Axion and Higgs Domain Walls

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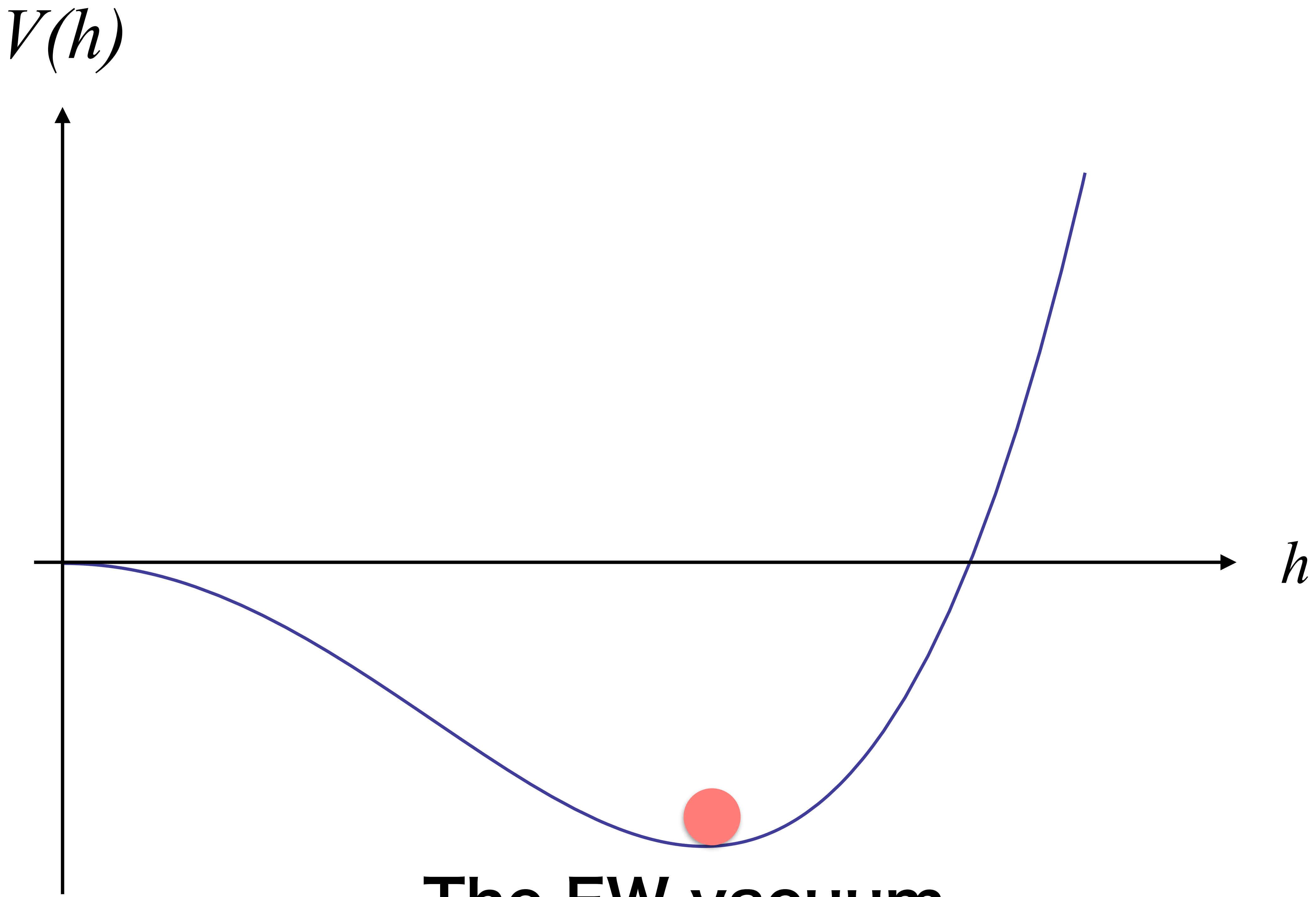
Fumi Takahashi
(Tohoku & IPMU)

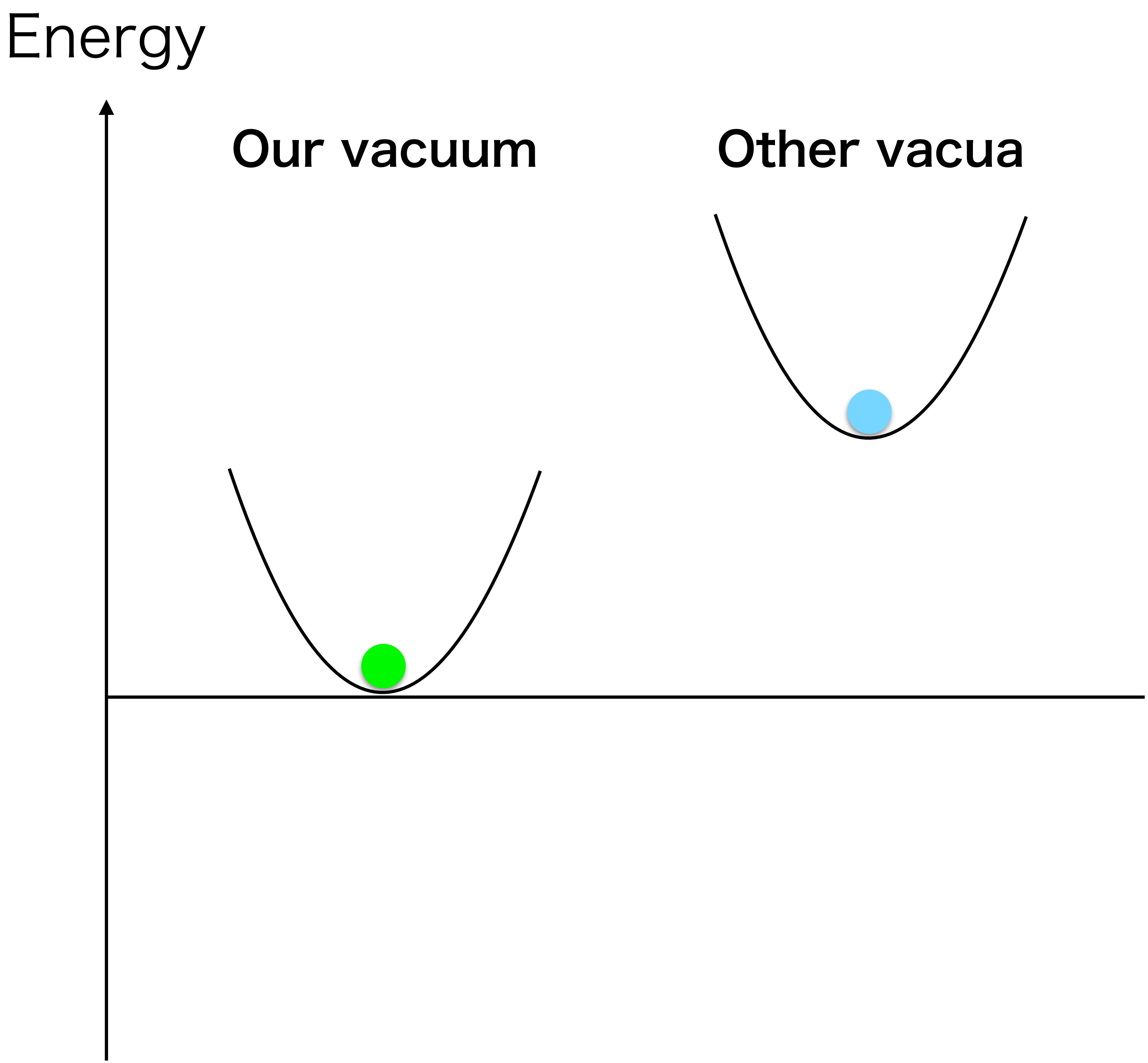
Hamada, Oda, FT, 1408.5556, Kitajima, FT 1411.2011, 1502.03725
Daido, Kitajima, FT, 1504.07917, 1505.07670



The EW vacuum

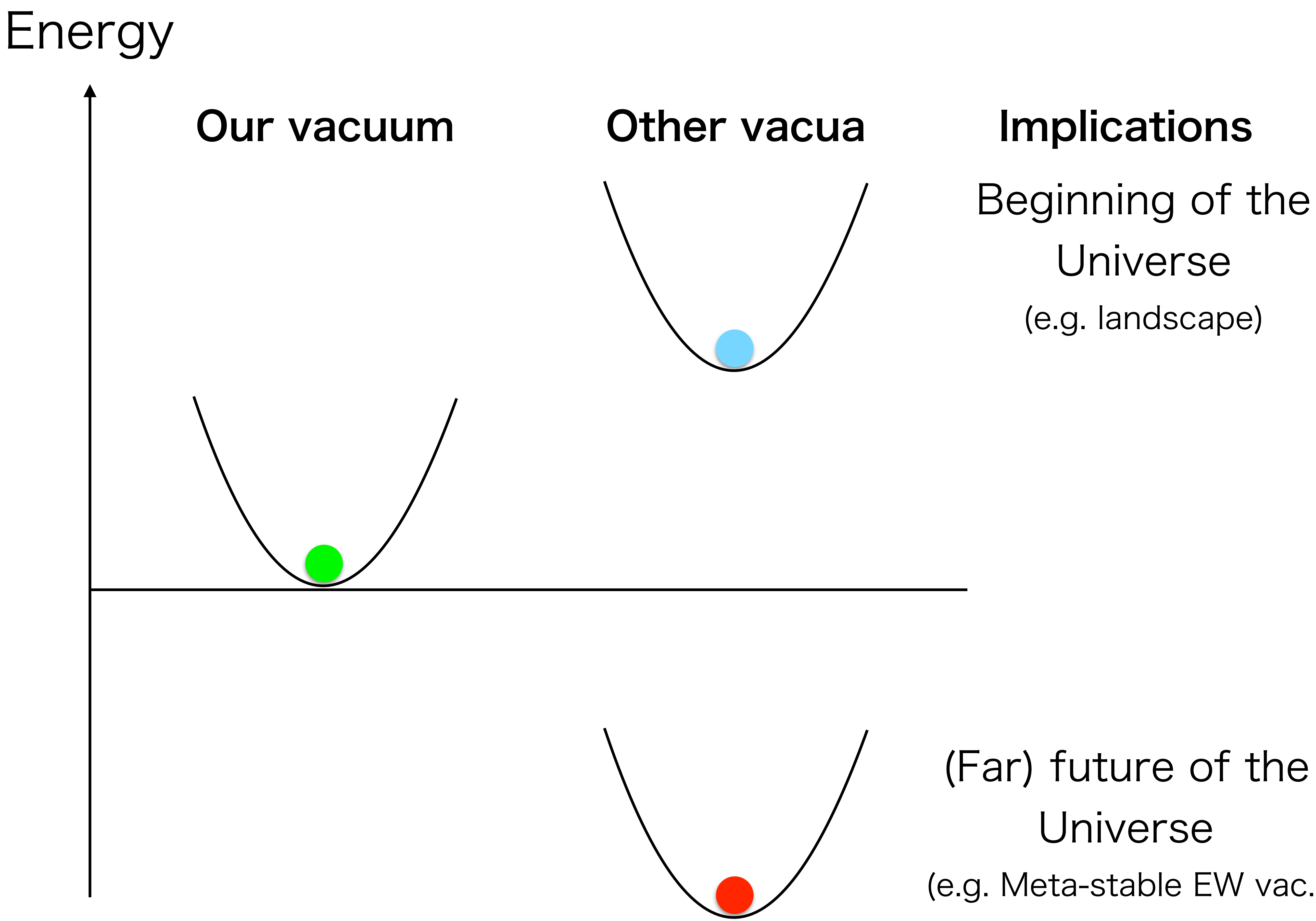
Are there any other vacua?

cf. Anthropic solution to the c.c. problem.



Implications

Beginning of the Universe
(e.g. landscape)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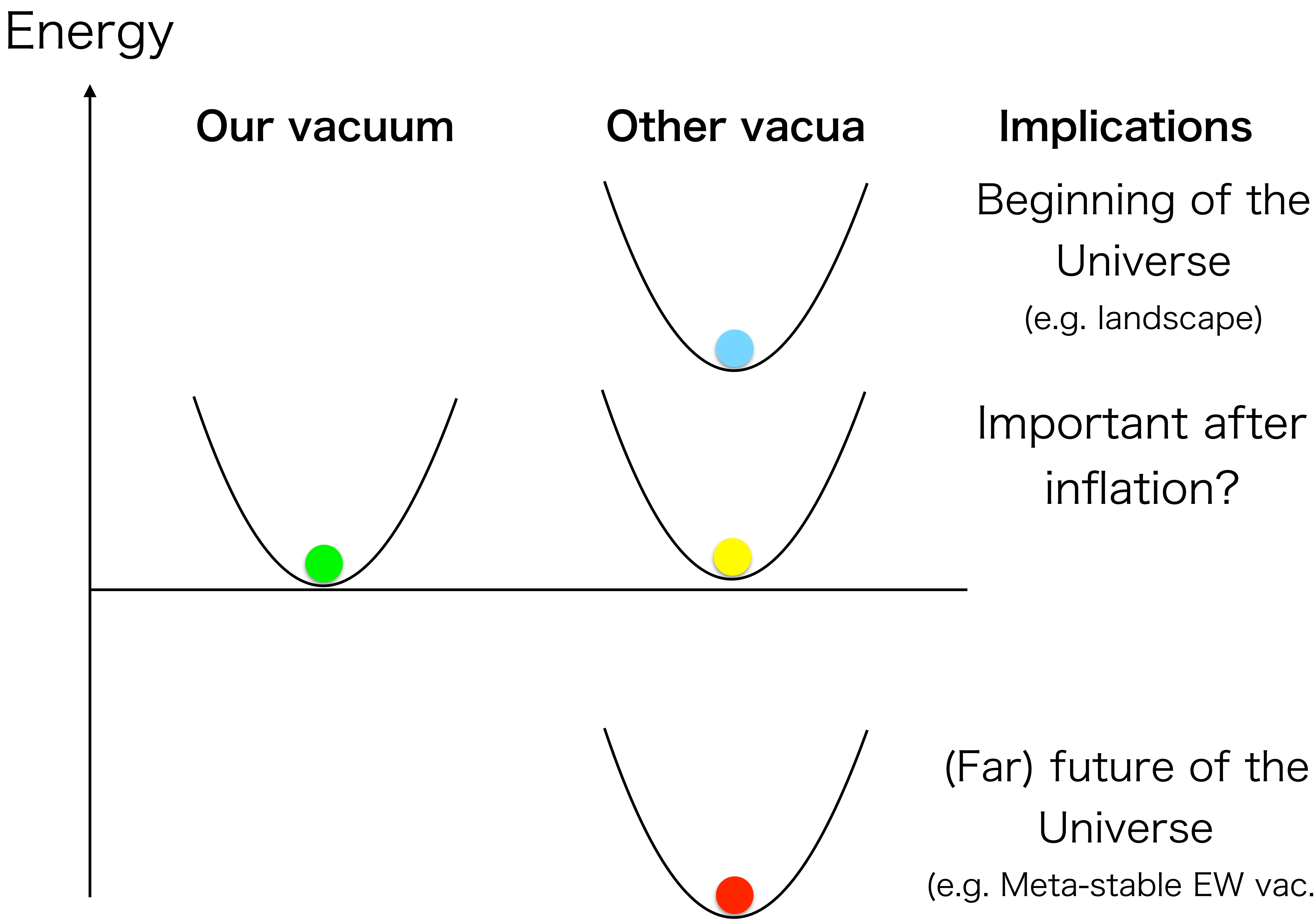
(Far) future of the Universe
(e.g. Meta-stable EW vac.)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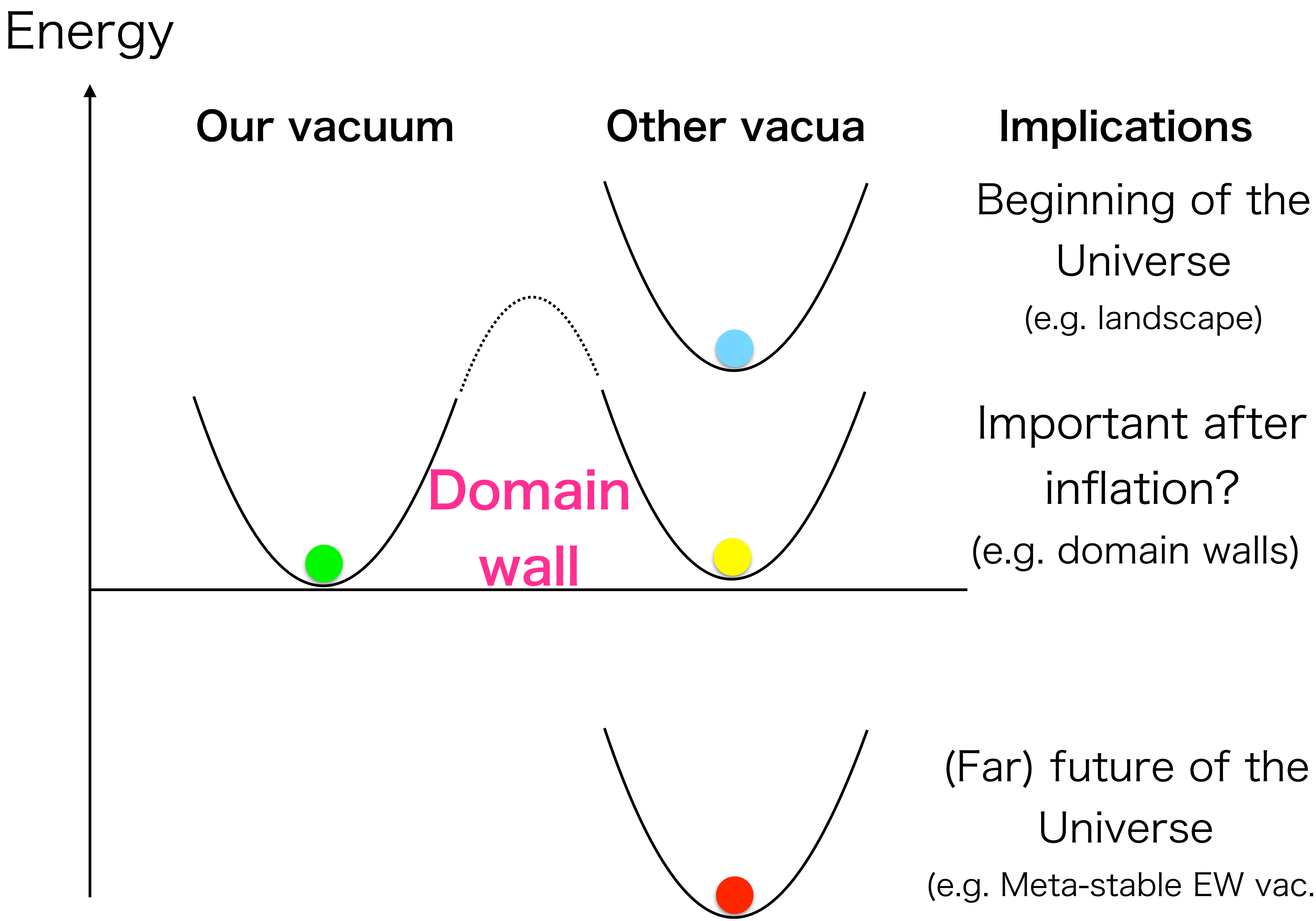
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Domain wall
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(e.g. domain walls)
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Degenerate vacua

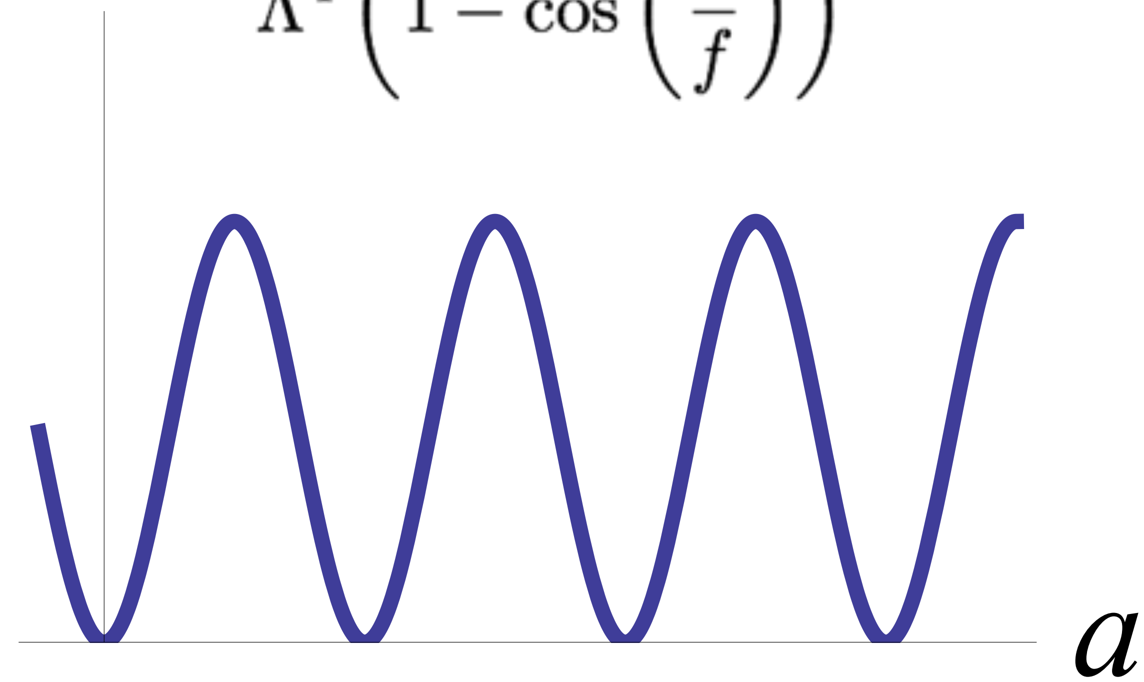
- **Axion**

$$\Lambda^4\left(1-\cos\left(\frac{a}{f}\right)\right)$$

Shift symmetry:

$$a \to a + C$$

broken by non-perturbative effects.



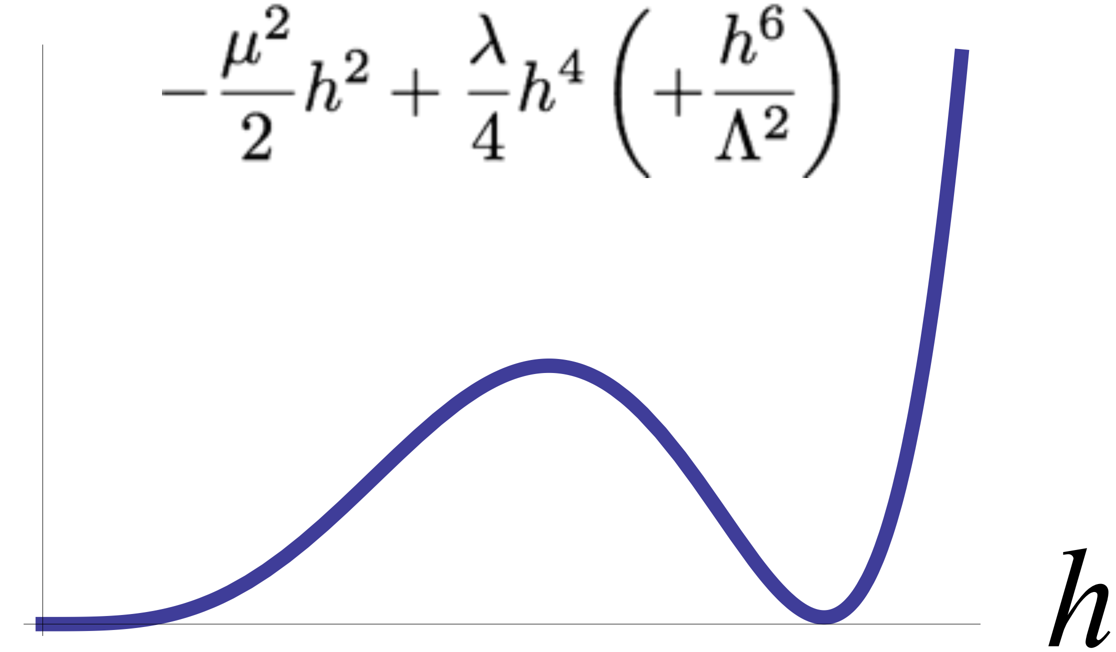
- **SM Higgs**

$$-\frac{\mu^2}{2}h^2+\frac{\lambda}{4}h^4\left(+\frac{h^6}{\Lambda^2}\right)$$

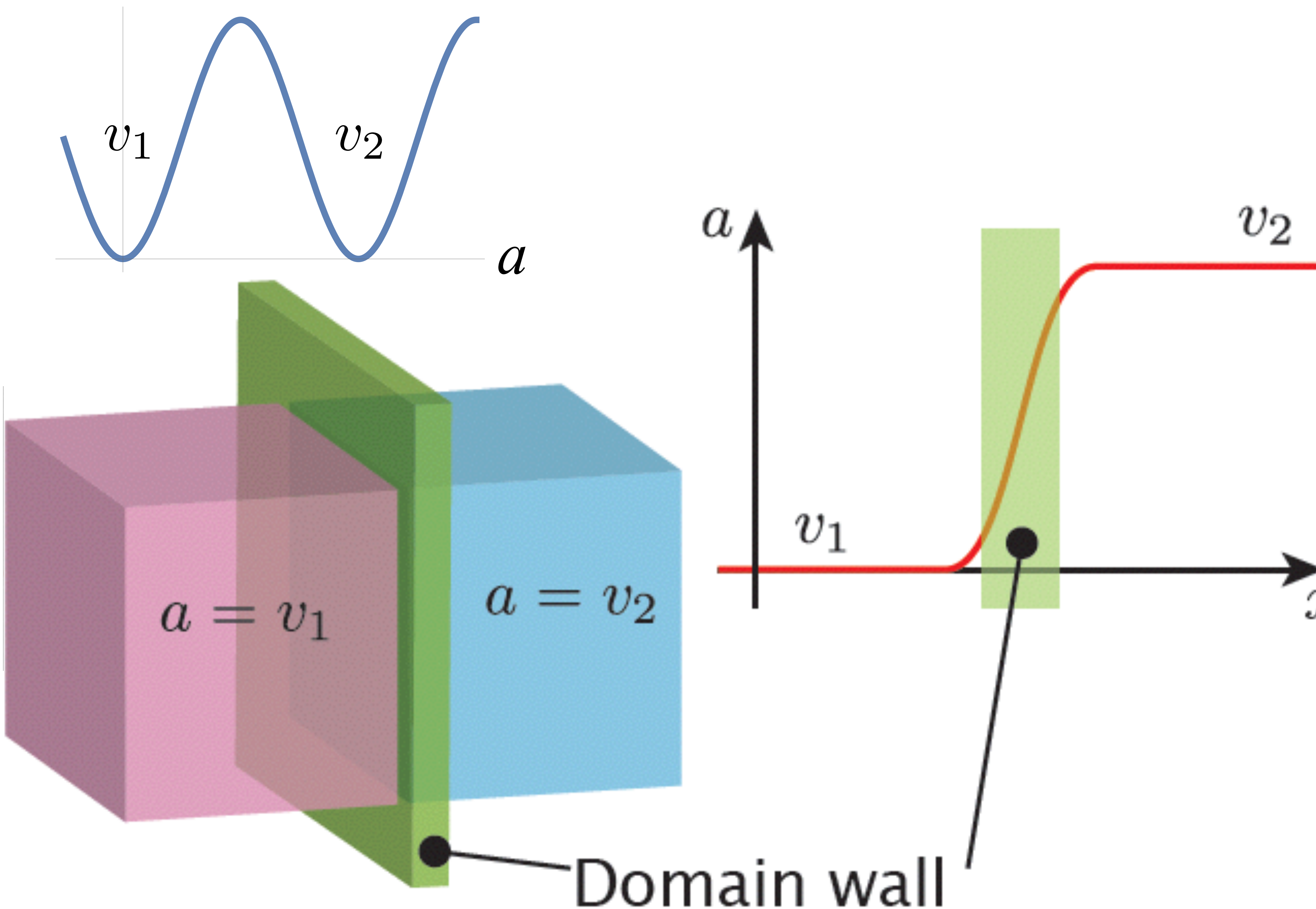
The SM criticality $h_{\min} \sim M_p$

or

Up-lift by new physics $h_{\min} \ll M_p$



Axion domain walls



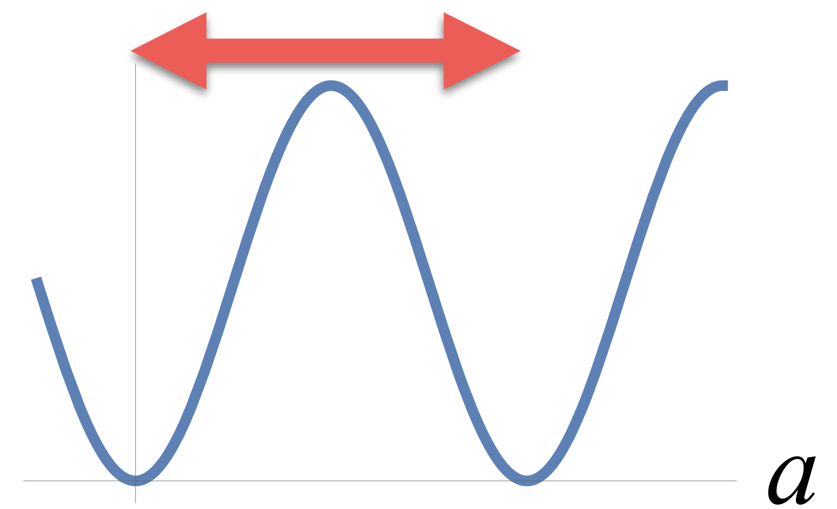
(Figure courtesy of Kitajima)

Axion domain walls

Domain wall formation

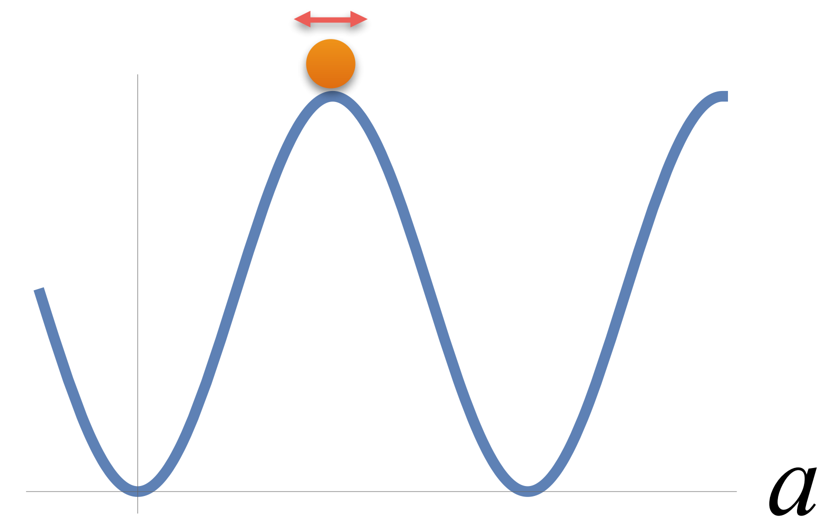
1.Large quantum fluctuations

$$\delta a = \frac{H_{\rm inf}}{2\pi} \sim f_a$$



2.Hilltop initial condition

$$|a_* - \pi f_a| < \delta a$$



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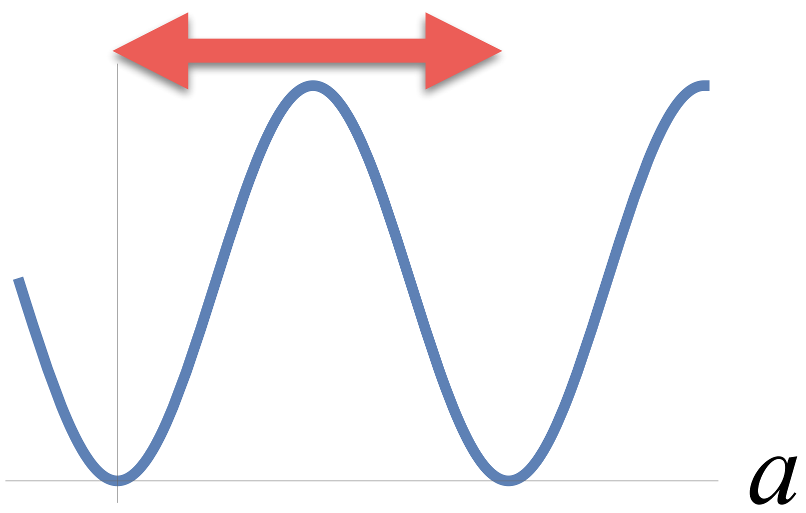

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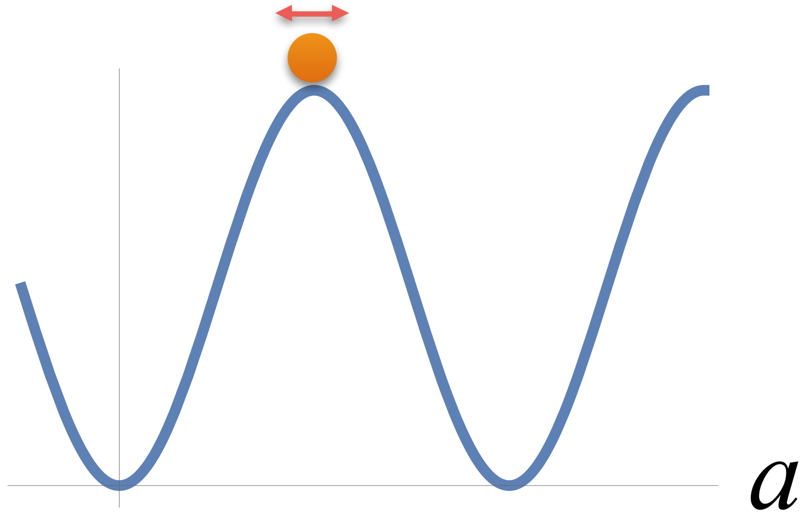


3.Level crossing New!

Kitajima, FT 1411.2011,
Daido, Kitajima, FT, 1505.07670

Level crossing of axions

Hill, Ross, NPB 311, 253 (1988), Kitajima, FT 1411.2011

- Mixings

e.g., $$V(a_1, a_2) = V_1(a_1, a_2) + V_2(a_1, a_2)$$

Mixing

$$= C_1 \left(1 - \cos\left(n_1 \frac{a_1}{f_1} + n_2 \frac{a_2}{f_2}\right)\right) + C_2 \left(1 - \cos\left(\frac{a_2}{f_2}\right)\right)$$

Effective decay constants:

$$f = \frac{\sqrt{n_2^2 f_1^2 + n_1^2 f_2^2}}{n_1}$$

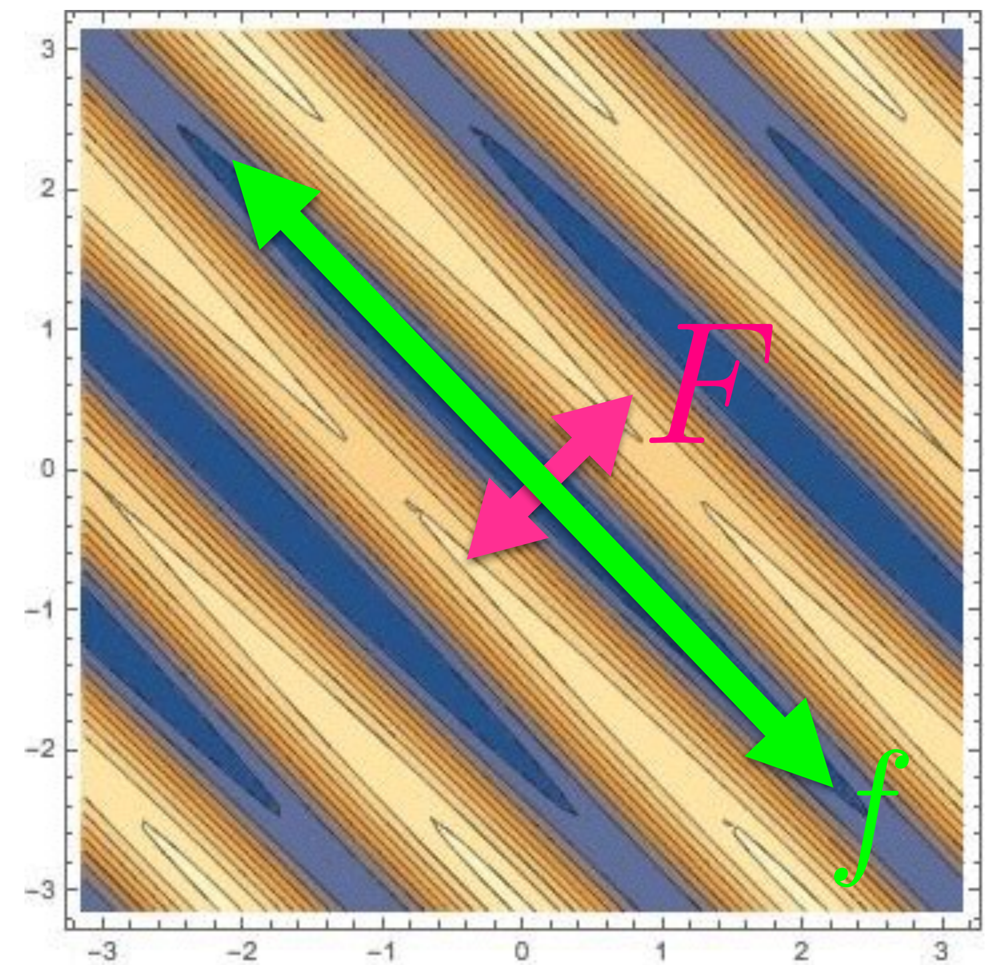
$$F = \frac{f_1 f_2}{\sqrt{n_2^2 f_1^2 + n_1^2 f_2^2}}$$

$f > F$ if n_1 and/or n_2 large

Kim, Nilles, Peloso,`04

Ben-Dayan, Pedro, Westphal, 1404.7773

Tye, Won, 1404.6988



$n_1 = n_2 = 3$

Level crossing of axions

Hill and Ross, NPB 311, 253 (1988), Kitajima, FT 1411.2011

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e.g., $V(a_1, a_2) = V_1(a_1, a_2) + V_2(a_1, a_2)$ *Mixing*

$$= C_1 \left(1 - \cos\left(n_1 \frac{a_1}{f_1} + n_2 \frac{a_2}{f_2}\right)\right) + C_2 \left(1 - \cos\left(\frac{a_2}{f_2}\right)\right)$$

- T-dependent mass

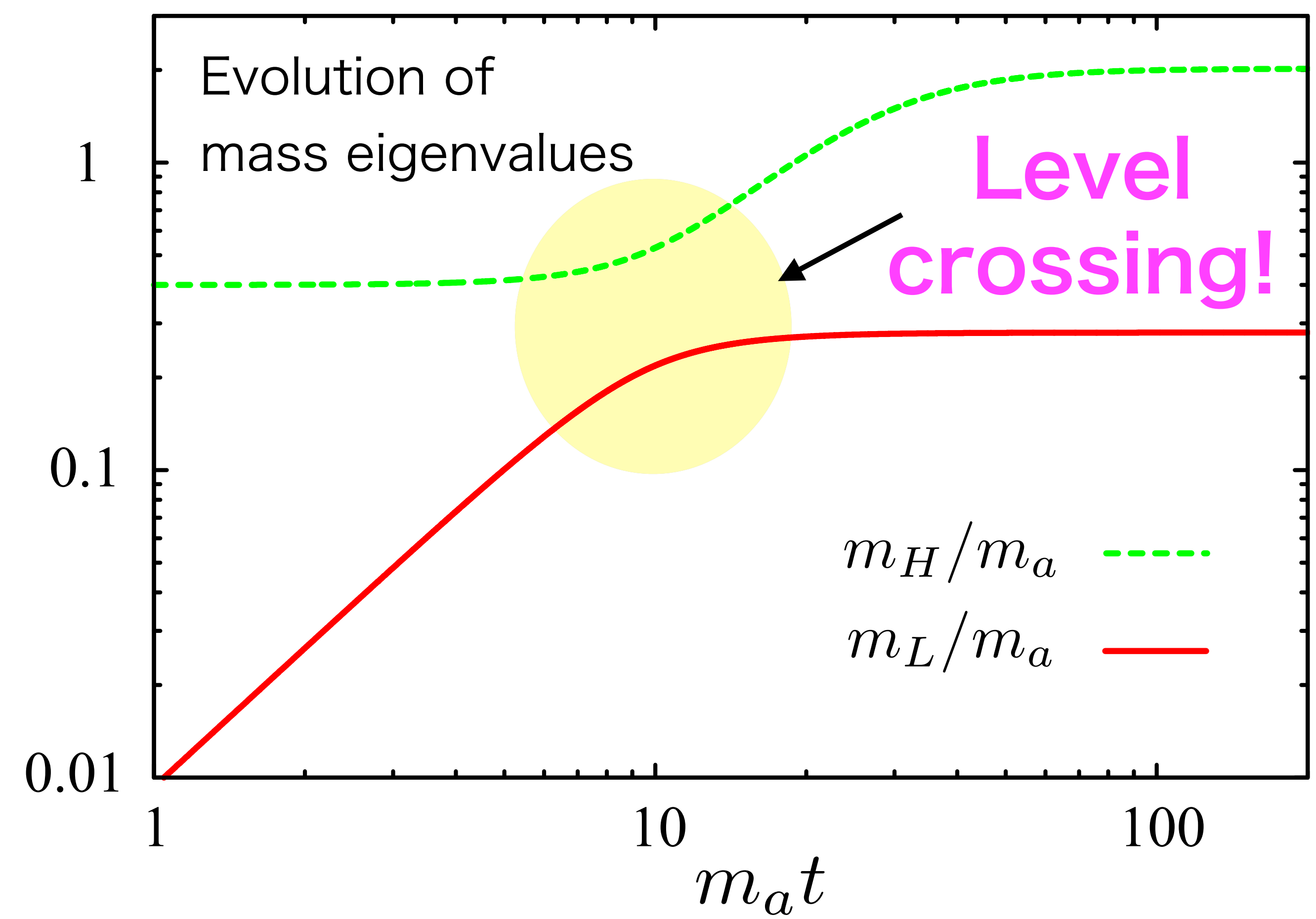
e.g., $C_1 = \Lambda_1^4, \quad C_2 = m_a(T)^2 f_2^2$

T-dependence

$$m_a(T) = m_a \min\left[\left(\frac{T}{\Lambda_2}\right)^p, 1\right]$$

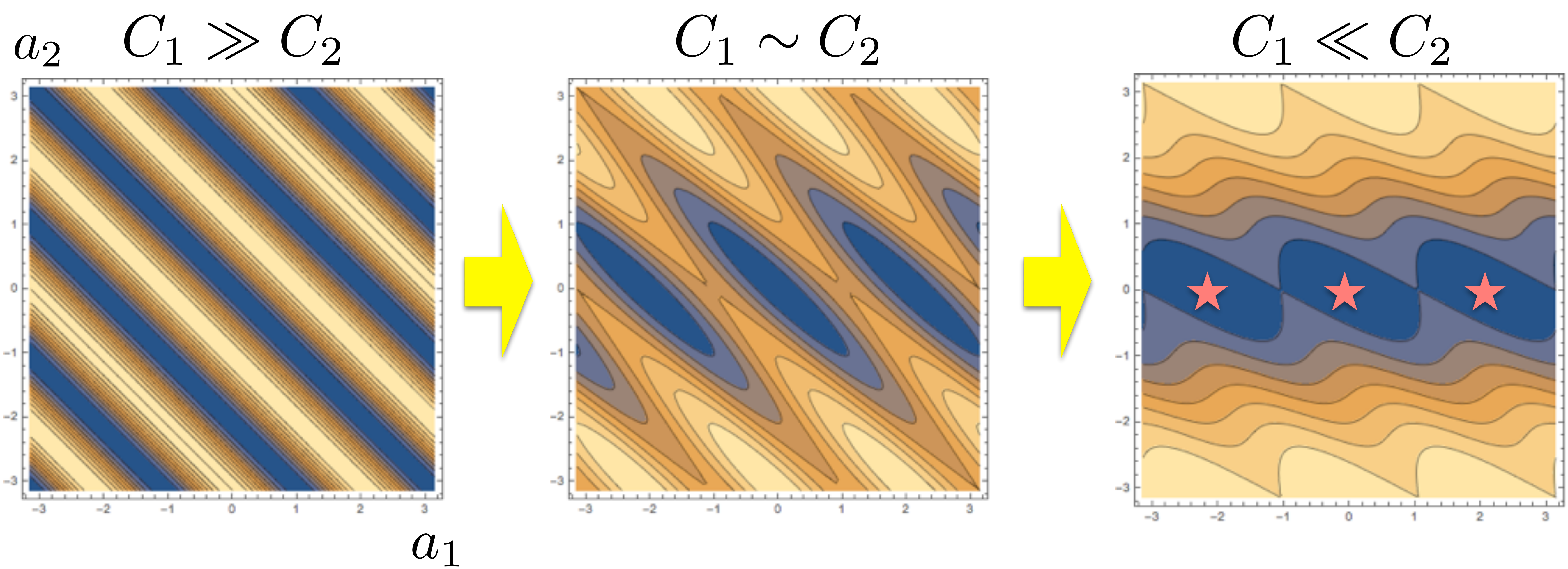
$p < 0$

cf. QCD axion



Level crossing of axions

During the level crossing the axion potential changes significantly.



$$V(a_1, a_2) = C_1 \left(1 - \cos\left(n_1 \frac{a_1}{f_1} + n_2 \frac{a_2}{f_2}\right)\right) + C_2 \left(1 - \cos\left(\frac{a_2}{f_2}\right)\right)$$

$$n_1 = n_2 = 3 \qquad C_1 = \Lambda_1^4, \quad C_2 = m_a(T)^2 f_2^2 \qquad m_a(T) = m_a \min\left[\left(\frac{T}{\Lambda_2}\right)^p, 1\right]$$

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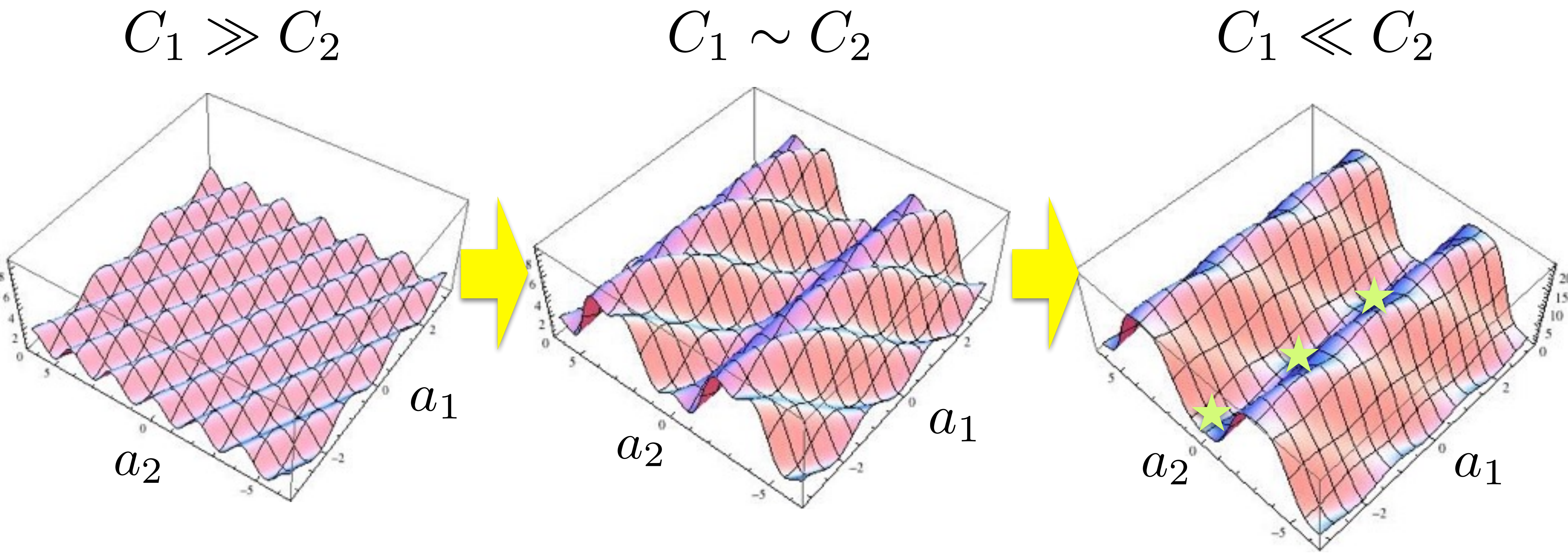

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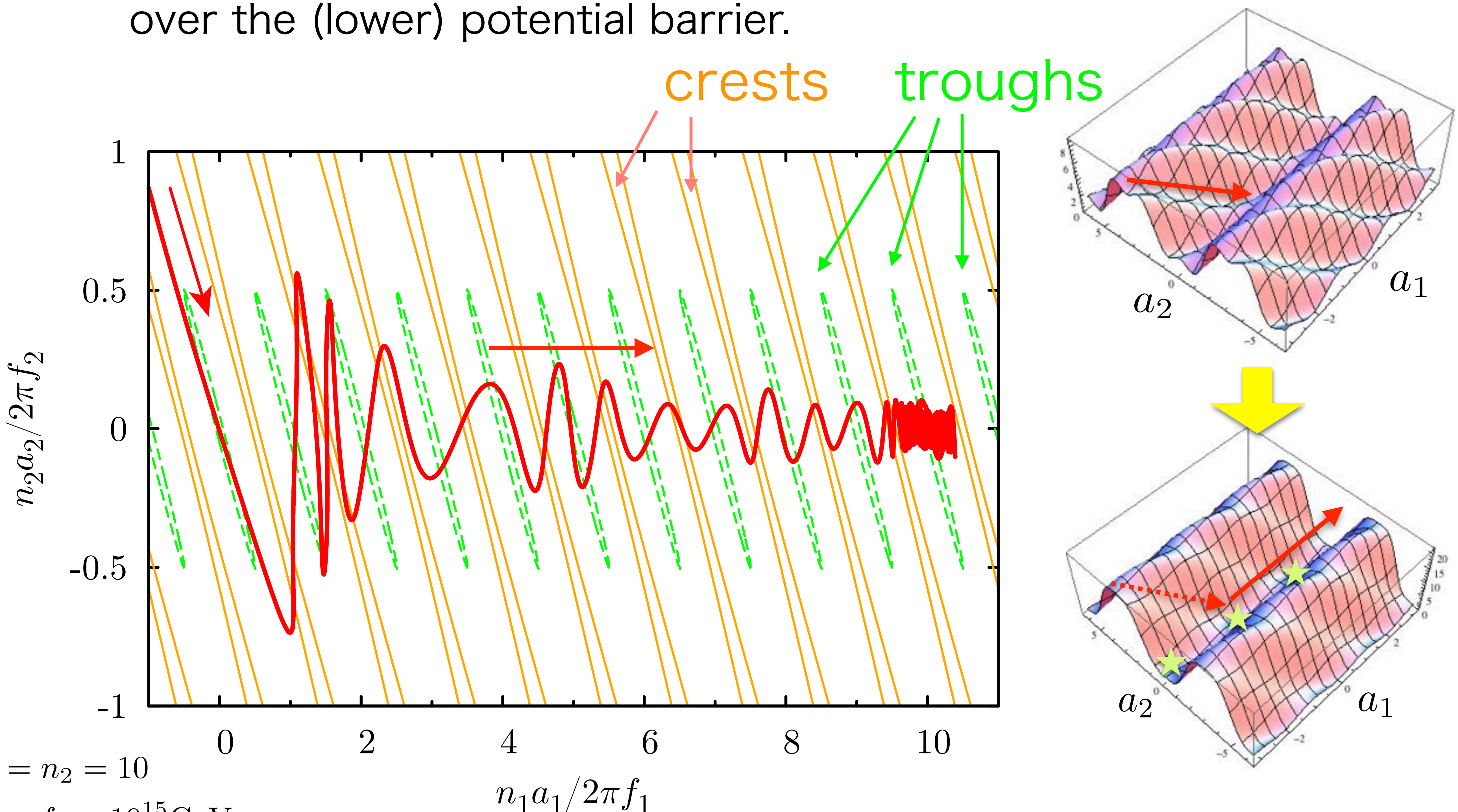
Level crossing of axions

- If the (lighter) axion starts to oscillate around or slightly before the time of the level crossing, it often climbs over the (lower) potential barrier.

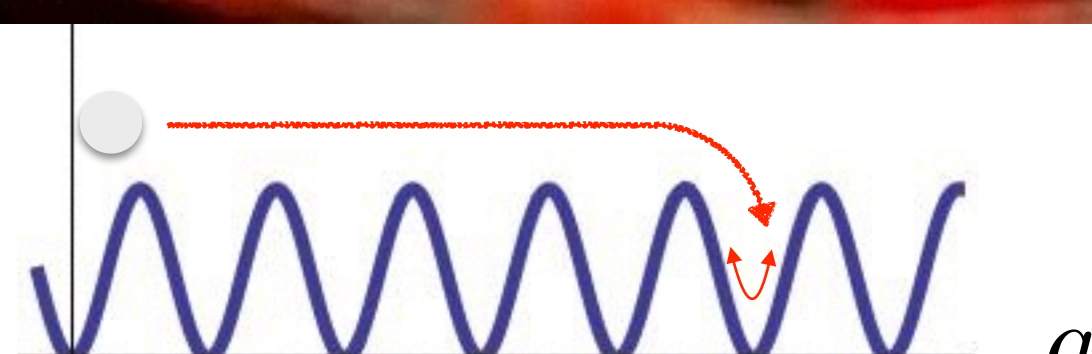


$n_1 = n_2 = 10$

$f_1 = f_2 = 10^{15}\mathrm{GeV}$

Kitajima, FT 1411.2011, Daido, Kitajima, FT, 1505.07670

Axion Roulette



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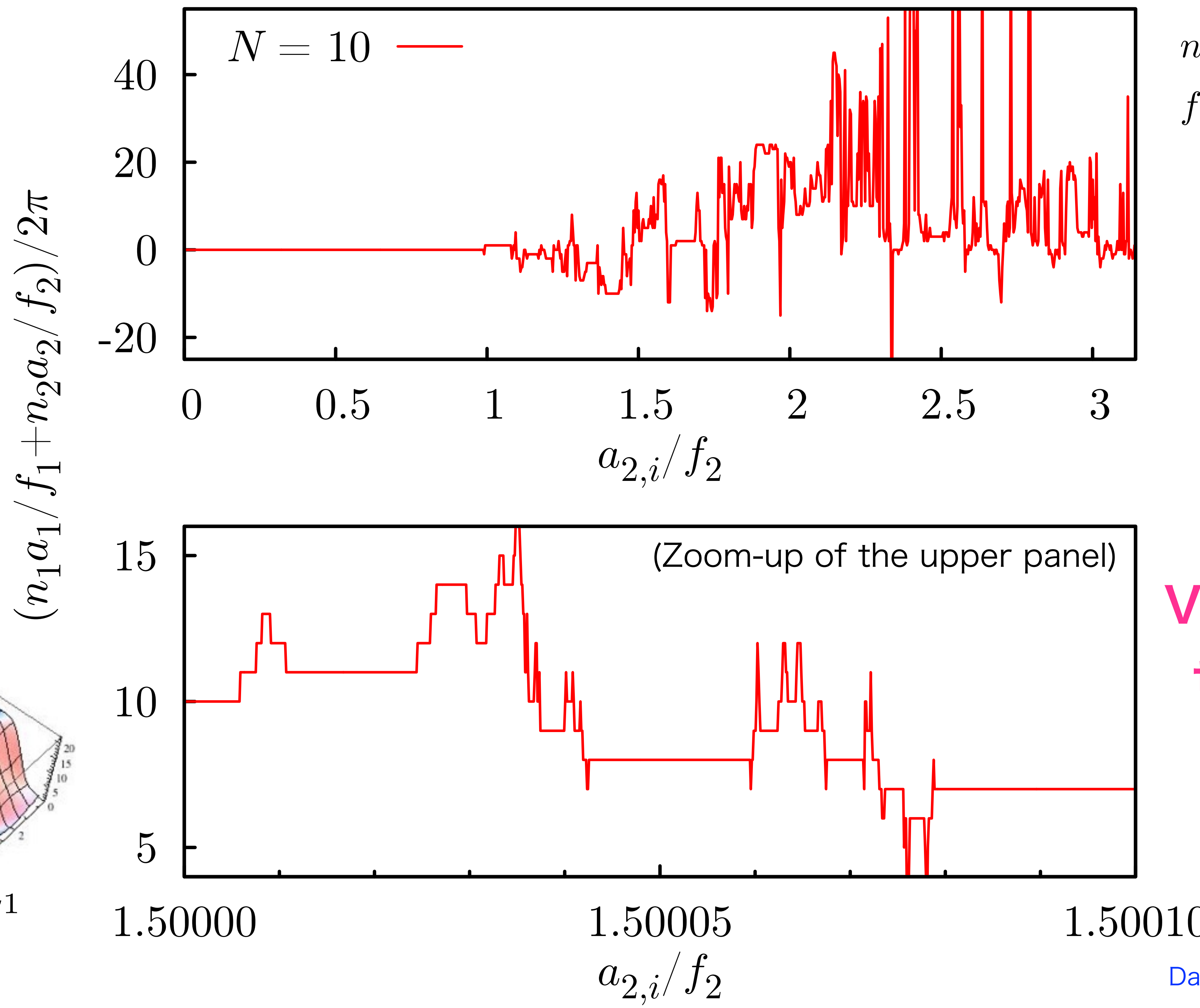

$n_1 = n_2 = N = 10$

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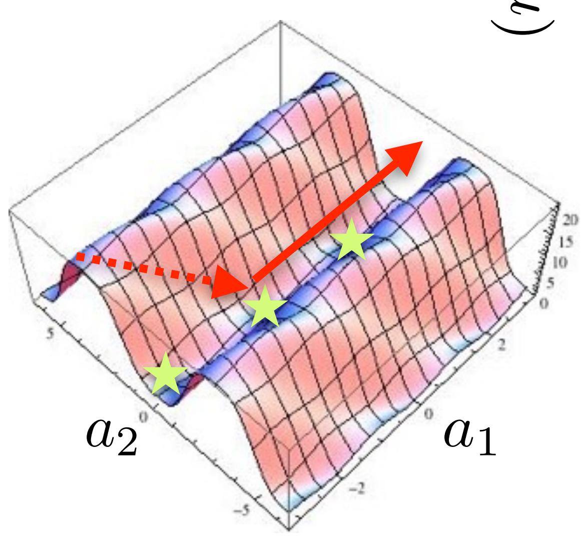


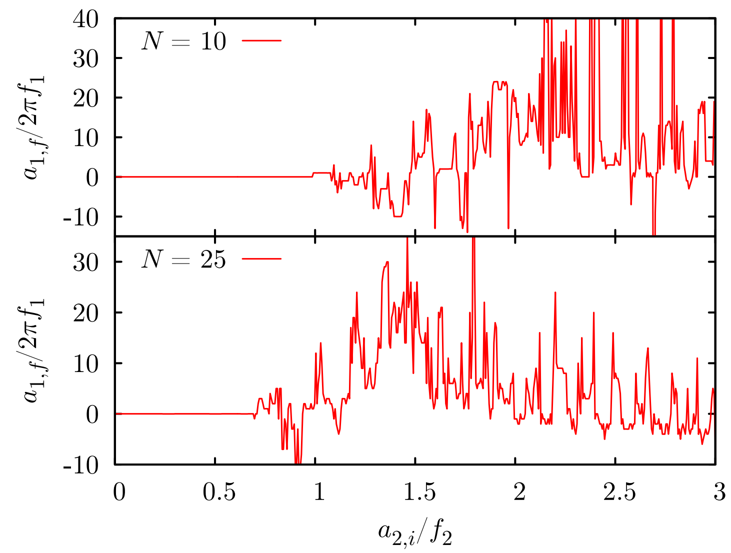
Very sensitive to the initial condition!

Daido, Kitajima, FT, 1505.07670

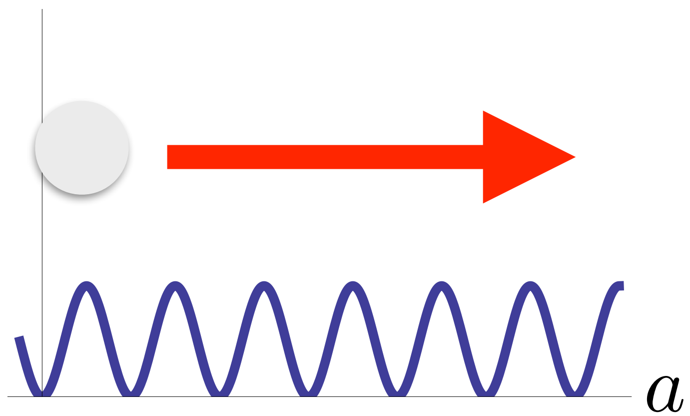
$$V(a_1, a_2) = \Lambda_1^4 \left(1 - \cos\left(n_1 \frac{a_1}{f_1} + n_2 \frac{a_2}{f_2}\right)\right) + m_a(T)^2 f_2^2 \left(1 - \cos\left(\frac{a_2}{f_2}\right)\right)$$

Axion Roulette and Domain walls

- The axion roulette exhibits a chaotic behavior.



- The axion fluctuations will grow at sub-horizon scales.



Axion roulette leads to DW formation, even if $\delta a < |a_* - \pi f_a|$.

Conditions for Axion Roulette

1. The axion starts to oscillate around or slightly before the level crossing.

$$\frac{H_{\rm osc}}{H_{\rm LC}} = \mathcal{O}\,(1-10)$$

No severe tuning is required.

2. The initial oscillation energy is larger than the potential barrier.

$$\rho_{a,{\rm osc}} \sim m_{L,{\rm osc}}^2 f^2 \gtrsim \Lambda_1^4 \sim m_{H,{\rm osc}}^2 F^2.$$

Easily satisfied if there is a mild hierarchy, $f/F \gtrsim 10.$

The KNP mechanism helps the axion roulette to take place.
(Here the decay constants are sub-Planckian, and only mild hierarchy needed.)

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Resonant transition

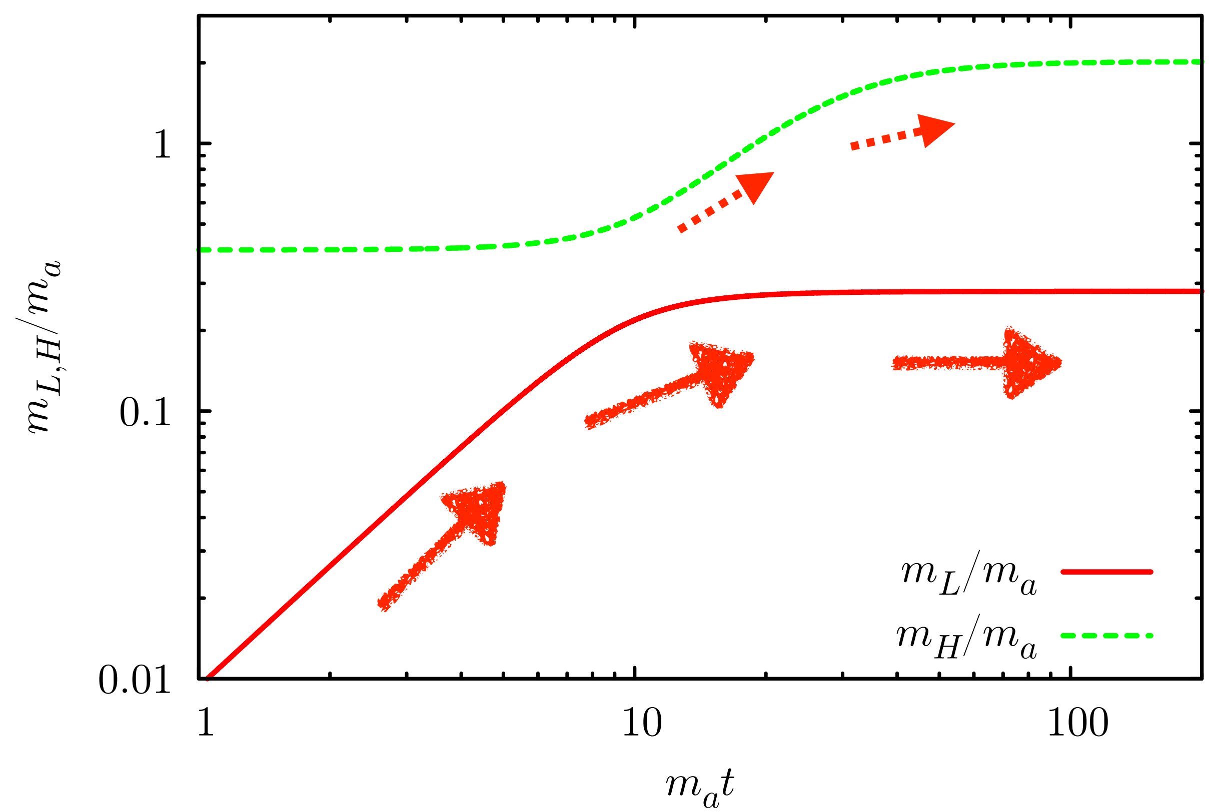
- If the (lighter) axion starts to oscillate <u>much before</u> the level crossing, the potential changes adiabatically.

➡ **Resonant transition** takes place. (cf. the MSW effect)

$$N_{\rm axion} = a^3 n_{\rm axion}$$: adiabatic invariant.

- The final axion density suppressed by m_L/m_H.
- Isocurvature perturbations can be suppressed if the adiabaticity is weakly broken by the hilltop initial condition.

Kitajima, FT 1411.2011



No domain wall formation.

Fate of Axion Domain Walls

Domain walls are cosmologically problematic and they must be either inflated away or unstable and decay rapidly.

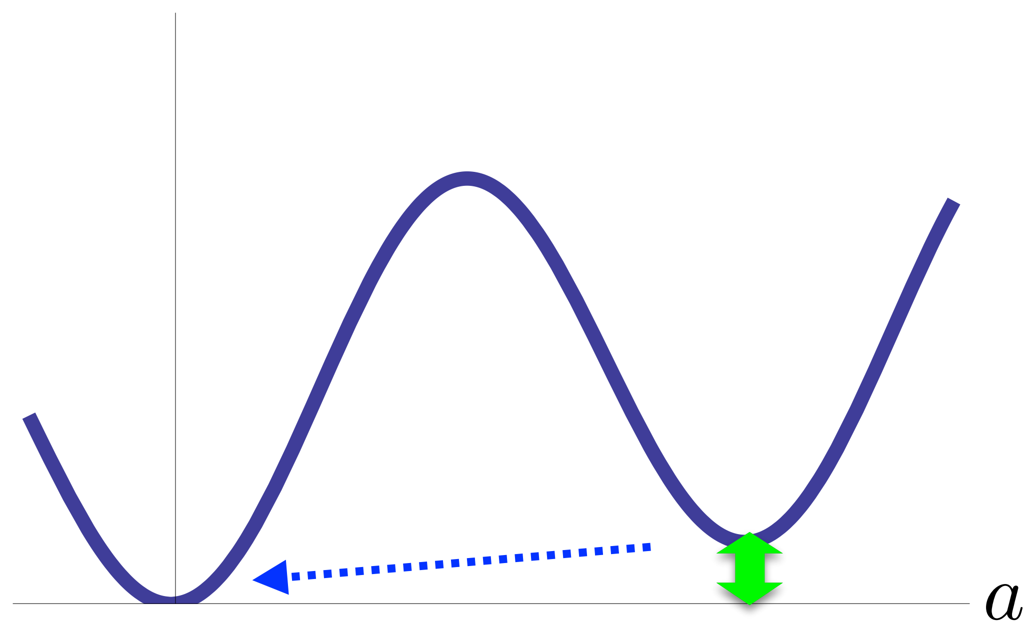
- Case of $N_{DW} = 1$

  DWs are cosmologically stable, as they are not bounded by strings. Must be inflated away.

  cf. Preskill, Trivedi, Wilczek `91

- Case of $N_{DW} > 1$

  The DWs are unstable and collapse if there is energy bias between the vacua.



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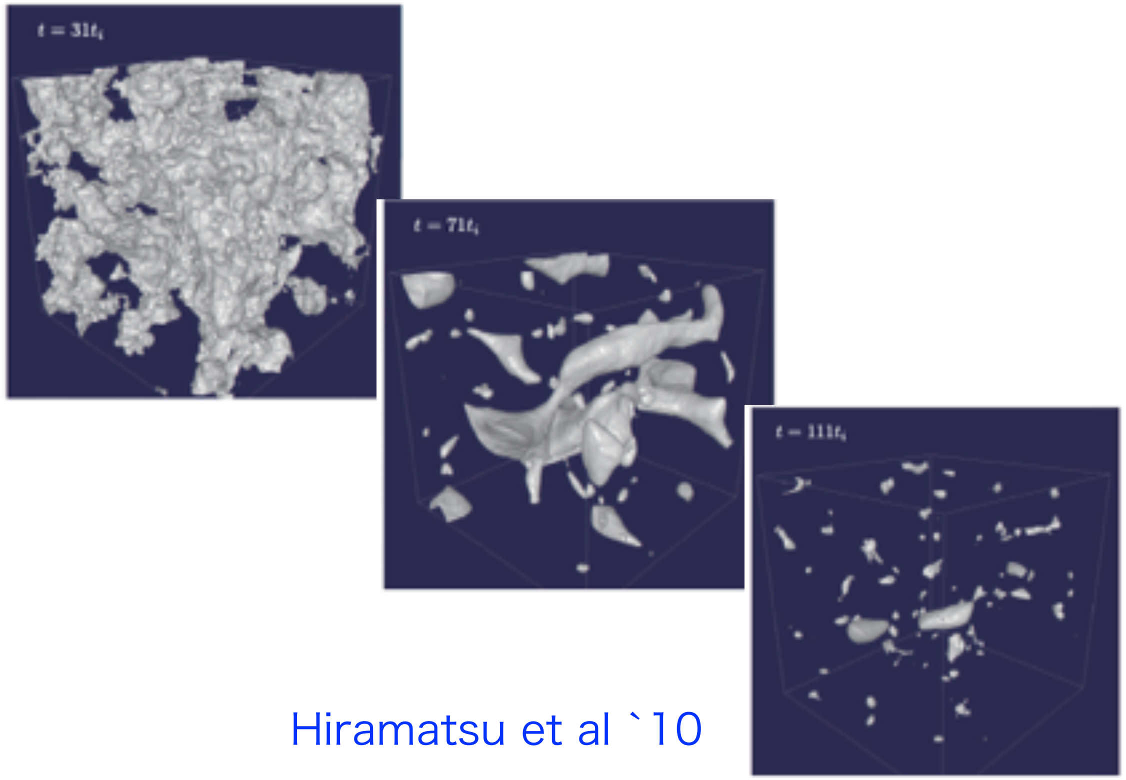
  → Gravitational Waves



Hiramatsu et al `10

Axion DW baryogenesis

Daido, Kitajima, FT, 1504.07917

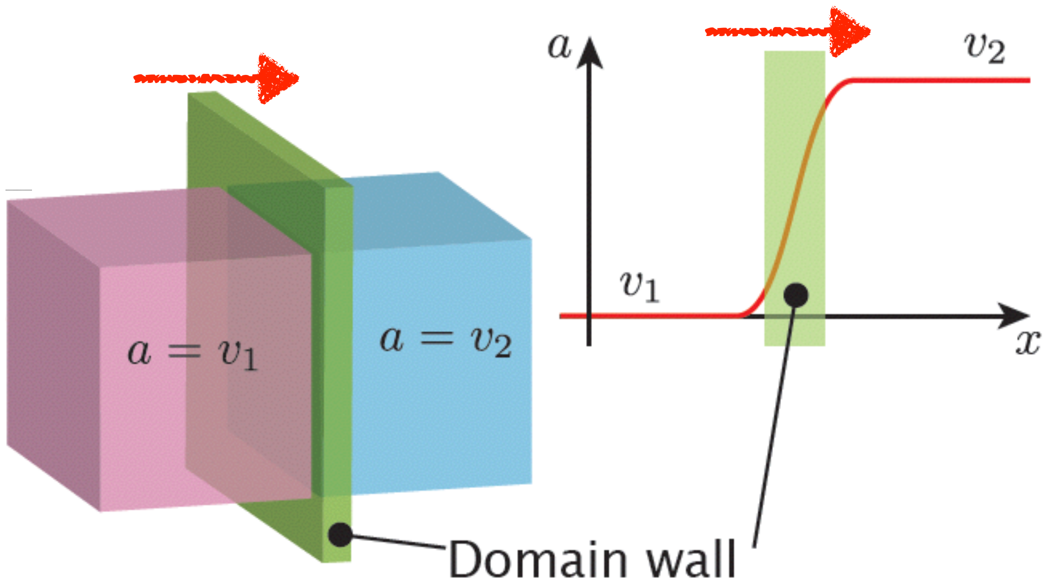
The passage of a wall generates a non-zero chemical potential:

e.g.

$$\mathcal{L} = \frac{\partial_\mu a}{f_a} j_L^\mu = \frac{\dot{a}}{f_a} n_L + \cdots \quad \Rightarrow \quad \mu_L = \frac{\dot{a}}{f_a}$$

$$\mathcal{L} = \frac{g_2^2}{32\pi^2} \frac{a}{f_a} W_{a\mu\nu} \tilde{W}^{a\mu\nu} \quad \Rightarrow \quad \mu_{B+L} = \frac{\dot{a}}{f_a}$$

(if sphalerons are in equilibrium)



(Figure courtesy of Kitajima)

cf. spontaneous baryogenesis

Cohen and Kaplan,`87, `88 Dine et al, `91, Cohen, Kaplan, Nelson `91

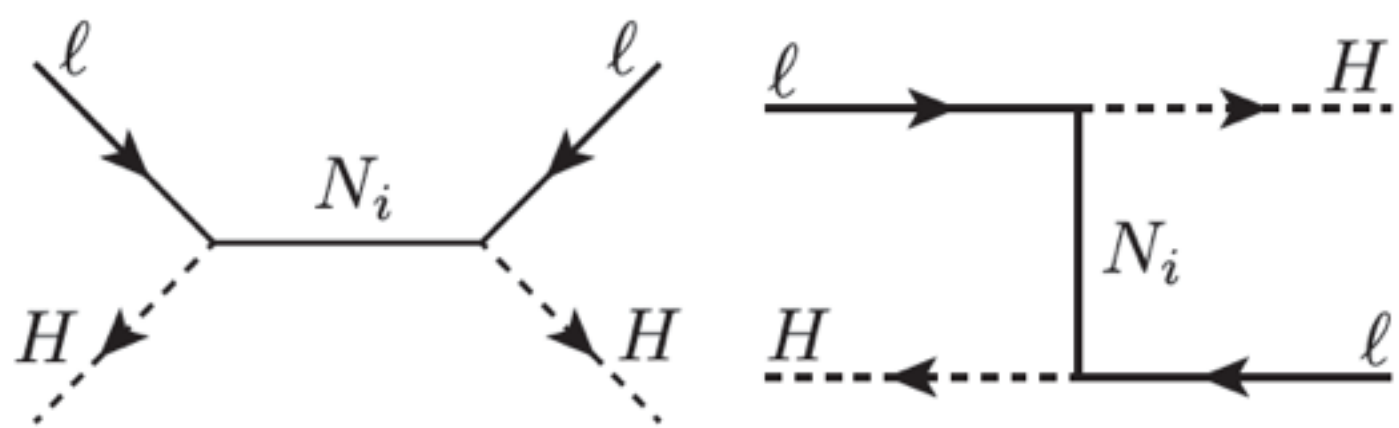
$\langle \dot{a} \rangle = 0$ in the scaling regime.

$\langle \dot{a} \rangle \neq 0$ during the DW annihilation.

Axion DW baryogenesis

Non-zero asymmetry is induced at the DW annihilation in the presence of the baryon- or lepton-number violation.

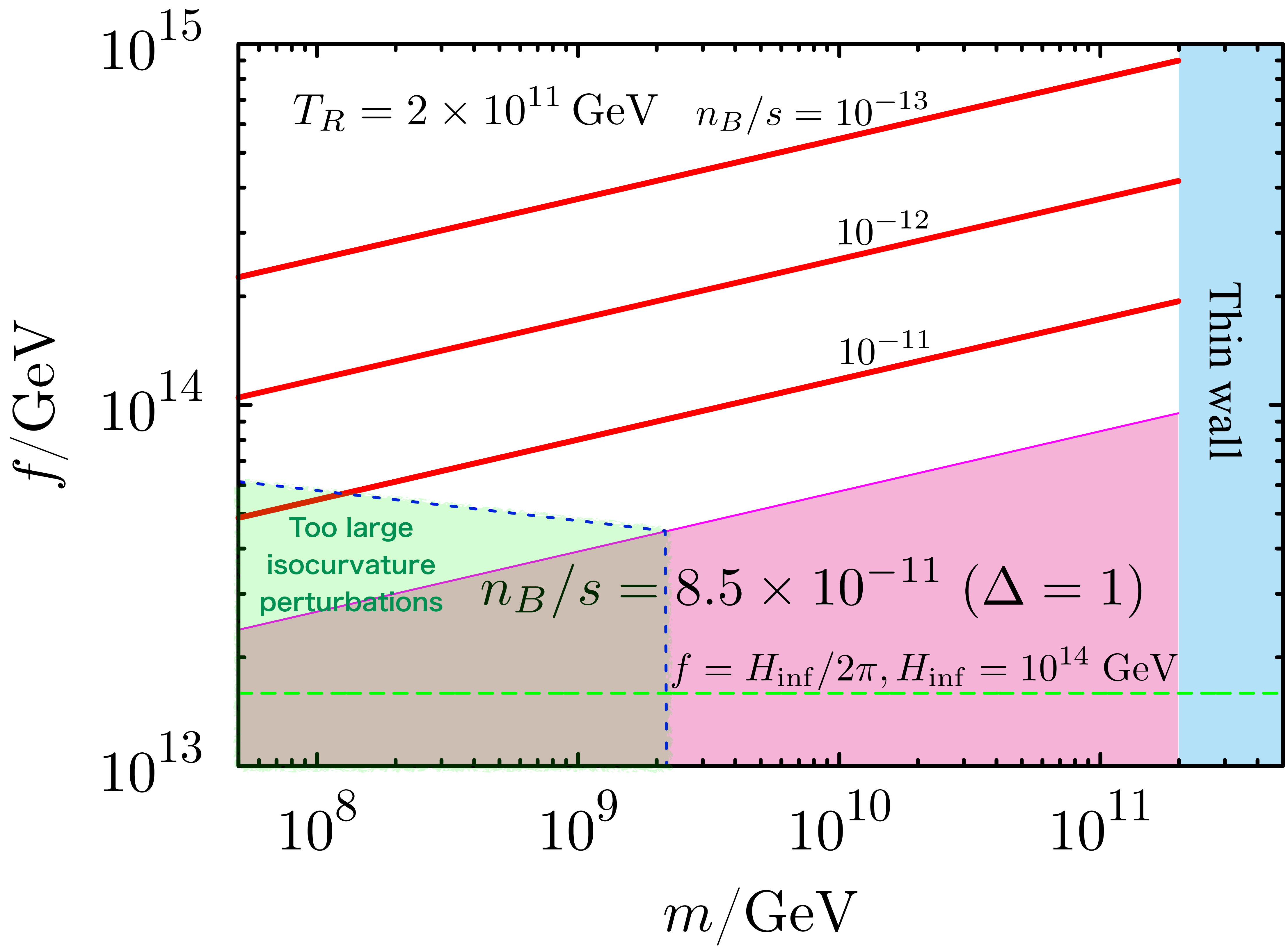
e.g. $\Delta L = 2$ $\quad \mathcal{L} = \frac{\ell H \ell H}{2M}$



$$\Gamma_{\Delta L=2} \sim \frac{T^3}{\pi^3} \frac{\sum m_\nu^2}{v_{\rm EW}^4}, \qquad T_{\rm dec} \sim 10^{13}\,{\rm GeV}$$

Axion DW baryogenesis

Daido, Kitajima, FT, 1504.07917



Axion DW baryogenesis

Daido, Kitajima, FT, 1504.07917

✓Baryonic isocurvature perturbations are generated if the axion is in the slow-roll regime.

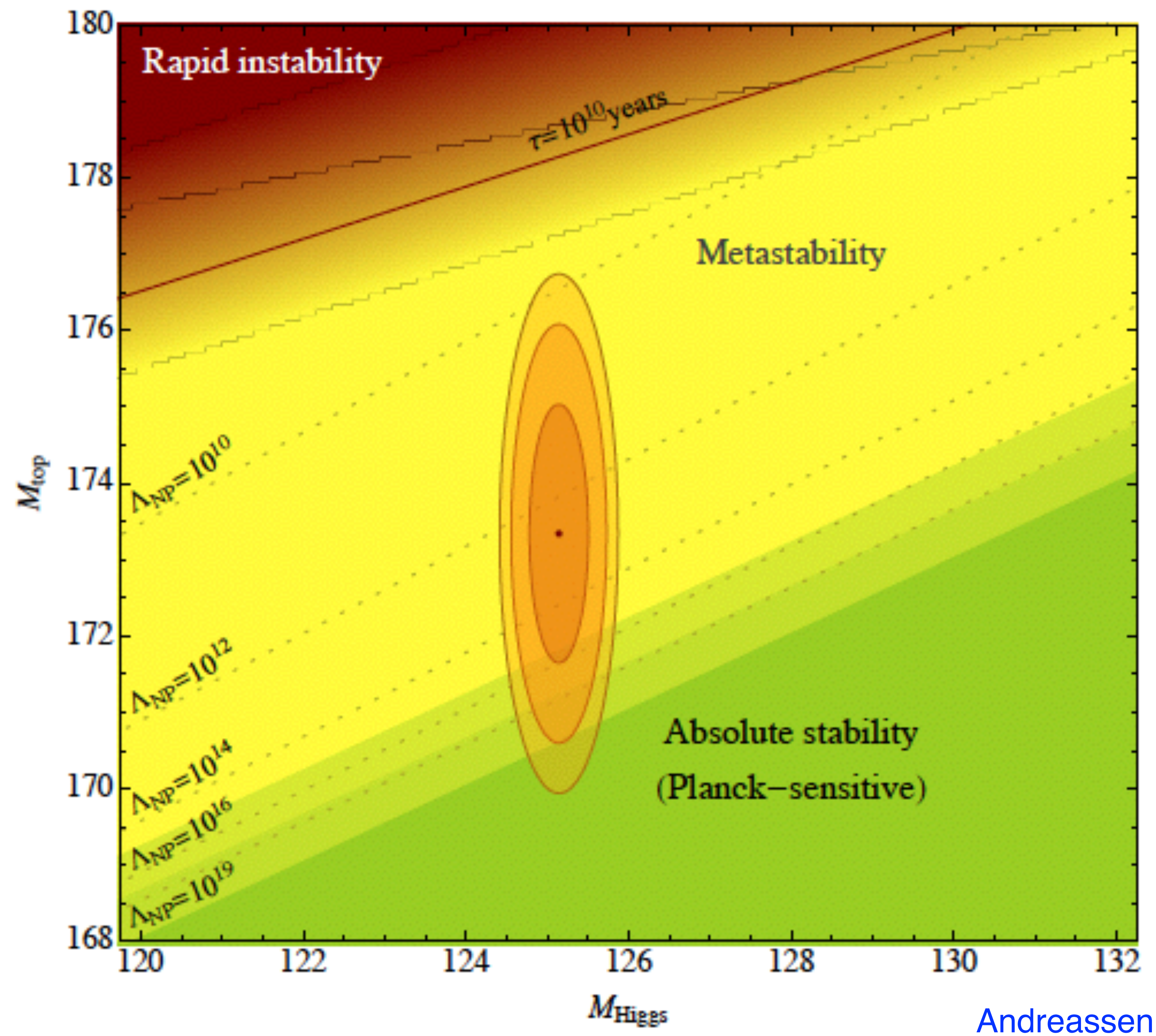
Turner, Cohen, Kaplan `89

e.g. $H_{\rm inf} \lesssim 10^{11}\,{\rm GeV}, \quad T_R \gtrsim 10^{12}\,{\rm GeV}$

cf. Kusenko, Schmitz, Yanagida, 1412.2043
"Leptogenesis via axion oscillations after inflation"

✓Isocurvature perturbations are suppressed in our scenario because of <u>the scaling behavior of DWs</u>. The tension between $H_{\rm inf}$ and T_R is relaxed.

The SM near-criticality

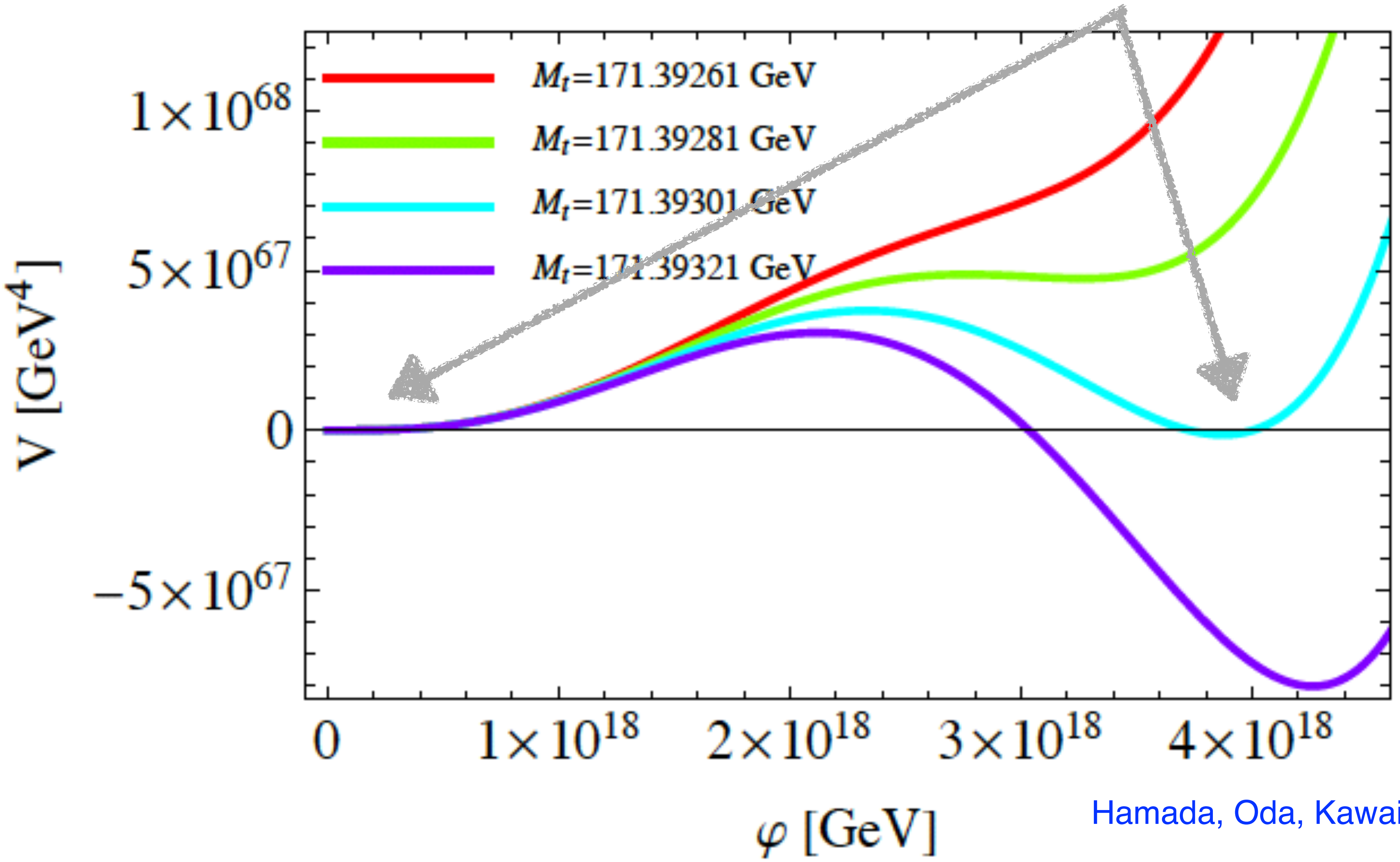


Andreassen, Frost, Schwartz, 1408.0292

The SM vacua is at the border between stability and meta-stability. Why??

The SM near-criticality

At the border, there is another minimum at around the Planck scale, which has the same energy as the EW vacuum.



Hamada, Oda, Kawai, Park, 1408.4864

cf. "Multiple point criticality principle" Bennett, Nielsen \`94 Froggatt, Nielsen \`96

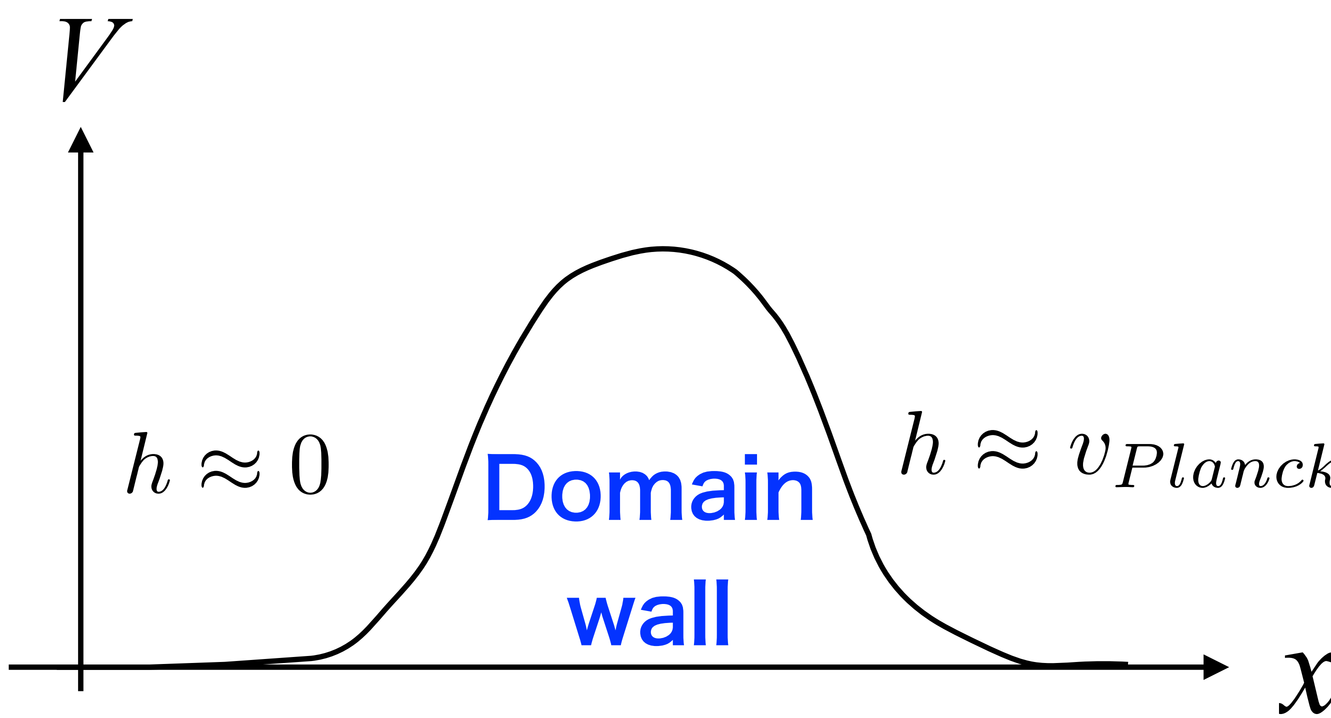
- There should be several degenerate vacua in energy.

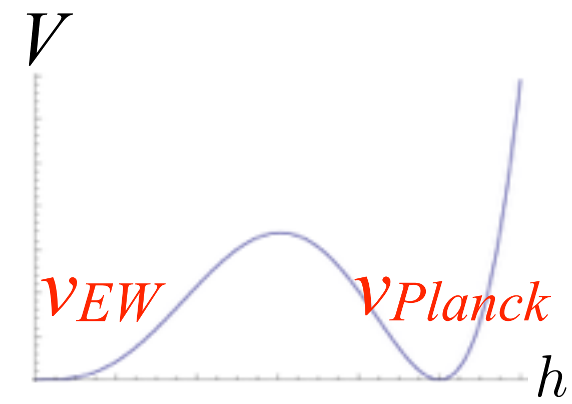
See 1212.5716 for arguments based on non-locality and various apps.

Topological Higgs Inflation

Hamada, Oda, FT 1408.5556

- Domain walls connecting the EW and Planck scale vacua.





Inflation occurs inside domain walls if they are sufficiently thick:

Linde `94, Vilenkin `94

$$v_{Planck} \gtrsim \text{a few } M_P$$

The non-minimal coupling to gravity $\xi = \mathcal{O}(0.1 - 10)$ helps to satisfy this bound.

The SM criticality may be related to the topological Higgs inflation.

N.B. Another inflation needed to generate $\delta \sim 10^{-5}$

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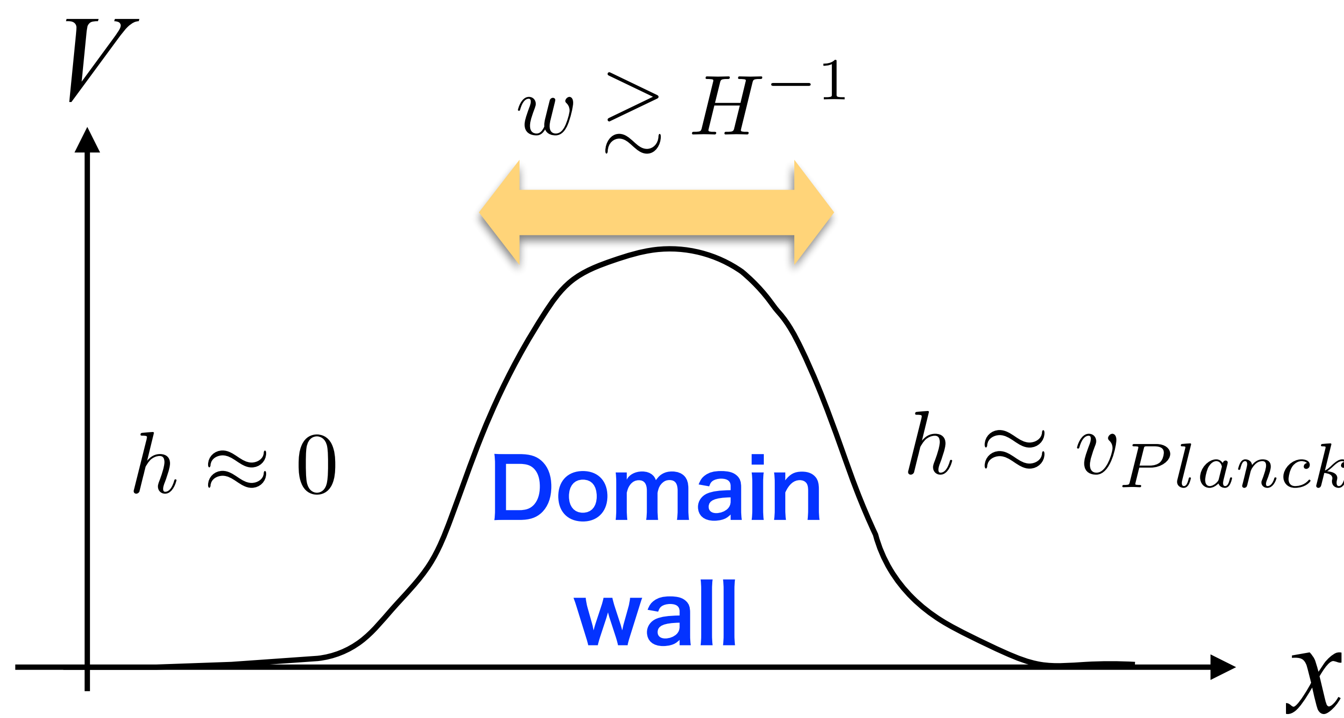

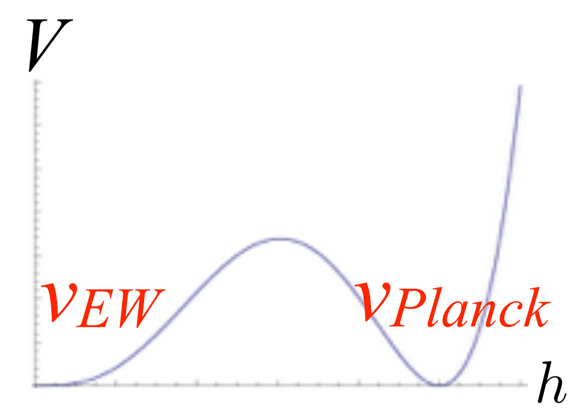

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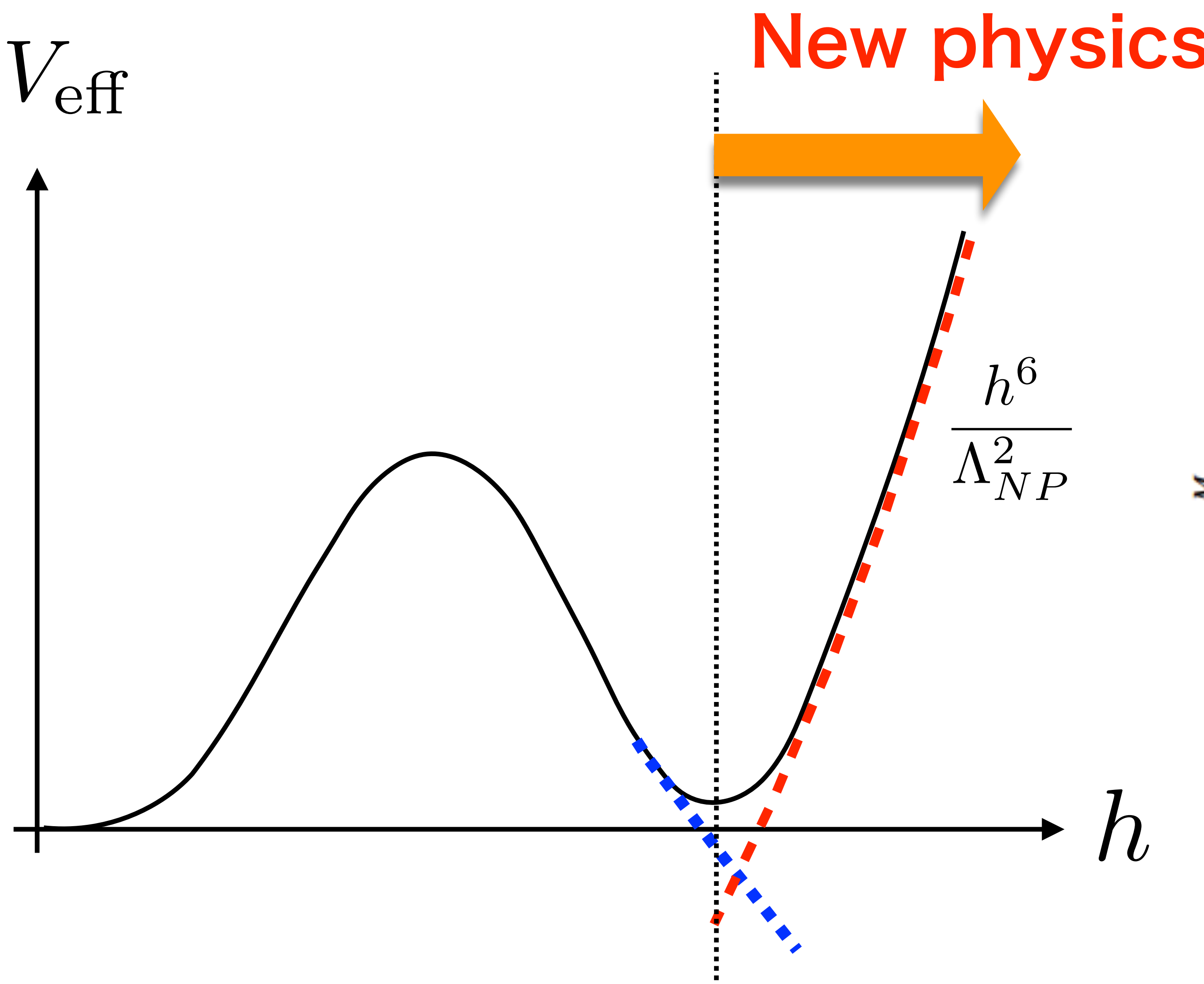
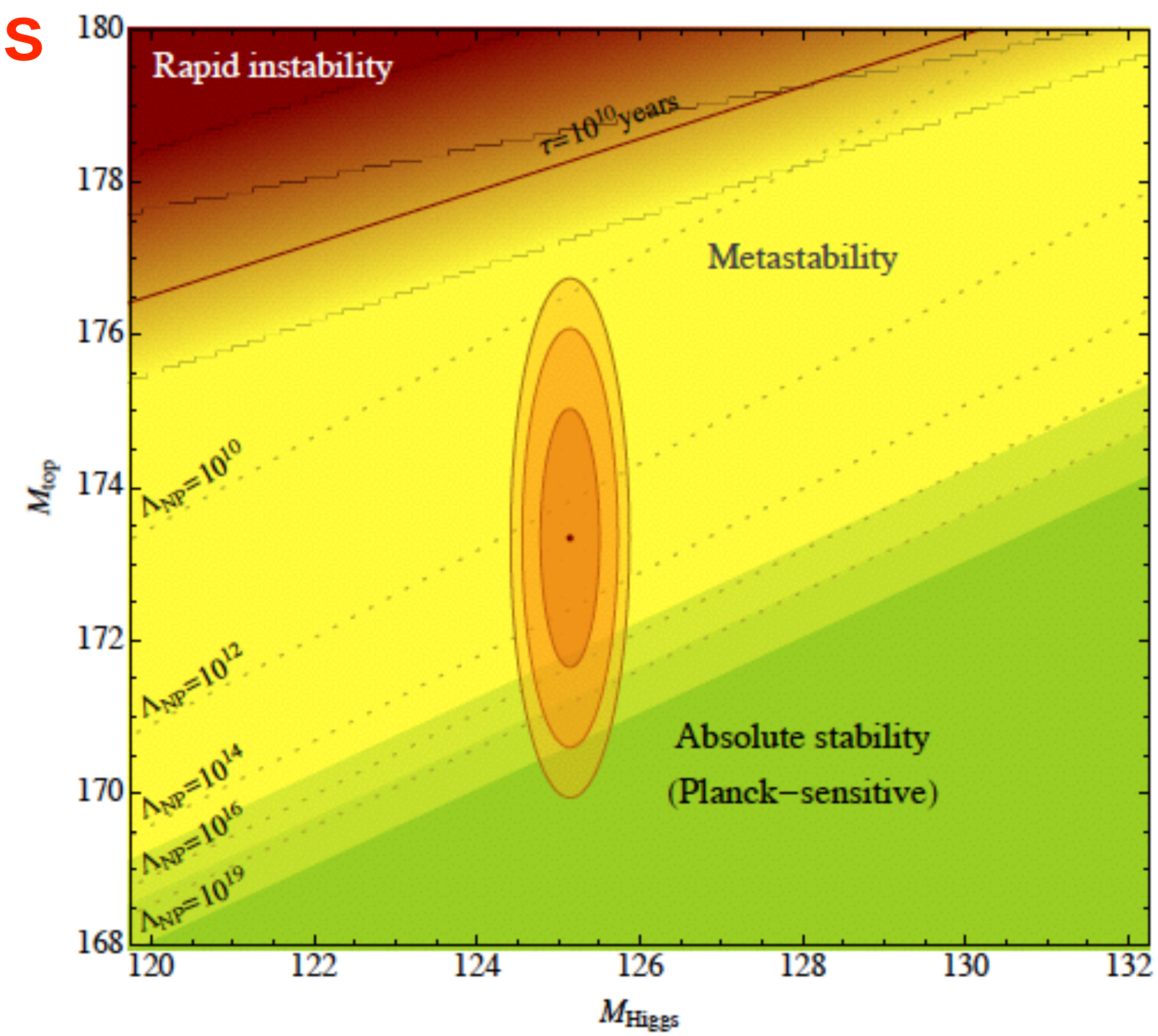
Uplifting by new physics

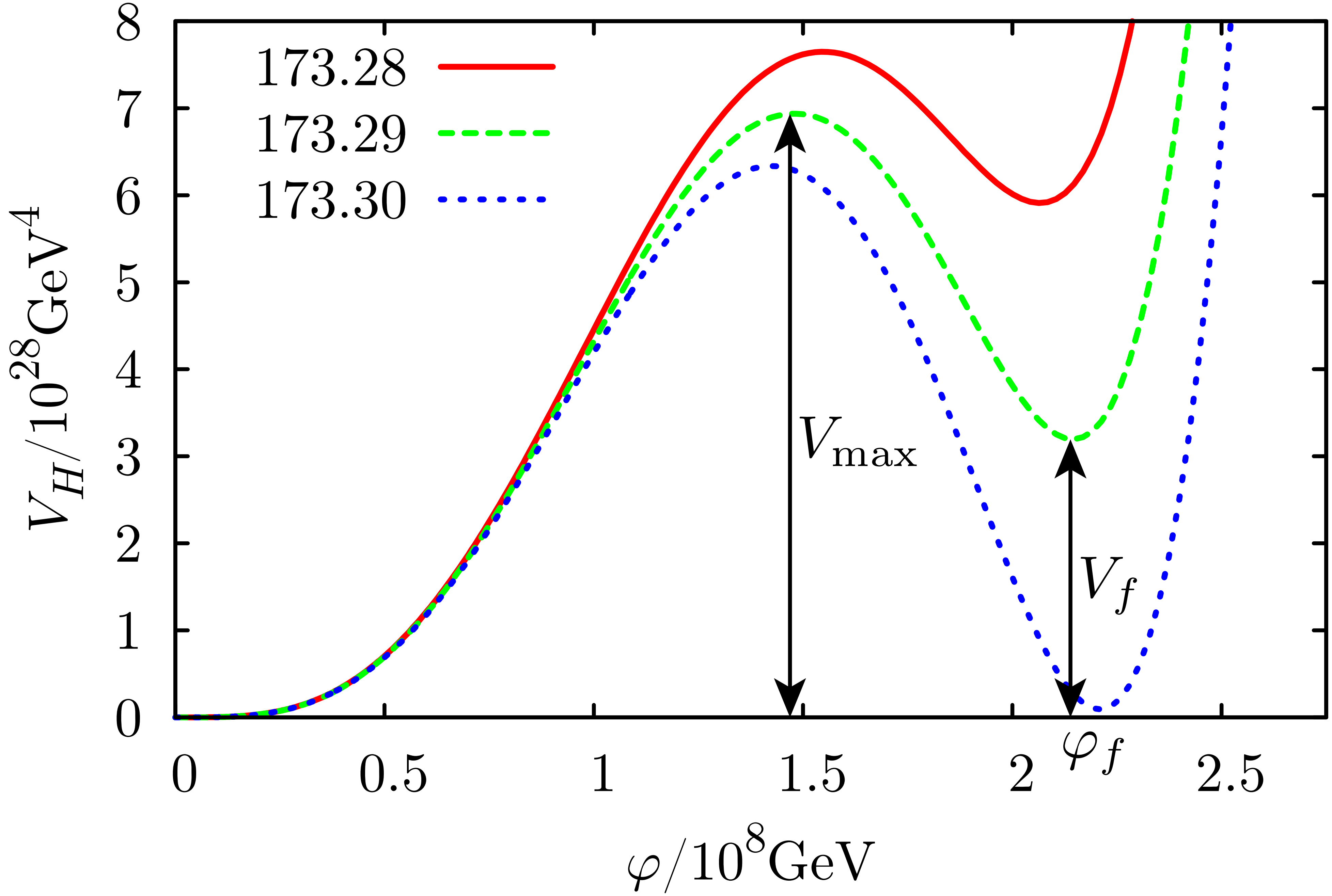
- Negative effective potential may be lifted by new physics effects above a certain scale.





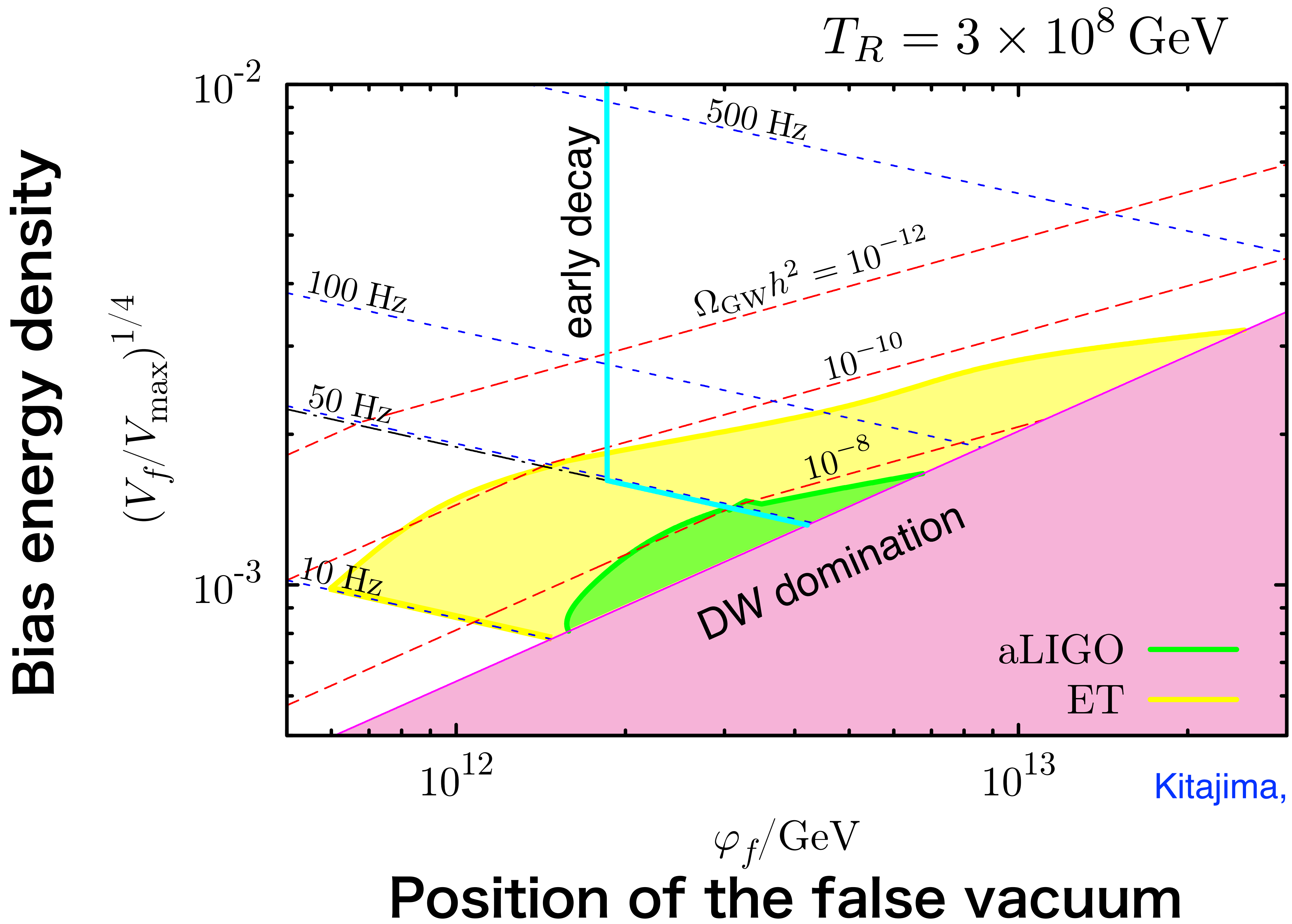
Domain walls in the Higgs potential

- Domain walls can be formed if the two vacua are (quasi)-degenerate.



Domain walls in the Higgs potential

- Unstable domain walls annihilate, generating GWs.



Kitajima, FT, 1502.03725

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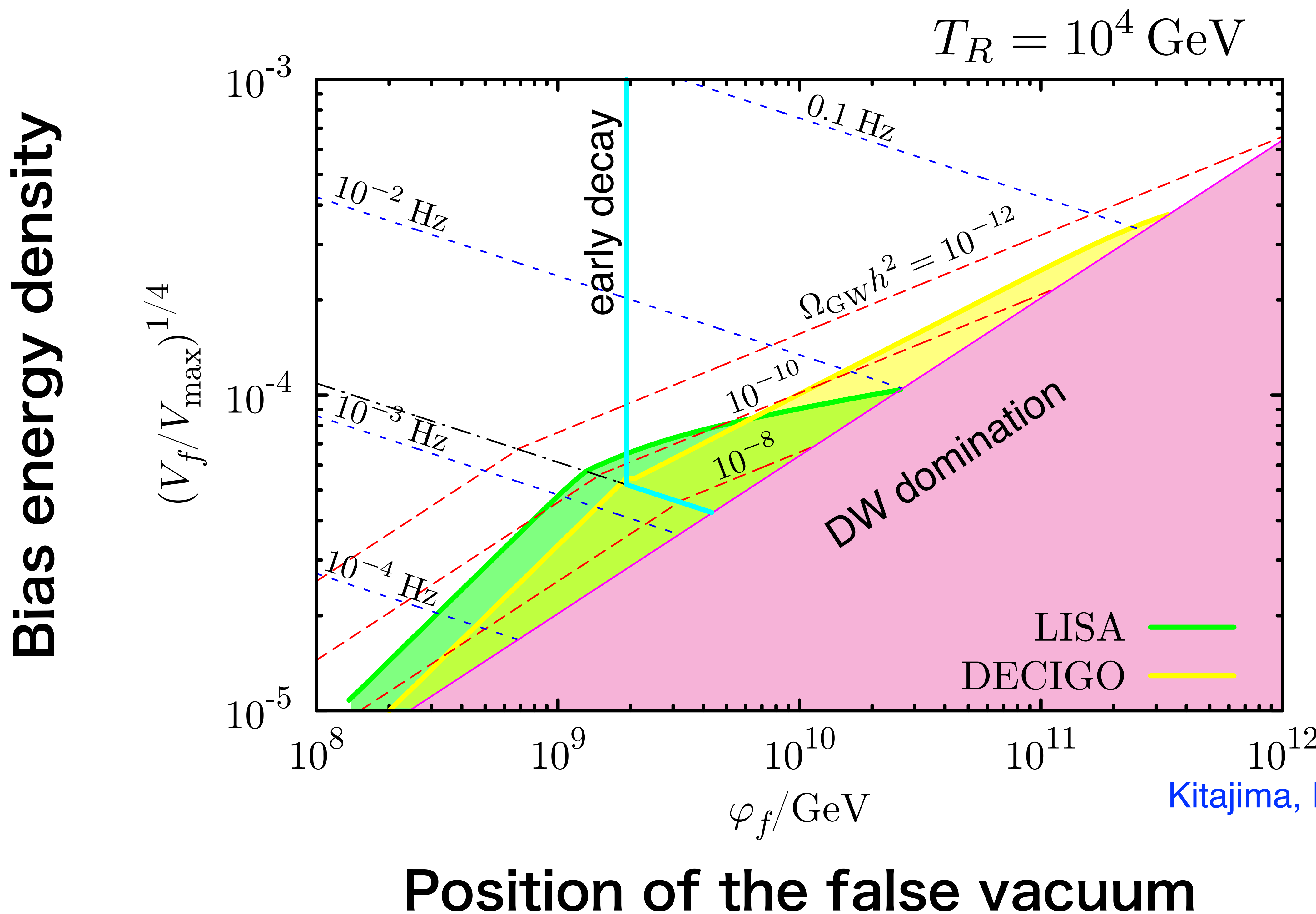


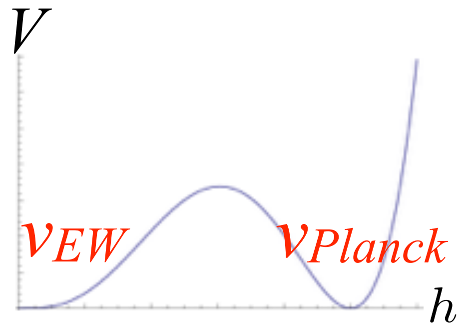
Kitajima, FT, 1502.03725

Summary

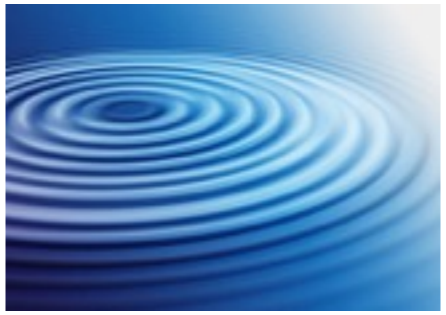
✓ The axion domain walls are formed during the level-crossing phenomenon. **"Axion Roulette"**

- If $N_{DW} = 1$, stable DWs.
- If $N_{DW} > 1$, DWs decay if there is bias.
  - DW annihilation induces gravitational waves.
  - Axion DW can generate baryon asymmetry.

✓ Topological Higgs inflation may be the origin of the SM criticality.



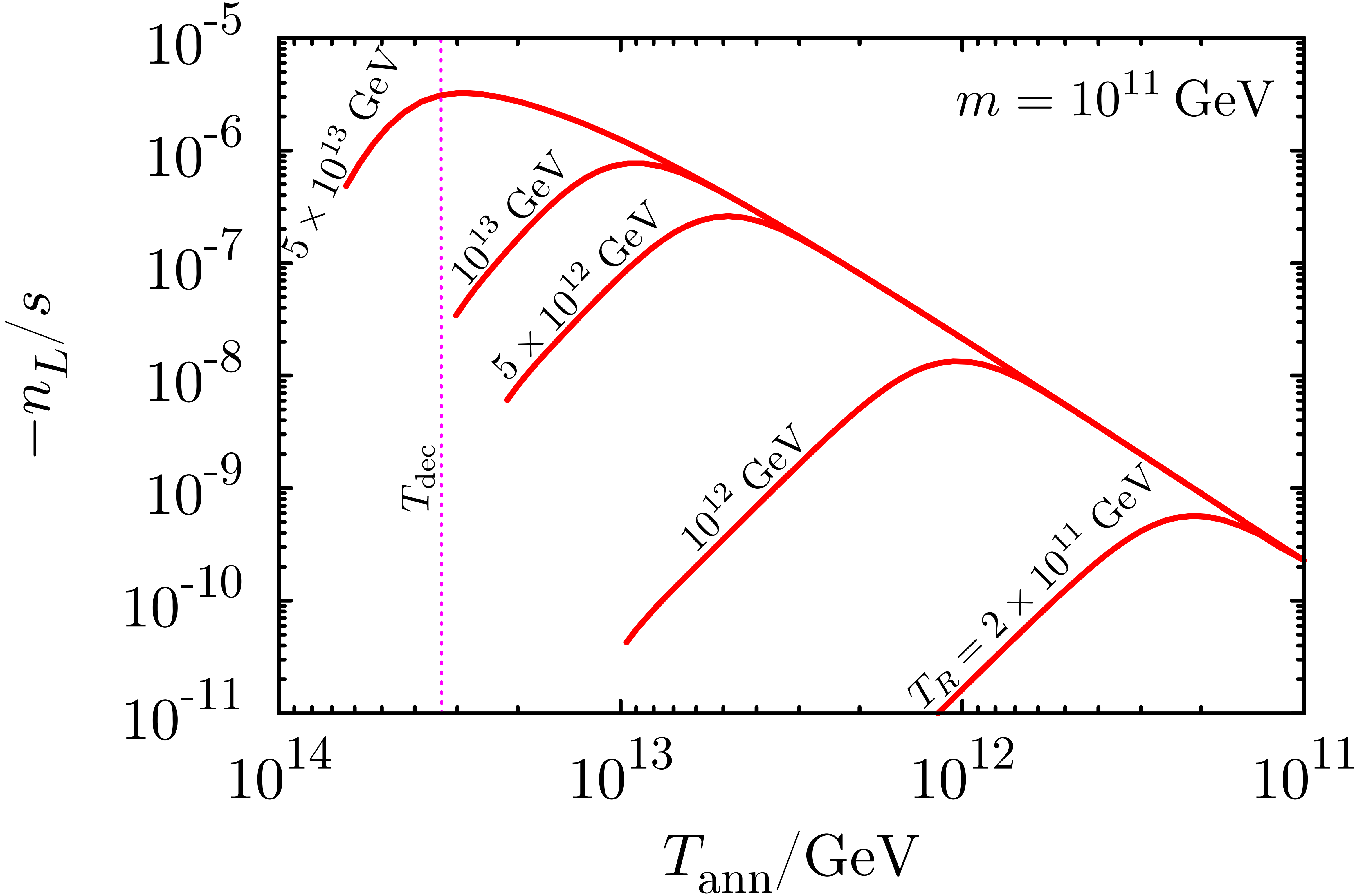
✓ Higgs DWs can generate gravitational waves within the reach of Advanced LIGO.



Back-ups

Axion DW baryogenesis

Daido, Kitajima, FT, 1504.07917



Axion DW baryogenesis

Daido, Kitajima, FT, 1504.07917