

Title: Decoherence of Inflationary Perturbations due to Gravity

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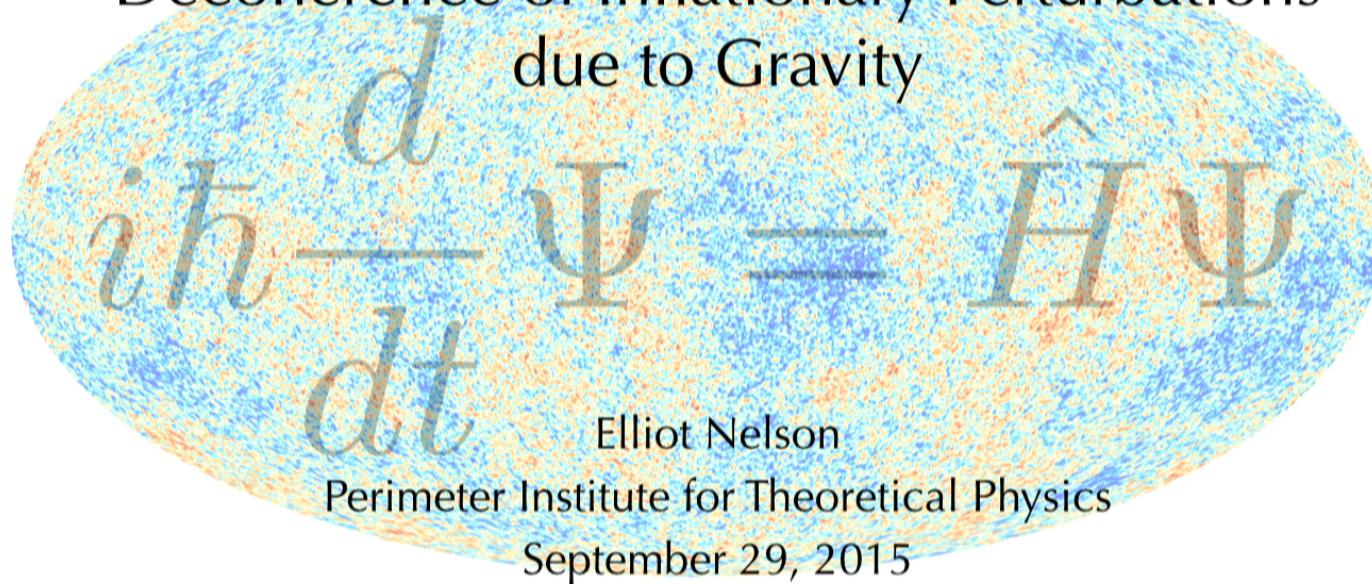
Abstract: <p>In order for quantum fluctuations during inflation to be converted to classical stochastic perturbations, they must couple to an environment which produces decoherence. Gravity introduces inevitable nonlinearities or mode couplings. We study their contribution to quantum-to-classical behavior during inflation. Working in the Schrodinger picture, we evolve the wavefunctional for scalar fluctuations, accounting for minimal gravitational nonlinearities. The reduced density matrix for a given mode is then found by integrating out shorter-scale modes. We find that the nonlinearities produce growing phase oscillations in the wavefunctional, which decohere the single-mode reduced density matrix into a diagonal mixed state. However, the weakness of the coupling delays decoherence until the mode is much longer than the Hubble scale environment modes. In summary, the gravitational coupling of long and short scales is sufficient to produce a mixed state of classical perturbations during inflation.</p>



PERIMETER INSTITUTE  
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# Decoherence of Inflationary Perturbations due to Gravity



Elliot Nelson

Perimeter Institute for Theoretical Physics

September 29, 2015

1510.xxxxx

Elliot Nelson

Perimeter Institute — Tuesday, Sept. 29, 2015



## Decoherence of Inflationary Perturbations due to Gravity

$$\frac{d\Psi}{dt} = \hat{H}\Psi$$

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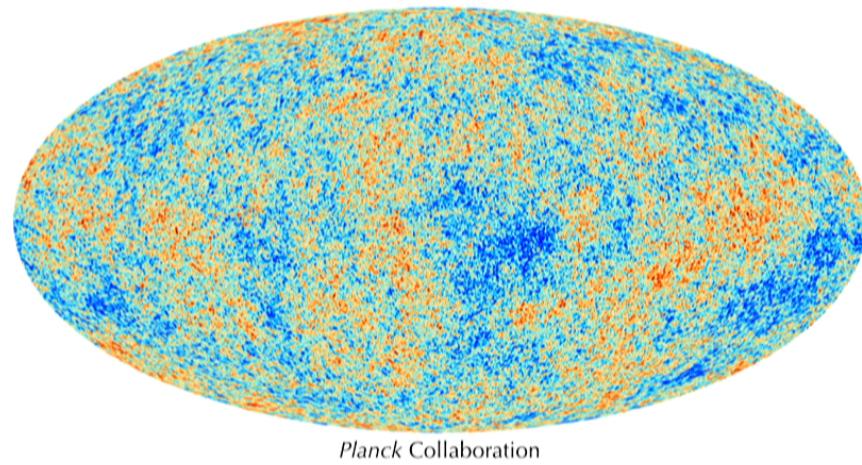
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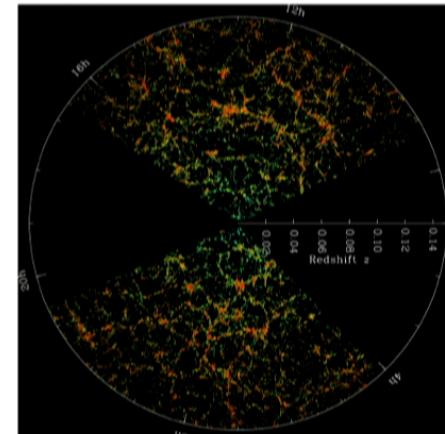
# Outline

1. Inflation and Quantum to Classical behavior
2. Decoherence of Scalar Curvature Perturbations
3. Open questions and summary

# Cosmology: Stochastic Initial Conditions



Planck Collaboration

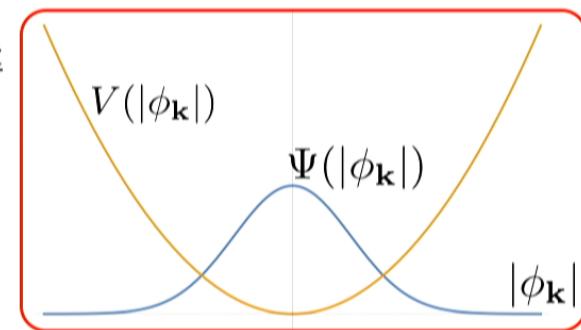


Sloan Digital Sky Survey

**Late universe:** structures form from classical, stochastic perturbations to gravitational field, energy density

**Early universe:** inflation stretches quantum modes of the vacuum to cosmological scales

Classical realization drawn from PDF  $\rho = |\Psi|^2$



# Background: Inflation

## Inflation

$$ds^2 = -dt^2 + a^2(t)d\mathbf{x}^2 = -a^2(\eta)(d\eta^2 + d\mathbf{x}^2)$$

Slow-roll parameters:  $\epsilon \equiv -\dot{H}/H^2$      $\eta_\epsilon \equiv \dot{\epsilon}/\epsilon H$

$$a = e^{Ht} = \frac{-1}{H\eta}$$

$$S = \frac{M_p^2}{2} \int d^4x \sqrt{-g} R_{EH} + S_{\text{matter}}$$

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## Fluctuations: Linear Theory

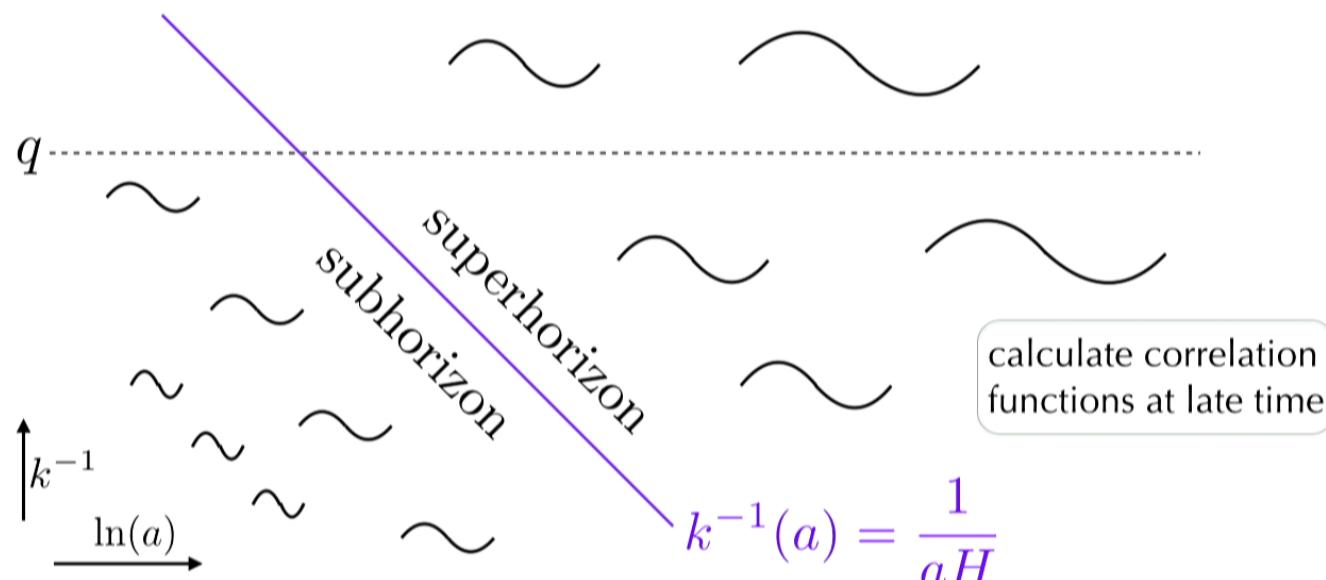
$$g_{ij} = a^2(t) e^{2\zeta(\mathbf{x}, t)} \delta_{ij}$$

$$S_{\text{free}} = \frac{1}{2} \int d^4x 2\epsilon M_p^2 a^3 \left( \dot{\zeta}^2 - \frac{1}{a^2} (\partial_i \zeta)^2 \right) \quad M_p = 1/\sqrt{8\pi G}$$

$\zeta$  = **scalar mode**, arises in **all inflation models** due to breaking time translation invariance of de Sitter space [Cheung et. al. 0709.0293]

- Determines primordial density perturbations & gravitational potential

# Background: Inflation



**Goal: follow the evolution of a mode into superhorizon regime**

# Quantum to Classical Transition

Why do cosmological perturbations look classical? [Kiefer & Polarski, 0810.0087]

Pragmatic perspective: **We can only measure in configuration basis, but not conjugate momentum**

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$$\langle |\zeta_{\mathbf{k}}|^2 \rangle \rightarrow \text{constant}$$

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[Albrecht+, Polarski & Starobinsky, Grishchuk & Sidorov, Guth & Pi]

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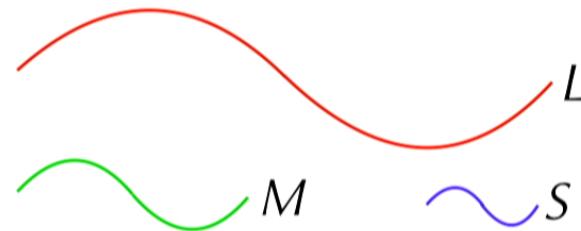
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# Decoherence: Toy Example

**Decoherence = dynamical, irreversible process of entanglement**

Consider a state with the following form:

$$|\Psi\rangle = \left( \sum_i \psi_i^{(L)} |L^{(i)}\rangle \right) \left( \sum_j \psi_j^{(M)} |M^{(j)}\rangle \right) \left( \sum_k \psi_k^{(S)} |S^{(k)}\rangle \right) \text{ (each mode in a coherent superposition)}$$

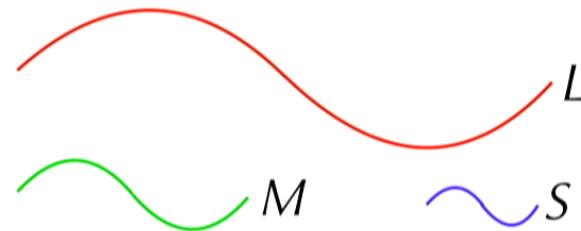


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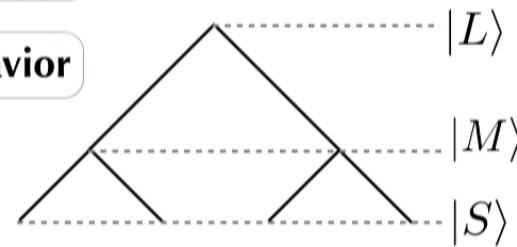
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So,  $\hat{\rho}_L = \sum_i |\psi_i^{(L)}|^2 |L^{(i)}\rangle \langle L^{(i)}|$  = totally decohered

Pure state → mixed state = stochastic behavior

What kind of interaction of  $\zeta$  with an environment will lead to these dynamics?

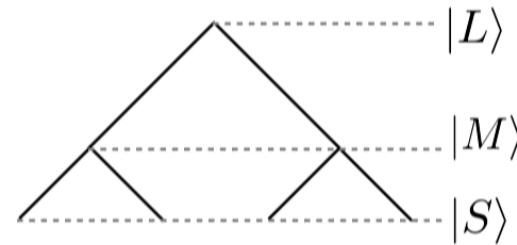
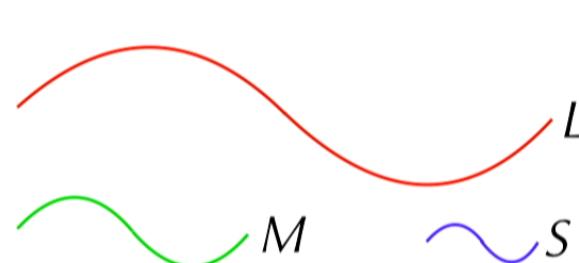


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# Quantum to Classical Transition

Linear theory: each mode evolves independently in a pure state:

$$\Psi = \prod_{\mathbf{q}} \psi(\zeta_{\mathbf{q}}) \quad \text{Need to go beyond linear level}$$

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## Possible environments? system-environment couplings?

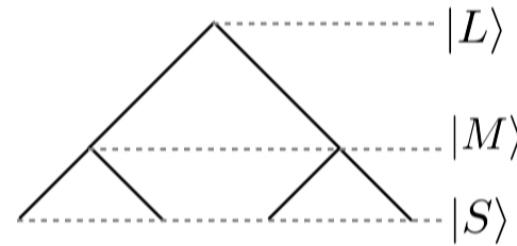
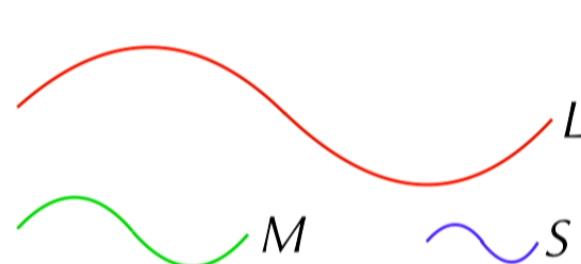
- inflaton self-interactions:  $\lambda\phi^4$  [Lombardo+ 0506051]
- additional field; isocurvature:  $\partial^\mu\phi\partial_\mu\sigma$ ,  $\phi\sigma^2$ , etc.  
[Sakagami (1988); Brandenberger+ (1990); Prokopev+ 0612067]
- high-frequency modes  $A[q_{\text{slow}}](\mathbf{x})B[q_{\text{fast}}](\mathbf{x})$  [Burgess+ 1408.5002]
- tensor modes  $h^{ij}\partial_i\zeta\partial_j\zeta$  [Franco+ 1103.0188; Calzetta+ 9505046]
- gravitational interactions [Franco+; Martineau, 0601134]
- ...

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# Gravitational Interactions

Nonlinearities: expand single-field action to  $\mathcal{O}(\zeta^3)$ , [Maldacena, 0210603]

$$\begin{aligned}
 S_3 = & \int dt d^3x \left\{ -a^3 \left( \Sigma \left( 1 - \frac{1}{c_s^2} \right) + 2\lambda \right) \frac{\dot{\zeta}^3}{H^3} + \frac{a^3 \epsilon}{c_s^4} (\epsilon - 3 + 3c_s^2) \zeta \dot{\zeta}^2 \right. \\
 & + \frac{a \epsilon}{c_s^2} (\epsilon - 2s + 1 - c_s^2) \zeta (\partial \zeta)^2 - 2a \frac{\epsilon}{c_s^2} \dot{\zeta} (\partial \zeta) (\partial \chi) \\
 & + \frac{a^3 \epsilon}{2c_s^2} \frac{d}{dt} \left( \frac{\eta}{c_s^2} \right) \zeta^2 \dot{\zeta} + \frac{\epsilon}{2a} (\partial \zeta) (\partial \chi) \partial^2 \chi + \frac{\epsilon}{4a} (\partial^2 \zeta) (\partial \chi)^2 \\
 & \left. + 2a \left( \frac{d \partial^2 \chi}{dt} + H \partial^2 \chi - \epsilon \partial^2 \zeta \right) \times \right. \\
 & \left. \left( \frac{\eta}{4c_s^2} \zeta^2 + \frac{1}{c_s^2 H} \zeta \dot{\zeta} + \frac{1}{4a^2 H^2} [-(\partial \zeta) (\partial \zeta) + \partial^{-2} (\partial_i \partial_j (\partial_i \zeta \partial_j \zeta))] \right. \right. \\
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 \end{aligned} \tag{4.26}$$

[Chen+, 0605045]

→ couplings between Fourier modes satisfying  $\mathbf{k} + \mathbf{k}' + \mathbf{k}'' = 0$



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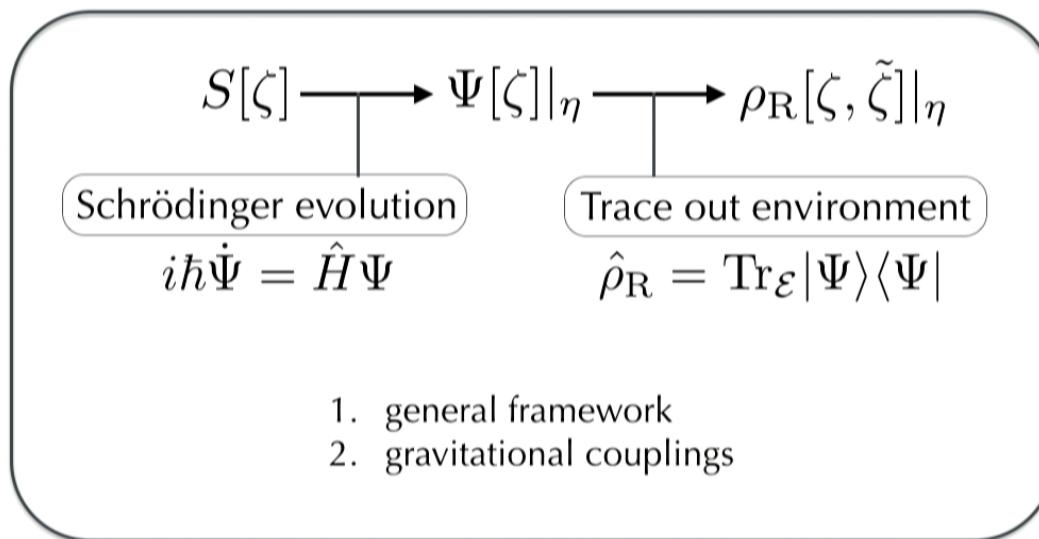
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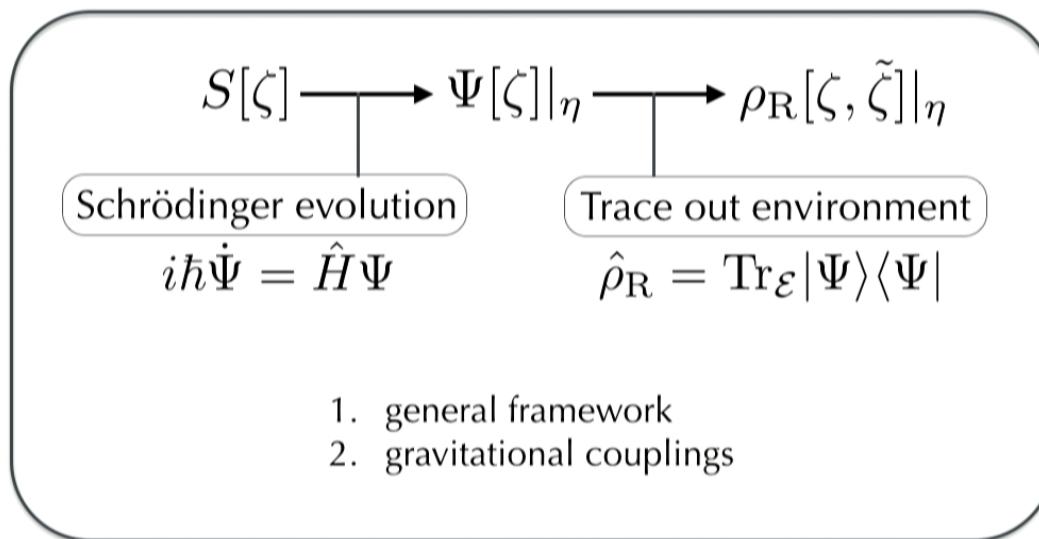
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Plan for the rest of the talk:



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# Schrödinger Picture Wave Functional

$$\Psi[\zeta] = \langle \zeta | \Psi \rangle$$

where  $\hat{\zeta}(\mathbf{x})|\zeta(\mathbf{x})\rangle = \zeta(\mathbf{x})|\zeta(\mathbf{x})\rangle$  defines configuration space eigenstates

Break into Gaussian (linear) and non-Gaussian parts:

$$\Psi[\zeta, \mathcal{E}] = \left( \Psi_G^{(\zeta)}[\zeta] \right) \times \left( \Psi_G^{(\mathcal{E})}[\mathcal{E}] \right) \times \left( \Psi_{NG}[\zeta, \mathcal{E}] \right)$$

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General Gaussian state (each mode starts in coherent superposition):

$$\Psi_G[\zeta](\eta) = N(\eta) \exp \left[ - \int \frac{d^3 \mathbf{k}}{(2\pi)^3} \zeta_{\mathbf{k}} \zeta_{\mathbf{k}}^* A_{\zeta}(\mathbf{k}, \eta) \right] = \prod_{\mathbf{k}} \psi_k$$

(same for  $\mathcal{E}$ )

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Interactions will generate non-Gaussian part:

$$\Psi_{NG}[\zeta, \mathcal{E}](\eta) = \exp \left[ \int_{\mathbf{k}, \mathbf{k}', \mathbf{k}''} \mathcal{E}_{\mathbf{k}} \mathcal{E}_{\mathbf{k}'} \zeta_{\mathbf{k}''} \mathcal{F}_{\mathbf{k}, \mathbf{k}', \mathbf{k}''}(\eta) \right]$$

Time-dependence captured in **k-dependent** complex functions

# Integrating Out the Environment

Reduced density matrix:  $\rho_R[\zeta, \tilde{\zeta}] = \int \mathcal{D}\mathcal{E} \Psi[\zeta, \mathcal{E}] \Psi^*[\tilde{\zeta}, \mathcal{E}] \quad \hat{\rho}_R = \text{Tr}_{\mathcal{E}} |\Psi\rangle\langle\Psi|$

Trace over environment

$$= \underbrace{\Psi_G^{(\zeta)}[\zeta] \left( \Psi_G^{(\zeta)}[\tilde{\zeta}] \right)^*}_{\text{Interference}} \underbrace{\int \mathcal{D}\mathcal{E} |\Psi_G^{(\mathcal{E})}|^2 \exp \left[ \int_{\mathbf{k}, \mathbf{k}', \mathbf{q}} \mathcal{E}_{\mathbf{k}} \mathcal{E}_{\mathbf{k}'} \left( \zeta_{\mathbf{q}} \mathcal{F}_{\mathbf{k}, \mathbf{k}', \mathbf{q}} + \tilde{\zeta}_{\mathbf{q}} \mathcal{F}_{\mathbf{k}, \mathbf{k}', \mathbf{q}}^* \right) \right]}_{\text{Free theory}}$$

$\approx i(\zeta_{\mathbf{q}} - \tilde{\zeta}_{\mathbf{q}}) \text{Im} \mathcal{F}_{\mathbf{k}, \mathbf{k}', \mathbf{q}}(\eta)$   
(Real part  $\rightarrow$  non-Gaussianity)

will grow with  $a(t)$

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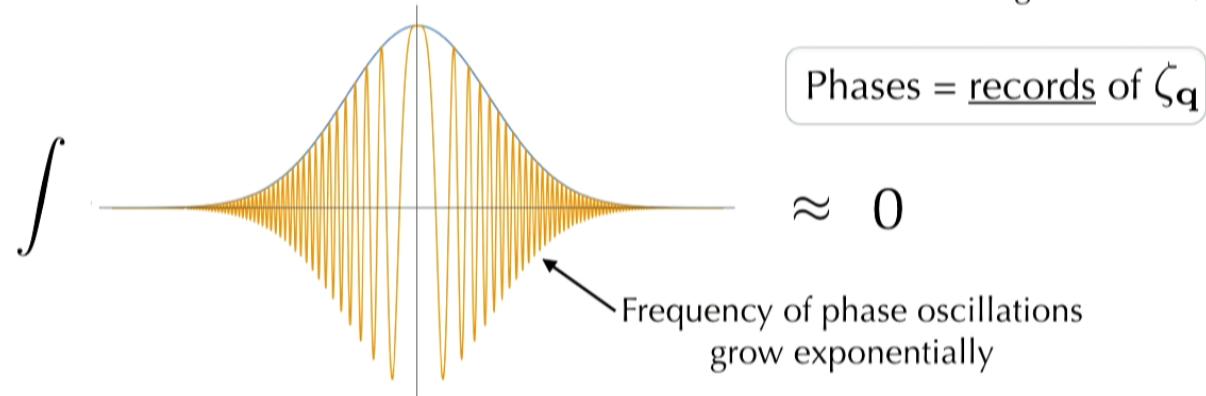
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**Phase oscillations** damp integral over environment,  
suppress off-diagonal elements of  $\rho_R[\zeta, \tilde{\zeta}]$  will grow with  $a(t)$



# Integrating Out the Environment

Decoherence factor quantifies  
this relative suppression,

$$D[\zeta, \tilde{\zeta}] \equiv \frac{|\rho_R[\zeta, \tilde{\zeta}]|}{\sqrt{\rho_R[\zeta, \zeta] \rho_R[\tilde{\zeta}, \tilde{\zeta}]}}$$

$$\begin{aligned} D[\zeta, \tilde{\zeta}] &= \int \mathcal{D}\mathcal{E} |\Psi_G^{(\mathcal{E})}|^2 \exp \left[ \int_{\mathbf{k}, \mathbf{k}', \mathbf{q}} \mathcal{E}_{\mathbf{k}} \mathcal{E}_{\mathbf{k}'} \left( \zeta_{\mathbf{q}} \mathcal{F}_{\mathbf{k}, \mathbf{k}', \mathbf{q}} + \tilde{\zeta}_{\mathbf{q}} \mathcal{F}_{\mathbf{k}, \mathbf{k}', \mathbf{q}}^* \right) \right] \\ &= 1/|\det(\text{covariance matrix})| \quad (\text{Gaussian integral}) \end{aligned}$$

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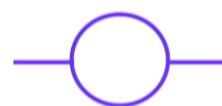
Compute the reduced density matrix for a single mode  $\zeta_{\mathbf{q}}$ , and let all other modes be the environment,  $\mathcal{E} = \zeta_{\mathbf{k} \neq \mathbf{q}}$

Result:

$$D(\zeta_{\mathbf{q}}, \tilde{\zeta}_{\mathbf{q}})|_{\eta} = \left[ 1 + \frac{1}{V^2} \sum_{\mathbf{k}} \frac{|\Delta \zeta_{\mathbf{q}}|^2 (\text{Im} \mathcal{F}_{\mathbf{k}, -\mathbf{k} + \mathbf{q}, \mathbf{q}}(\eta))^2}{\text{Re} A_{\zeta}(k, \eta) \text{Re} A_{\zeta}(|-\mathbf{k} + \mathbf{q}|, \eta)} + \mathcal{O}(\mathcal{F}^4) \right]^{-1}$$

↑ =  $\zeta_{\mathbf{q}} - \tilde{\zeta}_{\mathbf{q}}$

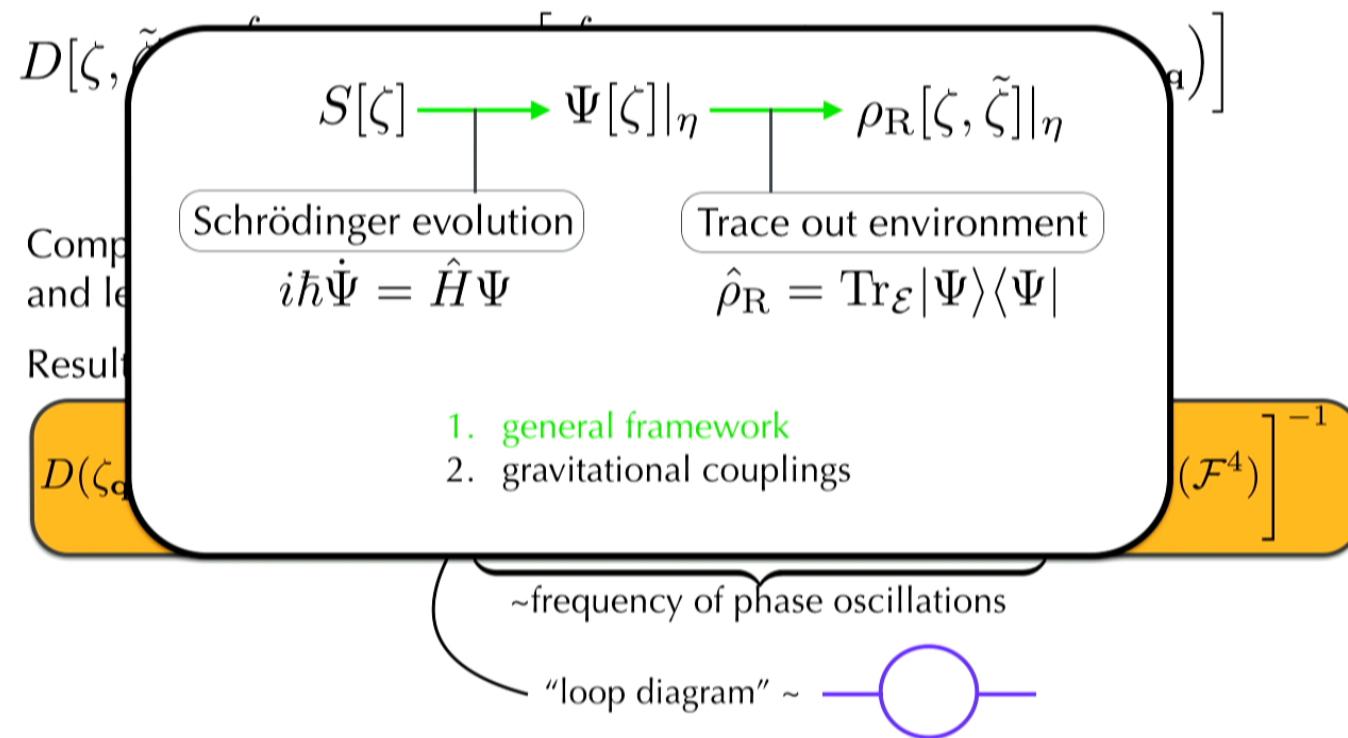
~frequency of phase oscillations

“loop diagram” ~ 

# Integrating Out the Environment

Decoherence factor quantifies  
this relative suppression,

$$D[\zeta, \tilde{\zeta}] \equiv \frac{|\rho_R[\zeta, \tilde{\zeta}]|}{\sqrt{\rho_R[\zeta, \zeta]\rho_R[\tilde{\zeta}, \tilde{\zeta}]}}$$



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$$\begin{aligned} D[\zeta, \tilde{\zeta}] &= \int \mathcal{D}\mathcal{E} |\Psi_G^{(\mathcal{E})}|^2 \exp \left[ \int_{\mathbf{k}, \mathbf{k}', \mathbf{q}} \mathcal{E}_{\mathbf{k}} \mathcal{E}_{\mathbf{k}'} \left( \zeta_{\mathbf{q}} \mathcal{F}_{\mathbf{k}, \mathbf{k}', \mathbf{q}} + \tilde{\zeta}_{\mathbf{q}} \mathcal{F}_{\mathbf{k}, \mathbf{k}', \mathbf{q}}^* \right) \right] \\ &= 1/|\det(\text{covariance matrix})| \quad (\text{Gaussian integral}) \end{aligned}$$

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↑  $= \zeta_{\mathbf{q}} - \tilde{\zeta}_{\mathbf{q}}$

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“loop diagram” ~ 

# Wave Functional Evolution: Linear Theory

Initial state: Bunch-Davies **vacuum** specifies  $\Psi_0[\zeta]$

$$\hat{a}_{\mathbf{k}}|\Psi\rangle|_{\eta \rightarrow -\infty} = 0$$

leads to

$$A_\zeta(k, \eta) = 2k^3 \frac{\epsilon M_p^2}{H^2} \frac{1 - \frac{i}{k\eta}}{1 + k^2\eta^2}$$

[Polarski & Starobinsky, 9504030]

↑  
late-time power spectrum  $\langle |\zeta_{\mathbf{k}}|^2 \rangle$

rapidly oscillating phase

This determines the linear evolution,

$$\Psi_G[\zeta](\eta) = N(\eta) \exp \left[ - \int \frac{d^3\mathbf{k}}{(2\pi)^3} \zeta_{\mathbf{k}} \zeta_{\mathbf{k}}^* A_\zeta(k, \eta) \right]$$

# Gravitational Couplings

Cubic action for  $\zeta$  :

[Maldacena, 0210603]

$$\begin{aligned} S_3 &= \int dt d^3x \left\{ -a^3 \left( \Sigma \left( 1 - \frac{1}{c_s^2} \right) + 2\lambda \right) \frac{\dot{\zeta}^3}{H^3} + \frac{a^3 \epsilon}{c_s^4} (\epsilon - 3 + 3c_s^2) \zeta \dot{\zeta}^2 \right. \\ &+ \frac{a\epsilon}{c_s^2} (\epsilon - 2s + 1 - c_s^2) \zeta (\partial\zeta)^2 - 2a \frac{\epsilon}{c_s^2} \dot{\zeta} (\partial\zeta)(\partial\chi) \\ &+ \frac{a^3 \epsilon}{2c_s^2} \frac{d}{dt} \left( \frac{\eta}{c_s^2} \right) \zeta^2 \dot{\zeta} + \frac{\epsilon}{2a} (\partial\zeta)(\partial\chi) \partial^2 \chi + \frac{\epsilon}{4a} (\partial^2 \zeta)(\partial\chi)^2 \\ &+ 2a \left( \frac{d\partial^2 \chi}{dt} + H\partial^2 \chi - \epsilon \partial^2 \zeta \right) \times \\ &\quad \left( \frac{\eta}{4c_s^2} \zeta^2 + \frac{1}{c_s^2 H} \zeta \dot{\zeta} + \frac{1}{4a^2 H^2} [-(\partial\zeta)(\partial\zeta) + \partial^{-2}(\partial_i \partial_j (\partial_i \zeta \partial_j \zeta))] \right. \\ &\quad \left. + \frac{1}{2a^2 H} [(\partial\zeta)(\partial\chi) - \partial^{-2}(\partial_i \partial_j (\partial_i \zeta \partial_j \chi))] \right) \end{aligned} \tag{4.26}$$

[Chen+, 0605045]

$$\partial^2 \chi = a^2 \frac{\epsilon}{c_s^2} \dot{\zeta}$$

$$\eta \equiv -\dot{\epsilon}/\epsilon H$$

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Effectively,

$$\mathcal{L}_{\text{int}} = \epsilon(\epsilon + \eta_\epsilon) a(t) \zeta (\partial \zeta)^2 + \dots$$

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# $\Psi[\zeta]$ from Gravitational Couplings

Recall general case:

$$\mathcal{F}_{\mathbf{k}, \mathbf{k}', \mathbf{q}}(\eta) = \int_{\eta_0}^{\eta} d\eta' s_{\mathbf{k}, \mathbf{k}', \mathbf{q}}(\eta') \exp \left[ i \underbrace{\int_{\eta'}^{\eta} d\eta'' \alpha_{k, k', q}(\eta'')}_{\approx \Theta(k, k', q < |\eta^{-1}|)} \right]$$

Gravitational mode couplings:

$$\alpha_{k, k', q}(\eta) = -\eta^2 \left( \frac{1 - i/k\eta}{1 + k^2\eta^2} k^3 + 2 \text{ perms.} \right) \quad (\Psi_{NG} \text{ "turns on" after horizon crossing})$$

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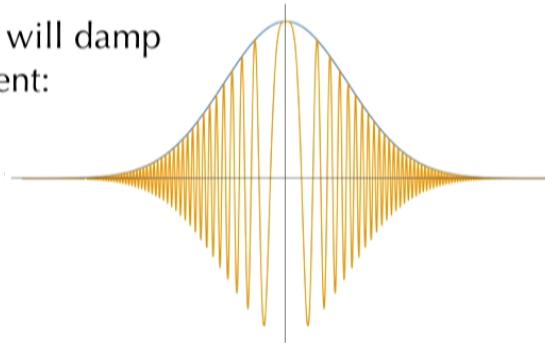
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Rapidly growing phase will damp integral over environment:



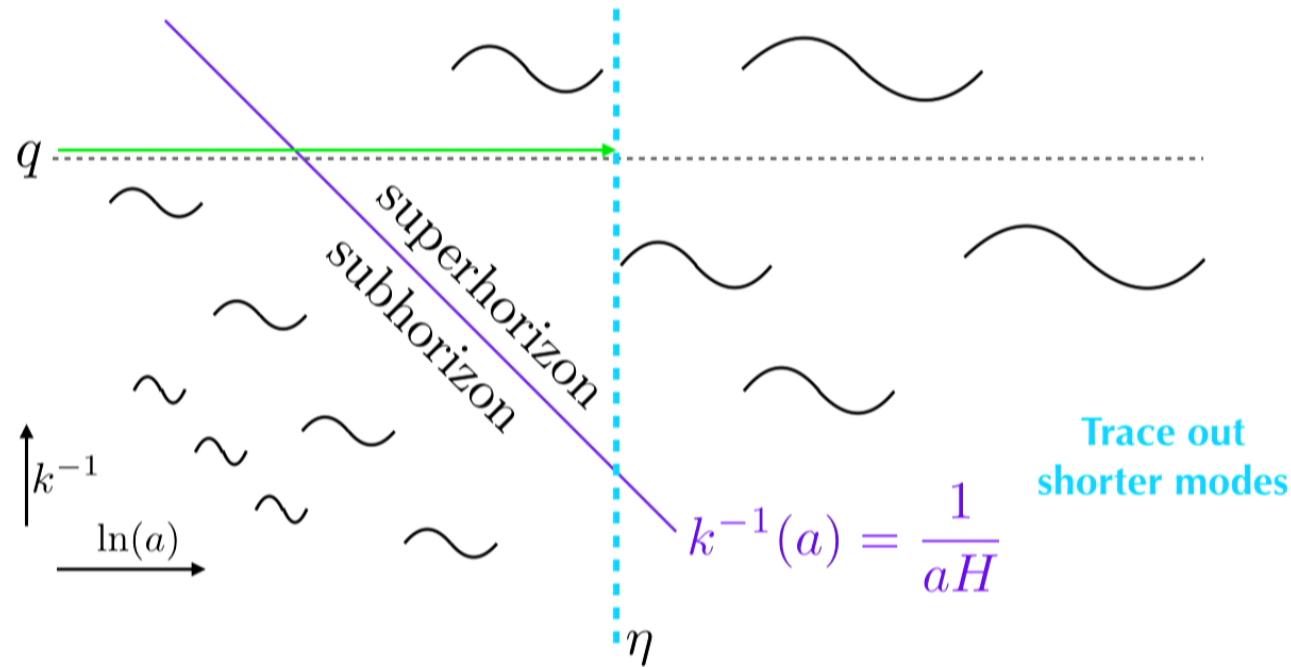
Slow roll suppression

affects  $\langle \zeta_{\mathbf{k}} \zeta_{\mathbf{k}'} \zeta_{\mathbf{q}} \rangle$

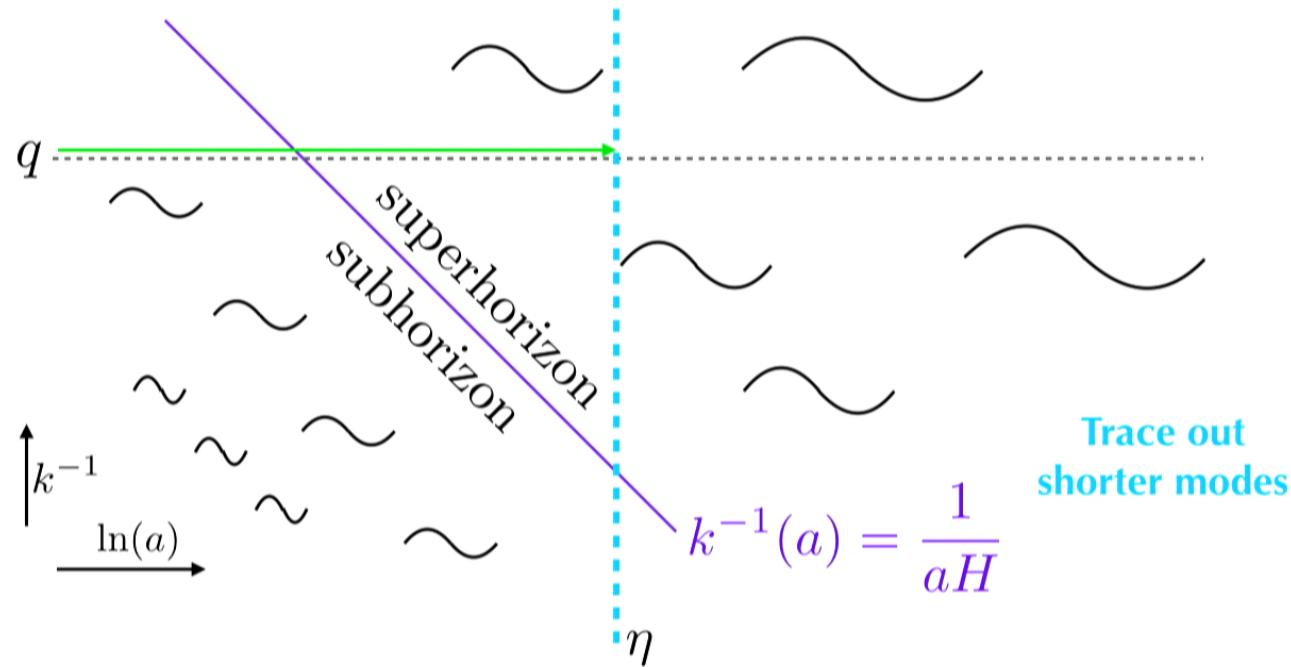
[Chen+, 0605045]

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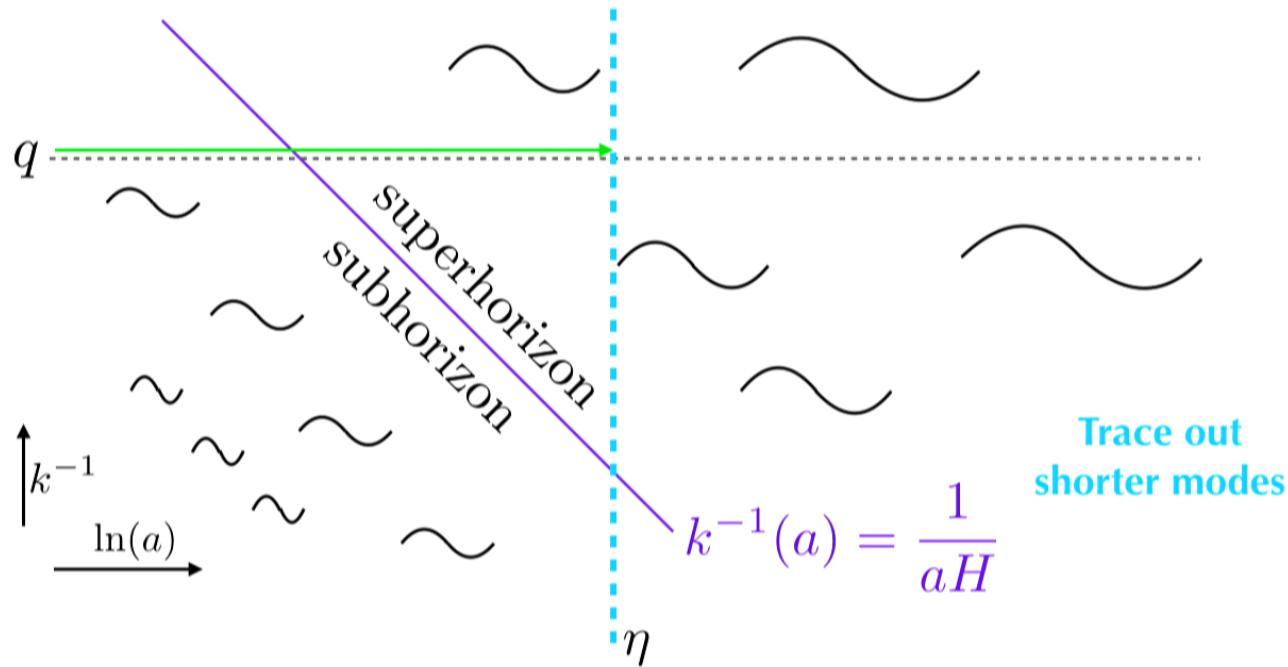
# Decoherence from Gravitational Couplings



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Recall general case:

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Plugging in gravitational couplings:

(when  $|q\eta| \ll 1$ )  
( $\epsilon = \text{const.}$  for simplicity)

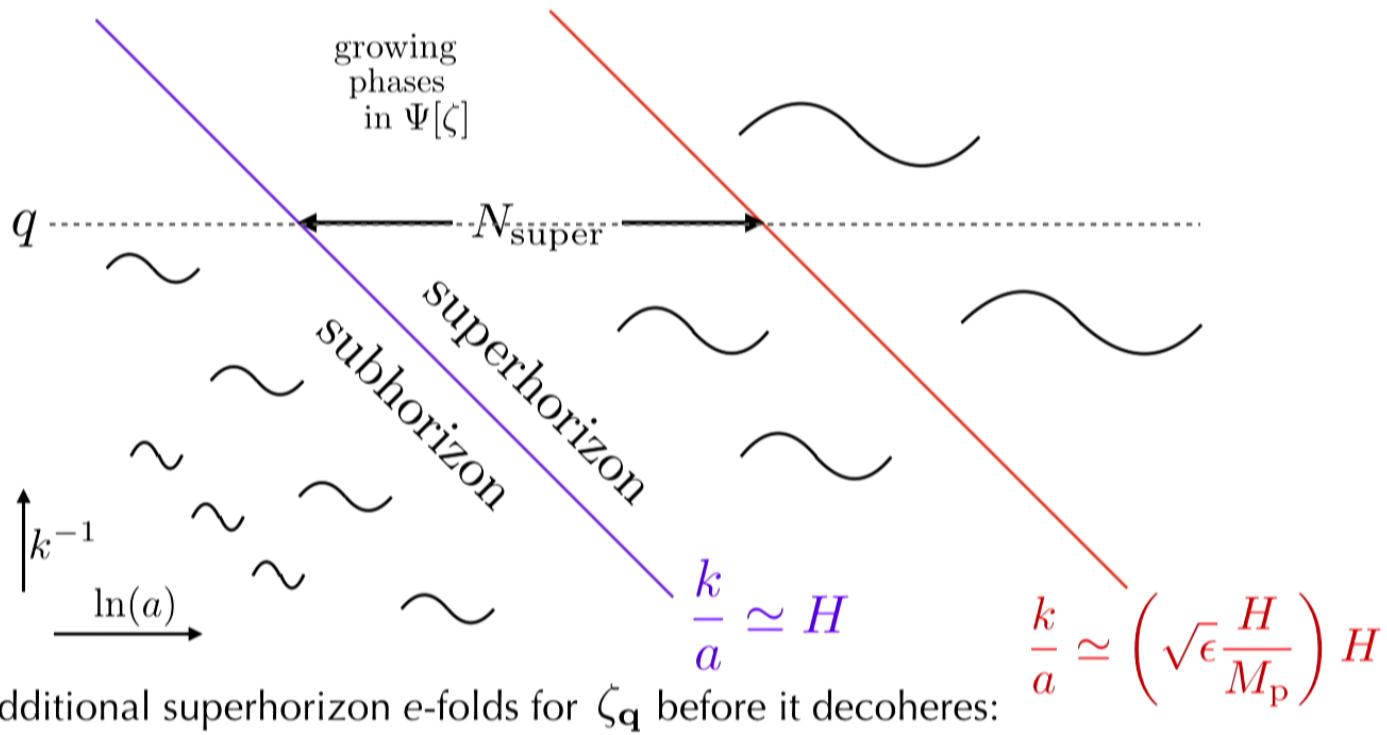
$$= \left( \frac{1}{4} \epsilon |\Delta\bar{\zeta}_{\mathbf{q}}| \right)^2 \left( \frac{aH}{q} \right)^3$$

( $\Delta\bar{\zeta}_{\mathbf{q}}$ =rescaled, dimensionless)

$\zeta_{\mathbf{q}}$  decoheres  
when this is  $\mathcal{O}(1)$

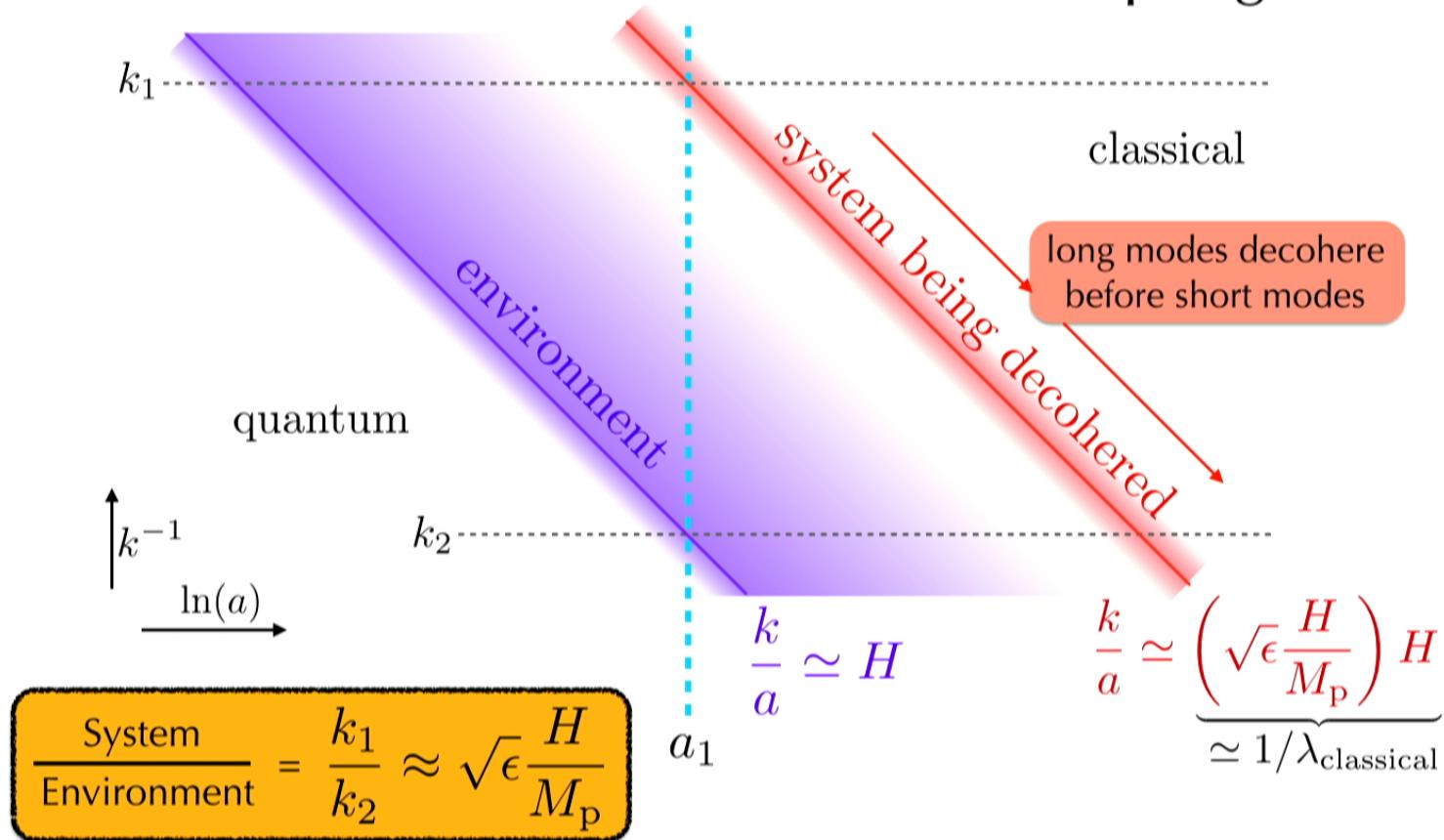
- \* Decoherence depends on *physical wavelength*, scales as **volume of the mode  $q$** , in Hubble units
- \* Decoherence is delayed by weakness of gravitational couplings  $\Gamma_{\text{deco}} \sim \epsilon^2$

# Decoherence from Gravitational Couplings



$$N_{\text{super}} \approx \frac{2}{3} \ln \left( \sqrt{\epsilon} \frac{H}{M_p} \right) \sim 10 \text{ for } \epsilon \sim 10^{-2}$$

# Decoherence from Gravitational Couplings



# $\Psi[\zeta]$ from Gravitational Couplings

Recall general case:

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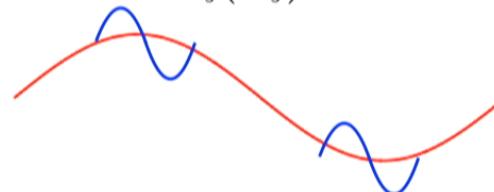
(when  $k, k', q \ll |\eta^{-1}|$ )

# Is this a Coordinate Artifact?

Single-clock inflation: short modes insensitive to long-wavelength background

$$\langle \zeta_{\mathbf{k}} \zeta_{\mathbf{k}'} \zeta_{\mathbf{q}} \rangle \propto \langle |\zeta_{\mathbf{k}}|^2 \rangle \langle |\zeta_{\mathbf{q}}|^2 \rangle \frac{q^2}{k^2}$$

Correlation of long and short modes from  $\zeta(\partial\zeta)^2$  interaction is removed in observer's *local* coordinates



**Is decoherence from squeezed-limit coupling also a coordinate artifact?**

Note 1: decoherence rate  $\propto \epsilon + \eta_\epsilon$ , but  $f_{\text{NL}}^{\text{sq.}} \propto 2\epsilon + \eta_\epsilon$

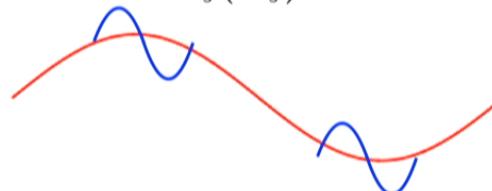
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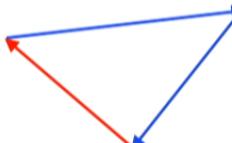


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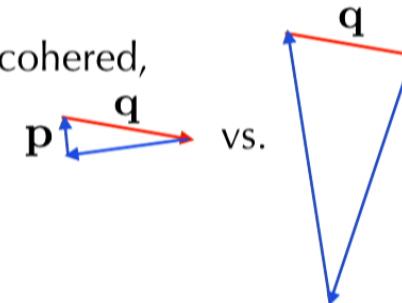
Note 2: Equilateral configurations are also a (slower) source of decoherence

$$\Gamma_{\text{equil}} \sim (\epsilon |\Delta\zeta|)^2 \left( \frac{aH}{q} \right)^2$$


# IR Log in Decoherence Rate

$$\text{Decoherence rate has a correction } \sim 1 + \frac{q}{aH} \ln \left( \frac{q}{k_{\min}} \right)$$

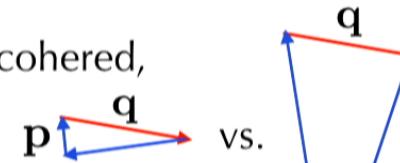
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from coupling to IR modes  $\mathbf{p}$  that have already decohered,



Becomes **strongest** source of decoherence after

$$\simeq (M_p / \sqrt{\epsilon} H)^{2/3} \text{ e-folds of inflation}$$

$$\sim 10^5 \text{ for } \epsilon \sim 10^{-2} \text{ (assuming scale-invariant spectrum)}$$

# Summary

- \* Gravitational couplings turn **pure** state  $\Psi(\zeta_{\mathbf{q}})$  into **classical mixture**

$$\rho_R(\zeta_{\mathbf{q}}, \tilde{\zeta}_{\mathbf{q}}) \rightarrow P(\zeta_{\mathbf{q}}) \delta^{(2)}(\zeta_{\mathbf{q}} - \tilde{\zeta}_{\mathbf{q}})$$

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mode-by-mode, large scales to small scales

(growing phase oscillations in global wave functional suppress off-diagonal parts)

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- \* **Long-to-short mode coupling:** Hubble scale modes act,  $k_{\text{env}} \sim aH$  as decohering environment for super-Hubble modes:  $k_{\text{deco}} \sim (\epsilon \Delta_{\zeta}) aH$

- \* Decoherence is **delayed due to weak coupling**, but occurs quickly after  $\sim \ln(1/g) = \ln(1/\epsilon \Delta_{\zeta})$  superhorizon e-folds

- \* **Minimal mechanism for generating classical stochastic perturbations from quantum fluctuations:**

- inflation (so modes can redshift to superhorizon scales)  
→ largest scales become the most classical
- vacuum fluctuations (no excitations needed)
- gravity (GR) (role of squeezed limit?)

# Future Directions

Post-inflation signatures of remaining coherence?

Role of decoherence in “Bell-violating” inflation models? [Maldacena, 1508.01082]

→ Fastest sources of decoherence in multi-field models?

(need  $H_{\text{int}} \sim a^{p>0}$ )

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**Tensor modes** couple to scalar curvature modes:

$$\mathcal{L}^{(\zeta\zeta\gamma)} \sim \epsilon a \zeta \partial_l \gamma_{ij} \partial_l \gamma_{ij} \quad \mathcal{L}^{(\zeta\gamma\gamma)} \sim \epsilon a \gamma_{ij} \partial_i \zeta \partial_j \zeta \quad [\text{Maldacena, 0210603}]$$

→ Expect that scalar modes will decohere tensor modes

Spatially local description of decoherence?