Axion-Gauge Coupling Quantization in Standard Model

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Reference

- [Yichul Choi, Matthew Forslund, HTL, Shu-Heng Shao] arXiv: 2309.03937

- See also
- [Matthew Reece] arXiv: 2309.03939
- [Prateek Agrawal, Arthur Plastschorre] arXiv: 2309.03934
- [Clay Cordova, Sungwoo Hong, Lian-Tao Wang] arXiv: 2309.05636

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- Theoretically, they are found ubiquitously in string theory.

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- A single axion field coupled to the Standard Model (SM) gauge fields

$$(F_3, F_2, F_1) \in su(3) \times su(2) \times u(1)_Y$$

$$\mathscr{L} \supset \frac{1}{2} f^2 (\partial_\mu \theta)^2 + \frac{K_3}{8\pi^2} \theta \, \mathrm{Tr}\, F_3 \wedge F_3 + \frac{K_2}{8\pi^2} \theta \, \mathrm{Tr}\, F_2 \wedge F_2 + \frac{K_1}{8\pi^2} \theta \, F_1 \wedge F_1$$

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- Naively, the axion coupling to the SM should be quantized similarly as $K_i \in \mathbb{Z}$.

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- But the $\mathbb{Z}_6$ center generated by

$$e^{2\pi i/3}\mathbf{1}_{3\times 3} \otimes -\mathbf{1}_{2\times 2} \otimes e^{2\pi i/6}$$

acts trivially on all of the SM fields

$$q: \ (\mathbf{3},\mathbf{2})_{+1} \qquad l: \ (\mathbf{1},\mathbf{2})_{-3} \qquad H: \ (\mathbf{1},\mathbf{2})_{-3}$$

$$\bar{u}: \ (\bar{\mathbf{3}},\mathbf{1})_{-4} \qquad \bar{d}: \ (\bar{\mathbf{3}},\mathbf{1})_{+2} \qquad \bar{e}: \ (\mathbf{1},\mathbf{1})_{+6}$$

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- Possible SM gauge group [Tong 2017]

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- Example:
  - $SU(5)$, $Spin(10)$, E_6 GUT models give $\Gamma = \mathbb{Z}_6$
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- Which one describes our world? How does it affect the physics of QCD axion?
- What is the difference between different choices of Γ?

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- Wilson lines: worldlines of electric probe particles

$$W_R = \mathrm{Tr}_R \mathscr{P} \exp \left(i \int A_\mu \, dx^\mu \right)$$

R: representation of the gauge group

We can assign every $SU(N)$ rep an electric charge $z_e \in \mathbb{Z}_N$ under the $\mathbb{Z}_N$ center.

$$SU(N) : z_e = 1, \ldots, N \mod N \qquad\qquad PSU(N) : z_e = 0 \mod N$$

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  Similarly, we can assign every ’t Hooft line a magnetic charge $z_m \in \mathbb{Z}_N$.

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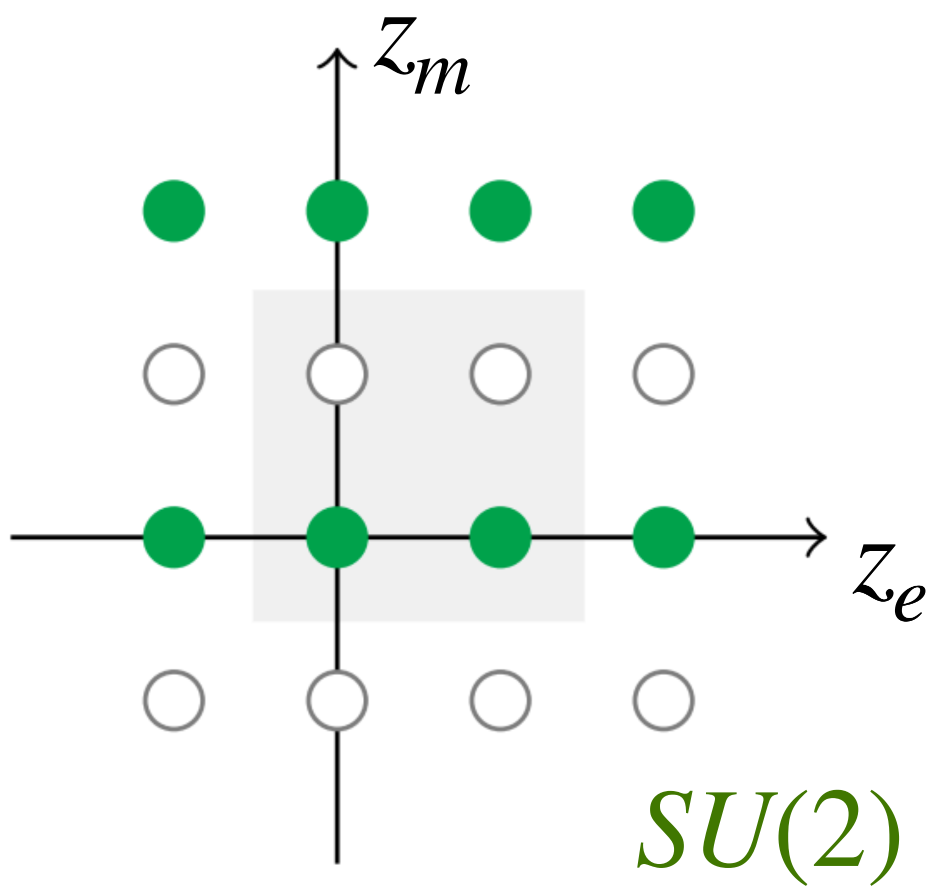

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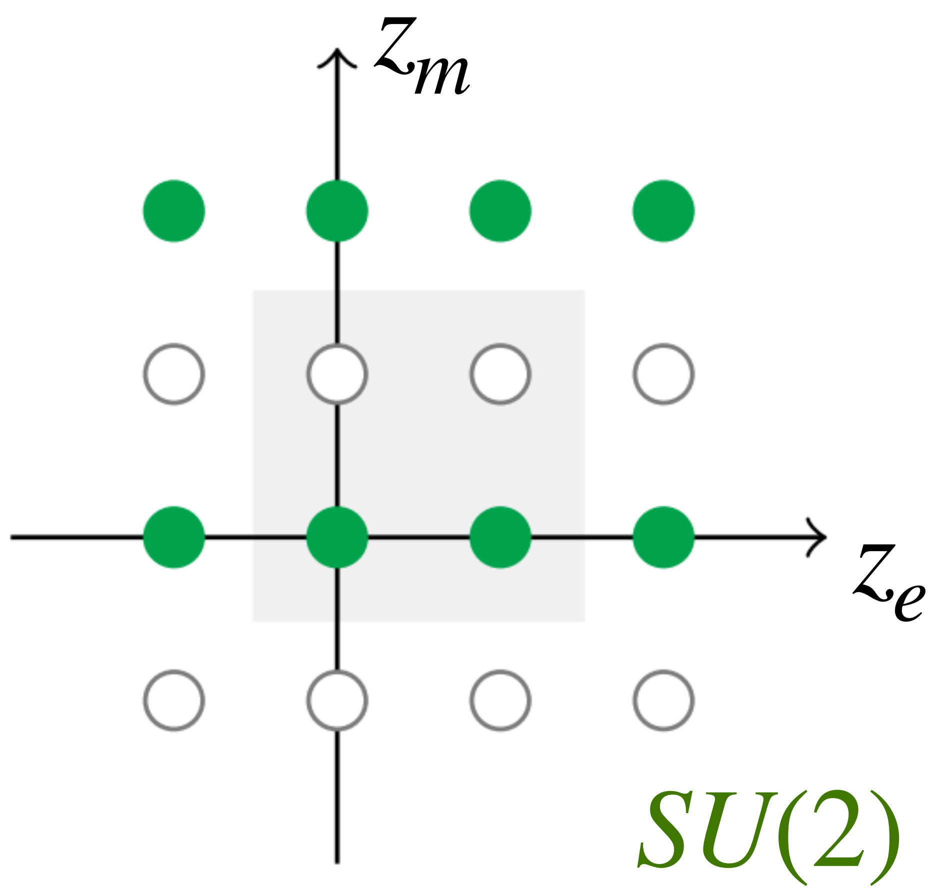

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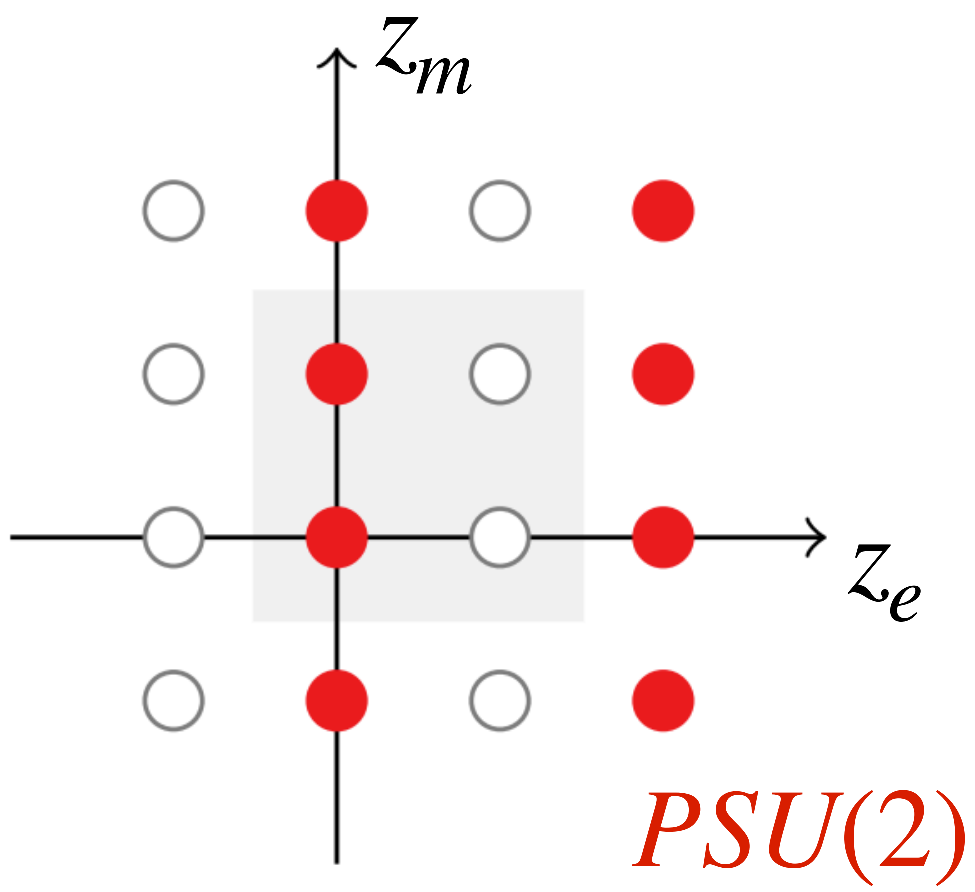

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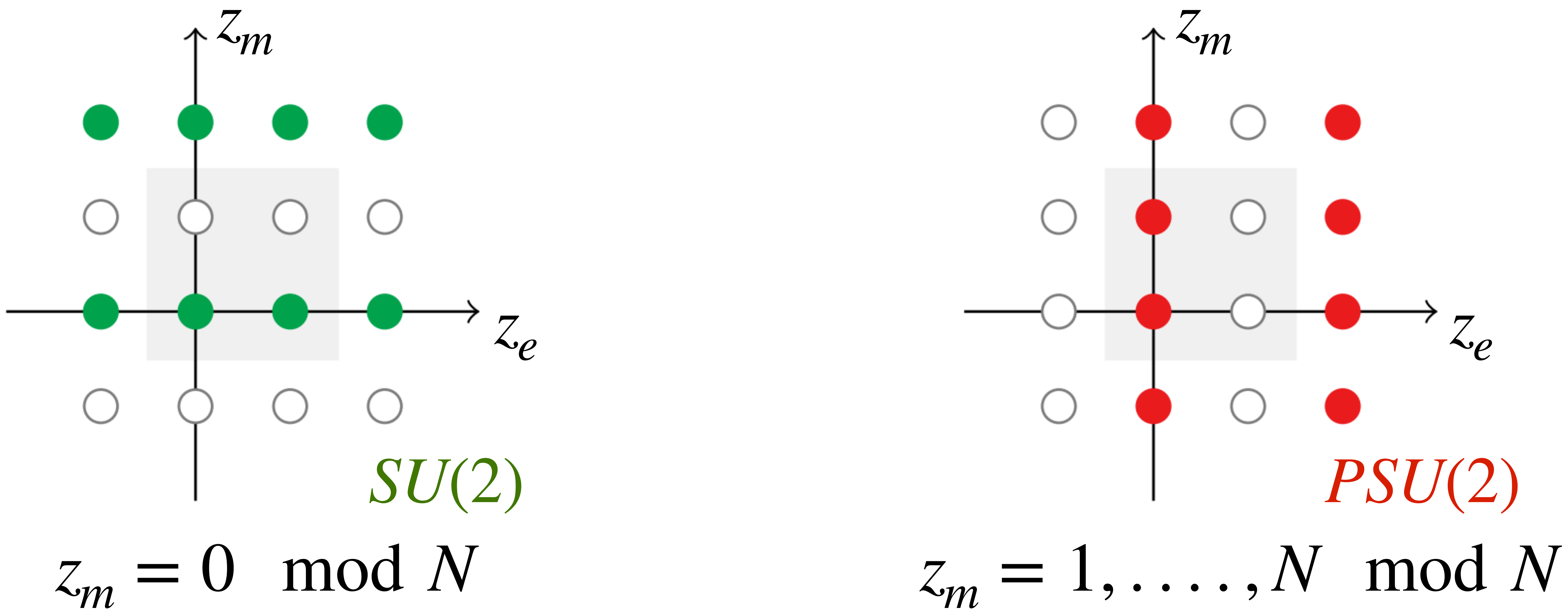

$PSU(N)$ theory has *less* Wilson lines but *more* ’t Hooft lines.

Figures are taken from [Aharony,Seiberg,Tachikawa 2013]

Fractional Instantons

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- The two theories also differ in the quantization of their instanton numbers.

$$n = \frac{1}{8\pi^2}\int \mathrm{Tr}\, F \wedge F$$

- $PSU(N)$ gauge theory contains fractional instantons

$$SU(N)\text{:}\ \ n \in \mathbb{Z} \qquad\qquad PSU(N)\text{:}\ \ n \in \frac{1}{N}\mathbb{Z}$$

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- The θ angle is 2π periodic in $SU(N)$ and $2\pi N$ periodic in $PSU(N)$.
  (Here, θ is a parameter of the theory not a dynamical axion field.)

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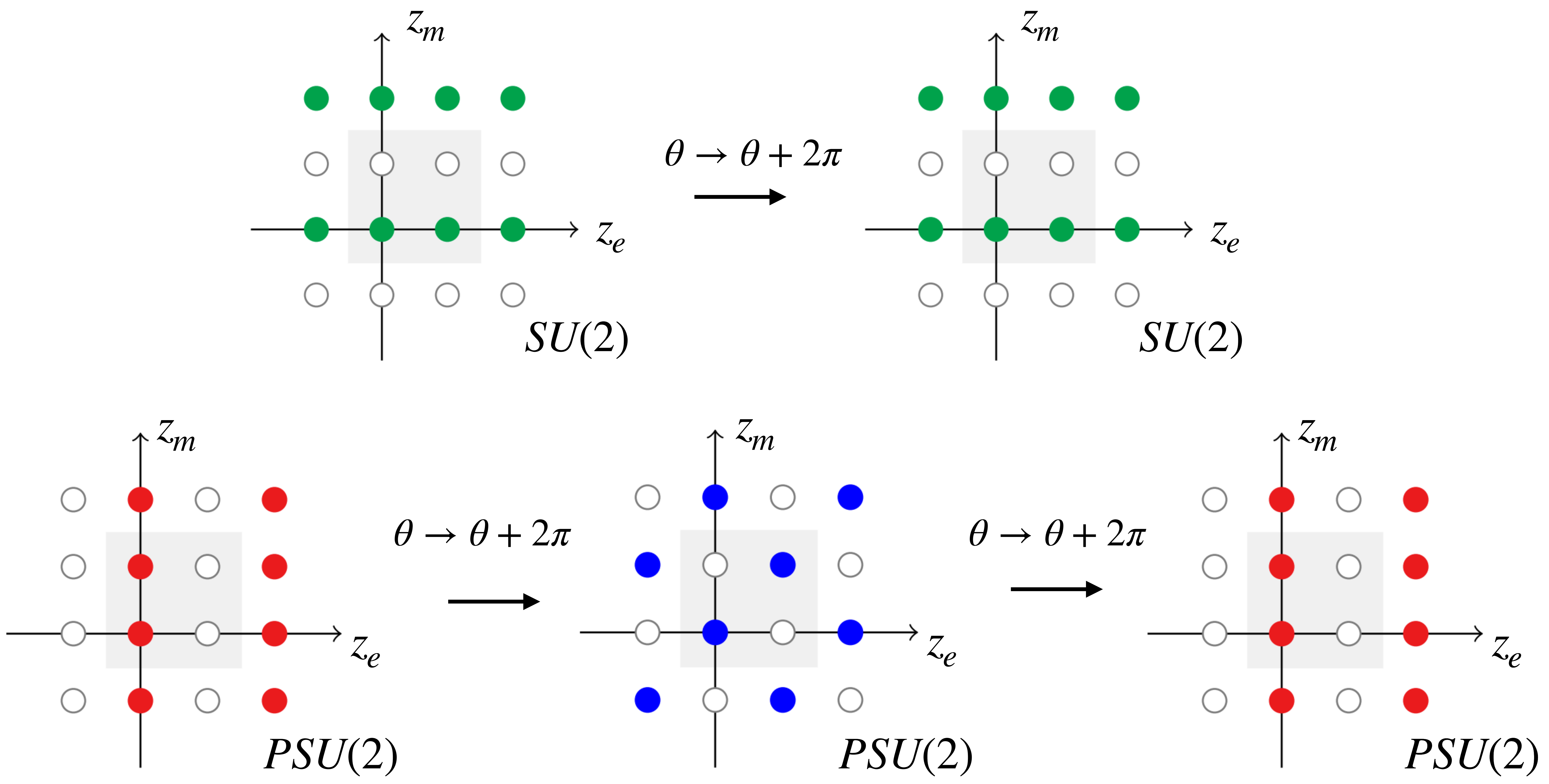

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- 4D gauge theories based on the same Lie algebra but with different global form of the gauge group, e.g., $SU(N)$ v.s $PSU(N)$ [Aharony,Seiberg,Tachikawa 2013]
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- In $PSU(N)$ theory, the coupling is quantized to be $K \in N\mathbb{Z}$, because of fractional instantons $n \in \mathbb{Z}/N$.

Quantization Conditions in Axion-SM

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so the instanton numbers are *correlated* (generalizing [Anber, Poppitz 2021])

$$n_3 \in \mathbb{Z}/3, \quad n_2 \in \mathbb{Z}/2, \quad n_1 \in \mathbb{Z}/36$$

$$n_3 - 24n_1 \in \mathbb{Z}, \quad n_2 - 18n_1 \in \mathbb{Z}, \quad 2n_3 + n_2 + 6n_1 \in \mathbb{Z}$$

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- This leads to *correlated* quantization conditions

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- Below electroweak scale, the three couplings K_i reduce to the axion couplings to the gluon and photon:

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$$N = K_3/2 \qquad E = (K_1 + 18K_2)/36$$

- For the minimal SM gauge group,

$$N \in \mathbb{Z}/2, \quad E \in \mathbb{Z}/3, \quad 4N + 3E \in 3\mathbb{Z}$$

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- QCD axion assumption: axion mass is generated by the coupling to QCD
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$$m_a = 5.70(6)(4)\mu\text{eV}\left(\frac{10^{12}\text{GeV}}{f/N}\right)$$

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- Below the QCD scale, the axion mixes with the pion generating an effective axion-photon coupling given by [Grilli di Cortona, Hardy, Pardo Vega, Villadoro 2015]

Fine structure constant

$$g_{a\gamma\gamma} = \frac{\alpha}{2\pi f/N}\left(\frac{E}{N} - 1.92(4)\right)$$

bare coupling

mixing with pions

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- Stable axion domain walls are in tension with the current observations if they are formed after inflation. Many proposed solutions.

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- If we don't want to face the axion domain wall problem, we want $N_{\mathrm{DW}} = 2N = 1$, which gives a lower bound on $|g_{a\gamma\gamma}|$:

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- The closest rational number E/N to 1.92 subject to our quantization conditions $N \in \mathbb{Z}/2, E \in \mathbb{Z}/3, 4N + 3E \in 3\mathbb{Z}$ is

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- It is realized by the minimal DFSZ model and $SU(5)$, $Spin(10)$, E_7 GUTs model.

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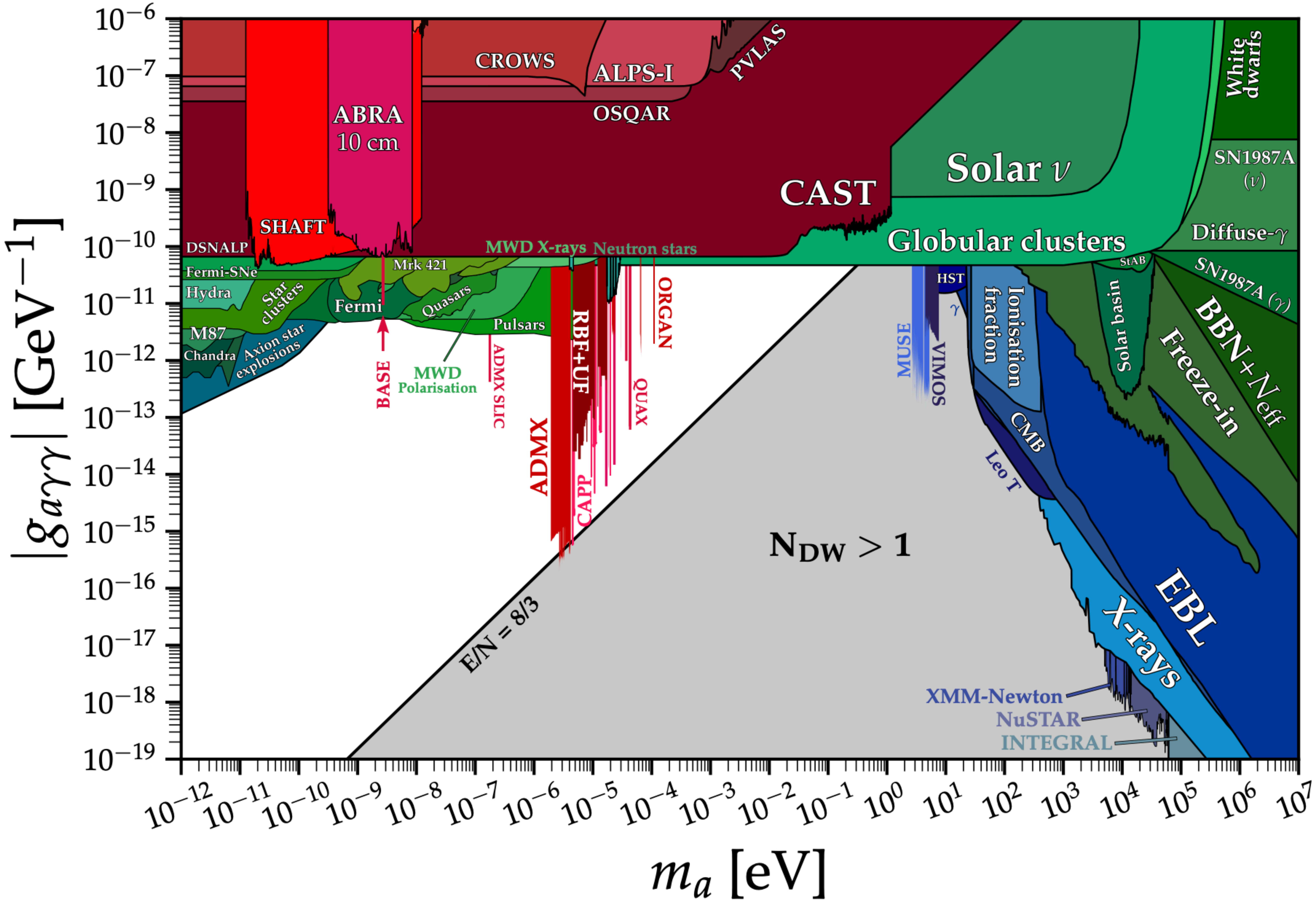

Quantization Condition

SM gauge group	Quantization of axion-gauge coupling	Quantization of N and E
$\tilde{G}$	$K_3, K_2, K_1 \in \mathbb{Z}$	$N \in \mathbb{Z}/2,\ E \in \mathbb{Z}/36$
$\tilde{G}/\mathbb{Z}_2$	$K_3, K_2 \in \mathbb{Z},\ K_1 \in 2\mathbb{Z}$ $2K_2 + K_1 \in 4\mathbb{Z}$	$N \in \mathbb{Z}/2,\ E \in \mathbb{Z}/9$
$\tilde{G}/\mathbb{Z}_3$	$K_3, K_2 \in \mathbb{Z},\ K_1 \in 3\mathbb{Z}$ $6K_2 + K_1 \in 9\mathbb{Z}$	$N \in \mathbb{Z}/2,\ E \in \mathbb{Z}/12$ $4N + 12E \in 3\mathbb{Z}$
$\tilde{G}/\mathbb{Z}_6$	$K_3, K_2 \in \mathbb{Z},\ K_1 \in 6\mathbb{Z}$ $24K_3 + 18K_2 + K_1 \in 36\mathbb{Z}$	$N \in \mathbb{Z}/2,\ E \in \mathbb{Z}/3$ $4N + 3E \in 3\mathbb{Z}$

$\tilde{G} = SU(3) \times SU(2) \times U(1)_Y$

Conclusion

- There is an ambiguity in the global form of the Standard Model (SM) gauge group

  $$(SU(3) \times SU(2) \times U(1)_Y)/\Gamma$$

  with $\Gamma = \mathbb{Z}_6, \mathbb{Z}_3, \mathbb{Z}_2, 1$, which hasn't been determined by the current experiments.

- We analyzed how different choices of Γ modify the quantization of the axion coupling to the SM and how they affect the observation of QCD axion.

- If QCD axion were discovered in the future, our quantization condition can be used to constrain the global form of the Standard Model gauge group.

- Assuming no axion domain walls, we showed that the ratio $|g_{a\gamma\gamma}|/m_a$ is minimized at $E/N = 8/3$ for $\Gamma = \mathbb{Z}_6$. It provides another motivation for targeting $E/N = 8/3$ in experiments.

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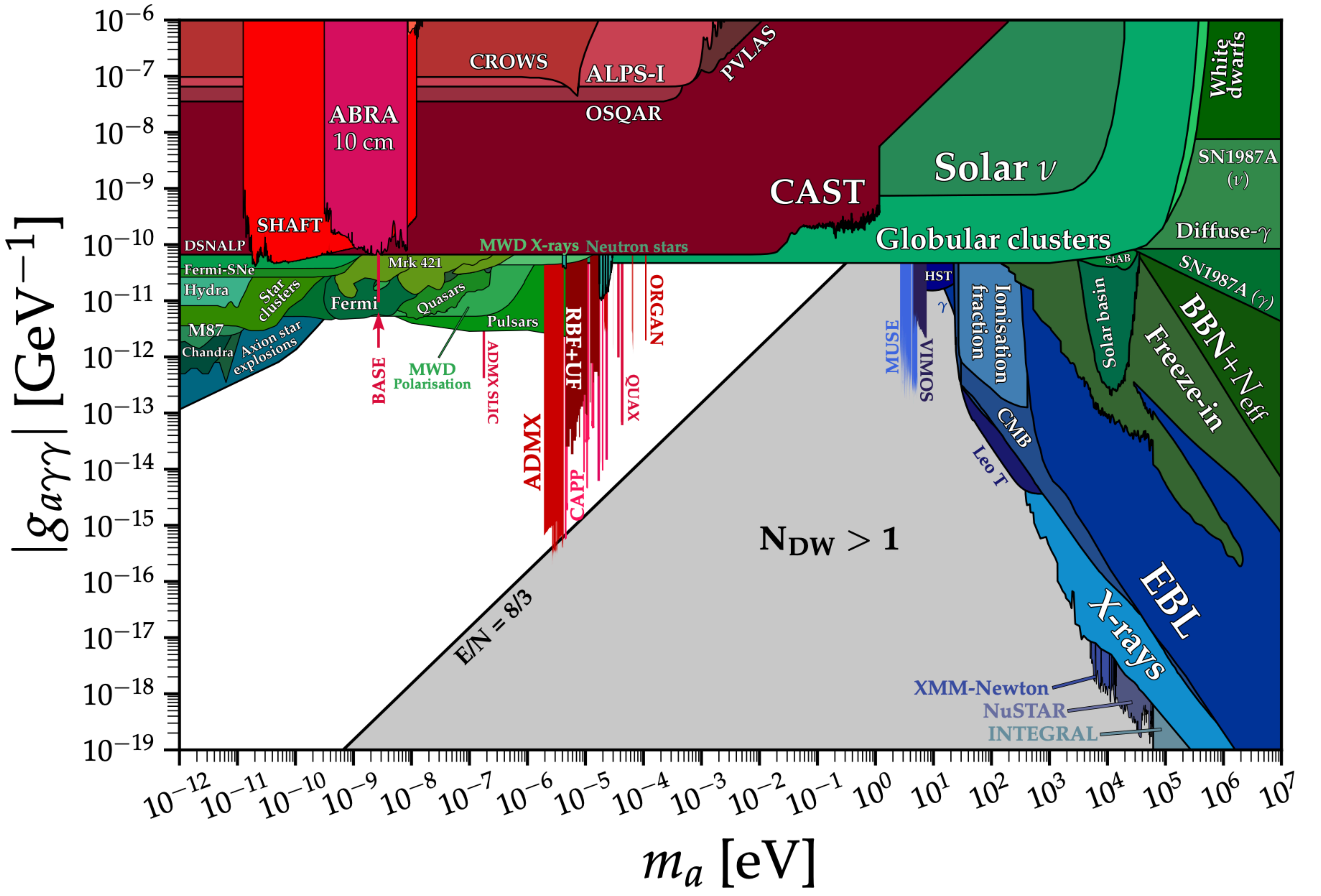
- These symmetries depend on the axion-gauge coupling K_i and the global form of the gauge group.

- *In some cases*, we can put a bound on m_{center}, mass of the lightest particle charged under the $\mathbb{Z}_6$ center

$$m_{\text{center}} \lesssim \sqrt{T}, \quad m_{\text{center}} \lesssim m_{\text{monopole}}$$

T : axion string tension

m_{monopole} : mass of the hypercharge monopole


$|g_{a\gamma\gamma}|$ [GeV^{-1}]
m_a [eV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-12}
10^{-11}
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
CROWS
ALPS-I
PVLAS
OSQAR
ABRA
10 cm
SHAFT
CAST
Solar ν
White dwarfs
SN1987A (ν)
Diffuse-γ
Globular clusters
DSNALP
MWD X-rays
Neutron stars
Fermi-SNe
Hydra
Star clusters
Mrk 421
Fermi
Quasars
Pulsars
M87
Chandra
Axion star explosions
BASE
MWD Polarisation
ADMX SLIC
ADMX
RBF+UF
CAPP
QUAX
ORGAN
E/N = 8/3
$\mathrm{N_{DW}} > 1$
MUSE
VIMOS
HST
γ
Ionisation fraction
Solar basin
StAB
SN1987A (γ)
BBN+$N_{\rm eff}$
Freeze-in
CMB
Leo T
EBL
X-rays
XMM-Newton
NuSTAR
INTEGRAL

Thank you!