



# WIMP Meets ALP: Coherent Freeze-out of Dark Matter

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S. Ferrante, MP, B. Yu, arXiv:2511.16731, Phys. Rev. Lett. 136, 201004 (2026)

S. Ferrante, L. Luo, MP, B. Yu, arXiv:2608.xxxxx

# WIMP Meets ALP

- WIMP and ALP are two best-known particle dark matter candidates
- Weakly-Interaction Massive Particle (WIMP): mass  $\sim 100$  GeV, annihilation cross section  $\sim 1$  pb. Thermal relic, present density set by freeze-out at  $T \sim m/10$ .
- Axion-Like Particle (ALP): light (pseudo-)scalar, mass  $\ll 100$  GeV, interactions suppressed by scale  $\gg 100$  GeV. Present density set by misalignment mechanism.
- What if both a WIMP and an ALP are present in the fundamental Lagrangian?

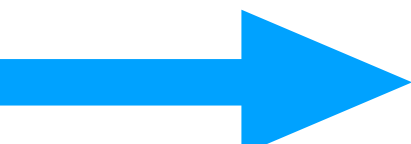
# Setup

- Consider a fermion WIMP  $\chi$  and a (pseudo-)scalar ALP  $\phi$  coupled via

$$\mathcal{L}_{\text{eff}} \supset \frac{1}{\Lambda} \bar{\chi} \chi \frac{\phi^2}{2} \quad \Lambda \gg m_\chi \gg m_\phi$$

- Motivation for this coupling: QCD axion coupling to nucleons

- Non-linear sigma-model contains  $\mathcal{L} \sim \frac{m_q}{f_\pi^2} \pi^2 \bar{N} N$

- Pion-axion mixing:  $\pi \rightarrow \pi + \frac{f_\pi}{f_a} a$    $\mathcal{L} \sim \frac{1}{\Lambda} a^2 \bar{N} N$

- This is the leading non-derivative coupling of QCD axion to matter

- Our model: axion  $\rightarrow$  ALP, nucleon  $\rightarrow$  WIMP. (UV completion: Dark QCD)



# Dynamics

- After reheating, WIMP is in equilibrium with the SM plasma, while ALP is not populated

- Coherent forward scattering generates a “plasma mass” for ALP:

$$m_{\phi,\text{eff}}^2 = m_{\phi}^2 - \frac{\langle \bar{\chi}\chi \rangle_T}{\Lambda} \qquad \langle \bar{\chi}\chi \rangle_T = g_{\chi} \int \frac{d^3\mathbf{k}}{(2\pi)^3} \frac{m_{\chi,\text{eff}}}{E_{\mathbf{k}}} f_{\chi}(\mathbf{k})$$

- Negative mass-squared indicates a symmetry breaking for ALP at high temperature. This in turn modifies the mass of the WIMP:

$$m_{\chi,\text{eff}} = \left| m_{\chi} - \frac{\phi^2}{2\Lambda} \right|$$

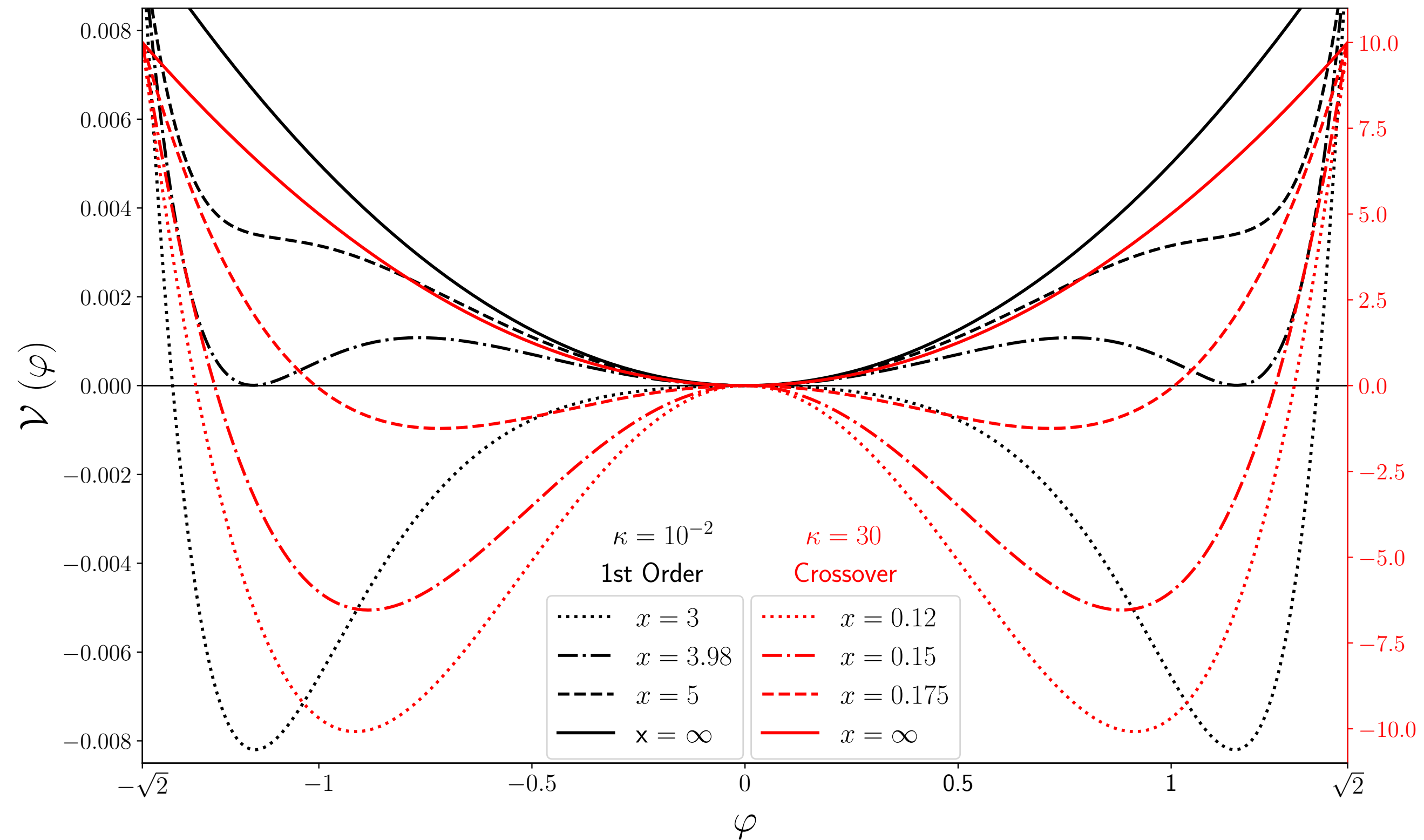
- As the universe expands and T decreases, the evolution of the two sectors is coupled via these effects.



# Inverse Phase Transition

- Coherent forward scattering on WIMP plasma causes the ALP field to get a v.e.v. at high temperature
- As WIMP density decreases, the ALP field undergoes a symmetry-restoring (inverse) phase transition
- Thermodynamic picture:  

$$F = E - TS$$
- Broken-symmetry phase has higher entropy, because **WIMPs are ~ massless** and so relativistic! It is therefore preferred at high T.



$$x \equiv m_\chi/T, \quad \varphi \equiv \phi/\sqrt{m_\chi\Lambda}, \quad \kappa \equiv \frac{2\pi^2}{g_\chi} \frac{m_\phi^2 \Lambda}{m_\chi^3}.$$

# Order of the Phase Transition

- The inverse phase transition can be a smooth cross-over or a first-order phase transition (FOPT).

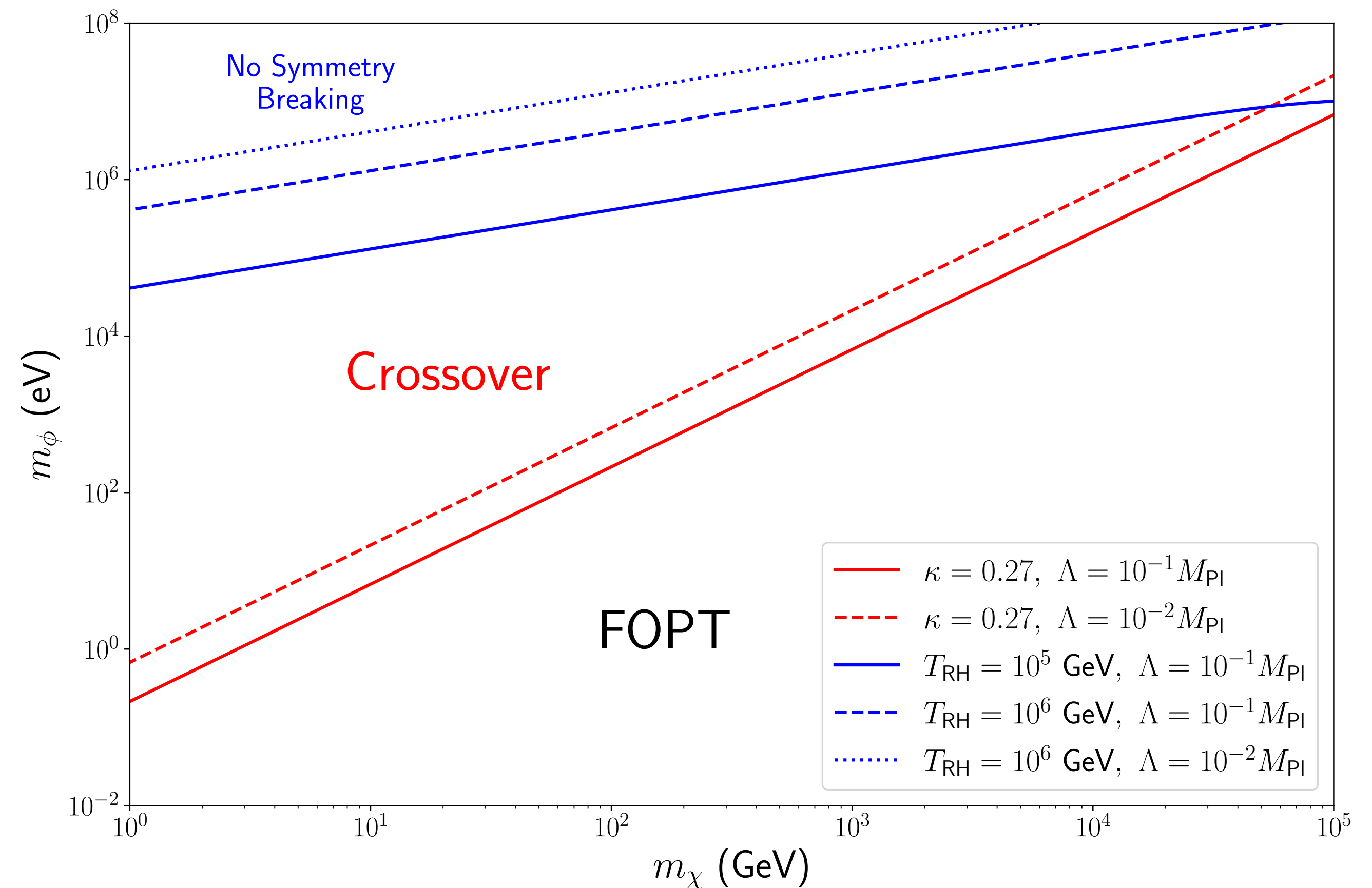
- The boundary between the two is dictated by the dimensionless parameter

$$\kappa \equiv \frac{2\pi^2}{g_\chi} \frac{m_\phi^2 \Lambda}{m_\chi^3}.$$

- At high T it can be shown that

$$\kappa \sim \frac{m_\phi^2}{|m_T^2| x^2}$$

- So  $\kappa$  is a measure of relative importance of the thermal vs. bare ALP mass



# First-Order Phase Transition

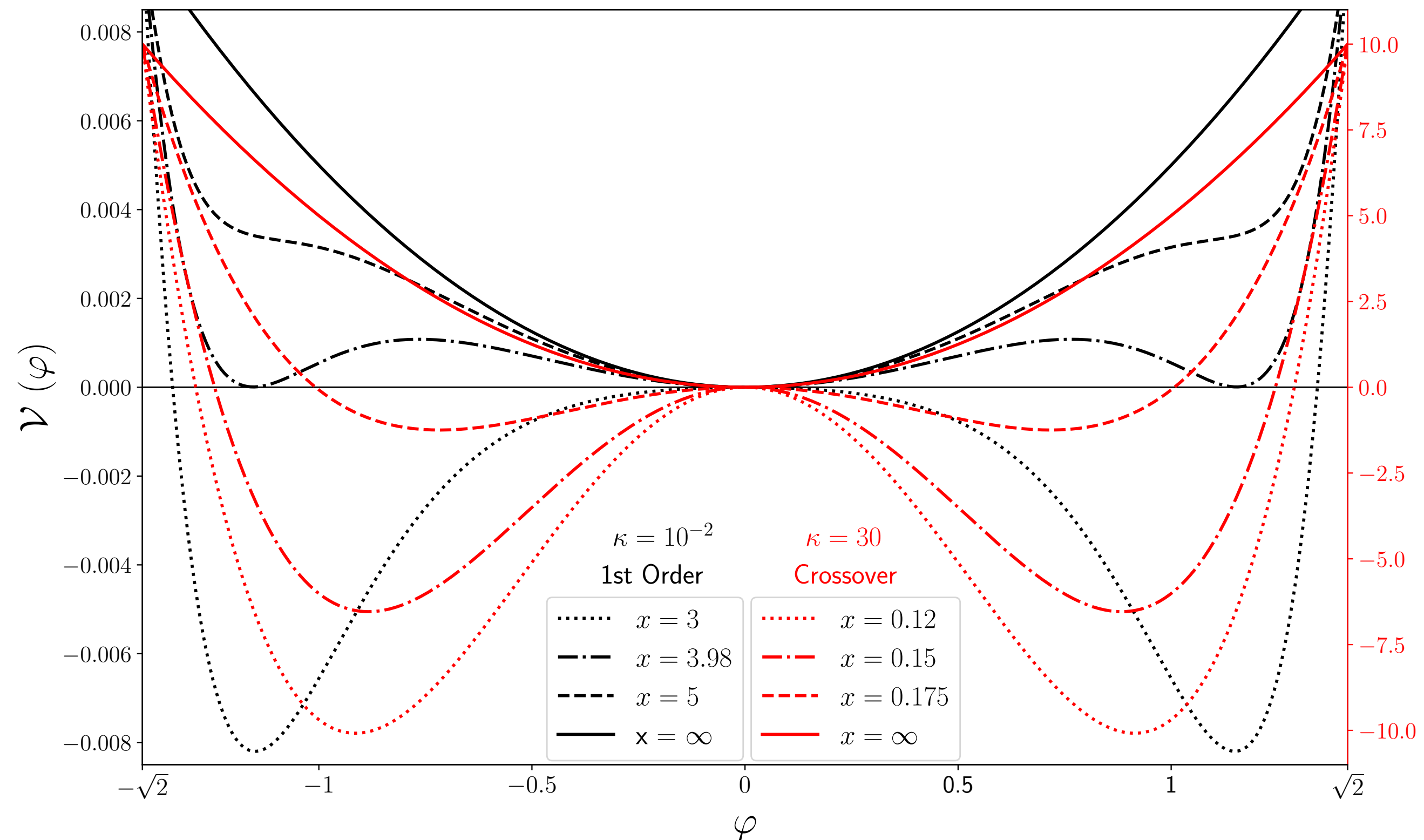
- Critical temperature is given by

$$T_c \approx \frac{m_\chi}{\sqrt[4]{2}} \kappa^{1/4}$$

- However, the ALP field remains stuck in the false vacuum long after that (tunneling rate is tiny). The PT occurs at

$$x_{\text{cfo}} = (c_2/\kappa)^{1/3} \approx 0.836 \kappa^{-1/3}$$

- As long as ALP has a vev, WIMP's effective mass is close to zero, and it does not freeze out!

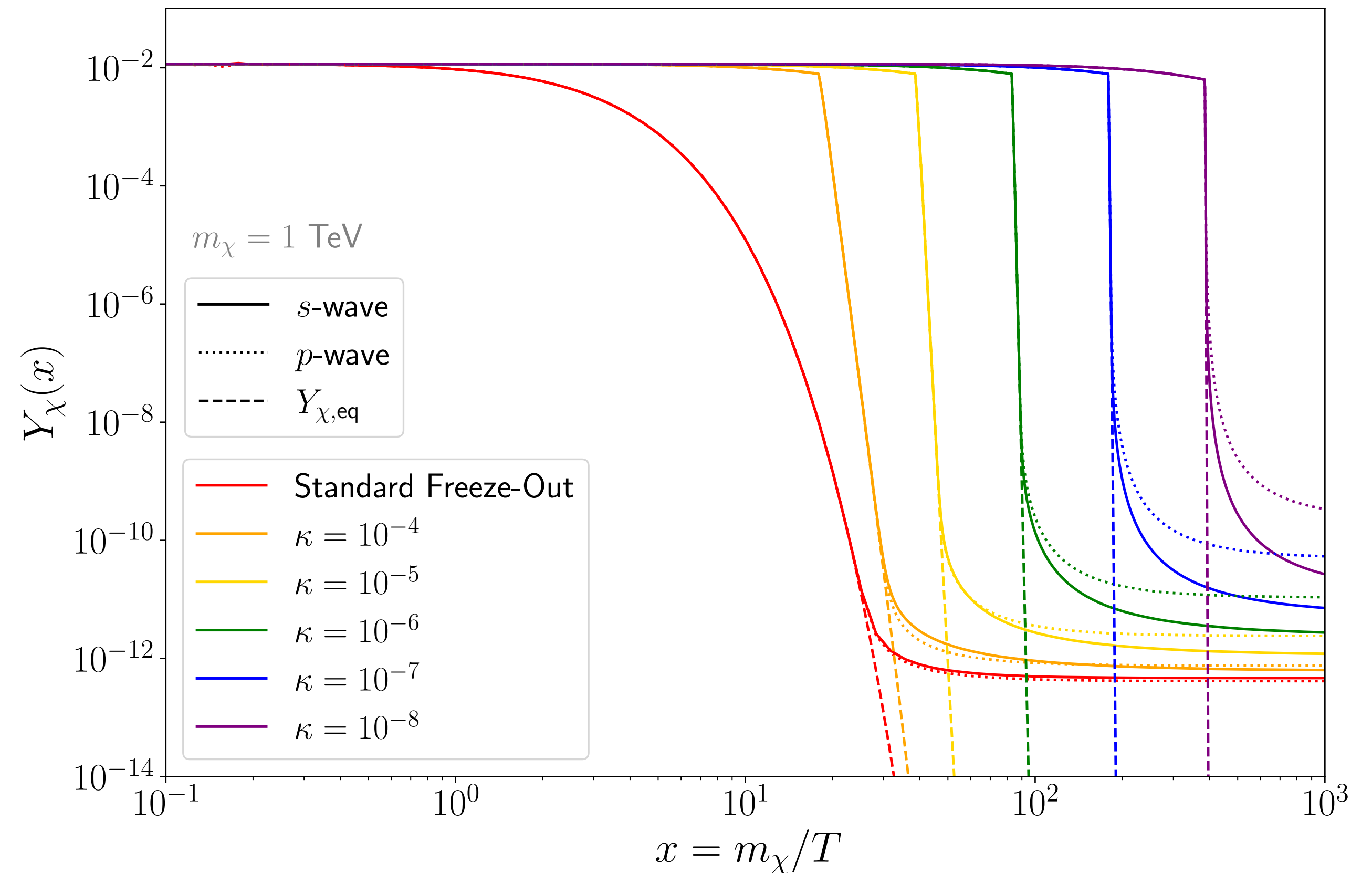


$$x \equiv m_\chi/T, \quad \varphi \equiv \phi/\sqrt{m_\chi\Lambda}, \quad \kappa \equiv \frac{2\pi^2}{g_\chi} \frac{m_\phi^2\Lambda}{m_\chi^3}.$$



# Coherent Freeze-Out

- The WIMP freeze-out occurs suddenly as the ALP v.e.v. disappears. i.e. at  $x_{\text{cfo}}$
- It can be delayed by 1-2 orders of magnitude compared to the usual thermal freeze-out value,  $x_{\text{fo}} \approx 25$
- If delay is too much, ALP vacuum energy starts to dominate and there is a burst of inflation
- There may be a way to have consistent cosmology with a short inflationary phase, at the expense of some fine-tuning (work in progress)

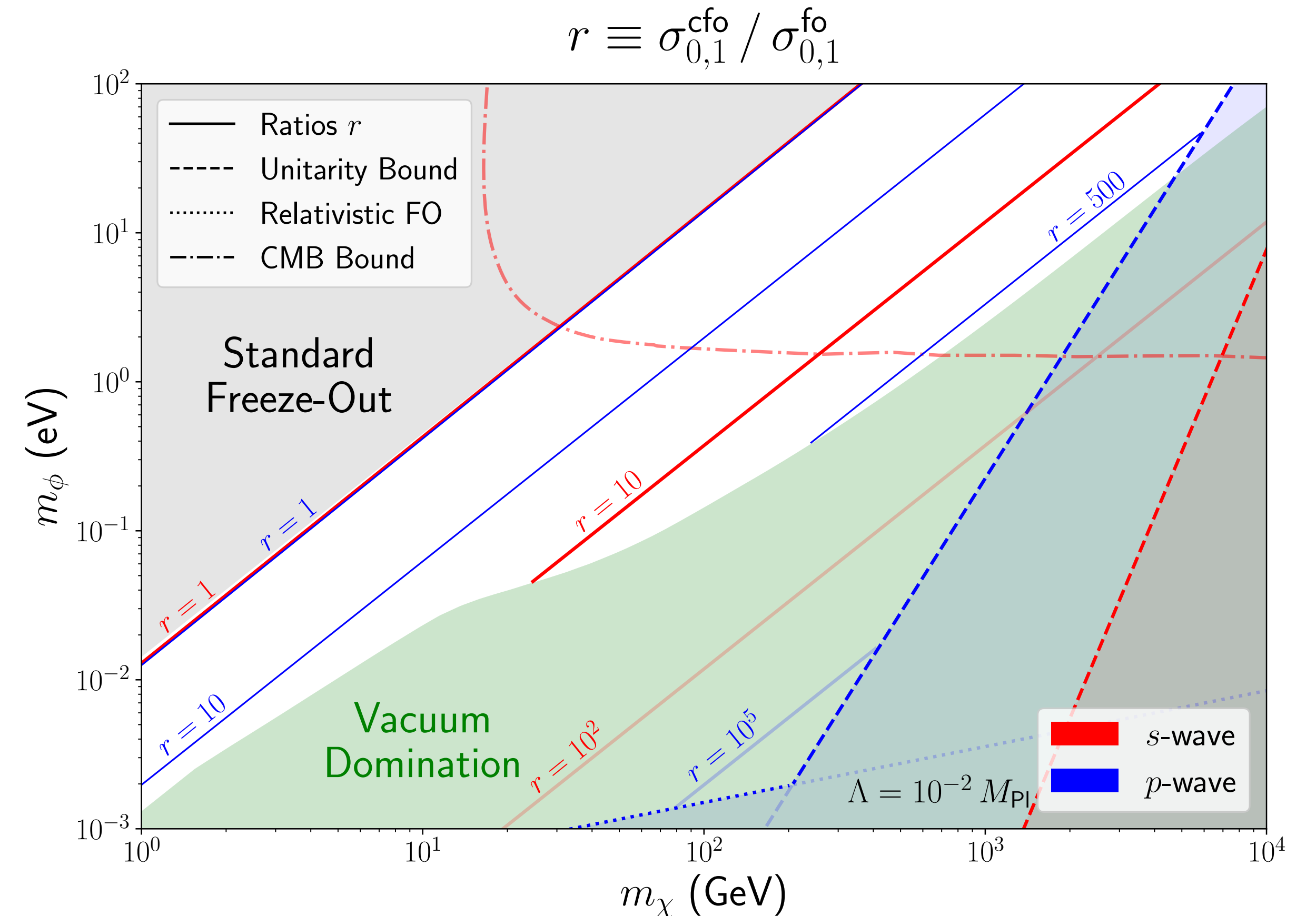


# Coherent Freeze-Out

- Later freeze-out modifies the predicted asymptotic yield ( $\sim$  present density):

$$\frac{Y_{\chi,\infty}^{\text{cfo}}}{Y_{\chi,\infty}^{\text{fo}}} = \frac{14}{9} \frac{x_{\text{cfo}}}{x_{\text{fo}}} \frac{\sigma_0^{\text{fo}} + 3\sigma_1^{\text{fo}}/x_{\text{fo}}}{\sigma_0^{\text{cfo}} + 21\sigma_1^{\text{cfo}}/(10x_{\text{cfo}})}$$

- As a result, the known current DM density\* corresponds to a larger WIMP annihilation cross section
- The effect can be as large as a factor of  $\sim 500$  without an inflationary burst
- In WIMP models, larger cross sections correspond to lower masses, which may actually be less constrained by the LHC and indirect detection



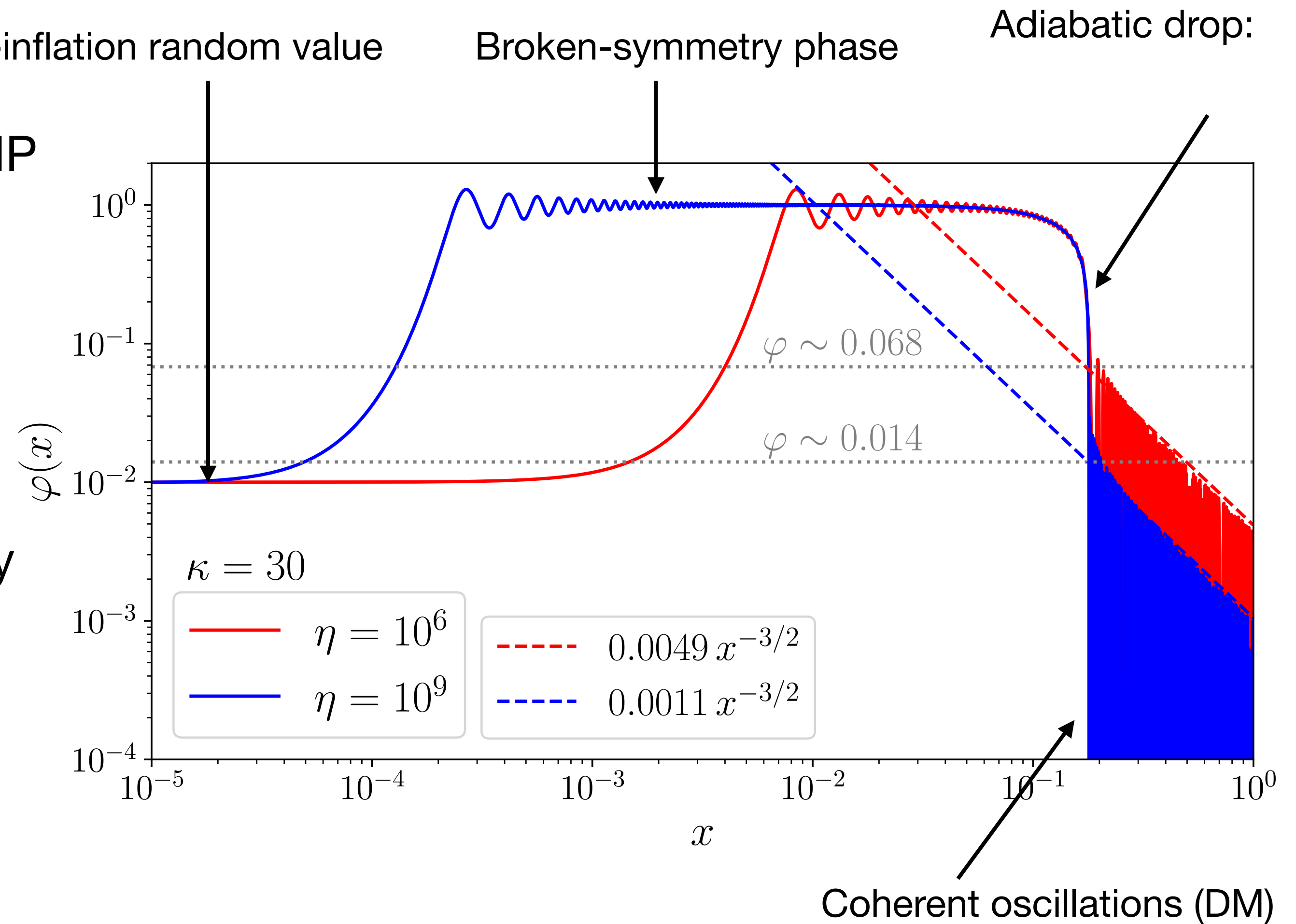
\* In the FOPT regime, ALP coherent oscillations must decay to avoid over-closure, so generically WIMP is 100% of DM



# Crossover Regime

- In the crossover regime, both ALP and WIMP can contribute to DM
- WIMP contribution is computed by the standard freeze-out
- ALP DM is coherent field oscillations as in misalignment, but the initial value is fixed by the v.e.v. due to thermal potential!
- More precisely:

$$\rho_\phi(x_0) \approx \underbrace{m_\phi^2 \phi^2(x_c)}_{\text{Value at PT}} \underbrace{\left(\frac{\kappa}{\eta}\right)^{\frac{1}{2}}}_{\text{Adiabatic drop}} \underbrace{\left(\frac{x_c}{x_0}\right)^3 \frac{g_{*S}(x_0)}{g_{*S}(x_c)}}_{\text{Matter-like scaling}}$$



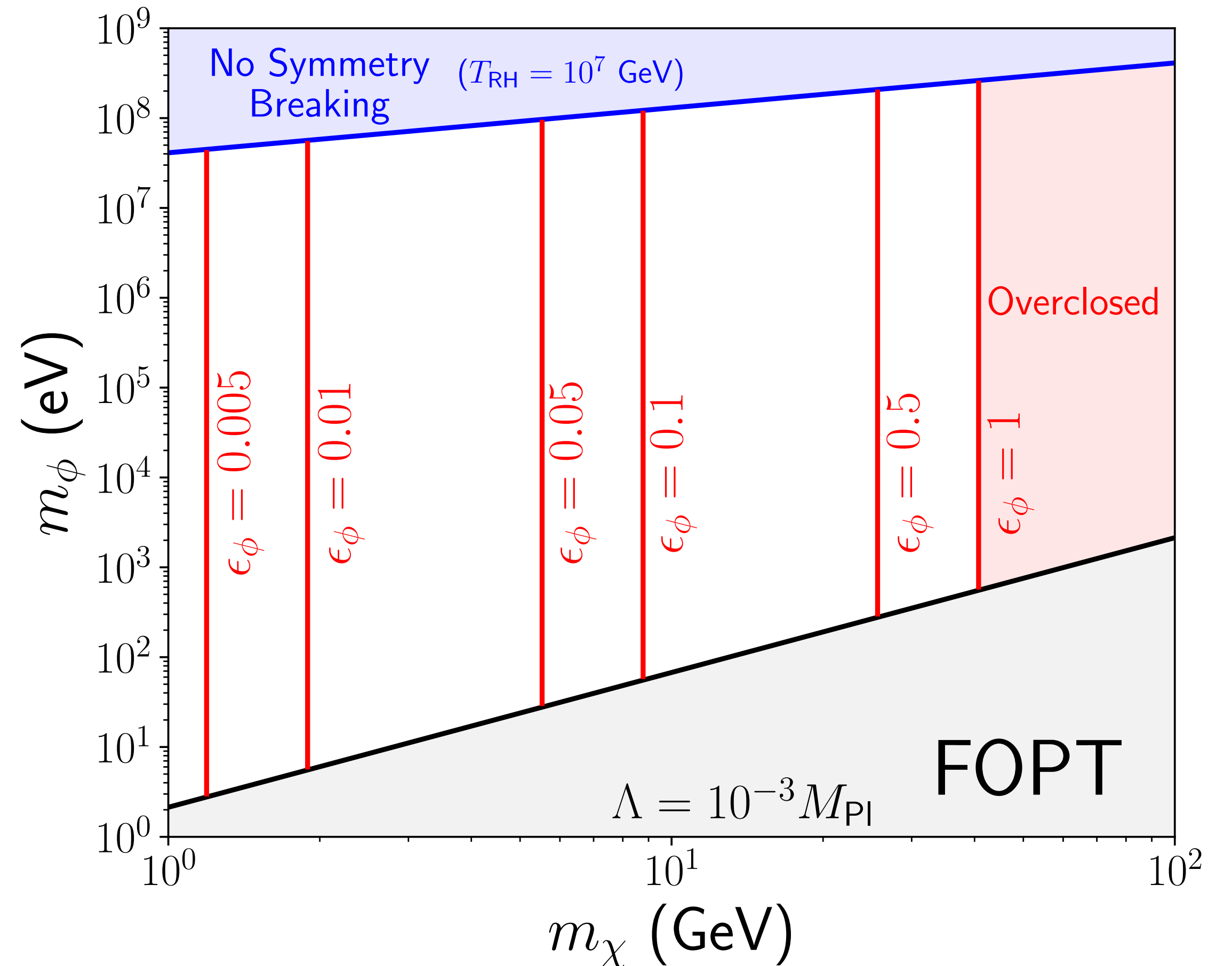
# ALP Dark Matter

- Predicted ALP relic abundance:

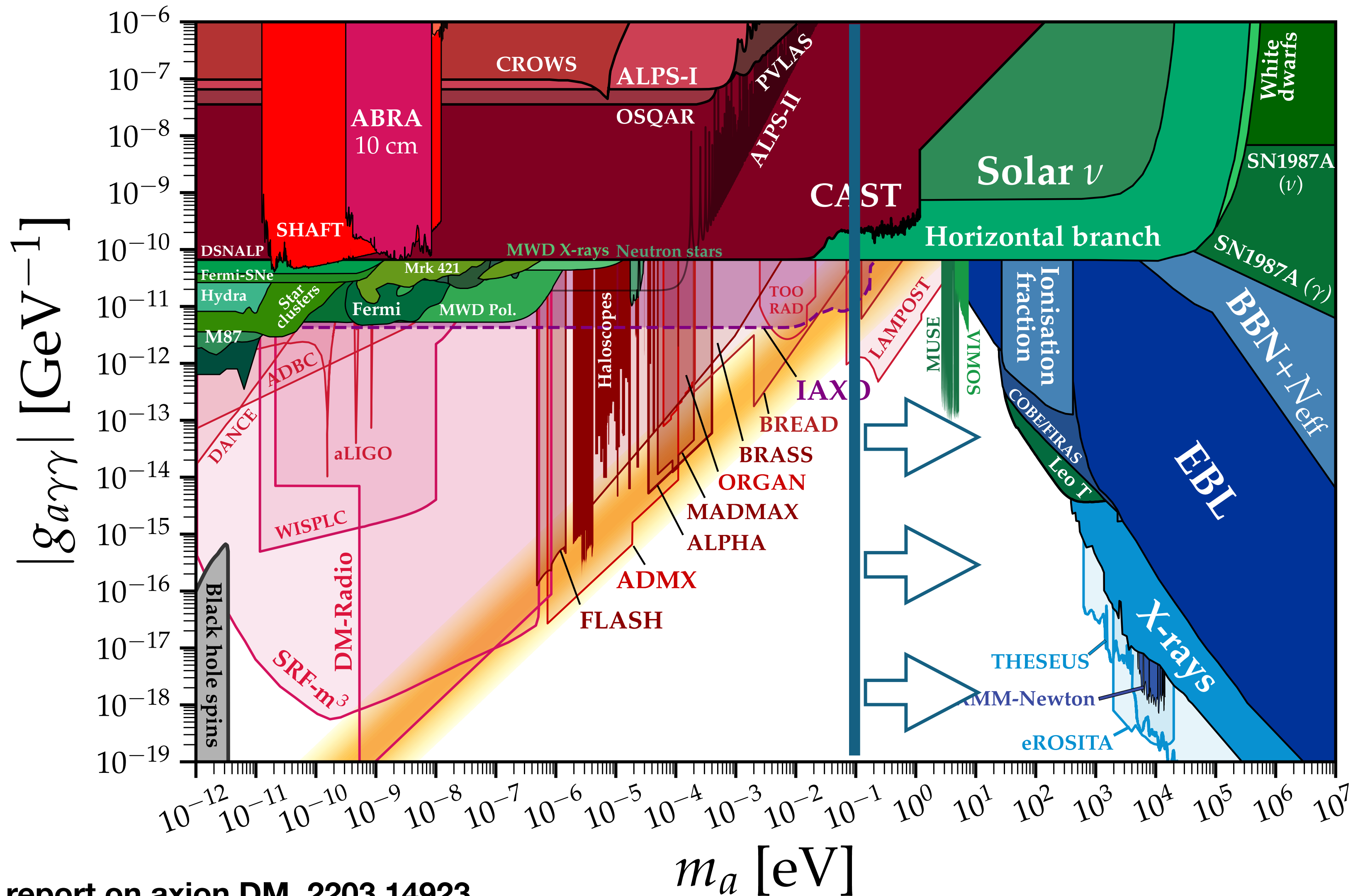
$$\Omega_\phi = \frac{1.66 \cdot 4g_{*S}(x_0) \sqrt{2g_\chi g_*(x_c)} m_\chi^{3/2} \Lambda^{1/2} T_0^3}{3g_{*S}(x_c) H_0^2 M_{\text{Pl}}^3}$$

$$\approx 0.3 \left( \frac{m_\chi}{10 \text{ GeV}} \right)^{3/2} \left( \frac{\Lambda}{0.1 M_{\text{Pl}}} \right)^{1/2},$$

- Correct relic density for reasonable values of WIMP mass and coupling! (“ALP miracle”)
- No dependence on initial conditions, as opposed to the usual misalignment
- The dependence on the ALP mass has dropped out (as long as it’s consistent with the cross-over regime)
- Works for **ALP mass  $\sim$  eV - MeV**



# Experimental Searches for ALPs





# Conclusions

- Considered a coupling between WIMP and ALP motivated by QCD axion-nucleon coupling
- Even a tiny (Planck-suppressed) coupling can drastically modify cosmological history of both WIMP and ALP
- This results in qualitatively different predictions for present-day abundances of either or both species
- Thus new regions of parameter space can be consistent with the observed DM - relevant for experiment



The story of “WIMP meets ALP”



# Backup Slides

# Equations

$$V(\phi, T) = \frac{g_\chi}{2\pi^2} m_\chi^4 \mathcal{V}(\varphi, x) \ , \qquad \mathcal{V}(\varphi, x) = -\frac{\varphi^2}{2} \frac{\gamma^2 K_1(\gamma x)}{x} + \kappa \frac{\varphi^2}{2}$$

$$\gamma \equiv |1 - \varphi^2/2|$$

$$\text{ALP:} \quad \varphi'' + \frac{2}{x} \varphi' - \eta x \left(1 - \frac{\varphi^2}{2}\right) \left[ (1 - \varphi^2) K_1(\gamma x) + \frac{\varphi^2}{2} \gamma x K_0(\gamma x) \right] \varphi + \eta \kappa x^2 \varphi = 0$$

$$\text{WIMP:} \quad \dot{n}_\chi + 3H n_\chi = -\langle \sigma v \rangle_{\text{eff}} (n_\chi^2 - n_{\chi, \text{eq}}^2) \qquad n_{\chi, \text{eq}} = \frac{g_\chi}{2\pi^2} m_{\chi, \text{eff}}^2 T K_2(m_{\chi, \text{eff}}/T)$$

$$m_{\chi, \text{eff}} = \left| m_\chi - \frac{\phi^2}{2\Lambda} \right|$$

# ALP Field Evolution

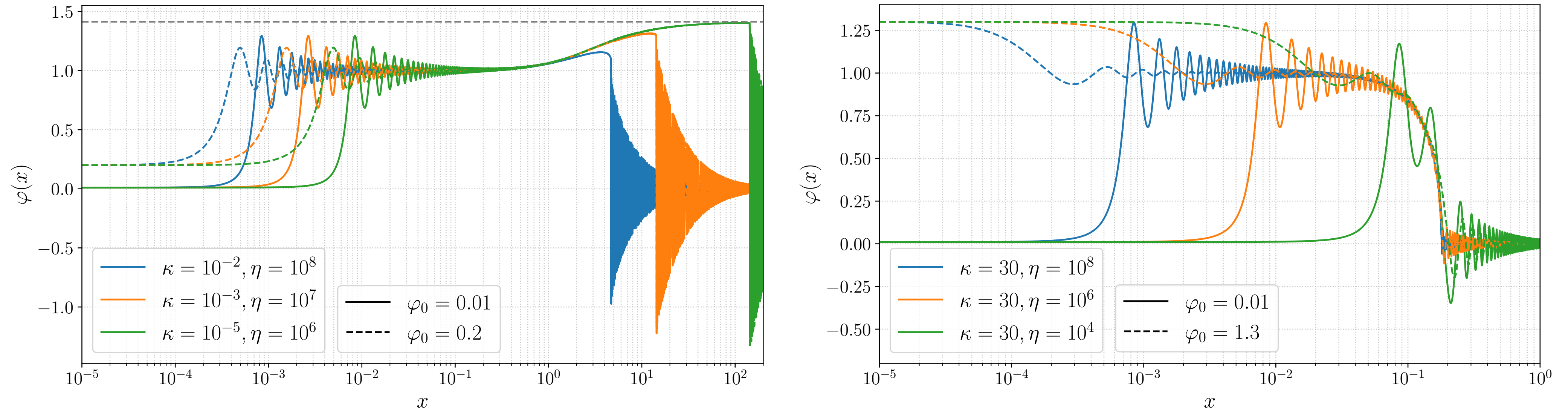


FIG. 5. Evolution of the ALP field in the first-order phase transition regime (left panel) and the crossover regime (right panel). Different colors correspond to different choices of  $\kappa$  and  $\eta$ , while different line styles denote different initial field displacements.



# WIMP Mass Evolution in FOPT

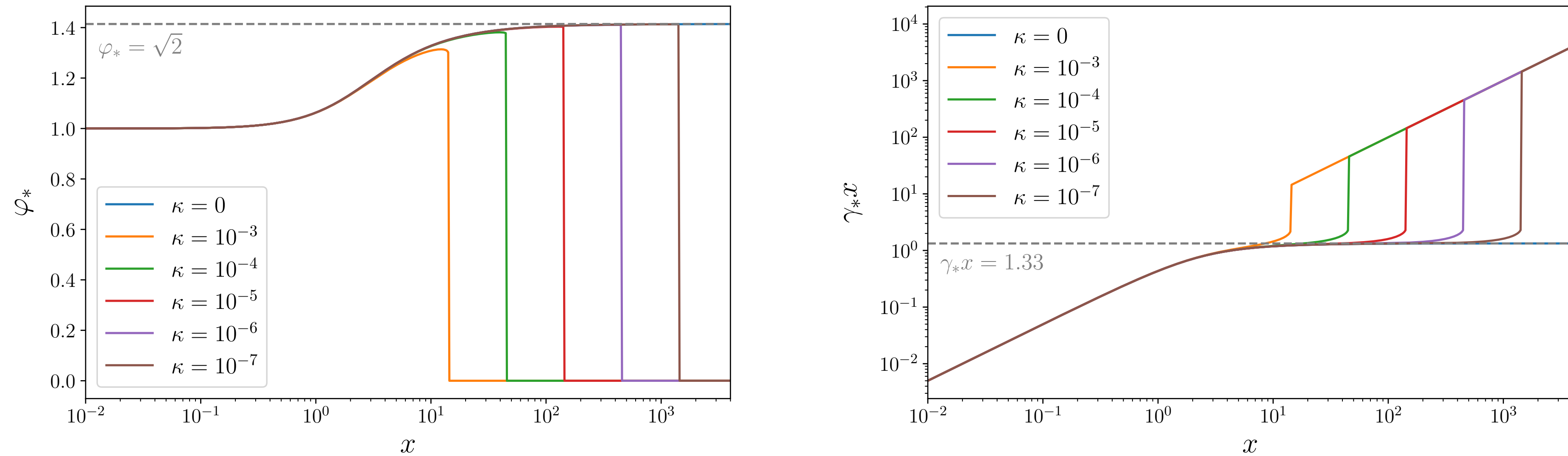


FIG. 7. The evolution of the symmetry-breaking vacuum  $\varphi_*$  (left panel) and the boost factor  $\gamma_* \equiv |1 - \varphi_*^2/2|$  (right panel) as a function of the inverse temperature  $x \equiv m_\chi/T$ . The ratio  $m_{\chi,\text{eff}}/T = \gamma_* x$  remains smaller than  $\mathcal{O}(1)$  until  $x$  reaches  $\tilde{x}_{\text{cfo}}$  (corresponding to the sudden drop of  $\varphi_*$  and the sharp increase of  $\gamma_* x$  in the plots), after which the coherent freeze-out begins.



# Making ALP Decay After FOPT

- ALP Coherent oscillations in FOPT regime would over-close the universe
- OK if they decay into SM radiation before BBN, but SM-ALP coupling must be small enough to not thermalize the ALP particles
- Solution: introduce dark photon with ALP-DP coupling  $\mathcal{L}_{\text{dark}} \supset -\frac{\phi}{4f_\phi} F_{\mu\nu} \tilde{F}^{\mu\nu}$
- Preheating quickly transfers energy from ALP to DP
- Dark photon then decays to SM  $e^+e^-$  before BBN
- See paper for details, consistency checks etc.