Matter Interactions in Effective Field Theories of Dark Energy

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Work in Progress with Scott Watson, Minjoon Park, Eva-Maria Mueller, Rachel Bean and Eanna Flanagan

Variety is the Spice of Life

- Quintessence
- k-essence
- Brans-Dicke theories
- Ghost Condensate
- Extra-dimensions a la UED/RS/ADD/DGP
- $f(R)$ gravity
- Gauss-Bonnet gravity
- ...

- In a low energy four-dimensional limit, all these theories essentially behave as GR + scalar field(s)
- Perhaps we can perform a general analysis in this regime?

Systematic Characterization

- **Effective Field Theory of gravity + scalar field** (eg, Weinberg, JB and Eanna Flanagan)
  - Generalizing inflationary models to allow for matter couplings
  - Identifying regimes of validity and constraints on UV theory
- Effective Field Theory of perturbations to FRW (eg, Creminelli *et al*.)
  - Incorporating interactions with matter in perturbative descriptions

Our Approach

Leading Order Action: GR + Canonical Scalar (Quintessence) Field

$$S_0 = \int d^4x\sqrt{-g}\left\{\frac{m_p^2}{2}R - \frac{1}{2}(\nabla\phi)^2 - U(\phi)\right\} + S_{\rm matter}\left[e^{\alpha(\phi)}g_{\mu\nu}, \{\psi\}\right]$$

Perturb the Action

$$\phi, g^{\mu\nu}, R_{\mu\nu\sigma\lambda}, \epsilon_{\mu\nu\sigma\lambda}, T_{\mu\nu}, \nabla_\mu, \Box \ldots$$

Rules of Analysis

- Use a derivative expansion to fourth order
- Remove higher order derivatives in equations of motion ("reduce" the action)
- Impose the Weak Equivalence Principle (Note: not a symmetry of the theory)

EFT Considerations

- Can use a pseudo-Nambu-Goldstone Boson (pNGB) construction to ensure light quintessence field
- pNGB construction yields expansion rules
- Expansion parameter given by

$$\frac{H_0^2}{M^2} \ll 1$$

  for some mass scale M of fields integrated out
- Also specifies scaling of operators. For an operator with d derivatives, mass dimension n, scaling is

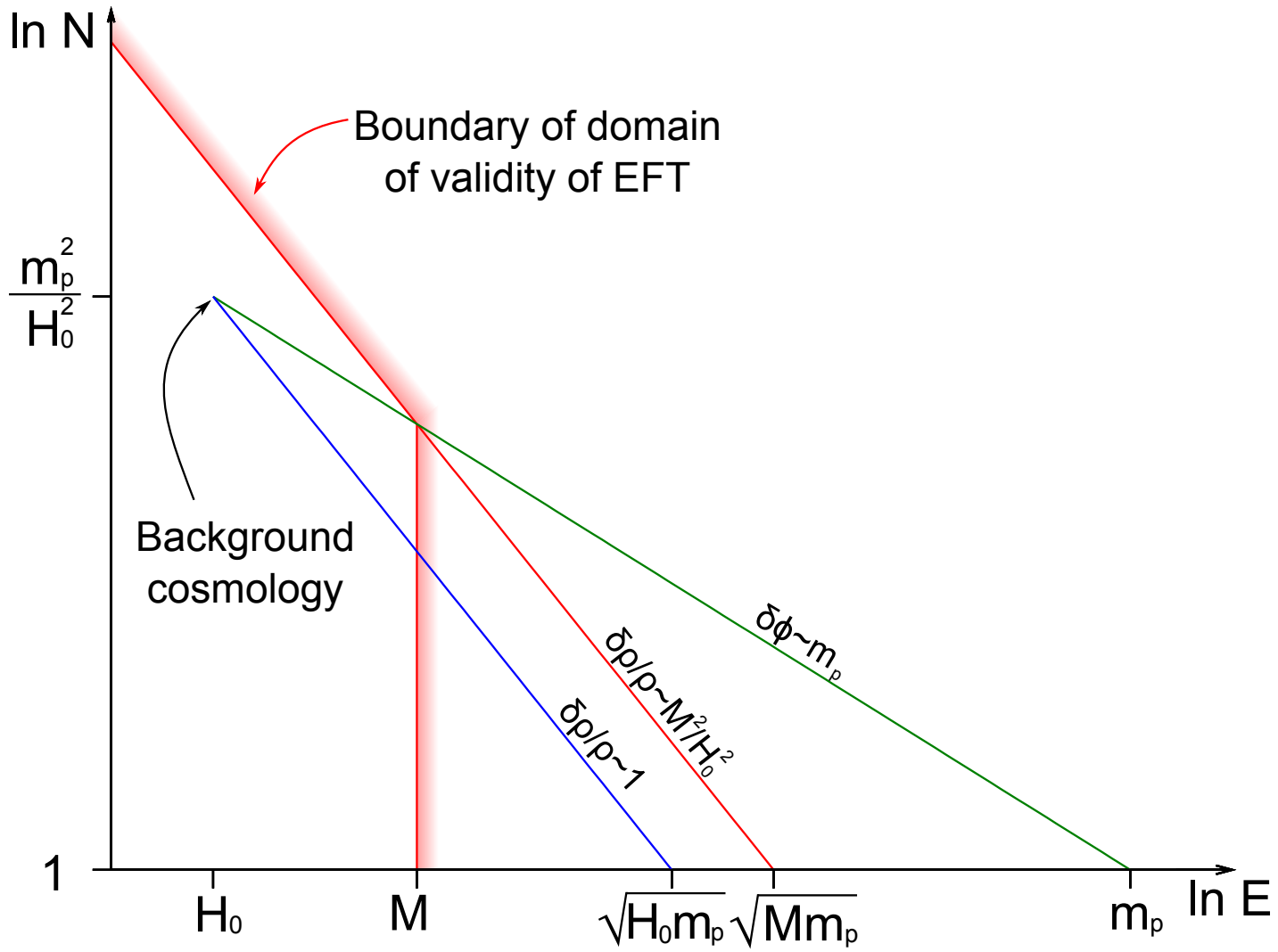
$$\sim M^{2-d} m_p^{2+d-n}$$

Results

$$S = \int d^4x\sqrt{-g}\left\{\frac{m_p^2}{2}R - \frac{1}{2}(\nabla\phi)^2 - U(\phi) + a_1(\nabla\phi)^4\right.$$
$$+ b_2 T(\nabla\phi)^2 + c_1 G^{\mu\nu}\nabla_\mu\phi\nabla_\nu\phi$$
$$+ d_3\left(R^2 - 4R^{\mu\nu}R_{\mu\nu} + R_{\mu\nu\sigma\rho}R^{\mu\nu\sigma\rho}\right)$$
$$+ d_4\epsilon^{\mu\nu\lambda\rho}C_{\mu\nu}{}^{\alpha\beta}C_{\lambda\rho\alpha\beta}$$
$$\left.+ e_1 T^{\mu\nu}T_{\mu\nu} + e_2 T^2\right\}$$
$$+ S_m\left[e^{\alpha(\phi)}g_{\mu\nu}\right]$$

- Coefficients are functions of ϕ with specific scalings
- Parameter space is given by nine free functions

Regime of Validity



Utility of this Approach

- Can describe background and perturbative evolution of the cosmology
- Radiative corrections under control, given constraints on UV theory
- Within regime of validity, yields a very general description

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Perturbative Analysis

- An EFT of perturbations about FRW has proved useful for inflation (Cheung *et al*.) as well as quintessence (Creminelli *et al*.)
- Background evolution must be specified
- Perturbative description more powerful
- Existing framework needs extending to treat dark energy-matter interactions generally

Idea of EFT of Inflation

- Work in Unitary Gauge (scalar eaten by metric) with broken time diffeomorphisms
- Specify background evolution of FRW cosmology
- Construct action as leading order terms + quadratic perturbations

$$S = \int d^4x\sqrt{-g}\left\{\frac{m_p^2}{2}R + \Lambda(t) + c(t)g^{00} + F^{(2)}(\delta g^{00}, \delta K_{\mu\nu}, \delta R_{\mu\nu\sigma\lambda}; t)\right\}$$

- Use Stuckelberg trick to restore quintessence field

Matter Couplings - Conformal Coupling

- Metric which the matter couples to can be conformally scaled

$$S_m\left[e^{\alpha(\phi)}g_{\mu\nu},\{\psi\}\right]$$

Extend EFT of Inflation by working in Jordan frame

$$S=\int d^4x\sqrt{-g}\Bigg\{f(t)\frac{m_p^2}{2}R+\Lambda(t)+c(t)g^{00}+F^{(2)}(\delta g^{00},\delta K_{\mu\nu},\delta R_{\mu\nu\sigma\lambda};t)\Bigg\}+S_m\left[g_{\mu\nu},\{\psi\}\right]$$

Matter Couplings - Stress Energy Tensor

- Stress-Energy Tensor terms need some representation in EFT of Inflation

Extra terms describe any stress-energy tensor dependency

$$S = \int d^4x\sqrt{-g}\Big\{ f(t)\frac{m_p^2}{2}R + \Lambda(t) + c(t)g^{00} + g(t)T^{00} + h(t)T + F^{(2)}(\delta g^{00}, \delta K_{\mu\nu}, \delta R_{\mu\nu\sigma\lambda}, \delta T_{\mu\nu}; t)\Big\} + S_m\left[g_{\mu\nu}, \{\psi\}\right]$$

Summary

- Have constructed an effective field theory to describe dark energy
- Framework for investigating perturbative behavior is in progress
- Hope to constrain parameters in general descriptions, based on cosmological history and the behavior of cosmic perturbations