Effectively Fielding Inflation

Large fields, open systems and inflation

Cliff Burgess
Why EFTs?

- *Decoupling*: short-distance physics is largely irrelevant for long-distance physics
- EFTs concisely express what is important at long distances
Why EFTs?

• *Decoupling*: short-distance physics is *largely* irrelevant for long-distance physics

• EFTs concisely express what is important at long distances

• *Cosmology likes the unnatural! (what UV completions hate)*
Naturalness?

- **Naturalness is so 20\textsuperscript{th} century...**

- LHC, inflation, ....

- Cosmological constant

What if there were a solution? Supersymmetric extra dimensions still seems to work (review: 1309.4133)
Outline

• Large fields and tensor perturbations
  • Trigonometric, exponential and power-law potentials
    \((1306.3512 \text{ and } 1404.6236)\)
    \(w\) Cicoli, Quevedo & Williams
Outline

• Large fields and tensor perturbations
  • Trigonometric, exponential and power-law potentials
    (1306.3512 and 1404.6236)
    \textit{w Cicoli, Quevedo \& Williams}

• Open EFTs and EFTs w/o effective lagrangians
  • Decoherence, stochastic inflation and the EFT outside the horizon (1406.xxxx and 1407.xxxxy)
    \textit{w Holman, Tasinato \& Williams}
Part I

LARGE FIELD EFTS
Large fields in EFT

Exponential potentials

If you absolutely must have $\phi^2$ inflation

LARGE FIELD EFTS
Large Fields in EFT

- Why large fields?
Large Fields in EFT

- Why large fields?

\[ P_s(k) = A_s k^{n_s-1} \quad r = \frac{A_T}{A_S} \]
n_s and r predicted in single-field slow roll inflation: \( V(\phi) \)

\[
\epsilon = \frac{1}{2} \left( \frac{M_p V'}{V} \right)^2 \quad \eta = \frac{M_p^2 V''}{V}
\]

\[
n_s - 1 = -6\epsilon + 2\eta \quad r = 16\epsilon
\]
Large Fields in EFT

Why large fields?

\[ n_s \text{ and } r \text{ predicted in single-field slow roll inflation: } V(f) \]

\[ \epsilon = \frac{1}{2} M_p V' V^2 \]

\[ n_s - 1 = -6 \epsilon + 2\eta \]

\[ r = 16 \epsilon \]

Usually large \( r \) corresponds to large excursions in field space

\[ \Delta \phi > M_p (r/4\pi)^{1/2} \quad (\text{Lyth}) \]

Can evade this, but

\text{SHOULD EMBRACE IT!}
Large Fields in EFT

Q: Need large fields be inconsistent with decoupling (as expressed eg by effective field theory techniques) and control of calculations?

A: Not in principle: EFT and decoupling rely on low energy, and not small fields.

*SUSY flat directions provide existence proof*

*Require asymptotic form for $V(\phi)$*
Large Fields in EFT

- Why large fields?

BUT Large field inflation is often NOT what you get from UV completions (not a theorem...)
Large Fields in EFT

- Why large fields?

*J. Polchinski ICHEP 08 summary talk*

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34th International Conference on High Energy Physics, Philadelphia, 2008

![Diagram showing plots of r vs. n_s with various data points and shaded regions representing different theories and observations.](image-url)
Large Fields in EFT

String models like small $r$

- Why large fields?
Large Fields in EFT

String models like small $r$
Large Fields in EFT

- Why large fields?

- What not to do: expand in powers of $\phi$
  - Need approximation that works at large fields
Large Fields in EFT

For example: *pseudo-Goldstone bosons*

*Perturb around symmetry limit:*

\[ L_{\text{kin}} = g_{ab}(\phi) \partial \phi^a \partial \phi^b \]

\[ V(\phi) = V_0 \]

*Once symmetry breaks find, eg:*

\[ V = V_0 + V_1 \cos(\phi/f) \]
Large Fields in EFT

For example: *pseudo-Goldstone bosons*

Or if symmetry is non-compact: \( \Phi = e^\varphi \rightarrow \gamma \Phi \)

\[
V = V_0 + V_1 \exp\left(-\varphi/f\right) + \cdots
\]
Large Fields in EFT

Exponential potentials fit the Planck data well:

- Why large fields?
- What not to do: expand in powers of $f$
- Need approximation that works at large fields

(And include the Starobinsky $R^2$ model)
Large Fields in EFT

Exponential potentials: progress on the \( \eta \) problem

\[
V(\varphi) = V_0 \left( 1 - e^{-k \varphi} + \cdots \right)
\]

so

\[
\varepsilon = e^{-2k \varphi} \quad \text{and} \quad \eta = e^{-k \varphi}
\]

so slow roll is same as large field
Large Fields in EFT

- Why large fields?
- What not to do: expand in powers of $f$
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**Exponential potentials: progress on the $\eta$ problem**

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since $\epsilon \sim \eta^2$ get prediction $r \sim (n_s-1)^2$
Large Fields in EFT

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can adjust \( k \) to vary \( r \) but hard to get \( r > 0.11 \)
Large Fields in EFT

Why large fields?

What not to do:

Expand in powers of $f$

Need approximation that works at large fields

Exponential potentials arise generically when modulus like extra-dimensional size, $r$, is the inflaton (though can also be more complicated):

$$V(\varphi) = V_0 \left(1 - \frac{1}{r^p} + \cdots\right) = V_0 \left(1 - e^{-k \varphi} + \cdots\right)$$

since $L = M^2 \frac{(\partial r)^2}{r^2}$ implies $\frac{r}{\ell} = e^{\varphi/M}$
Large Fields in EFT

• Why large fields?

• What not to do: expand in powers of $\phi$
  • Need approximation that works at large fields

• If you absolutely must have $\phi^2$ inflation…
When large fields are small:

* Large $r$ requires $\varphi > M_p$

* Taylor expansion requires $\varphi < f$

\[ V(\varphi / f) \approx V_0 + V_1 \varphi^2 + \ldots \]

* If

These can be consistent if: $f > M_p$
Large Fields in EFT

Summary:

- **Why large fields?**
  - Need approximation that works at large fields.
  - If you absolutely must have $f^2$ inflation...

- **What not to do:**
  - Expand in powers of $f$.

Large fields need not be inconsistent with low-energies, but must understand the large-field limit. Generically get trigonometric or exponential potentials, though others are possible (even $f^2$).

Large $r$ likely to be a great slayer of models, if true.
Part I

EFTS W/O EFF LAGRANGIANS
Open EFTs

Effective theory outside the horizon

EFTS W/O EFF LAGRANGIANS
EFTs w/o Effective Lagrangians

- Open EFTs
EFTs w/o Effective Lagrangians

- Usually EFTs rely on simplicity when $E < M$ to summarize high-energy effects for low-energy observables in terms of an effective Lagrangian.

\[
e^{iS_{\text{eff}}(\varphi)} = \int D\psi \ e^{iS(\varphi,\psi)}
\]

\[S_{\text{eff}} \text{ is simple when expanded in } \partial / M\]
EFTs w/o Effective Lagrangians

• Open EFTs

Such a description is not in general possible for open systems, even when degrees of freedom may be integrated out.

*eg: particle moving through a medium*

courtesy Scientific American
EFTs w/o Effective Lagrangians

Such a description is not in general possible for open systems, even when degrees of freedom may be integrated out.

*Open systems, e.g., particle moving through a medium*

$L_{\text{eff}}$ need not exist since in general pure states can evolve to mixed due to ability to exchange info.

courtesy Scientific American
EFTs w/o Effective Lagrangians

- Open EFTs

EFT nonetheless can exist: *ie things can simplify given a hierarchy of scales.*

Divide system into small observed subsystem, $A$, in presence of a large environment, $B$:

\[ H = H_A + H_B + V \]

then simplifications can arise when

\[ t_c \ll t_p \]

Where $t_c$ is the correlation time of $V$ in $B$ and $t_p$ is the time beyond which perturbation in $V$ fails.
EFTs w/o Effective Lagrangians

For such a system evolution over times $t \gg t_p$ can be computed by computing a coarse-grained evolution:

$$(d\rho_A/dt)_{cg} = \frac{1}{\Delta t} Tr_B \left[ U(\Delta t) \rho \ U^*(\Delta t) \right]$$

for $t_c \ll \Delta t \ll t_p$ and integrating.

for $A \ll B$ in this limit this is a Markov process
EFTs w/o Effective Lagrangians

• Open EFTs

For such a system evolution over times $t \gg t_p$ can be computed by computing a coarse-grained evolution:

$$\frac{d \rho_A}{dt} = U \Delta t$$

for $t_c \ll \Delta t \ll t_p$ and integrating.

This is what allows calculation of light propagation over distances for which scattering from atoms is 100% likely

for $A \ll B$ in this limit this

www.osa-opn.org
EFTs w/o Effective Lagrangians

- Open EFTs

- Effective theory outside the horizon
EFTs w/o Effective Lagrangians

Q: What is the effective theory outside the Hubble scale during inflation?

Claim: this is described by an Open EFT

System A: extra-Hubble modes: \( \frac{k}{a} \ll H \)

System B: intra-Hubble modes: \( \frac{k}{a} > H \)

Correlation time: \( t_c \approx H^{-1} \)
**EFTs w/o Effective Lagrangians**

**Calculation of off-diagonal matrix elements of $\rho_A$:**

- **Open EFTs**
  
  suppose $V = \int A^i B_i \, d^3x$

  and $\langle \delta B_i(x) \delta B_j(y) \rangle = U_{ij}(x) \delta(x - y)$

- **Effective theory outside the horizon**

  also extra-Hubble squeezing of modes implies

  $A^i(\Phi, \Pi)|\varphi > \rightarrow A^i(\Phi, 0)|\varphi > = \alpha^i(\varphi)|\varphi >$

  so $A^i$ is always diagonal in field eigenbasis
Calculation of off-diagonal matrix elements of $\rho_A$:

$\langle \varphi | \rho_A | \tilde{\varphi} \rangle = \langle \varphi | \rho_{A0} | \tilde{\varphi} \rangle e^{-\Gamma}$

where $\Gamma = \int d^3 x dt \ [\alpha^i - \tilde{\alpha}^i][\alpha^j - \tilde{\alpha}^j] U_{ij}$

implies off-diagonal elements *decohere* as with variance narrowing on Hubble times: $\sigma^{-2} \propto a^3$
What of the diagonal matrix elements of $\rho_A$?

For these $\Gamma = 0$ and so the probabilities are governed by initial quantum state.

$$P[\varphi] = \langle \varphi | \rho_A | \varphi \rangle = |\Psi(\varphi)|^2$$

Schrodinger evolution plus tracing of sub-Hubble modes implies $P$ satisfies

$$\frac{\partial P}{\partial t} = N \frac{\partial^2 P}{\partial \varphi^2}$$

with $N$ as in Starobinsky’s stochastic inflation.
EFTs w/o Effective Lagrangians

Summary:

- **Open**
  Open systems provide a *new type of EFT* where simplicity of scale hierarchy is not captured by an effective lagrangian.

- **Effective**
  Appropriate for EFT outside inflationary Hubble scale, and provides *derivation of Starobinsky’s stochastic inflation* as well as the rapid *decoherence of primordial quantum fluctuations*. 
Summary
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- Inflation with large fields
  - Requires understanding of large-field regime
  - Pseudo-Goldstone bosons lead to trig, exponential potentials (and even power laws sometimes)
  - $r$ larger than 0.1 a challenge for many models
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- Inflation and Open EFTs
  - EFT for open systems, without eff lagrangian
  - Gives extra-Hubble EFT: decoherence + Starobinsky
  - New domains of validity of EFT approximation
Fin
The CC message:

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- These dimensions must be supersymmetric (but need *NOT* require the MSSM)
“...when you have eliminated the impossible, whatever remains, however improbable, must be the truth.”

A. Conan Doyle
The CC message:

- The cosmological constant problem is telling us that there must be two micron-sized dimensions (plus possibly more smaller ones)
- These dimensions must be supersymmetric (but need *NOT* require the MSSM)
- *More generally:* back-reaction for higher codimension objects is a very promising, but largely unexplored area