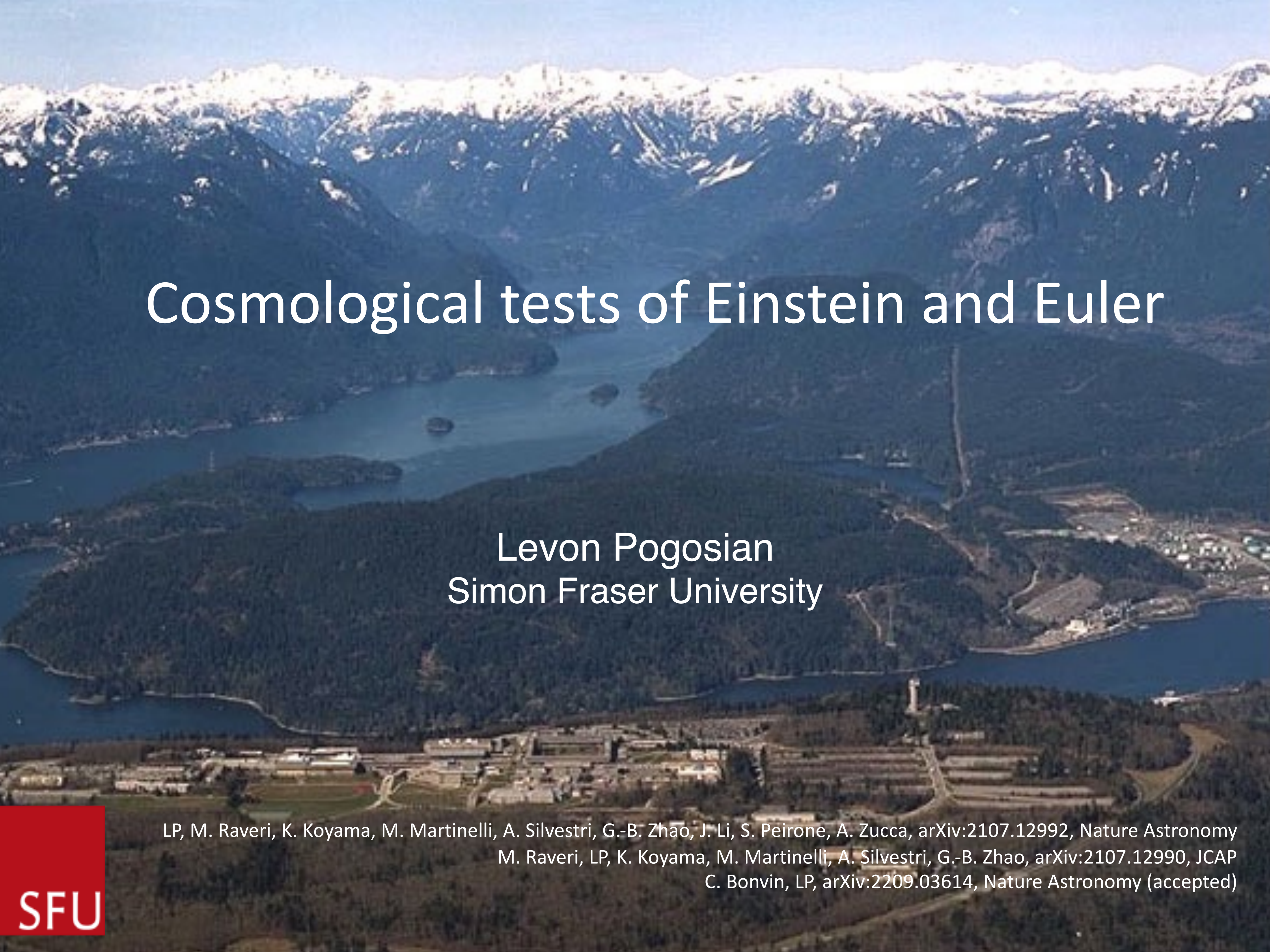

Cosmological tests of Einstein and Euler

Levon Pogosian
Simon Fraser University

LP, M. Raveri, K. Koyama, M. Martinelli, A. Silvestri, G.-B. Zhao, J. Li, S. Peirone, A. Zucca, arXiv:2107.12992, Nature Astronomy
M. Raveri, LP, K. Koyama, M. Martinelli, A. Silvestri, G.-B. Zhao, arXiv:2107.12990, JCAP
C. Bonvin, LP, arXiv:2209.03614, Nature Astronomy (accepted)

The phenomenology of modified gravity

Expansion history:
effective dark energy density X(a)
(X(a) = 1 in LCDM)

$$\frac{H^2}{H_0^2} = \frac{\Omega_{\rm r}}{a^4} + \frac{\Omega_{\rm M}}{a^3} + \Omega_{\rm DE} X(a)$$

Linear perturbations:
Modified Einstein equations
(μ = Σ = γ = 1 in LCDM)

$$\begin{aligned} -k^2\Psi &= 4\pi\ \mu(a,k)G\ a^2\delta\rho \\ \Phi &= \gamma(a,k)\ \Psi \\ -k^2\left(\frac{\Phi+\Psi}{2}\right) &= 4\pi\ \Sigma(a,k)G\ a^2\delta\rho \end{aligned}$$

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Modified Einstein equations

(μ = Σ = γ = 1 in LCDM)

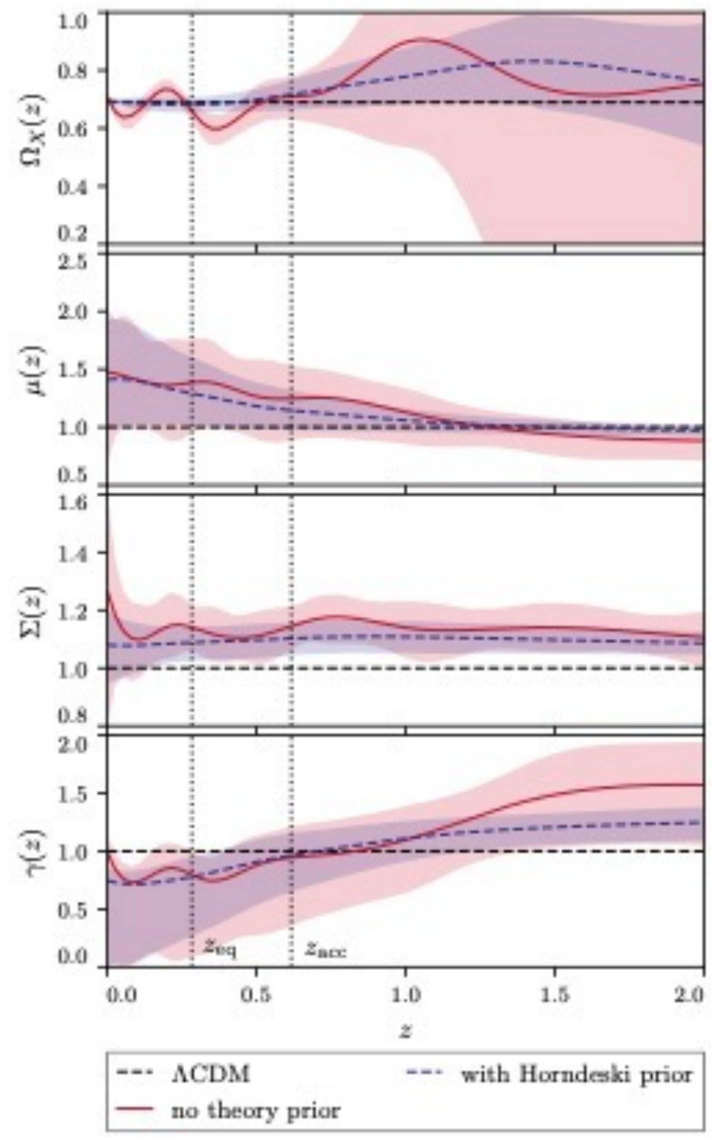
$$\begin{aligned} -k^2\Psi &= 4\pi\, \underbrace{\mu(a,k)G}_{\text{"}G_{matter}\text{"}}\, a^2\delta\rho \\ \Phi &= \gamma(a,k)\,\Psi \\ -k^2\left(\frac{\Phi+\Psi}{2}\right) &= 4\pi\, \underbrace{\Sigma(a,k)G}_{\text{"}G_{light}\text{"}}\, a^2\delta\rho \end{aligned}$$

A smoking gun of new gravitational physics: $\boxed{G_{matter} \neq G_{light} \quad \text{or} \quad \Phi \neq \Psi}$

(the "gravitational slip" γ is also known as η)

Reconstructing gravity from Planck+DES+RSD+BAO+SN

- First simultaneous reconstruction of $\mu(a)$, $\Sigma(a)$ and $\Omega_X(a)$
- Did it with and without a Horndeski prior: a way to separate features consistent with theory from potential systematics
- Current data can constrain 15 eigenmodes
- Late-time modified gravity is unlikely to resolve the tensions
- Implications for scalar-tensor theories

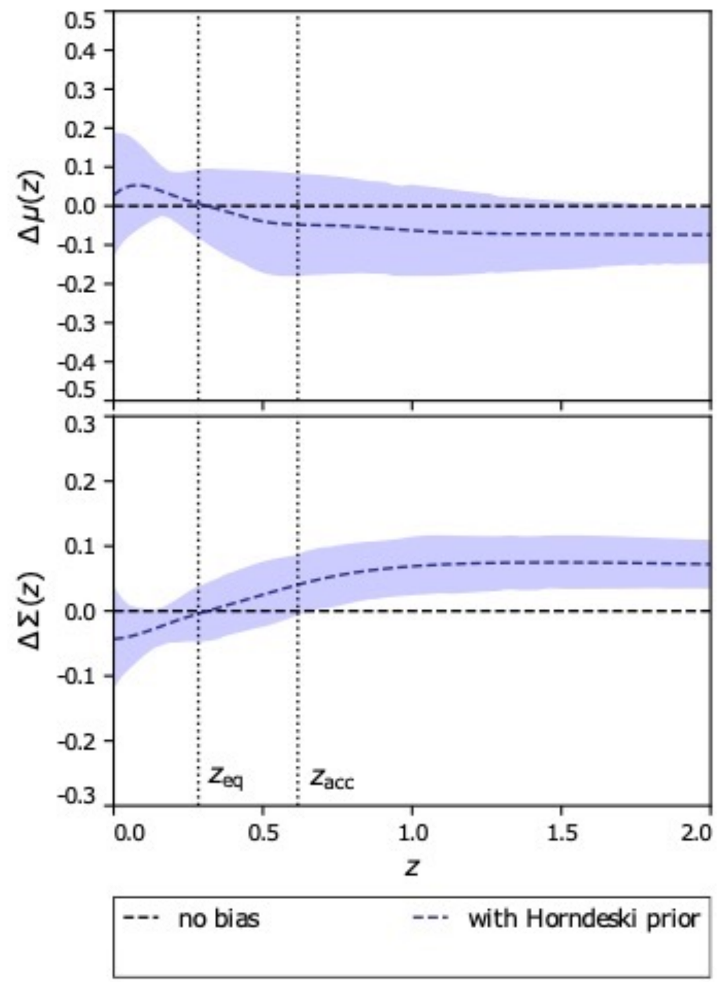


Imprints of cosmological tensions in reconstructed gravity, LP, M. Raveri, K. Koyama, M. Martinelli, A. Silvestri, G.-B. Zhao, J. Li, S. Peirone, A. Zucca, arXiv:2107.12992, Nature Astronomy (2022)
Principal reconstructed modes of dark energy and gravity, M. Raveri, LP, K. Koyama, M. Martinelli, A. Silvestri, G.-B. Zhao, arXiv:2107.12990, JCAP

How ~~good~~ bad are common parametrizations?

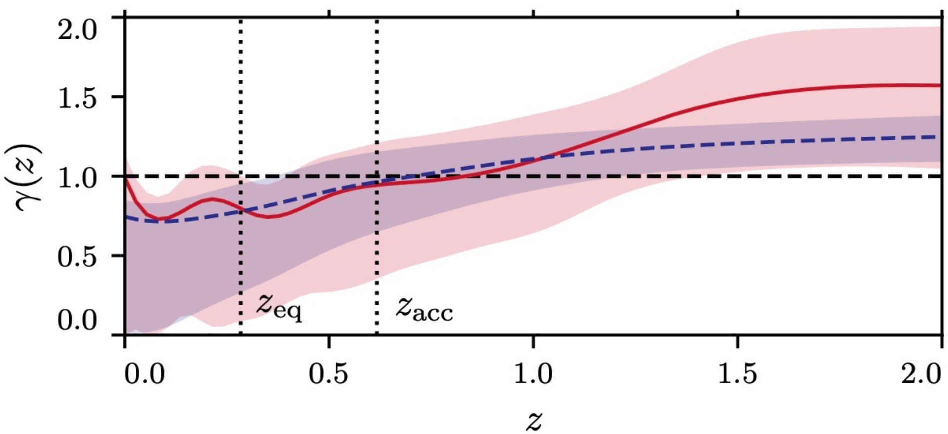
$$\mu(a) = 1 + \mu_0 \Omega_{\rm DE}(a)$$

$$\Sigma(a) = 1 + \Sigma_0 \Omega_{\rm DE}(a)$$



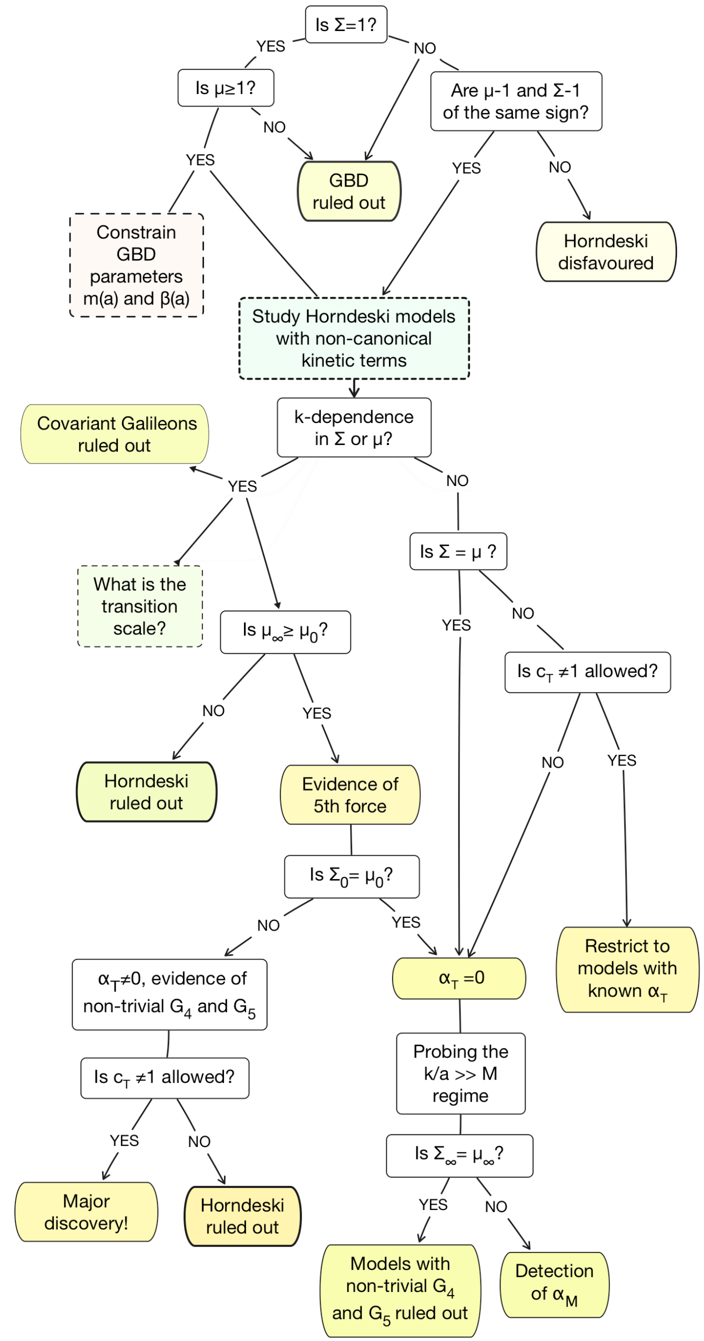
M. Raveri, LP, K. Koyama, M. Martinelli, A. Silvestri, G.-B. Zhao, arXiv:2107.12990, JCAP

What can cosmology tell us about gravity? Constraining Horndeski with Σ and μ

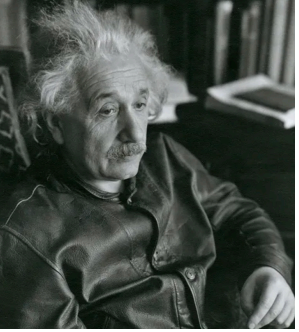


Hints from the reconstruction:

- LCDM is under some tension (but we knew it already)
- γ >1 would rule out Brans-Dicke theories
- $\Sigma \neq \mu$, or $\gamma \neq 1$, can only be due to $c_T \neq 1$ or a fifth force, would rule out Cubic Galileons
- No violation of $(\Sigma - 1)(\mu - 1) \geq 0$ expected in Horndeski theories



LP & Silvestri, arXiv:1606.05339, PRD



Modified Einstein vs modified Euler

The above reconstruction assumed that all matter (CDM and baryons) follow the same geodesics, *i.e.* the modified gravity affects all matter universally

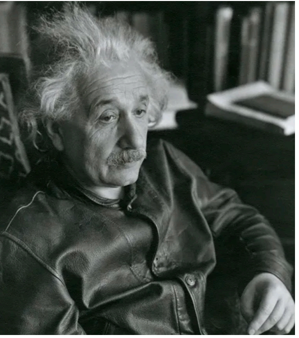
What if gravity was not modified, but there was a force acting only on CDM? Could we tell the difference?

A case study: Generalized Brans-Dicke vs Coupled Quintessence

$$S^{\rm GBD} = \int \mathrm{d}^4\sqrt{-g}\left[\frac{A^{-2}(\phi)}{16\pi G}R - \frac{1}{2}\partial_\mu\phi\,\partial^\mu\phi - V(\phi) + \mathcal{L}_{\rm m}(\psi_{\rm DM},\psi_{\rm SM},g_{\mu\nu})\right]$$

$$S^{\rm CQ} = \int \mathrm{d}^4\sqrt{-g}\left[\frac{1}{16\pi G}R - \frac{1}{2}\partial_\mu\phi\,\partial^\mu\phi - V(\phi) + \mathcal{L}_{\rm SM}(\psi_{\rm SM},g_{\mu\nu}) + \mathcal{L}_{\rm DM}(\psi_{\rm DM},A^2(\phi)g_{\mu\nu})\right]$$

C. Bonvin, LP, arXiv:2209.03614, Nature Astronomy (accepted)



Modified Einstein vs modified Euler

(quasistatic approximation)

Generalized Brans-Dicke (GBD)

$$k^2\Phi = -4\pi G a^2\left(\rho_b\delta_b + \rho_c\delta_c\right) - \beta k^2\delta\phi \qquad (21)$$

$$k^2(\Phi - \Psi) = -2\beta k^2\delta\phi \qquad (22)$$

$$\dot\delta_b + \theta_b = 0 \qquad (23)$$

$$\dot\theta_b + \mathcal{H}\theta_b = k^2\Psi \qquad (24)$$

$$\dot\delta_c + \theta_c = 0 \qquad (25)$$

$$\dot\theta_c + \mathcal{H}\theta_c = k^2\Psi \qquad (26)$$

$$\delta\phi = -\frac{\beta(\rho_c\delta_c + \rho_b\delta_b)}{m^2 + k^2/a^2} \qquad (27)$$

$$\Box\phi = V_{,\phi} + \beta(\rho_c + \rho_b) \equiv V^{\text{eff}}{}_{,\phi} \qquad (28)$$

$$\ddot\delta + \mathcal{H}\dot\delta = 4\pi G a^2\rho\delta\left[1 + \frac{2\tilde\beta^2 k^2}{a^2m^2 + k^2}\right] \qquad (29)$$

Coupled Quintessence (CQ)

$$k^2\Phi = -4\pi G a^2\left(\rho_b\delta_b + \rho_c\delta_c\right) \qquad (30)$$

$$k^2(\Phi - \Psi) = 0 \qquad (31)$$

$$\dot\delta_b + \theta_b = 0 \qquad (32)$$

$$\dot\theta_b + \mathcal{H}\theta_b = k^2\Psi \qquad (33)$$

$$\dot\delta_c + \theta_c = 0 \qquad (34)$$

$$\dot\theta_c + (\mathcal{H} + \beta\dot\phi)\theta_c = k^2\Psi + k^2\beta\delta\phi \qquad (35)$$

$$\delta\phi = -\frac{\beta\rho_c\delta_c}{m^2 + k^2/a^2} \qquad (36)$$

$$\Box\phi = V_{,\phi} + \beta\rho_c \equiv V^{\text{eff}}{}_{,\phi} \qquad (37)$$

$$\ddot\delta + \mathcal{H}\dot\delta = 4\pi G a^2\rho\delta\left[1 + \frac{2\tilde\beta^2 k^2}{a^2m^2 + k^2}\left(\frac{\rho_c}{\rho}\right)^2\left(\frac{\delta_c}{\delta}\right)\right] \qquad (38)$$

$$G_{\text{eff}}^{\text{GBD}} = G\left[1 + \frac{2\tilde\beta^2 k^2}{a^2m^2 + k^2}\right]$$

$$G_{\text{eff}}^{\text{CQ}} = G\left[1 + \frac{2\tilde\beta^2 k^2}{a^2m^2 + k^2}\left(\frac{\rho_c}{\rho}\right)^2\left(\frac{\delta_c}{\delta}\right)\right]$$

$\Sigma = A^2 \simeq 1,\ \mu > 1,\ \eta < 1$

$\Sigma = \mu = \eta = 1$

C. Bonvin, LP, arXiv:2209.03614, Nature Astronomy (accepted)

Theory vs practice

In theory, equations suggest that η could be the smoking gun

- Weak lensing probes $\Phi + \Psi$
- Redshift space distortions probe θ_b , hence Ψ

$$\dot{\theta}_b + \mathcal{H}\theta_b = k^2\Psi$$

- Combine WL and RSD to measure η

Theory vs practice

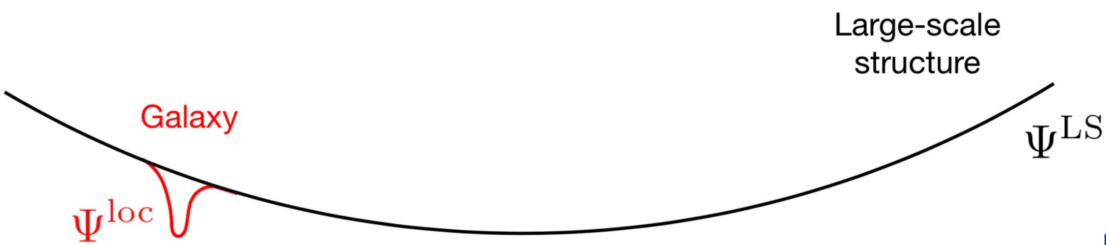
In theory, equations suggest that *η* could be the smoking gun

- Weak lensing probes *Φ + Ψ*
- Redshift space distortions probe θ_b , hence *Ψ*

$$\dot{\theta}_b + \mathcal{H}\theta_b = k^2\Psi$$

- Combine WL and RSD to measure *η*

In practice, the baryons we see are confined to galaxies made mostly of CDM



RSD of galaxies is not a measure of the true *Ψ*

$$\text{GBD}: \quad \dot{\theta}_g + \mathcal{H}\theta_g = k^2\Psi^{\rm LS},$$

$$\text{CQ}: \quad \dot{\theta}_g + \mathcal{H}\theta_g = k^2\Psi^{\rm LS} + \frac{\rho_c}{\rho}k^2\beta\delta\phi \equiv k^2\Psi^{\rm eff}$$

C. Bonvin, LP, arXiv:2209.03614, Nature Astronomy (accepted)

Fitting μ and Σ to RSD+WL (assuming Euler is valid)

RSD: $$P^{\rm gal}(k,\mu_k,z) = \left(b^2+\mu_k^2 f\right)^2 P_{\delta\delta}(k,z)$$

WL: $$P^{(\Phi+\Psi)}(k,z) = 9H_0^4\Omega_m^2(1+z)^2\Sigma^2(k,z)P_{\delta\delta}(k,z)$$

Generalized Brans-Dicke

$$G_{\rm eff}^{\rm GBD} = G\left[1+\frac{2\tilde\beta^2k^2}{a^2m^2+k^2}\right]$$

$$\mu^{\rm fit} = \frac{G_{\rm eff}^{\rm GBD}}{G} = \mu^{\rm GBD} > 1\,,$$

$$\eta^{\rm fit} = \frac{2\Sigma^{\rm fit}}{\mu^{\rm fit}} - 1 = \frac{2}{\mu^{\rm fit}} - 1 = \eta^{\rm GBD} < 1$$

Coupled Quintessence

$$G_{\rm eff}^{\rm CQ} = G\left[1+\frac{2\tilde\beta^2k^2}{a^2m^2+k^2}\left(\frac{\rho_c}{\rho}\right)^2\left(\frac{\delta_c}{\delta}\right)\right]$$

$$\mu^{\rm fit} = \frac{G_{\rm eff}^{\rm CQ}}{G} > 1$$

$$\eta^{\rm fit} = \frac{2\Sigma^{\rm fit}}{\mu^{\rm fit}} - 1 = \frac{2}{\mu^{\rm fit}} - 1 < 1$$

One would measure $\eta < 1$ in both cases!

C. Bonvin, LP, arXiv:2209.03614, Nature Astronomy (accepted)

Is it possible to measure the true Ψ ?

Observed galaxy distribution

Redshift-space distortion

The "standard" terms: $$\Delta(\mathbf{n}, z) = \delta_g - \frac{1}{\mathcal{H}}\partial_r(\mathbf{V}_b \cdot \mathbf{n})$$

Leading order corrections:

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

Gravitational redshift

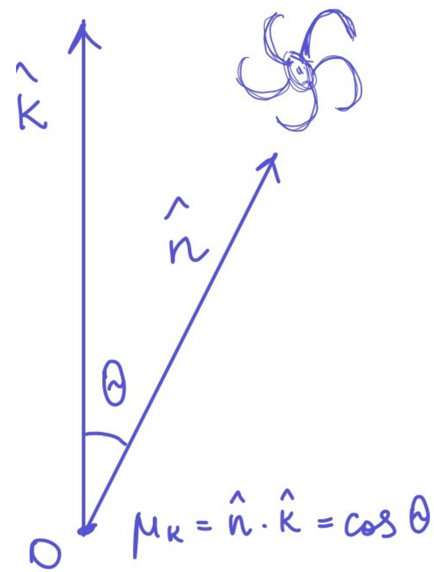
Yoo, Fitzpatrick, Zaldarriaga, Phys. Rev. D80, 083514 (2009)

Yoo, Phys. Rev. D82, 083508 (2010)

Bonvin, Durrer, Phys. Rev. D 84, 063505 (2011)

Challinor, Lewis, Phys. Rev. D84, 043516 (2011)

Observed galaxy distribution



The “standard” terms: $$\Delta(\mathbf{n}, z) = \delta_g - \frac{1}{\mathcal{H}}\partial_r(\mathbf{V}_b \cdot \mathbf{n})$$

In Fourier space: $$\Delta(\mathbf{k}, z) = b\,\delta(\mathbf{k}, z) - \frac{1}{\mathcal{H}}\mu_k^2\,\theta_b(\mathbf{k}, z)$$

Even power of μ_k

Leading order corrections:

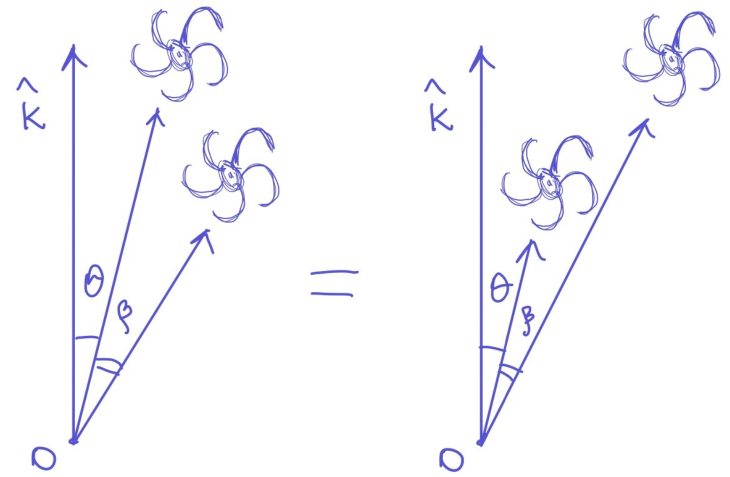
$$\Delta^{\rm rel}(\mathbf{n}, z) = \frac{1}{\mathcal{H}}\partial_r\Psi + \frac{1}{\mathcal{H}}\dot{\mathbf{V}} \cdot \mathbf{n} + \left(1 - 5s + \frac{5s-2}{\mathcal{H}r} - \frac{\dot{\mathcal{H}}}{\mathcal{H}^2} + f^{\rm evol}\right)\mathbf{V} \cdot \mathbf{n} + \ldots$$

$$\Delta^{\rm rel}(\mathbf{k}, z) = i\mu_k \left[-\frac{k}{\mathcal{H}}\Psi(\mathbf{k}, z) + \left(1 - 5s + \frac{5s-2}{\mathcal{H}r} - \frac{\dot{\mathcal{H}}}{\mathcal{H}^2} + f^{\rm evol}\right)\frac{\theta_g(\mathbf{k}, z)}{k} + \frac{\dot{\theta}_g(\mathbf{k}, z)}{k\mathcal{H}}\right] + \ldots$$

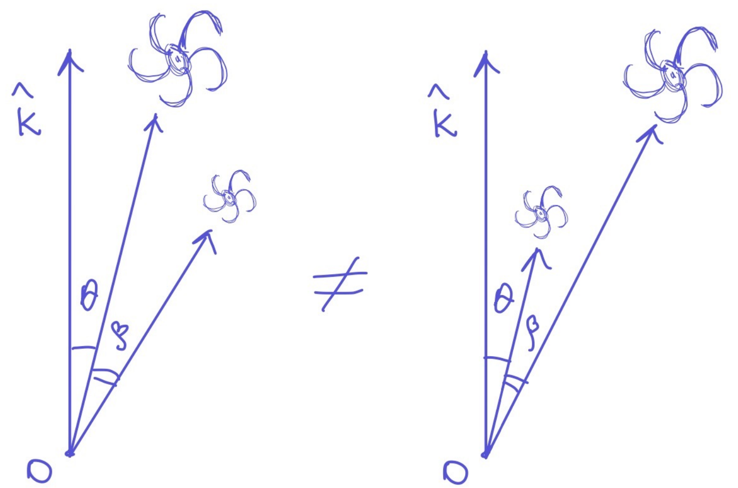
Odd power of μ_k

Can one isolate the dipolar distortion?

No, if galaxies are indistinguishable



Yes, if galaxies are distinguishable



C. Bonvin, L. Hui, E. Gaztanaga, arXiv:1309.1321, Phys Rev D

Multipole expansion of correlation between two galaxy populations: B (bright) and F (faint)

$$P^{\rm gal}_{\rm BF}(k,\mu_k,z)=\sum_\ell P^{(\ell)}_{\rm BF}(k,z)\mathcal{L}_\ell(\mu_k)$$

monopole: $$P^{(0)}_{\rm BF}(k,z)=\left[b_{\rm B}b_{\rm F}+\frac{1}{3}(b_{\rm B}+b_{\rm F})f_m+\frac{1}{5}f_m^2\right]P_{\delta\delta}(k,z)\,,$$

quadrupole: $$P^{(2)}_{\rm BF}(k,z)=\left[\frac{2}{3}(b_{\rm B}+b_{\rm F})f_m+\frac{4}{7}f_m^2\right]P_{\delta\delta}(k,z)\,,$$

hexadecapole: $$P^{(4)}_{\rm BF}(k,z)=\frac{8}{35}f_m^2P_{\delta\delta}(k,z)\,,$$

dipole: $$P^{(1)}_{\rm BF}(k,z)=i\,\alpha\left(f_m,\dot f_m,\Theta_{\rm B},\Theta_{\rm F}\right)\frac{\mathcal{H}}{k}P_{\delta\delta}(k,z)+\boxed{i(b_{\rm B}-b_{\rm F})\frac{k}{\mathcal{H}}P_{\delta\Psi}(k,z)},$$

octupole: $$P^{(3)}_{\rm BF}(k,z)=i\,\beta\left(f_m,\Theta_{\rm B},\Theta_{\rm F}\right)\frac{\mathcal{H}}{k}P_{\delta\delta}(k,z)\,,$$

C. Bonvin, P. Fleury, arXiv:1803.02771, JCAP
S. Castello, N. Grimm, C. Bonvin, arXiv:2204.11507, PRD
D. Sobral-Blanco and C. Bonvin, arXiv:2205.02567, MNRAS

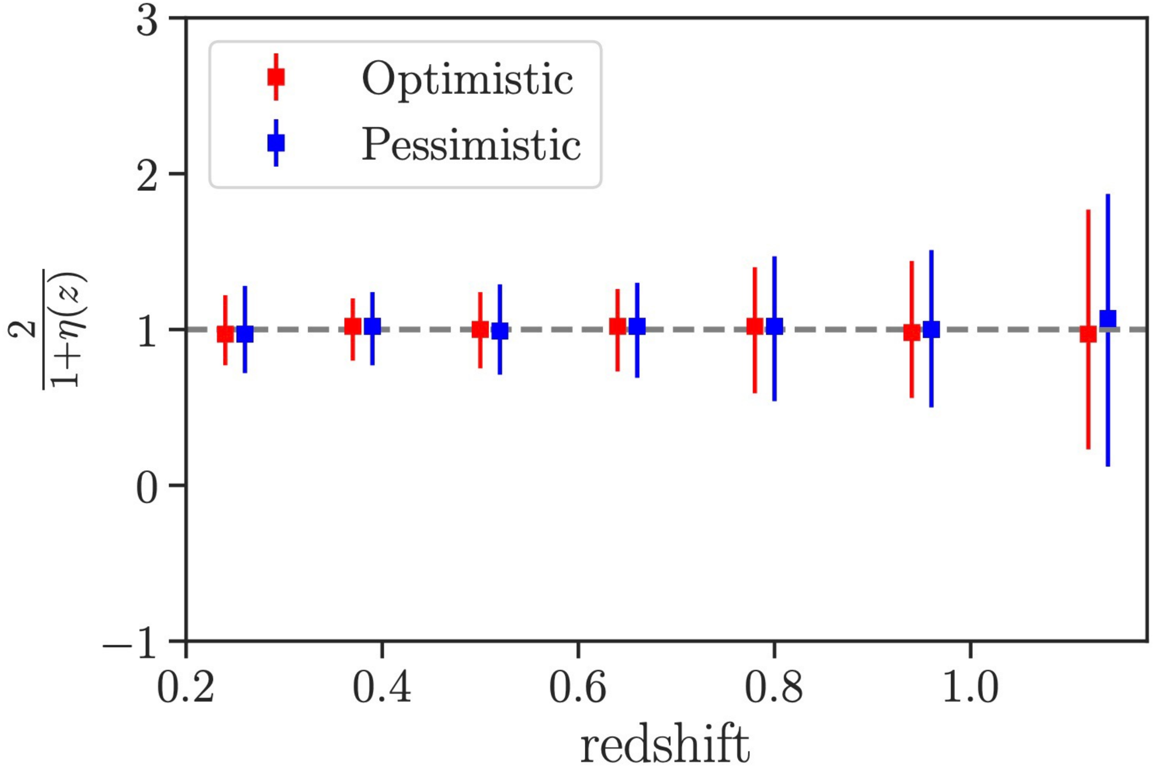
Galaxy – galaxy lensing correlation

Gravitational slip: $$\frac{P_{\delta(\Phi+\Psi)}(k,z)}{P_{\delta\Psi}(k,z)} = 1 + \eta(k,z)$$

Galaxy dipole: $P^{(1)}_{BF}$

C. Bonvin, LP, arXiv:2209.03614, Nature Astronomy (accepted)

LSST+SKA forecast



I. Tutusaus, D. Sobral-Blanco, C. Bonvin, arXiv:2209.08987, PRD

Summary

One can learn a lot more from today's data than w_0, w_a, Σ_0, μ_0
(the new version of MGCAMB includes the spline implementation)

Need to measure relativistic corrections (gravitational redshift) to distinguish a modification of gravity from a dark matter force. This may be possible with DESI, more likely with SKA, combined with LSST.