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DESY.

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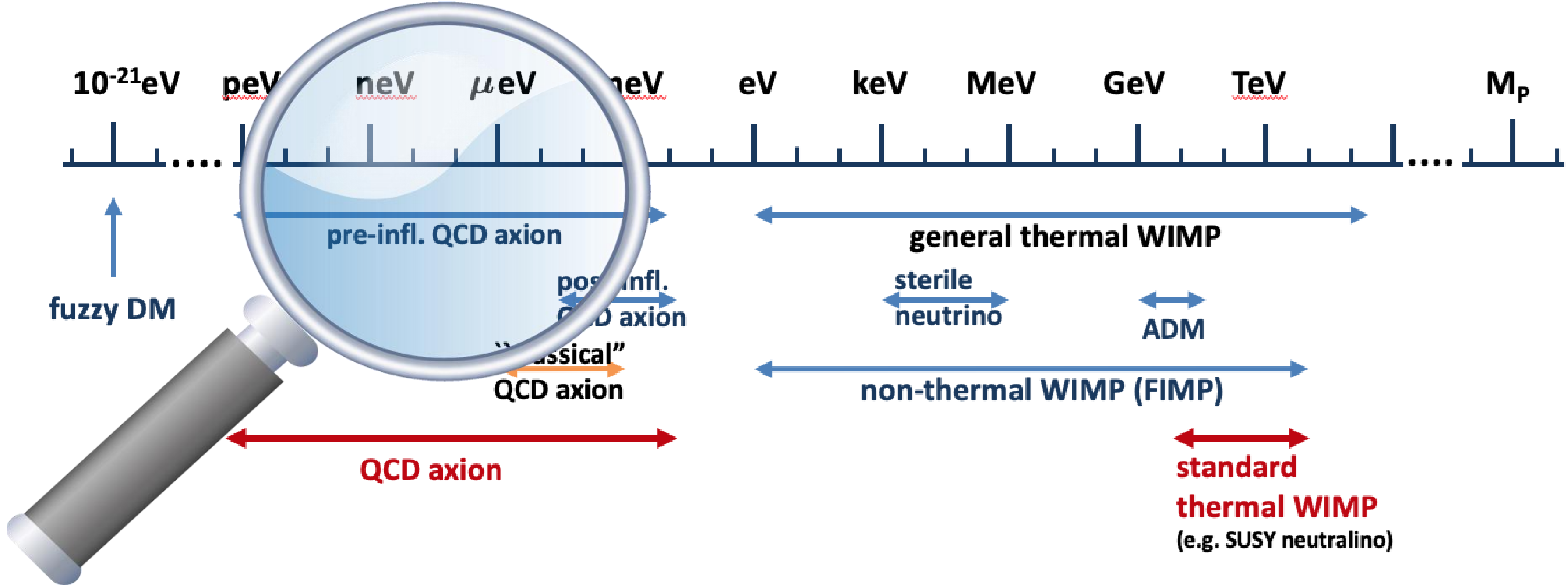
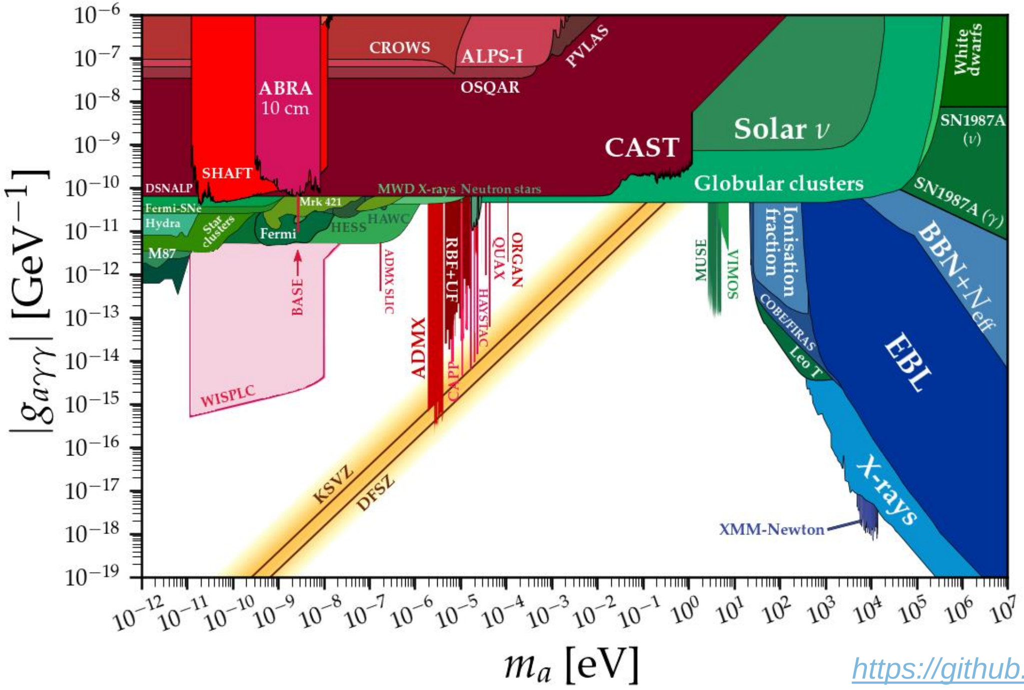
WISPLC: Search for Dark Matter with LC Circuit

Based on Phys. Rev. D 106, 023003 ***ZZ***, ***OG***, *Dieter Horns*

WIMPs and WISPs



Axion as Particle Dark Matter: Constraints



https://github.com/cajohare/AxionLimits

Axions and ALPs

- Axions are light bosons invoked to solve the strong CP problem
- ALPs are not bound by $m_a^2 f_a^2 \approx m_\pi^2 f_\pi^2$
- They can interact with Standard Model particles, electrons, protons, neutrons, photons etc.
- Most notably their coupling with photon $\mathscr{L}_{a\gamma} = \frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$
- In terms of electric and magnetic field $\mathscr{L}_{a\gamma} = g_{a\gamma} a \mathbf{E} \cdot \mathbf{B}$

ALPs Electromagnetism

In presence of axions, Maxwell's equations are modified as

$$\nabla \cdot \mathbf{E} = g\mathbf{B} \cdot \nabla a + \rho_{\text{el}}$$

$$\nabla \times \mathbf{B} - \frac{\partial \mathbf{E}}{\partial t} = g_{a\gamma\gamma}\left(\mathbf{E} \times \nabla a - \mathbf{B}\frac{\partial a}{\partial t}\right) + \mathbf{j}_{\text{el}}$$

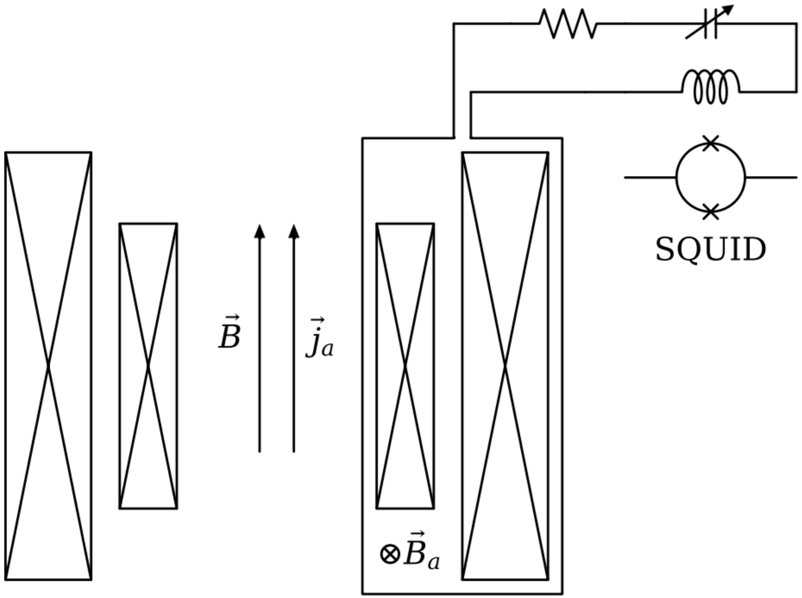
ALPs Electromagnetism

- Axion as a coherent oscillating scalar field $a(t) = a_0 \cos\left(m_a t\right) = \frac{\sqrt{2\rho_{\mathrm{DM}}}}{m_a} \cos\left(m_a t\right)$
- In presence of external B field, axion-sourced current density $\mathbf{j}_a(t) = -g_{a\gamma\gamma}\mathbf{B}\frac{\partial a}{\partial t}$

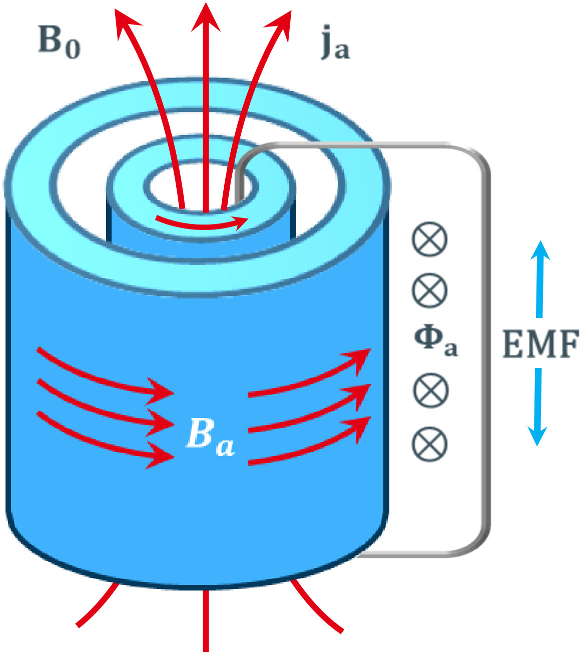
  such that $\nabla \times \mathbf{B}_a = \mathbf{j}_a$
- The current oscillates with frequency $\omega = m_a\left(1 + \frac{1}{2}\mathbf{v}\cdot\mathbf{v}\right)$

Detection Scheme

- The external magnetic field converts axions into an oscillating displacement current $\mathbf{j}_a$
- The oscillating current in turn induces a toroidal magnetic field $\mathbf{B}_a \perp \mathbf{j}_a$
- The toroidal magnetic field creates an alternating EMF
- EMF induces current in pickup loop
- Pumped by an LC circuit and picked up by SQUID magnetometer



Experimental Design



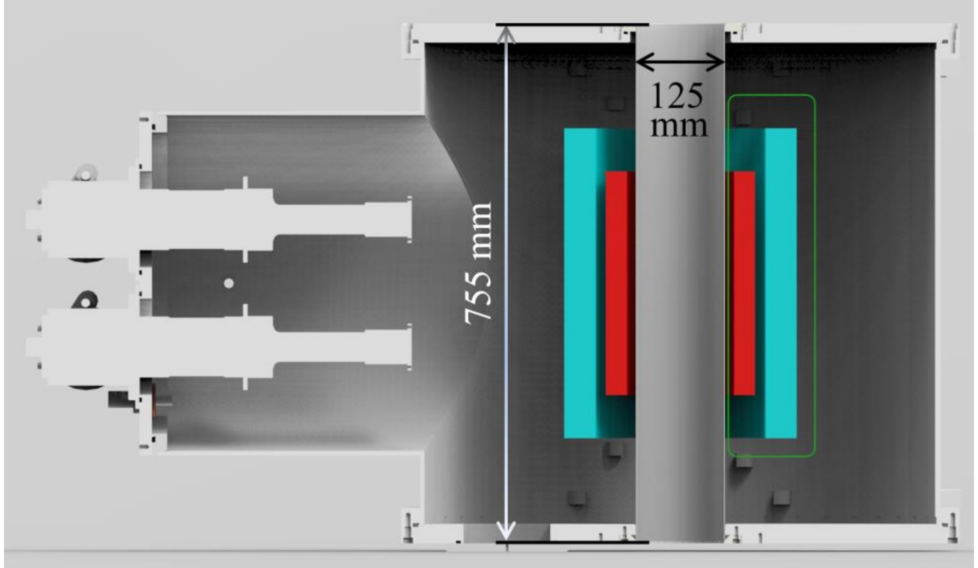
$$\mathbf{J}_\mathbf{a} = -g_{a\gamma\gamma}\, \mathbf{B}_0 \frac{\partial a}{\partial t} = g_{a\gamma\gamma}\sqrt{2\rho_{DM}}\, \mathbf{B}_0 \sin(m_a t)$$

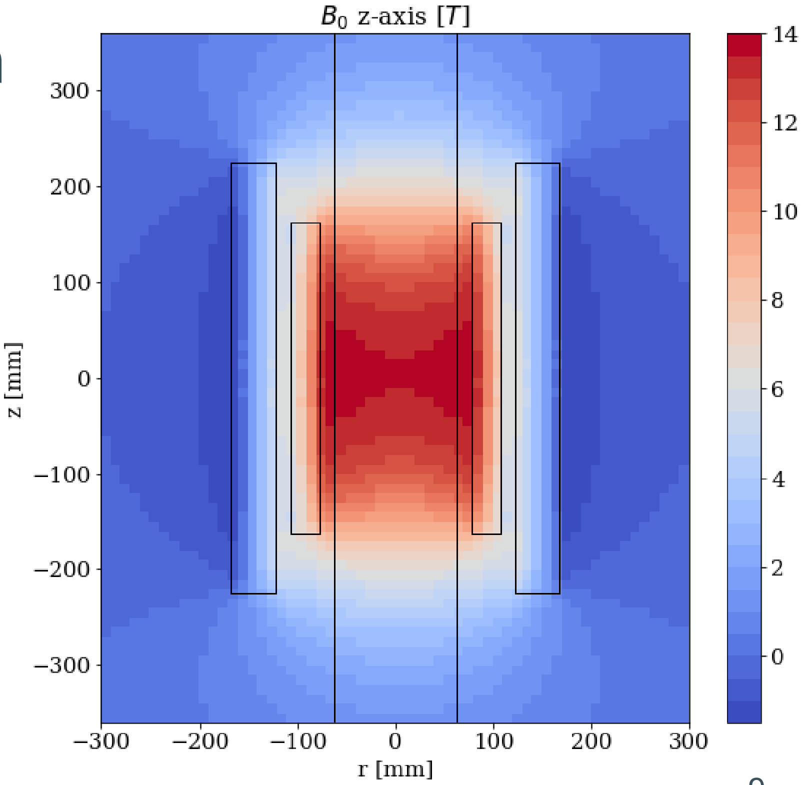
$$\mathbf{B}_\mathbf{a} = g_{a\gamma\gamma}\sqrt{2\rho_{DM}} \sin(m_a t) \int \frac{\mathbf{B}_0 \times (\mathbf{r} - \mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|^3} dV$$

$$\Phi_a = g_{a\gamma\gamma}\sqrt{2\rho_{DM}} \sin(m_a t) \int_{\text{loop}} dA \int \frac{\mathbf{B}_0 \times (\mathbf{r} - \mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|^3} dV \cdot \hat{\mathbf{n}}_{\text{loop}}$$

$$\text{EMF} = -\frac{d\Phi_a}{dt} \quad \Longrightarrow \quad I(t) \approx -\frac{\Phi_a}{L_{\text{sys}}}$$

14T Cryogen-free Magnet System





Comparison Factor *C*

$$\mathcal{G}_V = \frac{1}{|\mathbf{B}_{0,\max}| V_{\mathrm{magnet}}} \int_{\mathrm{loop}} dS \int \frac{\mathbf{B}_0(\mathrm{r}) \times (\mathbf{r} - \mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|^3} dV \cdot \hat{\mathbf{n}}_{\mathrm{loop}} \rightarrow |\Phi_{a,\max}| = g_{a\gamma\gamma}\sqrt{2\rho_{DM}}\, \underbrace{|\mathbf{B}_{0,\max}|\, \mathcal{G}_V\, V_{\mathrm{magnet}}}_{\text{comparison factor } C}$$

TABLE I. Comparison of experimental parameters between WISPLC, ABRA. and SHAFT, $C = |\mathbf{B}_{0,\max}| V_{\mathrm{magnet}} \mathcal{G}_{\mathrm{V}}$.

	$\lvert\mathbf{B}_{0,\max}\rvert$ (T)	$\mathcal{G}_{\mathrm{V}}$	V_{magnet} (m^3)	C/C_{SHAFT}
SHAFT[a]	1.5	0.108[b]	9.5×10^{-5}	1
ABRA.[c]	1	0.027	8.9×10^{-4}	1.55
WISPLC	14	0.074	2.4×10^{-2}	1.60×10^{3}

SQUID Current Sensor

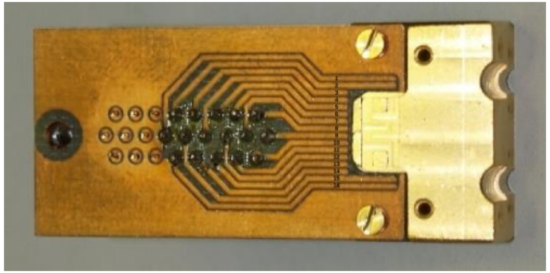
Integrated two-stage current sensor from Magnicon with 16-SQUID series array amplifier readout

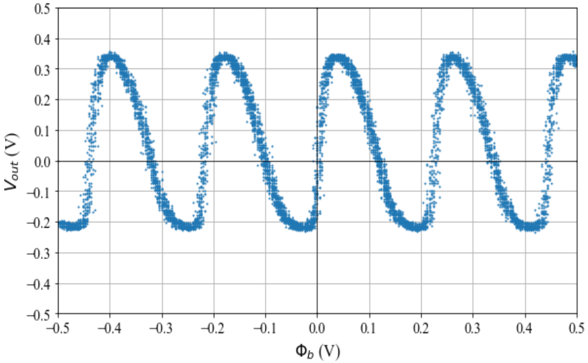
Characterised at 3 K

bandwidth ~ 2 MHz

$V_\Phi \approx 2500\ \mu V/\Phi_0$ @FLL

Measured flux noise $S_\Phi^{1/2} \approx 1\ \mu\Phi_0/\sqrt{\mathrm{Hz}}$



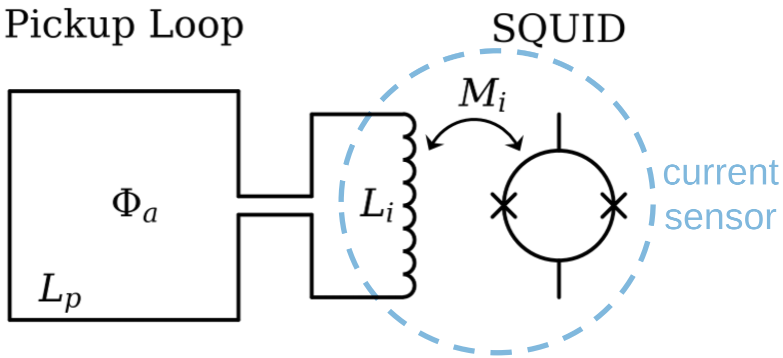


Experiment Design

- Broadband detection

$$\Phi_{\mathrm{SQUID}} \approx M_{\mathrm{i}}\left(L_{\mathrm{p}} + L_{\mathrm{i}}\right)^{-1} \Phi_a$$

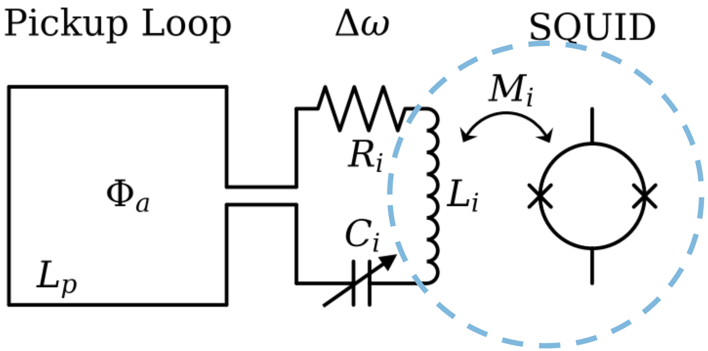
flux transfer eff.: $\kappa = \Phi_a / \Phi_{\mathrm{SQUID}} \approx 10^{-4}$



- Resonant detection

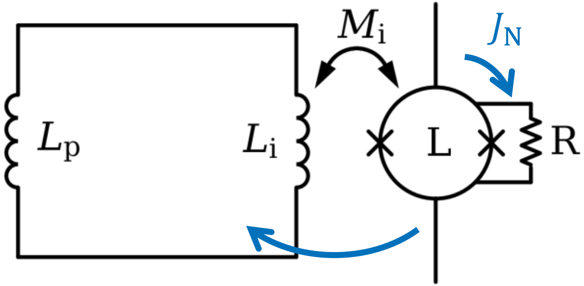
$$\Phi_{\mathrm{SQUID}} \approx Q M_{\mathrm{i}}\left(L_{\mathrm{p}} + L_{\mathrm{i}}\right)^{-1} \Phi_a$$

$$Q \sim 10^4$$



SQUID Noise

- Broadband



$Z_\mathrm{r} \approx \omega^2 M_\mathrm{i}^2/2R$

SQUID output voltage noise

$$S_{V,\mathrm{T}} = 2\gamma_V k_\mathrm{B}(T + T_\mathrm{N})R$$

reduced spectra $\gamma_V \approx 8,\ \gamma_J \approx 5.5$ and $\gamma_{VJ} \approx 6$

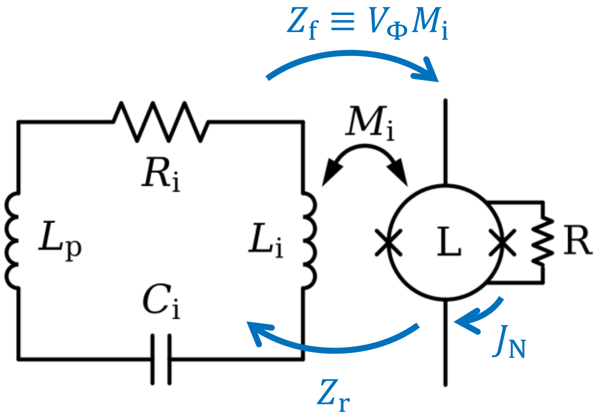
$$T_\mathrm{N} = \frac{\gamma_J \omega^2 M_\mathrm{i}^4 V_\Phi^2}{\gamma_V \left|j\omega(L_\mathrm{i} + L_\mathrm{p}) + Z_\mathrm{r}\right|^2 R^2} + \frac{2\gamma_{VJ}\omega M_\mathrm{i}^2 V_\Phi}{\left|j\omega(L_\mathrm{i} + L_\mathrm{p}) + Z_\mathrm{r}\right| R}$$

$j\omega(L_\mathrm{i} + L_\mathrm{p}) \gg Z_\mathrm{r}$, frequency independent

→ $T_\mathrm{N} \approx 10\ \mathrm{mK}$

SQUID Noise

- Resonant



Total SQUID output voltage noise

$$S_{V,\mathrm{T}} = S_V + \omega^2 M_\mathrm{i}^2 \left(\frac{Z_\mathrm{f}}{Z_\mathrm{T}}\right)^2 S_J + 2\omega M_\mathrm{i} \frac{Z_\mathrm{f}}{Z_\mathrm{T}} S_{VJ} + S_{R_\mathrm{i}} \left(\frac{Z_\mathrm{f}}{Z_\mathrm{T}}\right)^2$$

SQUID-sourced noise
at resonant freq. $\sim \mu\Phi_0/\sqrt{\mathrm{Hz}}$

Dominating output noise is the Johnson-Nyquist noise from the losses of the input circuit $S_{R_\mathrm{i}} = 4k_\mathrm{B}TR_\mathrm{i}$

can be significantly reduced by using superconducting resonator designs (Devlin et al. 2021)

Sensitivity

Axion coherence time: $\tau \sim \frac{10^{-6}}{m_a}$

$$\mathrm{SNR} = \begin{cases} \frac{\Phi_{\mathrm{SQUID}}}{S_{\Phi}^{1/2}}\, t^{1/2}, & t \leq \tau_a \\ \frac{\Phi_{\mathrm{SQUID}}}{S_{\Phi}^{1/2}}\, (t\,\tau_a)^{1/4}, & t > \tau_a \end{cases}$$

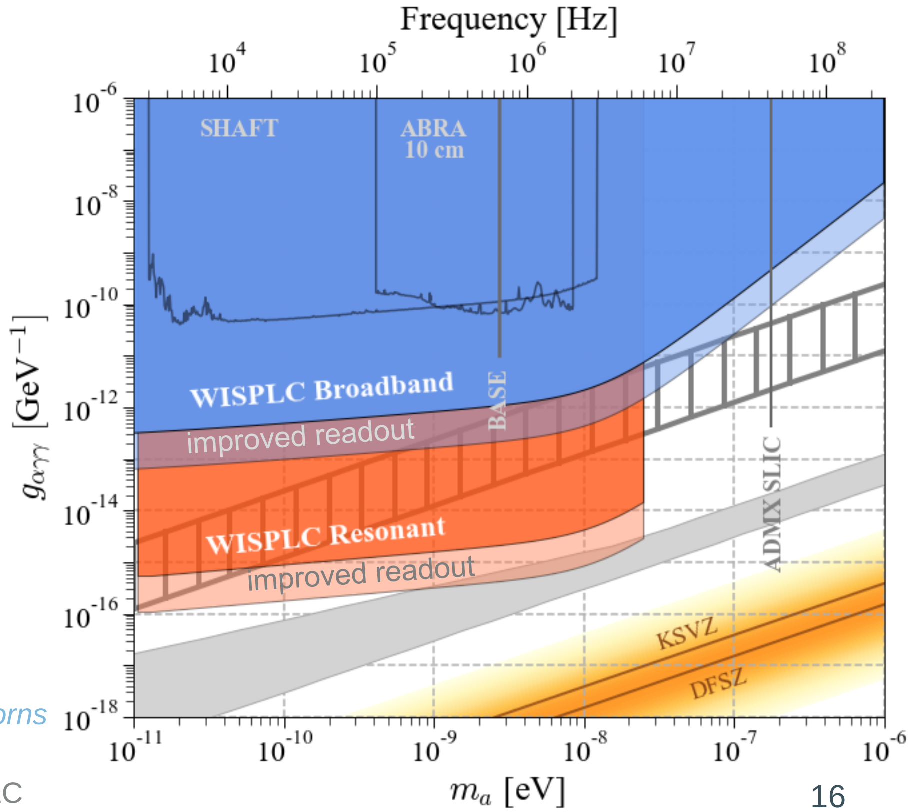
Sensitivity

$$g_{a\gamma\gamma,2\sigma} \gtrsim 8\times 10^{-13}\,\mathrm{GeV}^{-1}\left(\frac{m_a}{10^{-9}\,\mathrm{eV}}\right)^{1/4}\left(\frac{\sigma_v}{10^{-3}}\right)^{1/2}\left(\frac{\rho_{\mathrm{DM}}}{0.3\,\mathrm{GeV/cm^3}}\right)^{-1/2}\left(\frac{\kappa}{4\times 10^{-4}}\,\frac{C}{0.025\,\mathrm{m^3T}}\right)^{-1}\left(\frac{t}{100\text{ days}}\right)^{-1/4}\left(\frac{S_\Phi^{1/2}}{0.9\,\mu\Phi_0/\sqrt{\mathrm{Hz}}}\right)$$

Effective improvement of resonant readout:

$$Q_{\mathrm{res}} \approx 10^4\left(\frac{t_{\mathrm{Res}}}{t_{\mathrm{BB}}}\right)^{1/4} \approx 515$$

Phys. Rev. D 106, 023003 **ZZ**, **OG**, Dieter Horns



Current Status

- 14 T magnet in commissioning phase
- successfully reached full field
- next step: integration of the detector

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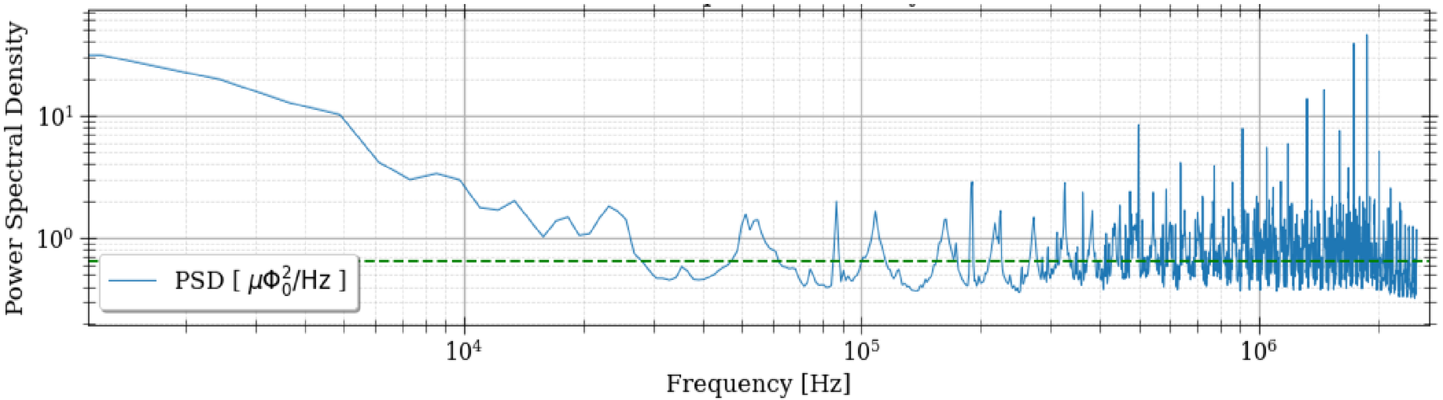
Thank You

Twitter: @goindrila @DH0rns

UHH Astroparticle: https://www.physik.uni-hamburg.de/en/iexp/gruppe-horns/forschung.html

Backup Slides

SQUID Noise measurement, 1 sec, unshielded



COMSOL Simulation