Quantum Discord and Decoherence of inflationary perturbations

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arXiv:2112.05037 AM, Jérôme Martin [2] , Vincent Vennin [2 3]

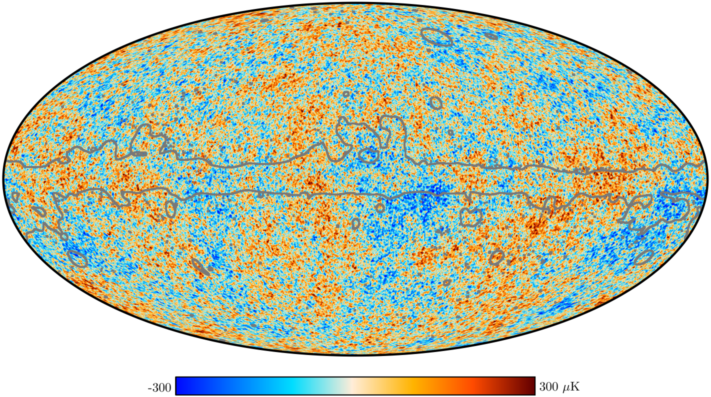
IJCLab, Orsay [1]

IAP, Paris [2] APC, Paris [3]

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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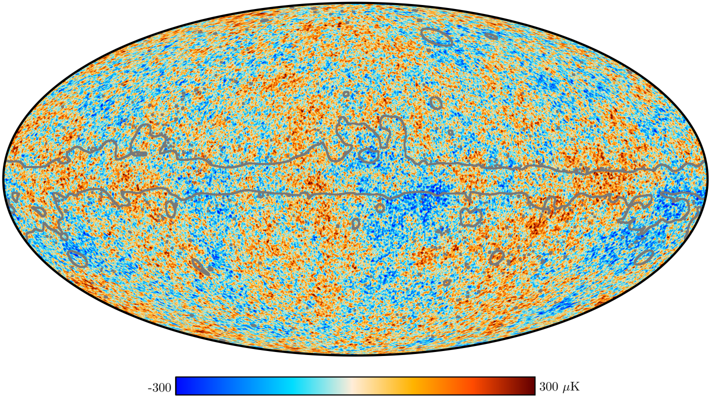

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→ Proposition $\sim$80s [2] : Inhomogeneities come from minimal (vacuum) quantum fluctuations at the beginning of inflation stretched to cosmological scales by expansion !

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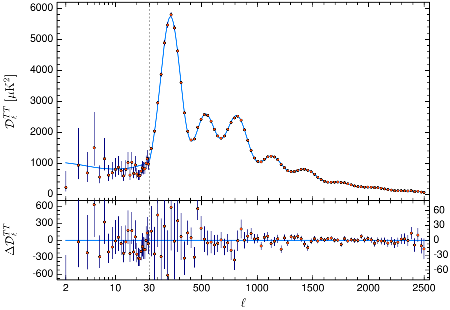

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- → We need **tools to measure the quantumness of a state** and hence study this transition : **Quantum Discord**
- → Interactions with extra d.o.f lead to **decoherence** of quantum systems : **ingredient of quantum-to-classical transition.**

CHARACTERIZING QUANTUMNESS OF INFLATIONNARY PERTURBATIONS

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

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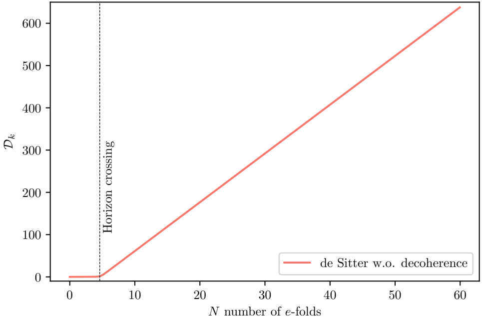

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Take-home message 1

Without decoherence Quantum Discord is strongly amplified by inflation and final state is very quantum in this sense. [2]

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Can this result be due to oversimplified models ?

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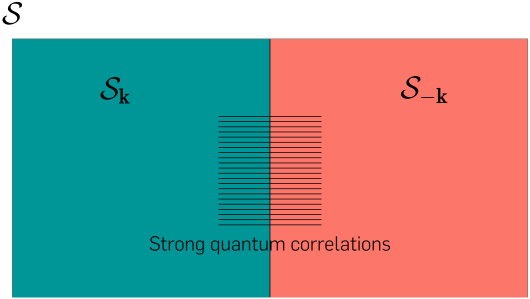
DECOHERENCE AND LOSS OF QUANTUMNESS

NON-LINEARITIES, INTERACTIONS : DECOHERENCE



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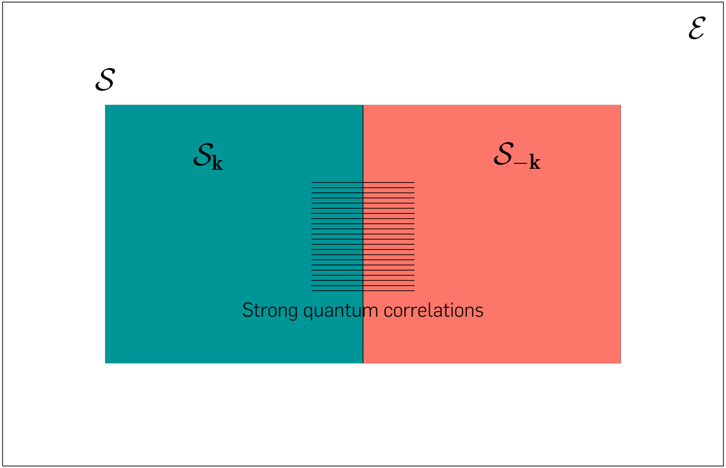

In fact $\mathcal{S}$ has an environment $\mathcal{E}$ (e.g. $\mathcal{S}_{\pm\mathbf{k}'}$ with $\mathbf{k}' \neq \mathbf{k}$) or other fields.

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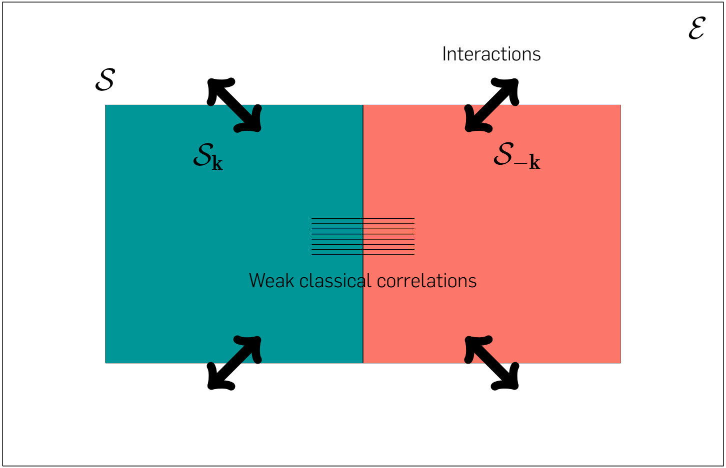

Interactions $\mathcal{S}$ / $\mathcal{E}$ destroy correlations $\mathcal{S}_{\mathbf{k}}$ / $\mathcal{S}_{-\mathbf{k}}$: decoherence.

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$$\frac{\mathrm{d}\hat{\rho}_{\mathcal{S}}}{\mathrm{d}\eta} = -g^2 \eta_{\mathrm{C}} \int \mathrm{d}^3\mathbf{x}\, \mathrm{d}^3\mathbf{y}\, C_{\mathcal{E}}\left(\mathbf{x}, \mathbf{y}\right) \left[\hat{O}_{\mathcal{S}}(\mathbf{x}), \left[\hat{O}_{\mathcal{S}}(\mathbf{y}), \hat{\rho}_{\mathcal{S}}\right]\right] \ .$$

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Assumptions :

→ Perturbation $g \ll 1$.

→ $\mathcal{E}$ stationnary and not perturbed by $\mathcal{S}$.

→ Consider evolution of $\mathcal{S}$ for $\eta \gg \eta_C$ auto-correlation time of $\mathcal{E}$.

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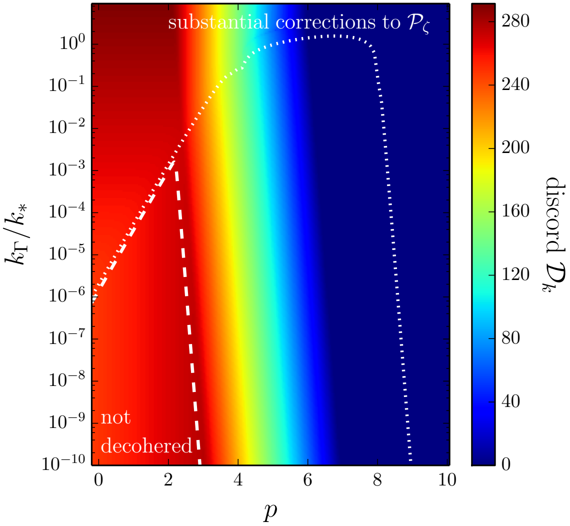
- → Free-parameters : k_Γ and p [3].

3. [Martin and Vennin, 2016]

Is Quantum Discord spoiled by decoherence ?

COMPETITION OF ENTANGLEMENT AND DECOHERENCE



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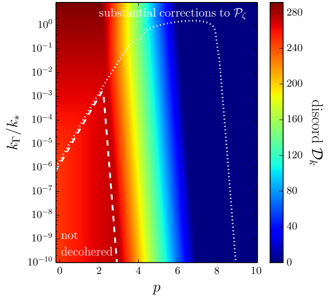

Take-home message 2 [4]

Fate 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]

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- → 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.
arXiv:2112.05037 [astro-ph, physics:hep-th, physics:quant-ph].

Martin, J. and Vennin, V. (2016).
Quantum Discord of Cosmic Inflation : Can we Show that CMB Anisotropies are of Quantum-Mechanical Origin ?
Physical Review D, 93(2):023505.

Mukhanov, V. F. and Chibisov, G. V. (1981).
Quantum fluctuations and a nonsingular universe.
ZhETF Pisma Redaktsiiu, 33:549–553.

Planck-Collaboration, Aghanim, N., Akrami, Y., Ashdown, M., Aumont, J., Baccigalupi, C., Ballardini, M., Banday, A. J., Barreiro, R. B., Bartolo, N., Basak, S., Battye, R., Benabed, K., Bernard, J.-P., Bersanelli, M., Bielewicz, P., Bock, J. J., Bond, J. R., Borrill, J., Bouchet, F. R., Boulanger, F., Bucher, M., Burigana, C., Butler, R. C., Calabrese, E., Cardoso, J.-F., Carron, J., Challinor, A., Chiang, H. C., Chluba, J., Colombo, L. P. L., Combet, C., Contreras, D., Crill, B. P., Cuttaia, F., de Bernardis, P., de Zotti, G., Delabrouille, J., Delouis, J.-M., Di Valentino, E., Diego, J. M., Doré, O., Douspis, M., Ducout, A., Dupac, X., Dusini, S., Efstathiou, G., Elsner, F., Enßlin, T. A., Eriksen, H. K., Fantaye, Y., Farhang, M., Fergusson, J., Fernandez-Cobos, R., Finelli, F., Forastieri, F., Frailis, M., Fraisse, A. A., Franceschi, E., Frolov, A., Galeotta, S., Galli, S., Ganga, K., Génova-Santos, R. T., Gerbino, M., Ghosh, T., González-Nuevo, J., Górski, K. M., Gratton, S., Gruppuso, A., Gudmundsson, J. E., Hamann, J., Handley, W., Hansen, F. K., Herranz, D., Hildebrandt, S. R.,

Hivon, E., Huang, Z., Jaffe, A. H., Jones, W. C., Karakci, A., Keihänen, E., Keskitalo, R., Kiiveri, K., Kim, J., Kisner, T. S., Knox, L., Krachmalnicoff, N., Kunz, M., Kurki-Suonio, H., Lagache, G., Lamarre, J.-M., Lasenby, A., Lattanzi, M., Lawrence, C. R., Jeune, M. L., Lemos, P., Lesgourgues, J., Levrier, F., Lewis, A., Liguori, M., Lilje, P. B., Lilley, M., Lindholm, V., López-Caniego, M., Lubin, P. M., Ma, Y.-Z., Macías-Pérez, J. F., Maggio, G., Maino, D., Mandolesi, N., Mangilli, A., Marcos-Caballero, A., Maris, M., Martin, P. G., Martinelli, M., Martínez-González, E., Matarrese, S., Mauri, N., McEwen, J. D., Meinhold, P. R., Melchiorri, A., Mennella, A., Migliaccio, M., Millea, M., Mitra, S., Miville-Deschênes, M.-A., Molinari, D., Montier, L., Morgante, G., Moss, A., Natoli, P., Nørgaard-Nielsen, H. U., Pagano, L., Paoletti, D., Partridge, B., Patanchon, G., Peiris, H. V., Perrotta, F., Pettorino, V., Piacentini, F., Polastri, L., Polenta, G., Puget, J.-L., Rachen, J. P., Reinecke, M., Remazeilles, M., Renzi, A., Rocha, G., Rosset, C., Roudier, G., Rubiño-Martín, J. A., Ruiz-Granados, B., Salvati, L., Sandri, M., Savelainen, M., Scott,

D., Shellard, E. P. S., Sirignano, C., Sirri, G., Spencer, L. D., Sunyaev, R., Suur-Uski, A.-S., Tauber, J. A., Tavagnacco, D., Tenti, M., Toffolatti, L., Tomasi, M., Trombetti, T., Valenziano, L., Valiviita, J., Van Tent, B., Vibert, L., Vielva, P., Villa, F., Vittorio, N., Wandelt, B. D., Wehus, I. K., White, M., White, S. D. M., Zacchei, A., and Zonca, A. (2020a).
Planck 2018 results. VI. Cosmological parameters.
Astronomy & Astrophysics, 641:A6.

Planck-Collaboration, Akrami, Y., Ashdown, M., Aumont, J., Baccigalupi, C., Ballardini, M., Banday, A. J., Barreiro, R. B., Bartolo, N., Basak, S., Benabed, K., Bersanelli, M., Bielewicz, P., Bond, J. R., Borrill, J., Bouchet, F. R., Boulanger, F., Bucher, M., Burigana, C., Calabrese, E., Cardoso, J.-F., Carron, J., Casaponsa, B., Challinor, A., Colombo, L. P. L., Combet, C., Crill, B. P., Cuttaia, F., de Bernardis, P., de Rosa, A., de Zotti, G., Delabrouille, J., Delouis, J.-M., Valentino, E. D., Dickinson, C., Diego, J. M., Donzelli, S., Doré, O., Ducout, A., Dupac, X., Efstathiou, G., Elsner, F., Enßlin, T. A., Eriksen, H. K., Falgarone, E., Fernandez-Cobos, R., Finelli, F., Forastieri, F., Frailis, M., Fraisse, A. A., Franceschi, E., Frolov, A., Galeotta, S., Galli, S., Ganga, K., Génova-Santos, R. T., Gerbino, M., Ghosh, T., González-Nuevo, J., Górski, K. M., Gratton, S., Gruppuso, A., Gudmundsson, J. E., Handley, W., Hansen, F. K., Helou, G., Herranz, D., Hildebrandt, S. R., Huang, Z., Jaffe, A. H., Karakci, A., Keihänen, E., Keskitalo, R., Kiiveri, K., Kim, J., Kisner, T. S., Krachmalnicoff, N., Kunz, M., Kurki-Suonio, H., Lagache, G., Lamarre, J.-M., Lasenby, A., Lattanzi, M., Lawrence, C. R., Jeune, M. L., Levrier, F., Liguori, M., Lilje, P. B., Lindholm, V., López-Caniego, M., Lubin, P. M., Ma, Y.-Z., Macías-Pérez, J. F., Maggio, G., Maino, D., Mandolesi, N., Mangilli, A., Marcos-Caballero, A., Maris, M., Martin, P. G., Martínez-González, E., Matarrese, S., Mauri, N., McEwen, J. D., Meinhold, P. R., Melchiorri, A., Mennella, A., Migliaccio, M., Miville-Deschênes, M.-A., Molinari, D., Moneti, A., Montier, L., Morgante, G., Natoli, P., Oppizzi, F., Pagano, L., Paoletti, D.,

Partridge, B., Peel, M., Pettorino, V., Piacentini, F., Polenta, G., Puget, J.-L., Rachen, J. P., Reinecke, M., Remazeilles, M., Renzi, A., Rocha, G., Roudier, G., Rubiño-Martín, J. A., Ruiz-Granados, B., Salvati, L., Sandri, M., Savelainen, M., Scott, D., Seljebotn, D. S., Sirignano, C., Spencer, L. D., Suur-Uski, A.-S., Tauber, J. A., Tavagnacco, D., Tenti, M., Thommesen, H., Toffolatti, L., Tomasi, M., Trombetti, T., Valiviita, J., Tent, B. V., Vielva, P., Villa, F., Vittorio, N., Wandelt, B. D., Wehus, I. K., Zacchei, A., and Zonca, A. (2020b).
Planck 2018 results - IV. Diffuse component separation.
Astronomy & Astrophysics, 641:A4.

EXTRA

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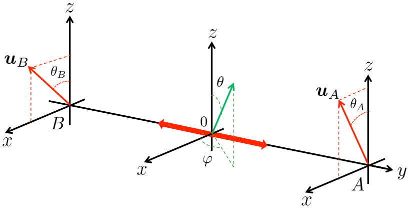

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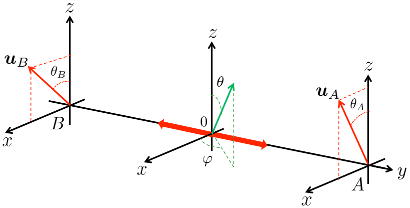

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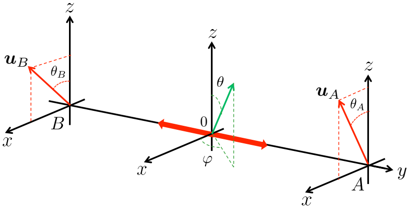

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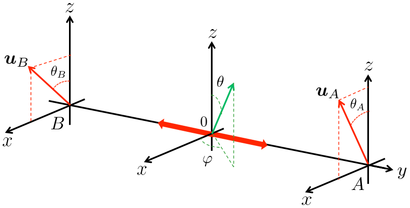

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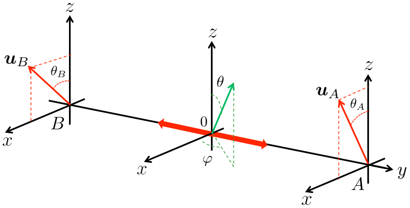

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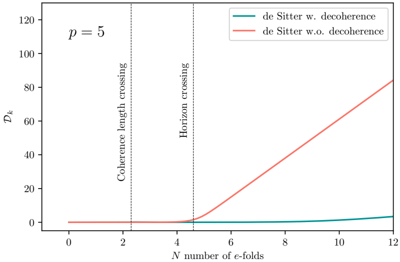
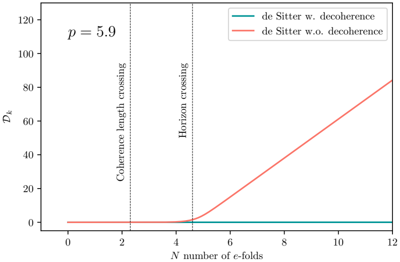
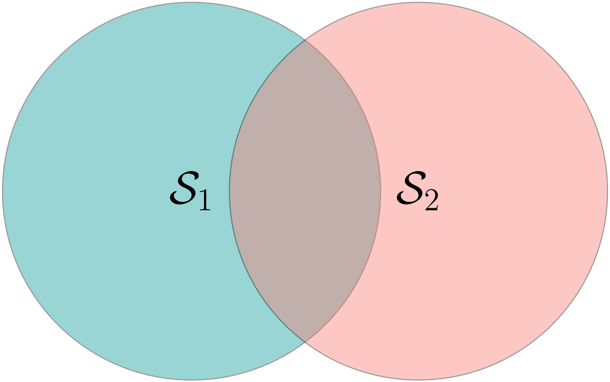
If measure $\langle \hat{\mathcal{O}} \rangle > 2$, correlations stronger than classical ones $\rightarrow$ quantum state.

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

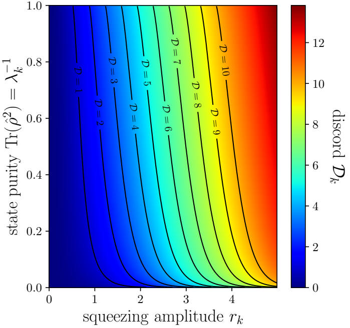
→ Environment for $\mathcal{S}$? Modeled by Lindblad equation + linear interaction with strength

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

COMPETITION BETWEEN DECOHERENCE AND INFLATION

Take-home message 2 [5]

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



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