Università degli Studi di Padova
1222·2022 800 anni

Dipartimento di Scienze Chimiche – Università degli Studi di Padova
prova finale: Laurea Triennale in
Scienza dei Materiali

development and characterization of Superconducting Microwave Cavities for Dark Matter search

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Supervisor: Dra. Braggio Caterina

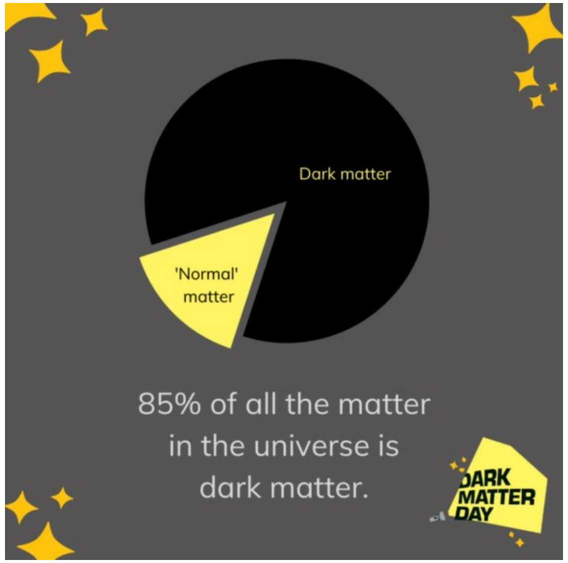
28 October 2022 – AA 2021/2022 – Coorte 2019

Contents

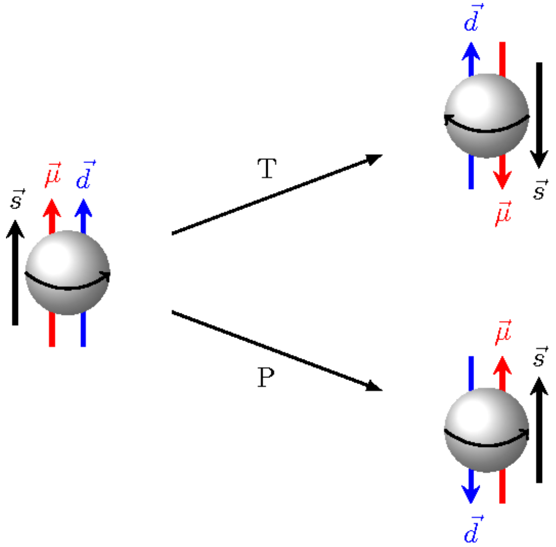
What is an Axion?

non-baryonic Dark Matter candidate
It solves two problems of fundamental physics in one

Weinberg & Wilczek, 1978



STRONG CP PROBLEM

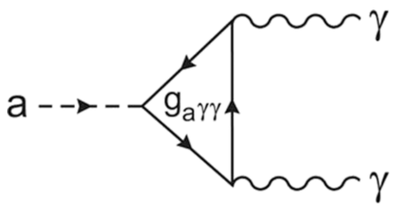


- $m_a \sim 10 - 10^3 \, \mu eV$
- $\rho_a = 0.45 \, GeV/cm^3$

Haloscopes

Dilution insert with
microwave cavity
and two magnets

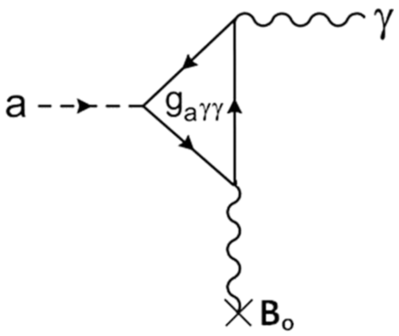
Proposed by P.Sikivie, 1985
Resonant cavity in a strong magnetic field



$$\mathcal{L}_{a\gamma\gamma} = g_{a\gamma\gamma} a \, \vec{E} \cdot \vec{B}$$

$$\tau_{a\gamma\gamma} \approx \left(\frac{10^5 \text{ eV}}{m_a} \right)^5$$

if $\mu\text{eV} \leqslant m_a \leqslant \text{meV} \rightarrow \tau_{a\gamma\gamma} \gg$ age of U



$$\mathcal{L}_{a\gamma\gamma} = g_{a\gamma\gamma} a \, \vec{E} \cdot \vec{B_0}$$

$$\tau_{a\gamma\gamma} \propto B_0^2$$

Inverse Primakoff effect,
conversion of an axion to a photon

Experimental requirements:

- Multi Tesla field

SC coils up to 8/10 T

High-Q cavities

Resonant frequency: $\nu_c = \dfrac{m_a c^2}{h}$

Axion signal: $P_a = \left(g_{a\gamma\gamma}^2 \dfrac{\alpha^2}{\pi^2} \dfrac{\hbar^3 c^3 \rho_a}{\Lambda^4} \right) \left(\dfrac{\beta}{1+\beta} \omega_c \dfrac{1}{\mu_0} B_0^2 V C_{mnl} Q_L \right)$

Scan rate: $\dfrac{d\nu}{dt} \propto Q (CV)^2$

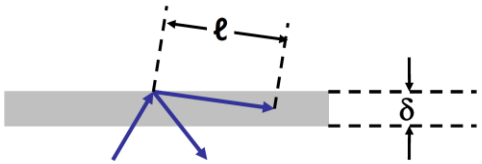
$$Q = \frac{\omega_0 U}{P_c} = \frac{G}{R_s}$$

→ $Q \sim 10^6$

Experimental requirements:

- Multi Tesla field
- Microwave cavity
- T $\sim 10^2\ mK$
- Ultra high vacuum

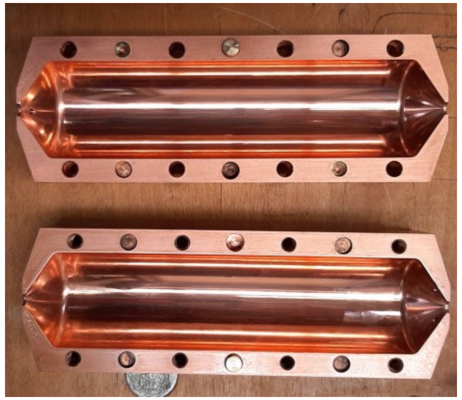
QUAX - aγ



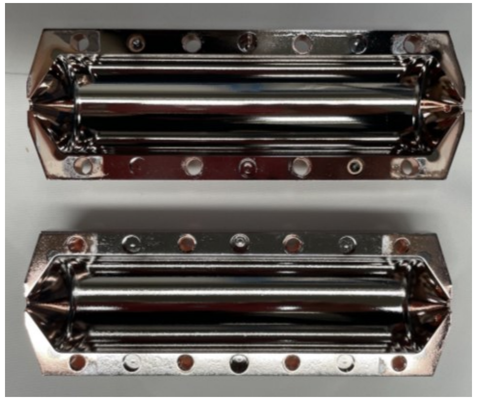
aγ: Primakoff Haloscope at high frequency ($\sim 6.991\ GHz$) $\longrightarrow$ $Q_{Cu} \lesssim 10^5$ (anomalous skin effect)

SC coated Cu cavities

Cu cavity



NbTi coating of about 2-4 µm



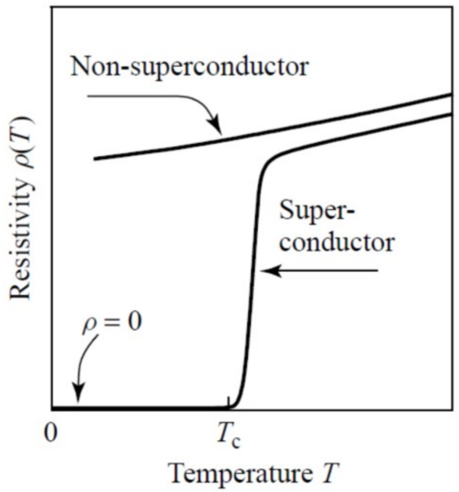
Dimensions of the cavity:

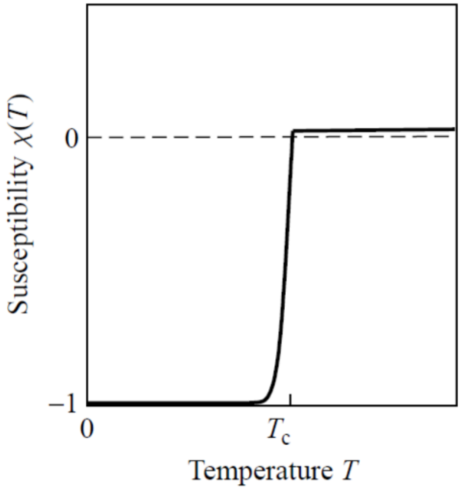
- $d_{cil} = 3,2\ cm$
- $h_{cil} = 12,5\ cm$
- $h_{con} = 1,1\ cm$

Superconductivity

Superconducting thermodynamic state

- Zero resistance
- Perfect diamagnetization
- Flux quantization





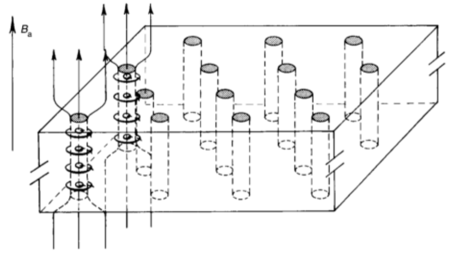
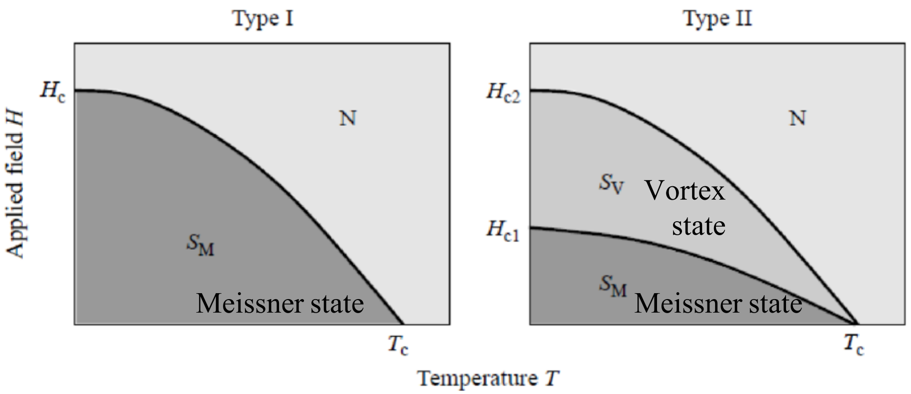
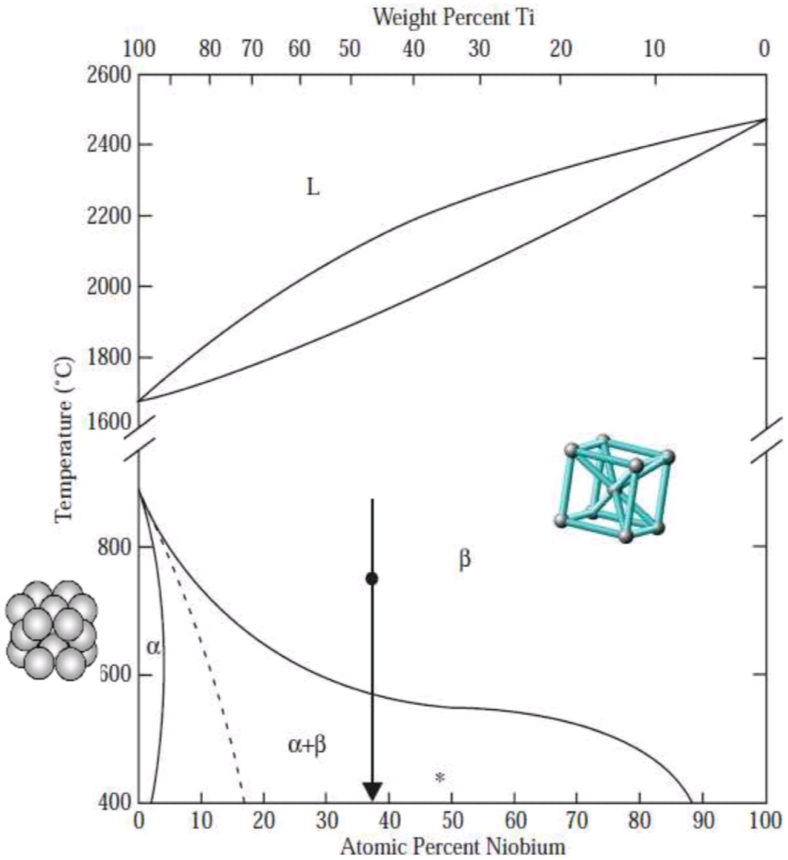


Figure 2.11: *Vortexes lattices arrangement.* B_a *is the external applied magnetic field.*



NbTi



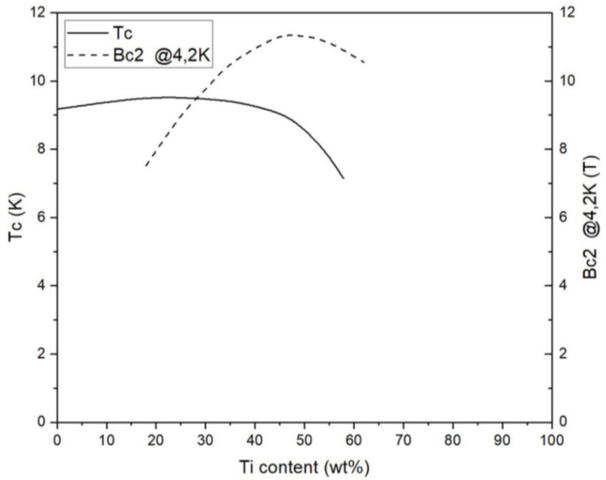


Figure 3.1: *Critical temperature and upper critical field of NbTi as a function of the weight percent of Ti. The composition around 50% of Ti offers the highest critical field at the expense of a lower* T_c .

$(8 < \boldsymbol{T_c} < 10)\ K$

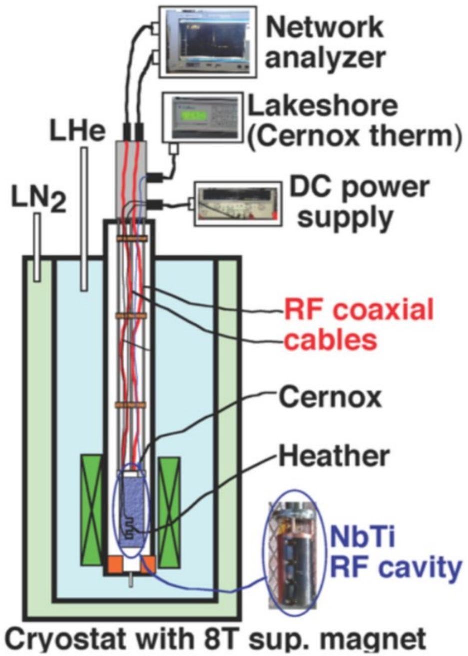
Bc2 $\leq$ 12 T

β: ductile, bcc phase

α precipitates: hexagonal non ductile phase

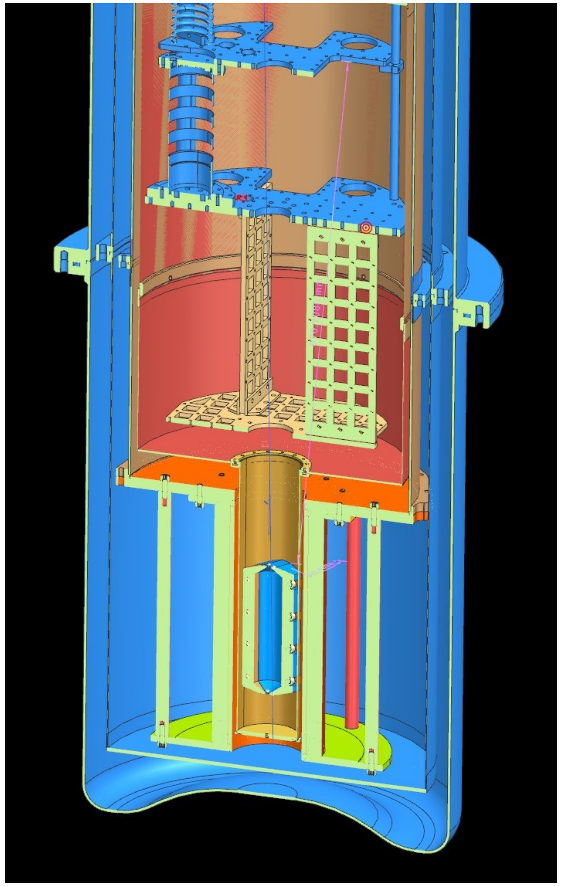
Cavity testing

He bath and steel chamber



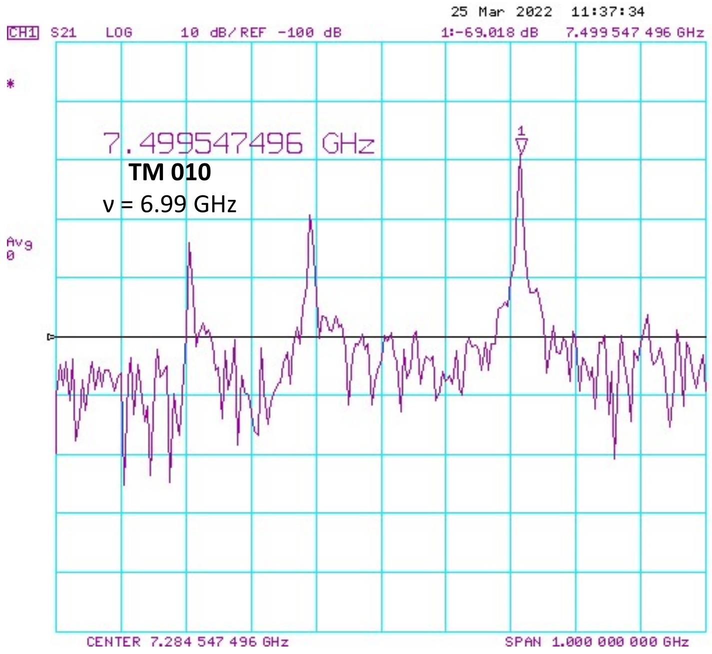
Testing setup:

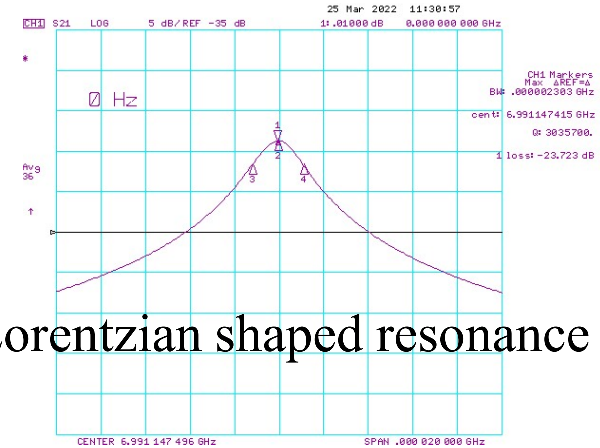
- VNA
- 2 RF coaxial cables
- He bath
- SC Magnet



Measurement of Q factor

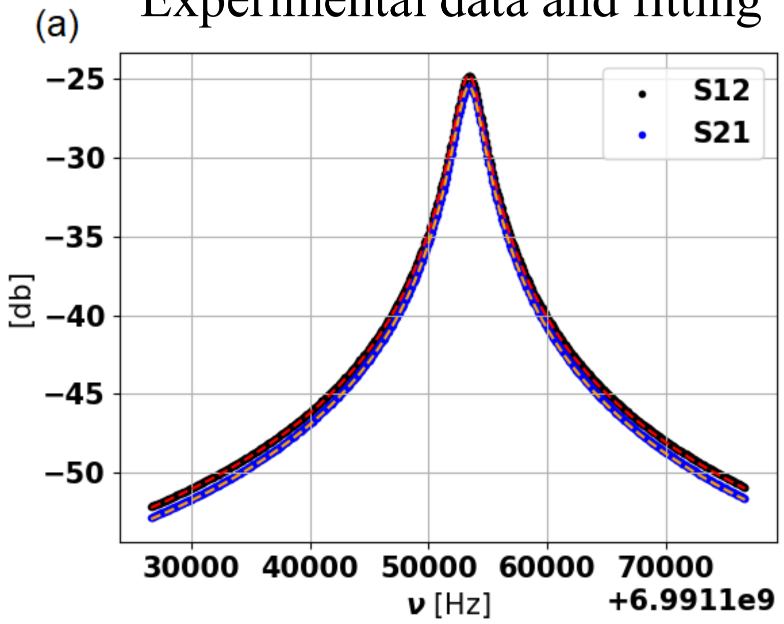
Transmission channel, S21
Broad spectrum from VNA





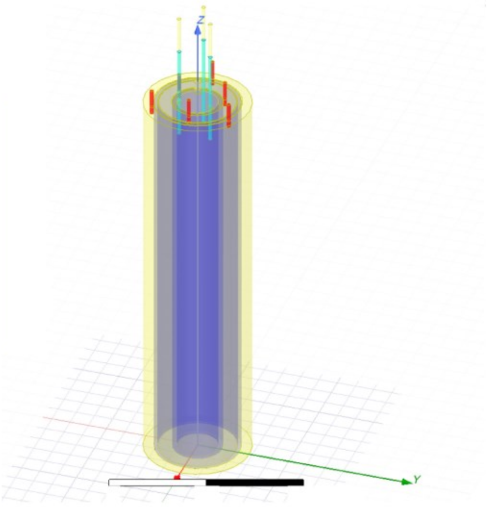
Lorentzian shaped resonance

Experimental data and fitting

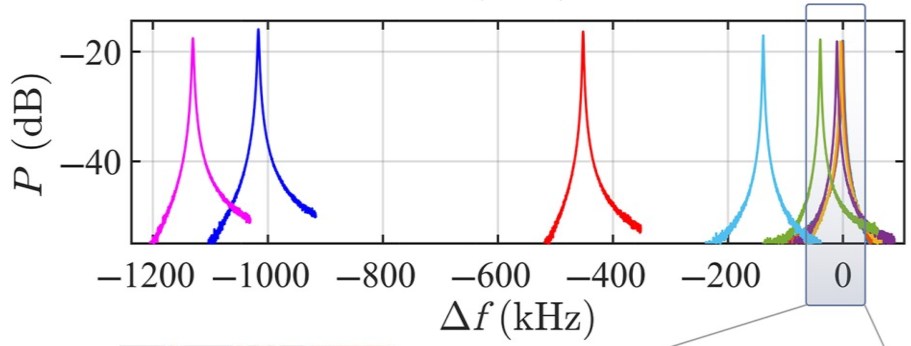


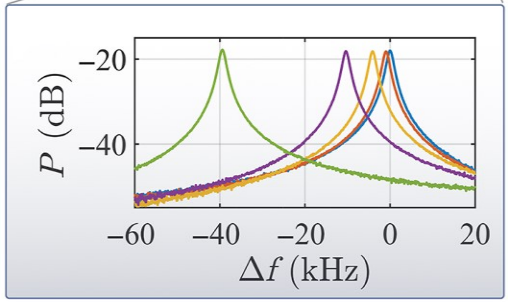
$$Q = \frac{\omega_0 U}{P_C} = \frac{G}{R_S} = \frac{\nu_C}{FWHM}$$

Tuning the cavity frequency

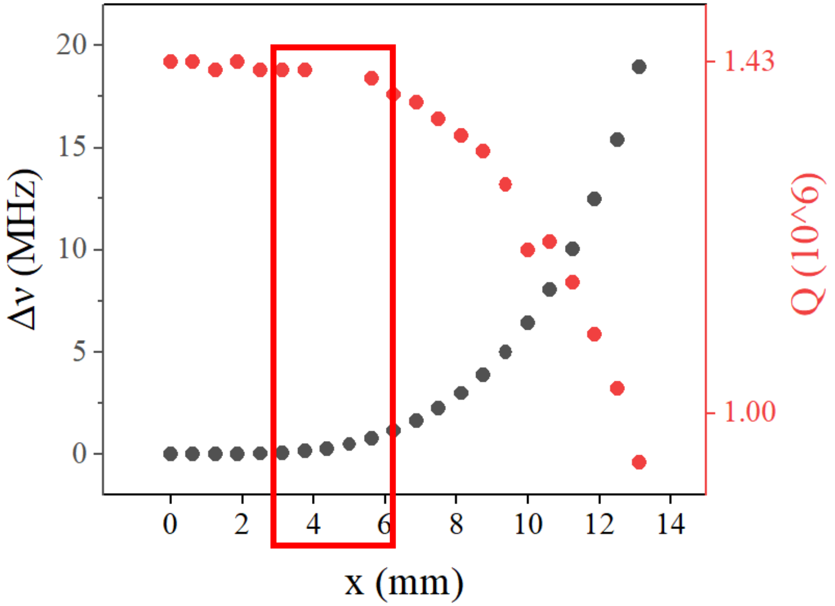


3 adjustable rods of dielectric material Sapphire (doped α-Al_2O_3)

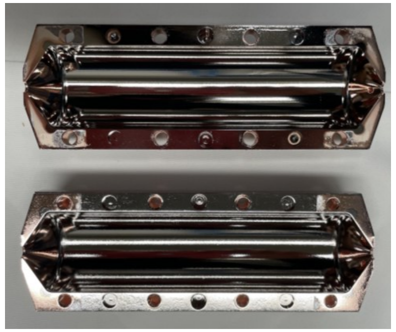


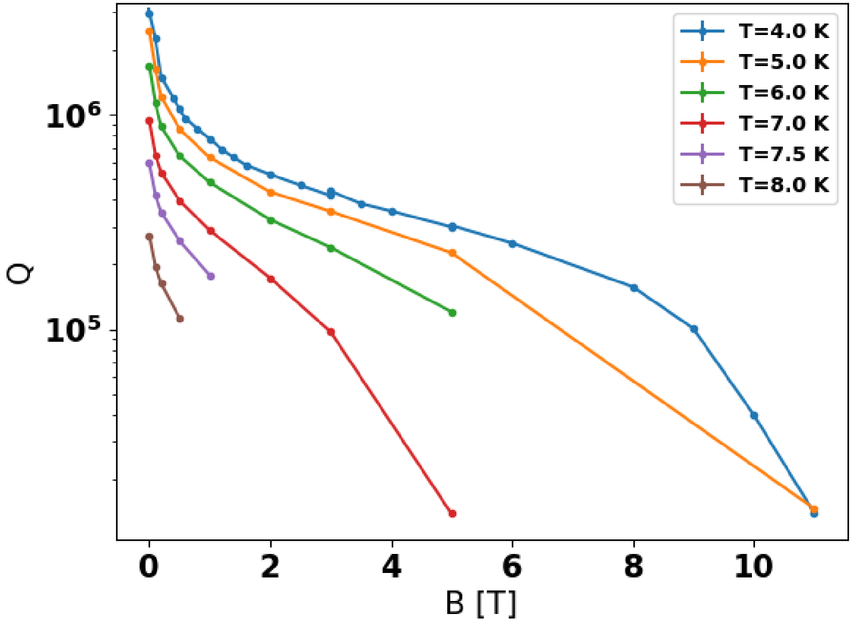


Tuning of ~2 MHz starting with the rods 4 mm inside



SC tolerance to intense Magnetic Field





- The higher the B field penetration, the higher the surface resistance, R_s
- Q factor stable up to 3T

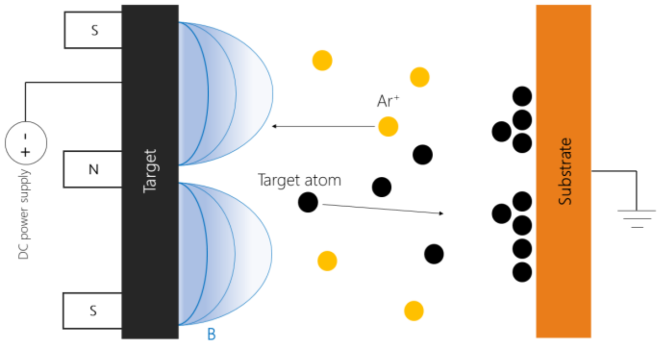
$Q \simeq 5 \times 10^5$

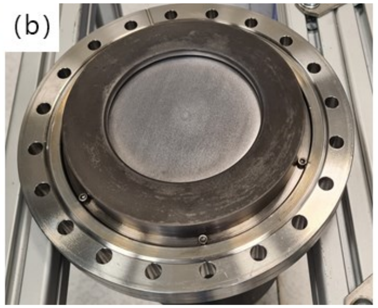
4.2 K, 3 T, 6.99 GHz

Cavity ready for a test at 3T (U. Paris-Saclay)

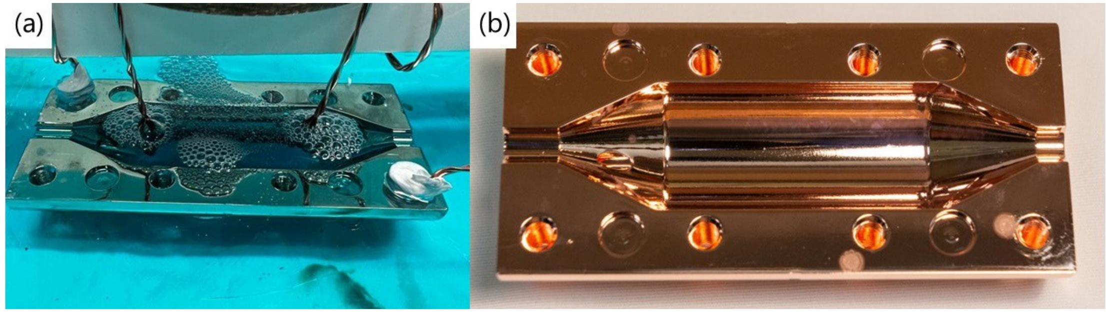
Thin film deposition

DC Magnetron Sputtering





NbTi target
47 wt%



Surface treatments

- Cleaning and degreasing
- Ultasonic bath
- EP
- HPR

Non conformal deposition of 2-4 µm of NbTi on Cu

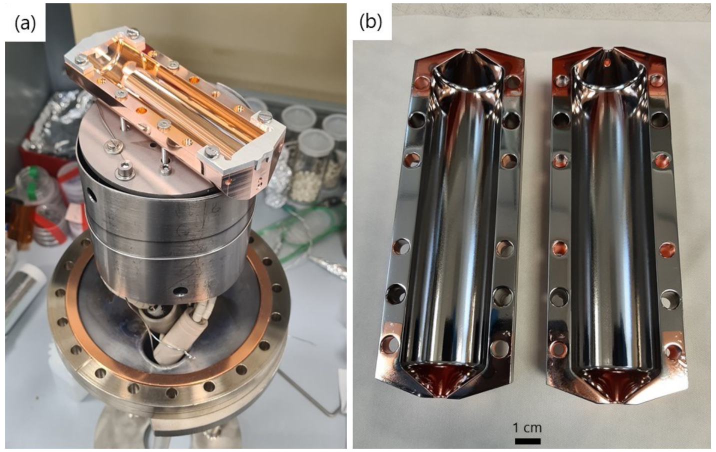


Table 1: Comparison of the results from this work to several previous studies of superconducting cavities in high magnetic fields for axion research.

Source	**Material**	***f*** **(GHz)**	B_a **(T)**	***T*** **(K)**	Q_0
This work	Nb_3Sn	3.9	6.0	4.2	$(5.3\pm0.3)\times10^5$
[13]	NbTi/Cu	9.08	5	4.2	2.95×10^5
[14]	Nb_3Sn	9	8	4.2	6×10^3
[14]	REBCO	9	11.6	4.2	7×10^4
[15]	YBCO	6.93	8.0	4.2	1.5×10^5

Any Questions?

References

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- D. Alesini et al., Physical Review D, vol. 99, 101101(R), May 2019
- K. Fossheim et al., «Superconductivity: Physics and Applications», John Wiley & Sons
- R. Kleiner et al., «Superconductivity: Fundamentals and Applications», Wiley-VCH
- A. Salmaso, «Development of NbTi and Nb3Sn thin films for innovative superconducting axion haloscopes», https://thesis.unipd.it/handle/20.500.12608/35175
- H. Padamsee et al., «RF Superconductivity for Accelerators», Cornel University
- C. Mattiroli, «Quantum sensing in axion dark matter search», https://thesis.unipd.it/handle/20.500.12608/34661
- R. Di Vora et al., Physical Review Applied, vol. 17, no. 5, Feb. 2022
- D. Di Gioacchino et al., IEEE Transactions on Applied Superconductivity, vol. 29, no. 5, pp. 1-5, Aug. 2019
- S. Posen et al., "Measurement of high quality factor superconducting cavities in tesla-scale magnetic fields for dark matter searches." arXiv preprint, arXiv:2201.10733 (2022).

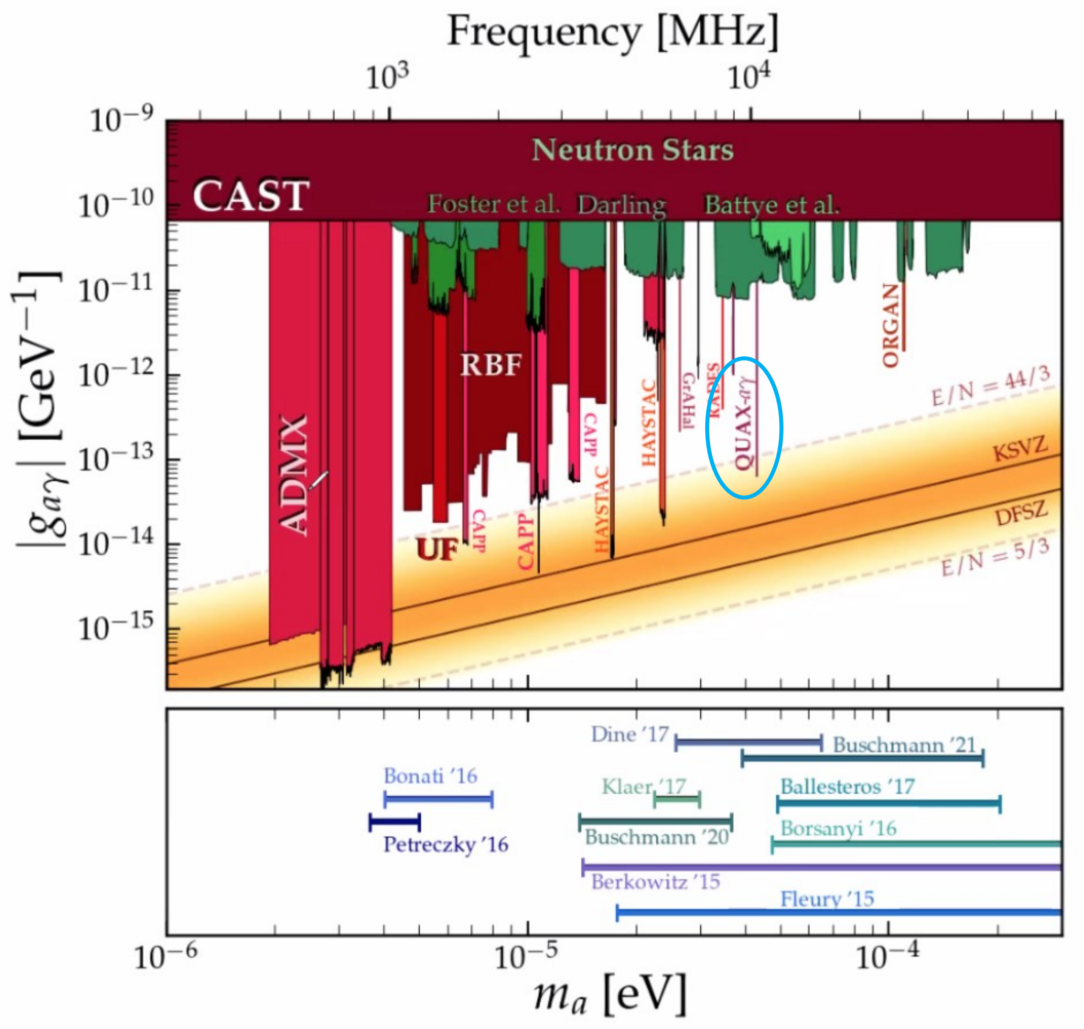
- Part of the images, data and information was gently provided by the QUAX team

Thank you for your attention!

Exclusion Plot

y-axis: Axion-photon coupling constant, $g_{a\gamma}$
x-axis: Axion mass, m_a

Main theoretical models predict:
$g_{a\gamma} \propto m_a$



Axion frequency matched by the resonant cavity

Target area

Further Cavity characterization

$$Q_L = Q_L(T)$$

$$P_a \propto B^2 Q_0$$

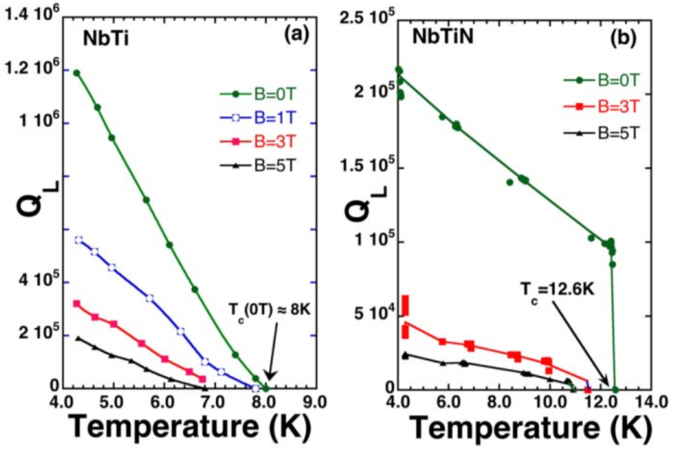
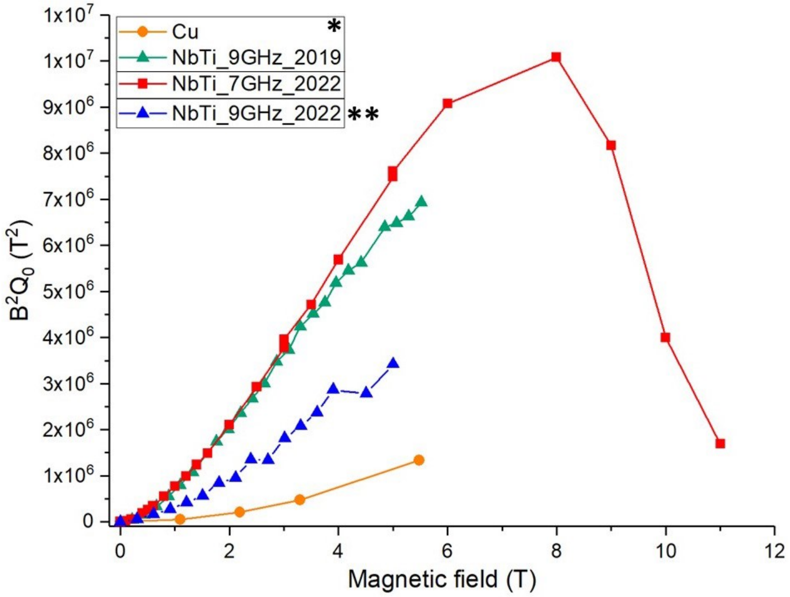


Fig. 2. Q_L versus T at 14.46 GHz (rotated TM_{110}) for (a) NbTi and (b) NbTiN cavities.



Signal gain with increasing magnetic field

Great improvement from copper cavity

$$Q \simeq 3 \times 10^5$$

4.2 K, 4 T, 14.46 GHz

Fluxon motion

IMPEDANCE: $\Delta Z = \Delta R_s + i\Delta X_s$

Gittleman-Rosenblum model advocates the fluxon motion to account for the dissipation

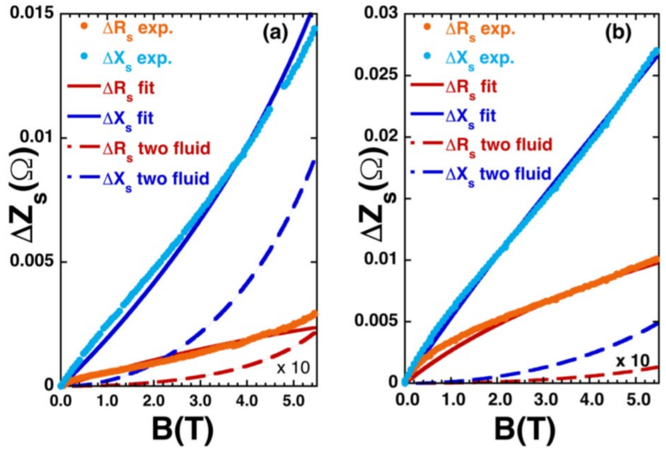


Fig. 5. ΔZ_s vs. B at ∼4.2 K for the NbTi (a) and NbTiN (b) cavity, mode TM_{110}. Experimental data (full dots), two-fluid only numerical model (dashed lines), two-fluid plus vortex motion numerical model (GR) (continuous line). Parameters values as in the body text.

These experimental interpolations allow us to measure with good precision

- London penetration depth, λ
- Depinning frequency, ν_p

in addition to a geometrical parameter for the alignment between fluxons and microwave currents