Effective Field Theory Violations during Inflation: a Critical Look

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Based on:

Arxiv:1203.0016 (JCAP)
1110.4081 (JCAP)

with S. Cremonini, A.C. Davis, R. Ribeiro,
K. Turzinski, S. Watson

Cosmological Inflation

Standard Cosmology suffers from:

horizon , flatness & monopole problems:

$$\tau = \int_0^t a(t)^{-1} dt$$

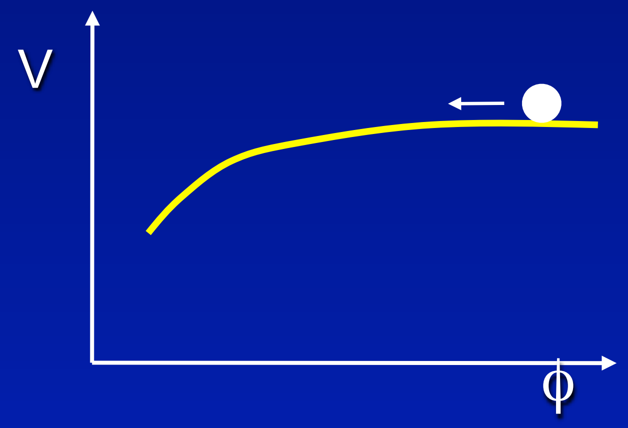
$$|\Omega - 1| = \frac{|k|}{a^2 H^2}$$

$$\pi_2(G/SM) \supset \pi_1(U(1)) \neq I$$

Inflation: exponential expansion with *H~const*

- Comoving Horizon Shrinks
- Expansion dilutes curvature & monoples

Typical Situation: scalar field slowly-rolling down a flat potential



Explains Structure Formation

Fundamental theory???

Inflation in Fundamental Theory

Naively, only need:

$$\mathcal{S} = -\int \mathrm{d}^4x \left(\frac{1}{2}(\partial\phi)^2 + V(\phi)\right)$$

$$\epsilon \equiv -\frac{\dot{H}}{H^2} \ll 1$$

But embedding inflation into fundamental theory spoils this simple picture: inflaton is coupled to many fields

In String Theory (D-branes):

$$S_3 = -T_3 \int d^4x\, e^{-\phi} \sqrt{\det(g_{AB}\partial_\mu y^A \partial_\nu y^B + B_{\mu\nu} + 2\pi\alpha' F_{\mu\nu})}$$

In SUGRA, have K(Φ,Φ†), W(Φ):

$$S = -\int d^4x \sqrt{-g} \left[\underbrace{\frac{1}{2}K_{i\bar{j}}\,\partial_\mu\phi^i\partial^\mu\bar{\phi}^{\bar{j}}}_{g_{ij}(\phi)\partial_\mu\phi^i\partial^\mu\phi^j} + \underbrace{e^{K/M_{pl}}\left(K^{i\bar{j}}D_iW D_{\bar{j}}\overline{W} - 3|W|^2/M_{pl}^2\right)}_{V(\phi)}\right]$$

__Best Hope__: Work in regime where all other fields are massive.
Only inflaton massless.

Non-trivial Kinetic Couplings

Simplest 2-field case:

$$S = \int d^4x\sqrt{-g}\left[\frac{RM_{\rm pl}^2}{2} - \frac{g^{\mu\nu}}{2}\partial_\mu\varphi\partial_\nu\varphi - \frac{e^{2b(\varphi)}}{2}g^{\mu\nu}\partial_\mu\chi\partial_\nu\chi - V(\varphi,\chi)\right]$$

Kinetic coupling ⇔ Coupling between adiabatic & isocurvature modes

(Di Marco, Finelli & Brandenberger, 2002)

Tolley & Wyman: consider case with $m_\varphi \gg H \gg m_\chi$ and "integrate out" massive field φ:

$$S = \int d^4x\sqrt{-g}\left[\frac{M_P^2}{2}R + p(X,\chi) + \ldots\right]$$

where $X = -\frac{1}{2}(\partial\chi)^2$

This is of the k-inflation type, admitting a low speed of sound.

In fact:

$$c_s^2 = \left(1 + \frac{4e^{2b}b_{,\varphi}^2\dot{\chi}^2}{m_\varphi^2}\right)^{-1}$$

Tolley & Wyman 2010

Strong Coupling? (Cremonini, Lalak & Turzinski, 2010)

Turns in Field Space

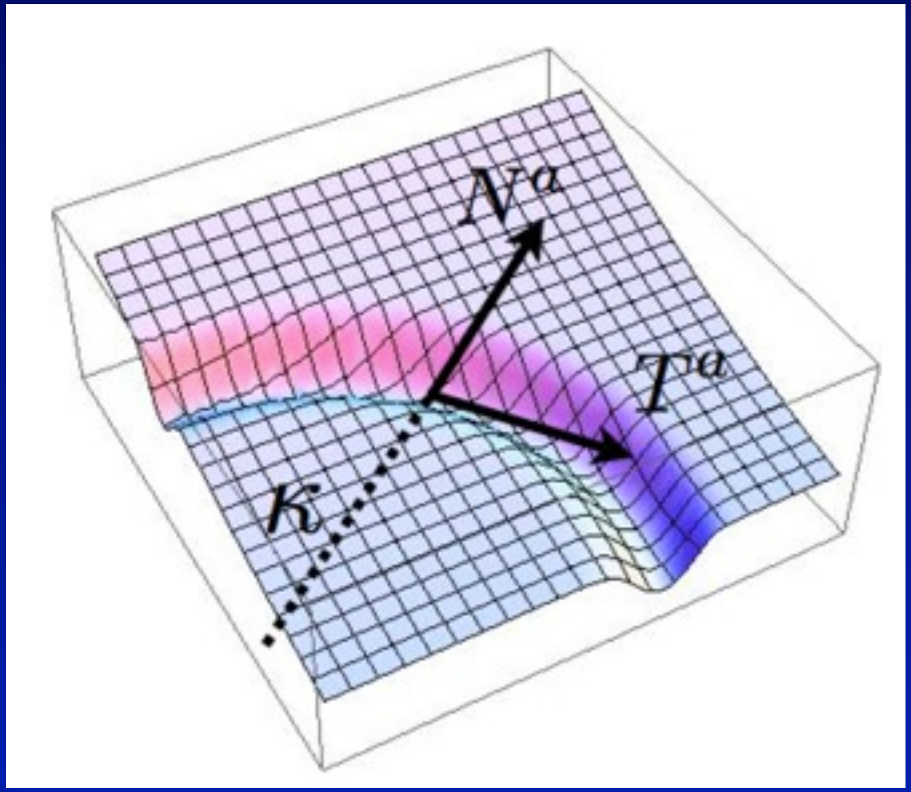
Achucarro et al considered general multi-field Lagrangians

$$S = \int \sqrt{-g}\, d^4x \left[\frac{M_{\rm Pl}^2}{2} R - \frac{1}{2} \gamma_{ab} g^{\mu\nu} \partial_\mu \phi^a \partial_\nu \phi^b - V(\phi) \right]$$

Scalar field eom is: $\Box \phi^a + \Gamma^a_{bc} \partial_\mu \phi^b \partial^\mu \phi^c - V^a = 0$

where Γ^a_{bc} the Cristoffels of γ_{ab}

In an *Inflationary Setup* have a light component $\phi_a = \phi_0(t)$
all transverse components being heavy



Earlier case with $c_s^2 \ll 1$ in fact
corresponds to sharp turns in field space

Split in tangential and transverse directions

Speed of sound controlled by
radius of curvature κ:

$$c_s^2 = \left(1 + 8\epsilon \frac{H^2 M_P^2}{\kappa^2 M^2} \right)^{-1}$$

Achucarro et al 2010
Caspedes et al 2012

Implications

Phenomenological:

- Ringing pattern in power-spectrum (Achucarro et al)
- $c_s^2 \ll 1$ is known to produce (equilateral) non-Gaussianity (Rigopoulos, Shellard & van Tent 2005)

➡ Predict power-spectrum features correlated with non-Gaussianities

Achucarro et al 2010

Theoretical: Violation of Decoupling ???

We may expect: $\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_0 + \mathcal{O}(H^2/M^2)$

with corrections $\rightarrow 0$ as $M \rightarrow \infty$

Kaloper et al 2002

(cf “trans planckian” effects)

What could have gone wrong ???

- Background
- Strong Coupling
- Effective Field Theory

Non-Adiabaticity

Heavy field displaced at sharp turns ➡ not in adiabatic vacuum

Consider Lagrangian: $\mathcal{L} = \frac{1}{2}m_p^2 R - \frac{1}{2}\partial_\mu \varphi_H \partial^\mu \varphi_H - \frac{1}{2} f(\varphi_H)\partial_\mu \varphi_L \partial^\mu \varphi_L - V(\varphi_H, \varphi_L)$

In inflationary background, expand heavy field perturbations:

$$\delta\varphi_H(x,\eta) = \int \frac{d^3k}{(2\pi)^{3/2} a(\eta)} \left(\hat{a}_k e^{i\vec{k}\cdot\vec{x}} \chi_k(\eta) + \hat{a}_k^\dagger e^{-i\vec{k}\cdot\vec{x}} \chi_k^*(\eta) \right)$$

Equation of motion gives: $\chi_k'' + \omega_k^2(\eta)\chi_k = 0$

with time dependent frequency $\omega^2 = k^2 + a^2 \left(\underbrace{M_{\text{eff}}^2}_{\partial_H^2 V - (1/2a^2)(\partial_H^2 f)\phi_L'^2} - \overbrace{M_g^2}^{(1/a^2)(\mathcal{H}^2 + \mathcal{H}')} \right)$

Adiabaticity conditions: $\boxed{\frac{\omega'}{\omega^2} \ll 1 \, , \; \frac{\omega''}{\omega^3} \ll 1}$

If violated, heavy particles produced with effect scaling as: $\exp\left(-\pi \frac{k^2 + m_H^2 - \frac{1}{2}\langle \partial_H^2 f \, \dot{\varphi}_L^2 \rangle}{\sqrt{|\langle \partial_H^2 f (\dot{\varphi}_L \ddot{\varphi}_L) \rangle|}} \right)$

(AA et al 2012)

Key Results 1/2

1) Breaking slow-roll: observability of effect requires $\epsilon \gtrsim 1$
if heavy field starts in its vacuum

$$\frac{1}{2}\langle \partial_H^2 f \dot{\varphi}_L^2 \rangle \sim \frac{\dot{\varphi}_L^2}{\Lambda^2} \sim \frac{\epsilon H^2 m_p^2}{\Lambda^2} \sim \epsilon H^2 \ll m_H^2$$

Need to violate slow-roll for short time interval $\Delta T \ll H^{-1}$

☑ Allowed for in Achucarro et al
☒ Requires fine tuning

2) Energy Conservation: an upper bound

Require Hubble parameter unchanged
during short period of non-adiabaticity ΔT : $3H^2 m_p^2 \simeq V$

Implies energy for particle production
must come from kinetic energy before turn : $\rho_H \ll \dot{\varphi}_L^2$

Key Results 2/2

2) *Energy Conservation*: an upper bound

In fact the requirement $\rho_H \ll \dot{\phi}_L^2$ gives the upper bound:

$$M_{\rm eff}\left(m_H\sqrt{\frac{\dot{\varphi}_L(r)\dddot{\varphi}_L(r)}{\Lambda^2 m_H^2}}\right)^{3/2} \ll \epsilon H^2 m_p^2$$

3) *Size of effect*: a lower bound

Recall non-adiabaticity controlled by:

$$\exp\left(-\pi\frac{k^2+m_H^2-\frac{1}{2}\langle\partial_H^2 f\,\dot{\varphi}_L^2\rangle}{\sqrt{|\langle\partial_H^2 f(\dot{\varphi}_L\dddot{\varphi}_L)\rangle|}}\right)$$

For this to have a significant effect (on c_s) mod exponent must be <1, giving:

$$\frac{|\dot{\varphi}_L(r)\dddot{\varphi}_L(r)|}{\Lambda^2 M_{\rm eff}^4} \gg 1$$

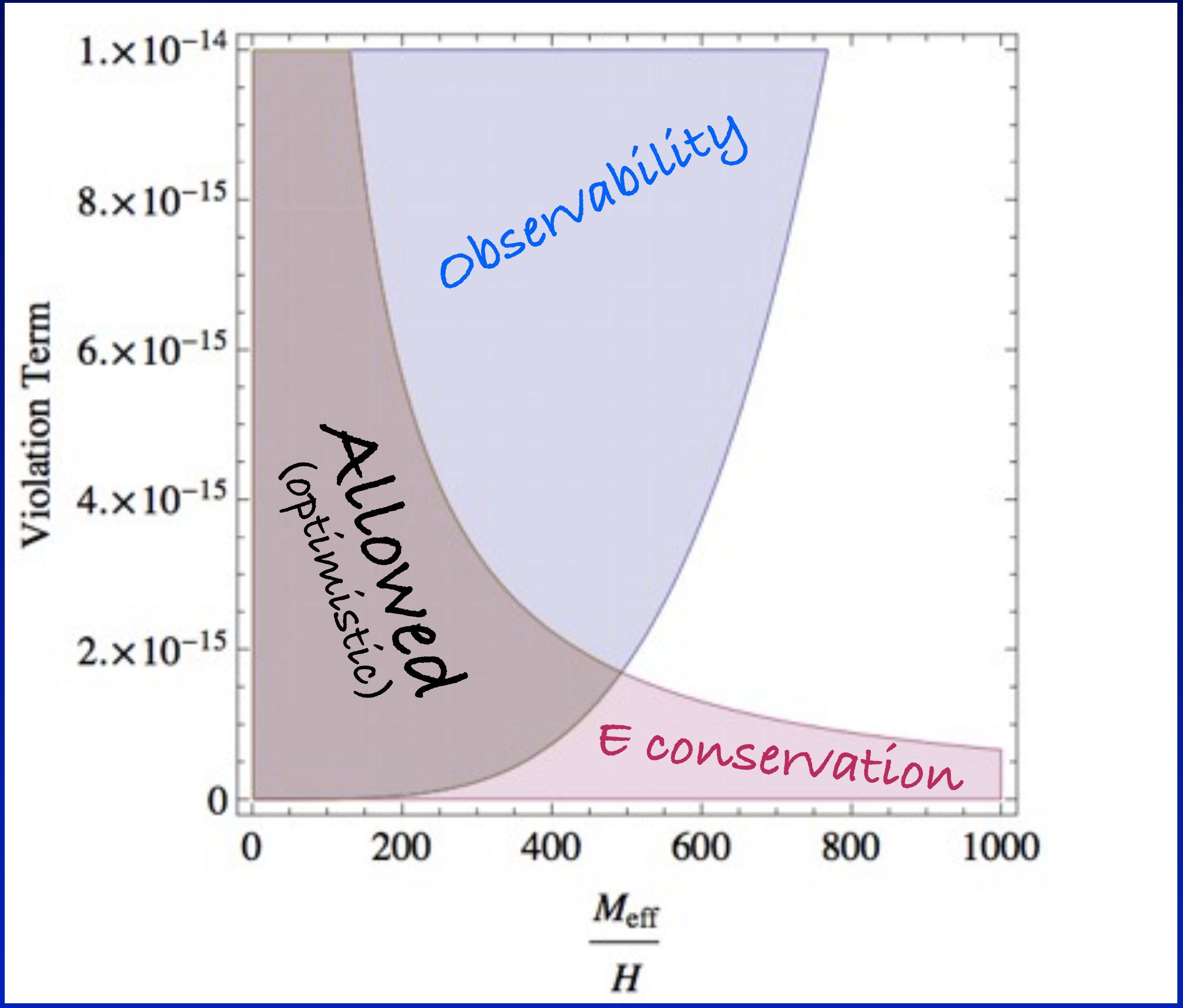
Summary of Constraints

AA, Cremonini, Davis, Ribeiro, Turzinski & Watson 2012

Putting the two constraints together gives:

$$1 \ll \frac{|\dot{\varphi}_L(r)\dddot{\varphi}_L(r)|}{\Lambda^2 M_{\text{eff}}^4} \ll 10^{13}\left(\frac{H}{M_{\text{eff}}}\right)^{16/3} \Rightarrow 10^{-3}\left(\frac{M_{\text{eff}}}{H}\right)^{1/3} \ll \frac{\Delta t}{H^{-1}} \ll \frac{H}{M_{\text{eff}}}$$

Constraint Contours



Contours saturate bounds
(overly optimistic)

Reliable region: $M_{\text{eff}} \lesssim 100H$

- Started with $M_{\text{eff}} \gg H$
- Discovered $M_{\text{eff}} \lesssim 100H$
  if heavy field starts in vacuum

☑ Decoulping Saved

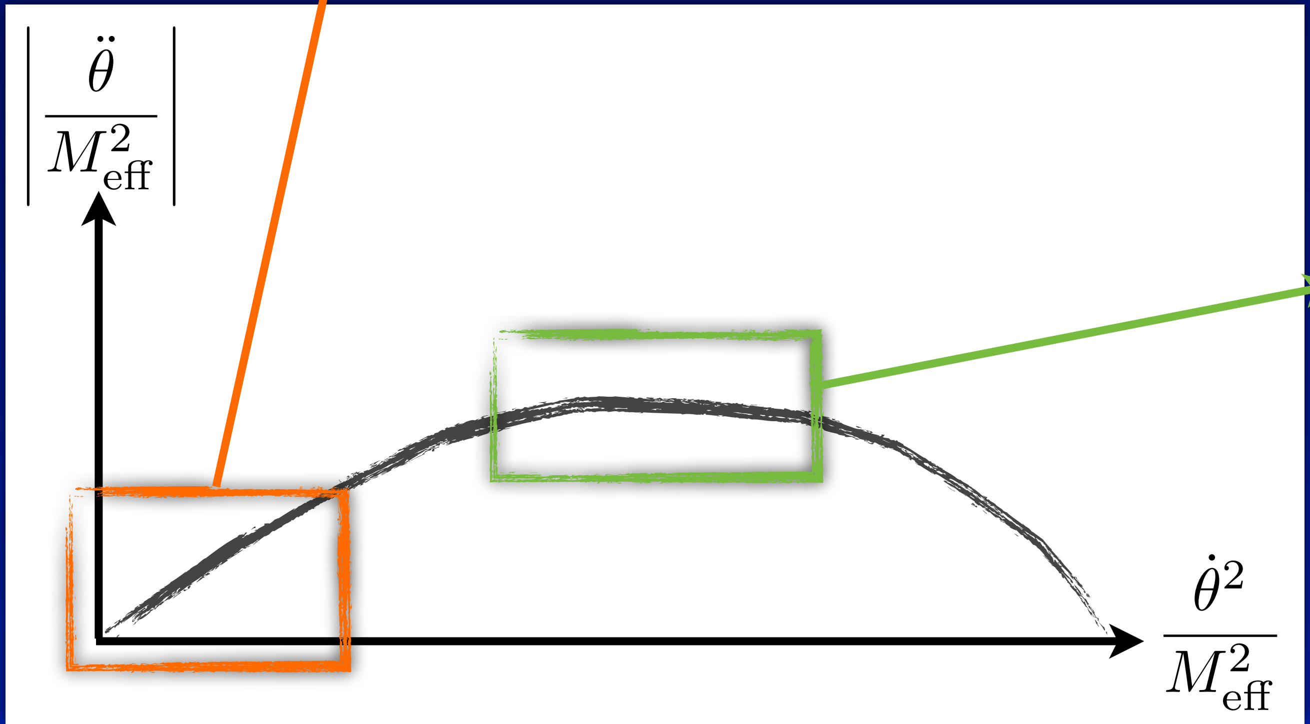
Full Parameter Range

The above analysis applies if heavy field starts in vacuum, which implies $\dot{\theta}^2 \ll M_{\text{eff}}^2$

Achucarro et al 2012 also allow for $\dot{\theta}^2 \gg M_{\text{eff}}^2$ and find adiabaticity condition :

$$\left|\frac{\ddot{\theta}}{\dot{\theta}}\right| \ll M_{\text{eff}}$$

Have ruled out this region



Much more complex case where one must carefully identify low and high energy modes mixing φ_L and φ_H

Conclusions

- Standard Decoupling arguments are valid for inflationary EFT
- Effects are suppressed by powers of $(H/M)^2$
- However, coefficients can be large at the expense of fine-tuning
- If heavy fields start in vacuum then "heavy" effects must be near Hubble scale to be observable
- More interesting cases exist where low energy modes receive contributions from "heavy" field
- Important phenomenological predictions, testability
- How natural are these models ?