Converting dark matter to dark radiation does not solve cosmological tensions

Fiona McCarthy

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with Colin Hill

UNIVERSITY OF CAMBRIDGE

FLATIRON INSTITUTE

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The Hubble constant

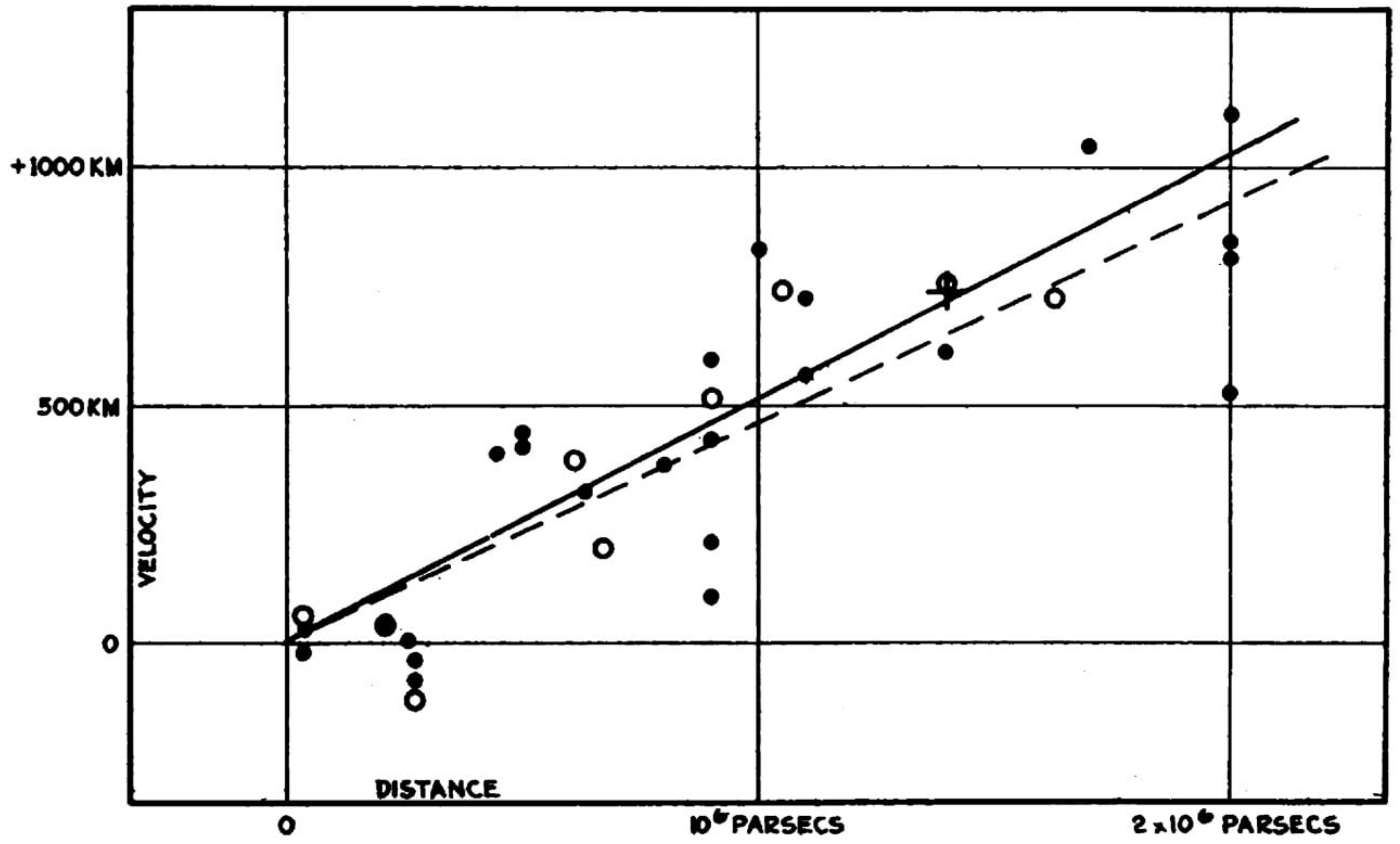
- H_0 measures the scale of the (local) expansion of the Universe today
- Measure the Hubble diagram with a standard(sizable) candle like a **Supernova**
- **Need to calibrate the intrinsic luminosity of a Supernova!!** → use the **cosmic distance ladder**
- The SH0ES collaboration (Riess et al) measures H_0 with Sne from Pantheon at $0.0233 < z < 0.15$

$$H_0 = 74.04 \pm 1.04 \text{ km/s/Mpc}$$

- Other collaborations use other standardizable candles (eg Freedman et al, using TRGB instead of cepheids)

$$v = z = H_0 D$$

Hubble's original Hubble diagram



Edwin Hubble 1929 (PNAS)

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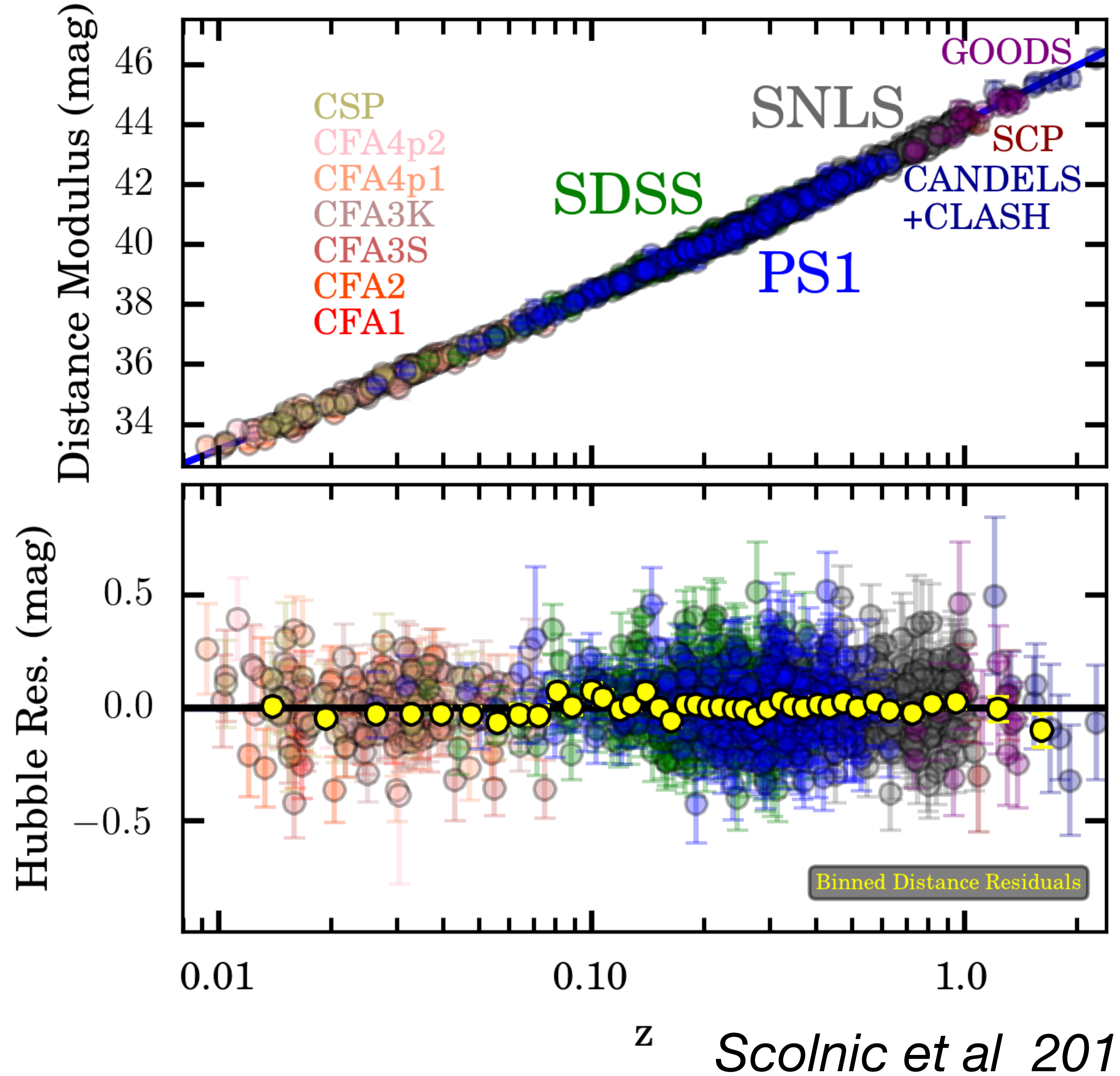
Hubble diagram for Pantheon+ Sne



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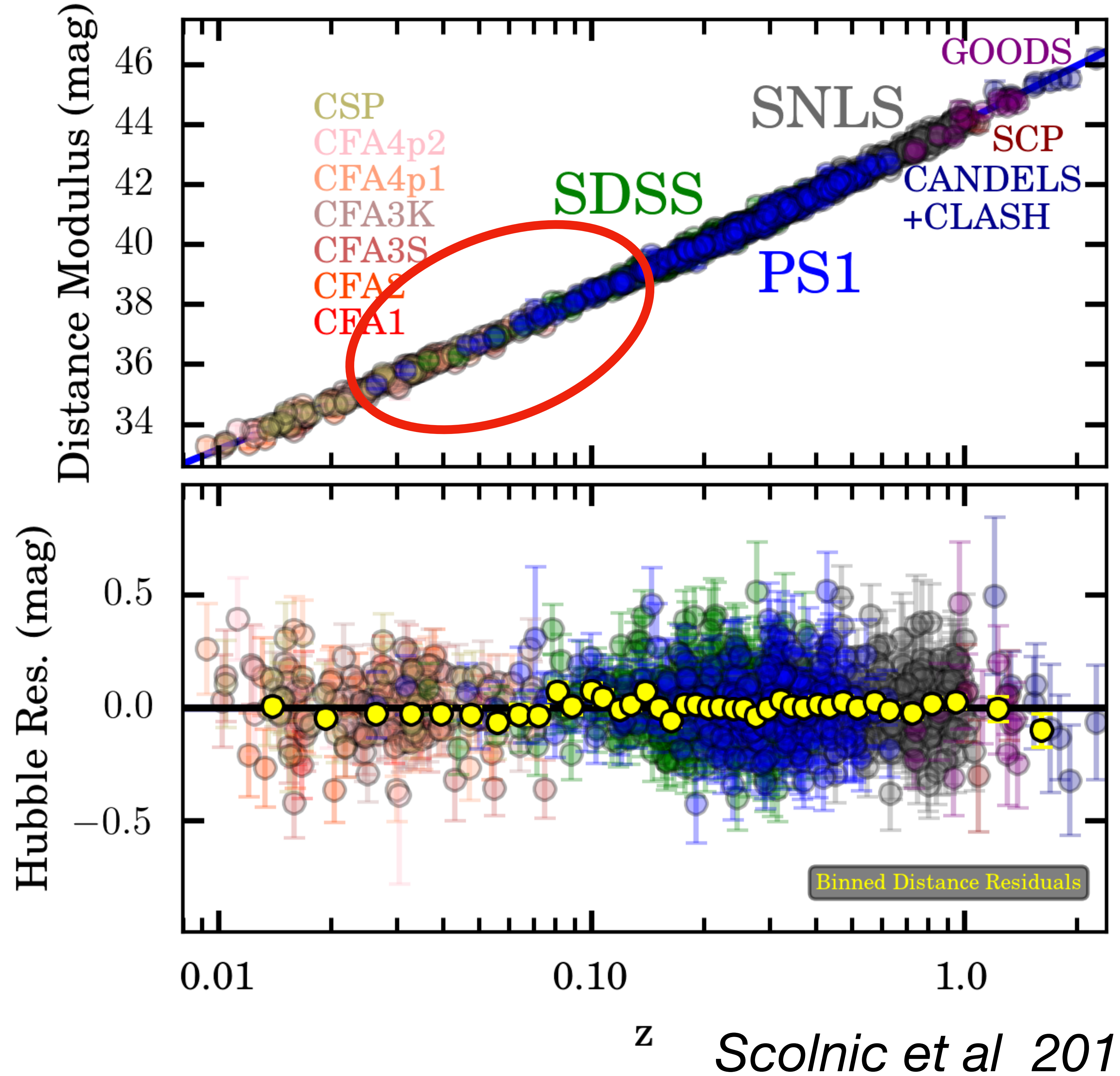

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H_0 from the BAO feature

- The BAO feature traces the size of the sound horizon across cosmic time

$$r_s(z) = \int_z^\infty \frac{dz'}{H(z')} c_s(z')$$

- We detect BAOs in the CMB and galaxy clustering as an angular feature

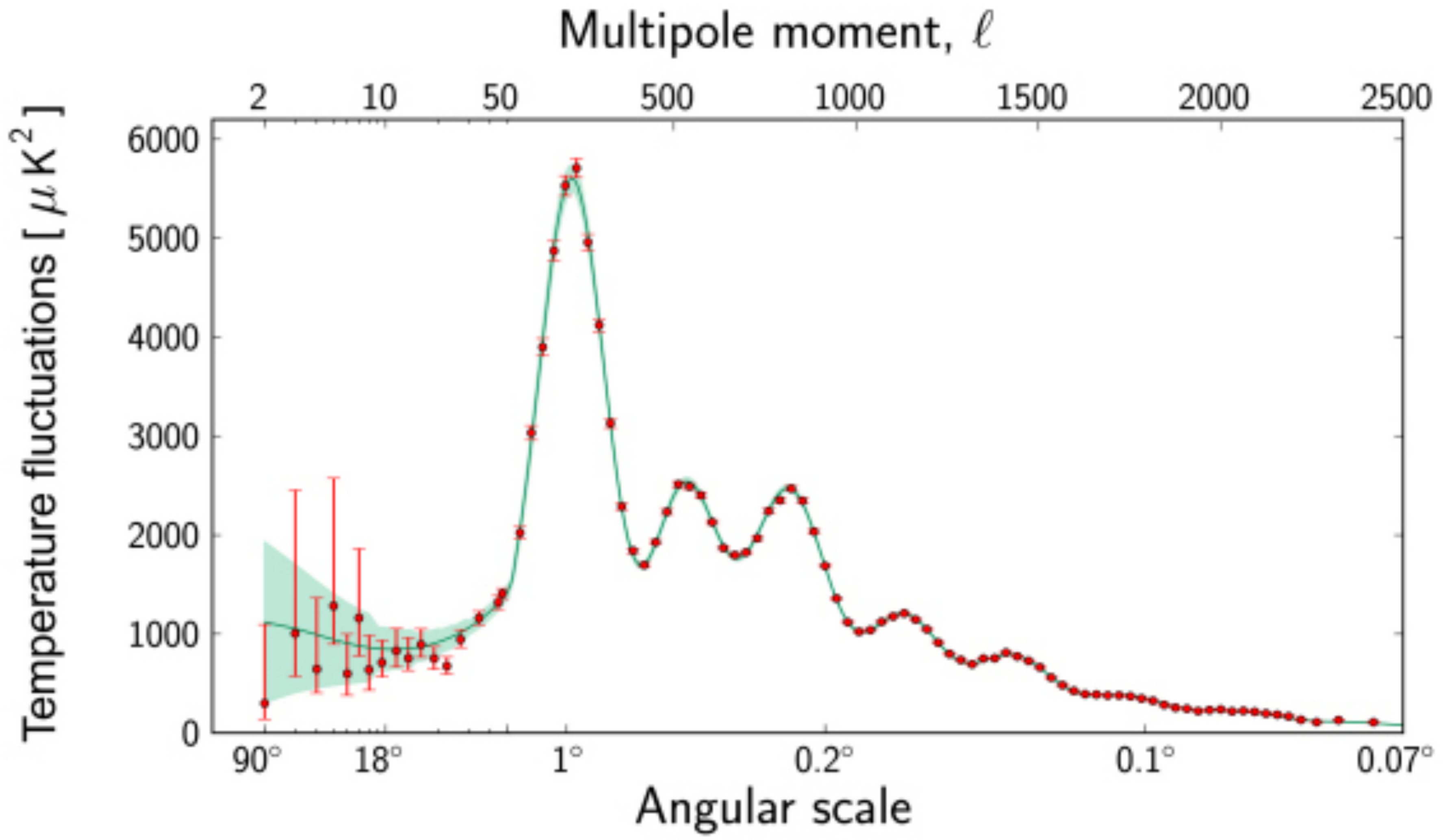
$$\theta_s(z) = \frac{r_s(z)}{D_A(z)} \qquad D_A(z) = \int_0^z \frac{dz'}{H(z')}$$

- We **parametrize and constrain H(z) within a model** (H_0 = H (z = 0))

- The CMB has a distinct angular feature at scales of about a degree

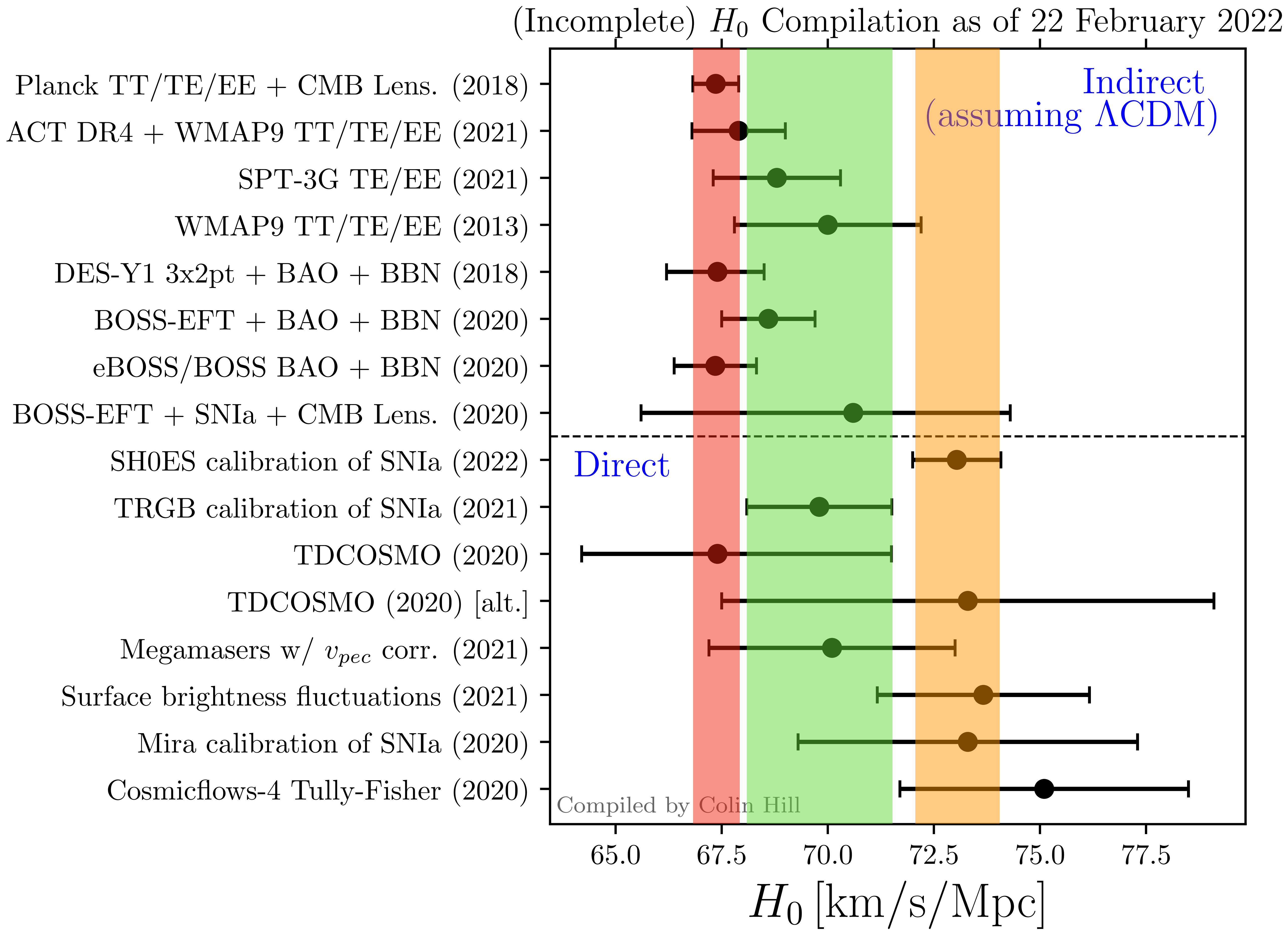
- **This is extremely precisely measured!!**

$$100\ \theta_s = 1.04110 \pm 0.00031 \rightarrow H_0^{\Lambda CDM} = 67.27 \pm 0.60 \text{ km/s/Mpc}$$



The CMB anisotropy power spectrum; credit: Planck, ESA

Summary of the H_0 tension(?)



- A 5σ tension between *Planck* and SH0ES!!
- TRGB measurements are in tension with neither and will get tighter, **this could be decisive**

The S_8 tension: hints at *more* new physics?

- *Is there a systematic suppression in clustering at low z?*

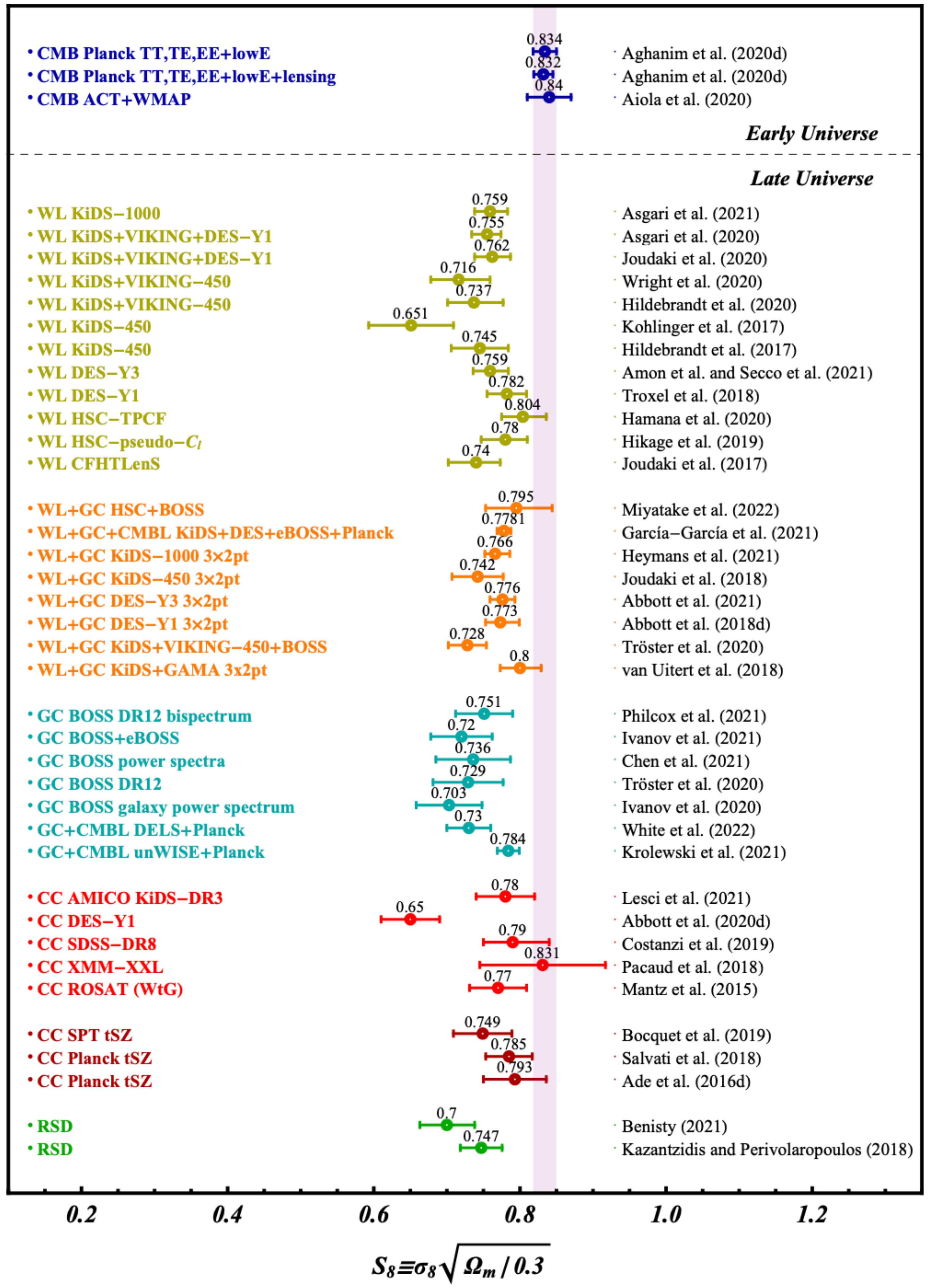
$$S_8 \equiv \sigma_8 \sqrt{\frac{\Omega_m}{0.3}} \qquad (\sigma_8)^2 = \frac{1}{2\pi^2} \int \frac{dk}{k} W^2(kR) k^3 P(k=0),$$

- *Planck* constraints:

$$S_8 = 0.834 \pm 0.016$$

- Galaxy clustering/lensing *tend* to be ~2σ lower

- Low-z vs high-z physics? Or Nonlinear vs linear (eg *Amon & Efstathiou 2022*)? Or systematics in galaxy surveys?



Credit: Cosmology Intertwined, Snowmass 2021

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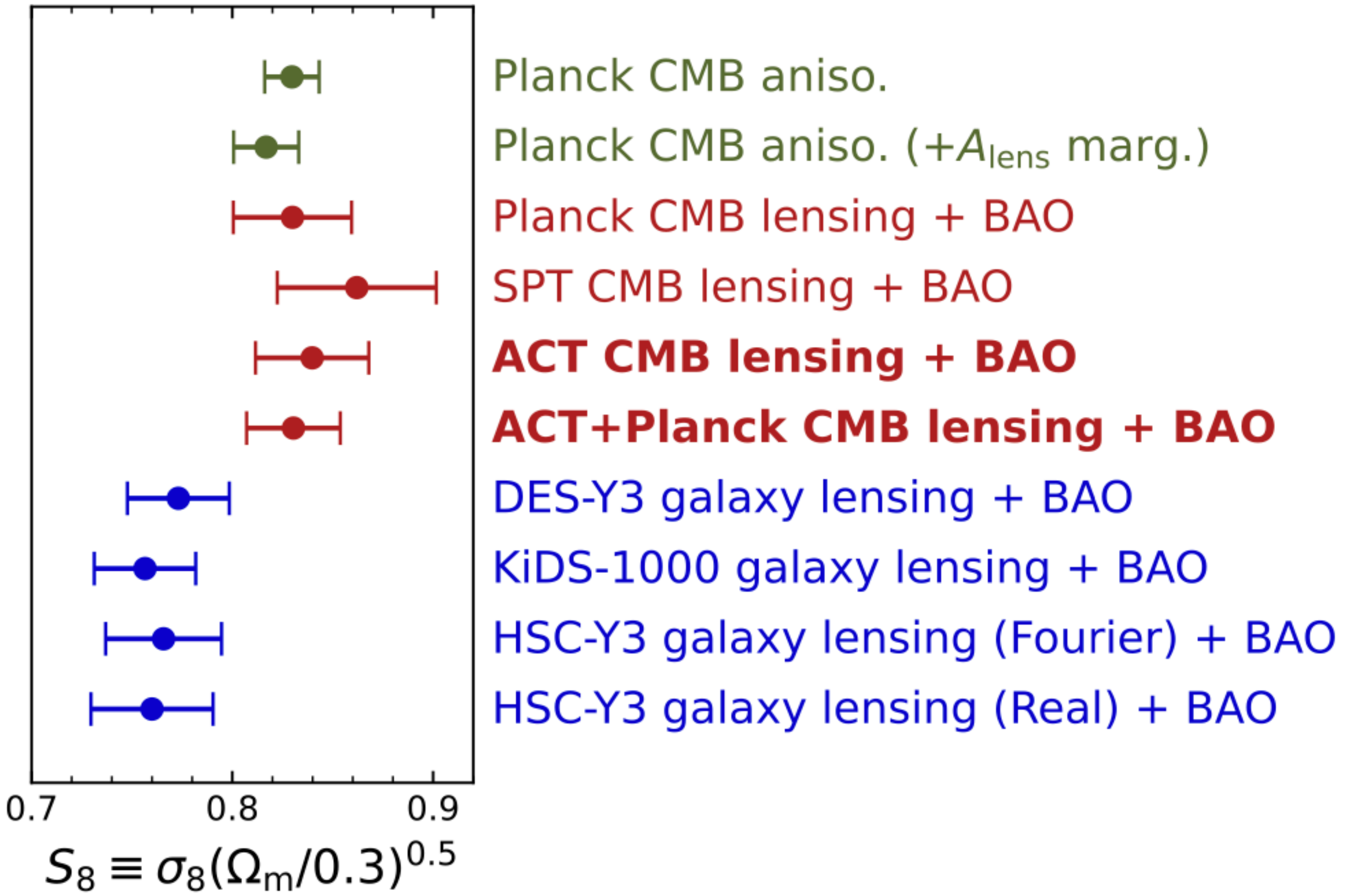

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Credit: Madhavacheril et al (ACT lensing cosmology)

Reconciling the H_0 tension: extending ΛCDM

- If the H_0 tension is real, the model-dependent measurement should be changed by changing **physics before reionization** (modifying $r_s(z)$) or **physics after reionization** (modifying $D_A(z)$)

- This has inspired many extensions / modifications to ΛCDM
  -Early dark energy, primordial magnetic fields, **non-standard dark sectors**, time-varying physical constants, …

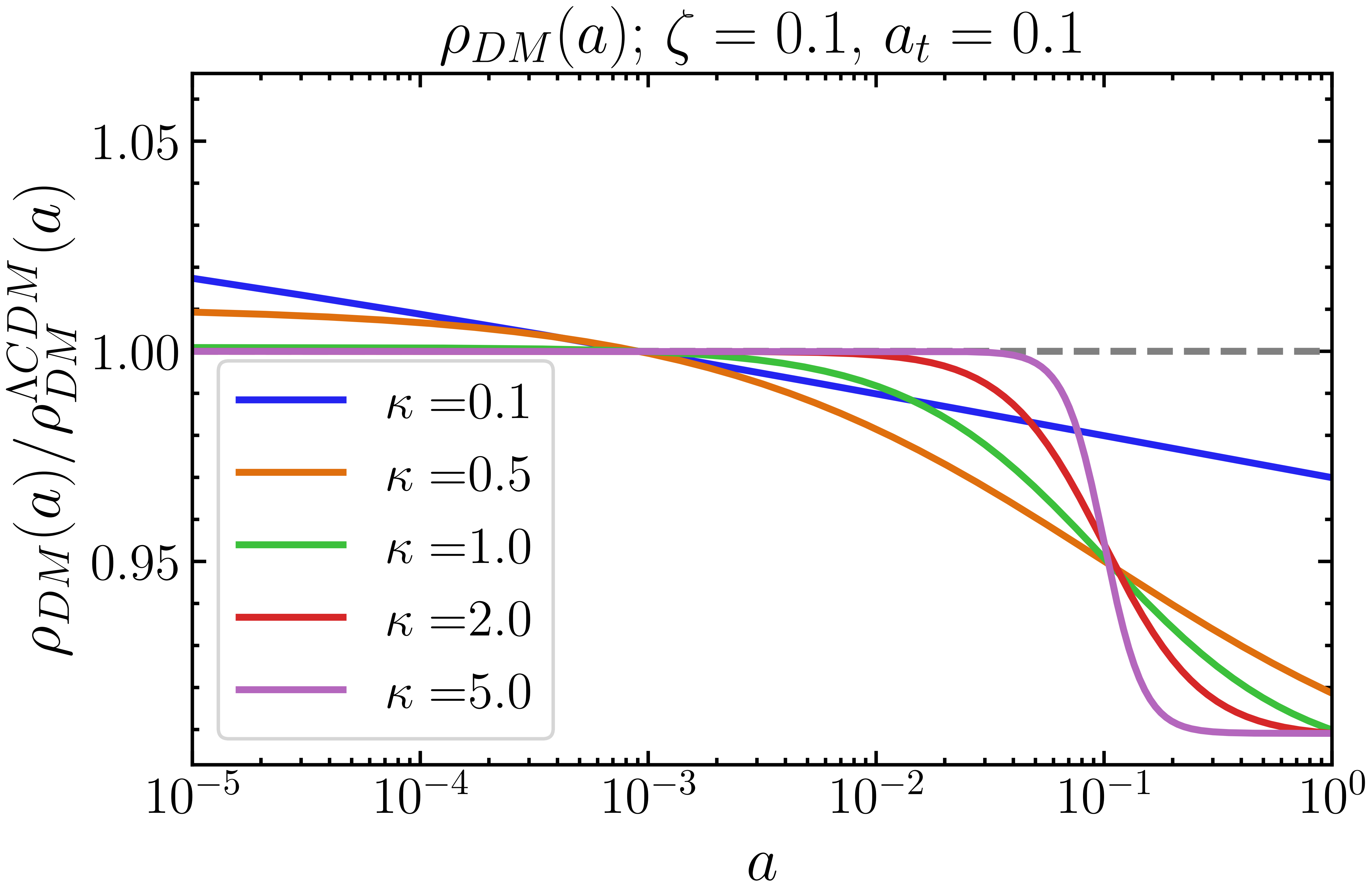
- The problem: ΛCDM fits the CMB so well, changing it is **hard**

- I will consider an extension of the dark sector where **dark matter converts into dark radiation** , *simultaneously allowing for lower* S_8

Dark matter conversion to dark radiation

- In ΛCDM, dark matter evolves as standard $\rho_{DM} = \rho_{DM}^{0}\, a^{-3}$. **Modify this** in a **time dependent, parametric way:** (See: Bringmann et al 2018, PRD)

$$\rho_{DM}(a) = \frac{\rho_{DM}^{0}}{a^{3}}\left(1 + \zeta\left(\frac{1 - a^{\kappa}}{1 + \left(a/a_t\right)^{\kappa}}\right)\right)$$

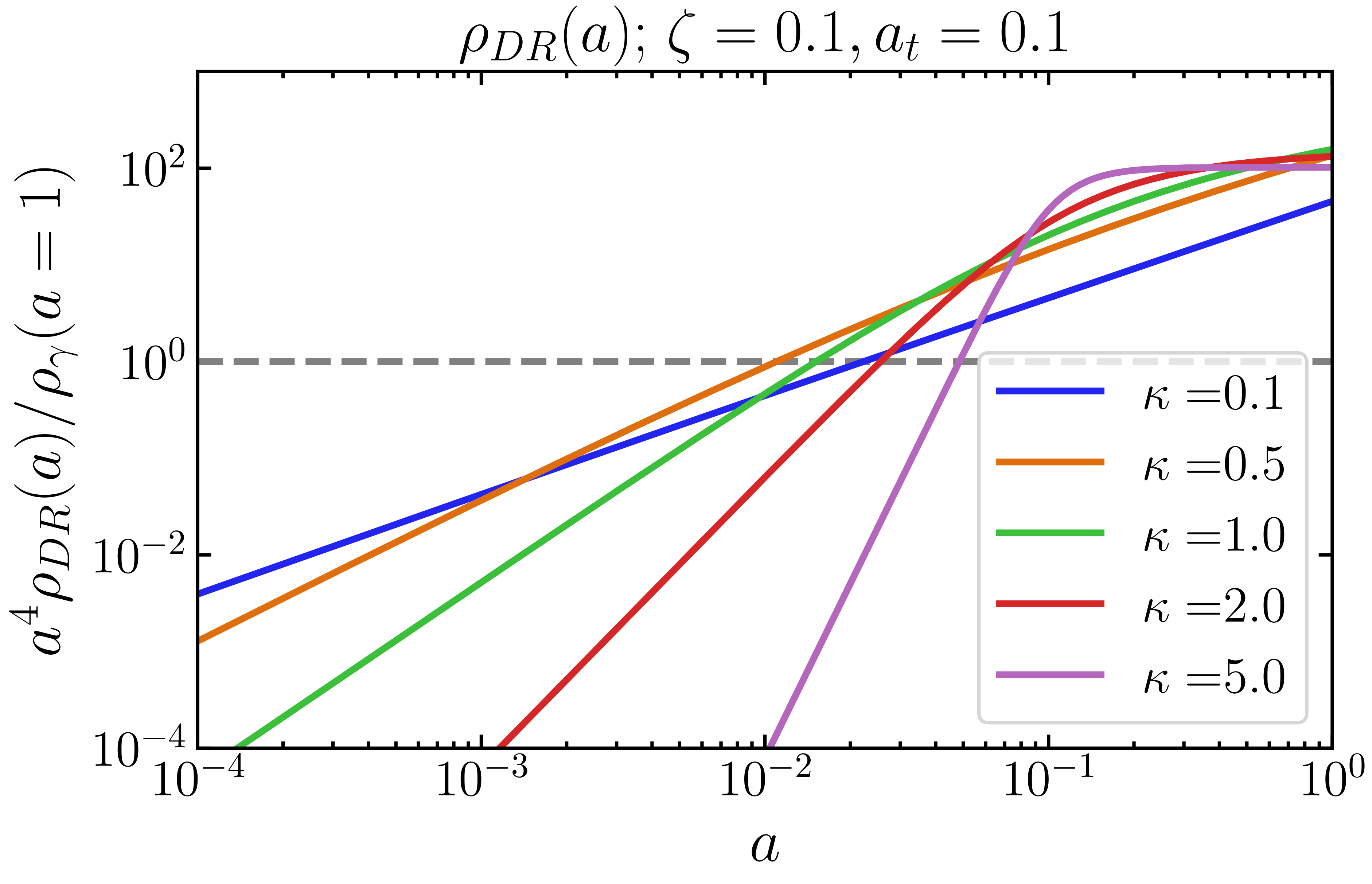


- ζ : the **fraction of DM that "converts"**
- a_t : gives a **time for the conversion**
- κ : describes the **rate of conversion**

Dark matter conversion to dark radiation

- The DM converts into **dark radiation** (in ΛCDM the DR density is 0)
- From conservation of energy $\left[\frac{1}{a^3}\frac{d}{dt}\left(a^3\rho_{DM}\right) = -\frac{1}{a^4}\frac{d}{dt}\left(a^4\rho_{DR}\right)\right]$ you get

$$\rho_{DR}(a) = \zeta\frac{\rho^0_{DM}}{a^3}\frac{\left(1+a_t^\kappa\right)}{\left(a^\kappa+a_t^\kappa\right)}\times\left(\left(a^\kappa+a_t^\kappa\right){}_2F_1\left[1,\frac{1}{\kappa};1+\frac{1}{\kappa};-\left(\frac{a}{a_t}\right)^\kappa\right]-a_t^\kappa\right)$$



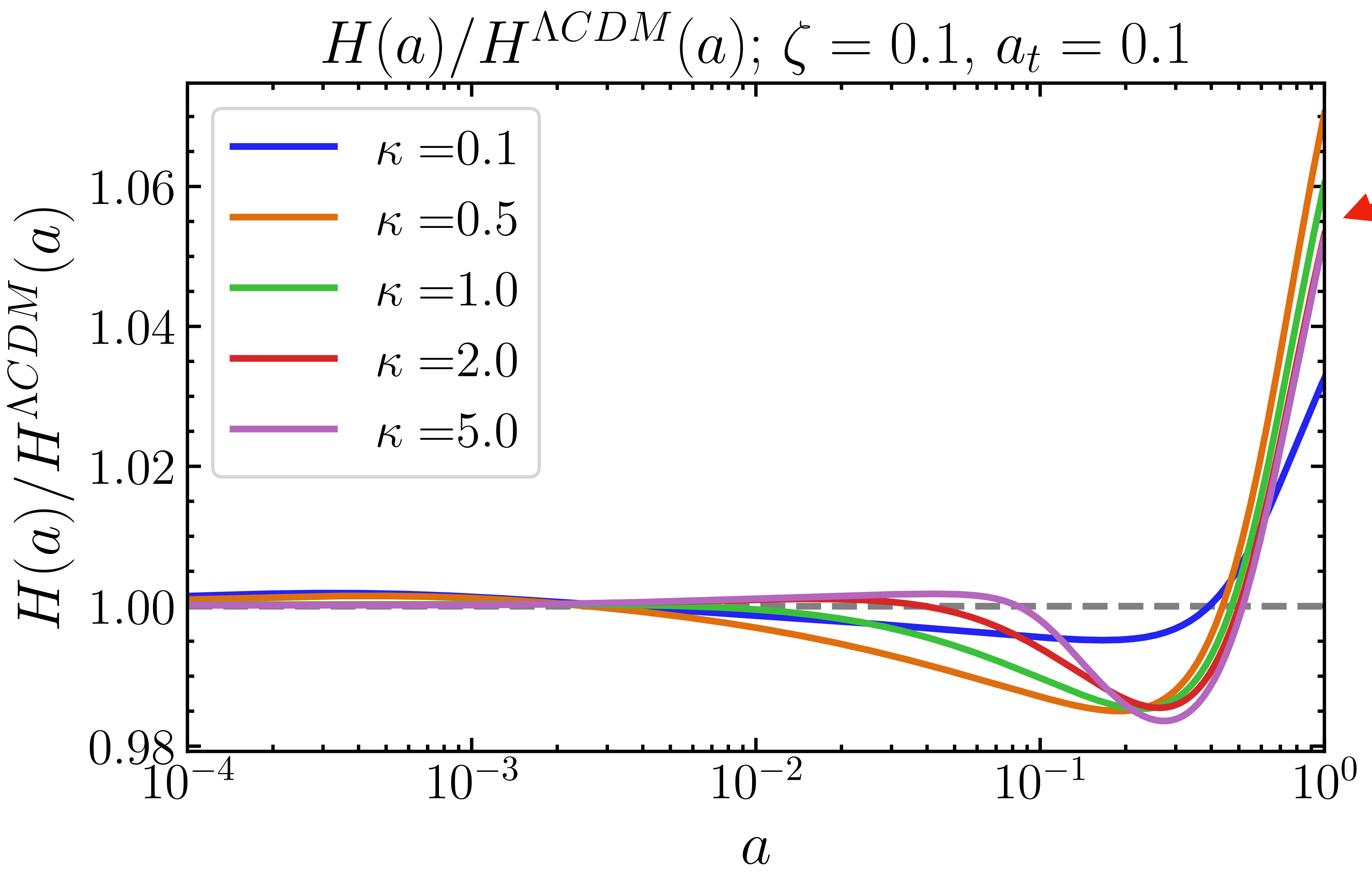
- This is a **generalization** of well-studied models, eg *decaying dark matter* and *annihilating dark matter*

DM→DR: background dynamics

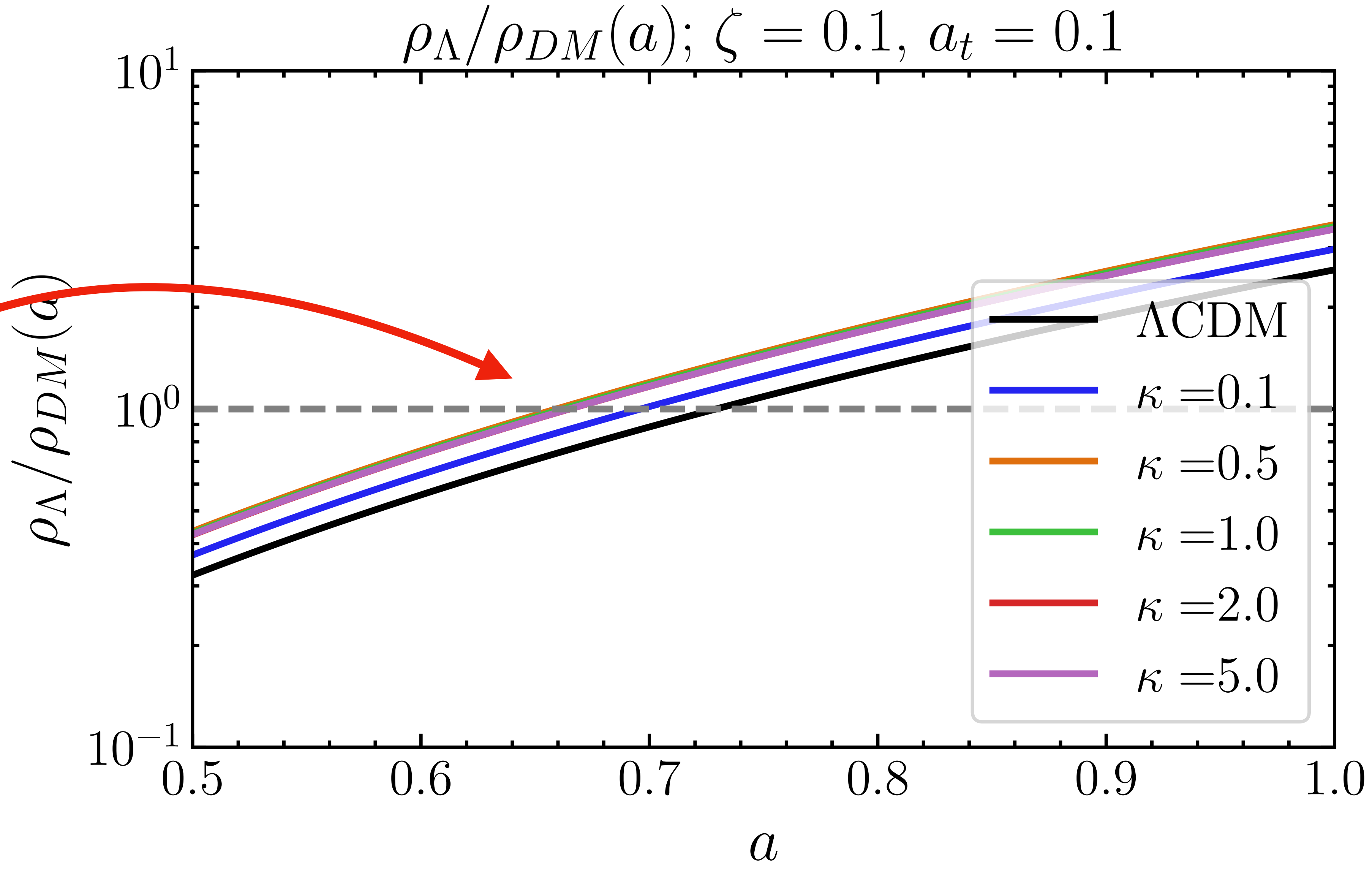
- This produces the correct background dynamics to increase H_0!

- Recall that we have *direct* constraints on $\rho_{DM}(z^\star)$ and θ_s from the CMB. What happens to H_0 within DM→DR **subject to these constraints from *Planck*?** (This is a [slightly] non-trivial calculation)

DM→DR: background dynamics



- H_0 increases!

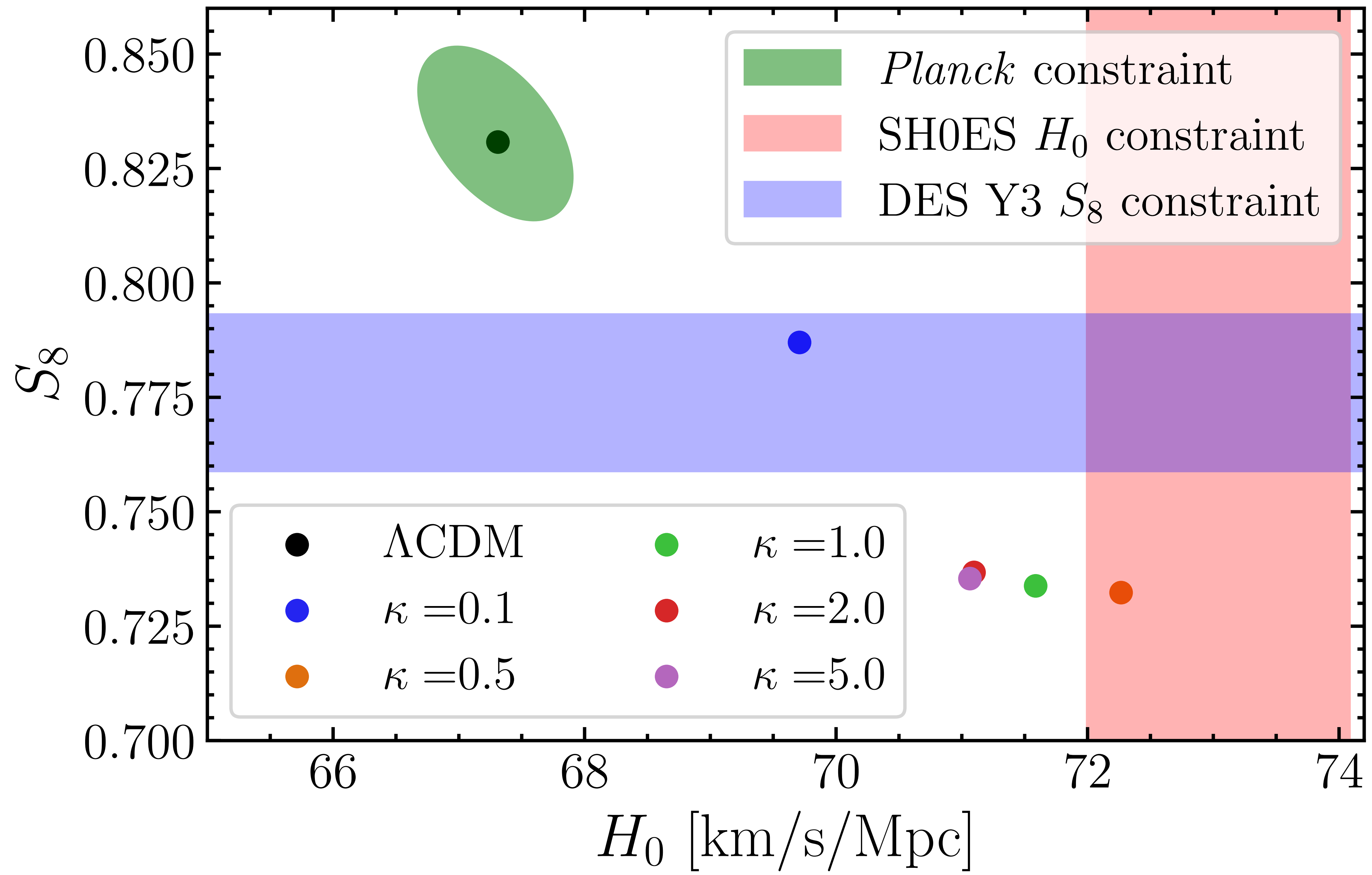


- Why? Λ-DM equality is earlier

DM→DR: background dynamics

- So H_0 increases. What about S_8? This also **naturally decreases** due to
  -lower Ω_m (some DM has converted)
  -Free streaming of DR suppressing clustering

- This model can simultaneously decrease both tensions!!



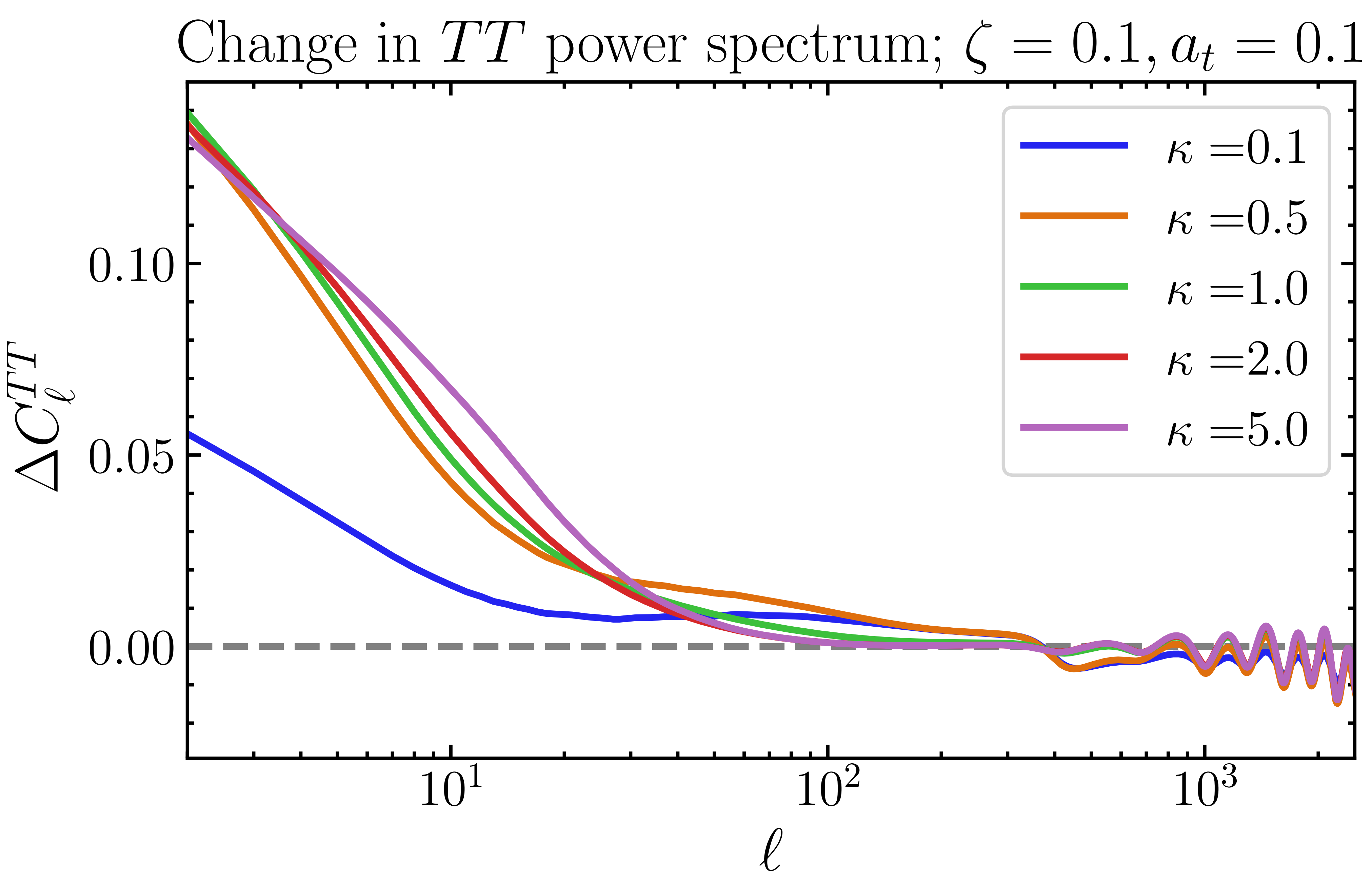
DM→DR: perturbation structure

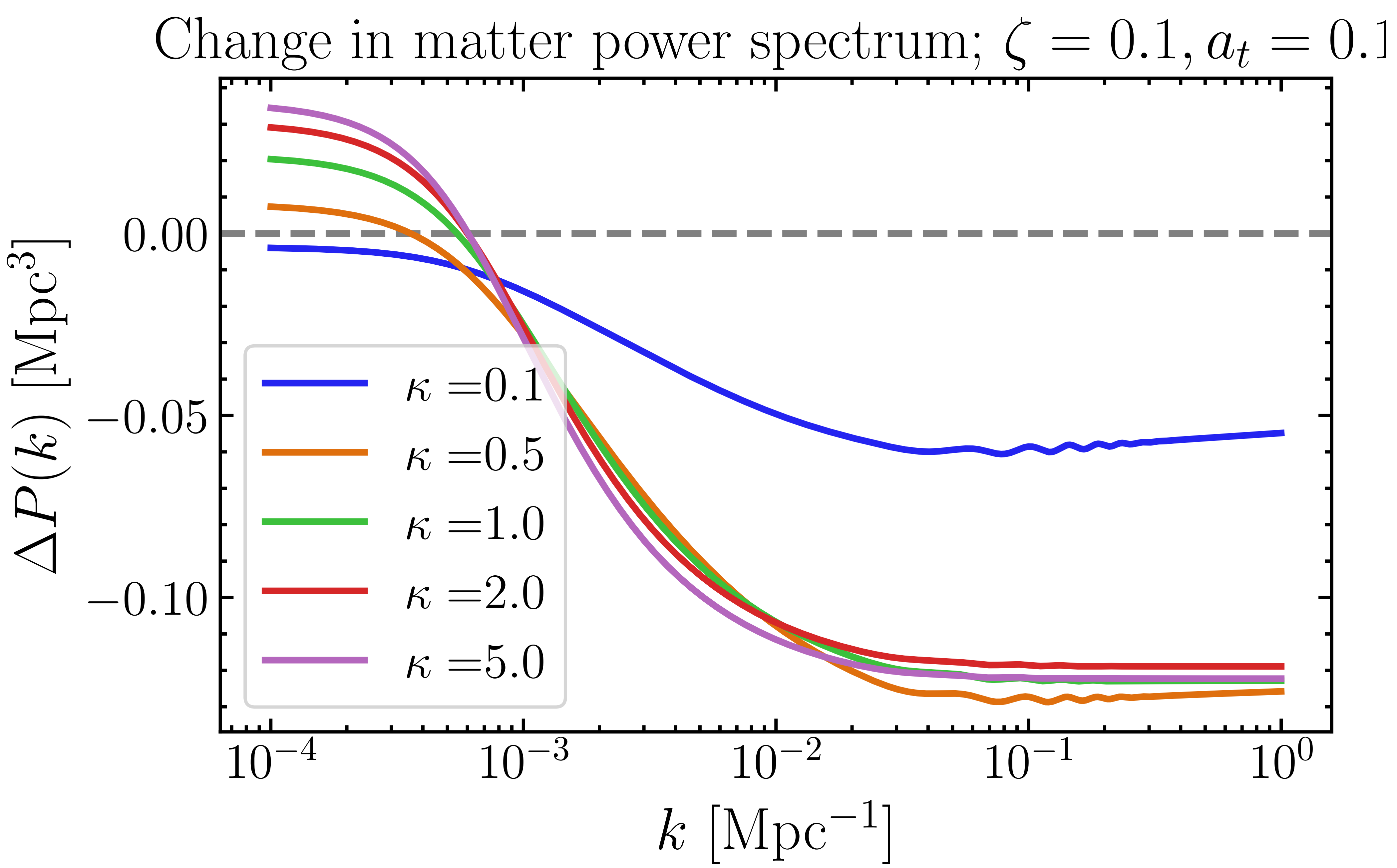
- Perturbation evolution is **non trivial**. The modified DM is easy as its perturbations trace the standard DM evolutions. **But we must evolve the DR perturbations as they interact with the gravitational perturbations**

- We have **modified the Boltzmann solver CLASS: CLASS_DMDR** (see https://github.com/fmccarthy/class_DMDR/)

- We built on the already-implemented **decaying dark matter** perturbation evolver

DM→DR: perturbation structure





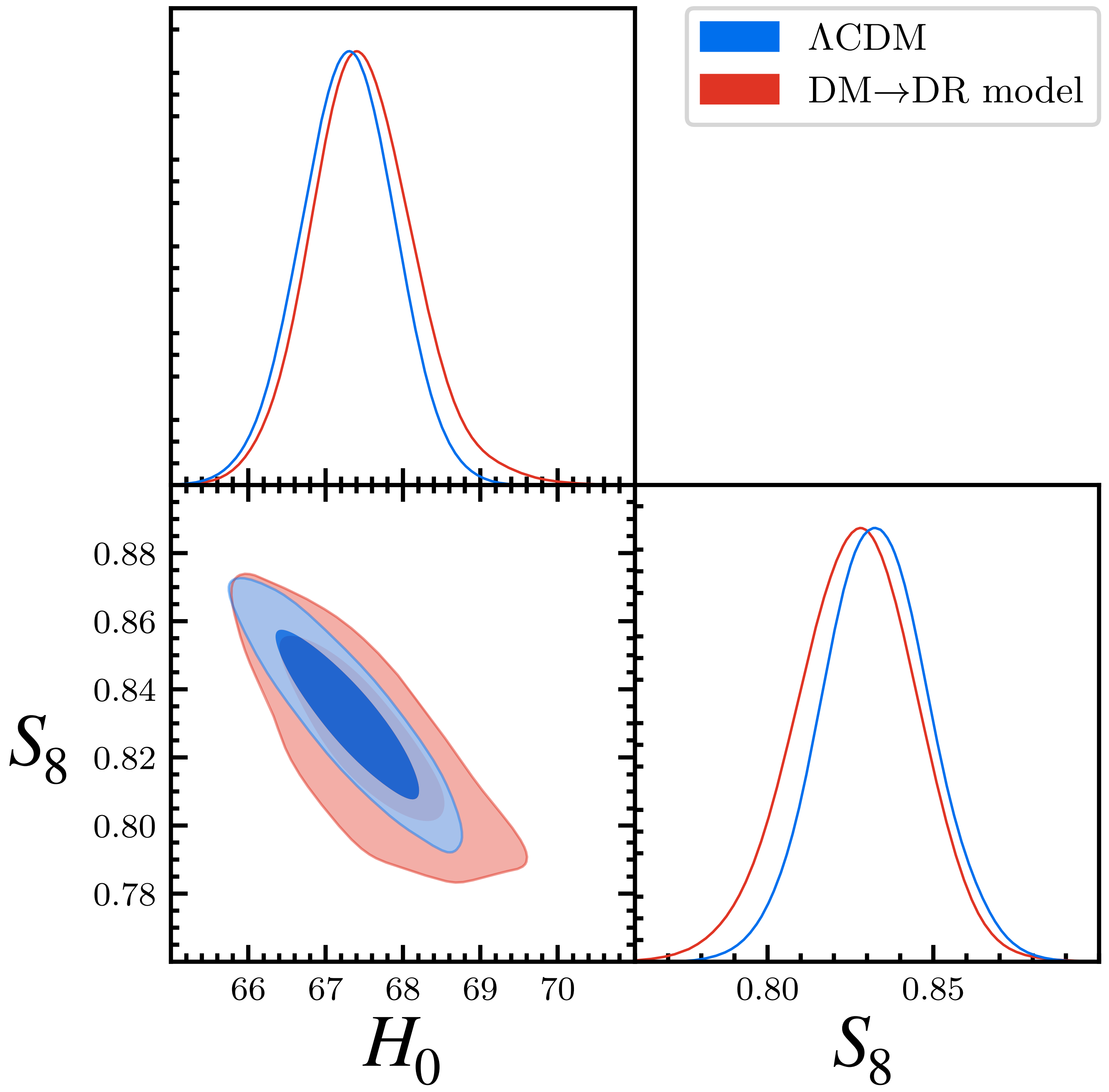
- Main changes:

-**increased ISW signal** due to **longer Λ-domination, decay of DM potentials**, and **DR effects**

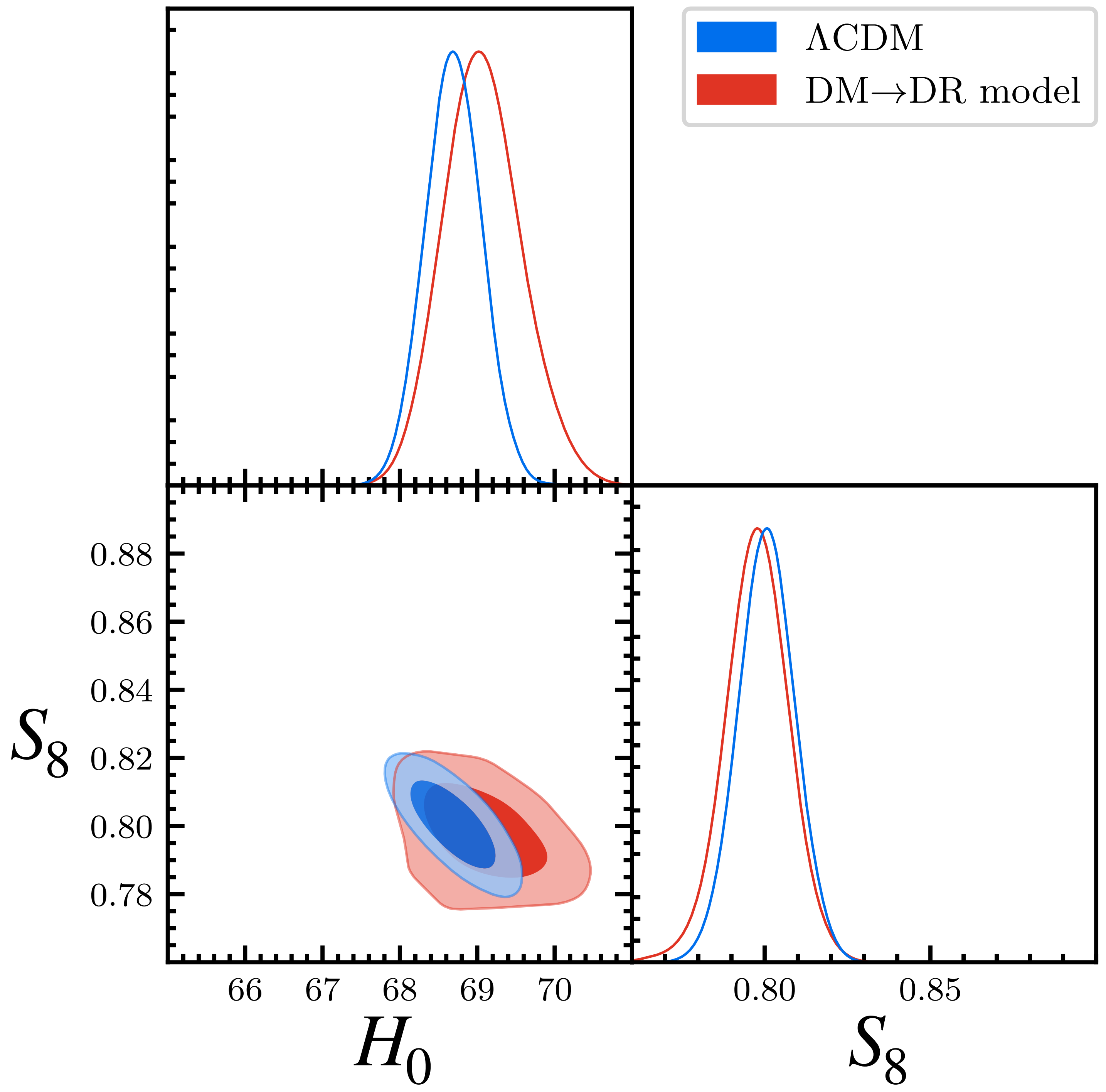
-**Suppression in P(k)**

DM→DR: constraints on H_0 and S_8

Planck CMB

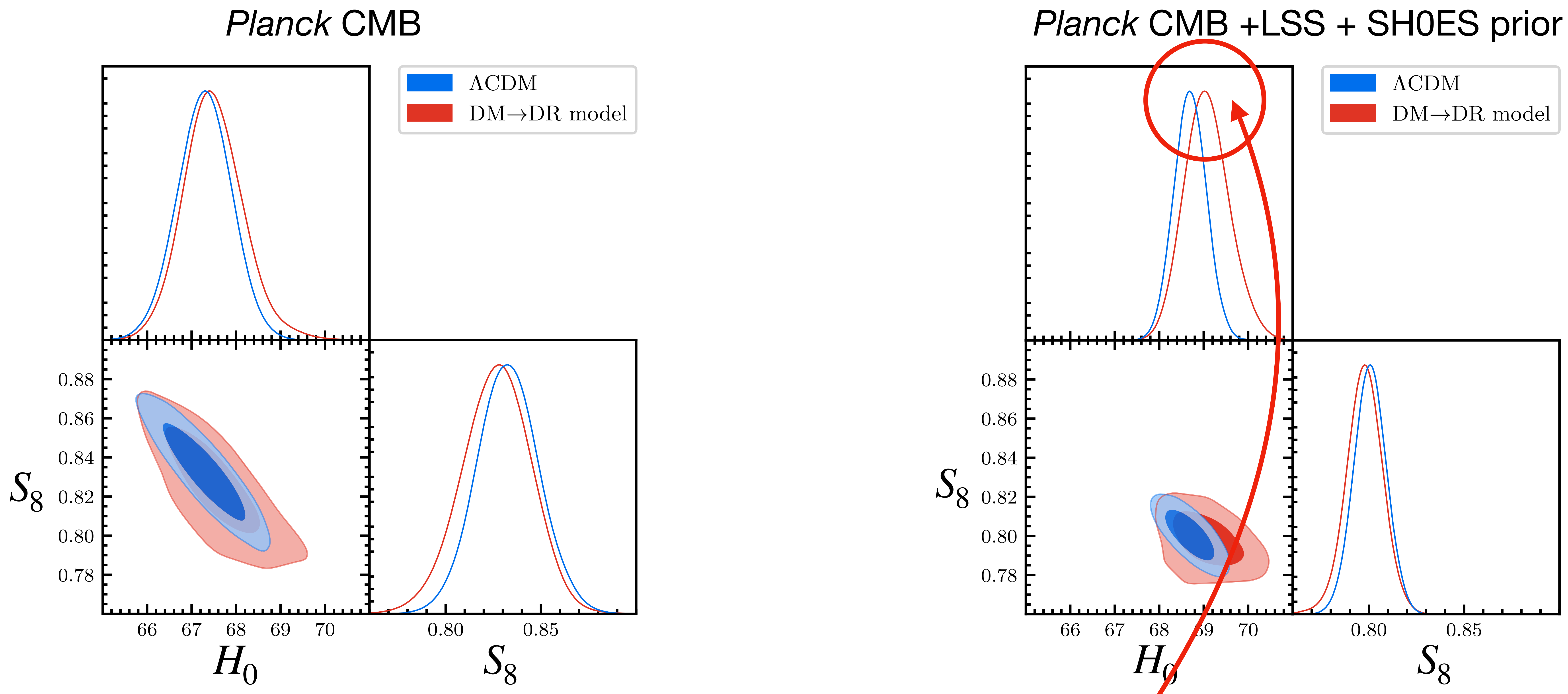


Planck CMB +LSS + SH0ES prior



- Mostly, the S_8 and H_0 posteriors are unshifted. Tensions persist.
- There is a *slight* upwards shift in H_0 compared to LCDM *when we include a prior from SH0ES*

DM→DR: constraints on H_0 and S_8



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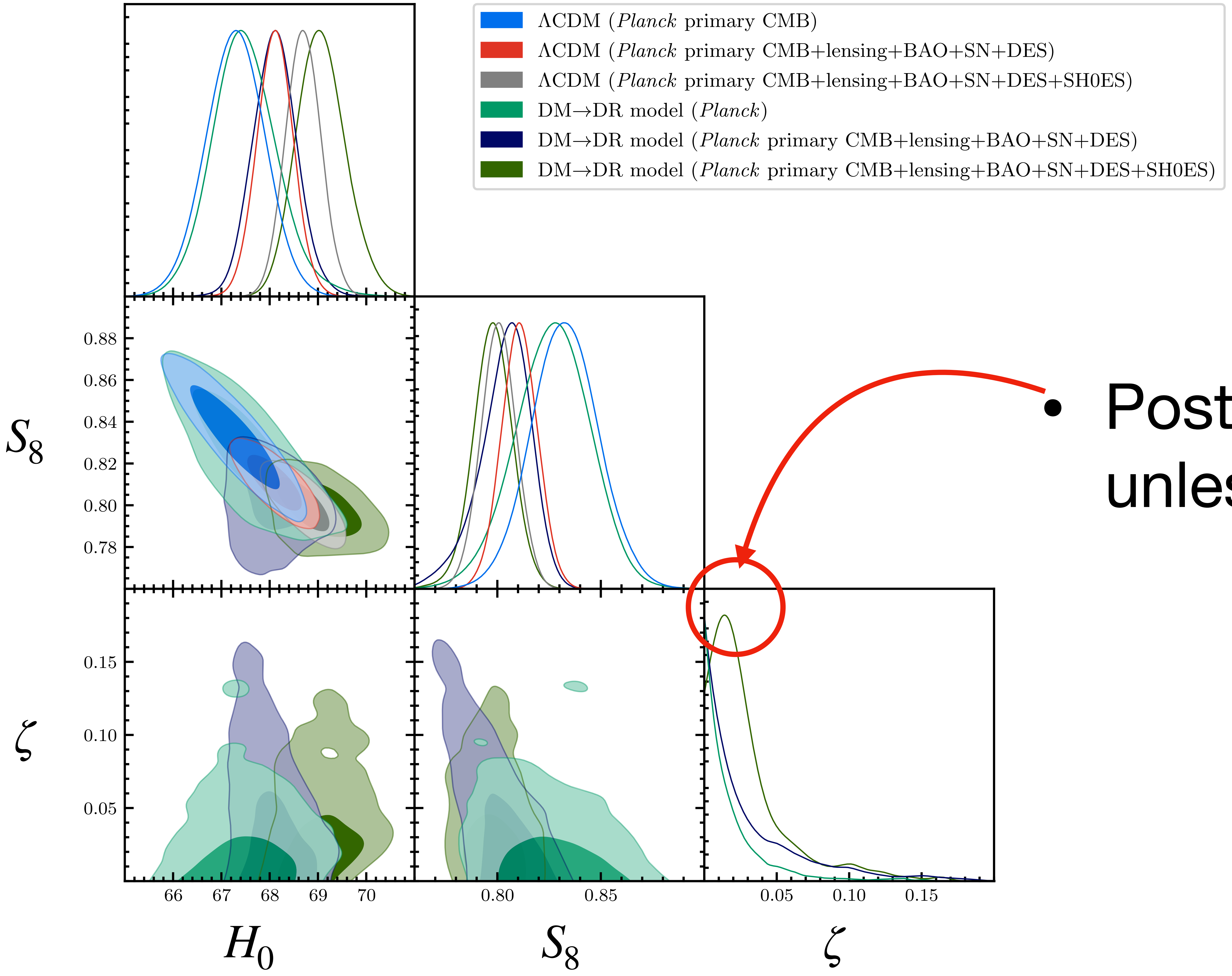
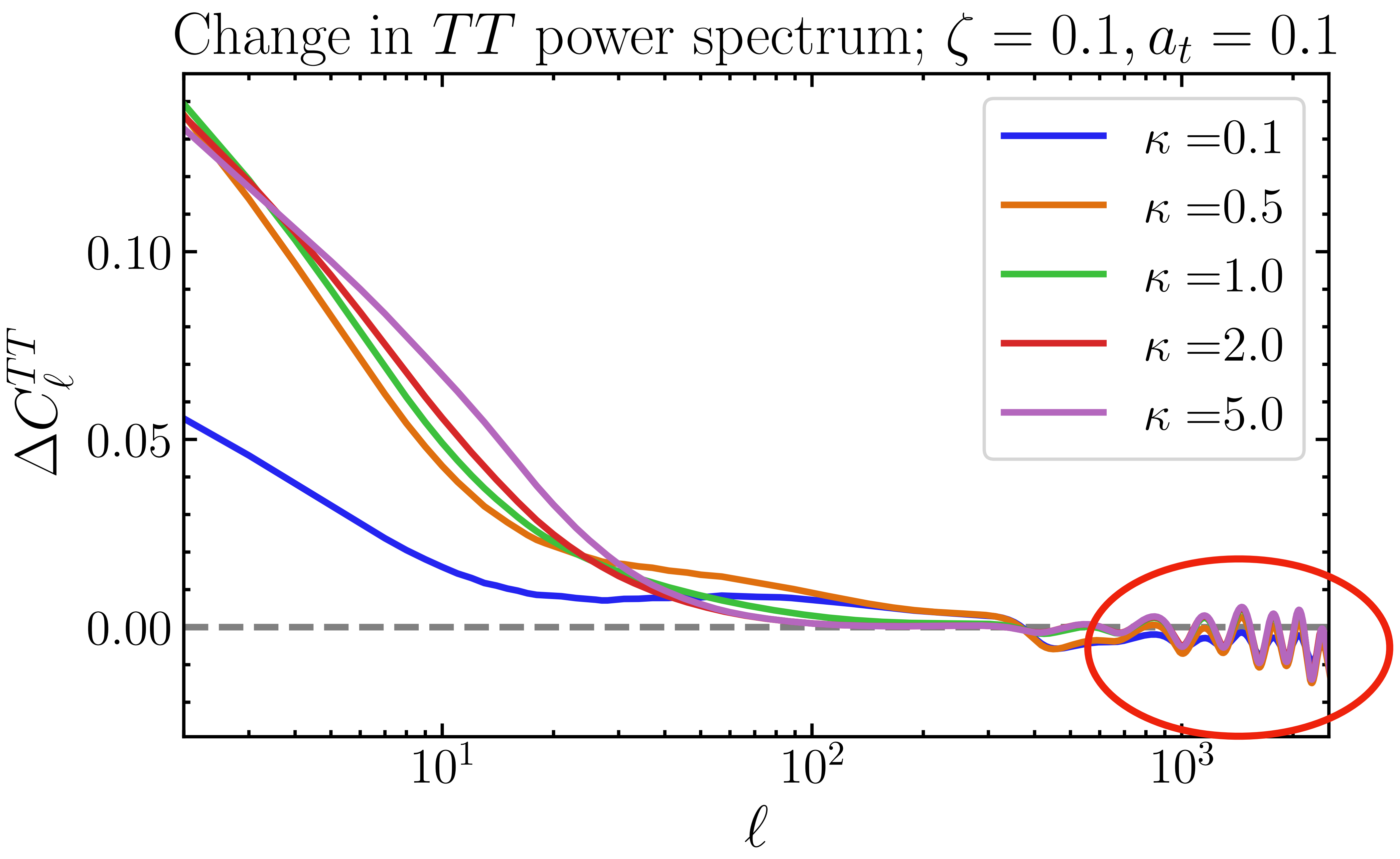
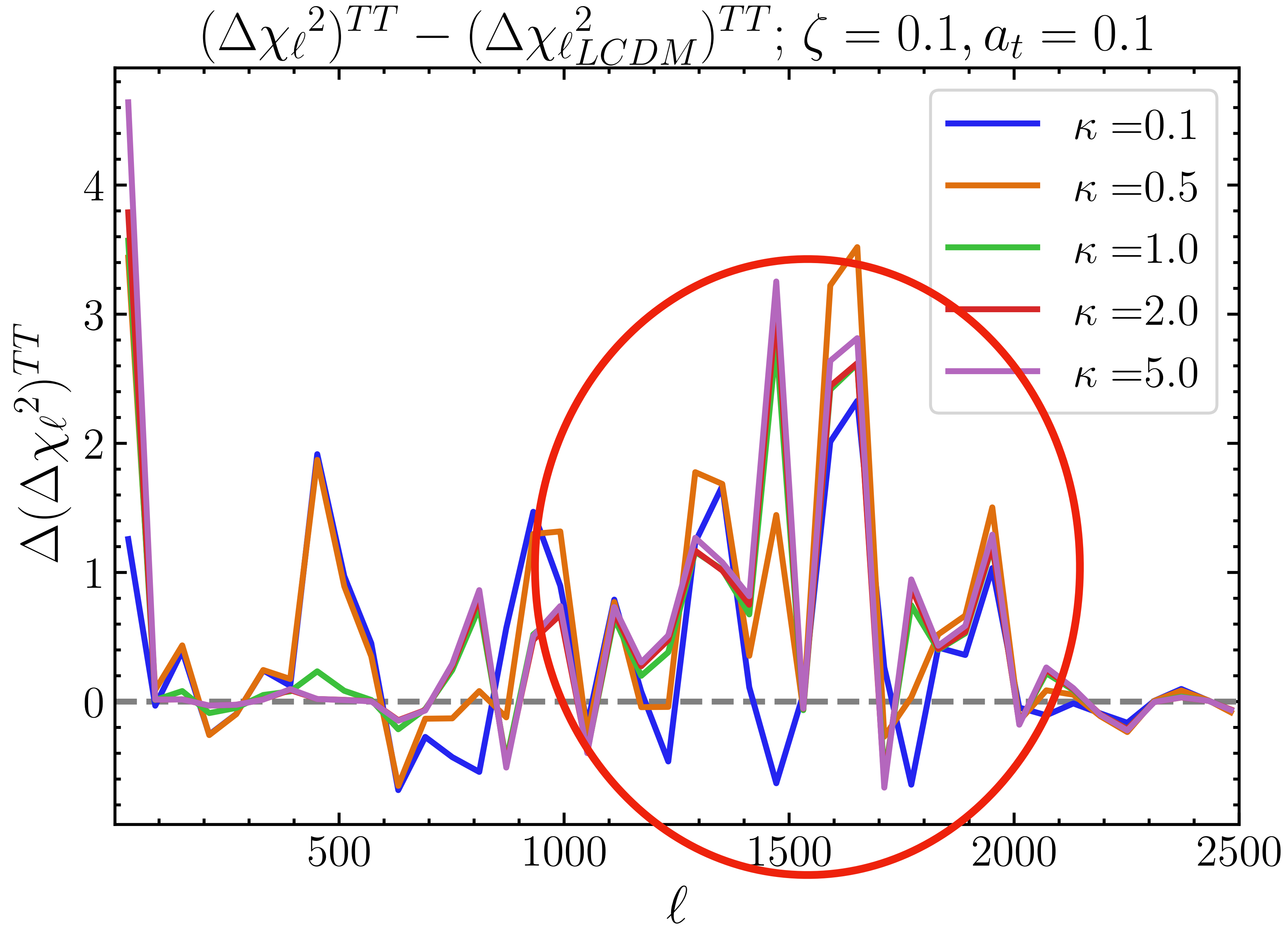
Constraints on the DM→DR parameters



- Posteriors prefer $\zeta = 0$ (no DM→DR) unless we include the SH0ES prior

Why do these models fail?





- The amount of **lensing** of the CMB is **constrained by the power spectrum**

- The CMB is truly an LSS probe that is consistent with ΛCDM!!

Conclusion

- Exensions to ΛCDM *motivated to solve the H_0 tension* have remained unsuccessful *at this goal.*

- However, this has renewed interest in a broad range of extended models with interesting effects

- The CMB, CMB lensing, these probes are all good tools for **exploring these models and placing upper limits on the fraction of non-standard DM**

- Modified Boltzmann code at https://github.com/fmccarthy/class_DMDR/