UNIVERSITÀ DEGLI STUDI DI PADOVA

HyperLSW – Experimental Setups for Determining the Amount of Axion Dark Matter After a Discovery

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with J. Jaeckel & G. Lucente [arXiv:2407.04772]

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msca_axitools

Imagine a haloscope discovery...

- Is it a QCD axion? Is it the only form of dark matter (DM)?

- Can measure m_a, but degeneracy in $\rho_a\, g_{a\gamma\gamma}^2$ remains

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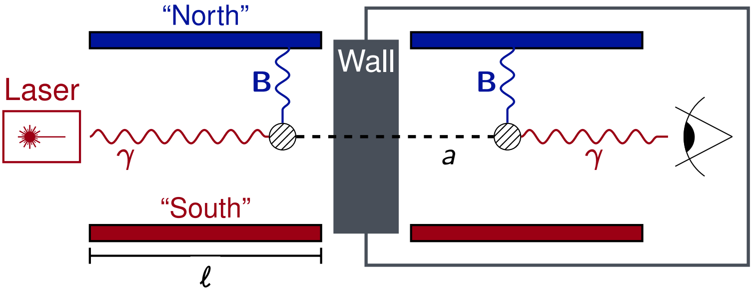
➽ In general: follow-up experiments are needed!

➽ Determine "worst-case value" for $g_{a\gamma\gamma}$, use known m_a to construct LSW setup with alternating magnet orientations

Light-shining-through-a-wall (LSW) experiments



- LSW experiments[Anselm '85, van Bibber+ '87] generate and detect axions via strong magnetic fields
- Works for non-DM axions, great experimental control; **but** signal scales with $g_{a\gamma\gamma}^4$

LSW signals

- Conversion probability for a single magnet,

$$p^2_{a\leftrightarrow\gamma} = \frac{\omega^2}{\omega^2 - m_a^2}\left(\frac{g_{a\gamma\gamma}B\ell}{2}\right)^4 |F|^4,$$

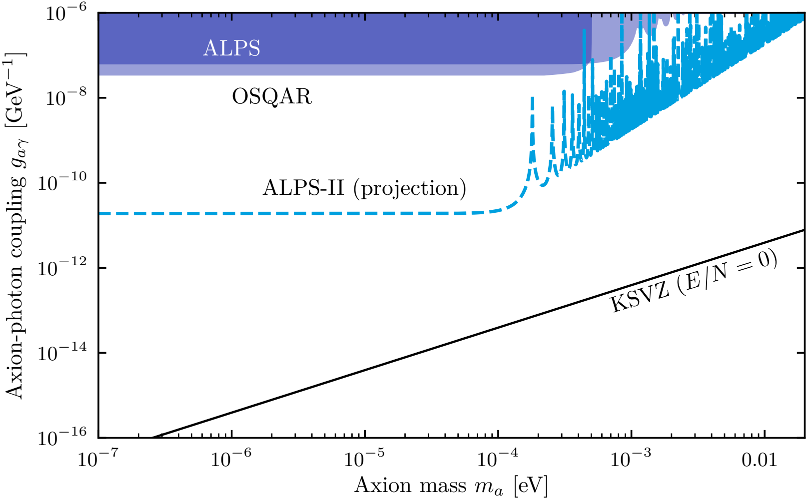
  crucially depends on the form factor F:

$$|F| = \left|\frac{\sin(x)}{x}\right| \quad \text{and} \quad x \equiv \frac{q\,\ell}{2} \approx \frac{m_a^2\ell}{4\omega}$$

- The signal can be boosted by a factor $\beta \sim 10^5$ by inserting two mirrors on each side (optical cavity/resonator)

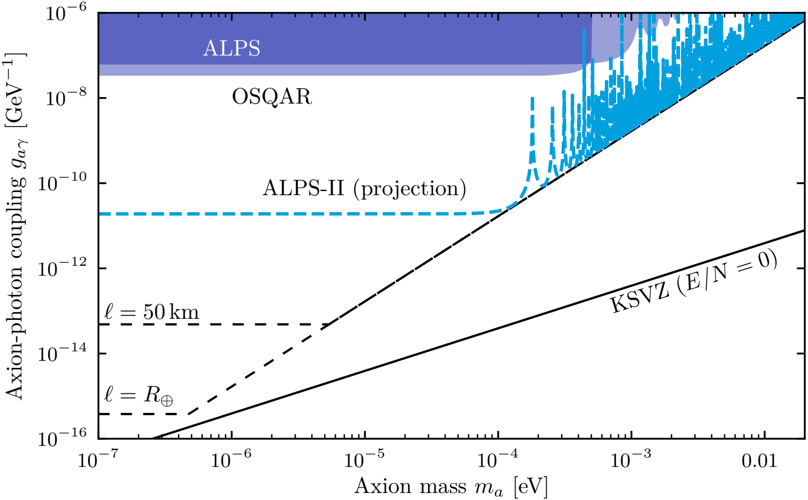
$$\mathcal{S} \equiv \varepsilon_{\text{eff}}\,\frac{P_\omega\,\tau}{\omega}\,\beta^2\,p^2_{a\leftrightarrow\gamma}$$

What is the maximal LSW length?



- Make LSW experiments longer to reach the QCD axion band?

What is the maximal LSW length?



- Make LSW experiments longer to reach the QCD axion band?
- Not really, incoherent conversion at lower masses ($x \sim \pi/2$)

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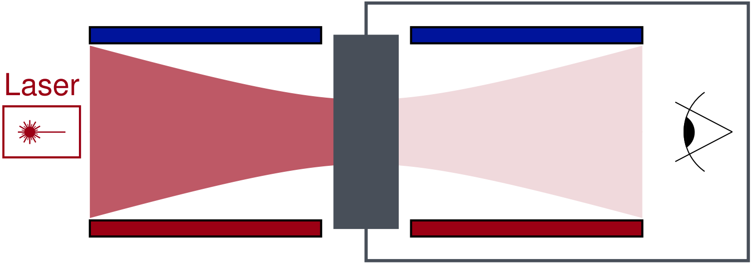

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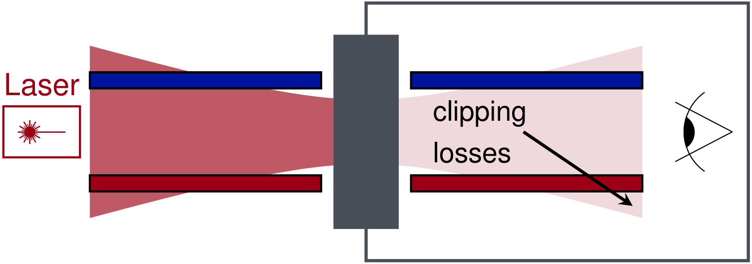
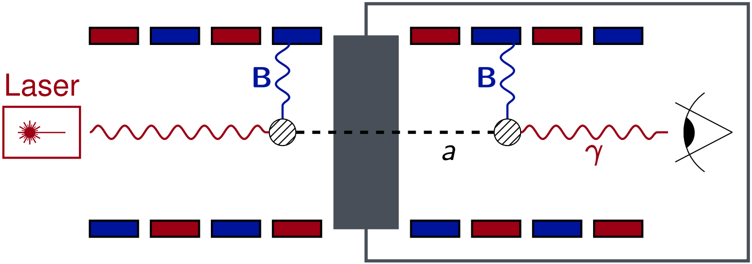


- Boosting the signal with mirrors leads to resonant mode
- Large aperture a avoids clipping losses, which reduce β
- Can compute an optimal total length L for e.g. $\beta \sim 10^5$:

$$L/2 \sim 94\,\text{km} \left(\frac{1064\,\text{nm}}{\lambda}\right) \left(\frac{a}{1.3\,\text{m}}\right)^2$$

- LSW = straight line: curvature of Earth becomes relevant!

Multi-magnet LSW



- Now: n_g groups of magnets with alternating polarity[van Bibber+ '87]
- n_s magnets in each group, gaps of size Δ between magnets
- Alternating B-field polarity = resonant conversion

Multi-magnet LSW form factor

- With $y \equiv x\,(1 + \Delta/\ell)$, the form factor becomes[Arias+ '10]

$$F = \frac{\sin(x)}{n_\mathrm{g}\, n_\mathrm{s}\, x}\,\frac{\tan\left(n_\mathrm{s}\, y\right)}{\sin(y)} \begin{cases} \sin\left(n_\mathrm{s} n_\mathrm{g}\, y\right) & \text{if } n_\mathrm{g} \text{ is even} \\ \cos\left(n_\mathrm{s} n_\mathrm{g}\, y\right) & \text{if } n_\mathrm{g} \text{ is odd} \end{cases} ,$$

- Resonant peaks at[Arias+ '10]

$$x_k(1 + \Delta/\ell) \approx \frac{(1 + 2k)\,\pi}{2 n_\mathrm{s}} \quad \text{for } k \in \mathbb{N}_0$$

- Global maximum for $k = 0$: try to match this to m_a!

Optimising the setup

Setup	B [T]	a [m]	ℓ [m]	$\Delta_{\rm min}$ [m]	P_λ [W]	$\beta_{\rm g}$	$\beta_{\rm r}$	λ [nm]	$\varepsilon_{\rm eff}$	τ [h]	b [s^{-1}]	$2\,z_{\rm opt}$ [km]
S1	9	1.3	4.0	2.0	3	10^5	10^5	1064	0.9	100	10^{-4}	2×94
S2	11	1.8	10.0	3.0	3	10^5	10^5	1064	0.9	100	10^{-4}	2×181
O1	9	1.3	4.0	2.0	300	10^5	10^6	1064	0.9	5000	10^{-6}	2×79
O2	11	1.8	10.0	3.0	300	10^5	10^6	1064	0.9	5000	10^{-6}	2×152

- Magnets ≈ MADMAX,[J. Egge (Mon)] optics ≈ ALPS II[Ch. Schwemmbauer (Tue)]

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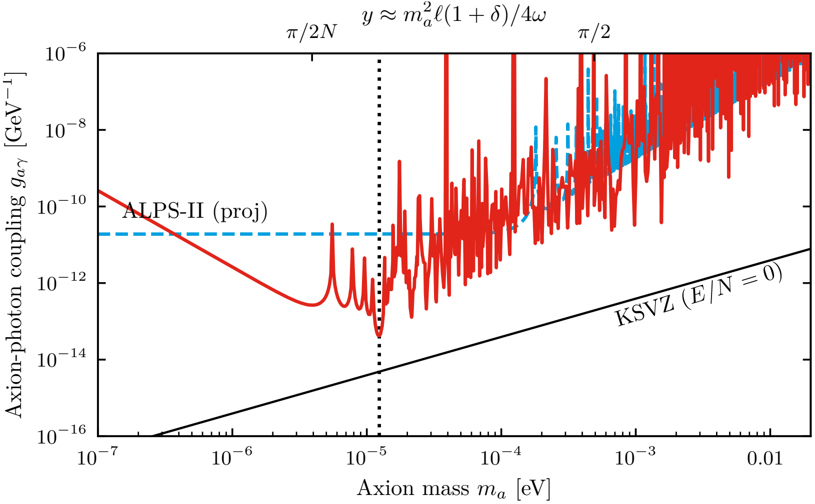
- Magnets ≈ MADMAX,[J. Egge (Mon)] optics ≈ ALPS II[Ch. Schwemmbauer (Tue)]
- Start from optimal length, then adjust n_g, n_s, and Δ
- Can we use a gas filling? Difficult: high losses, technical issues for very long setups; adjust ℓ instead

Setting up HyperLSW

Know $m_a \Rightarrow$ arrange magnets to be resonant at that m_a



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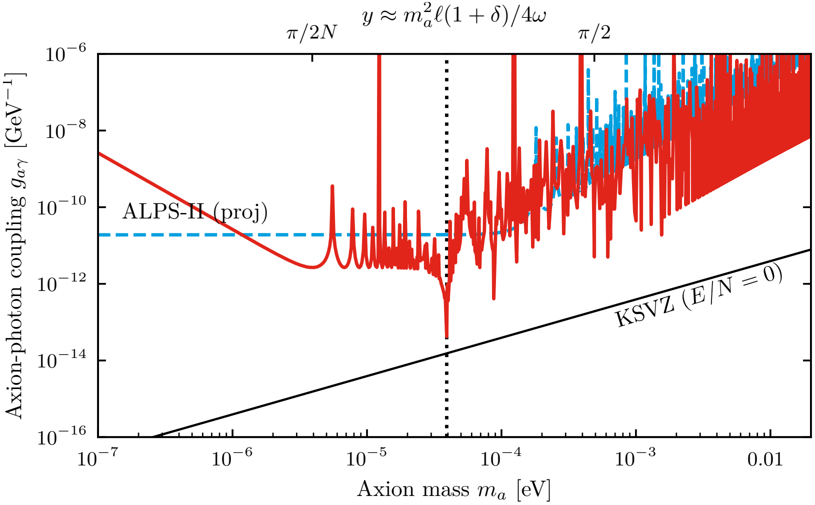

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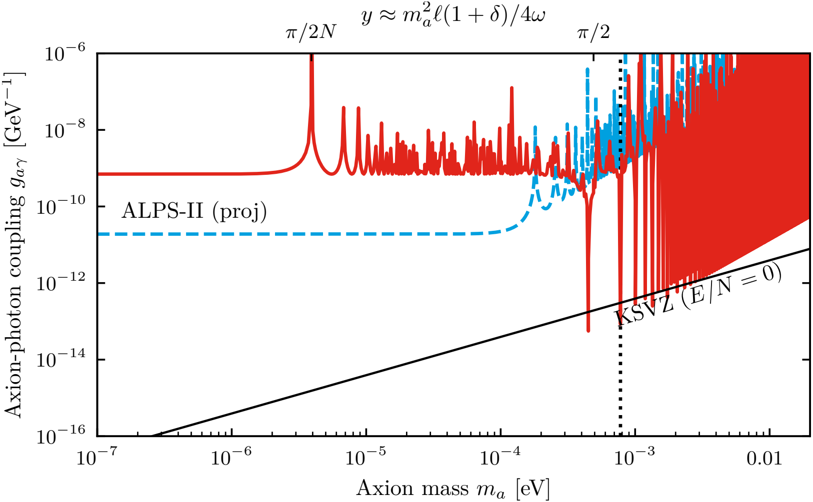
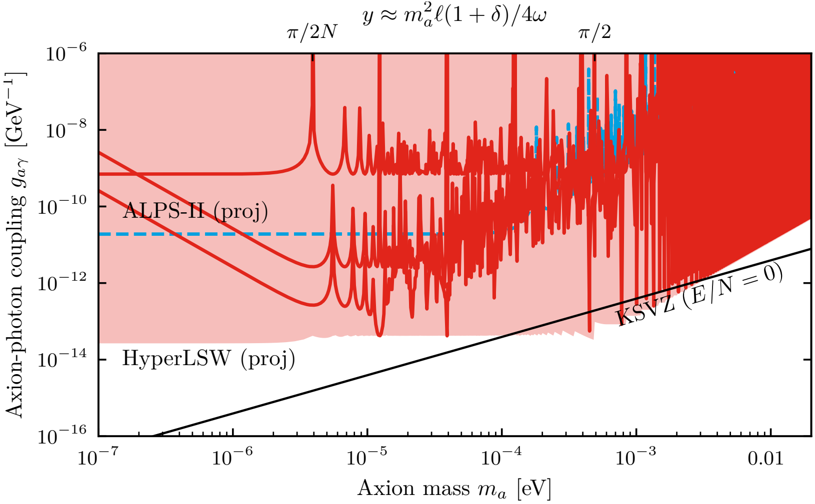


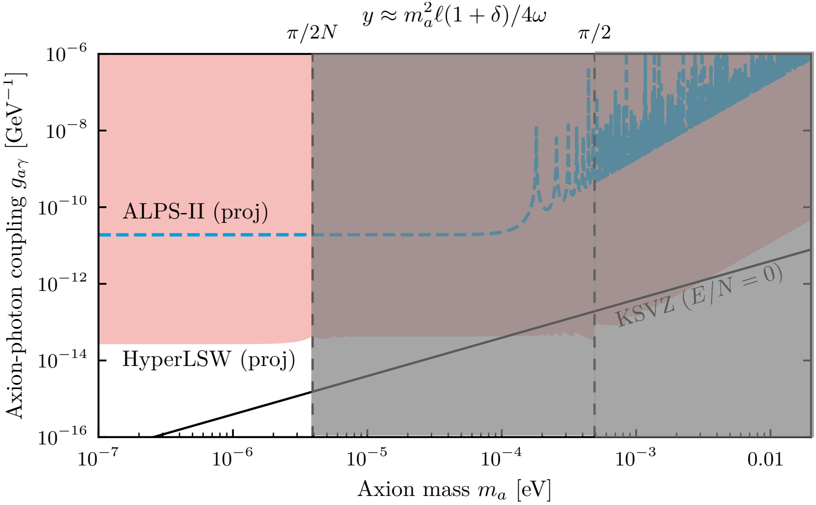
Setting up HyperLSW

Look at the combined reach for different setups:



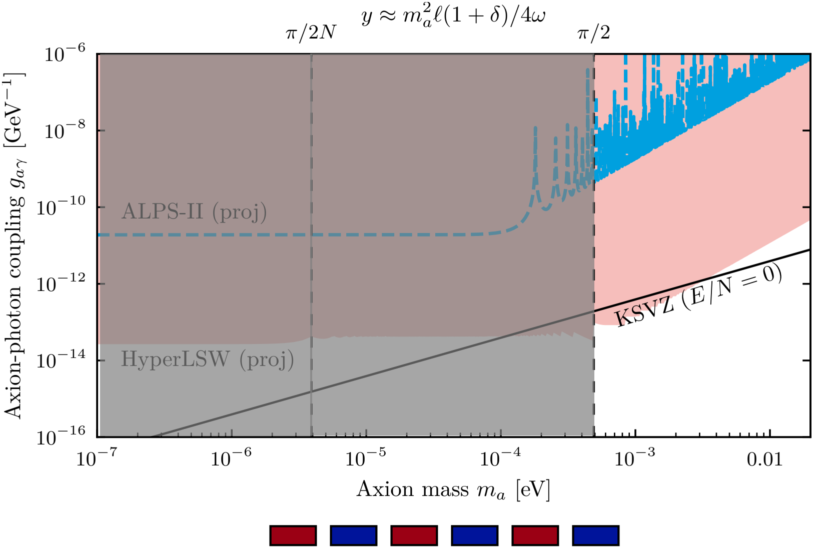
Setting up HyperLSW

Low m_a : all B-fields are aligned



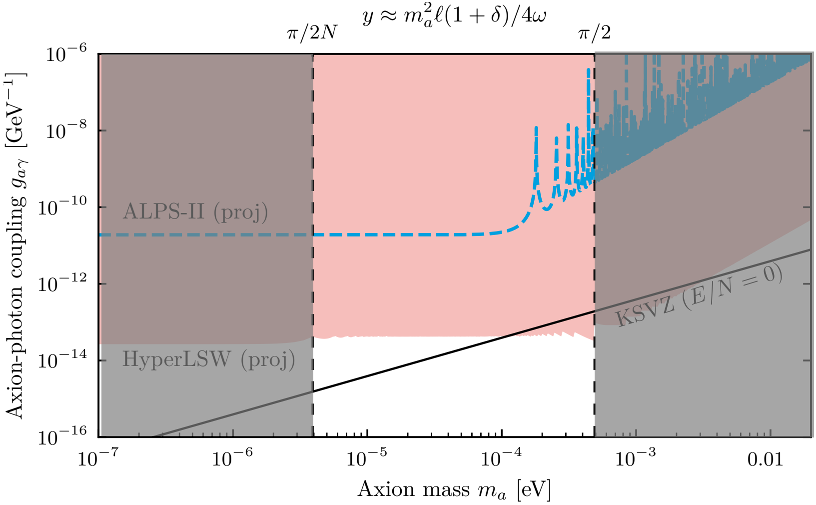
Setting up HyperLSW

High m_a : fully alternating B-fields, adjust magnet length

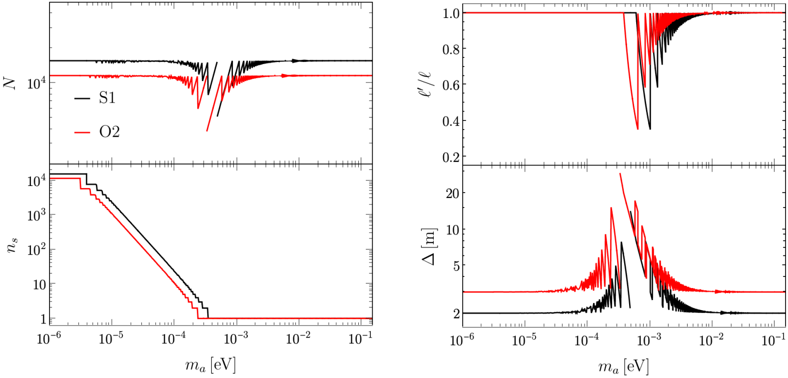


Setting up HyperLSW

Intermediate m_a : increase n_g as m_a increases see [2407.04772]



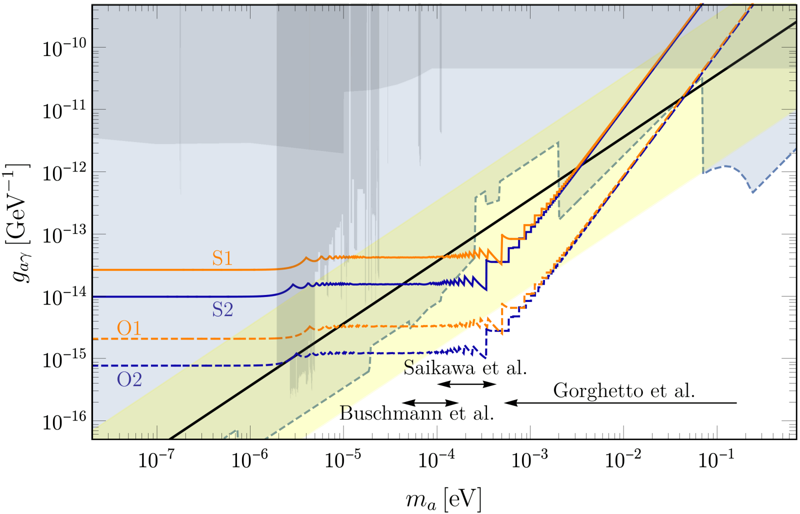
Optimal parameter choices



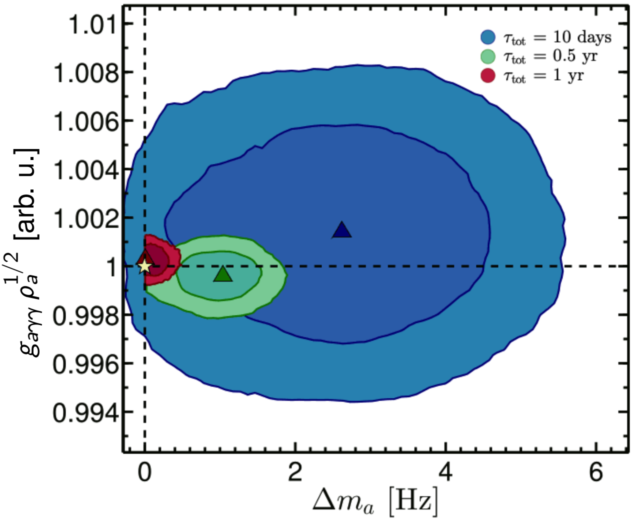
- We provide optimised setups for any mass[2407.04772]
- The lowest $g_{a\gamma\gamma}$ values require $\sim 15\,000$ magnets

Maximal HyperLSW reach

Goal: measure $g_{a\gamma\gamma}$ within 2%. Maximal reach of HyperLSW benchmarks vs haloscopes[many contribs @ IDM] and cosmic string sims



Haloscope mass determination



Can measure m_a precisely ($\Delta m_a / m_a \sim 10^{-8}$) O'Hare & Green '17

Potential issues

- Challenging for $m_a \gtrsim \mathrm{meV}$. We considered random magnet placement and B-field profile errors with Monte Carlo simulations, haloscope mass resolution

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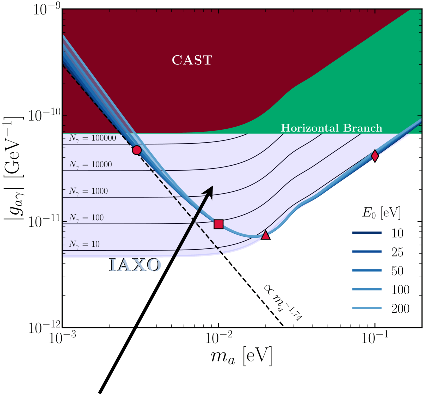
- Other uses. Re-use magnets, infrastructure for other physics experiments (axions, GWs, . . .), non-physics uses ("Hyperloop" transport network, . . .)

➽ See our preprint for more details[2407.04772]

Examples for complementarity with other probes



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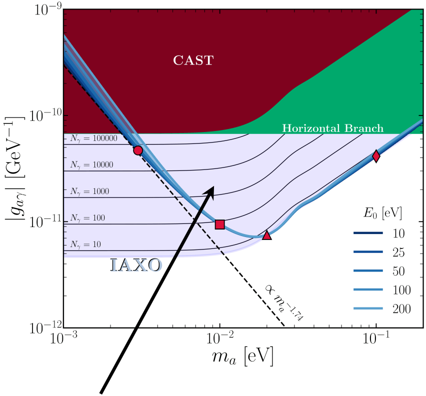

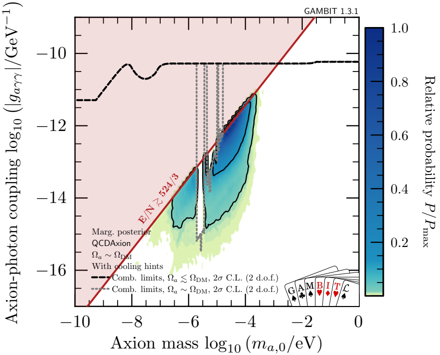

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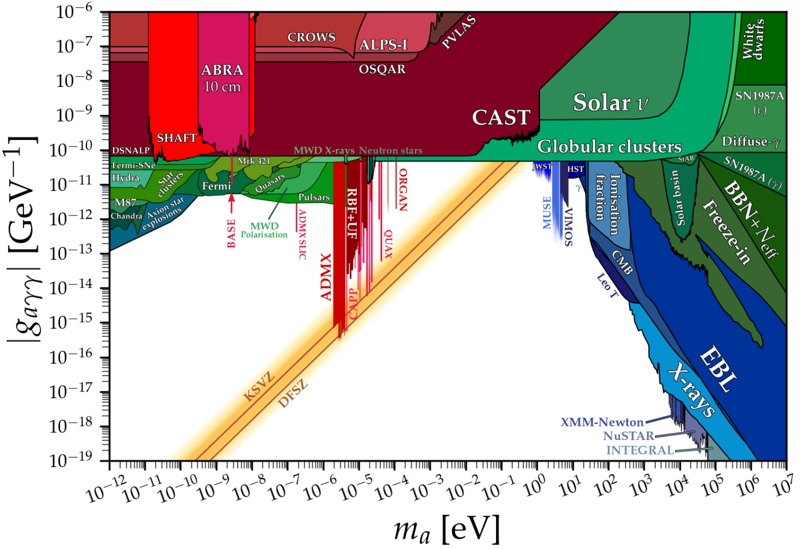
Know m_a = know f_a for QCD axions! Can we learn something about the PQ symmetry breaking scenario?[1810.07192]

Summary

- Axion DM can be discovered any day! What then?
- Magnets with large aperture and knowledge of m_a allow us to build HyperLSW
- “No lose” theorem: establish that axions = (most of) DM
- HyperLSW is expensive and challenging, but doesn’t require new technology!
- Complementarity with e.g. helisocopes, help to identify UV model? Re-use of components and infrastructure in physics or civil applications?

Bonus Slides

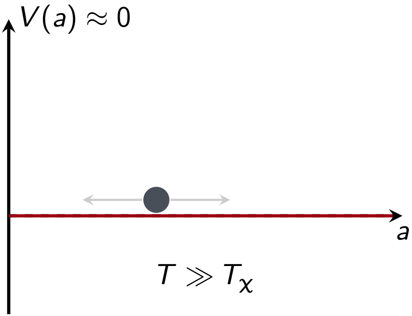
Current limits on the axion-photon coupling



Credit to C. O’Hare, “AxionLimits” repo

Axion dark matter – realignment mechanism

- At early times, $T \gg T_\chi \sim T_{\mathrm{QCD,c}} = 158.1(5)\,\mathrm{MeV}$,[2002.02821] the axion field a can fluctuate freely



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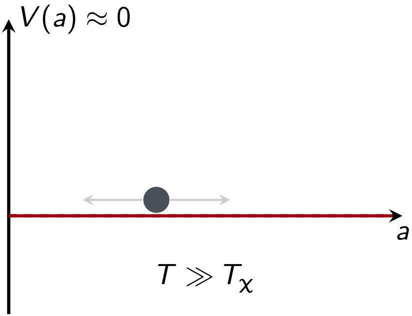

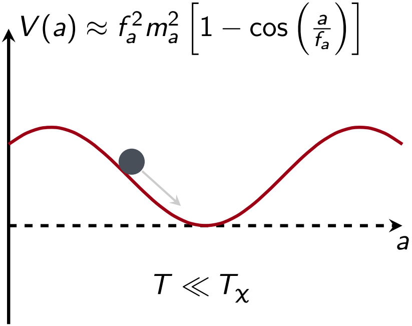

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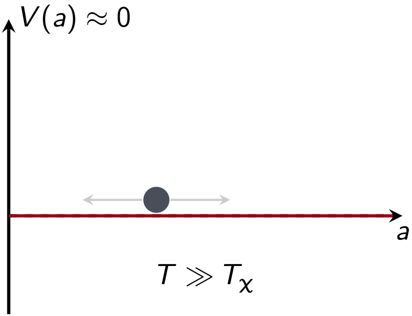
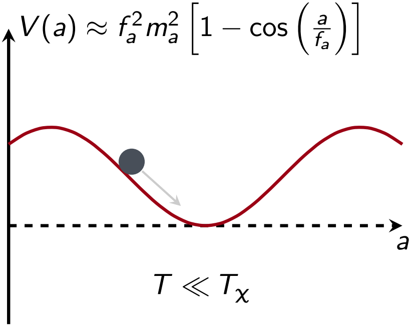
➽ *Strong CP problem solved dynamically by promoting $\theta \mapsto a/f_a$*

➽ *Oscillating scalar field behaves as DM*





Axion dark matter – predictions

Axion = pNGB from $\mathrm{U}(1)$ symmetry breaking (PQ symmetry)

Pre-inflationary PQ breaking

- Universe = single patch of constant θ stretched out by inflation
- Initial axion field value is random ☹
- Inflation dilutes away topological defects ☺

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Post-inflationary PQ breaking

- Universe = huge number of causally disconnected axion field patches
- Axion DM density from realignment = average ☺
- Contribution from top. defects, very difficult to compute ☹ [2007.04990, 2108.05368]

QCD axion properties

- QCD axion mass from chiral perturbation theory[1812.01008]

$$m_a = 5.69(5)\,\mu\text{eV}\left(\frac{10^{12}\,\text{GeV}}{f_a}\right)$$

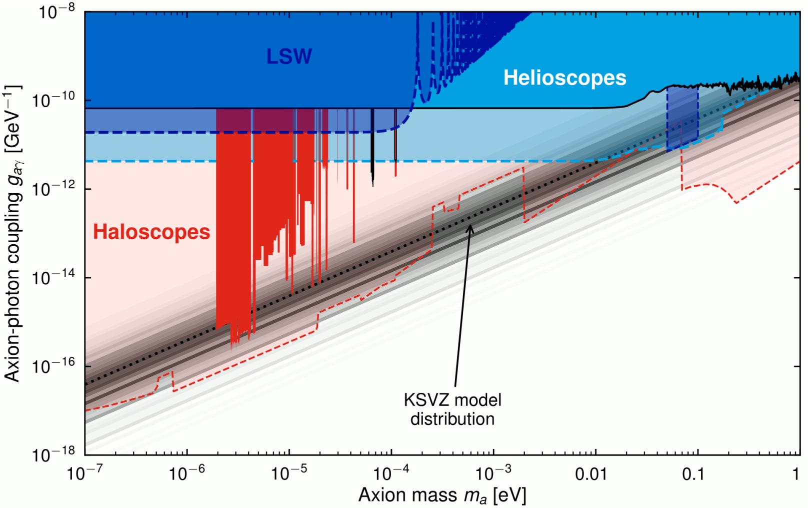
- Axion-photon coupling depends on UV model through anomaly ratio E/N and axion-meson mixing[1511.02867]

$$g_{a\gamma\gamma} = \frac{\alpha_{\text{EM}}}{2\pi f_a}\left[\frac{E}{N} - 1.92(4)\right] \propto m_a$$

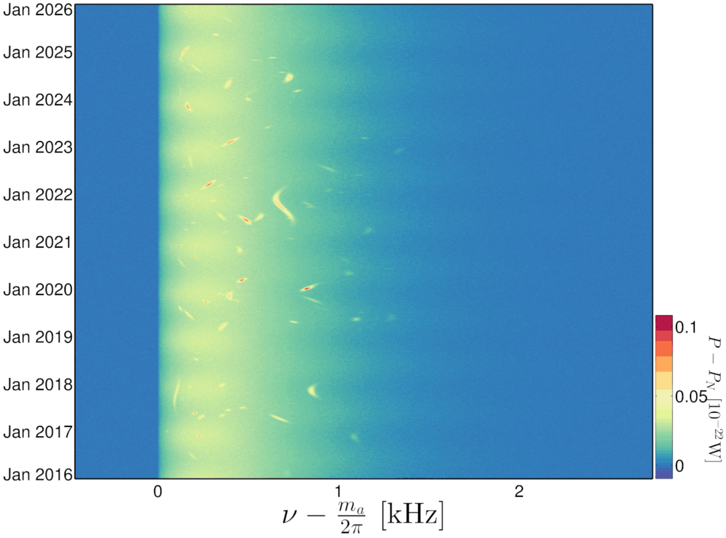
- Axion-like particles (ALPs): no connection to QCD = less predictable; however, e.g. mass spectra in string theory[2103.06812]

The KSVZ model band

Distribution of all equally probable, preferred reps for KSVZ models[2107.12378] (finite due to LP criterion) = theory prior on $|g_{a\gamma\gamma}|$

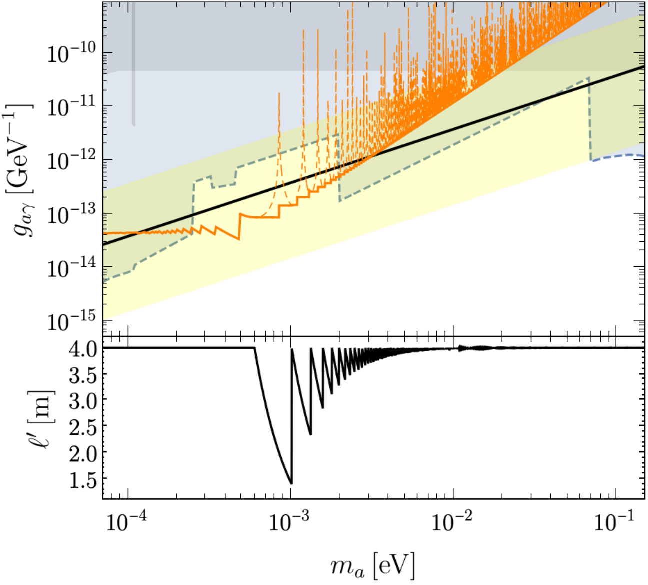


Caveats: substructures



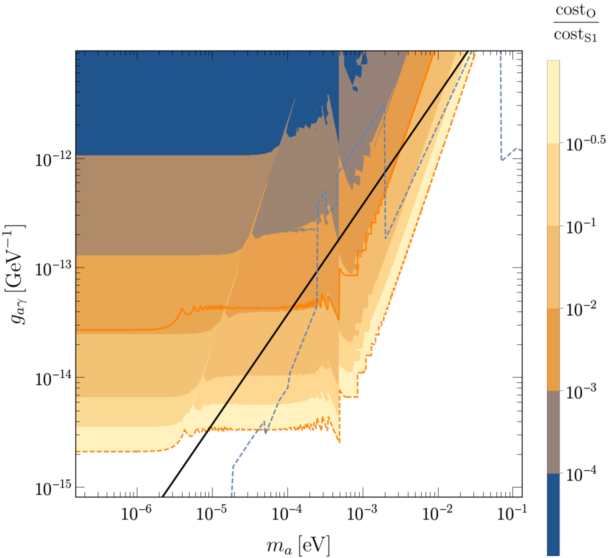
Can exclude non-constant ρ_a with multi-year obs O'Hare & Green '17

Shorten magnets to fine-tune sensitivity



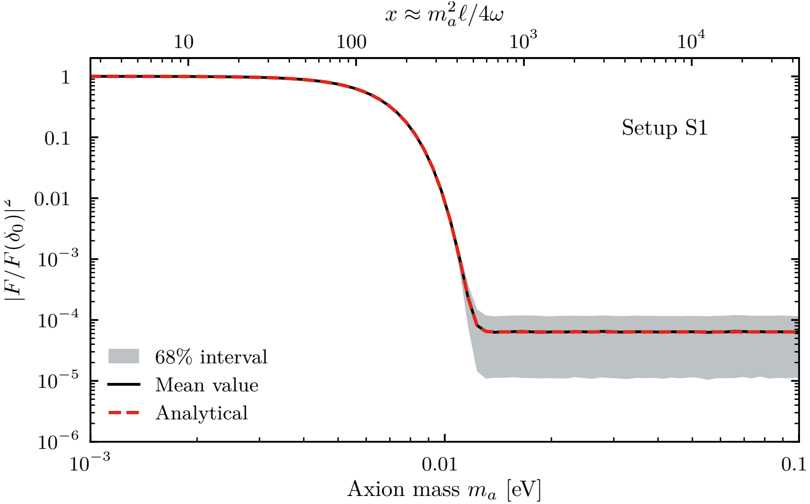
Possible cost savings

Detecting an axion with high couplings can reduce costs:



Monte Carlo simulations: positioning errors

Effects of random, absolute positioning uncertainties:



Monte Carlo simulations: *B*-field profiles

Effects of random *B*-field profile shifts and length fluctuations: