Nonlocal quantum effects in the early Universe

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work in collaboration with
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Quantum origins of the Universe

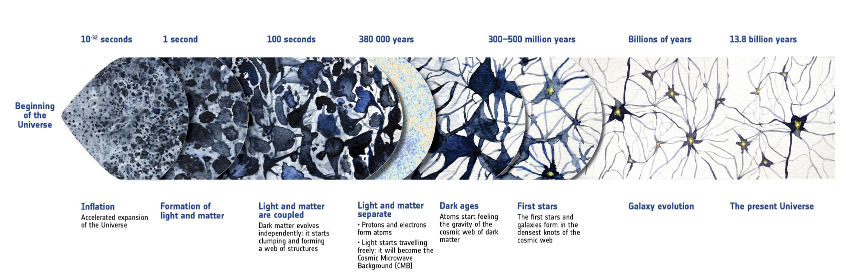

Photo Credit: ESA

$\hookrightarrow$ *Where did we come from?*

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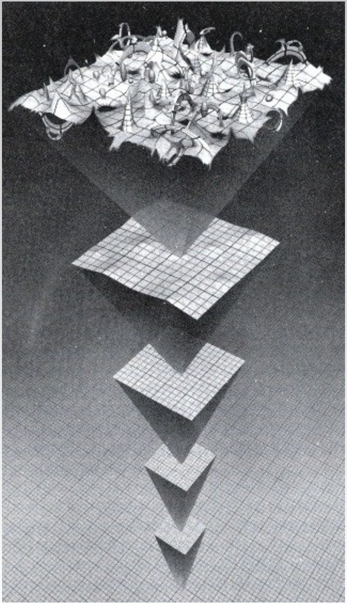

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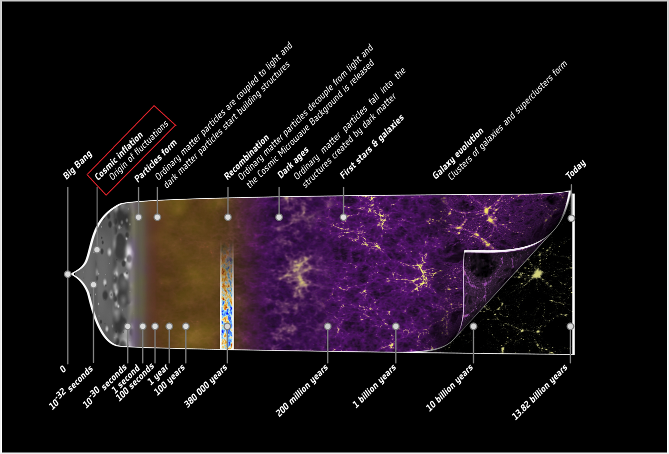
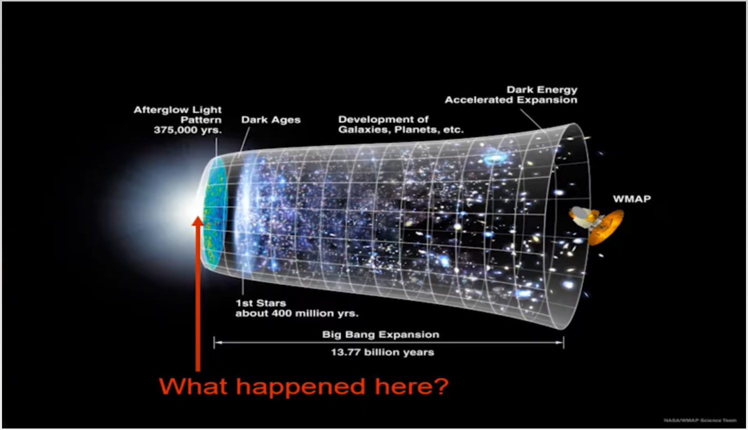


Photo Credit: ESA/PLANCK

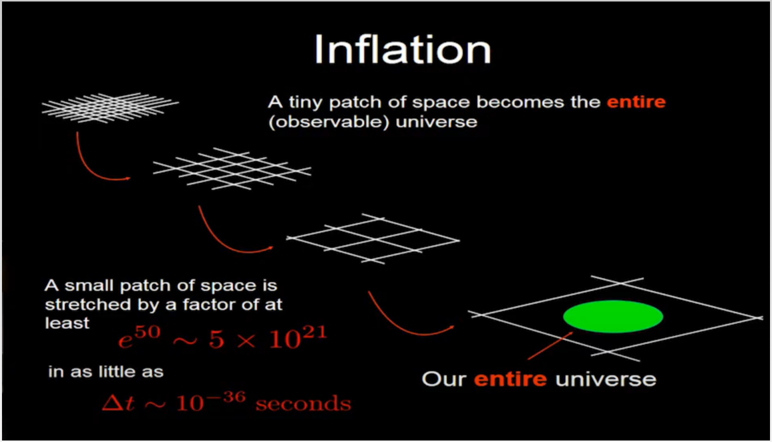
$\hookrightarrow$ Quantum seeds of structure in the early universe

Quantum effects in the early universe



Quantum effects in the early universe

$\hookrightarrow$ Inflation: Phase of accelerated expansion



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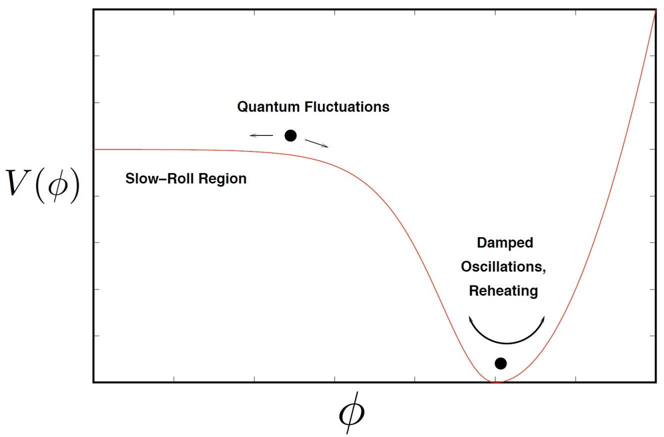

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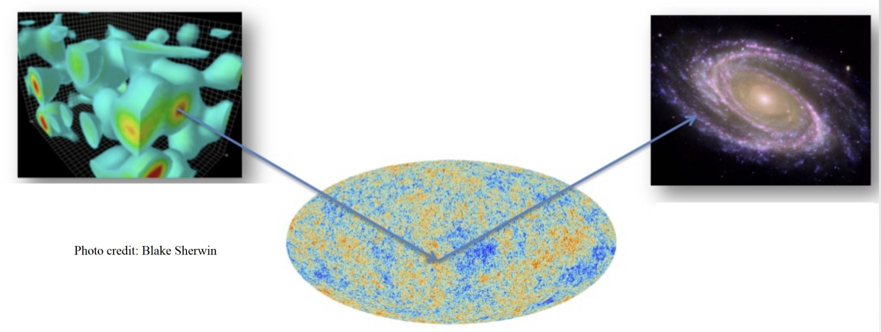
✓ Inflation: Not only solves standard cosmological puzzles but also explains late-time inhomogeneities as originating from quantum vacuum fluctuations

⇒ Rare *interplay* between microscopic and macroscopic scales!



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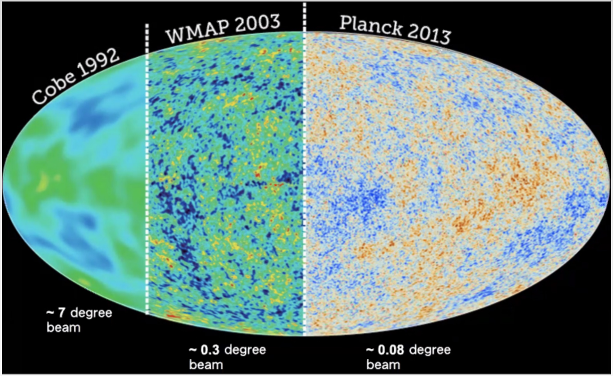

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Consistent early-universe paradigm: Requires new perspectives of (open) EFTs in curved space to explain non-unitary phenomenon

Cosmological open quantum systems

Effective theories beyond Wilson: Non-unitarity

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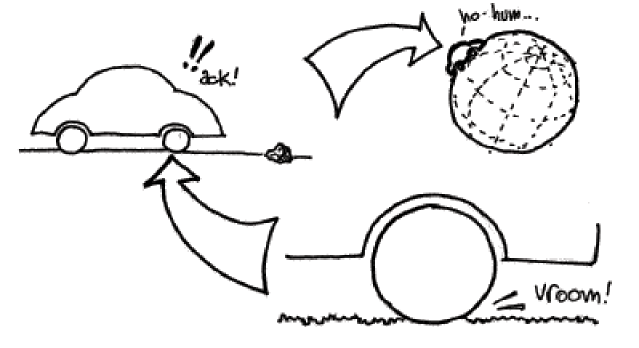

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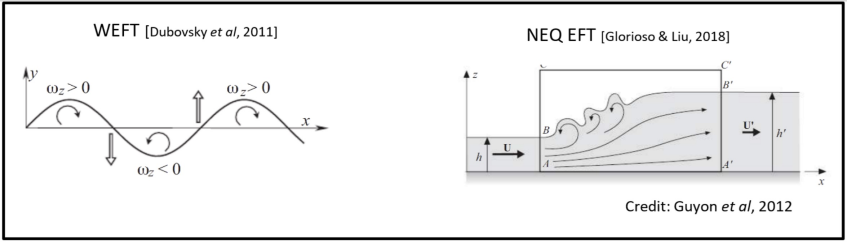

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$\hookrightarrow$ Comoving gauge: $\mathrm{d}s^2 = -a^2(\tau)\left[\mathrm{d}\tau^2 - (1+2\zeta)\mathrm{d}\mathbf{x}^2\right]$.
Canonical variable $\chi = z(\tau)\zeta$, where $z^2 = 2\epsilon a^2 M_{\mathrm{Pl}}^2$.

$\hookrightarrow$ The quadratic action $\mathcal{S}^{(2)} = \int \mathrm{d}^4x \,\left[(\partial_\mu\chi)^2 - \frac{z''}{z}\chi^2\right]$: 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 $\Rightarrow$ super-Hubble modes in the squeezed state.

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

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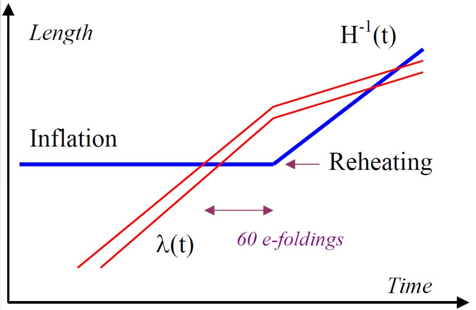

Picture credit: Cliff Burgess

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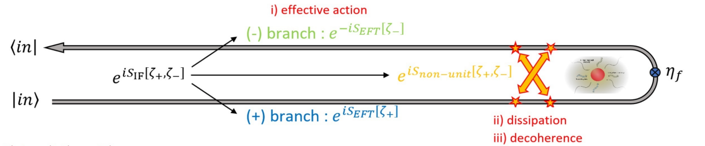

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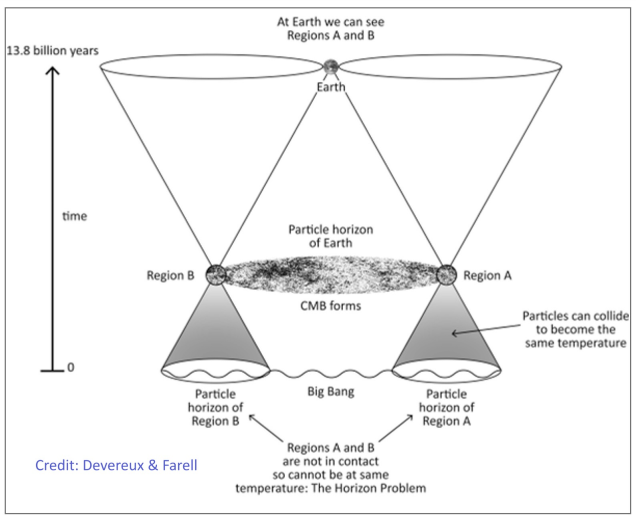
Derive an open inflationary EFT capable of incorporating dissipative & diffusive effects $\Rightarrow$ Find their *observational* signatures.

Inflation creates exponentially large scales

↪ How long did inflation last?



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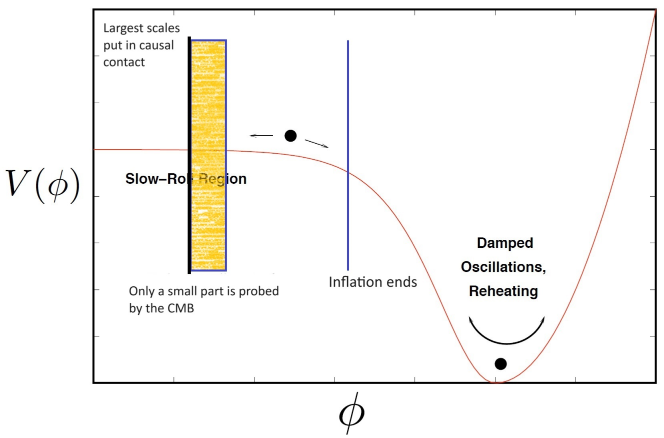

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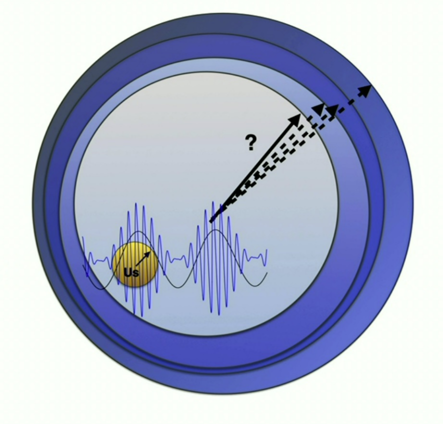

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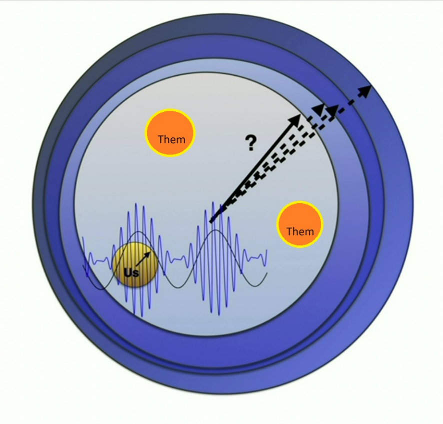

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✓ Observations probe effective theory for one given Hubble patch for realistic models.

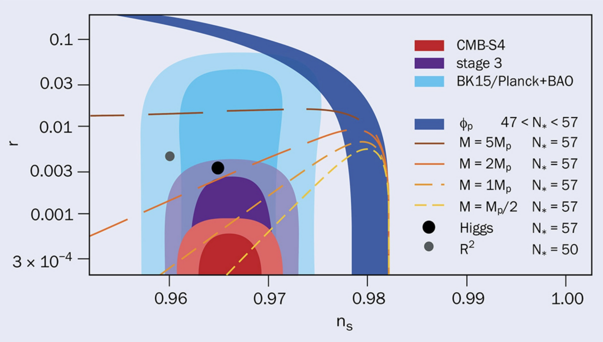

Photo credit: CMB S4

Spacetime Horizons imply open EFTs

✓ Gravity creates spacetime boundaries ⇒ Horizons limit what we can observe **without** restricting the flow of energy and information across it

✓ Horizons are sometimes observer-dependent ⇒ Different open EFTs for different observers!

↪ Open systems not a new concept → Entanglement structure of the quantum vacuum in BH or dS space. [Srednicki; Maldacena & Pimentel; Calzetta & Hu; Brandenberger, Mukhanov & Prokopec; . . .]

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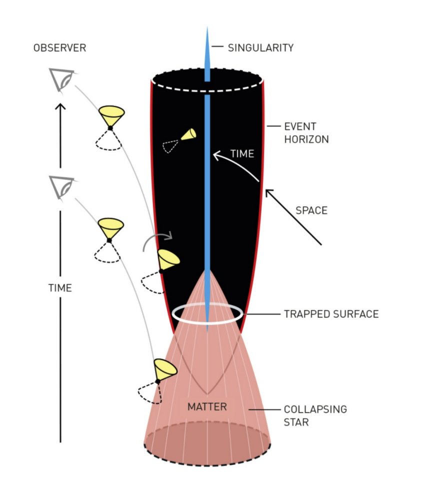

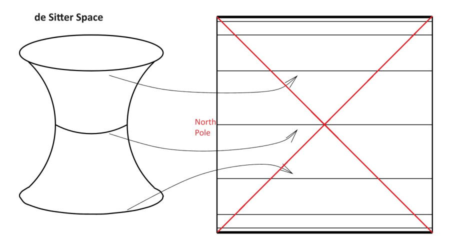

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- Mathematician $\rightarrow$ Theorist working on Fundamental Cosmology?

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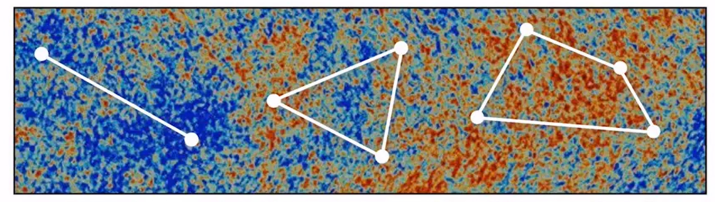

Photo credit: Daniel Baumann

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- We have **not** observed any NG yet → Need a fresh perspective! [Chen, Wang, Baumann, Green, Arkani-Hamed, Maldacena, Lee, Pimentel, Joyce, Pajer, Sleight, Taronna, Stefanyszyn, Pinol, Renaux-Petel . . . ;
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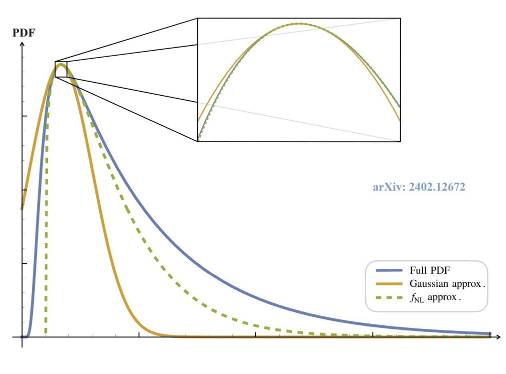

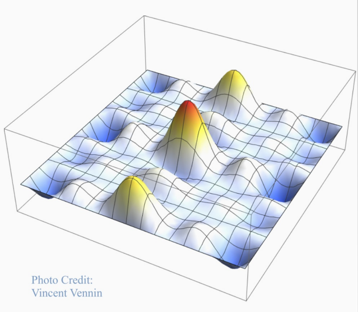

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✓ Dissipative/thermal effects ⇒ large primordial B fields, vector modes → **affects** structure, cosmic tensions, . . . [with Alexander, Berera, Toomey . . .]

✓ Better capture effects of clustering on GW propagation → Affects stochastic GW detections [with Kalomenopoulos, Khochfar]

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- **When** does dissipative effects affect **observations**? Signatures for *"quantum" origin* of inflation? [Salcedo, Colas & Pajer, 2024]
- Resolves **conceptual** issues: stochastic framework, EI, UV-completion? *"Swampland constraints"*

Secular divergences & Non-perturbative resummations

Late-time (secular) divergences

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✓ Although this is a generic issue, it does **not** show up in scattering problems due to having asymptotically free particles.

✓ However, there is no way to *turn-off* gravity! Gravity always acts as an ever-present medium.

• Late-time secular growth $\Rightarrow$ Breakdown of SPT in cosmology. [Woodard, Tsamis, Glavan, Miao, Prokopec, Kaplanek, Burgess, Holman, Leblond, Shandera, ...]

Late-time (secular) divergences

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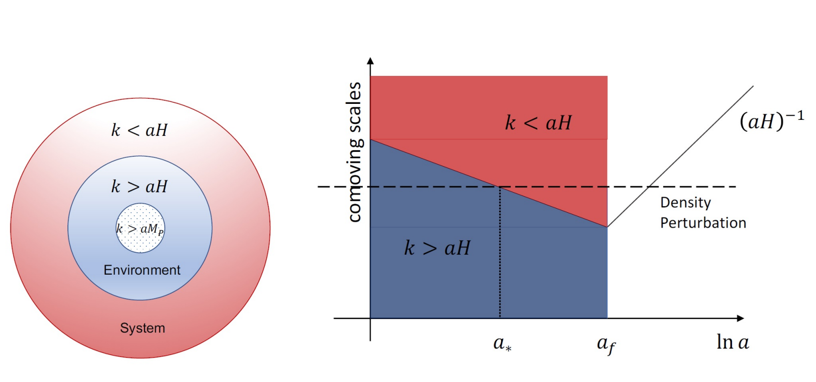

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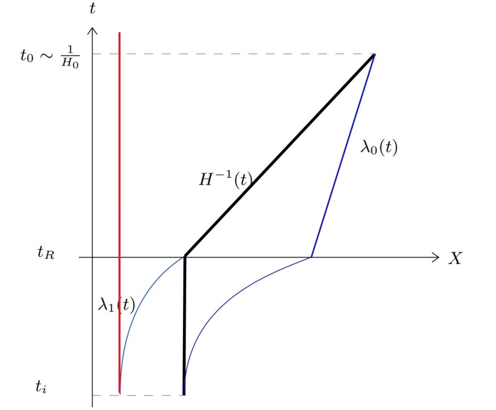
- Rapid Growth: Perturbative EE $\approx$ reheating (thermal) entropy $\Rightarrow$ Breakdown of perturbation theory around scrambling time of dS $[1/H \ln(M_{\rm pl}/H)]$.

Trans-Planckian Censorship



[Bedroya, Brandenberger, LoVerde, Vafa, 2019]

- Entropy growth typically signals deep puzzles for fundamental physics!

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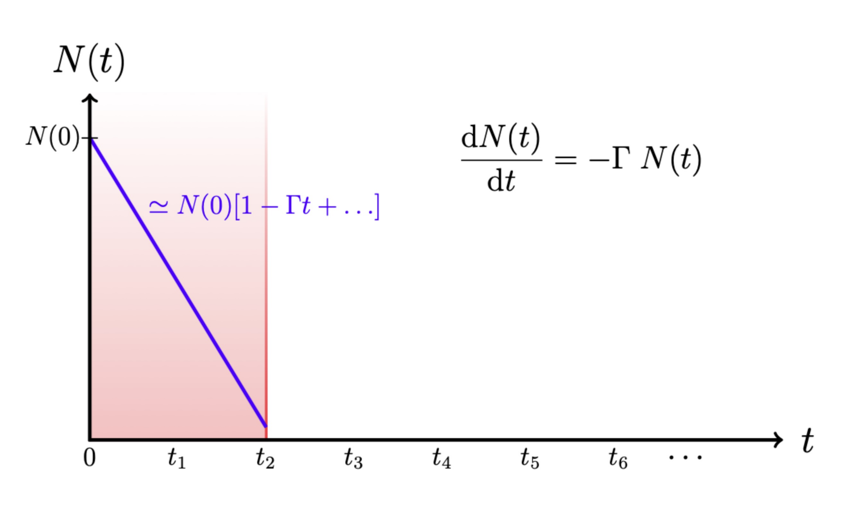

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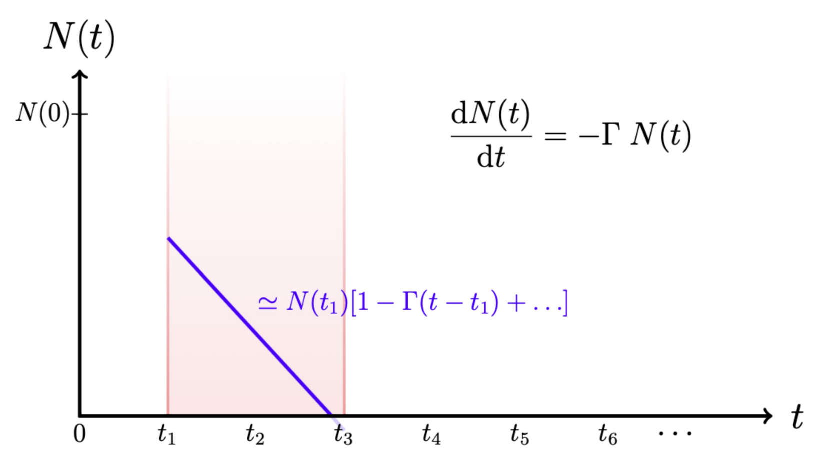

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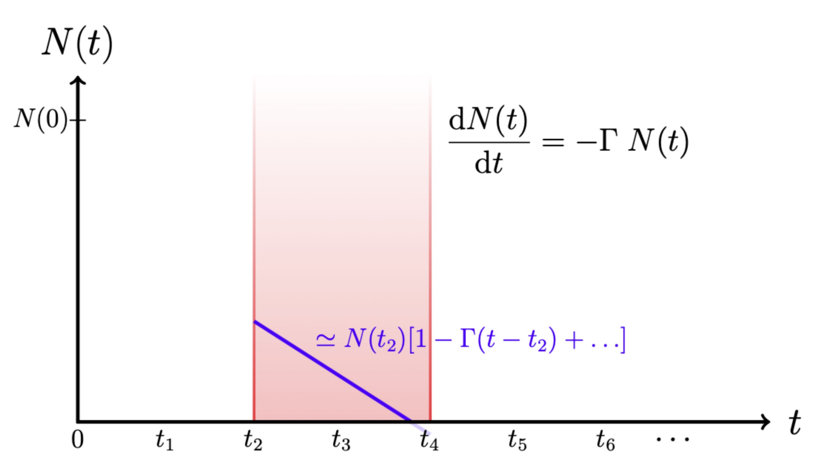

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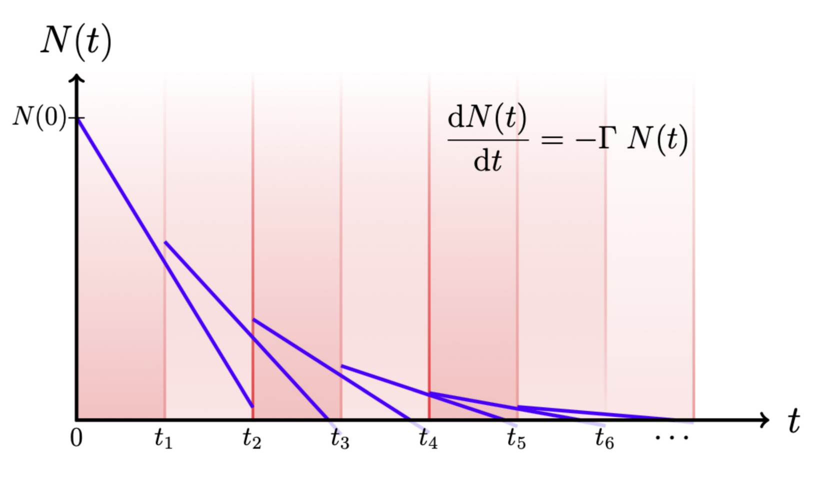

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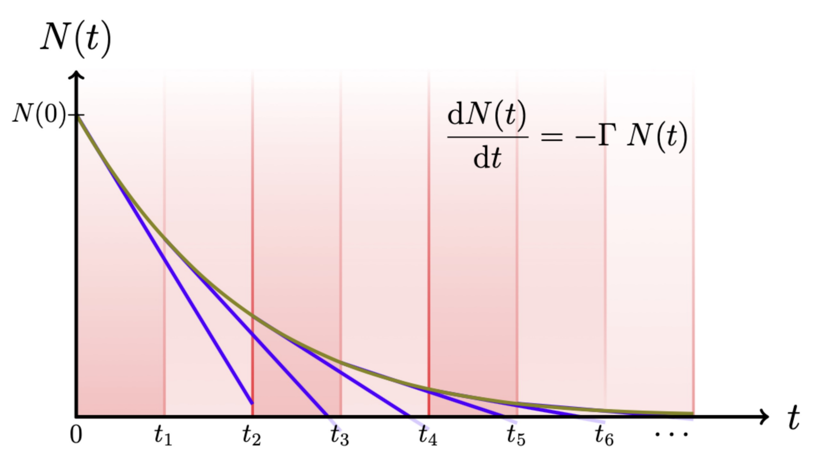

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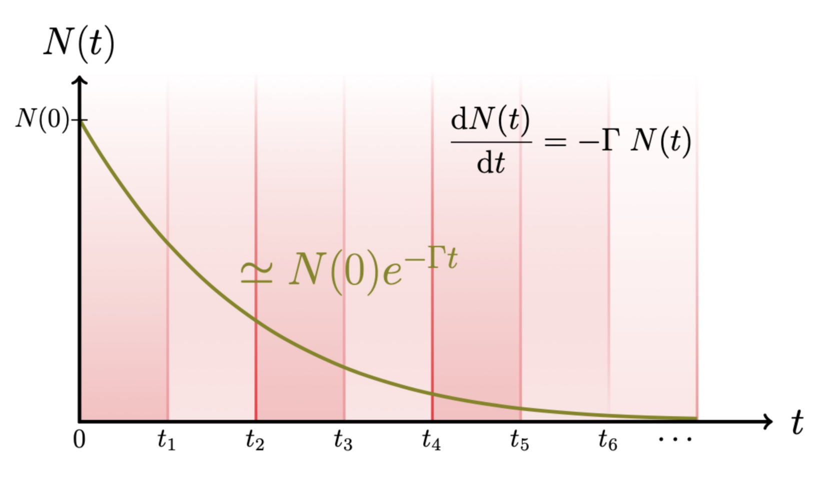

Non-perturbative resummation in cosmology

$\hookrightarrow$ Assume at τ_0, no coupling exists (there are *no superhorizon modes*)

- ✓ Born approximation (Weak coupling): $\rho_I(\tau) = \rho_{\mathcal{S}}(\tau) \otimes \rho_{\mathcal{E}}(\tau_0)$
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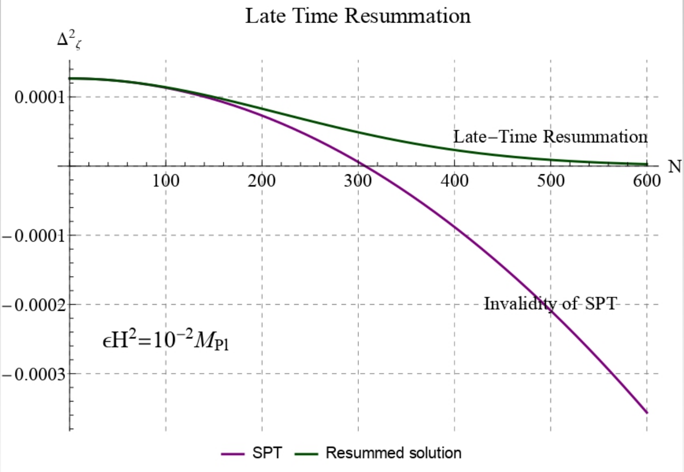
MEs allows non-perturbative resummation ⇒ Matches exact results **better** than *standard perturbation theory* in **toy models** [Colas, Grain & Vennin, 2022]

Non-perturbative resummation in cosmology



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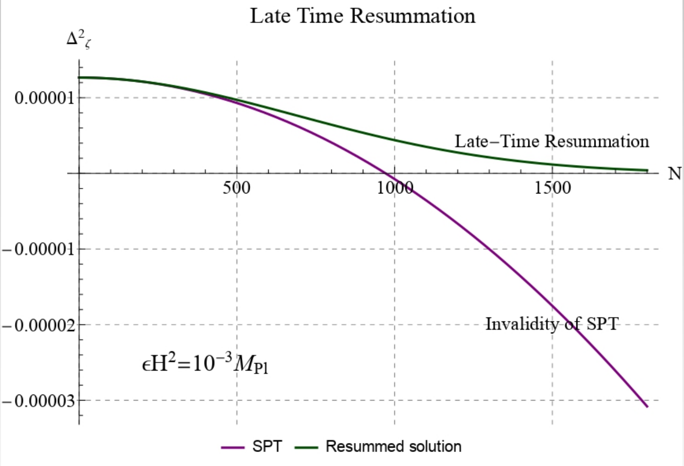

Why non-Markovianity in cosmology?

Environments in cosmology

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$$
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✓ Tracing over $\mathcal{E}$, Nakajima-Zwanzig equation (suppressing spatial indices):

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How do we know that cosmological MEs are non-Markovian?
Check kernel of environment correlations!

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✓ IR secular terms can be resummed as in the scalar case $\rightarrow$ Ignored above

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

Can non-local terms affect late-time dynamics?

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- Using a toy-model, we showed that [S.B., Calderón & Luo, 2407.12091] :
  - ✓ Secular divergences can just as easily **stem** from non-Markovian terms and, more importantly, such terms can still be resummed at late times following a precise algorithm that does not involve any arbitrary approximations.
  - ✓ The memory kernel, corresponding to the integrated-out (or coarse-grained) fields, in the same model can affect other physical quantities differently. More specifically, local and non-local parts of the kernel can become dominant for different physical observables.

Toy Model for Stochastic Inflation

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$$\mathcal{S} = \int \mathrm{d}\tau\ \mathrm{d}^3x \left\{ \frac{1}{2}\left[\chi'^2 - (\nabla\chi)^2 + \frac{a''}{a}\chi^2 + \psi'^2 - (\nabla\psi)^2\right] + \lambda\ a\ \chi : \psi^2 : \right\}$$

with BD initial conditions

$$\chi_k(\tau) = \frac{e^{-ik\tau}}{\sqrt{2k}}\left(1 - \frac{i}{k\tau}\right), \qquad \psi_k(\tau) = \frac{e^{-ik\tau}}{\sqrt{2k}}$$

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The memory kernel:

$$K_{\mathbf{p}}(\tau,\tau') = 2\int \frac{\mathrm{d}^3k}{(2\pi)^3}\, \psi_k(\tau)\psi_k^*(\tau')\psi_q(\tau)\psi_q^*(\tau')\,, \quad p = |\mathbf{k}+\mathbf{q}|$$

$$= -\frac{i}{8\pi^2} e^{-ip(\tau-\tau')}\mathcal{P}\left(\frac{1}{\tau-\tau'}\right) + \frac{1}{8\pi}\delta(\tau-\tau')$$

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- Simplifications:
  - ✓ Since the system field appears at most at quadratic order in the the full Lagrangian, the evolution equation for the density matrix can be written as a sum over independent momentum modes $\mathbf{p}$ without any mode-coupling.
  - ✓ The associated memory kernel of the environment field has the advantage of cleanly splitting into two different contributions, one that is clearly time-local while the other non-local.

Time-convolutionless master equation

- The TCL_2 master equation:

$$\frac{\mathrm{d}\rho_{\rm red}}{\mathrm{d}\tau} = \sum_{\mathbf{p}} \left(-iH^{(2)}_{ij}\left[\hat{z}_i\hat{z}_j^\dagger\,,\hat{\rho}_{\rm red}(\tau)\right] + \gamma_{ij}(\tau)\left(\hat{z}_i\hat{\rho}_{\rm red}(\tau)\hat{z}_j^\dagger - \frac{1}{2}\{\hat{z}_j^\dagger\hat{z}_i\,,\hat{\rho}_{\rm red}(\tau)\}\right)\right)$$

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with the effective quadratic Hamiltonian given by

$$H^{(2)}_{ij} = \frac{1}{2} \left[\hat{z}_2 \hat{z}^\dagger_2 + (k^2 + \Delta_{11}) \hat{z}_1 \hat{z}^\dagger_1 + \left(\frac{a'}{a} + \Delta_{12} \right) \left(\hat{z}_1 \hat{z}^\dagger_2 + \hat{z}_2 \hat{z}^\dagger_1 \right) \right]$$

and the dissipator matrix: $\gamma_{ij} \equiv D_{ij} - i\Delta_{12}\, \omega_{ij}$.

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$$D_{11} = -\frac{\lambda^2}{8\pi^2H^2p\tau^3}\Big[\gamma_E + \ln(-2p\tau) - \mathrm{Ci}(-2p\tau)\left[\cos(2p\tau) + p\tau\sin(2p\tau)\right]$$

$$+\,\mathrm{Si}(2p\tau)\left[p\tau\cos(2p\tau) - \sin(2p\tau)\right]\Big] + \frac{\lambda^2}{4\pi H^2\tau^2} + F_1[\tau,\tau_0]$$

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$$D_{12} = \frac{\lambda^2}{16\pi^2H^2p^3\tau^4}\Big[(1+p^2\tau^2)\left[\gamma_E + \ln(-2p\tau)\right] + \mathrm{Ci}(-2p\tau)\left[(-1+p^2\tau^2)\cos(2p\tau) - 2p\tau\sin\right.$$

$$\left.+\,\mathrm{Si}(2p\tau)\left[2p\tau\cos(2p\tau) + (-1+p^2\tau^2)\sin(2p\tau)\right]\Big] + 0 + F_3[\tau,\tau_0]$$

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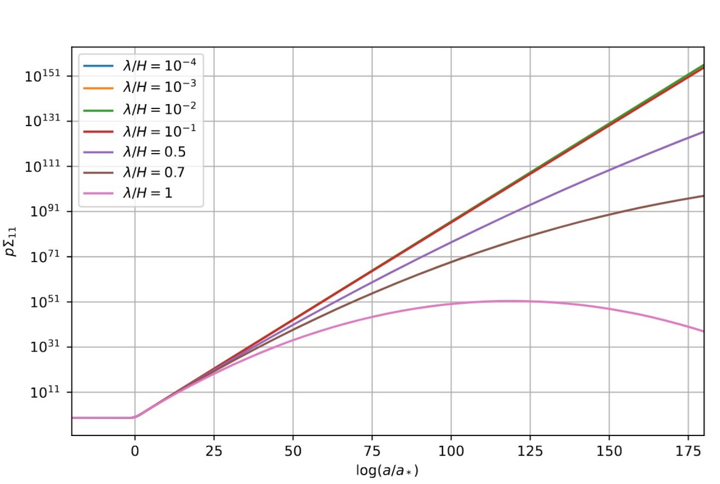
$$+\,\mathrm{Si}(2p\tau)\left[(-1+p^2\tau^2)\cos(2p\tau) - 2p\tau\sin(2p\tau)\right]\Big] + F_4[\tau,\tau_0]$$

Non-local terms dominate the power-spectrum

[S.B., Calderón & Luo, 2407.12091]

✓ The power spectrum:



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✓ Resummation is an exact result within the TCL_2 approximation.
Matches previous results without requiring arbitrary assumptions!

Non-local terms dominate the power-spectrum

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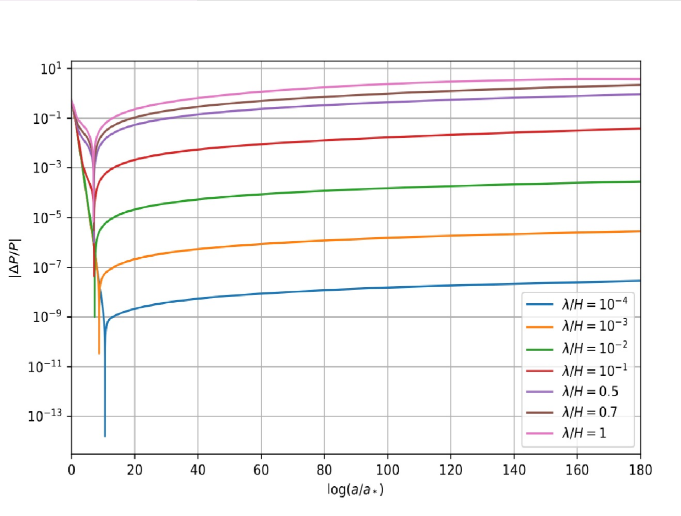

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Local contributions dominate decoherence

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✓ Purity is good measure for decoherence.

$$\gamma_{\mathbf{p}} = \mathrm{Tr}_{\mathcal{S}}\left[\left(\rho_{\mathbf{p}}^{\mathcal{S}}\right)^2\right] = \frac{1}{\sqrt{4\det[\mathbf{\Sigma}^{\mathcal{S}}]}}$$

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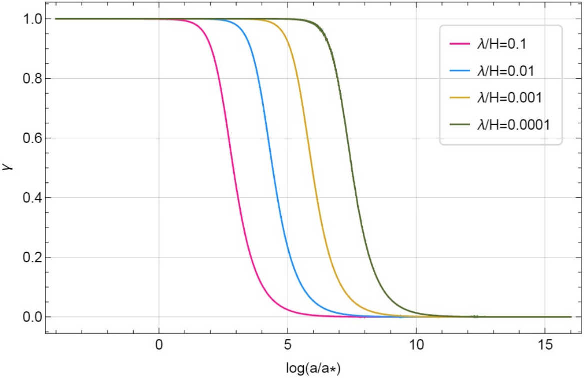

Figure 8: There is rapid decoherence phase occurring right after horizon crossing. As expected, for a system with weaker interaction with environment, the loss in purity occurs at later times.

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$\hookrightarrow$ Purity is dominated by the diffusion terms from the noise kernel.

$$D_{11} = -\frac{\lambda^2}{8\pi^2 H^2 p\tau^3}\Big[\gamma_E + \ln(-2p\tau) - \mathrm{Ci}(-2p\tau)\left[\cos(2p\tau) + p\tau\sin(2p\tau)\right]$$

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At late-times:

$$D_{11} \approx \frac{\lambda^2}{4\pi H^2\tau^2} + \frac{\lambda^2 p}{8\pi^2 H^2\tau} + \mathcal{O}(\tau)$$

Local contributions dominate decoherence

[S.B., Ca

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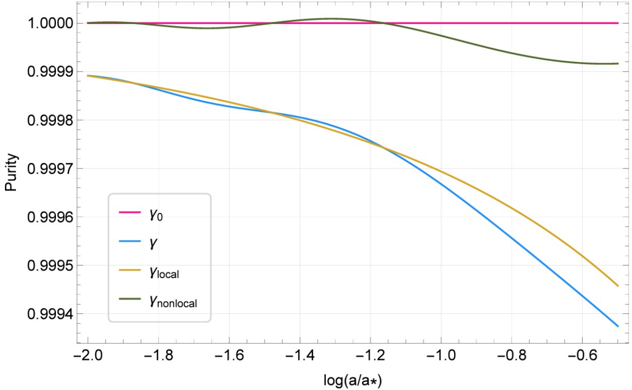

Figure 9: The pink plot, labelled as γ_0, is the purity for system with no interaction with environment, which is what is expected when the state remains pure. The green plot is the effect coming from non-local part in TCL_2 equation, we can see that it leads to oscillations due to information exchange between the system and environment. Comparing the purity when all the terms are retained (blue plot) with the one when only the local terms are kept (yellow plot), shows that the non-local terms have very little effect on the way purity evolves. This is why the system undergoes decoherence and inevitably evolves to a mixed state once the mode crosses the horizon.

Non-Markoviantity: Cosmic consequences

↪ Purity difficult to compute sometimes ⇒ Need new measures such as "**complexity**" for decoherence

[Bhattacharya, S.B., Haque, Lund & Paul, 2024 (JHEP)]

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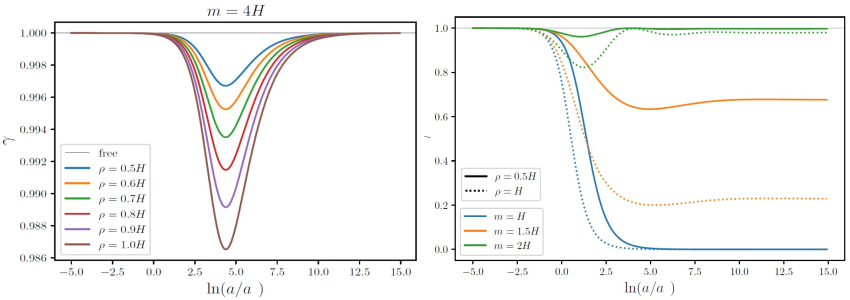

Colas, Grain & Vennin, 2023

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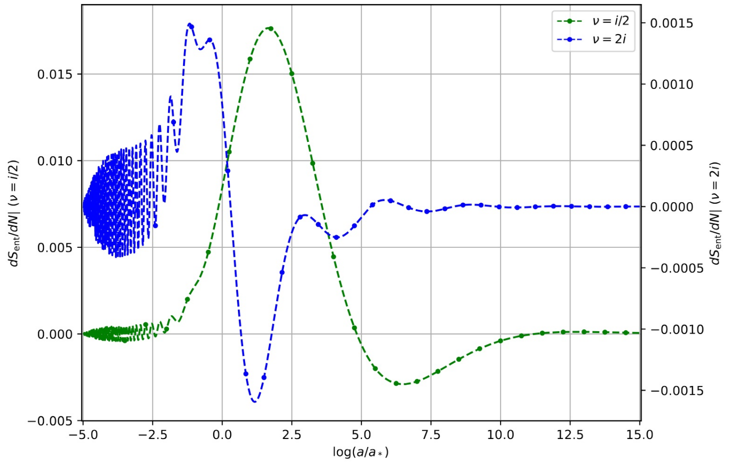

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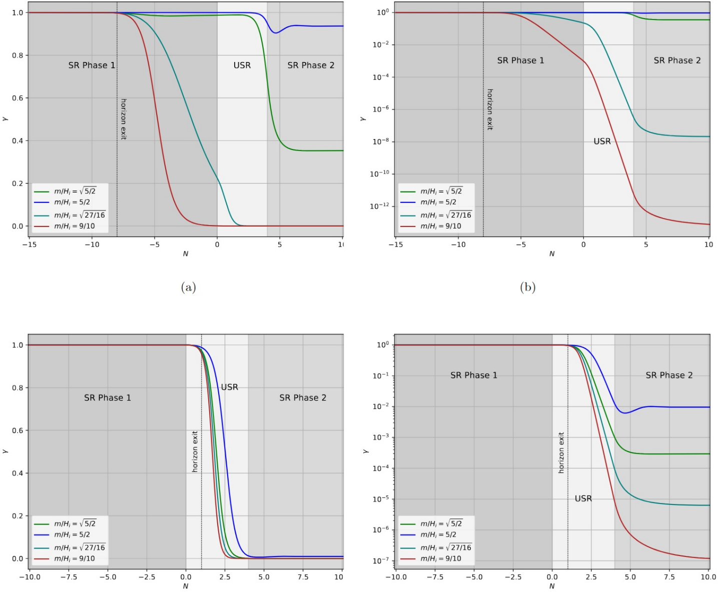
✓ Are **slow-roll attractor** models special? [with Calderón, Luo & Seery]

- What if there is a non-attractor ultra-slow roll phase? Does the same model, with non-Markovianity, show visible consequences for purity?
- The free theory noise term in the Fokker-Planck equation is suppressed as e^{-N} in SR whereas amplitude increases as e^{7N} for USR.

Non-


SR Phase 1
USR
SR Phase 2
horizon exit
$m/H_i = \sqrt{5/2}$
$m/H_i = 5/2$
$m/H_i = \sqrt{27/16}$
$m/H_i = 9/10$
γ
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(a) (b) (c) (d)

Non-Markovianity: Cosmic consequences

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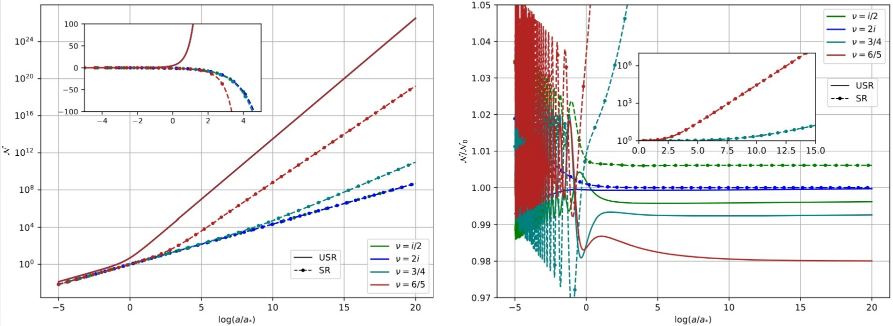

(a) (b)

Left: Noise for various ν values at a representative coupling strength $\lambda/H = 0.1$, on log scale. The inset illustrates that USR (SR) curves evolve towards positive (negative) values. Right: Ratio of the computed noise to the corresponding free-theory prediction. The box zooms in on the SR curves departing significantly from a ratio of 1.

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✓ Does *decoupling* of UV modes still still work? Loop corrections under control in EFT of inflation ⇒ Does non-Markovian open EFT remain so?

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

Example: Thermal states and primordial B-fields

[with Berera, Qiu & Ramos]

↪ Gauge-fields A_μ *do not feel curved space* → The magnetic field energy density goes as $\rho_B \propto 1/a^4$.

✓ Quantum fluctuations of the magnetic field produced during inflation is quickly redshifted away.

• Magnetic fields at $10\ kpc$ wavelengths have an **unobservably small magnitude** $B \sim 10^{-53} G$.

↪ To produce primordial magnetic fields during inflation, one needs to go beyond the Standard Model and modify Maxwell's equations. Even then it is very difficult to have magentogenesis!

✓ But what about dissipative effects?

✓ For warm inflation, sensible to have a thermal state for the gauge photons instead of a quantum vacuum state at $T \sim H$.

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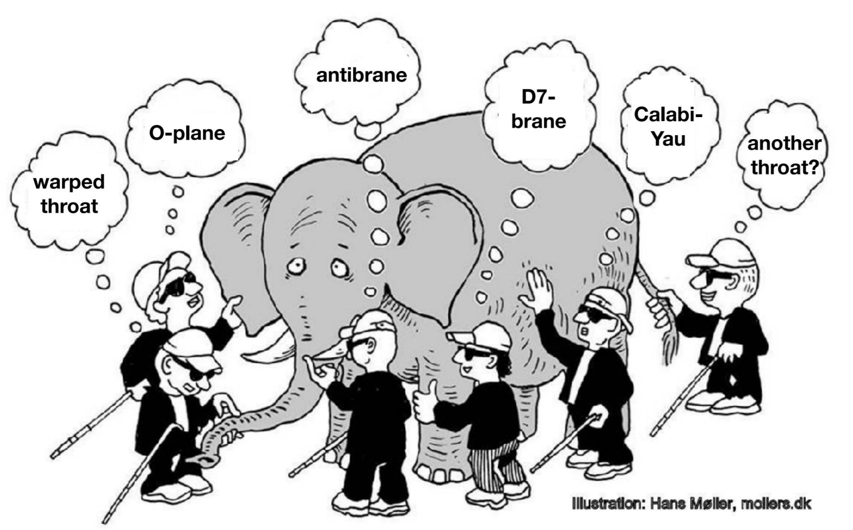
The Big Picture



The early-universe as an open quantum 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*.

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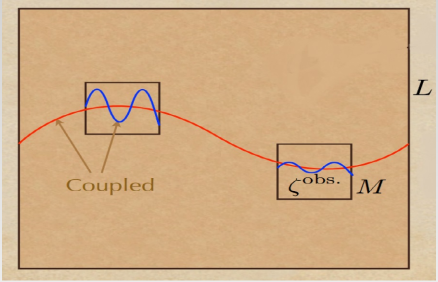
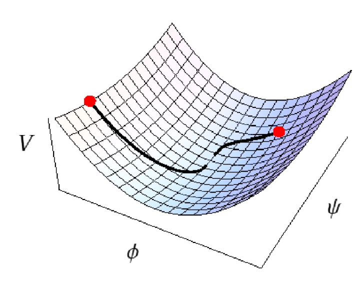
↪ Observed statistics depend on our position in the universe, on UV physics, couplings to SM fields etc. especially since GR is non-linear.





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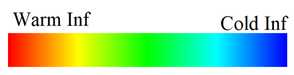

WI assumes thermal eq while cold models ignore dissipative effects.

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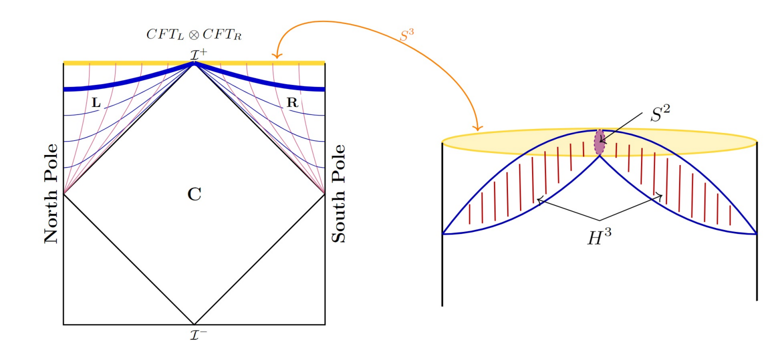
✓ Useful **tools** for studying spacetime emergence from de Sitter holography! [S.B., Hackl, Hassan & Luo, 2409.13932]

Finite complexity as evidence for *cosmic ER=EPR*

[S.B., Hackl, Hassan & Luo, 2409.13932]



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

$$\mathcal{H}_{\rm dS} = \mathcal{H}_{\rm CFT_1} \otimes \mathcal{H}_{\rm CFT_2}$$