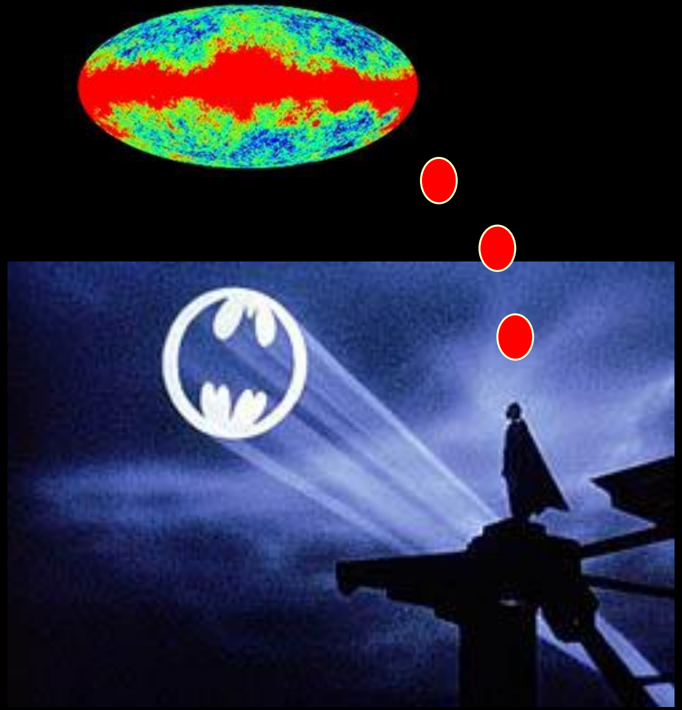
Effectively Fielding Inflation



Large fields,

open systems

and inflation

Cliff Burgess

Why EFTs?

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

Patron Saint of All Things Natural

Why EFTs?

- *Decouping:* 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)*

Patron Saint of All Things Natural

Naturalness?

- *Naturalness is so 20^{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 and 1404.6236)*
    w Cicoli, Quevedo & Williams

Outline

- Large fields and tensor perturbations
  - Trigonometric, exponential and power-law potentials *(1306.3512 and 1404.6236)*
    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.xxxy)*
    w Holman, Tasinato & Williams

Part I

LARGE FIELD EFTS

Large fields in EFT

Exponential potentials

If you absolutely must *have* ϕ^2 *inflation*

LARGE FIELD EFTS

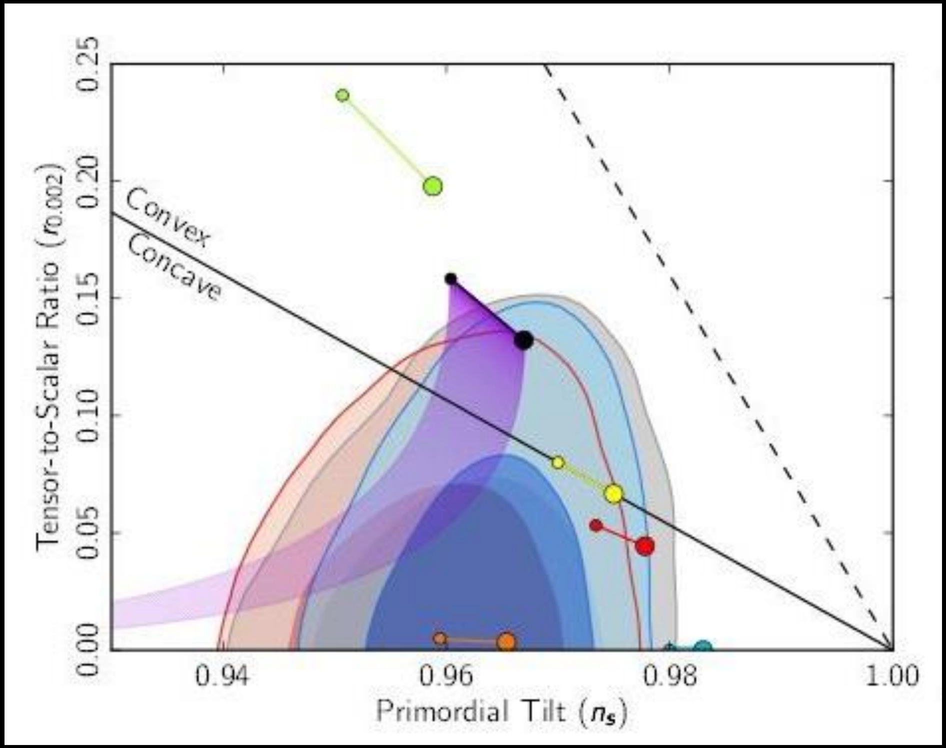
Large Fields in EFT

- Why large fields?

Large Fields in EFT

Planck 2013

- W



$$P_s(k) = A_s k^{n_s - 1} \qquad r = \frac{A_T}{A_S}$$

Large Fields in EFT

Liddle & Lyth 1992

- W

n_s and r predicted in single-field slow roll inflation: $V(\phi)$

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

$$n_s - 1 = -6\epsilon + 2\eta$$
$$r = 16\,\epsilon$$

Large Fields in EFT

Liddle & Lyth 1992

n_s *and* r

- W

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
SHOULD EMBRACE IT!

$\epsilon =$

$$r = 16\,\epsilon$$

Large Fields in EFT

- W

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 $V(\varphi)$

Large Fields in EFT

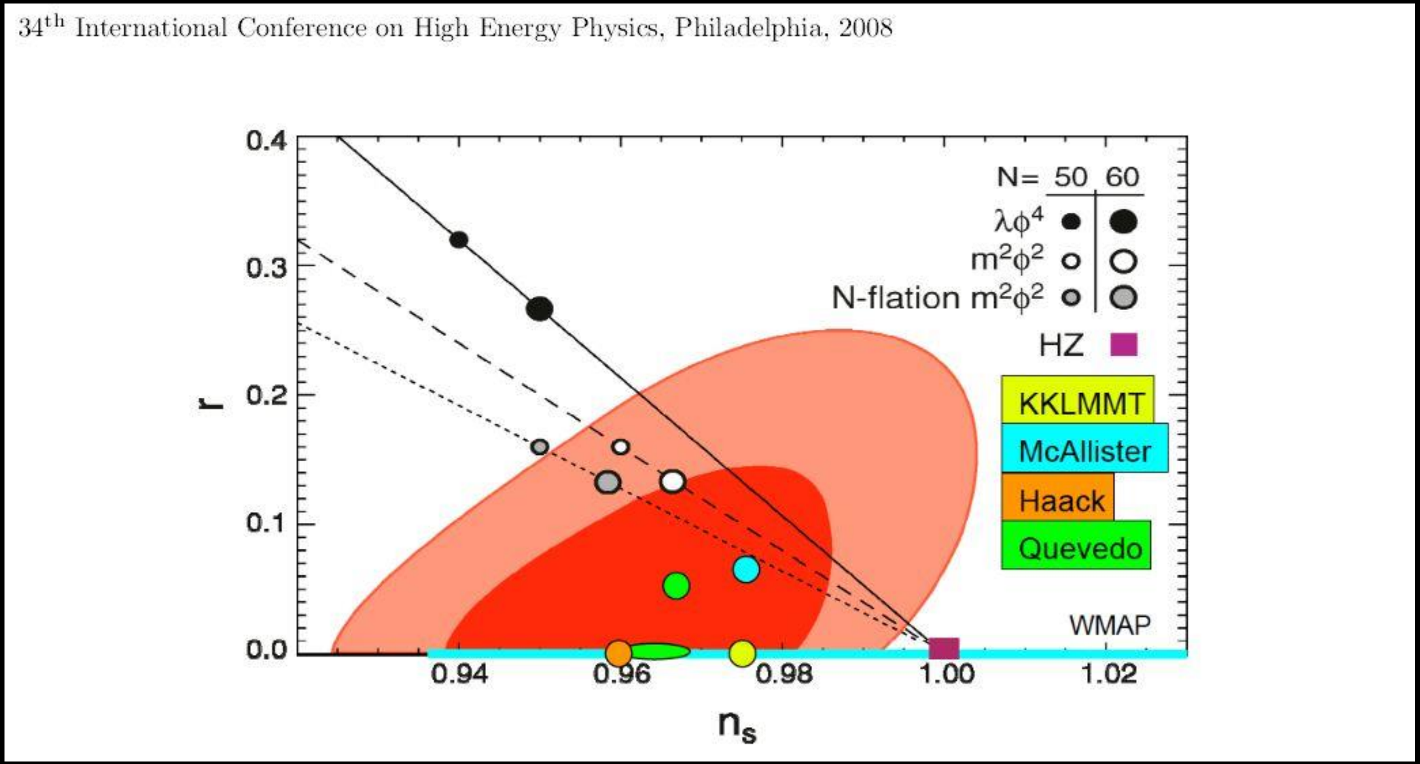
- W

BUT Large field inflation is often NOT what you get from UV completions (not a theorem…)

Large Fields in EFT

- W

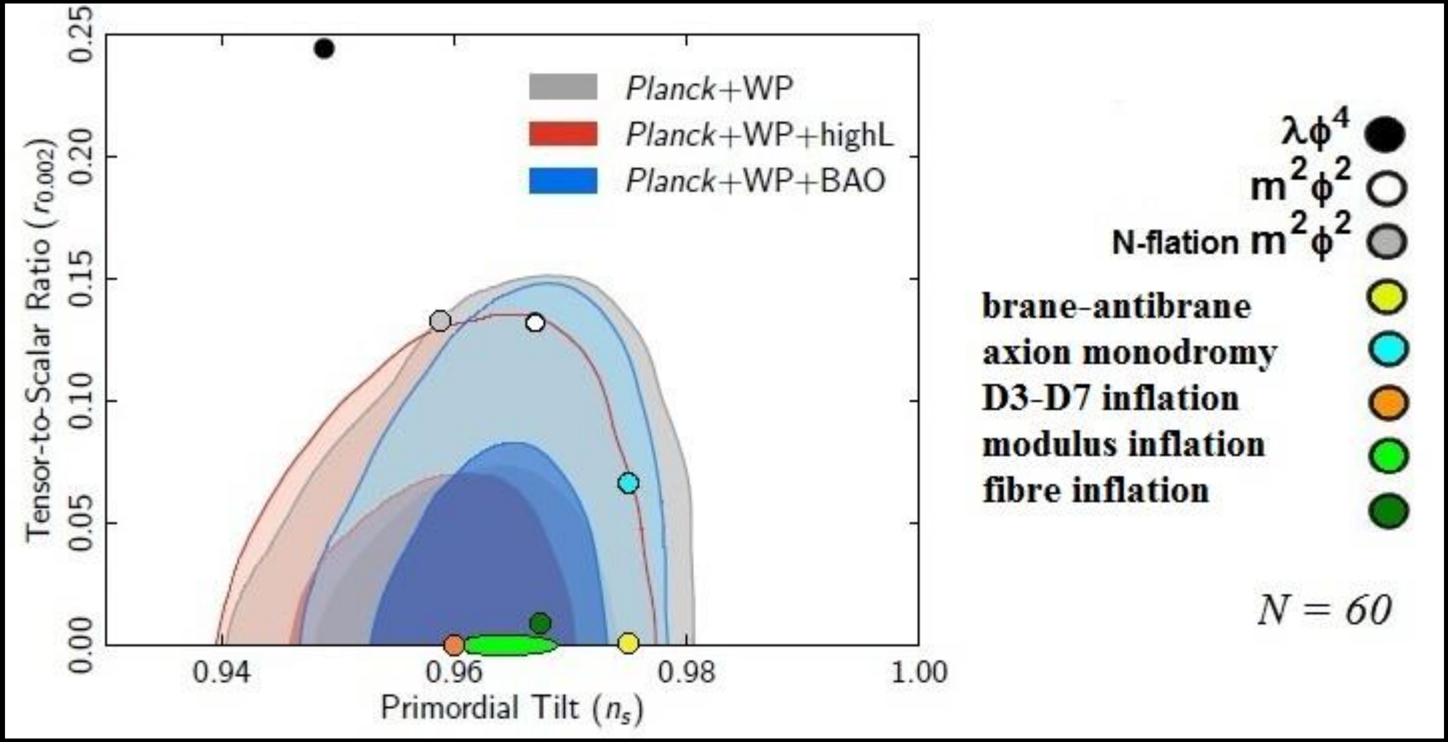
J. Polchinski ICHEP 08 summary talk



Large Fields in EFT

- W

String models like small r



Large Fields in EFT

- W

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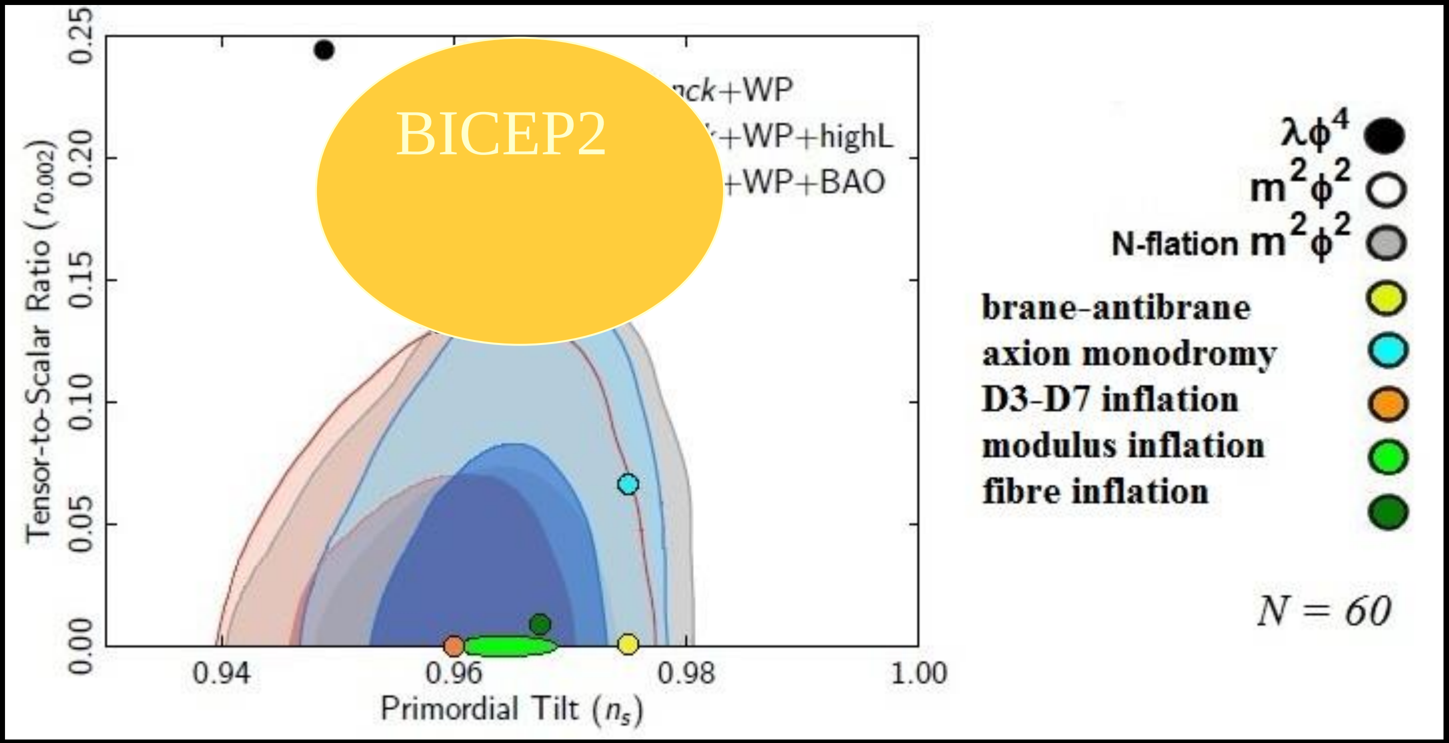


Large Fields in EFT

- Why large fields?

- What not to do: *expand in powers of ϕ*
  - *Need approximation that works at large fields*

Large Fields in EFT

Freese, Friedman & Olinto 1990

- W
- W
  -

For example: *pseudo-Goldstone bosons*

Perturb around symmetry limit:

$$L_{kin} = g_{ab}(\varphi)\partial\varphi^a\partial\varphi^b$$

$$V(\varphi) = V_0$$

Once symmetry breaks find, eg:

$$V = V_0 + V_1\cos(\varphi/f)$$

Large Fields in EFT

CB, Cicoli, Quevdo & Williams

- W
- W
  -

For example: *pseudo-Goldstone bosons*

Or if symmetry is non-compact: $\Phi = e^{\varphi} \to \gamma\Phi$

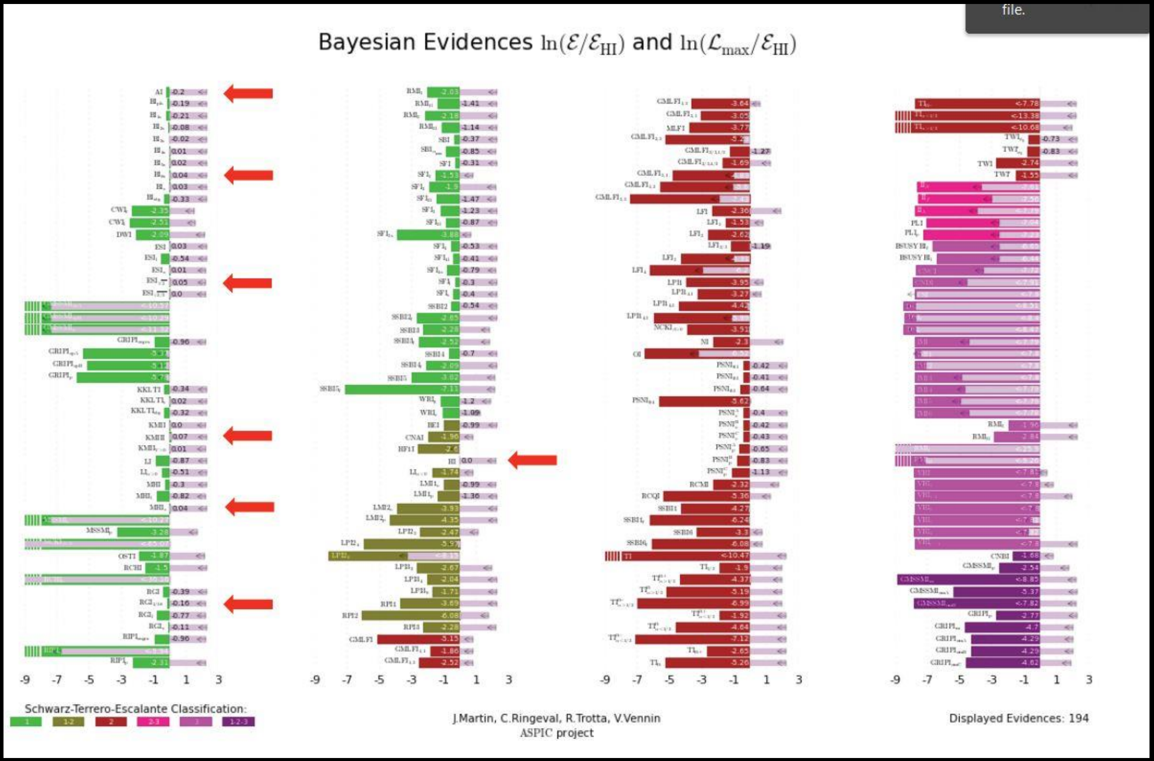
$$V = V_0 + V_1 \exp(-\varphi/f) + \cdots$$

Large Fields in EFT

Martin, Ringeval & Vennin 2013

- W
- W

Exponential potentials fit the Planck data well:



(and include the Starobinsky R^2 model)

Large Fields in EFT

BMQRZ th/0111025

- W
- W
  -

Exponential potentials: progress on the η problem

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

so

$$\epsilon = e^{-2k\,\varphi} \quad \textit{and} \quad \eta = e^{-k\,\varphi}$$

so slow roll is same as large field

Large Fields in EFT

BMQRZ th/0111025
Cicoli, CB & Quevedo 0808.0691

- W
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since $\varepsilon \sim \eta^2$ get prediction $r \sim (n_s\text{-}1)^2$

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

BMQRZ th/0111025
Conlon & Quevedo th/0509012
Cicoli, CB & Quevedo 0808.0691

- W
- W
  -

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* ϕ
  - *Need approximation that works at large fields*

- If you absolutely *must* have ϕ^2 inflation…

Large Fields in EFT

- W
- W
- If

When large fields are small:

Large r requires $\varphi > M_p$

Taylor expansion requires $\varphi < f$

$$V(\varphi/f) \approx V_0 + V_1\varphi^2 + \cdots$$

These can be consistent if: $f > M_p$

Large Fields in EFT

- W
- W
  -
- If

Summary:

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 ϕ^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

- Op

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

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

S_{eff} is simple when expanded in ∂/M

EFTs w/o Effective Lagrangians

- Op

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

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

EFTs w/o Effective Lagrangians

- O

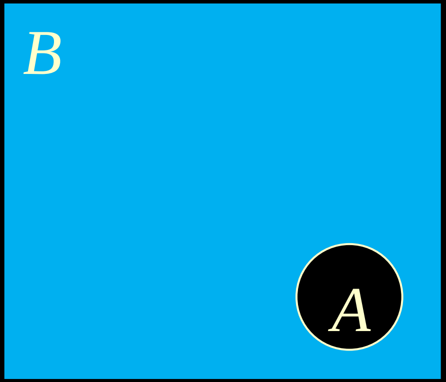
EFT nonetheless can exist: *ie things can simplify given a hierarchy of scales*.

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

- O[

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

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

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

for $A \ll B$ in this limit this is a Markov process

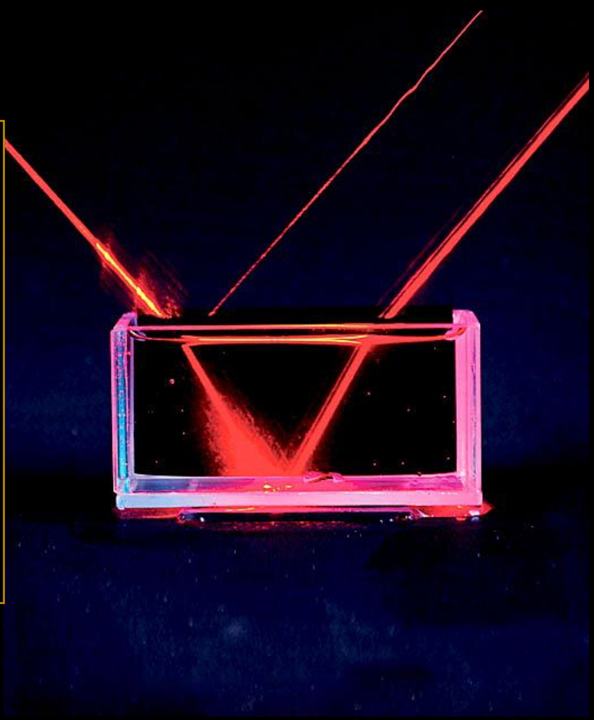
EFTs w/o Effective Lagrangians

- Op

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

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 thi*



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EFTs w/o Effective Lagrangians

- Open EFTs

- Effective theory outside the horizon

EFTs w/o Effective Lagrangians

CB, Holman, Tasinato & Williams

- Op
- Ef

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|

CB, Holman, Tasinato & Williams

- O[...]
- Ef[...]

Calculation of off-diagonal matrix elements of ρ_A:

suppose $V = \int A^i B_i \, d^3x$

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

also extra-Hubble squeezing of modes implies

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

so A^i is always diagonal in field eigenbasis

EFTs w/o Effective Lagrangians

CB, Holman, Tasinato & Williams

- Op
- Ef

Calculation of off-diagonal matrix elements of ρ_A:

then can integrate equation for ρ_A in field basis:

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

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

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

EFTs w/o Effective Lagrangians

CB, Holman, Tasinato & Williams

- Op
- Ef

What of the diagonal matrix elements of ρ_A?

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

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

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

- Op
- Ef

Summary:

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

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

Summary

- 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
- 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:

- The cosmological constant problem is telling us that there must be two micron-sized dimensions (plus possibly more smaller ones)

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- 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)

"...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*