Galileon Gravity in Light of CMB, BAO, ISW and $H_0$ data

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with Miguel Zumalacárregui, Francesco Montanari & Alexandre Barreira
Why Modify Gravity?

Galileons and CMB, BAO, ISW & H0 data
Why Modify Gravity?

parameter constraints from weak gravitational lensing

Hildebrandt et. al (KiDS coll.) '16
Why Modify Gravity?

Local Determination of Hubble Constant

Beaton et al. '16 & Freedman '17
Galileon Cosmology vs. Data

- No $\Lambda \rightarrow \text{“Self-accelerating”}$
- CMB Temperature & Lensing Spectra
- BAO data
- ISW data
- $H_0$ from distance ladder
- Testable
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($\sim 2$ sigma tension)
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- CMB Temperature & Lensing Spectra
- BAO data
  - (~2 sigma tension)
- ISW data
- $H_0$ from distance ladder
  - (without any prior)
- Testable

27/07/2017

Galileons and CMB, BAO, ISW & H0 data
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Covariant Galileons

- Acceleration driven by kinetic interactions of scalar field
Covariant Galileons

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u} \phi^{\mu\nu}$ |

$$X \equiv -\frac{(\partial \phi)^2}{2}$$
Covariant Galileons

(Local, 4D, Lorentz invariant, scalar-tensor theory with 2nd order EOM ⊂ Horndeski's Theory of Gravity)

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- Predict value for $H_0$ consistent with local measurements
- Require non-zero Neutrino masses

Fit to CMB and BAO data

Results obtained with hi\_class
(www.hiclass-code.net)
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Galileon Gravity vs. CMB
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$\ell (\ell + 1) / 2\pi C_{\ell}^T [\mu K^2]$

$\ell$

$C_{\ell}^T$

Test 2: CMB lensing at $\ell < 40$

→ Too much power on largest scales
Galileon Gravity vs. BAO

Galileons and CMB, BAO, ISW & H0 data
Galileon Gravity vs. BAO

~2σ tension with

- BOSS DR12 Galaxy

and

- BOSS DR11 Lyman alpha
Galileons and CMB, BAO, ISW & $H_0$ data

Galileon Parameter Space & ISW Effect

Fit to CMB and BAO data

\[ \xi = \frac{\dot{\phi} H}{H_0^2} \]

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$\xi = \dot{\phi}/H_0^2$
Galileon Parameter Space & ISW Effect

Fit to CMB and BAO data

BF to CMB+BAO: Fit to ISW data?

Data from Ferraro et al. '14
Galileon Parameter Space & ISW Effect

Fit to CMB and BAO data

Fit to ISW data

Data from Ferraro et al. '14

Galileons and CMB, BAO, ISW & H0 data
Galileon Parameter Space & ISW Effect

scale: $k = 0.01/\text{Mpc}$

Data from Ferraro et al. '14

Fit to ISW data

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Galileons and CMB, BAO, ISW & H0 data
Galileon Parameter Space & ISW Effect

Test 4: ISW with Galaxies \( z \gtrsim 0.75 \)

scale: \( k = 0.01/\text{Mpc} \)

Data from Ferraro et al. '14

Fit to ISW data
How to test Galileon Gravity

- Neutrino mass bounds
- CMB lensing on largest scales
- BAO measurements
- ISW measurements from high redshifts \((z \gtrsim 0.75)\)

![Graph showing the relationship between \(H_0\) and \(\sum m_\nu\) for different models.](image)
How to test Galileon Gravity

- Neutrino mass bounds
- CMB lensing on largest scales
- BAO measurements
- ISW measurements from high redshifts ($z \gtrsim 0.75$)
- Speed of gravitational waves
  - Bettoni et al. '16
- Weak lensing, structure growth
- Non-linear scales/screening
→ Covariant Galileons are not dead (yet)
Other ISW Probes

Correlation with CMB lensing potential

Correlation with NVSS galaxies

Error bands from Planck '15 results: The integrated Sachs-Wolfe effect
Covariant Galileon

\[ g_{\mu\nu} + \phi + \text{Local} + 4\text{-D} + \text{Lorentz theory with } 2^{nd} \text{ order Eqs.} \]

The action of the minimally coupled covariant Galileon model is given by

\[
S[g_{\mu\nu}, \phi] = \int d^4x \sqrt{-g} \left[ \sum_{i=2}^5 \mathcal{L}_i[g_{\mu\nu}, \phi] + \mathcal{L}_m[g_{\mu\nu}, \psi_m] \right],
\]

with

\[
\mathcal{L}_2 = c_2 X - \frac{c_1 M^3}{2} \phi,
\]

\[
\mathcal{L}_3 = 2 \frac{c_3}{M^3} X \square \phi,
\]

\[
\mathcal{L}_4 = \left( \frac{M_{Pl}^2}{2} + \frac{c_4}{M^6} X^2 \right) R + 2 \frac{c_4}{M^6} X \left[ \square (\phi)^2 - \phi_{;\mu\nu} \phi_{;\mu\nu} \right],
\]

\[
\mathcal{L}_5 = \frac{c_5}{M^9} X^2 G_{\mu\nu} \phi_{;\mu\nu} - \frac{1}{3} \frac{c_5}{M^9} X \left[ \square (\phi)^3 + 2 \phi_{;\mu} \phi_{;\mu} \phi_{;\alpha} \phi_{;\alpha} - 3 \phi_{;\mu\nu} \phi_{;\mu\nu} \square \phi \right]
\]
Horndeski's Theory of Gravity

\[ g_{\mu\nu} + \phi + \text{Local} + 4\text{-D} + \text{Lorentz theory with } 2^{nd} \text{ order Eqs.} \]

\[
G_2(X, \phi) - G_3(X, \phi)\Box \phi + G_4(\phi, X) R + G_{4,X} \left[ (\Box \phi)^2 - \phi_{;\mu\nu} \phi^{;\mu\nu} \right] \\
+ G_5 G_{\mu\nu} \phi^{;\mu\nu} - \frac{G_{5,X}}{6} \left[ (\Box \phi)^3 - 3(\Box \phi) \phi_{;\mu\nu} \phi^{;\mu\nu} + 2\phi_{;\mu}^{;\nu} \phi_{;\nu}^{;\lambda} \phi_{;\lambda}^{;\mu} \right]
\]

\[ X \equiv -(\partial \phi)^2 / 2 \]

\[ G_4 = \frac{1}{16\pi G} \]

\[ \text{GR, with } \quad G_4 = \frac{1}{16\pi G} \]

\[ \text{Quintessence, } f(R) \]

\[ \text{Covariant Galileons:} \]

- shift symmetry: \[ \partial_{\mu} \phi \rightarrow \partial_{\mu} \phi + b_{\mu} \]
- no quantum corrections to any loop order in perturbation field theory

\[ G_2 = -(\partial \phi)^2, \quad G_3 = c_3(\partial \phi)^2, \quad G_4, G_5 \propto (\partial \phi)^4 \]