Modified Gravity vs Dark Interactions: Settling the Dispute through the Distortion of Time

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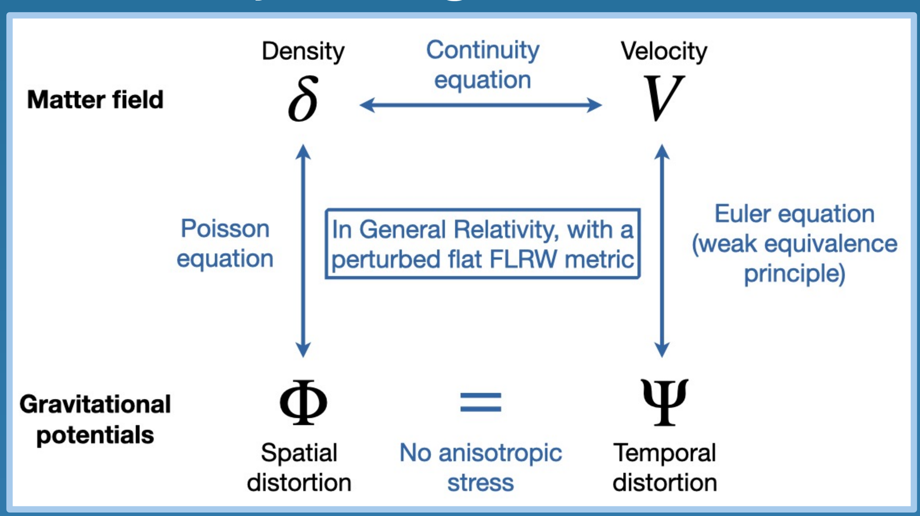
Motivation

Within linear perturbation theory, the Universe can be described with **four fields**. We can learn about fundamental physics on cosmological scales by **testing the relations** among them.

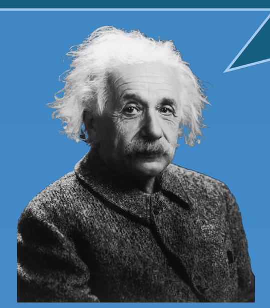


The standard cosmological model involves two obscure components, **dark energy and dark matter** (DM), motivating the search for deviations from this standard picture.

Two modified scenarios

Modified gravity: deviations from the **Einstein** equations of General Relativity.

Interactions in the dark sector: modifications in the **Euler** equation for DM.



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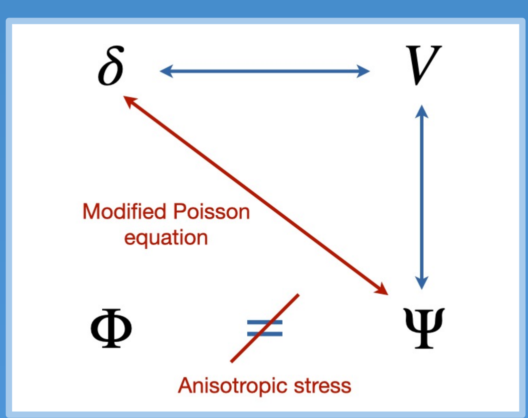
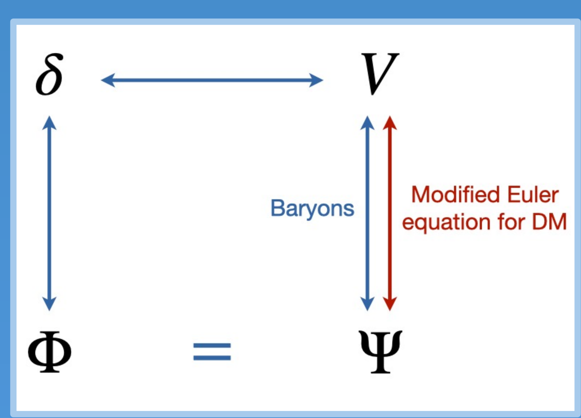




Key question

"Can cosmological observations distinguish between gravity modifications and interactions in the dark sector?"

Two **representative models** with an additional scalar field:

	Generalized Brans-Dicke (GBD)	**Coupled Quintessence (CQ)**
Coupling to	All matter	DM only
Coupling strength	β_1	β_2
Scalar field mass	m_1	m_2

Symmetron model: modifications relevant at late times $(z<1)$.

Standard observables

Growth of cosmic structure

In both scenarios, **density perturbations** evolve according to

$$\ddot{\delta} + \mathcal{H}\dot{\delta} = 4\pi G\left[1 + \frac{2Bk^2}{8\pi G(a^2 m_i^2 + k^2)}\right] a^2\rho\delta$$

with
$$\begin{cases} B^{\rm GBD} = \beta_1^2 \\ B^{\rm CQ} = \beta_2^2\left(\frac{\rho_{\rm DM}}{\rho}\right)^2\left(\frac{\delta_{\rm DM}}{\delta}\right)\end{cases}$$
yielding an **elliptical constraint** on $B^{\rm GBD} + B^{\rm CQ}$

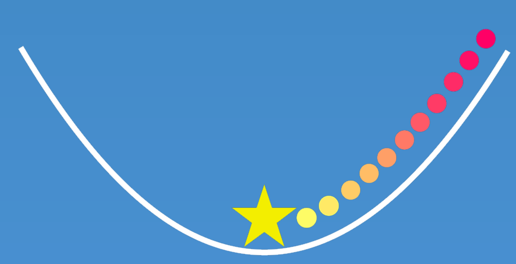
Weak lensing

Weak lensing (WL) **cannot distinguish** between the two scenarios, since in both cases it provides a constraint on the same relation:

$$k^2(\Phi + \Psi) = -8\pi G\rho\delta$$

Deus ex machina

A new observable comes to the rescue: **gravitational redshift.**



Photons emitted by galaxies lose energy in escaping the local gravitational potential, leading to an additional redshift contribution.

We can **extract this signal** by measuring **two-point correlations** of the galaxy number counts fluctuations $\Delta(\hat{\mathbf{n}}, z)$:

$$\Delta(\hat{\mathbf{n}}, z) = \delta - \frac{1}{\mathcal{H}}\partial_r(\mathbf{V}\cdot\hat{\mathbf{n}}) + \frac{1}{\mathcal{H}}\partial_r\Psi + \text{Doppler terms}$$

Standard terms: density and redshift-space distortions (RSD)	Relativistic corrections, including gravitational redshift
• Give a **symmetric** contribution to the correlation. • Probe the growth rate of structure.	• Give an **anti-symmetric** contribution. • Measurable by upcoming / future surveys (DESI, SKA2).

Gravitational redshift gives a measurement of the **temporal distortion** Ψ, providing a direct test of the Euler equation!

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Numerical proof

1. Generate a **mock data vector** with one kind of modification.
2. Perform a **fit** leaving the parameters of both models free.

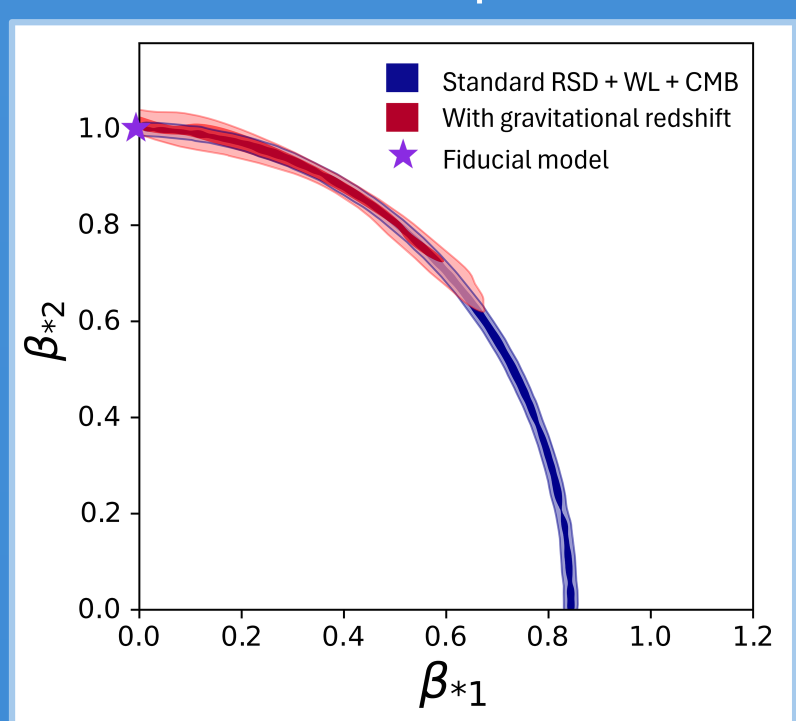
SKA2 forecast: RSD gives the expected elliptical constraint, while the inclusion of gravitational redshift breaks the degeneracy up to

$\beta_{*2} \sim 0.7$ for m_i = 0.1Mpc^{-1} $\beta_{*2} \sim 0.4$ for m_i = 0.01Mpc^{-1}

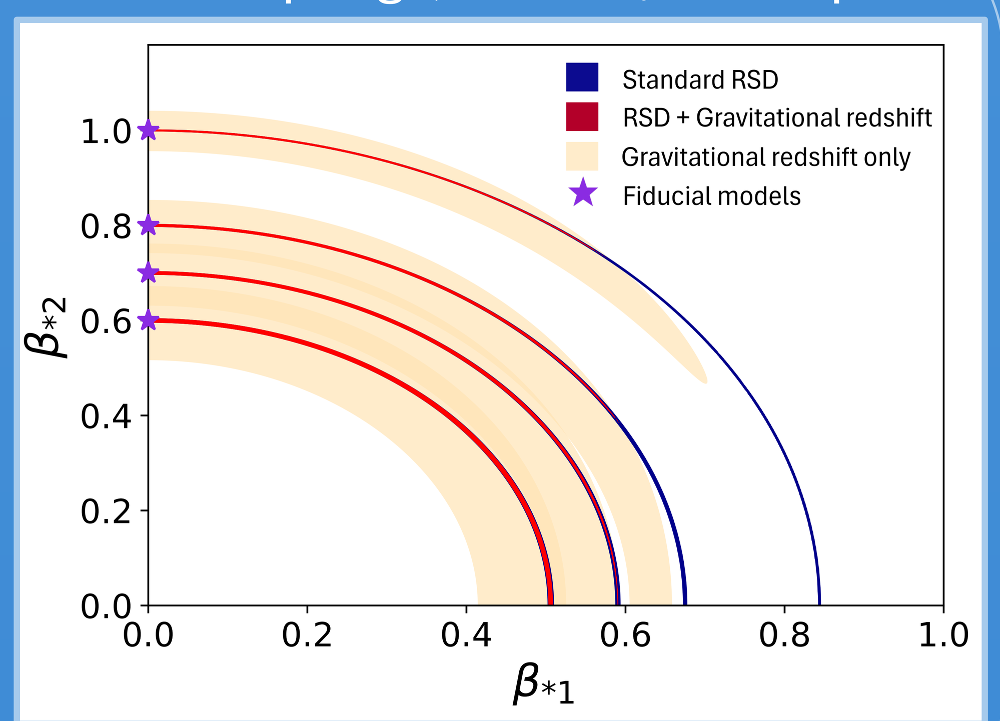
Physical intuition

The **growth of structure**, probed by RSD, can be modified in the same way by a change in the depth of the gravitational potentials (GBD) or by a fifth force (CQ). **Gravitational redshift** breaks the degeneracy by probing how photons escape from the potentials.

Constraints on the present values of the couplings, with m_i = 0.1Mpc^{-1}



Viable CQ fiducial $(\beta_{*2} = 1)$



Varying the coupling strength

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