Cosmology Between the Plancks
Open EFT & 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

Patron Saint of All Things Natural

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)*

Patron Saint of All Things Natural

Outline

- Natural inflation revisited
  - Trigonometric, exponential and power-law potentials *(1306.3512 and 1404.6236)*
    w Cicoli, Quevedo & Williams

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- Natural inflation revisited
  - Trigonometric, exponential and power-law potentials *(1306.3512 and 1404.6236)*
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- Open EFTs and EFTs w/o effective lagrangians
  - Decoherence, stochastic inflation and the EFT outside the horizon *(1408.5002)*
    w Holman, Tasinato & Williams

Part I

NATURAL INFLATION

What is special about Goldstone bosons?

Exponential potentials vs axions

What about large fields?

NATURAL INFLATION

Natural Inflation Revisited

- Why goldstone bosons?

Natural Inflation Revisited

Mukhanov & Chibisov 1980
Liddle & Lyth 1992

- W

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

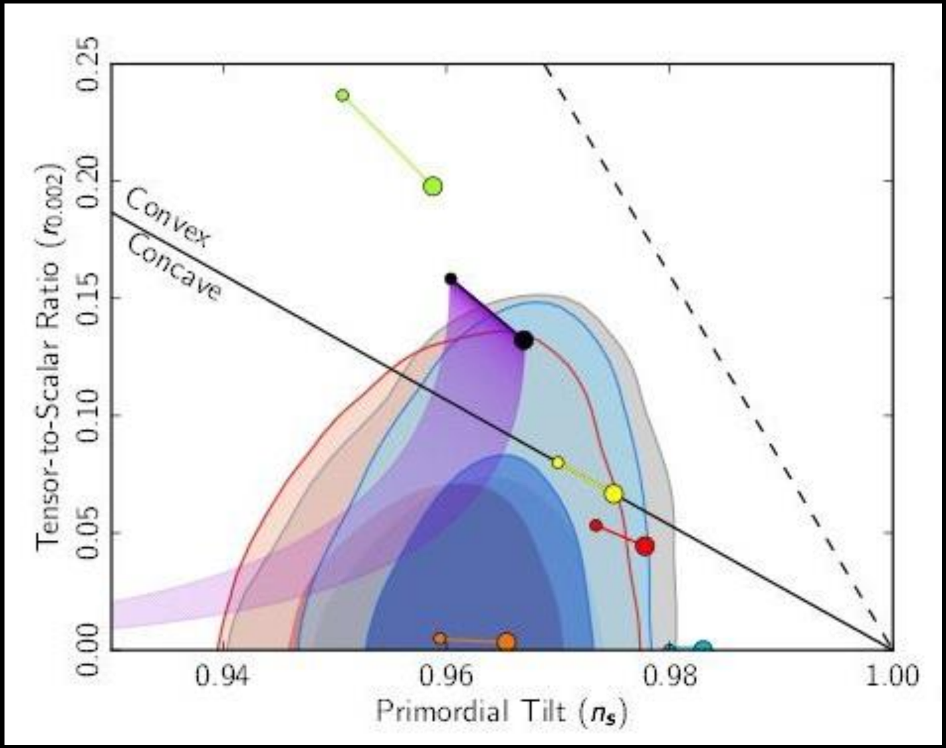
$$\epsilon = \frac{1}{2}\left(\frac{M_p V'}{V}\right)^2 \quad \eta = \frac{{M_p}^2 V''}{V}$$

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

Natural Inflation Revisited

Planck 2013

- W



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

Natural Inflation Revisited

- W

So what is the hard part?

$$\eta = \frac{{M_p}^2 V''}{V}$$

$$\eta \ll 1 \Rightarrow m^2 \ll H^2 \ll M^2$$

Hierarchy problem in spades!!

Natural Inflation Revisited

Freese, Friedman & Olinto 1990

- W

eg: *pseudo-Goldstone bosons* $\Phi = \Phi_0 e^{i\varphi} \to e^{ia}\Phi$

Perturb around symmetry limit:

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

$$V(\varphi) = V_0$$

Once symmetry breaks find, eg:

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

Corrections to V_1 are proportional to V_1

Natural Inflation Revisited

- Why goldstone bosons?

- Why exponential potentials?
  - *The 'other' kind of goldstone bosons…*

Natural Inflation Revisited

CB, Cicoli, Quevdo & Williams

- W
- W
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For example: *pseudo-Goldstone bosons*

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

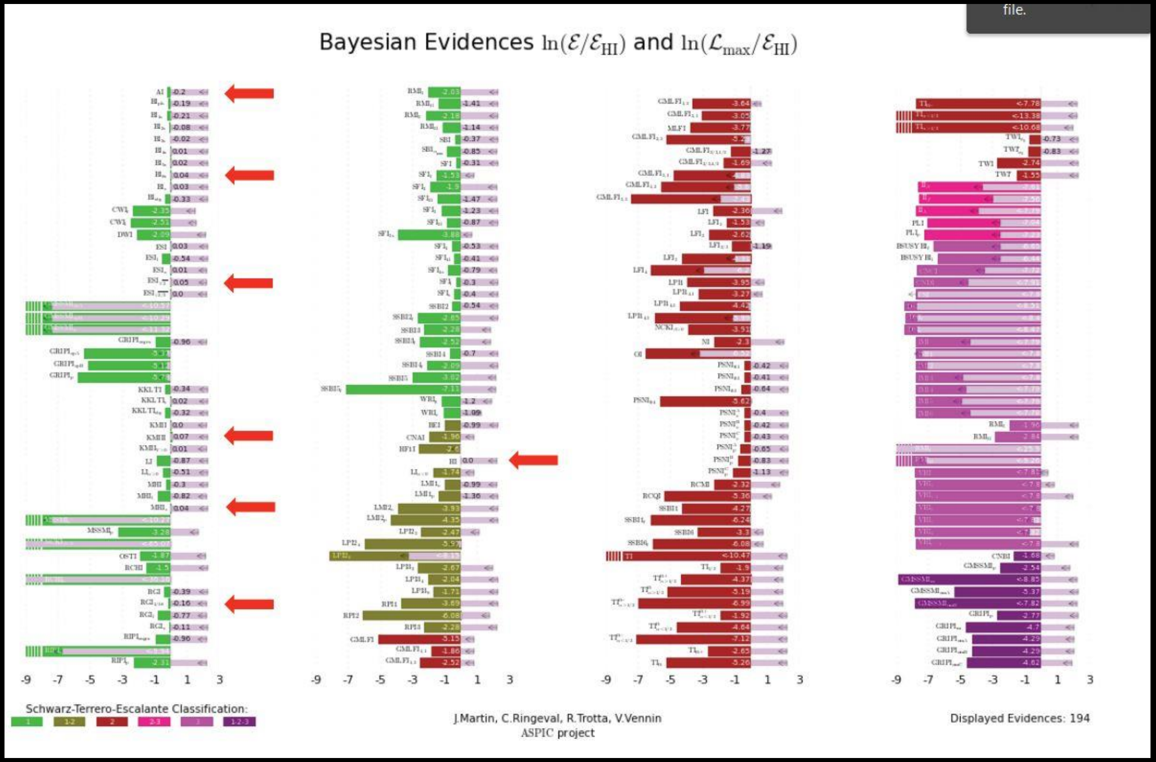
$$V = V_0 + V_1 \exp(-\varphi/f) + \cdots$$

Natural Inflation Revisited

Martin, Ringeval & Vennin 2013

- W
- W

Exponential potentials fit the Planck data best:



(and include the Higgs and Starobinsky R^2 models)

Natural Inflation Revisited

Martin, Ringeval & Vennin 2013

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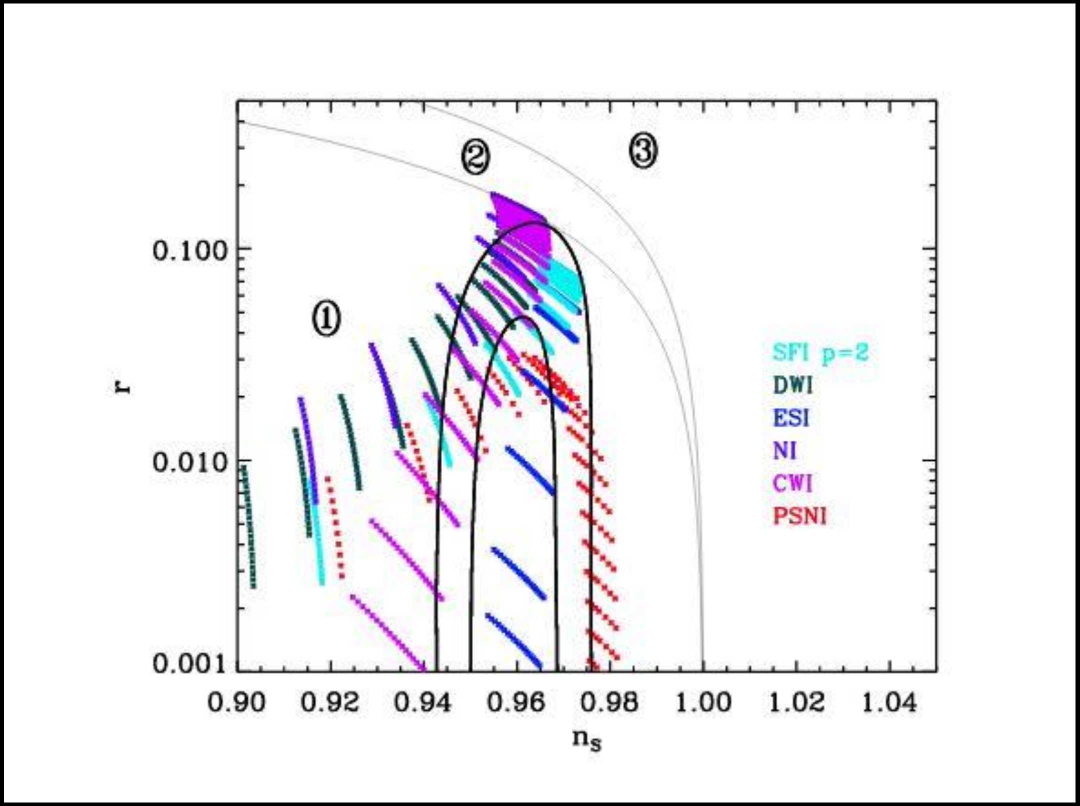
- W

Why some models do better than others…



Natural Inflation Revisited

BMQRZ th/0111025

- W
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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

Natural Inflation Revisited

BMQRZ th/0111025
Cicoli, CB & Quevedo 0808.0691

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can adjust k to vary r but hard to get r > 0.11

Natural Inflation Revisited

BMQRZ th/0111025

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Exponential potentials arise generically from UV completions, such as when 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* $\frac{r}{\ell} = e^{\varphi/M}$

Natural Inflation Revisited

- Why goldstone bosons?
- Why exponential potentials?
  - *The 'other' kind of goldstone bosons…*
- What about large fields?

Natural Inflation Revisited

- W
- W
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- 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!

Natural Inflation Revisited

- W
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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 $V(\varphi)$

Natural Inflation Revisited

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Generically should NOT expand in powers of φ :

Should understand large-field limit (eg as symmetry limit for goldstone bosons)

Natural Inflation Revisited

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But…sometimes CAN expand in powers of fields 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: $f > M_p$

Natural Inflation Revisited

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Summary:

Pseudo-goldstone bosons are natural inflatons

Generically get trigonometric or exponential potentials, though others are possible (even ϕ^2)

Large fields need not be inconsistent with low-energies, but must understand the large-field limit.

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

• Op

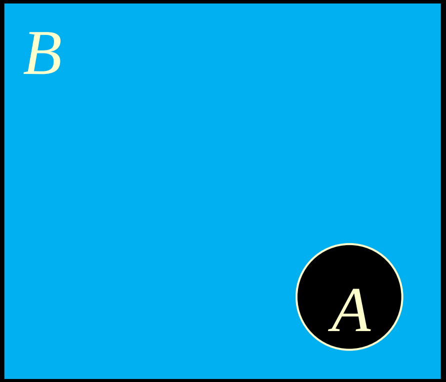
EFT nonetheless can exist: *ie things can simplify given a hierarchy of scales*.

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

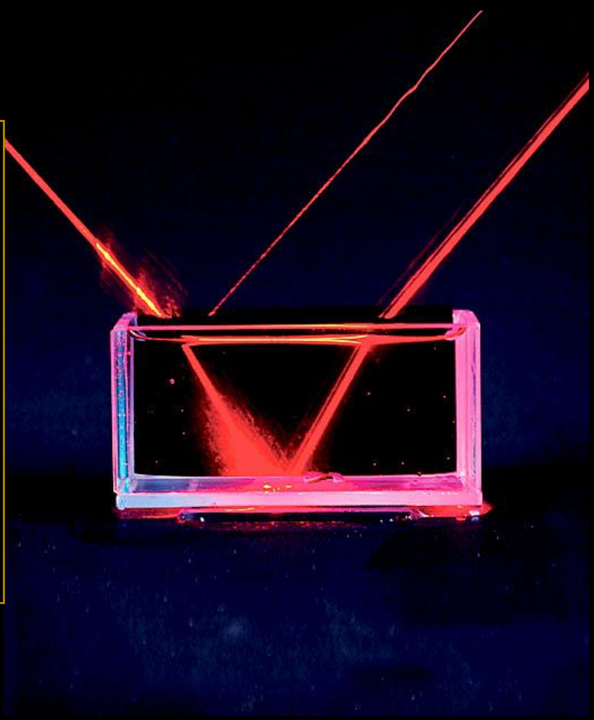
EFTs w/o Effective Lagrangians

- 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 $\langle \delta B_i(x)\, \delta B_j(x') \rangle = U_{ij}(x)\, \delta(t - t')$

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

- O[
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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 $N = H^3/8\pi^2$ as in *Starobinsky 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

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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
- 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