

# Quantum gravity, the strong CP problem and its companion axion solution

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Talk is based on:

S. Arunasalam, AK, Eur. Phys. J. C 79 (2019) 1, 49; e-Print: [1808.01796](#) [hep-th]

Z. Chen, AK, Eur. Phys. J. C 82 (2022) 7, 596; e-Print: [2108.05549](#) [hep-ph]

Z. Chen, AK, C.A.J. O'Hare, Z.S.C. Picker, G. Pierobon, e-Print: [2109.12920](#) [hep-ph]; [2110.11014](#) [hep-ph].

Are quantum gravity effects (phenomenologically)  
relevant for particle physics?

Perry, 79'

Deser, Duff & Isham 80'

Dvali 05', 22'; Dvali & Funcke 16'

# Instantons and CP violation in SM

$$\mathcal{L}_{\text{CPV}} = \frac{\theta_{\text{QCD}}}{32\pi^2} G_{\mu\nu}^a \tilde{G}^{a\mu\nu} + \frac{\theta_{\text{QED}}}{32\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Both of these terms are total 4-derivatives, e.g.,

$$F_{\mu\nu} \tilde{F}^{\mu\nu} \equiv \frac{1}{2} \epsilon^{\mu\nu\rho\sigma} F_{\mu\nu} F_{\rho\sigma} = \partial_\mu (K^\mu), \quad K^\mu = \epsilon^{\mu\nu\rho\sigma} A_\nu F_{\rho\sigma}$$

- The QED-term can be ignored – no physical effects
- The QCD-term is physical, e.g. describes vacuum-to-vacuum transition amplitudes ‘mediated’ by QCD instantons. This term is mandatory to preserve causality (‘cluster decomposition’)!
- Neutron EDM:  $d_n \simeq e\theta_{\text{QCD}} m_q / m_N^2 \implies \theta_{\text{QCD}} \lesssim 10^{-10}$  .  
The strong CP problem (Crewther, di Vecchia, Veneziano, Witten, 79')

# Axion solution to the strong CP problem

Introduce a new light pseudo-scalar  $a(x)$  (Peccei-Quinn 77')

$$\mathcal{L}_{axion} \propto \frac{\theta_{QCD} + N_{QCD}a(x)/f_a}{32\pi^2} G_{\mu\nu}^a \tilde{G}^{a\mu\nu}$$

Instanton-induced potential:

$$V(a) = -2K \cos(N_{QCD}a(x)/f_a + \theta_{QCD}), \quad K \approx m_\pi^2 f_\pi^2$$

In the minimum CP-violating phase cancels out:

$$\langle a \rangle = -f_a \theta_{QCD} / N_{QCD}$$

Light, feebly coupled, essentially stable => dark matter candidate

$$m_a \approx m_\pi \frac{f_\pi}{f_a} \quad (f_\pi \ll f_a)$$

# Anomalies and instantons

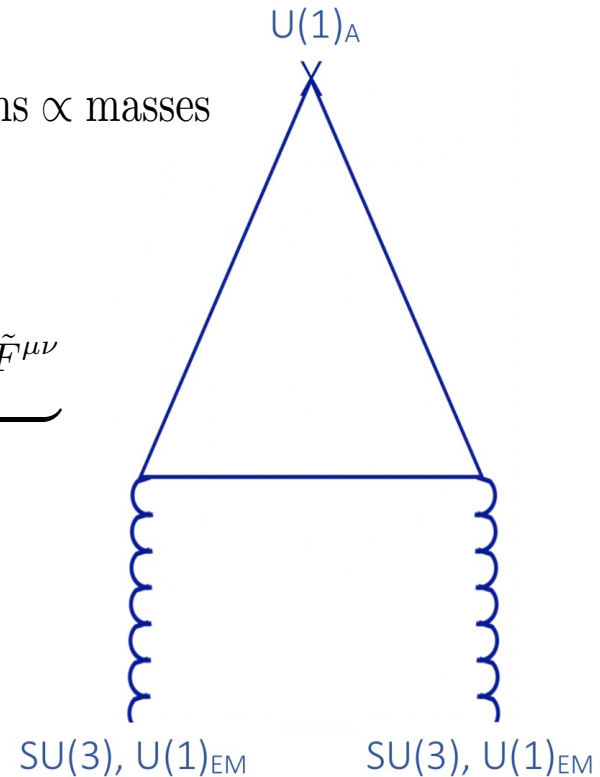
Mixed global-gauged anomalies (Adler; Bell & Jackiw, 69’):

$$\partial_\mu J_A^\mu = \frac{g^2 N_{QCD}}{16\pi^2} G_{\mu\nu}^a \tilde{G}^{a\mu\nu} + \frac{e^2 N_{QED}}{16\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu} + \text{terms } \propto \text{masses}$$

$$\Delta Q_A \propto N_{QCD} \underbrace{\int d^4x \frac{g^2}{16\pi^2} G_{\mu\nu}^a \tilde{G}^{a\mu\nu}} + N_{QED} \underbrace{\int d^4x \frac{e^2}{16\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu}}$$

Chern-Pontryagin index,  $P_{SU(2) \in SU(3)} = n \in \mathbb{Z}$ ;  
 $\pi_3(S^3) = \mathbb{Z}$

$P_{U(1)} = 0$

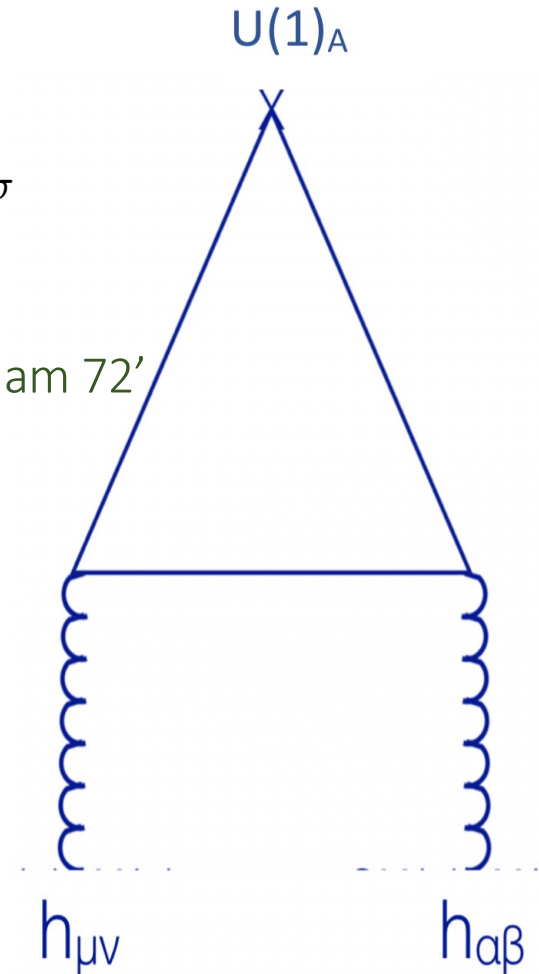


# Anomalies in the Standard Model + Gravity

$$\nabla_{\mu} J_A^{\mu} = \frac{N_g}{192\pi^2} R_{\mu\nu\rho\sigma} \tilde{R}^{\mu\nu\rho\sigma}, \quad \tilde{R}^{\mu\nu\rho\sigma} = \frac{1}{\sqrt{g}} \epsilon^{\mu\nu\alpha\beta} R_{\alpha\beta}{}^{\rho\sigma}$$

Delbourgo, Salam 72'

Gravitational instantons?



# Gravitational instantons: generalities

- In quantum gravity imitate instanton effects by summing up over manifolds  $(M, g_{\mu\nu})$  with an arbitrary topology in the Euclidean path integral
- Problem:

$$S_{\text{EG}} \lesssim 0$$

# Gravitational instantons: generalities

- Positive action theorem (Schoen, Yau 79'; Witten 81')

For Ricci flat,  $R=0$ , (a.k.a, vacuum manifolds):

- (a) Asymptotically Euclidean (AE) spaces,  $S_{EG} \geq 0$  ;  $S_{EG} = 0$  ,  
if and only if the space is flat
- (b) Asymptotically Locally Euclidean (ALE) spaces,  $S_{EG} \geq 0$  ;  $S_{EG} = 0$   
for self (anti-self)-dual configurations!

$$S_{EG}^{\text{inst}} = 0!$$



# Gravitational instantons: generalities

- For  $R=0$  AE/ALE there are no fermion zero-modes even for massless fermions

$$\begin{aligned}\not{\nabla}\psi &= 0, \quad \not{\nabla} = \gamma^\mu \nabla_\mu \\ &= \gamma^\mu \left( \partial_\mu + \frac{1}{4} \omega_\mu^{ab} \sigma_{ab} \right)\end{aligned}$$

- Hence,  $\bar{\not{\nabla}}\not{\nabla} = -\nabla^2 + \frac{1}{8} R_{\mu\nu ab} \sigma^{\mu\nu} \sigma^{ab} = -\nabla^2 > 0$

$$\nabla^2\psi = 0 \implies \psi = 0$$

Such instantons would not induce chiral symmetry breaking

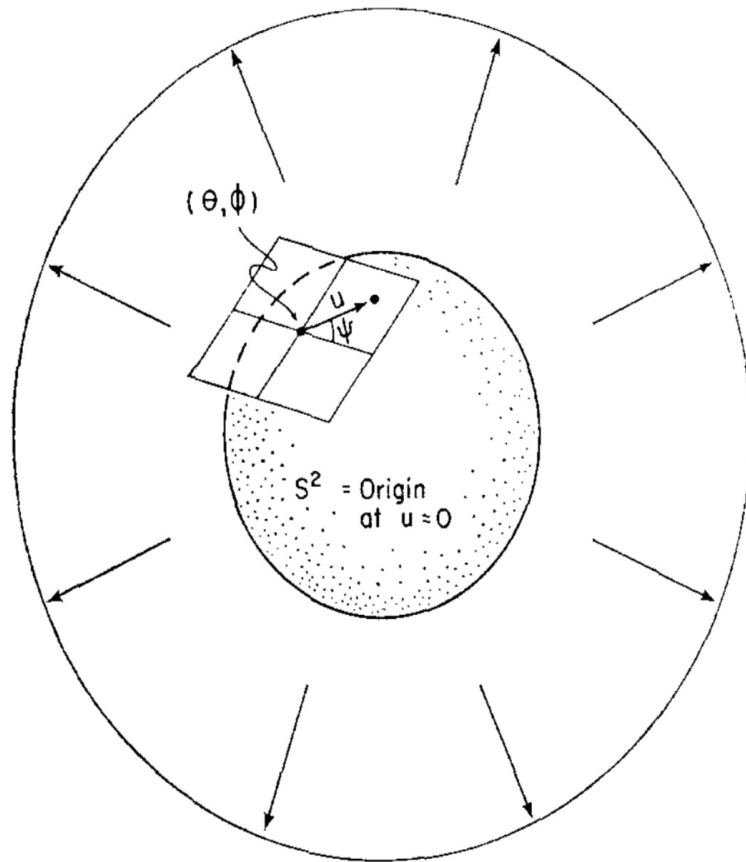
# Eguchi-Hanson instanton

- Anti-self dual solution:

$$ds^2 = \frac{dr^2}{1 - \left(\frac{a}{r}\right)^4} + r^2 \left( \sigma_x^2 + \sigma_y^2 + \left[ 1 - \left(\frac{a}{r}\right)^4 \right] \sigma_z^2 \right)$$

- (i)  $a$  is an arbitrary length parameter, the instanton size
- (ii)  $a \rightarrow 0$ , flat space limit
- (iii) Coordinate (non-physical) singularity at  $r=a$

# Eguchi-Hanson instanton



- Geodesic completeness:  $0 \leq \psi \leq 2\pi$
- We 'half' the space, it got a boundary  
 $r \rightarrow \infty, S^3/Z_2 = RP^3$

taken from Eguchi,  
Hanson, Annals of  
Physics 120, 82 (1979)

# Eguchi-Hanson instanton

$$\begin{aligned} S_{\text{EG}} &= \underbrace{\frac{-1}{16\pi G} \int d^4x \sqrt{g} R}_{=0, \text{ Ricci flat}} - \frac{1}{8\pi} \int_{\partial M(r \rightarrow \infty)} K d\Sigma \\ &= \frac{\pi}{8} \left[ 3r^2 - \frac{a^4}{r^2} - 3r^2 \left(1 - a^4/r^4\right)^{1/2} \right] \Big|_{r \rightarrow \infty} \\ &= \frac{\pi a^4}{16 r^2} \Big|_{r \rightarrow \infty} = 0 \end{aligned}$$

- Index of the Dirac operator:  $\nu_{1/2}(\not{\nabla}) = 0$

# Coloured Eguchi-Hanson instanton

- We can extend the above construction to Yang-Mills (SU(2))-Eguchi-Hanson instantons

$$A_{\mu}^a = \frac{1}{2} \eta_{AB}^a \omega_{\mu}^{AB} ,$$

$$\omega_{\theta}^{01} = \omega_{\theta}^{23} = \omega_{\phi}^{02} = \omega_{\phi}^{31} = \frac{1}{2} \sqrt{1 - \frac{a^4}{r^4}} ,$$

$$\omega_{\psi}^{03} = \omega_{\psi}^{12} = \frac{1}{2} \left( 1 + \frac{a^4}{r^4} \right) ,$$

- Action  $S_{\text{CEH}} = \frac{1}{4g^2} \int d^4x \sqrt{g} F^{a\mu\nu} F_{\mu\nu}^a = \frac{4\pi^2}{g^2} \times 3$

# Coloured Eguchi-Hanson instanton

- Chern-Pontryagin index

$$\begin{aligned} p &= \frac{1}{16\pi^2} \int d^4x \sqrt{g} R_{\mu\nu\rho\sigma} \tilde{R}^{\mu\nu\rho\sigma} \\ &= \frac{2}{32\pi^2} \int d^4x \sqrt{g} F_{\mu\nu}^a \tilde{F}^{a\mu\nu} = 3. \end{aligned}$$

- Fermion index (R – irrep of SU(2))

$$\nu_{1/2}^{(R)} = \begin{cases} \frac{1}{4} d_R (d_R^2 - 2), & \text{for } d_R = 2, 4, \dots \\ \frac{1}{4} d_R (d_R^2 - 1), & \text{for } d_R = 1, 3, \dots \end{cases}$$

- 'tHooft vertices:  $\propto e^{-\frac{12\pi^2}{g^2}} \det(\psi_L \bar{\psi}_R)$  vs  $\propto e^{-\frac{8\pi^2}{g^2}} \det(\psi_L \bar{\psi}_R)$

# Colored gravitational instantons and axion

- We have extra CP violation due to the colored gravitational instantons

$$S_{eff}[\Phi] = S[\Phi] + \frac{\theta_{QCD}}{32\pi^2} \int d^4x \sqrt{g} F_{\mu\nu}^a \tilde{F}^{a\mu\nu} \\ + \frac{\theta_{EH}}{48\pi^2} \int d^4x \sqrt{g} R_{\mu\nu\rho\sigma} \tilde{R}^{\mu\nu\rho\sigma}$$

- Effective vacuum angle  $\theta_g = 3\theta_{QCD}/2 + \theta_{EH}$
- Does the original axion solution to the strong CP problem hold?

## Computing the axion potential

$$\begin{aligned}
 \Delta\mathcal{L} = & -d \left( \frac{2\pi}{\alpha_s(\Lambda)} \right)^6 \exp \left[ -\frac{2\pi}{\alpha_s(\Lambda)} + iN \frac{a}{f_a} + i\theta \right] \\
 & \times \frac{d\rho}{\rho^5} (\Lambda\rho)^b \det (q_{iL} \bar{q}_{jR}) \\
 & - \bar{d} \left( \frac{2\pi}{\alpha_s(\Lambda)} \right)^8 \exp \left[ -\frac{3\pi}{\alpha_s(\Lambda)} + iN_g \frac{a}{f_a} + i\theta_g \right] \\
 & \times \frac{d\rho}{\rho^5} (\Lambda\rho)^{3b/2} \det (q_{iL} \bar{q}_{jR}) + \text{h.c.}
 \end{aligned}$$

$$V(a) = -2K \cos \left( N \frac{a}{f_a} + \theta \right) - 2\kappa K \cos \left( N_g \frac{a}{f_a} + \theta_g \right)$$

The CEH contribution is large  $-\kappa \approx 0.04 - 0.6$

The one-axion solution is no-longer valid!

Chen, AK 21'



# Companion axion model

- Extend PQ symmetry  $U(1)_{PQ} \times U(1)'_{PQ} \longrightarrow 1$
- Two coupled QCD axions

$$V(a, a') = -2K \cos \left( N \frac{a}{f_a} + N' \frac{a'}{f'_a} + \theta \right) \\ - 2\kappa K \cos \left( N_g \frac{a}{f_a} + N'_g \frac{a'}{f'_a} + \theta_g \right)$$

Chen, AK, O'Hare, Picker,  
Pierobon 21'

# Companion axion model

Masses and mixing

- Hierarchical case,  $\epsilon = f_a/f'_a \ll 1$

$$m_1^2 \approx \frac{2K(N^2 + \kappa N_g^2)}{f_a^2},$$

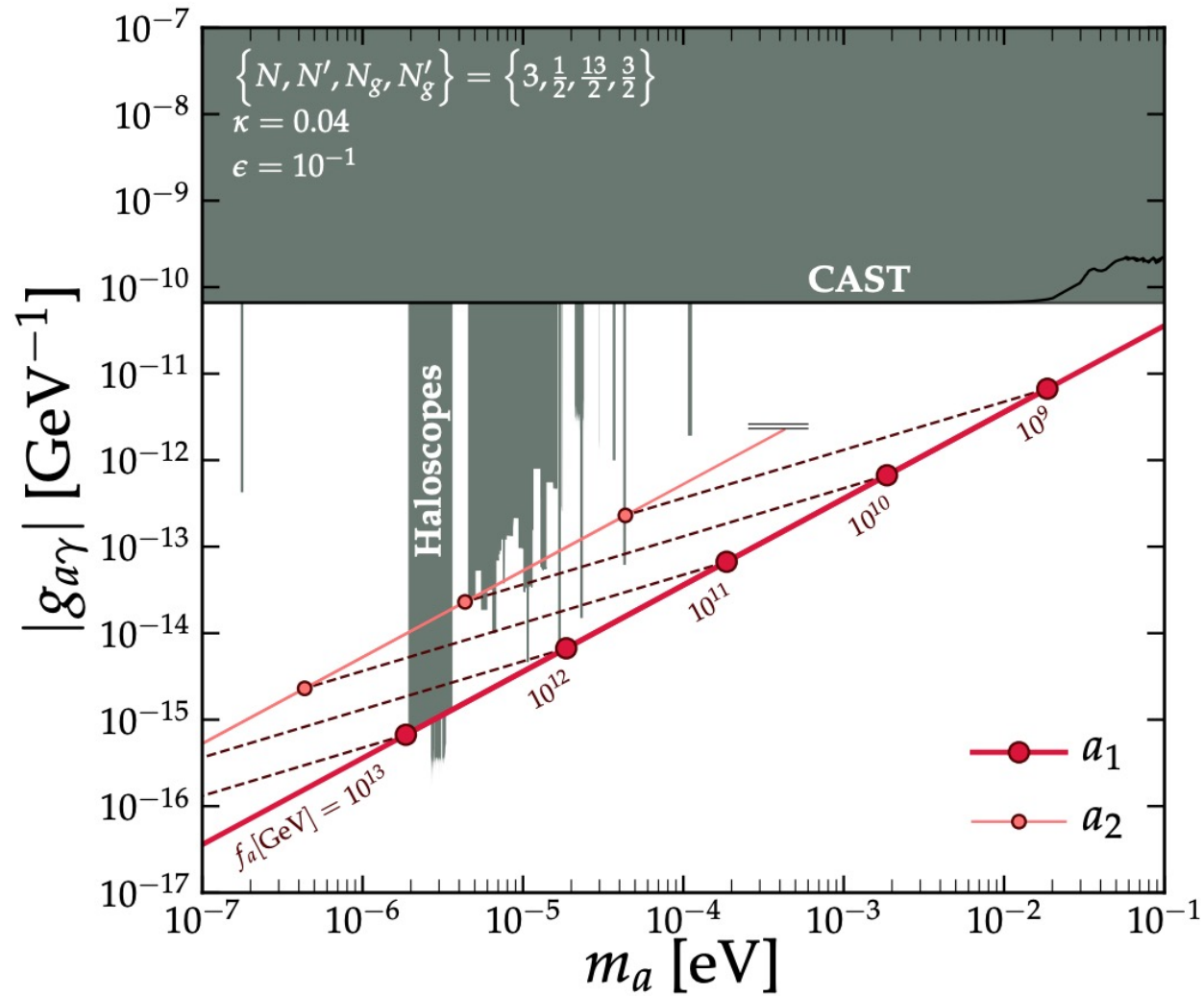
$$m_2^2 \approx \frac{\kappa(NN'_g - N_gN')^2}{N^4 + \kappa N^2 N_g^2} \epsilon^2 m_1^2 \sim \kappa \epsilon^2 m_1^2, \quad \alpha \approx \frac{NN' + \kappa N_g N'_g}{N'^2 + \kappa N_g'^2} \epsilon \sim \epsilon \ll 1.$$

- Large mixing,  $\epsilon \sim 1$  (axion-axion oscillation effects)

$$m_1^2 \approx \frac{2K}{f_a^2} \left[ N^2 + N'^2 + \kappa \frac{N^2 N_g^2 + N'^2 N_g'^2}{N^2 + N'^2} \right]$$

$$m_2^2 \approx \frac{2K\kappa}{f_a^2} \frac{N^2 N_g'^2 + N'^2 N_g^2}{N^2 + N'^2} \sim \kappa m_1^2 \quad \tan 2\alpha \approx -\frac{2(NN' + \kappa N_g N'_g)}{(N^2 - N'^2) + \kappa(N_g^2 - N_g'^2)}$$

# Companion axion model [[2109.12920](https://arxiv.org/abs/2109.12920)]



# Companion axion model: bounds and projections

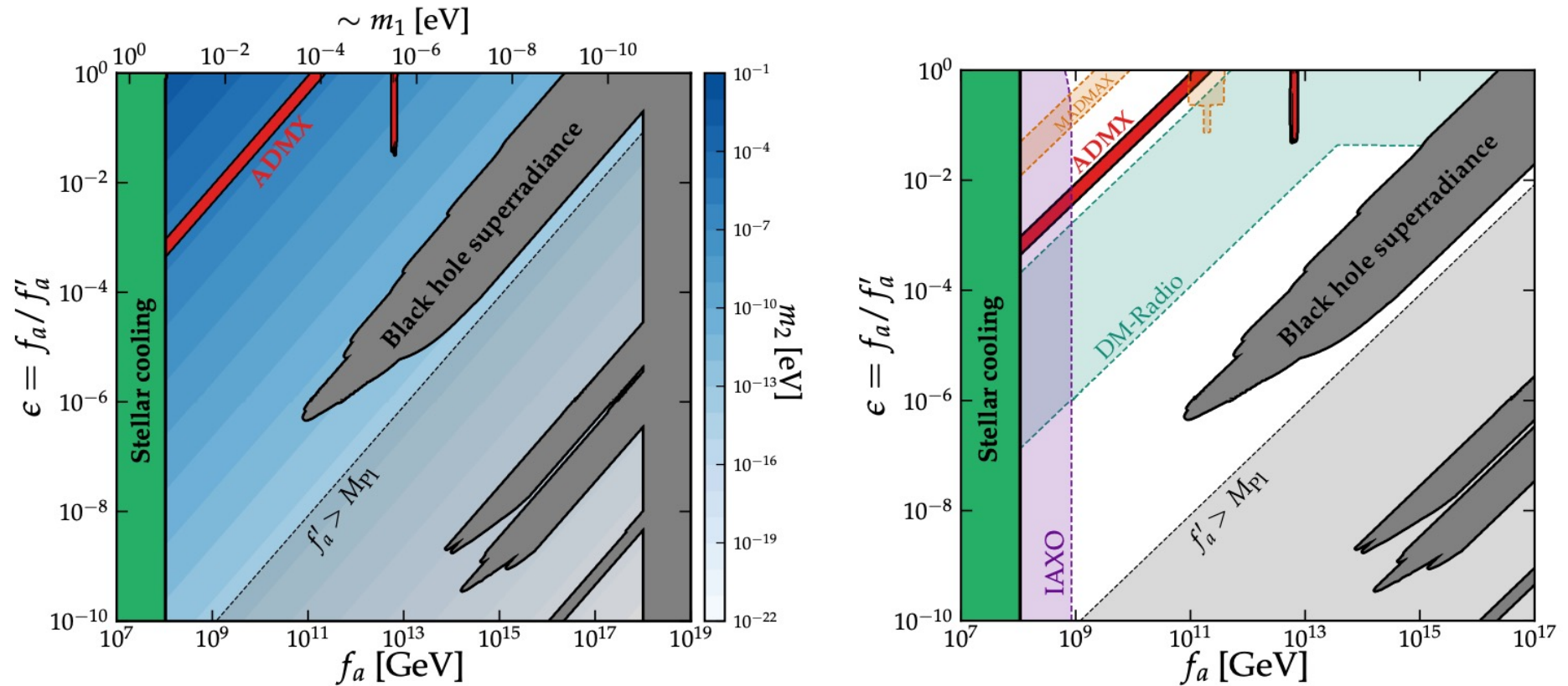
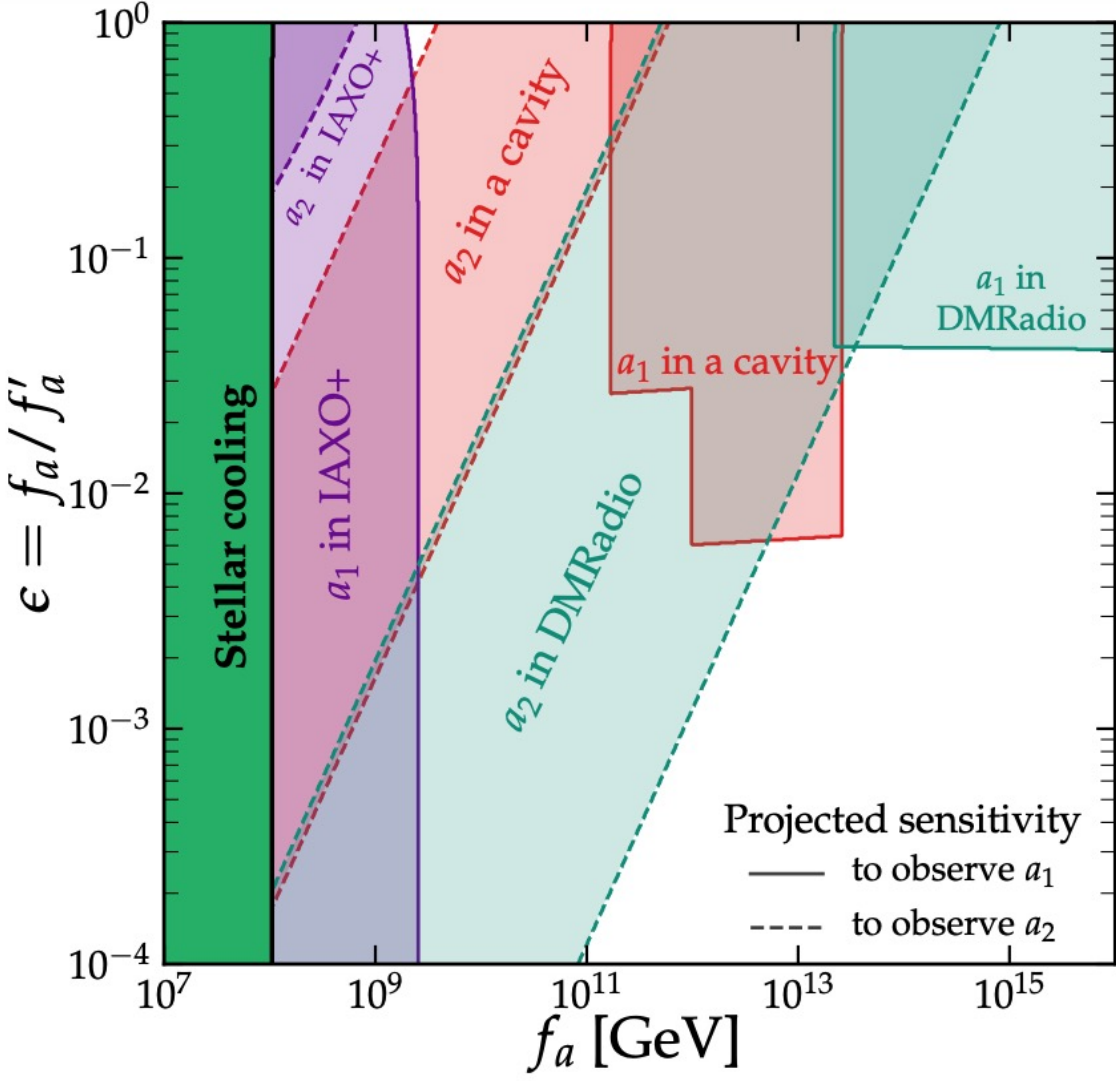
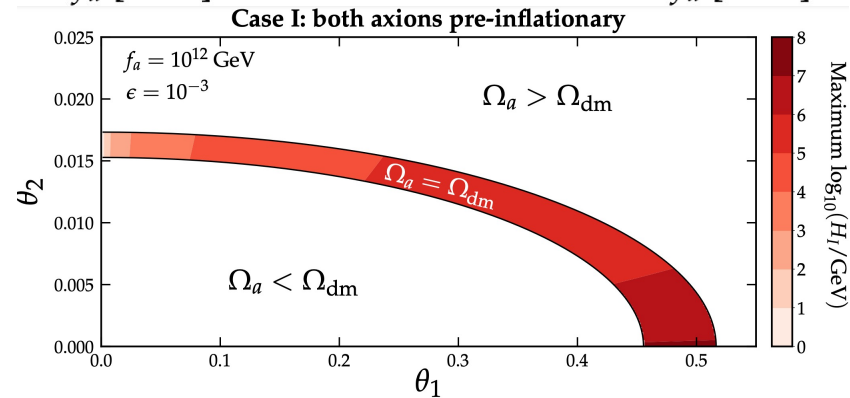
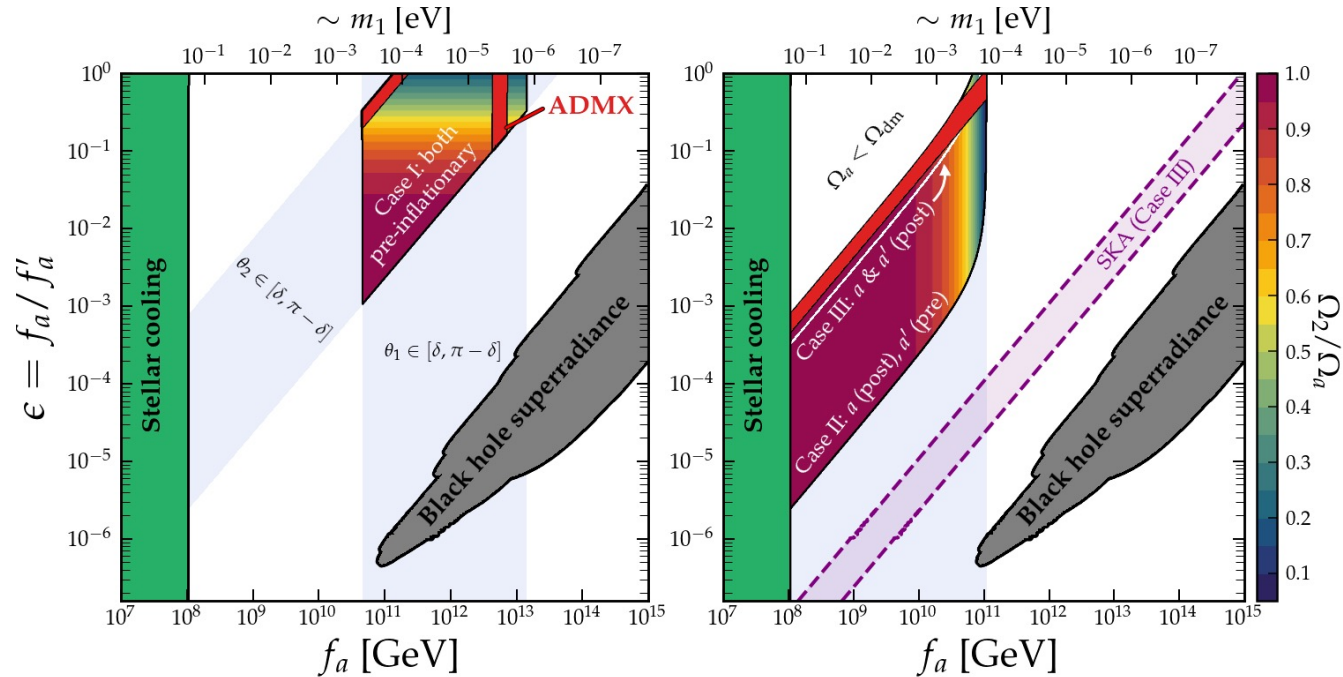


FIG. 2. **Left:** Current bounds on the companion-axion model. The colorscale corresponds to the value of the lighter axion’s mass, whereas the heavier axion’s mass is shown (roughly) by the upper horizontal axis. We can rule out parts of this parameter space using stellar cooling arguments, ADMX, and black hole superradiance. **Right:** As in the left-hand panel, but now showing projected constraints from future experiments: MADMAX [58], IAXO [59] and DMRadio/ABRACADABRA [60, 61].

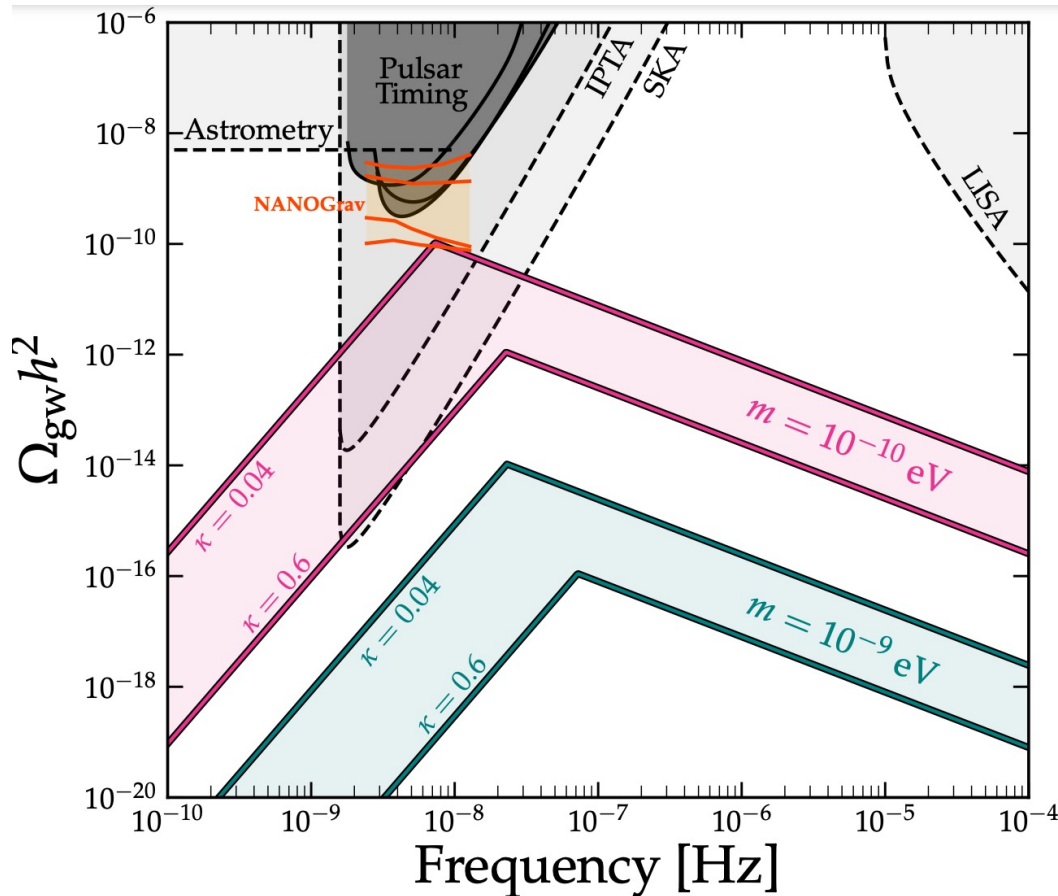
# Companion axion model: bounds and projections



# Companion axion dark matter [[2110.11014](https://arxiv.org/abs/2110.11014)]



# Gravitational waves and PBH predictions [[2110.11014](#)]



Collapse of the false vacuum domain walls of the horizon-size lead to black hole formation:

$$M_{\text{PBH}} \sim \frac{\sqrt{3}}{4\sqrt{2}} \frac{M_{\text{P}}^3}{(\pi\kappa K)^{1/2}} \sim 150 M_{\odot} \left(\frac{\kappa}{0.1}\right)^{-1/2}$$

$$p_{\text{coll}} \sim e^{-(T_{\text{ann}}/T_{\text{coll}})^2} \sim 10^{-22} - 10^{-9}$$

$$f_{\text{PBH}} = \frac{\rho_{\text{PBH}}}{\rho_{\text{dm}}} \simeq 34.9 p_{\text{coll}} \frac{M_{\text{P}}^4}{H_0^2 M_{\text{PBH}}^2} \left(\frac{T_0}{T_{\text{coll}}}\right)^3 \sim 10^{-13} - 1$$

# Conclusions

- Contrary to a widespread belief, (nonperturbative) quantum gravity effects may have significant phenomenological implications in particle physics
- Instanton picture: Gauge-Eguchi-Hanson instantons
  - Spin structure => electric charge quantisation;
  - Extra, unexplored sources of CP violation in the Standard Model;
  - Potential implications in cosmology & elsewhere
- Colored gravitational instantons -> additional companion axion
  - Rich phenomenology with interesting predictions for ongoing and planned axion searches
  - Cosmology – dark matter, nano-Hz gravitational wave signals; LIGO-sized PBHs