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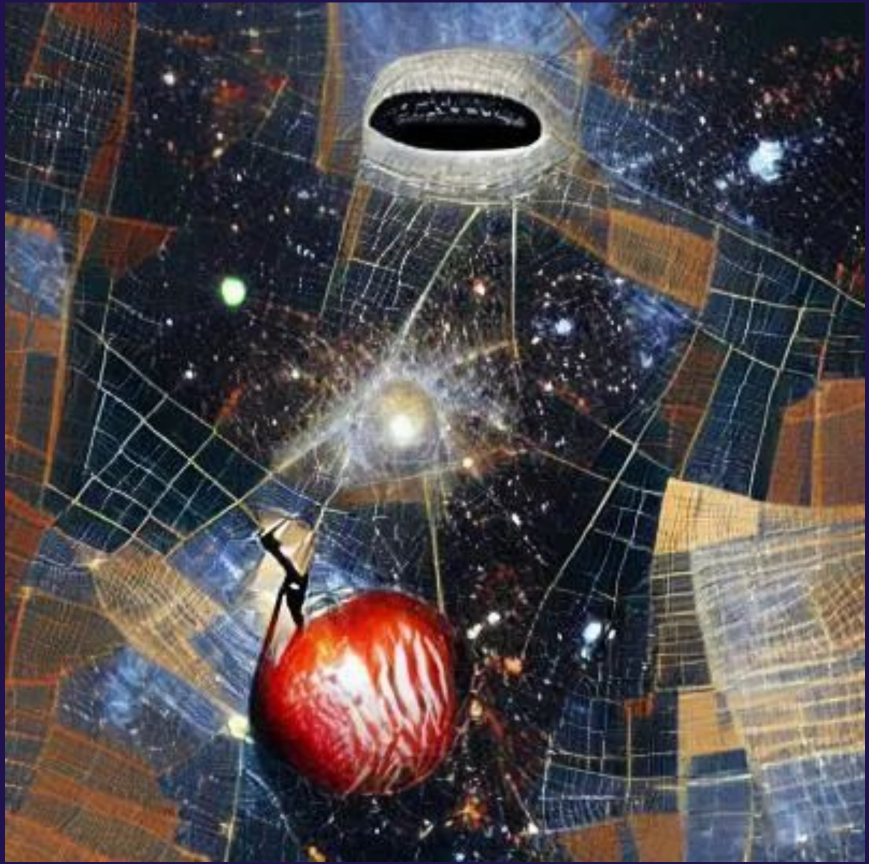
Saving the axion from gravity:
The 'Companion Axion'
and its phenomenology



Zachary Picker

Nov 2021

Axion theory (with gravity…)

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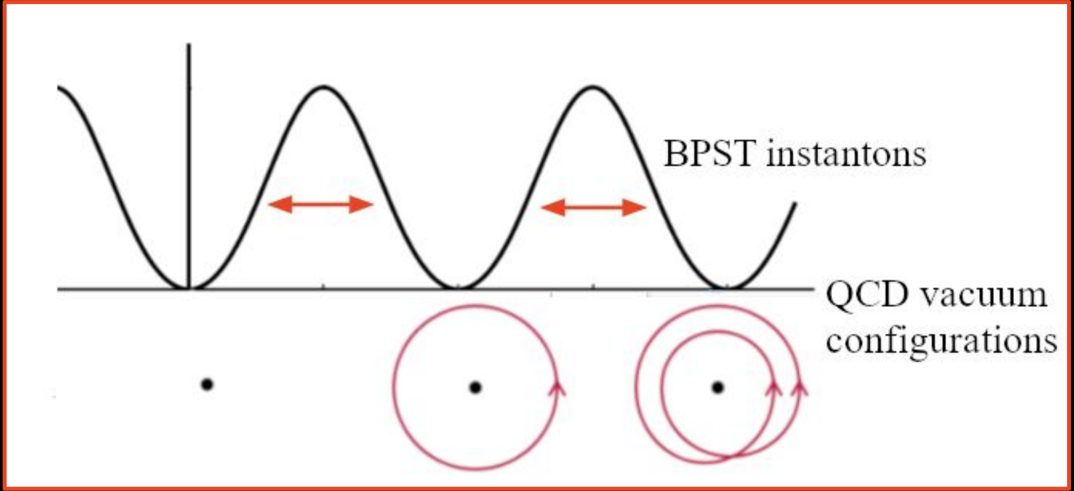
The QCD vacuum *should* have observable effects (eg neutron dipole moment) … but we don't see it



$$\delta\mathcal{L} \propto \theta \, G \cdot \widetilde{G}$$

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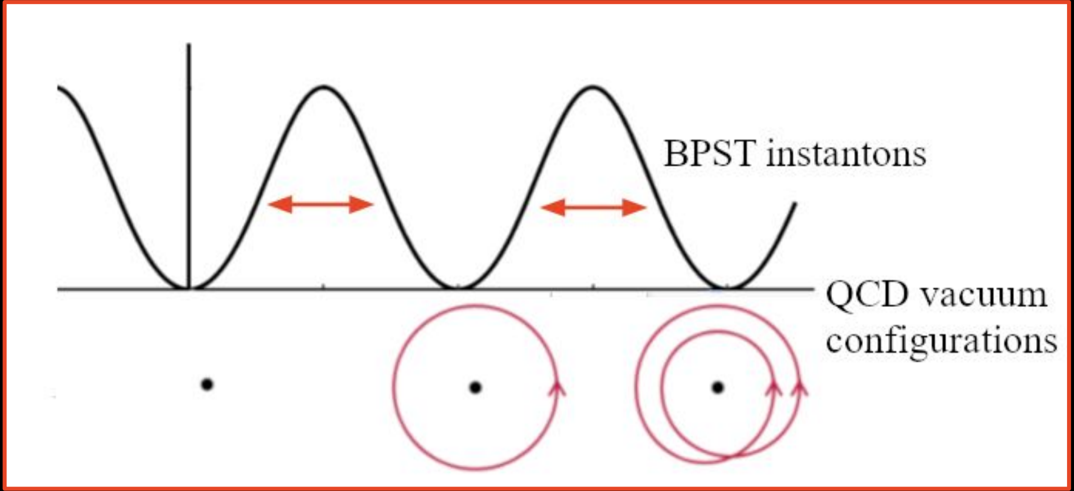
Peccei-Quinn: adding a single 'axion' scalar field can dynamically cancel this term



$$\delta\mathcal{L} \propto \theta\, G \cdot \widetilde{G}$$

$$\delta\mathcal{L} \propto \theta\, G \cdot \widetilde{G} + N \frac{a}{f_a} G \cdot \widetilde{G}$$

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

The combined gravity-QCD background adds a second unrelated term

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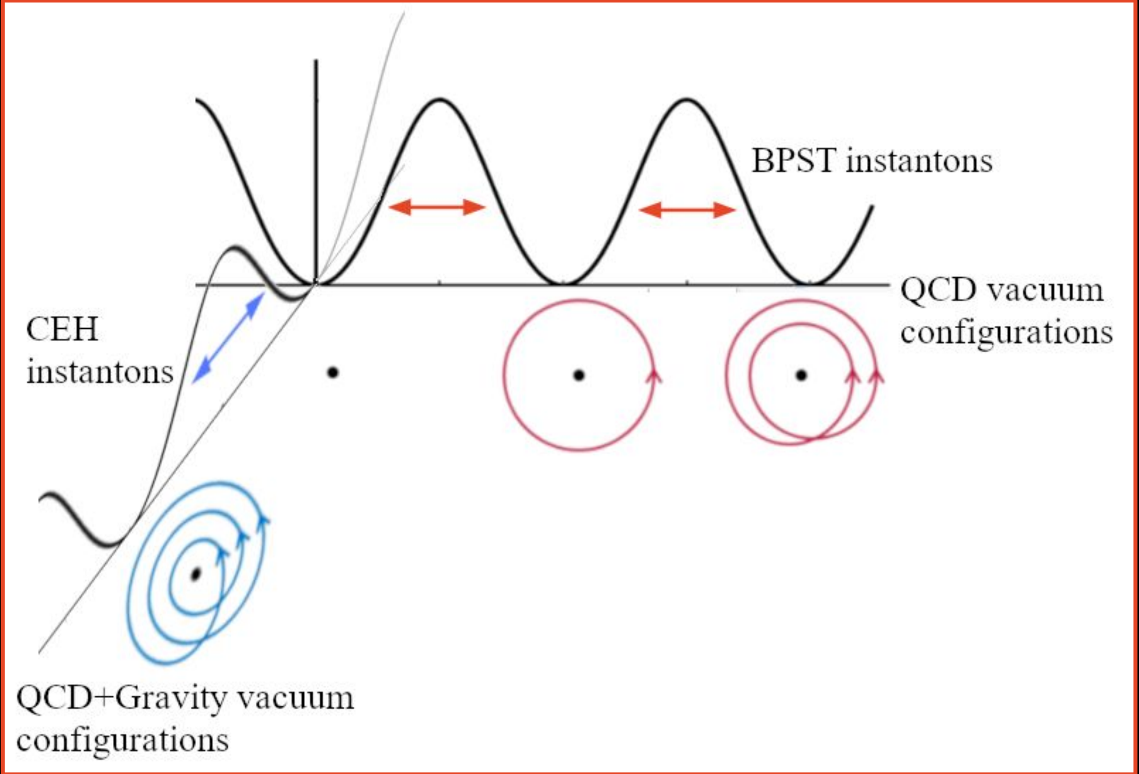

$$\delta\mathcal{L}_{\rm QCD} \propto \theta_{\rm QCD}\; G\cdot\widetilde{G}$$
$$\delta\mathcal{L}_{\rm CEH} \propto \theta_{\rm CEH}\; R\cdot\widetilde{R}$$

arXiv:2108.05549, Chen, Kobakhidze

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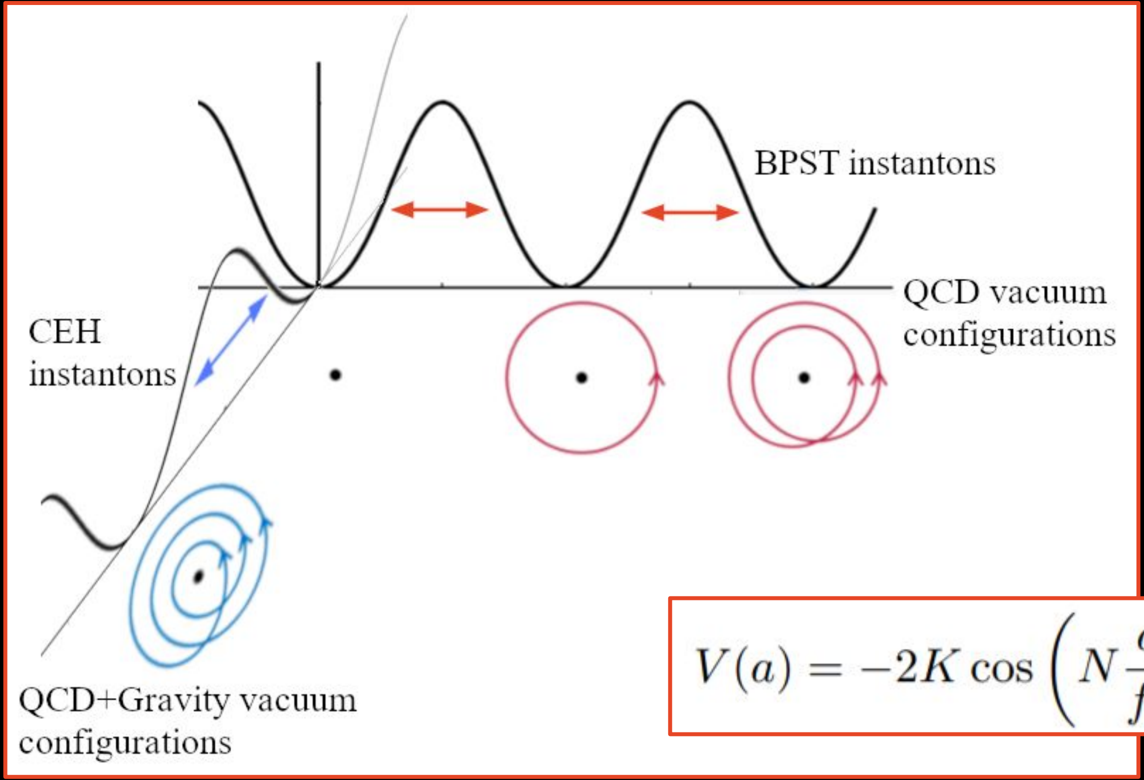
One axion cannot cancel both terms...



$$\delta\mathcal{L}_{\rm QCD} \propto \theta_{\rm QCD}\; G\cdot\widetilde{G}$$
$$\delta\mathcal{L}_{\rm CEH} \propto \theta_{\rm CEH}\; R\cdot\widetilde{R}$$

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

~ 0.04 — 0.6

arXiv:2108.05549, Chen, Kobakhidze

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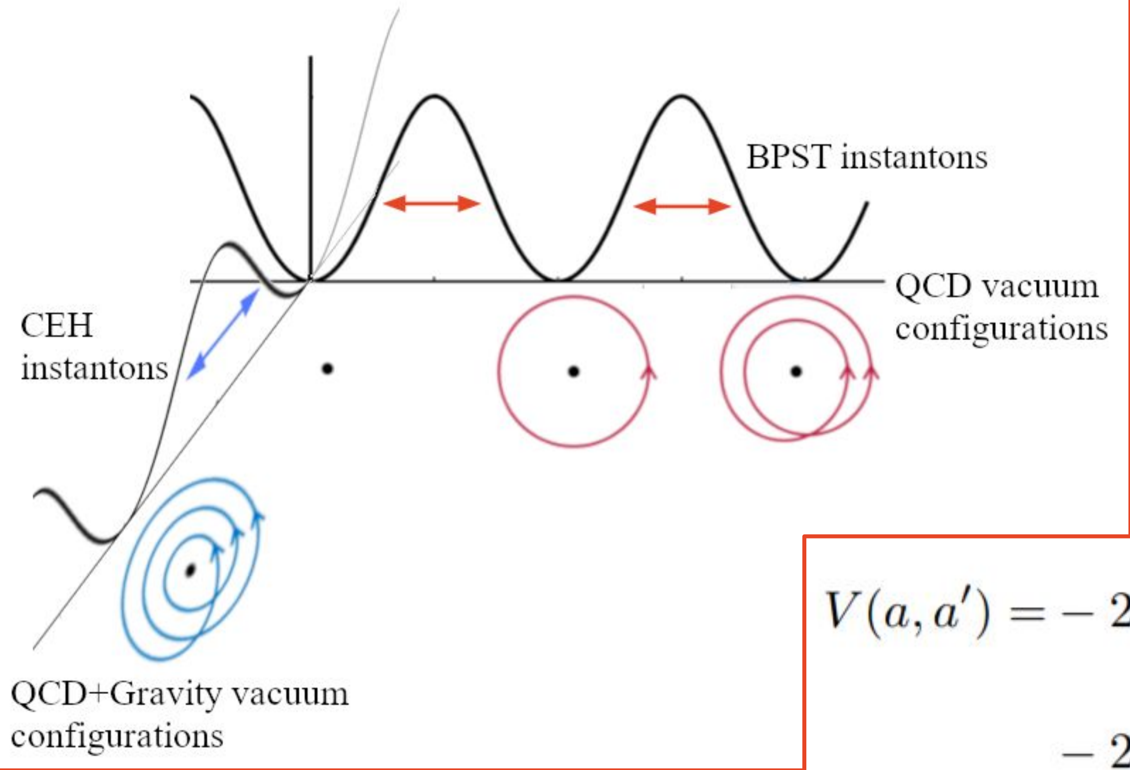
The simplest solution:
A *second* ‘companion’ axion



arXiv:2108.05549, Chen, Kobakhidze

$$\delta\mathcal{L}_{\text{QCD}} \propto \theta_{\text{QCD}}\ G\cdot\widetilde{G}$$
$$\delta\mathcal{L}_{\text{CEH}} \propto \theta_{\text{CEH}}\ R\cdot\widetilde{R}$$

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

Companion axion phenomenology

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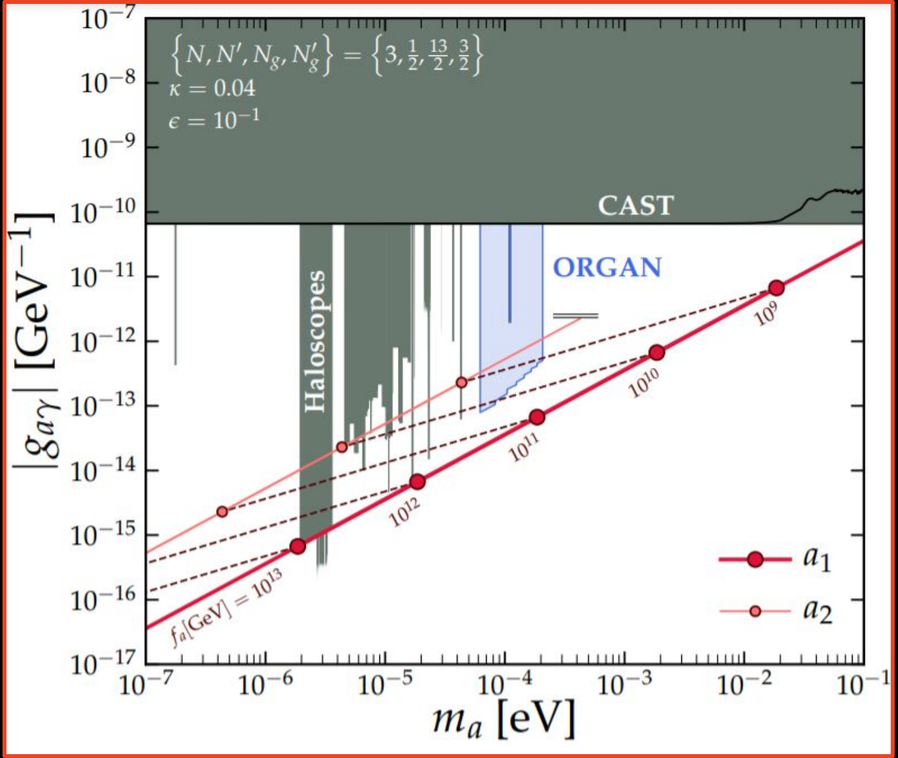
One axion is roughly the 'usual' mass, while the second is smaller



Masses:

$$m_1 \propto 1/f_a$$

$$m_2 \approx \epsilon \sqrt{\kappa}\, m_1$$
$$\epsilon \equiv f_a/f'_a$$

Photon couplings:

$$\mathcal{L}_{a\gamma} = \frac{1}{4}\left(a g_{a\gamma} + a' g'_{a\gamma}\right) F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$g_{a\gamma} = g'_{a\gamma}\frac{f'_a}{f_a}\frac{N}{N'} = -\frac{\alpha_{\rm em} N}{2\pi f_a}\zeta,$$

$$\zeta = \frac{2}{3}\frac{4m_d + m_u}{m_u + m_d}$$

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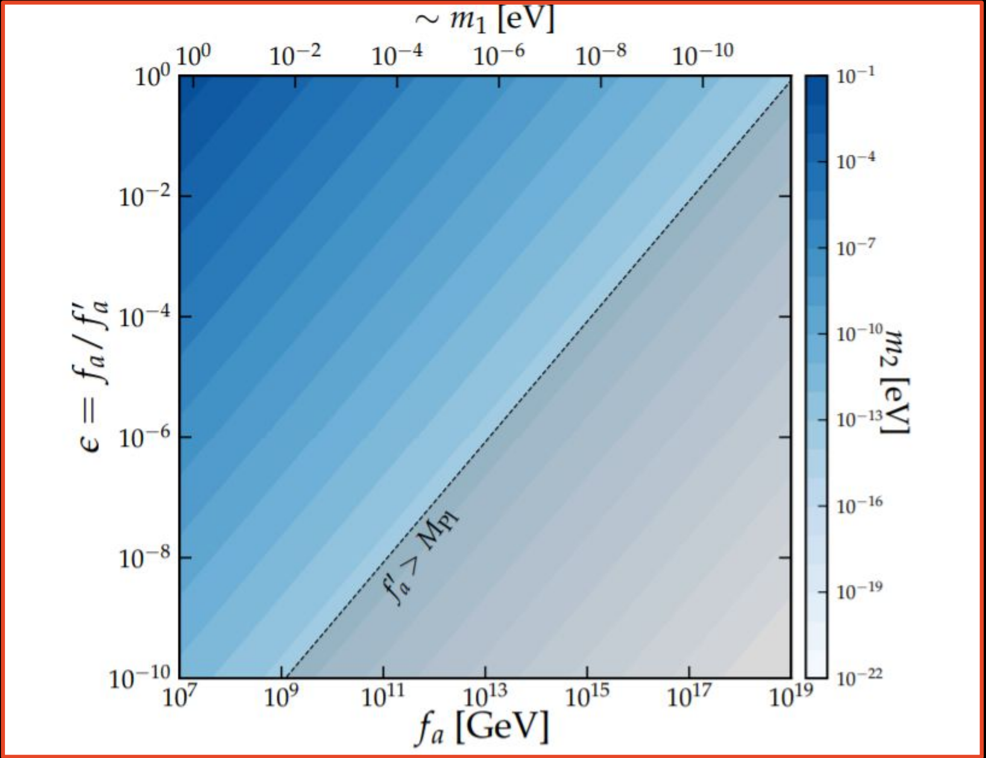
Solving this new Strong-CP problem couples the axions, forming a ‘QCD *area*’



$$m_1 \propto 1/f_a$$

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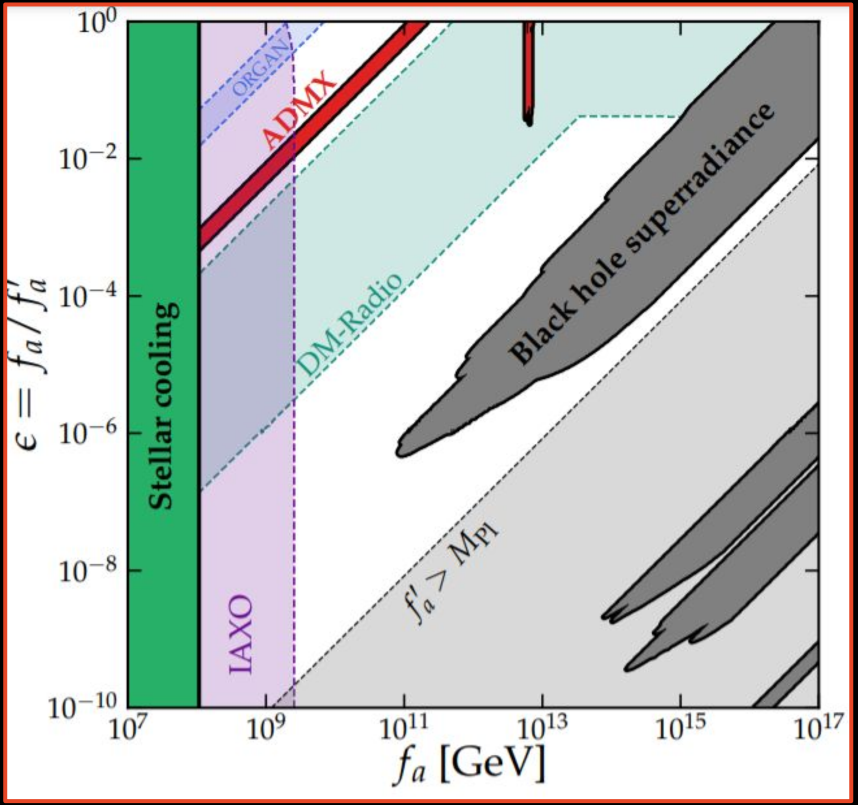
We can recast axion experimental constraints for axion-photon coupling to our area



arXiv:2109.12920, Chen, Kobakhidze, O’Hare, Picker, Pierobon

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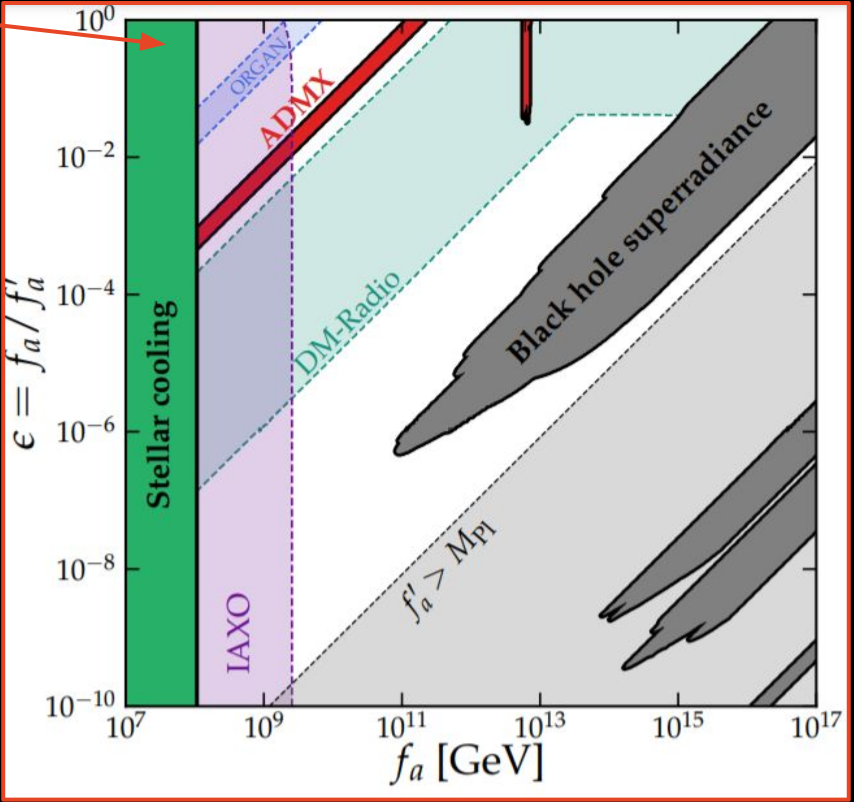
We can recast axion experimental constraints for axion-photon coupling to our area

– Axion production cools stars



arXiv:2109.12920, Chen, Kobakhidze, O'Hare, Picker, Pierobon

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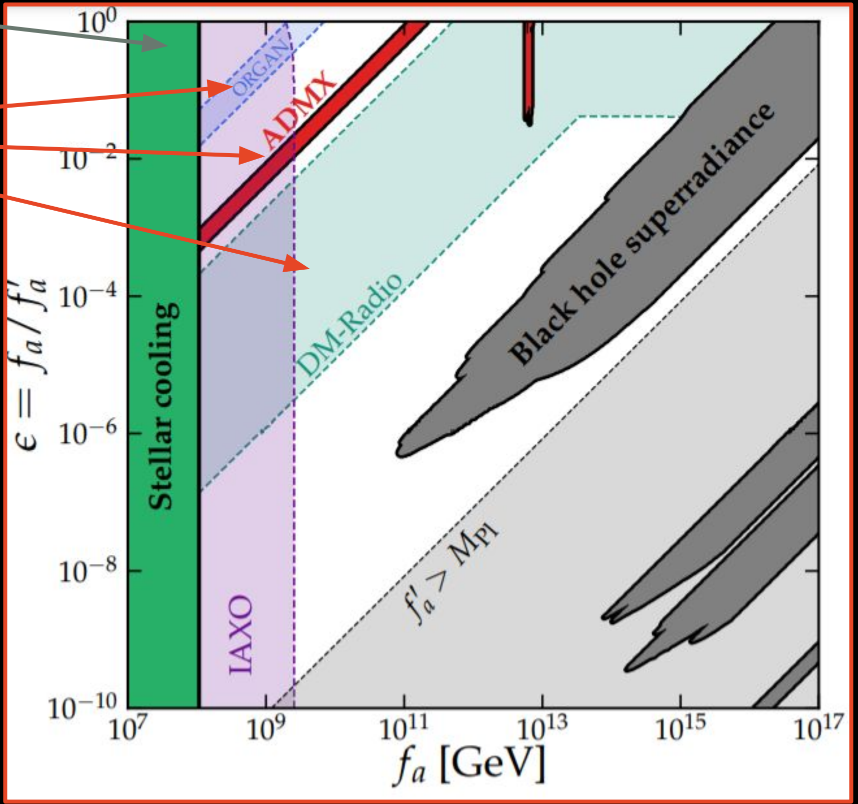
We can recast axion experimental constraints for axion-photon coupling to our case

– Axion production cools stars

– Haloscopes: detect axions in dark matter halo using resonant cavity



arXiv:2109.12920, Chen, Kobakhidze, O'Hare, Picker, Pierobon

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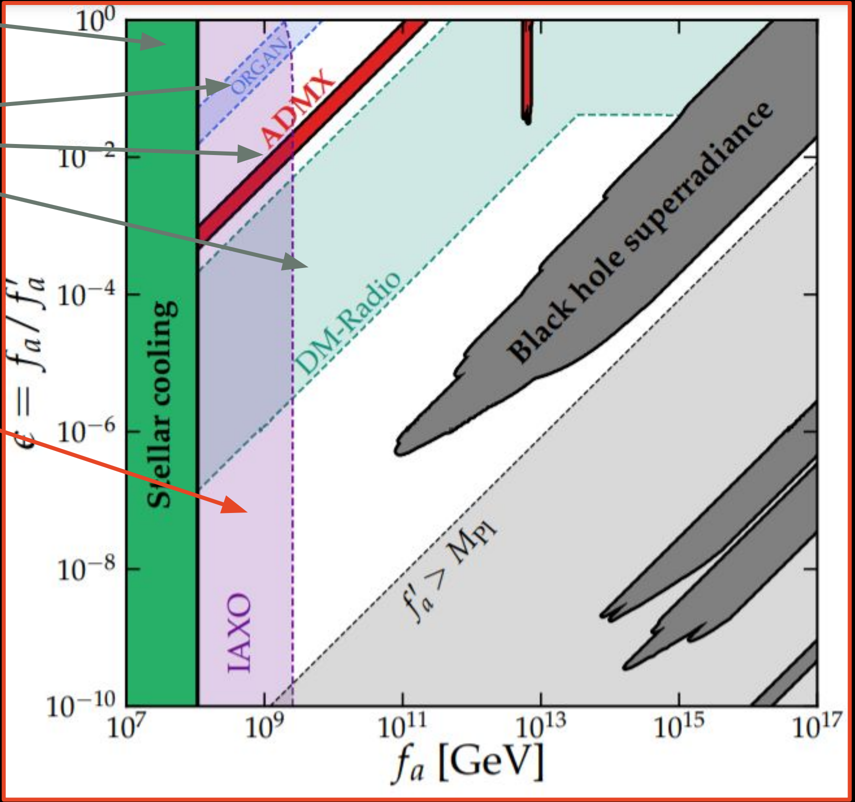
We can recast axion experimental constraints for axion-photon coupling to our case

- Axion production cools stars
- Haloscopes: detect axions in dark matter halo using resonant cavity
- Helioscopes: detect stellar axions by converting back to photons



arXiv:2109.12920, Chen, Kobakhidze, O'Hare, Picker, Pierobon

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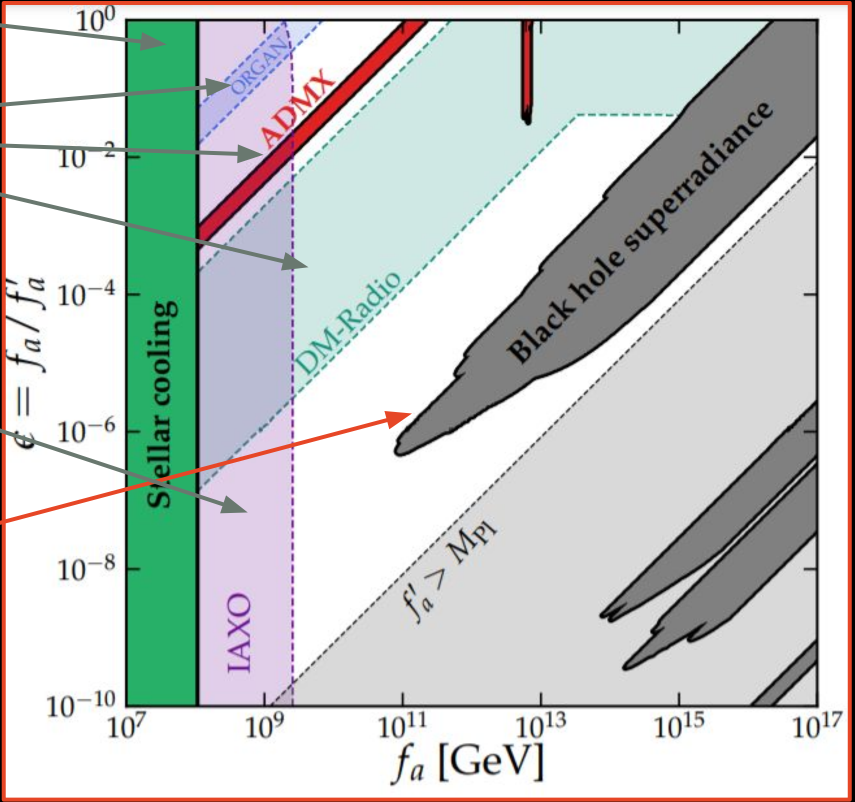
We can recast axion experimental constraints for axion-photon coupling to our case

- Axion production cools stars
- Haloscopes: detect axions in dark matter halo using resonant cavity
- Helioscopes: detect stellar axions by converting back to photons
- Spin down black holes



arXiv:2109.12920, Chen, Kobakhidze, O'Hare, Picker, Pierobon

Companion axion dark matter, using the misalignment mechanism

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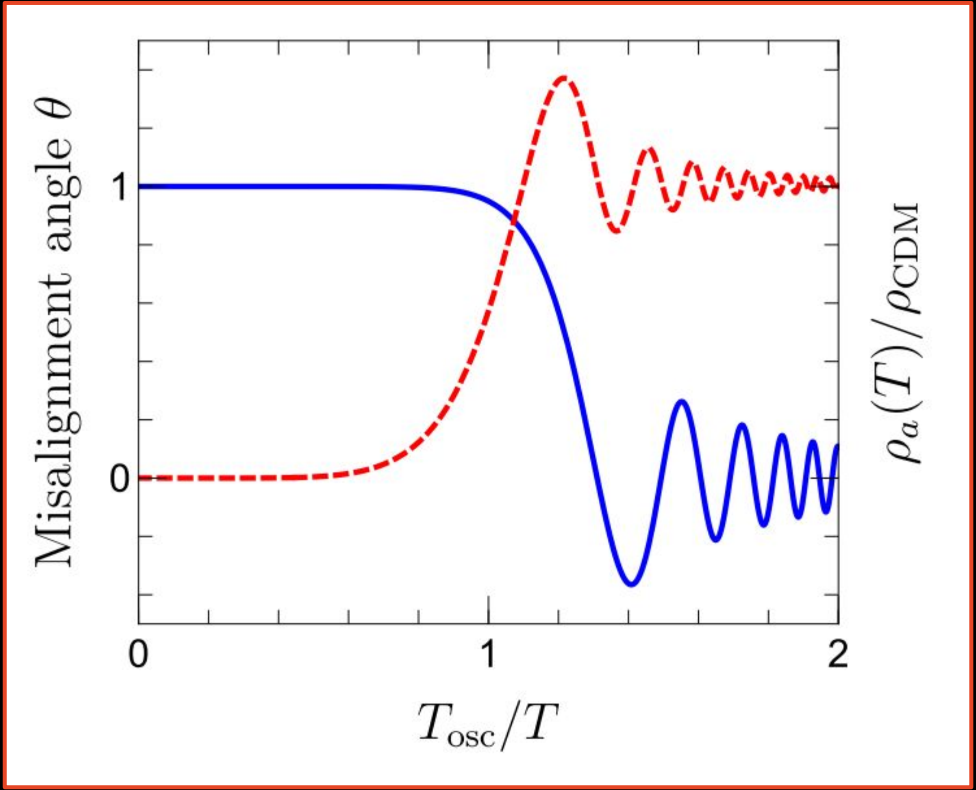

Luzio et al 2020

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Companion axion dark matter, using the misalignment mechanism

Scenarios:

I. Both symmetries break before inflation

Both initial misalignment angles are random

II. One symmetry breaks before inflation

One angle random, second angle is average ($\pi/\sqrt{3}$)

III. Both symmetries break after inflation

Both angles averaged

Dark matter parameter space without fine-tuning, for case I

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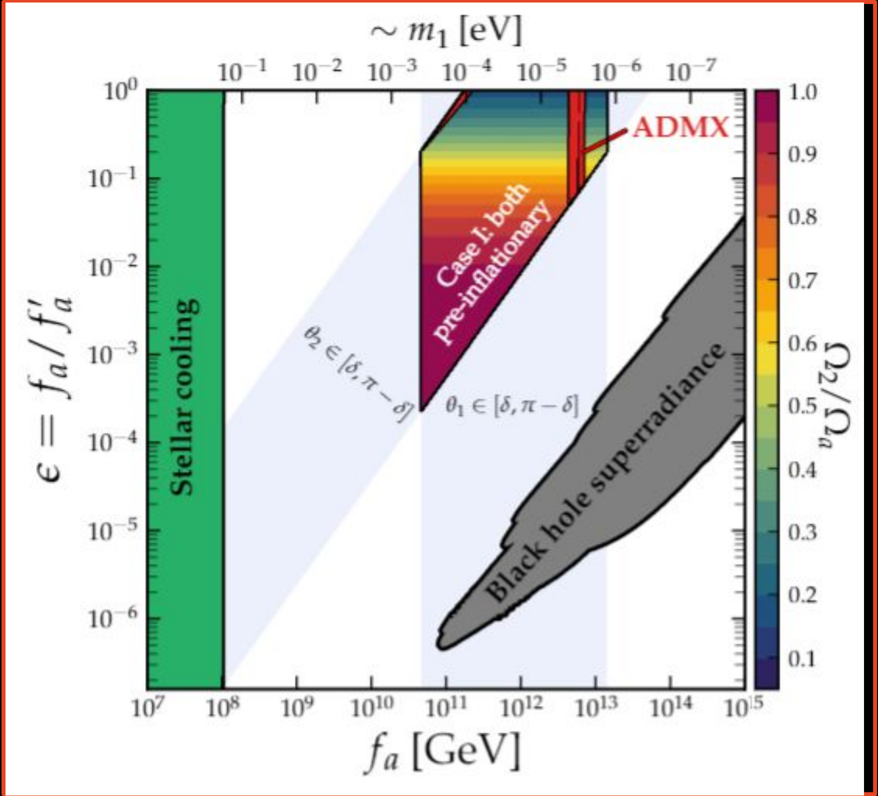

Coupled oscillation equations:

$$\partial_t^2 a + \frac{3}{2t}\partial_t a + M_{11} a + M_{12} a' = 0\,,$$
$$\partial_t^2 a' + \frac{3}{2t}\partial_t a' + M_{22} a' + M_{21} a = 0$$

Relative densities:

$$\frac{\Omega_{a_2}}{\Omega_{a_1}} \sim \frac{\theta_2^2}{\theta_1^2}\kappa^{0.41}\epsilon^{-1.19}$$

Dark matter parameter space without fine-tuning, cases II and III

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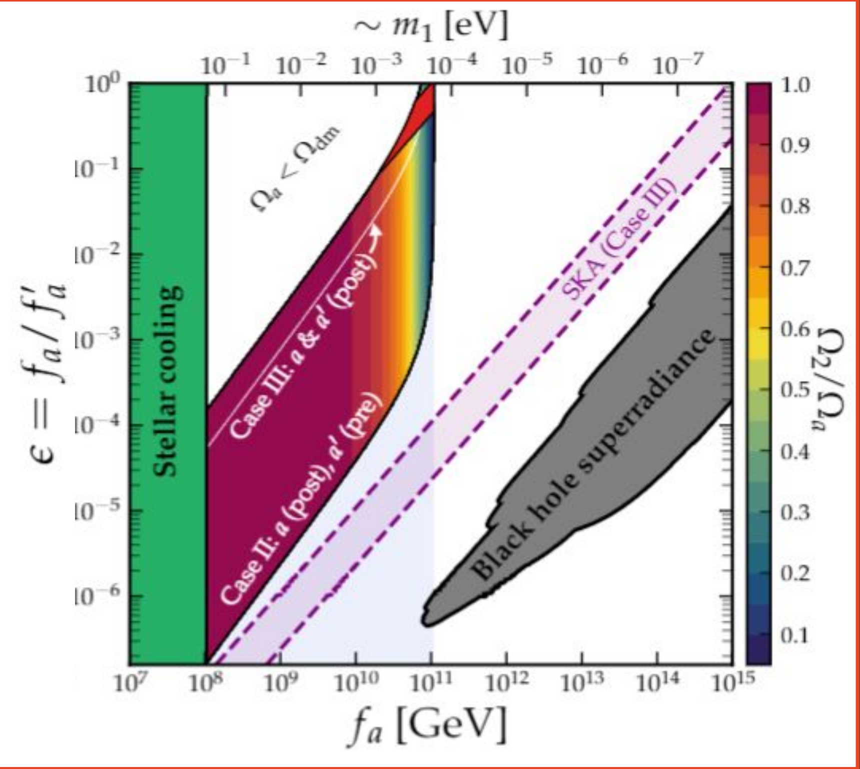

Coupled oscillation equations:

$$\partial_t^2 a + \frac{3}{2t}\partial_t a + M_{11}a + M_{12}a' = 0\,,$$
$$\partial_t^2 a' + \frac{3}{2t}\partial_t a' + M_{22}a' + M_{21}a = 0$$

Relative densities:

$$\frac{\Omega_{a_2}}{\Omega_{a_1}} \sim \frac{\theta_2^2}{\theta_1^2}\kappa^{0.41}\epsilon^{-1.19}$$

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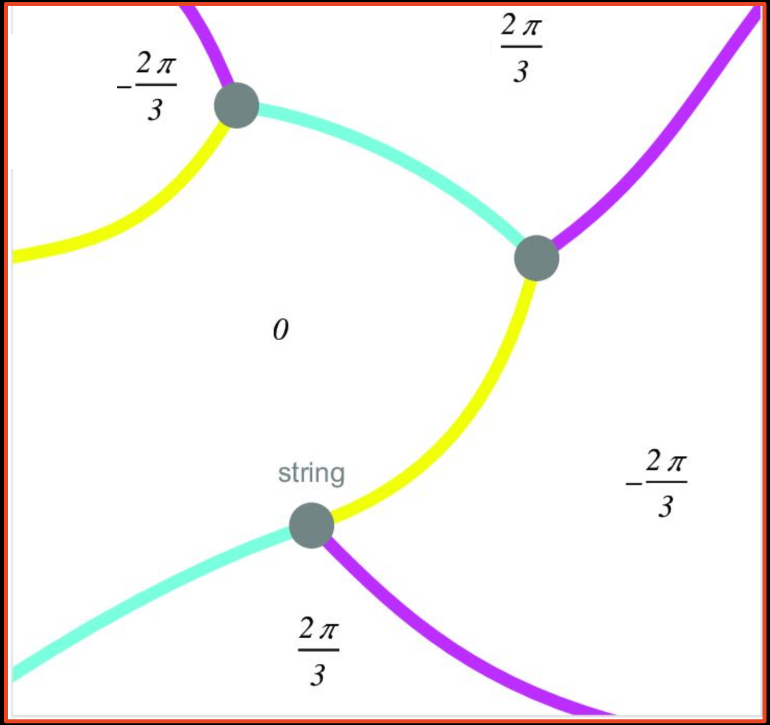
Companion axions can solve the 'domain wall problem'



- Each axion leaves a (different) discrete symmetry
- Energy difference ⇒ bias term preventing DWs

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

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The companion axion, in summary

- Single axion needs to be saved from gravity
  - Second, ‘companion’ axion rescues us
- Already some constraints, including novel effects, from photon coupling
- Rich and weird early universe behavior
  - Dark matter?
- So much more work to be (re)done!

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Thanks!

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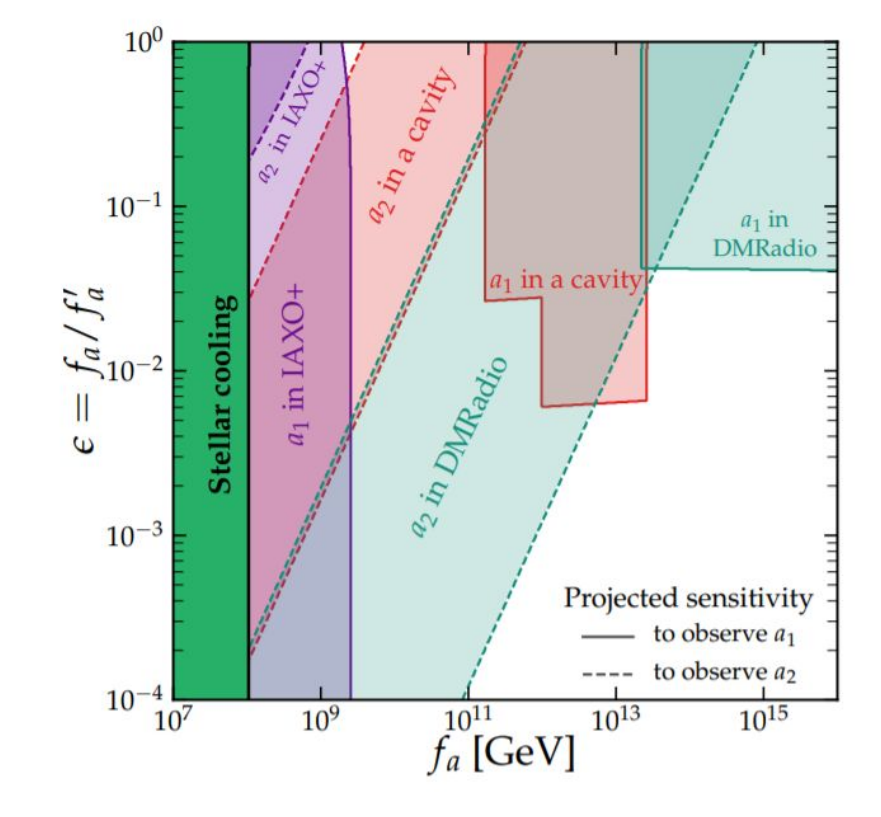
Bonus: unique/overlapping signals



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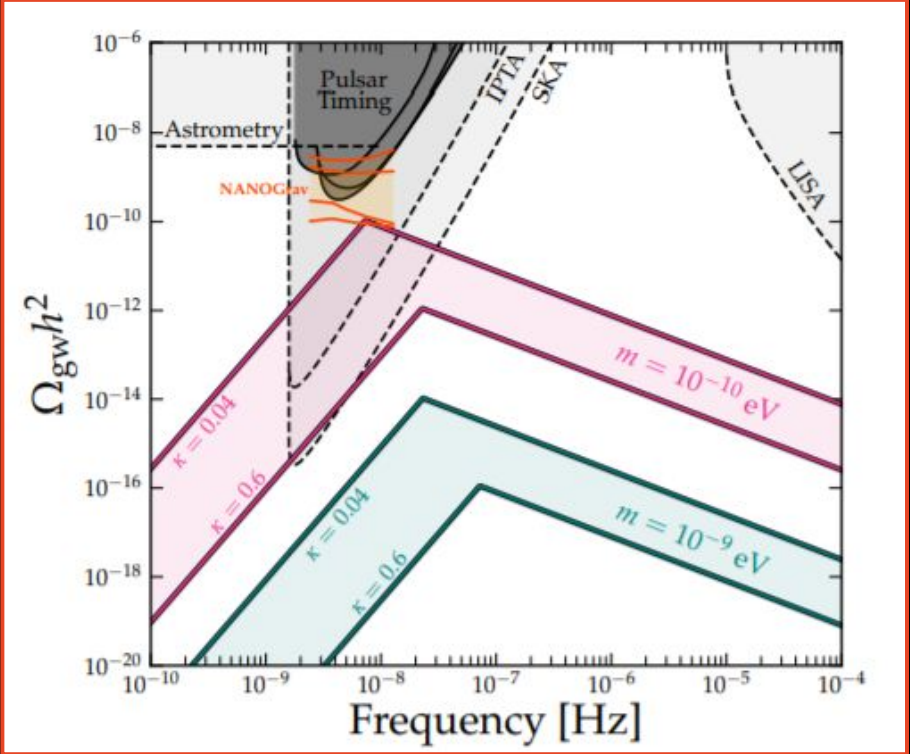
Bonus: domain walls in $10^{-10}\ \text{eV} \lesssim m_i \lesssim 10^{-9}\ \text{eV}$



- Lower bound: domain wall thickness ~ universe size
- Upper bound: bias term prevents DW formation
- Collapse: GWs and PBHs:

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

- Nb...too much dark matter in this regime!

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Bonus: companion axion details

Mass basis mixing angle:

$$\tan 2\alpha = \frac{2\epsilon(NN' + \kappa N_g N_g')}{(N^2 + \kappa N_g^2) - \epsilon^2(N'^2 + \kappa N_g'^2)}$$

Axion masses:

$$m_1^2 = \frac{\Delta m^2}{2} + \frac{K}{f_a^2}\Big((N^2 + \kappa N_g^2) + \epsilon^2(N^2 + \kappa N_g^2)\Big),$$

$$\Delta m^2 = \frac{2K}{f_a^2}\Big[4(NN' + \kappa N_g N_g')^2\epsilon^2 + \Big((N^2 + \kappa N_g^2) - \epsilon^2(N'^2 + \kappa N_g'^2)\Big)^2\Big]^{1/2}$$

Mass basis photon couplings:

$$g_1 = \frac{\alpha_{\rm em}\zeta}{2\pi f_a}(N\cos\alpha - \epsilon N'\sin\alpha)$$

$$g_2 = \frac{\alpha_{\rm em}\zeta}{2\pi f_a}(N\sin\alpha + \epsilon N'\cos\alpha)$$

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Bonus: more random bits

The mass matrix in this limit is,

$$M = m_1^2(T) \begin{pmatrix} 1 & -\epsilon^2 \\ -\epsilon^2 & \kappa\epsilon^2 \end{pmatrix} + \mathcal{O}(\epsilon^4) \tag{5}$$

where for the heavier mass we have adopted the standard thermal axion mass calculation from [19],

$$m_1^2(T) = \min\left[m_1^2, m_1^2\left(\frac{\widetilde{T}}{T}\right)^n\right], \tag{6}$$

with $n = 6.68$ and $\widetilde{T} = 103\,\mathrm{MeV}$ [19].