



# The consistent interactions between the axion and vector mesons

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# Outlines

- Axion general introduction
- Axion-scalar meson interactions
- Axion-vector meson interactions
- Phenomenology at BESIII and STCF
- Summary

# The QCD axion and the Strong CP problem

$$\mathcal{L} \supset -\frac{\theta g_s^2}{32\pi^2} G\tilde{G} - (\bar{u}_L M_u u_R + \bar{d}_L M_d d_R + \text{h.c.})$$

- The CKM matrix from  $M_{u,d}$ 
  - CP violating phase  $\theta_{\text{CP}} \sim 1.2$  radian
  - QCD induced CP violating phase,  $\bar{\theta}$

$$\bar{\theta} = \theta + \arg [\det [M_u M_d]]$$

- $\bar{\theta}$  is invariant under quark chiral rotation
- According to neutron EDM experiment

$$\bar{\theta} \lesssim 1.3 \times 10^{-10} \text{ radian}$$

$$d_{\text{EDM}}^n \sim \bar{\theta} \times 10^{-16} \text{ e cm}$$

$$d_{\text{exp}}^n < 10^{-26} \text{ e cm}$$

# The Peccei-Quinn solution to Strong CP problem

- Experiment requires  $\bar{\theta} = \theta + \arg [\det [M_u M_d]] \lesssim 10^{-1} \text{rad}$
- PQ: promote the constant  $\bar{\theta}$  to a dynamical field,  $a$
- Vafa-Witten theorem: vector-like theory (QCD) has ground state  $\langle \theta \rangle = 0$
- Introduce a *global* PQ-symmetry  $U(1)_{\text{PQ}}$ , *anomalous* under the QCD
  - The massless Goldstone boson  $a$  is called *axion*
  - $a \rightarrow a + \kappa f_a \Rightarrow \mathcal{S} \rightarrow \mathcal{S} + \frac{\kappa}{32\pi^2} \int d^4x G \tilde{G}$ , cancels  $\bar{\theta}$
  - Low energy:  $\mathcal{L} = \sum_q \bar{q} (i D_\mu \gamma^\mu - m_q) q - \frac{1}{4} G G + \frac{g_s^2}{32\pi^2} \frac{a}{f_a} G \tilde{G} + \frac{1}{2} (\partial_\mu a)^2 + \mathcal{L}_{\text{int}}[\partial_\mu a]$

# The invisible axion models

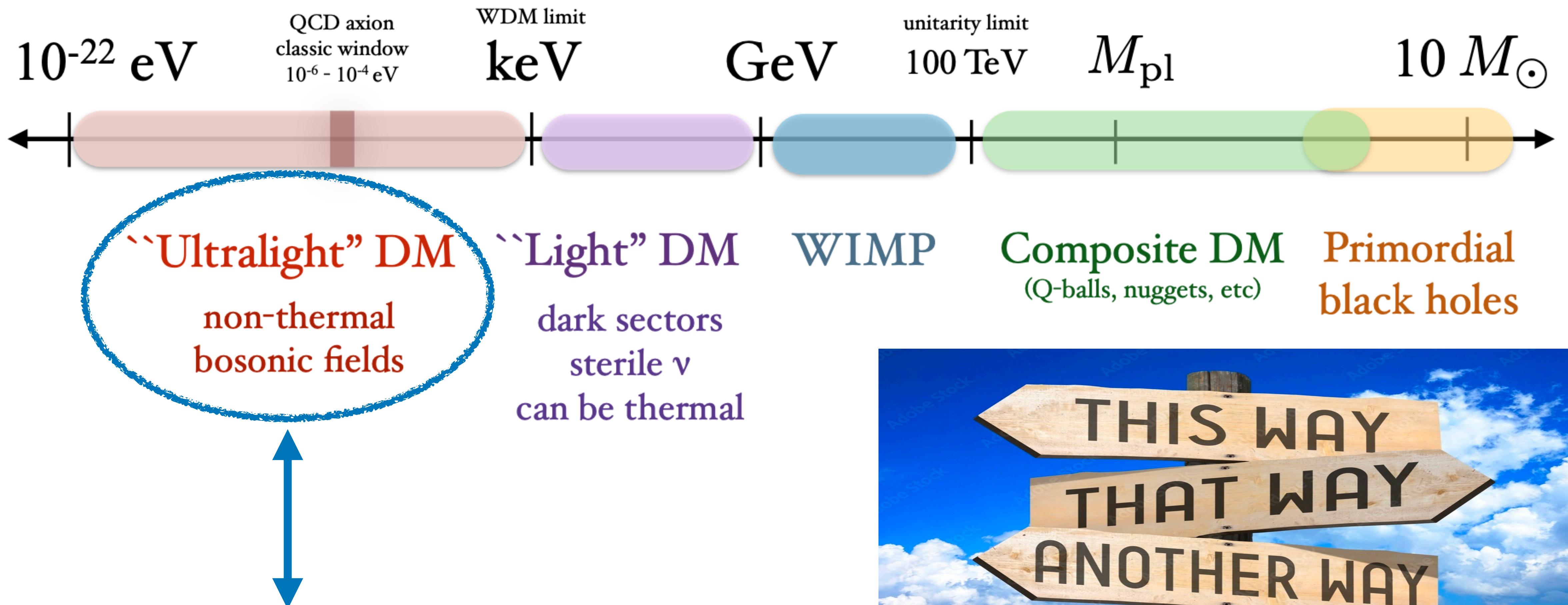
- SM particles does not directly charge under  $U(1)_{\text{PQ}}$ 
  - KSVZ model:
    - Heavy vector-like quark:  $Q_{L,R}$
    - $Q_L$  and  $Q_R$  has different charge under  $U(1)_{\text{PQ}}$
    - A heavy complex scalar  $\Phi = re^{ia}$  charge under  $U(1)_{\text{PQ}}$
  - Yukawa:  $y\Phi\bar{Q}_LQ_R \supset \frac{yf_a}{\sqrt{2}}e^{ia/f_a}\bar{Q}_LQ_R$
  - $\mathcal{L} \supset \frac{g_s^2}{32\pi^2}\frac{a}{f_a}G\tilde{G}$

# The invisible axion models

- DFSZ model:
  - Two Higgs doublet  $H_{u,d}$  and a complex singlet  $\Phi$  charged under  $U(1)_{\text{PQ}}$ , with phase factor  $e^{i\phi_{u,d,0}}$
  - Similar to previous UV model, but  $\langle \Phi \rangle \gg v_h$
  - Yukawa:  $(\bar{Q}Y_u H_u u_R + \bar{Q}Y_d H_d d_R + \bar{L}Y_e H_d e_R) + h.c.$
  - Potential term: e.g.  $H_u H_d \Phi^2$ , Axion mode:  $a = \frac{1}{f_a} \sum_{i=u,d,0} Q_i v_i \phi_i$
  - Axion have direct quark and lepton couplings
  - Low energy:  $\mathcal{L} \supset \frac{\alpha_s}{8\pi^2 f_a} \frac{a}{G} G \tilde{G} + \frac{\alpha_{em}}{8\pi} \frac{E}{N} \frac{a}{f_a} F \tilde{F} - \bar{f}_L M_f f_R + \frac{\partial_\mu a}{2f_a} \bar{f} c_f \gamma^\mu \gamma_5 f$

# The dark matter candidate models

1904.07915, TASI lecture



Axion and ALP dark matter



HEP at a cross-road: explore all directions!

# Misalignment and Axion Dark Matter

- Global  $U(1)_{\text{PQ}}$  symmetry

- Spontaneous broken leads to massless goldstone (**Axion**)

$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} = 0$$

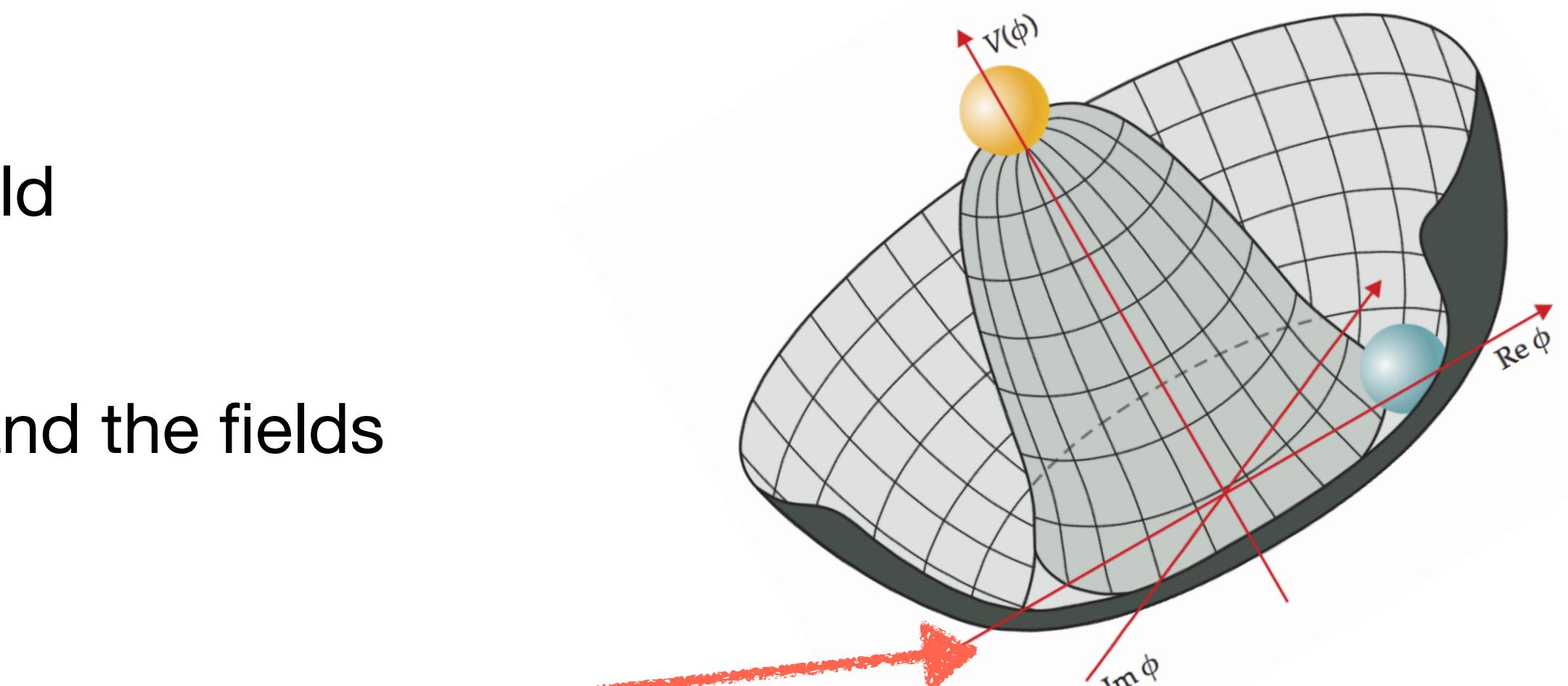
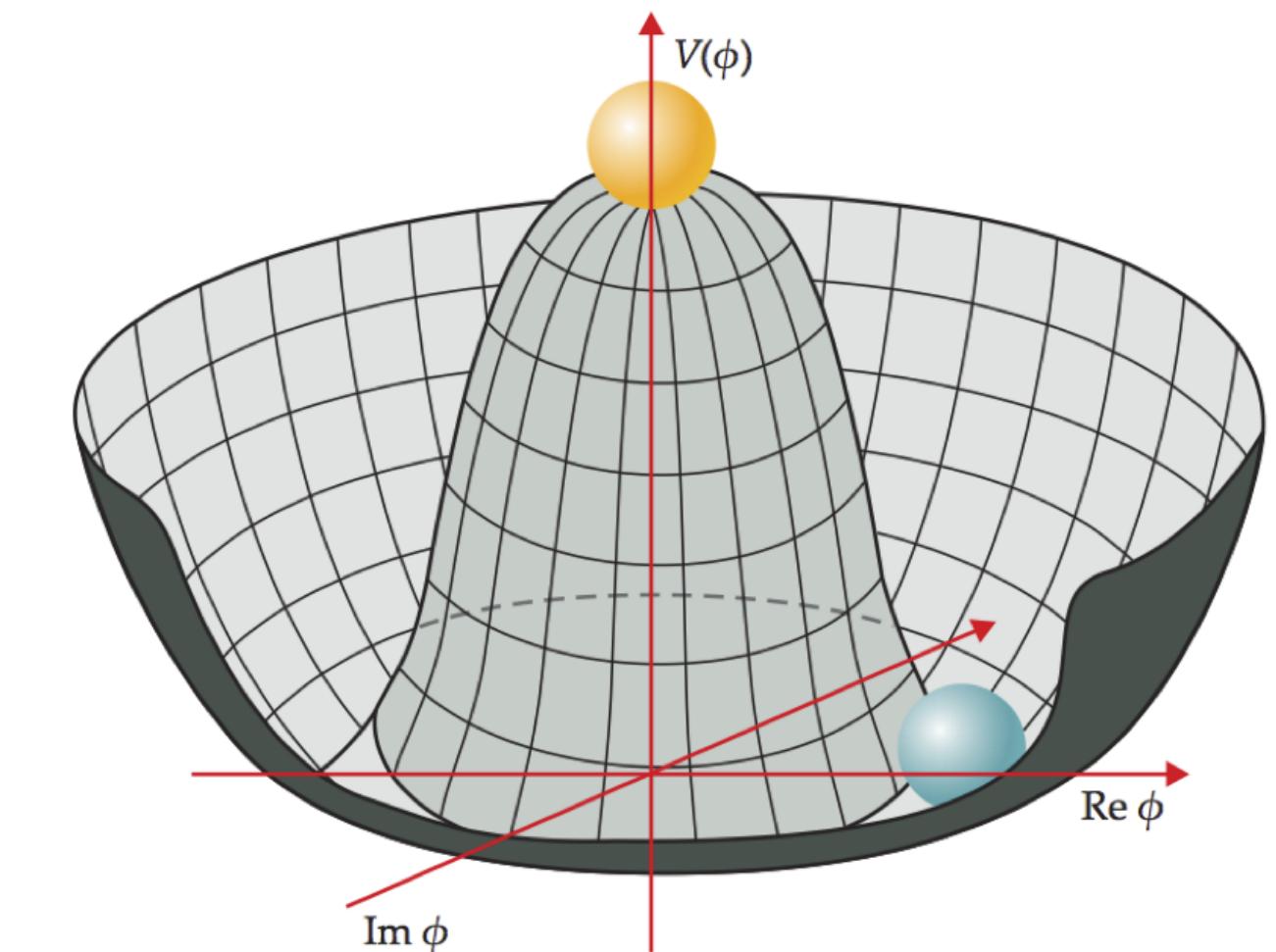
- At QCD scale  $\sim O(1)$  GeV,

- Potential from Chiral Lagrangian explicitly breaks the symmetry leads to massive axion

- Energy stored in coherent oscillation of axion field

- When  $m_\phi \sim \frac{\Lambda^2}{f_\phi} \sim H$ , misalignment happens and the fields turns into particles: **cold dark matter**

- QCD vacuum picks  $\Theta = \theta_{\text{QCD}} + \xi \langle a \rangle / f_a = 0$

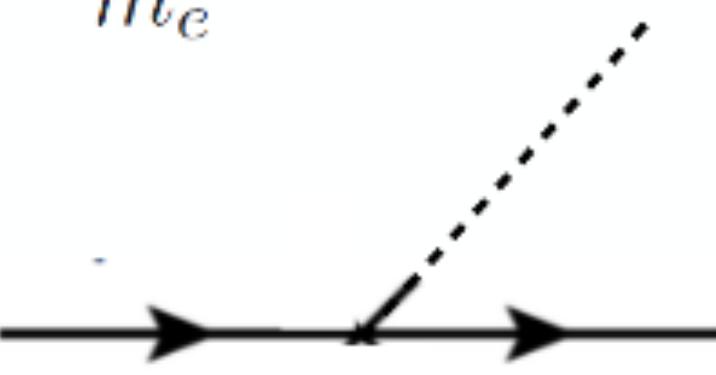
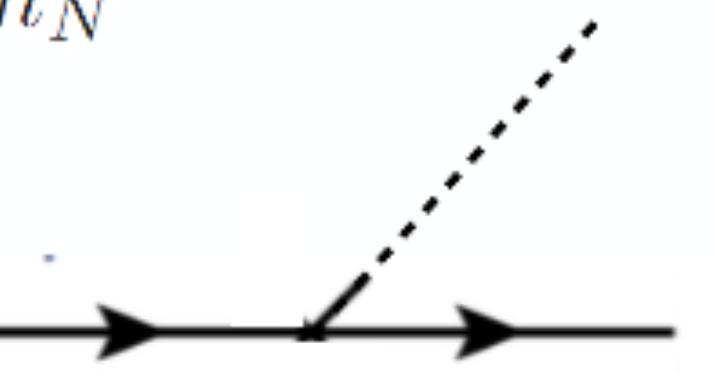
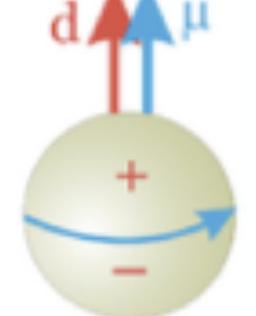


# The axion effective Lagrangian at quark-level

- Axion can couple to SM gauge bosons and fermions

$$\mathcal{L}_{\text{ALP}} = g_{ag} \frac{a}{f_a} G \tilde{G} + g_{a\gamma} \frac{a}{f_a} F \tilde{F} + g_{af} \frac{\partial_\mu a}{2f_a} \bar{f} \gamma^\mu \gamma_5 f$$

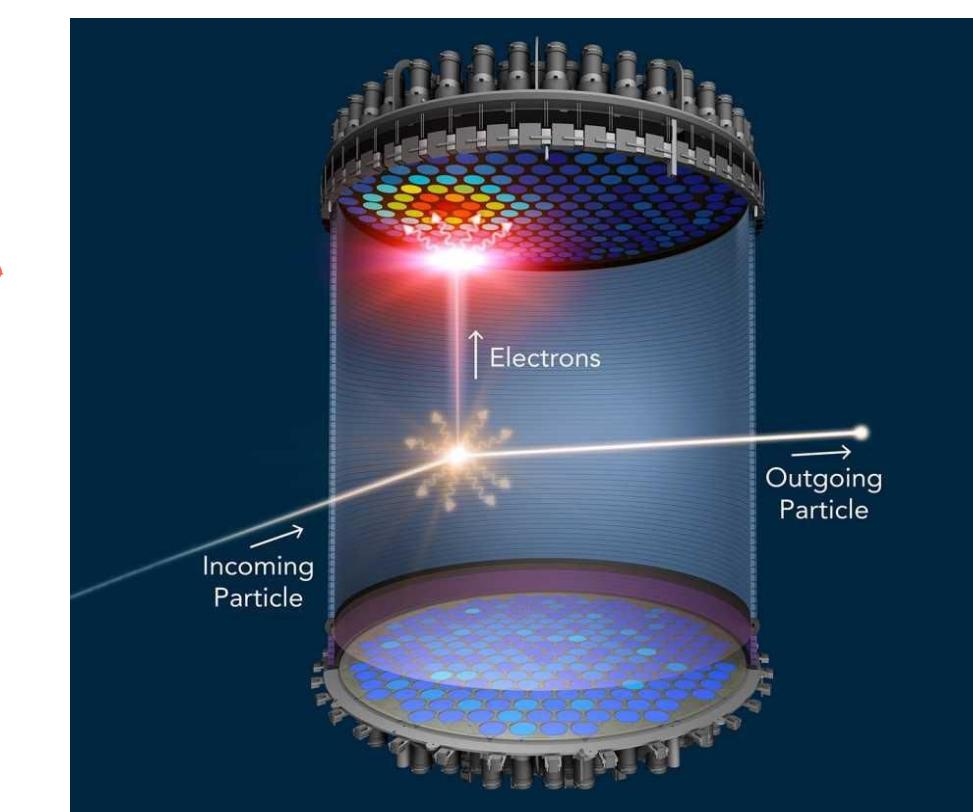
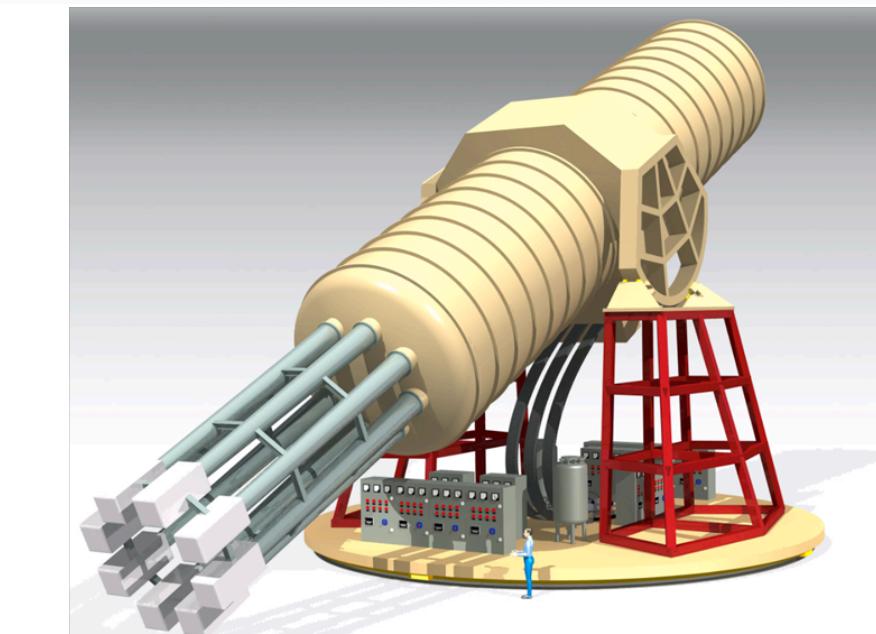
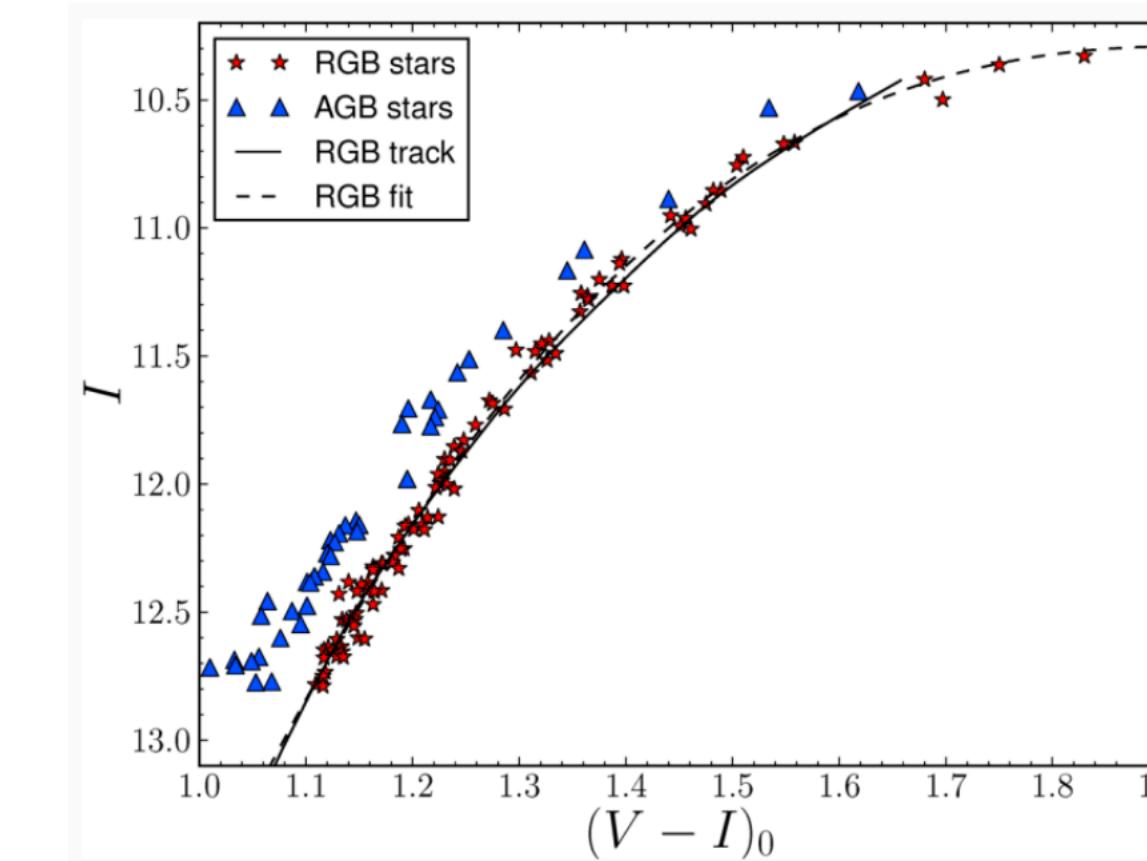
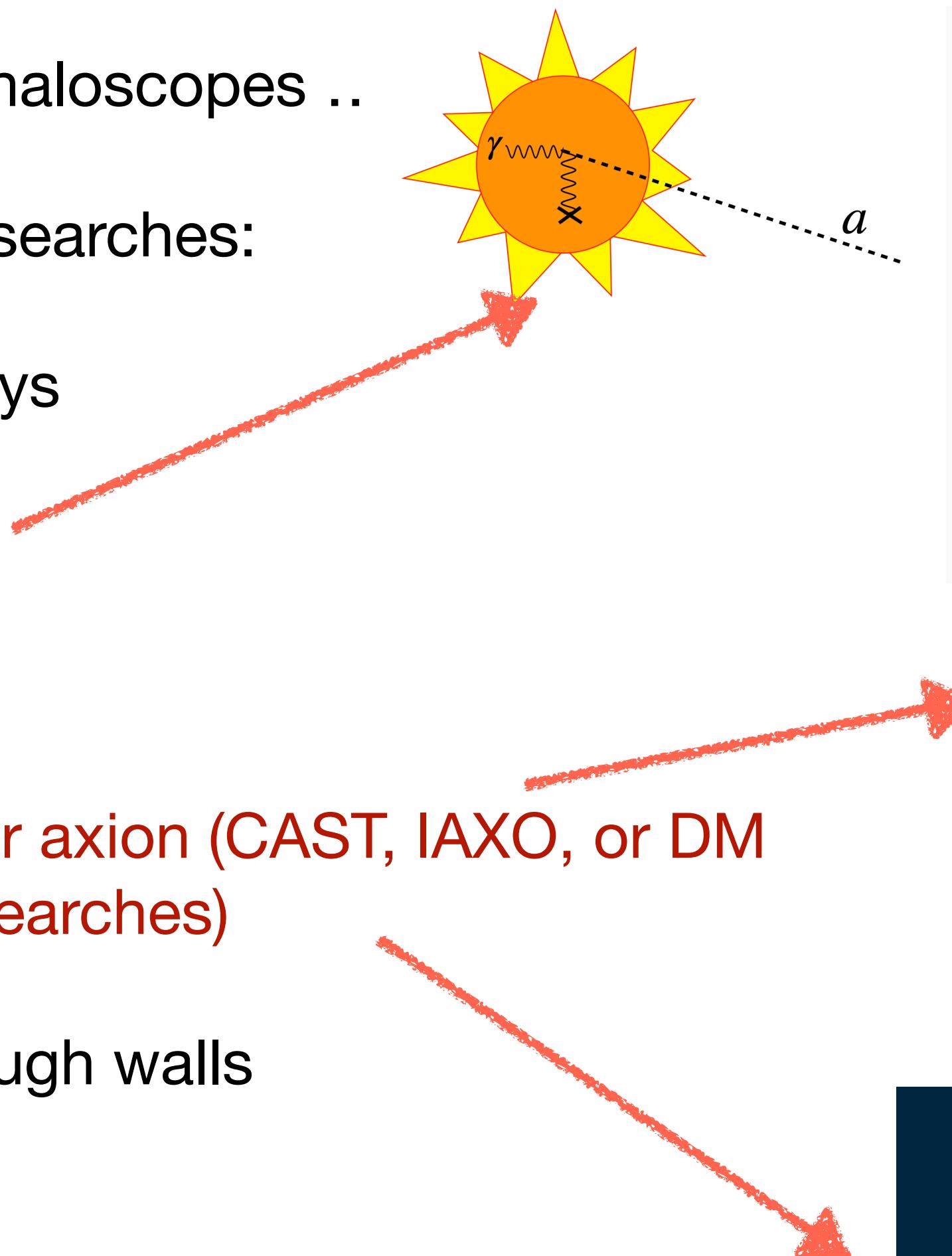
- Detection of axion through various couplings

photon coupling	electron coupling	nucleon coupling	CP Neutron electric dipole
$-\frac{g_{a\gamma}}{4} F_{\mu\nu} \tilde{F}^{\mu\nu} a$ 	$\frac{g_{ae}}{m_e} [\bar{e} \gamma^\mu \gamma^5 e] \partial_\mu a$ 	$\frac{g_{aN}}{m_N} [\bar{N} \gamma^\mu \gamma^5 N] \partial_\mu a$ 	 $\propto \frac{1}{m_n} [F_{\mu\nu} \bar{n} \sigma^{\mu\nu} \gamma_5 n] \frac{A}{f_A}$ 

# Experimental searches for Axion-Like Particles axion

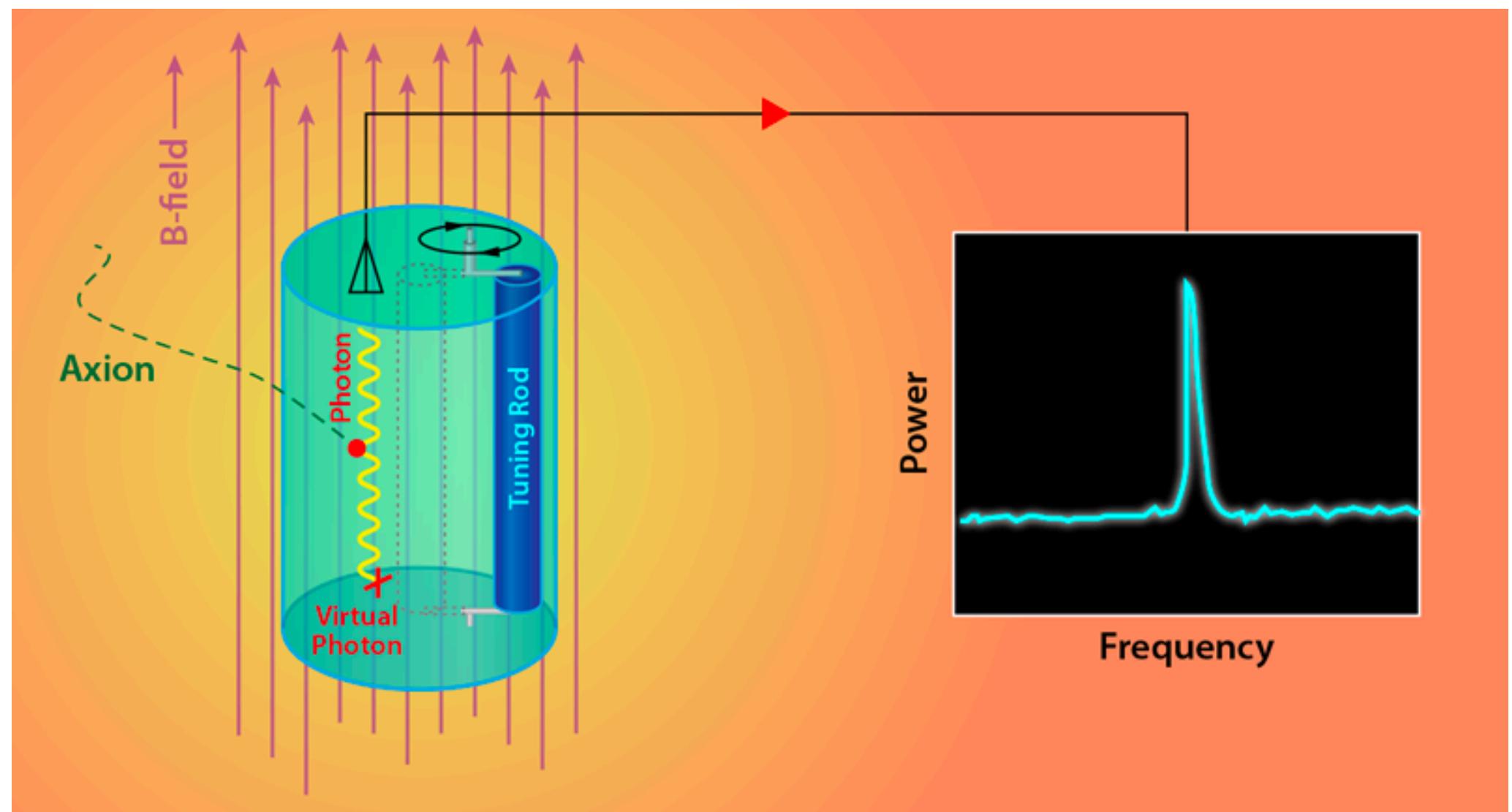
## Methodology:

- Dark Matter Axion: haloscopes ..
- Axion independent searches:
  - Rare meson decays
  - Stellar cooling
  - Supernova
  - Helioscopes: solar axion (CAST, IAXO, or DM direct detection searches)
  - Light shining through walls
  - Polarization
  - Fifth force
  - Radio wave detection



# The detection of ultralight bosonic dark matter

- Mass ranges from  $[10^{-22}, 10^3]$  eV, DM exist as **classical fields**
  - Interacting feebly with SM sector, interdisciplinary collaboration with **Atomic Molecular Optics, Astrophysics, Astronomy and Cosmology**
  - Various detection methods:
    - Star as Laboratory: exotic energy loss (A', ALP, S)
    - Early universe CMB, Gamma ray propagation, Black Hole picture and polarization (ALP、A')
    - Lab resonant cavity searches: (ADMX, HAYSTAC ...) (ALP, A')
    - Lab broad-band searches: (WISPMX, Dark E-field ) (ALP, A')
    - 5th force, Equivalent Principle test (S, A')
    - DM direct detection experiments (XENONnT, PANDAX-4T, CDEX) (ALP, A')
    - Radio astronomy (ALP, A')

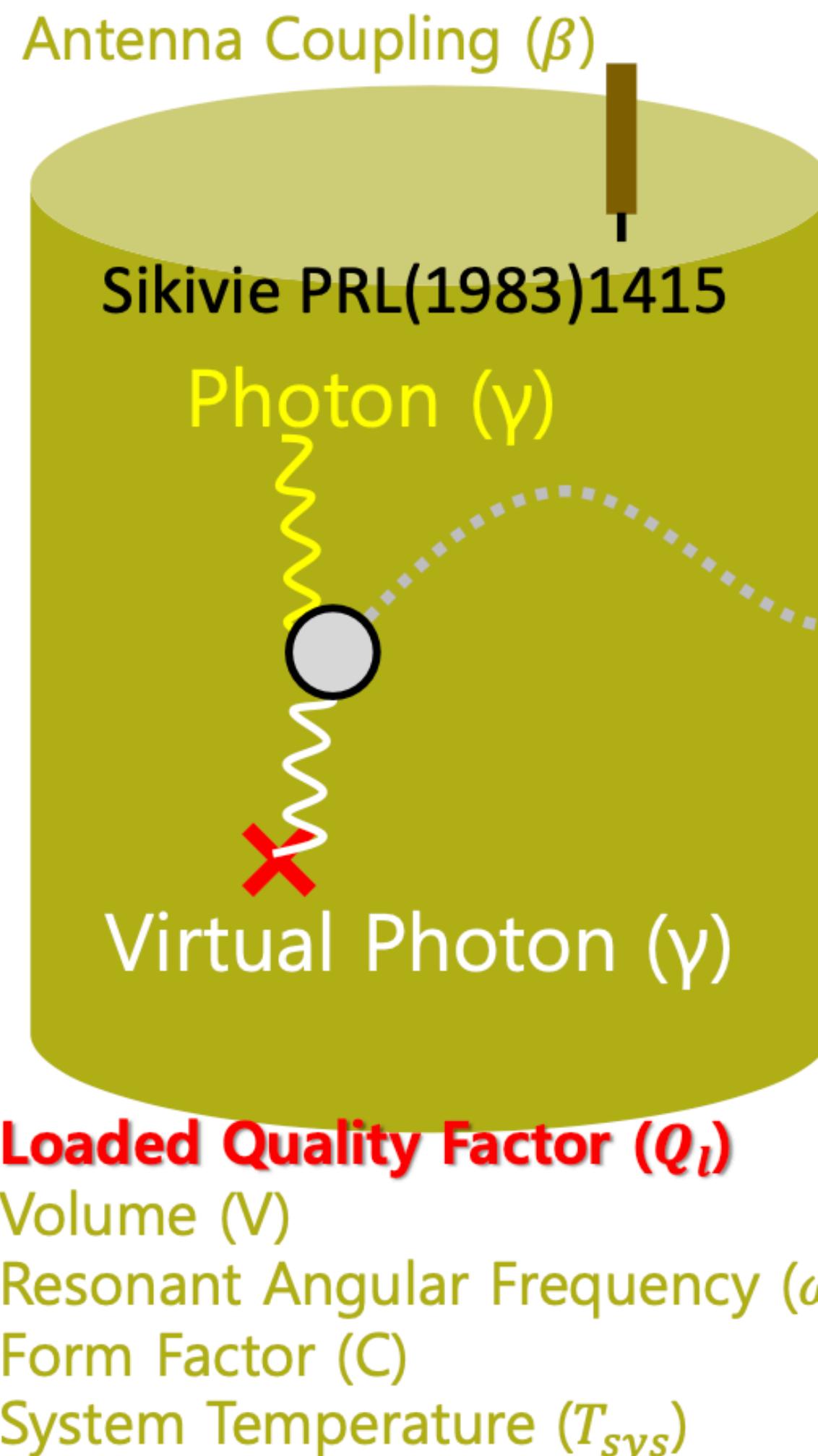


Experimental searches is related to model and couplings

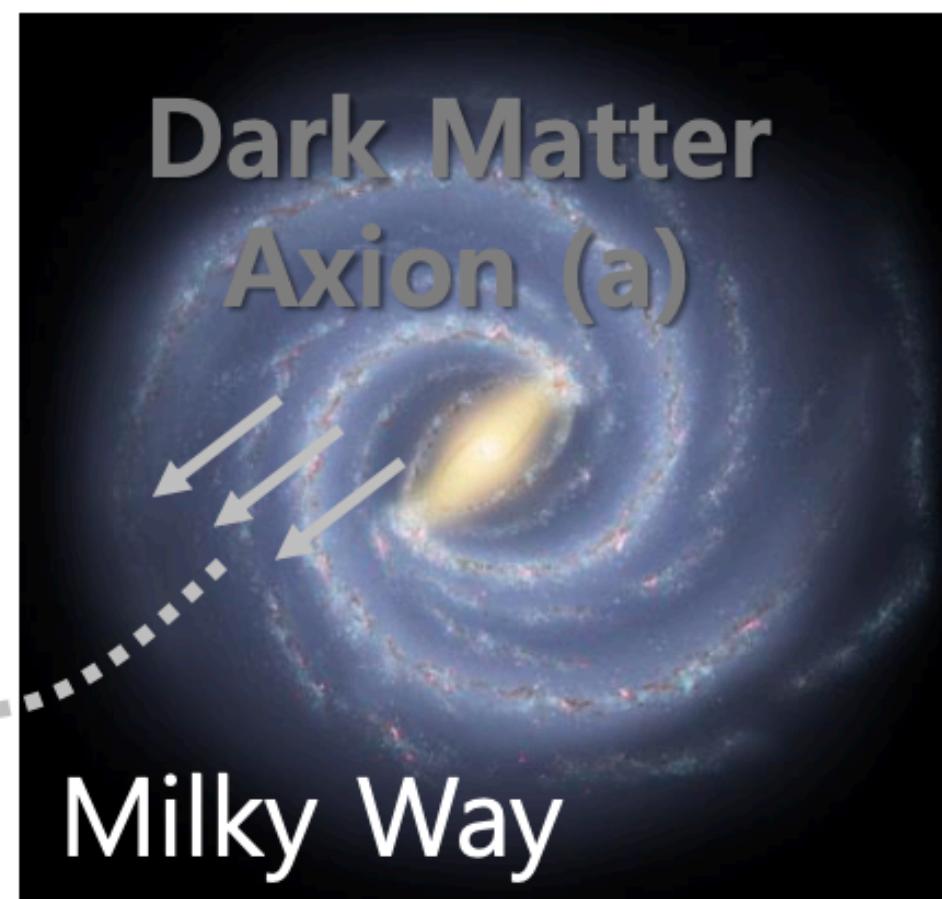
$$g_{a\gamma\gamma} a F_{\mu\nu} \epsilon^{\mu\nu\alpha\beta} F_{\alpha\beta} \sim g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$$

# The resonant searches for ALP via photon coupling

- Tuning cavity resonant frequency to match axion mass



From Danho Ahn@Patras2023



$$g_{a\gamma\gamma} a F_{\mu\nu} \epsilon^{\mu\nu\alpha\beta} F_{\alpha\beta} \sim g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$$

Signal Power  $P_{sig}$  =  $\frac{\beta}{1 + \beta} g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a^2} \mathbf{B}^2 V \omega_0 C \frac{Q_a Q_l}{Q_a + Q_l}$

Kim *et al.* JCAP03(2020)066

Coupling Constant, Dark Matter Axion Density, Axion Mass, Axion Quality Factor

Scan Rate  $\frac{df}{dt} \propto \frac{\mathbf{B}^4 V^2 C^2}{k_B^2 T_{sys}^2} Q_l Q_a$

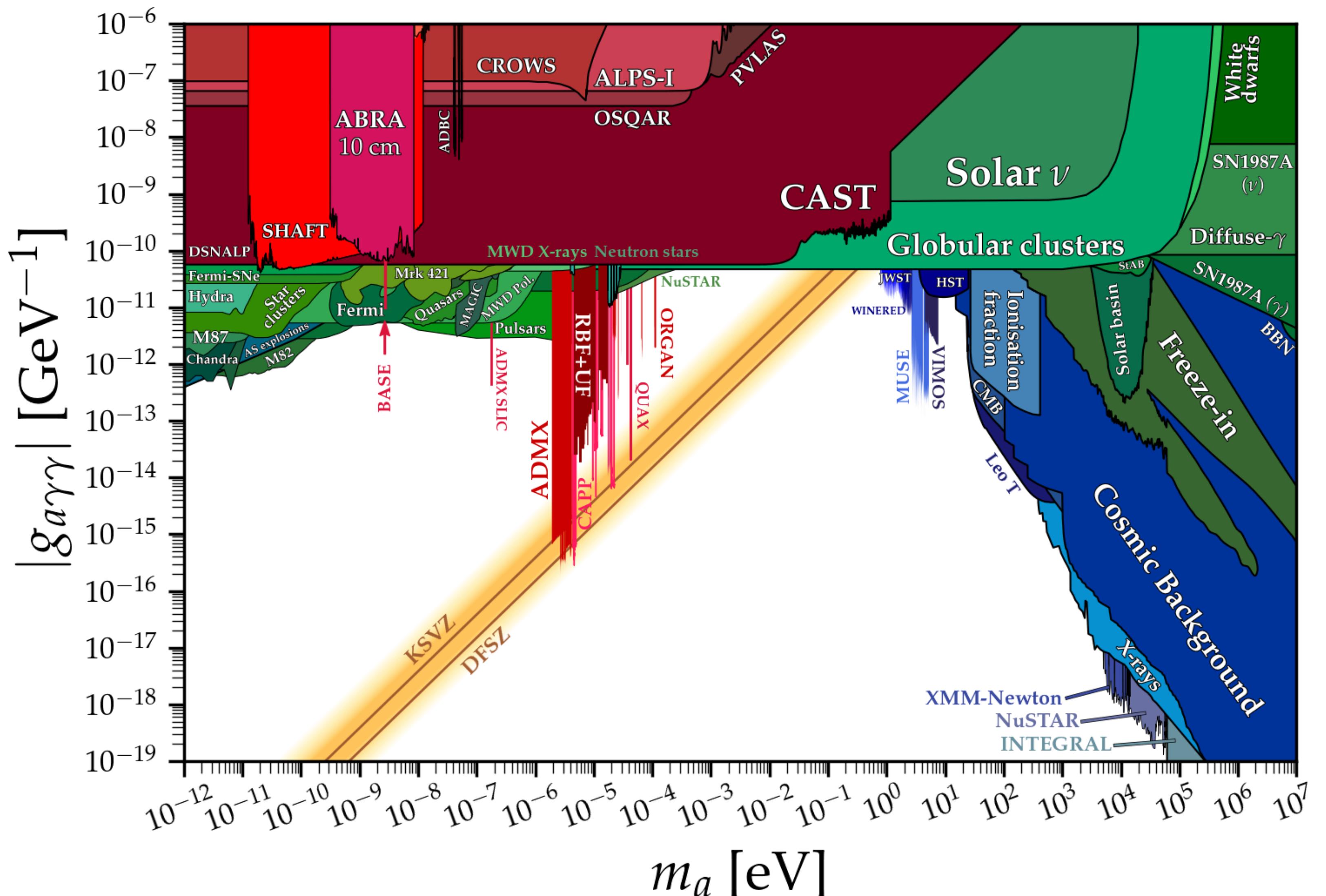
$Q_l \gg Q_a \sim 10^6$

System Noise Temperature  $\sim 200 \text{ mK}$

Refer to Session 02, Thu, Dr. Jinsu Kim

# The resonant searches for ALP via photon coupling

- The overview of ALP-photon coupling searches
- Very competitive research field



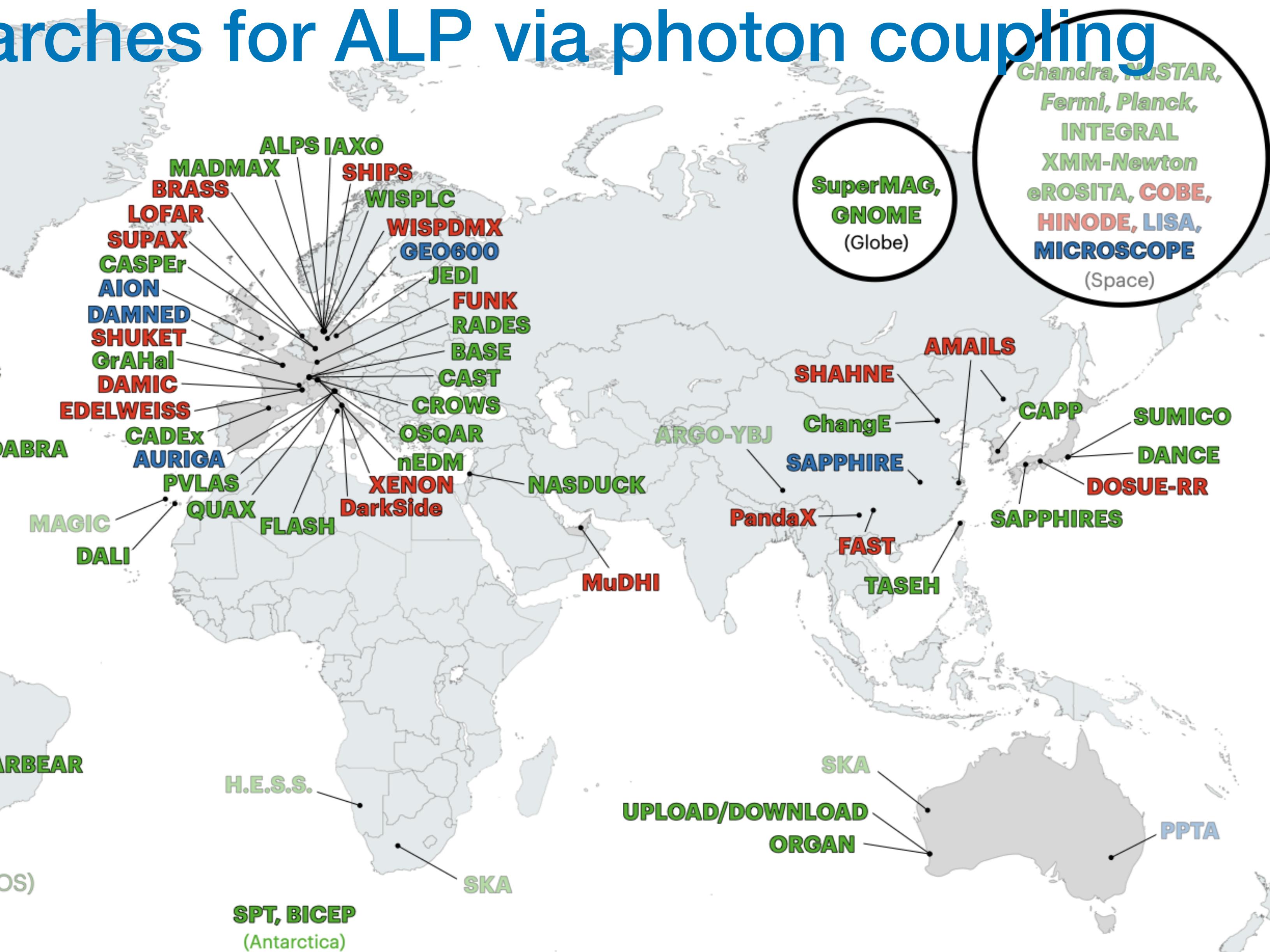
<https://cajohare.github.io/AxionLimits/>

# The resonant searches for ALP via photon coupling

A map of North America with various scientific experiment names labeled across the continent. The labels are color-coded: green for ARIADNE, SQuAD, BREAD, HAYSTAC, SHAFT, CASPER, ABRACADABRA, ALPHA, BACON, and HAWC; red for Eöt-Wash, ORPHEUS, LIGO, MAGIS, DM-Radio, QUALIPHIDE, Dark E-field Radio, SNIPE, LZ, and SNO; blue for SuperCDMS, SENSEI, and LAMPOST; and blue-green for ADMX. Lines connect the labels to specific locations on the map.

- ARIADNE**
- SQuAD**
- BREAD**
- HAYSTAC**
- SHAFT**
- CASPER**
- ABRACADABRA**
- ALPHA**
- BACON**
- HAWC**
- Eöt-Wash**
- ORPHEUS**
- LIGO**
- MAGIS**
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- QUALIPHIDE**
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# Axion Dark photon Scalar/vector



# The resonant searches of nucleon couplings

- The ALP DM field

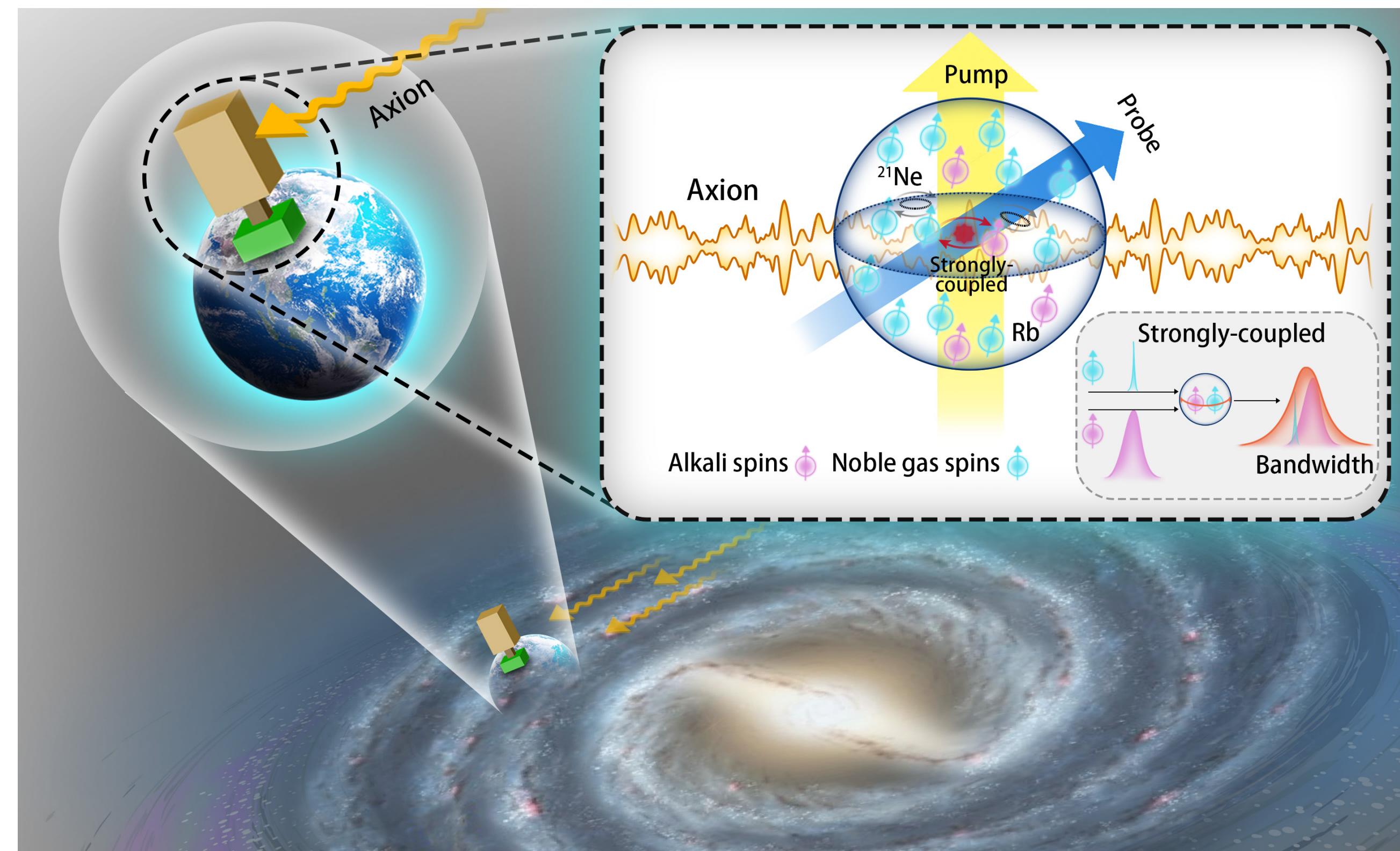
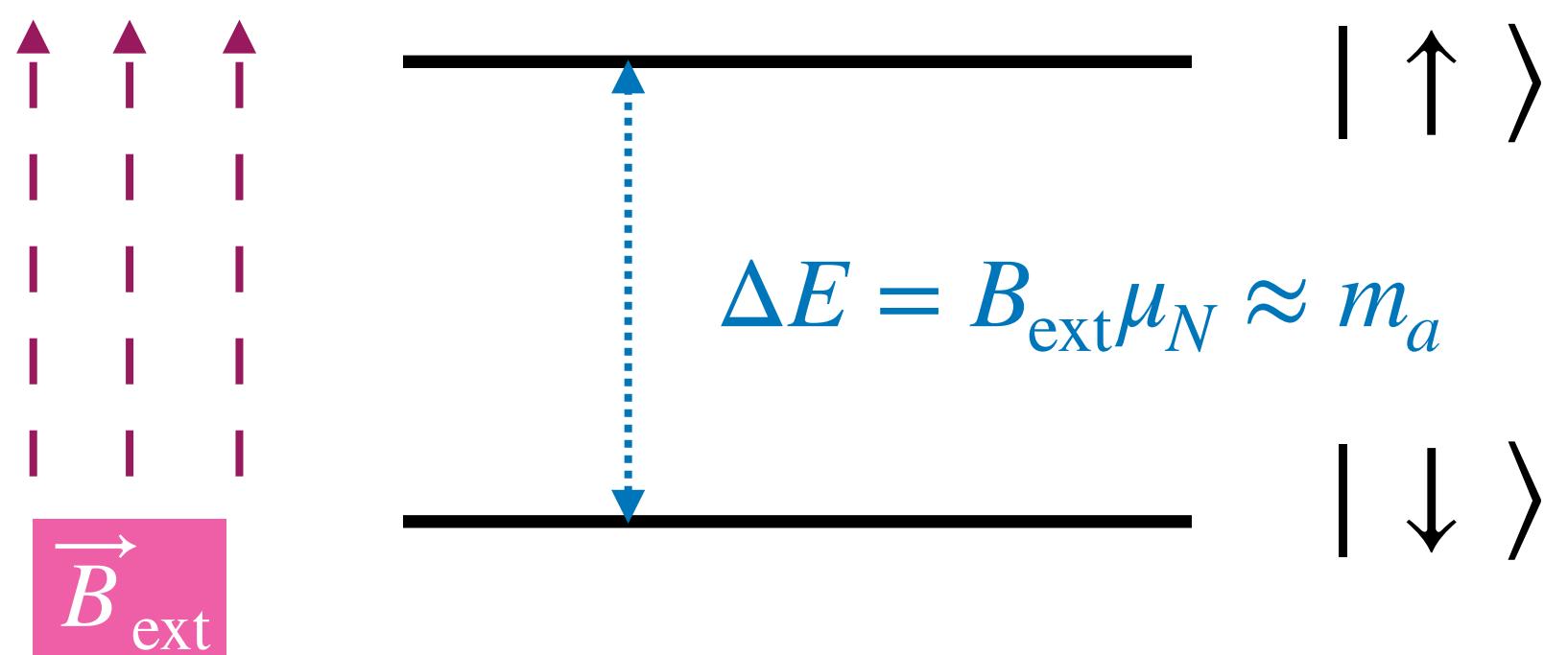
$$a(x, t) \approx a_0 \cos(\omega t - \vec{p} \cdot \vec{x} + \theta_0)$$

- The axion-wind Hamiltonian

$$H = g_{aNN} \frac{\partial_\mu a}{2f_a} \bar{N} \gamma^\mu \gamma_5 N = g_{aNN} \vec{\nabla} a \cdot \vec{\sigma}_N$$

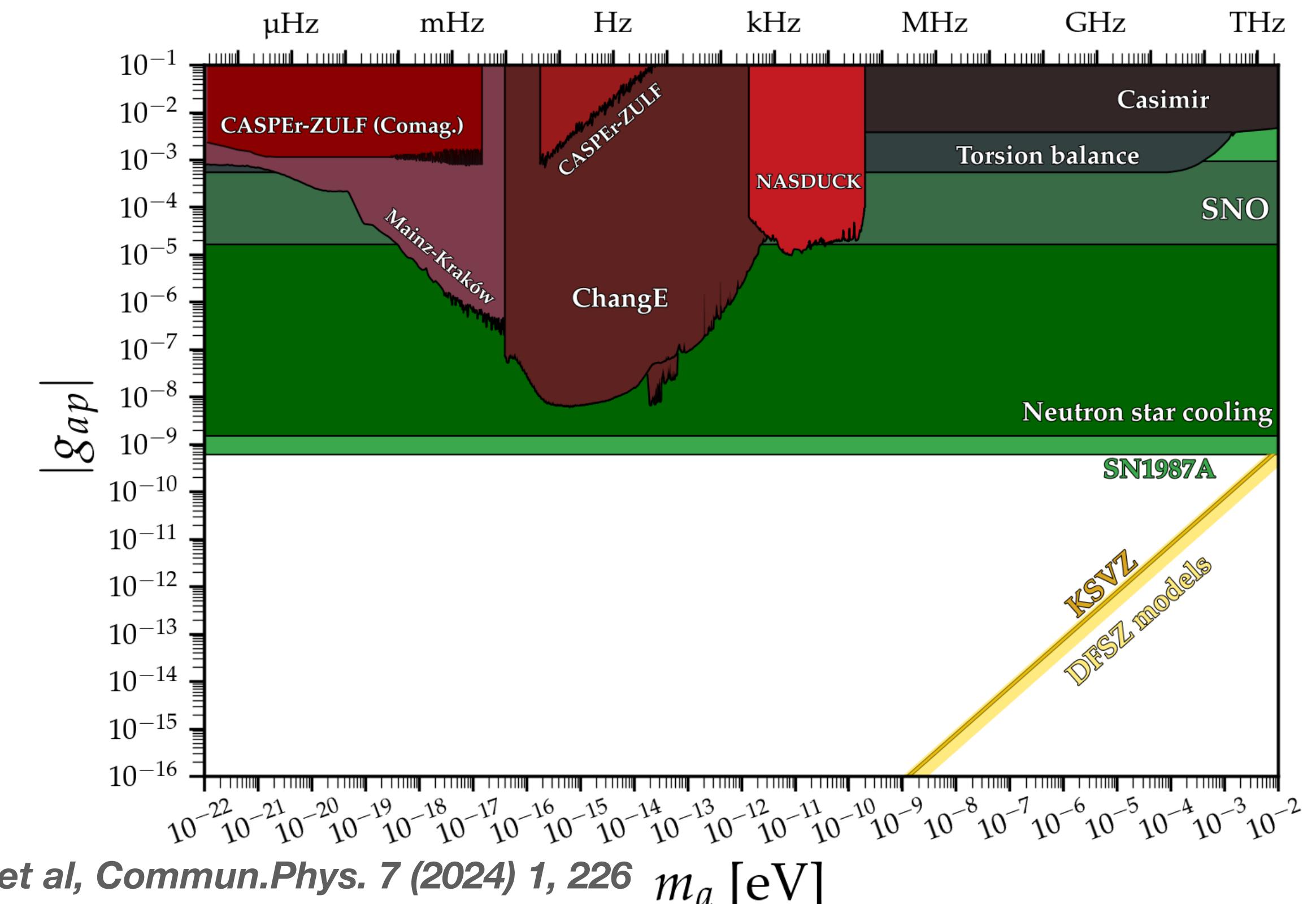
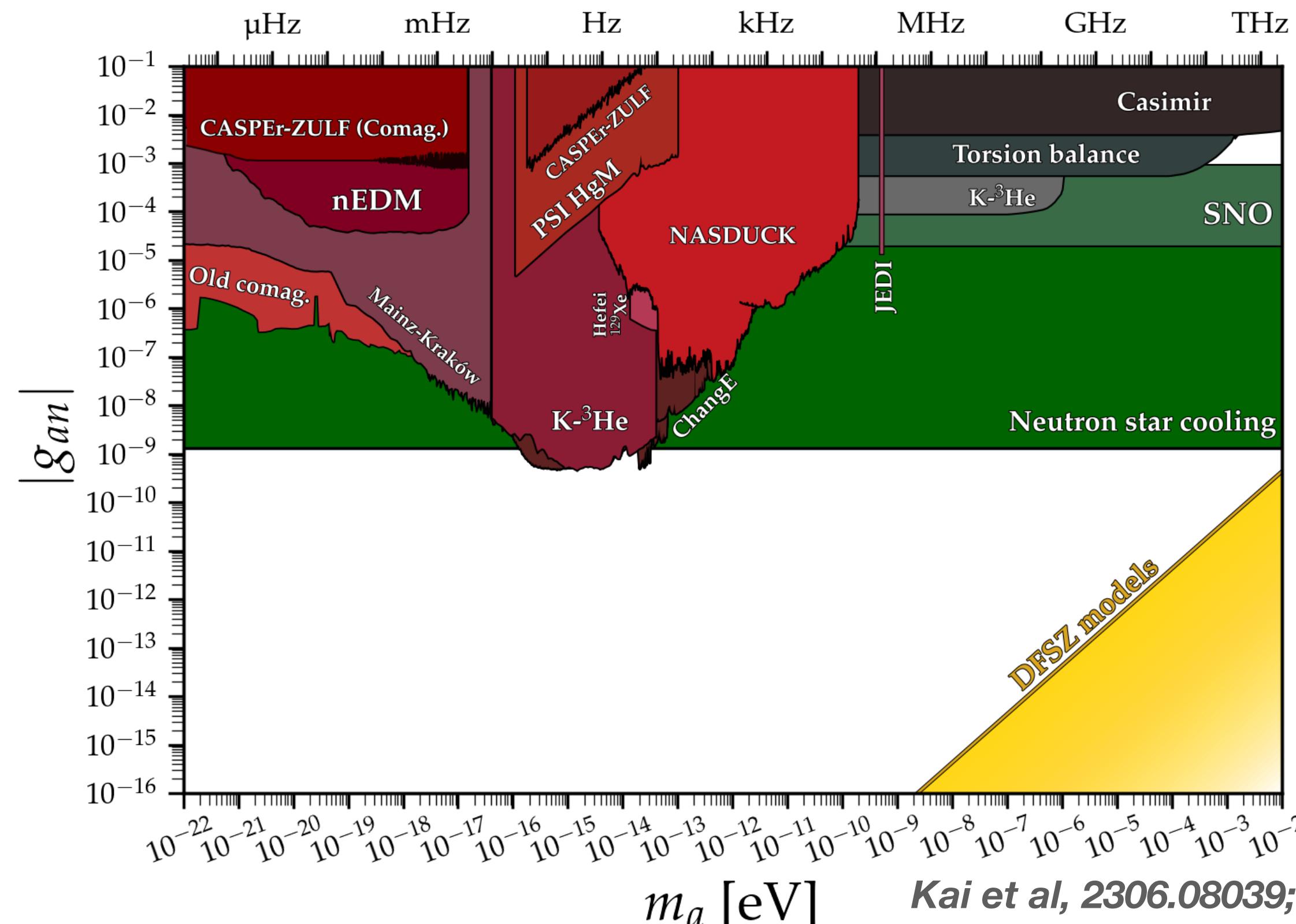
$$\approx g_{aNN} \vec{v}_a \cdot \vec{\sigma}_N \times \sqrt{2\rho_a} \sin(p \cdot x)$$

- A Zeeman split in B field



# ChangE results

- ChangE experiments set competitive limits on ALP-nucleon couplings (AxionLimits version)
- Improving ALP-proton coupling limits by  $10^5 - 10^6$
- Providing best limits on ALP-neutron couplings at  $\sim[0.02, 0.2]$  Hz and  $[10, 200]$  Hz



# Outlines

- Axion general introduction
- Axion-scalar meson interactions
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# The axion effective Lagrangian at quark-level

- A more detailed effective Lagrangian

$$\begin{aligned}\mathcal{L}_{\text{eff},0} = & \bar{q}_0(iD_\mu\gamma^\mu - \mathbf{m}_{q,0})q_0 + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}a^2 \\ & + g_{ag,0}\frac{a}{f_a}G\tilde{G} + g_{a\gamma,0}\frac{a}{f_a}F\tilde{F} + \frac{\partial_\mu a}{f_a} (\bar{q}_L \mathbf{k}_{L,0} \gamma^\mu q_L + \bar{q}_R \mathbf{k}_{R,0} \gamma^\mu q_R + \dots)\end{aligned}$$

Bauer et al, PRL 127 (2021), 081803

- Quark mass  $\mathbf{m}_{q,0}$  diagonal and real
- Coupling to both left/right fermions  $\mathbf{k}_{L,0}$  and  $\mathbf{k}_{R,0}$

# The axion-dependent chiral rotation

- Use an axion-dependent chiral rotation to eliminate  $aG\tilde{G}$  term

$$q_0(x) = \exp \left[ -i(\delta_{q,0} + \kappa_{q,0}\gamma_5)c_{gg} \frac{a(x)}{f_a} \right] q(x)$$

Bauer et al, PRL 127 (2021), 081803

$$\text{Tr}(\kappa_{q,0}) = 1$$

- New effective Lagrangian

$$\begin{aligned} \mathcal{L}_{\text{eff}} = & \bar{q}(iD_\mu\gamma^\mu - \mathbf{m}_q(a))q + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}a^2 \\ & + g_{a\gamma} \frac{a}{f_a} F\tilde{F} + \frac{\partial_\mu a}{f_a} (\bar{q}_L \mathbf{k}_L(a) \gamma^\mu q_L + \bar{q}_R \mathbf{k}_R(a) \gamma^\mu q_R + \dots) \end{aligned}$$

# The axion-dependent chiral rotation

- Define the chiral rotations (2-flavor for simplicity)

$$\theta_L \equiv \delta_{q,0} - \kappa_{q,0} \quad U_L \equiv \exp [-i\theta_L a/f_a]$$

$$\theta_R \equiv \delta_{q,0} + \kappa_{q,0} \quad U_R \equiv \exp [-i\theta_R a/f_a]$$

- The relations between parameters

$$\mathbf{m}_q(a) = U_L^\dagger \mathbf{m}_0 U_R \rightarrow \begin{pmatrix} m_{u,0} e^{-2i\kappa_{u,0} c_{gg}} & 0 \\ 0 & m_{d,0} e^{-2i\kappa_{d,0} c_{gg}} \end{pmatrix}$$

Anomalous axion contribution

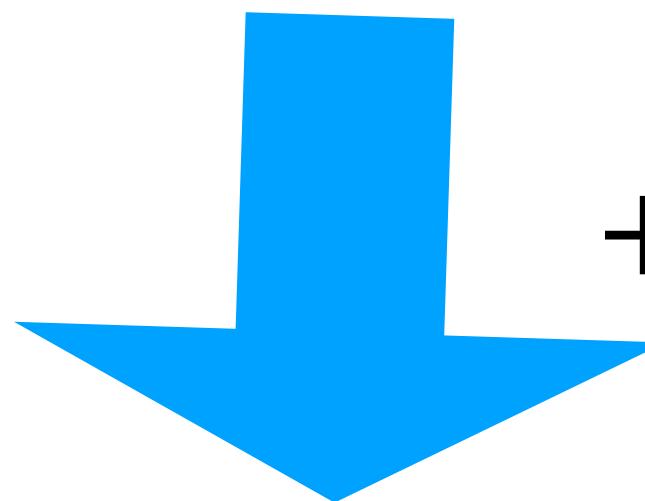
$$\mathbf{k}_L(a) = U_L^\dagger [\mathbf{k}_{L,0} + c_{gg} \boldsymbol{\theta}_{L,0}] U_L \rightarrow \mathbf{k}_{L,0} + c_{gg} \boldsymbol{\theta}_{L,0}$$

$$\mathbf{k}_R(a) = U_R^\dagger [\mathbf{k}_{R,0} + c_{gg} \boldsymbol{\theta}_{R,0}] U_R \rightarrow \mathbf{k}_{R,0} + c_{gg} \boldsymbol{\theta}_{R,0}$$

$$g_{a\gamma} = g_{a\gamma_0} - 2N_c c_{gg} \text{Tr} [\mathbf{Q}^2 \boldsymbol{\kappa}_{q,0}]$$

# The consistent ChPT axion Lagrangian

$$\mathcal{L}_{\text{eff}} = \bar{q}(iD_\mu\gamma^\mu - \mathbf{m}_q(a))q + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}a^2$$



$$+ g_{a\gamma} \frac{a}{f_a} F\tilde{F} + \frac{\partial_\mu a}{f_a} (\bar{q}_L \mathbf{k}_L(a) \gamma^\mu q_L + \bar{q}_R \mathbf{k}_R(a) \gamma^\mu q_R + \dots)$$

- ChPT Lagrangian matching

$$U = \exp[(\sqrt{2}i/f_\pi)\pi^a \boldsymbol{\tau}^a]$$

$$\mathcal{L}_{\chi\text{PT}} = \frac{f_\pi^2}{8} \left[ (D^\mu U)(D_\mu U)^\dagger \right] + \frac{f_\pi^2}{4} B_0 \text{Tr} \left[ \mathbf{m}_q(a) U^\dagger + h.c. \right] + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}a^2 + g_{a\gamma} \frac{a}{f_a} F\tilde{F}$$

- The axion derivative coupling

Bauer et al, PRL 127 (2021), 081803

$$D^\mu U \rightarrow D^\mu U - i \frac{\partial^\mu a}{f_a} (\mathbf{k}_L U - U \mathbf{k}_R)$$

# The importance of consistency

- The physical results should be independent of auxiliary parameters

$$q_0(x) = \exp \left[ -i(\delta_{q,0} + \kappa_{q,0}\gamma_5)c_{gg} \frac{a(x)}{f_a} \right] q(x)$$

- The most important channel  $\text{BR}(K \rightarrow \pi a)$  is off by a factor of 37 for 35 years

H. Georgi, D. B. Kaplan and L. Randall, Phys. Lett. B 169, 73-78 (1986)

- Model-independent expression for  $K \rightarrow \pi a$  and  $\pi^- \rightarrow e^- \bar{\nu}_e a$  have been obtained for all axion couplings

Bauer et al, PRL 127 (2021), 081803

# Axion couplings to other mesons/baryons/EFT

- Axion couplings to other mesons , e.g.  $\eta$ ,  $\eta'$  etc

Gao, Guo, Oller, Zhou JHEP04(2023)022; Wang, Guo, Zhou PRD 109(2024)075030; Wang, Guo Lu, Zhou 2403.16064; Cao, Guo, 2408.15825

- Axion couplings to baryons

Vonk, Guo, Meissner JHEP03(2020)138, Lu, Du, Guo, Meissner, Vonk JHEP05(2020)001, Vonk Guo, Meissner JHEP08(2021)024 ...

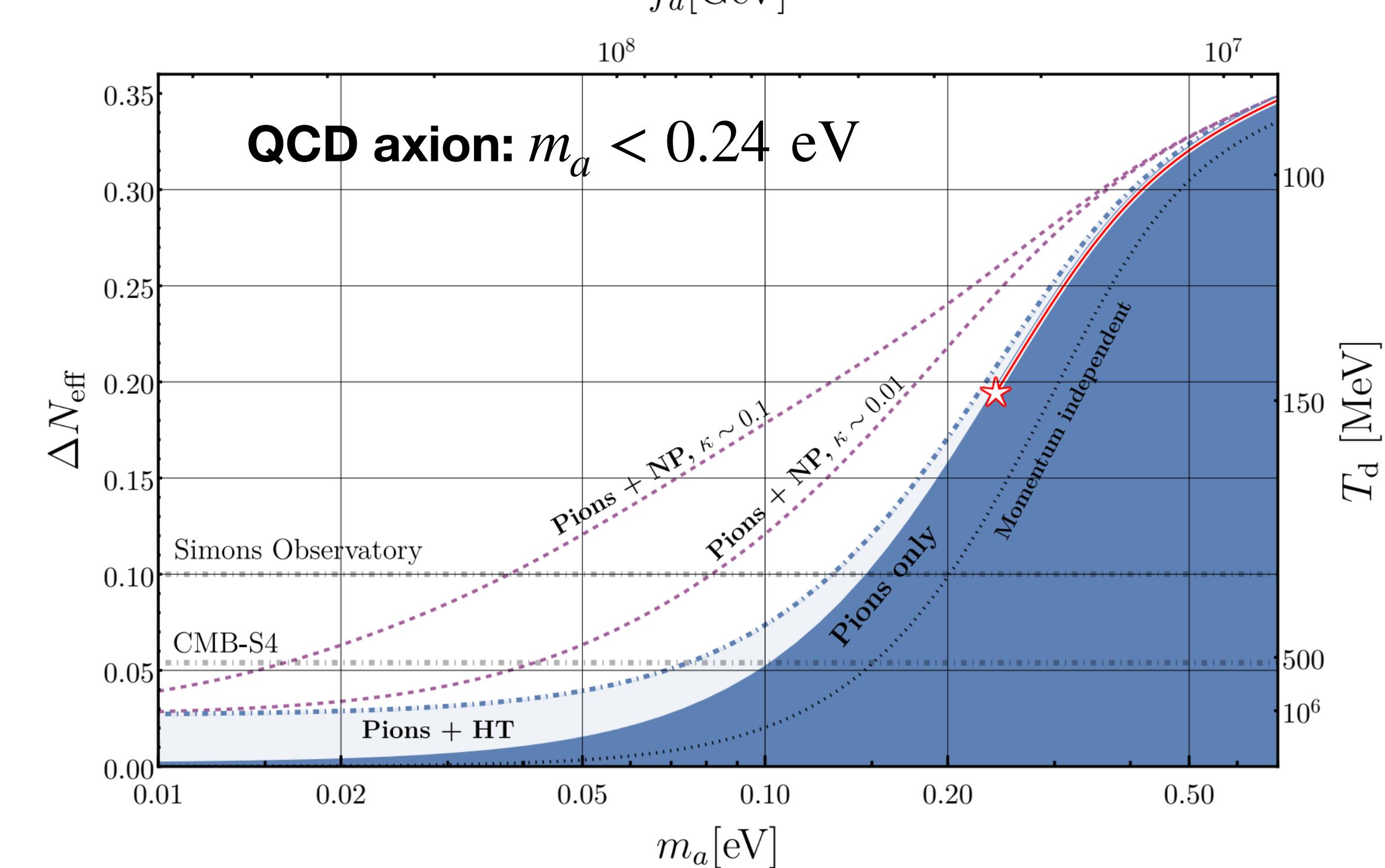
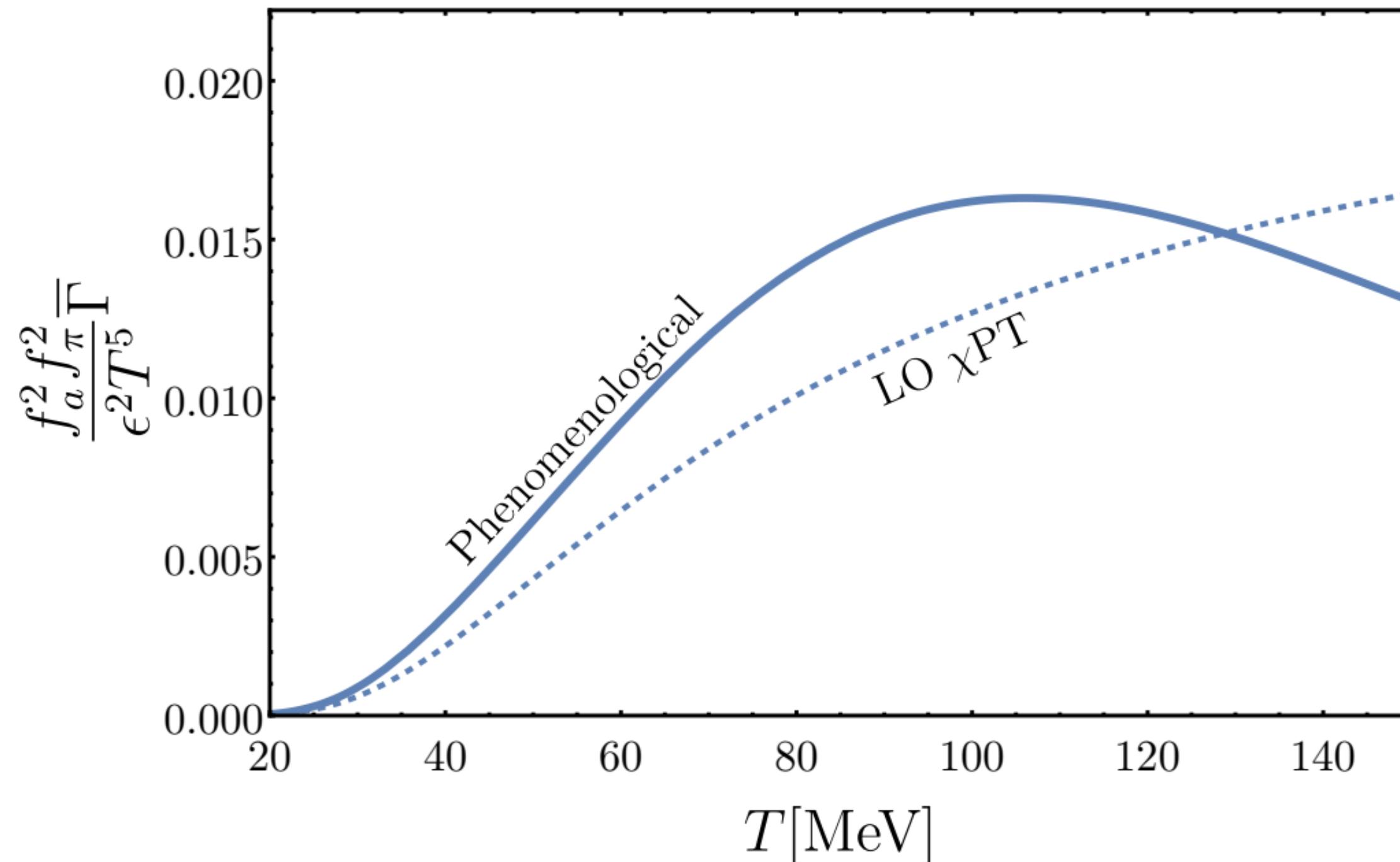
- Axion EFT

Hu, Jiang, Li, Xiao, Yu, PRD 103(2021)095025; Song, Sun, Yu JHEP01(2024)161

- ...

# Why accurate interactions are important?

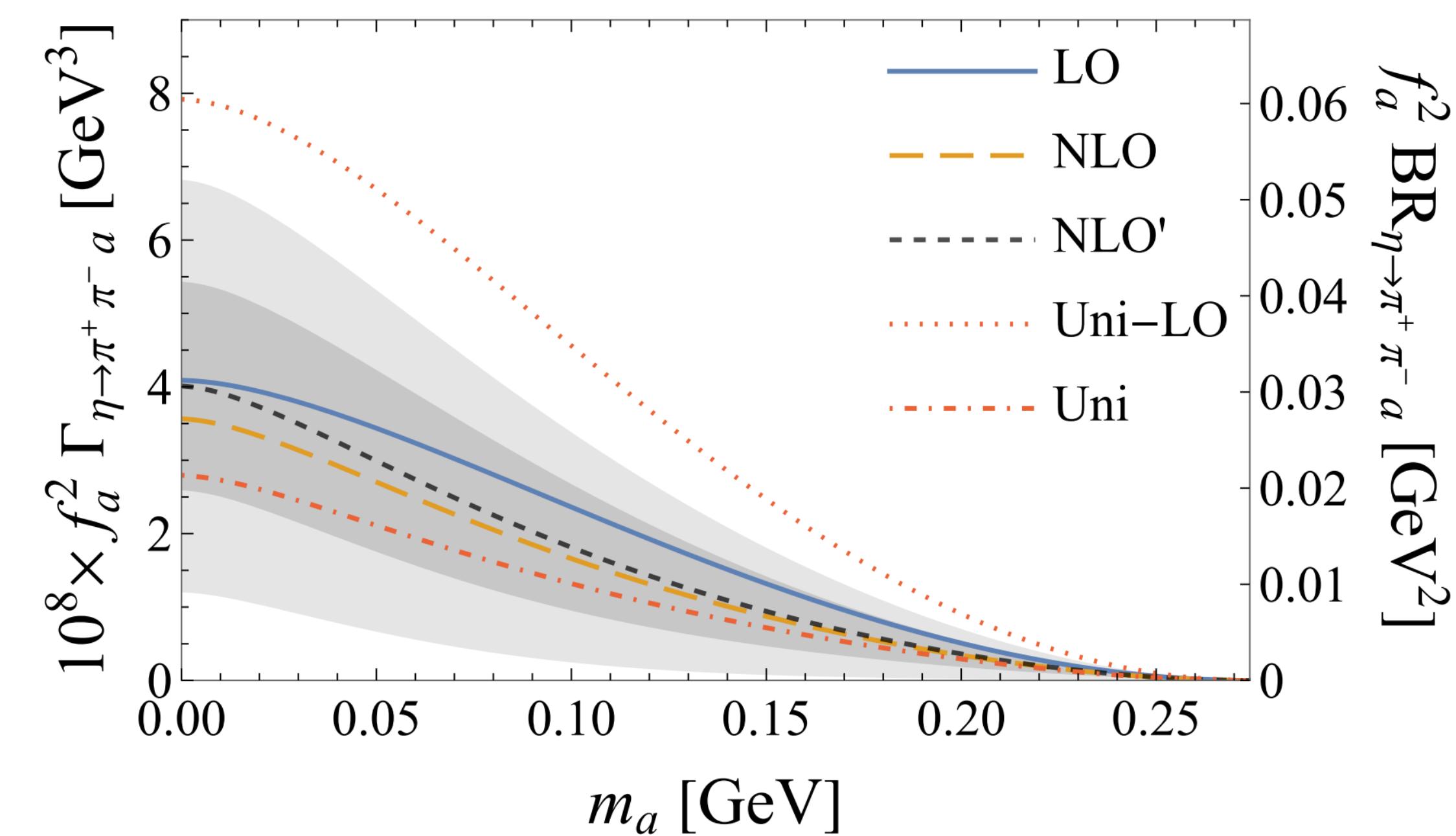
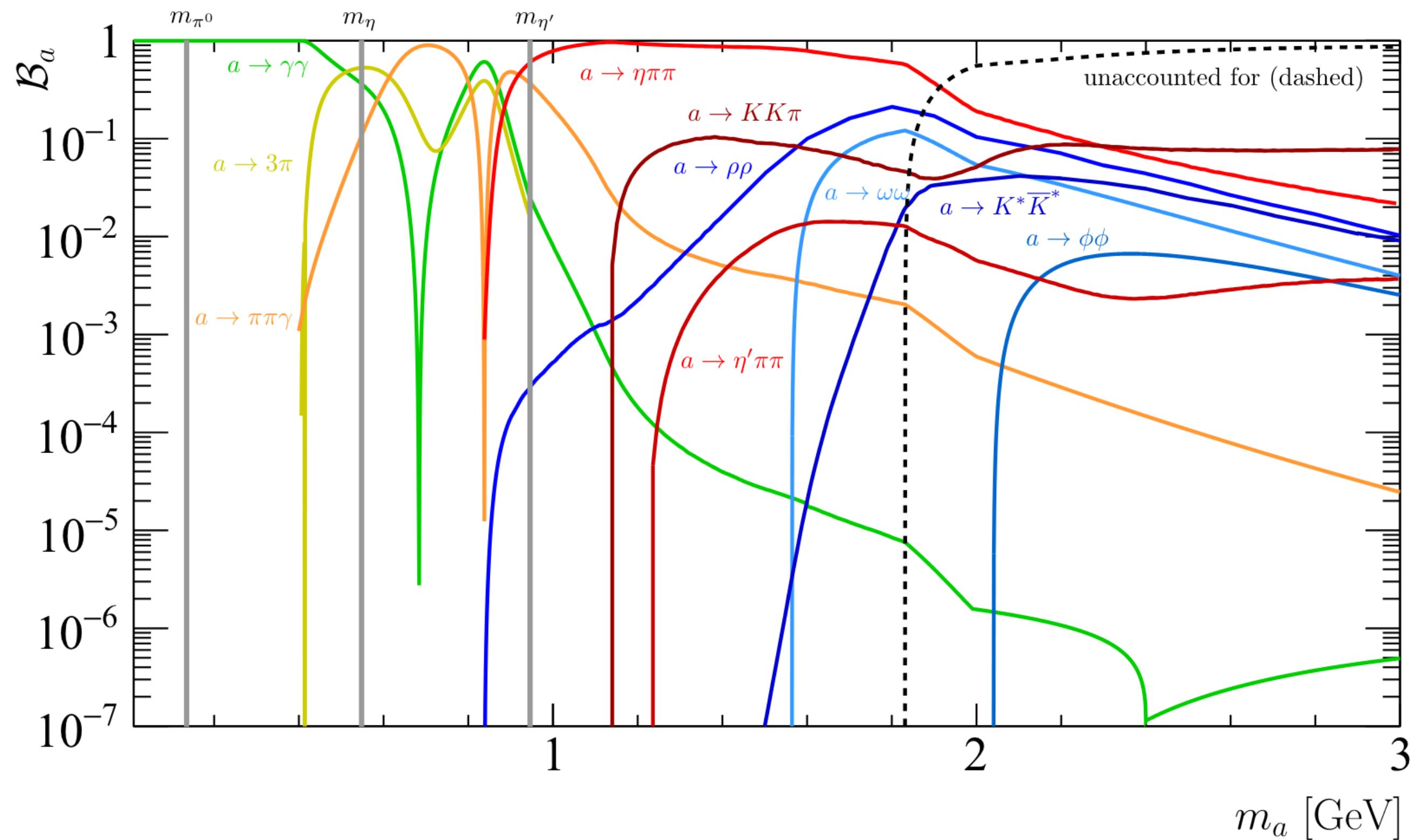
- 1. Prediction for thermal axion and its near future test by CMB observation
  - Thermal axion production (high T):  $q\bar{q} \rightarrow ga, qg \rightarrow qa$  *Ferreira, Notari PRL 120 (2018)191301*
  - QCD phase transition: *D'Eramo, Hajkarim, Yun PRL 128 (2022)152001*
  - Improved axion-pion scattering production:  $\pi\pi \leftrightarrow \pi a$  *Notari, Rompineve, Villadoro PRL 131 (2023)011004*



# Why accurate interactions are important?

- 2. Axion related exotic decay width and BR
  - Axion decay BR: *Aloni, Soreq, Williams PRL 123 (2019) 031803*
  - Other meson decays to Axion:  $K \rightarrow \pi a, \eta \rightarrow \pi \pi a$  etc...

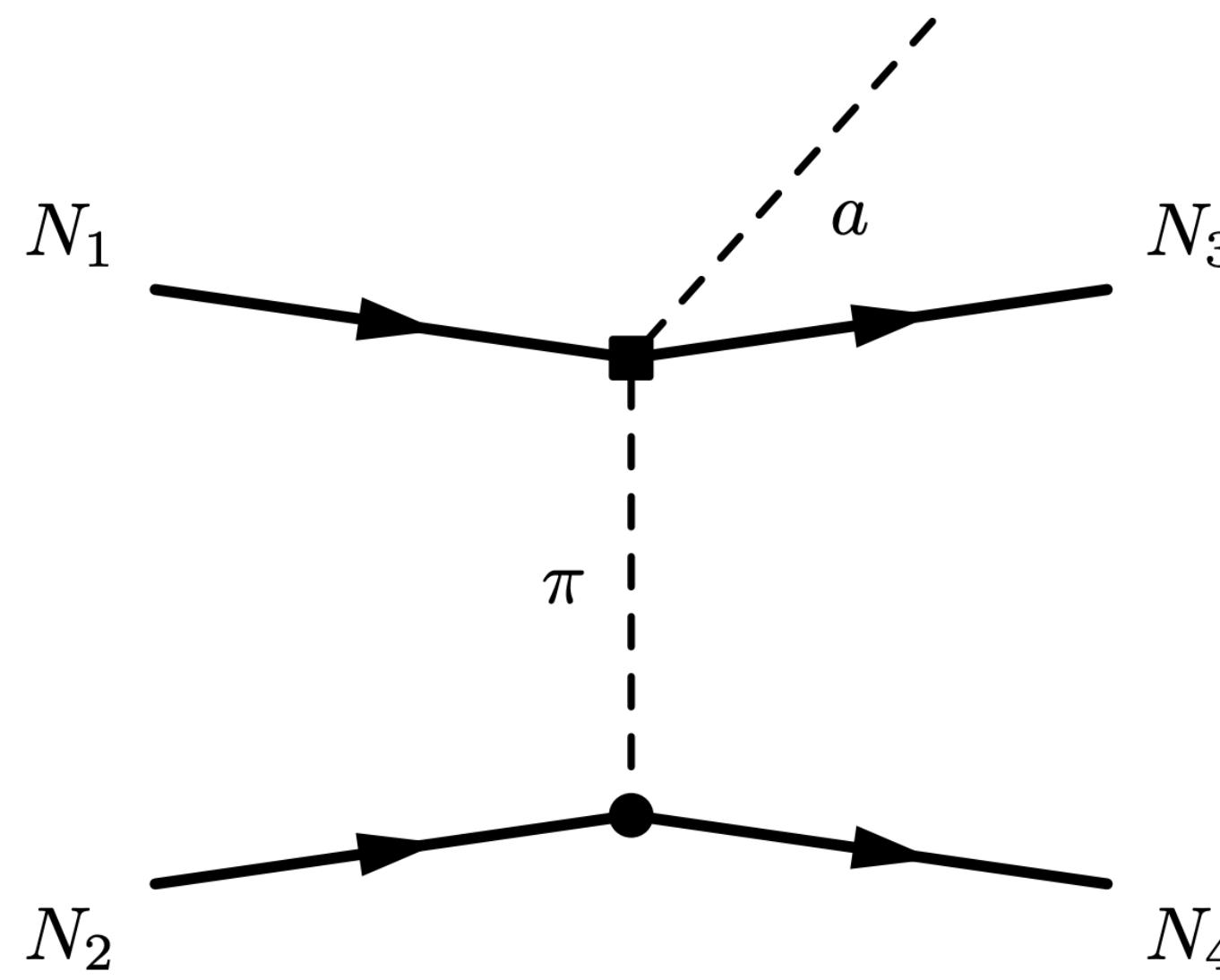
*Bauer et al, PRL 127 (2021), 081803  
Wang, Guo Lu, Zhou 2403.16064*



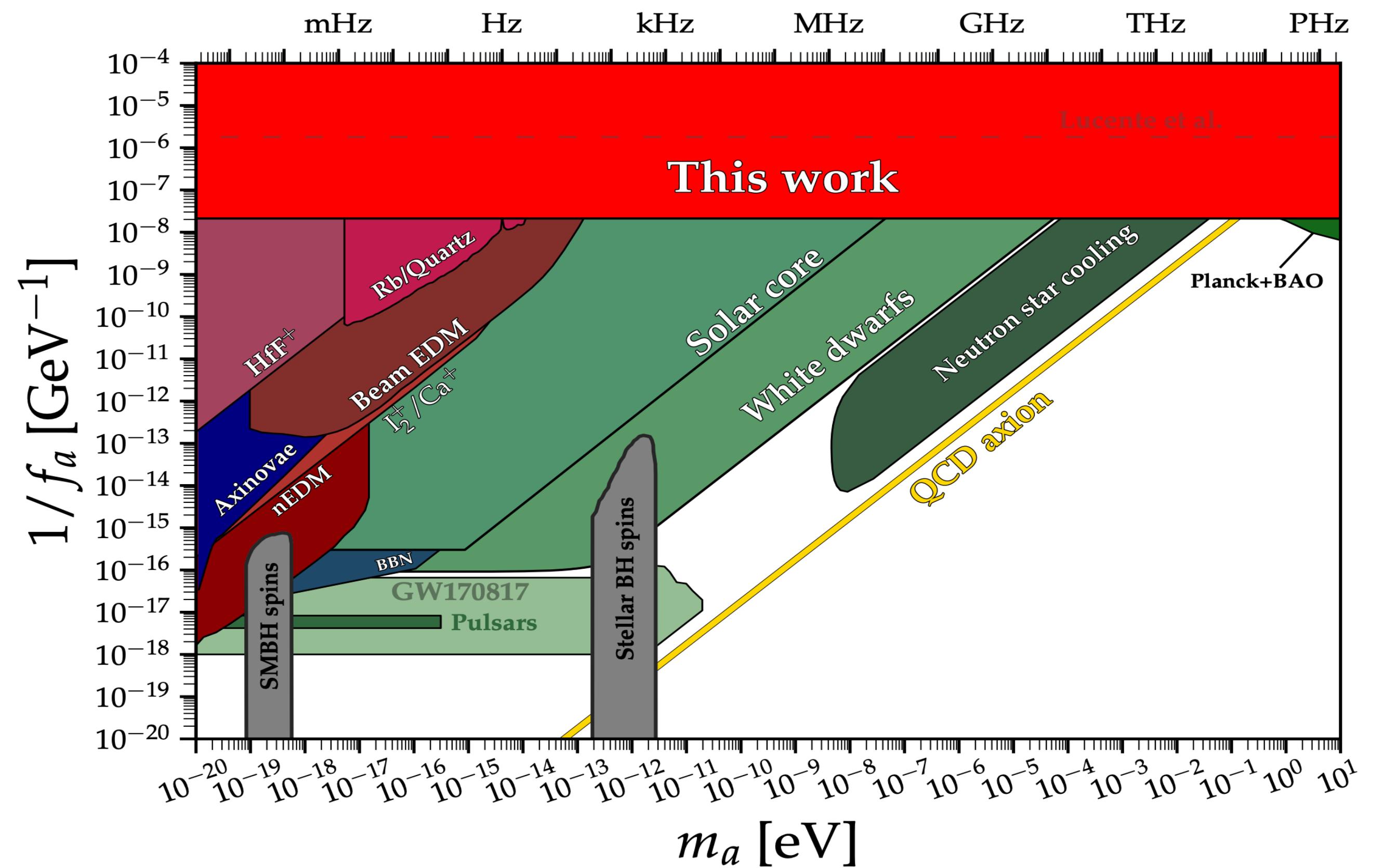
# Why accurate interactions are important?

- 3. Astrophysical bounds for axions
- Supernova constraints on axion coupling  $f_a$ :
- Isospin breaking operator at NLO improves bound by two orders?

$$\mathcal{L}_{\pi N}^{(2)} \supset -\hat{c}_5 m_\pi^2 \frac{4z}{(1+z)^2} \bar{N} \left( \frac{\pi^a a}{f_\pi f_a} \right) \tau^a N,$$



*Springmann, Stadlbauer, Stelzl, Weiler 2410.19902*



# Outlines

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# Wess-Zumino-Witten Interactions in QCD

- Describing anomalies in QCD
- Ensuring gauge invariance and completing chiral L
- Low-energy dynamics of mesons  
e.g. multiple mesons and photons interactions,  $\pi_0 \rightarrow \gamma\gamma$

$$\begin{aligned} \Gamma_{WZW}(U, \mathcal{A}_L, \mathcal{A}_R) = & \Gamma_0(U) + \mathcal{C} \int \text{Tr} \left\{ (\mathcal{A}_L \alpha^3 + \mathcal{A}_R \beta^3) - \frac{i}{2} [(\mathcal{A}_L \alpha)^2 - (\mathcal{A}_R \beta)^2] \right. \\ & + i(\mathcal{A}_L U \mathcal{A}_R U^\dagger \alpha^2 - \mathcal{A}_R U^\dagger \mathcal{A}_L U \beta^2) + i(d\mathcal{A}_R dU^\dagger \mathcal{A}_L U - d\mathcal{A}_L dU \mathcal{A}_R U^\dagger) \\ & + i[(d\mathcal{A}_L \mathcal{A}_L + \mathcal{A}_L d\mathcal{A}_L)\alpha + (d\mathcal{A}_R \mathcal{A}_R + \mathcal{A}_R d\mathcal{A}_R)\beta] + (\mathcal{A}_L^3 \alpha + \mathcal{A}_R^3 \beta) \\ & - (d\mathcal{A}_L \mathcal{A}_L + \mathcal{A}_L d\mathcal{A}_L)U \mathcal{A}_R U^\dagger + (d\mathcal{A}_R \mathcal{A}_R + \mathcal{A}_R d\mathcal{A}_R)U^\dagger \mathcal{A}_L U \\ & \left. + (\mathcal{A}_L U \mathcal{A}_R U^\dagger \mathcal{A}_L \alpha + \mathcal{A}_R U^\dagger \mathcal{A}_L U \mathcal{A}_R \beta) + i \left[ \mathcal{A}_L^3 U \mathcal{A}_R U^\dagger - \mathcal{A}_R^3 U^\dagger \mathcal{A}_L U - \frac{1}{2} (U \mathcal{A}_R U^\dagger \mathcal{A}_L)^2 \right] \right\}. \end{aligned}$$

$$\Gamma_0(U) = -\frac{i\mathcal{C}}{5} \int_{M^5} \text{Tr}(\alpha^5) = \frac{iN_c}{240\pi^2} \int d^5x \epsilon^{ABCDE} \text{Tr}(\alpha_A \alpha_B \alpha_C \alpha_D \alpha_E),$$

$$\begin{aligned} \alpha &= dUU^\dagger \\ \beta &= U^\dagger dU \end{aligned}$$

# Global currents and background vector fields

- Background fields can couple to currents of  $\mathcal{L}_{\chi\text{PT}}$ 
  - Baryon currents  $U(1)_B$  in neutron star,  $\omega$  meson
  - Z boson vector in neutrino dense environment
- SM gauge invariance needs counter terms

$$\partial^\mu j_\mu^5 = \frac{1}{48\pi^2} \epsilon_{\mu\nu\rho\sigma} F^{\mu\nu} F^{\rho\sigma}$$

Feynman diagram A: A global current  $\partial^\mu j_\mu^5$  (represented by a wavy line) enters from the left and splits into two lines. One line continues straight down, and the other line splits again into two lines that meet at a vertex. From this vertex, a vertical line goes down, and another line goes up to a wavy line labeled  $A$ . Another wavy line labeled  $A$  is shown below it.

$$\delta\partial^\mu j_\mu^5 \propto \epsilon_{\mu\nu\rho\sigma} A^{\mu\nu} B^{\rho\sigma}$$

Feynman diagram B: A global current  $\partial^\mu j_\mu^5$  (represented by a wavy line) enters from the left and splits into two lines. One line continues straight down, and the other line splits again into two lines that meet at a vertex. From this vertex, a vertical line goes down, and another line goes up to a wavy line labeled  $A$ . Below this, another wavy line labeled  $B$  enters from the bottom and splits into two lines that meet at a vertex. From this vertex, a vertical line goes down, and another line goes up to a wavy line labeled  $A$ .

# WZW counter terms for global symmetry

- Generic WZW interactions with counter terms

J. A. Harvey, C. T. Hill, and R. J. Hill,  
PRL 99 (2007) 261601,  
PRD 77(2008) 085017

- Vector fields in 1-form:  $\mathcal{A}_{L/R} \equiv \mathbb{A}_{L/R} + \mathbb{B}_{L/R}$   
Similar to Hidden Local Symmetry

$$\mathcal{L}_{\text{WZW}}^{\text{full}}(U, \mathcal{A}_{L/R}) = \mathcal{L}_{\text{WZW}}(U, \mathcal{A}_L, \mathcal{A}_R) + \mathcal{L}_c(\mathbb{A}_{L/R}, \mathbb{B}_{L/R})$$

- Counter terms ensures SM invariance

$$\Gamma_c = -2\mathcal{C} \int Tr \left[ (\mathbb{A}_L d\mathbb{A}_L + d\mathbb{A}_L \mathbb{A}_L) \mathbb{B}_L + \frac{1}{2} \mathbb{A}_L (\mathbb{B}_L d\mathbb{B}_L + d\mathbb{B}_L \mathbb{B}_L) - \frac{3}{2} i \mathbb{A}_L^3 \mathbb{B}_L - \frac{3}{4} i \mathbb{A}_L \mathbb{B}_L \mathbb{A}_L \mathbb{B}_L - \frac{i}{2} \mathbb{A}_L \mathbb{B}_L^3 \right] - (L \leftrightarrow R)$$

- Suitable for chiral gauge fields and background fields

# Axion treatment as a fictitious background field

$$\mathcal{L}_{\text{eff}} = \bar{q}(iD_\mu\gamma^\mu - \mathbf{m}_q(a))q + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}a^2$$

Yang Bai, Ting-Kuo Chen, JL, Xiaolin Ma  
2406.11948

$$+ g_{a\gamma} \frac{a}{f_a} F\tilde{F} + \frac{\partial_\mu a}{f_a} (\bar{q}_L \mathbf{k}_L(a) \gamma^\mu q_L + \bar{q}_R \mathbf{k}_R(a) \gamma^\mu q_R + \dots)$$

- $D_\mu = \partial_\mu - ig(A_L P_L + A_R P_R)$
- Hints from quark-level L:  $D_\mu \rightarrow D_\mu + i \frac{\partial_\mu a}{f_a} (\mathbf{k}_L P_L + \mathbf{k}_R P_R)$
- Hints from ChPT L:  $D^\mu U \rightarrow D^\mu U - i \frac{\partial^\mu a}{f_a} (\mathbf{k}_L U - U \mathbf{k}_R)$

$$\mathcal{L}_{\chi\text{PT}} = \frac{f_\pi^2}{8} \left[ (D^\mu U)(D_\mu U)^\dagger \right] + \frac{f_\pi^2}{4} B_0 \text{Tr} \left[ \mathbf{m}_q(a) U^\dagger + h.c. \right] + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}a^2 + g_{a\gamma} \frac{a}{f_a} F\tilde{F}$$

# Axion treatment as a fictitious background field

- Vector fields in 1-form:  $\mathcal{A}_{L/R} \equiv \mathbb{A}_{L/R} + \mathbb{B}_{L/R}$   
Similar to Hidden Local Symmetry
- Axion 1-form field can be added into background fields:

$$\mathbb{B}_{L/R} \rightarrow \mathbb{B}_{L/R} + \mathbf{k}_{L/R,0} \frac{da}{f_a}$$

- 2-flavor ChPT with SM gauge bosons and background fields

$$\mathbb{A}_L = \frac{e}{s_w} W^a \frac{\boldsymbol{\tau}^a}{2} + \frac{e}{c_w} W^0 \mathbf{Y}_Q, \quad \mathbb{A}_R = \frac{e}{c_w} W^0 \mathbf{Y}_q$$

$$\mathbb{B}_V \equiv \mathbb{B}_L + \mathbb{B}_R = g \begin{pmatrix} \rho_0 & \sqrt{2}\rho^+ \\ \sqrt{2}\rho^- & -\rho_0 \end{pmatrix} + g' \begin{pmatrix} \omega & \\ & \omega \end{pmatrix} + (\mathbf{k}_{L,0} + \mathbf{k}_{R,0}) \frac{da}{f}$$

$$\mathbb{B}_A \equiv \mathbb{B}_L - \mathbb{B}_R = g \begin{pmatrix} a_1 & \sqrt{2}a^+ \\ \sqrt{2}a^- & -a_1 \end{pmatrix} + g' \begin{pmatrix} f_1 & \\ & f_1 \end{pmatrix} + (\mathbf{k}_{L,0} - \mathbf{k}_{R,0}) \frac{da}{f}$$

# The consistent axion Lagrangian at low energy

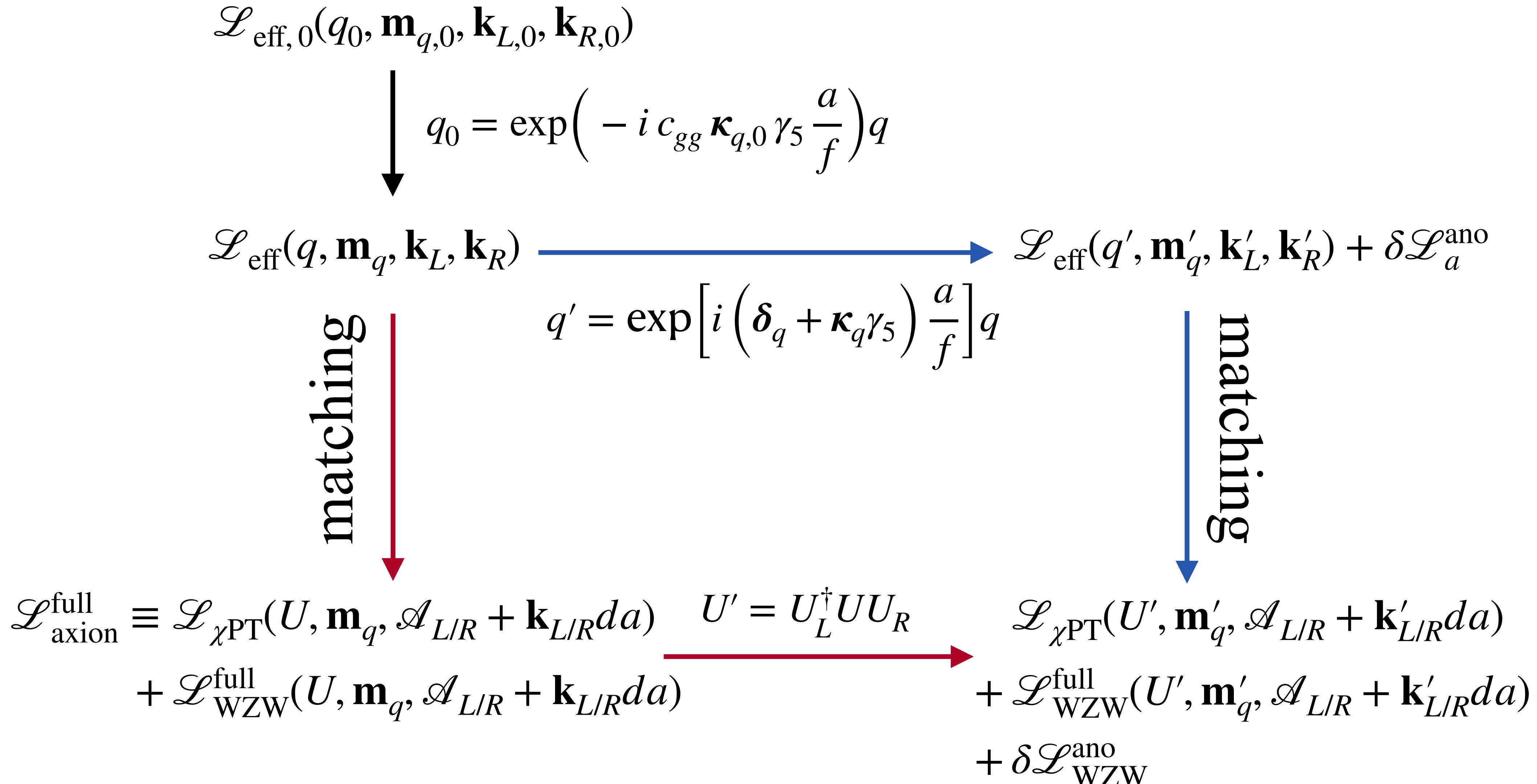
- ChPT:

$$\mathcal{L}_{\chi\text{PT}} = \frac{f_\pi^2}{8} \text{Tr} [(D^\mu U)(D_\mu U)^\dagger] + \frac{f_\pi^2}{4} B_0 \text{Tr} [\mathbf{m}_q(a) U^\dagger + h.c.] + \frac{1}{2} (\partial_\mu a) (\partial^\mu a) - \frac{m_{a,0}^2}{2} a^2 + \frac{a}{f} \sum_{\mathcal{A}_{1,2}} c_{\mathcal{A}_1 \mathcal{A}_2} F_{\mathcal{A}_1 \mu \nu} \tilde{F}_{\mathcal{A}_2}^{\mu \nu}$$

- Full WZW:  $\mathcal{L}_{\text{WZW}}^{\text{full}}(U, \mathcal{A}_{L/R}) = \mathcal{L}_{\text{WZW}}(U, \mathcal{A}_L, \mathcal{A}_R) + \mathcal{L}_c(\mathbb{A}_{L/R}, \mathbb{B}_{L/R})$

- Full  $\mathcal{L}$ :  $\mathcal{L}_{\text{axion}}^{\text{full}} \equiv [\mathcal{L}_{\chi\text{PT}} + \mathcal{L}_{\text{WZW}}^{\text{full}}] (U, \mathbf{m}_q(a), \mathcal{A}_{L/R} + \mathbf{k}_{L/R}(a) da/f_a)$

# Matching between $\mathcal{L}_{\text{eff}}$ and $\mathcal{L}_{\text{axion}}^{\text{full}}$



# Effective Lagrangian for axions

- Initial effective Lagrangian:

$$\mathcal{L}_{\text{eff},0} = \mathcal{L}_{\text{SM}} + \bar{q}_0(iD - \mathbf{m}_{q,0})q_0 + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}a^2 + c_{gg}\frac{\alpha_s}{4\pi}\frac{a}{f}G_{\mu\nu}\tilde{G}^{\mu\nu} + \frac{a}{f}\sum_{\mathcal{A}_{1,2}}c_{\mathcal{A}_1\mathcal{A}_2}^0F_{\mathcal{A}_1\mu\nu}\tilde{F}_{\mathcal{A}_2}^{\mu\nu} + \mathcal{L}_c$$

- Eliminating aGG term:

$$q_0(x) = \exp\left[-i(\boldsymbol{\delta}_{q,0} + \boldsymbol{\kappa}_{q,0}\gamma_5)c_{gg}\frac{a(x)}{f}\right]q(x), \quad \text{with } \text{Tr}(\boldsymbol{\kappa}_{q,0}) = 1$$

- New effective Lagrangian:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \bar{q}iDq - [\bar{q}_L \mathbf{m}_q(a) q_R + h.c.] + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}a^2 + \frac{a}{f}\sum_{\mathcal{A}_{1,2}}c_{\mathcal{A}_1\mathcal{A}_2}F_{\mathcal{A}_1\mu\nu}\tilde{F}_{\mathcal{A}_2}^{\mu\nu} + \mathcal{L}_c$$

# Auxiliary chiral rotation for effective Lagrangian

- Chiral rotation without regenerating aGG term  $\text{Tr}(\kappa_q) = 0$

$$q' = \exp\left[i\left(\delta_q + \kappa_q\gamma_5\right)a/f\right]q$$

- Left/right rotation matrices

$$\theta_{L/R} \equiv \delta_q \mp \kappa_q \quad U_{L/R} \equiv \exp[-i\theta_{L/R}a/f]$$

- Mass and coupling shifts

$$\mathbf{m}'_q = U_L^\dagger \mathbf{m}_q U_R, \quad \mathbf{k}'_{L/R} = U_{L/R}^\dagger (\mathbf{k}_{L/R} + \theta_{L/R}) U_{L/R} = \mathbf{k}_{L/R} + \theta_{L/R}$$

- Chiral basis change for effective Lagrangian

$$\mathcal{L}_{\text{eff}}(q, \mathbf{m}_q, \mathbf{k}_L, \mathbf{k}_R) \rightarrow \mathcal{L}_{\text{eff}}(q', \mathbf{m}'_q, \mathbf{k}'_L, \mathbf{k}'_R) + \delta\mathcal{L}_a^{\text{ano}}$$

# The axion anomalous interactions

$$\delta \mathcal{L}_a^{\text{ano}} = -\delta [\mathcal{L}_{\text{WZW}} + \mathcal{L}_c](\theta_L, \theta_R)$$

- The exact expressions

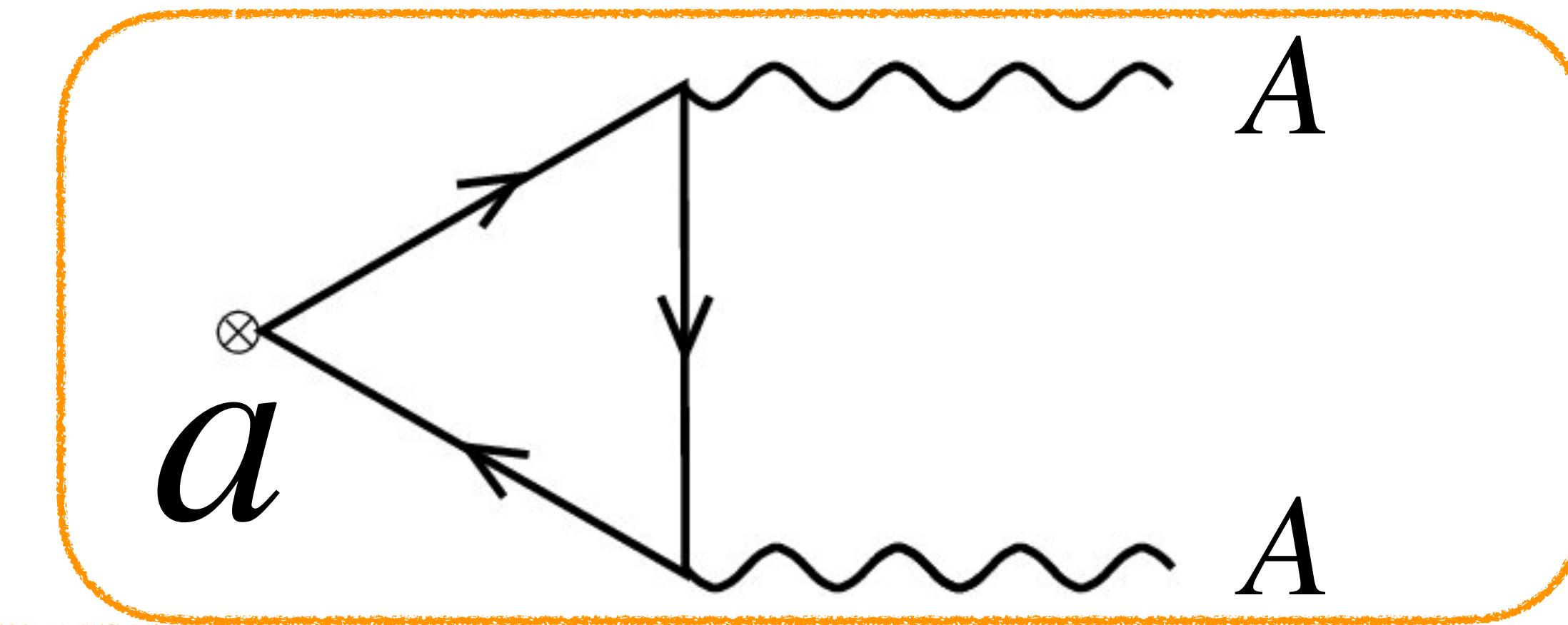
$$\begin{aligned} \delta [\Gamma_{\text{WZW}} + \Gamma_c](\boldsymbol{\theta}_L, \boldsymbol{\theta}_R) = & -2\mathcal{C} \frac{a}{f} \int \text{Tr} \left\{ \boldsymbol{\theta}_L \left[ 3(d\mathbb{A}_L - i\mathbb{A}_L^2)^2 + 3(d\mathbb{A}_L - i\mathbb{A}_L^2)(D\mathbb{B}_L) + D\mathbb{B}_L D\mathbb{B}_L - \frac{i}{2} D(\mathbb{B}_L^3) \right. \right. \\ & \left. \left. + i\mathbb{B}_L(d\mathbb{A}_L - i\mathbb{A}_L^2)\mathbb{B}_L - i(d\mathbb{A}_L - i\mathbb{A}_L^2)\mathbb{B}_L^2 \right] \right\} - (L \leftrightarrow R), \end{aligned}$$

- Covariant derivative  $D\mathbb{B}_{L,R} = d\mathbb{B}_{L,R} - i\mathbb{A}_{L,R}\mathbb{B}_{L,R} - i\mathbb{B}_{L,R}\mathbb{A}_{L,R}$
- Covariant field strength:  $F = d\mathbb{A}_L - i\mathbb{A}_L^2$

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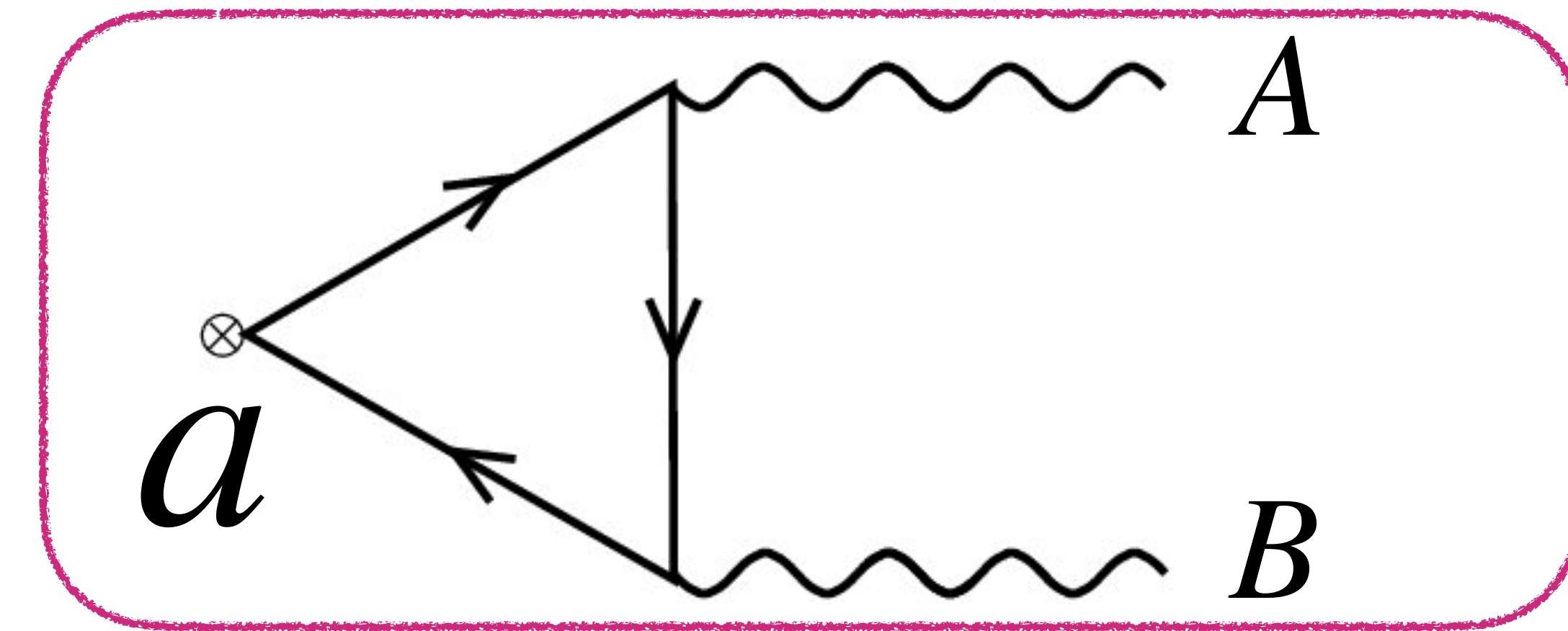
$$\begin{aligned} \delta [\Gamma_{\text{WZW}} + \Gamma_c](\boldsymbol{\theta}_L, \boldsymbol{\theta}_R) = & -2\mathcal{C} \frac{a}{f} \int \text{Tr} \left\{ \boldsymbol{\theta}_L \left[ 3(d\mathbb{A}_L - i\mathbb{A}_L^2)^2 + 3(d\mathbb{A}_L - i\mathbb{A}_L^2)(D\mathbb{B}_L) + D\mathbb{B}_L D\mathbb{B}_L - \frac{i}{2} D(\mathbb{B}_L^3) \right. \right. \\ & \left. \left. + i\mathbb{B}_L(d\mathbb{A}_L - i\mathbb{A}_L^2)\mathbb{B}_L - i(d\mathbb{A}_L - i\mathbb{A}_L^2)\mathbb{B}_L^2 \right] \right\} - (L \leftrightarrow R), \end{aligned}$$

- Covariant derivative  $D\mathbb{B}_{L,R} = d\mathbb{B}_{L,R} - i\mathbb{A}_{L,R}\mathbb{B}_{L,R} - i\mathbb{B}_{L,R}\mathbb{A}_{L,R}$
- Covariant field strength:  $F = d\mathbb{A}_L - i\mathbb{A}_L^2$

# The axion anomalous interactions

$$\delta \mathcal{L}_a^{\text{ano}} = -\delta [\mathcal{L}_{\text{WZW}} + \mathcal{L}_c](\theta_L, \theta_R)$$

- The exact expressions



$$\begin{aligned} \delta [\Gamma_{\text{WZW}} + \Gamma_c](\boldsymbol{\theta}_L, \boldsymbol{\theta}_R) = & -2\mathcal{C} \frac{a}{f} \int \text{Tr} \left\{ \boldsymbol{\theta}_L \left[ 3(d\mathbb{A}_L - i\mathbb{A}_L^2)^2 + \boxed{3(d\mathbb{A}_L - i\mathbb{A}_L^2)(D\mathbb{B}_L)} + D\mathbb{B}_L D\mathbb{B}_L - \frac{i}{2} D(\mathbb{B}_L^3) \right. \right. \\ & \left. \left. + i\mathbb{B}_L(d\mathbb{A}_L - i\mathbb{A}_L^2)\mathbb{B}_L - i(d\mathbb{A}_L - i\mathbb{A}_L^2)\mathbb{B}_L^2 \right] \right\} - (L \leftrightarrow R), \end{aligned}$$

- Covariant derivative  $D\mathbb{B}_{L,R} = d\mathbb{B}_{L,R} - i\mathbb{A}_{L,R}\mathbb{B}_{L,R} - i\mathbb{B}_{L,R}\mathbb{A}_{L,R}$
- Covariant field strength:  $F = d\mathbb{A}_L - i\mathbb{A}_L^2$

# Effective and Chiral Lagrangian matching

$$\mathcal{L}_{\text{eff}}(q, \mathbf{m}_q, \mathbf{k}_L, \mathbf{k}_R) \rightarrow \mathcal{L}_{\chi\text{PT}}(q, \mathbf{m}_q, \mathbf{k}_L, \mathbf{k}_R)$$

- The correspondence

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \bar{q} iD^\mu q - [\bar{q}_L \mathbf{m}_q(a) q_R + h.c.] + \frac{1}{2} (\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2} a^2 - \boxed{\frac{a}{f} \sum_{\mathcal{A}_{1,2}} c_{\mathcal{A}_1 \mathcal{A}_2} F_{\mathcal{A}_1 \mu\nu} \tilde{F}_{\mathcal{A}_2}^{\mu\nu}} + \mathcal{L}_c$$

$$\mathcal{L}_{\chi\text{PT}} = \frac{f_\pi^2}{8} \text{Tr} [(D^\mu U)(D_\mu U)^\dagger] + \frac{f_\pi^2}{4} B_0 \text{Tr} [\mathbf{m}_q(a) U^\dagger + h.c.] + \frac{1}{2} (\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2} a^2 + \boxed{\frac{a}{f} \sum_{\mathcal{A}_{1,2}} c_{\mathcal{A}_1 \mathcal{A}_2} F_{\mathcal{A}_1 \mu\nu} \tilde{F}_{\mathcal{A}_2}^{\mu\nu}}$$

- The anomalous matching condition between UV and IR

$$\mathcal{L}_{\chi\text{PT}}^{\text{ano}} \equiv \frac{a}{f_a} \sum_{\mathcal{A}_{1,2}} c_{\mathcal{A}_1 \mathcal{A}_2} F_{\mathcal{A}_1 \mu\nu} \tilde{F}_{\mathcal{A}_2}^{\mu\nu}$$

# Effective and Chiral Lagrangian matching

$$\mathcal{L}_{\text{eff}}(q, \mathbf{m}_q, \mathbf{k}_L, \mathbf{k}_R) \rightarrow \mathcal{L}_{\text{axion}}^{\text{full}} = \mathcal{L}_{\chi\text{PT}}(q, \mathbf{m}_q, \mathbf{k}_L, \mathbf{k}_R) + \mathcal{L}_{\text{WZW}}^{\text{full}}(U, \mathcal{A}_{L/R})$$

- The correspondence

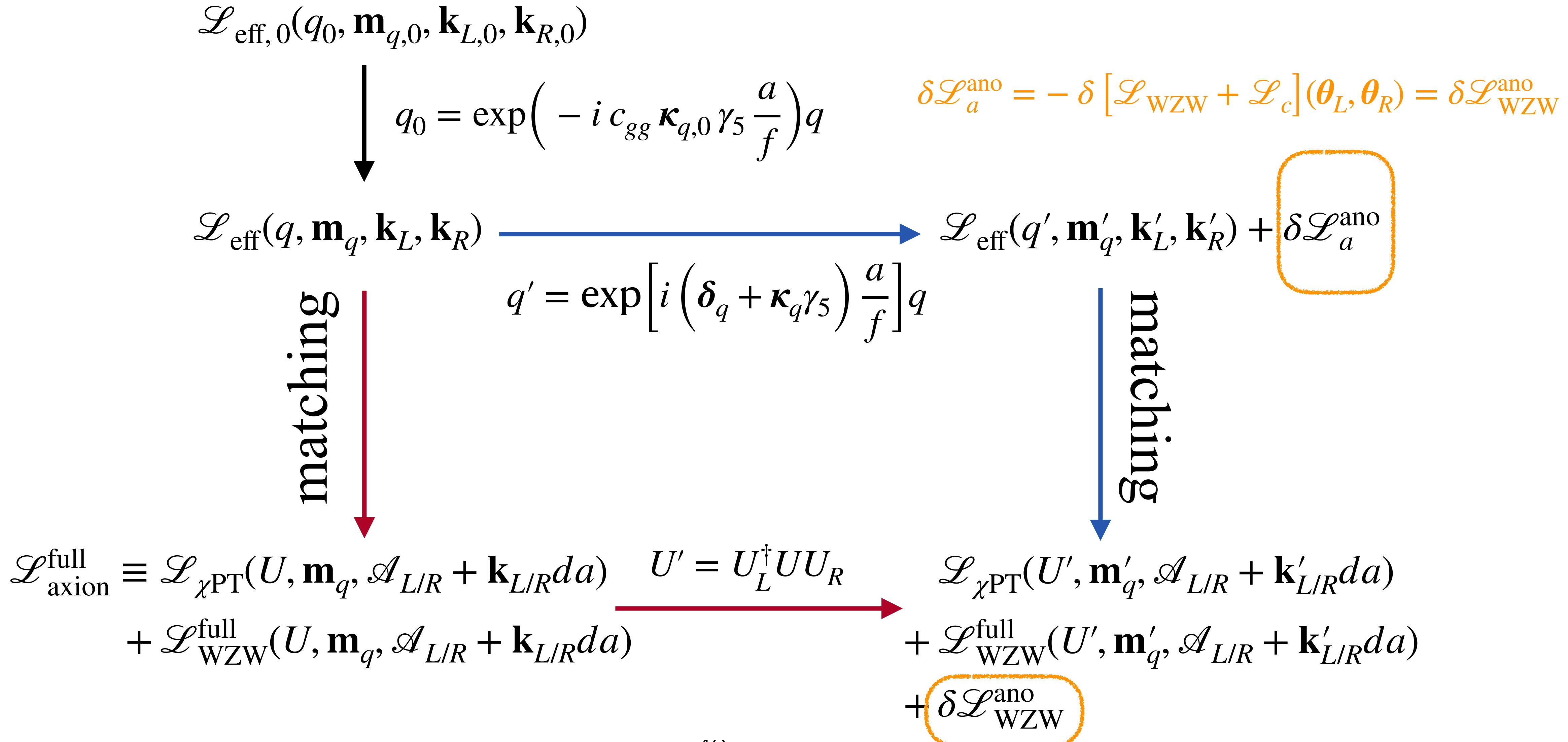
$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \bar{q} i \not{D} q - [\bar{q}_L \mathbf{m}_q(a) q_R + h.c.] + \frac{1}{2} (\partial_\mu a) (\partial^\mu a) - \frac{m_{a,0}^2}{2} a^2 + \frac{a}{f} \sum_{\mathcal{A}_{1,2}} c_{\mathcal{A}_1 \mathcal{A}_2} F_{\mathcal{A}_1 \mu \nu} \tilde{F}_{\mathcal{A}_2}^{\mu \nu} + \mathcal{L}_c$$

$$\mathcal{L}_{\chi\text{PT}} = \frac{f_\pi^2}{8} \text{Tr} [(D^\mu U)(D_\mu U)^\dagger] + \frac{f_\pi^2}{4} B_0 \text{Tr} [\mathbf{m}_q(a) U^\dagger + h.c.] + \frac{1}{2} (\partial_\mu a) (\partial^\mu a) - \frac{m_{a,0}^2}{2} a^2 + \frac{a}{f} \sum_{\mathcal{A}_{1,2}} c_{\mathcal{A}_1 \mathcal{A}_2} F_{\mathcal{A}_1 \mu \nu} \tilde{F}_{\mathcal{A}_2}^{\mu \nu}$$

- WZW term and counter terms

$$\mathcal{L}_{\text{WZW}}^{\text{full}}(U, \mathcal{A}_{L/R}) = \mathcal{L}_{\text{WZW}}(U, \mathcal{A}_L, \mathcal{A}_R) + \mathcal{L}_c(\mathbb{A}_{L/R}, \mathbb{B}_{L/R})$$

# Consistent matching between $\mathcal{L}_{\text{eff}}$ and $\mathcal{L}_{\text{axion}}^{\text{full}}$

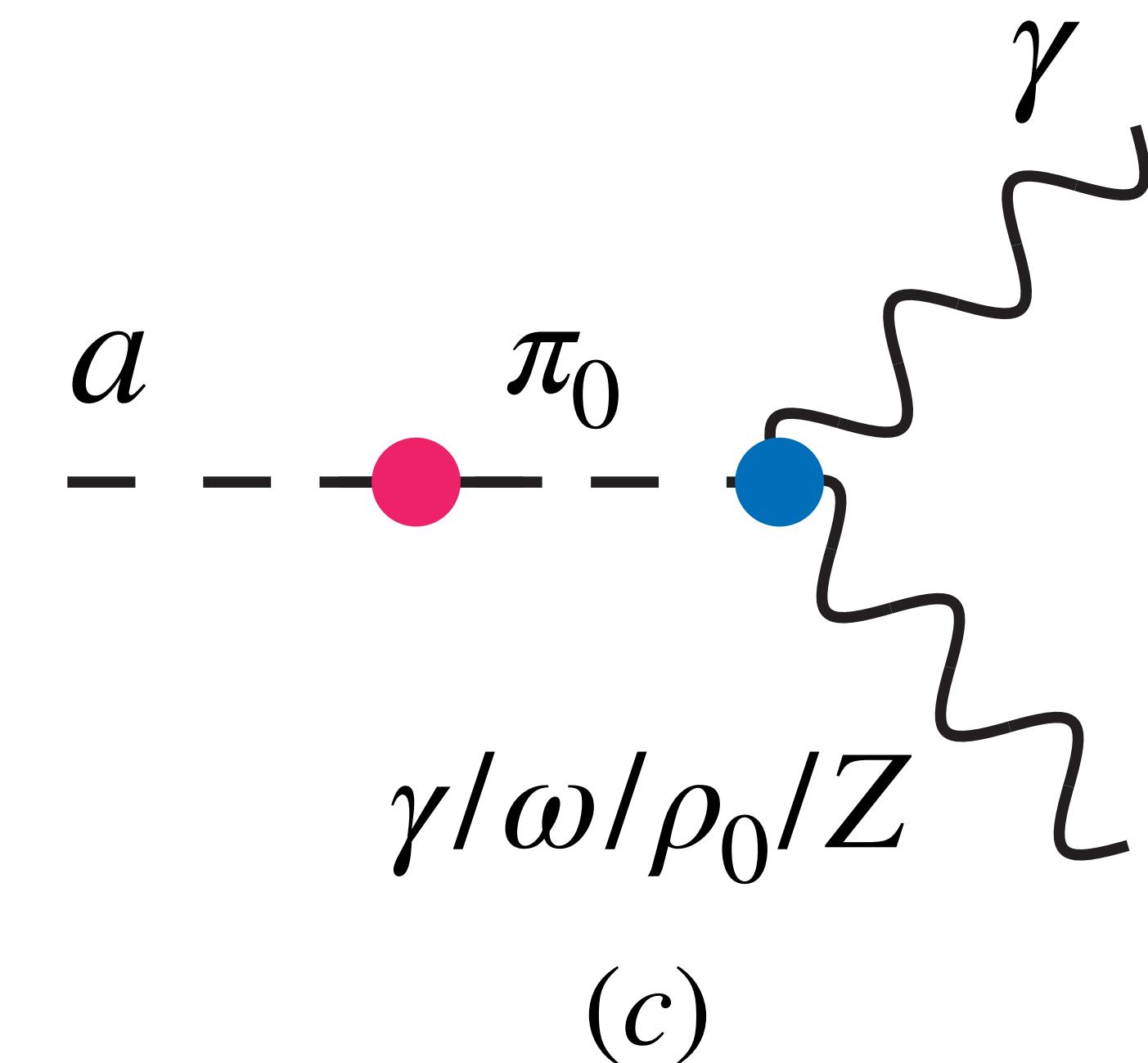
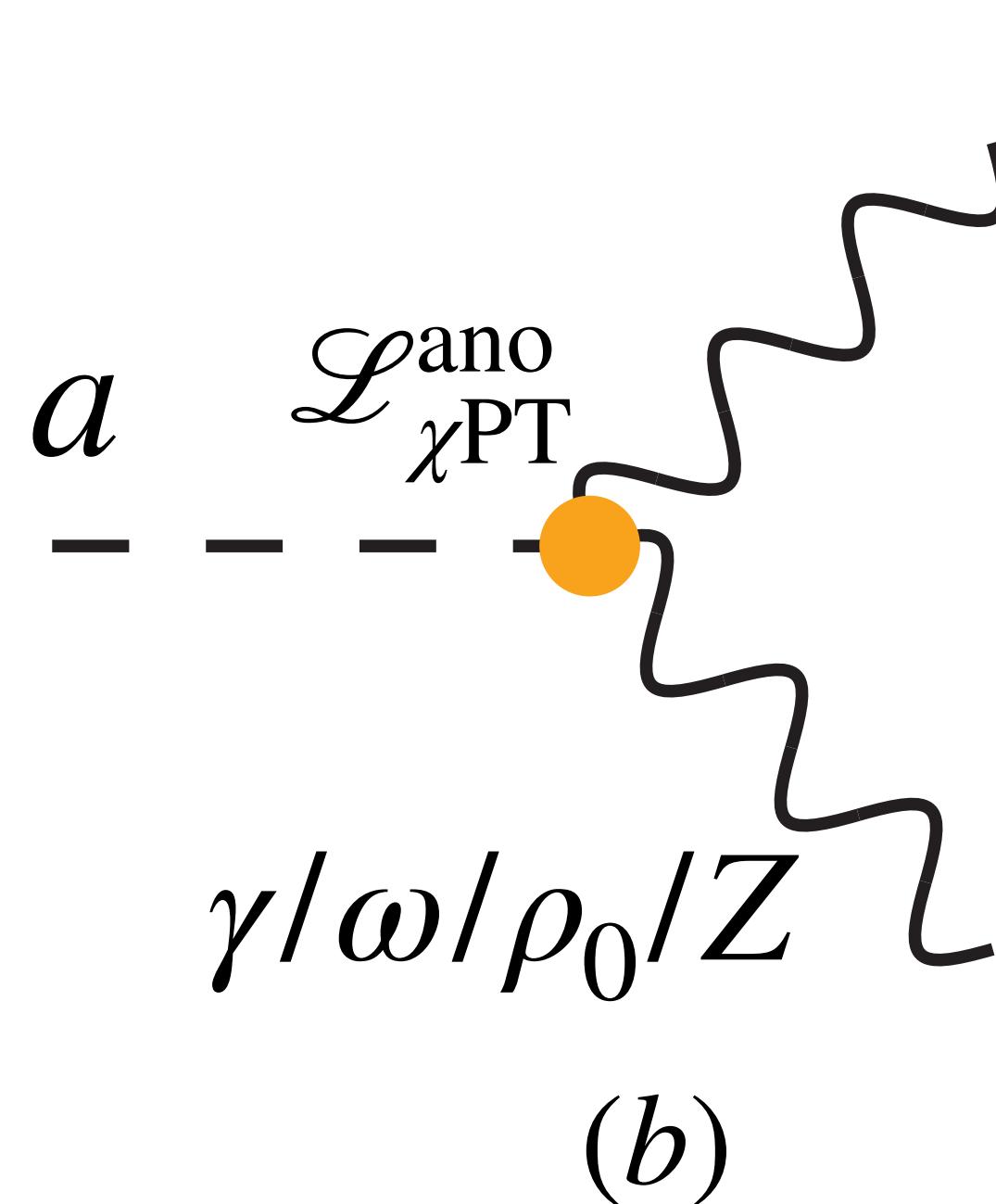
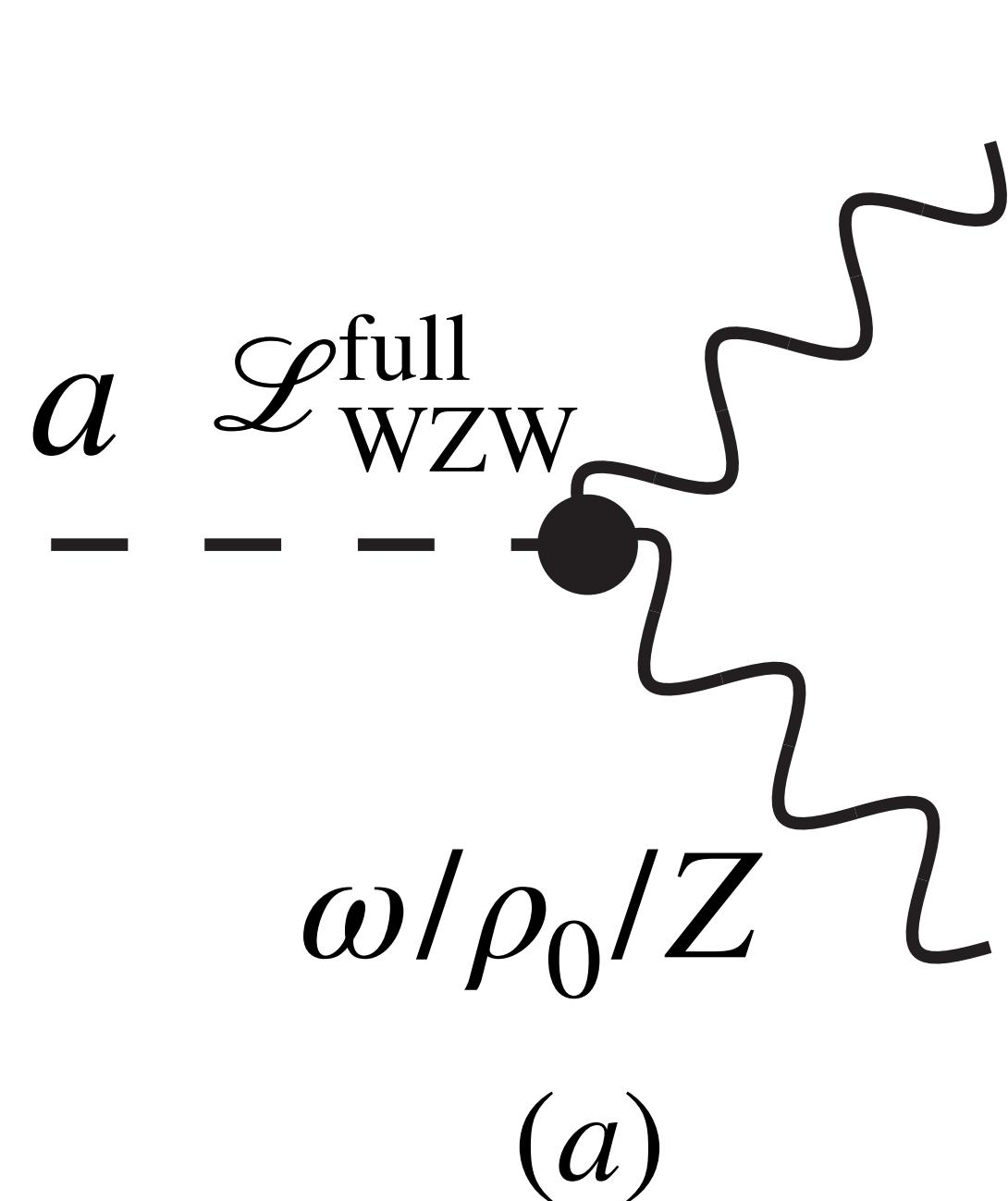


# Outlines

- Axion general introduction
- Axion-scalar meson interactions
- Axion-vector meson interactions
- Phenomenology at BESIII and STCF
- Summary

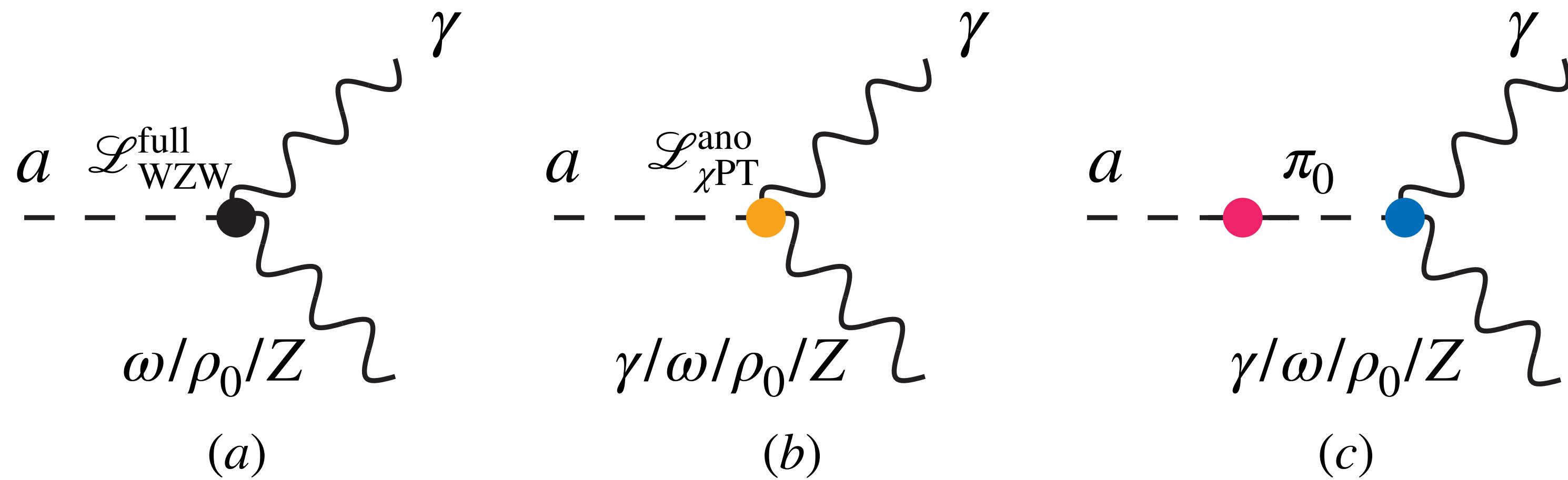
# Consistent physical amplitudes

- A consistent Lagrangian will give physical amplitudes independent of auxiliary rotations
- Full WZW interactions are important for a-A-B amplitudes



# Consistent physical amplitudes for $a - \gamma - \gamma$

- Auxiliary rotations are cancelled



$$ad\gamma d\gamma: c_{\text{WZW}} \equiv 0$$

$$ad\gamma d\gamma: c_{\text{ano}} \equiv -\frac{e^2 N_c}{48\pi^2 f} 12(Q_u^2 \kappa_u + Q_d^2 \kappa_d)$$

$$\pi_0 d\gamma d\gamma: c_{\pi_0} \equiv \frac{e^2 N_c}{48\pi^2 f_\pi} 6\sqrt{2}(Q_d^2 - Q_u^2)$$

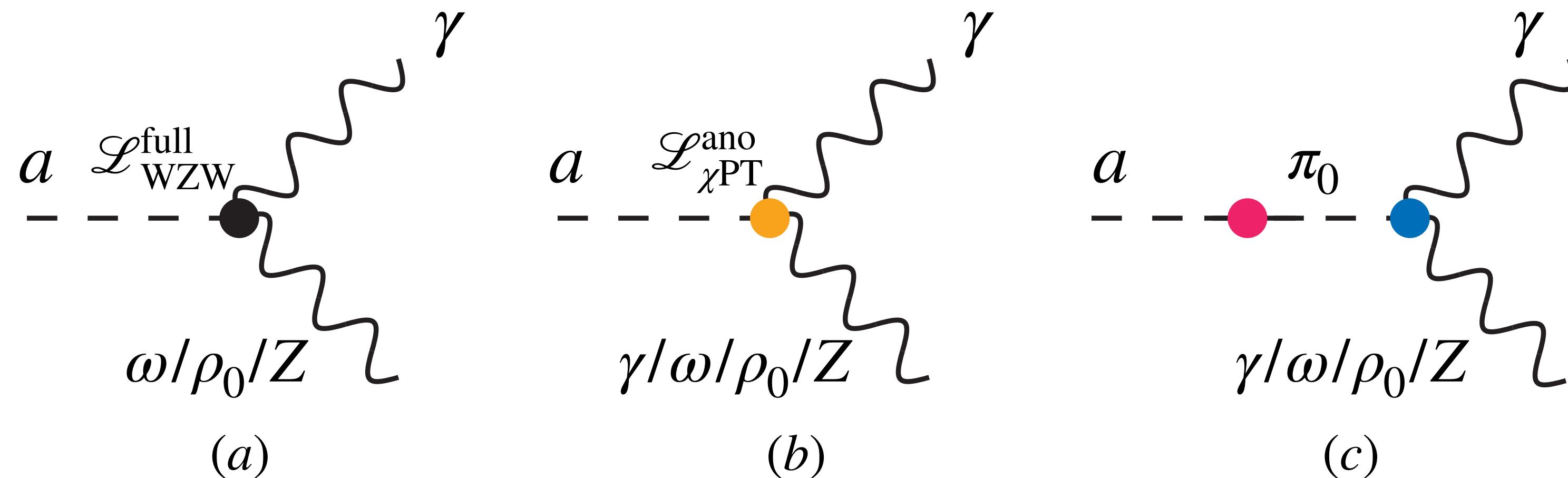
$$\mathcal{M}(a \rightarrow \gamma\gamma)(\text{auxiliary}) = CF \times \left( c_{\text{ano}} + \theta'_{a-\pi_0} c_{\pi_0} + c_{\text{WZW}} \right)$$

$$= CF \times e^2 \left\{ \frac{-N_c}{48\pi^2 f_a} 12(Q_u^2 \kappa_u + Q_d^2 \kappa_d) + i \frac{f_\pi}{\sqrt{2}f} \left[ (\kappa_u - \kappa_d)p_a^2 - 2 \frac{m_u \kappa_u - m_d \kappa_d}{m_u + m_d} m_\pi^2 \right] \frac{i}{p_a^2 - m_\pi^2} \times \frac{N_c}{48\pi^2 f_\pi} 6\sqrt{2}(Q_d^2 - Q_u^2) \right\}$$

$$\begin{aligned} \kappa_u + \kappa_d &= 0 & \rightarrow 0 \\ p_a^2 &= m_a^2 \end{aligned}$$

# Consistent physical amplitudes for $a - \gamma - \omega$

- Auxiliary rotations are cancelled



$$ad\omega d\gamma: \quad c_{\text{WZW}} = \frac{-eg'N_c}{48\pi^2 f} 6(Q_u \kappa_u + Q_d \kappa_d)$$

$$ad\omega d\gamma: \quad c_{\text{ano}} = \frac{-eg'N_c}{48\pi^2 f} 6(Q_u \kappa_u + Q_d \kappa_d)$$

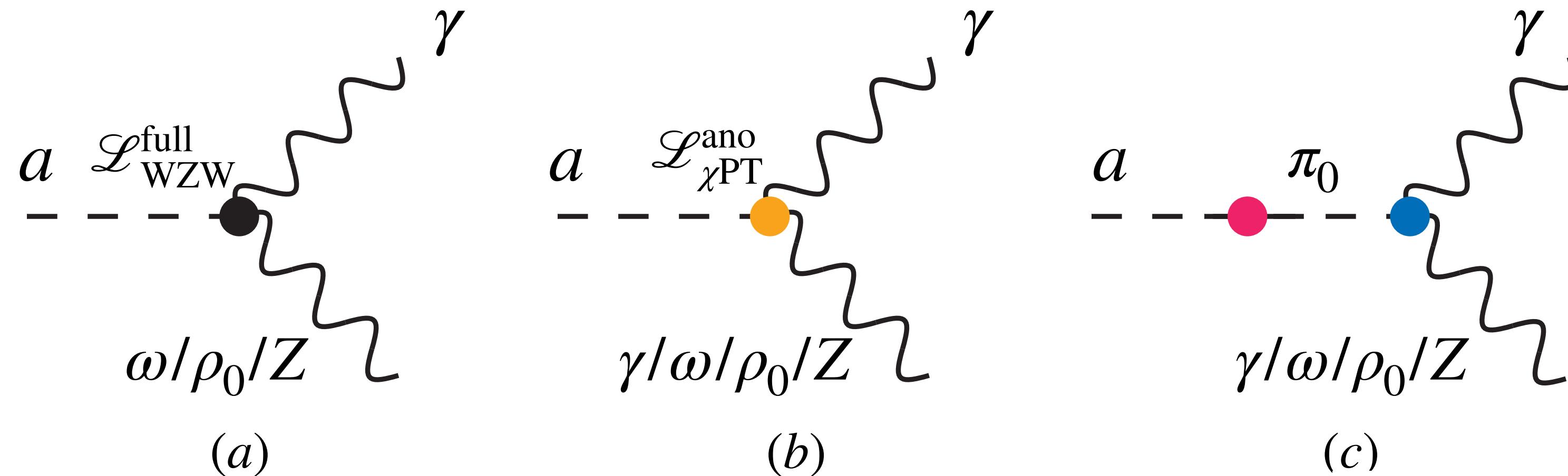
$$\pi_0 d\omega d\gamma: \quad c_{\pi_0} = \frac{eg'N_c}{48\pi^2 f_\pi} 6\sqrt{2}(Q_d - Q_u)$$

$$\begin{aligned} \mathcal{M}(a \rightarrow \omega\gamma) & (\textbf{auxiliary}) = CF \times (c_{\text{ano}} + \theta'_{a-\pi_0} c_{\pi_0} + c_{\text{WZW}}) \\ & = CF \times eg' \left[ \frac{-N_c}{48\pi^2 f} 12(Q_u \kappa_u + Q_d \kappa_d) + i \frac{f_\pi}{\sqrt{2}f} ((\kappa_u - \kappa_d)p_a^2 - 2 \frac{m_u \kappa_u - m_d \kappa_d}{m_u + m_d} m_\pi^2) \frac{i}{p_a^2 - m_\pi^2} \times \frac{N_c}{48\pi^2 f_\pi} 6\sqrt{2}(Q_d - Q_u) \right] \\ & \rightarrow 0 \end{aligned}$$

# Consistent physical amplitudes for $a - \gamma - Z$

- Auxiliary rotations are cancelled

$$ad\gamma dZ : \quad c_{\text{ano}} = \frac{N_c}{48\pi^2 f} \frac{2e^2}{3c_w s_w} [3\delta_d + 6\delta_u - 3\kappa_d - 6\kappa_u + 4s_w^2(\kappa_d + 4\kappa_u)]$$



$$ad\gamma dZ : \quad c_{\text{WZW}} = \frac{-2e^2 N_c}{48\pi^2 f_{S_W} c_W} (\delta_d + 2\delta_u)$$

$$\pi_0 d\gamma dZ : \quad c_{\pi_0} = \frac{-e^2 N_c}{48\pi^2 f_\pi s_w c_w} \sqrt{2}(c_w^2 - 3s_w^2)$$

$$\begin{aligned} \mathcal{M}(a \rightarrow Z^*\gamma) &= CF \times (c_{\text{ano}} + \theta'_{a-\pi_0} c_{\pi_0} + c_{\text{WZW}}) \\ &= CF \times \left[ c_{\text{WZW}} + c_{\text{ano}} + i \frac{f_\pi}{\sqrt{2}f} \left( (\kappa_u - \kappa_d)p_a^2 - 2 \frac{m_u \kappa_u - m_d \kappa_d}{m_u + m_d} m_\pi^2 \right) \frac{i}{p_a^2 - m_\pi^2} \times c_{\pi_0} \right] \\ &\rightarrow 0 \end{aligned}$$

# Consistent amplitudes for three point vertex

$$c_{\gamma\gamma}^{\text{eff}} = c_{\gamma\gamma}^0 + \boxed{\frac{e^2 c_{gg}}{16\pi^2 f}} \left( -\frac{10}{3} - 2 \frac{m_u - m_d}{m_u + m_d} \frac{m_\pi^2}{m_a^2 - m_\pi^2} \right) - \frac{e^2}{16\pi^2 f} \frac{m_a^2}{m_\pi^2 - m_a^2} (c_u - c_d)$$

$$c_{\omega\gamma}^{\text{eff}} = \boxed{eg'} \left\{ \frac{-c_{gg}}{8\pi^2 f} - \frac{3}{8\pi^2 f} \left[ \frac{m_a^2}{m_\pi^2 - m_a^2} \left( \frac{c_u - c_d}{2} \right) + c_{gg} \frac{m_u - m_d}{m_u + m_d} \frac{m_\pi^2}{m_a^2 - m_\pi^2} \right] + \frac{1}{16\pi^2 f} (c_d + c_Q - 2c_u) \right\}$$

$$c_{\rho\gamma}^{\text{eff}} = eg \left\{ \frac{-3c_{gg}}{8\pi^2 f} - \frac{1}{8\pi^2 f} \left[ \frac{m_a^2}{m_\pi^2 - m_a^2} \left( \frac{c_u - c_d}{2} \right) + c_{gg} \frac{m_u - m_d}{m_u + m_d} \frac{m_\pi^2}{m_a^2 - m_\pi^2} \right] + \frac{1}{16\pi^2 f} (3c_Q - 2c_u - c_d) \right\}$$

$$c_{\gamma Z}^{\text{eff}} = c_{\gamma Z}^0 + \frac{N_c c_{gg}}{48\pi^2 f s_w c_w} \frac{e^2}{s_w c_w} (-9 + 20s_w^2) - c_{\pi_0} \frac{f_\pi}{\sqrt{2}f} \left( \frac{m_a^2}{m_\pi^2 - m_a^2} \frac{c_d - c_u}{2} - c_{gg} \frac{m_u - m_d}{m_u + m_d} \frac{m_\pi^2}{m_a^2 - m_\pi^2} \right) - \frac{N_c}{48\pi^2 f s_{2w}} \frac{2e^2}{s_{2w}} (c_d + 2c_u + 3c_Q)$$

- Vertex  $\omega \rightarrow \gamma a$  benefit from large  $g' \approx 5.7 \gg e$

$$\mathbf{k}_{L,0} = \{c_Q, c_Q\} \quad \mathbf{k}_{R,0} = \{c_u, c_d\}$$

# Phenomenology at BESIII and STCF

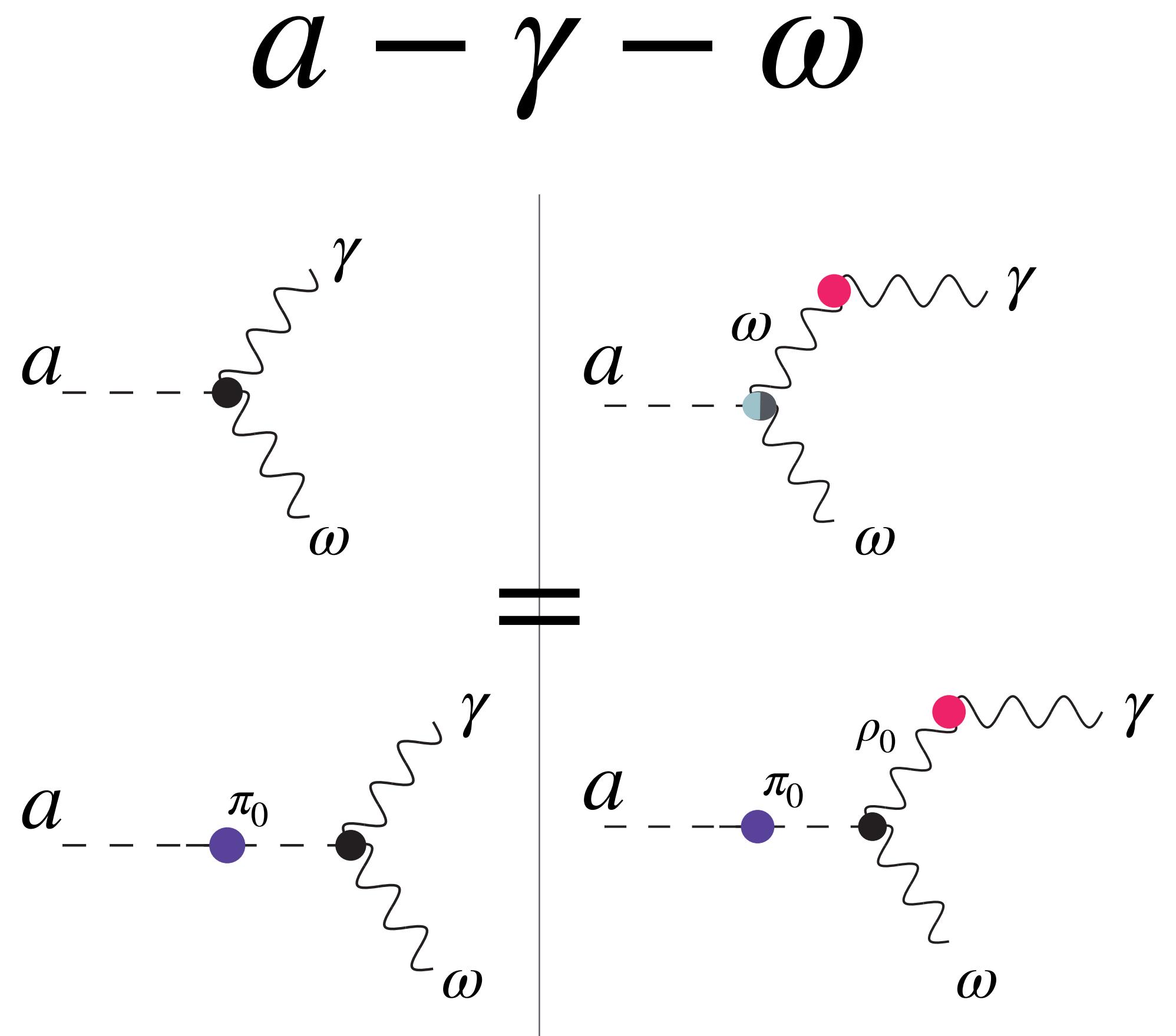
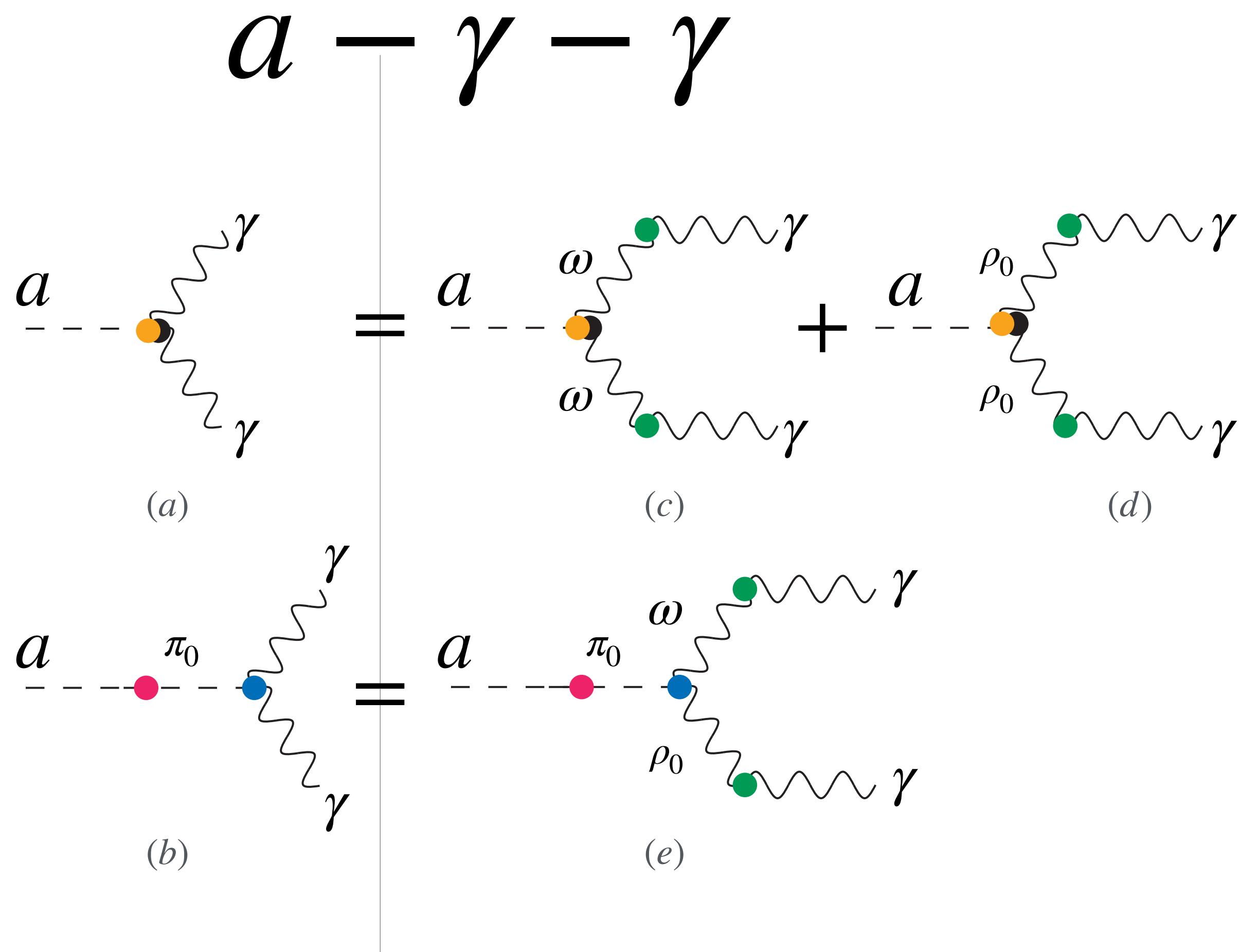
- New channel  $e^+e^- \rightarrow \gamma^*(J/\Psi) \rightarrow \omega a$

$$c_{\omega\gamma}^{\text{eff}}(q^2) = -\frac{eg'c_{gg}}{8\pi^2f} \frac{m_\omega^2}{m_\omega^2 - q^2 - i\sqrt{q^2}\Gamma_\omega} - \frac{3eg'c_{gg}}{8\pi^2f} \frac{m_u - m_d}{m_u + m_d} \frac{m_\pi^2}{m_a^2 - m_\pi^2} \sum_{i=0}^3 \frac{A_i M_i^2 e^{i\phi_i}}{M_i^2 - q^2 - i\sqrt{q^2}\Gamma_i(\sqrt{q^2})}$$

- The model satisfies partial Vector Meson Dominance, therefore we can use form factor for  $\gamma^* - \omega - a$
- The differential cross-section

$$\frac{d\sigma(e^+e^- \rightarrow \omega a)}{d\cos\theta} = \frac{\alpha |c_{\omega\gamma}^{\text{eff}}(q^2)|^2 [m_a^4 + (m_\omega^2 - s)^2 - 2m_a^2(m_\omega^2 + s)]}{64f^2s^2}(1 + \cos\theta^2)$$

# Vector Meson Dominance

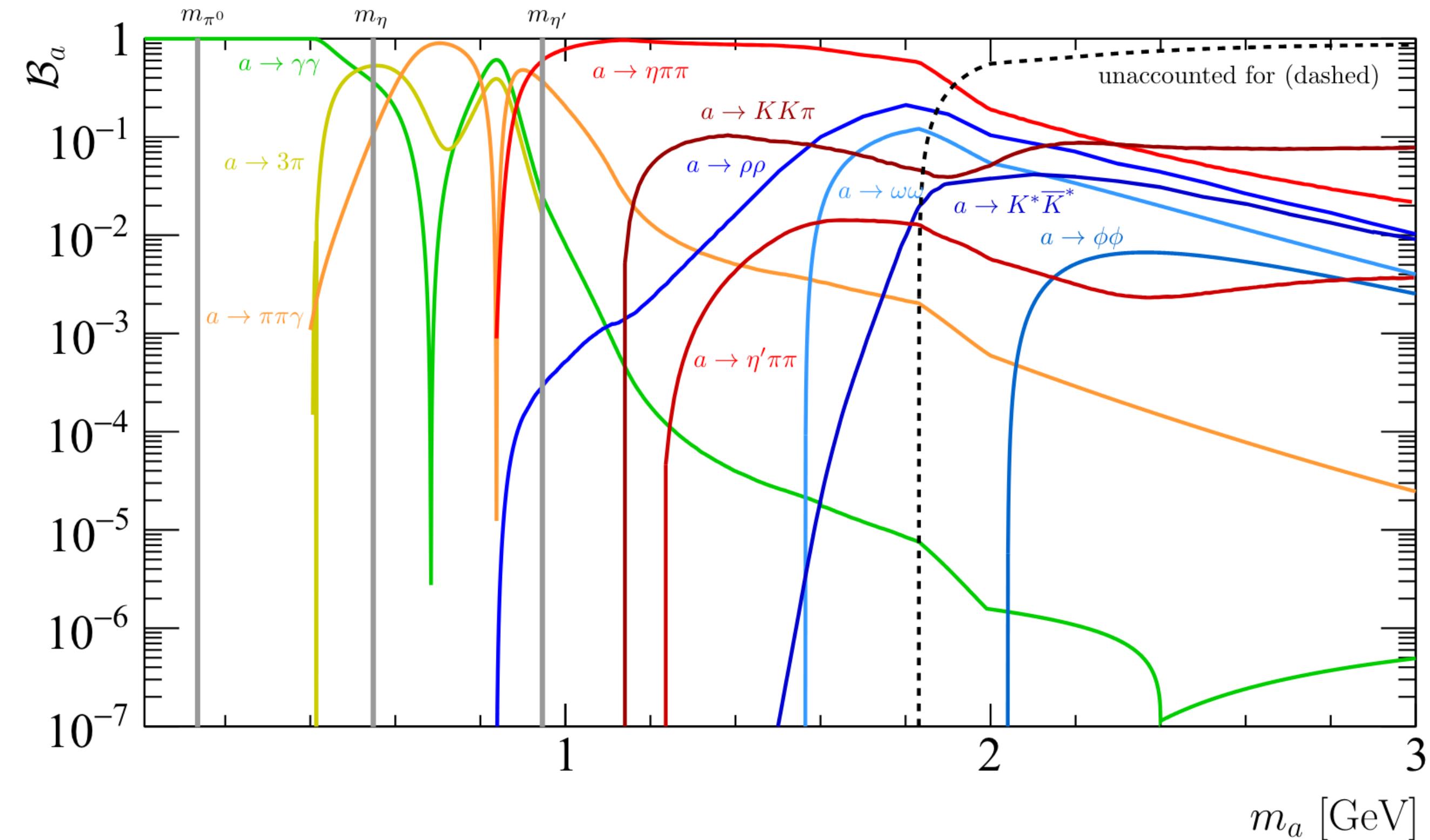


# The decay of axion

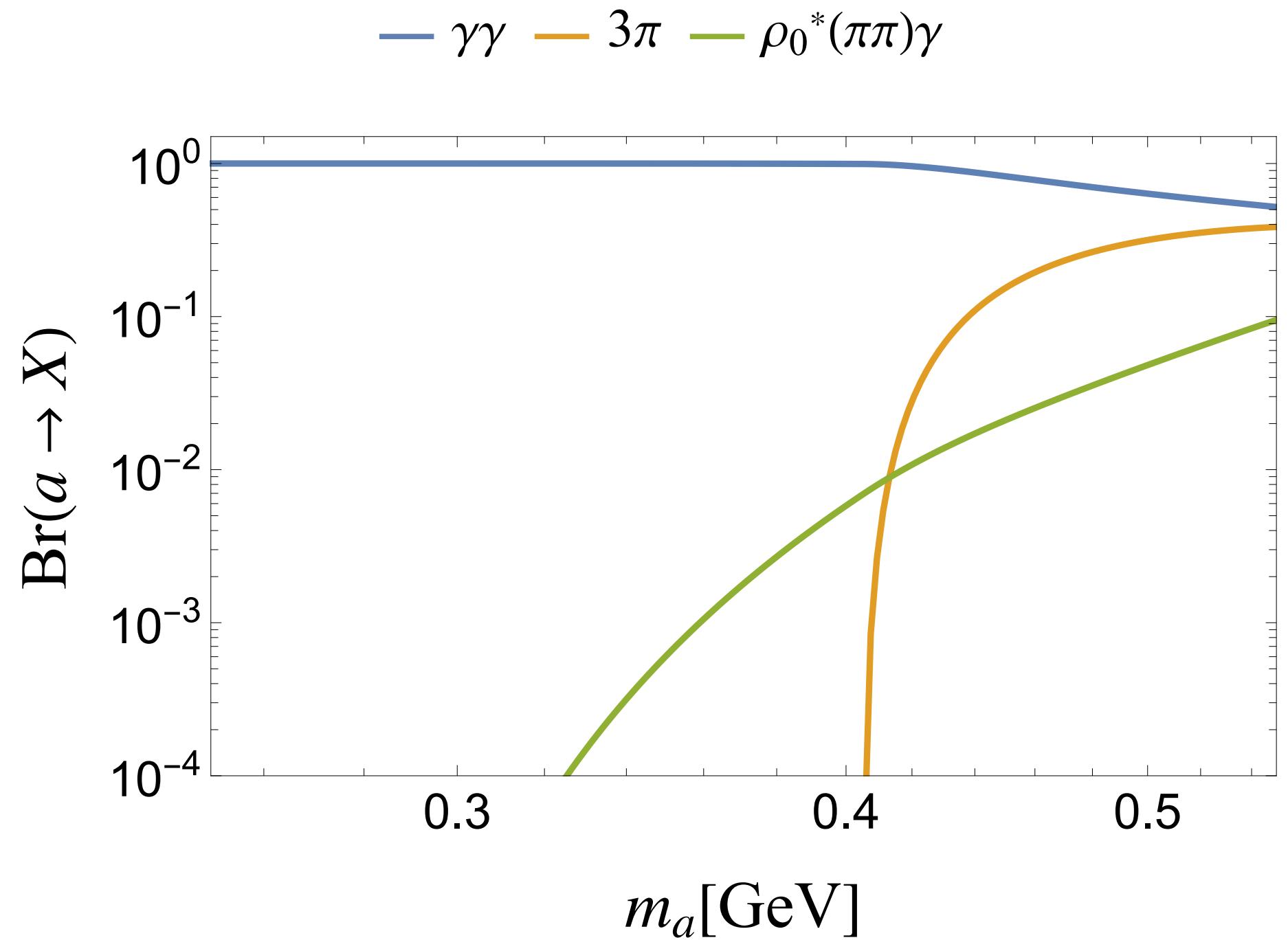
- Previous work (PRL 123 (2019) 031803) use Hidden Local Symmetry to describe pseudo scalar meson + vector meson interactions

- Assume axion mixes with  $\pi, \eta, \eta'$
- Use data driven method to obtain form factor

- Lacks first chiral rotation contribution from  $\mathcal{L}_{\chi\text{PT}}^{\text{ano}}$
- Lacks full WZW contribution from  $\mathcal{L}_{\text{WZW}}^{\text{full}}$

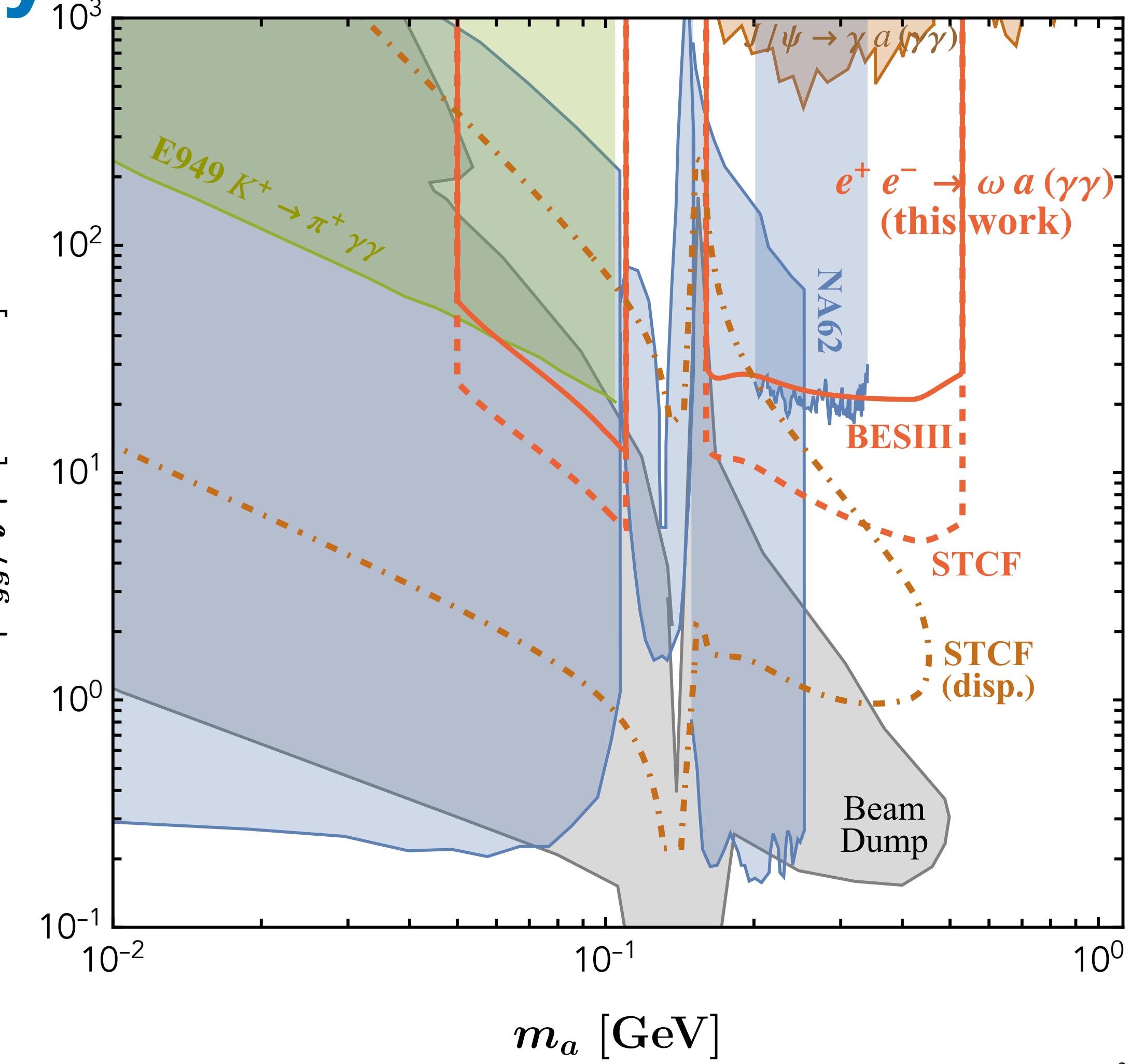


# Light axion phenomenology at BESIII and STCF



- Production  $e^+e^- \rightarrow \gamma^*(J/\Psi) \rightarrow \omega a$
- Prompt decay:  $a \rightarrow \gamma\gamma$
- Displaced decay of  $a$

$$\frac{\text{BR}(J/\psi \rightarrow \omega a)}{\text{BR}(J/\psi \rightarrow ee)} = \frac{m_{J/\psi}^2}{32\pi\alpha} \left| c_{\omega\gamma}^{\text{eff}}(q^2 = m_{J/\psi}^2) \right|^2 \left[ \left( 1 - \frac{(m_a + m_\omega)^2}{m_{J/\psi}^2} \right) \left( 1 - \frac{(m_a - m_\omega)^2}{m_{J/\psi}^2} \right) \right]^{\frac{3}{2}}$$



# Summary

- A full chiral axion Lagrangian for axion-pseudo-vector meson
  - Wess-Zumino-Witten counter term is necessary for gauge invariance
  - $\mathbb{B}_{L/R} \rightarrow \mathbb{B}_{L/R} + \mathbf{k}_{L/R} da/f_a$
  - UV-IR anomaly matching is necessary
- Consistent physical amplitudes without auxiliary rotation parameters
- New search channel involving  $\omega \rightarrow \gamma a$  vertex at BESIII & STCF
- Future plan: extending to three light quarks scheme  
Needs to deal with  $\eta'$ ; vector meson mediated processes in astrophysics

# Backup: axion related WZW interactions

- Convention  $\int d^4x \epsilon_{\mu\nu\rho\sigma} A^\mu B^\nu \partial^\rho C^\sigma \equiv \int ABdC$

$$\begin{aligned}
\Gamma_{Xdyda} = & \frac{\mathcal{C}}{f} \int da \left\{ \frac{2e^2}{s_{2w}} (k_d + 2k_u + 3k_Q) \gamma dZ + eg(k_d + 2k_u + 3k_Q) \gamma da_1 - eg'(k_d - k_Q - 2k_u) \gamma df_1 \right. \\
& + eg(k_d - 3k_Q + 2k_u) \gamma d\rho_0 - eg'(k_d + k_Q - 2k_u) \gamma d\omega + \frac{2e^2}{s_{2w}^2} \left[ (k_d + 4k_Q + k_u) - 2s_w^2(k_d + 3k_Q + 2k_u) \right] Z dZ \\
& + \frac{eg}{s_{2w}} \left[ (k_d + 4k_Q + k_u) - 2s_w^2(k_d + 3k_Q + 2k_u) \right] Z da_1 - \frac{eg'}{s_{2w}} \left[ k_d - k_u + s_w^2(-2k_d + 2k_Q + 4k_u) \right] Z df_1 \\
& - \frac{eg}{s_{2w}} \left[ -3k_d - 3k_u + 2s_w^2(k_d - 3k_Q + 2k_u) \right] Z d\rho_0 - \frac{eg'}{s_{2w}} \left[ 3k_d - 3k_u - 2s_w^2(k_d + k_Q - 2k_u) \right] Z d\omega \\
& + g^2(k_d + 2k_Q + k_u) a_1 d\rho_0 + gg'(k_u - k_d) a_1 d\omega + gg'(k_u - k_d) f_1 d\rho_0 + g'^2(k_d + 2k_Q + k_u) f_1 d\omega \\
& + g^2(k_d - 2k_Q + k_u) \rho_0 d\rho_0 + 2gg'(k_u - k_d) \rho_0 d\omega + g'^2(k_d - 2k_Q + k_u) \omega d\omega + \frac{3eg}{2s_w} (k_u + k_d) W^\pm d\rho^\mp \\
& \left. + \frac{eg}{2s_w} (k_d + 4k_Q + k_u) a^\mp dW^\pm + g^2(k_d + 2k_Q + k_u) a^\mp d\rho^\pm + \frac{e^2}{s_w^2} (k_d + 4k_Q + k_u) W^- dW^+ \right\}
\end{aligned}$$