First measurement of the Weyl potential evolution from DES Y3 data

- Isaac Tutusaus

isaac.tutusaus@irap.omp.eu

arXiv:2209.08987 (w/ Sobral Blanco & Bonvin)
arXiv:2312.06434 (w/ Bonvin & Grimm)
arXiv:2403.13709 (w/ Grimm & Bonvin)

Observatoire Midi-Pyrénées OMP
irap astrophysique & planétologie
UNIVERSITÉ TOULOUSE III PAUL SABATIER
Université de Toulouse

Contents

Introduction

- LCDM: concordance model
  - Unknown nature of the dark components
  - Increasing tensions for some parameters
- Beyond LCDM:
  - Theory: Test each proposed model one at a time (infeasible)
  - Theory: Horndeski theories (hard to break degeneracies with current data)
  - Phenomenology: Parametrization of deviations from GR

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

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

Introduction

- Beyond LCDM:

  - Phenomenology: Parametrization of deviations from 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

- Caveats:
  - Constraints on μ and Σ at a given redshift z depend on the evolution of the function at all redshifts above z
    - Need to assume a time dependence
    - Need to reconstruct the time dependence for a set of nodes
  - Validity of Euler's equation for dark matter
    - μ cannot be constrained from RSD — fully degenerate with changes in Euler's equation (Bonvin & Pogosian 2023)

Introduction

- Beyond LCDM:
  - Phenomenology: Parametrization of deviations from GR

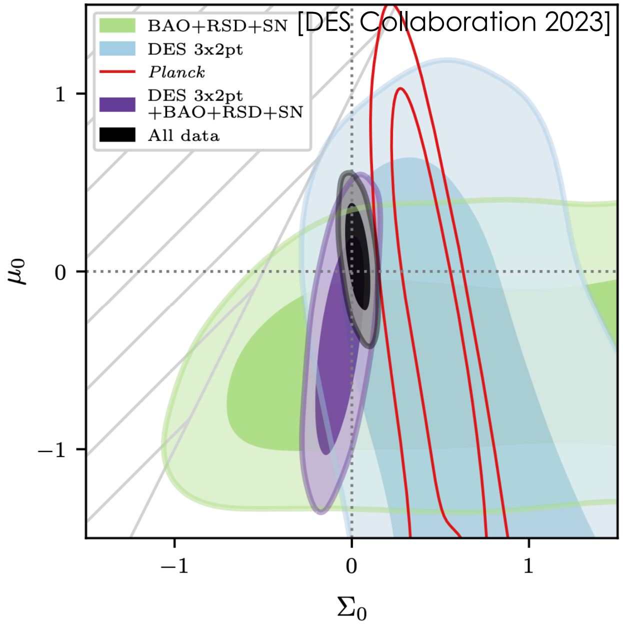
$$k^2\Psi = -4\pi\mu(a,k)Ga^2\rho\delta$$

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

  - Assuming a time dependence

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

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



Introduction

- Beyond LCDM:
  - Phenomenology:

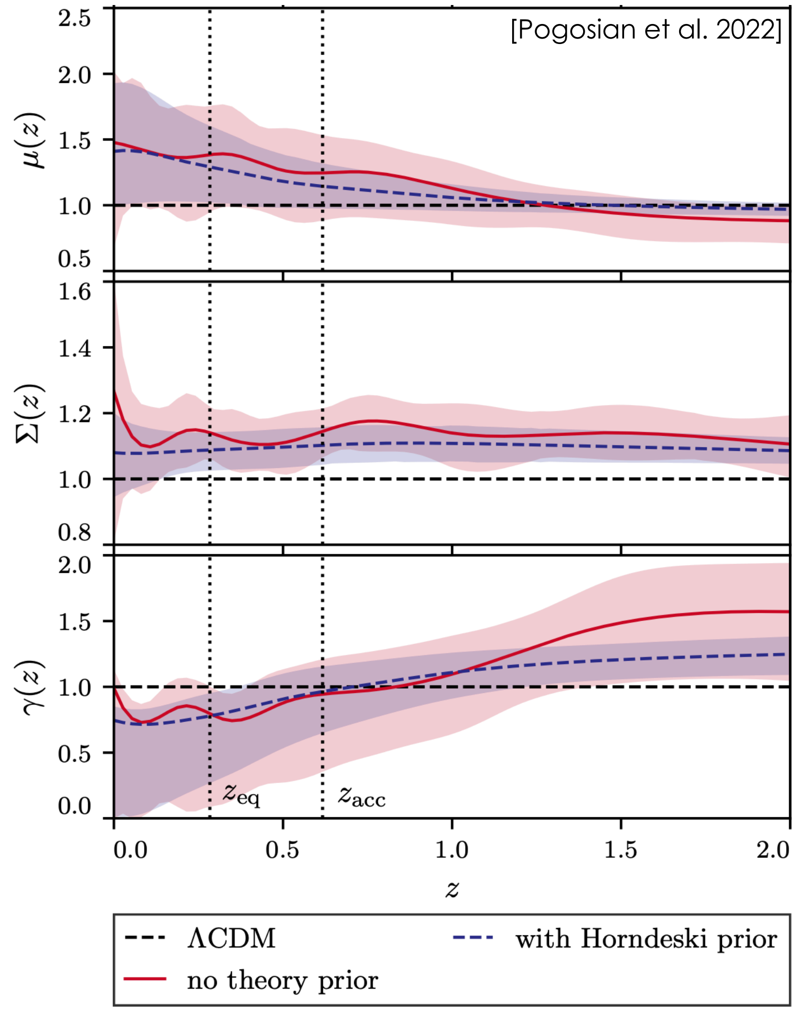
    Parametrization of deviations

    from GR

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

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

  - Reconstruction



Introduction

- What can we really directly measure in a model-independent way?
  - Approach used for RSD: $f\sigma_8$
  - Can be compared with GR predictions
  - Can be used to constrain parameters of MG models
- Goal: Use a similar approach for the first time with real gravitational lensing observations
  - First direct and model-independent measurement of the evolution of the perturbed geometry of our Universe

Gravitational lensing

- Gravitational lensing is directly 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 MG, Einstein's equations are modified => different Ψ_W evolution

Gravitational lensing

- Our parametrization:

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

- z_* well in the matter-dominated area
- $\mathcal{H}$ Hubble parameter in conformal time
- B Boost factor for the nonlinear evolution of matter density perturbations
- J Free function that encodes any deviation in the Weyl potential evolution (similar to *L* in Amendola et al. 2013, 2014)

- Measuring $J(z)$ we can reconstruct the Weyl potential evolution and compare against GR or MG predictions

Gravitational lensing

- 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

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

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

- Since $\hat{J}$ and $\hat{b}_i$ vary slowly with redshift, we can take them out of the integral and evaluate them at the mean redshift of the bin
  - GGL measurements at a given redshift provide direct measurements of $\hat{J}$ and $\hat{b}_i$
  - Model-independent measurement: no theory of gravity assumed, nor a redshift evolution for $\hat{J}$

Gravitational lensing

- Caveat: $\hat{J}$ and $\hat{b}_i$ are fully degenerate

- Additional observable: galaxy clustering (Limber approximation)

$$C_\ell^{\Delta\Delta}(z_i, z_j) = \int \mathrm{d}z\, n_i(z) n_j(z) \frac{\mathcal{H}(z)(1+z)}{\chi^2(z)} \hat{b}_i(z) \hat{b}_j(z) B\left(k_\ell, \chi\right) \frac{P_{\delta\delta}^{\mathrm{lin}}\left(k_\ell, z_*\right)}{\sigma_8^2(z_*)}\,, \quad \text{for } \ell \geq 200$$

- Additional observable: galaxy clustering (Beyond Limber)

$$P_{\delta\delta}^{\mathrm{nl}} = P_{\delta\delta}^{\mathrm{lin}} + (P_{\delta\delta}^{\mathrm{nl}} - P_{\delta\delta}^{\mathrm{lin}})$$

exact ← → Limber

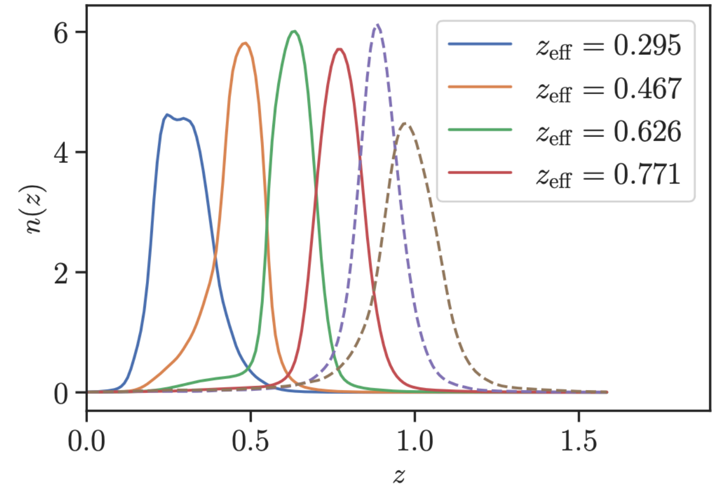
$$C_\ell^{\Delta\Delta}(z_i, z_j)\big|_{\mathrm{lin}} = \frac{2}{\pi} \int \mathrm{d}\chi_1\, n_i(\chi_1)(1+z(\chi_1))\mathcal{H}(\chi_1)\hat{b}_i(\chi_1) \int \mathrm{d}\chi_2\, n_j(\chi_2)(1+z(\chi_2))\mathcal{H}(\chi_2)\hat{b}_j(\chi_2)$$
$$\times \int_0^\infty \mathrm{d}k\, k^2 \frac{P_{\delta\delta}^{\mathrm{lin}}(k, z_*)}{\sigma_8^2(z_*)} j_\ell(k\chi_1) j_\ell(k\chi_2)\,, \quad \text{for } \ell < 200\,.$$

Dark Energy Survey Year 3 data

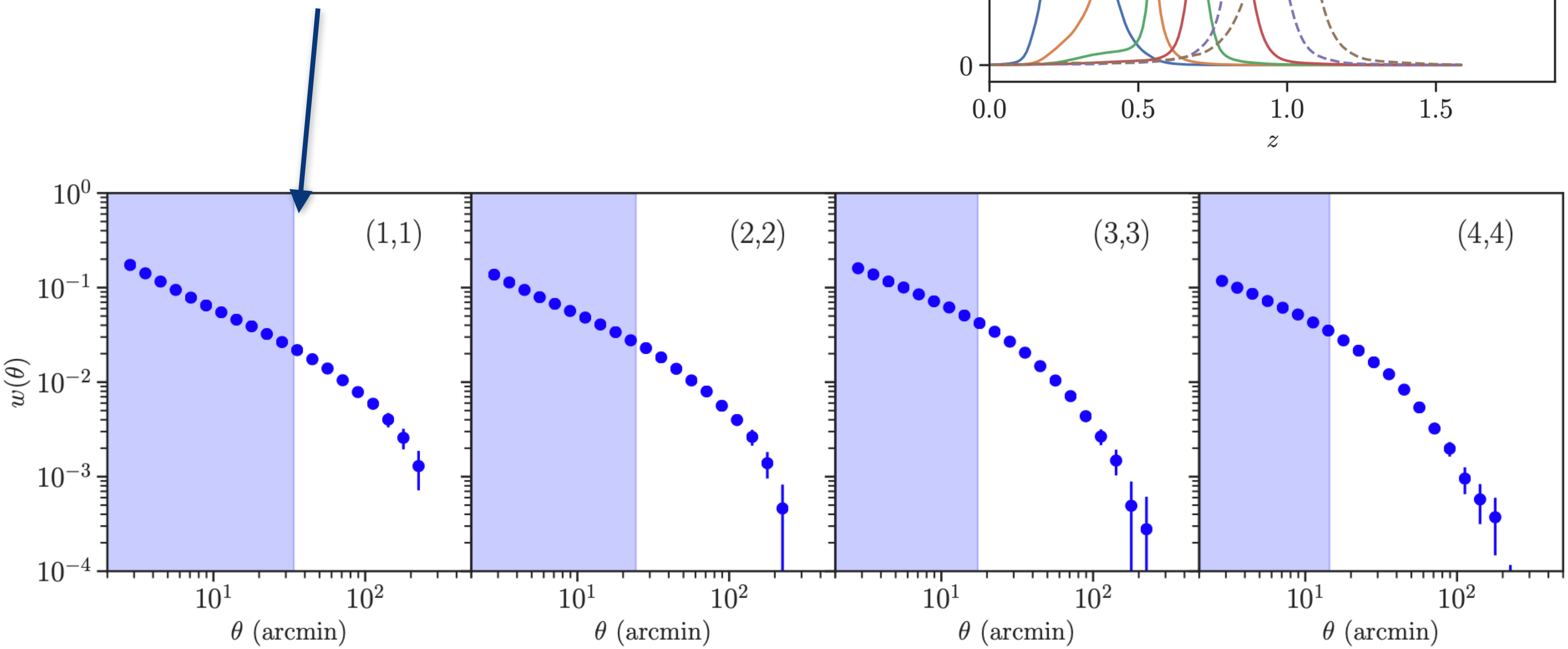
- 2x2pt analysis: galaxy clustering and galaxy-galaxy lensing
- MagLim (lenses) and Metacalibration (sources)
- Similar configuration compared to the official analysis (Porredon et al. 2022):
  - Configuration space
  - Nuisance parameters for the width and position of the lenses and positions of the sources
  - Intrinsic alignments (NLA model in GR)
  - Magnification effects for the lenses (GR)
  - RSD (GR)
  - Linear galaxy bias
  - Shear multiplicative bias
  - Point-mass marginalization for the tangential shear
  - No information from shear ratios
  - Two sets of scale cuts

Dark Energy Survey Year 3 data

- Galaxy clustering

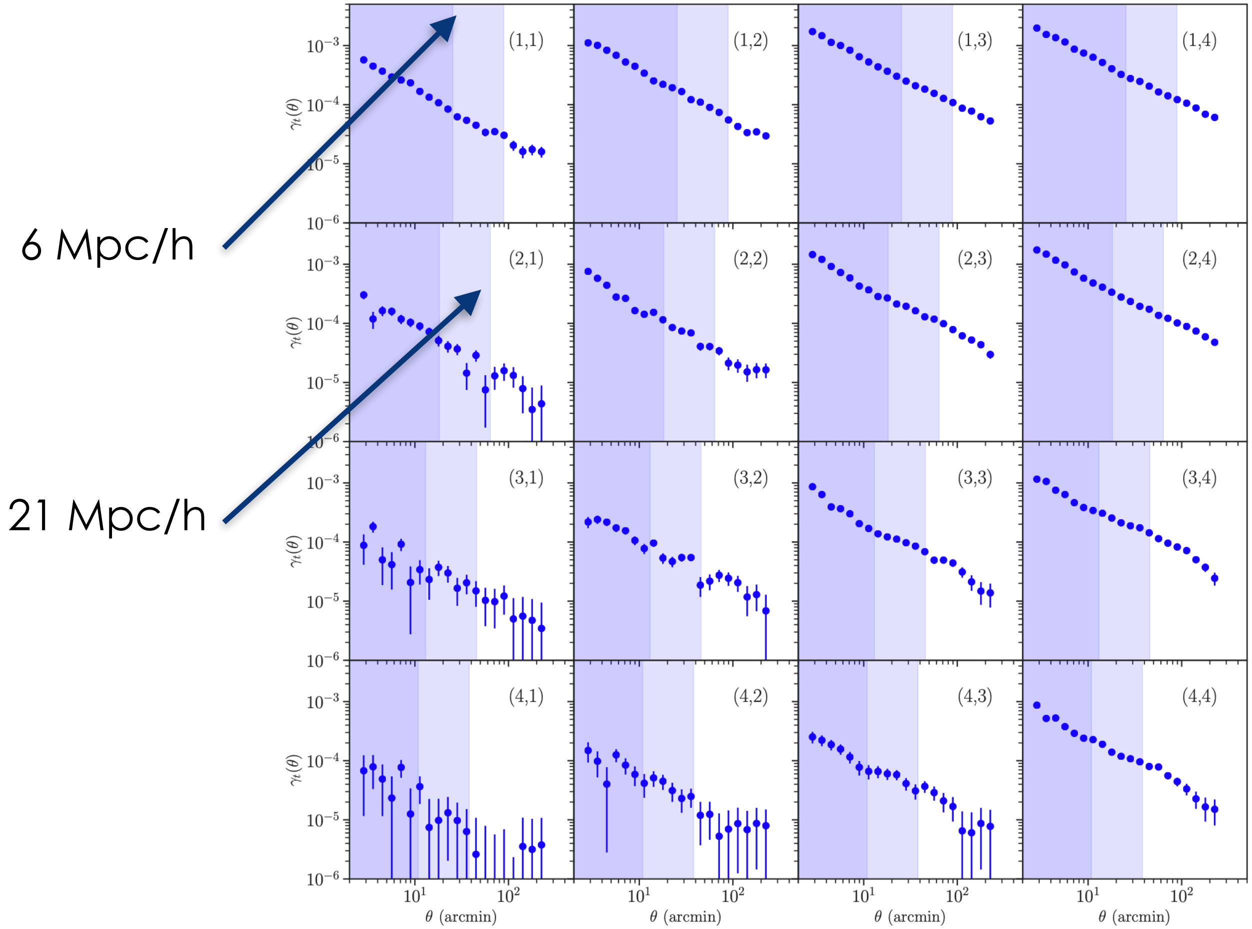


8 Mpc/h

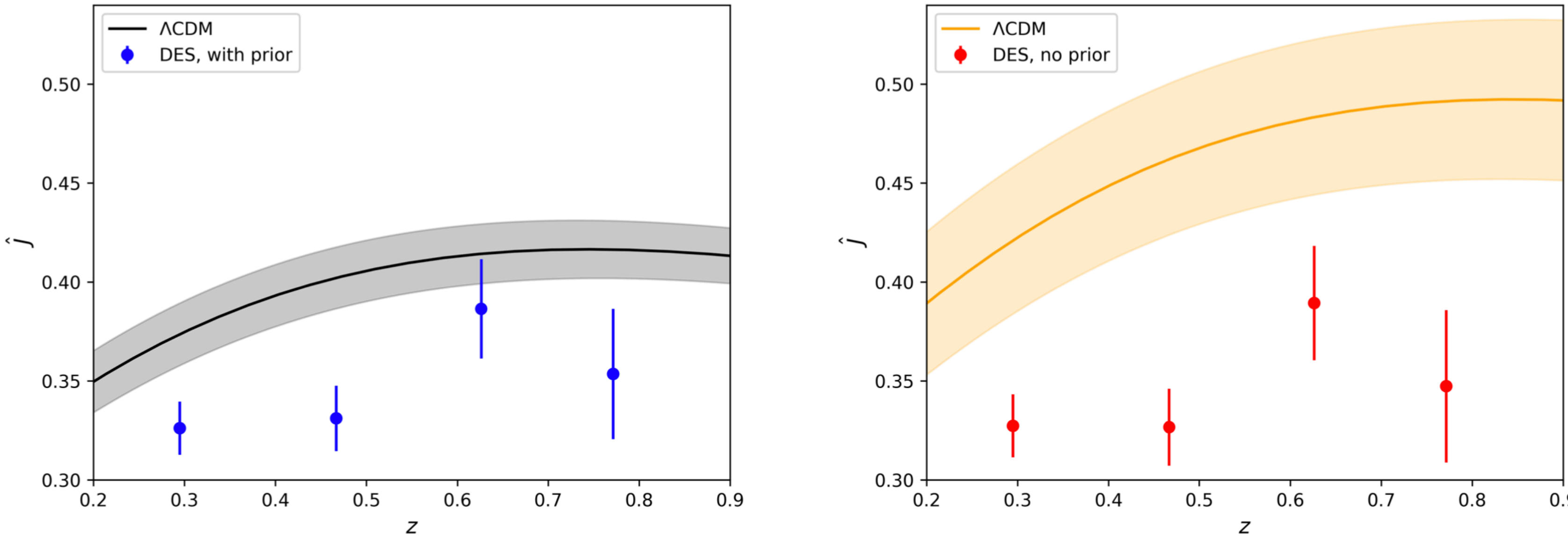


Dark Energy Survey Year 3 data

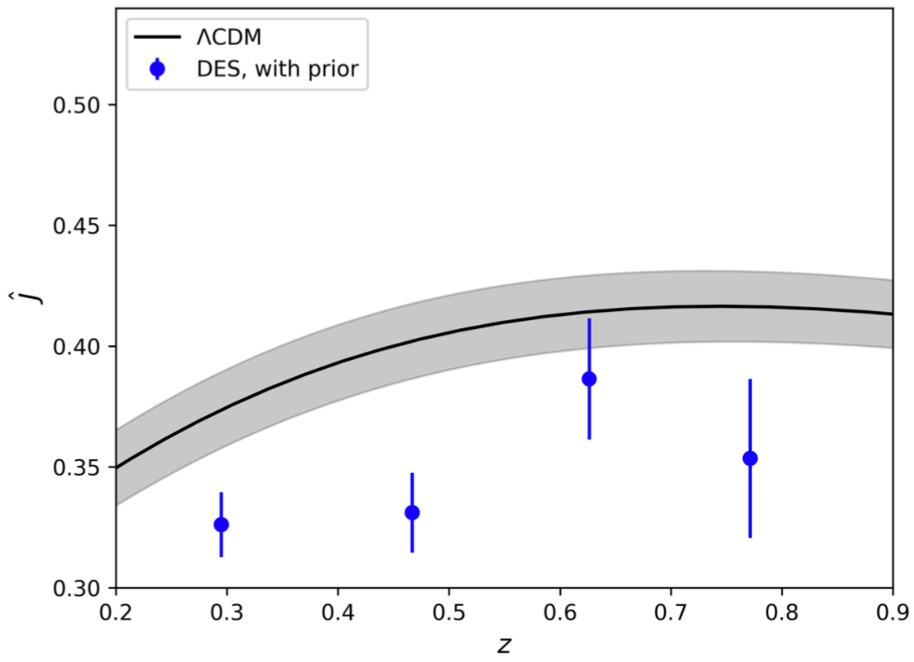
- Galaxy-galaxy lensing



First measurement of the Weyl potential



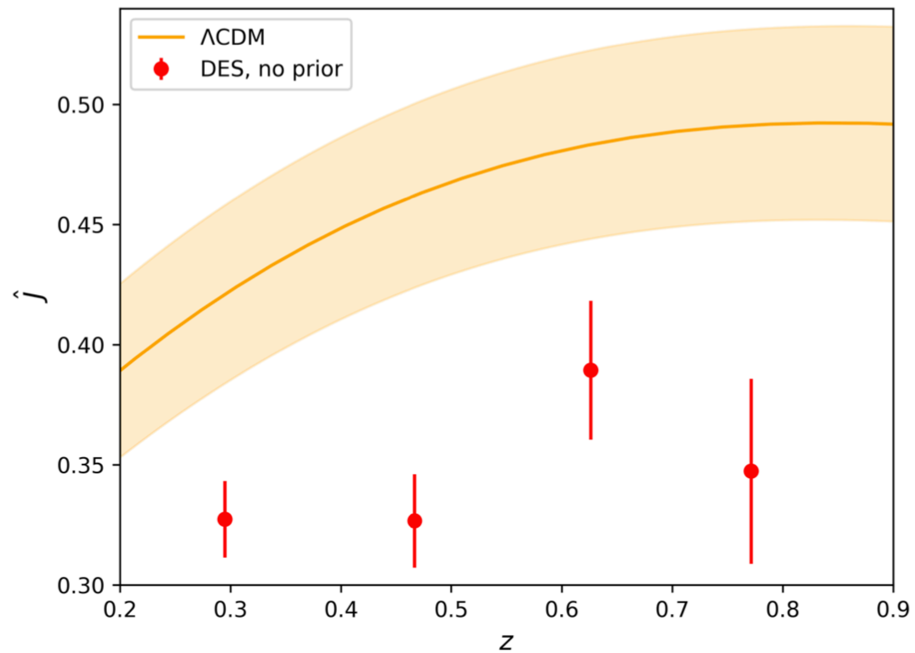
First measurement of the Weyl potential



- Precise model-independent measurement of $\hat{J}$ (4-9%)
- 2.3σ and 3.1σ below the LCDM prediction in the first 2 bins
- 3σ Planck priors on early-time cosmological parameters

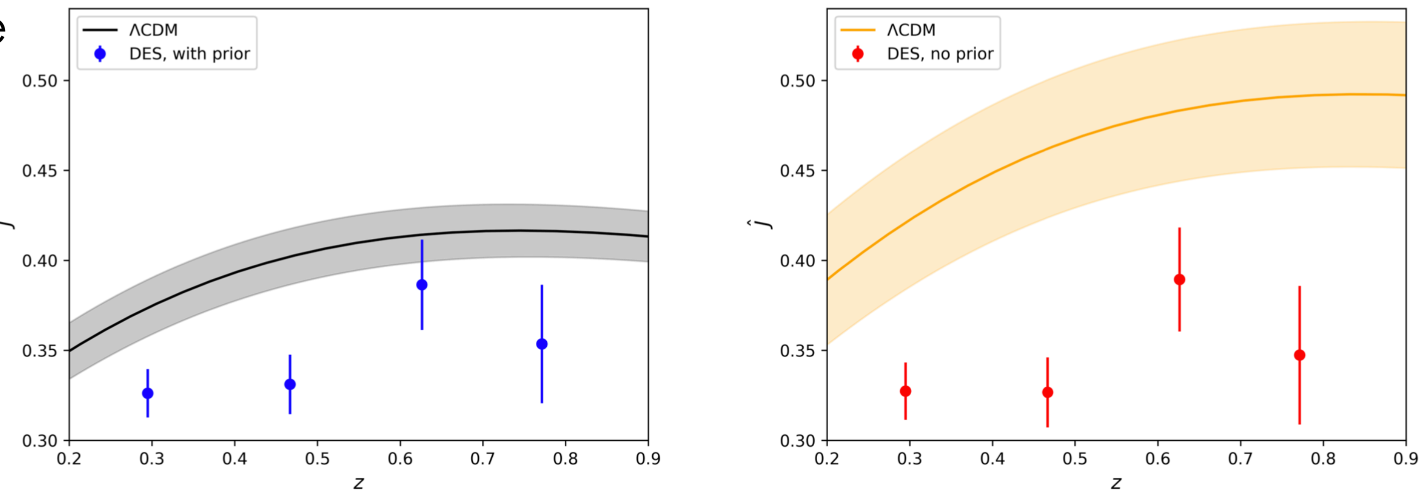
First measurement of the Weyl potential

- No Planck priors
- Uncertainties increase only by 20%
- Slightly larger tension between the measurements and LCDM
- Preference for higher amplitude of perturbations at high redshift and slower growth of the Weyl potential at low redshifts

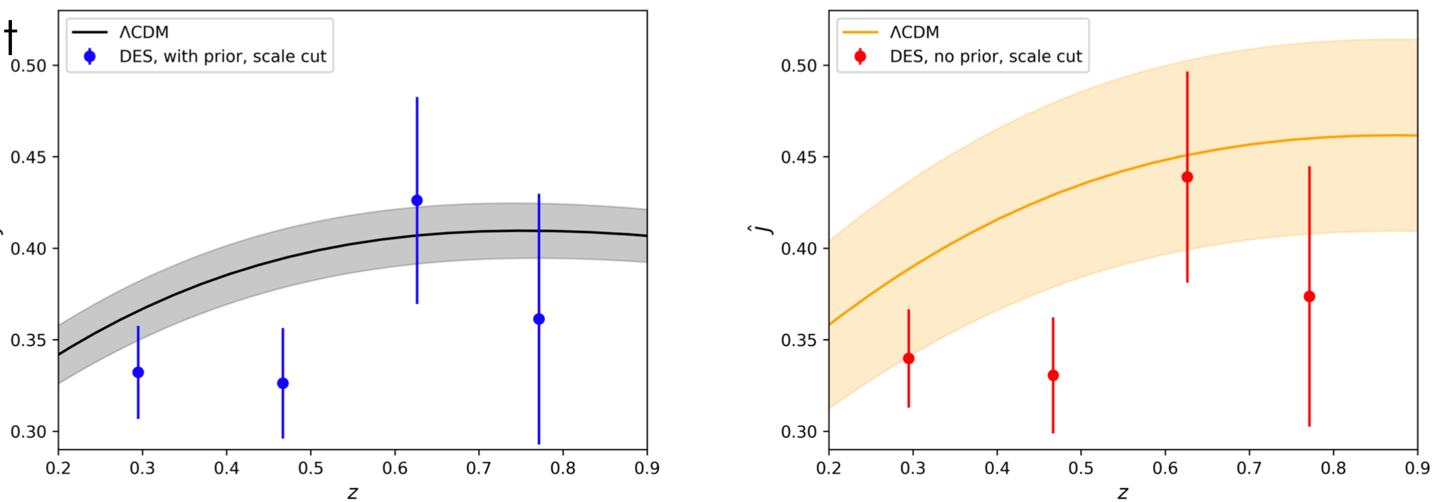


First measurement of the Weyl potential

Baseline

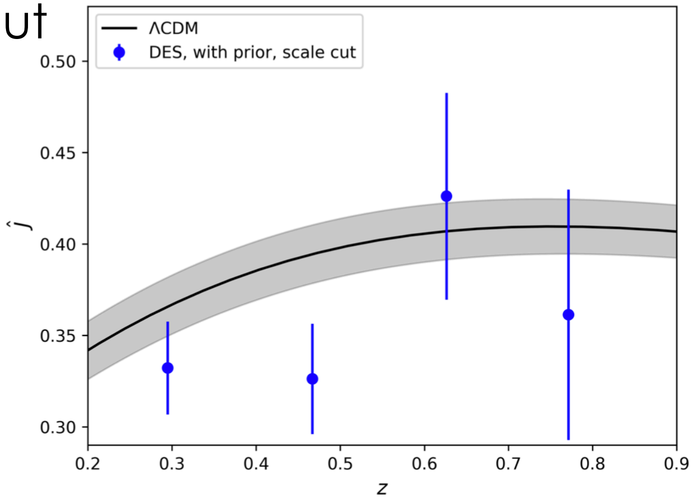


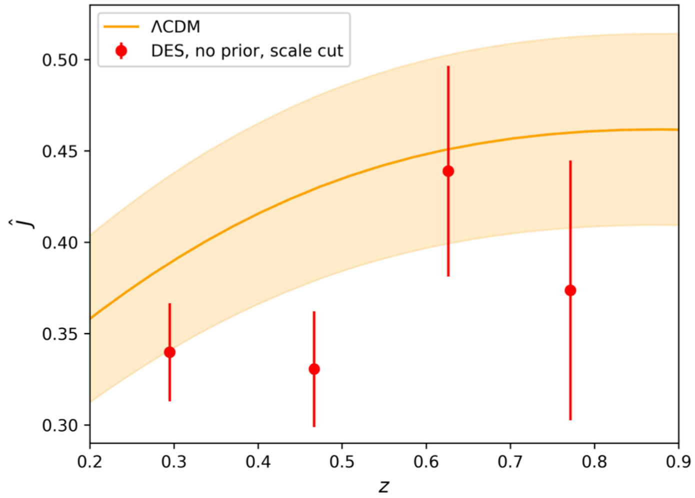
Scale cut



First measurement of the Weyl potential

Scale cut





- Uncertainties increase by a factor of 2. Mean values not affected
- Uncertainties on the LCDM prediction increase by 30%
- Less tension because of the uncertainties, but still below the prediction

First measurement of the Weyl potential

- Once we have measured $\hat{J}$. What can we do?
  - We can infer $\sigma_8(z=0)$ assuming LCDM:

$$\hat{J}(z) = \Omega_{\rm m}(z)\frac{D_1(z)}{D_1(z=0)}\sigma_8(z=0)$$

  - much lower value $\mathbf{0.741 \pm 0.035}$ compared to the one derived from the early-time parameters $\mathbf{0.852 \pm 0.027}$
  - We can pinpoint the σ_8 tension to behavior of the Weyl potential in the first 2 redshift bins

First measurement of the Weyl potential

- Once we have measured $\hat{J}$. What can we do?

  - Look at MG:

$$\hat{J}(z) = \Sigma(z)\Omega_{\rm m}(z)D_1(z)\frac{\sigma_8(z_*)}{D_1(z_*)}$$

  - Note: Dependency on μ through the evolution of $D_1(z)$

  - We fix $\mu = 1$ and test 3 different choices of time evolution for Σ

$$\Sigma(z) = 1 + \Sigma_0 g(z)$$

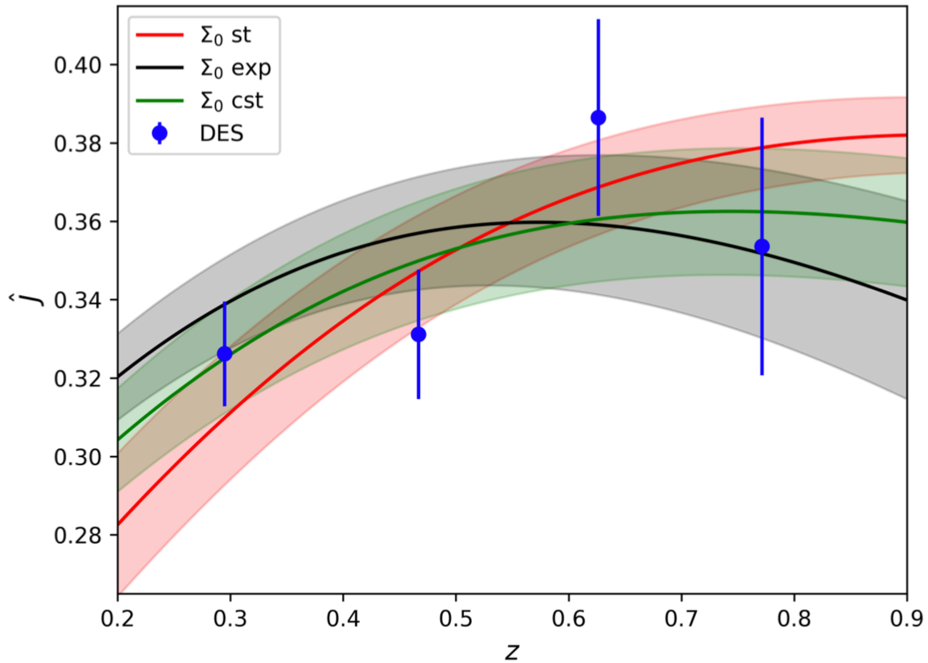
with $g(z) = \Omega_\Lambda(z)$

$g(z) = 1$ for $z \in [0, 1]$ and 0 elsewhere

$g(z) = \exp(1+z)$ for $z \in [0, 1]$

First measurement of the Weyl potential

- Once we have measured $\hat{J}$. What can we do?



- Data are still not able to discriminate between different time evolutions

Combining with spectroscopic data

- Powerful way of testing deviations from GR: comparison of the distortion of space-time and galaxy velocities
- E_G statistic (Zhang et al. 2007):

$$E_G = \Gamma \frac{C_l^{\kappa g}}{\beta C_l^{gg}}$$

  - $\beta \equiv f/b$
  - Ratio of GGL and galaxy clustering angular power spectra
  - Need to use the exact same galaxy sample for spectroscopy and photometry

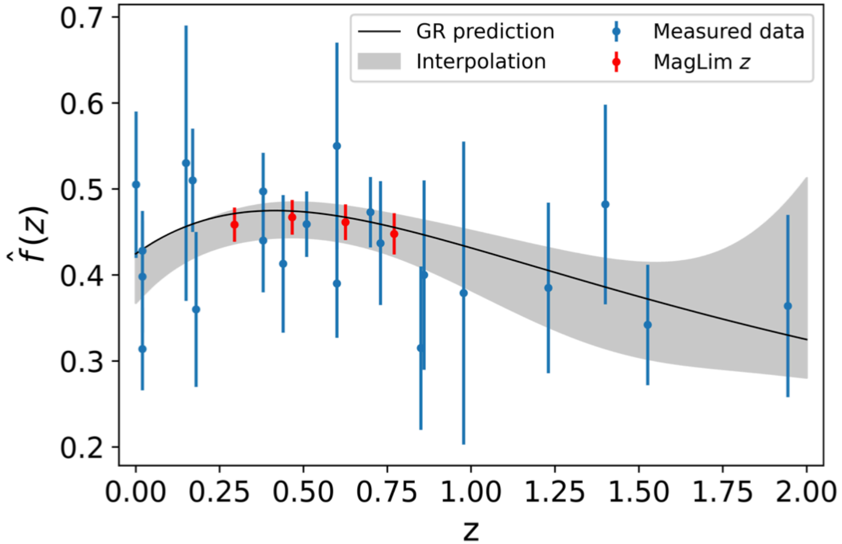
Combining with spectroscopic data

- We can use $\hat{J}$ — analogous of $\hat{f}(z) \equiv f(z)\sigma_8(z)$

$$E_G(z) \equiv \left(\frac{\mathcal{H}(z)}{\mathcal{H}_0}\right)^2 \frac{1}{1+z} \frac{\hat{J}(z)}{\hat{f}(z)}$$

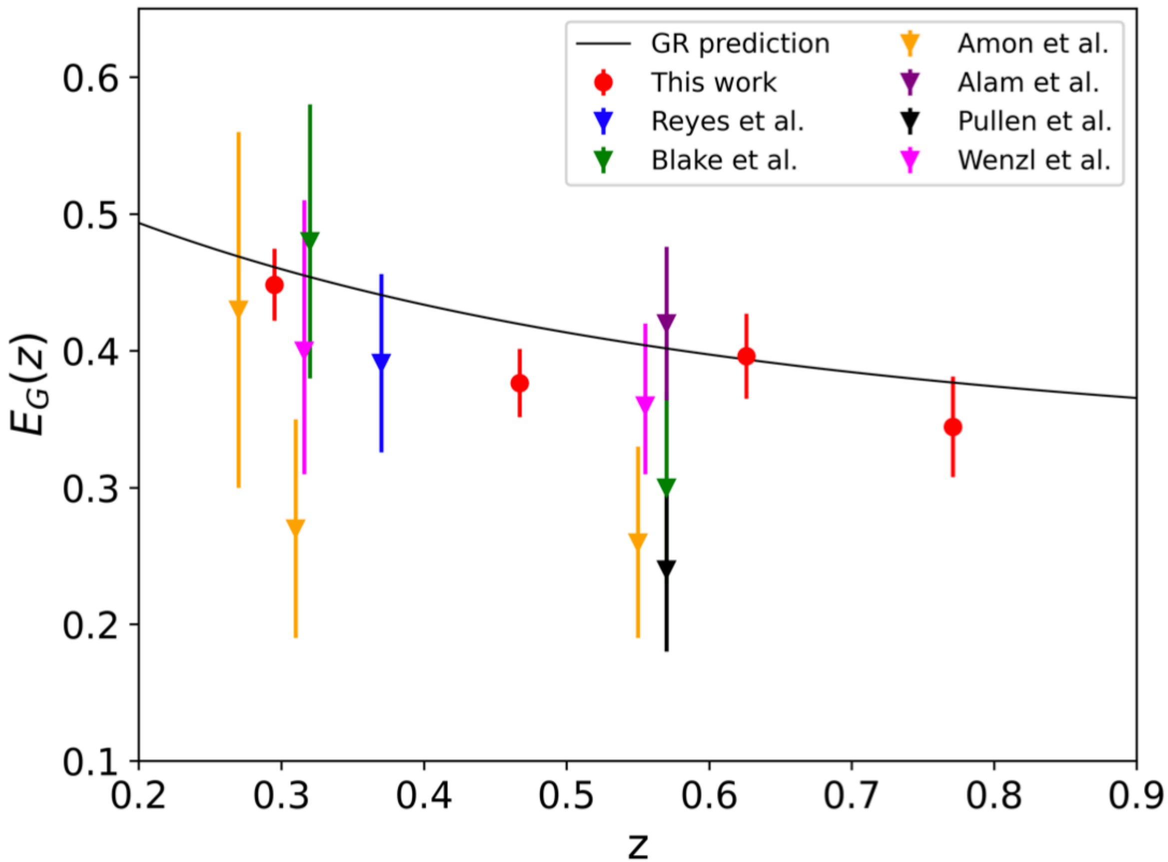
- No need to consider the same sample for the two quantities

- We interpolate the available $\hat{f}$ measurements at the MagLim redshifts



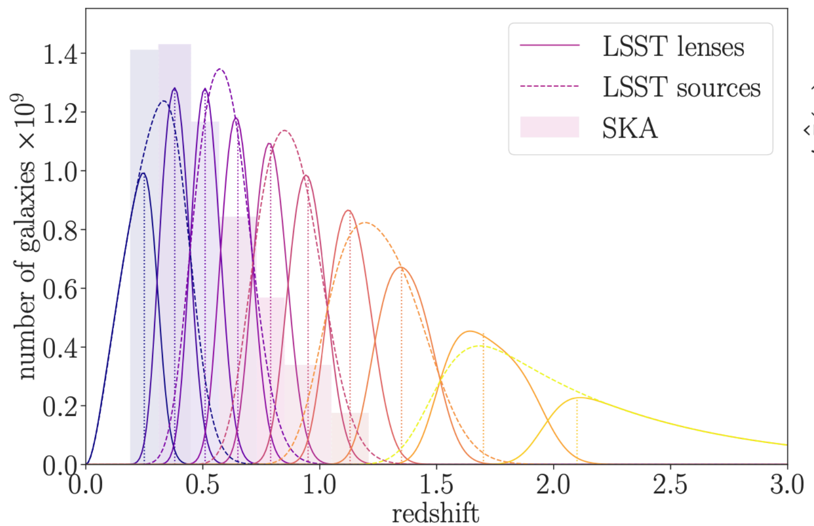
Combining with spectroscopic data

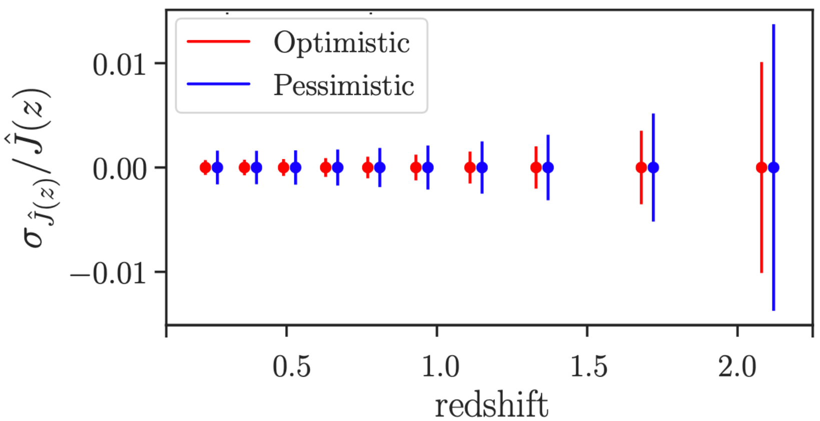
- New E_G measurements:



Next?

- Stage-IV surveys will provide more resolution in redshift (more bins for the lenses)
- LSST: Sub-percent constraints in ~10 different redshifts:





Conclusions

- First measurement of the Weyl potential from galaxy-galaxy lensing
- Mild tension with LCDM at low redshift
- No use of information from matter density fluctuations
- Weyl potential directly measured (no redshift evolution assumed)
- Efficient tests of different MG models (no need to re-analyze the data)
- Combining with spectroscopic data, we can test both the growth rate of structures and the growth of the geometry distortions
- Sub-percent measurements in the near future!