Cosmic Growth, Gravitational Waves, and the CMB

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New Connections

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

- Gravitational Waves
- CMB

\[ \Delta \left( \frac{D_{GW}}{D_{EM}} \right) \leftrightarrow \Delta \text{growth} \]

\[ \Delta \text{gravity} \leftrightarrow \Delta \text{CMB lensing} + \text{B-modes} \]

\[ \Delta \text{growth} \leftrightarrow \Delta \text{CMB lensing} + \text{ISW} \]
Gravitational Wave Distances

GW propagation: not just speed $c_T$ but also friction $\alpha_M$.

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

$\alpha_M = \frac{d \ln M^2_*}{d \ln a}$

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

GW amplitude is proportional to $1/\text{distance}$
(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.

Nishizawa 1710.04825; Arai & Nishizawa 1711.03776; Belgacem+ 1712.08108; Amendola+ 1712.08623; Linder 1801.01503
Gravitational Waves and Cosmic Growth

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.
Redshift space distortions ($f\sigma_8$) prefer weak gravity. Note “mirage” models matching $d_{\text{ls}}$ match growth.

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

Brando, Falciano, Linder, Velten 1904.12903
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).
CMB B-modes and Gravity

Effective field theory approach to modified gravity defines property functions $\alpha_B$, $\alpha_K$, $\alpha_M$, $\alpha_T$. (We know* $\alpha_T=0$, and $\alpha_K$ is only important on horizon scales.)

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

Low $l$ bump is primordial GW. Clear impact of (only) $\alpha_M$.

High $l$ bump is lensing. Matter growth suppression by $\alpha_M$, $\alpha_B$.

hi_class with $\alpha_i=\alpha_{i,0}a^1$
CMB B-modes and Gravity

No Slip Gravity ($\alpha_B = -2\alpha_M$).

**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.

Gravitational Waves

Δ(D_{GW}/D_{EM}) ↔ Δ growth

Cosmic Growth

Density

Velocity

Δ growth ↔ Δ CMB lensing + ISW

Δ gravity ↔ Δ CMB lensing + B-modes

CMB

Cosmic Growth