Constraining constant and tomographic coupled dark energy with low- and high-redshift probes

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Context/Motivation

The concordance ΛCDM model has been very successful at describing our Universe, yet some questions remain:

- What is the **true nature** of 'dark energy'?
- Why is there a **~5σ tension** between the value of the Hubble constant derived from the Cosmic Microwave Background at high redshifts ($H_0 = (67.4 \pm 0.5)$ km/s/Mpc), and lower-redshift distance ladder measurements ($H_0 = (73.04 \pm 1.04)$ km/s/Mpc)?

IS THE ΛCDM MODEL SUFFICIENT?

Coupled Dark Energy Formalism

- ΛCDM model extensions typically involve modifying Einstein's Field Equations:

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \boxed{\frac{8\pi G}{c^4} T_{\mu\nu}}$$

- We study a form of a **Coupled Quintessence model**
  - Dark energy takes on the form of a scalar field ϕ
  - Mediates interactions between dark matter particles — these particles feel a 'fifth force'
  - Mass of DM particles m(ϕ) is dependent on the field

Coupled Dark Energy Formalism

- In coupled dark energy models, we start from the energy-momentum tensor:

$$\nabla^\mu T^{\phi}_{\mu\nu} = \kappa\beta T^{\rm dm}\nabla_\nu\phi \quad ; \quad \nabla^\mu T^{\rm dm}_{\mu\nu} = -\kappa\beta T^{\rm dm}\nabla_\nu\phi \,,$$

where β quantifies the **coupling strength** between dark matter (DM) and the dark energy (DE) field (in ΛCDM, $\beta = 0$)

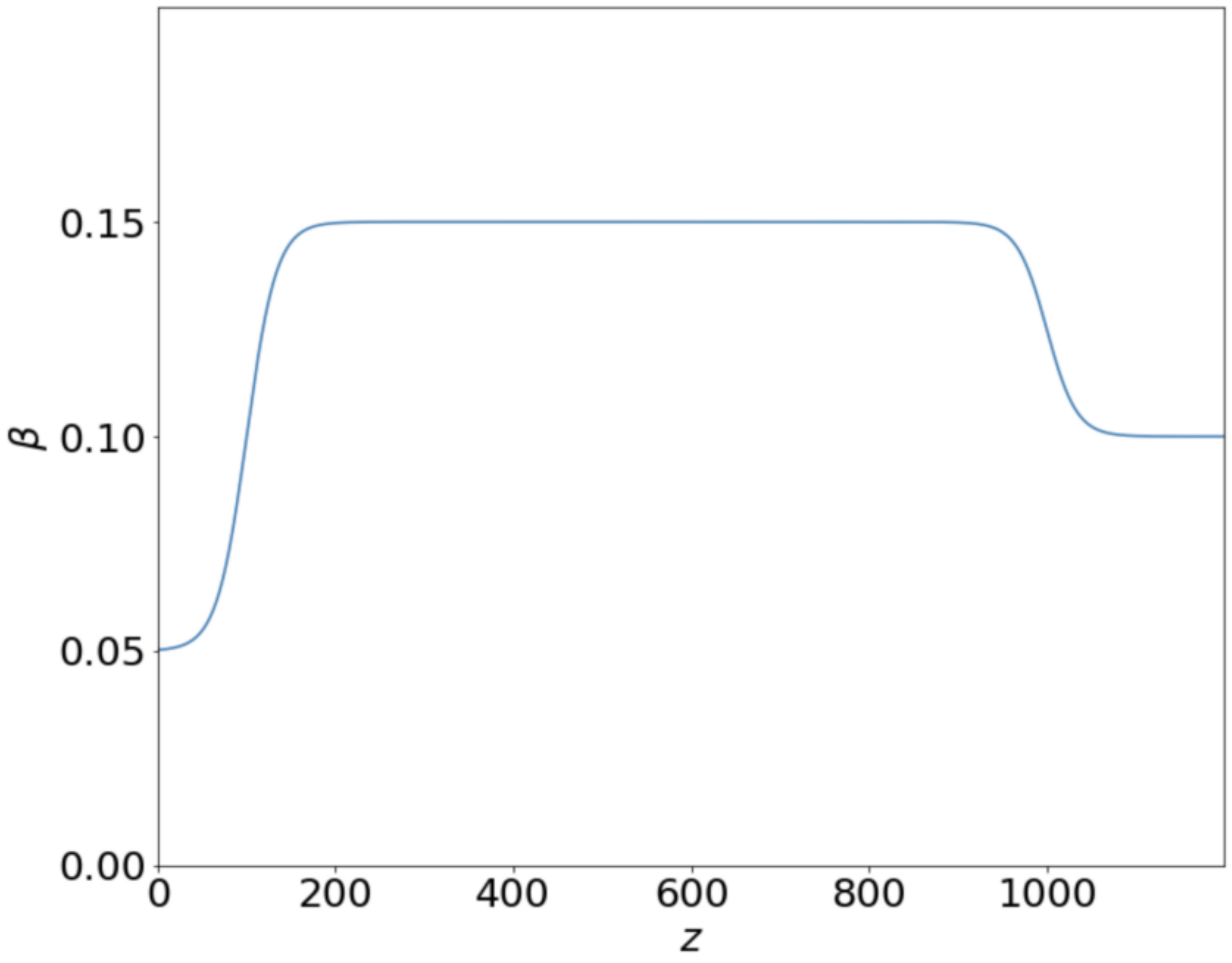
- Coupling strength β has been constrained to be on the order of $\mathcal{O}(10^{-1})$ or less

Tomographic Coupled Dark Energy

- The case of a constant coupling has been studied substantially in literature
- Here we propose a form of parametrisation for β, where it can **vary with redshift**:

$$\beta(z) = \frac{\beta_1 + \beta_n}{2} + \frac{1}{2}\sum_{i=1}^{n-1}(\beta_{i+1} - \beta_i)\tanh[s_i(z - z_i)]$$

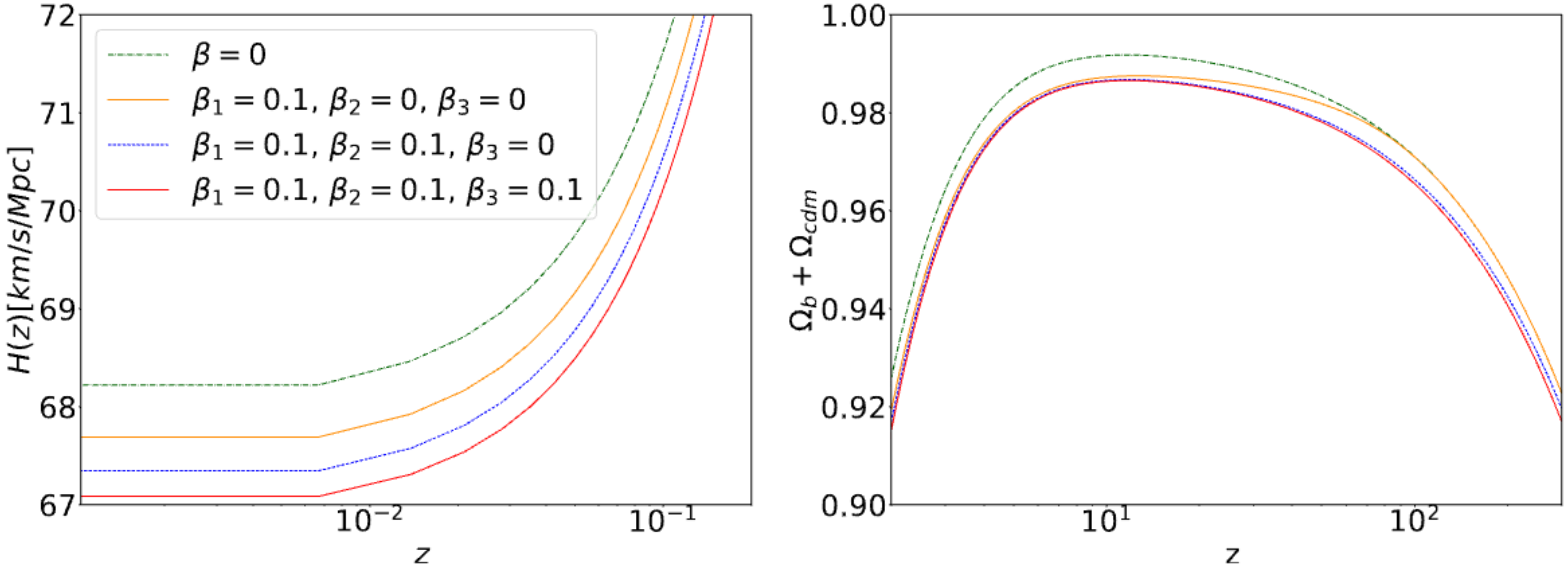
where β_i is the amplitude of coupling in each bin, s_i is the smoothing factor and z_i is the value of the bin edge



Tomographic Coupled Dark Energy

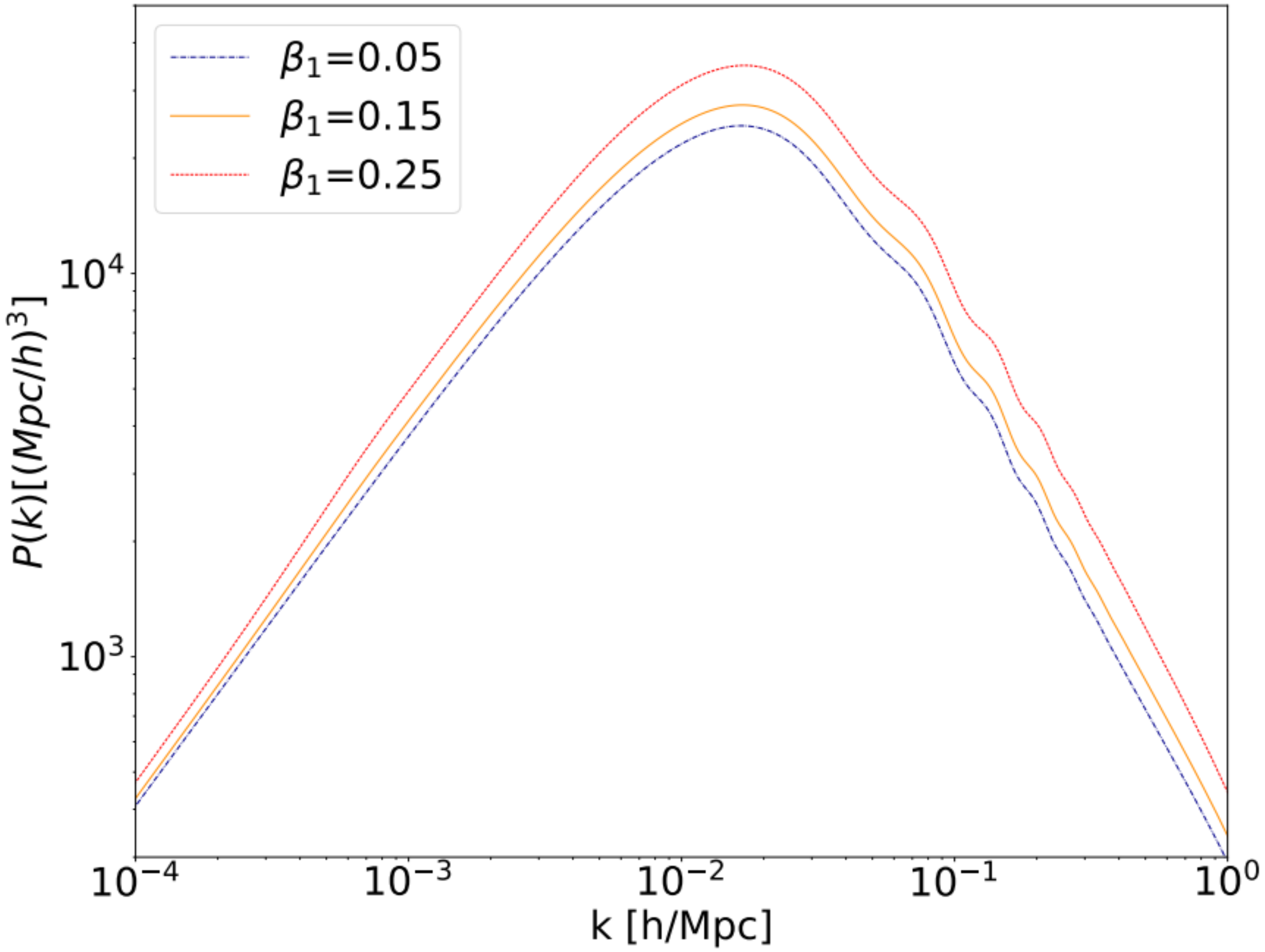
Physical Consequences

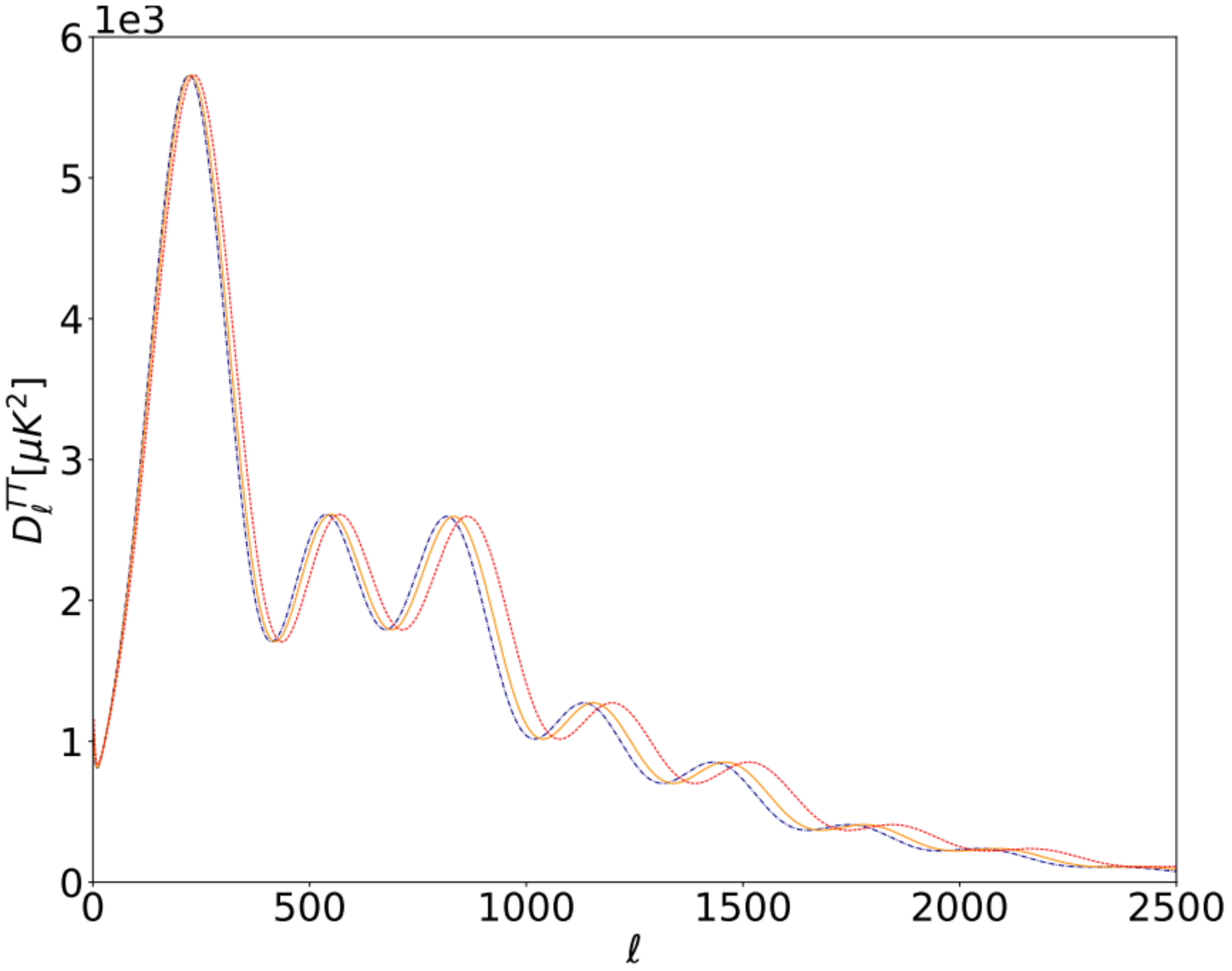
- How do background quantities change?
  - Value of H_0 shifts
  - Ω_m decreases



Tomographic Coupled Dark Energy

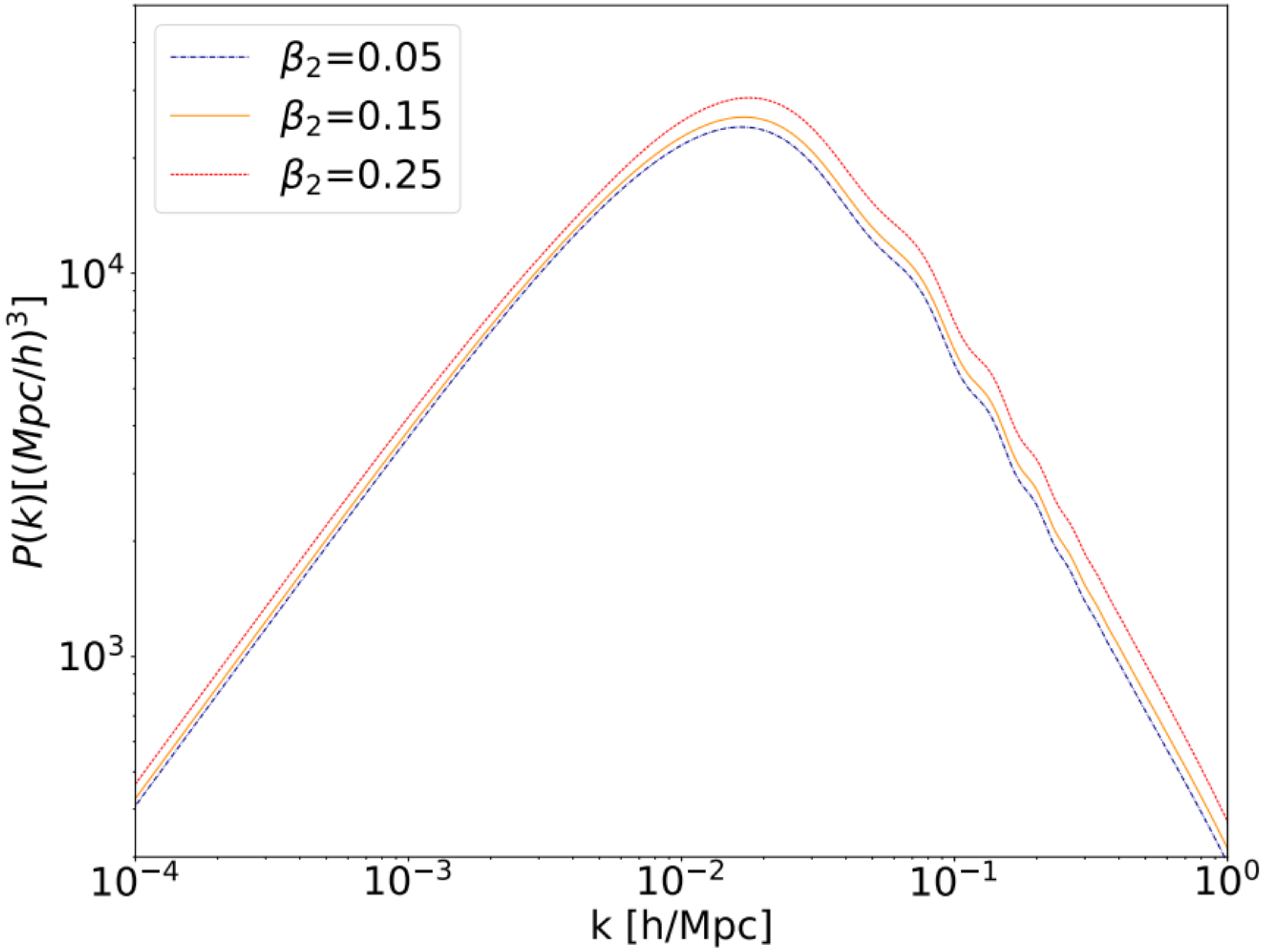
Physical Consequences

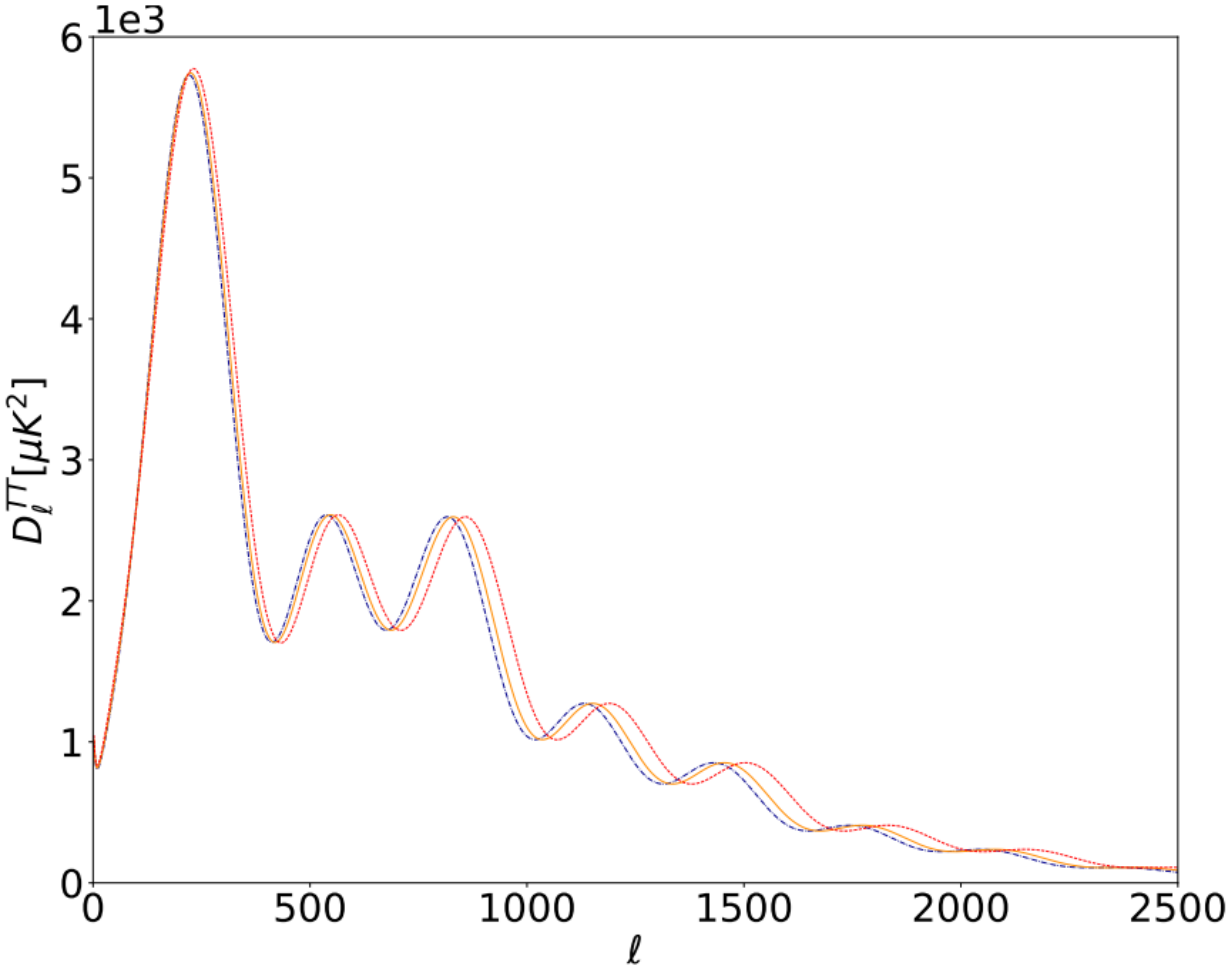




Tomographic Coupled Dark Energy

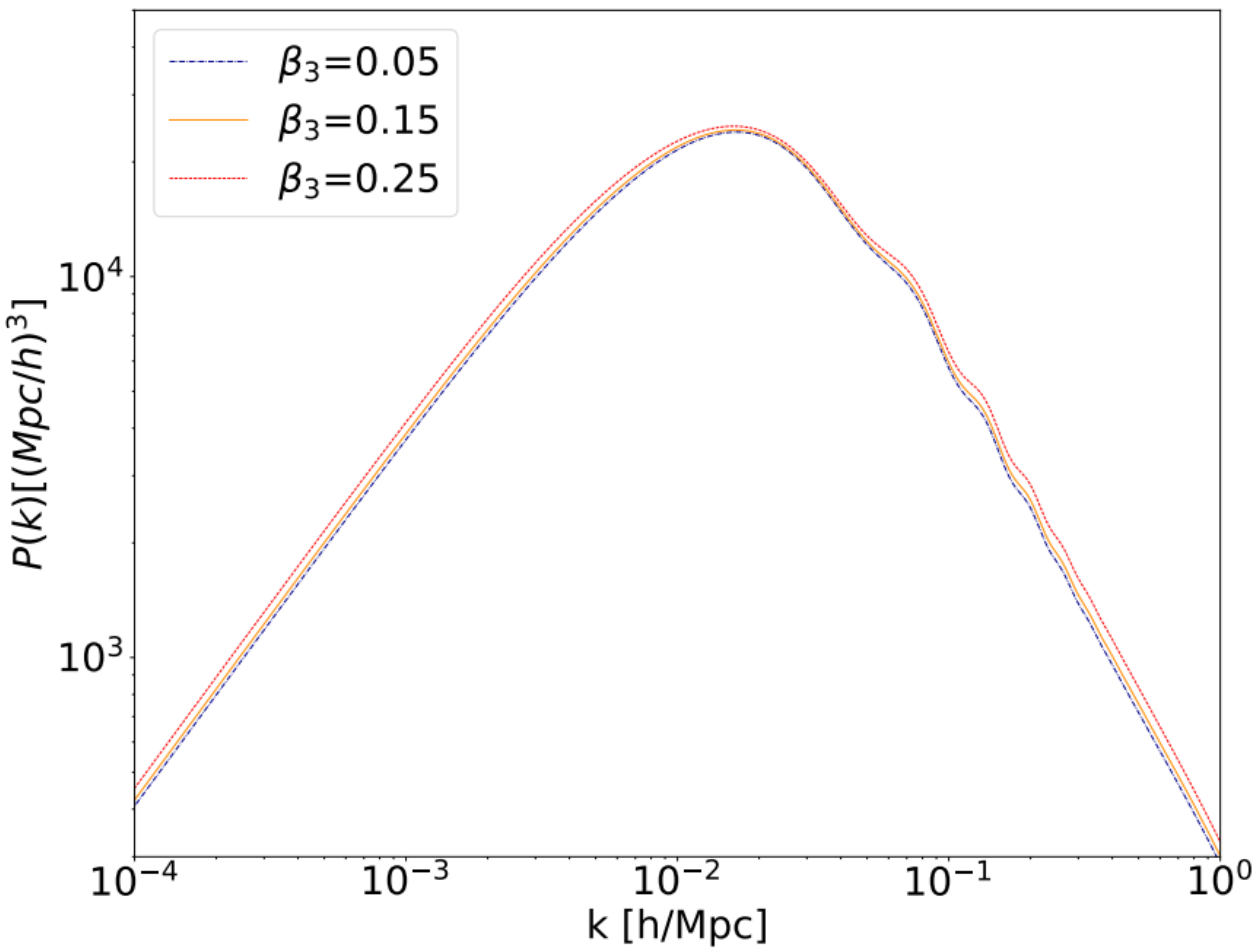
Physical Consequences

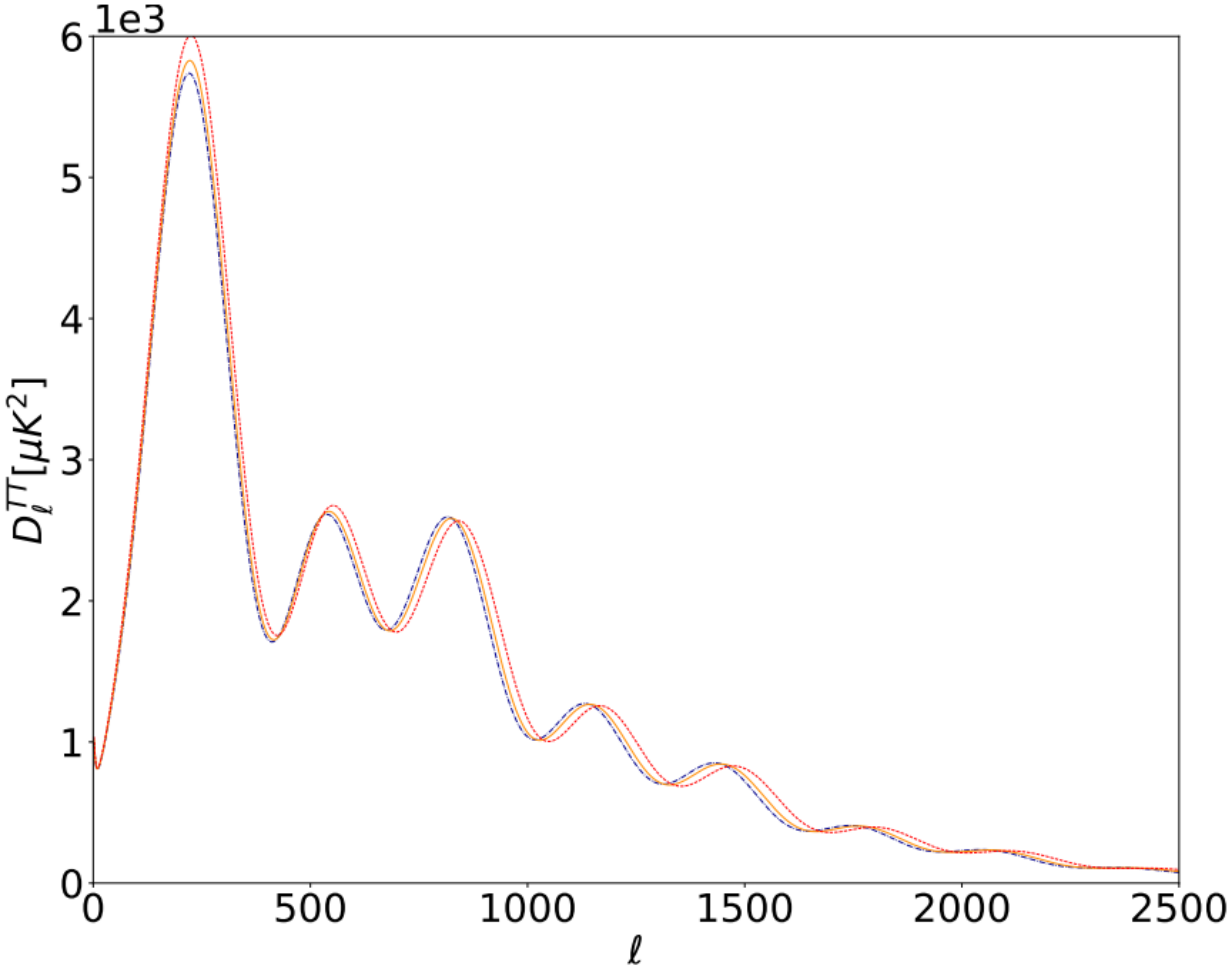




Tomographic Coupled Dark Energy

Physical Consequences





Methodology

Data

1. **Cosmic Microwave Background**:
   - Planck 2018 TT, TE and EE
   - Atacama Cosmology Telescope (ACT) Data Release 4 TT, TE and EE
   - South Pole Telescope (SPT) TE and EE
2. **Baryonic Acoustic Oscillations** (BOSS, eBOSS, WiggleZ, DES Y3): $0.122 < z < 2.34$
3. **Redshift Space Distortions** (BOSS, WiggleZ, VIMOS, SDSS): $0.03 < z < 1.36$
4. **Type 1a Supernovae** (Pantheon, DES Y3 SN)
5. **Cosmic Chronometers** (measurements of H(z) from evolving galaxies): $0.07 < z < 1.905$
6. **SHoES** prior: $H_0 = (73.04 \pm 1.04)\ \mathrm{km/s/Mpc}$
7. **Weak Lensing**: KiDS-1000 cosmic shear, BOSS DR12 spectroscopic galaxy clustering and their 3x2pt

Methodology

Binning Parametrisations

1. 3-bins with edges **z={0,100,1000}**
   - Probed with **CMB** data (Planck, Planck+ACT1800, Planck+ACT1800+SPT, Planck650+ACT+SPT)

2. 7-bins with edges **z={0,1,2,5,100,500,1000}**
   - Probed with **CMB** (Planck650+ACT+SPT and Planck+ACT1800+SPT)and low-redshift data: **BAO**, **SNe1a**, **Cosmic Chronometers (CCH)**, **RSD** and **SH0ES**

3. 4-bins with edges **z={0,0.5,1,2}**
   - Probed with **Weak Lensing+Galaxy Clustering+3x2pt**

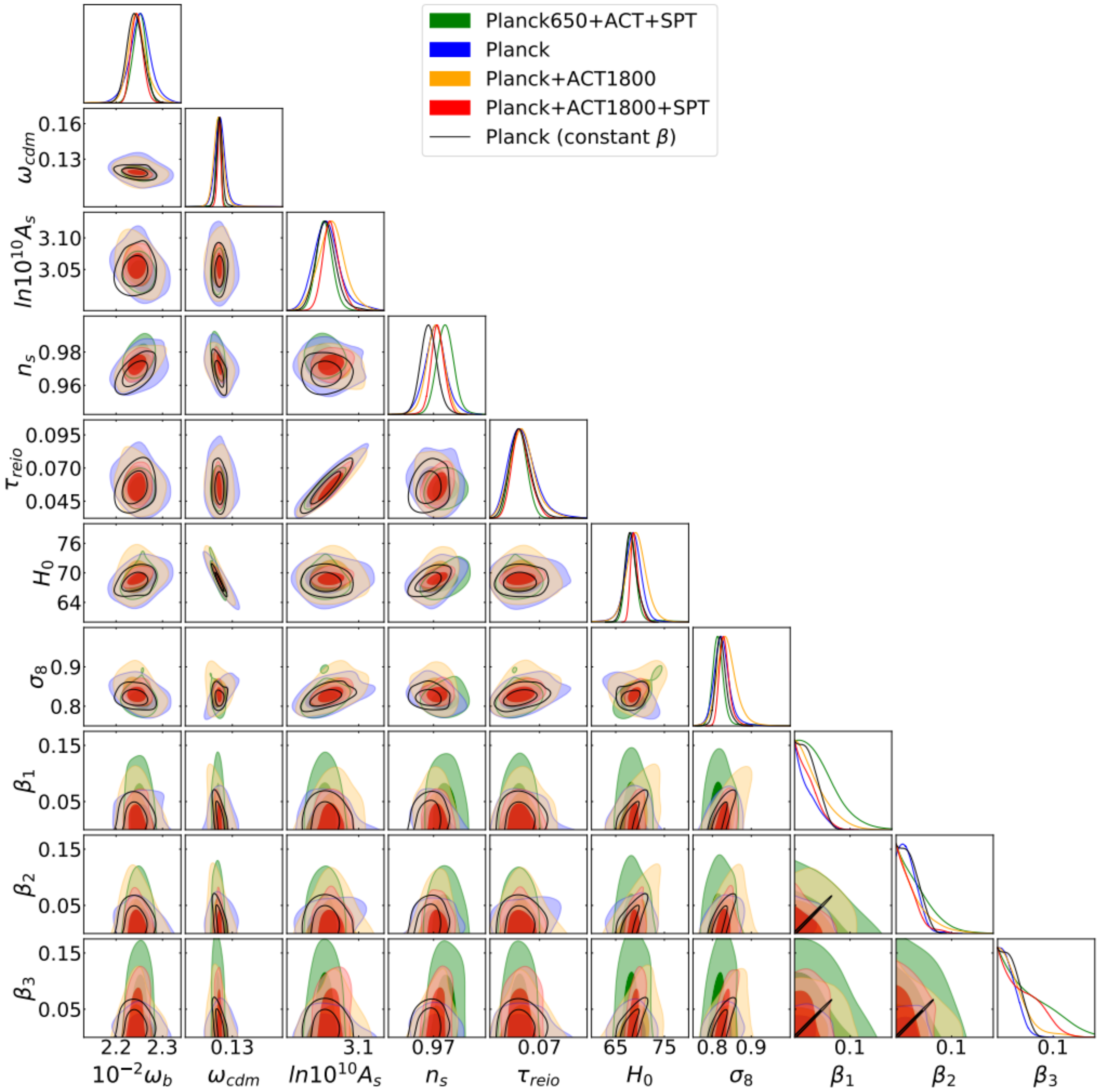
Methodology

- We modify the Boltzmann solver **Cosmic Linear Anisotropy Solving System (CLASS)** and run Monte Carlo Markov Chains, performing a likelihood analysis to constrain our tomographic coupling model
- How will different combinations of datasets affect constraints on β(z)?

Results

3-bin model with CMB
z={0,100,1000}

- Planck650+ACT+SPT allows for **largest values** of β(z): most of constraining power comes from high multipoles of Planck
- Constraints on coupling in tomographic CDE generally looser than in constant coupling case

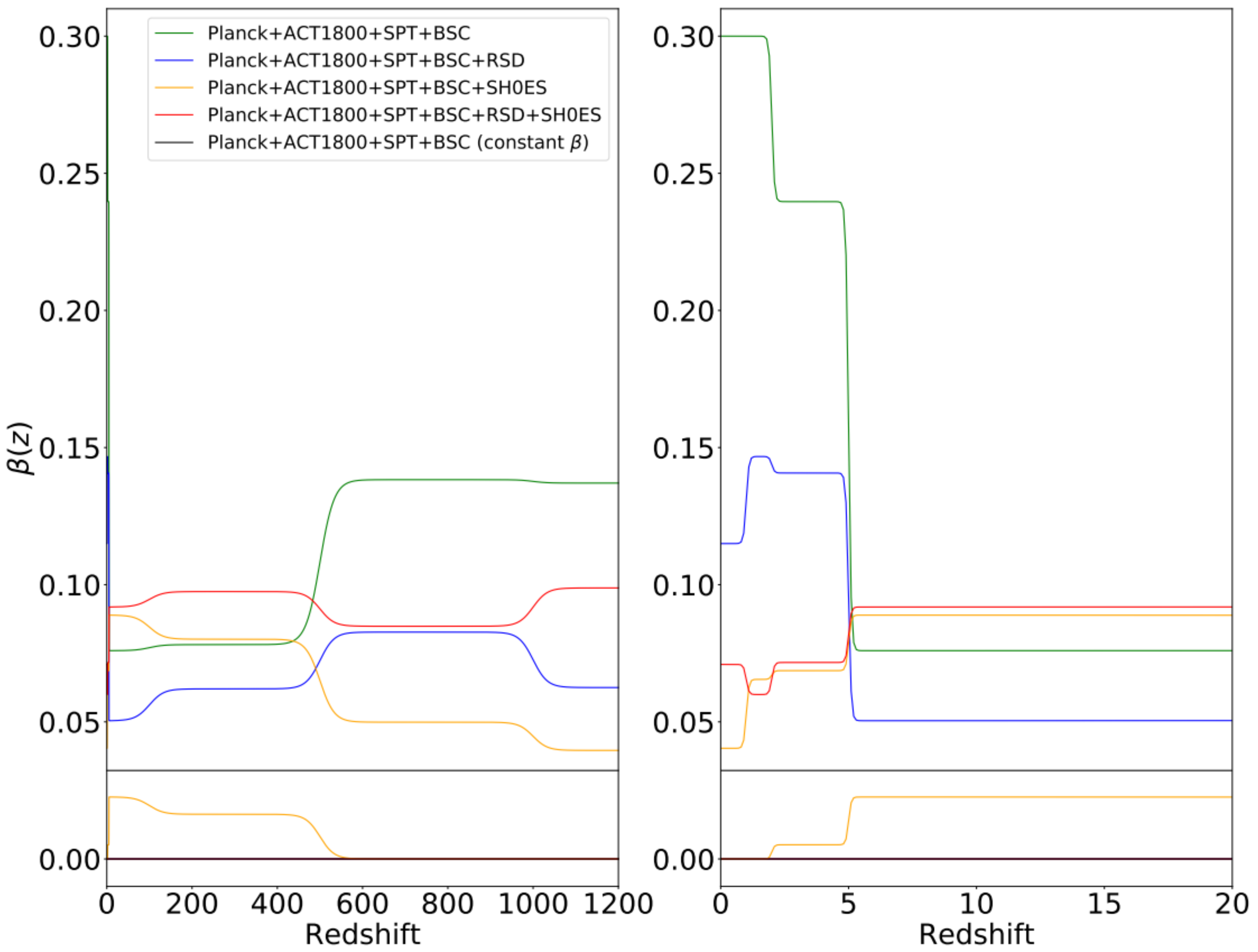


Results

7-bin model with BAO+SNe1a+CCH(BSC), RSD, SHOES

z={0,1,2,5,100,500,1000}

- SHoES prior **favours** $\beta(z) > 0$ at 2σ level
- This could be due to degeneracy between H_0 and $\beta(z)$
- Tightest constraints during **epoch of large scale structure formation** (5 < z <500)

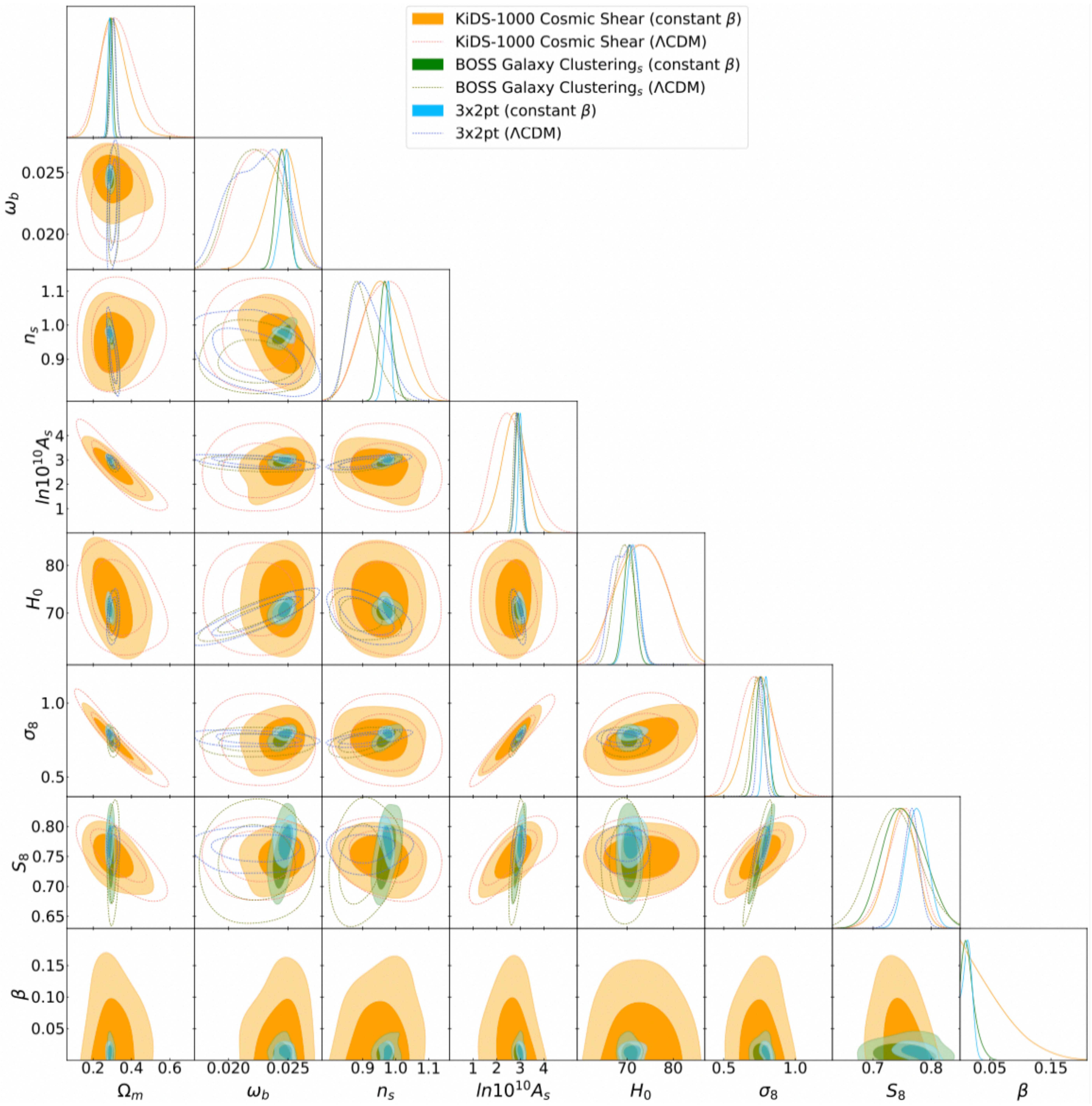


Results

Constant Coupling with Cosmic Shear (CS), Galaxy Clustering (GC), 3x2pt

z={0,1,1.5,2}

- Cosmic shear alone not as effective at constraining coupling: degeneracy in $\sigma_8 - \Omega_m$ plane
- Galaxy Clustering and 3x2pt give **very tight constraints**

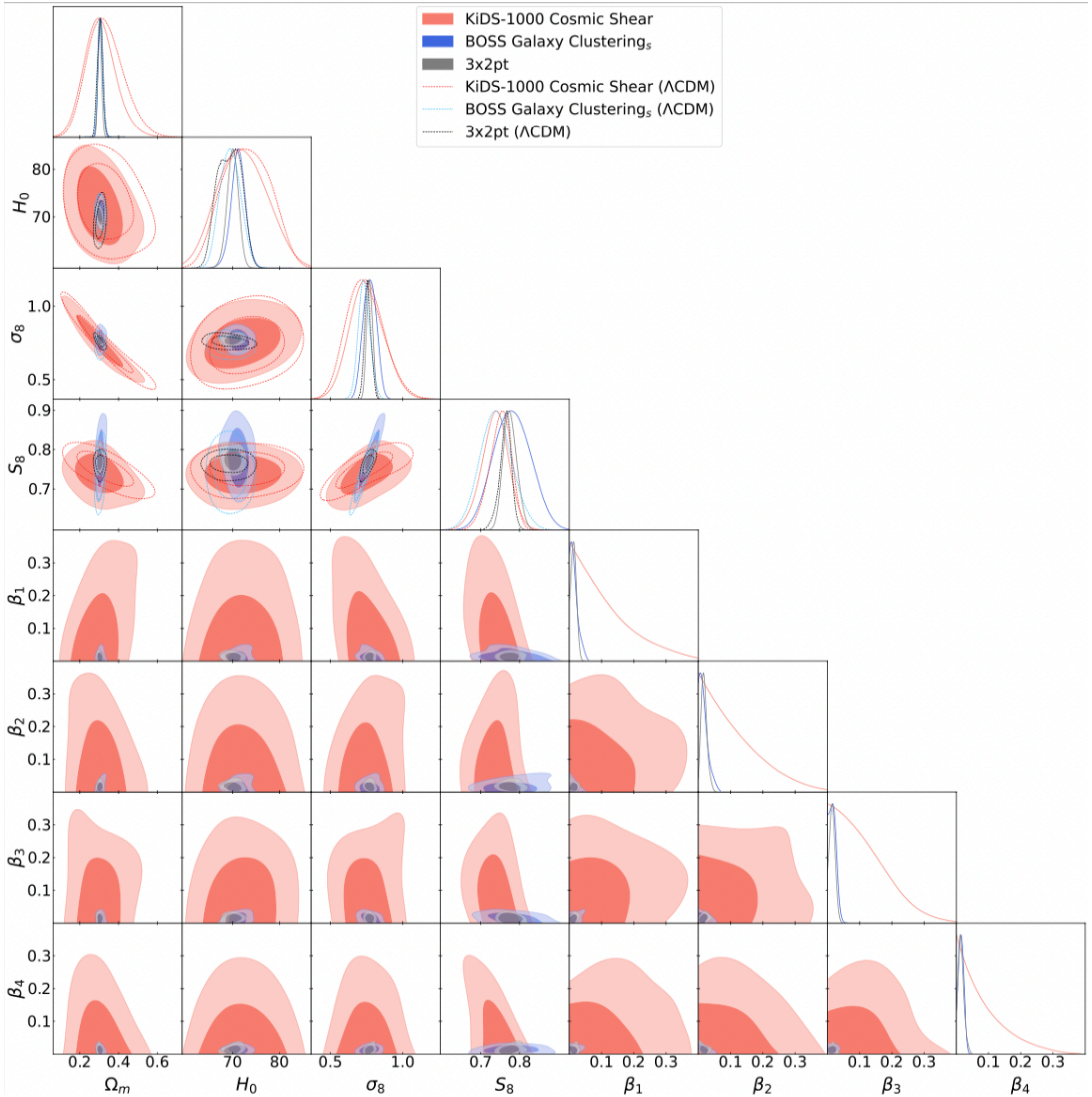


Results

4-bin Coupling with Cosmic Shear, Galaxy Clustering, 3x2pt

z={0,1,1.5,2}

- Cosmic shear can still constrain coupling at $z > 2$
- More accurate models for the nonlinear power spectrum could yield better results
- Galaxy clustering and 3x2pt once again give **very tight constraints across all redshifts**



Results

Cosmic Shear, Galaxy Clustering, 3x2pt

z={0,1,1.5,2}

- Also combined weak lensing probe with CMB+BSC: **results closely in agreement with *Planck***
- In a tomographic CDE framework, tension in S_8 (between 3x2pt and CMB) reduces from ~2.8σ to ~1.3σ
- GC and 3x2pt: constraining power comparable with CMB!

Conclusions

- We study a class of CDE models, where **dark energy is a scalar field that mediates interaction between dark matter** particles
- The strength of coupling is quantified by β, which can be a **function of redshift**
- We test **3 different tomographic binning regimes**, largely motivated by the choice of probes
- A tomographic CDE model **loosens coupling constraints** compared to constant coupling
- A coupling model can **reduce tension in H_0 and S_8**
- **First time weak lensing and galaxy clustering** used as a probe to constrain coupled dark energy models: showing promising results!

Thank you!

Questions?