Quantum entanglement across cosmological distances

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JHEP 08, 071 (2020) & work in peer review (with A. Berera & J. Calderón)
arXiv:2007.11611 (To appear in JHEP) (with K. Dasgupta & R. Tatar)
PRD 102, 043529 (2020) (with O. Alaryani & R. Brandenberger)
arXiv:2009.12653 (To appear in JCAP) (with R. Brandenberger & Z. Wang)
JHEP 1903, 006 (2019) & JHEP 1906, 070 (2019) (with W. Hossain)
PRL 121, 201301 (2018) & PRL 121, 201602 (2018) (with M. Bojowald)
JHEP 1911, 016 (2019) (with S. Shandera)
PRD 101, 046013 (2020) & PRD 101, 023526 (2020)

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McGill
Department of Physics

Outline

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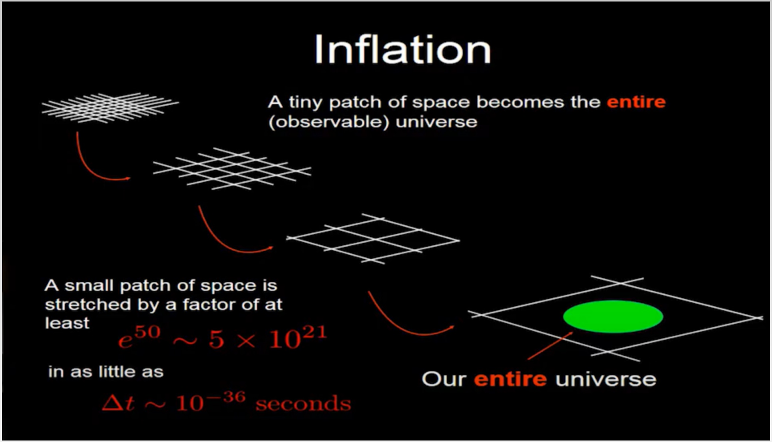

Inflation

A tiny patch of space becomes the **entire** (observable) universe

A small patch of space is stretched by a factor of at least

$$e^{50} \sim 5 \times 10^{21}$$

in as little as

$$\Delta t \sim 10^{-36} \text{ seconds}$$

Our **entire** universe

Photo credit: P. Adshead

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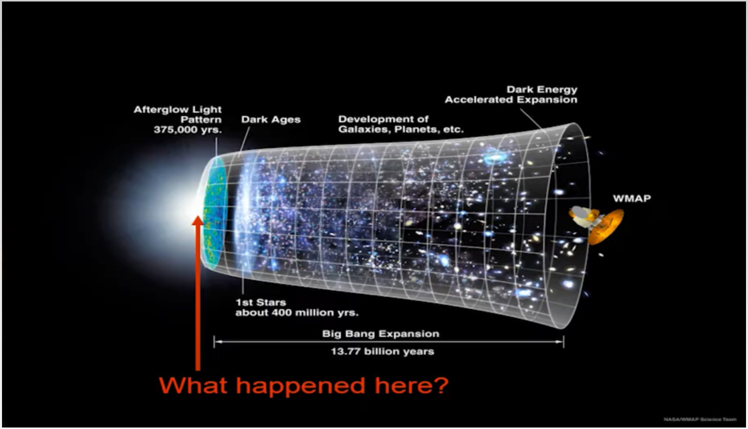

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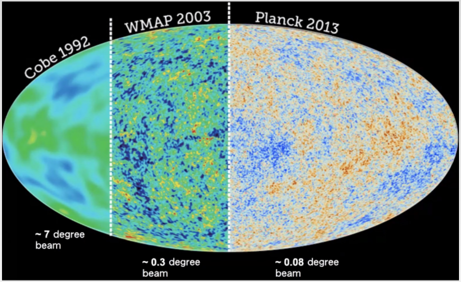

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$\rightsquigarrow$ Quantum entanglement and non-local behaviour *hallmarks* of quantum theory. Is standard Wilsonian EFT applicable to inflation? Open EFT & connection to *decoherence* & *stochastic inflation*!

✓ What can we learn about the quantum gravity completion of inflation from open EFT for inflationary spacetimes?

✓ What role does entanglement play in cosmological observations?

Quantum gravity & Inflation: Challenges & Promises

The landscape & the swampland

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$\hookrightarrow$ Very powerful proposal to constrain the space of all low energy EFTs required for phenomenology $\Rightarrow$ Analogy with quantum mechanics.

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✓ Almost *all of* Horndeski theories, compatible with current observational bounds on dark energy, have been found to *be in the swampland* [Heisenberg, Bartelmann, Brandenberger & Refregier, 2019]

⇝ Cubic Galileon model allows for $c \sim 1$ and is yet *consistent* with current observational bounds. [S.B. & W. Hossain, 2019; 2020]

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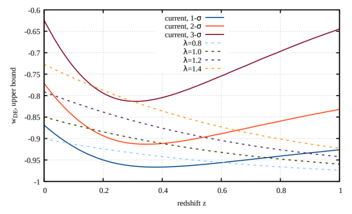
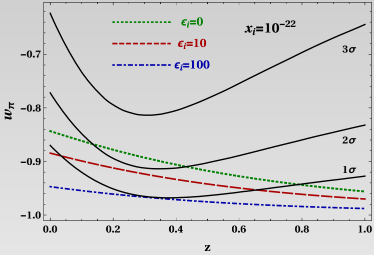
Low energy effective field theory involving accelerating spacetimes ⇒ Constrained by consistency conditions from QG

Rescuing dark energy from the swampland

$$\mathcal{S} = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{M_{pl}^2}{2}R - \frac{1}{2}(\nabla\pi)^2\left(1 + \frac{\alpha}{M^3}\Box\pi\right) - V(\pi)\right] + \mathcal{S}_\mathrm{m} + \mathcal{S}_\mathrm{r}$$



The exponential potential assumed here is the *least* constrained case: $\lambda = 1$ is ruled out at 2σ from observations. The solid lines represent the 1σ, 2σ and 3σ contours from bottom to top respectively for the dark energy EoS considering CPL parameterization.



Green (dotted), red (dashed) and blue (dot dashed) curves correspond to $\epsilon_i = 0,\ 10,\ 100$ respectively. We have assumed $\lambda = 1$ here

Cubic Galileon model ⇒ An explicit model which allows for $c \sim 1$ and is yet *consistent* with current observational bounds. [S.B. & W. Hossain, 2019; 2020]

Evidence against (quasi) dS spacetime?

↪ Difficulty of constructing meta-stable dS vacua (& inflation) in String Theory [Danielsson & Van Riet, 2018; S.B., K. Dasgupta, & R. Tatar, 2020 ; Sethi, 2018; Moritz, Retolaza & Westphal, 2017; . . .]

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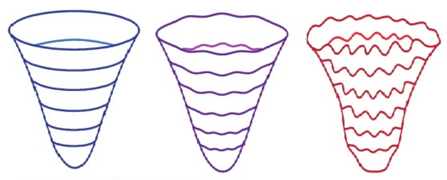

Photo from FLT (arXiv:1705.00192)

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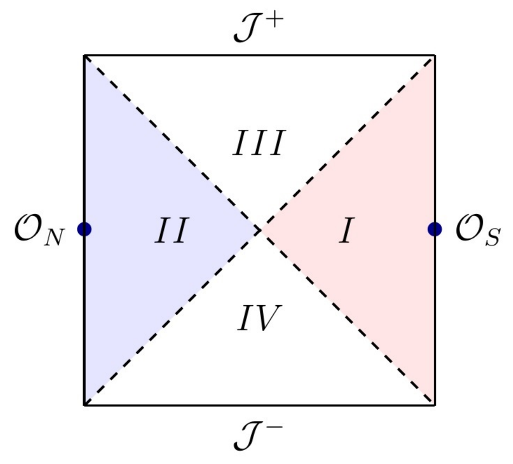

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↪ The trans-Planckian censorship conjecture: Upper bound on the lifetime of dS & inflation [Bedroya & Vafa, 2019]

QFT in dS spacetimes: Different corners of the swampand

Quantum Swampland: Teaser for the TCC

↪ Even if there is a *classical* potential which allows a meta-stable dS ⇒ Do radiative (loop) corrections *destabilize* it?

YES! [U. Danielsson, 2018]

↪ One-loop effective potential has dS-invariant term alone *only* on choosing the Bunch-Davies vacuum! [J. Martin, 2012]

But how natural is it to *assume* the BD vacuum? [Polyakov … vs. Susskind …]

↪ If we make a mode expansion, and trace a given mode back in time until it is so blue-shifted that its wavelength is much smaller than Hubble scale. Then it is so far inside the horizon that it does not "feel" gravity and we can 'forget' about dS space and pick the unique Minkowski vacuum: $a_k(\eta_0)|0_{\eta_0}\rangle$ with $\eta_0 \to -\infty$, then we get the BD vacuum. [Bunch & Davies, 1978]

↪ Should not blue-shift a mode beyond the cut-off scale of the theory ⇒ Parametrize ignorance about *pre-inflationary dynamics* in initial state ⇒ Below cut-off scale, new vacuum is Bogolubov transformation of BD, *i.e.* Non-BD state ⇒ Quantum swampland! [U. Danielsson, 2004; 2005; 2018]

↪ dS quantum 'no-hair' theorem does *not* apply for short-lived inflation ⇒ BD not a quantum attractor [Kaloper, Kleban, Lawrence, Shenker & Susskind, 2002]

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Quantum Swampland: Teaser for the TCC

↪ Even if there is a *classical* potential which allows a meta-stable dS ⇒ Do radiative (loop) corrections *destabilize* it?

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The trans-Planckian censorship conjecture

↪ Crowning glory of inflation: Explain the origin the observed macroscopic density perturbations in quantum vacuum fluctuations.

↪ If we look at the physical wavelength of a classical perturbation mode at late times and blue-shift it *backwards in time*, due to the expansion of spacetime, one might end up with a physical wavelength that is smaller than the ℓ_{Pl}. [Martin & Brandenberger, 2000; . . .]

↪ For sufficiently long periods of accelerated expansion, one would have macroscopic perturbations *originating* from TP quantum fluctuations ⇒ *Inflation needs to be valid up until energy ranges beyond the Planck scale as an EFT*, which is clearly in conflict with our understanding of QG.

↪ A naive cut-off doesn't work for accelerating spacetimes ⇒ Non-unitary evolution due to a time-dependent Hilbert space. [Weiss, 1985; Jacobson, 2000]

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TCC and Inflation

↪ TCC prohibits TP modes from crossing $1/H \Rightarrow e^N < M_{\rm Pl}/H_{\rm inf}$

↪ Comoving Hubble radius today must have been sub-horizon at the beginning of inflation to be in causal contact ⇒ *Hierarchy* for N ⏩ Diag

⇝ Upper bound on the energy scale of inflation $H_{\rm inf} < 3\sqrt{3} \times 10^{-20} M_{\rm Pl}$.

From observed scalar power spectrum $\Rightarrow \epsilon < 10^{-31}$ & $r < 10^{-30}$!

⇝ From the spectral tilt, $n_s - 1 = 2\eta - 6\epsilon \Rightarrow |\eta| \sim 0.02 \Rightarrow$ Swampland favors *Hilltop* models

- Strict bounds on r not easy to evade:

  ⇝ Part of predictions of inflation [Bedroya, Brandenberger, Loverde, Vafa, 2019]

  ⇝ Invoke alternate mechanism for production of primordial tensor modes (TCC compatible with $r < 0.001$) [S.B. , 2019]

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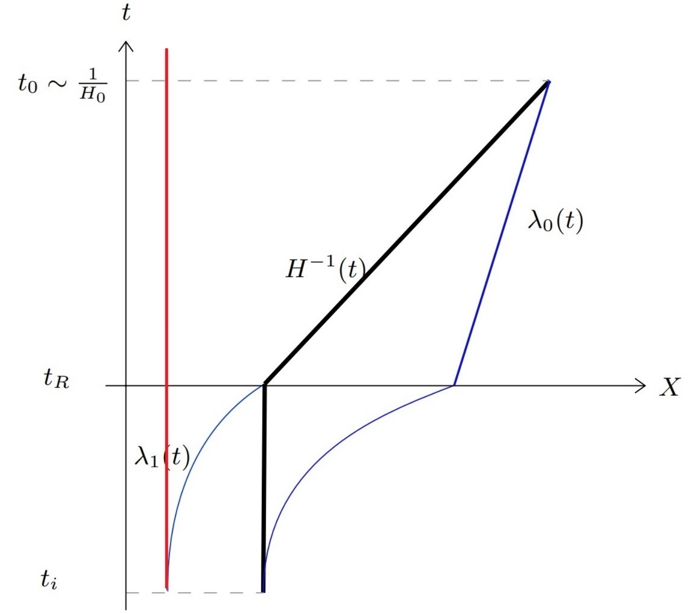
Figure from [Bedroya, Brandenberger, LoVerde, Vafa, 2019]



How long did inflation last?

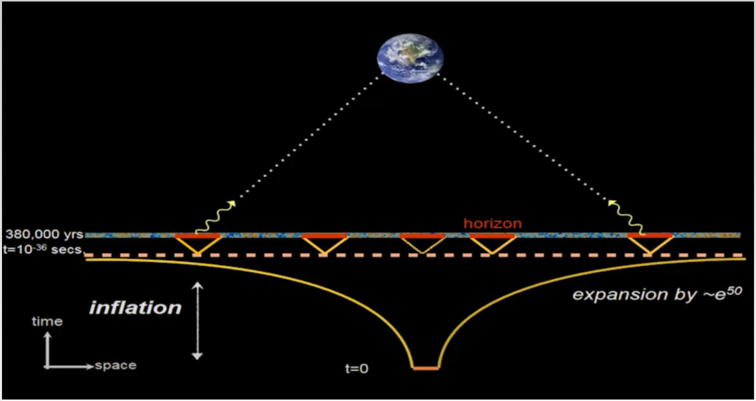


Photo credit: P. Adshead

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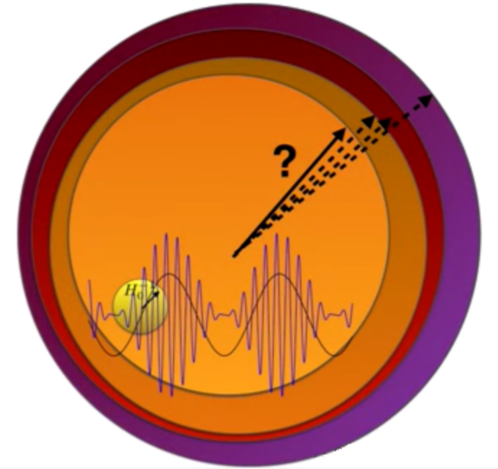

Photo credit: S. Shandera

Upper bound on duration of inflation

↪ There seems to be a deep structure underlying the swampland:

✓ TCC *implies* the dS conjecture: [A. Bedroya & C. Vafa, 2019]

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✓ Refined versions of TCC has also been shown to follow from the sWGC, the scrambling time of dS or other entropy arguments [Cai & Wang, 2019; Sun & Zhang, 2019; Aalsma & Shiu, 2019; A. Berera, S.B. & J. Calderón, 2020 ; . . .]

↪ No eternal inflation principle: dS Conjecture rules out (perturvative) stochastic eternal inflation [S.B. & Shandera, 2019]

✓ Independently, stochastic EI à la Fokker-Plank equation, for most potentials, shown to be in tension with the Swampland.

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↪ Inflation is not eternal into the past & an inflating region must have a past boundary (with new physics at this boundary). [Guth, 2006]

Multiple indications that QG seems to disfavour long duration of inflating spacetimes $\Longleftrightarrow$ Upper bound on the duration of inflation

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Inflation as an open quantum system: Lessons for UV-completion?

New techniques for quantum effects during inflation

Why open systems for inflation?

[Martin, Vennin, Burgess, Holman, Shandera, Boyanovsky, Gong, Seo, Nelson, Martineau, . . .]

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✓ Crucially, decoherence essential for *quantum to classical* transition ⇒ Observable modes must be "Interacting" with some environment!

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Open cosmological system: Vanilla slow-roll inflation

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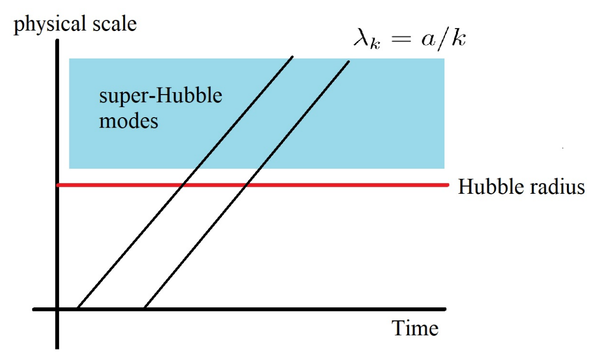

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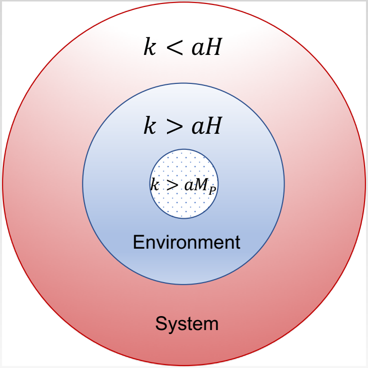

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Universal lower bound on the effects of entanglement & indirect signature of cubic non-Gaussianities!

Primordial cosmological Perturbations: Review

[Albrecht, Ferreira, Joyce & Prokopec, '94]

↪ Comoving gauge: $\mathrm{d}s^2 = -a^2(\tau)\left[\mathrm{d}\tau^2 - (1+2\zeta)\mathrm{d}\mathbf{x}^2\right]$.
Canonical variable $\chi = z(\tau)\zeta$, where $z^2 = 2\epsilon a^2 M_{\mathrm{Pl}}^2$.

↪ The quadratic action $\mathcal{S}^{(2)} = \int d^4x\, \left[(\partial_\mu \chi)^2 - \frac{z''}{z}\chi^2\right]$: collection of harmonic oscillators with a time-dependent mass term.

$$\hat{H}^{(2)} = \frac{1}{2}\int \frac{d^3k}{(2\pi)^3}\left(\underbrace{k\left[\hat{c}_{\mathbf{k}}\hat{c}_{\mathbf{k}}^{\dagger} + \hat{c}_{-\mathbf{k}}\hat{c}_{-\mathbf{k}}^{\dagger}\right]}_{\text{Usual scalar field in flat space}} - \underbrace{i\frac{z'}{z}\left[\hat{c}_{\mathbf{k}}\hat{c}_{-\mathbf{k}} - \hat{c}_{\mathbf{k}}^{\dagger}\hat{c}_{-\mathbf{k}}^{\dagger}\right]}_{\text{Squeezing due to curved space}}\right)$$

✓ $k \ll z'/z \approx aH$: Squeezing term dominant ⇒ super-Hubble modes in the squeezed state.

✓ $k \gg z'/z \approx aH$: first term dominant ⇒ sub-Hubble modes in their quantum (BD) vacuum.

↪ The quantum vacuum unitarily evolves to the squeezed state under the action of the evolution operator $U_0(\tau,\tau_0)$ corresponding to $H^{(2)}$:
$|SQ(k,\tau)\rangle := U_0(\tau,\tau_0)\,|0_{\mathbf{k}}, 0_{-\mathbf{k}}\rangle$.

↪ Sq vacuum of all modes is the product state $|SQ(\tau)\rangle = \prod_k |SQ(k,\tau)\rangle$.

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Gravitational nonliniearities

[Maldacena, 2003]

$$\mathcal{S}^{(3)} = M_{\rm Pl}^2 \int \mathrm{d}t\, \mathrm{d}^3x \left[a^3\epsilon^2\zeta\dot{\zeta}^2 + a\epsilon^2\zeta(\partial\zeta)^2 - 2a\epsilon\dot{\zeta}\partial_i\zeta\partial_i\tilde{\chi} + a^3\epsilon(\dot{\epsilon}-\dot{\eta})\zeta^2\dot{\zeta} \right.$$
$$\left. + \frac{\epsilon^2}{2}a\partial_i\zeta\partial_i\tilde{\chi} - \frac{\mathrm{d}}{\mathrm{d}t}\left(a^3\epsilon(\epsilon-\eta)\zeta^2\dot{\zeta}\right)\right]; \quad \tilde{\chi} = a^2\epsilon\partial^{-2}\dot{\zeta}$$

↪ ζ "freezes" outside the horizon ⇒ Leading order cubic coupling:

$$\boxed{H_{\rm int} = \frac{M_{\rm Pl}^2}{2}\int d^3x\, \epsilon^2\, a\, \zeta(\partial\zeta)^2}$$

↪ Difference with flat space QFT (three *different roles* of gravity):

- ✓ Time-dependent background acts as a *pump* to source zero-momentum correlated pairs.
- ✓ Comoving Hubble horizon $(aH)^{-1}$ acts as a natural scale demarcating long and short dof's.
- ✓ Cubic action due to GR provides leading order interaction term.

↪ Hilbert space: $\mathcal{H} = \mathcal{H}_\mathcal{S} \otimes \mathcal{H}_\mathcal{E}$ where $\mathcal{H}_\mathcal{S}(t) = \prod_k \mathcal{H}_k, \quad |k| < aH$. Here, $\mathcal{H}_k$ is the usual Fock space.

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Gravitational nonliniearities

↪ ζ "freezes" outside the horizon ⇒ Leading order cubic coupling:

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↪ Difference with flat space QFT (three *different roles* of gravity):

- ✓ Time-dependent background acts as a *pump* to source zero-momentum correlated pairs.
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Entanglement Entropy of Cosmological Perturbations

Entanglement entropy: Generalities

[Balasubramanian, McDermott & Raamsdonk, 2011]

↪ Consider simplest case of scalar QFT in Minkowski & momentum-space entanglement.

✓ $\mathcal{H} = \mathcal{H}_{\mathcal{S}} \otimes \mathcal{H}_{\mathcal{E}} \longrightarrow H = H_{\mathcal{S}} \otimes \mathbb{I} + \mathbb{I} \otimes H_{\mathcal{E}} + \lambda H_{\mathrm{int}}$

✓ Free vacuum: $|0,0\rangle = |0\rangle_{\mathcal{S}} \otimes |0\rangle_{\mathcal{E}}$

✓ Interacting: $|\Omega\rangle = |0,0\rangle + \sum_{n\neq 0} A_n |n,0\rangle + \sum_{n\neq 0} B_N |0,N\rangle + \sum_{n,N\neq 0} C_{n,N} |n,N\rangle$

✓ Result: $\boxed{S_{\mathrm{ent}} = -\lambda^2 \log \lambda^2 \sum_{n,N\neq 0} \frac{|\langle n,N|H_{\mathrm{int}}|0,0\rangle|^2}{(E_0 + \tilde{E}_0 - E_n - \tilde{E}_N)^2}}$

↪ $|n\rangle$: 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.

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Entanglement entropy for inflationary perturbations

[S.B., Alaryani & Brandenberger, 2020]

↪ Modifications required for curved spacetime:

- ✓ $|0,0\rangle = |0\rangle_{\mathcal{E}:k>aH} \otimes |SQ\rangle_{\mathcal{S}:k<aH}$
- ✓ Need time-dependent perturbation theory $(\lambda(t) = \sqrt{\epsilon}/(2\sqrt{2}aM_{\rm Pl}))$
- ✓ No *well-defined notion* for the energy of the squeezed state $\longrightarrow$ Luckily, we only need energy difference between the first excited state and the corresponding vacuum.
- ✓ $c_{\mathbf{k}}|0\rangle = 0$ but $c_{\mathbf{k}}|SQ(k,\tau)\rangle \neq 0 \Rightarrow$ New interaction terms need to considered like $c_{\mathbf{k}}c^{\dagger}_{-\mathbf{k}}c^{\dagger}_{-\mathbf{k}}$ and $c_{\mathbf{k}}c_{\mathbf{k}}c^{\dagger}_{-\mathbf{k}}$, in addition to $c^{\dagger}_{-\mathbf{k}}c^{\dagger}_{-\mathbf{k}}c^{\dagger}_{-\mathbf{k}}$.
- ✓ An illustration: $\langle SQ(k,\tau)|\, c_{\mathbf{p}}c^{\dagger}_{-\mathbf{q}}\, |SQ(k,\tau)\rangle \sim (1+\sinh^2 r_p)\delta^3(\mathbf{p}+\mathbf{q})$
- ✓ Dominant contribution from the squeezed configuration.

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

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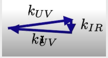

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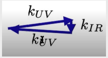

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Squeezing Entropy: An aside

↪ The density matrix (only considering free Hamiltonian) in the two-mode occupation number basis:

$$\rho = \prod_k \prod_p \sum_{n=0}^{\infty} \sum_{m=0}^{\infty} \frac{e^{-2i\phi_k(n-m)}}{\cosh r_k \cosh r_p} \tanh^n r_k \tanh^m r_p \left| n_{\mathbf{k}}, n_{-\mathbf{k}} \right\rangle \left\langle m_{\mathbf{p}}, m_{-\mathbf{p}} \right|$$

↪ This is still a *pure* density matrix → Need to coarse-grain it in a suitable way to get a ρ_{red} with a non-zero von Neumann entropy.

↪ Coarse-graining: Consider only the diagonal elements. Justifications:

- Effect of decohernece is to *suppress off-diagonal terms* of ρ_{red} → Interactions are automatically assumed!
- Averaging over the squeezing angle.

↪ Reduced density matrix $\rho_{\text{sq}} = \prod_k \sum_{n=0}^{\infty} \frac{1}{\cosh^2 r_k} \tanh^{2n} r_k \left| n_{\mathbf{k}}, n_{-\mathbf{k}} \right\rangle \left\langle n_{\mathbf{k}}, n_{-\mathbf{k}} \right| \Rightarrow$

Squeezing entropy $\boxed{s_{\text{sq}} \sim \sum_k \ln(sinh^2 r_k)}$ for large squeezing.

Estimate this by integrating over super-Hubble modes and assume no modes larger than H^{-1} at the beginning of inflation $s_{\text{sq}} \sim H^3$ (per physical volume).

Cosmological entanglement entropy: Implications

- ✓ The squeezing entropy matches previous results for entropy of inflationary perturbations. [Brandenberger, Mukhanov & Prokopec, '92; '93; Gasperini & Giovannini, '93; '95; Prokopec, '93; Campo & Parentani, 2008]

- ✓ $s_{\rm ent} > s_{\rm sq}$ since $s_{\rm ent}/s_{\rm sq} \sim 10^9 (H/M_{\rm Pl})^2 e^{2N}$, provided N is not *fine-tuned to be extremely small.* Remarkable result ⇒ Interaction effects can become very important! (analogy with decoherence) [Martin & Vennin]

- ✓ Further assume that the thermal entropy produced during reheating is *greater* than EE ⇒ $N < \frac{5}{4}\ln(\frac{H}{M_{\rm Pl}}) - \frac{9}{2}\ln(10)$.

↪ The bound is very close to the TCC!

↪ Need additional assumption but it is quite *natural* from perspective of graceful exit plus second law.

↪ More general than inflation ⟶ Same analyses applies to other formulations such as *Ekpyrosis*. Put upper bound on the energy scale of the bounce in that case. [Brahma, Brandenberger & Wang, 2020]

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Non-unitary evolution: Corrections to the power spectrum

Non-unitary dynamics & Cosmological observables

↪ Predict detectable effects of primordial entanglement:

- Prove the quantum origin of inflation (or for alternate paradigms and distinguish between them).
- Indirect signal for cubic NG for vanilla single-clock models (Otherwise undetectable from direct observations $f_{NL} \sim 0$) [Pajer, Schmidt & Zaldarriaga, 2013]

↪ Non-unitary dynamics since only part of the Hilbert space forms the system modes. [Agón, Balasubramanian, Kasko & Lawrence; Shandera, Kamal & Agarwal]

- ✓ Full ρ: $\rho(t) = U^\dagger(t, t_0)\rho(t_0)U(t, t_0)$
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↪ The *dissipative* Lindblad terms denote deviations from Hamiltonian evolution → Losses/gains from Environment. Lindblad terms equivalent to adding new Hamiltonian terms with randomly varying source → close connection to the stochastic inflation formalism.[Banks, Susskind & Peskin, '84]

↪ Cosmological setup remains the same as before.

↪ We will work in the *interaction picture* and solve the *master equation* perturbatively. [Brahma, Berera & Calderón, 2021]

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✓ Evolution equation: $\frac{d\rho_{\rm sys}}{dt} = \frac{1}{ih}\left[H, \rho_{\rm sys}\right] + f\left(L_n, \rho_{\rm sys}\right)$

↪ The *dissipative* Lindblad terms denote deviations from Hamiltonian evolution → Losses/gains from Environment. Lindblad terms equivalent to adding new Hamiltonian terms with randomly varying source → close connection to the stochastic inflation formalism.[Banks, Susskind & Peskin, '84]

↪ Cosmological setup remains the same as before.

↪ We will work in the *interaction picture* and solve the *master equation* perturbatively. [Brahma, Berera & Calderón, 2021]

Non-unitary dynamics & Cosmological observables

↪ Predict detectable effects of primordial entanglement:

- Prove the quantum origin of inflation (or for alternate paradigms and distinguish between them).
- Indirect signal for cubic NG for vanilla single-clock models (Otherwise undetectable from direct observations $f_{NL} \sim 0$) [Pajer, Schmidt & Zaldarriaga, 2013]

↪ Non-unitary dynamics since only part of the Hilbert space forms the system modes. [Agón, Balasubramanian, Kasko & Lawrence; Shandera, Kamal & Agarwal]

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New quantum corrections to power spectrum - I

↪ Time-evolution of ρ_I ($\mathcal{O}_I = U_0^\dagger \mathcal{O} U_0$) governed by von-Neumann equation:

$$\begin{aligned}\frac{d\rho_I}{d\tau} &= -i[\hat{H}_I(\tau), \rho_I(\tau_0)] - \int_{\tau_0}^{\tau} d\tau' \left\{\hat{H}_I(\tau)\hat{H}_I(\tau')\rho_I(\tau') - \hat{H}_I(\tau)\rho_I(\tau')\hat{H}_I(\tau')\right. \\ &\quad \left. - \hat{H}_I(\tau')\rho_I(\tau')\hat{H}_I(\tau) + \rho_I(\tau')\hat{H}_I(\tau')\hat{H}_I(\tau)\right\}\end{aligned}$$

↪ Rewrite the same cubic Hamiltonian as before, but now in the interaction picture (Leading order term – 2 $\mathcal{E}$ and 1 $\mathcal{S}$ mode).

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New quantum corrections to power spectrum - II

↪ The kernel $K_{p_1}(\tau,\tau') = -2\int \frac{d^3p_2}{(2\pi)^3}\,(\mathbf{p_2}\cdot\mathbf{p_3})^2\,\chi^{\mathcal{E}}_{p_2}(\tau)\chi^{\mathcal{E}}_{p_2}(\tau')^*\chi^{\mathcal{E}}_{p_3}(\tau)\chi^{\mathcal{E}}_{p_3}(\tau')^*$ with $\mathbf{p_3} = -(\mathbf{p_1}+\mathbf{p_2})$ is *sensitively dependent* on the choice of the BD mode: $\chi_k(\tau) = \frac{e^{-ik\tau}}{\sqrt{2k}}\left(1-\frac{i}{k\tau}\right)$.

⇝ Its leading order behaviour:

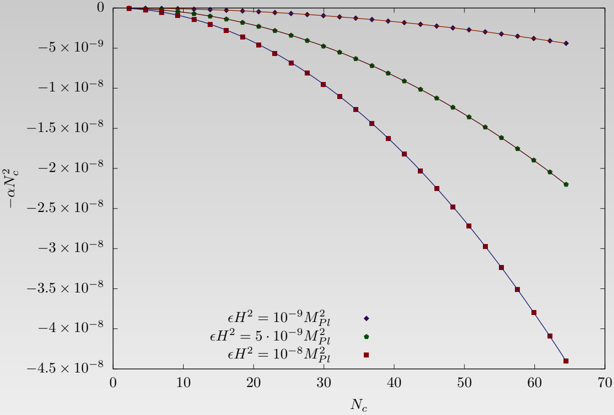
$$K_p(\tau,\tau') \approx -\frac{e^{2i(\tau-\tau')/\tau}\left[1-e^{-ip(\tau-\tau')}\right]\left[\tau-(1-i)\tau'\right]^2}{8\pi^2 p\tau^4(\tau')^2(\tau-\tau')^2}\,.$$

↪ The power spectrum:

$$\Delta^2_\zeta(q\tau) = \frac{q^3}{2\pi^2 z^2}\left\langle\hat{\chi}^{\mathcal{S}}_{\mathbf{q}}(\tau)\hat{\chi}^{\mathcal{S}}_{-\mathbf{q}}(\tau)\right\rangle = \frac{q^3}{2\pi^2 z^2}\mathrm{Tr}\left[\hat{\chi}^{\mathcal{S}}_{\mathbf{q}}(\tau)\hat{\chi}^{\mathcal{S}}_{-\mathbf{q}}(\tau)\rho_r(\tau)\right]$$

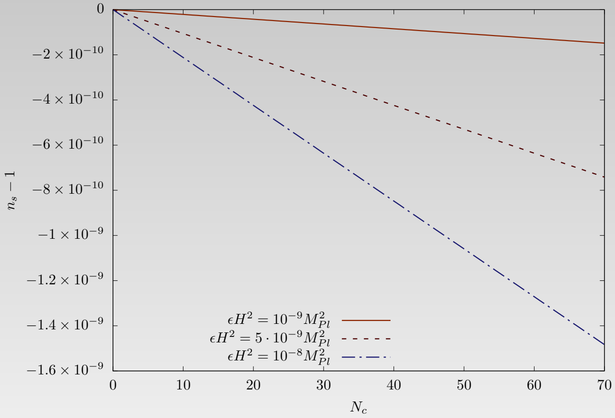
- ✓ The zeroth order approximation: $\Delta^2_\zeta(q) \approx \frac{1}{2\epsilon M^2_{\mathrm{Pl}}}\left(\frac{H}{2\pi}\right)^2$
- ✓ The first order correction: $\boxed{\Delta^2_\zeta(q\tau) = \frac{1}{2\epsilon M^2_{\mathrm{Pl}}}\left(\frac{H}{2\pi}\right)^2\left(1-\alpha N_c^2\right)}$ where $\alpha \approx 0.00211886\,\epsilon H^2/2M^2_{\mathrm{Pl}}$ and $N_c = \ln(-1/q\tau)$.

Results



Fixing $\epsilon = 0.01$ and $H^2 \sim M_{\rm GUT}^4/M_{\rm Pl}^2$, consistent with an energy scale of inflation close to GUT scale, the correction to the power spectrum is of the order of $\mathcal{O}(10^{-8})$ for a period of $N_c \sim 10^2$ $e-$folds of expansion.

Results-II



Corrections to the spectral index, and its running, are of the order $\mathcal{O}(10^{-9})$ and $\mathcal{O}(10^{-11})$, respectively, for the above-mentioned values.

Implications: Non-unitary evolution

$\hookrightarrow$ The first-order effect is a result of a mixture of dissipative and radiative corrections.

- ✓ The suppression factor $\epsilon H^2/M_{\rm Pl}^2$ can be estimated by power counting from loop corrections.
- ✓ Even the N_c^2 factor can be guessed from loop corrections to the propagator although this is much *less* straightforward.
- ✓ The scale-dependence of this effect very different from loop corrections. [Weinberg, 2005; 2006; Sloth, 2007]
- ✓ We find this effect without assuming any specific form of the potential.

$\hookrightarrow$ Upper bound on inflation for theory to be within perturbative regime. Allowed e-foldings: $\mathcal{O}(10^5)$ come from the relation $\Rightarrow \quad N \lesssim \alpha^{-1/2}$.

- ✓ Much larger than TCC & EE bound but no additional assumptions!
- ✓ If inflation is at reasonably high scale, potentially detectable.
- ✓ $(n_s - 1)$ & its running *increases* with N! Typically, for single-field models, they decrease with N. [Easther & Peiris, 2006]
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Discussion

→ Conclusions:

- ✓ QG important (all constraints go away when $M_{pl} \to \infty$) for theories explaining current data ⇒ New challenge for cosmologists coming from UV-physics.
- ✓ A lot can be learnt about general aspects of UV-completions from studying (open) QFT on curved spacetime. Effects of general initial states (for which standard Coleman-Weinberg doesn't apply) similar to those from curvature of field space. [Bojowald, S.B., Crowe, Ding & McCracken, 2020]

→ Looking ahead:

- Easy to generalize our methods to alternate mechanisms beyond inflation. Dissipative terms (as well as decay of vacuum energy) have promise of first-principles derivation of warm energy.
- Generalize to tensor modes (interactions can come without being slow-roll suppressed) and for couplings to other fields. Effects for non-Markovian evolution?
- dS space has been realized as a Glauber-Sudarshan state in String theory. In this case, a bound on the lifetime comes from when system becomes strongly-coupled! [S.B., Dasgupta & Tatar, 2020] Same idea for inflation?
- Can entanglement entropy and/or non-Hamiltonian/non-Markovian dynamics be used to find unequivocal quantum signatures? Discriminate between different approaches?

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- ✓ A lot can be learnt about general aspects of UV-completions from studying (open) QFT on curved spacetime. Effects of general initial states (for which standard Coleman-Weinberg doesn't apply) similar to those from curvature of field space. [Bojowald, S.B., Crowe, Ding & McCracken, 2020]

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- dS space has been realized as a Glauber-Sudarshan state in String theory. In this case, a bound on the lifetime comes from when system becomes strongly-coupled! [S.B., Dasgupta & Tatar, 2020] Same idea for inflation?
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