TOHOKU UNIVERSITY

GPPU GRADUATE PROGRAM ON PHYSICS FOR THE UNIVERSE

宇宙創成物理学国際共同大学院

Sign-Flipping Axion Potentials via Kapitza-Type Modulation by Heavy Axions

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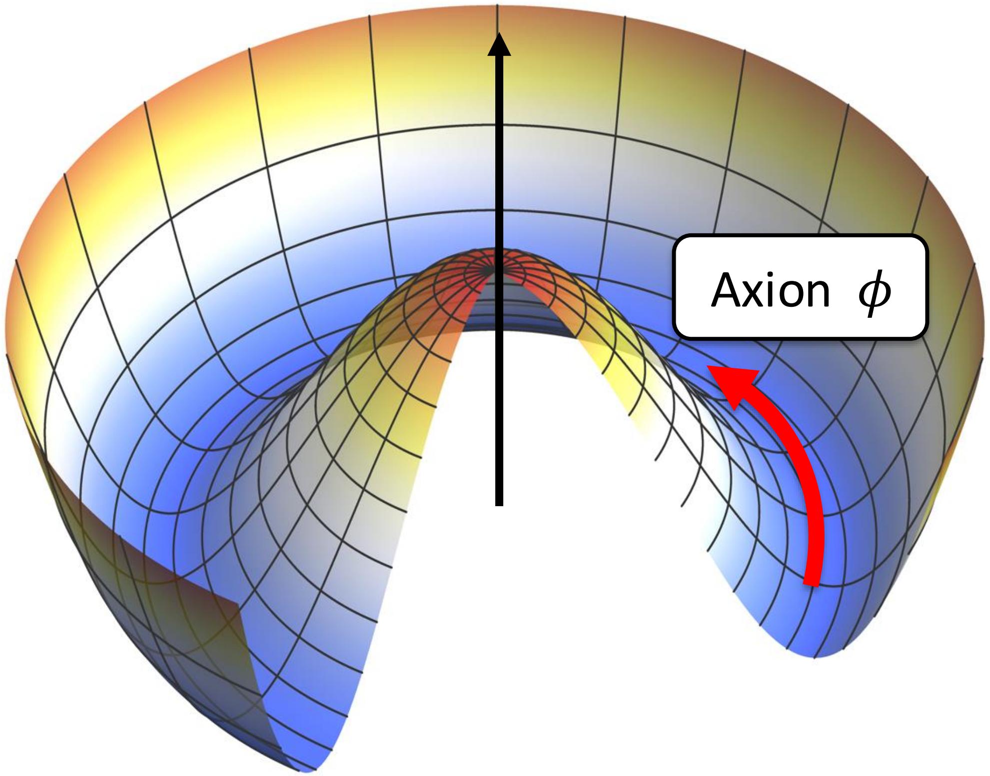
arXiv: 2509.1103, JHEP_012P_1025,   Kai Murai, Fuminobu Takahashi, KT

Axion

Peccei, Quinn `77, Weinberg `78, Wilczek `78

The **axion** is a pseudo-Nambu-Goldstone Boson arising from SSB of the global U(1) Peccei-Quinn symmetry

The axion is
- an angular degree of freedom
- **BSM candidate that can address several open problems**
  (dark matter, inflation, strong CP, ⋯)



Axion Dark Matter Production

Preskill, Wise, Wilczek `83, Abbott, Sikivie `83, Dine, Fischler `83

- Misalignment mechanism

  The axion is initially misaligned from the potential minimum

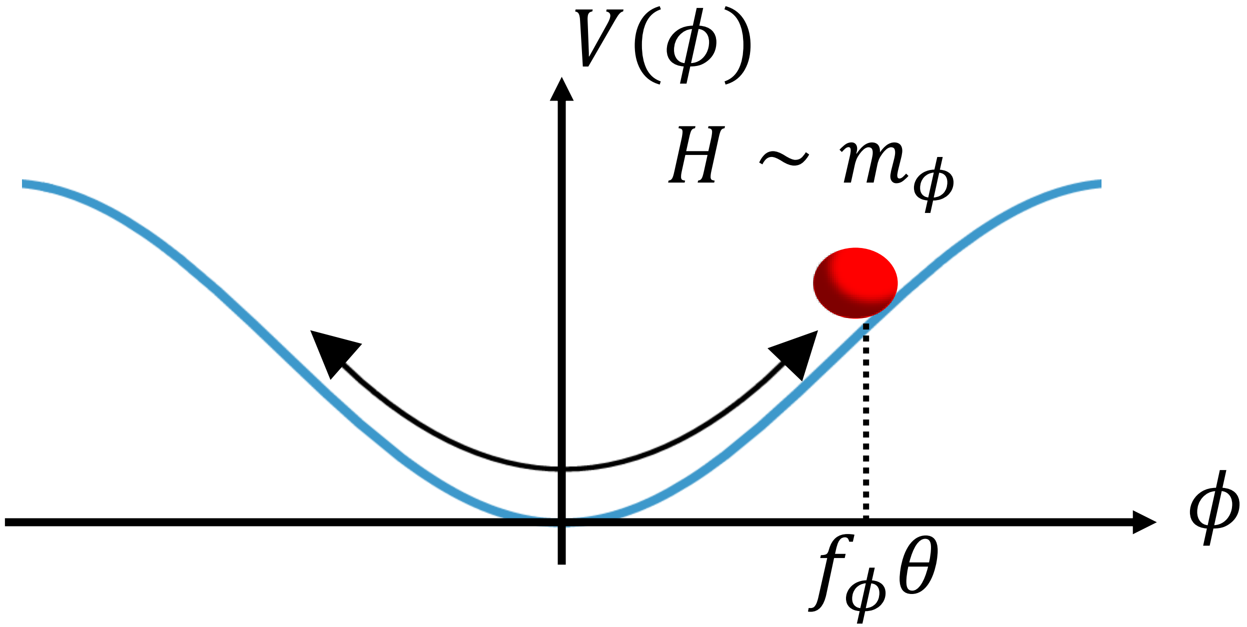
  As the Universe cools, the axion starts to oscillate

Oscillating energy = Dark Matter

Initial energy density

$$\boldsymbol{\rho_\phi \sim \frac{1}{2} m_\phi^2 f_\phi^2 \theta^2}$$

depends on the initial amplitude



The axion energy density is diluted by the cosmic expansion

Multi Axion Systems

✓ **Rich dynamics arising from axion mixing have been actively studied**

-e.g) level crossing, topological defects, clockwork mechanism

Hill, Ross `88, Kitajima, Takahashi `15, Daido, Kitajima, Takahashi, `15, Kaplan, Rattazzi `15, Choi & Im `16, Guidice et al `16

✓ **Such systems are well motivated by string theory (Axiverse)**

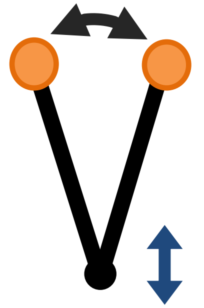
-The axiverse predicts multiple axions over a wide range of masses
These axion are generically mixed with each other Arvanitakis et al. `09

Axion mixing can significantly affect the axion abundance and its cosmological evolution

Short Summary

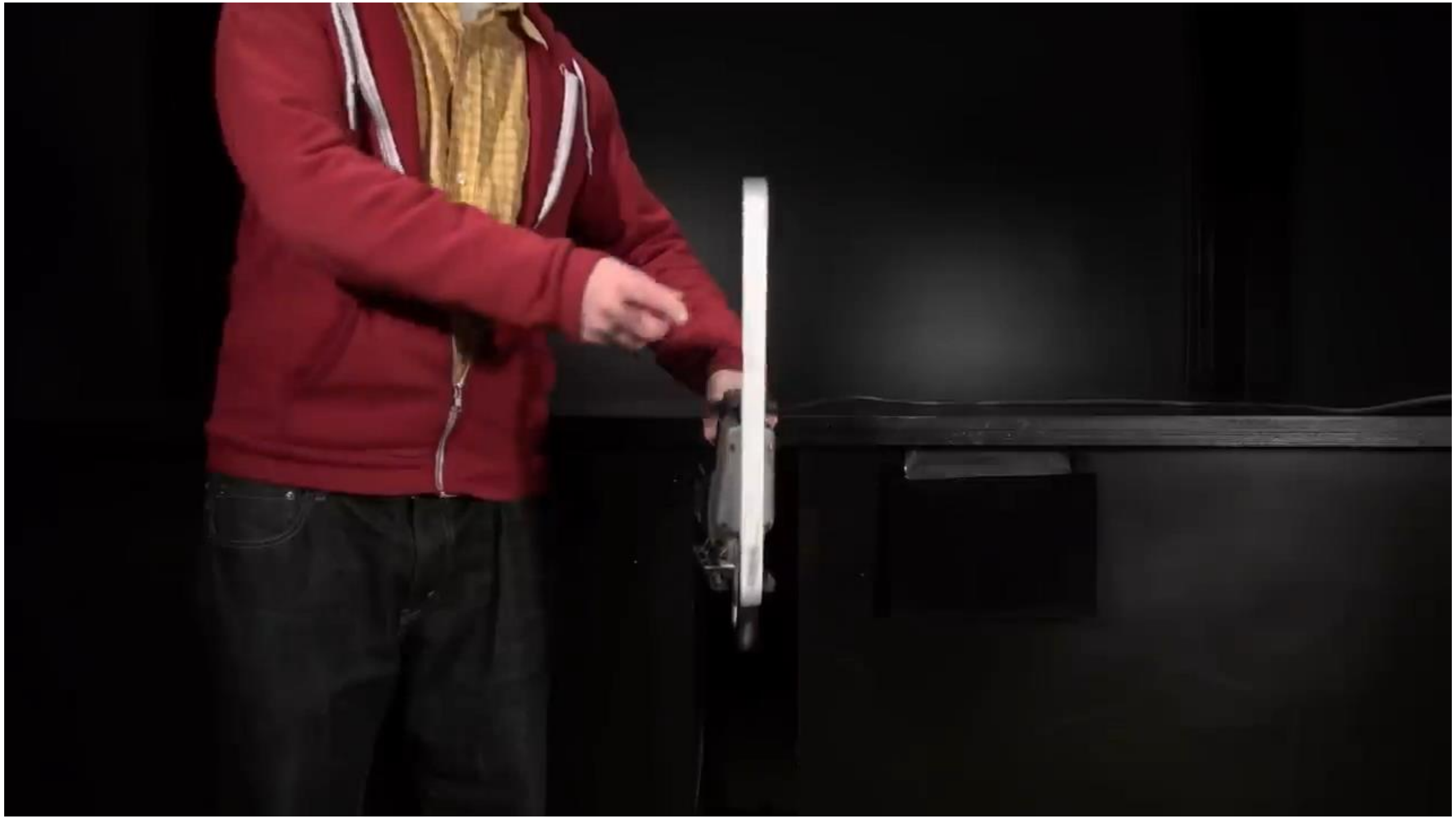
- We consider two spatially homogeneous axion fields (ϕ, χ) with mixing and a large mass hierarchy $m_\phi \gg m_\chi$

- The heavy axion dynamically stabilizes the light axion
  This is analogous to the Kapitza inverted pendulum



- This mechanism can significantly enhance the light-axion relic abundance.

Kapitza’s inverted pendulum



Main Topic

YouTube (Harvard Natural Sciences Lecture Demonstrations,“Inverted Pendulum”, 2012)

Model

Let us consider the mixing of two axion, ϕ(heavy) and χ(light) :

$$V(\phi,\chi) = \boldsymbol{m_\phi^2 f_\phi^2 \left[1 - \cos\left(\frac{\phi}{f_\phi}\right)\right] + \underline{m_\chi^2 f_\chi^2 \left[1 - \cos\left(N\frac{\phi}{f_\phi} + \frac{\chi}{f_\chi}\right)\right]}}$$

Mixing potential $\boldsymbol{V_{\mathrm{mix}}}$

Model

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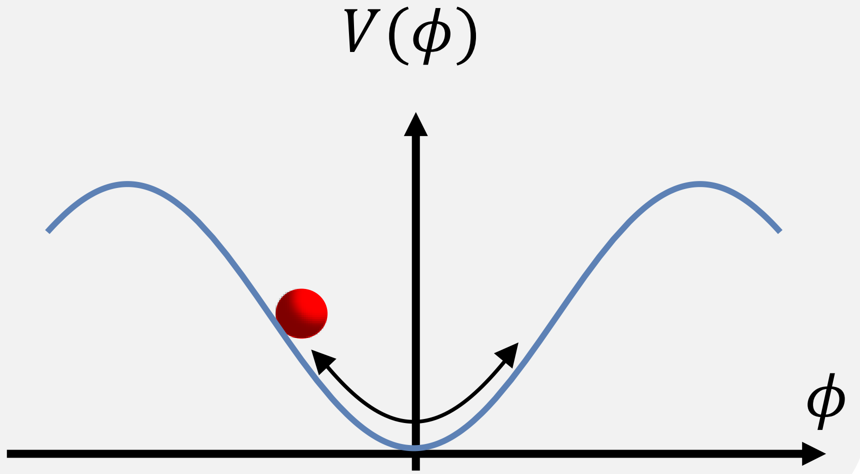
■ Dynamics of ϕ (typical axion behavior)

neglect backreaction,
the heavy axion evolves in a typical axion potential

ϕ oscillate with frequency m_ϕ

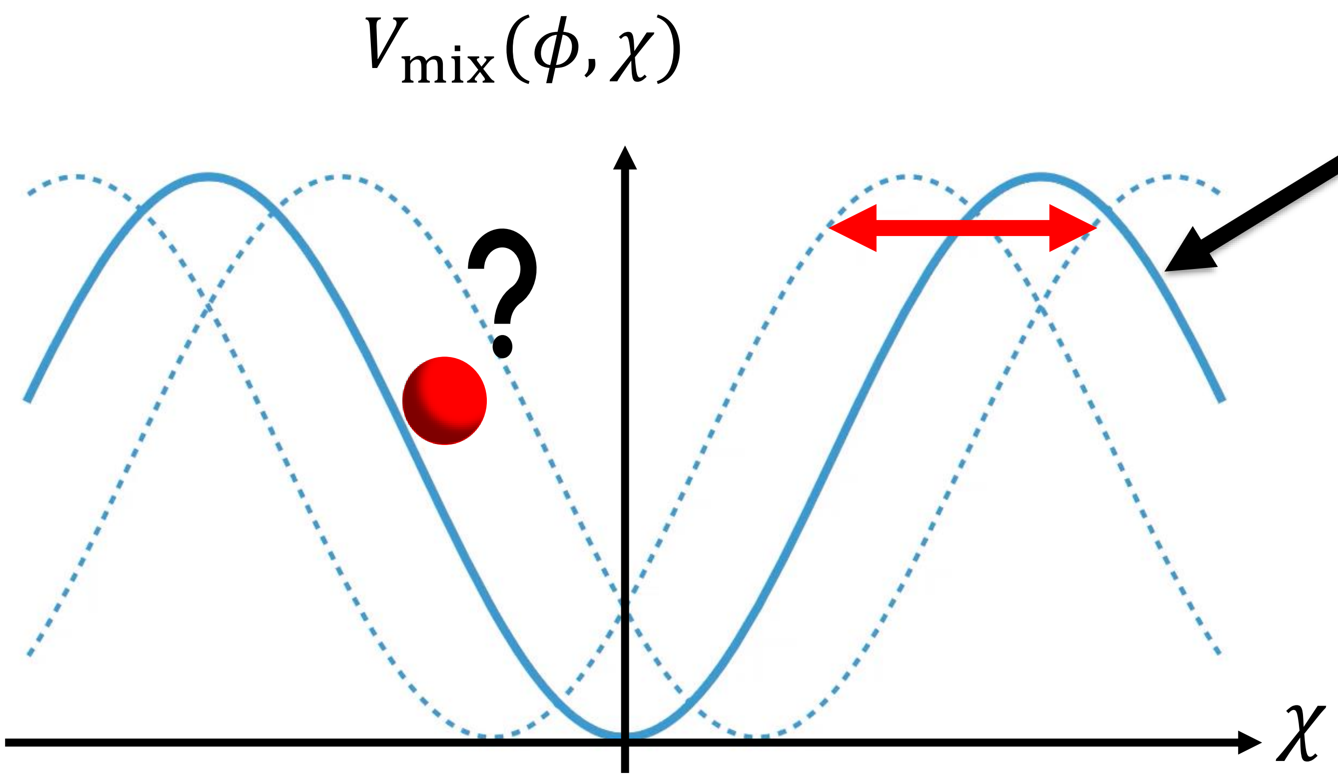
$$\boldsymbol{\phi = \phi_{\mathrm{amp}}\cos(m_\phi t)}$$



Mixing Potential

$$V_{\text{mix}} = m_\chi^2 f_\chi^2 \left[1 - \cos\left(N\frac{\phi}{f_\phi} + \frac{\chi}{f_\chi}\right)\right]$$

Fast oscillation



Potential without mixing

$$V = m_\chi^2 f_\chi^2 \left[1 - \cos\frac{\chi}{f_\chi}\right]$$

χ evolves in an oscillating potential induced by oscillations of ϕ

What effects arise from axion mixing？

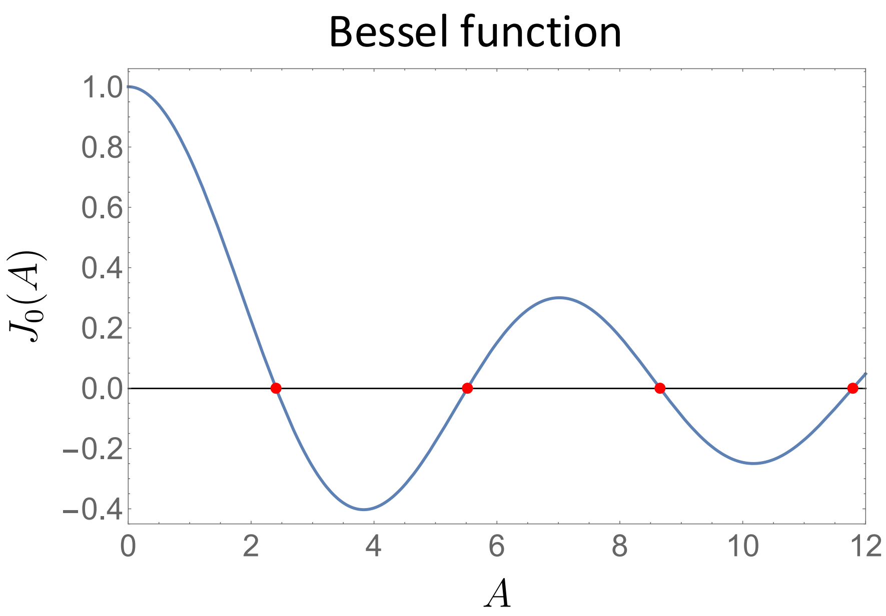
Effective Potential

Deriving the effective potential for χ by time-averaging the oscillations of ϕ

$$V_{\text{eff}}(\chi) = \frac{m_\phi}{2\pi}\int_0^{2\pi/m_\phi} dt\, m_\chi^2 f_\chi^2\left[1-\cos\left(N\frac{\phi}{f_\phi}+\frac{\chi}{f_\chi}\right)\right] \simeq \boldsymbol{J_0(A)} \boldsymbol{m_\chi^2 f_\chi^2}\left[\mathbf{1}-\mathbf{cos}\left(\frac{\boldsymbol{\chi}}{\boldsymbol{f_\chi}}\right)\right]$$

$A = N\phi_{\text{amp}}/f_\phi,\quad J_0(\text{A})$: Bessel function

- ✓ The effective potential depends on the amplitude of the heavy axion ϕ_{amp}
- ✓ The Bessel function takes both positive and negative values

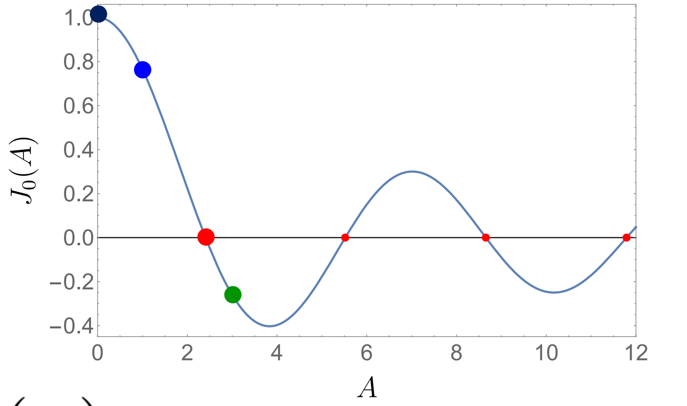


The sign of the effective potential can change!

➡ **Kapitza effect**

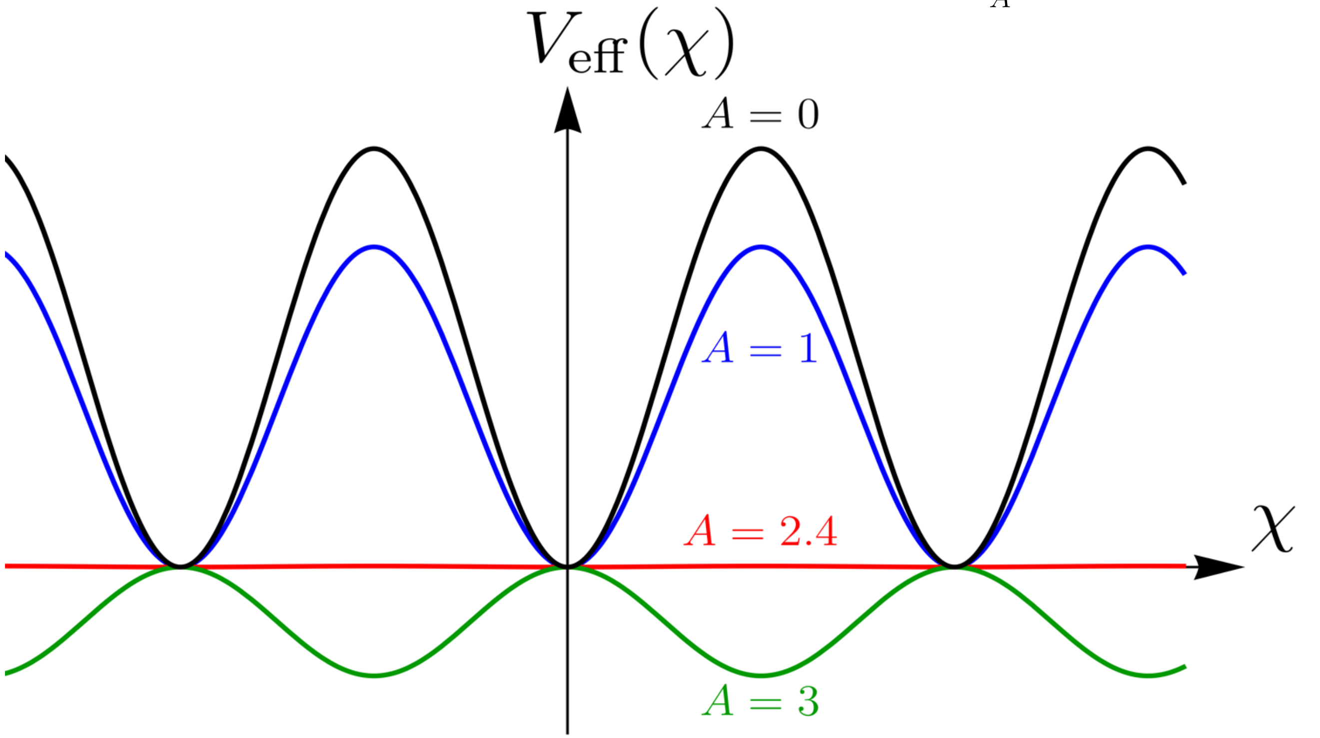
Kapitza Effect on axion mixing

$$V_{\text{eff}} = J_0(\mathrm{A}) m_\chi^2 f_\chi^2 \left[1 - \cos\left(\frac{\chi}{f_\chi}\right)\right] \qquad A = N\phi_{\text{amp}}/f_\phi$$



- ✓ Potential flip interchanges maximun and minimum
  - **dynamical stabilization**

- ✓ The potential height also varies with the amplitude of the heavy axion



Time-Dependent Effective Potential

$$V_{\text{eff}} = J_0(\mathrm{A}) m_\chi^2 f_\chi^2 \left[1 - \cos\left(\frac{\chi}{f_\chi}\right)\right]$$

$$A = N\phi_{amp}/f_\phi$$

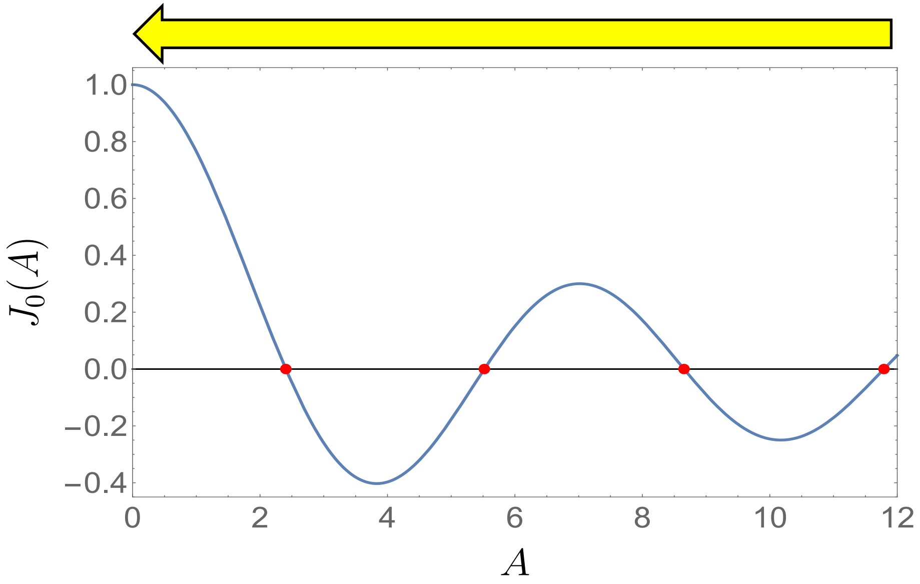
Due to cosmic expansion, ϕ amplitude decays

$$\boldsymbol{\phi_{amp} \propto a(t)^{-3/2}}$$

$$\mathbf{A(t)} = \boldsymbol{A_{\mathbf{in}} a(t)^{-3/2}}$$

t_{in}: where $H \sim m_\chi$
$A_{\text{in}} = A(t_{\text{in}})$,

Time evolution

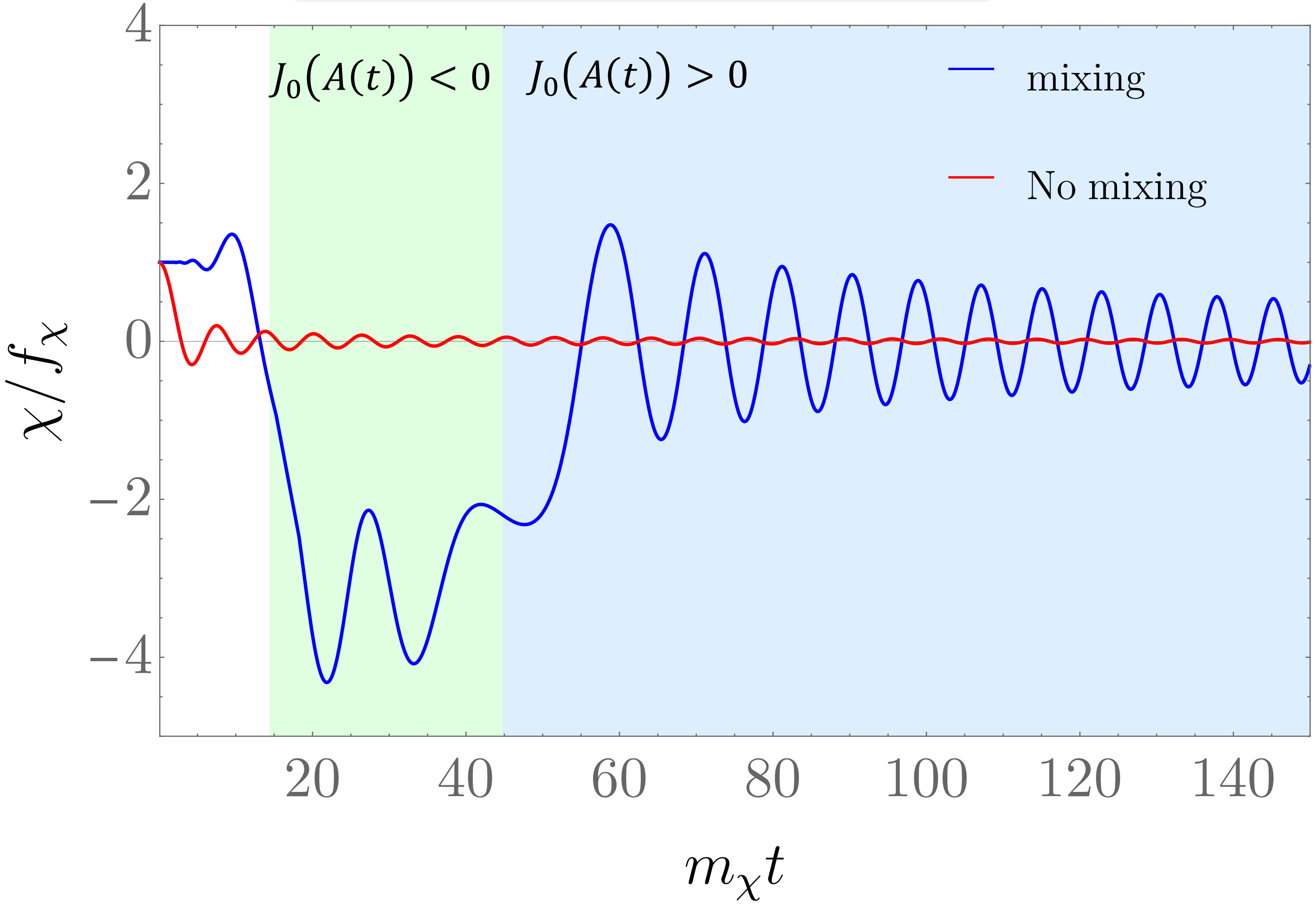


The effective potential evolves and repeatedly flips as the Universe expands

Cosmological Kapitza Effect

$$V_{\text{eff}} = J_0(\mathrm{A}) m_\chi^2 f_\chi^2 \left[1 - \cos\left(\frac{\chi}{f_\chi}\right)\right]$$

$A_{\text{in}} = 70,$
$m_\chi / m_\phi = 0.01$



Cosmological Kapitza Effect

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$A_{\text{in}} = 70$,
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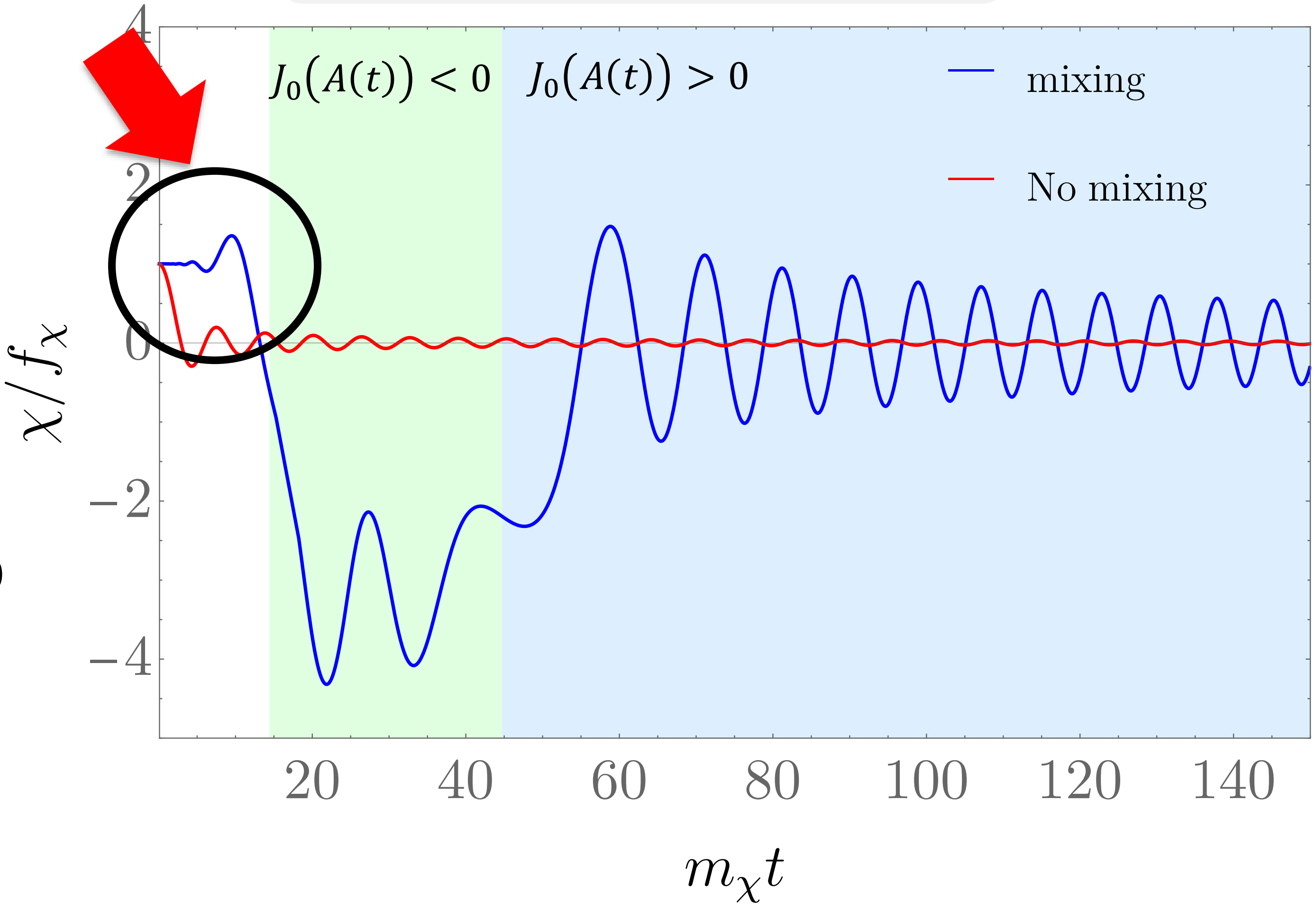
White regime

- $J_0(A)$: fast oscillate
- Minimum : fast flip

The light axion remains frozen at its initial value as the potentia flip rapidly



Cosmological Kapitza Effect

Green regime

- $J_0(A)$: $-$
- Minimum : $\chi/f_\chi = -\pi, \cdots$

The light axion begins to oscillate and gradually settles near the potential minimum

$$V_{\mathrm{eff}} = J_0(\mathrm{A}) m_\chi^2 f_\chi^2 \left[1 - \cos\left(\frac{\chi}{f_\chi}\right)\right]$$

$A_{\mathrm{in}} = 70,$
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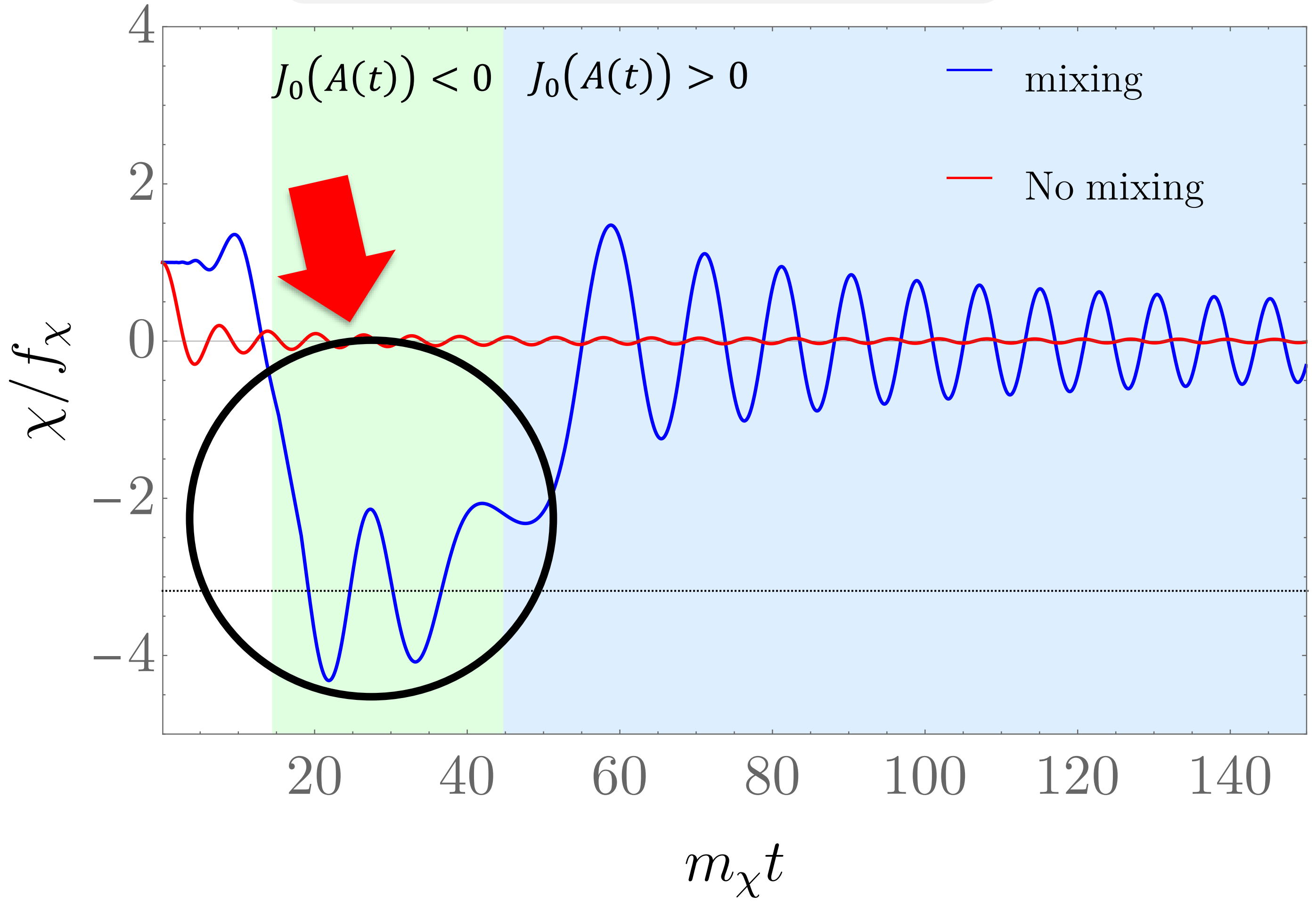


Cosmological Kapitza Effect

$$V_{\text{eff}} = J_0(\text{A}) m_\chi^2 f_\chi^2 \left[1 - \cos\left(\frac{\chi}{f_\chi}\right)\right]$$

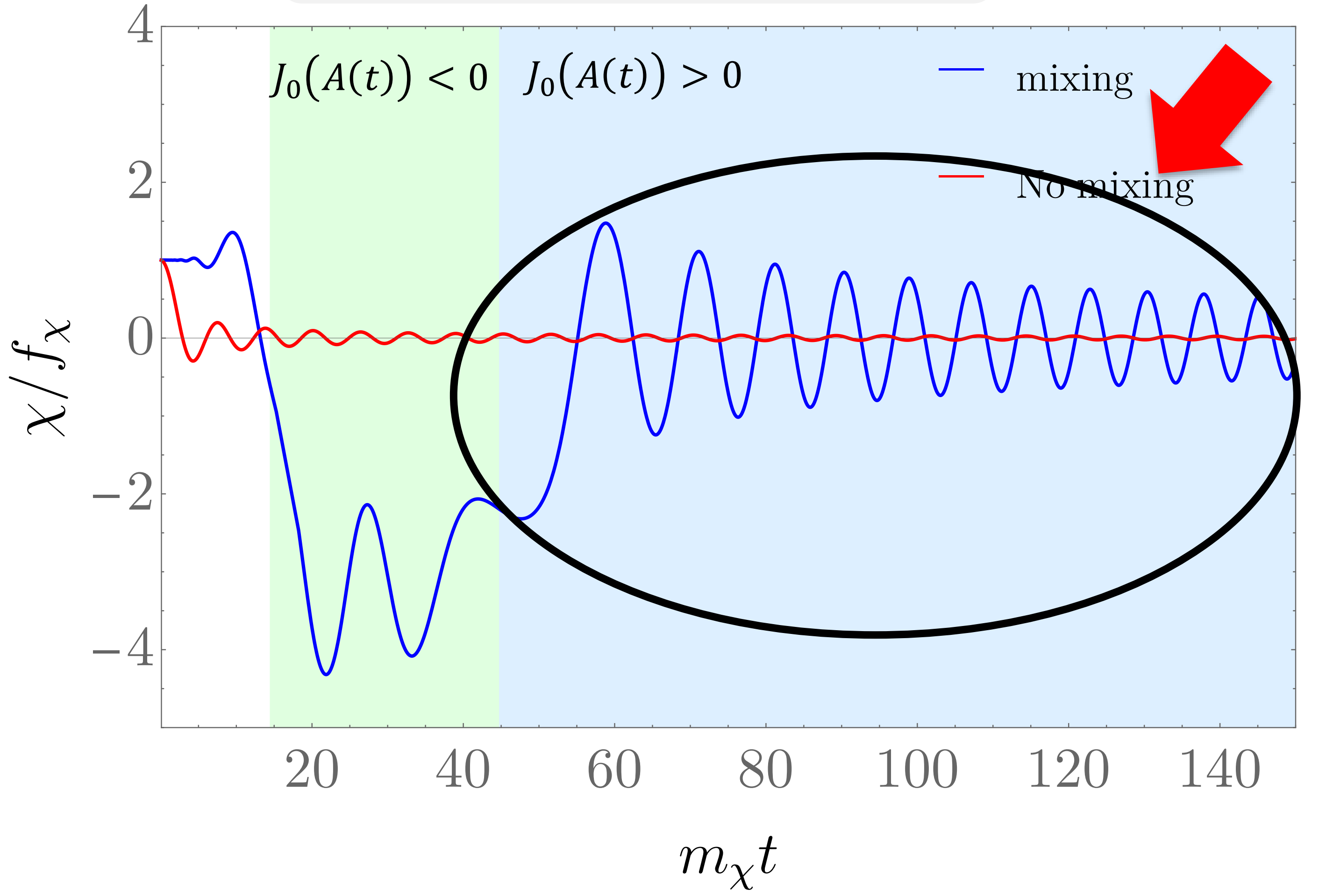
$A_{\text{in}} = 70,$
$m_\chi / m_\phi = 0.01$

Blue regime

- $J_0(A) : +$
- Minimum : $\chi/f_\chi = 0, \cdots$

The effective potential flips, exchanging its Min and Max

The oscillation center shifts

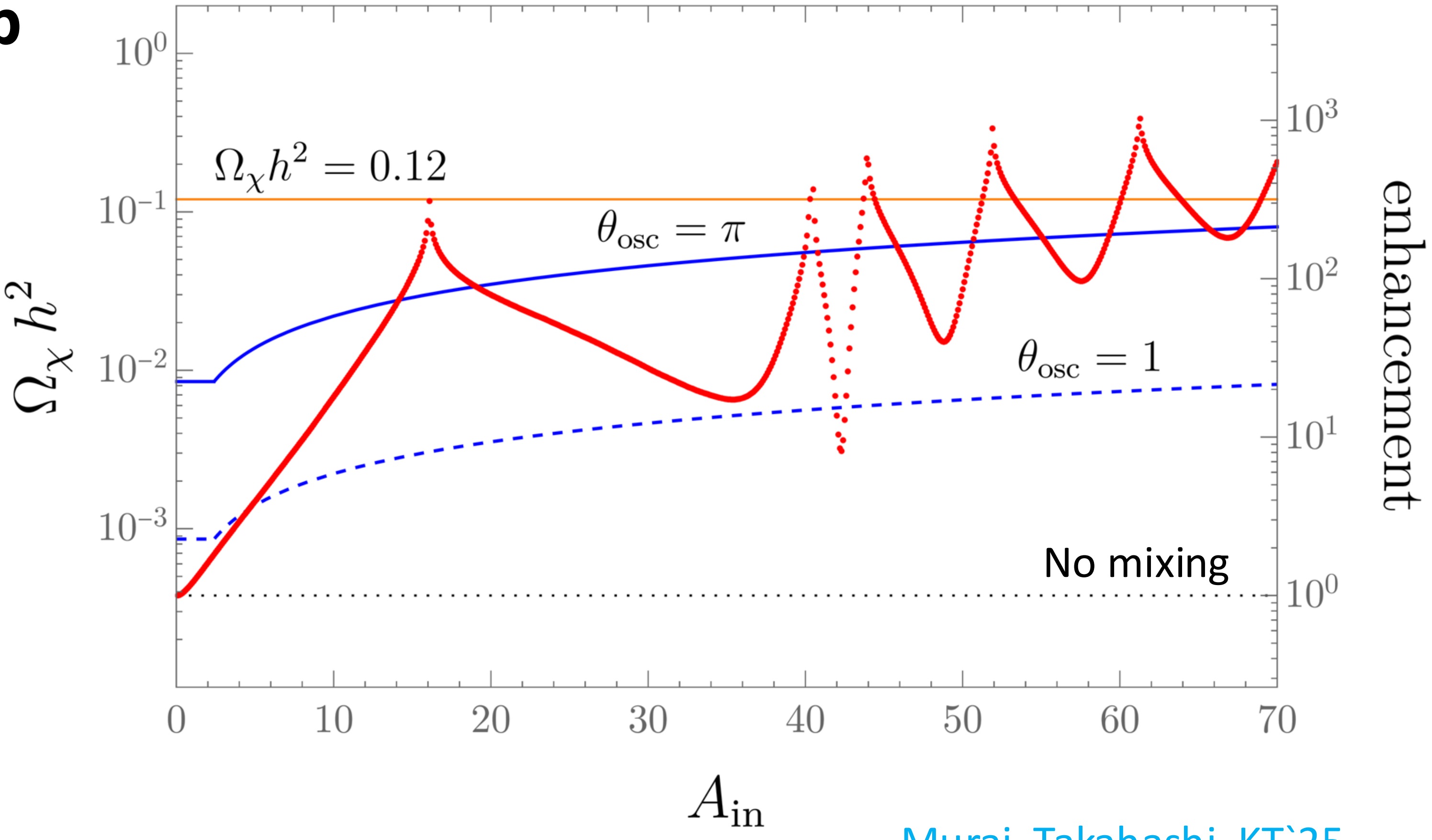


Enhancement of abundance

The effects of potential sign flip

- ✓ dynamically freeze the axion near its initial value.
- ✓ Oscillations starts near the top of the potential

The abundance of the light axion χ is strongly enhanced



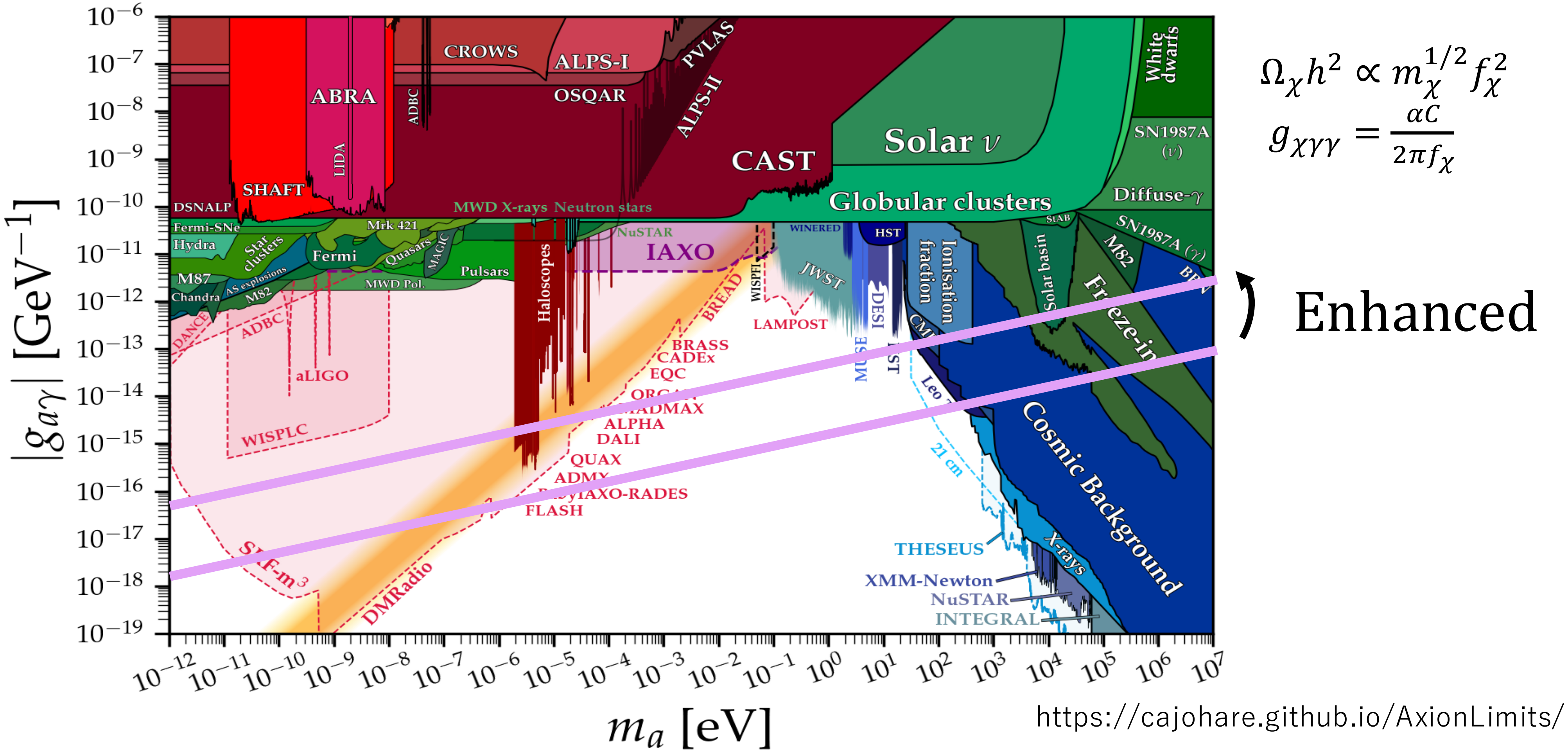
$m_\chi = 10^{-2}\mathrm{eV}, f_\chi = 10^{12}\mathrm{GeV}$

Murai, Takahashi, KT`25

$\theta_{\rm osc} = \chi_{\rm osc}/f_\chi$: Initial amplitude of the final oscillation

Expansion of the parameter space

The Kapitza effect shifts the dark matter parameter space



$$\Omega_\chi h^2 \propto m_\chi^{1/2} f_\chi^2$$
$$g_{\chi\gamma\gamma} = \frac{\alpha C}{2\pi f_\chi}$$

https://cajohare.github.io/AxionLimits/

Conclusion

- Time-averaging the heavy axion oscillations generates an effective potential for the light axion.
- We found that the effective potential for the light axion flips depending on the amplitude of the heavy axion.
- Through the Kapitza effect, the light axion abundance is significantly enhanced.