QUANTUM SIGNATURES AND DECOHERENCE DURING INFLATION FROM DEEP SUBHORIZON PERTURBATIONS

Arxiv: 2503.23150

Francescopaolo Lopez

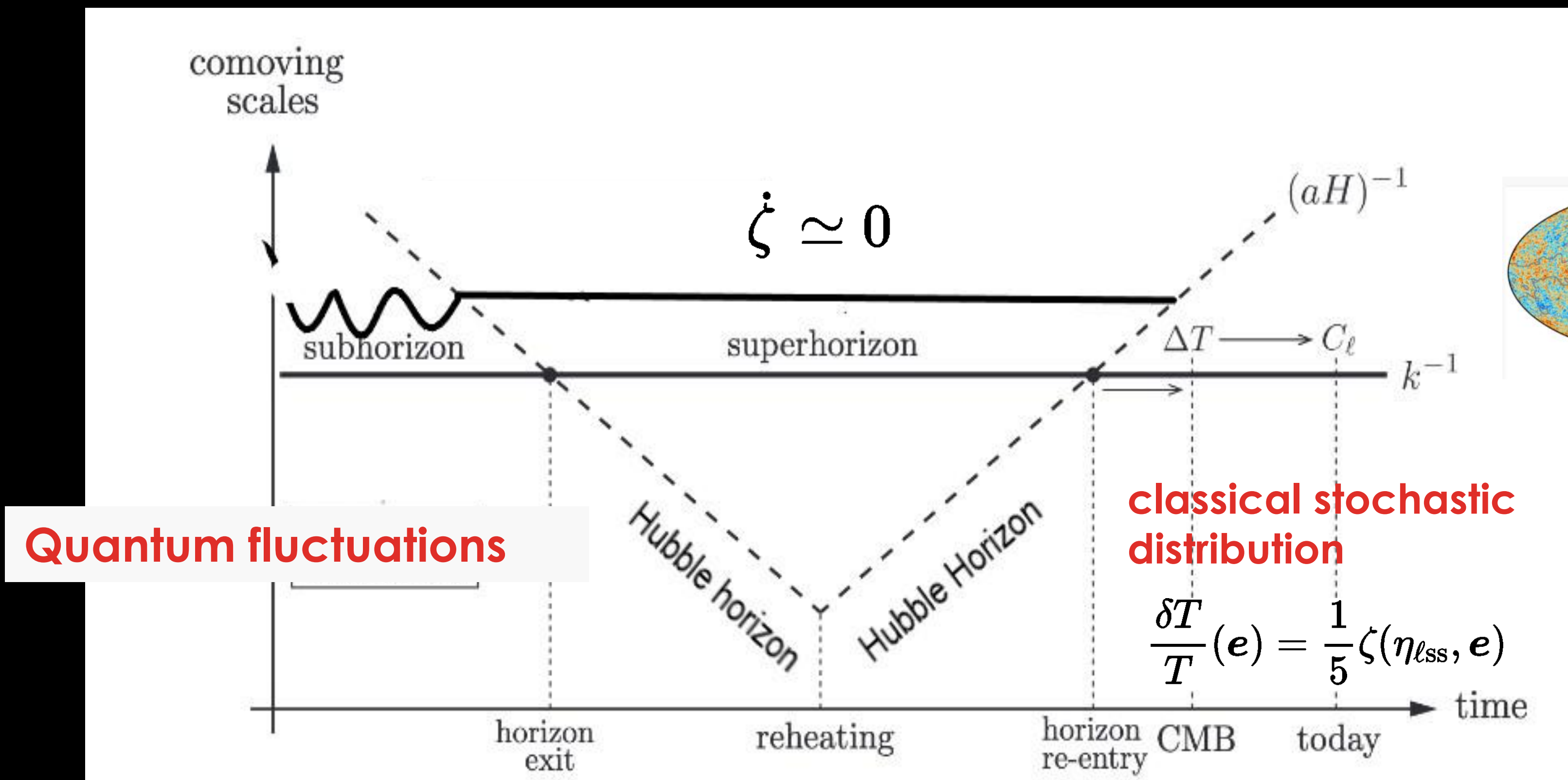
With Nicola Bartolo(UniPd)

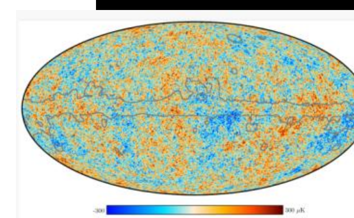
4th year Phd student @SISSA, Trieste,Italy
Supervisors: Takeshi Kobayashi, Nicola Bartolo

Inflation 2025, Iap, 02/12/2025

QUANTUM TO CLASSICAL TRANSITION IN COSMOLOGY

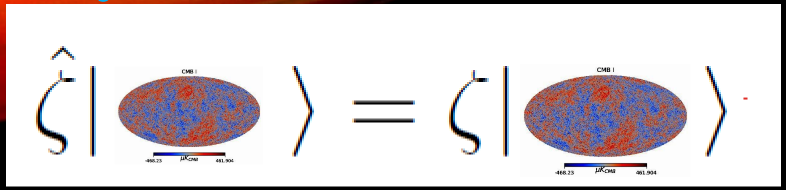
•Inflation provides a mechanism to **explain anisotropies and inhomogeneities** in the present universe from the tiny quantum fluctuations of the scalar field.



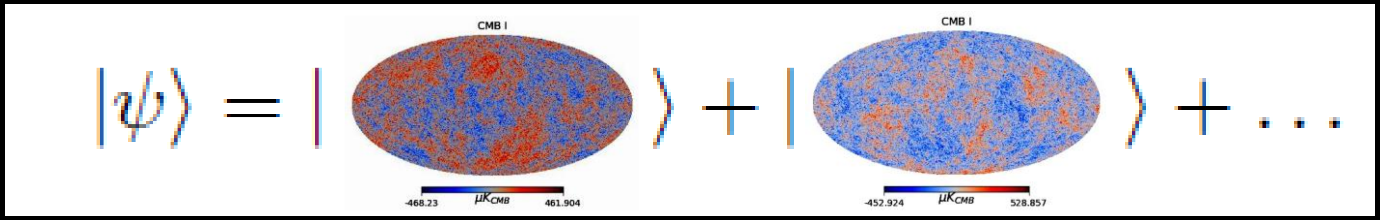


• Credits:Coles and Lucchin,Cosmology,,D.Baumann, Lectures on Inflation.

How could quantum fluctuations become classical objects?



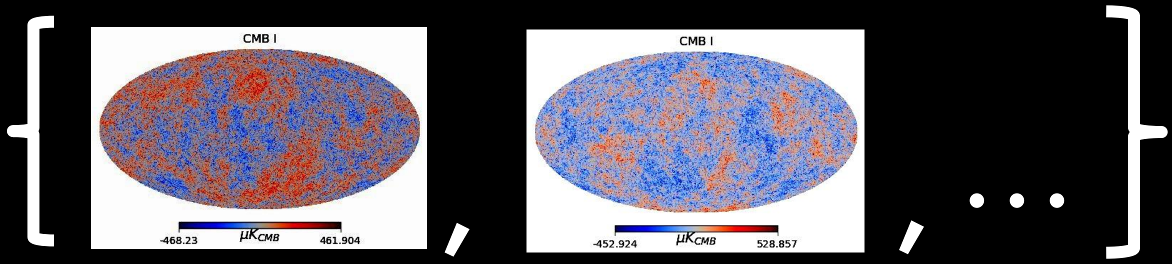
- ζ quantum operator;
- Configuration of perturbations (~CMB Maps) are eigenvectors of ζ



COHERENT **SUPERPOSITION**

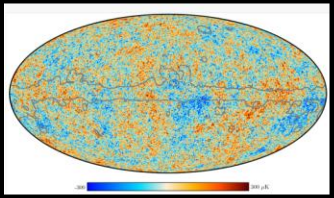
DECOHERENCE
(after interaction, and entanglement with unobservable environment)

Quantum to classical transition!



STATISTICAL ENSEMBLE

BUT ONLY ONE REALIZATION!



Credits:mock maps,Claudio Ranucci; real map, Planck 2018

WHAT DOES DECOEHERENCE DO?

Interaction with an unobsevable environment: **OPEN QUANTUM SYSTEM** → Entanglement, suppress quantum coherence between different possible outcomes

Interference terms in red

$$\rho_{sys} = \begin{pmatrix} |\zeta_1\rangle\langle\zeta_1| & |\zeta_1\rangle\langle\zeta_2| \\ |\zeta_2\rangle\langle\zeta_1| & |\zeta_2\rangle\langle\zeta_2| \end{pmatrix} \xrightarrow{\text{decoherence}} \rho_{sys} = \mathrm{Tr}_{ENV}\, \rho_{sys+env} = \begin{pmatrix} |\zeta_1\rangle\langle\zeta_1| & 0 \\ 0 & |\zeta_2\rangle\langle\zeta_2| \end{pmatrix}$$

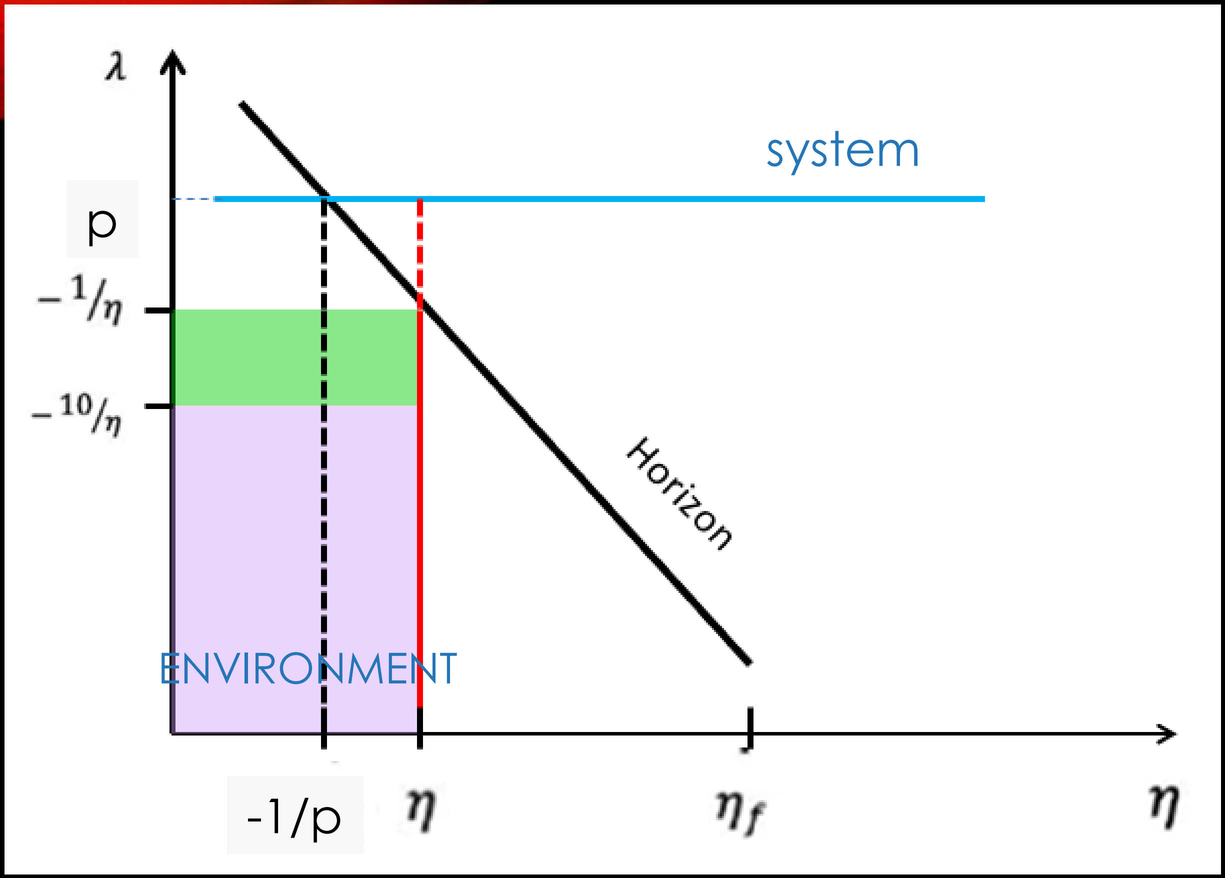
↓

Statistical ensemble!

How to quantify? Purity!

$$\gamma = \mathrm{Tr}\,\rho^2 = 1 \xrightarrow{\text{decoherence}} \gamma = \mathrm{Tr}\,\rho_r^2 \to 0$$

SINGLE FIELD INFLATION



NON LINEAR GRAVITATIONAL INTERACTIONS

SYSTEM: **Superhorizon** Scalar Mode.

↕ **Entanglement**

ENVIRONMENT:
Subhorizon modes
Of **Gravitational waves**.

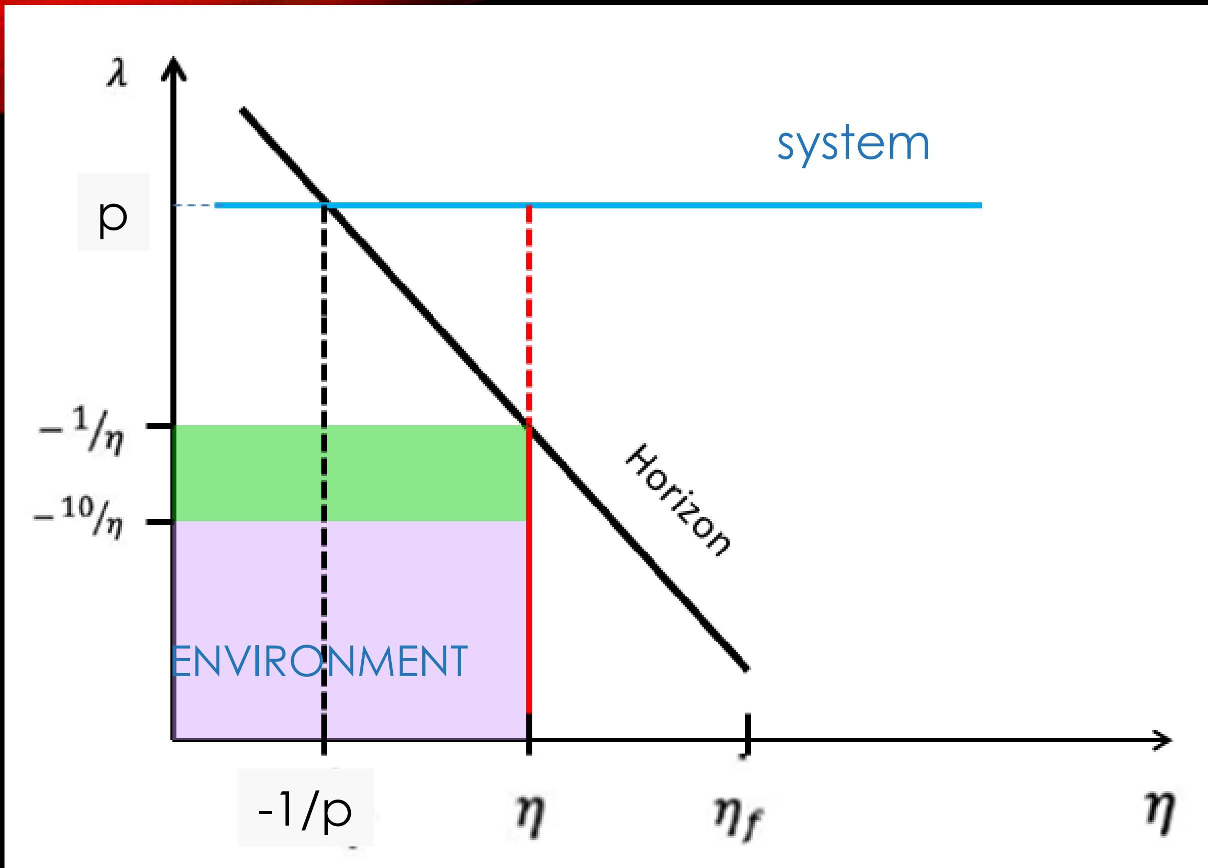
1. **Time dependent environment**

2. **Short Correlation time**

$\tau_{env} \ll \tau_{sys}$

MARKOVIAN APPROXIMATION!

SINGLE FIELD INFLATION



NON LINEAR GRAVITATIONAL INTERACTIONS

SYSTEM: **Superhorizon** Scalar Mode.

↕ **Entanglement**

ENVIRONMENT: **Subhorizon** modes Of **Gravitational waves.**

1. **Time dependent environment**

2. **Short Correlation time**

$$\tau_{env} \ll \tau_{sys}$$

MARKOVIAN APPROXIMATION!

DECOHERENCE IN SINGLE FIELD INFLATION

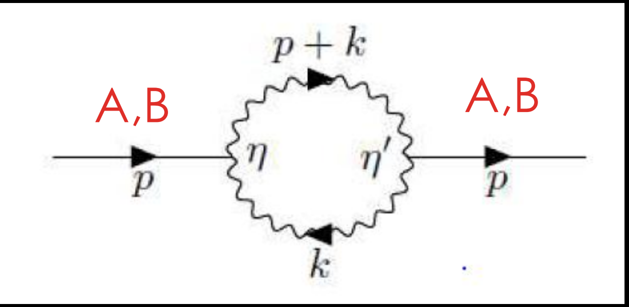
•GR non linear gravitational interactions (Gangui+1993,Maldacena 2003)

$$S = \frac{\epsilon M_{pl}^2}{8} \int dt d^3x \left(a^3 \zeta \dot{h}_{ij} \dot{h}_{ij} + a\zeta \partial_l h_{ij} \partial_l h_{ij} - 2a^3 \dot{h}_{ij} \partial_l h_{ij} \partial_l \left(\nabla^2\right)^{-1} \dot{\zeta} \right)$$

WE CONSIDER THE INTERPLAY BETWEEN ALL INTERACTIONS!
Rewriting the action we have:

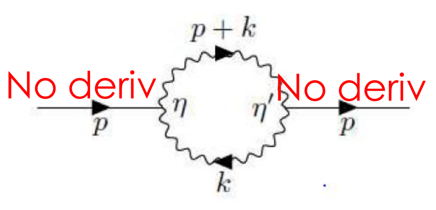
A)DERIVATIVELESS interaction,more important contributions.

B) DERIVATIVE interactions, just like the circled one, analyzed previously



See also: Burgess et al, Arxiv:2509.07769

DERIVATIVELESS INTERACTIONS



$$\frac{1}{\gamma^2} = 1 + \int_{-1/k}^{\eta} d\eta' D_{11}\left(\eta'\right) P_{vv}\left(\eta', k\right)$$

D_{11} :

- **environmental kernel**
- **interactions**

- We can achieve decoherence when $\gamma \to 0 \quad \Leftrightarrow \frac{1}{\gamma} \to \infty$

$$\frac{1}{\gamma^2} = 1 + \frac{\epsilon H^2}{\pi^2 M_p^2} 1.25 \times 10^{-3} \left(\frac{aH}{p}\right)^3 \lesssim 10^{-18} e^{3(N_{\text{end}} - N_\star)}$$

$$\frac{\epsilon H^2}{M_{pl}^2} \lesssim 10^{-13}$$

$$\left(\frac{\lambda_{phys}}{R_H}\right)^3 = e^{3(N_{end} - N_*)}$$

Decoherence happens when system is superhorizon!

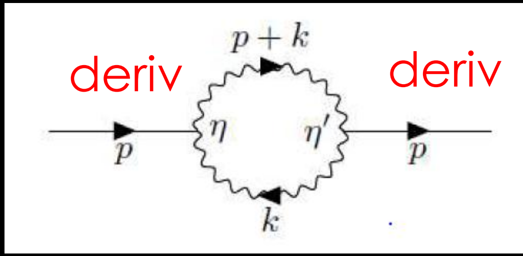
If saturating the bounds, then at least: $N_{\text{end}} - N_* \simeq 15 \text{ efolds}$

CMB well decohered!! But what about smaller scales?

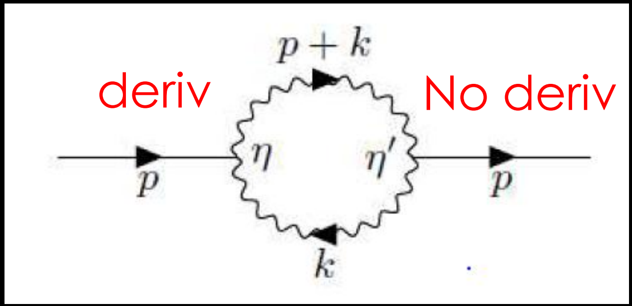
$$\frac{1}{\gamma^2} = 1 + \int_{-1/k}^{\eta} d\eta' D_{11}(\eta') P_{vv}(\eta', k)$$

DERIVATIVE INTERACTIONS

- NEGLIGIBLE!! (Just for deep subhorizon modes)



MIXED DERIVATIVE-DERIVATIVELESS INTERACTIONS



•**Mixed terms give** NEGATIVE CONTRIBUTIONS

$$D_{11}^{int1-23} < 0$$

NON-MARKOVIANITY!!

$$D_{11}^{SMAR} = D_{11}^{int11} + D_{11}^{int1-23} \simeq \frac{\epsilon H^2}{4M_{pl}^2\eta^2} 5 \times 10^{-4}$$

$$N_{end} - N_{*} \simeq 17 efolds$$

QUANTUM SIGNATURES:LAMB SHIFT

From trilinear interactions, loop corrections to Power Spetrum in unitary in-in formalism:

$$\Delta P_{vv} \propto \log(-k\eta_f), \log^2(-k\eta_f), \dots \log^n(-k\eta_f) \dots = \log \frac{k}{aH}, \log^2 \frac{k}{aH}, \dots \log^n \frac{k}{aH} \dots$$

By solving quantum master equation: $\mathcal{P}(k,\eta) \propto e^{\frac{2\epsilon H^2}{4\pi^2 M_{pl}^2}\ln(-k\eta)} + \text{ quartic interactions}$

- **NON-Perturbative resummation!!**
- Quantum "loop" corrections are **"authomatically" resummed by solving the quantum master equation.**

- LAMB SHIFT: Unitary correction. Entanglement with environment "renormalizes" in a finite way energy levels of the system (in this case, mass);

- Analogous resummation also for Bispectrum:

$$B(k_1, k_2, k_3, \eta) = B\left(k_1, k_2, k_3, -\frac{1}{k_1}\right) e^{\frac{3.6\epsilon A^2}{4\pi^2 M_{pl}^2}\ln(-k_1\eta)} + \text{other terms}$$

QUANTUM SIGNATURES:PHENOMENOLOGY

LAMB SHIFT

$$\mathcal{P}(k) = A_s \left(\frac{k}{k_0}\right)^{n_s-1}$$

Only from trilinear interactions, modifies spectral index in Curvature Power Spectrum:

- Blue Correction to spectral index n_s
- No logaritmic secular corrections.
- Cancelled by the quartic terms?

$$\delta n_S \simeq \frac{\varepsilon H^2}{4M_{pl}^2\pi^2}2$$

CORRECTIONS FROM NON UNITARY PARTS:

Same order, different form (scale invariant)

$$\frac{\Delta P_{vv}}{P_{vv}} = \left(\frac{\pi}{2} - 1.5\right)\frac{\epsilon H^2}{432\pi^2 M_{pl}^2}$$

Of course, too little (Gravitational interactions)!

$$\frac{\epsilon H^2}{M_{pl}^2} \lesssim 10^{-13}$$

What about specific models with multifield and stronger non gaussianity?

CONCLUSIONS

- We computed **decoherence and quantum corrections to observables, in single field inflation,** in an environment only of subhorizon modes;

- For the first time we considered more than just one interaction at a time, but also **the interplay between them**;

- We found resummation of Lamb Shift corrections to the **Bispectrum** and to the Power Spectrum.

- ***Open quantum field theory during inflation is needed for explaining quantum to classical transition. Non unitary effects*** **should be there even** in a minimal setting

- Small-scale modes

-If modes cross the horizon in the last e-folds of inflation *may not have the time to decohere? There may be genuine quantum features! Gravitational waves?*

THANK YOU FOR YOUR ATTENTION!

TAKE HOME MESSAGE AND FUTURE PROJECTS

- ***Open quantum system during inflation is needed for explaining quantum to classical transition. Non unitary effects* should be there even** in a minimal setting.

BURGESS+'22;PART TWO

D_{11}>0? No!!! **Is the model unphysical?**

$$\rho_r'(\eta) = -g(\eta)\int_{\eta_0}^{\eta} \mathrm{d}\eta' g(\eta') \sum_k v_k(\eta) v_{-k}(\eta') \rho_r(\eta) K(k,\eta,\eta') + (\leftrightarrow) \, similar\ terms$$

Adopt "**Strong Markovian approximation**": $v_k(\eta') \to v_k(\eta)$

Stronger than the usual one $\rho_r(\eta') \to \rho_r(\eta) + O(g^2)$

CONDITIONS:

- ENVIRONMENTAL CORRELATION FUNCTIONS K(η,η') HAVE REALLY SHORT MEMORY;
- SYSTEM OPERATORS v_k (η), EVOLVE SLOWLY

$$T_{ENV} << T_{SYS}$$

Then, D_{11} >0!!!

$$D_{11}^{FIX\,ENV} = \frac{\varepsilon H^2}{1024\pi^2 M_{\mathrm{p}}^2}\frac{80\pi}{\eta^2} \simeq 0.98\frac{\varepsilon H^2}{4\pi^2 M_{\mathrm{p}}^2}$$

Claim: Remove "unphysical" memory, extract
Only the markovian part of the quantum master equation

Markovian approximation: $\rho_r(\eta') \to \rho_r(\eta) + O(g^2)$

System memory

$$D_{11} = g(\eta)\int_{-\frac{1}{p}}^{\eta} d\eta' g(\eta') 2\Re K(\eta,\eta') A(k,\eta,\eta')$$

'22 Burgess+,'21 Kaplanek+: if $D_{11} < 0$, Strong Markovian approximation!

Conditions:

•environmental **short memory**;

•system operators evolve **slowly.**

$$A(k,\eta,\eta') \to A(k,\eta,\eta) = 1$$

In our **case very well justified** because **different scales** of **typical time of evolution**:

$$T_{ENV} \simeq \frac{1}{10aH} << T_{SYS} \simeq \frac{1}{aH}$$

The sum is now positive again!!

$$D_{11}^{SMAR} = D_{11}^{int11} + D_{11}^{int1-23} \simeq \frac{\epsilon H^2}{4M_{pl}^2\eta^2} 5\times 10^{-4}$$

In the end, decoherence is nevertheless effective: $N_{end} - N_* \simeq 17 efolds$

TIME DEPENDENT ENVIRONMENT

- Also used in: ('19 Gong-Seo, '21-'22 Brahma et al.,…)

'23 Burgess: nobody computed the effect

$$\mathrm{Tr}_{ENV(\eta)} \frac{\mathrm{d}}{\mathrm{d}\eta}\rho(\eta) \not\to \frac{\mathrm{d}}{\mathrm{d}\eta}\mathrm{Tr}_{ENV(\eta)}\,\rho(\eta) = \frac{\mathrm{d}}{\mathrm{d}\eta}\rho_{\mathrm{r}}(\eta)$$

$$\rho_{r,I}(\eta+\Delta\eta) - \rho_{r,I}(\eta) = -\Delta\eta g(\eta)\int_{\eta_0}^{\eta} d\eta_2 g(\eta_2)\,\mathrm{Tr}_{E(\eta)}\left[H_{\mathrm{int}}(\eta),\left[H_{\mathrm{int}}(\eta_2),\rho(\eta_2)\right]\right]$$
$$-\int_{\eta_0}^{\eta} d\eta_1 g(\eta_1)\int_{\eta_0}^{\eta_1} d\eta_2 g(\eta_2)\,\mathrm{Tr}_{E(\eta+\Delta\eta)-E(\eta)}\left[H_{\mathrm{int}}(\eta_1),\left[H_{\mathrm{int}}(\eta_2),\rho(\eta_2)\right]\right]$$

THE CANONICAL FORM IS RESPECTED!!

- **Just a modification of D_{11}**

$$\Delta D_{11} \simeq -0.02\frac{H^2\epsilon}{8\pi^2 M_{pl}^2}$$

- **Negligible!!**

QUANTUM MASTER EQUATION AND TCL$_2$

- "Equation of motion" for the Density Matrix of the System **MEMORY!**

$$\mathrm{Tr}_{\mathcal{E}} \frac{\mathrm{d}}{\mathrm{d}\eta}\rho(\eta) = \frac{\mathrm{d}\rho_{\mathrm{r}}}{\mathrm{d}\eta}(\eta) = -g^2 \int_{\eta_{\mathrm{in}}}^{\eta} \mathrm{d}\eta' \, \mathrm{Tr}_{\mathcal{E}} \left[H_{\mathrm{int\,i}}(\eta), \left[H_{\mathrm{int\,j}}(\eta'), \rho_r(\eta')\right]\right] \quad i,j = 1,2,3$$

Convolution!

- BORN-MARKOVIAN APPROXIMATION: memory corrections are higher order in the coupling constant;

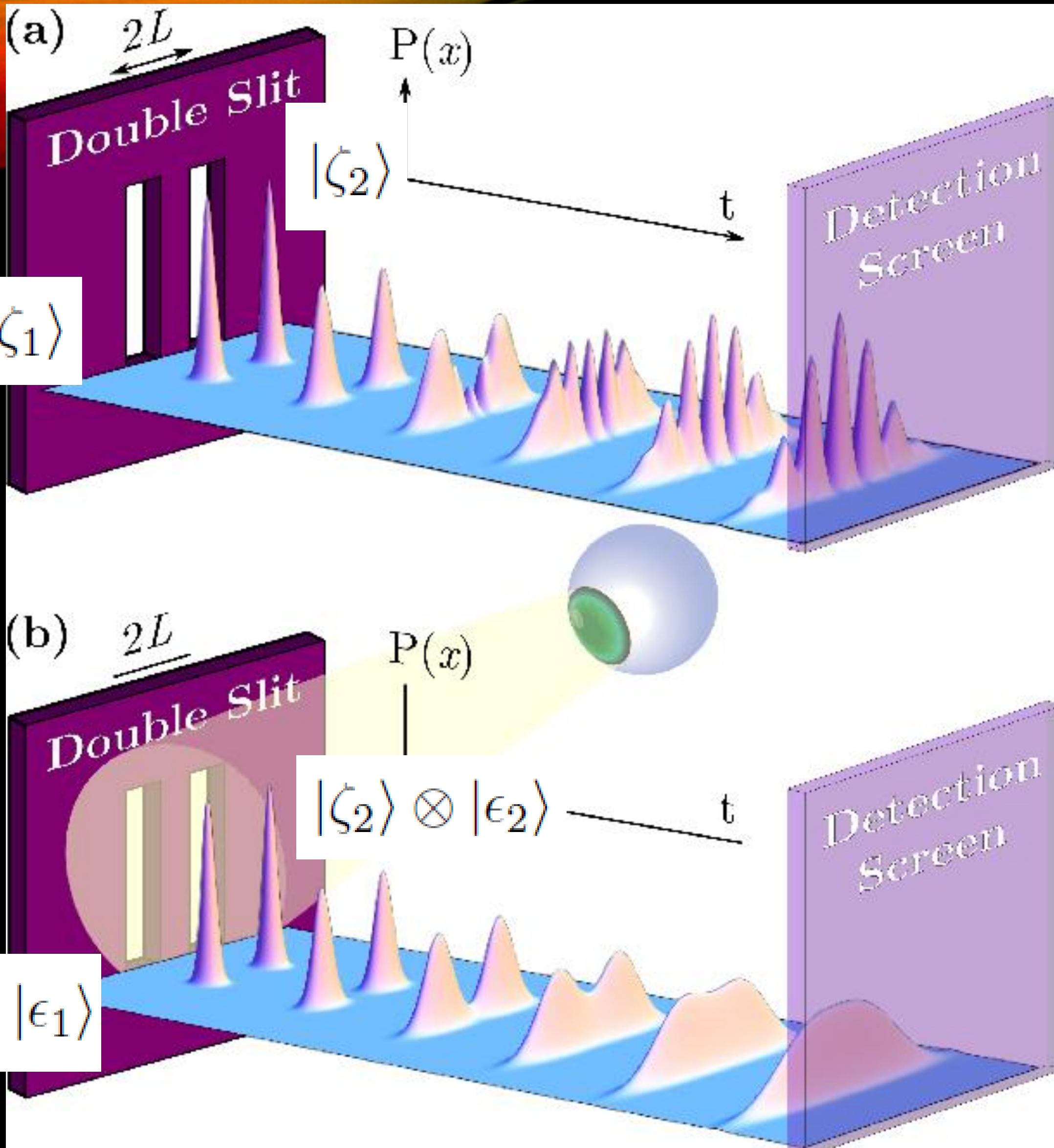
$$\rho_r(\eta') \to \rho_r(\eta) + O(g^2)$$

TCL$_2$: TIME CONVOLUTIONLESS EQUATION(at 2° order)

$$\rho_r'(\eta) = -g(\eta) \int_{\eta_0}^{\eta} \mathrm{d}\eta' g(\eta') \sum_{\boldsymbol{k}} \left[v_{\boldsymbol{k}}(\eta) v_{-\boldsymbol{k}}(\eta') \rho_r(\eta) K(k,\eta,\eta') + \rho_r(\eta) v_{-\boldsymbol{k}}(\eta') v_{\boldsymbol{k}}(\eta) K^*(k,\eta,\eta') - v_{\boldsymbol{k}}(\eta)\rho_r(\eta) v_{-\boldsymbol{k}}(\eta') K^*(k,\eta,\eta') - v_{-\boldsymbol{k}}(\eta') \rho_r(\eta) v_{\boldsymbol{k}}(\eta) K(k,\eta,\eta')\right]$$

MEMORY!

ENVIRONMENTAL CORRELATION FUNCTIONS



$|\zeta_1\rangle$

$|\zeta_2\rangle$

$|\zeta_2\rangle \otimes |\epsilon_2\rangle$

$|\zeta_1\rangle \otimes |\epsilon_1\rangle$

Interference!

Waves of probability

DECOHERENCE

GAUSSIAN
DISTRIBUTION

DECOHERENCE: TOY MODEL

Of course, we can have infinite possible configurations all over the Universe for scalar perturbations. (Infinite dimensional Hilbert space)

As a TOY MODEL, consider ζ as a TWO STATES OPERATOR, with only two possibile eigenvalues:

$$\hat{\zeta}\,|\zeta_1\rangle = \zeta_1\,|\zeta_1\rangle \qquad \hat{\zeta}\,|\zeta_2\rangle = \zeta_2\,|\zeta_2\rangle$$

Consider a coherent superposition:

$$|\psi\rangle = c_1\,|\zeta_1\rangle + c_2\,|\zeta_2\rangle$$

But what we usually have to consider is the density matrix:

$$\rho = |\psi\rangle\langle\psi|$$

Expanding (interference terms in red):

$$\rho = |c_1|^2|\zeta_1\rangle\langle\zeta_1| + |c_2|^2|\zeta_2\rangle\langle\zeta_2| + c_1^* c_2|\zeta_1\rangle\langle\zeta_2| + c_1 c_2^*|\zeta_2\rangle\langle\zeta_1|$$

Purity γ:

$$\gamma = \mathrm{Tr}\,\rho^2 = (|c_1|^4 + |c_2|^4 + 2|c_1|^2|c_2|^2) = (|c_1|^2 + |c_2|^2)^2 = 1$$

Full quantum coherence

Introduce an Environment (TWO STATES)

$$|\epsilon_1\rangle, |\epsilon_2\rangle \quad such\ that \quad \langle\epsilon_1|\epsilon_2\rangle = 0$$

System environment interaction → Creates entanglement

$$|\zeta_1\rangle \otimes |\epsilon_1\rangle, \qquad |\zeta_2\rangle \otimes |\epsilon_2\rangle$$

We CANNOT observe the environment, so we trace over it:

$$\rho_{reduced} = \mathrm{Tr}_\epsilon\, \rho = \mathrm{Tr}_\epsilon \left(|c_1|^2 |\zeta_1\rangle|\epsilon_1\rangle\langle\epsilon_1|\langle\zeta_1| + |c_2|^2 |\zeta_2\rangle|\epsilon_2\rangle\langle\epsilon_2|\langle\zeta_2| \right.$$
$$\left. + c_1^* c_2 |\zeta_1\rangle|\epsilon_1\rangle\langle\epsilon_2|\langle\zeta_2| + c_1 c_2^* |\zeta_2\rangle|\epsilon_2\rangle\langle\epsilon_1|\langle\zeta_1| \right)$$

$$\rho_r = \left(|c_1|^2 |\zeta_1\rangle\langle\epsilon_1|\epsilon_1\rangle\langle\zeta_1| + |c_2|^2 |\zeta_2\rangle\langle\epsilon_2|\epsilon_2\rangle\langle\zeta_2| \right.$$
$$\left. + c_1^* c_2 |\zeta_1\langle\epsilon_1|\epsilon_2\rangle\langle\zeta_2| + c_1 c_2^* |\zeta_2\rangle\langle\epsilon_2|\epsilon_1\rangle\langle\zeta_1| \right)$$

System environment interaction → Creates entanglement

$$|\zeta_1\rangle \otimes |\epsilon_1\rangle, \qquad |\zeta_2\rangle \otimes |\epsilon_2\rangle$$

We CANNOT observe the environment, so we trace on it:

$$\rho_{reduced} = \mathrm{Tr}_\epsilon\, \rho = \mathrm{Tr}_\epsilon \big(|c_1|^2|\zeta_1\rangle|\epsilon_1\rangle\langle\epsilon_1|\langle\zeta_1| + |c_2|^2|\zeta_2\rangle|\epsilon_2\rangle\langle\epsilon_2|\langle\zeta_2| \\ + c_1^* c_2|\zeta_1\rangle|\epsilon_1\rangle\langle\epsilon_2|\langle\zeta_2| + c_1 c_2^*|\zeta_2\rangle|\epsilon_2\rangle\langle\epsilon_1|\langle\zeta_1|\big)$$

$$\rho_r = \big(|c_1|^2|\zeta_1\rangle\langle\epsilon_1|\epsilon_1\rangle\langle\zeta_1| + |c_2|^2|\zeta_2\rangle\langle\epsilon_2|\epsilon_2\rangle\langle\zeta_2| \\ + c_1^* c_2|\zeta_1\rangle\langle\epsilon_1|\epsilon_2\rangle\langle\zeta_2| + c_1 c_2^*|\zeta_2\rangle\langle\epsilon_2|\epsilon_1\rangle\langle\zeta_1|\big)$$

Purity:

$$0 < \gamma = \mathrm{Tr}_{system}\, \rho_r^2 = |c_1|^4 + |c_2|^4 + NO\,INTERFERENCE < 1$$

Take Home message: **Purity<<1, No Interference** → Decoherence!

During inflation:

Sasaki-Mukhanov variable for curvature perturbations (during inflation, canonically normalized): $\hat{v} = a\sqrt{2\epsilon}M_{pl}\hat{\zeta}$

Quantum operators during Inflation: $\hat{v}_{\boldsymbol{k}} = u_{\boldsymbol{k}}\hat{c}_{\boldsymbol{k}} + u^*_{\boldsymbol{k}}\hat{c}^\dagger_{-\boldsymbol{k}}$

Possible configurations of perturbations: $\hat{v}|v\rangle = v|v\rangle$

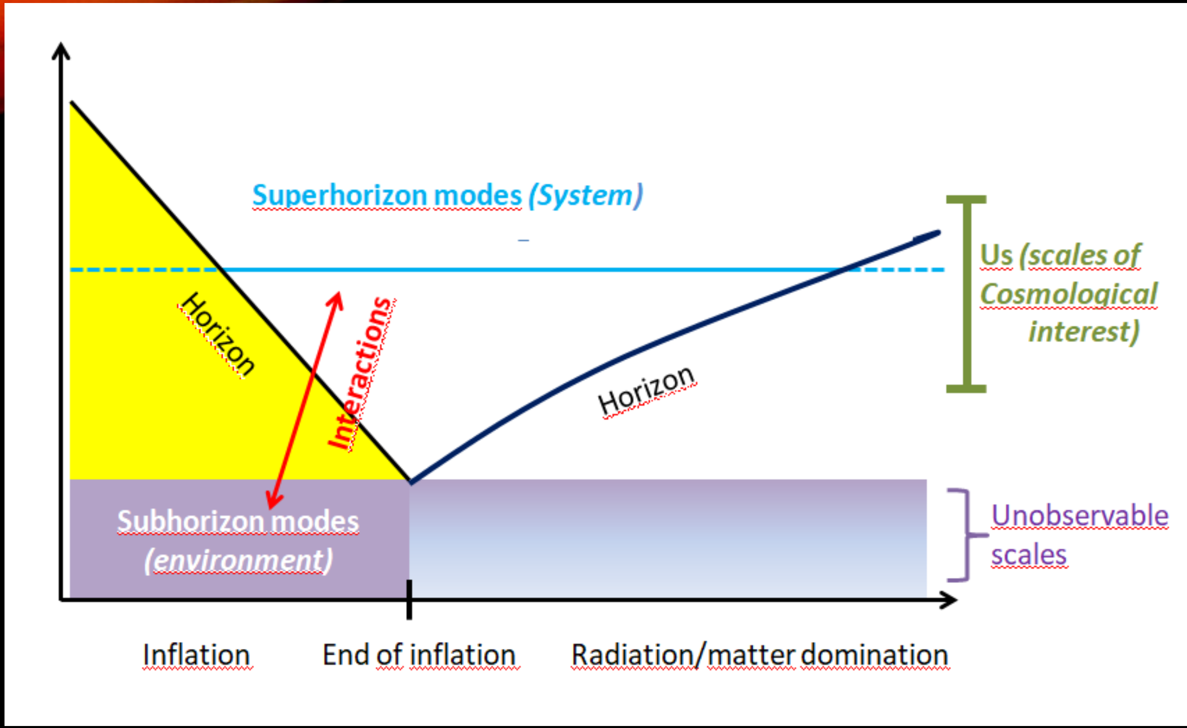
State of perturbations during inflation $|\psi\rangle = c_1|v_1\rangle + c_2|v_2\rangle + \ldots$

After inflation:

Stochastic (quasi) gaussian distribution of Temperature anisotropies in CMB:

$$\frac{\delta T}{T}(\boldsymbol{e}) = \frac{1}{5}\zeta(\eta_{\ell ss}, \boldsymbol{e})$$

OPEN QUANTUM SYSTEMS

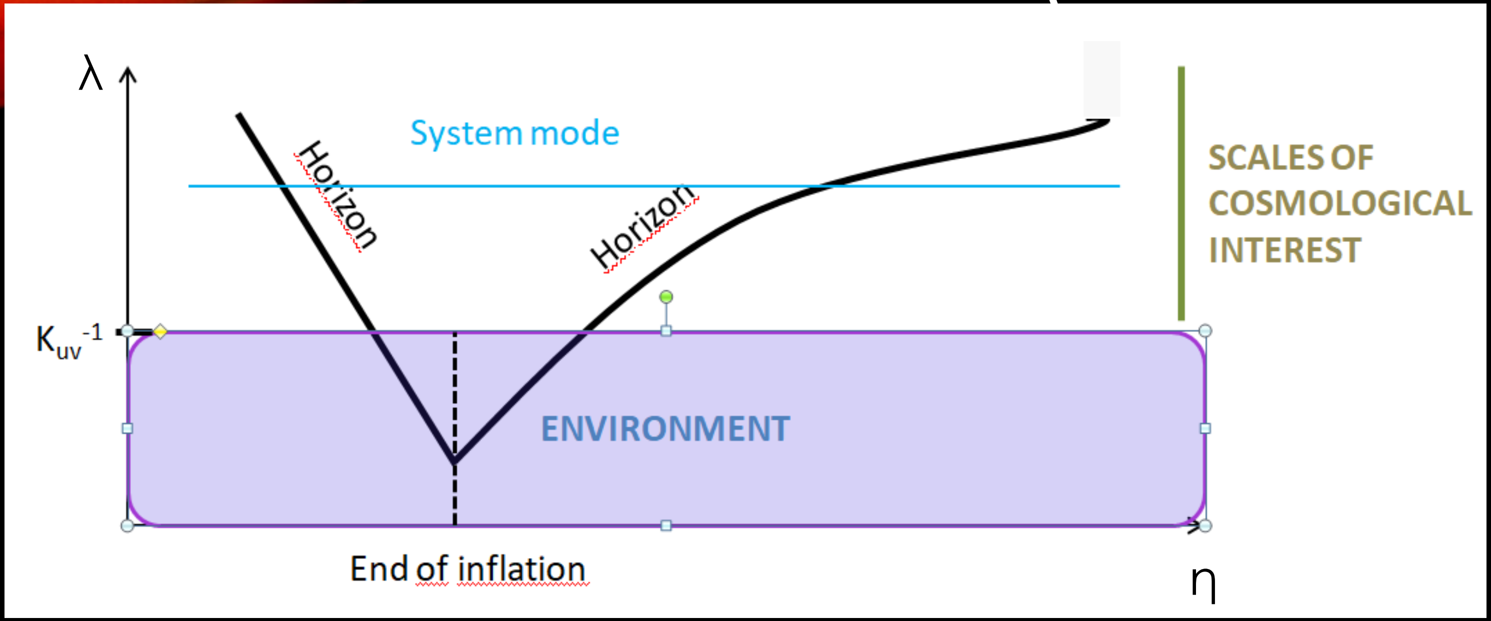


Decoherence :

- already during inflation, after Horizon crossing: Superhorizon phenomenon.

System	Environment	N. e-folds	Authors
Scalar	Scalar	10-20	Nelson,'16;Burgess+,22
Tensor	Tensor	5-10	Seo et al., 2019
Scalar	Tensor+Scalar	13	Burgess et al. , 2022

MINIMAL DECOHERENCE(BURGESS+,22)



- **Fixed** Environment: k>125/Mpc $=k_{UV}$ System: Scalar perturbation, $k<k_{UV}$.

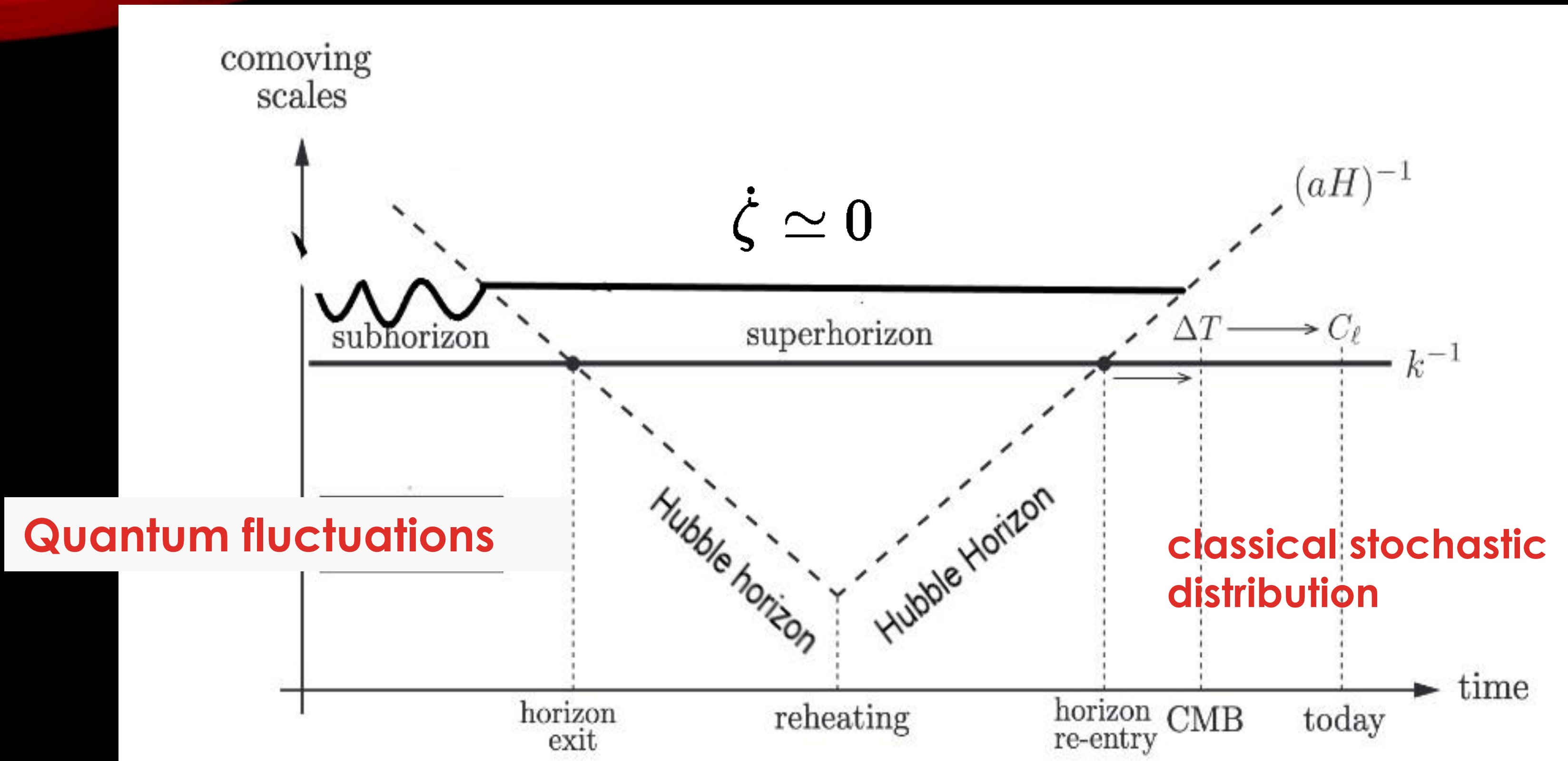
ASSUMPTION: most of decoherence comes from the Superhorizon modes in the environment.

- Time derivative interactions are suppressed!
- GR nonlinear gravitational interactions (Maldacena, 2003);

$$S=\frac{\epsilon M_{pl}^2}{8}\int dtd^3x\left(a^3\zeta\dot{h}_{ij}\dot{h}_{ij}+a\zeta\partial_l h_{ij}\partial_l h_{ij}-2a^3\dot{h}_{ij}\partial_l h_{ij}\partial_l\left(\nabla^2\right)^{-1}\dot{\zeta}\right)$$

QUANTUM TO CLASSICAL

Guth, Pi(1985), Polarski,Starobinski (1996++),…

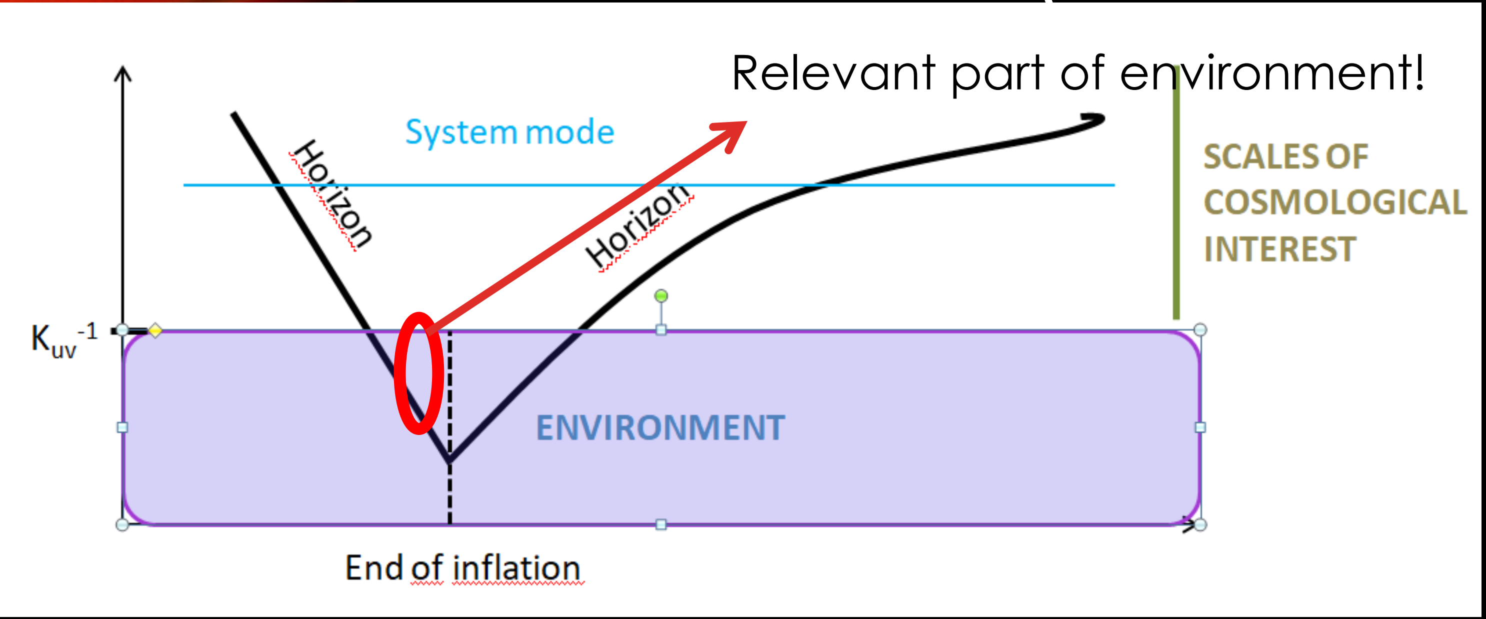


$$\frac{\delta T}{T}(\boldsymbol{e}) = \frac{1}{5}\zeta(\eta_{\ell ss}, \boldsymbol{e})$$

- Credits:D.Baumann, Lectures on Inflation; Coles and Lucchin,Cosmology.

How could quantum fluctuations become classical objects?

MINIMAL DECOHERENCE(BURGESS+,22)



•**Fixed** Environment: k>125/Mpc =k_{UV} System: Scalar perturbation, k<k_{UV}.

ASSUMPTION: most of decoherence comes from the Superhorizon modes in the environment.

•Time derivative interactions are suppressed!

• GR nonlinear gravitational interactions (Maldacena, 2003);

$$S=\frac{\epsilon M_{pl}^2}{8}\int dt d^3x\left(a^3\zeta\dot{h}_{ij}\dot{h}_{ij}+a\zeta\partial_l h_{ij}\partial_l h_{ij}-2a^3\dot{h}_{ij}\partial_l h_{ij}\partial_l\left(\nabla^2\right)^{-1}\dot{\zeta}\right)$$

DO WE NEED INTERACTIONS?

No: "Decoherence without decoherence" (Starobinski et al.,, 1996)

Yes: Only Interactions with an **unobservable environment** induce **decoherence**

OPEN QUANTUM SYSTEMS

QUANTUM OR CLASSICAL PERTURBATIONS?

"Decoherence without decoherence" (Starobinski et al, 1996): after horizon crossing, quantum states freely evolve into "squeezed" quantum states

$$ {}_S\left\langle 0,\eta \middle| G(v(\vec{k}))\, G^{\dagger}(v(\vec{k})) \middle| 0,\eta \right\rangle_S = \iint d\Re v(\vec{k})\ d\Im v(\vec{k})\ \rho(|v(\vec{k})|)\, |G(v(\vec{k}))|^2 $$

Quantum vacuum expectation value, in squeezed quantum states

Statistical average with a Gaussian stochastic distribution

They are indistinguishable! *(in the free case)*

How is it possible to prove the quantum origin of inflation primordial perturbations?

QUANTUM OR CLASSICAL PERTURBATIONS?

"Decoherence without decoherence"(Starobinski et al, 1996): after horizon crossing, quantum states freely evolve into "squeezed" quantum states

$$ {}_S\left\langle 0,\eta \middle| G(v(\vec{k}))\, G^{\dagger}(v(\vec{k})) \middle| 0,\eta \right\rangle_S = \iint d\Re v(\vec{k})\; d\Im v(\vec{k})\; \rho(|v(\vec{k})|)\, |G(v(\vec{k}))|^2 $$

Quantum vacuum expectation value, in squeezed quantum states

Statistical average with a Gaussian stochastic distribution

They are indistinguishable! *(in the free case)*

How is it possible to prove the quantum origin of inflation primordial perturbations?

1) This is indistinguishability is not sufficient for QtoCl, Unitary evolution does not break symmetries!

~~"Decoherence without decoherence"(Starobinski et al.,, 1996)~~

Only Interactions with an **unobservable environment** induce **decoherence**

OPEN QUANTUM SYSTEMS

2)How is it possible to prove the quantum origin of inflation primordial perturbations?

THE THEORY OF INFLATION

- Accelerated expansion driven by one (or more) quantum scalar field(s) in the very first instants of the universe

•(quasi) de Sitter metric, but de Sitter approximation for the scale factor:

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

Scalar (curvature) perturbations ζ ⟷ Quantum fluctuations of the scalar field

$$\hat{\zeta}\,|\zeta\rangle = \zeta|\zeta\rangle$$

Tensor perturbation h_{ij} (Stochastic Gravitational Waves Background)

$$\hat{v} = a\sqrt{2\epsilon}M_{pl}\hat{\zeta}$$

QUANTUM MASTER EQUATION

- Equation of motion of the density matrix

$$\frac{d\rho_r}{d\eta} = -\mathrm{i}\left[H + H_{LS}, \rho_r(\eta)\right] + \sum_{\boldsymbol{p}} D_{11}(\eta)\left(v_{\boldsymbol{p}}(\eta)\rho_r(\eta)v_{\boldsymbol{p}}^{\dagger}(\eta) - \frac{1}{2}\left\{v_{\boldsymbol{p}}^{\dagger}(\eta)v_{\boldsymbol{p}}(\eta), \rho_r(\eta)\right\}\right)$$

Many approximations, but main one is **MARKOVIAN APPROXIMATION**:

D_{11} (η) "canonical decay rate":

$$D_{11} = g(\eta)\int_{-\frac{1}{p}}^{\eta} d\eta' g\left(\eta'\right) 2\Re K\left(\eta, \eta'\right)$$

$$K\left(\eta, \eta'\right) \propto \delta\left(\eta - \eta'\right) - \ \text{nonMarkovian terms}$$

Markovian part **Long non-Markovian tails…**

QUANTUM MASTER EQUATION

- Equation of motion of the density matrix

$$\frac{d\rho_r}{d\eta} = -\mathrm{i}\left[H + H_{LS}, \rho_r(\eta)\right] + \sum_{\boldsymbol{p}} D_{11}(\eta)\left(v_{\boldsymbol{p}}(\eta)\rho_r(\eta)v_{\boldsymbol{p}}^{\dagger}(\eta) - \frac{1}{2}\left\{v_{\boldsymbol{p}}^{\dagger}(\eta)v_{\boldsymbol{p}}(\eta), \rho_r(\eta)\right\}\right)$$

Lamb Shift Hamiltonian
-finite **renormalization of the unitary** hamiltonian
-corrections to the **mass of perturbations and spectral index of** Power Spectrum.

Non Unitary part:
-Decoherence;
-non-Unitary correction to observables.

D_{11} (η) "canonical decay rate": contains environmental correlation

$$D_{11} = g(\eta)\int_{-\frac{1}{p}}^{\eta} d\eta' g\left(\eta'\right) 2\Re K\left(\eta, \eta'\right)$$

QUANTUM MASTER EQUATION

- "Equation of motion" for the Density Matrix of the System

$$\frac{d\rho_r}{d\eta} = -\mathrm{i}\left[H + H_{LS}, \rho_r(\eta)\right] + \sum_{\boldsymbol{p}} D_{11}(\eta)\left(v_{\boldsymbol{p}}(\eta)\rho_r(\eta)v_{\boldsymbol{p}}^\dagger(\eta) - \frac{1}{2}\left\{v_{\boldsymbol{p}}^\dagger(\eta)v_{\boldsymbol{p}}(\eta), \rho_r(\eta)\right\}\right)$$

D_{11} (η) "canonical decay rate": contains environmental correlation

$$D_{11} = g(\eta)\int_{-\frac{1}{p}}^{\eta} d\eta' g\left(\eta'\right) 2\Re K\left(\eta, \eta'\right)$$

Markovian Approximation! $\rho_r\left(\eta'\right) \rightarrow \rho_r(\eta)$

QUANTUM MASTER EQUATION

- "Equation of motion" for the Density Matrix of the System

$$\frac{d\rho_r}{d\eta} = -\mathrm{i}\left[H + H_{LS}, \rho_r(\eta)\right] + \sum_{\boldsymbol{p}} D_{11}(\eta)\left(v_{\boldsymbol{p}}(\eta)\rho_r(\eta)v^{\dagger}_{\boldsymbol{p}}(\eta) - \frac{1}{2}\left\{v^{\dagger}_{\boldsymbol{p}}(\eta)v_{\boldsymbol{p}}(\eta), \rho_r(\eta)\right\}\right)$$

D_{11} (η) "canonical decay rate": contains environmental correlation

$$D_{11} = g(\eta)\int_{-\frac{1}{p}}^{\eta} d\eta' g\left(\eta'\right) 2\Re K\left(\eta, \eta'\right)$$

Markovian Approximation! $\rho_r\left(\eta'\right) \to \rho_r(\eta)$

$D_{11}^{\mathrm{mark}} > 0$ ⟺ **Markovian! Lindblad theorem!**

If $\tau_{env} \ll \tau_{sys}$ as e.g. $K\left(\eta, \eta'\right) \propto \delta\left(\eta - \eta'\right)$ **NO MEMORY**

QUANTUM MASTER EQUATION

- "Equation of motion" for the Density Matrix of the System

$$\frac{d\rho_r}{d\eta} = -\mathrm{i}\left[H + H_{LS}, \rho_r(\eta)\right] + \sum_{\boldsymbol{p}} D_{11}(\eta)\left(v_{\boldsymbol{p}}(\eta)\rho_r(\eta)v_{\boldsymbol{p}}^{\dagger}(\eta) - \frac{1}{2}\left\{v_{\boldsymbol{p}}^{\dagger}(\eta)v_{\boldsymbol{p}}(\eta), \rho_r(\eta)\right\}\right)$$

D_{11} (η) "canonical decay rate": contains environmental correlation

$$D_{11} = g(\eta)\int_{-\frac{1}{p}}^{\eta} d\eta' g\left(\eta'\right) 2\Re K\left(\eta, \eta'\right)$$

Markovian Approximation! $\rho_r\left(\eta'\right) \rightarrow \rho_r(\eta)$

$D_{11}^{\text{mark}} > 0$ ⟺ **Markovian! Lindblad theorem!**

If $\tau_{env} \ll \tau_{sys}$ as e.g. $K\left(\eta, \eta'\right) \propto \delta\left(\eta - \eta'\right)$ **NO MEMORY**

BUT IN INFLATION....

$K\left(\eta, \eta'\right) \propto \delta\left(\eta - \eta'\right) - \text{ nonMark}$ ⟺ $D_{11}^{tot} = D_{11}^{mark} + \delta D_{11}^{N\text{ mark}}$ $\delta D_{11}^{Nmark} < 0$

Non-Markovian :ENVIRONMENT HAS MEMORY! OK for Lindblad, if $D_{11}^{tot} > 0$

If $D_{11}^{tot} < 0$ **system highly non-Markovian: requires numerical simulations!**