Axion Detection Experiments Meet the Majoron

—— Presentation for Workshop on Cosmic Indicators of Dark Matter 2024

2406.19083, 2408.12146 Q.Liang, R.Okabe, X-P. Diaz, T.Yanagida

Qiuyue Liang 梁秋月

Kavli IPMU (WPI), University of Tokyo

10/17/2024

KAVLI IPMU

THE UNIVERSITY OF TOKYO

Content

- Introduction of axion physics include the experiment constraints
- Majoron as a dark matter candidate that can be detected through axion experiments
- Three-zero texture quark mass matrix to solve strong CP problem
- Discussion

Introduction to strong CP and axion

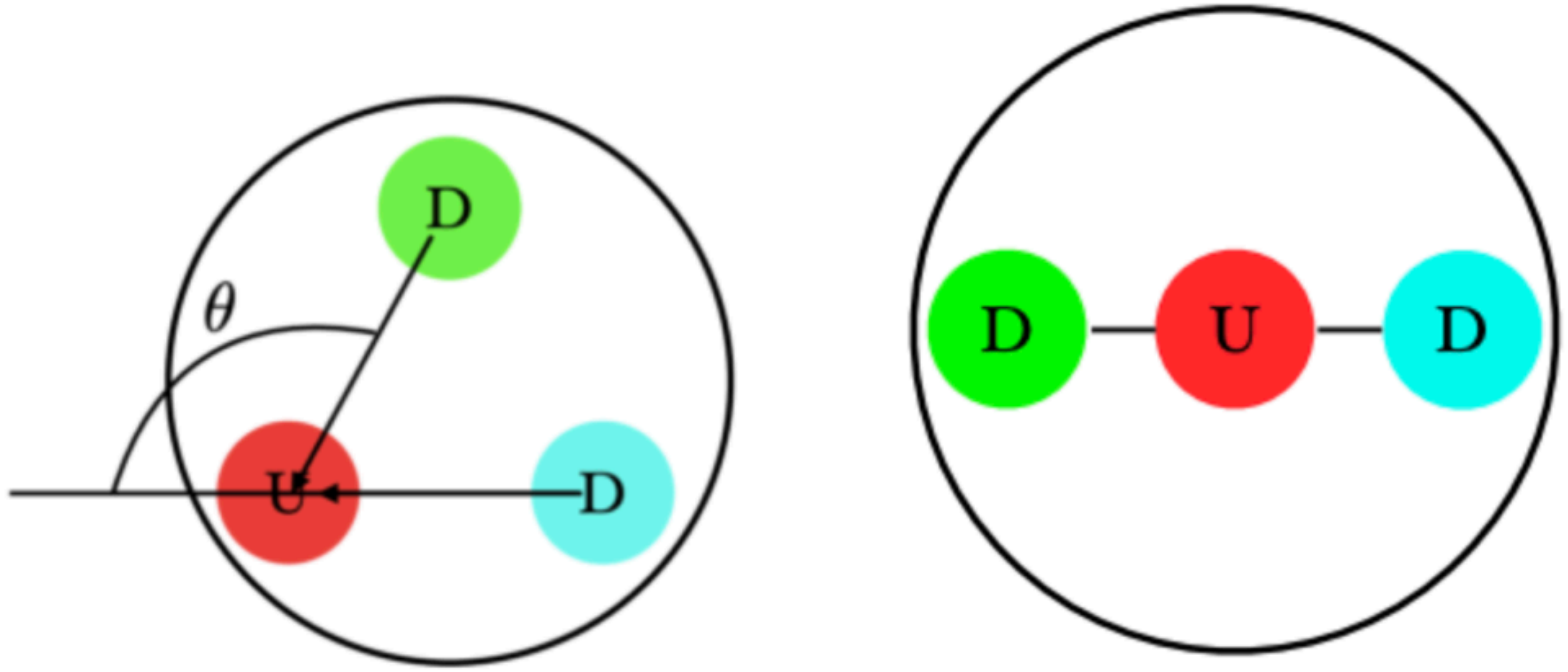
- Strong CP problem in SM

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \theta\frac{g^2}{32\pi^2}F_{\mu\nu}\tilde{F}^{\mu\nu} + \bar{\psi}(i\gamma^\mu D_\mu - me^{i\theta'\gamma_5})\psi.$$

- The theory is CP invariant only when $\theta = -\theta'$.
- Physical CP violating angle: $\bar{\theta} = \theta_0 + \mathrm{Arg}[\det(M_d)\det(M_u)]$ Mu and Md are up/down quark mass matrix.
- Neutron electric dipole moment is proportional to physical CP violating angle $d_N = (5.2 \times 10^{-16}\mathrm{e}\cdot\mathrm{cm})\bar{\theta}.$
- Experiments put a tight constraint on $\bar{\theta} < 10^{-10}$

Introduction to strong CP and axion

- QCD axion is the solution that the angle θ is dynamical and can change, and its expectation value is zero. The effective potential in Peccei-Quinn theory is $V_{\text{eff}} \sim \cos\left(\theta + \xi \frac{\langle a \rangle}{f_a}\right)$
-

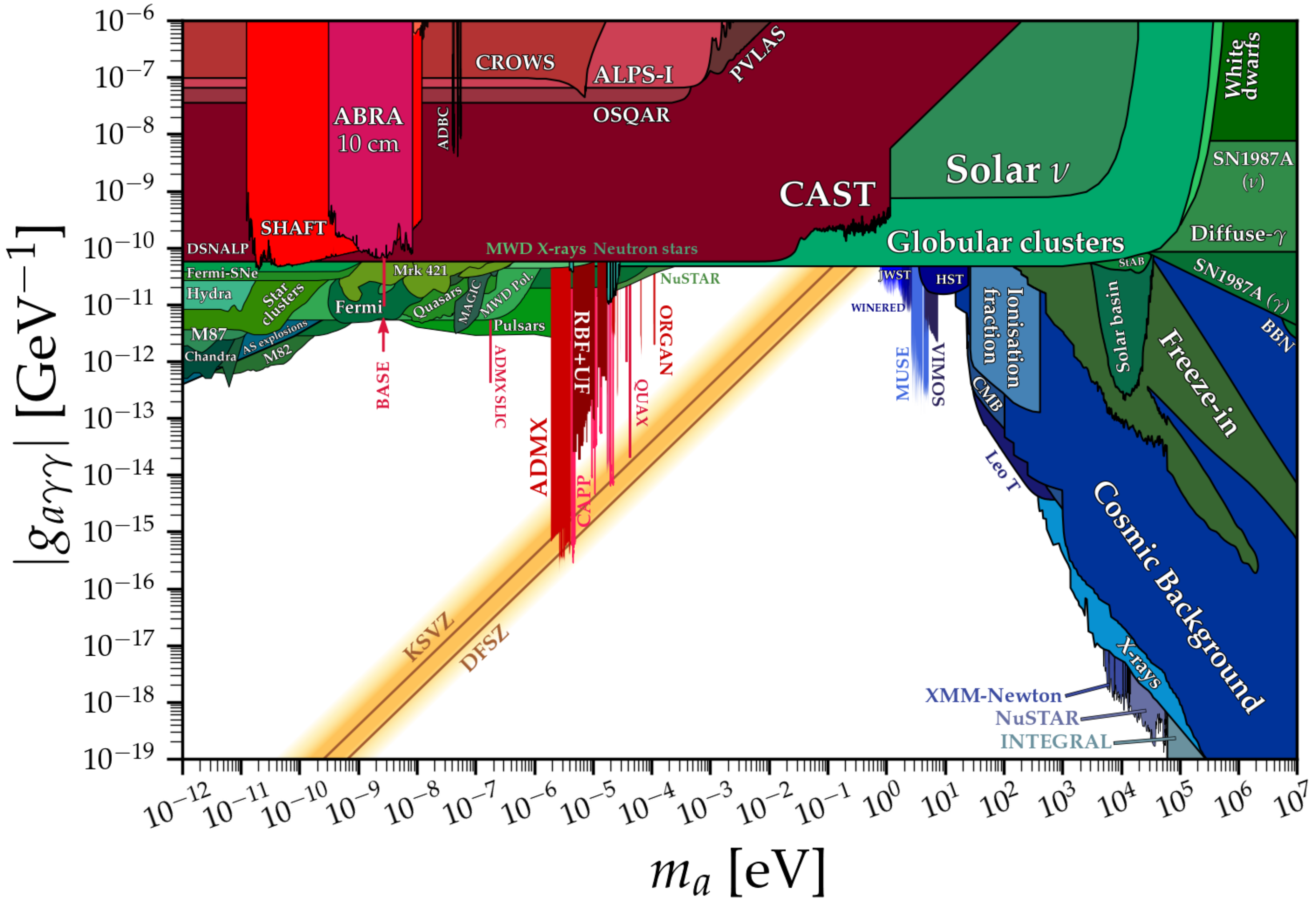


1812.02669.

Qiuyue Liang, K IPMU

Introduction to strong CP and axion

- QCD axion: prompt the theta angle to a field whose vacuum expectation value is zero. The effective potential in Peccei-Quinn theory is $V_{\text{eff}} \sim \cos\left(\theta + \xi \frac{\langle a \rangle}{f_a}\right)$
- QCD axion is also a popular dark matter candidate. Constraints through their anomalous coupling to electromagnetic :
- Can arise from string theory. hep-th/0605206.



https://cajohare.github.io/AxionLimits/docs/ap.html

Qiuyue Liang, K IPMU

Axion

- However, axion has not been identified by experiments.
- Moreover, it has been claimed that axion generally has the quality problem. (Quantum correction will generally lead to a non-zero vev)
- 1. From Effective filed theory point of view, without symmetry, axion should not have the desired coupling: $\mathcal{L} \supset \left(\frac{a}{f_a} + \theta\right) \frac{1}{32\pi^2} G\tilde{G}.$
- 2. Quantum gravity should break all symmetries that are not gauged. Gravitational effects will induce additional mass terms that are not centered at zero.
- This also seems incompatible with cosmology:

2301.00549 [hep-th]
2312.07650 [hep-ph].
Phys. Rev. D 32 (1985) 3178.

- We need alternatives to axion that can be dark matter candidate (2406.19083, Q.Liang, X.P.Diaz, T.Yanagida) and solve strong CP problem (2408.12146, Q.Liang, R.Okabe, T.Yanagida)!

Majoron as DM candidate

- Majorons are pseudo-goldstone boson of U(1)L symmetry breaking, aiming to give heavy Majorana mass to right handed neutrino, which is essential for seesaw mechanism and leptogenesis.

Standard model neutrino

$\sum m_\nu \lesssim 0.1\text{eV}$

Heavy right-handed neutrino

$M_N \approx 10^{14}\text{GeV}$

Majoron as DM candidate

- Majorons are pseudo-goldstone boson of U(1)L symmetry breaking, aiming to give heavy Majorana mass to right handed neutrino, which is essential for seesaw mechanism and leptogenesis.

Standard model neutrino

$\sum m_\nu \lesssim 0.1\mathrm{eV}$

Neutrino decay generate lepton. Since B-L is conserved, baryon is generated

Heavy right-handed neutrino

$M_N \approx 10^{14}\mathrm{GeV}$

Majoron as DM candidate

- Majorons are pseudo-goldstone boson of U(1)L symmetry breaking, aiming to give heavy Majorana mass to right handed neutrino, which is essential for seesaw mechanism and leptogenesis.
- $\mathcal{L} \supset \bar{\ell}_L Y_e e_R H + \bar{\ell}_L Y_D N_R \widetilde{H} + \frac{1}{2} \bar{N}_R^c Y_N N_R \phi^*$ U(1)L number: $\mathcal{X}_N = +1/2$ $\mathcal{X}_e = 1/2$ $\mathcal{X}_\phi = 1$ $\mathcal{X}_\ell = 1/2$
- Usually the interest focus on the MeV region, and direct detections are related to neutrino experiments.
- How about lighter mass region?

Majoron as DM candidate

$$\mathcal{L} \supset \bar{\ell}_L Y_e e_R H + \bar{\ell}_L Y_D N_R \widetilde{H} + \frac{1}{2}\bar{N}_R^c Y_N N_R \phi^*$$

U(1)L number: $\mathcal{X}_N = +1/2 \quad \mathcal{X}_e = 1/2$

$\mathcal{X}_\phi = 1 \quad \mathcal{X}_\ell = 1/2$

- Since right-handed electron and left handed lepton have the same lepton number, the coupling is anomaly free in electromagnetic sector.
- Introduce the second Higgs, we can introduce an anomalous coupling in EM: $\mathcal{L} = \bar{\ell}_L Y_e e_R H_2 + \bar{\ell}_L Y_D N_R \widetilde{H}_1 + \frac{1}{2}\bar{N}_R^c Y_N N_R \phi^* + \mu_\phi H_2^\dagger H_1 \phi + V(H_1,\, H_2,\, \phi) + \text{h.c.}$ where two Higgs carry different charges: $\mathcal{X}_2 - \mathcal{X}_1 = \mathcal{X}_\phi = 1.$
- We are able to assign different lepton number to right-handed electron and left handed lepton $\mathcal{X}_e = -1/2, \quad \mathcal{X}_\ell = 1/2.$

Majoron as DM candidate

- This gives the anomaly coupling as

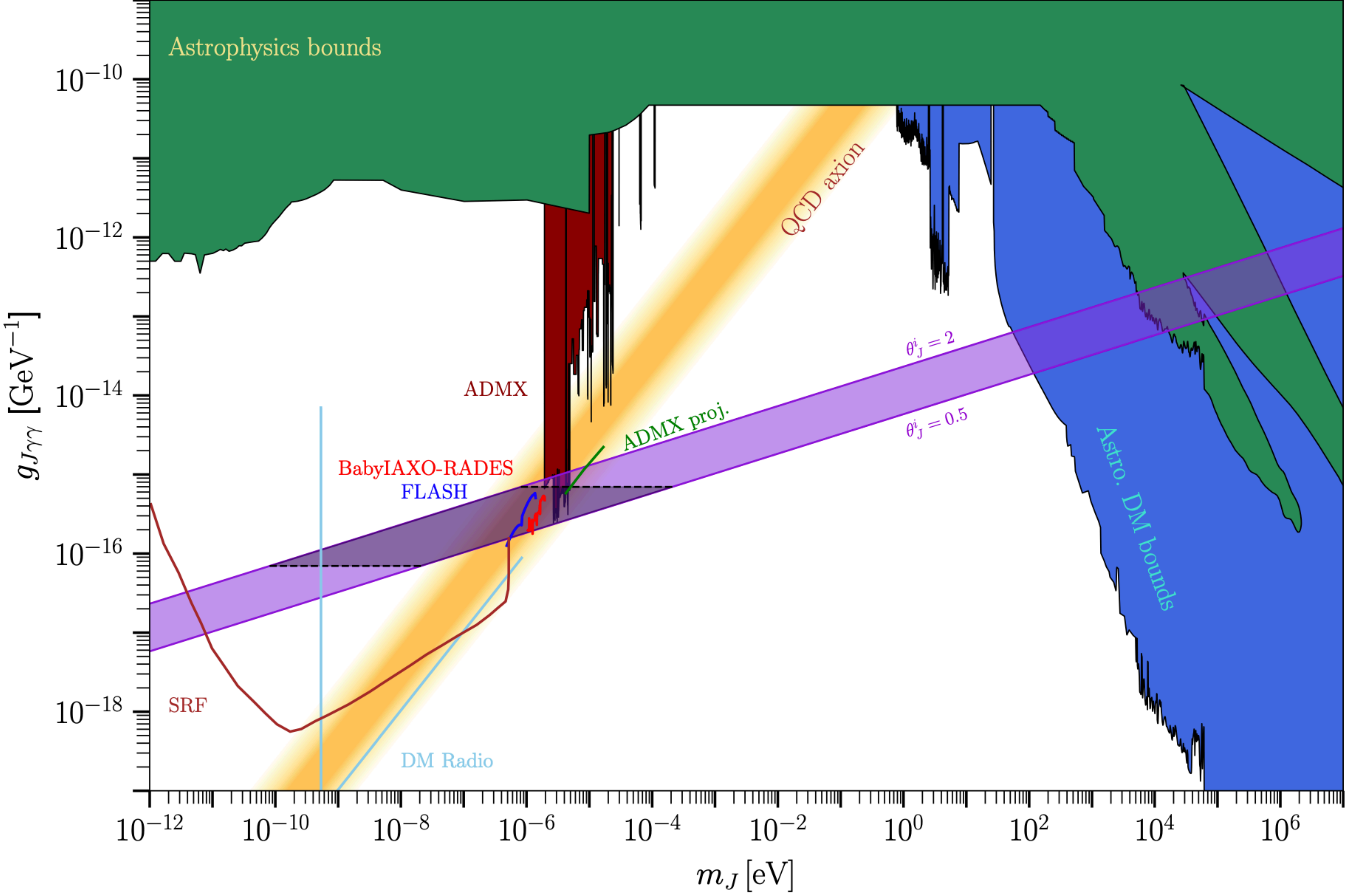
$$\mathcal{L}_{\text{anom.}} = 3\frac{\alpha_{\text{em}}}{4\pi}\frac{J}{F_J}F_{\mu\nu}\widetilde{F}^{\mu\nu} = \frac{g_{J\gamma\gamma}}{4}JF_{\mu\nu}\widetilde{F}^{\mu\nu}$$

- We ``prompt'' majoron to an axion-like-particle candidate that can be produced through misalignment mechanism, which relates the DM abundance with mass, decay constant and initial angle of majoron:

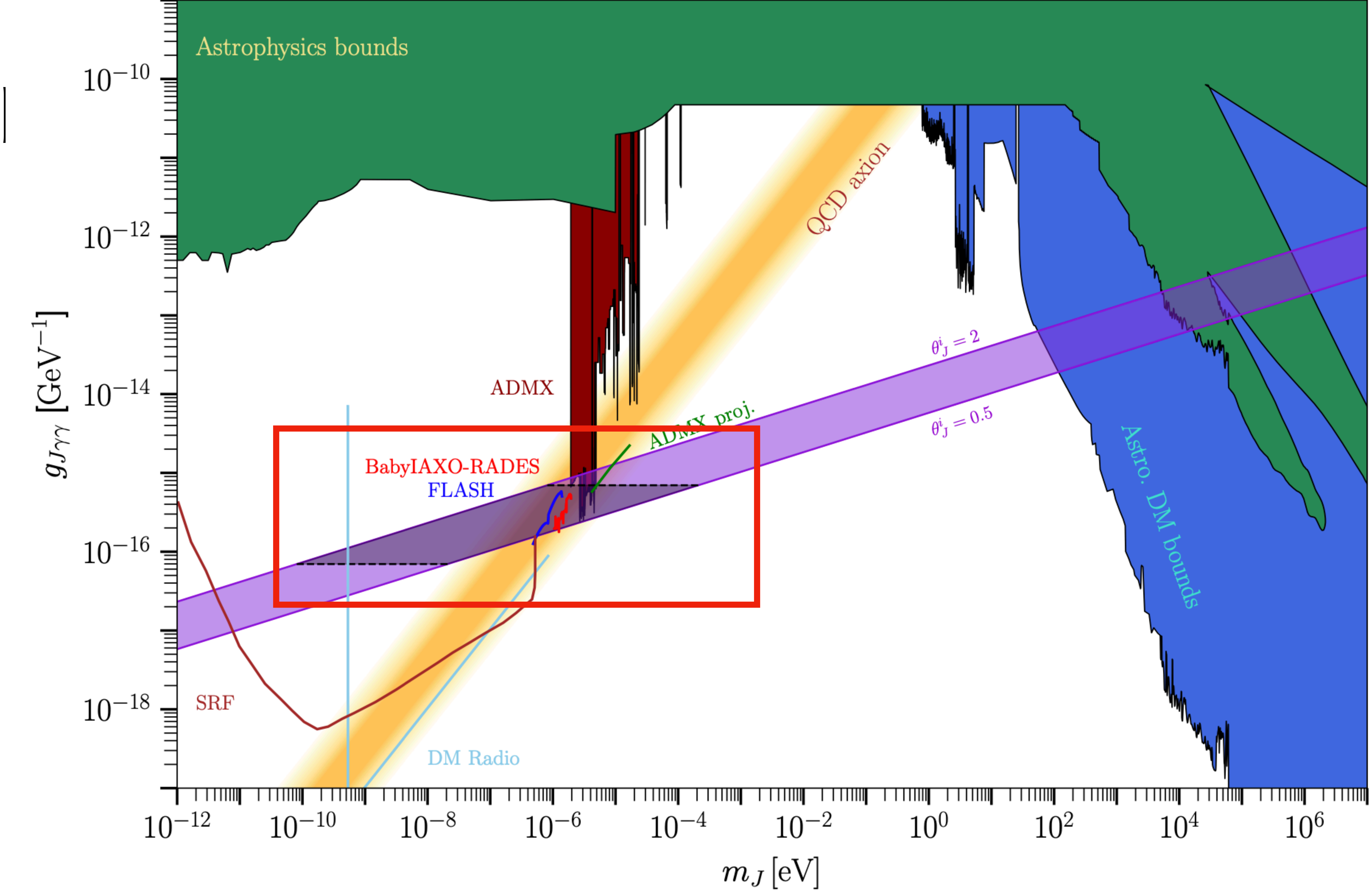
$$\Omega_J h^2 \simeq 0.12\left(\frac{m_J}{\mu\text{eV}}\right)^{1/2}\left(\frac{F_J\theta_J^i}{1.9\times 10^{13}\,\text{GeV}}\right)^2$$

- We further obtain the relation between mass and anomalous coupling

$$m_J \simeq \left(\frac{\pi}{3\alpha_{\text{em}}\theta_J^i}\frac{g_{J\gamma\gamma}}{1.9\times 10^{-13}\text{GeV}}\right)^4 \mu\text{eV}$$



Astrophysics bounds
QCD axion
ADMX
ADMX proj.
BabyIAXO-RADES
FLASH
SRF
DM Radio
Astro. DM bounds
$\theta_J^i = 2$
$\theta_J^i = 0.5$
$g_{J\gamma\gamma}$ [GeV^{-1}]
m_J [eV]
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-12} 10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 10^{0} 10^{2} 10^{4} 10^{6}



https://arxiv.org/pdf/2406.19083

What about the strong CP problem?

What about the strong CP problem?

- 2408.12146, Q.Liang, R.Okabe, T.Yanagida

Alternatives to strong CP problem

- Turn back to the original question about the strong CP.

$$\bar{\theta} = \theta_0 + \mathrm{Arg}[\det(M_d)\det(M_u)] \qquad \bar{\theta} < 10^{-10}$$

- Spontaneous CP violation as an alternative: $\theta_0 = 0$

- For this type of solutions, one need to have real mass matrix determinant: $\mathrm{Arg}[\det(M_d)\det(M_u)] = 0$

- This is not easy to construct since quark mass matrix contains complex phases.

Three-zero texture of quark mass matrix

- It has been proposed that 7 three-zero textures of quark mass matrix can fit data well. One such example of the down quark mass matrix is

$$M_d = \begin{pmatrix} 0 & a & 0 \\ a' & be^{-i\phi} & c \\ 0 & c' & d \end{pmatrix}$$

a [MeV]	a' [MeV]	b [MeV]	c [MeV]	c' [GeV]	d [GeV]	ϕ [$\circ$]
16 - 17.5	10 - 15	92 - 104	78 - 95	1.65 - 2.0	2.0 - 2.3	37 - 48

- M. Tanimoto and T. T. Yanagida, "Occam's Razor in Quark Mass Matrices," PTEP 2016 no. 4, (2016) 043B03, arXiv:1601.04459 [hep-ph].

Three-zero texture of quark mass matrix

- It has been proposed that 7 three-zero textures of quark mass matrix can fit data well. One such example of the down quark mass matrix is

$$M_d = \begin{pmatrix} 0 & \boxed{a} & 0 \\ \boxed{a'} & be^{-i\phi} & c \\ 0 & c' & \boxed{d} \end{pmatrix}$$

a [MeV]	a' [MeV]	b [MeV]	c [MeV]	c' [GeV]	d [GeV]	ϕ [∘]
16 - 17.5	10 - 15	92 - 104	78 - 95	1.65 - 2.0	2.0 - 2.3	37 - 48

- M. Tanimoto and T. T. Yanagida, "Occam's Razor in Quark Mass Matrices," PTEP 2016 no. 4, (2016) 043B03, arXiv:1601.04459 [hep-ph].

- More interestingly, the determinant of this matrix is real even it contains complex elements!

- This looks like a good way to solve strong CP. But why these elements have to be exact zero? Is there any symmetry protecting them?

Three-zero texture of quark mass matrix for strong CP

- We first want to show that 4D ordinary symmetry does not work
-

$\mathbf{10}_1 H \bar{\mathbf{5}}_2$ Neutral

$$M_d = \begin{pmatrix} 0 & a & 0 \\ a' & be^{-i\phi} & c \\ 0 & c' & d \end{pmatrix}$$

$\mathbf{10}_2 H \bar{\mathbf{5}}_1$ Neutral

$$\mathbf{10}_i = (q_L, \bar{u}_R)_i$$

$$\bar{\mathbf{5}}_i = (\bar{d}_R)_i$$

Three-zero texture of quark mass matrix for strong CP

- We first want to show that 4D ordinary symmetry does not work
-

$\mathbf{10}_1 H \bar{\mathbf{5}}_2$ Neutral

$$M_d = \begin{pmatrix} 0 & a & 0 \\ a' & be^{-i\phi} & c \\ 0 & c' & d \end{pmatrix}$$

Md11 should have opposite charge of Md 22, no reason to be zero!

$\mathbf{10}_2 H \bar{\mathbf{5}}_1$ Neutral

$\mathbf{10}_2 H \bar{\mathbf{5}}_2 \eta_{1,2}$

$$\mathbf{10}_i = (q_L, \bar{u}_R)_i$$
$$\bar{\mathbf{5}}_i = (\bar{d}_R)_i$$

Three-zero texture of quark mass matrix for strong CP

- We first want to show that 4D ordinary symmetry does not work
-

$\mathbf{10}_1 H \bar{\mathbf{5}}_2$ Neutral

$$M_d = \begin{pmatrix} 0 & a & 0 \\ a' & be^{-i\phi} & c \\ 0 & c' & d \end{pmatrix}$$

Md11 should have opposite charge of Md 22, no reason to be zero!

$\mathbf{10}_2 H \bar{\mathbf{5}}_1$ Neutral

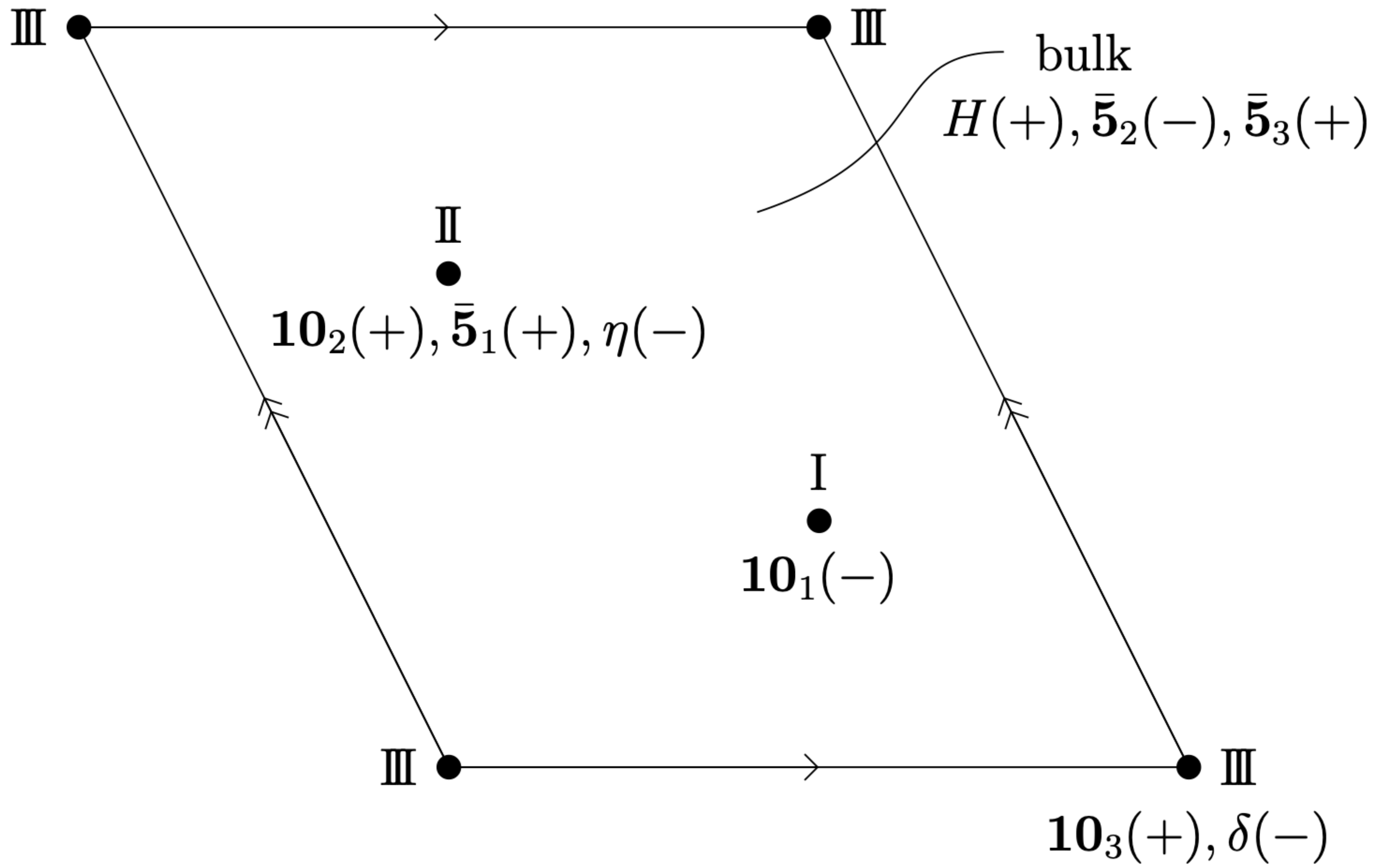
$\mathbf{10}_2 H \bar{\mathbf{5}}_2 \eta_{1,2}$

$$\mathbf{10}_i = (q_L, \bar{u}_R)_i$$
$$\bar{\mathbf{5}}_i = (\bar{d}_R)_i$$

- Maybe generalized symmetry?

Three-zero texture of quark mass matrix for strong CP

- We go to higher dimension $\mathbf{T}^2/\mathbb{Z}_3$ orbifold with fixed points.



	$\mathbf{10}_1$	$\mathbf{10}_2$	$\mathbf{10}_3$	$\bar{\mathbf{5}}_1$	$\bar{\mathbf{5}}_2$	$\bar{\mathbf{5}}_3$	H	η	δ
$\mathbb{Z}_2$	$-$	$+$	$+$	$+$	$-$	$+$	$+$	$-$	$-$

TABLE II. $\mathbb{Z}_2$ charge for each particle.

- Loop corrections are also manageable!

Conclusion and Discussion

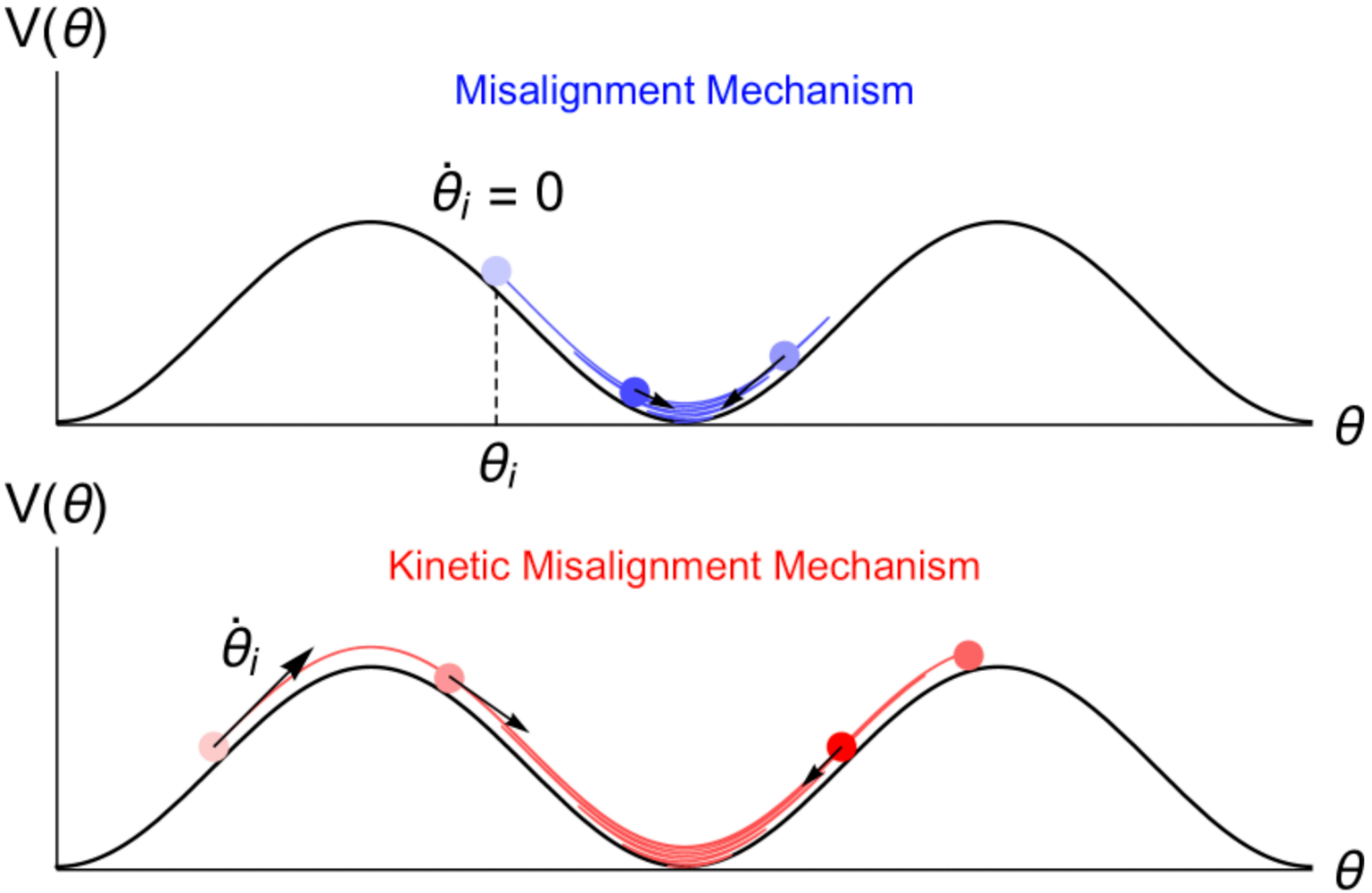
- It is worth thinking about the alternative theories to axion.
- Majoron as a DM candidate that gives the correct neutrino mass through seesaw mechanism, leptogenesis, and DM.
- We can use the three-zero texture of the quark matrix to solve strong CP problem
- To explain the origin of the three- zero texture, we study the higher dimension compactification orbifold.

Qiuyue Liang, K IPMU

Thanks for your attention!

Misalignment mechanism

•



1910.14152