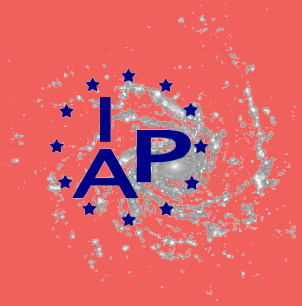


Quantum Discord and decoherence of inflationary perturbations

TUG Workshop 2021

13th December 2021

Amaury Micheli [1] [2]

arXiv:2112.05037 AM, Jérôme Martin [2] , Vincent Vennin [2]

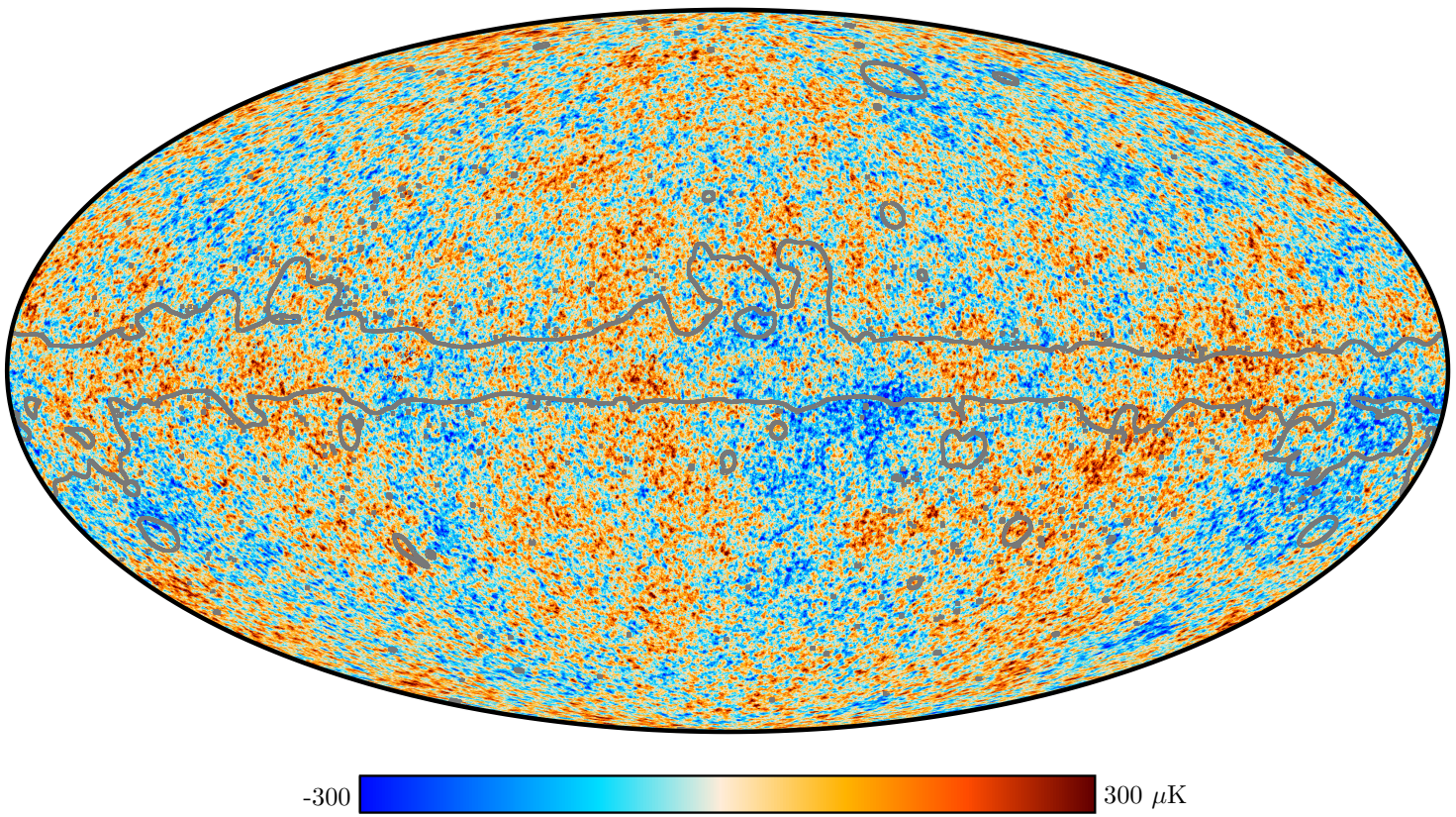
IJCLab, Orsay [1]

IAP, Paris [2]

INTRODUCTION : QUANTUM FEATURES IN THE EARLY UNIVERSE ?

CONTEXT I, INHOMOGENEITIES IN THE EARLY UNIVERSE

→ Early Universe is homogeneous within a very good approximation[1] $\Delta T/T \sim 10^{-4}$



1. [Planck-Collaboration et al., 2020b]

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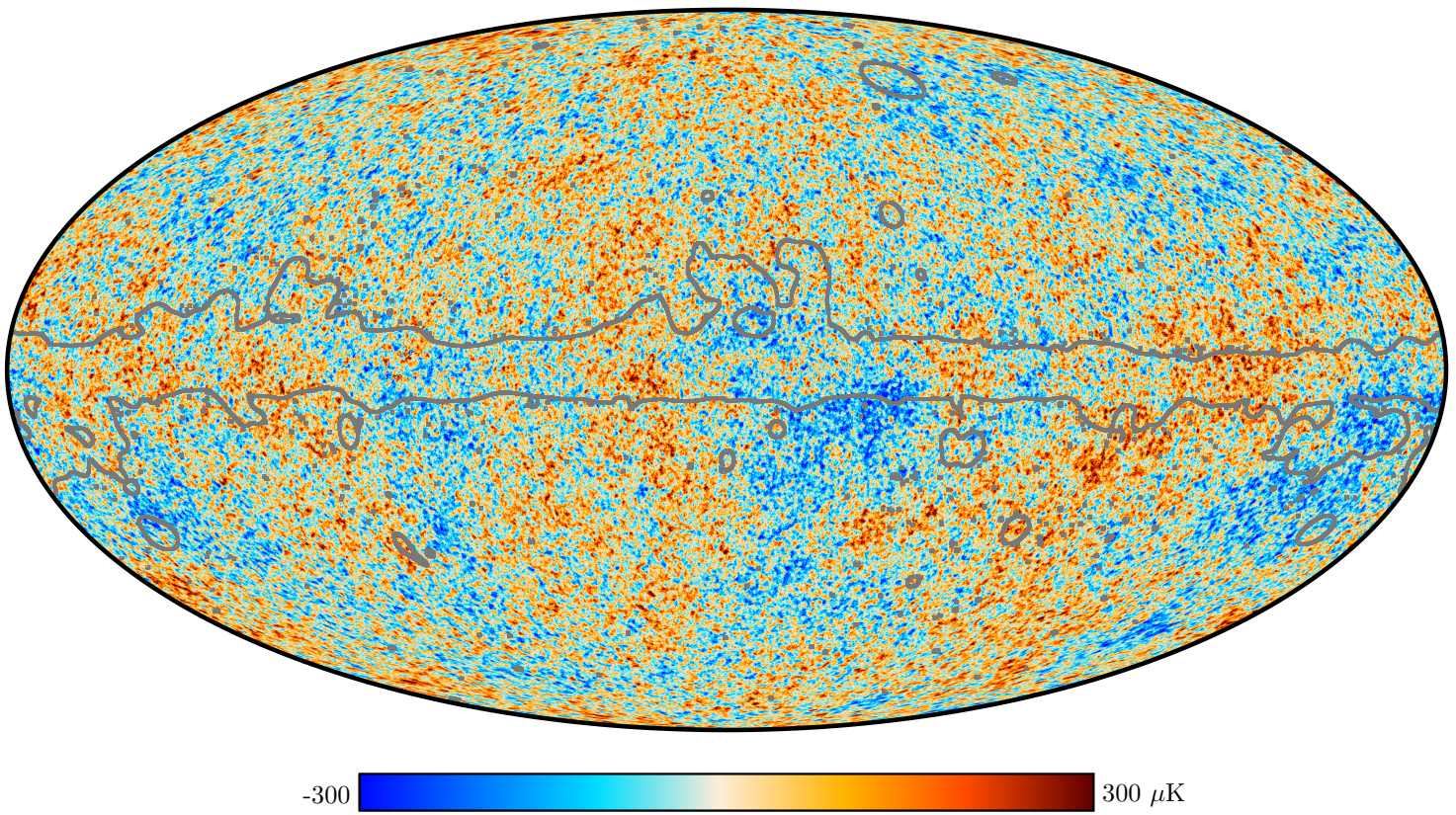

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CONTEXT II, INHOMOGENEITIES IN THE EARLY UNIVERSE

→ Proposition ∼80s [2] : Inhomogeneities come from minimal (vacuum) quantum fluctuations at the beginning of inflation stretched to cosmological scales by expansion !

2. [Mukhanov and Chibisov, 1981]

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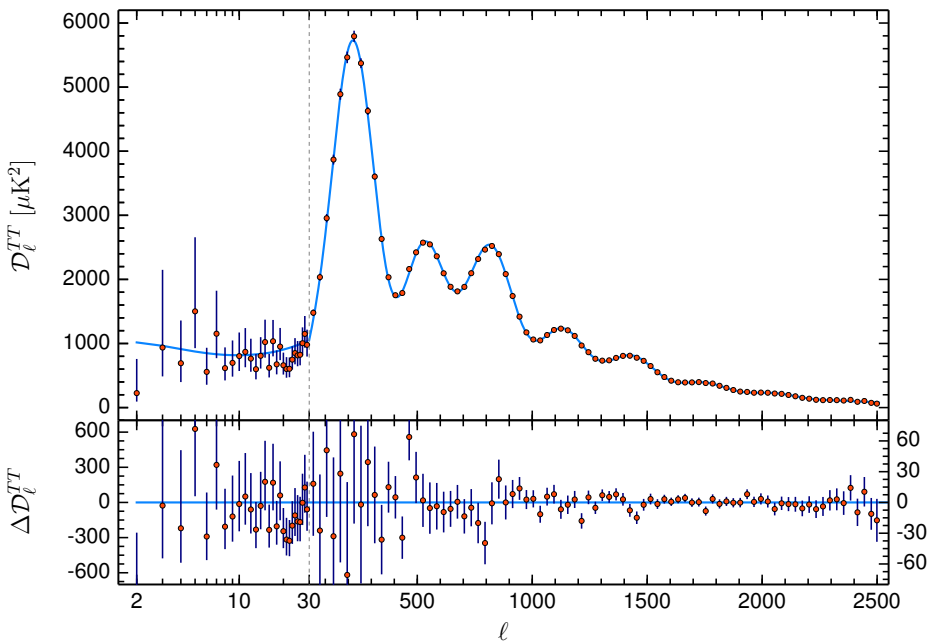

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→ Interactions with extra d.o.f lead to **decoherence** of quantum systems : **ingredient of quantum-to-classical transition.**

CHARACTERIZING QUANTUMNESS OF INFLATIONNARY PERTURBATIONS

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If $\mathcal{S}_i$ described by classical probabilities $\mathcal{D}(\mathcal{S}_1, \mathcal{S}_2) = 0$.
Quantum description $\mathcal{D}(\mathcal{S}_1, \mathcal{S}_2) \geq 0$.

WARM-UP : DISCORD W.O. DECOHERENCE

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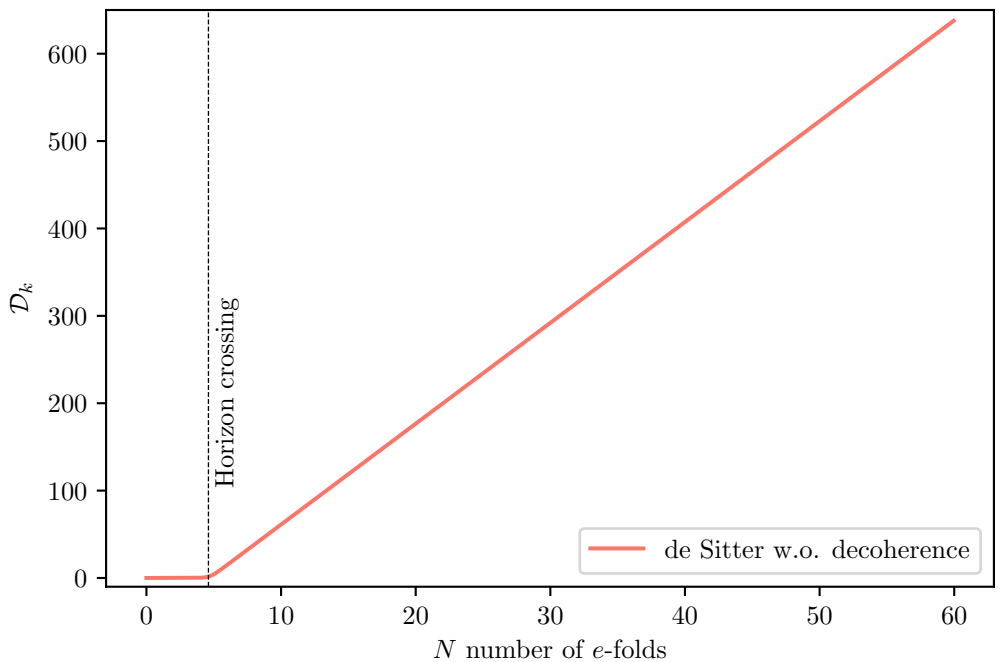

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Take-home message 1

Without decoherence, according to any criterion, quantumness is strongly amplified by inflation and final state is very quantum. [2] [3]

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Without decoherence, according to any criterion, quantumness is strongly amplified by inflation and final state is very quantum. [2] [3]

Can this result be due to oversimplified models ?

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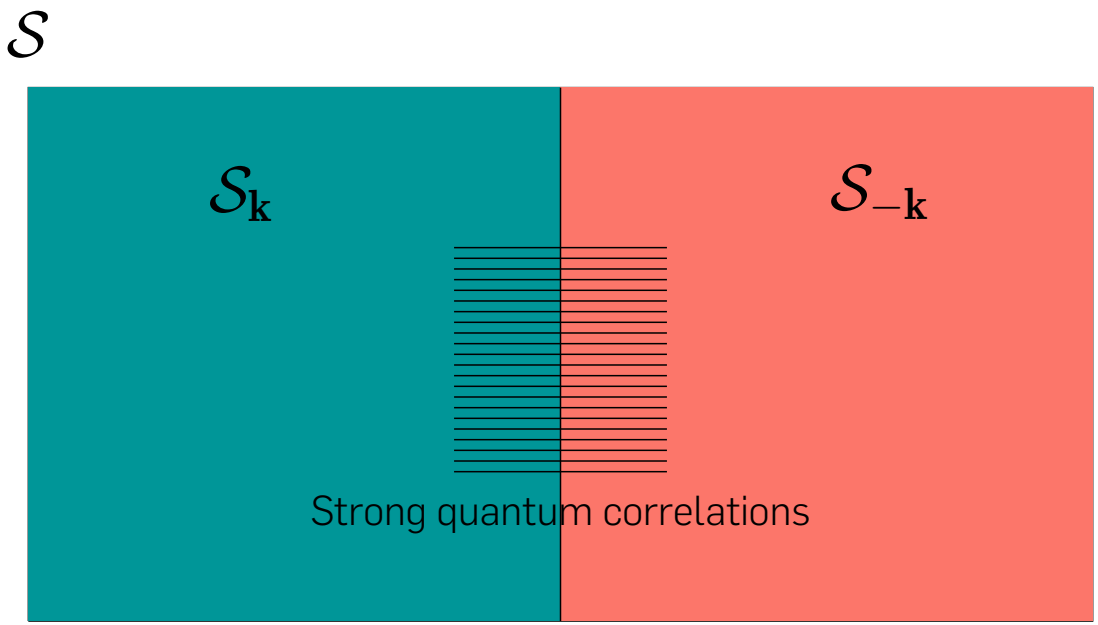
DECOHERENCE AND LOSS OF QUANTUMNESS

NON-LINEARITIES, INTERACTIONS : DECOHERENCE



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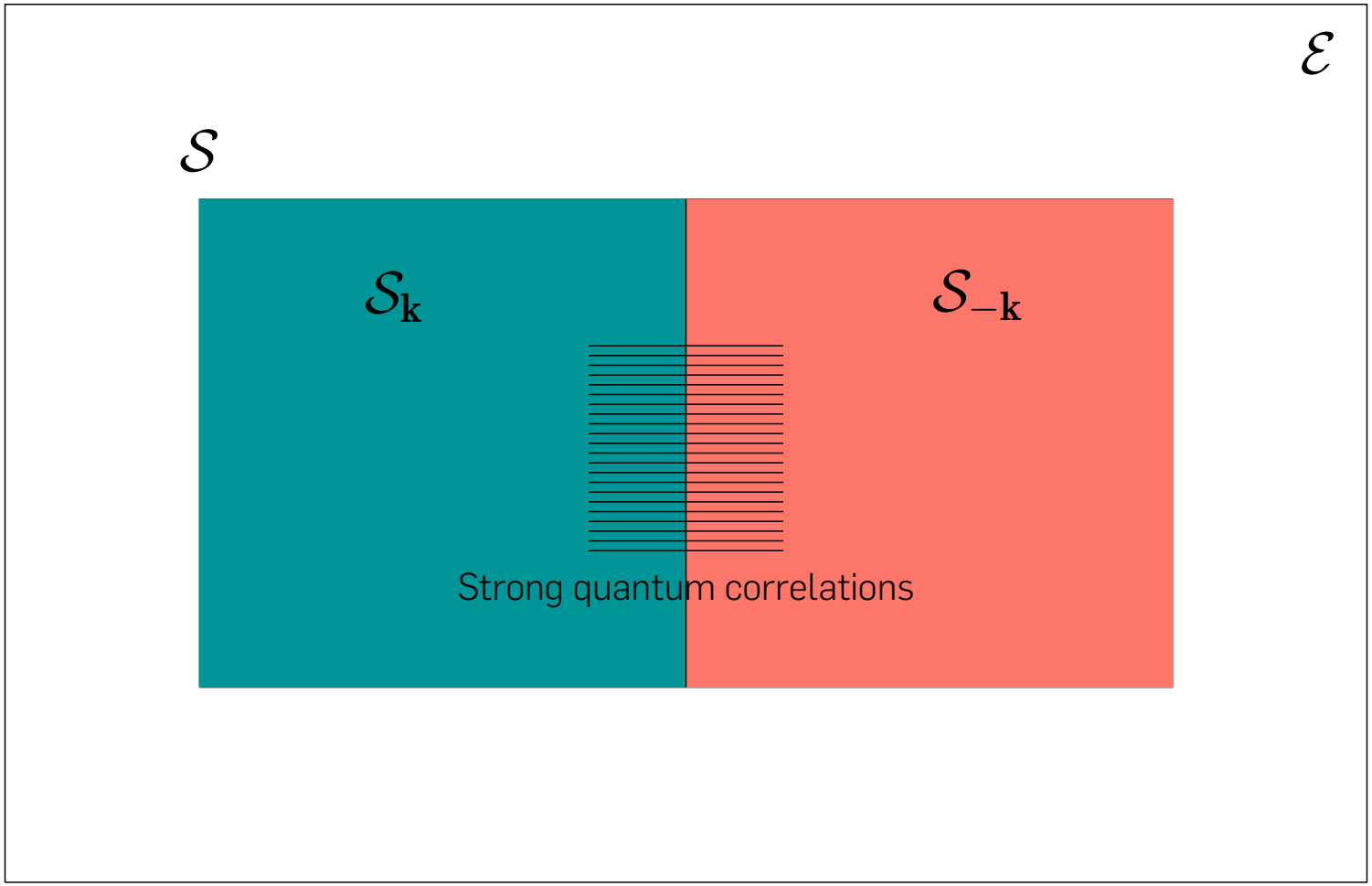
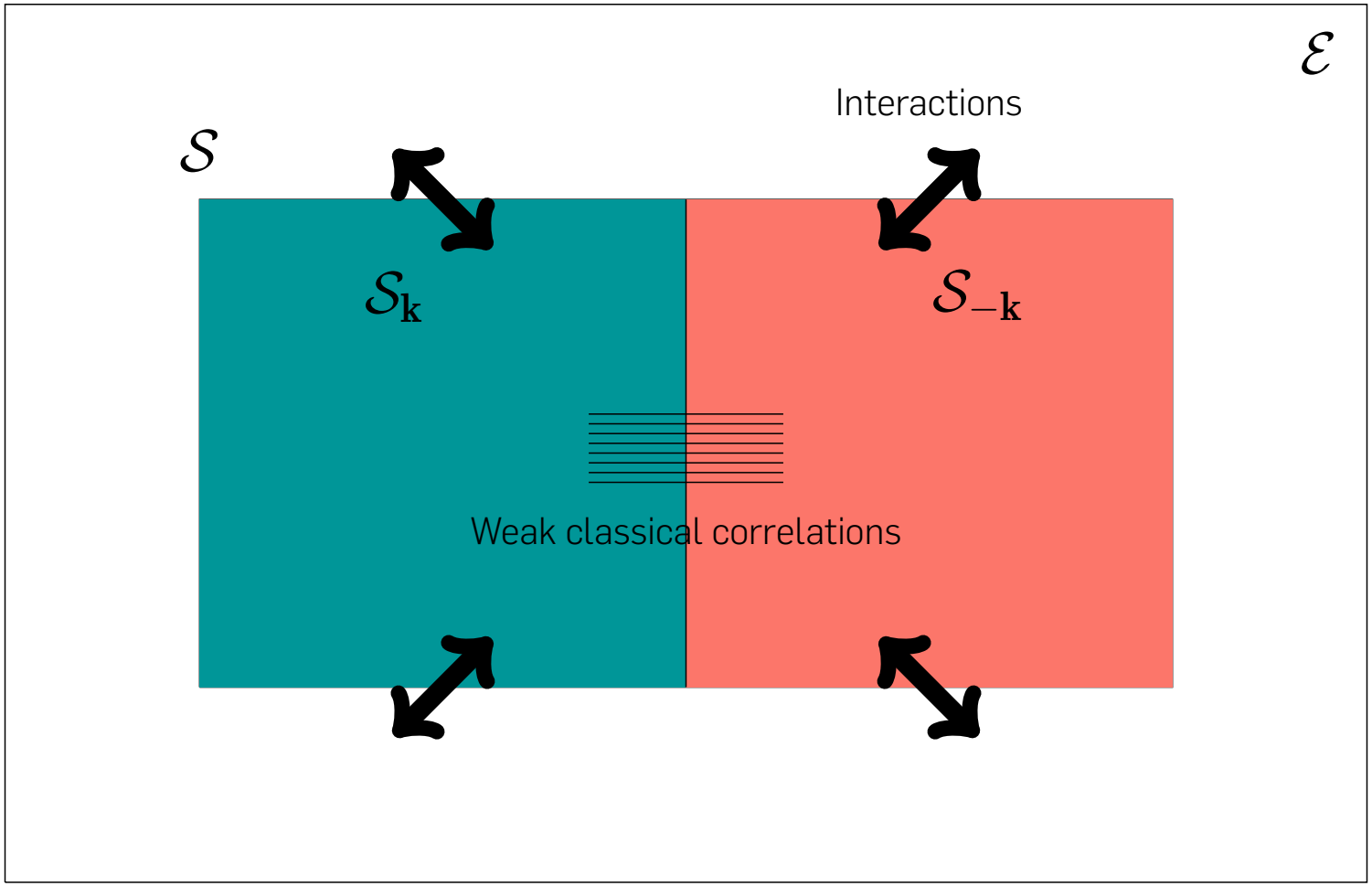


In fact $\mathcal{S}$ has an environment $\mathcal{E}$ (e.g. $\mathcal{S}_{\pm\mathbf{k}'}$ with $\mathbf{k}' \neq \mathbf{k}$) or other fields.

NON-LINEARITIES, INTERACTIONS : DECOHERENCE



Interactions $\mathcal{S}$ / $\mathcal{E}$ destroy correlations $\mathcal{S}_{\mathbf{k}}$ / $\mathcal{S}_{-\mathbf{k}}$: decoherence.

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DECOHERED INFLATIONNARY PERTURBATIONS

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Take-home message 2 [4]

Loss or preservation of Quantum Discord is the result of a competition between generation of entanglement by inflation and decoherence due to interactions.

4. [arXiv:2112.05037 Martin et al., 2021]

COMPETITION OF ENTANGLEMENT AND DECOHERENCE

→ **Strength** of interaction $\mathcal{S}/\mathcal{E}$, hence **decoherence** $k_\Gamma^2 \left(\frac{a}{a_\star}\right)^{p-3}$.

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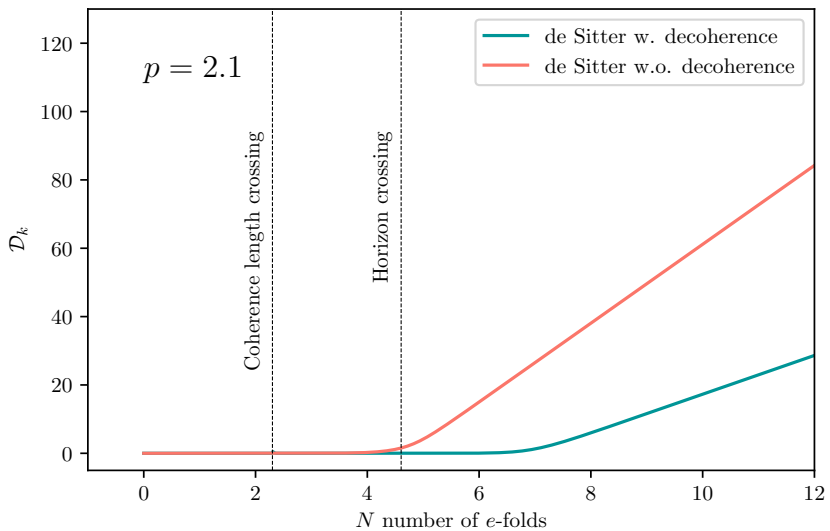

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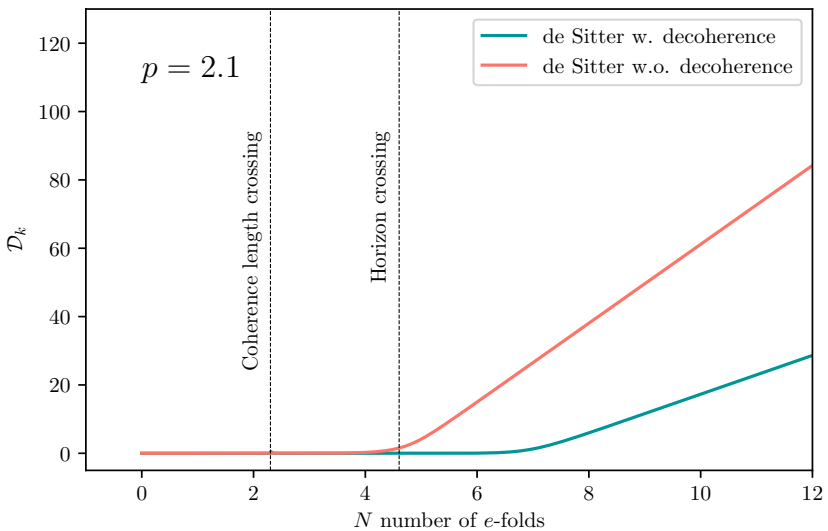

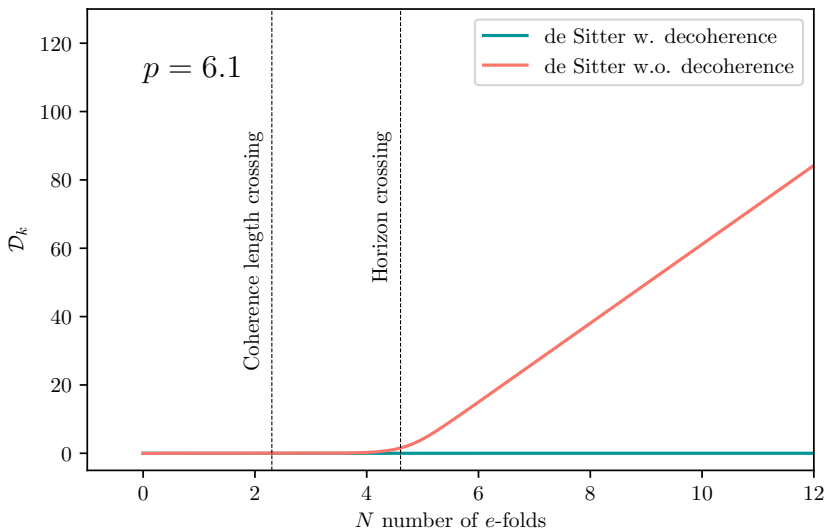

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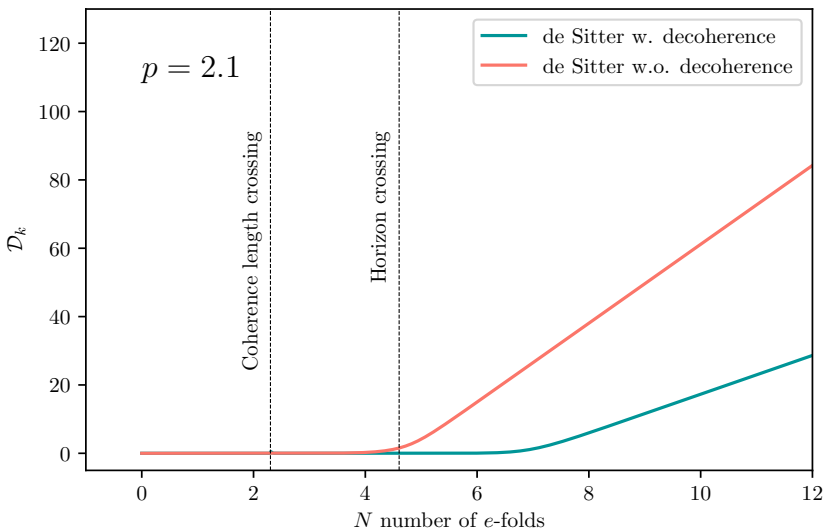

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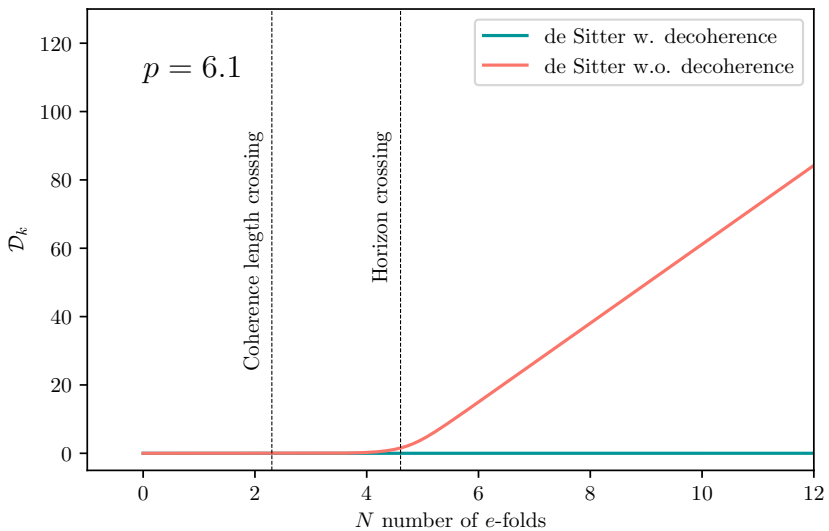

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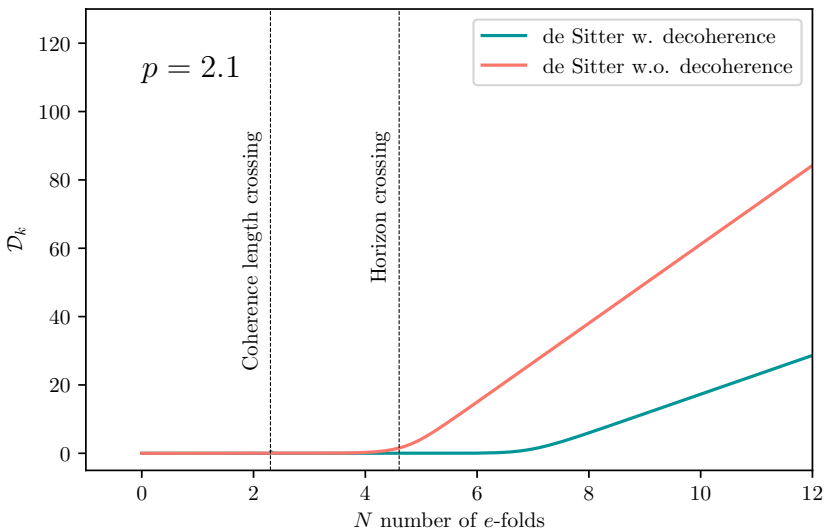

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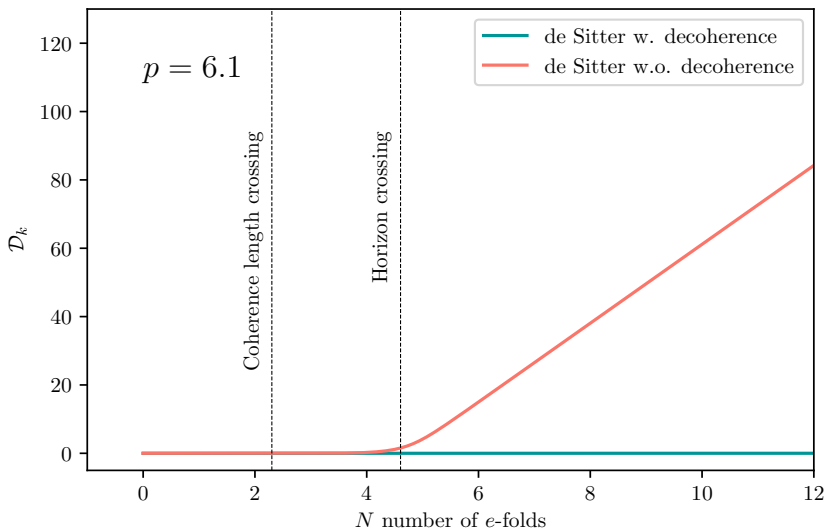

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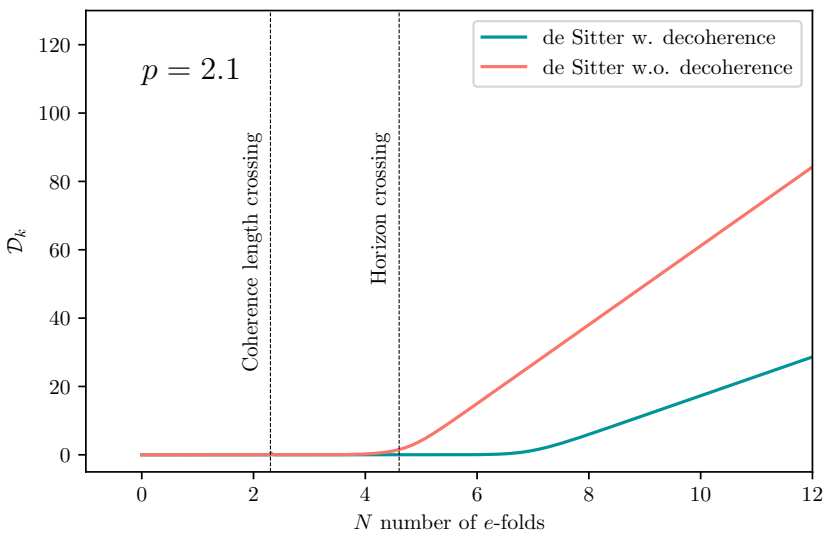

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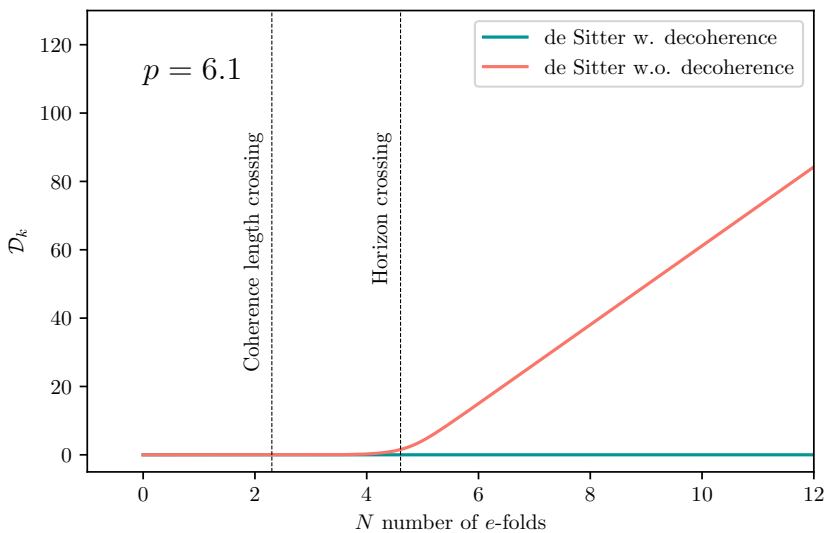

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Is there a way to understand this competition visually ?

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WHAT DOES QUANTUM DISCORD MEASURE ?

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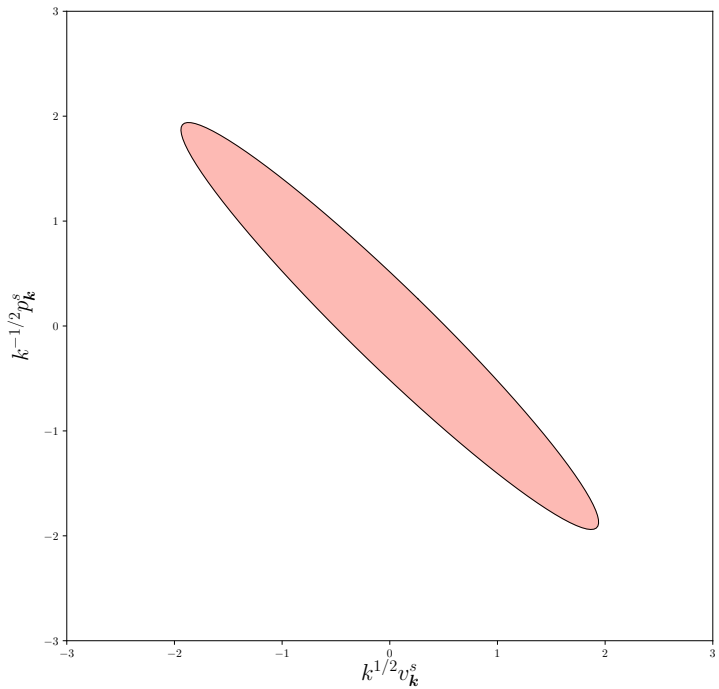
→ **Gaussian state** can represented as **probability distribution in phase space** using their Wigner function. Contours levels are **ellipses**.



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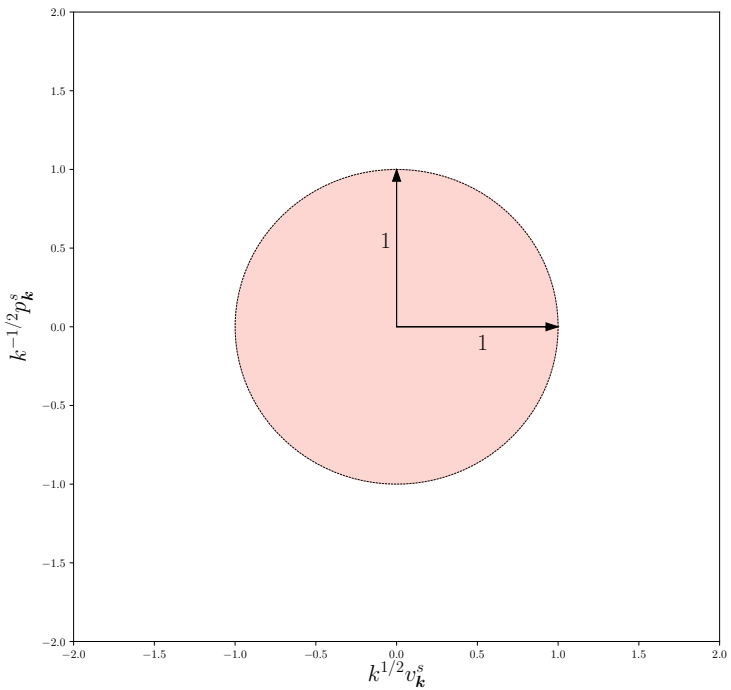

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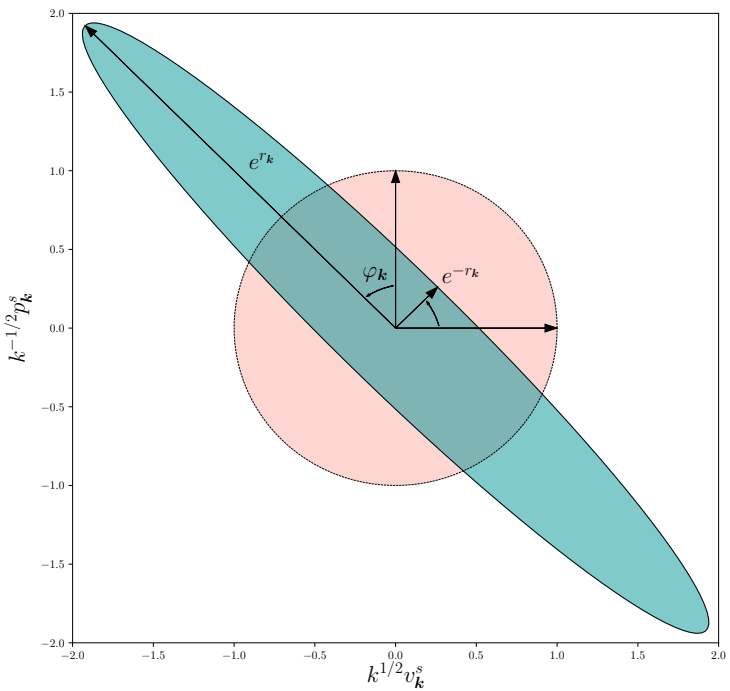
→ Evolution under quadratic hamiltonian : **squeezing of the contour, preserving area. Creates a sub-fluctuant direction** $e^{-r_{\mathbf{k}}}$.



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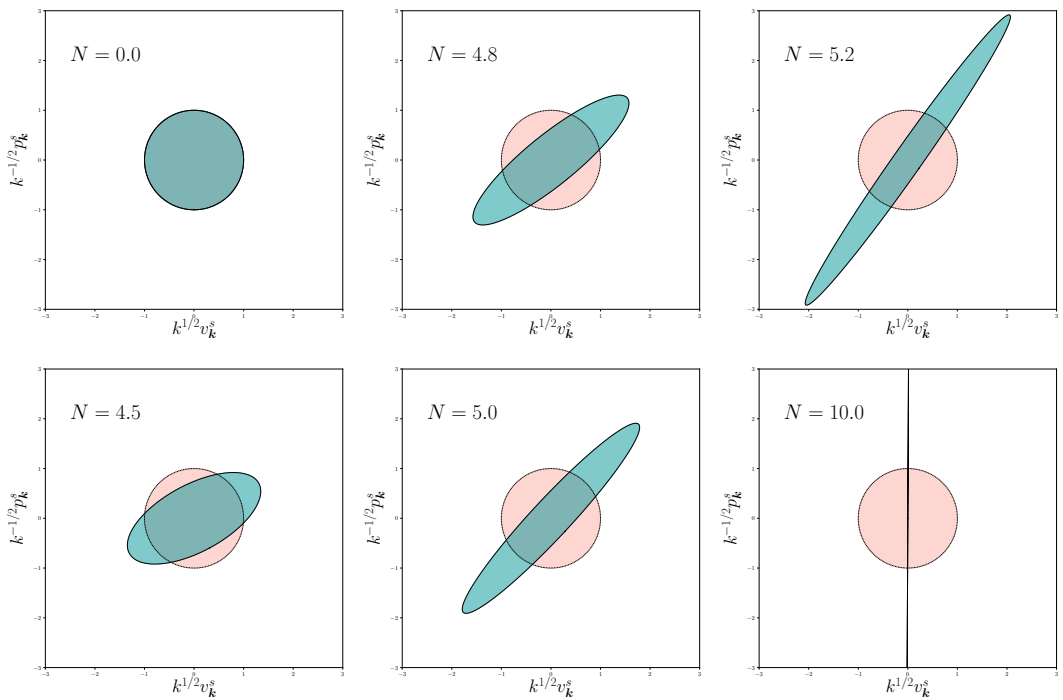
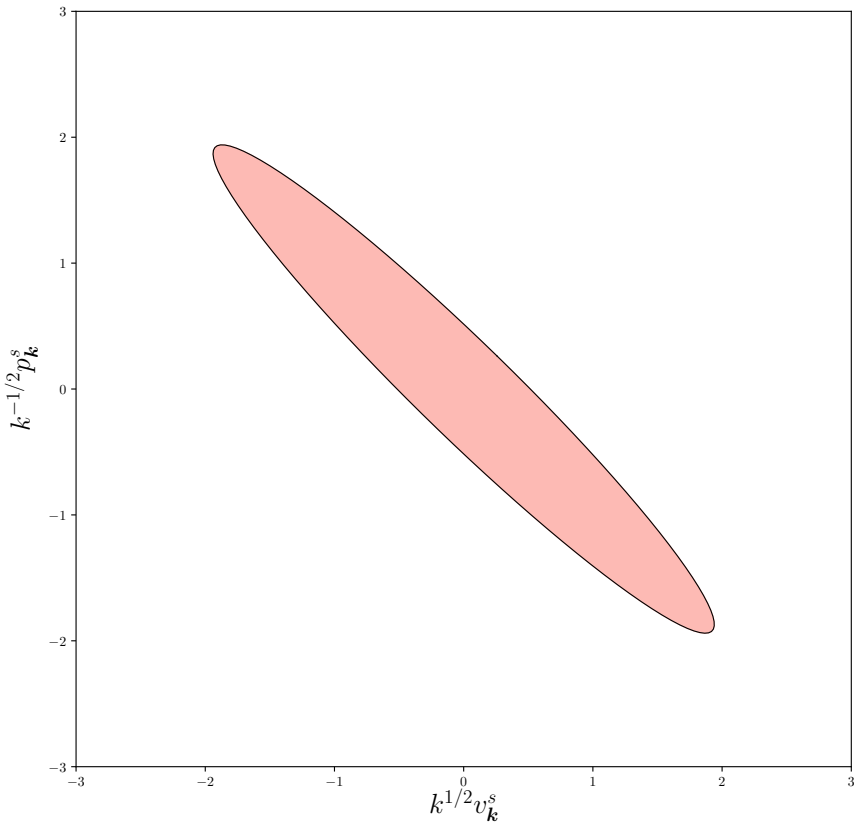
→ Inflation leads to strong squeezing hence **very sub-fluctuant mode**.



GEO. REP. DECOHERED 2-MODE SQUEEZED STATES

→ Decoherence in phase space ?



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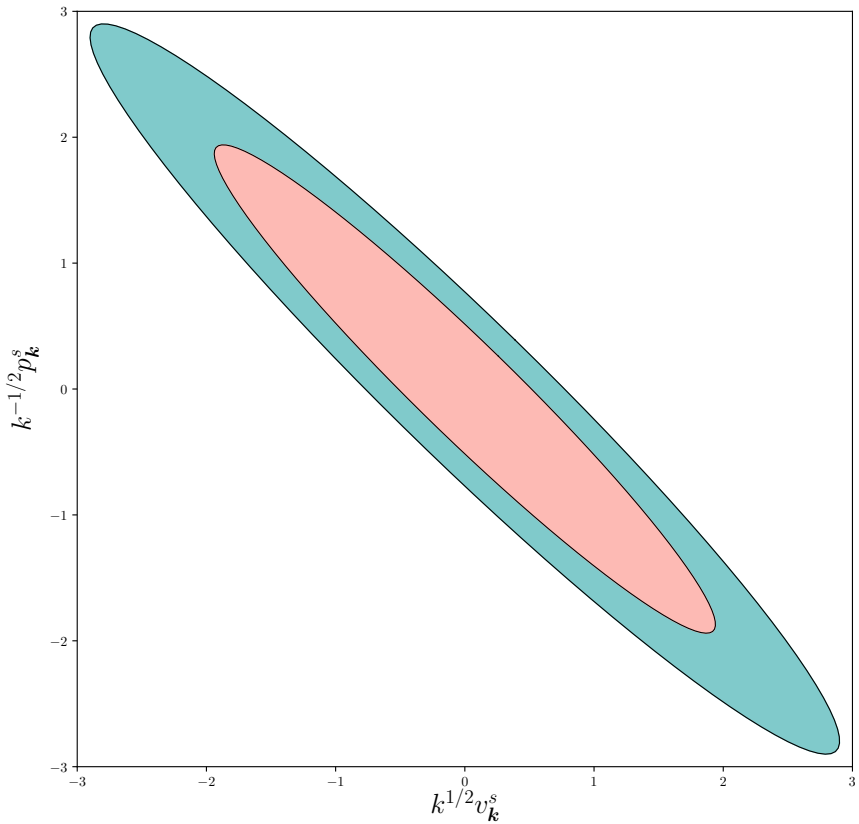

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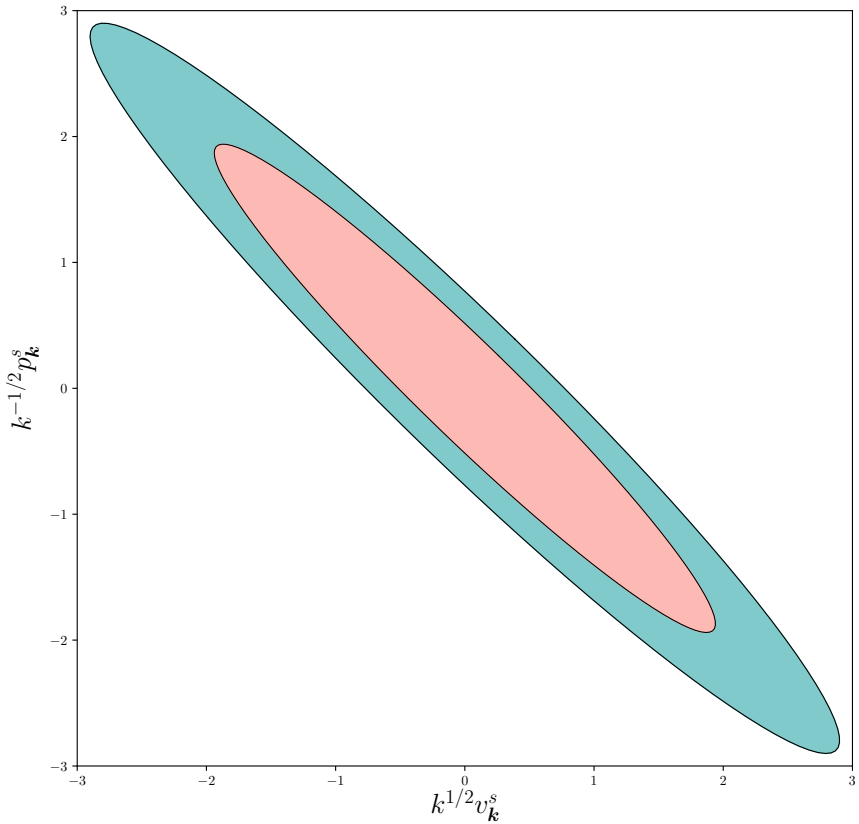
→ Decoherence in phase space ? Growth of ellipse area → **growth of semi-minor axis : can remove sub-fluctuant direction.**



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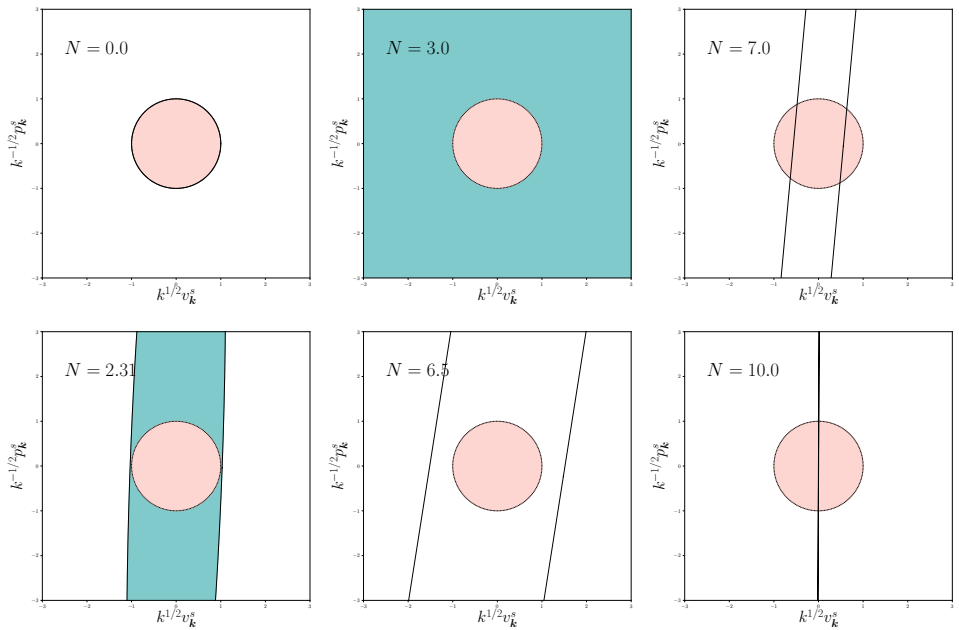

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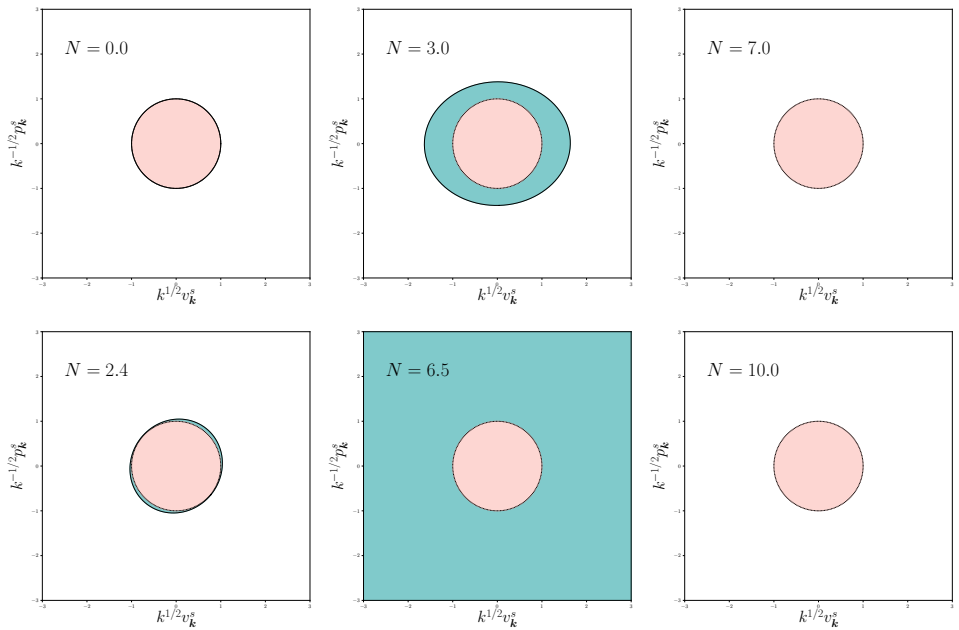

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Take-home message 3

For decohered 2-mode squeezed states the value of Quantum Discord is related to the size of the semi-minor axis.

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SUMMARY & FUTURE DIRECTIONS

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→ Computed the Quantum Discord of inflationnary pertubations in presence of decoherence.

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FUTURE DIRECTIONS

→ Compare the effect of decoherence on different criteria (Bell Inequalities, non-separability etc.).

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- → Compare the effect of decoherence on different criteria (Bell Inequalities, non-separability etc.).
- → Use a more realistic interaction for decoherence, for instance non-linearities of pure gravity and see if we recover similar results.

Thank you for your attention !


Adesso, G. and Datta, A. (2010).
Quantum versus classical correlations in Gaussian states.
Physical Review Letters, 105(3):030501.


arXiv:2112.05037 Martin, J., Micheli, A., and Vennin, V. (2021).
Discord and Decoherence.
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EXTRA

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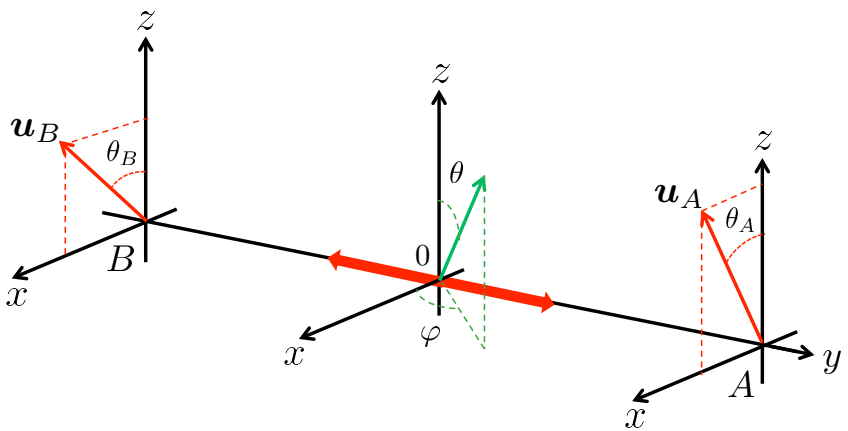

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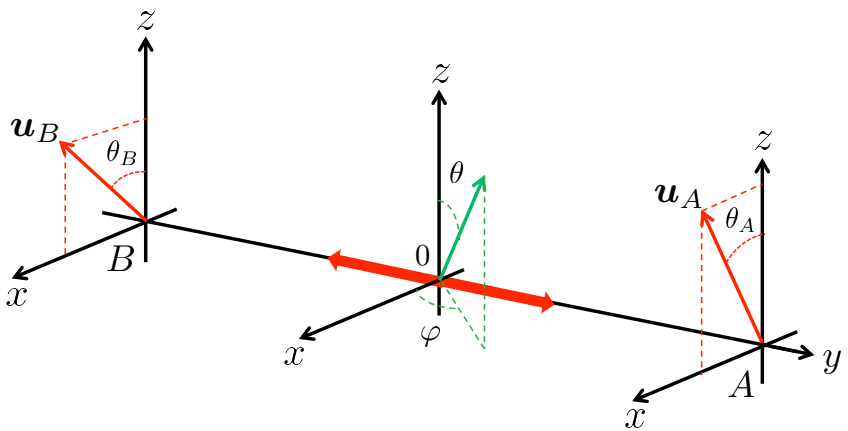

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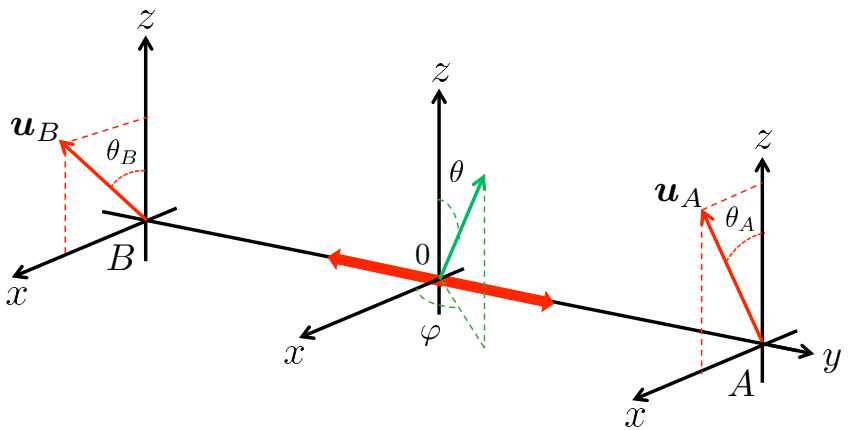

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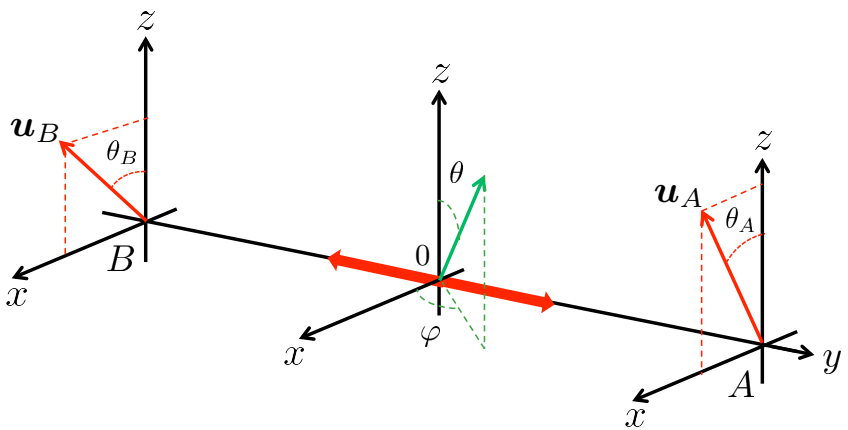

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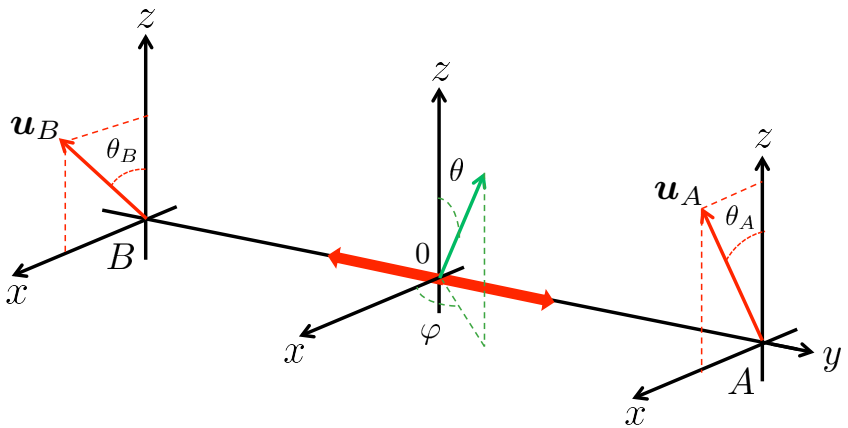

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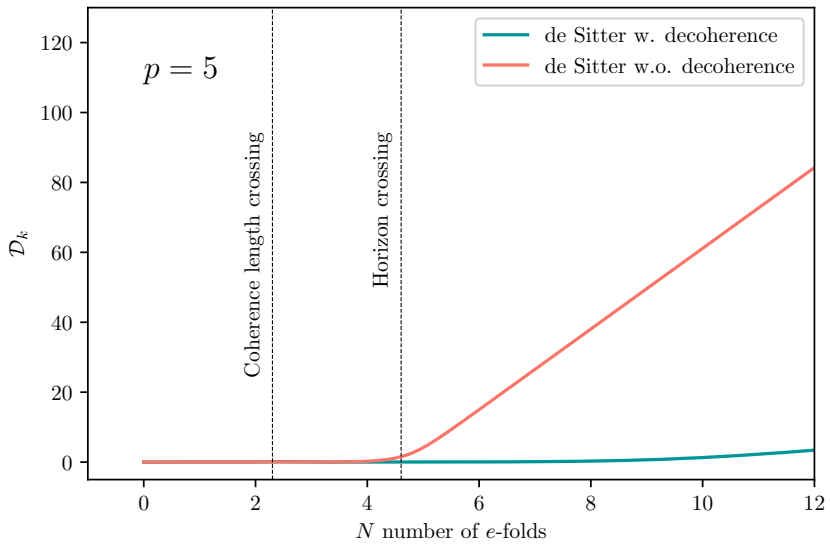
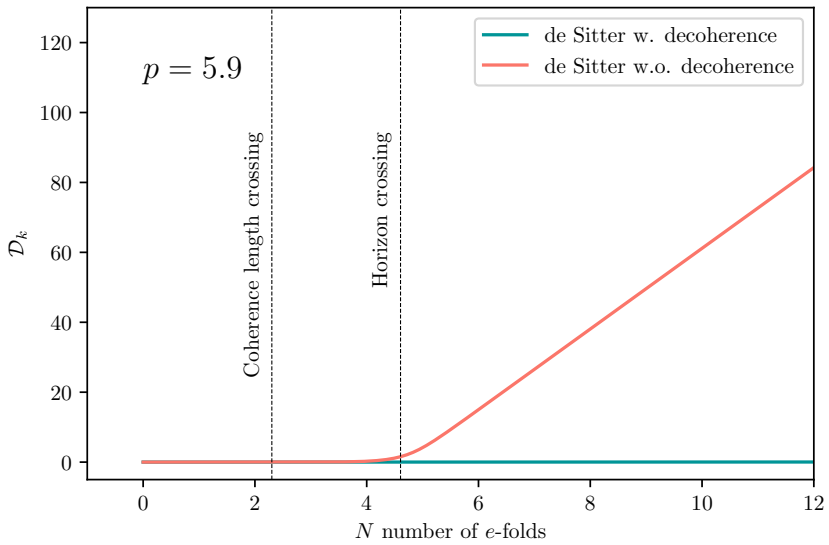
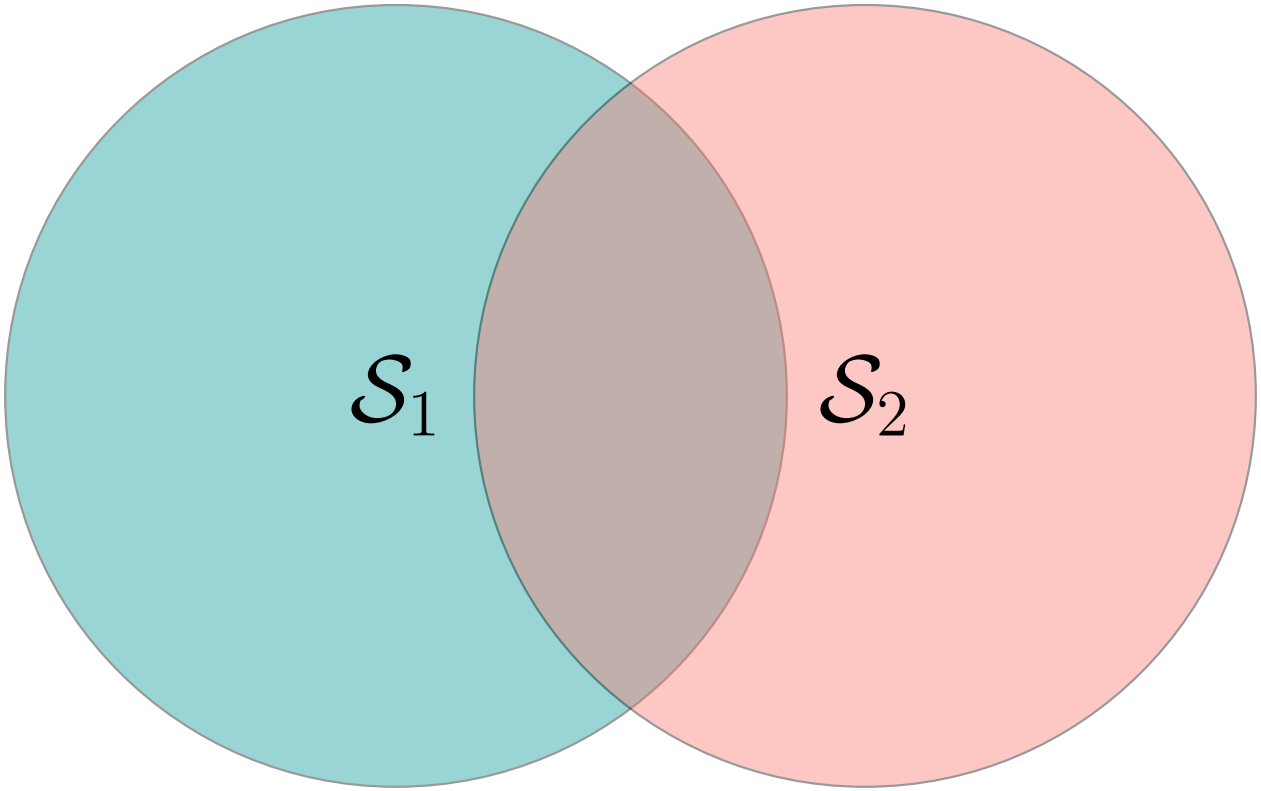
If measure $\langle \hat{\mathcal{O}} \rangle > 2$, correlations stronger than classical ones $\rightarrow$ quantum state.

GROWTH OF $\mathcal{D}_K$ AND VALUES p





MUTUAL INFORMATION



$$\mathcal{I}\left(\mathcal{S}_1, \mathcal{S}_2\right) = H\left(\mathcal{S}_1\right) + H\left(\mathcal{S}_2\right) - H\left(\mathcal{S}\right)$$

DECOHERED INFLATIONNARY FLUCTUATIONS

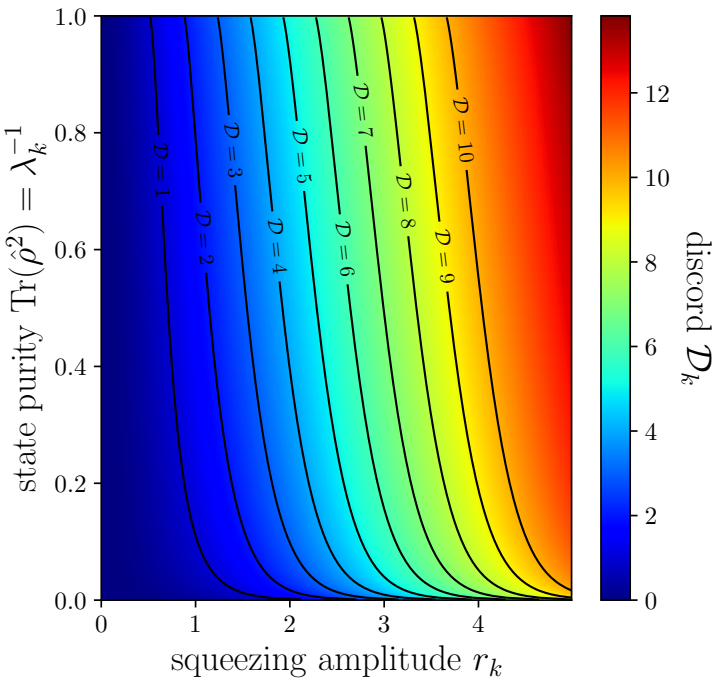
→ Environment for $\mathcal{S}$? Modeled by Lindblad equation + linear interaction with strength

$$k_\Gamma^2 \left(\frac{a}{a_\star}\right)^{p-3} H \left(1 - \frac{k\ell_E}{a}\right) . \tag{1}$$

COMPETITION BETWEEN DECOHERENCE AND INFLATION

Take-home message 2 [6]

Loss or preservation of Quantum Discord is the result of a competition between generation of entanglement by inflation and decoherence due to interactions.



6. [arXiv:2112.05037 Martin et al., 2021]