Inflaxion dark matter

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[arXiv:1907.00984] JHEP **1908** (2019) 147

Takeshi Kobayashi, LU

Madrid, October 24th, 2019

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~~Inflation~~

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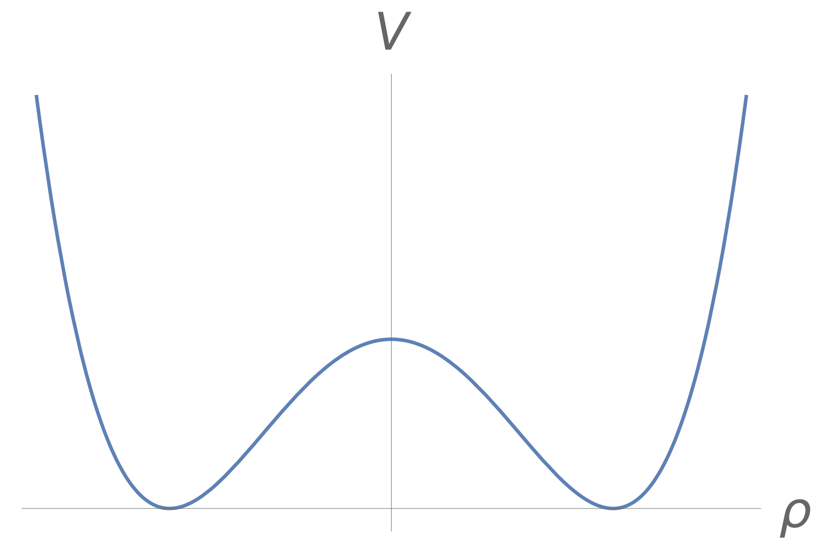
Notation and conventions

$$V(\Phi) = (|\Phi|^2 - f^2)^2$$

$$\Phi = \rho e^{i\sigma/f}$$

$U(1)_{PQ}$ spontaneously broken



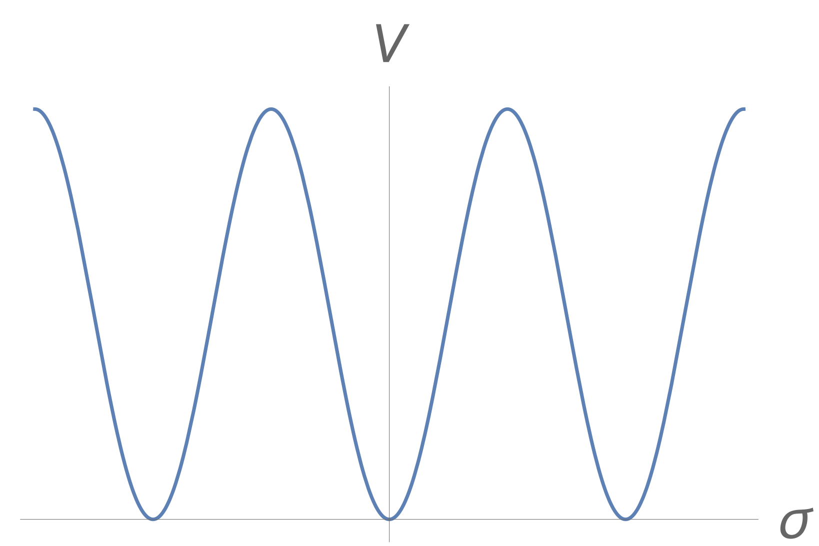
$$ds^2 = -dt^2 + a(t)^2 d\vec{x}^2$$

$$-\frac{\mathcal{L}}{\sqrt{-g}} = \frac{1}{2} g^{\mu\nu}\partial_\mu\sigma\partial_\nu\sigma + m_\sigma^2 f^2 \left(1 - \cos\frac{\sigma}{f}\right)$$

$$\approx \frac{1}{2} g^{\mu\nu}\partial_\mu\sigma\partial_\nu\sigma + \frac{1}{2} m_\sigma^2 \sigma^2$$

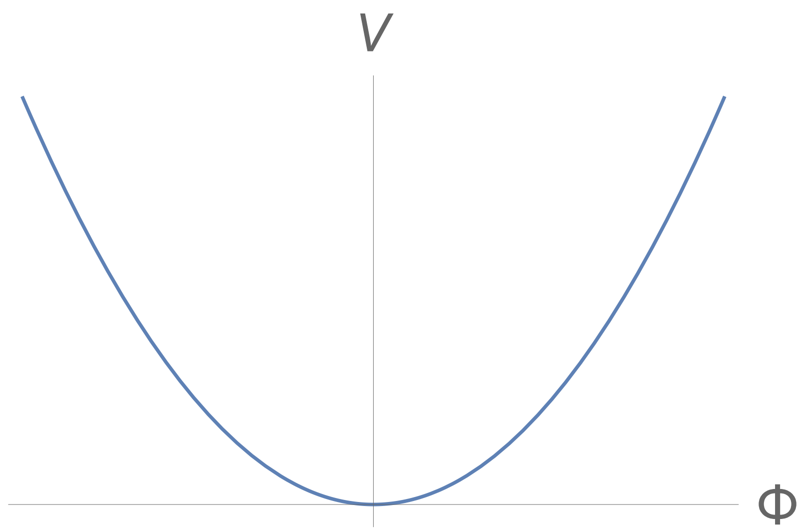
$U(1)_{PQ}$ explicitly broken

σ in this talk is a generic ALP, not the QCD axion.



Axion dark matter - 1

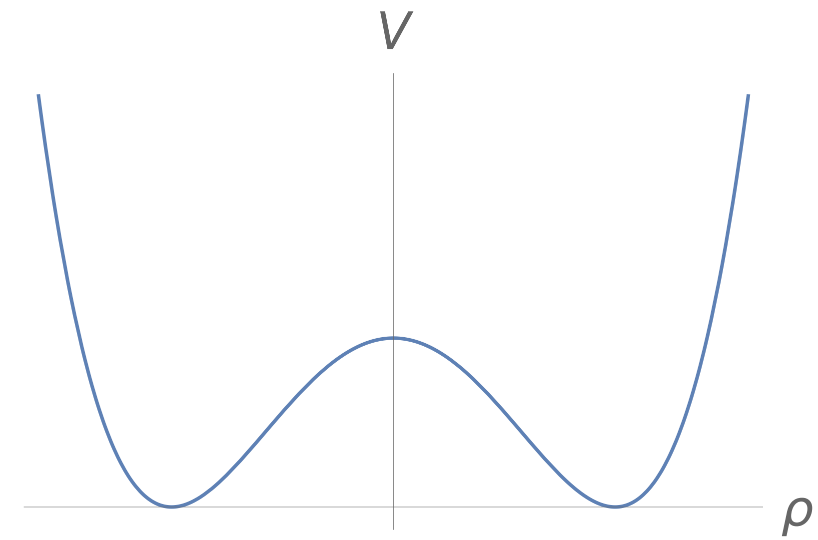
$$T_{\mathrm{RH}} > f$$



PQ phase transition

$\longrightarrow$

$T \sim f$

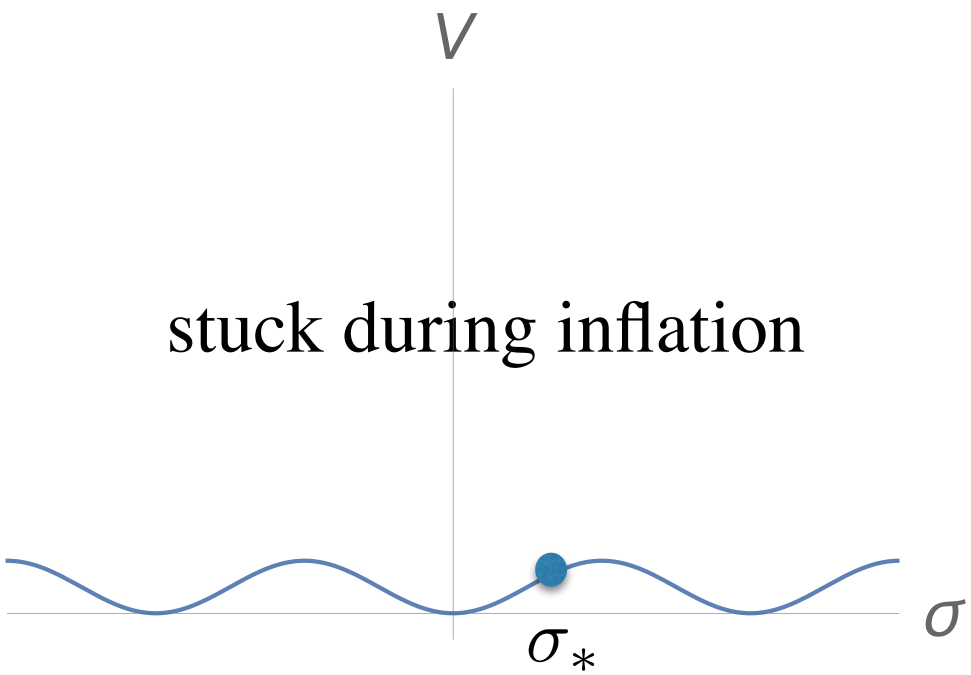


Relic axions from misalignment and from axionic strings

Abundance calculable in principle, technically difficult in practice

Axion dark matter - 2

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



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

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

θ_* incalculable

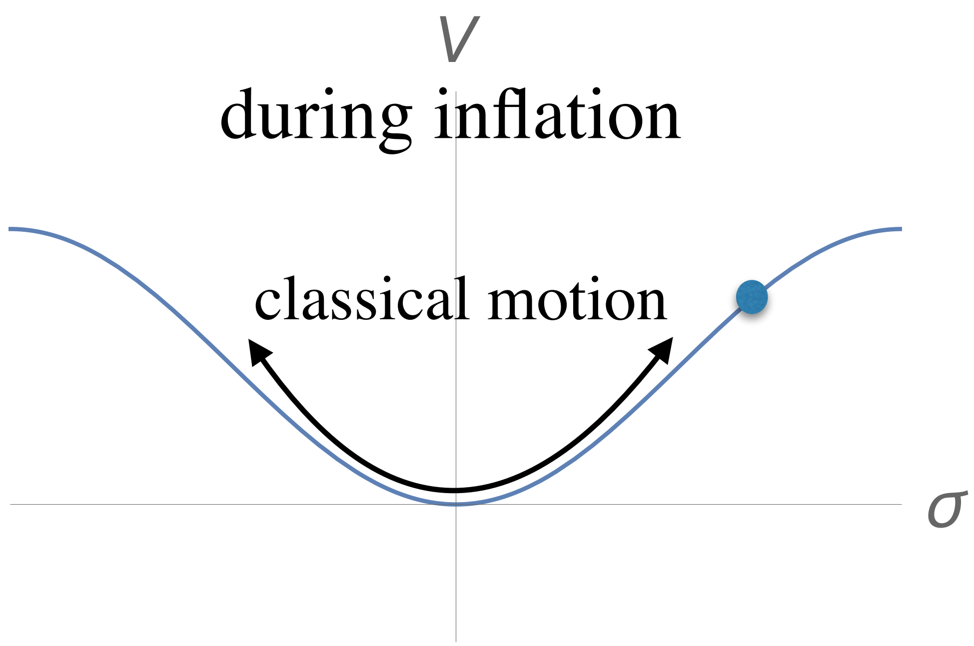
Starts oscillating when $$H \approx \frac{T^2}{M_P} \approx m_\sigma$$

The energy density of the coherent oscillating field redshifts like matter

$$\Omega_\sigma \sim 0.1 \times \left(\frac{\theta_\star f}{10^{17}\,\mathrm{GeV}}\right)^2 \left(\frac{m_\sigma}{10^{-22}\,\mathrm{eV}}\right)^{1/2}$$

Axion dark matter - 3

$$H_I \ll m_\sigma \ll \sqrt{m_\sigma f} \ll f$$

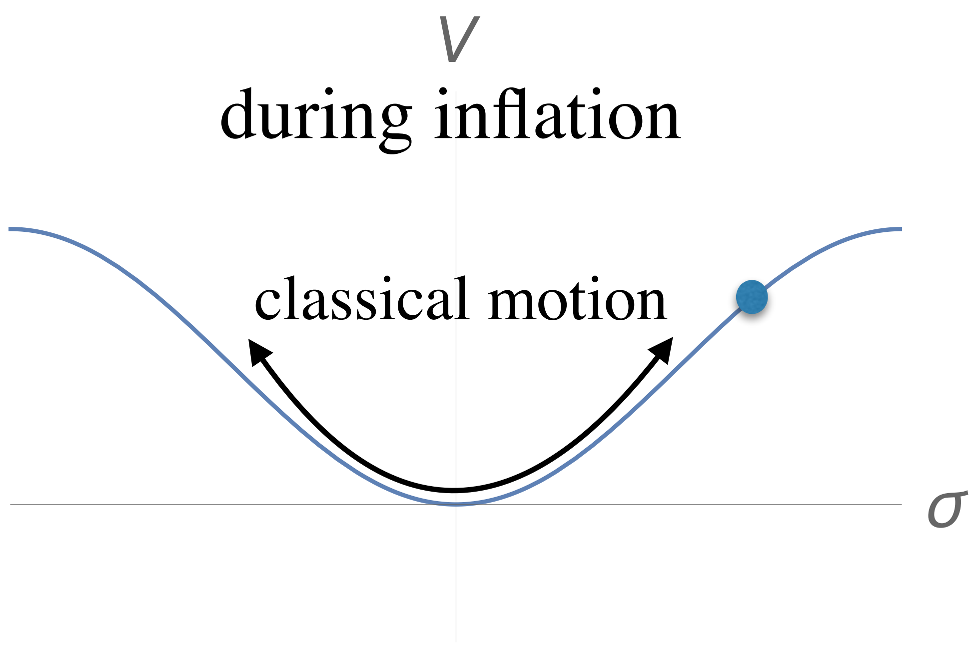


$$\ddot{\sigma} + 3H\dot{\sigma} + m_\sigma^2 \sigma = 0$$

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

Axion dark matter - 3

$$H_I \ll m_\sigma \ll \sqrt{m_\sigma f} \ll f$$



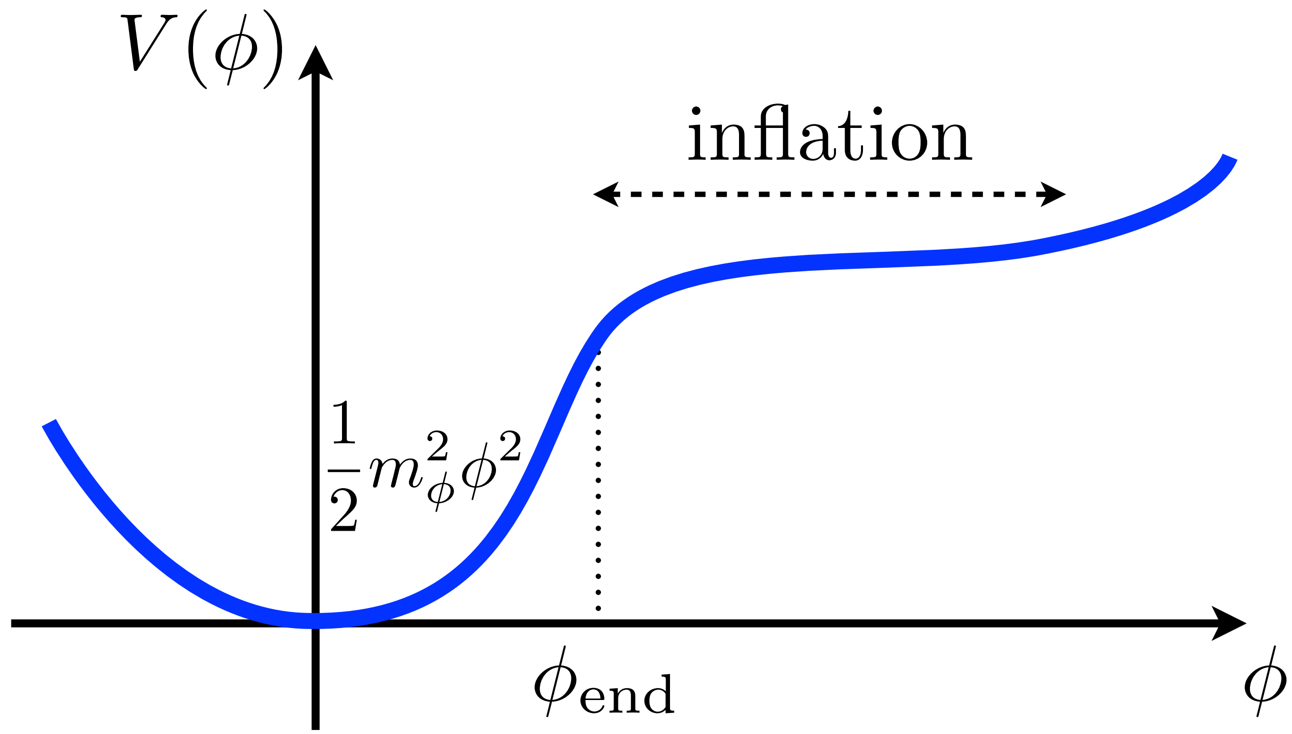
$$\ddot{\sigma} + 3H\dot{\sigma} + m_\sigma^2 \sigma = 0$$

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

No axion dark matter

But

What drives inflation?



Why wouldn't the inflaton and the axion couple?

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

Kinetic mixing

Exact equations of motion

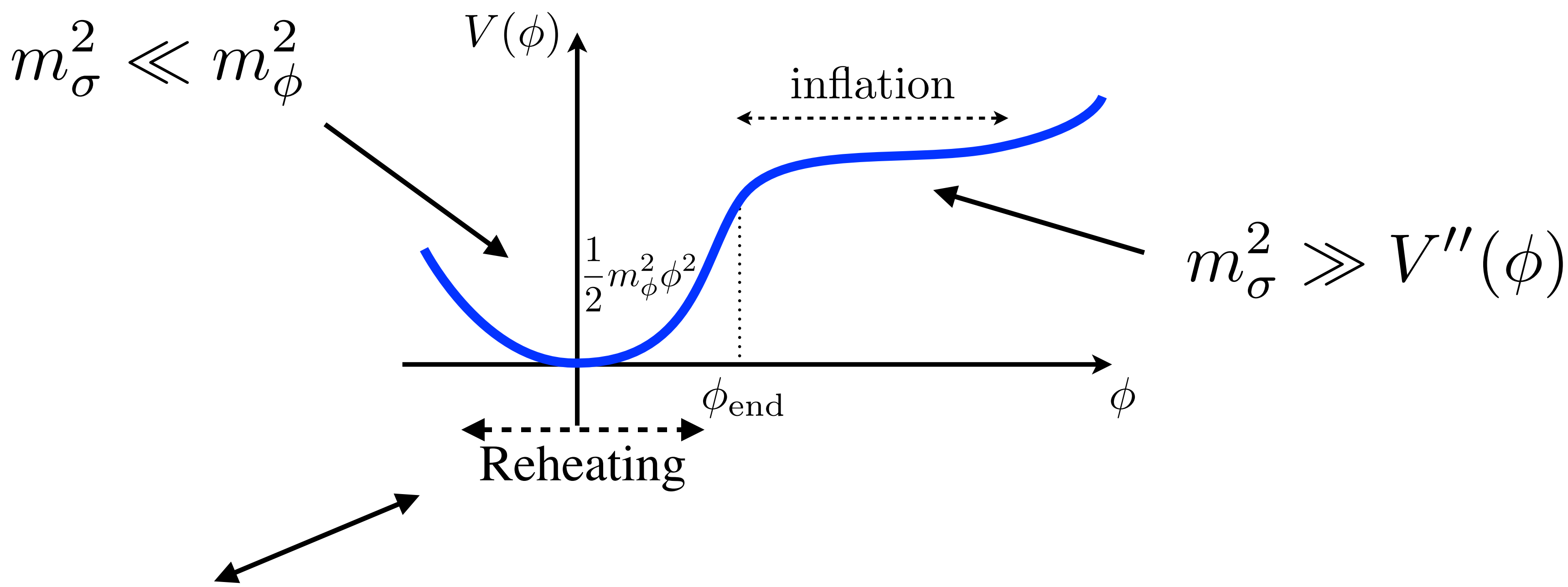
$$(1-\alpha^2)(\ddot{\sigma}+3H\dot{\sigma}) = \alpha V'(\phi) - m_\sigma^2\sigma,$$
$$(1-\alpha^2)(\ddot{\phi}+3H\dot{\phi}) = -V'(\phi) + \alpha\, m_\sigma^2\sigma$$

Attractor: $\dot{\sigma} = \ddot{\sigma} = 0$

$$\sigma = \frac{\alpha V'(\phi)}{m_\sigma^2}$$

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0 \quad \rightarrow \quad \dot{\phi} \approx -\frac{V'(\phi)}{3H}$$

Single field inflation



Diagonal basis

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

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

$$\ddot{\varphi}_i + 3H\dot{\varphi}_i + m_i^2\varphi_i = 0$$

Reheating

$$\frac{G_{\phi\gamma\gamma}}{4}\phi F\tilde{F}$$

Due to kinetic mixing, the axion also has a decay channel

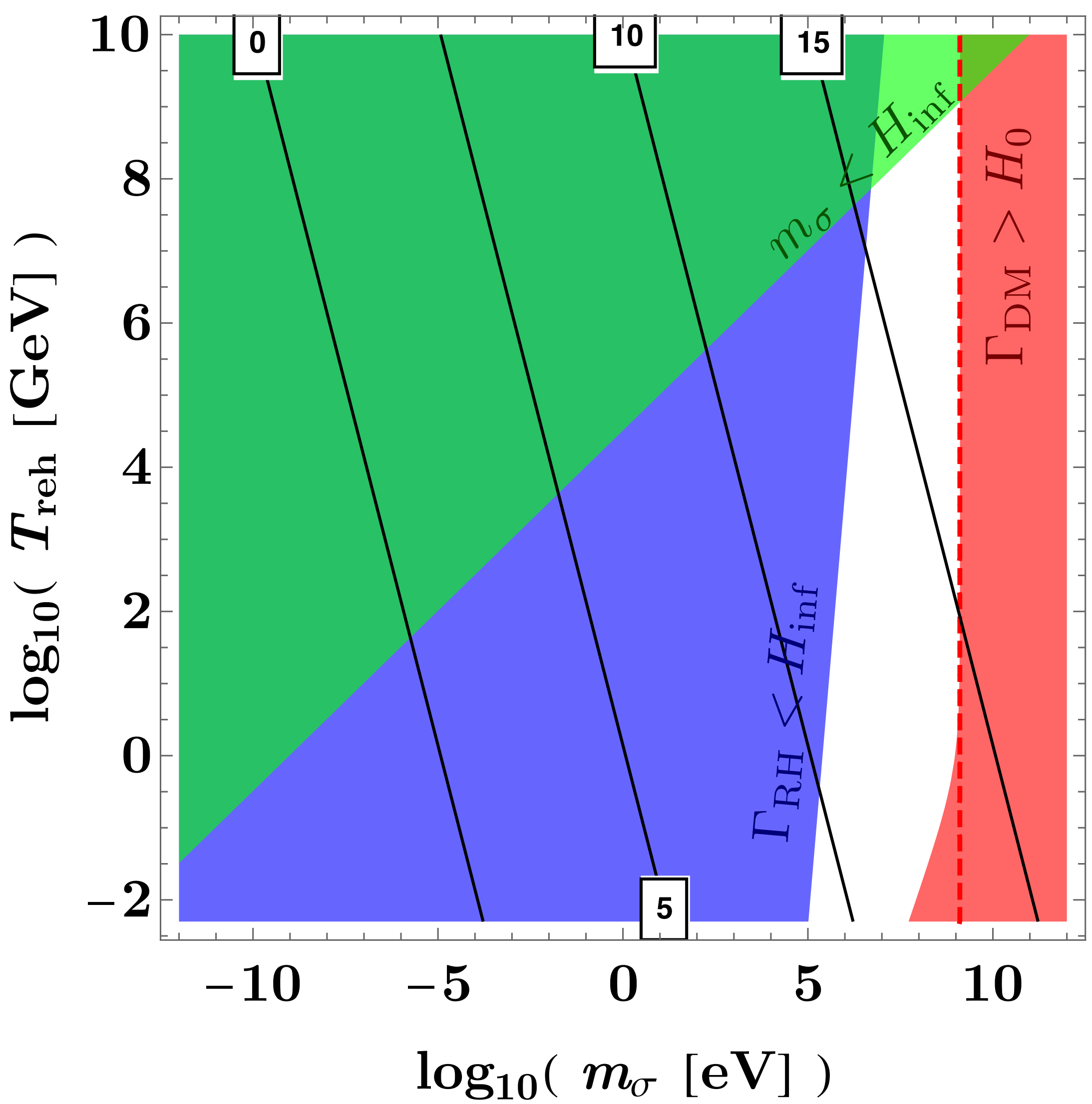
$$\Gamma(\varphi_{\rm DM}\to\gamma\gamma)\simeq\alpha^2\frac{G^2_{\phi\gamma\gamma}}{64\pi}\frac{m_\sigma^7}{m_\phi^4},\quad \Gamma(\varphi_{\rm RH}\to\gamma\gamma)\simeq\frac{1}{(1-\alpha^2)^{5/2}}\frac{G^2_{\phi\gamma\gamma}}{64\pi}m_\phi^3$$

$$3M_p^2\Gamma^2_{\rm RH}=3M_p^2H^2_{\rm reh}=\frac{\pi^2}{30}g_*(T_{\rm reh})\,T^4_{\rm reh}$$

Final relic abundance

$$\Omega_{\rm DM}\simeq\frac{C^2\alpha^2}{6}\frac{m_\sigma^2}{m_\phi^2}\frac{H^2_{\rm reh}}{H_0^2}\frac{s_0}{s_{\rm reh}}\sim 10^{-2}\,\alpha^2\frac{m_\sigma^2}{m_\phi^2}\left(\frac{H_{\rm reh}}{H_0}\right)^{1/2}$$

Parameter space



$$\alpha = 1/2\,, \quad f = 10^{17}\ \text{GeV}$$

$$G_{\phi\gamma\gamma} = 10^{-10}\ \text{GeV}^{-1}$$

Assumptions and constraints

$$\Gamma_{\rm RH} > H_{\rm end} \quad \Rightarrow \quad H_{\rm reh} = H_{\rm end}$$

Instantaneous reheating

$$4\ \text{MeV} < T_{\rm reh} < f$$

$$\Gamma_{\rm DM} < H_0$$

Long lived DM

Conclusions

An axion which mixes kinetically with the inflaton can provide a good dark matter candidate even if the scale of inflation is low.

The mechanism can also work for the QCD axion. Work in progress …