Quantum Decoherence during Inflation

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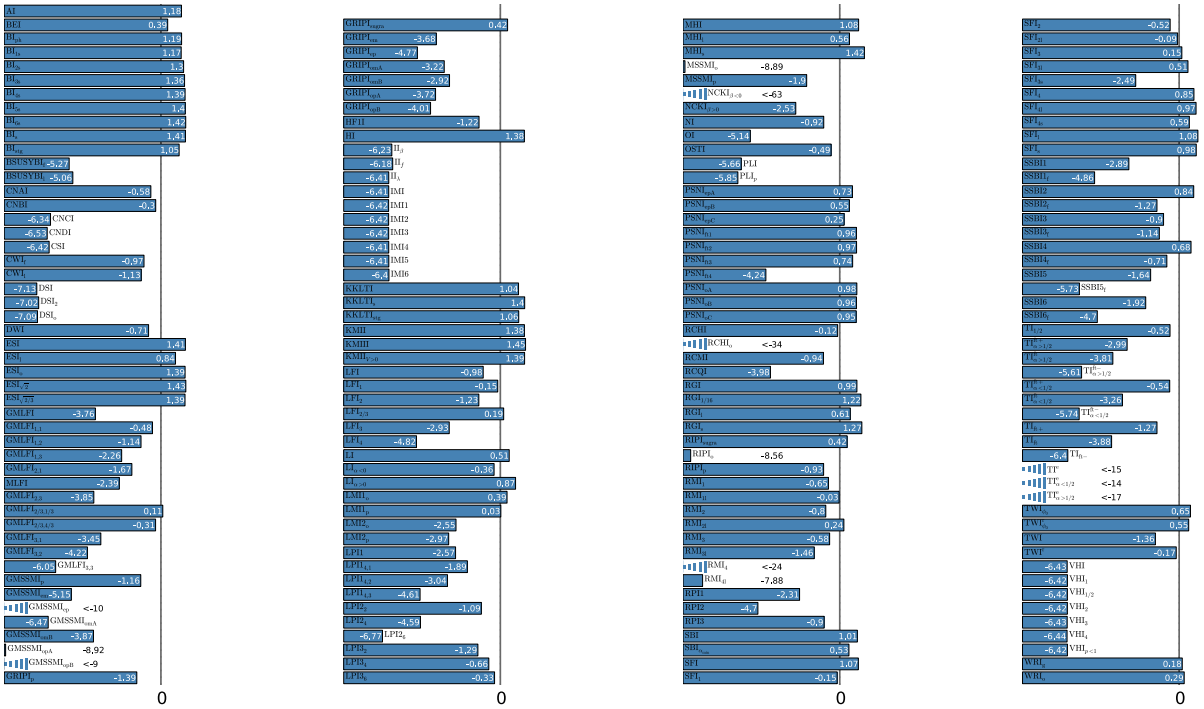
The primordial Universe is a high-energy laboratory

- Inflation is a **high-energy** phase of accelerated expansion in the early Universe

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t)\,\mathrm{d}\vec{x}^2 \quad \text{with} \quad \ddot{a} > 0 \quad \text{and} \quad \rho \leq \left(10^{16}\,\mathrm{GeV}\right)^4$$



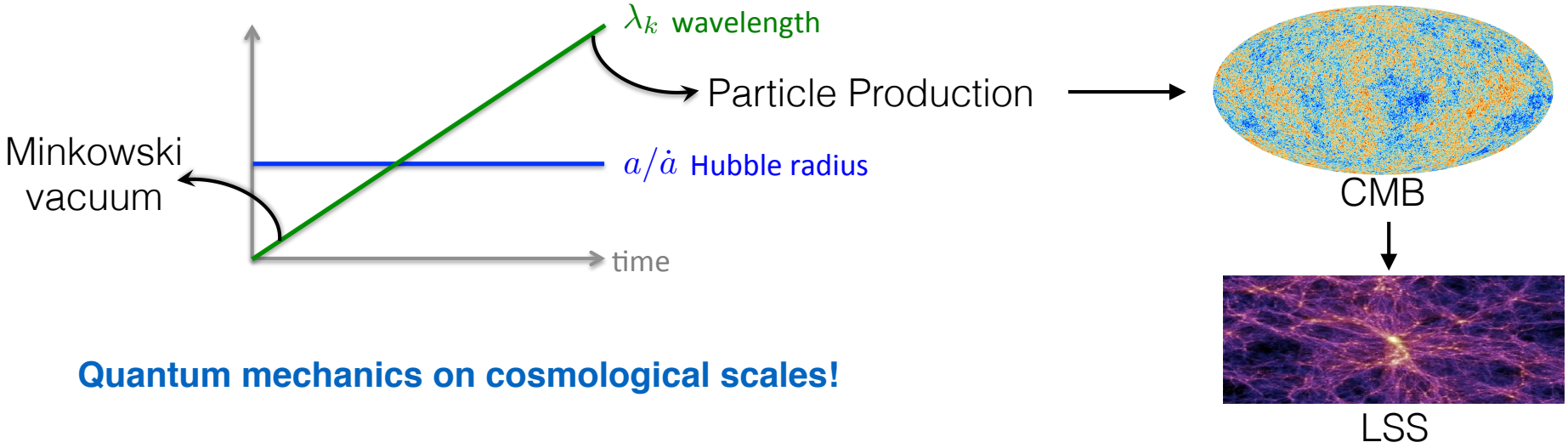
Bayesian evidence of single-field models [*Martin, Ringeval, VV 2014*]

The primordial Universe is a high-energy laboratory

- Inflation is a **high-energy** phase of accelerated expansion in the early Universe

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t)\,\mathrm{d}\vec{x}^2 \quad \text{with} \quad \ddot{a} > 0 \quad \text{and} \quad \rho \leq \left(10^{16}\,\mathrm{GeV}\right)^4$$

- Quantum vacuum fluctuations are stretched to cosmological distances and seed the large-scale structure of our Universe



Quantum mechanics on cosmological scales!

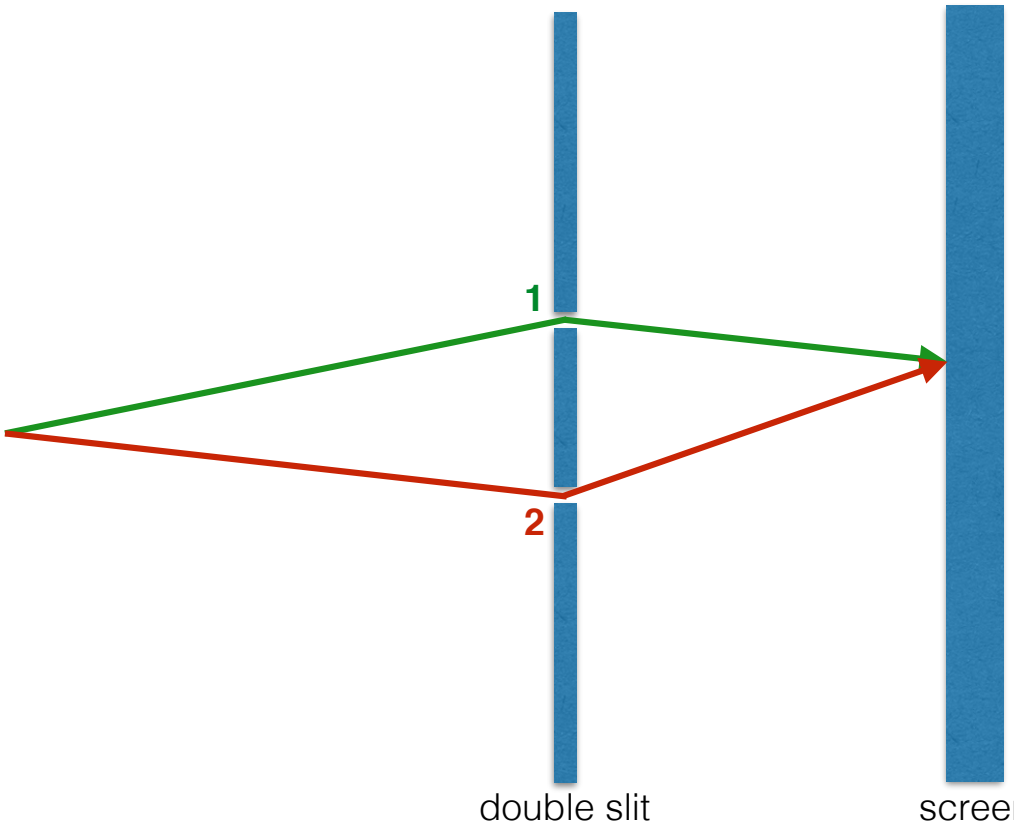
Outline

Based on arXiv:1801.09949, J. Martin & V. Vennin
arXiv:1805.05609, J. Martin & V. Vennin

- Quantum decoherence and the quantum-to-classical transition of cosmological fluctuations
- Modelling the influence of the environment with a Lindblad equation
- Power Spectrum & Non-Gaussianities
- Decoherence parameter

Can we achieve decoherence without spoiling scale invariance?

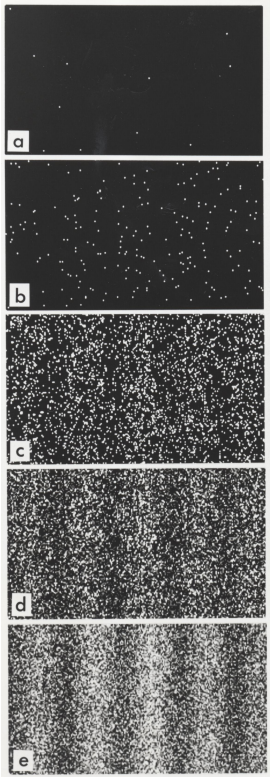
Quantum Decoherence: The double-slit experiment



$$|\Psi\rangle = |\Psi_1\rangle + |\Psi_2\rangle$$

interference

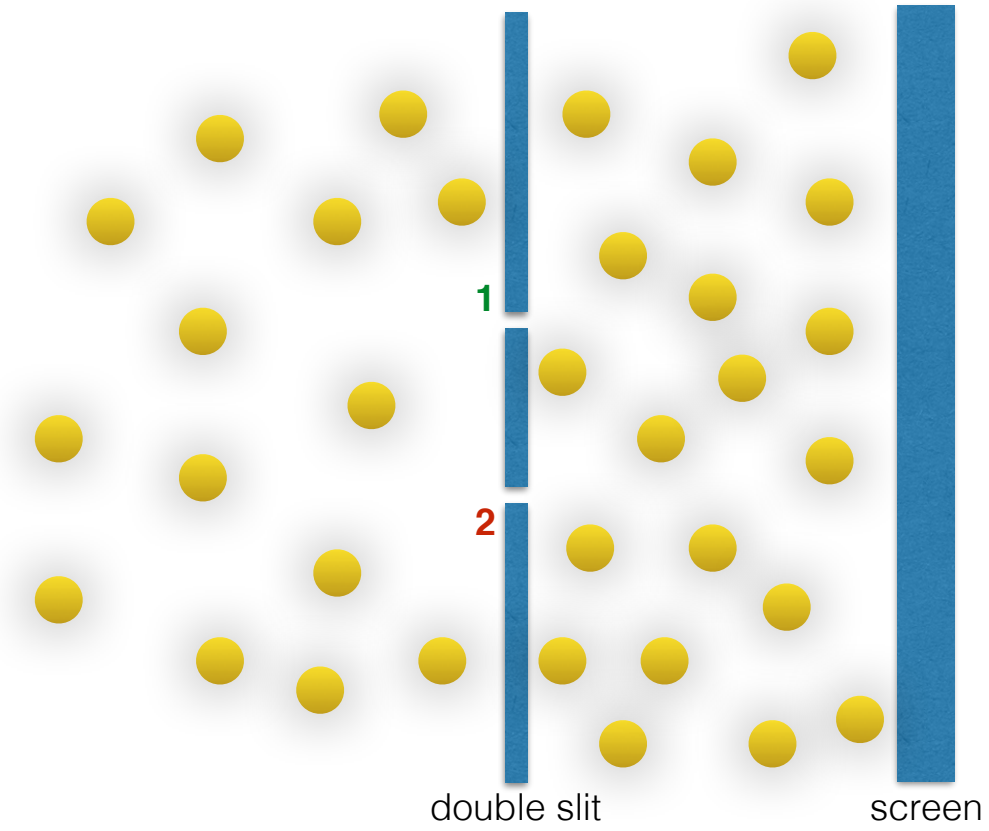
phase coherence



$$\Psi(x) = \Psi_1(x) + \Psi_2(x)$$
$$\propto e^{i\phi_1(x)} + e^{i\phi_2(x)}$$

$$p(x) = |\Psi(x)|^2$$
$$= |\Psi_1(x)|^2 + |\Psi_2(x)|^2 + \Psi_1(x)\Psi_2^*(x) + \Psi_1^*(x)\Psi_2(x)$$
$$= 2 + 2\cos(\phi_1 - \phi_2)$$

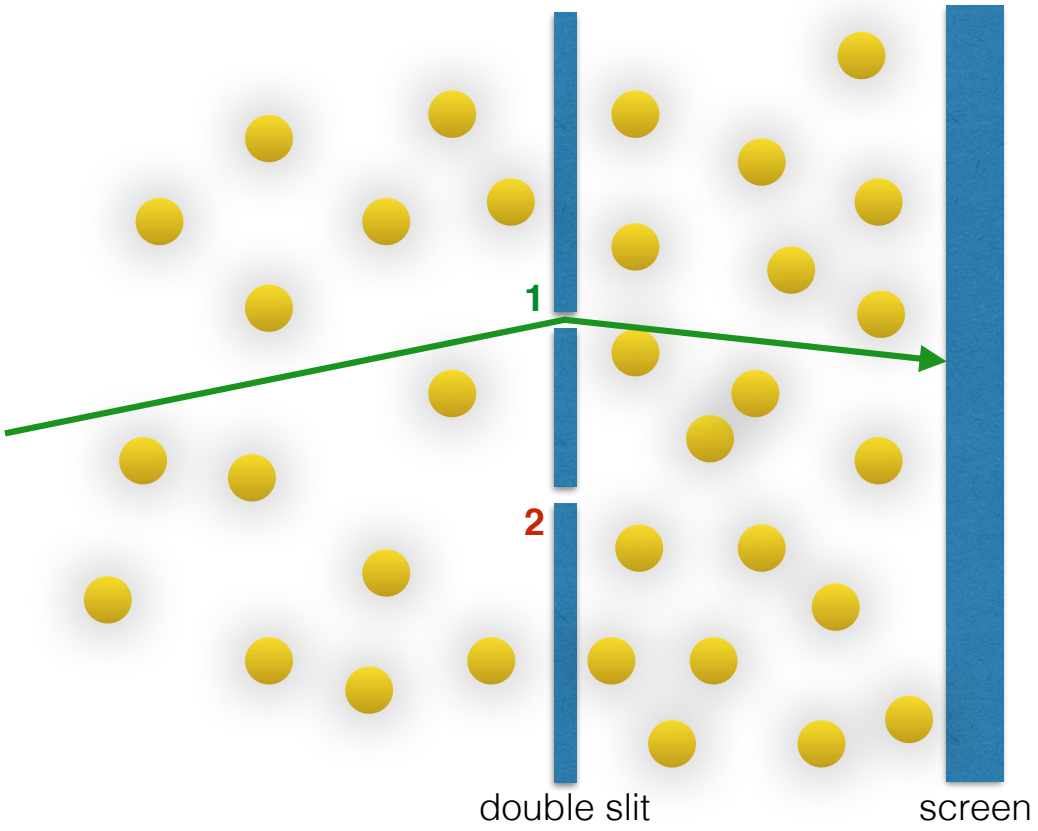
Quantum Decoherence: The double-slit experiment



Adding the environment

$|\mathcal{E}\rangle$

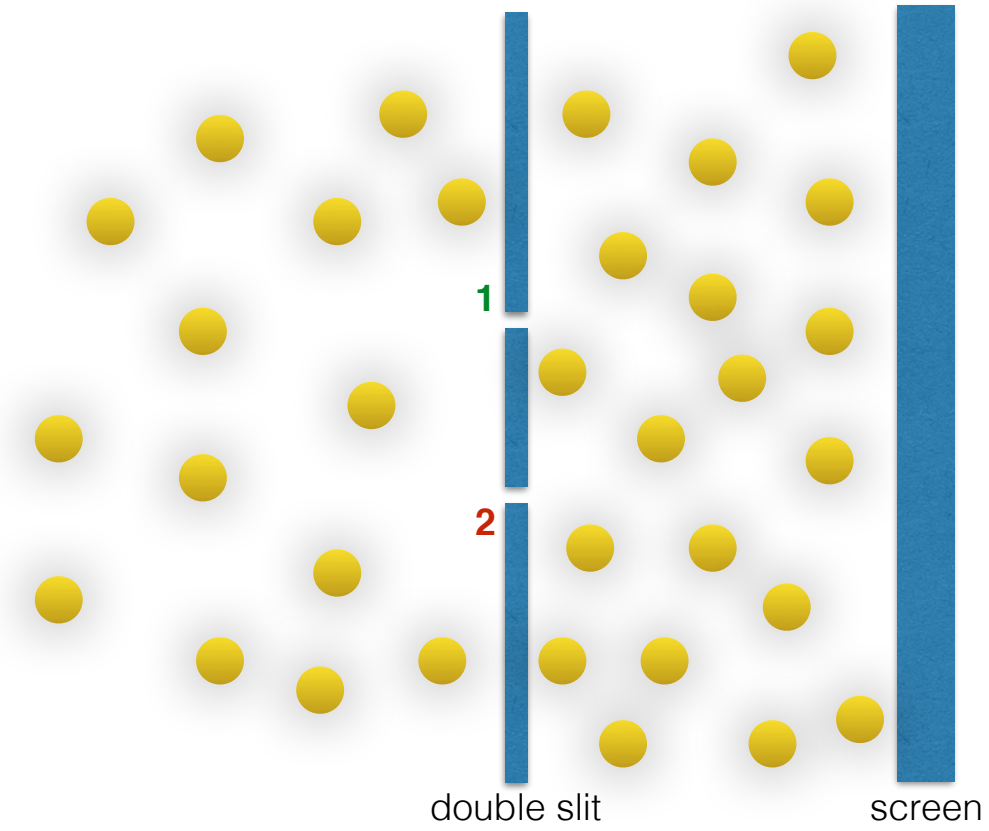
Quantum Decoherence: The double-slit experiment



Adding the environment

$$|\mathcal{E}\rangle \longrightarrow |\mathcal{E}_1\rangle$$

Quantum Decoherence: The double-slit experiment



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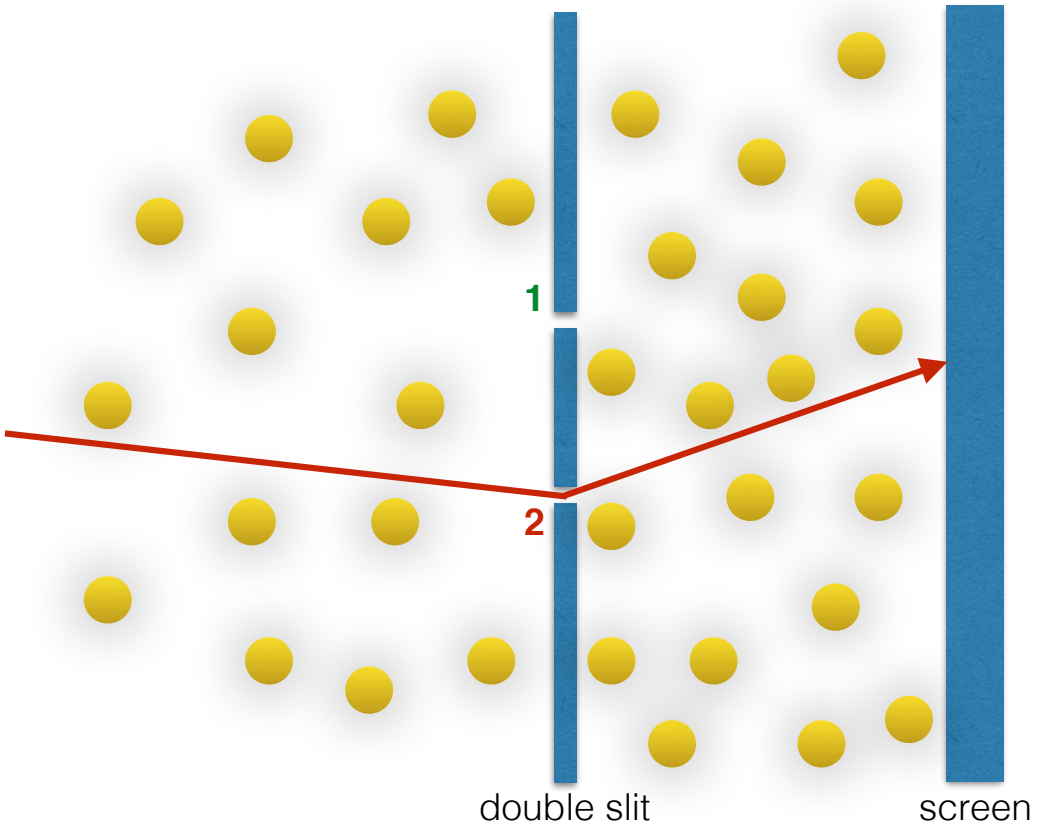
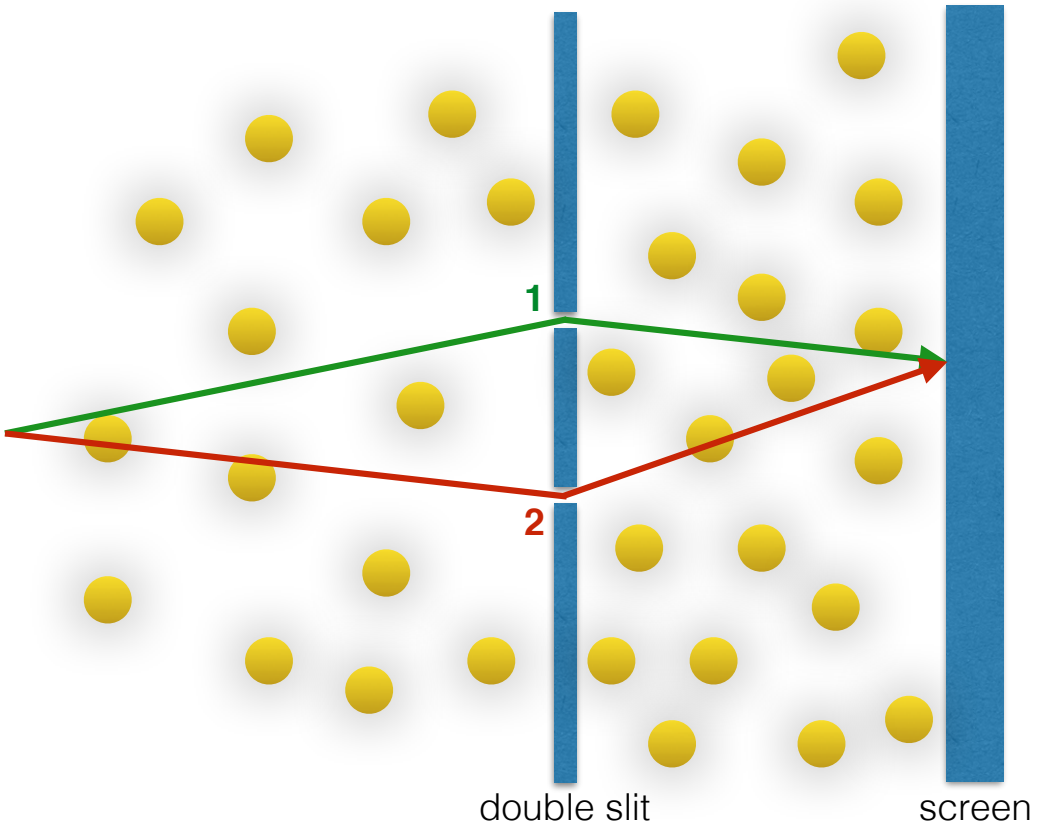


Adding the environment

$$|\mathcal{E}\rangle \longrightarrow |\mathcal{E}_2\rangle$$

Quantum Decoherence: The double-slit experiment



$$|\Psi\rangle = |\Psi_1\rangle \otimes |\mathcal{E}_1\rangle + |\Psi_2\rangle \otimes |\mathcal{E}_2\rangle$$

system becomes entangled with environment

$$\langle \mathcal{E}_i | \mathcal{E}_j \rangle = \delta_{ij}$$

↓

destruction of interferences

↓

loss of phase coherence

↓

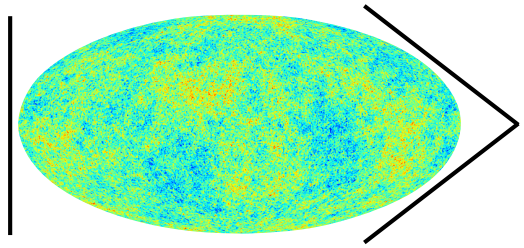
"decoherence"

H.D. Zeh 1970

$$\langle \Psi | \hat{O}_S | \Psi \rangle = \langle \Psi_1 | \hat{O}_S | \Psi_1 \rangle \langle \mathcal{E}_1 | \mathcal{E}_1 \rangle + \langle \Psi_2 | \hat{O}_S | \Psi_2 \rangle \langle \mathcal{E}_2 | \mathcal{E}_2 \rangle + \langle \Psi_1 | \hat{O}_S | \Psi_2 \rangle \langle \mathcal{E}_1 | \mathcal{E}_2 \rangle + \langle \Psi_2 | \hat{O}_S | \Psi_1 \rangle \langle \mathcal{E}_2 | \mathcal{E}_1 \rangle$$

Quantum-to-classical transition of primordial fluctuations

$|\mathrm{CMB}\rangle$ =



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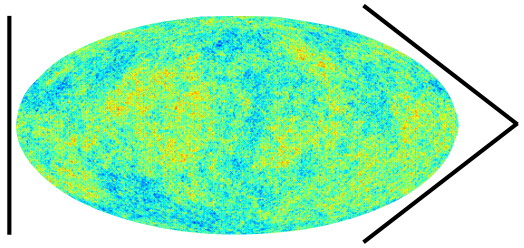

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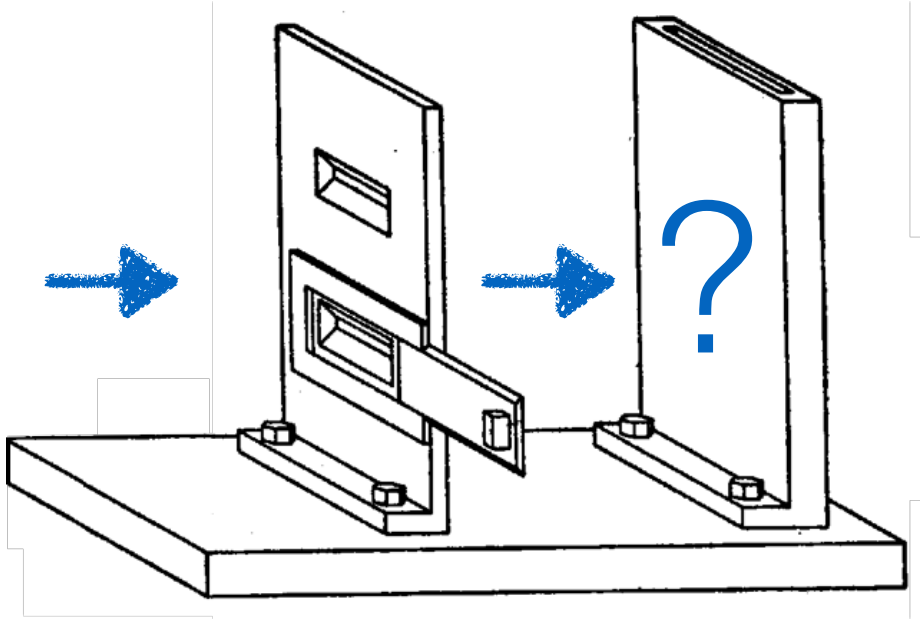
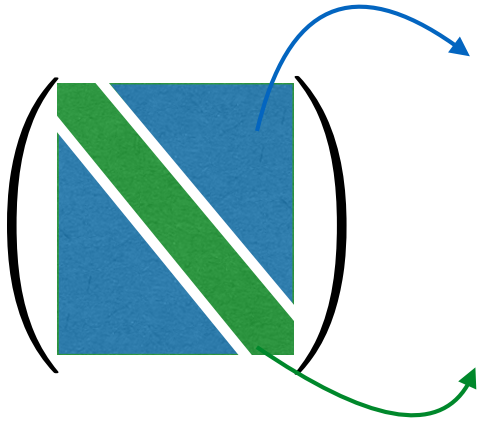


ρ =



Phase coherence between the different outcomes

Probability of observing the different outcomes

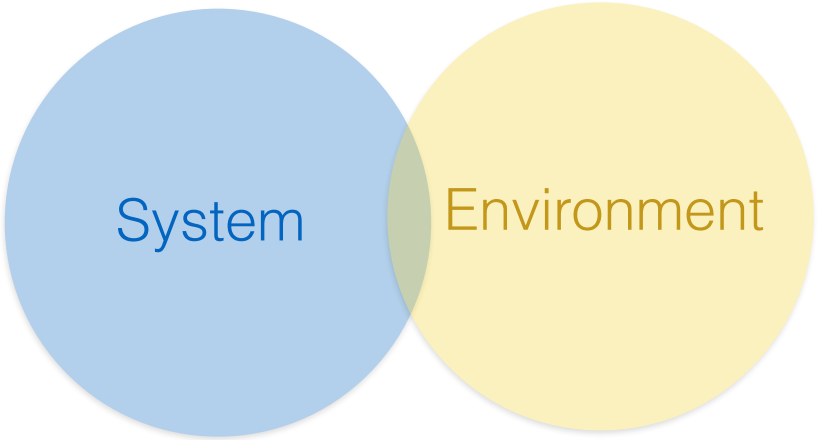
Can we change one without the other?

Interaction with an environment is inevitable anyway!

The Lindblad equation

cosmological perturbations

$v\left(\eta, \boldsymbol{x}\right)$



-other fields

-cosmological perturbations outside our causal horizon

-physics beyond the UV or IR cutoffs of the theory

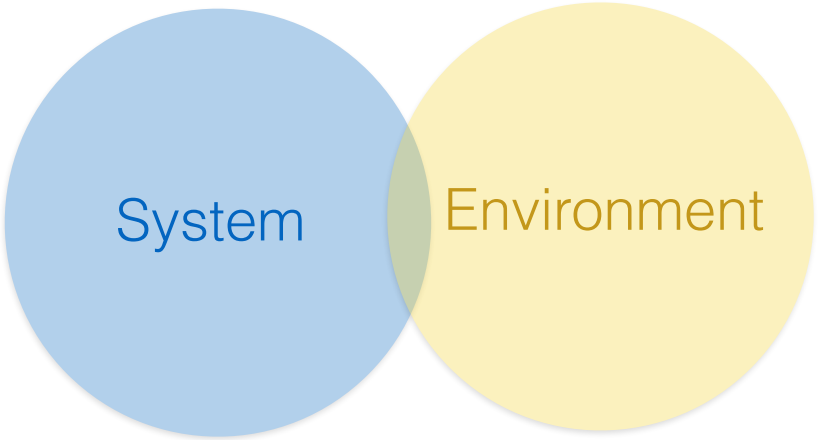
…

$$\hat{H} = \hat{H}_v \otimes \hat{\mathbb{I}}_{\rm env} + \hat{\mathbb{I}}_v \otimes \hat{H}_{\rm env} + g\hat{H}_{\rm int}$$

The Lindblad equation

cosmological perturbations

$v\left(\eta, \boldsymbol{x}\right)$



-other fields

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$$\hat{H} = \hat{H}_v \otimes \hat{\mathbb{I}}_{\rm env} + \hat{\mathbb{I}}_v \otimes \hat{H}_{\rm env} + g \int \mathrm{d}^3\boldsymbol{x}\, \hat{A}\left(\eta, \boldsymbol{x}\right) \otimes \hat{R}\left(\eta, \boldsymbol{x}\right)$$

$$\frac{\mathrm{d}\hat{\rho}_v}{\mathrm{d}\eta} = -i\left[\hat{H}_v, \hat{\rho}_v\right] - \frac{\gamma}{2}\int \mathrm{d}^3\boldsymbol{x}\, \mathrm{d}^3\boldsymbol{y}\, C_R\left(\boldsymbol{x}, \boldsymbol{y}\right)\left[\hat{A}(\boldsymbol{x}), \left[\hat{A}(\boldsymbol{y}), \hat{\rho}_v\right]\right]$$

$\hat{\rho}_v = \mathrm{Tr}_{\rm env}\left(|v, \mathrm{env}\rangle\langle v, \mathrm{env}|\right)$

$\gamma = 2g^2\eta_{\rm c}$

$C_R\left(\boldsymbol{x}, \boldsymbol{y}\right) = \langle \hat{R}(\eta, \boldsymbol{x})\hat{R}(\eta, \boldsymbol{y})\rangle$

Main validity condition: $\eta_{\rm c} \ll \eta_v$

Most generic equation for quantum dynamical semi group!

The Lindblad equation

$$\frac{\mathrm{d}\hat{\rho}_v}{\mathrm{d}\eta} = -i\left[\hat{H}_v, \hat{\rho}_v\right] - \frac{\gamma}{2}\int \mathrm{d}^3\boldsymbol{x}\,\mathrm{d}^3\boldsymbol{y}\, C_R\left(\boldsymbol{x},\boldsymbol{y}\right)\left[\hat{A}(\boldsymbol{x}),\left[\hat{A}(\boldsymbol{y}),\hat{\rho}_v\right]\right]$$

$\mathrm{Tr}_{\mathrm{env}}\left(|v,\mathrm{env}\rangle\langle v,\mathrm{env}|\right)$ — $\hat{v}^n$ — $2g^2\eta_{\mathrm{c}}$ — $\langle\hat{R}(\eta,\boldsymbol{x})\hat{R}(\eta,\boldsymbol{y})\rangle$

$$\gamma_* = \frac{\lambda}{M}\mu^{8-2n-2m} \qquad \bar{C}_R = \left(\frac{H^3}{M^2}\right)^{2m}$$

$$\gamma_*\left(\frac{a}{a_*}\right)^p \qquad \bar{C}_R\,\theta\left(\frac{a\,|x-y|}{\ell_{\mathrm{E}}}\right)$$

Bunch, Davies 1978

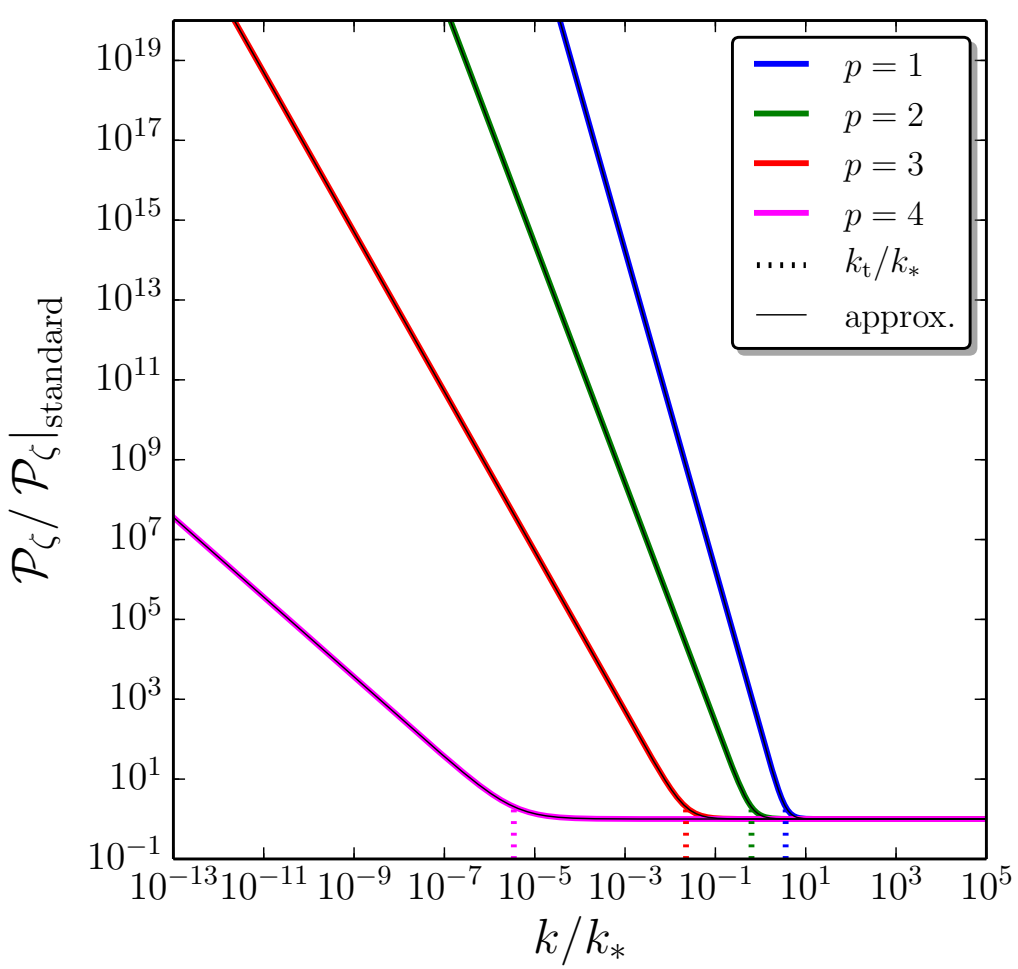
$$p = 7 - 2n + 6m\epsilon_{1*} \qquad t_{\mathrm{c}} = \ell_{\mathrm{E}} = \frac{1}{M} \ll t_v \sim \frac{1}{H}$$

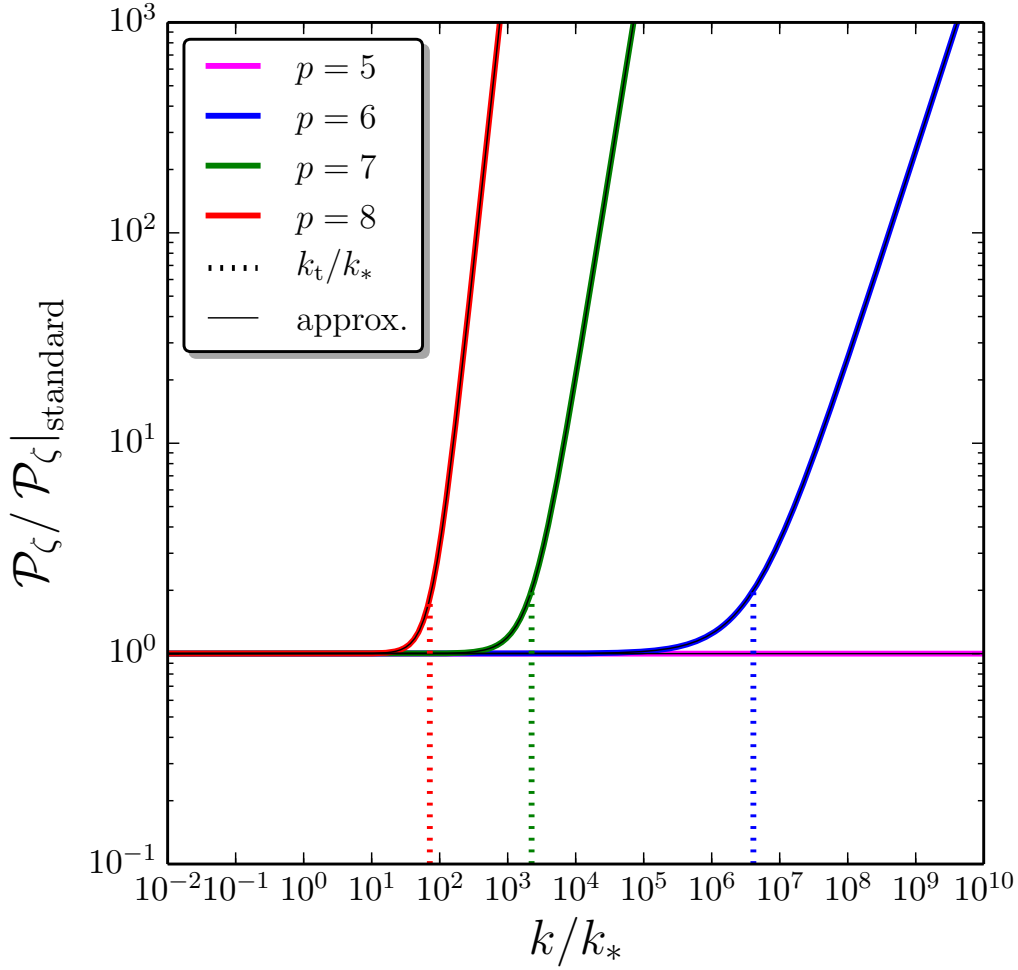
Example: heavy test scalar field as the environment

$$\hat{H}_{\mathrm{int}} = \lambda\mu^{4-n-m}\int \mathrm{d}^3\boldsymbol{x}\sqrt{-g}\hat{\phi}^n\left(\eta,\boldsymbol{x}\right)\hat{\psi}^m\left(\eta,\boldsymbol{x}\right) \qquad \text{with} \qquad \hat{\phi} = \hat{v}/a$$

Power Spectrum

linear coupling $(n = 1)$





Observed quasi scale invariance ——> upper bound on interaction strength

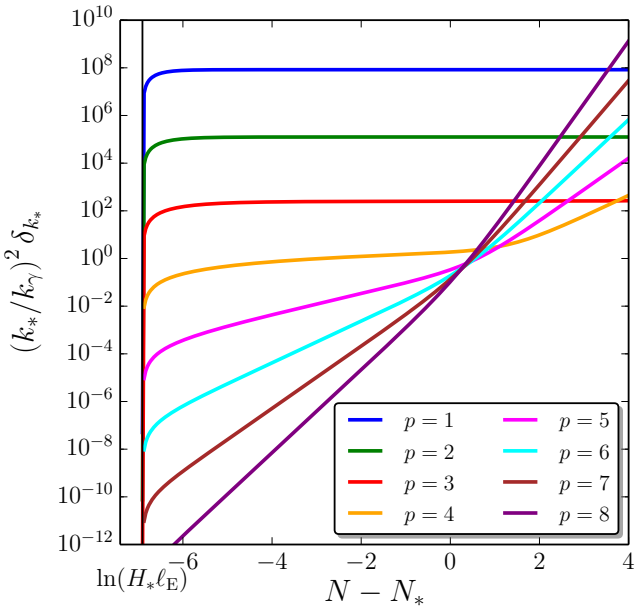
Decoherence parameter

linear coupling $(n = 1)$

Off-diagonal elements decay:

$$\left|\left\langle v_{\boldsymbol{k}}^{s} + \frac{\Delta v_{\boldsymbol{k}}}{2}\right| \hat{\rho}_{\boldsymbol{k}}^{s} \left|v_{\boldsymbol{k}}^{s} - \frac{\Delta v_{\boldsymbol{k}}}{2}\right\rangle\right| = \left|\left\langle v_{\boldsymbol{k}}^{s}\right| \hat{\rho}_{\boldsymbol{k}}^{s} \left|v_{\boldsymbol{k}}^{s}\right\rangle\right| \exp\left[-\frac{\delta_{\boldsymbol{k}} + \frac{1}{4}}{2} \frac{\Delta v_{\boldsymbol{k}}^{2}}{P_{vv}(k)}\right]$$

State purity: $\mathrm{Tr}\left(\hat{\rho}_{\boldsymbol{k}}^{s\,2}\right) = \int_{-\infty}^{\infty} \mathrm{d}v_{\boldsymbol{k}}^{s,(1)} \int_{-\infty}^{\infty} \mathrm{d}v_{\boldsymbol{k}}^{s,(2)} \left\langle v_{\boldsymbol{k}}^{s,(1)}\right| \hat{\rho}_{\boldsymbol{k}}^{s} \left|v_{\boldsymbol{k}}^{s,(2)}\right\rangle = \frac{1}{\sqrt{1 + 4\delta_{\boldsymbol{k}}}}$

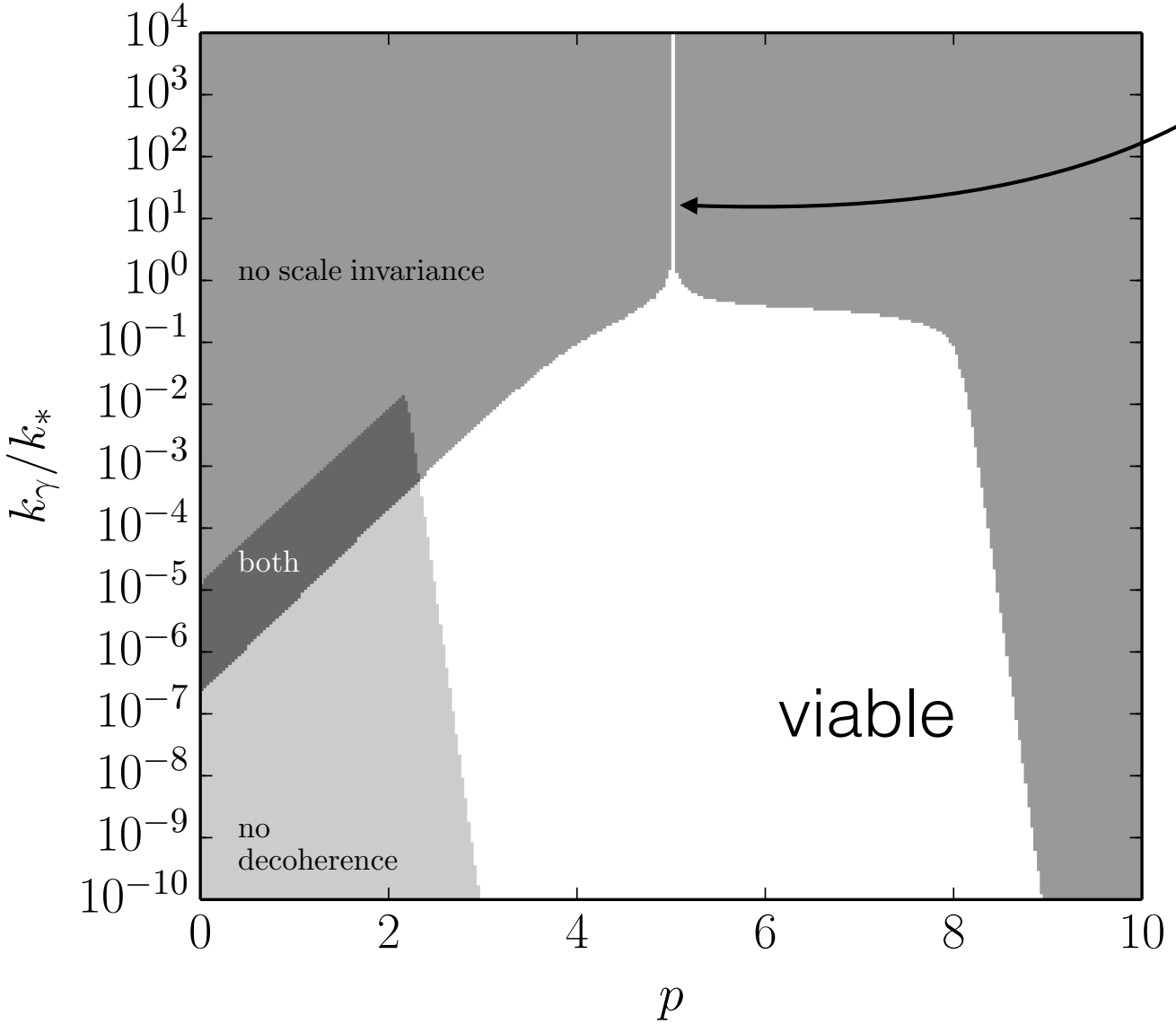


Decoherence on observable scales ——> lower bound on interaction strength

Combining Constraints

$$e^{\frac{2-p}{2}\Delta N_*} \ll \frac{k_\gamma}{k_*} \ll \begin{cases} (H_*\ell_{\rm E})^{\frac{4-p}{2}} & \text{if} \quad 2<p<4 \\ 1 \quad \text{if} \quad 4<p<8 \\ e^{-\frac{p-8}{2}\Delta N_*} & \text{if} \quad p>8 \end{cases}$$

heavy test scalar field as the environment



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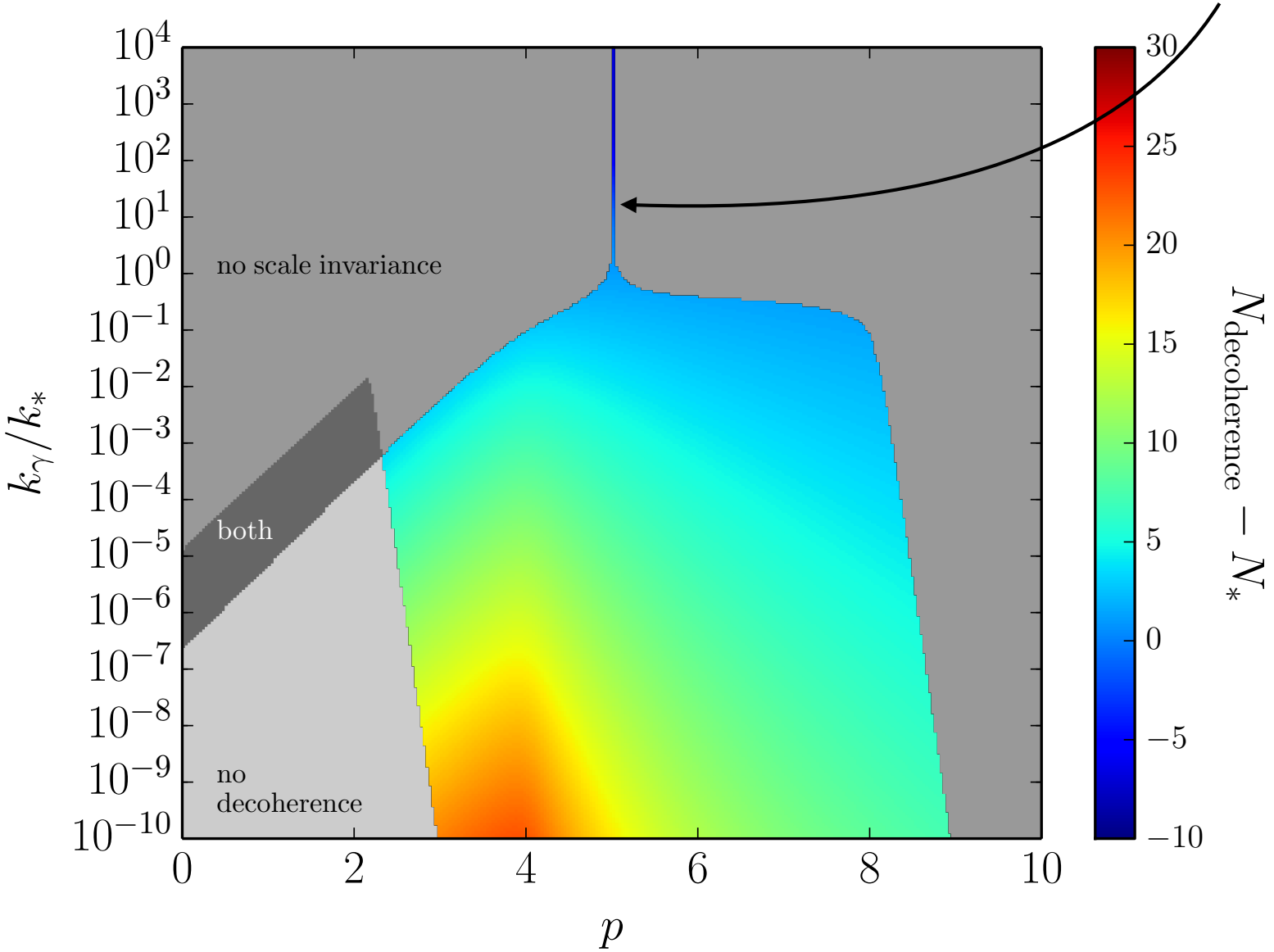
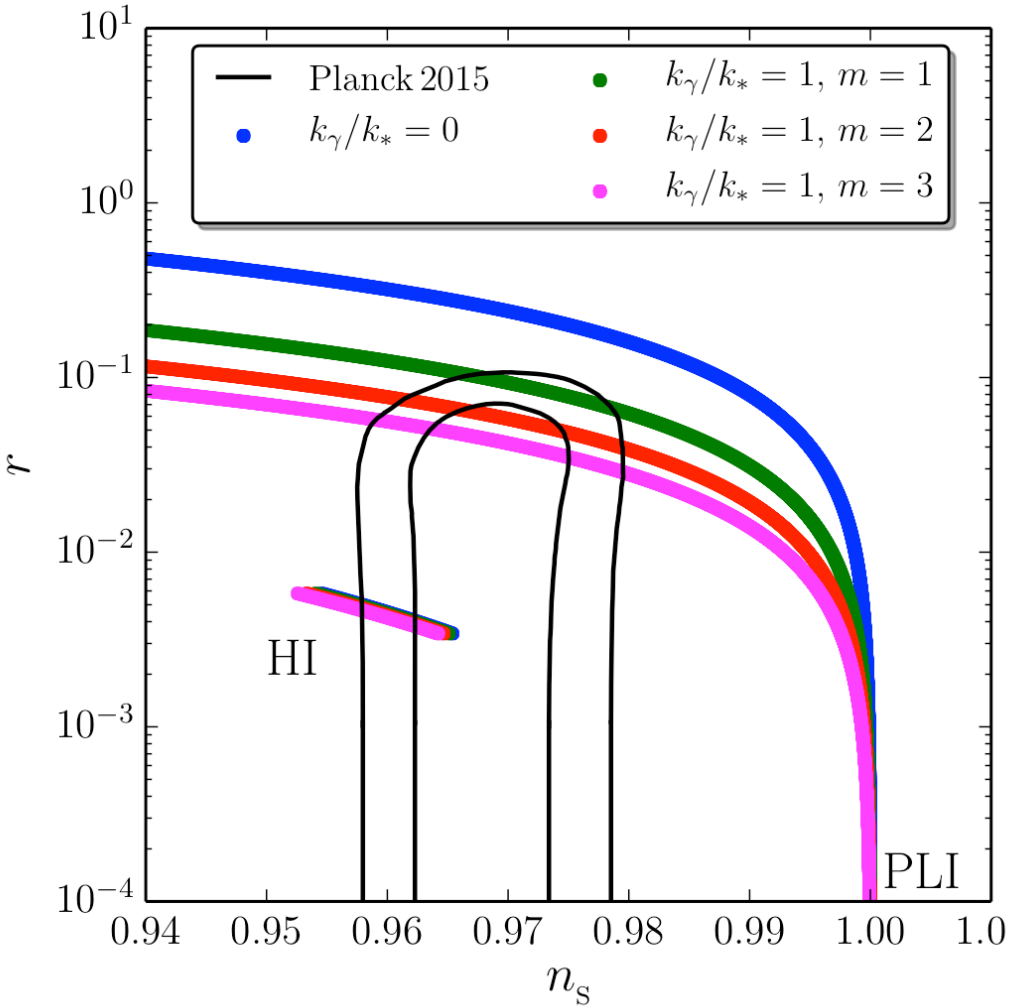
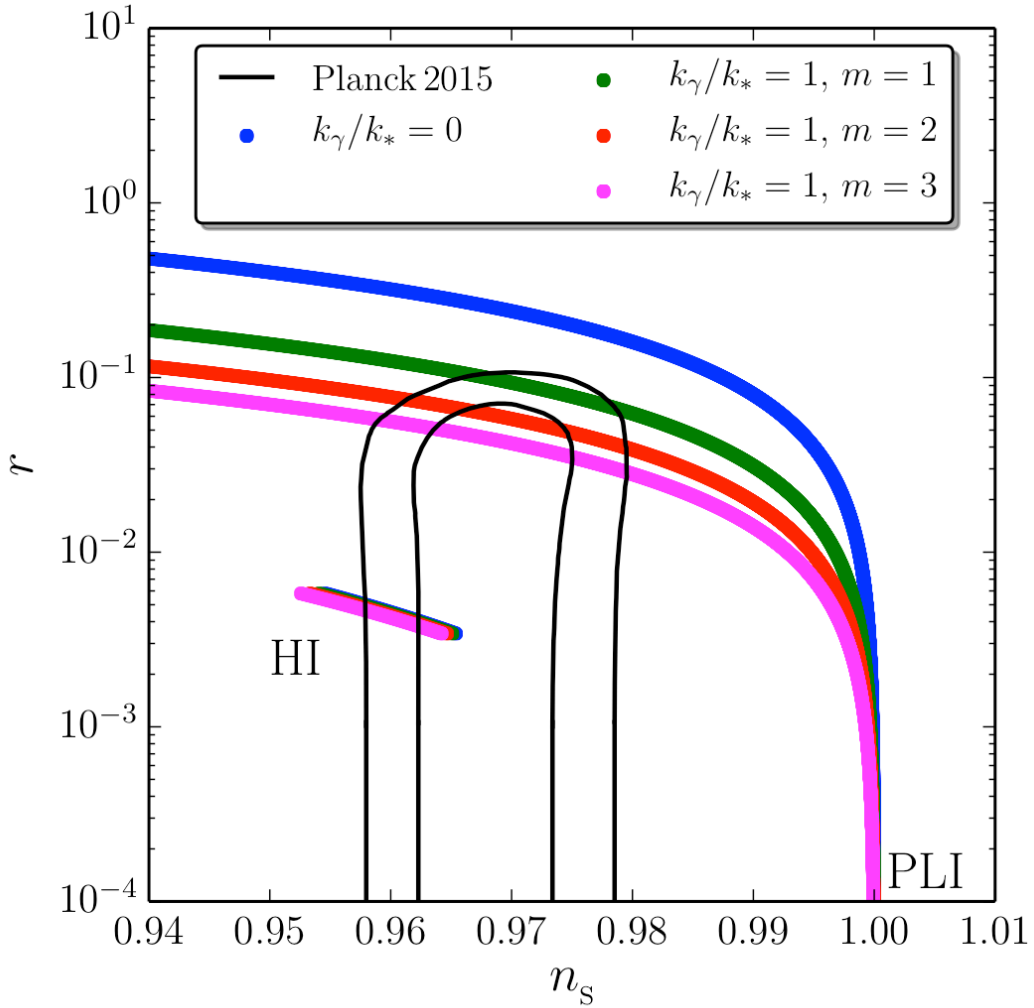


Heavy test scalar field as the environment

$$n_{\rm S} = n_{\rm S}\big|_{\rm standard} - \frac{\frac{\pi}{6}\frac{k_\gamma^2}{k_*^2}}{1+\frac{\pi}{6}\frac{k_\gamma^2}{k_*^2}}\,(6m-2)\,\epsilon_{1*} \qquad r = \frac{r\big|_{\rm standard}}{1+\frac{\pi}{6}\frac{k_\gamma^2}{k_*^2}}$$

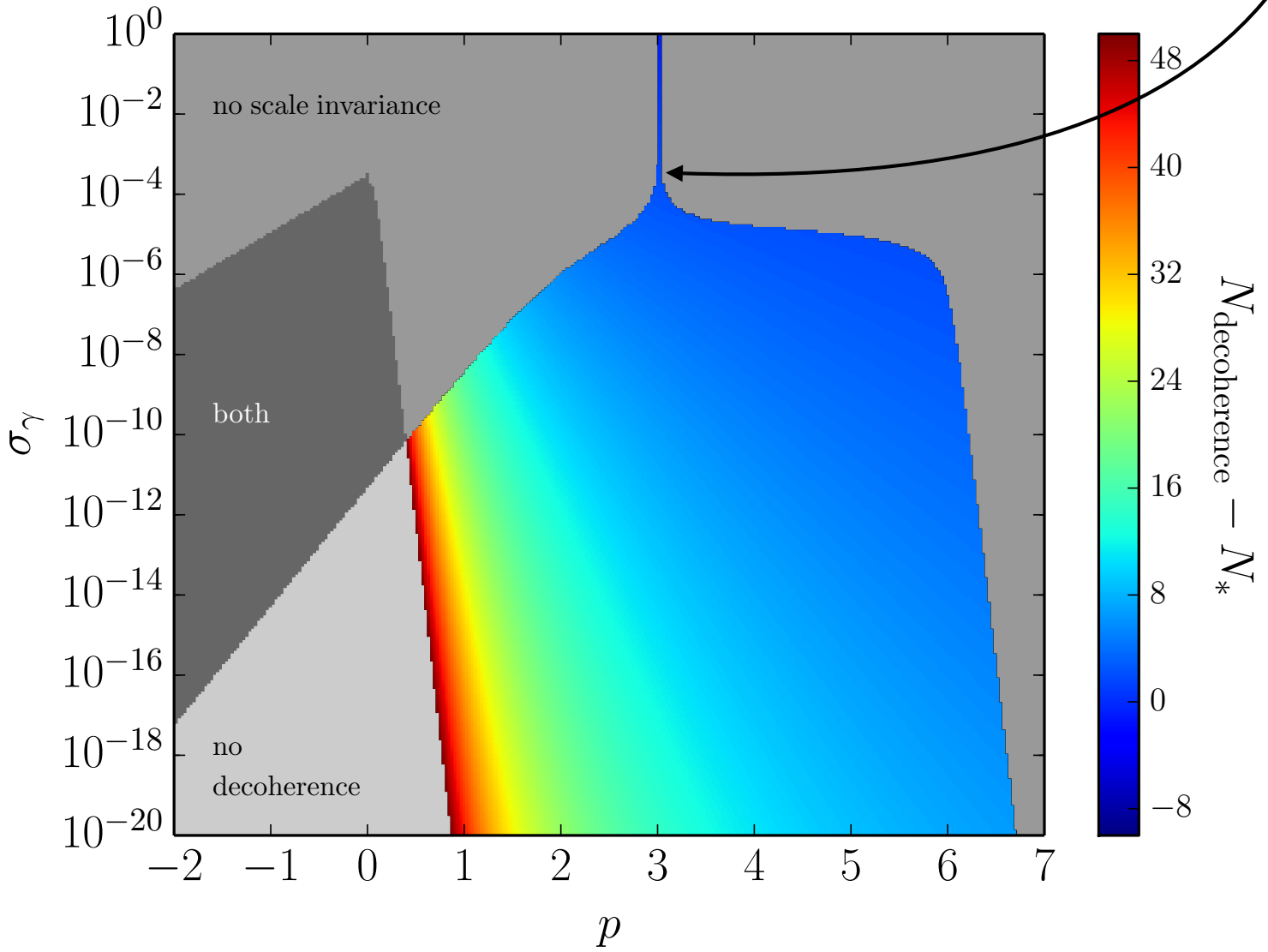




Combining Constraints

quadratic coupling $(n = 2)$

heavy test scalar field as the environment

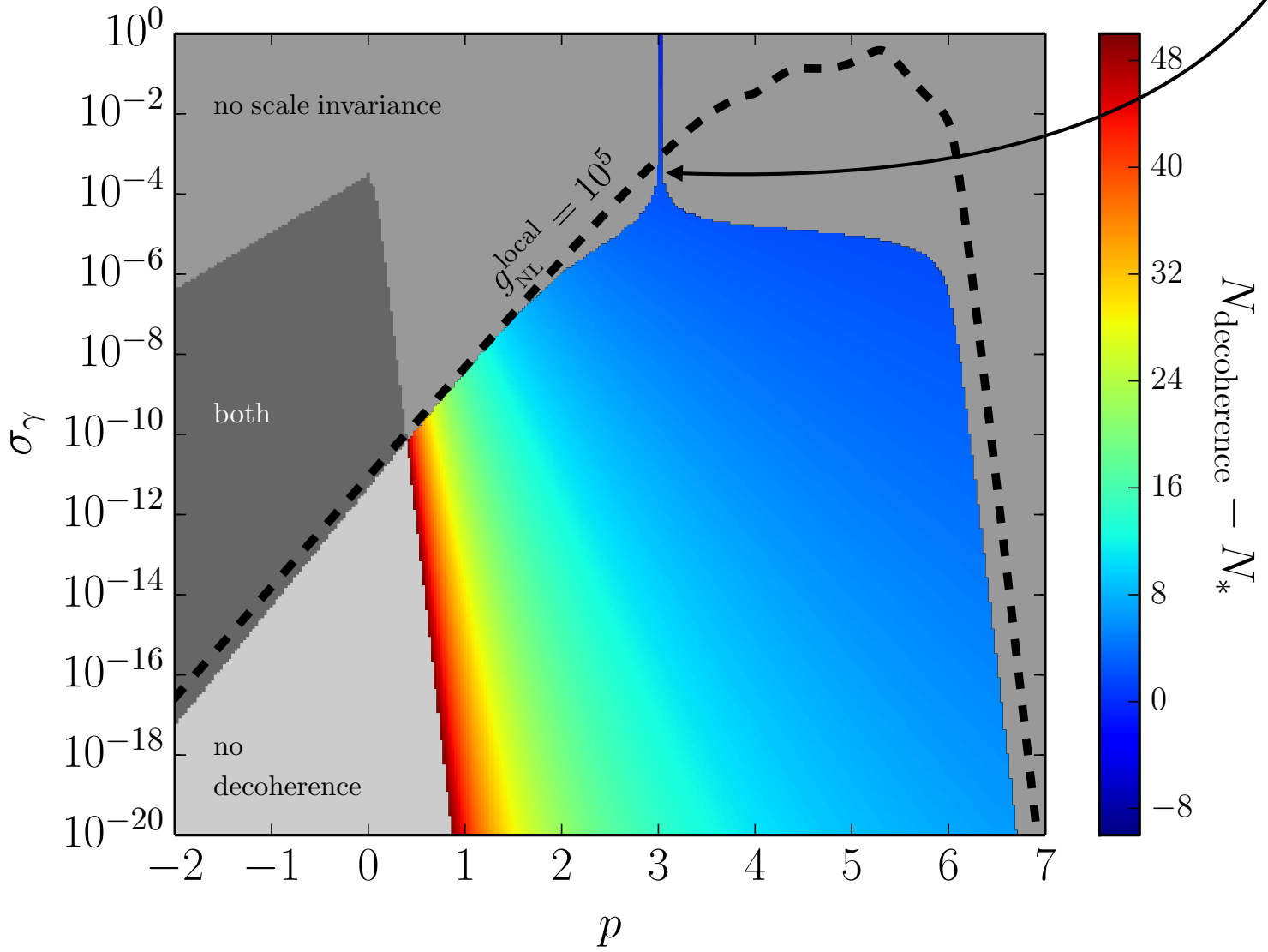


Combining Constraints

quadratic coupling $(n = 2)$

$H_* \ell_{\rm E} = 10^{-3}$

heavy test scalar field as the environment

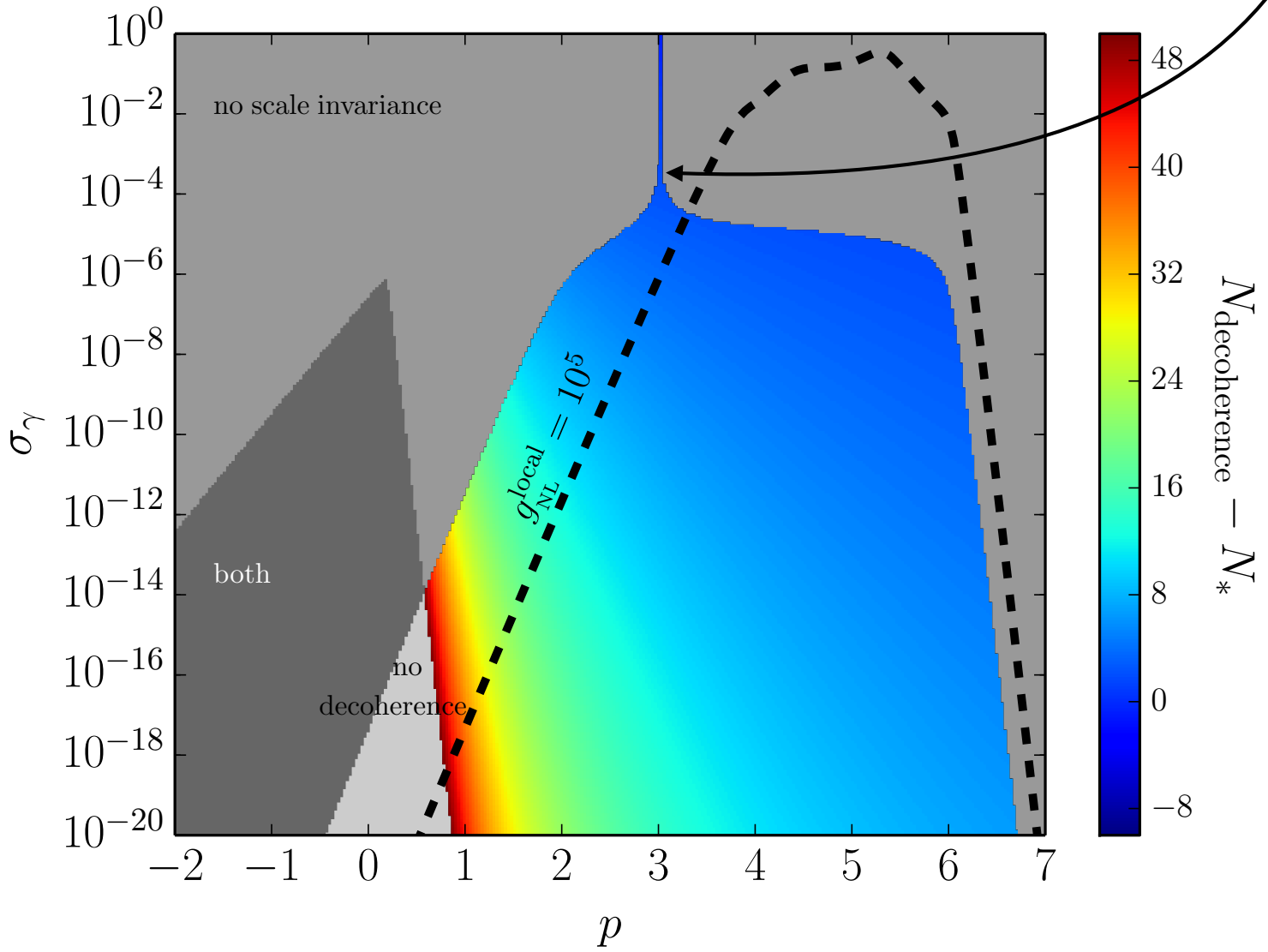


Combining Constraints

quadratic coupling $(n = 2)$

$H_* \ell_{\rm E} = 10^{-6}$

heavy test scalar field as the environment



Conclusion

- Primordial cosmological fluctuations must be modelled as an open quantum system interacting with an environment

- This interaction gives rise to quantum decoherence if the interaction strength is sufficiently large

- It can also modify observables from inflation such as the power spectrum and the amount of non-Gaussianities, unless the interaction strength is sufficiently small

  $\longrightarrow$ Observational constraints on interacting environments

- If the environment is made of a heavy test scalar field, the correction to the power spectrum is quasi scale invariant.

  $\longrightarrow$ Decoherence may change which models are preferred