



北京大學  
PEKING UNIVERSITY

## First Constraint on the Dimensionless Axion-Photon Coupling from Neutron Star Observations

Jun-Chen Wang

In collaboration with Qing-Hong Cao, Lijing Shao,  
Yandong Liu, Shunshun Cao and Jinchen Jiang

arXiv: 2506.07546

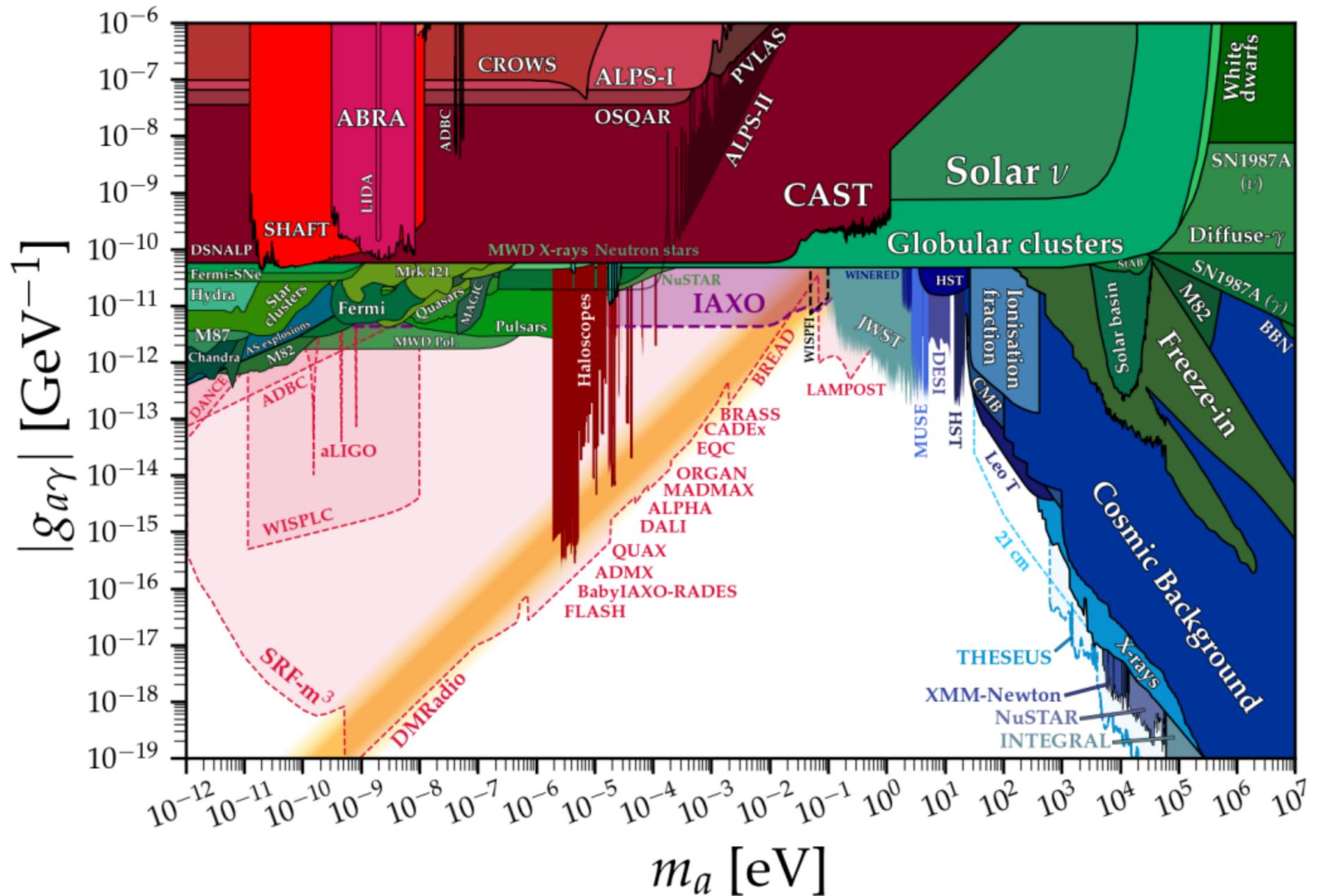
# Introduction

## Axion

- Strong CP problem
- Dark matter
- Quantized coupling
- Non-trivial topology

## Core Problem:

How to detect / constrain axion parameters ?



## One classification of axion research

**Axion Detection**

**Fluctuation  
around VEV**

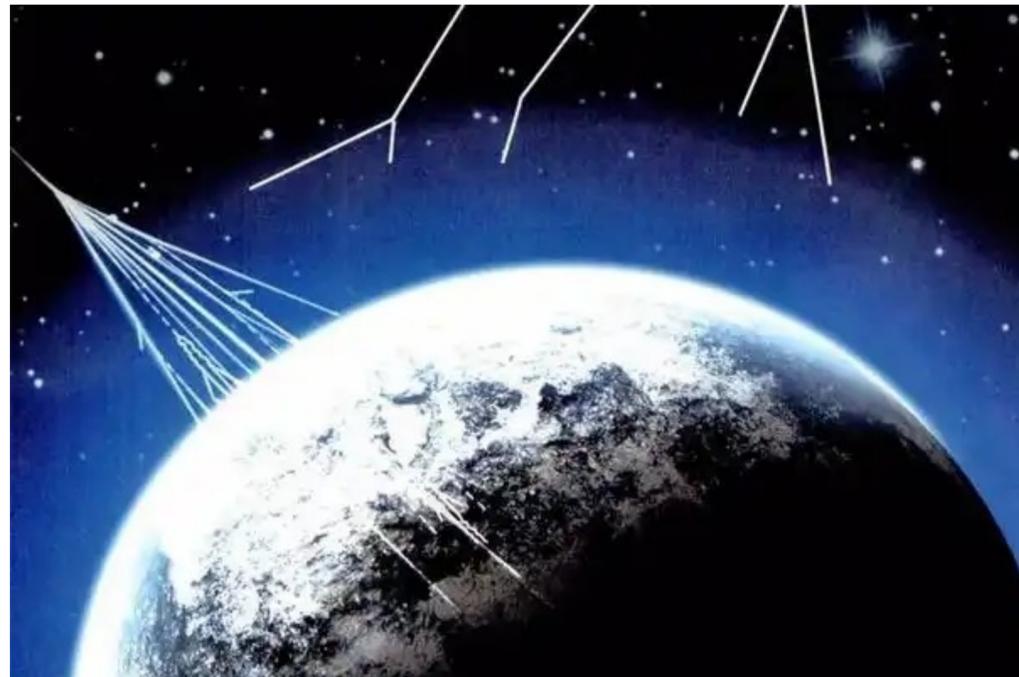
**Different VEVs**

- **Dark matter hypothesis**
- **Suppressed signal**
- **Many detection methods**
- **Wave-like properties**
- **No dark matter hypothesis**
- **Obvious signal**
- **Difficult to realize**
- **Topological properties**

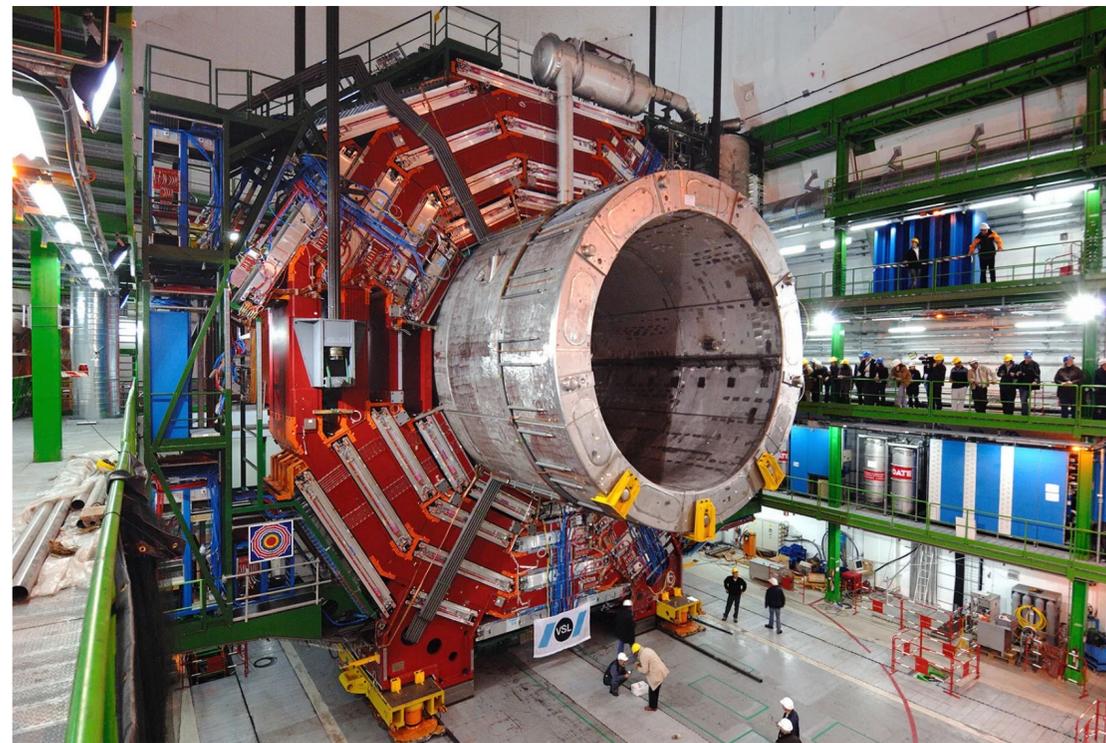
# Introduction

- **Detect axion fluctuation around vacuum expectation value**

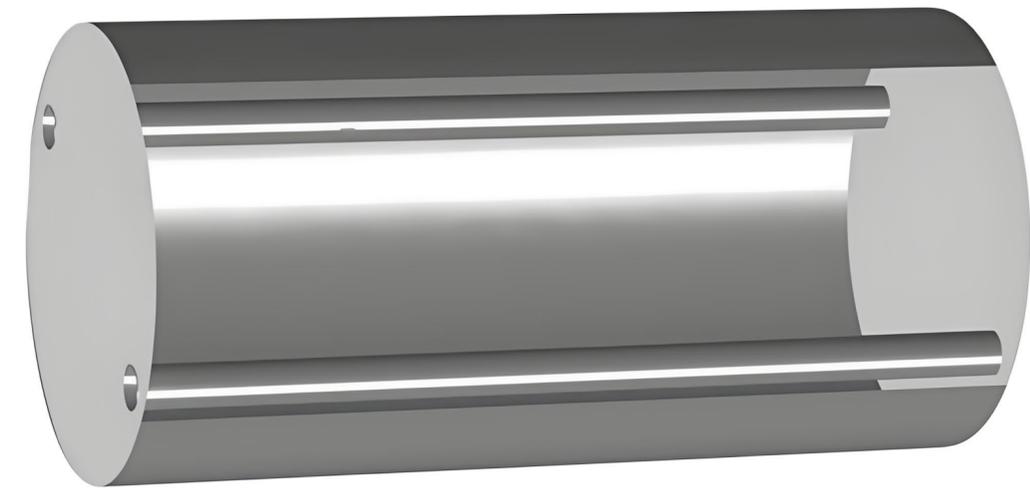
Cosmic Ray



Ring Experiment



Cavity Detection



- **Detect the axion global profiles (nontrivial VEVs)**

- **Domain wall and cosmic string (not-trivial topology)**

[M. Pospelov et al. Phys. Rev. Lett. 110, 021803](#)

- **Axion cloud (gravitational effects)**

[Yifan Chen et al. Phys.Rev.Lett. 124 \(2020\) 6, 061102](#)

[Yifan Chen et al. Nature Astron. 6 \(2022\) 5, 592-598](#)

- **Berry Phase and Neutron Star**

[arXiv: 2411.04749](#), [arXiv: 2506.07546](#)

# Axion Potential

- How to obtain non-trivial vacuum expectation value?  $\left. \frac{dV(a)}{da} \right|_{\text{vev}} = 0$
- Special axion potential  $V(a)$

Axion comes from the spontaneous breaking of the **global**  $U(1)_{\text{PQ}}$  symmetry.

$$\mathcal{L}_{ag} = \frac{\alpha_s}{8\pi} \frac{a}{f_a} G_{\mu\nu}^b \tilde{G}^{b\mu\nu} \quad \Rightarrow \quad V_{\text{QCD}} = m_q \langle \bar{q}q \rangle \left| \cos \left( \frac{a}{2f_a} \right) \right|$$

$$U(1)_{\text{PQ}} \text{ symmetry breaking} \quad \Rightarrow \quad \Delta V = \Lambda^4 \sum_{n=1}^{\infty} 2^{1-\frac{n}{2}} |\lambda_n| \left( \frac{f_a}{\Lambda} \right)^n \cos \left( n \frac{a}{f_a} + \beta_n \right)$$

## The total axion potential on Earth

$$V(a) \simeq m_q \langle \bar{q}q \rangle \left| \cos \left( \frac{a}{2f_a} \right) \right| + \sqrt{2} \Lambda^3 f_a |\lambda_1| \cos \left( \frac{a}{f_a} + \beta_1 \right)$$

Requirements of solving the Strong CP problem **on Earth**

$$\beta_1 = \pi$$

$$m_q |\langle \bar{q}q \rangle| > 4\sqrt{2} \Lambda^3 f_a |\lambda_1|$$
$$\beta_1 = 0$$

# Axion Potential

$V_{QCD}$  originated from the SSB of chiral symmetry



QCD Chiral Symmetry  $\leftrightarrow$  Quark Condensate  $\langle \bar{q}q \rangle$

High temperature and density will change  $\langle \bar{q}q \rangle$

# Axion Potential

- **Small nucleon number density,  $n_N \ll n_{\text{sat}} = (110 \text{ MeV})^3$**

$$\langle \bar{q}q \rangle \rightarrow \langle \bar{q}q \rangle + n_N \sigma_N / m_q \quad \sigma_N \equiv m_q \frac{dm_N}{dm_q}$$

- **Large nucleon number density,  $n_N > n_{\text{sat}} = (110 \text{ MeV})^3$**

$$\langle \bar{q}q \rangle \rightarrow 0 \quad \text{QCD chiral symmetry is totally restored}$$

V. Radhakrishnan and D. Cooke, (1969).

## The total axion potential on neutron star

$$V(a) \simeq m_q \langle \bar{q}q \rangle \left| \cos \left( \frac{a}{2f_a} \right) \right| + \sqrt{2} \Lambda^3 f_a |\lambda_1| \cos \left( \frac{a}{f_a} + \beta_1 \right)$$

$$\langle \bar{q}q \rangle \rightarrow \langle \bar{q}q \rangle + n_N \sigma_N / m_q$$

$$m_q |\langle \bar{q}q \rangle| > 4\sqrt{2} \Lambda^3 f_a |\lambda_1|$$



## The axion VEV

$$a = 0 \quad \rightarrow \quad a_{\text{NS}} = 2f_a \arccos \left( \frac{m_q |\langle \bar{q}q \rangle| - n_N \sigma_N}{4\sqrt{2} \Lambda^3 f_a |\lambda_1|} \right) \quad \rightarrow \quad a_{\text{NS}} = \pi f_a$$

**The axion profile around the Neutron Star**

$$\partial_\mu \partial^\mu a = -\frac{dV(a)}{da}$$

$$a(r) = \begin{cases} \pi f_a, & r < R_{\text{NS}} \\ \pi f_a \frac{R_{\text{NS}}}{r} e^{-m_a(r-R_{\text{NS}})}, & r > R_{\text{NS}} \end{cases}$$

**Detect through the birefringence**

$$\mathcal{L}_{a\gamma} = \frac{1}{4} \frac{g_\gamma}{f_a} a F^{\mu\nu} \tilde{F}_{\mu\nu} \Rightarrow \Delta\alpha = -\frac{g_\gamma}{2f_a} a(r)$$

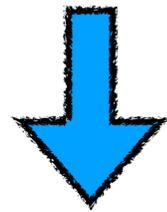
**$f_a$  is cancelled out**

**$r$  is difficult to measure**

## Radius-Frequency Mapping

photons emitted at different distances away from the neutron star center have varying frequencies

$$\omega_c = \frac{9}{8}(2\pi)^{\frac{1}{2}}\gamma^3 P_{\text{NS}}^{-\frac{1}{2}} r^{-\frac{1}{2}} \simeq 2.82 \frac{\gamma^3}{\sqrt{P_{\text{NS}} r}} \quad \Delta\alpha = -\frac{g_\gamma}{2f_a} a_{\text{NS}} \frac{R_{\text{NS}}}{r} e^{-m_a(r-R_{\text{NS}})}$$



$$\Delta\alpha(\omega_c) = -\frac{g_\gamma a_{\text{NS}}}{2f_a} \frac{R_{\text{NS}} P_{\text{NS}} \omega_c^2}{7.95\gamma^6} e^{-m_a \left( \frac{7.95\gamma^6}{P_{\text{NS}} \omega_c^2} - R_{\text{NS}} \right)}$$

**Detectable  
Experimentally**

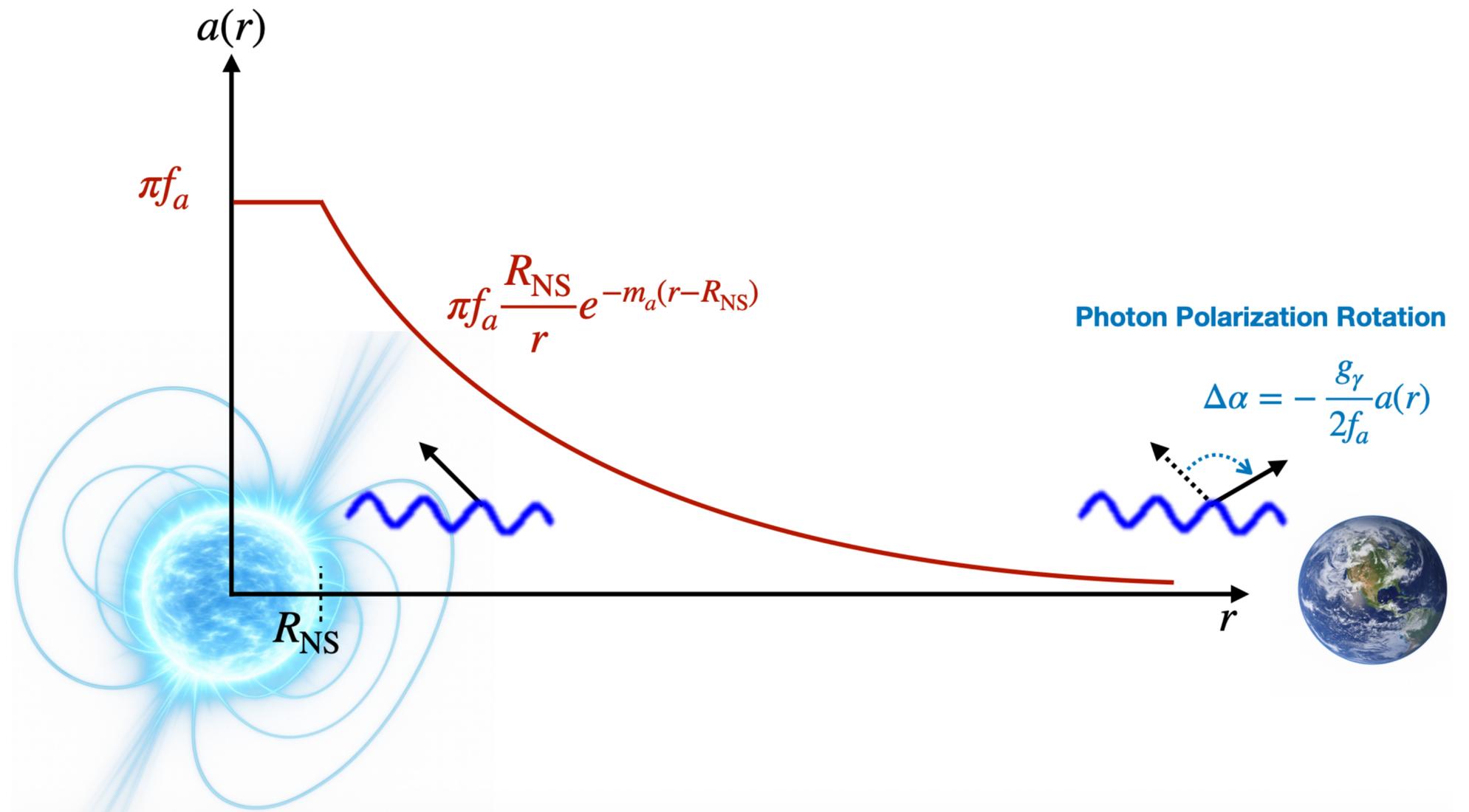
# Axion Detection

$$\Delta\alpha = -6.59 g_\gamma \mathcal{A} \left( \frac{\omega_c}{\text{GHz}} \right)^2 e^{-m_a R_{\text{NS}}} \left[ \frac{0.24}{\mathcal{A}} \left( \frac{\text{GHz}}{\omega_c} \right)^2 - 1 \right]$$

$$\mathcal{A} = \left( \frac{R_{\text{NS}}}{10 \text{ km}} \right) \left( \frac{P_{\text{NS}}}{1 \text{ s}} \right) \left( \frac{100}{\gamma} \right)^6$$

**Independent of large axion decay constant  $f_a$**

$$\mathcal{L}_{a\gamma} = \frac{1}{4} \frac{g_\gamma}{f_a} a F^{\mu\nu} \tilde{F}_{\mu\nu}$$

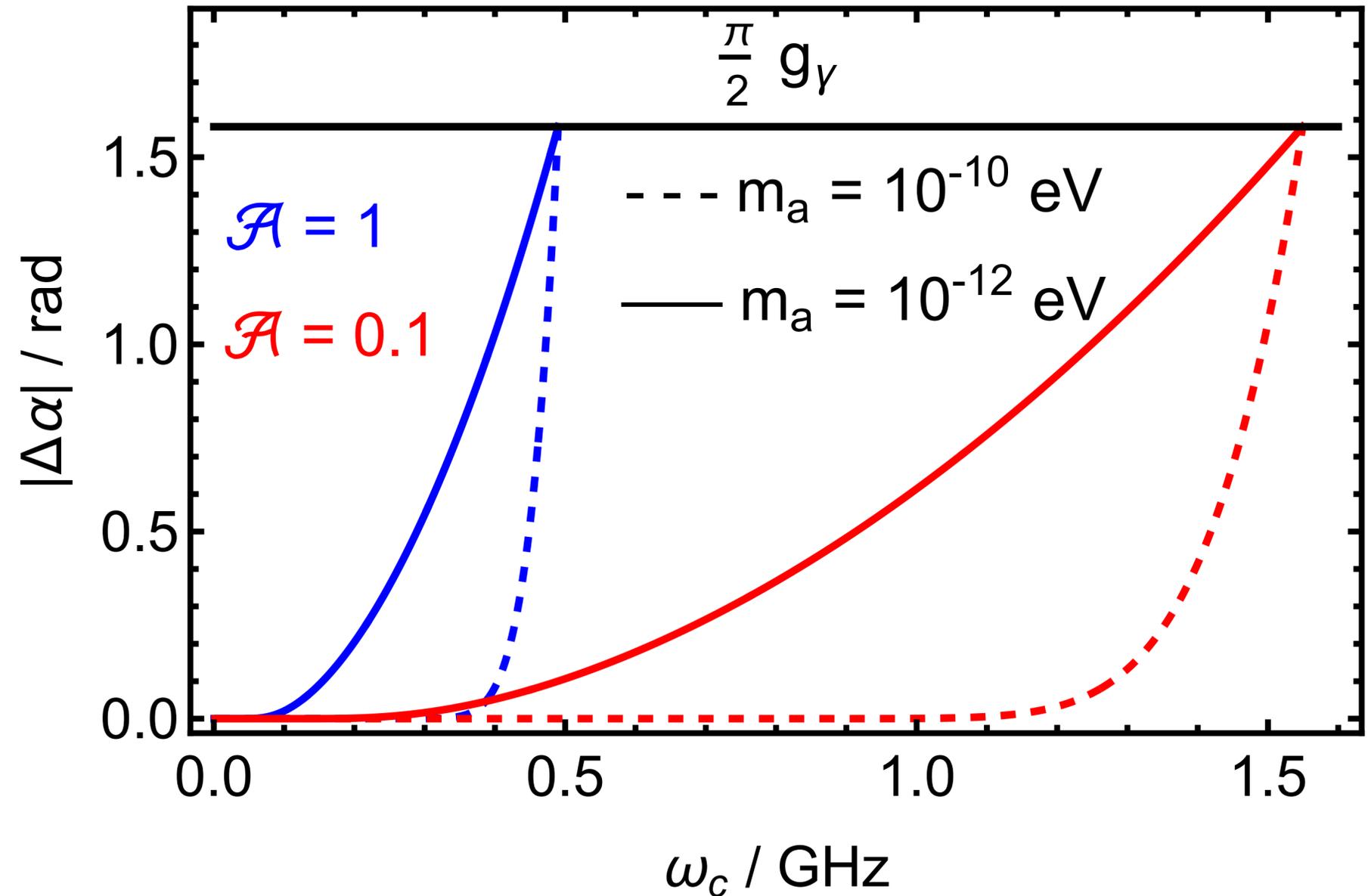


## Small axion mass leads to obvious signals

$$\Delta\alpha = -6.59 g_\gamma \mathcal{A} \left( \frac{\omega_c}{\text{GHz}} \right)^2$$

$$\mathcal{A} = \left( \frac{R_{\text{NS}}}{10 \text{ km}} \right) \left( \frac{P_{\text{NS}}}{1 \text{ s}} \right) \left( \frac{100}{\gamma} \right)^6$$

$$\Delta\alpha|_{\text{max}} = \Delta\alpha(\omega_{\text{max}}) = \frac{\pi}{2} g_\gamma$$



# Axion Constraint

- Neutron star PSR B1919+21 data from FAST

- Initial angle  $\alpha_0$  is a constant

- Four free parameters:  $g_\gamma$   $m_a$   $\mathcal{A}$   $\alpha_0$  

$\chi^2$  fitting

Monte Carlo Markov chain

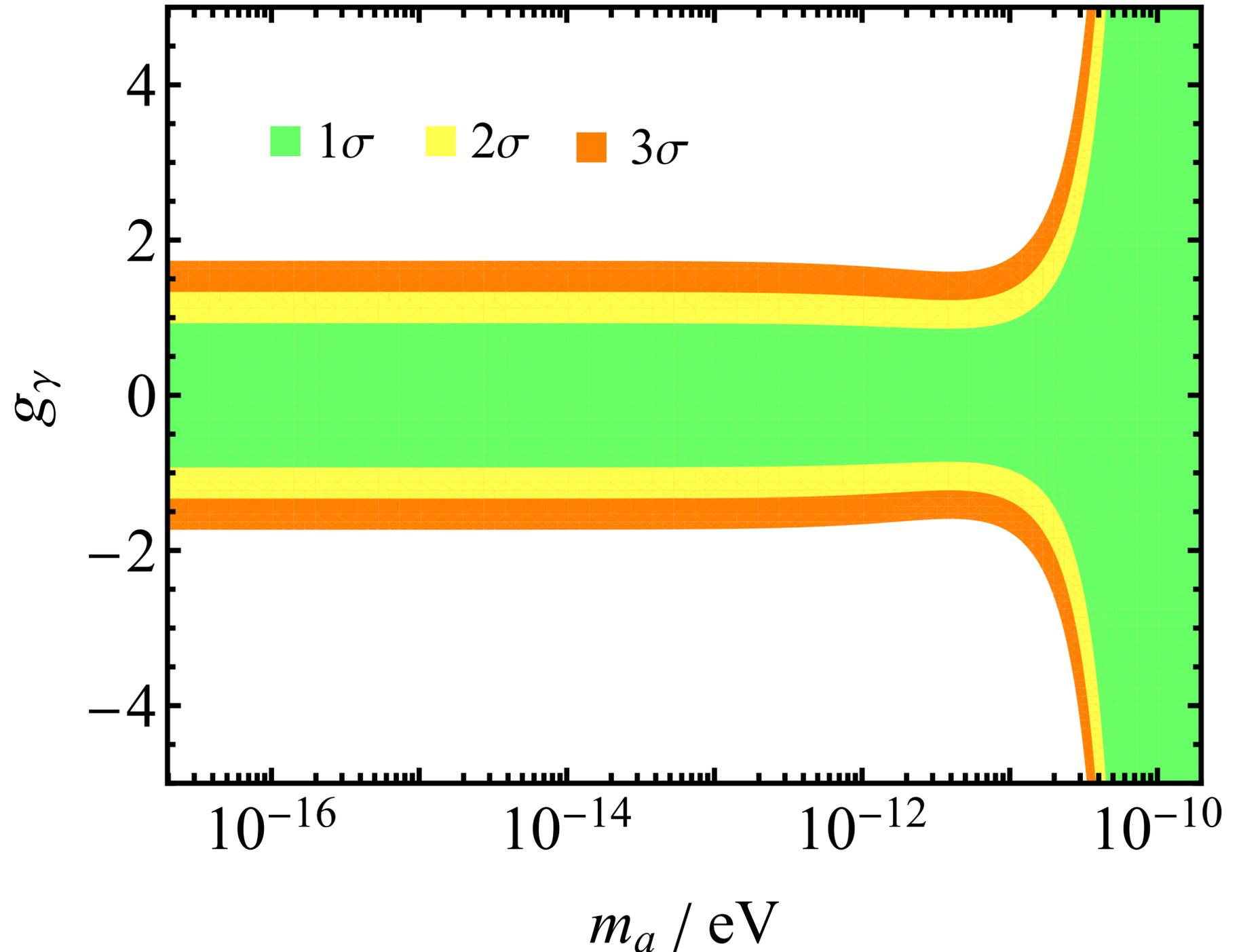
$$\mathcal{A} = \left( \frac{R_{\text{NS}}}{10 \text{ km}} \right) \left( \frac{P_{\text{NS}}}{1 \text{ s}} \right) \left( \frac{100}{\gamma} \right)^6$$

$$\Delta\alpha = -6.59 g_\gamma \mathcal{A} \left( \frac{\omega_c}{\text{GHz}} \right)^2 e^{-m_a R_{\text{NS}} \left[ \frac{0.24}{\mathcal{A}} \left( \frac{\text{GHz}}{\omega_c} \right)^2 - 1 \right]}$$

# Axion Constraint

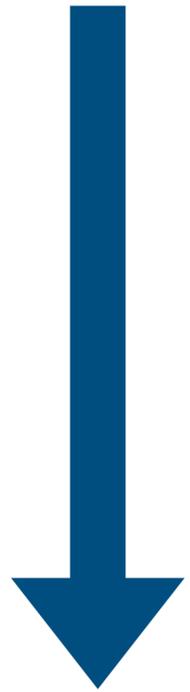
- We obtain  $|g_\gamma| < 0.93$  at  $1\sigma$  level for  $m_a < 10^{-11}$  eV
- Ultra-light axions leads to better constraints
- Far from the constraint of QCD axion scenario

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



# Implication

$$G_{\text{SM}} = SU(3) \times SU(2) \times U(1)$$



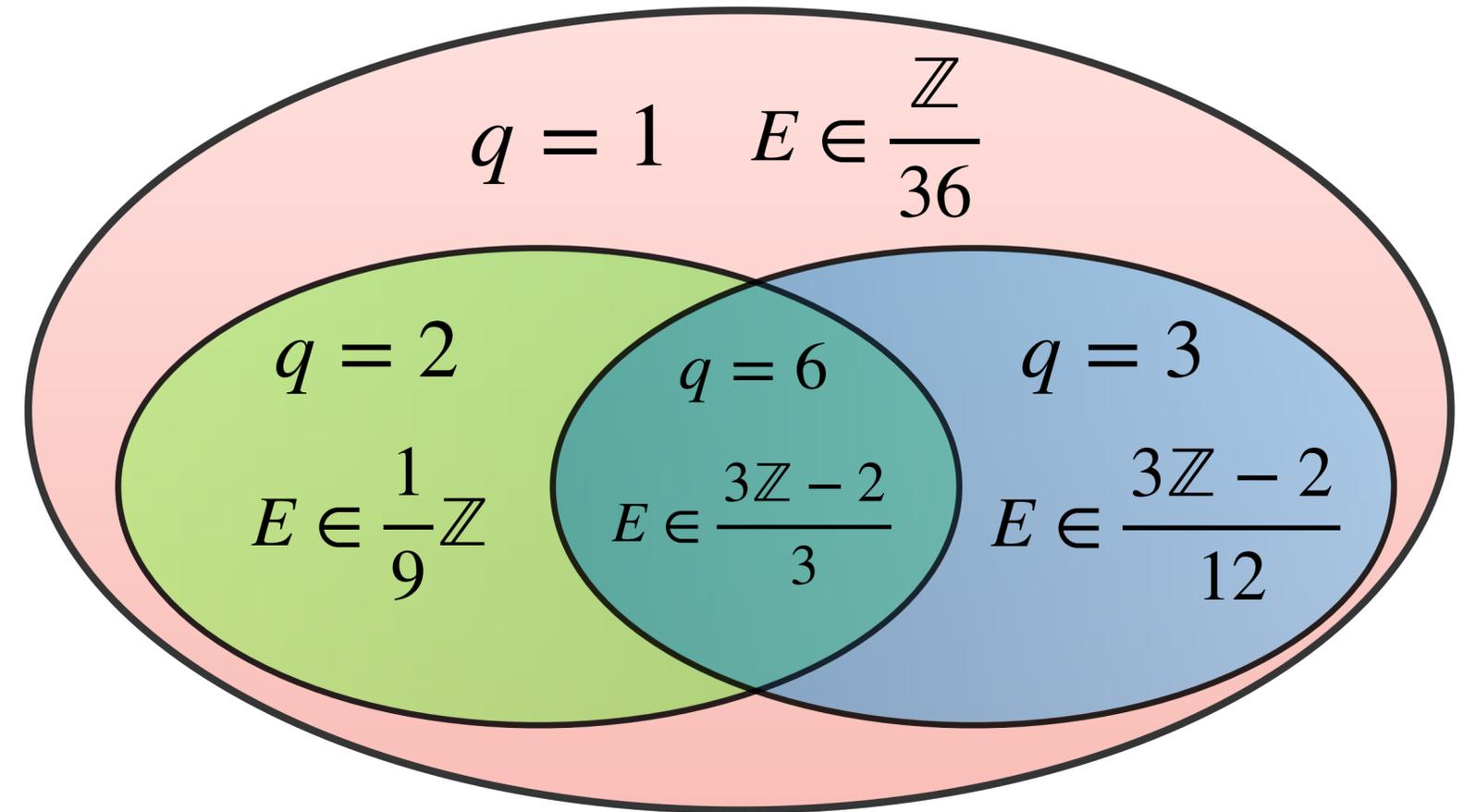
**Quantized coupling**

$$\mathcal{L}_{a\gamma} = \frac{1}{4} \frac{g_\gamma}{f_a} a F^{\mu\nu} \tilde{F}_{\mu\nu}$$

$$g_\gamma = \frac{\alpha}{\pi} (E - 0.96)$$

$$G_{\text{SM}} = SU(3) \times SU(2) \times U(1)/\mathbb{Z}_q$$

$$q = 1, 2, 3, 6$$

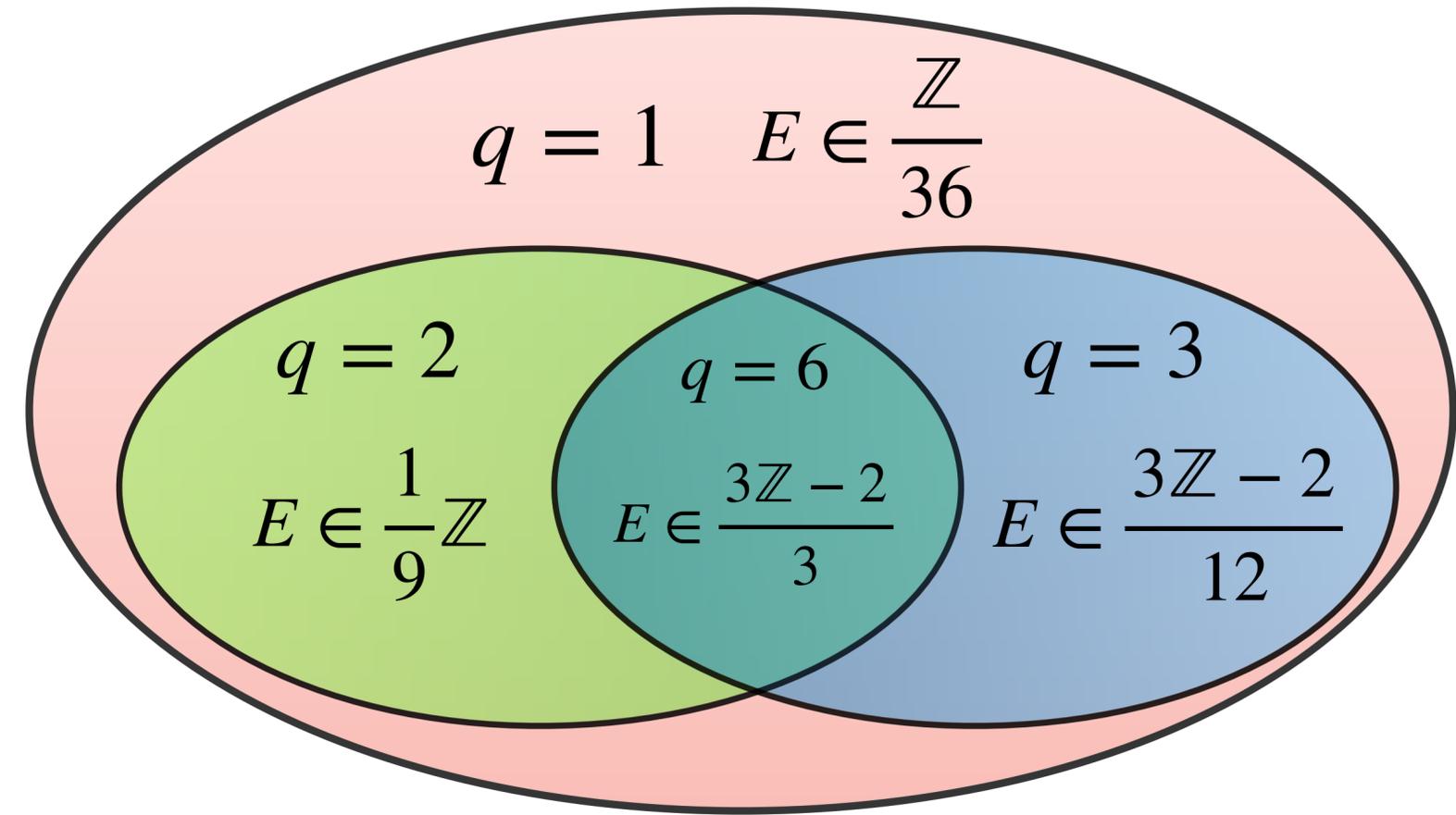


# Implication

- Measuring  $g_\gamma$  can exclude structure with  $q = 2, 3, 6$
- Or distinguish structure with  $q = 2$  and  $q = 3$

$$|g_\gamma| < 0.93$$

- Precision requirement :  $10^{-4}$
- Current precision :  $10^{-1}$



**Higher precision is essential**

# Conclusion

- We analyze the **neutron-star-modified** axion potential and the corresponding axion profile
- We can detect axions by measuring the **polarization** of neutron star emissions and explore **SM global structure**
- Using **FAST data**, we have placed the direct constraint on the dimensionless axion-photon coupling with  $|g_\gamma| < 0.93$

Thank You!