Model-independent tests of General Relativity combining the Weyl Potential and Galaxy Velocities

Nastassia Grimm

Université de Genève

Based on arXiv:2312.06434 and arXiv:2403.13709

In collaboration with Isaac Tutusaus (IRAP, U. de Toulouse) and Camille Bonvin (U. de Genève)

nastassia.grimm@unige.ch

UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

CASTLE
19 September 2024

European Research Council
Established by the European Commission

How can we test modified gravity?
Possibility 1

Pick a modified gravity model → Data analysis with additional parameters → Obtain constraints for one model

How can we test modified gravity?
Possibility 1

Pick a modified gravity model → Data analysis with additional parameters → Obtain constraints for one model

Repeat for each model!

How can we test modified gravity?
Possibility 1

Pick a modified gravity model → Data analysis with additional parameters → Obtain constraints for one model

Repeat for each model!

How can we test modified gravity?
Possibility 2: Model-independent approach

Identify model-independent observable → Obtain observable from data → Check which theory fits the measurement

How can we test modified gravity?
Possibility 2: Model-independent approach

Identify model-independent observable → Obtain observable from data → Check which theory fits the measurement

One and done

Repeat for each model

How can we test modified gravity?
Possibility 2: Model-independent approach

Identify model-independent observable → Obtain observable from data → Check which theory fits the measurement

One and done

Repeat for each model

Model-independent observable for gravitational lensing?

Lensing is sensitive to the perturbed geometry of the Universe:

Lensing $\propto$ $\Psi_W = (\Phi + \Psi)/2$ ⟶ Weyl potential

Weyl potential in General Relativity:

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

↙ Growth of matter perturbations

↘ Matter content in the Universe

Model-independent observable for gravitational lensing?

Lensing is sensitive to the perturbed geometry of the Universe:

$$\textbf{Lensing} \quad \propto \quad \Psi_W = (\Phi + \Psi)/2 \quad \longrightarrow \quad \text{Weyl potential}$$

Weyl potential in ~~General Relativity:~~ **any gravity theory:**

$$\Psi_W \quad \propto \quad \cancel{D_1(z)\,\Omega_m(z)} \quad J(z)$$

$D_1(z)$ → Growth of matter perturbations

$\Omega_m(z)$ → Matter content in the Universe

I. Tutusaus, D. Sobral-Blanco & C. Bonvin (2022), arXiv:2209.08987

Galaxy-galaxy lensing angular power spectrum

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

lens bin   source bin

$$\hat{J}(z) \equiv \frac{J(z)\sigma_8(z)}{D_1(z)} \quad \text{(Weyl evolution)}\,, \qquad \hat{b}_i(z) \equiv b_i(z)\sigma_8(z)\,.$$

Galaxy clustering: Depends on $\hat{b}_i(z)\hat{b}_j(z)$

Galaxy-galaxy lensing angular power spectrum

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

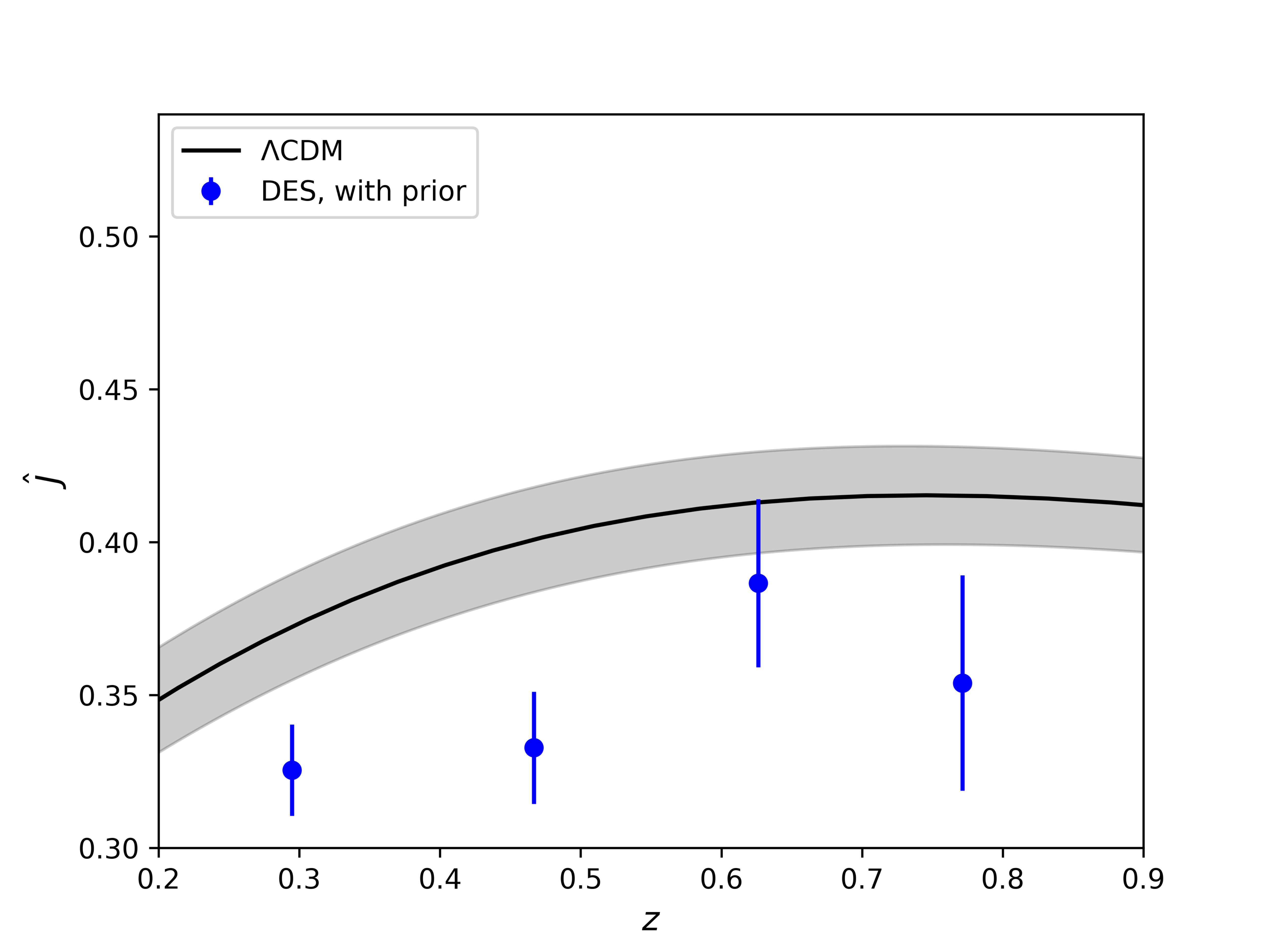
lens bin — source bin

$$\hat{J}(z) \equiv \frac{J(z)\sigma_8(z)}{D_1(z)} \quad \text{(Weyl evolution)}, \qquad \hat{b}_i(z) \equiv b_i(z)\sigma_8(z)\,.$$

Galaxy clustering: Depends on $\hat{b}_i(z)\hat{b}_j(z)$

Combining galaxy-galaxy lensing and galaxy clustering → Measurement of $\hat{J}(z)$

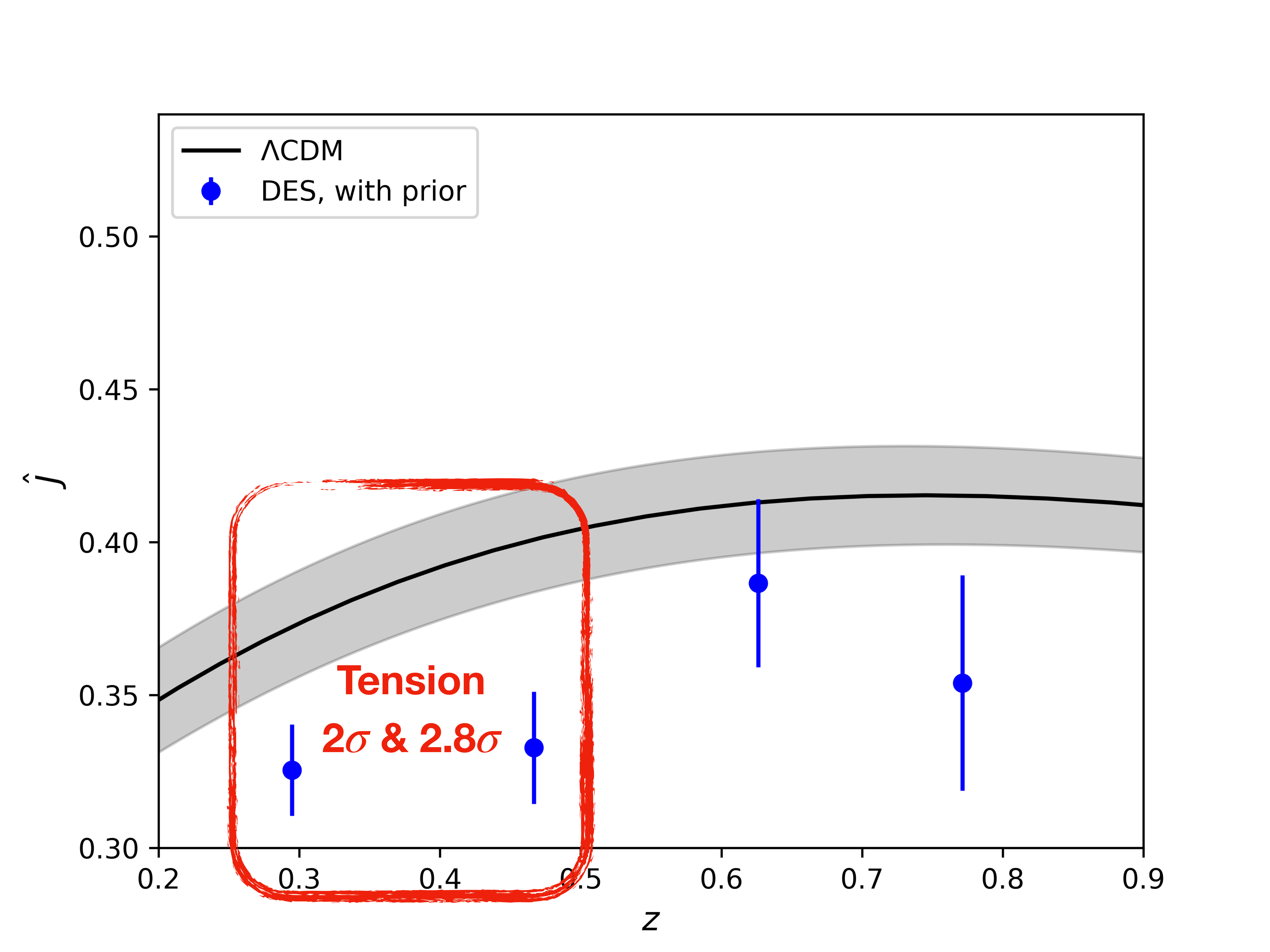
Measurement of $\hat{J}(z)$ from Dark Energy Survey data



I. Tutusaus, C. Bonvin & NG, arXiv:2312.06434 (accepted for publication in *Nature Communications*)

Measurement in 4 bins of the MagLim sample, with 3σ Planck priors

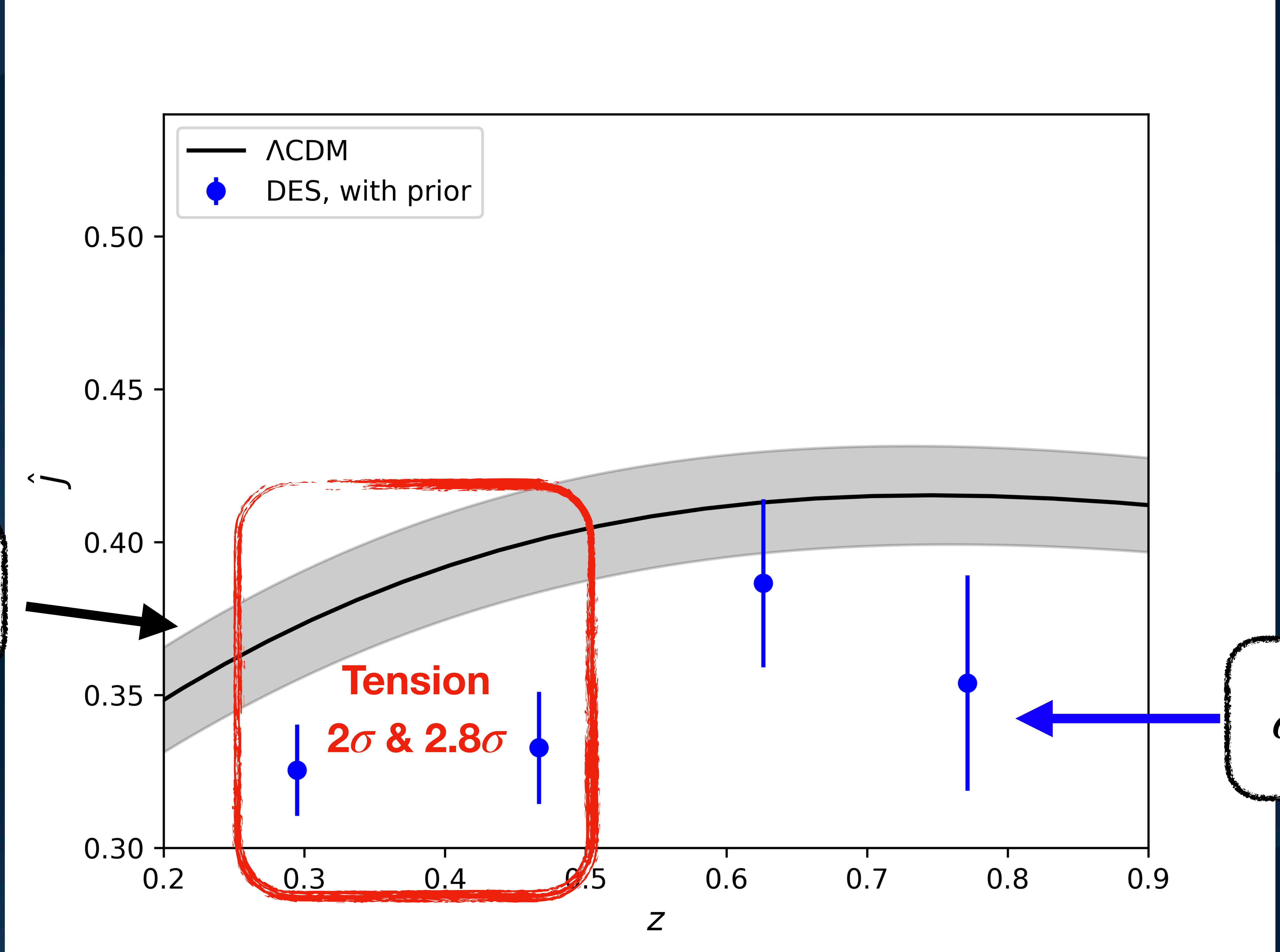
Measurement of $\hat{J}(z)$ from Dark Energy Survey data



I. Tutusaus, C. Bonvin & NG, arXiv:2312.06434 (accepted for publication in *Nature Communications*)

Measurement in 4 bins of the MagLim sample, with 3σ Planck priors

Measurement of $\hat{J}(z)$ from Dark Energy Survey data



I. Tutusaus, C. Bonvin & NG, arXiv:2312.06434 (accepted for publication in *Nature Communications*)

$\sigma_8(z=0) = 0.85 \pm 0.03$

$\sigma_8(z=0) = 0.74 \pm 0.04$

Measurement in 4 bins of the MagLim sample, with 3σ Planck priors

Can we combine $\hat{J}$ with other model-independent observables?

Weak gravitational lensing

↓

$\hat{J}(z)$

Redshift-space distortions

↓

$\hat{f}(z) = f\sigma_8$

Can we combine $\hat{J}$ with other model-independent observables?

Weak gravitational lensing → $\hat{J}(z)$

Redshift-space distortions → $\hat{f}(z) = f\sigma_8$

$\hat{J}(z)$ and $\hat{f}(z)$ → E_G statistic

The E_G statistic

Theoretically described in Zhang et al. (2007):

$$E_G(l) = \frac{a}{3H_0^2}\frac{C_{\kappa g}(l)}{C_{gv}(l)}$$

Galaxy-galaxy lensing

Galaxy-velocity correlations

In practise:

$$E_G(l) \propto \frac{C_{\kappa g}(l)}{(\,f/b\,)\cdot C_{gg}(l)}$$

Measured from RSD

The E_G statistic

Theoretically described in Zhang et al. (2007):

$$E_G(l) = \frac{a}{3H_0^2}\frac{C_{\kappa g}(l)}{C_{gv}(l)}$$

Galaxy-galaxy lensing

Galaxy-velocity correlations

In practise:

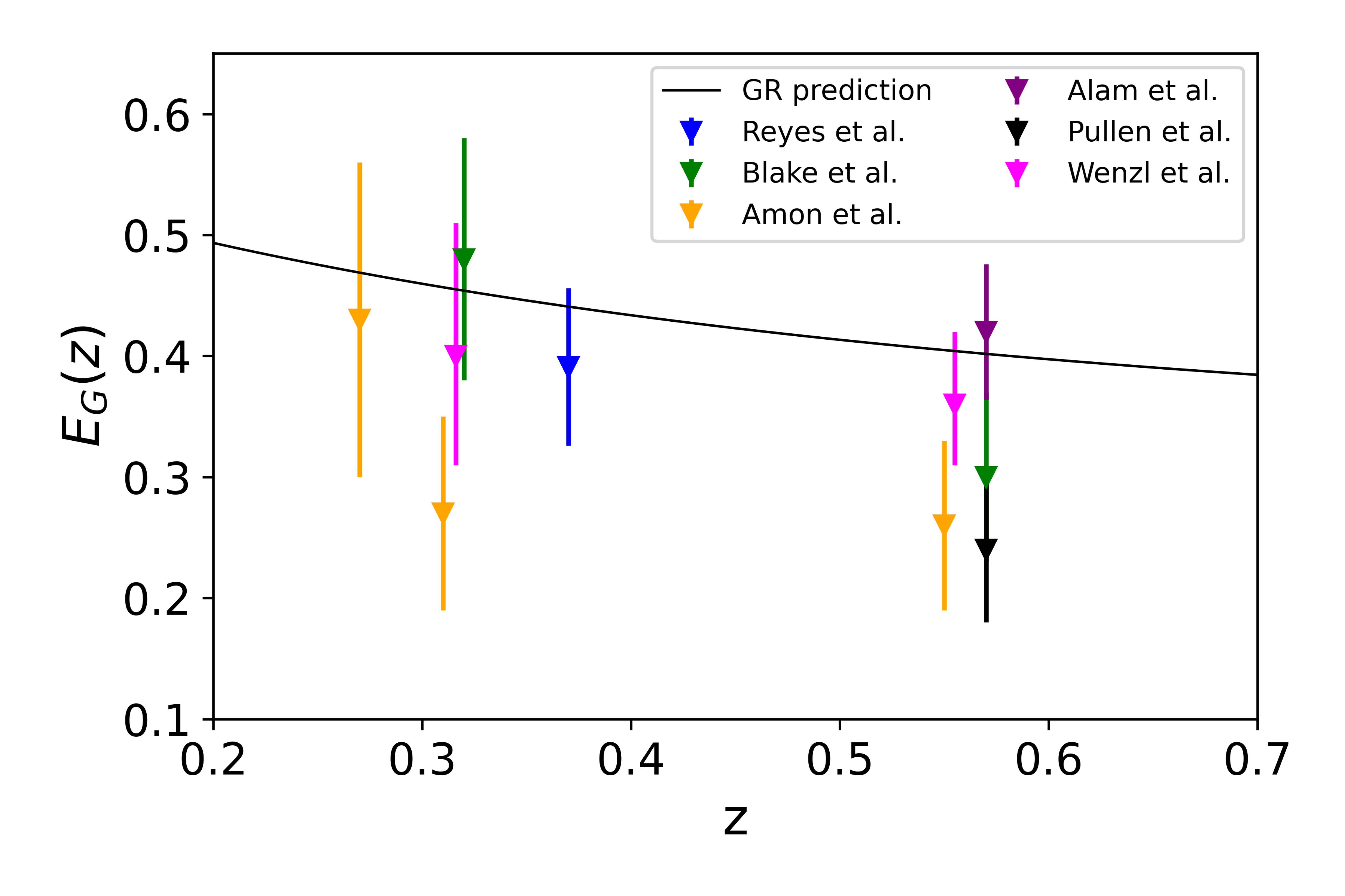
$$E_G(l) \propto \frac{C_{\kappa g}(l)}{(\,f/b\,)\cdot C_{gg}(l)}$$

Measured from RSD

Why is it useful?

- Galaxy bias b cancels out.
- Measurements of E_G can be compared to their ΛCDM prediction, $E_G = \Omega_{m,0}/f(z)$.

The E_G statistic: Past measurements



Some literature values show mild tensions (up to 2.6σ) with GR.

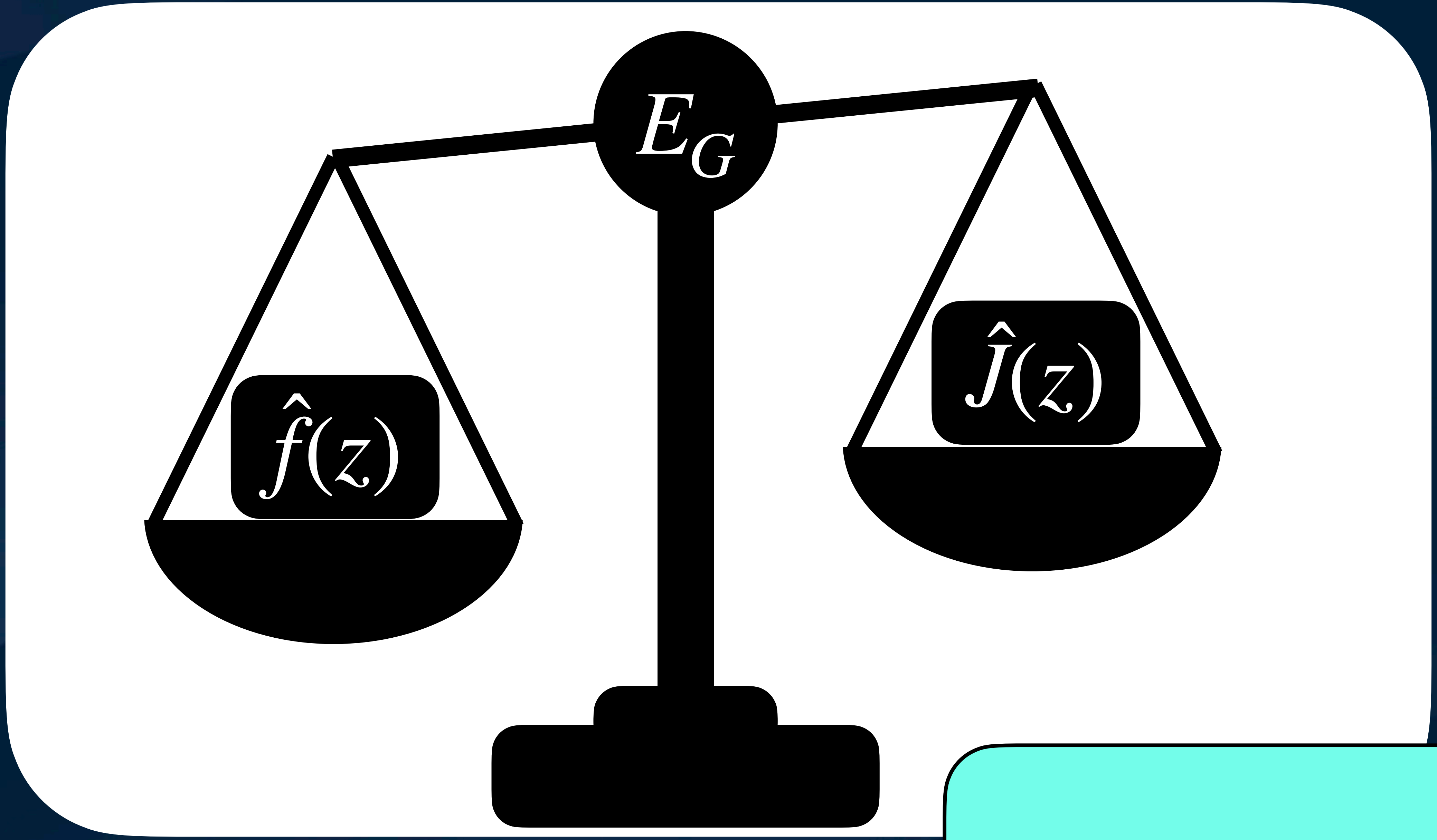
A limitation:

All these measurements need one common spectroscopic data set to cancel out galaxy bias.

The E_G statistic: A new method

E_G can be written as the ratio of model-independent observables:

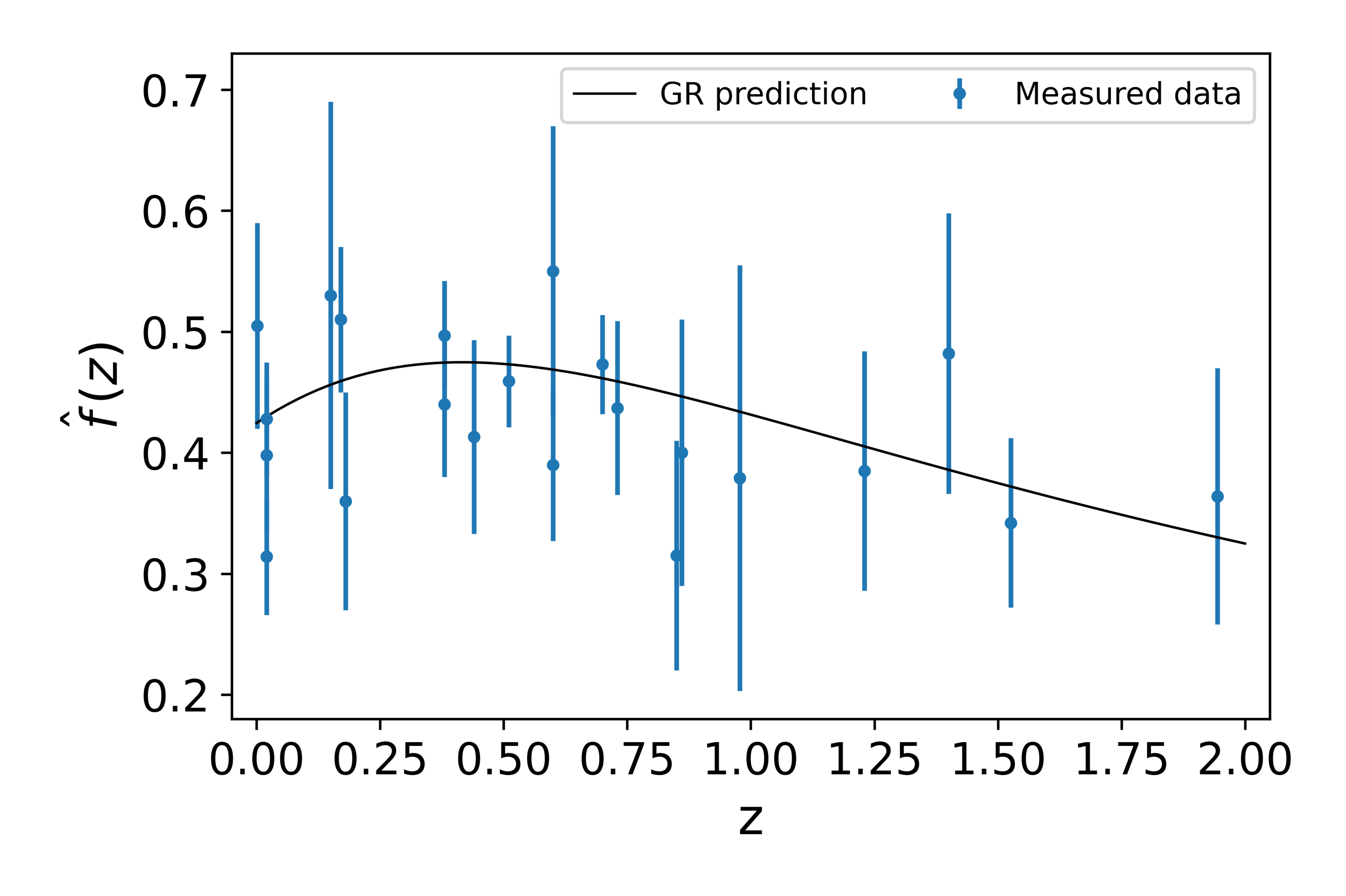
$$E_G(z) = \left(\frac{H(z)}{H_0}\right)^2 \frac{1}{1+z} \frac{\hat{J}(z)}{\hat{f}(z)}$$



- $\hat{J}(z)$ and $\hat{f}(z)$ can come from different data sets.
- $\hat{J}(z)$ and $\hat{f}(z)$ need to be obtained at the same z.
- $\hat{J}(z)$ is currently available at only 4 redshifts.

NG, C. Bonvin and I. Tutusaus, arXiv:2403.13709

$\hat{f}(z)$ data

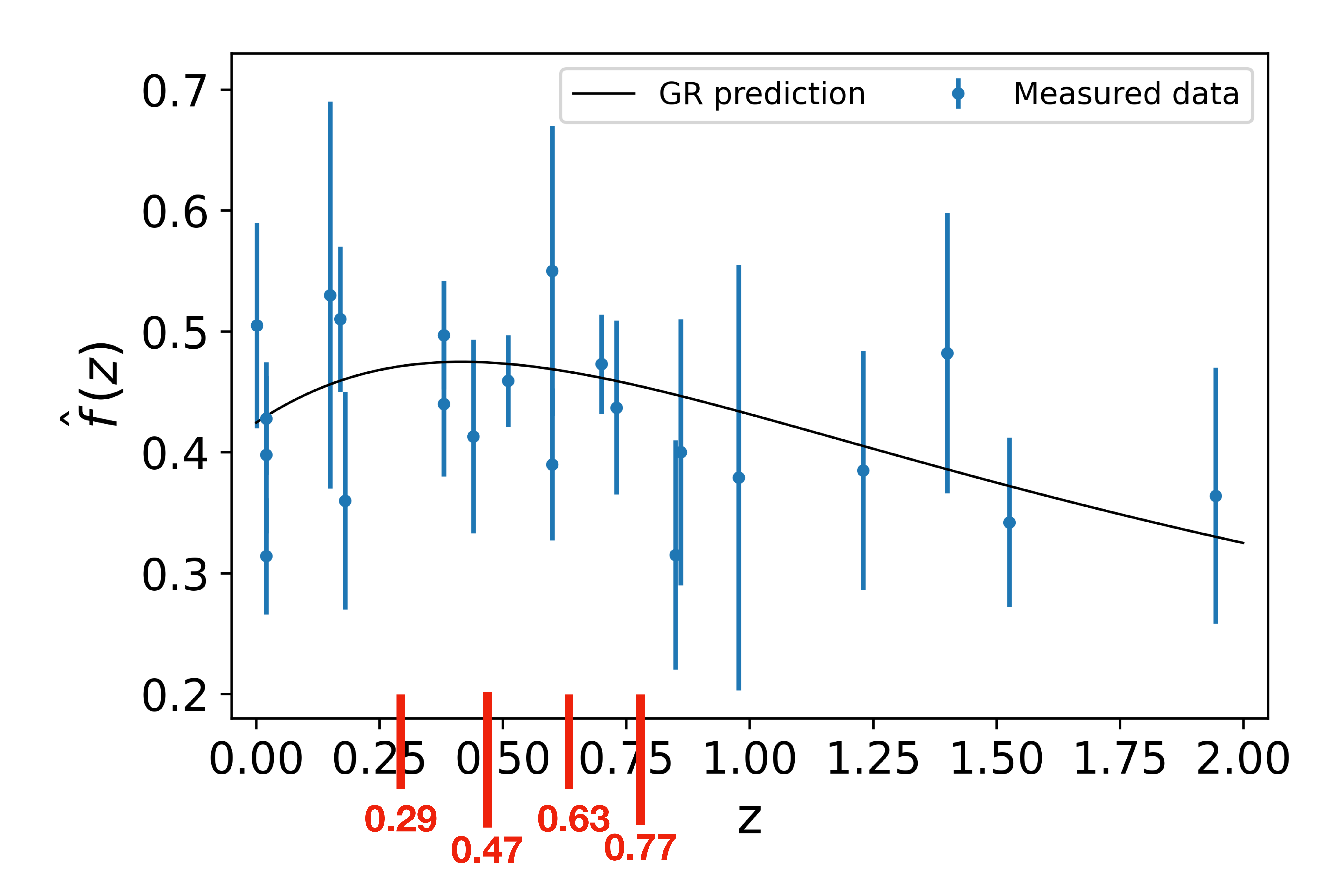


Data:

- 22 measurements of $\hat{f}$ between $z = 0.001$ and $z = 1.944$.
- Based on the Gold-2017 compilation (Nesseris et al. 2017), with updated data from SDSS-IV.

→ **Robust and independent data set!**

$\hat{f}(z)$ data

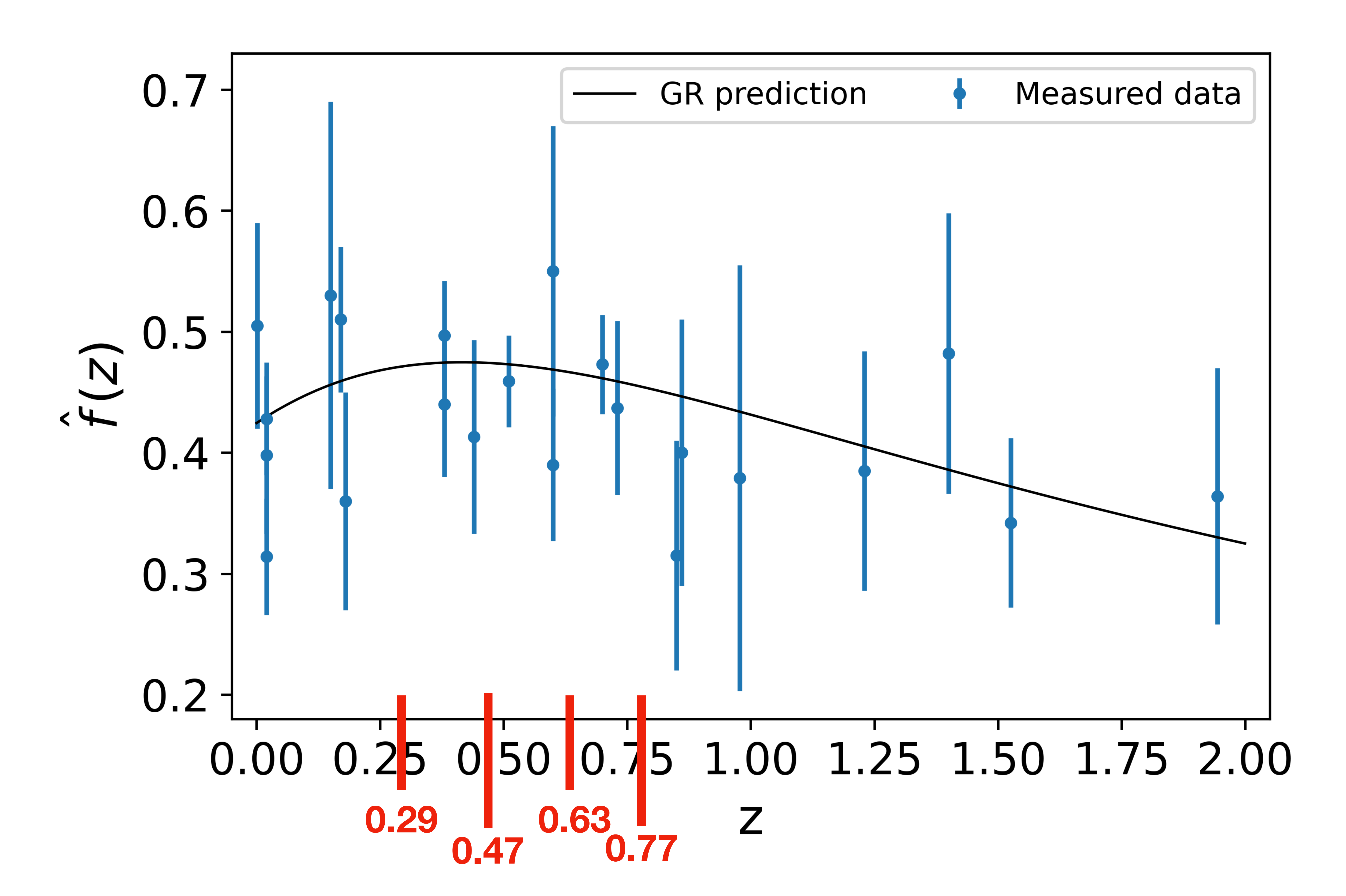


Data:

- 22 measurements of $\hat{f}$ between $z = 0.001$ and $z = 1.944$.
- Based on the Gold-2017 compilation (Nesseris et al. 2017), with updated data from SDSS-IV.

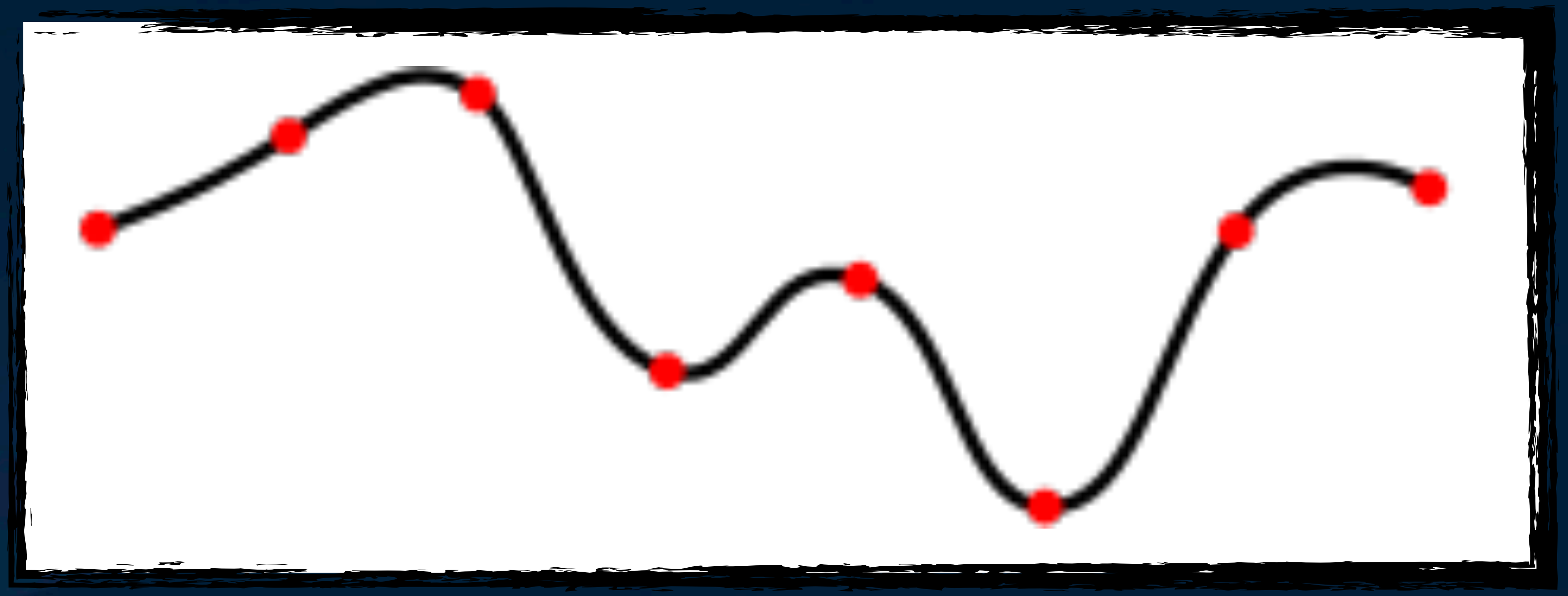
$\rightarrow$ **Robust and independent data set!**

$\hat{f}(z)$ data

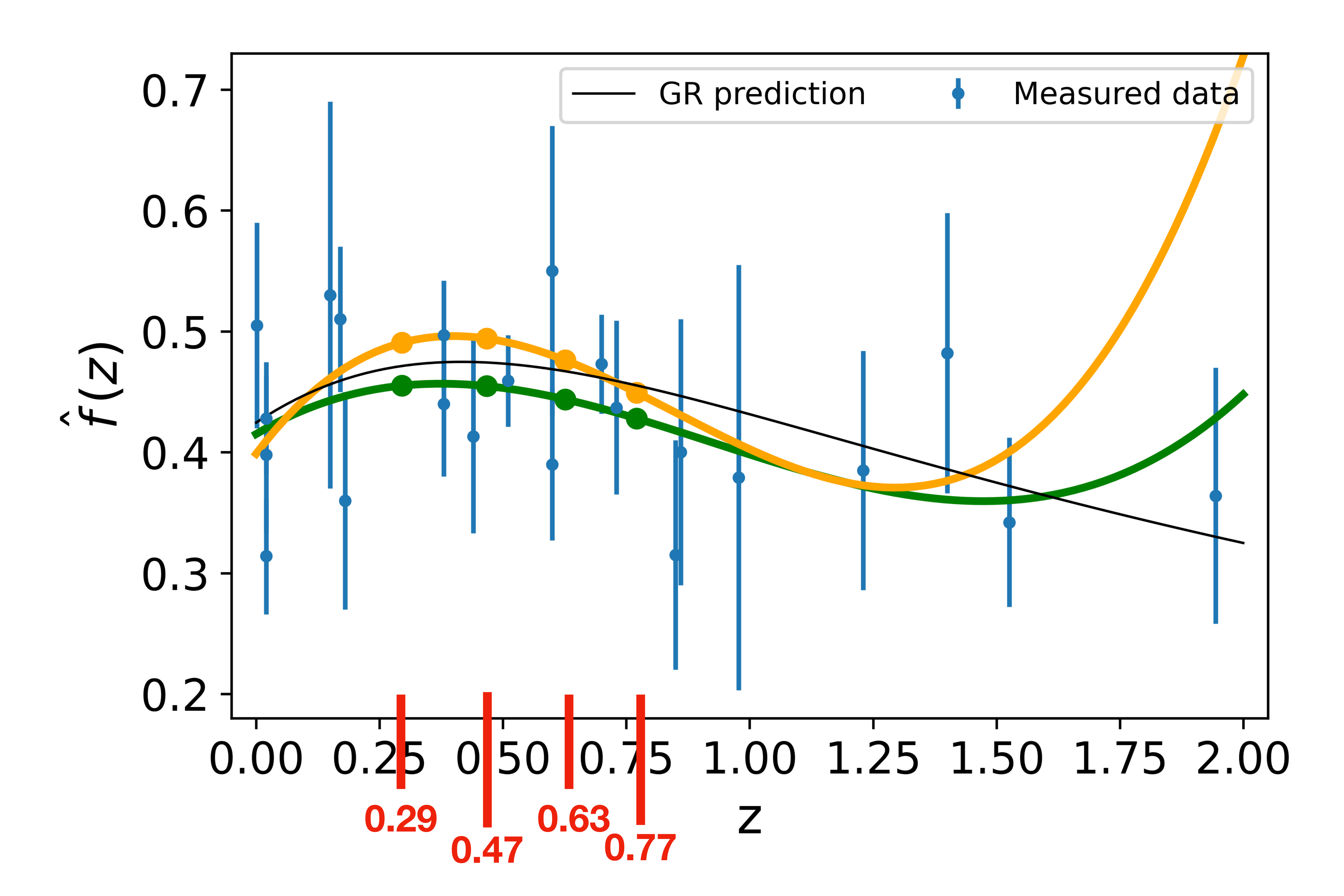


Interpolation Method:

- Cubic spline interpolation

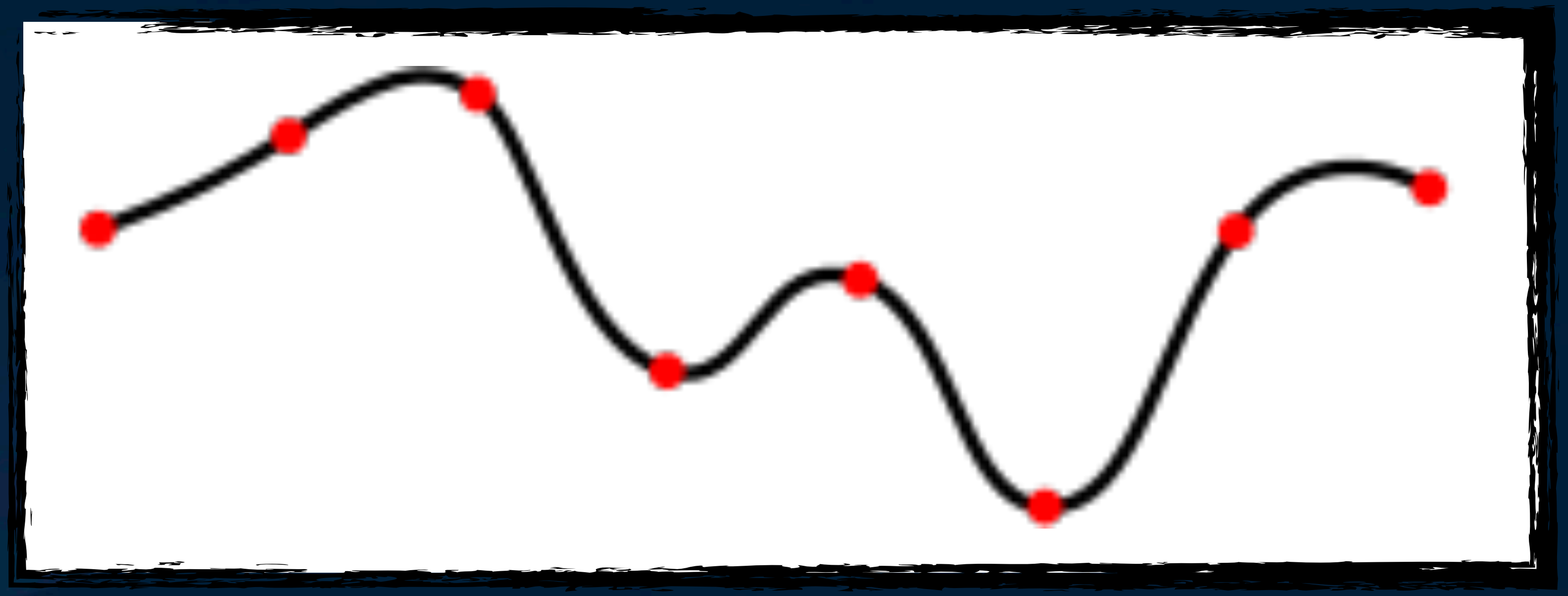


$\hat{f}(z)$ data



Interpolation Method:

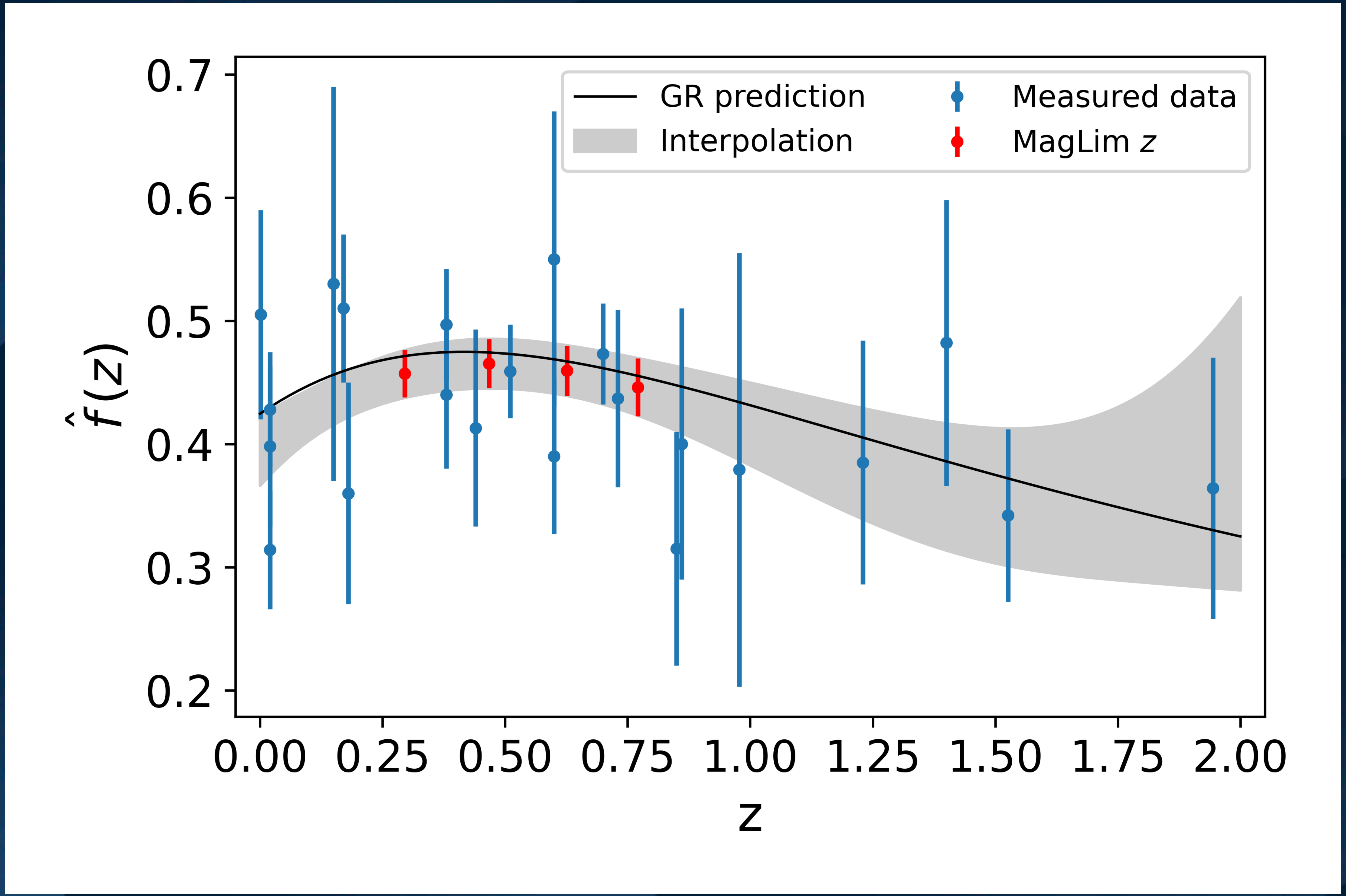
- Cubic spline interpolation



- We set the nodes to the 4 values $z = 0.29, 0.47, 0.63, 0.77$.
- The associated values $\hat{f}_1, \hat{f}_2, \hat{f}_3, \hat{f}_4$ are free parameters.

→ Minimize χ^2 between interpolated values and data points.

Spline interpolation of $\hat{f}(z)$ data

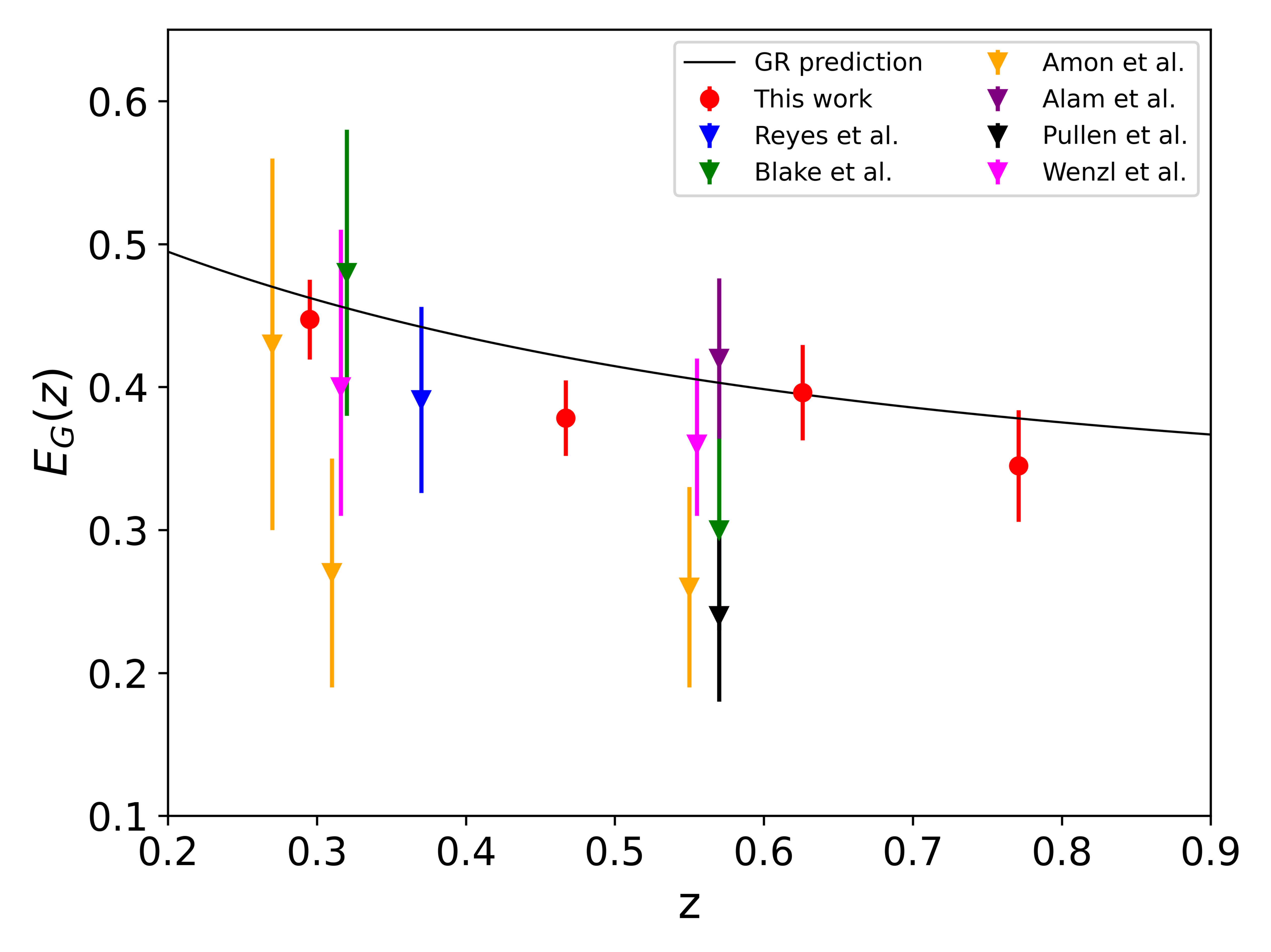


Result:

We obtain measurements of $\hat{f}(z)$ at the 4 MagLim effective redshifts, with 4–5% precision.

NG, C. Bonvin and I. Tutusaus, arXiv:2403.13709

New E_G measurement



Result:

- We can measure E_G with 6—11% precision (compared to 13 – 30% for previous measurements.)
- Agreement with GR (1.6σ deviation in the second bin)

NG, C. Bonvin and I. Tutusaus, arXiv:2403.13709

Conclusion & Outlook

Measurement of $\hat{J}$:

- Achieved with 5-10% precision from DES Y3 data.
- Mild tension of 2.6σ at $z = 0.47$.

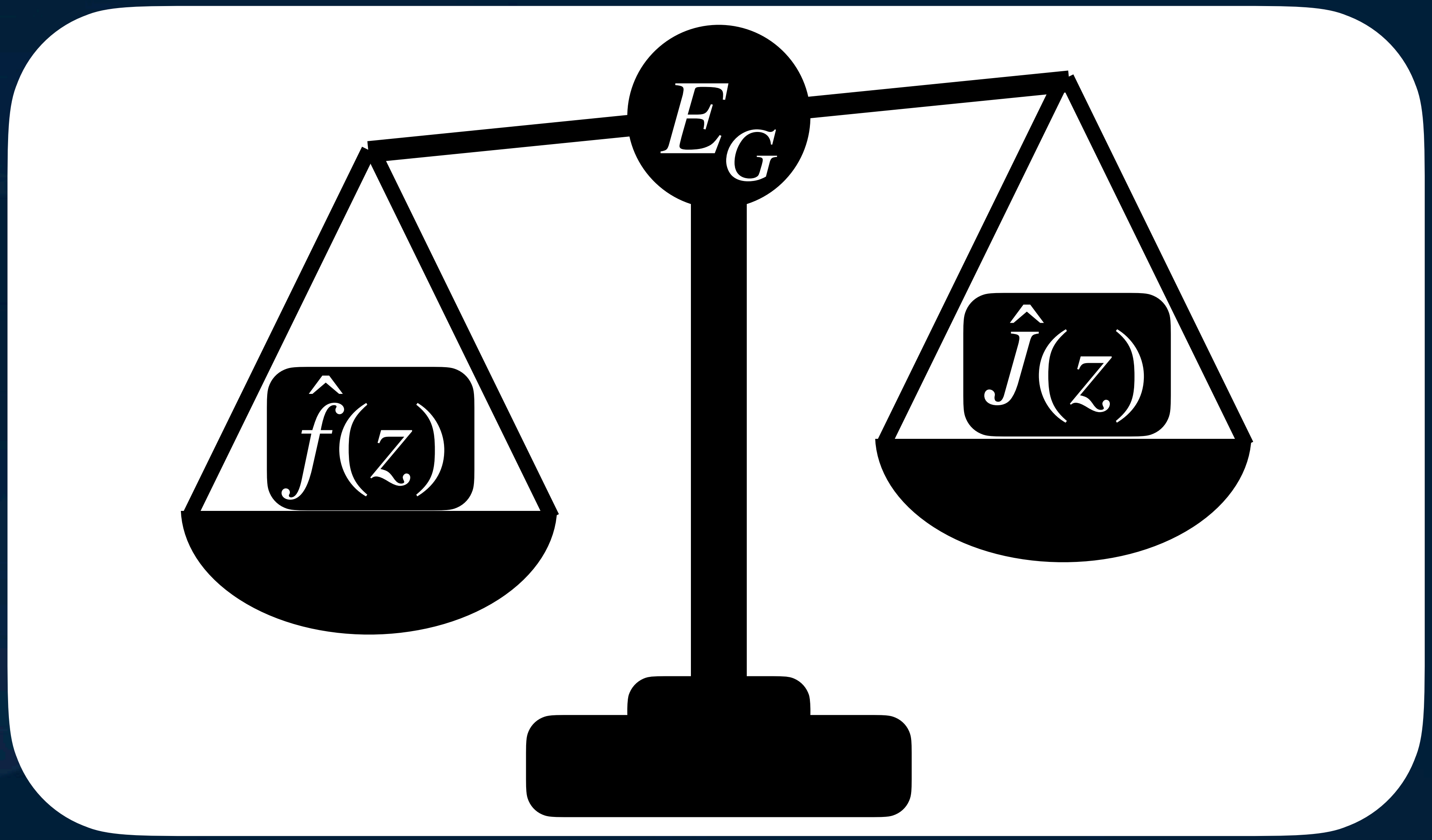
Conclusion & Outlook

Measurement of $\hat{J}$:

- Achieved with 5-10% precision from DES Y3 data.
- Mild tension of 2.6σ at $z = 0.47$.

The E_G statistic:

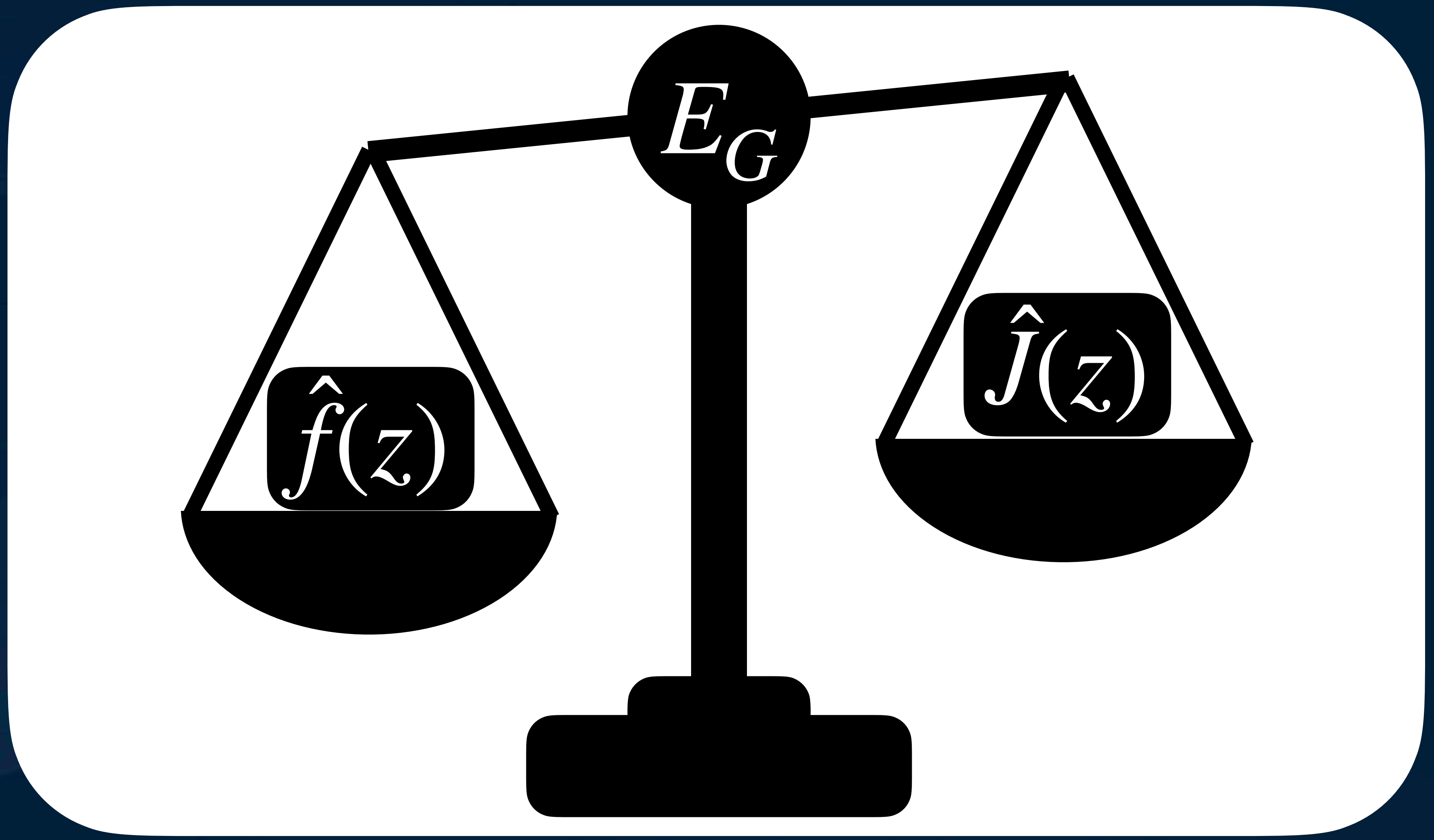
- has been used in the past to provide a robust, model-independent test of gravity.
- **But some modifications of gravity could be hidden!**



Conclusion & Outlook

Measurement of $\hat{J}$:

- Achieved with 5-10% precision from DES Y3 data.
- Mild tension of 2.6σ at $z = 0.47$.



The E_G statistic:

- has been used in the past to provide a robust, model-independent test of gravity.
- **But some modifications of gravity could be hidden!**

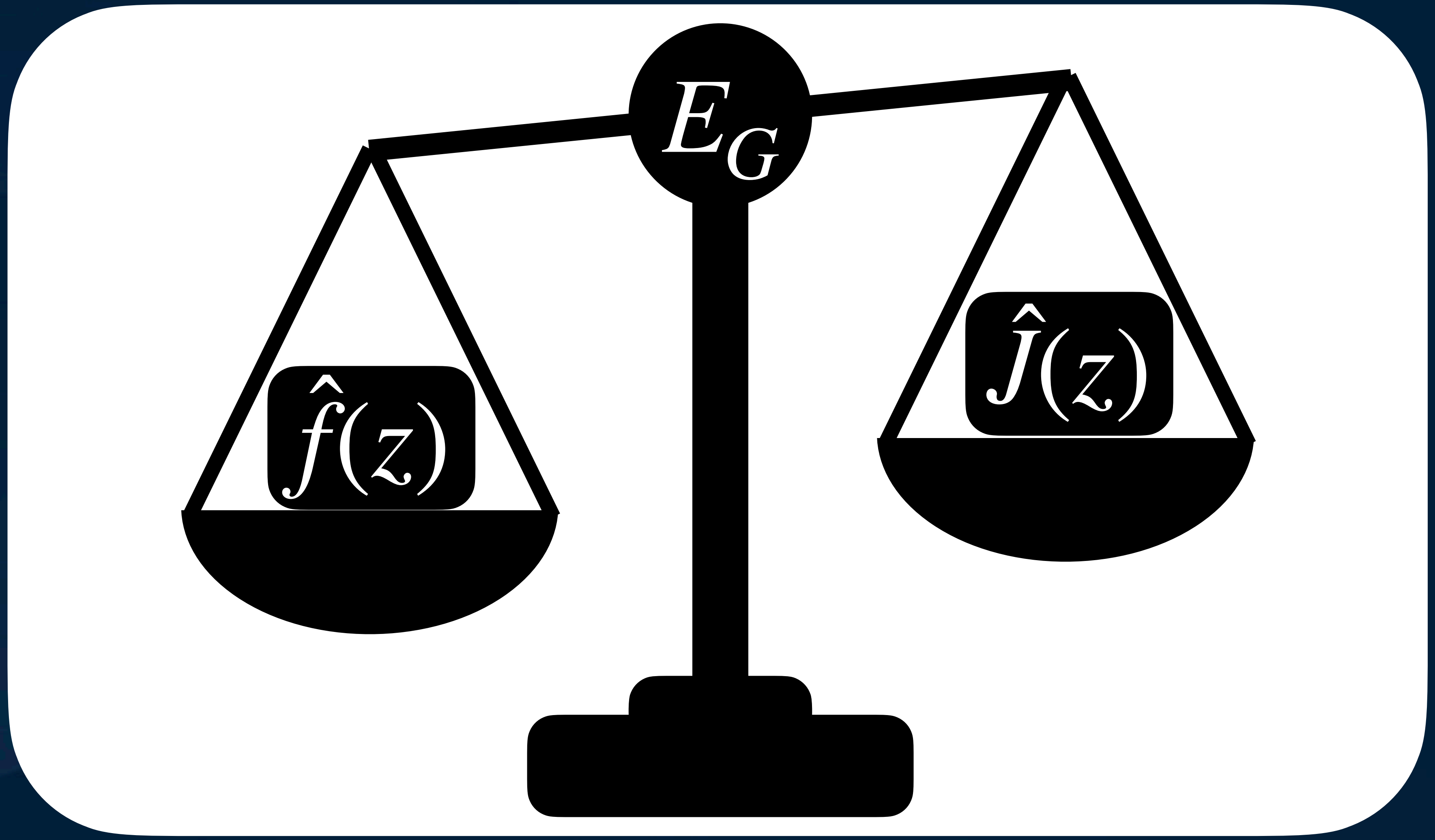
Upcoming work:

Alternative ways of combining $\hat{f}$ and $\hat{J}$, e.g. for a test of Euler's equation.

Conclusion & Outlook

Measurement of $\hat{J}$:

- Achieved with 5-10% precision from DES Y3 data.
- Mild tension of 2.6σ at $z = 0.47$.



The E_G statistic:

- has been used in the past to provide a robust, model-independent test of gravity.
- **But some modifications of gravity could be hidden!**

Upcoming work:

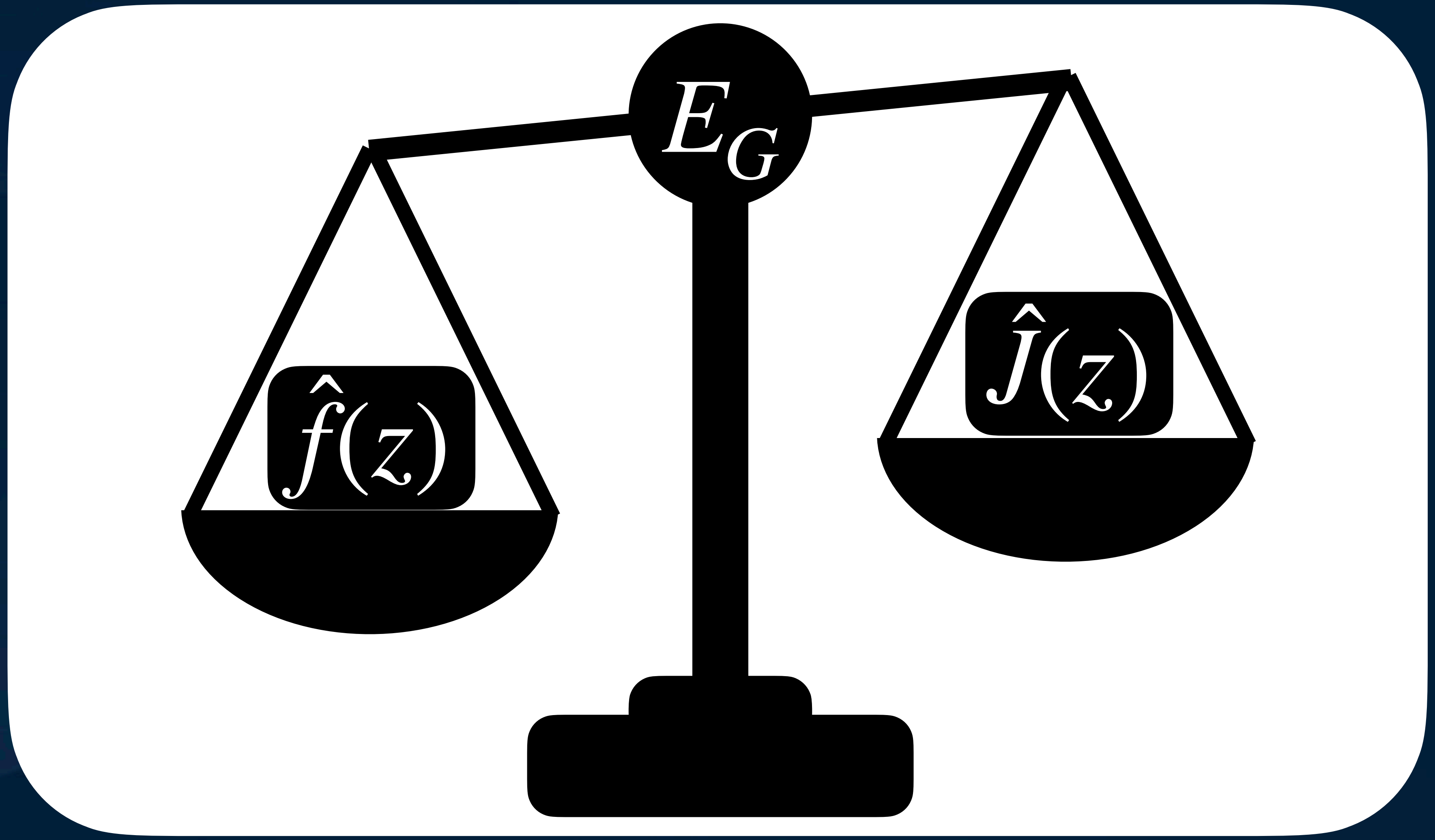
Alternative ways of combining $\hat{f}$ and $\hat{J}$, e.g. for a test of Euler's equation.

Investigate the improvement expected from upcoming survey data (DESI, LSST, Euclid)

Conclusion & Outlook

Measurement of $\hat{J}$:

- Achieved with 5-10% precision from DES Y3 data.
- Mild tension of 2.6σ at $z = 0.47$.



The E_G statistic:

- has been used in the past to provide a robust, model-independent test of gravity.
- **But some modifications of gravity could be hidden!**

Upcoming work:

Alternative ways of combining $\hat{f}$ and $\hat{J}$, e.g. for a test of Euler's equation.	Investigate the improvement expected from upcoming survey data (DESI, LSST, Euclid)	Investigate alternative interpolation methods, in particular Gaussian processes.

Conclusion & Outlook

Measurement of $\hat{J}$:

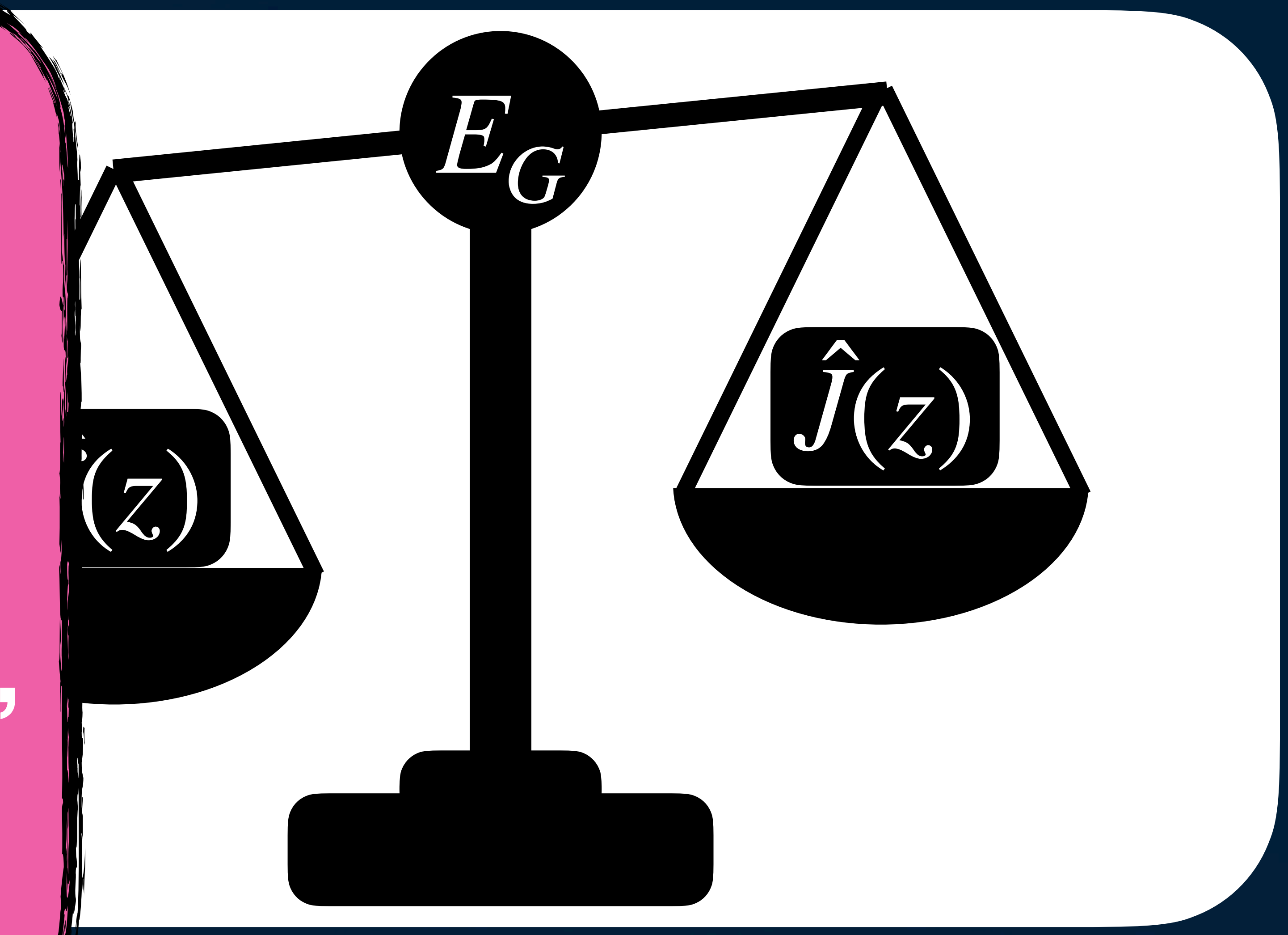
- Achieved with 5-10% pre
- Mild tension of 2.6σ at z

The E_G statistic:

- has been used in the pas independent test of gravi
- **But some modifications**

Thanks for listening!

Also, talk to me about galaxy anisotropies + pulsar timing arrays, arXiv:2404.05670 :)



Upcoming work:

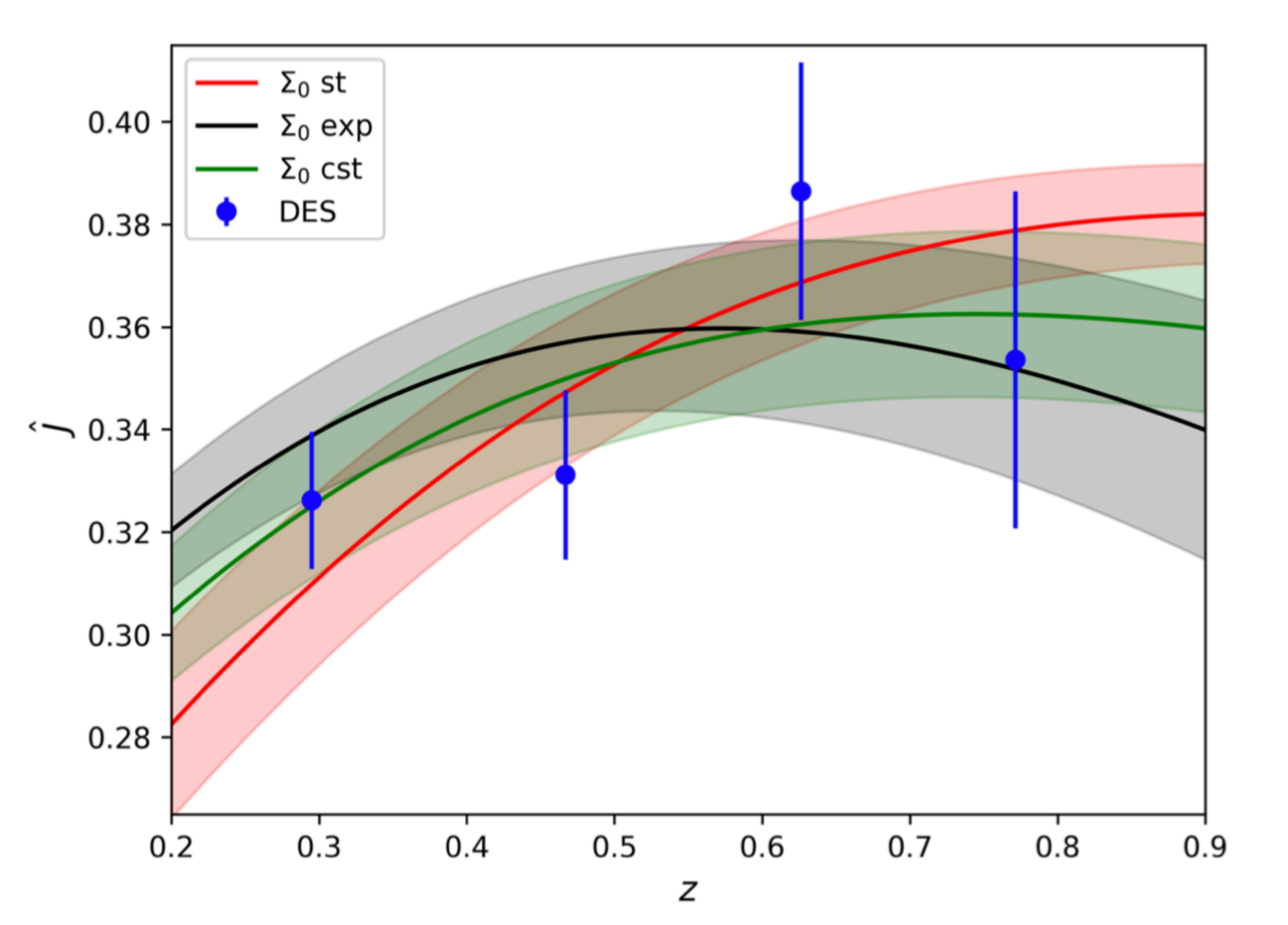
Alternative ways of combining $\hat{f}$ and $\hat{J}$, e.g. for a test of Euler's equation.

Investigate the improvement expected from upcoming survey data (DESI, LSST, Euclid)

Investigate alternative interpolation methods, in particular Gaussian processes.

Backup

$\hat{J}(z)$ measurements and $\mu - \Sigma$ parameterisation



$\hat{J}(z)$ measurements: some technical details

- 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

Table I. List of $\hat{f}(z)$ measurements used in this work.

Dataset	z	$\hat{f}(z)$	Ref.
2MTF	0.001	0.505 ± 0.085	[5]
6dFGS+SNIa	0.02	0.4280 ± 0.0465	[6]
IRAS+SNIa	0.02	0.398 ± 0.065	[7, 8]
2MASS	0.02	0.314 ± 0.048	[7, 9]
2dFGRS	0.17	0.510 ± 0.060	[20]
GAMA	0.18	0.360 ± 0.090	[21]
GAMA	0.38	0.440 ± 0.060	[21]
SDSS-IV (MGS)	0.15	0.53 ± 0.16	[22]
SDSS-IV (BOSS Galaxy)	0.38	0.497 ± 0.045	[22]
SDSS-IV (BOSS Galaxy)	0.51	0.459 ± 0.038	[22]
SDSS-IV (eBOSS LRG)	0.70	0.473 ± 0.041	[22]
SDSS-IV (eBOSS ELG)	0.85	0.315 ± 0.095	[22]
WiggleZ	0.44	0.413 ± 0.080	[23]
WiggleZ	0.60	0.390 ± 0.063	[23]
WiggleZ	0.73	0.437 ± 0.072	[23]
Vipers PDR-2	0.60	0.550 ± 0.120	[24]
Vipers PDR-2	0.86	0.400 ± 0.110	[24]
FastSound	1.40	0.482 ± 0.116	[25]
SDSS-IV (eBOSS Quasar)	0.978	0.379 ± 0.176	[26]
SDSS-IV (eBOSS Quasar)	1.230	0.385 ± 0.099	[26]
SDSS-IV (eBOSS Quasar)	1.526	0.342 ± 0.070	[26]
SDSS-IV (eBOSS Quasar)	1.944	0.364 ± 0.106	[26]

$\hat{f}(z)$ data