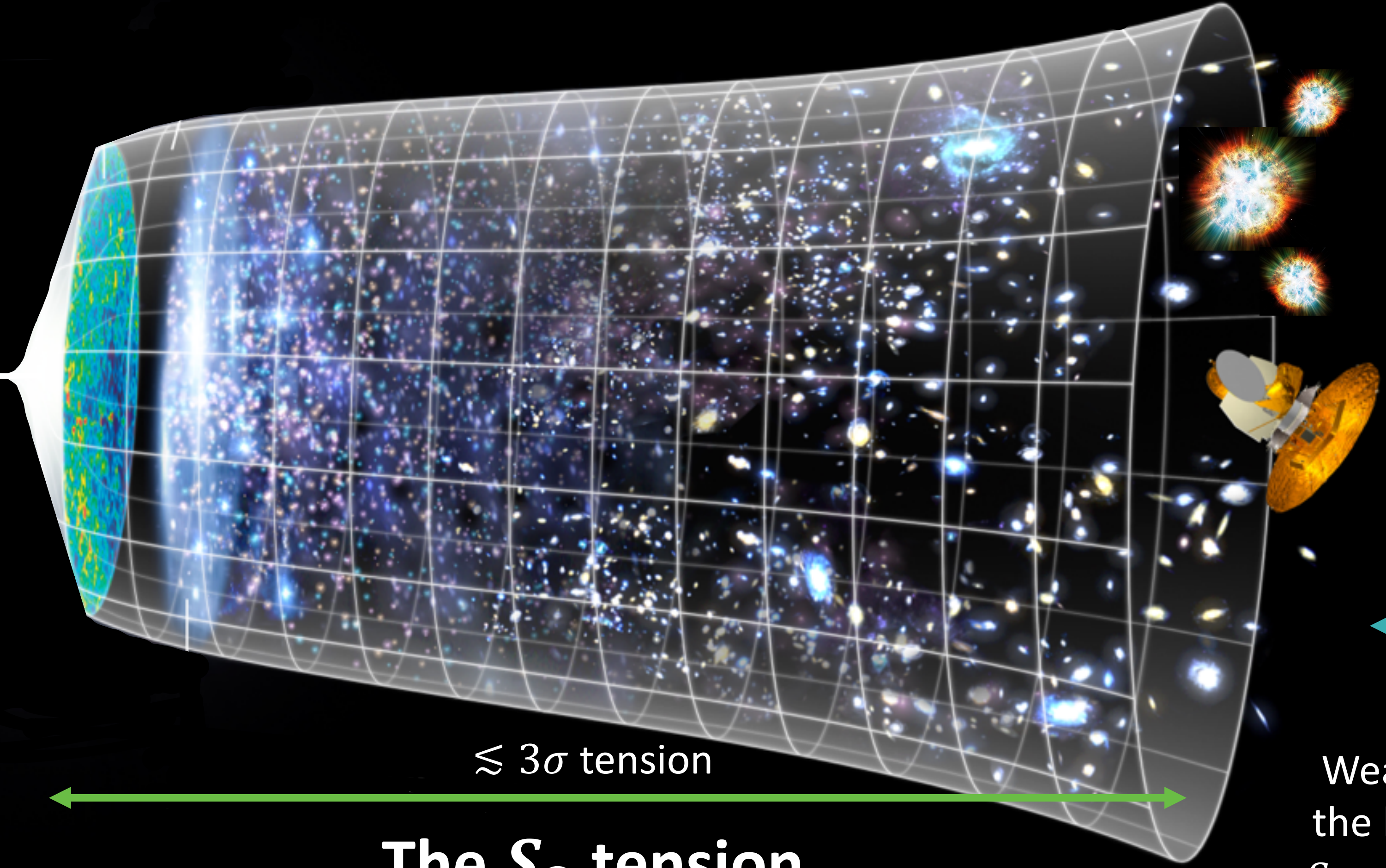
Fit ΛCDM to the CMB
$H_0 = 67.4 \pm 0.5$
km/s/Mpc

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

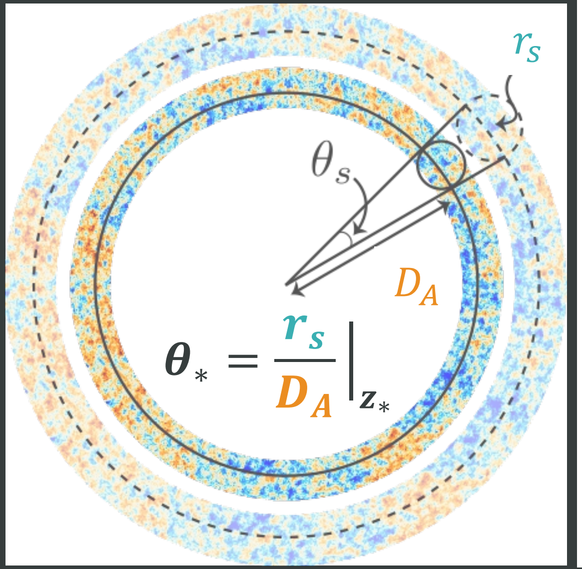
Model-building insights for cosmic tensions

- How to solve the Hubble tension
- Potential H_0 solutions

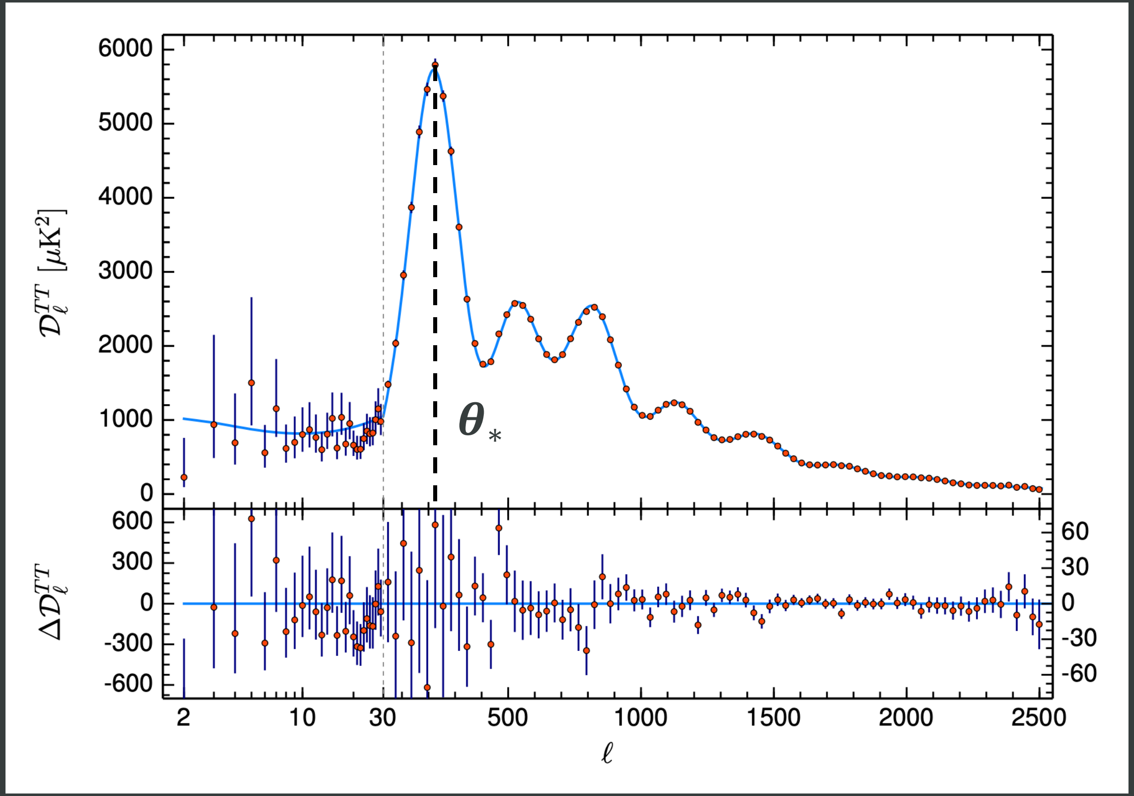
- How to solve the weak-lensing tension
- Potential S_8 solutions

How to solve the Hubble tension

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



Cartoon by Tristan L. Smith



Planck 2018

$$r_s = \int dz \frac{c_s}{H_{pre}}$$
$$= f_{\Lambda CDM}(\omega_b, \omega_c)$$
$$D_A \propto 1/H_{post}$$

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

For constant θ_* ,
$r_s \propto 1/H_0$

In support of an
early-universe modification:

Karwal et al [1608.01309]]
Bernal et al [1607.05617]
Evslin et al [1711.01051]
Planck [1807.06209]
Aylor et al [1811.00537]
Raveri et al [2002.11707]
Schöneberg et al [2107.10291]
…

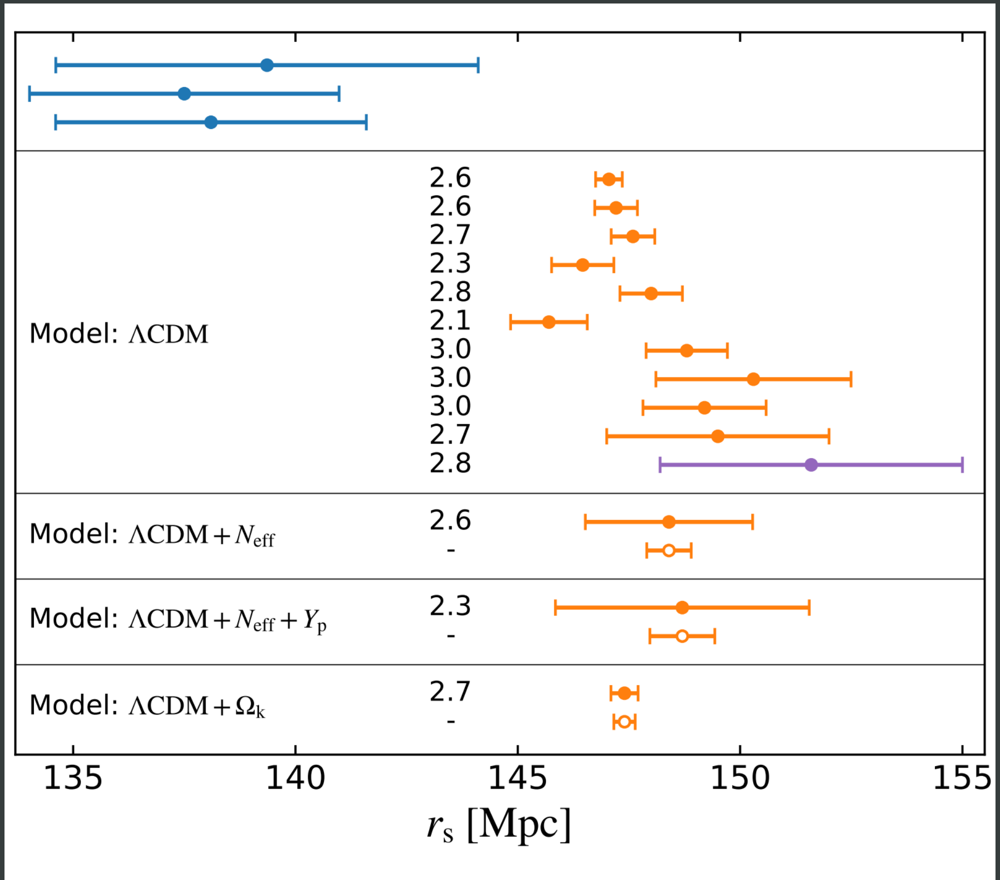
How to solve the Hubble tension

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]

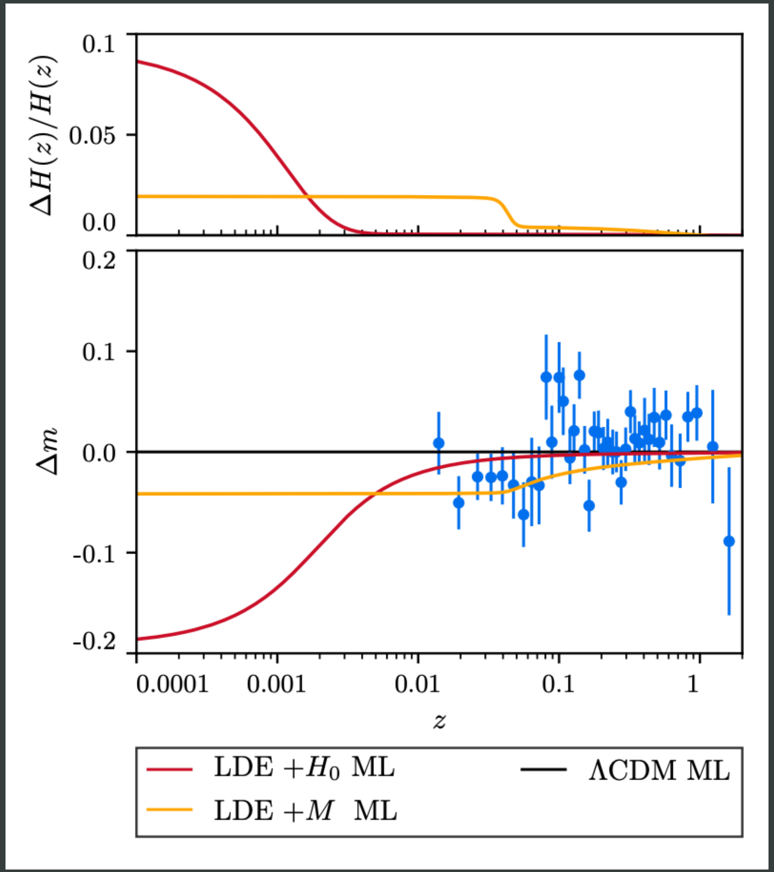
How to solve the Hubble tension

- 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

How not to solve the Hubble tension

Late transitions in dark energy

- The distance-ladder H_0 is not actually a measurement at $z = 0$
- The true source of the tension is at $z \simeq 0.15$
- Late proposals of resolution must target the SN absolute magnitude calibration M_b



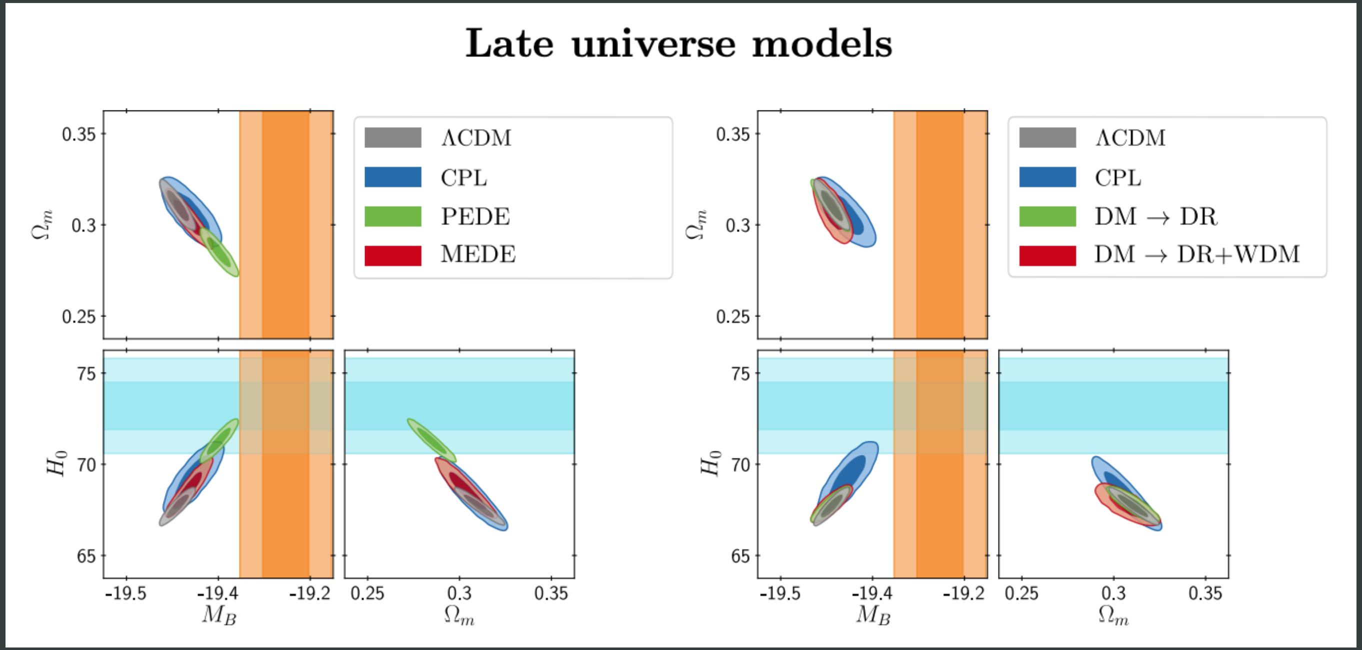
Benevento, Hu, Raveri [2002.11707]

Also Bernal et al [2102.05066]

Efstathiou [2103.08723]

How not to solve the Hubble tension

Schöneberg et al [2107.10291]



Late-universe solutions are strongly constrained by data

- CMB lensing
- CMB low-ℓ ISW
- CMB-BAO agreement
- Pantheon supernovae

How to solve the Hubble tension

- Decrease the sound horizon r_s to increase the predicted H_0. So new physics must be added before the CMB
- New physics must vanish post recombination
  - Very-late $H(z)$ modifications do not resolve the tension more correctly parameterised by M_b
  - Modifications to D_A introduce new tensions between CMB and BAO
  - Late-universe modifications to $w(z)$ are tightly constrained by supernovae

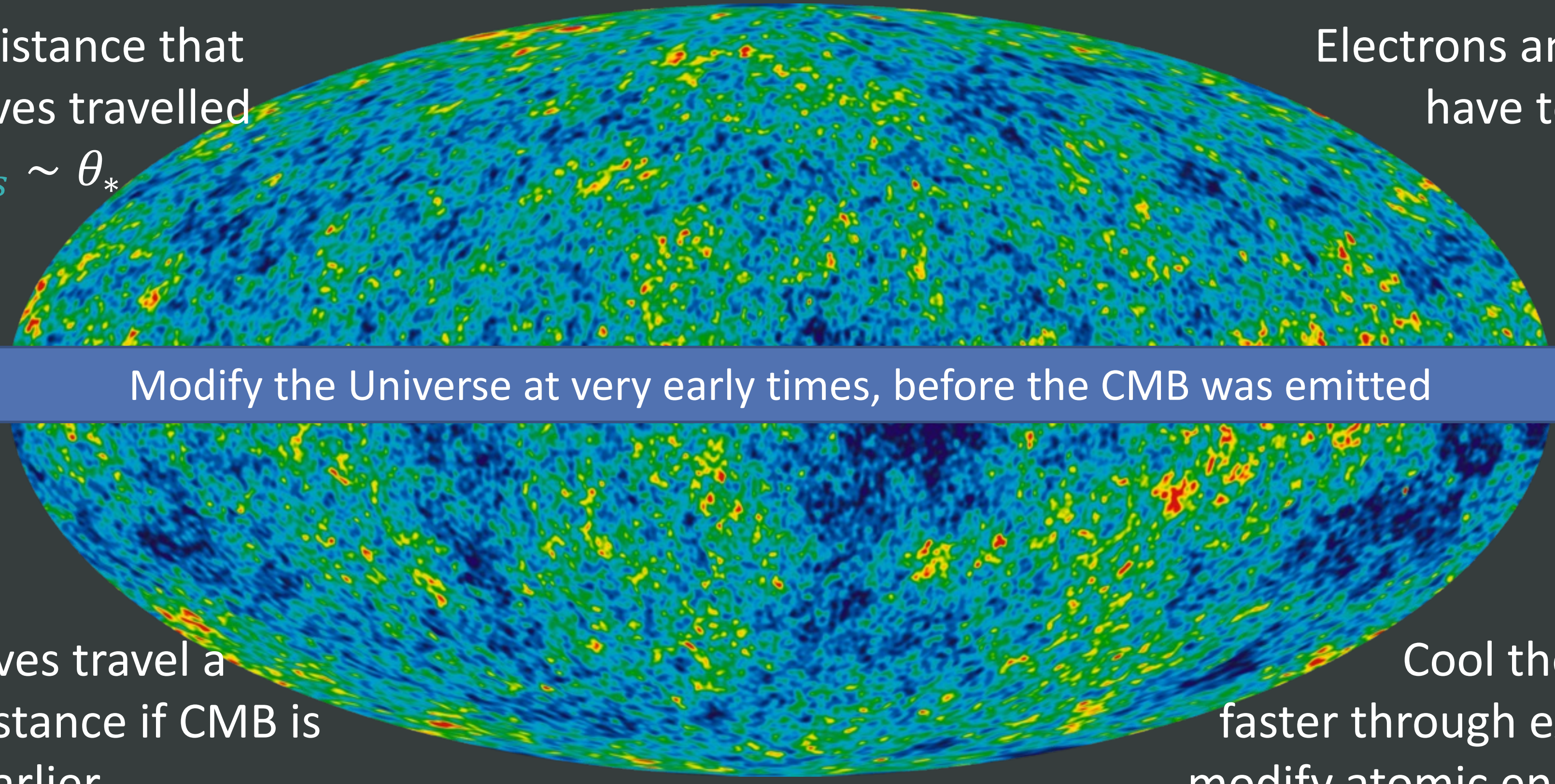
Models that work

- Early dark energy
- Early modified gravity / coupled scalar fields
- Varying the electron mass
- Certain dark radiation models

Models that work

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

Electrons and protons have to combine sooner



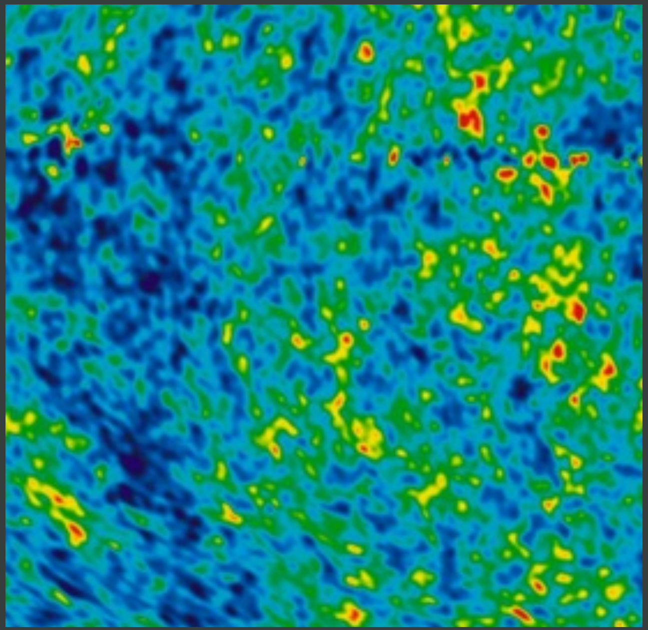
Modify the Universe at very early times, before the CMB was emitted

Sound waves travel a shorter distance if CMB is emitted earlier

Cool the Universe faster through expansion / modify atomic energy levels

WMAP, NASA

Models that work

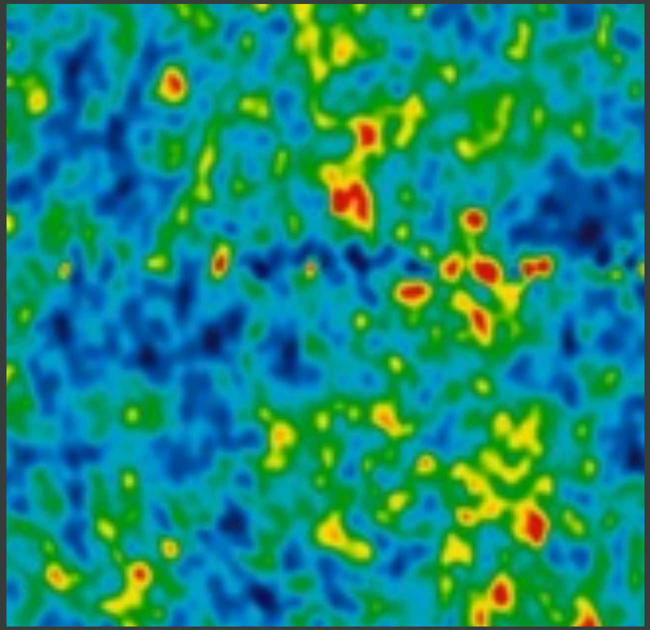


Observed CMB

Increase
H_0

Add modification to early ΛCDM

Decrease
r_s



Disagreement with observed CMB

Models that work
Early dark energy

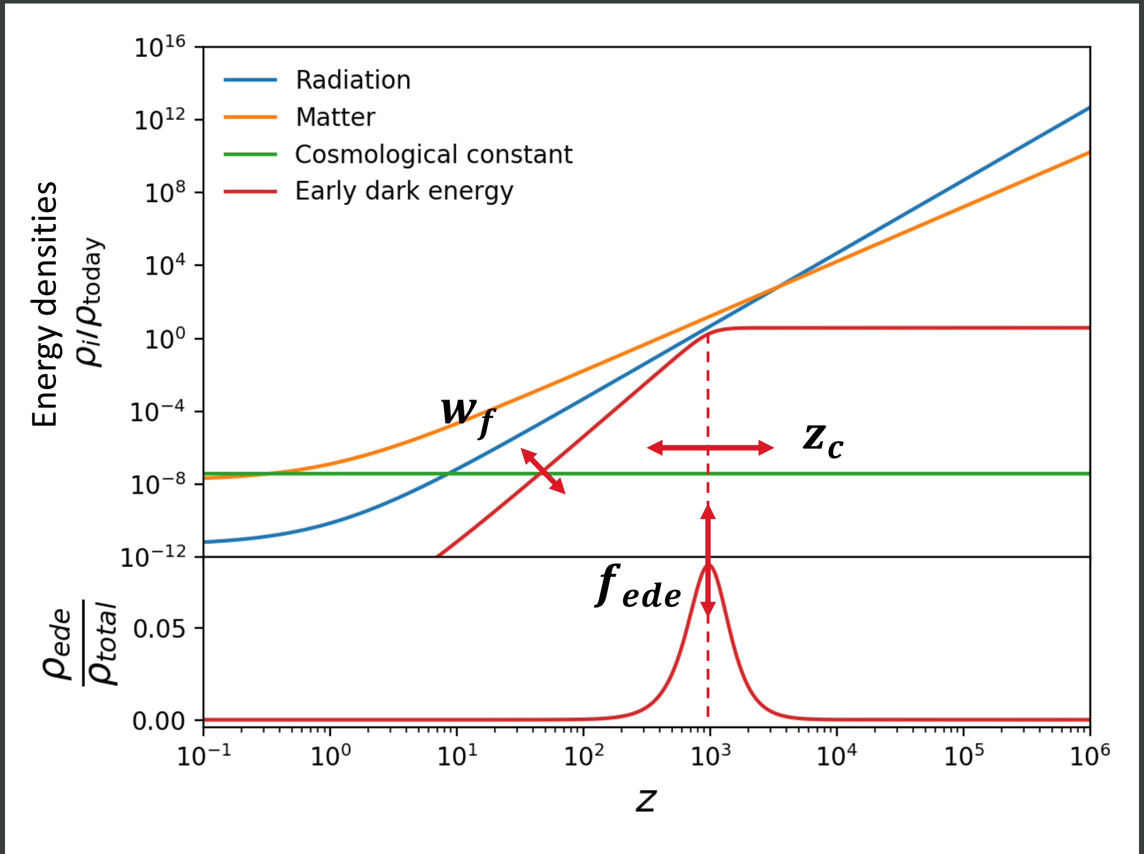
$$H^2 \sim \rho_{total}$$

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



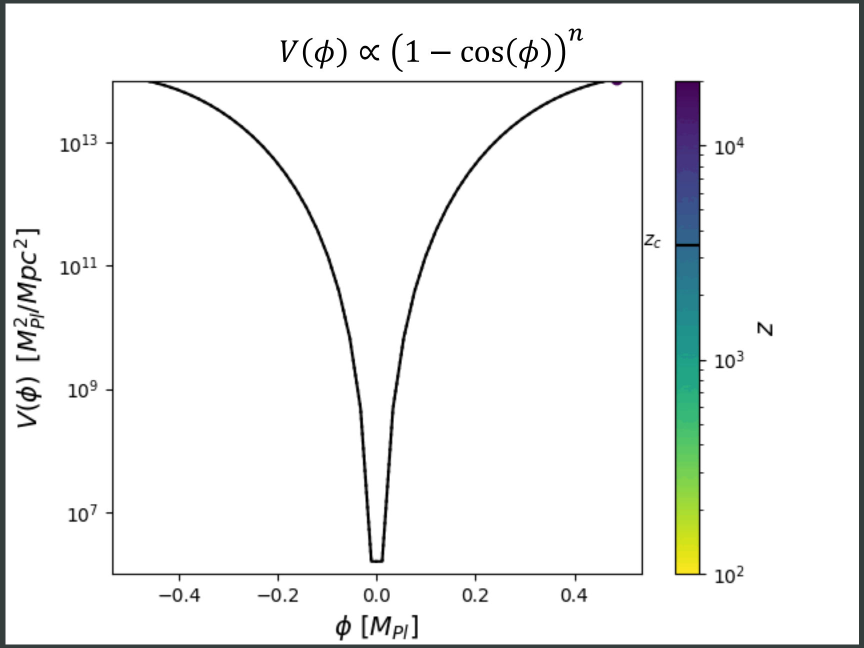
Models that work
Early dark energies

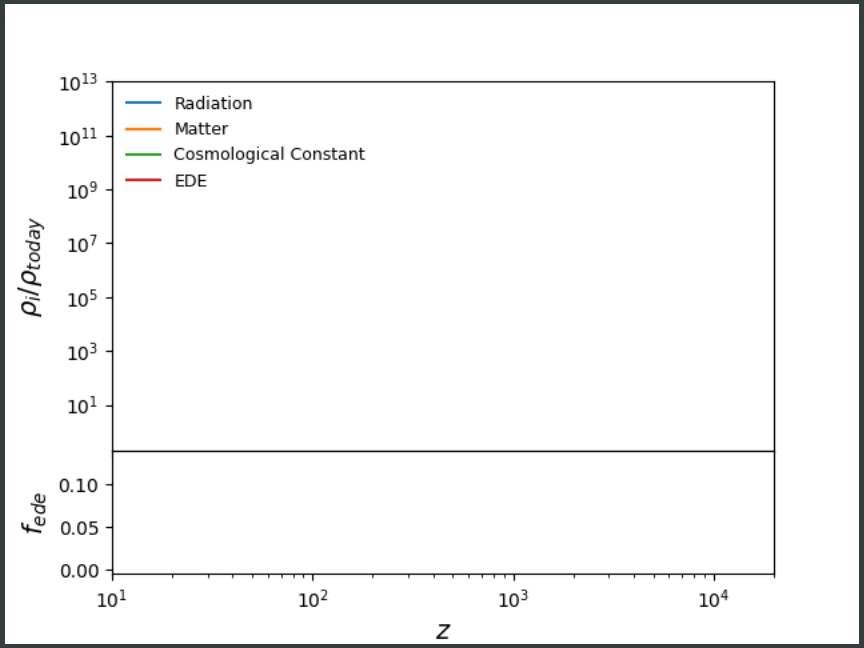
- Dark energy at early times, the Hubble parameter, and the string axiverse
  TK & Kamionkowski [1608.01309]
- Cosmological implications of ultralight axionlike fields
  Poulin, TK et al [1806.10608]
- Early Dark Energy Can Resolve The Hubble Tension
  Poulin, TK et al [1811.04083]
- Thermal Friction 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]
- Also ask Kim Boddy, José Luis Bernal and Anthony Lewis

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]
- …

Models that work
Early dark energy – Ultra-light axions EDE





Based on Poulin, Smith, TK, Kamionkowski
[arxiv:1806.10608]

Models that work
Early dark energy – ULA

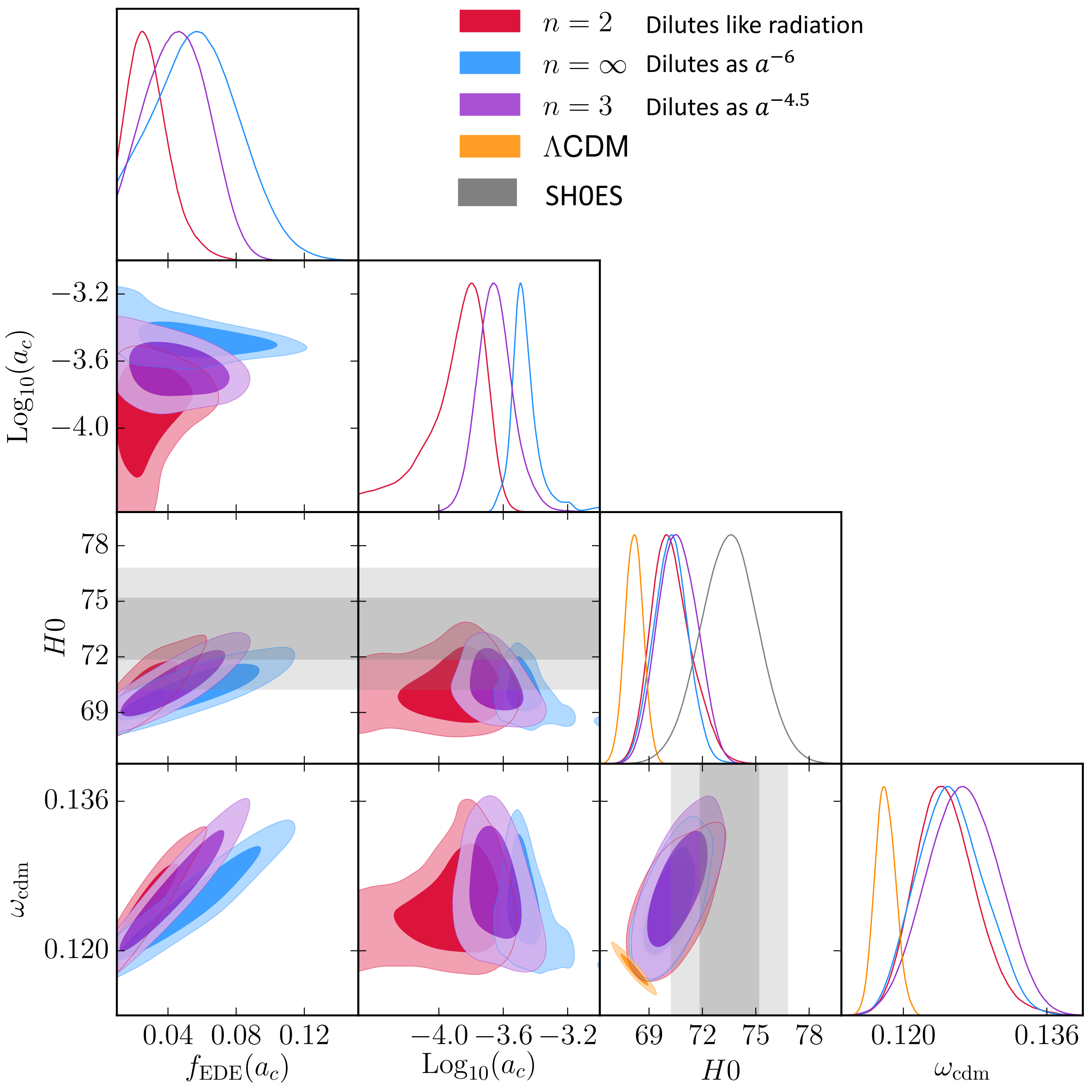
Fit to CMB+BAO+SNe+H0

- 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

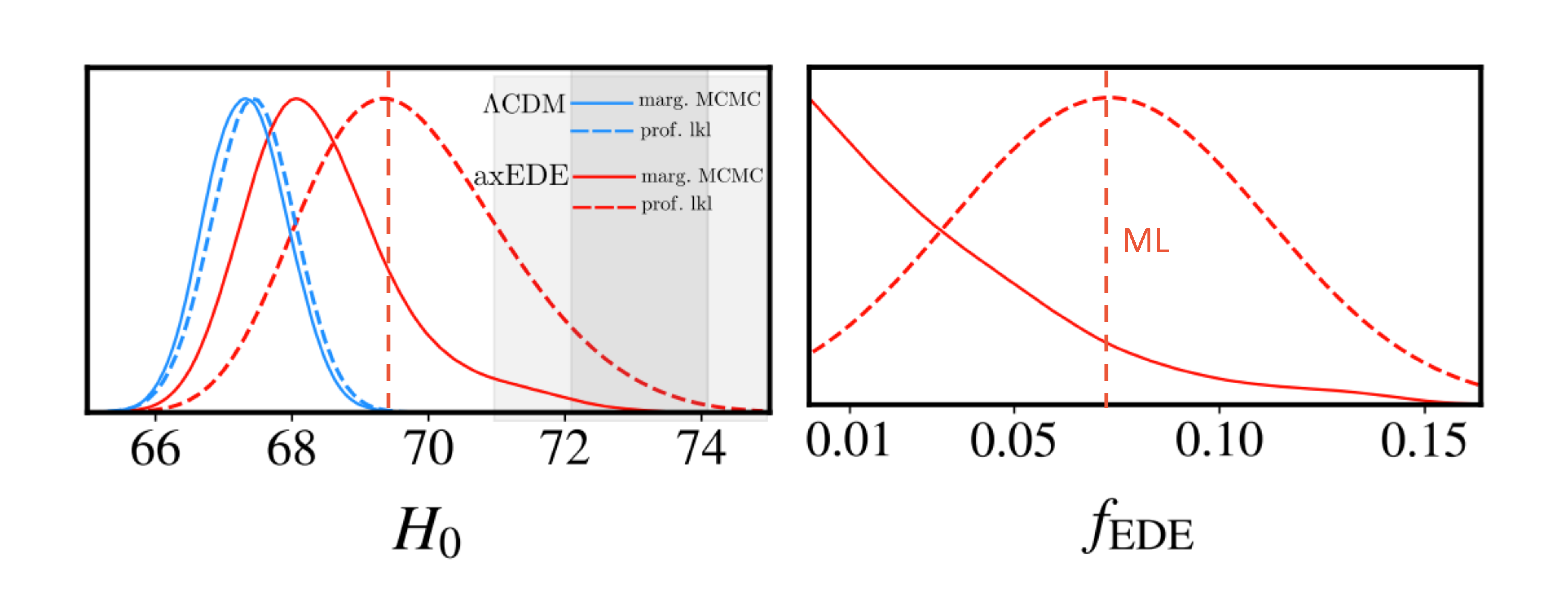
Poulin, TK et al [1811.04083]



Models that work
Early dark energy – without a SH0ES prior

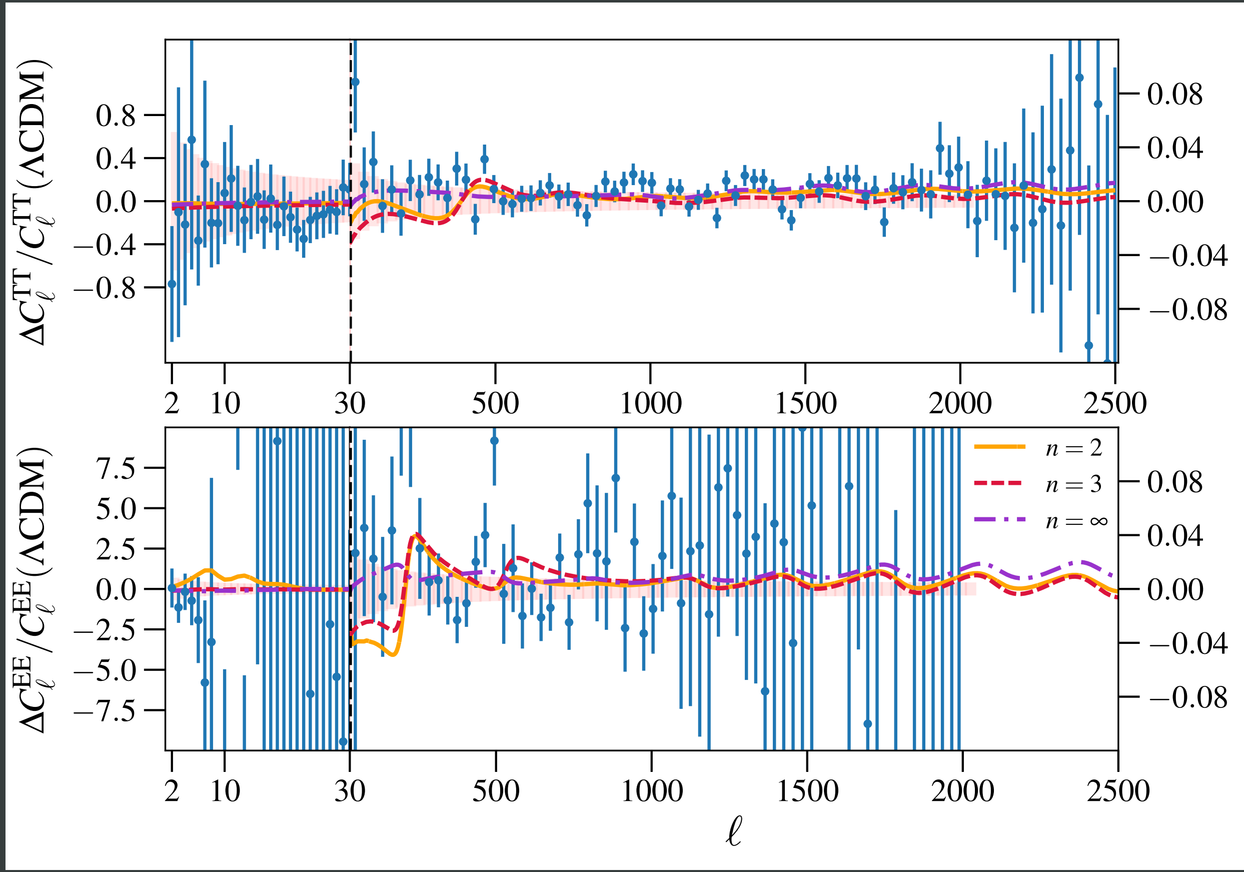
Fit to CMB+BAO+SNe, no H_0 prior

Prior volume increases as $f_{ede} \to 0$
z_c and w_f become unconstrained



Poulin, Smith and TK [2302.09032]

Models that work
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 show preference for EDE at $\geq 3\sigma$ level when high-ℓ CMB TT data is excluded

Smith et al [2202.09379]
Hill et al [2109.04451]

Also
Lin et al [2009.08974]
Chudaykin et al [2004.13046] and [2011.04682]

Models that work
Chameleon early dark energy

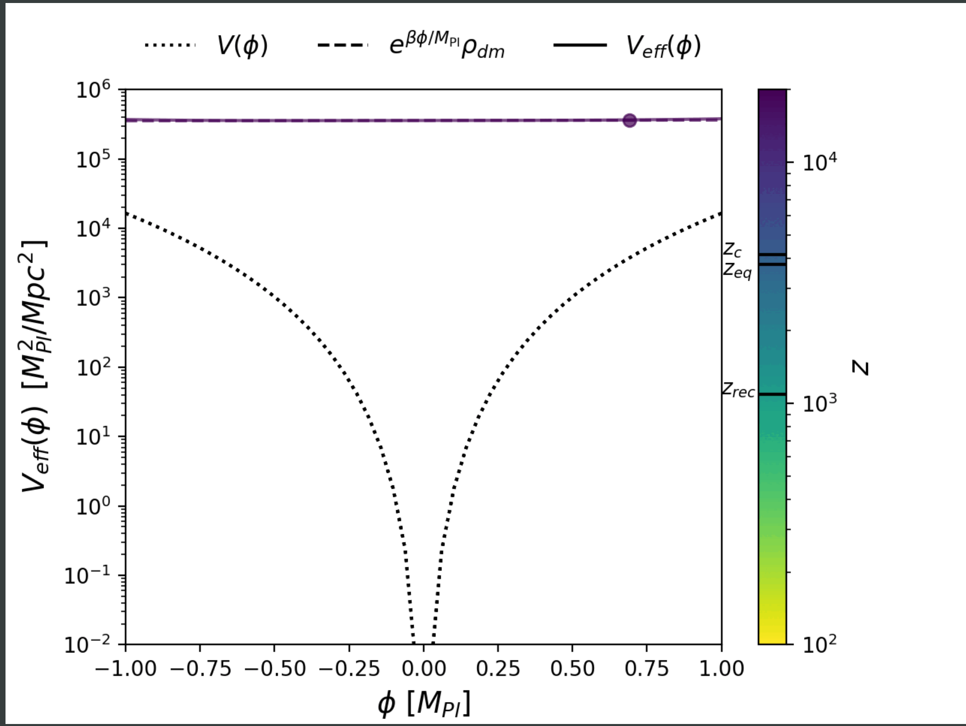
Conformally couple a scalar field to dark matter

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

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

- 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]

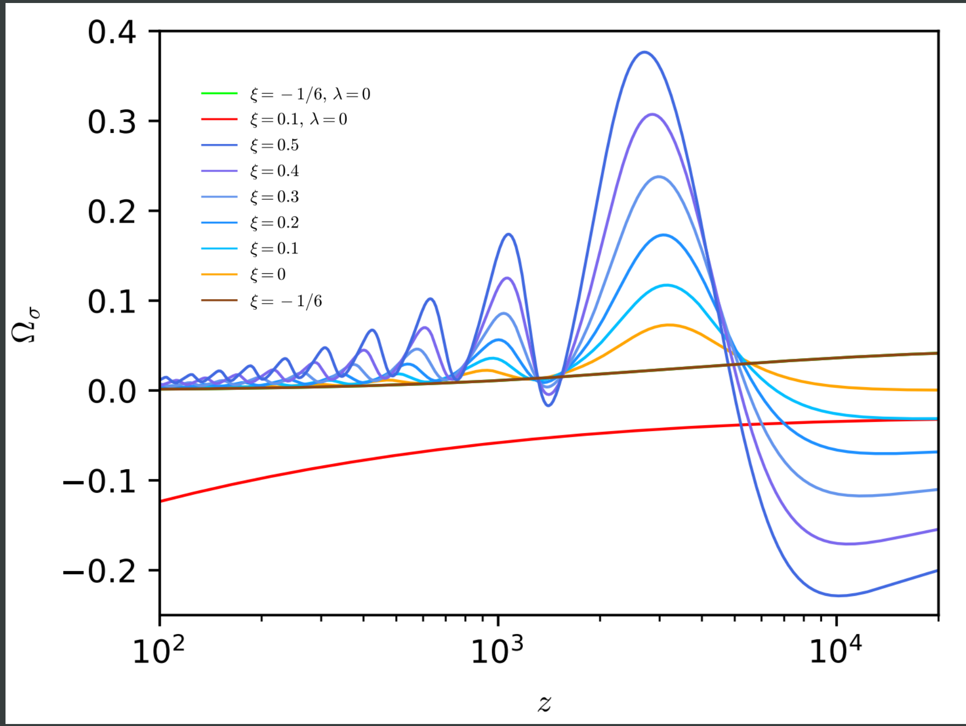
Models that work
Early modified gravity

Early dark energy scalar field σ coupled to the Ricci scalar R

$$\mathcal{S} \ni \int d^4x\sqrt{-g}\,\frac{\xi\sigma^2}{2}R$$

Similar EDE models that introduce couplings to DM/ν:

- Neutrino-assisted EDE
  Sakstein and Trodden [1911.11760]
- Chameleon EDE
  Karwal et al [2106.13290]
- Early dark sector
  McDonough et al [2112.09128]
  Lin et al [2212.08098]

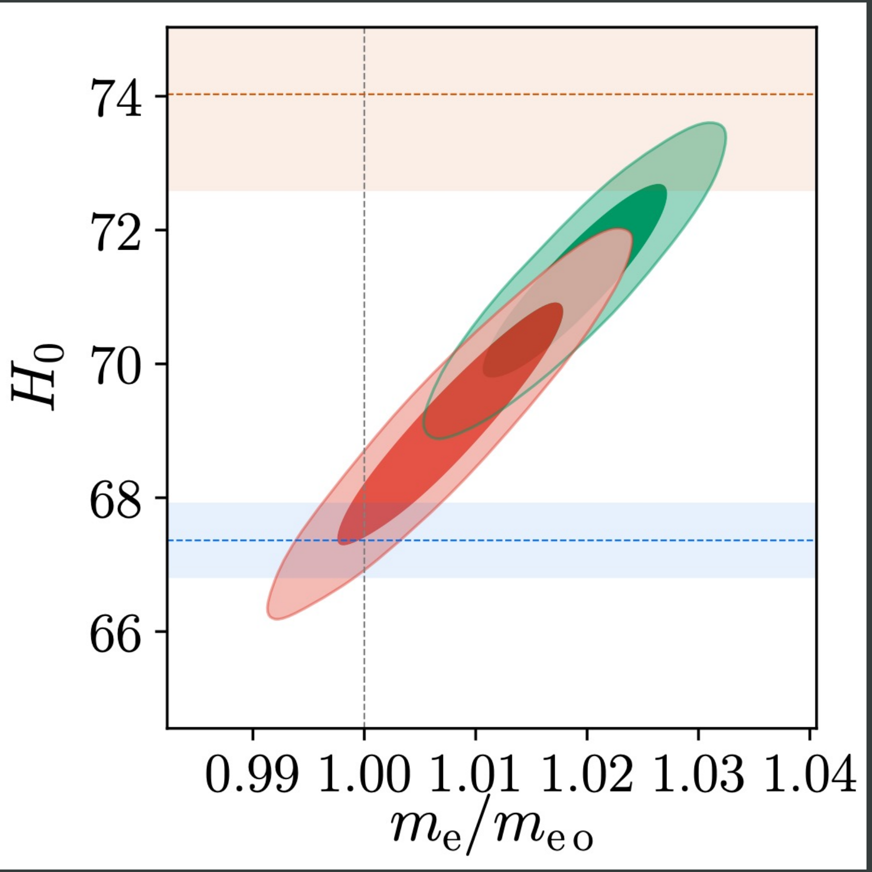


Braglia et al [2011.12934]

Models that work
Varying the electron mass m_e

- Atomic energy levels $\propto m_e$
- Higher ionisation energy for H
- Earlier recombination
- Smaller r_s

Also Sekiguchi and Takahashi [2007.03381]



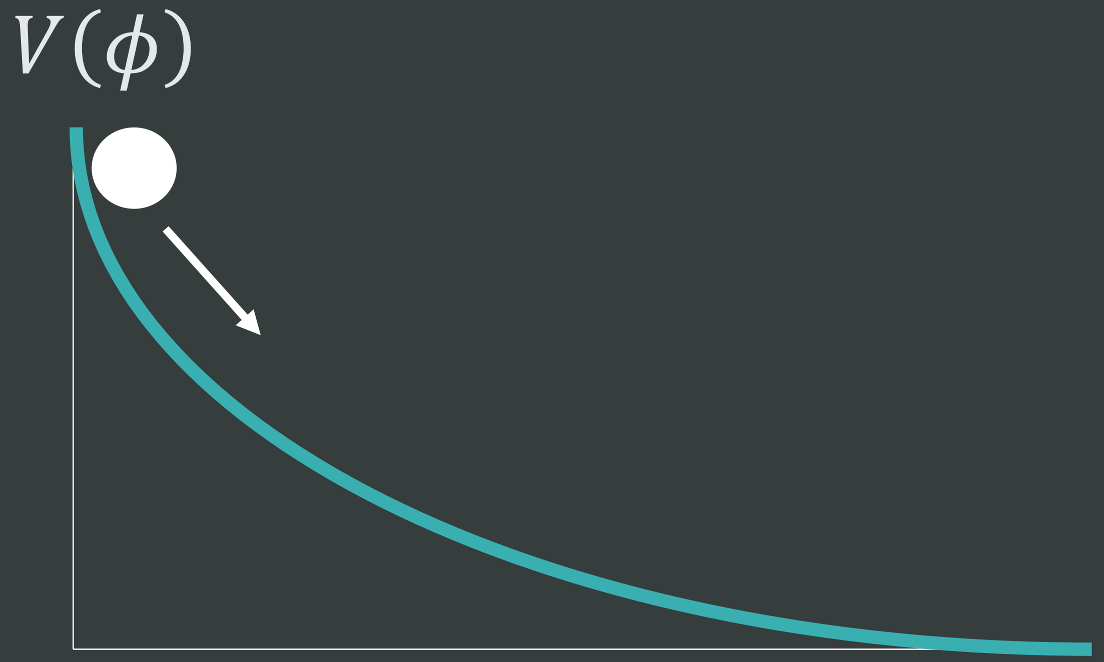
Hart and Chluba [1912.03986]

Models that work ?
Dark radiation – Dissipative axion EDE

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

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

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



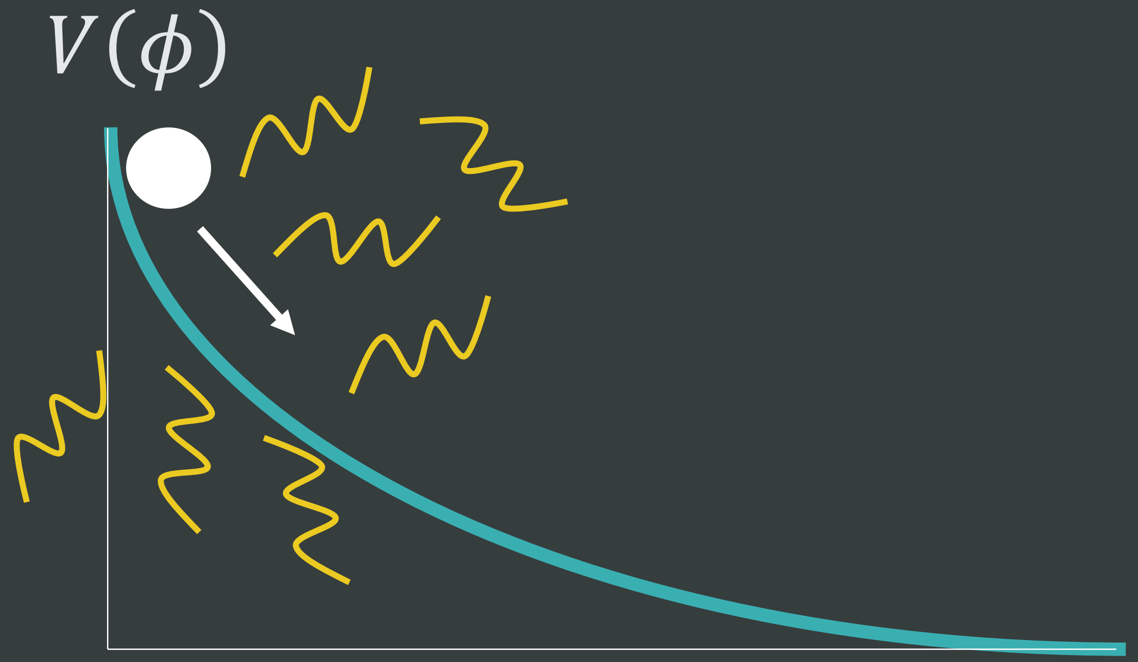
Berghaus & Karwal [1911.06281]

Models that work ?
Dark radiation – Dissipative axion EDE

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]

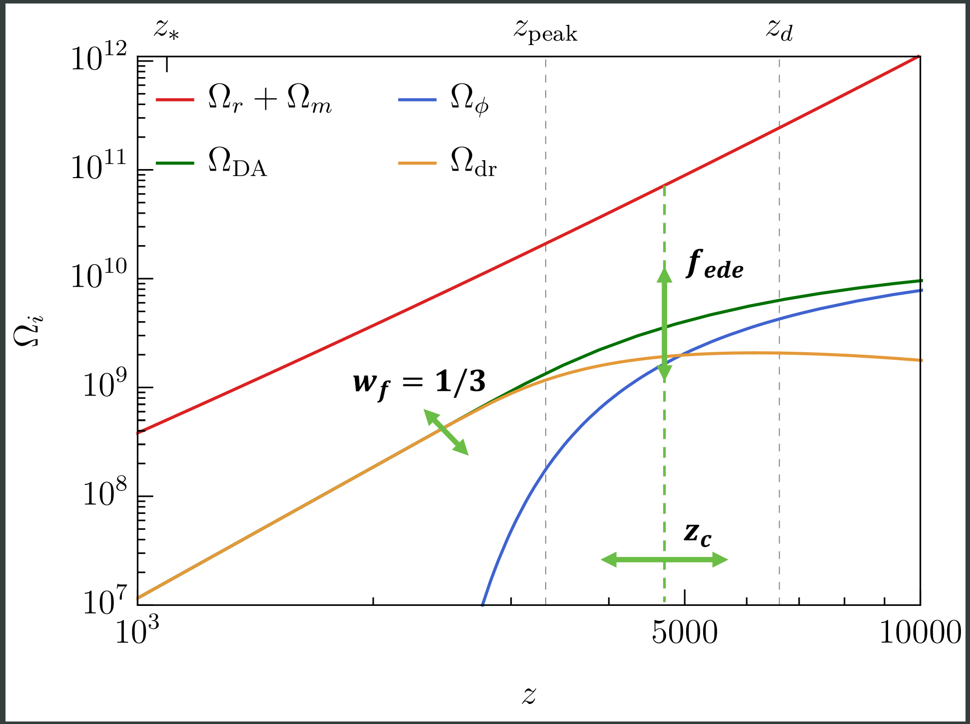
Models that work ?
Dark radiation – Dissipative axion EDE

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

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

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

Robust to choice of $V(\phi)$



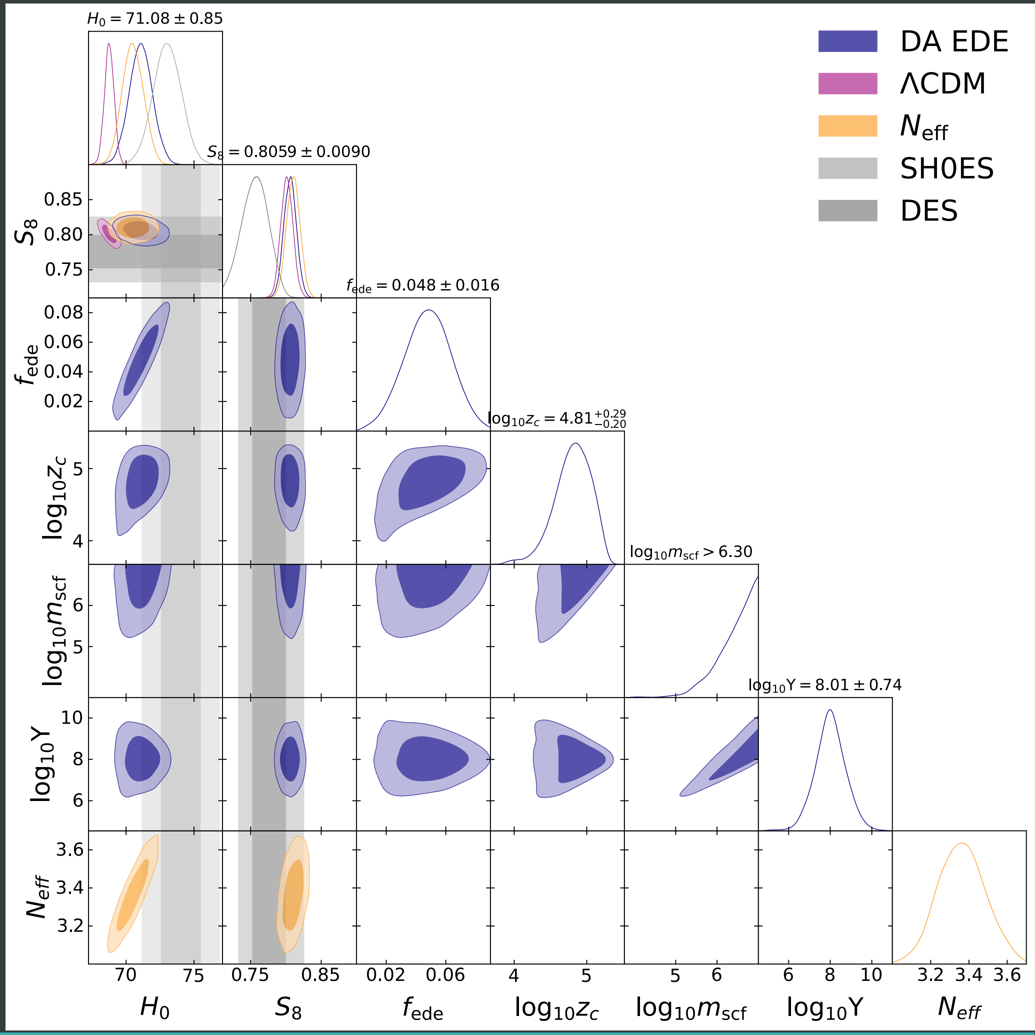
Berghaus & Karwal [1911.06281]

Models that don't work
Dark radiation – Dissipative axion EDE

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 & TK [2204.09133]

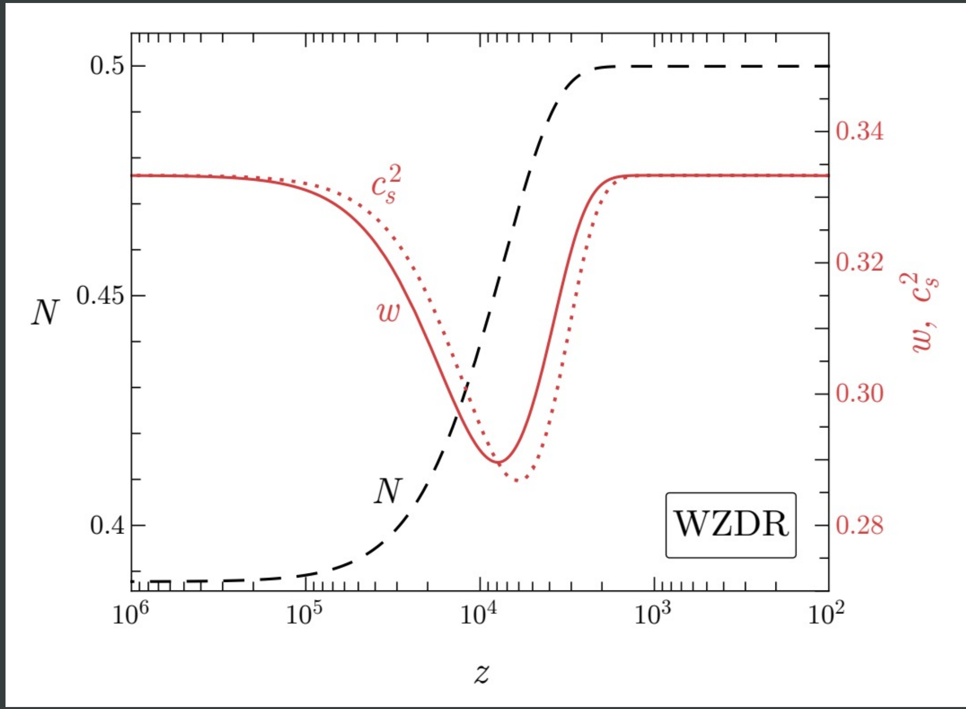
Models that work
Certain dark radiation models

Not all DR models work:

- N_{eff} – Planck [1807.06209]
- DA EDE – Berghaus and TK [2204.09133]
- Free-streaming / self-interacting DR, both Brinckmann et al [2012.11830]
- SIDR that scatters on DM see Schöneberg et al [2107.10291]
- SI-ν and free-streaming DR Kreisch et al [1902.00534] and others
- SI-ν with an energy injection Sandner et al [2305.01692]

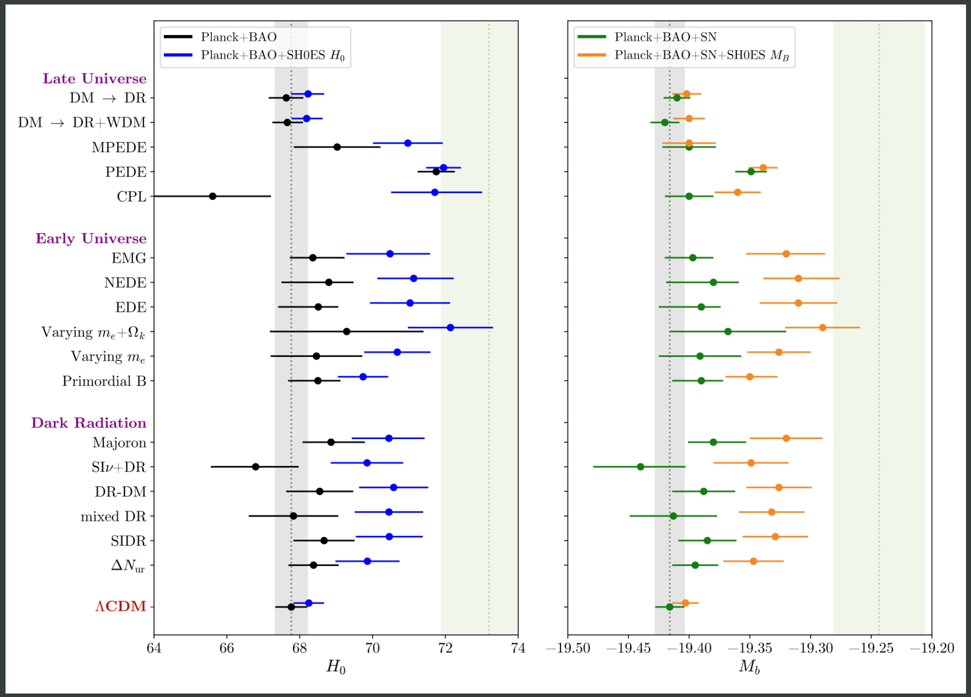
But some do:

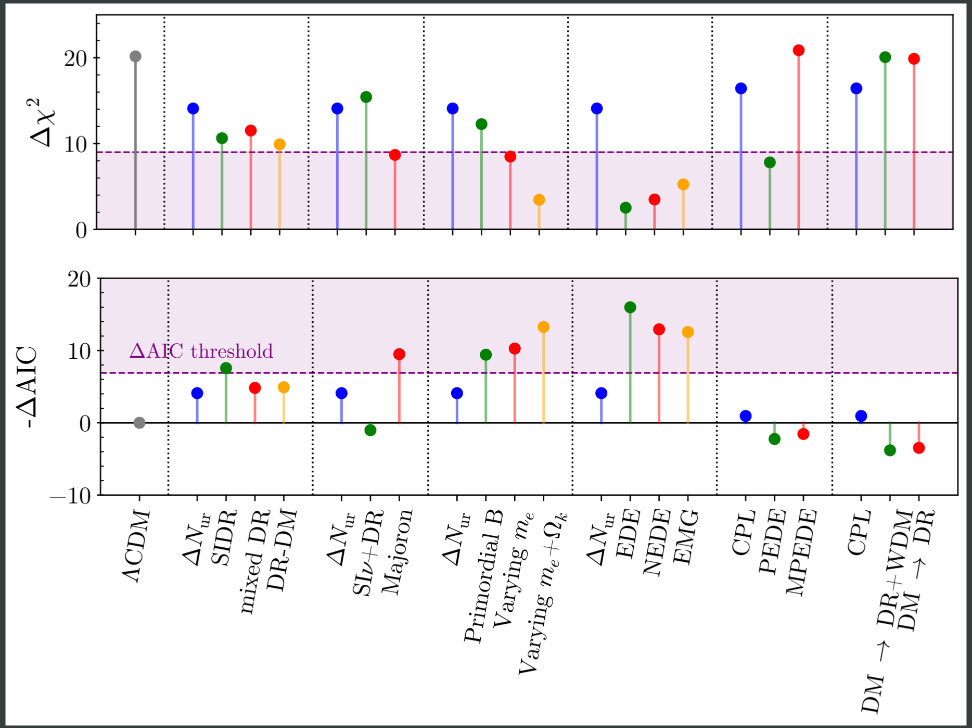
- WZDR - SIDR with an energy injection →



Aloni et al [2111.00014]

Models that work
Posteriors and χ^2's





Schöneberg et al [2107.10291]

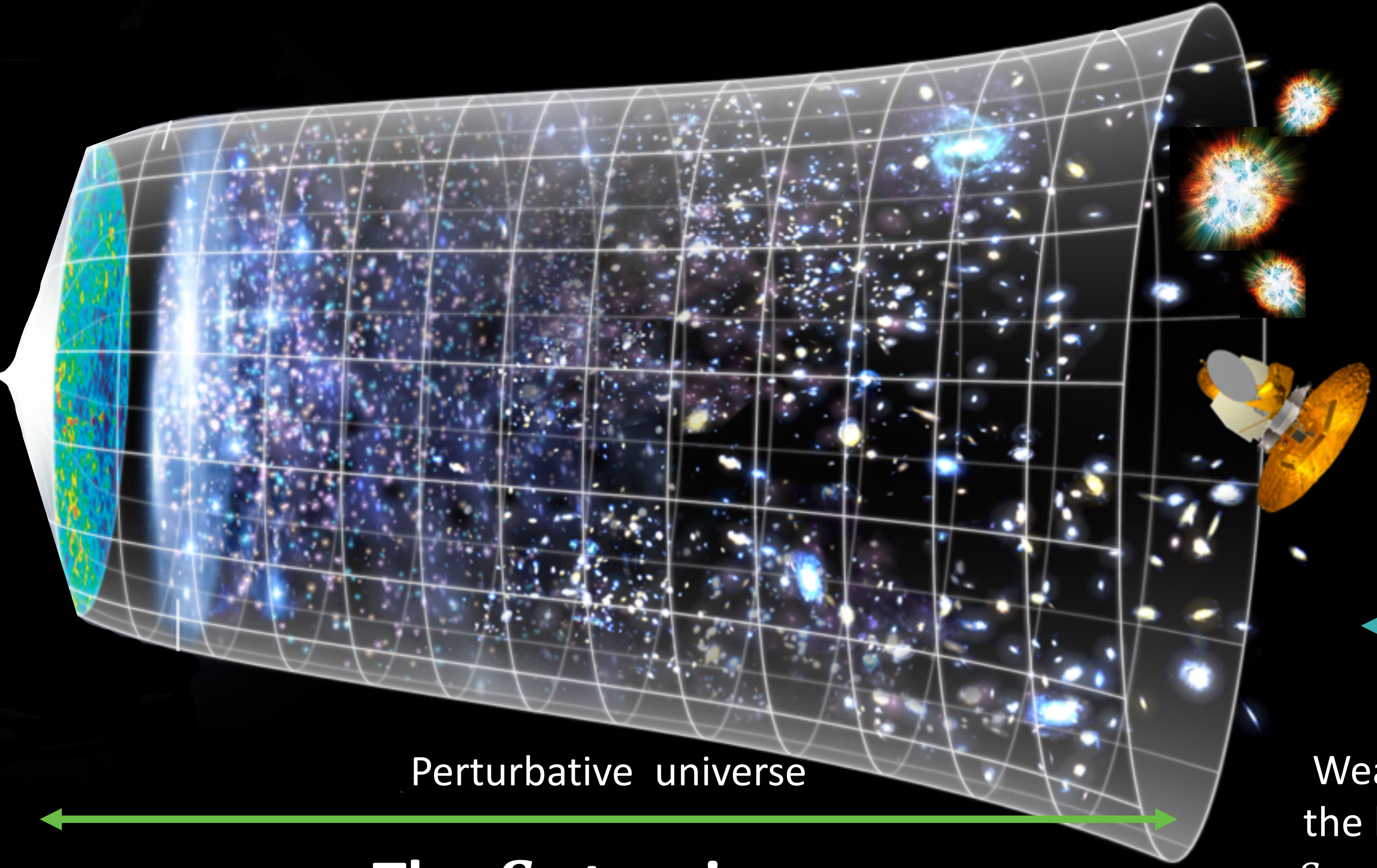
Fit ΛCDM to the CMB
$H_0 = 67.4 \pm 0.5$
km/s/Mpc

Homogeneous, isotropic background

The Hubble tension

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

Cosmic microwave background



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

Perturbative universe

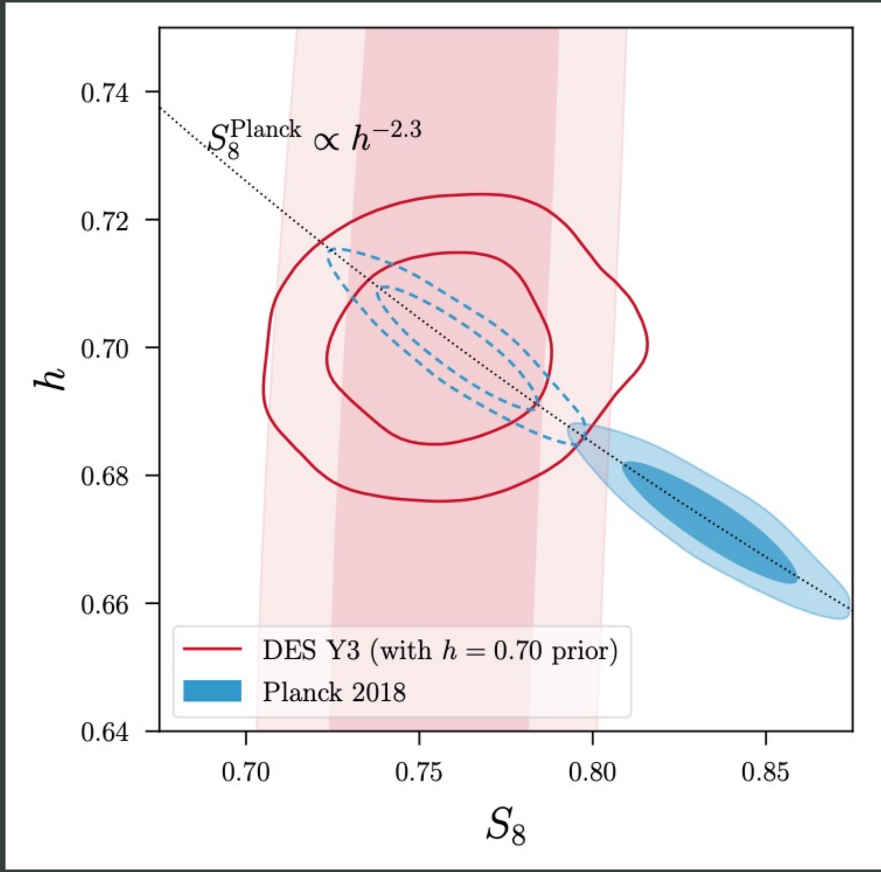
The S_8 tension

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

NASA/WMAP Science Team

How to solve the S_8 tension

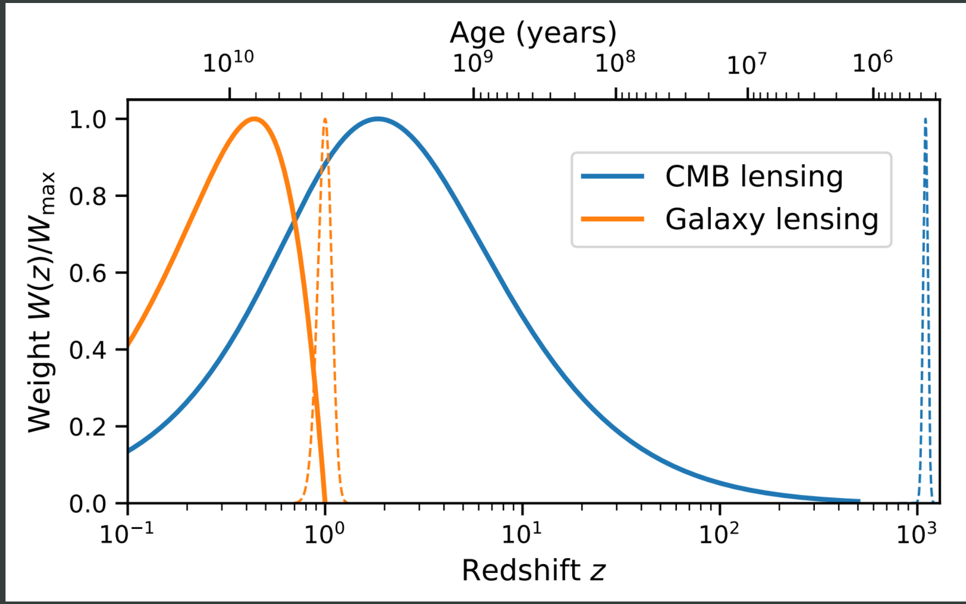
- CMB and WL are both model-dependent
- $S_8 = \sigma_8\sqrt{\Omega_m/0.3}$ in WL
  - Best-constrained parameter direction
  - Independent of H_0
- S_8 in CMB
  - Complicated function of $(\omega_b, \omega_c, A_s, n_s, h, G)$
  - Both background and perturbations



Secco, TK, Krause, Hu
[2209.12997]

How to solve the S_8 tension

- CMB lensing does not find tension
- Peak sensitivity at different redshifts
  → when to introduce new physics
  - Late-universe H_0 tension caveats apply
- Probe different scales → what scales to impact



Madhavacheril, ACT [2304.05203]
And numerous ACT members at Bensaque

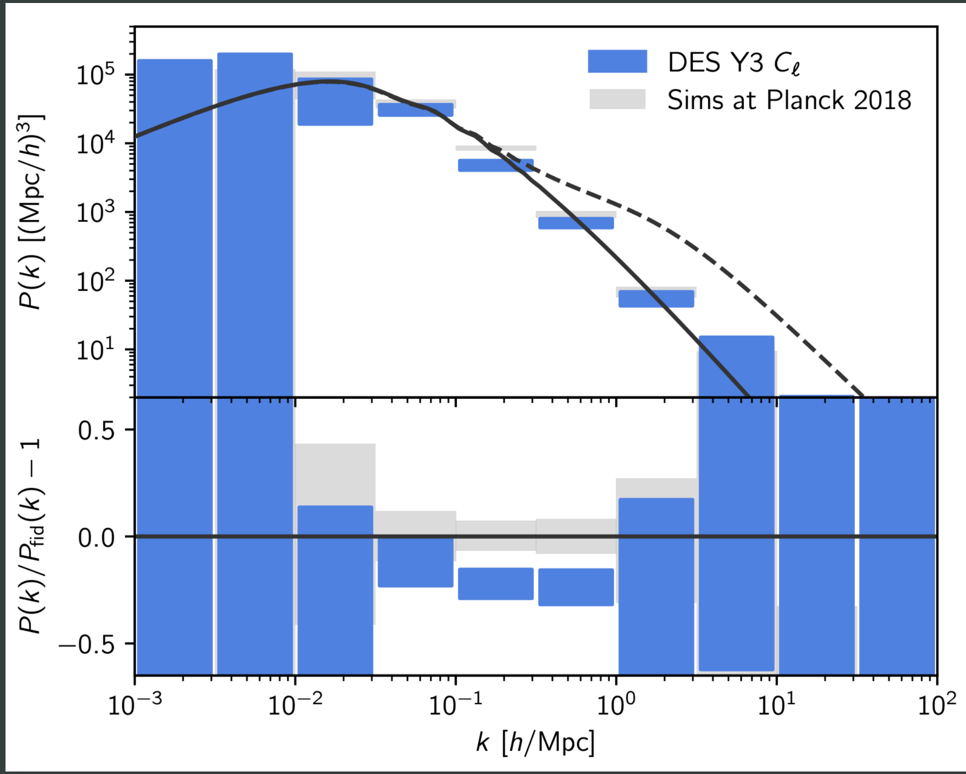
How to solve the S_8 tension

Consistency test between DES and Planck:

- Fix cosmology to Planck 2018
- Predict Planck linear $P(k)$ at $z = 0$
- Use DES C_ℓ to predict linear $P(k)$ at $z = 0$

Observe scale-dependent suppression of power

New physics can target these scales to improve the tension



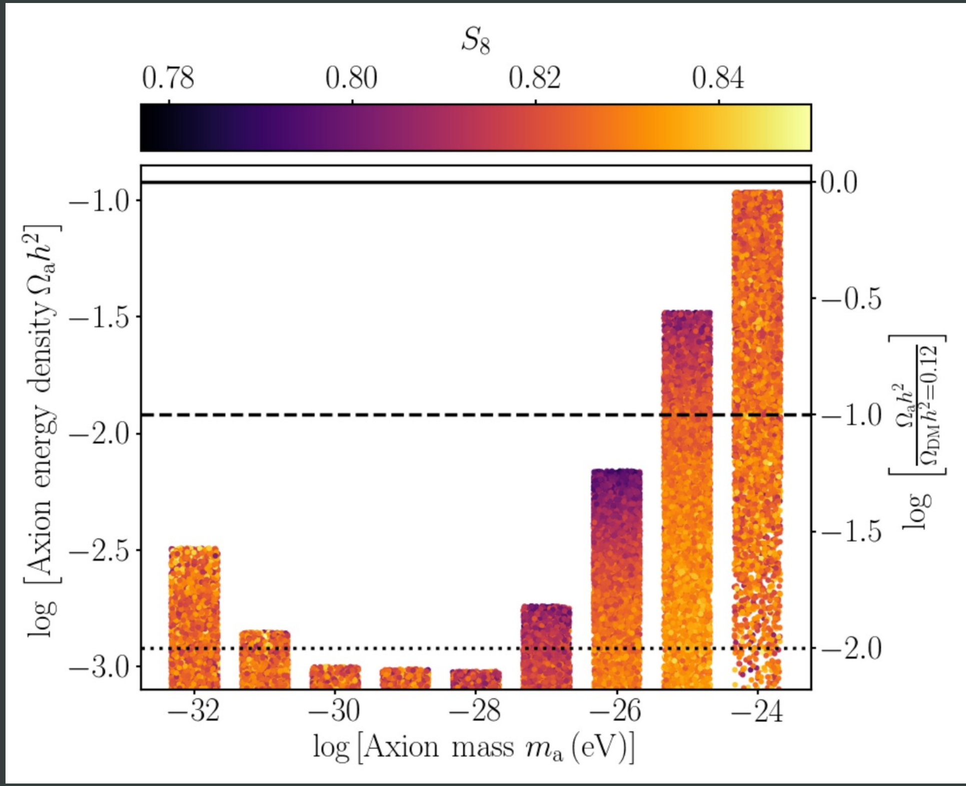
Doux et al [2203.07128]

Models that work
But worsen the H_0 tension

Ultra-light axions in the mass range
$10^{-28}\, eV \leq m_a \leq 10^{-25} eV$

- Injected pre-recombination
- Form a fraction of DM today
- Reduce S_8 tension to 1.6σ
- Worsen H_0 tension because the energy injection lingers in the late universe

Ask Mateja Gosenca about ULA DM

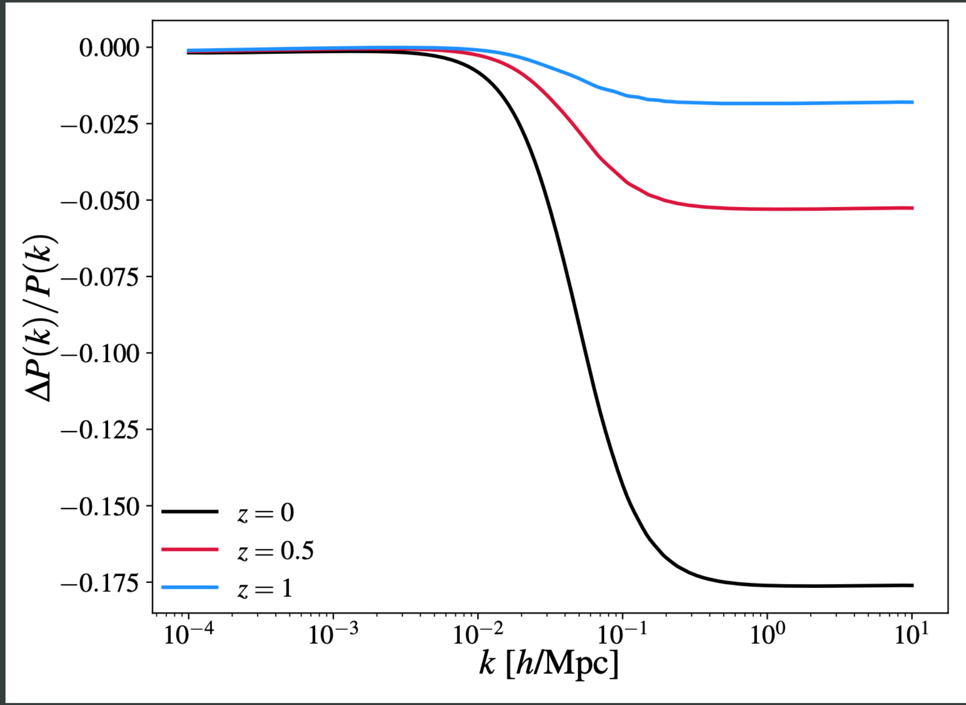


Rogers et al [2301.08361]

Models that work
Perturbative modifications

Friction drag between DM and DE

- Turns on around matter-DE equality
- Resolves the tension
- Possible non-linear imprints in WL
- No modification to background

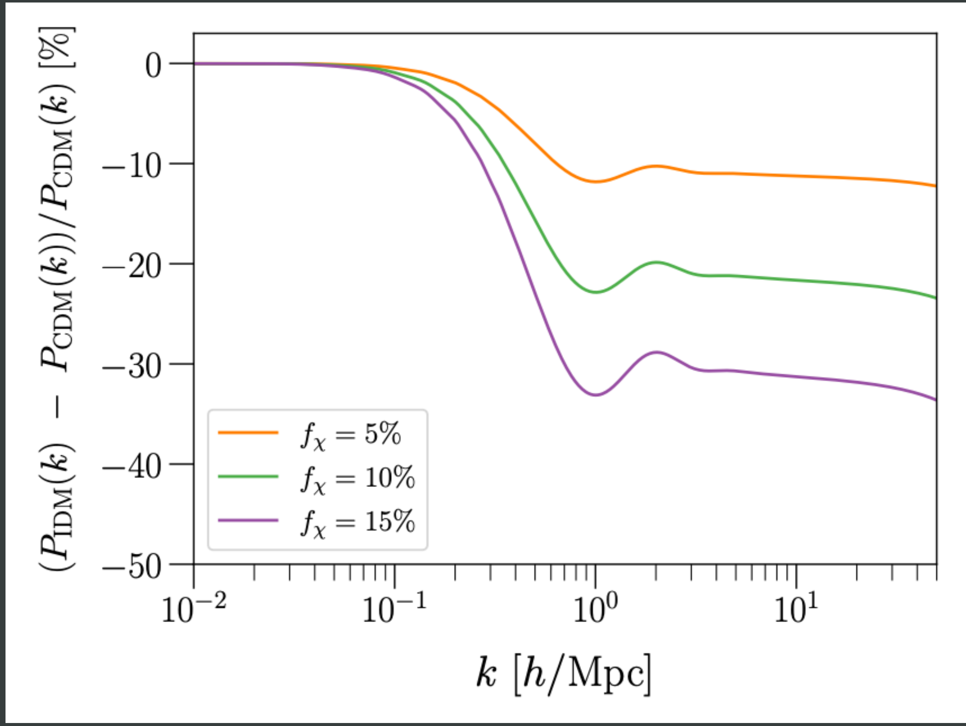


Poulin et al [2209.06217]

Models that work
Perturbative modifications

Fraction of DM scatters off baryons

- 10% DM of mass $1\ MeV$ interacts
- Small-scale power suppressed
- No background modifications



He et al [2301.08260]

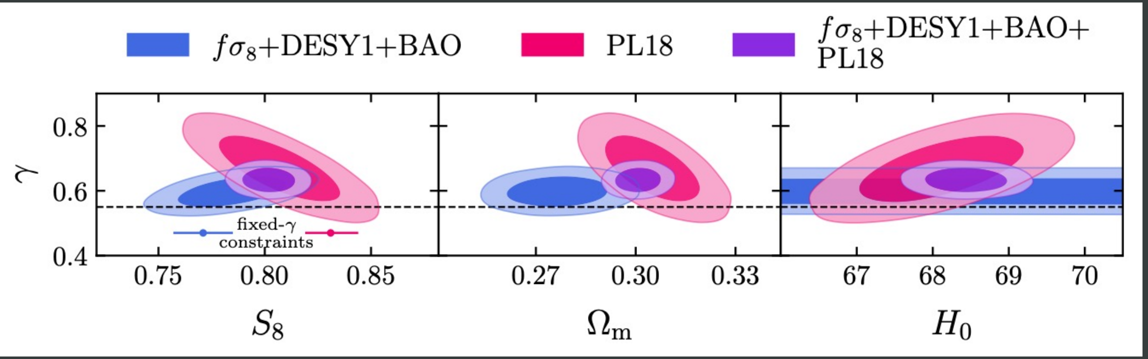
Models that work
Phenomenological insight

Allow growth index γ to vary

$$f(a) = \Omega_m^{\gamma}(a)$$

relative to $\gamma_{\Lambda CDM} = 0.55$

- $\gamma > 0.55$ implies suppression of growth
- $\gamma = 0.55$ excluded at $\sim 4\sigma$
- Shifts both WL and CMB S_8 resolving tension
  - WL S_8 increases
  - CMB S_8 decreases

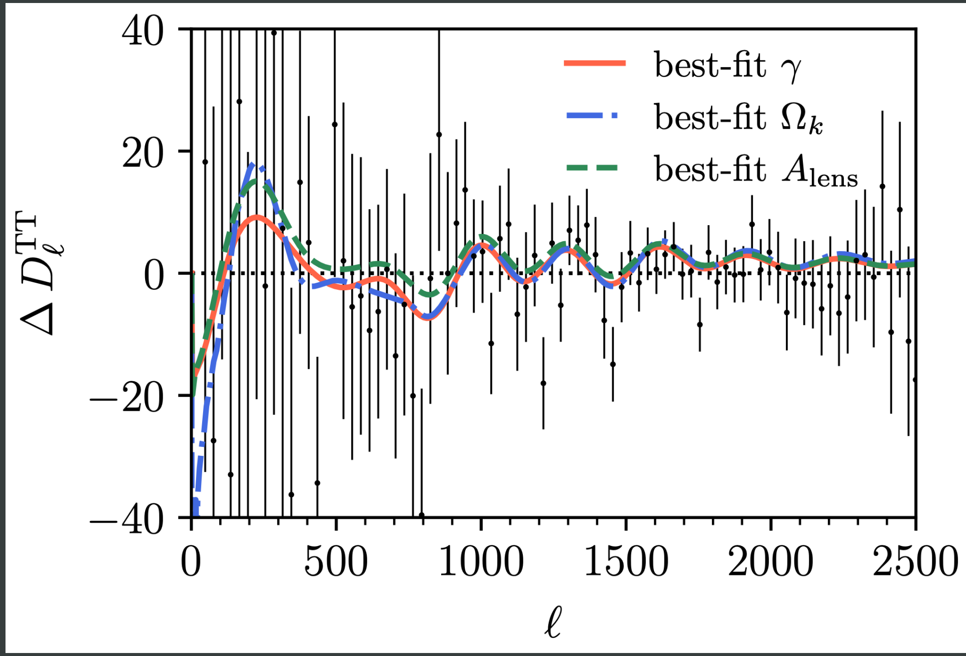


Nguyen et al [2302.01331]

Models that work
Phenomenological insight

Varying growth index γ

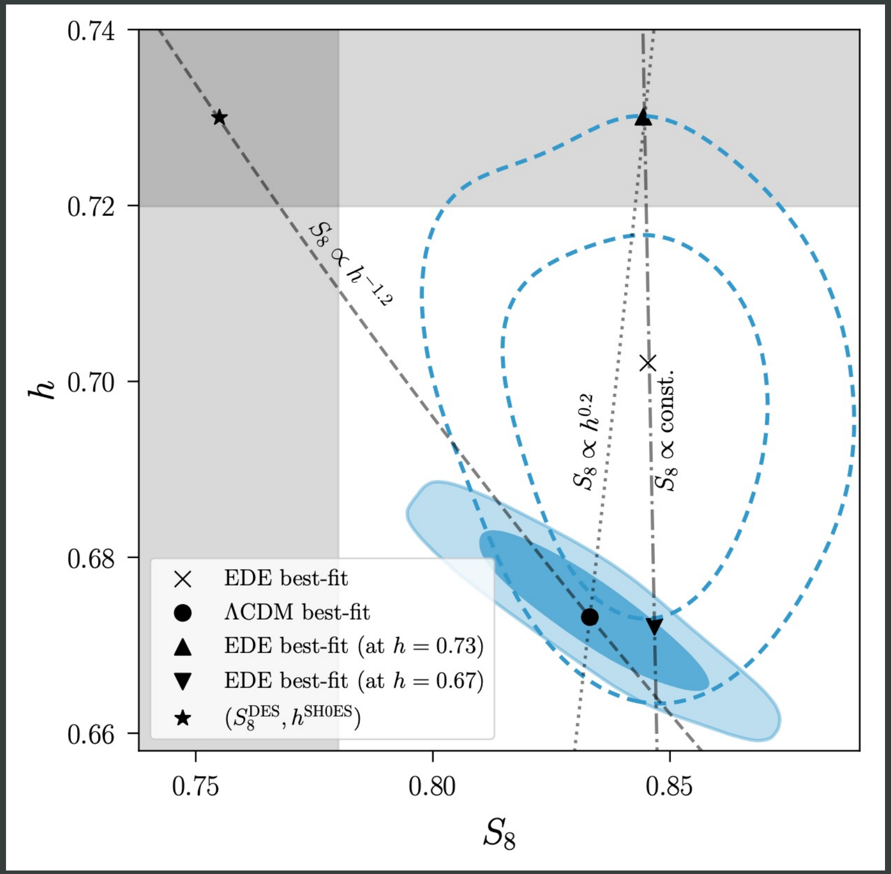
- Mimics the effect of varying Ω_k or A_{lens} in the CMB residuals
- No background modification



Nguyen et al [2302.01331]

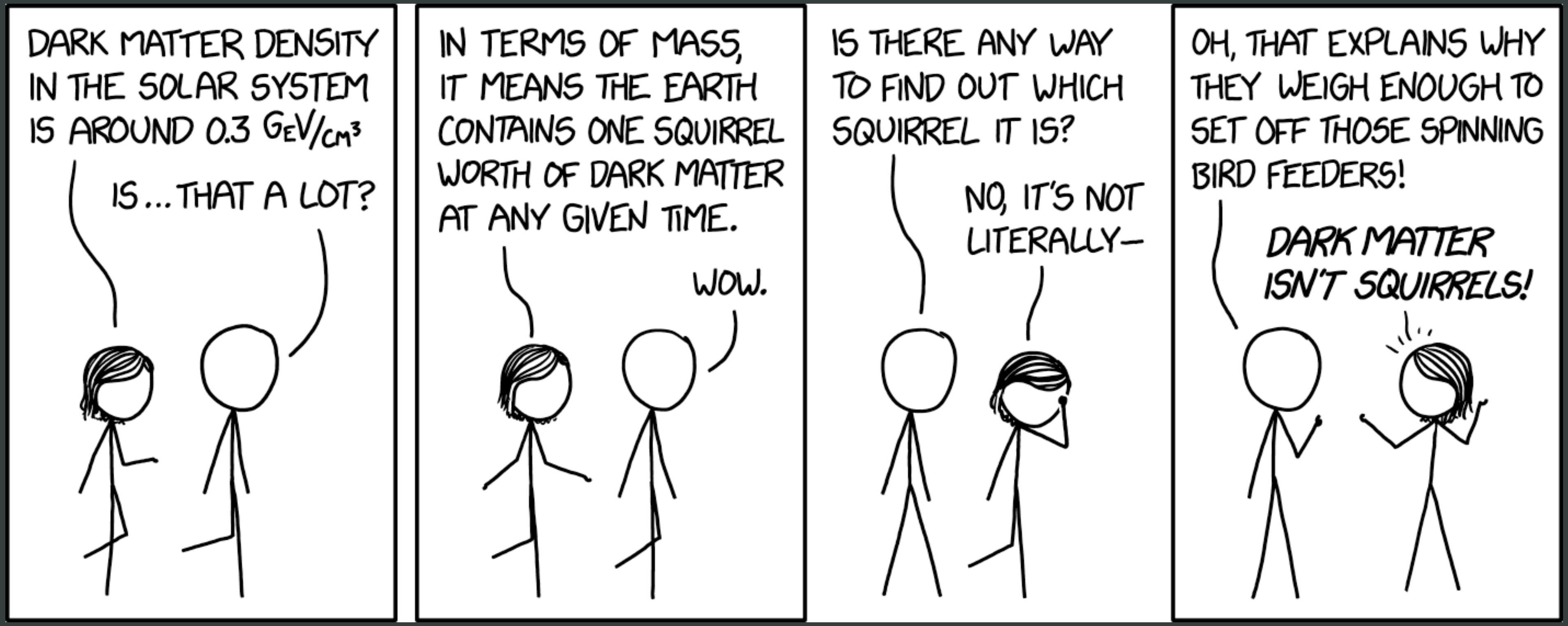
How to solve cosmic tensions

- New physics that targets both tension simultaneously must modify the background and perturbative universe
  - Modify the early background, not late for H_0
  - Scale-dependent impact on $P(k)$ for S_8
- Background modifications that target only one tension tend worsen the other
- If we split them up:
  - The Hubble tension requires an early background modification
  - The S_8 tension can be targeted with just perturbative modifications



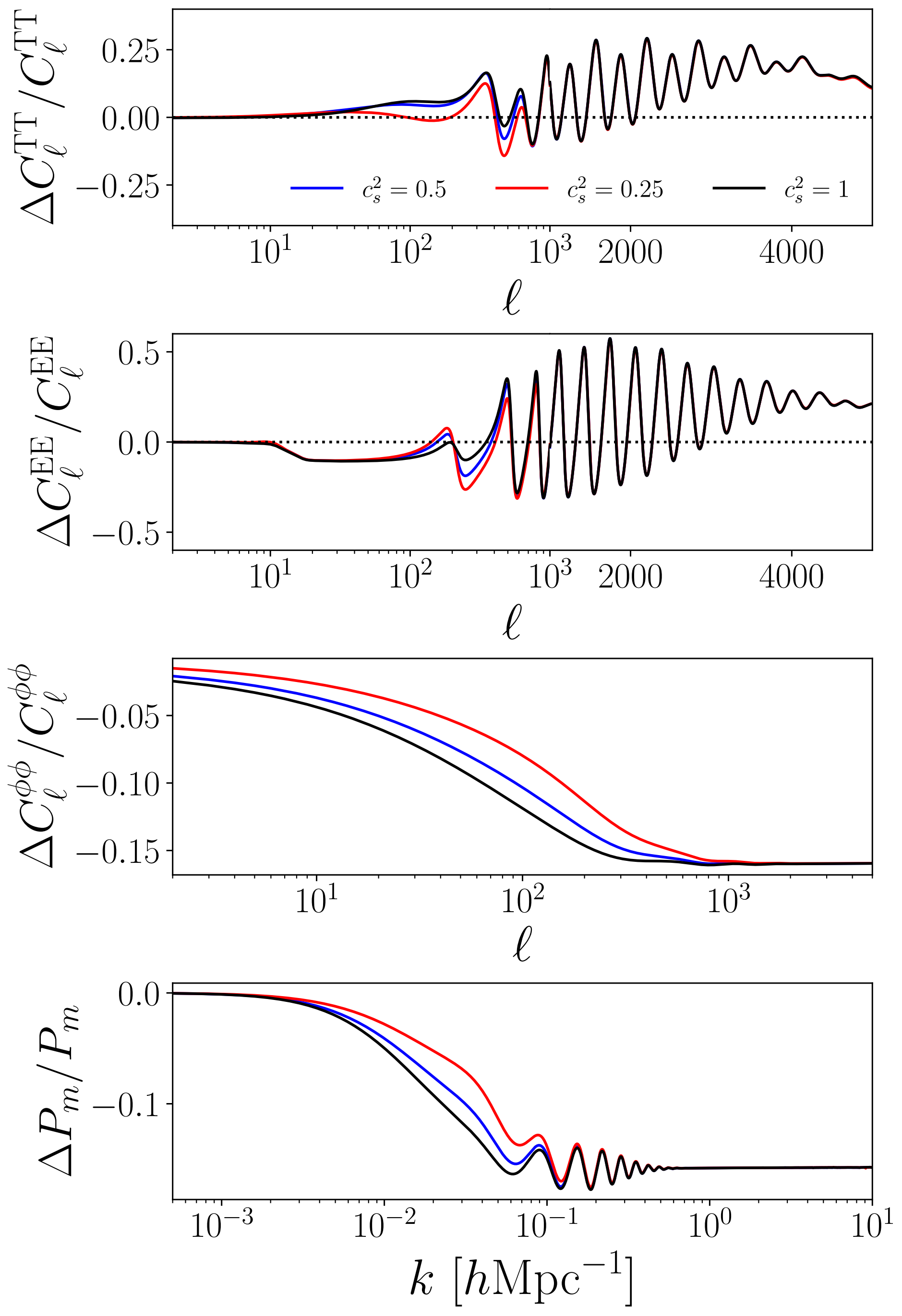
Secco, TK, Krause, Hu [2209.12997]

Lets get creative with dark sector physics!



XKCD: 2186

Differentiation in CMB data



Poulin, Smith and TK [2302.09032]