Dark Energy or Modified Gravity? An Effective Field Theory Approach

Jolyon Bloomfield

Cornell University

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Why Study Modified Gravity?

- Dark Energy

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- Inflation
- Dark Matter

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Testbeds

- **Cosmology**
- Solar System
- Black Holes

Observables in Cosmology

Background

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Perturbations

- Matter density perturbation δ
- Matter velocity perturbation v
- Can lift degeneracy in background

Understanding Perturbations

Matter Equations

- Assume Weak Equivalence Principle (WEP)
- Work in Jordan Frame
- Matter equations are independent of gravitational model
- Depend only on ψ, ϕ (Newtonian gauge)

Understanding Perturbations

Modified Gravity

$$\frac{k^2}{a^2}\psi = -4\pi G\rho Q(a,k)(\delta + 3aHv/k)$$

$$\phi = R(a,k)\psi$$

- In GR, $Q = R = 1$
- Aim: Construct theoretical priors on Q, R

General Parametrization of Single (Effective) Scalar Field Models

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- Apply Effective Field Theory rules to select terms
- Restore perturbations

Allowed Objects

- $f(t)$
- h_{ij}
- $g^{00} - 1 = \delta g^{00}$
- $K_{ij} + 3H = \delta K_{ij}$
- $R^{(3)} - 6k = \delta R^{(3)}$
- D_i
- $\partial_t - \mathcal{L}_{\vec{N}}$

Action in Unitary Gauge

$$S = \int d^4x \sqrt{-g} \left\{ \frac{m_P^2}{2} R \right\} + S_{\text{matter}}$$

- General Relativity

Action in Unitary Gauge

$$S = \int d^4x\sqrt{-g}\left\{\frac{m_P^2}{2}R + \Lambda(t) - c(t)\delta g^{00}\right\} + S_{\rm matter}$$

- Quintessence

Action in Unitary Gauge

$$S = \int d^4x \sqrt{-g} \left\{ \frac{m_P^2}{2} \Omega(t) R + \Lambda(t) - c(t) \delta g^{00} \right\} + S_{\text{matter}}$$

- Non-minimal coupling

Action in Unitary Gauge

$$S = \int d^4x \sqrt{-g} \left\{ \frac{m_P^2}{2}\Omega(t)R + \Lambda(t) - c(t)\delta g^{00} + \frac{M_2^4(t)}{2}(\delta g^{00})^2 \right\} + S_{\text{matter}}$$

- k-essence

Action in Unitary Gauge

$$S = \int d^4x \sqrt{-g} \left\{ \frac{m_P^2}{2} \Omega(t) R + \Lambda(t) - c(t) \delta g^{00} + \frac{M_2^4(t)}{2} (\delta g^{00})^2 - \frac{\bar{M}_1^3(t)}{2} \delta g^{00} \delta K^i_i \right\} + S_{\text{matter}}$$

- Galileon/Kinetic Braiding

Action in Unitary Gauge

$$S = \int d^4x \sqrt{-g} \left\{ \frac{m_P^2}{2}\Omega(t)R + \Lambda(t) - c(t)\delta g^{00} + \frac{M_2^4(t)}{2}(\delta g^{00})^2 \right.$$
$$- \frac{\bar{M}_1^3(t)}{2}\delta g^{00}\delta K^i{}_i - \frac{\bar{M}_2^2(t)}{2}(\delta K^i{}_i)^2 - \frac{\bar{M}_3^2(t)}{2}\delta K^i{}_j \delta K^j{}_i$$
$$\left. + \frac{\hat{M}^2(t)}{2}\delta g^{00}\delta R^{(3)} \right\}$$
$$+ S_{\text{matter}}$$

- Horndeski's General Theory

Action in Unitary Gauge

$$S = \int d^4x\sqrt{-g}\left\{\frac{m_P^2}{2}\Omega(t)R + \Lambda(t) - c(t)\delta g^{00} + \frac{M_2^4(t)}{2}(\delta g^{00})^2 - \frac{\bar{M}_1^3(t)}{2}\delta g^{00}\delta K^i{}_i - \frac{\bar{M}_2^2(t)}{2}(\delta K^i{}_i)^2 - \frac{\bar{M}_3^2(t)}{2}\delta K^i{}_j\delta K^j{}_i + \frac{\hat{M}^2(t)}{2}\delta g^{00}\delta R^{(3)} + m_2^2(t)h^{ij}\partial_i g^{00}\partial_j g^{00}\right\} + S_{\mathrm{matter}}$$

- Hořava-Lifshitz Gravity

What can we use it for?

Investigating:

- Effective stress-energy tensor, scalar equation of motion
- $Q(a, k)$, $R(a, k)$
- Effective Newtonian constant
- Speed of sound of perturbations
- Stability

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- Expresses $Q(a, k)$, $R(a, k)$ in terms of coefficients in the action
- Reduces two functions of scale and time to a handful of functions of time
- Stronger theoretical prior on theory space of modified gravity models

Benefits of This Approach

- Time dependence arises from a small number of coefficients in the action
- General parametrization of theory space
- Quantum corrections are under control
- Allows for model-independent constraints

Limitations

- Agnostic as to background evolution
- Only applies to single (effective) scalar field models
- Requires $\phi_0(t)$ to be strictly monotonic in regime of interest

Future Work

- Understand regime of validity
- Relate to other formalisms and models
- Identify further theoretical constraints
- Begin exploring parameter space

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