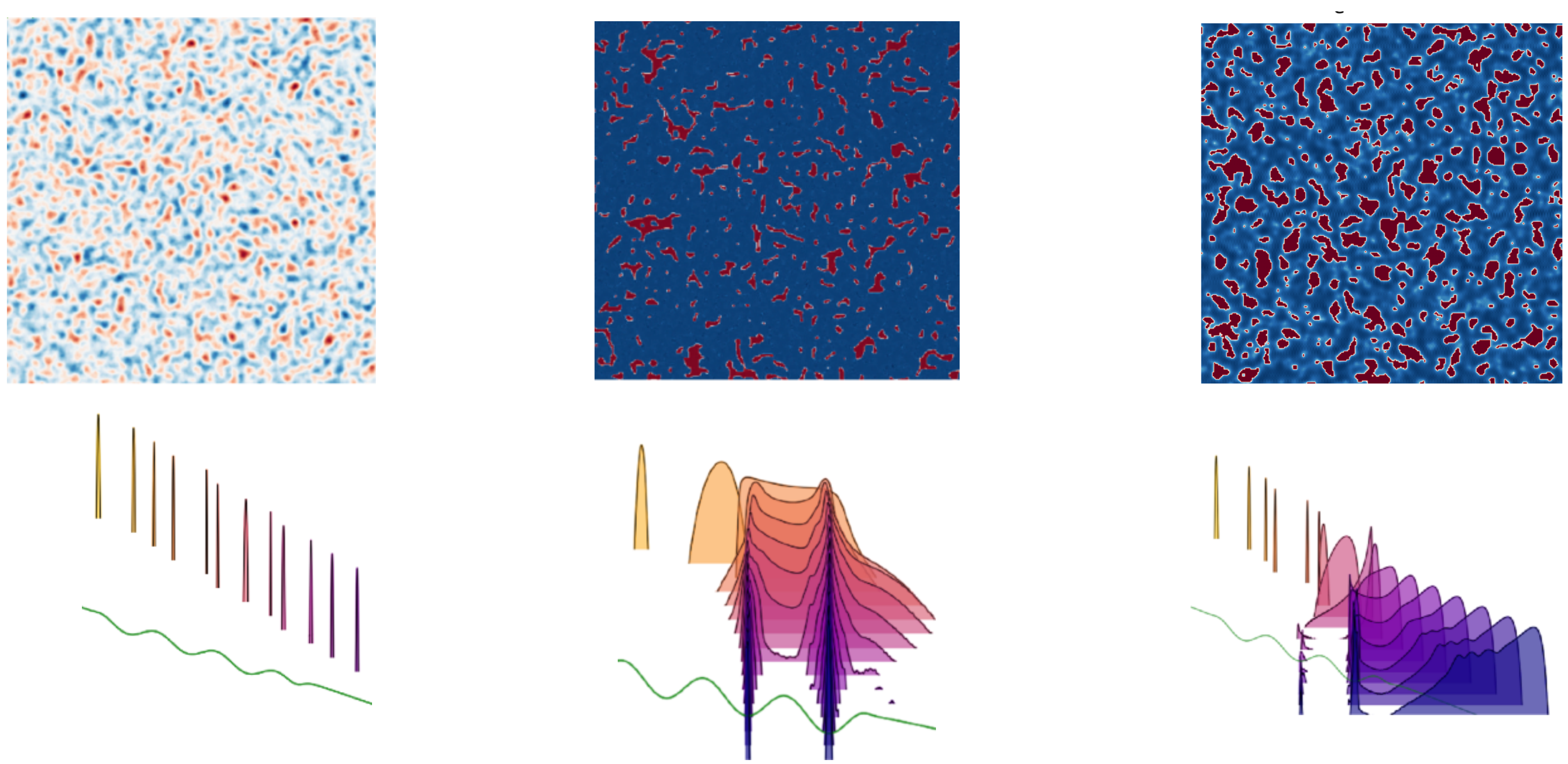
The Inflationary Butterfly Effect

Non-perturbative dynamics from small-scale features

Angelo Caravano (IPI fellow @ IAP, Paris)

collaborators: S.Renaux-Petel, K.Inomata arXiv:2403.12811



Roadmap

0) Context and motivation

1) Lattice simulations inflation

AC, E. Komatsu, K. D. Lozanov, J. Weller

arXiv
2102.06378
2110.10695
2204.12874

AC 2209.13616

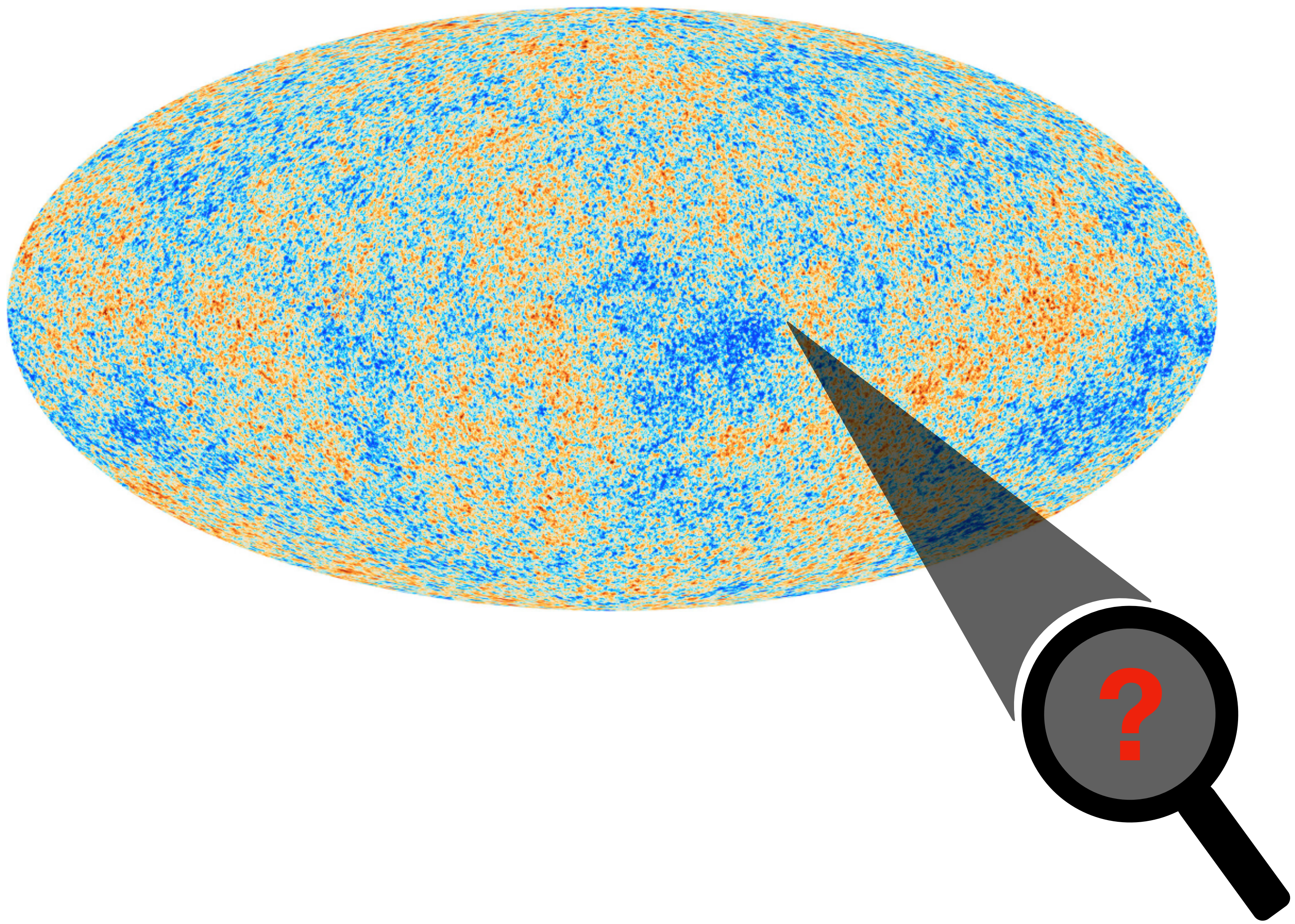
AC, D. Jamieson, E. Komatsu [in preparation]

2) The Inflationary Butterfly Effect

AC, S. Renaux-Petel, K. Inomata 2403.12811

The early Universe at small scales

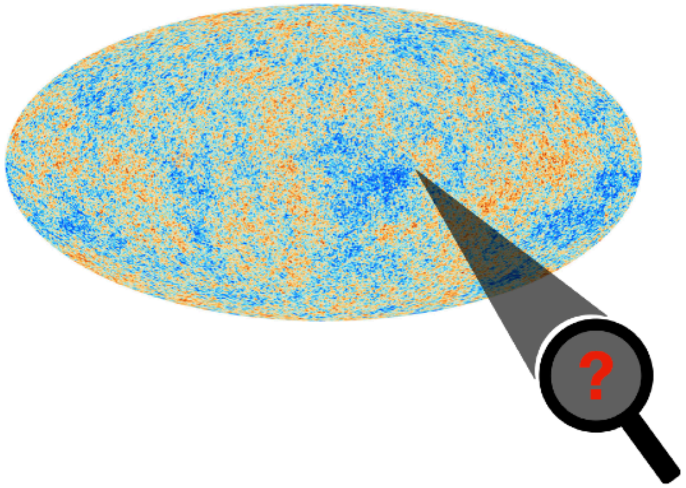
What is the physics of inflation at scales $\lambda \ll \lambda_{CMB}$?



Inflation generates fluctuations at scales $\sim e^{40}$ smaller than CMB scales

Inflation at small scales

What is the physics of inflation at scales $\lambda \ll \lambda_{CMB}$?



Observable thanks to PBH and GWs!

For sizeable effect, however:

$$\mathscr{P}_\zeta \sim 10^{-2} - 10^{-4} \longrightarrow \boxed{\zeta \sim 10^{-1} - 10^{-2}}$$

Possible nonlinear physics?

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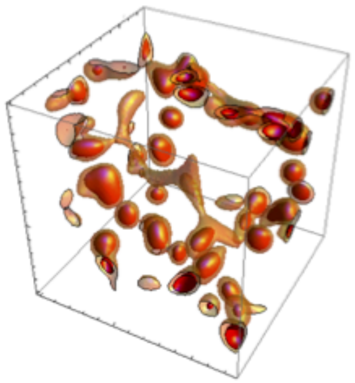
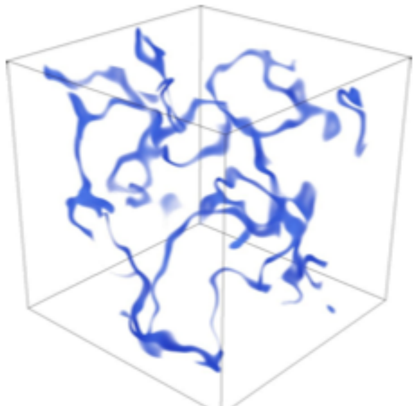
Lattice simulations

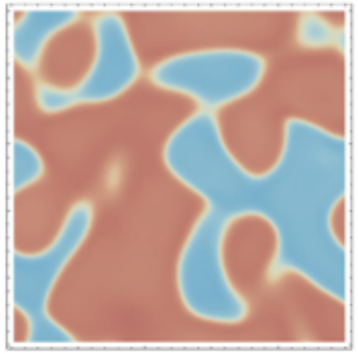
- Numerical tool to study non-perturbative cosmological phenomena.
- Examples: reheating phase after inflation, cosmological phase transitions.



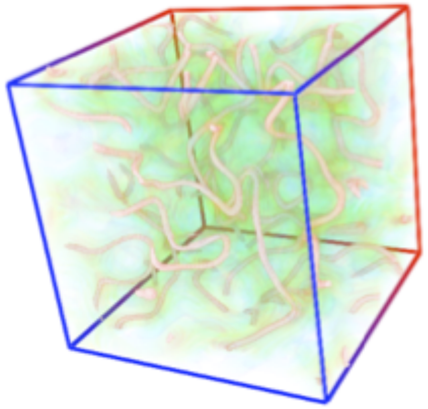
[M. A. Amin, R. Easther, H. Finkel, arXiv:1009.2505]



[A. V. Frolov, arXiv:1004.3559]



[M. A. Amin, J. Fan, K. D. Lozanov, M. Reece, arXiv:1802.00444]



[J. Dufaux, D.G. Figueroa, J. Garcia-Bellido, arXiv:1006.0217]

My goal:

Develop lattice techniques for inflation

	arXiv
AC, E. Komatsu, K. D. Lozanov, J. Weller	2102.06378
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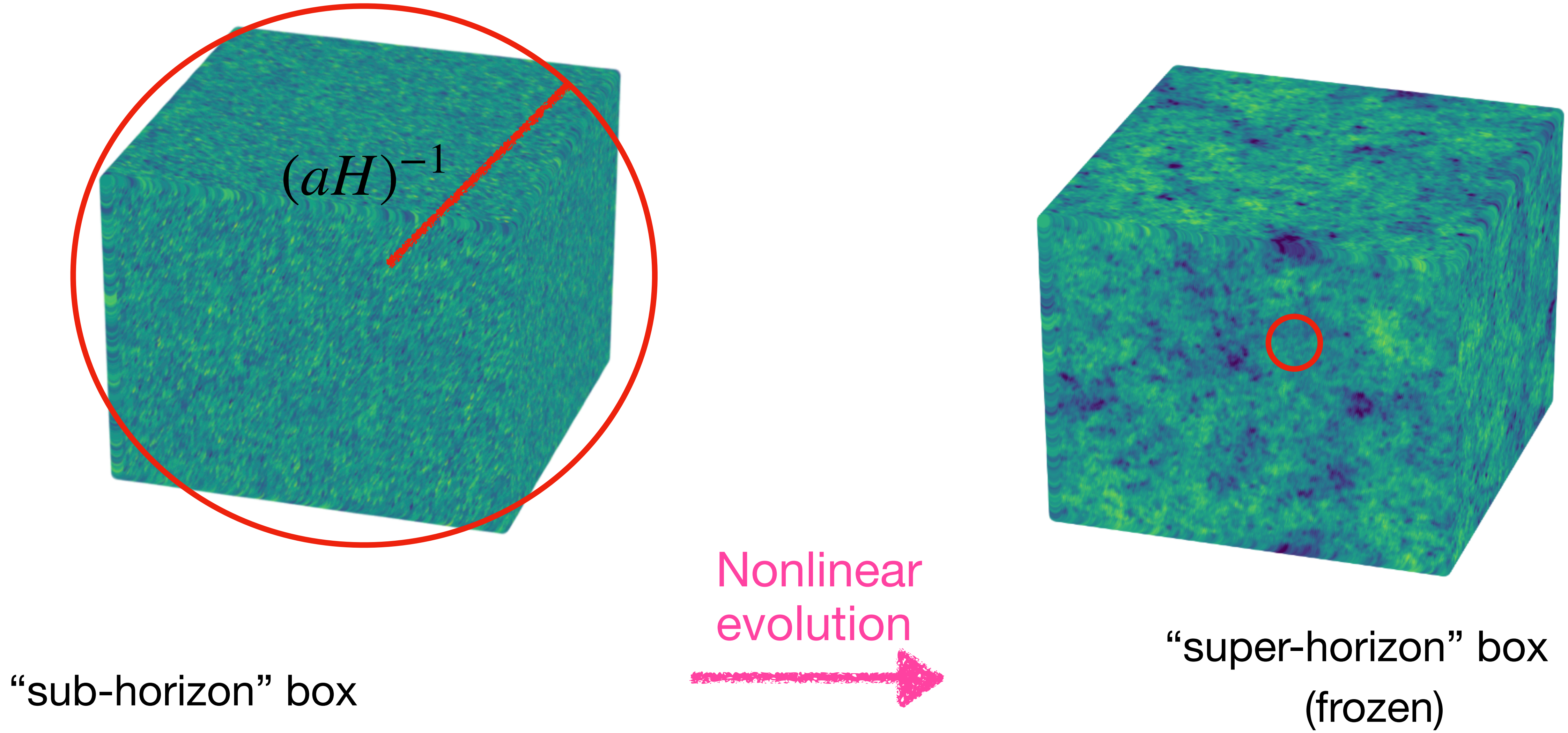
Lattice simulations of Inflation

[AC 2209.13616]



- Key point: non-perturbative $\phi(\vec{x}, t) \neq \bar{\phi}(t) + \delta\phi(\vec{x}, t)$

- Assumptions: 1) Neglect gravitational interaction fixed metric $ds^2 = a(\tau)\left(-d\tau^2 + d\vec{x}^2\right)$

  2) Semi-classical approach (neglect quantum tunneling, interference, etc…)

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Inflationary Butterfly Effect

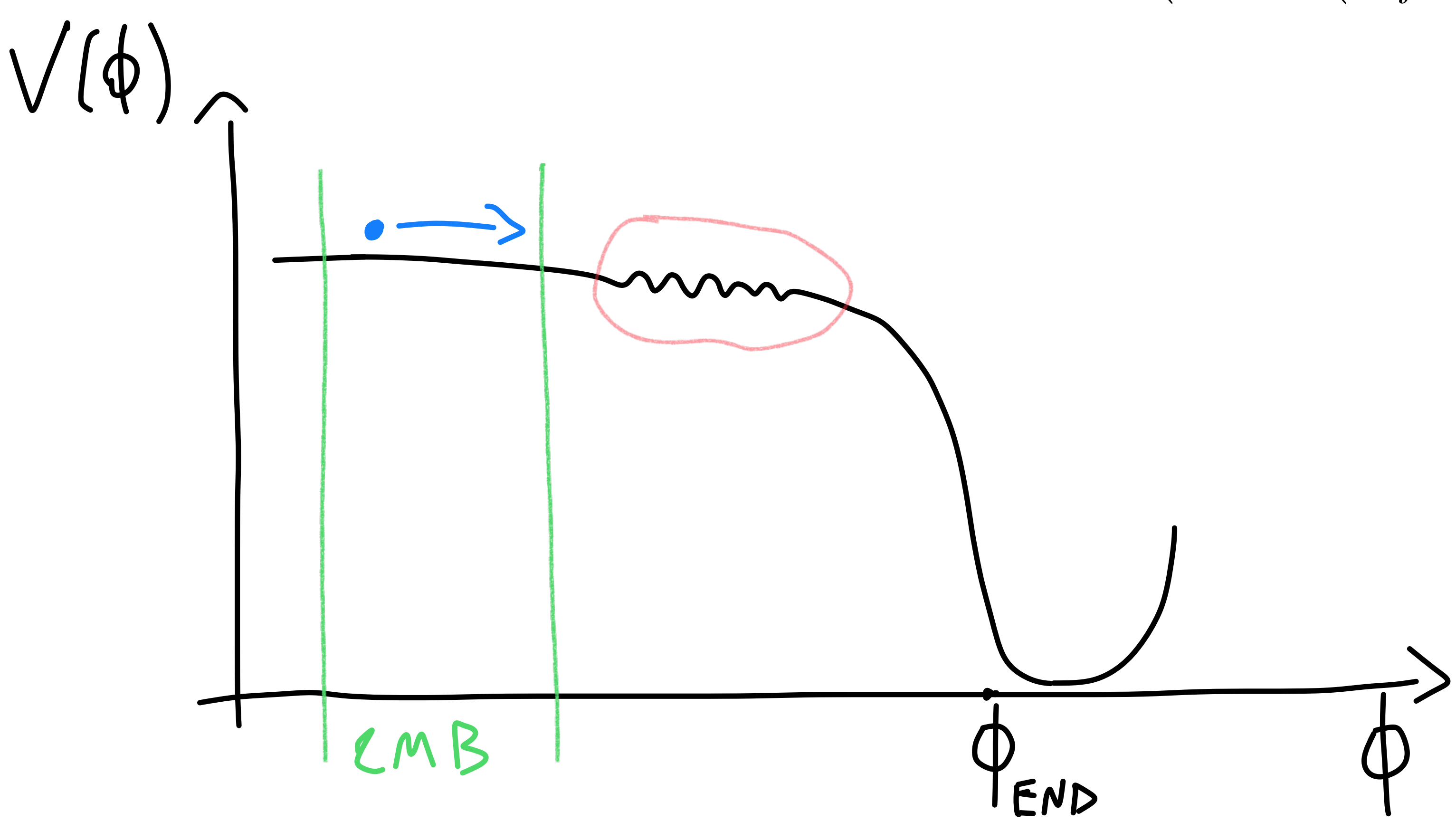
Consider a **small-scale modification** of the inflaton potential

$$V(\phi) = V_{\rm sr}(\phi) + \Lambda^4 W(\phi)\left[\cos\left(\frac{\phi-\phi_0}{f}\right) - 1\right]$$

Slow-roll potential

Localised oscillation

$$W(\phi) = \frac{1}{4}\left(1+\tanh\left(\frac{\phi-\phi_0}{f}\right)\right)\left(1+\tanh\left(\frac{\phi_0-\phi+\Delta\phi}{f}\right)\right)$$



Oscillatory potential

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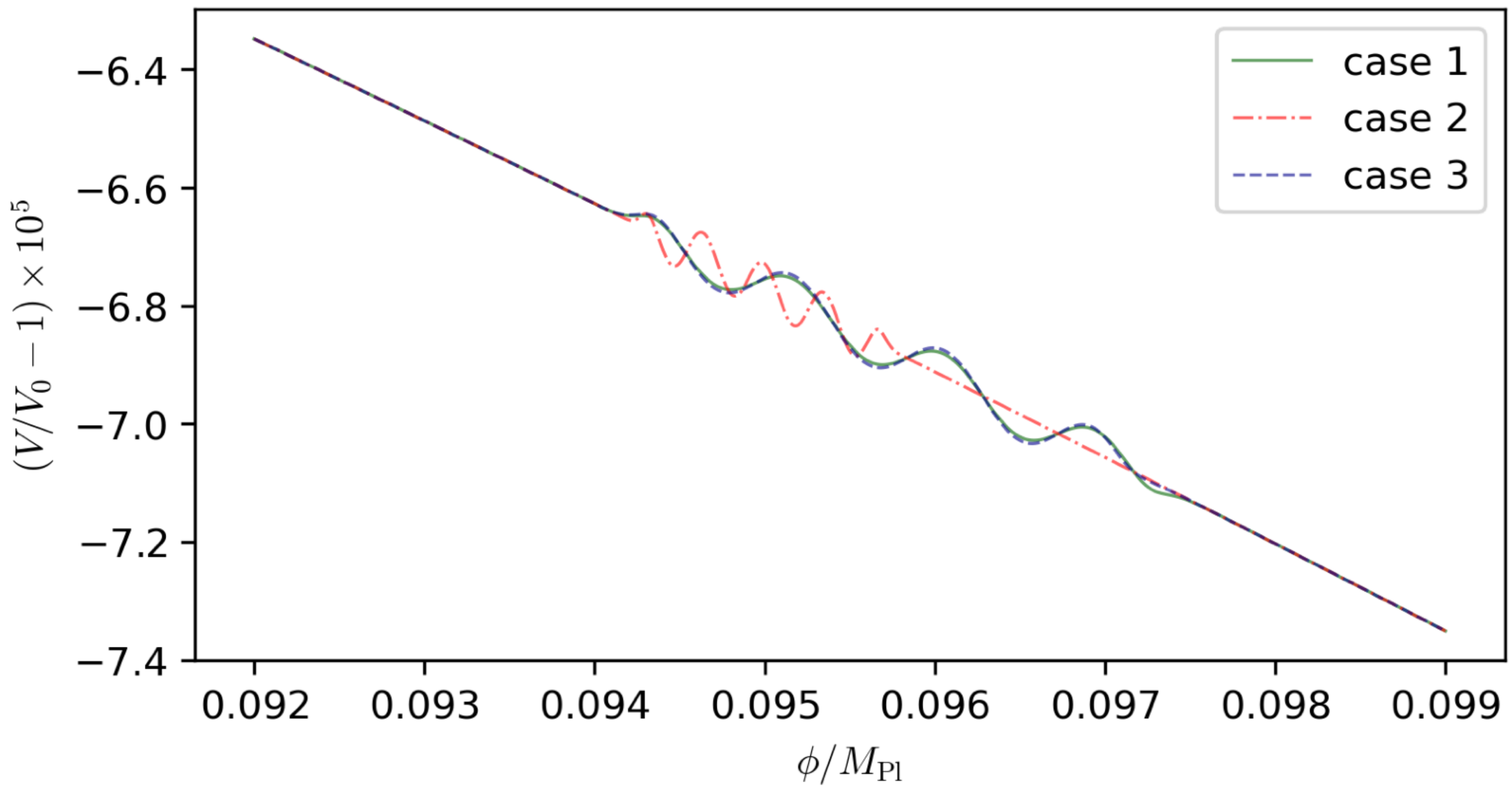
oscillation → parametric resonance → exponential growth of perturbations

Oscillatory potential

$$V(\phi) = V_{sr}(\phi) + \Lambda^4 W(\phi)\left[\cos\left(\frac{\phi - \phi_0}{f}\right) - 1\right]$$

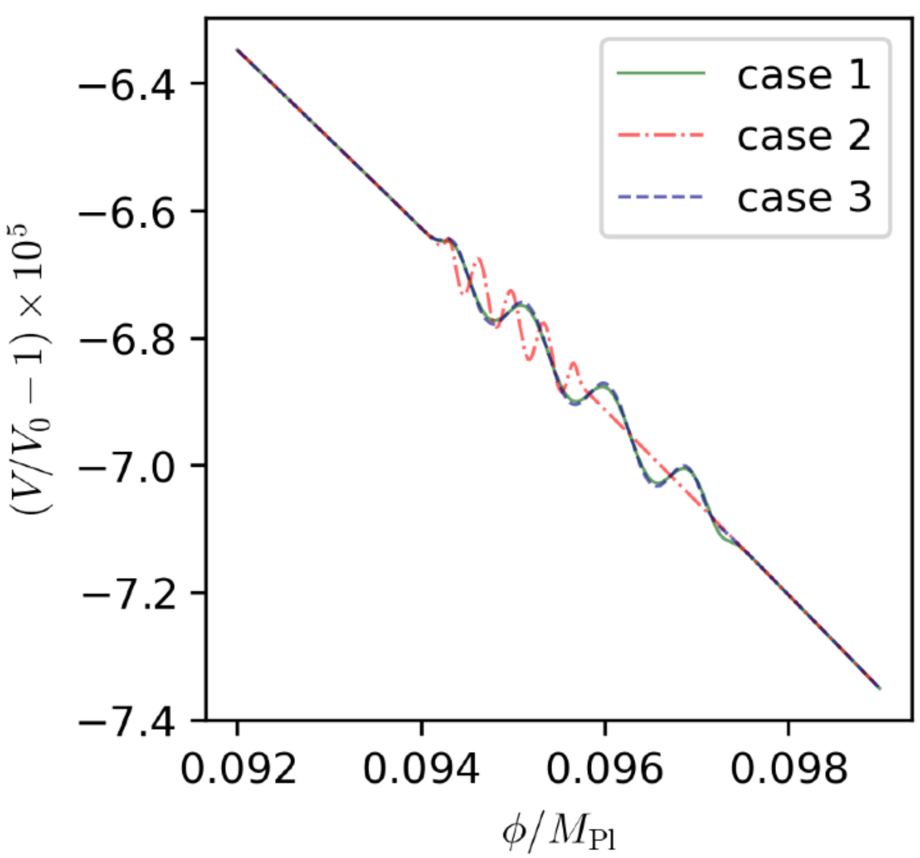
Let's consider the following three cases:

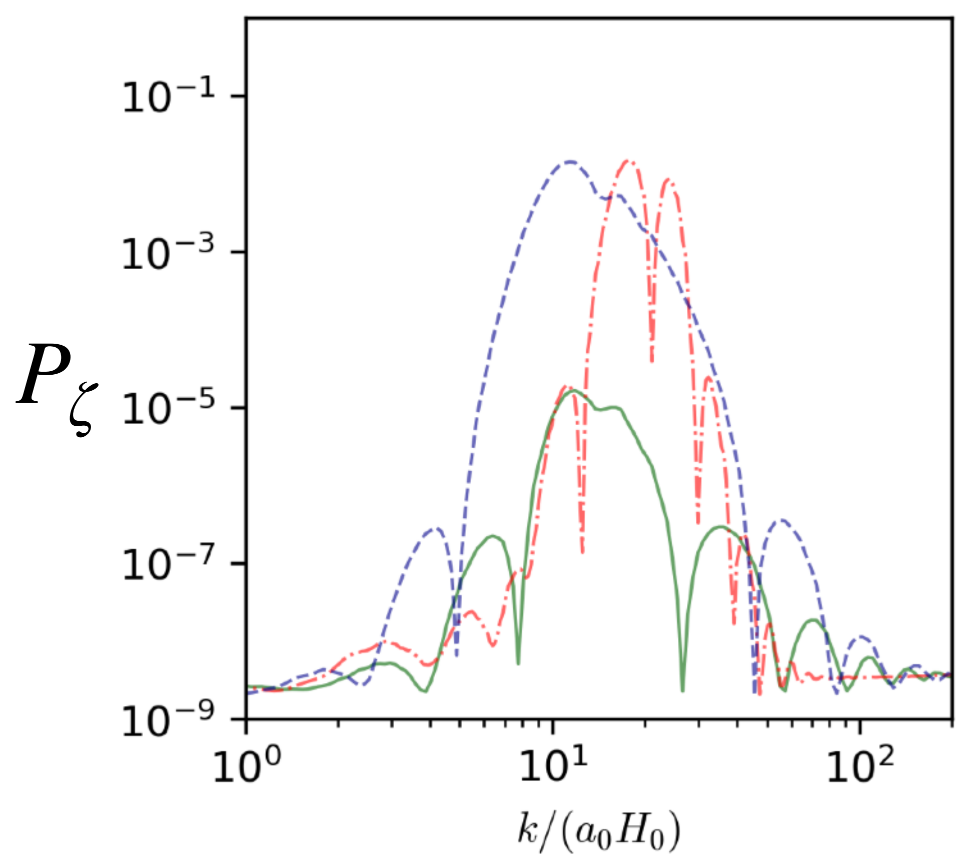


Oscillatory potential

$$V(\phi) = V_{\rm sr}(\phi) + \Lambda^4 W(\phi)\left[\cos\left(\frac{\phi-\phi_0}{f}\right) - 1\right]$$

The feature induces a growth of the power spectrum:





Case 1: $P_\zeta \simeq 10^{-5}$

Case 2: $P_\zeta \simeq 10^{-2}$

Case 3: $P_\zeta \simeq 10^{-2}$

Oscillatory potential

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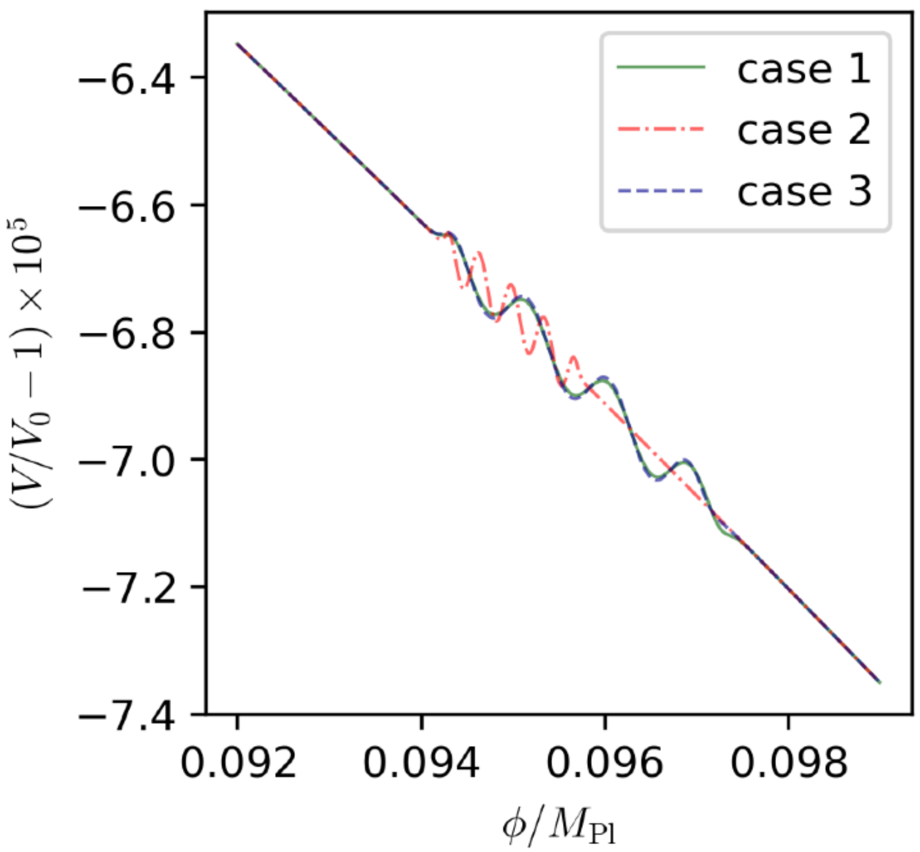
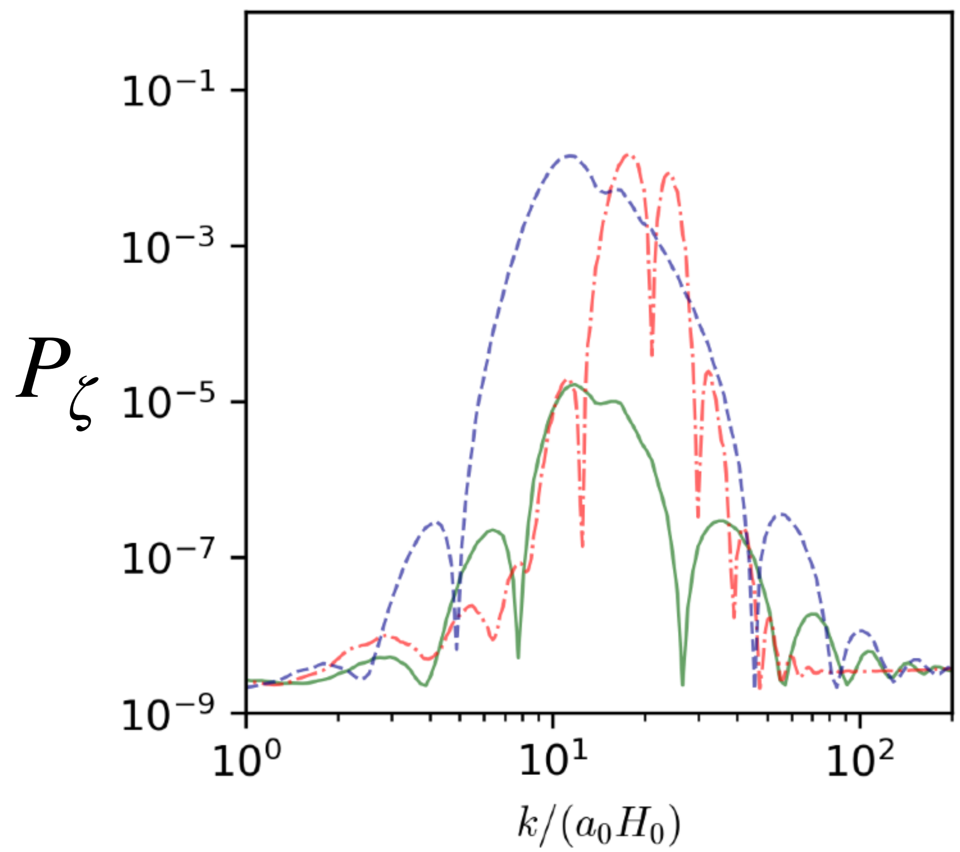




Case 1: $P_\zeta \simeq 10^{-5}$
Case 2: $P_\zeta \simeq 10^{-2}$
Case 3: $P_\zeta \simeq 10^{-2}$

[K. Inomata, M. Braglia, X. Chen, S. Renaux-Petel 2211.02586]

$$P_{\zeta,1-\rm loop} \gtrsim P_{\zeta,\rm tree}$$

In case 3 and 2, but not 1

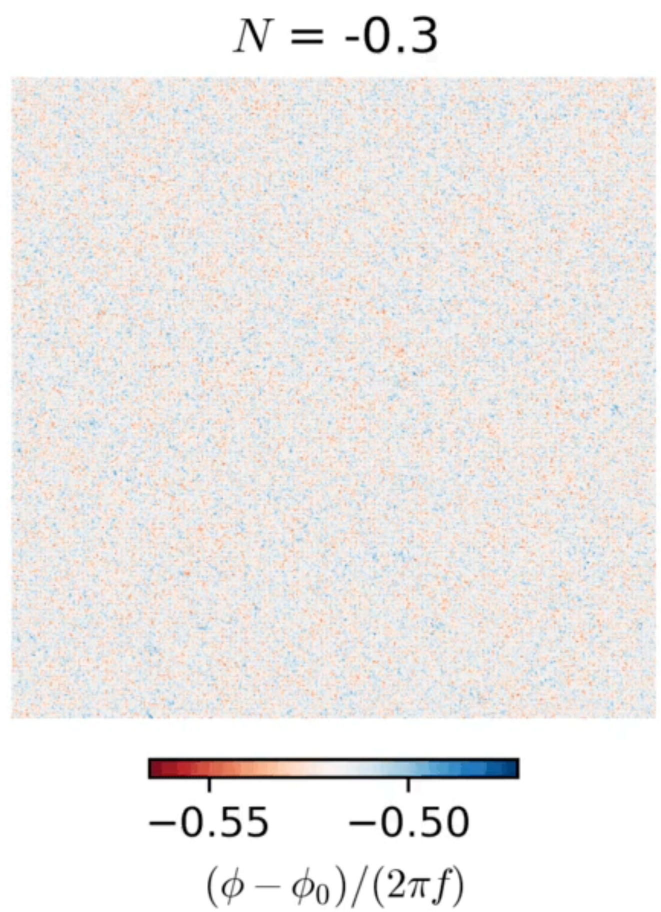
AC, S. Renaux-Petel, K. Inomata [2403.12811]

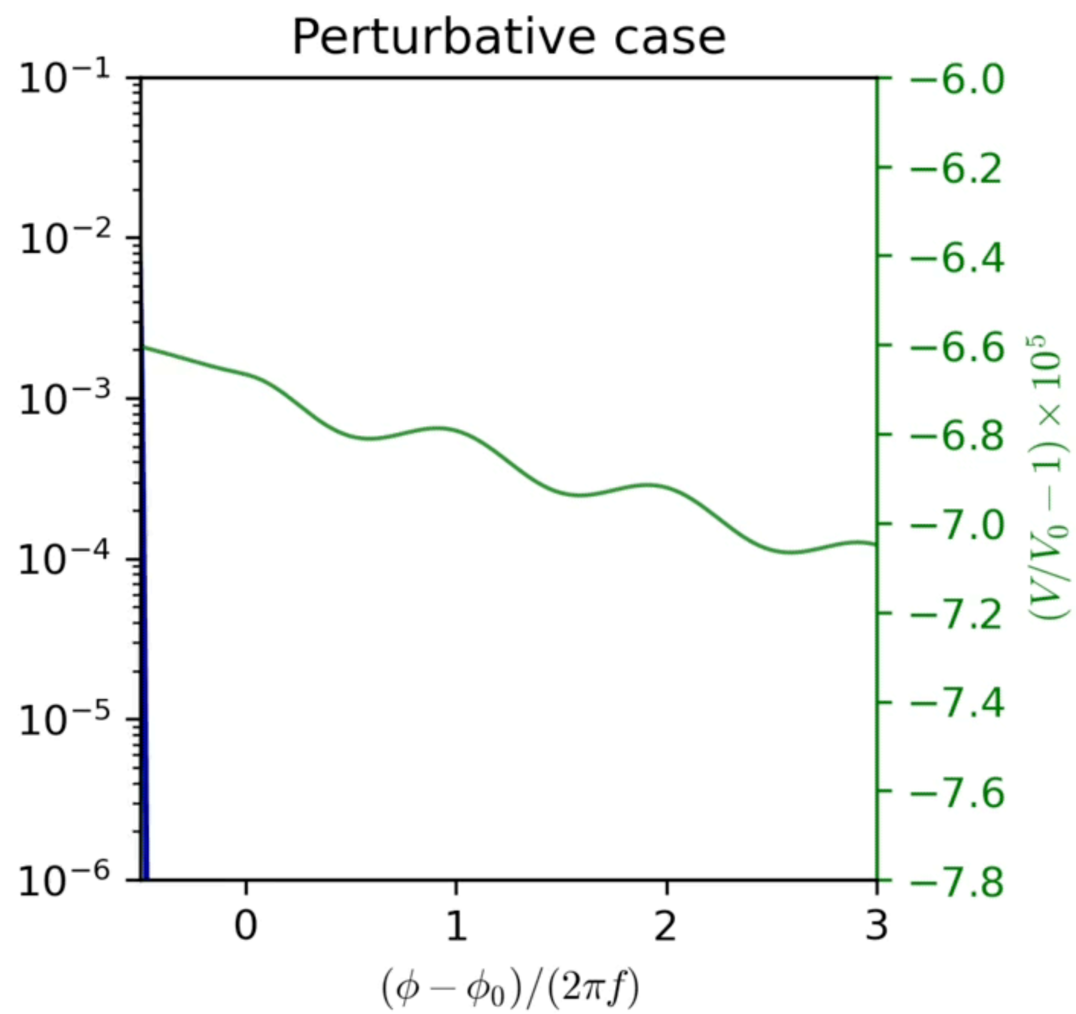
Case 1. $(P_\zeta \sim 10^{-5})$

Case 1 is perturbative

Animations:

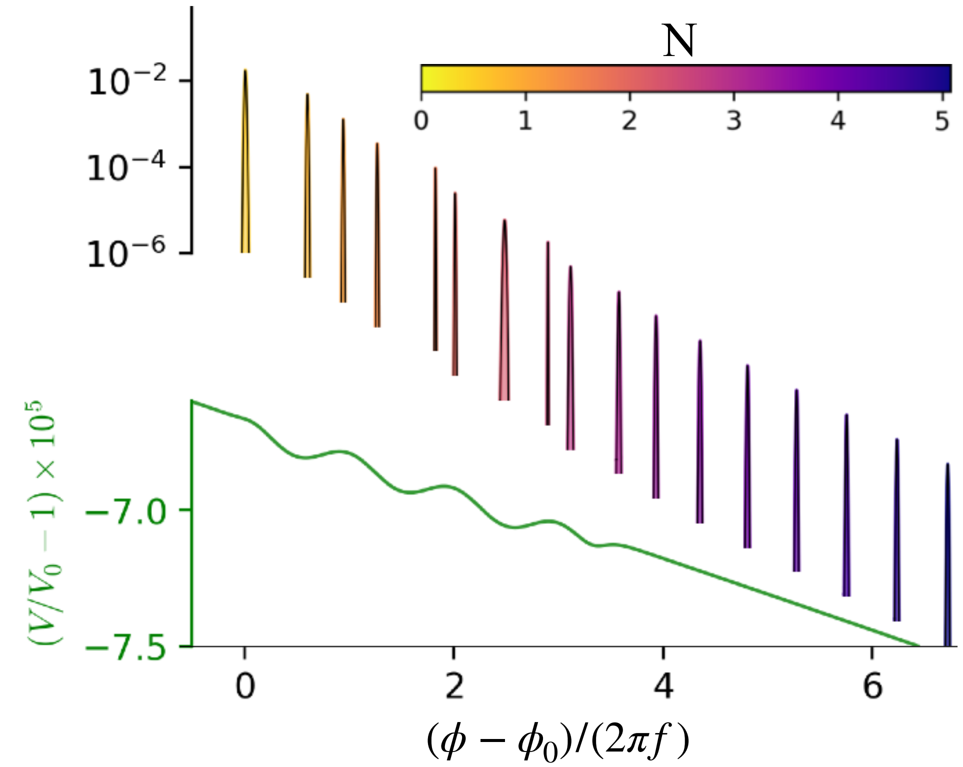
(link is also in the paper)

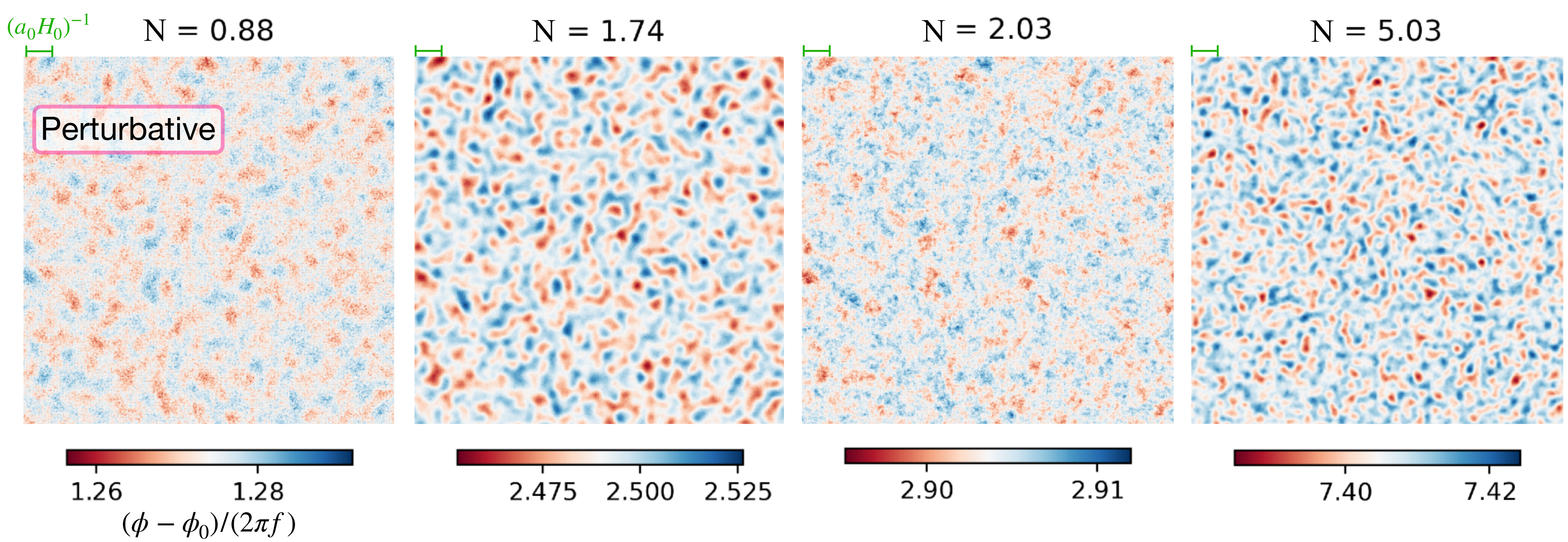




Case 1. ($P_\zeta \sim 10^{-5}$)

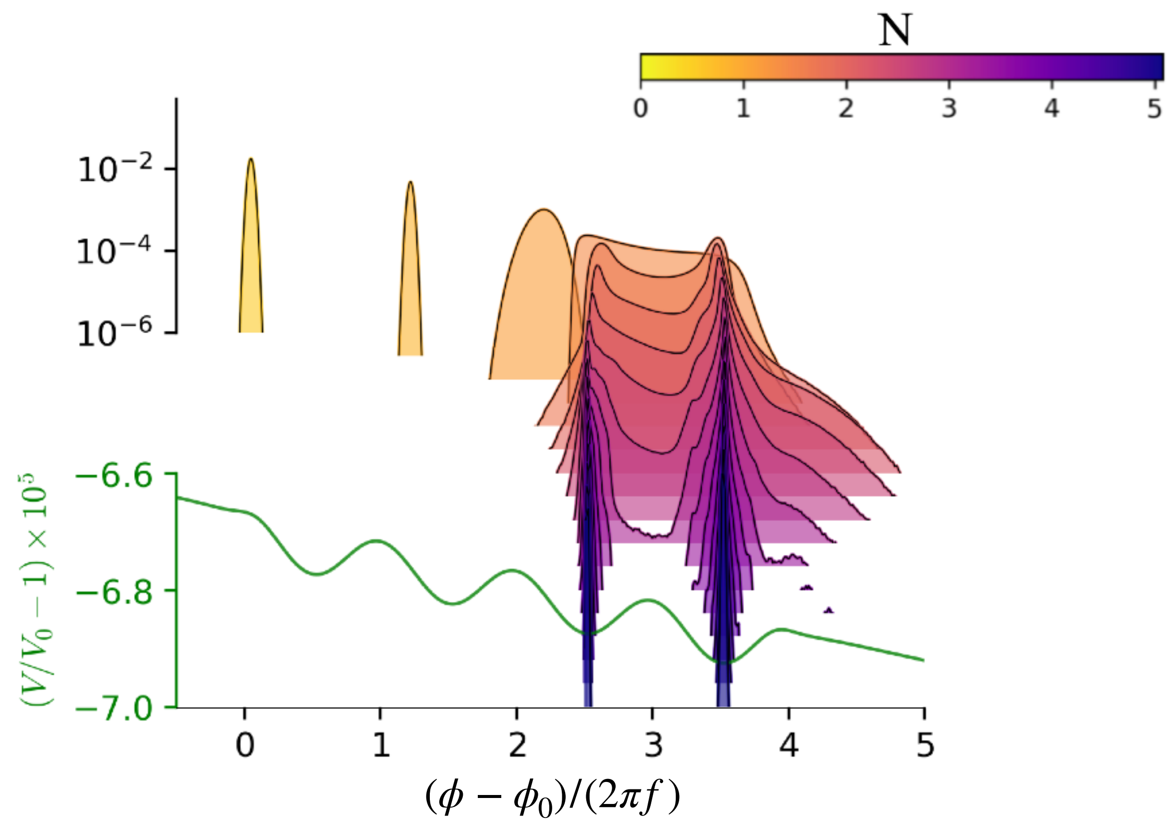
Case 1 is perturbative

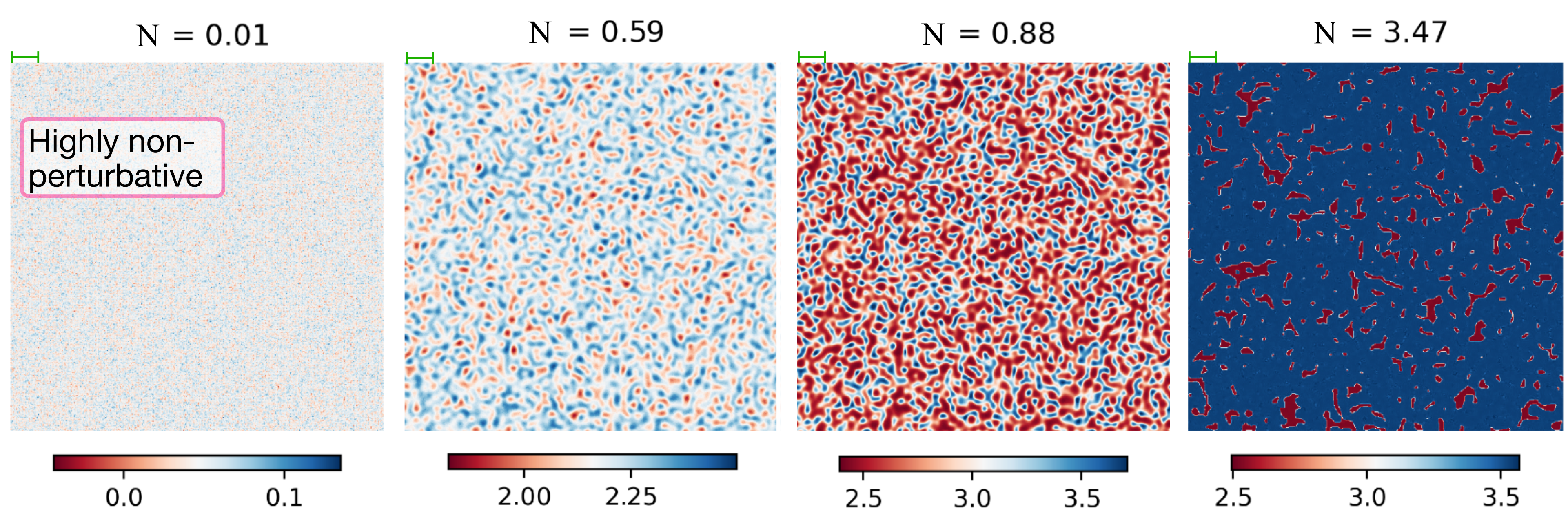




Case 2. ($P_\zeta \sim 10^{-2}$)

Case 2: Inflaton is stuck inside the oscillatory potential

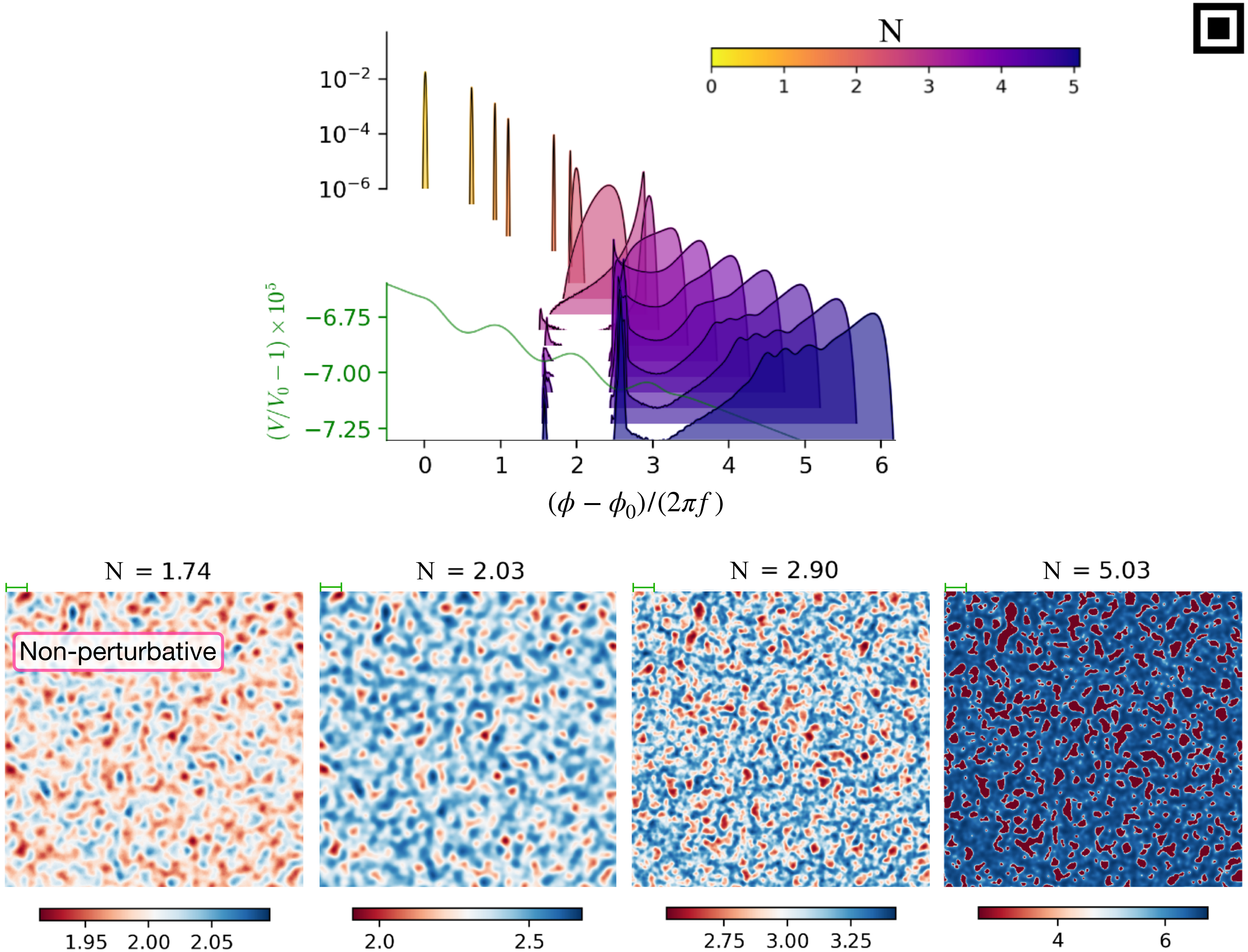




Case 3. ($P_\zeta \sim 10^{-2}$)

Case 3: Only some patches are stuck in the resonant potential!

The rest continues slow-rolling

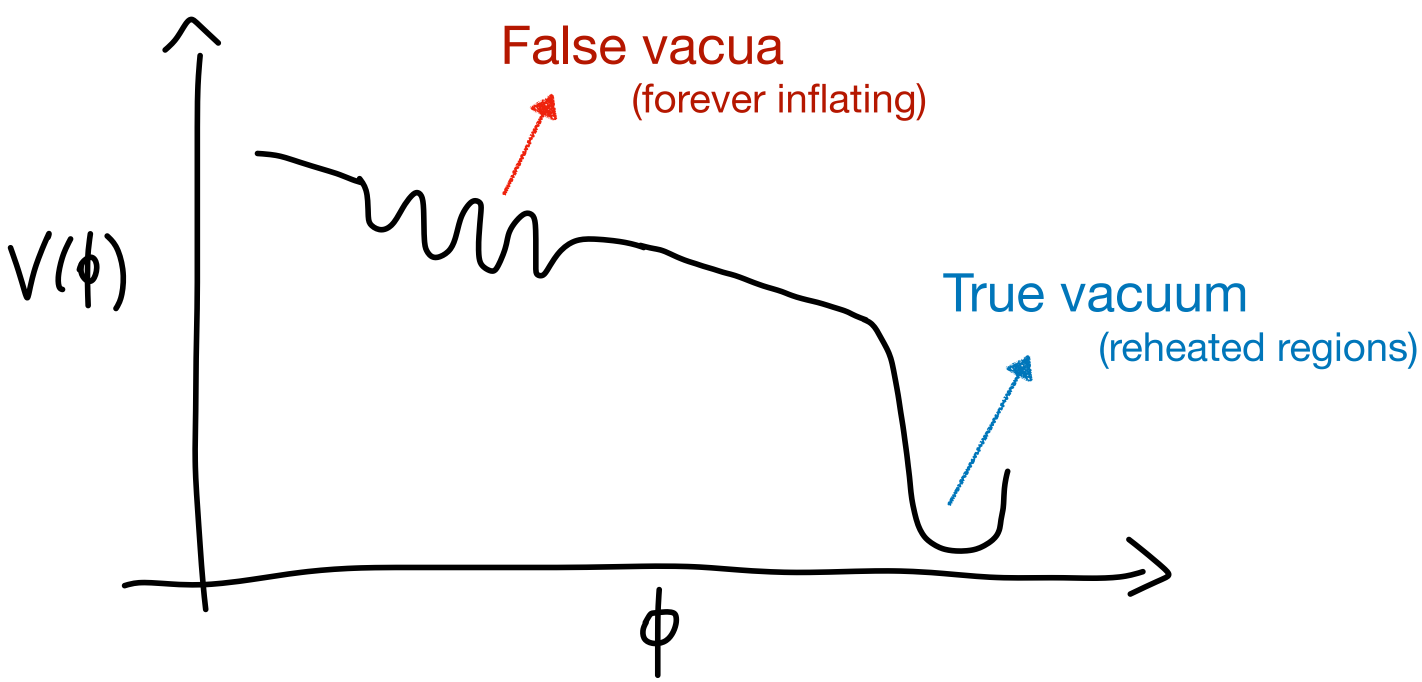


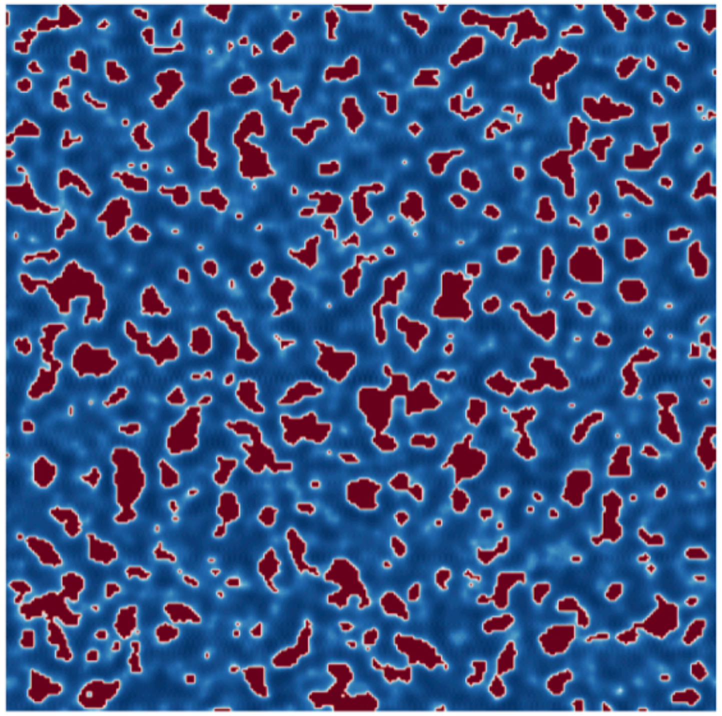
Case 3: inflaton trapping

Case 3:

What happens to the trapped regions at the end of inflation?

Their fate is <u>analogous to false vacuum trapping</u>.





Inflaton trapping and PBHs

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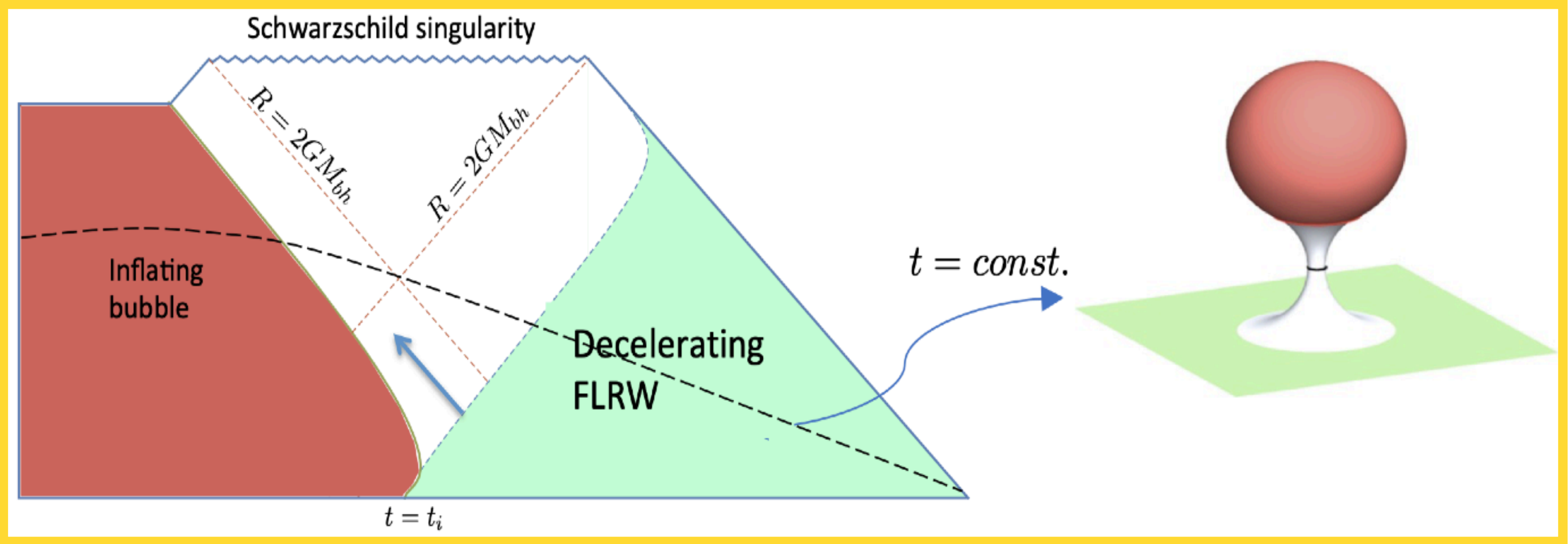
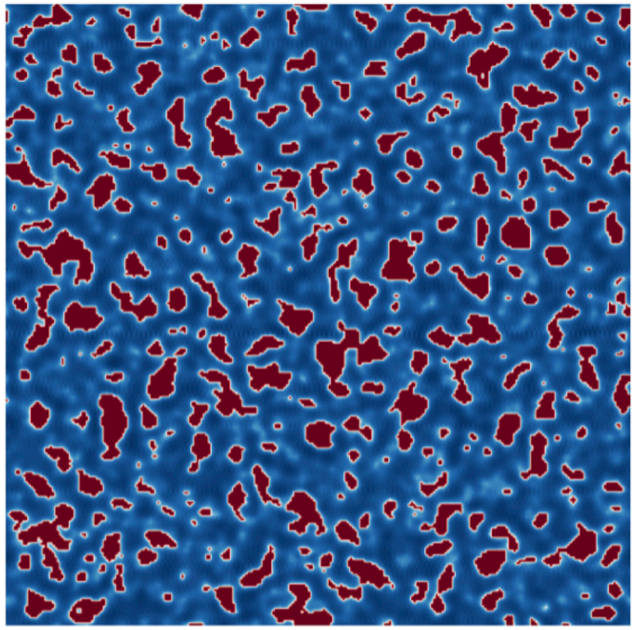


Figure credit:
[J. Garriga, A. Vilenkin, J. Zhang arXiv:1512.01819]



The trapped regions become PBHs at the end of inflation! (in the form of baby universes)

PBH abundance

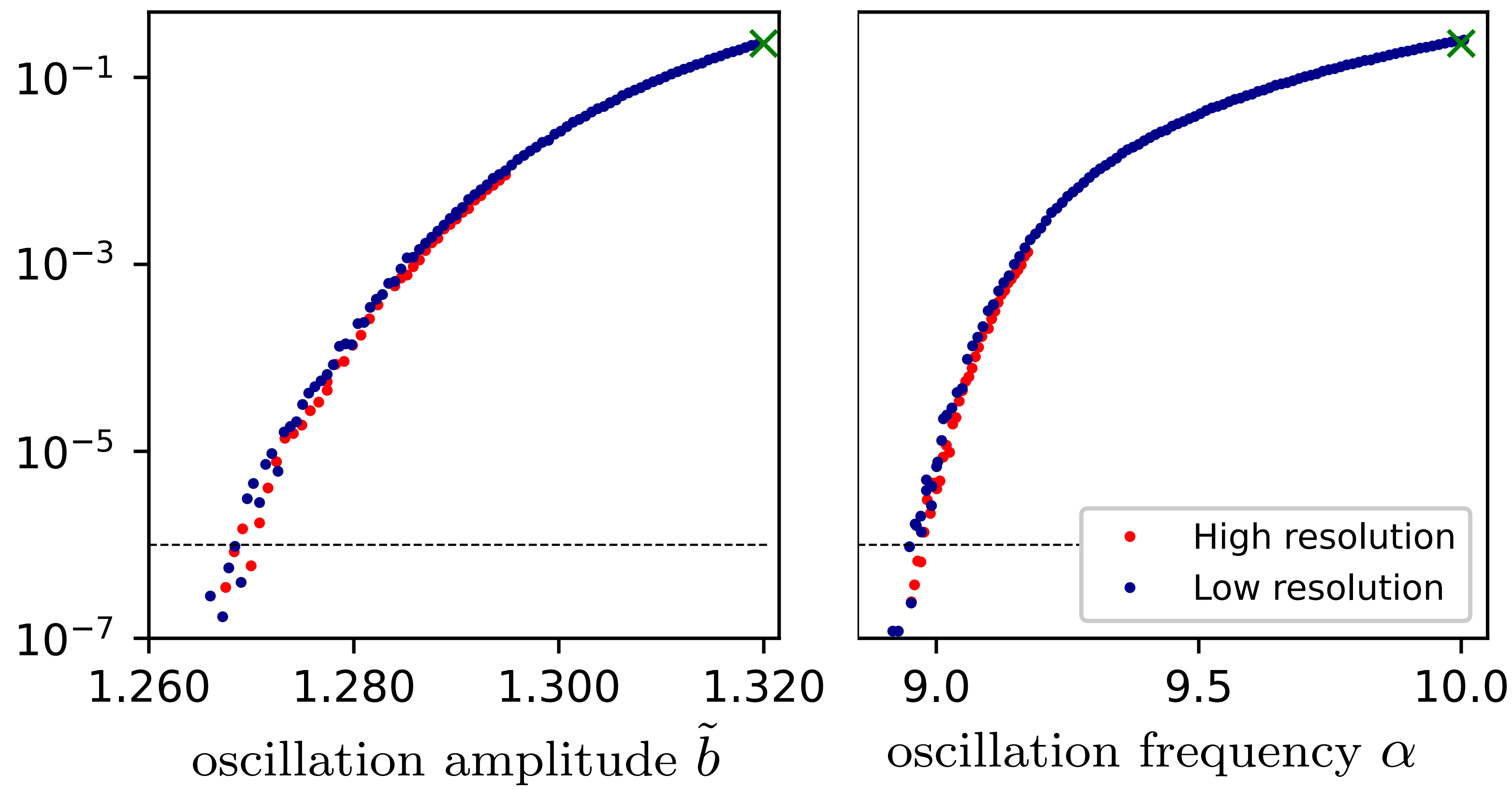
Case 3:

The trapped regions become PBHs at the end of inflation!

How many PBHs?

Mass fraction in PBHs at the time of formation

Trapped volume fraction $\mathcal{F}_t = V_{\text{trapped}}/V_{\text{total}} \simeq \beta$



500 lattice simulations in this plot

Inflationary Butterfly Effect

Lorenz (1972):

"Can the Flap of a Butterfly's Wings in Brazil Set Off a Tornado in Texas?" [1]

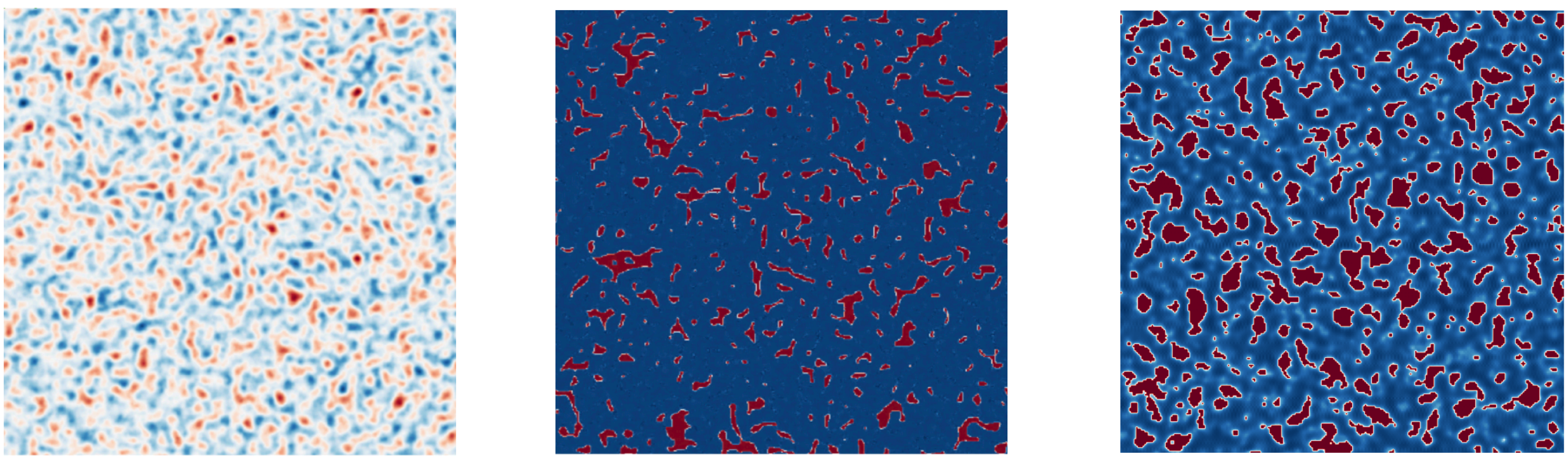
Can tiny, small-scale quantum fluctuations affect the dynamics of the entire Universe?

[1]: E. N. Lorenz, American Association for the Advancement of Science (1972).

Inflationary Butterfly Effect

Main lesson:

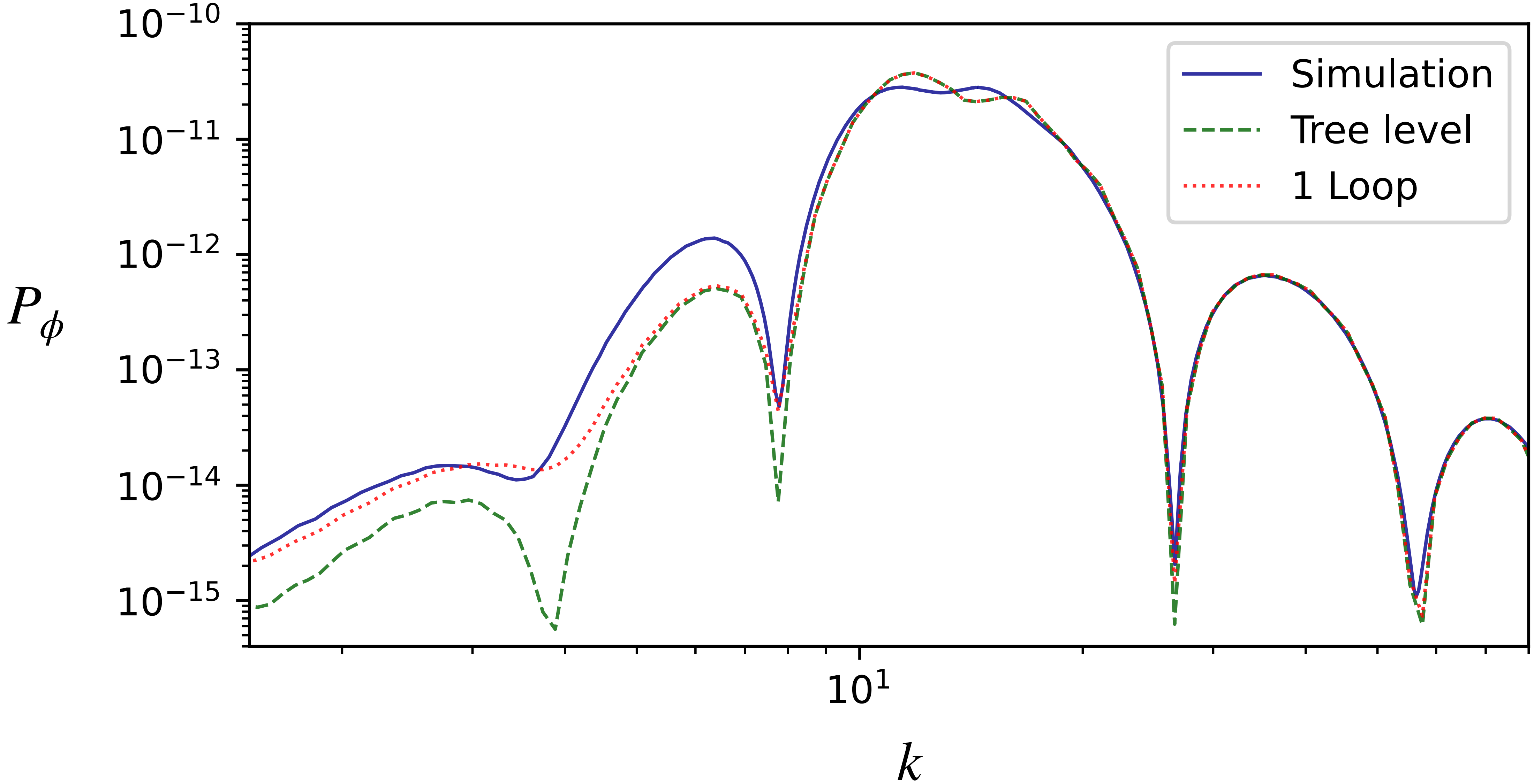
<u>Non-perturbative physics</u> at small scales can have drastic effects on the inflationary dynamics when $\mathscr{P}_\zeta \sim 10^{-2}$



Loop effects

In the perturbative setup,

first **quantitative comparison** between full nonlinear, tree-level and 1-loop



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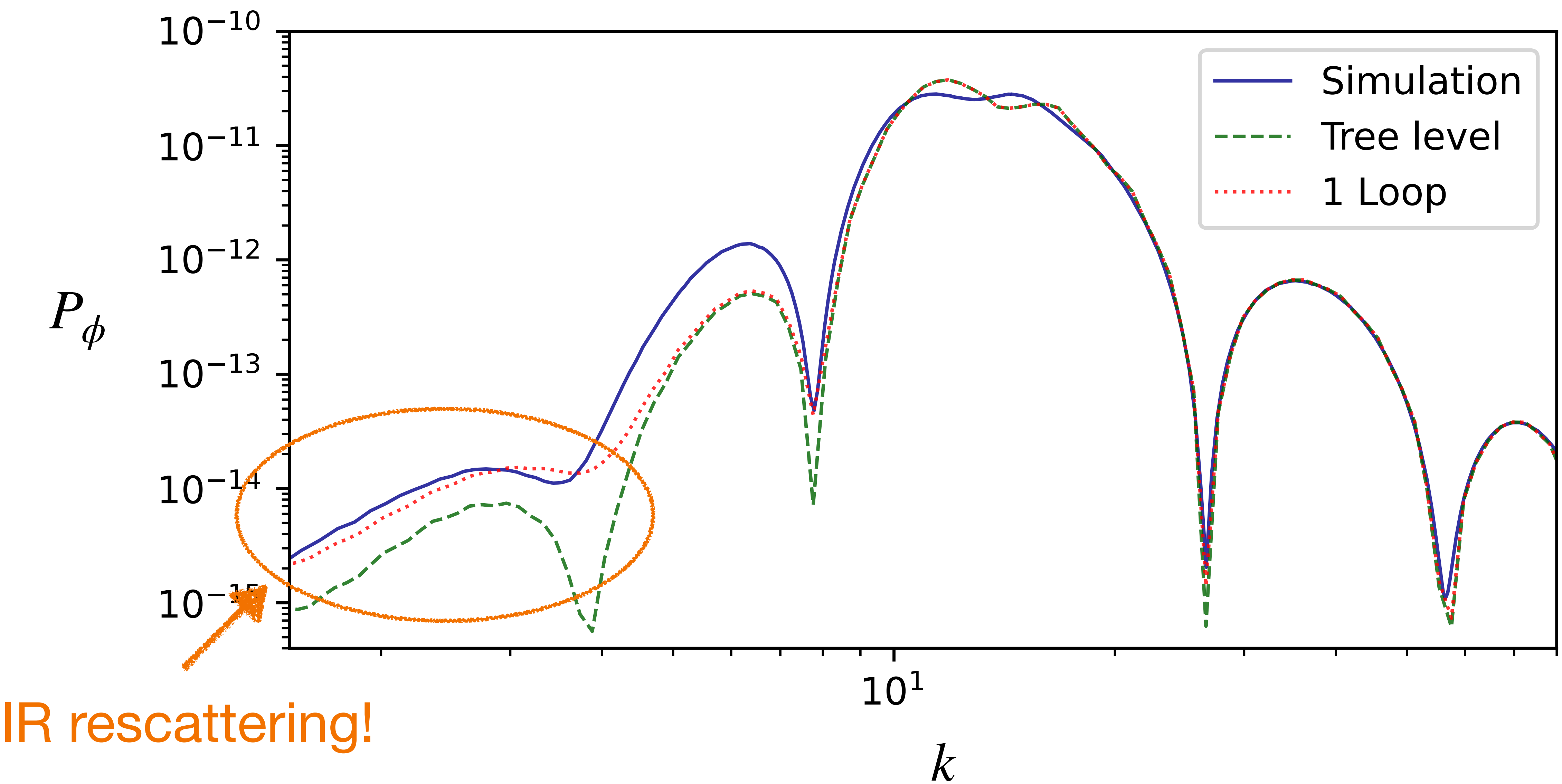

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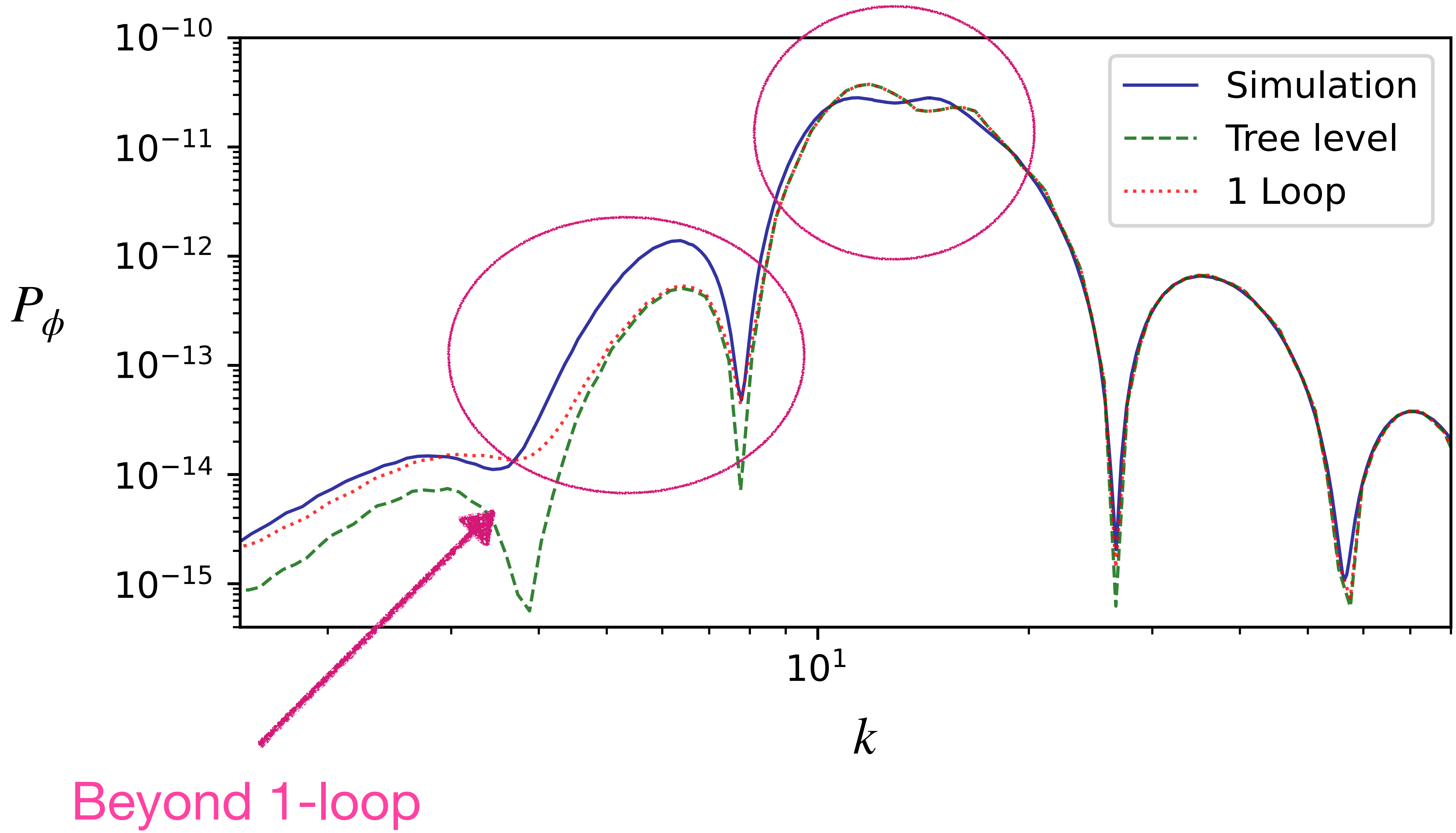

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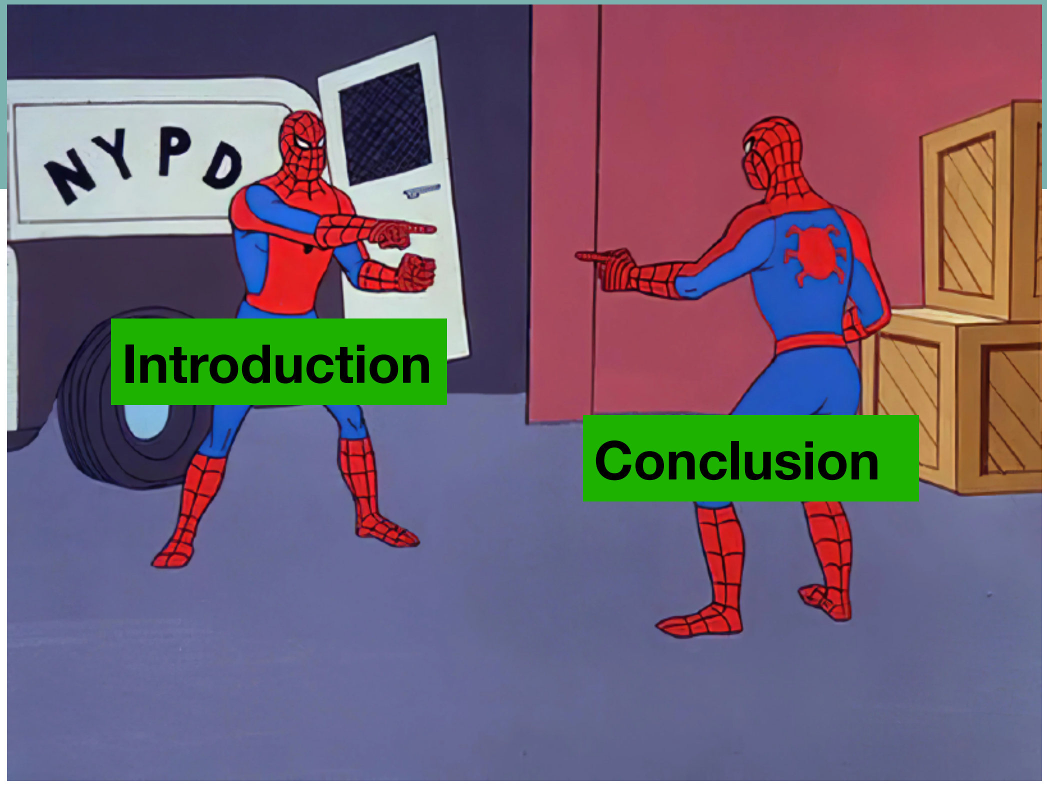

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