Universität Hamburg
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FAKULTÄT
FÜR MATHEMATIK, INFORMATIK
UND NATURWISSENSCHAFTEN

DESY.

Colloquium for the Bachelor Thesis

Parametrics of Heterodyne Axion Detection with SRF Cavities

Speaker: Tom Krokotsch

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Universität Hamburg, DESY

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Outline

1) A new particle?

2) Heterodyne axion detection

3) Limiting factors

4) Prospective sensitivity

A New Particle?

Strong CP problem → **QCD Axions**

Nature of dark matter → **DM Axions**

Properties of axions:

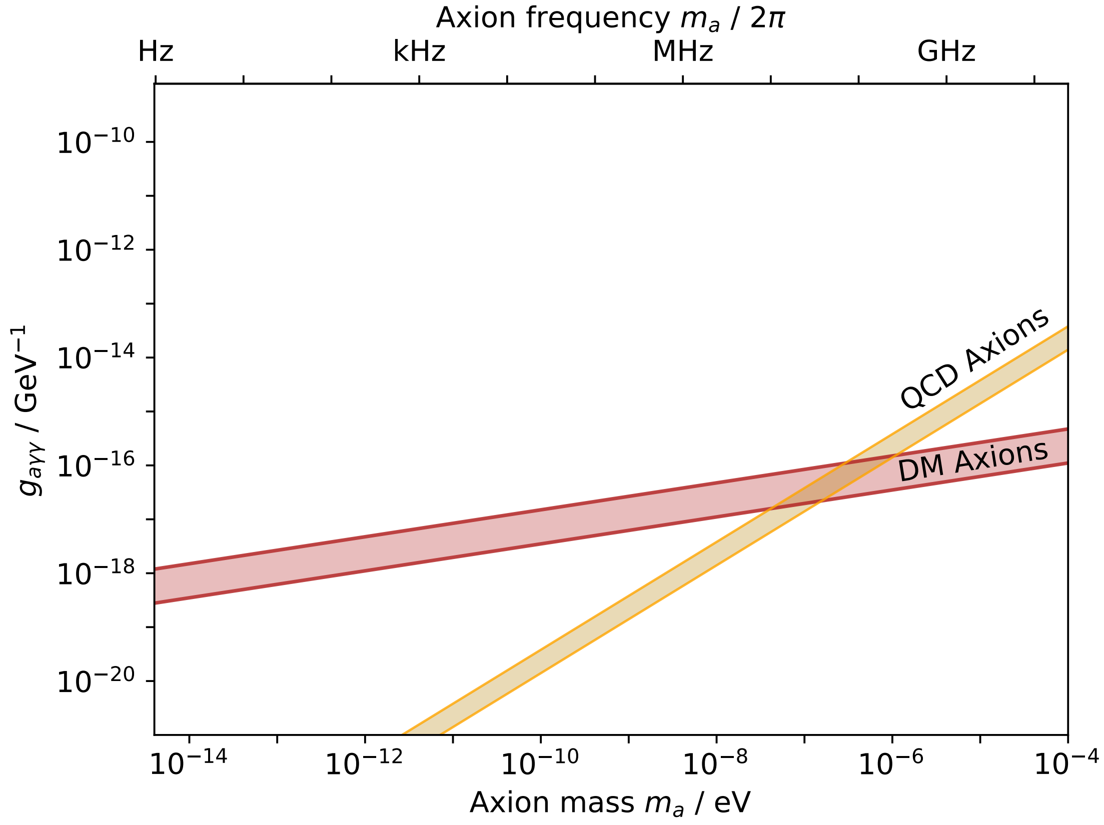
Charge: $q = 0$

Spin: $S = 0$

EM-interaction: $\mathcal{L} \supset -g_{a\gamma\gamma}\, a\, \mathbf{E} \cdot \mathbf{B}$

Axion field: $a(t) \propto \cos m_a t$

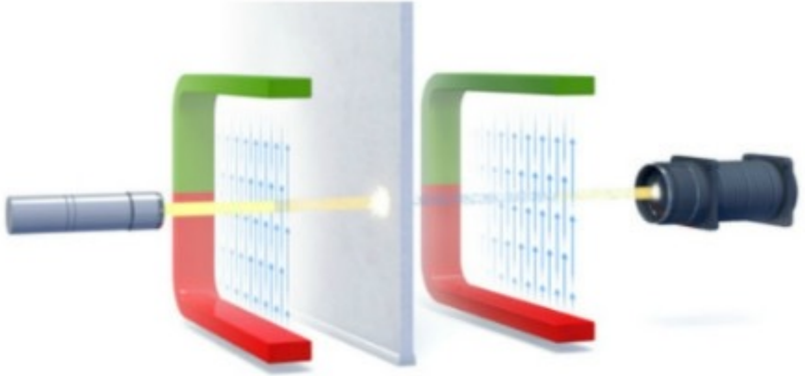
m_a and $g_{a\gamma\gamma}$: Barely constrained



Current Axion Searches

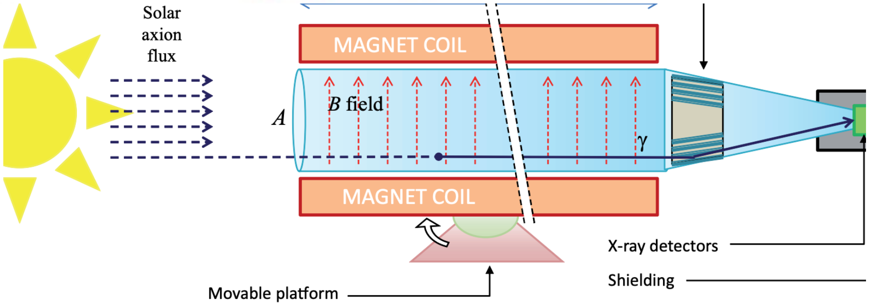
Laboratory Axions: **ALPS II**

alps.desy.de



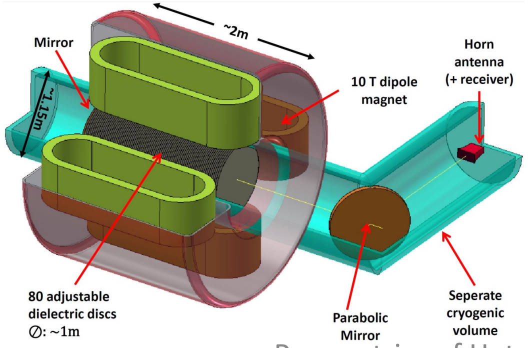
Solar Axions: **(Baby)-IAXO**

Majorovits, 2017
(arXiv:1712.01062)

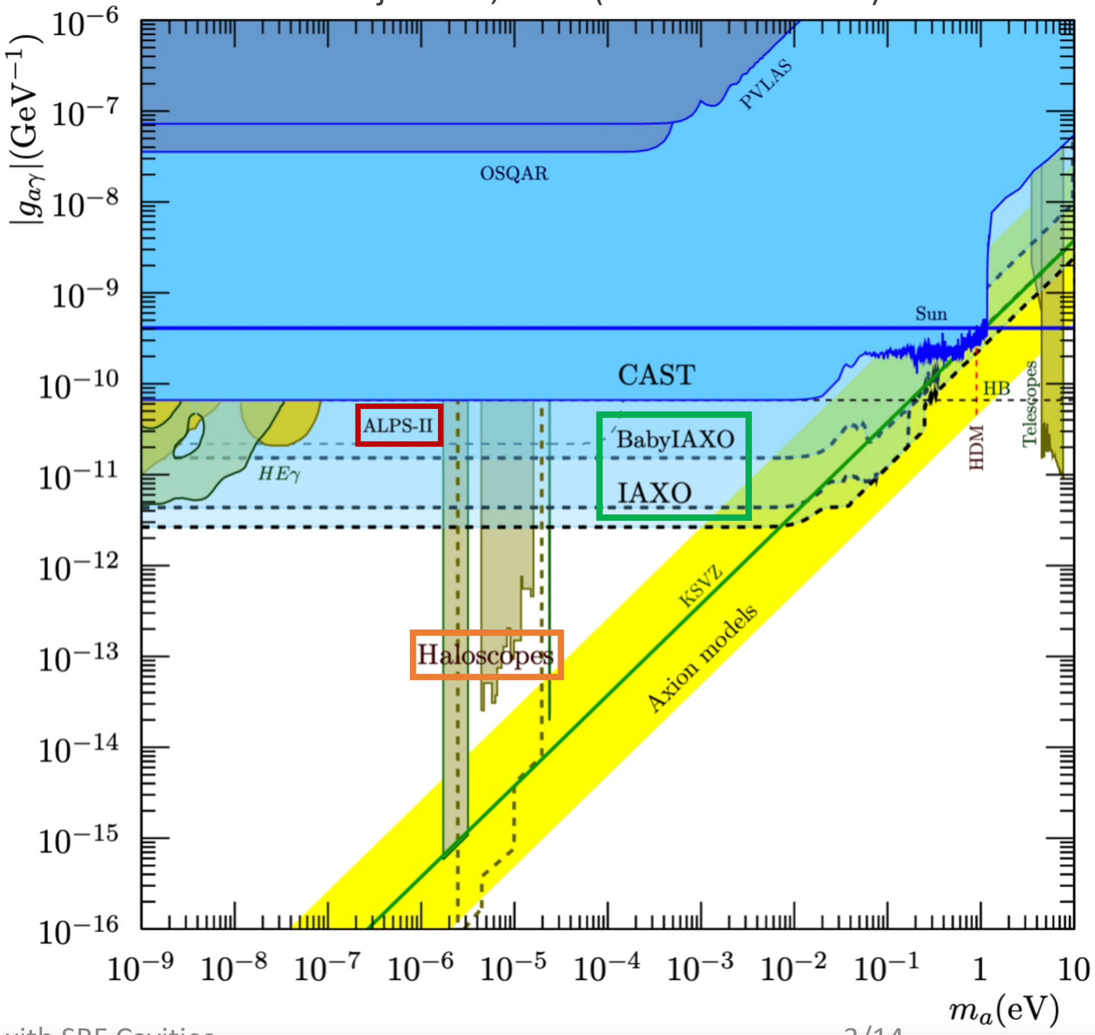


Cosmic Axions: **MADMAX**

Armengaud et al., 2019
(arXiv:1904.09155)

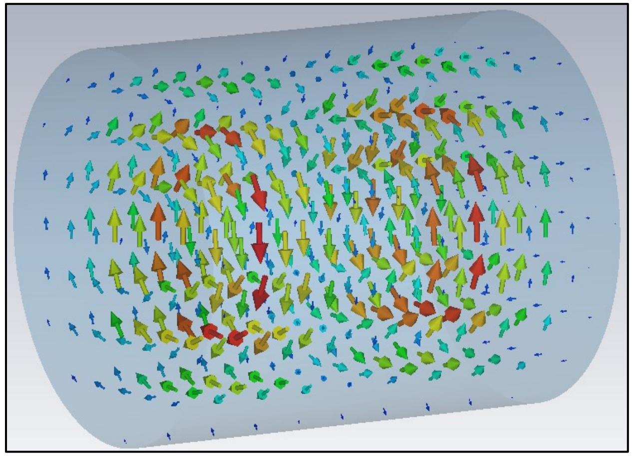


Majorovits, 2017 (arXiv:1712.01062)



Superconducting Radio Frequency Cavities

E-field of an eigenmode in a cylindrical cavity



9-cell cavity designed for modern particle accelerators

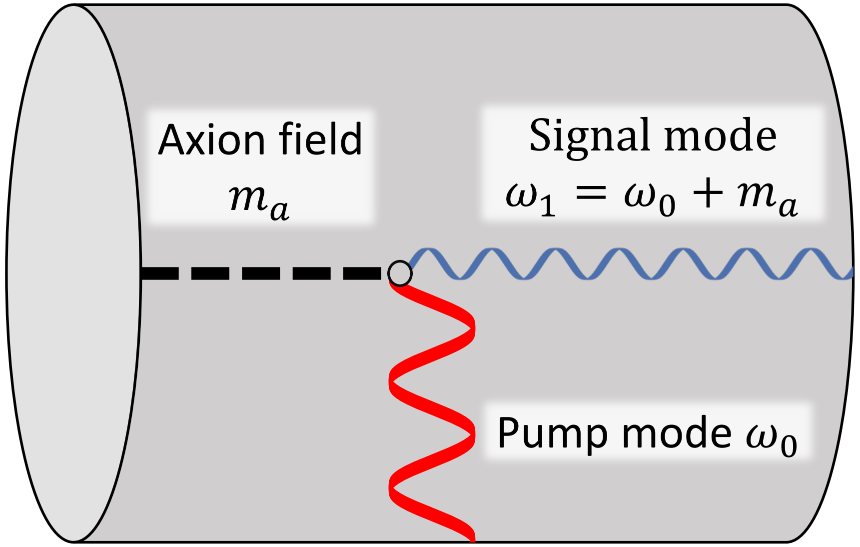
Quality factor: $Q_{SRF} \propto \frac{\text{stored energy}}{\text{dissipated energy per cycle}} \propto 10^{10}$ $(Q_{\text{normal conducting}} \propto 10^4)$

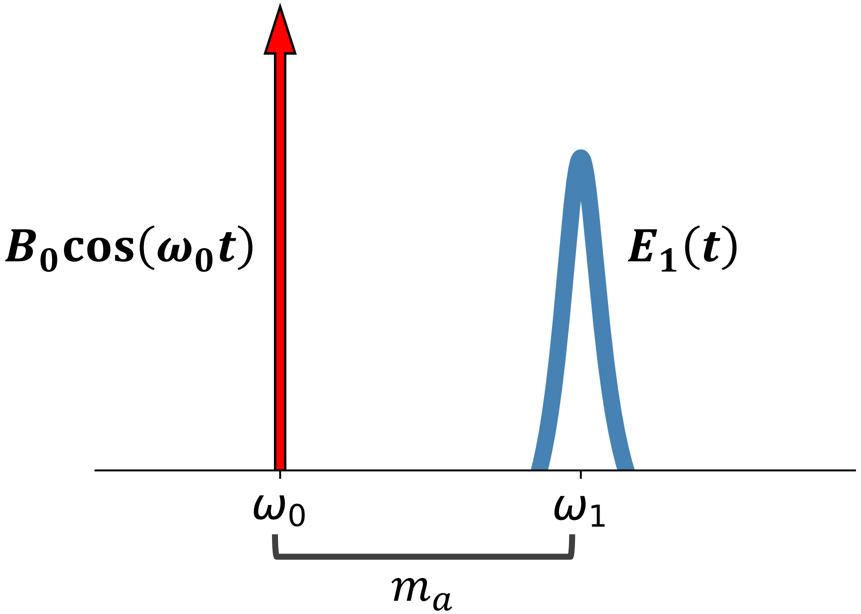
Frequencies: $f \propto \text{GHz}$

Material: Niobium ($T_c \approx 9.2\text{ K},\ B_c \approx 0.2\text{ T}$)

Heterodyne Axion Detection

$\mathcal{L} \supset -g_{a\gamma\gamma}\, a\, \mathbf{E}\cdot\mathbf{B} \quad \Rightarrow \quad$ current density: $\quad J_{\text{eff}}(\omega_1) \propto g_{a\gamma\gamma}\, B_0(t)\, \partial_t a(m_a t)$



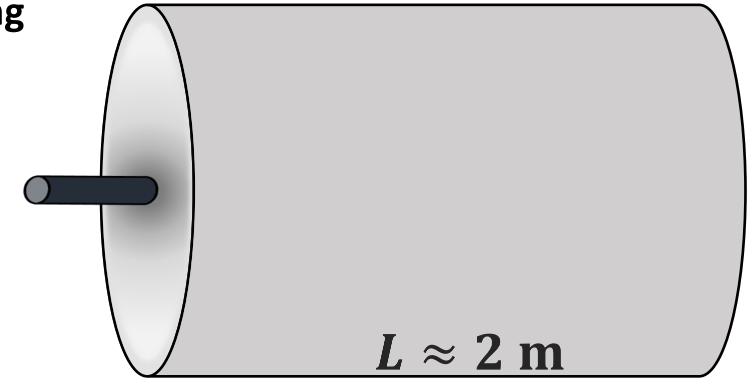


Coupling strength $\longrightarrow$ Overlap factor $C_{01} = \dfrac{\left|\int_V \mathbf{E}_1^*\cdot\mathbf{B_0}\right|^2}{\int_V|\mathbf{E_1}|^2\cdot\int_V|\mathbf{B}_0|^2}$

Scanning Over Axion Masses

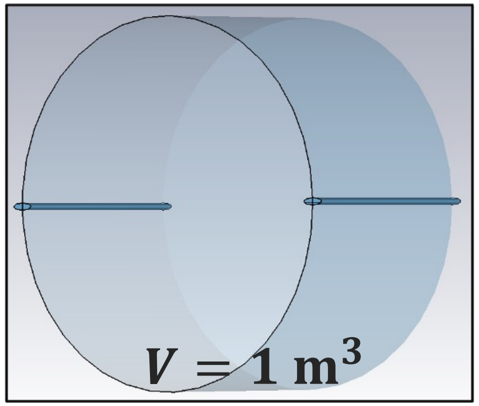
Piezo element pressing into cavity wall:

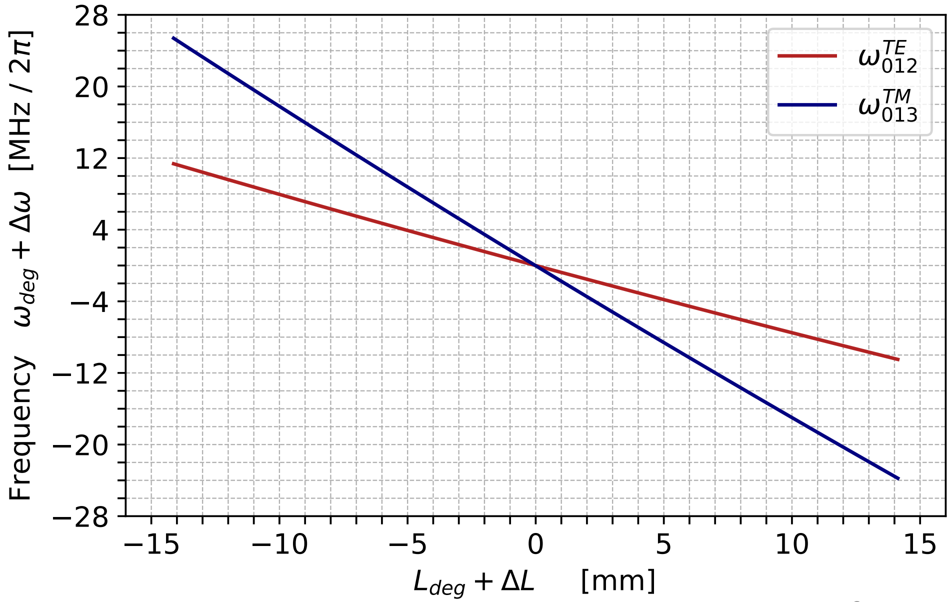
$\Delta m_a \propto 1 \text{ MHz}$

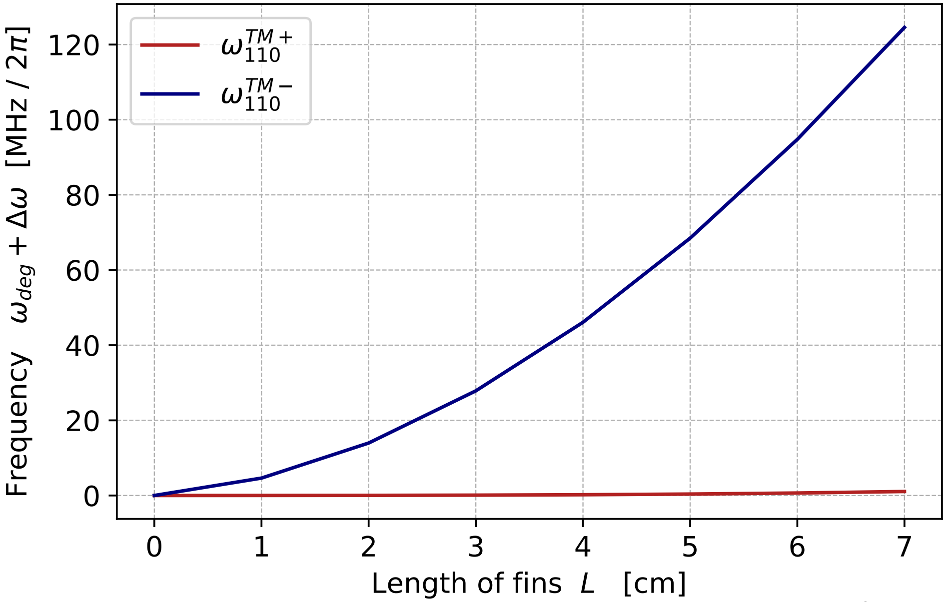


Introducing retractable fins:

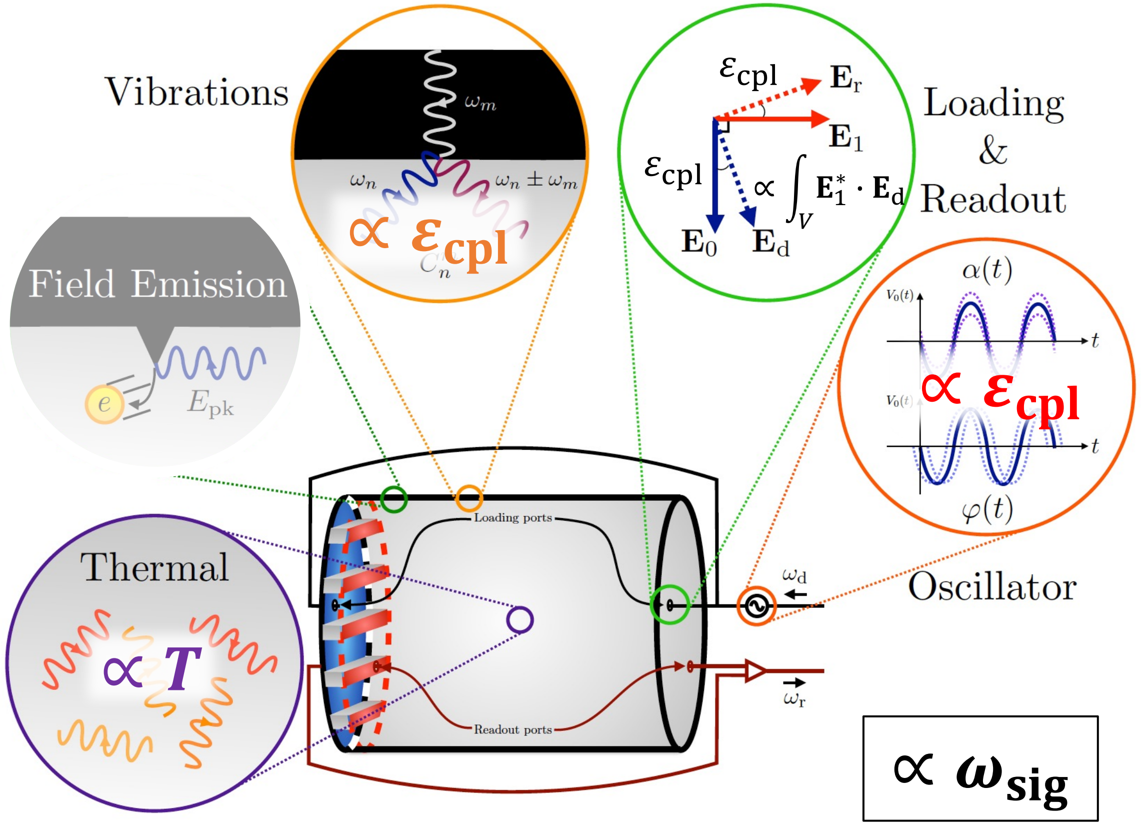
$\Delta m_a \propto 100 \text{ MHz}$



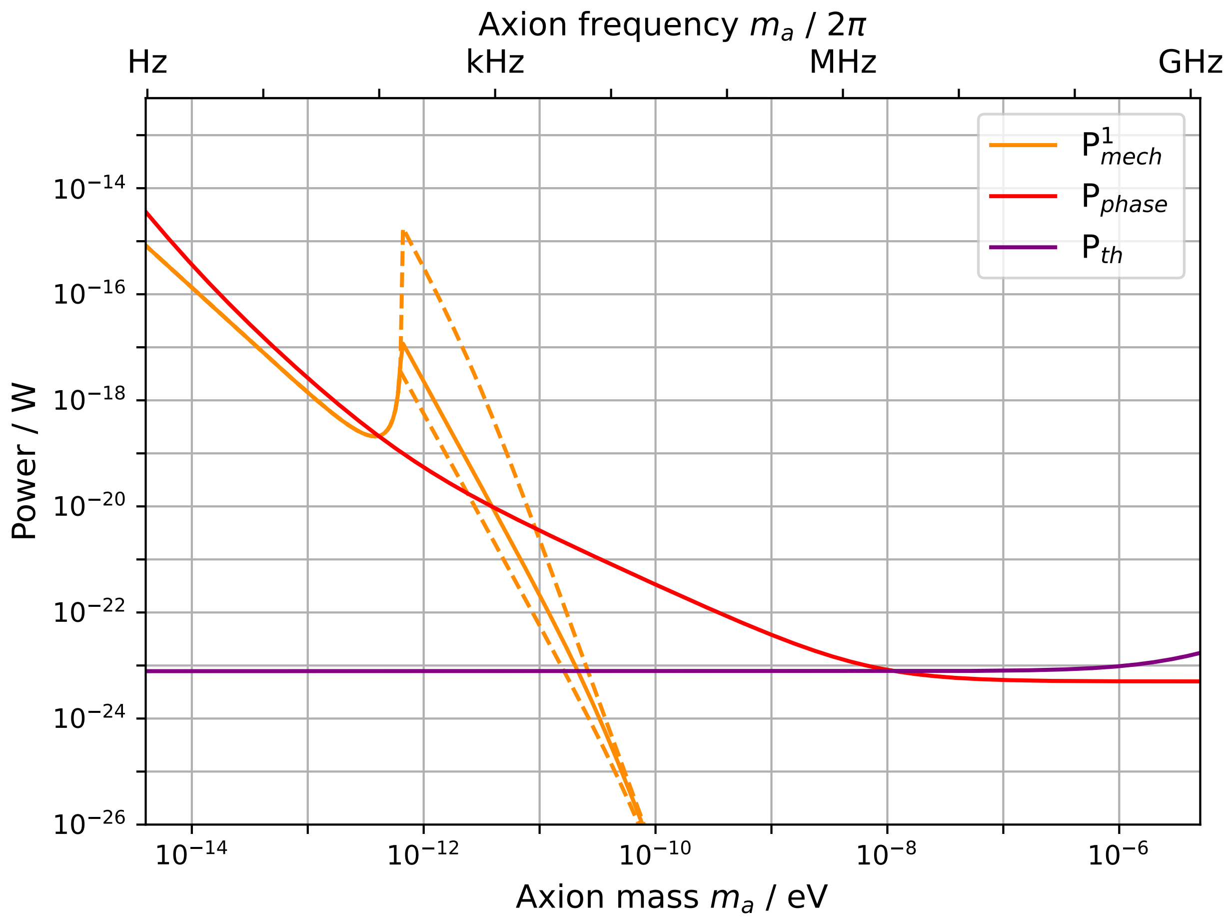




Noise Sources

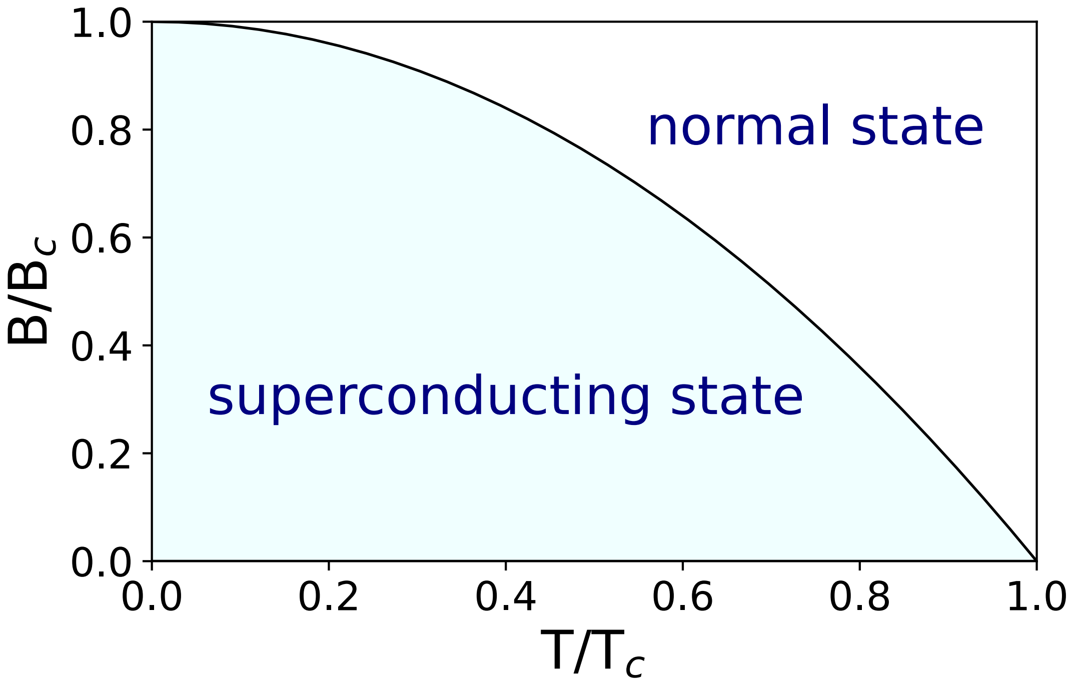


Berlin, D'Agnolo, Ellis et al., 2019 (arXiv:1912.11048v1)

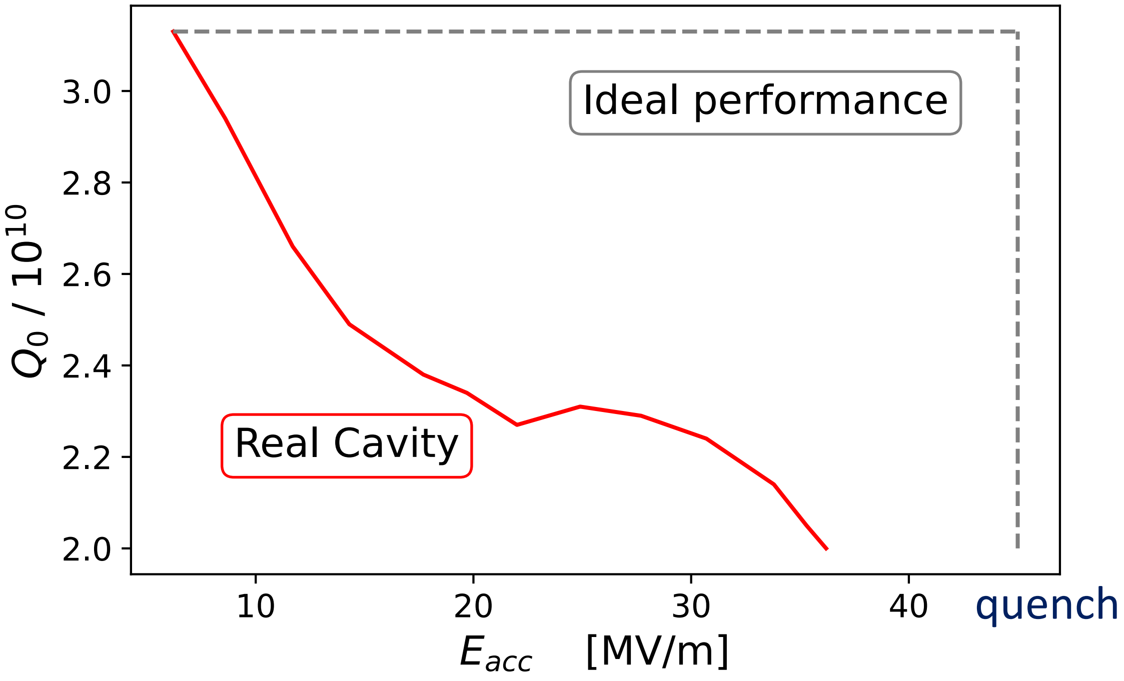


Quench Limit

Superconductivity breakdown:



Quality factor behaviour:



$B_c \approx 0.2$ T for Niobium $\quad\Longrightarrow\quad$ Energy in pump mode $U_{\text{pump}} \propto \int_V |\boldsymbol{B}(\boldsymbol{r})|^2$ limited

Axion Sensitivity

$$P_{\text{signal}} \propto g_{a\gamma\gamma}^2\, C_{01}\, U_{\text{pump}} \cdot \begin{cases} Q_1/\omega_1\,, & \frac{m_a}{Q_a} \ll \frac{\omega_1}{Q_1} \\ Q_a/m_a\,, & \frac{m_a}{Q_a} \gg \frac{\omega_1}{Q_1} \end{cases}$$

Experimental setup:

$Q_{\text{signal}} \sim 10^{10}$

$V \sim \text{m}^3$

$T \sim 1.8\ \text{K}$

$\varepsilon_{\text{cpl}} \sim 10^{-5}$

$t_{\text{int}} \sim 10^7\ \text{s}$

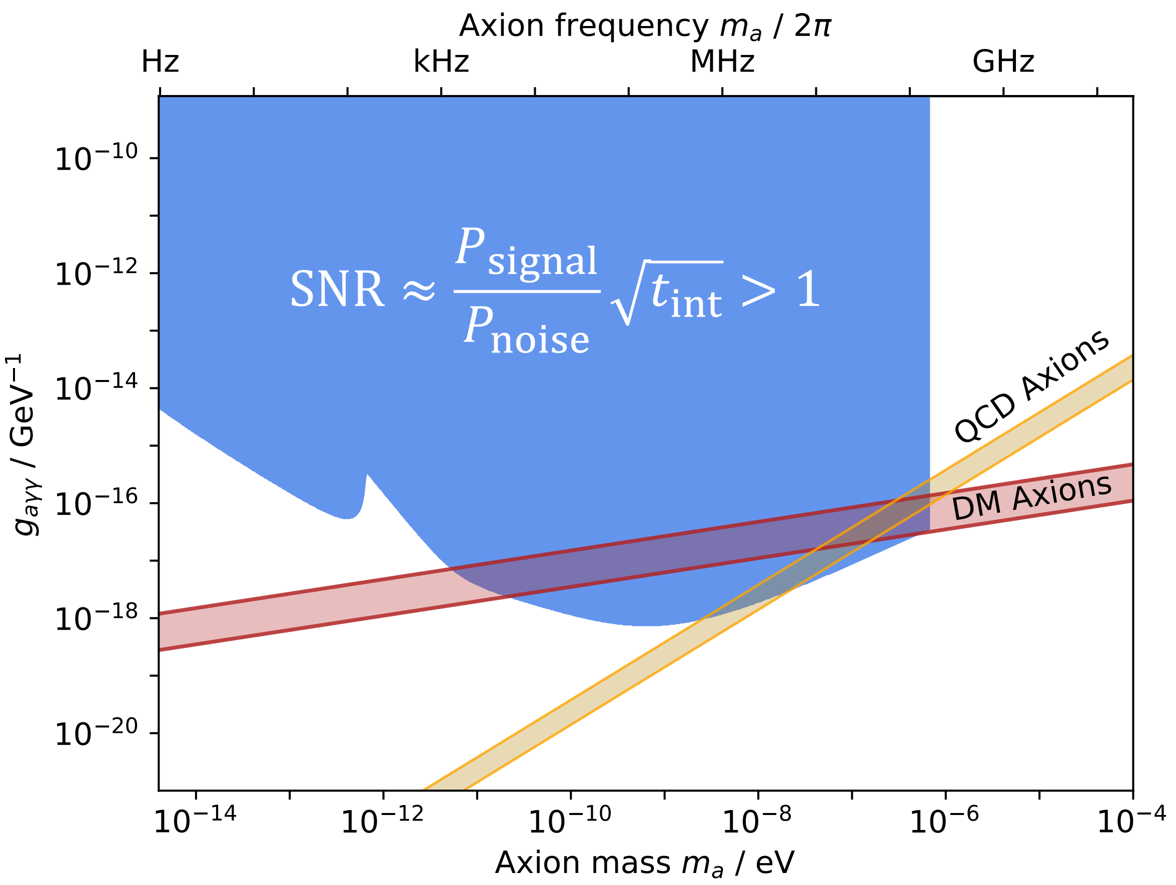
Choice of modes:

$C_{01} \sim 1$

$\omega_{\text{signal}} \sim \text{GHz}$

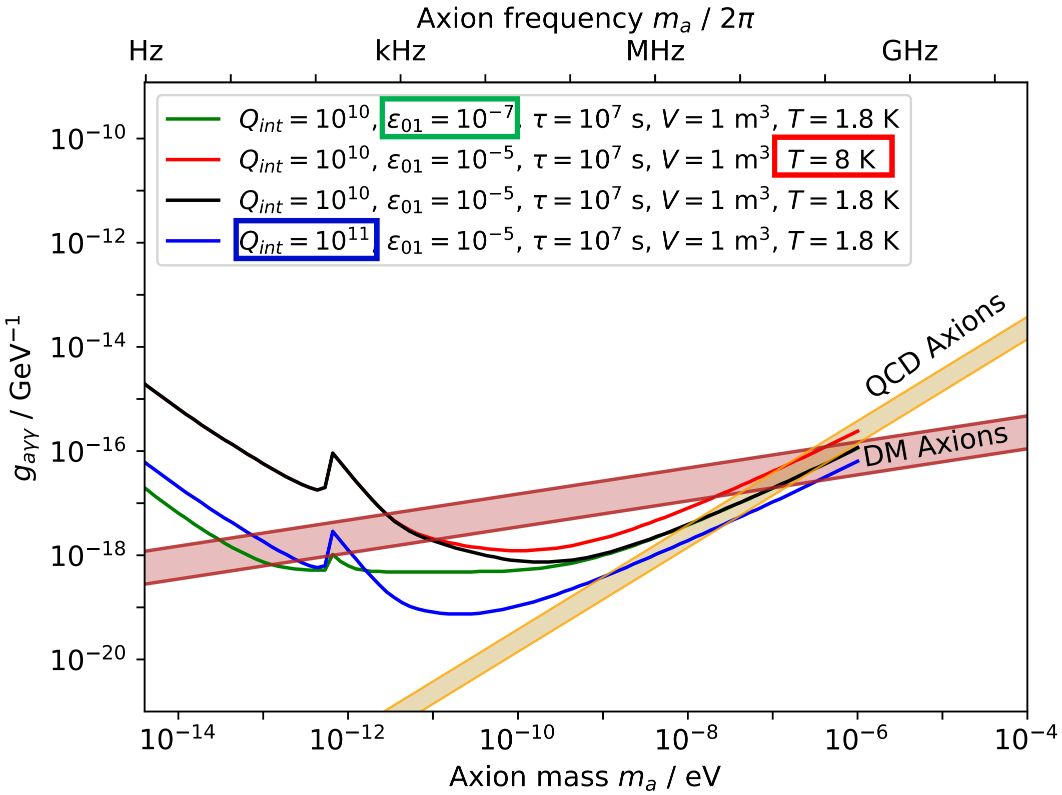
$U_{\text{pump}} \sim (0.2\ \text{T})^2 \cdot V$

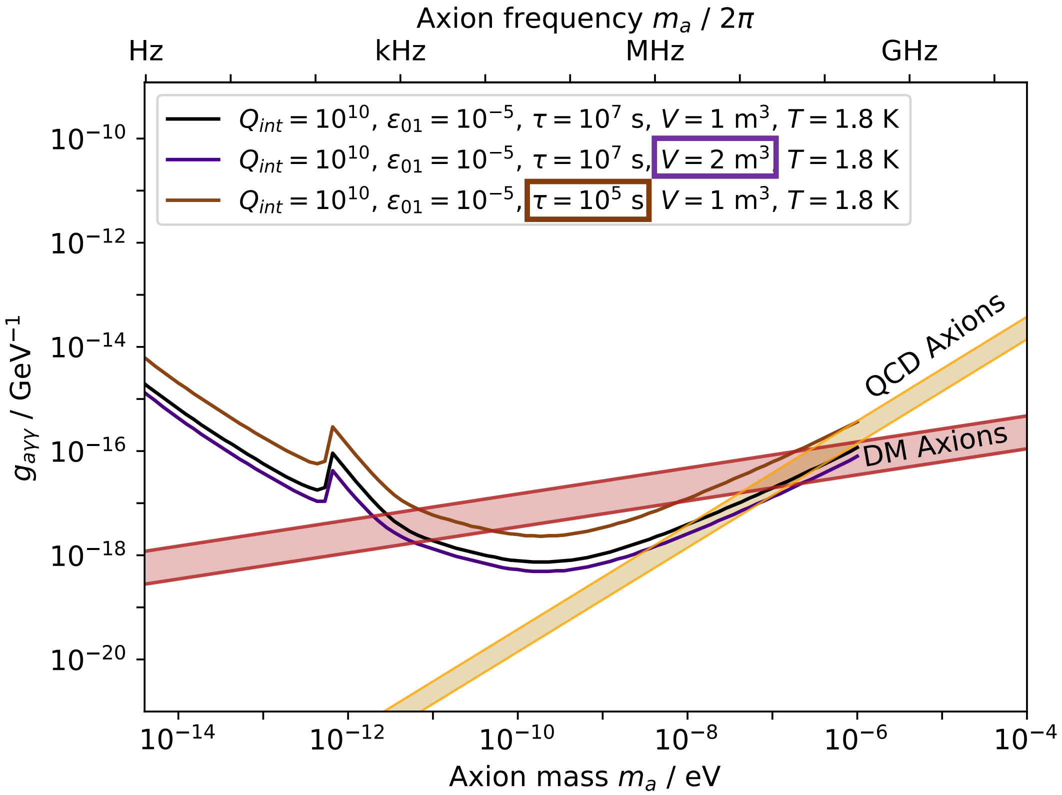
B_c of Niobium



Effects of the Experimental Parameters

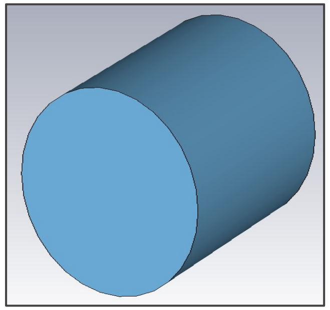
Transition	ω_{modes} (GHz)	C_{01} (%)	U_{pump}/V
Idealised	1.0	100	$(0.2\ \text{T})^2$

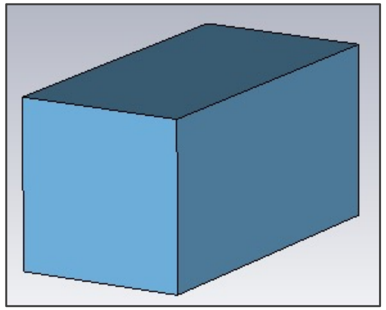




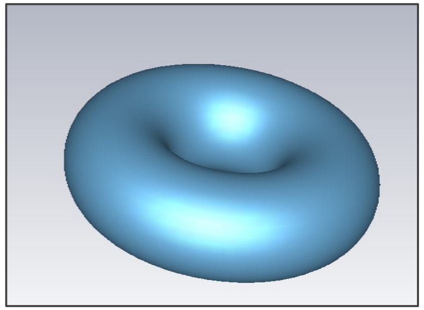
Maximising the Mode Overlap

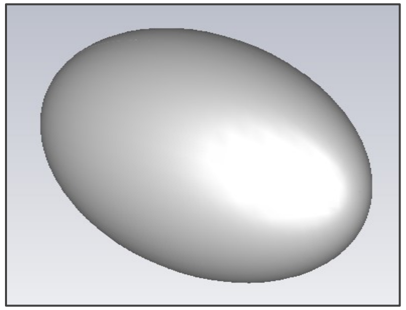
$$P_{\mathrm{sig}} \propto U_{\mathrm{pump}} \cdot C_{01} \cdot g_{a\gamma\gamma}^2 / m_a \,, \qquad V = 1\ \mathrm{m}^3, \qquad C_{01} = \frac{\left|\int_V \mathbf{E}_1^* \cdot \mathbf{B}_0\right|^2}{\int_V |\mathbf{E}_1|^2 \cdot \int_V |\mathbf{B}_0|^2}$$



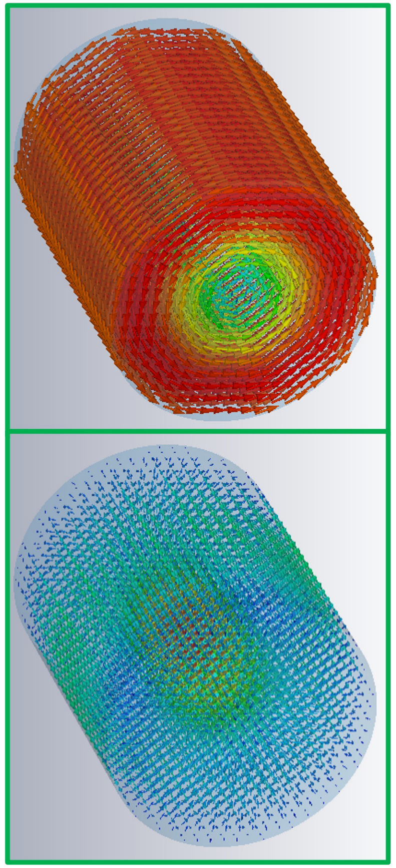


Cavity	ω_{modes} (GHz)		C_{01} (%)
Idealised	*1.0*		***100***
Degenerate:			
Cylinder	0.43		**19**
Cuboid	0.27		**47**
Non-Degenerate:	ω_0	ω_1	
Cylinder	0.22	0.37	**59**
Torus	0.42	0.44	**23**
Ellipsoid	0.25	0.40	**71**





Maximising the Pump Energy



$$P_{\mathrm{sig}} \propto U_{\mathrm{pump}} \cdot C_{01} \cdot g_{a\gamma\gamma}^2 / m_a \,, \quad V = 1\ \mathrm{m}^3, \quad \mathrm{B}_{\mathrm{eff}} = \sqrt{U_{\mathrm{pump}}/V}$$

$$P_{\text{thermal noise}} \not\sim U_{\mathrm{pump}}$$

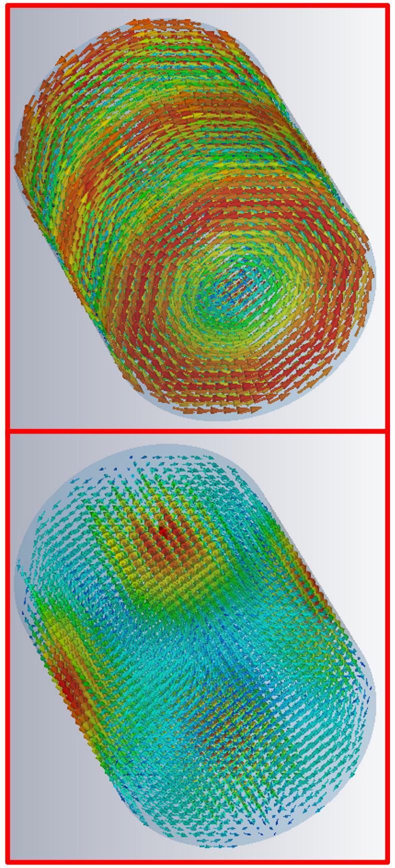
Cavity	ω_{modes} (GHz)	C_{01} (%)	$\mathbf{B_{eff}}$ **(T)**	$C_{01}\ \mathrm{B_{eff}}^2\ (T^2)$
Idealised	*1.0*	*100*	***0.20***	*0.0400*

Degenerate:

Cavity	ω_{modes} (GHz)	C_{01} (%)	$\mathbf{B_{eff}}$ **(T)**	$C_{01}\ \mathrm{B_{eff}}^2\ (T^2)$
Cylinder	0.43	19	**0.12**	0.0027
Cuboid	0.27	47	**0.10**	0.0047

Non-Degenerate:

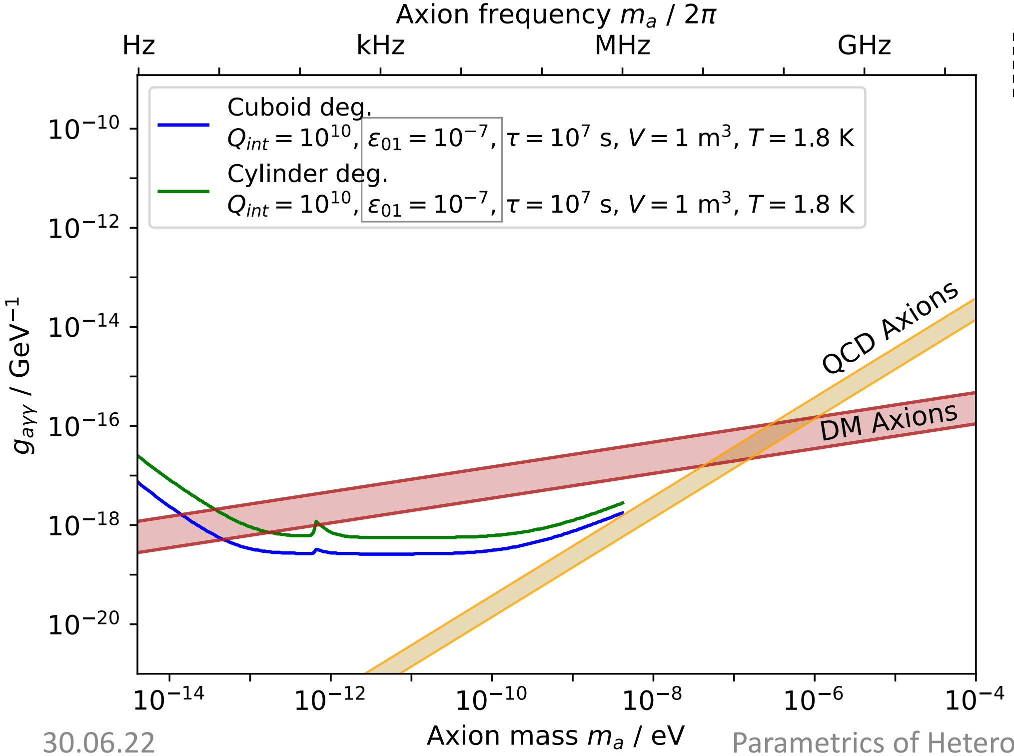
Cavity	ω_0	ω_1	C_{01} (%)	$\mathbf{B_{eff}}$ **(T)**	$C_{01}\ \mathrm{B_{eff}}^2\ (T^2)$
Cylinder	0.22	0.37	59	**0.13**	0.0096
Torus	0.42	0.44	23	**0.09**	0.0018
Ellipsoid	0.25	0.40	71	**0.10**	0.0071



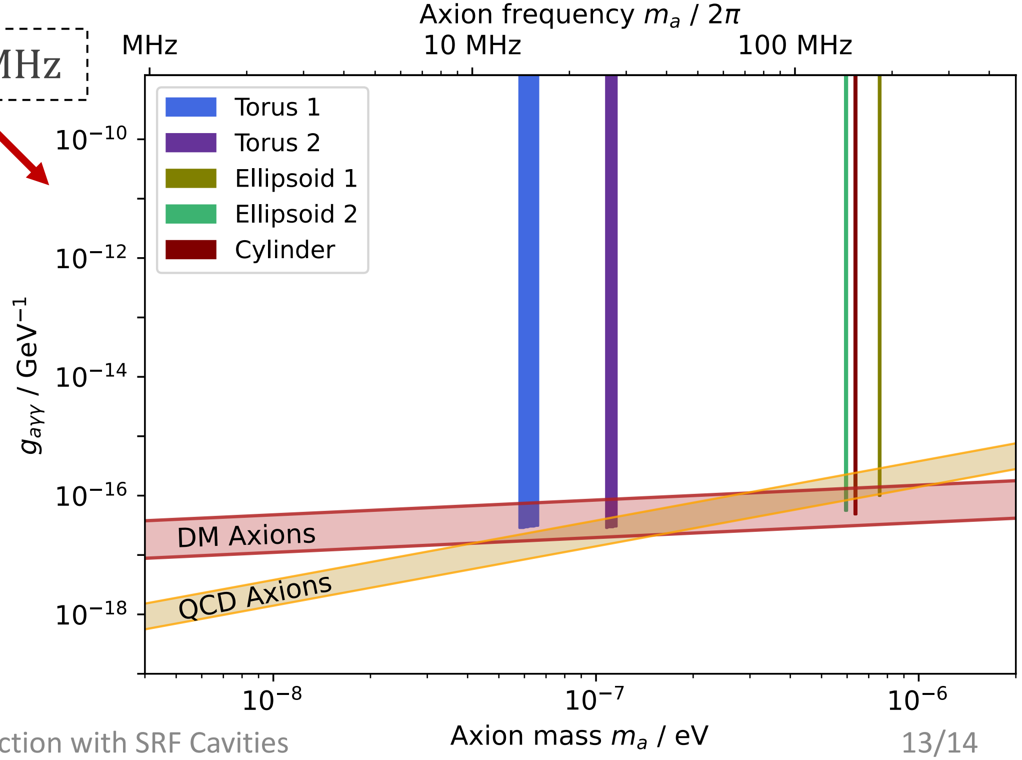
Effects of the Mode Choice

Transition	ω_0 (GHz)	C_{01} (%)	B_{eff} (T)
Cylinder deg.	0.43	19	0.12
Cuboid deg.	0.27	47	0.10

Transition	ω_0 (GHz)	ω_1 (GHz)	C_{01} (%)	B_{eff} (T)
Cylinder	0.22	0.37	59	0.13
Torus 2	0.42	0.44	23	0.09
Ellipsoid 2	0.25	0.40	71	0.10



$\Delta m_a = 1$ MHz



Conclusion and Outlook

What heterodyne axion detection can do:

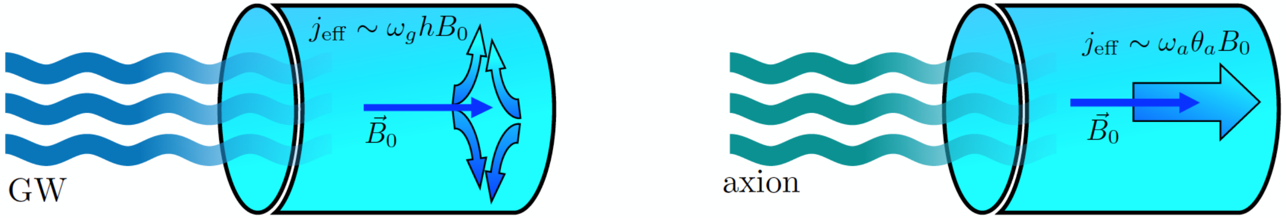
- Axion reach of $\mathbf{Hz} < \boldsymbol{m_a} < \mathbf{GHz}$
- High sensitivities in $\boldsymbol{V} \propto \mathbf{m}^3$ cavities
- Scan over $\boldsymbol{m_a} \propto \mathbf{1 - 100\ MHz}$ in one setup

What is needed:

- SRF cavities with $\boldsymbol{Q} > \mathbf{10^{10}}$
- Good **noise control** (low T, low $\varepsilon_{\mathrm{cpl}}$)
- Mode transition with high **overlap** C_{01} and **pump energy** (in suitable cavity geometry)

Outlook:

- Prototype at CERN
- Gravitational wave detection



Berlin et al., 2021 (arXiv:2112.11465v1)