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Cosmic Growth, Gravitational Waves, and CMB

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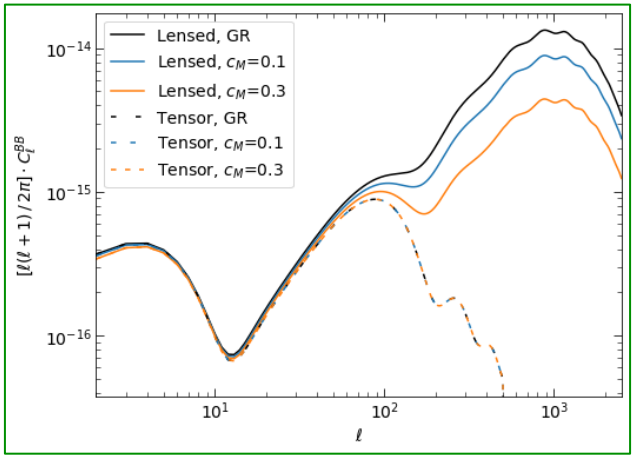
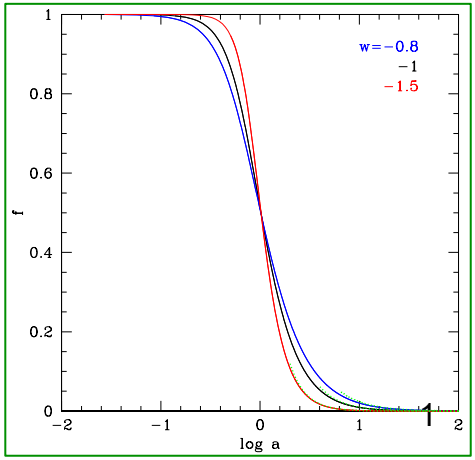
8th KIAS Workshop on Cosmology

5 November 2018





New Connections

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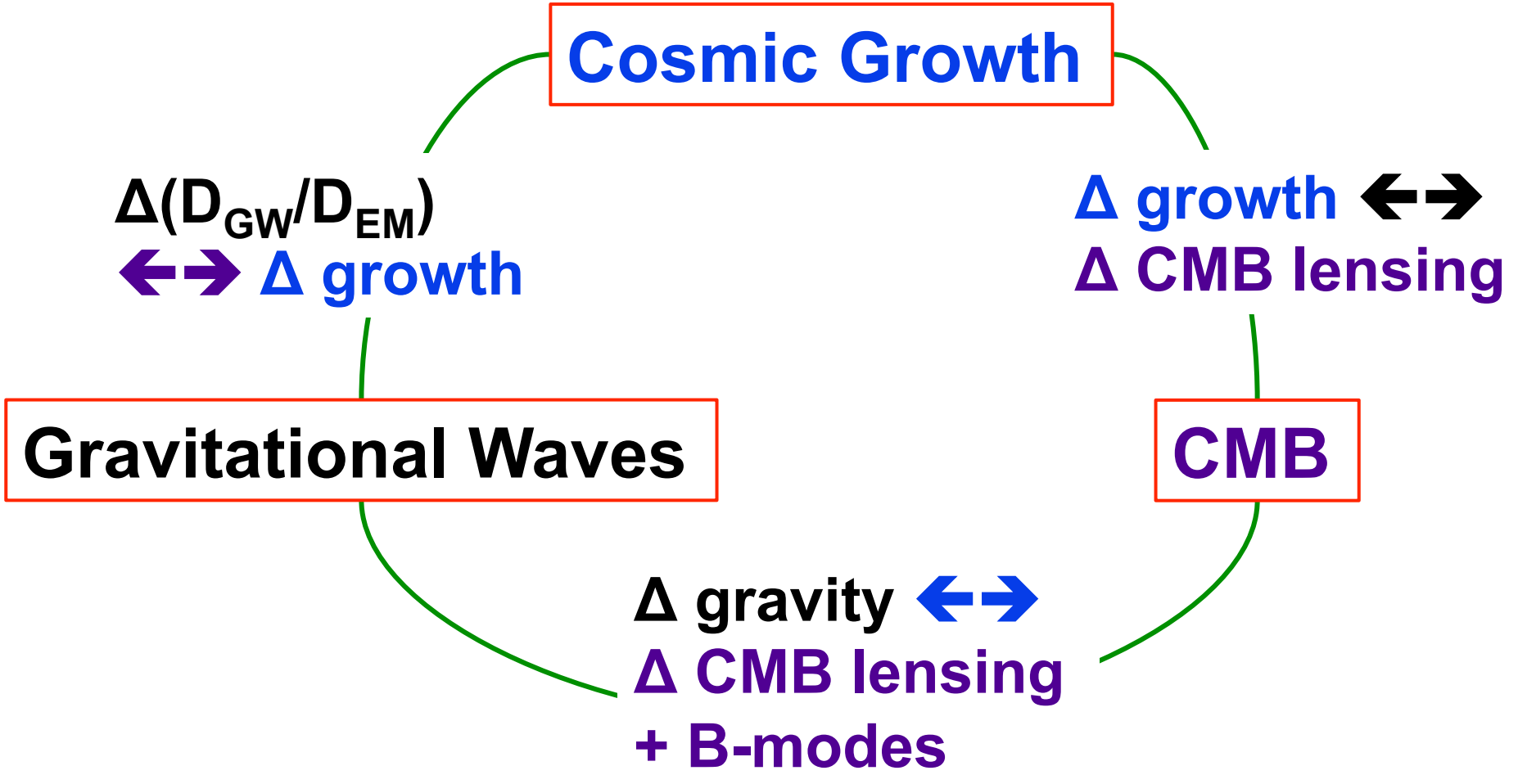
In just the last couple of years, we have fully recognized close connections:



Implications of $c_T = c$

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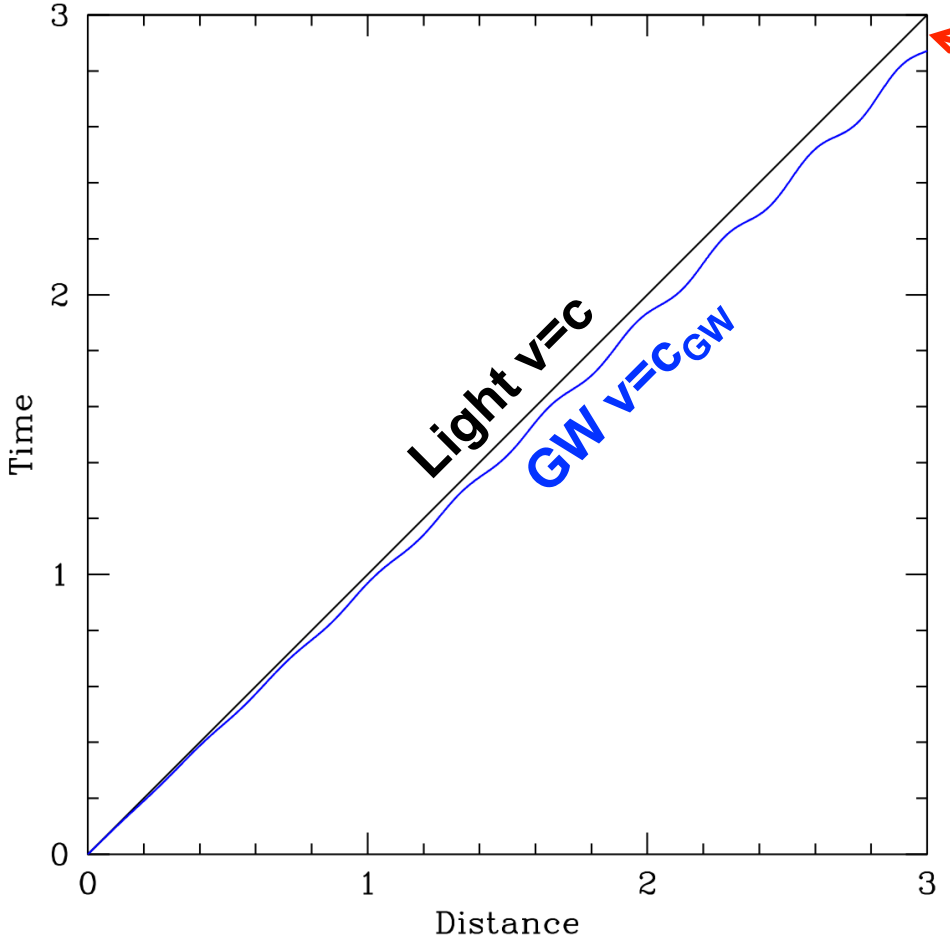
GW170817 + GRB1070817A: synchronicity of GW and photon arrival within 2 seconds after signal propagation for 130 My (400×10^{13} s) limits $c_T/c - 1 < 10^{-15}$.

Any theory with $c_T \neq c$ is essentially* ruled out.



Δt

Light follows null geodesics. $g_{\mu\nu}dx^\mu dx^\nu = 0$

If GW follows disformal → Δt. $\mathcal{G}_{\mu\nu}dx^\mu dx^\nu = 0$

$$\mathcal{G}_{\mu\nu} = g_{\mu\nu} + D(\phi, X)\,\partial_\mu\phi\partial_\nu\phi$$

Only conformal theories survive.

$$\mathcal{G}_{\mu\nu} = C(\phi, X)\,g_{\mu\nu}$$

For nonrelativists:

"Additive" gravity is dead
"Multiplicative" gravity is ok

Gravitational Wave Distances

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Just because c_T=c doesn't mean no effect on GW propagation.

$$\ddot{h} + (2 + \alpha_M)\mathcal{H}\dot{h} + c_T^2 k^2 h = 0$$

GW amplitude is proportional to 1 / distance
(energy goes as inverse square)

$$h \sim 1/D_L^{GW}$$

So we can measure changes in gravity by comparing the GW distance to the photon luminosity distance to the same object.

Horndeski α_M (running of Planck mass) damps h.

Nishizawa 1710.04825
Arai & Nishizawa 1711.03776
Belgacem+ 1712.08108
Amendola+ 1712.08623
Linder 1801.01503

Gravitational Wave Distances

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Modified gravity α_M (running of Planck mass)

$$\alpha_M = \frac{d\ln M_\star^2}{d\ln a}$$

damps h

$$\begin{aligned} h &= h^{GR} e^{-(1/2)\int_{\rm em}^{\rm obs} d\ln a\, \alpha_M(a)} = h^{GR} e^{-(1/2)\int_{\rm em}^{\rm obs} d\ln M_\star^2(a)} \\ &= h^{GR}\left[\frac{M^2_{\star,\rm em}}{M^2_{\star,\rm obs}}\right]^{1/2} \end{aligned}$$

So

$$d_{L,GW}(a) = d_L^{GR}(a)\left[\frac{M_\star^2(a=1)}{M_\star^2(a)}\right]^{1/2}$$

but M_* also affects growth, so GW distance tied to growth!

Linder 1801.01503

e.g. in No Slip Gravity

$$d_{L,GW}(a) = d_L^{GR}(a)\left[\frac{G_{\rm matter}(a)}{G_{\rm matter}(a=1)}\right]^{1/2}$$

(also in nonlocal gravity)

Gravitational Waves and Cosmic Growth

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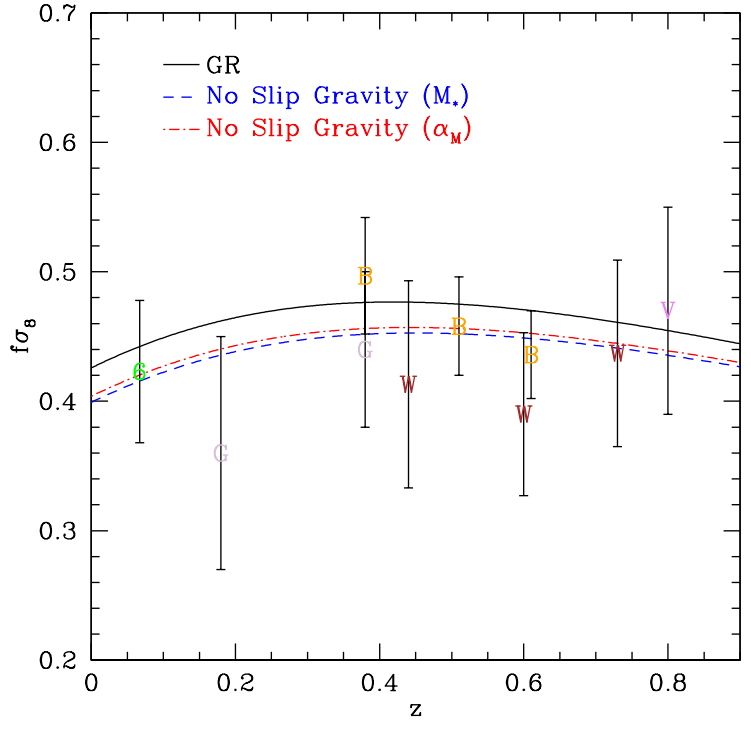
GW distance tied to growth!

If we detect, e.g., a suppression in growth, then this can be checked vs GW distances different than GR.



Example: No Slip Gravity (1 free function) fits growth from redshift space distortions, better than GR.

It predicts ~5% deviation in GW distances.

Galaxy surveys have deep complementarity with GW and CMB surveys.

CMB B-modes and Gravity

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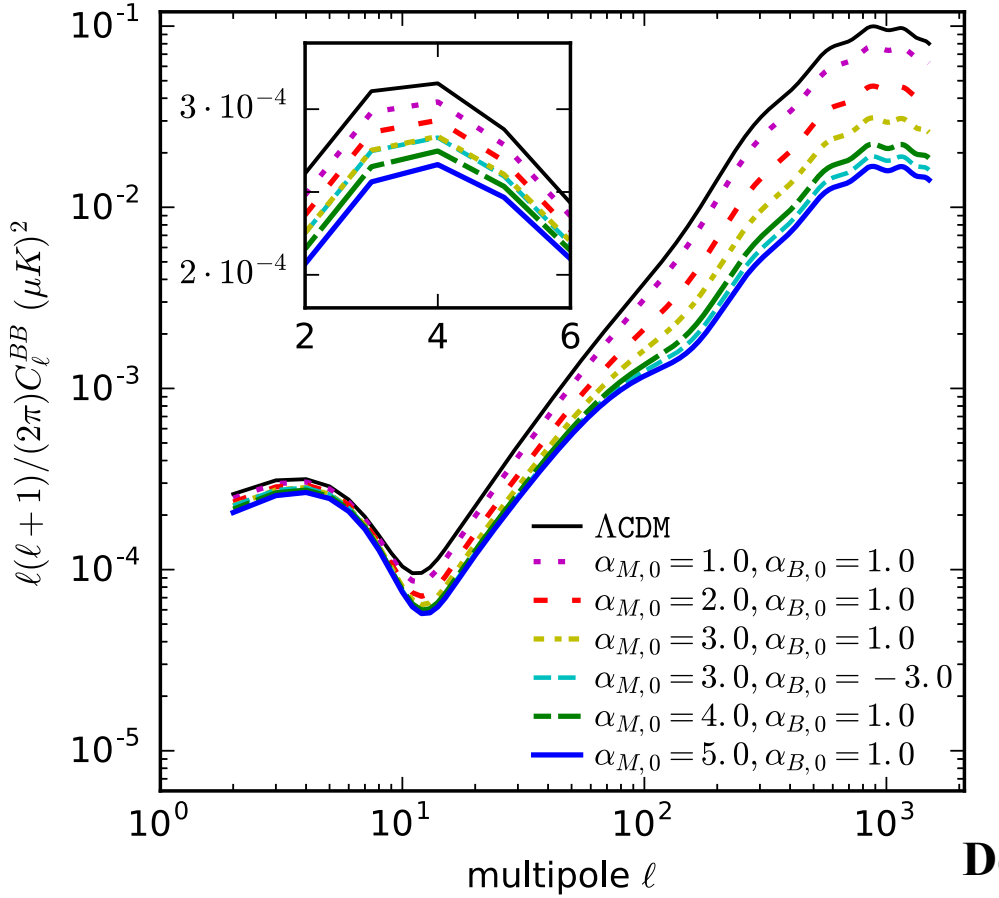
Effective field theory approach to modified gravity defines property functions α_B, α_K, α_M, α_T. We know* $\alpha_T=0$, and α_K is only important on horizon scales.

Even with $\alpha_T=0$, GW propagation affected by α_M.



Low *l* bump is primordial GW. Clear impact of (only) α_M.

High *l* bump is lensing. Matter growth suppression by α_M, α_B.

hi_class with $\alpha_i=\alpha_{i,0}a^1$

Denissenya & Linder 1808.00013

CMB B-modes and Gravity

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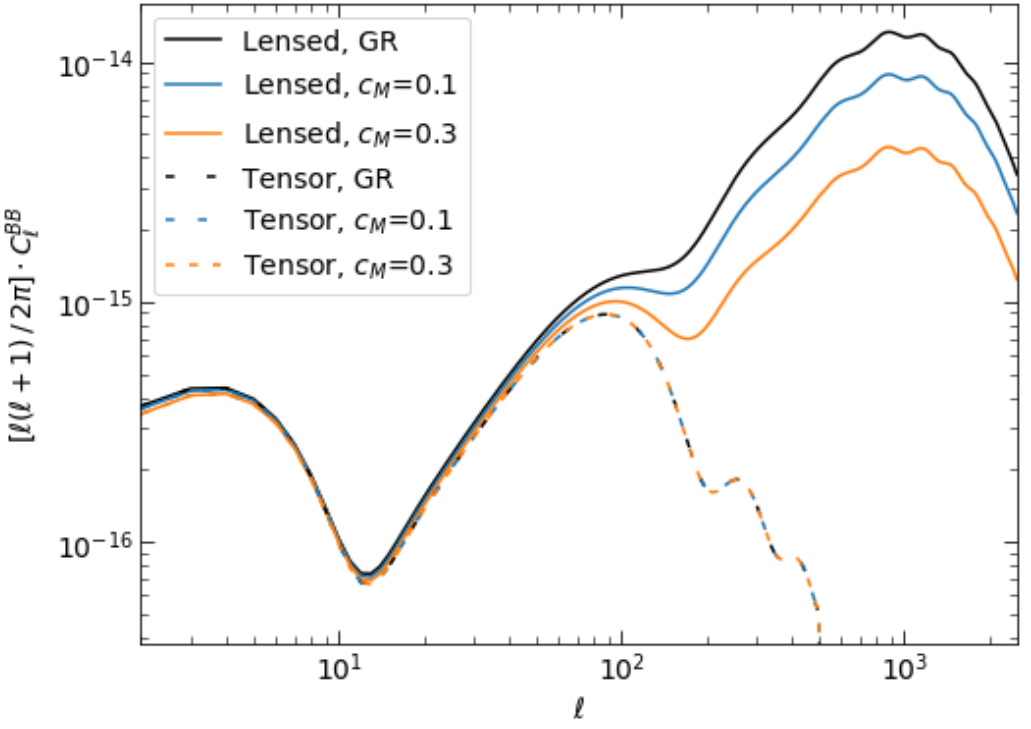
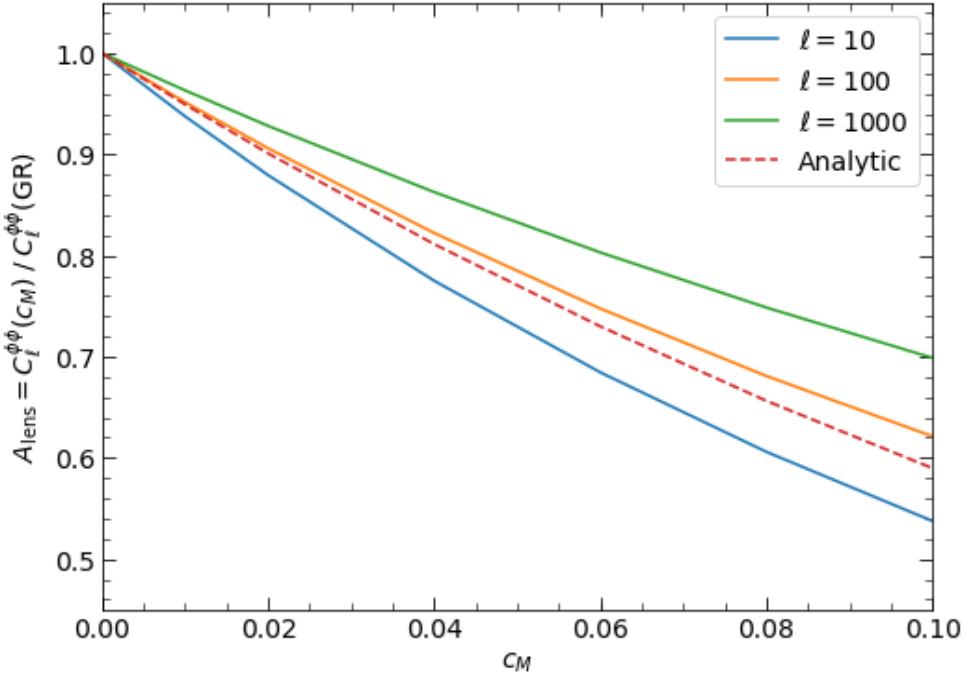
No Slip Gravity with $\alpha_B = -2\alpha_M$.





B-modes modified: GW + Lensing

Lensing power modified: Analytic prediction based on cosmic growth

Brush, Linder, Zumalacárregui 1810.12337

Cosmic Growth and Why Now?

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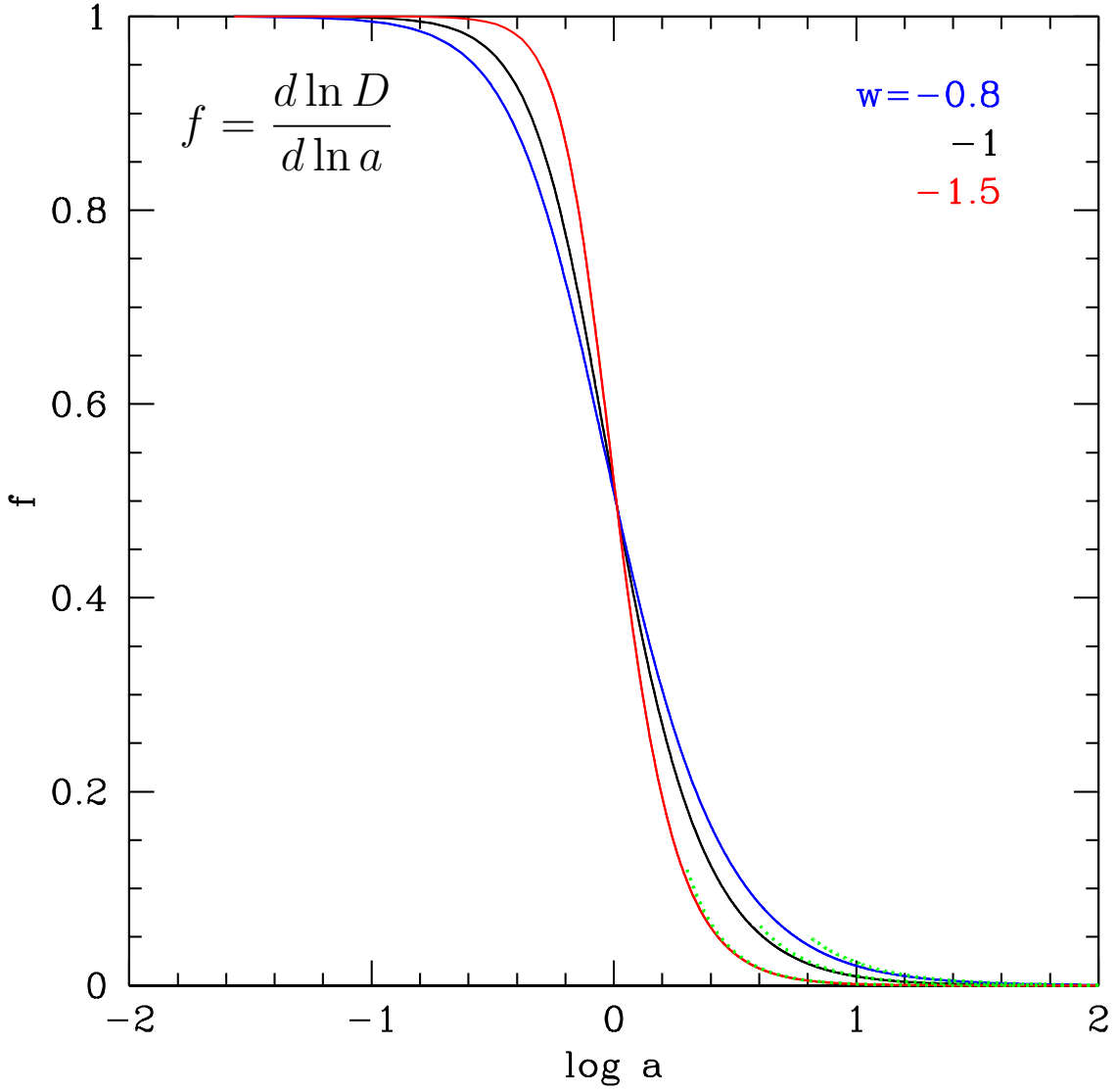
Growth is a battle between gravitational attraction and cosmic acceleration.



Gravity loses – growth ends.

Falls from 1 to 0 in 2 efolds, with today in middle.

Linder & Polarski 1810.10547

Growth index transition

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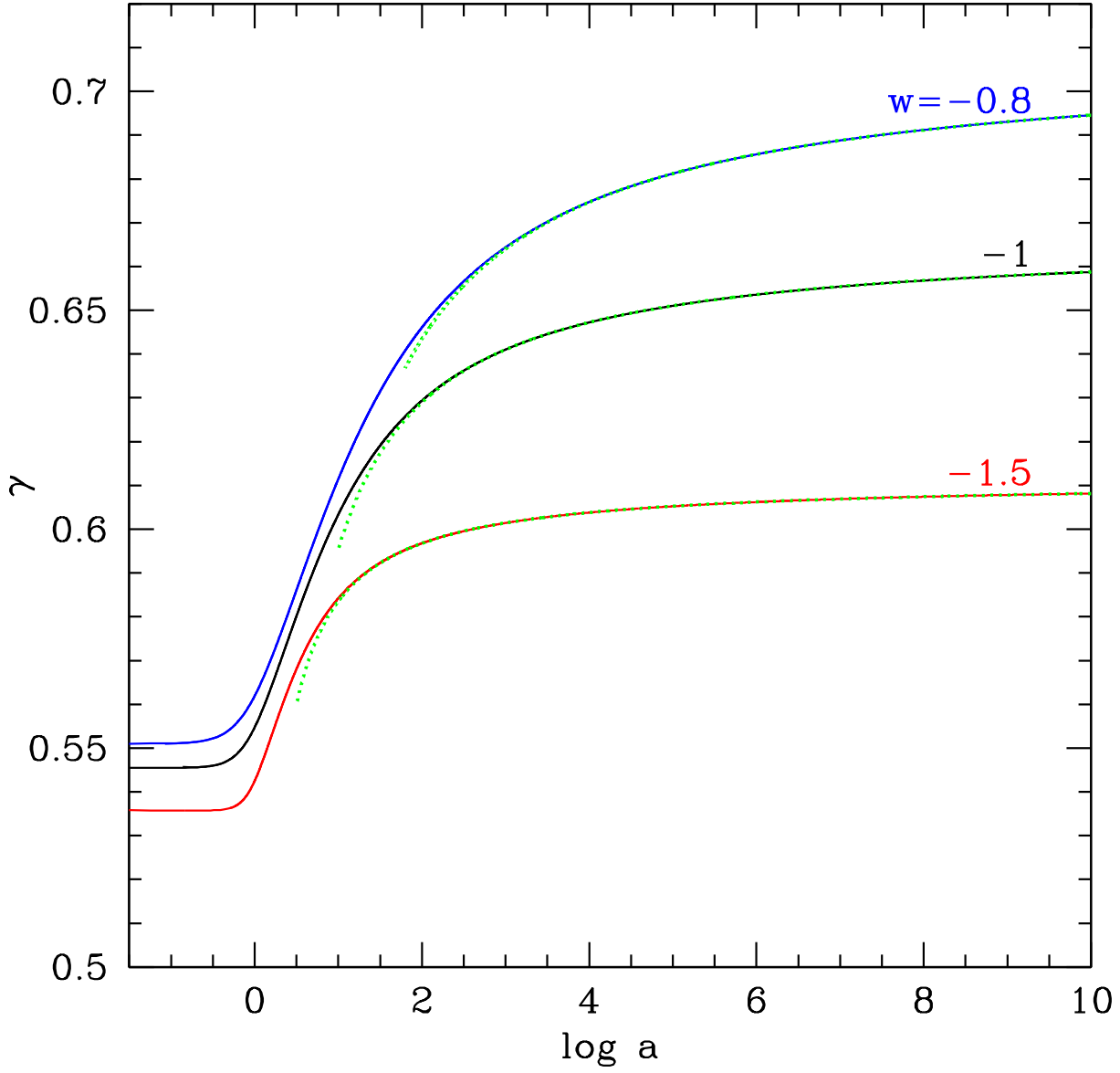
Define growth index by $f = \Omega_m^\gamma(a)$



Transitions today from past constant to future asymptote.

f(R) gravity → GR

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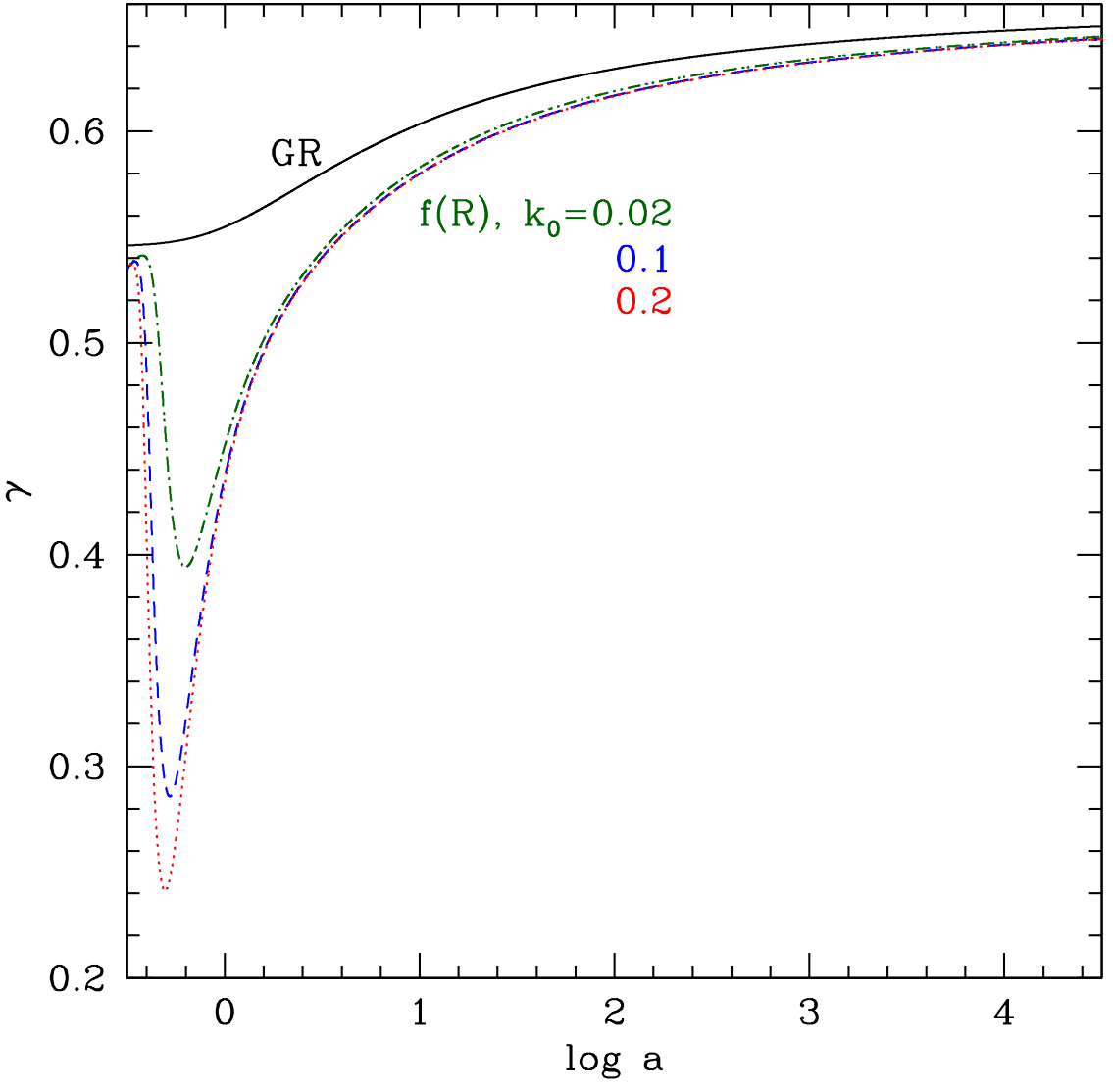
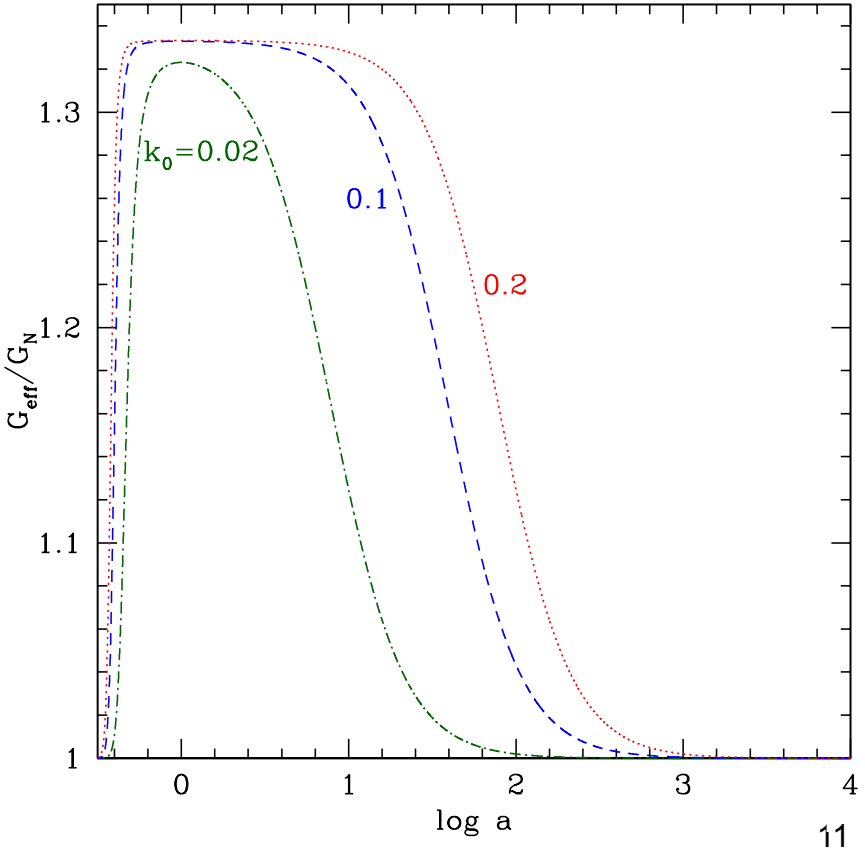


Today is the maximal deviation of G_{eff} in f(R).

Do surveys today, not an e-fold from now!



Summary

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The tensor sector of modified gravity can be probed by interferometers, CMB, and cosmic surveys.