Inflaxion dark matter

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[arXiv:2006.09389] JHEP **09** (2020) 052

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Axion dark matter - 1

$$T_{\rm max} > f$$

$$V(\Phi) = (|\Phi|^2 - f^2)^2$$ U(1)$_{\rm PQ}$ spontaneously broken at scale f

$$\Phi = \rho e^{i\sigma/f}$$ σ is the axion

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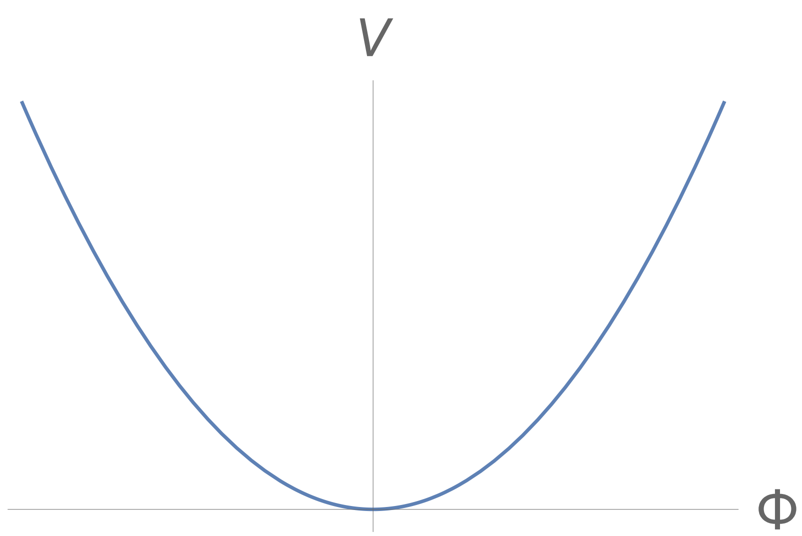
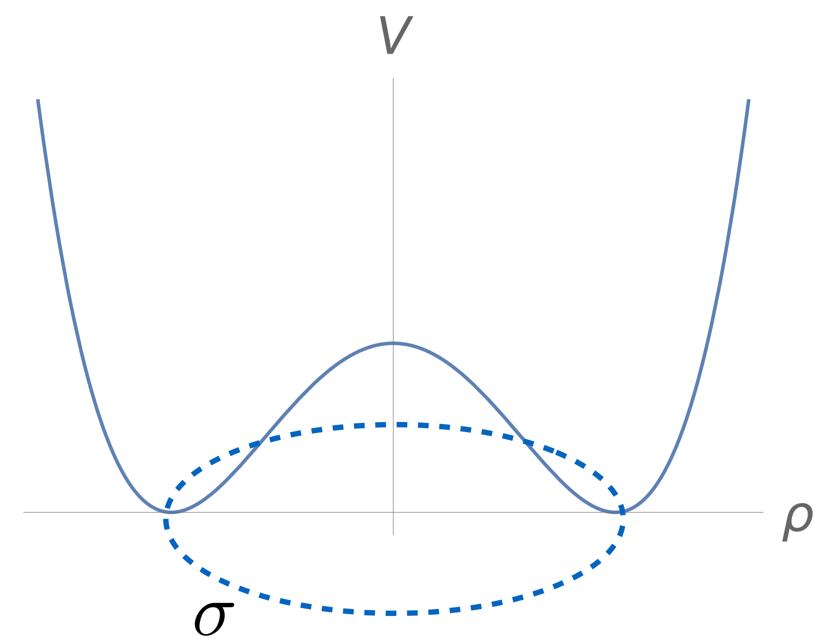


$T > f$

PQ phase transition

$\longrightarrow$

$T \sim f$



$T < f$

Axion dark matter - 1

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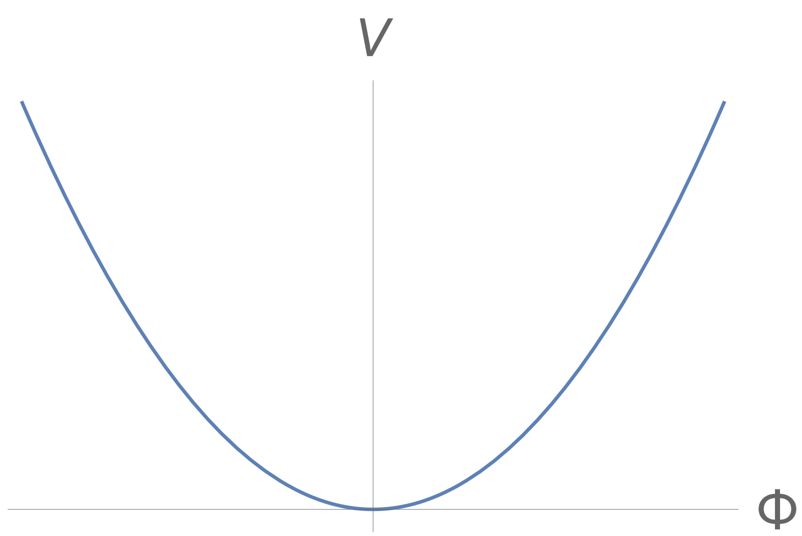

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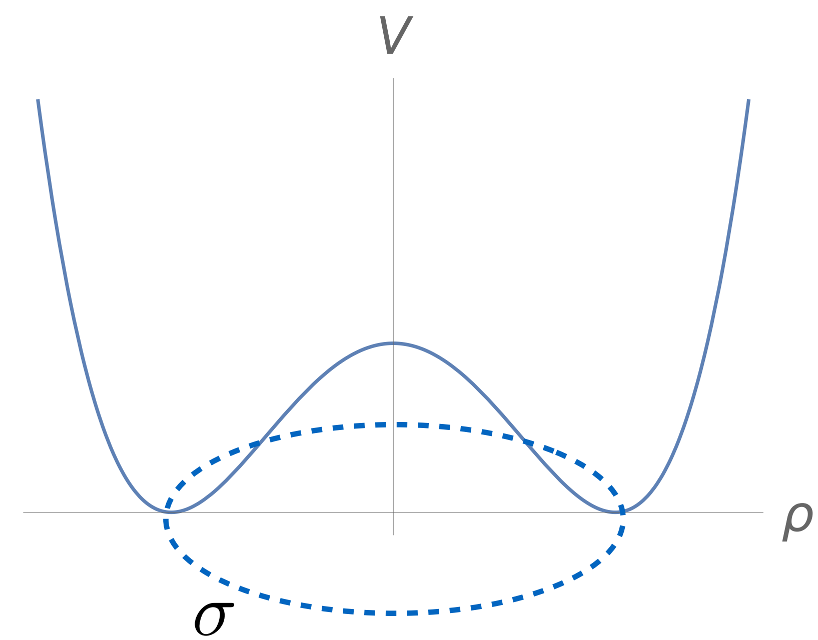

$T > f$

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Relic axions from misalignment and from axionic strings

Axion dark matter - 1

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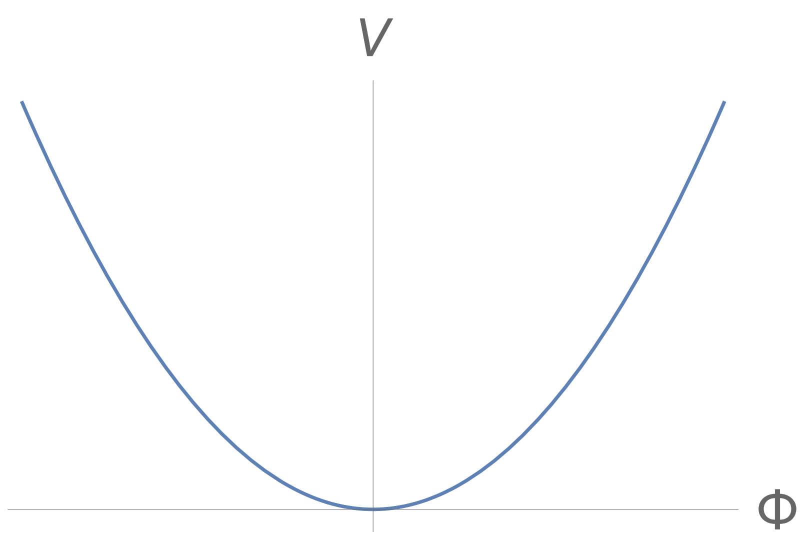

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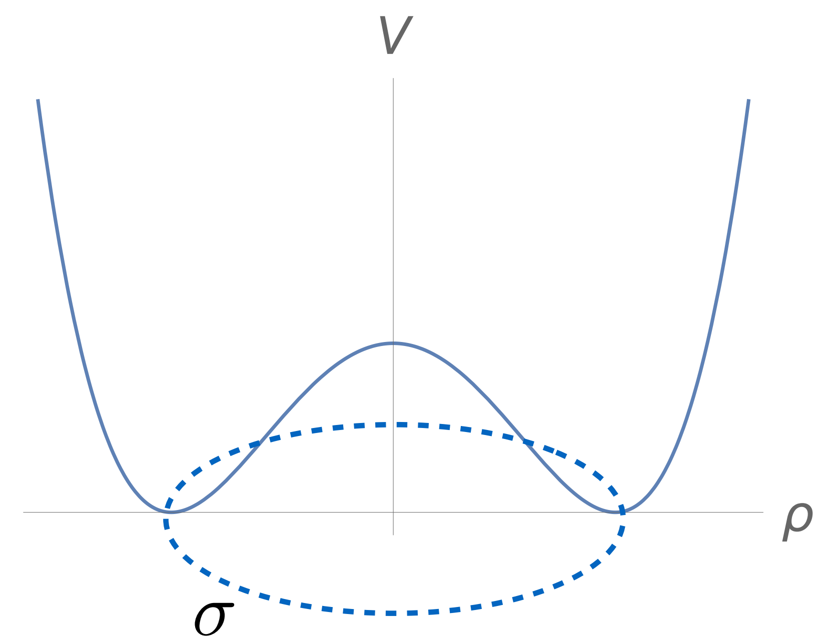


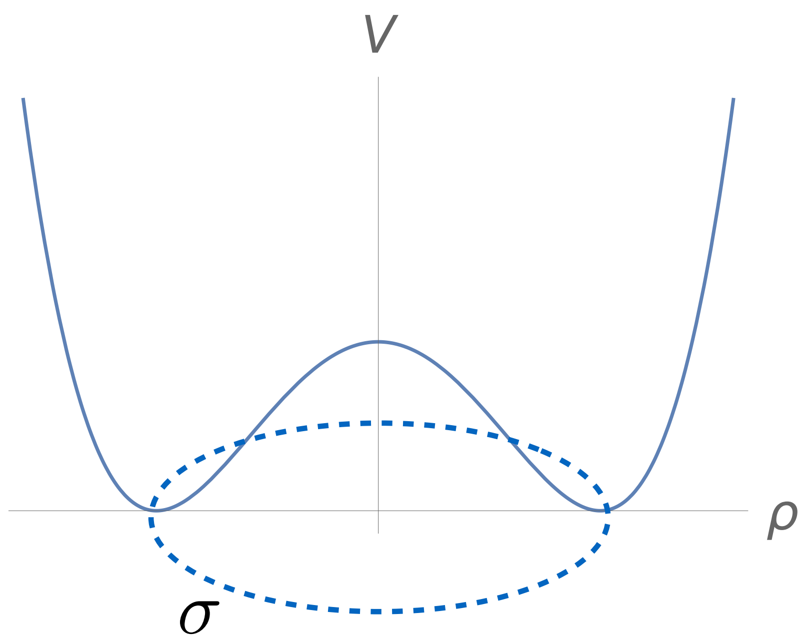
$$T > f \qquad\qquad T < f$$

Relic axions from misalignment and from axionic strings

Abundance calculable in principle, technically difficult in practice

Axion dark matter - 2

$$m_\sigma \ll \Lambda \ll \mathrm{Max}[H_I, T_{\mathrm{max}}] < f$$



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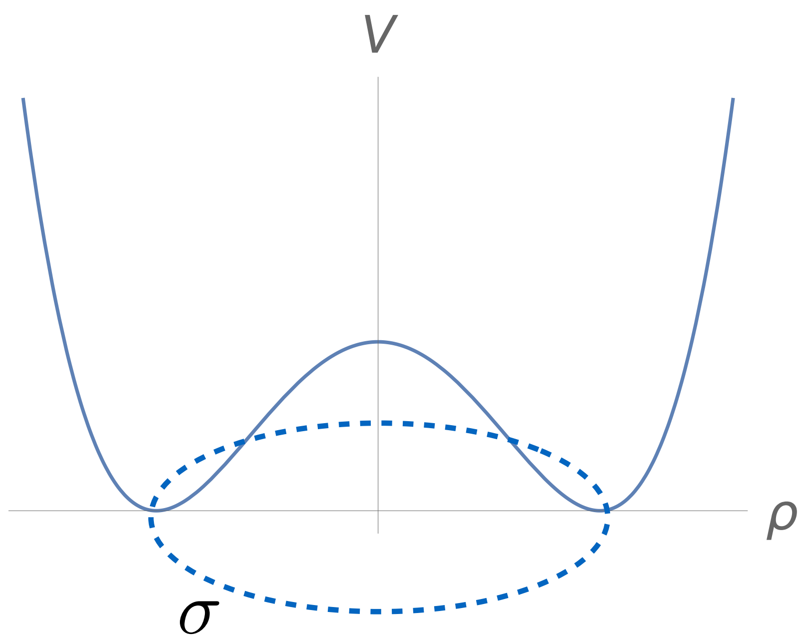

U(1)$_{\mathrm{PQ}}$ explicitly broken at scale $\Lambda \ll f$

$$V(\sigma) = \Lambda^4 \left(1 - \cos\frac{\sigma}{f}\right) \simeq \frac{1}{2} m_\sigma^2 \sigma^2$$

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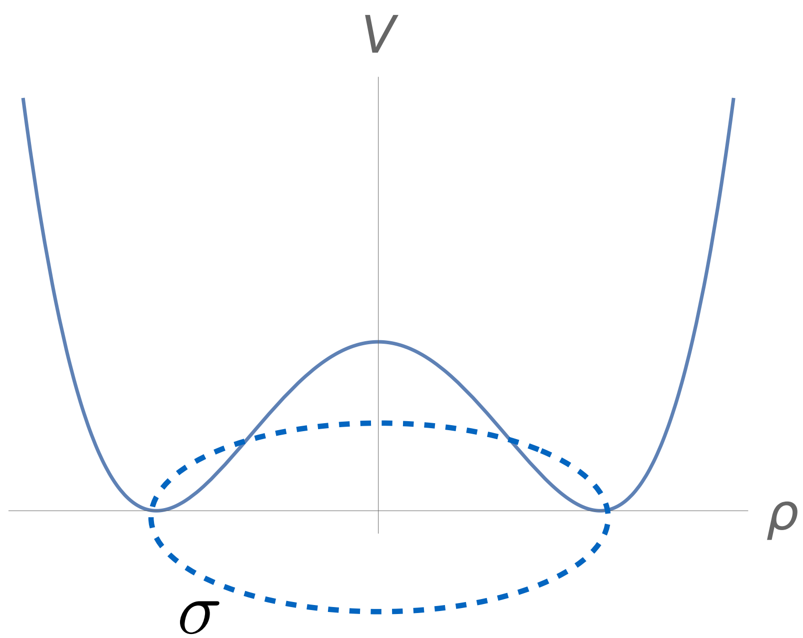

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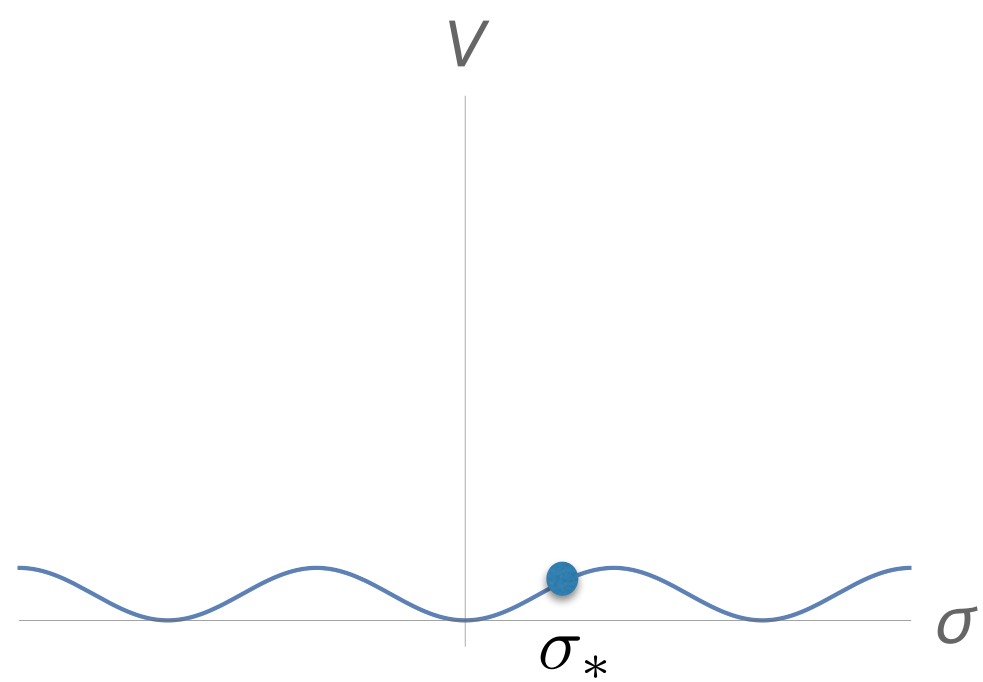
during inflation

$$\ddot{\sigma} + 3H_I\dot{\sigma} + m_\sigma^2\sigma = 0$$

$$H_I \gg m_\sigma$$



the axion is stuck

$$-\pi < \frac{\sigma_*}{f} \equiv \theta_* < \pi$$

Axion dark matter - 2

$$m_\sigma \ll \Lambda \ll \mathrm{Max}[H_I, T_{\rm max}] < f$$

Λ : confinement scale of a strong gauge group

At zero temperature $\quad m_{\sigma 0} = \xi \dfrac{\Lambda^2}{f}$

At finite temperature $\quad m_\sigma(T) \simeq \begin{cases} \lambda\, m_{\sigma 0} \left(\dfrac{\Lambda}{T}\right)^p & \text{for } T \gg \Lambda, \\ m_{\sigma 0} & \text{for } T \ll \Lambda, \end{cases}$

For the QCD axion: $\quad \Lambda \approx 200~\mathrm{MeV}, \quad p \approx 4, \quad \lambda \approx 0.1, \quad \xi \approx 0.1$

Axion dark matter - 2

$$m_\sigma \ll \Lambda \ll \mathrm{Max}[H_I, T_{\mathrm{max}}] < f$$

After reheating the Hubble parameter decreases as $H = \dfrac{T^2}{M_P}$

$$\ddot{\sigma} + 3H\dot{\sigma} + m_\sigma^2(T)\sigma = 0$$

When $H \sim m_\sigma(T)$ the axion field starts to oscillate.
Soon after, the energy density of the oscillating field redshifts like non relativistic matter.

$$\rho_\sigma \propto a^{-3}$$

Relic abundance today

$$\Omega_\sigma h^2 = \kappa_p\, \theta_\star^2 \left(\frac{g_{s*}(T_{\mathrm{osc}})}{100}\right)^{-1} \left(\frac{g_*(T_{\mathrm{osc}})}{100}\right)^{\frac{p+3}{2p+4}} \left(\frac{\lambda}{0.1}\right)^{-\frac{1}{p+2}} \left(\frac{\xi}{0.1}\right)^{\frac{p+1}{p+2}} \left(\frac{\Lambda}{200\,\mathrm{MeV}}\right) \left(\frac{f}{10^{12}\,\mathrm{GeV}}\right)^{\frac{p+3}{p+2}}$$

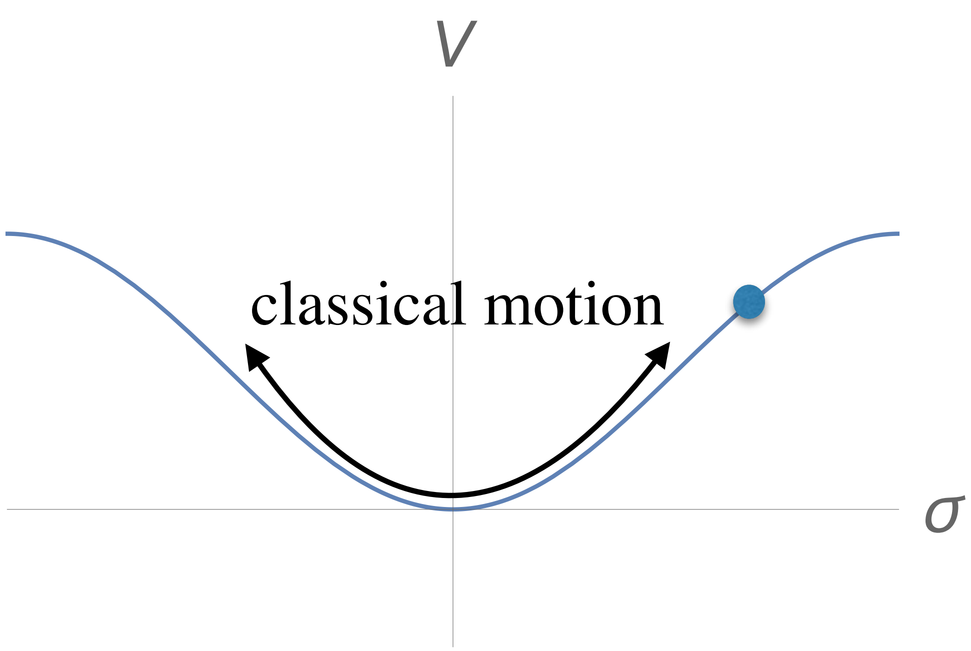
Axion dark matter - 3

What if the scale of inflation is as low as

$$H_I \ll m_\sigma$$

$$\ddot{\sigma} + 3H_I\dot{\sigma} + m_\sigma^2\sigma = 0$$

$$\sigma(t) = \sigma_* e^{-\frac{3}{2}H_I t}\cos(m_\sigma t) \to 0$$



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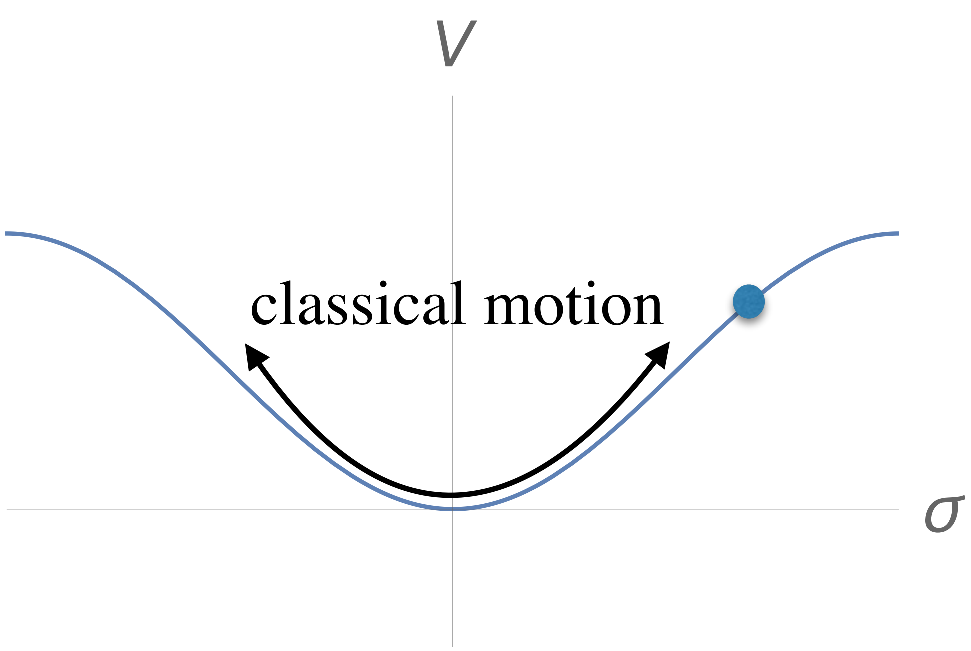

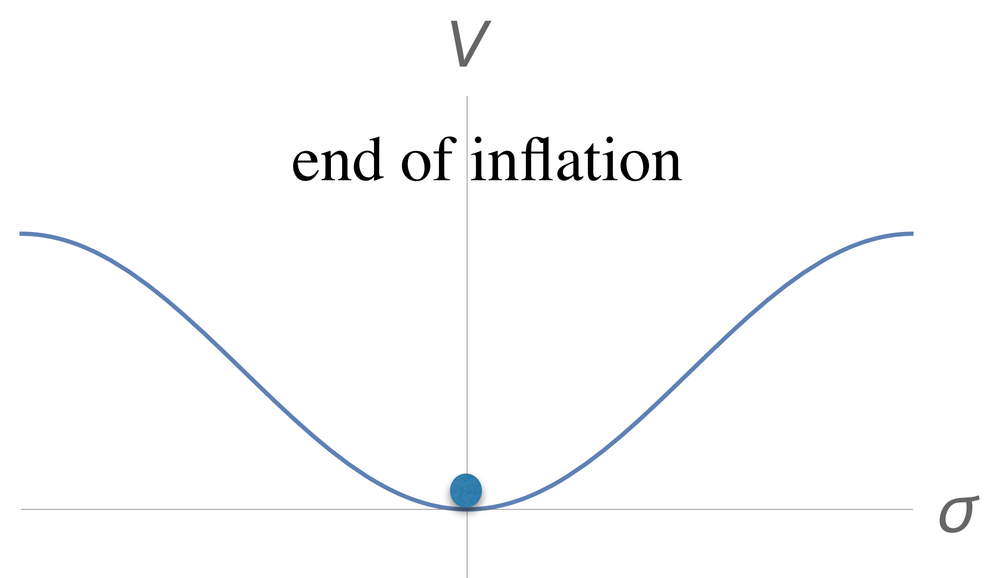

no axion dark matter

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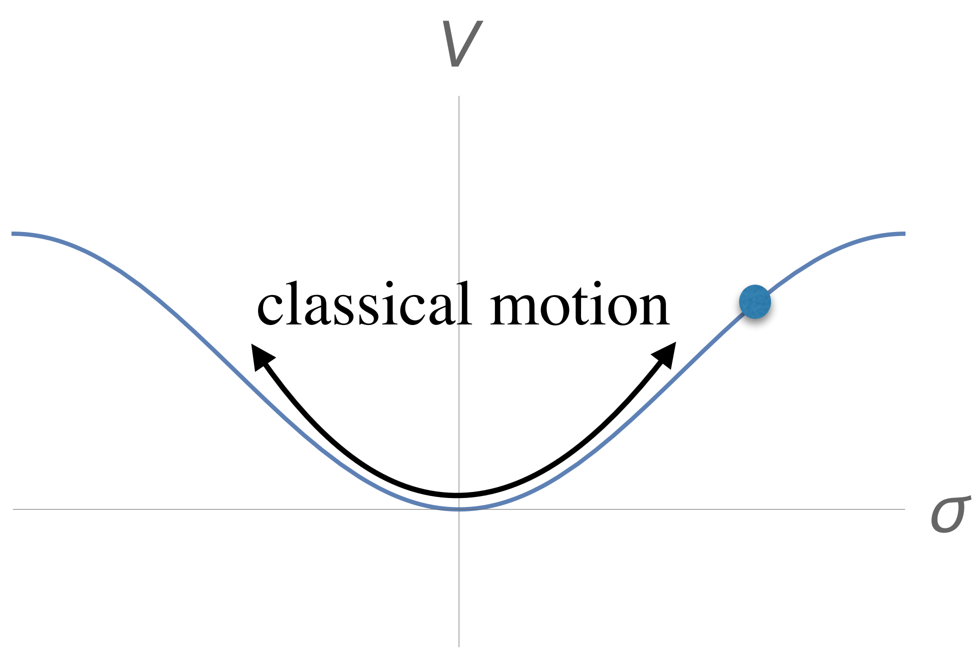
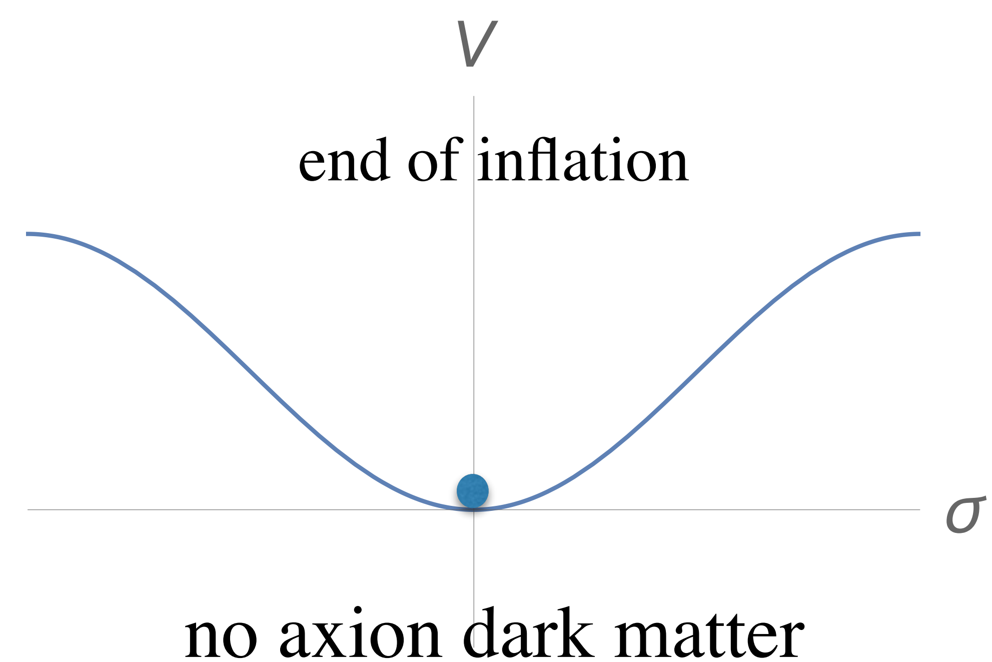
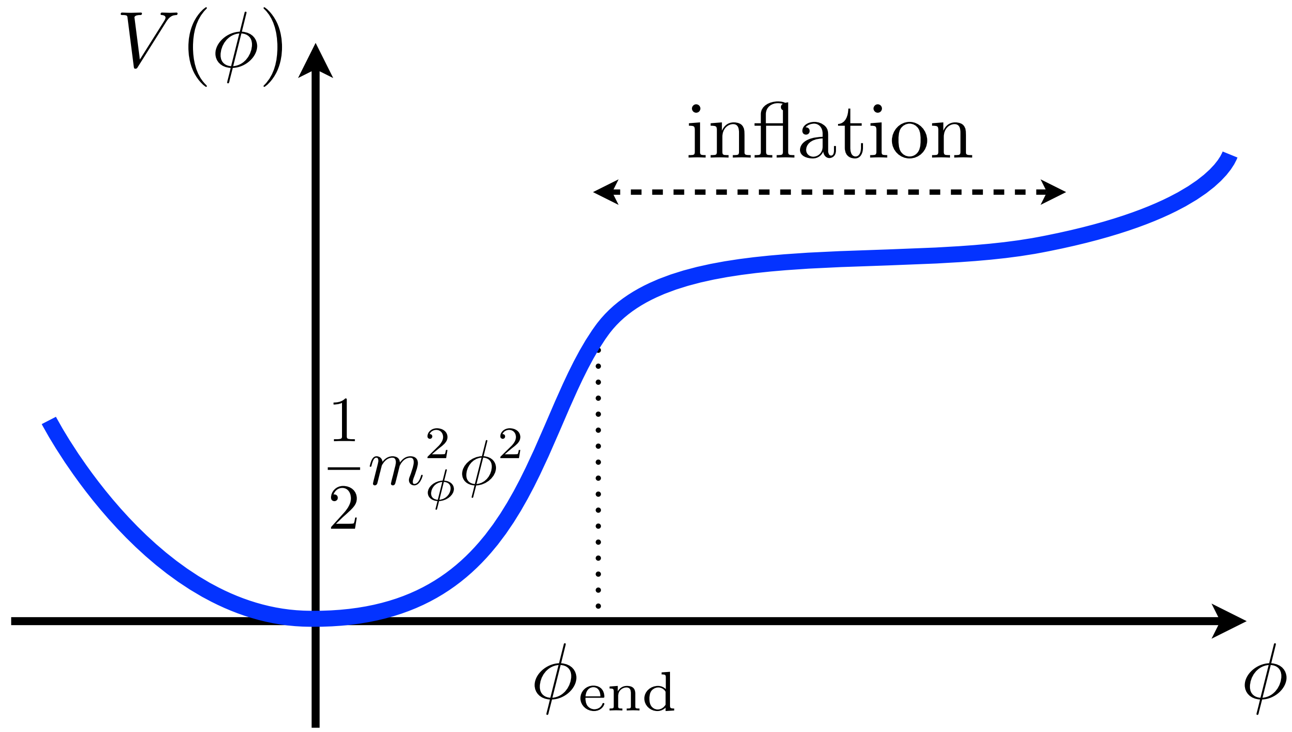




Are there ways to obtain a relic abundance of axions in this scenario?

σ : axion ϕ : inflaton



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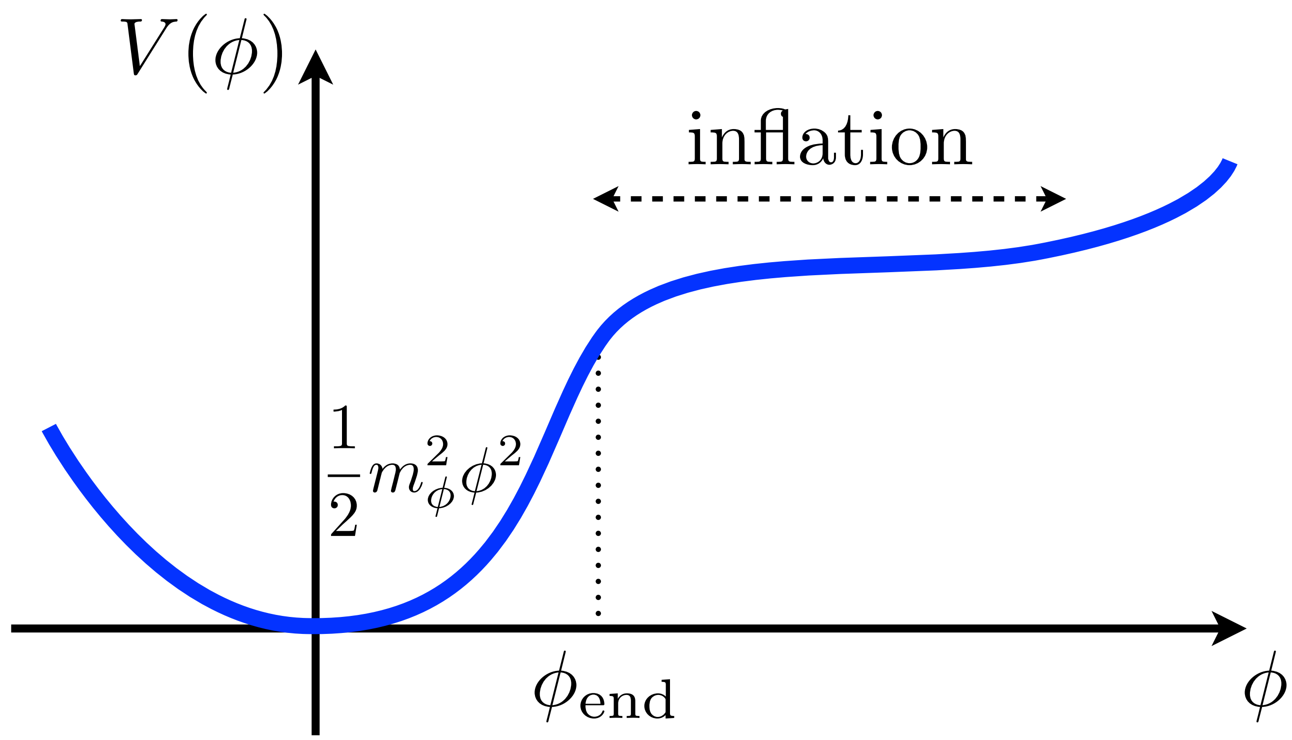


What if the inflaton and the axion are coupled?

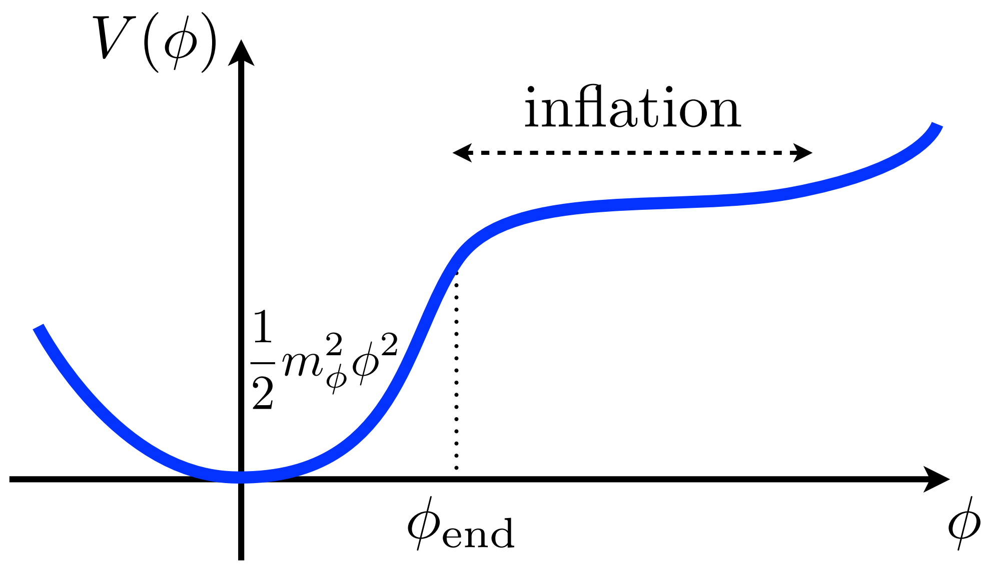
$$-\frac{\mathcal{L}}{\sqrt{-g}} = \frac{1}{2}g^{\mu\nu}(\partial_\mu\sigma\partial_\nu\sigma + \partial_\mu\phi\partial_\nu\phi + 2\alpha\partial_\mu\sigma\partial_\nu\phi) + \frac{1}{2}m_\sigma^2\sigma^2 + V(\phi)$$

Kinetic mixing

Via the kinetic mixing, when the inflaton starts oscillating around the minimum of its potential (reheating) it will kick the axion away from its minimum.

The axion displacement, in turn, allows for the re-alignment mechanism of dark matter production to take place.

End of inflation

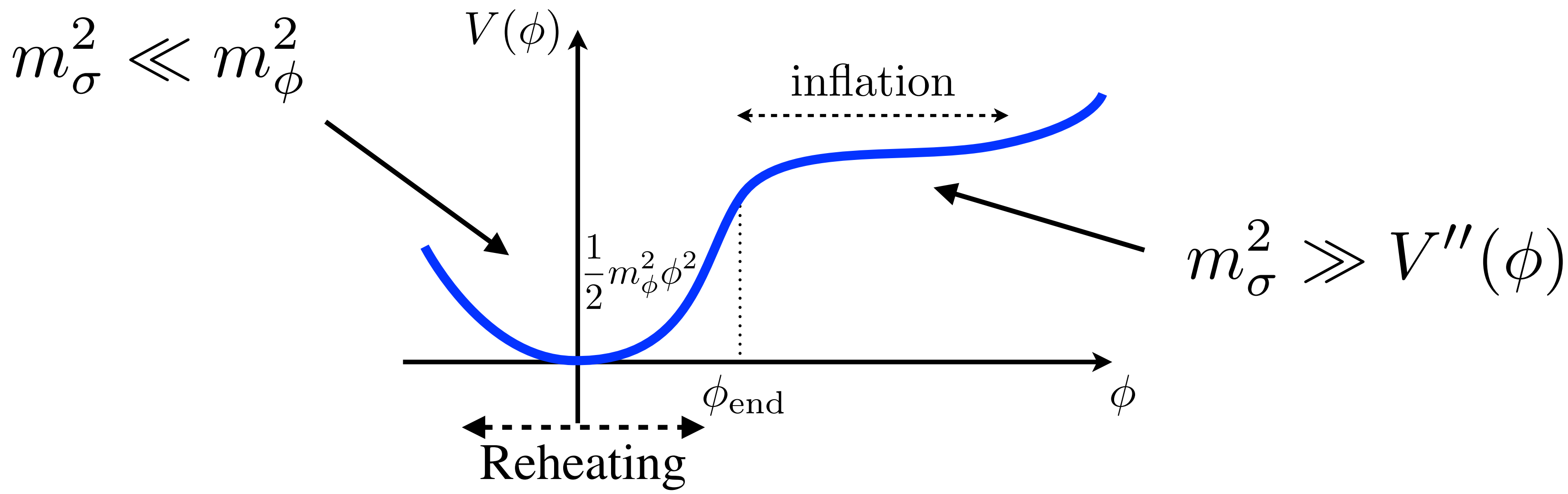


$$-\frac{\dot{H}}{H^2} = 1$$

$$\dot{\phi}^2 = V(\phi) = 2M_P^2 H^2$$

$$\phi_{\rm end} \simeq \frac{2M_P H_{\rm end}}{m_\phi}$$

Diagonal basis at reheating



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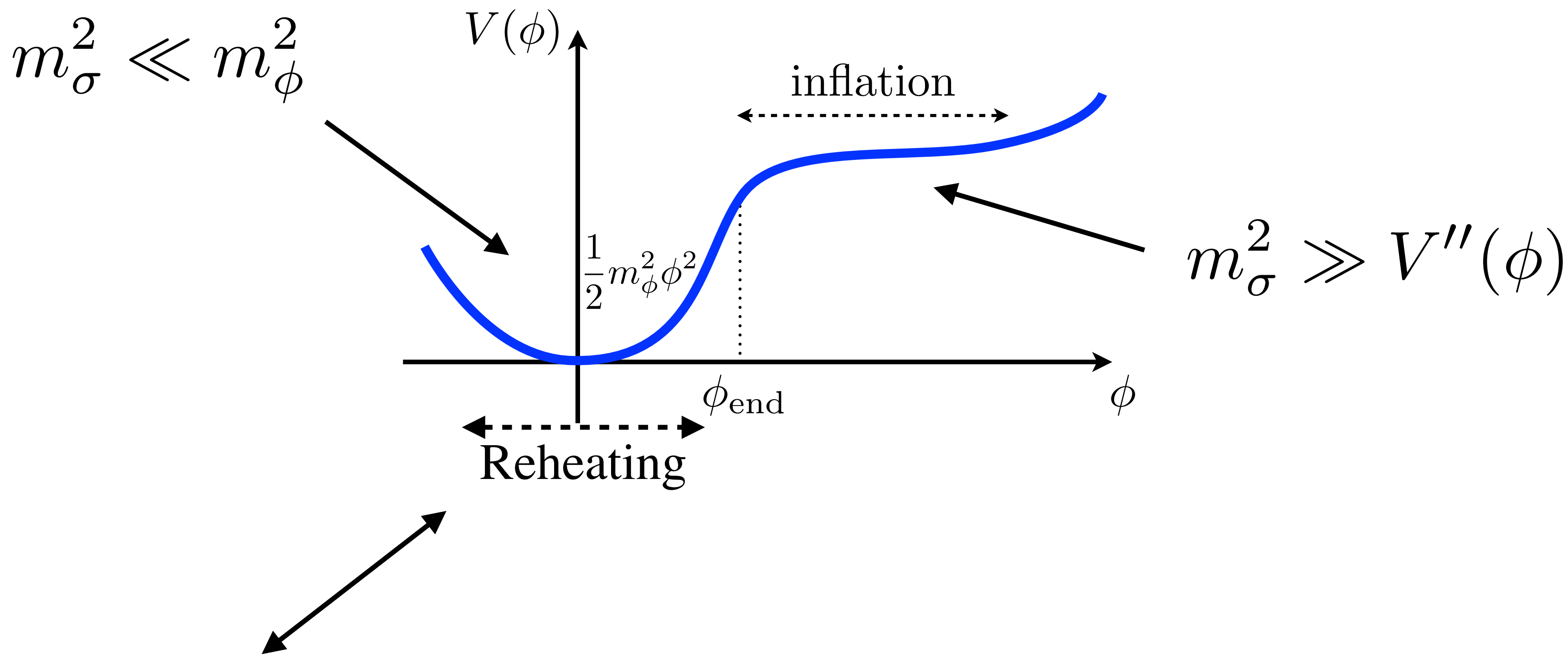
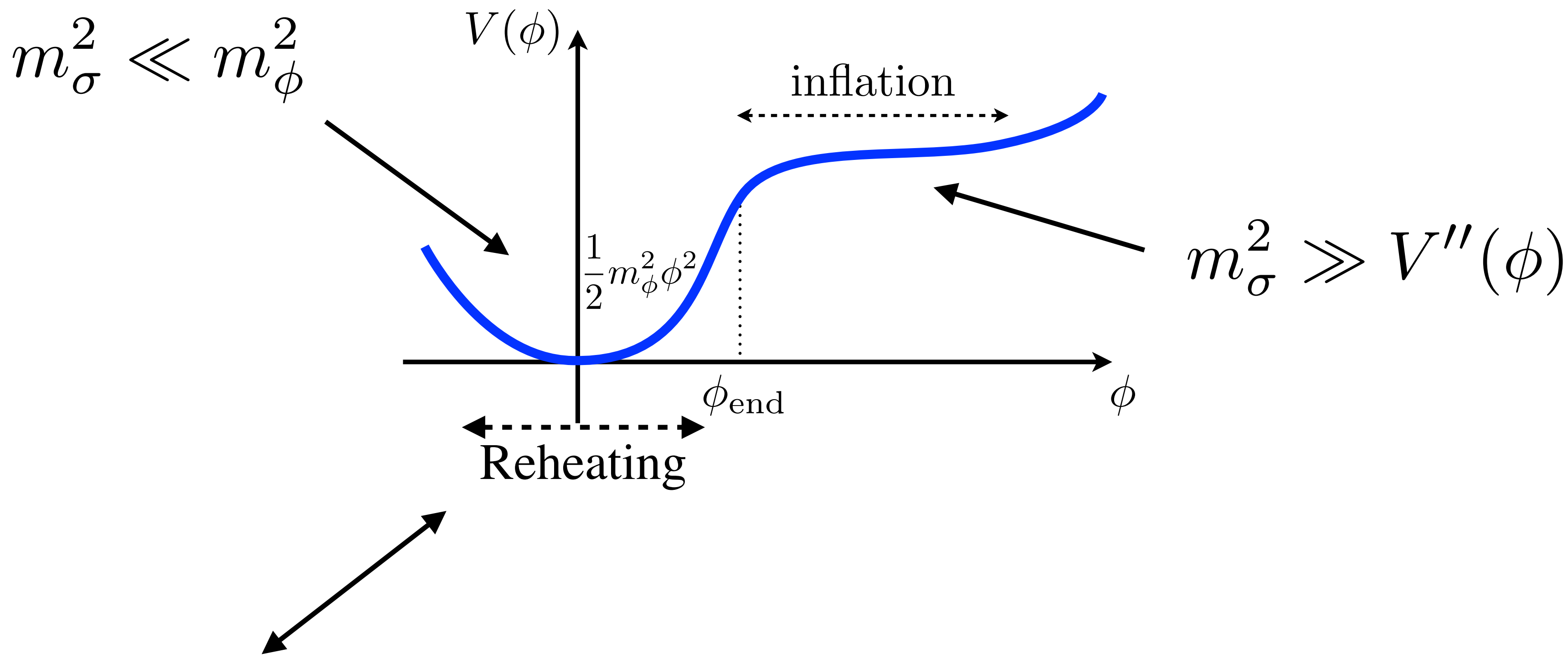


Diagonal basis during reheating

$$\varphi_{\rm DM} \simeq \alpha\,\phi + \sigma, \quad \varphi_{\rm RH} \simeq \sqrt{1-\alpha^2}\left(\phi - \alpha\frac{m_\sigma^2}{m_\phi^2}\,\sigma\right)$$

$$m_{\rm DM}^2 \simeq m_\sigma^2, \quad m_{\rm RH}^2 \simeq \frac{m_\phi^2}{1-\alpha^2}$$

Diagonal basis at reheating



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$$m_{\rm DM}^2 \simeq m_\sigma^2, \quad m_{\rm RH}^2 \simeq \frac{m_\phi^2}{1-\alpha^2}$$

At the end of inflation

$$\phi_{\rm end} \simeq \frac{2 M_P H_{\rm end}}{m_\phi}$$

$$\varphi_{\rm DMend} = \alpha\phi_{\rm end} + \sigma_{\rm end} \simeq \alpha\phi_{\rm end}$$

$$= \frac{C\alpha M_P H_{\rm end}}{m_\phi}$$

Reheating

$$\frac{\alpha_\gamma}{8\pi f}\sigma F_{\mu\nu}\tilde{F}^{\mu\nu} + g_{\phi f f}\,\phi\bar{\psi}i\gamma^5\psi$$

$$\Gamma(\varphi_{\rm DM}\to\gamma\gamma)\simeq\frac{\alpha_\gamma^2}{256\pi^3 f^2}m_\sigma^3$$

$$\Gamma(\varphi_{\rm RH}\to\gamma\gamma)\simeq\frac{\alpha^2}{(1-\alpha^2)^{5/2}}\frac{\alpha_\gamma^2}{256\pi^3 f^2}m_\phi^3$$

$$\Gamma(\varphi_{\rm DM}\to f\bar{f})\simeq\alpha^2\frac{g_{\phi f f}^2}{8\pi}\frac{m_\sigma^5}{m_\phi^4}$$

$$\boxed{\Gamma(\varphi_{\rm RH}\to f\bar{f})\simeq\frac{1}{(1-\alpha^2)^{3/2}}\frac{g_{\phi f f}^2}{8\pi}m_\phi}$$

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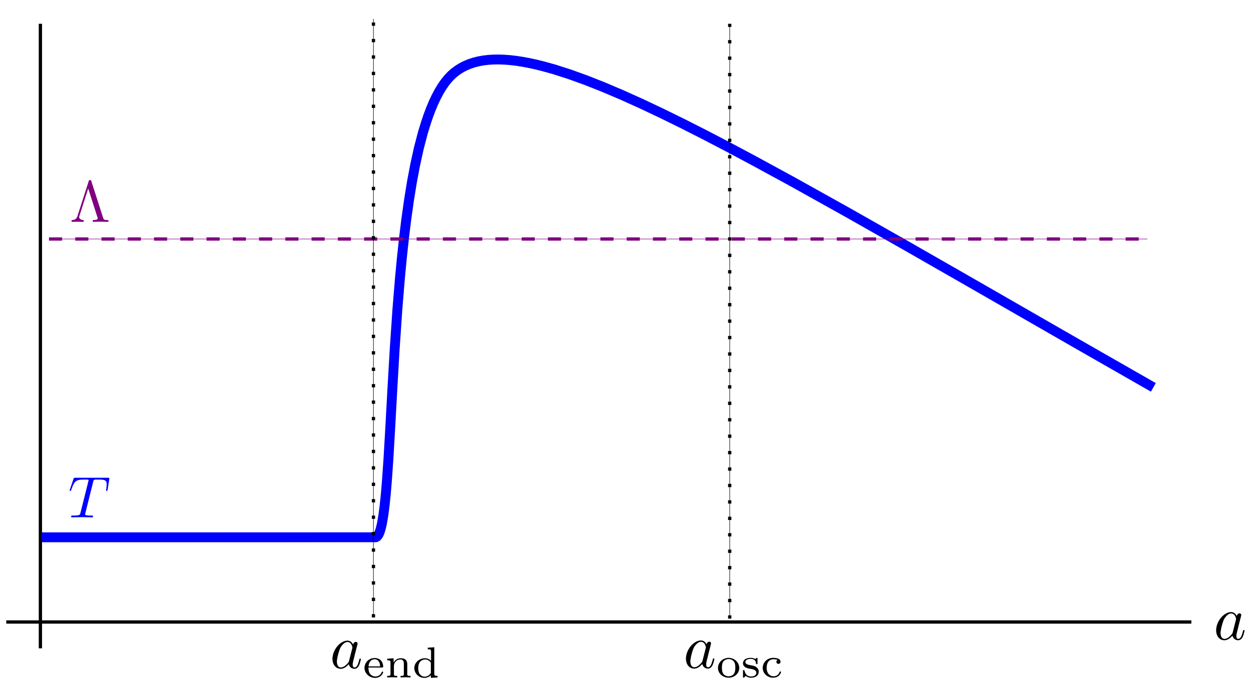
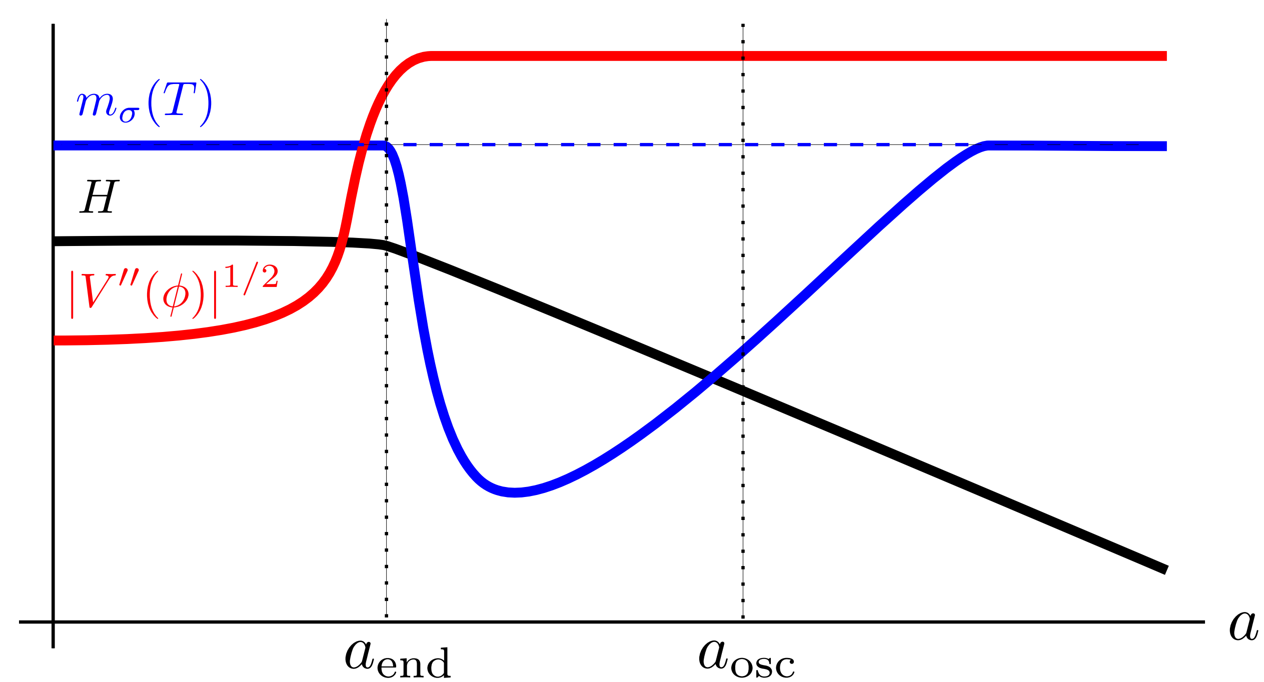
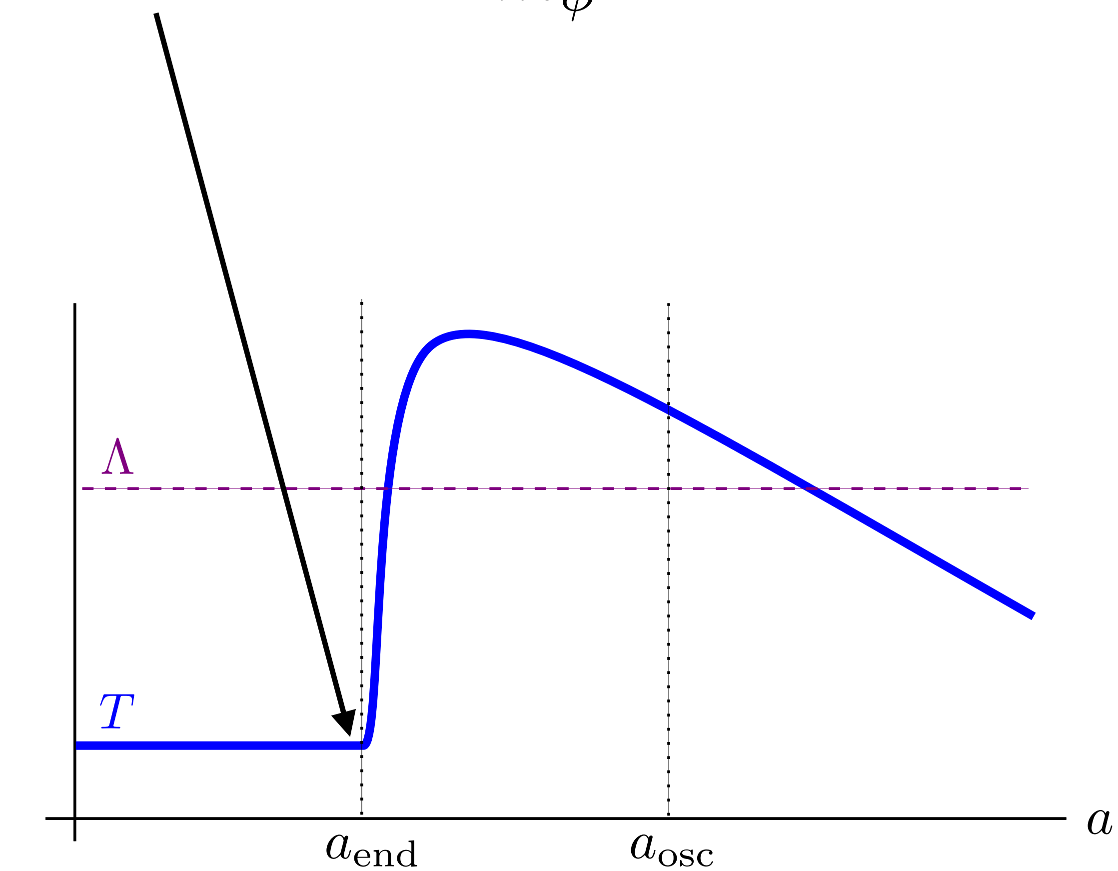




$$\varphi_{\text{DMend}} = \frac{C\alpha M_P H_{\text{end}}}{m_\phi}$$



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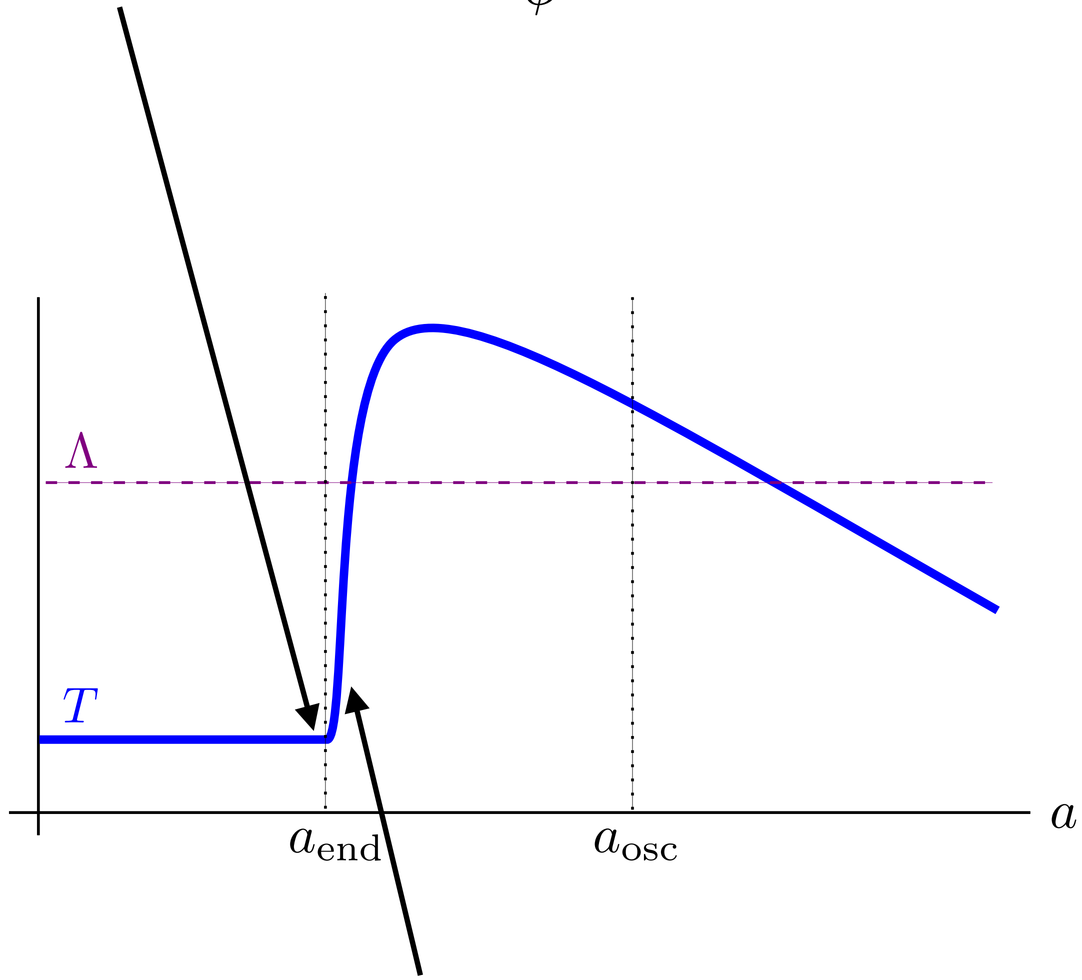


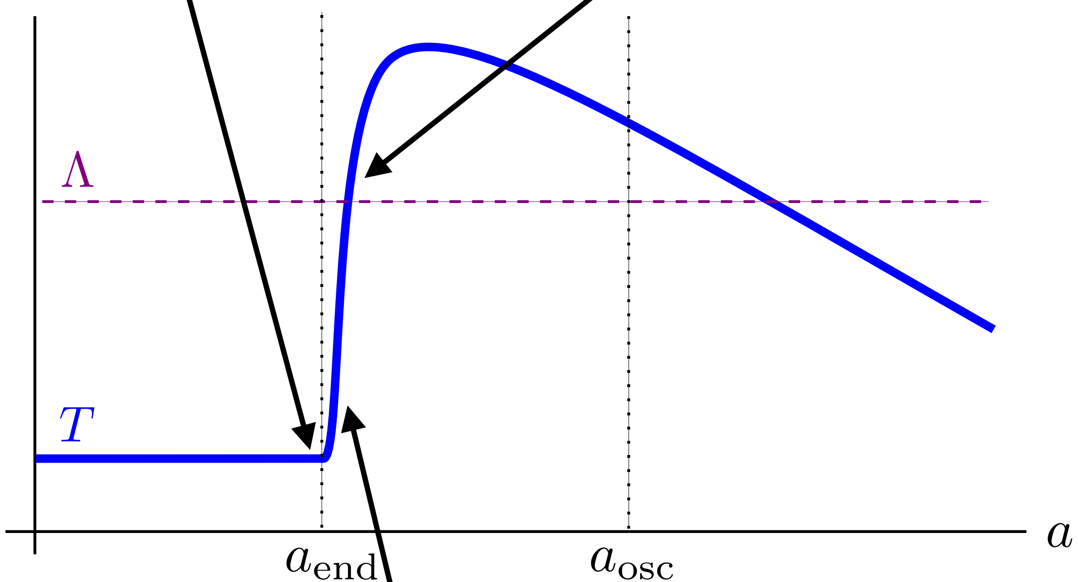
$$\varphi_{\rm DM} = a^{-3/2} \varphi_{\rm DMend} \cos(m_{\sigma 0} t)$$

$$|\dot{\varphi}_{\rm DMend}| \approx m_{\sigma 0} |\varphi_{\rm DMend}|$$

$$\varphi_{\rm DMend} = \frac{C\alpha M_P H_{\rm end}}{m_\phi}$$

The field drifts on a flat potential and stops within a few Hubble times

$$\ddot{\varphi}_{\rm DM} + 3H\dot{\varphi}_{\rm DM} \approx 0$$



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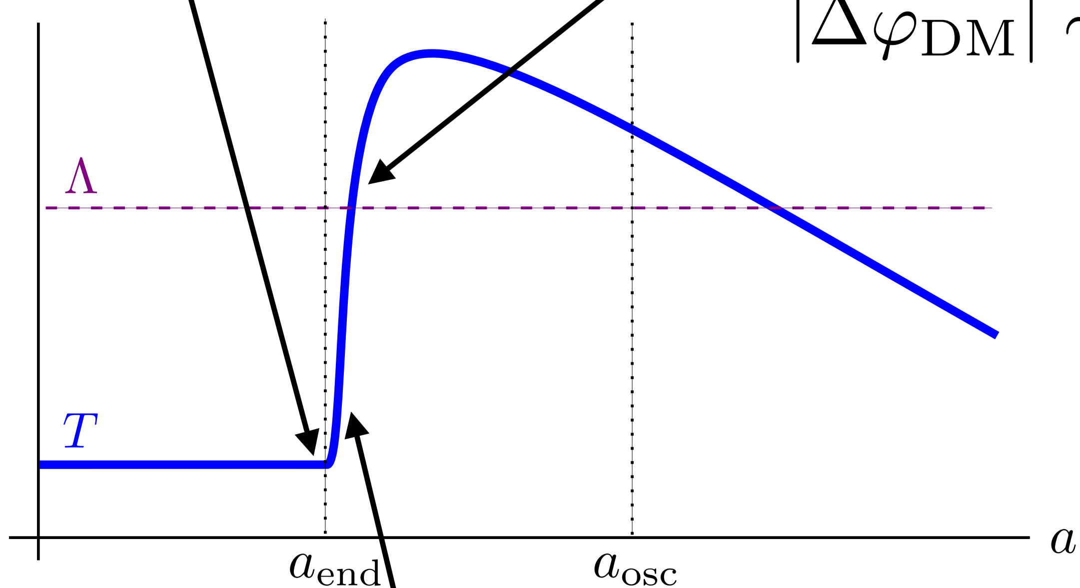
$$|\Delta\varphi_{\rm DM}| \sim \left|\frac{\dot{\varphi}_{\rm DMend}}{H_{\rm end}}\right| \sim \frac{m_{\sigma 0}}{H_{\rm end}}|\varphi_{\rm DMend}| > |\varphi_{\rm DMend}|$$



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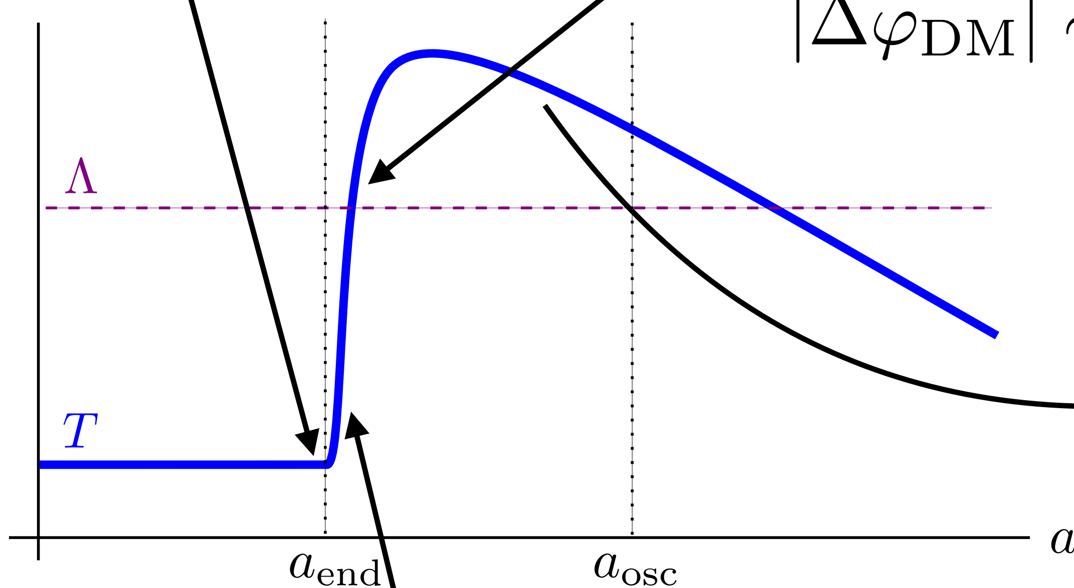

$$\varphi_{\rm DM\star} = \frac{B\alpha M_P m_{\sigma 0}}{m_\phi}$$

B is a number of order 1

$$\varphi_{\rm DM} = a^{-3/2}\varphi_{\rm DMend}\cos(m_{\sigma 0} t)$$

$$|\dot{\varphi}_{\rm DMend}| \approx m_{\sigma 0}|\varphi_{\rm DMend}|$$

Summary so far

The dark matter field

$$\varphi_{\rm DM} \simeq \alpha\phi + \sigma$$

is a linear combination of axion and inflaton, hence we dub it inflaxion dark matter.

After the dynamics that happen during reheating, it is stuck at

$$\varphi_{\rm DM\star} = \frac{B\alpha M_P m_{\sigma 0}}{m_\phi}$$

away from the minimum of its potential.

That is the misalignment. From that point on, the calculation of the relic abundance proceeds in the same way as for scenario 2.

Final relic abundance

$$\Omega_\sigma h^2 = \kappa_p \, \theta_\star^2 \left(\frac{g_{s*}(T_{\rm osc})}{100} \right)^{-1} \left(\frac{g_*(T_{\rm osc})}{100} \right)^{\frac{p+3}{2p+4}} \left(\frac{\lambda}{0.1} \right)^{-\frac{1}{p+2}} \left(\frac{\xi}{0.1} \right)^{\frac{p+1}{p+2}} \left(\frac{\Lambda}{200\,\mathrm{MeV}} \right) \left(\frac{f}{10^{12}\,\mathrm{GeV}} \right)^{\frac{p+3}{p+2}}$$

$$\theta_\star = \frac{\varphi_{\mathrm{DM}\star}}{f} = \frac{B\alpha M_P m_{\sigma 0}}{f m_\phi}$$

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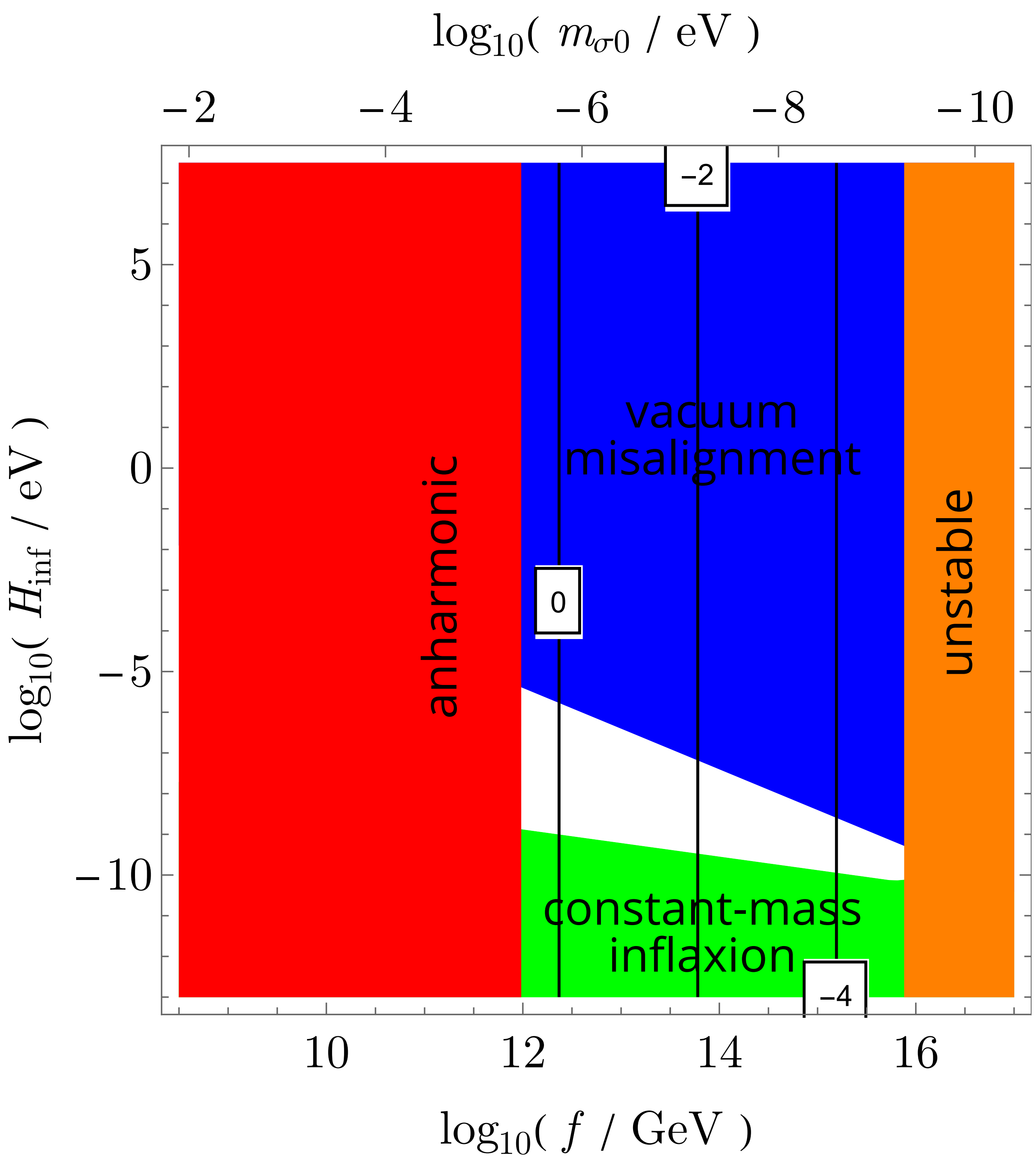
$$\theta_\star = \frac{\varphi_{\rm DM\star}}{f} = \frac{B\alpha M_P m_{\sigma 0}}{f m_\phi}$$

Whereas in scenario 2 the initial misalignment angle is not calculable, in the inflaxion scenario it is given in terms of the parameters in the Lagrangian.

Parameter space



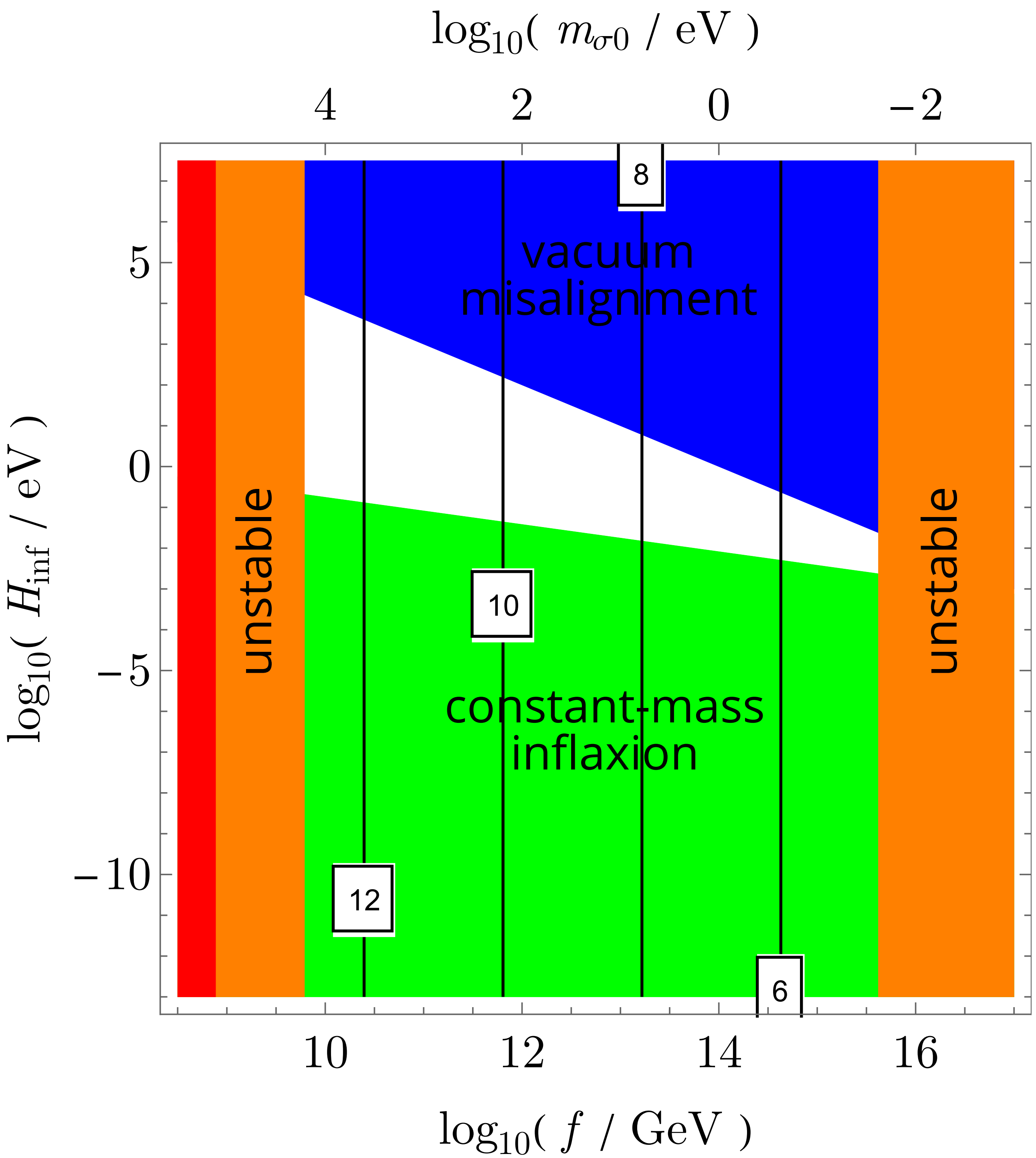
(a) $\Lambda = 200\,\mathrm{MeV}$ (QCD axion)

Excluded regions, violation of:

$m_{\sigma 0} > H_{\rm inf}$	blue
$m_\sigma(T_{\rm max}) < H_{\rm inf}$	green
$\theta_\star < 1$	red
$\Gamma_{\rm DM} < H_0$	orange

$\alpha = 1/3 \qquad g_{\phi f f} = 10^{-2}$

Parameter space



(c) $\Lambda = 10^3$ GeV

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$\alpha = 1/3 \qquad g_{\phi f f} = 10^{-2}$

Conclusion

An axion (or any scalar) which mixes kinetically with the inflaton can provide a good dark matter candidate even if the scale of inflation is lower than its mass!