QCD axion cosmology with natural initial conditions

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QCD Axion

- Elegant solution to the strong CP problem:

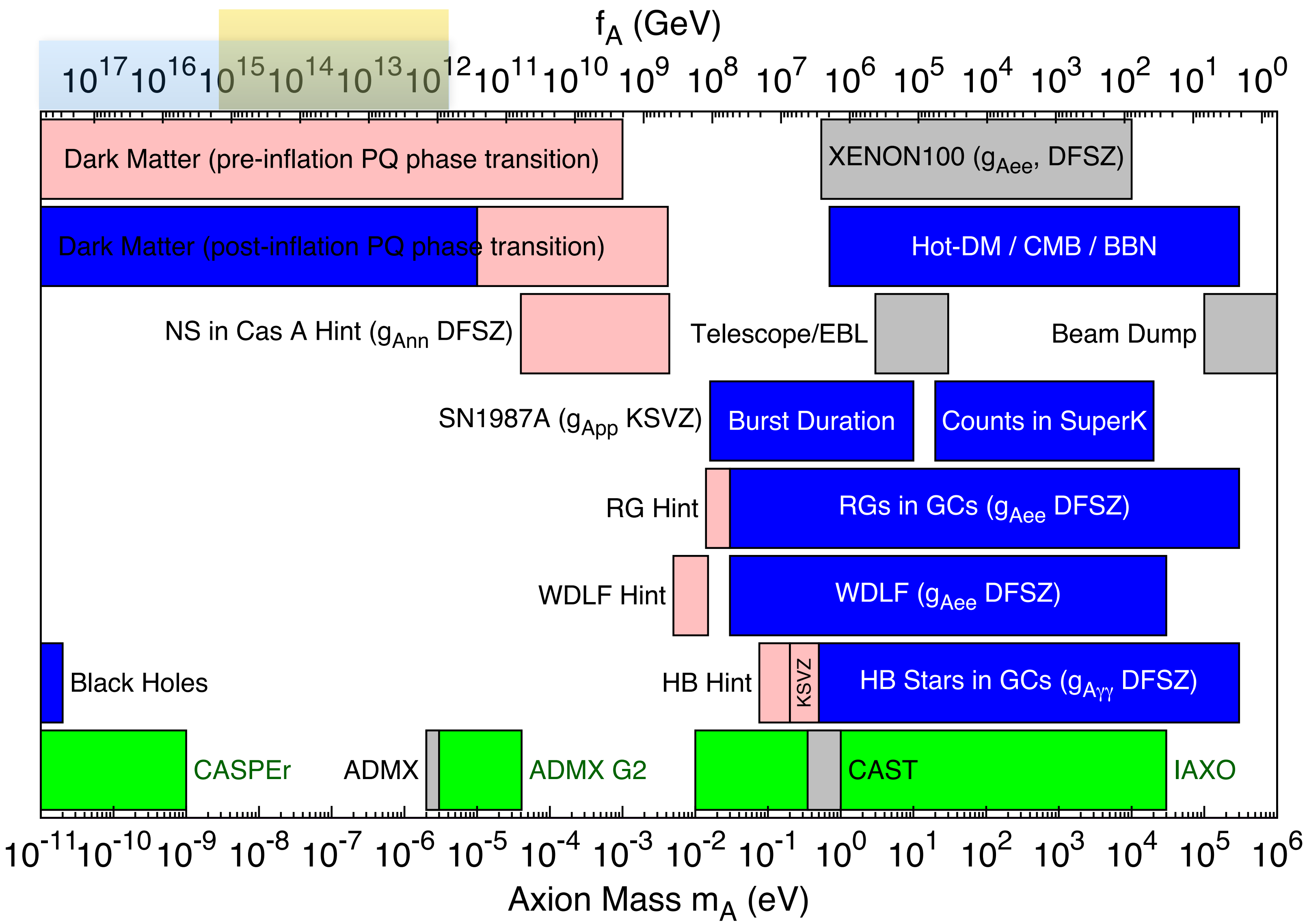
$$\mathcal{L}_{SM} \supset u^c M_u u + d^c M_d d + h.c. + \frac{\alpha_s \theta}{8\pi} G^{a\,\mu\nu} \tilde{G}^a_{\mu\nu}$$

$$\bar{\theta} = \theta + \mathrm{Arg}\, det(M_u M_d) \lesssim 10^{-10}$$

- Dark matter candidate (non-thermally produced)

QCD Axion

$$m_a \approx \frac{m_\pi f_\pi}{f_a}$$



Outline

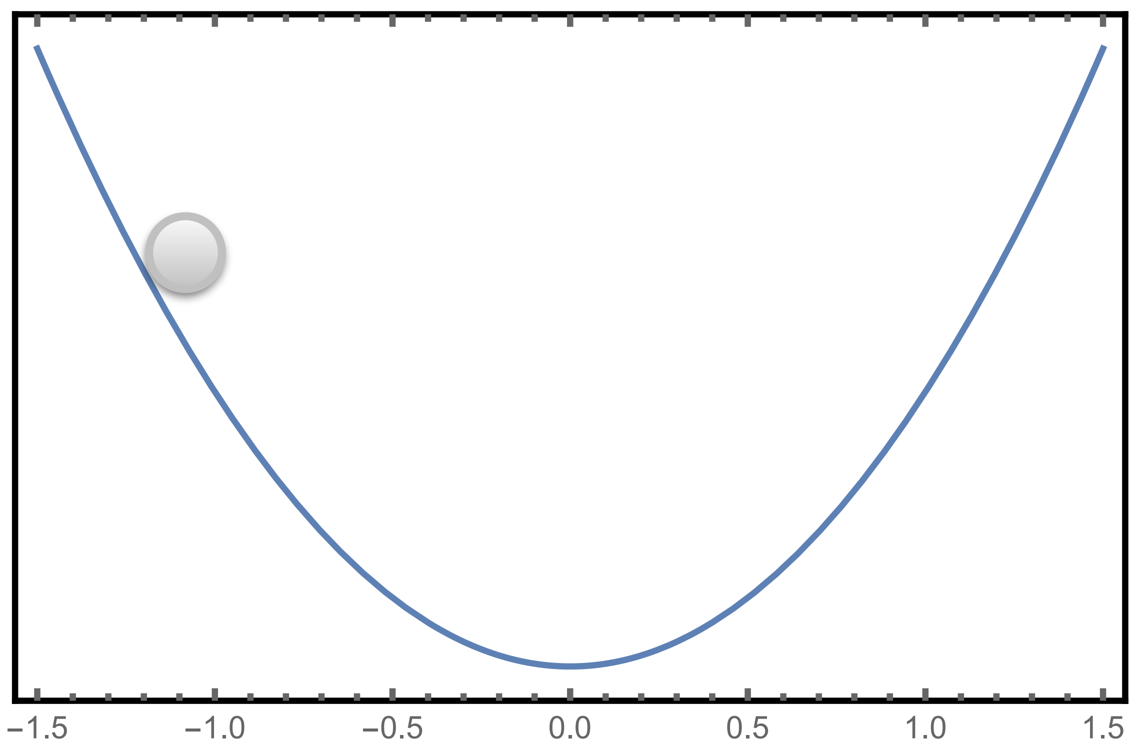
- Axion DM overview
- Dynamical mechanisms to change axion density
  - Entropy Injection
  - Particle production
- Conclusions and remarks

Axion condensate as CDM

Peccei-Quinn symmetry broken
during inflation

$$\phi(x) = \phi_0$$

Axion condensate as CDM

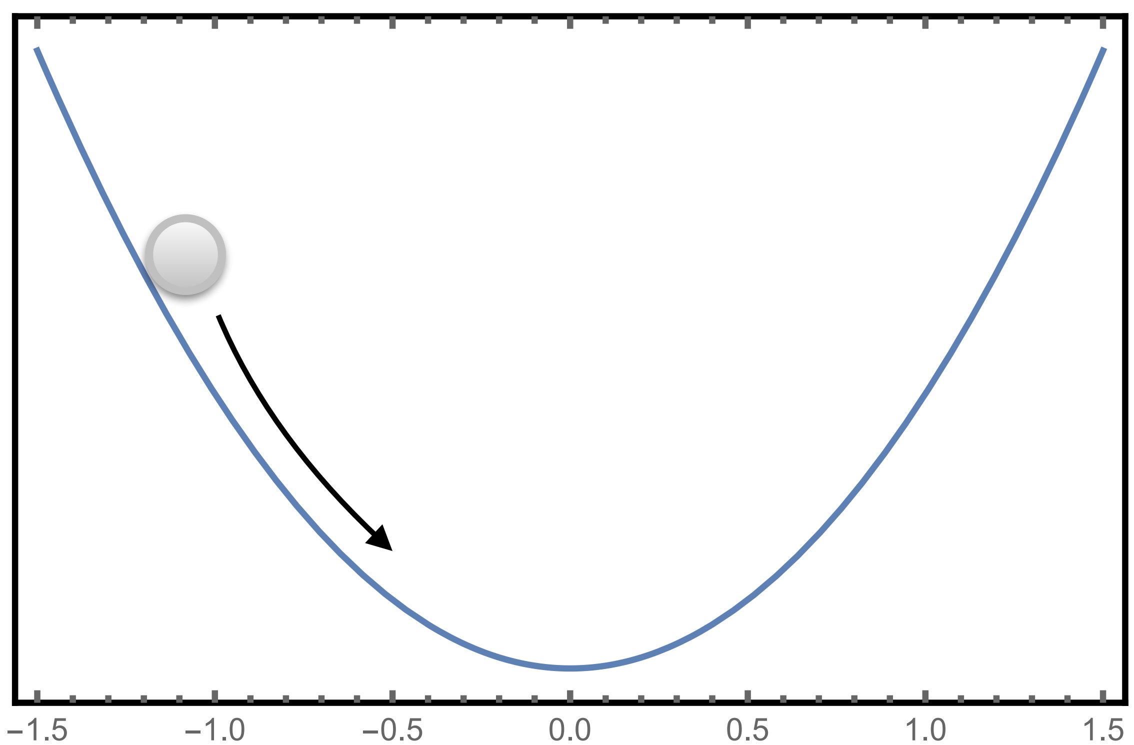


$$\ddot{\phi}(t) + 3H\dot{\phi}(t) = -m_a^2\phi(t)$$

While $H > m_a$

$$\phi = \theta_0 \, f_a \approx \mathrm{const}$$

Axion condensate as CDM



$$\ddot{\phi}(t) + 3H\dot{\phi}(t) = -m_a^2\phi(t)$$

Once $\quad H < m_a$

$$\phi(t) \approx \frac{\theta_0\, f_a\, \cos(m_a t)}{a(t)^{3/2}}$$

$$\rho_a \approx \frac{1}{2}\frac{m_a^2 f_a^2\, \theta_0^2}{a(t)^3} \longrightarrow \sim \frac{m_\pi^2 f_\pi^2 \theta_0^2}{a(t)^3}$$

Axion condensate as CDM

$$H \approx \frac{T^2}{M_p}$$

$$m_a = \frac{m_\pi f_\pi}{f_a} \approx \frac{(100\,\mathrm{MeV})^2}{f_a}$$

Axion condensate as CDM

$$H \approx \frac{T^2}{M_p} \qquad\qquad m_a = \frac{m_\pi f_\pi}{f_a} \approx \frac{(100\,\mathrm{MeV})^2}{f_a}$$

Very large f_a , $f_a \sim M_p$, axion starts rolling when:

$$T \sim \Lambda_c \sim 100\,\mathrm{MeV}$$

$$\left.\begin{aligned} &\rho_{\mathrm{rad}} \sim T^4 \\ &\rho_{\mathrm{a}} \sim m_a^2 \phi_0^2 \sim m_\pi^2 f_\pi^2 \theta_0^2 \end{aligned}\right\}$$

Matter-radiation eq
before BBN if

$$\theta_0 \sim 1$$

Axion abundance

$$m_a(T) = 5.7\,\mu eV \left(\frac{10^{12}\,\mathrm{GeV}}{f_a}\right) \times \begin{cases} c\left(\frac{T}{\Lambda_{QCD}}\right)^{-n}, & T \gtrsim 1\ \mathrm{GeV} \\ 1\,, & T < \Lambda_{QCD} \end{cases}$$

For concreteness take: $c = 0.02 \quad n = 4$

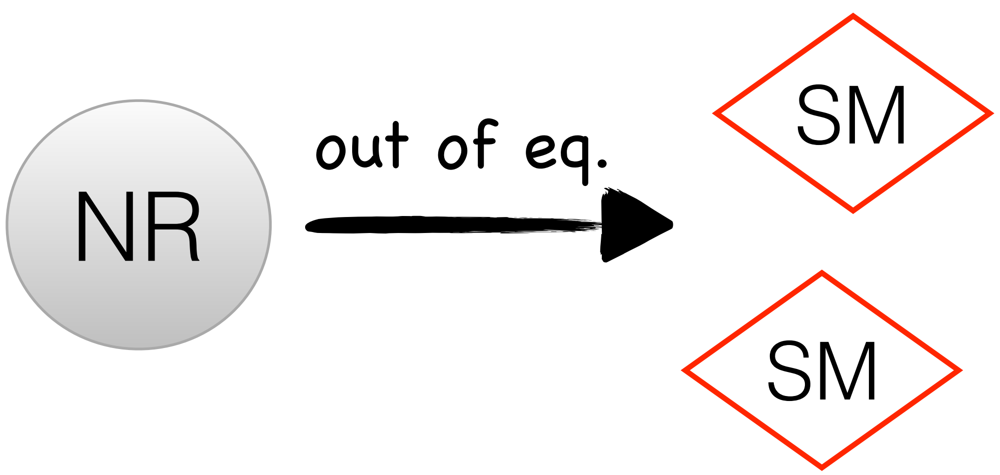
$$\Omega_a h^2 \sim \begin{cases} 0.4\ \left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^{7/6} \theta_0^2\,, & f_a \lesssim 10^{15}\,\mathrm{GeV} \\ 1.5 \times 10^6 \left(\frac{f_a}{10^{17}\,\mathrm{GeV}}\right)^{3/2} \theta_0^2\,, & f_a \gtrsim 10^{17}\,\mathrm{GeV} \end{cases}$$

$$f_a \sim 10^{17}\,\mathrm{GeV} \ \Rightarrow \theta_0 \sim 10^{-3.5}$$

How to change the axion abundance?

Entropy injection

Dilute axion energy density through late entropy dump



$$\rho_x > \rho_r \Rightarrow H \approx \frac{\sqrt{\rho_x}}{M_p}$$

$$\boxed{\left(\frac{\rho_a}{\rho_r}\right)_{\mathrm{BBN}} \gtrsim \left(\frac{f_a}{M_p}\right)^2 \theta_0^2}$$

$\theta_0 \sim 1$

$f_a \sim 10^{15}$ GeV

$T_{\mathrm{decay}} \sim 5\,\mathrm{MeV}$

Entropy injection

Entropy dump: ρ_{axion} ρ_{SM}

Decrease $\dfrac{\rho_a}{\rho_{\mathrm{SM}}}$

New mechanism

Entropy dump:

ρ_{axion}

ρ_{SM}

ρ_{axion}

ρ_{SM}

Model

$$\mathcal{L} \supset \frac{\alpha_s \phi}{8\pi f_a} G^{a\mu\nu} \tilde{G}^a_{\mu\nu} + \frac{\phi}{4 f_d} F^{\mu\nu} \tilde{F}_{\mu\nu}$$

dark photon

Model

$$\mathcal{L} \supset \frac{\alpha_s \phi}{8\pi f_a} G^{a\mu\nu} \tilde{G}^a_{\mu\nu} + \frac{\phi}{4 f_d} F^{\mu\nu} \tilde{F}_{\mu\nu}$$

Particle production: use time dependence of ϕ

$$A''_\pm + \underbrace{\left(k^2 \mp \frac{k\,\phi'}{f_d}\right)}_{\Omega_k^2(\phi')} A_\pm = 0$$

$$\phi' \approx \text{const} \;\Rightarrow\; A(k \sim \phi'/f_d) \sim e^{\frac{\phi'}{f_d}\tau}$$

Model

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Particle production: use time dependence of ϕ

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No plasma effect

$$\phi' \approx \text{const} \;\; \Rightarrow \;\; A(k \sim \phi'/f_d) \sim e^{\frac{\phi'}{f_d}\tau}$$

Particle Production

$$\ddot{A}_\pm + H\dot{A}_\pm + \underbrace{\left(\frac{k^2}{a^2} \mp \frac{k\dot{\phi}}{af_d}\right)}_{\tilde{\Omega}_k^2 = \Omega_k^2/a^2} A_\pm = 0$$

$$dt = a d\tau$$
$$(a \propto \tau)$$

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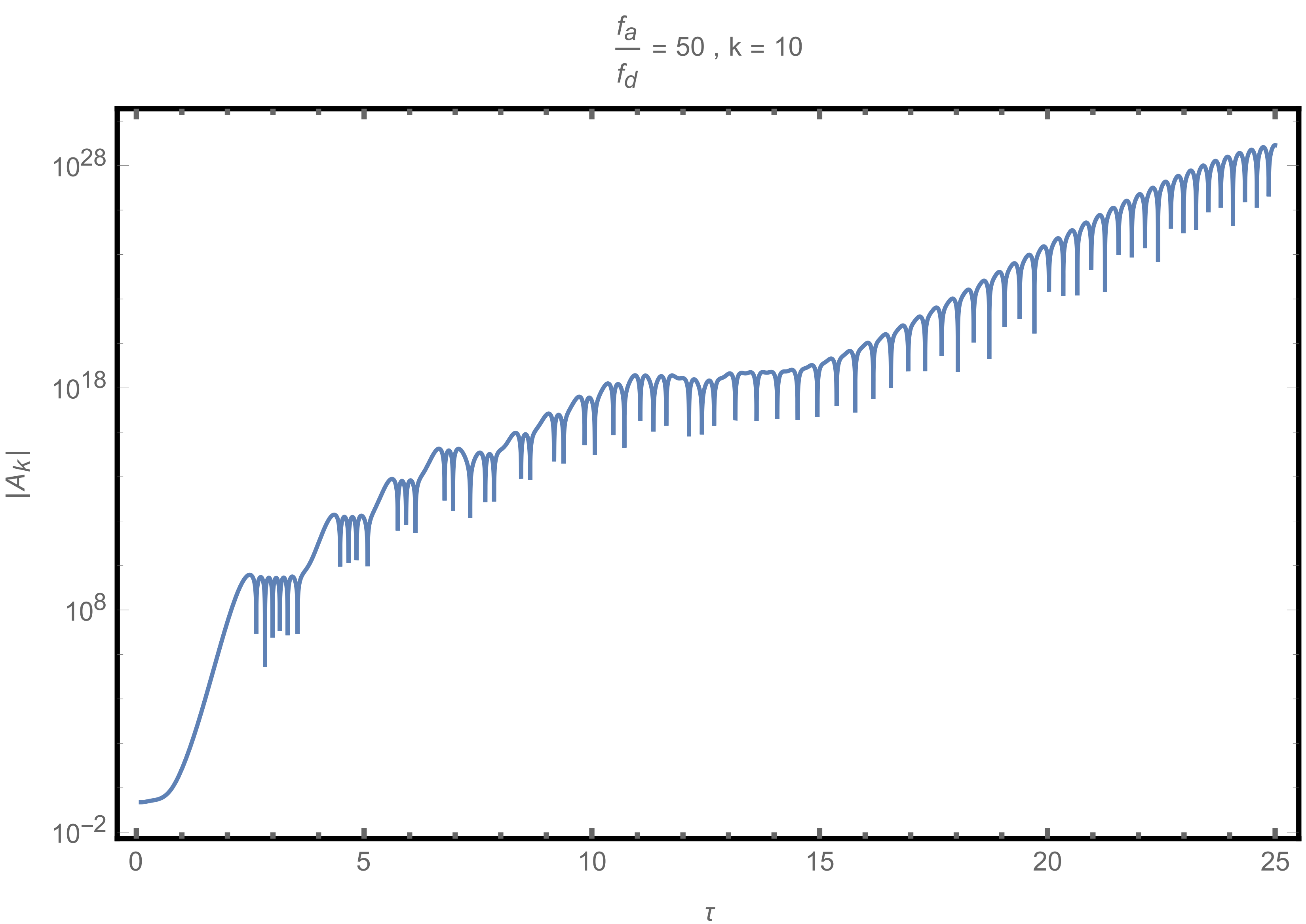
$$A''_\pm + \left(k^2 \mp \frac{k\,\phi'}{f_d}\right) A_\pm = 0$$

Ignore feedback: $$\phi \approx \frac{\theta_0\, f_a \cos(m_a t)}{a^{3/2}} = \frac{\theta_0\, f_a \cos(a\, m_a \tau/2)}{a^{3/2}}$$

$$\min\left(\frac{k^2}{a^2} \mp \frac{k\dot{\phi}}{a\, f_d}\right) = -\left(\frac{\dot{\phi}}{2f_d}\right)^2$$

$$|\tilde{\Omega}_k| \lesssim \frac{\theta_0\, m_a\, f_a}{2\, f_d}\,(a_i/a)^{3/2}$$

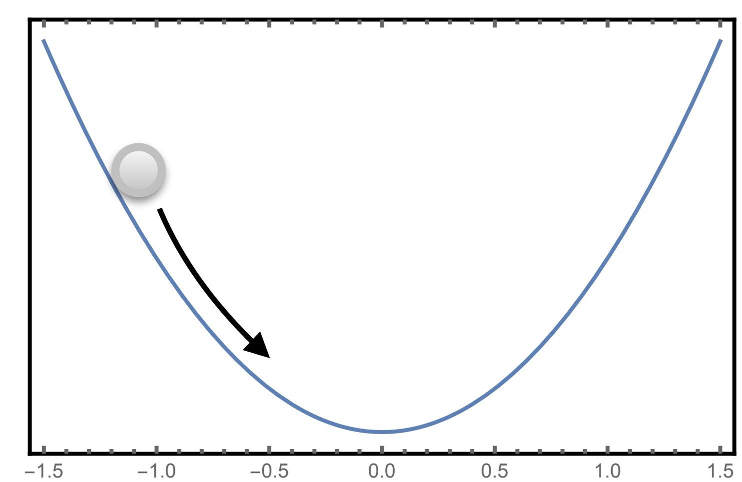
Particle Production



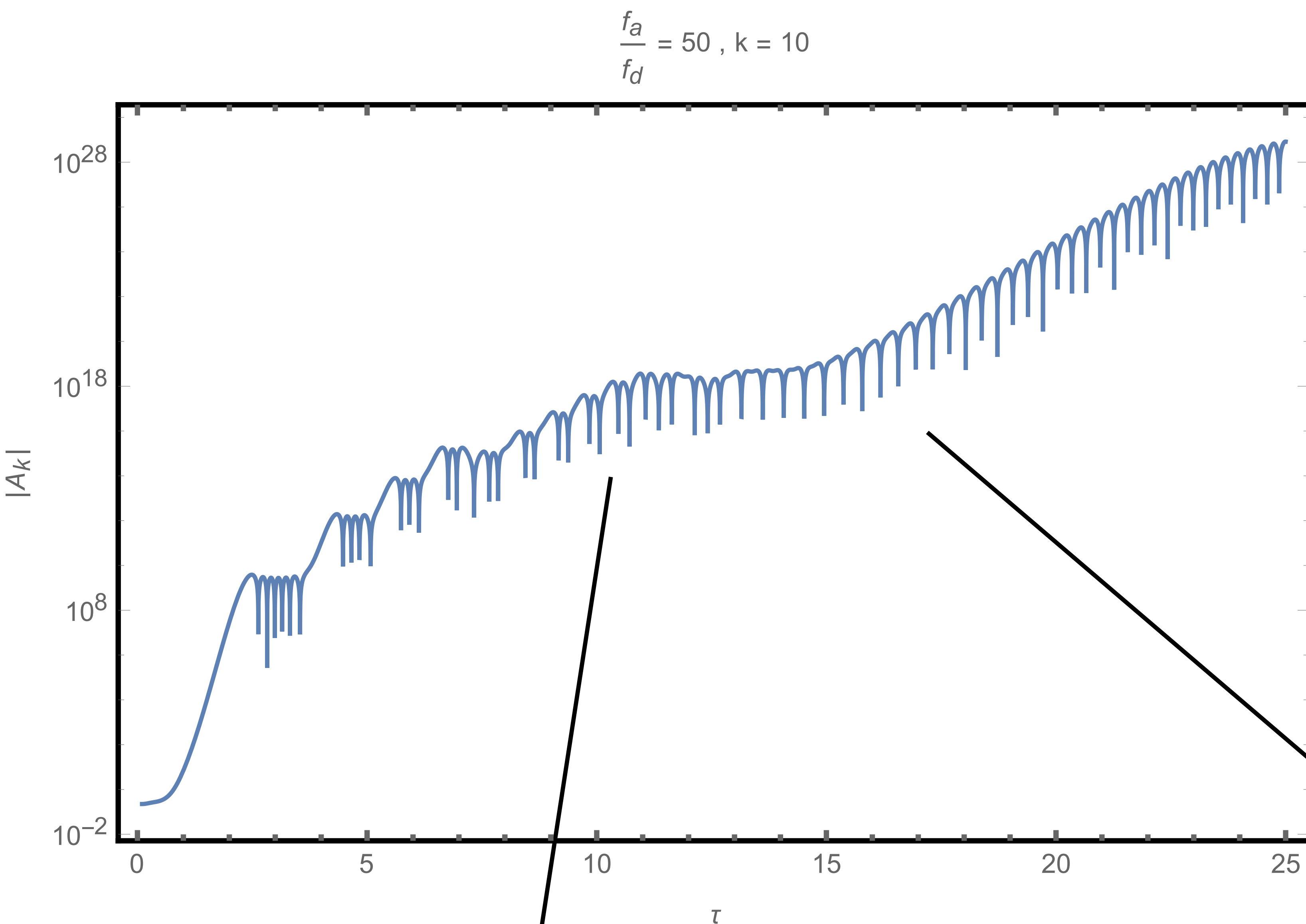
$$A''_{\pm} + \left(k^2 \mp \frac{k\,\phi'}{f_d}\right) A_{\pm} = 0$$

$$|\tilde{\Omega}_k| \lesssim \frac{\theta_0\, m_a\, f_a}{2\, f_d\, a^{3/2}}$$

$$\cos(mt) = \cos(m^2\tau^2/2)$$



Particle Production



$$A''_{\pm} + \left(k^2 \mp \frac{k\,\phi'}{f_d}\right) A_{\pm} = 0$$

$$|\tilde{\Omega}_k| \lesssim \frac{\theta_0\, m_a\, f_a}{2\, f_d\, a^{3/2}}$$

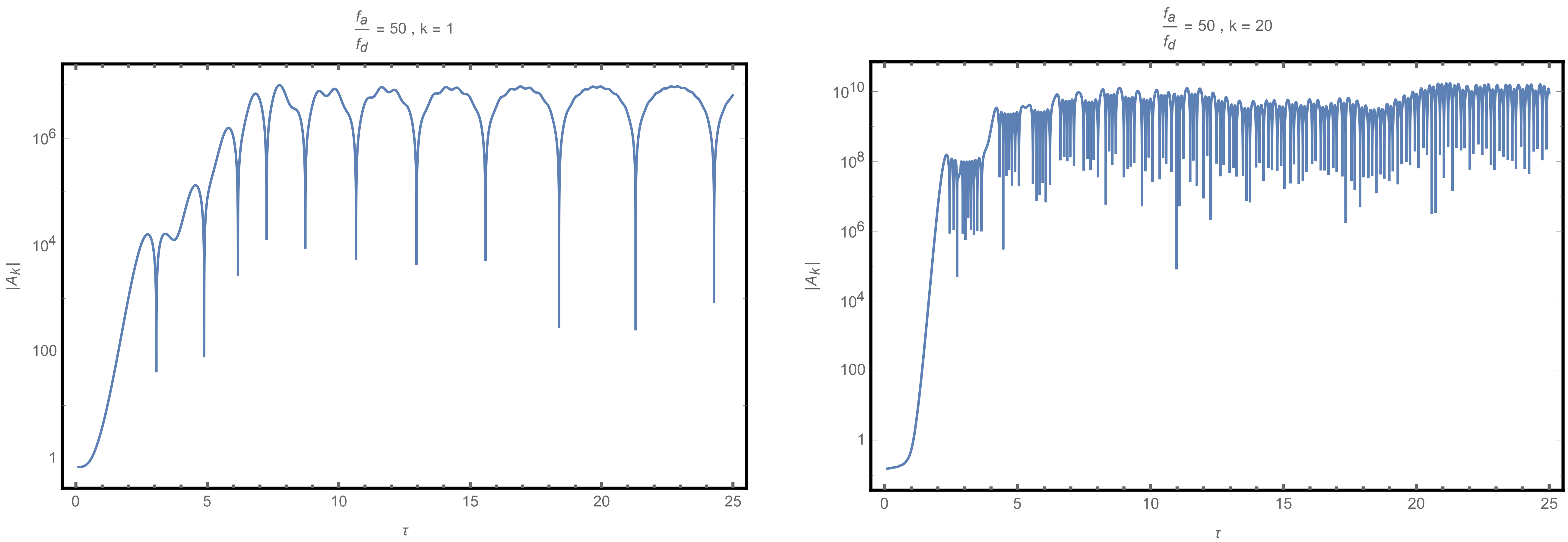
$$\frac{f_a}{2\, f_d\, a^{3/2}} \lesssim 1 \;\Rightarrow\; a \sim 10$$

Parametric Resonance

$$\phi \propto \cos(\tau^2/2)$$
$$\omega_\phi \sim \tau$$

Particle Production

$$\Omega_k^2 = k^2 \mp \frac{k\,\theta_0\, m_a\, f_a\, \sin(m^2\tau^2/2)}{f_d a^{1/2}}$$



$$k_* \sim \frac{1}{q}\,\frac{f_a}{f_d}\, m_a$$

Include feedback

$$\phi'' + 2aH\phi' + a^2m^2\phi = \frac{a^2}{4f_d}F^{\mu\nu}\tilde{F}_{\mu\nu}$$

$$A''_{\pm} + (k^2 \mp \frac{k\phi'}{f_d})A_{\pm} = 0$$

Include feedback

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Will use Hartree approximation: $\frac{1}{4}F^{\mu\nu}\tilde{F}_{\mu\nu} \to \langle \vec{E}\cdot\vec{B}\rangle$

$$\vec{A}(\tau,\vec{x}) = \sum_{\lambda=\pm}\int \frac{d^3k}{(2\pi)^{3/2}}\left[\vec{\epsilon}_\lambda(\vec{k})b_\lambda(k)A_\lambda(\tau,k)e^{i\vec{k}\cdot\vec{x}} + \mathrm{h.c.}\right]$$

$$[b_\lambda(\vec{k}),\, b^\dagger_{\lambda'}(\vec{k}')] = \delta_{\lambda\,\lambda'}\,\delta^{(3)}(\vec{k}-\vec{k}')$$

$$A_\lambda(\tau \ll m_a, k) \to \frac{e^{-ik\tau}}{\sqrt{2k}}$$

Include feedback

$$\phi'' + 2aH\phi' + a^2m^2\phi = \frac{a^2}{f_d}\langle\vec{E}\cdot\vec{B}\rangle$$

$$A''_\pm + (k^2 \mp \frac{k\phi'}{f_d})A_\pm = 0$$

$$\langle\vec{E}\cdot\vec{B}\rangle = -\frac{1}{2a^4}\int \frac{d^3k}{(2\pi)^3}|\vec{k}|\frac{\partial}{\partial\tau}\left(|A_+|^2 - |A_-|^2\right)$$

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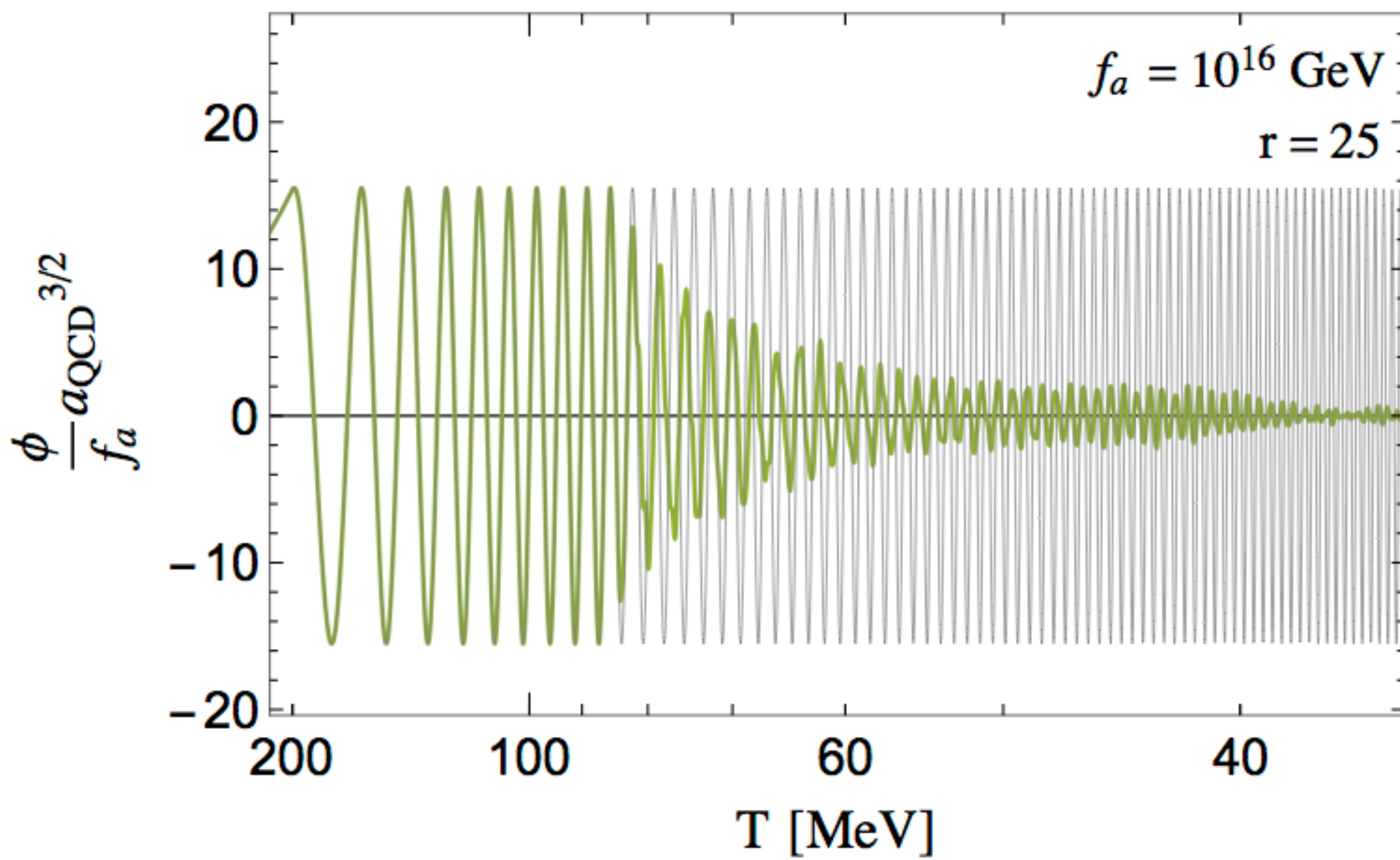
Affects axion once:

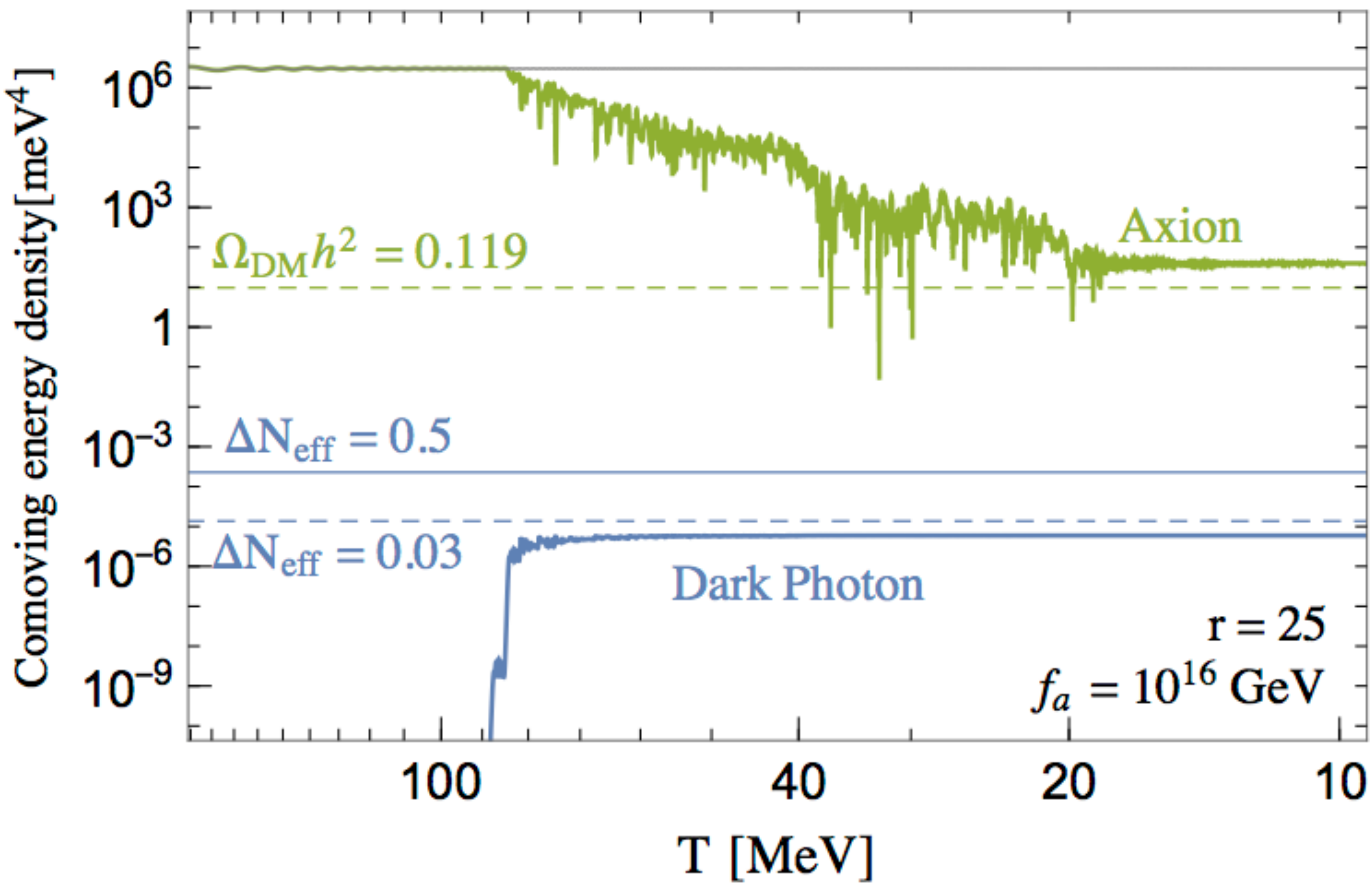
$$\frac{k^4}{f_d a^4}\frac{|A_\lambda|^2}{|A_\lambda(\tau_0)|^2} \sim m_a^2 f_a \frac{\theta_0}{a^{3/2}} \quad \Rightarrow \quad \frac{|A_\lambda|^2}{|A_\lambda(\tau_0)|^2} \sim \frac{f_a f_d}{m_a^2}$$

Numerical results

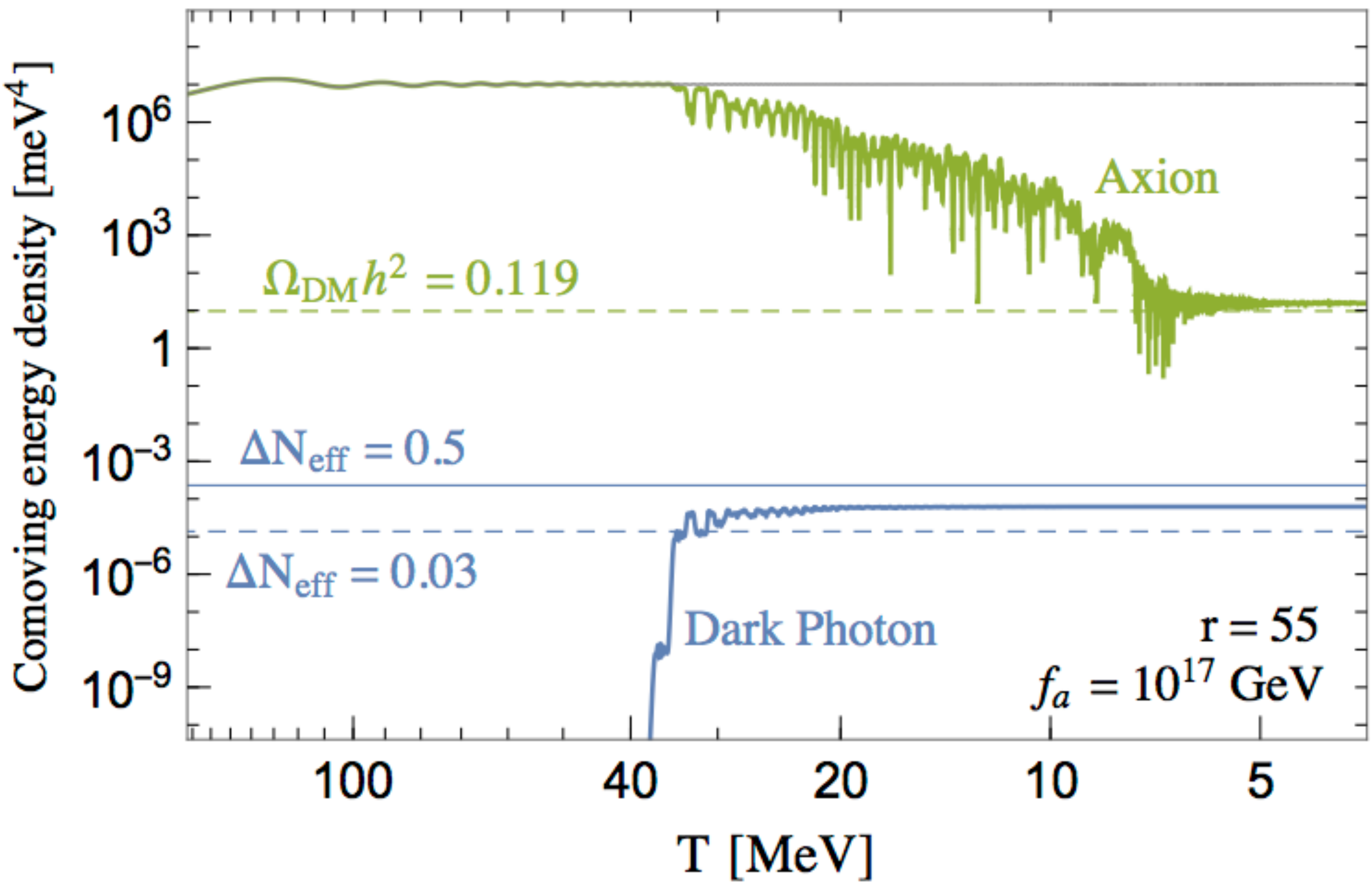


$r = f_a/f_d$

Numerical results



Numerical results



Conclusions

- Particle production can change relic density of axions (also of other ALPs)

- Axions with f_a up to 10^{17} GeV and order one misalignment are allowed. Axion must couple more strongly to a dark sector than to SM $(\sim \times 10^3)$

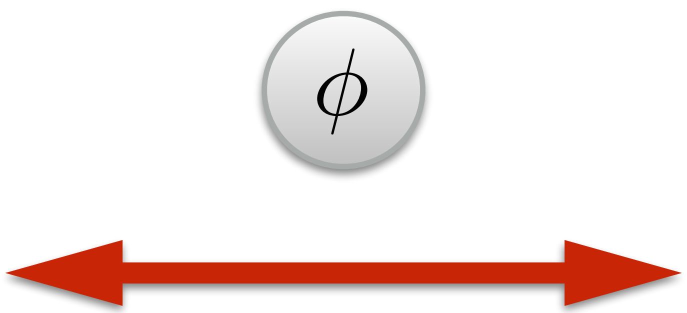
- Relaxes isocurvature perturbation constraints*

- Potentially testable through other effects
  - N_{eff}
  - LSS (*to be seen)*

extra material

Isocurvature Constraints

During Inflation



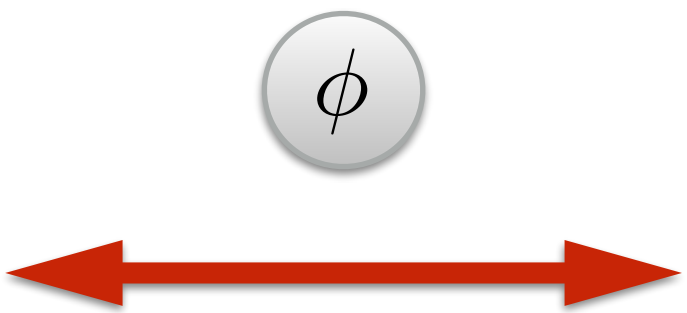
$$\delta\phi \sim H_I$$

Locally

$$\frac{\delta\theta}{\theta} \sim \frac{H_I/f_a}{\theta_0}$$

Isocurvature Constraints

During Inflation



$$\delta\phi \sim H_I$$

Locally

$$\frac{\delta\theta}{\theta} \sim \frac{H_I/f_a}{\theta_0}$$

Isocurvature Constraints

$$\left(\frac{\delta T}{T}\right)_{\rm iso} \sim \frac{H_I/f_a}{\theta_0} \lesssim 10^{-6}$$

$$H_I \lesssim 10^{-6}\underline{\theta_0} f_a$$