Primordial Decoherence & Reliable Late-time Predictions

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Overview

Many QG puzzles are to do with horizons:

Black hole information loss; eternal inflation;…

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Natural description using Open Quantum Systems

These can interestingly differ from Wilsonian description

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Perturbative methods usually fail at late times

Inferences based on nearly free toy systems can be suspect

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Black hole information loss; eternal inflation;…

Perturbative methods usually fail at late times

Inferences based on nearly free toy systems can be suspect

Open EFT tools can also allow predictions at late times

Decoherence of primordial fluctuations as an example…

Overview

In expanding universe Hubble length
sets natural upper scale on correlations

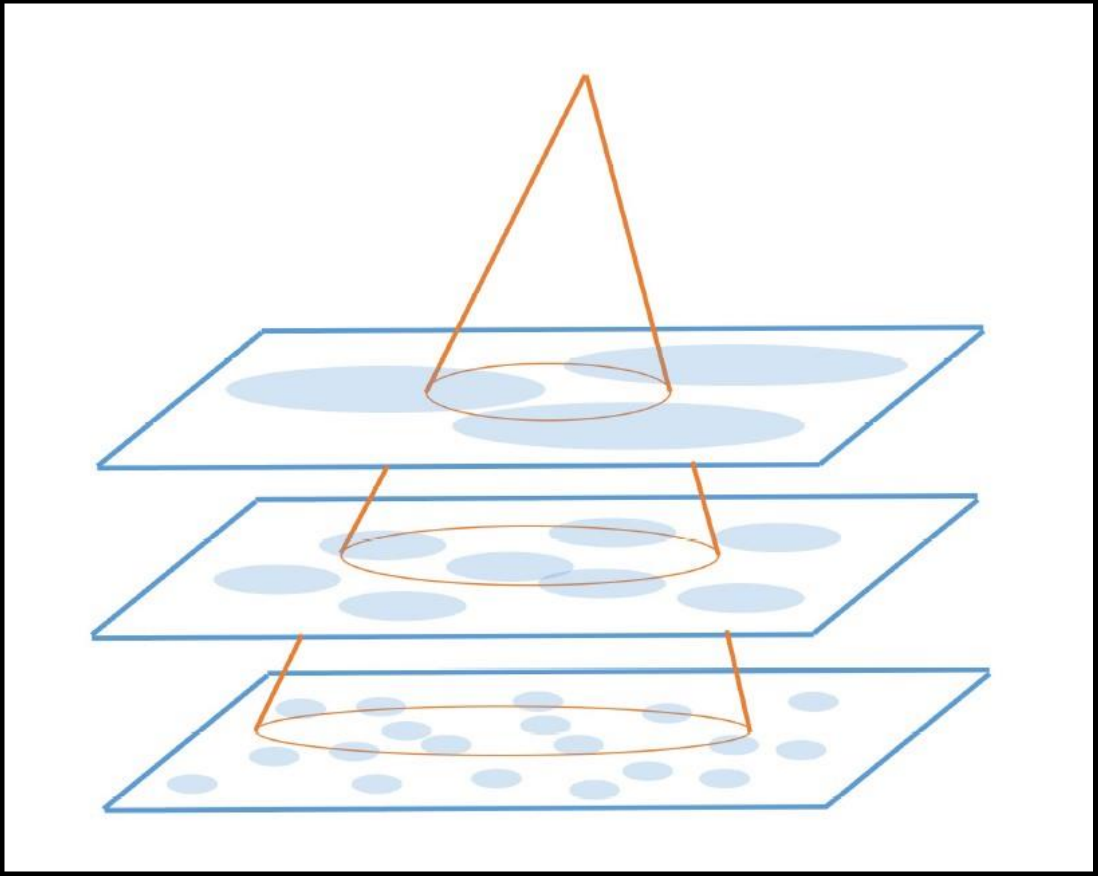
$$-\triangle\,\phi = \ddot{\phi} + \boxed{3H\dot{\phi}} + \frac{k^2}{a^2}\phi = 0$$

with $H = \dfrac{\dot{a}}{a}$

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

Overview

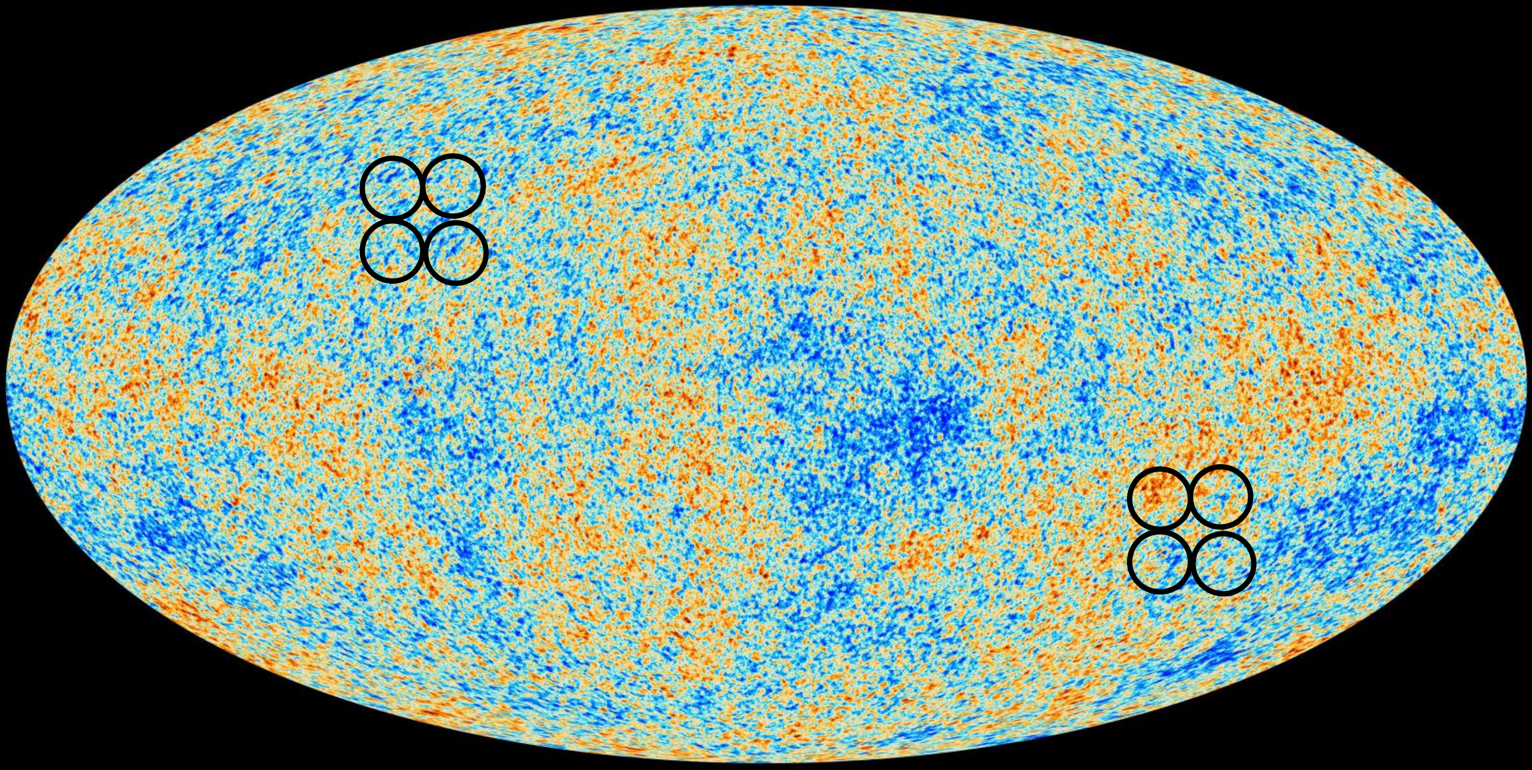
Looking back into the past reveals ever more distant & disconnected Hubble patches



Overview

Primordial correlations require explanation

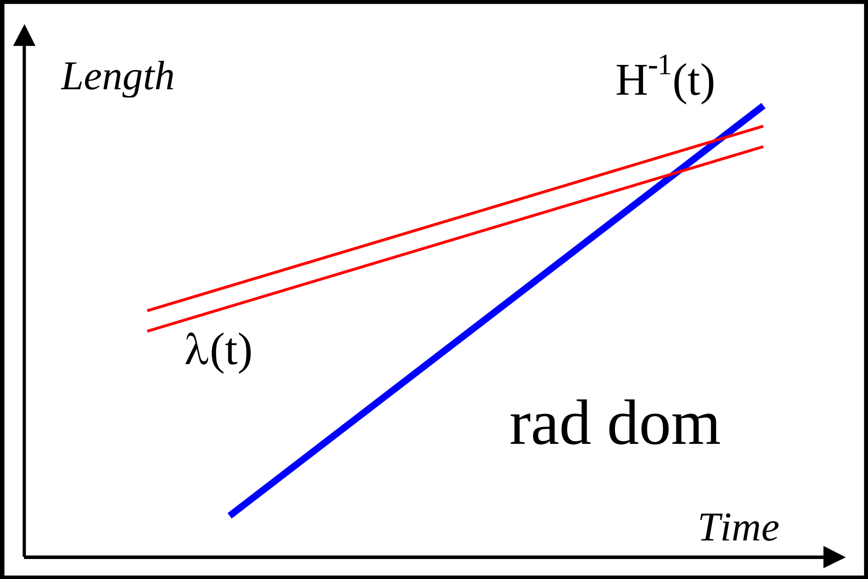
Leading explanations require quantum/gravity interplay



Planck

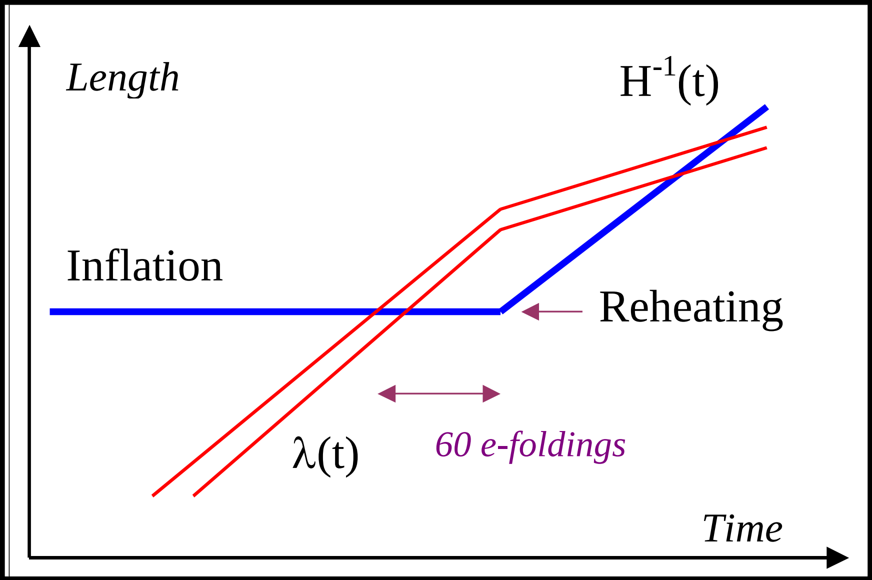
Overview

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



Overview

Solutions (eg inflation or bounces) change the naïve extrapolation

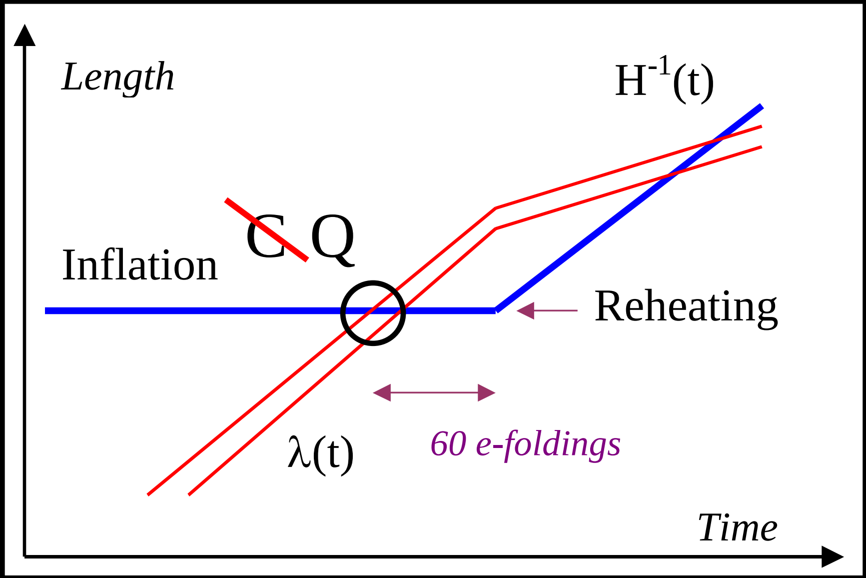


Guth 81, Linde 82, Albrecht & Steinhardt 82

If H is constant then $a(t) = e^{Ht}$

Overview

eg: inflation flattens out classical perturbations
but constantly generates new quantum ones

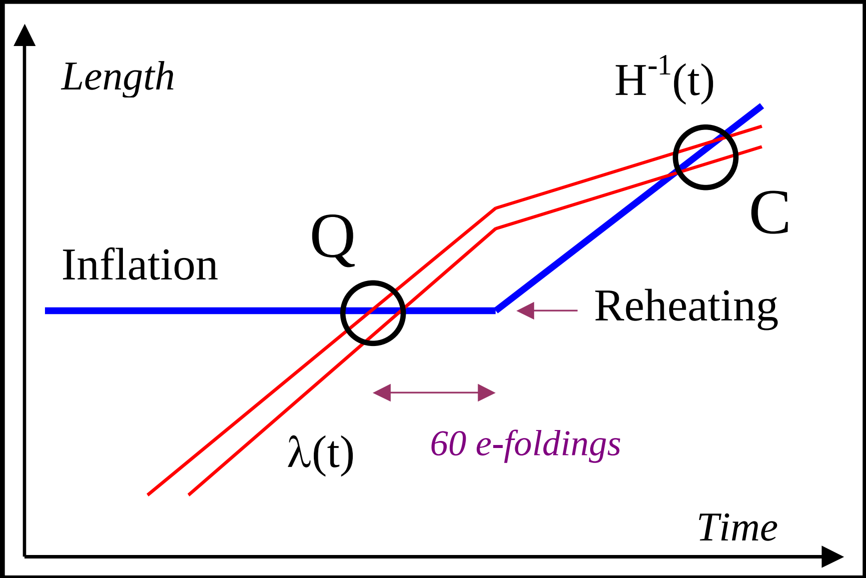


Mukhanov & Chibisov 81, Guth & Pi 82, Starobinsky 82, Hawking 82

Resulting spectrum of fluctuations describes
well the observed structure at later times

Overview

eg: inflation flattens out classical perturbations
but constantly generates new quantum ones



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

Decoherence

Why does this: $$\langle\varphi_1|\rho|\varphi_2\rangle = \Psi[\varphi_1]\,\Psi^*[\varphi_2]$$

Turn into this: $$P[\varphi] = \langle\varphi|\rho|\varphi\rangle = \Big|\Psi[\varphi]\Big|^2$$

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Turn into this: $$P[\varphi] = \langle\varphi|\rho|\varphi\rangle = \Big|\Psi[\varphi]\Big|^2$$

The subject of late-time (stochastic) cosmology

Starobinsky 86; Salopek & Bond 91; Starobinsky & Yokoyama 94;
CPB, Holman & Tasinato 16; Baumgart & Sundrum 19;
Gorbenko & Senatore 19; Mirbabayi 20, Cohen & Green 20

$$\partial_t P = \frac{H^3}{8\pi^2}\left(\frac{\partial^2 P}{\partial\varphi^2}\right) + \frac{\partial}{\partial\varphi}\left(\frac{\partial V}{\partial\varphi}P\right)$$

Decoherence

Why does this: $$\langle \varphi_1 | \rho | \varphi_2 \rangle = \Psi[\varphi_1] \, \Psi^*[\varphi_2]$$

Turn into this: $$P[\varphi] = \langle \varphi | \rho | \varphi \rangle = \Big| \Psi[\varphi] \Big|^2$$

Does the density matrix become diagonal?
If so, why is the field basis the 'pointer' basis?

$$\langle \varphi_1 | \rho | \varphi_2 \rangle \to |\Psi[\varphi_1]|^2 \; \delta[\varphi_1 - \varphi_2]$$

Decoherence

Why does this: $\langle \varphi_1 | \rho | \varphi_2 \rangle = \Psi[\varphi_1] \, \Psi^*[\varphi_2]$

Turn into this: $P[\varphi] = \langle \varphi | \rho | \varphi \rangle = \Big| \Psi[\varphi] \Big|^2$

Does this question really need answering?

(Decoherence w/o decoherence)

$$\langle F[\phi] \rangle = \mathrm{Tr}\,(F\,\rho) = \int \mathcal{D}\varphi P[\varphi] F[\varphi]$$

Starobinsky 86, Salopek & Bond 90, Grischuk & Sidorov 90

Decoherence

Does this question really need answering (part 2)?

State squeezing makes super-Hubble modes `WKB-classical'

Albrecht, et al 93, Starobinsky & Polarski 95

$$\hat{p}\, e^{\lambda S[\varphi]} = -i\lambda S'[\varphi]\, e^{\lambda S[\varphi]}$$

so $[\hat{p}, \hat{\phi}]$ *is subdominant in* $1/\lambda \; [\text{or } \; k/(aH)]$

Decoherence

Even if not required, evolution of density matrix can be computed

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If decoherence occurs before horizon re-entry then quantum effects are unlikely to survive to be measured in the visible sky

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Many have sought different sources for decoherence (other fields, thermal effects, stochastic evolution, etc)

Sakagami 88; Grischuk & Sidorov 89;

Brandenberger et al 90

Calzetta & Hu 95; Lesgourges et al 97; Kiefer et al 98;

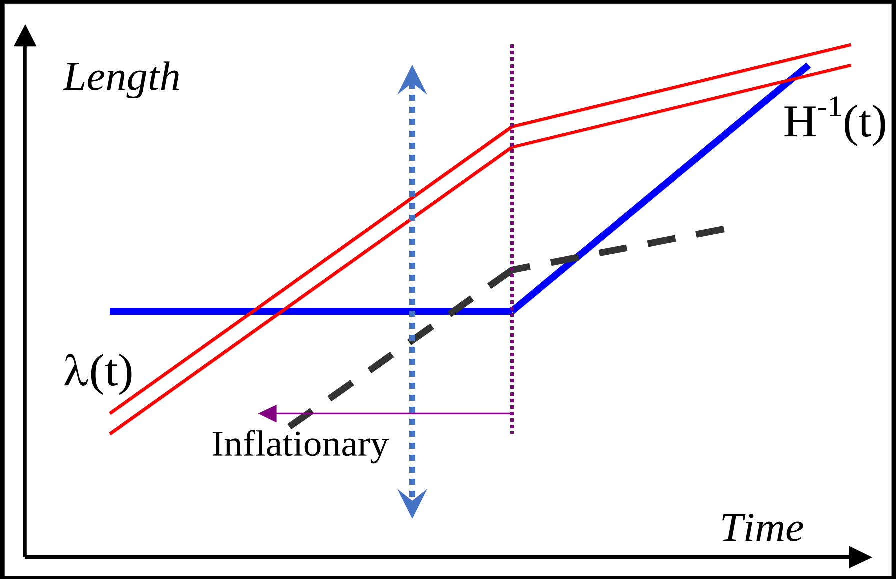
…

Lombardo & Nacir 05; CPB Holman & Hoover 06; Sharman & Moore 07; Kiefer et al 07; Kocksma & Prokopec 11; CPB, Holman, Tasinato & Williams 14; Nelson 16

…

Overview

Here argue that gravitational interactions amongst metric modes during inflation suffice to rapidly diagonalize super-Hubble density matrix in field basis



$$\delta_k(t) \sim \frac{\epsilon H^2}{M_p^2}\left(\frac{Ha}{k}\right)^3 \propto e^{3Ht}$$

CPB et al 14; Nelson 16

Outline

Open EFTs

Late-time control

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Open EFTs

Late-time control

Cosmic decoherence

Metric fluctuations

& gravitational self-interactions

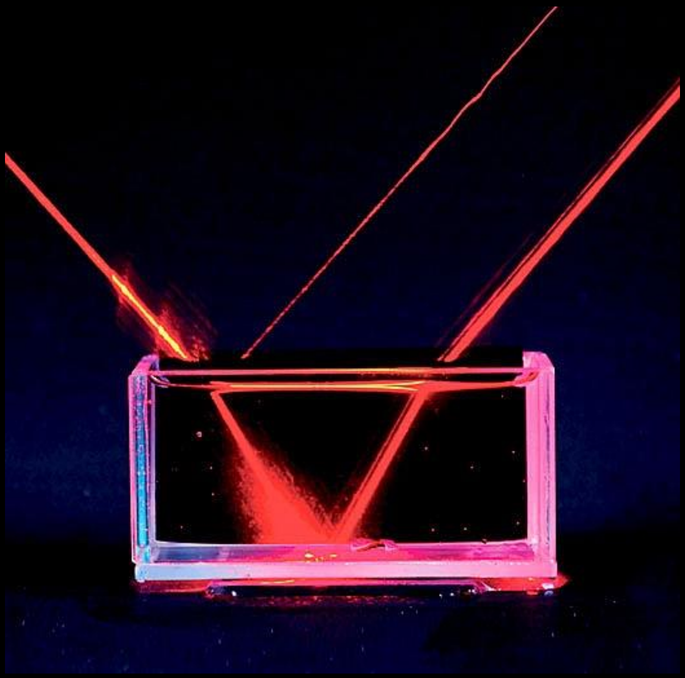
Open EFTs

Late-time control

Late-time perturbative breakdown

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

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



Late-time perturbative breakdown

Perturbative methods generically break down at late times
(also happens in cosmology)

$$\mathcal{L} = -\sqrt{-g}\left[(\partial\phi)^2 + \frac{\lambda}{4!}\,\phi^4\right]$$

$$\langle\phi^{2n}\rangle = (2n-1)!!\left(\frac{H^2}{4\pi^2}\,\ln a\right)^n\left[1 - \frac{n(n+1)}{2}\left(\frac{\lambda}{36\pi^2}\right)\ln^2 a + \cdots\right]$$

Tsamis & Woodard 05

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$$a/a_0 = e^{H(t-t_0)}$$

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$$\langle F[\phi] \rangle = \int \mathcal{D}\varphi P[\varphi] F[\varphi]$$

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Starobinsky 86

Starobinsky & Yokoyama 94

Stochastic inflation captures time evolution of IR sensitive correlations

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$$P_\infty(\varphi) = P_0 \exp\left(-\frac{8\pi^2 V(\varphi)}{3} \right)$$

In this case secular growth signals non-Gaussian late-time distributions.

Late-time perturbative breakdown

Pedantic version of resummation argument

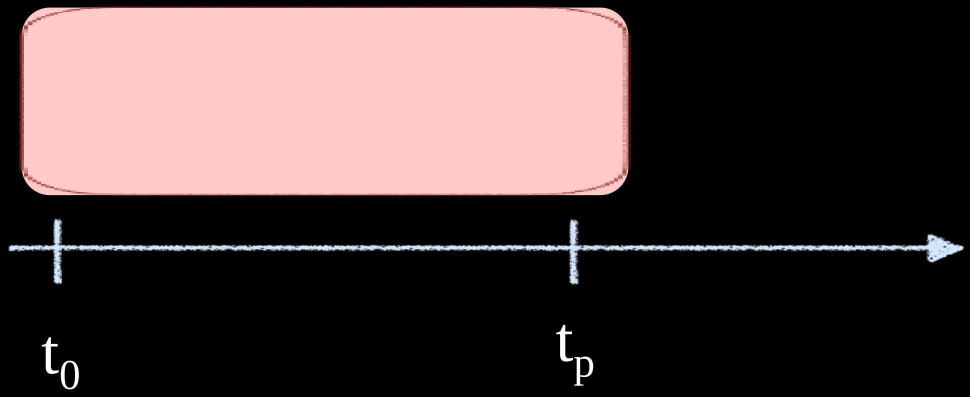
$$n(t) = n_0\, e^{-\Gamma t} \quad \text{vs} \quad n(t) = n_0 - \Gamma n_0\, t + \cdots$$

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

Late-time perturbative breakdown

Pedantic version of resummation argument

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



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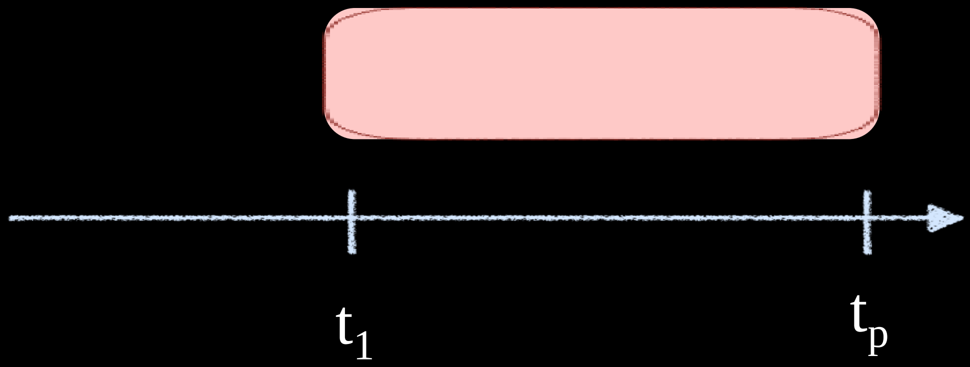
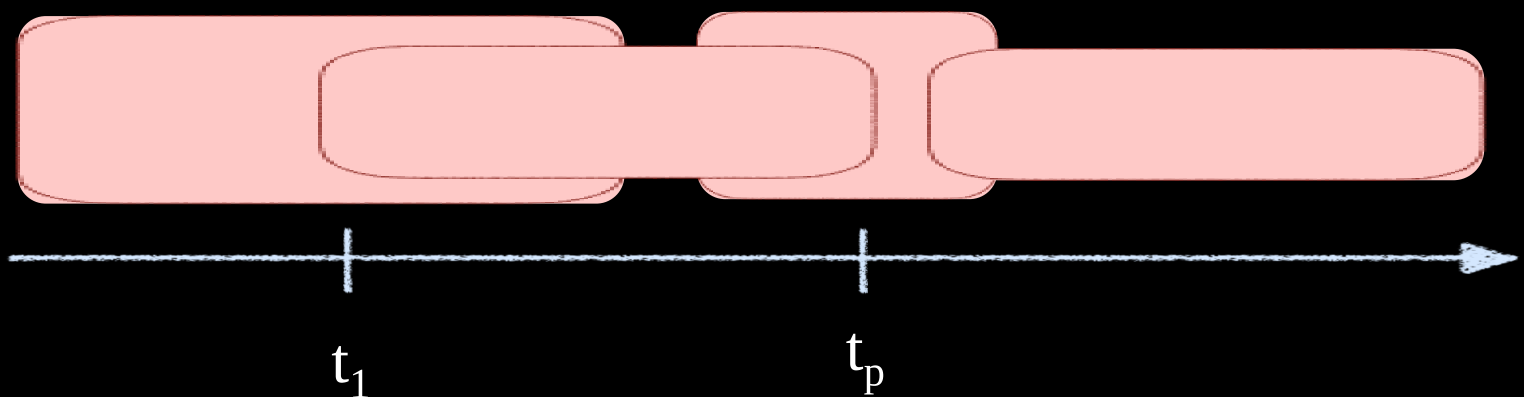


Late-time perturbative breakdown

Pedantic version of resummation argument

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

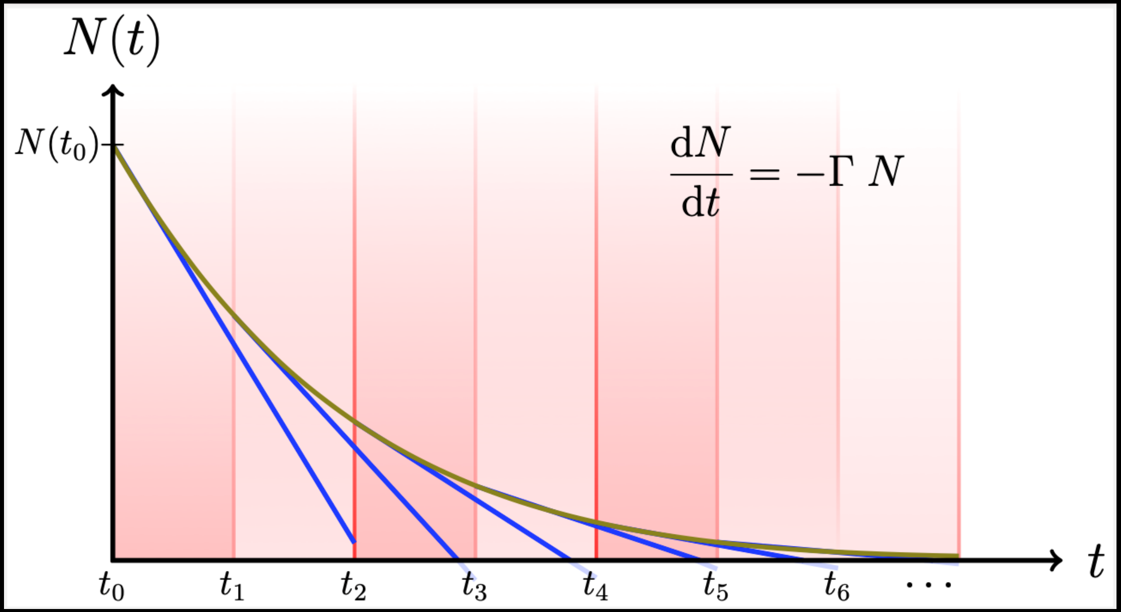


Late-time perturbative breakdown

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

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

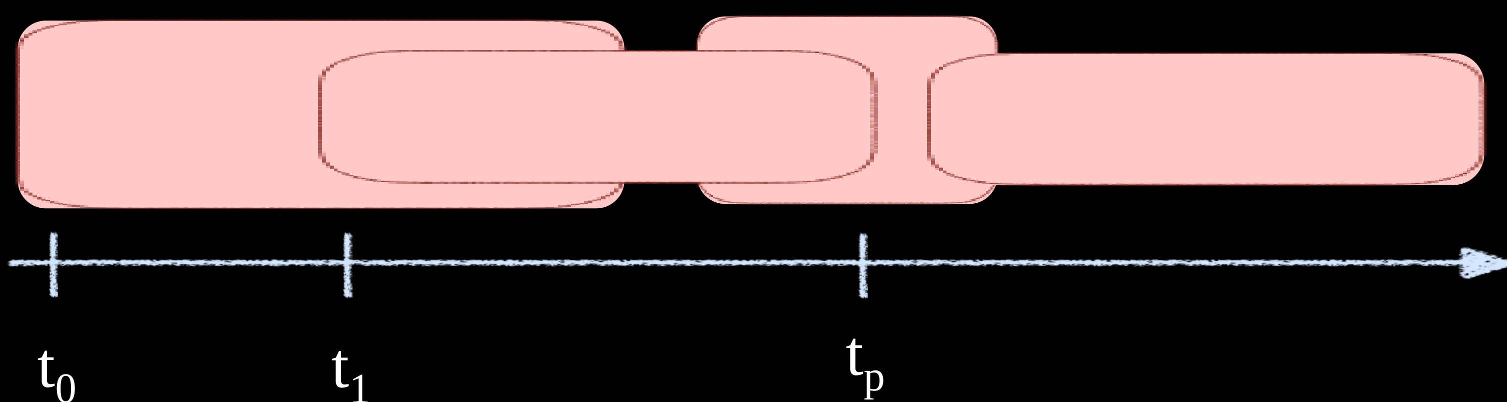
$$\text{with} \quad \Gamma \simeq \mathcal{O}(g^2)$$



Late-time perturbative breakdown

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

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



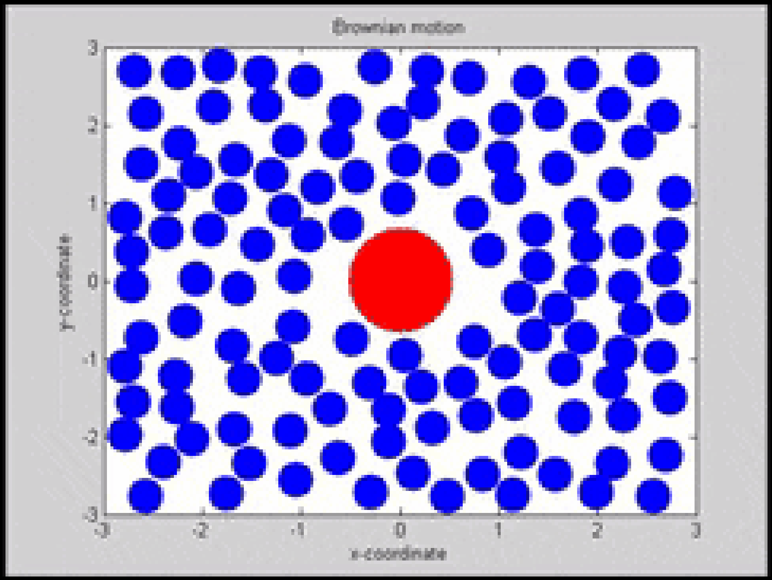
Open systems

Wish to compute evolution when observations are restricted to a subsystem

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

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

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



gfycat.com

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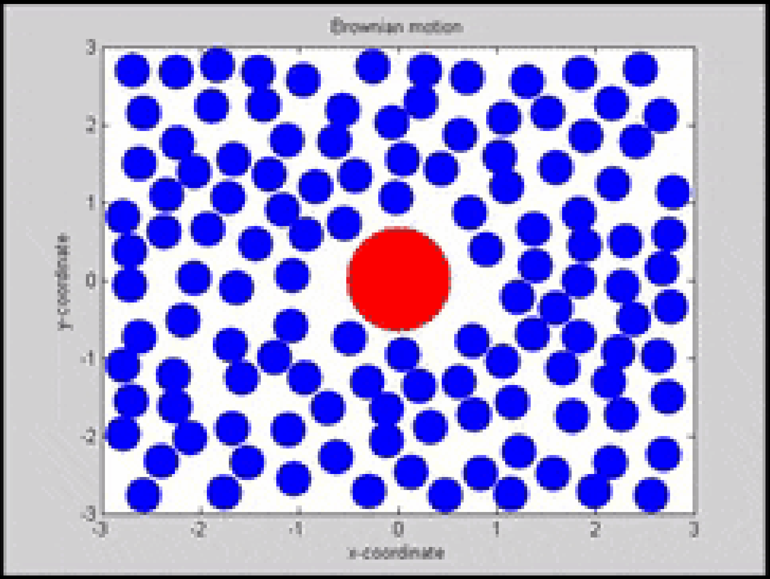

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Problem: RHS of evolution equation not expressed in terms of $\rho_{\rm sys}$ only

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

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

$$\partial_t \varrho_{\rm sys} = -i\Big[A\,,\,\varrho_{\rm sys}(t)\Big]\langle B\rangle_{\rm env}$$
$$+\int_{t_0}^{t} {\rm d}s\Big\{C(s,t)\Big[A(t)\,,\,\varrho_{\rm sys}(s)A(s)\Big] - C(t,s)\Big[A(t)\,,\,A(s)\varrho_{\rm sys}(s)\Big]\Big\}$$
$$+\cdots$$

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

Open systems

Starting at second order the convolution over time makes NZ equation not generically useful for late-time resummation

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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 systems

When such hierarchies exist then evolution becomes Markovian

(*Lindblad equation)*

Lindblad 76, Gorini et al 78

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

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

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$$+\cdots$$

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

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

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

Relevance for decoherence

Second order term inequivalent to Hamiltonian evolution

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

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Second order term is simplest in basis for which A is diagonal and tends to drive off-diagonal components of ρ to zero in this basis

$$\text{e.g. if}\quad A|\alpha\rangle=\alpha|\alpha\rangle$$

$$\partial_t\langle\alpha_1|\varrho_{\rm sys}|\alpha_2\rangle \ni -F\,(\alpha_1-\alpha_2)^2\langle\alpha_1|\varrho_{\rm sys}|\alpha_2\rangle$$

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During inflation squeezing of the state ensures it is the field basis that generically diagonalizes A

Kiefer, Polarski & Starobinsky 98; CPB, Holman & Williams 06; Kiefer et al 07

Relevance for decoherence

Dependence of decoherence on scale factor is determined if correlations are localized in space

$$\text{e.g. if} \quad H_{\rm int}(t) = \int \mathrm{d}^3x \; a^3 \, \mathcal{A}(x,t) \otimes \mathcal{B}(x,t)$$

$$\text{and} \quad \langle \delta\mathcal{B}(x,t)\, \delta\mathcal{B}(x',t') \rangle = \frac{U(x,t)\, \delta^3(x-x')\, \delta(t-t')}{a^3}$$

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$$\text{then} \quad \langle \alpha_1 | \varrho_{\rm sys}(t) | \alpha_2 \rangle = \langle \alpha_1 | \varrho_{\rm sys}(t_0) | \alpha_2 \rangle\; e^{-\Gamma(t)}$$

$$\text{where} \quad \Gamma(t) = \int \mathrm{d}^3x\, \mathrm{d}t\, \Big[\alpha_1(x) - \alpha_2(x)\Big]^2 a^3\, U(x,t)$$

$$\text{has width } \sigma \text{ with} \quad \sigma^{-1} \propto a^3\, U(x,t)$$

Relevance for decoherence

scale factor is

ized in space

$c, t)$

$(t - t')$

e.g. if $\mathcal{A}(x) \propto n(x)$

then for thermal fluctuations

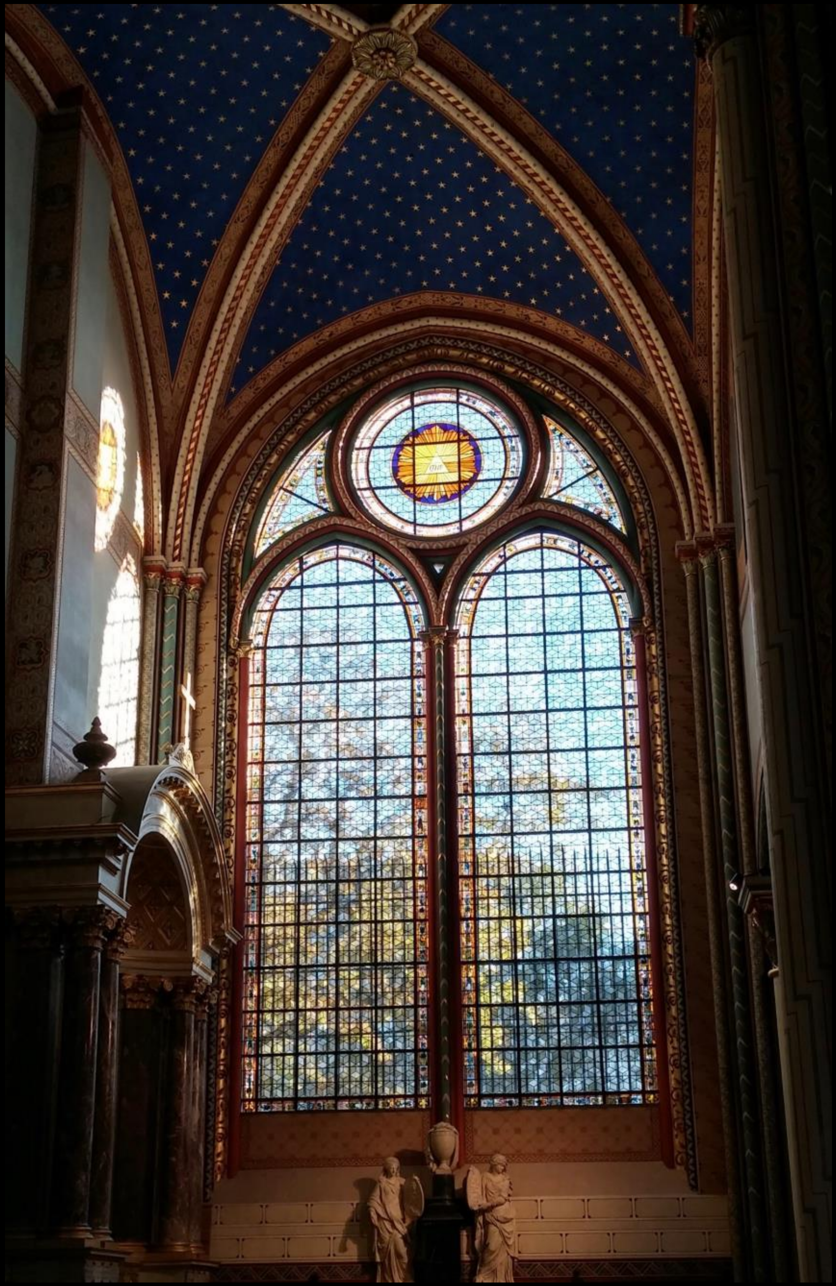
$$U = n^2 \, \kappa_T \, T$$

so width is inversely proportional to temperature

then $\langle \alpha_1 | \varrho_{\rm sys}(t) | \alpha_2 \rangle = \langle \alpha_1 | \varrho_{\rm sys}(t_0) | \alpha_2 \rangle \, e^{-\Gamma(t)}$

where $\Gamma(t) = \int \mathrm{d}^3x \, \mathrm{d}t \, \Big[\alpha_1(x) - \alpha_2(x) \Big]^2 a^3 \, U(x,t)$

has width σ with $\sigma^{-1} \propto a^3 \, U(x,t)$



Cosmic Decoherence

Lindblad for metric fluctuations

Single clock metric fluctuations

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

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

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

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

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

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

Single clock metric fluctuations

Primordial fluctuations are described by deviations from homogeneous background

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

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

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

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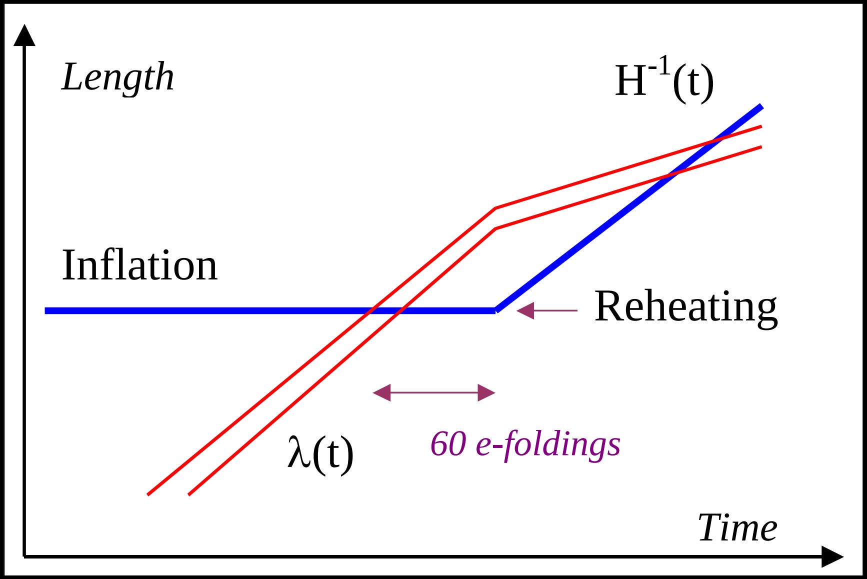
other useful variables

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

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

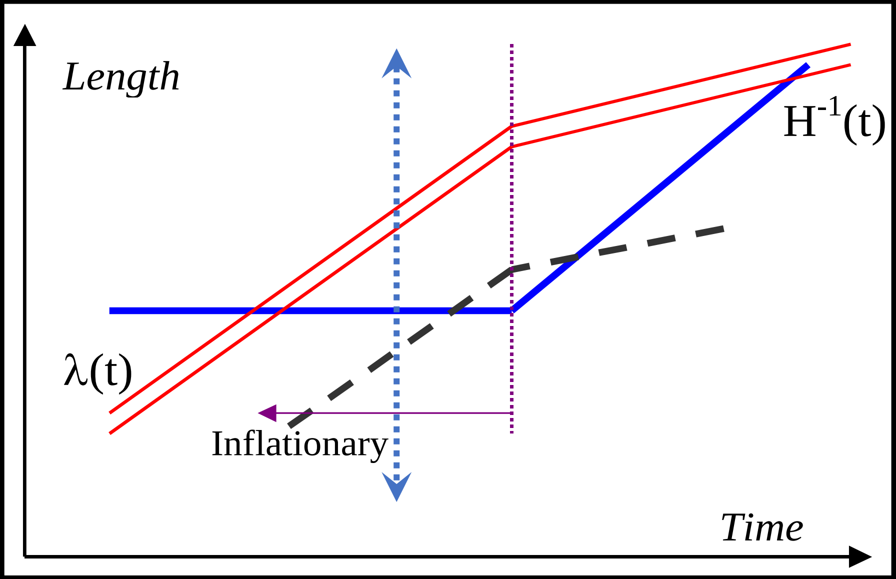
System vs environment

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



System vs environment

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



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

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 arises at order M_p^{-2} and so is 2nd order in cubic interactions or first order in quartic interactions

BUT first order never contributes to decoherence: ***leaves only cubic terms***

System vs environment

Complete basis of cubic interactions amongst metric fluctuations is known

Maldacena 04

$$\mathcal{L}_{sss} = \epsilon^2 M_p^2 \, a(\partial\zeta)^2\zeta + \cdots$$

$$\mathcal{L}_{stt} = \epsilon M_p^2 \, a(\partial_k h_{ij})^2\zeta + \cdots$$

$$\mathcal{L}_{sst} = \epsilon M_p^2 \, a(\partial_i\zeta\partial_j\zeta)h^{ij} + \cdots$$

plus subdominant terms (higher order in slow roll; $d\zeta/dt$ terms; …)

System vs environment

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

$$\mathcal{L} = \epsilon^2 M_p^2 \, a(\partial\zeta)^2\zeta + \cdots$$

Only linear and cubic terms possible for long-wavelength sector

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

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Doesn't couple system to environment

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Subdominant because derivatives are small

Gravitational Lindblad equation

Following general steps leads to Markovian evolution for super-Hubble modes

$$\mathcal{L} = \epsilon^2 M_p^2 \; a(\partial\zeta)^2\zeta + \cdots$$

Environment and system coupled to one another through

$$H_{\rm int} = \int {\rm d}^3x \, \frac{\sqrt{\epsilon}}{a\, M_p} v_{\rm sys} \otimes \mathcal{B}_{\rm env}$$

and so to second order evolution ***does not change mode label k*** and involves environmental correlations of

$$\mathcal{B}_{\rm env} \propto \delta^{ij} \partial_i v_{\rm env} \, \partial_j v_{\rm env}$$

Gravitational Lindblad equation

Evolution of each mode is Markovian at late times for super-Hubble modes, with Schrodinger-picture Lindblad equation:

$$\frac{\mathcal{V}}{(2\pi)^3}\frac{\partial \varrho_k}{\partial \eta} \simeq -\,\mathrm{Re}F_k(\eta,\eta_{\mathrm{in}})\,\Big[v_k,\big[v_k,\varrho_k(\eta)\big]\Big] -i\Big[\,\mathcal{H}^0_k(\eta) - \mathrm{Im}F_k(\eta,\eta_{\mathrm{in}})v_k^2,\ \varrho_k(\eta)\,\Big]$$

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where Im F_k contains a ***UV divergence*** with the right form to be absorbed into the standard Einstein-Hilbert and curvature-squared counterterms

$$\mathrm{Im}\,F_k(\eta,\eta_{\rm in}) \ni \frac{\epsilon H^2 k^2}{1024\pi^2 M_p^2}\left(\frac{40}{(-k\eta)^2} - \frac{92}{3} + \frac{43}{15}(-k\eta)^2\right) \times\left[\frac{2}{n-4} + \log\left(\frac{2k_* + k}{\mu}\right)\right]$$

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Decoherence comes purely from Re F_k which is ***UV finite*** and has a ***universal form*** (independent of k_* and η_{in}) at late super-Hubble times

$$\mathrm{Re}F_k(\eta,\eta_{\rm in}) \simeq \frac{\epsilon H^2 k^2}{1024\pi^2 M_p^2}(1+2)\left[\frac{20\pi}{(-k\eta)^2} + \frac{g(k_*/k, -k\eta_{\rm in})}{(-k\eta)} + \cdots\right]$$

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Scalar environment contributes 1 while tensor environment contributes 2

Cosmic decoherence

Can quantify the decoherence for each mode using

$$\mathrm{Tr}\left[\varrho_k^2\right] = \frac{1}{\sqrt{1 + 4\delta_k(\eta)}}$$

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Lindblad evolution makes the following late-time prediction

$$\delta_k(\eta) \simeq \frac{5(1+2)\epsilon H^2}{96\pi M_p^2(-k\eta)^3} \simeq \frac{5\epsilon H^2}{32\pi M_p^2}\left(\frac{aH}{k}\right)^3$$

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Starts small: $\epsilon^2\left(\frac{H^2}{32\pi\epsilon M_p^2}\right) < 10^{-4}\times 10^{-10}$

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Grows quickly: $\propto \exp(+3Ht)$

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Similar calculation gives effects of scalar environment on tensors

$$\delta_k(\eta) \simeq \boxed{\frac{H^2}{72\pi M_p^2}}\left(\frac{aH}{k}\right)^3$$

For tensor modes decoherence is not slow-roll suppressed

The way forward

Takeaway messages

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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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Are there observable consequences?

Possibly so, but quantum coherence effects only possible if observed fluctuations do not spend too much super-Hubble time during inflation

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

Many tools exist elsewhere in physics to deal with this kind of situation and it behooves us to use them for gravitational settings too.

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Some predictions can be controlled

Small things can accumulate to cause dramatic effects at very late times. These effects need not carry lots of energy or destabilize the geometry.

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