DOMAIN WALLS IN THE AXIVERSE

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Tohoku University

from October 2015

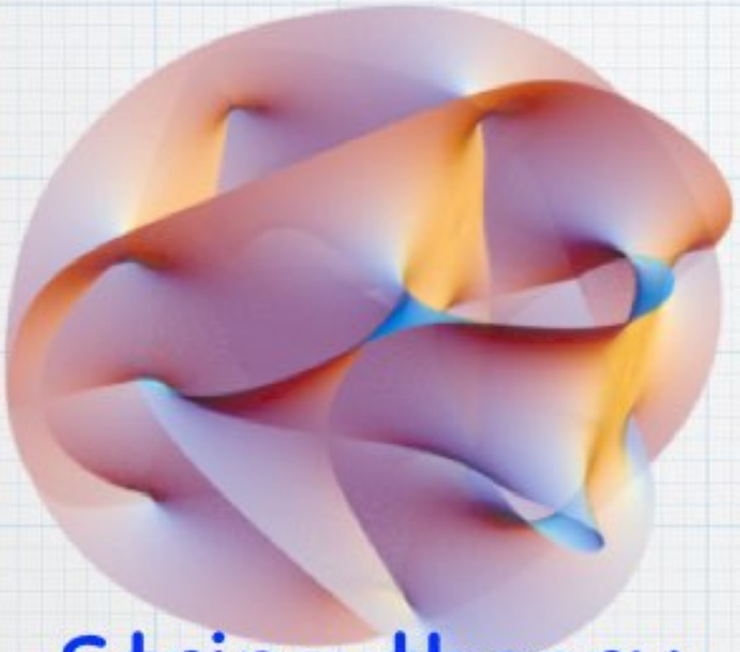
arXiv:1504.07917, 1505.07670

Collaboration with Ryuji Daido & Fuminobu Takahashi

APCTP-TUS joint workshop, 8/3-5, 2005

TOKYO UNIVERSITY OF SCIENCE

String Axion



String theory

Axions

+

moduli

AXIVERSE

Arvanitaki et al (2010)

AXIVERSE

Arvanitaki et al (2010)

Dark matter

Inflaton

Solving strong CP problem

baryogenesis

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

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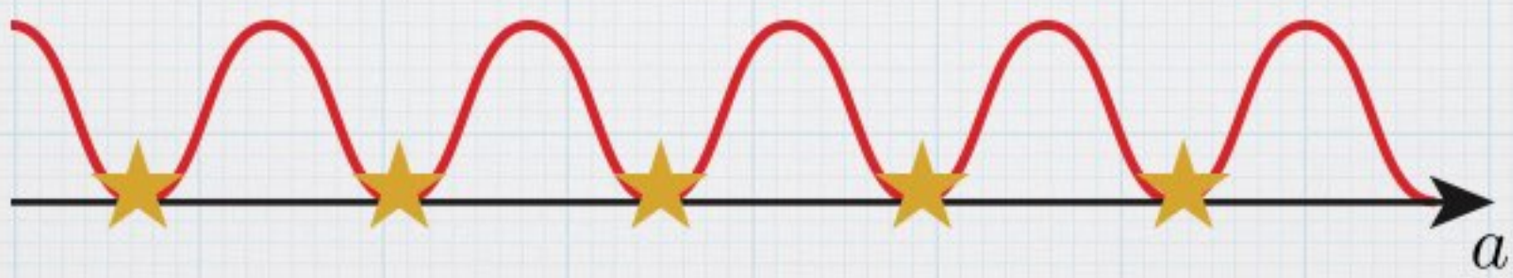
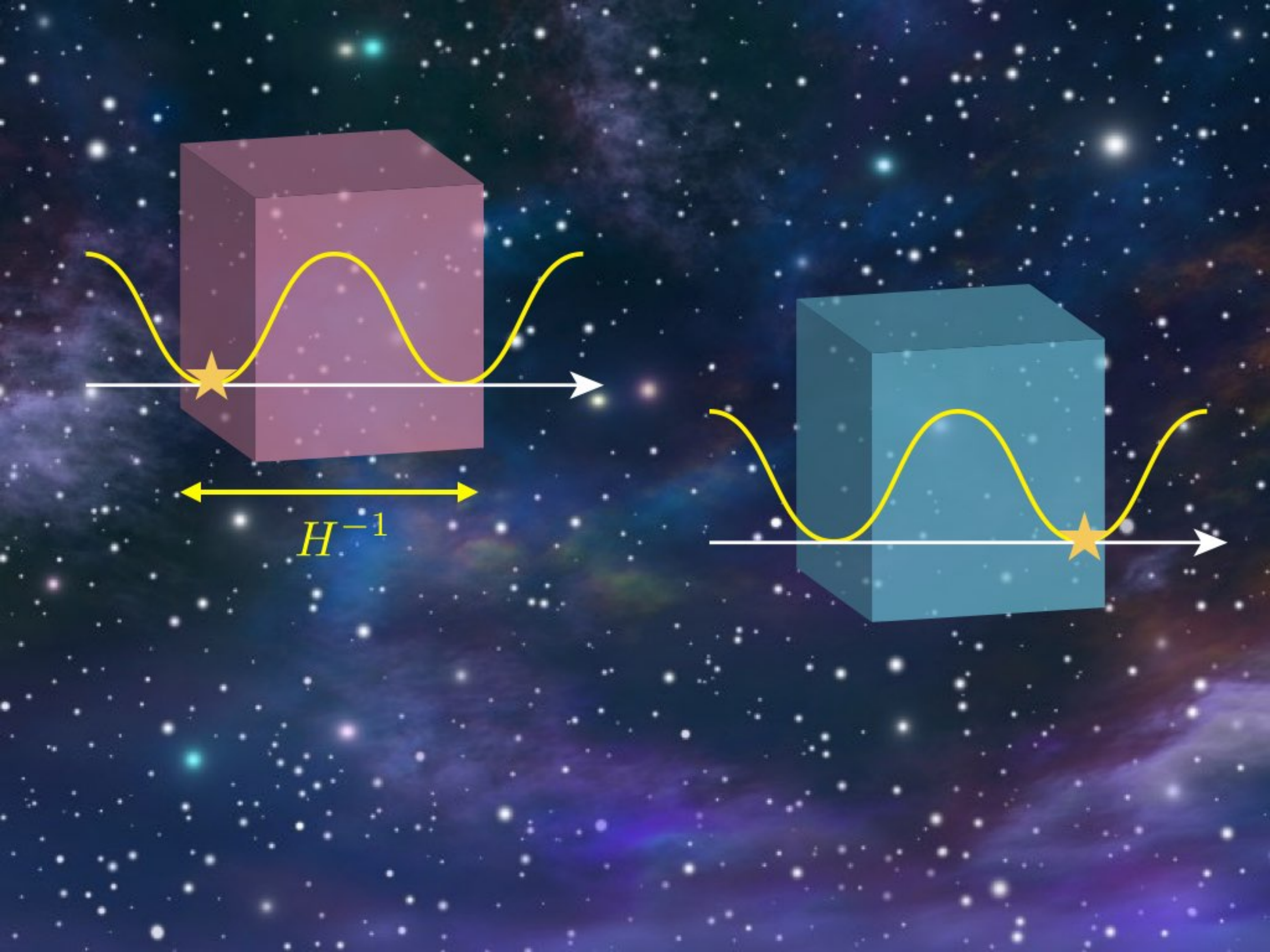
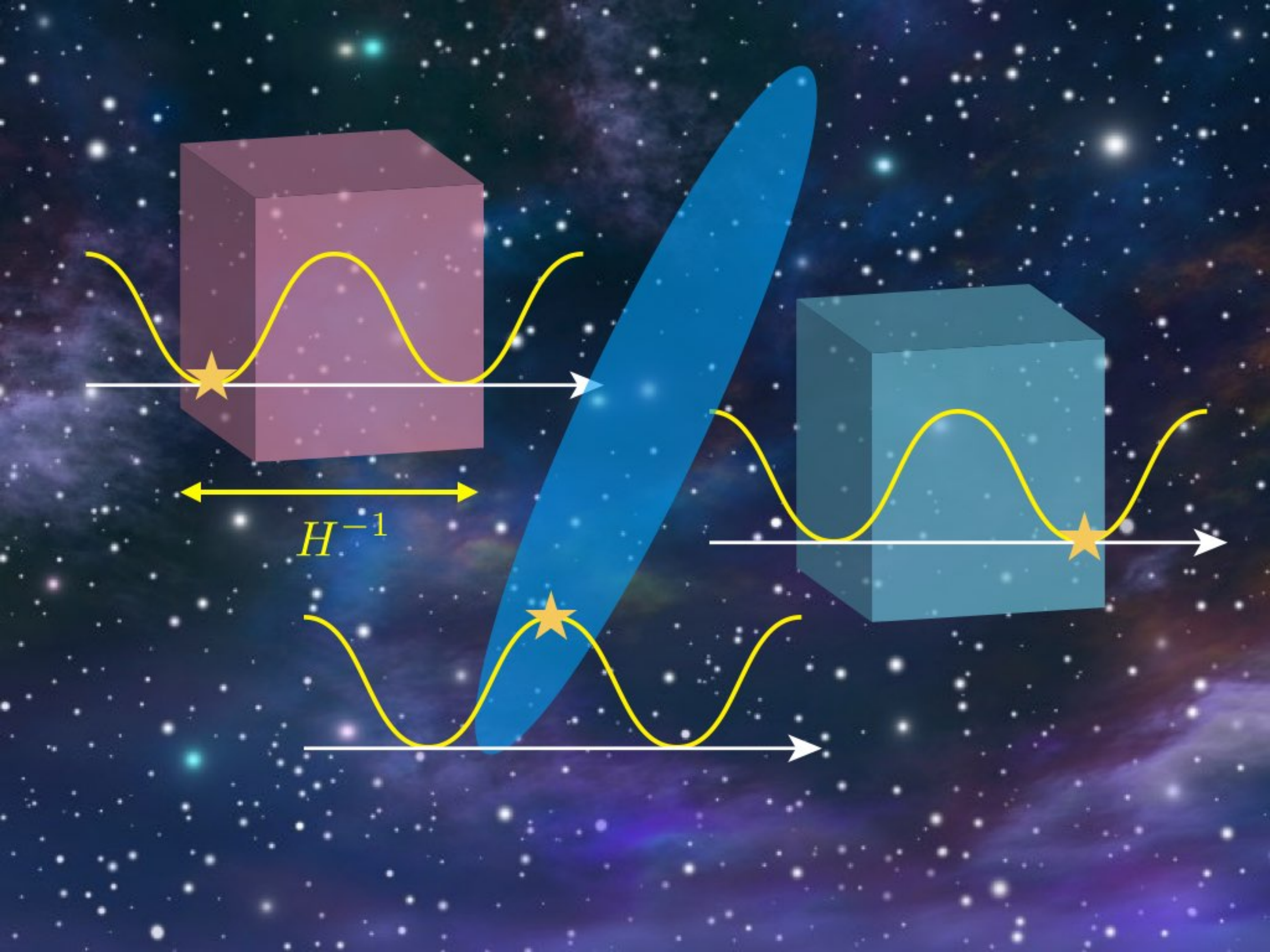


many degenerate minima!


H^{-1}

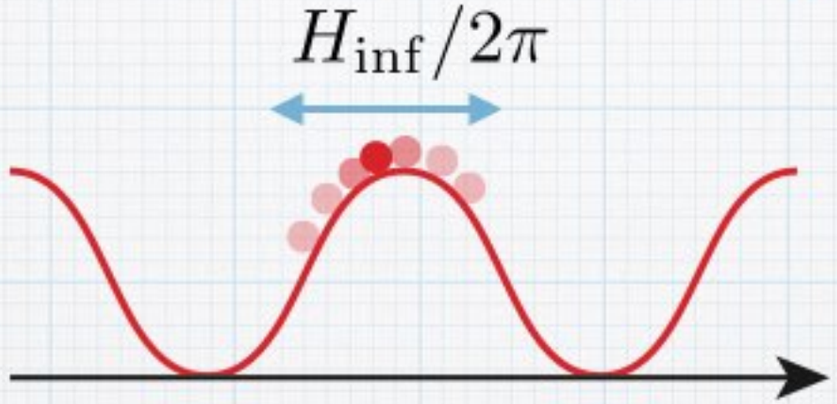

H^{-1}

Domain wall

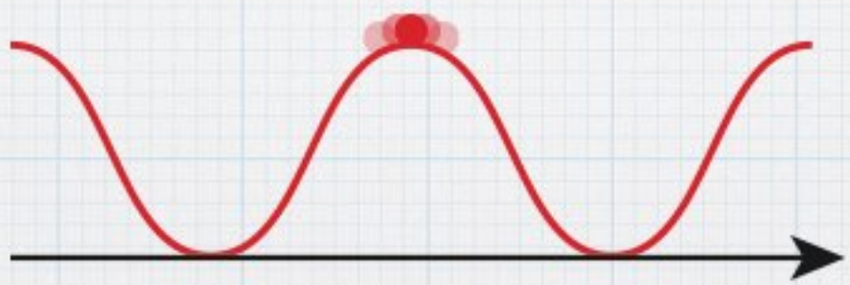
H^{-1}

Axion domain wall formation

- Large quantum fluctuation during inflation



- Hilltop initial condition



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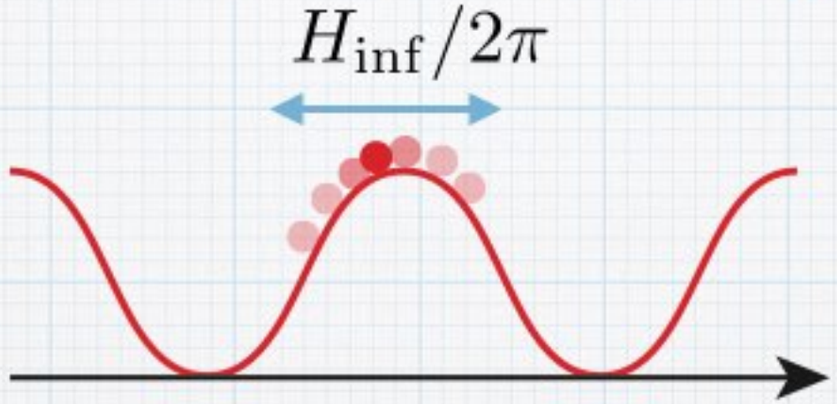

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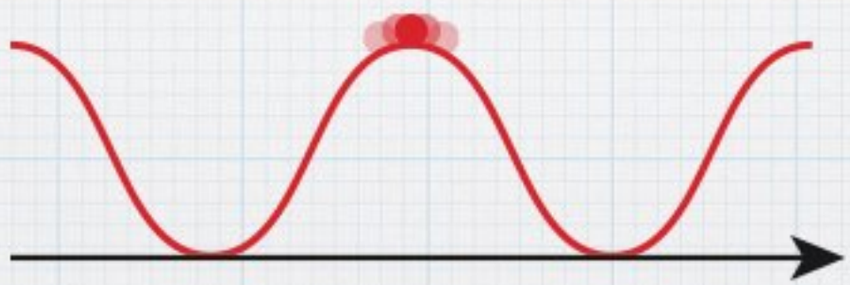

- Level crossing

New!

Domain wall abundance & evolution

A few domain walls exist per Hubble volume

— scaling law : $\rho_{\rm dw} \sim \sigma H$

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Domain walls soon dominate the universe

-> The universe becomes highly inhomogeneous!

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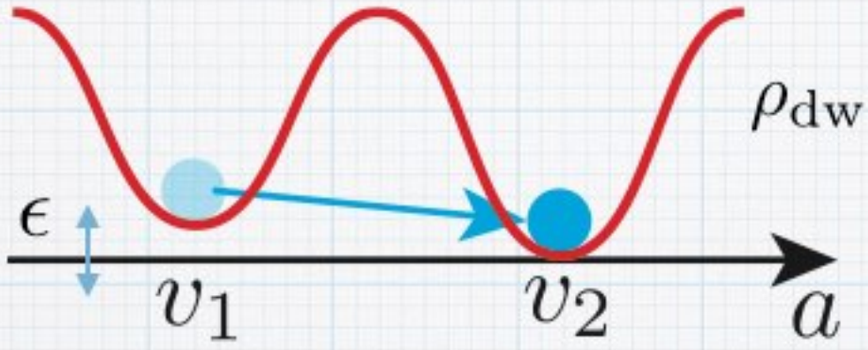
Cosmological catastrophe

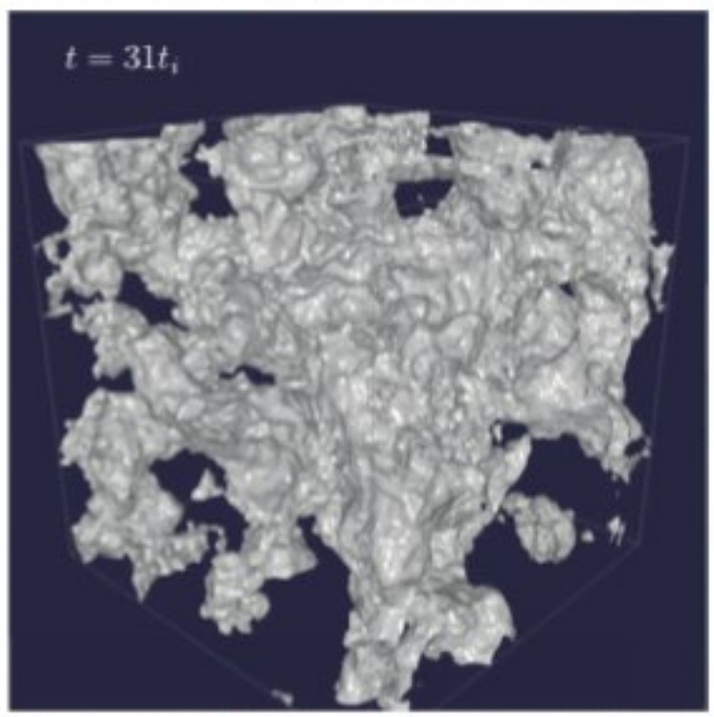
Domain wall annihilation

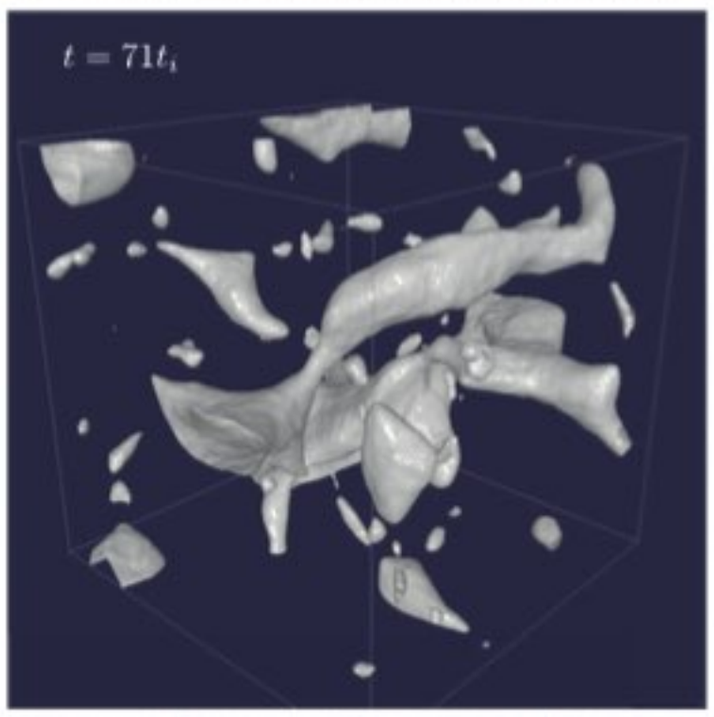
energy bias → domain wall annihilation

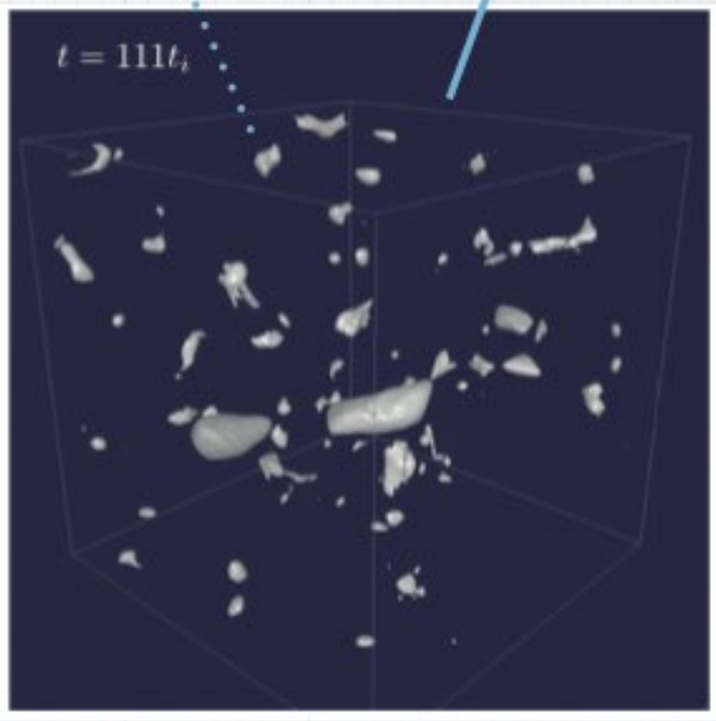


GW

axion

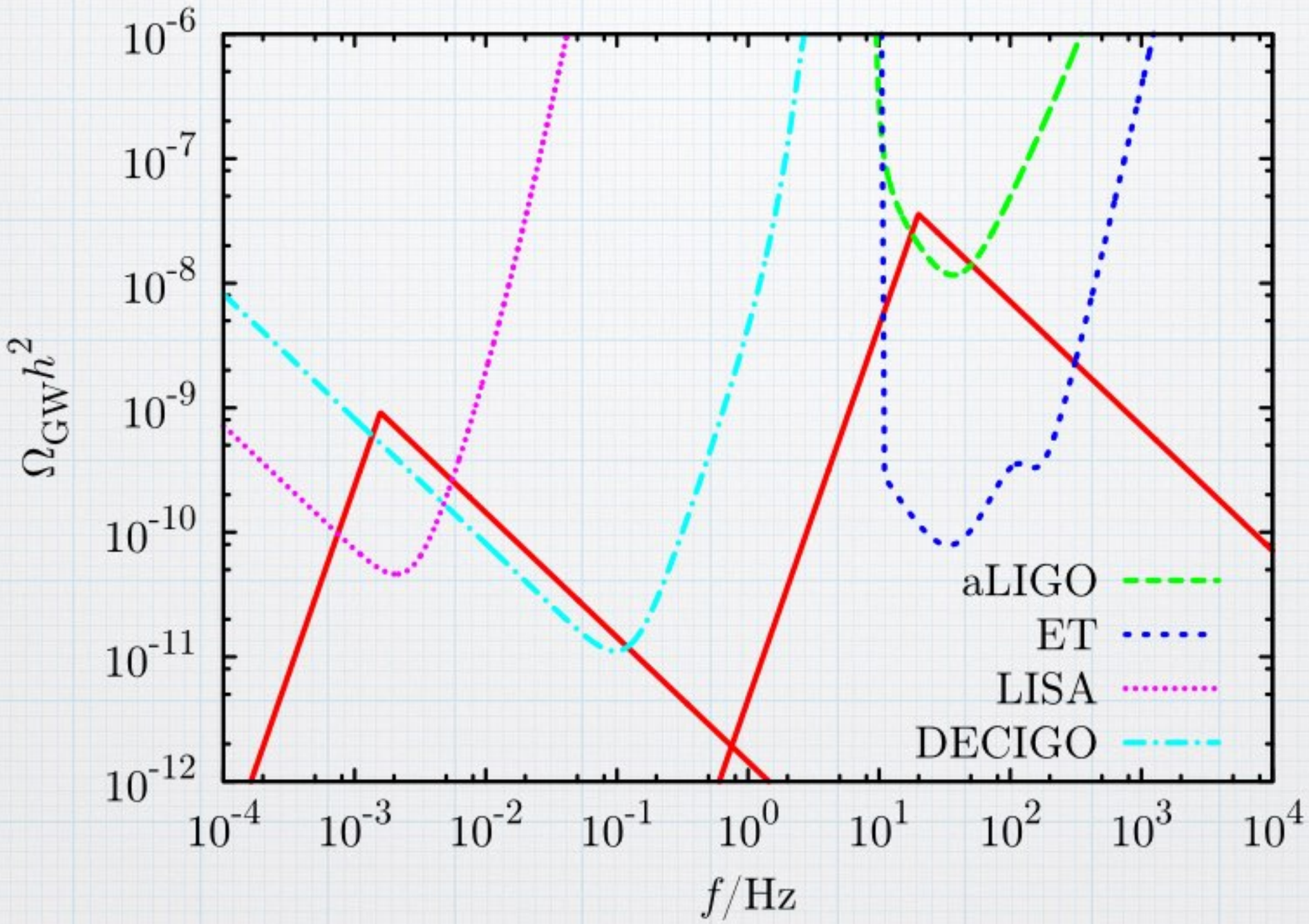






Hiramatsu, Kawasaki, Saikawa (2010)

Gravitational waves from domain walls



Hiramatsu, Kawasaki, Saikawa (2014)

Domain wall formation via axion roulette

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

Two axion model

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

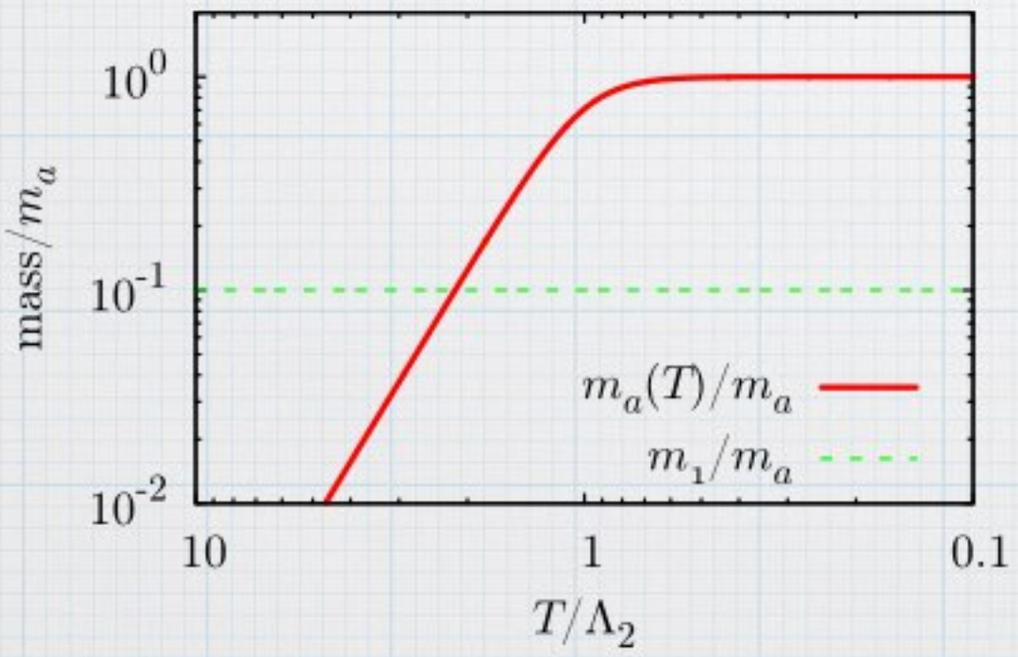
$$\mathcal{L} = \sum_{i=1,2} \frac{1}{2}\partial^\mu a_i \partial_\mu a_i - V_1(a_1, a_2) - V_2(a_1, a_2)$$

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

Axion mixing

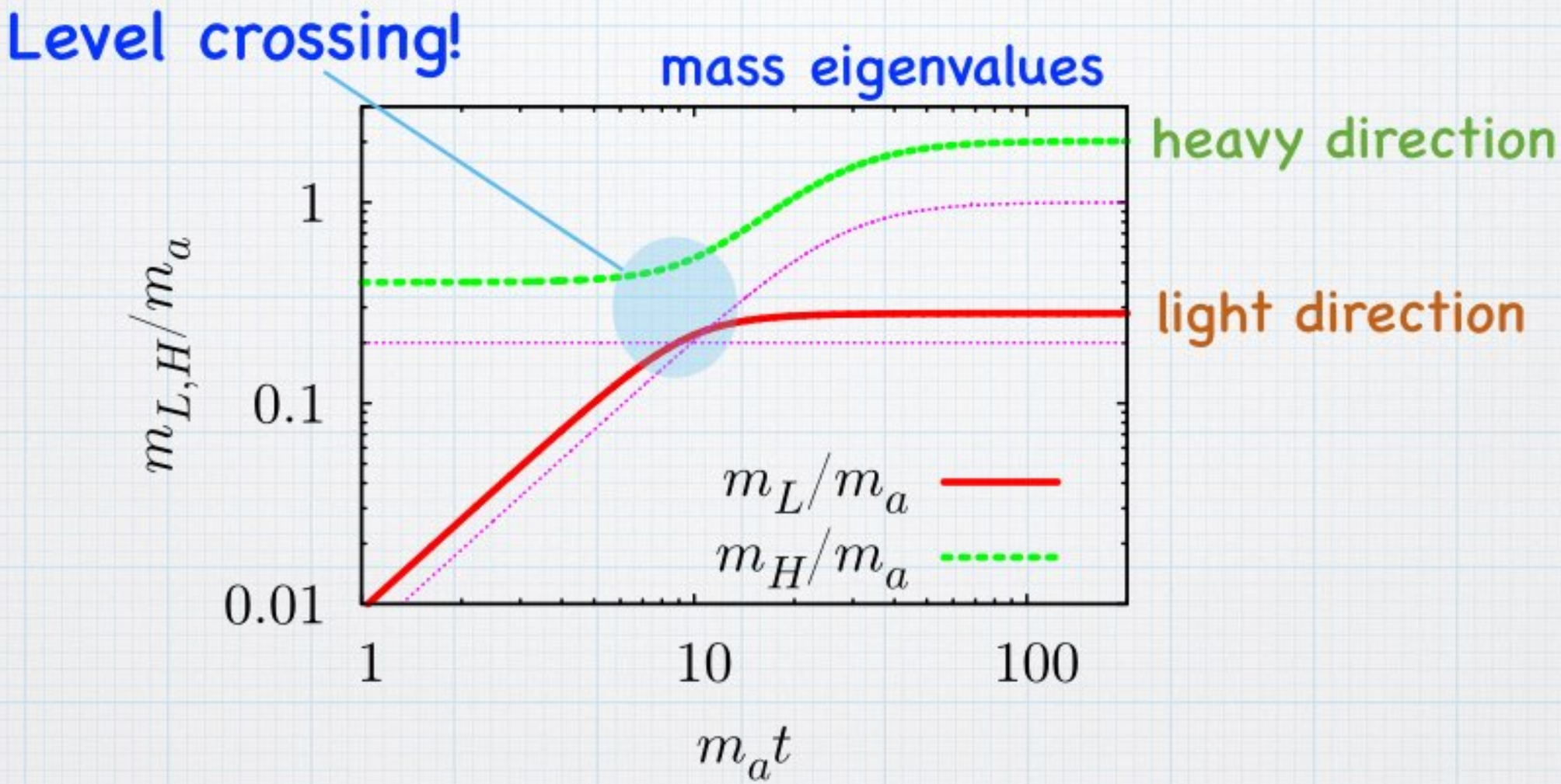
$$V_2(a_1, a_2) = m_a^2(T) f_2^2 \left(1 - \cos\left(\frac{a_2}{f_2}\right)\right)$$

Temperature-dependent mass



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

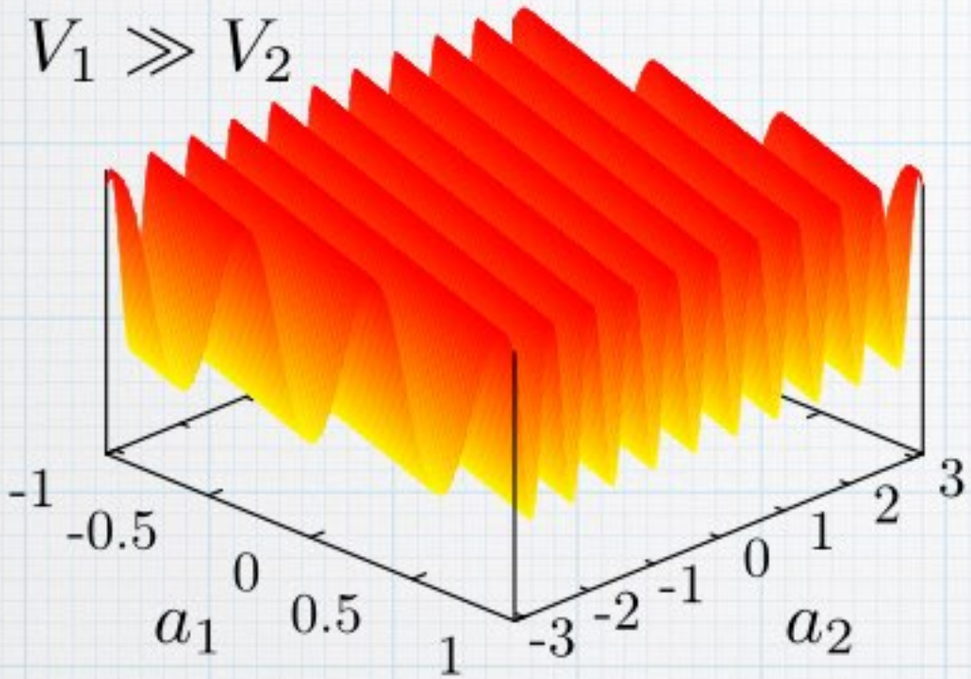
Level crossing

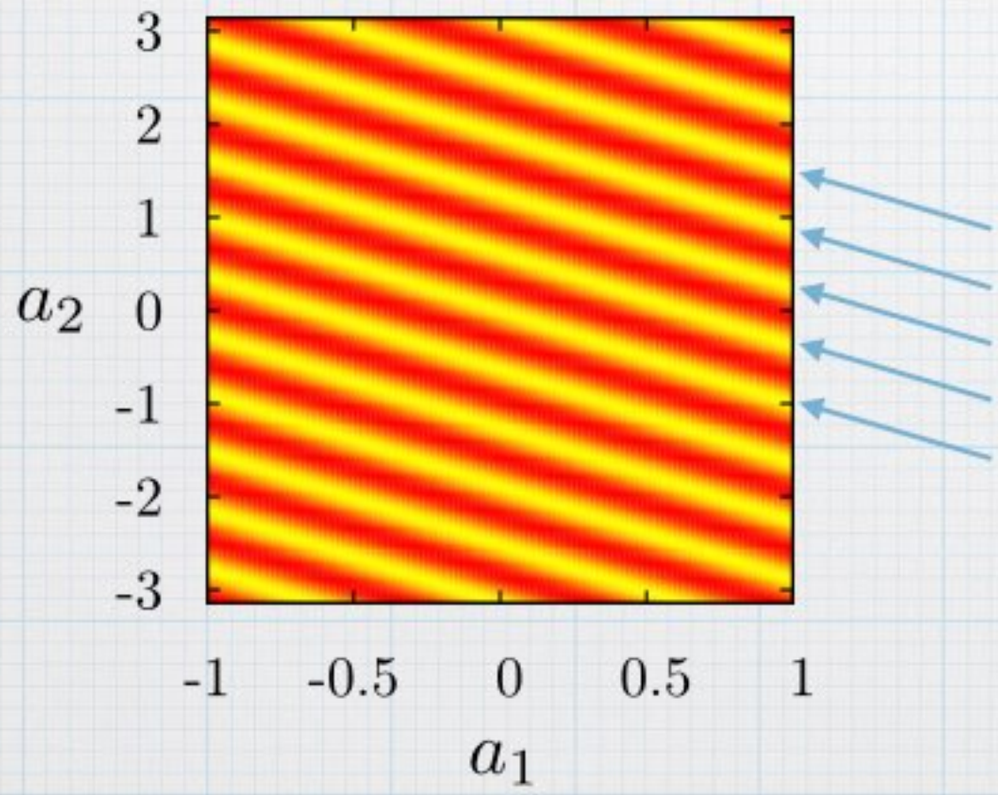


$$V_1(a_1, a_2) = \Lambda_1^4 \left(1 - \cos\left(n_1 \frac{a_1}{f_1} + n_2 \frac{a_2}{f_2}\right)\right)$$

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

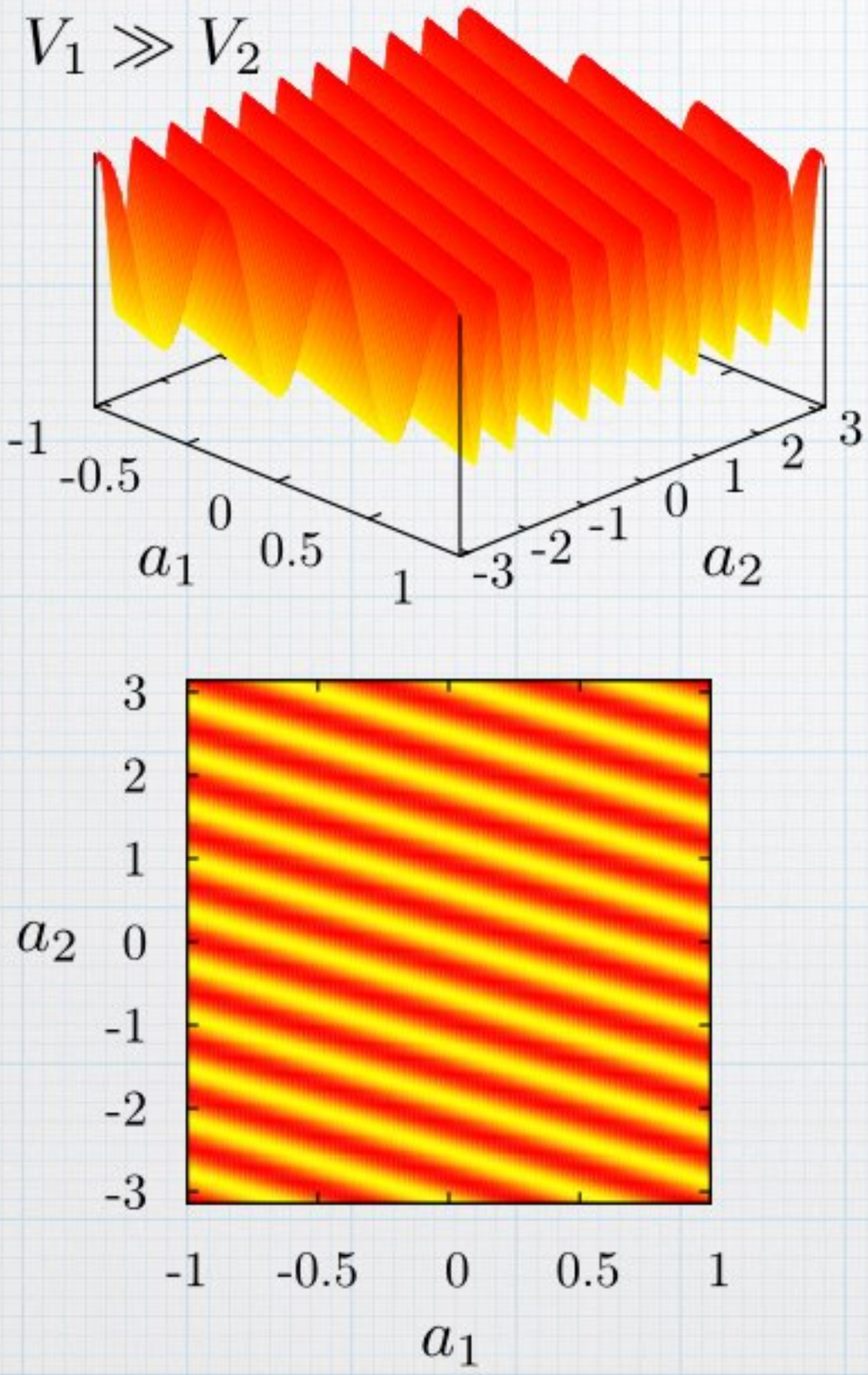
Evolution of the axion potential





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

Evolution of the axion potential



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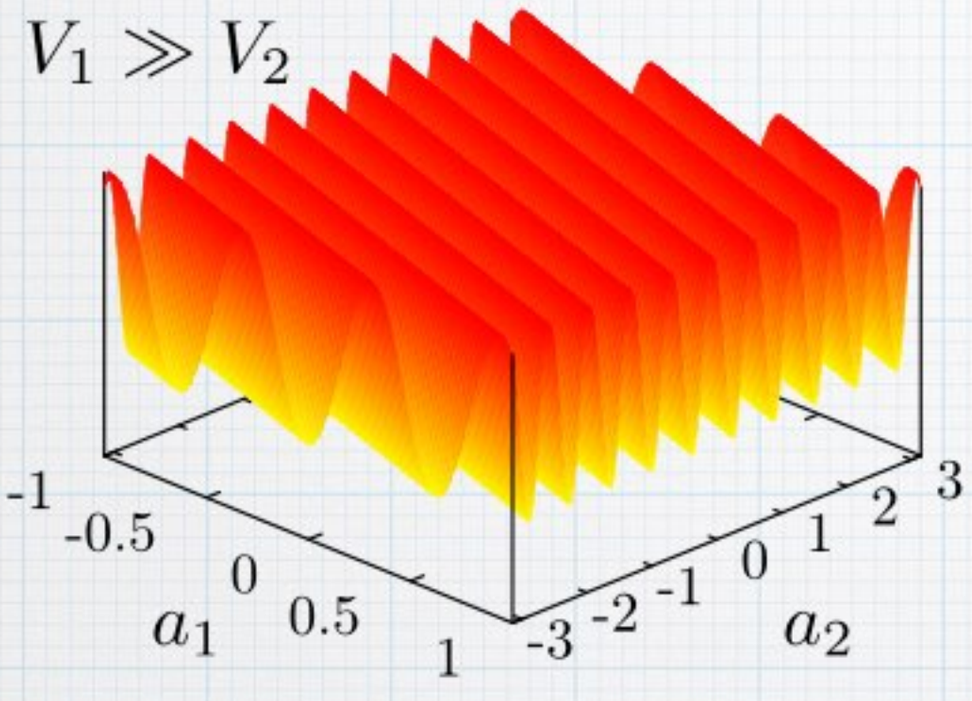
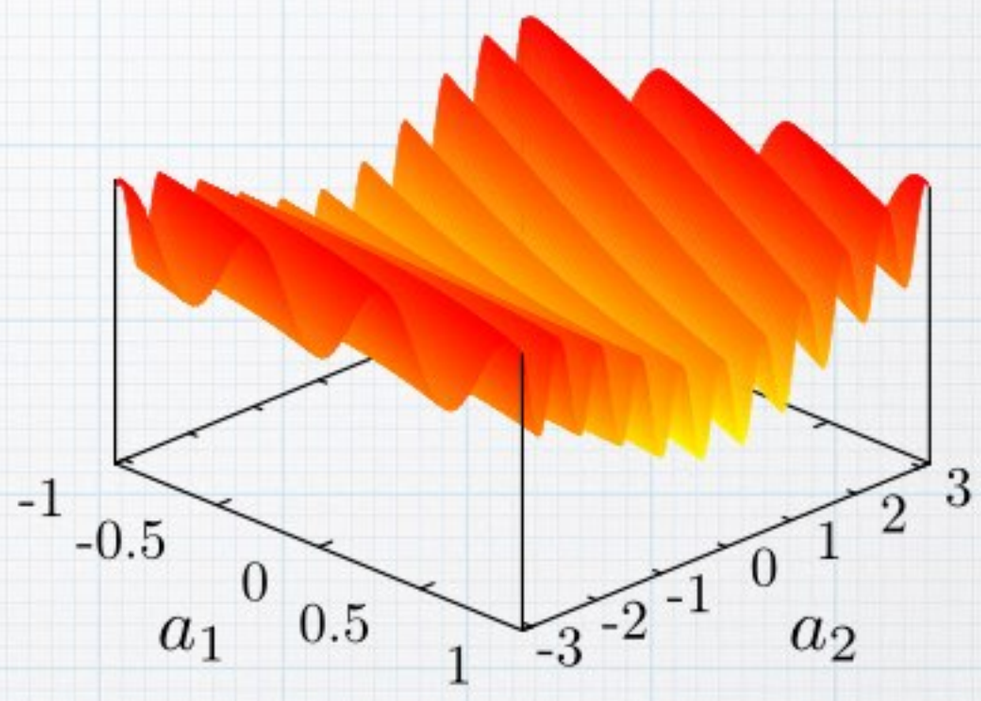
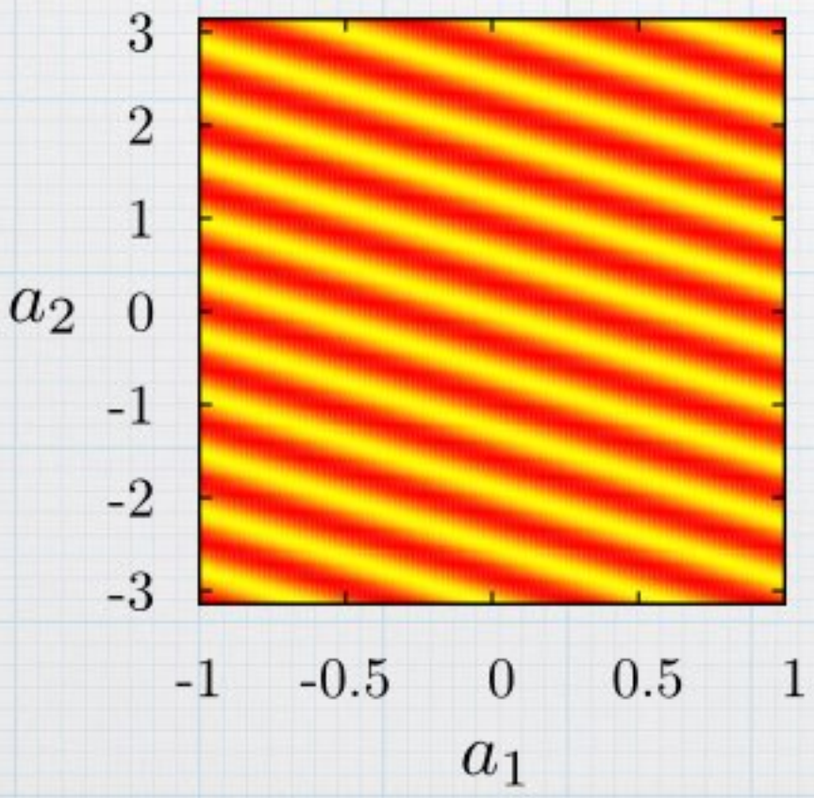
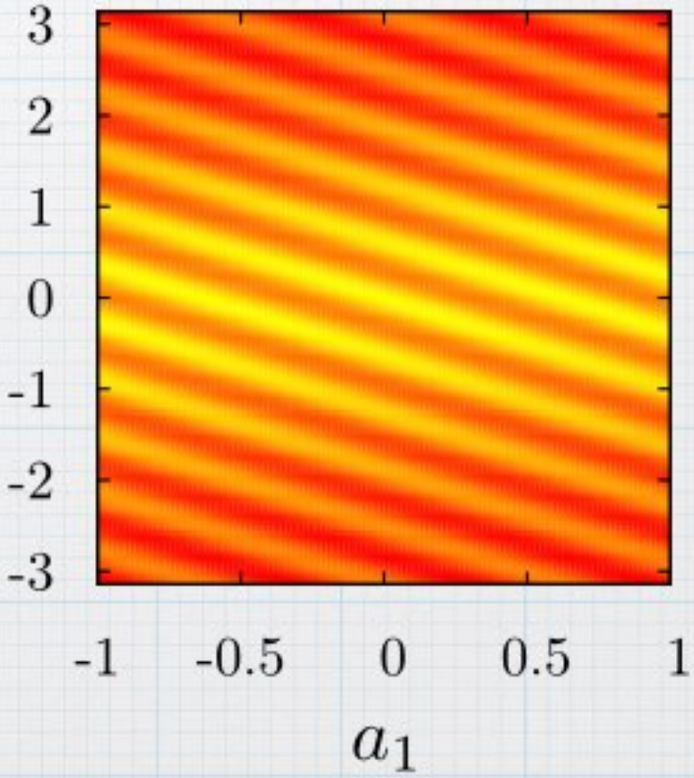
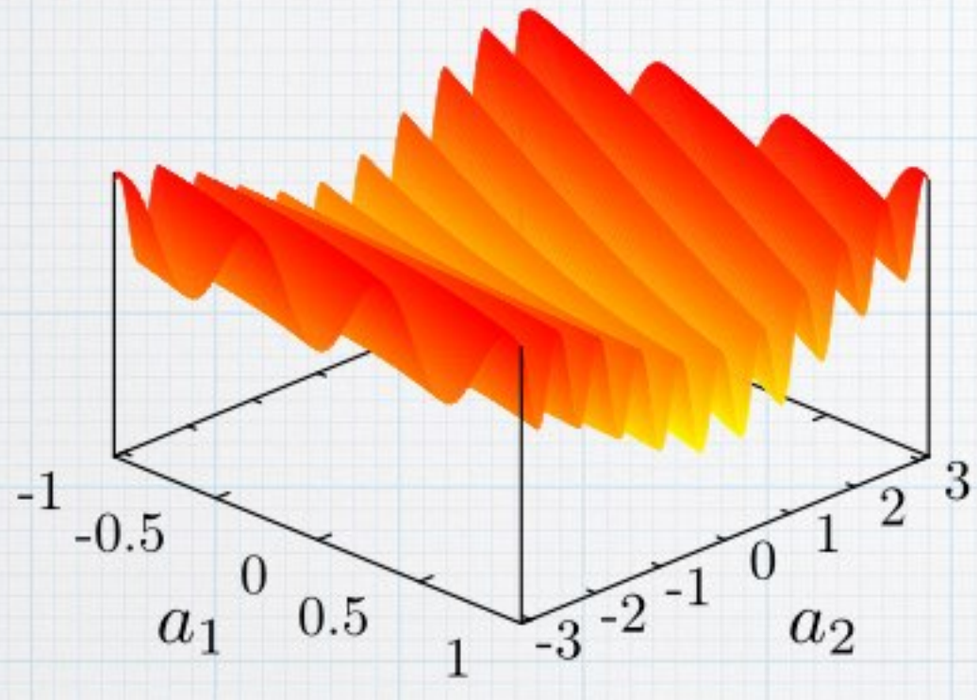


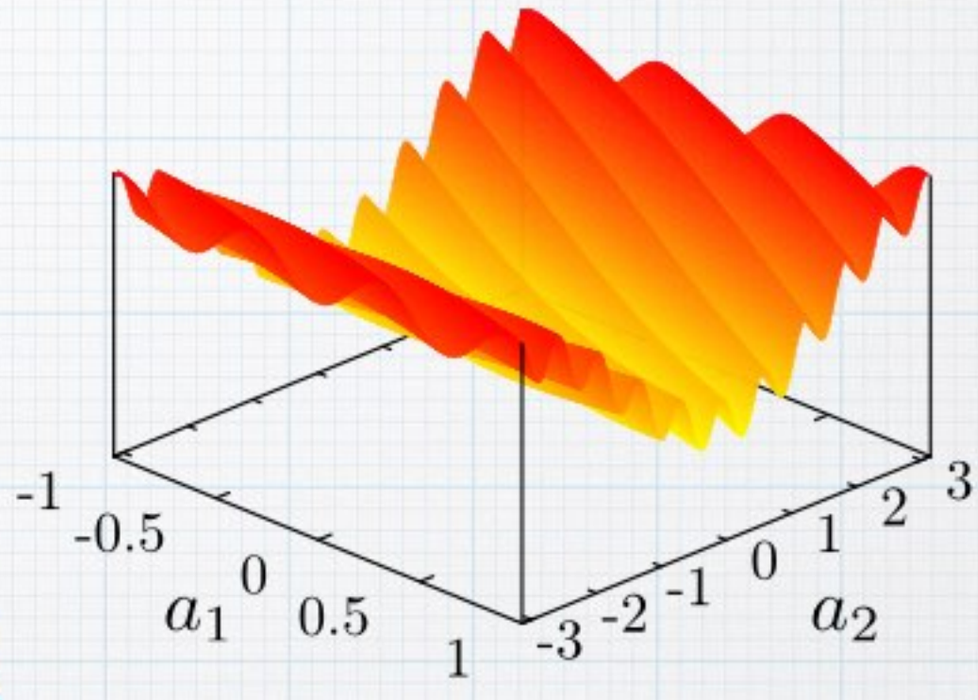


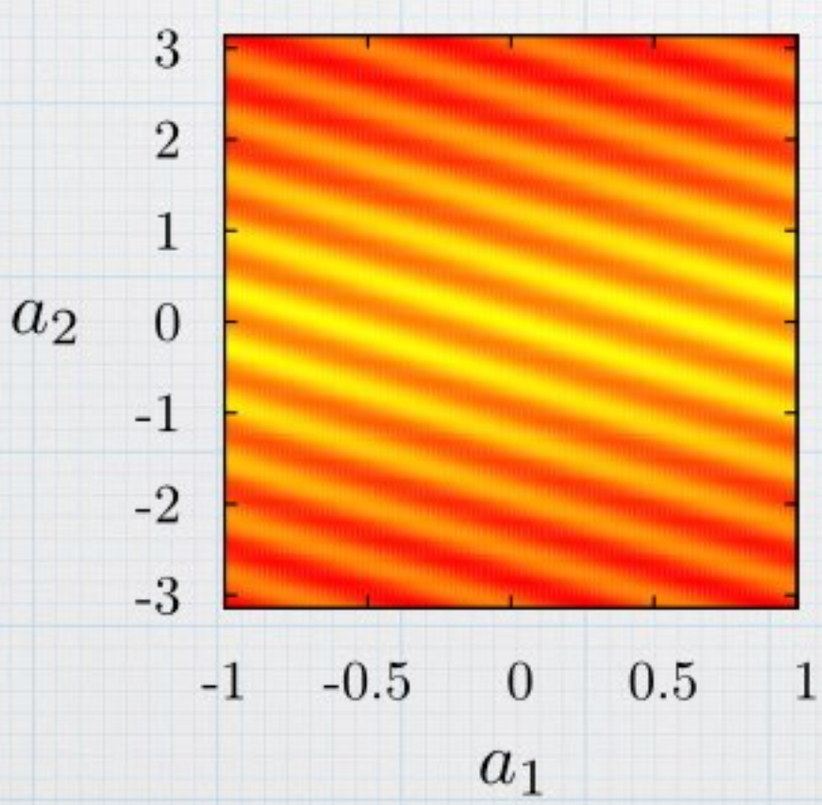


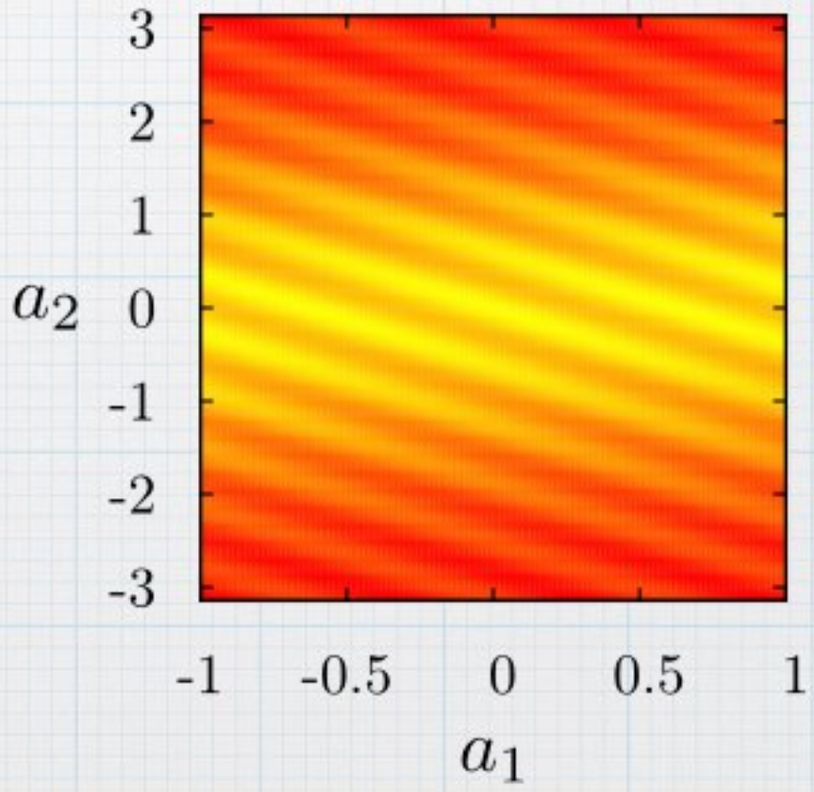


Evolution of the axion potential

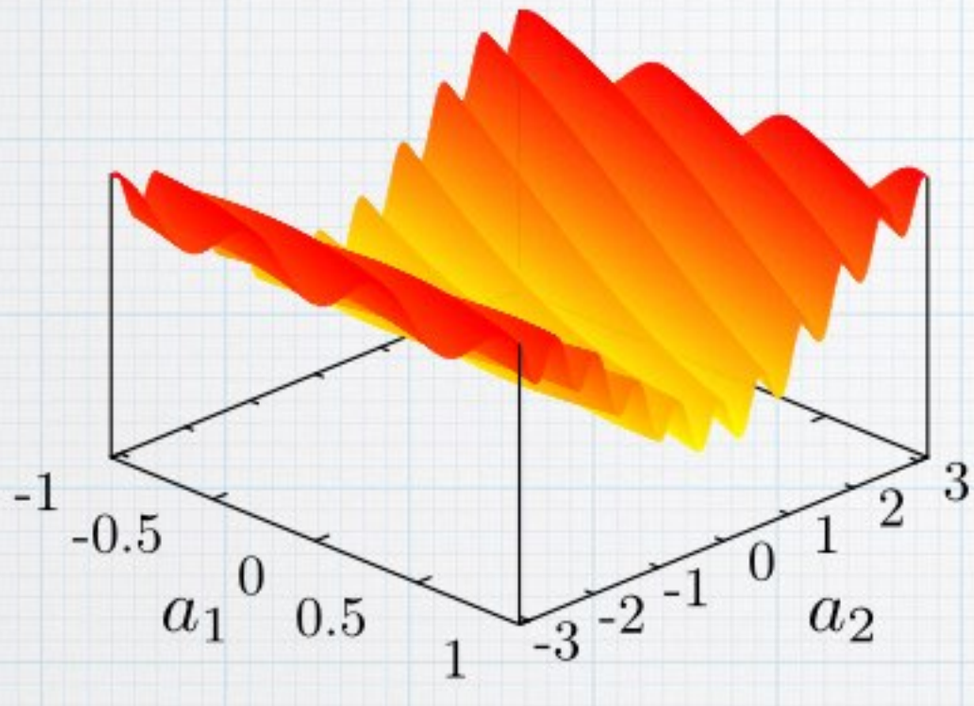


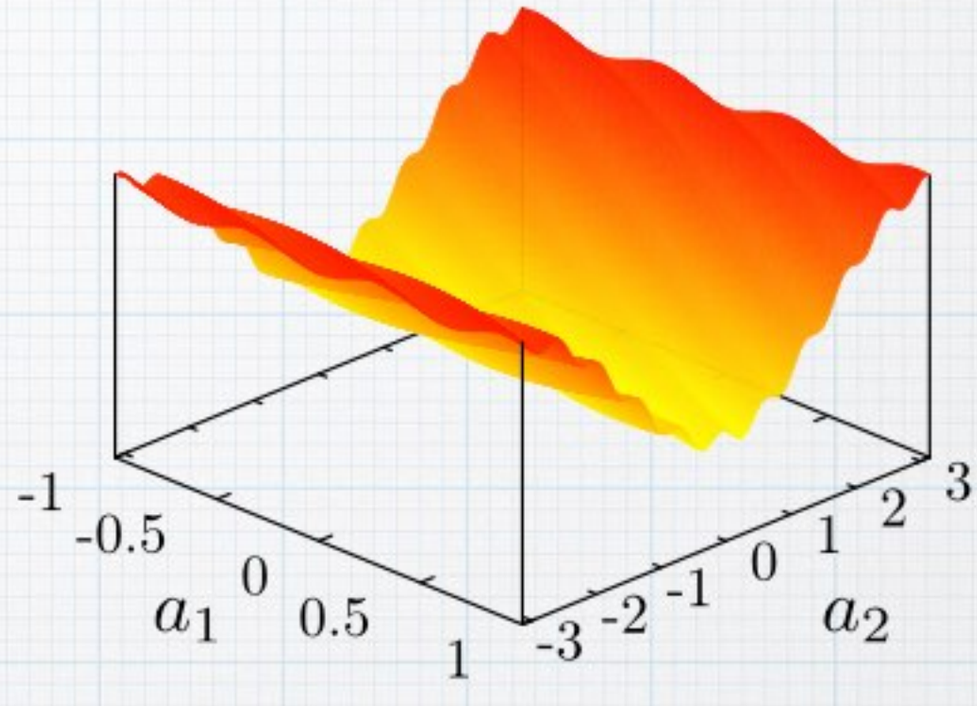


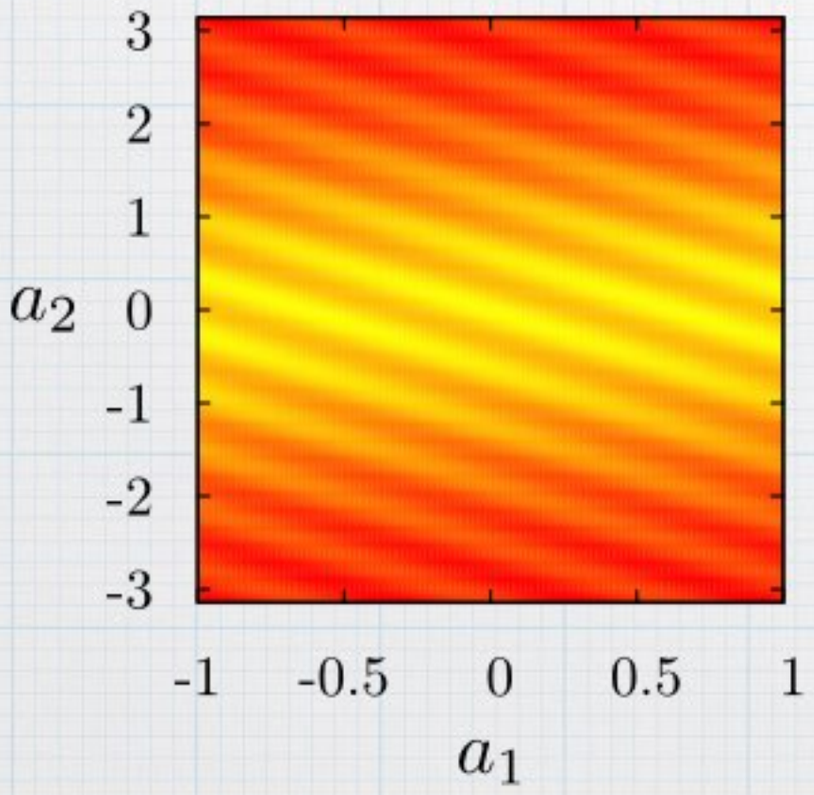


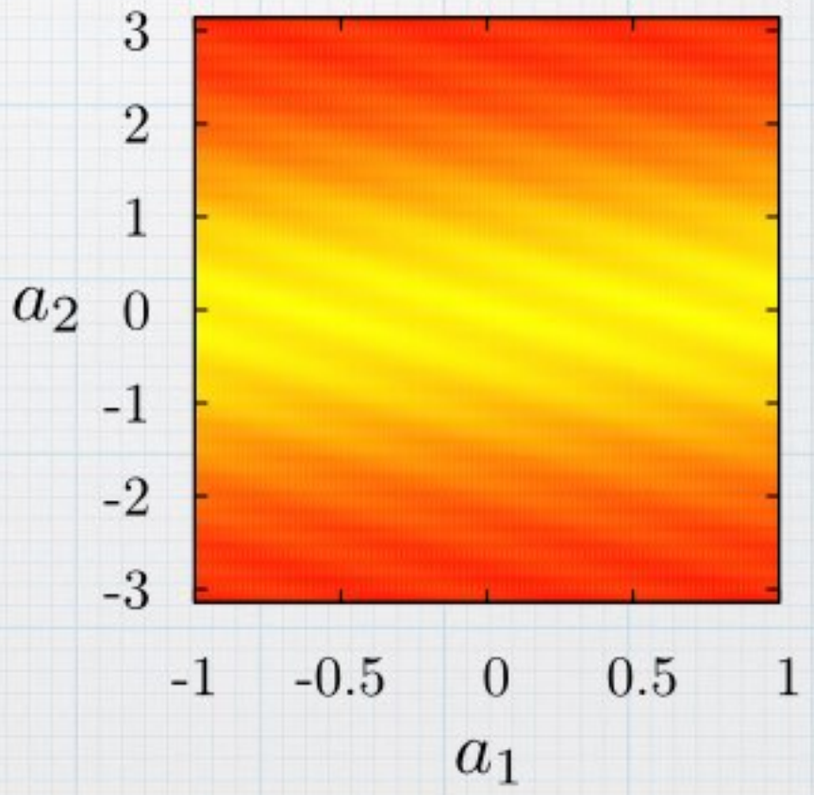


Evolution of the axion potential



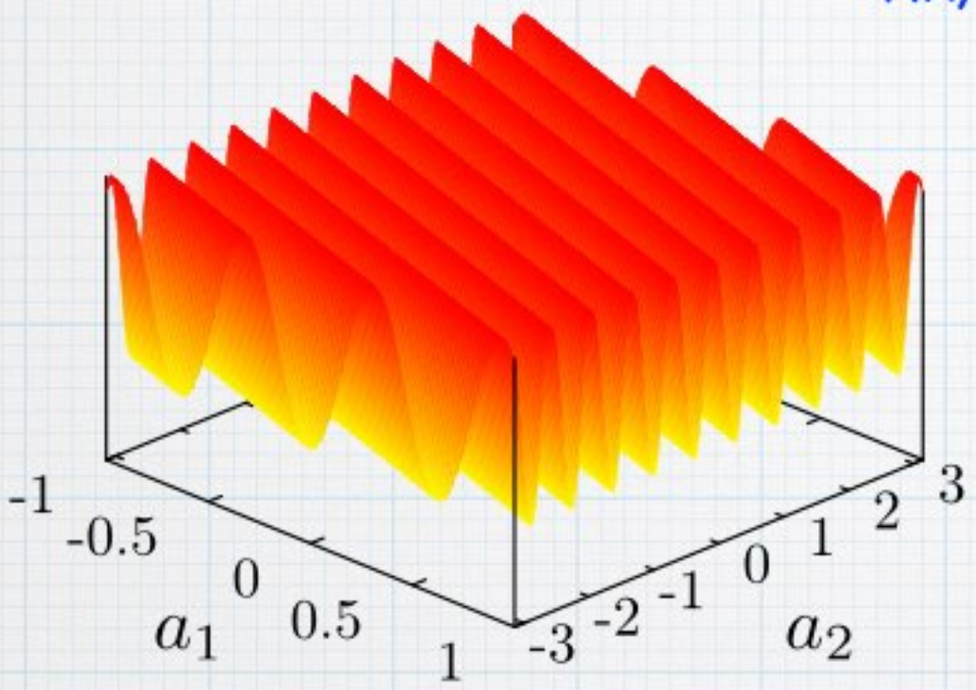


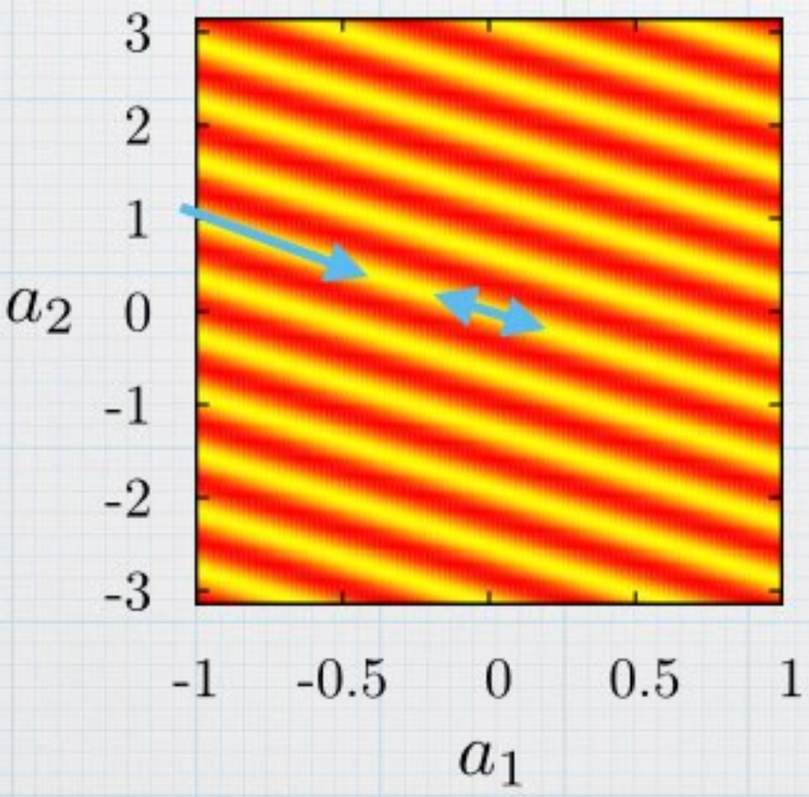


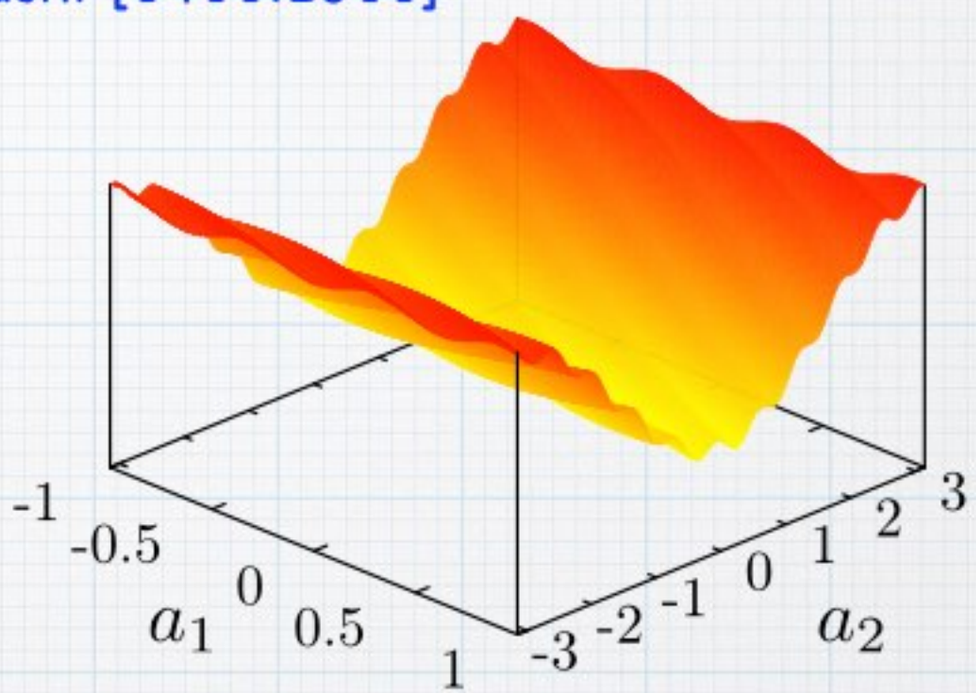


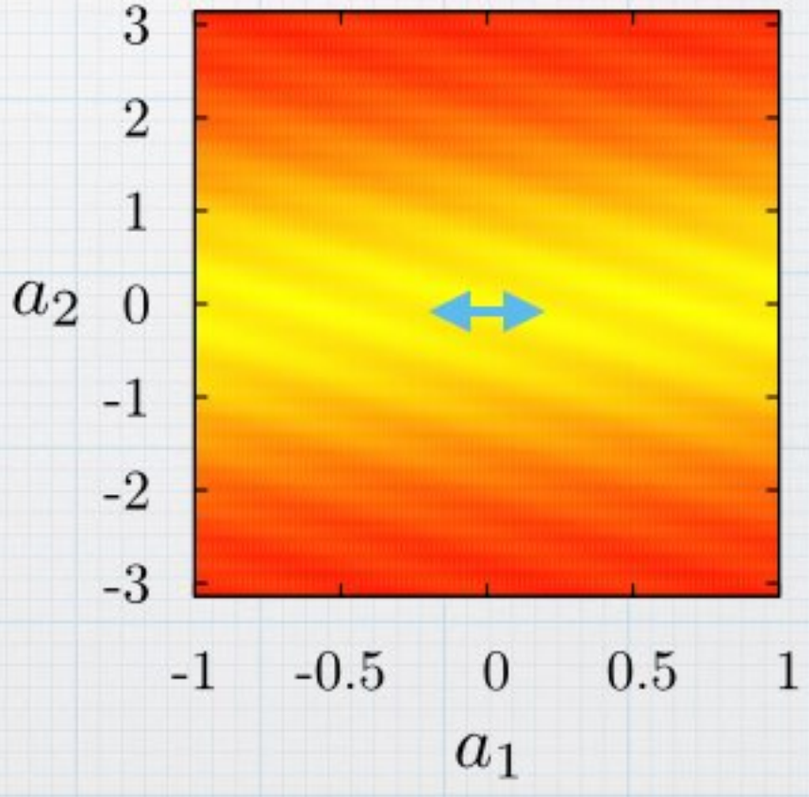
(i) Resonant conversion : $H_{\rm lc} \gg H_{\rm osc}$

NK, F. Takahashi [1411.2011]









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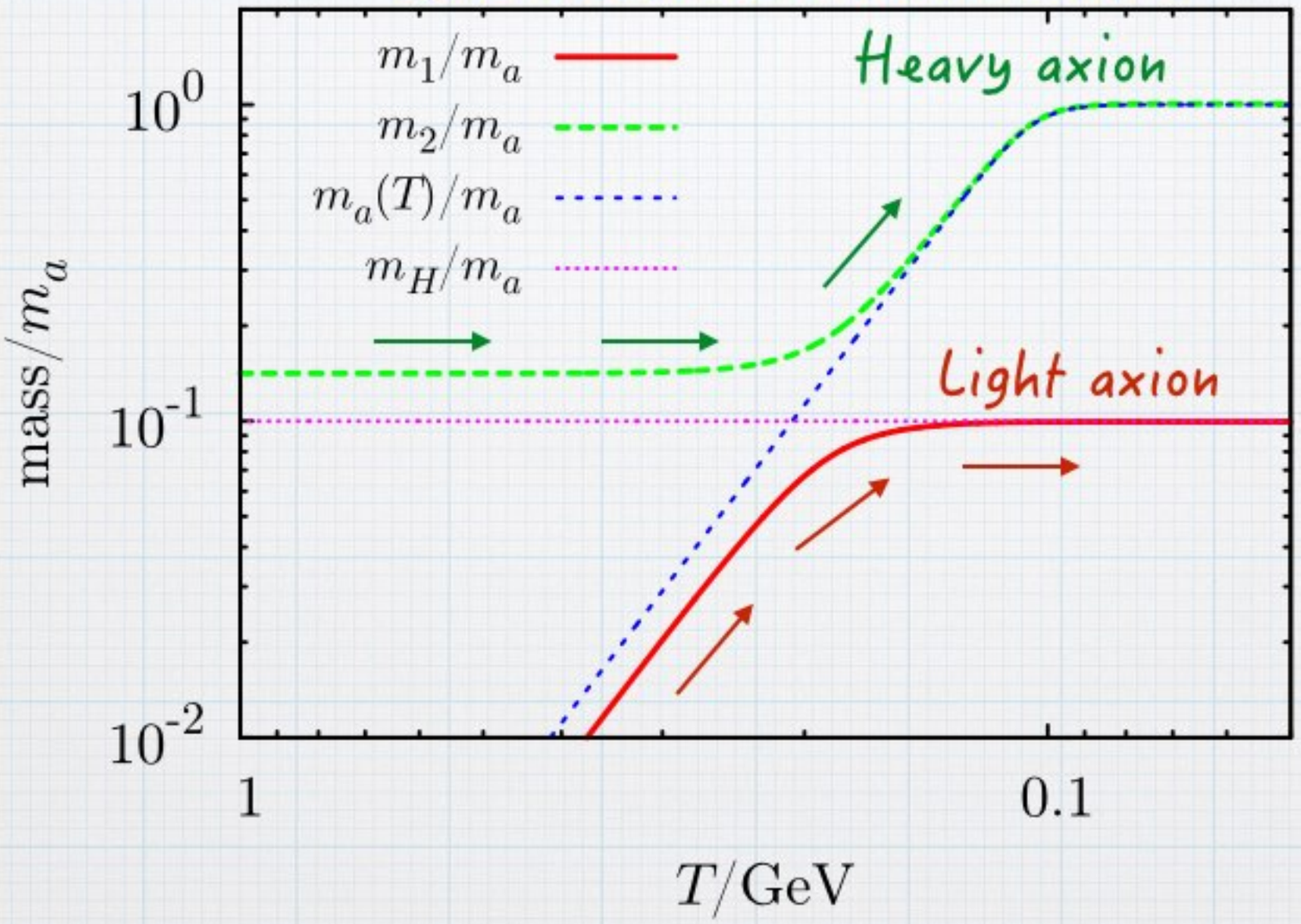
QCD axion + hidden axion



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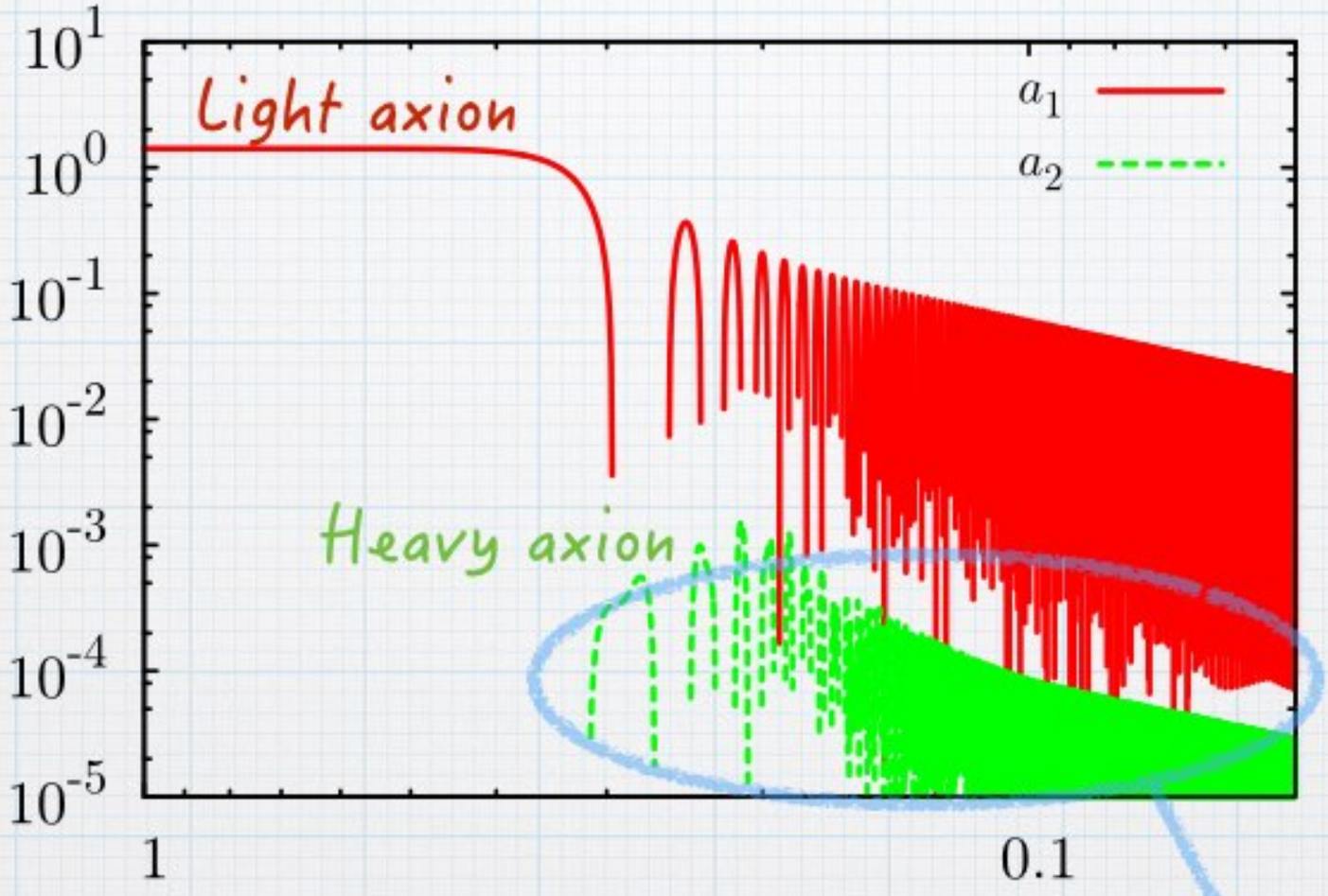
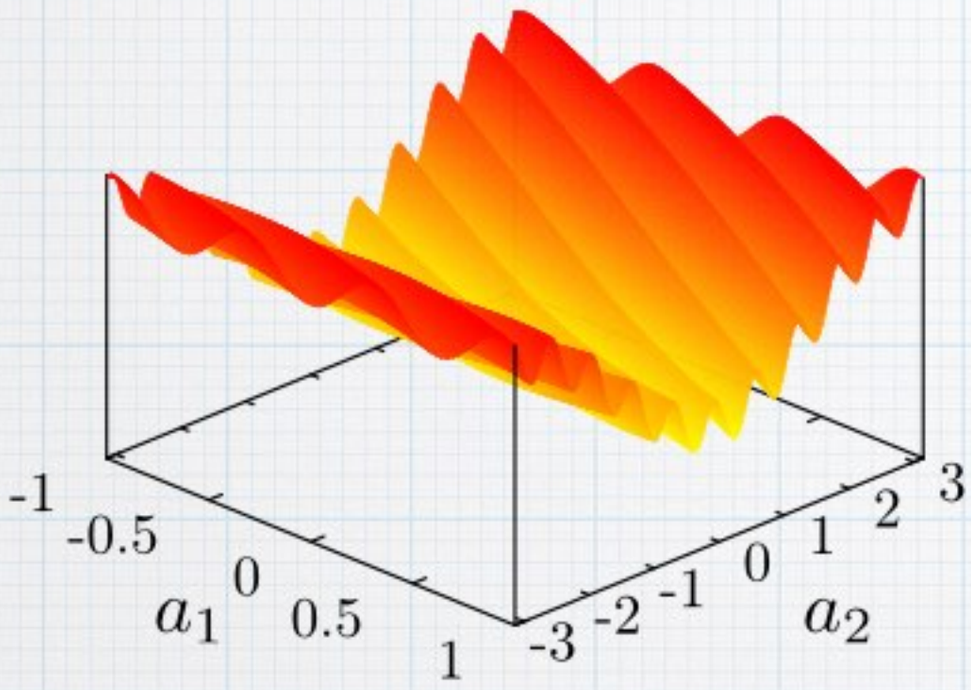
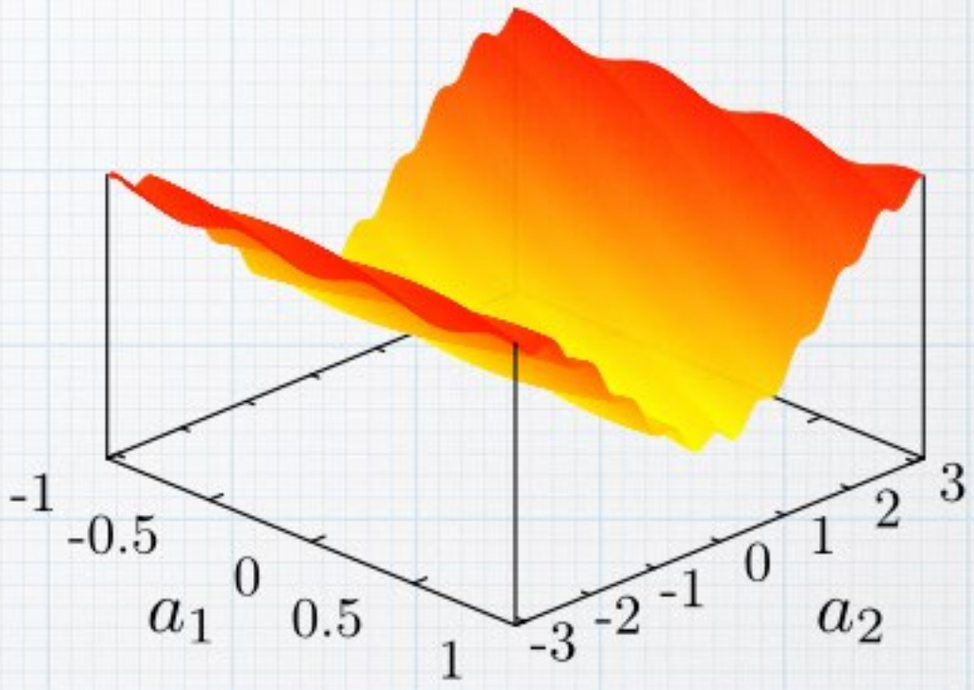


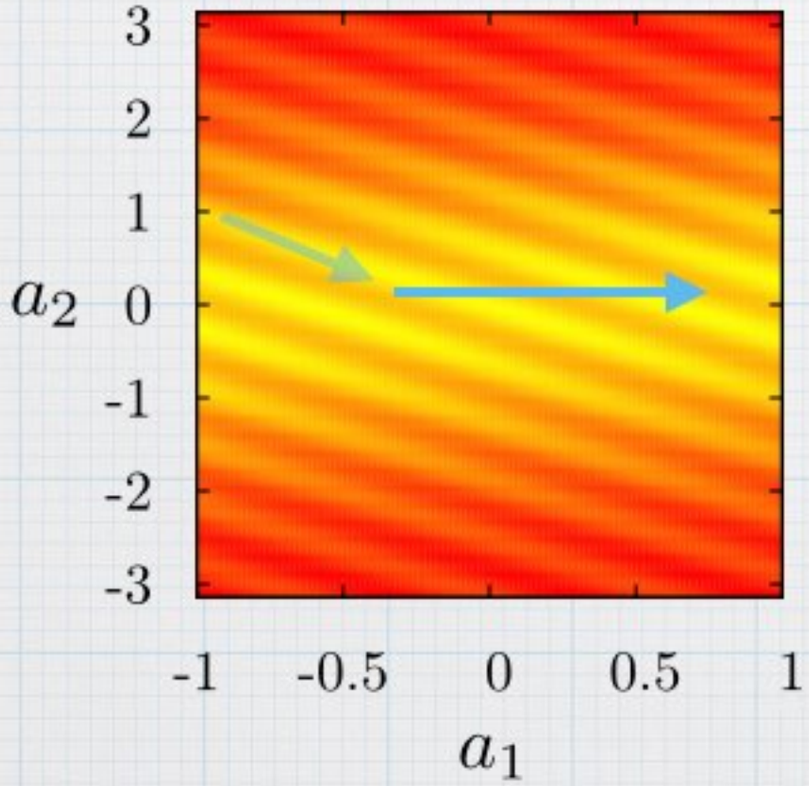
Heavy axion is suppressed

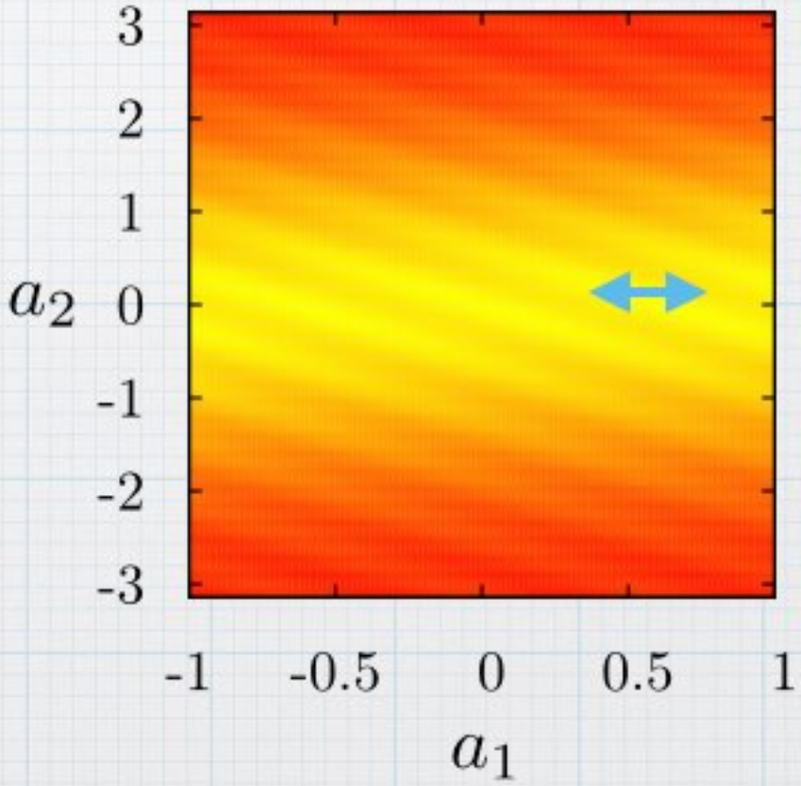
$$\rho_a \sim (m_L/m_H)\rho_a|_{\rm no-resonance}$$

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

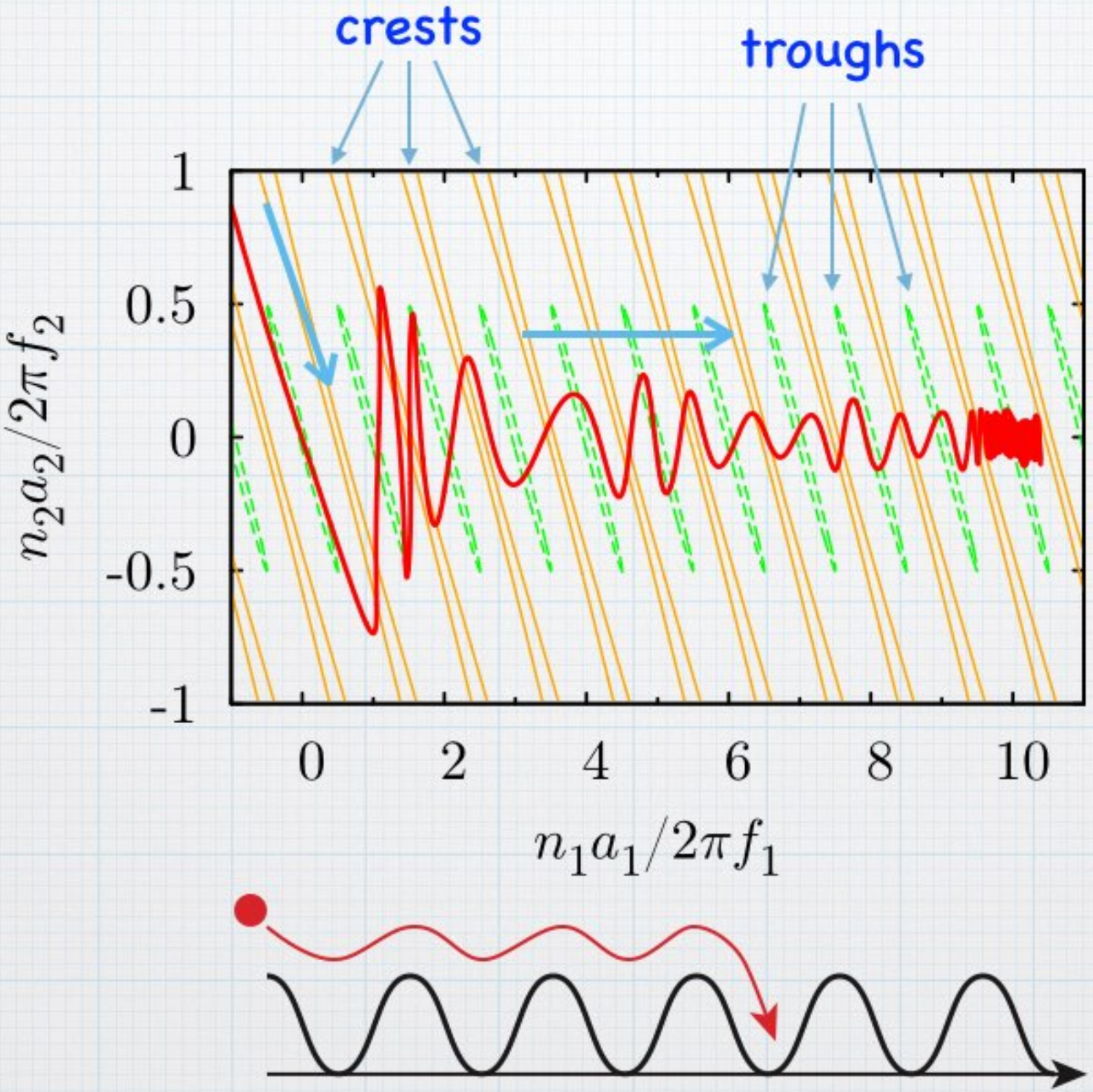








Axion trajectory



The conditions to climb over the potential barrier

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

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

—> kinetic energy > potential barrier

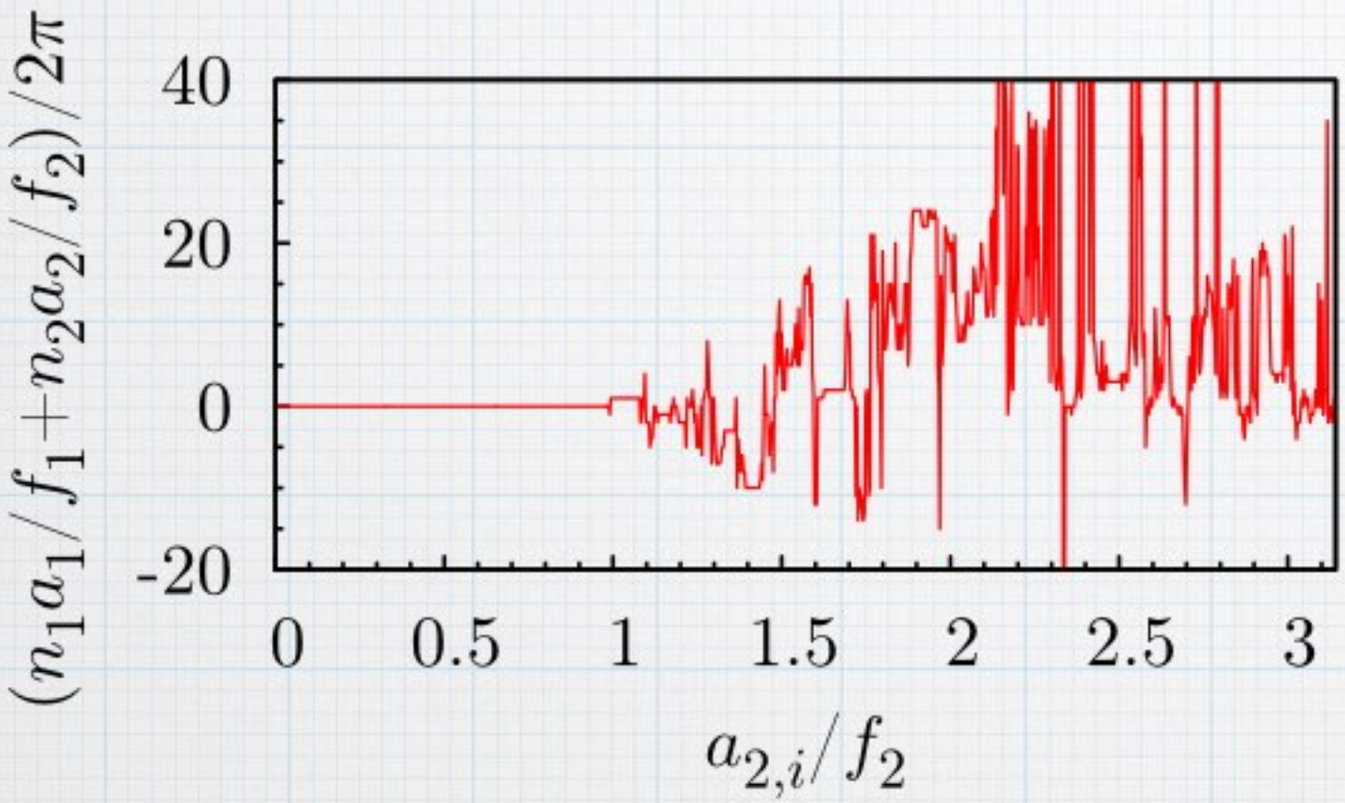
$$(2)\ \ H_{\mathrm{lc}} \sim (0.1 - 1) H_{\mathrm{osc}}$$

—> 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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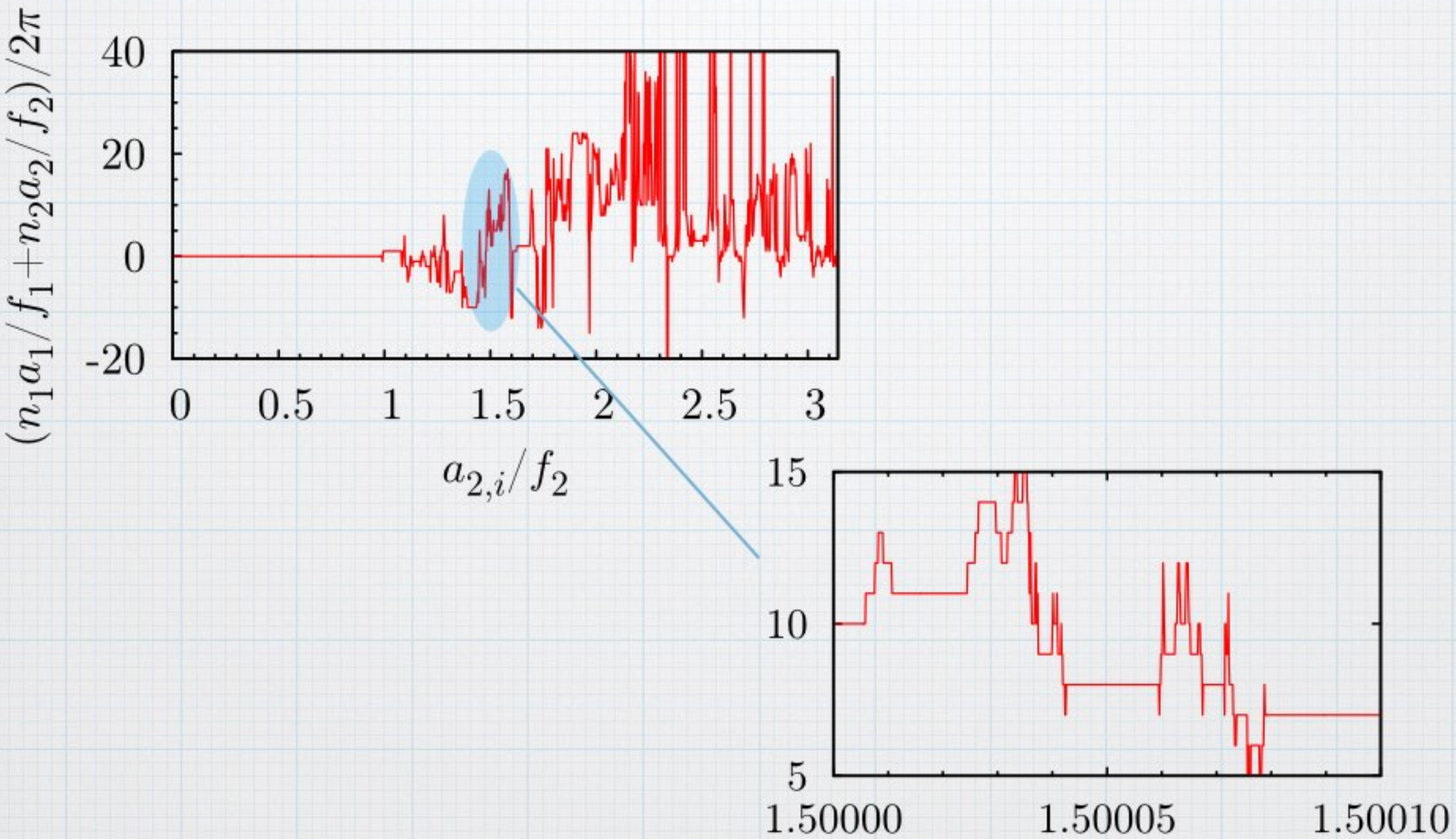

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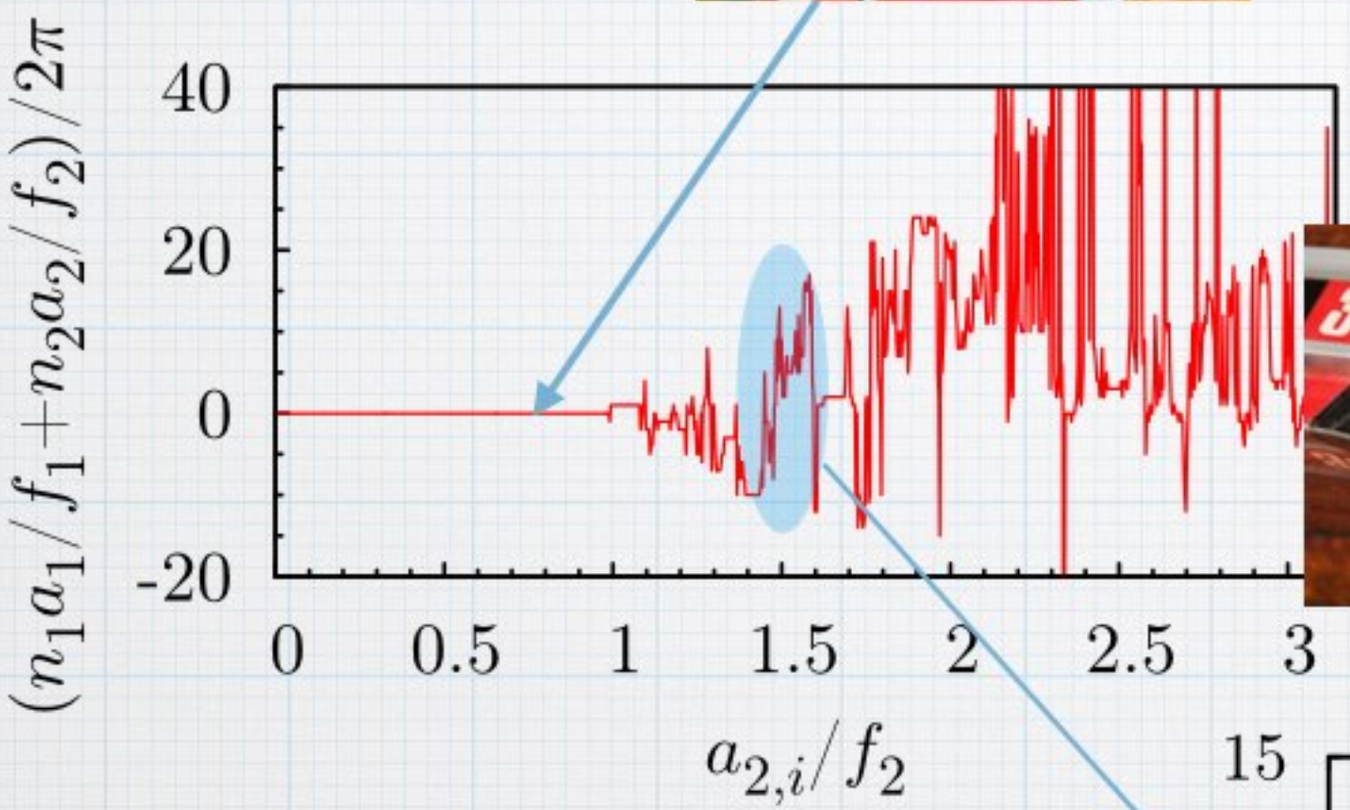
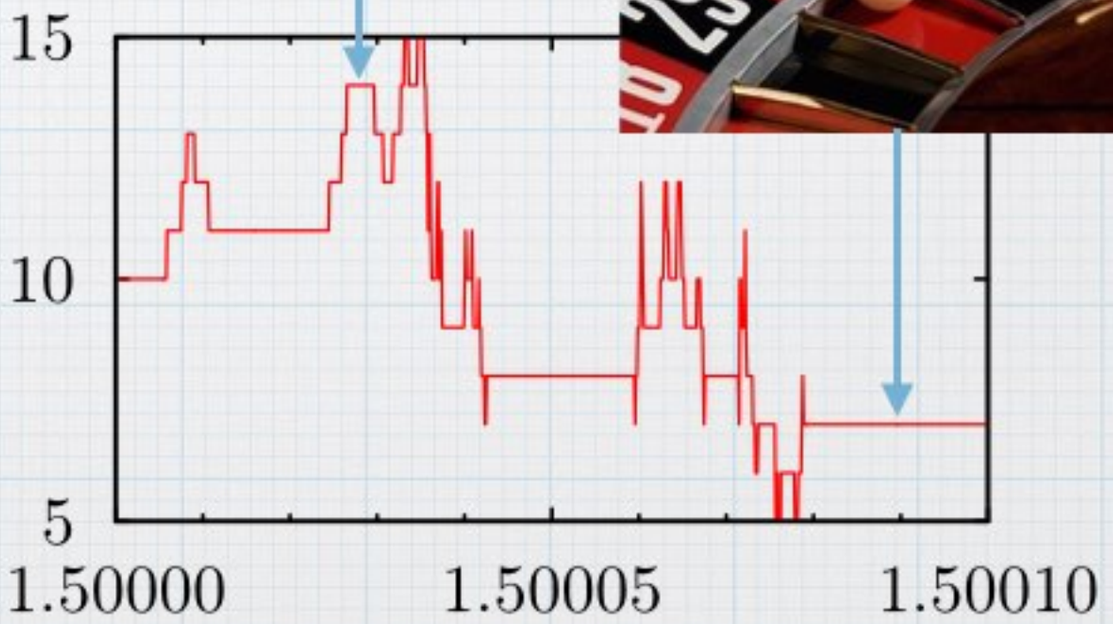




Axion "ROULETTE"

H^{-1}

Domain wall

H^{-1}

Domain wall

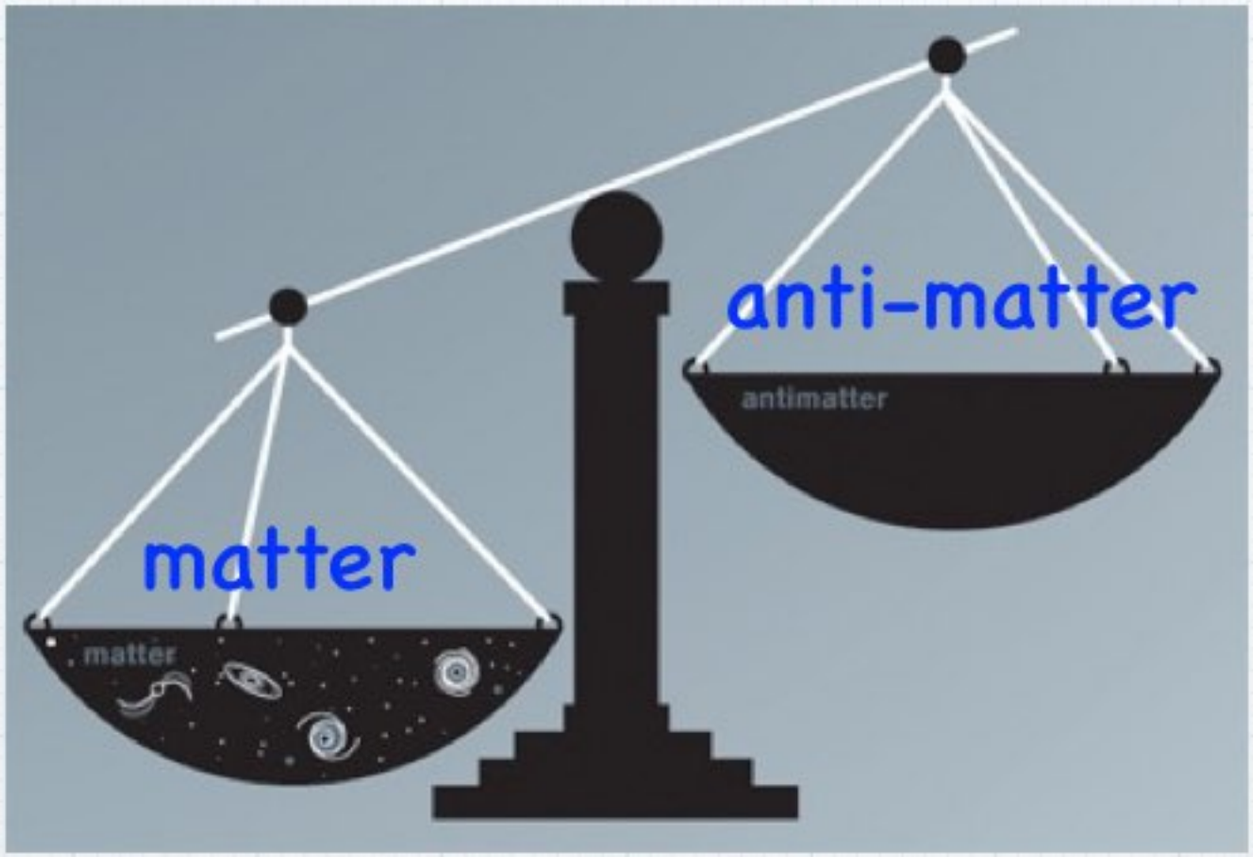
H^{-1}

II

Axion domain wall Baryogenesis

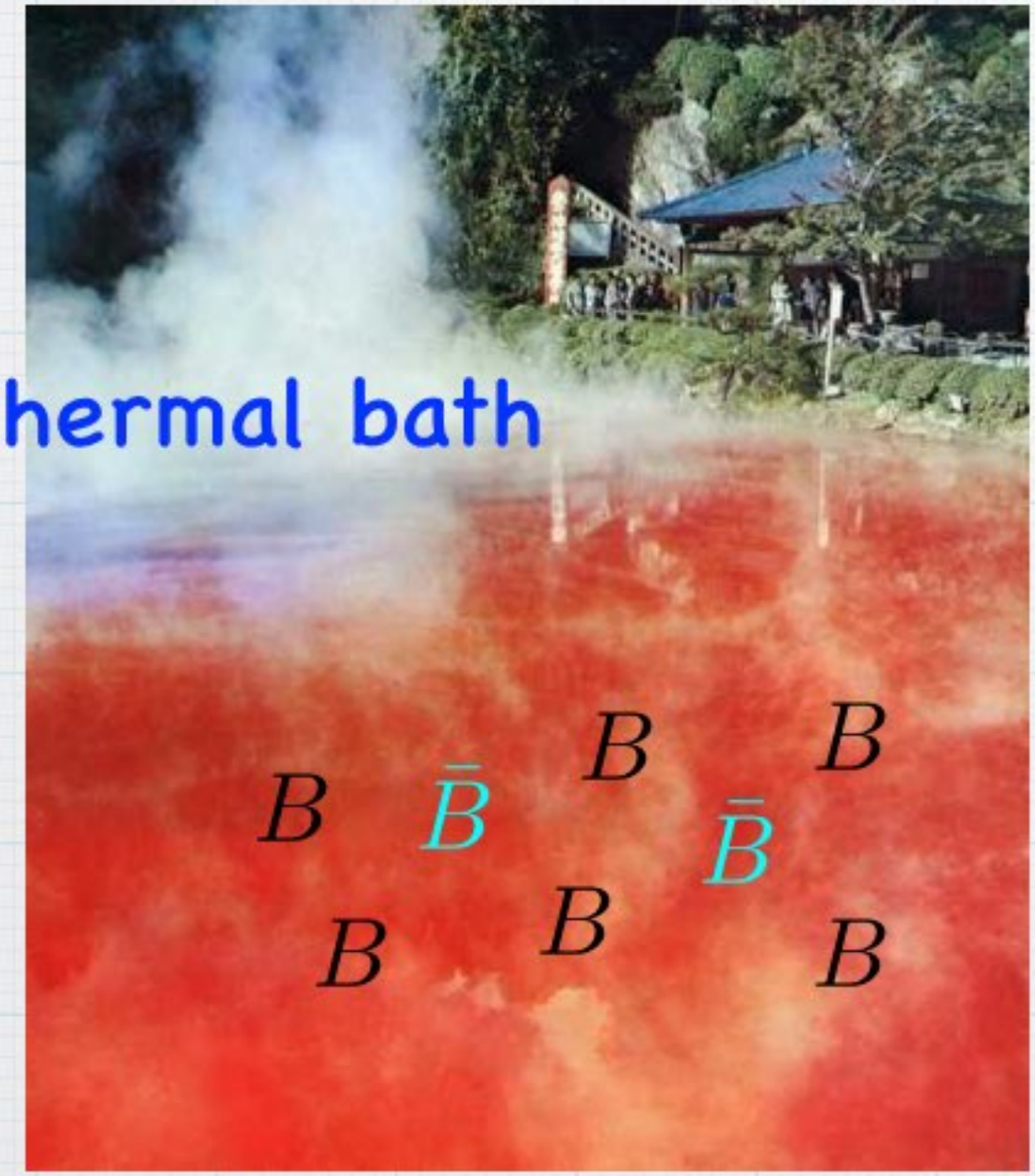
R. Daido, NK, F. Takahashi, arXiv:1504.07917

Baryon asymmetry



$$\frac{n_B}{s} = 8.4 \times 10^{-11}$$

Spontaneous Baryogenesis



nonzero chemical potential : $\mu \neq 0$

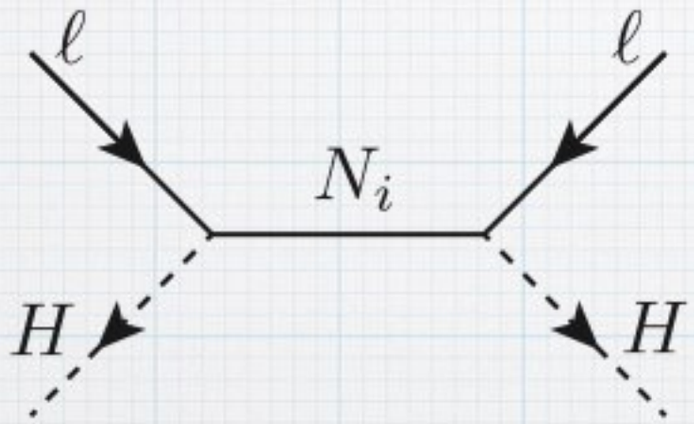
$$n_\ell^{\rm eq} - n_{\bar{\ell}}^{\rm eq} \simeq 2\mu T^2$$

baryon asymmetry is generated even in thermal equilibrium!

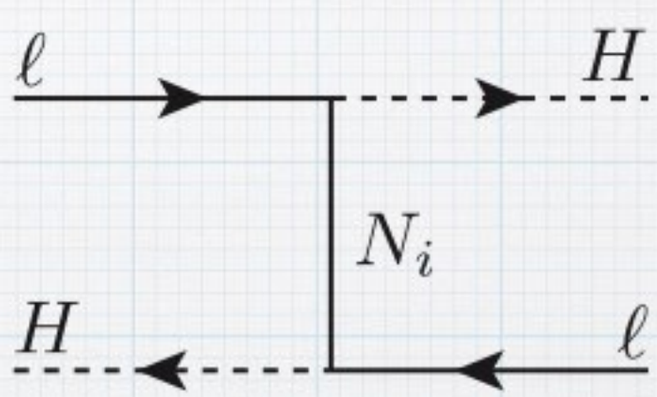
Lepton number violating processes

Seesaw model
(Standard Model + right-handed neutrinos)

$\ell\ell \leftrightarrow HH$



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



interaction rate

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

decoupling temperature

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

Axion potential

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

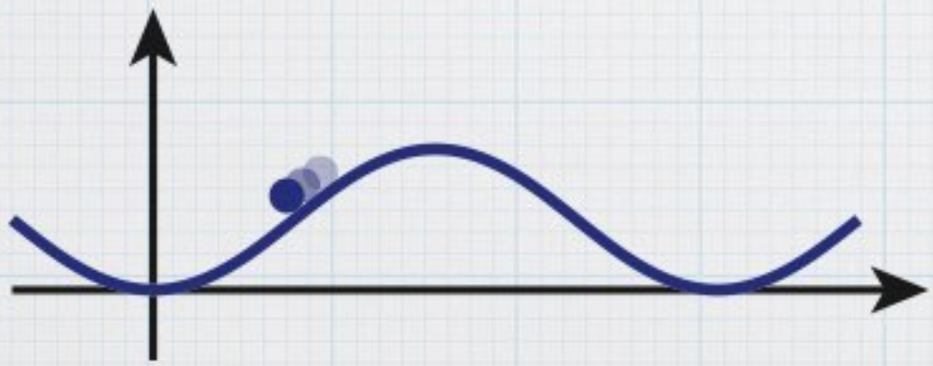
derivative coupling with lepton currents

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

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

effective chemical potential: $\mu_{\rm eff} = \frac{\dot{a}}{f}$

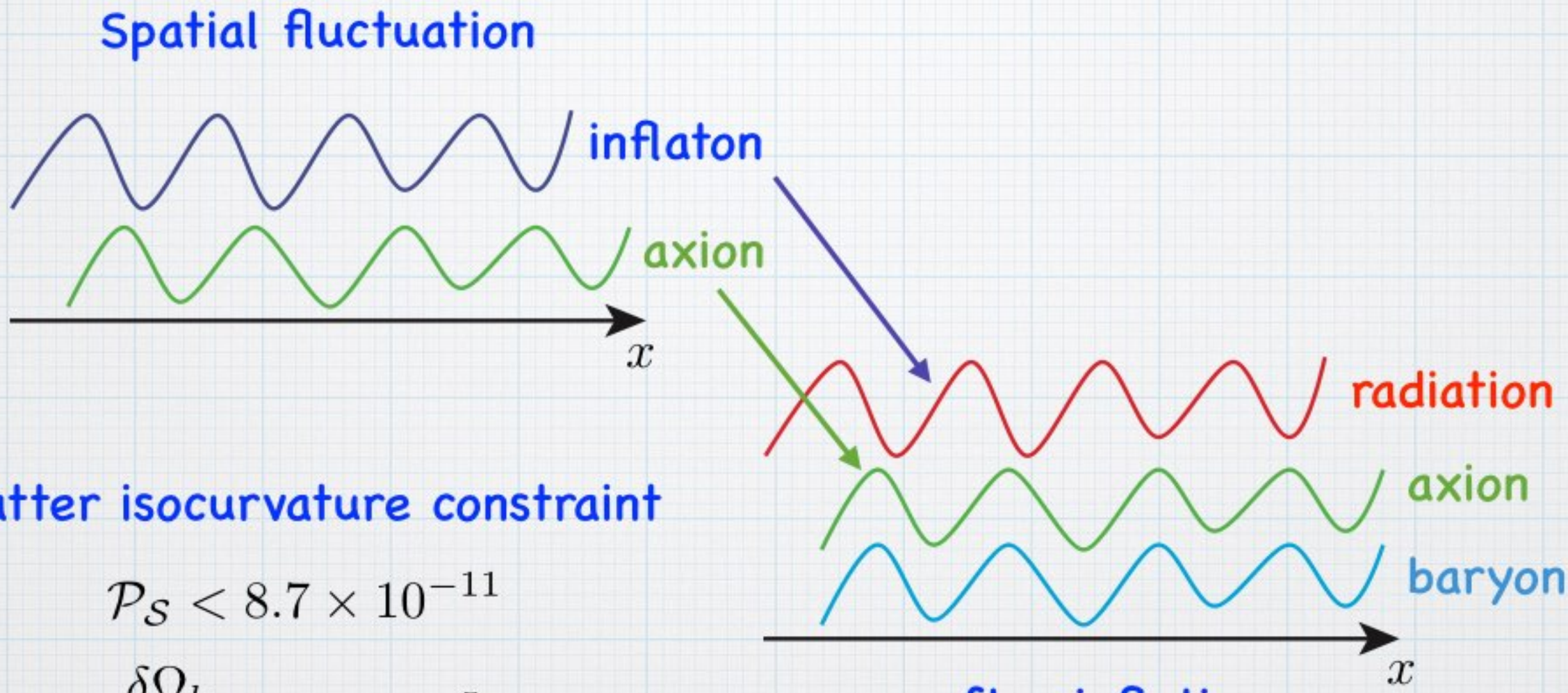
At the onset of axion oscillation -> $\mu_{\rm eff} \neq 0$



spontaneous baryogenesis works

Kusenko,Schmitz,Yanagida (2014)

Baryon isocurvature problem



matter isocurvature constraint

$$\mathcal{P}_{\mathcal{S}} < 8.7 \times 10^{-11}$$

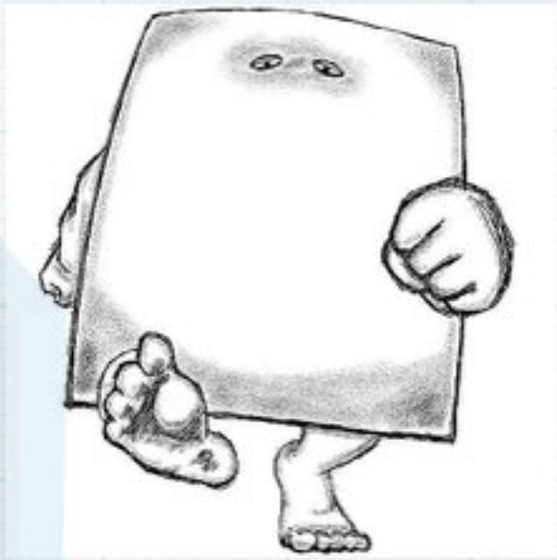
$$\frac{\delta\Omega_b}{\Omega_b} \lesssim 6 \times 10^{-5}$$

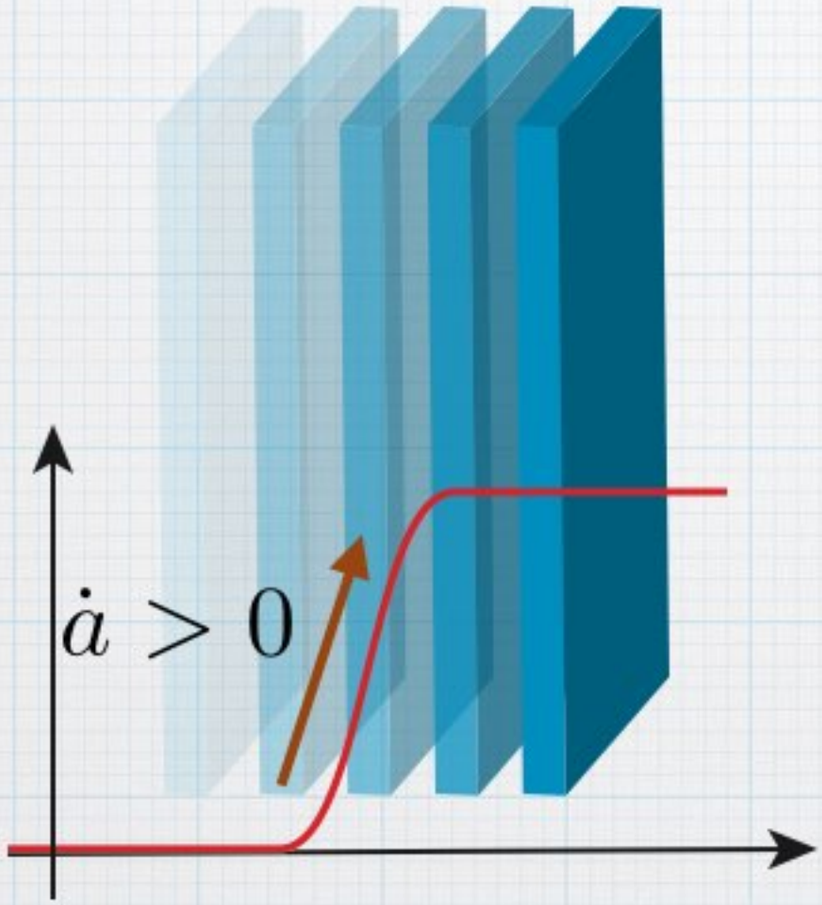
$$H_{\rm inf} \lesssim 6 \times 10^{11}\ {\rm GeV} \left(\frac{f}{10^{15}{\rm GeV}}\right)$$

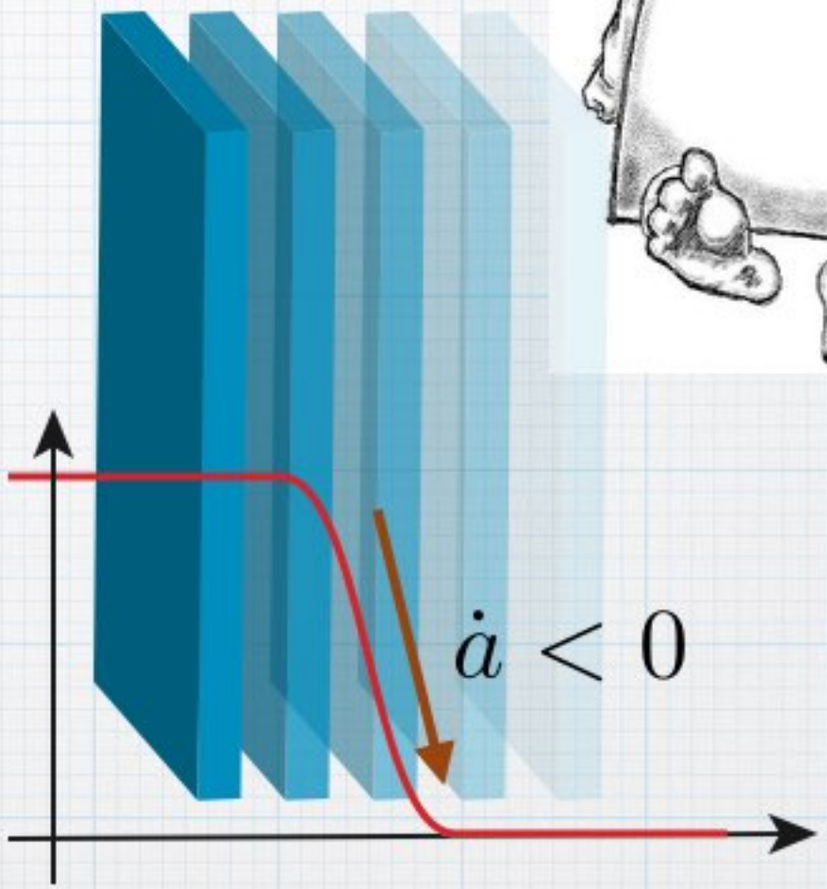
Baryogenesis by domain walls

R. Daido, NK, F. Takahashi, 1504.07917

moving domain walls
in the scaling regime





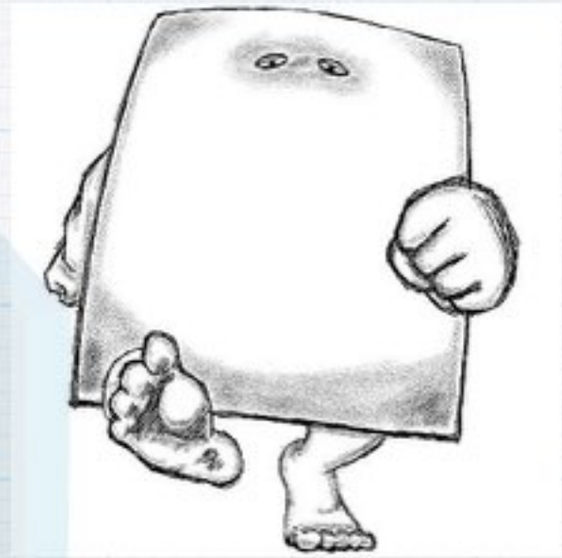


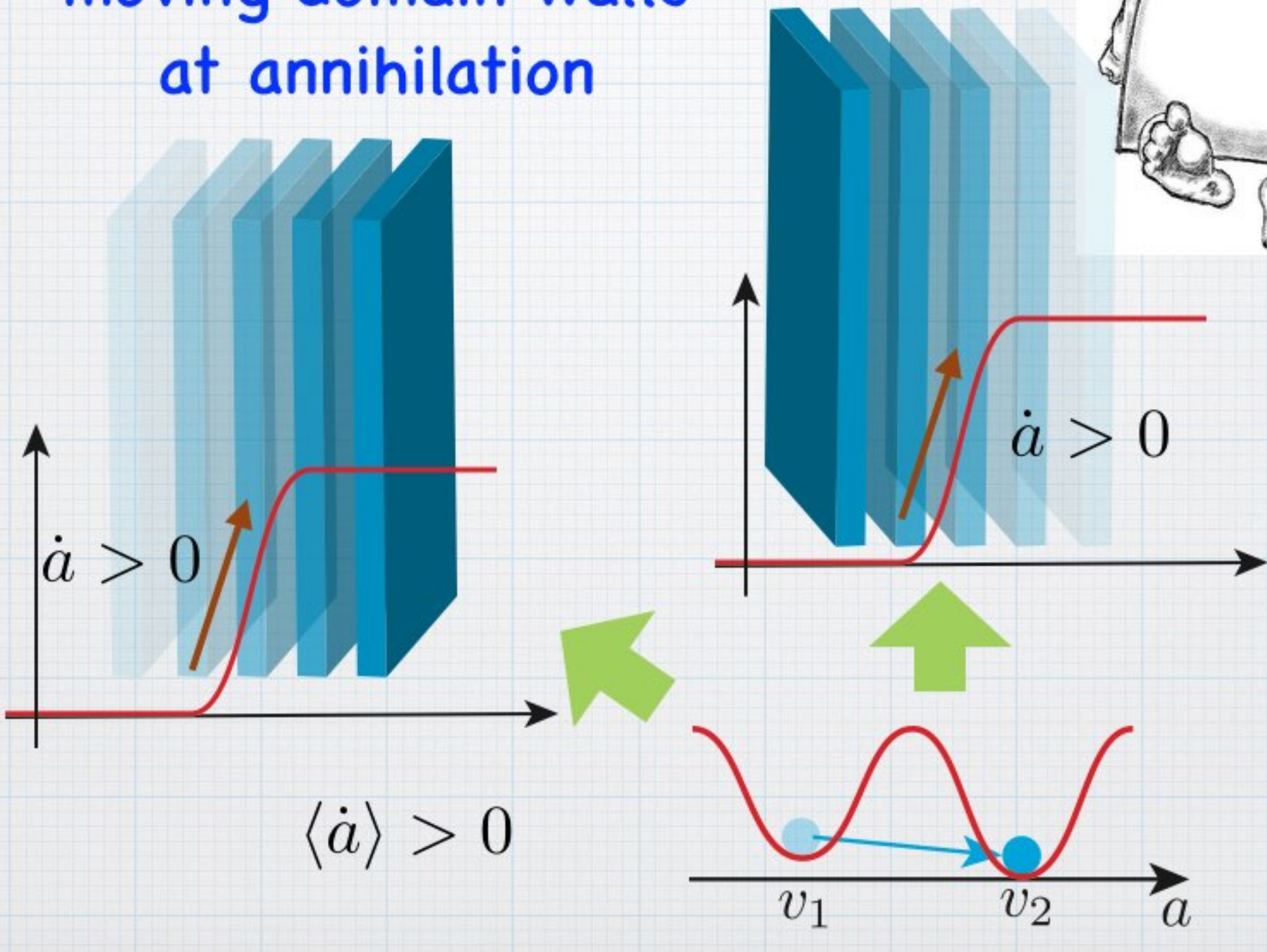
$\langle \dot{a} \rangle = 0$ — no net baryon number

Baryogenesis by domain walls

R. Daido, NK, F. Takahashi, 1504.07917

moving domain walls
at annihilation





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 :

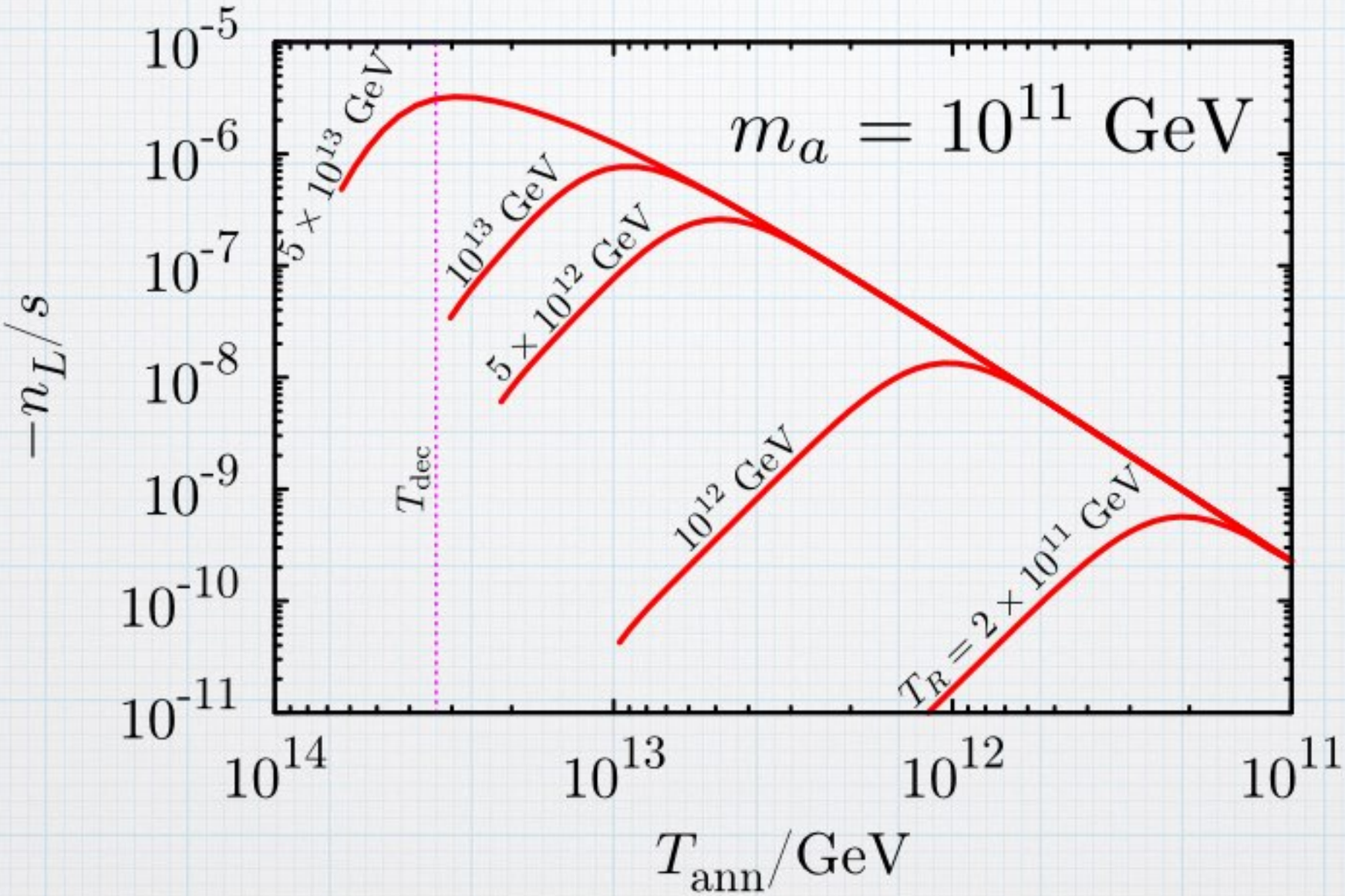
$$a_{\rm dw}(t,\vec{x}) = 4f\tan^{-1}\exp[m\gamma(x-vt)] \quad \textbf{with} \quad \gamma = 1/\sqrt{1-v^2}$$

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

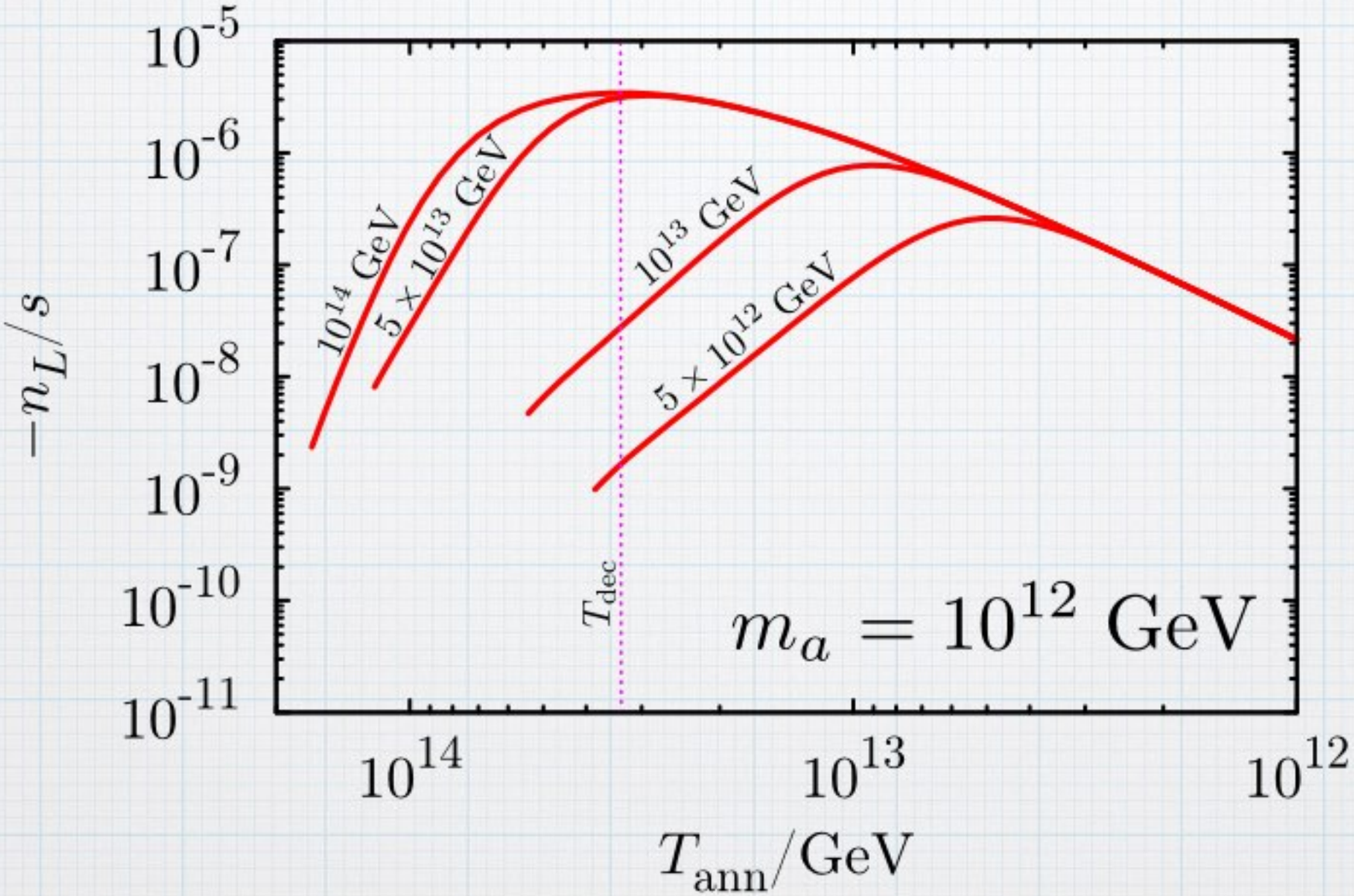
$$(x = 0 \ \text{ at } \ t = t_{\rm dw})$$

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

Numerical results



Numerical results



Axion decay

Long lifetime & axion domination

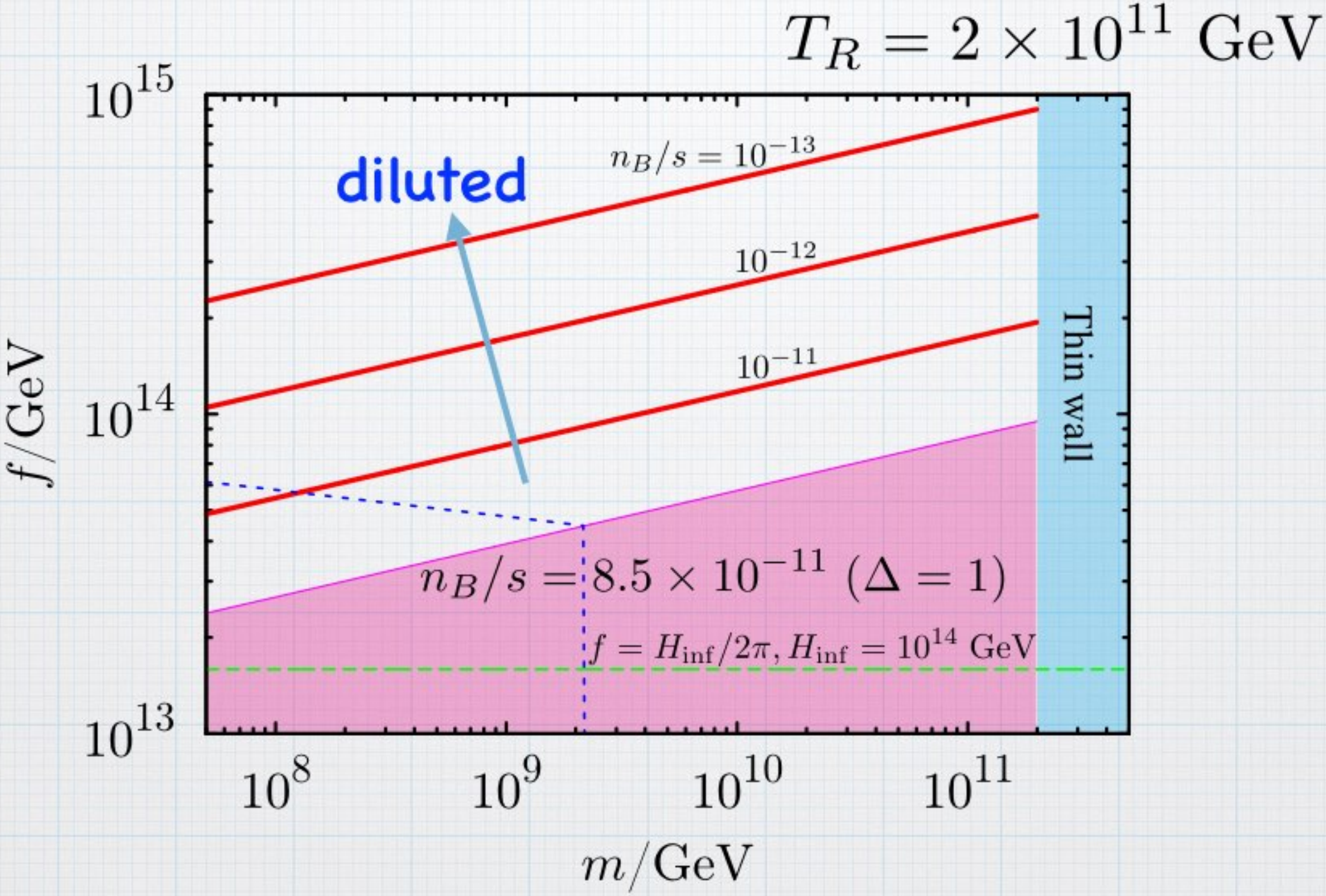
-> Baryon number is diluted after the axion decay

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

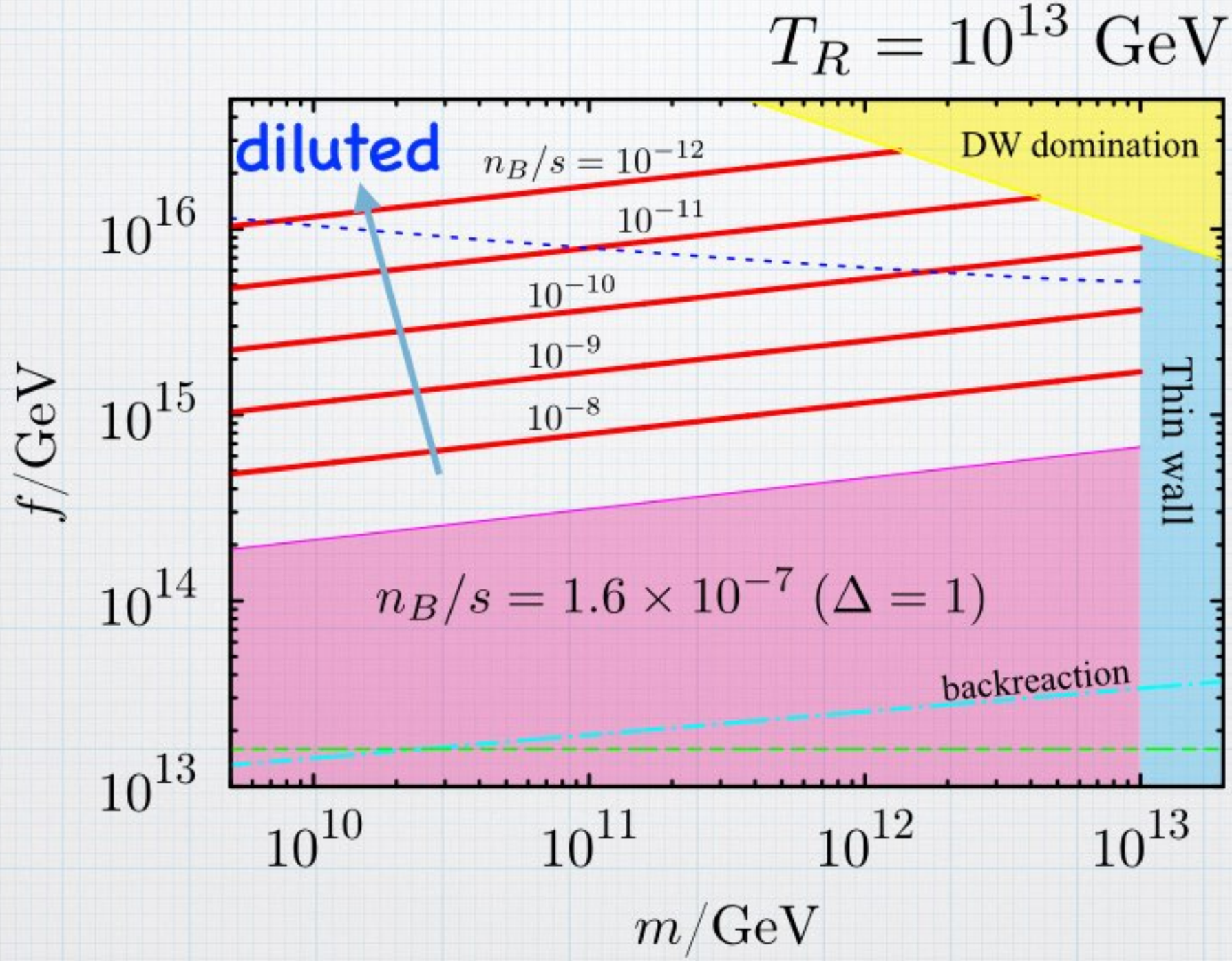
Decay temperature :

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

Numerical results



Numerical results



Conclusions

- Axion can be ubiquitous in nature — "Axiverse"

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

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