Theory of Axions and ALPs: where to find them

Andreas Ringwald
FH Particle Physics Discussion:
Axions at LHC and ALPS II
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ALP

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$$\mathcal{L}_{\text{eff}} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m^2_{a,0}}{2}a^2 + \frac{\partial^\mu a}{f_a}\sum_F \bar{\psi}_F \gamma_\mu C_F \psi_F$$
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ALP

Field theoretic UV completion

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- This low-energy Lagrangian realises the approximate Abelian global symmetry non-linearly through an approximate symmetry under constant shifts, $a \to a + \kappa f_a$
  - The latter arises from field-theoretic UV completions in which SM extended by complex scalar field realising a spontaneously broken global Abelian symmetry

$$\mathcal{L} \supset |\partial_\mu\sigma|^2 - \lambda_\sigma\left(|\sigma|^2 - \frac{f_a^2}{2}\right)^2$$

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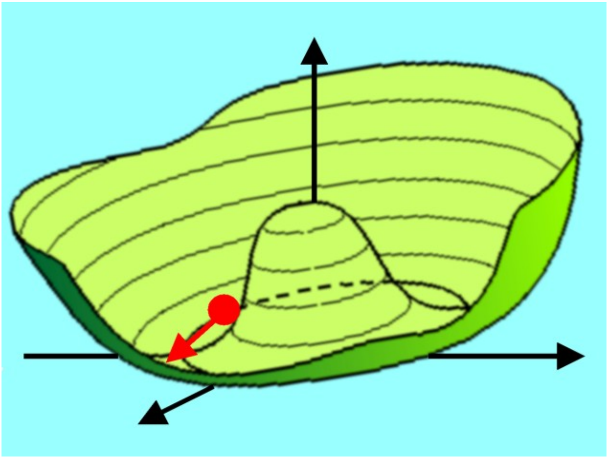

[Raffelt]

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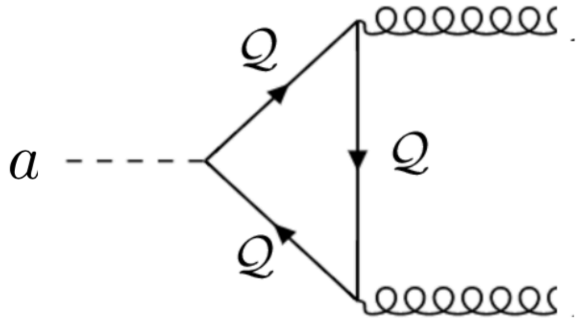

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  - **Couplings to gauge fields** arise from fermionic triangle loop diagrams

ALP

Violations of shift symmetry

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- Since interactions with SM inversely proportional to f_a : ALPs with $f_a \gg v$ are feebly-interacting pseudoscalar particles

Axion

[Peccei,Quinn `77; Weinberg `78; Wilczek `78]

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  - Non-perturbative topological fluctuations of the gluon fields in QCD induce a potential for the shifted field whose minimum is at zero field value, thereby ensuring CP conservation of strong interactions
  - The second derivative of the dynamically induced potential gives the axion mass. It is inversely proportional to the scale f_a and proportional to the square root of the topological susceptibility χ of QCD, which can be determined either using chiral effective field theory or lattice QCD, resulting in the prediction

$$m_a = C_{aGG} \frac{\sqrt{\chi}}{f_a} \simeq 5.7 \left(\frac{10^9 \text{ GeV}}{f_a / C_{aGG}} \right) \text{meV}$$

Axion

Axion “bands”

$$\mathcal{L}_{\rm eff} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{1}{2}\left(C_{aGG}\frac{\sqrt{\chi}}{f_a}\right)^2 a^2 + \frac{\partial^\mu a}{f_a}\sum_F \bar\psi_F\gamma_\mu C_F\psi_F + [C_{a\gamma\gamma} - 1.92(4)C_{aGG}]\,\frac{\alpha}{8\pi}\,\frac{a}{f_a}\,F_{\mu\nu}\tilde F^{\mu\nu}$$

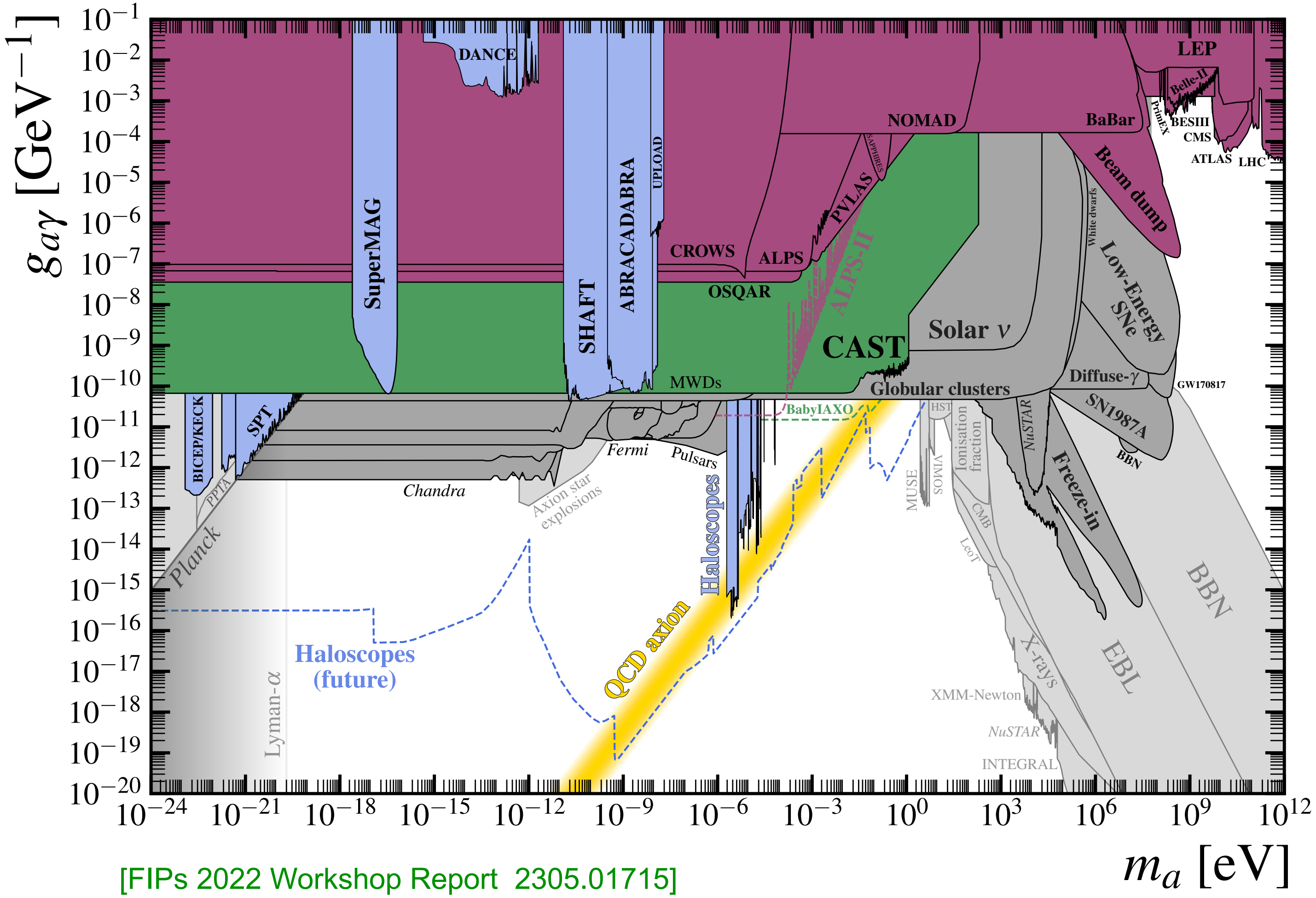
Correspondingly, axion couplings to SM grow proportional to axion mass, while their magnitude depend on the specific model-dependent coefficients of the relevant operators in the effective Lagrangian.

This gives rise to the so called axion bands in plots of coupling constant versus mass, e.g. for the coupling to electromagnetism

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

$$g_{a\gamma} = \frac{\alpha}{2\pi f_a}\,[C_{a\gamma\gamma} - 1.92(4)C_{aGG}]$$

- KSVZ model: $C_{a\gamma\gamma} = 0, C_{aGG} = 1$
  [Kim 79;Shifman,Vainshtein,Zakharov 80]
- DFSZ model: $C_{a\gamma\gamma} = 16, C_{aGG} = 6$
  [Zhitnitsky 80;Dine,Fischler,Srednicki 81]



[FIPs 2022 Workshop Report 2305.01715]

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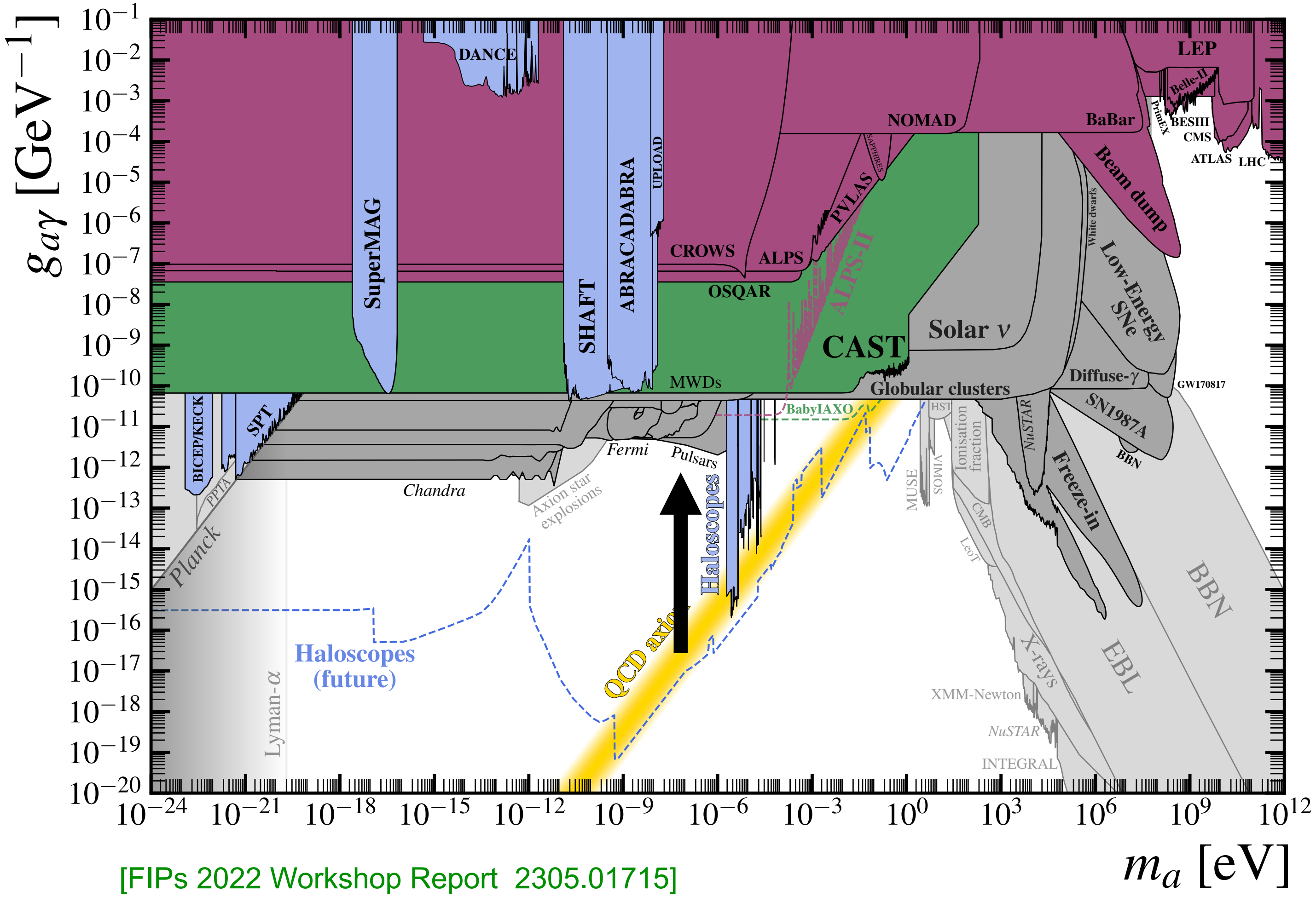

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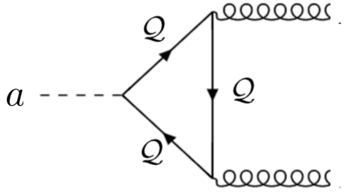
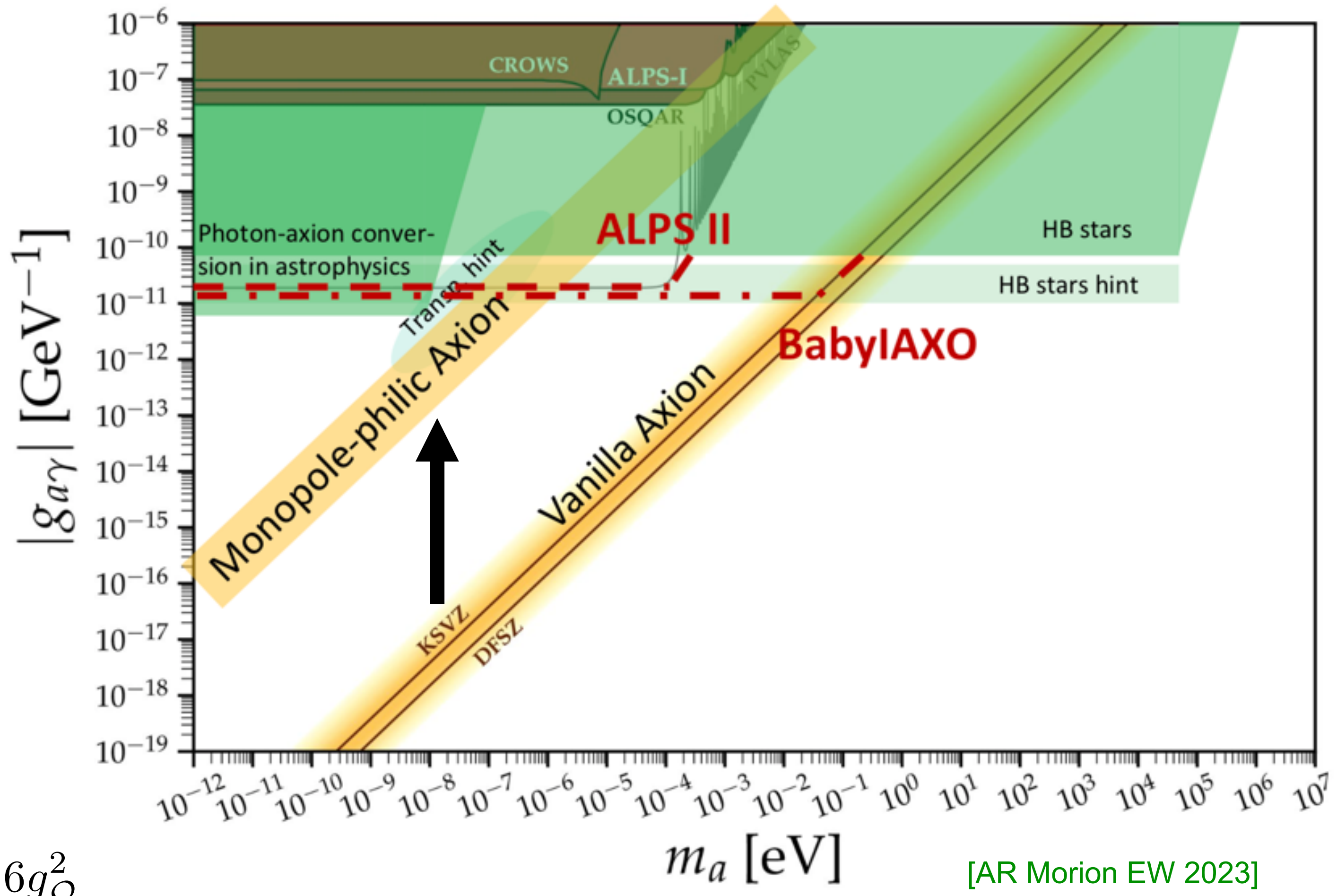
Particular enhancement in electromagnetic coupling if fermion in triangle loop carries magnetic charge, i.e. it is a magnetic monopole

[Sokolov,AR 21, 22, 23]





[AR Morion EW 2023]

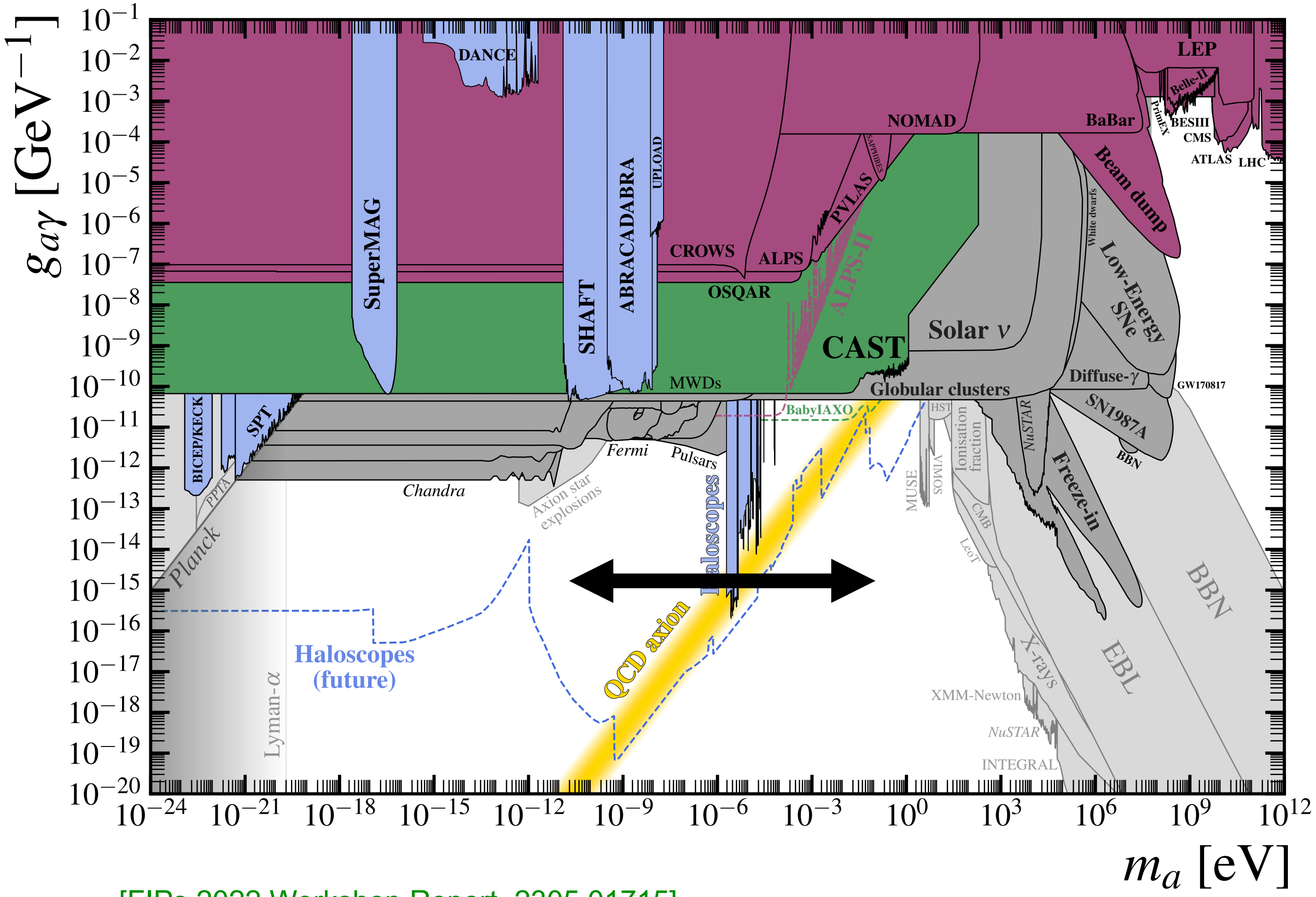
$$g_{aMM} = \frac{\alpha_m}{2\pi f_a} C_{aMM}, \qquad \alpha_m = \frac{g_0^2}{4\pi}, \qquad C_{aMM} = 6 g_{\mathcal{Q}}^2$$

$$g_{aMM}/g_{a\gamma\gamma} = (\alpha_m/\alpha)(C_{aMM}/C_{a\gamma\gamma}) = (9/4)\,\alpha^{-2}(g_{\mathcal{Q}}/q_{\mathcal{Q}})^2 \sim 10^5$$

Axion

Axion "bands"

The axion bands can be alternatively changed enlarging the confining sector beyond QCD. New contributions of topologically non-trivial gauge field fluctuations give then additional contributions to the axion mass



[FIPs 2022 Workshop Report 2305.01715]

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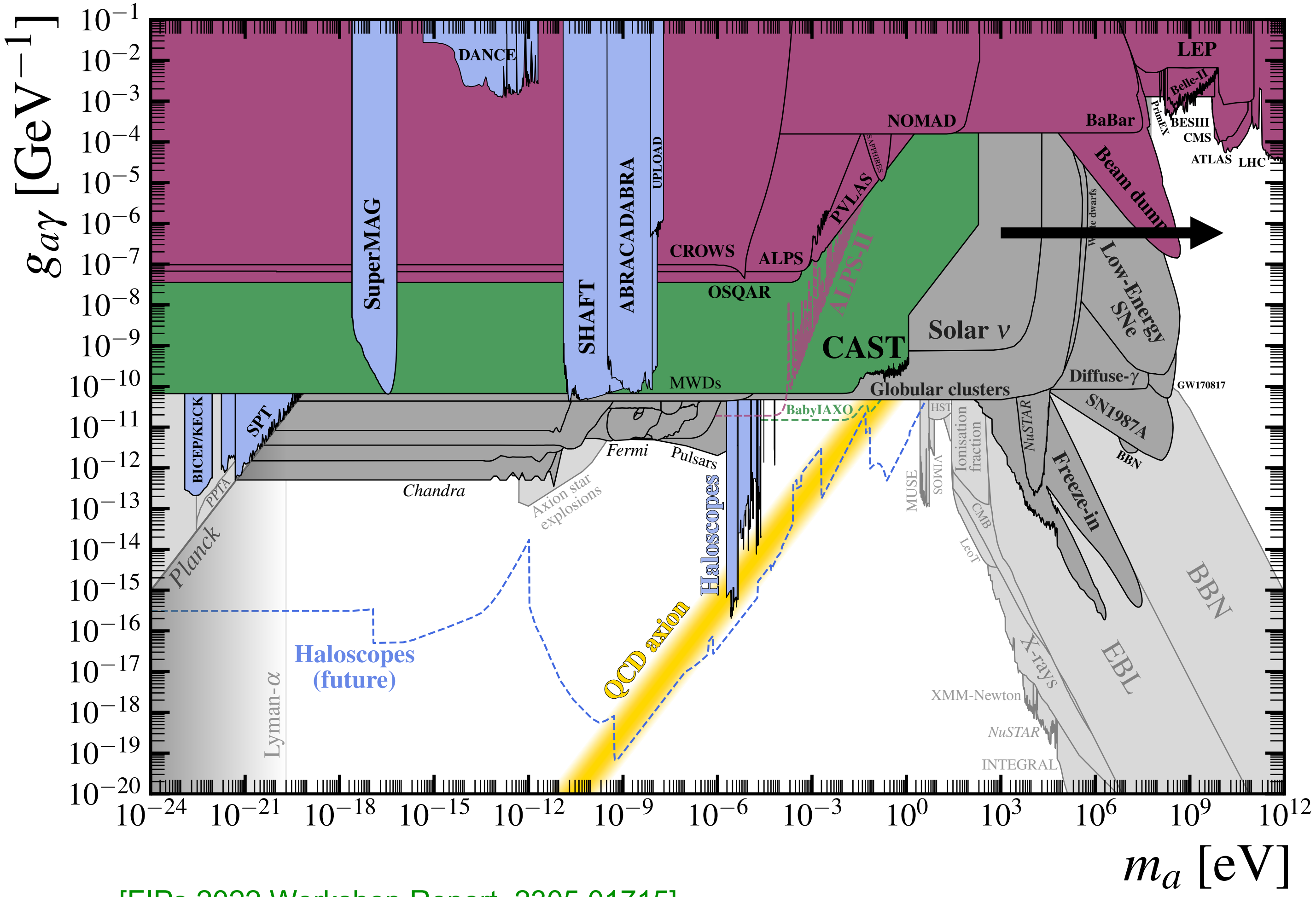
Examples of horizontal enlargement of the parameter space towards the

- right of the canonical axion band are heavy axion models that solve the strong CP problem at low scales (e.g. $f_a \sim \mathrm{TeV}$)

[Rubakov, 97; Berezhiani et al. 01; Fukuda et al, 01;...]



[FIPs 2022 Workshop Report 2305.01715]

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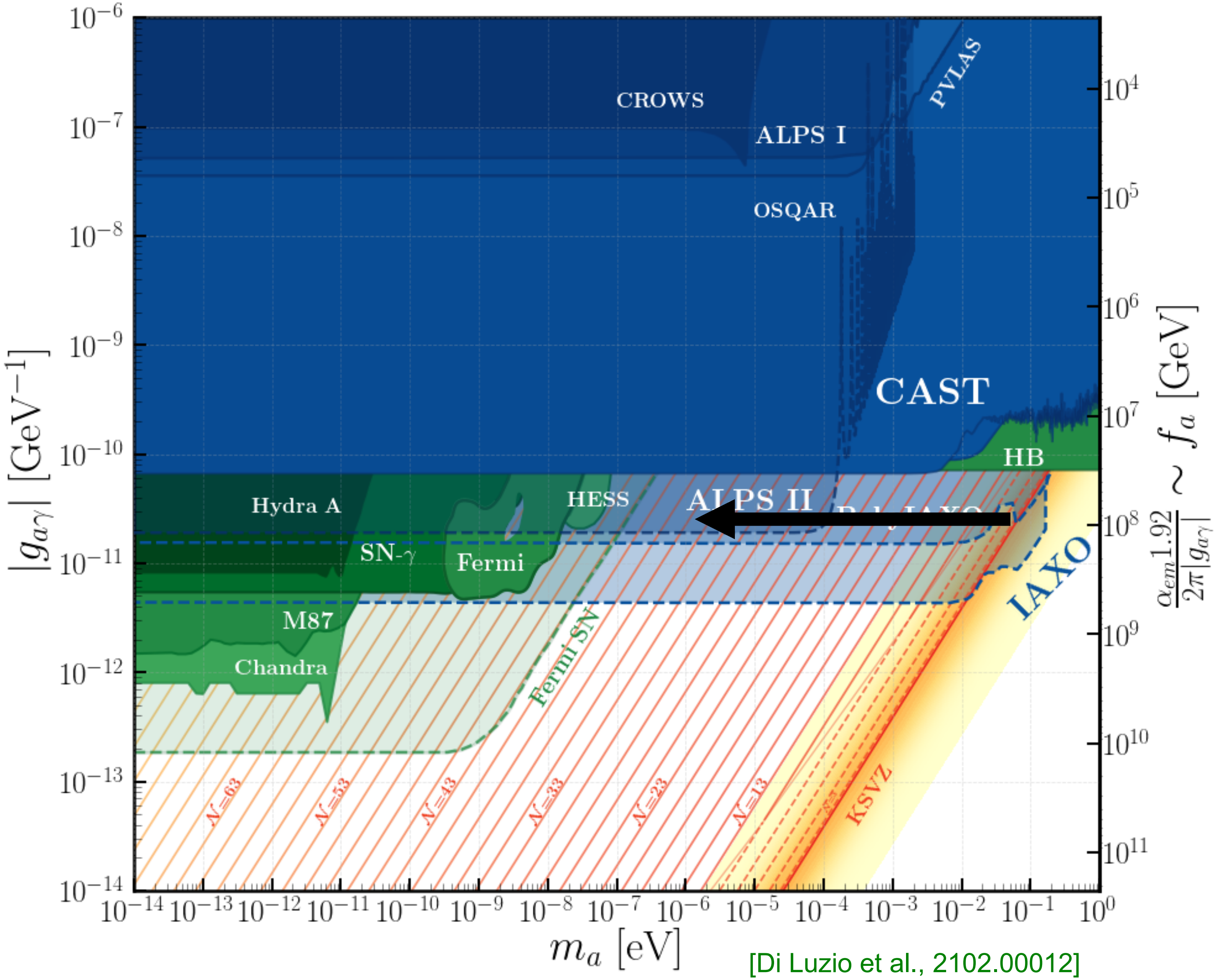
- left of the canonical axion band is the Z_N axion model exploiting N hidden copies of the SM linked by the axion, realising a Z_N symmetry

  [Hook 18; Di Luzio, Gavela, Quilez, AR 21]

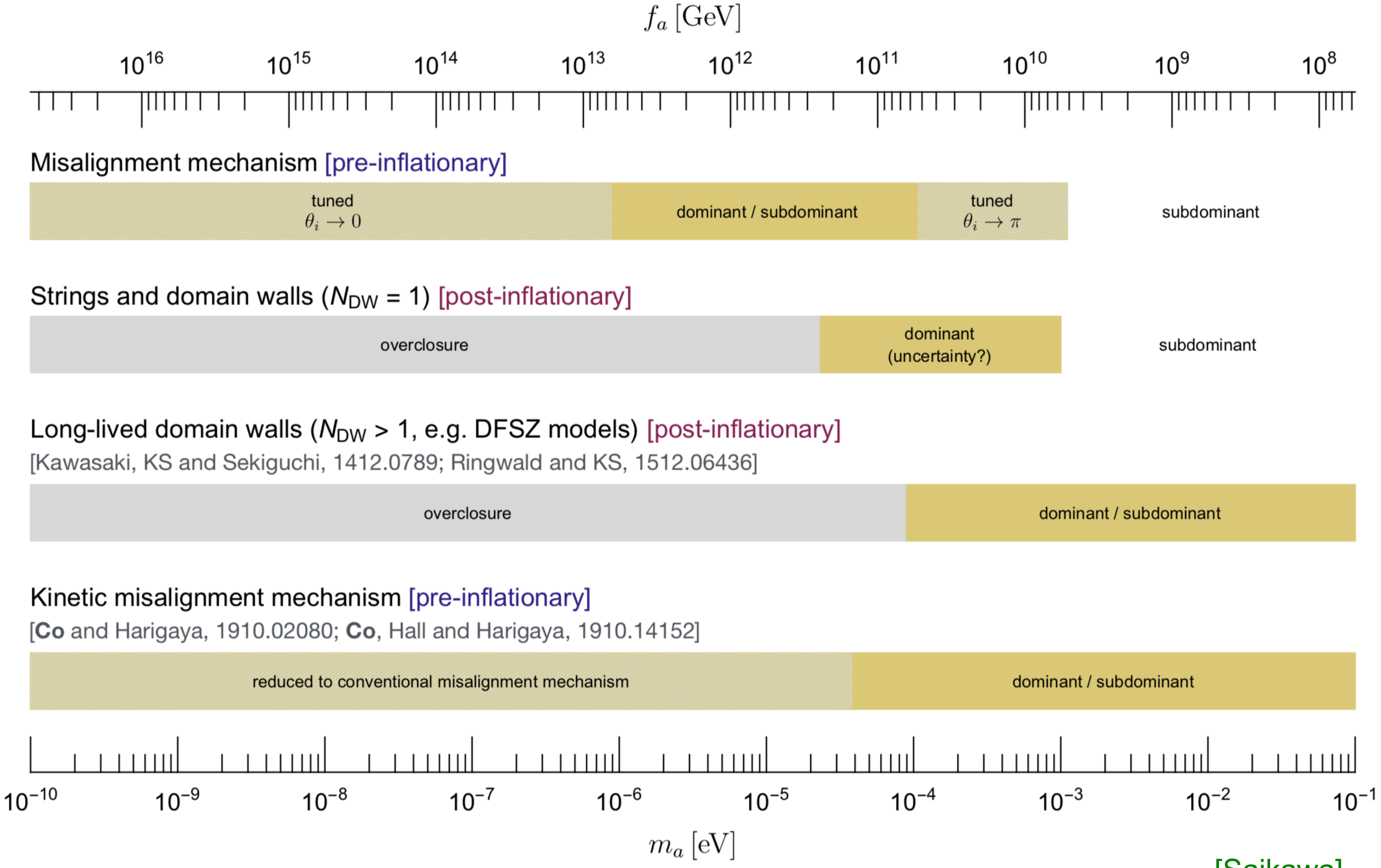


[Di Luzio et al., 2102.00012]

Dark Matter

Mass range

- Sub-eV mass axions are excellent dark matter (DM) candidates:



[Saikawa]

Dark Matter

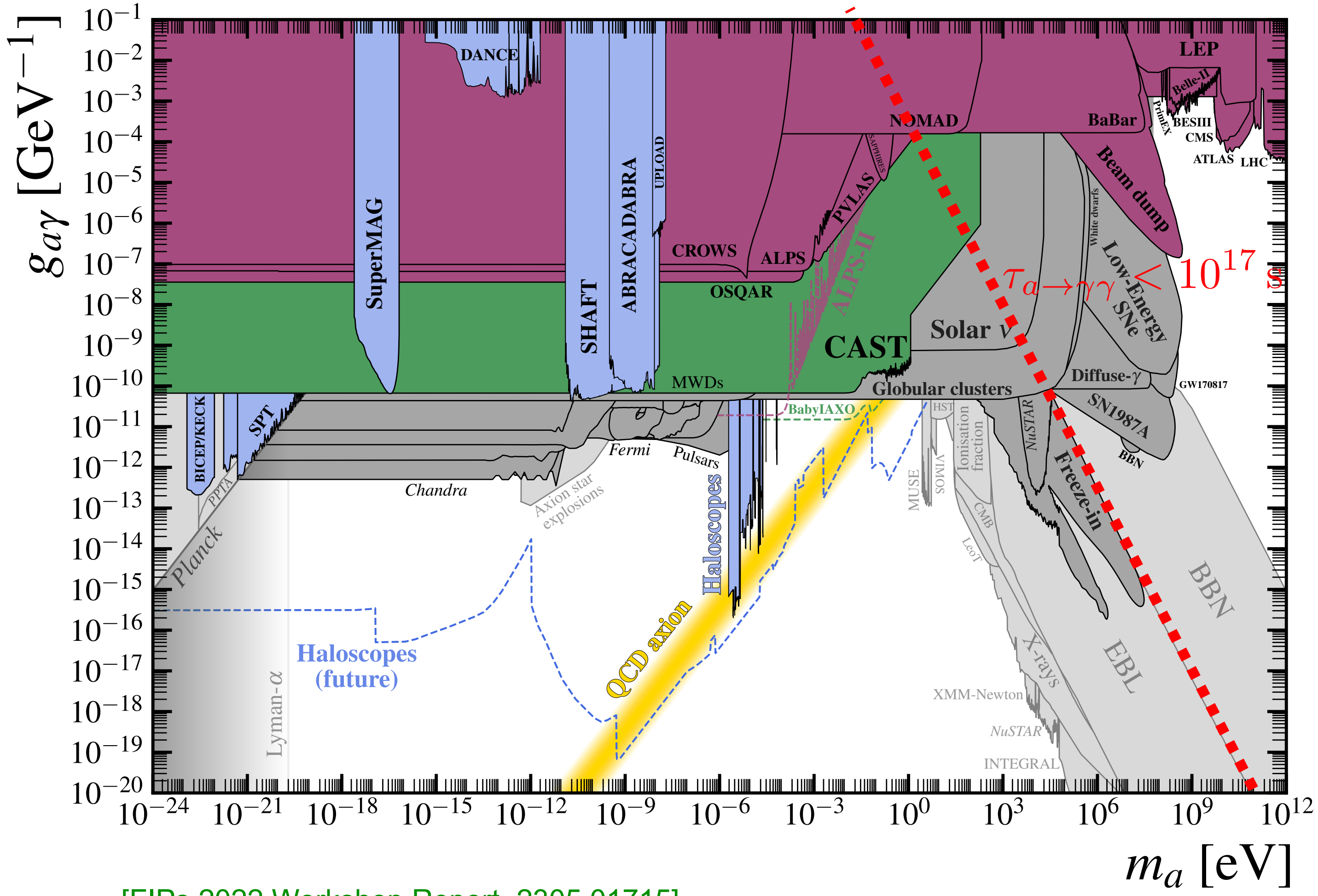
Mass range

Heavy axions or ALPs with too large two-photon coupling, however, cannot be the dark matter, since their lifetime,

$$\tau_{a\to\gamma\gamma} = \frac{64\,\pi}{g_{a\gamma}^2 m_a^3}$$

$$= 1.3\times 10^{16}\,\mathrm{s}\left(\frac{10^{-10}\,\mathrm{GeV}^{-1}}{g_{a\gamma}}\right)^2\left(\frac{\mathrm{keV}}{m_a}\right)^3$$

tends to be smaller than the age of the universe



[FIPs 2022 Workshop Report 2305.01715]