Decoherence of Primordial Scalar Perturbations

Tensor Catalysis and Late-time Resummations

CPB @ McMaster University

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

Quantum Crossroads

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Builds on:

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Punchline

The purity of primordial super-Hubble scalar metric fluctuations provides a diagnosis of decoherence

$$\gamma_k(t) = \mathrm{Tr}\,\left(\varrho_k^2\right)$$

Claim: these evolve due to gravitational interactions within the simplest 'single-clock' inflationary models at leading order perturbation theory as follows:

$$\boxed{\gamma_k(t) \simeq 1 - \frac{32H^2}{45\pi^2 M_p^2}\left(\frac{aH}{k_{UV}}\right)^2 \frac{k}{k_{UV}}}$$

This prediction breaks down well before inflation ends

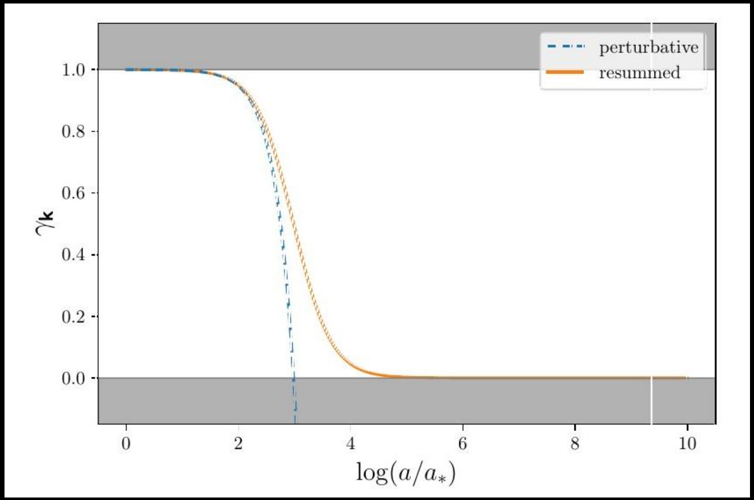
Punchline

But resummation gives a reliable late-time result:

$$\gamma_k(t) \simeq \frac{1}{\sqrt{1+\Xi_k(t)}}$$

with

$$\Xi_k(t) \simeq \frac{64H^2}{45\pi^2 M_p^2}\left(\frac{aH}{k_{UV}}\right)^2 \frac{k}{k_{UV}}$$



Outline

Why decoherence in cosmology?

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Decoherence and Open EFTs

some easy errors to make

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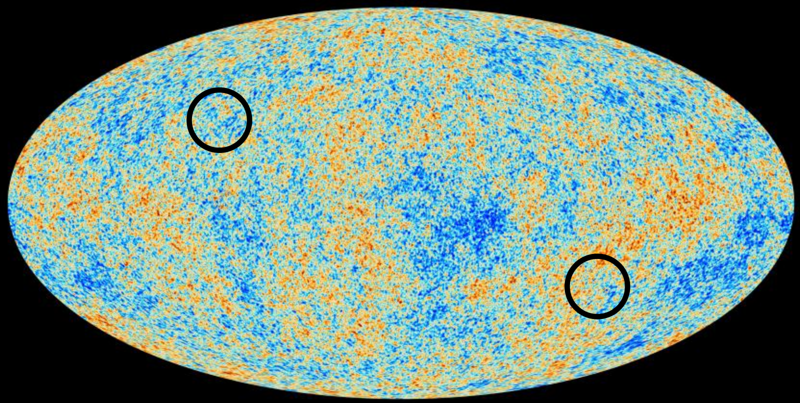
Cosmic Correlations

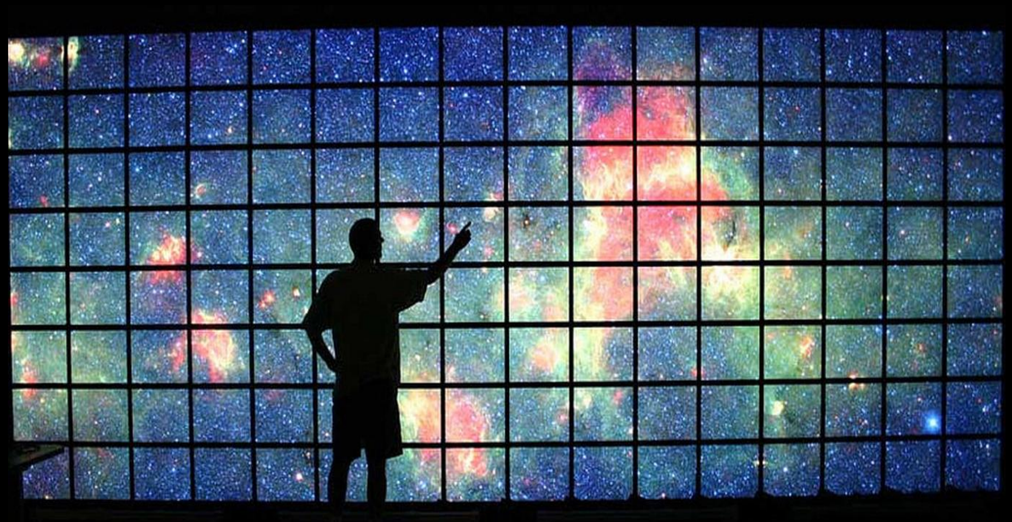


Planck

The CMB provides a snapshot of the early universe when atoms were first forming, with surprising correlations across the sky

Primordial correlations require explanation

Leading ones require QM interplay w gravity



thinkmarketingmagazine.com

Why are correlations surprising?

In an expanding universe of size *a(t)* the Hubble length sets natural upper scale on correlations

$$H = \frac{\dot{a}}{a}$$

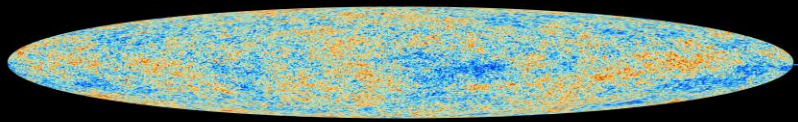
$$-\triangle\,\phi = \ddot{\phi} + \boxed{3H\dot{\phi}} + \frac{k^2}{a^2}\phi = 0$$

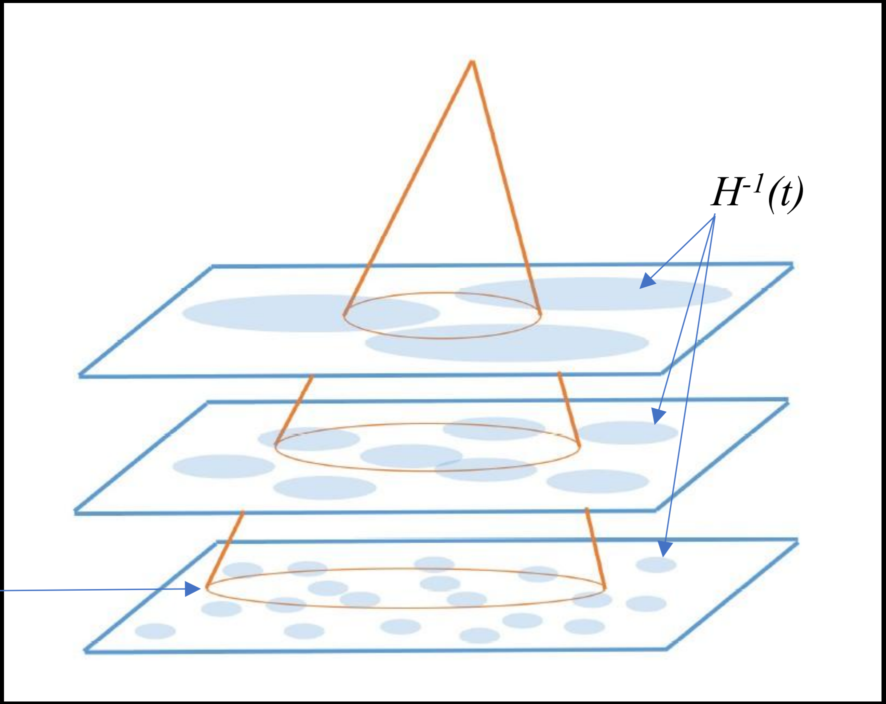
Modes are overdamped and freeze when $k/a << H$

Why are correlations surprising?

Widely separated regions in the past were never within a Hubble length of one another

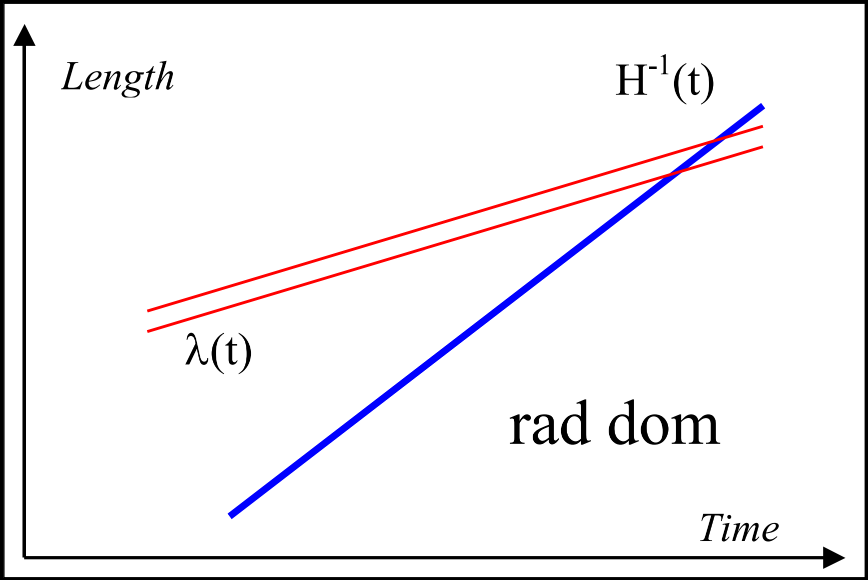
Sound horizon at CMB subtends about a degree





Primordial Fluctuations

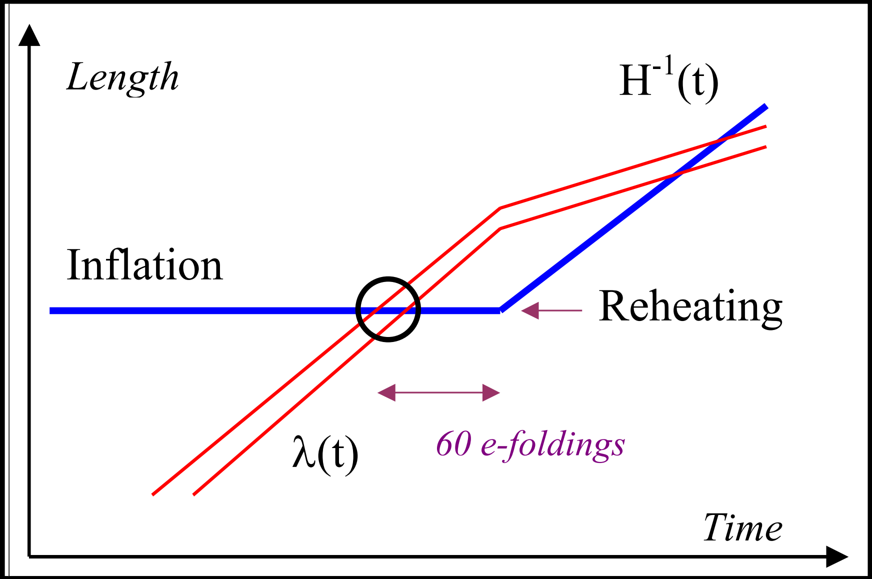
Correlations are a problem because relevant scales in past were super- Hubble



Primordial Fluctuations

Solutions (eg inflation or bounces) change the naïve extrapolation

For inflation H is constant so $a(t) = e^{Ht}$

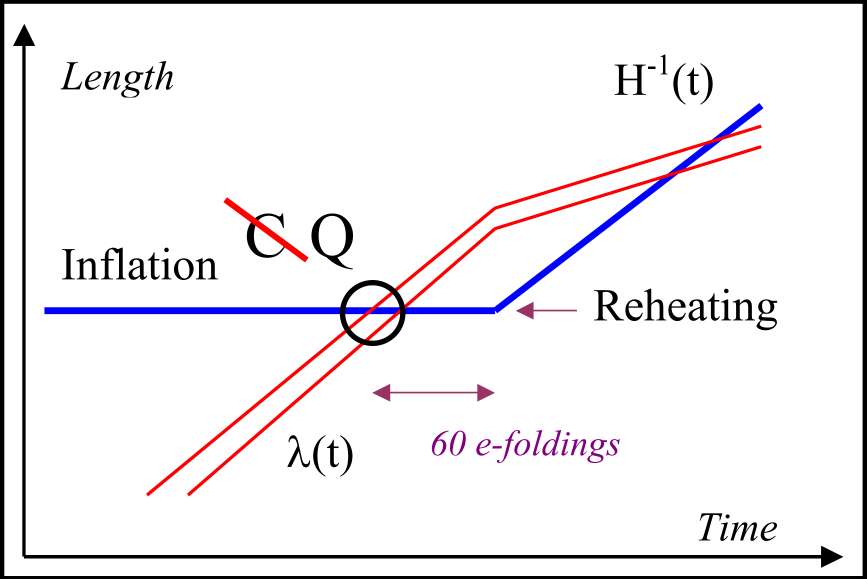


Guth 81, Linde 82, Albrecht & Steinhardt 82

At first sight inflation just moves the problem back to earlier times

Primordial Fluctuations

But inflation ruthlessly irons out classical fluctuations

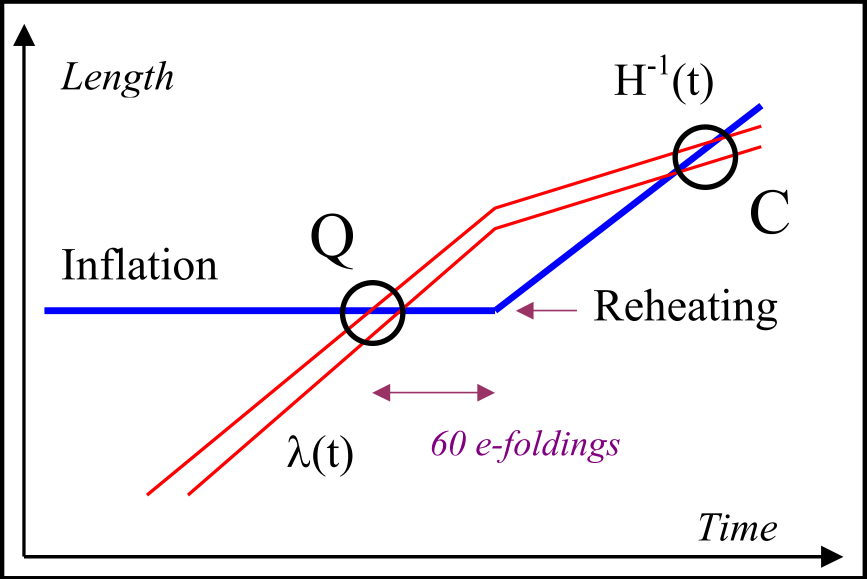


Mukhanov & Chibisov 81, Guth & Pi 82, Starobinsky 82, Hawking 82

Happily, inflation perpetually generates quantum fluctuations at horizon exit with amplitude set by *H*

Quantum Primordial Fluctuations

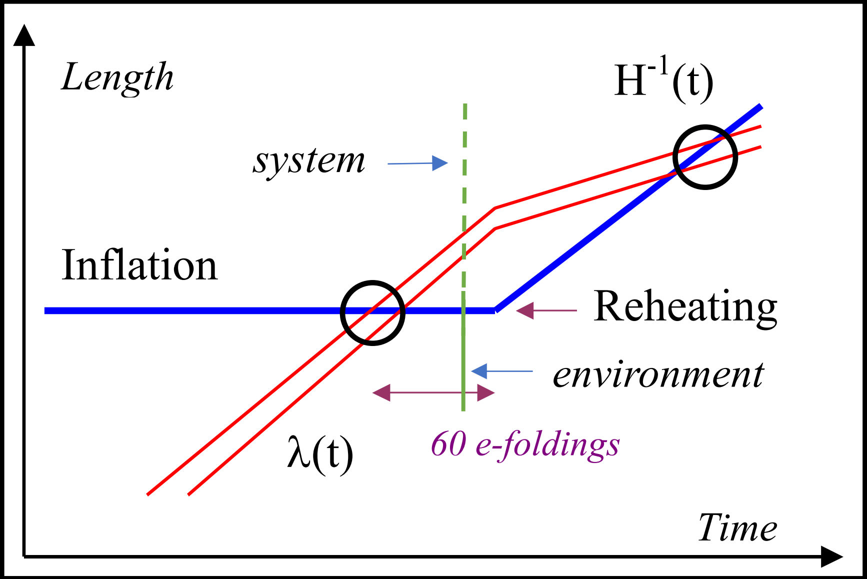
inflation flattens out classical perturbations
but constantly generates new quantum ones



Why do these initially quantum fluctuations look classical when seen at late times?

Quantum Primordial Fluctuations

inflation flattens out classical perturbations
but constantly generates new quantum ones



Here compute decoherence of long wavelength super-Hubble modes by shorter-wavelength ones due to gravity and show it is efficient during inflation.

Brandenberger & LaFlamme 90

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Decoherence and Open EFTs

some easy errors to make

Primordial Decoherence

tensor catalysis

Late-time resummations

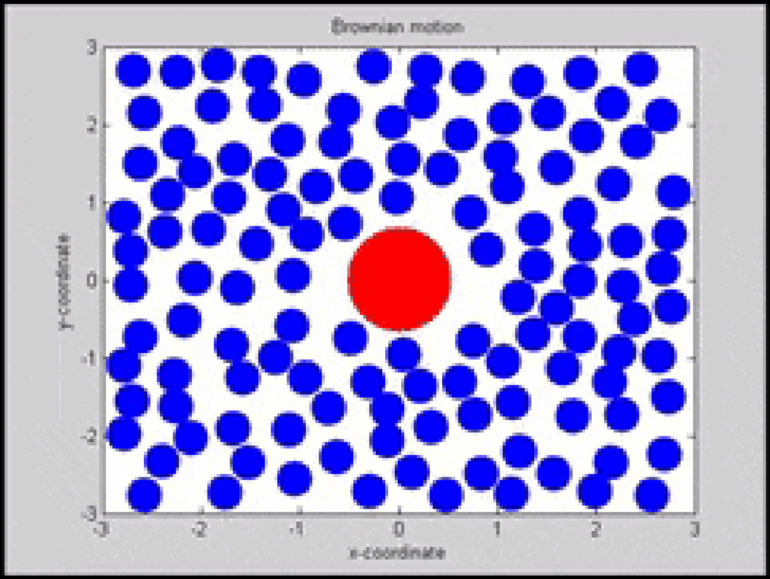
Open systems

Wish to compute evolution when observations are restricted to a subsystem

$$H = H_{\rm sys} + H_{\rm env} + H_{\rm int}$$

$$\varrho_{\rm sys}(t) = {\rm Tr}_{\rm env}\Big[\rho_{\rm tot}(t)\Big]$$

$$\frac{\partial \rho_{\rm tot}}{\partial t} = -i\Big[H\ , \rho_{\rm tot}(t)\Big]$$



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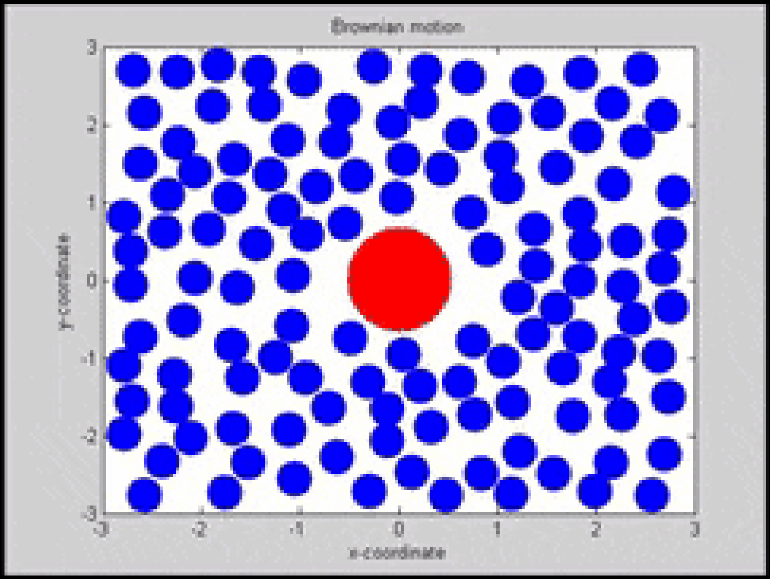

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Problem: RHS of evolution equation not expressed in terms of ρ_{sys} only

Open systems

Can very generally eliminate unobserved sector to obtain evolution for the system state in terms of environmental correlations

(*Nakajima – Zwanzig equation*)

Nakajima 58, Zwanzig 60

$$\text{e.g. if} \quad H_{\text{int}}(t) = A(t) \otimes B(t)$$

$$\partial_t \varrho_{\text{sys}} = -i\Big[A\,, \varrho_{\text{sys}}(t)\Big]\langle B\rangle_{\text{env}}$$

$$+\int_{t_0}^{t} \mathrm{d}s \Big\{ C(s,t)\Big[A(t)\,, \varrho_{\text{sys}}(s)A(s)\Big] - C(t,s)\Big[A(t)\,, A(s)\varrho_{\text{sys}}(s)\Big]\Big\}$$

$$+\cdots$$

$$\text{where} \quad C(s,t) := \langle \delta B(s)\, \delta B(t)\rangle_{\text{env}}$$

Open systems

Starting at second order there is a convolution over time that makes NZ equation hard to use

$$\partial_t \varrho_{\text{sys}}(t) = -i\Big[A\,,\varrho_{\text{sys}}(t)\Big]\langle B\rangle_{\text{env}}$$

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$$+\cdots$$

$$\text{where}\quad C(s,t):=\langle\delta B(s)\,\delta B(t)\rangle_{\rm env}$$

EFT PART: If C is sharply peaked at s = t with width τ and if rest of integrand varies slowly compared to τ then can Taylor expand around s = t

Open EFTs

When such hierarchies exist then evolution can become time local

(*Lindblad equation)*

Lindblad 76, Gorini et al 78

$$\partial_t \varrho_{\rm sys}(t) \simeq -i\Big[A\,,\varrho_{\rm sys}(t)\Big]\langle B\rangle_{\rm env}$$

$$+\Big\{F(t_0,t)\Big[A(t)\,,\varrho_{\rm sys}(t)A(t)\Big] - F(t,t_0)\Big[A(t)\,,A(t)\varrho_{\rm sys}(t)\Big]\Big\}$$

$$+\cdots$$

$$\text{where}\quad F(t,t_0) := \int_{t_0}^{t} {\rm d}s\; C(s,t)$$

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$$+\cdots$$

$$\text{where} \quad F(t,t_0) := \int_{t_0}^{t} \mathrm{d}s\, C(s,t)$$

This can be useful for resummation if F is independent of t_0

Relevance for decoherence

First order term predicts Liouville evolution and so never contributes to decoherence

$$\partial_t \varrho_{\rm sys}(t) \simeq -i\Big[A\,,\varrho_{\rm sys}(t)\Big]\langle B\rangle_{\rm env}$$

Second order term inequivalent to Hamiltonian evolution and so is the leading contribution to decoherence

$$+\Big\{F(t_0,t)\Big[A(t)\,,\varrho_{\rm sys}(t)A(t)\Big] - F(t,t_0)\Big[A(t)\,,A(t)\varrho_{\rm sys}(t)\Big]\Big\}$$

If interactions have the form (suggested by GR)

$$\boxed{\mathcal{L}_{\rm int} = \lambda v(\partial v)^2 + \lambda^2 v^2(\partial v)^2 + \lambda^3 v^3(\partial v)^2 + \cdots}$$

Then leading decoherence is order λ^2 and involves only cubic interactions

System vs environment

Must divide these up into system and environmental parts, for example for

$$\mathcal{L}_{\rm int} = \lambda v \, (\partial v)^2 + \cdots$$

with $$v = v_{\rm sys}(k < k_*) + v_{\rm env}(k > k_*)$$

Then couplings between short and long-wavelength sectors are

$$\mathcal{L} \ni v_{\rm sys}(\partial v_{\rm sys})^2 \,,\; v_{\rm sys}(\partial v_{\rm env})^2 \,,\; v_{\rm env}(\partial v_{\rm env} \cdot \partial v_{\rm sys}) \,,$$
$$v_{\rm env}(\partial v_{\rm sys})^2 \,,\; v_{\rm env}(\partial v_{\rm env})^2 \,, \cdots$$

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$$v_{\text{env}}(\partial v_{\text{sys}})^2 \, , \; v_{\text{env}}(\cancel{\partial v_{\text{env}}})^2 \, , \cdots$$

Doesn't couple system to environment

System vs environment

Must divide these up into system and environmental parts, for example for

$$\mathcal{L}_{\rm int} = \lambda v \left(\partial v\right)^2 + \cdots$$

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$$\mathcal{L} \ni v_{\rm sys}(\cancel{\partial v_{\rm sys}})^2\,,\; v_{\rm sys}(\partial v_{\rm env})^2\,,\; v_{\rm env}(\partial v_{\rm env}\cdot\partial v_{\rm sys})\,,$$
$$v_{\rm env}(\cancel{\partial v_{\rm sys}})^2\,,\; v_{\rm env}(\cancel{\partial v_{\rm env}})^2\,,\cdots$$

Forbidden by momentum conservation

2211.11046

System vs environment

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$$\mathcal{L} \ni v_{\rm sys}(\partial \cancel{v}_{\rm sys})^2\,,\ \boxed{v_{\rm sys}(\partial v_{\rm env})^2\,,\ v_{\rm env}(\partial v_{\rm env}\cdot\partial v_{\rm sys})},$$
$$v_{\rm env}(\partial \cancel{v}_{\rm sys})^2\,,\ v_{\rm env}(\partial \cancel{v}_{\rm env})^2\,,\cdots$$

Leading interactions are *linear* in the system fields

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Gaussian Leading Behaviour

Because the leading interactions are linear in the system field the system's leading Lindblad evolution **is gaussian**

$$\mathcal{L} \ni \lambda \Big[v_{\rm sys} (\partial v_{\rm env})^2 + v_{\rm env} (\partial v_{\rm env} \cdot \partial v_{\rm sys}) \Big] \,,$$

In particular, all of the leading decoherence information can be determined from the 2-point functions

If different wavenumbers start off uncorrelated then they remain uncorrelated in Gaussian limit

$$\rho(t) = |\Psi\rangle \langle\Psi| = \prod_{\mathbf{k}} \otimes \rho_{\mathbf{k}}(t)$$

Decoherence can be computed wave-number by wave-number

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Toy model: two spectator scalar fields

Consider two scalars on dS coupled through a trilinear interaction where only one of the fields is measured

$$\mathcal{L} = -\sqrt{-g}\Big[(\partial\phi)^2 + (\partial\sigma)^2 + V(\phi,\sigma)\Big]$$

$$V(\phi) = \tfrac{1}{2}\Big(m_e^2\phi^2 + m_s^2\sigma^2 + g\sigma\phi^2\Big)$$

$$\mathrm{d}s^2 = (H\eta)^{-2}\Big[-\mathrm{d}\eta^2 + \delta_{ij}\mathrm{d}x^i\mathrm{d}x^j\Big]$$

Prepare both fields in the Bunch-Davies vacuum and ask how the purity for the field σ evolves in the late-time $\eta \to 0$ limit if ϕ is traced out

$$\varrho_{\mathbf{k}}(\eta) = \mathrm{Tr}_\phi\Big[\rho_{\mathbf{k}}(\eta)\Big] \qquad \gamma_{\mathbf{k}}(\eta) = \mathrm{Tr}_\sigma\Big[\varrho^2_{\mathbf{k}}(\eta)\Big] \quad \text{and so} \quad 0 \le \gamma_{\mathbf{k}} \le 1$$

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$$V(\phi) = \tfrac{1}{2}\Big(m_e^2\phi^2 + m_s^2\sigma^2 + g\sigma\phi^2\Big)$$

Flat space limit carries an important warning: if not done carefully the decoherence falls only like an inverse power of m_e!

$$\gamma_{\mathbf{k}}(t) \simeq 1 - \frac{g^2}{64\pi^2\omega_k m_e}$$ in adiabatic limit

But heavy environment should decouple and be described by a low energy EFT (ie Hamiltonian evolution) to all orders in inverse masses

Open systems

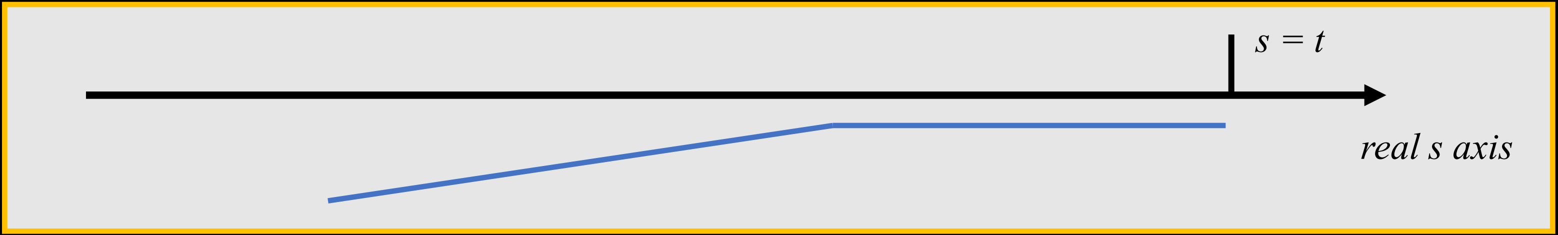
Spurious decoherence can arise if the trace over the high-energy environment is done using only ***approximate*** energy eigenstates

$$\langle i|\varrho_{\rm sys}(t)\,|j\rangle = \sum_n \langle i,n|\rho(t)\,|j,n\rangle$$

Accurate eigenstates can be implemented by evaluating correlators at *t = T(1 – iε)* where the imaginary part ***tends to infinity*** in remote past

$$\partial_t \varrho \ni \int_{-\infty}^t {\rm d}s \Big\{ C(s,t)\Big[A(t)\,,\varrho_{\rm sys}(s)A(s)\Big] - C(t,s)\Big[A(t)\,,A(s)\varrho_{\rm sys}(s)\Big]\Big\}$$

$$\text{where} \quad C(s,t) := \langle \delta B(s)\,\delta B(t)\rangle_{\rm env}$$



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tensor catalysis

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Single clock metric fluctuations

For simplest inflationary models a single field controls breaking of de Sitter symmetries near horizon exit

$$\mathcal{L} = -\sqrt{-g}\Big[M_p^2\mathcal{R} + (\partial\phi)^2 + V(\phi)\Big]$$

$$\phi = \varphi(t)$$

$$\text{and} \quad \mathrm{d}s^2 = -\mathrm{d}t^2 + a^2\delta_{ij}\mathrm{d}x^i\mathrm{d}x^j$$

$$\text{with} \quad 3M_p^2H^2 = \rho = \frac{1}{2}\,\dot{\varphi}^2 + V(\varphi)$$

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$$\text{with} \quad 3M_p^2 H^2 = \rho = \frac{1}{2}\dot{\varphi}^2 + V(\varphi)$$

$$\boxed{\text{slow-roll parameter} \quad \epsilon_1 = -\frac{\dot{H}}{H^2} \simeq \frac{1}{2}(M_p V'/V)^2 \ll 1}$$

Single clock metric fluctuations

Primordial fluctuations are described by deviations from homogeneous background

$$\mathcal{L} = -\sqrt{-g}\Big[M_p^2\mathcal{R} + (\partial\phi)^2 + V(\phi)\Big]$$

$$\phi = \varphi(\eta) + \delta\phi(x,\eta)$$

$$\text{and} \quad \mathrm{d}s^2 = a^2\Big[-(1+2\psi)\mathrm{d}\eta^2 + e^{2\zeta}(\delta_{ij} + h_{ij})\mathrm{d}x^i\mathrm{d}x^j\Big]$$

Single clock metric fluctuations

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$$\boxed{\text{semiclassical control parameter}\quad (H^2/4\pi M_p^2) \ll 1}$$

Single clock metric fluctuations

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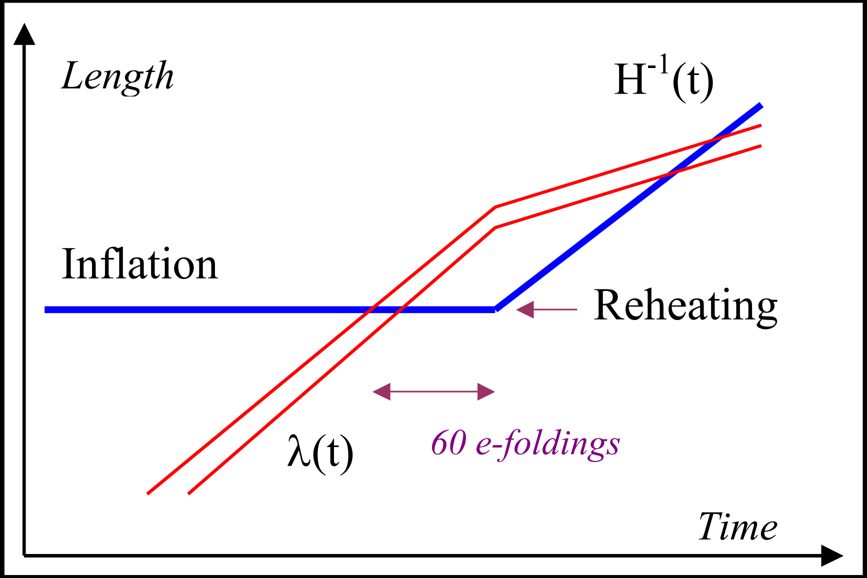
Only one independent scalar variable up to gauge transformations

$$v = a\Big(\delta\phi + \varphi'\psi/H\Big)$$ spatially flat gauge

$$\zeta = (\delta\phi/\sqrt{\epsilon}M_p) + \cdots$$ comoving gauge

System vs environment

Only a specific range of fluctuation modes is visible to late-time cosmologists



Define environment to be the unobserved (in particular shorter wavelength) modes

$$v = v_{\rm sys}(k < k_*) + v_{\rm env}(k > k_*)$$

System vs environment

Nonlinearity of GR implies many self interactions amongst metric fluctuations:

$$\mathcal{L}_{\rm int} = \frac{\partial^2 h^3}{M_p} + \frac{\partial^2 h^4}{M_p^2} + \frac{\partial^2 h^5}{M_p^3} + \cdots$$

Dominant contribution to decoherence arises at order M_p^{-2} and involves only cubic interactions

Can compute evolution and show that it becomes time-local for super-Hubble modes at times long compared with the Hubble time

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System vs environment

Complete basis of cubic interactions amongst metric fluctuations is known

Maldacena 04

$$\mathcal{L}_{sss} = \frac{\sqrt{\epsilon}}{aM_p} \, (\partial v)^2 v + \cdots$$

$$\mathcal{L}_{stt} = \frac{\sqrt{\epsilon}}{aM_p} \, (\partial_k h_{ij})^2 v + \cdots$$

$$\mathcal{L}_{sst} = \frac{1}{aM_p} \, (\partial_i v \partial_j v) h^{ij} + \cdots$$

$$\mathcal{L}_{ttt} = \frac{1}{aM_p} \, h(\partial h)^2 + \cdots$$

tensor decoherence is ***not*** slow-roll suppressed

$$\partial_t \gamma_k \sim \frac{H^2}{M_p^2}$$

ellipses include both competitive and subdominant terms

System vs environment

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Many authors expected that scalar decoherence *is* slow-roll suppressed

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Complete basis of cubic interactions amongst metric fluctuations is known

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$$\mathcal{L}_{sss} = \frac{\sqrt{\epsilon}}{aM_p}\,(\partial v)^2 v + \cdots$$

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$$\mathcal{L}_{ttt} = \frac{1}{aM_p}\,h(\partial h)^2 + \cdots$$

But scalar decoherence also ***NOT*** slow-roll suppressed

$$\partial_t \gamma_k \sim \frac{H^2}{M_p^2}$$

requires ***BOTH*** tensor and scalar environments

2607.22914

Purity evolution

Evolution of each mode is Markovian at late times for super-Hubble modes, leading to the following evolution of the purity

$$\frac{1}{k}\frac{\partial \gamma_k}{\partial \eta} \simeq -\frac{8H^2}{5\pi^2 M_p^2}\left(\frac{aH}{k_{UV}}\right)^3\left(\frac{8}{9}-\frac{k^2}{5k_{UV}^2}\right)$$

where $\eta = -H^{-1}e^{-Ht}$ is conformal time

Integrating implies $$\boxed{\gamma_k \simeq 1 - \frac{32H^2}{45\pi^2 M_p^2}\left(\frac{aH}{k_{UV}}\right)^2 \frac{k}{k_{UV}}}$$

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Result is ***UV finite*** (as it must be since all UV divergences can be renormalized into an effective Hamiltonian (and so cannot decohere at leading order)

Result grows exponentially without limit with time, eventually signalling the breakdown of perturbation theory

2607.22914

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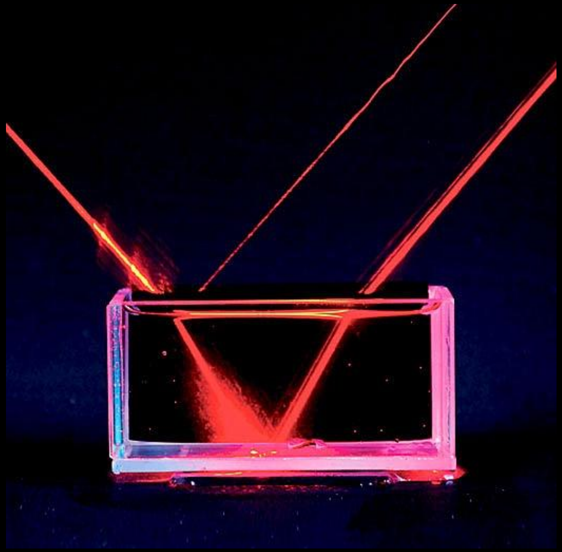
Late-time perturbative breakdown

Perturbative methods ***generically*** break down at late times (except possibly for scattering problems)

$$\exp\Big[-i(H_0 + H_{\rm int})t\Big] \quad \text{vs} \quad e^{-iH_0 t}\Big(1 - iH_{\rm int}t + \cdots\Big)$$



We often can make reliable statements about late-time evolution anyhow (another use for Open EFT methods)

Late-time perturbative breakdown

Pedantic version of resummation argument

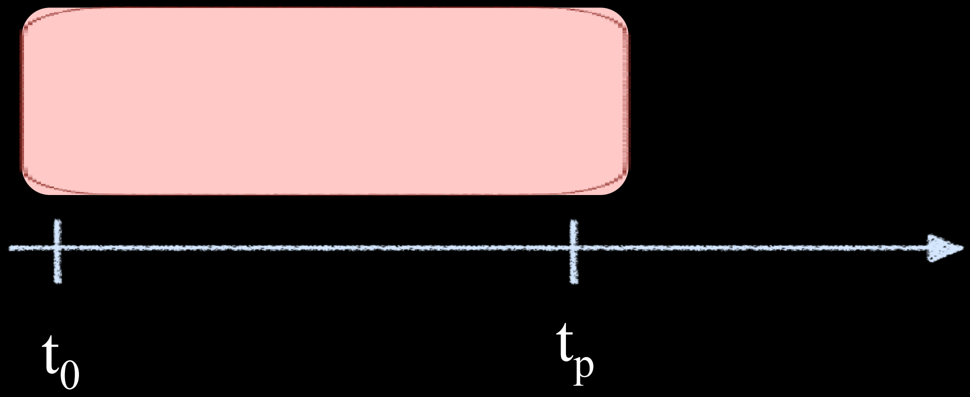
$$n(t) = n_0\, e^{-\Gamma t} \quad \text{vs} \quad n(t) = n_0 - \Gamma n_0\, t + \cdots$$

$$\text{with} \quad \Gamma \simeq \mathcal{O}(g^2)$$

Late-time perturbative breakdown

Pedantic version of resummation argument

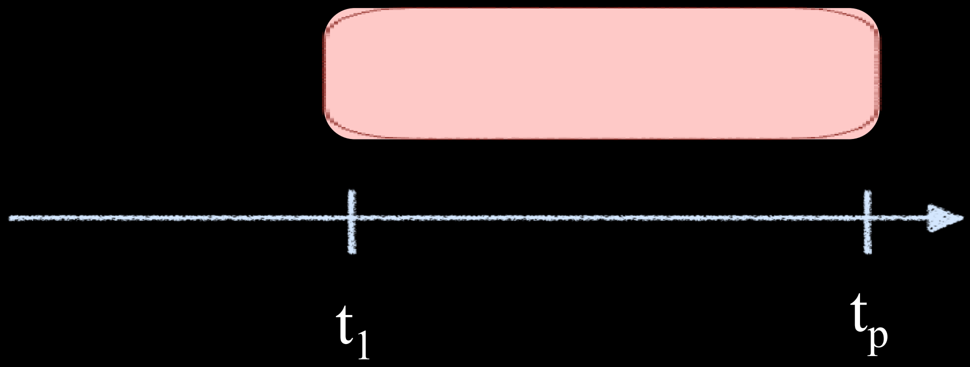
$$n(t) \simeq n(t_0)\Big[1 - \Gamma\,(t - t_0) + \cdots\Big]$$



Late-time perturbative breakdown

Pedantic version of resummation argument

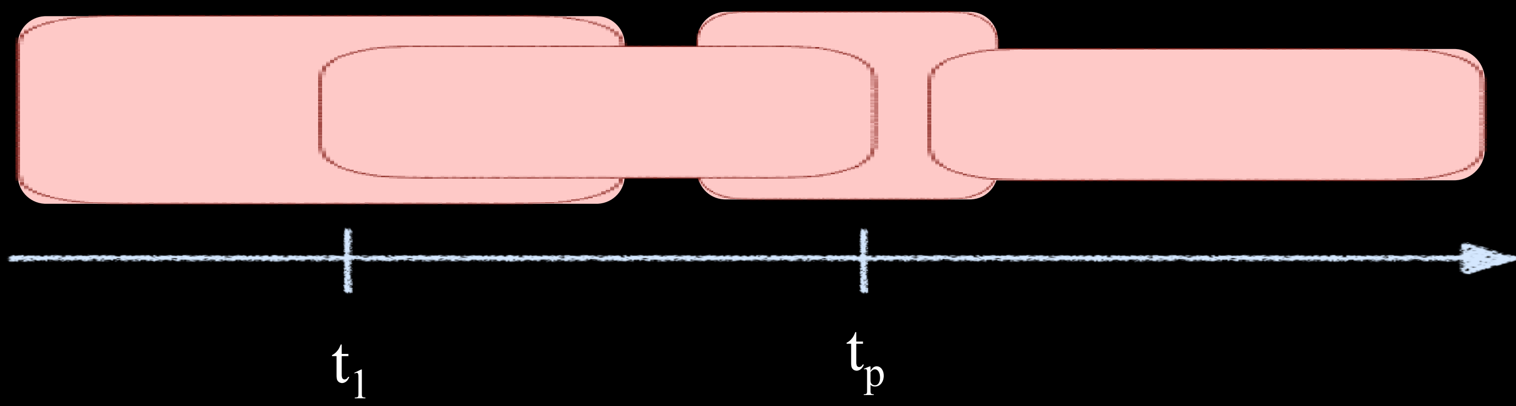
$$n(t) \simeq n(t_1)\left[1 - \Gamma\,(t - t_1) + \cdots\right]$$



Late-time perturbative breakdown

Pedantic version of resummation argument

$$\boxed{\frac{\partial n}{\partial t} = -\Gamma\, n}$$

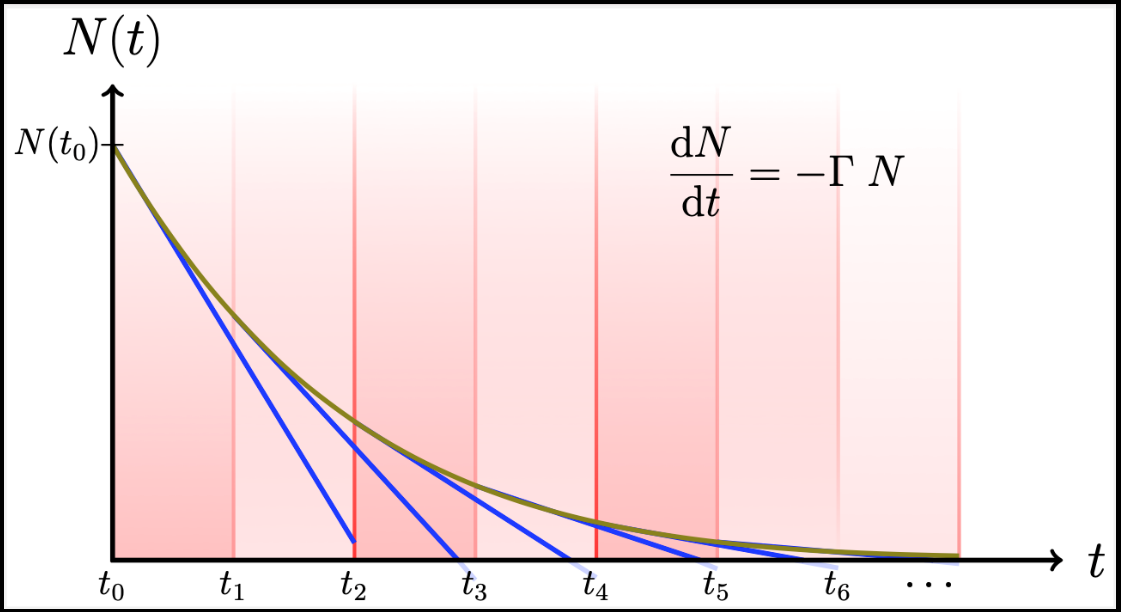


Late-time perturbative breakdown

Integrating differential evolution resums all orders in $g^2\, t$

$$n(t) = n_0\, e^{-\Gamma t}\left[1 + \mathcal{O}(g^4 t)\right]$$

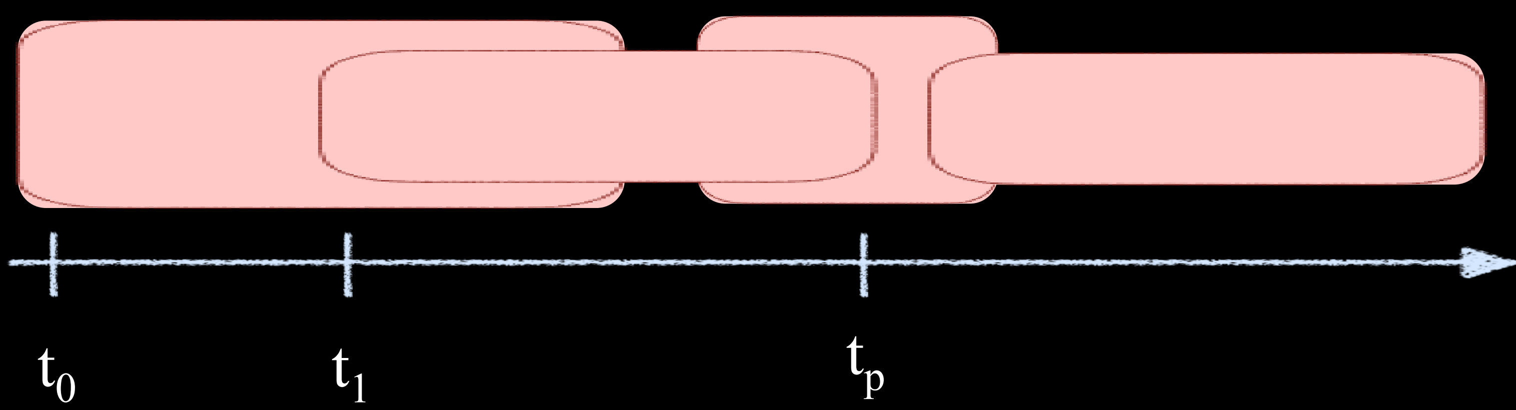
$$\text{with} \quad \Gamma \simeq \mathcal{O}(g^2)$$



Late-time perturbative breakdown

Would NOT have worked if e.g. the differential eq depends on t_0

$$\frac{\partial n}{\partial t} = \int_{t_0}^{t} \mathrm{d}s \, \Gamma(s) \, n(t-s)$$



Late-time Resummation

Can use the Lindblad evolution to derive an evolution equation for purity in the super-Hubble limit

$$\frac{\partial \gamma_{\mathbf{k}}}{\partial \eta} \simeq -C \left(\frac{\gamma_{\mathbf{k}}}{\eta} \right)^3$$

and use perturbation theory to compute the value of C

This has a broader domain of validity (similar to the argument used for exponential decays), and integration gives

$$\boxed{\gamma_k(\eta) \simeq \frac{1}{\sqrt{1 + \Xi_k(\eta)}} \quad \text{with} \quad \Xi_k(\eta) \simeq \frac{64 H^2}{45 \pi^2 M_p^2} \left(\frac{aH}{k_{UV}} \right)^2 \frac{k}{k_{UV}}}$$

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Late-time Resummation

BUT if perturbative results grow and are resummed at late time then should we believe the standard inflationary predictions for the properties of primordial fluctuations?

(Expect so, due to general arguments about super-Hubble modes)

Can use gaussianity to check resummation explicitly by computing the late-time limit of 2-point correlators:

$$\Sigma = \begin{pmatrix} \Sigma_{11} & \Sigma_{12} \\ \Sigma_{21} & \Sigma_{22} \end{pmatrix} = \begin{pmatrix} \mathrm{Tr}\,\left[\zeta_k \zeta_k \varrho_k\right] & \frac{1}{2}\mathrm{Tr}\,\left[\{\zeta_k, p_k\}\varrho_k\right] \\ \frac{1}{2}\mathrm{Tr}\,\left[\{\zeta_k, p_k\}\varrho_k\right] & \mathrm{Tr}\,\left[p_k p_k \varrho_k\right] \end{pmatrix}$$

Where standard calculations compute the leading late time limit of Σ_{11}

Late-time Resummation

The same resummation arguments used for the purity lead to the following evolution equation for these correlators

$$\frac{\partial \Sigma_{ij}}{\partial \eta} = A_{ijkl}(\eta)\, \Sigma_{kl} + B_{ij}(\eta)$$

with coefficients that are calculable at late times

Integrating shows that the correlators have the late-time asymptotic form

$$\Sigma_{11} \simeq s_{11}\,, \quad \Sigma_{12} = \Sigma_{21} \simeq \frac{s_{12}}{\eta} \qquad \Sigma_{22} \simeq \frac{s_{22}}{\eta^2}$$

Where s_{11} remains unchanged from leading order but s_{12} and s_{22} are changed but calculable

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The way forward

Takeaway messages

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Do not yet know definitively, but Open EFT reasoning
provides tools for deciding within any particular scenario

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Preliminary evidence is that unseen short wavelength modes have ample time to decohere observed fluctuations even if they only couple with gravitational strength as predicted by GR. Likely a floor for how quickly primordial fluctuations decohere.

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Is quantum generation detectable?

Possibly, but quantum coherence effects likely only visible in very particular situations

Takeaway Messages

Perturbative methods are usually unreliable at late times

It can be dangerous to extrapolate free-field behaviour arbitrarily far into the future since this is implicitly perturbative

Likely has implications outside of cosmology (such as for black hole information loss puzzles)

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Some predictions can be controlled

Many tools exist elsewhere in physics to deal with this kind of situation – eg Open EFTs - and we should use them for gravitational settings too.


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