
Credit: A. Papadopoulos

Measuring the evolution of the Weyl potential

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Outline

- Introduction
- Gravitational lensing and the Weyl potential — IT, Sobral Blanco, & Bonvin (2023)
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- Weyl potential with evolving dark energy — Rosatello, Ye, Berti, IT, Grimm, & Bonvin (2026)
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Introduction

- Beyond LCDM:
  - Test **each model** one at a time – infeasible in practice
  - Test **families of models** (e.g., Horndeski) – degeneracies with current data
  - **Phenomenologically** parametrise deviations from general relativity (GR):

$$k^2\Psi = -4\pi\mu(a,k)Ga^2\rho\delta$$

$$k^2\Psi_W = -4\pi\Sigma(a,k)Ga^2\rho\delta$$

Currently constrained combining gravitational lensing and galaxy clustering measurements

Introduction

❖ **Gravitational lensing** (galaxy-galaxy lensing, GGL) angular power spectrum (Limber approximation):

$$C_\ell^{\Delta\kappa}(z_i, z_j) = \frac{3}{2} \int \mathrm{d}z \, n_i(z) \mathcal{H}^2(z) \Omega_\mathrm{m}(z) b_i(z) \Sigma(z) \\ \times B\left(k_\ell, \chi\right) P_{\delta\delta}^{\mathrm{lin}}\left(k_\ell, \chi\right) \\ \times \int \mathrm{d}z' n_j(z') \frac{\chi'(z') - \chi(z)}{\chi(z)\chi'(z')} \,,$$

➢ $\mathcal{H}$ Hubble parameter in conformal time

➢ B boost for the nonlinear evolution of matter density perturbations

Introduction

❖ **Caveats**:

➢ GGL depends on Σ **but also on** μ via the the evolution of δ and consequently of $P^{\rm lin}_{\delta\delta}(k_\ell, \chi) \rightarrow$ need to combine with redshift-space distortions (RSDs)

➢ Constraints on μ at a given redshift depend on its **evolution at higher redshifts** (need to solve the evolution equation for δ):

- Assume (or reconstruct) a time dependence

$$\delta''(k,a) + \left(1 + \frac{\mathcal{H}'(a)}{\mathcal{H}(a)}\right)\delta'(k,a) - \frac{3}{2}\frac{\Omega_{m,0}}{a}\left(\frac{\mathcal{H}_0}{\mathcal{H}(a)}\right)^2 \mu(a)\,\delta(k,a) = 0$$

➢ Validity of **Euler's equation** for dark matter:

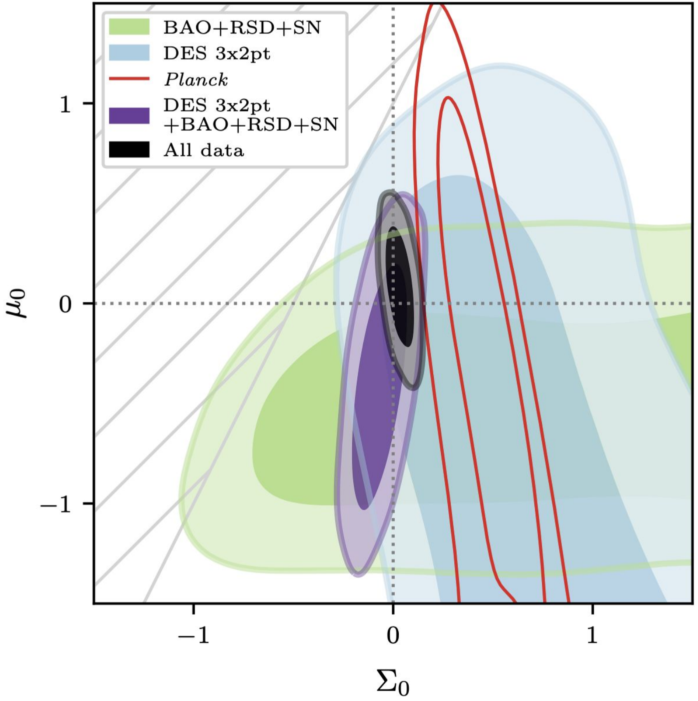
- With RSDs, μ is degenerate with changes in Euler's equation (Bonvin & Pogosian 2023)

Introduction

- Example:

$$\Sigma(a,k) = 1 + \Sigma_0 \frac{\Omega_\Lambda(a)}{\Omega_{\Lambda,0}}$$

$$\mu(a,k) = 1 + \mu_0 \frac{\Omega_\Lambda(a)}{\Omega_{\Lambda,0}}$$



[DES Collaboration 2023]

Gravitational lensing and the Weyl potential

- Can we directly measure in a more **model-independent** way the **evolution of the perturbed geometry** of the Universe?

- Gravitational lensing is sensitive to the **Weyl** potential:

$$\Psi_W \equiv (\Phi + \Psi)/2$$

- Weyl transfer function:
  - In GR, proportional to $D_1(z)\Omega_{\rm m}(z)$. Hence, same information with the evolution of δ or Ψ_W
  - In modified gravity, Einstein's equations are modified → different Ψ_W evolution

Gravitational lensing and the Weyl potential

❖ **Parametrisation**:

$$T_{\Psi_W}(k,z) = \frac{\mathcal{H}^2(z)J(k,z)}{\mathcal{H}^2(z_*)D_1(z_*)}\frac{\sqrt{B(k,z)}}{\sqrt{B(k,z_*)}}T_{\Psi_W}(k,z_*)$$

➢ z_* well in the matter-dominated era

➢ J free function encoding the evolution of the Weyl potential (see also Amendola et al. 2013; 2014)

❖ Measuring $J(z)$ we can **reconstruct** the Weyl potential evolution and can compare against **GR** or **modified gravity predictions**

Gravitational lensing and the Weyl potential

- **Observable**: galaxy-galaxy lensing angular power spectrum (Limber approximation):

$$C_\ell^{\Delta\kappa}(z_i, z_j) = \frac{3}{2} \int \mathrm{d}z\, n_i(z) \mathcal{H}^2(z) \hat{b}_i(z) \hat{J}(z) B\left(k_\ell, \chi\right) \frac{P_{\delta\delta}^{\mathrm{lin}}\left(k_\ell, z_*\right)}{\sigma_8^2(z_*)} \int \mathrm{d}z' n_j(z') \frac{\chi'(z') - \chi(z)}{\chi(z)\chi'(z')}$$

- It depends on:
  - density fluctuations at z_* (GR is recovered)
  - evolution of background quantities $\mathcal{H}$ and χ (LCDM background)
  - the functions $\hat{J}$ and $\hat{b}_i$:

$$\hat{J}(z) \equiv \frac{J(z)\sigma_8(z)}{D_1(z)}$$

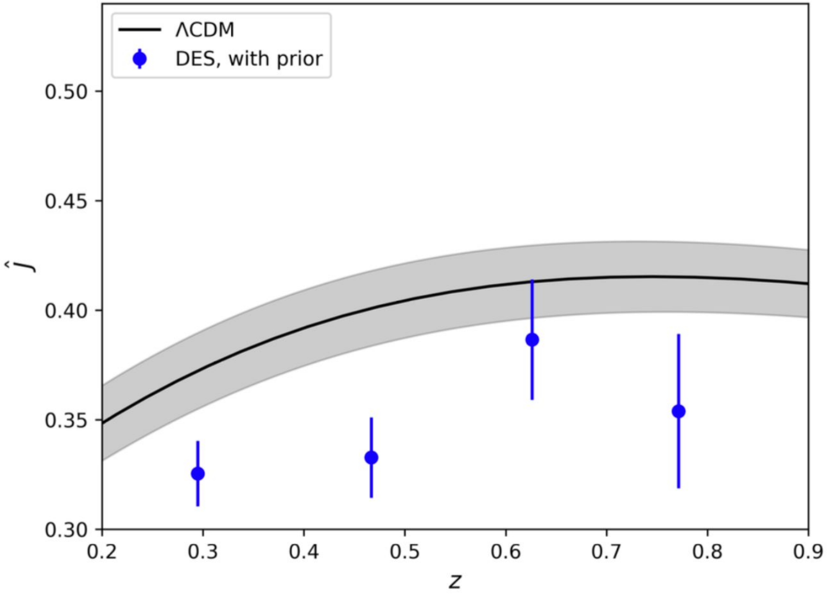
$$\hat{b}_i(z) \equiv b_i(z)\sigma_8(z)$$

Gravitational lensing and the Weyl potential

- Since $\hat{J}$ and $\hat{b}_i$ vary slowly with redshift, we can take them out of the integral and evaluate them at the effective redshift of the bin:
  - GGL measurements at a given bin provide direct measurements of $\hat{J}$ and $\hat{b}_i$
  - Clear separation of the information that can be measured from lensing and RSDs
  - Model-independent measurement: no theory of gravity assumed

- **Caveat**: $\hat{J}$ and $\hat{b}_i$ are fully degenerate $\rightarrow$ we add the galaxy clustering angular power spectrum
- **2x2pt analysis** – similar configuration compared to the standard analysis (Porredon et al. 2022)

Measuring the Weyl potential from DES-Y3 data

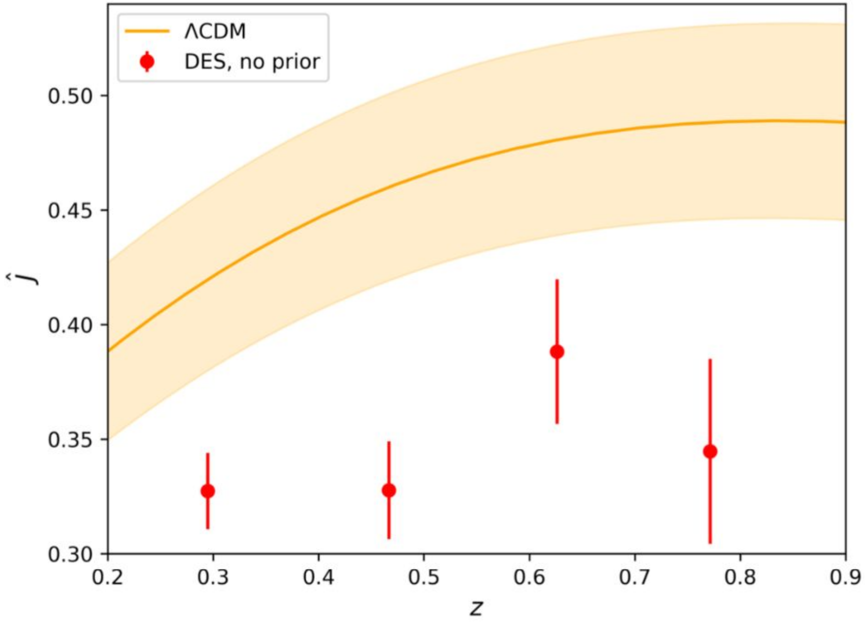


[IT, Bonvin, & Grimm 2024]

- Precise model-independent measurement of $\hat{J}$ (4.6–9.9%)
- 2σ and 2.8σ below the LCDM prediction in the first two bins
- 3σ Planck priors on early-time cosmological parameters
- Reduces to the σ_8 tension once GR is assumed (see, e.g., García-García et al. 2021)
- With linear scale cuts: uncertainties x2. Mean values unaffected

Measuring the Weyl potential from DES-Y3 data

- No Planck priors
- Marginal increase in the uncertainties (5.2–11.6%)
- Preference for higher amplitude of perturbations at high redshift and slower growth of the Weyl potential at low redshifts

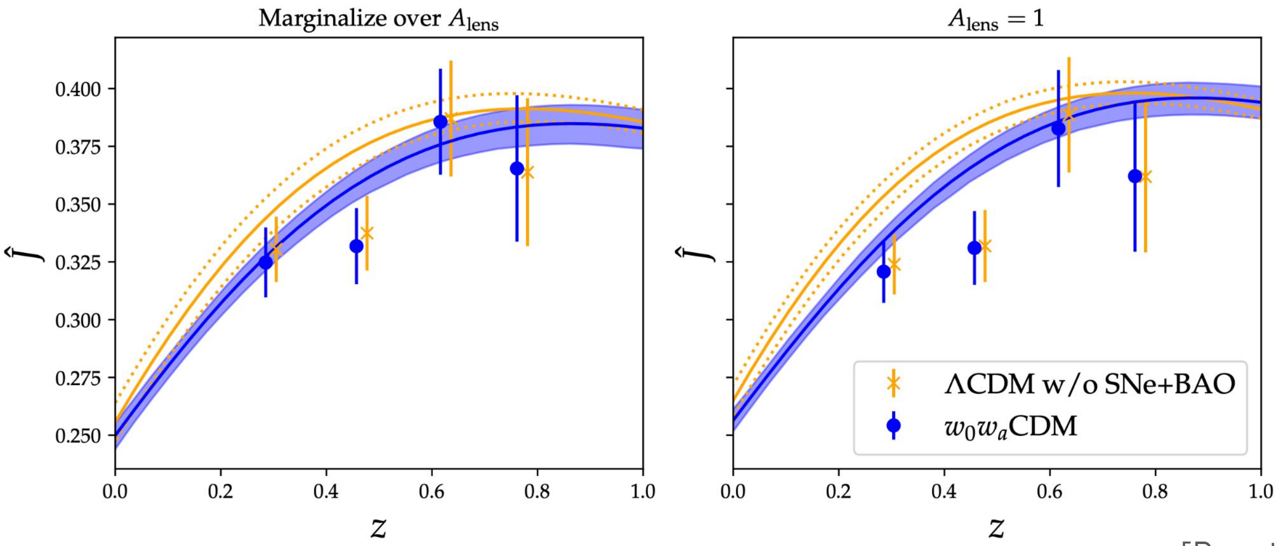


[IT, Bonvin, & Grimm 2024]

Weyl potential with evolving dark energy

- Can **evolving dark energy** compensate for the slower evolution of the Weyl potential?
- We redo the analysis including **type-Ia supernovae** (SNIa), **baryon acoustic oscillations** (BAO), and **cosmic microwave background** (CMB) measurements to help constrain the background
- CMB measurements:
  - Conservative choice: marginalise over A_{lens} to mitigate the impact of lensing to the primordial CMB spectra
  - Aggressive choice: fix A_{lens} to 1
  - No lensing reconstruction added in any scenario

Weyl potential with evolving dark energy



[Rosatello et al. 2026]

- ❖ Evolving dark energy reduces the discrepancy down to a level of 1.6–2.2 σ
- ❖ No degradation on the Weyl constraints. Major change from evolving dark energy on GR predictions

Conclusions

- New methodology to directly measure the perturbed geometry of the Universe via the Weyl potential
- Mild tension with LCDM at low redshift, partially alleviated with evolving dark energy
- Can be combined with galaxy velocities to obtain precise constraints on the E_G statistic (Grimm, Bonvin, & IT 2024)
- Can be combined with galaxy velocities to constrain the strength of a potential fifth force (Grimm, Bonvin, & IT 2025)
- Stay tuned for precise constraints in the near future from *Euclid* DR1 data (Grimm et al.)