Model-Independent Tests of Gravity using the Weyl Potential Evolution

Nastassia Grimm, University of Geneva
nastassia.grimm@unige.ch

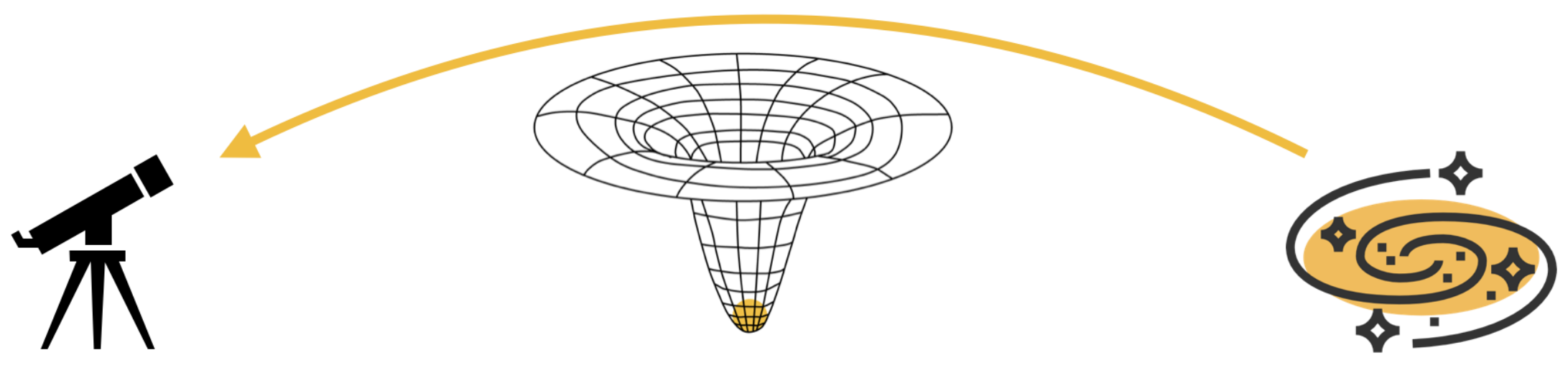
Why do we want to test gravity model-independently?

The standard ΛCDM model of our Universe successfully describes many observations, but cosmological tensions still remain. Therefore, a wide range of **modified gravity theories**, deviating from the assumptions of General Relativity (GR), has been proposed. Due to the large computational cost of cosmological data analysis, testing each of them individually is not feasible. Therefore, we need to identify **model-independent observables**.

Here, we present the first measurements of $\hat{J}$, a model-independent observable from **gravitational lensing** that captures the **Weyl potential evolution**. Moreover, we have performed **new measurements of the E_G statistic**, combining $\hat{J}$ with galaxy velocities. In both cases, we find an interesting tension at redshift $z = \mathbf{0.47}$.

A model-independent observable from gravitational lensing

Gravitational lensing is often described as being directly sensitive to the distribution of matter. More precisely though, it is determined by the depth of gravitational potentials, $\Phi + \Psi$, along the line of sight.



Lights paths are deflected by the presence of gravitational potentials between source and observer.

Being sensitive to the **Weyl potential**, $\Psi_W = \Phi + \Psi$, gravitational lensing is an ideal probe for testing modified gravity:

- In GR, the Weyl potential $\Psi_W = 2\Phi = 2\Psi$ is directly linked to the growth $D_1(z)$ of matter perturbations and the overall matter content $\Omega_m(z)$,

$$\Psi_W \quad \propto \quad \Omega_m(z) D_1(z)\,.$$

- In modified gravity, Φ and Ψ can be different, and their relation to the matter content depends on the specific theory. To capture this, $\Omega_m(z) D_1(z)$ is replaced by a generic function $J(z)$,

$$\Psi_W \quad \propto \quad J(z)\,.$$

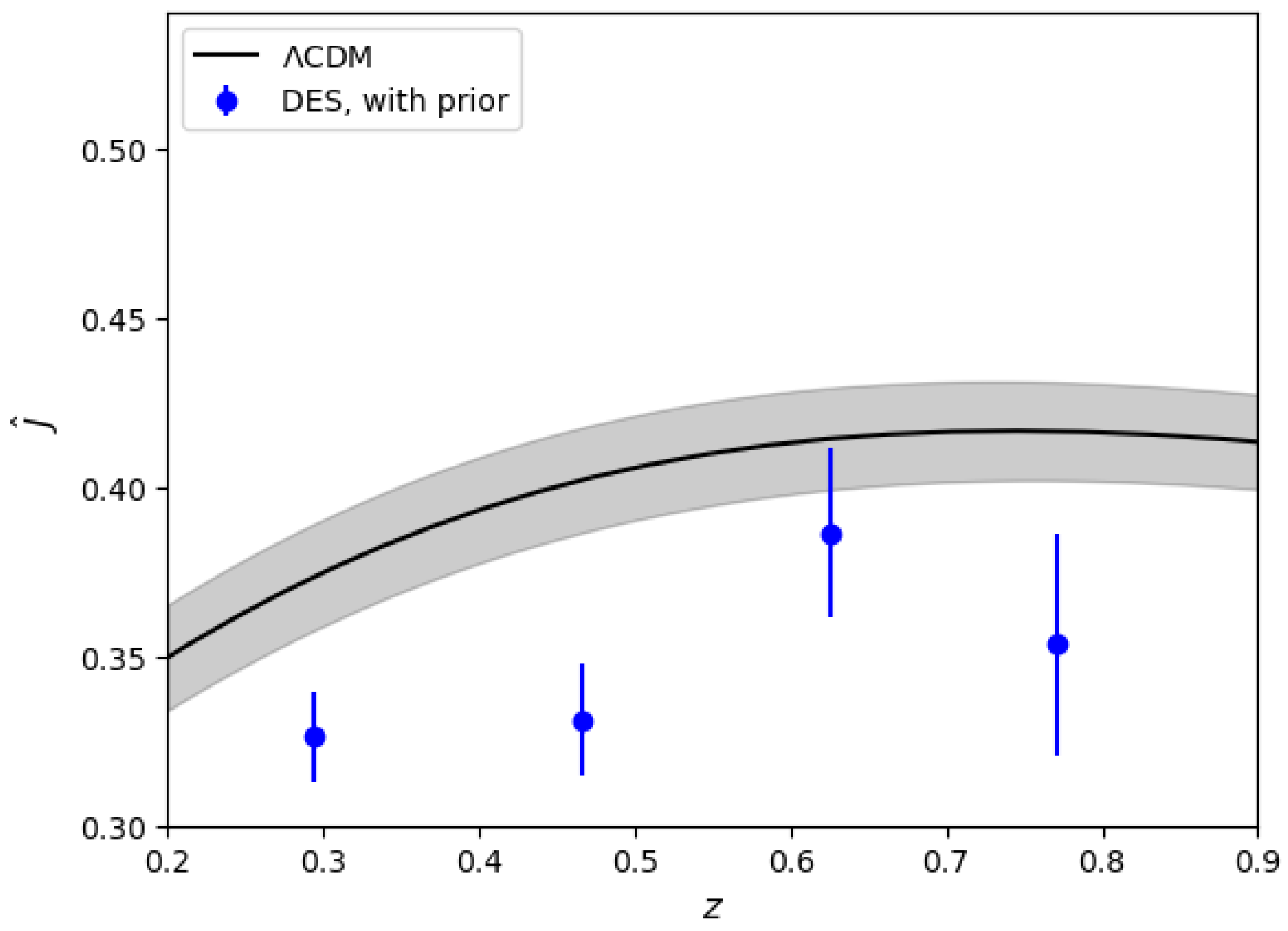
Our observable: Using galaxy-galaxy lensing (correlation of galaxy position in the foreground with galaxy shapes in the background), one can measure [1]:

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

with σ_8 being the matter fluctuation amplitude.

Measurement of $\hat{J}$ from Year 3 Dark Energy Survey data

Using gravitational lensing to determine $\hat{J}$, the evolution of the Weyl potential Ψ_W, is already possible: In Ref. [2], we have performed its first measurement from the Year 3 data release of the Dark Energy Survey (DES).



Measurement of $\hat{J}(z)$ compared to the ΛCDM prediction, at the effective redshifts of the four first DES MagLim lens bins.

The figure shows the measured values of $\hat{J}$, compared with the ΛCDM prediction. Interestingly, the measured values in the first two redshift bins are significantly (at 2.3σ and 3.1σ) below the prediction.

Combining lensing with galaxy velocities: The E_G statistic

The E_G statistic has been recognised in literature as a powerful test of gravity, free from the impact of galaxy bias. It is obtained by comparing galaxy-galaxy lensing (i.e., density-lensing correlations) with correlations between densities and the galaxy velocity field,

$$E_G \propto \frac{\textbf{density} - \textbf{lensing}}{\textbf{density} - \textbf{velocity}}\,.$$

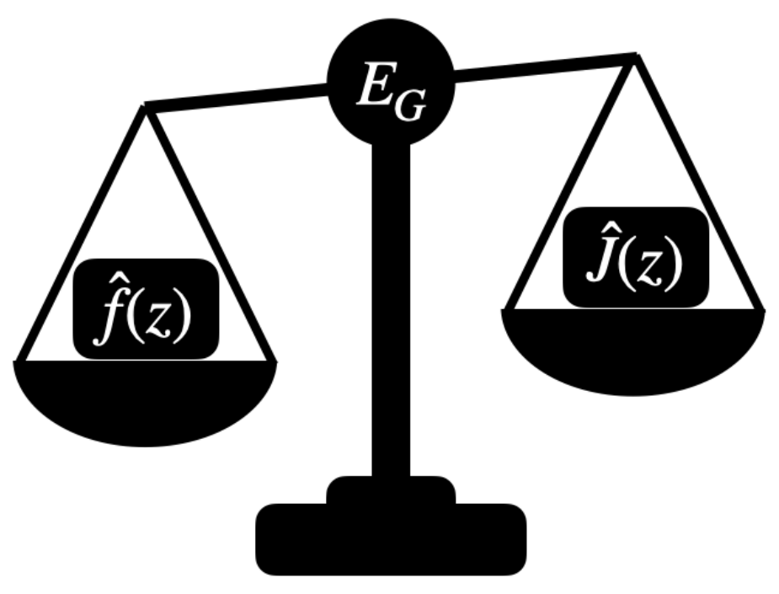
Conventional methods rely on a common galaxy sample with spectroscopic resolution to measure two types of correlations and cancel the impact of the galaxy bias. On the contrary, our novel approach directly combines two model-independent observables [3].

Combining $\hat{J}(z)$ and $\hat{f}(z)$: A novel approach to the E_G statistic

In Ref. [3], we combine $\hat{J}(z)$ with another model-independent observable measured from galaxy velocities: $\hat{f} = f\sigma_8$, where f is the growth rate of structure. The ratio of these two quantities allows us to reconstruct the E_G statistic,

$$E_G(z) \quad \propto \quad \frac{\hat{J}(z)}{\hat{f}(z)}\,.$$

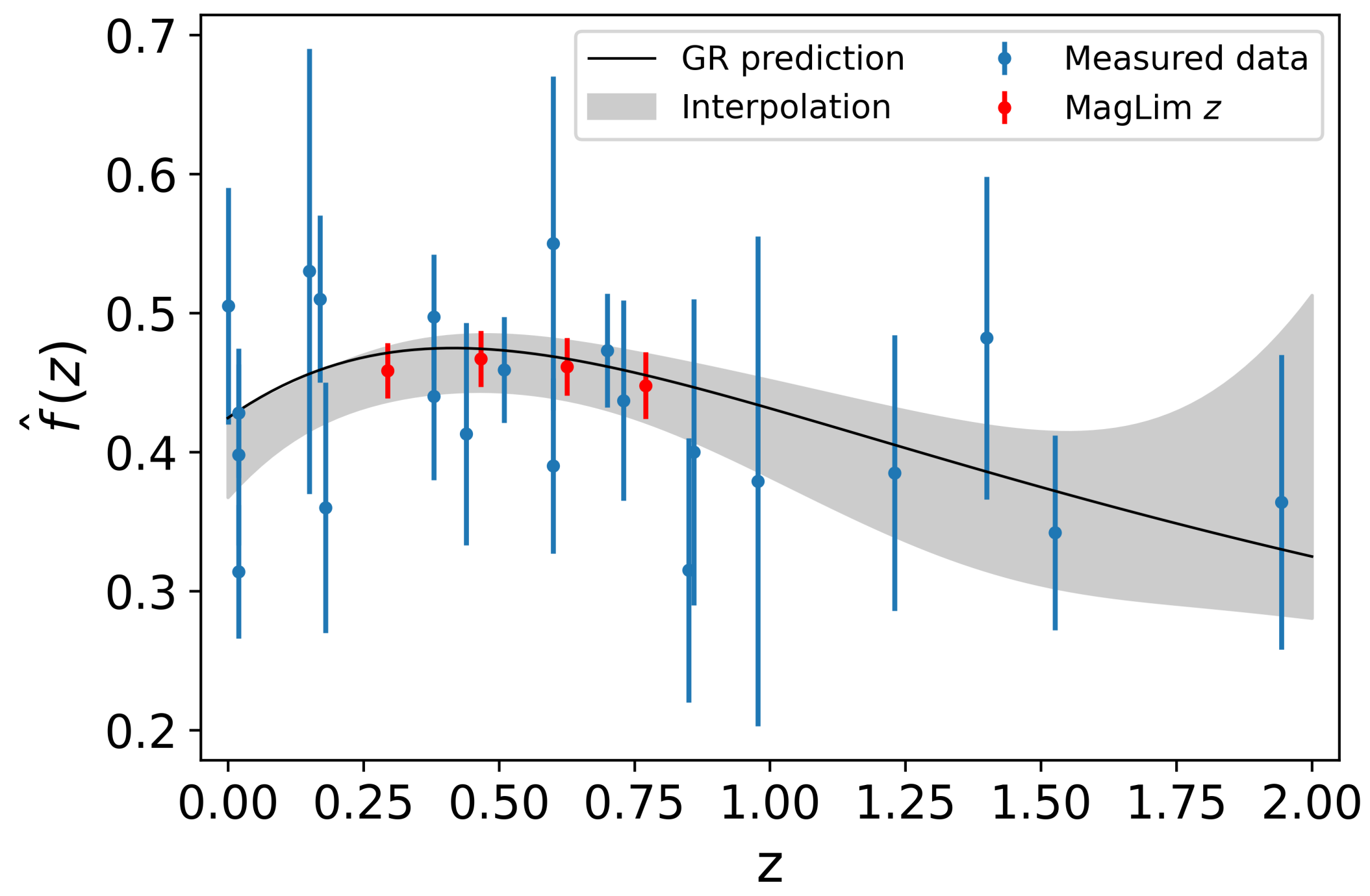
As previous measurements of E_G have been inconclusive, this novel approach is vital to assess the compatibility with GR.



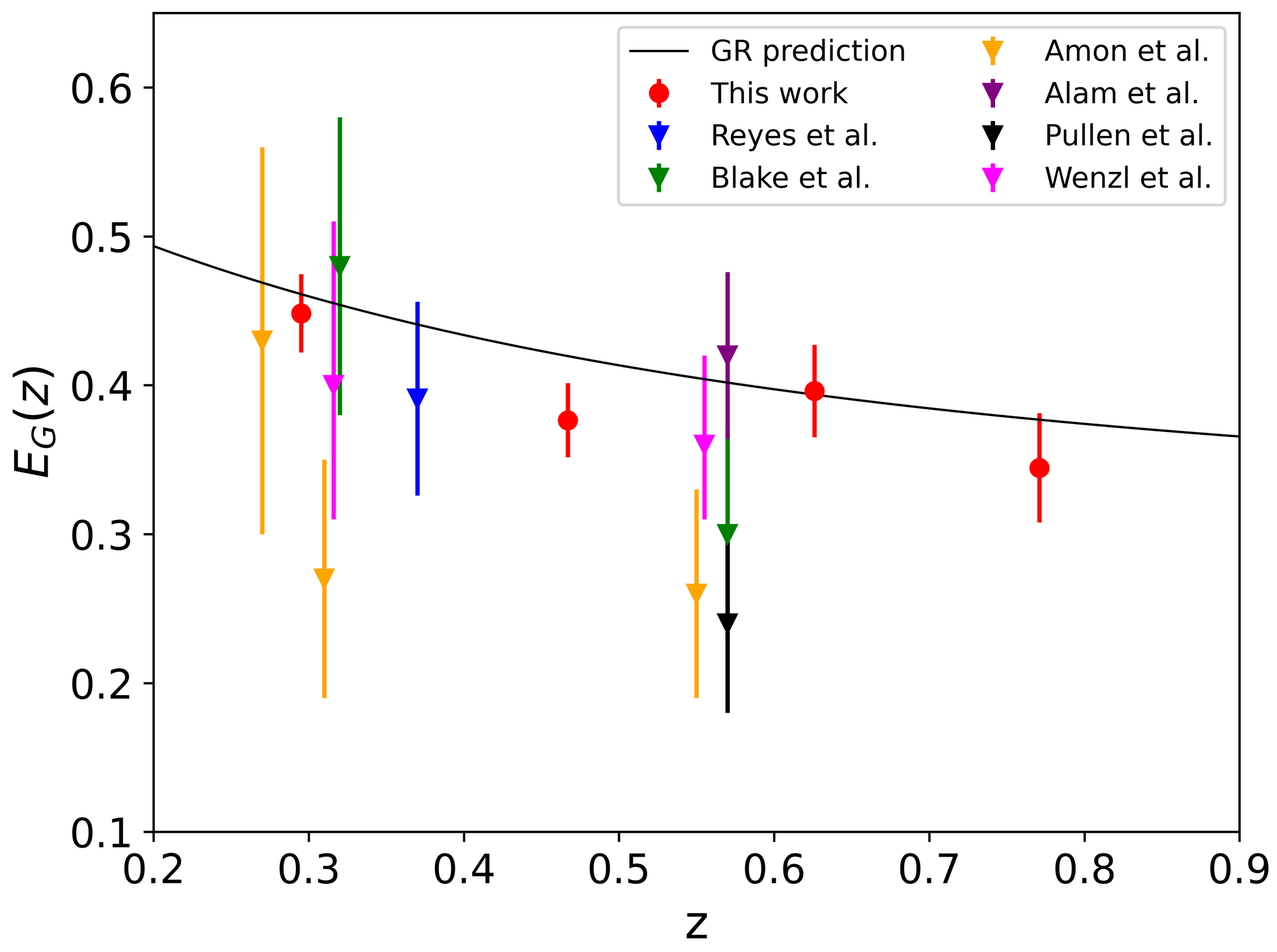
Are $\hat{J}(z)$ and $\hat{f}(z)$ perfectly balanced, leading to $E_G(z)$ compatible with GR, or is there an incline towards modified gravity? Our new measurements in Ref. [3] gives new insights.

New measurement of E_G

We perform a measurement of the E_G statistic in two steps. First, we use 22 literature values of $\hat{f}$ and apply spline interpolation to obtain values of $\hat{f}$ at the four effective redshifts where measurements of $\hat{J}$ are available.



Literature values of $\hat{f}(z)$ (blue), and our reconstruction at the DES MagLim effective redshifts (red).



Our measurements of $E_G(z)$ (red) compared to various literature values.

Then, from the ratio of $\hat{J}$ and $\hat{f}$ at equal redshifts, we obtain new measurements of E_G, surpassing the precision of previous measurements. We find agreement with GR in three bins, and a tension of 2.5σ at $z = \mathbf{0.47}$, resulting from the tension in the $\hat{J}$ measurement [3].

Conclusion

- **DES data** already gives us a first measurement of $\hat{J}$ with a precision of $4 - 9\,\%$. A mismatch to the ΛCDM prediction hints either at unknown systematics or a modification of gravity in the first two bins.
- **The combination with** $\hat{f}$ allows a reconstruction of E_G with $6 - 11\,\%$ precision. The tension in the second bin is visible as well in the E_G statistic.
- **Future surveys** (e.g. Euclid and LSST) will measure $\hat{J}$ and E_G with more precision and provide refined redshift information, which will help us to better understand these tensions.

Key references

[1] I. Tutusaus, Daniel Sobral-Blanco & C. Bonvin, "*Combining gravitational lensing and gravitational redshift to measure the anisotropic stress with future galaxy surveys*", Phys.Rev.D 107 (2023) 8, 083526, arXiv:2209.08987.

[2] I. Tutusaus, C. Bonvin & **Nastassia Grimm**, "*First measurement of the Weyl potential evolution from the Year 3 Dark Energy Survey data: Localising the σ_8 tension*", arXiv:2312.06434.

[3] **Nastassia Grimm**, C. Bonvin & I. Tutusaus, "*New measurements of E_G: Testing General Relativity with the Weyl potential and galaxy velocities*", arXiv:2403.13709.