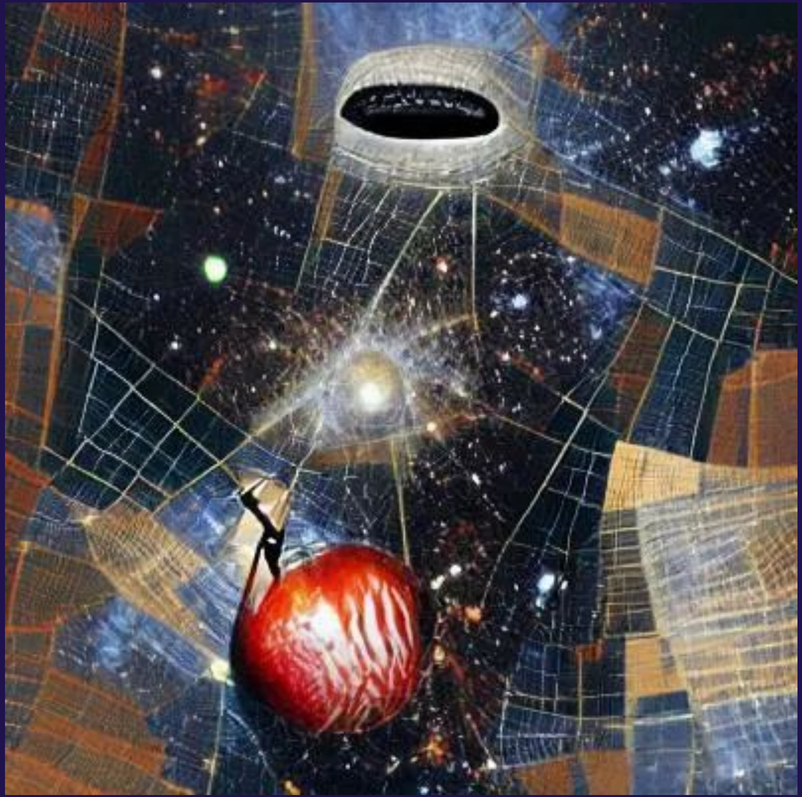
The 'Companion Axion': Solving the Strong-Gravity-CP problem



Zachary S. C. Picker

AstroDark 2021

With: Zhe Chen, Archil Kobakhidze,
Ciaran O'Hare, and Giovanni Pierobon (UNSW)

Adding gravity to the axion

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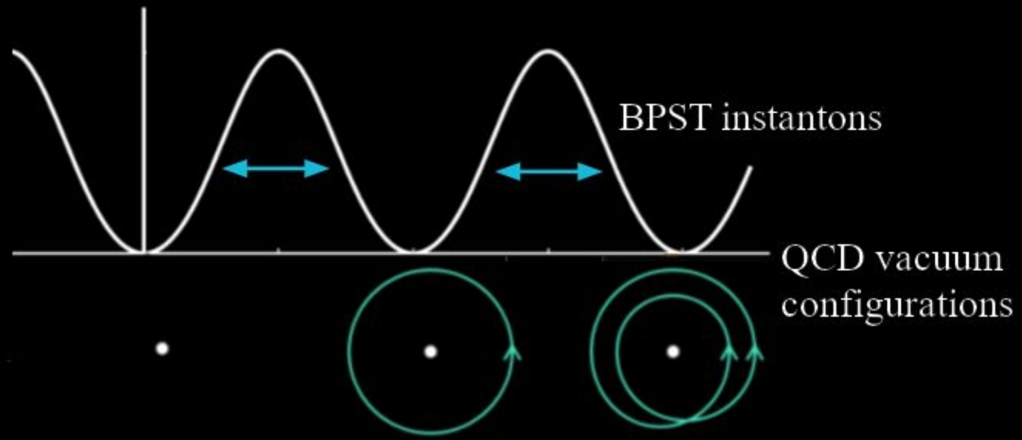
The QCD vacuum *should* lead to CP-violating terms for the strong force



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

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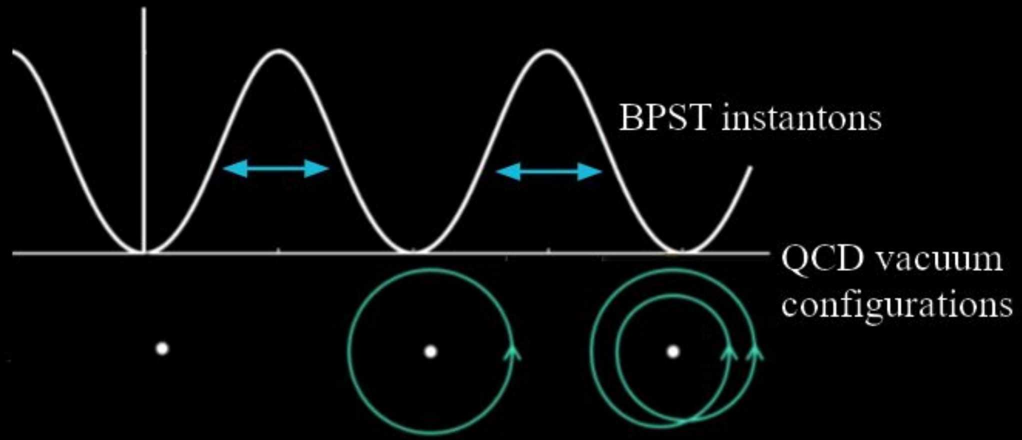
Peccei-Quinn: adding a single 'axion' scalar field can dynamically cancel this term



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

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

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

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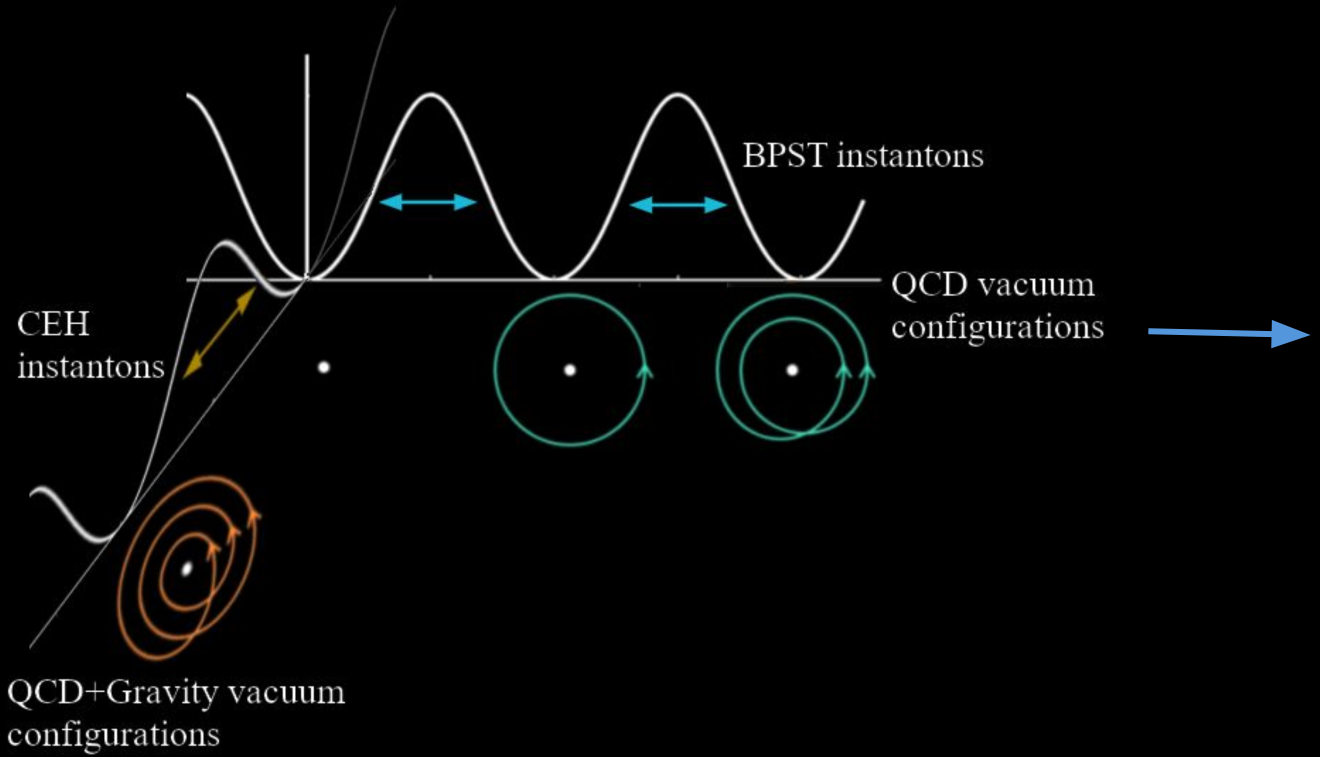
The combined gravity-QCD background adds a second unrelated term



$$\delta\mathcal{L}_{\mathrm{QCD}} \propto \theta_{\mathrm{QCD}}\ G\cdot\widetilde{G}$$

$$\delta\mathcal{L}_{\mathrm{CEH}} \propto \theta_{\mathrm{CEH}}\ R\cdot\widetilde{R}$$

arXiv:2108.05549, Chen, Kobakhidze

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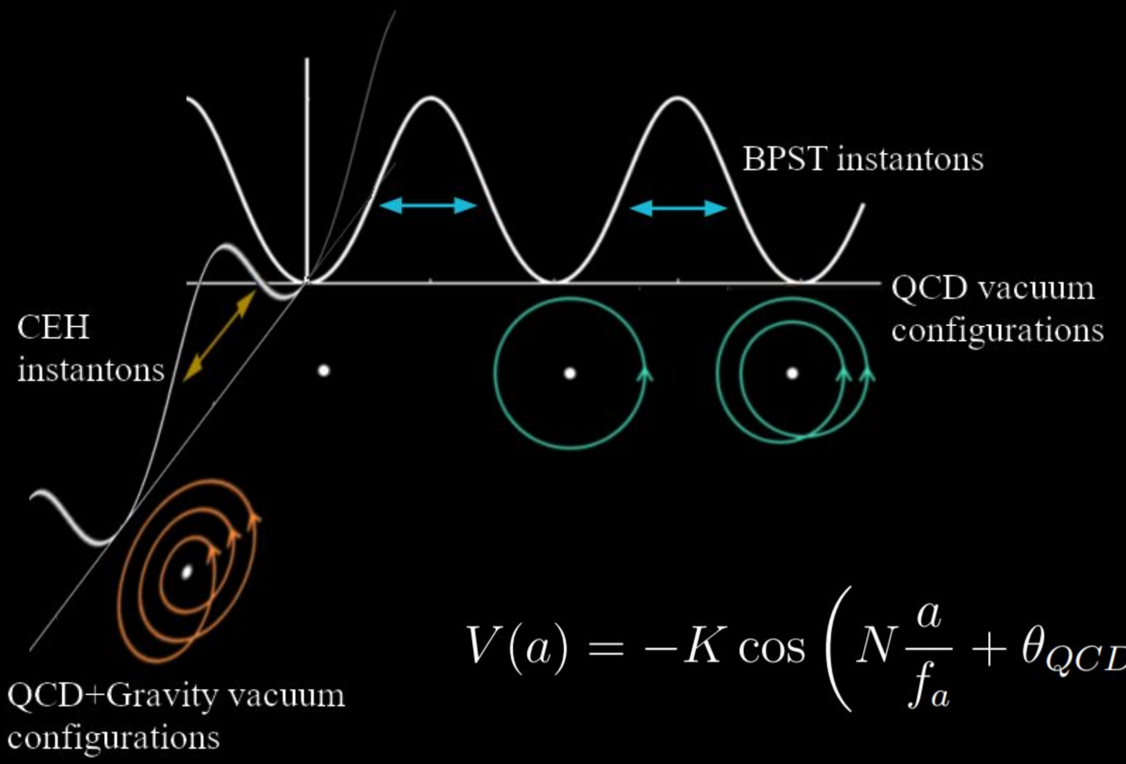
One axion cannot cancel both terms...



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

$$V(a) = -K\cos\left(N\frac{a}{f_a} + \theta_{QCD}\right) - \kappa K\cos\left(N_g\frac{a}{f_a} + \theta_{CEH}\right)$$

$\kappa \approx 0.04 — 0.6$

arXiv:2108.05549, Chen, Kobakhidze

The simplest solution:
a second, coupled, 'companion' axion

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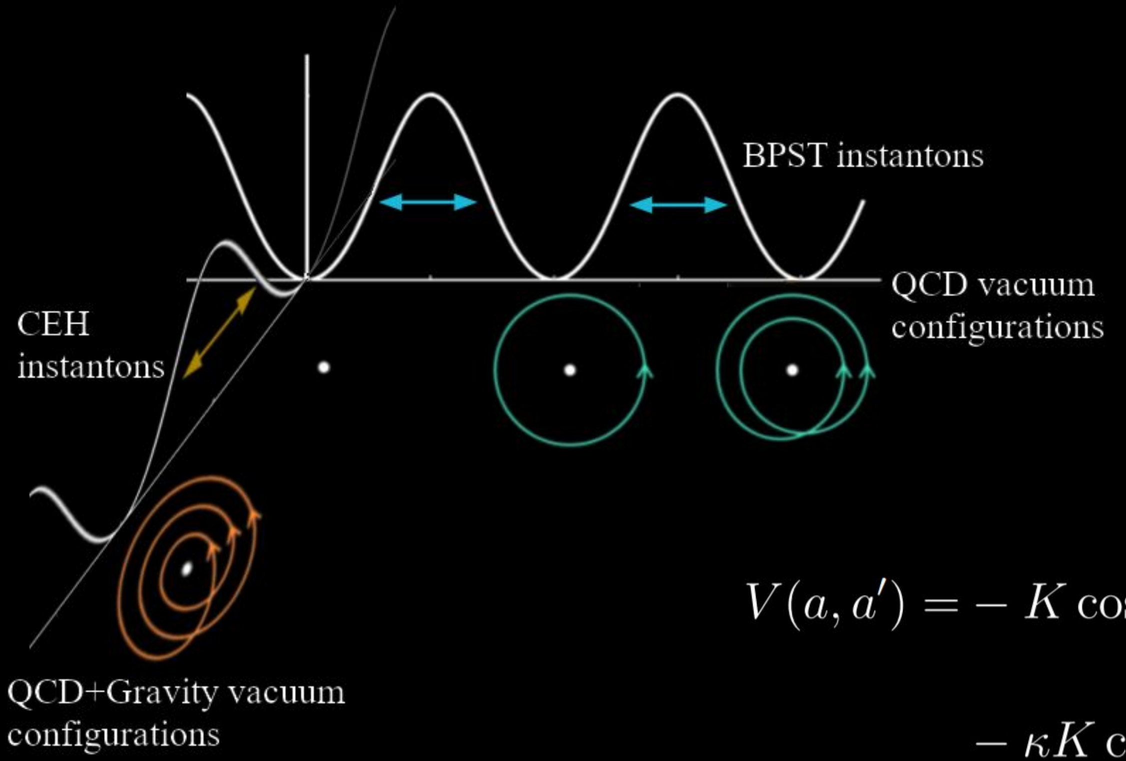

$$\delta\mathcal{L}_{\rm QCD} \propto \theta_{\rm QCD}\; G\cdot\widetilde{G}$$

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

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

arXiv:2108.05549, Chen, Kobakhidze

This work was done by my collaborators (worth checking out, if you love maths)

Coloured gravitational instantons, the strong CP problem and the companion axion solution.

Zhe Chen* and Archil Kobakhidze†
Sydney Consortium for Particle Physics and Cosmology,
School of Physics, The University of Sydney, NSW 2006, Australia

Quantum gravity introduces a new source of the combined parity (CP) violation in gauge theories. We argue that this new CP violation gets bundled with the strong CP violation through the coloured gravitational instantons. Consequently, the standard axion solution to the strong CP problem is compromised. Further, we argue that the ultimate solution to the strong CP problem must involve at least one additional axion particle.

ArXiv:2108.05549

Companion axion phenomenology

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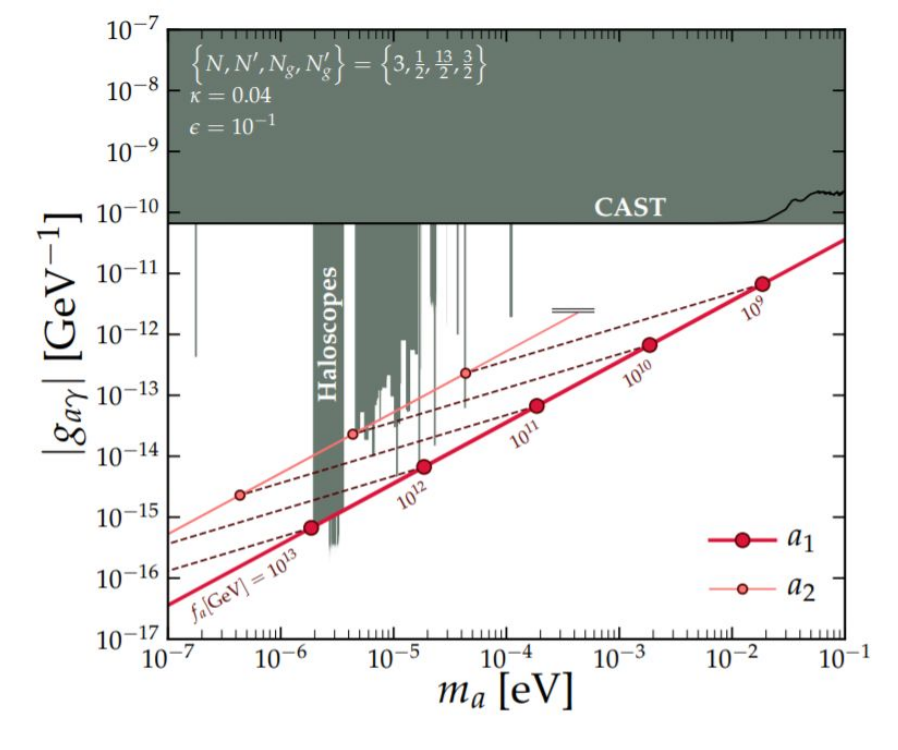
One axion is roughly the ‘usual’ mass, while the second is smaller



Masses:

$$m_1 \propto 1/f_a$$

$$m_2 \approx \epsilon\sqrt{\kappa}\, m_1$$

$$\epsilon \equiv f_a/f'_a$$

Photon couplings:

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

$$g_{a\gamma} = g'_{a\gamma}\frac{f'_a}{f_a}\frac{N}{N'} = -\frac{\alpha_{\rm em} N}{2\pi f_a}\zeta, \quad \zeta = \frac{2}{3}\frac{4m_d + m_u}{m_u + m_d}$$

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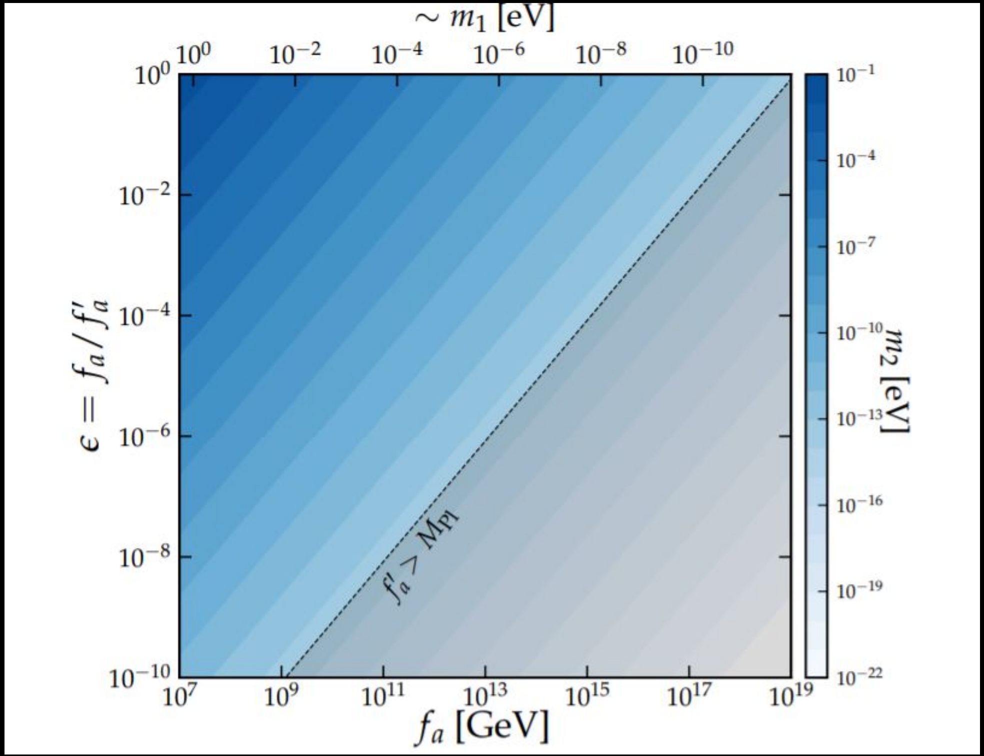
Solving this new Strong-CP problem couples the axions, forming a 'QCD *area*'



$$m_1 \propto 1/f_a$$

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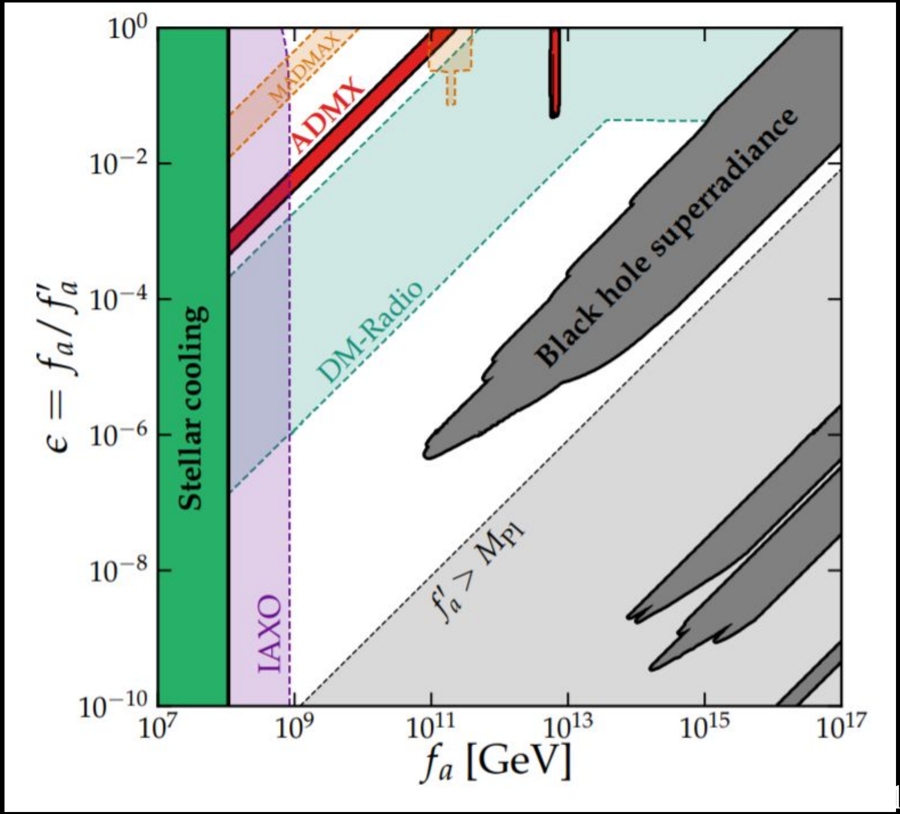
We can recast axion experimental constraints for axion-photon coupling to our area



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

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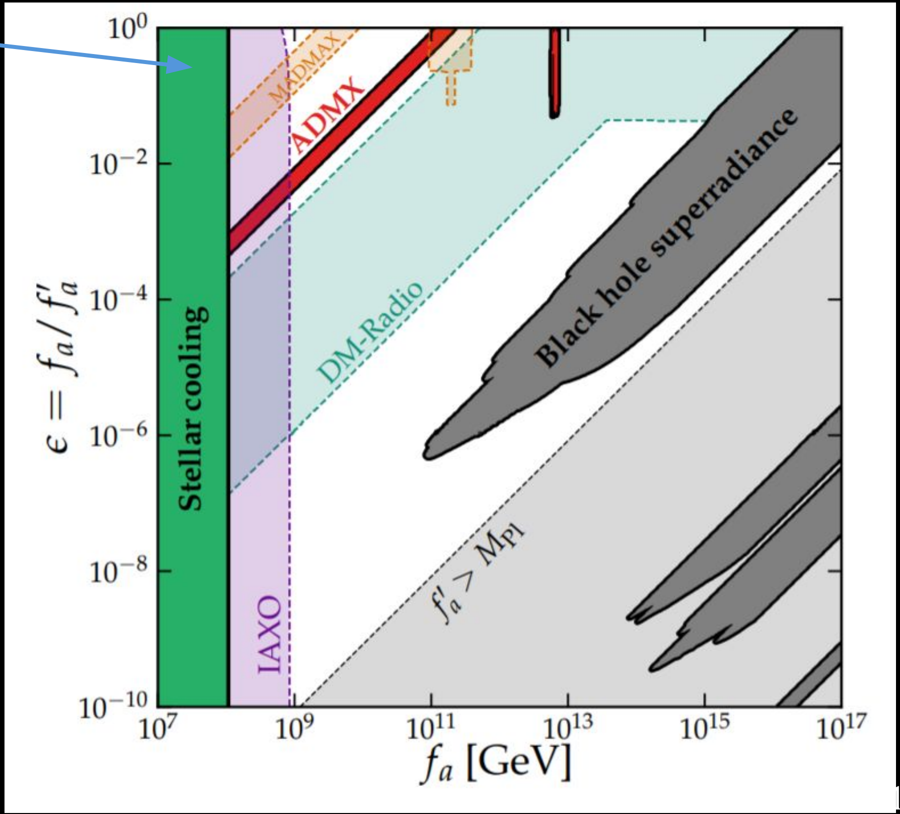
We can recast axion experimental constraints for axion-photon coupling to our area

– Axion production cools stars



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

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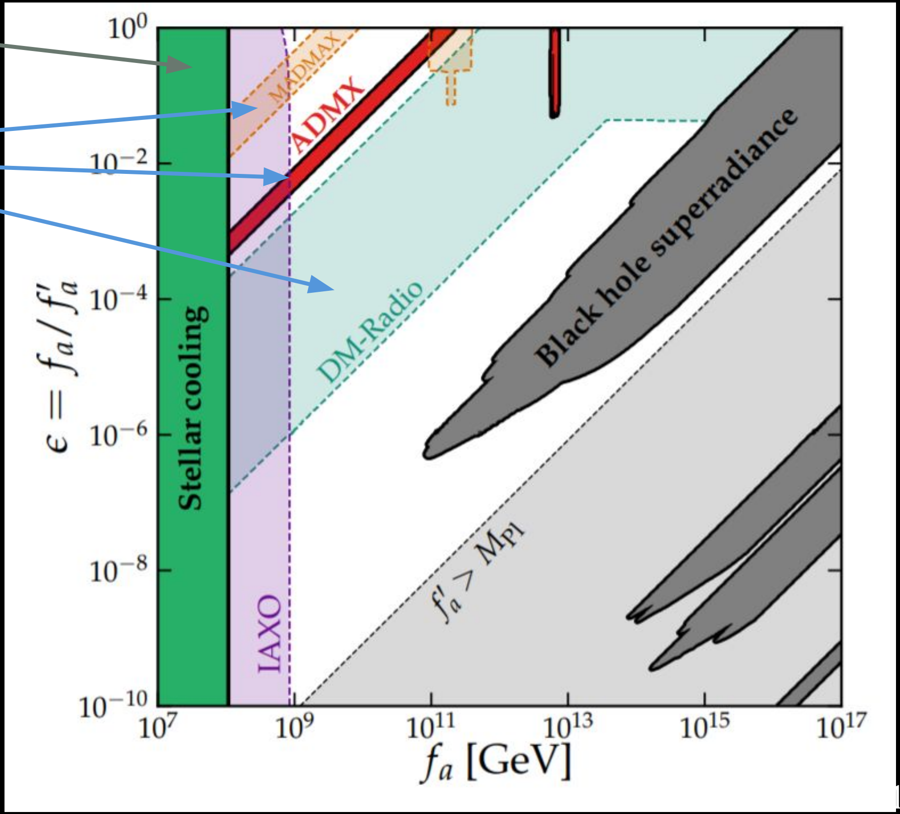
We can recast axion experimental constraints for axion-photon coupling to our case

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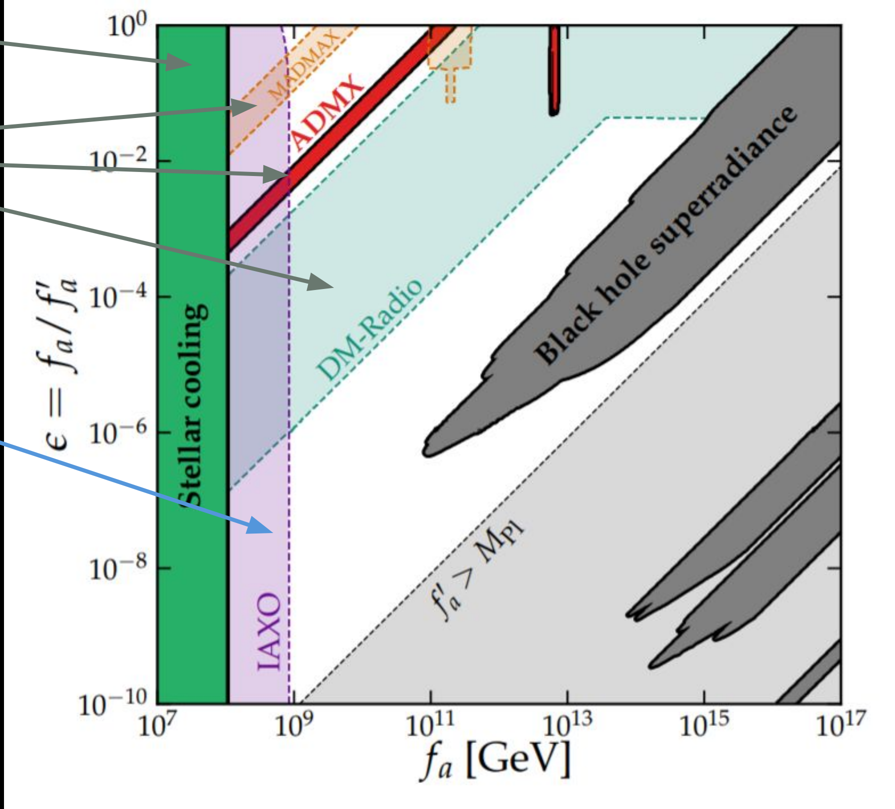
We can recast axion experimental constraints for axion-photon coupling to our case

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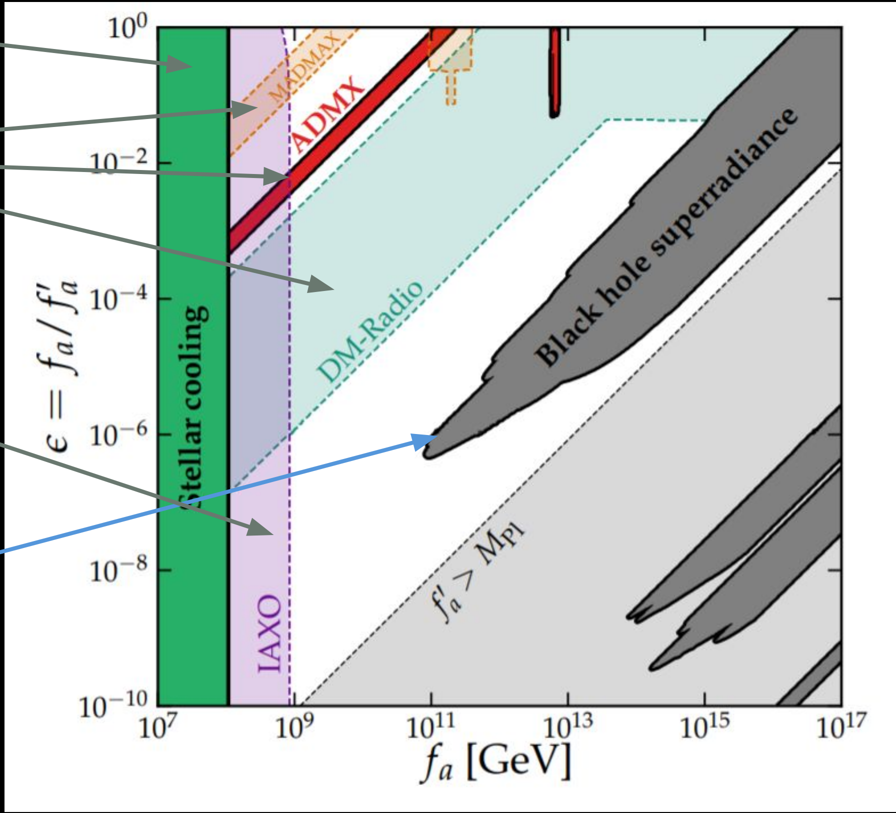
We can recast axion experimental constraints for axion-photon coupling to our case

- 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

Future experiments may be able to see both axions at once

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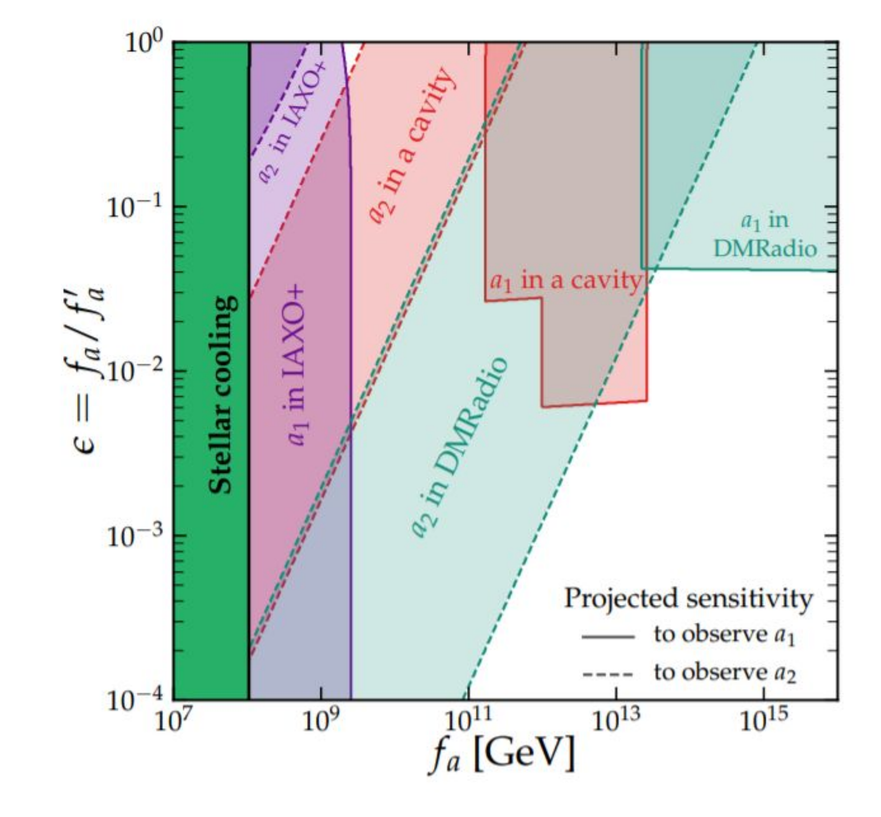

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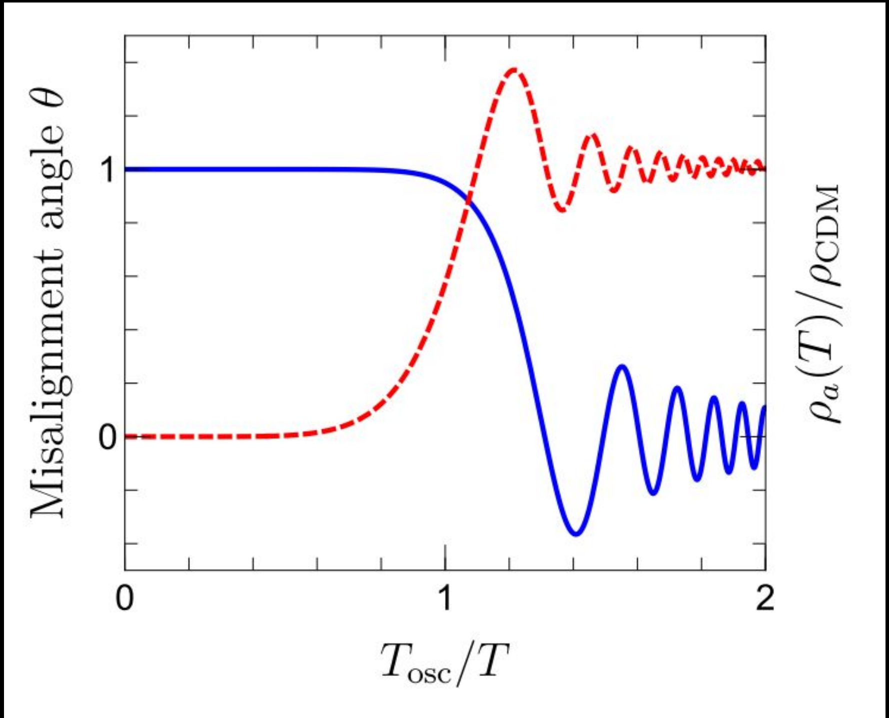
We can produce dark matter now with two misalignment angles



$$\theta_1 = \langle a_1(t_1)\rangle / f_a$$

$$\theta_2 = \langle a_2(t_2)\rangle \epsilon / f_a$$

Plot from Luzio et al 2020

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Companion axion dark matter, using the misalignment mechanism

	Case I	Case II	Case III
Before/during inflation	$\theta_{1,2} \in [-\pi, \pi]$	$\theta_2 \in [-\pi, \pi]$	
After/no inflation		$\theta_1 \equiv \sqrt{\langle \theta^2 \rangle} = \pi/\sqrt{3}$	$\theta_{1,2} \equiv \sqrt{\langle \theta^2 \rangle} = \pi/\sqrt{3}$

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

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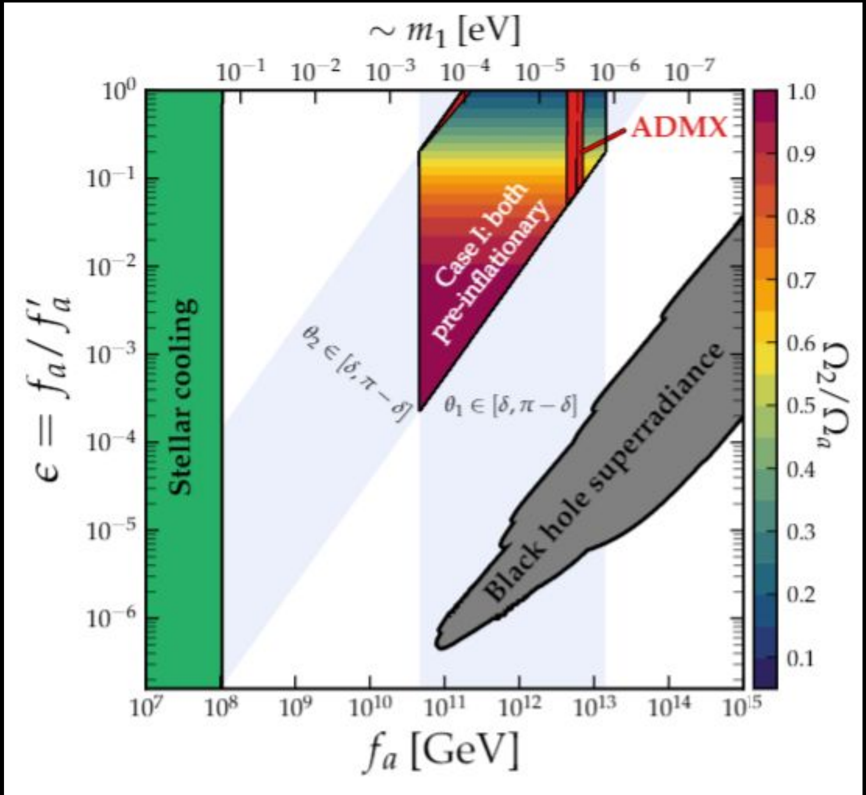

Coupled oscillation equations:

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

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

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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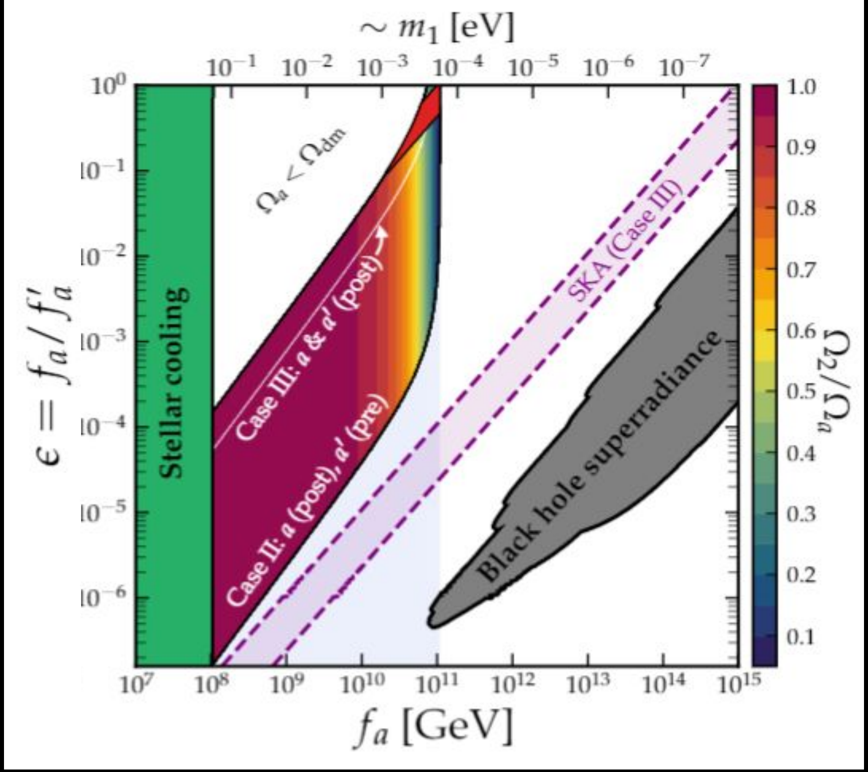

Coupled oscillation equations:

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

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 may solve the domain wall problem

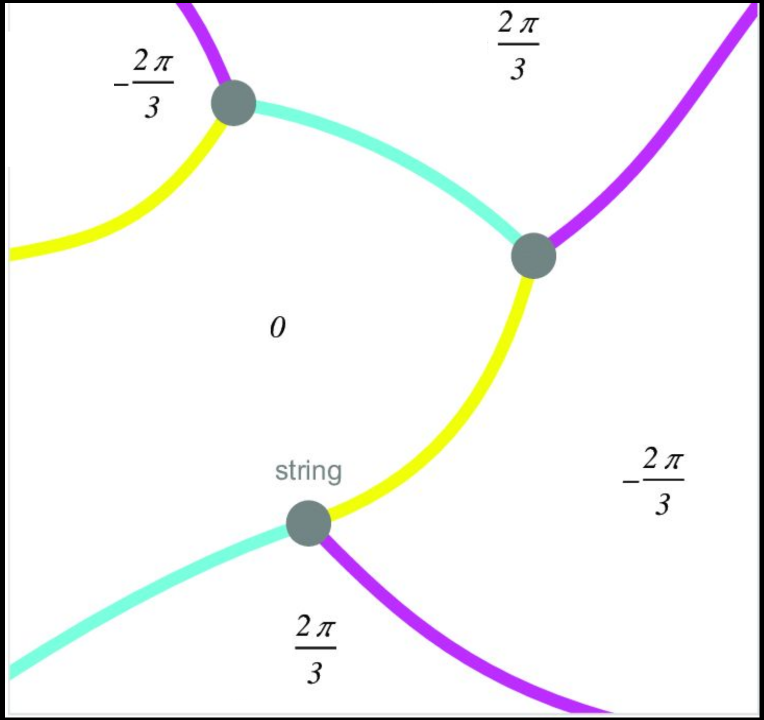

Diagram from Armengaud et al, 2019

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

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

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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!

Thanks!

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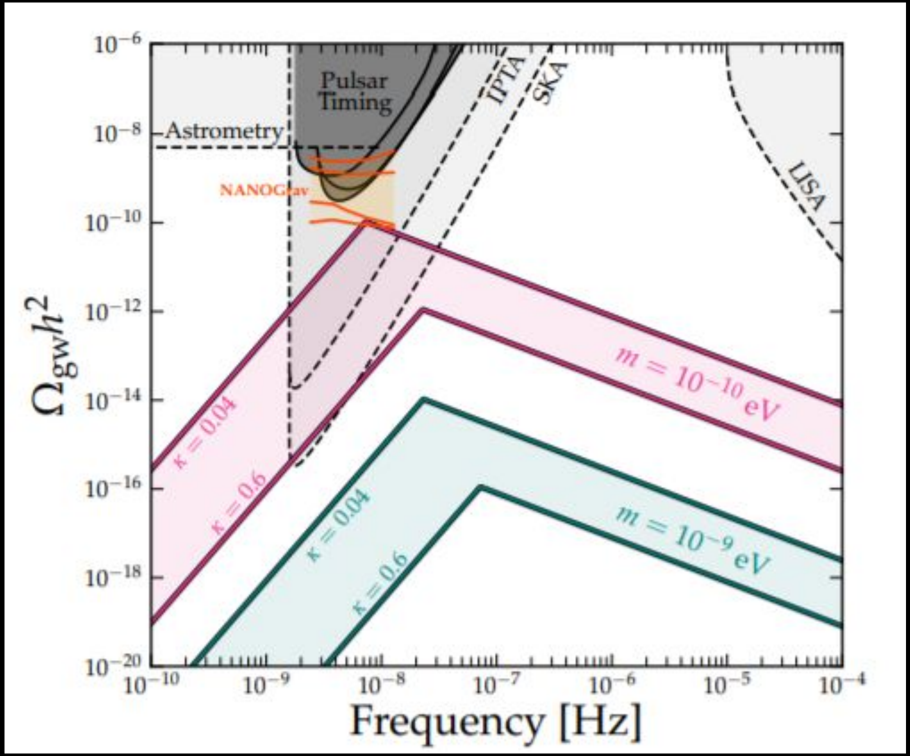
Bonus: domain walls in $10^{-10}\ \text{eV} \lesssim m_i \lesssim 10^{-9}\ \text{eV}$



- 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:

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

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

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: Eguchi-Hanson details

Pure EH metric:

$$ds^2 = \frac{1}{1-\frac{a^4}{r^4}}dr^2 + \frac{r^2}{4}\left[d\theta^2 + \sin^2\theta d\phi^2 + \left(1-\frac{a^4}{r^4}\right)(d\psi + \cos\theta d\phi)^2\right] ,$$

SU(2) embedding in EH spin-connection:

$$A^a_\mu = \frac{1}{2}\eta^a_{AB}\omega^{AB}_\mu ,$$

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

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

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Bonus: temperature dependent masses

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].