Cosmological evolution of axion and hidden sector

Dec. 20 2017 @Osaka Univ.

"Axion physics and dark matter cosmology"

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(Tohoku)

Kitajima, Sekiguchi, FT, 1711.06590

Kawasaki, FT, Yamada,1511.05030,1708.06047

1. Introduction

The QCD axion is a plausible candidate for physics beyond the standard model:

See talk by Jihn E Kim

- Dynamically solves the strong CP problem

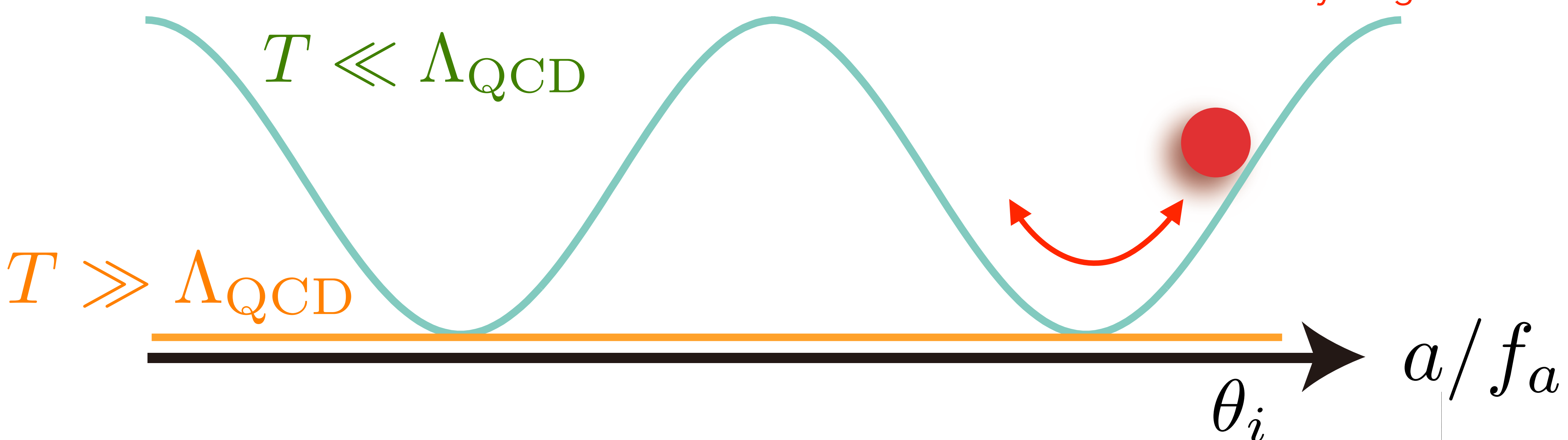
Peccei, Quinn `77, Weinberg `78, Wilczek `78

- Explains the observed dark matter

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

  - Cold and long-lived DM with the correct abundance

See talk by Nagamine



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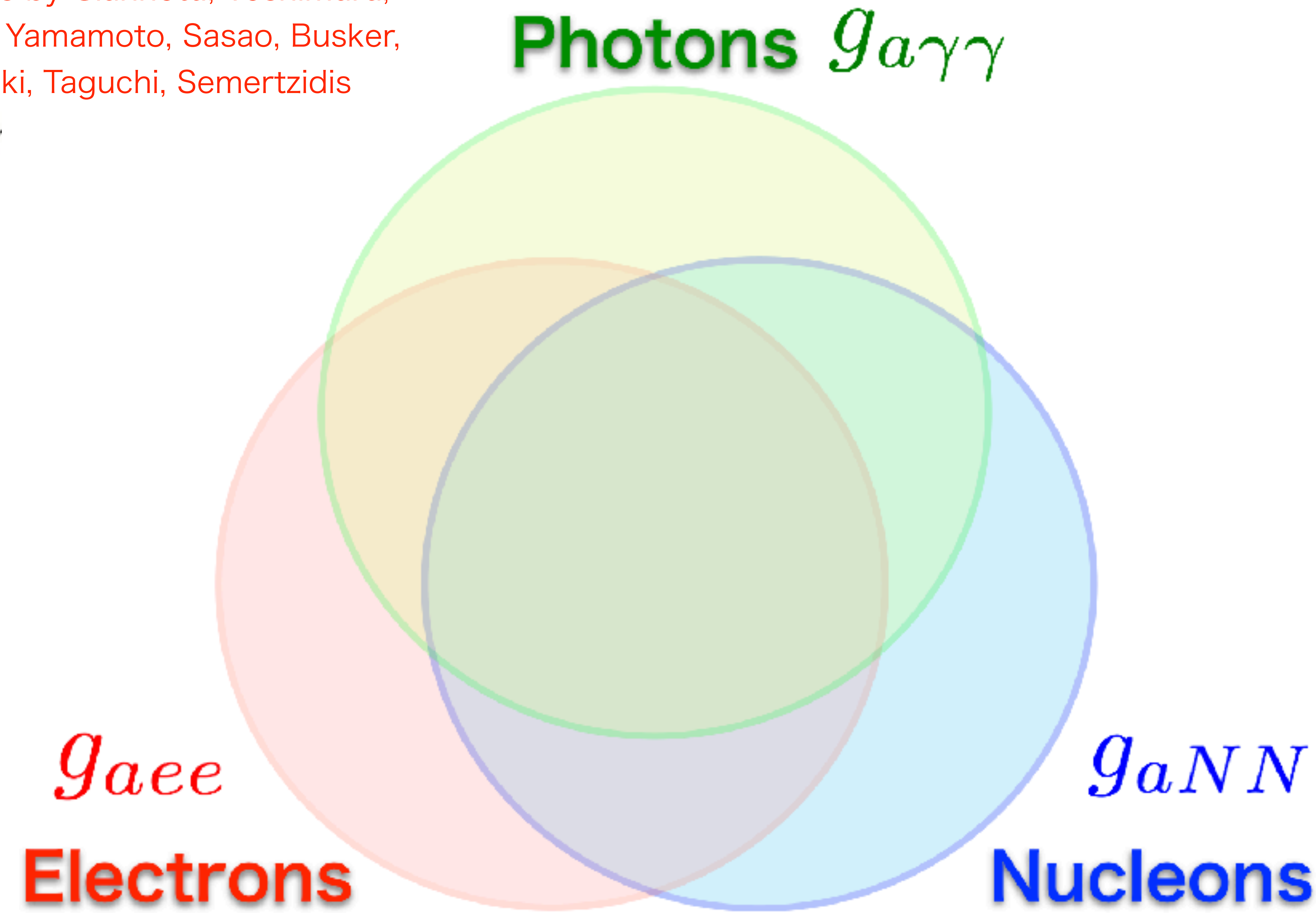
See talks by Giannotti, Yoshimura, Spector, Yamamoto, Sasao, Busker, Iwasaki, Taguchi, Semertzidis



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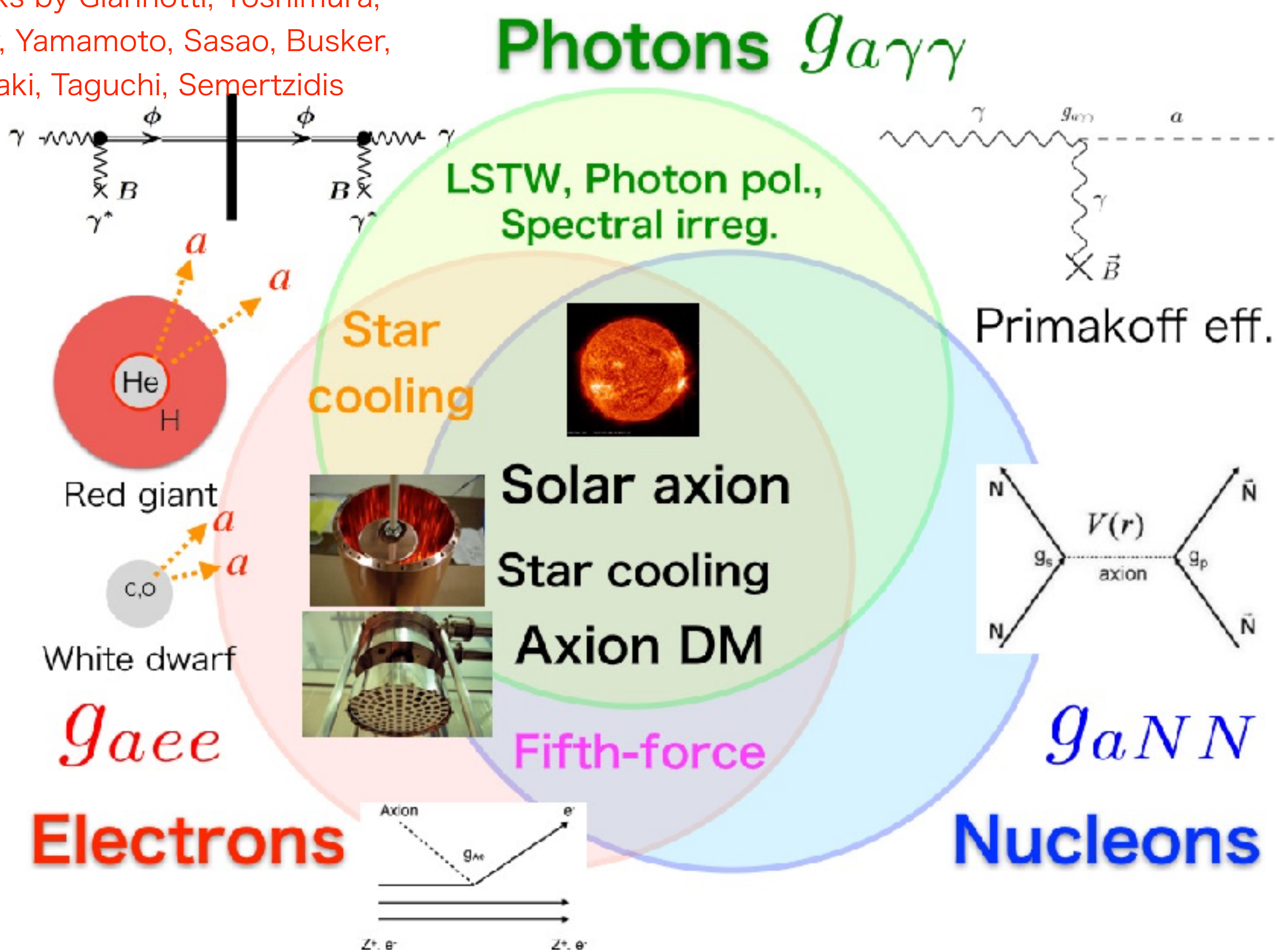

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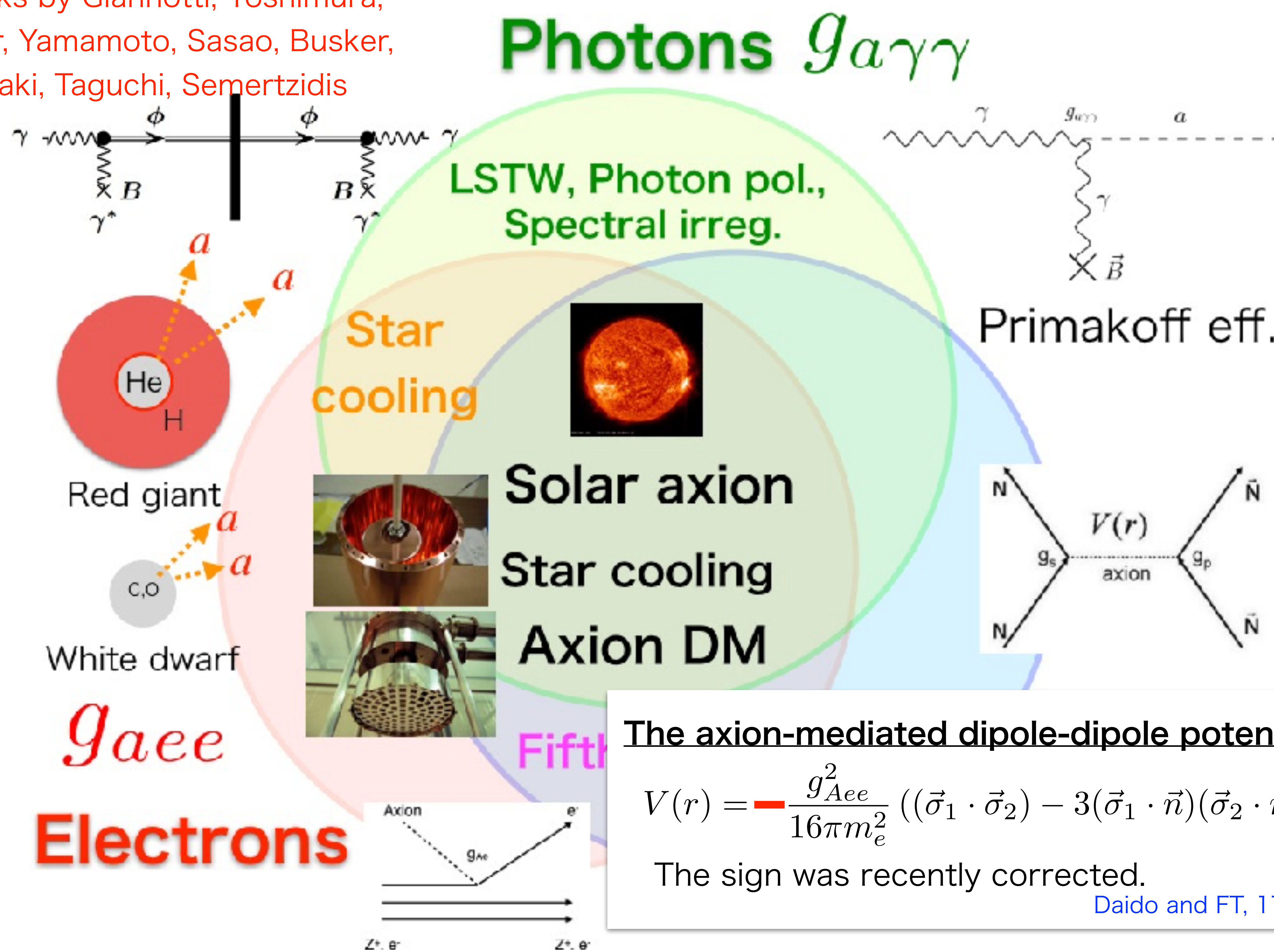

The axion-mediated dipole-dipole potential:

$$V(r) = -\frac{g_{Aee}^2}{16\pi m_e^2}\left((\vec{\sigma}_1\cdot\vec{\sigma}_2) - 3(\vec{\sigma}_1\cdot\vec{n})(\vec{\sigma}_2\cdot\vec{n})\right)/r^3$$

The sign was recently corrected.

Daido and FT, 1704.00155

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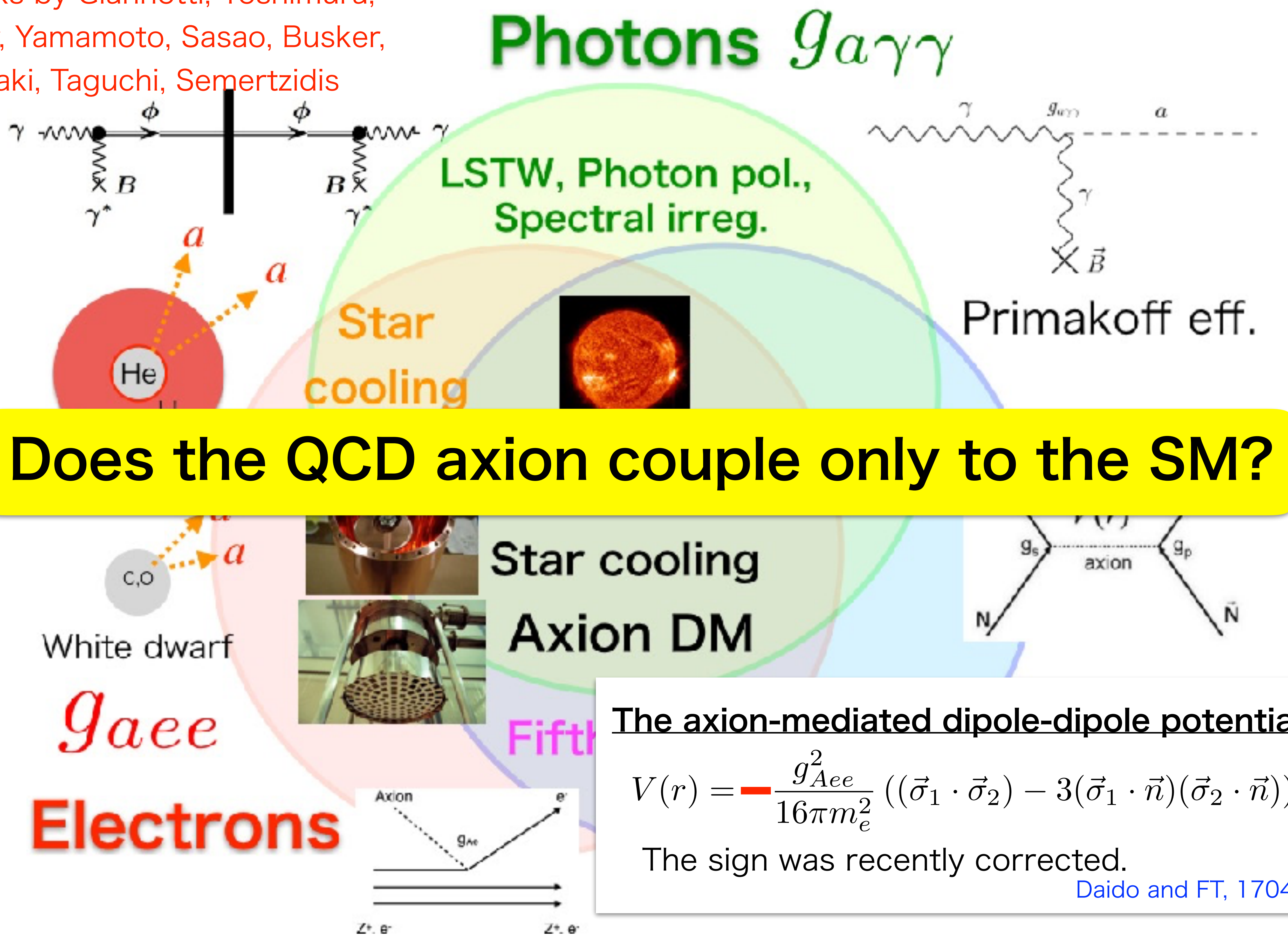

Does the QCD axion couple only to the SM?

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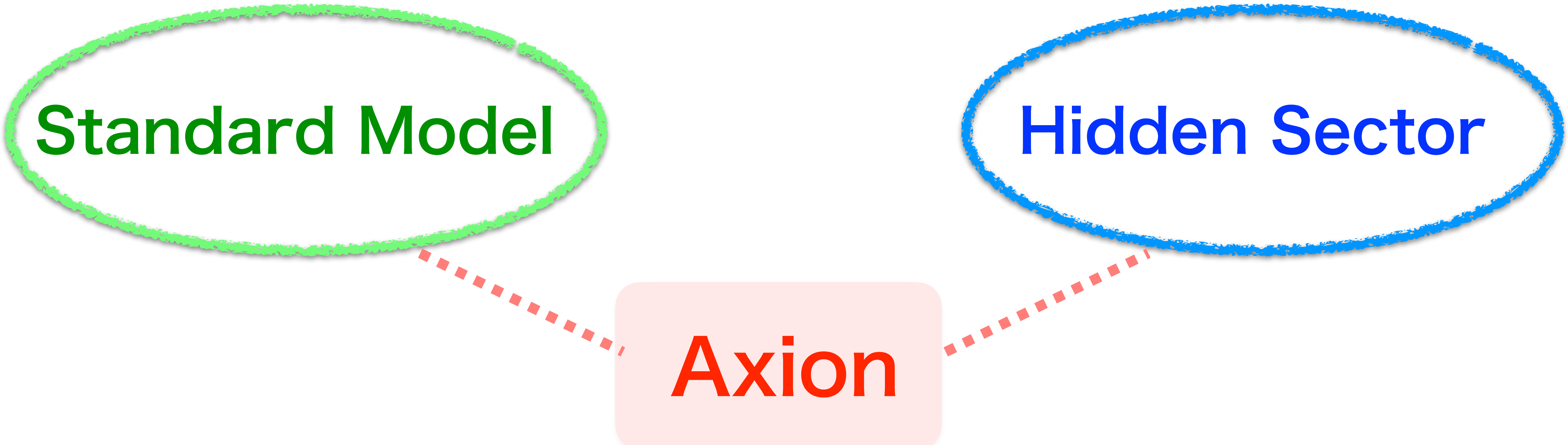
In this talk, I discuss a scenario where axion is the portal to a hidden sector.



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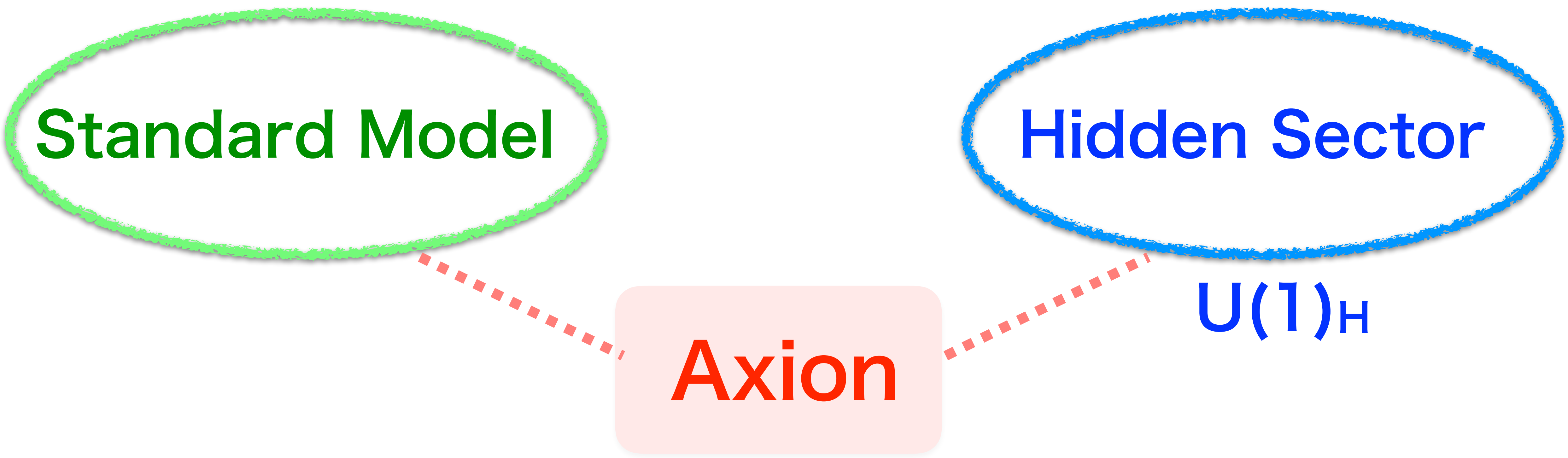

1) Case with moderately large coupling to $U(1)_H$
2) Case of $U(1)_H$ w/ monopoles

2. Axion coupled to hidden photons

Kitajima, Sekiguchi, FT, 1711.06590

Coupling to hidden photons

The relevant part of the Lagrangian is

$$\mathcal{L} = \frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi - \chi_{\rm QCD}(T)\left[1-\cos\left(\frac{\phi}{f_a}\right)\right]$$

$$-\frac{1}{4}F_{\mathrm{H}\mu\nu}F_{\mathrm{H}}^{\mu\nu} - \frac{\beta_{\mathrm{H}}}{4f_a}\phi F_{\mathrm{H}\mu\nu}\tilde{F}_{\mathrm{H}}^{\mu\nu} + \text{(coupling to SM)}$$

ϕ : axion, A_H, F_H : hidden photon and field strength

$$\chi_{\rm QCD}(T) = \frac{\chi_0}{1+(T/T_c)^b} \qquad \chi_0 = (7.6\times 10^{-2}\,\mathrm{GeV})^4,\quad T_c = 0.16\,\mathrm{GeV},\ \ b = 8.2$$

P S. Borsanyi et al,1606.07494

$$\beta_{\mathrm{H}} = \frac{\alpha_H c_{\gamma'}}{2\pi} \quad \text{with} \quad c_{\gamma'} = \frac{E'}{N}$$

(The ratio of the anomaly coefficients)

N.B. β_{H} can be larger than unity in the clockwork axion.

[Alignment/clockwork]: Kim, Nilles, Peloso, hep-ph/0409138, Choi, Kim, Yun, 1404.6209, Choi and Im 1511.00132, Kaplan and Rattazzi, 1511.01827. Giudice and McCullough 1610.07962,
[Clockwork QCD axion]: Higaki, Jeong, Kitajima, FT, 1512.05295, 1603.02090, Farina, Pappadopulo, Rompineve, and Tesi, 1611.09855.

Coupling to hidden photons

Equations of motion:

$$\ddot{\phi} + 2\mathcal{H}\dot{\phi} - \nabla^2\phi + a^2\frac{\partial V}{\partial \phi} = -\frac{\beta_{\rm H}}{f_a a^2}\dot{\boldsymbol{A}}_{\rm H}\cdot(\nabla\times\boldsymbol{A}_{\rm H}),$$

$$\ddot{\boldsymbol{A}}_{\rm H} + \nabla\times(\nabla\times\boldsymbol{A}_{\rm H}) = \frac{\beta_{\rm H}}{f_a}\left[\dot{\phi}(\nabla\times\boldsymbol{A}_{\rm H}) - (\nabla\phi)\times\dot{\boldsymbol{A}}_{\rm H}\right],$$

$$\nabla\cdot\dot{\boldsymbol{A}}_{\rm H} = \frac{\beta_{\rm H}}{f_a}(\nabla\phi)\cdot(\nabla\times\boldsymbol{A}_{\rm H}),$$

Overdot is a derivative w.r.t. conformal time

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For spatially homogeneous axion,

$$\ddot{A}_{{\rm H}\boldsymbol{k},\pm} + k\left(k \mp \frac{\beta_{\rm H}\dot{\phi}}{f_a}\right)A_{{\rm H}\boldsymbol{k},\pm} = 0$$

$\pm$: helicity

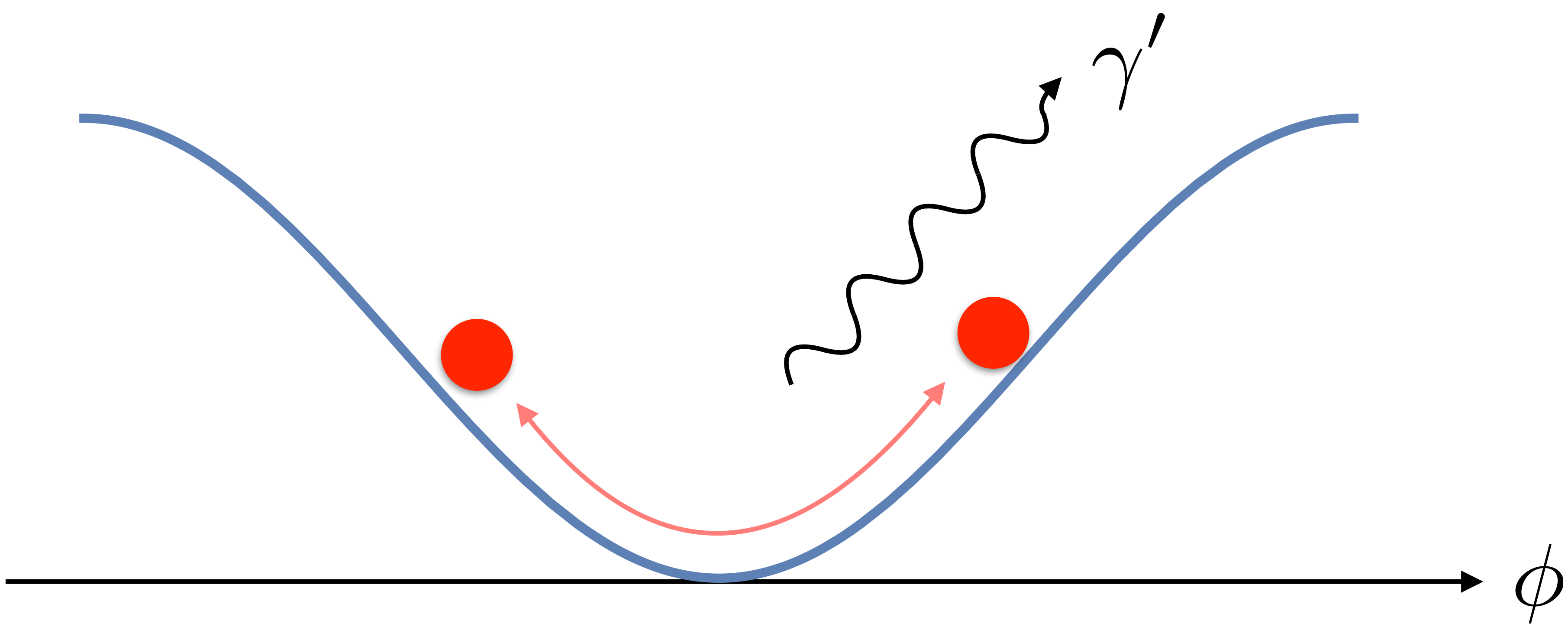
Tachyonic instability exists if $k < \beta_{\rm H}|\dot{\phi}|/f_a$ **!**

Garretson, G. B. Field, and S. M. Carroll, hep-ph/9209238

The effect was studied in a context of natural inflation (warm inflation, non-Gaussianity, reheating), magnetogenesis, and relaxion.

Effects on the axion dynamics

So, if coupling is moderately large, the QCD axion produces hidden photons efficiently, and the abundance may be reduced.



Ω_a ↘

Effects on the axion dynamics

The axion DM is produced as coherent oscillations [misalignment mechanism].

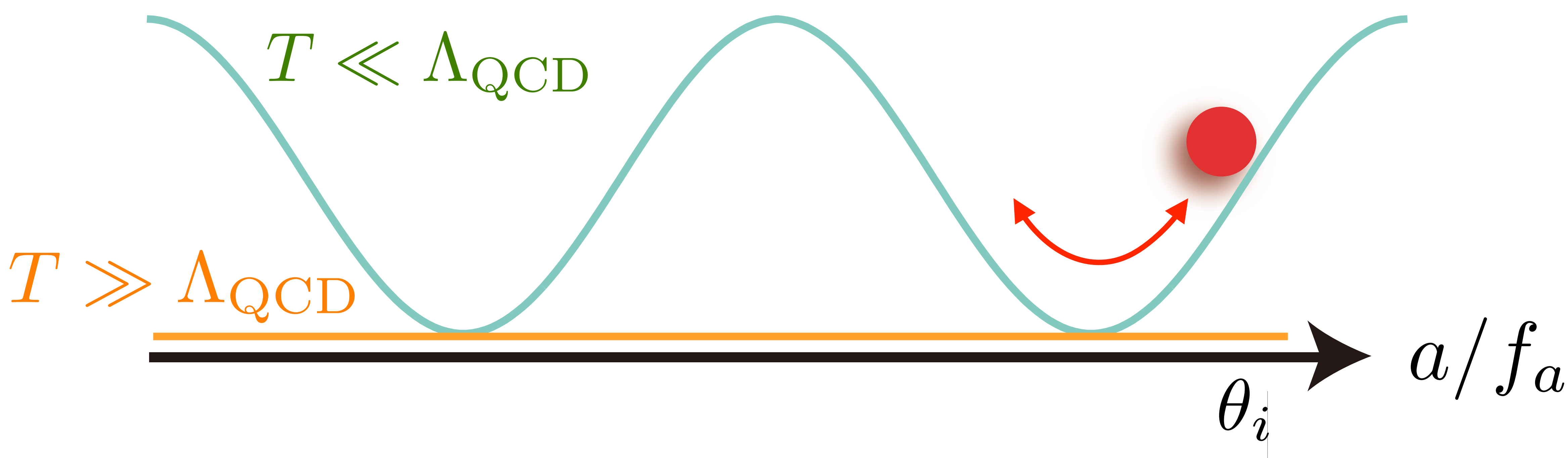
Preskill, Wise, Wilczek `83, Abbott, Sikivie, `83, Dine, Fischler, `83

$$\Omega_a h^2 \simeq 0.11\, \theta_i^2 C(\theta_i) \left(\frac{f_a}{5 \times 10^{11}\,\mathrm{GeV}} \right)^{1.184}$$

CDM

↑ Anharmonic effect

Bae, Huh, Kim `08, Visinelli and Gondolo `08



Effects on the axion dynamics

"Axion window"

$$10^8\,\mathrm{GeV} \lesssim f_a \lesssim 10^{12}\,\mathrm{GeV}$$

Preskill, Wise, Wilczek `83, Abbott, Sikivie `83, Dine, Fischler `83
Mayle et al `88, Raffelt and Seckel `88, Turner 88.

If $f_a = \mathcal{O}(10^{16})\,\mathrm{GeV}$, the axion abundance exceeds the DM abundance by $\mathcal{O}(10^5)$.

The axion abundance can be suppressed if

1. Fine-tuning of the initial angle, $\theta_i = \mathcal{O}(10^{-3})$
2. Late-time entropy production.

Dine, Fischler `83, Steinhardt and Turner `83, Lazarides et al `90,
Kawasaki, Moroi, Yanagida `96, Kawasaki, FT, `04

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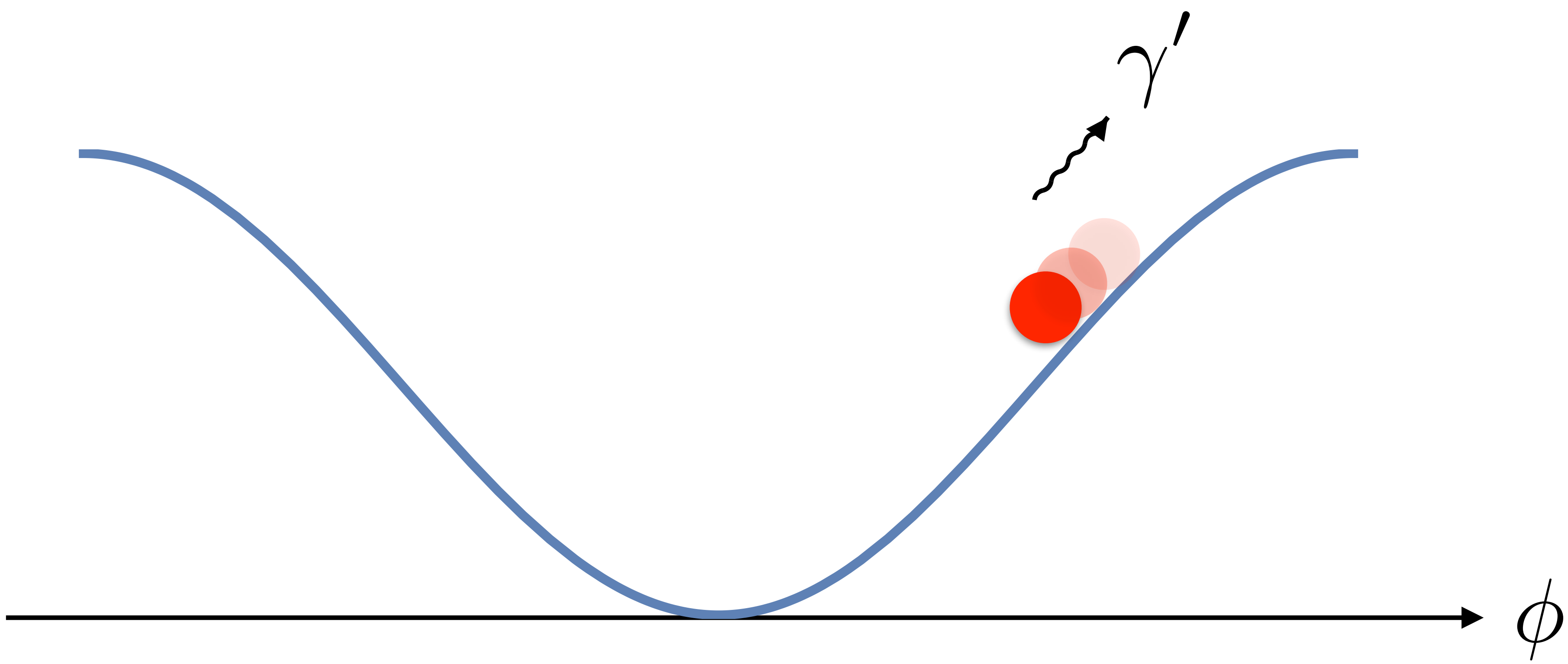
3. Dissipation into hidden photon (?)

Effects on the axion dynamics

However, it may not be that simple.
If the coupling is too large, it may acts as an extra frictional force, which may delay the beginning of the oscillation and enhance the abundance ?



Ω_a ↗ ?

Effects on the axion dynamics

- The abundance of the axion zero mode is reduced (dissipation), or enhanced (friction)?

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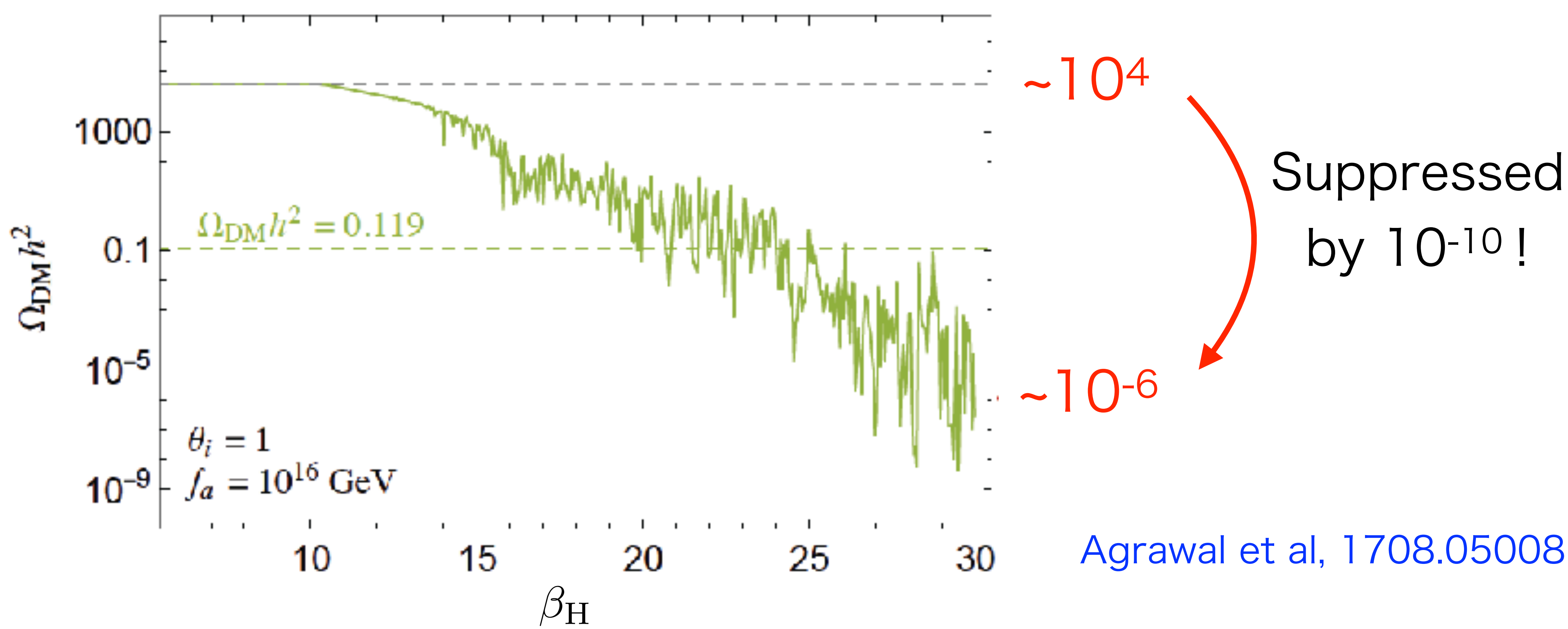
The back reaction on the axion dynamics can be studied by lattice simulations.

A comment on related work

- Agrawal et al studied the effects on the axion abundance in the same set-up, and found a large suppression.

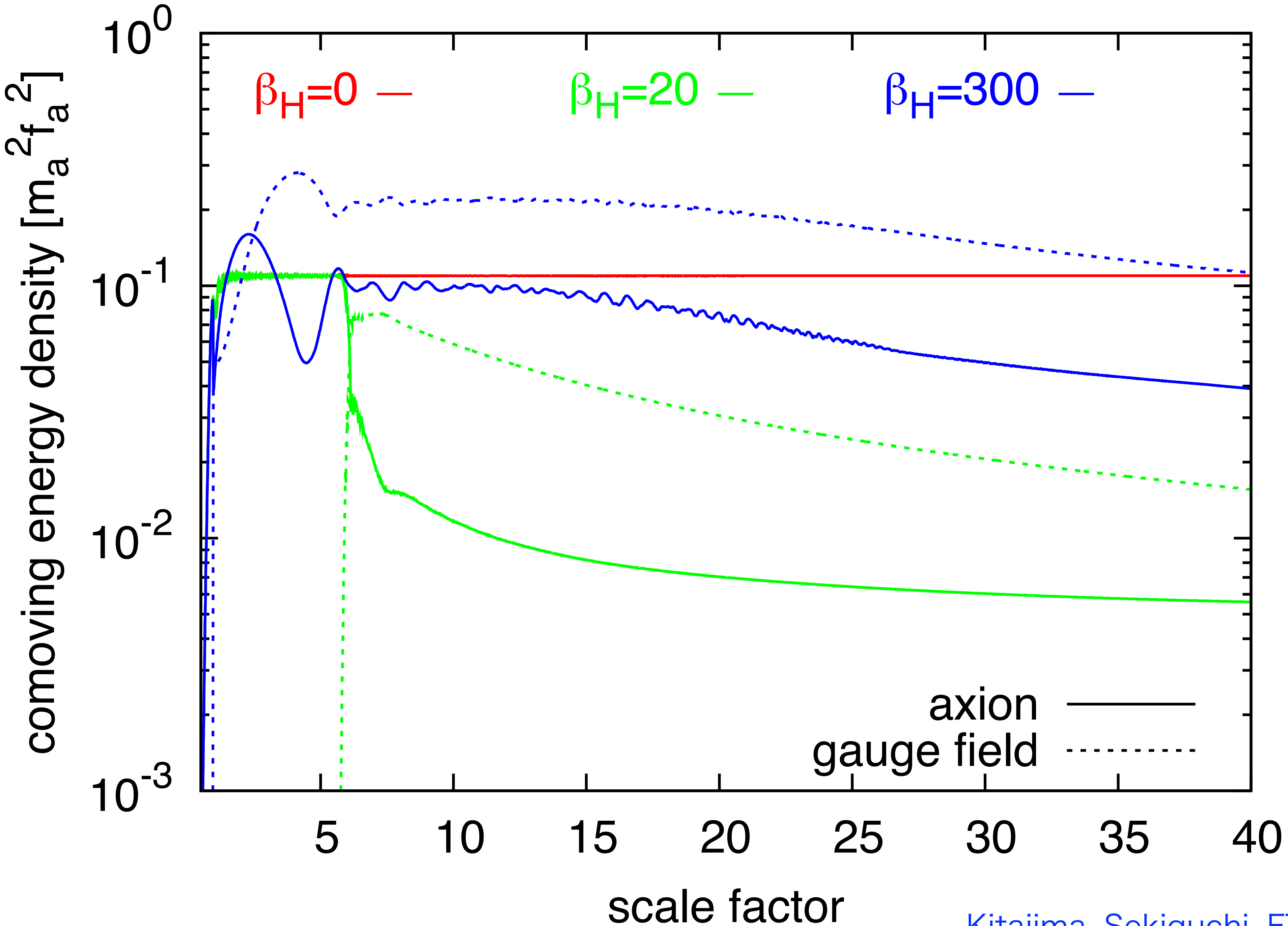


Agrawal et al, 1708.05008

- The upper bound on the decay constant would be relaxed to $f_a \simeq 10^{17}\,{\rm GeV}$, if this is true.
- They presumed that production of the axion nonzero modes is negligible in their analysis.

Numerical results

We performed a simulation of the axion electrodynamics using extended Yee's algorithm, and adopted a periodic comoving box with a grid number $N_{grid} = 256^3$.



Kitajima, Sekiguchi, FT, 1711.06590

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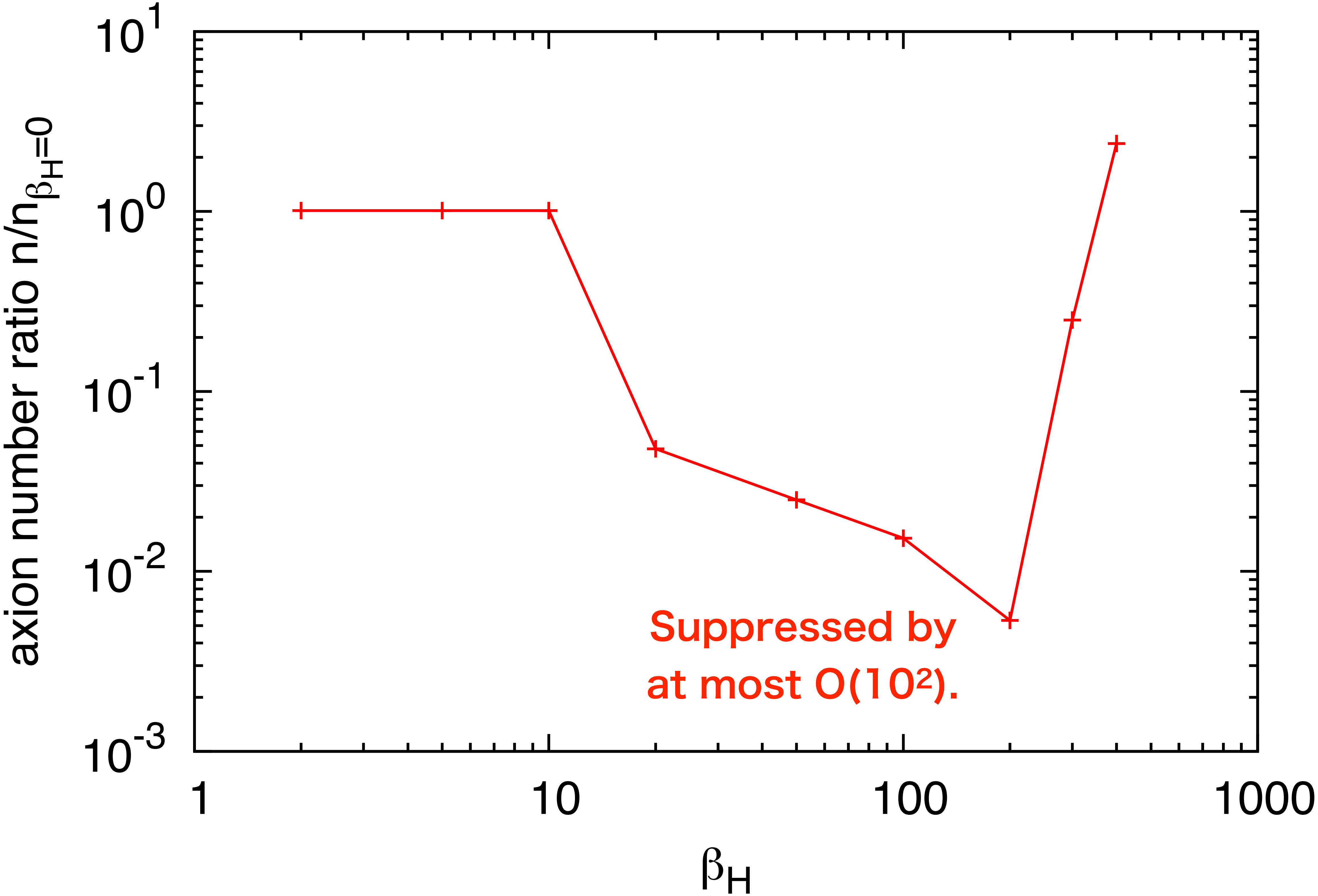

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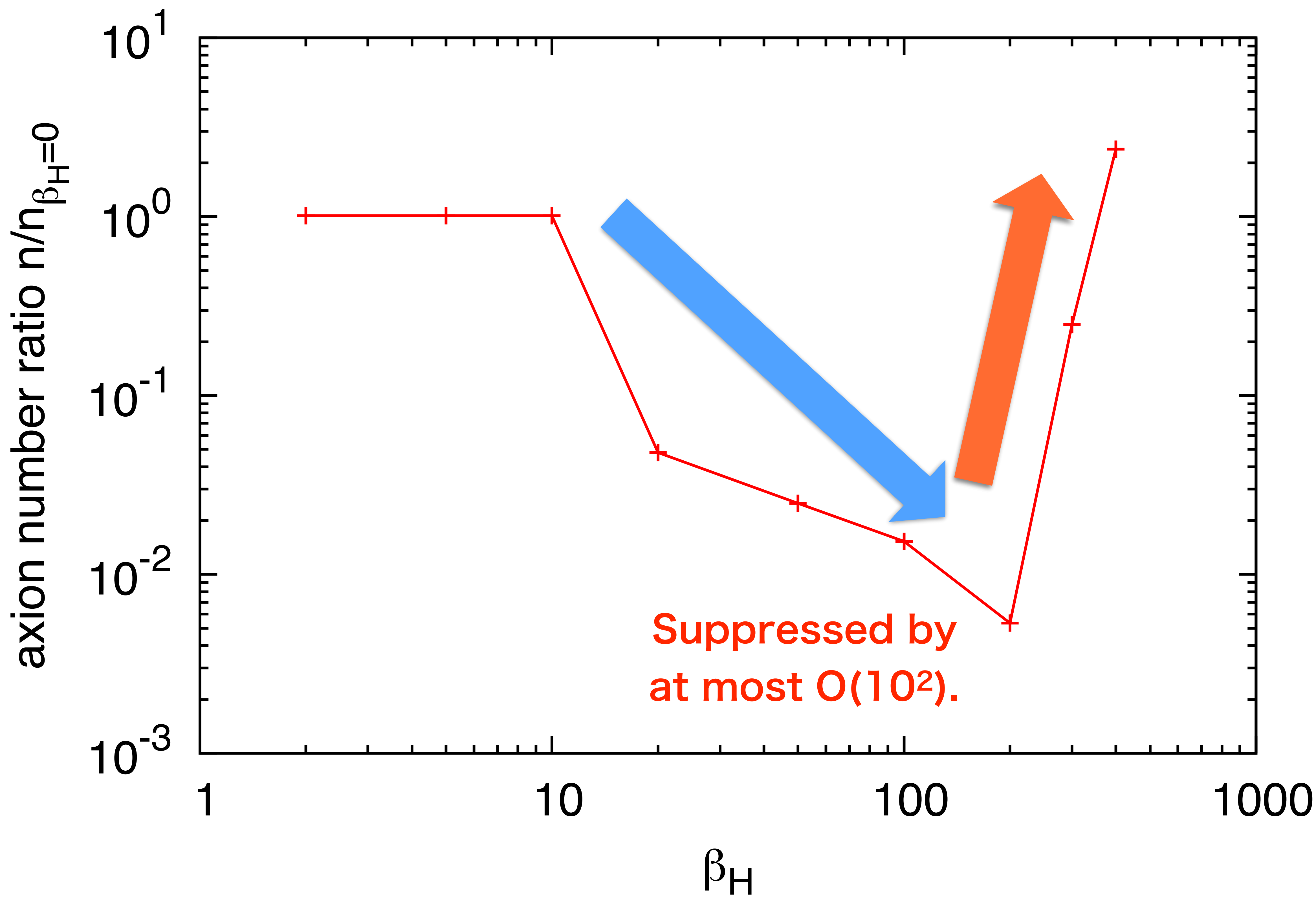

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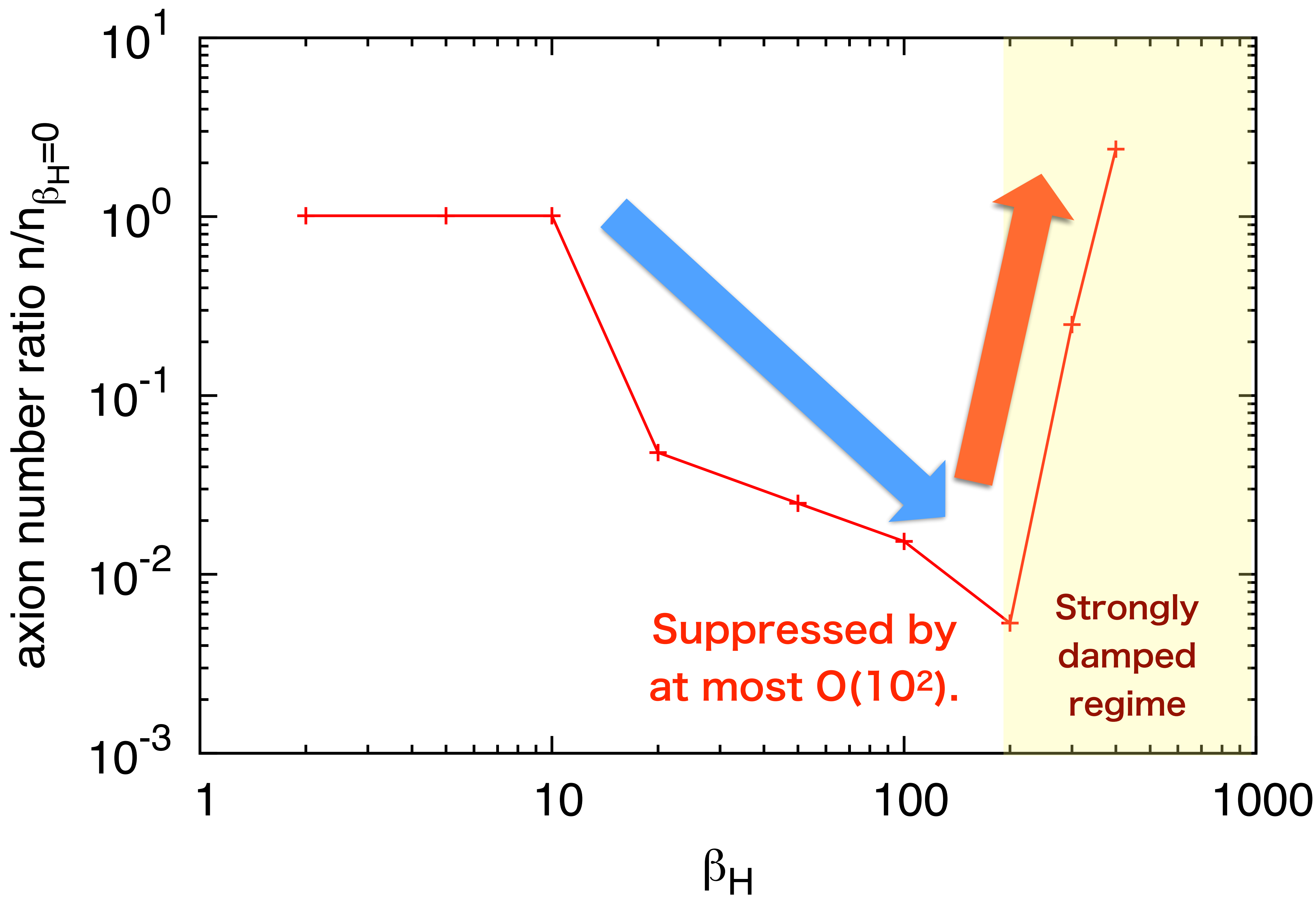

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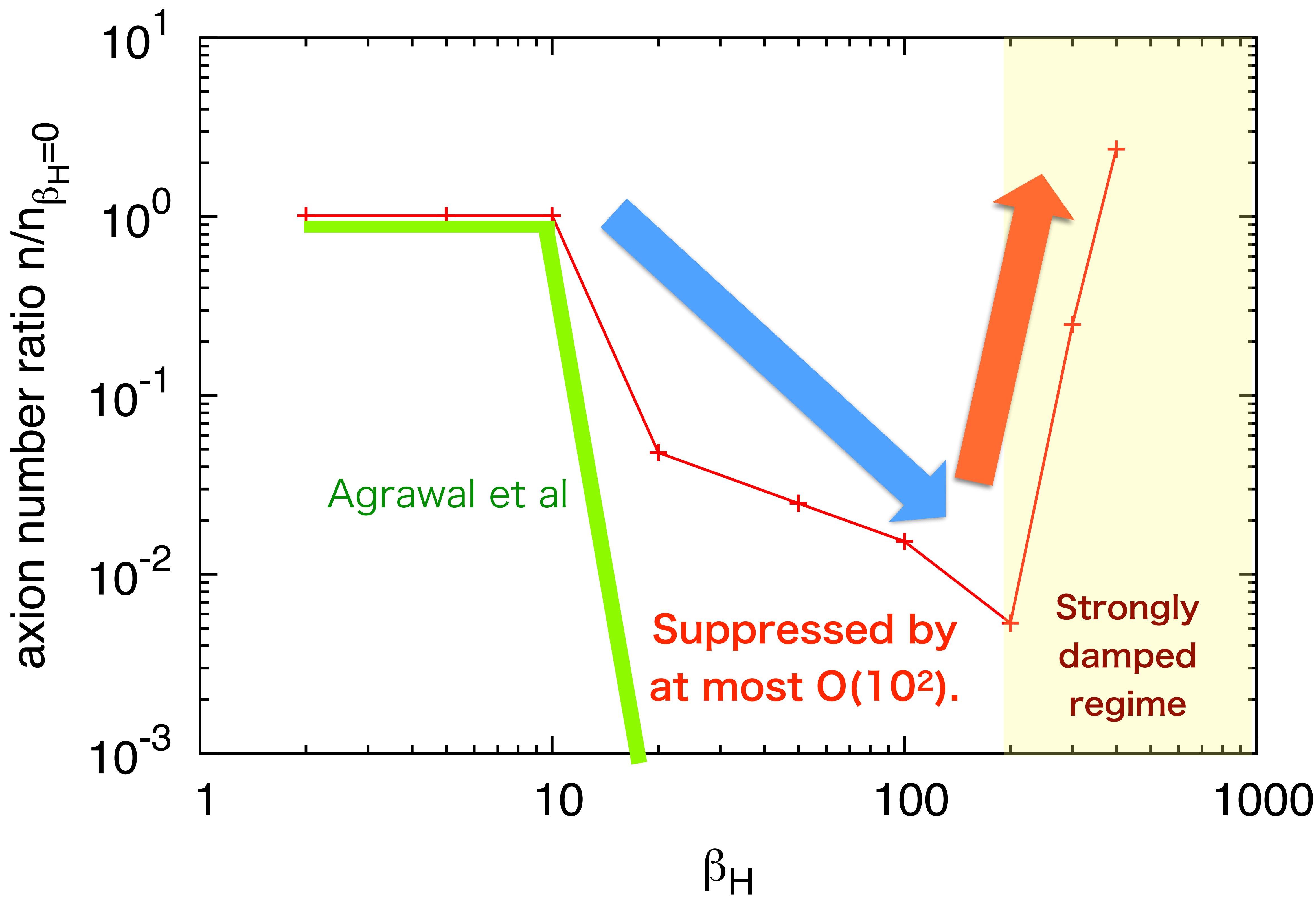


Kitajima, Sekiguchi, FT, 1711.06590

3. Axion coupled to hidden photons and monopoles

Kawasaki, FT, Yamada,1511.05030,1708.06047

Witten effect

Witten `79

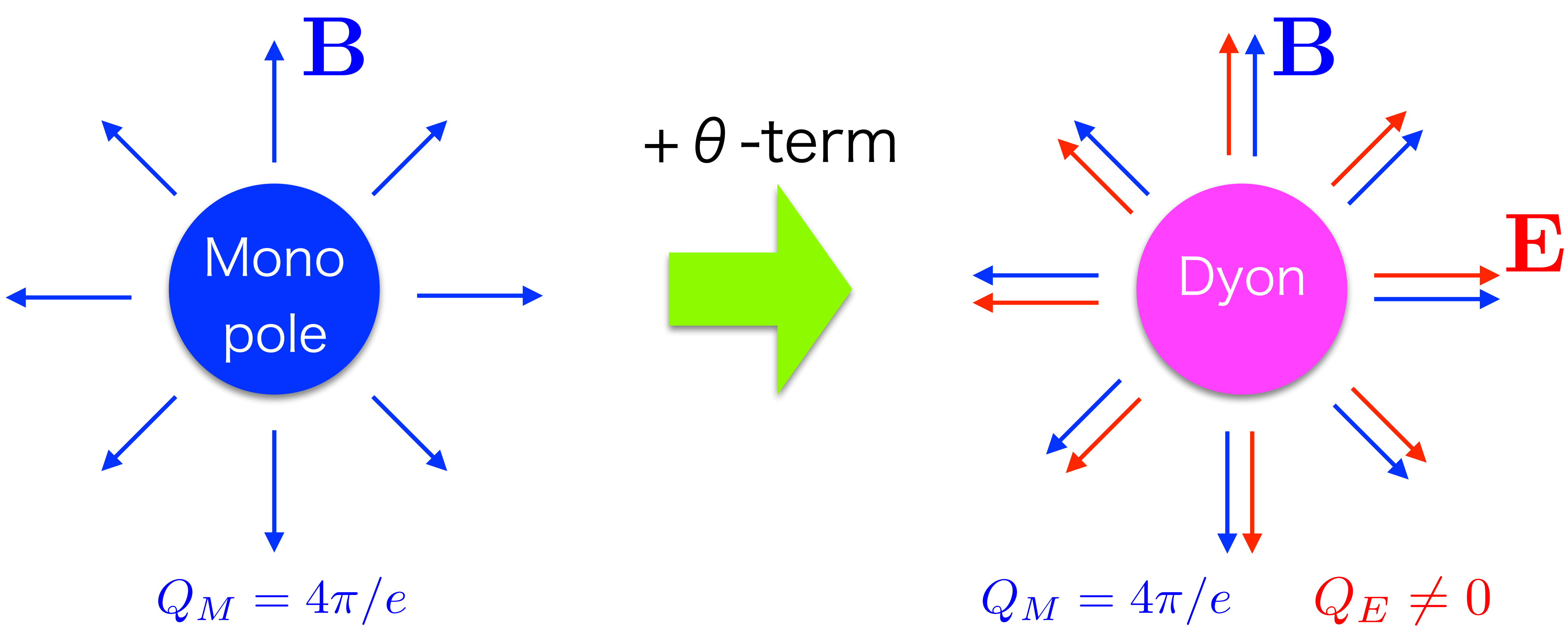
Let us first consider the θ-term of hidden U(1):

This θ is not the strong CP phase.

$$\mathcal{L}_\theta = \frac{\theta e^2}{32\pi^2} F_{\mu\nu}\tilde{F}^{\mu\nu} = -\frac{\theta e^2}{8\pi^2}\mathbf{E}\cdot\mathbf{B}$$

which usually has no effect as it is a total derivative.

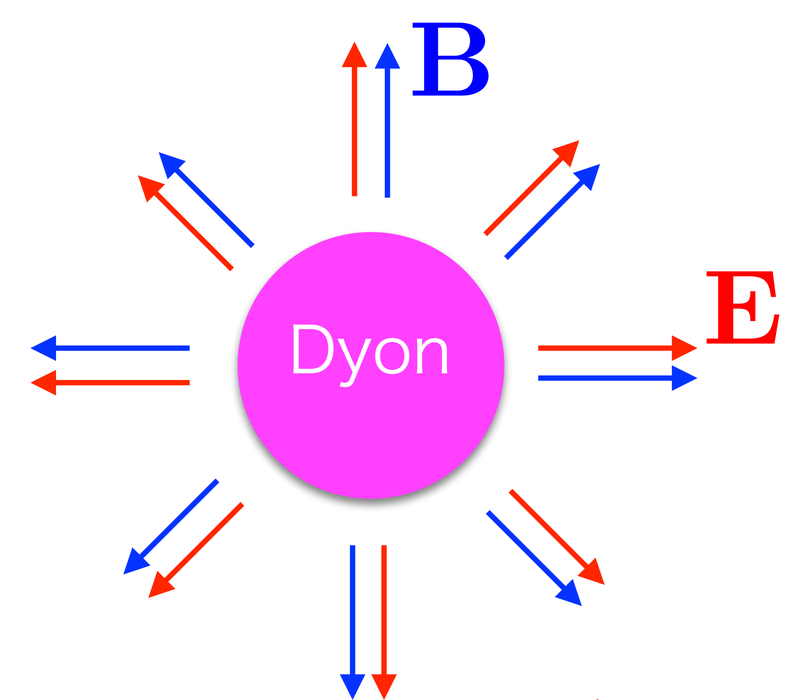
The term, however, has an interesting effect in the **monopole background**.



Witten effect

Witten `79

A monopole acquires an electric charge, and becomes a dyon if $\theta \neq 0$.



$$Q_E = ne + \frac{e\theta}{2\pi} \quad n = 0, \pm 1, \pm 2, \cdots$$

A monopole magnetic charge $Q_M = 4\pi/e$ is used.

The mass of dyons is heavier than the monopole mass:

$$M_D = M_M + \frac{1}{2}\frac{m_W^2}{M_M}\left(n - \frac{\theta}{2\pi}\right)^2$$

$$\simeq v\sqrt{Q_M^2 + Q_E^2}$$

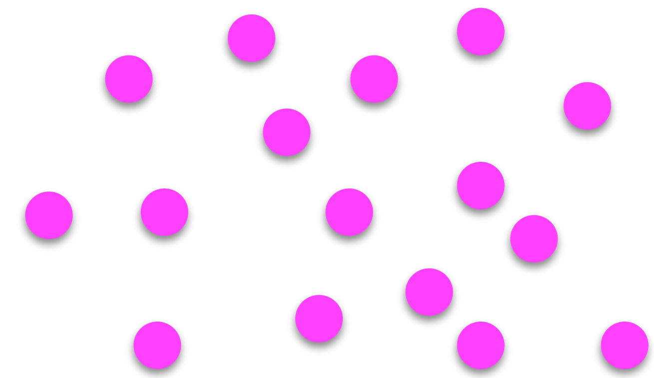
The non-zero value of θ costs more energy as it induces an electric field around the monopole.

Axion coupled to hidden monopoles

Kawasaki, FT, Yamada, 1511.05030

Consider the axion coupling to U(1)H:

$$\mathcal{L}_\theta = \frac{e^2 a}{32\pi^2 f_a} F_{\mu\nu}\tilde{F}^{\mu\nu} = -\frac{e^2 a}{8\pi^2 f_a}\mathbf{E}\cdot\mathbf{B}$$



Then, the QCD axion acquires an extra mass about $a = 0$ by the Witten effect in the presence of hidden monopoles:

$$m_{a,M}^2 \simeq \frac{\alpha}{16\pi^2}\frac{n_M}{r_c f_a^2}$$

cf. Fischler and Preskill, `83

n_M :(anti-)monopole number density

$$\alpha = \frac{e^2}{4\pi}$$

$r_c \simeq \frac{1}{ev} = \frac{1}{m_W}$: monopole radius

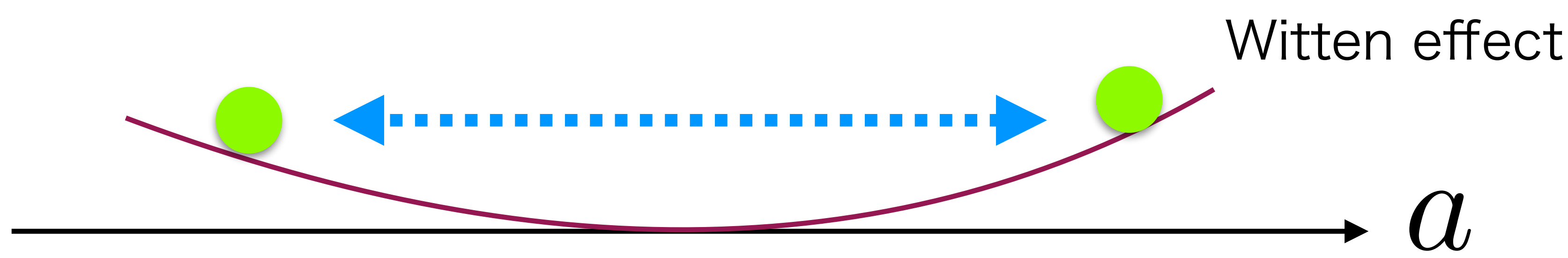
- <u>The extra axion mass naturally decreases as the monopole density is diluted by the cosmic expansion.</u>

Consistent w/ the neutron EDM constraint.

Evolution of axion

- The axion starts to oscillate when $m_{a,M}^2 \simeq H^2$.

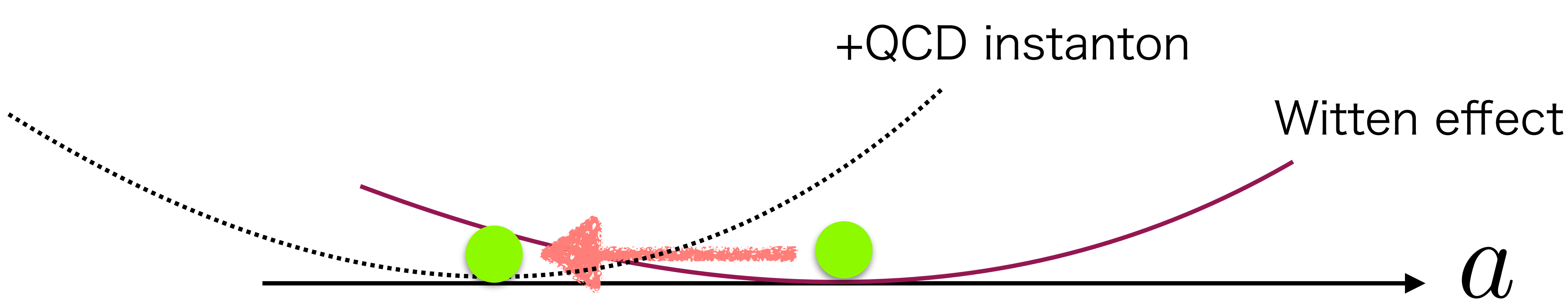
$$T_{\mathrm{osc},1} \simeq 65\,\mathrm{GeV}\,\alpha^2 \left(\frac{\Omega_M h^2}{0.12}\right)\left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^{-2}.$$



- No extra axion coherent oscillations are induced during the QCD phase transition if $m_{a,M}/H \gtrsim \mathcal{O}(10)$.

$$f_a \lesssim 10^{12}\,\mathrm{GeV}\,\alpha^{1.1}\left(\frac{\Omega_M h^2}{0.12}\right)^{0.55}.$$

"Adiabatic suppression mechanism"
Linde `96.



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Axion abundance

Kawasaki, FT, Yamada, 1511.05030

The final axion abundance is given by

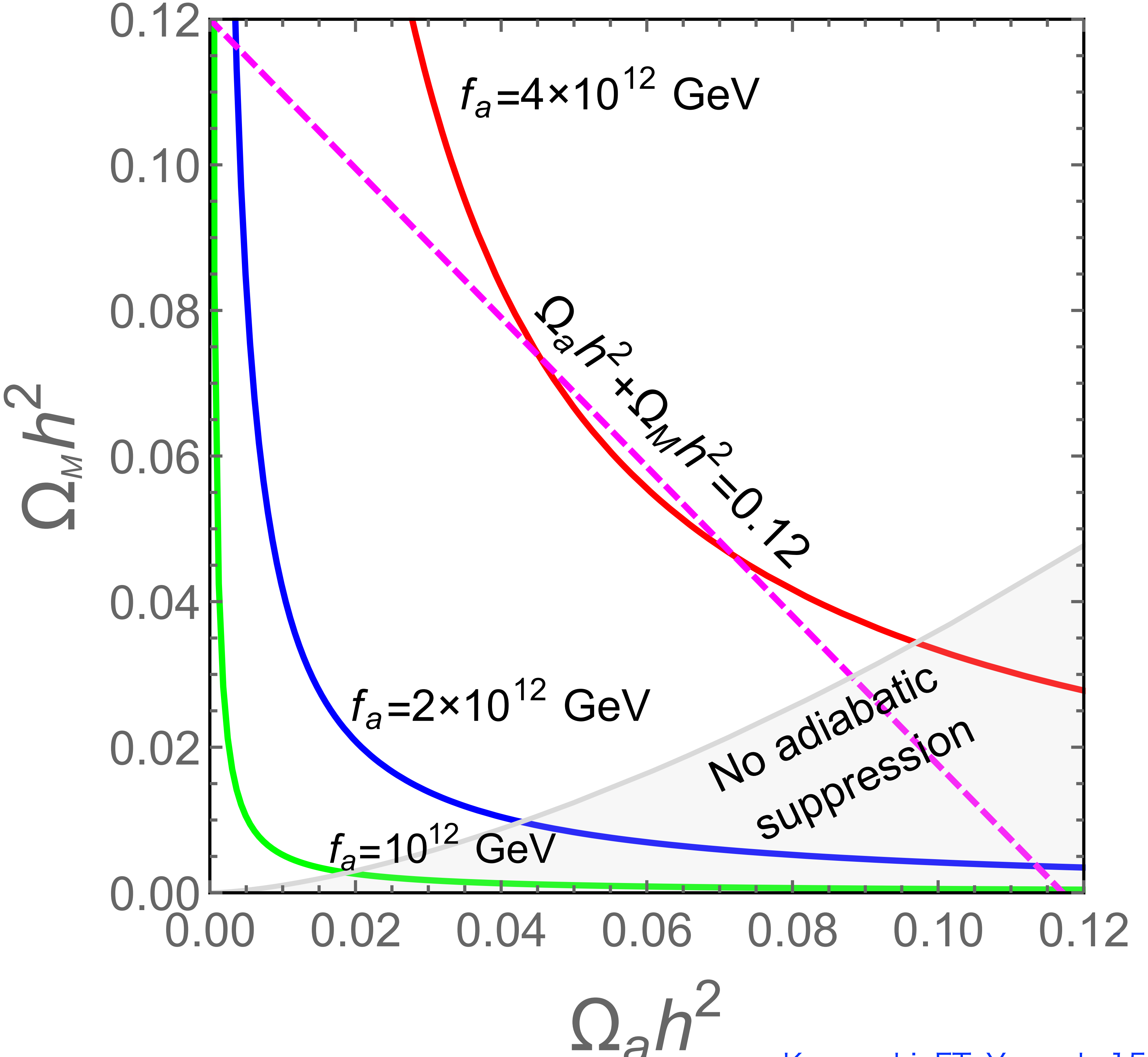
$$\Omega_a h^2 \simeq 3 \times 10^{-4} \alpha^{-2} \theta_i^2 \left(\frac{0.12}{\Omega_M h^2} \right) \left(\frac{f_a}{10^{12}\,\mathrm{GeV}} \right)^3$$

The axion abundance is suppressed, and it is inversely proportional to the monopole abundance!

The Witten effect also solves the axion domain wall problem when the PQ symmetry spontaneously broken after inflation.

See talk by Kawasaki

QCD axion and monopole DM



Kawasaki, FT, Yamada,1511.05030,1708.06047

Hidden monopole DM

The monopoles with mass $M_M = (1-10)\,\mathrm{PeV}$ account for the observed DM.

Murayama, Shu 0905.1720

In the minimal case of the 't Hooft-Polyakov monopole w/o other charged particles, the massive gauge bosons give a larger contribution.

Baek, Ko, Park 1311.1035, Khoze, Ro 1406.2291

e.g. The observed DM is realized with $v \simeq 10^2\,\mathrm{TeV}, \alpha = \mathcal{O}(0.1)$

for which the monopole fraction is O(10)%.

N.B. The massive gauge boson abundance can be reduced by adding matter fields.

Summary

✓We have studied the cosmological evolution of the axion coupled to hidden photons.

✓The axion density can be suppressed by O(10^2) by tachyonic resonance.

- The fine-tuning of the misalignment angle can be relaxed from O(10^{-3}) to O(0.1) for $f_a = 10^{16}\,\mathrm{GeV}$.
- The axion abundance enhanced for sufficiently large coupling.

✓In the presence of hidden monoples, the Witten effect suppresses the QCD axion abundance.

- Hidden monopoles become self-interacting DM.