Axion in Reach of ALPS II?

Andreas Ringwald

ALPS Collaboration Meeting
Mainz, D
6-8 March 2017

HELMHOLTZ ASSOCIATION

DESY

Plan

> The axion window in photon coupling vs. mass parameter space is much wider than previously thought:

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Redefining the Axion Window

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A major goal of axion searches is to reach inside the parameter space region of realistic axion models. Currently, the boundaries of this region depend on somewhat arbitrary criteria, and it would be desirable to specify them in terms of precise phenomenological requirements. We consider hadronic axion models and classify the representations R_Q of the new heavy quarks Q. By requiring that (i) the Q's are sufficiently short lived to avoid issues with long-lived strongly interacting relics, (ii) no Landau poles are induced below the Planck scale; 15 cases are selected which define a phenomenologically preferred axion window bounded by a maximum (minimum) value of the axion-photon coupling about 2 times (4 times) larger than is commonly assumed. Allowing for more than one R_Q, larger couplings, as well as complete axion-photon decoupling, become possible.

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The photo-philic QCD axion

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ABSTRACT: We propose a framework in which the QCD axion has an exponentially large coupling to photons, relying on the "clockwork" mechanism. We discuss the impact of present and future axion experiments on the parameter space of the model. In addition to the axion, the model predicts a large number of pseudoscalars which can be light and observable at the LHC. In the most favorable scenario, axion Dark Matter will give a signal in multiple axion detection experiments and the pseudo-scalars will be discovered at the LHC, allowing us to determine most of the parameters of the model.

KEYWORDS: Beyond Standard Model, CP violation

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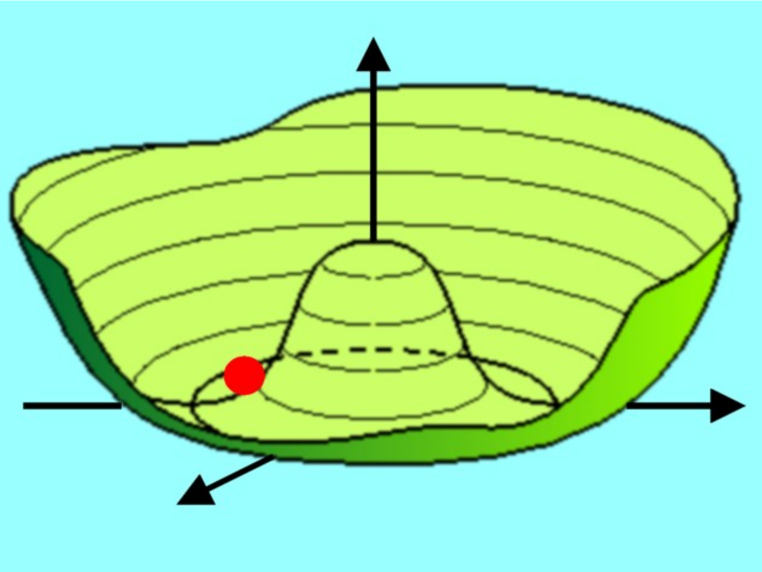
Axionic solution of strong CP problem

- A singlet complex scalar field σ featuring a global $U(1)_{\rm PQ}$ symmetry is added to SM
- Symmetry is broken by vev $\langle\sigma\rangle = v_{\rm PQ}/\sqrt{2}$

$$\sigma(x) = \frac{1}{2}\left(v_{\rm PQ} + \rho(x)\right) {\rm e}^{{\rm i}A(x)/v_{\rm PQ}}$$

  - Excitation of modulus: $m_\rho \sim v_{\rm PQ}$
  - Excitation of angle: NGB $m_A \ll v_{\rm PQ}$



[Raffelt]

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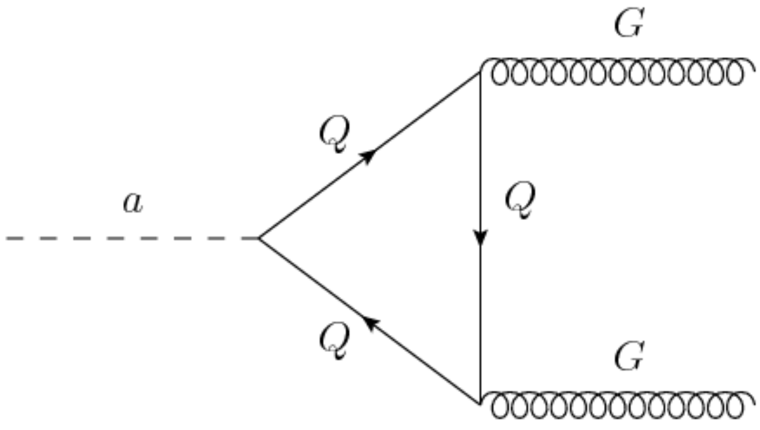

- Quarks (SM or extra) carry PQ charges such that $U(1)_{\rm PQ}$ is anomalously broken due to a gluonic triangle anomaly

$$\partial_\mu J^\mu_{U(1)_{\rm PQ}} = -\frac{\alpha_s}{8\pi}\, N\, G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu} - \frac{\alpha}{8\pi}\, E\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$

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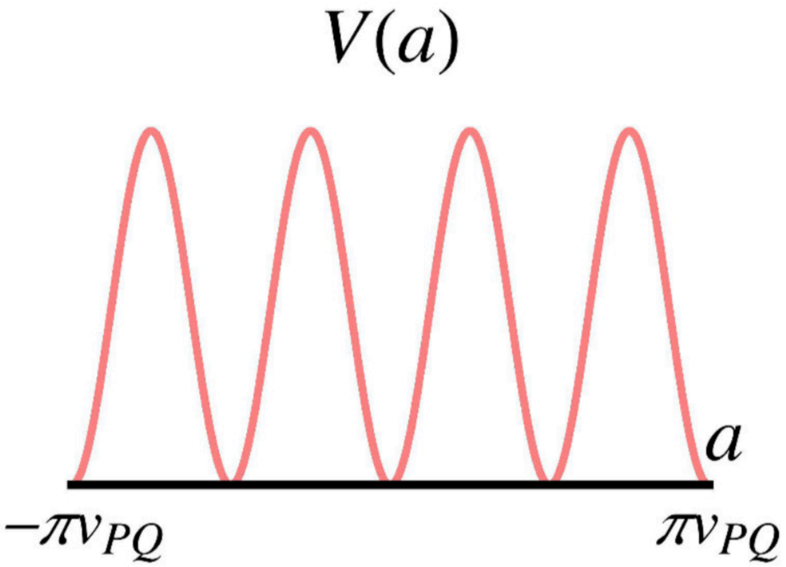

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- No strong CP problem, since axion field acts as x-dependent theta parameter [Peccei,Quinn 77; Weinberg 78; Wilczek 78]

$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi}\frac{A(x)}{f_A} G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu} - \frac{\alpha}{8\pi}\frac{E}{N}\frac{A(x)}{f_A} F_{\mu\nu}\tilde{F}^{\mu\nu}; \qquad f_A = v_{\rm PQ}/N$$

QCD dynamics: $\langle A(x)\rangle = 0; \qquad m_A = 57.0(7)\left(\frac{10^{11}{\rm GeV}}{f_A}\right)\mu{\rm eV},$

How wide is the axion window?

- Coupling to photons most important for experimental searches

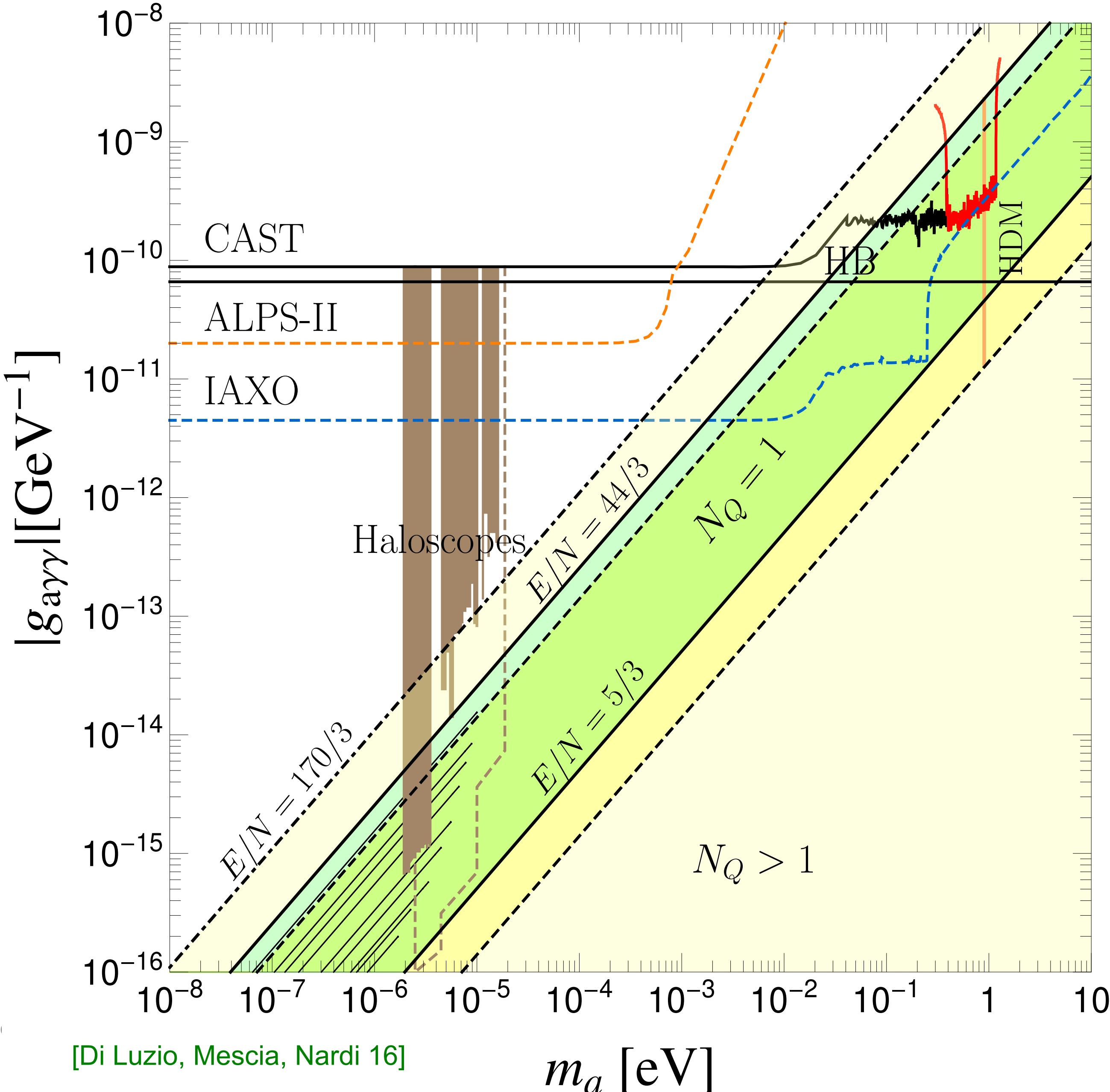
$$\mathcal{L} \supset -\frac{\alpha}{8\pi}\frac{E}{N}\frac{A(x)}{f_A}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

- How wide is the axion window, i.e. what is realistic range of E/N?
- Consider KSVZ-type axion models: Anomaly induced by heavy fermions Q in the representation $R_Q = (\mathcal{C}_Q, \mathcal{I}_Q, \mathcal{Y}_Q)$ under $SU(3)_C \times SU(2)_I \times U(1)_Y$
- Fifteen cases survive phenomenological requirements
  - Q sufficiently short lived to avoid issues with long-lived strongly interacting relics,
  - no Landau poles induced below Planck scale

R_Q	$\mathcal{O}_{Qq}$	$\Lambda_{LP}^{R_Q}$[GeV]	E/N	N_{DW}
$R_1: (3,1,-\frac{1}{3})$	$\overline{Q}_L d_R$	$9.3\cdot 10^{38}(g_1)$	$2/3$	1
$R_2: (3,1,+\frac{2}{3})$	$\overline{Q}_L u_R$	$5.4\cdot 10^{34}(g_1)$	$8/3$	1
$R_3: (3,2,+\frac{1}{6})$	$\overline{Q}_R q_L$	$6.5\cdot 10^{39}(g_1)$	$5/3$	2
$R_4: (3,2,-\frac{5}{6})$	$\overline{Q}_L d_R H^\dagger$	$4.3\cdot 10^{27}(g_1)$	$17/3$	2
$R_5: (3,2,+\frac{7}{6})$	$\overline{Q}_L u_R H$	$5.6\cdot 10^{22}(g_1)$	$29/3$	2
$R_6: (3,3,-\frac{1}{3})$	$\overline{Q}_R q_L H^\dagger$	$5.1\cdot 10^{30}(g_2)$	$14/3$	3
$R_7: (3,3,+\frac{2}{3})$	$\overline{Q}_R q_L H$	$6.6\cdot 10^{27}(g_2)$	$20/3$	3
$R_8: (3,3,-\frac{4}{3})$	$\overline{Q}_L d_R H^{\dagger 2}$	$3.5\cdot 10^{18}(g_1)$	$44/3$	3
$R_9: (\overline{6},1,-\frac{1}{3})$	$\overline{Q}_L \sigma d_R \cdot G$	$2.3\cdot 10^{37}(g_1)$	$4/15$	5
$R_{10}: (\overline{6},1,+\frac{2}{3})$	$\overline{Q}_L \sigma u_R \cdot G$	$5.1\cdot 10^{30}(g_1)$	$16/15$	5
$R_{11}: (\overline{6},2,+\frac{1}{6})$	$\overline{Q}_R \sigma q_L \cdot G$	$7.3\cdot 10^{38}(g_1)$	$2/3$	10
$R_{12}: (8,1,-1)$	$\overline{Q}_L \sigma e_R \cdot G$	$7.6\cdot 10^{22}(g_1)$	$8/3$	6
$R_{13}: (8,2,-\frac{1}{2})$	$\overline{Q}_R \sigma \ell_L \cdot G$	$6.7\cdot 10^{27}(g_1)$	$4/3$	12
$R_{14}: (15,1,-\frac{1}{3})$	$\overline{Q}_L \sigma d_R \cdot G$	$8.3\cdot 10^{21}(g_3)$	$1/6$	20
$R_{15}: (15,1,+\frac{2}{3})$	$\overline{Q}_L \sigma u_R \cdot G$	$7.6\cdot 10^{21}(g_3)$	$2/3$	20

How wide is the axion window?

- Axion window in photon coupling much wider than commonly assumed
- ALPS II discovery reach nearly touches extended axion window



[Di Luzio, Mescia, Nardi 16]

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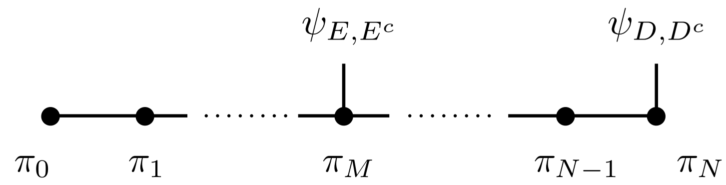
- Even wider window in clockwork axion models involving additional N pseudo NGBs

$$\mathcal{L} \supset \frac{1}{2}\sum_{j=0}^{N} \partial_\mu \pi_j \partial^\mu \pi_j - \frac{m^2}{2}\sum_{j=0}^{N-1} \left(\pi_j - q\,\pi_{j+1}\right)^2$$

$$-\frac{\alpha_s}{8\pi}\frac{\pi_N}{f} G_{\mu\nu}\widetilde{G}^{\mu\nu} - \frac{\alpha_s}{8\pi}\frac{\pi_M}{f} F_{\mu\nu}\widetilde{F}^{\mu\nu}$$



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- Particle spectrum: one massless NGB A and N pseudo NGBs with mass $\propto m$
- Couplings of axion:

$$\mathcal{L} \supset \frac{1}{2}\partial_\mu A \partial^\mu A - \frac{\alpha_s}{8\pi}\frac{A}{f_A} G_{\mu\nu}\widetilde{G}^{\mu\nu}$$

$$- \frac{\alpha_s}{8\pi} q^{N-M} \frac{A}{f_A} F_{\mu\nu}\widetilde{F}^{\mu\nu}$$

  - Photon coupling exponentially enhanced compared to gluon coupling

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[Giudice, McCullough 16]

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  - Photon coupling exponentially enhanced compared to gluon coupling
  - Boosted decay constant:

$$f_A \equiv \frac{q^N}{\mathcal{N}_0} f; \qquad \mathcal{N}_0 \equiv \sqrt{\frac{q^2-1}{q^2-q^{-2N}}}$$

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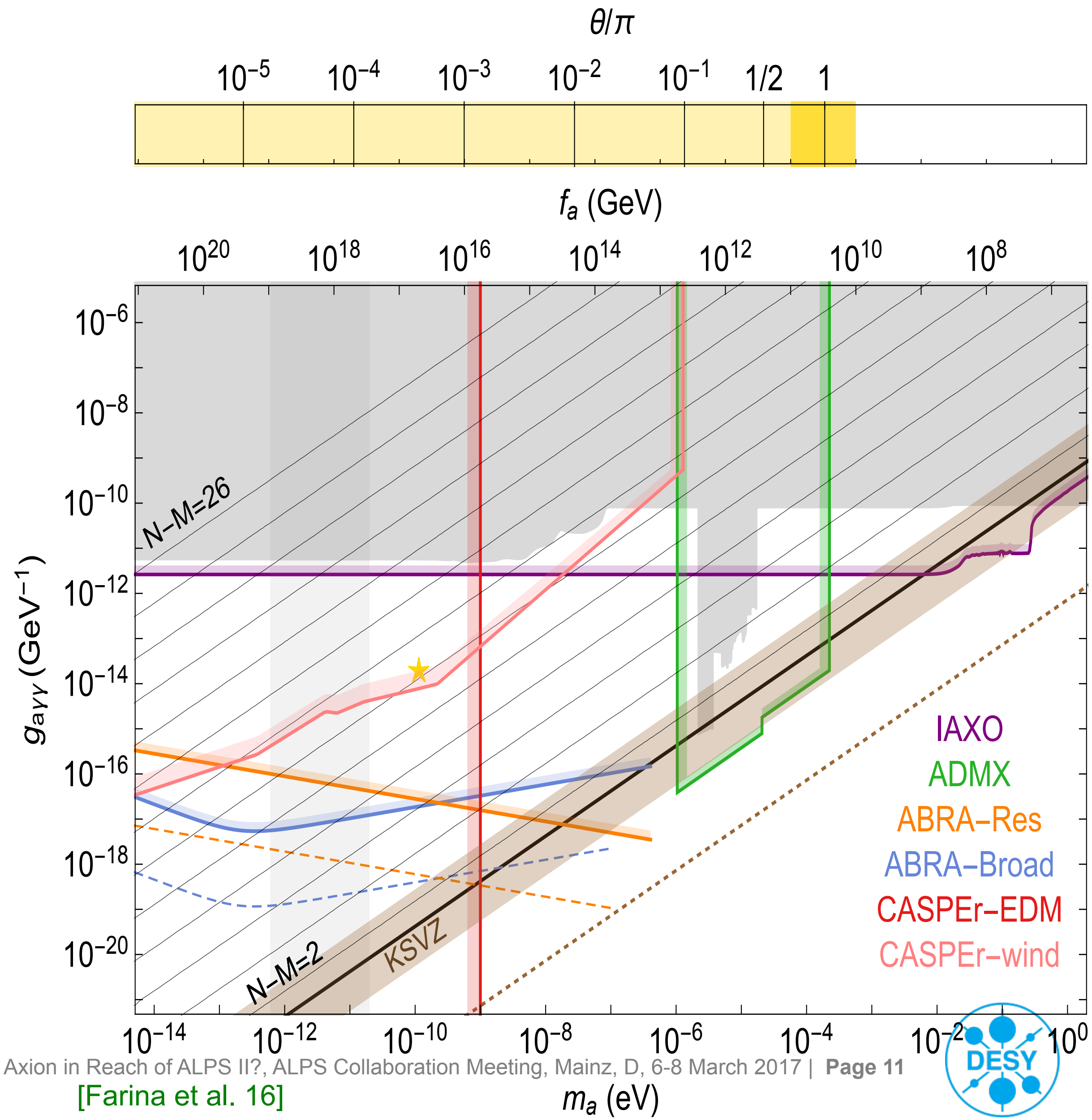
  - For large N axion in reach of ALPS II



[Farina et al. 16]

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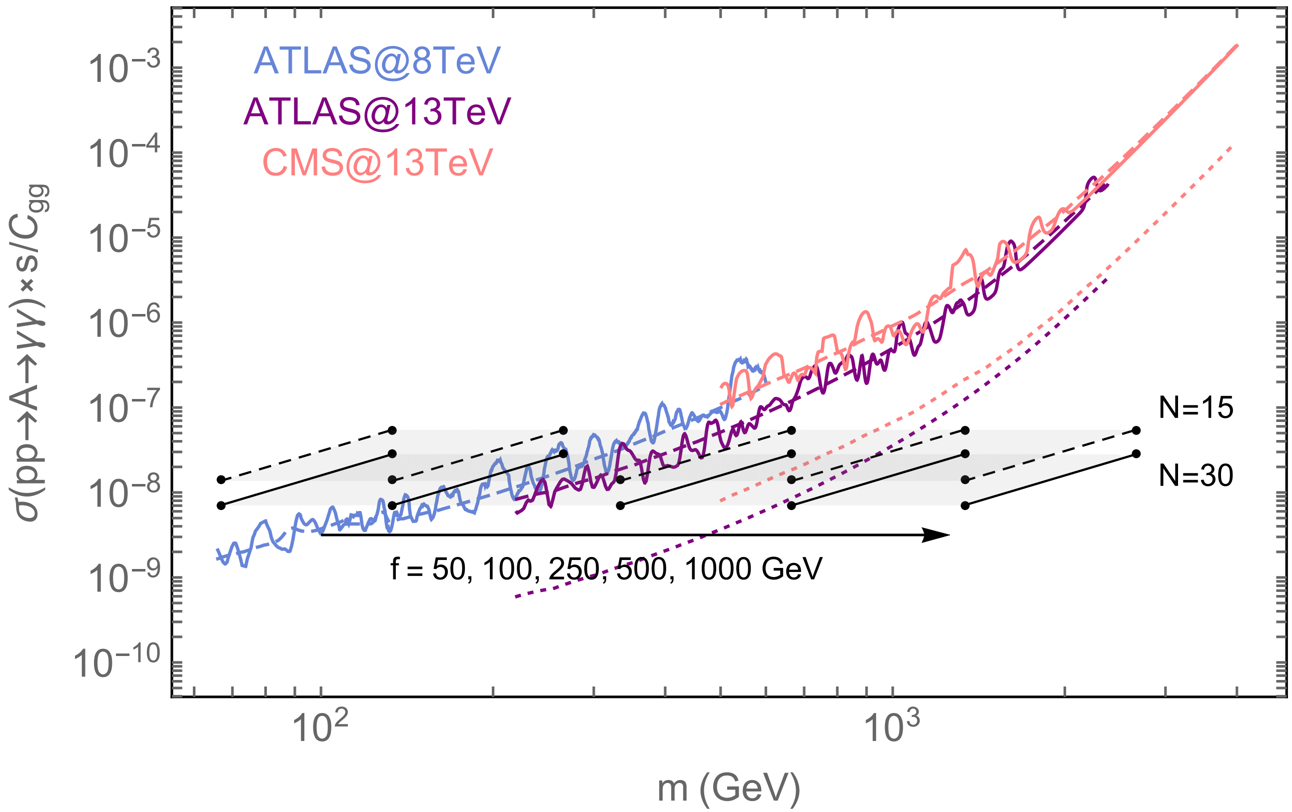
- Even wider window in clockwork axion models involving additional N pseudo NGBs
  - For large N axion in reach of ALPS II
  - Additional ALPs may be searched for at LHC



[Farina et al. 16]