EFT and Gravitational Response for Dark Vortices & Other Sources

Galiano Island 2015

Cliff Burgess

Open EFTs, Decoherence & Secular Evolution in Inflation

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Outline

- Motivation
  - What is the effective description of inflation on super-Hubble scales?
- Diagonal evolution
  - Stochastic inflation and resummation of late-time behaviour
- Off-diagonal evolution
  - Decoherence of primordial fluctuations

Part I

MOTIVATION

What is the EFT for super-Hubble modes?

EFTs for Open Systems

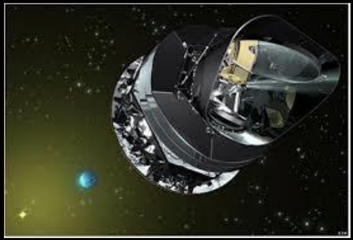
MOTIVATION

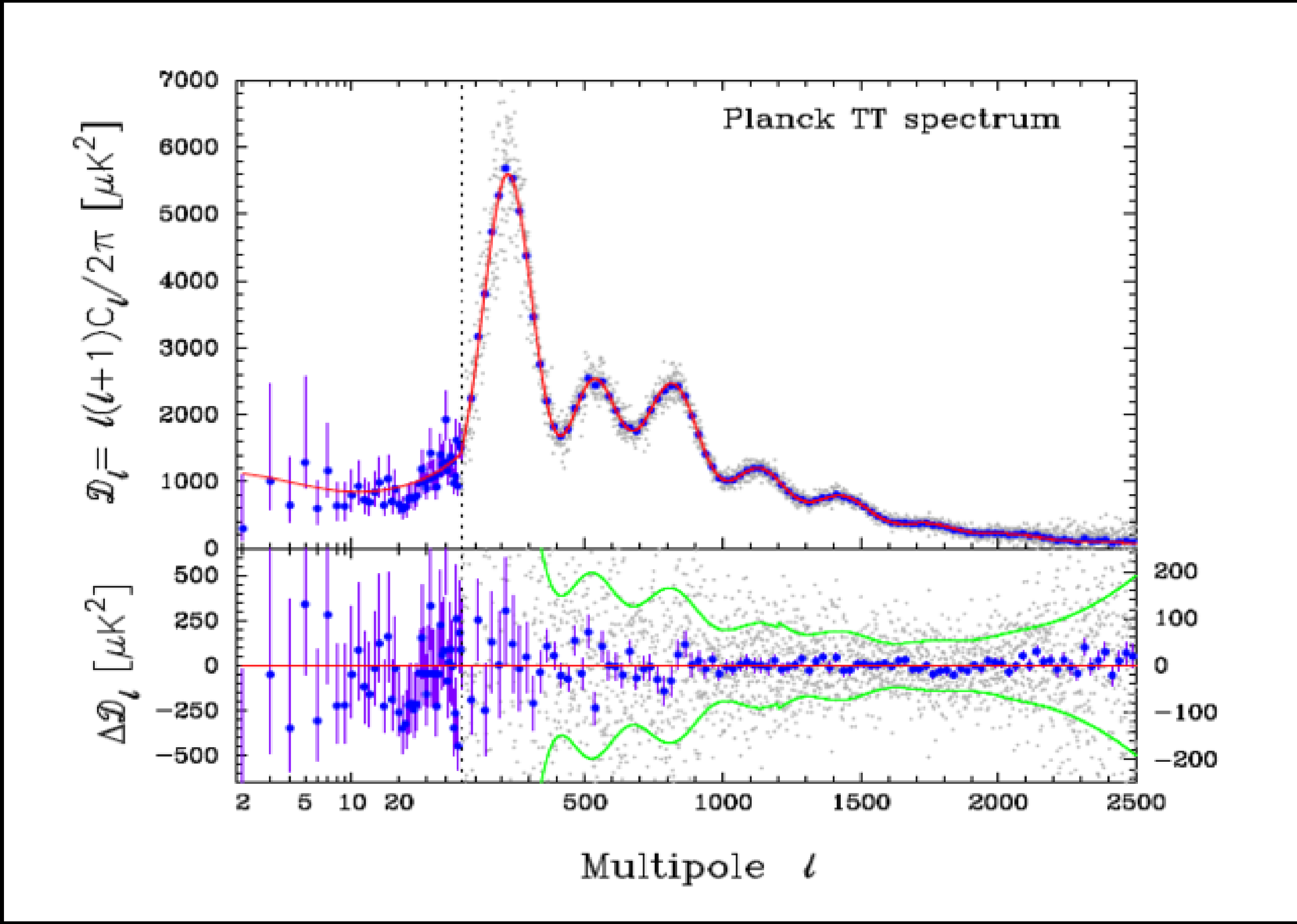
Language Issue

- What is the right language for EFTs in an inflationary model?
  - *Effective lagrangian?*
  - *Master equation?*
  - *Something else?*

Divided by a common language

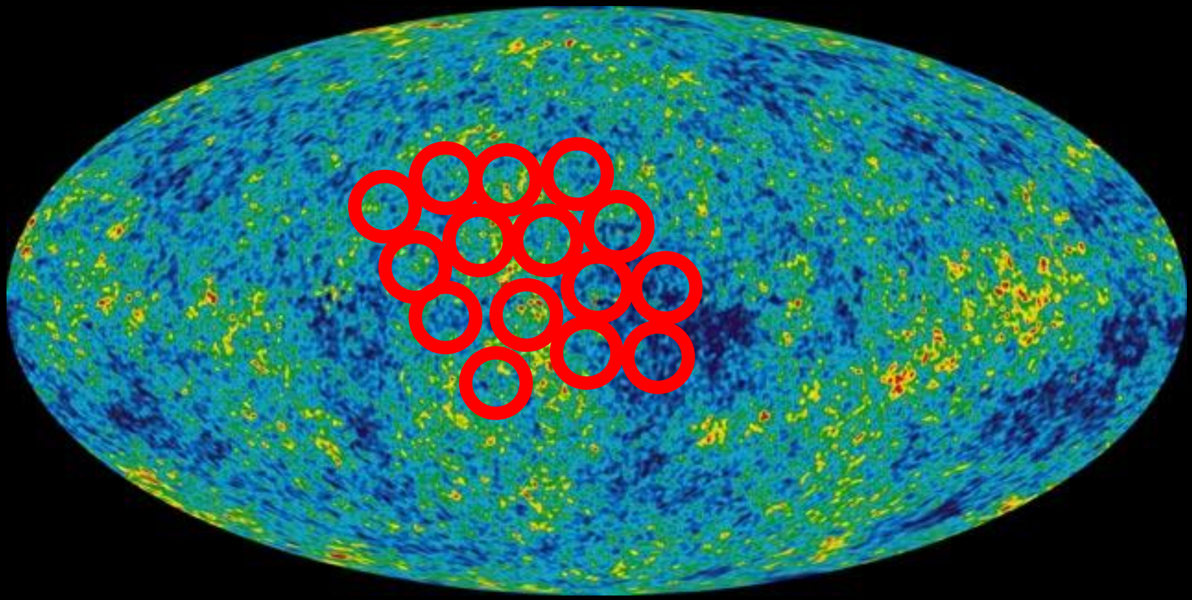
CMB Observations





CMB Observations

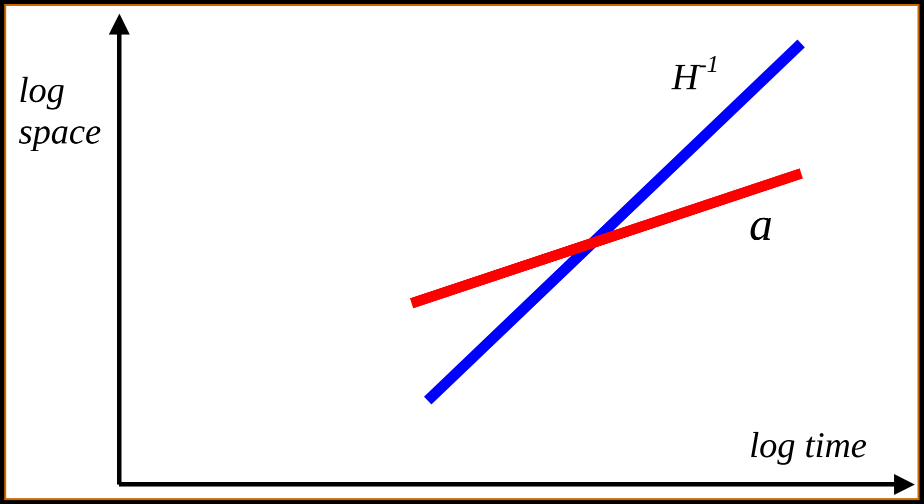
- CMB exhibits correlations on super-Hubble scales



Inflationary Party Line

- Super-Hubble wavelengths in inflation

  are the ones most relevant for CMB observations



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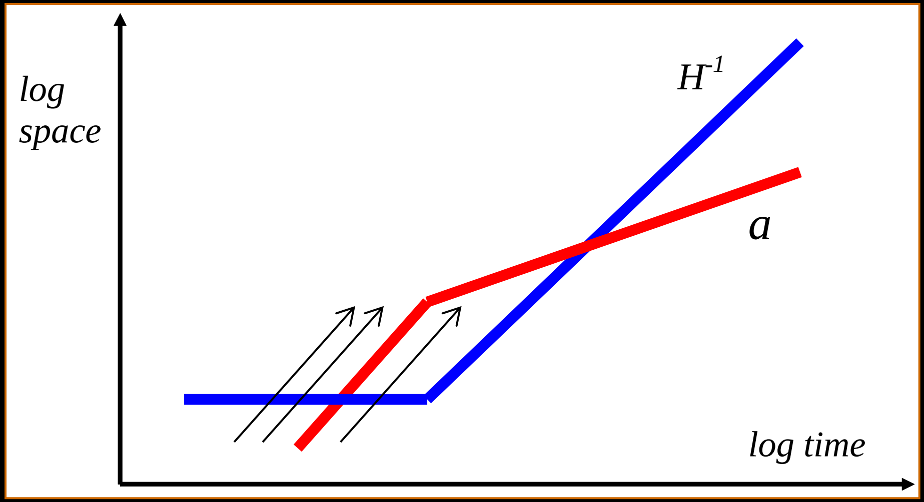


Long-standing Puzzle

- Super-Hubble wavelengths in inflation
  are the ones most relevant for CMB observations
- Longest wavelength modes in general
  are most efficiently described by appropriate EFT
- What is the EFT for these modes?

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.

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

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

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.

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.

eg: particle moving through a medium

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

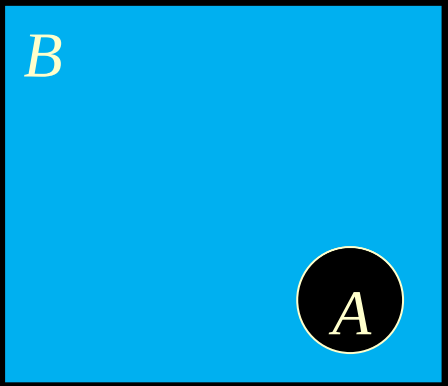
courtesy Scientific American

EFTs w/o Effective Lagrangians

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:

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

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

for $A \ll B$ this limit can be a Markov process

EFTs w/o Effective Lagrangians

Perturbatively:

$$(d\rho_A/dt)_{cg} = i[W, \rho_A\,]$$
$$\qquad\qquad + \int dt' Tr_B\big[V, [V', \rho_A]\big] + \cdots$$

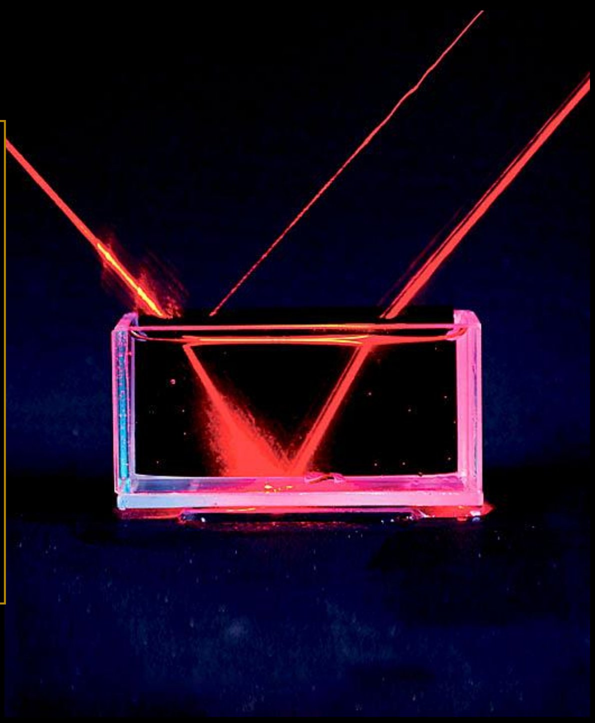
where $\mathrm{W} = Tr_B V$

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:

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

for $A \ll B$ *this limit can be* (



www.osa-opn.org

EFTs w/o Effective Lagrangians

arXiv: 1408:5002

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: $t_c \approx H^{-1}$

Part II

DIAGONAL EVOLUTION

How do diagonal elements evolve?

Late time evolution

DIAGONAL EVOLUTION

Diagonal Evolution|

What is implied for the diagonal part of ρ_A?

Inflationary fact: modes with wavelength longer than the Hubble scale become squeezed, with the spread of momenta shrinking after several Hubble times.

Quantum analog of the classical freezing of modes

$$\nabla^2\varphi = \ddot{\varphi} + 3H\dot{\varphi}$$

Diagonal Evolution|

What is implied for the diagonal part of ρ_A?

Inflationary fact: modes with wavelength longer than the Hubble scale become squeezed, with the spread of momenta shrinking after several Hubble times.

Because of this correlation functions largely care only about diagonal elements of ρ_A in a field basis.

Diagonal Evolution|

How do the diagonal parts of ρ_A evolve?

For these the free evolution gives probabilities governed by initial quantum state.

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

Diagonal Evolution

Starobsinky, Yokoyama

How do the diagonal parts of ρ_A evolve?

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

$$\frac{\partial P}{\partial t} = N\frac{\partial^2 P}{\partial \varphi^2} + \frac{\partial}{\partial \varphi}(V'P)$$

with $N = H^3/8\pi^2$ and V the scalar potential

as in *Starobinsky's stochastic inflation*

Late-time Secular Evolution|

Why care that Stochastic inflation works?

Late-time evolution of massless fields in de Sitter space can be problematic due to accumulation of secular effects

$$\sigma = \sigma_0 + \sigma_1 log^2 a + \cdots$$

indicating possible breakdown of perturbative evolution for large times

Late-time Secular Evolution|

Why care that Stochastic inflation works?

Late-time evolution of massless fields in de Sitter space can be problematic due to accumulation of secular effects

Woodard and Tsamis have shown for $\lambda\varphi^4$ theory that these secular effects are captured by the late-time static stochastic solutions

$$P = exp(-V/H^4)$$

Late-time Secular Evolution|

Why should this happen?

Master equation is *designed* to handle late-time evolution. Coarse-grained equation

$$\frac{d\rho}{dt} = F(\rho)$$

works provided $t_c \ll t_p$ but solutions can be trusted *even for* $t \gg t_p$ provided that coarse-grained evolution eq holds for overlapping intervals throughout the entire region

Late-time Secular Evolution|

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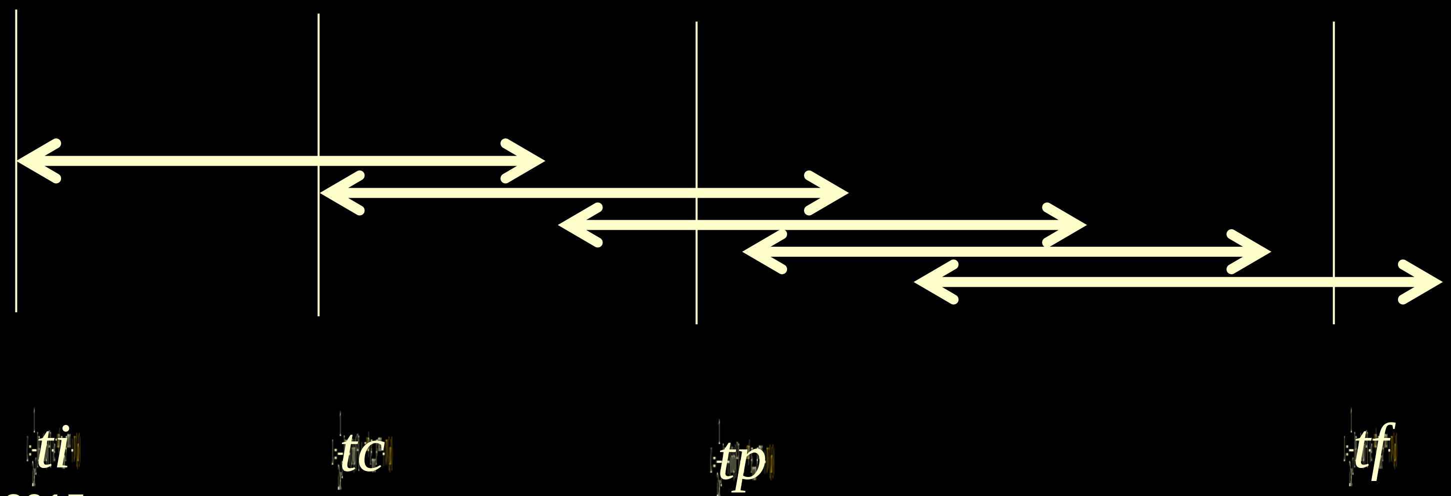

Part III

OFF-DIAGONAL EVOLUTION

How do off-diagonal elements evolve?

OFF-DIAGONAL EVOLUTION

Off-diagonal Evolution|

Master equation alters off-diagonal terms in an interesting way at second order

$$(d\rho_A/dt)_{cg} = i[Tr_B\, V, \rho_A\,] \\ + \int dt' Tr_B\big[V, [V', \rho_A]\big] + \cdots$$

Off-diagonal Evolution

Calculation of off-diagonal matrix elements of ρ_A:

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

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

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 becomes diagonal in field eigenbasis

Off-diagonal Evolution|

Calculation of off-diagonal matrix elements of ρ_A:

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

If variance shrinks with time then system decoheres and squeezing ensures field basis is pointer basis

Off-diagonal Evolution|

Calculation of off-diagonal matrix elements of ρ_A:

Does variance shrink?

If interactions are local and if the only scale in autocorrelation is H then variance narrows on Hubble times:

$$\sigma^{-2} \propto a^3$$

Summary

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 and possibly rapid decoherence of primordial quantum fluctuations.

Summary

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

Potentially allows systematic resummation of secular evolution in late-time limit in variety of settings

Applications to Black Holes?

Fin

Galiano Island Aug 2015