Probing the Early Universe with Gravity — 23 November 2016

More Gravitational Waves From Axion Monodromy

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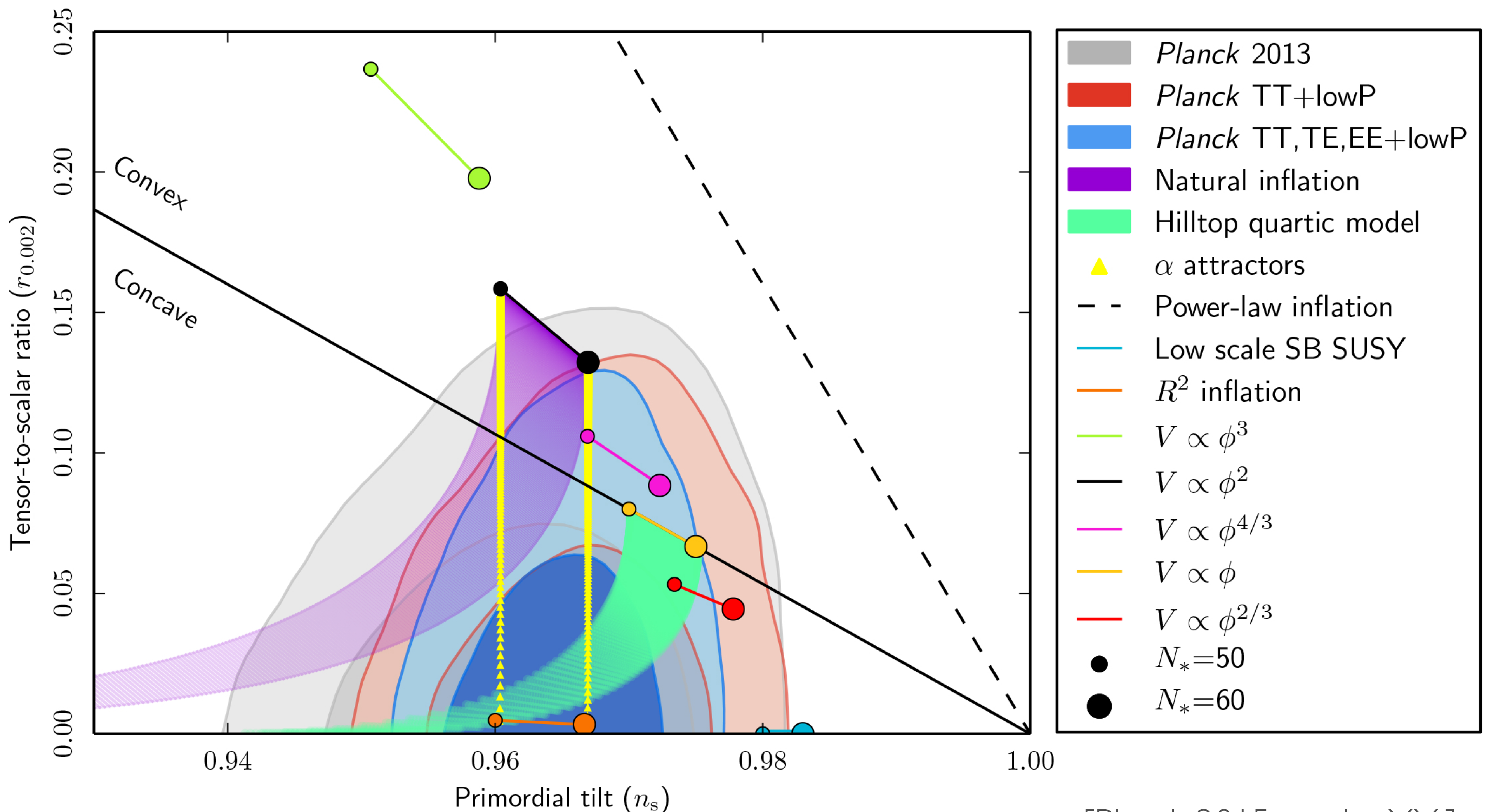
1606.07812

with Arthur Hebecker, Joerg Jaeckel & Fabrizio Rompineve

Motivation

Many Inflation models are consistent with a given n_s and r.



[Planck 2015 results: XX.]

How can we distinguish between models?

Motivation

Here: focus on **axion monodromy inflation.** [Silverstein, Westphal 2008; McAllister, Silverstein, Westphal 2008]

- One of the most promising approaches to large field inflation.

- Model of axion inflation inflation with a potential:

$$V \sim \mu^{4-p}\phi^p + \Lambda^4 \cos\left(\frac{\phi}{f} + \gamma\right)$$

Polynomial potential
(due to branes / fluxes)

"Instantonic"
contribution

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$$V \sim \underbrace{\mu^{4-p}\phi^p}_{\textbf{Inflaton potential}} + \underbrace{\Lambda^4 \cos\left(\frac{\phi}{f}+\gamma\right)}_{\textbf{Modulations}}$$

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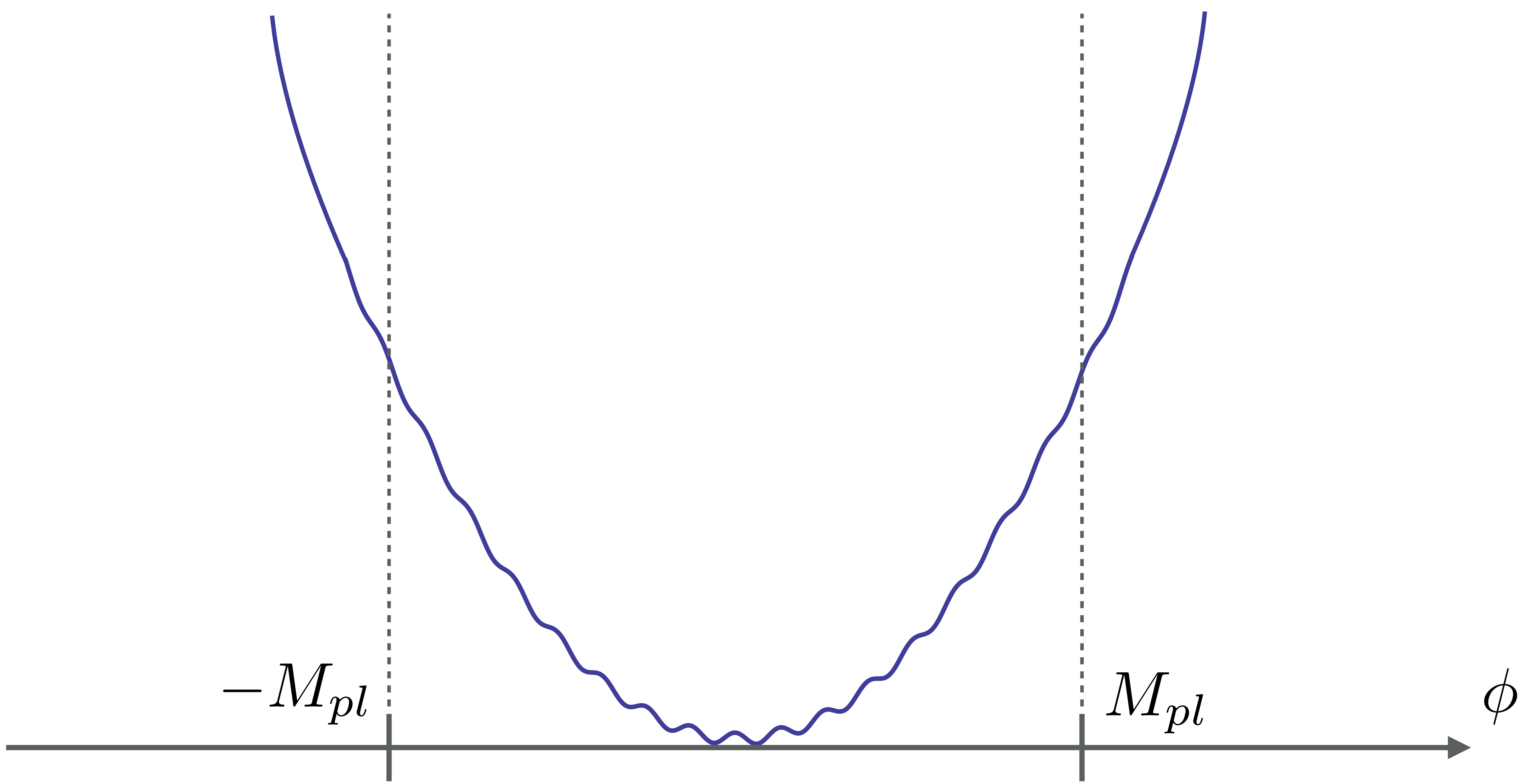

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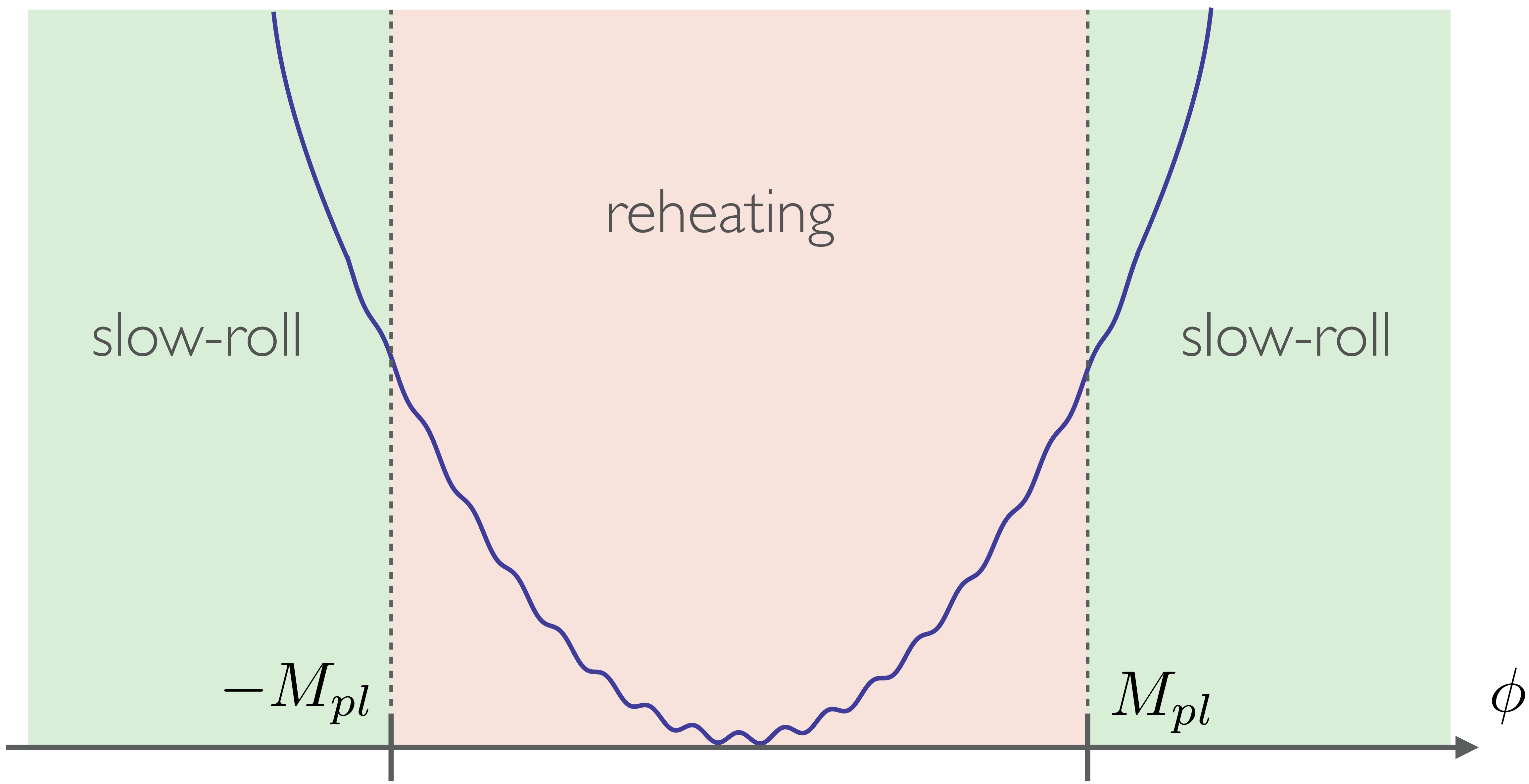

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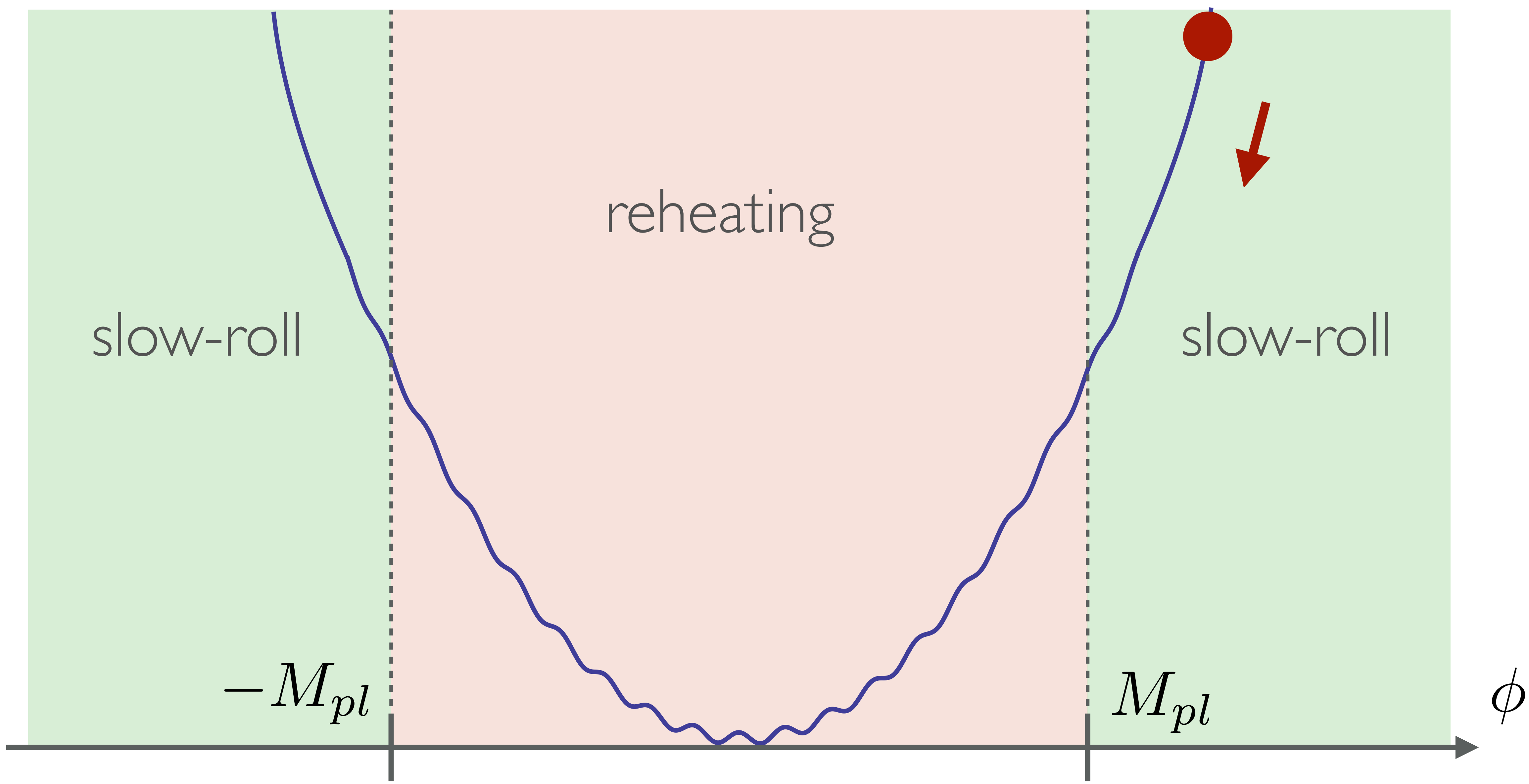

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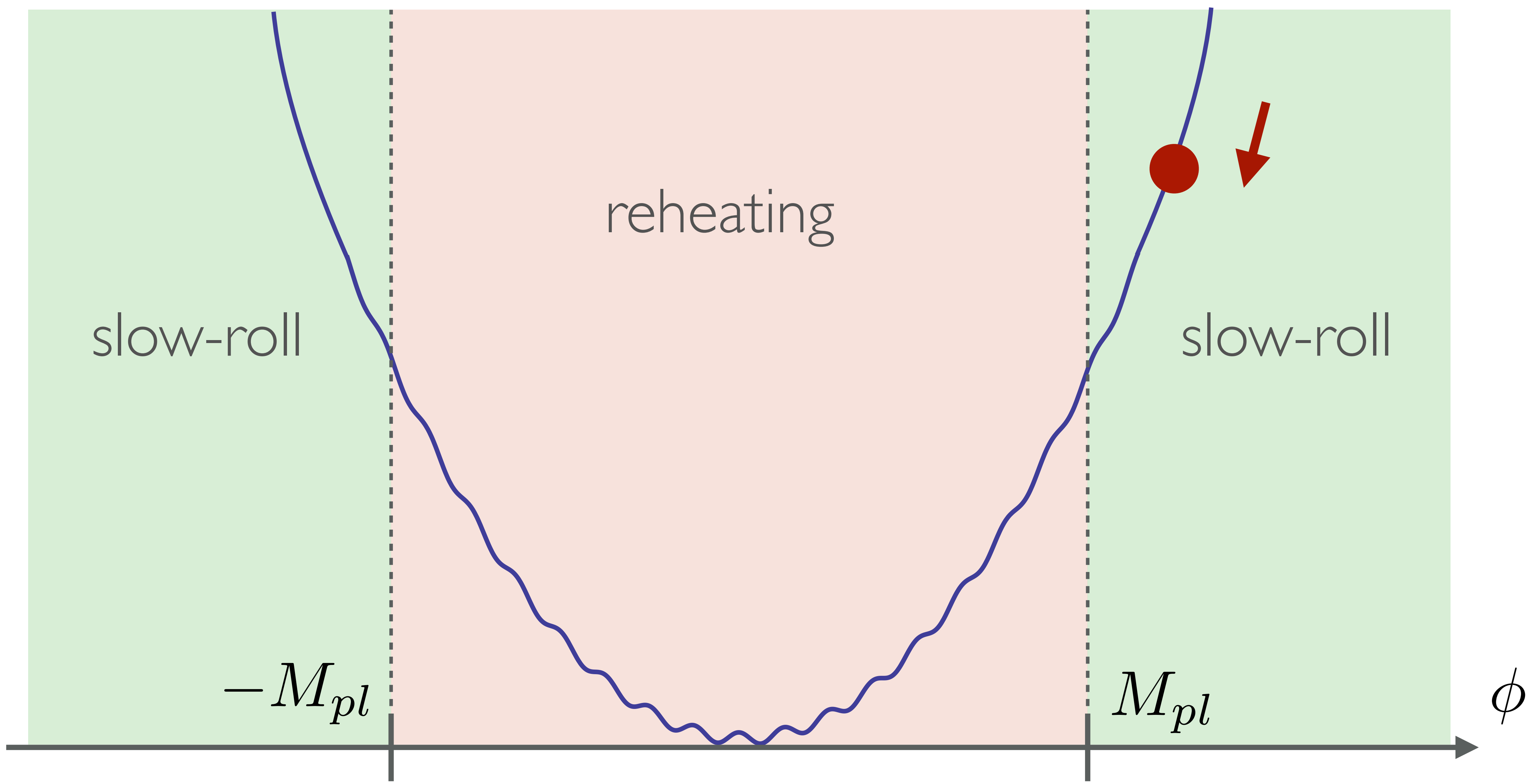

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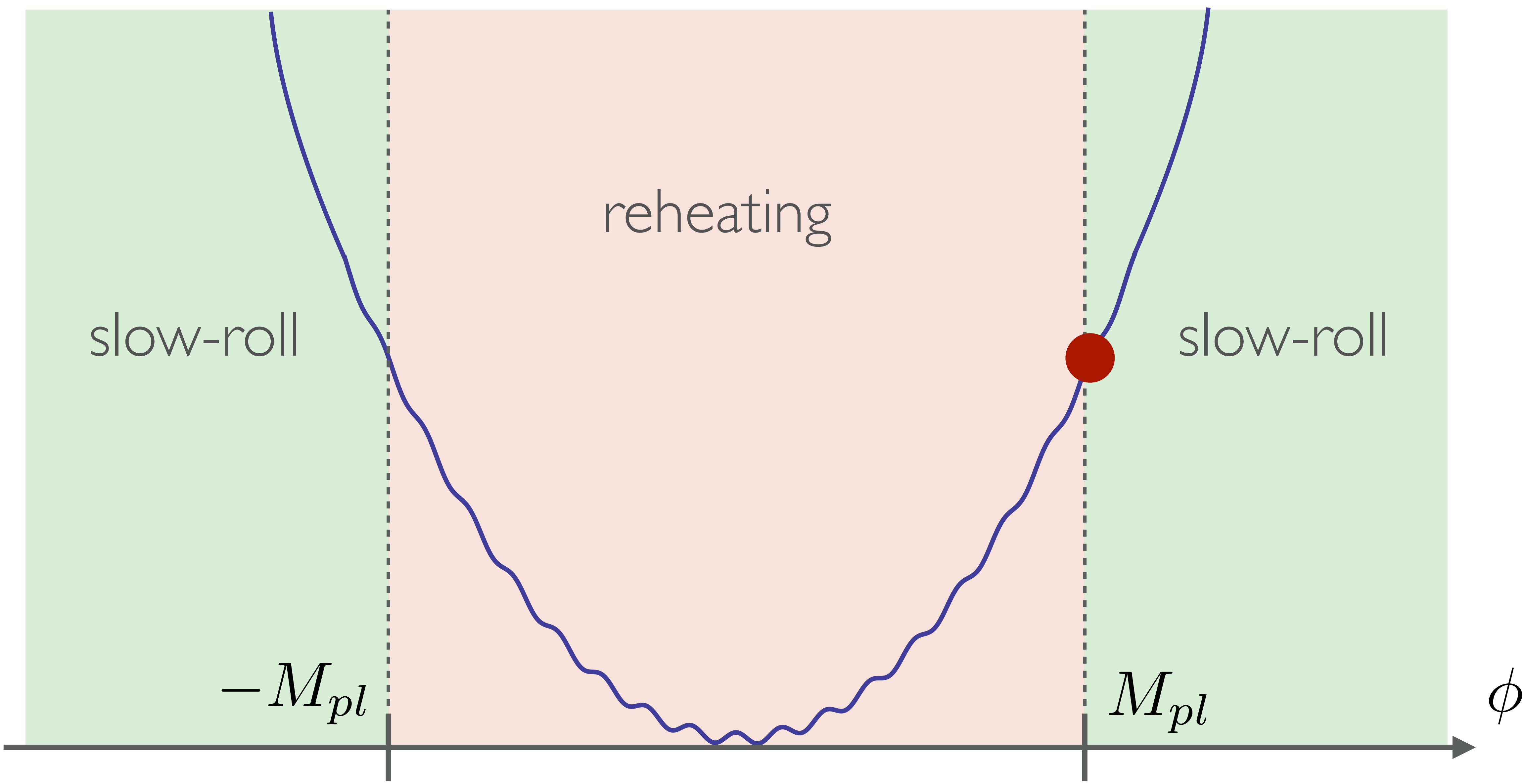

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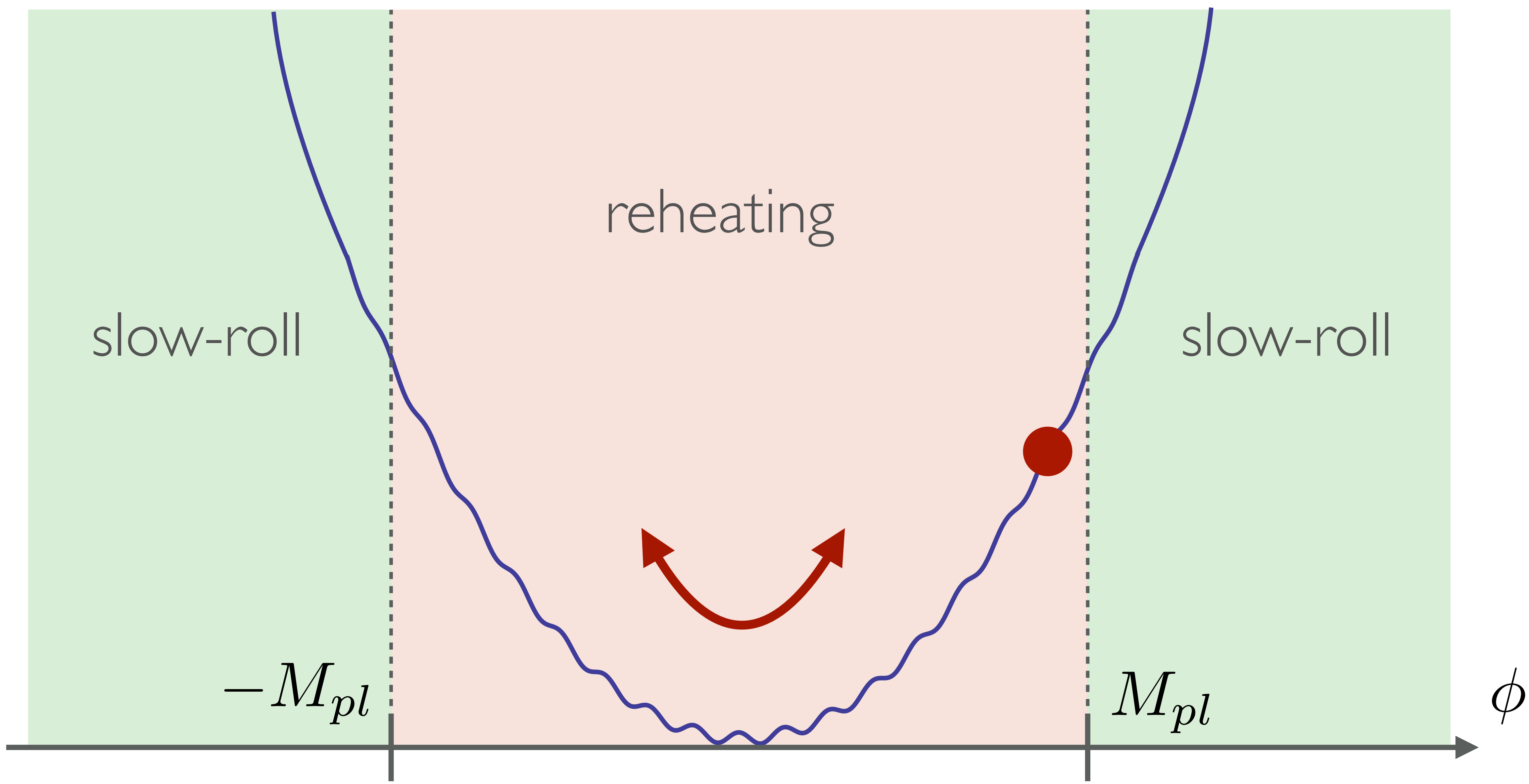

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From now on focus on the 'reheating region' of the potential

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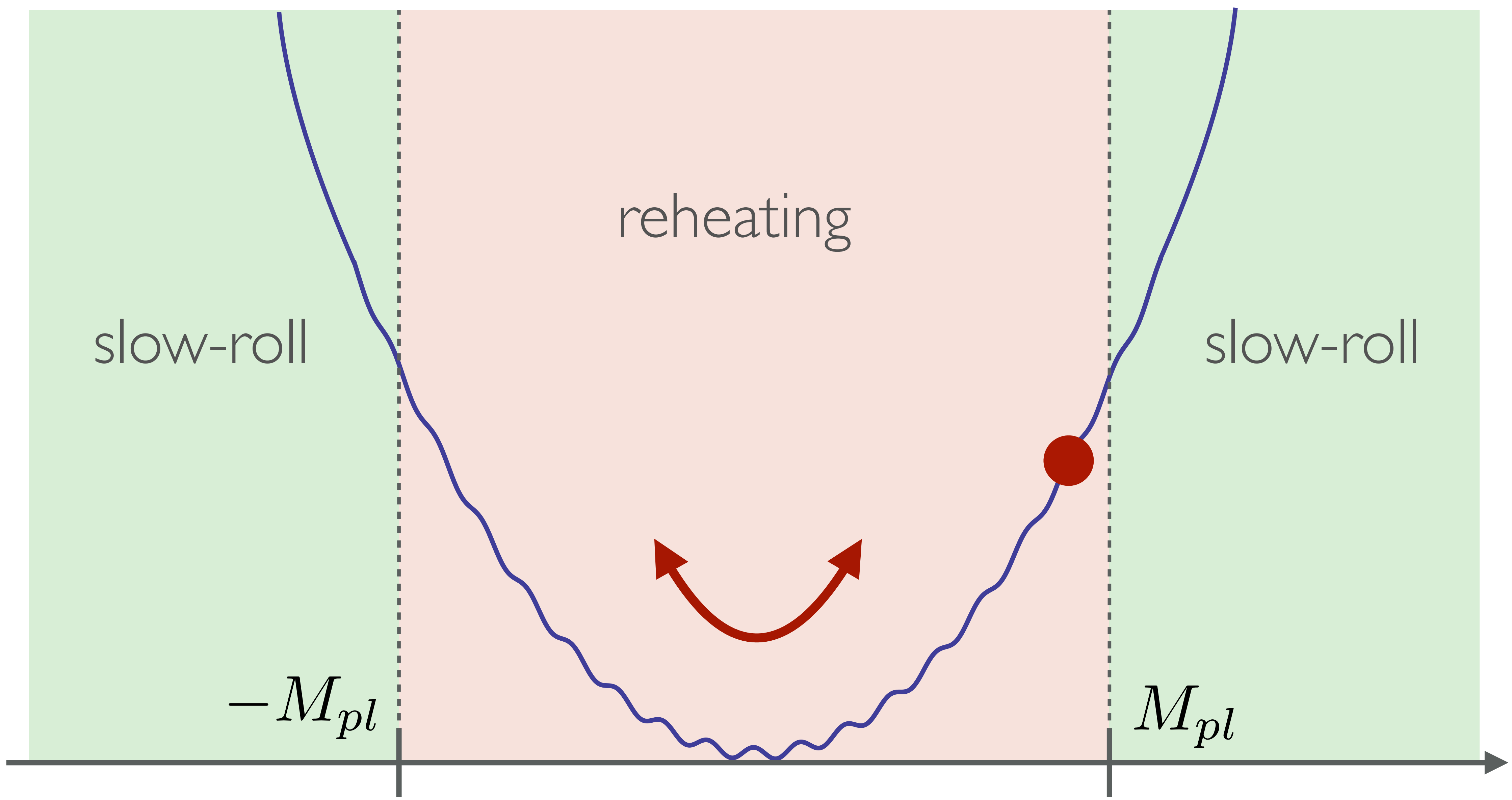

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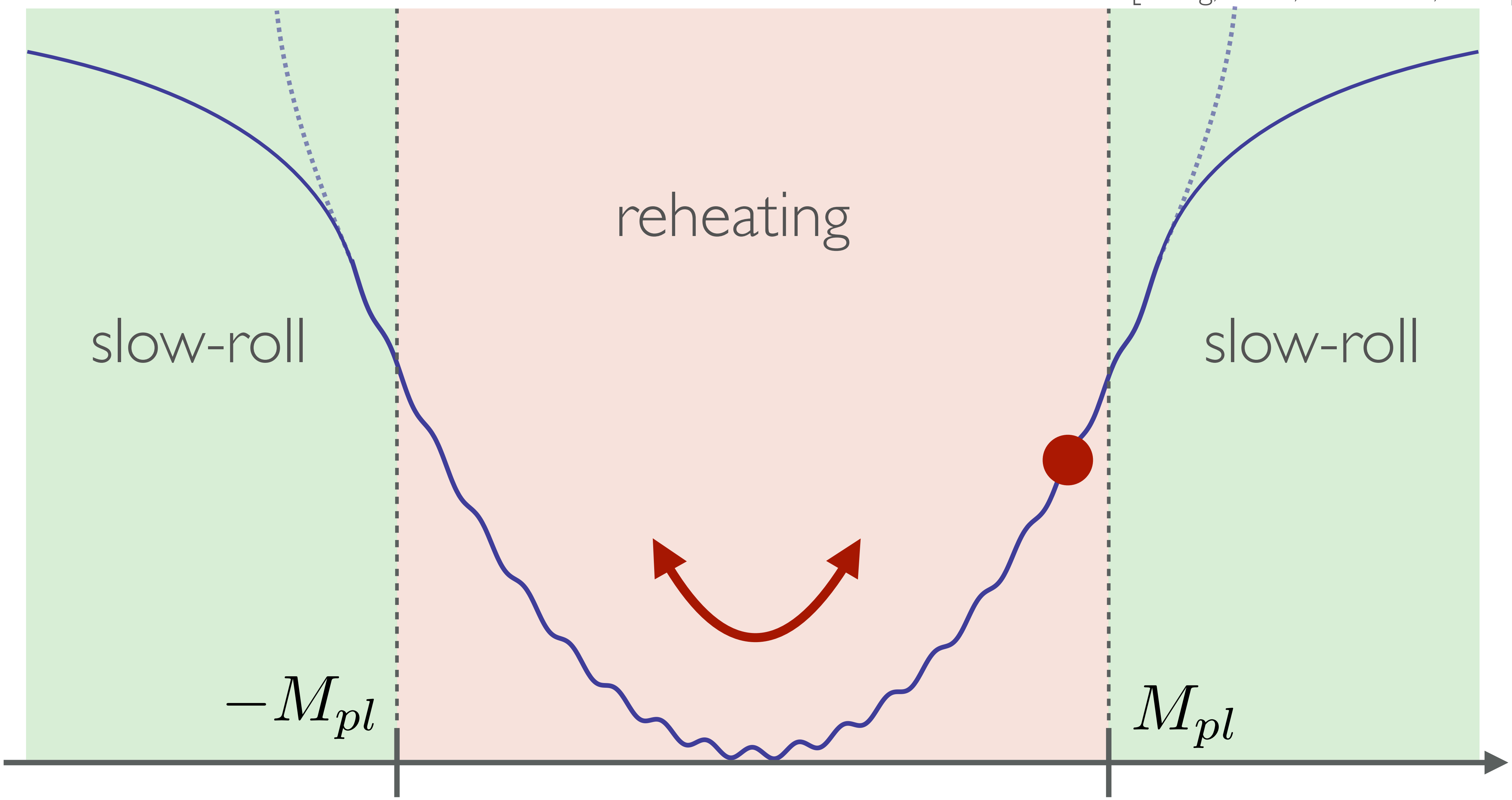
[Dong, Horn, Silverstein, Westphal 2010]



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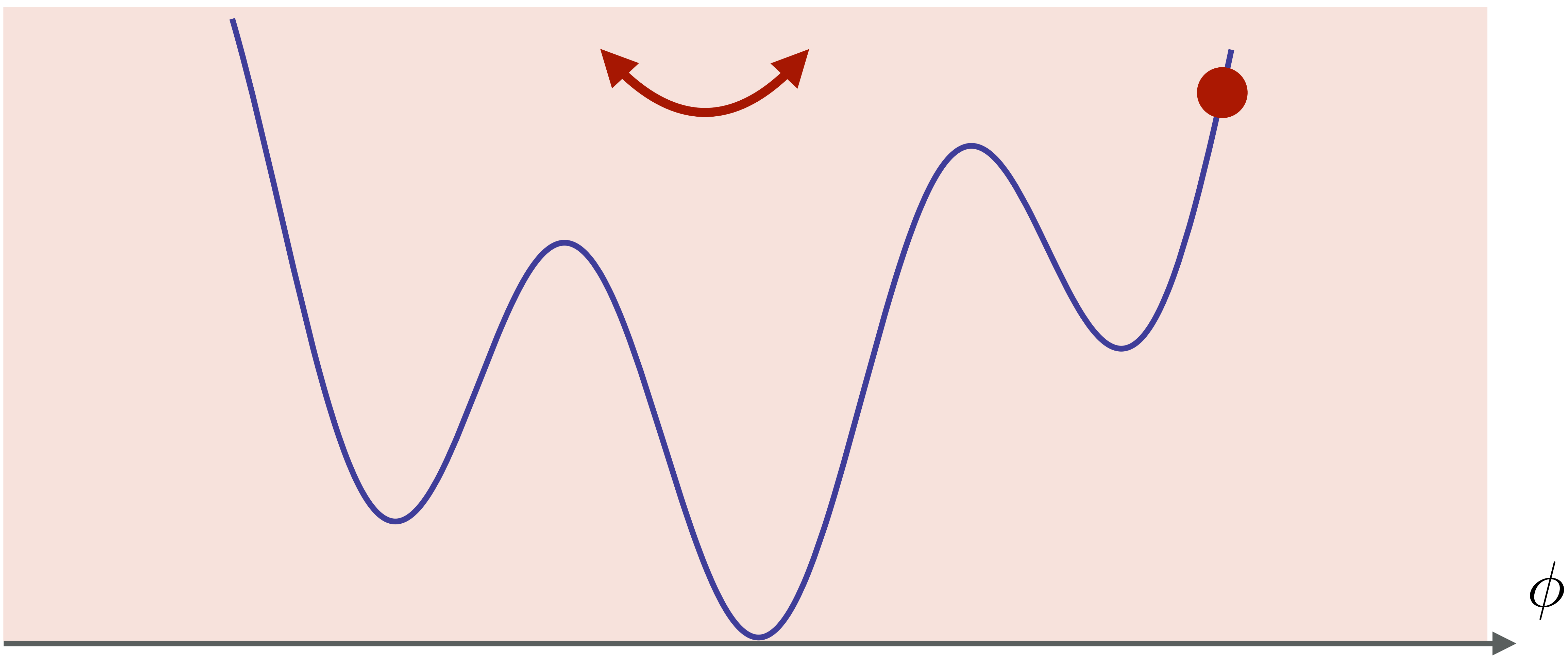
- If the modulations are large enough the potential exhibits many minima.
- The inflaton will eventually settle in one of the minima.
- **Interestingly, a phase decomposition can occur.**



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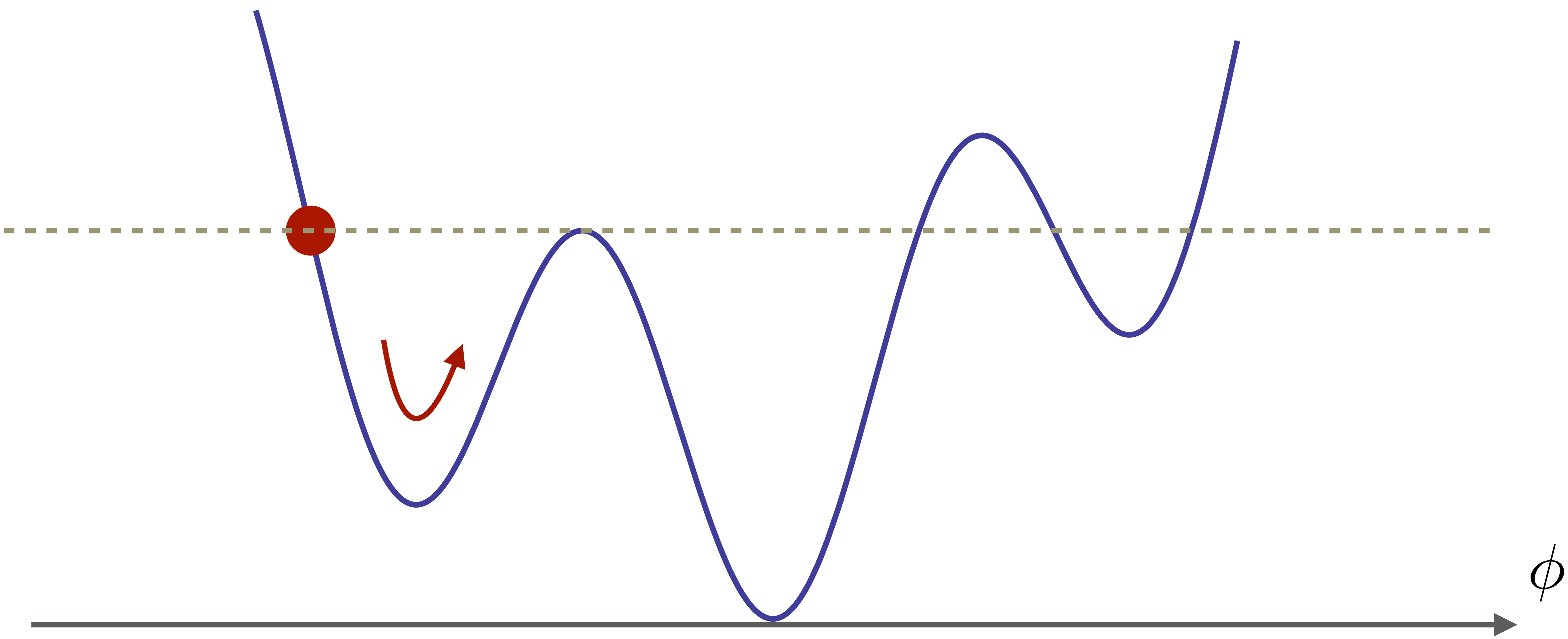

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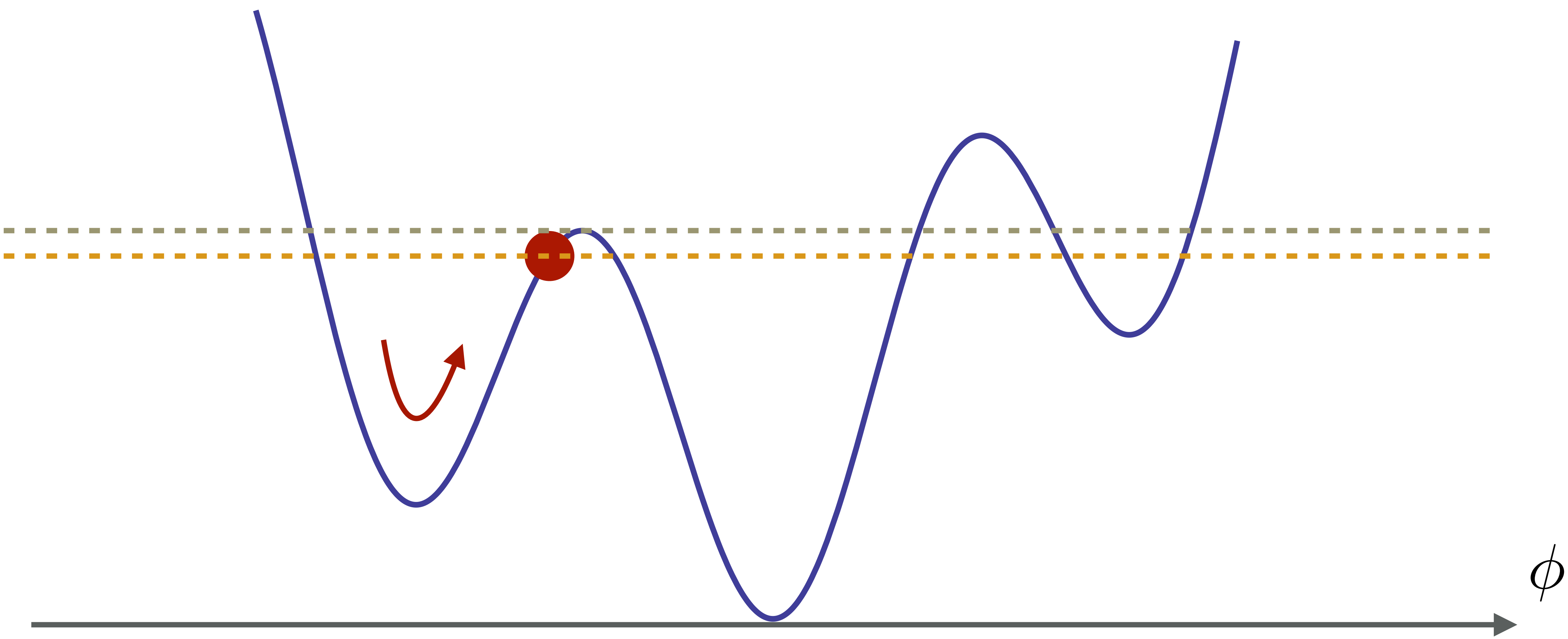

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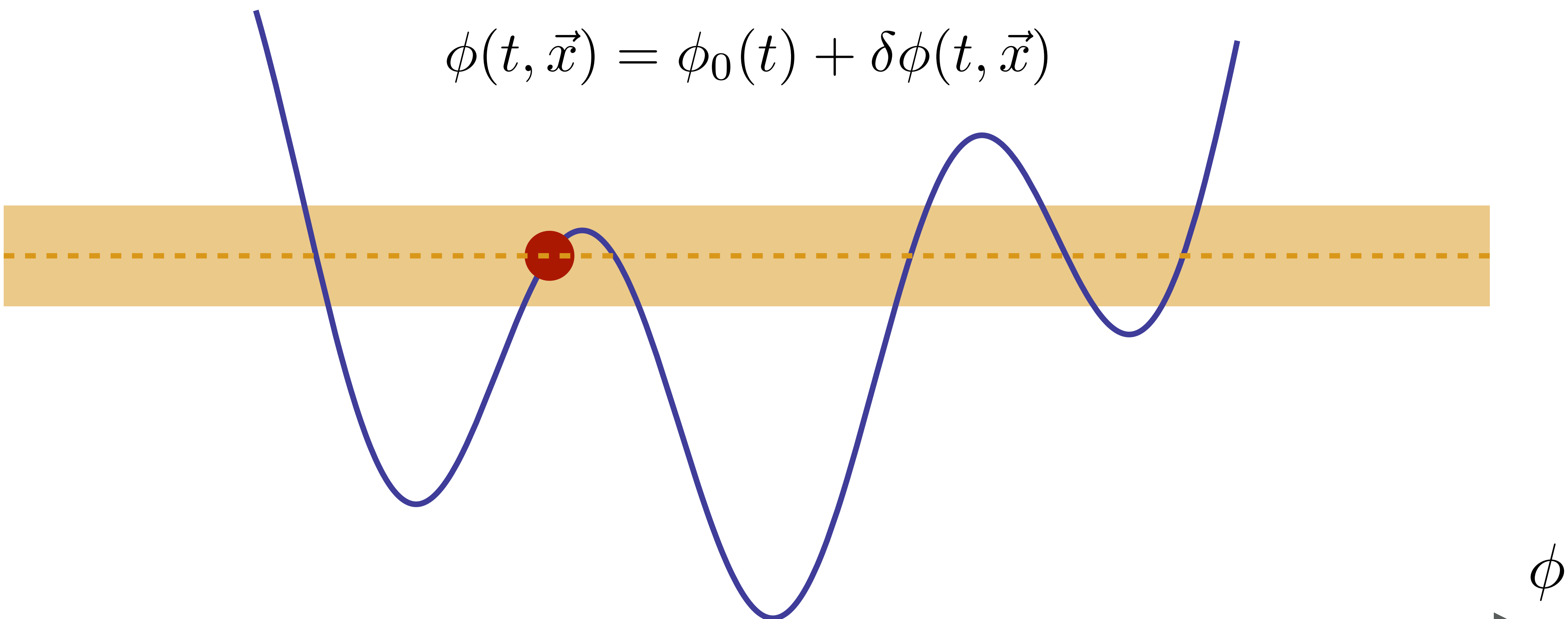

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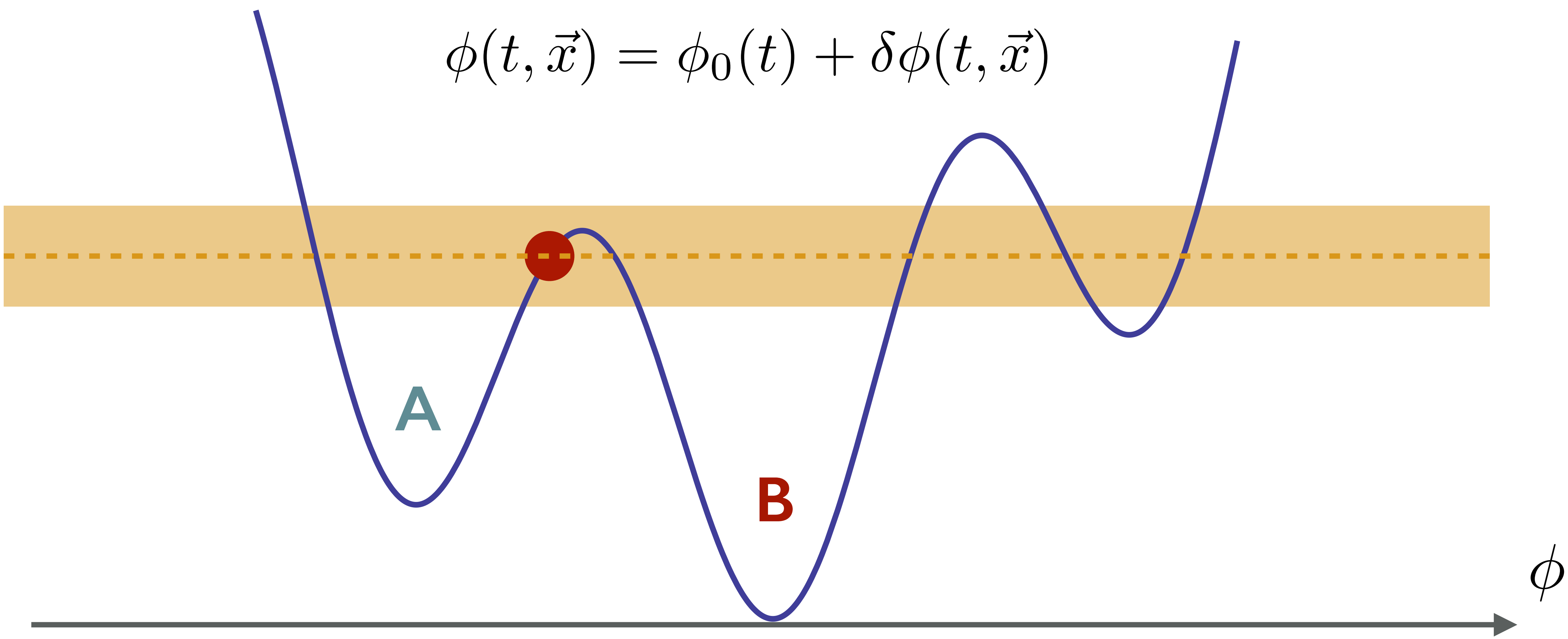

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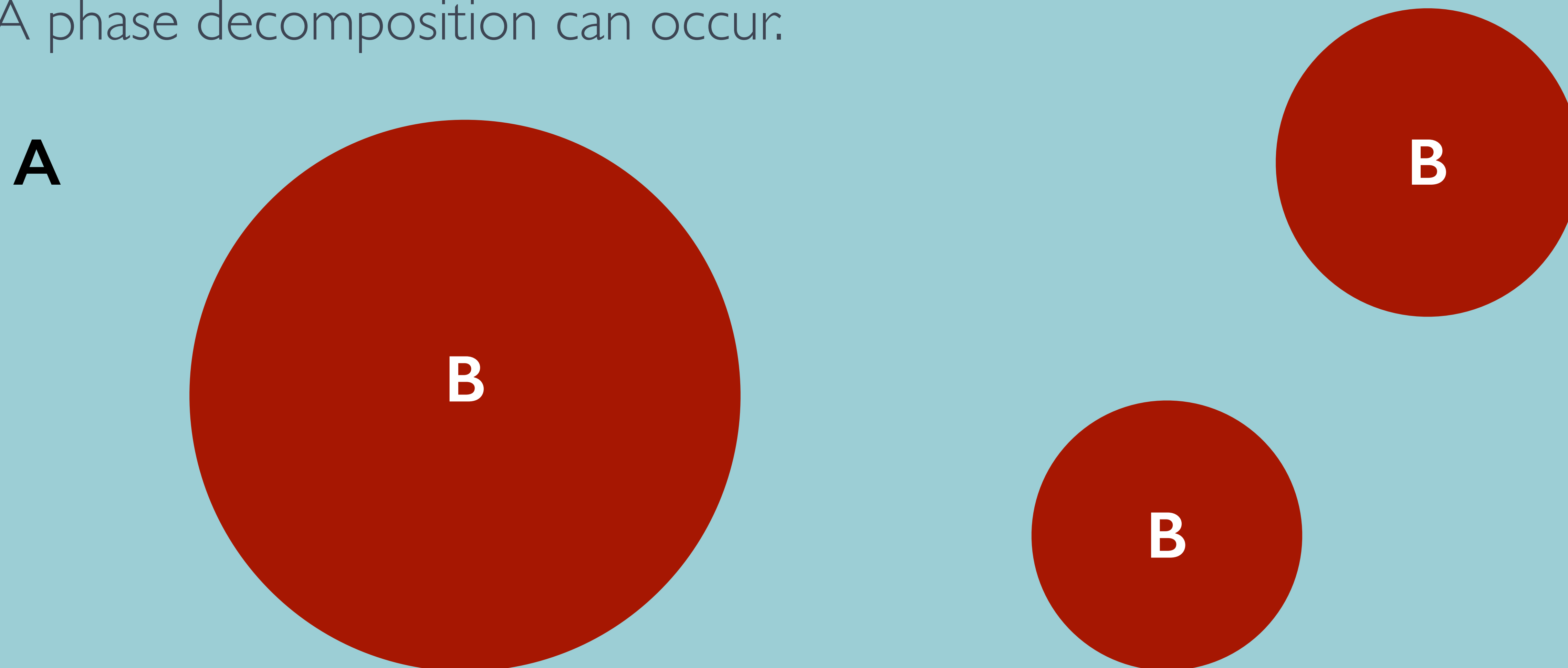
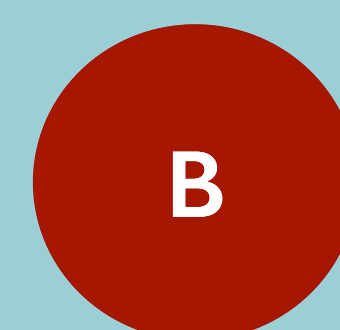


- Bubbles of the true vacuum **B** will expand and collide.
- Expect the emission of **Gravitational Waves.**



Outline

A

1. When can we have a phase decomposition?

B

B

2. Quantify the Gravitational Wave signal

B

Phase Decomposition?

- Quantify the **probability** for phase decomposition.

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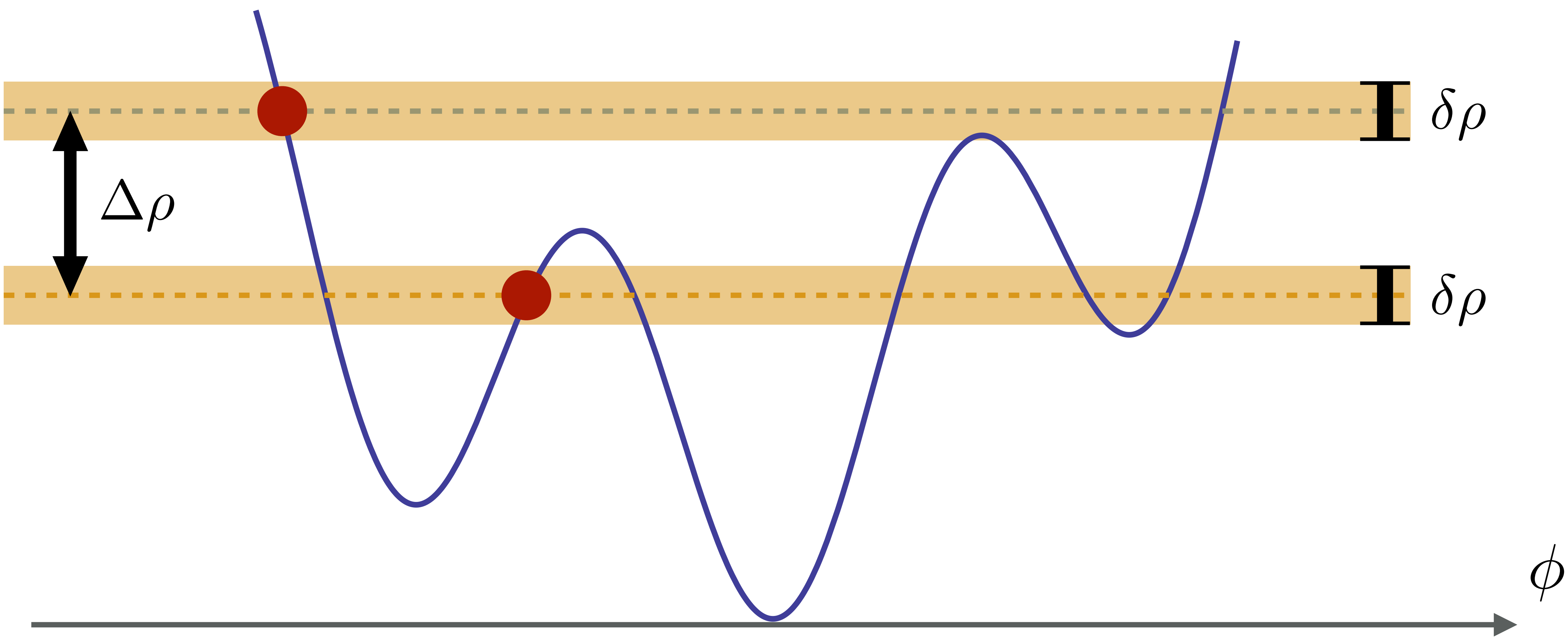
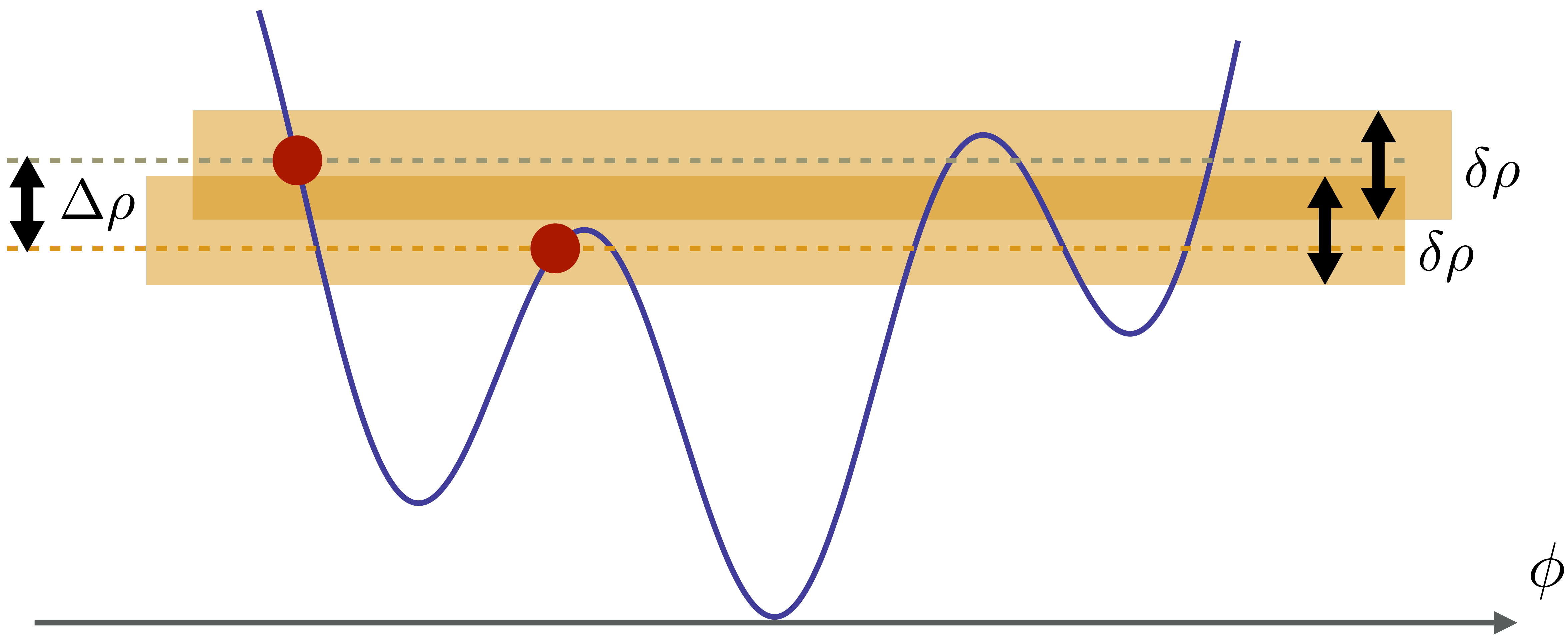
Phase decomposition unlikely



Phase Decomposition?

- Quantify the **probability** for phase decomposition.

Phase decomposition observed

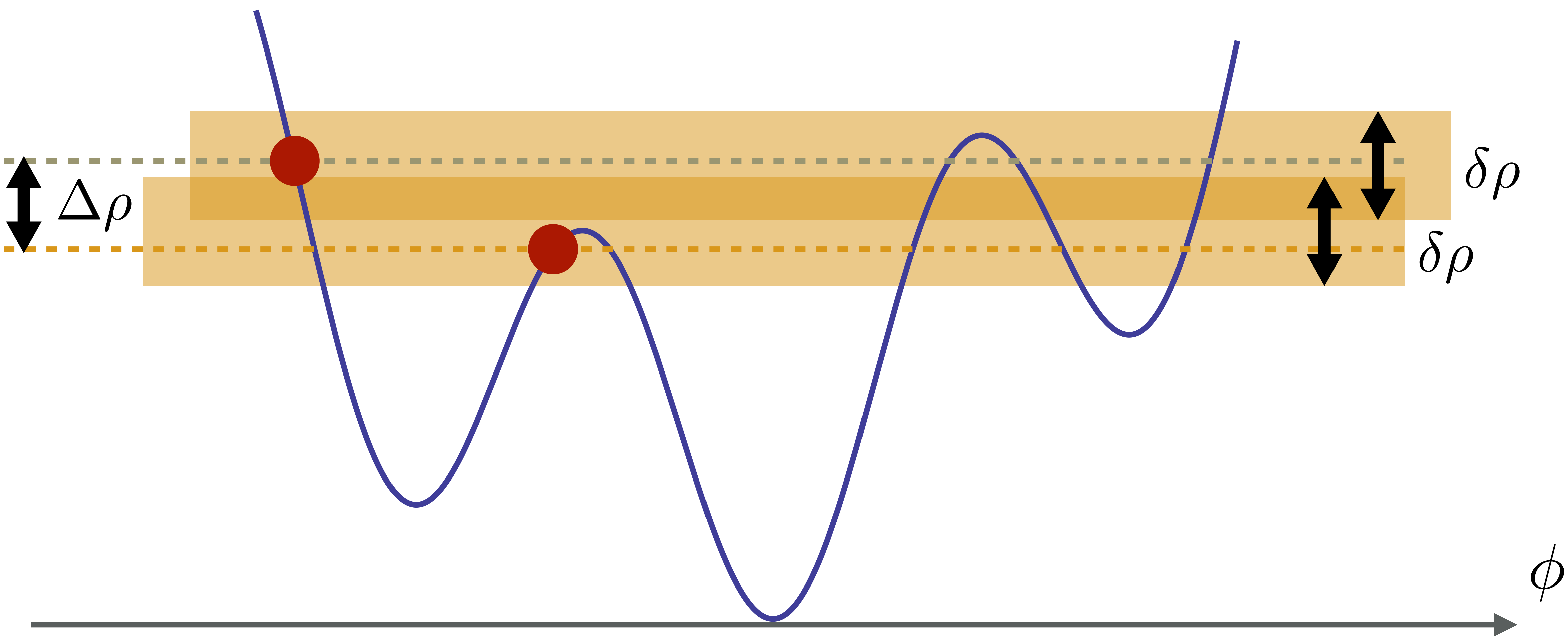


Phase Decomposition?

- Quantify the **probability** for phase decomposition:

$$\mathcal{P} \sim \frac{\delta\rho}{\Delta\rho}$$

- Now determine $\delta\rho$ and $\Delta\rho$ in terms of the model parameters.



Phase Decomposition?

$$V \;\sim\; \tfrac{1}{2}m^2\phi^2 \;+\; \kappa\, m^2 f^2 \cos\left(\frac{\phi}{f} + \gamma\right)$$

- Have many minima for $\kappa \gtrsim 1$.

Calculate loss of energy density $\Delta\rho$ in a half-period.

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Calculate loss of energy density $\Delta\rho$ in a half-period.

- At time of question universe is matter-dominated by coherent oscillations of inflaton.
- The period of oscillation is set by the curvature of the wells.
- Know the energy density in the lowest wells.

$$\Delta\rho \sim \kappa \frac{m^2 f^3}{M_{pl}}$$

Phase Decomposition?

Now turn to the size of **fluctuations**.

We will consider **2 sources** of fluctuations:

1. **Classical fluctuations from Inflation:** $\delta\phi_k^{inf}$

   Start as quantum $\rightarrow$ stretched to superhorizon scales $\rightarrow$ classicalize $\rightarrow$ re-enter horizon after inflation when $H \sim k$.

2. **Quantum fluctuations:** $\delta\phi_k^{qu} \sim k$

   Consider the inherent quantum fluctuation of any quantum field.

Translate this into expressions for $\delta\rho$.

Phase Decomposition?

Decomposition probabilities:

1. **Classical fluctuations:** $$\mathcal{P}^{inf} = \frac{\delta\rho^{inf}}{\Delta\rho} \sim \kappa^{-1/3}\left(\frac{m}{M_{pl}}\right)\left(\frac{M_{pl}}{f}\right)^{5/3}$$

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Numerical example: $\kappa \sim \mathcal{O}(10)\,,\quad m \sim 10^{-5} M_{pl}\ .$

	$\mathcal{P}^{inf}$	$\mathcal{P}^{qu}$
$f \sim 10^{-2} M_{pl}$	~ 0.01	~ 0.001
$f \sim 10^{-3} M_{pl}$	~ 0.1	~ 1

Phase Decomposition!

Decomposition probabilities:

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Observations:

- **Phase decomposition can generically occur** in axion monodromy potentials with sufficiently large modulations.
- There can be further **enhancement** of fluctuations due to parametric resonance. Difficult to study analytically. Turn to numerics…

Quantify the Gravitational Wave signal

Gravitational Wave Signal

Review **Gravitational Wave generation** from **bubble collisions** during a first-order phase transition.

[Kosowsky, Turner, Watkins 1992; Grojean, Servant 2006]

1. **GWs generated by 3 effects:**
   - Collision of bubble walls
   - Sound waves in the fluid
   - Turbulence in the fluid

Gravitational Wave Signal

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1. **GWs generated by 3 effects:**
   - **Collision of bubble walls**
   - Sound waves in the fluid
   - Turbulence in the fluid

2. **Envelope approximation works well** [Kosowsky, Turner, Watkins 1992]
   - neglect complicated overlap regions
   - only focus on bubble walls and their evolution
   - agrees well with numerical results

Gravitational Wave Signal

Overall, **spectrum and amount of gravitational radiation** depended only on the **gross features** of the bubble collisions.

Relevant quantities: [Grojean, Servant 2006]

- Typical time scale / bubble separation: β^{-1}
- Ratio of energy density released ϵ vs. energy density of thermal bath ρ_{rad}:

$$\eta \equiv \frac{\epsilon}{\rho_{rad}}$$

- Efficiency factor: λ
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Results:

- Energy released in GW at peak frequency $\omega \simeq \sigma\beta$:

$$\Omega_{GW} = \frac{\rho_{GW}}{\rho_{tot}} = \theta \left(\frac{H}{\beta}\right) \lambda \frac{\eta^2}{(1+\eta)^2} v_b^3$$

Gravitational Wave Signal

Specialise to our situation: have bubbles in a 'fluid' due to coherent oscillations of the inflaton.

Relevant quantities:

- Take optimistic value: $\beta \sim H$
- Ratio of energy density released ϵ vs. energy density of ~~thermal bath~~ matter fluid ρ_{mat}:

$$\eta \equiv \frac{\epsilon}{\rho_{mat}} = \frac{m^2 \Delta\phi^2}{\Lambda^4} = \frac{m^2 f^2}{\kappa m^2 f^2} = \kappa^{-1}$$

Results:

- Energy released in GW at peak frequency $\omega \simeq \sigma\beta$:

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Gravitational Wave Signal

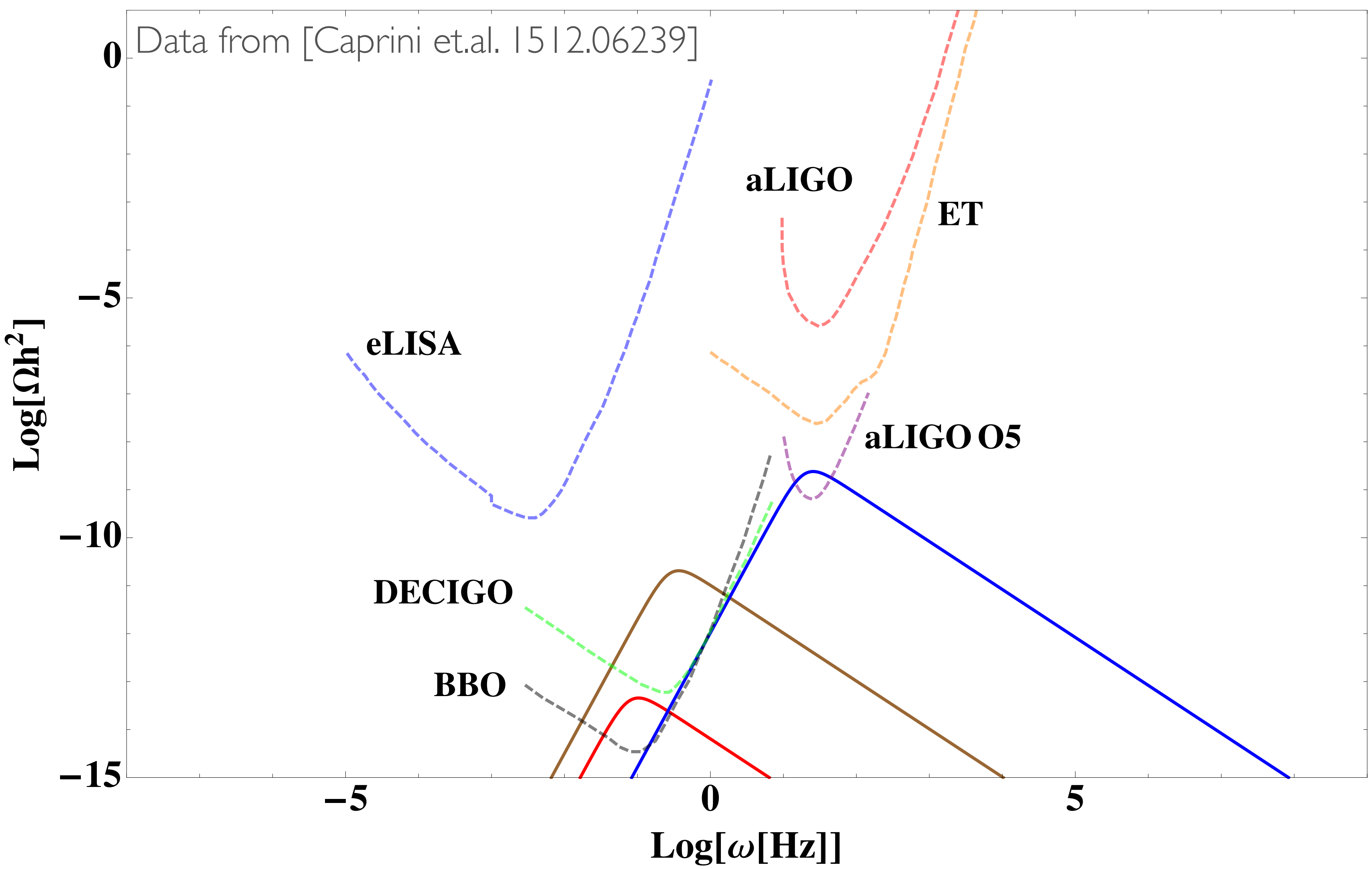
$$\Omega_{GW} = \frac{\rho_{GW}}{\rho_{tot}} = \theta_0 \left(\frac{H}{\beta}\right) \frac{\eta^2}{(1+\eta)^2} \qquad \text{for} \qquad \omega \simeq \sigma\beta$$

- In the envelope approximation, one can calculate the **full spectrum** rather than just the value at the peak. Multiply the above by $S_{env}(\omega)$.

- Finally, propagate the result to today. Need to make assumptions regarding **matter vs. radiation domination** immediately after phase transition

- **Here:** assume **radiation-domination** immediately after transition

Gravitational Wave Signal



$$\theta_0 = 10^{-2}$$

$$\sigma = 10^{-1}$$

$$m = 10^{-5} M_{pl}$$

$$\Omega_{GW}(t_0)h^2 \sim \frac{T_{RH}^{4/3}}{\kappa^{8/3}}$$

$$\omega_0 \sim \frac{T_{RH}^{7/3}}{\kappa^{5/12} f^{1/2}}$$

Blue: $f = 10^{-1} M_{pl}$ $\kappa = 5$ $T_{RH} = 10^{12}\mathrm{GeV}$

Brown: $f = 10^{-2} M_{pl}$ $\kappa = 10$ $T_{RH} = 10^{11}\mathrm{GeV}$

Red: $f = 10^{-3} M_{pl}$ $\kappa = 70$ $T_{RH} = 10^{11}\mathrm{GeV}$

Conclusions

- **Modulations** of axion monodromy potential may dynamically induce a **phase decomposition** after inflation.
- **Gravitational Waves** are then sourced by **bubble collisions**. Interesting signature of axion monodromy models.
- For $f \gtrsim 10^{-2} M_{pl}$ a phase decomposition is **unlikely**, but a GW signal would be **stronger**.
- For $f \lesssim 10^{-2} M_{pl}$ phase decompositions can **generically occur**, but the GW signal is **weakened** if many bubbles are created.
- A better understanding of bubble collisions in a matter fluid is desirable!

Many

Thanks!