QUANTUM SIGNATURES AND DECOHERENCE DURING INFLATION FROM DEEP SUBHORIZON PERTUBATIONS

Arxiv:2503.23150

4 year PHD @ SISSA, Astroparticle group

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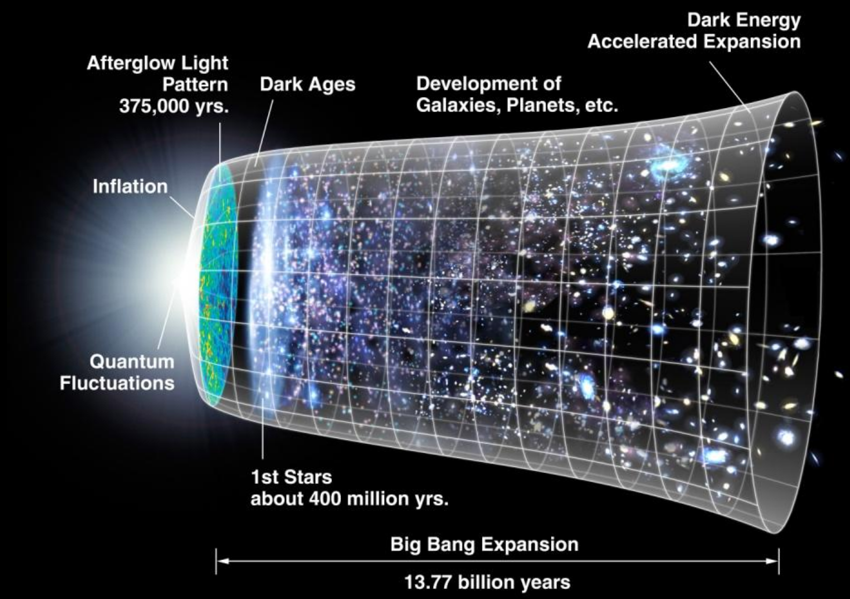
Mainz, OQS, 22/04/2026

INFLATION AND QUANTUM TO CLASSICAL TRANSITION

- Accelerated expansion driven by one (or more) quantum scalar field(s)
- ***Quantum fluctuations*** of the scalar field are the seeds for the anisotropies we observe in CMB and for the clusters of galaxies ***(classical)***



How these **quantum fluctuations** became **classical objects**?

INDEX

- Cosmological perturbations: why we need inflation?
- The problem of the Quantum to classical transition
- Decoherence in single field inflation: state of the art
- Quantum signatures and decoherence during inflation from deep subhorizon perturbations
- Conclusions

HISTORY OF OUR UNIVERSE

- Universe is expanding

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t)\mathrm{d}x^2 = a^2(\eta)\left(-\mathrm{d}\eta^2 + \mathrm{d}x^2\right)$$

- Scale factor a

Radiation domination	$a \propto t^{1/2}$
Non − Relativistic Matter domination	$a \propto t^{1/3}$

$$\text{proper length } l(t) \propto a(t)\, x \quad \text{comoving length}$$

- Initially whole Universe in thermal equilibrium
- Temperature is decreasing with expansion $T \propto 1/a$

HISTORY OF OUR UNIVERSE: WHAT WE KNOW

- Big Bang Nucleosynthesis (BBN) first direct probe $T \simeq O(1)\ \mathrm{MeV}$

To match observed abundance of light elements (H, He) in the Universe must happen in **Radiation Domination**

- Photons γ in equilibrium with electrons, protons until $T \simeq O(1)\ \mathrm{eV}$

(after, Compton scattering are inefficient)

- Then photons propagate freely to us: Cosmic Microwave Background that we now observe

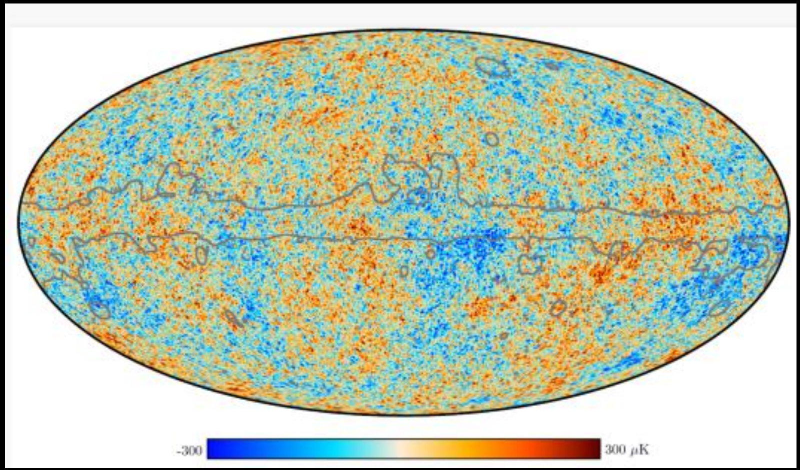
$$T \simeq 10^{-4}\ \mathrm{eV} \simeq 2.7\ \mathrm{K}$$

CMB

•Universe is globally isotropic and homogeneous: Very finely tuned!

But small inhomogeneities…

$$\frac{\delta T}{T} \simeq 10^{-5}$$



Planck 2018

Gaussian, stochastic, quasi scale invariant fluctuations; power spectrum (FT 2 point correlation function) against scale k

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

•A amplitude 2×10^{-9}
•n_s spectral index 0.9469±0.0042 (Planck 2018)

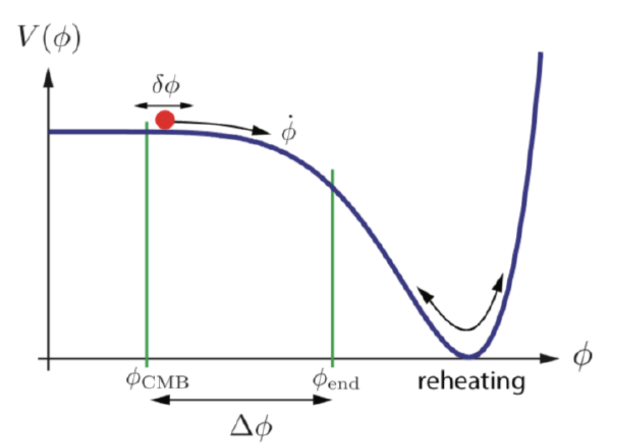
INFLATION

- Accelerated expansion driven by one (or more) quantum scalar field(s)
- Solves fine tuning problem: homogeneous and isotropic;

(quasi)de Sitter metric $$\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t)\mathrm{d}x^2 = a^2(\eta)\left(-\mathrm{d}\eta^2 + \mathrm{d}x^2\right)$$

Scale factor: $$a(t) \simeq e^{Ht} = e^{N_{efolds}} \qquad a = -\frac{1}{H\eta}$$

Hubble (energy) scale H : connected to horizon $1/H$ Hubble radius



H almost constant for a long period of time; deviations parametrized by

$$\varepsilon = -\frac{\dot{H}}{H^2}$$

THE THEORY OF INFLATION

- **Provides a mechanism to explain anisotropies and inhomogeneities from the tiny quantum fluctuations of the scalar field**

Quantum fluctuations of the scalar field $\delta\hat{\phi}$ ⟷ $\hat{v} = a\sqrt{2\epsilon}M_{pl}\hat{\zeta}$

Scalar (curvature) perturbations ζ, or canonical Sasaki Mukhanov variable v
Region where the universe is **slightly over or underdense**

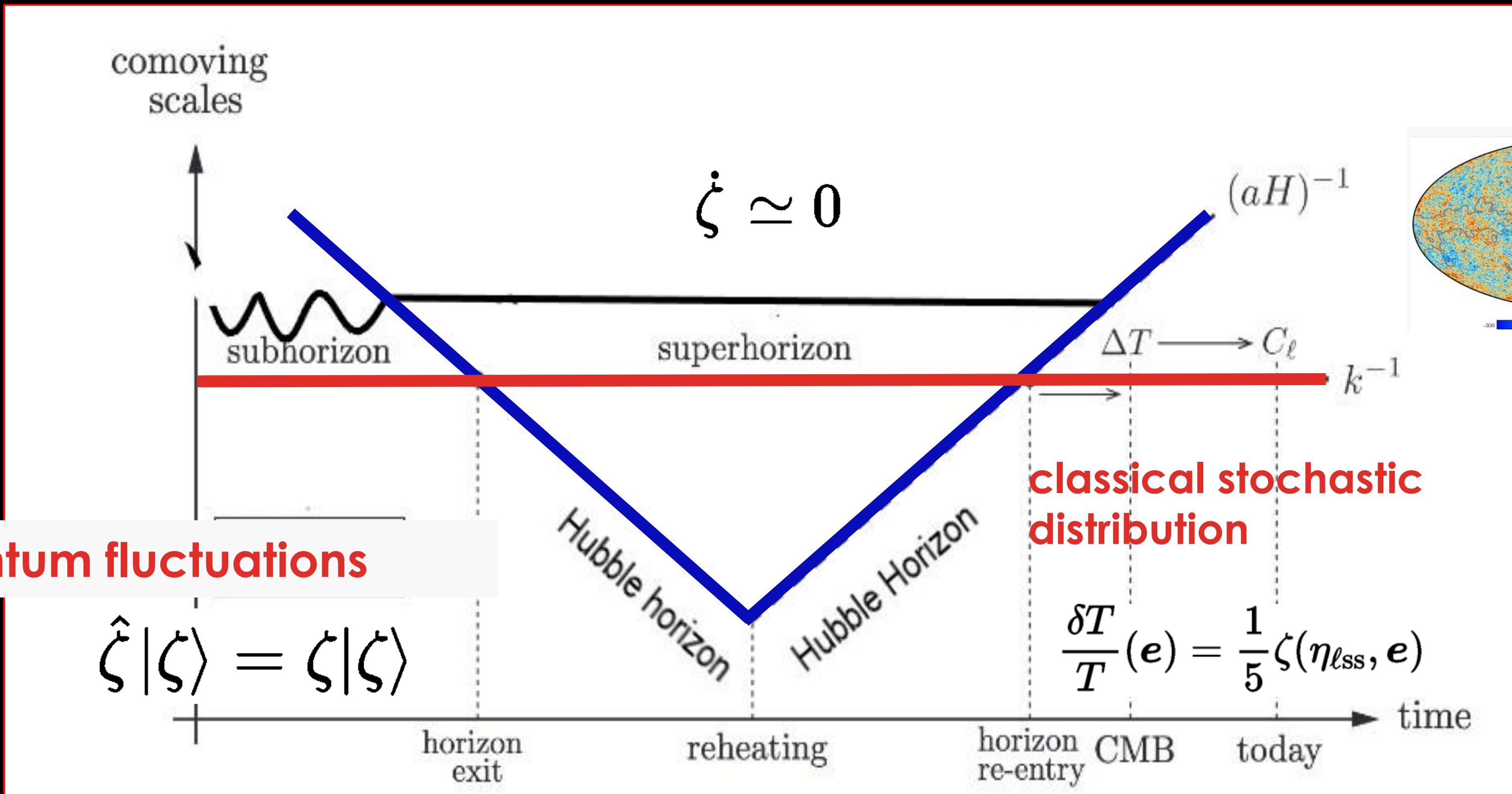
$$\hat{\zeta}|\zeta\rangle = \zeta|\zeta\rangle$$

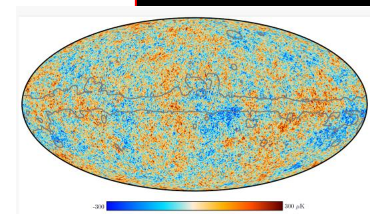
- ζ quantum operator;
- Configuration of perturbations are eigenvectors of ζ

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

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

•quantum fluctuations of the scalar field are the seeds for the anisotropies we observe in CMB.





Quantum fluctuations

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

classical stochastic distribution

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

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

How could quantum fluctuations become classical objects?

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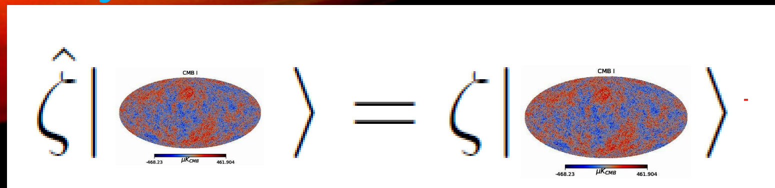
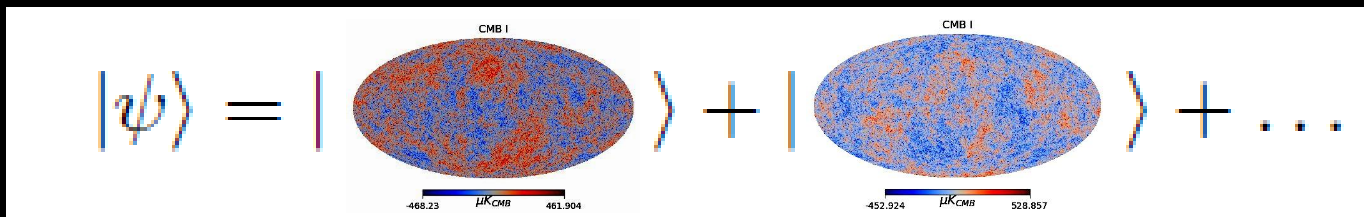


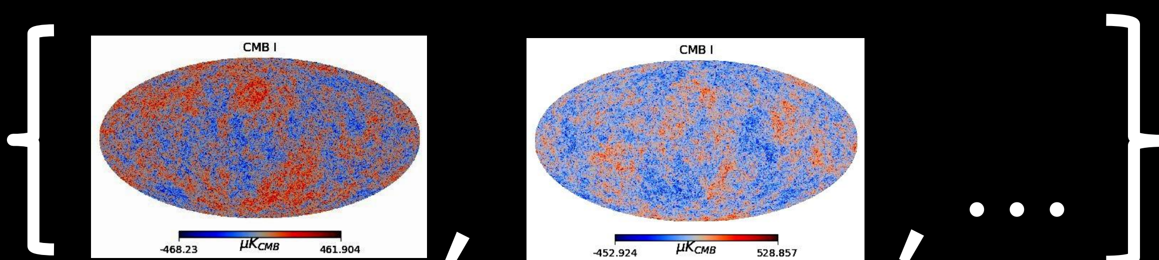
- ζ quantum operator;
- Configuration of perturbations (~CMB Maps) are eigenvectors of ζ



COHERENT **SUPERPOSITION**

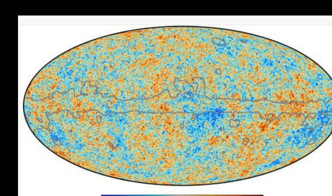
DECOHERENCE!
(after interaction, and entanglement with unobservable environment)

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

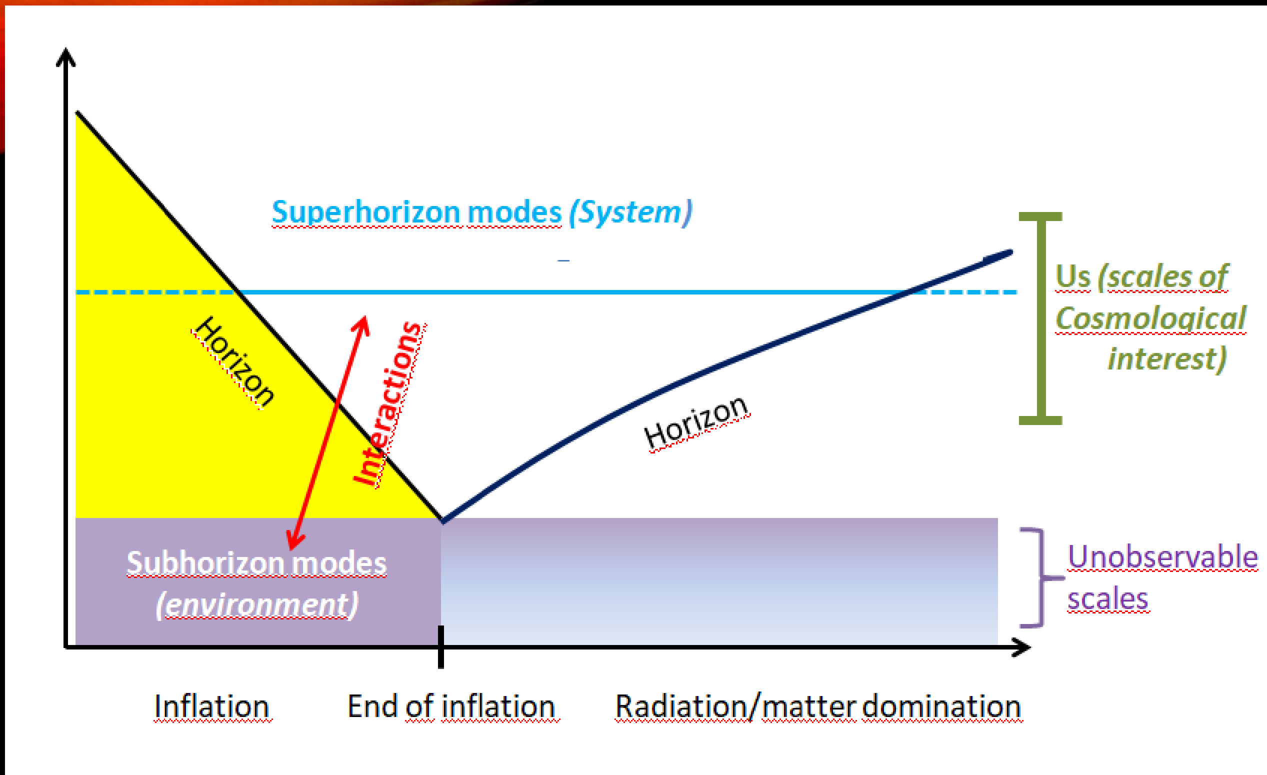
$$\rho_{sys} = \begin{pmatrix} |\zeta_1\rangle\langle\zeta_1| & |\zeta_1\rangle\langle\zeta_2| \\ |\zeta_2\rangle\langle\zeta_1| & |\zeta_2\rangle\langle\zeta_2| \end{pmatrix} \xrightarrow{\text{decoherence}} \rho_{sys} = \mathrm{Tr}_{ENV}\, \rho_{sys+env} = \begin{pmatrix} |\zeta_1\rangle\langle\zeta_1|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

How to quantify? Purity!

Statistical ensemble!

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

OPEN QUANTUM SYSTEMS



Single field inflation

$$\zeta = \zeta_S + \zeta_L$$

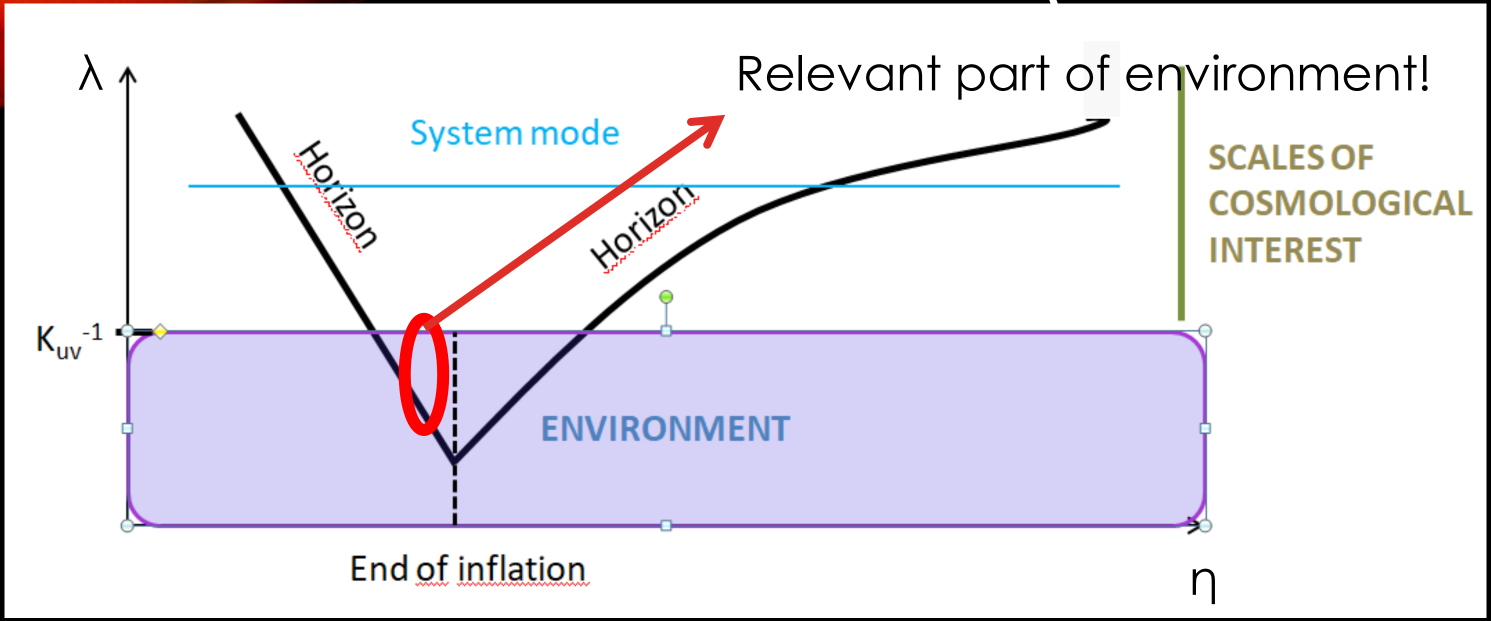
(Nonlinear) **gravitational Interaction (GR)**

- **long wavelength system;**
- **short wavelength environment.**

Entanglement

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

MINIMAL DECOHERENCE(BURGESS+,22)



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

ASSUMPTION: Superhorizon environment. **ONLY in this case** time derivative interactions are suppressed!

- GR nonlinear gravitational interactions (Maldacena, 2003);

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

- Considered ONLY spatial derivatives interactions (circled ones)!

OUR WORK

MAIN ORIGINAL POINTS:

•Consider a time dependent environment of **subhorizon modes;**

•Show that decoherence can be achieved also by **just subhorizon environment: dominant interactions are derivativeless interactions;**

•We consider for the first time **all the interactions,** underlining the importance **of the interplay between mixed couples.**

•**Resummation to some quantum corrections to the v correlators:**
-Lamb Shift (unitary corrections) for power-spectrum and bispectrum of the Sasaki Mukhanov variable v;
-Non unitary corrections to the power spectrum.

IN THE MEANTIME:

- Comment on **Quantum master equation**, **Markovianity/non-Markovianity;**
- Evaluate effects on the quantum master equation of **time dependent environment.**

OUR WORK

- Environment of subhorizon tensorial modes (i.e. GW, h_{ij});
- System of superhorizon curvature scalar modes, ζ (canonically norm., v)

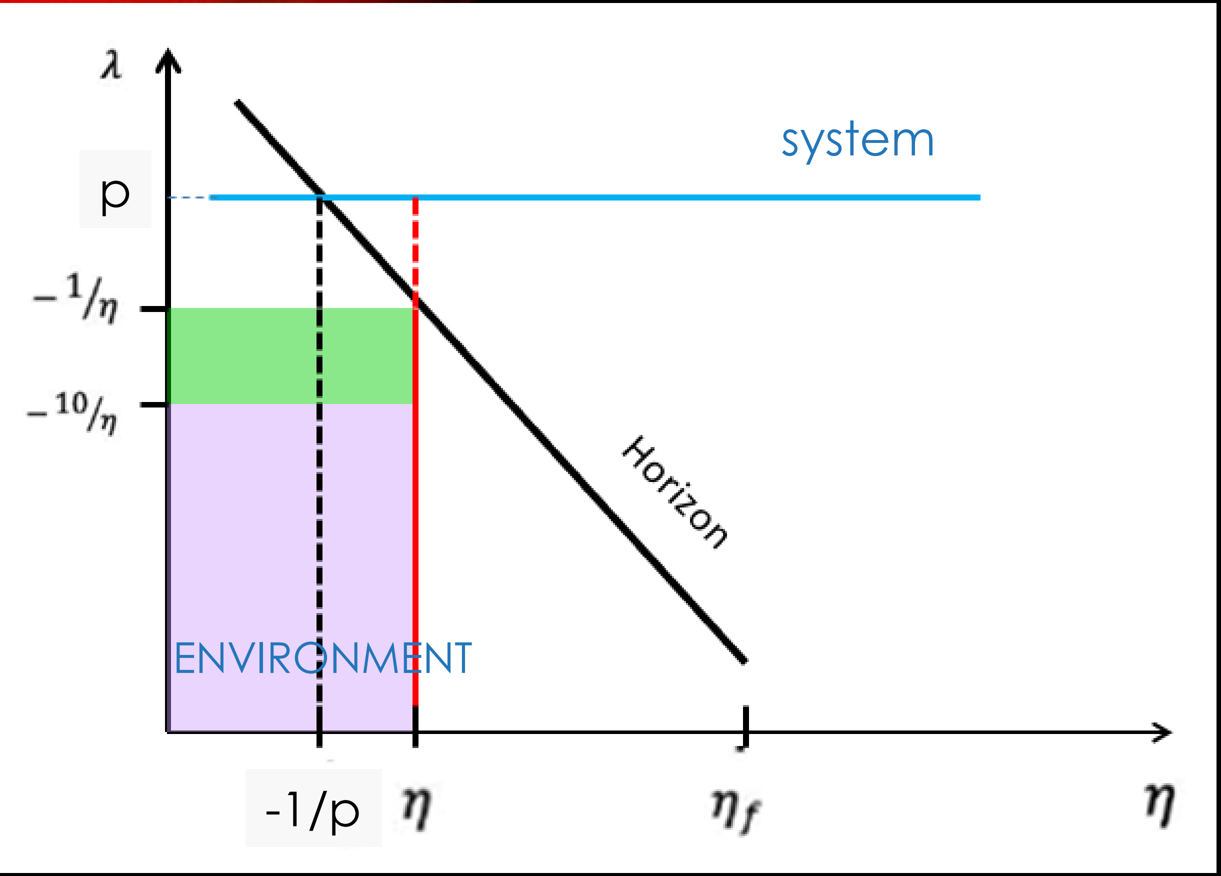
- GR non linear gravitational interactions (Gangui+1993,Maldacena 2003)

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

SUBHORIZON ENVIRONMENT: WE CONSIDER THE INTERPLAY BETWEEN ALL INTERACTIONS!

See also: Burgess et al, Arxiv:2509.07769

OUR MODEL:THE ENVIRONMENT



SYSTEM: **Superhorizon** Scalar Mode.

Entanglement

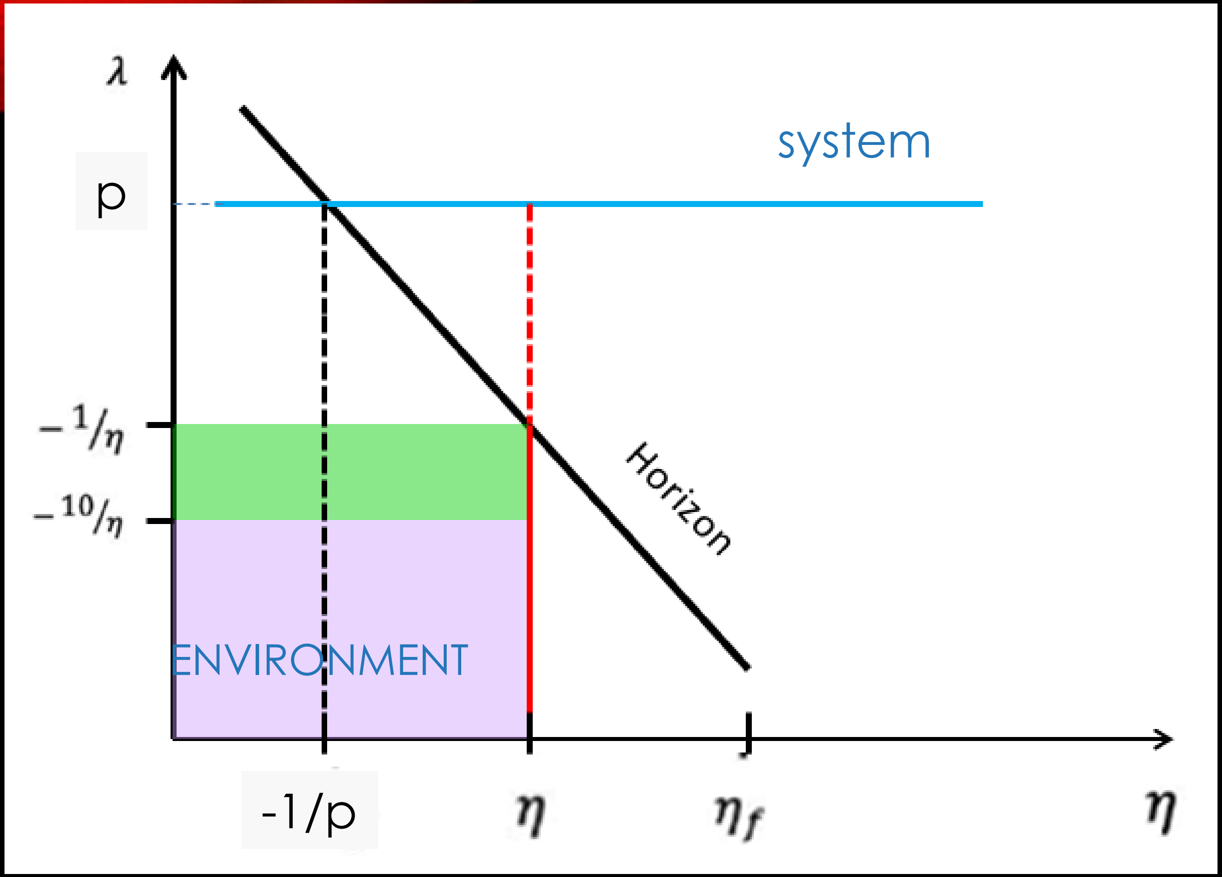
ENVIRONMENT:
Deep subhorizon modes Of **Gravitational waves.**

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

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

$\tau_{env} \ll \tau_{int}$

OUR MODEL:THE ENVIRONMENT



SYSTEM: **Superhorizon** Scalar Mode.

Entanglement

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

$\tau_{env} \ll \tau_{int}$

QUANTUM MASTER EQUATION

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

Convolution!

•BORN-MARKOV APPROXIMATION: density matrix evolves slowly (Interaction picture)

$$\rho_r(\eta') \to \rho_r(\eta) \qquad \tau_{env} \ll \tau_{int} \propto 1/g^2$$

Quantum master equation:

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

Memory in: **Interactions** | **Free system operator!** | ENVIRONMENTAL CORRELATION FUNCTIONS (FAST, peaked around η'~η)

QUANTUM MASTER EQUATION

- "Equation of motion" for the Density Matrix of the System (canonical form)

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

Lamb Shift Hamiltonian

-finite renormalization of the Unitary hamiltonian, gives corrections to **spectral index of** Power Spectrum.

Non Unitary part:

-Decoherence;

-non-Unitary correction to observables.

$D_{11}(\eta)$ "canonical decay rate"

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

System operator memory:

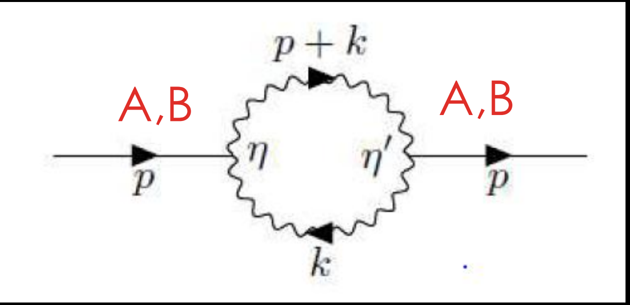
$$v_p(\eta') = v_p(\eta) A(p, \eta, \eta') + \ldots$$

SUBHORIZON ENVIRONMENT: WE CONSIDER THE INTERPLAY BETWEEN ALL INTERACTIONS!

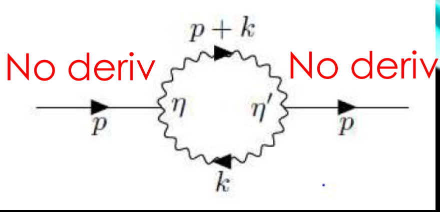
$$S=\frac{\epsilon M_{pl}^2}{8}\int dtd^3x\left(a^3\zeta\dot{h}_{ij}\dot{h}_{ij}+a\zeta\partial_l h_{ij}\partial_l h_{ij}-2a^3\dot{h}_{ij}\partial_l h_{ij}\partial_l\left(\nabla^2\right)^{-1}\dot{\zeta}\right)$$

A)DERIVATIVELESS interaction,more important contributions.

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



DERIVATIVELESS INTERACTIONS



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

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

Derivativeless interactions gives **Markovian evolution**!

- We can achieve decoherence by just environment of **subhorizon modes!**

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

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

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

Decoherence happens when system is superhorizon!

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

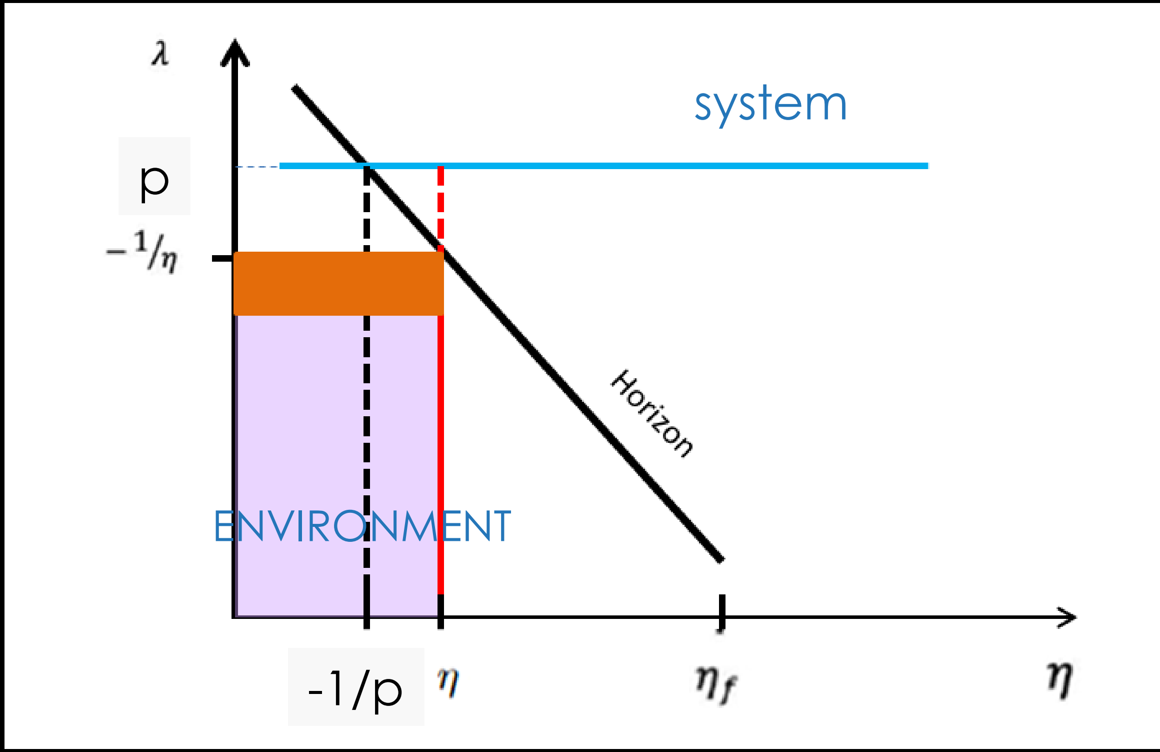
CMB well decohered!!

TIME DEPENDENT ENVIRONMENT

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

'23 Burgess: nobody computed the effect

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



Orange modes: Crossing the horizon in $\Delta\eta$

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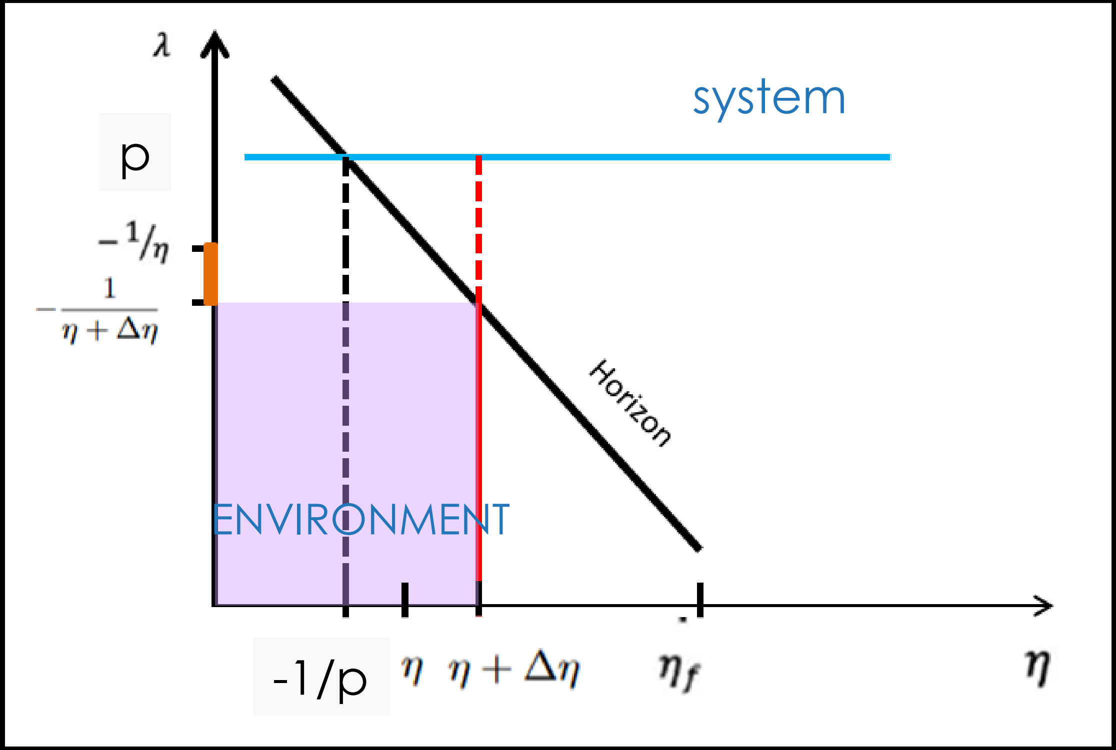

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$$\rho_{r,I}(\eta+\Delta\eta)-\rho_{r,I}(\eta) = -\Delta\eta g(\eta)\int_{\eta_0}^{\eta} d\eta_2 g(\eta_2)\,\mathrm{Tr}_{E(\eta)}\left[H_{\text{int}}(\eta),\left[H_{\text{int}}(\eta_2),\rho(\eta_2)\right]\right]$$
$$-\int_{\eta_0}^{\eta} d\eta_1 g(\eta_1)\int_{\eta_0}^{\eta_1}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

THE CANONICAL FORM IS RESPECTED!!

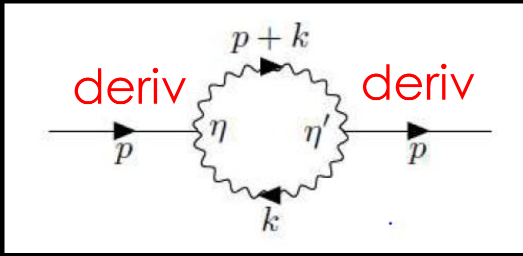
- **Just a modification of D_{11}**

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

- **Smaller, does not change sign to D_{11}**

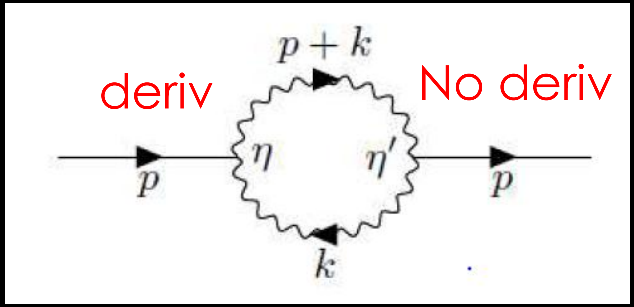
INTERPLAY WITH OTHER INTERACTIONS

DERIVATIVE INTERACTIONS



- NEGLIGIBLE!! (Just for deep subhorizon modes)

MIXED DERIVATIVE-DERIVATIVELESS INTERACTIONS



•**Mixed terms give** NEGATIVE CONTRIBUTIONS

$$D_{11}^{int1-23} \simeq -\frac{\epsilon H^2}{4M_{pl}^2\eta^2}0.11$$

•**More negative** than the previous one**! NON MARKOVIAN!**

$$D_{11}^{TOT} \simeq -\frac{\epsilon H^2}{4M_{pl}^2\eta^2}0.06$$

TOT:D_{11}<0!

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

$\tau_{env} \ll \tau_{int}$ **Markovian approximation:** $\rho_r(\eta') \to \rho_r(\eta)$

System memory

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

Neglects also FREE SYSTEM MEMORY! $v_p(\eta') \to v_p(\eta)$ $A(p,\eta,\eta') \to 1$

For us **very well justified**: $\tau_{env} \simeq \frac{1}{10aH} \ll \tau_{sys} \simeq \frac{1}{aH}$

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

Still, no definitive proof…

QUANTUM MASTER EQUATION

- "Equation of motion" for the Density Matrix of the System (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, gives corrections to **spectral index of** Power Spectrum.

Non Unitary part:

-Decoherence;

-non-Unitary correction to observables.

LAMB SHIFT

- Compute corrections to Power Spectrum due to **trilinear interactions** at second order:"**loop quantum correction**";
- Method: in-in formalism, just a **unitary** dynamics;
- But…late time secular effects: large logarithms in corrections (Seery'10 for a review)

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

•**May break perturbation theory!**

•Many methods in the past for resummation.
•By solving QME you authomatically resum!

$$\mathcal{P}(k,\eta) \propto e^{\frac{2\epsilon H^2}{4\pi^2 M_{pl}^2} \ln(-k\eta)} + \text{ other terms}$$

In general, **not in single field inflation**, where there are also quartic Interactions and backreaction effects that cancel this effect!
But here we are interested in showing the resummation

LAMB SHIFT:UNITARY RENORMALIZATION

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

Modifies spectral index in the v Power Spectrum:

$$\delta n_S \simeq \frac{\varepsilon H^2}{4M_{nl}^2\pi^2} 2.4$$

- Blue Correction to spectral index n_s (bigger power at smaller scales)
- No secular corrections.

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

- **NON-Perturbative resummation!!**
- Quantum "loop" corrections, but **"authomatically" produce resummation by considering the interaction with an environment for decoherence.**

$$\mathcal{P}(k,\eta) \propto e^{\frac{2\epsilon H^2}{4\pi^2 M_{pl}^2}\ln(-k\eta)} + \text{ other terms}$$

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

Corrections from non unitary part:

Same order, different form

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

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**

$$\left\langle v\left(\vec{k}_1\right)v\left(\vec{k}_2\right)v\left(\vec{k}_3\right)\right\rangle = (2\pi)^3 B\left(k_1,k_2,k_3\right)\delta^3\left(\vec{k}_1+\vec{k}_2+\vec{k}_3\right)$$

FT of the 3-point correlation function
Important for the investigation of non gaussianity

- Dealt with(in a different way) in Daddi Hammou+'22, Martin+'18, A.Salcedo+24

- Three modes k_1, k_2, k_3 superhorizon at the end of inflation

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

Again, **NON PERTURBATIVE RESUMMATION**!

CONCLUSIONS

- We computed **decoherence in single field inflation,** in an environment only of subhorizon modes;
- We considered more than just one interaction at a time, but also the interplay between them, underlining the importance **of non-Markovian effects;**
- We elaborated on possible ways to deal with non-Markovianity, and the possible limits of application of the **Strong Markovian approximation;**
- We evaluated the impact of a **time dependent environment** onto the quantum master equations;
- We show the resummation properties of the quantum master equation by applying it to some corrections to the **Power spectrum and Bispectrum.**

TAKE HOME MESSAGE AND FUTURE PROJECTS

- ***Non unitary evolution during inflation is needed for explaining quantum to classical transition. Non unitary effects should be there even*** in a minimal setting:
- The evolution of perturbations is never closed: in cosmology multiple environments are always present! Open quantum system investigation needed!
- (non-)Markovianity is ubiquitous in inflation! 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?

GRAVITATIONAL WAVE-LENSING BEYOND RAYS: A DISORDER SYSTEM APPROACH

Arxiv: 2604.15313

With R. Amoruso (UniPd), G.Braga (GSSI), A.Garoffolo (Upenn), N.Bartolo (UniPd), S.Matarrese (UniPd)

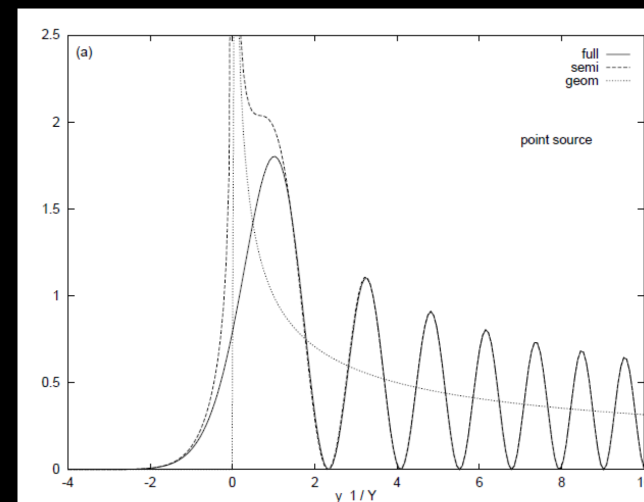

Figure taken from Nakamura+, 2003

Structures give random phase shifts to the gravitational waves, thus **destroying interference**

THANK YOU FOR YOUR ATTENTION!