Model-independent tests of modified gravity from galaxy surveys

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Based on arXiv:2312.06434 and arXiv:2311.14425
In collaboration with I. Tutusaus (IRAP, Toulouse), C. Bonvin (UNIGE), S. Castello (UNIGE), M. Mancarella (INFN, Milan) and D. Sobral Blanco (UNIGE)

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UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

Rencontres de cosmologie des lacs alpins

18 January 2024

European Research Council
Established by the European Commission

Topics covered in this talk

Model-independent tests of gravity

Using gravitational lensing

Measurement from DES Year 3 data

arXiv:2312.06434

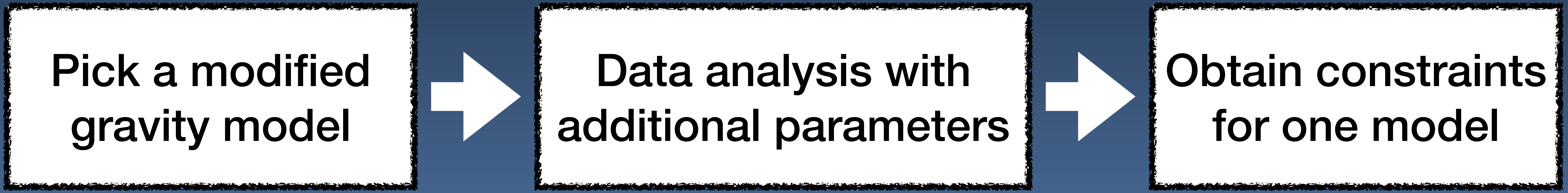
Using gravitational redshift

Forecast for SKA phase 2

arXiv:2311.14425

How can we test modified gravity?

Possibility 1



Pick a modified gravity model

Data analysis with additional parameters

Obtain constraints for one model

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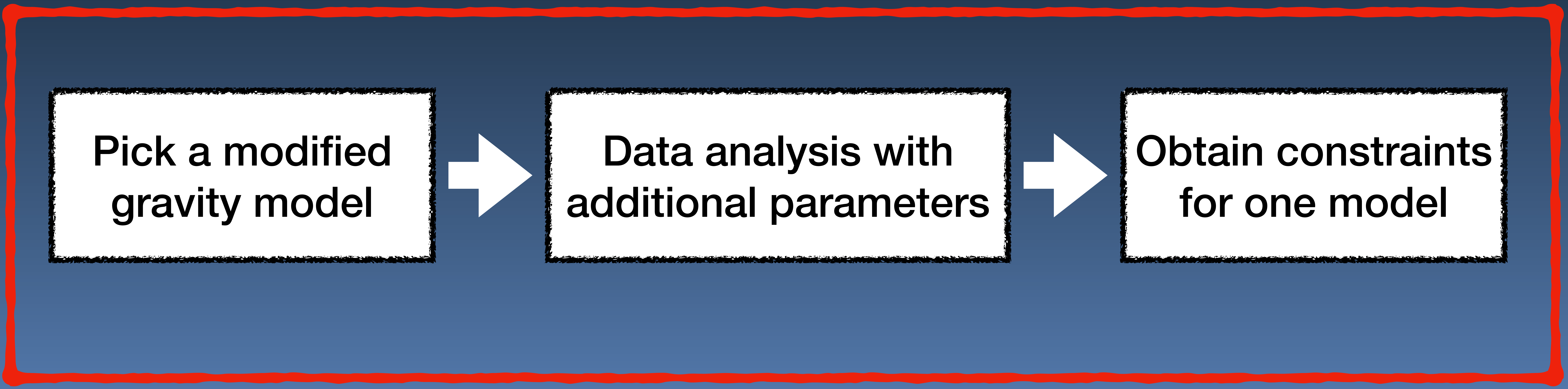

Pick a modified gravity model → Data analysis with additional parameters → Obtain constraints for one model

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

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Model-independent observable for gravitational lensing?

Lensing is sensitive to the perturbed geometry of the Universe:

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

Weyl potential in General Relativity:

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

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:

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

Growth of matter perturbations

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 $\hat{b}_i(z)\hat{b}_j(z)$

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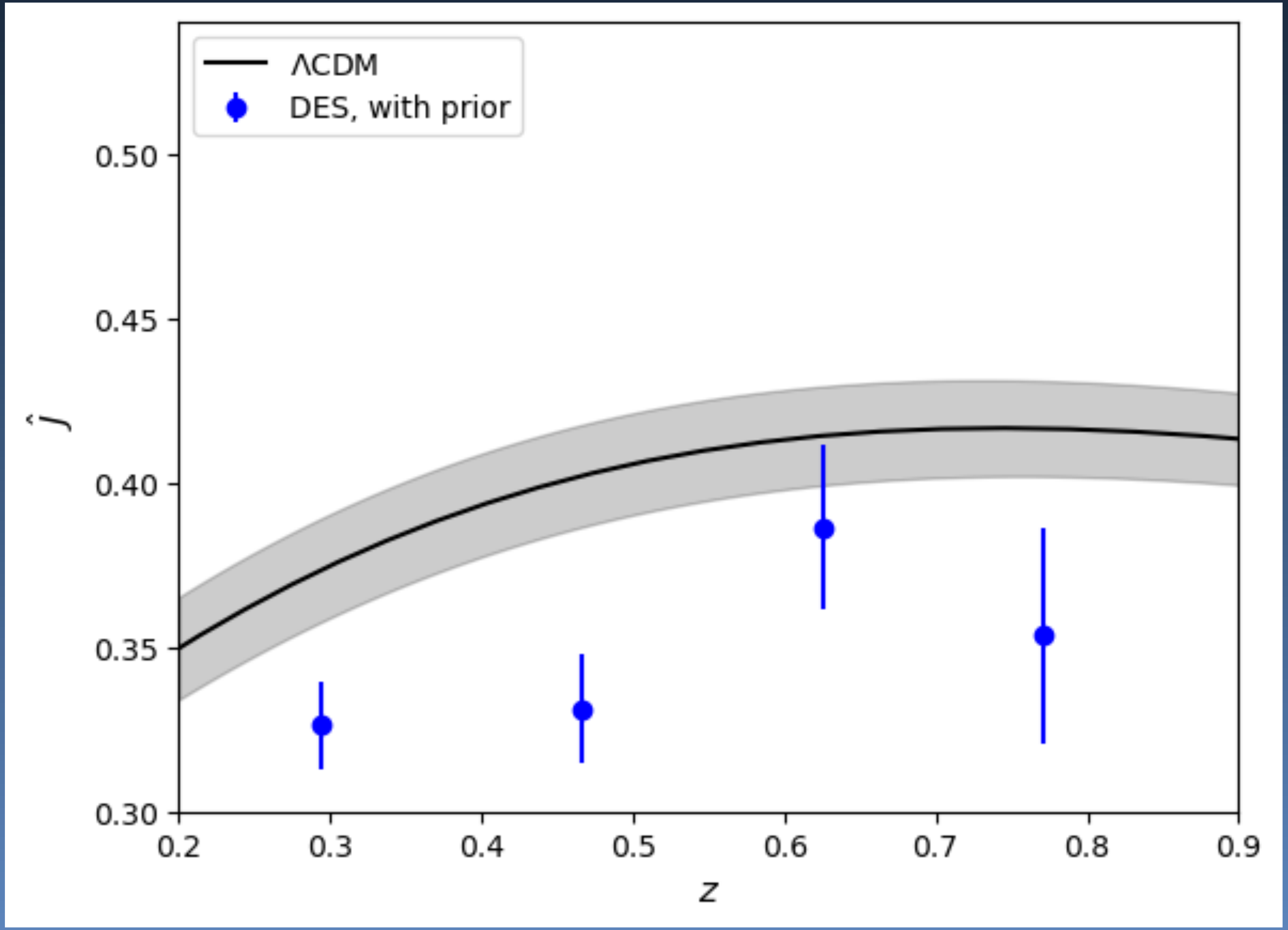
Galaxy clustering: Depends on $\hat{b}_i(z)\hat{b}_j(z)$

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

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



I. Tutusaus, C. Bonvin & NG, arXiv:2312.06434

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

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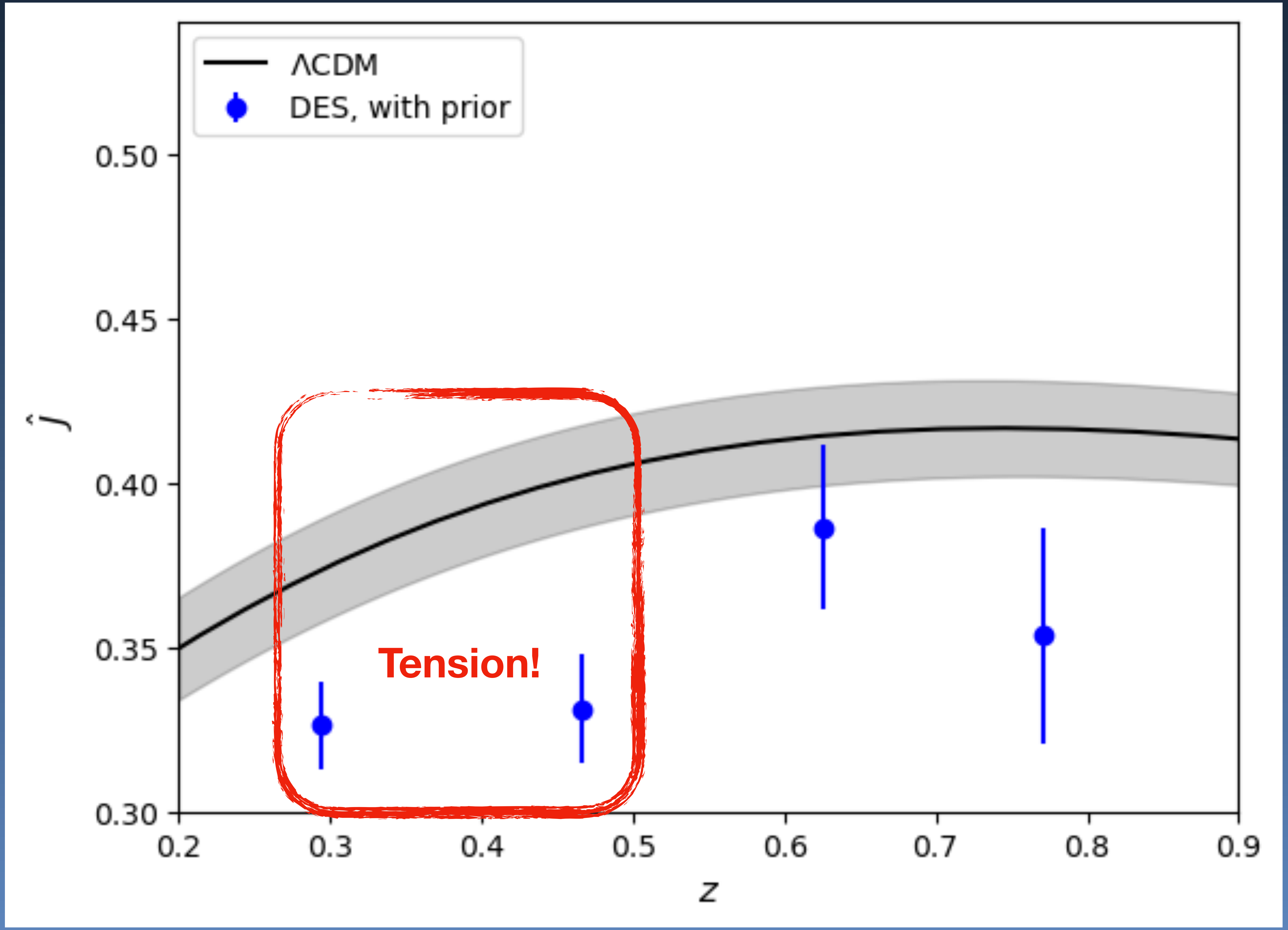

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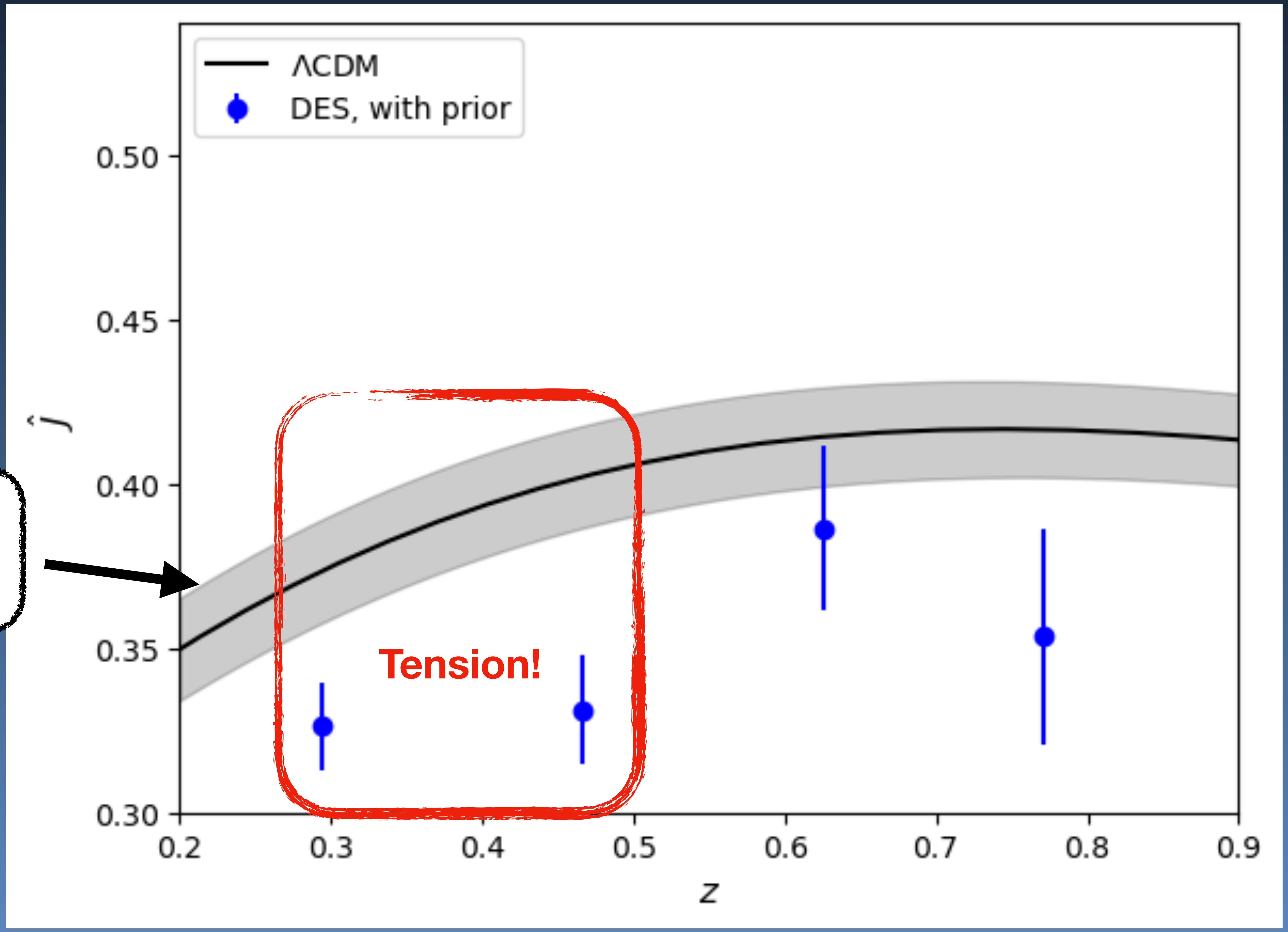
$\sigma_8(z=0) = 0.85 \pm 0.03$



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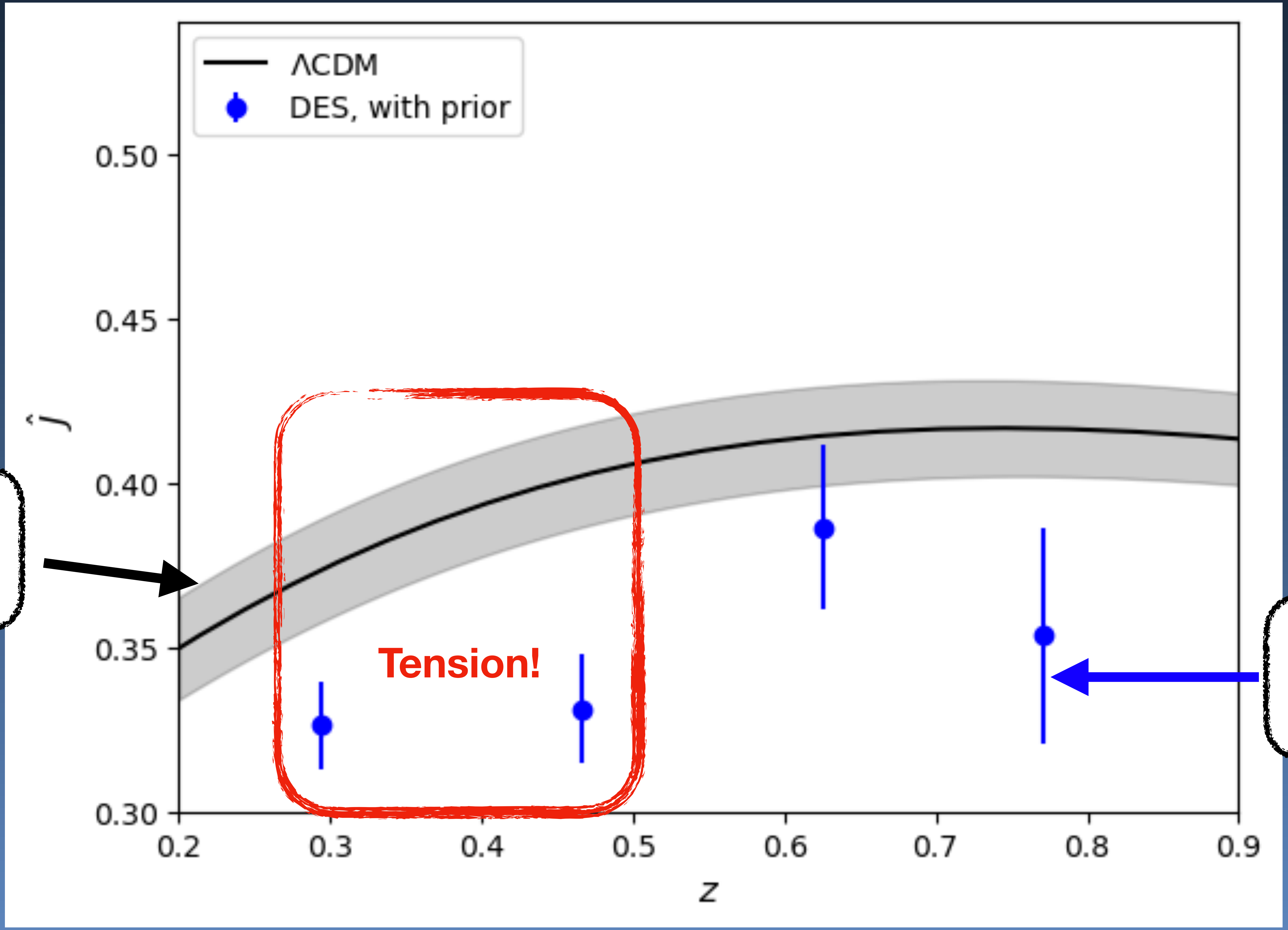


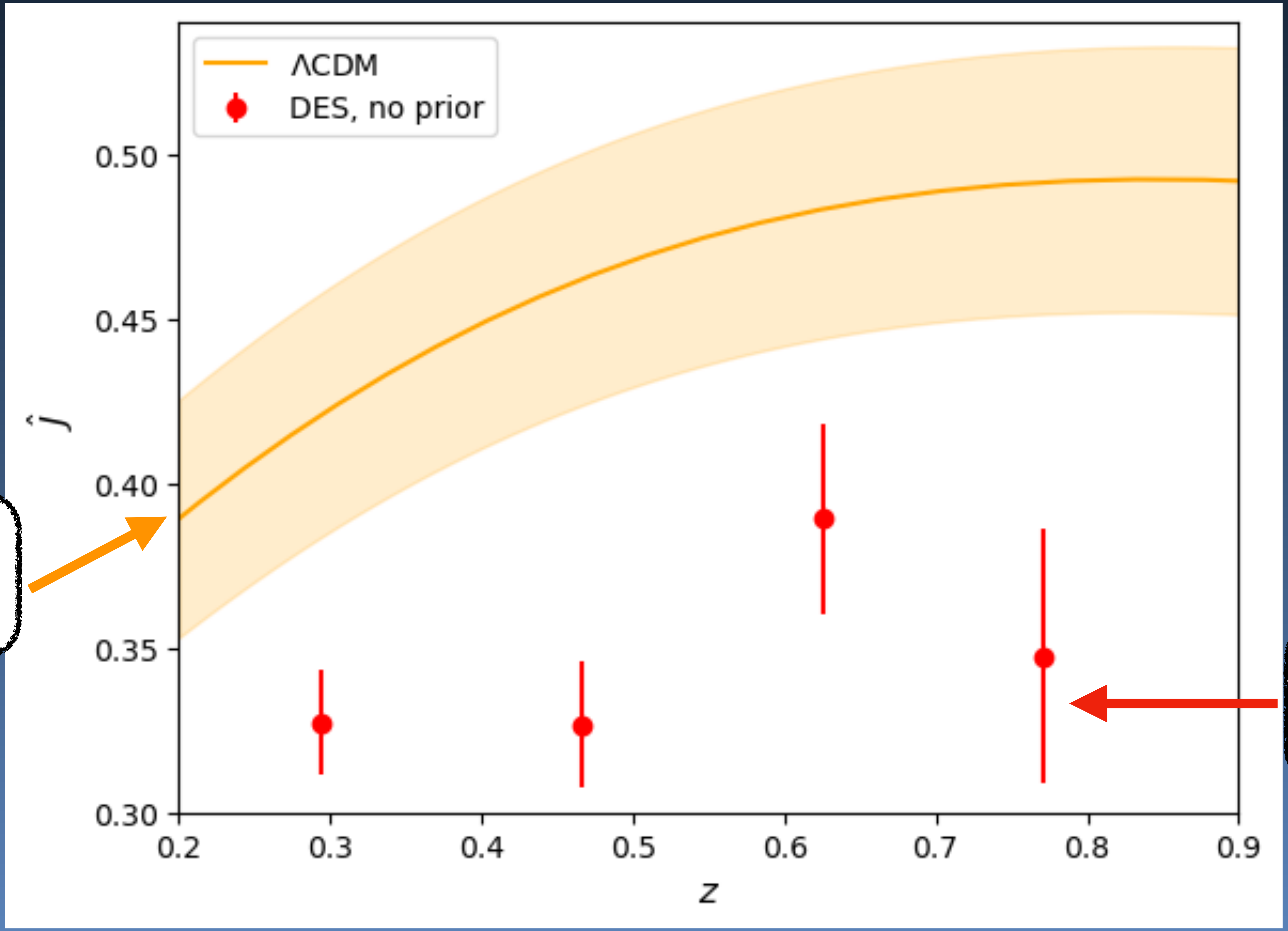
I. Tutusaus, C. Bonvin & NG, arXiv:2312.06434

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

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

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

Measurement of $\hat{J}(z)$ without CMB priors



I. Tutusaus, C. Bonvin & NG, arXiv:2312.06434

$\sigma_8(z=0) = 1.04 \pm 0.09$

$\sigma_8(z=0) = 0.78 \pm 0.07$

Measurement in 4 bins of the MagLim sample, without priors

How can we test modified gravity?
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Horndeski theories

Horndeski theories:

- Lagrangian-based models
- Scalar-tensor theories leading to 2nd order equations of motion
- Encompass various subclasses (Brans-Dicke, $f(R)$, quintessence, kinetic braiding…)

Effective theory approach: Horndeski theories are described by 3 free functions *(see e.g. Bellini & Sawicki, arXiv:1404.3713),*

- α_K : kineticity (kinetic energy of scalar perturbations)
- α_B : braiding (mixing of scalar & metric kinetic terms)
- α_M : Planck-mass run rate
- The tensor speed excess $|\alpha_T| \lesssim 10^{-15}$ has been tightly constrained (GW170817).

Horndeski models + Breaking of the Weak Equivalence Principle

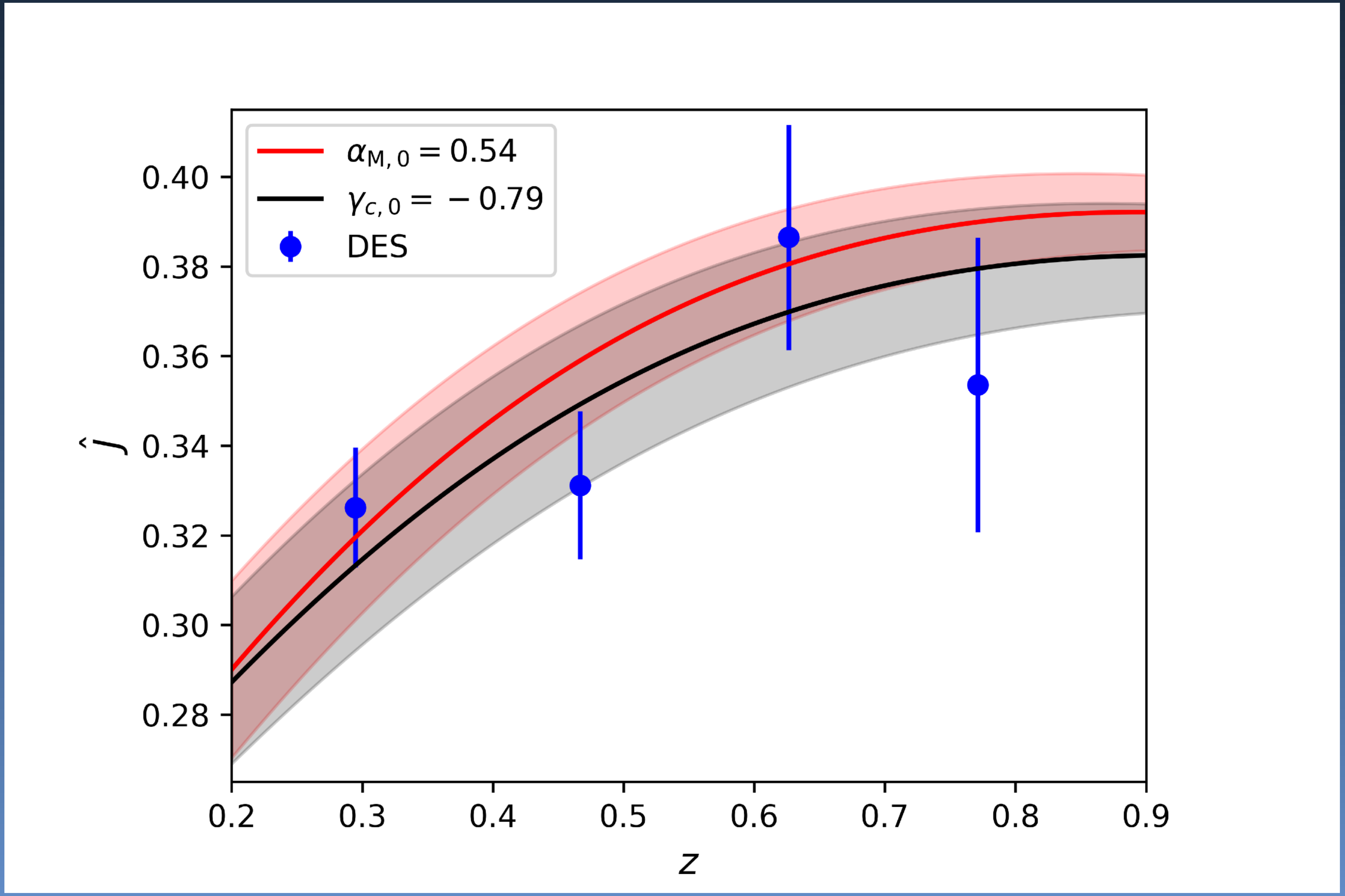
Weak Equivalence Principle (WEP): has never been tested for the unknown dark matter component.

⇒ The additional free function γ_c describes a non-minimal coupling of DM to the metric.

$\gamma_c \neq 0\ldots$ **Breaking of the WEP**

See Gleyzes et al., arXiv:1504.05481, arXiv:1509.02191 for details.

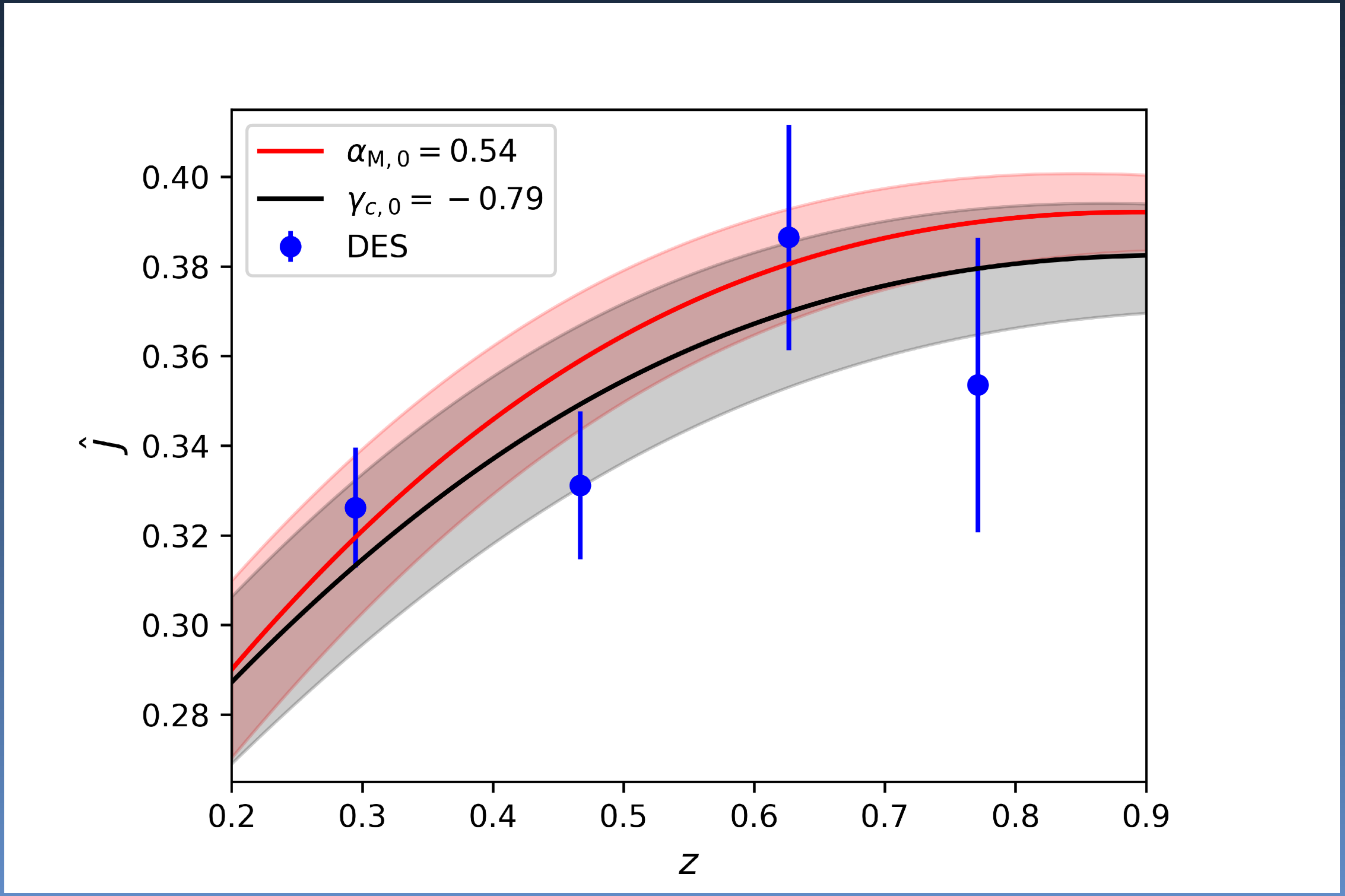
Horndeski models + Breaking of the Weak Equivalence Principle



2 different models:

- $\alpha_M = 2\alpha_B \neq 0$ (corresponding to Brans-Dicke, some $f(R)$ models)
- $\gamma_c \neq 0$ (Breaking of the weak equivalence principle for DM)

Horndeski models + Breaking of the Weak Equivalence Principle



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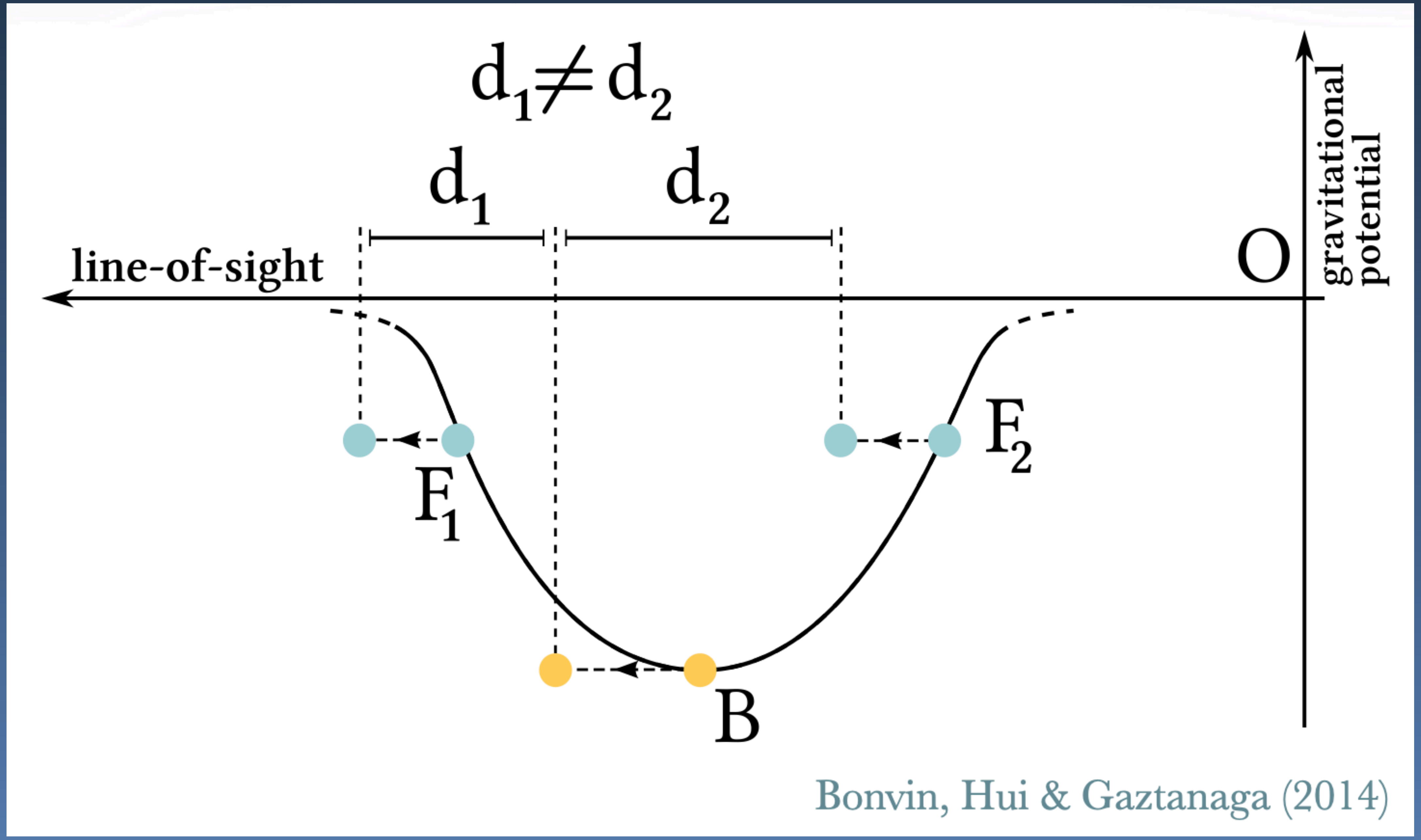
Almost identical behaviour!

Measuring $\hat{J}$ is not enough to distinguish between various models!

A novel observable to distinguish different models: Gravitational Redshift

Photons emitted by galaxies need to leave their high-density environments to reach us.



Bonvin, Hui & Gaztanaga (2014)

Gravitational redshift is directly sensitive to the potential Ψ.

The **bright galaxy** at the bottom of the potential well is more affected by gravitational redshift than the **faint galaxies**.

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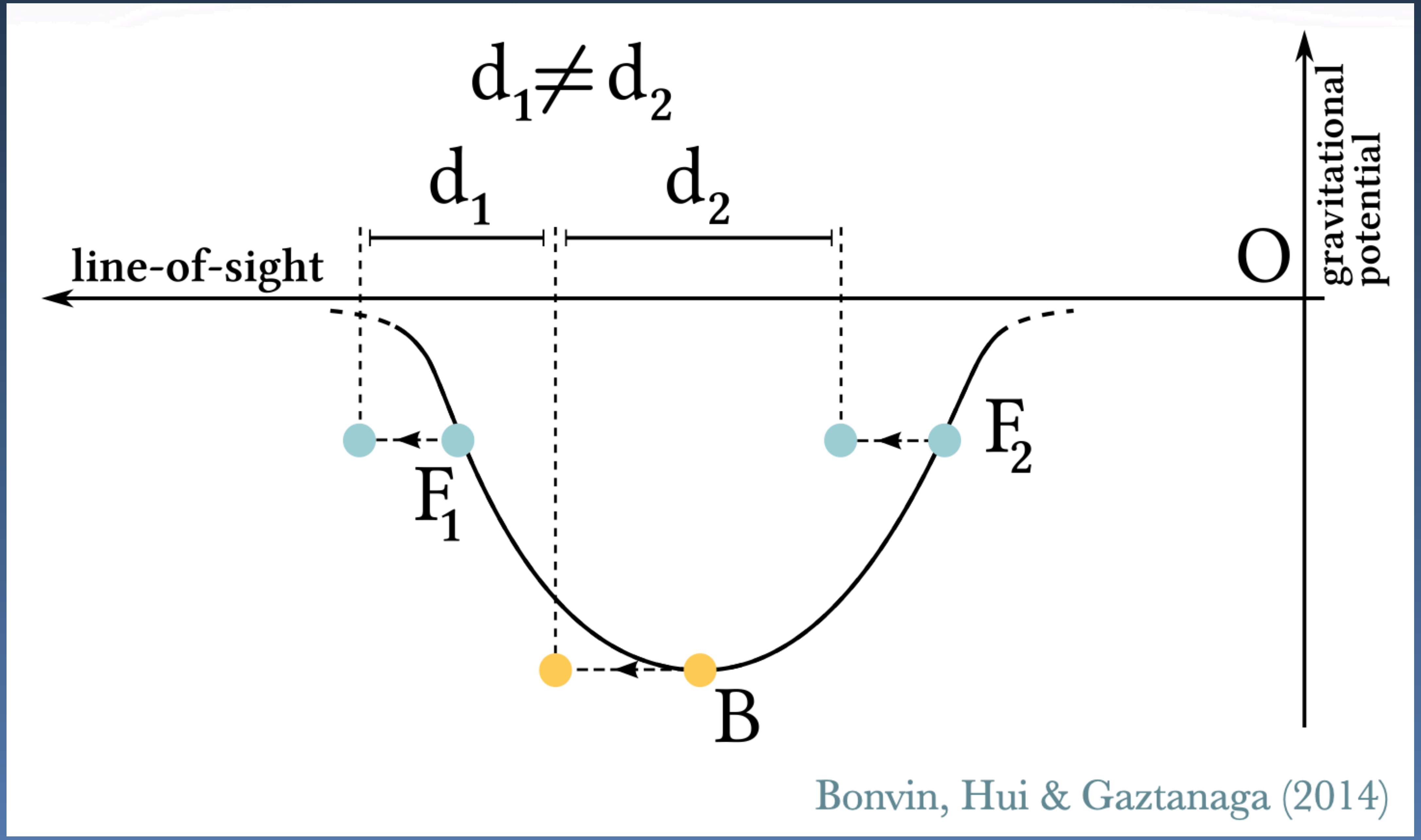

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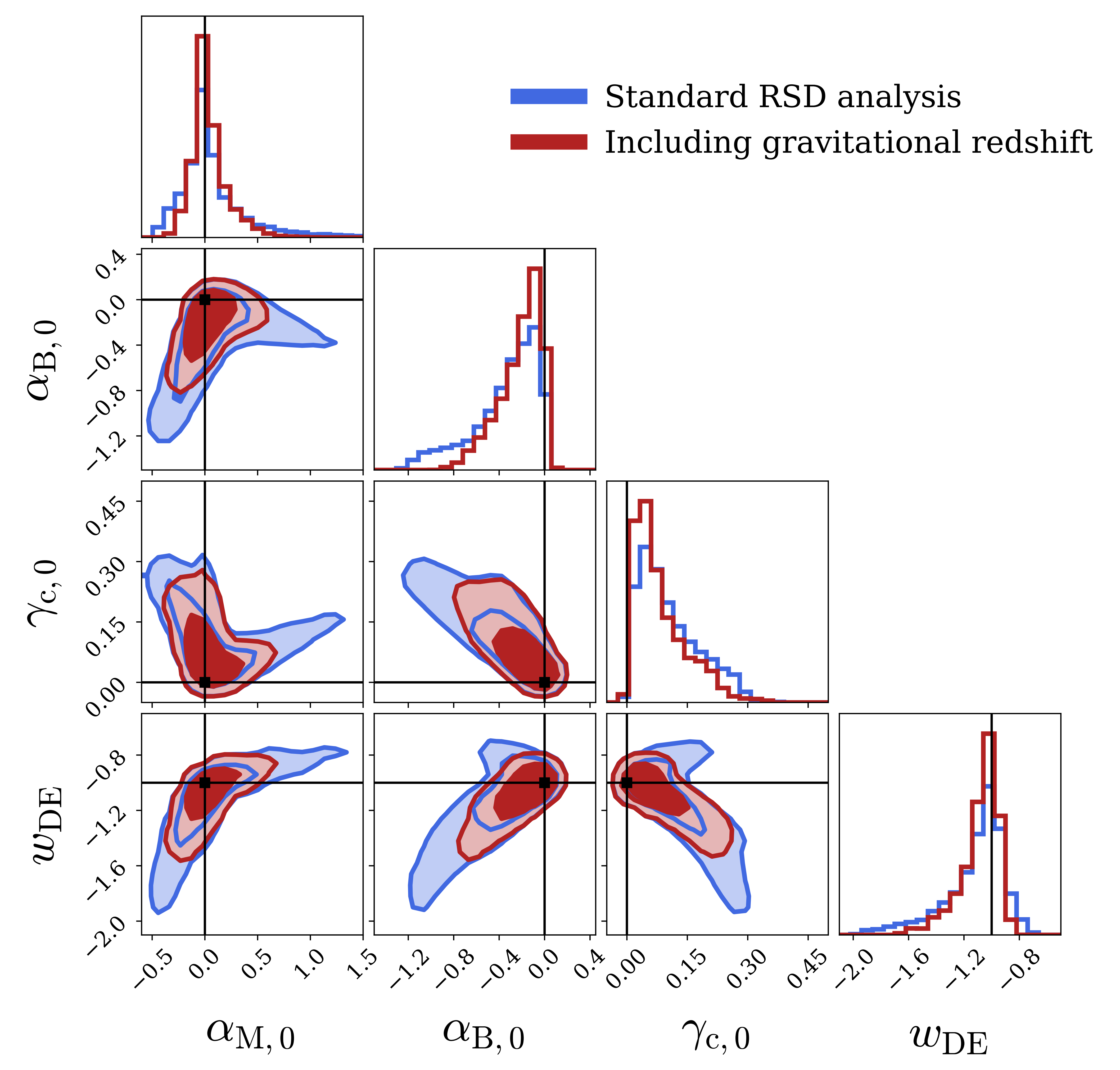
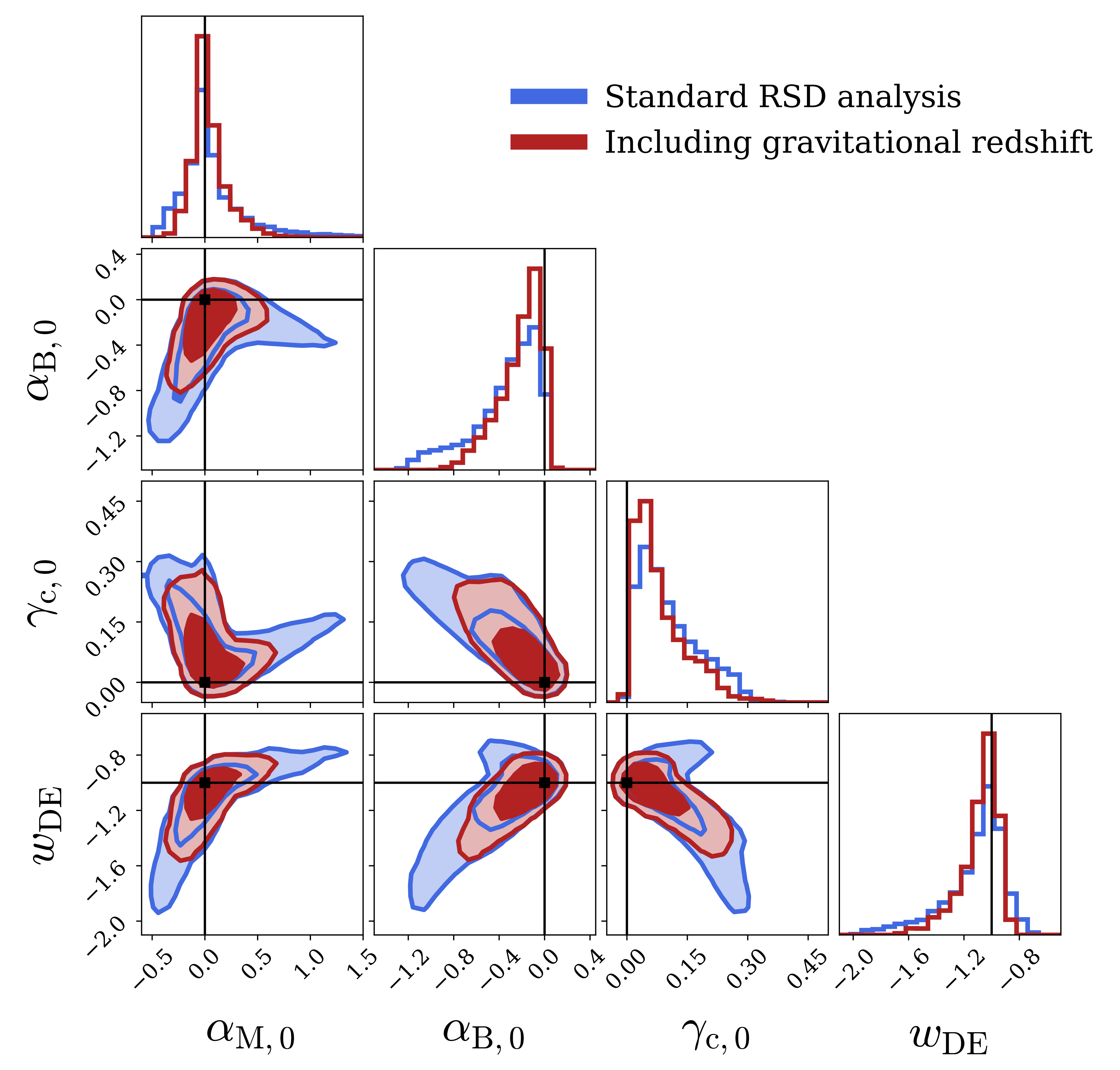
Gravitational redshift creates an asymmetry in redshift-space for two distinct galaxy populations.

Forecast for SKA2



S. Castello, M. Mancarella, NG, D. Sobral Blanco, I. Tutusaus and C. Bonvin
arXiv:2311.14425

Forecast for SKA2



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The inclusion of gravitational redshift significantly restricts the parameter space!

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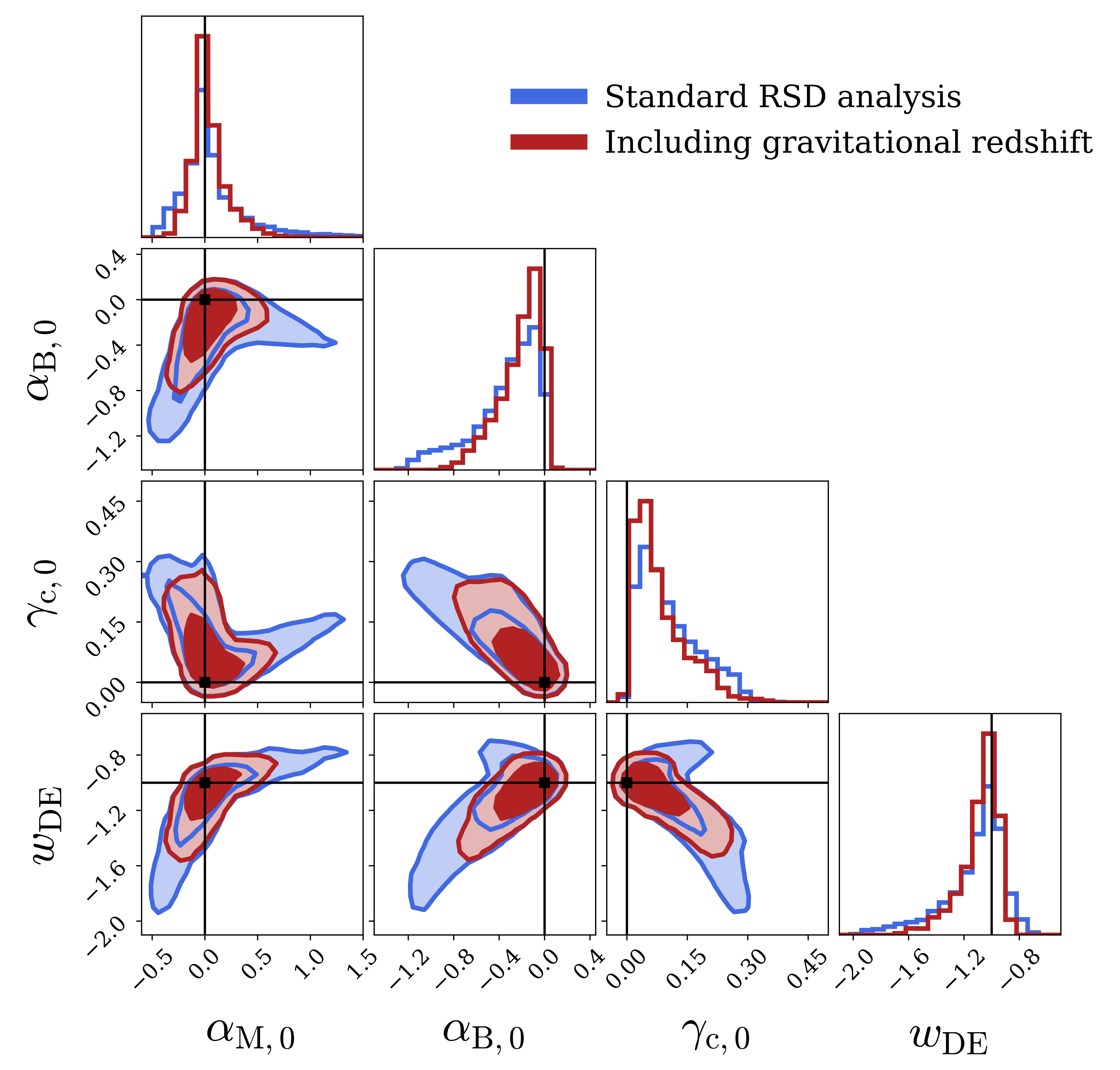

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The inclusion of gravitational redshift significantly restricts the parameter space!

Forecast based on the **EF-TIGRE** (**E**ffective **F**ield **T**heory of **I**nteracting dark energy with **G**ravitation **RE**dshift code):
https://github.com/Mik3M4n/EF-TIGRE

Summary and Conclusions

Measurement of $\hat{J}$:

- achieved with 4-9% precision from the DES Y3 data release.
- σ_8 tension remains even when not using any CMB prior.
- tension points at either unknown systematics or new physics at first two redshift bins.

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Gravitational redshift:

- will be measurable with SKA2.
- can help to distinguish between different models of modified gravity.

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Future work:

- Explore the constraining power of $\hat{J}$ measurements from Euclid.
- Combine various observables (standard RSD, gravitational redshift and gravitational lensing).

Thanks for your attention!

arXiv:2312.06434

(Gravitational Lensing)

arXiv:2311.14425

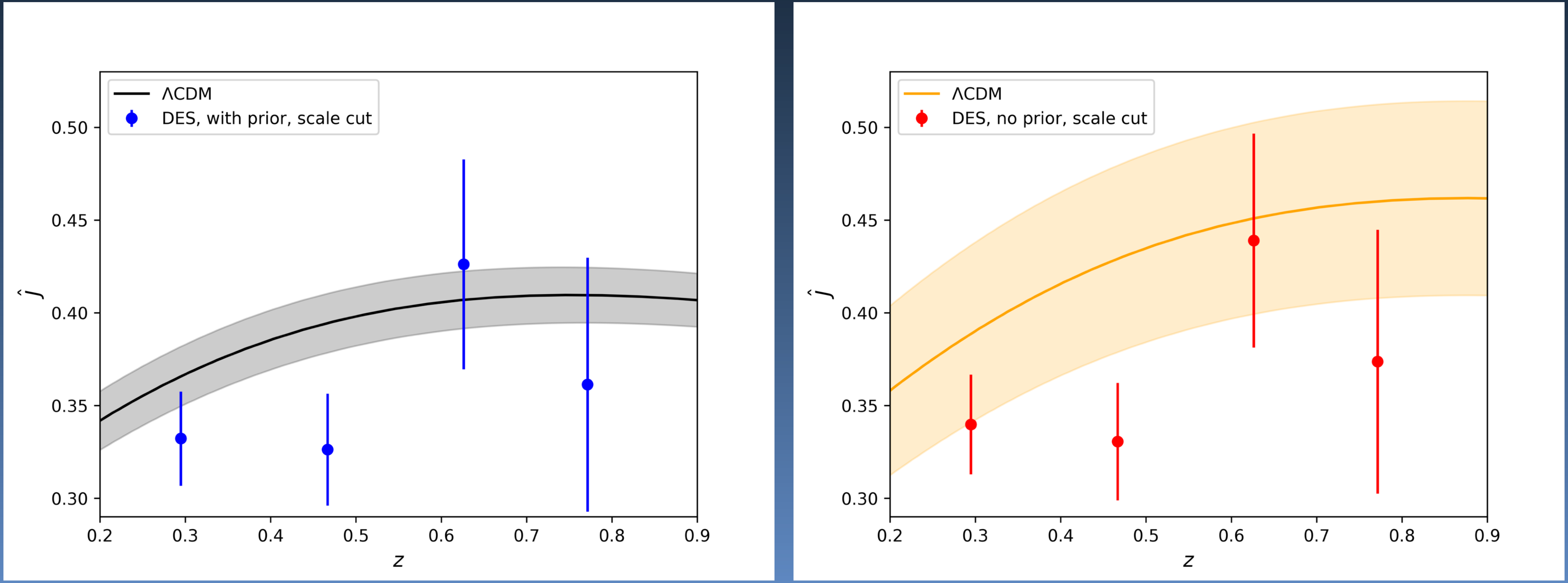
(Gravitational Redshift)

Cosmic Blueshift
YouTube Channel

(Includes outreach videos on arXiv:2312.06434 and 2311.14425)

Bonus slides: Gravitational Lensing

Measurement of $\hat{J}(z)$ with pessimistic scale cuts



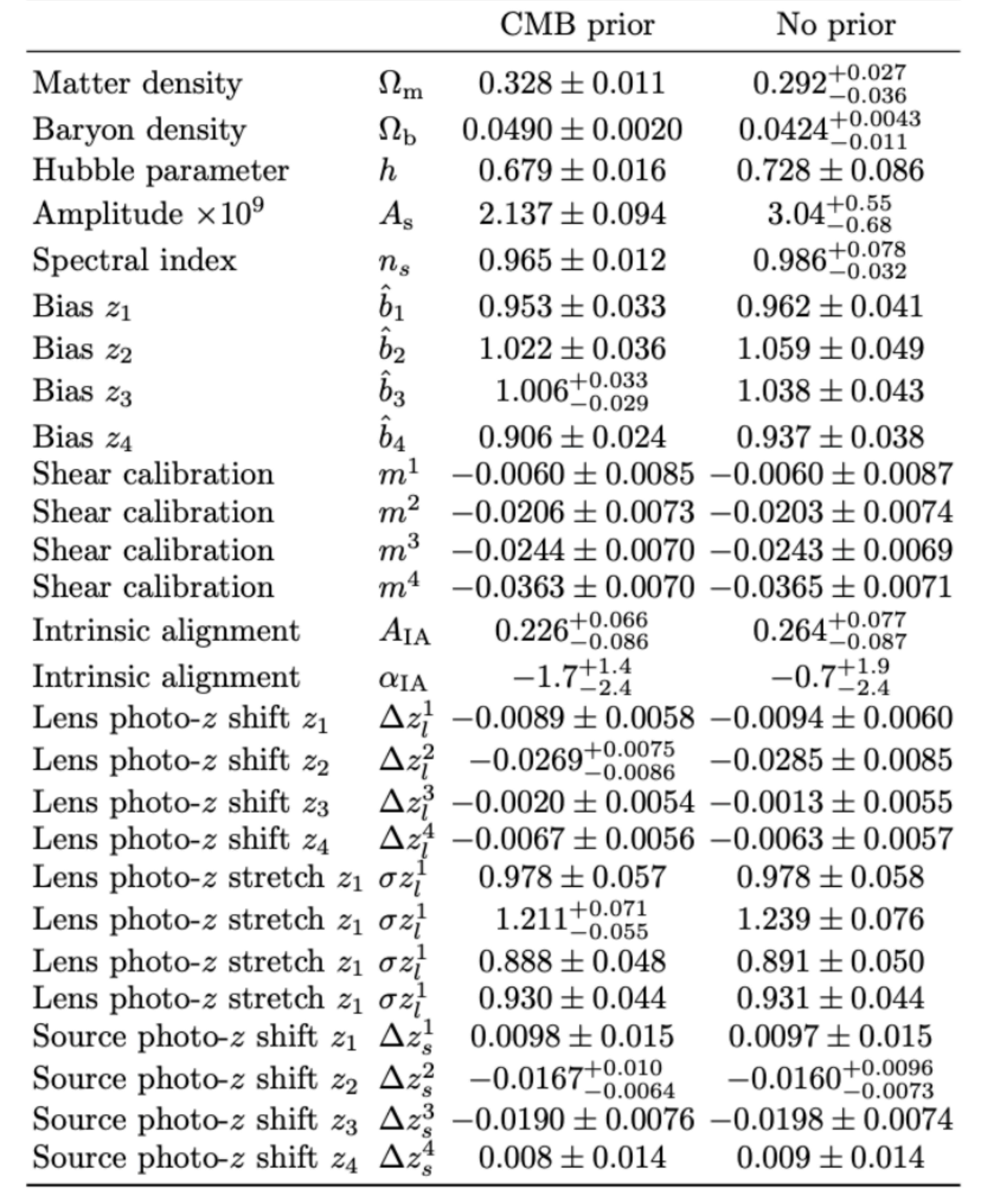
Measurement of $\hat{J}(z)$: Modelling

Modelling of observables and systematics:
Follow DES baseline analysis for galaxy clustering and galaxy-galaxy lensing, arXiv:2105.13549

We use the publicly available CosmoSIS software:
https://cosmosis.readthedocs.io/en/latest/

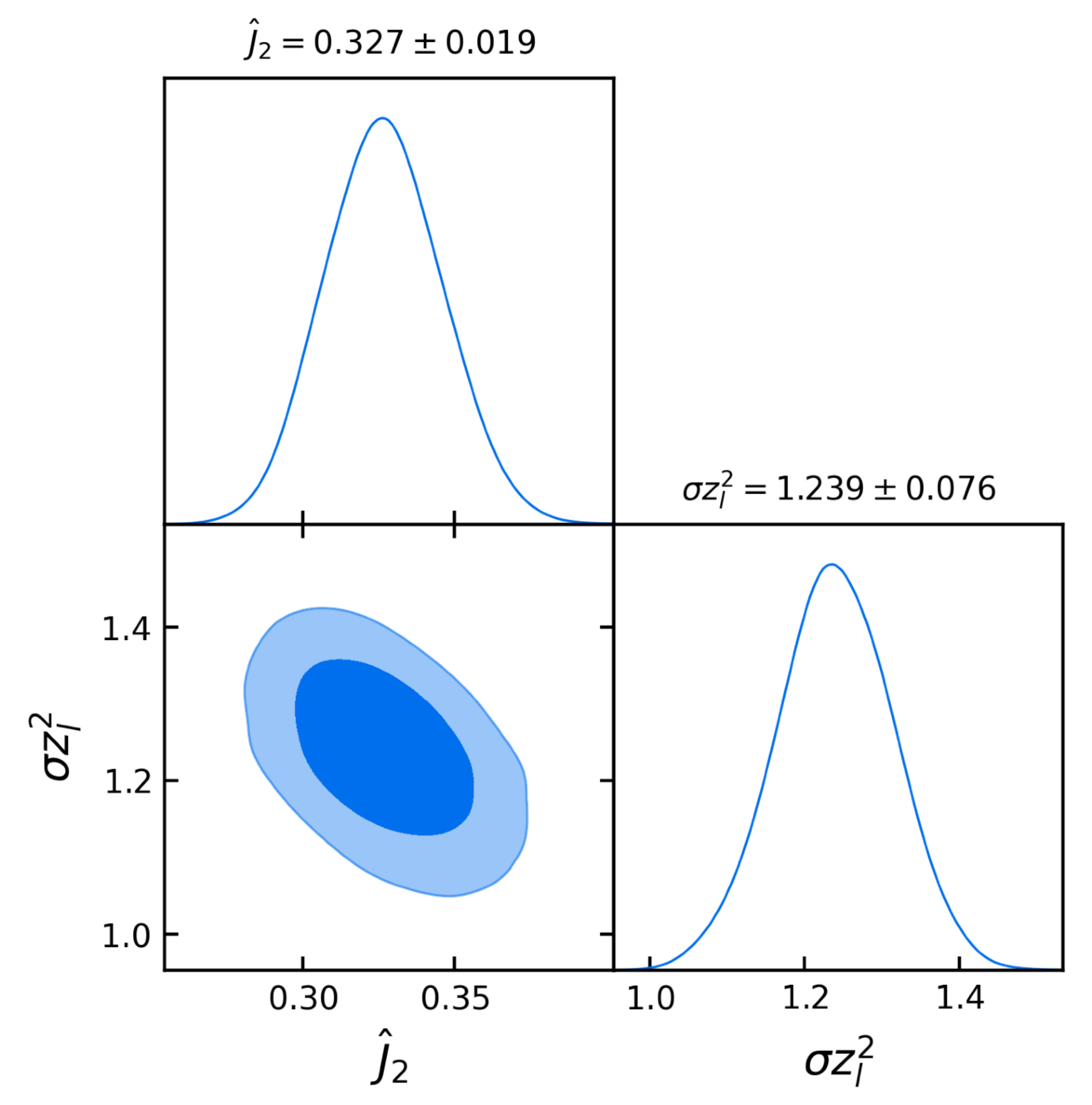
Intrinsic Alignments	Non-linear alignment model (as used by the DES collaboration for extended models, see arXiv:0705.0166)
Other nuisance parameters	Shear calibration, width and shift of the lens distribution, shift of the source distributions
Scale cuts	Optimistic: standard DES scale cuts of DES, see arXiv:2105.13546; pessimistic: only scales above 21 Mpc/h.
Sampling Algorithm	MultiNest (slight increase in error bars when switching to PolyChord)

Full set of cosmological & nuisance parameters



		CMB prior	No prior
Matter density	Ω_m	0.328 ± 0.011	$0.292^{+0.027}_{-0.036}$
Baryon density	Ω_b	0.0490 ± 0.0020	$0.0424^{+0.0043}_{-0.011}$
Hubble parameter	h	0.679 ± 0.016	0.728 ± 0.086
Amplitude $\times 10^9$	A_s	2.137 ± 0.094	$3.04^{+0.55}_{-0.68}$
Spectral index	n_s	0.965 ± 0.012	$0.986^{+0.078}_{-0.032}$
Bias z_1	$\hat{b}_1$	0.953 ± 0.033	0.962 ± 0.041
Bias z_2	$\hat{b}_2$	1.022 ± 0.036	1.059 ± 0.049
Bias z_3	$\hat{b}_3$	$1.006^{+0.033}_{-0.029}$	1.038 ± 0.043
Bias z_4	$\hat{b}_4$	0.906 ± 0.024	0.937 ± 0.038
Shear calibration	m^1	-0.0060 ± 0.0085	-0.0060 ± 0.0087
Shear calibration	m^2	-0.0206 ± 0.0073	-0.0203 ± 0.0074
Shear calibration	m^3	-0.0244 ± 0.0070	-0.0243 ± 0.0069
Shear calibration	m^4	-0.0363 ± 0.0070	-0.0365 ± 0.0071
Intrinsic alignment	A_IA	$0.226^{+0.066}_{-0.086}$	$0.264^{+0.077}_{-0.087}$
Intrinsic alignment	α_IA	$-1.7^{+1.4}_{-2.4}$	$-0.7^{+1.9}_{-2.4}$
Lens photo-z shift z_1	Δz_l^1	-0.0089 ± 0.0058	-0.0094 ± 0.0060
Lens photo-z shift z_2	Δz_l^2	$-0.0269^{+0.0075}_{-0.0086}$	-0.0285 ± 0.0085
Lens photo-z shift z_3	Δz_l^3	-0.0020 ± 0.0054	-0.0013 ± 0.0055
Lens photo-z shift z_4	Δz_l^4	-0.0067 ± 0.0056	-0.0063 ± 0.0057
Lens photo-z stretch z_1	σz_l^1	0.978 ± 0.057	0.978 ± 0.058
Lens photo-z stretch z_1	σz_l^1	$1.211^{+0.071}_{-0.055}$	1.239 ± 0.076
Lens photo-z stretch z_1	σz_l^1	0.888 ± 0.048	0.891 ± 0.050
Lens photo-z stretch z_1	σz_l^1	0.930 ± 0.044	0.931 ± 0.044
Source photo-z shift z_1	Δz_s^1	0.0098 ± 0.015	0.0097 ± 0.015
Source photo-z shift z_2	Δz_s^2	$-0.0167^{+0.010}_{-0.0064}$	$-0.0160^{+0.0096}_{-0.0073}$
Source photo-z shift z_3	Δz_s^3	-0.0190 ± 0.0076	-0.0198 ± 0.0074
Source photo-z shift z_4	Δz_s^4	0.008 ± 0.014	0.009 ± 0.014

Degeneracy of $\hat{J}$ with photo-z stretch



We would need to lower σz_l to a value of 0.94 to have 1σ agreement of $\hat{J}_2$ with the ΛCDM prediction.

$\Rightarrow$ Would be in tension with the officially provided DES priors from calibration!

Bonus slides: Gravitational Redshift

Galaxy number density with relativistic effects

Standard terms

Gravitational redshift

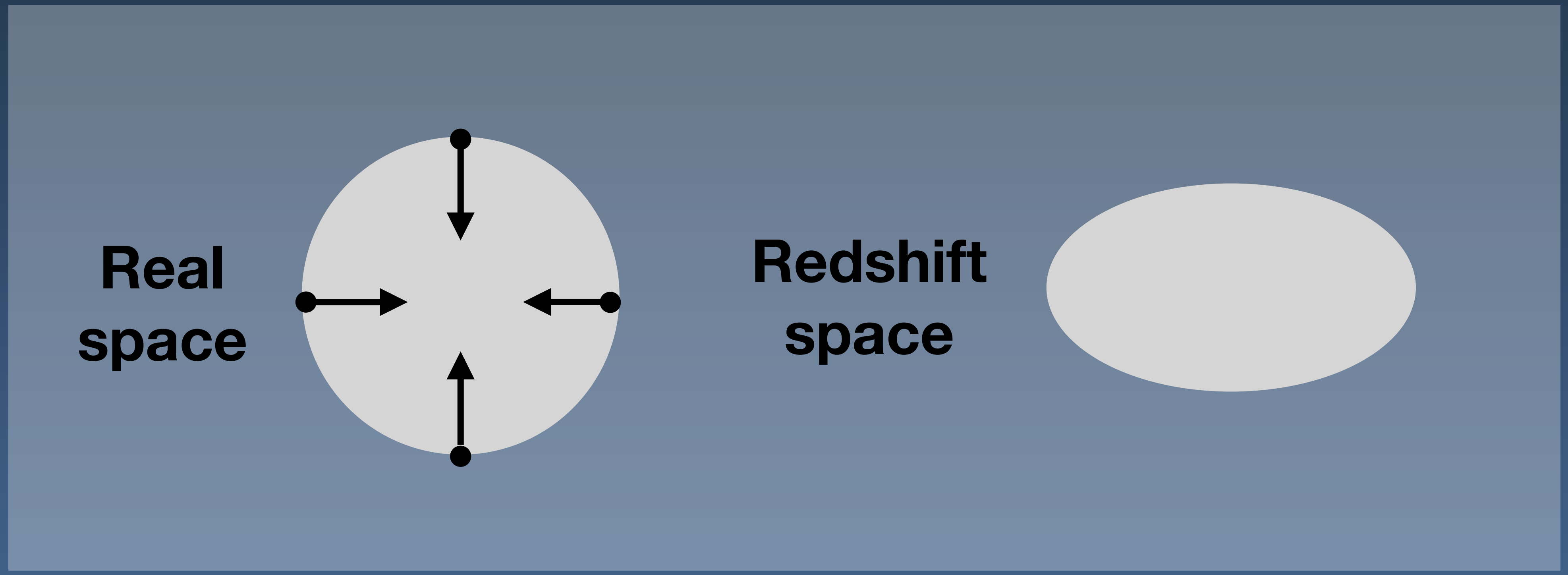
$$\Delta(\mathbf{n},z) = \boxed{b\,\delta - \frac{1}{\mathcal{H}}\partial_r(\mathbf{V}\cdot\mathbf{n})} + \boxed{\frac{1}{\mathcal{H}}\partial_r\Psi} + \boxed{\frac{1}{\mathcal{H}}\dot{\mathbf{V}}\cdot\mathbf{n} + \mathbf{V}\cdot\mathbf{n}}$$

$$\boxed{+\left(5s+\frac{5s-2}{\mathcal{H}r}-\frac{\dot{\mathcal{H}}}{\mathcal{H}^2}+f^{\text{evol}}\right)\mathbf{V}\cdot\mathbf{n}}$$

Doppler terms

Standard RSD vs. Gravitational Redshift

Standard Redshift-Space Distortions (RSD)

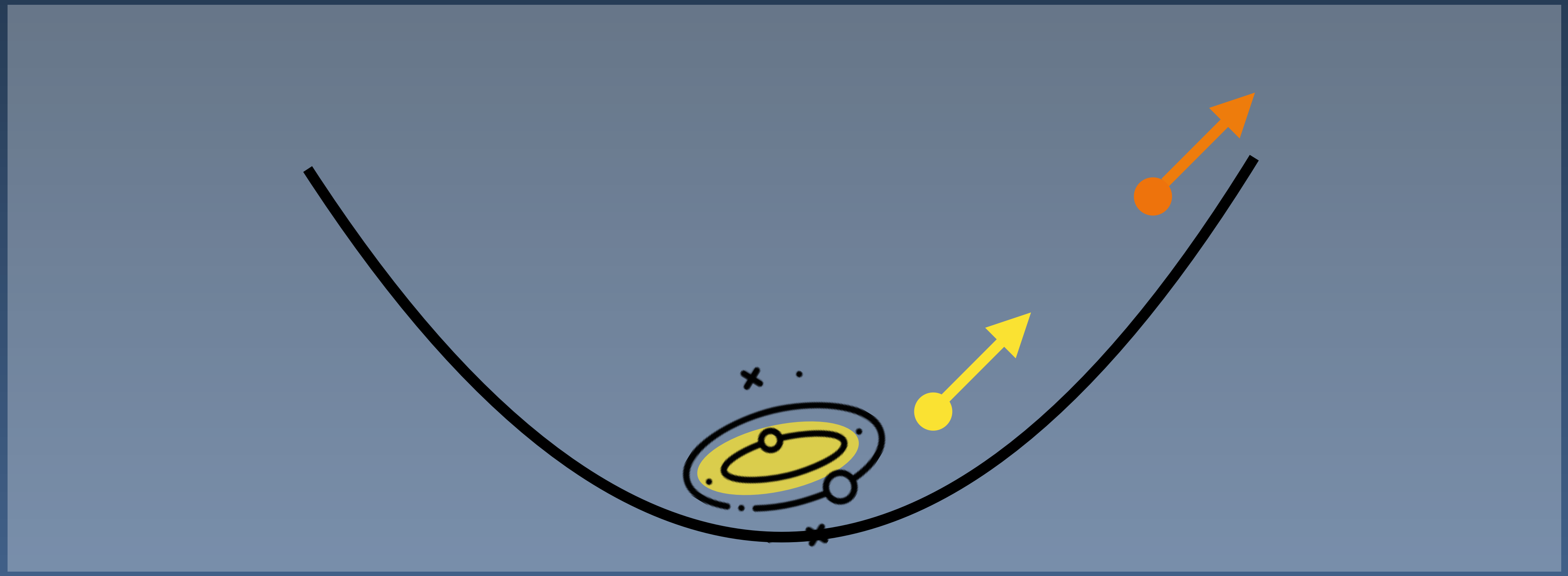


Standard effect, caused by peculiar velocities of galaxies.

Causes even multipoles ($l = 0, 2, 4$) in the galaxy correlation function.

Has been measured many times.

Gravitational Redshift



Relativistic correction, sensitive directly to the gravitational potential Ψ.

Causes a dipole ($l = 1$) in the galaxy correlation function.

Will be measurable with SKA phase 2!