# Domain wall formation and baryogenesis in the Axiverse


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arXiv:1504.07917, 1505.07670



with Ryuji Daido & Fuminobu Takahashi (Tohoku University)


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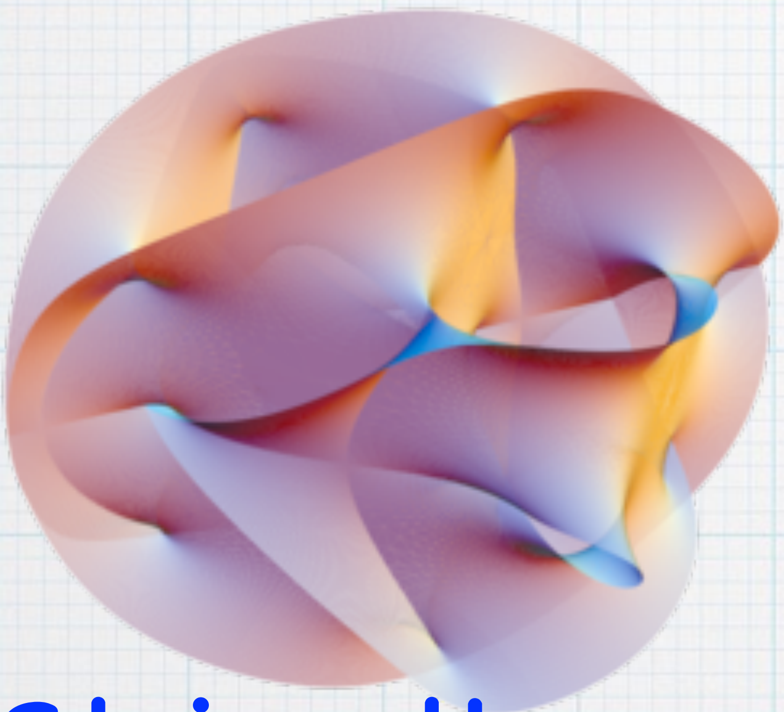
# Axions



String theory


String Axion

+

Field theoretic axions (QCD axion, etc...)

# AXIVERSE

Arvanitaki et al (2010)

# AXIVERSE

Arvanitaki et al (2010)


Dark matter

Inflaton

Solving strong CP problem

baryogenesis (this talk)

Dark energy

# AXION

Shift symmetry: $a \to a + C$

non-perturbative effect breaks shift symmetry

Axion potential: $V(a) \simeq \Lambda^4 \left(1 - \cos\left(\frac{a}{f}\right)\right)$

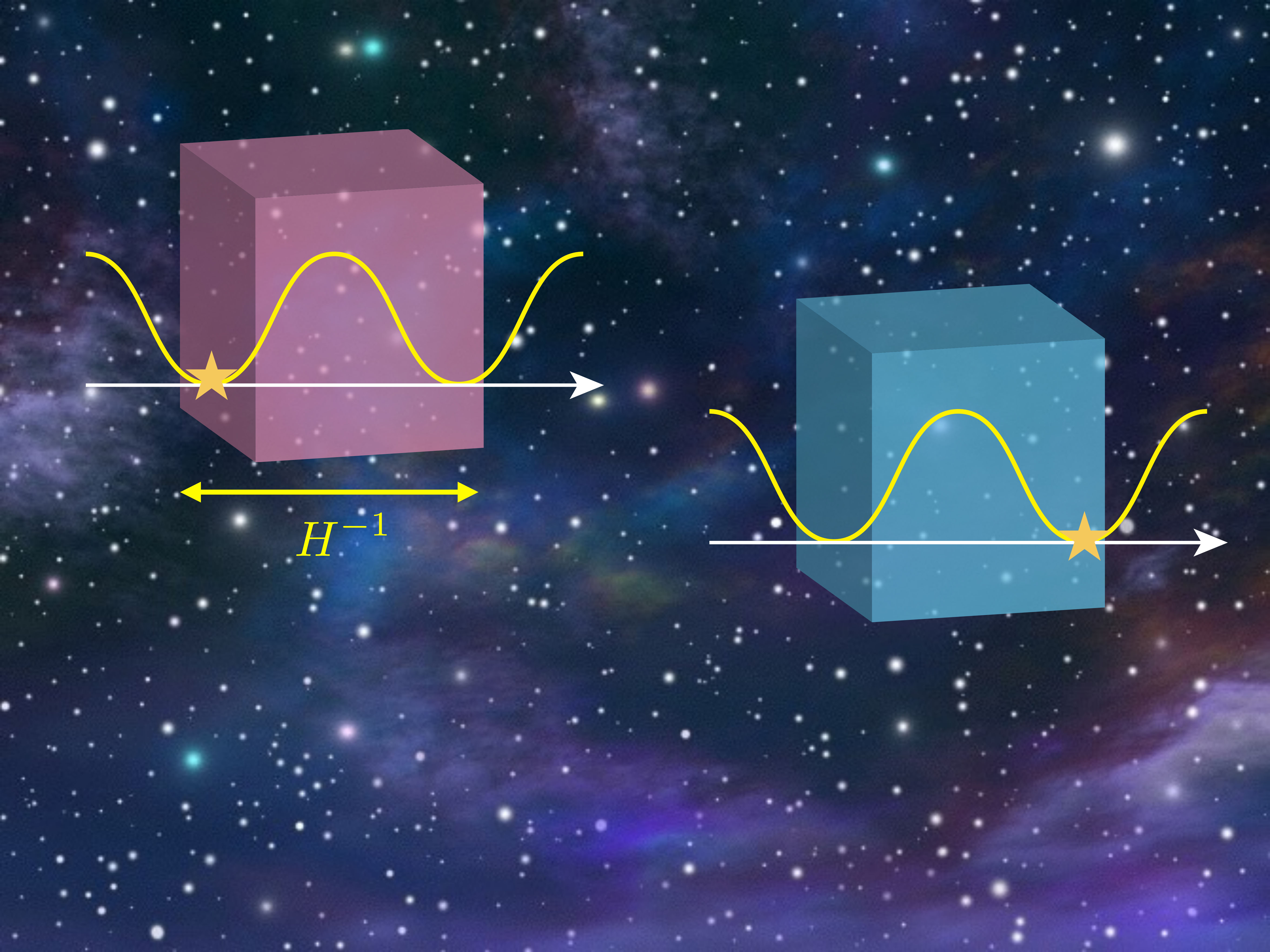
# AXION

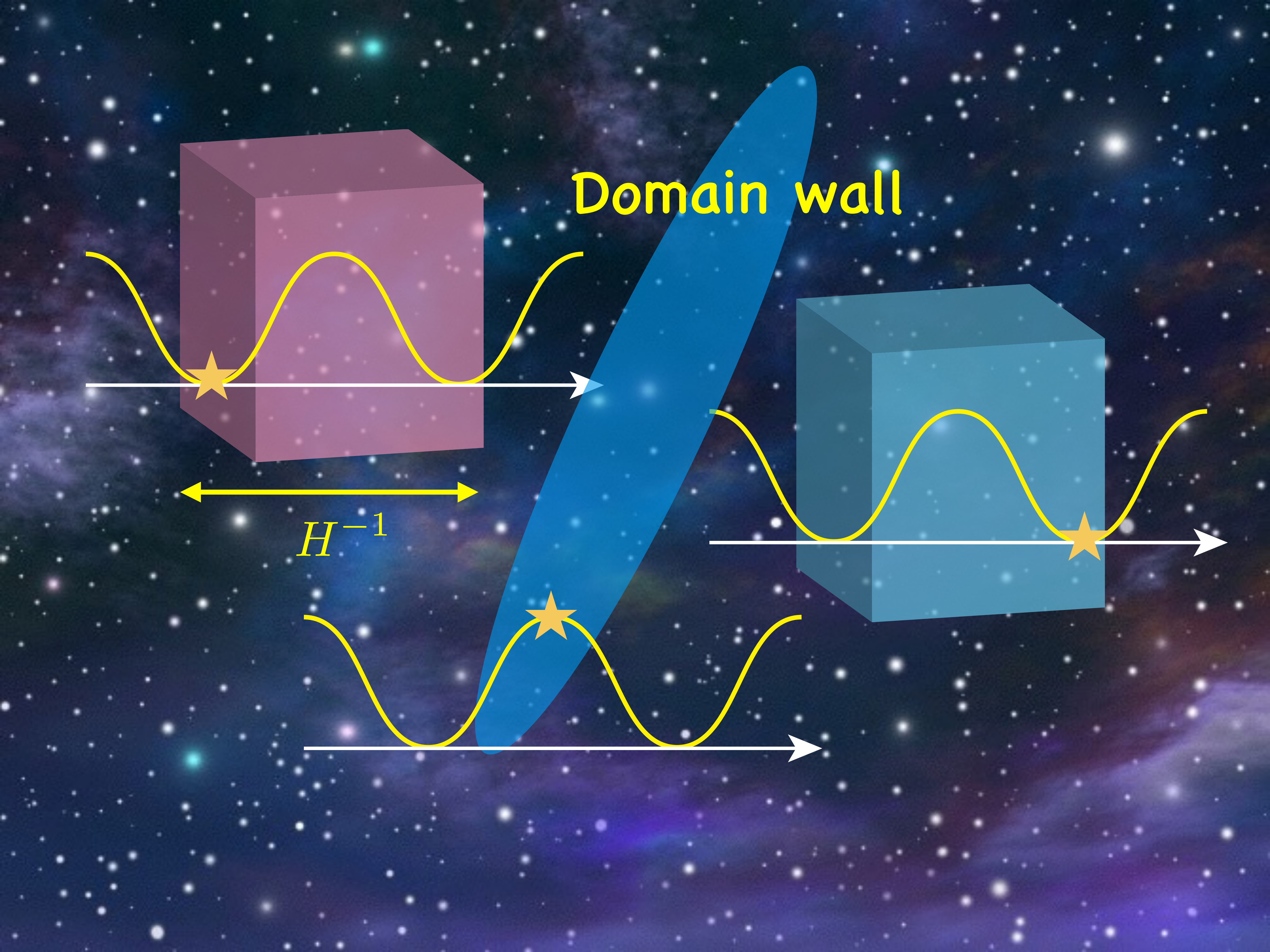
Shift symmetry: $a \to a + C$

non-perturbative effect breaks shift symmetry

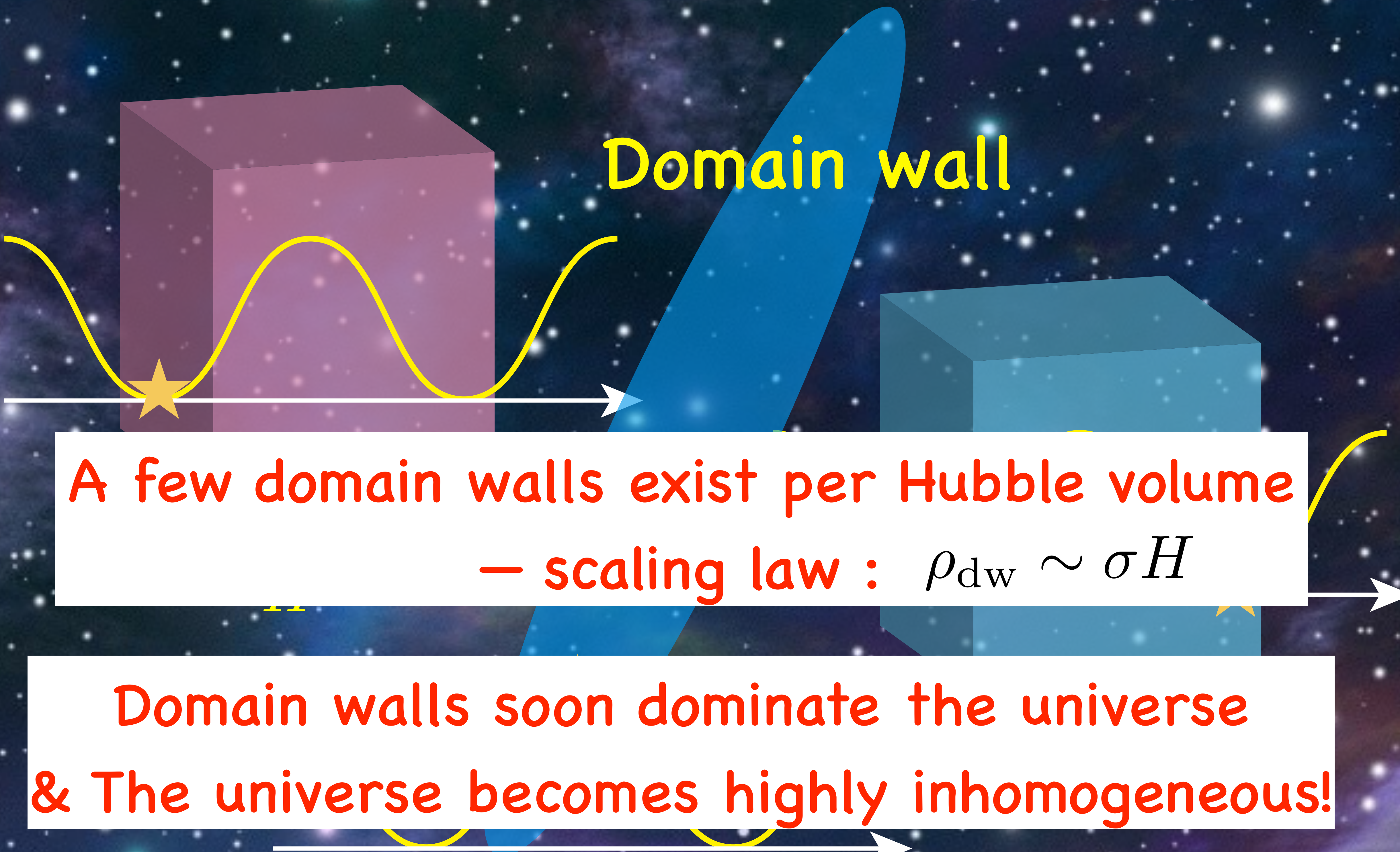
Axion potential: $V(a) \simeq \Lambda^4 \left(1 - \cos\left(\frac{a}{f}\right)\right)$


many degenerate minima!


$H^{-1}$



Domain wall
$H^{-1}$




A few domain walls exist per Hubble volume

– scaling law : $\rho_{\mathrm{dw}} \sim \sigma H$

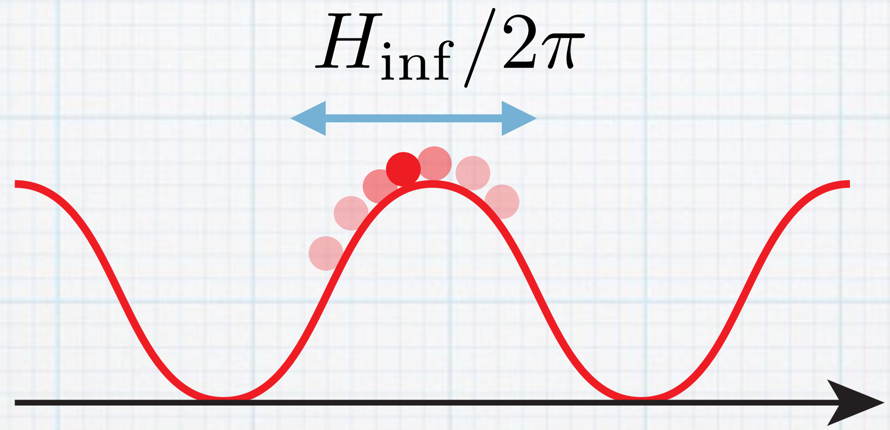
Domain walls soon dominate the universe

& The universe becomes highly inhomogeneous!

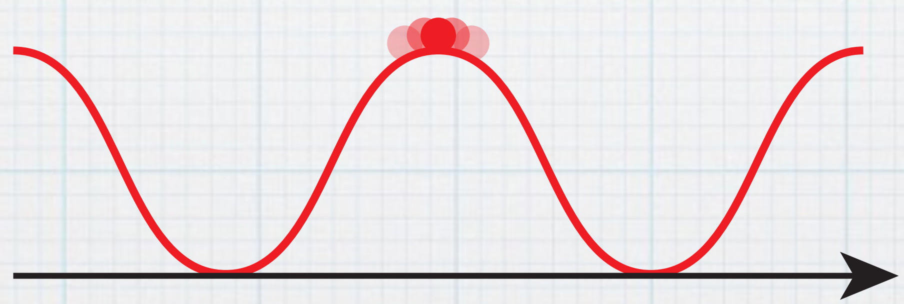
# Cosmological catastrophe

# Axion domain wall formation

- Large quantum fluctuation during inflation

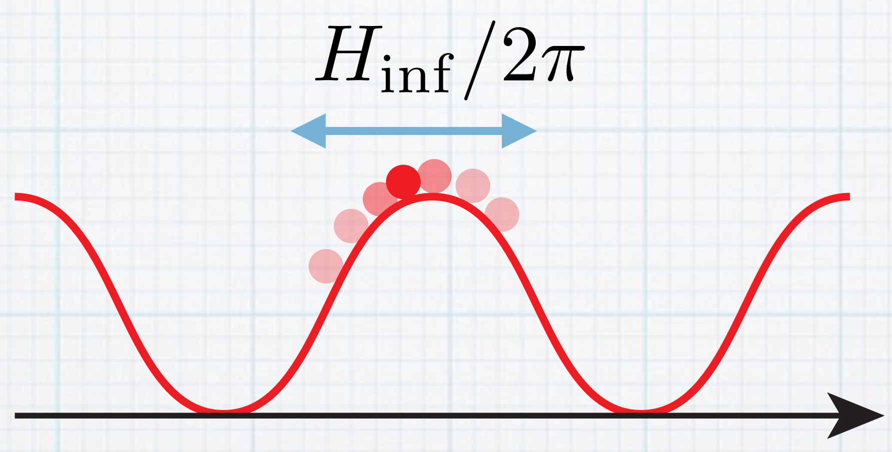



- Hilltop initial condition



# Axion domain wall formation

- Large quantum fluctuation during inflation

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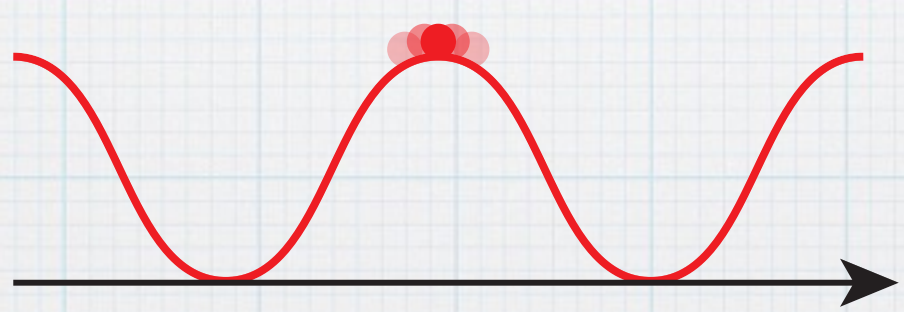


- Level crossing

New!

# I

# Domain wall formation via level crossing

R. Daido, NK, F. Takahashi, arXiv:1505.07670

# Two axion model

C. T. Hill, G. G. Ross (1988), NK, F. Takahashi (2014)

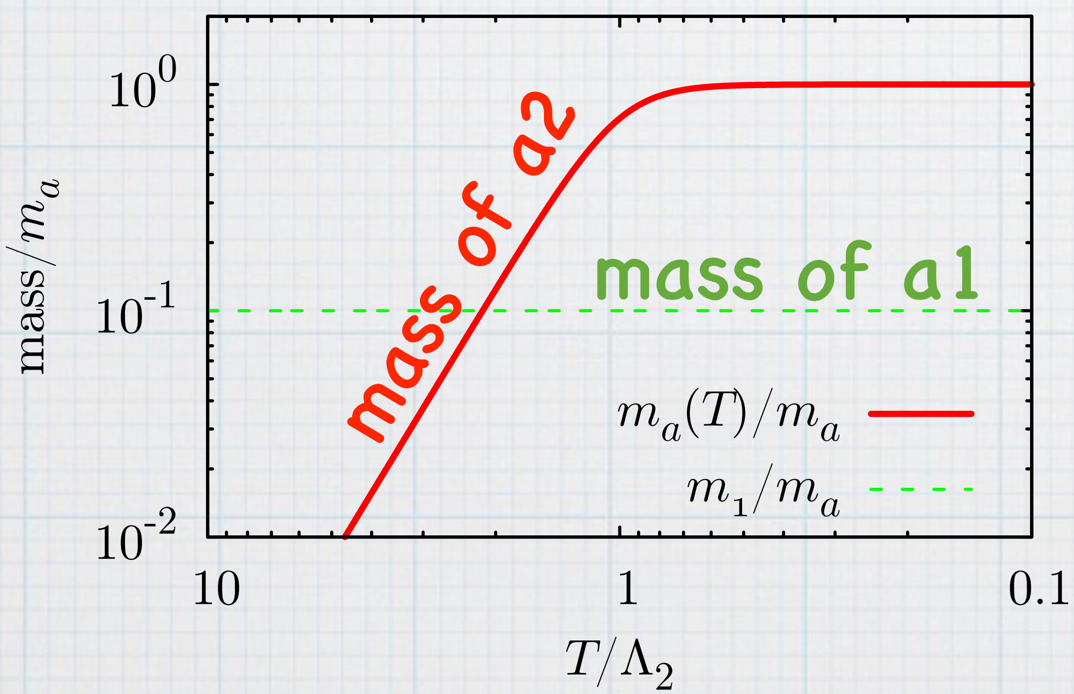
$$\mathcal{L} = \sum_{i=1,2} \frac{1}{2}\partial^\mu a_i \partial_\mu a_i - V_1(a_1, a_2) - V_2(a_1, a_2)$$

Axion mixing

$$V_1(a_1, a_2) = \Lambda_1^4 \left(1 - \cos\left(n_1 \frac{a_1}{f_1} + n_2 \frac{a_2}{f_2}\right)\right)$$

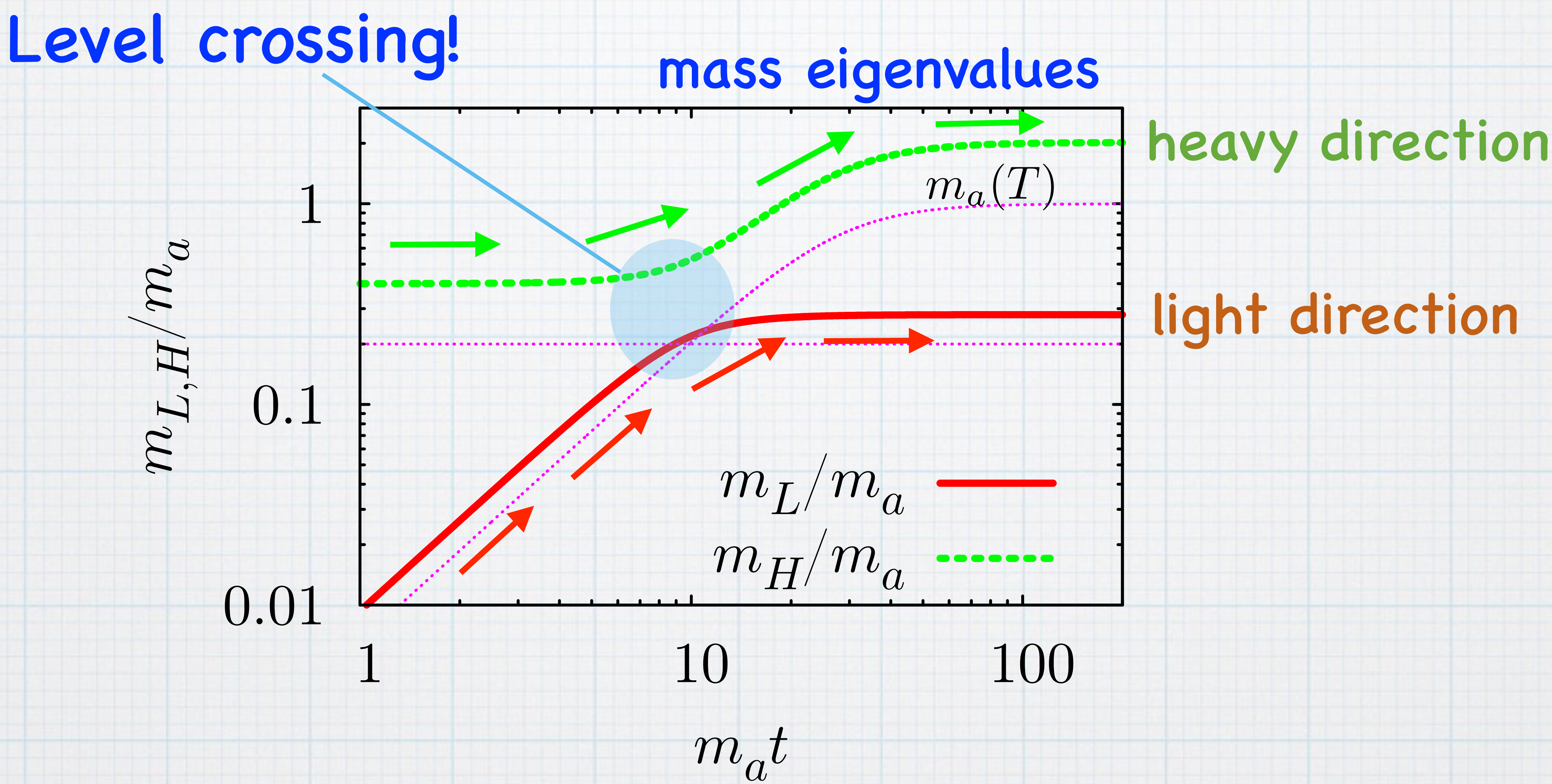
$$V_2(a_1, a_2) = m_a^2(T) f_2^2 \left(1 - \cos\left(\frac{a_2}{f_2}\right)\right)$$

Temperature-dependent mass




$$m_a(T) = \min\left[m_a \left(\frac{T}{\Lambda_2}\right)^p,\ m_a\right]$$

# Level crossing

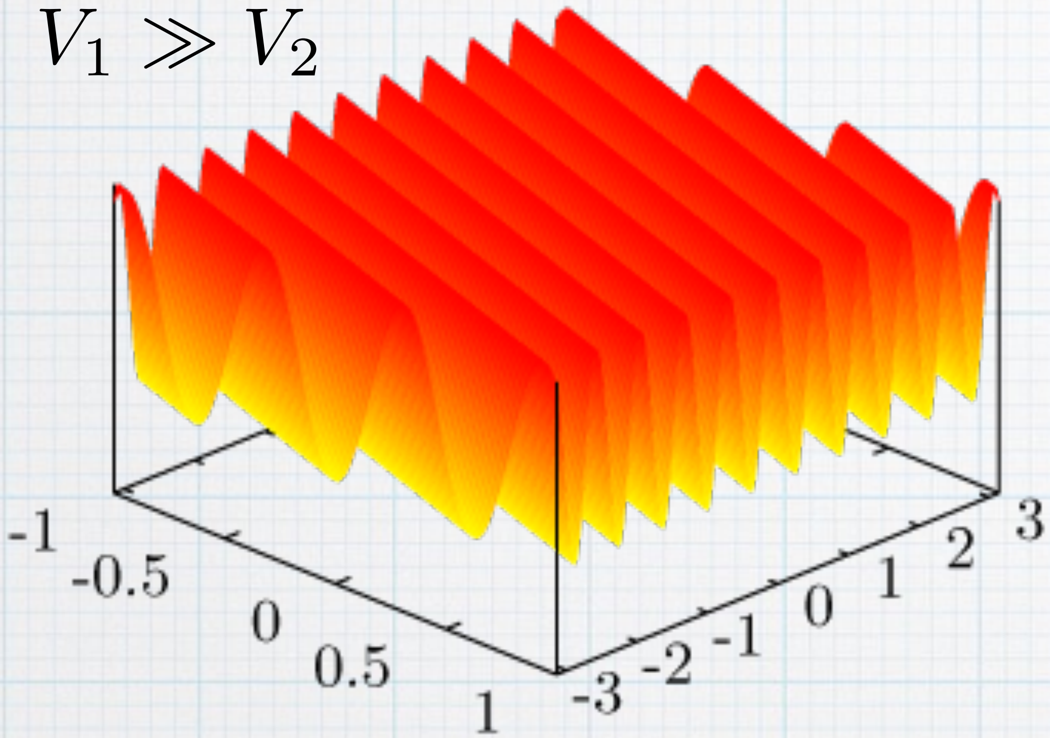


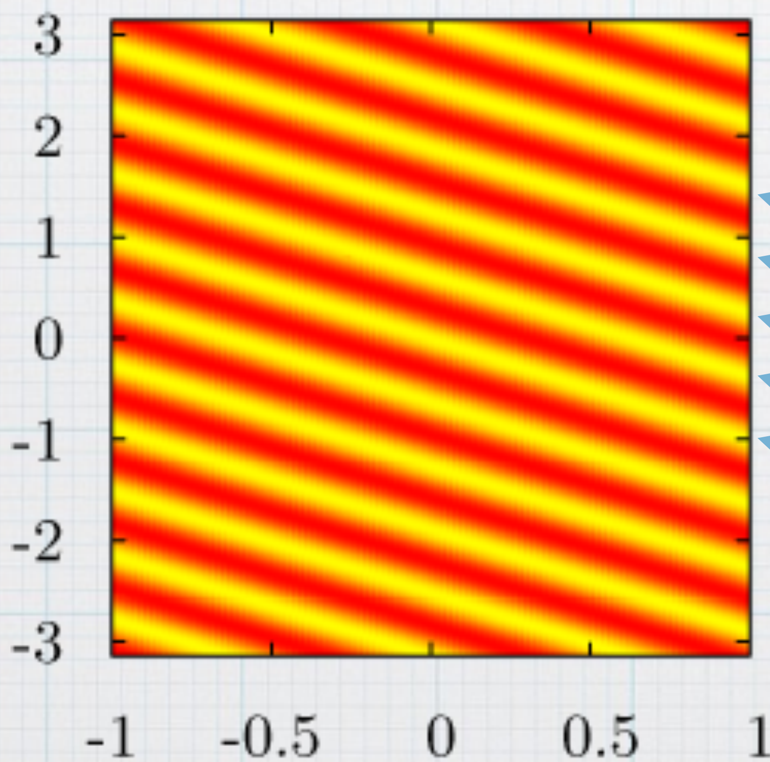

$$V_1(a_1,a_2) = \Lambda_1^4\left(1-\cos\left(n_1\frac{a_1}{f_1}+n_2\frac{a_2}{f_2}\right)\right)$$

$$V_2(a_1,a_2) = m_a^2(T)f_2^2\left(1-\cos\left(\frac{a_2}{f_2}\right)\right) \qquad m_a(T) = \min\left[m_a\left(\frac{T}{\Lambda_2}\right)^p,\ m_a\right]$$

# Evolution of the axion potential

$V_1 \gg V_2$

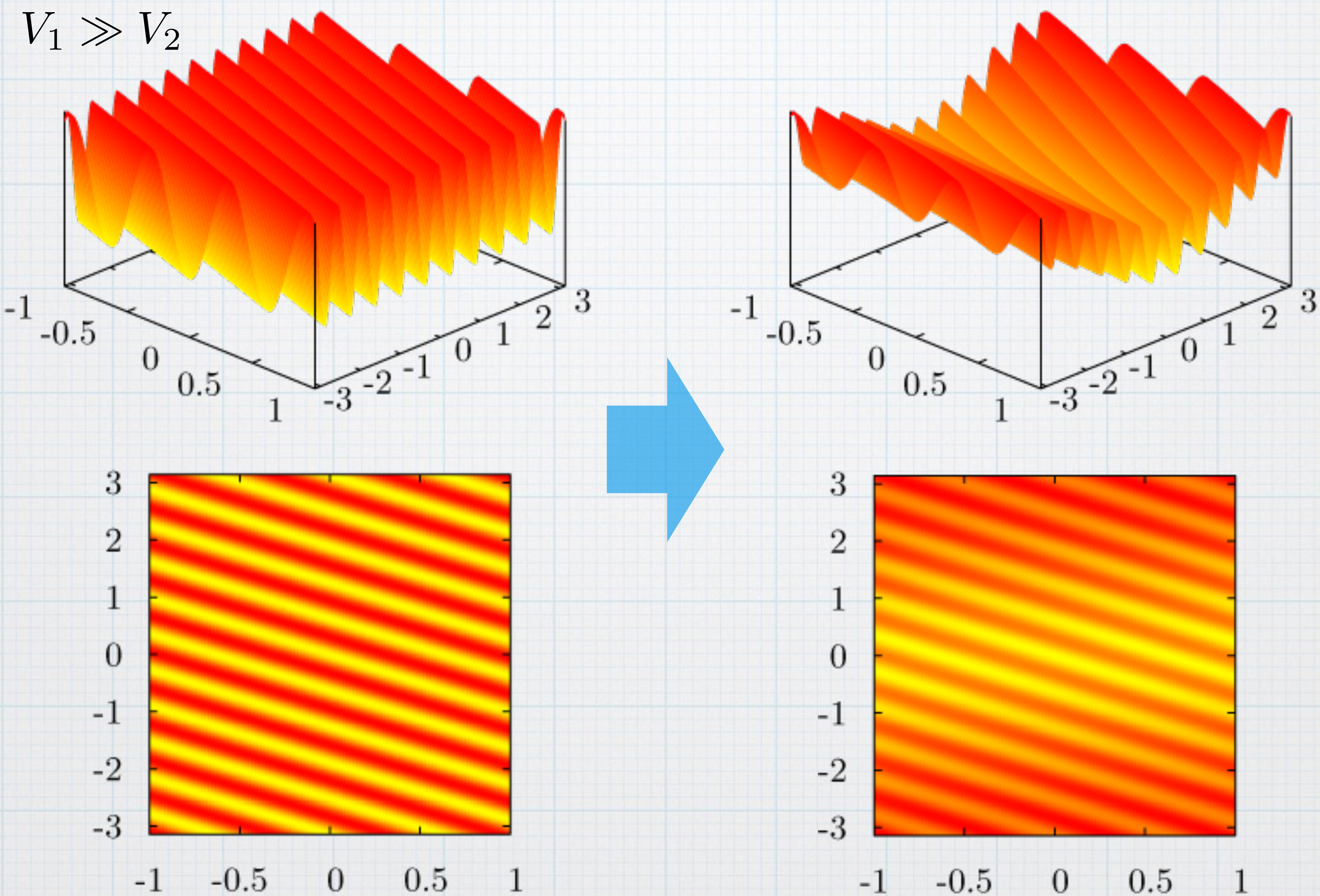


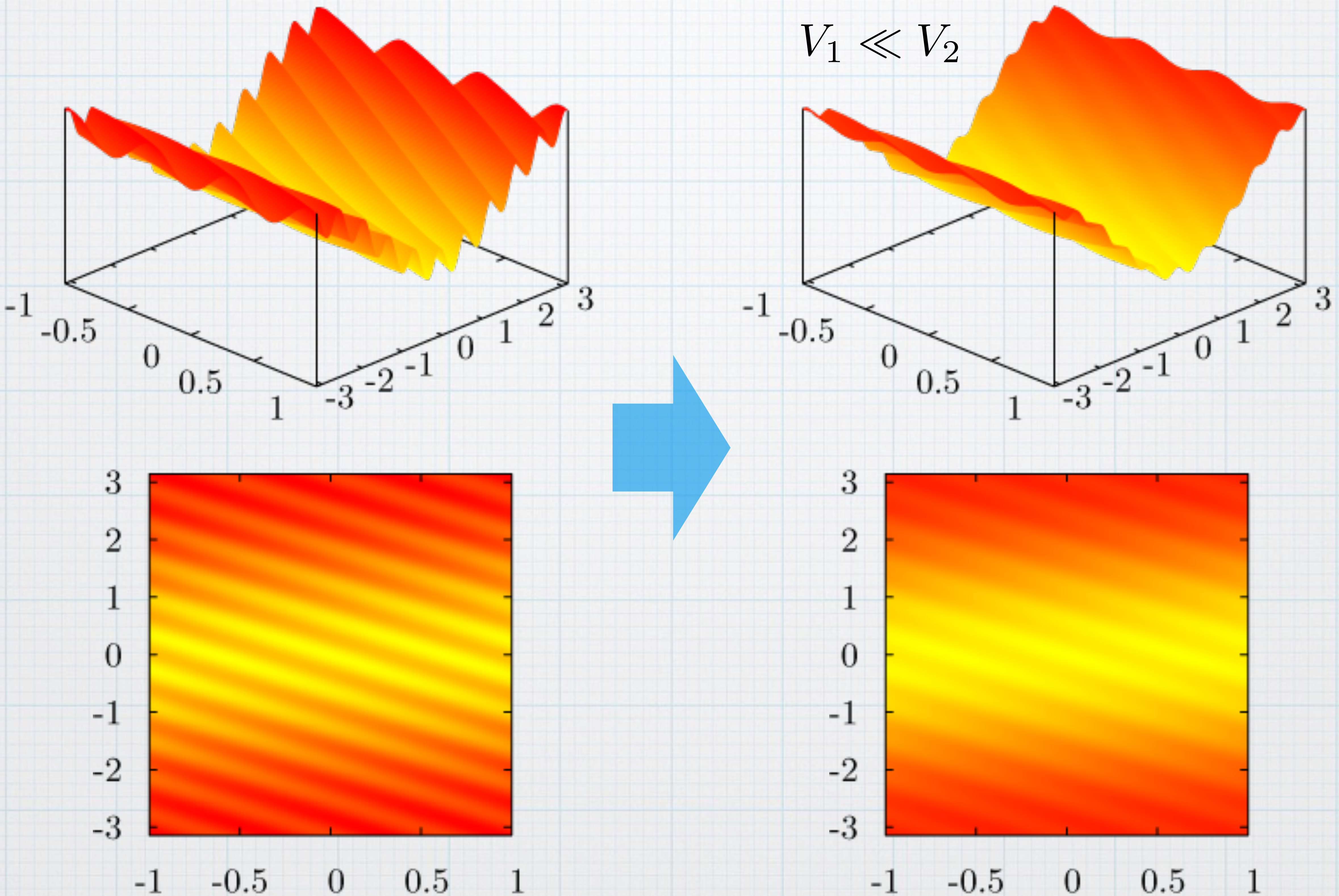

flat direction

$$n_1 \frac{a_1}{f_1} + n_2 \frac{a_2}{f_2} = \text{const.}$$

# Evolution of the axion potential

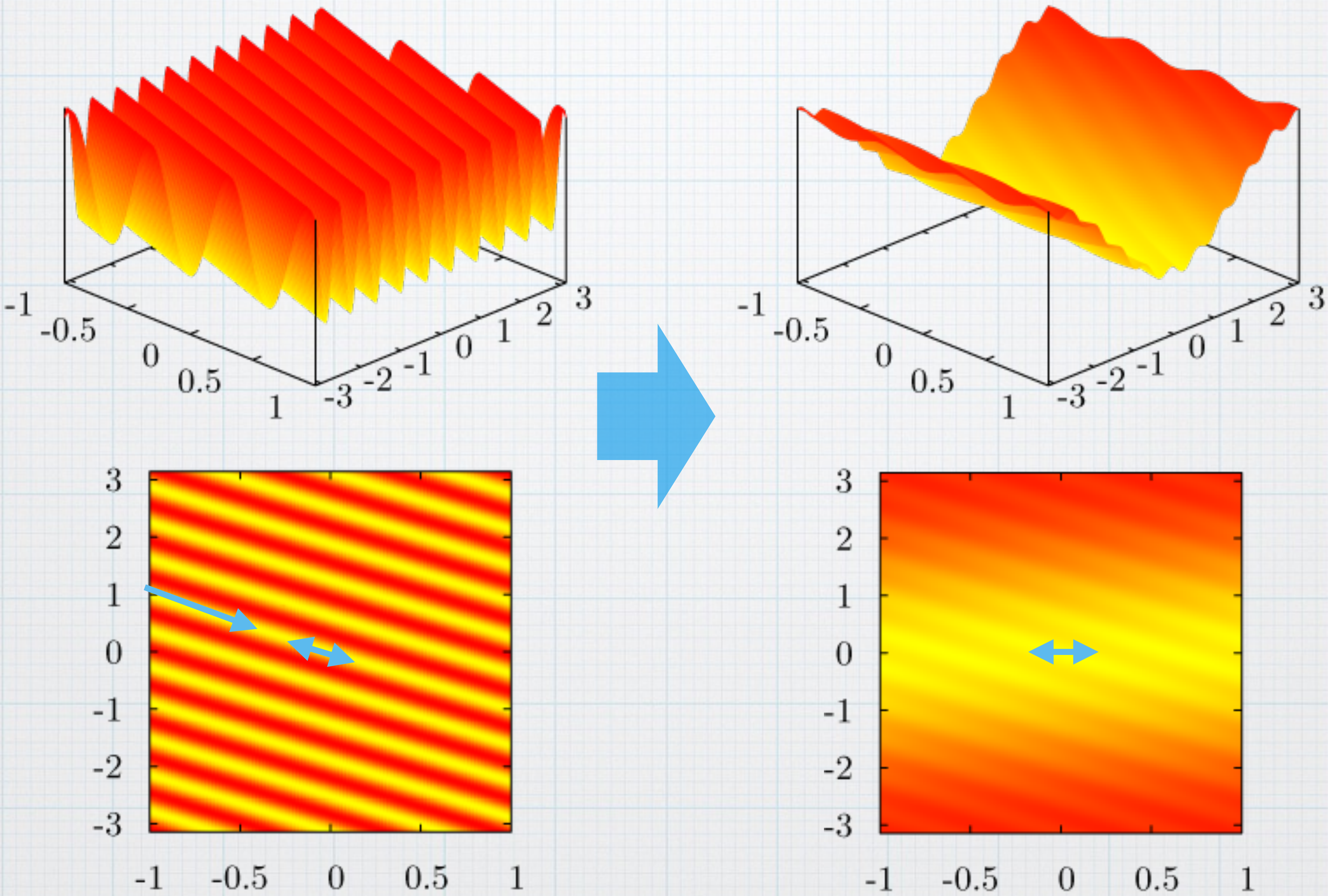


# Evolution of the axion potential



# (i) Resonant conversion : $H_{\rm lc} \gg H_{\rm osc}$

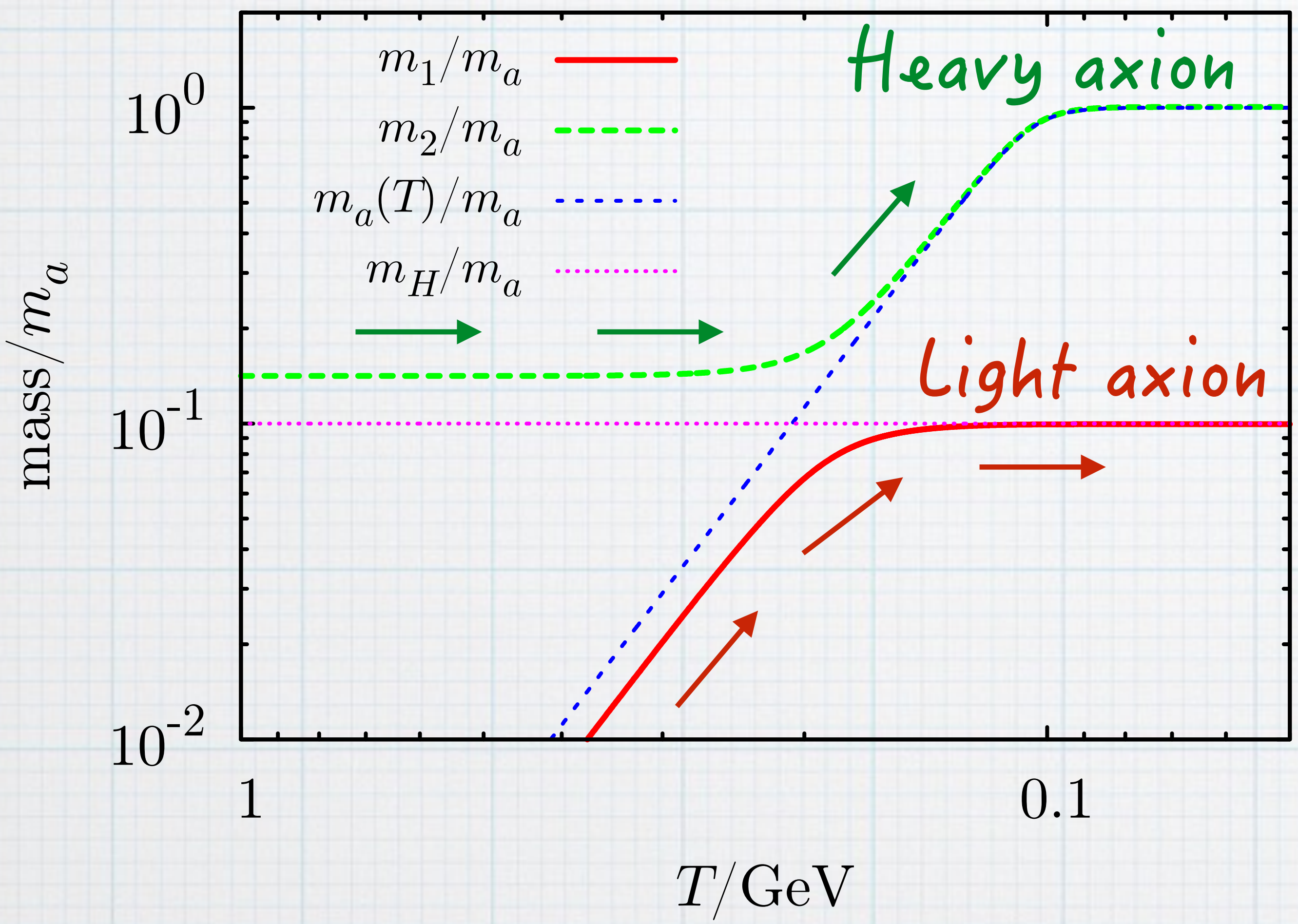
NK, F. Takahashi [1411.2011]

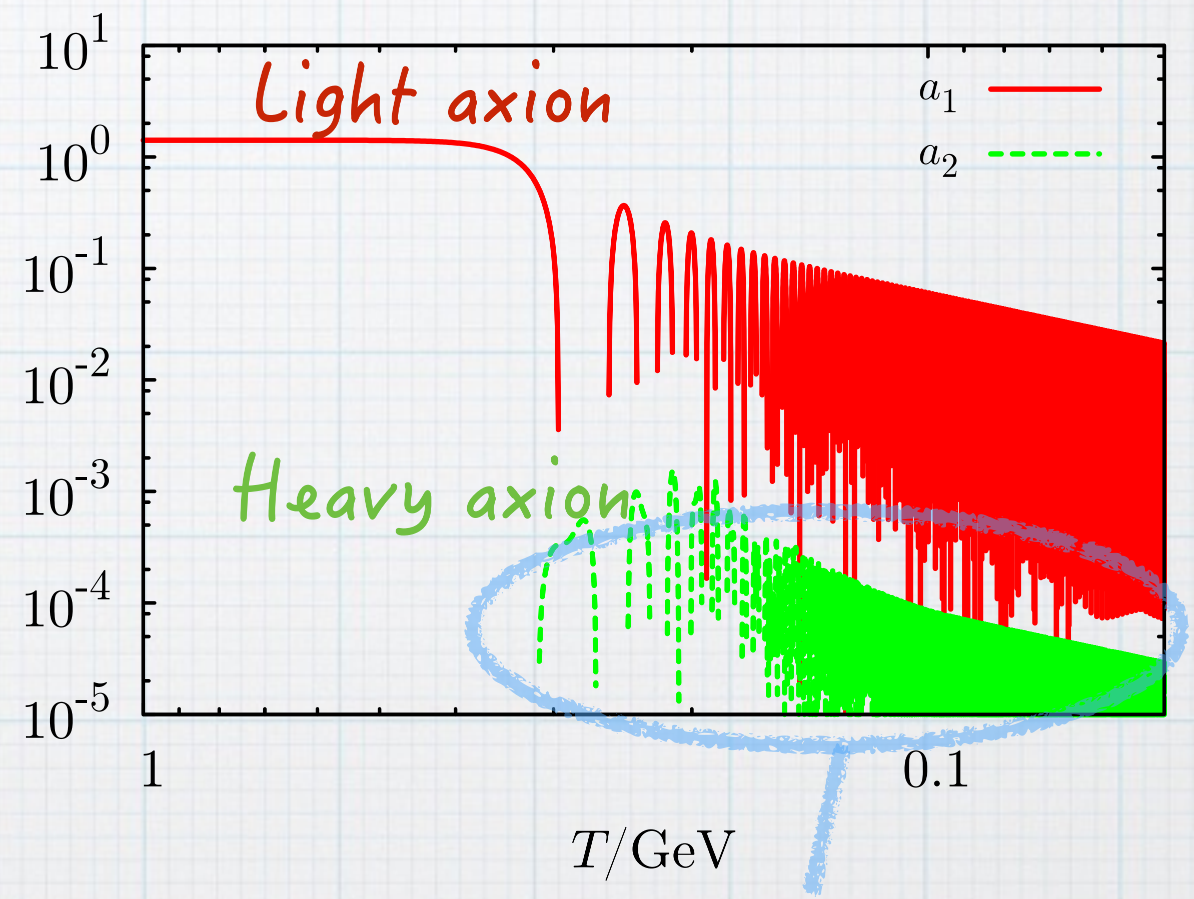


# (i) Resonant conversion : $H_{\rm lc} \gg H_{\rm osc}$

NK, F. Takahashi [1411.2011]

QCD axion + hidden axion

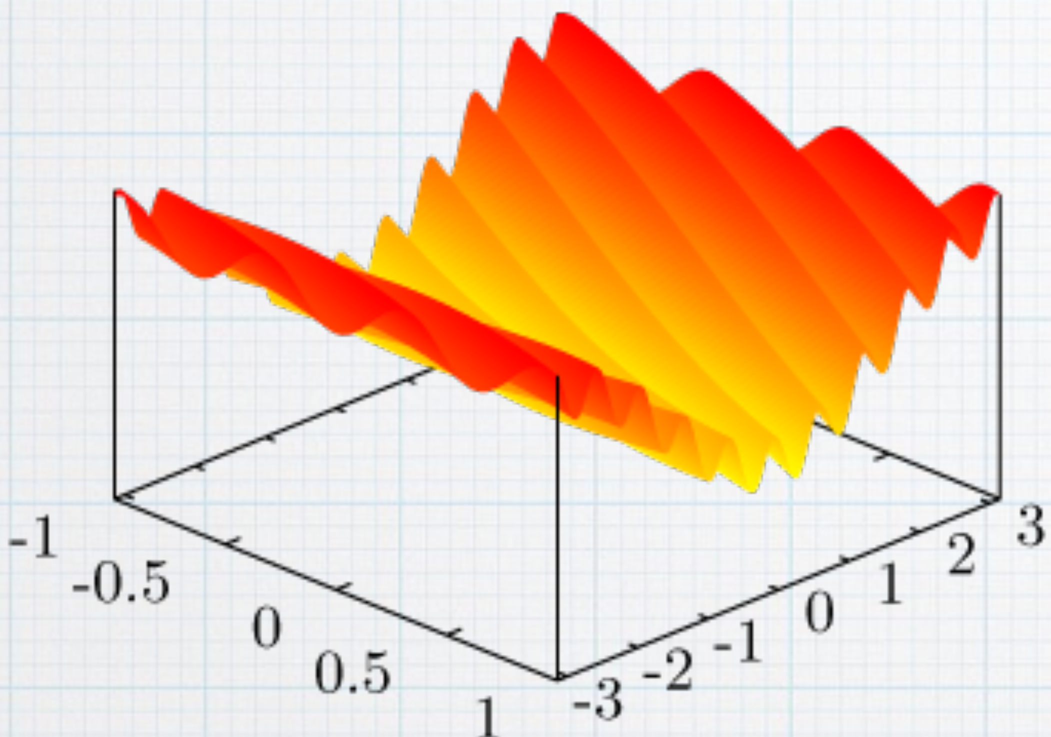


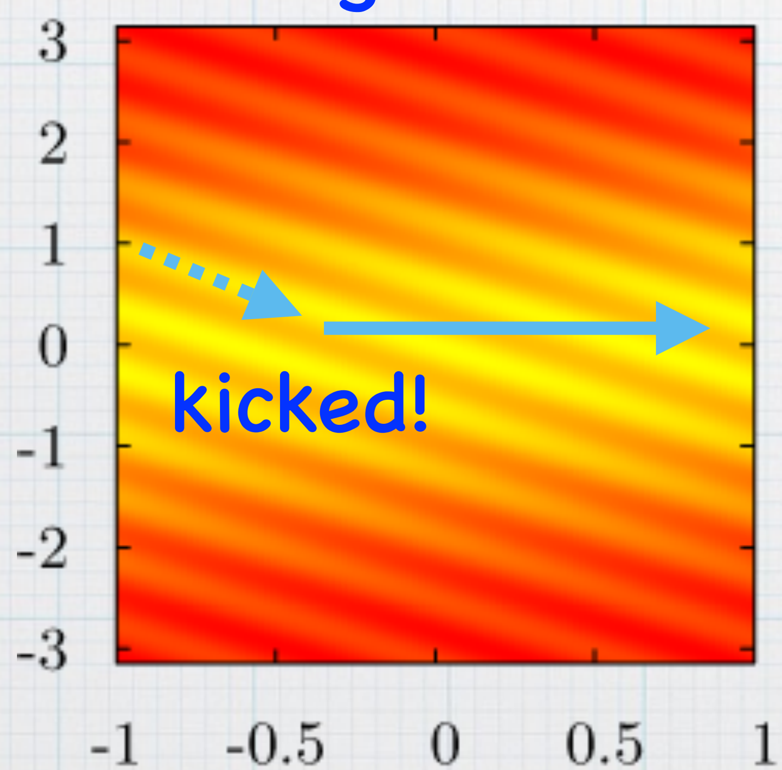

Heavy axion is suppressed

$$\rho_a \sim (m_L/m_H)\rho_a|_{\rm no-resonance}$$

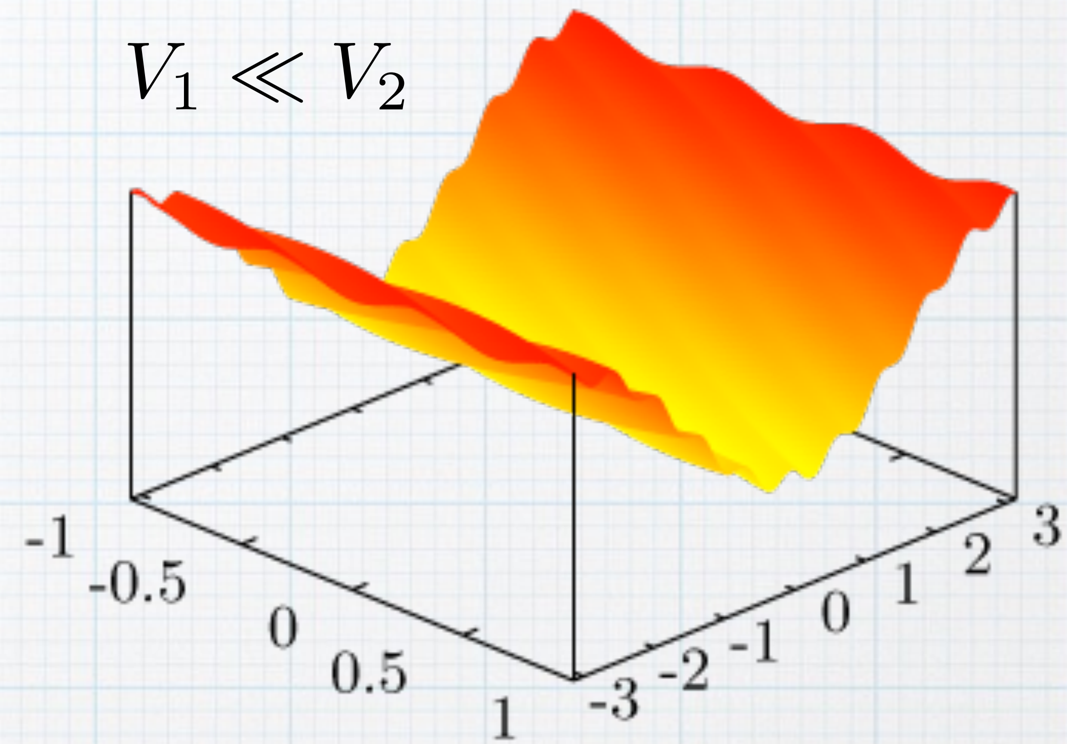
## (ii) ~~Resonant conversion~~ : $H_{\rm lc} \sim H_{\rm osc}$

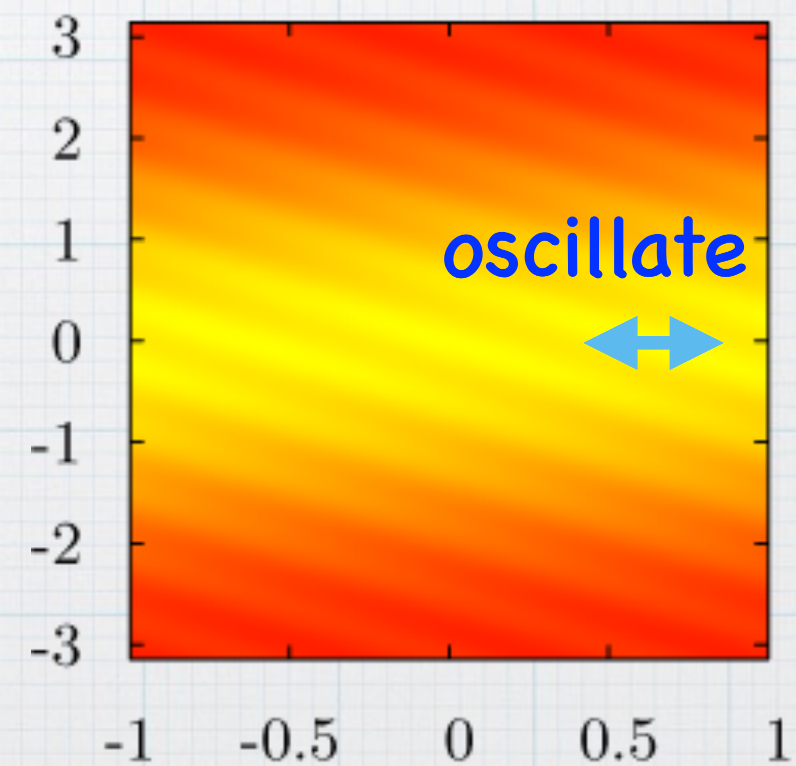


Level crossing ≈ oscillation

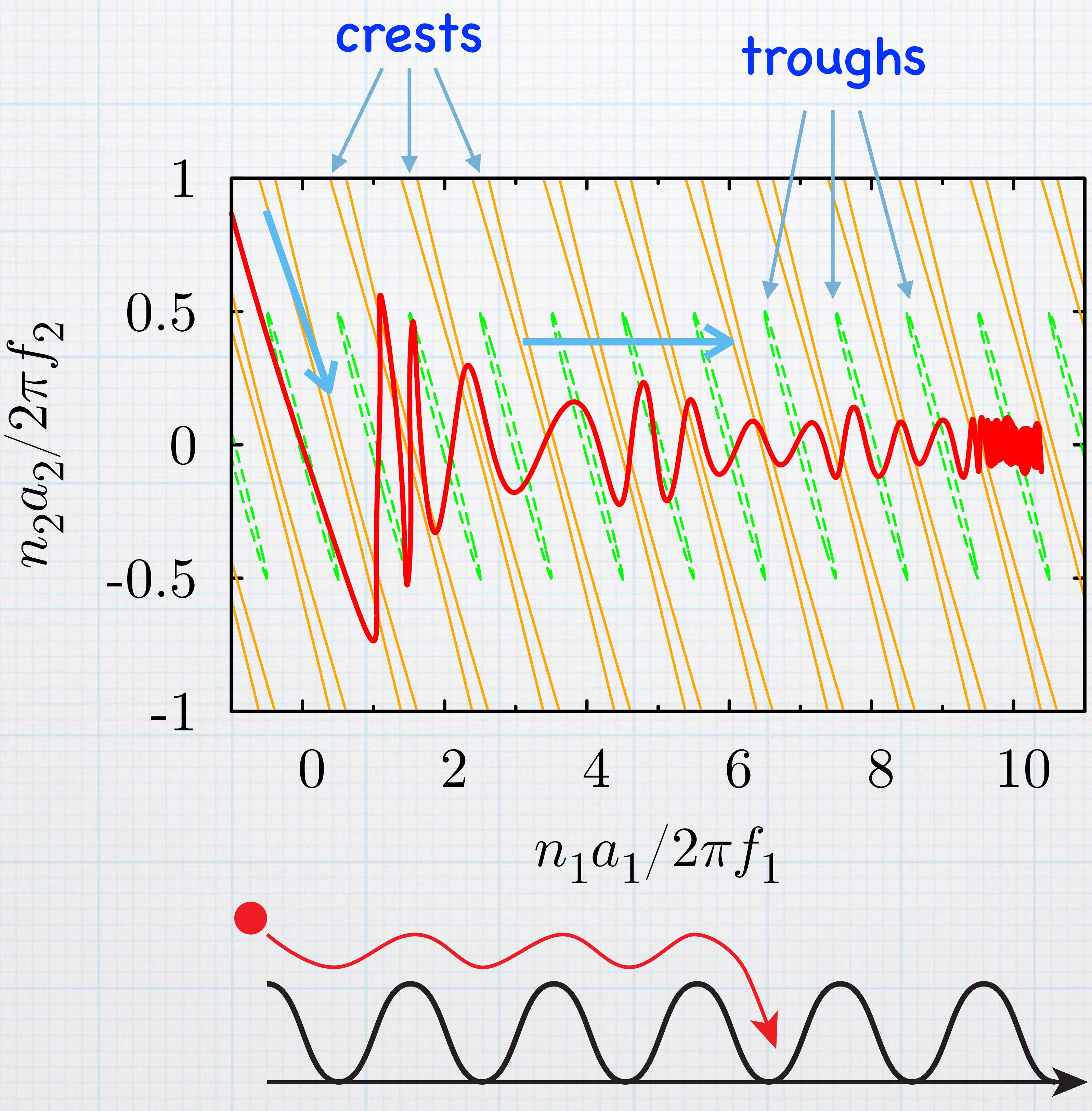



$V_1 \ll V_2$





# Axion trajectory



# The conditions to climb over the potential barrier

$$(1)\quad \rho_{L,\mathrm{osc}} \sim m_{\mathrm{osc}}^2 f^2 > \Lambda_1^4 \sim m_{H,\mathrm{osc}}^2 F^2$$

effective decay constants: $f = \dfrac{\sqrt{n_2^2 f_1^2 + n_1^2 f_2^2}}{n_1}, \quad F = \dfrac{f_1 f_2}{\sqrt{n_2^2 f_1^2 + n_1^2 f_2^2}}$

Kim, Nilles, Peloso (2005)

—> kinetic energy > potential barrier

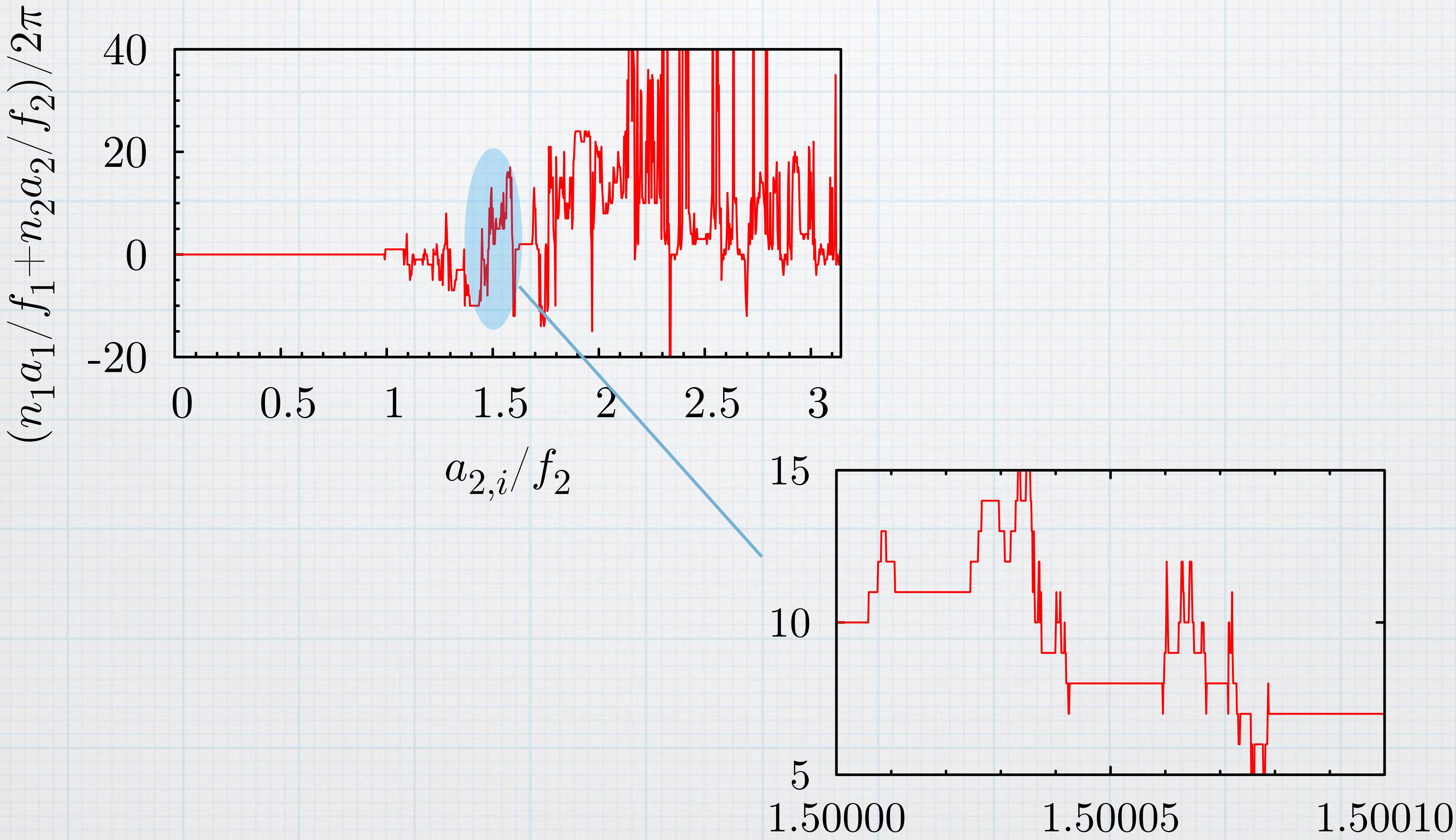
$$(2)\quad H_{\mathrm{lc}} \sim (0.1-1) H_{\mathrm{osc}}$$

—> Level crossing occurs soon after the onset of axion oscillation

$$V_1(a_1, a_2) = \Lambda_1^4 \left(1 - \cos\left(n_1 \frac{a_1}{f_1} + n_2 \frac{a_2}{f_2}\right)\right)$$

$$V_2(a_1, a_2) = m_a^2(T) f_2^2 \left(1 - \cos\left(\frac{a_2}{f_2}\right)\right)$$

The eventual minimum is very sensitive to the initial position!!



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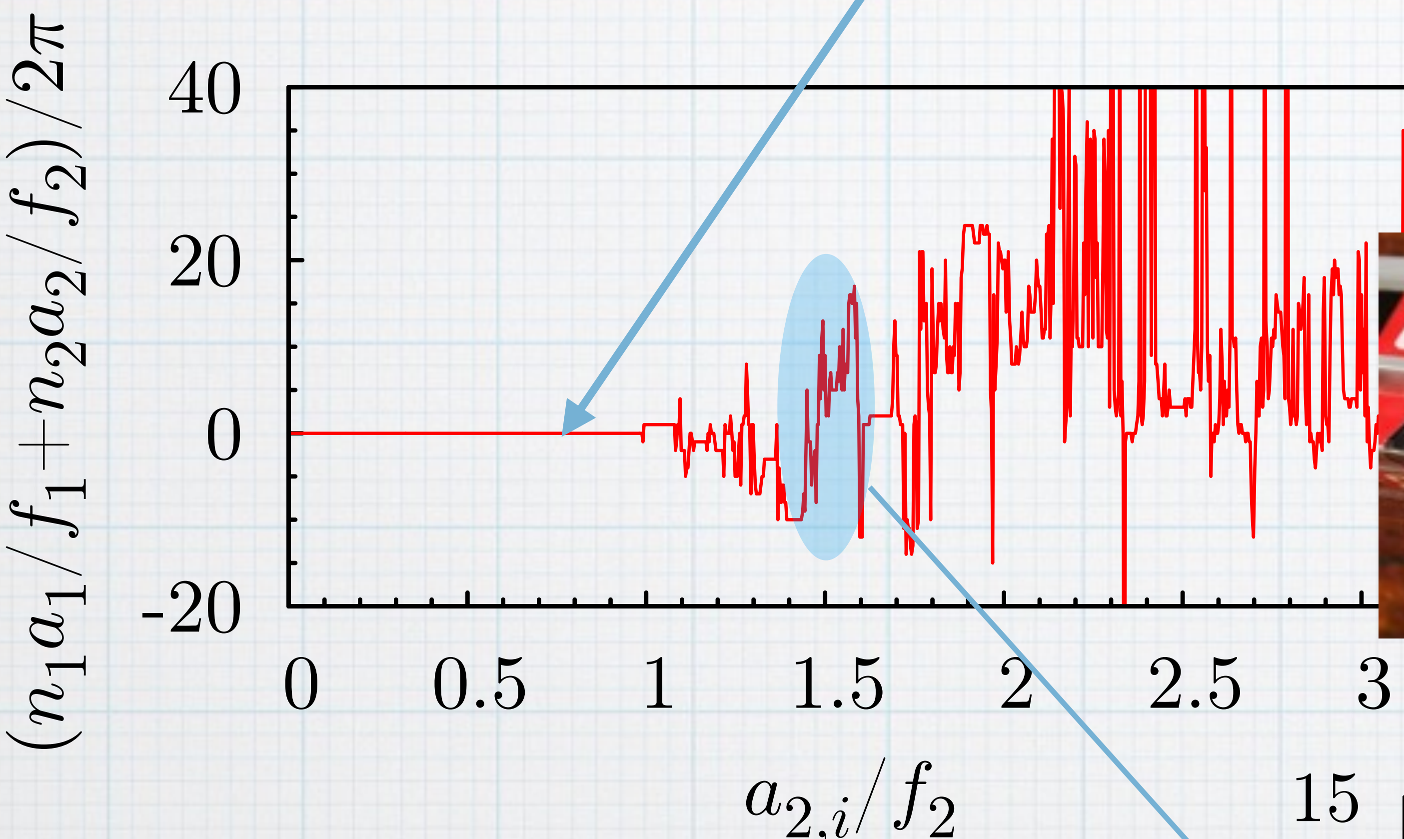
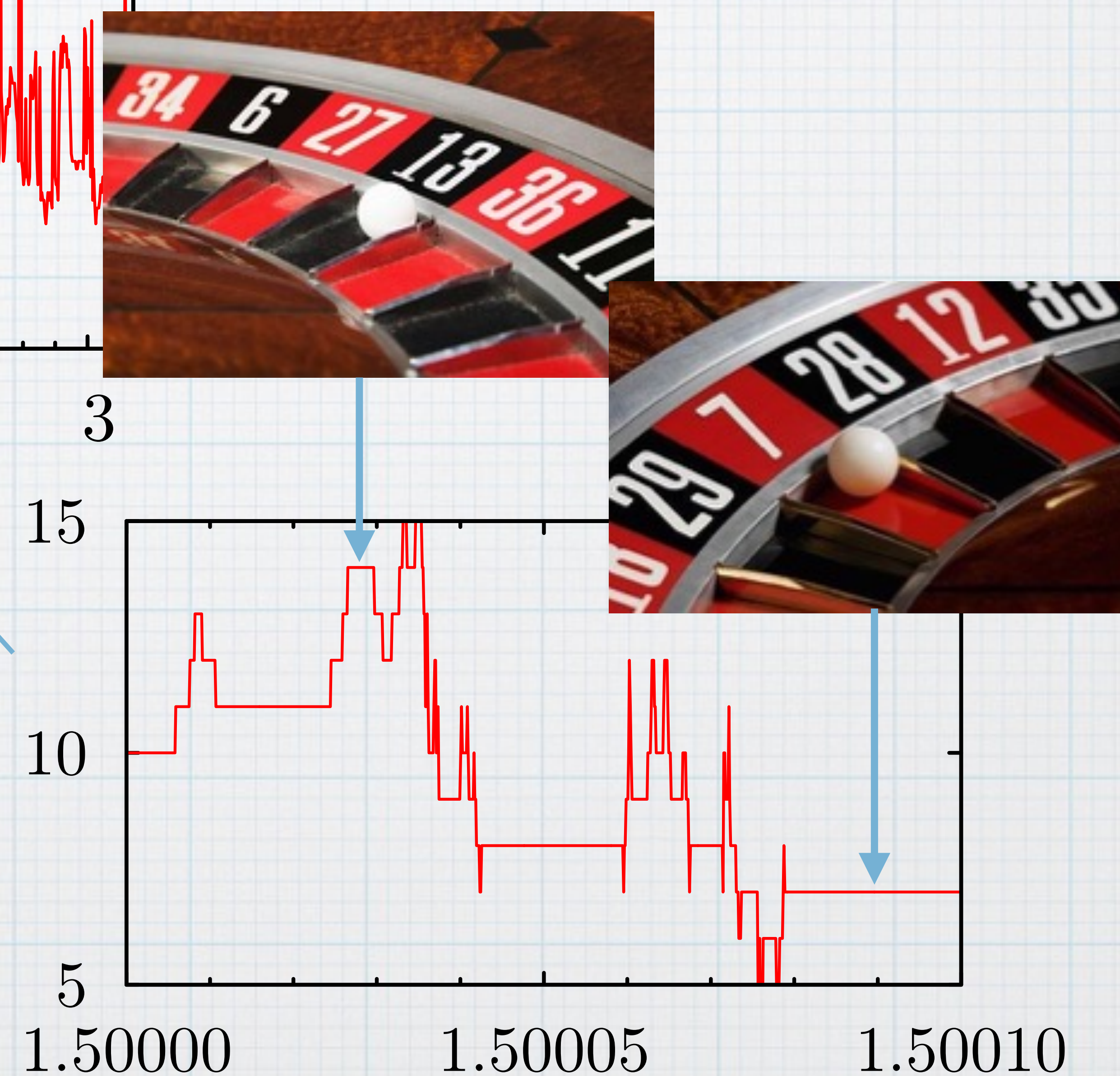



# Axion "ROULETTE"

Domain wall
$H^{-1}$

II

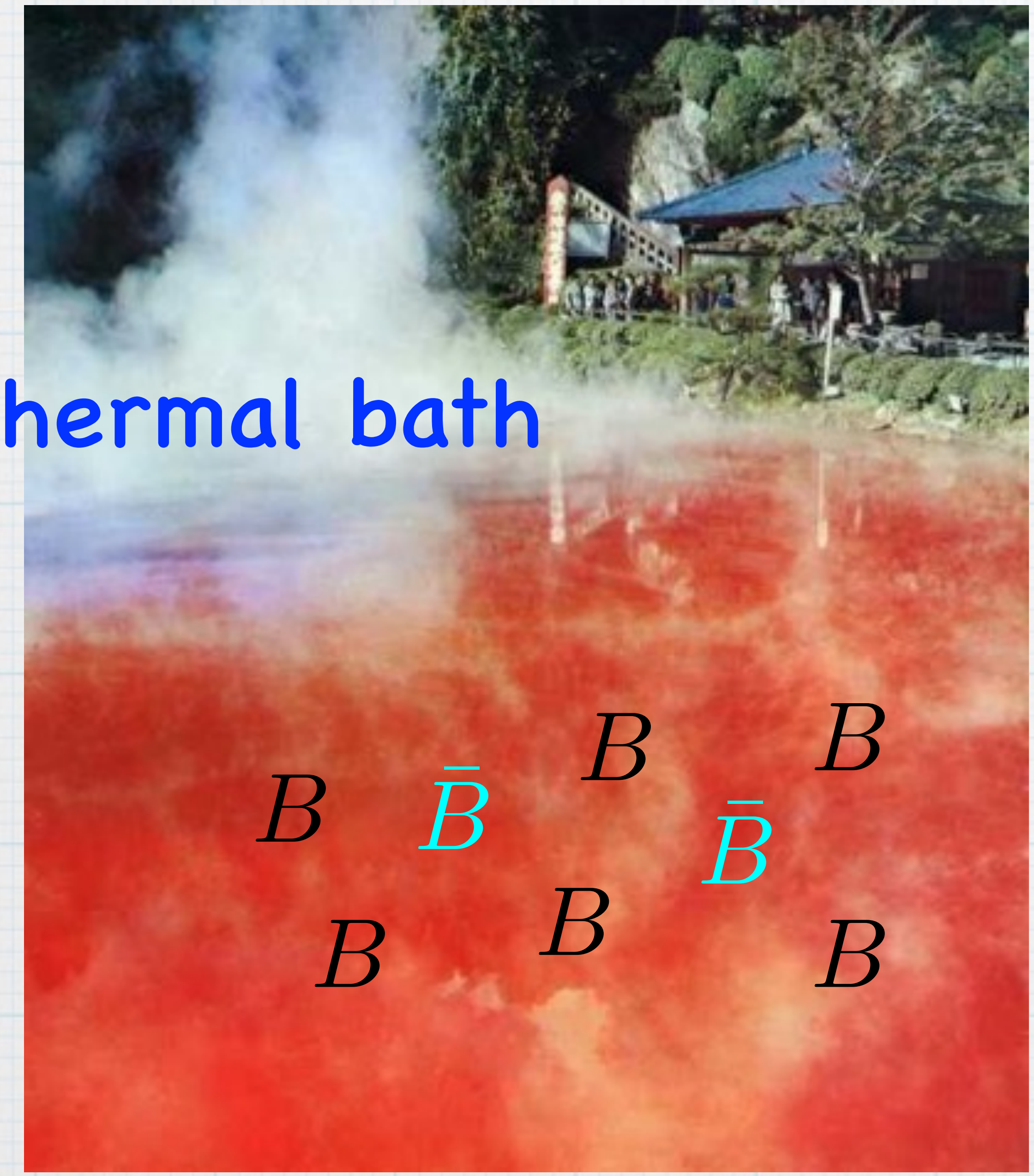
# Axion domain wall Baryogenesis

R. Daido, NK, F. Takahashi, arXiv:1504.07917

# Spontaneous Baryogenesis

A. G. Cohen, D. B. Kaplan (1987)

Thermal bath




nonzero chemical potential : $\mu \neq 0$

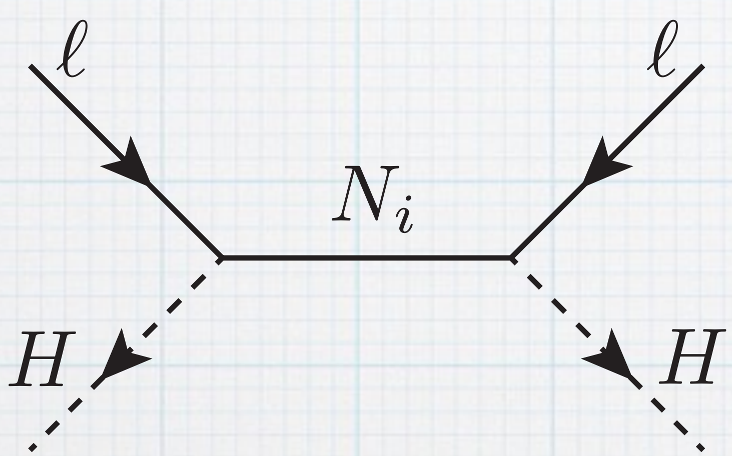
$$n_\ell^{\rm eq} - n_{\bar{\ell}}^{\rm eq} \simeq 2\mu T^2$$

baryon asymmetry is generated even in thermal equilibrium!

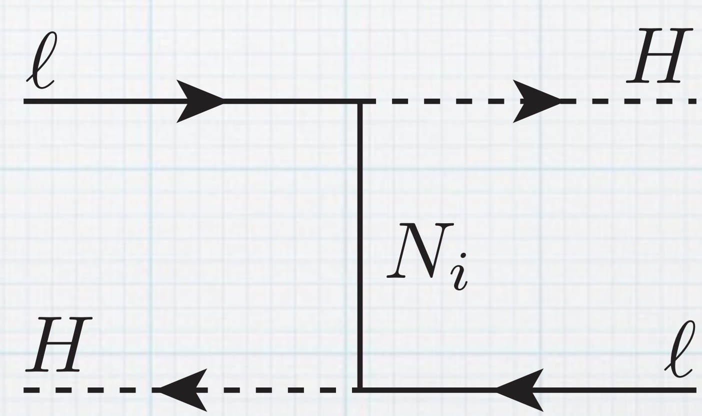
# Lepton number violating processes

## Seesaw model
## (Standard Model + right-handed neutrinos)

$$\ell\ell \leftrightarrow HH$$




$$\ell H \leftrightarrow \bar{\ell}\bar{H}$$




**interaction rate**

$$\Gamma_{\mathrm{int}} \sim \frac{T^3}{\pi^3}\frac{\sum m_i^2}{v_{\mathrm{EW}}^4}$$

**decoupling temperature**

$$T_{\mathrm{dec}} \sim 3 \times 10^{13}\ \mathrm{GeV}$$

# Derivative coupling with lepton currents

$$\mathcal{L} \ni \frac{\partial_\mu a}{f} \sum_{i=e,\mu,\tau} \bar{L}_i \gamma^\mu L_i \equiv \frac{\partial_\mu a}{f} j_L^\mu = \frac{\dot{a}}{f} j_L^0 + \dots$$

or anomalous coupling : $\mathcal{L} \ni \frac{g^2}{32\pi^2} \frac{a}{f} F\tilde{F}$

$$\mu_{\text{eff}} = \frac{\dot{a}}{f}$$ Effective chemical potential

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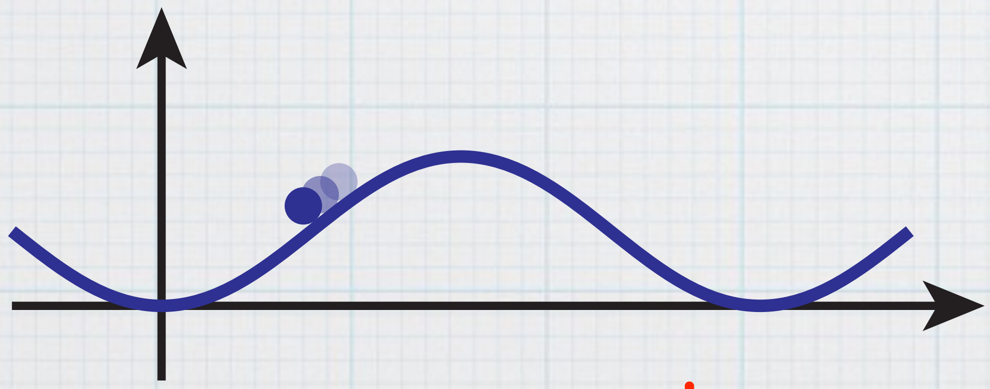
At the onset of axion oscillation -> $\mu_{\text{eff}} \neq 0$



spontaneous baryogenesis works

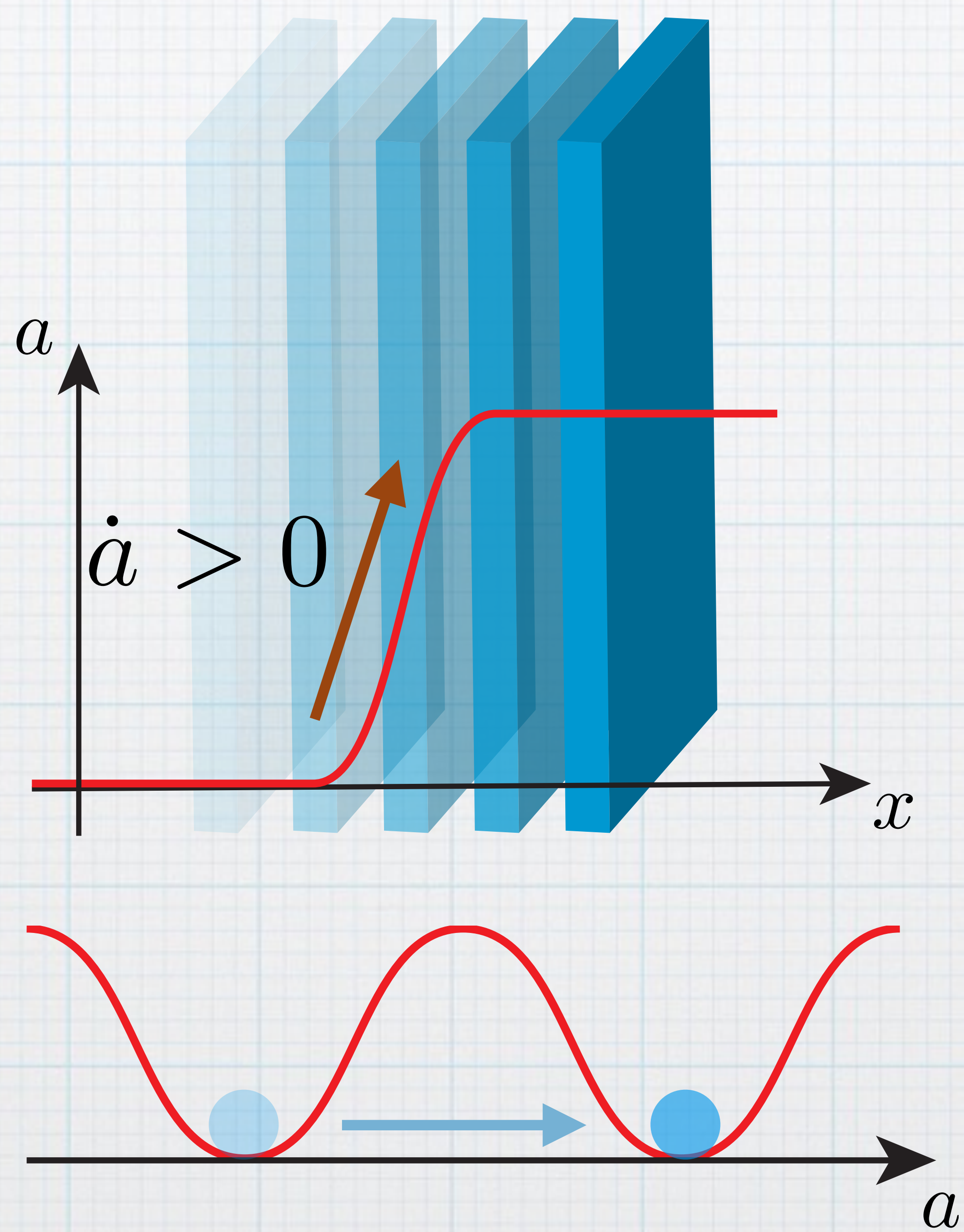
Kusenko,Schmitz,Yanagida (2014)

! severe baryon isocurvature problem

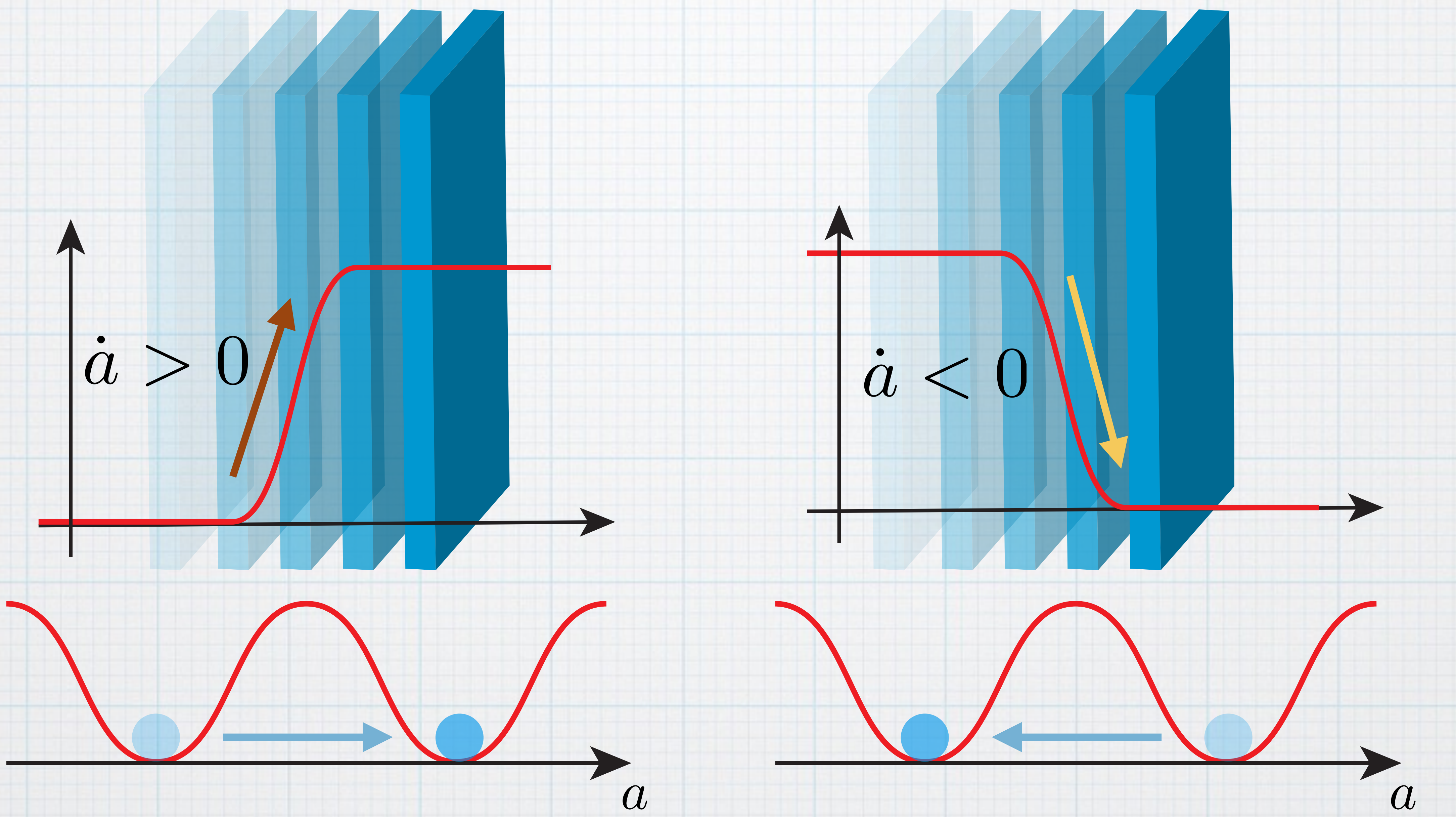
# Domain wall baryogenesis

R. Daido, NK, F. Takahashi, 1504.07917

## Moving domain walls can generate effective chemical potential



# 2 types of moving domain walls

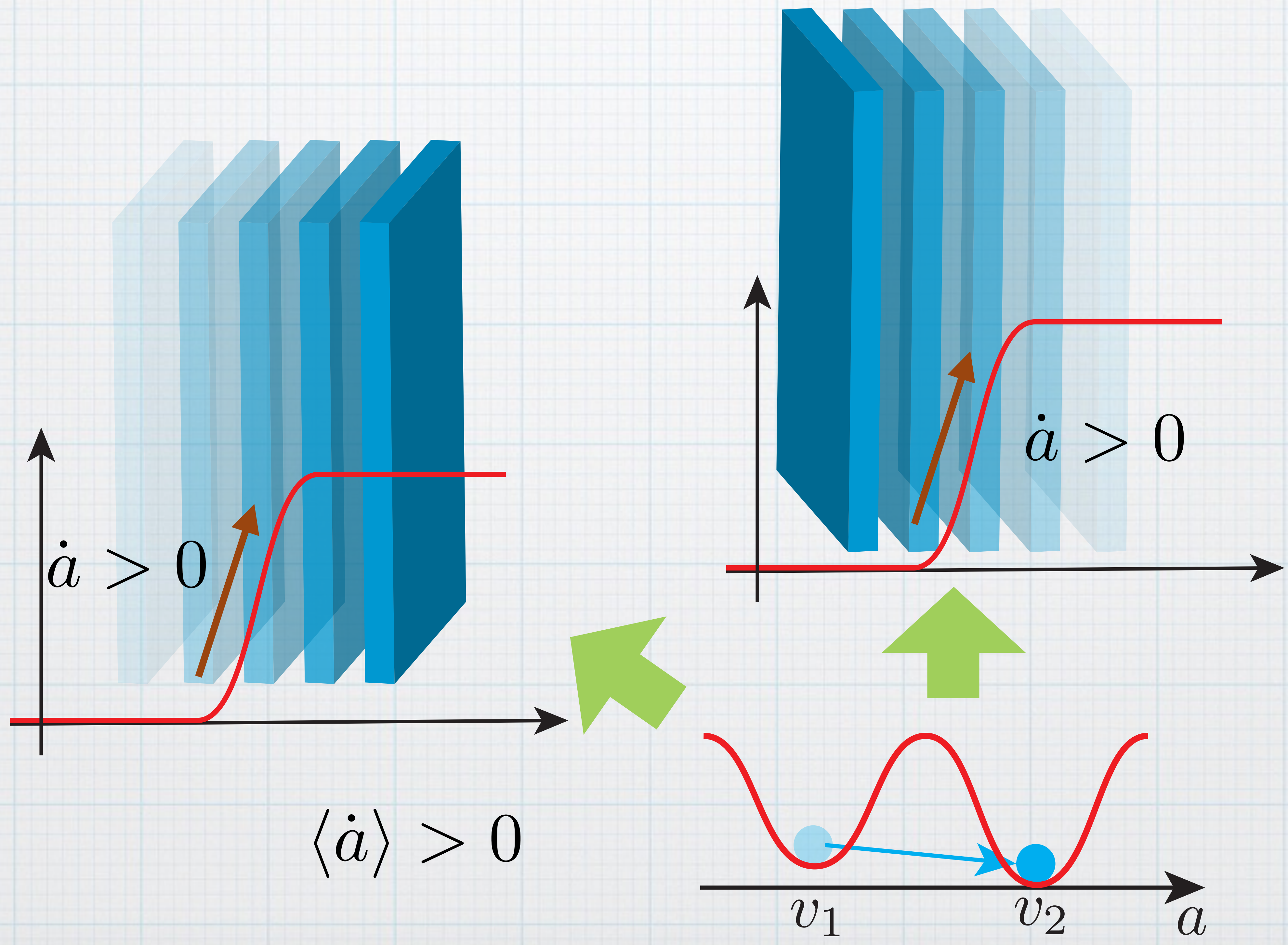



$\langle \dot{a} \rangle = 0$ — no net baryon number

# Baryogenesis by domain walls

R. Daido, NK, F. Takahashi, 1504.07917

## moving domain walls at annihilation



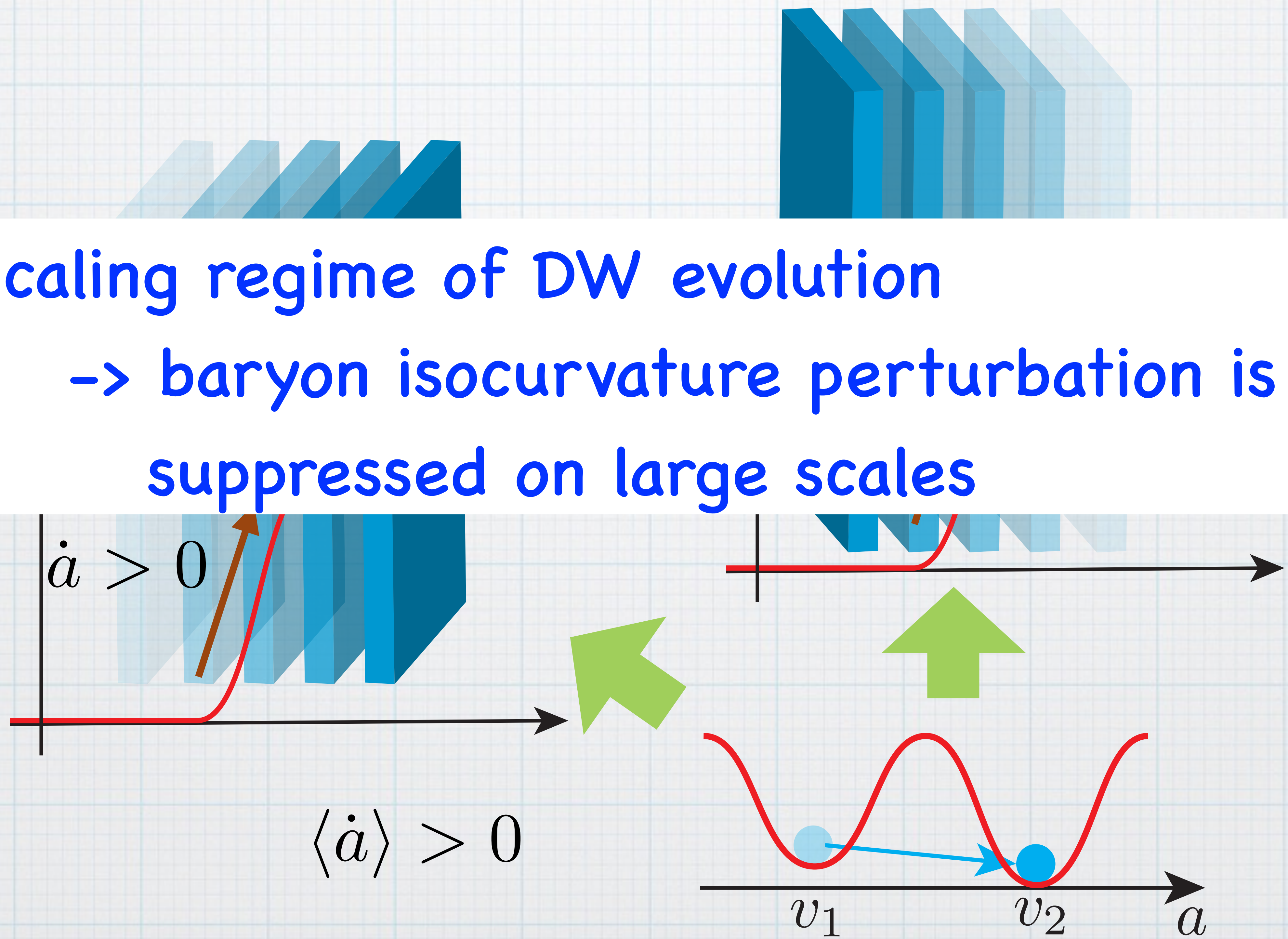
# Baryogenesis by domain walls

R. Daido, NK, F. Takahashi, 1504.07917

## moving domain walls at annihilation

Scaling regime of DW evolution

-> baryon isocurvature perturbation is suppressed on large scales



# Numerical calculation

**Boltzmann equation :** $\dot{n}_L + 3Hn_L = -\Gamma_{\rm int}(n_L - n_L^{\rm eq})$

$$n_L = n_\ell - n_{\bar{\ell}}$$

**Domain wall solution :**

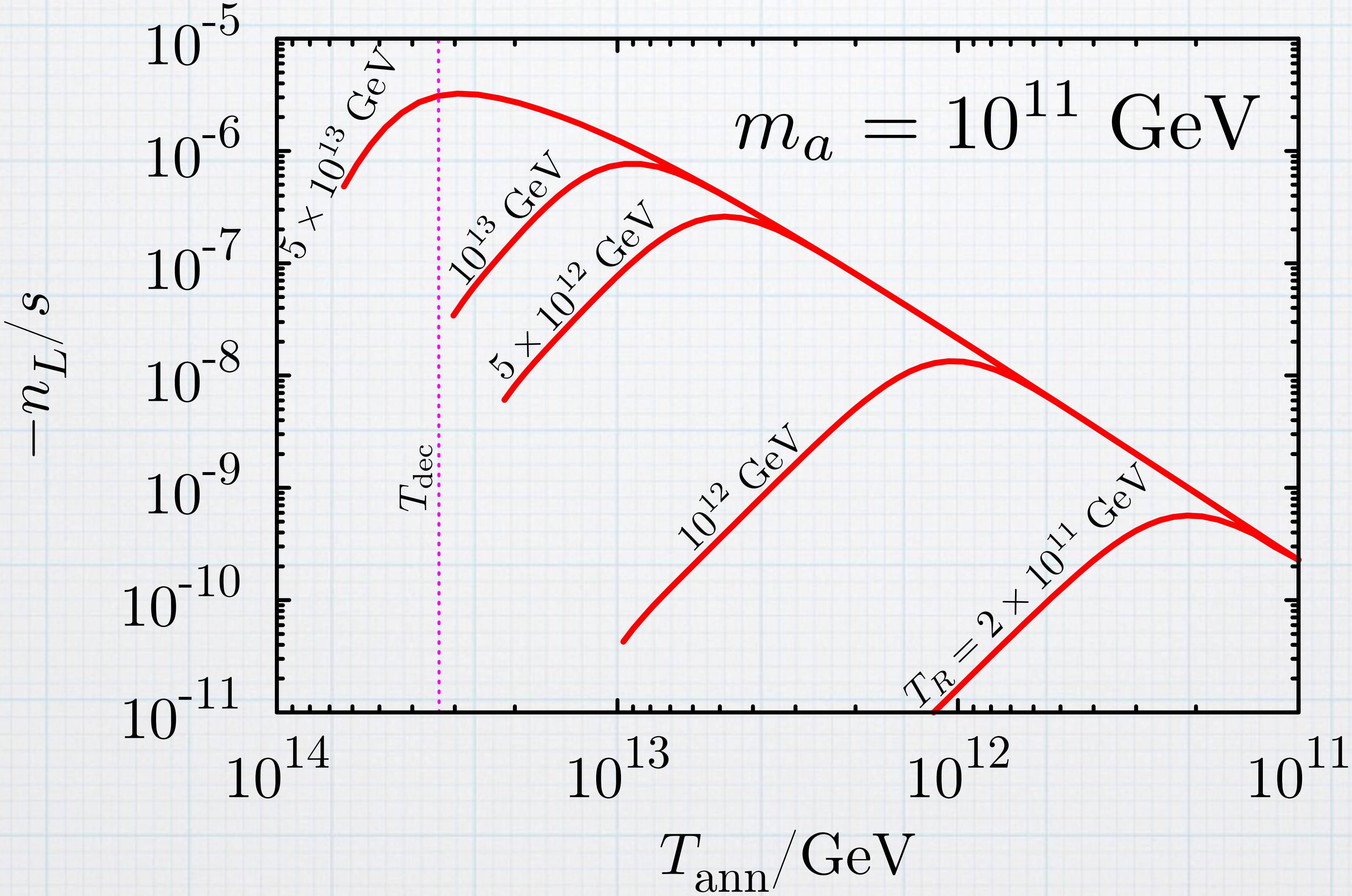
$$a_{\rm dw}(t,\vec{x}) = 4f\tan^{-1}\exp[m\gamma(x - vt)] \quad \textbf{with} \quad \gamma = 1/\sqrt{1-v^2}$$

$$\Rightarrow \quad \mu_{\rm eff} = \frac{\dot{a}}{f} = -\frac{2m\gamma v}{\cosh[m\gamma v(t - t_{\rm dw})]}$$

$$(x = 0 \ \text{ at } \ t = t_{\rm dw})$$

$$V = m^2 f^2\left(1 - \cos\left(\frac{a}{f}\right)\right)$$

# Numerical results



# Axion decay

Long lifetime & axion domination

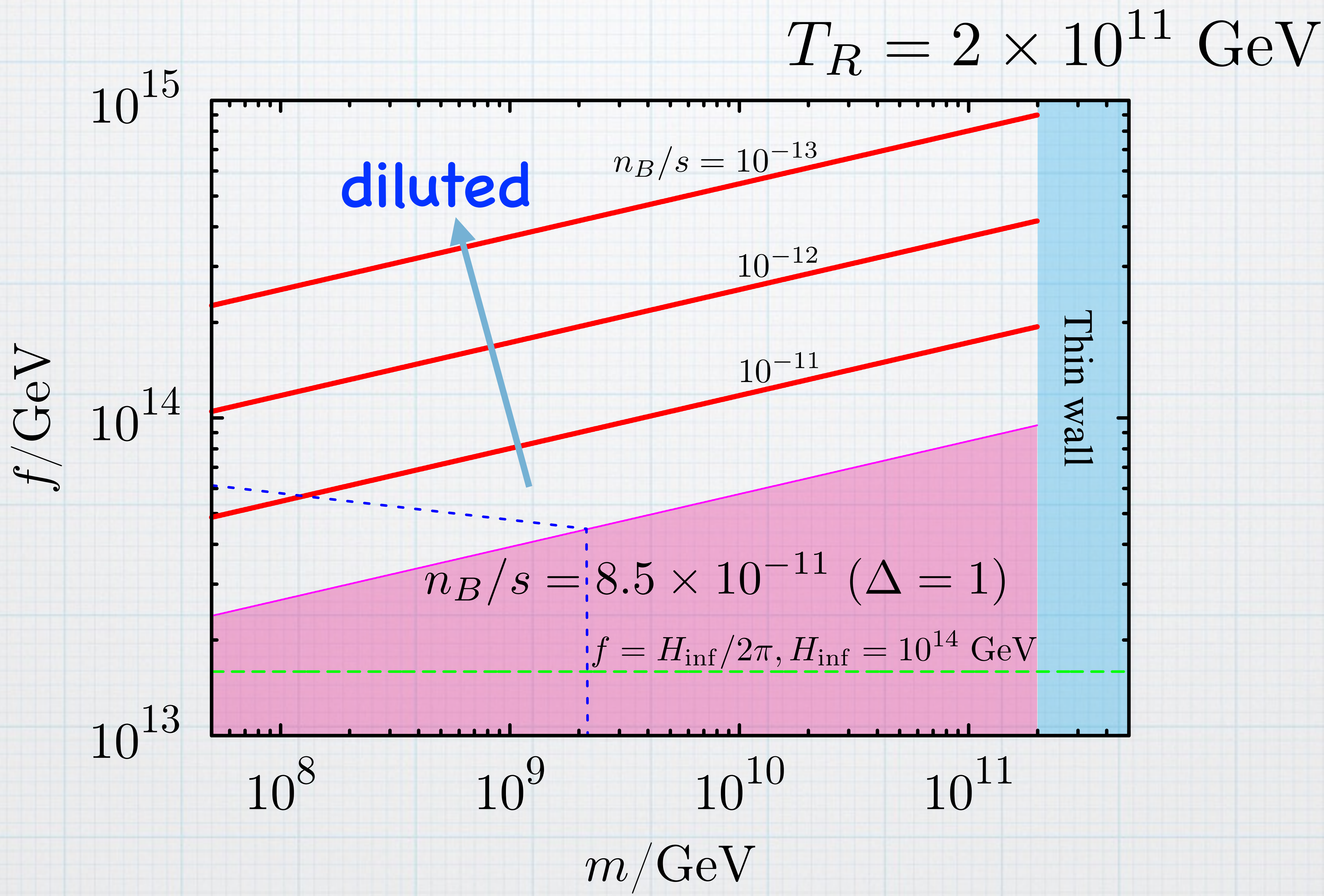
-> Baryon number is diluted after the axion decay

Decay rate : $\Gamma_a \simeq \left( \frac{3\alpha_2^2}{256\pi^3} + \frac{\alpha'^2}{1024\pi^3} \right) \frac{N_f^2 m^3}{f^2}$

Decay temperature :

$$T_a \simeq 3 \times 10^7 \text{ GeV} \left( \frac{m}{10^{11} \text{ GeV}} \right)^{3/2} \left( \frac{10^{15} \text{ GeV}}{f} \right)$$

# Numerical results



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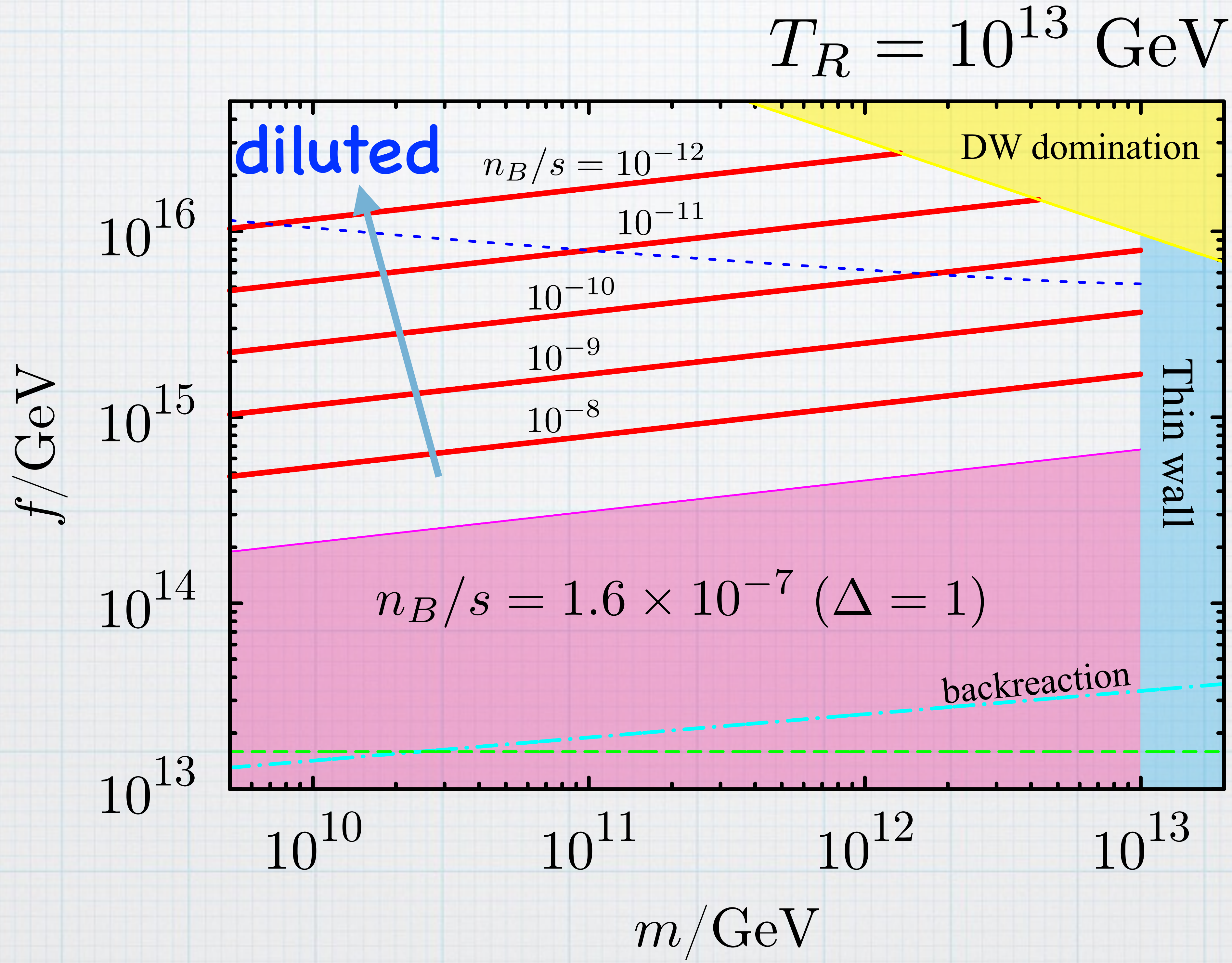

# Conclusions

- Level crossing can induces the "Axion Roulette" & Axion domain wall formation is a more common phenomenon than previously thought

! Domain walls are not attached by Cosmic string
-> They cannot decay

- A sizable baryon number can be generated at the axion domain wall annihilation

! without inducing baryon isocurvature

# Numerical results