Mini-Review: Physics with Axions and ALPs

Felix Yu, Johannes Gutenberg Universität Mainz

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JOHANNES GUTENBERG UNIVERSITÄT MAINZ

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PRiSMA+

Outline

- The Strong CP problem and the PQ mechanism
- Basics of axion cosmology
- The ALP EFT
- Probes of light axions/ALPs
- Probes of heavy axions/ALPs
- The axion quality problem
- Conclusions

Longstanding strong CP problem

- Search for nEDM indicates absence of CPV in strong interactions
  - $|d_n| < 1.8 \cdot 10^{-26} e\ cm$ Abel, et. al. [nEDM collaboration], 2001.11966
    - For low energy SM, $d_n = C_{\text{EDM}}\, e\, \overline{\theta}$, with $C_{EDM} = 2.4\ (1.0) \cdot 10^{-16}$ and $\bar{\theta} = \theta + \arg\det Y_u Y_d$ Pospelov, Ritz, hep-ph/9908508
  - Get severe constraint on $|\bar{\theta}| < 10^{-10}$
- Two *unrelated* origins for $\bar{\theta}$
  - QCD θ is a vacuum angle parameter, $\theta \in [0,2\pi)$
  - **Unknown** Y_u and Y_d matrices give rise to $J_{CKM} = \left(3.08^{+0.15}_{-0.13}\right) \cdot 10^{-5} \Rightarrow \delta_{\text{KM}} = 1.144 \pm 0.027$

PDG

Longstanding strong CP problem

- Traditionally, three classes of solutions
  - Massless up quark (now excluded by lattice QCD)
    Fodor, Hoebling, Krieg, Lellouch, Lippert, Portelli, Sastre, Szabo, Varnhorst [1604.07112]
    - The SM with a massless up quark enjoys an *enhanced symmetry*: $\arg\det Y_u Y_d$ is undefined and renders $\bar{\theta}$ a basis-dependent parameter
  - Nelson-Barr: CPV only arises spontaneously
    Review: see Dine, Draper [1506.05433]
    - Difficult to control radiative corrections that spoil pure Nelson-Barr solution to strong CP, since must also generate KM phase
  - Peccei-Quinn mechanism and QCD axion
    - Peccei, Quinn, PRL **38**, 1440 (1977)
      - Weinberg, PRL **40**, 223 (1978); Wilczek, PRL **40**, 279 (1978)

The PQ mechanism in a nutshell

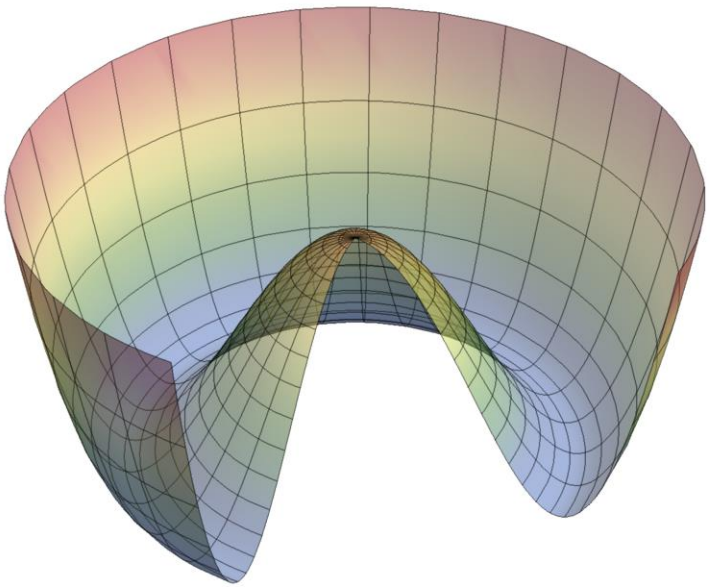
- In the UV, consider a complex (SM gauge singlet) scalar field that spontaneously breaks a global U(1) symmetry
  - As usual, we parametrize with radial (Higgs) and angular (Goldstone) modes: $\Phi = \left(\frac{v+h}{\sqrt{2}}\right) e^{ia/v}$
- Lagrangian separates to exhibit massive radial mode and **massless** Goldstone mode

$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 + \frac{1}{2}(\partial_\mu a)^2 + \frac{1}{4}\lambda v^4 - \lambda v^2 h^2 - \lambda v h^3 - \frac{1}{4}\lambda h^4$$

  - Simple manifestation of Goldstone's theorem

The PQ mechanism in a nutshell

- More formally: vacuum manifold is compact U(1) field space parametrized by Goldstone mode *a*
    - vev condition only fixes magnitude of SSB, not the phase
- Classical shift symmetry = continuous shift in *a* is a basis redefinition of Lagrangian = no effect on EOMs



The PQ mechanism in a nutshell

- Require that $\mathcal{A}(U(1)_{PQ} \times SU(3)_C^2) \neq 0$: PQ symmetry is an anomalous U(1) global symmetry under SM color
  - Necessarily generated by coupling colored fermions to PQ scalar field
  - Two canonical, vanilla 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)

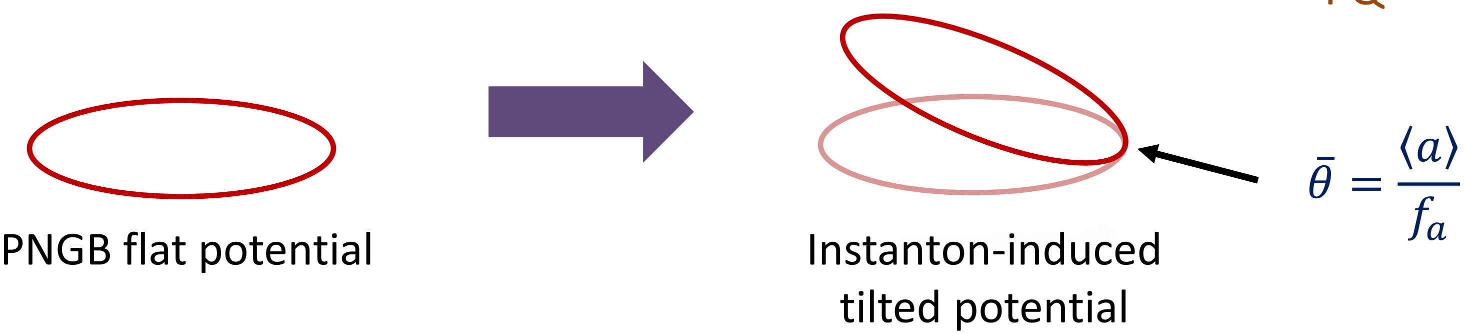
The PQ mechanism in a nutshell

- Instanton-induced potential is consequence of $U(1)_{PQ} \times SU(3)_C^2$ anomaly

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

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

  – Below Λ_{QCD}, evaluating instanton diagrams leads to approximate cosine potential for PNGB of $U(1)_{PQ}$



  – Axion serves as a *spurion* for $\bar{\theta}$
    - ***Spurion***: treat numerical constants as the vev of a scalar field (the field formally transforms to restore a new symmetry)

Classic calculation: The Θ-Vacuum Energy

- 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

- $G\tilde{G}$ term integrates to $(n_+ - n_-)$ winding number
- 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

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

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

Basic axion phenomenology

- Given spurion nature of axion (dictated by $U(1)_{PQ}$ anomaly), we develop a cosine potential for *a*

$$\mathcal{L} \simeq \Lambda_{QCD}^4 \cos\left(\frac{a}{f_a}\right)$$

  – Vanilla axion mass driven by topological susceptibility of QCD: $m_a f_a \simeq \sqrt{\chi} \approx m_\pi f_\pi$ in SM
    - Also need mixing with SM neutral mesons

  – Can derive improved potential from chiral perturbation theory

- Classical shift symmetry now *periodic* with f_a scale
    - Diverse cosmological implications from possible axion misalignment and strings from multiple PQ vacua

Basic axion cosmology

- If PQ symmetry has multiple windings, domain walls separate distinct PQ vacua
  - For PQ scale above inflation scale, "our" PQ vacuum is only one that lies within our Hubble patch
  - For PQ scale below inflation scale, can generally get problematic domain walls within our Hubble patch
    - Axion strings between PQ vacua have network structure
- At high T (early universe times), QCD potential is flat
  - At turn-on of QCD potential, the "origin" of field space is *misaligned* with the spurion-favored minimum at $\bar{\theta}$
  - Hubble friction responsible for removing kinetic energy in axion field
    - Possible to have large kinetic energy in radial mode: kination cosmology
    - DM axion field generally still oscillates around $\bar{\theta}$ today!
    - Treat as coherent scalar field $\bar{\theta}$

Pivot to ALPs – Standard ALP EFT

- Since $m_a f_a \simeq \sqrt{\chi}$, vanilla QCD axions are a **one-parameter model**
- Axion-like particles treat (m_a, f_a) as independent
  - Lose connection to strong CP and DM? (…see quality problem)
  - Still concrete benchmark scenario for PBC/FIPs program
- Reintroduces entire suite of SM effective operators
  – ALPs couple via PQ current or anomaly operators

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

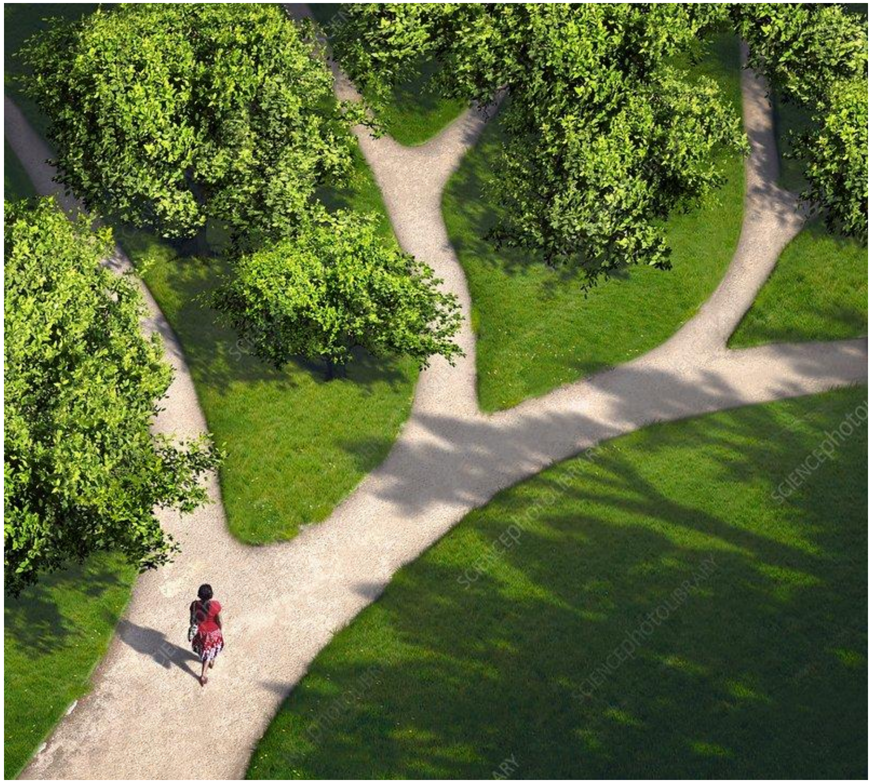
Brivio, et. al [1701.05379], Bauer, et. al. [1708.00443], Gavela, et. al. [1905.12953]

How do we see axions?

- Axion/ALP parameter space spans decades of masses and couplings – huge suite of experiments

$$F\tilde{F} \cong E \cdot B$$

$G\tilde{G}$



Collider probes

QCD mesons/flavor probes

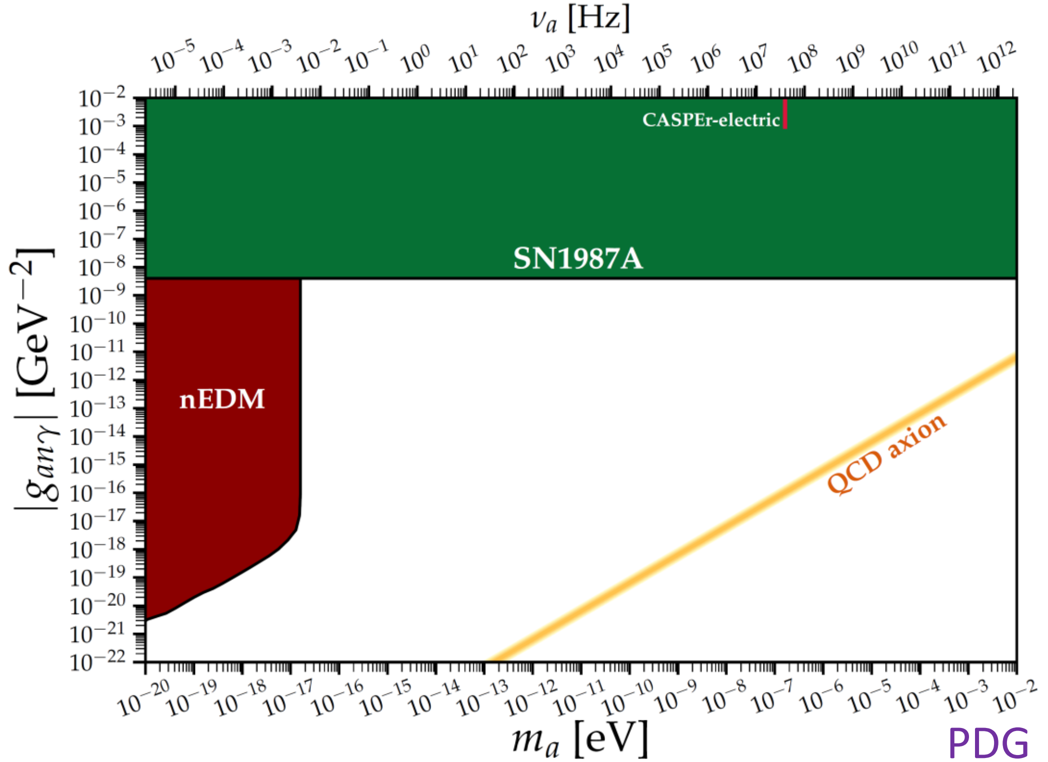
Photo credit: SMETEK / Science Photo Library

Axion probes in nucleons

$$C_p = -0.47(3) + 0.88(3)C_u - 0.39(2)C_d - 0.038(5)C_s - 0.012(5)C_c - 0.009(2)C_b - 0.0035(4)C_t\,,$$
$$C_n = -0.02(3) + 0.88(3)C_d - 0.39(2)C_u - 0.038(5)C_s - 0.012(5)C_c - 0.009(2)C_b - 0.0035(4)C_t\,,$$

- Axion effective couplings to quarks imprinted onto protons and neutrons
- Additional studies of axion physics in nuclear densities (neutron stars+ and QCD equation of state)

see, e.g. Balkin, et. al. [2211.02661]



PDG

Light axion probes in photons

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

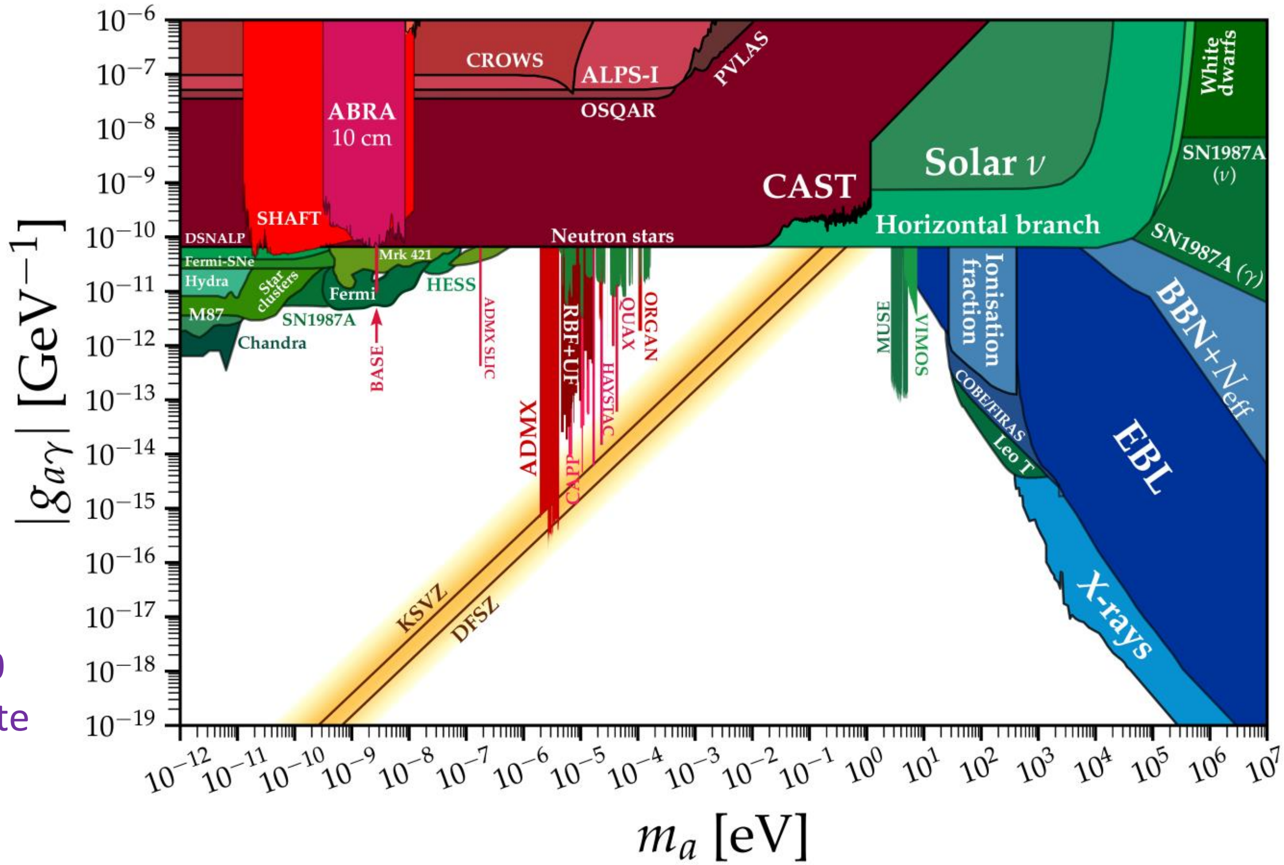
$$g_{a\gamma\gamma} = \frac{\alpha_{EM}}{2\pi f_a}\left(\frac{E}{N} - 1.92(4)\right)$$

m_a: quark mass and higher order uncertainties
$g_{a\gamma\gamma}$: $O(\alpha)$ 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

Vanilla $\tau_{\text{Axion}} > \tau_{\text{Universe}}$ for $m_a < 20$ eV: attractive Dark Matter candidate (requires very important cosmological simulation)



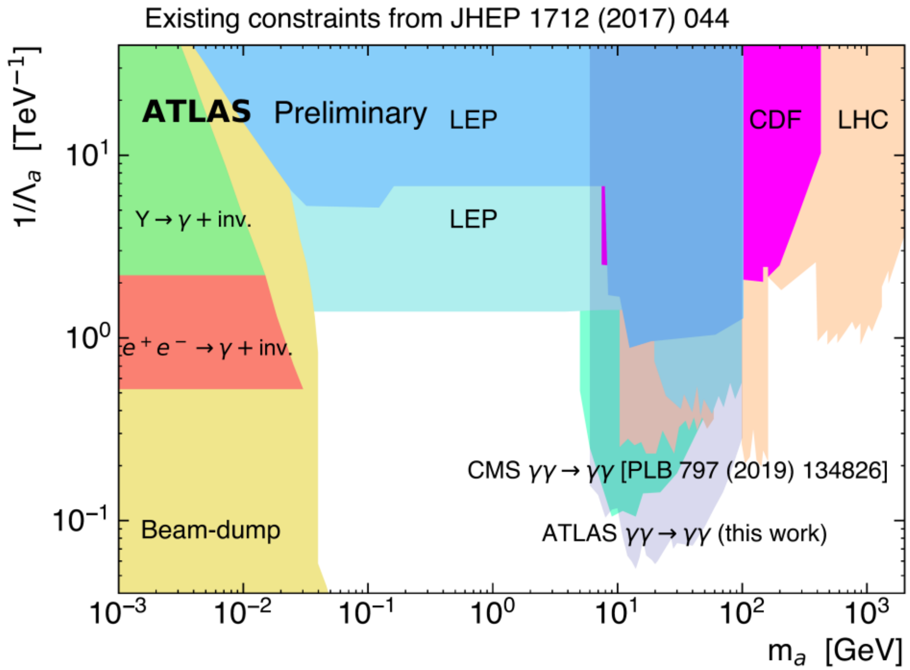
PDG (from AxionLimits by Ciaran O'Hare)

Categories of light axion exp. probes

  - Light shining through walls (LSWs), cavity experiments
  - Helioscopes (solar production of axions, flux diffuses to earth)
  - DM haloscopes (Earth movement through axion background)
  - Spin-dependent 5th force tests see, e.g. PDG; Afach, et. al. [2305.01785]
- Typically, have $1/f_a^2$ suppression in each production and detection unless DM abundance assumed
- Classical/quantum field behavior important for wave-like mass regime $m_a \ll 1\,\text{eV}$
- Measurement of nEDM

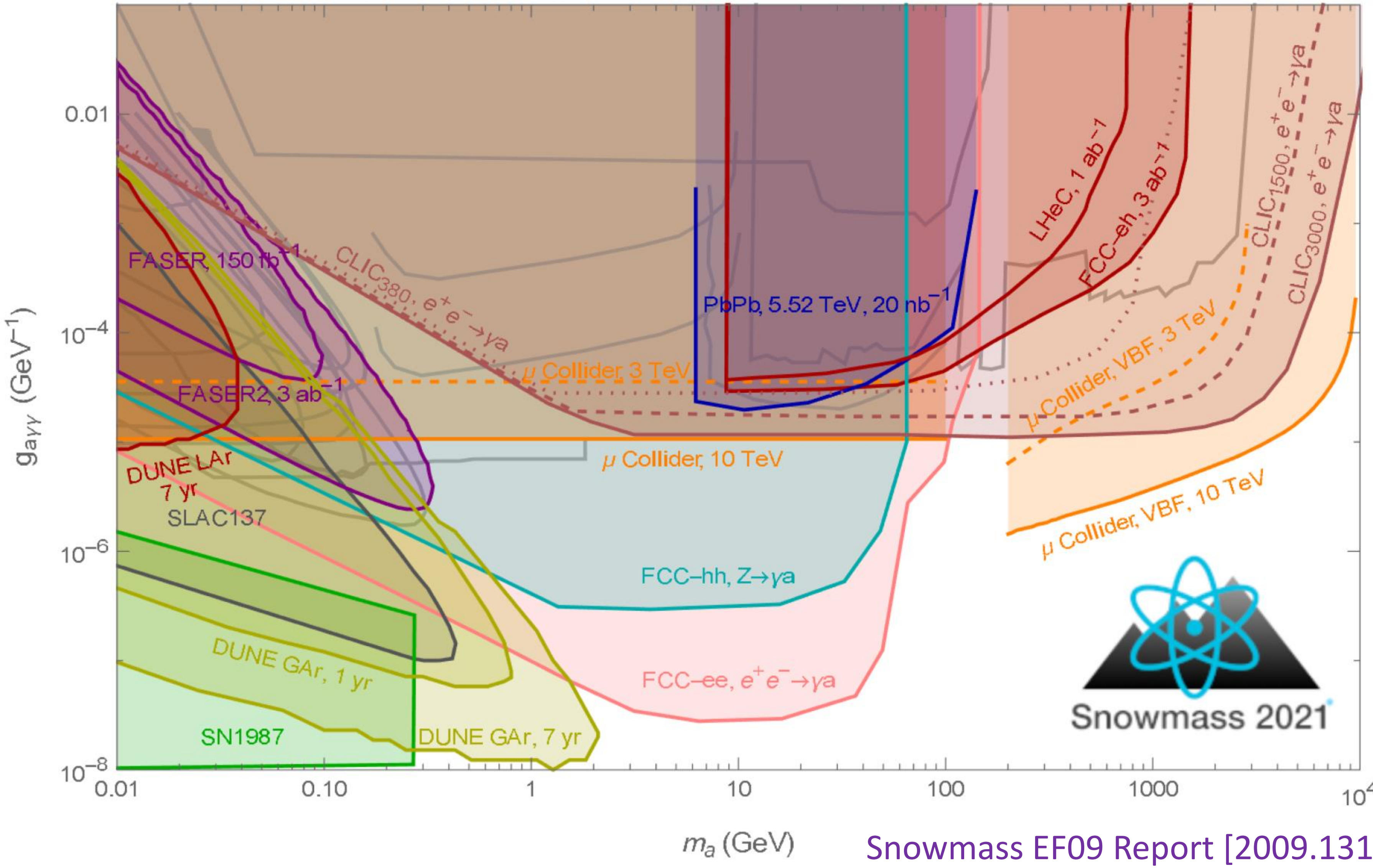
Categories of heavy axion exp. probes

- Dictated by ALP EFT operators
  - Meson decays
  - Interactions with Higgs sector and EW field strengths
  - Elastic scattering of heavy ions/protons



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

ALPs at future expts – standard benchmark



Snowmass EF09 Report [2009.13128]

Quality problem

- 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 only 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
        - Thought experiment: vacuum angles of SU(3) x SU(3) vs. SU(6)

Making axions heavier – see, e.g. Kivel, Laux, FY [2207.08740]

Making axions lighter – see e.g., Elahi, Elor, Kivel, Laux, Najjari, FY [2301.08760]

Conclusions

- Axion field theory is rich with phenomenological applications and diverse model-building tools
  - Immense growth in diversity and sensitivity of axion experiments – spurred by close collaboration between theory and experiment
- Axion/ALP physics ***leads*** the interface of quantum sensors and quantum technologies, cosmology, weak gravity + UV/IR mixing, beam dumps/colliders + lifetime frontier, hierarchy solutions
  - Important field theory connections to generalized global symmetries (see Wed. plenary by Clay Cordova)

Additional review/pedagogical references

†Personal list

- Kim, Carosi [0807.3125]
- Hook [1812.02669]
- Di Luzio, Giannotti, Nardi, Visinelli [2003.01100]
- Reece [2304.08512]
- *Also look forward to FY [230x.xxxxx]*

Refresher: SM instanton effects

- SM + axion Lagrangian

$$\mathcal{L} = \frac{1}{2}\partial_\mu a \partial^\mu a + \frac{\partial_\mu a}{F_a}\left(\sum_{i=1}^{N_f} c_1^i \bar{q}_i \gamma_\mu \gamma_5 q_i\right) - \left(\sum_{i=1}^{N_f} m_i \bar{q}_L^i e^{ic_2^i a/F_a} q_R^i + \text{h.c.}\right)$$

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

Kim, Carosi (2008)

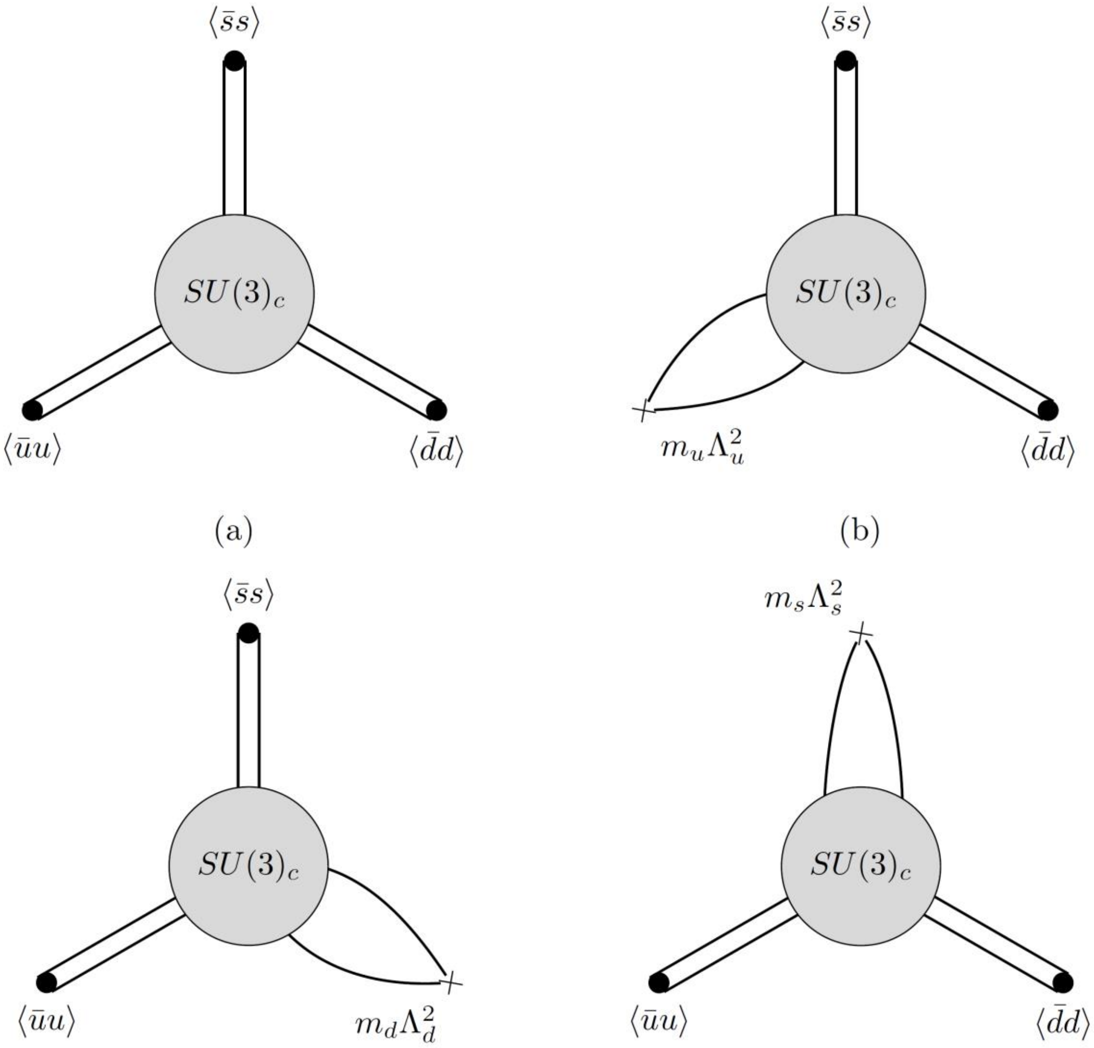
- Axion mass is generated by gluon operator
  - Via index theorem, instanton action induces ‘t Hooft determinantal operator according to PQ color anomaly

$$\mathcal{L}_{\text{det}} = (-1)^{N_f} K^{4-3N_f} \left(\prod_{i=1}^{N_f} \det\left(\bar{q}_L^i q_R^i\right)\right) e^{-ic_3^G \frac{a}{F_a}} + \text{h.c.}$$

Refresher: SM instanton effects

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

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



Refresher: SM instanton effects

- Operators lead to mixing of π^0, η, η' and axion

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

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

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

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

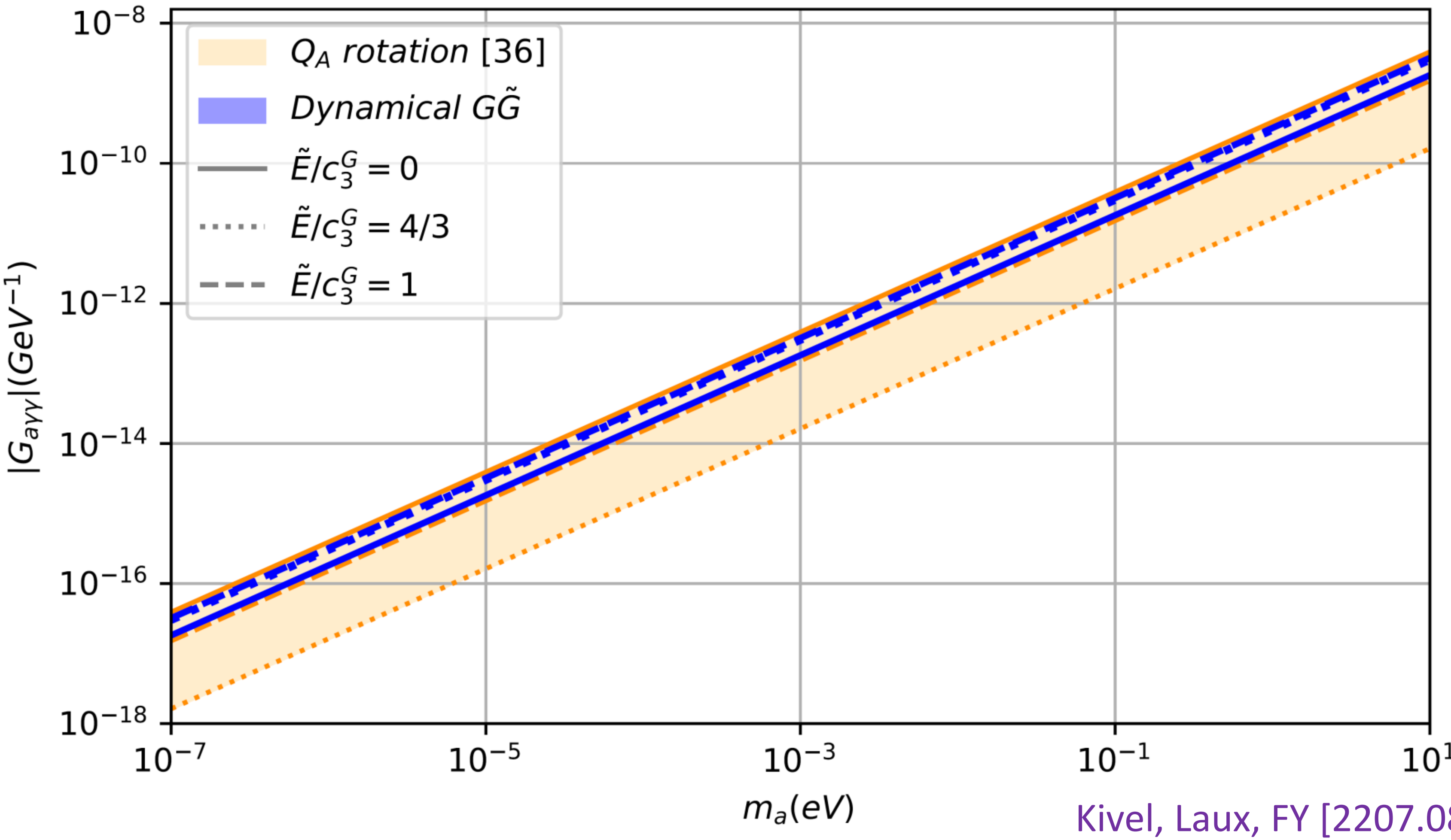
$$A_3 = \frac{v^6}{2} m_d \Lambda_d^2 \cos\big(-\theta_{\pi^0} + \theta_{\eta'} - c_3^G\theta_a\big)\ ,$$

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

  - Encapsulate relevant instanton effects via chiral insertions

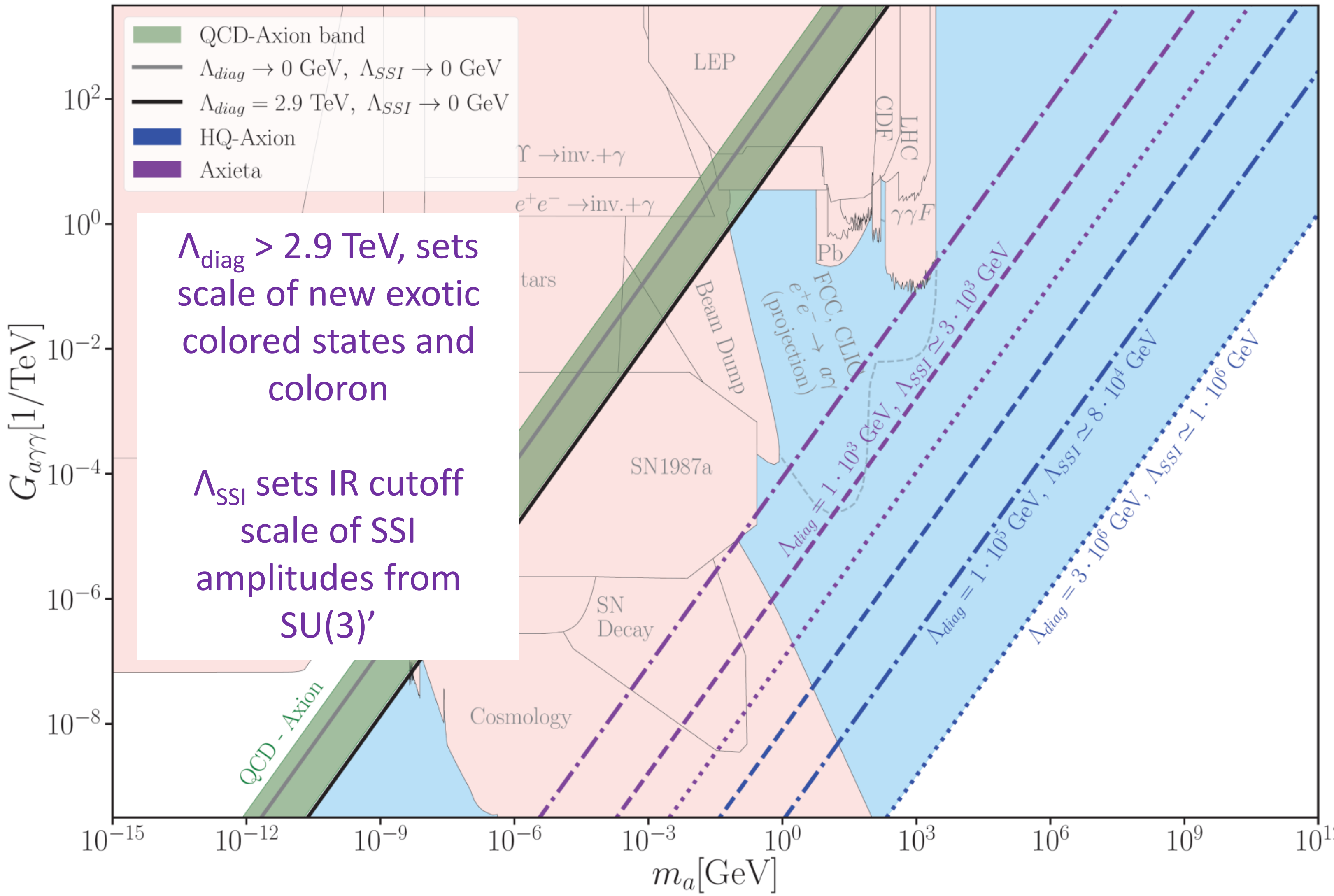
Cross-check: no SSIs

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



Kivel, Laux, FY [2207.08740]

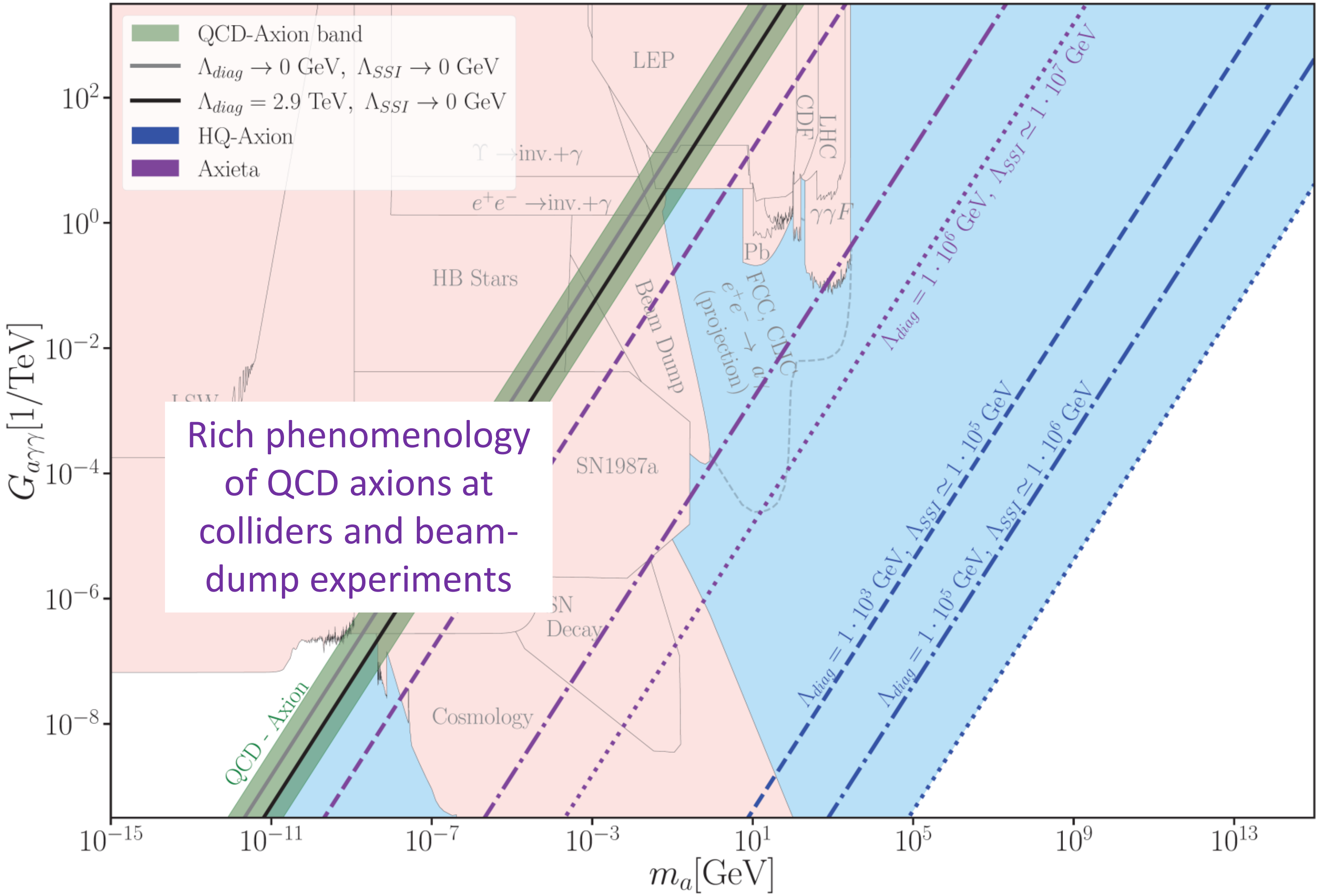
SSI-driven mass enhancements – M1 variant



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

Λ_{SSI} sets IR cutoff scale of SSI amplitudes from SU(3)'

SSI-driven mass enhancements – M2 variant



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

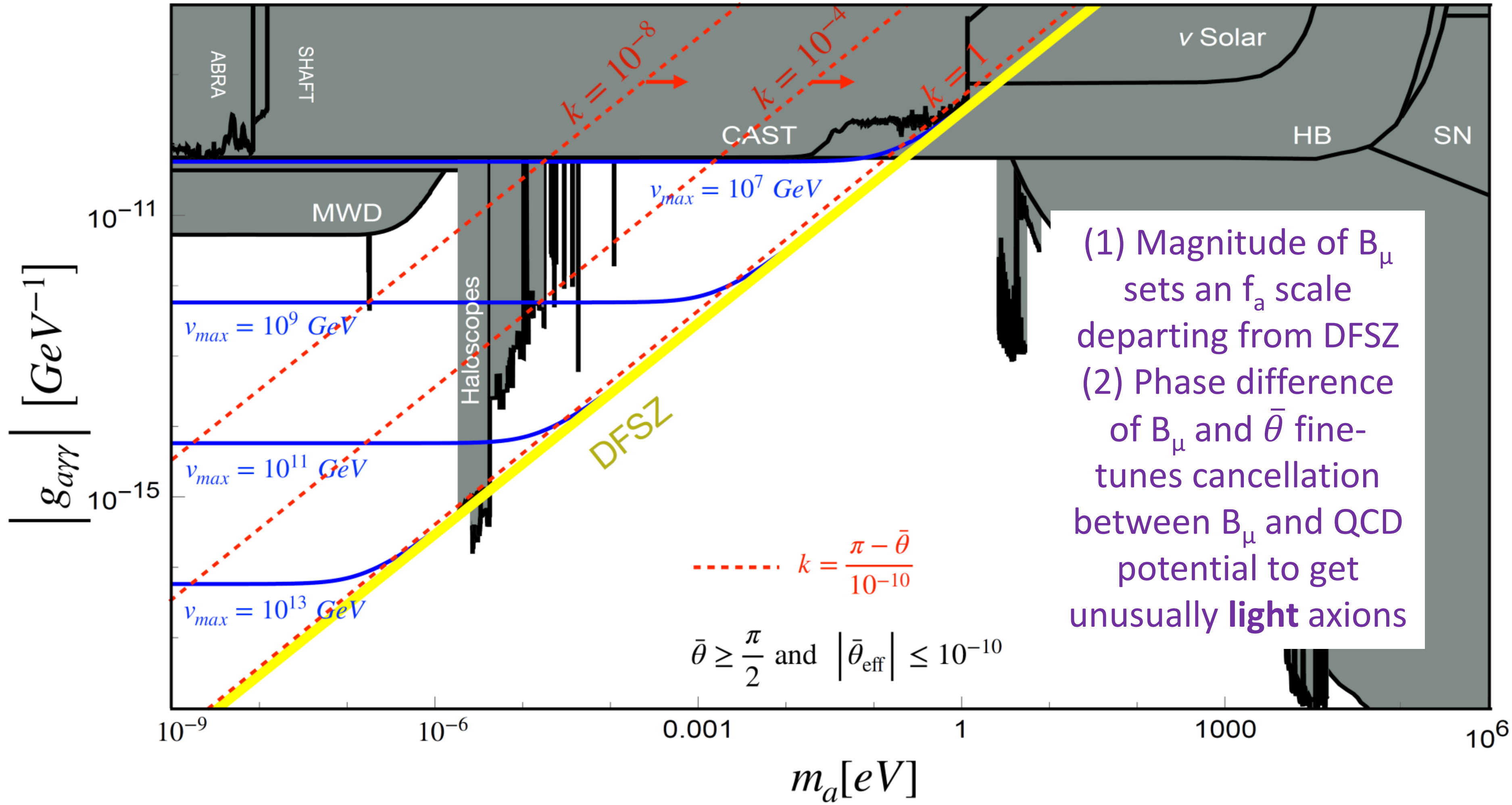
Building anarchy

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

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

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

Anarchic axion deviates from DFSZ band



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

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.

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)

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

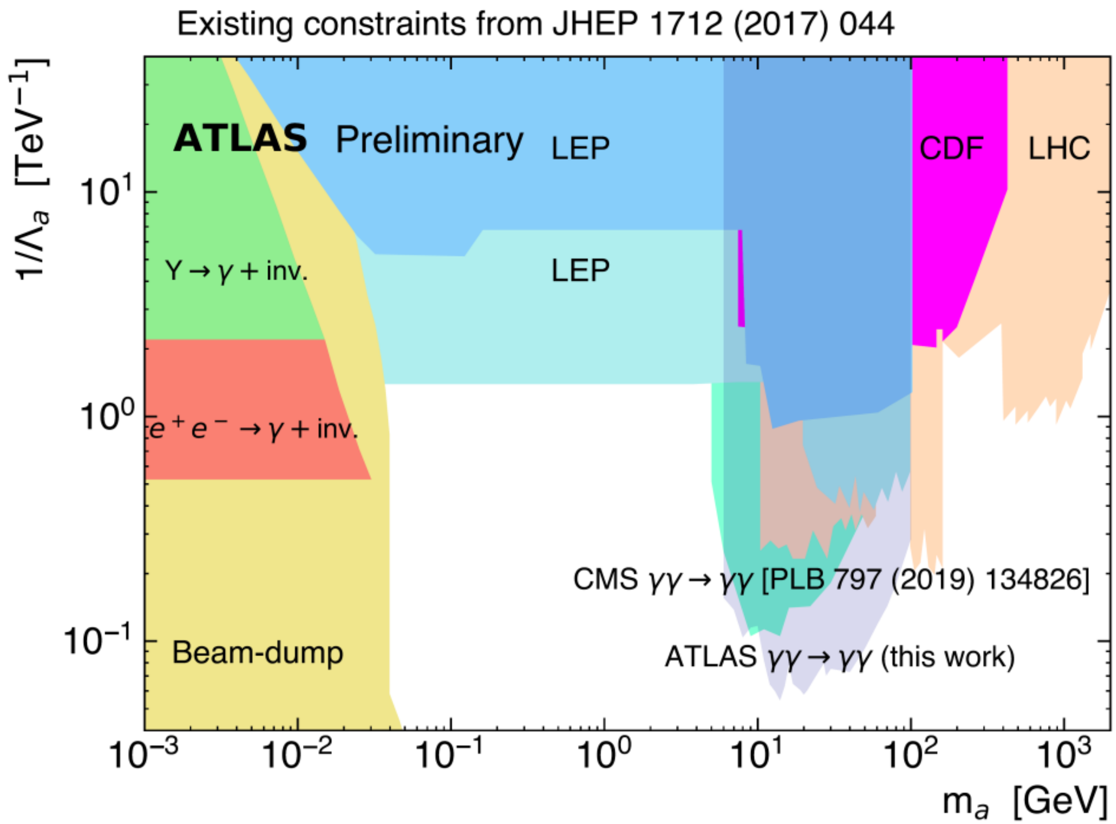
- Axion lives longer than age of universe for $m_a \lesssim 20$ eV
  - Very cold dark matter (can have coherent oscillations with negligible velocity dispersion)

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

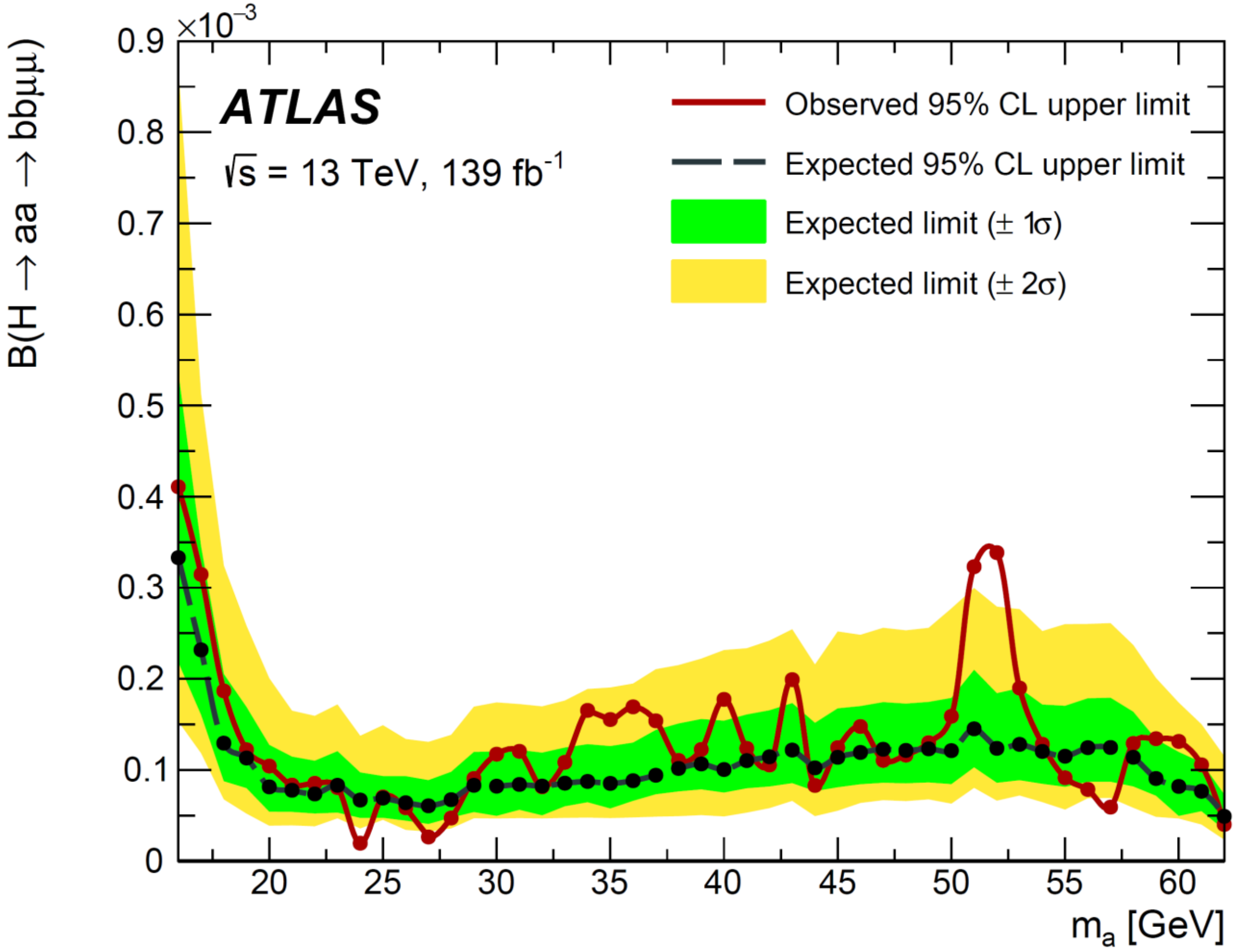
- Focus on diphoton coupling using atomic number enhancement



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

ALPs at colliders – Exotic Higgs decays

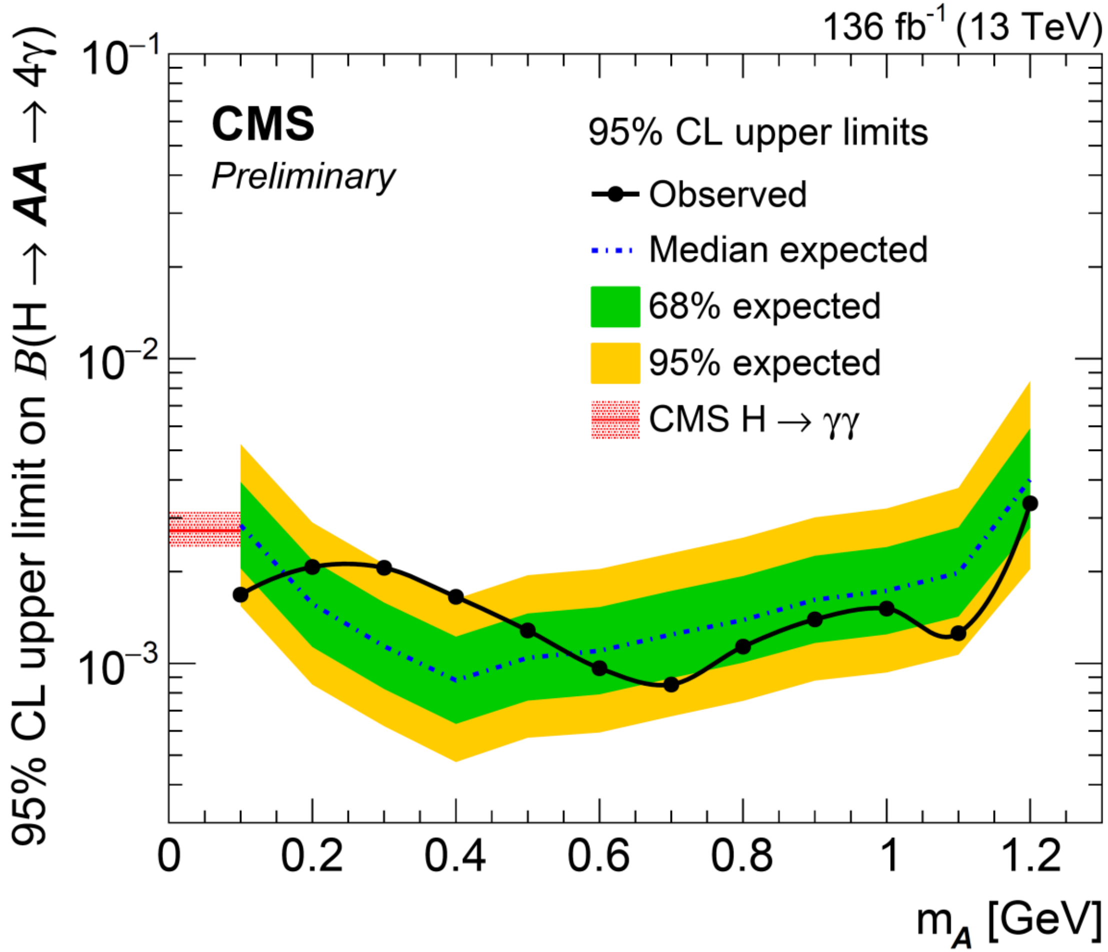
- Higgs decay to aa, decay to (bb)(μμ)



ATLAS [2110.00313]

ALPs at colliders – Exotic Higgs decay

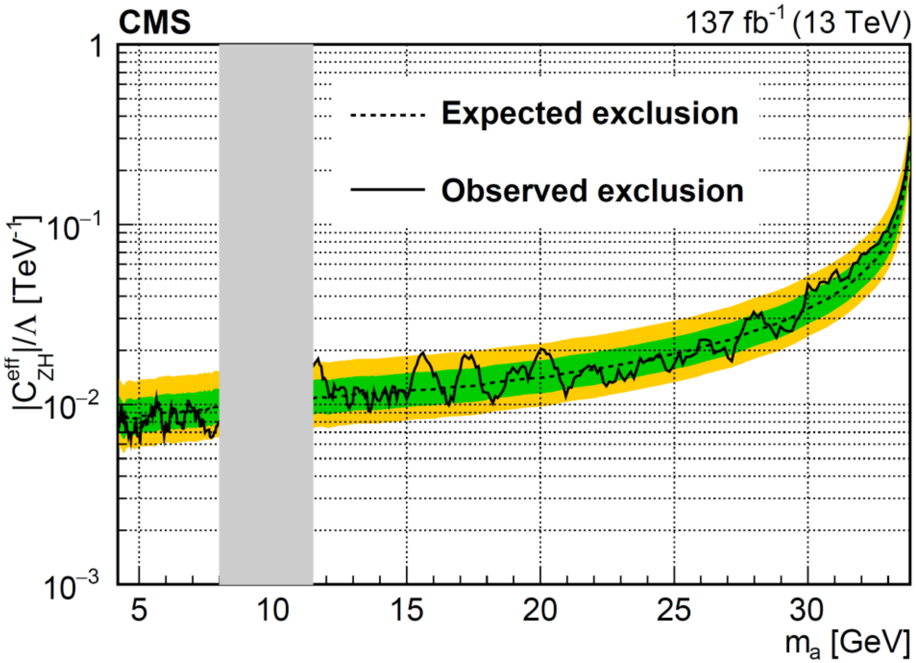
- Higgs decay to aa, decay to (γγ)(γγ)

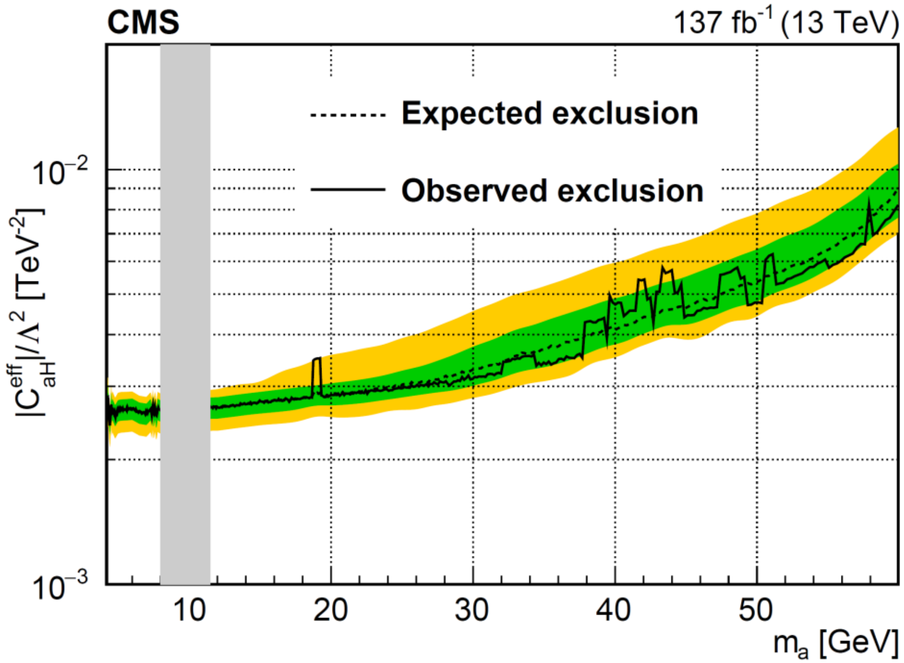


CMS HIG-21-016

ALPs at colliders – Exotic Higgs decay

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

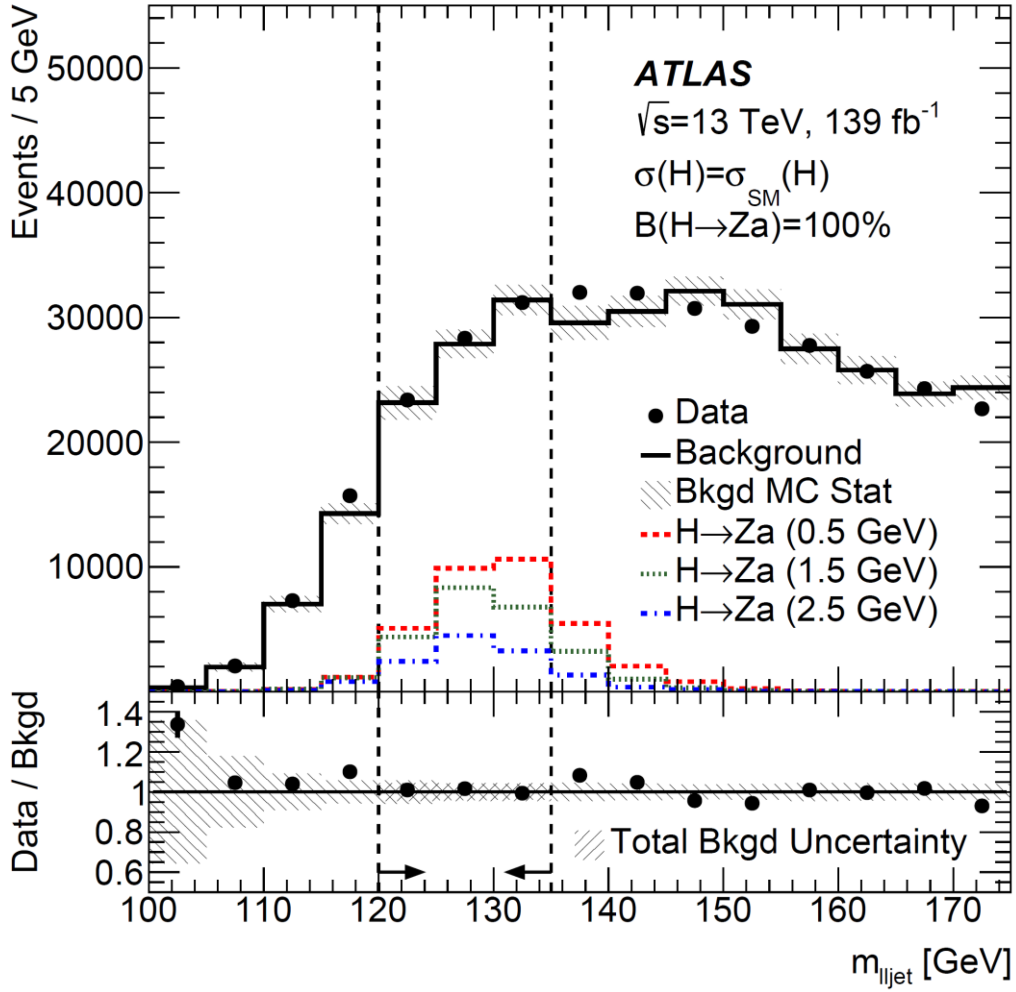




CMS [2111.01299]

ALPs at colliders – Exotic Higgs decays

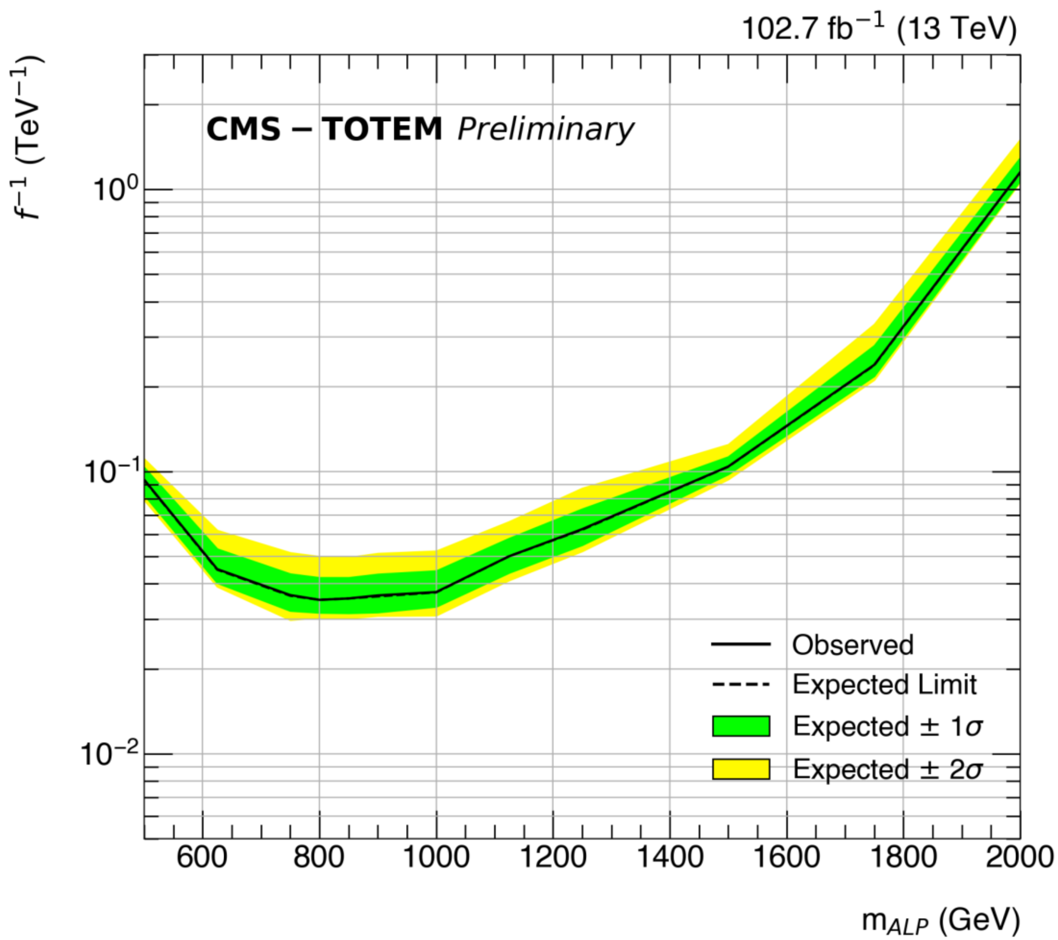
- Focus on Higgs decay to Z and light hadronic resonance, m < 4 GeV



ATLAS [2004.01678]

ALPs at colliders

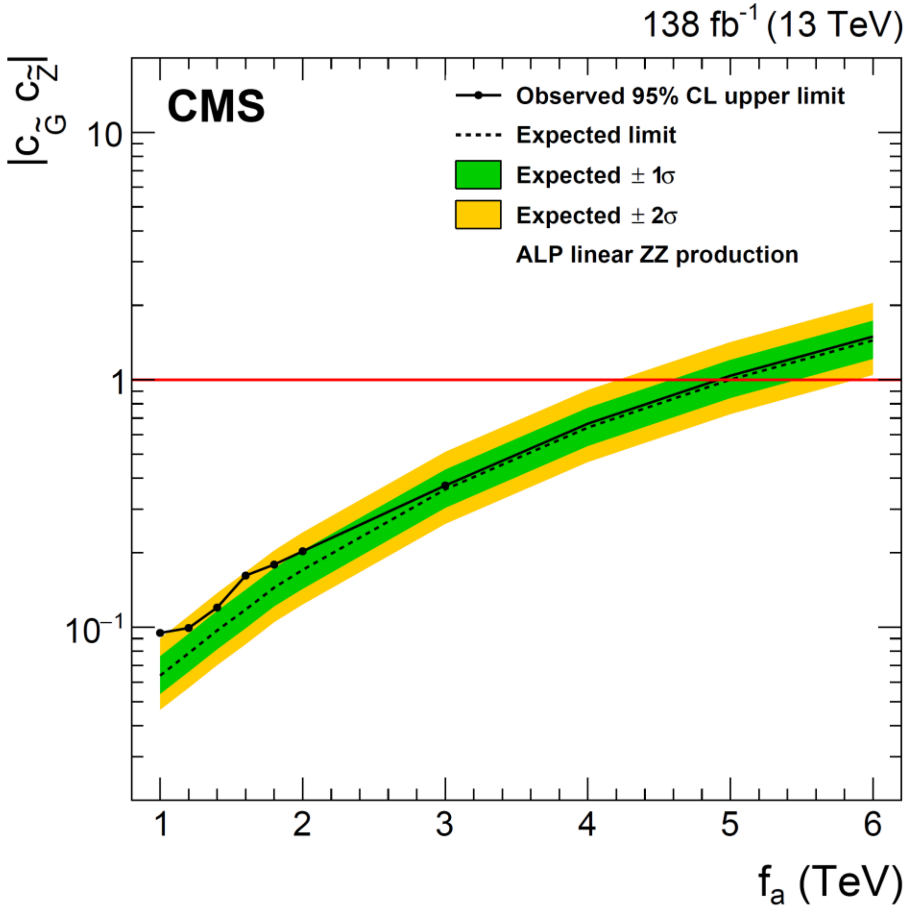
- CMS+TOTEM – high-mass ALP production from diphotons

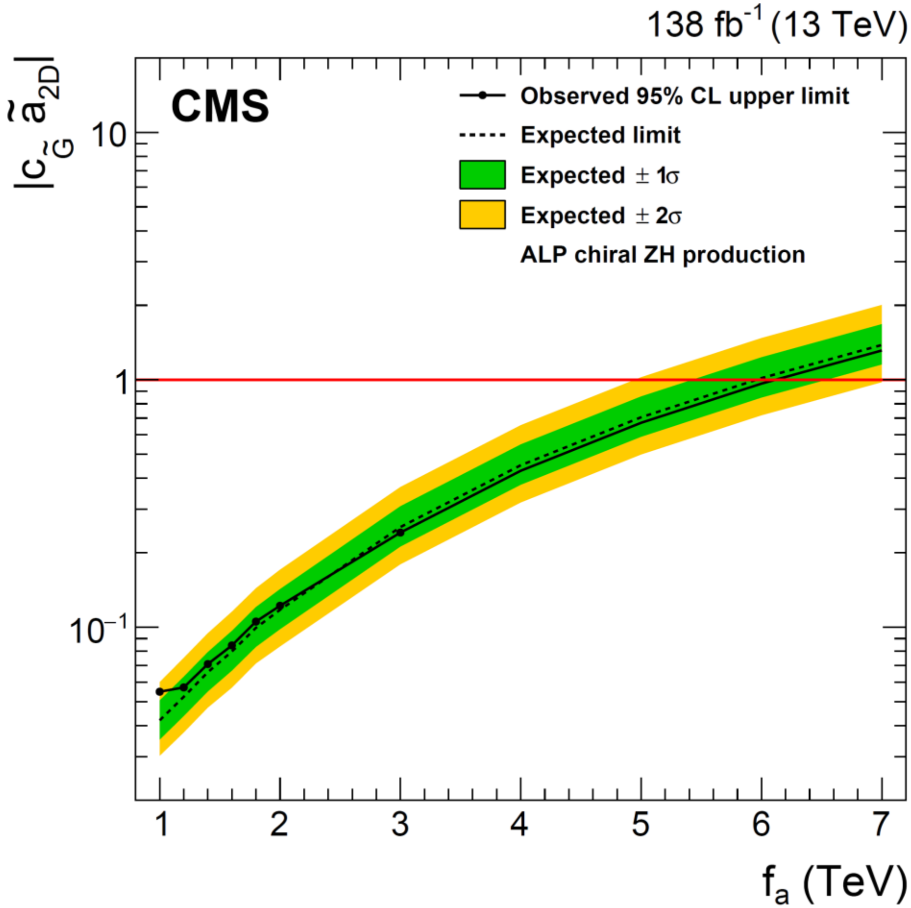


CMS EXO-21-007

ALPs at colliders

- ALPs mediating non-resonant ZZ or ZH production





CMS [2111.13669]