Based on **2401.04064** with Joe Conlon, Ed Copeland, Martin Mosny and Filippo Revello

String theory and the first half of the Universe, Part I

Fien Apers

University of Oxford

See Filippo Revellos' talk for Part II!

- Goal: String Theory predictions for Cosmology

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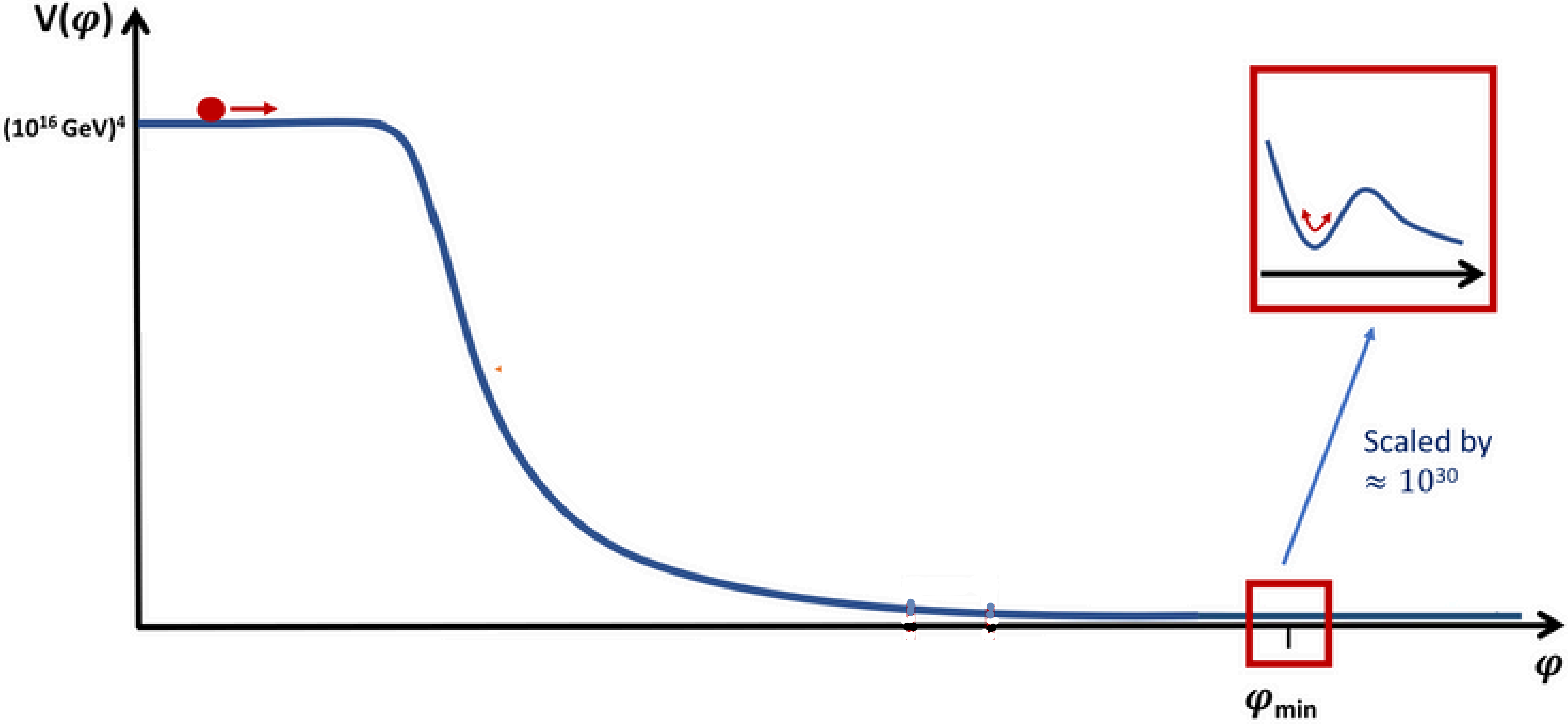
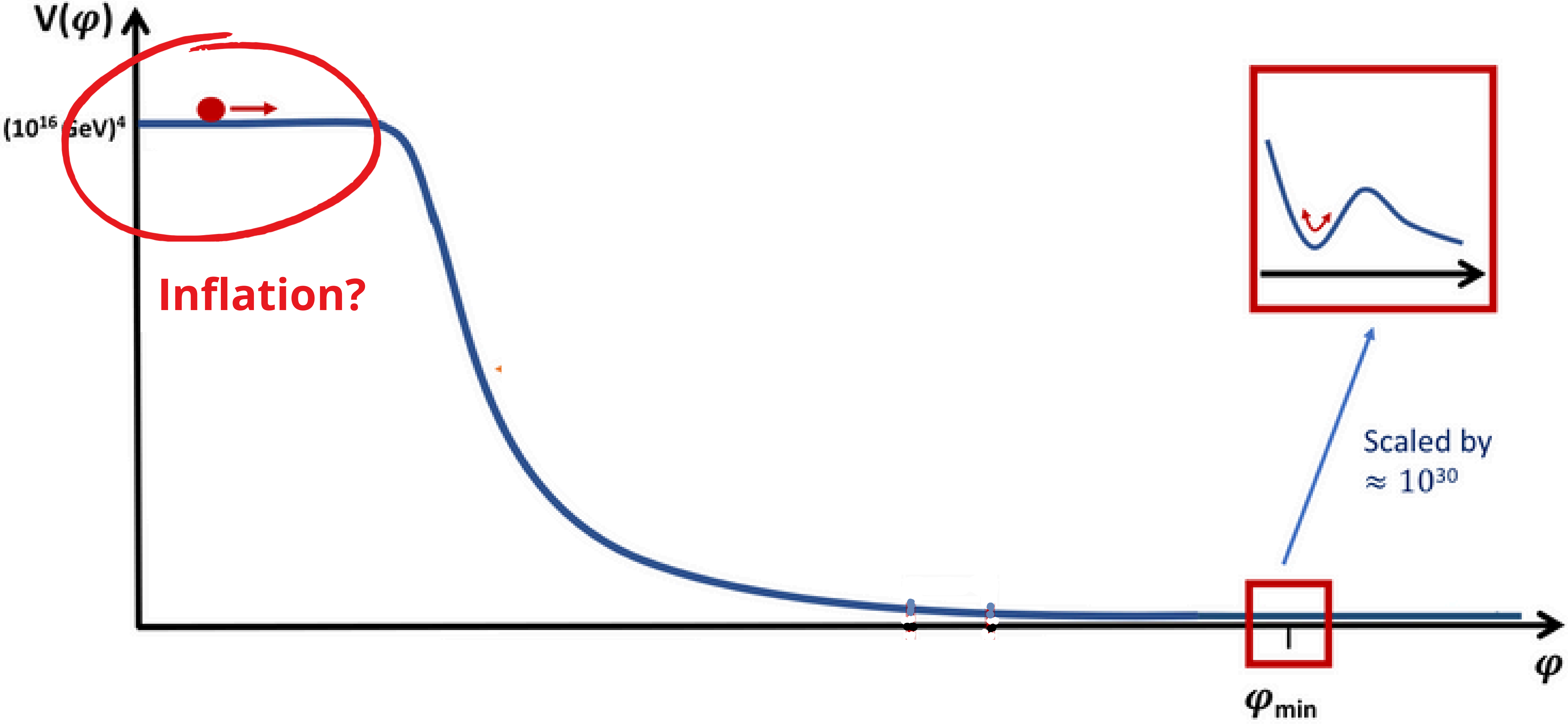
- Focus on typical dynamics that can easily be obtained from string theory, such as
  - **fast rolling moduli**
  - **steep exponential potentials**
- We will not focus on things that hard to get in String Theory such as
  - late-time accelerated expansion
  - inflation



$V(\varphi)$
$(10^{16}\,\mathrm{GeV})^4$
Scaled by
$\approx 10^{30}$
φ
$\varphi_{\min}$



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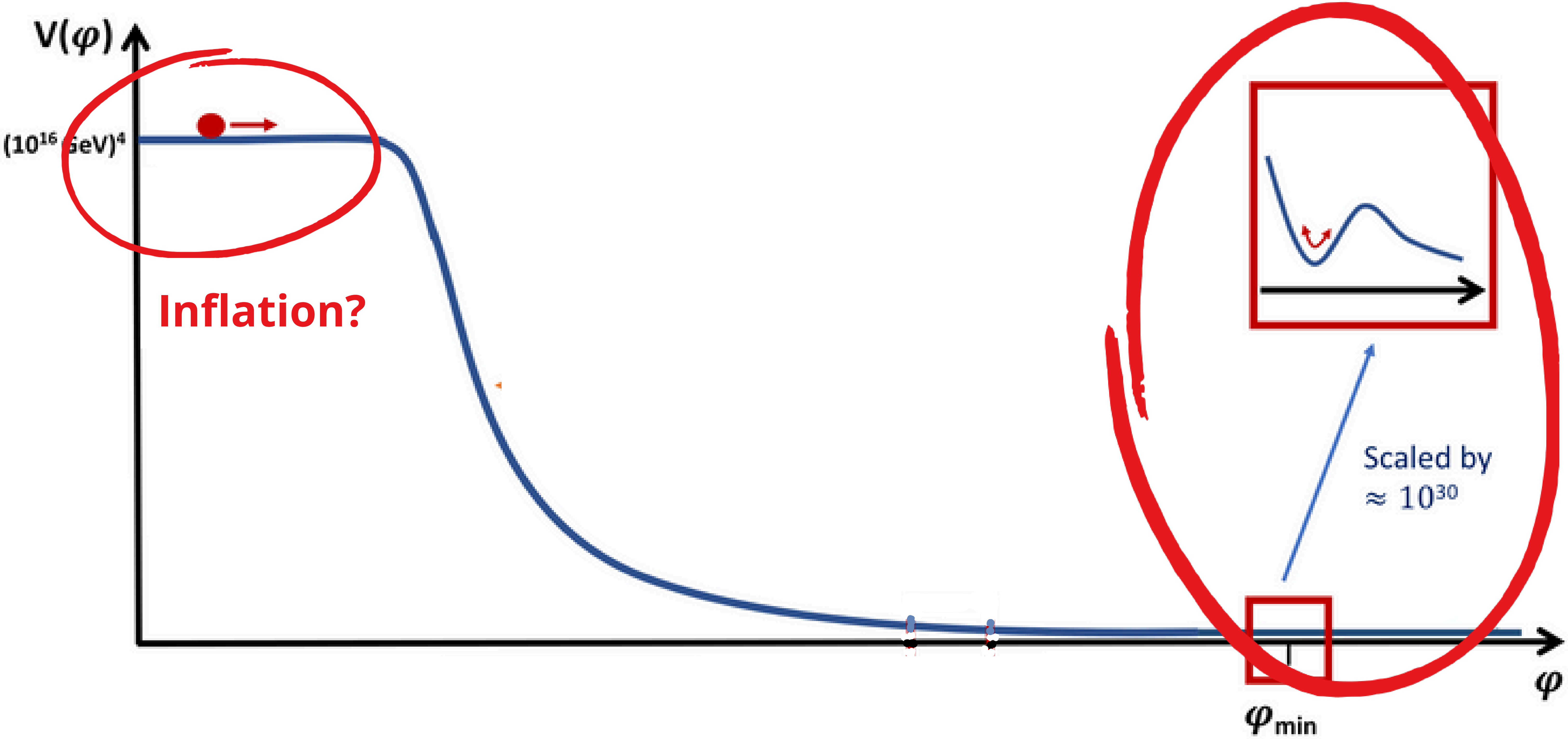
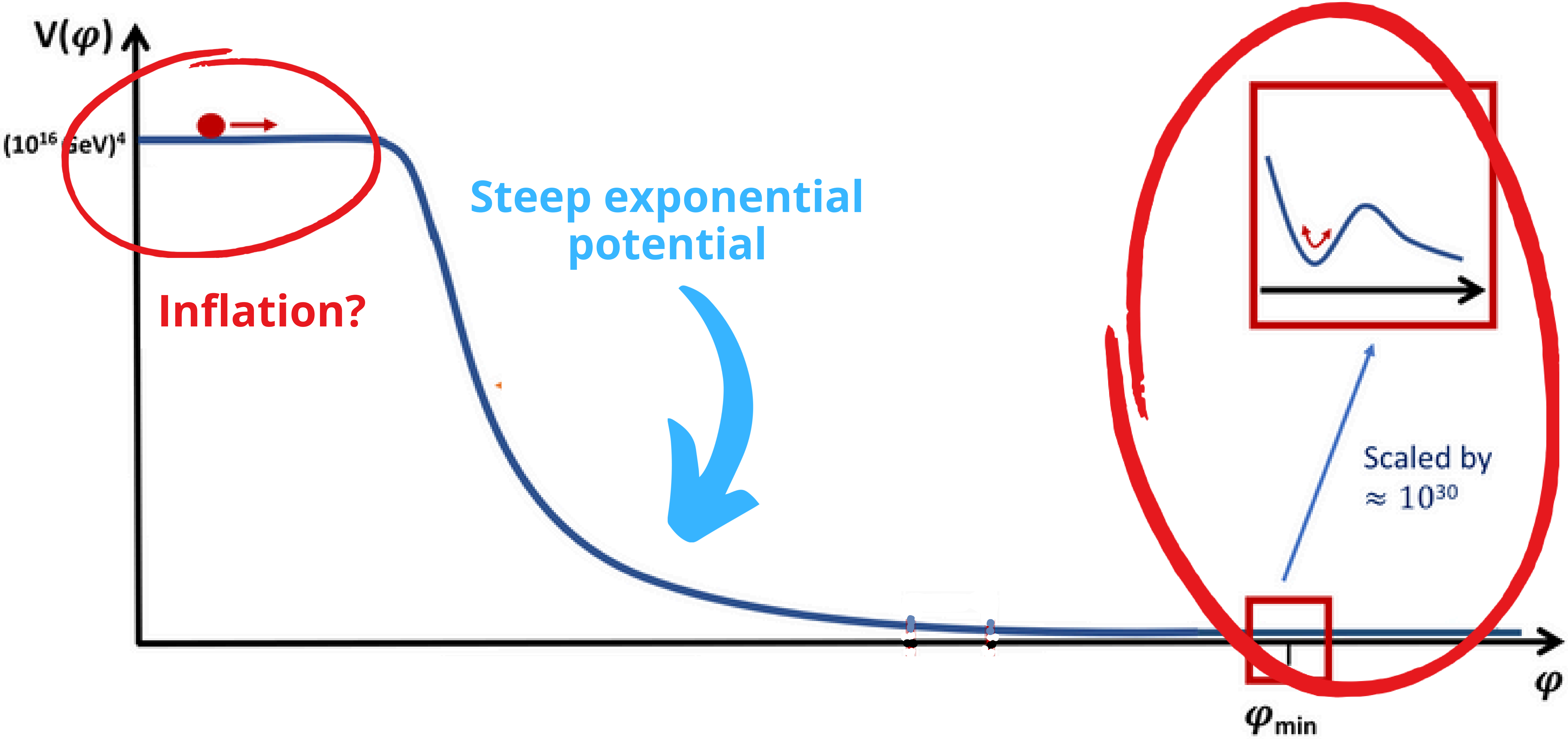


Inflation?

Late time accelerated expansion?



Steep exponential potential

Inflation?

Late time accelerated expansion?

t

Before radiation domination?

- *Inflation ending instantaneously in reheating?*
- *Less observationally constrained*

Radiation domination

the Hot Big Bang

Matter domination

Structure formation

Dark energy domination

Current epoch

Inflation?

t

'Stringy Transition' *Ending in reheating* $w = ?$

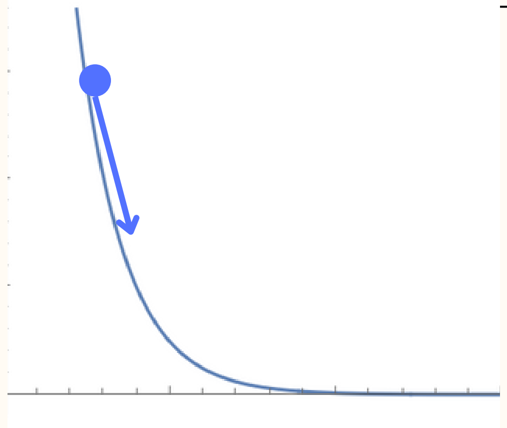
Radiation domination *the Hot Big Bang* $w = 1/3$

Matter domination *Structure formation* $w = 0$

Dark energy domination *Current epoch* $w \leq -0.85$

t

Inflation?



‘Stringy Transition’ **Energy density: kinetic energy of string moduli**

Radiation domination *the Hot Big Bang* $w = 1/3$

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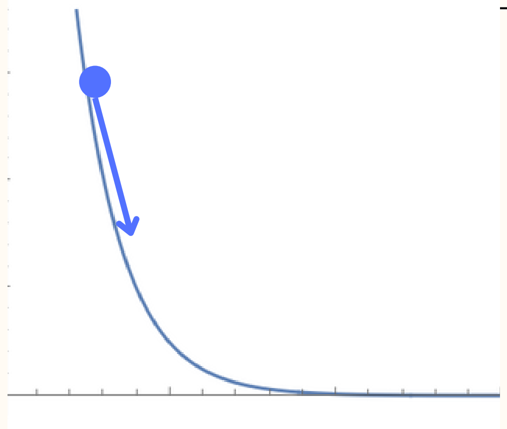
Dark energy domination *Current epoch* $w \leq -0.85$

t

Inflation? $t_f \approx 10^{-35} s$



'Stringy Transition' *Ending in reheating* $t_i \approx 10^{-35} s - t_f \approx 10^{-5} s$

Radiation domination *the Hot Big Bang* $t_i \approx 10^{-5} s - t_f \approx 10^{12} s$

Matter domination *Structure formation* $t_i \approx 10^{12} s - t_f \approx 10^{18} s$

Dark energy domination *Current epoch* $t_i \approx 10^{18} s$

Inflation?

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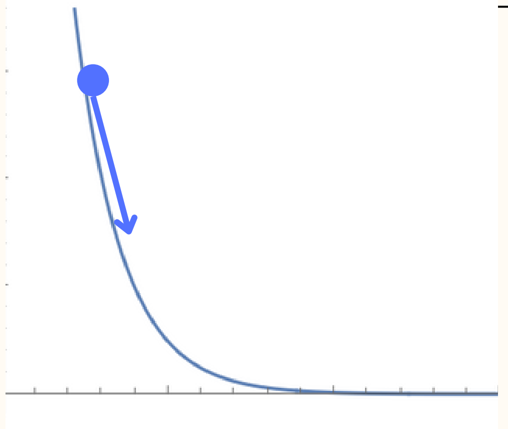


‘Stringy Transition’

Ending in reheating $t_i \approx 10^{-35} s - t_f \approx 10^{-5} s$

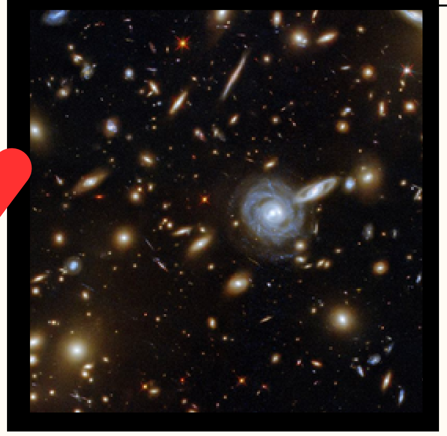
`The first half of the Universe’ $\frac{t_f}{t_i} \approx 10^{30}$

Radiation domination

the Hot Big Bang $t_i \approx 10^{-5} s - t_f \approx 10^{12} s$

Matter domination

Structure formation $t_i \approx 10^{12} s - t_f \approx 10^{18} s$



Dark energy domination

Current epoch $t_i \approx 10^{18} s$

$\frac{t_f}{t_i} \approx 10^{53}$

Rolling towards the end of the world

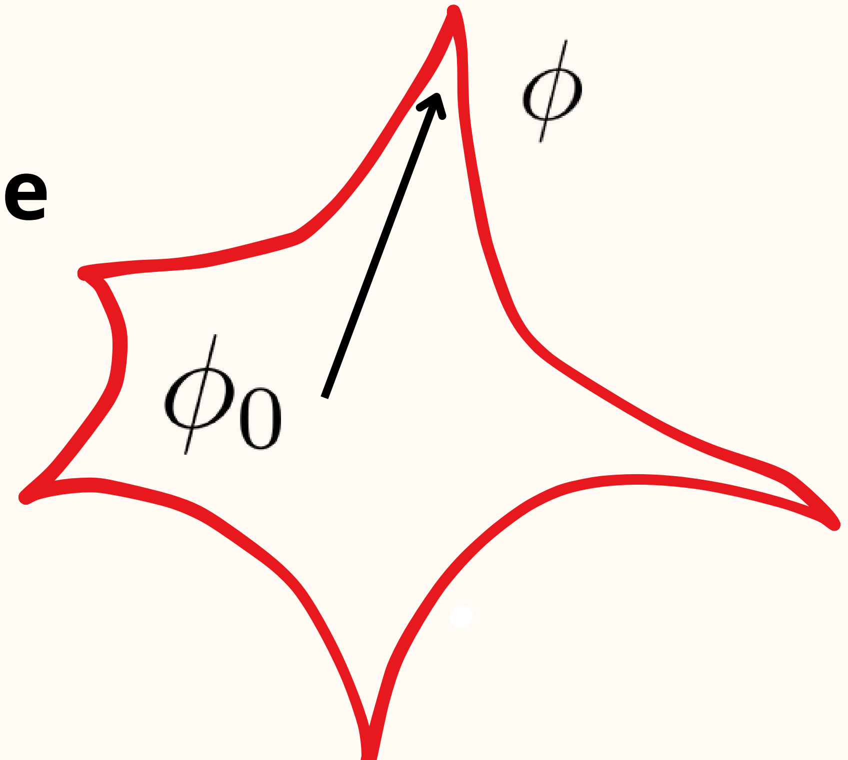
- Our universe: weak couplings, hierarchies etc.

e.g. $\Lambda_{\mathrm{EW}} \sim 10^{-16} M_p, \quad \Lambda_{\mathrm{cc}} \sim 10^{-120} M_p^4, \quad \theta_{QCD} \sim 10^{-10}$

- In string theory, couplings are determined by the values of moduli fields.

- So let's **assume we live near an asymptotic boundary of moduli space** $\frac{\phi}{M_p} \to \text{large}$

- **and that this stringy transition epoch brings us there**



Dynamics on steep potentials + radiation

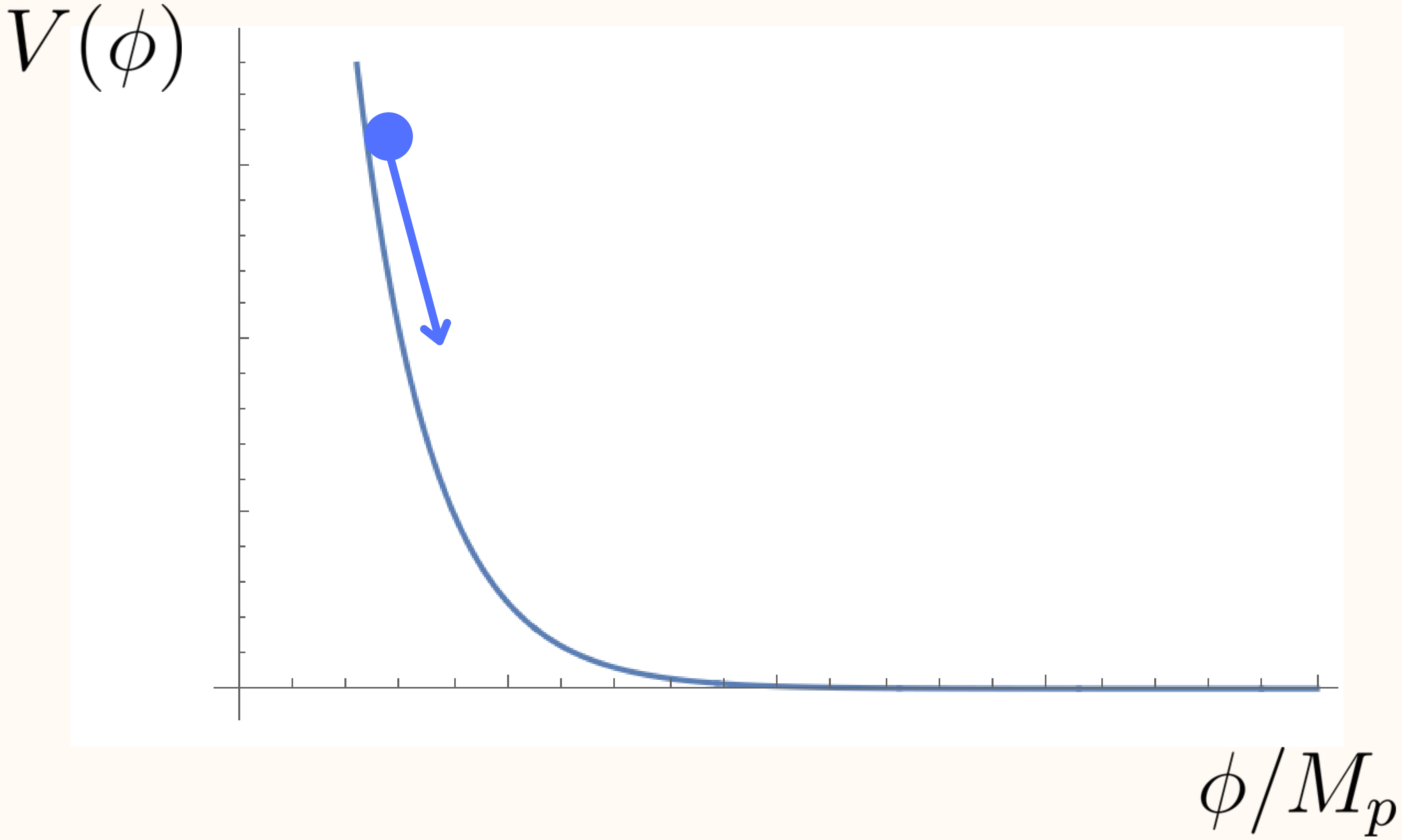
[Copeland, Liddle, Wands 1998]

- scalar field

$$V(\phi) = e^{-\lambda\phi} \qquad \lambda \geq \sqrt{6}$$

- a small amount of radiation

$$w = P/\rho = 1/3$$



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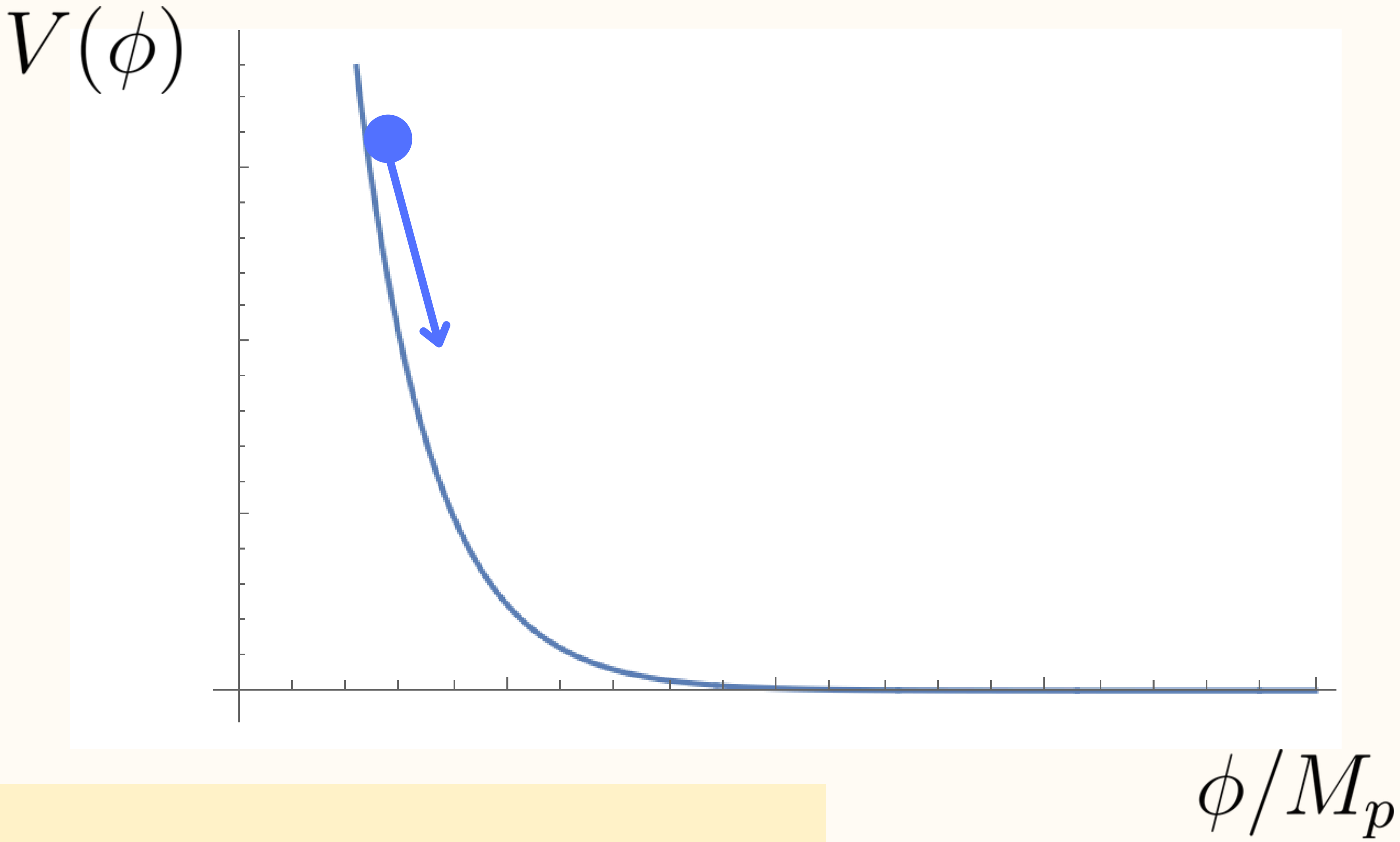

Possible sources of radiation: axions (the volume axion), radiation from cosmic strings, SM degrees of freedom

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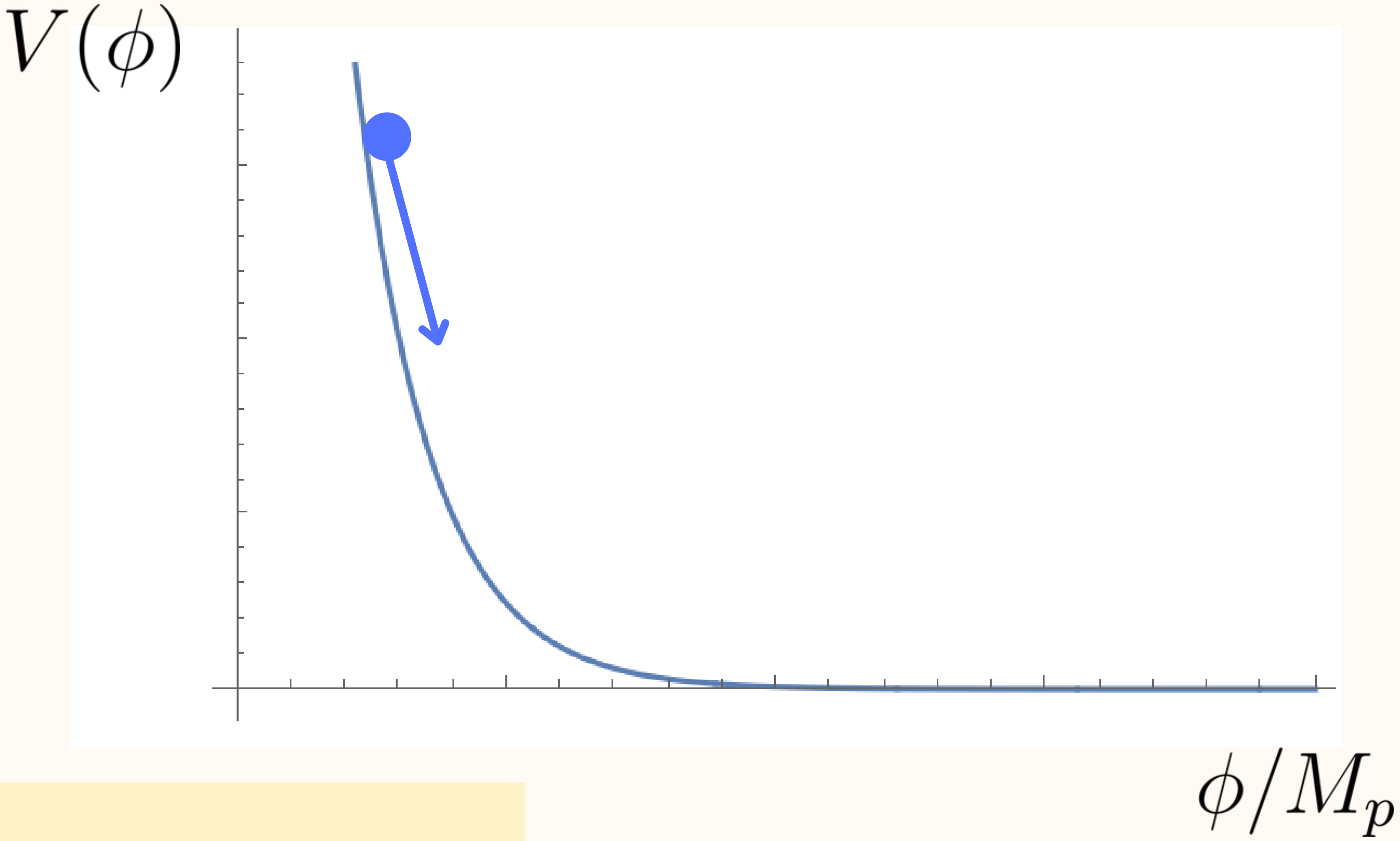

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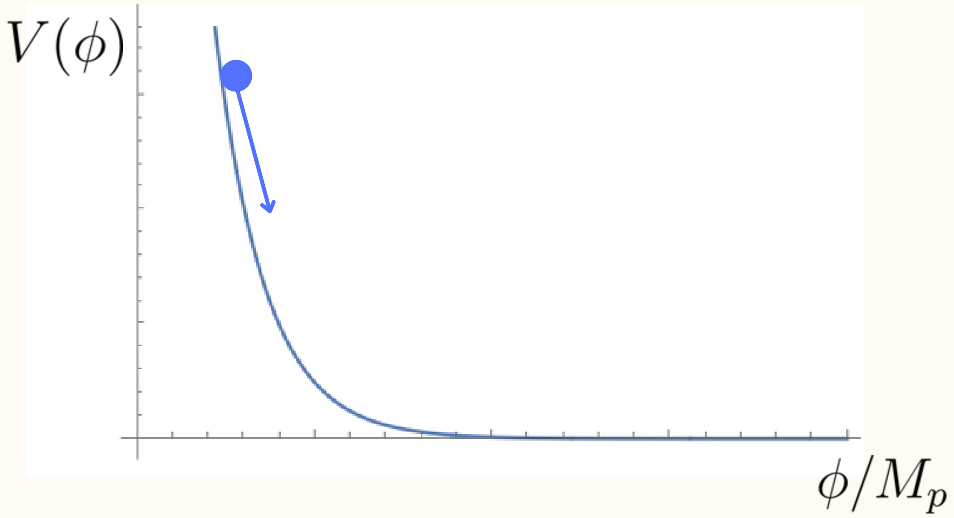
What happens?

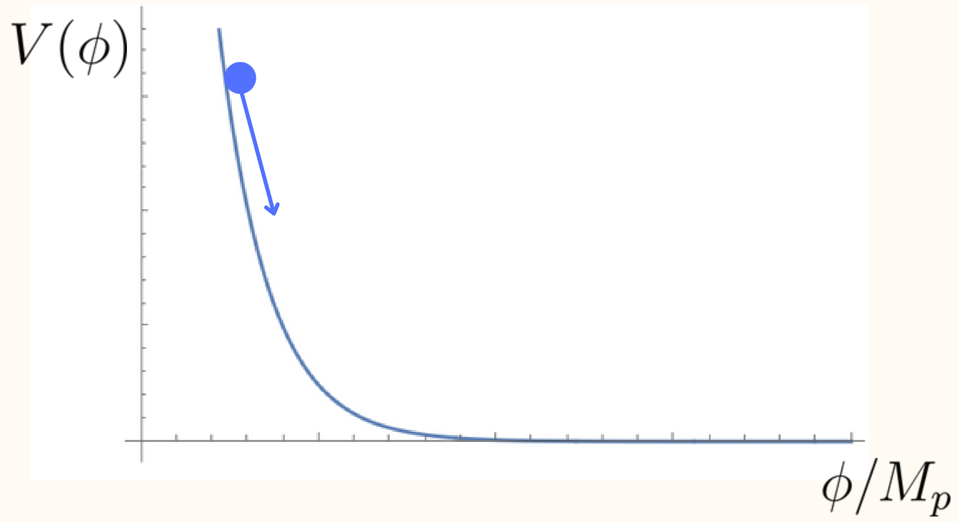
Dynamics on steep potentials + radiation



1. Kination

When rolling down a steep exponential potential, the scalar field will gain speed and we go into a regime that is **dominated by the kinetic energy** of the scalar field.

Dynamics on steep potentials + radiation



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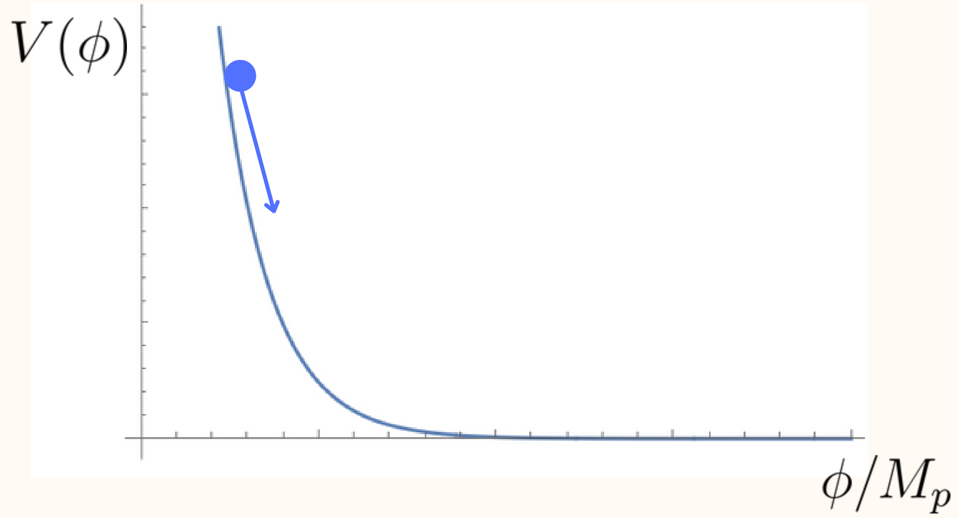
When rolling down a steep exponential potential, the scalar field will gain speed and we go into a regime that is **dominated by the kinetic energy** of the scalar field.

- Energy density dominated by the kinetic energy of a scalar field $\dot{\phi}^2/2 \gg V$
- Equation of state $w = \frac{P}{\rho} = \frac{\dot{\phi}^2/2 - V}{\dot{\phi}^2/2 + V} = 1$
- Slowest possible expansion $a(t) \sim t^{\frac{2}{3(1+w)}} = t^{\frac{1}{3}}$

Dynamics on steep potentials + radiation



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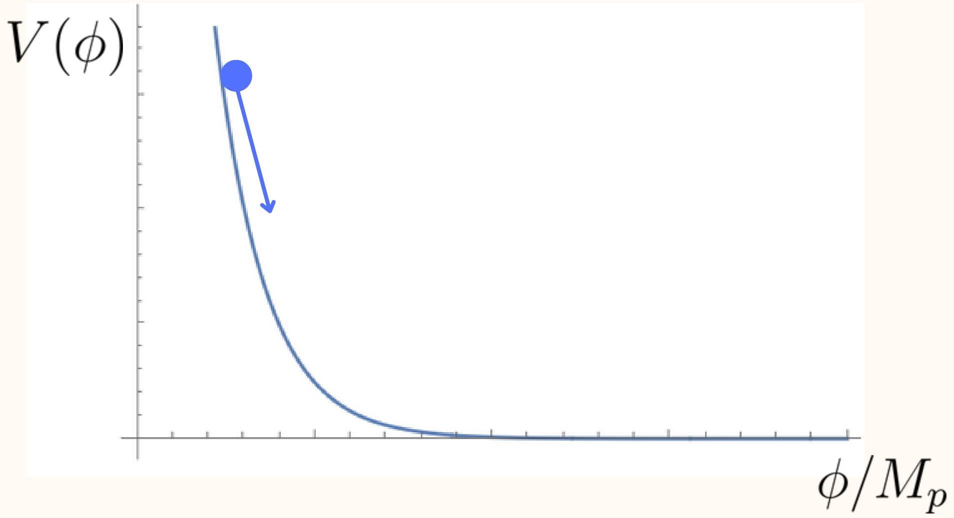
- The scalar equation $\ddot{\phi} + 3H\dot{\phi} = 0$ is solved by

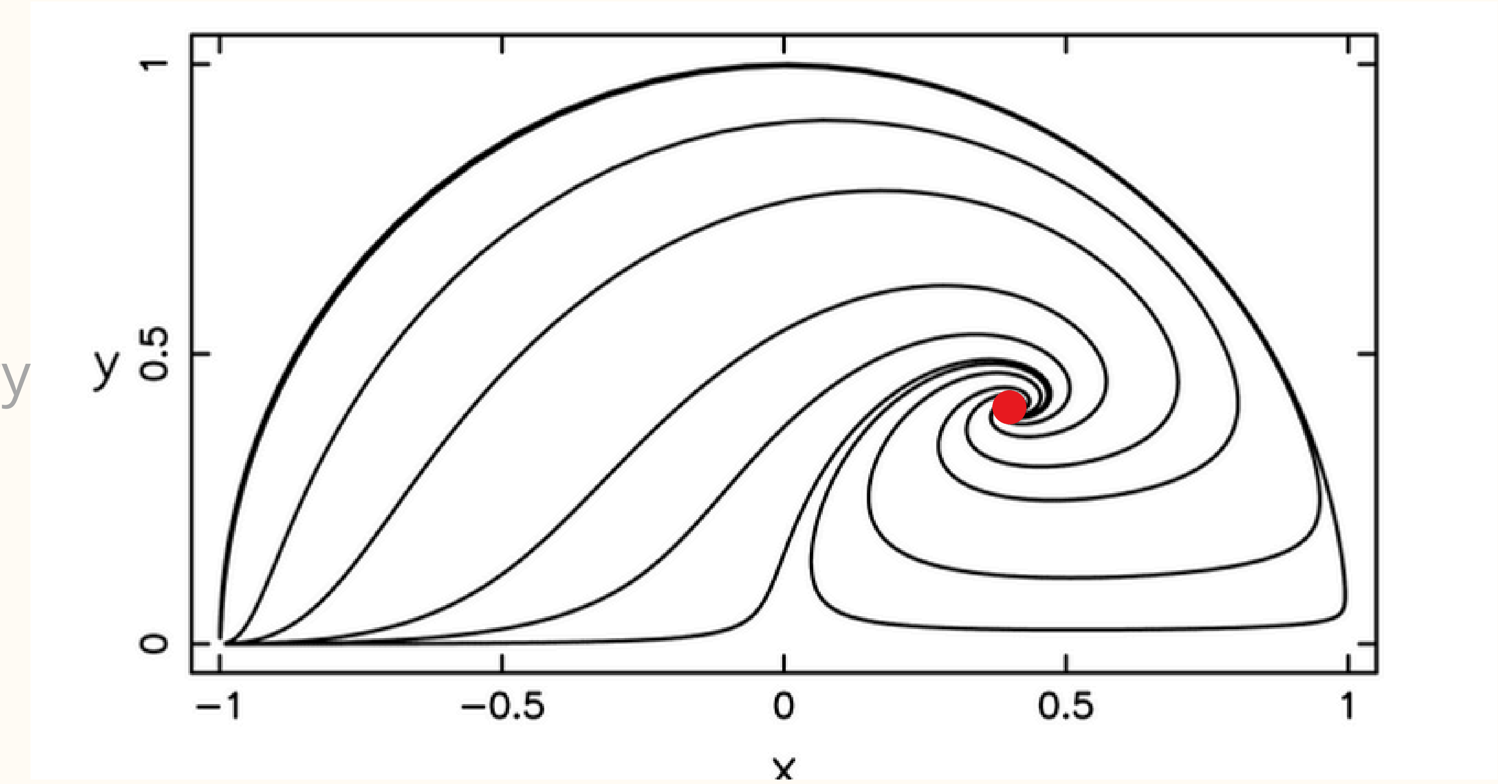
$$\phi = \phi_0 + \sqrt{\frac{2}{3}} M_p \ln\left(\frac{t}{t_0}\right)$$

and the scalar field will likely move **multiple Planckian distances**.

Dynamics on steep potentials + radiation



2. Tracker [cosmological scaling solution]



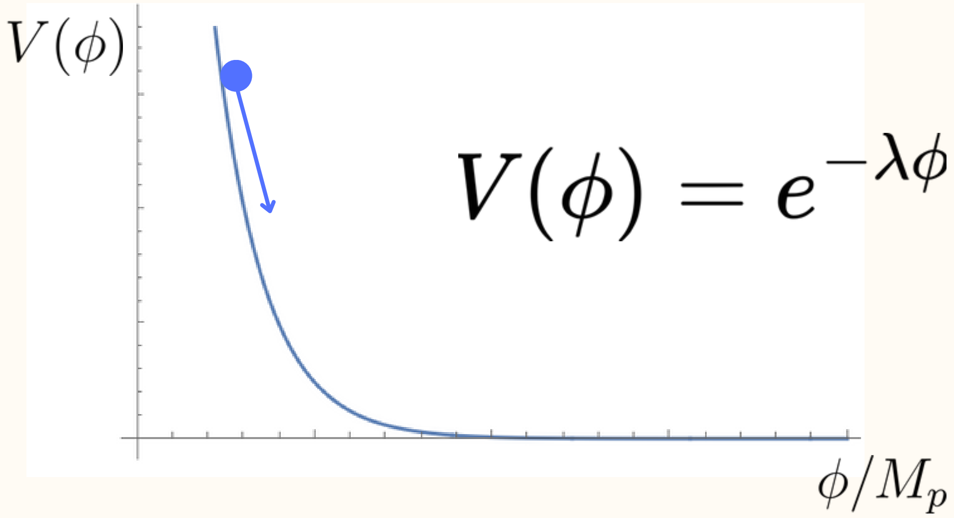
Potential energy

Kinetic energy

Attractor solution for a scalar field on an exponential potential in the presence of a fluid like radiation.

Scalar field starts tracking/mimicking the radiation

Dynamics on steep potentials + radiation



$$V(\phi) = e^{-\lambda\phi}$$

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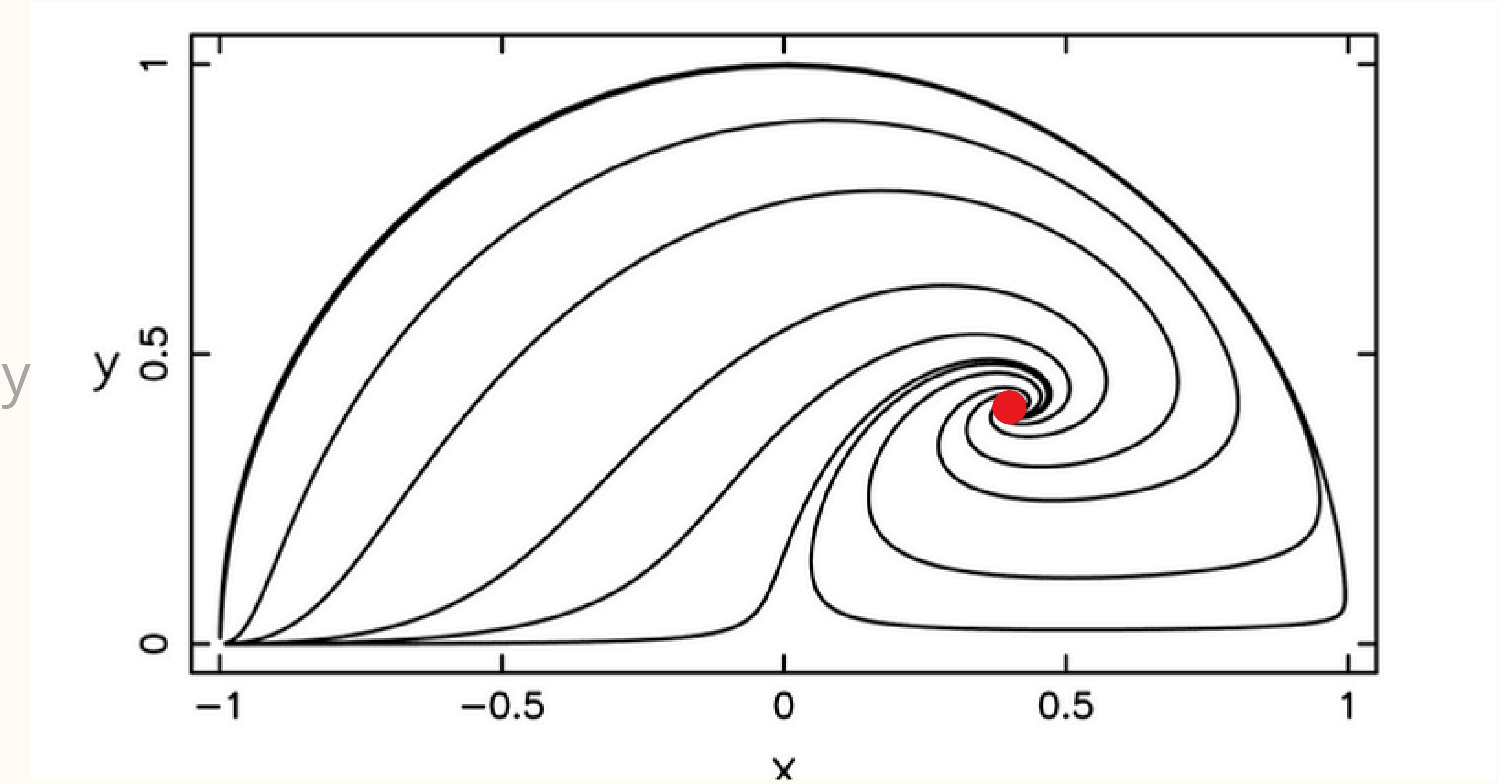
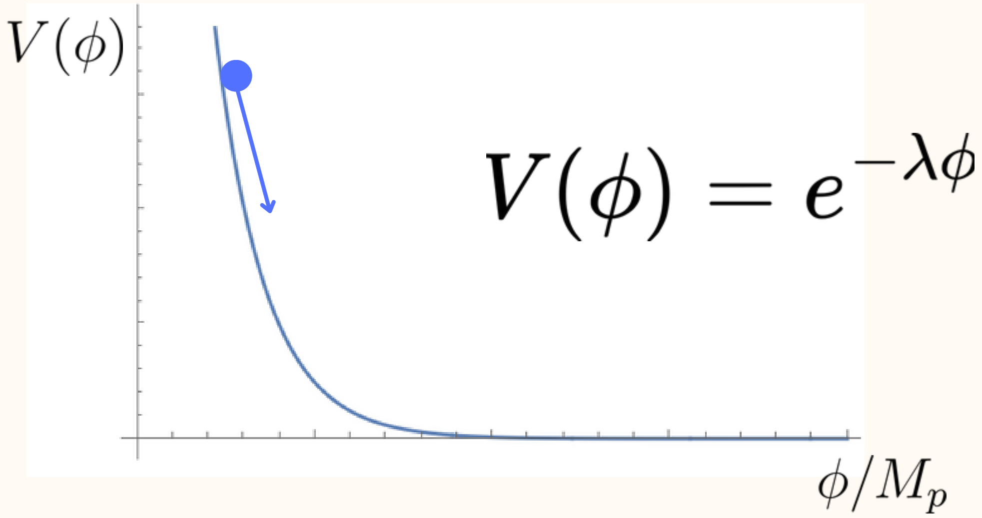


Kinetic energy

$$\Omega_r = 1 - \frac{4}{\lambda^2}, \quad \Omega_\phi = \frac{4}{\lambda^2}$$

Scalar field starts tracking/**mimicking** the radiation

Dynamics on steep potentials + radiation



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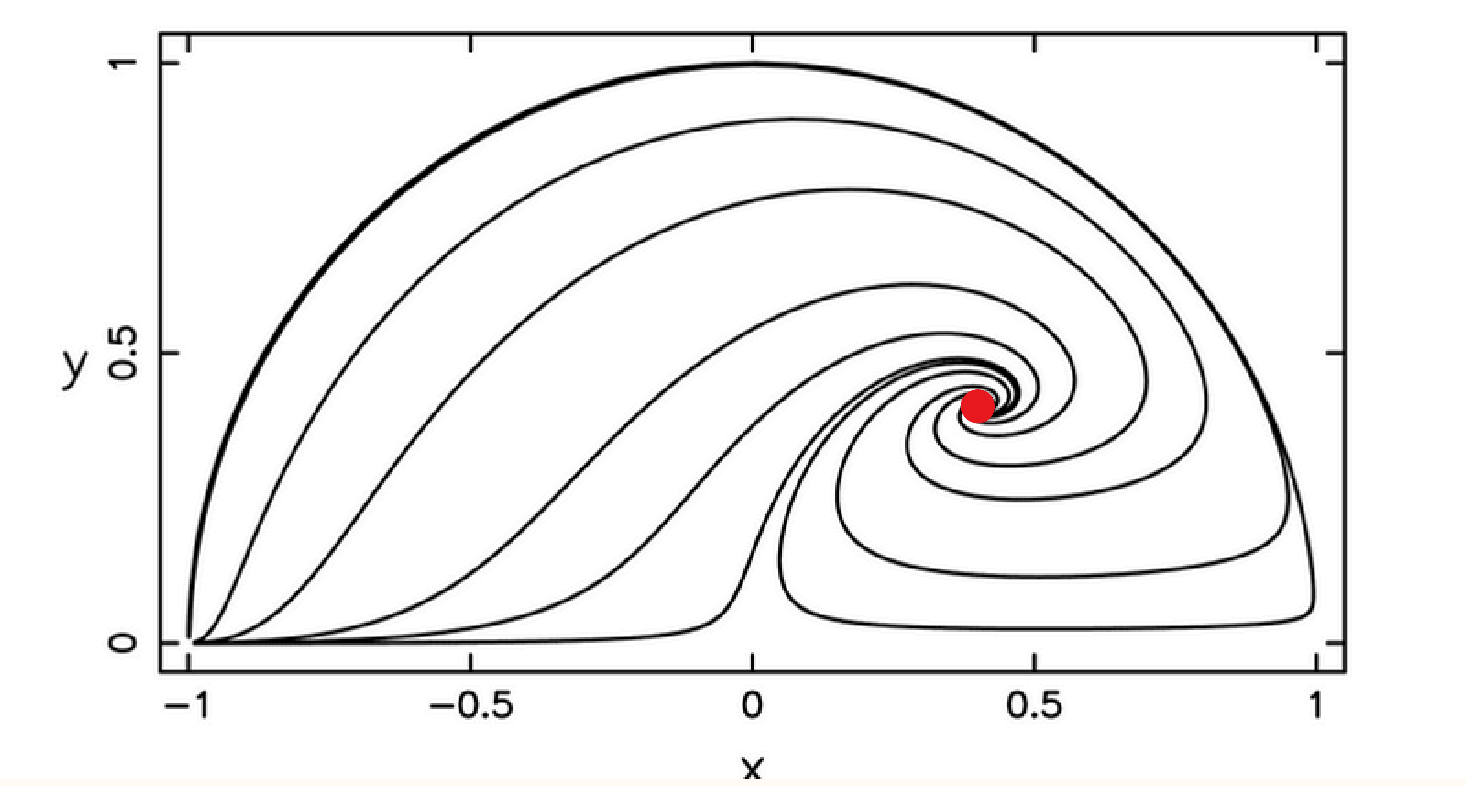

Kinetic energy

$$\phi = \phi_0 + \frac{2}{\lambda} M_p \ln\left(\frac{t}{t_0}\right)$$

Again, we can in principle move **multiple Planckian distances**

Moving to the asymptotics of moduli space in a cosmological context

1. Kination $$\phi = \phi_{\mathbf{0}} + \sqrt{\mathbf{\frac{2}{3}}}\mathbf{M_p} \ln\left(\frac{\mathbf{t}}{\mathbf{t_0}}\right)$$

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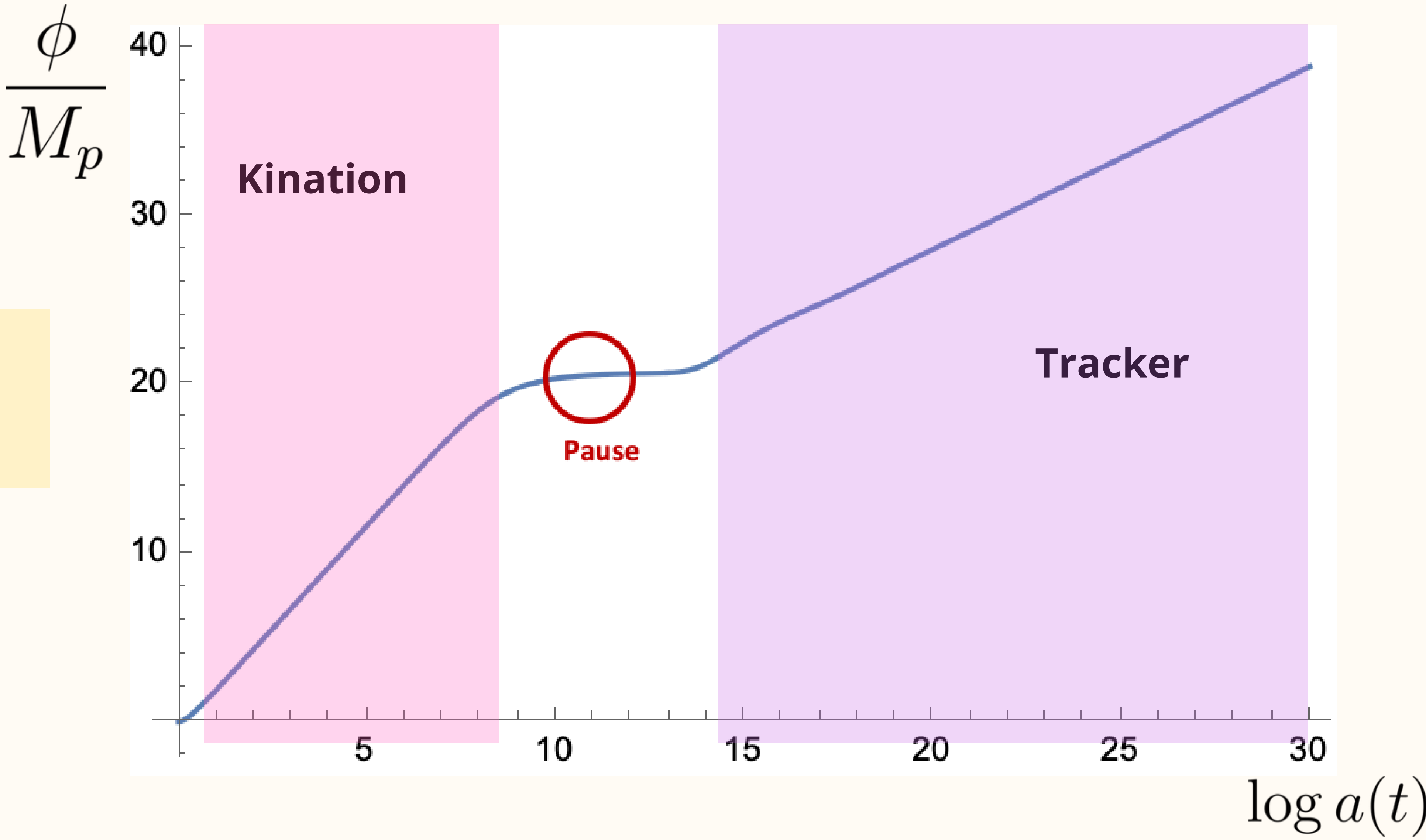
moving **multiple Planckian distances**



Moving to the asymptotics of moduli space in a cosmological context

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$$\phi = \phi_{\mathbf{0}} + \sqrt{\frac{\mathbf{2}}{\mathbf{3}}}\mathbf{M_p}\ln\left(\frac{\mathbf{t}}{\mathbf{t_0}}\right)$$

$$m_{\mathrm{KK}}(t) \sim t^{-2/3} \sim H(t)^{2/3}$$

2. Tracker

$$\phi \underbrace{= \phi_0 + \frac{2}{\lambda}M_p \ln\left(\frac{t}{t_0}\right)}_{\text{moving } \textbf{multiple Planckian distances}}$$

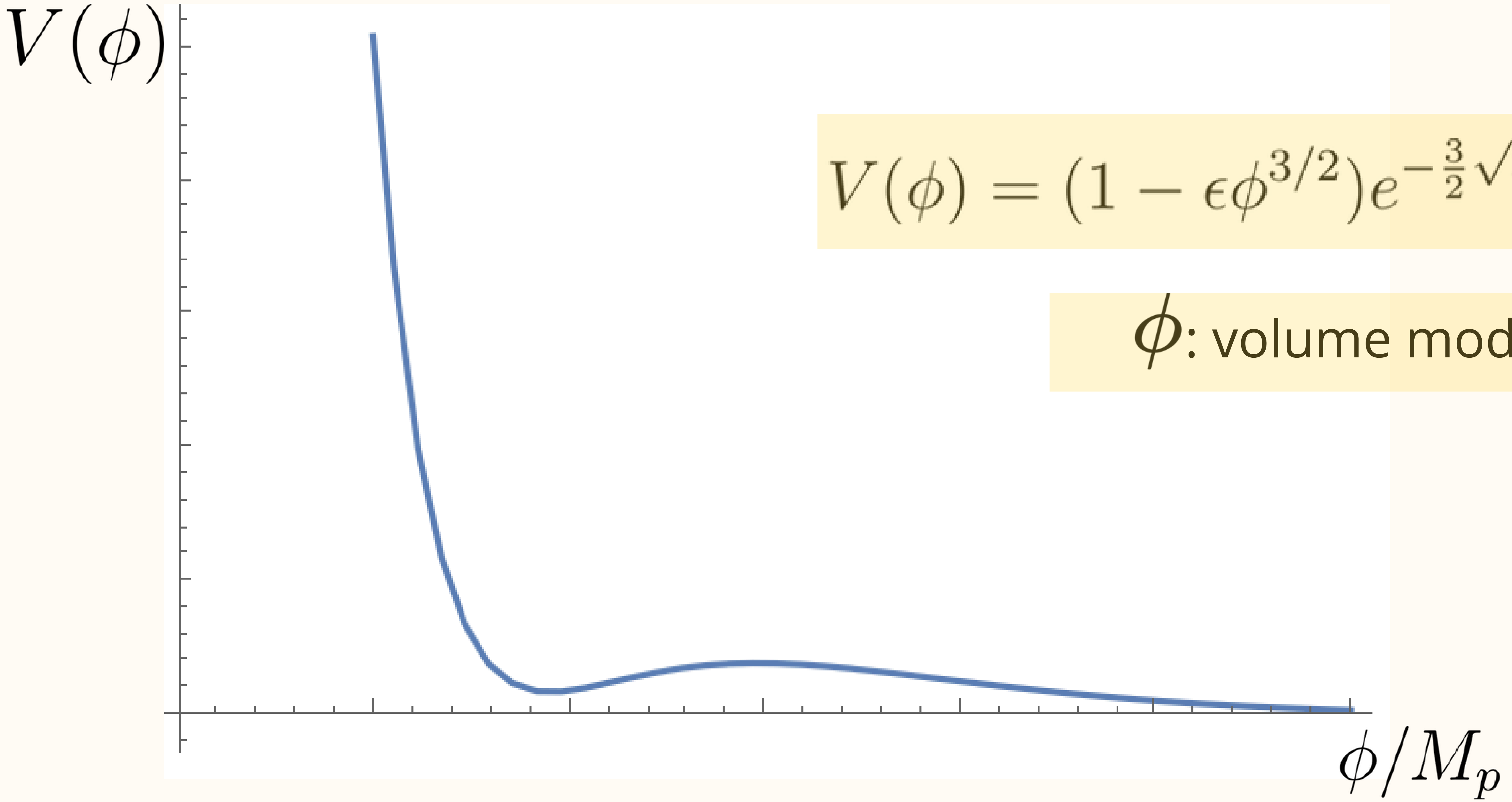
$$m_{KK}(t) \sim H(t)^{\sqrt{\frac{2}{3}}\frac{2}{\lambda}}$$

F.e. **decompactification** limit: a Kaluza-Klein tower is becoming light

$$m_{\mathrm{KK}}(t) \gg H(t)$$

Example: Large Volume Scenario

[Balasubramanian,Berglund,Conlon,Quevedo ’05]



$$V(\phi) = (1 - \epsilon\phi^{3/2})e^{-\frac{3}{2}\sqrt{3}\phi} + \delta e^{-\sqrt{6}\phi}$$

ϕ: volume modulus

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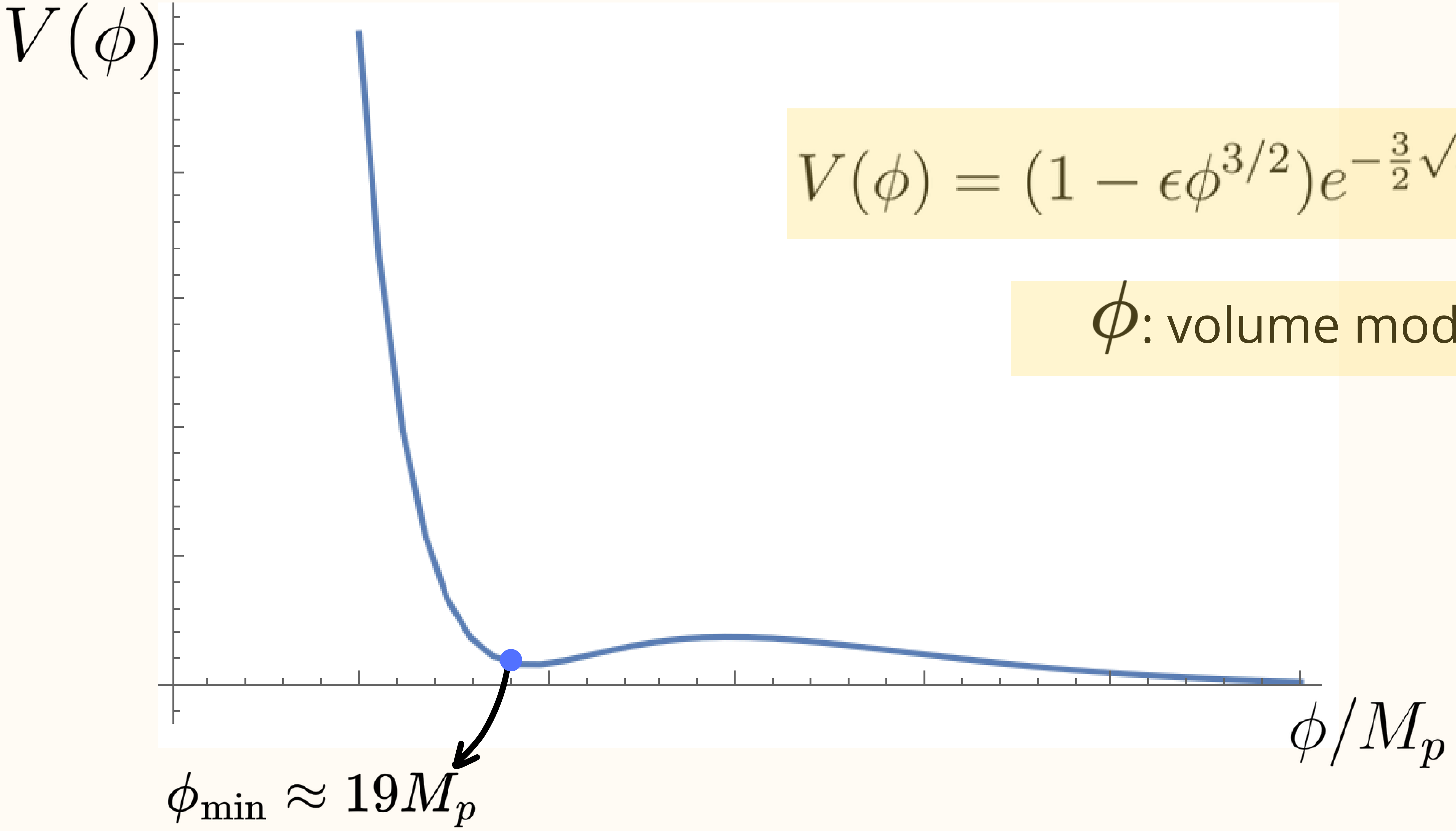

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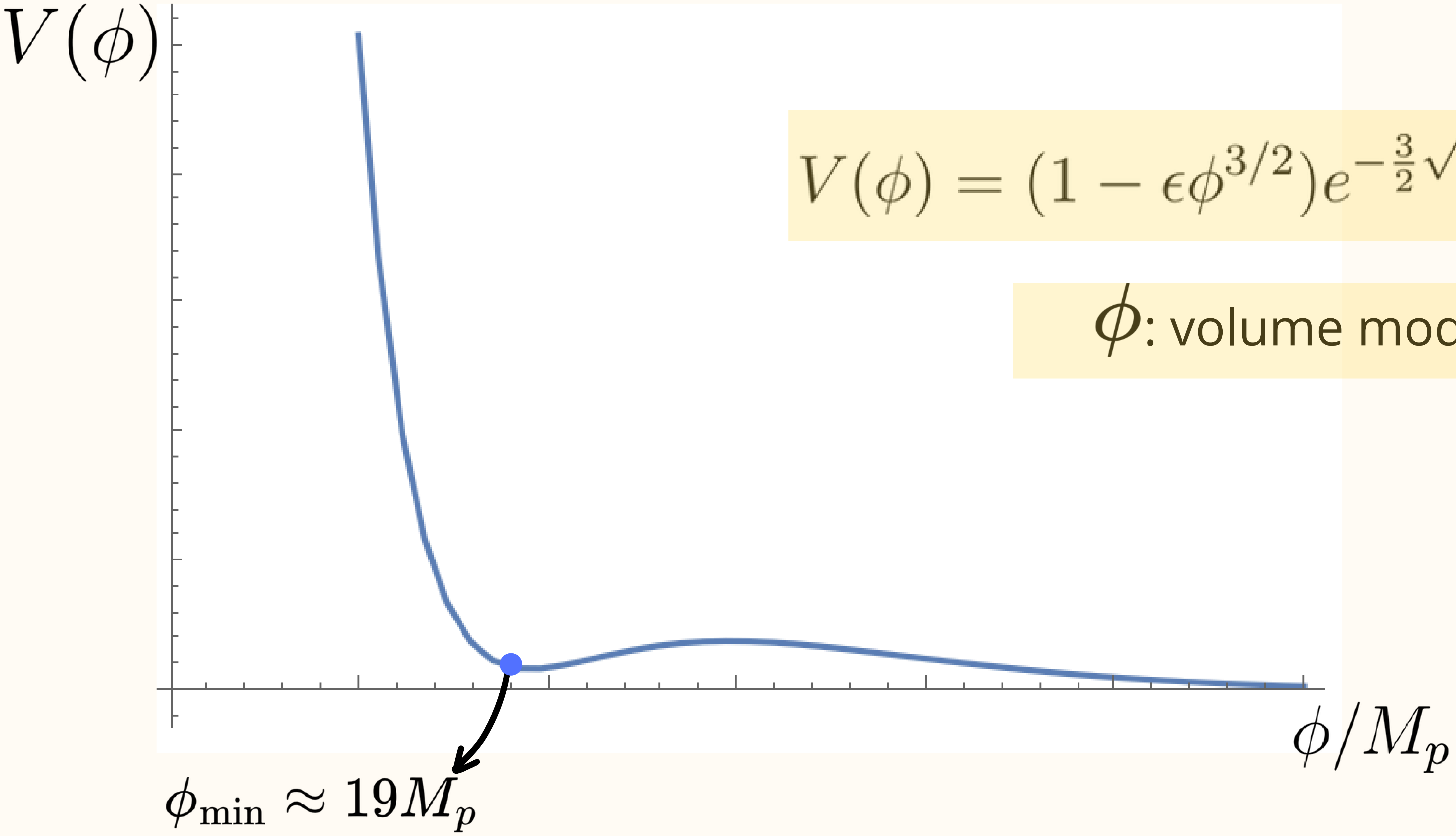

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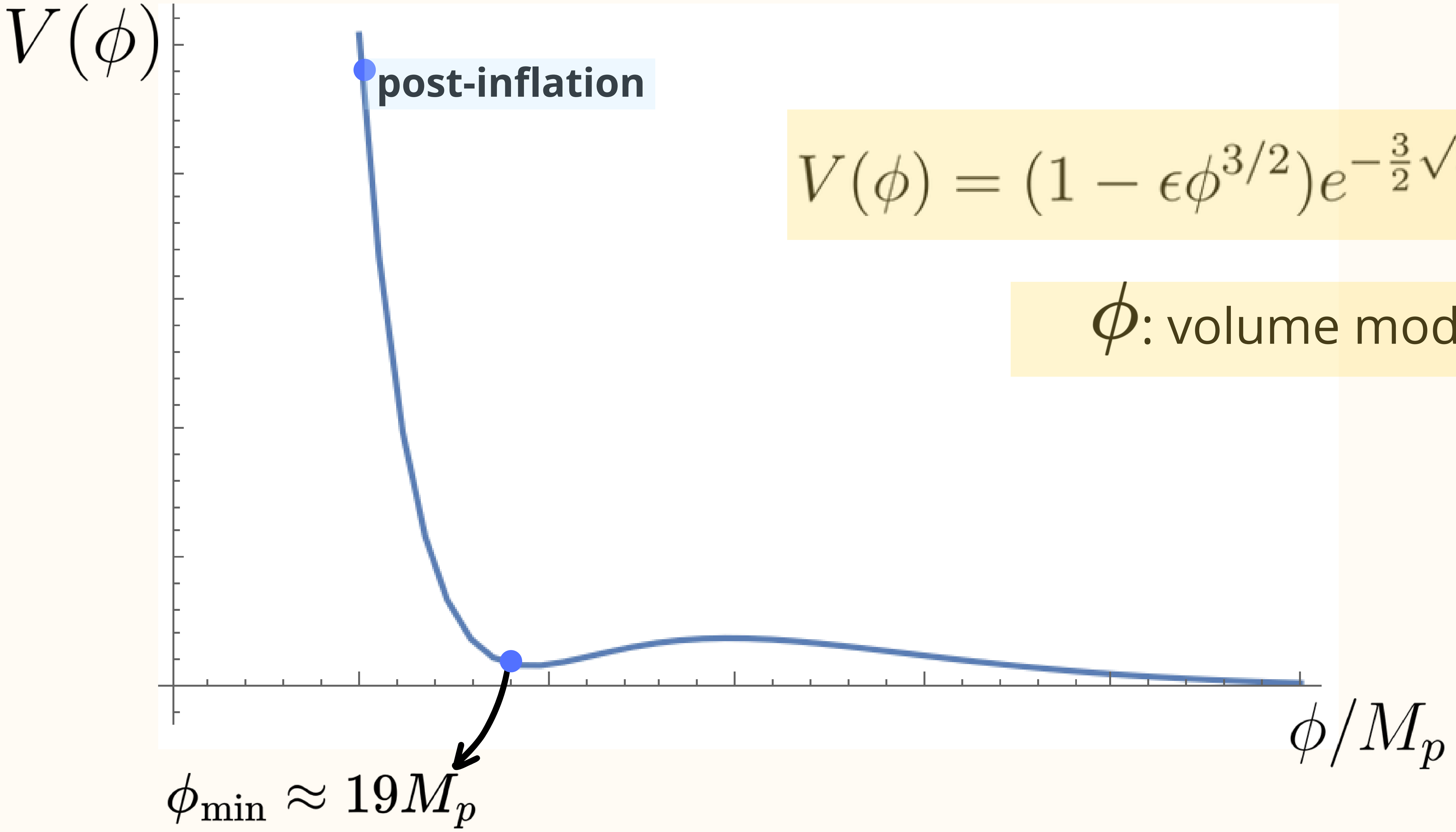

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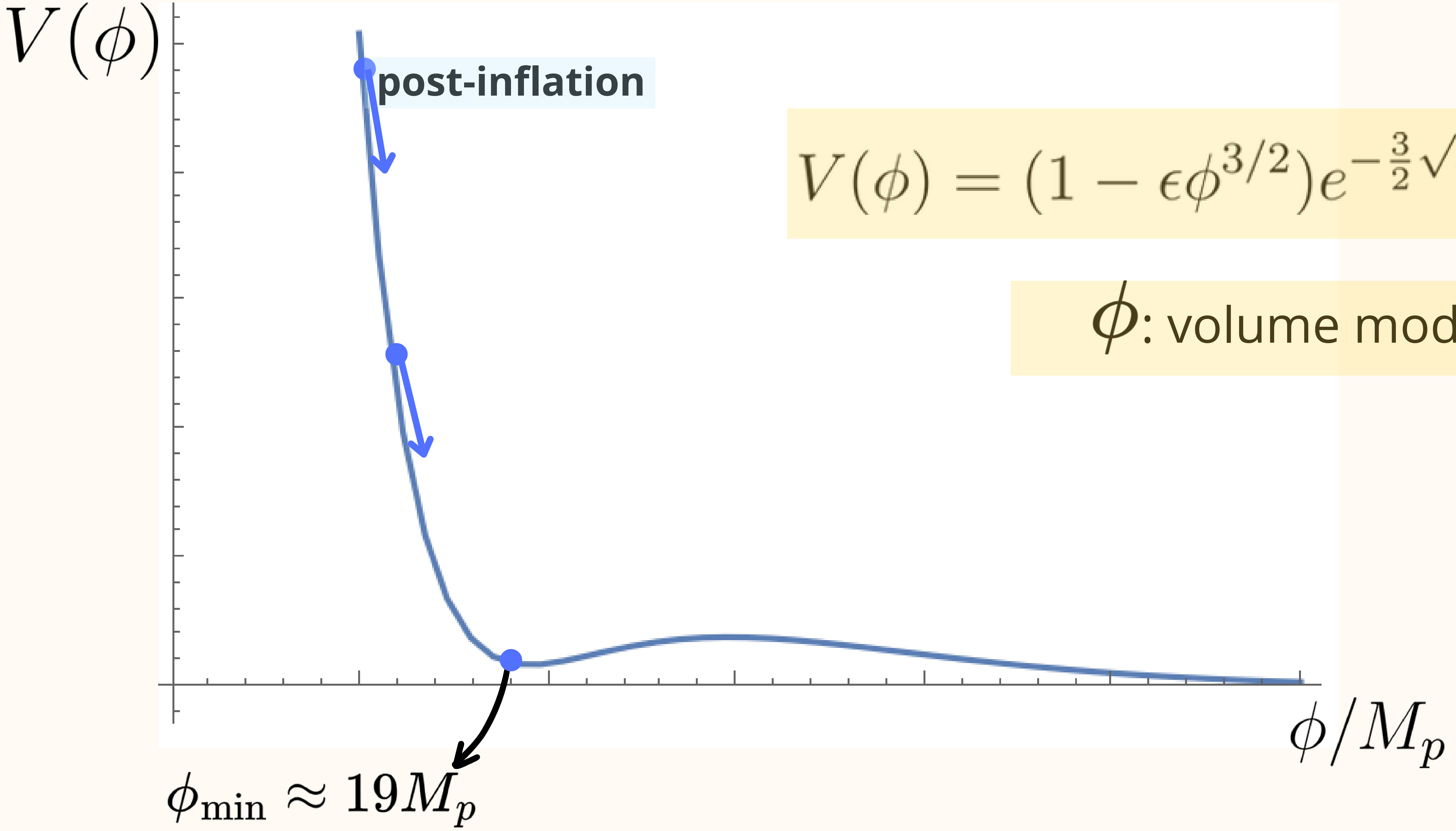

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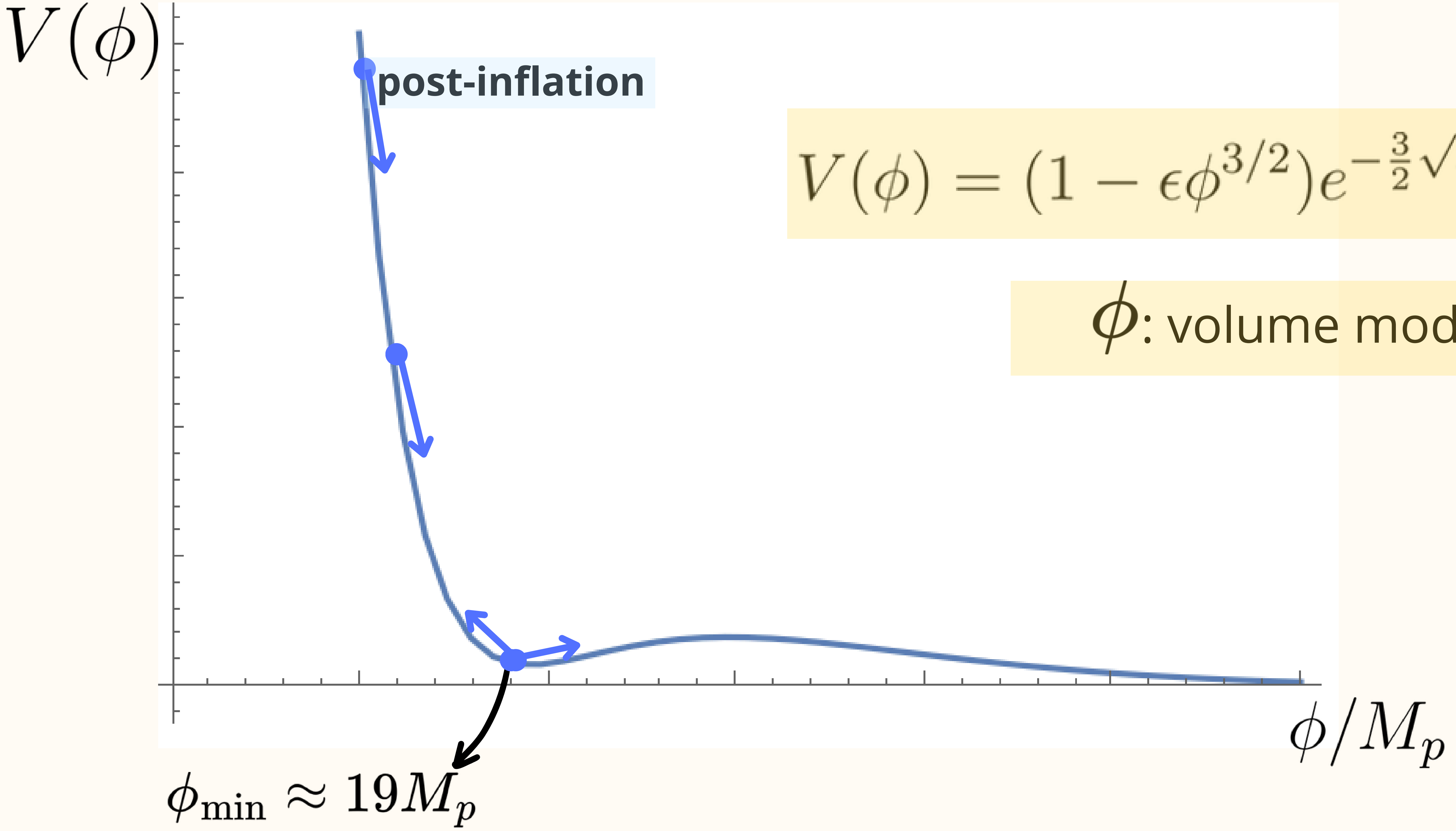

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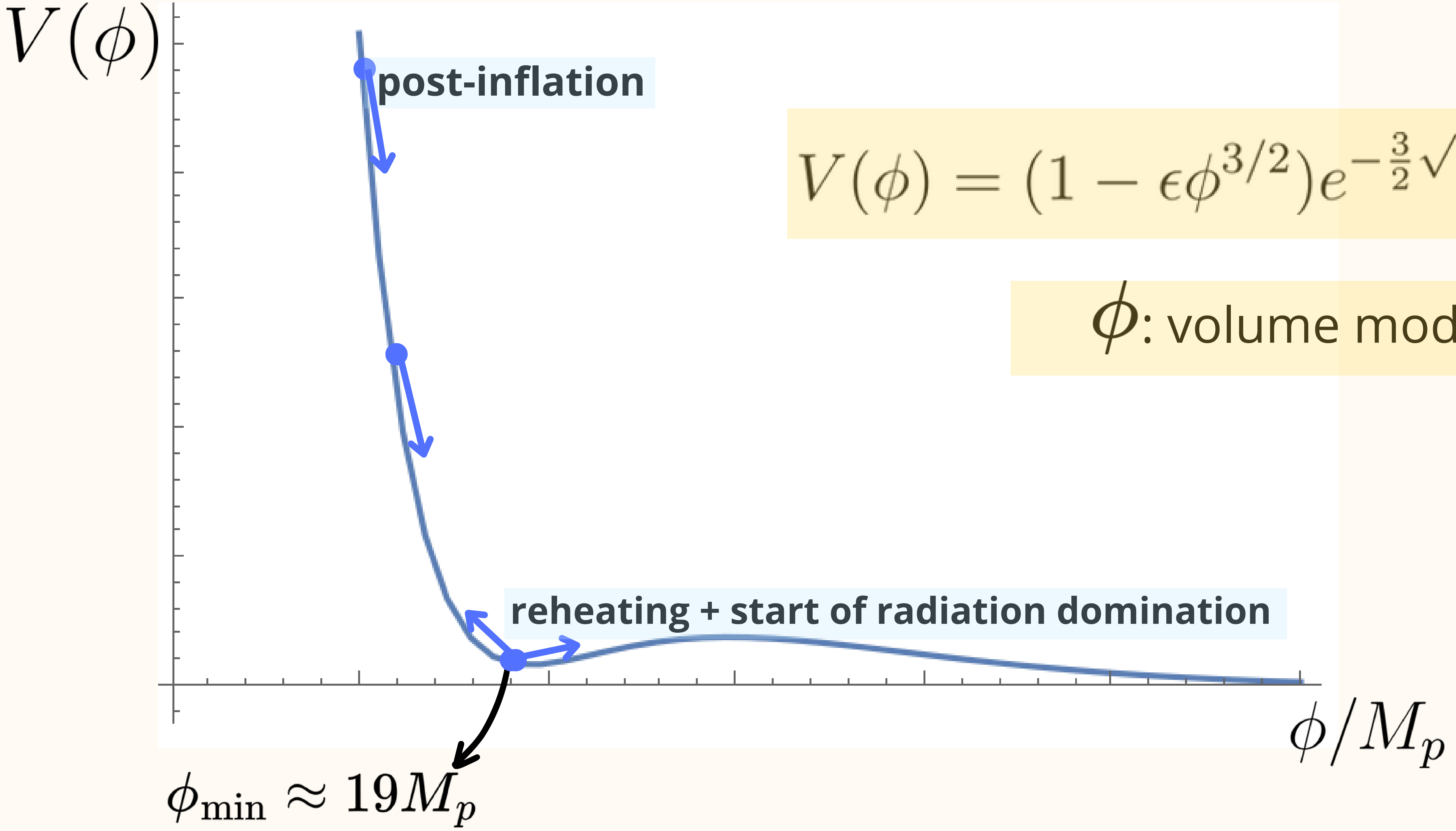

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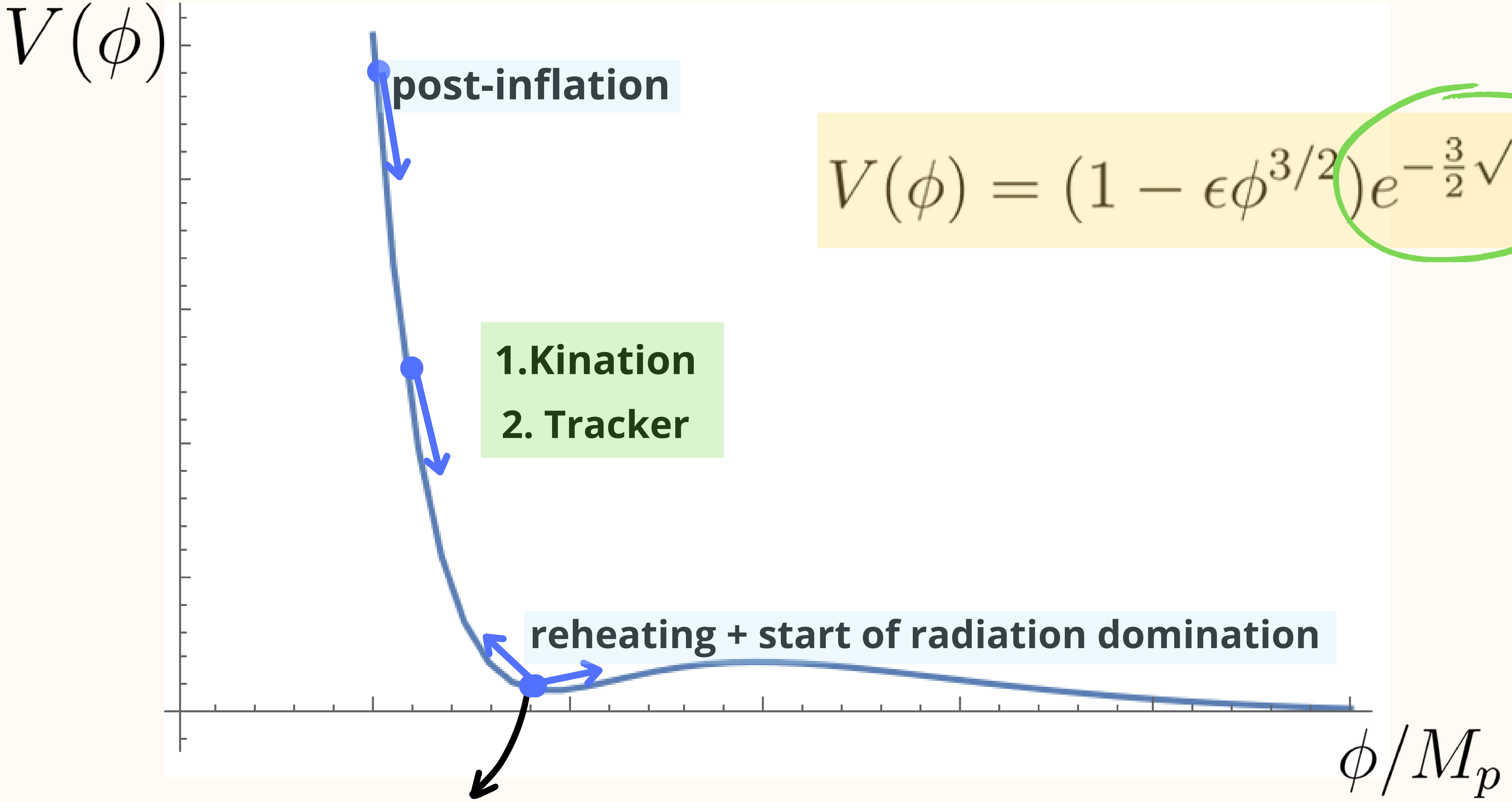


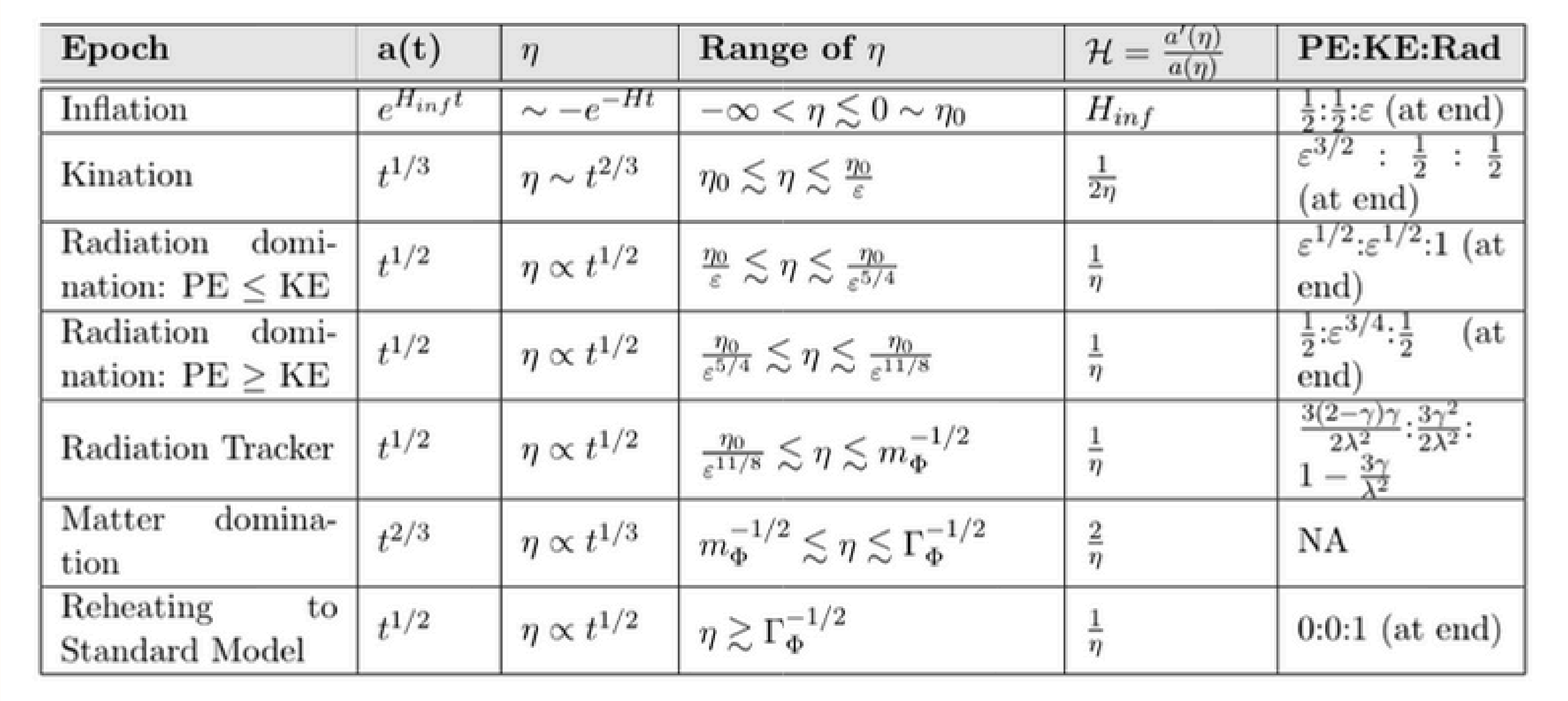
$$V(\phi) = (1 - \epsilon\phi^{3/2})\boxed{e^{-\frac{3}{2}\sqrt{3}\phi}} + \delta e^{-\sqrt{6}\phi}$$

$\phi_{\rm min} \approx 19 M_p$

For details... background evolution and cosmological perturbations

String Theory and the First Half of the Universe

Fien Apers,[a] Joseph P. Conlon,[a] Edmund J. Copeland,[b] Martin Mosny[a] and Filippo Revello[c]



Epoch	a(t)	η	Range of η	$\mathcal{H} = \frac{a'(\eta)}{a(\eta)}$	PE:KE:Rad
Inflation	$e^{H_{inf}t}$	$\sim -e^{-Ht}$	$-\infty < \eta \lesssim 0 \sim \eta_0$	H_{inf}	$\frac{1}{2}$:$\frac{1}{2}$:ε (at end)
Kination	$t^{1/3}$	$\eta \sim t^{2/3}$	$\eta_0 \lesssim \eta \lesssim \frac{\eta_0}{\varepsilon}$	$\frac{1}{2\eta}$	$\varepsilon^{3/2}$: $\frac{1}{2}$: $\frac{1}{2}$ (at end)
Radiation domination: PE $\leq$ KE	$t^{1/2}$	$\eta \propto t^{1/2}$	$\frac{\eta_0}{\varepsilon} \lesssim \eta \lesssim \frac{\eta_0}{\varepsilon^{5/4}}$	$\frac{1}{\eta}$	$\varepsilon^{1/2}$:$\varepsilon^{1/2}$:1 (at end)
Radiation domination: PE $\geq$ KE	$t^{1/2}$	$\eta \propto t^{1/2}$	$\frac{\eta_0}{\varepsilon^{5/4}} \lesssim \eta \lesssim \frac{\eta_0}{\varepsilon^{11/8}}$	$\frac{1}{\eta}$	$\frac{1}{2}$:$\varepsilon^{3/4}$:$\frac{1}{2}$ (at end)
Radiation Tracker	$t^{1/2}$	$\eta \propto t^{1/2}$	$\frac{\eta_0}{\varepsilon^{11/8}} \lesssim \eta \lesssim m_\Phi^{-1/2}$	$\frac{1}{\eta}$	$\frac{3(2-\gamma)\gamma}{2\lambda^2}$:$\frac{3\gamma^2}{2\lambda^2}$: $1-\frac{3\gamma}{\lambda^2}$
Matter domination	$t^{2/3}$	$\eta \propto t^{1/3}$	$m_\Phi^{-1/2} \lesssim \eta \lesssim \Gamma_\Phi^{-1/2}$	$\frac{2}{\eta}$	NA
Reheating to Standard Model	$t^{1/2}$	$\eta \propto t^{1/2}$	$\eta \gtrsim \Gamma_\Phi^{-1/2}$	$\frac{1}{\eta}$	0:0:1 (at end)

Summary

- There is an epoch in the early universe, in between inflation and the start of radiation domination, where large part of the energy density is in string theory moduli
- If we live at the **end of the world** (near boundary of moduli space) there is a **general description** of this epoch with a **scalar field rolling down a steep exponential** $V(\phi) = V_0 e^{-\lambda\phi/M_p}$ and going through periods of
    - **kination**
    - **tracker** (cosmological scaling solutions).
- This may be followed by a period of **moduli domination**.

Kination	$\phi = \sqrt{\frac{2}{3}} \ln t$	$a(t) \sim t^{1/3}$	$\Omega_\phi = 1$
Radiation Tracker	$\phi = \frac{2}{\lambda} \ln t$	$a(t) \sim t^{1/2}$	$\Omega_\phi = \frac{4}{\lambda^2}$