

Axions in the Lab and in the Cosmos
17/07/2019

Axion-model building

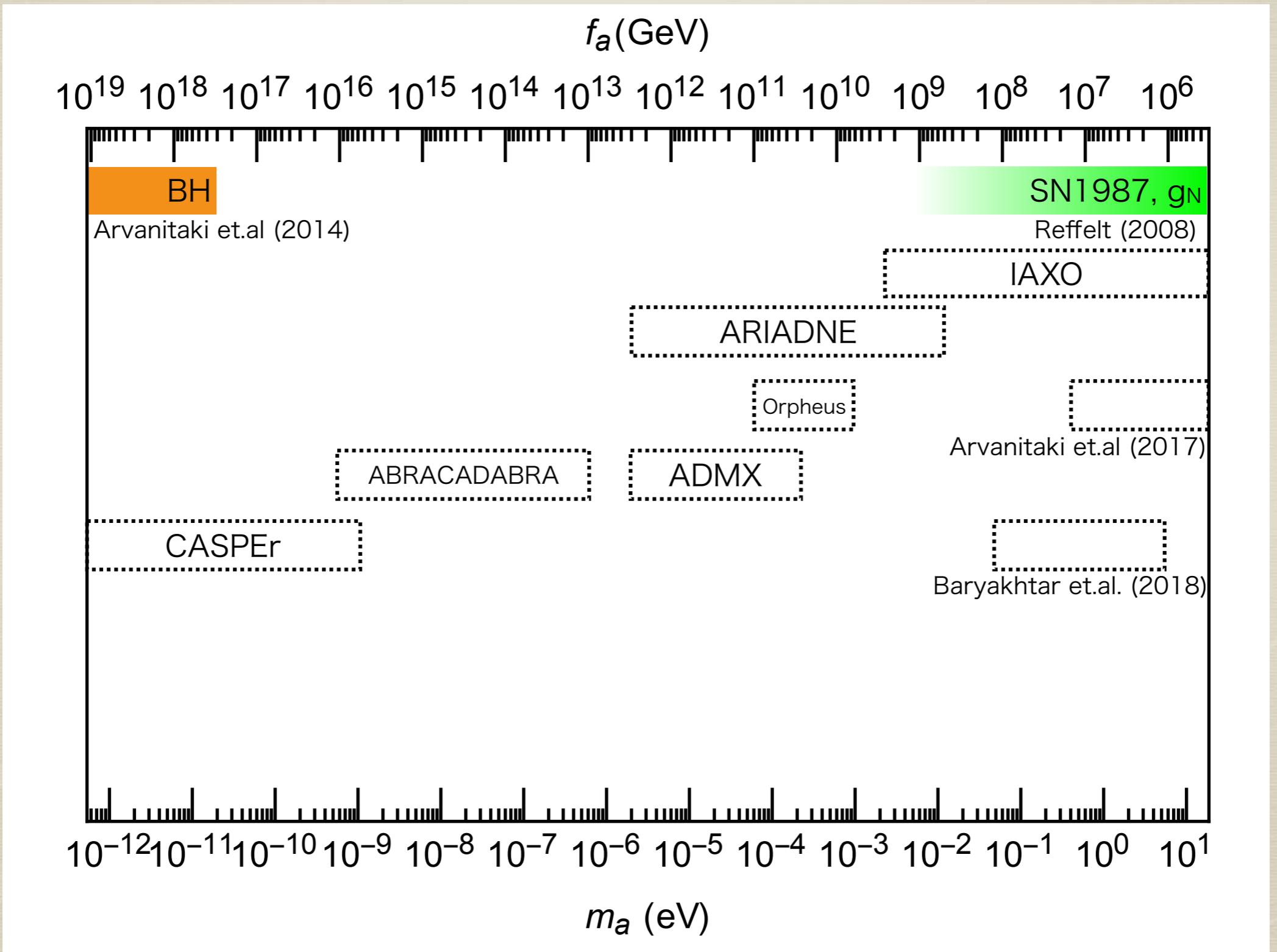
Keisuke Harigaya
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QCD

Axion-model building

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Axion searches



Decay constant

$$\mathcal{L} = \frac{a}{8\pi^2 f_a} G \tilde{G}$$

It will be measured in **Lab** in the next decades

- I) What will we learn from it?
- 2) Any impacts on **Cosmos?**

Overview

$$\mathcal{L} = \frac{a}{8\pi^2 f_a} G \tilde{G}$$

- * Motivations: Small f_a VS large f_a
- * DM production mechanisms for ranges of decay constants and signatures

Overview

$$\mathcal{L} = \frac{a}{8\pi^2 f_a} G \tilde{G}$$

- * Motivations: Small f_a VS large f_a
- * DM production mechanisms for ranges of decay constants and signatures



Small decay constant

$$10^8 \text{ GeV} \lesssim f_a \lesssim 10^{15} \text{ GeV}$$



GUT scale

Why we like small decay constant

To stimulate discussion, I will introduce what I recognize

- * Accidental PQ symmetry?
- * Unification with Higgs?
- * Unification with supersymmetry breaking
- * Axion DM in the minimal setup

Accidental PQ symmetry

$$V(a) = 0$$

PQ symmetric

$$+ \Lambda^4 \cos \frac{a}{f_a}$$

NOT PQ symmetric

What is the origin of such a special structure?

Accidental PQ symmetry

IR Field theoretical approach : accidental symmetry

Lazarides, Panagiotakeopoulos, Shafi (1986)
Holman, Hsu, Kephert, Kolb, Watkins, Widrow (1992), Dine (1992)
Barr and Seckel (1982), Kamionkowski and March-Russel (1992)
KH, Ibe, Schmitz and Yanagida (2012, 2015), and many literatures

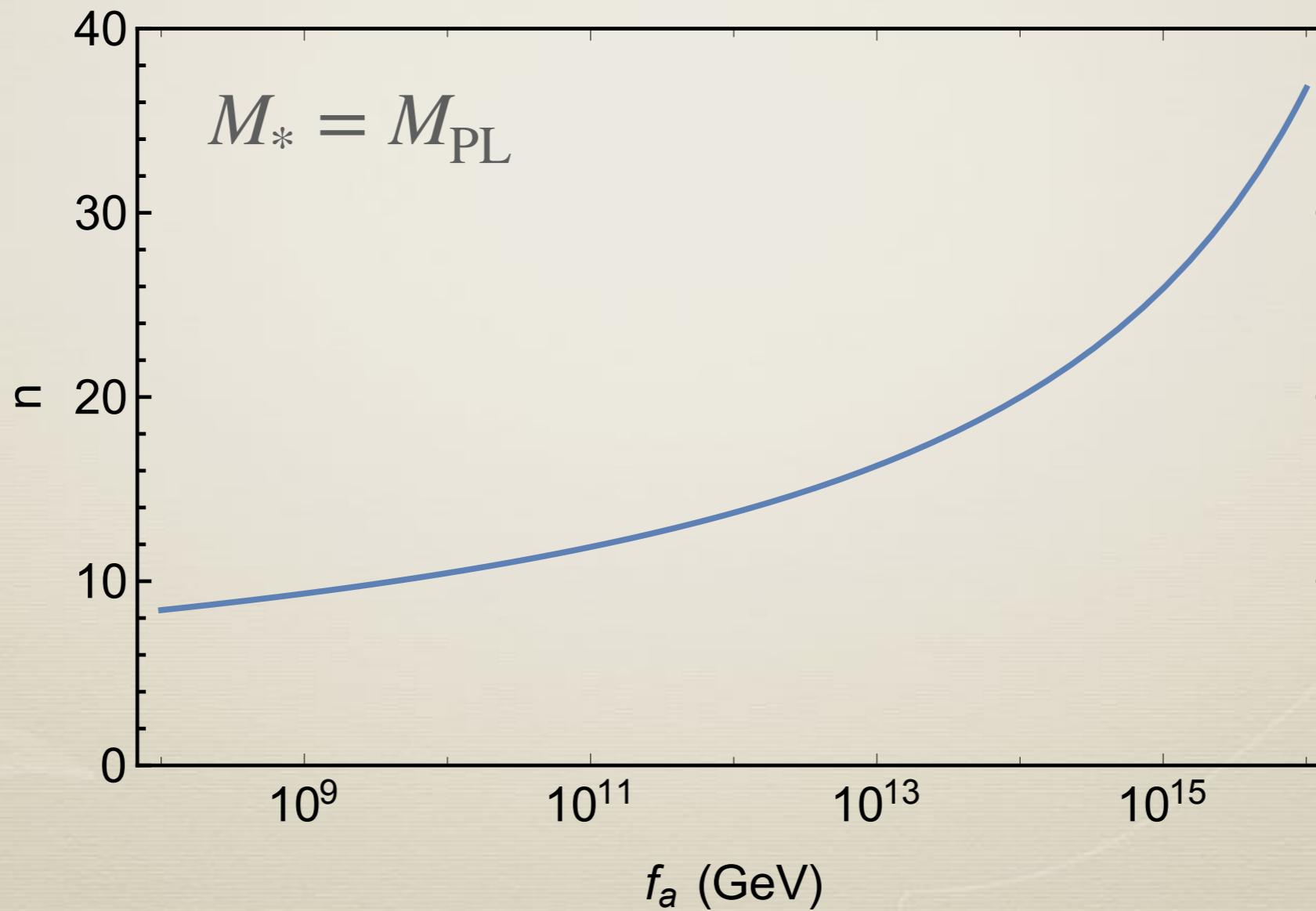
Ex: baryon number is practically a good symmetry

$$\mathcal{L} = \frac{1}{M_*^2} u \bar{u} d \bar{d}$$

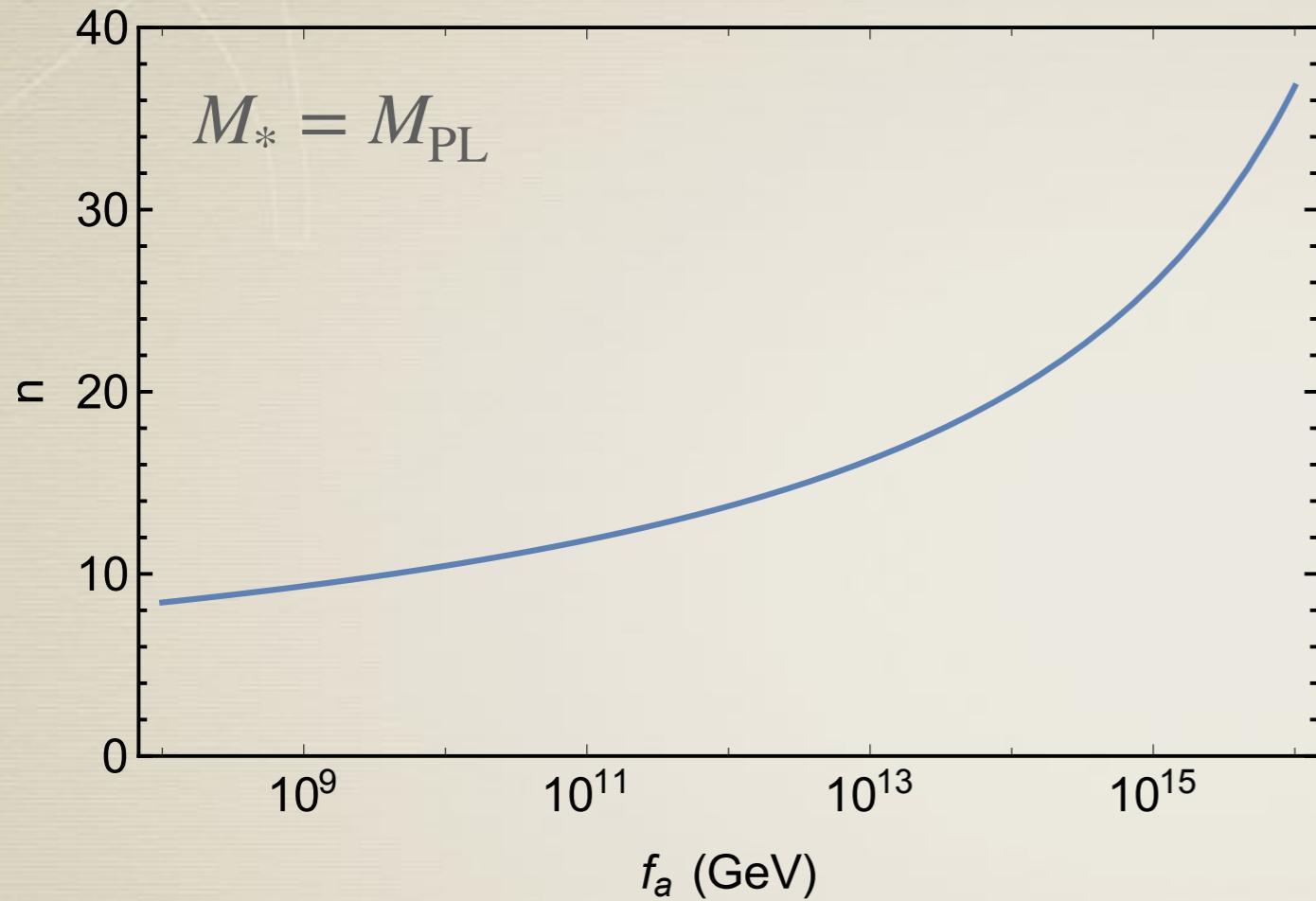
$$\Gamma_{\text{proton}} \sim \frac{\text{GeV}^5}{M_*^4} \sim (10^{40} \text{years})^{-1} \left(\frac{10^{18} \text{GeV}}{M_*} \right)^4$$

Accidental PQ symmetry

$$\mathcal{L} = \frac{O_n}{M_*^{n-4}} \quad \frac{\langle O_n \rangle}{M_*^{n-4}} \sim \frac{f_a^n}{M_*^{n-4}} < 10^{-10} m_\pi^2 f_\pi^2$$



Accidental PQ symmetry



Ex. Dynamical PQ breaking

Choi and Kim (1985)

$$\langle \psi \bar{\psi} \rangle \sim f_a^3$$

$$f_a = 10^8 \text{ GeV}$$

$$\cancel{\psi \bar{\psi}}, (\cancel{\psi \bar{\psi}})^2$$

$$f_a = 10^{15} \text{ GeV}$$

$$\cancel{\psi \bar{\psi}}, (\cancel{\psi \bar{\psi}})^2, \dots (\cancel{\psi \bar{\psi}})^8$$

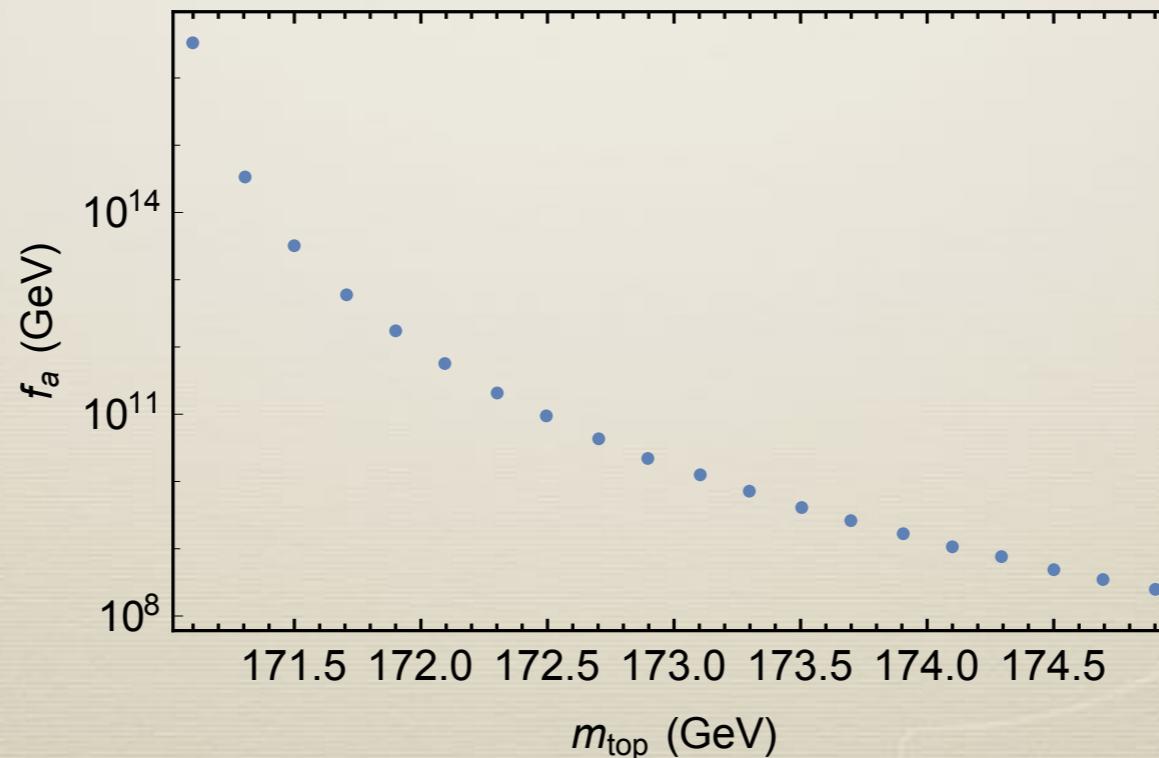
Unification with Higgs?

Composite Nambu-Goldstone Higgs at high energy

Redi and Strumia (2012)

$G \rightarrow H$ SM Higgs, axion in G/H

$$V(h) = \lambda(\mu) |h|^4, \lambda(f_a) \simeq 0$$



Unification with SUSY breaking?

Global symmetry breaking is one of
the sufficient conditions of SUSY breaking

Affleck, Dine and Seiberg (1984)

Suppose that SUSY and PQ symmetry
are simultaneously broken

J.E. Kim (Wed.)

KH, Ibe, Schmitz and Yanagida (2015)
KH and Leedom (2017)

$$m_{3/2} \sim \frac{f_a^2}{M_{\text{PL}}} = 100 \text{ GeV} \left(\frac{f_a}{10^{10} \text{GeV}} \right)^2$$

Axion DM production

* Mis-alignment

Preskill, Wise, Wilczek (1983)
Abbott, Sikivie (1983)
Dine, Fischler (1983)

$$\Omega_a h^2 \simeq 0.01 \theta_{\text{mis}}^2 \left(\frac{f_a}{10^{11} \text{GeV}} \right)^{1.19}$$

* Emission from string-domain wall net work

Davis (1986)

$$\Omega_a h^2 \simeq 0.1 - 0.01 \left(\frac{f_a}{10^{11} \text{GeV}} \right)^{1.19}$$

Villadoro (Mon.)
Buschmann (Mon.)

$$f_a = 10^{11} - 10^{12} \text{ GeV}$$

Anything else ?

Large decay constant

$$10^{15} \text{ GeV} \lesssim f_a \lesssim 10^{18} \text{ GeV}$$

Why we like large decay constant

- * Unification with GUT symmetry breaking
- * String axion

GUT + PQ

GUT and PQ breaking may occur simultaneously

Wise, Georgi and Glashow (1981),
Nilles and Raby (1981)
Lazarides and Shafi (1982),

* Minimality

* Fit in DFSZ models

$$\mathcal{L} = yQ\bar{u}H_u + yQ\bar{d}H_d + \mathcal{O}_{\text{PQ}}H_uH_d$$

* Requirement in SUSY SU(5) DFSZ models

Goodmann, Witten (1986)
KH, Ibe, Suzuki (2015)

String axion

$$V(a) = 0$$

PQ symmetric

$$+ \Lambda^4 \cos \frac{a}{f_a}$$

NOT PQ symmetric

What is the origin of such a special structure?

String axion

UV approach : moduli in string theory

Witten (1984)

J.E. Kim (Wed.)

Gauge symmetries in higher dimension



Compactification

Remnant anomalous PQ symmetry

Decay constant not much below the fundamental scale

Choi, Kim (1985), Svrcek, Witten (2006)

Anything else?

Axion DM

Production mechanisms

I will review mechanisms I recognize

- * Mis-alignment
- * Emission from string-domain wall net work
- * Collapse of long-lived domain walls
- * Parametric resonance
- * Dynamical determination of mis-alignment

Standard ones

- * Mis-alignment

Preskill, Wise, Wilczek (1983)
Abbott, Sikivie (1983)
Dine, Fischler (1983)

$$\Omega_a h^2 \simeq 0.01 \theta_{\text{mis}}^2 \left(\frac{f_a}{10^{11} \text{GeV}} \right)^{1.19}$$

- * Emission from string-domain wall net work

Davis (1986)

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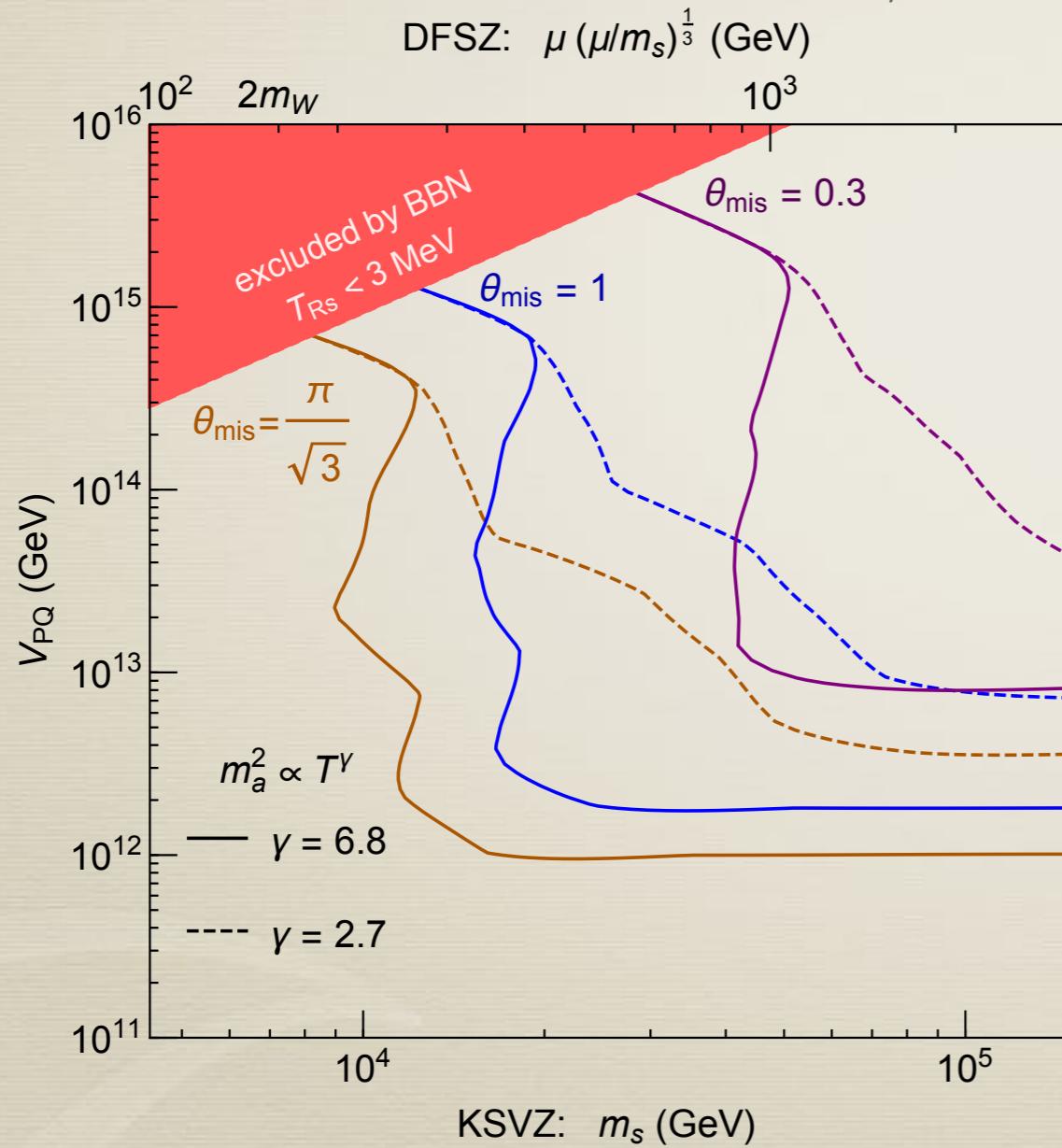
Entropy production from saxion

Lazarides, Panagiotakopoulos and Shafi (1987)

Kawasaki, Moroi and Yanagida (1996)

Hashimoto, Izawa, Yamaguchi and Yanagida (1998)

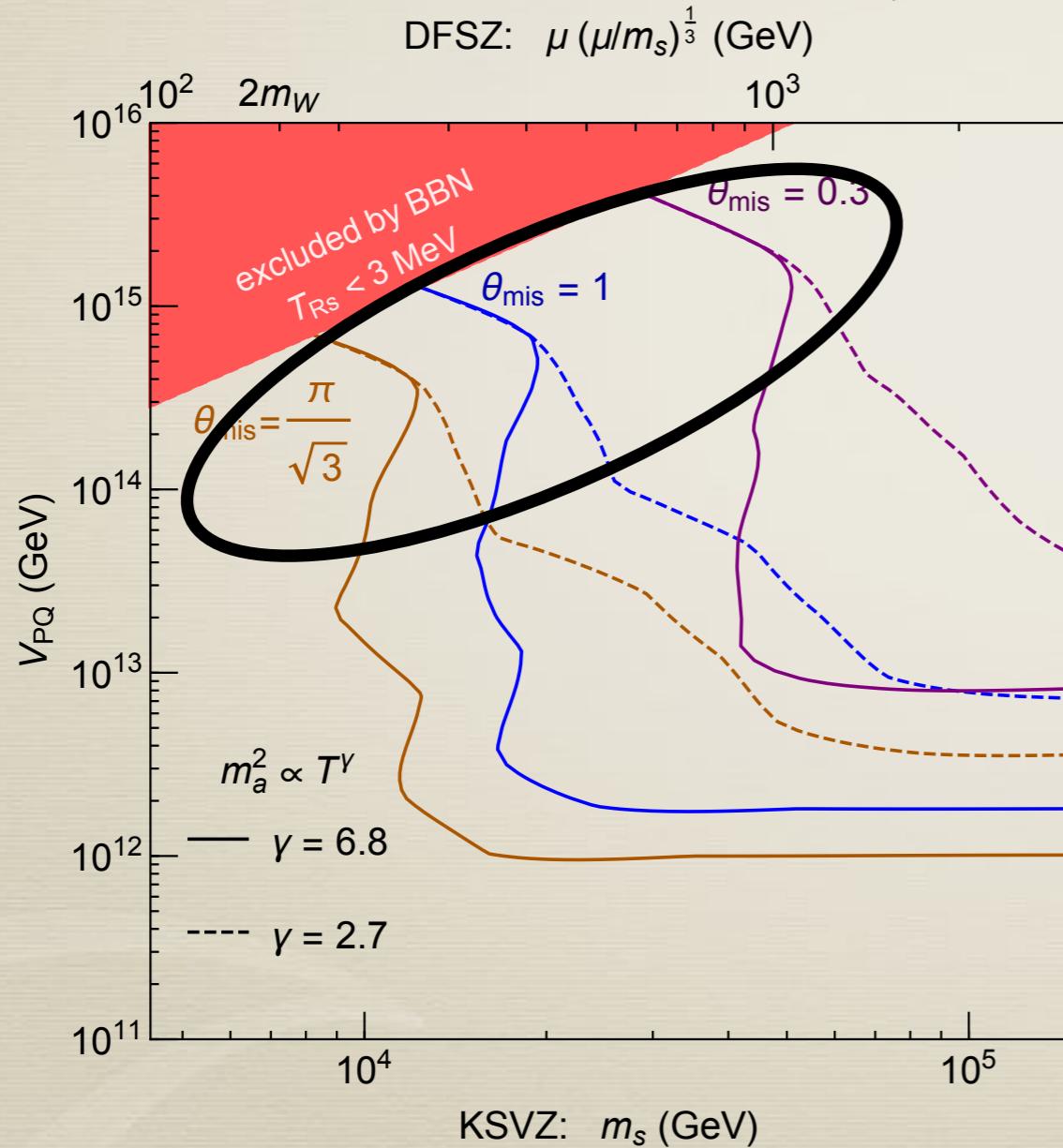
Co, D'Eramo, Hall. KH (2017)



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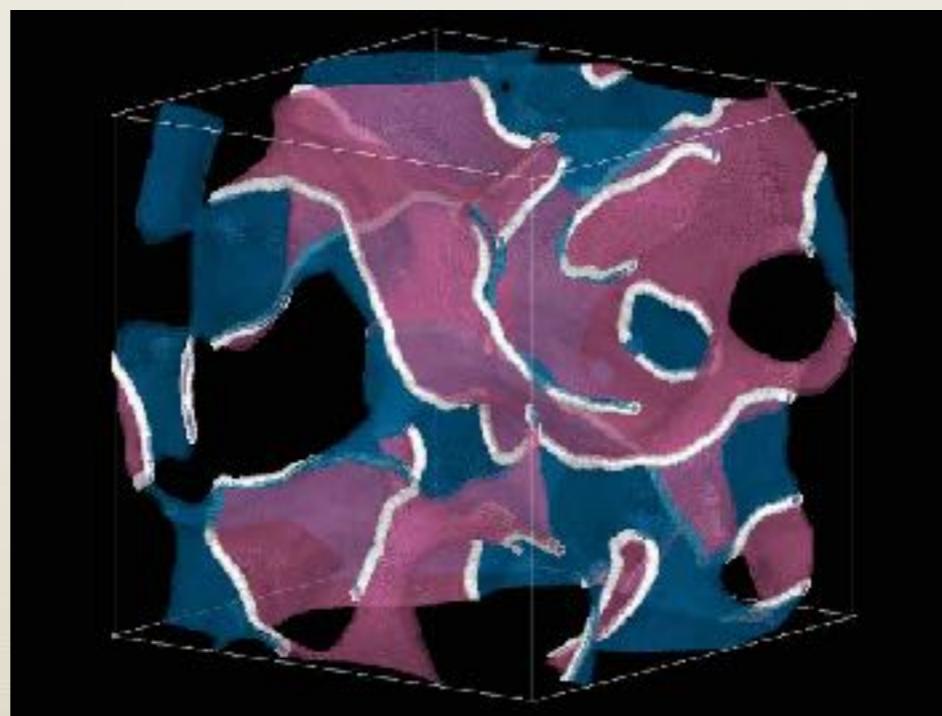
Enhanced structure formation
from early matter domination?

Erickcek and Sigurdson (2011)
Choi and Takahashi (2017)

Long-lived domain walls

$$N_{\text{DW}} > 1$$

Topologically stable domain walls

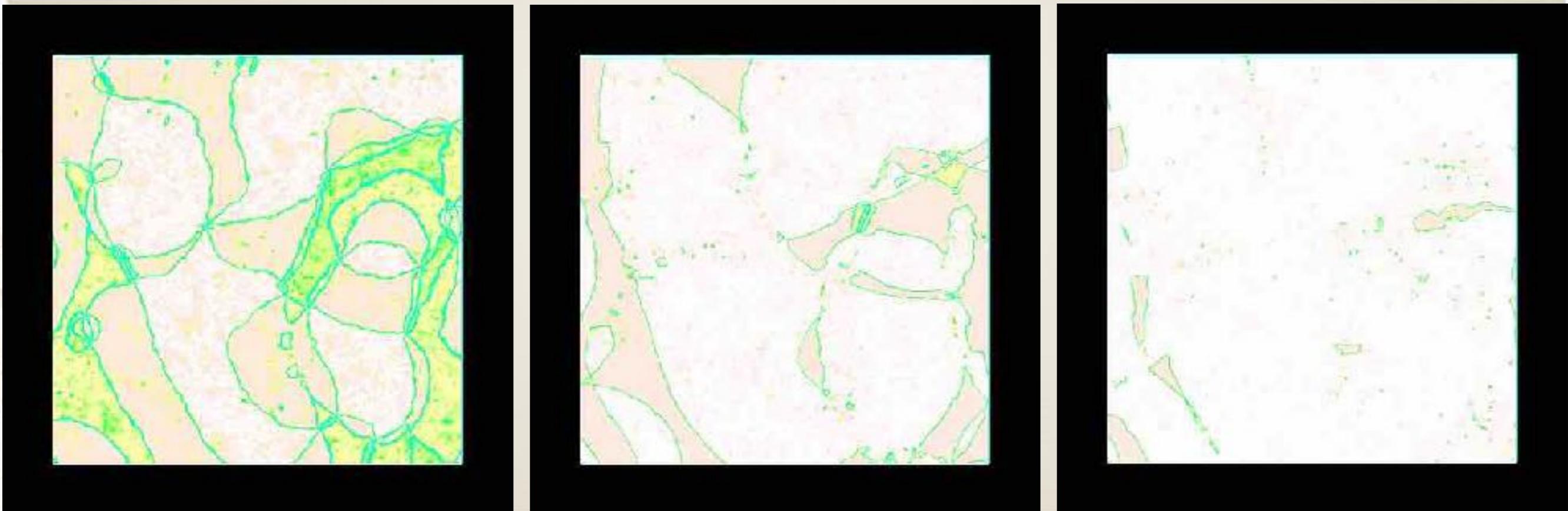


$$\rho_{\text{DW}} \propto R^{-2}$$

Pic. from Hiramatsu, Kawasaki, Saikawa and Sekiguchi (2012)

Long-lived domain walls

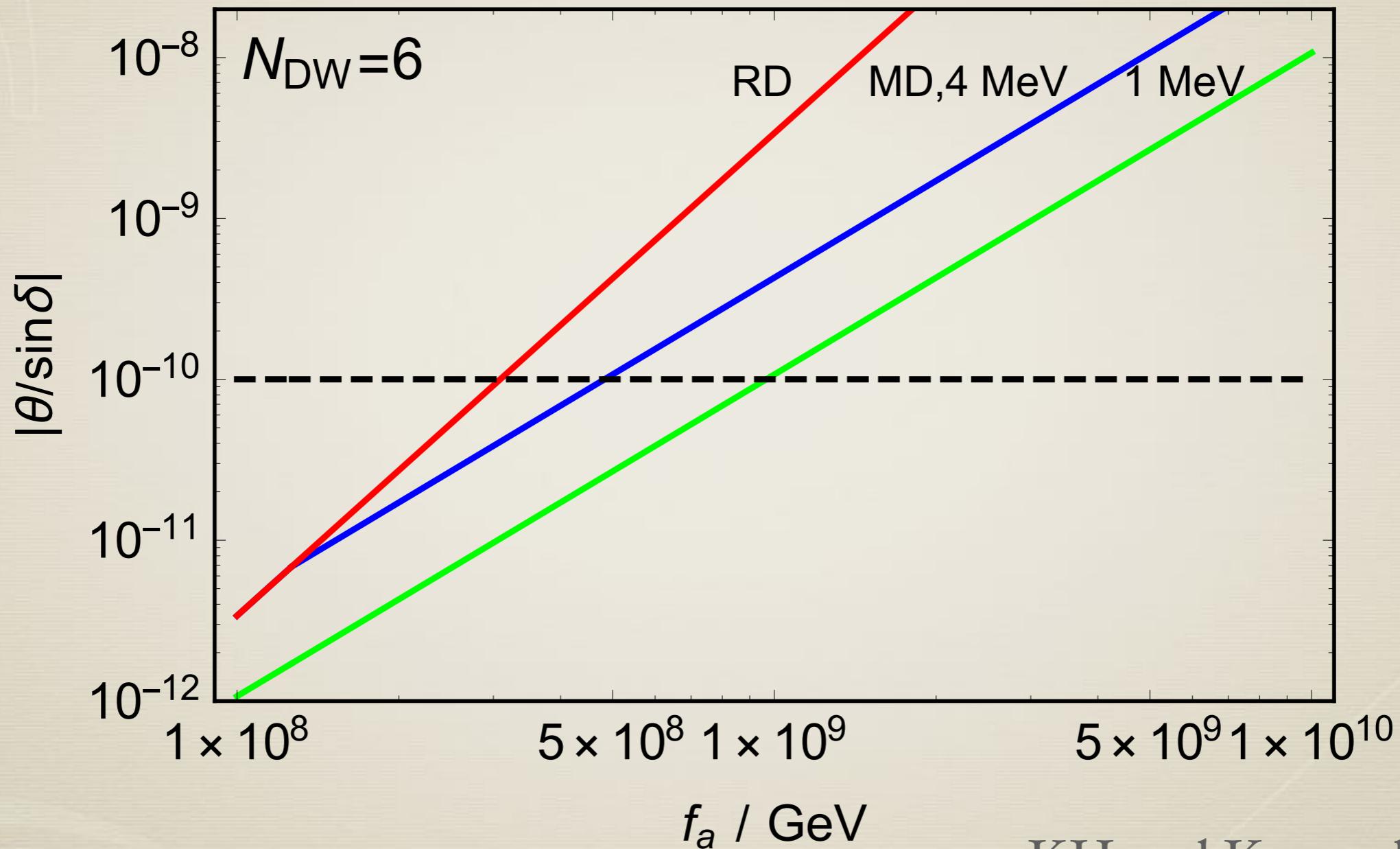
$$\Delta V = -2\Xi V_{\text{PQ}}^4 \cos\left(\frac{a}{V_{\text{PQ}}} + \delta\right), \quad V_{\text{PQ}} = N_{\text{DW}} f_a$$



Kawasaki, Saikawa and Sekiguchi (2015)

produce axions

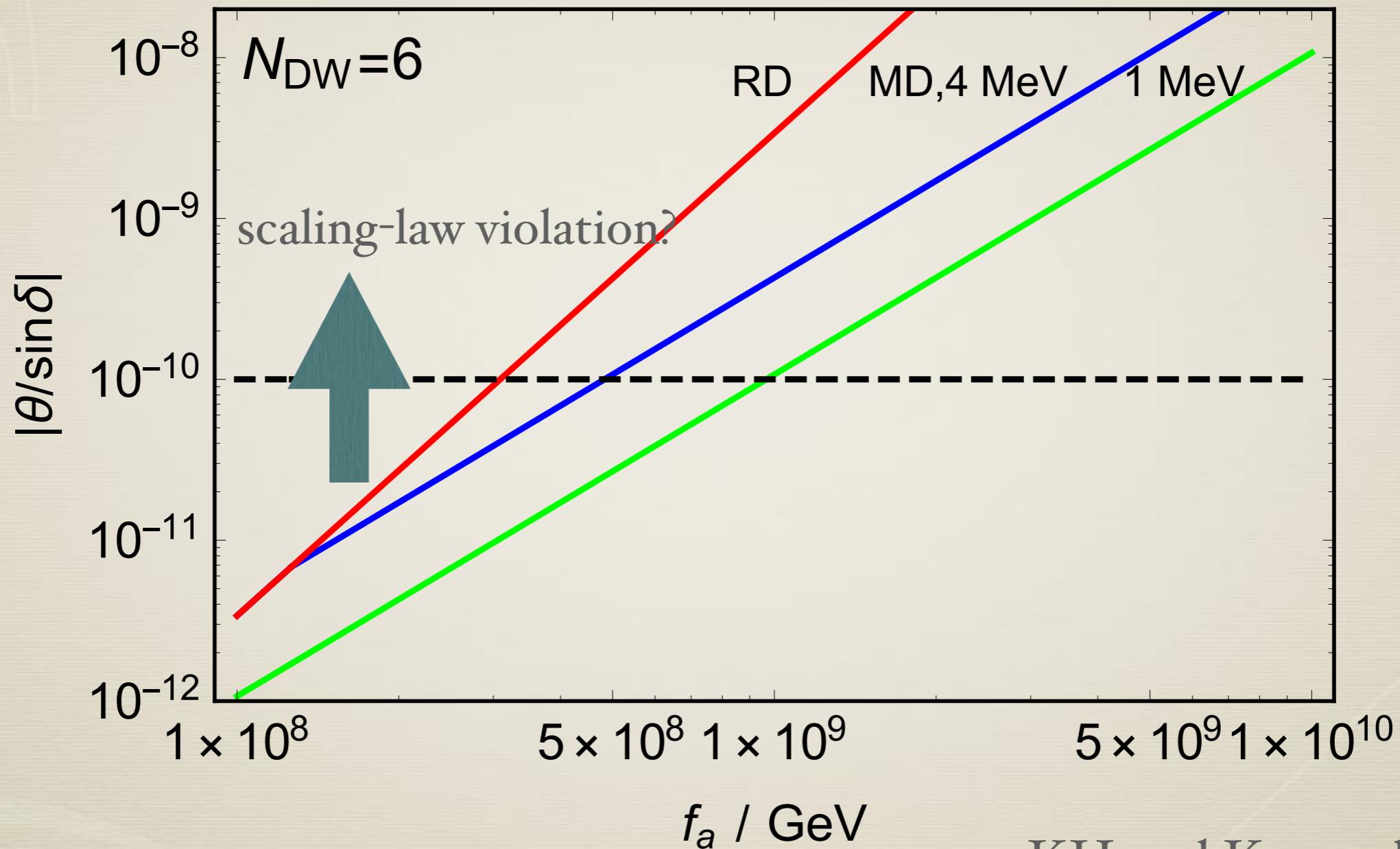
Long-lived domain walls



neutron-EDM expected

KH and Kawasaki (2018)

Long-lived domain walls



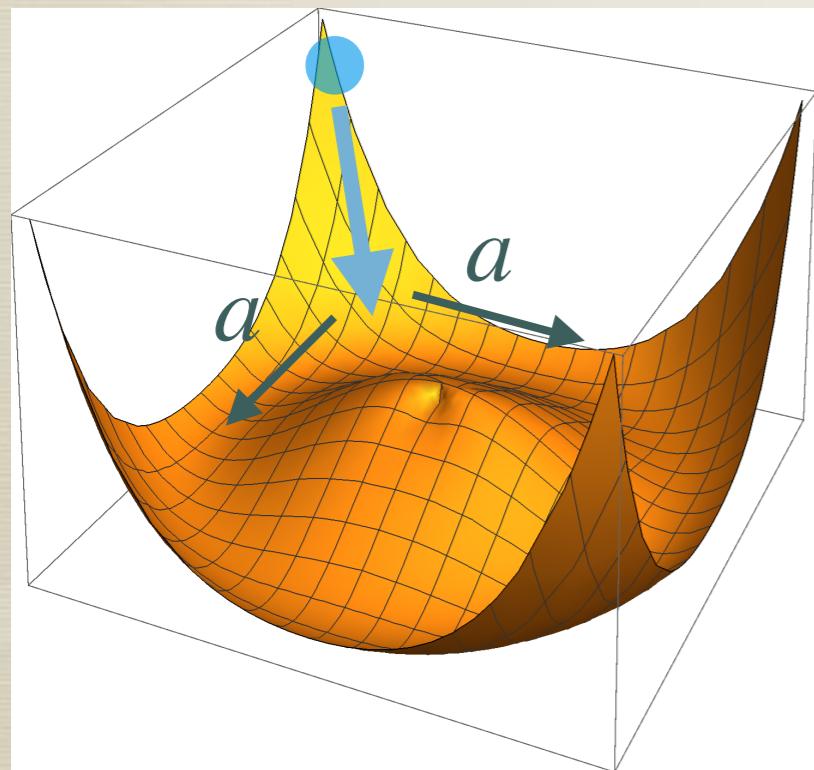
KH and Kawasaki (2018)

neutron-EDM expected

Parametric resonance

SUSY : scalar partner of axion, S, is nearly massless

Large initial value, oscillate



$$\Omega_a h^2 \simeq 0.1 \left(\frac{S_i}{10^{16} \text{ GeV}} \right)^2 \left(\frac{10 \text{ TeV}}{m_{S,i}} \right)^{1/2} \frac{10^9 \text{ GeV}}{f_a},$$

$$v_a|_{\text{eV}} \sim 10^{-4} \times \left(\frac{m_{S,i}}{10^6 \text{ GeV}} \right)^{1/2} \frac{f_a}{10^9 \text{ GeV}}.$$

Co, Hall, KH(2017)

Can be warm

DAMP

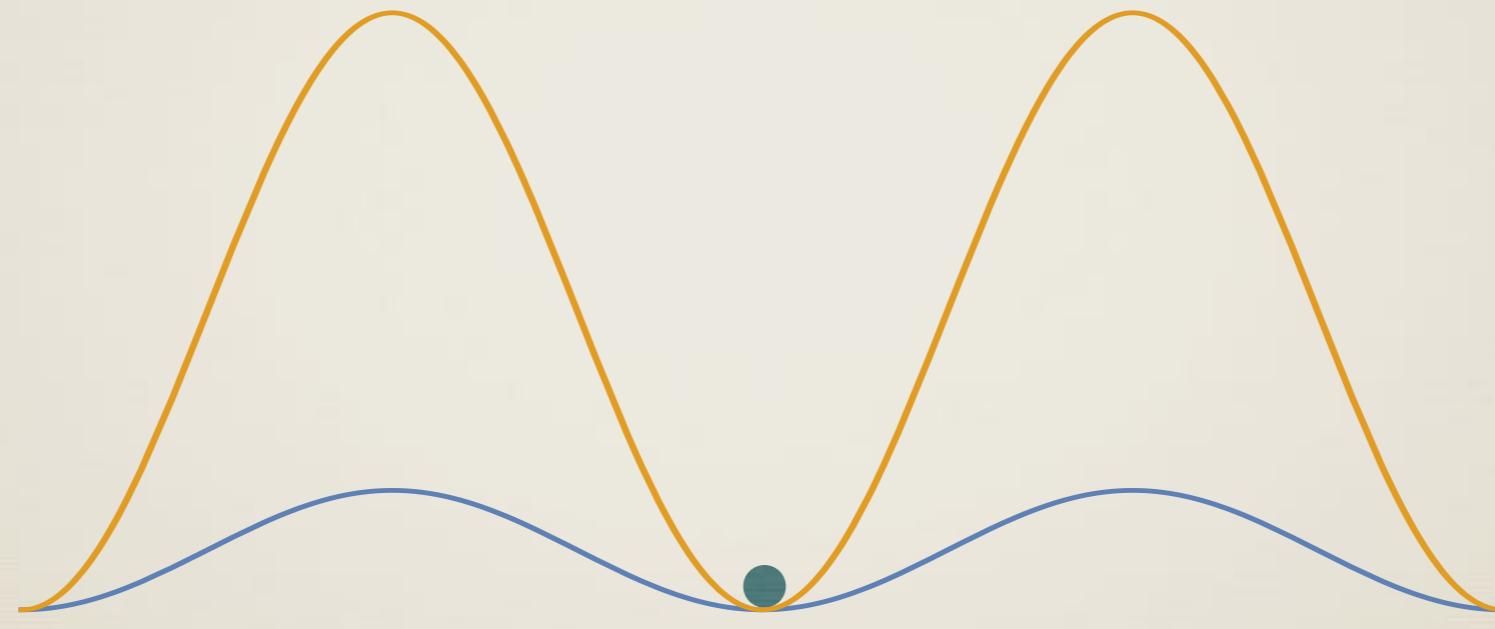
Dynamical Axion Mis-alignment Production

Large QCD scale, approximate CP

Dvali (1985)
Banks and Dine (1997)
Co, Gonzalez, KH (2018)

early
universe 

vacuum 



$$\theta_{\text{mis}} \sim 0$$

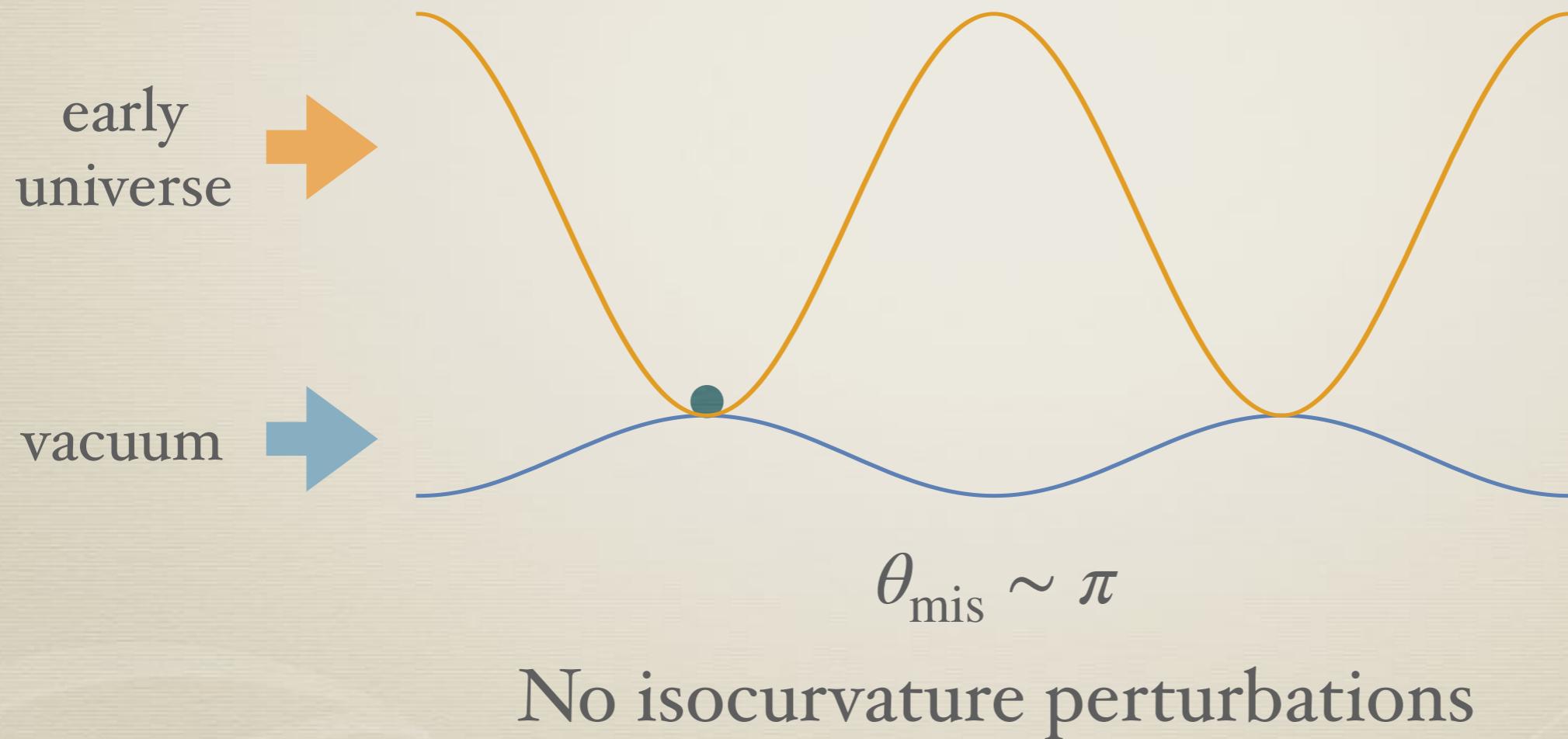
No isocurvature perturbations

DAMP

Dynamical Axion Mis-alignment Production

Co, Gonzalez, KH (2018)

Large QCD scale, approximate CP, flip sign (e.g. from two Higgs doublets)



Axion DM production

- * Mis-alignment
- * Emission from string-domain wall net work
- * Collapse of long-lived domain walls
- * Parametric resonance
- * Dynamical determination of mis-alignment

Can we discriminate the mechanisms?

Axion DM production

$$f_a \sim 10^{11} \text{ GeV}$$

- * Mis-alignment
- * Emission from string-domain wall net work
Precise determination of f_a
- * ~~Collapse of long-lived domain walls~~
- * Parametric resonance Warmness? Structure?
- * ~~Dynamical determination of mis-alignment~~

Axion DM production

$$f_a \ll 10^{11} \text{ GeV}$$

- * ~~Mis-alignment~~
- * ~~Emission from string-domain wall net work~~
- * Collapse of long-lived domain walls **neutron-EDM**
- * Parametric resonance ← **Axion small scale structures?**
- * Dynamical determination of mis-alignment A. Arvanitaki (Mon.)

Axion DM production

Anthropic selection?

* (Mis-alignment)

* ~~Emission from string-domain wall net work~~

* ~~Collapse of long-lived domain walls~~

* Parametric resonance Warmness? Structure?

* Dynamical determination of mis-alignment

No isocurvature even for high inflation scale

$$f_a \gg 10^{11} \text{ GeV}$$

$f_a \lesssim 10^{16} \text{ GeV}$ Can be saved by
entropy production

Enhanced small scale structures?

Anything else?

Back up

GUT + PQ

GUT and PQ breaking may occur simultaneously

* Minimality

* Requirement in SUSY DFSZ model

$$\mathcal{L} = yQ\bar{u}H_u + yQ\bar{d}H_d + \mathcal{O}_{\text{PQ}}H_uH_d$$

Wise, Georgi and Glashow (1981),
Nilles and Raby (1981)
Lazarides and Shafi (1982),

KH, Ibe, Suzuki (2015)

Q	\bar{u}	\bar{d}	H_u	H_d
-1	-1	-1	2	2

Above GUT scale

$$A(PQ - SU(2)^2) = A(PQ - SU(3)^2) = A(PQ - SU(5)^2)$$

Below GUT scale

$$A(PQ - SU(2)^2) \neq A(PQ - SU(3)^2)$$

Anthropic bound on DM

Larger DM abundance

Earlier matter dominance

Earlier Collapse of Halo

Denser Halo

Environment of Earth destroyed?

Tegmark, Aguirre, Rees and Wilczek (2006)

Anthropic bound on DM

Smaller DM abundance

Later matter dominance

No halo collapse before Lambda dominance

No halo

Weinberg (1978)

Tegmark, Aguirre, Rees and Wilczek (2006)

Can be compensated by larger primordial perturbation
Prior of it?

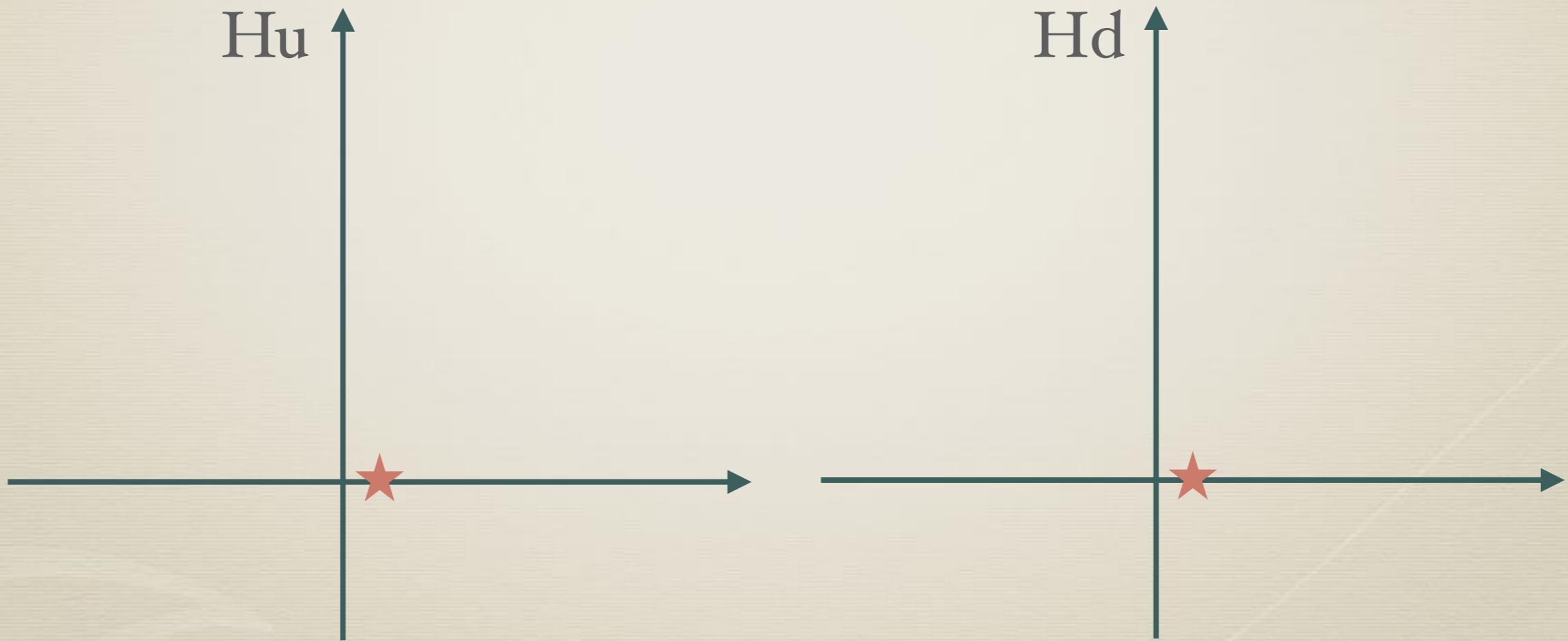
e.g. Chiang, KH (2018)

Small decay constant

Co, Gonzalez, KH (2018)

$$\frac{1}{32\pi^2} (a + \theta_{\text{QCD}} + \arg \det(m_u m_d)) G \tilde{G}$$

$$\mathcal{L} = y_u H_u Q \bar{u} + y_d H_d Q \bar{d}$$



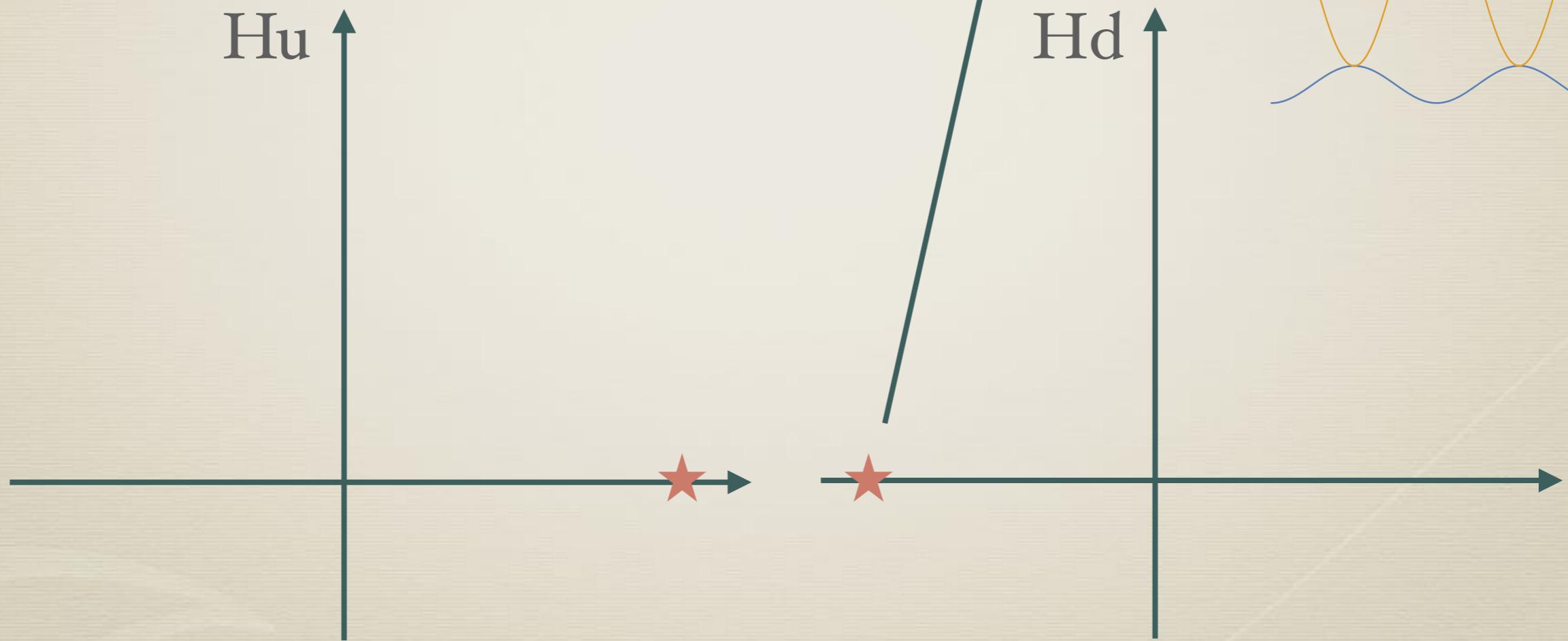
$$V = -B\mu H_u H_d$$

Small decay constant

Co, Gonzalez, KH (2018)

$$\frac{1}{32\pi^2} (a + \theta_{\text{QCD}} + \arg \det(m_u m_d)) G \tilde{G}$$

$$\mathcal{L} = y_u H_u Q \bar{u} + y_d H_d Q \bar{d}$$



$$V = -B\mu H_u H_d + cH_I^2 H_u H_d \quad \text{Assume approximate CP}$$

Small decay constant

Co, Gonzalez, KH (2018)

