INVISIBLES24

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HyperLSW: An ultimate experiment to Determine the amount of dark matter axions

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HIDDeN
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

Based on
S. Hoof, J. Jaeckel, GL, ArXiv:2407:XXXXX

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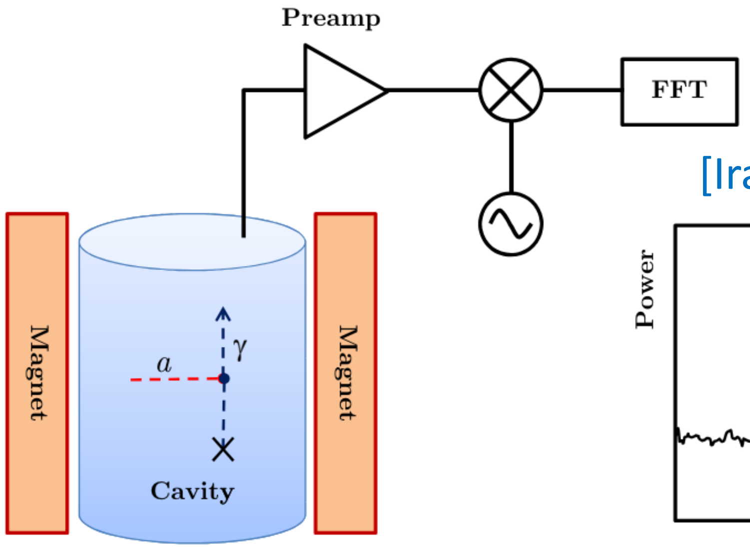
GENERAL STRATEGY

$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma}\, \tilde{F}^{\mu\nu}\, F_{\mu\nu}\, a$$

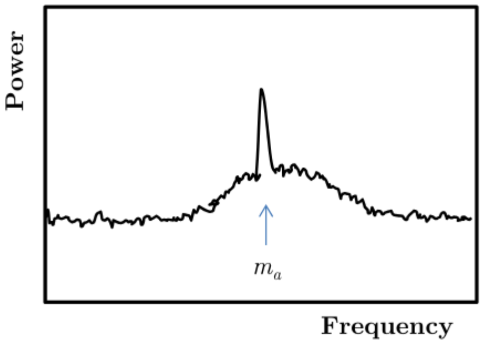
HALOSCOPE DISCOVERY

[Sikivie (1983)]

$$P \propto g_{a\gamma}^2\, \eta_a\, \rho_{\mathrm{DM},\odot}$$



[Irastorza (2021)]



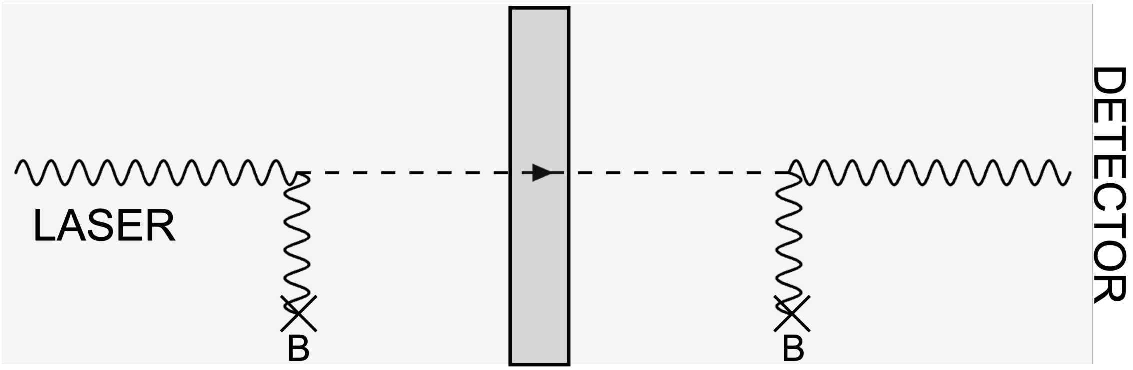
m_a measured with extreme precision.

[O'Hare & Green (2017)]

LSW FOLLOW-UP

[Van Bibber et al. (1987), Arias et al. (2010)]

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

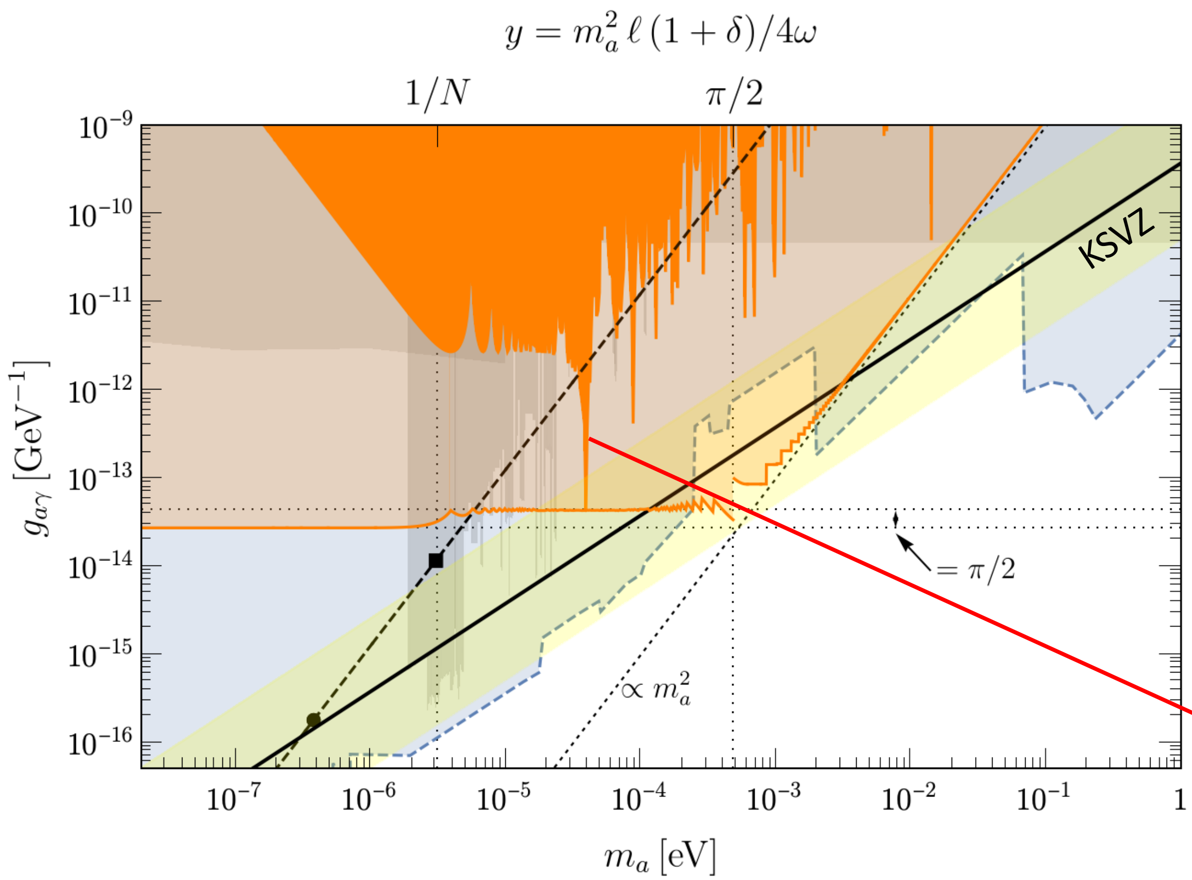


Pure laboratory experiment to measure $g_{a\gamma}$.

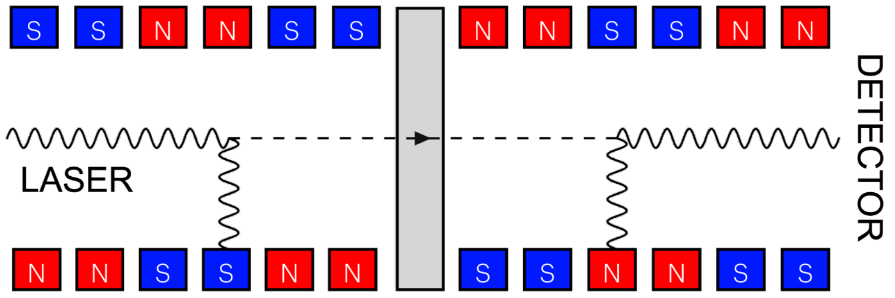
OPTMIZING LSW SETUPS

[Van Bibber et al. (1987), Arias et al. (2010)]

Single long magnet not sufficient to probe the QCD band (coherence is lost when $L \sim 2\pi\, \omega/m_a^2$)



Optmize magnet configuration → Alternating magnets



Resonance at $m_a \approx \sqrt{\dfrac{2\,\pi\,\omega}{n_s\, l\, (1+\delta)}}$

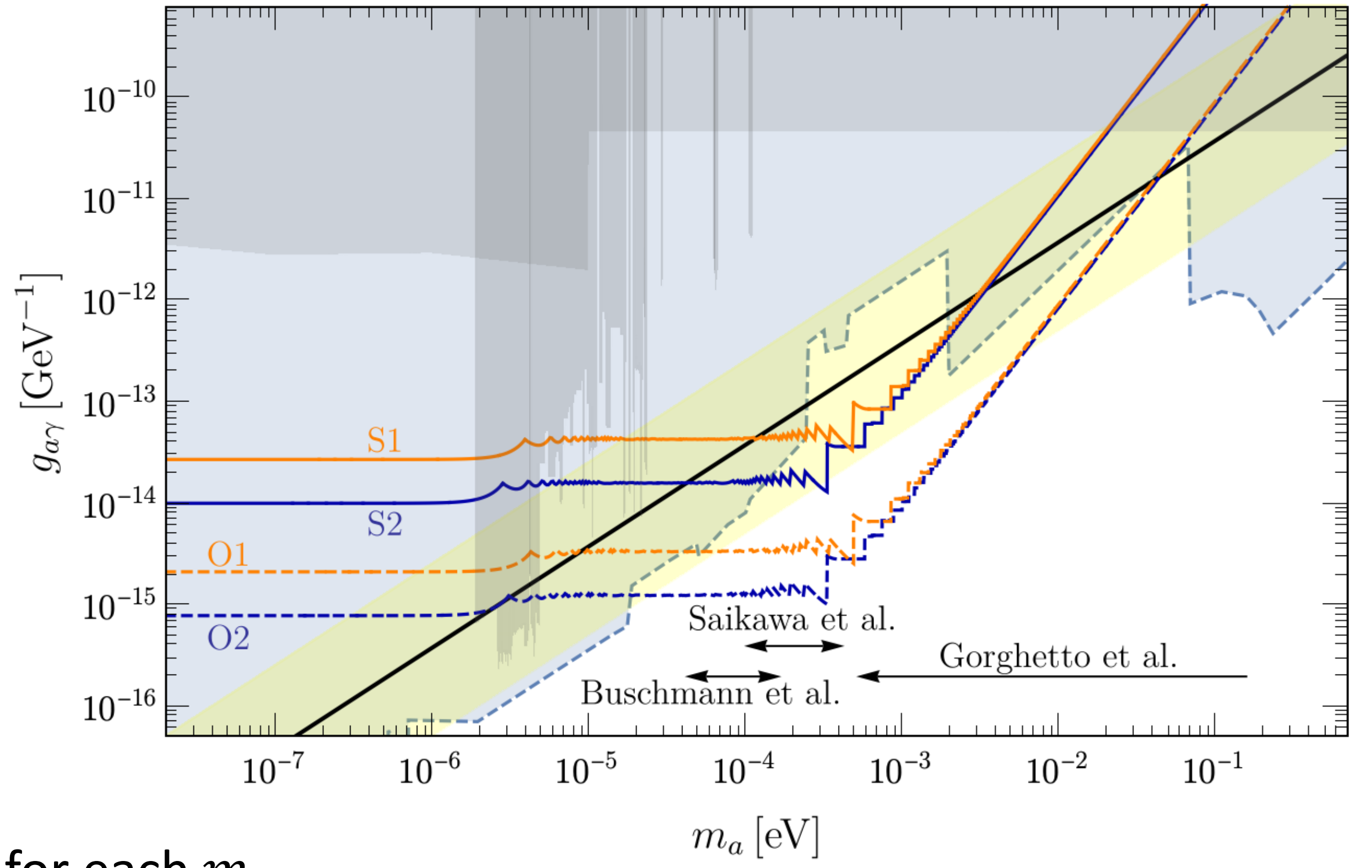
SENSITIVITY FOR BENCHMARK SETUPS

Setup	B [T]	a [m]	ℓ [m]	$\Delta_{\rm min}$ [m]	P_λ [W]	β_g	β_r	λ [nm]	$\varepsilon_{\rm eff}$	τ [h]	b [s^{-1}]	$2\,z_{\rm opt}$ [km]	$\mathcal{S}_{\rm crit}$
S1	9	1.3	4.0	2.0	3	10^5	10^5	1064	0.95	100	10^{-4}	2×94	186.42
S2	11	1.8	10.0	3.0	3	10^5	10^5	1064	0.95	100	10^{-4}	2×181	186.42
O1	9	1.3	4.0	2.0	300	10^5	10^6	1064	0.95	5000	10^{-6}	2×79	172.55
O2	11	1.8	10.0	3.0	300	10^5	10^6	1064	0.95	5000	10^{-6}	2×152	172.55

Avoid clipping losses:

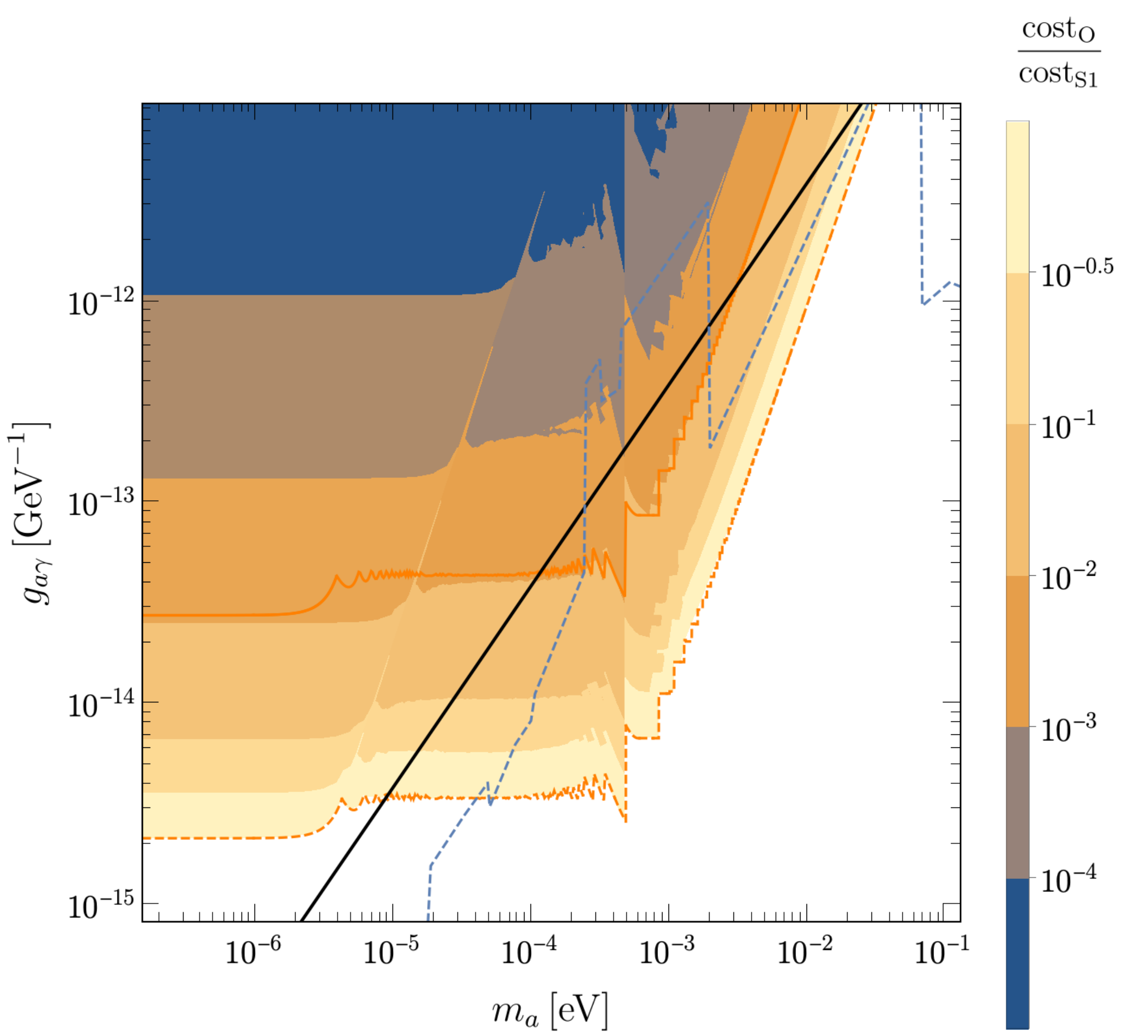
$$z_{\rm opt} \approx 94.2\ {\rm km}\,\frac{1064\ {\rm nm}}{\lambda}\left(\frac{a}{1.3\ {\rm m}}\right)^2$$

[Arias et al. (2010)]



Optimal configurations for each m_a.

CHALLENGING REALIZATION



Long tunnel + many strong magnets $\approx O(100)$ GEur

[Grose (2021)] [Calvelli et al. (2020, 2023)]

Improvements in the optical setup can help: pick the cheapest solution!

TAKE-AWAY MESSAGES

- HyperLSW experiments sensitive to KSVZ axions with $3\ \mu\text{eV} \lesssim m_a \lesssim 45\ \text{meV}$.
- Very costly, error control and magnetic field profiling required.
- BUT No technological breakthroughs needed and infrastructure useful for non-axion physics!

Thank you and
Come to see my poster!

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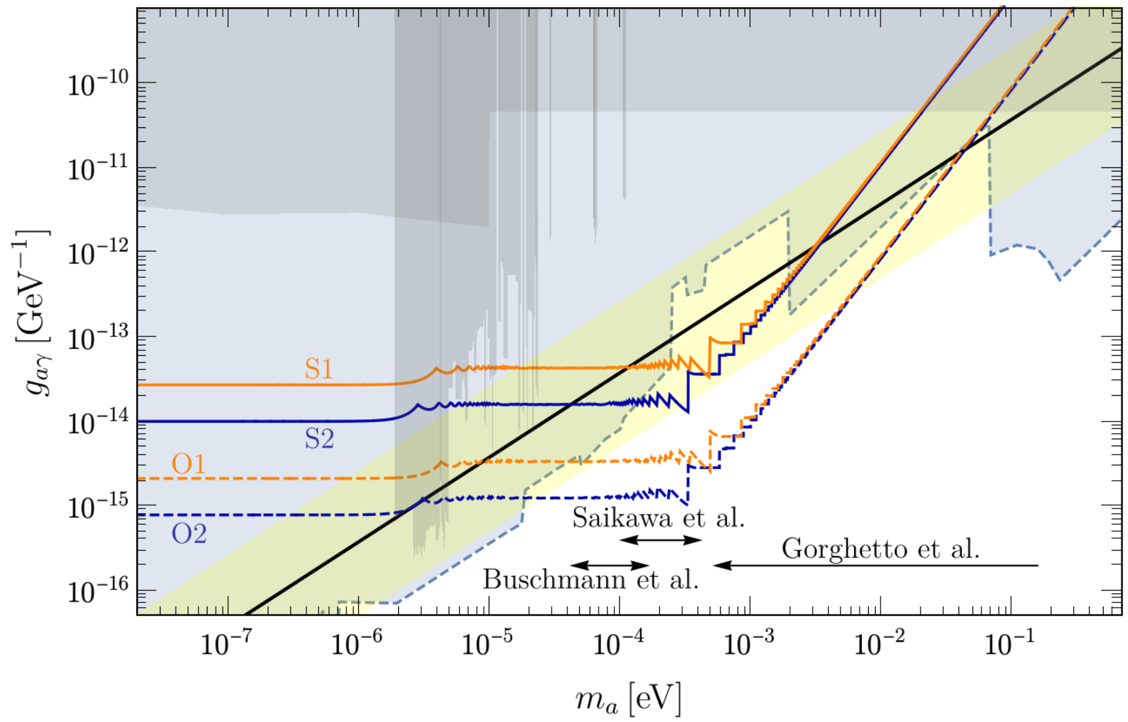


BACKUP

FORM FACTOR

[Arias et al. (2010)]

$$F \equiv \frac{1}{L}\int_0^L \mathrm{d}z\, f(z)\, \mathrm{e}^{\mathrm{i}qz} \qquad q \equiv n_{\mathrm{r}}\,\omega - \sqrt{\omega^2 - m_a^2} \approx (n_{\mathrm{r}}-1)\,\omega + \frac{m_a^2}{2\omega}$$

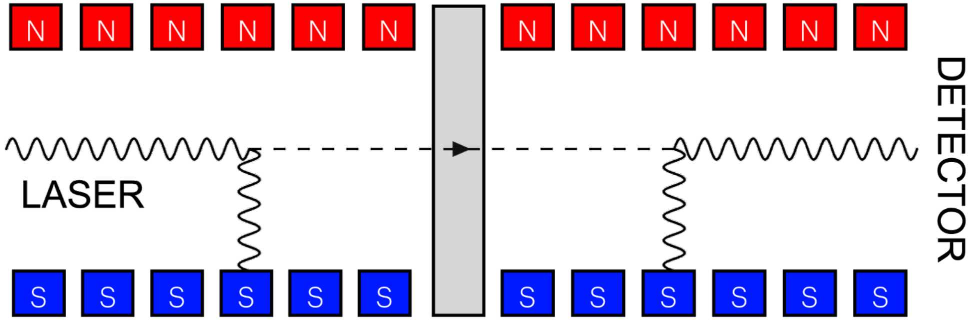
- **General configuration**

$$F_{n_{\mathrm{s}},n_{\mathrm{g}}}(x;\delta) = \frac{\mathrm{sinc}(x)}{n_{\mathrm{g}}n_{\mathrm{s}}}\,\frac{\tan(n_{\mathrm{s}}\,y)}{\sin(y)} \begin{cases} \sin(n_{\mathrm{s}}n_{\mathrm{g}}\,y) & \text{if } n_{\mathrm{g}} \text{ is even} \\ \cos(n_{\mathrm{s}}n_{\mathrm{g}}\,y) & \text{if } n_{\mathrm{g}} \text{ is odd} \end{cases}$$

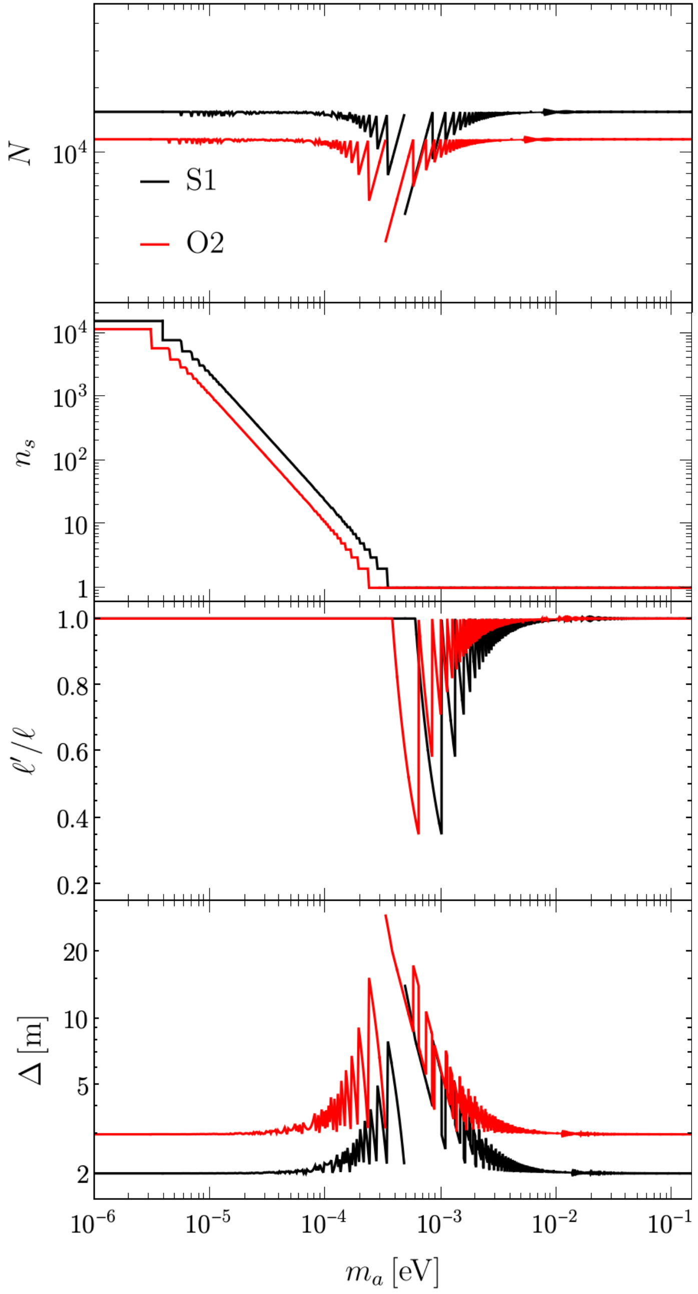
where $\mathrm{sinc}(x) \equiv \sin(x)/x,\ x \equiv q\ell/2,\ y \equiv x(1+\delta),\ \text{and } \delta \equiv \Delta/\ell$

Maxima close to $x_k = \frac{(2k+1)\pi}{2n_{\mathrm{s}}(1+\delta)}$ for $k \in \mathbb{N}_0$ → $\left|\frac{F_{n_{\mathrm{s}},n_{\mathrm{g}}}(x;\delta)}{F_{1,1}(x;\delta)}\right| \to \left|\frac{1}{n_{\mathrm{s}}\sin(\pi/2n_{\mathrm{s}})}\right| \simeq \frac{2}{\pi} \quad (x \to x_0),$

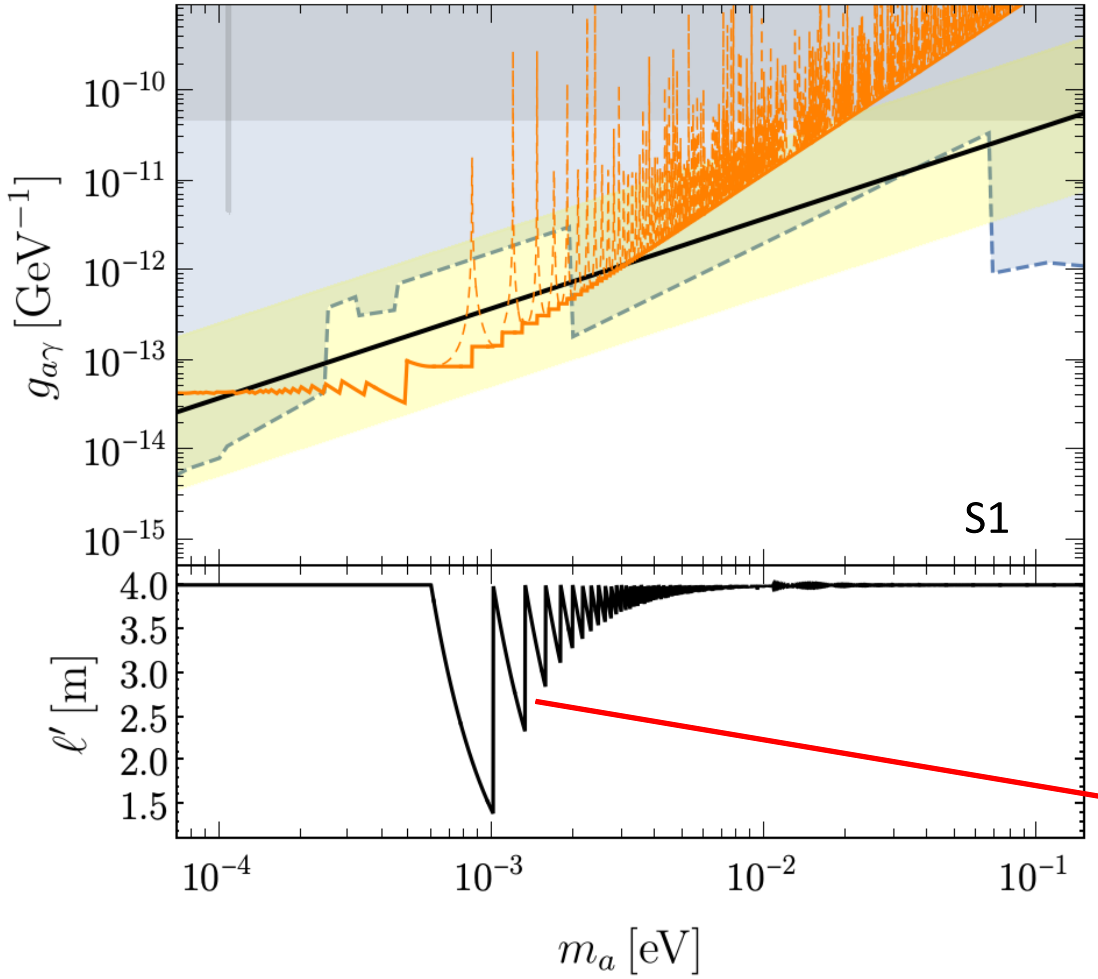
- **Fully-aligned setup** $F_{N,1}(x) = \frac{\mathrm{sinc}(x)}{N}\,\frac{\sin(Ny)}{\sin(y)}$



OPTIMAL SETUPS



At large masses we modify $\ell \to \ell'$ to maximize the single magnet form factor.



$F_{1,N}(x) \to F_{1,1}(x) \quad (x \to x_k)$

$F_{1,1} = \mathrm{sinc}(x)$

$$x_k = \frac{(2k+1)\pi}{2n_s(1+\delta)} \quad \text{for } k \in \mathbb{N}_0$$

(1) $\ell(1+\delta) = \ell'(1+\delta')$

$\mathrm{sinc}(x')$ maximized at

(2) $x'_{k'} = \frac{\pi}{2} + k'\pi \quad \text{for } k' \in \mathbb{N}$

where $x' = q\frac{\ell'}{2}$

Find the largest $\ell' \leq \ell$ satisfying (1) and (2).

SENSITIVITY

$$\mathcal{S} = \varepsilon_{\rm eff} \frac{P_\lambda\, \tau}{\omega}\, \beta_{\rm g}\, \beta_{\rm r}\, p^2_{\gamma\leftrightarrow a}$$

Figure of merit $\quad \Phi = \dfrac{\mathcal{S}}{\sqrt{\mathcal{S}+\mathcal{B}}}$

$$p^2_{\gamma\leftrightarrow a} = \frac{\omega^2}{\omega^2 - m_a^2}\left(\frac{g_{a\gamma}\, B\, L}{2}\right)^4 |F|^4 \;\Rightarrow\; \mathcal{S} \propto g^4_{a\gamma} \;\to \Pi = \frac{\Delta g_{a\gamma}}{g_{a\gamma}} = \frac{1}{4\Phi}$$

Signal threshold for precision Π: $\quad \mathcal{S}_{\rm crit} = \dfrac{1}{32\,\Pi^2}\left(1 + \sqrt{1 + 64\mathcal{B}\Pi^2}\right)$

$\Pi = 2\%$

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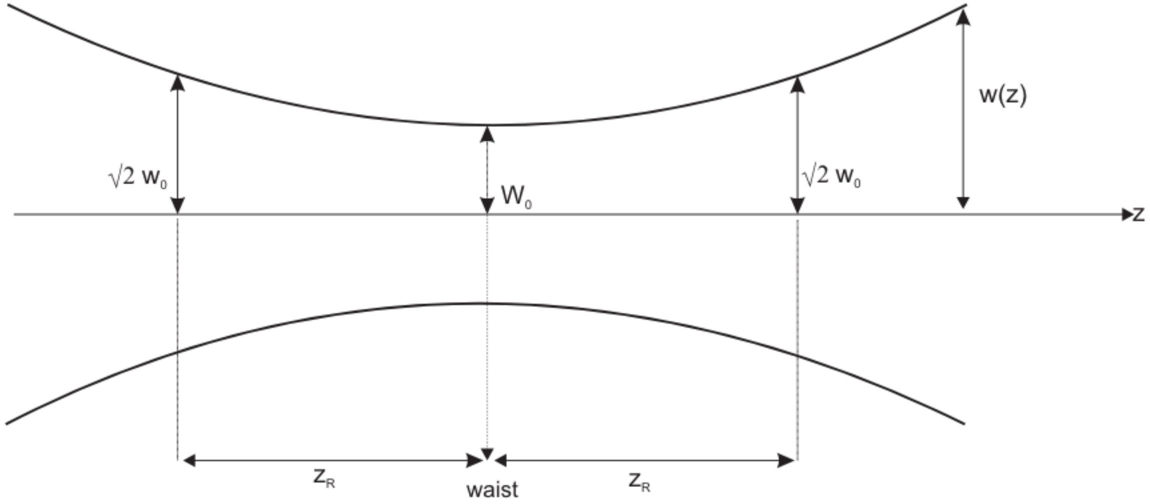
OPTIMAL LENGTH

[Arias et al. (2010)]

$$\frac{w(z)}{w_0} = \sqrt{1 + \left(\frac{z - z_N}{z_R}\right)^2} \qquad z_R = \pi\, w_0^2/\lambda$$



Fraction of power transmitted through a circular aperture of diamater a: $1 - e^{-a^2/2\,w^2}$

$$g_{\rm sens} \propto L^{-1}\beta^{-1/2} = L^{-1}\left(\beta_0^{-1} + e^{-\zeta}\right)^{1/2} \quad \xrightarrow{L\,\sim\,Z} \quad \text{Minimum at } \; e^{-\zeta}\left(\frac{\zeta}{2} - 1\right) - \beta_0^{-1} = 0, \quad \zeta = \pi\, a^2/4\lambda Z$$

$$\beta \approx \beta_0 = 10^5: \quad z_{\rm opt} \approx 94.2\ \text{km}\,\frac{1064\ \text{nm}}{\lambda}\left(\frac{a}{1.3\ \text{m}}\right)^2$$

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