Quantum Gravity in de Sitter space

Suddhasattwa Brahma

Higgs Centre for Theoretical Physics, University of Edinburgh

(in collaboration with A. Berera, R. Brandenberger, J. Calderón & others:
2302.13894, 2206.05797, 2107.06910, 2005.09688

Ongoing work with: L. Hackl, M. Hassan & X. Luo
and with: T. Colas, J. Grain & V. Vennin)

12th July, 2023

Quantum Gravity (= Quantum Information) in de Sitter space

Suddhasattwa Brahma

Higgs Centre for Theoretical Physics, University of Edinburgh

(in collaboration with A. Berera, R. Brandenberger, J. Calderón & others:
2302.13894, 2206.05797, 2107.06910, 2005.09688

Ongoing work with: L. Hackl, M. Hassan & X. Luo
and with: T. Colas, J. Grain & V. Vennin)

12th July, 2023

Quantum physics in de Sitter space

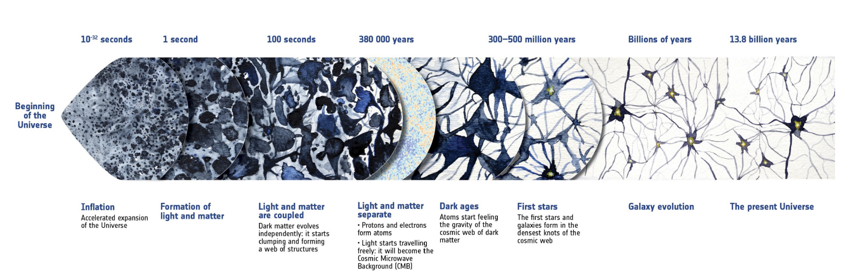


Photo Credit: ESA

$\hookrightarrow$ dS: cosmic evolution as a whole – Why do we need quantum physics?

Quantum physics in de Sitter space

$\hookrightarrow$ dS: cosmic evolution as a whole – Why do we need quantum physics?

✓ Inflation: Not only solves the standard cosmological puzzles but also explains late-time inhomogeneities as originating from quantum vacuum fluctuations $\Rightarrow$ Rare *interplay* between microscopic & macroscopic scales!

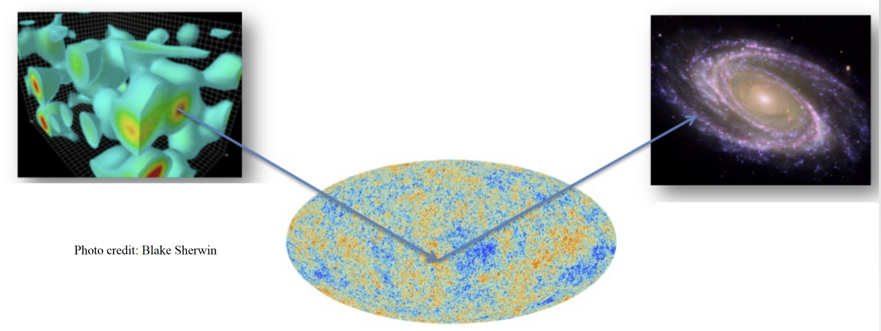


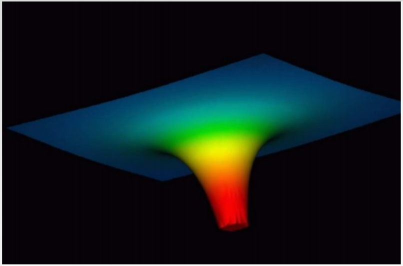
Photo credit: Blake Sherwin

Quantum physics in de Sitter space

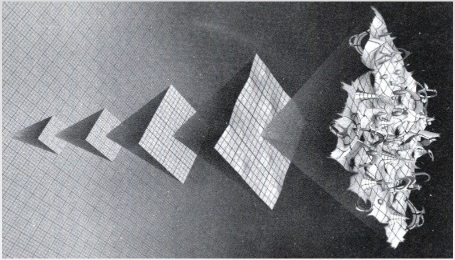
↪ dS: cosmic evolution as a whole – Why do we need quantum physics?

✓ Inflation: Not only solves the standard cosmological puzzles but also explains late-time inhomogeneities as originating from quantum vacuum fluctuations ⇒ Rare *interplay* between microscopic & macroscopic scales!

✓ The *quantum origins* of spacetime itself ⇒ UV-completion? Emergence of bulk states from quantum entanglement of dual degrees of freedom in dS?



Credit: Pablo Laguna



Quantum physics in de Sitter space

$\hookrightarrow$ dS: cosmic evolution as a whole – Why do we need quantum physics?

✓ Inflation: Not only solves the standard cosmological puzzles but also explains late-time inhomogeneities as originating from quantum vacuum fluctuations $\Rightarrow$ Rare *interplay* between microscopic & macroscopic scales!

✓ The *quantum origins* of spacetime itself $\Rightarrow$ UV-completion? Emergence of bulk states from quantum entanglement of dual degrees of freedom in dS?

$\rightarrow$ Observations access part of Hilbert space: Dissipation & Decoherence. Nature of environment *special* in cosmology $\Rightarrow$ Non-Markovianity.

Quantum physics in de Sitter space

$\hookrightarrow$ dS: cosmic evolution as a whole – Why do we need quantum physics?

✓ Inflation: Not only solves the standard cosmological puzzles but also explains late-time inhomogeneities as originating from quantum vacuum fluctuations $\Rightarrow$ Rare *interplay* between microscopic & macroscopic scales!

✓ The *quantum origins* of spacetime itself $\Rightarrow$ UV-completion? Emergence of bulk states from quantum entanglement of dual degrees of freedom in dS?

$\rightarrow$ Observations access part of Hilbert space: Dissipation & Decoherence. Nature of environment *special* in cosmology $\Rightarrow$ Non-Markovianity.

$\rightarrow$ Complexity as quantitative measure of *difficulty* of constructing entangled EPR state in de Sitter holography!

Quantum physics in de Sitter space

↪ dS: cosmic evolution as a whole – Why do we need quantum physics?

✓ Inflation: Not only solves the standard cosmological puzzles but also explains late-time inhomogeneities as originating from quantum vacuum fluctuations ⇒ Rare *interplay* between microscopic & macroscopic scales!

✓ The *quantum origins* of spacetime itself ⇒ UV-completion? Emergence of bulk states from quantum entanglement of dual degrees of freedom in dS?

→ Observations access part of Hilbert space: Dissipation & Decoherence. Nature of environment *special* in cosmology ⇒ Non-Markovianity.

→ Complexity as quantitative measure of *difficulty* of constructing entangled EPR state in de Sitter holography!

- Open EFTs for inflation: *Momentum-space EE quantifies non-unitarity*

Quantum physics in de Sitter space

↪ dS: cosmic evolution as a whole – Why do we need quantum physics?

✓ Inflation: Not only solves the standard cosmological puzzles but also explains late-time inhomogeneities as originating from quantum vacuum fluctuations ⇒ Rare *interplay* between microscopic & macroscopic scales!

✓ The *quantum origins* of spacetime itself ⇒ UV-completion? Emergence of bulk states from quantum entanglement of dual degrees of freedom in dS?

→ Observations access part of Hilbert space: Dissipation & Decoherence. Nature of environment *special* in cosmology ⇒ Non-Markovianity.

→ Complexity as quantitative measure of *difficulty* of constructing entangled EPR state in de Sitter holography!

- Open EFTs for inflation: *Momentum-space EE quantifies non-unitarity*
  - Cosmic version of $ER = EPR$: Complexity of Bunch-Davies vacuum

Quantum physics in de Sitter space

$\hookrightarrow$ dS: cosmic evolution as a whole – Why do we need quantum physics?

✓ Inflation: Not only solves the standard cosmological puzzles but also explains late-time inhomogeneities as originating from quantum vacuum fluctuations $\Rightarrow$ Rare *interplay* between microscopic & macroscopic scales!

✓ The *quantum origins* of spacetime itself $\Rightarrow$ UV-completion? Emergence of bulk states from quantum entanglement of dual degrees of freedom in dS?

$\rightarrow$ Observations access part of Hilbert space: Dissipation & Decoherence. Nature of environment *special* in cosmology $\Rightarrow$ Non-Markovianity.

$\rightarrow$ Complexity as quantitative measure of *difficulty* of constructing entangled EPR state in de Sitter holography!

- Open EFTs for inflation: *Momentum-space EE quantifies non-unitarity*
  - Cosmic version of $ER = EPR$: Complexity of Bunch-Davies vacuum

Quantum informatic tools, *e.g.* Entanglement and Complexity, provide unique and deep insights for quantum gravity in de Sitter space.

Inflation as an open EFT: Non-unitarity & non-Markovianity

Inferring early universe physics from observations

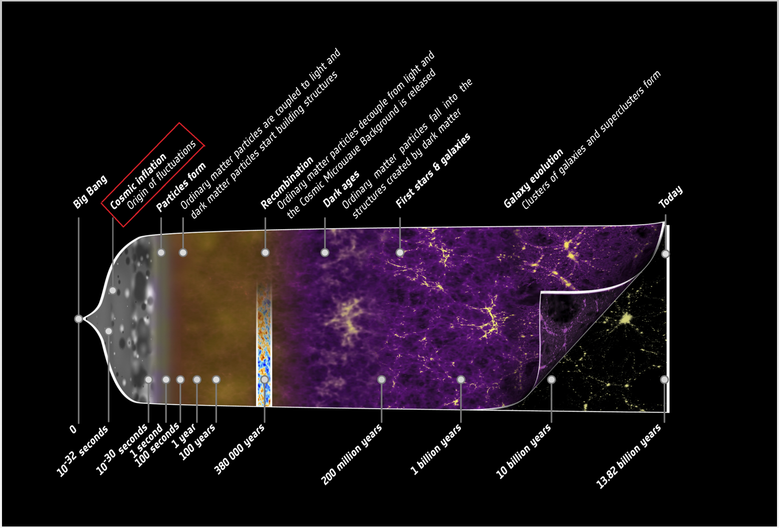


Photo credit: ESA/PLANCK

Inferring early universe physics from observations

$\hookrightarrow$ Learn about inflationary physics from higher order correlation functions: Non-Gaussianities $\rightarrow$ Constraints on model-space. [Chen, Wang, Baumann, Green, Arkani-Hamed, Maldacena, Lee, Pimentel, Joyce, Pajer, Sleight, Taronna, Stefanyszyn . . . ; S.B., Nelson & Shandera, 2014 (PRD); Bonga, S.B., Deutsch & Shandera, 2016 (JCAP) , . . .]

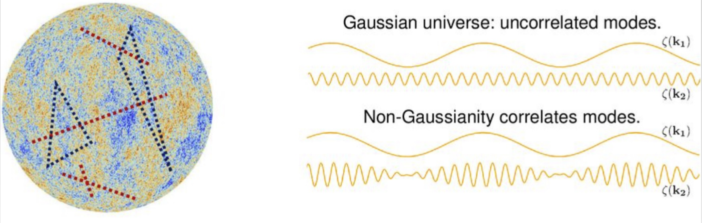


Photo credit: Andrea Ravenni

Inferring early universe physics from observations

↪ Learn about inflationary physics from higher order correlation functions: Non-Gaussianities → Constraints on model-space. [Chen, Wang, Baumann, Green, Arkani-Hamed, Maldacena, Lee, Pimentel, Joyce, Pajer, Sleight, Taronna, Stefanyszyn . . . ; S.B., Nelson & Shandera, 2014 (PRD); Bonga, S.B., Deutsch & Shandera, 2016 (JCAP) , . . .]

✓ We have **not** observed any NG yet → Need a fresh perspective!

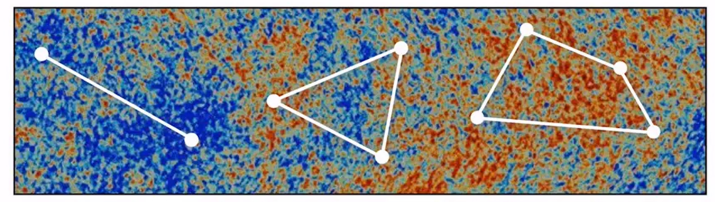


Photo credit: Daniel Baumann

Inferring early universe physics from observations

$\hookrightarrow$ Learn about inflationary physics from higher order correlation functions: Non-Gaussianities $\rightarrow$ Constraints on model-space. [Chen, Wang, Baumann, Green, Arkani-Hamed, Maldacena, Lee, Pimentel, Joyce, Pajer, Sleight, Taronna, Stefanyszyn . . . ; S.B., Nelson & Shandera, 2014 (PRD); Bonga, S.B., Deutsch & Shandera, 2016 (JCAP) , . . .]

✓ We have **not** observed any NG yet $\rightarrow$ Need a fresh perspective!

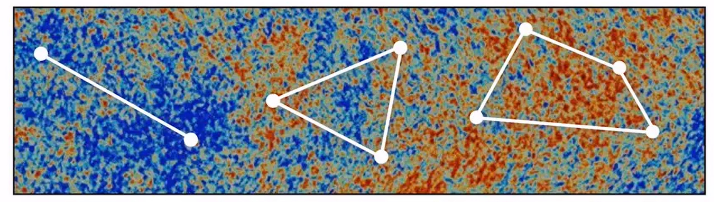


Photo credit: Daniel Baumann

- Cosmological Collider Physics/Cosmological Bootstrap

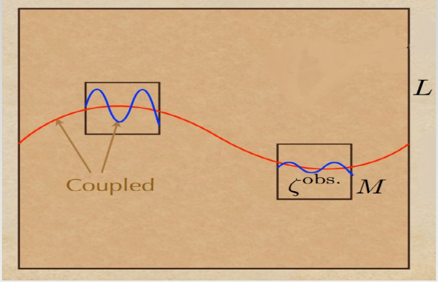
Open quantum cosmological system

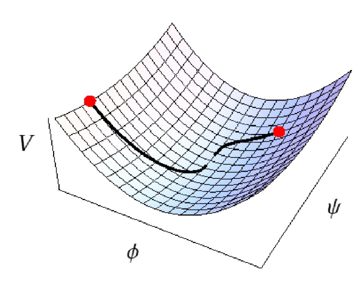
$\hookrightarrow$ Observable dofs in the universe is *necessarily* part of a larger system with an environment $\rightarrow$ Modes of interest coupled to *unobservable stuff*.

Open quantum cosmological system

↪ Observable dofs in the universe is *necessarily* part of a larger system with an environment → Modes of interest coupled to *unobservable stuff*.

↪ Observed statistics depend on our position in the universe, on UV physics, couplings to SM fields etc. especially since GR is non-linear.





Open quantum cosmological system

$\hookrightarrow$ Observable dofs in the universe is *necessarily* part of a larger system with an environment $\rightarrow$ Modes of interest coupled to *unobservable stuff*.

$\hookrightarrow$ Wilsonian EFT does not apply directly to cosmology $\rightarrow$ "Integrated out" subhorizon modes are not excluded by any conservation law.

Open quantum cosmological system

$\hookrightarrow$ Observable dofs in the universe is *necessarily* part of a larger system with an environment $\rightarrow$ Modes of interest coupled to *unobservable stuff*.

$\hookrightarrow$ Wilsonian EFT does not apply directly to cosmology $\rightarrow$ "Integrated out" subhorizon modes are not excluded by any conservation law.

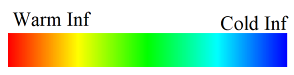
- ⋆ Non-unitary evolution: Full $\rho(t) \to \rho_{\rm sys} = Tr_{\mathcal{E}}\,\rho(t)$
- ⋆ System dof's can exchange energy & lose information to environment
  $\Rightarrow$ Incorporate Dissipation & Decoherence: Both *affects* observations.
- ⋆ Evolution ME: $d\rho_{\rm sys}/dt \sim [H, \rho_{\rm sys}] + f\,(L_n, \rho_{\rm sys})$ (quantum optics)

Open quantum cosmological system

$\hookrightarrow$ Observable dofs in the universe is *necessarily* part of a larger system with an environment $\to$ Modes of interest coupled to *unobservable stuff*.

$\hookrightarrow$ Wilsonian EFT does not apply directly to cosmology $\to$ "Integrated out" subhorizon modes are not excluded by any conservation law.

- $\star$ Non-unitary evolution: Full $\rho(t) \to \rho_{\rm sys} = Tr_{\mathcal{E}}\, \rho(t)$
- $\star$ System dof's can exchange energy & lose information to environment $\Rightarrow$ Incorporate Dissipation & Decoherence: Both *affects* observations.
- $\star$ Evolution ME: $d\rho_{\rm sys}/dt \sim [H, \rho_{\rm sys}] + f\,(L_n, \rho_{\rm sys})$ (quantum optics)



WI assumes thermal eq while cold models ignore dissipation. [Berera, . . .]

Open quantum cosmological system

$\hookrightarrow$ Observable dofs in the universe is *necessarily* part of a larger system with an environment $\rightarrow$ Modes of interest coupled to *unobservable stuff*.

$\hookrightarrow$ Wilsonian EFT does not apply directly to cosmology $\rightarrow$ "Integrated out" subhorizon modes are not excluded by any conservation law.

- $\star$ Non-unitary evolution: Full $\rho(t) \rightarrow \rho_{\rm sys} = Tr_{\mathcal{E}}\,\rho(t)$
- $\star$ System dof's can exchange energy & lose information to environment $\Rightarrow$ Incorporate Dissipation & Decoherence: Both *affects* observations.
- $\star$ Evolution ME: $d\rho_{\rm sys}/dt \sim [H, \rho_{\rm sys}] + f\left(L_n, \rho_{\rm sys}\right)$ (quantum optics)

Env is neither stationary nor thermal $\rightarrow$ Lindblad theorem **doesn't** apply.
Out-of-equilibrium env $\rightarrow$ Non-Markovian master equation for cosmology!

Open quantum cosmological system

$\hookrightarrow$ Observable dofs in the universe is *necessarily* part of a larger system with an environment $\rightarrow$ Modes of interest coupled to *unobservable stuff*.

$\hookrightarrow$ Wilsonian EFT does not apply directly to cosmology $\rightarrow$ "Integrated out" subhorizon modes are not excluded by any conservation law.

- ⋆ Non-unitary evolution: Full $\rho(t) \rightarrow \rho_{\rm sys} = Tr_{\mathcal{E}}\,\rho(t)$
- ⋆ System dof's can exchange energy & lose information to environment $\Rightarrow$ Incorporate Dissipation & Decoherence: Both *affects* observations.
- ⋆ Evolution ME: $d\rho_{\rm sys}/dt \sim [H, \rho_{\rm sys}] + f\,(L_n, \rho_{\rm sys})$ (quantum optics)

Env is neither stationary nor thermal $\rightarrow$ Lindblad theorem **doesn't** apply.
Out-of-equilibrium env $\rightarrow$ Non-Markovian master equation for cosmology!

- Open *quantum* systems for inflation: [Kaplanek, Burgess, Holman, Martin, Vennin, Colas, Grain, Shandera, Boyanovsky, Nelson, Hu, Hsiang, McDonald, Prokopec, . . .]

Open quantum cosmological system

↪ Observable dofs in the universe is *necessarily* part of a larger system with an environment → Modes of interest coupled to *unobservable stuff*.

↪ Wilsonian EFT does not apply directly to cosmology → "Integrated out" subhorizon modes are not excluded by any conservation law.

- ⋆ Non-unitary evolution: Full $\rho(t) \to \rho_{\rm sys} = Tr_{\mathcal{E}}\,\rho(t)$
- ⋆ System dof's can exchange energy & lose information to environment
  ⇒ Incorporate Dissipation & Decoherence: Both *affects* observations.
- ⋆ Evolution ME: $d\rho_{\rm sys}/dt \sim [H, \rho_{\rm sys}] + f\,(L_n, \rho_{\rm sys})$ (quantum optics)

Env is neither stationary nor thermal → Lindblad theorem **doesn't** apply.
Out-of-equilibrium env → Non-Markovian master equation for cosmology!

- Open *quantum* systems for inflation: [Kaplanek, Burgess, Holman, Martin, Vennin, Colas, Grain, Shandera, Boyanovsky, Nelson, Hu, Hsiang, McDonald, Prokopec, ...]

✓ Late-time secular growth ⇒ Breakdown of SPT in grav systems! No way to *turn-off* gravity. [Kaplanek & Burgess; Burgess, Holman, Leblond & Shandera; ...]

Open quantum cosmological system

↪ Observable dofs in the universe is *necessarily* part of a larger system with an environment → Modes of interest coupled to *unobservable stuff*.

↪ Wilsonian EFT does not apply directly to cosmology → "Integrated out" subhorizon modes are not excluded by any conservation law.

- ⋆ Non-unitary evolution: Full $\rho(t) \to \rho_{\rm sys} = Tr_{\mathcal{E}}\,\rho(t)$
- ⋆ System dof's can exchange energy & lose information to environment ⇒ Incorporate Dissipation & Decoherence: Both *affects* observations.
- ⋆ Evolution ME: $d\rho_{\rm sys}/dt \sim [H, \rho_{\rm sys}] + f\,(L_n, \rho_{\rm sys})$ (quantum optics)

Env is neither stationary nor thermal → Lindblad theorem **doesn't** apply.
Out-of-equilibrium env → Non-Markovian master equation for cosmology!

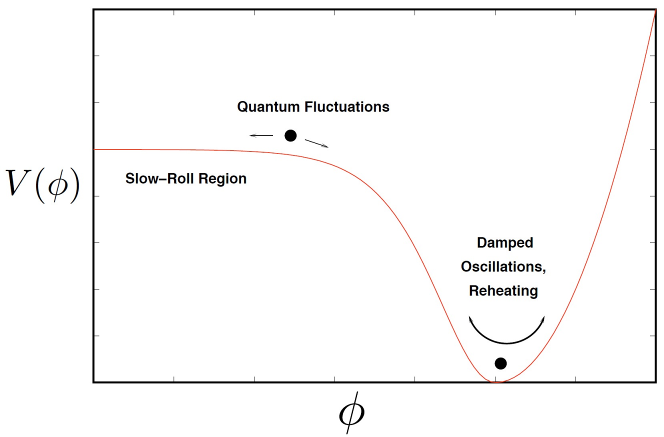
- Open *quantum* systems for inflation: [Kaplanek, Burgess, Holman, Martin, Vennin, Colas, Grain, Shandera, Boyanovsky, Nelson, Hu, Hsiang, McDonald, Prokopec, ...]

✓ Late-time secular growth ⇒ Breakdown of SPT in grav systems! No way to *turn-off* gravity. [Kaplanek & Burgess; Burgess, Holman, Leblond & Shandera; ...]

⋆ Open EFT techniques **not** exclusive to inflation → *Ekpyrosis*: upper bound on $E_{\rm bounce}$. [Brandenberger, S.B. & Wang, 2009.12653 (JCAP)]

Open EFT: Vanilla slow-roll single clock inflation

$\hookrightarrow$ Consider short wavelength modes of the *same* curvature perturbation field to be the environment of the observable long wavelength system modes.



Open EFT: Vanilla slow-roll single clock inflation

$\hookrightarrow$ Consider short wavelength modes of the *same* curvature perturbation field to be the environment of the observable long wavelength system modes.

$\hookrightarrow$ The coupling between long and short modes provided by the leading order cubic non-linearity arising solely from GR: $H_{\rm int} \propto \epsilon^2\, a\, \zeta\, (\partial\zeta)^2$

Open EFT: Vanilla slow-roll single clock inflation

$\hookrightarrow$ Consider short wavelength modes of the *same* curvature perturbation field to be the environment of the observable long wavelength system modes.

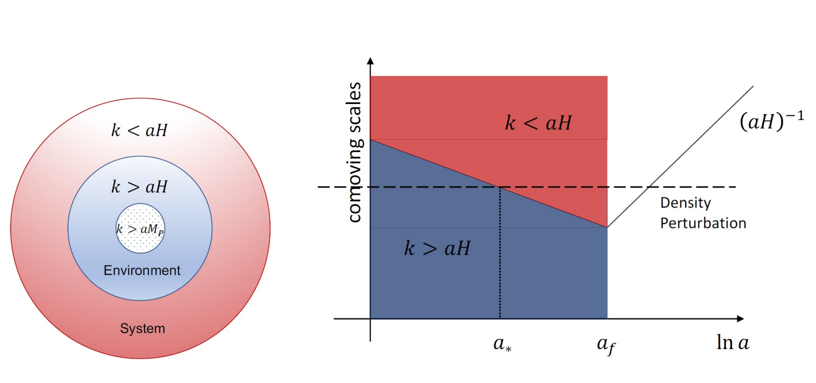
$\hookrightarrow$ The coupling between long and short modes provided by the leading order cubic non-linearity arising solely from GR: $H_{\rm int} \propto \epsilon^2\, a\, \zeta\, (\partial\zeta)^2$

✓ Any additional field will lead to extra couplings & lead to more *entanglement*, magnifying our findings. Any specifically stronger interactions (such as DBI, non-minimal coupling, multi-field etc.) will also enhance our result.

Open EFT: Vanilla slow-roll single clock inflation

↪ Consider short wavelength modes of the *same* curvature perturbation field to be the environment of the observable long wavelength system modes.

↪ The coupling between long and short modes provided by the leading order cubic non-linearity arising solely from GR: $H_{\rm int} \propto \epsilon^2 \, a \, \zeta \, (\partial\zeta)^2$



Open EFT: Vanilla slow-roll single clock inflation

$\hookrightarrow$ Consider short wavelength modes of the *same* curvature perturbation field to be the environment of the observable long wavelength system modes.

$\hookrightarrow$ The coupling between long and short modes provided by the leading order cubic non-linearity arising solely from GR: $H_{\rm int} \propto \epsilon^2 \, a \, \zeta \, (\partial\zeta)^2$

$\star$ Observable signature of entanglement $\rightarrow$ *Smoking gun* signal for quantum origin of inflation or for alternate paradigms and distinguish between them. Very hard problem!

Construct bottom up open EFTs for accelerating backgrounds $\Rightarrow$ Estimate effects of non-unitary evolution (dissipation and dechorence) on observations.

Momentum space entanglement entropy

↪ Consider bands of momenta as subalgebras to define the subsystem and partition the full Hilbert space.

↪ Perturbative momentum space EE between fluctuation modes of the system and the environment on cosmological backgrounds → *Quantifies* the effect of non-unitary evolution.

[Balasubramanian, McDermott & Raamsdonk, 2011]

↪ Consider the simplest case of scalar QFT in Minkowski:

- ✓ $\mathcal{H} = \mathcal{H}_{\mathcal{S}} \otimes \mathcal{H}_{\mathcal{E}} \longrightarrow H = H_{\mathcal{S}} \otimes \mathbb{I} + \mathbb{I} \otimes H_{\mathcal{E}} + \lambda H_{\rm int}$
- ✓ Some arbitrary scale μ defines the partitioning.
- ✓ Result: $\boxed{S_{\rm ent} = -\lambda^2 \log \lambda^2 \sum_{n,N\neq 0} \frac{|\langle n, N| H_{\rm int} |0,0\rangle|^2}{(E_0 + \tilde{E}_0 - E_n - \tilde{E}_N)^2}}$

↪ $|n\rangle$: n-particle state of the system (in fact, a product state over all super-Hubble k modes) and similarly for $|N\rangle$.

↪ Standard perturbation theory used to calculate the matrix element.

Momentum space entanglement entropy

↪ Consider bands of momenta as subalgebras to define the subsystem and partition the full Hilbert space.

↪ Perturbative momentum space EE between fluctuation modes of the system and the environment on cosmological backgrounds → *Quantifies* the effect of non-unitary evolution.

[Balasubramanian, McDermott & Raamsdonk, 2011]

↪ Consider the simplest case of scalar QFT in Minkowski:

- ✓ $\mathcal{H} = \mathcal{H}_{\mathcal{S}} \otimes \mathcal{H}_{\mathcal{E}} \longrightarrow H = H_{\mathcal{S}} \otimes \mathbb{I} + \mathbb{I} \otimes H_{\mathcal{E}} + \lambda H_{\rm int}$
- ✓ Some arbitrary scale μ defines the partitioning.
- ✓ Result: $\boxed{S_{\rm ent} = -\lambda^2 \log \lambda^2 \sum_{n,N\neq 0} \frac{|\langle n, N | H_{\rm int} | 0, 0\rangle|^2}{(E_0 + \tilde{E}_0 - E_n - \tilde{E}_N)^2}}$

↪ $|n\rangle$: n-particle state of the system (in fact, a product state over all super-Hubble k modes) and similarly for $|N\rangle$.

↪ Standard perturbation theory used to calculate the matrix element.

Momentum space entanglement entropy

$\hookrightarrow$ Consider bands of momenta as subalgebras to define the subsystem and partition the full Hilbert space.

$\hookrightarrow$ Perturbative momentum space EE between fluctuation modes of the system and the environment on cosmological backgrounds $\rightarrow$ *Quantifies* the effect of non-unitary evolution.

[Balasubramanian, McDermott & Raamsdonk, 2011]

$\hookrightarrow$ Consider the simplest case of scalar QFT in Minkowski:

- ✓ $\mathcal{H} = \mathcal{H}_{\mathcal{S}} \otimes \mathcal{H}_{\mathcal{E}} \longrightarrow H = H_{\mathcal{S}} \otimes \mathbb{I} + \mathbb{I} \otimes H_{\mathcal{E}} + \lambda H_{\text{int}}$
- ✓ Some arbitrary scale μ defines the partitioning.
- ✓ Result: $\boxed{S_{\text{ent}} = -\lambda^2 \log \lambda^2 \sum_{n,N\neq 0} \frac{|\langle n, N| H_{\text{int}} |0,0\rangle|^2}{(E_0 + \tilde{E}_0 - E_n - \tilde{E}_N)^2}}$

$\hookrightarrow$ $|n\rangle$: n-particle state of the system (in fact, a product state over all super-Hubble k modes) and similarly for $|N\rangle$.

$\hookrightarrow$ Standard perturbation theory used to calculate the matrix element.

Entanglement entropy of inflationary perturbations

[S.B., Alaryani & Brandenberger, 2005.09688 (PRD)]

↪ Modifications required for quasi-dS spacetime:

✓ Time-dependent background acts as a *pump* to source zero-momentum correlated pairs ⇒ $|0,0\rangle = |0\rangle_{\mathcal{E}:k>aH} \otimes |SQ\rangle_{\mathcal{S}:k<aH}$

✓ Hubble horizon acts as natural scale demarcating long/short dofs.

✓ Cubic action due to GR provides leading order interaction term ⇒ Need time-dependent perturbation theory ($\lambda(t) = \sqrt{\epsilon}/(2\sqrt{2}aM_{\rm Pl})$)

✓ Dominant contribution from the squeezed configuration.

Entanglement entropy (per unit physical vol) : $s_{\rm ent} \sim \epsilon\, H^2\, M_{\rm pl}\, (a/a_i)^2$

• Similar results for EE of spectator field with ϕ^3 interaction in de Sitter!

[S.B., Calderón, Hassan & Mi, 2302.13894]

• Rapid Growth: Perturbative EE ≈ reheating entropy/background GH entropy ⇒ Breakdown of perturbation theory around scrambling time of dS $[1/H \ln(M_{\rm pl}/H)]$.

Entanglement entropy of inflationary perturbations

[S.B., Alaryani & Brandenberger, 2005.09688 (PRD)]

$\hookrightarrow$ Modifications required for quasi-dS spacetime:

- ✓ Time-dependent background acts as a *pump* to source zero-momentum correlated pairs $\Rightarrow |0,0\rangle = |0\rangle_{\mathcal{E}:k>aH} \otimes |SQ\rangle_{\mathcal{S}:k<aH}$
- ✓ Hubble horizon acts as natural scale demarcating long/short dofs.
- ✓ Cubic action due to GR provides leading order interaction term $\Rightarrow$ Need time-dependent perturbation theory $(\lambda(t) = \sqrt{\epsilon}/(2\sqrt{2}aM_{\rm Pl}))$
- ✓ Dominant contribution from the squeezed configuration.

Entanglement entropy (per unit physical vol) : $s_{\rm ent} \sim \epsilon\, H^2\, M_{\rm pl}\, (a/a_i)^2$

• Similar results for EE of spectator field with ϕ^3 interaction in de Sitter!

[S.B., Calderón, Hassan & Mi, 2302.13894]

• Rapid Growth: Perturbative EE $\approx$ reheating entropy/background GH entropy $\Rightarrow$ Breakdown of perturbation theory around scrambling time of dS $[1/H \ln(M_{\rm pl}/H)]$.

Entanglement entropy of inflationary perturbations

[S.B., Alaryani & Brandenberger, 2005.09688 (PRD)]

↪ Modifications required for quasi-dS spacetime:

- ✓ Time-dependent background acts as a *pump* to source zero-momentum correlated pairs $\Rightarrow |0,0\rangle = |0\rangle_{\mathcal{E}:k>aH} \otimes |SQ\rangle_{\mathcal{S}:k<aH}$
- ✓ Hubble horizon acts as natural scale demarcating long/short dofs.
- ✓ Cubic action due to GR provides leading order interaction term $\Rightarrow$ Need time-dependent perturbation theory $(\lambda(t) = \sqrt{\epsilon}/(2\sqrt{2}aM_{\rm Pl}))$
- ✓ Dominant contribution from the squeezed configuration.

Entanglement entropy (per unit physical vol) : $s_{\rm ent} \sim \epsilon\, H^2\, M_{\rm pl}\, (a/a_i)^2$

- Similar results for EE of spectator field with ϕ^3 interaction in de Sitter!

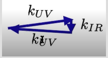
[S.B., Calderón, Hassan & Mi, 2302.13894]

- Rapid Growth: Perturbative EE ≈ reheating entropy/background GH entropy ⇒ Breakdown of perturbation theory around scrambling time of dS $[1/H \ln(M_{\rm pl}/H)]$.

Entanglement entropy of inflationary perturbations

[S.B., Alaryani & Brandenberger, 2005.09688 (PRD)]

$\hookrightarrow$ Modifications required for quasi-dS spacetime:

- ✓ Time-dependent background acts as a *pump* to source zero-momentum correlated pairs $\Rightarrow |0,0\rangle = |0\rangle_{\mathcal{E}:k>aH} \otimes |SQ\rangle_{\mathcal{S}:k<aH}$
- ✓ Hubble horizon acts as natural scale demarcating long/short dofs.
- ✓ Cubic action due to GR provides leading order interaction term $\Rightarrow$ Need time-dependent perturbation theory $(\lambda(t) = \sqrt{\epsilon}/(2\sqrt{2}aM_{\rm Pl}))$
- ✓ Dominant contribution from the squeezed configuration. 

Entanglement entropy (per unit physical vol) : $s_{\rm ent} \sim \epsilon\, H^2\, M_{\rm pl}\, (a/a_i)^2$

- Similar results for EE of spectator field with ϕ^3 interaction in de Sitter!

[S.B., Calderón, Hassan & Mi, 2302.13894]

- Rapid Growth: Perturbative EE $\approx$ reheating entropy/background GH entropy $\Rightarrow$ Breakdown of perturbation theory around scrambling time of dS $[1/H \ln(M_{\rm pl}/H)]$.

Entanglement entropy of inflationary perturbations

[S.B., Alaryani & Brandenberger, 2005.09688 (PRD)]

↪ Modifications required for quasi-dS spacetime:

- ✓ Time-dependent background acts as a *pump* to source zero-momentum correlated pairs $\Rightarrow |0,0\rangle = |0\rangle_{\mathcal{E}:k>aH} \otimes |SQ\rangle_{\mathcal{S}:k<aH}$
- ✓ Hubble horizon acts as natural scale demarcating long/short dofs.
- ✓ Cubic action due to GR provides leading order interaction term $\Rightarrow$ Need time-dependent perturbation theory $(\lambda(t) = \sqrt{\epsilon}/(2\sqrt{2}aM_{\rm Pl}))$
- ✓ Dominant contribution from the squeezed configuration.

Entanglement entropy (per unit physical vol) : $s_{\rm ent} \sim \epsilon\, H^2\, M_{\rm pl}\, (a/a_i)^2$

- Similar results for EE of spectator field with ϕ^3 interaction in de Sitter!

[S.B., Calderón, Hassan & Mi, 2302.13894]

- Rapid Growth: Perturbative EE ≈ reheating entropy/background GH entropy ⇒ Breakdown of perturbation theory around scrambling time of dS $[1/H \ln(M_{\rm pl}/H)]$.

Entanglement entropy of inflationary perturbations

[S.B., Alaryani & Brandenberger, 2005.09688 (PRD)]

$\hookrightarrow$ Modifications required for quasi-dS spacetime:

- ✓ Time-dependent background acts as a *pump* to source zero-momentum correlated pairs $\Rightarrow |0,0\rangle = |0\rangle_{\mathcal{E}:k>aH} \otimes |SQ\rangle_{\mathcal{S}:k<aH}$
- ✓ Hubble horizon acts as natural scale demarcating long/short dofs.
- ✓ Cubic action due to GR provides leading order interaction term $\Rightarrow$ Need time-dependent perturbation theory $(\lambda(t) = \sqrt{\epsilon}/(2\sqrt{2}aM_{\rm Pl}))$
- ✓ Dominant contribution from the squeezed configuration.

Entanglement entropy (per unit physical vol) : $s_{\rm ent} \sim \epsilon\, H^2\, M_{\rm pl}\, (a/a_i)^2$

- Similar results for EE of spectator field with ϕ^3 interaction in de Sitter!

[S.B., Calderón, Hassan & Mi, 2302.13894]

- Rapid Growth: Perturbative EE $\approx$ reheating entropy/background GH entropy $\Rightarrow$ Breakdown of perturbation theory around scrambling time of dS $[1/H \ln(M_{\rm pl}/H)]$.

Entanglement entropy of inflationary perturbations

[S.B., Alaryani & Brandenberger, 2005.09688 (PRD)]

$\hookrightarrow$ Modifications required for quasi-dS spacetime:

- ✓ Time-dependent background acts as a *pump* to source zero-momentum correlated pairs $\Rightarrow |0,0\rangle = |0\rangle_{\mathcal{E}:k>aH} \otimes |SQ\rangle_{\mathcal{S}:k<aH}$
- ✓ Hubble horizon acts as natural scale demarcating long/short dofs.
- ✓ Cubic action due to GR provides leading order interaction term $\Rightarrow$ Need time-dependent perturbation theory $(\lambda(t) = \sqrt{\epsilon}/(2\sqrt{2}aM_{\rm Pl}))$
- ✓ Dominant contribution from the squeezed configuration.

Entanglement entropy (per unit physical vol) : $s_{\rm ent} \sim \epsilon\, H^2\, M_{\rm pl}\, (a/a_i)^2$

- Similar results for EE of spectator field with ϕ^3 interaction in de Sitter!

[S.B., Calderón, Hassan & Mi, 2302.13894]

- Rapid Growth: Perturbative EE $\approx$ reheating entropy/background GH entropy $\Rightarrow$ Breakdown of perturbation theory around scrambling time of dS $[1/H \ln(M_{\rm pl}/H)]$.

Example: Non-Markovianity & decoupling of modes

- Perturbative expansion not trustworthy after scrambling time of dS: Trans-Planckian problem?
- Quantum corrections stay small $\Rightarrow$ EFT applies. Loop corrections do *remain under control*. [Senatore & Zaldarriaga; Woodard; Prokopec; ...]
- Does the *open EFT* of inflationary perturbations remain valid?

Example: Non-Markovianity & decoupling of modes

- Perturbative expansion not trustworthy after scrambling time of dS: Trans-Planckian problem?
- Quantum corrections stay small $\Rightarrow$ EFT applies. Loop corrections do *remain* under control. [Senatore & Zaldarriaga; Woodard; Prokopec; ...]
- Does the *open EFT* of inflationary perturbations remain valid?

Example: Non-Markovianity & decoupling of modes

- Perturbative expansion not trustworthy after scrambling time of dS: Trans-Planckian problem?
- Quantum corrections stay small $\Rightarrow$ EFT applies. Loop corrections do *remain* under control. [Senatore & Zaldarriaga; Woodard; Prokopec; . . .]
- Does the *open EFT* of inflationary perturbations remain valid?

Example: Non-Markovianity & decoupling of modes

$\hookrightarrow$ Perturbative correction to graviton propagator from tensor loops:

$$\Delta_t^2 \simeq -\frac{256}{5\pi^4}\left(\frac{H}{\mathrm{M_p}}\right)^4 \left\{\left[2+\cos 2+\mathrm{Ci}\ 2-\sin 2\right]\ln\left(\frac{H}{\mu}\right)+\mathcal{O}(1)\right\}$$

[S.B., Berera & Calderón, 2206.05797 (JHEP)]

Example: Non-Markovianity & decoupling of modes

$\hookrightarrow$ Perturbative correction to graviton propagator from tensor loops:

$$\boxed{\Delta_t^2 \simeq -\frac{256}{5\pi^4}\left(\frac{H}{\mathrm{M_p}}\right)^4 \left\{\left[2+\cos 2+\mathrm{Ci}\ 2-\sin 2\right]\ln\left(\frac{H}{\mu}\right)+\mathcal{O}(1)\right\}}$$

[S.B., Berera & Calderón, 2206.05797 (JHEP)]

$\hookrightarrow$ Exactly ***matches*** **loop corrections** to graviton propagator under Markovian approximation [Fröb, Roura & Verdaguer, 2012; Tan, 2020; Tanaka & Urakawa, 2013; . . .] No spurious $\ln(k/\mu)$ term [Adshead, Easther & Lim, 2009; . . .]

Example: Non-Markovianity & decoupling of modes

$\hookrightarrow$ Perturbative correction to graviton propagator from tensor loops:

$$\boxed{\Delta_t^2 \simeq -\frac{256}{5\pi^4}\left(\frac{H}{\mathrm{M_P}}\right)^4\left\{\left[2+\cos 2+\mathrm{Ci}\ 2-\sin 2\right]\ln\left(\frac{H}{\mu}\right)+\mathcal{O}(1)\right\}}$$

[S.B., Berera & Calderón, 2206.05797 (JHEP)]

$\hookrightarrow$ Exactly ***matches* loop corrections** to graviton propagator under Markovian approximation [Fröb, Roura & Verdaguer, 2012; Tan, 2020; Tanaka & Urakawa, 2013; . . .] No spurious $\ln(k/\mu)$ term [Adshead, Easther & Lim, 2009; . . .]

$\hookrightarrow$ Markovian behaviour: 'Fast' decay of environment correlations $K_k(\tau,\tau') \xrightarrow[\text{graining}]{\text{Coarse}} \delta(\tau-\tau')$. In this limit, the ME takes the Lindblad form!

Example: Non-Markovianity & decoupling of modes

$\hookrightarrow$ Perturbative correction to graviton propagator from tensor loops:

$$\boxed{\Delta_t^2 \simeq -\frac{256}{5\pi^4}\left(\frac{H}{\mathrm{M_p}}\right)^4\left\{\left[2+\cos 2+\mathrm{Ci}\ 2-\sin 2\right]\ln\left(\frac{H}{\mu}\right)+\mathcal{O}(1)\right\}}$$

[S.B., Berera & Calderón, 2206.05797 (JHEP)]

$\hookrightarrow$ Exactly ***matches*** **loop corrections** to graviton propagator under Markovian approximation [Fröb, Roura & Verdaguer, 2012; Tan, 2020; Tanaka & Urakawa, 2013; ...] No spurious $\ln(k/\mu)$ term [Adshead, Easther & Lim, 2009; ...]

$\hookrightarrow$ Markovian behaviour: 'Fast' decay of environment correlations $K_k(\tau,\tau') \xrightarrow[\text{graining}]{\text{Coarse}} \delta(\tau-\tau')$. In this limit, the ME takes the Lindblad form!

✓ Dissipation Kernel is sharply-peaked but not delta-function peaked:

$$K_k(\tau,\tau') \approx -\frac{ie^{2i(\tau-\tau')/\tau}\left[3k(\tau-\tau')\cos(k(\tau-\tau'))+(k^2(\tau-\tau')^2-3)\sin(k(\tau-\tau'))\right]}{\pi^2 k^5(\tau-\tau')^6}$$

Example: Non-Markovianity & decoupling of modes

↪ Perturbative correction to graviton propagator from tensor loops:

$$\boxed{\Delta_t^2 \simeq -\frac{256}{5\pi^4}\left(\frac{H}{\mathrm{M_P}}\right)^4 \left\{\left[2+\cos 2+\mathrm{Ci}\ 2-\sin 2\right]\ln\left(\frac{H}{\mu}\right)+\mathcal{O}(1)\right\}}$$

[S.B., Berera & Calderón, 2206.05797 (JHEP)]

↪ Exactly ***matches*** **loop corrections** to graviton propagator under Markovian approximation [Fröb, Roura & Verdaguer, 2012; Tan, 2020; Tanaka & Urakawa, 2013; . . .] No spurious $\ln(k/\mu)$ term [Adshead, Easther & Lim, 2009; . . .]

↪ Markovian behaviour: 'Fast' decay of environment correlations $K_k(\tau,\tau') \xrightarrow[\textit{graining}]{\textit{Coarse}} \delta(\tau-\tau')$. In this limit, the ME takes the Lindblad form!

✓ Dissipation Kernel is sharply-peaked but not delta-function peaked.

✓ Novel phenomenon such as *recoherence* due to non-Markovian memory kernel! [Colas, Grain & Vennin, 2022] [S.B., Calderón, Colas, Grain & Vennin]

Example: Non-Markovianity & decoupling of modes

↪ Perturbative correction to graviton propagator from tensor loops:

$$\boxed{\Delta_t^2 \simeq -\frac{256}{5\pi^4}\left(\frac{H}{\mathrm{M_P}}\right)^4 \left\{\left[2+\cos 2+\mathrm{Ci}\ 2-\sin 2\right]\ln\left(\frac{H}{\mu}\right)+\mathcal{O}(1)\right\}}$$

[S.B., Berera & Calderón, 2206.05797 (JHEP)]

↪ Exactly ***matches*** **loop corrections** to graviton propagator under Markovian approximation [Fröb, Roura & Verdaguer, 2012; Tan, 2020; Tanaka & Urakawa, 2013; …] No spurious $\ln(k/\mu)$ term [Adshead, Easther & Lim, 2009; …]

↪ Markovian behaviour: 'Fast' decay of environment correlations $K_k(\tau,\tau') \xrightarrow[graining]{Coarse} \delta(\tau-\tau')$. In this limit, the ME takes the Lindblad form!

✓ Dissipation Kernel is sharply-peaked but not delta-function peaked.

✓ Novel phenomenon such as *recoherence* due to non-Markovian memory kernel! [Colas, Grain & Vennin, 2022] [S.B., Calderón, Colas, Grain & Vennin]

Markovian environments difficult in cosmology → Important to check non-Markovian effects: Does *decoupling* of UV modes still work?

Complexity and the dS vacuum as a thermofield double state

Entanglement & Emergence of spacetime

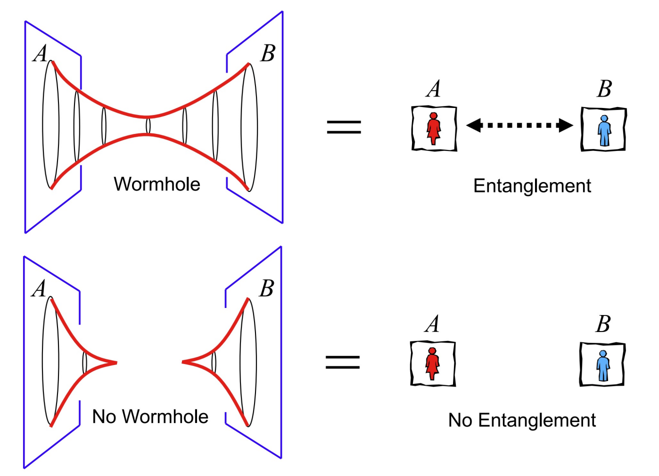
$\hookrightarrow$ ER=EPR: Pair of entangled BHs have their interior connected by a non-traversable wormhole. $|TFD\rangle \sim \sum_i e^{-\beta E_i/2} |E_i\rangle_L |E_i\rangle_R$

[Maldacena; Raamsdonk; Maldacena & Susskind]

Entanglement & Emergence of spacetime

↪ ER=EPR: Pair of entangled BHs have their interior connected by a non-traversable wormhole. $|TFD\rangle \sim \sum_i e^{-\beta E_i/2} |E_i\rangle_L |E_i\rangle_R$

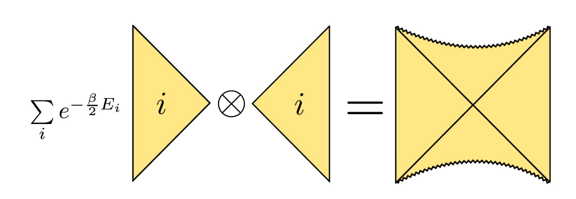
[Maldacena; Raamsdonk; Maldacena & Susskind]



Entanglement & Emergence of spacetime

↪ ER=EPR: Pair of entangled BHs have their interior connected by a non-traversable wormhole. $|TFD\rangle \sim \sum_i e^{-\beta E_i/2} |E_i\rangle_L |E_i\rangle_R$

[Maldacena; Raamsdonk; Maldacena & Susskind]



Complexity of the Euclidean vacuum

$\hookrightarrow$ Need to go beyond Entanglement: Quantum states continue to evolve after thermalization. [Susskind, ...]

Complexity of the Euclidean vacuum

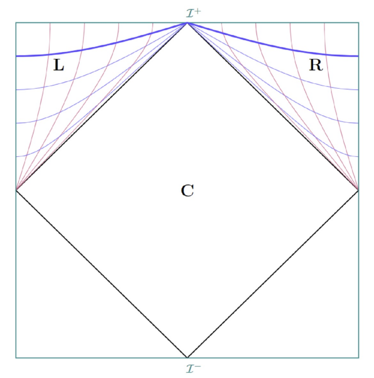
$\hookrightarrow$ Need to go beyond Entanglement: Quantum states continue to evolve after thermalization. [Susskind, ...]

$\hookrightarrow$ Computational Complexity: Quantifies the difficulty (min. no. of operations) to construct a quantum state starting from another one.

Complexity of the Euclidean vacuum

$\hookrightarrow$ Computational Complexity: Quantifies the difficulty (min. no. of operations) to construct a quantum state starting from another one.

- dS in hyperbolic slicing: $ds^2 = H^{-2}\left(-dt^2 + \sinh^2 t\left(dr^2 + \sinh^2 r\, d\Omega^2\right)\right)$ in both (L, R). [Maldacena & Pimentel, 2012; Parikh, van der Schaar *et al*, 2015; ...]



Complexity of the Euclidean vacuum

$\hookrightarrow$ Computational Complexity: Quantifies the difficulty (min. no. of operations) to construct a quantum state starting from another one.

• dS in hyperbolic slicing: $ds^2 = H^{-2}\left(-dt^2 + \sinh^2 t\left(dr^2 + \sinh^2 r\, d\Omega^2\right)\right)$ in both (L, R). [Maldacena & Pimentel, 2012; Parikh, van der Schaar *et al*, 2015; ...]

✓ Factorized reference state: $|\Psi_r\rangle = |L\rangle \otimes |R\rangle$

Complexity of the Euclidean vacuum

$\hookrightarrow$ Computational Complexity: Quantifies the difficulty (min. no. of operations) to construct a quantum state starting from another one.

- dS in hyperbolic slicing: $ds^2 = H^{-2}\left(-dt^2 + \sinh^2 t\left(dr^2 + \sinh^2 r\, d\Omega^2\right)\right)$ in both (L, R). [Maldacena & Pimentel, 2012; Parikh, van der Schaar *et al*, 2015; ...]

✓ Factorized reference state: $|\Psi_r\rangle = |L\rangle \otimes |R\rangle$

✓ BD as an entangled state: $|\Psi_{\rm BD}\rangle \sim e^{\frac{1}{2}\sum_{i,j=R,L} m_{ij} b_i^\dagger b_j^\dagger}|L\rangle|R\rangle$

Complexity of the Euclidean vacuum

$\hookrightarrow$ Computational Complexity: Quantifies the difficulty (min. no. of operations) to construct a quantum state starting from another one.

- dS in hyperbolic slicing: $ds^2 = H^{-2}\left(-dt^2 + \sinh^2 t\left(dr^2 + \sinh^2 r\, d\Omega^2\right)\right)$ in both (L, R). [Maldacena & Pimentel, 2012; Parikh, van der Schaar *et al*, 2015; ...]

✓ Factorized reference state: $|\Psi_r\rangle = |L\rangle \otimes |R\rangle$

✓ BD as an entangled state: $|\Psi_{\rm BD}\rangle \sim e^{\frac{1}{2}\sum_{i,j=R,L} m_{ij} b_i^\dagger b_j^\dagger}|L\rangle|R\rangle$

$$m_{ij} = e^{i\theta}\frac{\sqrt{2}e^{-p\pi}}{\sqrt{\cosh 2\pi p + \cos 2\pi\nu}}\begin{pmatrix}\cos\pi\nu & i\sinh p\pi\\ i\sinh p\pi & \cos\pi\nu\end{pmatrix}$$

Complexity of the Euclidean vacuum

↪ Computational Complexity: Quantifies the difficulty (min. no. of operations) to construct a quantum state starting from another one.

• dS in hyperbolic slicing: $ds^2 = H^{-2}\left(-dt^2 + \sinh^2 t\left(dr^2 + \sinh^2 r\, d\Omega^2\right)\right)$ in both (L, R). [Maldacena & Pimentel, 2012; Parikh, van der Schaar *et al*, 2015; ...]

✓ Factorized reference state: $|\Psi_r\rangle = |L\rangle \otimes |R\rangle$

✓ BD as an entangled state: $|\Psi_{\rm BD}\rangle \sim e^{\frac{1}{2}\sum_{i,j=R,L} m_{ij} b_i^\dagger b_j^\dagger}|L\rangle|R\rangle$

✓ Geometric Approach: Complexity as the min geodesic on the space of *Gaussian* unitary operators: Covariance matrix of states sufficient. Metric characterized by cost function: $F_2^2 = \sum_I (Y^I)^2$ [Nielson, 2005; Chapman, Heller, Marrochio, Pastawski, 2017; Chapman, Eisert, Hackl, Heller, Jefferson, Marrochio, Myers, 2018]

Complexity of the Euclidean vacuum

$\hookrightarrow$ Computational Complexity: Quantifies the difficulty (min. no. of operations) to construct a quantum state starting from another one.

• dS in hyperbolic slicing: $ds^2 = H^{-2}\left(-dt^2 + \sinh^2 t\left(dr^2 + \sinh^2 r\, d\Omega^2\right)\right)$ in both (L, R). [Maldacena & Pimentel, 2012; Parikh, van der Schaar *et al*, 2015; ...]

✓ Factorized reference state: $|\Psi_r\rangle = |L\rangle \otimes |R\rangle$

✓ BD as an entangled state: $|\Psi_{\rm BD}\rangle \sim e^{\frac{1}{2}\sum_{i,j=R,L} m_{ij} b_i^\dagger b_j^\dagger}|L\rangle|R\rangle$

✓ Geometric Approach: Complexity as the min geodesic on the space of *Gaussian* unitary operators: Covariance matrix of states sufficient. Metric characterized by cost function: $F_2^2 = \sum_I (Y^I)^2$ [Nielson, 2005; Chapman, Heller, Marrochio, Pastawski, 2017; Chapman, Eisert, Hackl, Heller, Jefferson, Marrochio, Myers, 2018]

• Complexity of formation of BD vacuum from the (R, L) vacua: $\mathcal{C}\left(G_{\rm r}, G_{\rm t}\right) = \frac{1}{8}\,\mathrm{Tr}\left[\log^2(G_t G_r^{-1})\right]$. Diagonalizing the covariance matrices:

$$\mathcal{C} \sim V_{\mathbf{H}^3}\int \frac{p^2}{2\pi^2}\log^2\left[\tanh\left(\frac{p\pi}{2}\right)\right] dp$$

Complexity of the Euclidean vacuum

$\hookrightarrow$ Computational Complexity: Quantifies the difficulty (min. no. of operations) to construct a quantum state starting from another one.

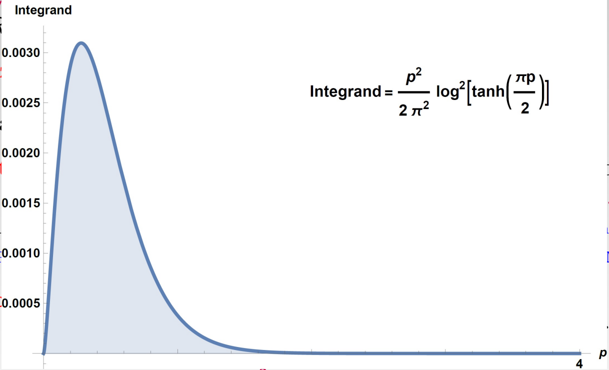
• dS in hyperbolic slicing: $ds^2 = H^{-2}\left(-dt^2 + \sinh^2 t\left(dr^2 + \sinh^2 r\, d\Omega^2\right)\right)$ in both $(L, R$ … ..]

✓ Factori…

✓ BD as …

✓ Geomet… …pace of *Gaussian* … . Metric characteri… …, Heller, Marrochio, P… …Myers, 2018]

• Comple… $\mathcal{C}\left(G_{\mathrm{r}}, G_{\mathrm{t}}\right)$ … …ices:



$$\mathcal{C} \sim V_{\mathbf{H}^3}\int \frac{p^2}{2\pi^2}\log^2\left[\tanh\left(\frac{p\pi}{2}\right)\right] dp$$

dS complexity: Implications

Complexity of dS vacuum is finite *both in the IR and the UV*!

[S.B., Hackl, Hassan & Luo, *forthcoming*]

- Contrast with the complexity of TFD or Minkowski vacuum state from an ultralocal vacuum (product state of lattice sites). The BD vacuum can thus be 'built' by long-range interactions between the two causally disconnected regions. It can be constructed with **finite complexity** $\Rightarrow$ *It lives in the* $\mathcal{H}_L \otimes \mathcal{H}_R$ *Hilbert space.* [Jefferson & Myers, 2017]
- Explicit field theory computation (for free scalar) in dS reproduces expectations from holographic conjectures. It was conjectured that the time-dependence in this case is fully fixed by dS symmetries ($\sim 1/\eta^3$) and goes as proper volume of the spacelike slice (unlike for entanglement in dS: $\sim 1/\eta^2 + \log\eta + \text{indep of } \eta$) [Reynolds & Ross, 2017]
- For our choice of reference state, the complexity is a *universal quantity* and **independent** of the parameters in the Lagrangian (mass of the field) and depends only on the geometry of spacetime.

dS complexity: Implications

Complexity of dS vacuum is finite *both in the IR and the UV*!

[S.B., Hackl, Hassan & Luo, *forthcoming*]

- Contrast with the complexity of TFD or Minkowski vacuum state from an ultralocal vacuum (product state of lattice sites). The BD vacuum can thus be 'built' by long-range interactions between the two causally disconnected regions. It can be constructed with **finite complexity** $\Rightarrow$ *It lives in the $\mathcal{H}_L \otimes \mathcal{H}_R$ Hilbert space.* [Jefferson & Myers, 2017]
- Explicit field theory computation (for free scalar) in dS reproduces expectations from holographic conjectures. It was conjectured that the time-dependence in this case is fully fixed by dS symmetries ($\sim 1/\eta^3$) and goes as proper volume of the spacelike slice (unlike for entanglement in dS: $\sim\ 1/\eta^2 + \log\,\eta + \text{indep of}\ \eta$) [Reynolds & Ross, 2017]
- For our choice of reference state, the complexity is a *universal quantity* and **independent** of the parameters in the Lagrangian (mass of the field) and depends only on the geometry of spacetime.

dS complexity: Implications

Complexity of dS vacuum is finite *both in the IR and the UV*!

[S.B., Hackl, Hassan & Luo, *forthcoming*]

- Contrast with the complexity of TFD or Minkowski vacuum state from an ultralocal vacuum (product state of lattice sites). The BD vacuum can thus be 'built' by long-range interactions between the two causally disconnected regions. It can be constructed with **finite complexity** $\Rightarrow$ *It lives in the* $\mathcal{H}_L \otimes \mathcal{H}_R$ *Hilbert space.* [Jefferson & Myers, 2017]
- Explicit field theory computation (for free scalar) **in dS** reproduces expectations from holographic conjectures. It was conjectured that the time-dependence in this case is fully fixed by dS symmetries ($\sim 1/\eta^3$) and goes as proper volume of the spacelike slice (unlike for entanglement in dS: $\sim\ 1/\eta^2 + \log\,\eta + \text{indep of}\ \eta$) [Reynolds & Ross, 2017]
- For our choice of reference state, the complexity is a *universal quantity* and **independent** of the parameters in the Lagrangian (mass of the field) and depends only on the geometry of spacetime.

dS complexity: Implications

Complexity of dS vacuum is finite *both in the IR and the UV*!

[S.B., Hackl, Hassan & Luo, *forthcoming*]

- Contrast with the complexity of TFD or Minkowski vacuum state from an ultralocal vacuum (product state of lattice sites). The BD vacuum can thus be 'built' by long-range interactions between the two causally disconnected regions. It can be constructed with **finite complexity** $\Rightarrow$ *It lives in the* $\mathcal{H}_L \otimes \mathcal{H}_R$ *Hilbert space.* [Jefferson & Myers, 2017]
- Explicit field theory computation (for free scalar) **in dS** reproduces expectations from holographic conjectures. It was conjectured that the time-dependence in this case is fully fixed by dS symmetries ($\sim 1/\eta^3$) and goes as proper volume of the spacelike slice (unlike for entanglement in dS: $\sim\ 1/\eta^2 + \log\,\eta + \text{indep of}\ \eta$) [Reynolds & Ross, 2017]
- For our choice of reference state, the complexity is a *universal quantity* and **independent** of the parameters in the Lagrangian (mass of the field) and depends only on the geometry of spacetime.

Finite complexity as evidence for *Cosmic ER=EPR*

$\hookrightarrow$ Cosmic ER=EPR: Global dS geometry **emerges** from quantum entanglement between two copies of the (dual) CFT at future infinity $\mathcal{I}^+$. [Cotler & Strominger, 2023] Caveat: Our results for complexity do **not** hold for other forms of dS/CFT such as static patch holography.

- Analog of QNM basis for global dS $\leftrightarrow$ Hyperbolic dS in (L, R) basis.

Following Cotler-Storminger:

✓ Identify $|L\rangle$ and $|R\rangle$ with the vacua of the two boundary CFTs.

✓ Both $|L\rangle$ and $|R\rangle$ do not have dS isometries but $|\Psi_{\mathrm{BD}}\rangle$ **does**!

✓ In the dual picture, the bulk $|\Psi_{\mathrm{BD}}\rangle$ *emerges as a TFD* state between the two boundary CFT states.

✓ The reduced density matrix when traced over, say, the R region, can be interpreted as a thermal one. [Maldacena & Pimentel, 2012]

Finite complexity of bulk states is evidence for *Cosmic ER=EPR*:

$$\mathcal{H}_{\mathrm{dS}} = \mathcal{H}_{\mathrm{CFT}_1} \otimes \mathcal{H}_{\mathrm{CFT}_2} .$$

[S.B., Hackl, Hassan & Luo, *forthcoming*]

Finite complexity as evidence for *Cosmic ER=EPR*

$\hookrightarrow$ Cosmic ER=EPR: Global dS geometry **emerges** from quantum entanglement between two copies of the (dual) CFT at future infinity $\mathcal{I}^+$. [Cotler & Strominger, 2023] Caveat: Our results for complexity do **not** hold for other forms of dS/CFT such as static patch holography.

- Analog of QNM basis for global dS $\leftrightarrow$ Hyperbolic dS in (L, R) basis.

Following Cotler-Storminger:

- ✓ Identify $|L\rangle$ and $|R\rangle$ with the vacua of the two boundary CFTs.
- ✓ Both $|L\rangle$ and $|R\rangle$ do not have dS isometries but $|\Psi_{\mathrm{BD}}\rangle$ **does**!
- ✓ In the dual picture, the bulk $|\Psi_{\mathrm{BD}}\rangle$ *emerges as a TFD* state between the two boundary CFT states.
- ✓ The reduced density matrix when traced over, say, the R region, can be interpreted as a thermal one. [Maldacena & Pimentel, 2012]

Finite complexity of bulk states is evidence for *Cosmic ER=EPR*:

$$\mathcal{H}_{\mathrm{dS}} = \mathcal{H}_{\mathrm{CFT}_1} \otimes \mathcal{H}_{\mathrm{CFT}_2}.$$

[S.B., Hackl, Hassan & Luo, *forthcoming*]

Finite complexity as evidence for *Cosmic ER=EPR*

$\hookrightarrow$ Cosmic ER=EPR: Global dS geometry **emerges** from quantum entanglement between two copies of the (dual) CFT at future infinity $\mathcal{I}^+$. [Cotler & Strominger, 2023] Caveat: Our results for complexity do **not** hold for other forms of dS/CFT such as static patch holography.

- Analog of QNM basis for global dS $\leftrightarrow$ Hyperbolic dS in (L, R) basis.

Following Cotler-Storminger:

- ✓ Identify $|L\rangle$ and $|R\rangle$ with the vacua of the two boundary CFTs.
- ✓ Both $|L\rangle$ and $|R\rangle$ do not have dS isometries but $|\Psi_{\mathrm{BD}}\rangle$ **does**!
- ✓ In the dual picture, the bulk $|\Psi_{\mathrm{BD}}\rangle$ *emerges as a TFD* state between the two boundary CFT states.
- ✓ The reduced density matrix when traced over, say, the R region, can be interpreted as a thermal one. [Maldacena & Pimentel, 2012]

Finite complexity of bulk states is evidence for *Cosmic ER=EPR*:

$$\mathcal{H}_{\mathrm{dS}} = \mathcal{H}_{\mathrm{CFT}_1} \otimes \mathcal{H}_{\mathrm{CFT}_2}.$$

[S.B., Hackl, Hassan & Luo, *forthcoming*]

Discussion

- Conclusions:
  - ✓ Open EFTs are a novel perspective on QFTs in curved space. Non-Markovian open EFTs unveil dissipation and decoherence which always modify observables (only question is if this is detectable).
  - ✓ Backreaction of IR modes → Goes beyond standard perturbation theory for resumming late-time effects. Implications for EI?
  - ✓ Central role of 'complexity' in cosmic ER=EPR for dS/CFT. Emergence of spacetime in matrix models [S.B., Brandenberger & Laliberte]

- Looking ahead:
  - ⋆ Apply to phenomenologically interesting models → QSF inflation! [S.B., Caderón, Colas, Grain & Vennin]
  - ⋆ Construct bottom up open EFTs for accelerating backgrounds.
  - ⋆ Complexity of fermions in dS. [S.B., Hackl, Hassan, & Luo]
  - ⋆ Complexity of Minkowski vacuum as a TFD state over Rindler vacua also finite → Robustness: Complexity corresponding to long-range entanglement between regions separated by Killing horizons.
  - ⋆ Universality: Complexity is independent of parameters in the Lagrangian and depends only on the geometry of spacetime itself (for natural choice of reference state). [S.B., Hassan, & Luo]

Discussion

- Conclusions:
  - ✓ Open EFTs are a novel perspective on QFTs in curved space. Non-Markovian open EFTs unveil dissipation and decoherence which always modify observables (only question is if this is detectable).
  - ✓ Backreaction of IR modes → Goes beyond standard perturbation theory for resumming late-time effects. Implications for EI?
  - ✓ Central role of 'complexity' in cosmic ER=EPR for dS/CFT. Emergence of spacetime in matrix models [S.B., Brandenberger & Laliberte]
- Looking ahead:
  - ⋆ Apply to phenomenologically interesting models → QSF inflation! [S.B., Caderón, Colas, Grain & Vennin]
  - ⋆ Construct bottom up open EFTs for accelerating backgrounds.
  - ⋆ Complexity of fermions in dS. [S.B., Hackl, Hassan, & Luo]
  - ⋆ Complexity of Minkowski vacuum as a TFD state over Rindler vacua also finite → Robustness: Complexity corresponding to long-range entanglement between regions separated by Killing horizons.
  - ⋆ Universality: Complexity is independent of parameters in the Lagrangian and depends only on the geometry of spacetime itself (for natural choice of reference state). [S.B., Hassan, & Luo]

Euclidean vacuum as TFD state

We have

$$|\Psi_{BD}\rangle = [\det(\mathbb{I} - \gamma^\dagger \gamma)]^{\frac{1}{4}} e^{\frac{1}{2}\sum_{i,j=R,L} \gamma_{ij} c_i^\dagger c_j^\dagger} |R\rangle |L\rangle$$

The density matrix after tracing out R patch is:

$$\rho_L = \left(1 - |\gamma_p|^2\right) \sum_{n=0}^{\infty} |\gamma_p|^{2n} |n; p\ell m\rangle \langle n; p\ell m|$$

Thus the Euclidean vacuum can also be written as:

$$|\Psi_{BD}\rangle = \sqrt{1 - |\gamma_p|^2} \sum |\gamma_p|^n |n; p\ell m\rangle_L |n; p\ell m\rangle_R$$

where we need to identify $|\gamma_p|^n = \exp(-\beta E_n/2)$.
We identify the $|L\rangle$ and $|R\rangle$ with the vacua of the two boundary CFTs.

Open EFTs in inflation: Dissipative effects

[with Shandera; with Brandenberger; with Calderón, Colas, Grain & Vennin]

✓ Quantum correction to scalar power spectrum → Non-perturbative resummation of IR effects & analytic: $\Delta_\zeta^2(q\tau) = \frac{1}{2\epsilon M_{\rm Pl}^2}\left(\frac{H}{2\pi}\right)^2 e^{-\alpha N_c^2}$

$\alpha = \epsilon H^2/(96\pi^2 M_{\rm Pl}^2) \sim 0.00211086\, \epsilon H^2/(2M_{\rm Pl}^2)$ (matches numerical 1st order correction ~ 0.00211886!) [S.B., Berera & Calderón, 2107.06910 (CQG)]

Open EFTs in inflation: Dissipative effects

[with Shandera; with Brandenberger; with Calderón, Colas, Grain & Vennin]

✓ Quantum correction to scalar power spectrum → Non-perturbative resummation of IR effects & analytic: $\Delta^2_\zeta(q\tau) = \frac{1}{2\epsilon M_{\rm Pl}^2}\left(\frac{H}{2\pi}\right)^2 e^{-\alpha N_c^2}$

$\alpha = \epsilon H^2/(96\pi^2 M_{\rm Pl}^2) \sim 0.00211086\, \epsilon H^2/(2M_{\rm Pl}^2)$ (matches numerical 1st order correction ~ 0.00211886!) [S.B., Berera & Calderón, 2107.06910 (CQG)]

- This effect *missed* in loop corrections. [Woodard; Senatore & Zaldarriaga; ...]

Open EFTs in inflation: Dissipative effects

[with Shandera; with Brandenberger; with Calderón, Colas, Grain & Vennin]

✓ Quantum correction to scalar power spectrum → Non-perturbative resummation of IR effects & analytic: $\Delta^2_\zeta(q\tau) = \frac{1}{2\epsilon M_{\rm Pl}^2}\left(\frac{H}{2\pi}\right)^2 e^{-\alpha N_c^2}$

$\alpha = \epsilon H^2/(96\pi^2 M_{\rm Pl}^2) \sim 0.00211086\, \epsilon H^2/(2M_{\rm Pl}^2)$ (matches numerical 1st order correction ~ 0.00211886!) [S.B., Berera & Calderón, 2107.06910 (CQG)]

- This effect *missed* in loop corrections. [Woodard; Senatore & Zaldarriaga; . . .]

✓ Important to understand the effect of IR modes in cosmology.

Open EFTs in inflation: Dissipative effects

[with Shandera; with Brandenberger; with Calderón, Colas, Grain & Vennin]

✓ Quantum correction to scalar power spectrum → Non-perturbative resummation of IR effects & analytic: $\Delta^2_\zeta(q\tau) = \frac{1}{2\epsilon M_{\rm Pl}^2}\left(\frac{H}{2\pi}\right)^2 e^{-\alpha N_c^2}$

$\alpha = \epsilon H^2/(96\pi^2 M_{\rm Pl}^2) \sim 0.00211086\, \epsilon H^2/(2M_{\rm Pl}^2)$ (matches numerical 1st order correction ~ 0.00211886!) [S.B., Berera & Calderón, 2107.06910 (CQG)]

- This effect *missed* in loop corrections. [Woodard; Senatore & Zaldarriaga; ...]

✓ Important to understand the effect of IR modes in cosmology.

✓ Effects of Non-Markovianity: ME is **not** time-local! Interaction memory

Open EFTs in inflation: Dissipative effects

[with Shandera; with Brandenberger; with Calderón, Colas, Grain & Vennin]

✓ Quantum correction to scalar power spectrum → Non-perturbative resummation of IR effects & analytic: $\Delta_\zeta^2(q\tau) = \frac{1}{2\epsilon M_{\rm Pl}^2}\left(\frac{H}{2\pi}\right)^2 e^{-\alpha N_c^2}$

$\alpha = \epsilon H^2/(96\pi^2 M_{\rm Pl}^2) \sim 0.00211086\, \epsilon H^2/(2M_{\rm Pl}^2)$ (matches numerical 1st order correction ~ 0.00211886!) [S.B., Berera & Calderón, 2107.06910 (CQG)]

- This effect *missed* in loop corrections. [Woodard; Senatore & Zaldarriaga; ...]

✓ Important to understand the effect of IR modes in cosmology.

✓ Effects of Non-Markovianity: ME is **not** time-local! Interaction memory

⋆ Observable signature of entanglement → *Smoking gun* signal for quantum origin of inflation or for alternate paradigms and distinguish between them.

Construct bottom up open EFTs for accelerating backgrounds ⇒ estimate effects of non-unitary evolution on observations.