Credit: NASA

Gravitational lensing and gravitational redshift to measure the anisotropic stress

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Contents

Introduction

- Key test of gravity: Compare the 2 gravitational potentials:
  - Time distortion Ψ and spatial distortion Φ.
  - In LCDM, $\Psi = \Phi$.
  - Most modified gravity (MG) models do not preserve this equality.
  - Anisotropic stress: $\eta = \frac{\Phi}{\Psi}$, smoking gun for MG.

Introduction

- Current measurements of the anisotropic stress:
  - Peculiar velocities (RSD) + Weyl potential measurements from gravitational lensing.
  - RSD + Euler's equation -> constraints on Ψ.
  - Gravitational lensing -> constraints on $(\Phi + \Psi)/2$.
  - Anisotropic stress consistent with zero [DES Collaboration 2019, 2022; eBOSS Collaboration 2021]
  - Fails if galaxies do not obey Euler's equation [Amendola 2000; Bonvin & Pogosian 2022]

Introduction

- Goal:
  - Model-independent method to measure η.
  - Direct measurements of Ψ with the gravitational redshift.
  - Weyl potential measurements with gravitational lensing.
  - No assumptions on the MG model, nor on dark matter. No time-evolution assumptions. Valid if the weak equivalence principle is violated.

Gravitational lensing

- Standard method:
  - Link the potentials to the matter density allowing for a non-zero anisotropic stress and a modified Poisson's equation.
- Our approach:
  - Reparametrize the lensing observable to directly measure the $(\Phi + \Psi)/2$ evolution with redshift (template-fitting approach).

Gravitational lensing

- In LCDM:

$$T_{\Phi+\Psi}(k,z) = 2T_{\Phi}(k,z) = -3\Omega_{\rm m}(z)\left[\frac{\mathcal{H}(z)}{k}\right]^2 T_\delta(k,z)$$

- using:

$$T_\delta(k,z) = T_\delta^{\rm lin}(k,z)\sqrt{B(k,z)} \qquad T_\delta^{\rm lin}(k,z) = \frac{D_1(z)}{D_1(z_*)}T_\delta^{\rm lin}(k,z_*)$$

- we get:

$$T_{\Phi+\Psi}(k,z) = \frac{\mathcal{H}^2(z)\Omega_{\rm m}(z)D_1(z)}{\mathcal{H}^2(z_*)\Omega_{\rm m}(z_*)D_1(z_*)} \times \sqrt{B(k,z)}T_{\Phi+\Psi}(k,z_*)$$

- The evolution of $\Phi+\Psi$ is governed by $\Omega_{\rm m}(z)D_1(z)$.

Gravitational lensing

- In MG the potentials can be different and may not be related to density via Poisson's equation -> we replace $\Omega_{\rm m}(z)D_1(z)$ by an agnostic function $J(k,z)$

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

- using:

$$T_\delta(k,z) = T_\delta^{\rm lin}(k,z)\sqrt{B(k,z)} \qquad T_\delta^{\rm lin}(k,z) = \frac{D_1(z)}{D_1(z_*)}T_\delta^{\rm lin}(k,z_*)$$

- and that we recover GR at z_*, we get:

$$T_{\Phi+\Psi}(k,z) = -3\left[\frac{\mathcal{H}(z)}{k}\right]^2 J(k,z)\sqrt{B(k,z)}\frac{T_\delta^{\rm lin}(k,z_*)}{D_1(z_*)}$$

- The evolution of $\Phi+\Psi$ is governed by $J(k,z)$.

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Gravitational lensing

- In practice we use galaxy-galaxy lensing measurements:

$$C_\ell^{\Delta\kappa}(z_i, z_j) = \int \mathrm{d}z\, n_i(z) b_i(z) \int \mathrm{d}z' n_j(z') \frac{\chi' - \chi}{\chi\chi'} \times \frac{3\ell(\ell+1)}{2(\ell+1/2)^2} \mathcal{H}^2(z) \frac{J(z)}{D_1(z)} P_{\delta\delta}\left(k_\ell, \chi\right) ,$$

- with:

$$P_{\delta\delta}\left(k_\ell, \chi\right) = \left[\frac{D_1(z)}{D_1(z_*)}\right]^2 P_{\delta\delta}^{\mathrm{lin}}\left(k_\ell, \chi_*\right) B\left(k_\ell, \chi\right) \qquad \hat{J}(z) \equiv \frac{J(z)\sigma_8(z)}{D_1(z)} = \frac{J(z)\sigma_8(z_*)}{D_1(z_*)}$$

- we get:

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

Gravitational redshift

- Approach from Sobral Blanco & Bonvin (2022)
- We can introduce an agnostic function $I(k,z)$ to encode the evolution of Ψ

$$T_\Psi(k,z) = \frac{\mathcal{H}^2(z) I(k,z)}{\mathcal{H}^2(z_*) D_1(z_*)} T_\Psi(k, z_*)$$

- It can be measured from the relativistic dipole of over-densities of a bright and a faint galaxy population:

$$\begin{aligned}\Delta^{\rm rel}(z,\mathbf{n}) =& \frac{1}{\mathcal{H}}\partial_r\Psi + \frac{1}{\mathcal{H}}\dot{\mathbf{V}}\cdot\mathbf{n} \\ &+ \left(1 - 5s + \frac{5s-2}{\mathcal{H}r} - \frac{\dot{\mathcal{H}}}{\mathcal{H}^2} + f^{\rm evol}\right)\mathbf{V}\cdot\mathbf{n}\end{aligned}$$

Anisotropic stress

- Combining gravitational lensing and gravitational redshift:

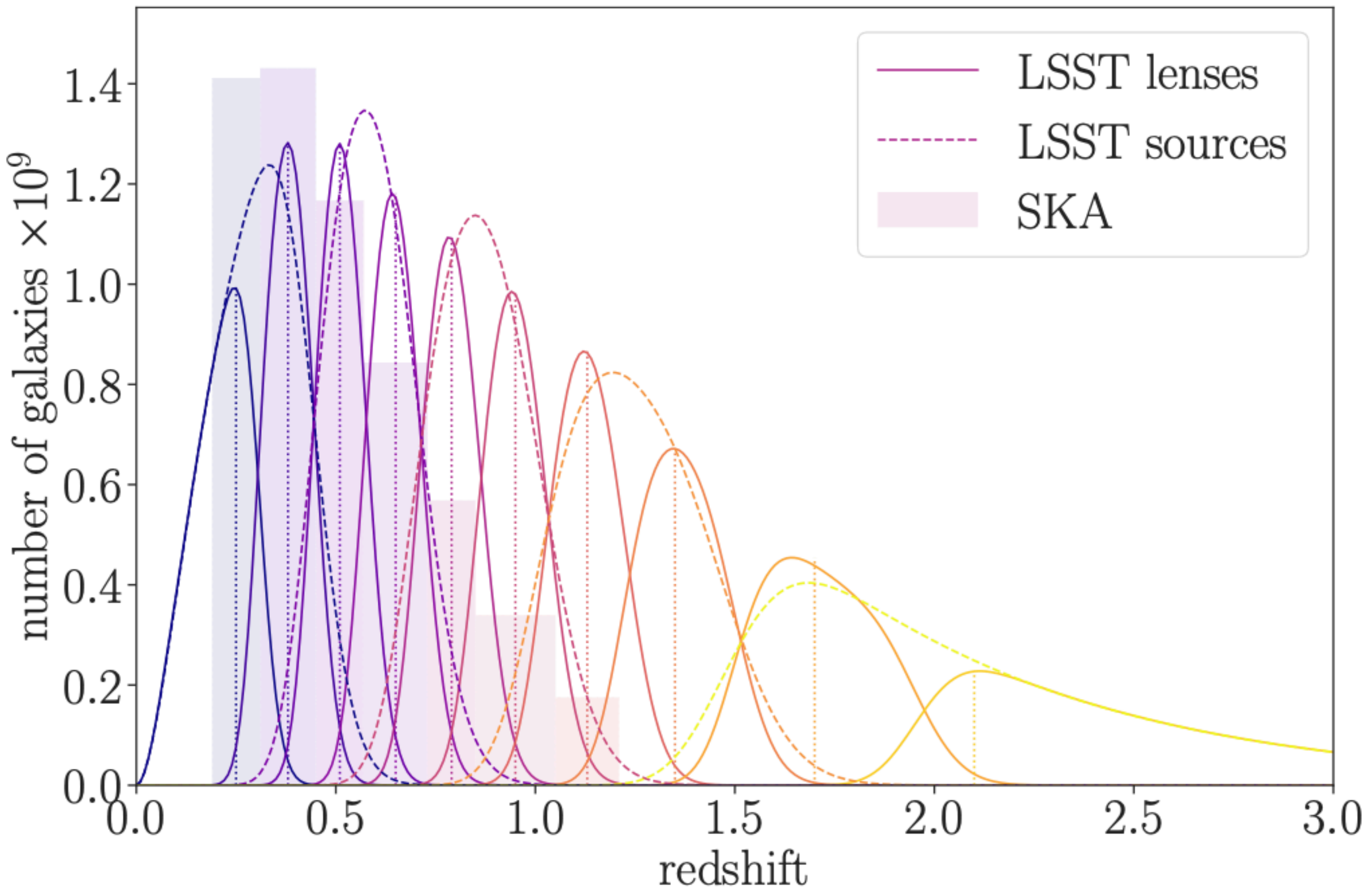
$$\frac{\hat{I}(z)}{\hat{J}(z)} = \frac{T_{\Phi+\Psi}(k, z_*)}{T_{\Psi}(k, z_*)} \frac{T_{\Psi}(k, z)}{T_{\Phi+\Psi}(k, z)} = \frac{2\Psi}{\Phi + \Psi} = \frac{2}{1+\eta}$$

- Novel estimator of the anisotropic stress:
  - model-independent
  - directly built from measurements of $\hat{J}$ and $\hat{I}$ in the bins of the surveys
  - if the ratio differs from 1, we can unambiguously conclude that gravity is modified

Results

- Gravitational lensing with LSST:
  - 5 equi-populated bins for the sources + 10 equi-populated bins for the lenses
  - 27 galaxies/arcmin2
  - Linear galaxy bias and intrinsic alignments models (marginalized over)
  - Optimistic (lmax = 2627) and pessimistic (lmax = 750) scenarios
  - Ellipticity total dispersion of 0.3
  - Cosmology fixed
- Gravitational redshift with SKAO:
  - Number density and volume from Bull 2016
  - Split between bright and faint following Sobral Blanco & Bonvin 2022
  - Linear galaxy bias (marginalized over) and magnification bias included
  - Optimistic (dmin = 20 Mpc/h) and pessimistic (dmin = 32 Mpc/h) scenarios
  - Cosmology fixed

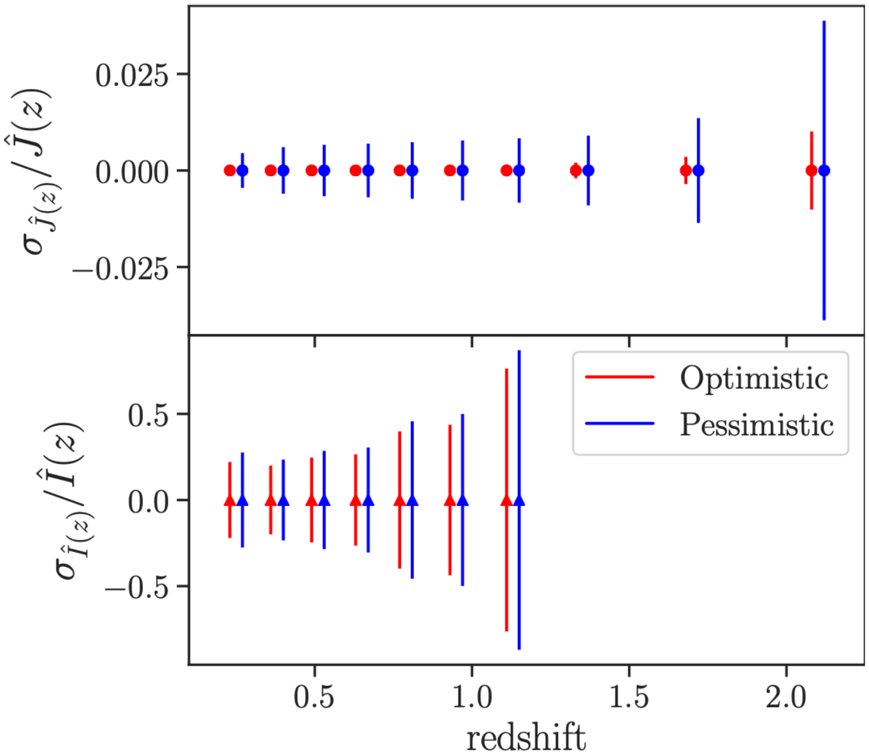
Results



LSST lenses
LSST sources
SKA
number of galaxies ×10^9
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
0.0
0.5
1.0
1.5
2.0
2.5
3.0
redshift

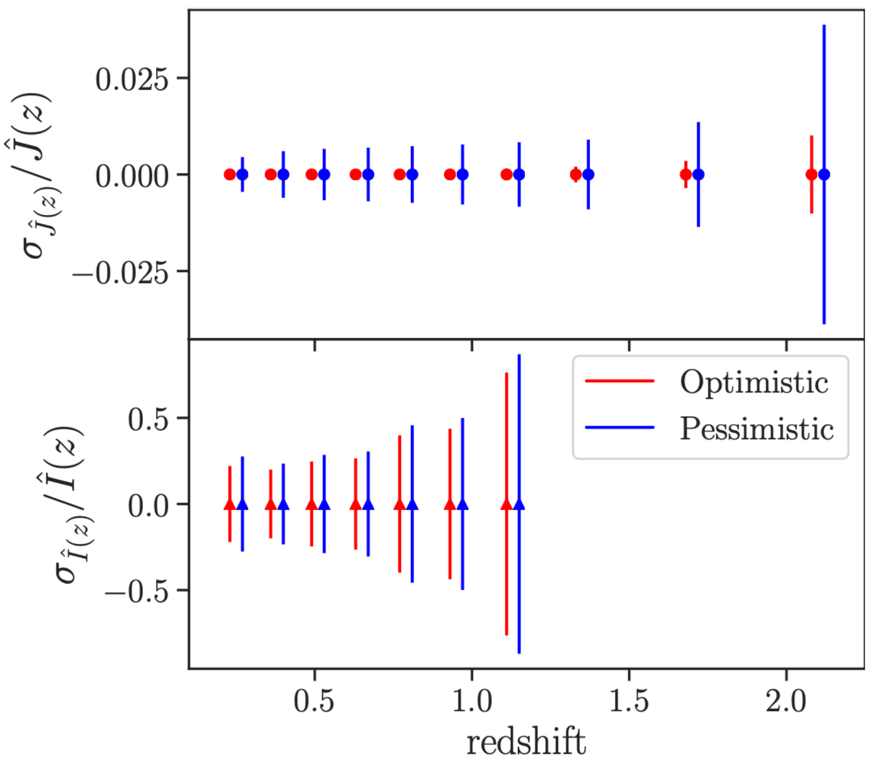
Results

- Gravitational lensing:
  - Degradation as a function of redshift (wider bins -> lower galaxy-galaxy lensing signal; lenses closer to sources)
  - Measurement at the percent level



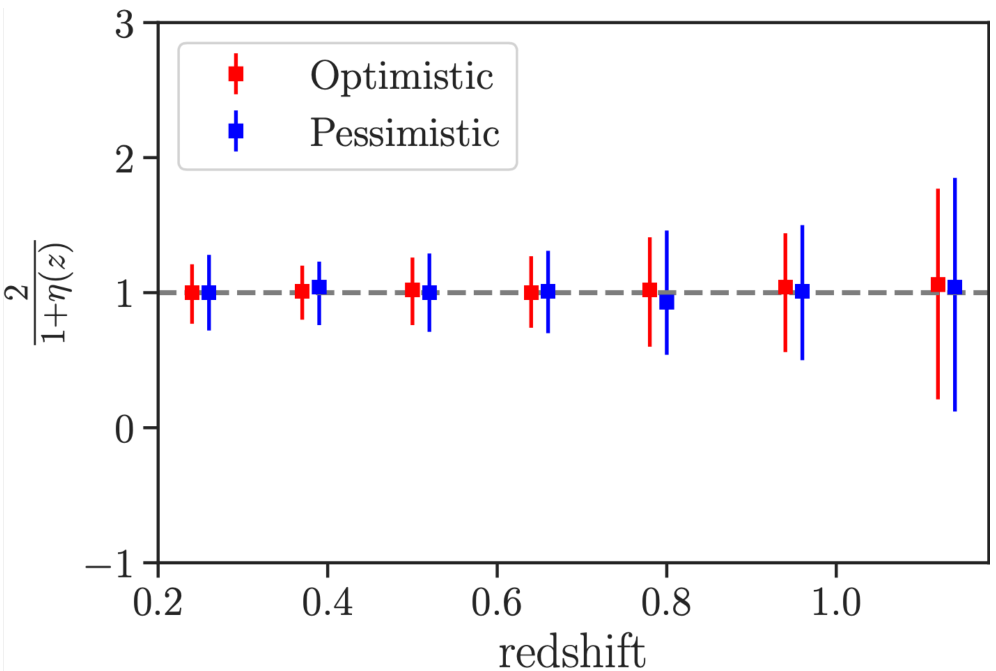
Results

- Gravitational redshift:
  - Degradation as a function of redshift (decreasing growth and increasing shot-noise)
  - Measurement at the ~20% level



Results

- Anisotropic stress:
  - LSST+SKAO will constrain the anisotropic stress in a model-independent way:



Conclusions

- The anisotropic stress is a smoking gun for modified gravity.
- Current constraints and forecasts rely on galaxies obeying Euler's equation.
- Combining gravitational lensing (sensitive to $(\Phi+\Psi)/2$) and gravitational redshift measurements through the relativistic dipole (directly sensitive to Ψ), we can constrain the anisotropic stress in a model-independent way.
- Future surveys like LSST and SKAO will constrain $\frac{2}{1+\eta(z)}$ at the level of ~20%.