QUANTUM SIGNATURES AND DECOHERENCE DURING INFLATION FROM PRIMORDIAL GRAVITATIONAL WAVES

Arxiv: 2503.23150

Francescopaolo Lopez

With Nicola Bartolo(UniPd)

3° year Phd student @SISSA, Trieste,Italy
Supervisors: Takeshi Kobayashi, Nicola Bartolo

Padova,Planck 2025, 27/05/2025

THE THEORY OF INFLATION

- Accelerated expansion driven by one (or more) quantum scalar field(s)
- Provides a mechanism to **explain anisotropies and inhomogeneities** in the present universe from the tiny quantum fluctuations of the scalar field.

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

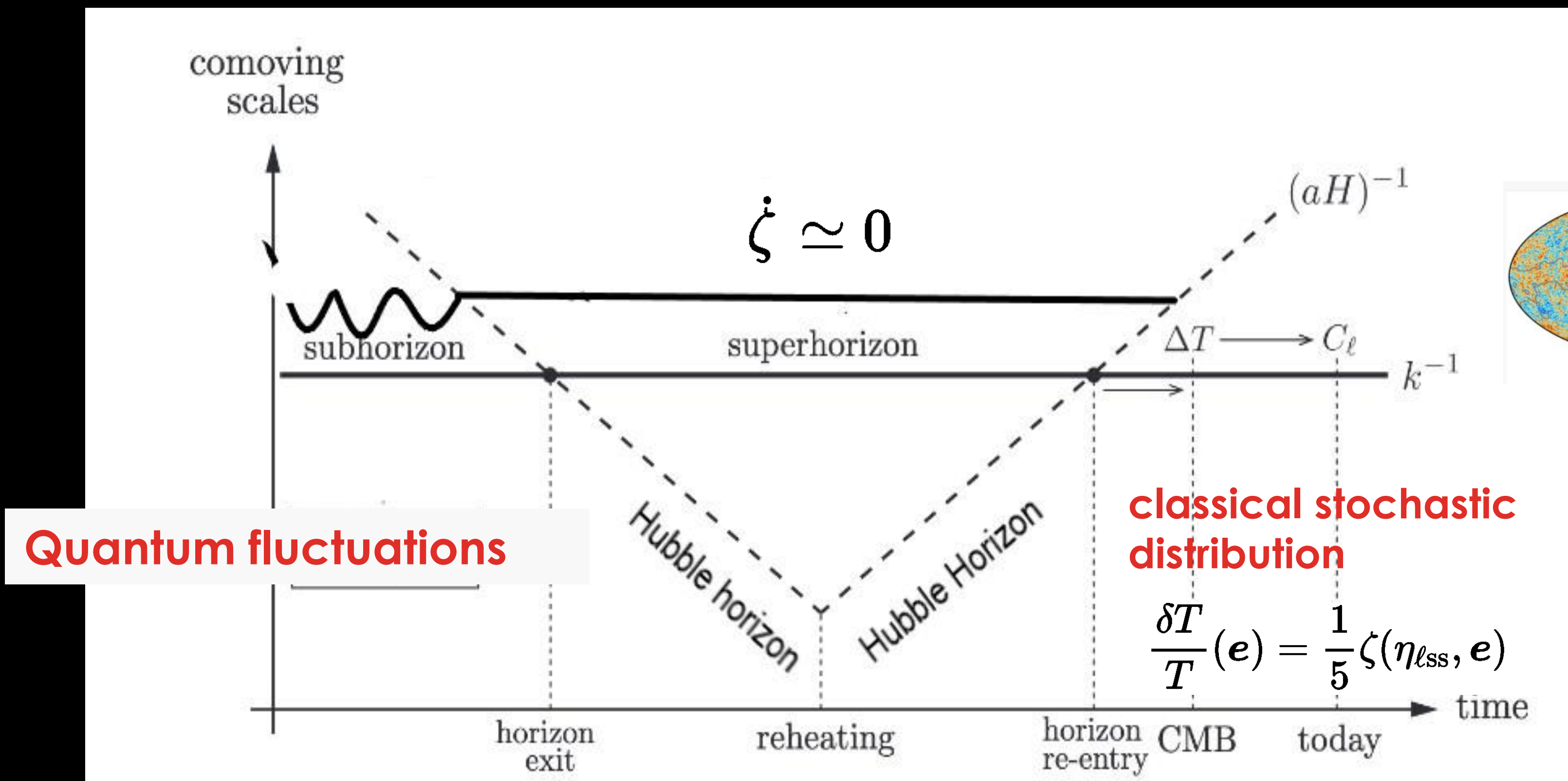
- Tensor perturbation h_{ij} (Stochastic Gravitational Waves Background)

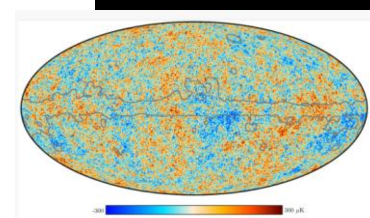
- Scalar (curvature) perturbations ζ or Sasaki Mukhanov variable

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

QUANTUM TO CLASSICAL TRANSITION IN COSMOLOGY

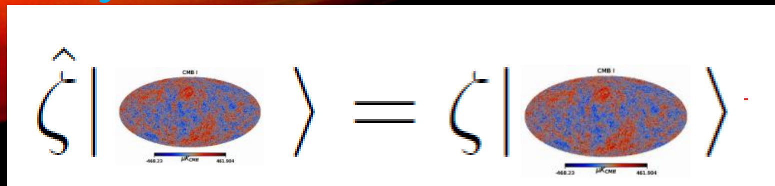
- Quantum fluctuations of the scalar field driving the accelerated expansion are the seeds for the anisotropies we observe in CMB.



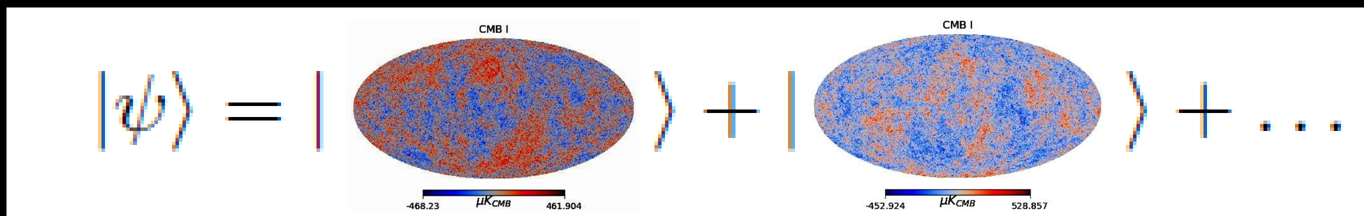


- Credits:Coles and Lucchin,Cosmology,,D.Baumann, Lectures on Inflation.

How could quantum fluctuations become classical objects?



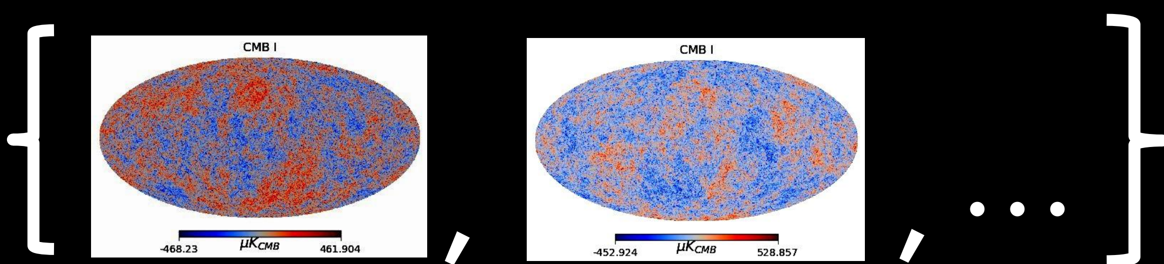
•ζ quantum operator;
• Configuration of perturbations (~CMB Maps) are eigenvectors of ζ



COHERENT **SUPERPOSITION**

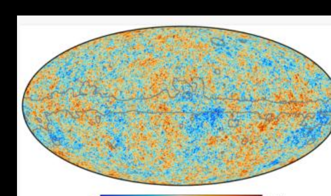
DECOHERENCE
(after interaction, and entanglement with unobservable environment)

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 → Entanglement, suppress quantum coherence between different possible outcomes

Interference terms in red

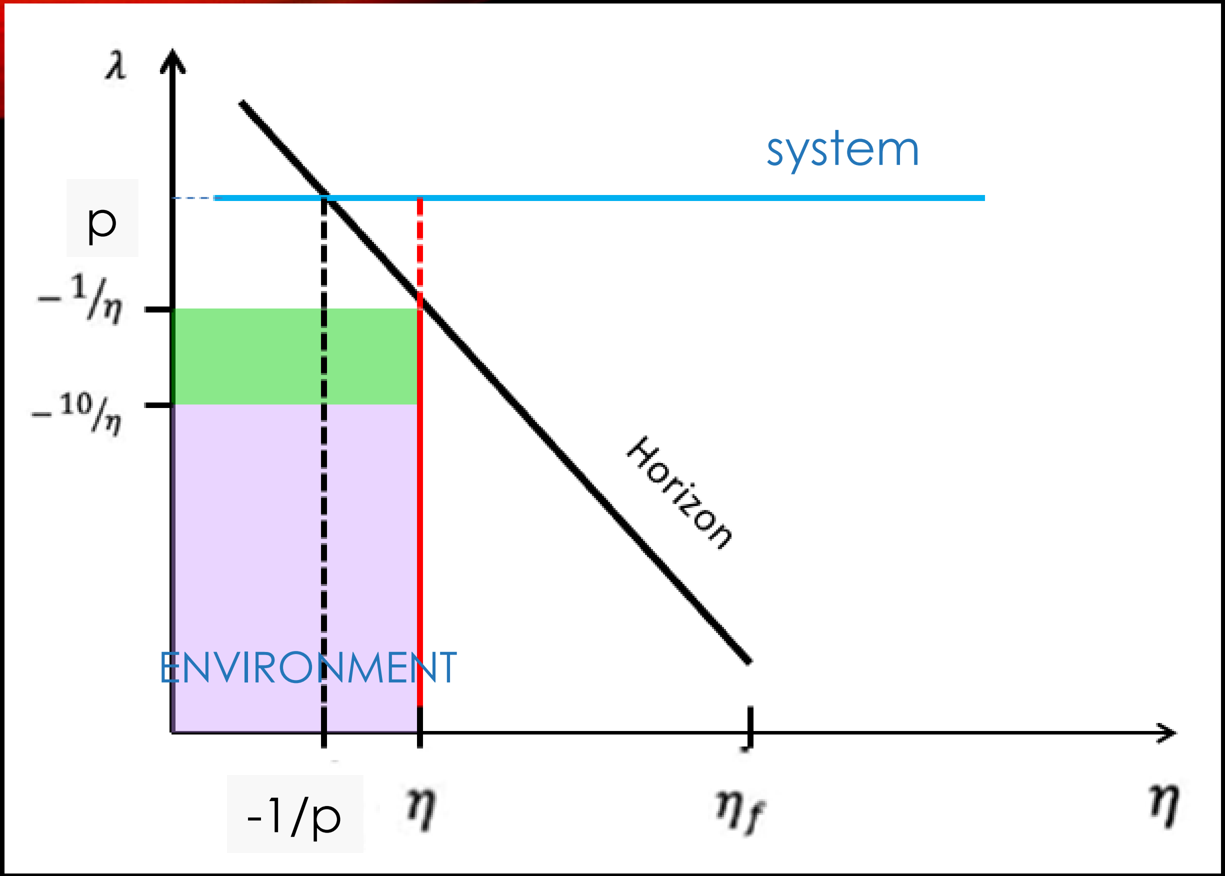
$$\rho_{sys} = \begin{pmatrix} |\zeta_1\rangle\langle\zeta_1| & |\zeta_1\rangle\langle\zeta_2| \\ |\zeta_2\rangle\langle\zeta_1| & |\zeta_2\rangle\langle\zeta_2| \end{pmatrix} \xrightarrow{\textbf{decoherence}} \rho_r = \mathrm{Tr}_{ENV}\, \rho_{sys+env} = \begin{pmatrix} |\zeta_1\rangle\langle\zeta_1|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

How to quantify? Purity!

Statistical ensemble!

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

SINGLE FIELD INFLATION



SYSTEM: **Superhorizon** Scalar Mode.

Entanglement

ENVIRONMENT: Deep **subhorizon** modes Of Gravitational waves.

1. **Time dependent environment**
2. **Short Correlation time!**

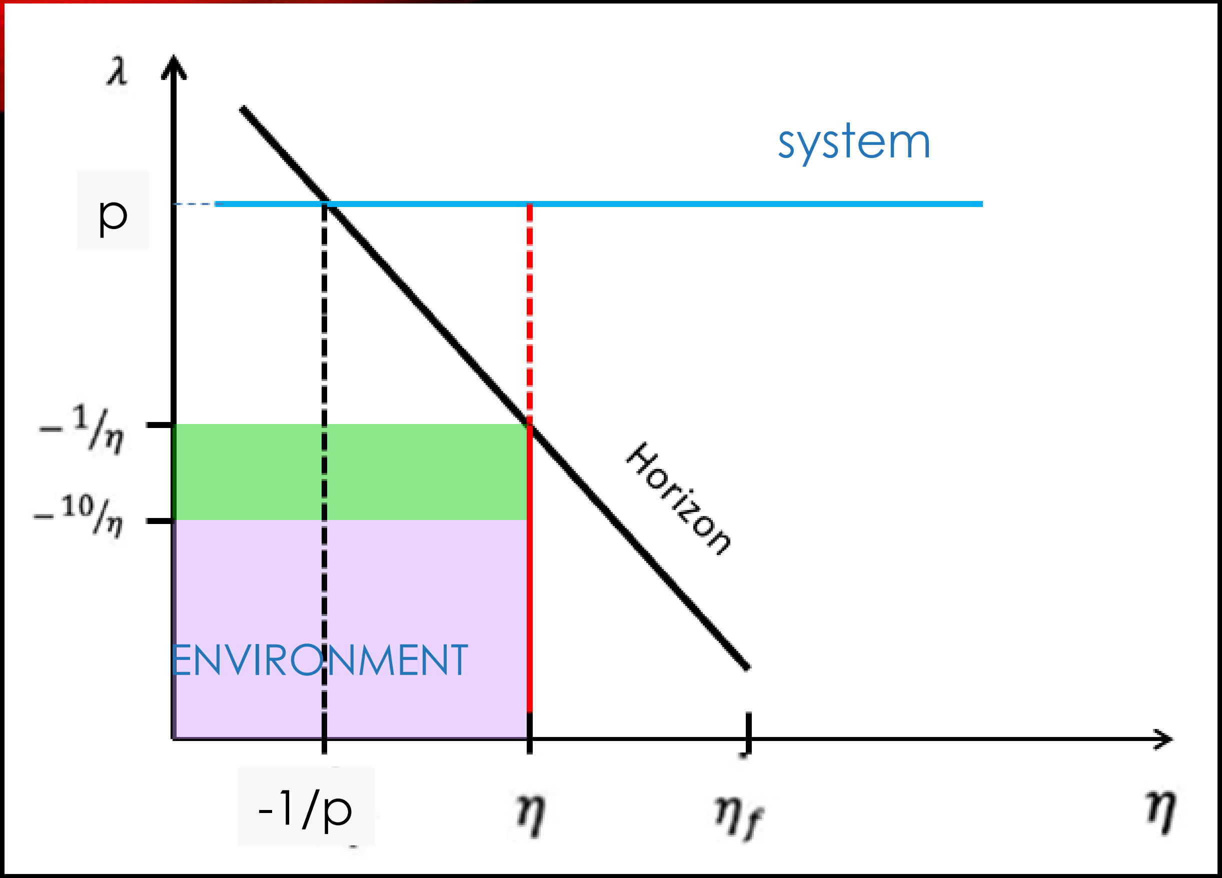
$$\tau_{env} \ll \tau_{sys}$$

HORIZON CROSSING MODES:to be analyzed in future works.

(Nonlinear) **gravitational Interaction (GR)**

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

SINGLE FIELD INFLATION



SYSTEM: **Superhorizon** Scalar Mode.

Entanglement

ENVIRONMENT:
Deep **subhorizon** modes Of Gravitational waves.

1. **Time dependent environment**
2. **Short Correlation time!**

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

HORIZON CROSSING MODES:to be analyzed in future works.

(Nonlinear) **gravitational Interaction (GR)**

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

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 function

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

Many approximations to derive it….but most important is the **Markovian Approximation!** If $\tau_{env} \ll \tau_{sys}$ then $\rho_r\left(\eta'\right) \to \rho_r(\eta)$ $v_p\left(\eta'\right) \to v_p(\eta)$

If fully Markovian environment: No memory

$$K\left(\eta, \eta'\right) \propto \delta\left(\eta - \eta'\right)$$

BUT IN INFLATION….

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

Non-Markovian terms due to long memory tails

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 function

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

IN INFLATION

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

Lindblad theorem

POSITIVITY: if **D_{11}>0, approximations work well, and dynamics is physical for sure!**

- **So…there may be some small non-Markovian corrections (δD_{11}<0) , as long as total D_{11}>0**

Our case!

CANONICAL FORM QME

- Canonical form

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

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.

DECOHERENCE IN SINGLE FIELD INFLATION

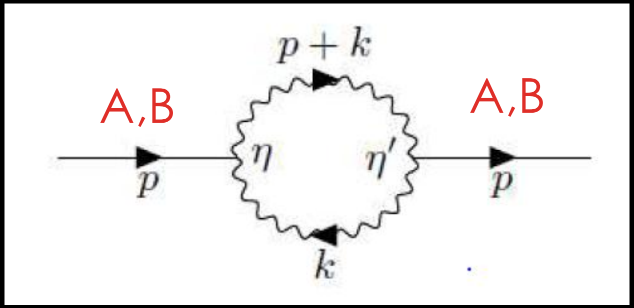
- GR non linear gravitational interactions (Gangui+1993,Maldacena 2003)

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

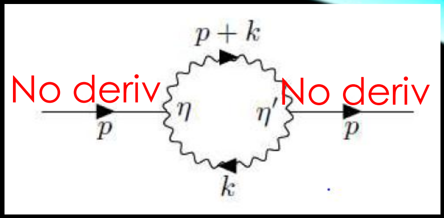
WE CONSIDER THE INTERPLAY BETWEEN ALL INTERACTIONS!
Rewriting the action we have:

A)DERIVATIVELESS interaction,more important contributions.

B) DERIVATIVE interactions (just like the circled one).



DERIVATIVELESS INTERACTIONS



- D_{11}>0 **positive!**

$$D_{11}^{int11} = \frac{\epsilon H^2}{4\pi^2 M_{pl}^2 \eta^2}\left(\frac{\pi}{2} - 1.52\right) \simeq \frac{\epsilon H^2}{4\pi^2 M_{pl}^2 \eta^2} 0.05$$

- We can achieve decoherence when

$$\gamma \to 0 \quad \Leftrightarrow \frac{1}{\gamma} \to \infty$$

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

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

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

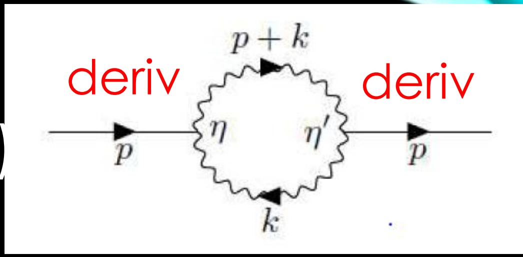
Decoherence happens when system is superhorizon!

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

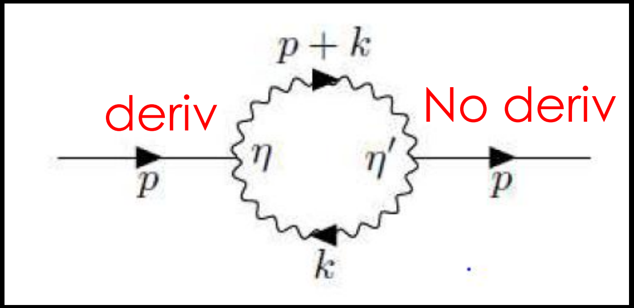
CMB well decohered!! But what about smaller scales?

DERIVATIVE INTERACTIONS

- NEGLIGIBLE!! (Just for deep subhorizon modes)



MIXED DERIVATIVE-DERIVATIVELESS INTERACTIONS



•**Mixed terms give** NEGATIVE CONTRIBUTIONS

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

NON-MARKOVIANITY!!

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

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

LAMB SHIFT:UNITARY RENORMALIZATION

- **Weinberg '05**: compute corrections to Power Spectrum due to interaction at second order:**"loop quantum correction"**;
- Method: in-in formalism, just a **unitary** dynamics;
- But…late time secular effects: very large logarithms in corrections

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

•**May break perturbation theory!**

•Many methods in the past for resummation.

LAMB SHIFT:UNITARY RENORMALIZATION

- Entanglement with environment "renormalizes" in a finite way energy levels of the system (in this case, mass);

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

- **Decay in time of the power spectrum after horizon crossing:**

$$\mathcal{P}(k,\eta) \propto e^{\frac{2\varepsilon H^2}{4\pi^2 M_{pl}^2}\ln(-k\eta)}$$

Or: blue correction to spectral index n_s
No logarithmic secular corrections!

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

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

Lamb Shift: unitary corrections

Modifies spectral index in Curvature Power Spectrum:

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

- Blue Correction to spectral index n_s
- No logaritmic secular corrections.

Corrections from non unitary part:

Same order, different form

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

Of course, too little (Gravitational interactions)!

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

What about specific models with stronger non Gaussianity?

Lamb Shift for the Bispectrum

Tensorial environment on **scalar system**

$$\left\langle \zeta(\vec{k_1})\zeta(\vec{k_2})\zeta(\vec{k_3}) \right\rangle = (2\pi)^3 B(k_1, k_2, k_3)\delta^3\left(\vec{k_1} + \vec{k_2} + \vec{k_3}\right)$$

Important for the investigation of non gaussianity

- Dealt with(in a different way) in Daddi Hammou+'22, Martin+'18, Colas+24
- Three modes k_1, k_2, k_3 superhorizon at the end of inflation
- **Decay in time after** the smallest wavelentgh mode k_1 crosses the horizon (akin to Power Spectrum)

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

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 considered **time dependent environment** and appropriately modified for the first time the quantum master equation to take it into account.
- We found Lamb Shift corrections to the **Bispectrum**(decay in time) and to the Power Spectrum.

FUTURE PROJECTS

- ***Non unitary evolution during inflation is needed for quantum to classical transition,*** **and should be there even** in a minimal setting. Can this change any conclusion?
- Non-Markovianity in an expanding background: how to deal with it?
- Can we prove, either directly, or indirectly, e.g. through corrections by decoherence, the quantum nature of inflationary perturbations?

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!

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;

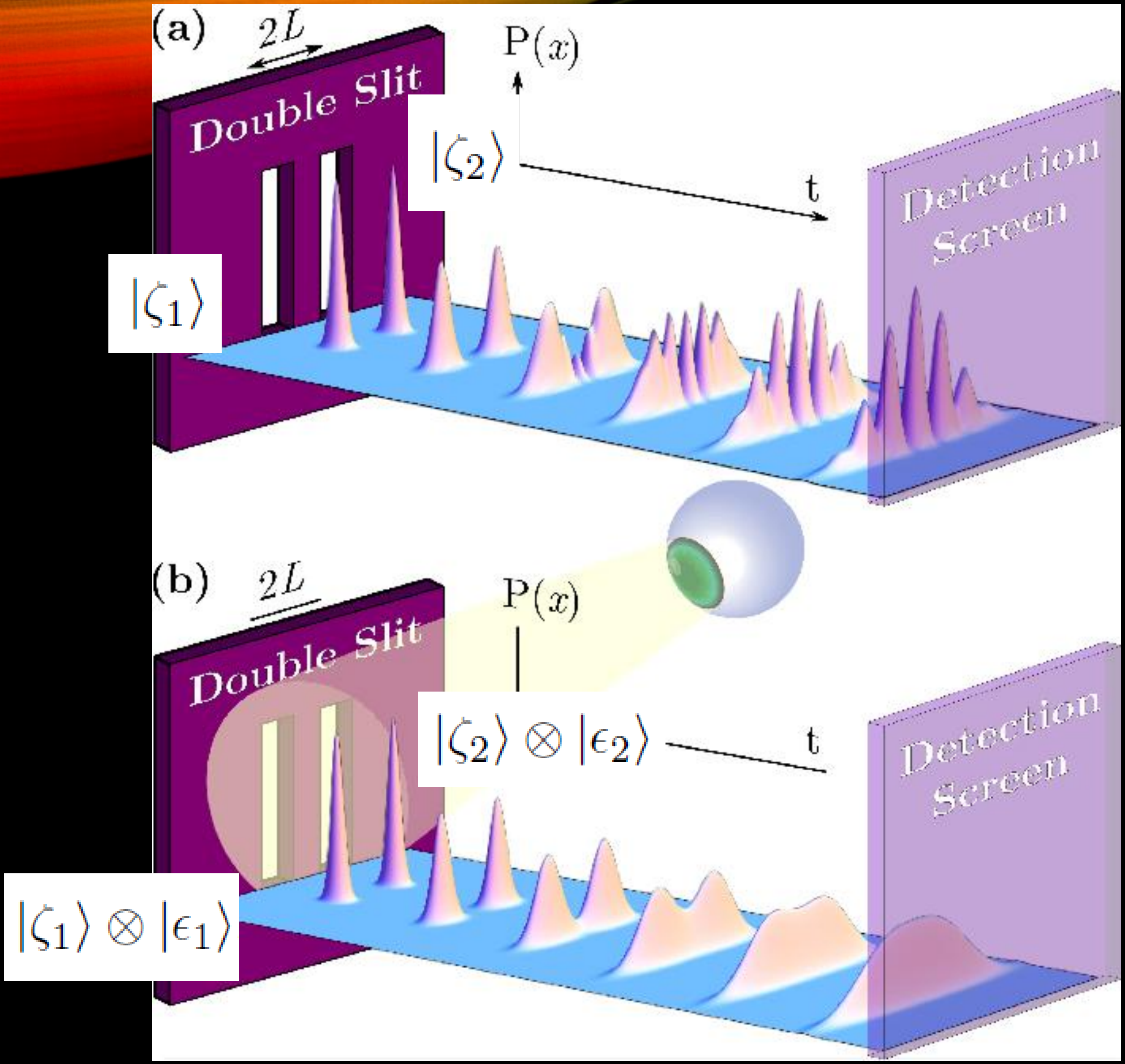
$$\rho_r(\eta')\to\rho_r(\eta)+O(g^2)$$

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

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

MEMORY!

ENVIRONMENTAL CORRELATION FUNCTIONS



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)

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

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:

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

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

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

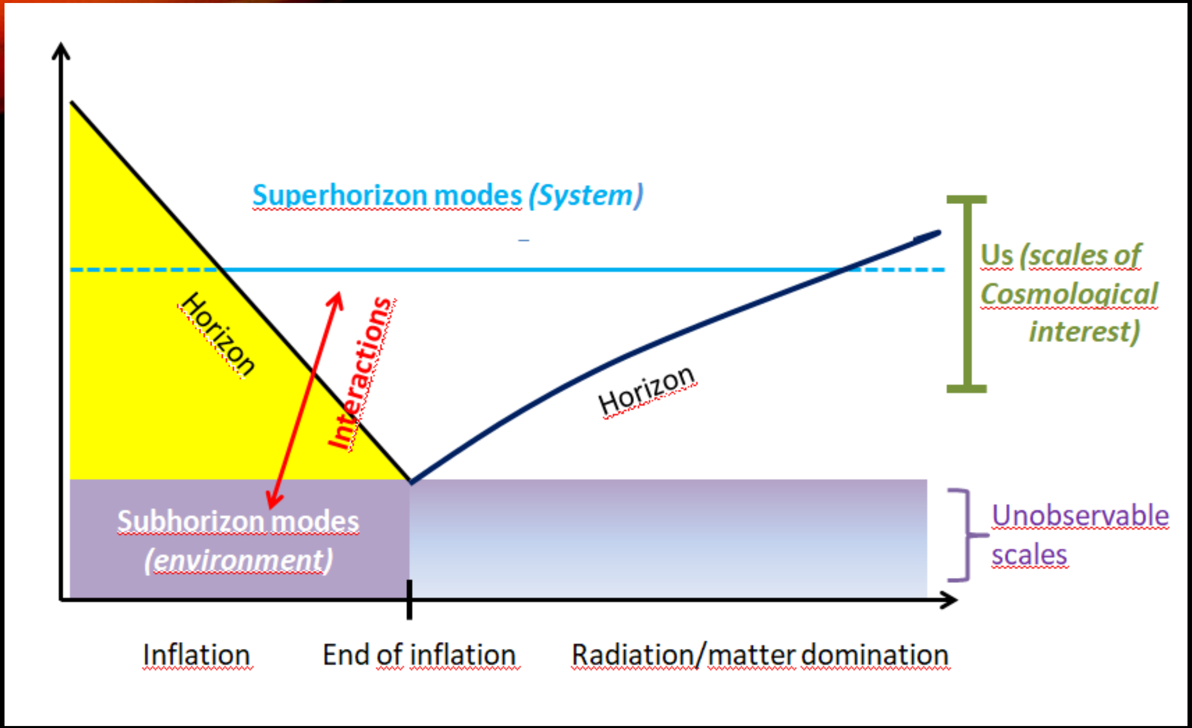
$$|\psi\rangle = c_1|v_1\rangle + c_2|v_2\rangle + \dots$$

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

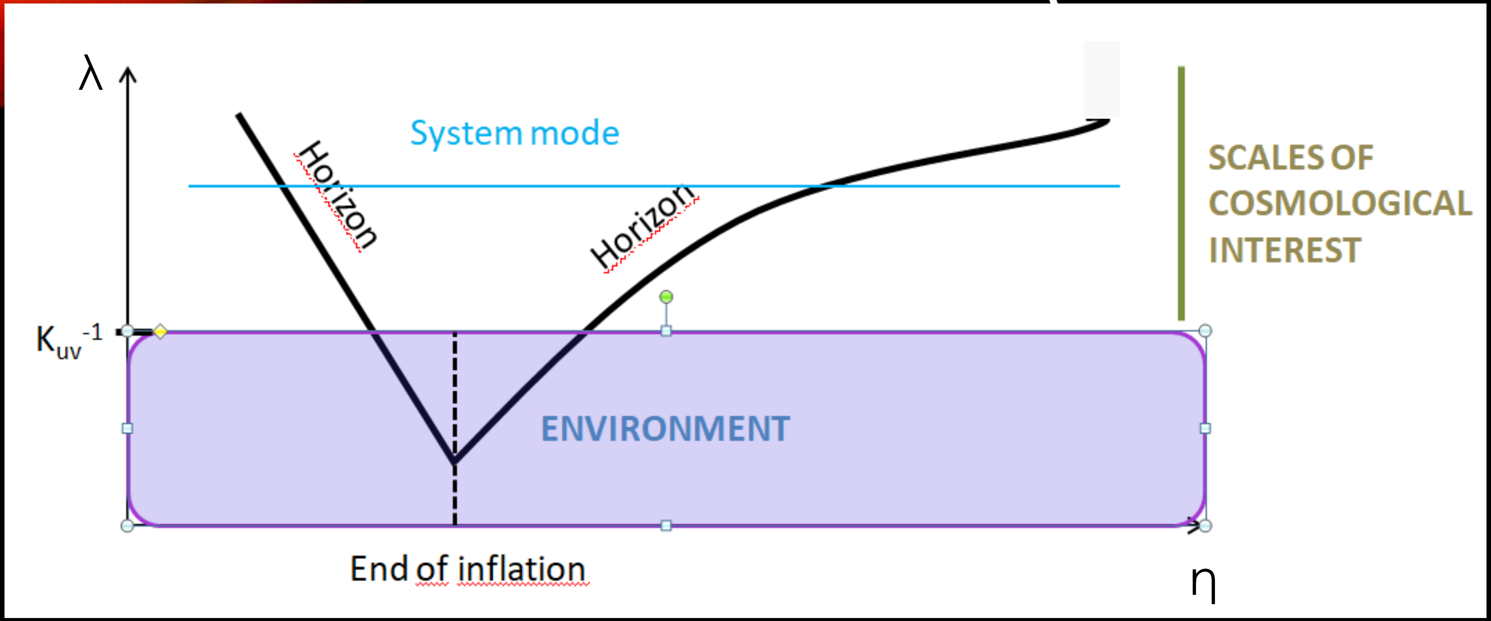


Decoherence :

- 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: $k>125/\mathrm{Mpc} = k_{UV}$ System: Scalar perturbation, $k<k_{UV}$.

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

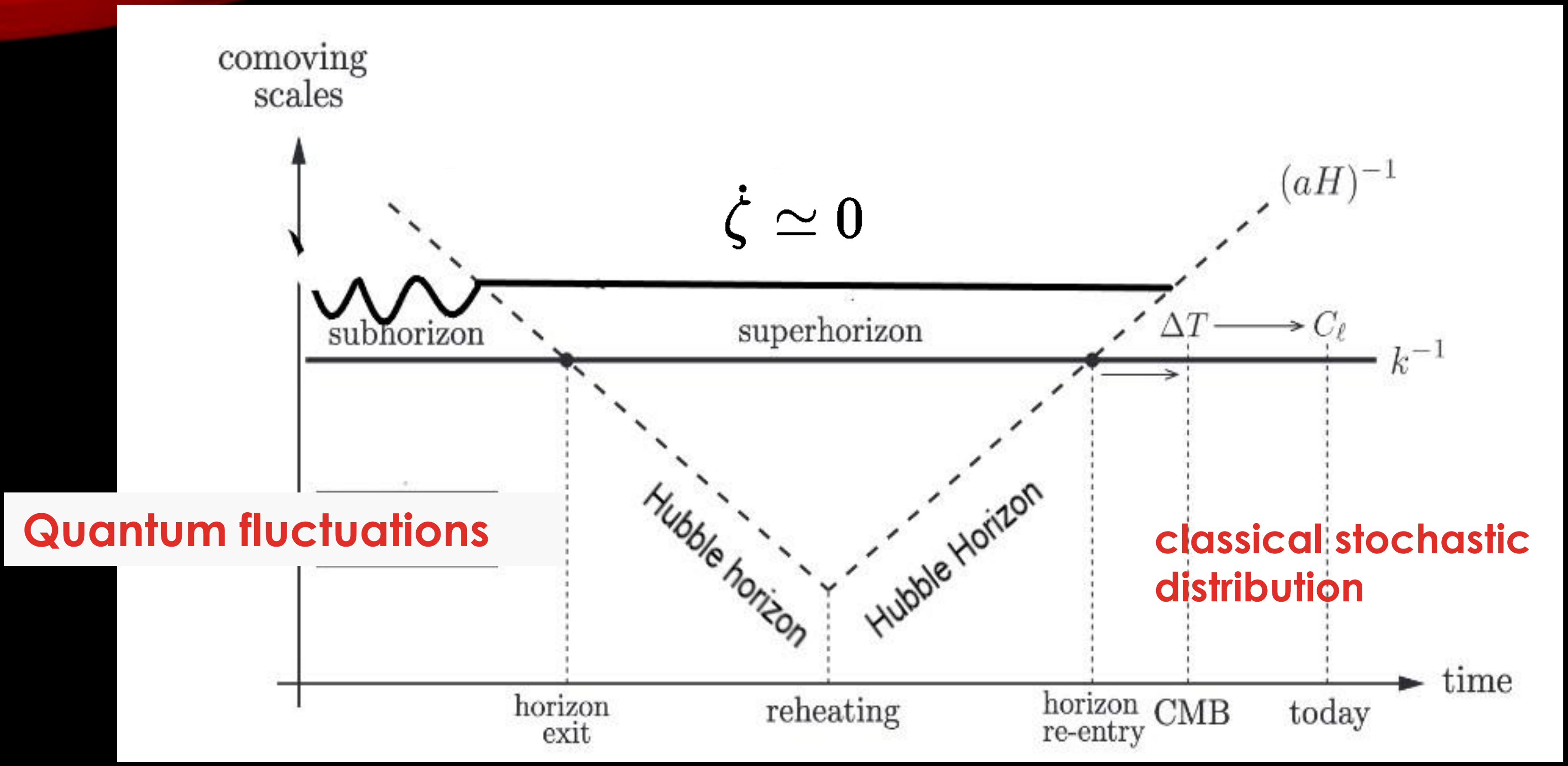
•Time derivative interactions are suppressed!

• GR nonlinear gravitational interactions (Maldacena, 2003);

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

QUANTUM TO CLASSICAL

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

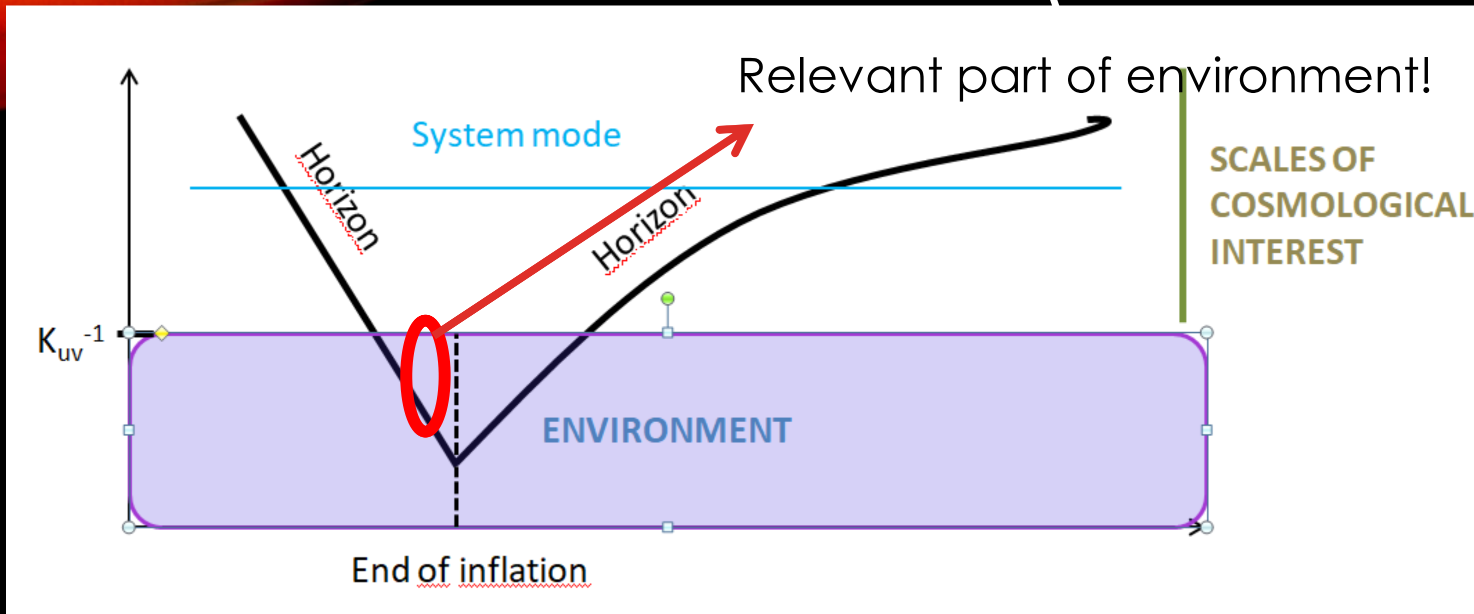


$$\frac{\delta T}{T}(\boldsymbol{e}) = \frac{1}{5}\zeta(\eta_{\ell ss}, \boldsymbol{e})$$

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

How could quantum fluctuations become classical objects?

MINIMAL DECOHERENCE(BURGESS+,22)



•**Fixed** Environment: $k>125/\mathrm{Mpc} = k_{UV}$ 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 $\Longleftrightarrow$ Quantum fluctuations of the scalar field

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

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

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

WHAT DOES DECOEHERENCE DO?

Interaction with an unobsevable environment $\Rightarrow$ Entanglement, suppress quantum coherence between different possible outcomes

Interference terms in red

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

$\Downarrow$

Statistical ensemble!

How to quantify? Purity!

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