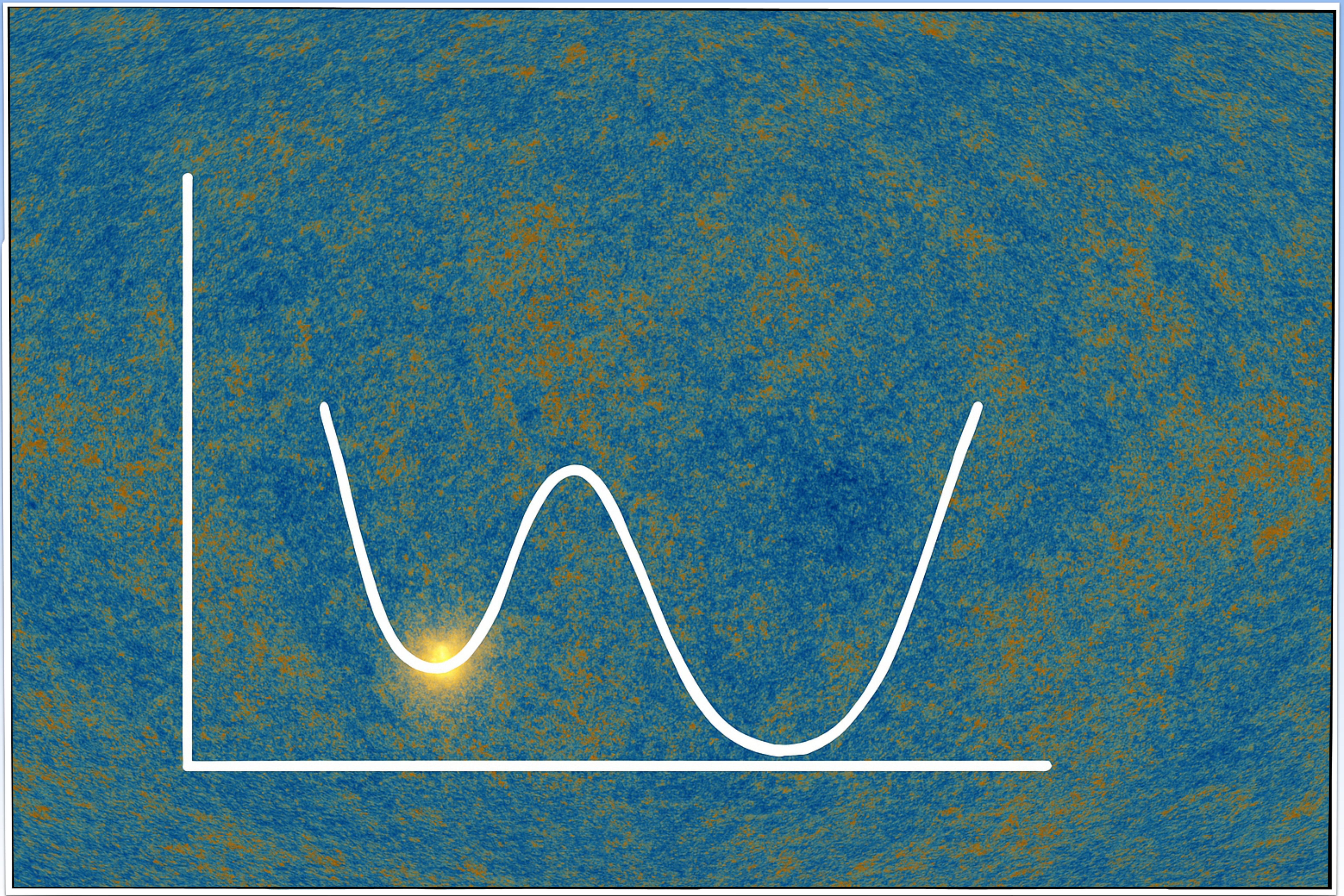
Cosmic Lockdown:

when decoherence saves the universe from tunneling



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Scientists Simulated a Quantum Apocalypse. Then the Universe Disappeared.

Luckily "false vacuum decay" would take millions of years to occur, if it happens at all.

BY DARREN ORF PUBLISHED: FEB 12, 202

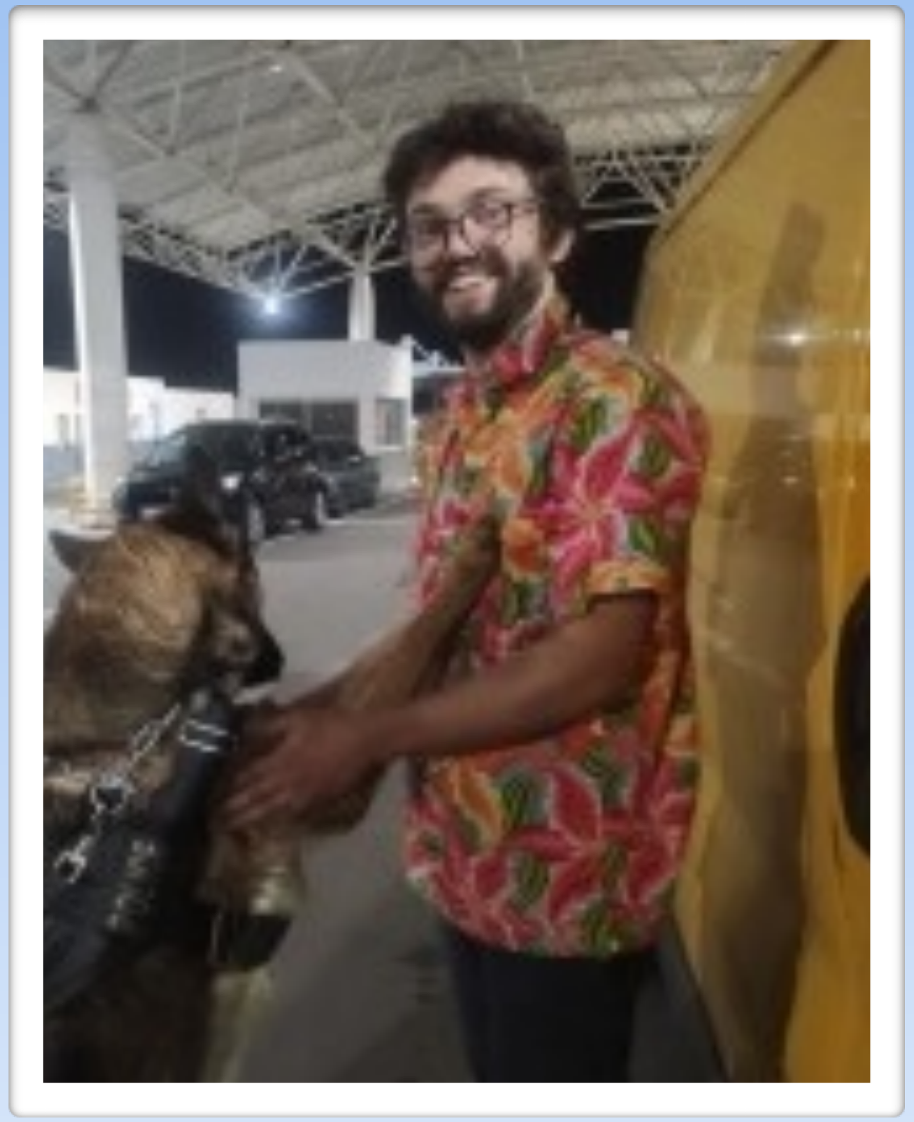
Cosmic Lockdown:

when decoherence saves the universe from tunneling

Cosmic Lockdown:

On the interplay between vacuum selection & decoherence in de Sitter space

[2512.xxxxx] coming soon…



Robson Christie

Jaewoo Joo

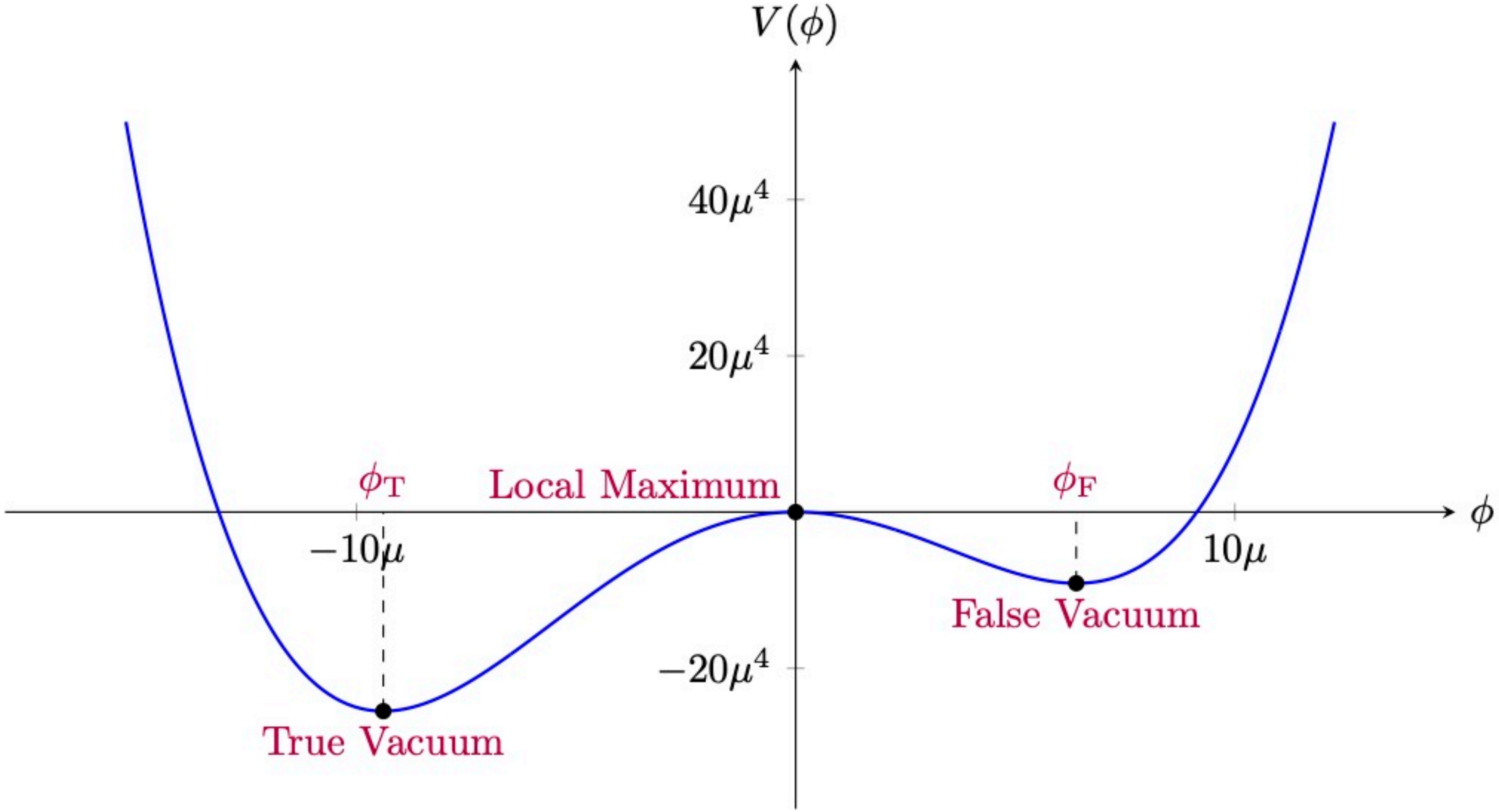
Vincent Vennin

David Wands

Higgs metastability in the Standard Model

- The Standard Model Higgs is an SU(2) doublet H, with potential $V(H) = -m^2|H|^2 + \lambda|H|^4$, leads to electroweak symmetry breaking, with a physical Higgs scalar h fluctuating around the minimum (vev).
- At high field values, quantum corrections and RG running modify the effective potential: the quartic coupling becomes scale dependent $\lambda \to \lambda(\mu)$ [1205.6497 Degrassi et. al.]
- For measured SM parameters, $\lambda(\mu)$ can run negative at high scale $\Longrightarrow$ effective potential develops a deeper minimum at very large H (assuming no new physics)
- In that case, the usual electroweak vacuum becomes a *false vacuum*, while the large-field minimum is a *true vacuum.* False vacuum is extremely long lived, but not absolutely stable.
- We might have to worry about tunneling to state with radically different physics

Potential for toy scalar ϕ



Vacuum Decay in Quantum Field Theory

- In QFT, false-vacuum decay is often described using a *bounce instanton*: a finite-action Euclidean solution $\delta S_{\mathrm{E}}/\delta\phi = 0$ that dominates the tunnelling probability $\Gamma/V \propto e^{-S_{\mathrm{E}}}$
- Classic analyses include the flat-space calculation of [Coleman, Callan 1977] and gravitational extension of [Coleman, DeLuccia 1980].
- Hawking-Moss (1981) calculation most relevant: treats false-vacuum decay in de Sitter space as a thermal activation of the homogeneous (zero) mode of the field, computing the transition probability by comparing the Euclidean de Sitter actions of the field sitting in the false vacuum and at the top of the barrier.

Why Open System effects matter

- Instanton methods describe vacuum decay in a *closed* quantum system. The field evolves unitarily, and quantum coherence between different field values is preserved. The tunnelling amplitude is determined entirely by the Euclidean bounce or Hawking–Moss solution.
- In realistic settings quantum fields are rarely isolated. Interactions with additional degrees of freedom (“the environment”) can convert quantum superpositions into classical mixtures. This process — *decoherence* — can strongly suppress the interference terms needed for tunnelling
- **Motivation**: Understand how vacuum selection actually proceeds in a cosmological background, we must move beyond closed-system instanton methods and study the *open-system dynamics* of the zero mode. This requires a framework that can track:
- **Model:** a spectator field in de Sitter spacetime interacting with an environment (2 choices).

De Sitter space

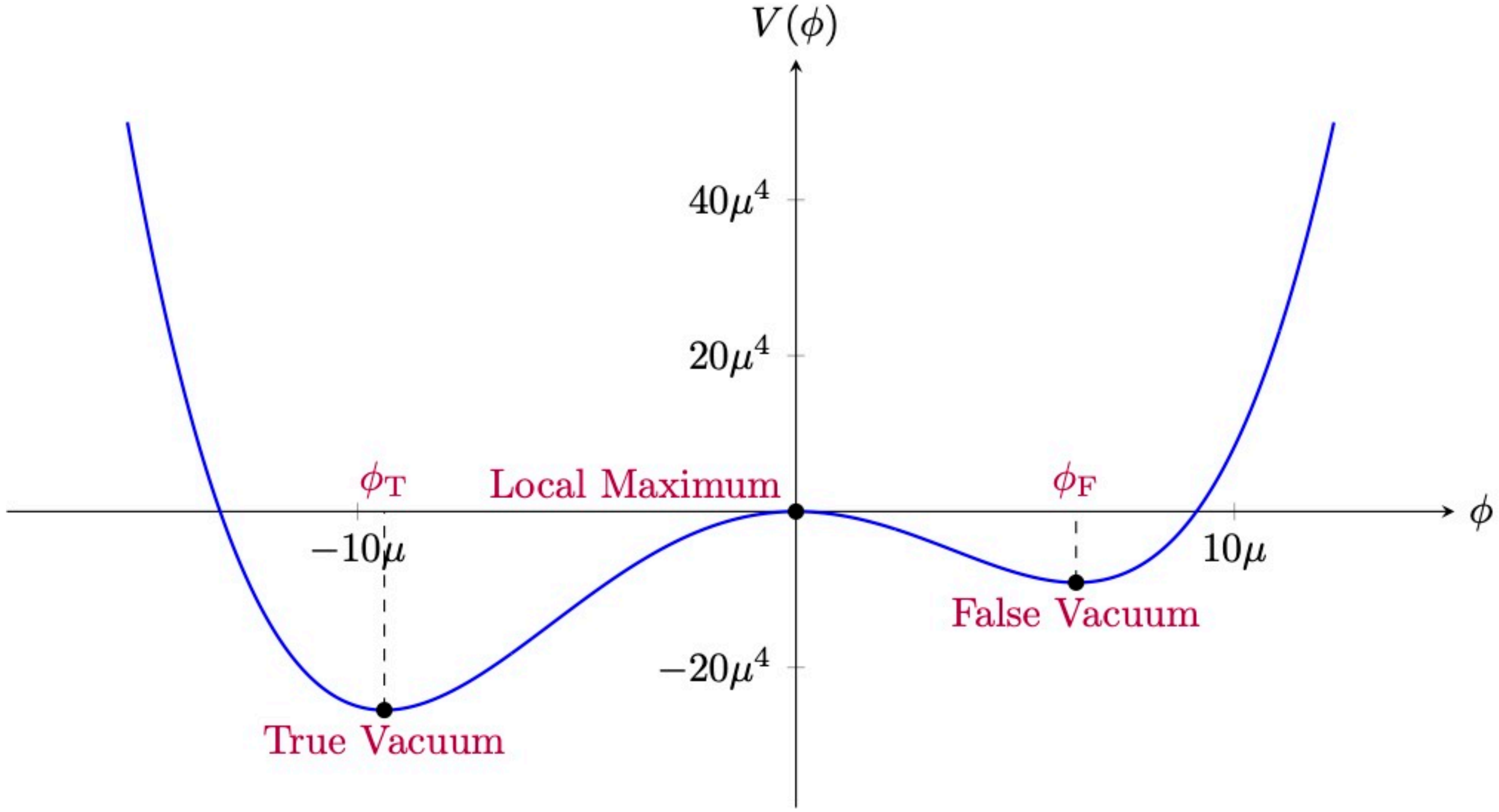
- De Sitter space: constant positive curvature and cosmological horizon with metric $\mathrm{d}s^2 = -\,\mathrm{d}t^2 + a^2(t)\mathrm{d}\mathbf{x}^2$ and scale factor $a(t) = e^{Ht}$. Hubble rate H sets the expansion scale such that $\dot{a}/a = H$
- Real spectator scalar $\Phi(t, \mathbf{x})$ couples to the background such that its equation of motion is $\ddot{\Phi} + 3H\dot{\Phi} + a^{-2}\,\nabla^2\Phi_{\mathbf{k}} + V'(\Phi) = 0$ (damped)
- We will use isotropy and spatial translation symmetry and focus on the $\mathbf{k} = 0$ mode:

$$\Phi(N, \mathbf{x}) = \int \frac{\mathrm{d}^3\mathbf{k}}{(2\pi)^3}\,\Phi_{\mathbf{k}}(t)e^{i\mathbf{k}\cdot\mathbf{x}} \qquad \Longrightarrow \qquad \phi(N) = \Phi_{\mathbf{k}=0}(t)$$

- The EoM for zero mode is $\quad \ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$
- Convenient time variable $N(t) = Ht$ so that $a(N) = e^N$.

Spectator Field in double well potential

$$V(\phi) = -\frac{1}{2}\mu^2\phi^2 + \frac{2}{3}\beta_3\mu\phi^3 + \frac{1}{4}(\beta_4^2 - \beta_3^2)\phi^4$$



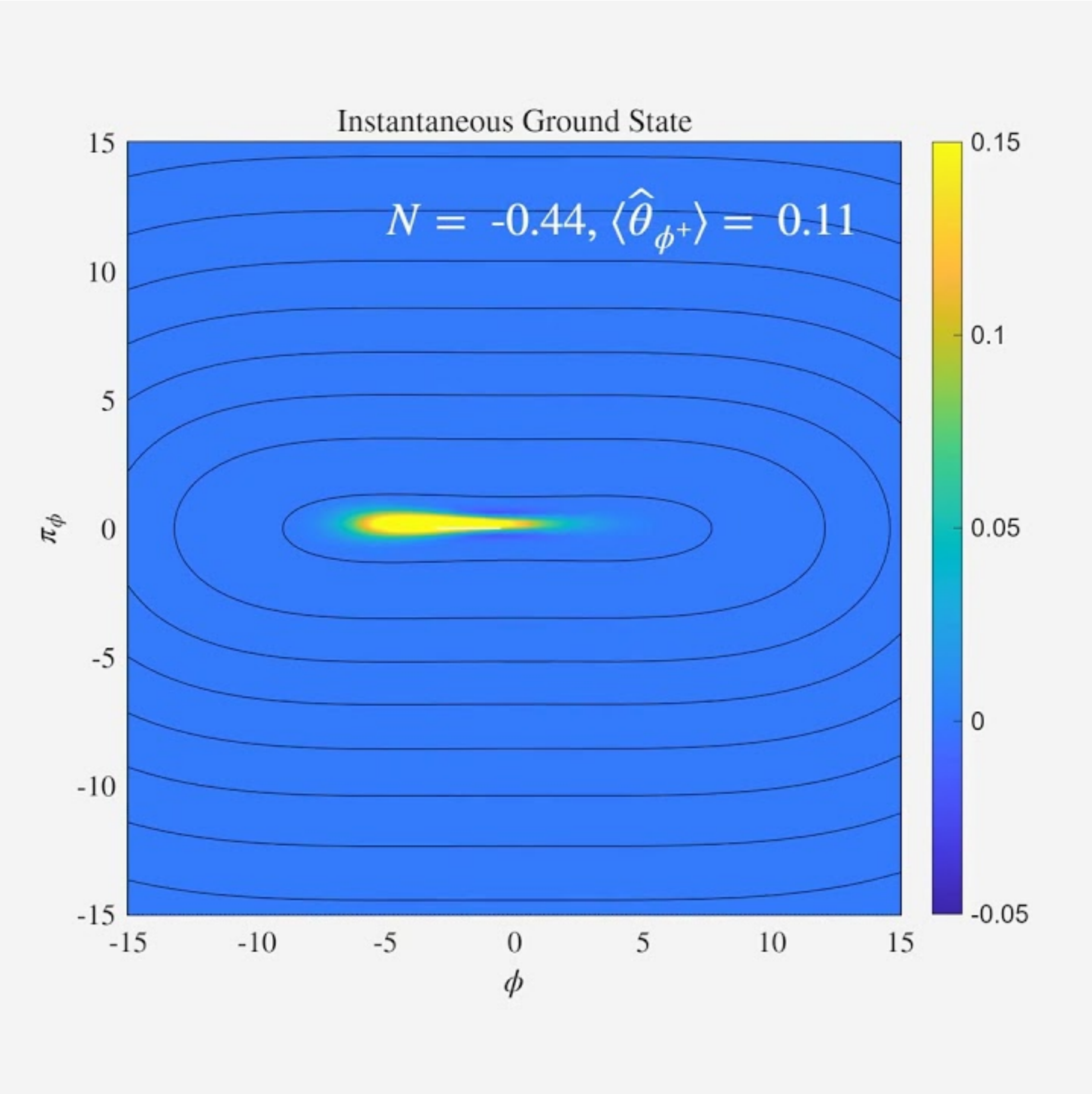
- We take $\mu > 0$, $\beta_4 > 0$ and $\beta_4^2 > \beta_3^2$
- $\phi_M = 0$ local maximum
- Minima $\phi_T = -\dfrac{\mu}{\beta_4 - \beta_3}$ and $\phi_T = +\dfrac{\mu}{\beta_4 + \beta_3}$
- Instability scale at barrier $V''(\phi_M) = -\mu^2$
- Adiabaticity parameter $\widetilde{\mu} = \dfrac{\mu}{H}$ tell us whether ϕ evolves faster (adiabatic $\widetilde{\mu} \gg 1$) or slower (non-adiabatic $\widetilde{\mu} \ll 1$) than background

(Closed) Unitary evolution under double well potential

- Free hamiltonian $\hat{K}_{\rm S}(N) = \dfrac{e^{-3N}}{2H}\hat{\pi}_\phi^2 + \dfrac{e^{3N}}{H}\Big[-\dfrac{1}{2}\mu^2\phi^2 + \dfrac{2}{3}\,\beta_3\mu\phi^3 + \dfrac{1}{4}\,(\beta_4^2 - \beta_3^2)\,\phi^4 \Big]$
- Canonical momentum $\hat{\pi}_\phi(N) = e^{3N}H\partial_N\phi$ with $[\hat{\phi}, \hat{\pi}_\phi] = i$
- Solve $\partial_N\hat{\rho}(N) = -\,i[\hat{K}_{\rm S}(N), \hat{\rho}(N)] \quad \Longrightarrow \quad$ Numerical simulations needed!
- Monitor right-well occupation: $P_{\rm false}(N) := {\rm Tr}\left[\hat{\theta}_{\phi^+}\hat{\rho}(N)\right] \quad$ with $\hat{\theta}_{\phi^+} = \displaystyle\int_0^\infty {\rm d}\phi\ |\phi\rangle\langle\phi|$
- Pick parameters so that Kinetic $\sim$ Potential in Hamiltonian near $N = 0$ (barrier-switch on period)
- Start in instantaneous ground state.
- This means $P_{\rm false}(N \simeq -2) \simeq 0.5$ (kinetic dominates by $\propto e^{6N}$).
- Also track Wigner function $W(\phi, \pi_\phi; N)$
- Can also track Purity $:= {\rm Tr}[\rho^2(N)]$ (but it is 1 here for closed evolution)

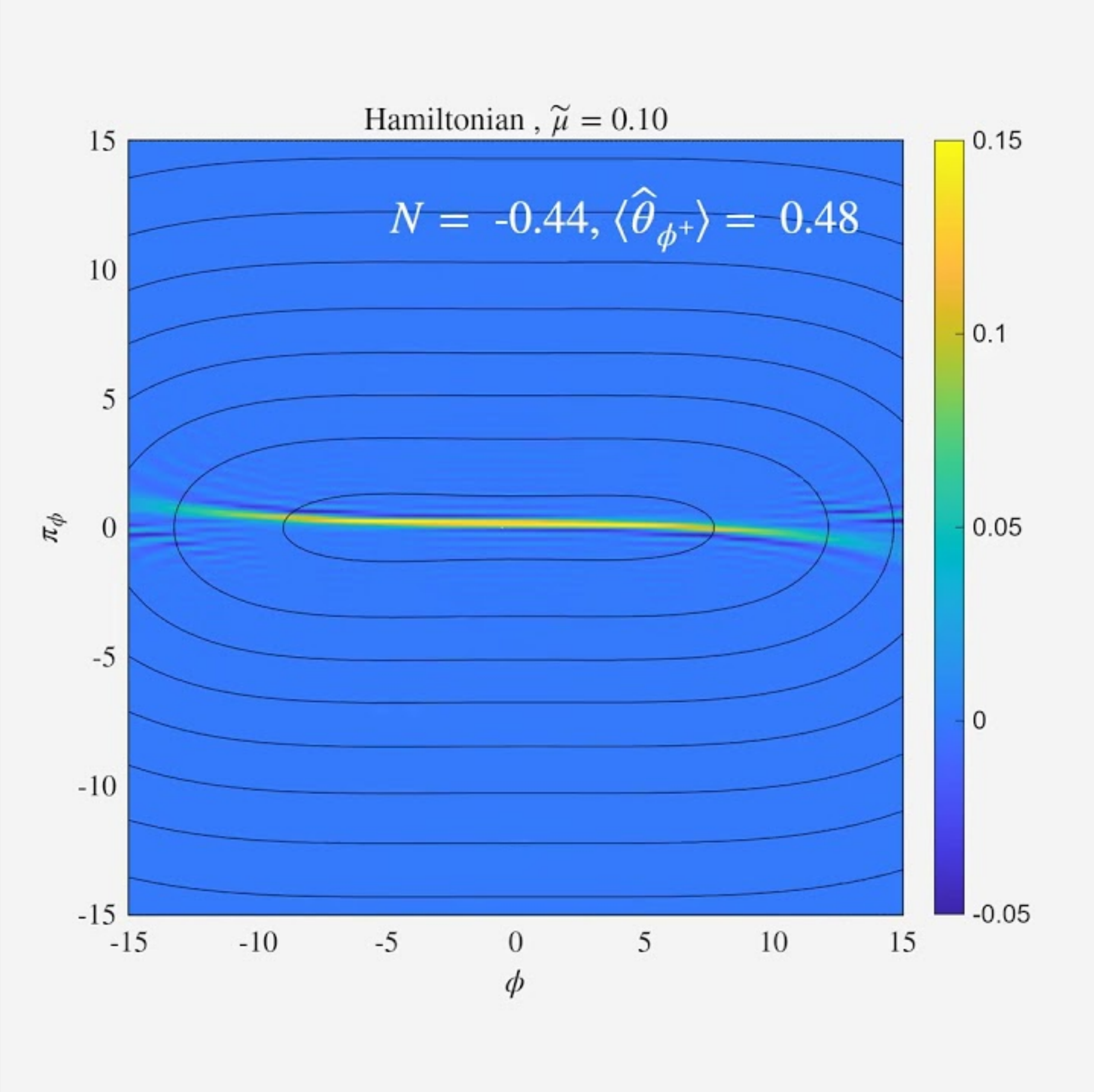
Closed evolution: Adiabatic limit $\widetilde{\mu} \to \infty$

- Solve $\partial_N \hat{\rho}(N) = -i[\hat{K}_\mathrm{S}(N), \hat{\rho}(N)]$ with free hamiltonian $\hat{K}_\mathrm{S}(N) = \frac{e^{-3N}}{2H}\hat{\pi}_\phi^2 + \frac{e^{3N}}{H}V(\phi)$



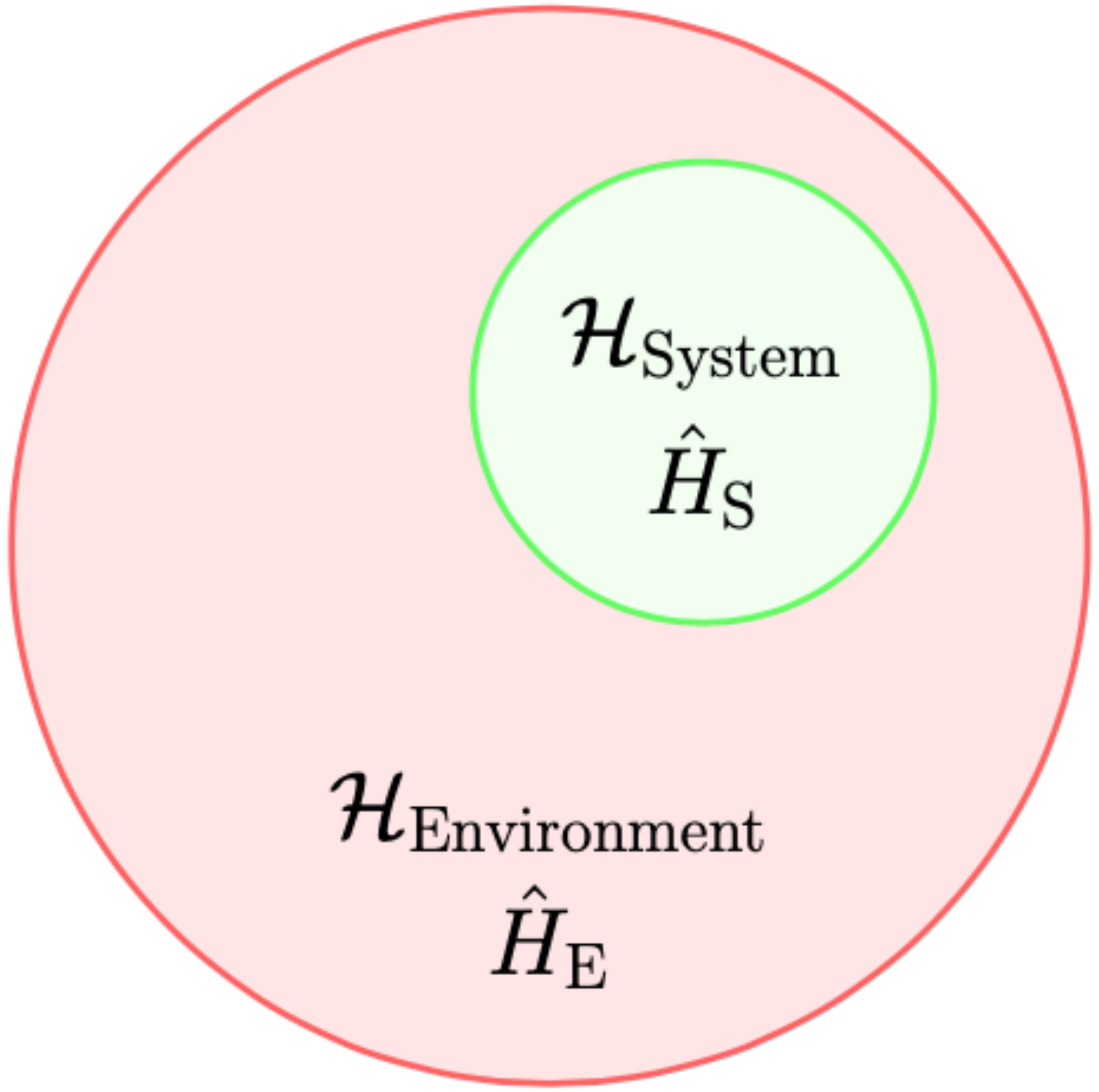
(Closed) Unitary evolution: NON-Adiabatic

- Solve $\partial_N \hat{\rho}(N) = -i[\hat{K}_S(N), \hat{\rho}(N)]$ with free hamiltonian $\hat{K}_S(N) = \frac{e^{-3N}}{2H}\hat{\pi}_\phi^2 + \frac{e^{3N}}{H}V(\phi)$



- Interference fringes: freezes into a superposition over both vacuua

Open quantum systems: “no system is really isolated”



$$\hat{H} = \hat{H}_{\text{S}} \otimes \mathbb{I}_{\text{E}} + \mathbb{I}_{\text{S}} \otimes \hat{H}_{\text{E}}$$

- Will now generalize to a GKLS/Lindblad equation:
$$\partial_N \hat{\rho} = -i\left[\hat{K}_S(N), \hat{\rho}\right] - \frac{1}{2}\sum_\alpha \gamma_\alpha(N)\left[\hat{L}_\alpha, \left[\hat{L}_\alpha, \hat{\rho}\right]\right]$$
- Open (non-unitary) evolution Jump operators $\hat{L}_\alpha$
- Stochastic unravelling: Ito form of stochastic Schrodinger equation for $|\psi\rangle$:
$$\mathrm{d}|\psi\rangle = -i\hat{K}_S(N)|\psi\rangle \mathrm{d}N - \frac{1}{2}\sum_\alpha \gamma_\alpha(N)\hat{L}_\alpha^2|\psi\rangle \mathrm{d}N + i\sum_\alpha \sqrt{\gamma_\alpha(N)}\hat{L}_\alpha|\psi\rangle\, \mathrm{d}W_\alpha$$
- Wiener increments $\mathrm{d}W_\alpha$
- Averaging over trajectories reproduces the Lindblad $\hat{\rho}$

Two Sources of Open-System Dynamics in de Sitter

We treat the long-wavelength modes of ϕ as an *open quantum system*. Two mechanisms generate open-system effects:

1. **Stochastic Inflation**
   - As modes cross the Hubble radius, they are traced out of the long-wavelength sector.
   - Creates *stochastic noise* in the dynamics of the coarse-grained field

2. Extra Environment Fields

- Other fields well-motivated; gravity couples universally
- Consider multiple extra fields $\chi_{\mathfrak{a}}$ interacting like a quartic $\mathscr{L}_{\text{int}} \sim \lambda\phi\chi_{\mathfrak{a}}^3$

Open dynamics: Stochastic Inflation

- Starting from the zero mode of the field ϕ and $k < \sigma a H$, take $\sigma \ll 1$

$$\mathrm{d}\phi = \frac{e^{-3N}}{H}\pi_\phi\,\mathrm{d}N + \frac{H}{2\pi}\mathrm{d}W \quad \text{and} \quad \mathrm{d}\pi_\phi = -\frac{e^{3N}}{H}V'(\phi)\mathrm{d}N$$

- Assumes the field is light so that $\widetilde{\mu} = \dfrac{\mu}{H} \ll 1$

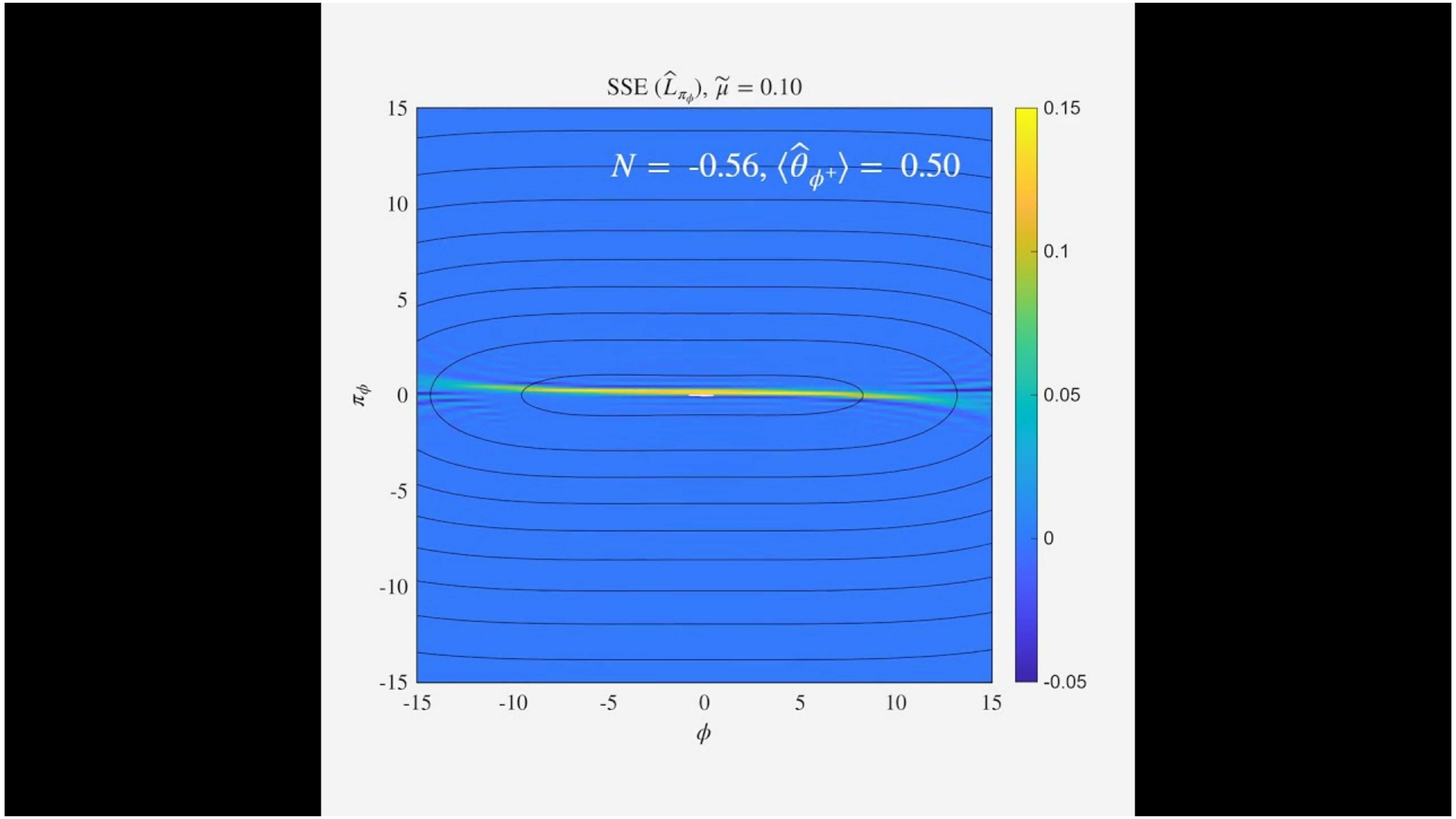
- Unique normalized SSE

$$\mathrm{d}\,|\psi\rangle = -\,i\hat{K}_S(N)\,|\psi\rangle\mathrm{d}N - \frac{1}{2}\Gamma_\pi\,\hat{\pi}_\phi^2\,|\psi\rangle\mathrm{d}N - i\sqrt{\Gamma_\pi}\,\hat{\pi}_\phi\,|\psi\rangle\,\mathrm{d}W_\pi \quad \text{with} \quad \Gamma_\pi = \frac{H^2}{4\pi^2}$$

- Lindblad equation is $\partial_N\hat{\rho} = -\,i\left[\hat{K}_S(N), \hat{\rho}\right] - \dfrac{1}{2}\Gamma_\pi\,[\hat{\pi}_\phi, [\hat{\pi}_\phi, \hat{\rho}]]$

Stochastic Inflation: example SSE trajectory

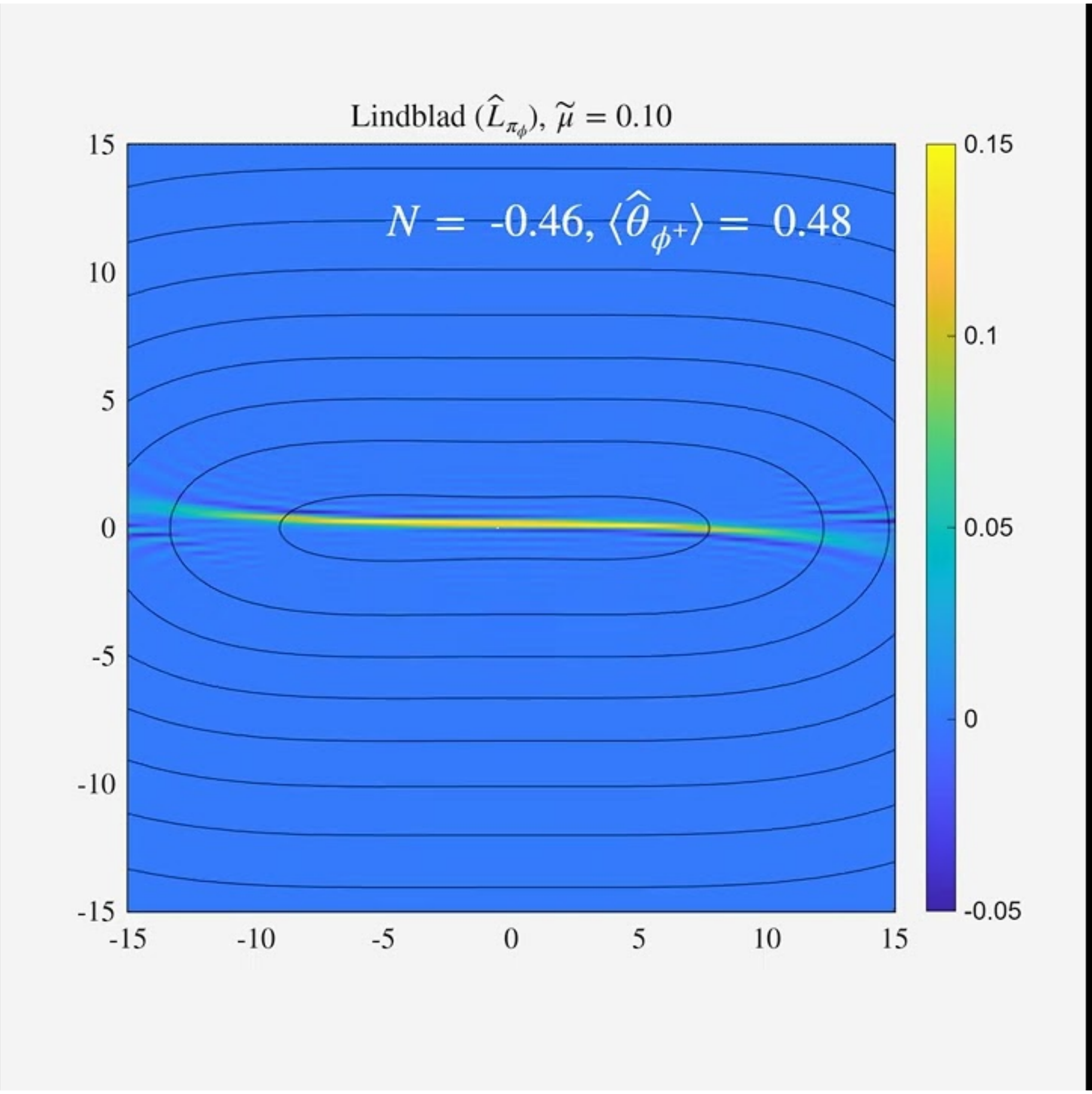
- Solve $\mathrm{d}\,|\psi\rangle = -\,i\hat{K}_S(N)\,|\psi\rangle\mathrm{d}N - \frac{1}{2}\Gamma_\pi\,\hat{\pi}_\phi^2\,|\psi\rangle\mathrm{d}N - i\sqrt{\Gamma_\pi}\,\hat{\pi}_\phi\,|\psi\rangle\,\mathrm{d}W_\pi$ with $\Gamma_\pi = \frac{H^2}{4\pi^2}$



- The $\hat{\pi}_\phi$ kicks shift things left or right; no vacuum picked. Lots of nterferences

Stochastic Inflation: Lindblad

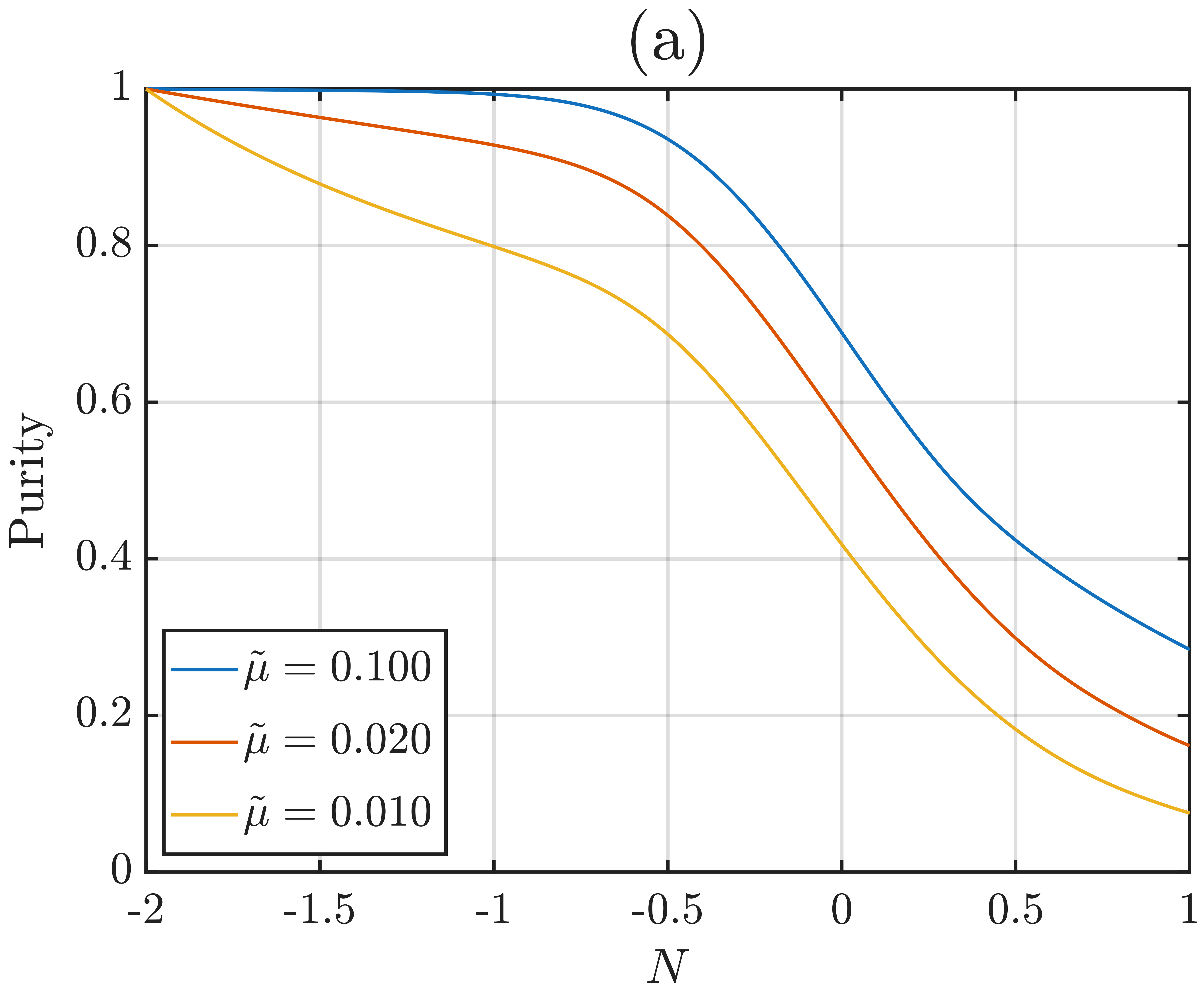
- Solve $\partial_N \hat{\rho} = -i\left[\hat{K}_S(N), \hat{\rho}\right] - \frac{1}{2}\Gamma_\pi [\hat{\pi}_\phi, [\hat{\pi}_\phi, \hat{\rho}]]$



- Lots of interference still. 0 average movement. State is mixed after averaging

Stochastic Inflation: Purity

- State is clearly mixed

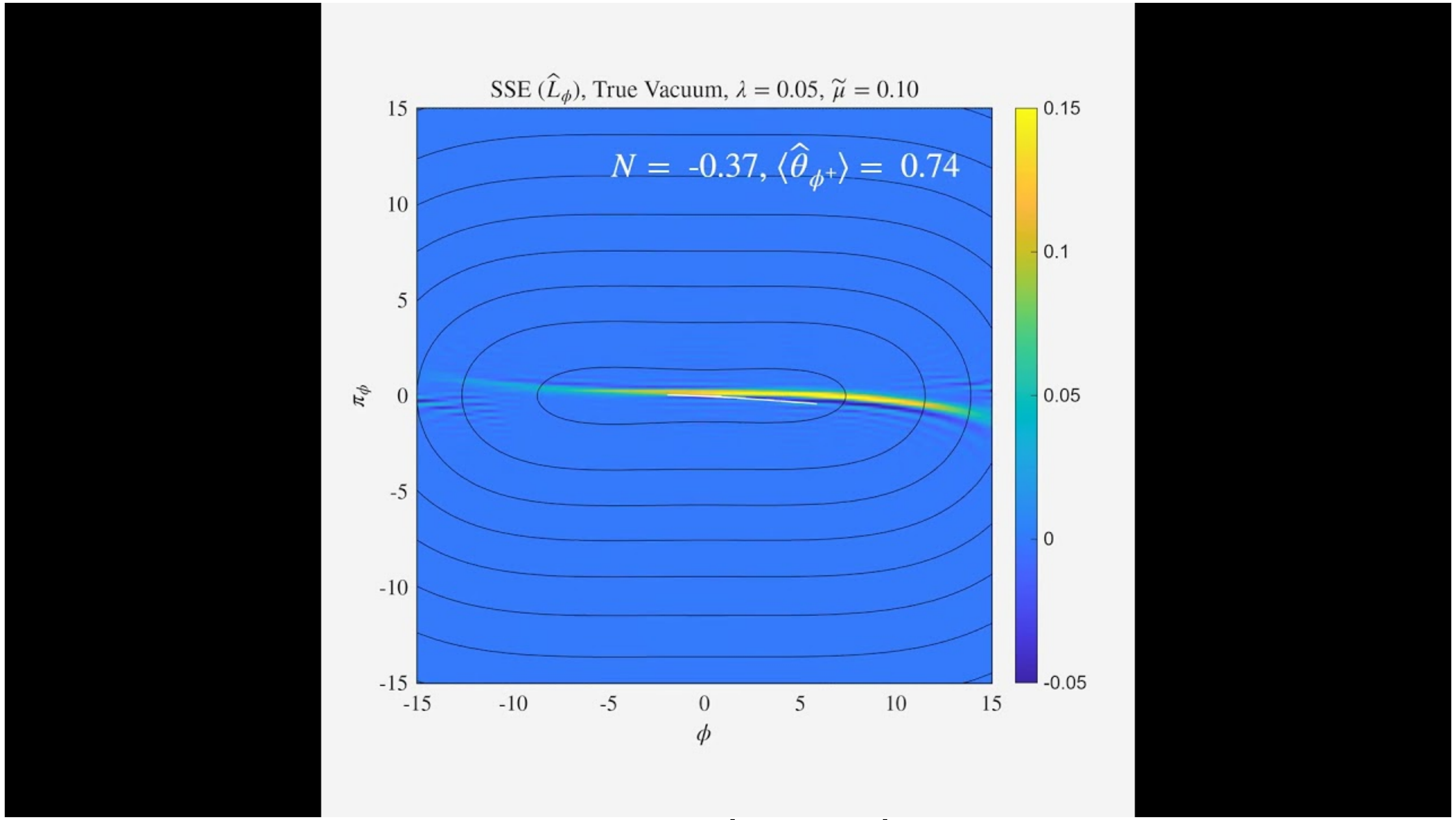


Open dynamics: extra environmental fields

- Turn on quartic interaction at initial time: $\mathscr{L}_{\rm int} \sim \lambda \sum_{\mathfrak{a}} \phi \chi_{\mathfrak{a}}^3$
- Pick many, MANY field and choose their spectrum (a la Caldeira-Leggett) so Markovian dynamics emerge
- Lindblad equation is
$$\partial_N \hat{\rho} = -i\left[\hat{K}_S(N), \hat{\rho}\right] - \frac{1}{2}\Gamma_\phi(N)\,[\hat{\phi}, [\hat{\phi}, \hat{\rho}]] \quad \text{with } \Gamma_\phi(N) = \frac{131\pi\lambda^2 e^{6N}}{256\,\mu^5}$$
- Convenient SSE unravelling (better suited for environmental monitoring)
$$\mathrm{d}\,|\psi\rangle = -\,i\hat{K}_S\,|\psi\rangle \mathrm{d}N - \tfrac{1}{2}\Gamma_\phi(N)\left(\hat{\phi} - \langle\hat{\phi}\rangle\right)^2 |\psi\rangle \mathrm{d}N + \sqrt{\Gamma_\phi(N)}\left(\hat{\phi} - \langle\hat{\phi}\rangle\right)|\psi\rangle\,\mathrm{d}W_\phi$$

Extra fields: example SSE trajectory

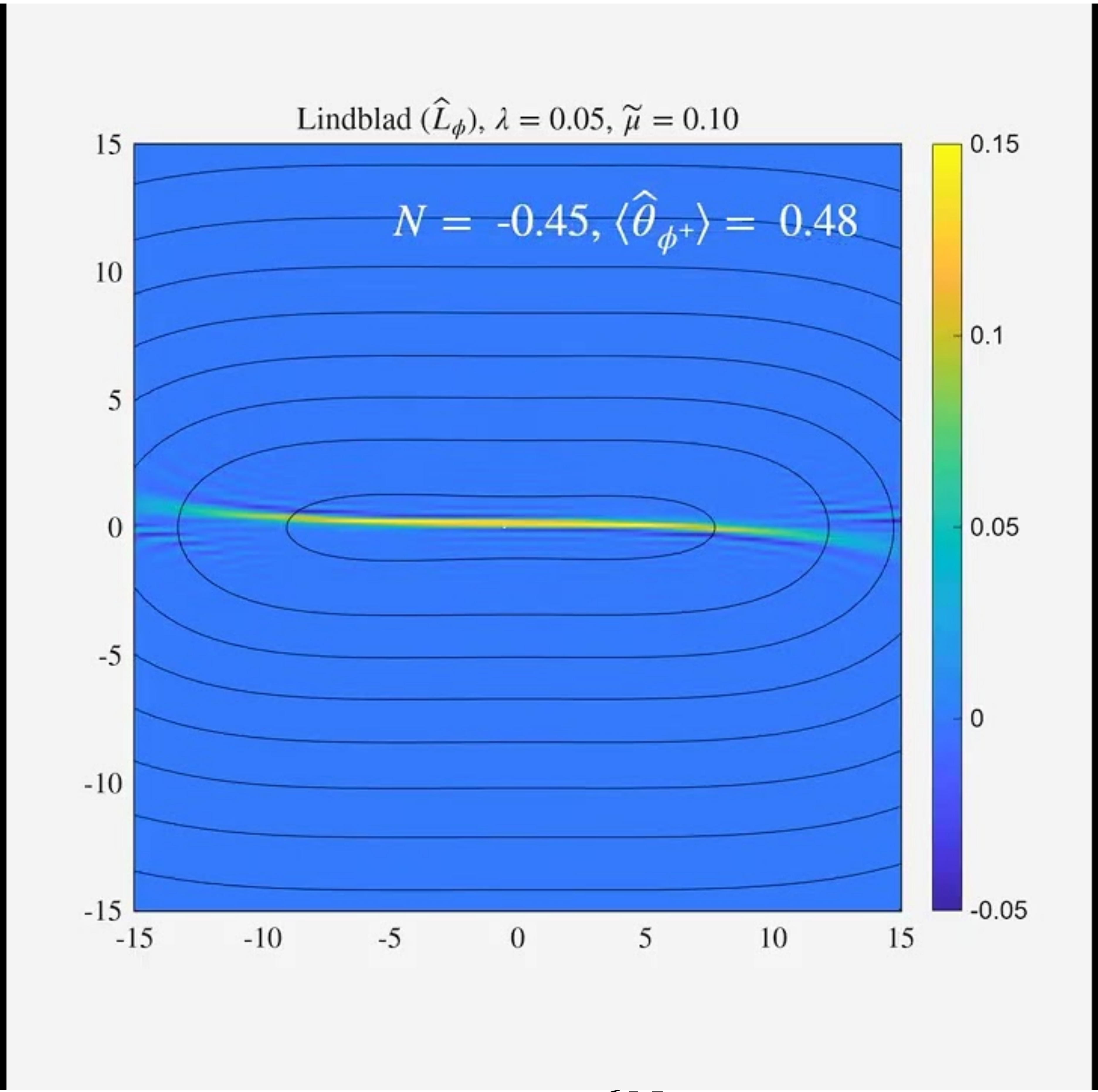
- Solve $\mathrm{d}\,|\psi\rangle = -\,i\hat{K}_S\,|\psi\rangle\mathrm{d}N - \frac{1}{2}\Gamma_\phi(N)\left(\hat{\phi} - \langle\hat{\phi}\rangle\right)^2|\psi\rangle\mathrm{d}N + \sqrt{\Gamma_\phi(N)}\left(\hat{\phi} - \langle\hat{\phi}\rangle\right)|\psi\rangle\;\mathrm{d}W_\phi$



- Always picks a vacuum. Gets very localized $\hat{\phi} \to \langle\hat{\phi}\rangle$ and stays there (less and less hopping). "Cosmic Lockdown"

Extra fields: Lindblad

- Solve $\partial_N \hat{\rho} = -i\left[\hat{K}_S(N), \hat{\rho}\right] - \frac{1}{2}\Gamma_\phi(N)\,[\hat{\phi}, [\hat{\phi}, \hat{\rho}]]$



- Very faint/diffusive: fringes killed by strong e^{6N} decoherence. It picked a well.

“Cosmic Lockdown”

The phenomenon in which strong environment-induced decoherence rapidly localizes the field into one of the potential minima and then continually suppresses coherences, thereby locking the system into whichever vacuum it has stochastically selected.

What about both?

- Including both effects may change the story; stochastic inflation kicks could cause (thermal-like) barrier hopping after the field has localized.

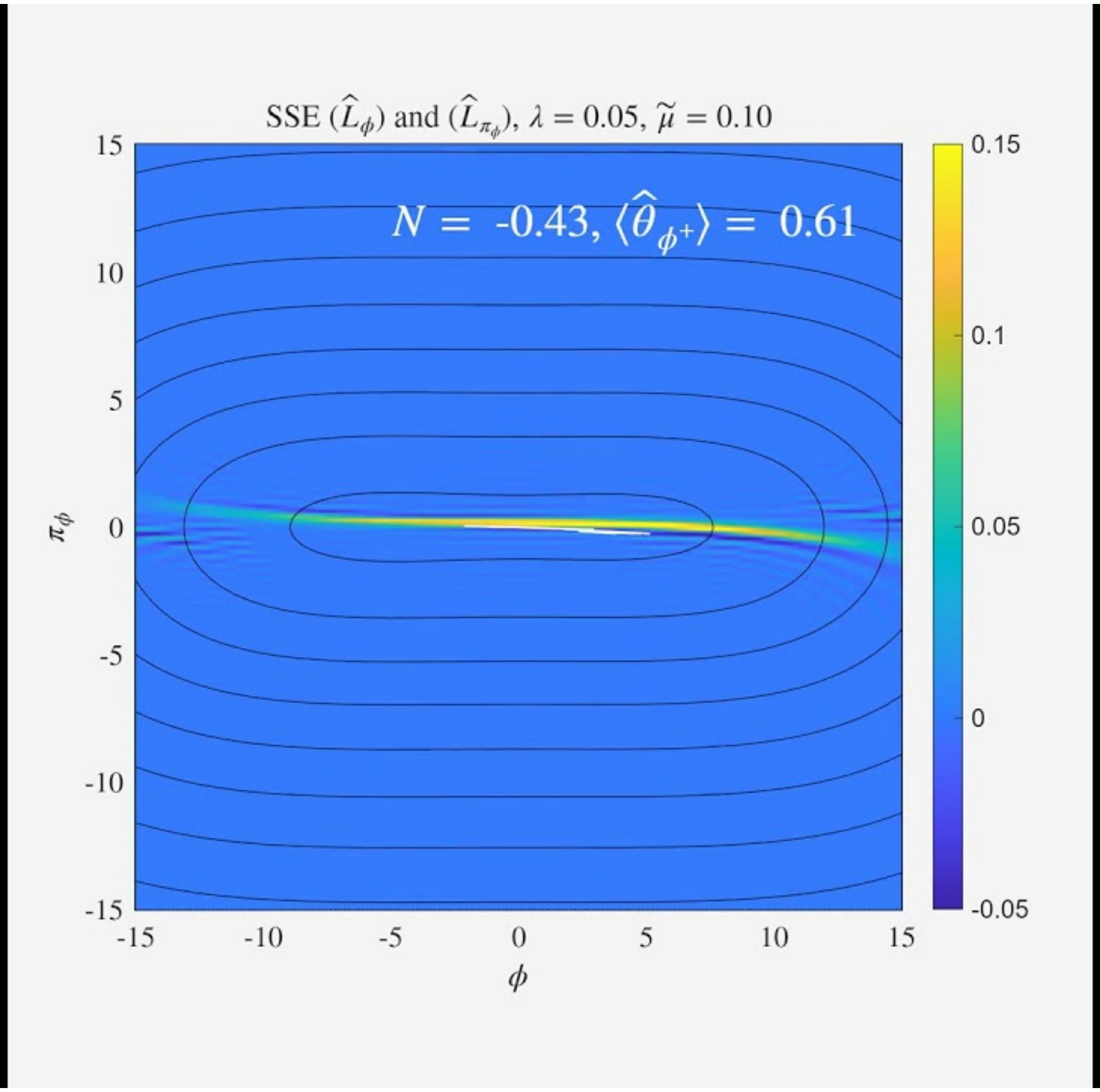
- Lindblad equation is $\partial_N \hat{\rho} = -i\left[\hat{K}_S(N), \hat{\rho}\right] + \dfrac{131\pi\lambda^2 e^{6N}}{512\,\mu^5}\,[\hat{\phi}, [\hat{\phi}, \hat{\rho}]] + \dfrac{H^2}{8\pi^2}\,[\hat{\pi}_\phi, [\hat{\pi}_\phi, \hat{\rho}]]$

- SSE unravelling is also combined:

$$\mathrm{d}\,|\psi\rangle = -\,i\hat{K}_S\,|\psi\rangle \mathrm{d}N - \frac{131\pi\lambda^2 e^{6N}}{512\mu^5}\left(\hat{\phi} - \langle\hat{\phi}\rangle\right)^2 |\psi\rangle \mathrm{d}N - \frac{H^2}{8\pi^2}\hat{\pi}_\phi^2\,|\psi\rangle \mathrm{d}N$$
$$+\sqrt{\frac{131\pi\lambda^2 e^{6N}}{256\mu^5}}\left(\hat{\phi} - \langle\hat{\phi}\rangle\right)|\psi\rangle\,\mathrm{d}W_1 - \frac{iH}{2\pi}\hat{\pi}_\phi\,|\psi\rangle\,\mathrm{d}W_2$$

Combined: example SSE trajectory

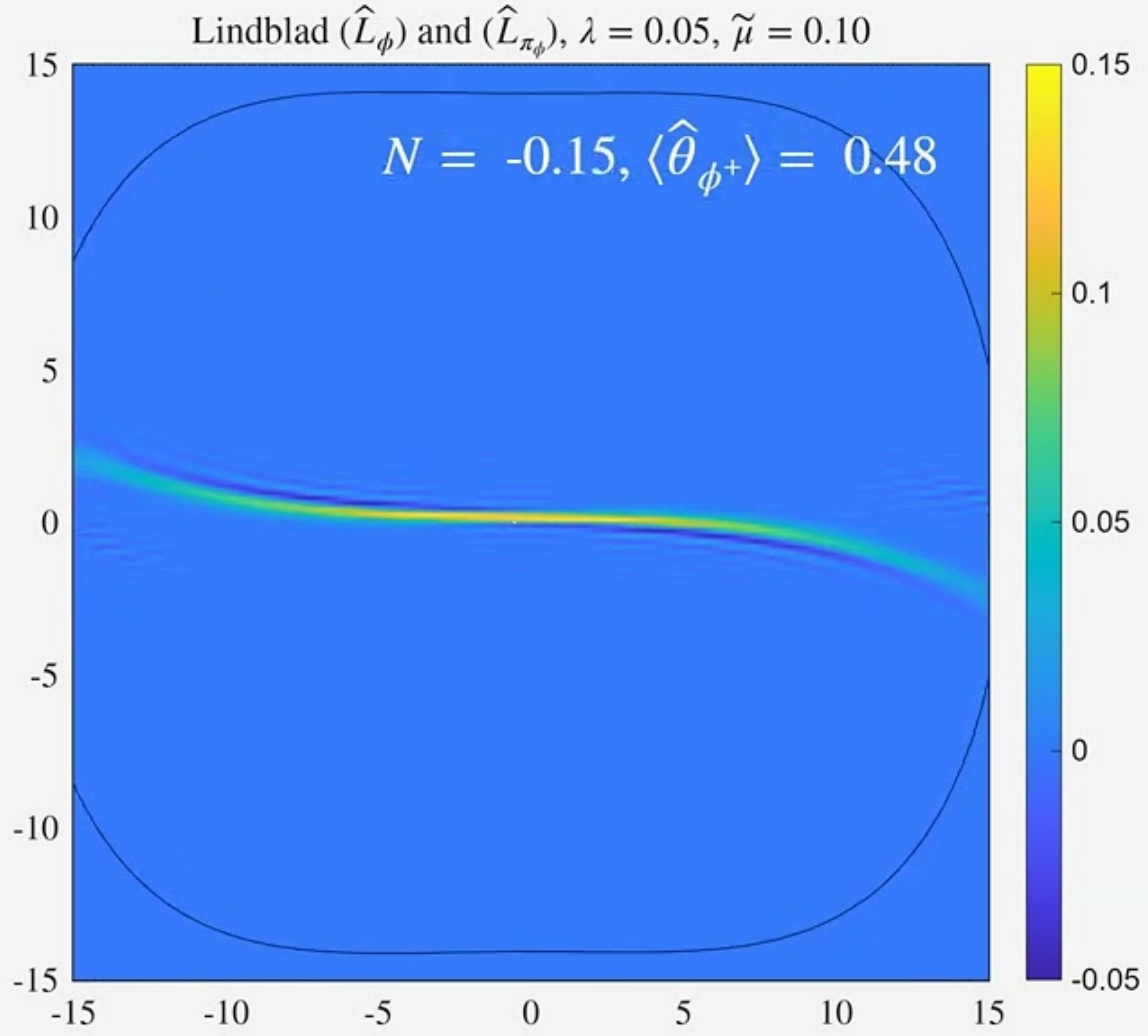
- Solve $\mathrm{d}|\psi\rangle = -i\hat{K}_S|\psi\rangle\mathrm{d}N - \frac{131\pi\lambda^2 e^{6N}}{512\mu^5}\left(\hat{\phi} - \langle\hat{\phi}\rangle\right)^2|\psi\rangle\mathrm{d}N - \frac{H^2}{8\pi^2}\hat{\pi}_\phi^2|\psi\rangle\mathrm{d}N + \sqrt{\frac{131\pi\lambda^2 e^{6N}}{256\mu^5}}\left(\hat{\phi} - \langle\hat{\phi}\rangle\right)|\psi\rangle\,\mathrm{d}W_1 - \frac{iH}{2\pi}\hat{\pi}_\phi|\psi\rangle\,\mathrm{d}W_2$



- Always picks a vacuum (but takes a little longer, a little more active)

Combined: Lindblad

- Solve $\partial_N \hat{\rho} = -i\left[\hat{K}_S(N), \hat{\rho}\right] + \frac{131\pi\lambda^2 e^{6N}}{512\,\mu^5}\,[\hat{\phi}, [\hat{\phi}, \hat{\rho}]] + \frac{H^2}{8\pi^2}\,[\hat{\pi}_\phi, [\hat{\pi}_\phi, \hat{\rho}]]$



- Very similar to before: strong decoherence

Combined dynamics: how likely to hop over?

- At late times we saw $\hat{\phi} - \langle \hat{\phi} \rangle \simeq 0$ and the system has entered classical over-damped regime
- Only way a vacuum transition can happen is through thermal-like, over-the-barrier hopping
- False-vacuum escape rate is given by the **Eyring–Kramers (Arrhenius) formula:**
$$\langle N_{\mathrm{F}\to\mathrm{T}} \rangle = \frac{3H^2\pi}{\mu^2}\sqrt{\frac{2(\beta_3+\beta_4)}{\beta_4}}\exp\left(\frac{\pi^2(\beta_3+3\beta_4)\mu^4}{9(\beta_3+\beta_4)^3H^4}\right)$$
- The mean escape time is *exponentially* sensitive to the barrier height. For our parameters $\langle N_{\mathrm{F}\to\mathrm{T}} \rangle \simeq 400$ e-folds
- Once decoherence has locked the system into a vacuum, classical over-the-barrier transitions are exponentially suppressed: reinforces the "cosmic lockdown"

Conclusions

- Environment-induced decoherence rapidly suppresses interference, producing a *cosmic lockdown* where the system remains in whichever vacuum it stochastically selects.
- **Late-time transitions** occur only through classical Arrhenius hopping and are *exponentially unlikely* over realistic inflationary durations.
- How generic is the effect?
- **Future work:** extend beyond the zero-mode approximation to include spatial correlations, mode coupling, and Hubble-patch statistics. Beyond light fields? More realistic interactions?

Thank you!