# BUILDING NON-VANILLA QCD AXION MODELS

**Felix Yu, Johannes Gutenberg Universität Mainz**

Based on

*Kivel, Laux, FY: JHEP* ***11*** *(2022) 88, [2207.08740];*
*Elahi, Elor, Kivel, Laux, Najjari, FY [2301.08760]*

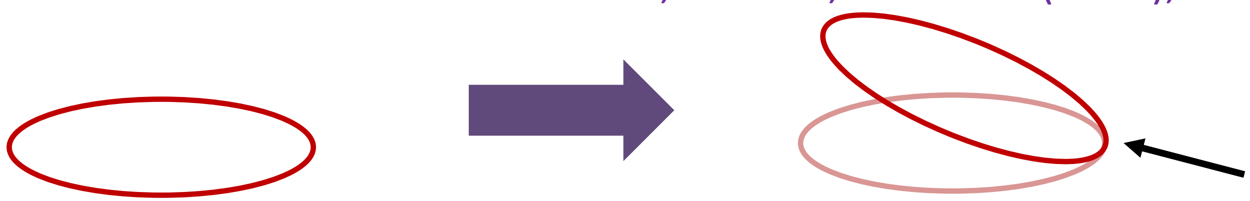
The Mitchell Conference on Collider, Dark Matter, and Neutrino Physics
Texas A&M U., May 18, 2023

# The vanilla axion story

Hill Country Honey & Vanilla Bean


- Two canonical benchmark models
  - **KSVZ** – PQ scalar field couples to SU(3) via heavy VLQ
  - **DFSZ** – PQ scalar field couples to 2HDM which have Yukawa interactions with SM quarks

Kim (1979), Shifman, Vainshtein, Zakharov (1980);
Dine, Fischler, Srednicki (1981), Zhitnitsky (1980)



$$\bar{\theta} = \frac{\langle a \rangle}{f_a}$$

PNGB flat potential

Instanton-induced tilted potential

- Classical shift symmetry becomes periodic with $f_a$ scale

In both cases, global PQ symmetry is exact and accidental at renormalizable level

# Vanilla axion phenomenology

- Axion mass driven by QCD topological susceptibility
  - Also need mixing with SM neutral mesons

    $\mathcal{L} \simeq \Lambda_{\mathrm{QCD}}^4 \cos\left(\frac{a}{f_a}\right)$ gives $m_a f_a = \sqrt{\chi} \approx m_\pi f_\pi$ in SM
- Main consequence: Vanilla QCD axion physics is essentially a one-parameter model
  - Primary target: axion-photon coupling
    - Some residual dependence on UV model via EM and color anomaly factors

# Current status of vanilla QCD axions

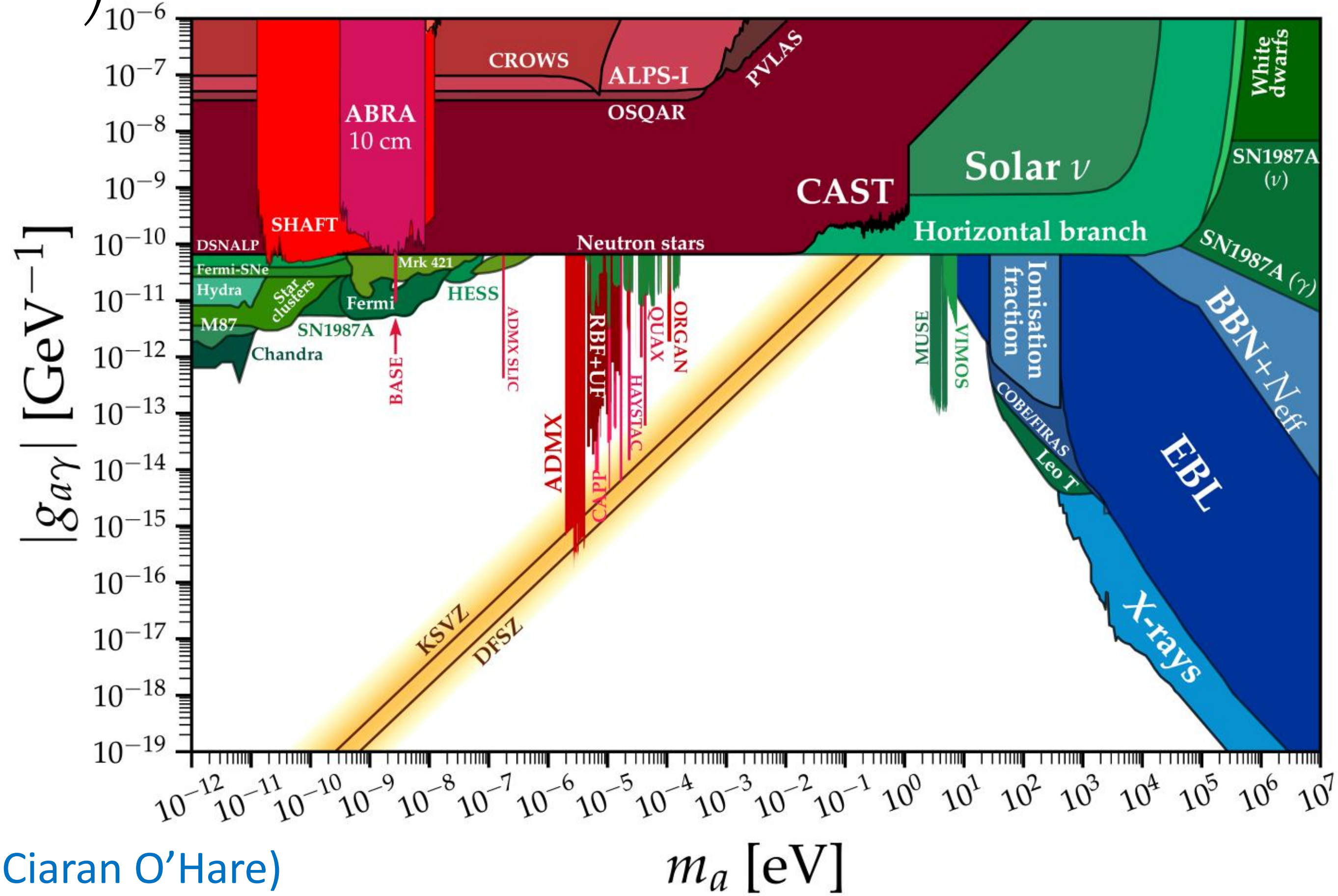
$$m_a = 5.70 \pm 0.06 \pm 0.04\,\mu\text{eV}\left(\frac{10^{12}\text{GeV}}{f_a}\right)$$

$$g_{a\gamma\gamma} = \frac{\alpha_{EM}}{2\pi f_a}\left(\frac{E}{N} - 1.92(4)\right)$$

$m_a$: quark mass and higher order uncertainties
$g_{a\gamma\gamma}$: O(α) in QED and NNLO in χPT
Gorghetto, Villadoro [1812.01008]

The standard QCD axion band focuses on sub-eV axion masses and tiny axion-photon couplings

Width of band roughly given by E/N = 44/3 and E/N = 5/3 as boundary values




PDG (from AxionLimits by Ciaran O'Hare)

# Pivot to ALP physics – Standard ALP EFT

- Axion-like particles treat ($m_a$, $f_a$) as independent
  - Lose possible connection to strong CP and DM?
    - Still concrete benchmark scenario for PBC/FIPs program
- Reintroduces entire suite of SM effective operators
  - ALPs couple via PQ current or anomaly operators

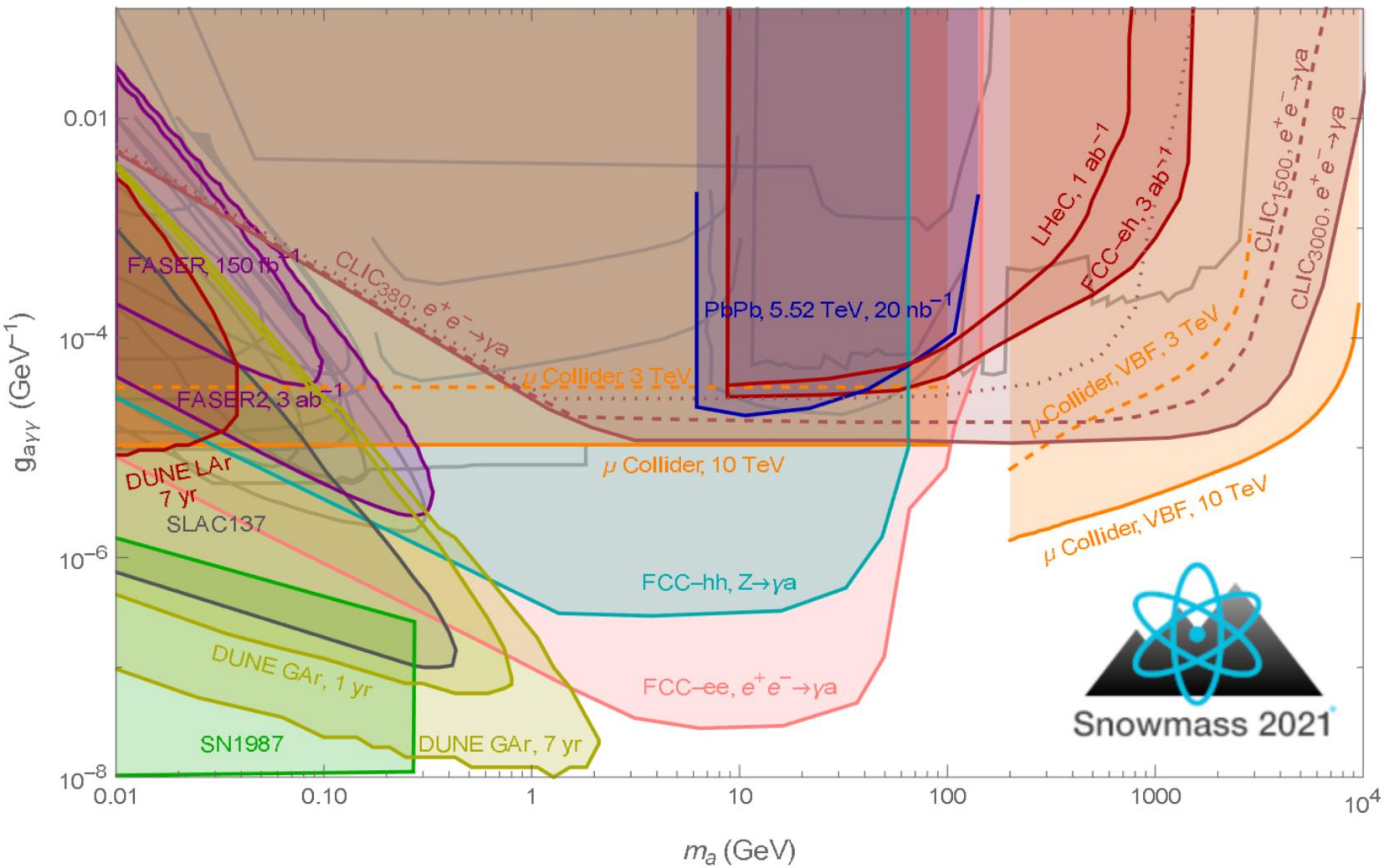
$$\mathcal{L}^{d\leq 5}_{\text{ALP-EFT}} \supset \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{1}{2} m_a^2 a^2 + C_{\text{PQ}} \frac{\partial_\mu a}{2 f_a} J^\mu_{\text{PQ}} + C_{\gamma\gamma} \frac{e^2}{(4\pi)^2} \frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$$
$$+ C_{ZZ} \frac{e^2}{s_W^2 c_W^2} \frac{1}{(4\pi)^2} \frac{a}{f_a} Z_{\mu\nu} \tilde{Z}^{\mu\nu} + C_{Z\gamma} \frac{e^2}{s_W c_W} \frac{1}{(4\pi)^2} \frac{a}{f_a} Z_{\mu\nu} \tilde{F}^{\mu\nu}$$
$$+ C_{WW} \frac{g_L^2}{(4\pi)^2} \frac{a}{f_a} W_{\mu\nu} \tilde{W}^{\mu\nu} + C_{gg} \frac{g_s^2}{(4\pi)^2} \frac{a}{f_a} G^a_{\mu\nu} \tilde{G}^{a\mu\nu} + \mathcal{O}\left(\frac{1}{f_a^2}\right).$$

Brivio, et. al [1701.05379], Bauer, et. al. [1708.00443], Gavela, et. al. [1905.12953]

# ALPs at future expts

Snowmass EF09 Report [2009.13128]

- Concrete benchmark scenario for PBC/FIPs program



# The vanilla quality axion

- Recall fundamental origin of PQ symmetry: anomalous global symmetry
  - In general, global symmetries stem from field content multiplicity, explicit breaking by Lagrangian interaction terms
    - Not necessarily renormalizable
- Vanilla axion: sole source of PQ breaking arises from $U(1)_{PQ} \times SU(3)^2$ anomaly
  - But no generally rigorous embedding between low-scale PQ symmetry and UV PQ symmetries = quality problem

# Qualitative change in perspective

- UV sensitivity of vacuum angle drives strengthening of axion potential from small-size instantons
  - Generally realized in embeddings of SM color gauge symmetry to larger gauge groups giving small-size instanton corrections to axion potential
  - Leads to **heavier** QCD axions
- Separately, soft breaking of PQ symmetry is *understudied*
    - Distinct from explicit breaking of shift symmetry by ALP mass
  - Leads to **lighter** QCD axions (with *calculable* fine-tuning)

# Outline

- Brief review of vanilla QCD axions
- Increasing the axion mass with small-size instanton effects in extended color gauge theories
- Soft-breaking PQ symmetry to decrease the axion mass and quantitative study of fine-tuning
- Conclusions

Texas Sheet Cake
© Lick Honest Ice Cream

# Supersizing axions with small-size instantons

Kivel, Laux, FY, JHEP **11** (2022) 88 [2207.08740]

# Small-size instanton effects

- Key point: Use axion sensitivity to UV physics to enhance quality of axion solution

Agrawal, Howe [1710.04213, 1712.05803]

  – Embed $SU(3)_C$ in larger UV gauge group
    - Confinement of extended color gauge group will give additional instanton-induced potential terms to light axion
    - Requires non-trivial book-keeping to trace PQ symmetry from IR to UV
  – Practical consequence: Extended color groups typically involve coloron/axigluon color octet vectors and additional collider signatures

See, e.g. Dobrescu, FY [1306.2629]

# Refresher: SM instanton effects

- SM + axion Lagrangian

$$\mathcal{L} = \frac{1}{2}\partial_\mu a \partial^\mu a + \frac{\partial_\mu a}{F_a}\left(\sum_{i=1}^{N_f} c_1^i \bar{q}_i \gamma_\mu \gamma_5 q_i\right) - \left(\sum_{i=1}^{N_f} m_i \bar{q}_L^i e^{i c_2^i a/F_a} q_R^i + \text{h.c.}\right)$$

$$- \frac{a}{F_a}\left(c_3^G \frac{g_s^2}{32\pi^2} G\tilde{G} + c_3^W \frac{g^2}{32\pi^2} W\tilde{W} + c_3^B \frac{g'^2}{32\pi^2} B\tilde{B}\right) ,$$

Kim, Carosi (2008)

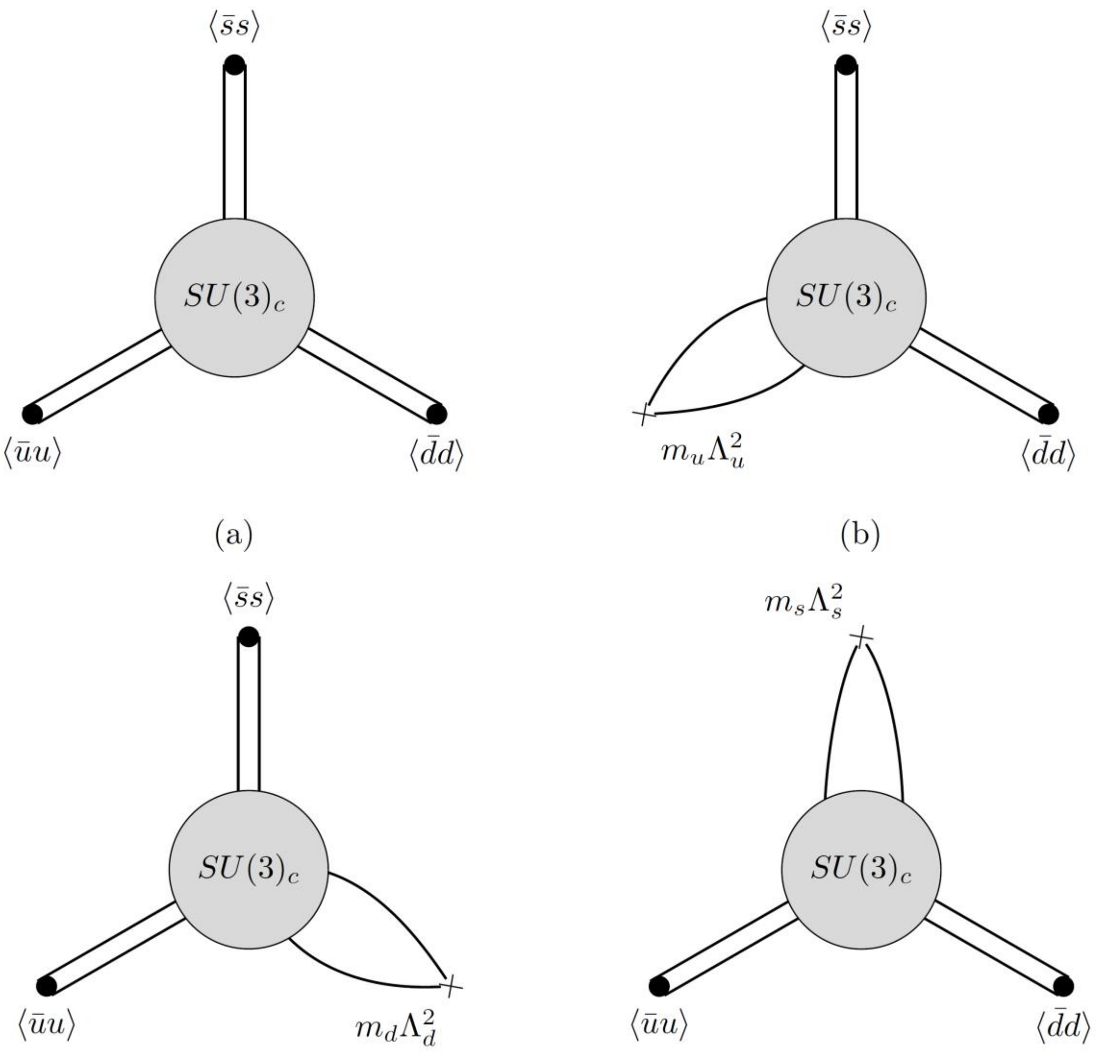
- Axion mass is generated by gluon operator
  - Via index theorem, instanton action induces ‘t Hooft determinantal operator according to PQ color anomaly

$$\mathcal{L}_{\text{det}} = (-1)^{N_f} K^{4-3N_f} \left(\prod_{i=1}^{N_f} \det\left(\bar{q}_L^i q_R^i\right)\right) e^{-i c_3^G \frac{a}{F_a}} + \text{h.c.}$$

# Refresher: SM instanton effects

- Calculate leading determinantal operators
  - Correspond to “instanton flower” diagrams
  - Power counting in chiral symmetry breaking parameters

$$\mathcal{L}_{\rm det} = -\frac{1}{K^5} \sum_i A_i$$



# Refresher: SM instanton effects

- Operators lead to mixing of $\pi^0$, η, η' and axion

$$A_1 = \left(\prod_i \det(\bar{q}_{i,L}\, q_{i,R})\right) e^{-ic_3^G \theta_a} + \text{ h.c. },$$

$$\sim \left(\frac{v^3}{2}\exp\big(i(\theta_{\pi^0}+\theta_{\eta'})\big)\right)\left(\frac{v^3}{2}\exp\big(i(-\theta_{\pi^0}+\theta_{\eta'})\big)\right)\left(\frac{v^3}{2}\right) e^{-ic_3^G\theta_a} + \text{ h.c. },$$

$$= \frac{v^9}{8}\left(\exp\big(i(2\theta_{\eta'} - c_3^G\theta_a)\big) + \text{h.c.}\right) = \frac{v^9}{4}\cos\big(2\theta_{\eta'} - c_3^G\theta_a\big) ,$$

$$A_2 = \frac{v^6}{2} m_u \Lambda_u^2 \cos\big(\theta_{\pi^0} + \theta_{\eta'} - c_3^G\theta_a\big) ,$$

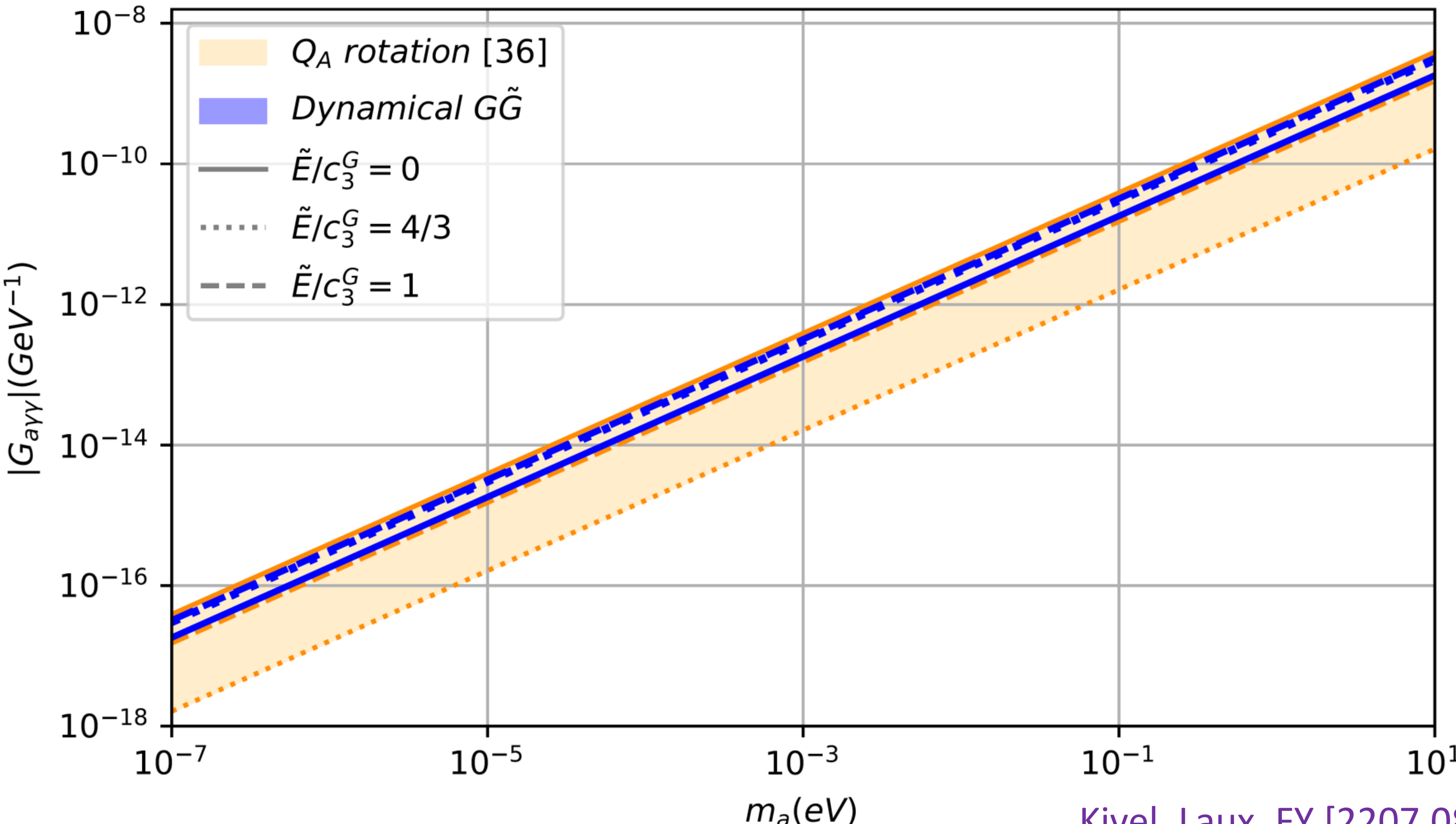
$$A_3 = \frac{v^6}{2} m_d \Lambda_d^2 \cos\big(-\theta_{\pi^0} + \theta_{\eta'} - c_3^G\theta_a\big) ,$$

$$A_4 = \frac{v^6}{2} m_s \Lambda_s^2 \cos\big(2\theta_{\eta'} - c_3^G\theta_a\big) .$$

  – Encapsulate relevant instanton effects via chiral insertions

# Cross-check: no SSIs

- Even neglecting η-mixing, we reproduce QCD axion band




Kivel, Laux, FY [2207.08740]

# Adding small-size instanton effects

- Determinantal approach readily accounts for SSIs
  - In contrast to χEFT, we capture alignment of explicit and instanton PQ breaking by different PNGBs
  - Can embed vacuum angle θ in different ways in UV
    - Thought experiment: SU(3) x SU(3) vs. SU(6)
    - SU(3) × SU(3) – original model by Agrawal, Howe
    - SU(6) × SU(3)' – model by Gaillard, et. al.
      - Embeds $SU(3)_C$ into SU(6) and adopts massless up' solution for SU(6)
    - Intuitively, the mixing of PNGBs induced by $SU(3)_C$ instantons and small-size instantons determines the embedding of PQ symmetry from low to high scales

Gaillard, Gavela, Houtz, Quilez, del Rey [1805.064365]

# Color-Unified SU(6) x SU(3)′ model

Gaillard, Gavela, Houtz, Quilez, del Rey [1805.064365]

- Embed $SU(3)_c$ into SU(6) at high scales
  - SU(6) has massless Q fermion to solve $\theta_6$ → get axieta dof
  - Add SU(3)′ to make SM-charged exotic multiplets decouple at $\Lambda_{CUT}$ scale by bifundamental scalar Δ

$$SU(6) \times SU(3') \xrightarrow{\Lambda_{\rm CUT}} SU(3)_c \times SU(3)_{\rm diag} \xrightarrow{v_{\rm diag}} SU(3)_c$$

– M1 (KSVZ) or M2 (DFSZ) variants solve θ′ → get axion

| | $SU(3)_{\rm diag}$ | $SU(3)_c$ | $SU(3')$ | $SU(6)$ |
|---|---|---|---|---|
| $Q$ | $\bar{\square}$ | $\square$ | 1 | 20 |
| $q$ | $\square$ | 1 | $\square$ | 1 |

| | $SU(3)_{\rm diag}$ | $SU(3)_c$ | $SU(3')$ | $SU(6)$ |
|---|---|---|---|---|
| $Q$ | $\bar{\square}$ | $\square$ | 1 | 20 |
| $\Delta_2$ | - | - | $\bar{\square}$ | $\square$ |

- Exotic quark confinement scale $v_{diag}$ separates exotic states from EW scale

# M1 variant

- QCD axion inherited from M1 composite axion and axieta admixture
  - Exotic quark fields after SU(6) breaking to $SU(3)_{diag}$

$$\begin{aligned}\mathcal{L} \supset \bar{Q}_{I,i} &\left(i\delta_{IJ}\ \delta_{ij}\ \not{\partial} - g_{\text{diag}}\ T^A_{IJ} \not{A}^A_{\text{diag}} \delta_{ij} - g_s\ \delta_{IJ} T^a_{ij} \not{A}^a\right) Q_{J,j} \\ &+ \bar{q}_{I,i'} \left(i\delta_{IJ}\ \delta_{i'j'} \not{\partial} - g_{\text{diag}}\ T^A_{IJ} \not{A}^A_{\text{diag}} \delta_{i'j'} - g'\ \delta_{IJ} T^b_{i'j'} \not{A}^{\prime,b}\right) q_{J,j'} \\ &+ \theta_{\text{diag}} \frac{\alpha_{\text{diag}}}{8\pi} G_{\text{diag}} \tilde{G}_{\text{diag}} + \bar{\theta} \frac{\alpha_s}{8\pi} G\tilde{G} + \theta' \frac{\alpha'}{8\pi} G'\tilde{G}' + \frac{(g')^2\ \Lambda^2_{\text{CUT}}}{2} A'_\mu A'^\mu\end{aligned}$$

- Treat all field strength duals via ‘t Hooft determinantal operators to calculate instanton effects

# M1 variant – SSI amplitudes

$$\mathcal{L}_{\rm det} = -K' A_1 - \frac{1}{K_{\rm diag}^2} A_2 - \frac{1}{K^8}(A_3 + A_4 + A_5)$$

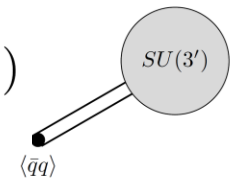
$$A_1 = v_{\rm diag}^3 \cos\left(\frac{2\eta_d}{F_a}\right) ,$$

$$A_2 = \frac{v_{\rm diag}^6}{2} \cos\left(\frac{2\eta_d}{F_a} + \frac{\sqrt{6}a}{F_a}\right) ,$$

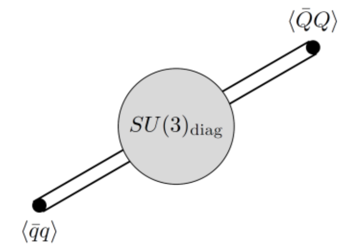
$$A_3 = \frac{v_{\rm diag}^3 v^9}{4} \cos\left(\frac{\sqrt{6}a}{F_a} + 2\frac{\eta'}{F_{\eta'}}\right) ,$$

$$A_4 = \frac{v_{\rm diag}^3 v^6}{2} m_u \Lambda_u^2 \cos\left(\frac{\sqrt{6}a}{F_a} + \frac{\eta'}{F_{\eta'}} + \frac{\pi^0}{F_{\pi^0}}\right)$$

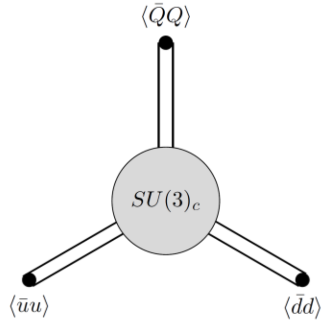
$$A_5 = \frac{v_{\rm diag}^3 v^6}{2} m_d \Lambda_d^2 \cos\left(\frac{\sqrt{6}a}{F_a} + \frac{\eta'}{F_{\eta'}} - \frac{\pi^0}{F_{\pi^0}}\right)$$



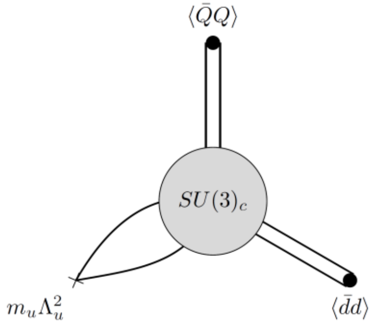
(a)



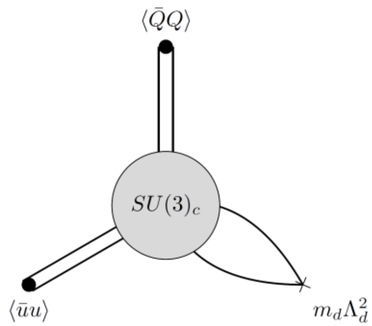
(b)



(c)



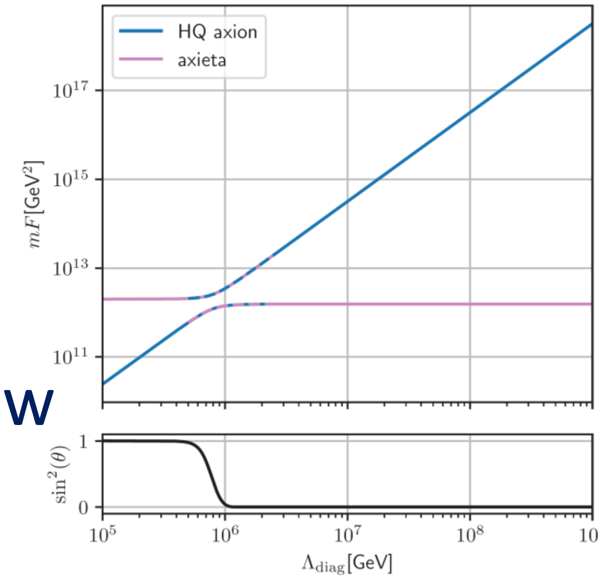
(d)

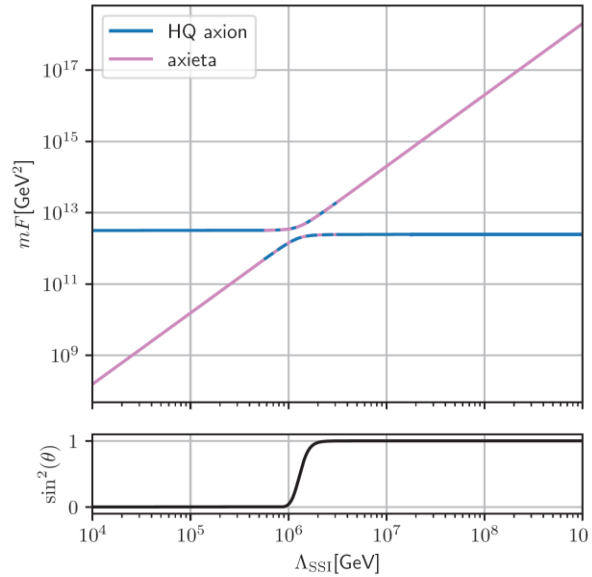


(e)

# Axion and axieta masses and mixing

- Diagonalize PNGB matrix to get axion and axieta masses and mixings with new $\Lambda_{SSI}$ dependence

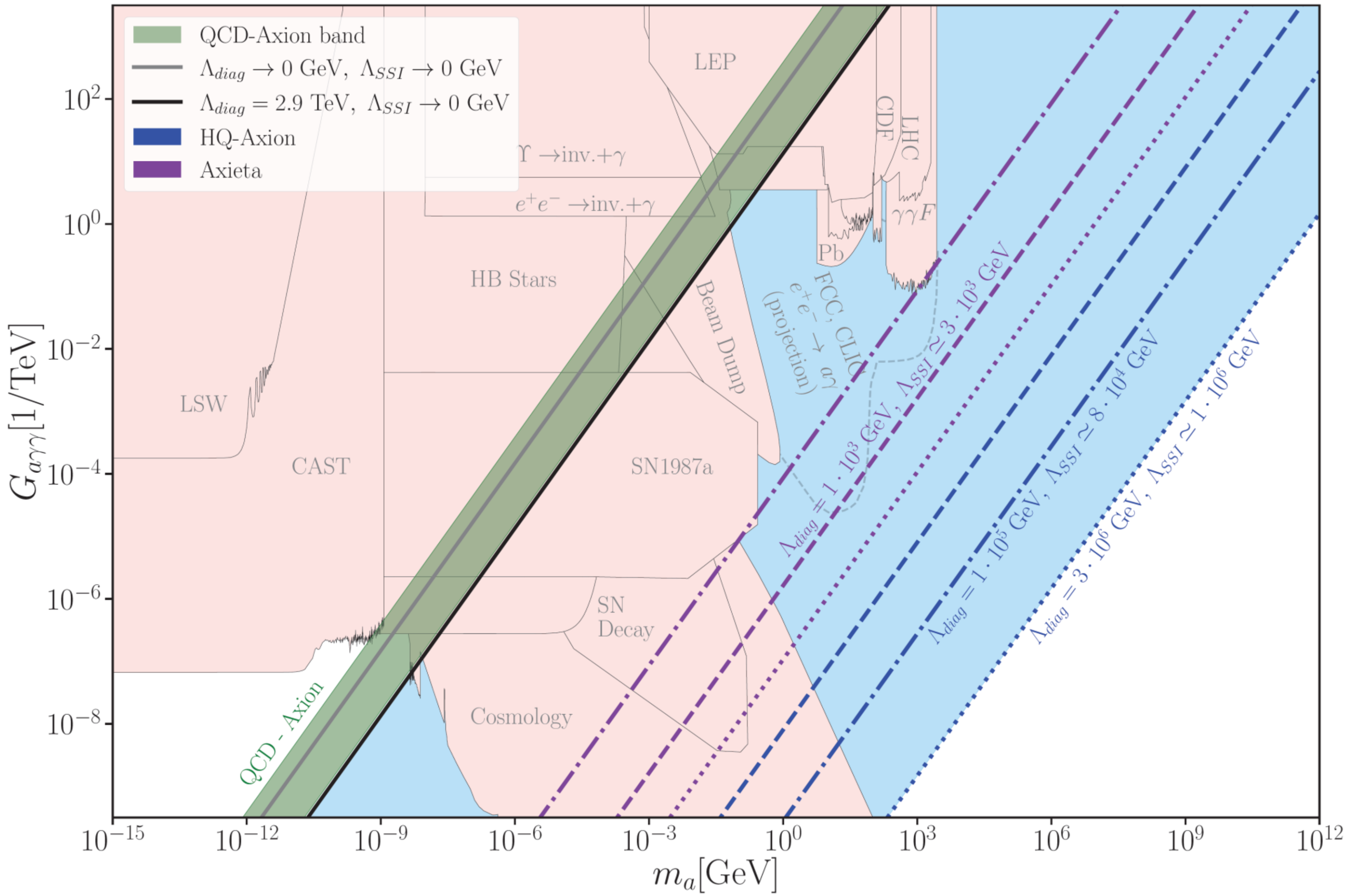


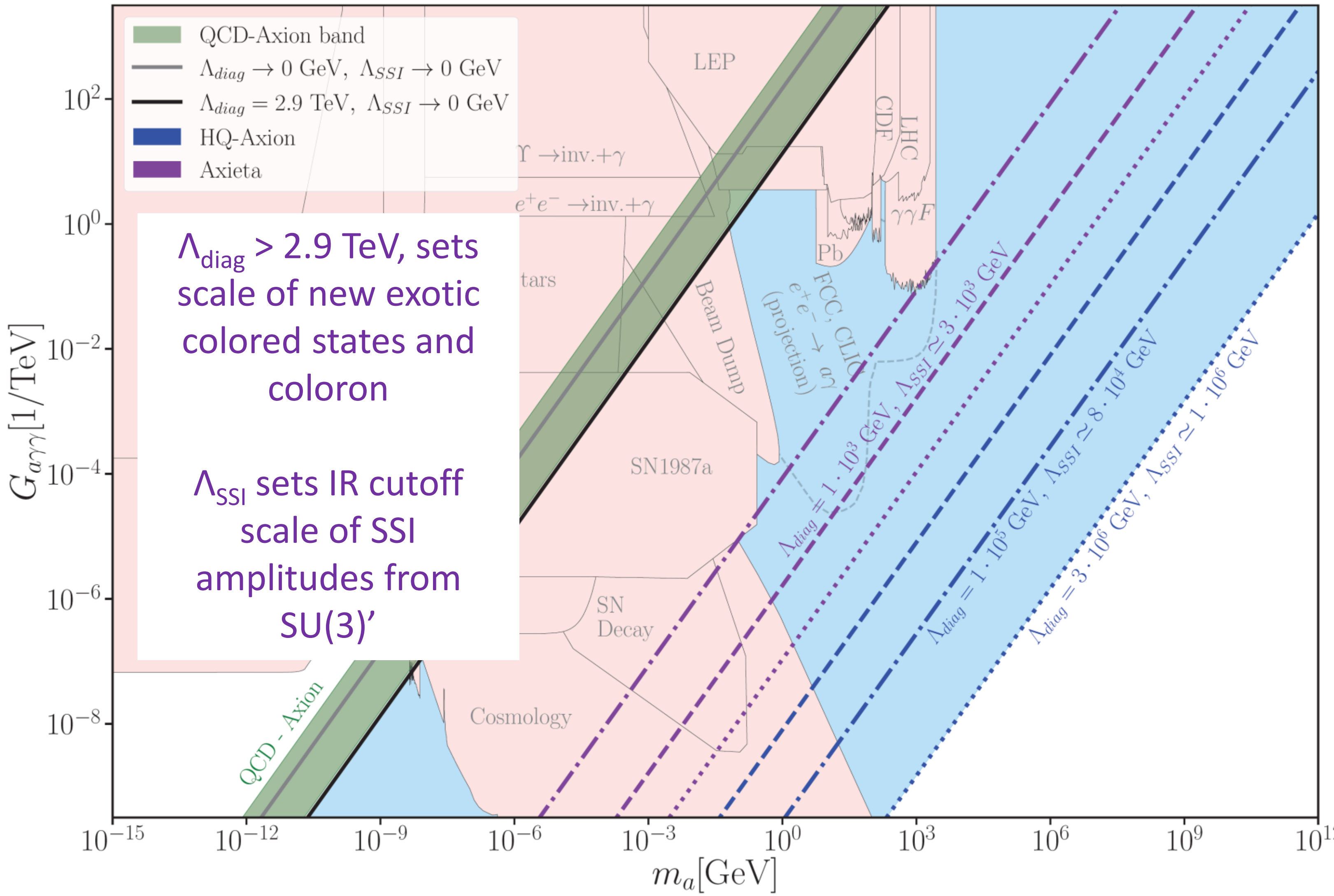

$$m_a^2 F_a^2 = 4(\Lambda_{\rm diag}^4 + \Lambda_{\rm SSI}^4) - 24\Lambda_{\rm diag}^8 \times \left| 2\Lambda_{\rm SSI}^4 - \Lambda_{\rm diag}^4 - 3(m_a^2F_a^2)^{\rm KSVZ} - \sqrt{\left(2\Lambda_{\rm SSI}^4 - \Lambda_{\rm diag}^4 - 3(m_a^2F_a^2)^{\rm KSVZ}\right)^2 + 24\Lambda_{\rm diag}^8} \right|^{-1}$$

$$m_{\eta_d}^2 F_a^2 = 2\Lambda_{\rm SSI}^4 + 5\Lambda_{\rm diag}^4 + 3(m_a^2F_a^2)^{\rm KSVZ} + \sqrt{\left(2\Lambda_{\rm SSI}^4 - \Lambda_{\rm diag}^4 - 3(m_a^2F_a^2)^{\rm KSVZ}\right)^2 + 24\Lambda_{\rm diag}^8}\ ,$$

# SSI-driven mass enhancements – M1 variant



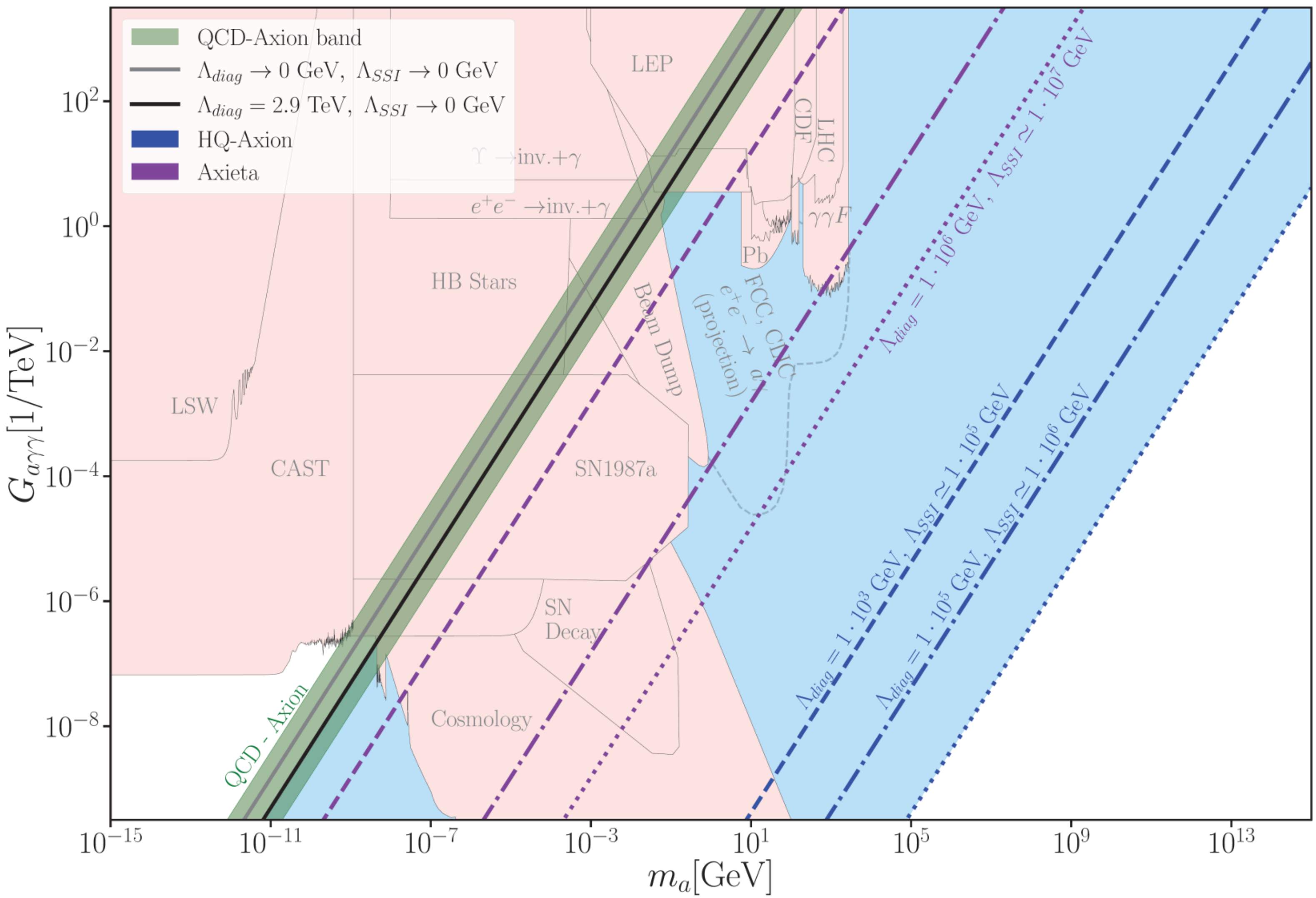
# SSI-driven mass enhancements – M1 variant



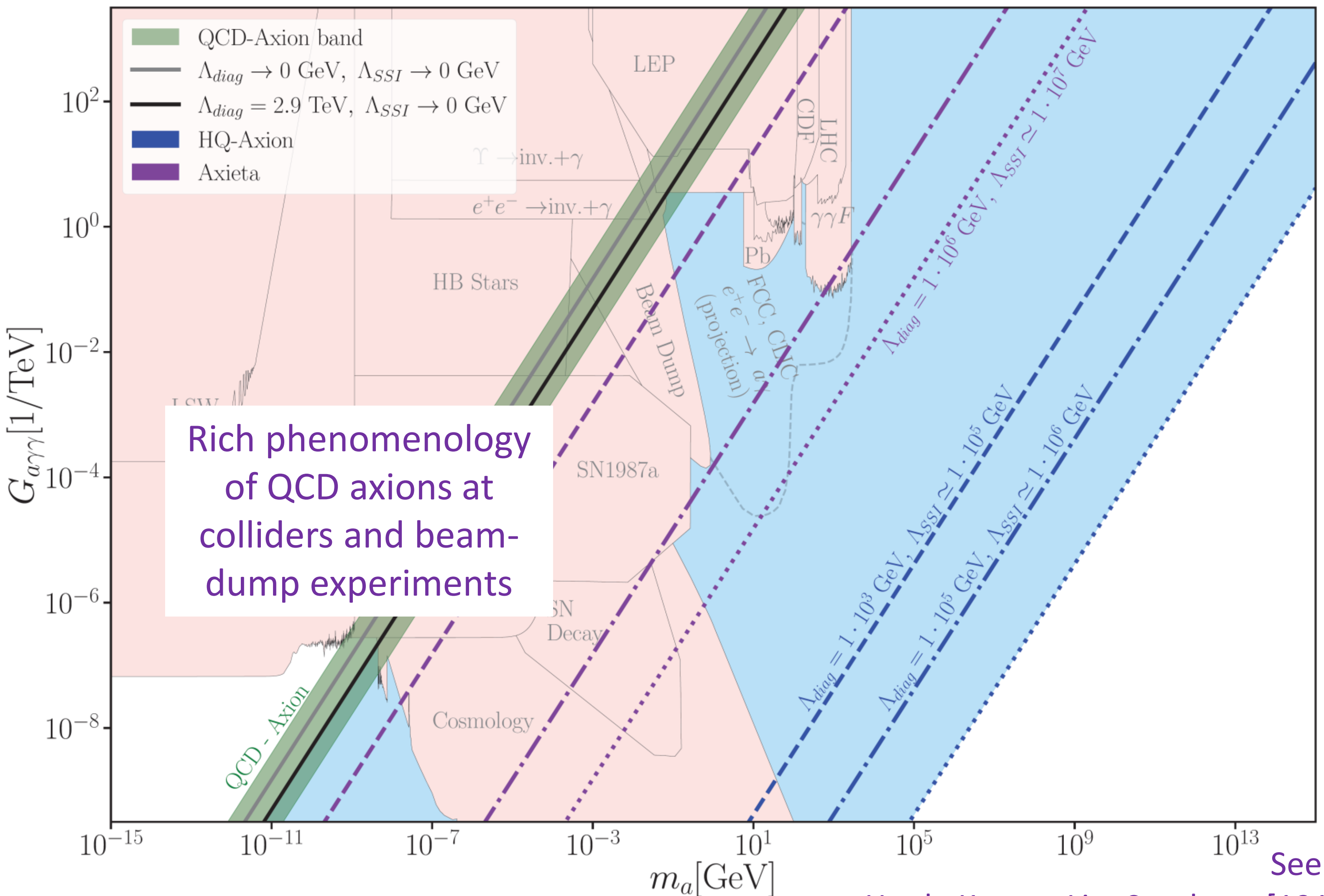

$\Lambda_{diag}$ > 2.9 TeV, sets scale of new exotic colored states and coloron

$\Lambda_{SSI}$ sets IR cutoff scale of SSI amplitudes from SU(3)'

# SSI-driven mass enhancements – M2 variant



# SSI-driven mass enhancements – M2 variant




Rich phenomenology of QCD axions at colliders and beam-dump experiments

See also, e.g.
Hook, Kumar, Liu, Sundrum [1911.12364]

Roasted Beets & Fresh Mint
© Lick Honest Ice Cream

# The anarchic axion

Elahi, Elor, Kivel, Laux, Najjari, FY [2301.08760]

# Building anarchy

- Break PQ softly
- Begin with DFSZ axion

| Field | $SU(3)_c$ | $SU(2)_L$ | $U(1)_Y$ | $\mathbb{Z}_5$ | $U(1)_{PQ}$ |
|---|---|---|---|---|---|
| $Q_L^i$ | 3 | 2 | 1/6 | 0 | $X_Q$ |
| $u_R^i$ | 3 | 1 | 2/3 | 1 | $X_Q$-$X_1$ |
| $d_R^i$ | 3 | 1 | -1/3 | 0 | $X_Q$-$X_2$ |
| $L_L^i$ | 1 | 2 | -1/2 | 0 | $X_L$ |
| $e_R^i$ | 1 | 1 | -1 | 0 | $X_L$-$X_2$ |
| $H_1$ | 1 | 2 | -1/2 | 4 | $X_1$ |
| $H_2$ | 1 | 2 | 1/2 | 0 | $X_2$ |
| $\Phi$ | 1 | 1 | 0 | 1 | $X_3$ |

- Scalar potential (1a) leaves global $U(1)_{H1} \times U(1)_{H2} \times U(1)_{\Phi}$ symmetry charges undefined
- Canonical DFSZ scalar term (1b) defines PQ charges

$$V = \sum_{i=1,2} \left(\mu_i^2|H_i|^2 + \lambda_i|H_i|^4\right) + \lambda|H_1|^2|H_2|^2 + \lambda'|H_1H_2|^2$$
$$+ \mu_3^2|\Phi|^2 + \lambda_3|\Phi|^4 + \lambda_{13}|H_1|^2|\Phi|^2 + \lambda_{23}|H_2|^2|\Phi|^2 \,, \tag{1a}$$

$$V_{\text{break}}^{C_\lambda} = -C_\lambda H_1 H_2 \Phi + \text{h.c.} \,, \tag{1b}$$

# Building anarchy

$$V = \sum_{i=1,2} \left(\mu_i^2 |H_i|^2 + \lambda_i |H_i|^4\right) + \lambda |H_1|^2 |H_2|^2 + \lambda' |H_1 H_2|^2$$
$$+ \mu_3^2 |\Phi|^2 + \lambda_3 |\Phi|^4 + \lambda_{13} |H_1|^2 |\Phi|^2 + \lambda_{23} |H_2|^2 |\Phi|^2 , \tag{1a}$$

$$V_{\text{break}}^{C_\lambda} = -C_\lambda H_1 H_2 \Phi + \text{h.c.} , \tag{1b}$$

- With global PQ symmetry set, now add PQ soft breaking term

$$V_{\text{break}}^{B_\mu} = -B_\mu H_1 H_2 + \text{h.c.} ,$$

- Two sources of PQ breaking: color anomaly and $B_\mu$
  - Three neutral Goldstones: one for SM Z, one 2HDM A, one axion
  - “Standard” 2HDM potential terms forbidden by $Z_5$ symmetry

# Building anarchy

- Define angular fields $\alpha \equiv a/v_a,\ \alpha' \equiv A/v_A$
- Use $C_\lambda$ to effectively decouple 2HDM A

$$
\begin{aligned}
-V_{\rm ang} = \ & \Lambda_{\rm QCD}^4 \cos\left(N_g\left(\alpha + \alpha'\delta^2\right)\right) \\
& + \Lambda_{\rm QCD}^4 \frac{v_a}{v_{\rm max}} \cos\left(\alpha + \alpha'\delta^2 + \bar\theta\right) \\
& + \frac{|C_\lambda| v v_A^2}{\sqrt{2}\delta(1+\delta^2)} \cos\left(\alpha'(1+\delta^2)\right)
\end{aligned}
$$

$$
\begin{aligned}
v_{\rm max} &\equiv \frac{\Lambda_{\rm QCD}^4}{|B_\mu| v}\sqrt{1+\delta^2} \\
\delta &= v_A/v_a
\end{aligned}
$$

  - Second line is effect of finite $B_\mu$
  - $v_{max}$ = maximal value of PQ vev $v_a$

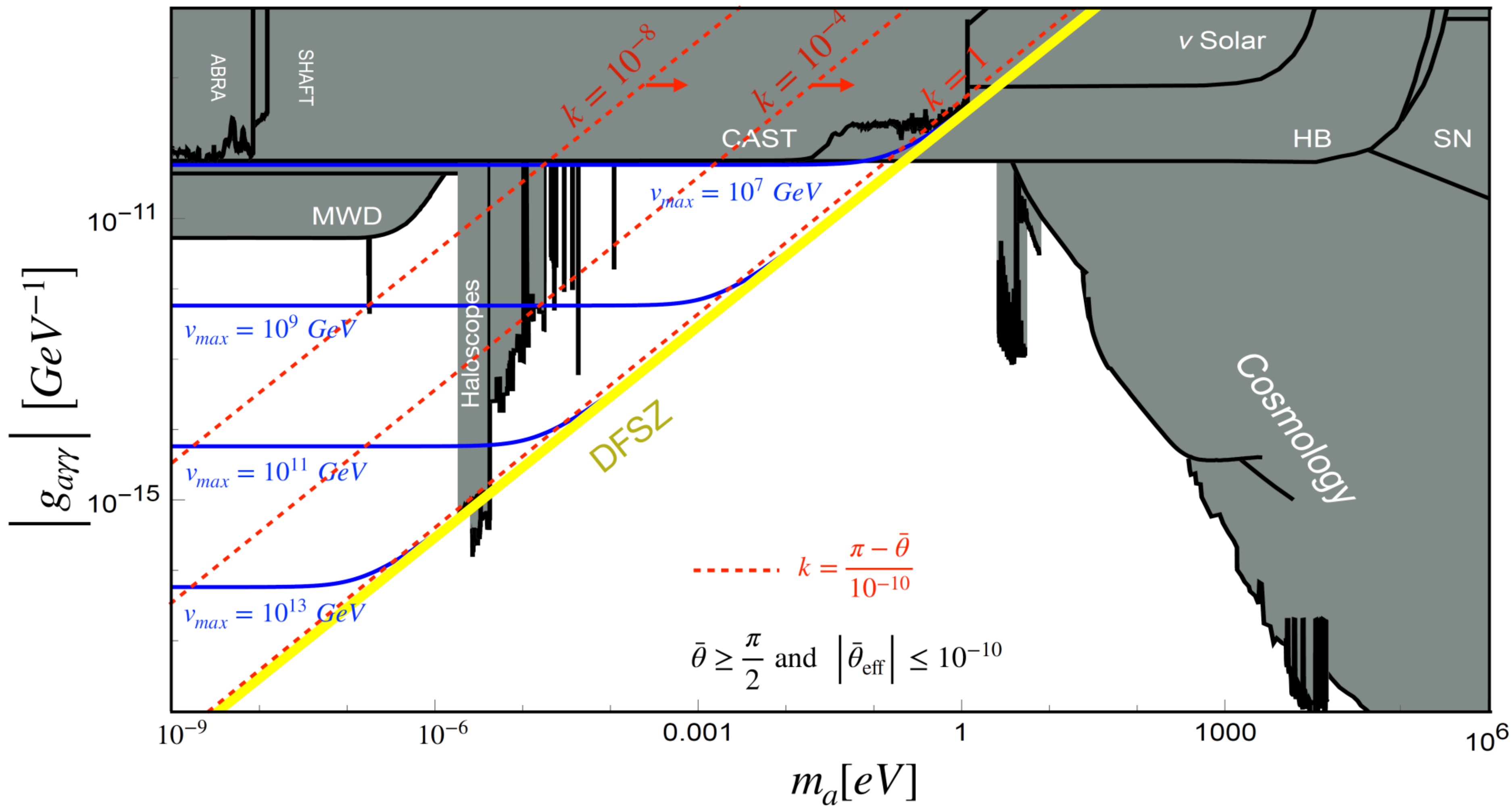
# Building anarchy

- UV phases shuffled into $N_g\,\bar{\theta} = \theta_{SM} - \; N_g \theta_\mu$
- Tadpole of axion = observable $|\theta_{\text{eff}}|$
- Axion mass arises from canonical DFSZ contribution and soft-breaking $B_\mu$ piece

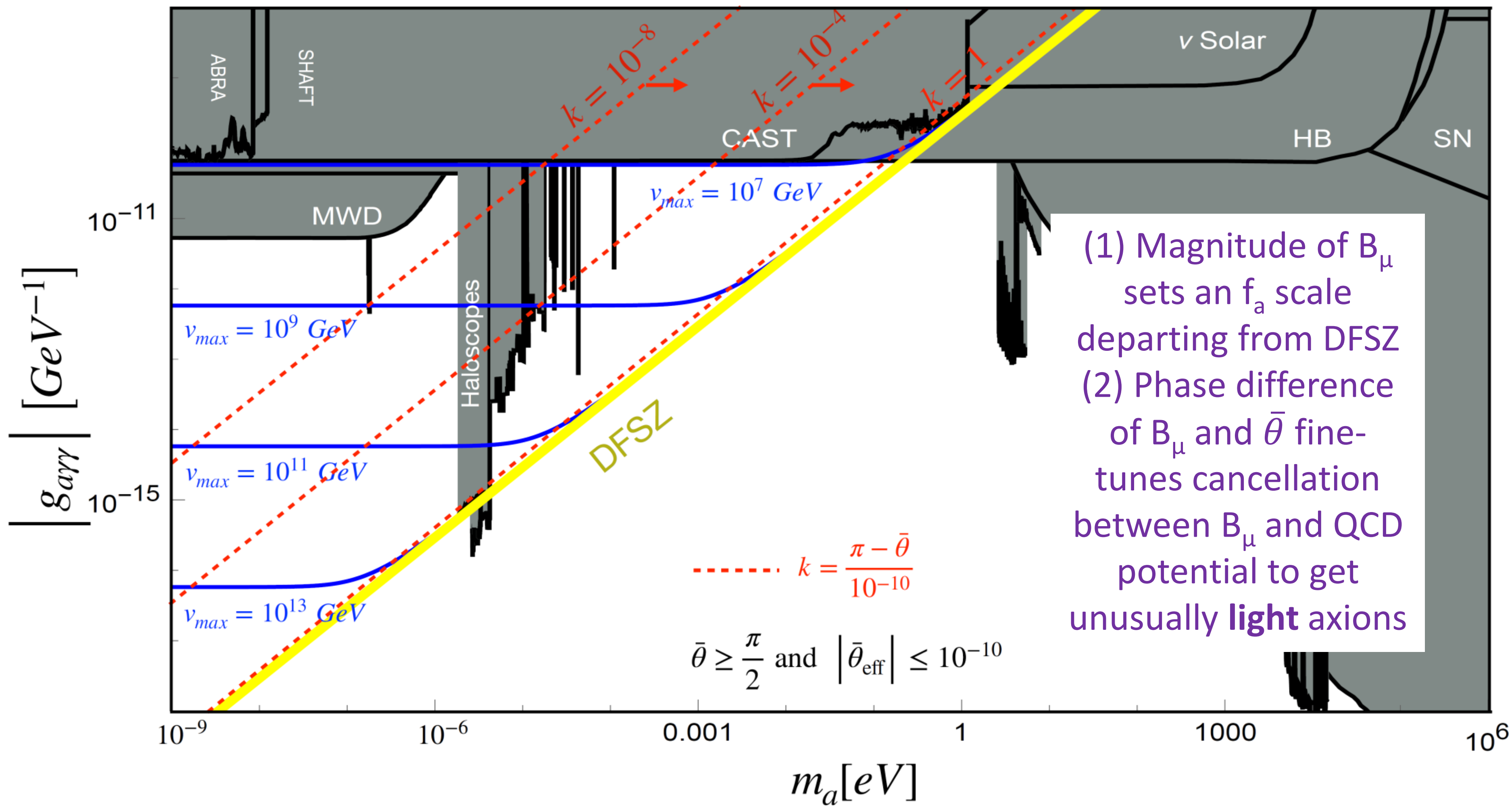
$$m_a^2 = \frac{\Lambda_{\text{QCD}}^4}{v_a^2}\left(N_g^2 \cos\left(N_g \bar{\theta}_{\text{eff}}\right) + \frac{v_a}{v_{\max}} \cos\left(\bar{\theta} - \bar{\theta}_{\text{eff}}\right)\right)$$

$$\frac{1}{f_a} \equiv \frac{N_g}{v_a} = -\frac{\cos\left(\bar{\theta} - \bar{\theta}_{\text{eff}}\right)}{2N_g v_{\max} \cos\left(N_g \bar{\theta}_{\text{eff}}\right)} \tag{11}$$
$$+ \sqrt{\frac{m_a^2}{\Lambda_{\text{QCD}}^4 \cos\left(N_g \bar{\theta}_{\text{eff}}\right)} + \left(\frac{\cos\left(\bar{\theta} - \bar{\theta}_{\text{eff}}\right)}{2N_g v_{\max} \cos\left(N_g \bar{\theta}_{\text{eff}}\right)}\right)^2}\,.$$

# Anarchic axion deviates from DFSZ band



# Anarchic axion deviates from DFSZ band

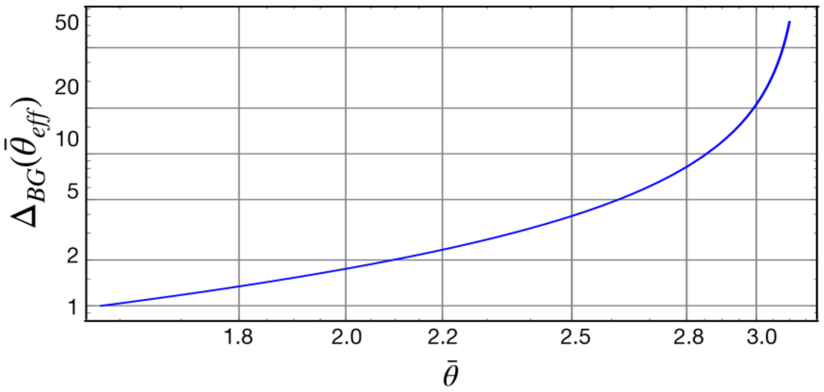



(1) Magnitude of $B_\mu$ sets an $f_a$ scale departing from DFSZ
(2) Phase difference of $B_\mu$ and $\bar{\theta}$ fine-tunes cancellation between $B_\mu$ and QCD potential to get unusually **light** axions

# Fine-tuning measure

- Since finite residual nEDM is *calculable*, can use Giudice-Barbieri fine-tuning measure

$$\Delta_{\mathrm{BG}}(\bar{\theta}_{\mathrm{eff}}) \equiv \left| \frac{\bar{\theta}}{\bar{\theta}_{\mathrm{eff}}} \frac{\partial \bar{\theta}_{\mathrm{eff}}}{\partial \bar{\theta}} \right|$$




- Open model-building question whether more complicated UV model can reduce fine-tuning
  – Ongoing work with Nelson-Barr origin of $B_\mu$ term
- Anarchic axion model serves as target toy effective description aiming for light axions

# My key questions for axions and ALPs

1. Rigorous understanding of PQ mechanism and anomalous global symmetry breaking
   A. Uniqueness of PQ symmetry vs. other UV global symmetries and PNGBs
      i. Relation to UV flavor structure and NP flavor problem
   B. Reformulation of quality problem
2. Expansion of axion parameter space beyond vanilla QCD band
   A. Post-discovery tests for QCD axion discovery in naïve ALP parameter space
   B. Novel axion cosmology (under study)

# Conclusions

- Axion field theory is rich with phenomenological applications and diverse model-building tools
  - Viable strong CP axion models with SSIs **enhance axion mass** into collider reach and beyond
  - Soft-breaking PQ symmetry motivates **unusually light** axions – prime targets for host of experiments
- Future work will focus on Goldstone field theories and their breaking (beyond CCWZ)
  - Field theoretic synthesis of other PNGB EFTs
    - Relaxion, clockwork, linear dilaton, etc.
  - Connections to generalized global symmetries

# Intro: Longstanding strong CP problem

- nEDM: $|d_n| < 1.8 \cdot 10^{-26} e\ \text{cm} \Longrightarrow |\bar{\theta}| < 10^{-10}$
  - For low energy SM, $d_n = C_{\text{EDM}}\, e\, \bar{\theta}$, with $C_{\text{EDM}} = 2.4\ (1.0) \cdot 10^{-16}$ and $\bar{\theta} = \theta + \arg\det Y_u Y_d$

nEDM collaboration, [2001.11966];
Pospelov, Ritz, hep-ph/9908508

    – Naïvely, QCD $\theta$ is O(1) vacuum angle; unknown $Y_u$ and $Y_d$ matrices give rise to $J_{\text{CKM}} = (3.08^{+0.15}_{-0.13}) \cdot 10^{-5}$

- Most attractive current solution is QCD axion
  – PNGB of U(1) Peccei-Quinn global anomalous symmetry gains instanton-induced potential from $U(1)_{PQ} \times SU(3)_C^2$ anomaly

Peccei, Quinn PRL 38, 1440 (1977)
Weinberg PRL 40 (1978) 223; Wilczek PRL 40 (1978) 279

$$\mathcal{L} = \left(\frac{a}{f_a} - \bar{\theta}\right) \frac{1}{32\pi^2} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

  – QCD axion acts as spurion for $\bar{\theta}$, rolls to cancel $\bar{\theta}$

't Hooft (1976, 1978); Callen, Dashen, Gross (1976)

# Topological field configurations

- Instantons are a type of topological soliton, i.e. a field configuration that carries a topological index
  - Example of a topological soliton: scalar field in a double well potential in 1+1 dimensions interpolating between the two wells
  - $SU(3)_C$ instantons are gauge field configurations characterized integer winding numbers
    - Arising from the homotopy classification $\Pi_3(S_3) = \mathbb{Z}$
- Original phenomenological calculation by ‘t Hooft in the context of the U(1) problem and the η’ meson

**Computation of the quantum effects due to a four-dimensional pseudoparticle***

G. 't Hooft†
*Physics Laboratories, Harvard University, Cambridge, Massachusetts 02138*
(Received 28 June 1976)

A detailed quantitative calculation is carried out of the tunneling process described by the Belavin-Polyakov-Schwarz-Tyupkin field configuration. A certain chiral symmetry is violated as a consequence of the Adler-Bell-Jackiw anomaly. The collective motions of the pseudoparticle and all contributions from single loops of scalar, spinor, and vector fields are taken into account. The result is an effective interaction Lagrangian for the spinors.

# The Energy of the Θ-Vacuum

- Calculate $e^{-\varepsilon VT} = \int \mathcal{D}A\, e^{-S[A]}$ using a functional integral
  - S[A] is Euclidean action, ε is vacuum energy density, VT is spacetime volume
- Can separate $\mathcal{D}A$ path integrals into discrete sum over topological sectors
  - Each successive instanton path includes additional suppression factor $e^{-8\pi/g^2(\rho)}$, where ρ is the instanton size
- Characteristic term for $n_+$ instantons and $n_-$ anti-instantons

$$\frac{1}{n_+!\ n_-!}\left[\int d^4x_0\, \frac{d\rho}{\rho^5} C\, \frac{1}{g^8} e^{-8\pi/g^2(\rho)}\right]^{n_+ n_-}$$

$$C = 2^{10}\pi^6 e^{7.0539\ldots}$$

't Hooft (1976, 1978)

  - Dilute instanton gas approximation integrates over well-separated instantons with integral over instanton centers and size

# The Energy of the Θ-Vacuum

- Recognize the topological sector sum is an exponential

$$e^{-\varepsilon VT} = \sum_{n_+ n_-} \left[ \int d^4x_0 \, \frac{d\rho}{\rho^5} C \, \frac{1}{g^8} e^{-8\pi/g^2(\rho)} \right]^{n_+ n_-} \frac{1}{n_+! \; n_-!} e^{i\theta(n_+ - n_-)}$$

$$e^{-\varepsilon VT} = exp\left( \left(e^{i\theta} + e^{-i\theta}\right) VT \int \frac{d\rho}{\rho^5} C \, \frac{1}{g^8} e^{-8\pi/g^2(\rho)} \right)$$

- Extract energy density of the θ-vacuum

$$\varepsilon = -2\cos\theta \int \frac{d\rho}{\rho^5} C \, \frac{1}{g^8} e^{-8\pi/g^2(\rho)}$$

't Hooft (1976, 1978)
Callen, Dashen, Gross (1976)

# Axion decay width vs. stability

- The primary target for QCD axion detection is the diphoton coupling

$$\mathcal{L}_{a\gamma\gamma} = -\frac{g_{a\gamma\gamma}}{4}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} = g_{a\gamma\gamma}\, a\, \mathbf{E}\cdot\mathbf{B}$$

- Gives a decay width of (using E/N = 0)

$$\Gamma_{a\to\gamma\gamma} = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi} = 1.1\times 10^{-24} s^{-1} \left(\frac{m_a}{eV}\right)^5$$

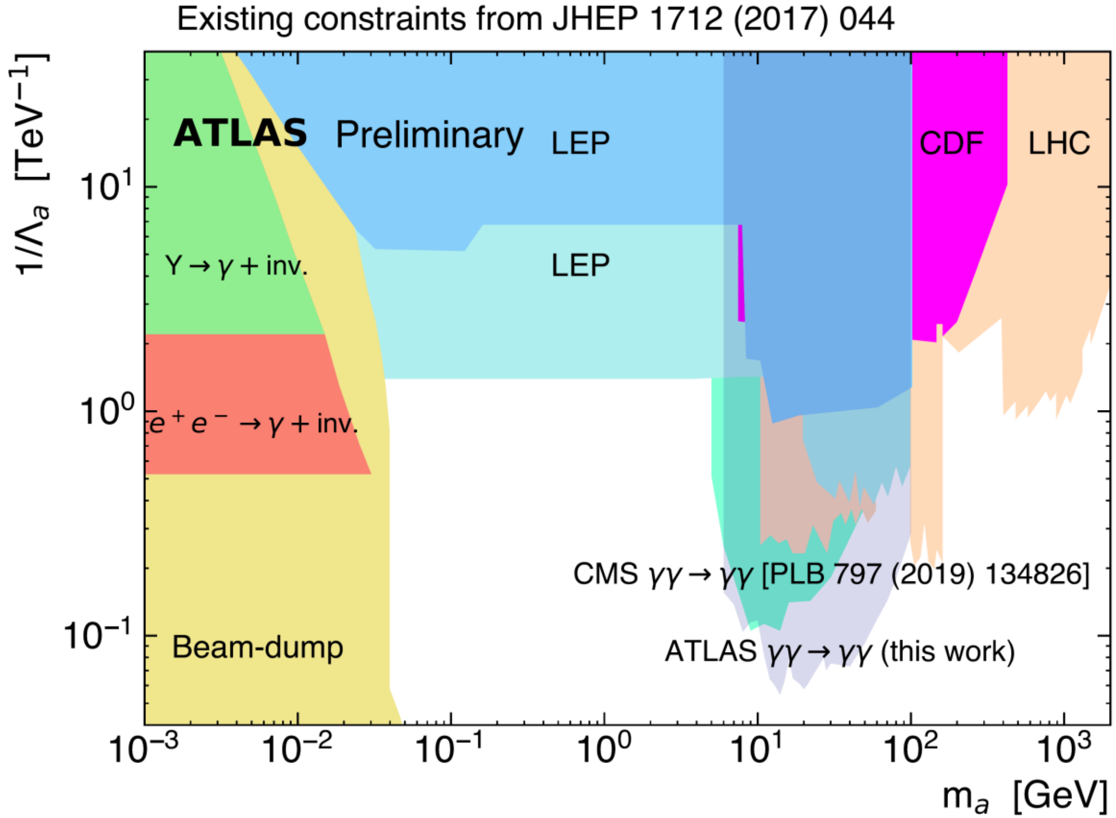
- Axion lives longer than age of universe for $m_a \lesssim 20\ eV$
  - Very cold dark matter (can have coherent oscillations with negligible velocity dispersion)

# ALPs at collider scales

- Axion-like particles treat ($m_a$, $f_a$) as independent
  - Lose possible connection to strong CP and DM?
    - Still concrete benchmark scenario for PBC/FIPs program
- Many collider signatures
  - LbL scattering at Pb+Pb — ATLAS [1904.03536], ATLAS-CONF-2020-10, CMS[1810.04602]
  - Higgs decay to aa
    - bb+μμ; 4γ; 4l — ATLAS [2110.00313]; CMS HIG-21-016; CMS[2111.01299]
  - Higgs decay to Za, a → jj — ATLAS [2004.01678]
  - ALP production from γγ — CMS EXO-21-007
  - ALPs in non-resonant ZZ or ZH production — CMS [2111.13669]

# ALPs at colliders – LbL scattering in Pb+Pb

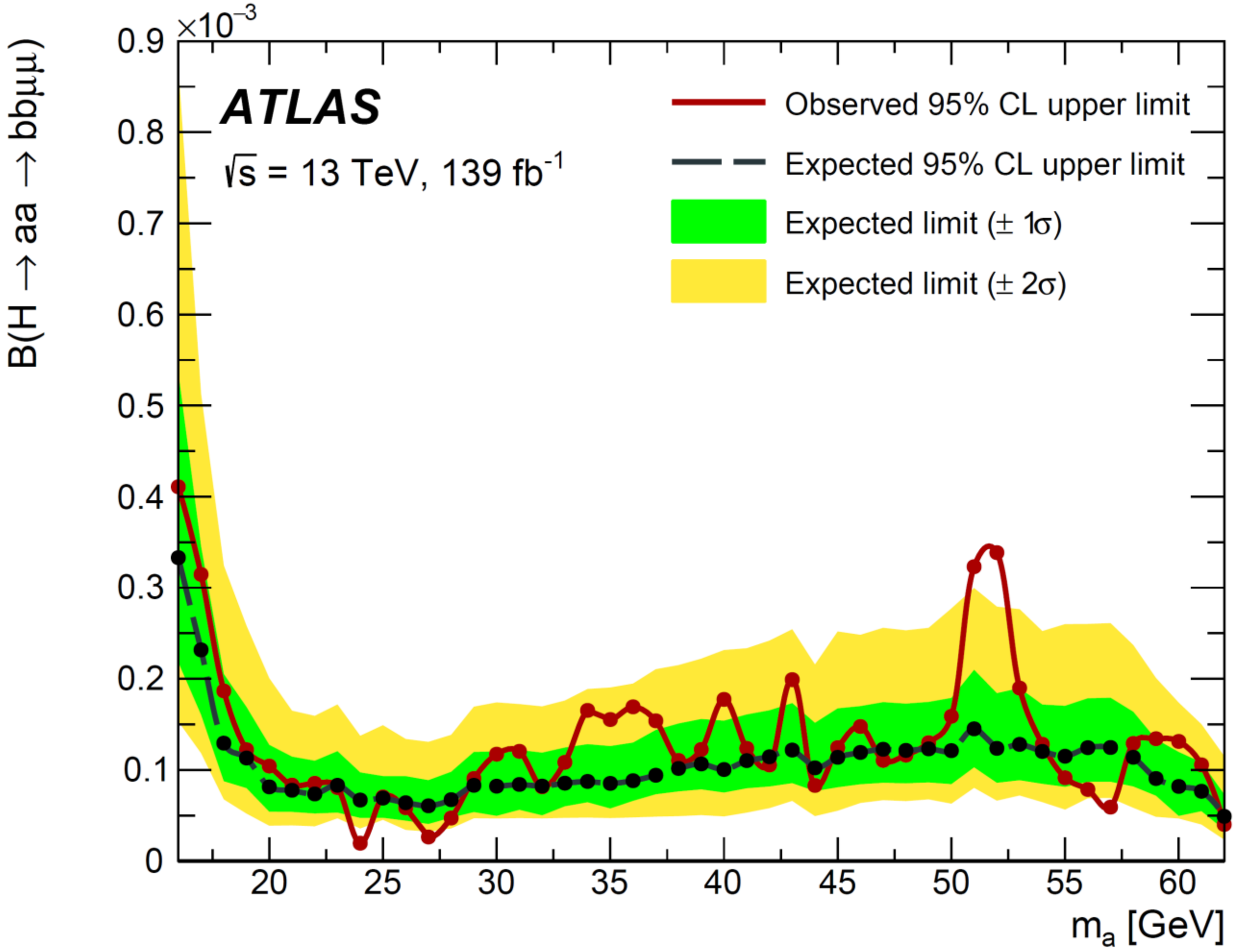
- Focus on diphoton coupling using atomic number enhancement




ATLAS [1904.03536], CONF-2020-010
CMS [1810.04602]

# ALPs at colliders – Exotic Higgs decays

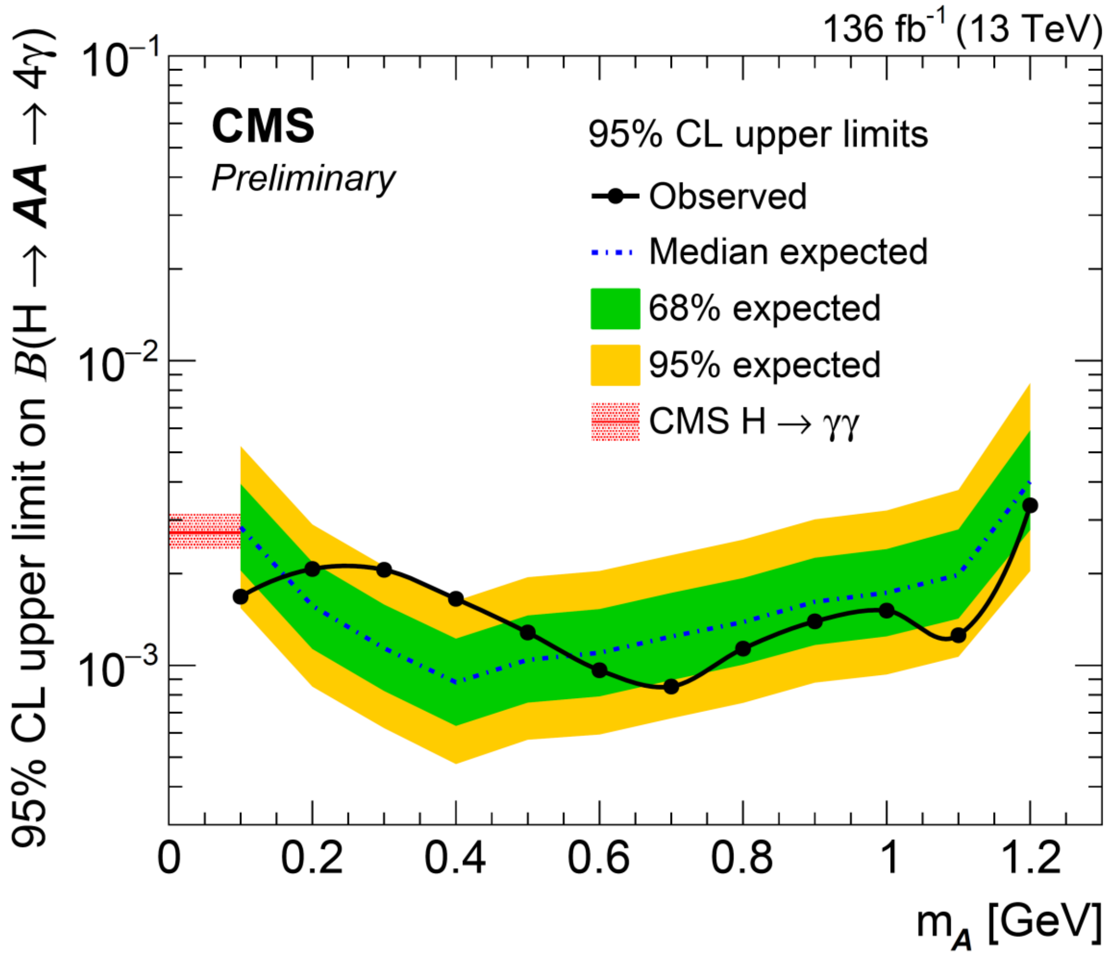
- Higgs decay to aa, decay to (bb)(μμ)




ATLAS [2110.00313]

# ALPs at colliders – Exotic Higgs decay

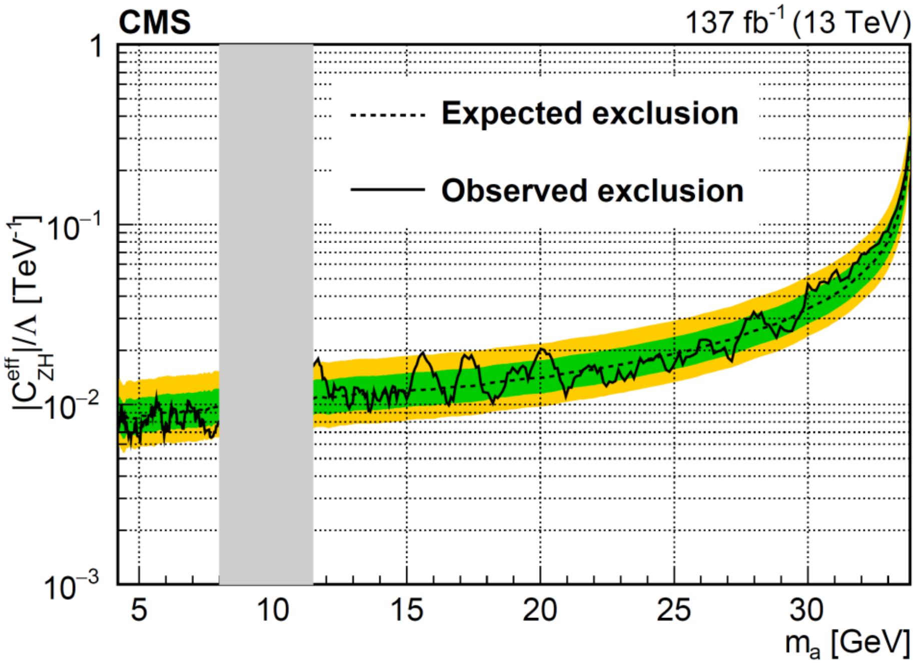
- Higgs decay to aa, decay to (γγ)(γγ)

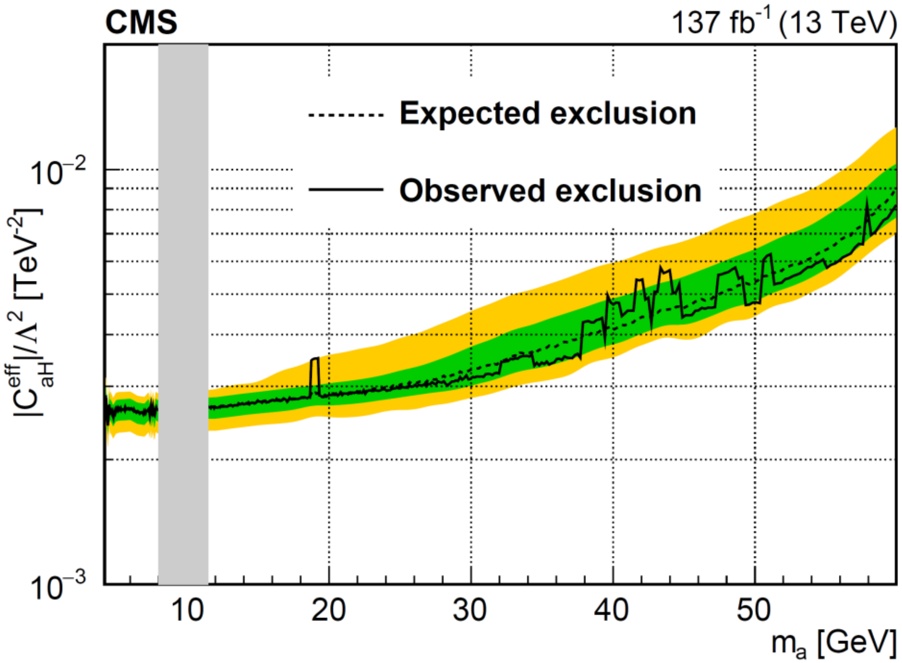



CMS HIG-21-016

# ALPs at colliders – Exotic Higgs decay

- Higgs decay to aa, decay to (ll)(ll)

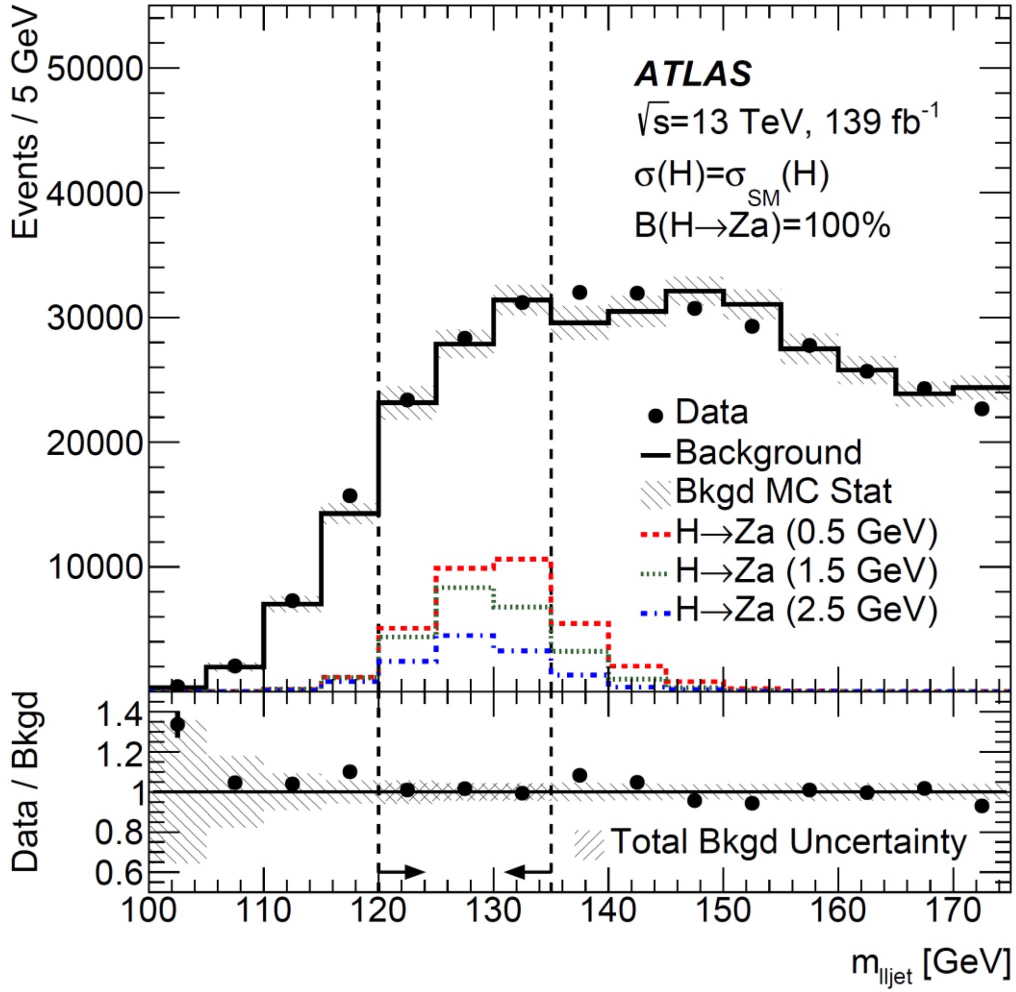



CMS [2111.01299]

# ALPs at colliders – Exotic Higgs decays

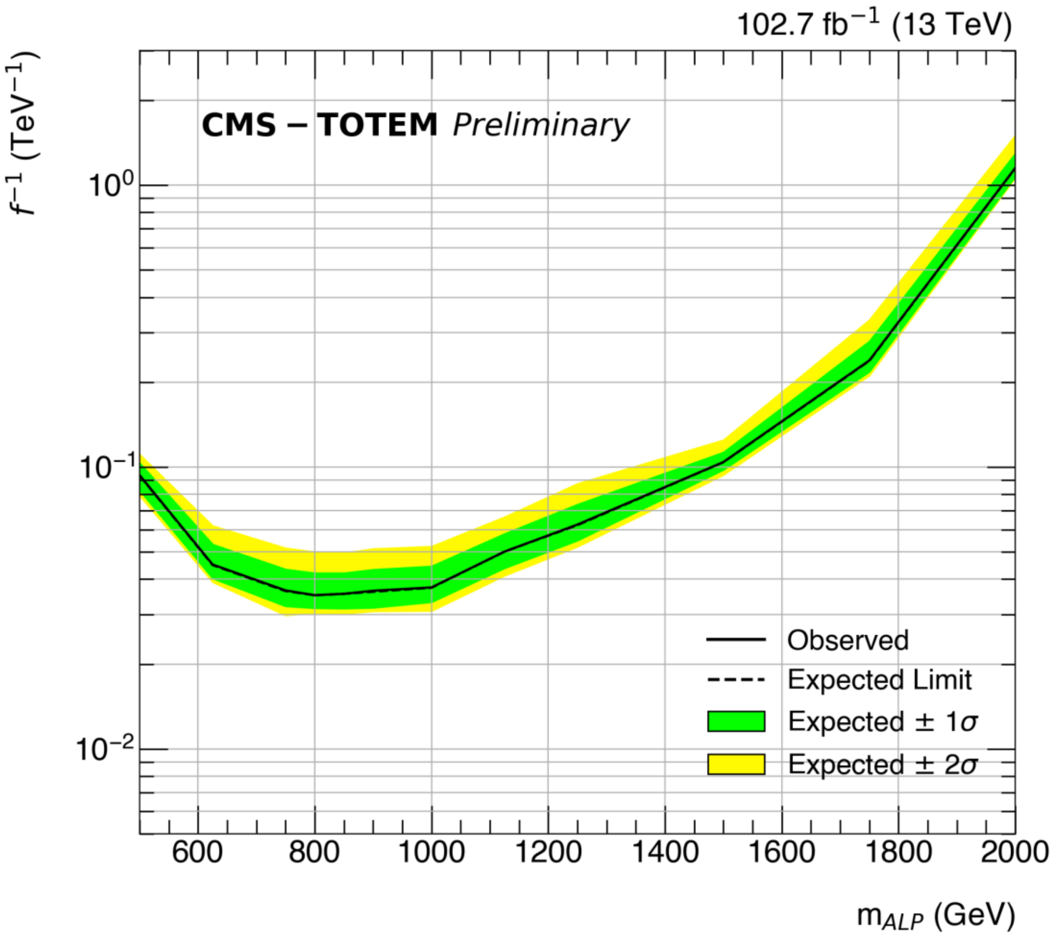
- Focus on Higgs decay to Z and light hadronic resonance, m < 4 GeV




ATLAS [2004.01678]

# ALPs at colliders

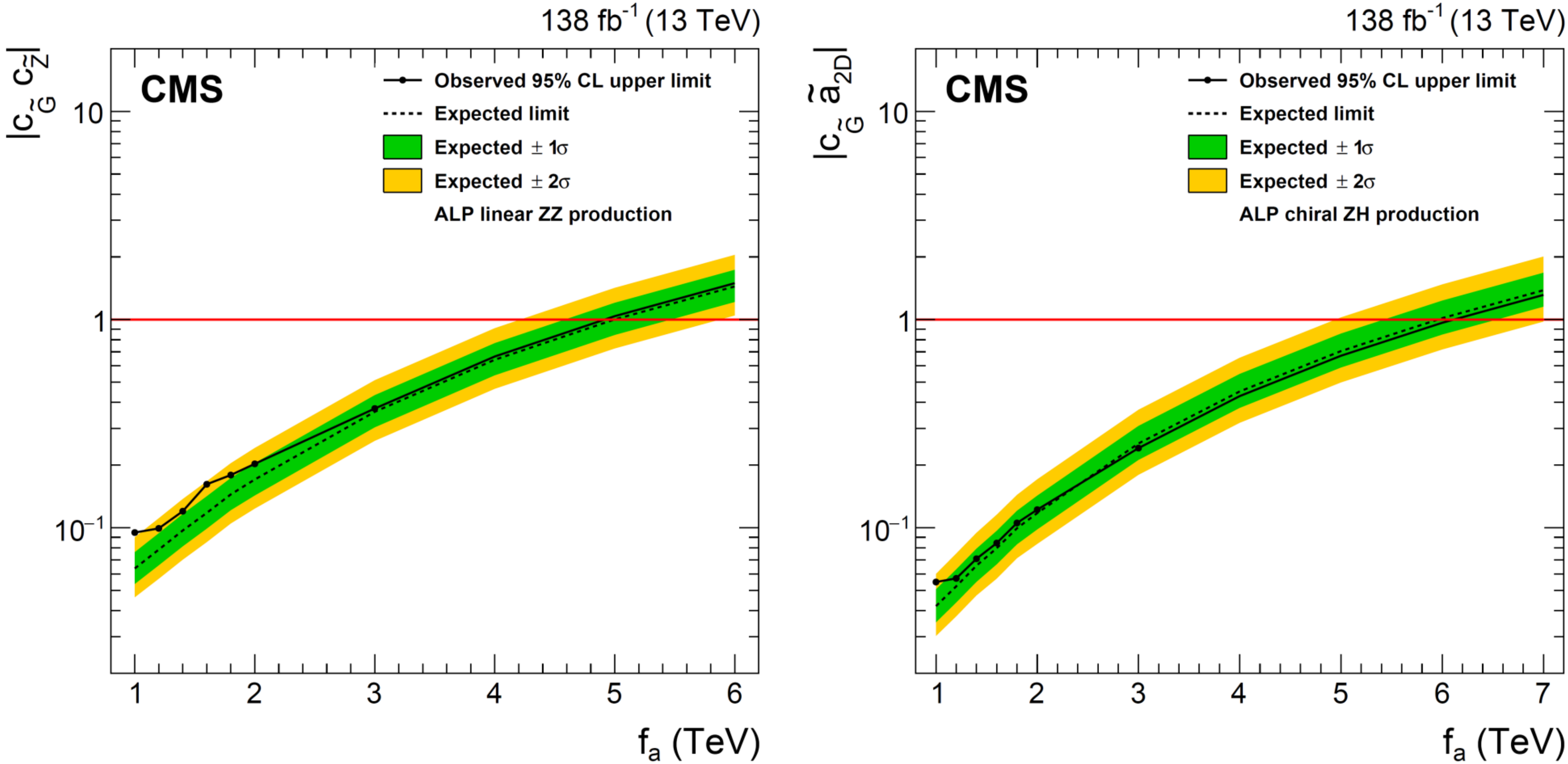
- CMS+TOTEM – high-mass ALP production from diphotons




CMS EXO-21-007

# ALPs at colliders

- ALPs mediating non-resonant ZZ or ZH production




CMS [2111.13669]

# SSI-driven mass enhancements – M1 variant

## Mass terms, parameters and notation

$$
\begin{aligned}
\mathcal{L} \supset\ & \frac{1}{2}\left(\frac{\eta_d}{F_a}\right)^2 4\left(K' v_{\rm diag}^3 + \frac{v_{\rm diag}^6}{2K_{\rm diag}^2}\right) \\
&+ \frac{1}{2}\left(\frac{a}{F_a}\right)^2 6\left(\frac{v_{\rm diag}^6}{2K_{\rm diag}^2} + \frac{v_{\rm diag}^3 v^9}{4K^8} + \frac{v^6 v_{\rm diag}^3}{2K^8} m_u \Lambda_u^2 + \frac{v^6 v_{\rm diag}^3}{2K^8} m_d \Lambda_d^2\right) \\
&+ \frac{1}{2}\left(\frac{\eta'}{F_{\eta'}}\right)^2 \left(m_u v^3 + m_d v^3 + \frac{v_{\rm diag}^3 v^9}{K^8} + \frac{v^6 v_{\rm diag}^3}{2K^8} m_u \Lambda_u^2 + \frac{v^6 v_{\rm diag}^3}{2K^8} m_d \Lambda_d^2\right) \\
&+ \frac{1}{2}\left(\frac{\pi^0}{F_{\pi^0}}\right)^2 \left(m_u v^3 + m_d v^3 + \frac{v^6 v_{\rm diag}^3}{2K^8} m_u \Lambda_u^2 + \frac{v^6 v_{\rm diag}^3}{2K^8} m_d \Lambda_d^2\right) \\
&+ \left(\frac{\eta_d}{F_a}\right)\left(\frac{a}{F_a}\right)\left(2\sqrt{6}\frac{v_{\rm diag}^6}{2K_{\rm diag}^2}\right) \\
&+ \left(\frac{a}{F_a}\right)\left(\frac{\eta'}{F_{\eta'}}\right)\left(\sqrt{6}\right)\left(\frac{v_{\rm diag}^3 v^9}{2K^8} + \frac{v^6 v_{\rm diag}^3}{2K^8} m_u \Lambda_u^2 + \frac{v^6 v_{\rm diag}^3}{2K^8} m_d \Lambda_d^2\right) \\
&+ \left(\frac{\eta'}{F_{\eta'}}\right)\left(\frac{\pi^0}{F_{\pi^0}}\right)\left(m_u v^3 - m_d v^3\right) ,
\end{aligned}
$$

$$
m_+ = m_u + m_d , \quad m_- = m_d - m_u , \quad \mu = \frac{m_u m_d}{m_u + m_d} ,
$$

$$
\mu L^2 = m_u \Lambda_u^2 + m_d \Lambda_d^2 , \quad \Lambda_{\rm inst}^3 = \frac{L^2}{4K^8} v^6 v_{\rm diag}^3 , \quad \Lambda_{\eta'}^4 = \frac{v_{\rm diag}^3 v^9}{4K^8}
$$

$$
\Lambda_{\rm SSI}^4 = K' v_{\rm diag}^3 , \quad \Lambda_{\rm diag}^4 = \frac{v_{\rm diag}^6}{2K_{\rm diag}^2} .
$$

# Supplemental definitions

$$v_1 = v\sin\phi\,, \quad v_2 = v\cos\phi\,, \quad v_3 = v_a\sin\beta = v_A\cos\beta\,, \quad v_a\cos\beta = v\sin\phi\cos\phi$$

$$\tan\phi = v_1/v_2,\ \tan\beta = v_A/v_a$$

- Goldstones aligned with their vevs

$$\begin{pmatrix} G \\ a \\ A \end{pmatrix} = \begin{pmatrix} s_\phi c_\gamma & -c_\phi c_\gamma & -s_\gamma \\ c_\phi c_\beta - s_\phi s_\beta s_\gamma & s_\phi c_\beta + c_\phi s_\beta s_\gamma & -s_\beta c_\gamma \\ c_\phi s_\beta + s_\phi c_\beta s_\gamma & s_\phi s_\beta - c_\phi c_\beta s_\gamma & c_\beta c_\gamma \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \\ a_3 \end{pmatrix}$$

$$V_{\rm ang} = -\,|B_\mu|\Big[\prod_{i=1}^{2}(v_i+h_i)\Big]\cos\left(\sum_{i=1}^{2}\frac{a_i}{v_i}-\theta_\mu\right) - \frac{|C_\lambda|}{\sqrt{2}}\Big[\prod_{i=1}^{3}(v_i+h_i)\Big]\cos\left(\sum_{i=1}^{3}\frac{a_i}{v_i}-\theta_\lambda\right)$$

$$\xrightarrow{O(3)} -\,|B_\mu|\Big[\prod_{i=1}^{2}(v_i+h_i)\Big]\cos\left(\frac{a}{v_a}+\frac{A}{v_A}\tan^2\beta-\theta_\mu\right) - \frac{|C_\lambda|}{\sqrt{2}}\Big[\prod_{i=1}^{3}(v_i+h_i)\Big]\cos\left(\frac{A}{v_A}\sec^2\beta-\theta_\lambda\right)$$

# Axion couplings in gauged U(1)' extensions of the Standard Model

Kivel, Laux, FY [2211.12155]

# Axion/ALP EFT in gauged U(1)' theories

- Build DFSZ axion model with gauged U(1)' baryon number
  - Minimal set of anomalons satisfy trace condition from kinetic mixing
  - DFSZ-like axion is light Goldstone orthogonal to 2HDM $A_0$

| | $SU(3)_C$ | $SU(2)_L$ | $U(1)_Y$ | $U(1)_B$ | $\mathbb{Z}_4$ | $U(1)_{PQ}$ |
|---|---|---|---|---|---|---|
| $Q_L^i$ | 3 | 2 | 1/6 | 1/3 | +1 | $X_Q$ |
| $u_R^i$ | 3 | 1 | 2/3 | 1/3 | -i | $X_Q$-$X_u$ |
| $d_R^i$ | 3 | 1 | -1/3 | 1/3 | +1 | $X_Q$-$X_d$ |
| $L_L^i$ | 1 | 2 | -1/2 | 0 | +1 | $X_L$ |
| $e_R^i$ | 1 | 1 | -1 | 0 | +1 | $X_L$-$X_d$ |
| $H_u$ | 1 | 2 | -1/2 | 0 | +i | $X_u$ |
| $H_d$ | 1 | 2 | 1/2 | 0 | +1 | $X_d$ |
| $L'_L$ | 1 | 2 | -1/2 | -1 | +1 | $X'$ |
| $L'_R$ | 1 | 2 | -1/2 | 2 | +i | $X'$-$X_B$ |
| $E'_L$ | 1 | 1 | -1 | 2 | +i | $X'$-$X_d$-$X_B$ |
| $E'_R$ | 1 | 1 | -1 | -1 | +1 | $X'$-$X_d$ |
| $N'_L$ | 1 | 1 | 0 | 2 | +1 | $X'$-$X_u$-$X_B$ |
| $N'_R$ | 1 | 1 | 0 | -1 | -i | $X'$-$X_u$ |
| $\Phi_A$ | 1 | 1 | 0 | -3 | -1 | $-X_A$ |
| $\Phi_B$ | 1 | 1 | 0 | 3 | +i | $-X_B$ |

# Axion/ALP EFT in gauged U(1)' theories

- Study Z' and axion/ALP as light dofs
- (Non-)decoupling of anomalons dictates new pattern of PQ symmetry on ALP Wilson coefficients

$$
\begin{aligned}
\mathcal{L}_{\text{axion}} \supset &+ \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_a^2}{2}a^2 + \frac{\partial_\mu a}{f_a} J^\mu_{\text{PQ,SM}} - C^{\text{eff}}_{Zh} h Z_\mu \partial^\mu a - C^{\text{eff}}_{Z'h} h Z'_\mu \partial^\mu a \\
&+ \left(C^{\text{SM}}_{\gamma\gamma} + C^{\text{eff}}_{\gamma\gamma}\right) \frac{e^2}{(4\pi)^2} \frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu} + \left(C^{\text{SM}}_{Z\gamma} + C^{\text{eff}}_{Z\gamma}\right) \frac{e^2}{s_W c_W} \frac{1}{(4\pi)^2} \frac{a}{f_a} Z_{\mu\nu}\tilde{F}^{\mu\nu} \\
&+ \left(C^{\text{SM}}_{ZZ} + C^{\text{eff}}_{ZZ}\right) \frac{e^2}{s_W^2 c_W^2} \frac{1}{(4\pi)^2} \frac{a}{f_a} Z_{\mu\nu}\tilde{Z}^{\mu\nu} + \left(C^{\text{SM}}_{Z'\gamma} + C^{\text{eff}}_{Z'\gamma}\right) \frac{g_B e}{(4\pi)^2} \frac{a}{f_a} Z'_{\mu\nu}\tilde{F}^{\mu\nu} \\
&+ \left(C^{\text{SM}}_{Z'Z'} + C^{\text{eff}}_{Z'Z'}\right) \frac{g_B^2}{(4\pi)^2} \frac{a}{f_a} Z'_{\mu\nu}\tilde{Z}'^{\mu\nu} + \left(C^{\text{SM}}_{Z'Z} + C^{\text{eff}}_{Z'Z}\right) \frac{g_B e}{s_W c_W} \frac{1}{(4\pi)^2} \frac{a}{f_a} Z'_{\mu\nu}\tilde{Z}^{\mu\nu} \\
&+ \left(C^{\text{SM}}_{WW} + C^{\text{eff}}_{WW}\right) \frac{g_L^2}{(4\pi)^2} \frac{a}{f_a} W_{\mu\nu}\tilde{W}^{\mu\nu} + C^{\text{SM}}_{gg} \frac{g_s^2}{(4\pi)^2} \frac{a}{f_a} G^a_{\mu\nu}\tilde{G}^{a\mu\nu} \\
&+ i \frac{a}{f_a} \frac{e}{\sqrt{2} s_W} \left(W^-_\mu \left(X_d J^{+\mu}_W - X_u J^{+\mu}_{W,\ell}\right) + \text{h.c.}\right) .
\end{aligned}
$$

# Imprint of FCNCs and PQ symmetries

- Axion FCNCs reflected as commutator structures in EFT operators

$$\mathcal{L}_{\psi,\mathrm{Yuk}} \simeq -\sum_K \frac{v_K + \phi_K}{\sqrt{2}} \bar{\psi} \exp\left( i(\mathbf{X}_V^\psi - \mathbf{X}_A^\psi \gamma_5) \frac{a}{f_a} \right) \mathbf{Y}_K^\psi \exp\left( -i(\mathbf{X}_V^\psi + \mathbf{X}_A^\psi \gamma_5) \frac{a}{f_a} \right) \psi$$

$$\mathbf{X}_A^E = X_B \mathbf{C}_E \text{ and } \mathbf{X}_V^E = X_d \mathbf{C}_E,$$

- Necessary step when considering intermediate axion/ALP masses with dynamical fermions

$$\begin{aligned} \mathcal{L}_{\psi,\mathrm{axion}} \supset & -\frac{\partial_\mu a}{2 f_a} \bar{\psi} \gamma^\mu (\mathbf{C}_{1V}^\psi + \mathbf{C}_{1A}^\psi \gamma_5) \psi + \frac{i}{2} \frac{a}{f_a} \bar{\psi} [\mathbf{M}^\psi, \mathbf{C}_{2V}^\psi] \psi + \frac{i}{2} \frac{a}{f_a} \bar{\psi} \{\mathbf{M}^\psi, \mathbf{C}_{2A}^\psi\} \gamma_5 \psi \\ & + \frac{i}{2} \frac{a}{f_a} \sum_K \frac{\phi_K}{\sqrt{2}} \bar{\psi} [\mathbf{Y}_K^\psi, \mathbf{C}_{KV}^\psi] \psi + \frac{i}{2} \frac{a}{f_a} \sum_K \frac{\phi_K}{\sqrt{2}} \bar{\psi} \{\mathbf{Y}_K^\psi, \mathbf{C}_{KA}^\psi\} \gamma_5 \psi \\ & - \frac{i}{2} \frac{a}{f_a} \sum_I g_I \bar{\psi} A_\mu^I \gamma^\mu [\mathbf{Q}_{IV}^\psi + \mathbf{Q}_{IA}^\psi \gamma_5, \mathbf{C}_{IV}^\psi + \mathbf{C}_{IA}^\psi \gamma_5] \psi + \frac{a}{f_a} \sum_{I,J} C_3^{IJ} \frac{g_I g_J}{(4\pi)^2} F_{I\mu\nu}^a \tilde{F}_J^{a,\mu\nu} \end{aligned}$$