

Cosmic Growth, Gravitational Waves, and the CMB

Eric Linder

UC Berkeley

Energetic Cosmos Laboratory

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New Connections



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



Gravitational Wave Distances



GW propagation: not just speed \mathbf{c}_{T} **but also friction** α_{M} . $\ddot{h} + (2 + \alpha_M)\mathcal{H}\dot{h} + (c_T^2)k^2h = 0$ $\alpha_M = \frac{d\ln M_\star^2}{d\ln a}$

Running of Planck mass, i.e. gravity strength, damps h.

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

h ~ 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.

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

Gravitational Waves and Cosmic Growth Serkeley CENTER for COSMOLOGICAL PHYSI

$$h = h^{GR} e^{-(1/2) \int_{em}^{obs} d\ln a \, \alpha_M(a)} = h^{GR} e^{-(1/2) \int_{em}^{obs} d\ln M_{\star}^2(a)} = h^{GR} \left[\frac{M_{\star,em}^2}{M_{\star,obs}^2} \right]^{1/2}$$
$$d_{L,GW}(a) = d_L^{GR}(a) \left[\frac{M_{\star}^2(a=1)}{M_{\star}^2(a)} \right]^{1/2}$$

But M_{*} also affects growth, so GW distance tied to growth!

e.g. in No Slip Gravity (also in nonlocal gravity)

$$\frac{G_{\text{matter}}(a)}{G_{\text{matter}}(a=1)} = \frac{M_{\star}^2(a=1)}{M_{\star}^2(a)}$$

Linder 1801.01503

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

Galaxy surveys have deep complementarity with GW and CMB surveys.

Gravity Predictions and Crosschecks Serkeley CENTER for COSMOLOGICAL PHYSICS

Redshift space distortions (f σ_8) prefer weak gravity. Note "mirage" models matching d_{lss} match growth.



Deviation in GW predicts deviation in growth, and v.v.

Brando, Falciano, Linder, Velten 1904.12903

ISW Crosscorrelation



Crosscorrelating CMB integrated Sachs-Wolfe (ISW) effect with galaxy density gives a *positive* value in agreement with observations, unlike some modified gravity (e.g. Galileon-3).





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



No Slip Gravity (α_{B} = -2 α_{M}).



B-modes modified: GW + Lensing

Lensing power modified: Analytic prediction is based on cosmic growth

Brush, Linder, Zumalacárregui 1810.12337

Inflationary Freedom



Freedom in dark energy beyond LCDM. Freedom in gravity beyond General Relativity. Freedom in inflation beyond power law primordial PS. Data can explore all these "beyond"s.



Planck + MegaMapper (z=2-5) constrain early+late universe.

Summary



The next several years – and abundant data – will bring these close connections to reality.

