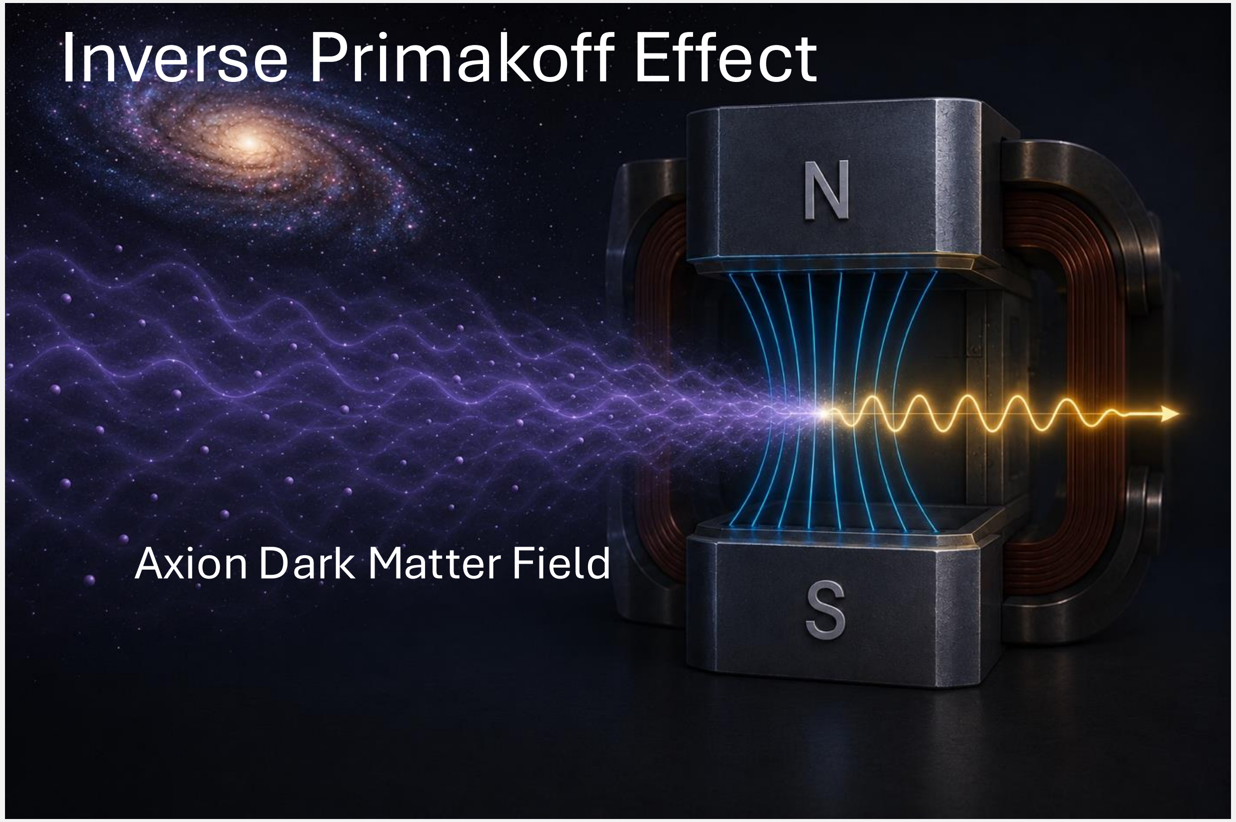
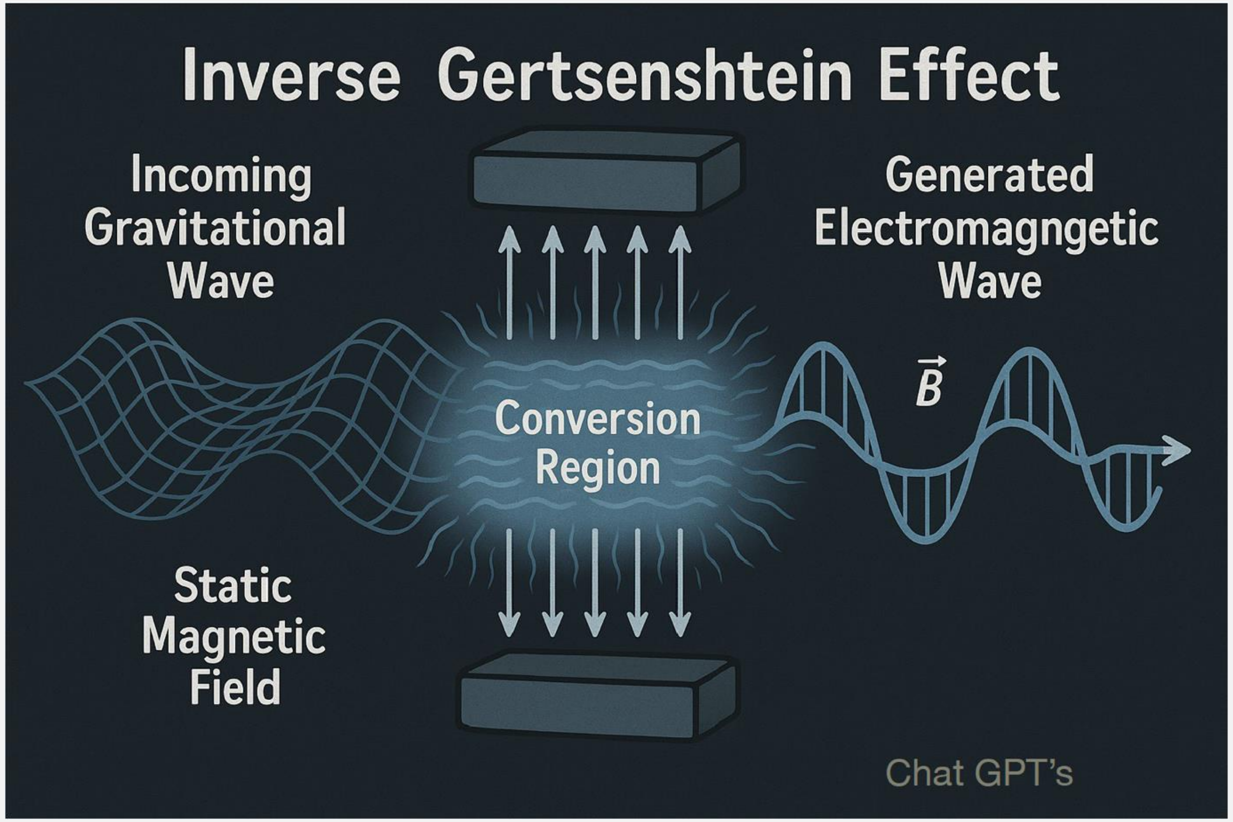
Advancing Axion and High Frequency Gravitational Wave Searches at LNF

Claudio Gatti
LNF INFN

High Precision Experiments for Light Dark Matter
IPPP Durham University, 7-10 September 2026

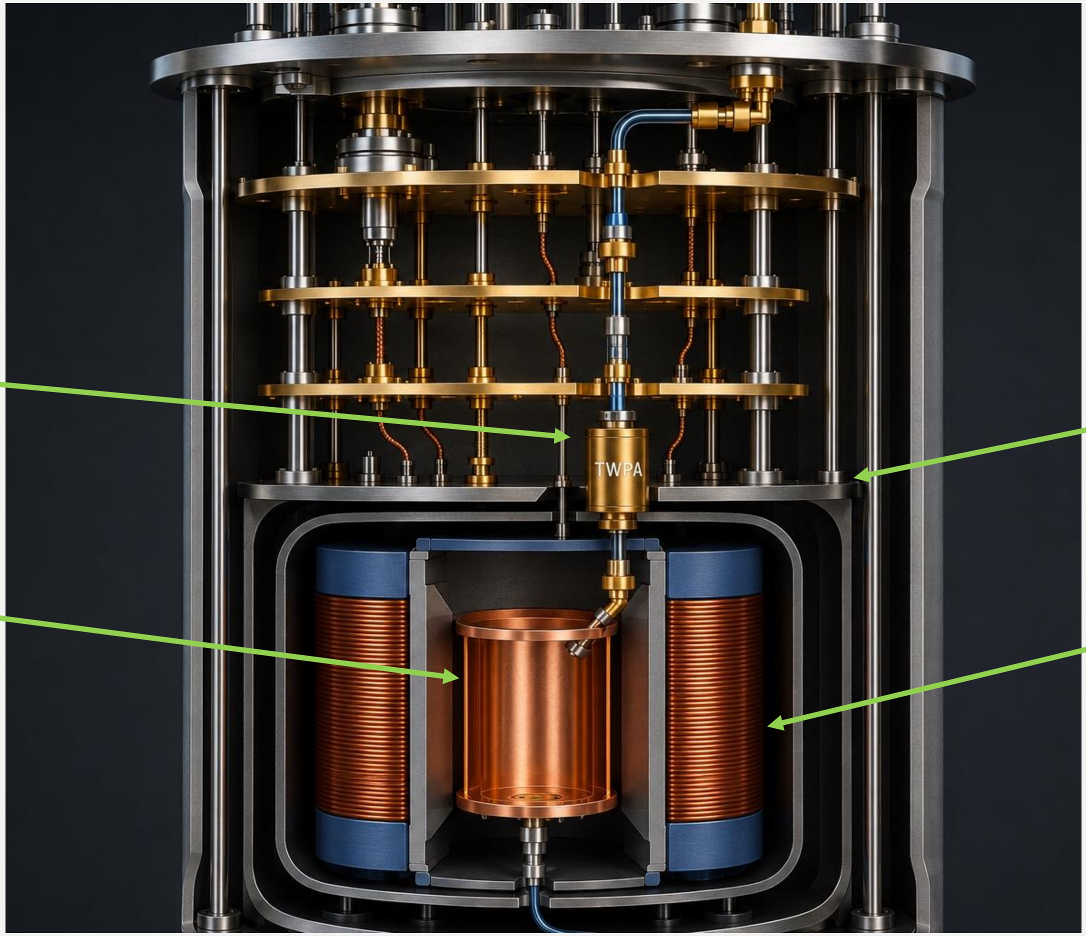
Axion and GW Conversion in B Field

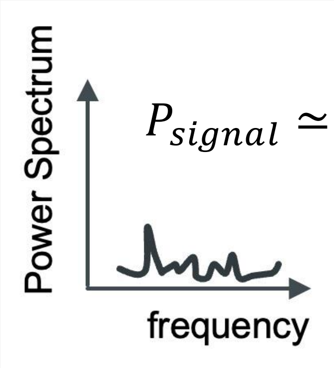




State of Art Sikivie’s Axion Haloscope

Room Temperature Amplifiers





$P_{signal} \simeq 10^{-22} - 10^{-23} W$

Quantum-Limited Amplifier

Dilution Refrigeretor T<100 mK

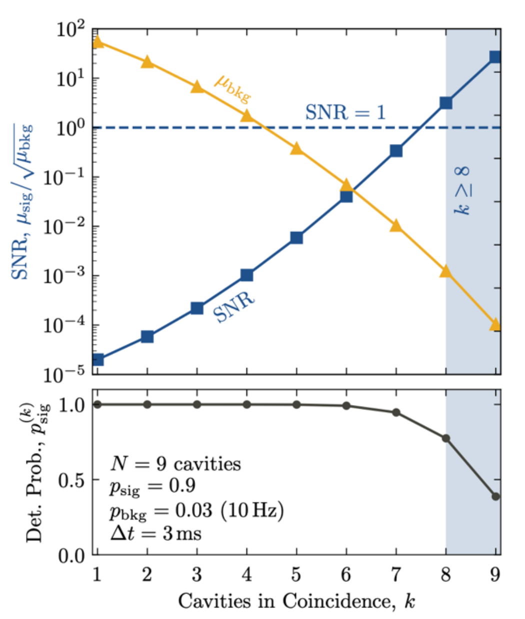
Resonant Cavity

SC Magnet (~10 T)

GravNet A Global Network for the Search of High Frequency Gravitational Waves

Funded by the European Union

European Research Council
Established by the European Commission



Claudio Gatti (INFN), Dmitry Budker (Mainz), Matthias Schott (Bonn), Diego Blas (IFAE)

GravNet CDR arXiv:2603.24645

GravNet

LNF contribution:

FLASH	INFN QUAX	COLD LNF
Radio haloscope	X-band haloscope	Quantum Sensing

GravNet Collaboration

FLASH
FINUDA Light Axion Search Haloscope

FLASH Collaboration

GravNet

INFN FLASH GravNet

Istituto Nazionale di Fisica Nucleare INFN LNF

TIFPA

UNI BONN

UNICAM

UNIVERSITY OF LIVERPOOL

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

INFN PISA

VNIVERSITAT DE VALÈNCIA

IFAE Institut de Física d'Altes Energies

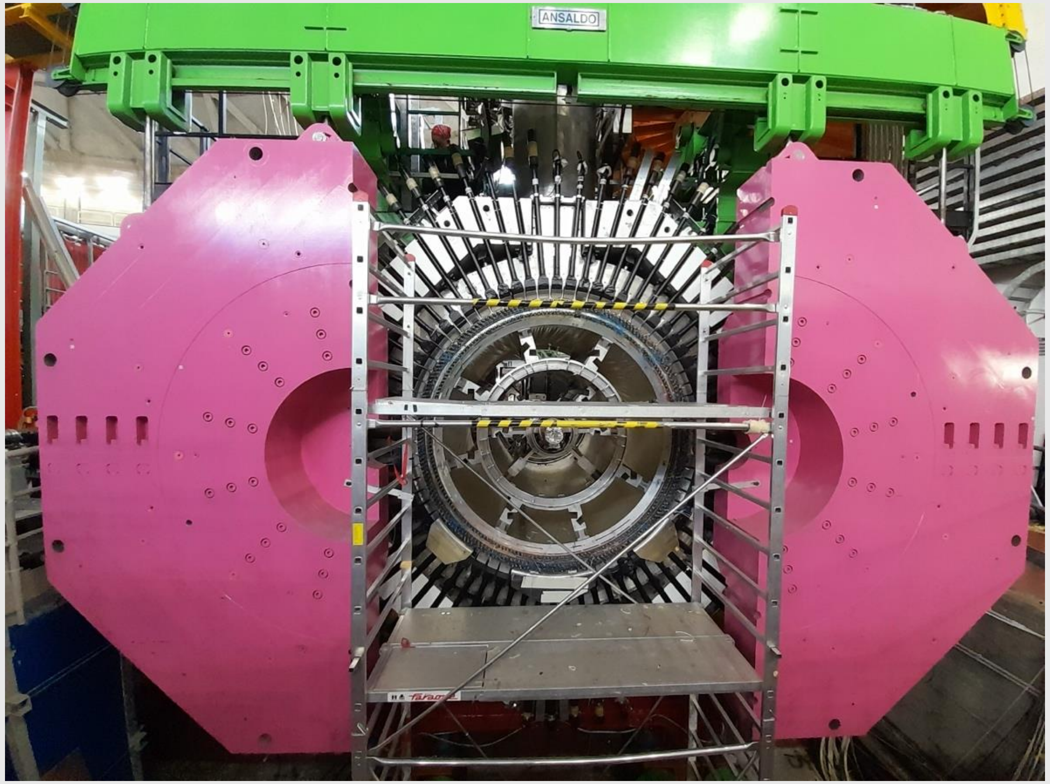
UNIVERSITÀ DI PISA

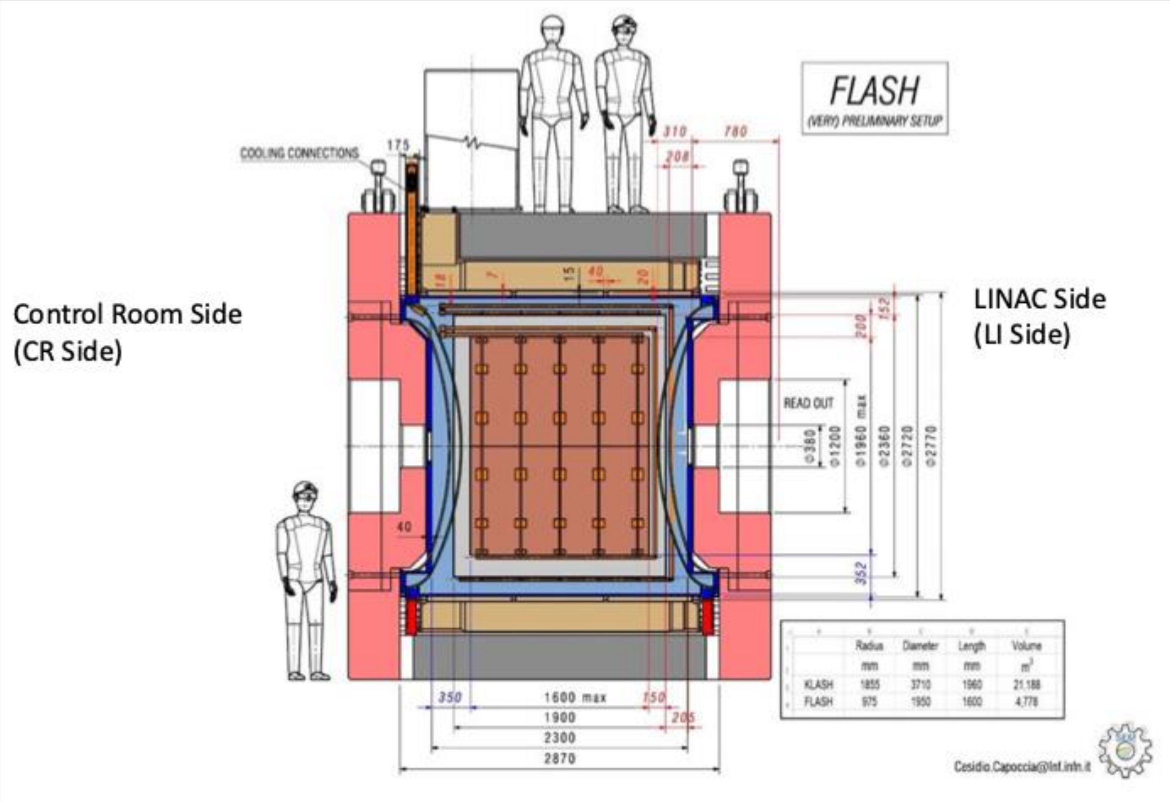
Universidad Politécnica de Cartagena

IFIC INSTITUT DE FÍSICA CORPUSCULAR

Bilkent University

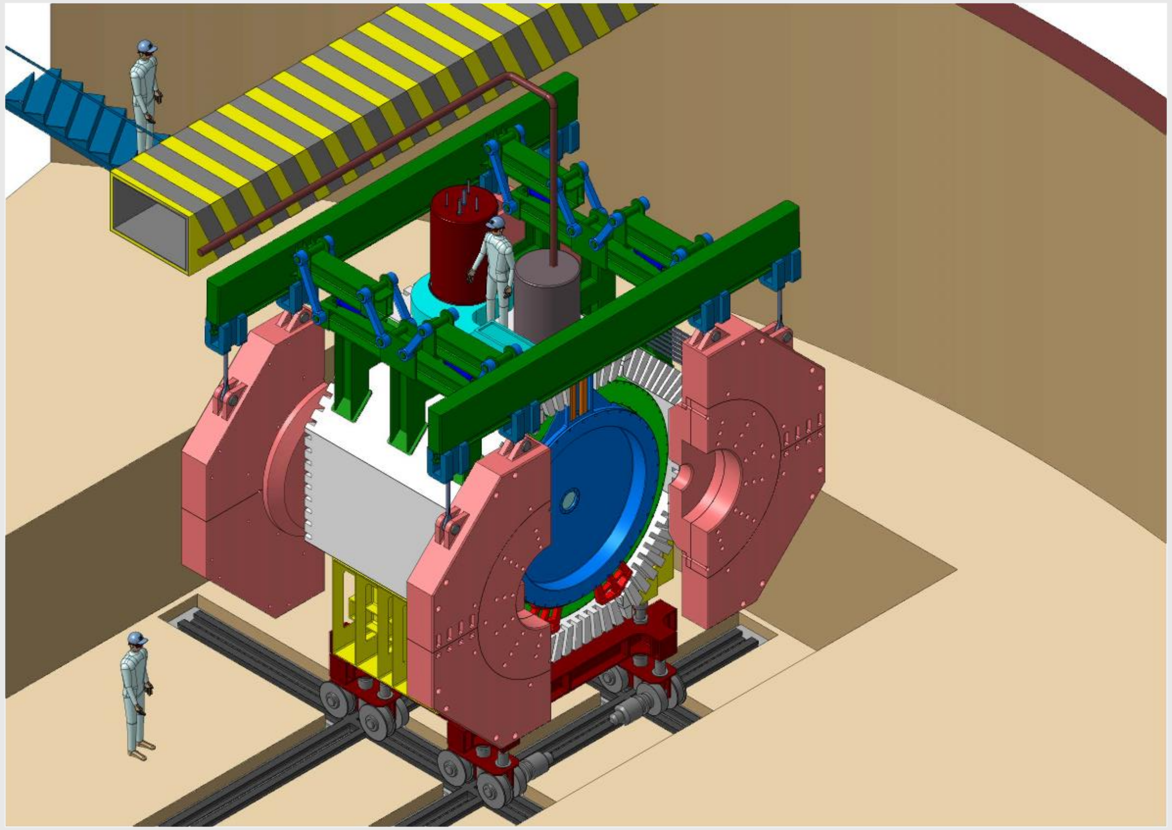
FLASH – 100 MHz Haloscope

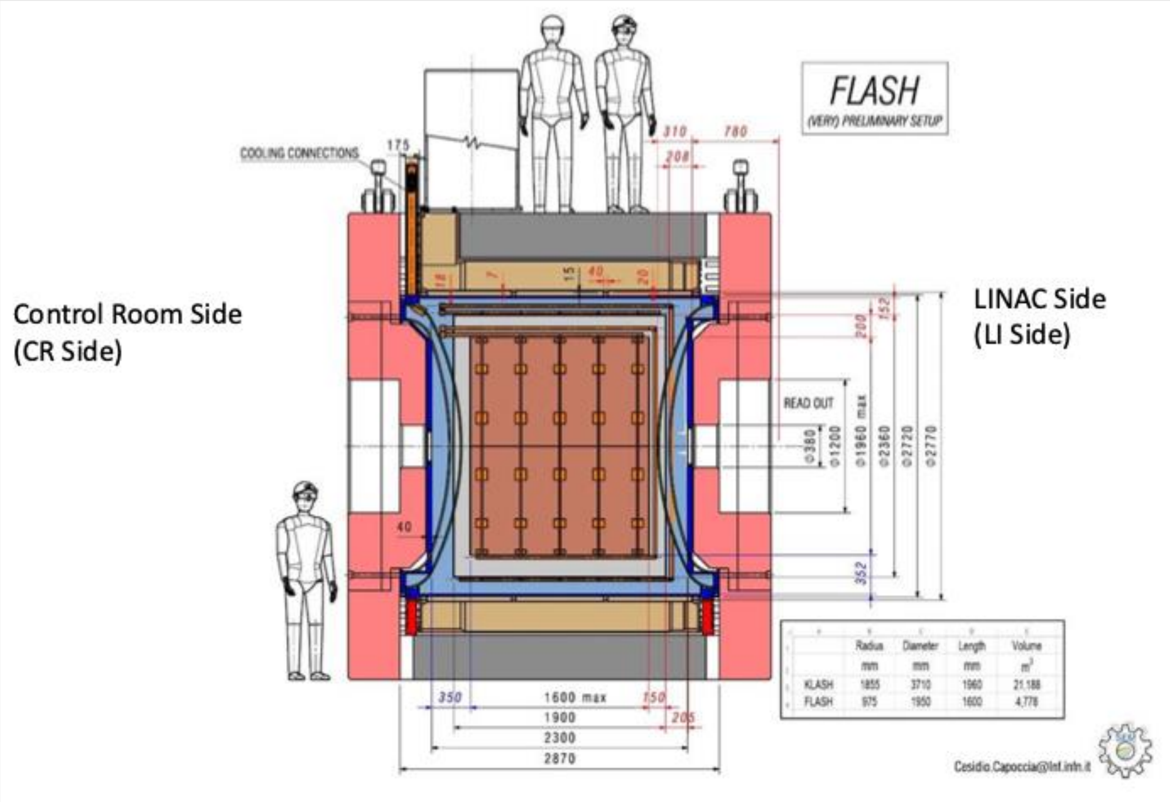




“The future search for low-frequency axions and new physics with the FLASH resonant cavity experiment at Frascati National Laboratories”
Physics of the Dark Universe 42 (2023) 101370

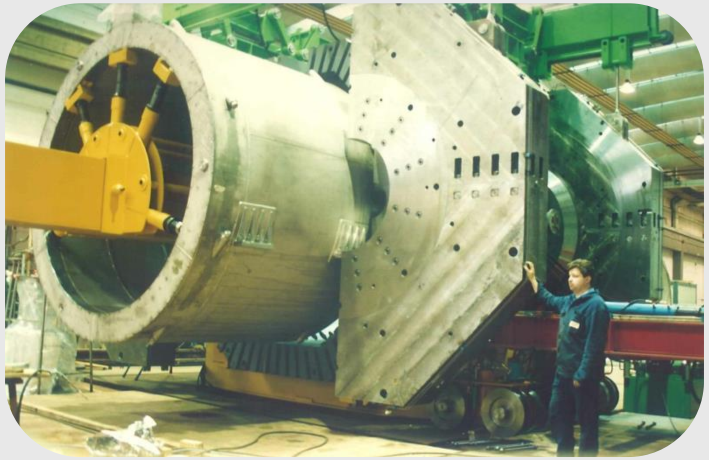
FLASH – 100 MHz Haloscope





	Radius	Diameter	Length	Volume
	mm	mm	mm	m^3
KLASH	1855	3710	1960	21.188
FLASH	975	1950	1600	4.778

“The future search for low-frequency axions and new physics with the FLASH resonant cavity experiment at Frascati National Laboratories”
Physics of the Dark Universe 42 (2023) 101370

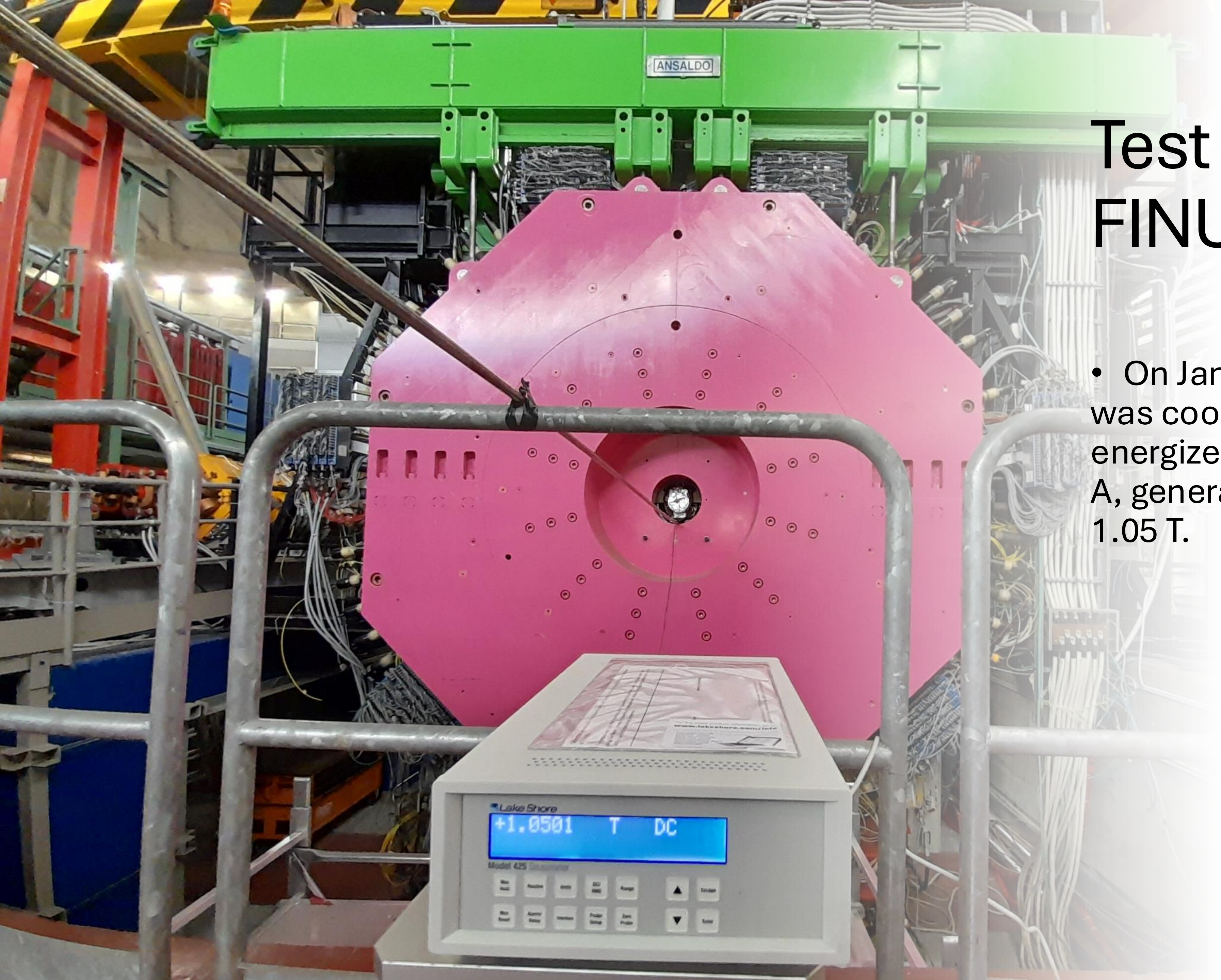


FINUDA

Fisica Nucleare a DAFNE

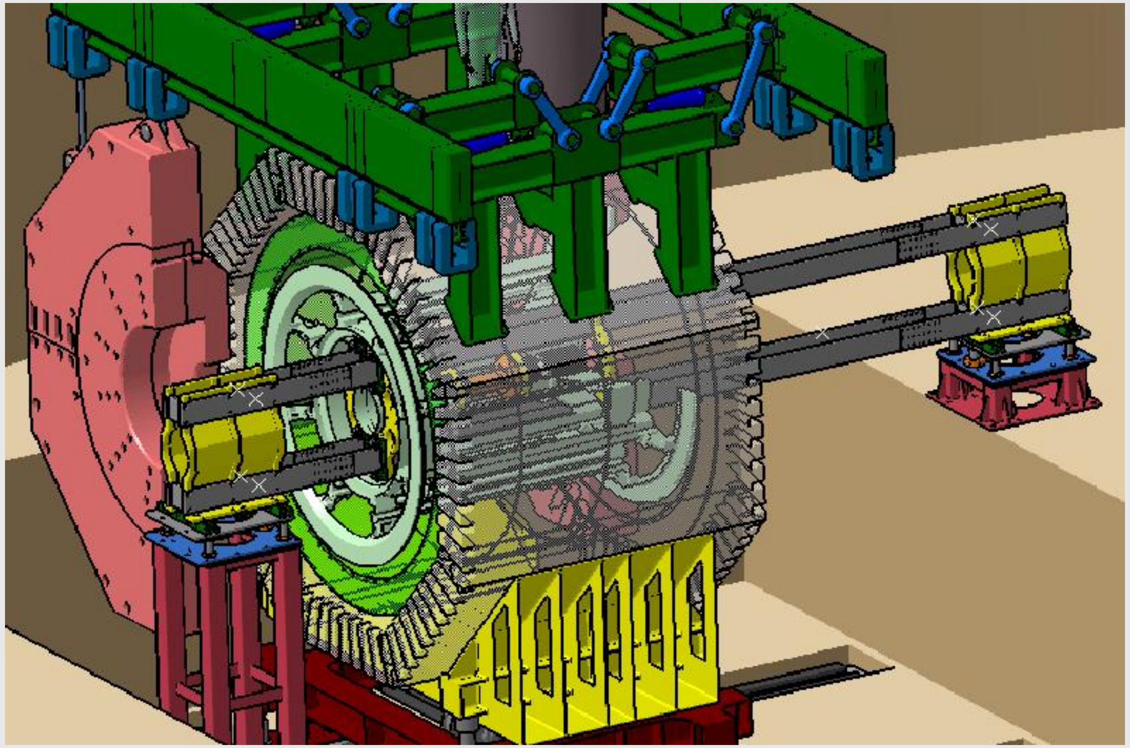
B(T)	**1.1**
I(A)	2845
R(m)	1.4
L(m)	2.2

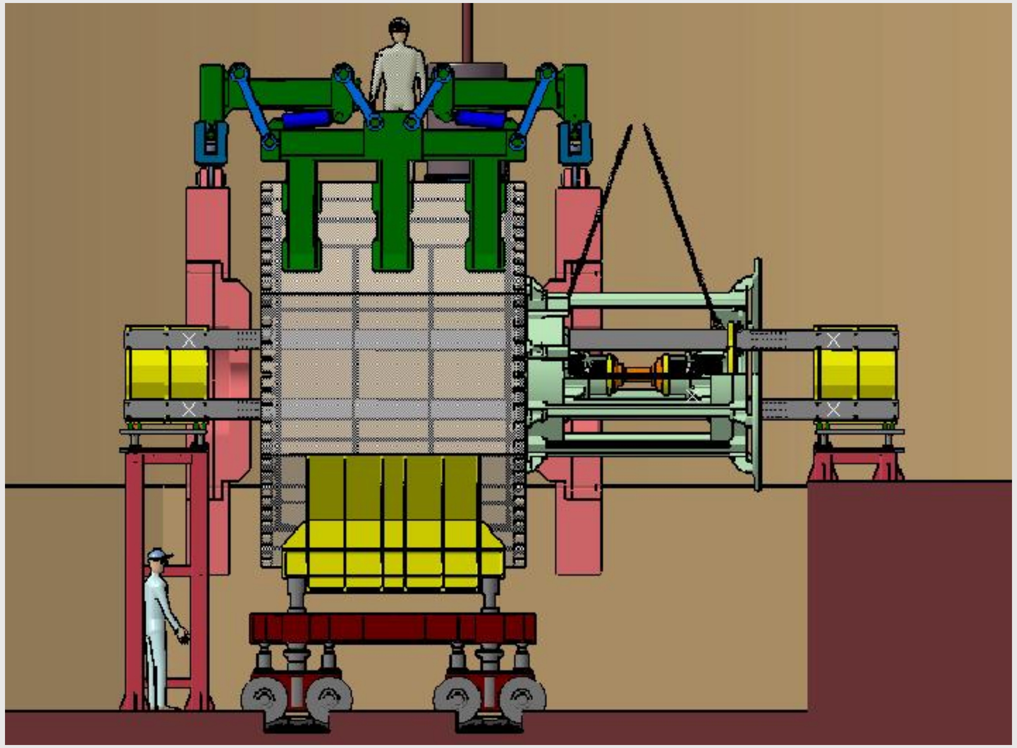
Test of the FINUDA Magnet

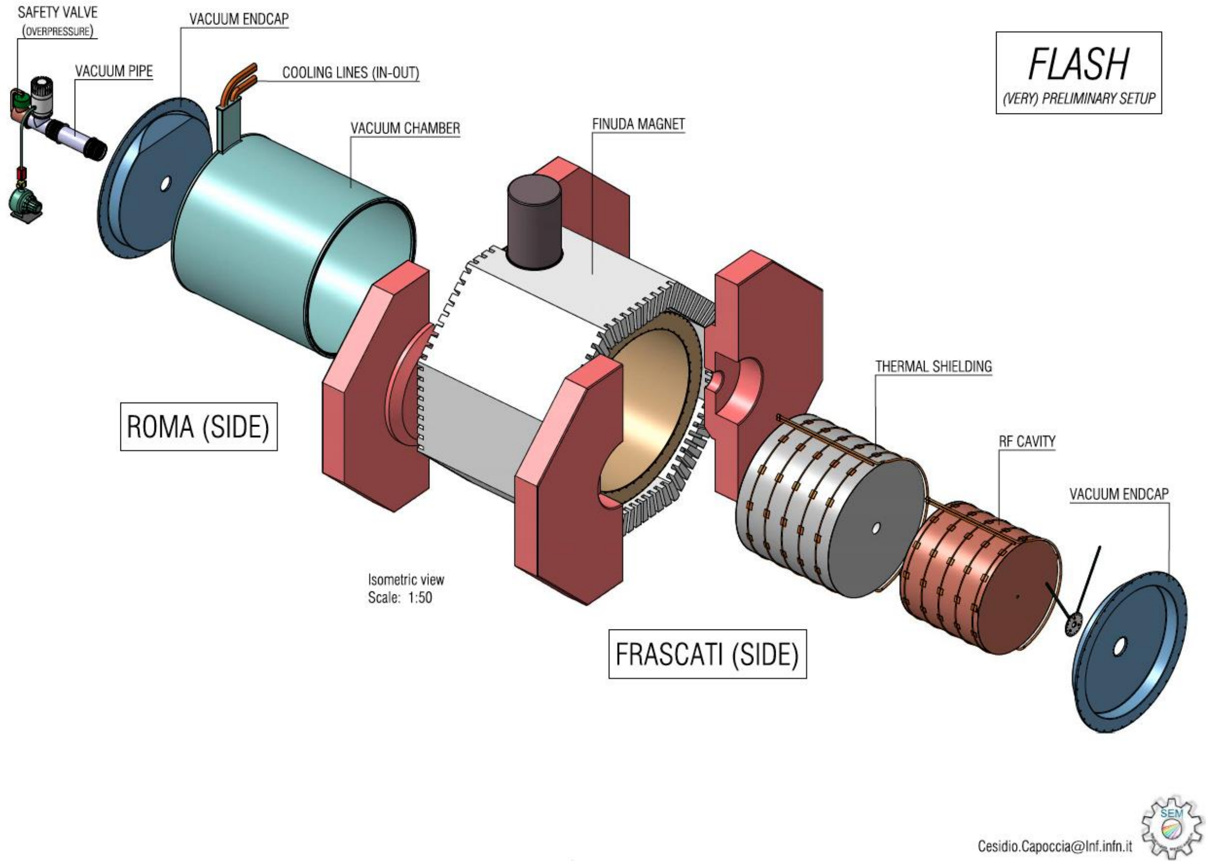


- On Jan the 19th 2024, FINUDA was cooled down to 4 K and energized with a current of 2706 A, generating a magnetic field of 1.05 T.

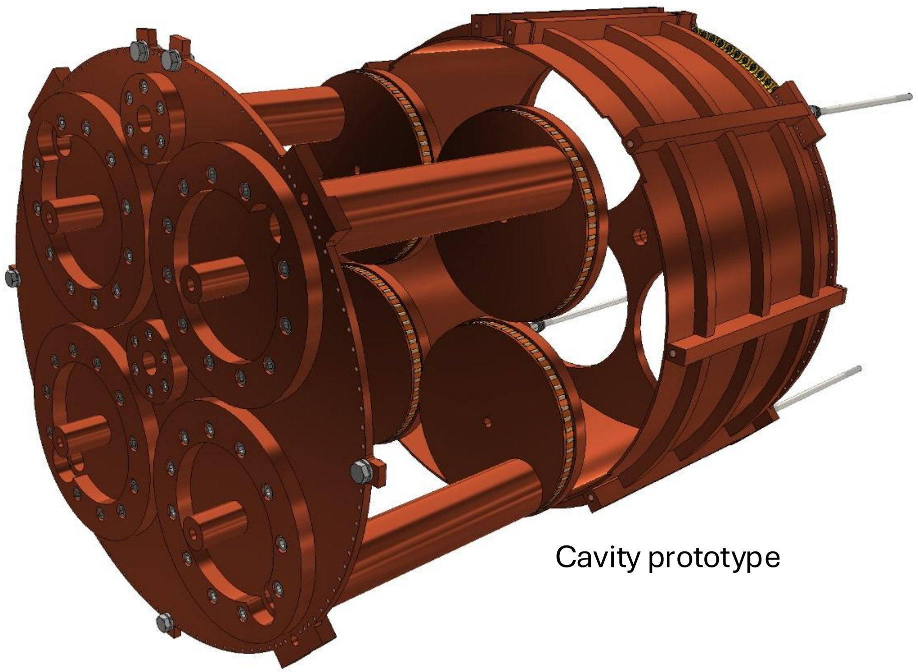
FINUDA Extraction



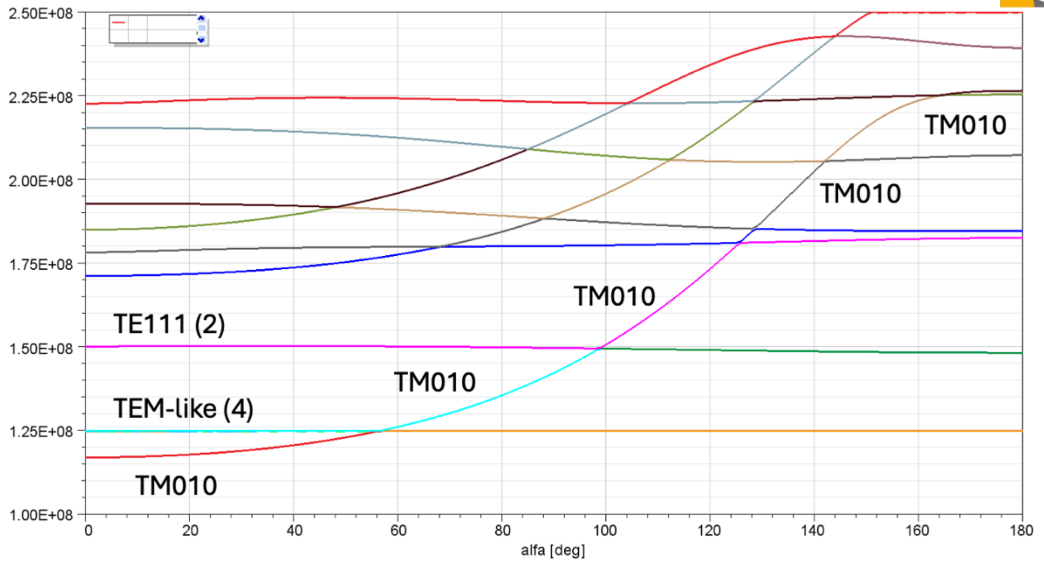




Cryostat and He II Cooling of the Cavity



Cavity prototype



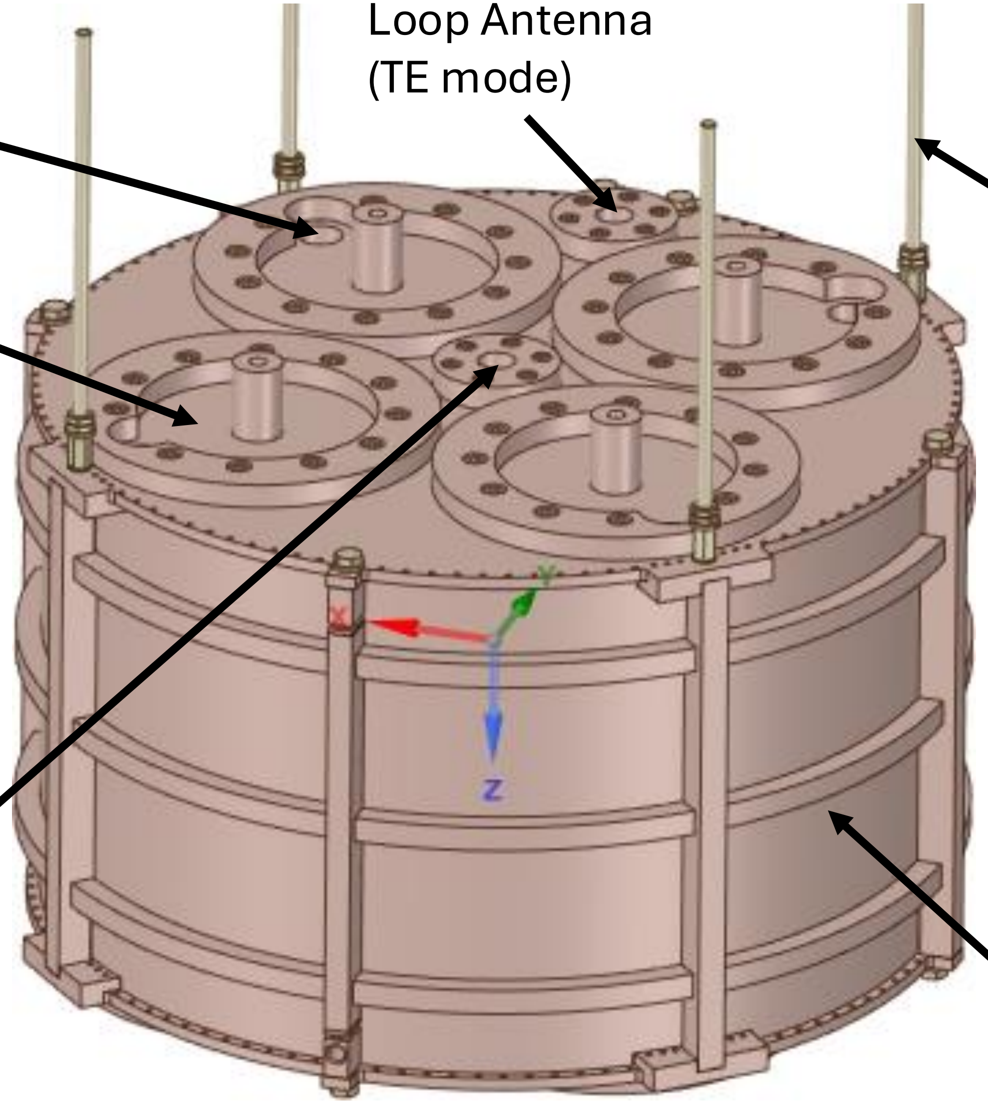
Tuning System

Cavity Prototype

Tuner

Loop Antenna
(TE mode)

Rotating disk

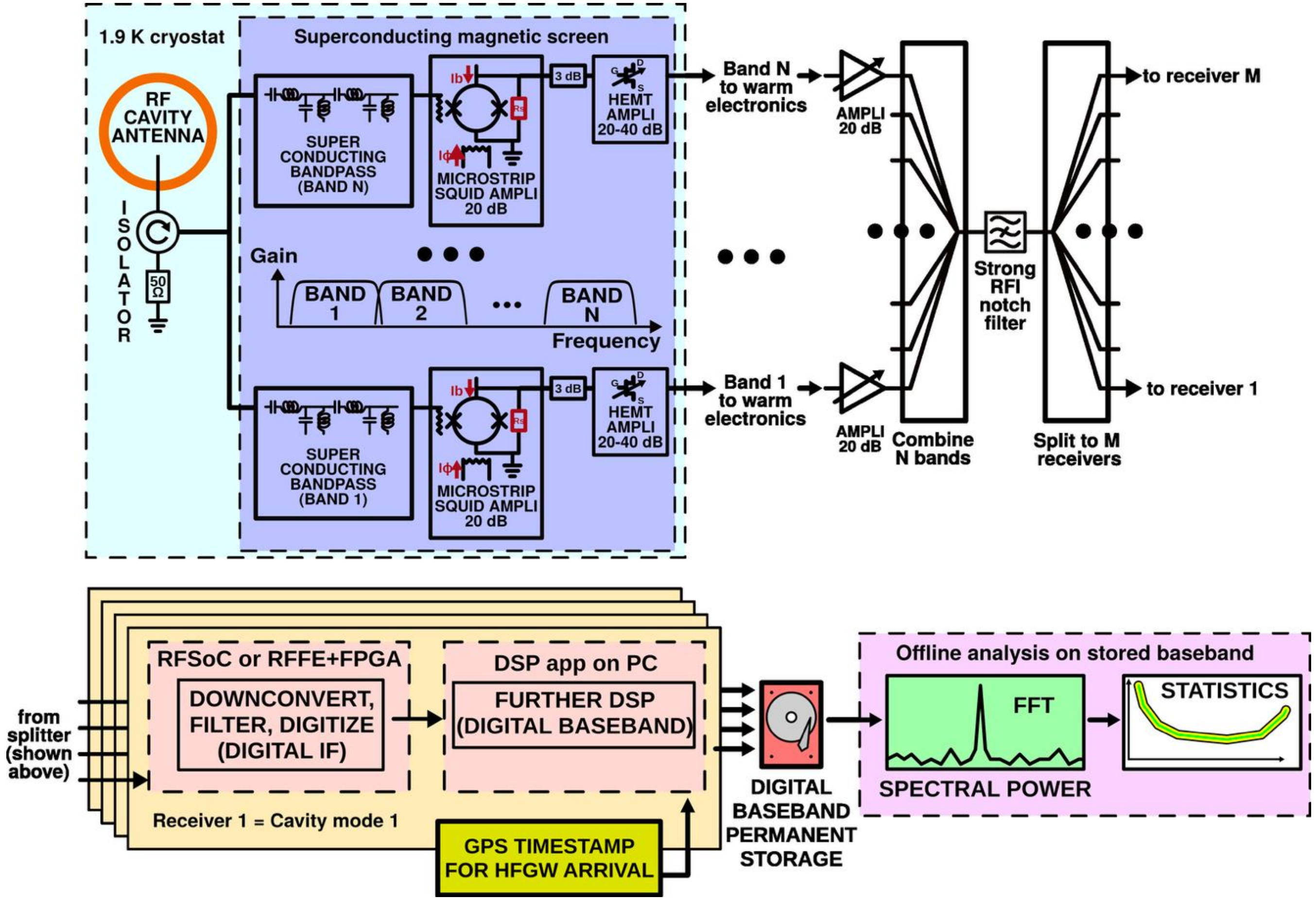


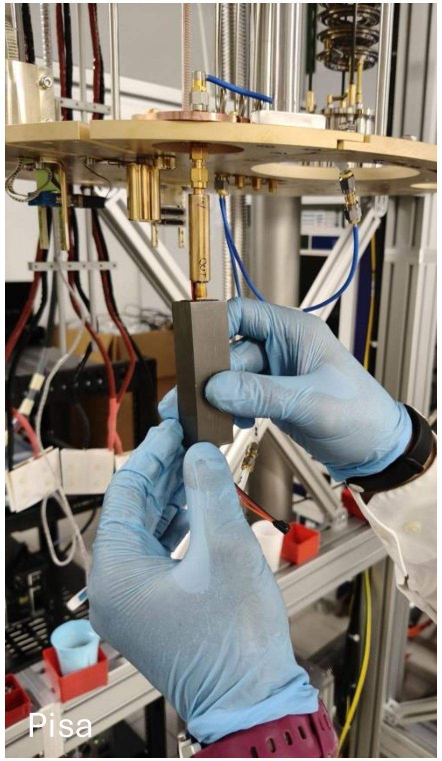
Cooling/connection rods for prototype only

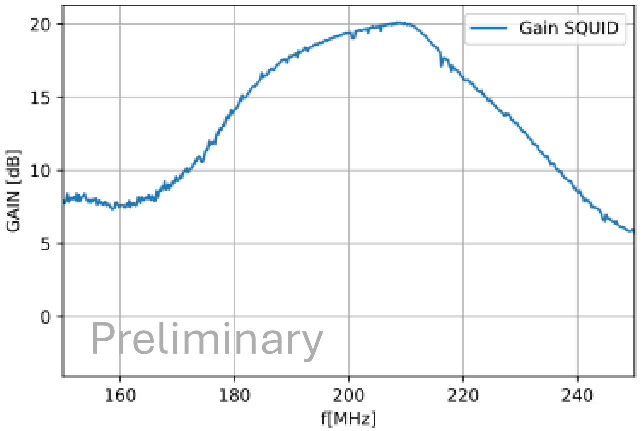
Monopole Antenna
(TM mode)

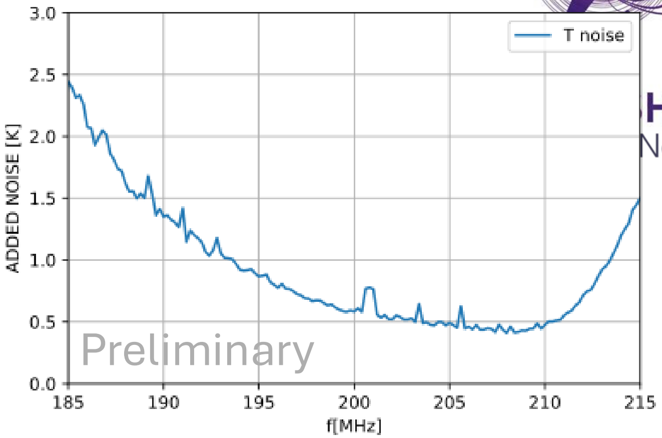
Cooling manifold is not needed for prototype

Signal Amplification and DAQ



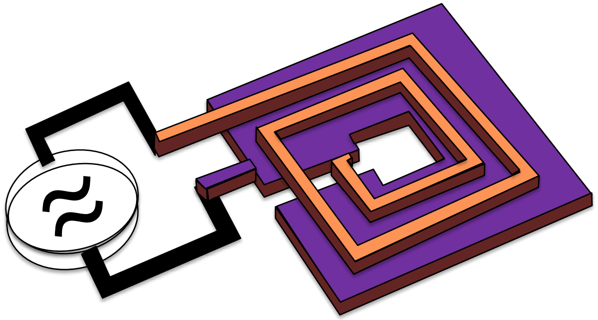






$$T_{noise} = (1.6K)_{bath} + 0.34K\left(\frac{f}{120\ MHz}\right)\left(\frac{T}{1.9K}\right)$$

MSA SQUID



Physics Reach

Mode	f_r (MHz)	L_{inMo} (mm)	β
TM_{010}	129.18	45	1.05
TM_{011}	163.31	40	0.98
TM_{110}	204.17	40	0.96
TM_{111}	227.30	36	0.99
TM_{012}	237.97	43	0.97
TM_{210}	259.26	61	1.03
TM_{211}	277.83	55	0.96
TM_{112}	285.69	37	1.04
TM_{020}	289.97	29	0.97
TM_{212}	327.33	56	1.00

Axion, Dark Photons, HFGW

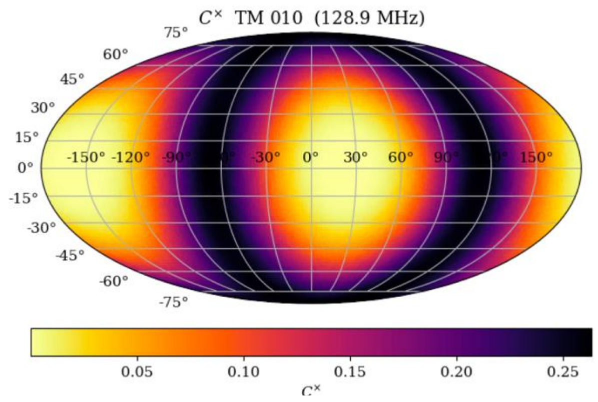
HFGW

HFGW

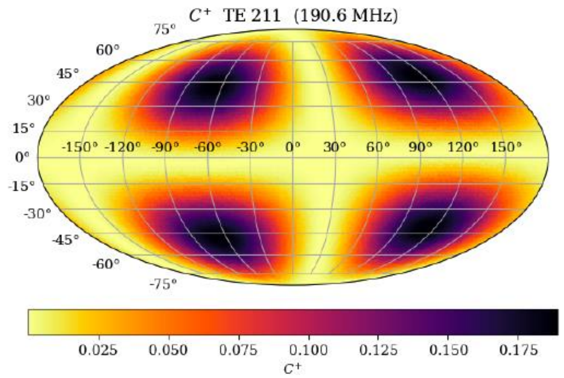
Axion, Dark Photons

Mode	f_r (MHz)	β	BW_{-3dB} (KHz)	$Q_L\ (\cdot 10^5)$	$Q_0\ (\cdot 10^5)$
TE_{111}	135.891	0.775	0.53	2.83	5.02
TE_{211}	190.583	0.665	0.70	2.75	4.58
TE_{011}	218.340	0.718	1.00	2.34	4.03
TE_{112}	220.057	0.681	1.20	2.19	3.69
TE_{212}	257.449	1.500	1.10	2.63	6.58

Scalars
HFGW
Chameleons,
HFGW, Scalars

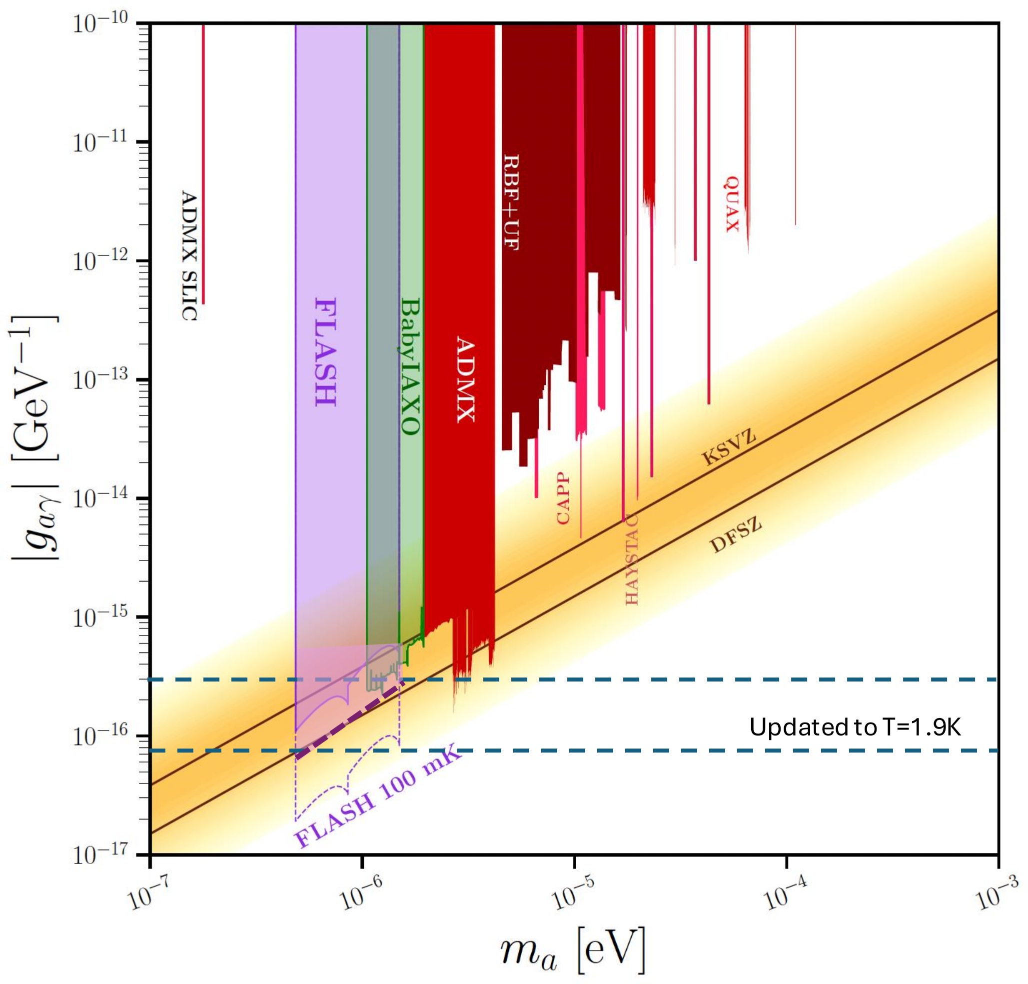


TM010



TE011

AXION Sensitivity



With OFHC Cu cavity at 1.9 K

Parameter	Value
ν_c [MHz]	150
m_a [μeV]	0.62
$g_{a\gamma\gamma}^{\mathrm{KSVZ}}$ [GeV^{-1}]	2.45×10^{-16}
Q_L	1.4×10^5
C_{010}	0.53
$B_{\max}$ [T]	1.1
β	2
τ [min]	5
T_{sys} [K]	2 K
P_{sig} [W]	0.9×10^{-22}
Scan rate [Hz s^{-1}]	8
m_a [μeV]	0.49 - 1.49
$g_{a\gamma\gamma}$ 90% c.l. [GeV^{-1}]	(0.8- 3.96) $\times 10^{-16}$

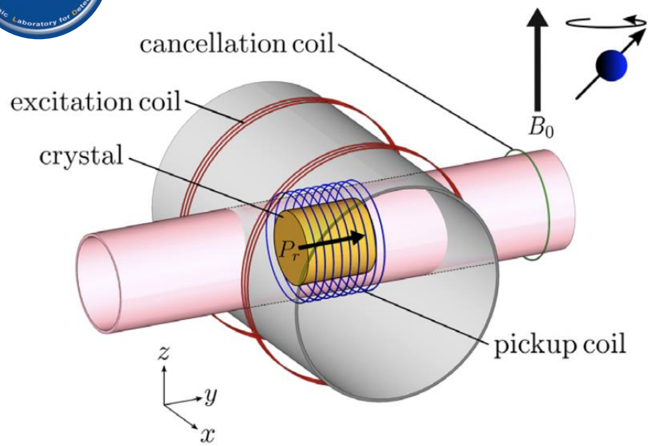
“Cross correlation”

What do we gain if we correlate “axion” signals measured at the same frequency with NMR and cavity experiments within one De Broglie wavelength (10Km)? (Sreemanti Chakraborti)

From left:
CG, Deniz Aybas and Sreemanti Chakraborti

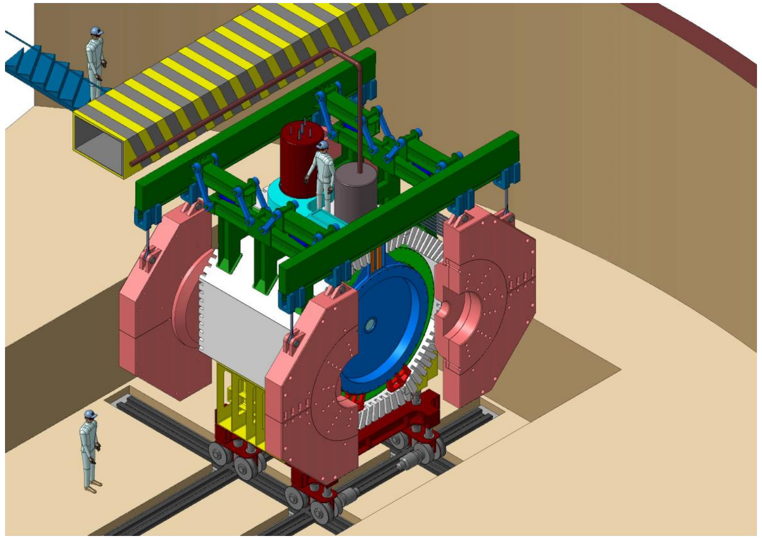
Axion De Broglie wavelenght ~ few Km

COLD Lab



[Aybas et al., PRL **126,** 141802 (2021)]

Dafne Hall



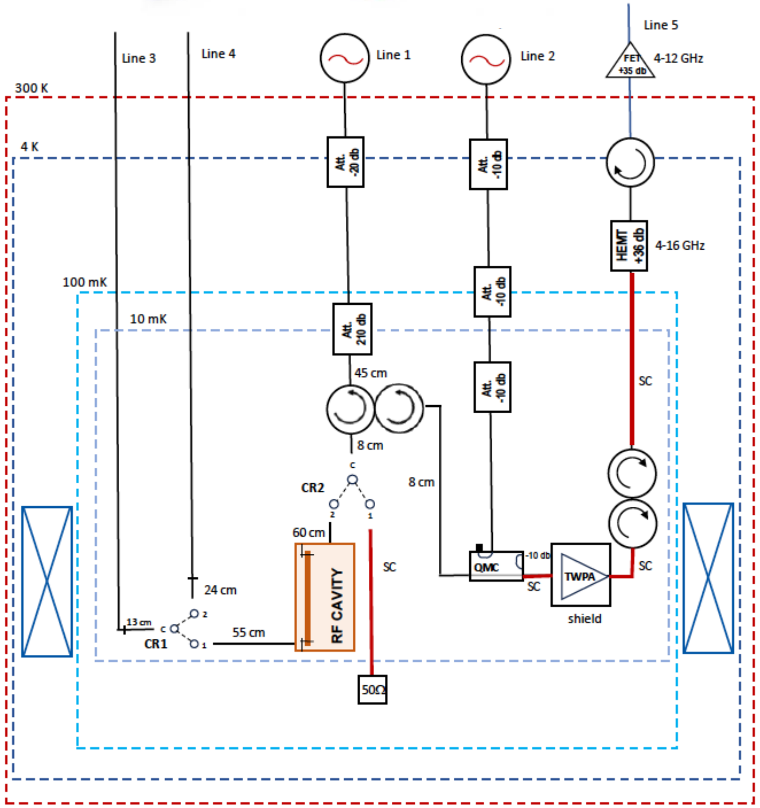
Cross Correlation

INFN GravNet

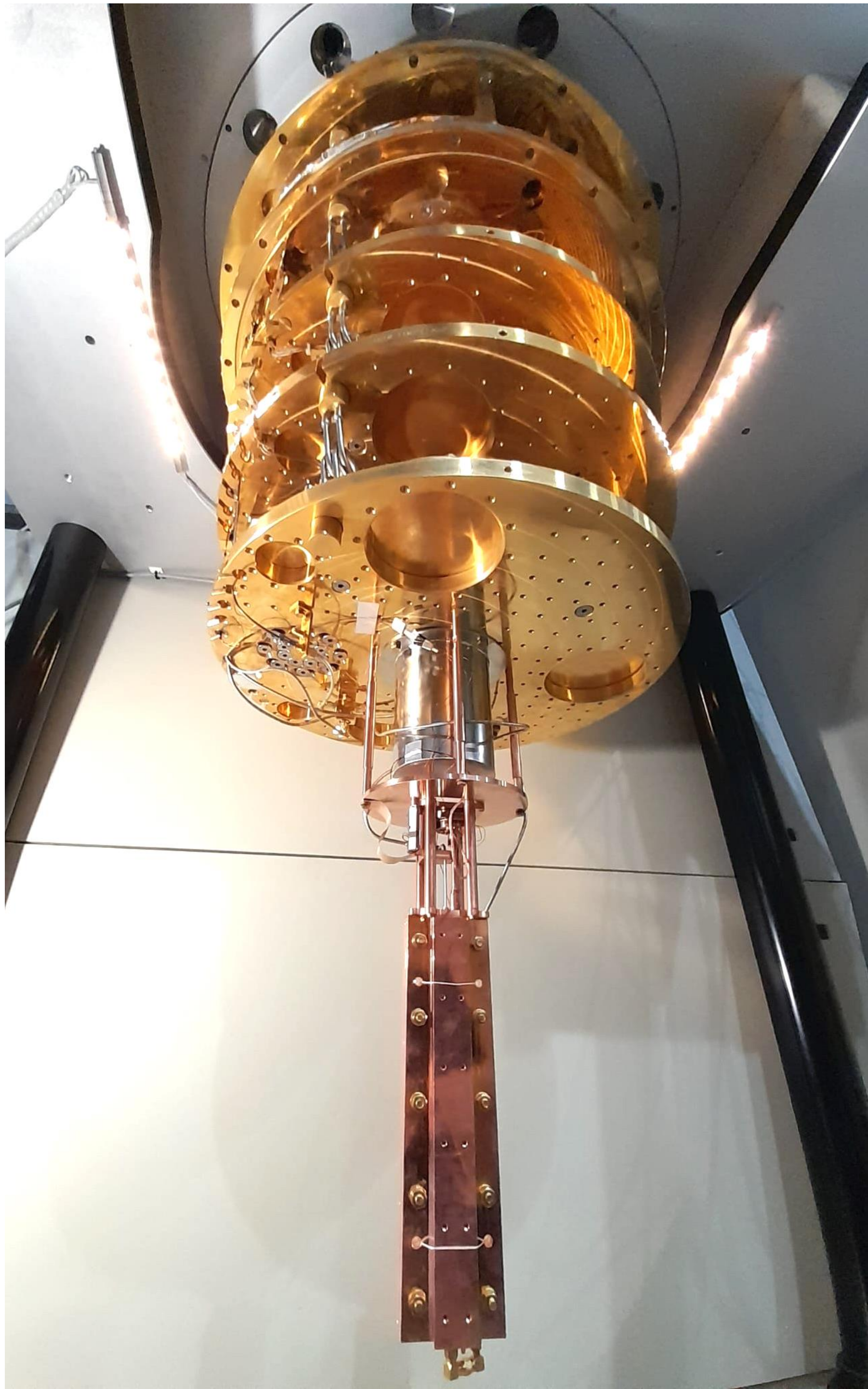
QUAX @LNF

QUAX@LNF – 9 GHz Haloscope

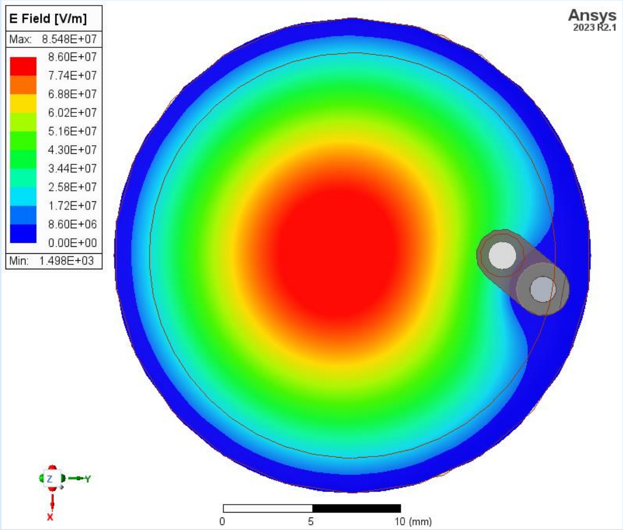
INFN QUAX@LNF GravNet

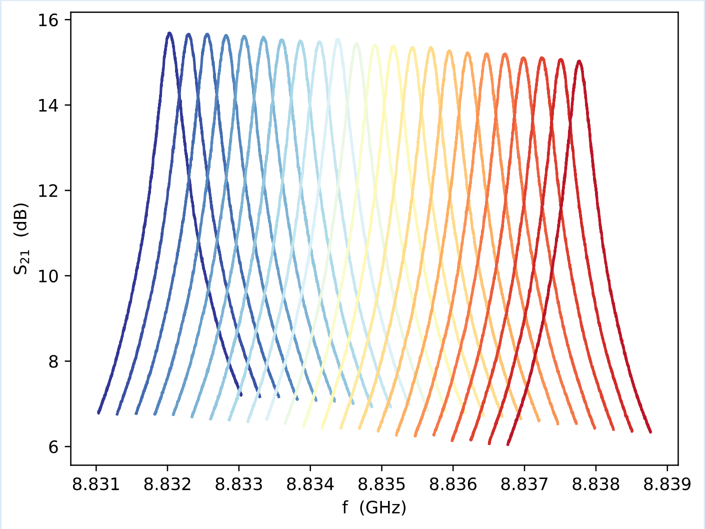


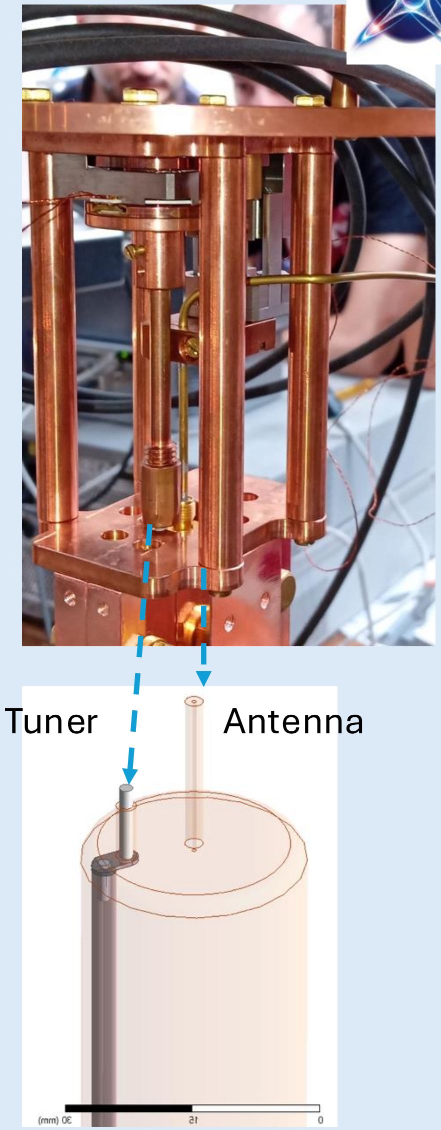
Phys. Rev. D 110, 022008 (2024)



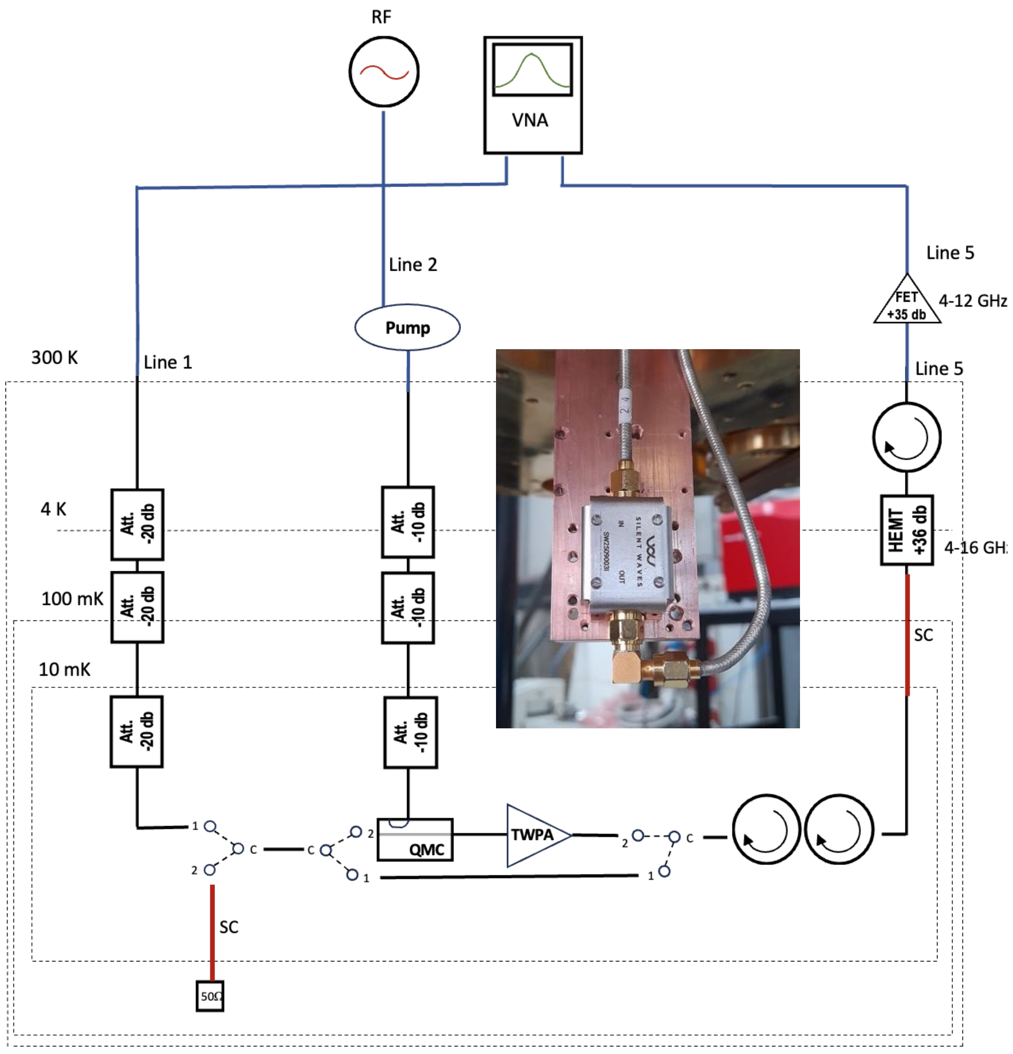
QUAX @LNF


E Field [V/m]
Max: 8.548E+07
8.60E+07
7.74E+07
6.88E+07
6.02E+07
5.16E+07
4.30E+07
3.44E+07
2.58E+07
1.72E+07
8.60E+06
0.00E+00
Min: 1.498E+03
Ansys
2023 R2.1
0
5
10 (mm)

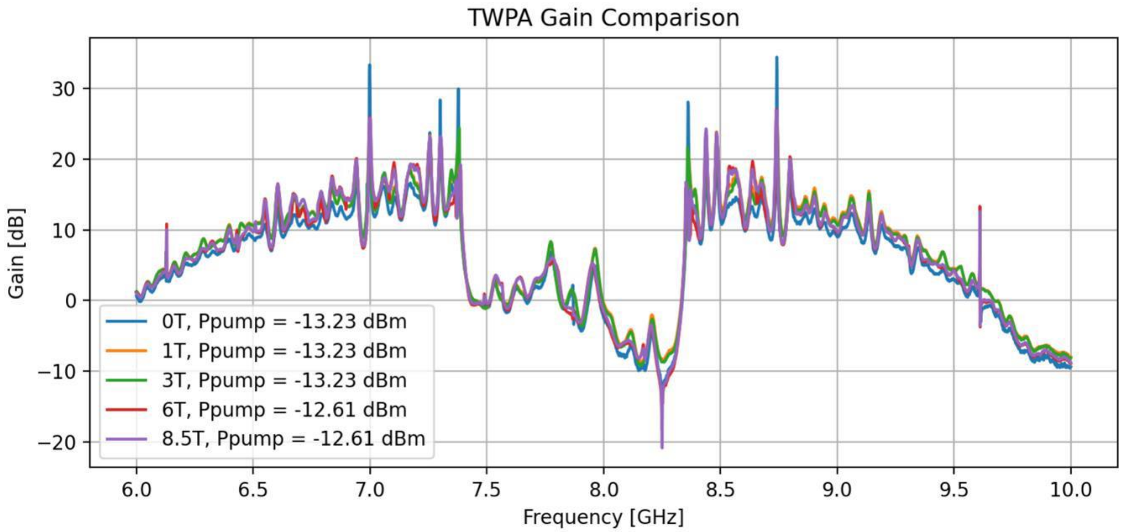

S21 (dB)
16
14
12
10
8
6
8.831
8.832
8.833
8.834
8.835
8.836
8.837
8.838
8.839
f (GHz)


Tuner
Antenna

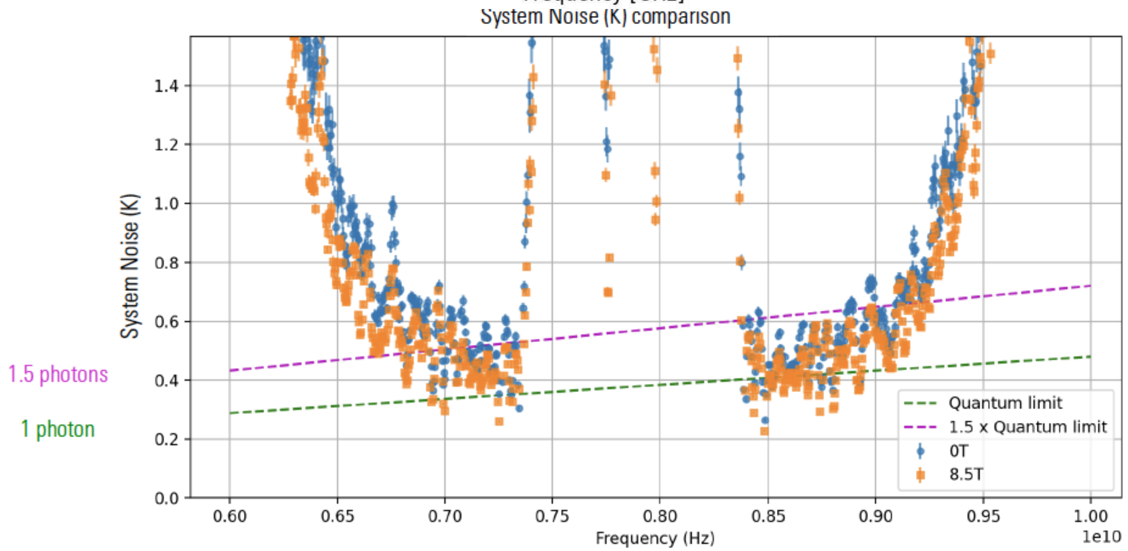
TWPA



RF
VNA
Line 2
Line 5
Pump
FET +35 db
4-12 GHz
300 K
Line 1
Line 5
4 K
Att. -20 db
Att. -10 db
HEMT +36 db
4-16 GH
100 mK
Att. -20 db
Att. -10 db
SC
10 mK
Att. -20 db
Att. -10 db
QMC
TWPA
SC
50Ω

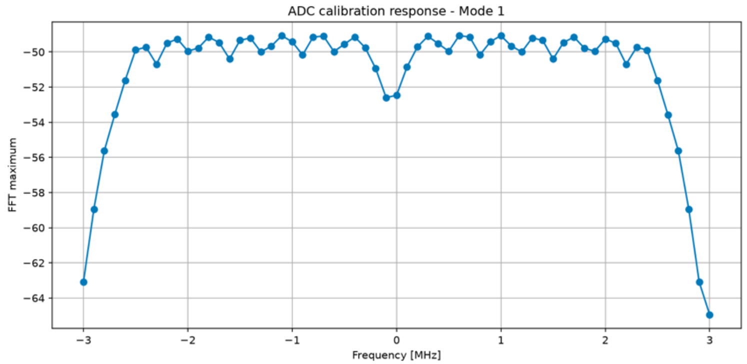


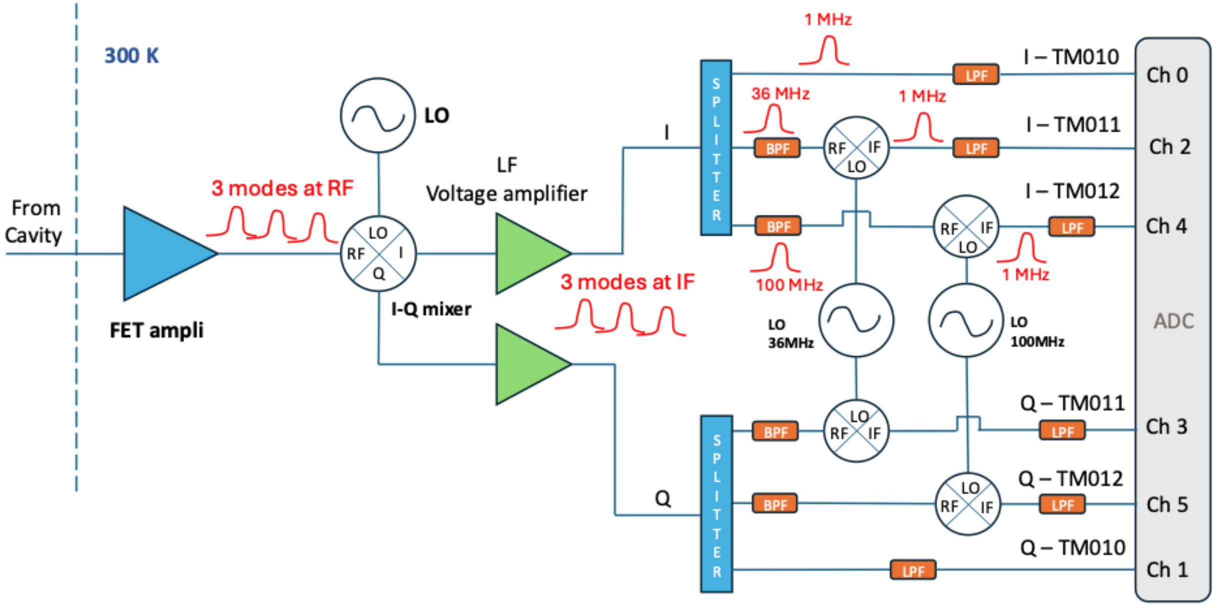
TWPA Gain Comparison
Gain [dB]
30
20
10
0
−10
−20
6.0
6.5
7.0
7.5
8.0
8.5
9.0
9.5
10.0
Frequency [GHz]
0T, Ppump = -13.23 dBm
1T, Ppump = -13.23 dBm
3T, Ppump = -13.23 dBm
6T, Ppump = -12.61 dBm
8.5T, Ppump = -12.61 dBm

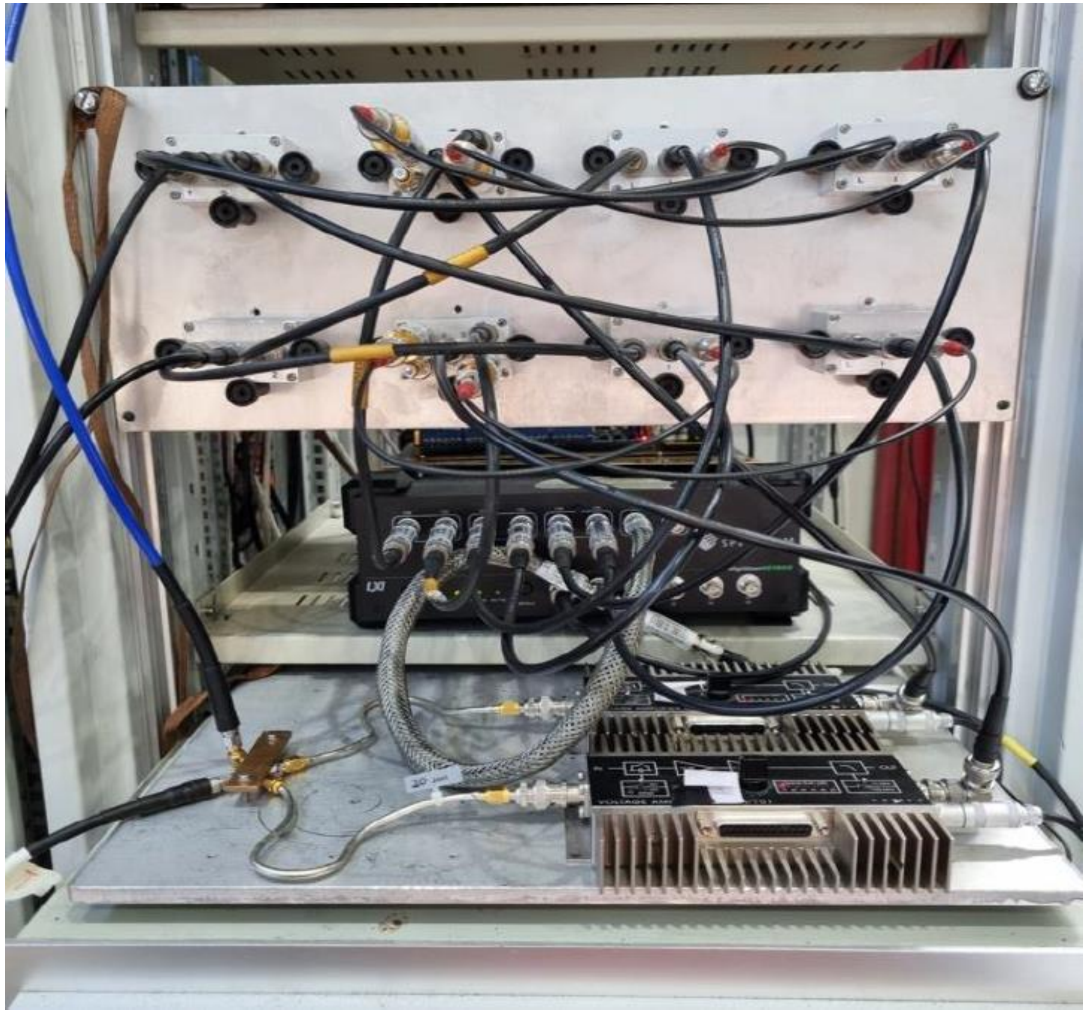


System Noise (K) comparison
System Noise (K)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.60
0.65
0.70
0.75
0.80
0.85
0.90
0.95
1.00
Frequency (Hz)
1e10
1.5 photons
1 photon
Quantum limit
1.5 x Quantum limit
0T
8.5T

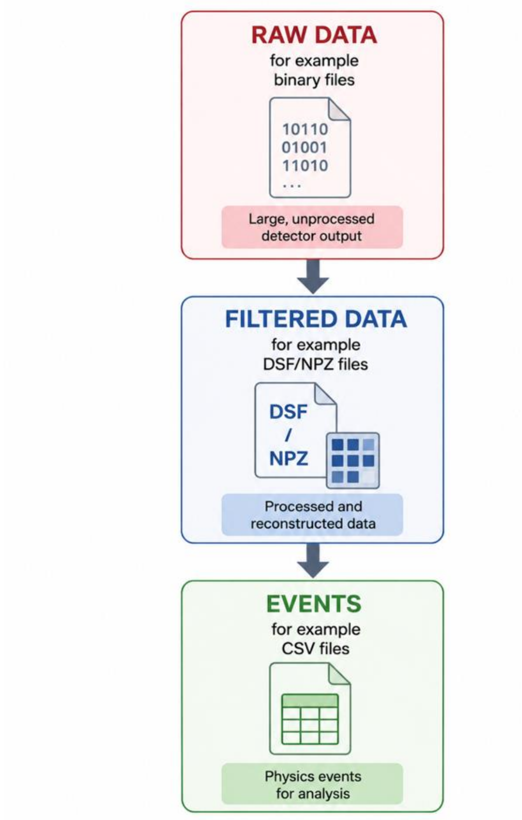
DAQ for TM010 TM011 TM012 Modes

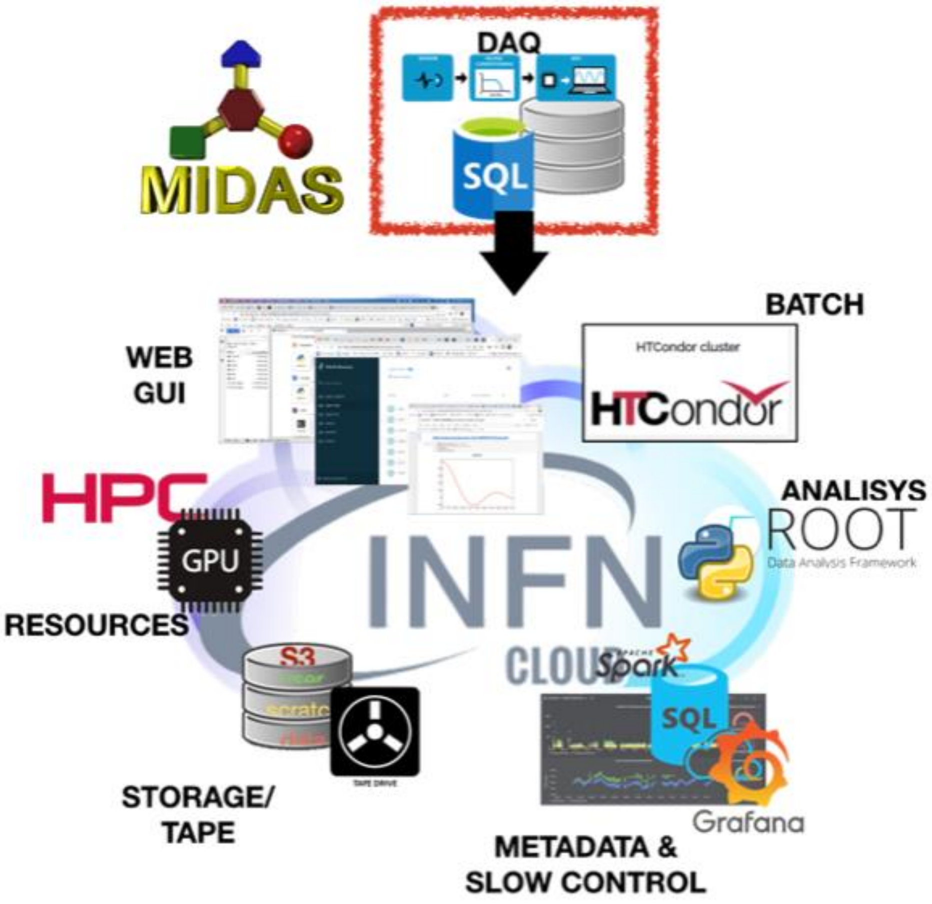


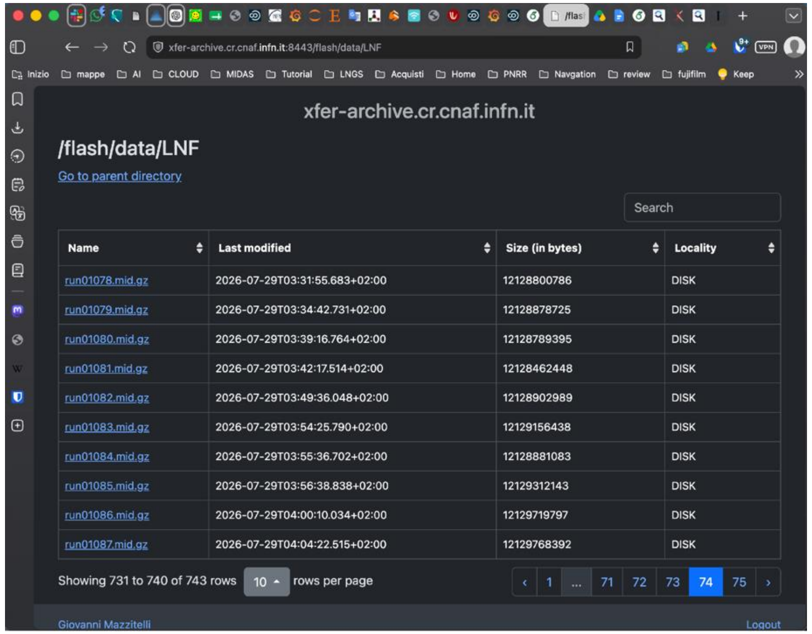




New Data Taking Started!!!







xfer-archive.cr.cnaf.infn.it:8443/flash/data/LNF

xfer-archive.cr.cnaf.infn.it

/flash/data/LNF

Go to parent directory

Search

Name	Last modified	Size (in bytes)	Locality
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run01079.mid.gz	2026-07-29T03:34:42.731+02:00	12128878725	DISK
run01080.mid.gz	2026-07-29T03:39:16.764+02:00	12128789395	DISK
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run01082.mid.gz	2026-07-29T03:49:36.048+02:00	12128902989	DISK
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run01087.mid.gz	2026-07-29T04:04:22.515+02:00	12129768392	DISK

Showing 731 to 740 of 743 rows 10 rows per page ‹ 1 ... 71 72 73 74 75 ›

Giovanni Mazzitelli Logout

COLD

LNF

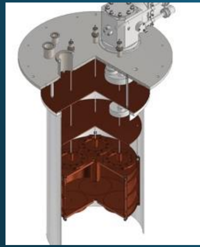
CryOgenic Laboratory for Detectors

COLD Lab@LNF

https://coldlab.lnf.infn.it

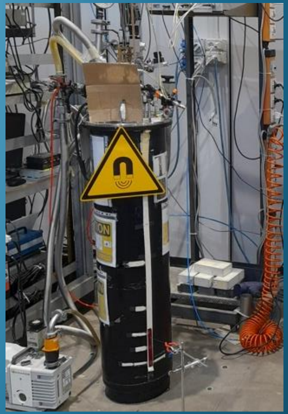
DR for qubit tests

NbSe2 qubit Lab



4K dry cryostat for FLASH prototype

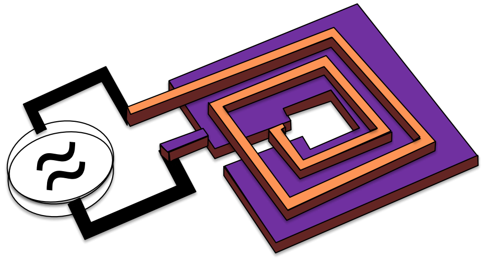
X-band Haloscope

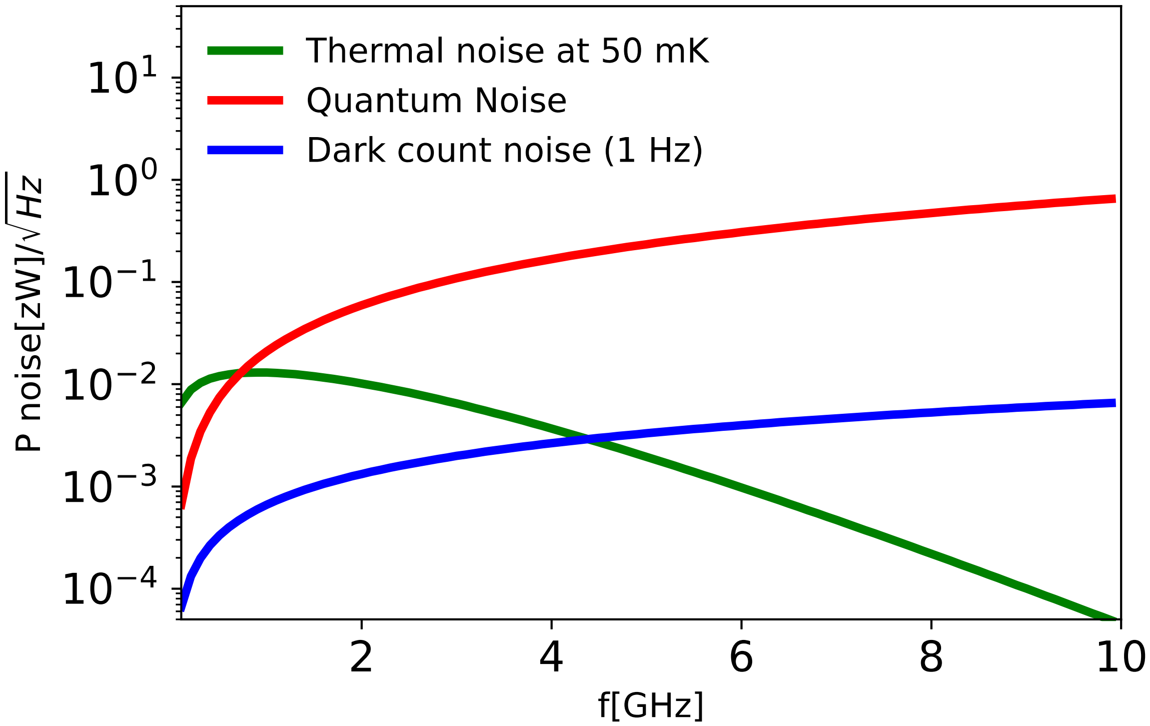


LHe 8T cryostat SC cavities

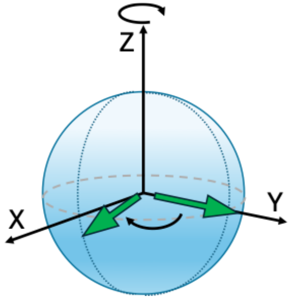
Beyond Quantum Limit with Quantum Sensing

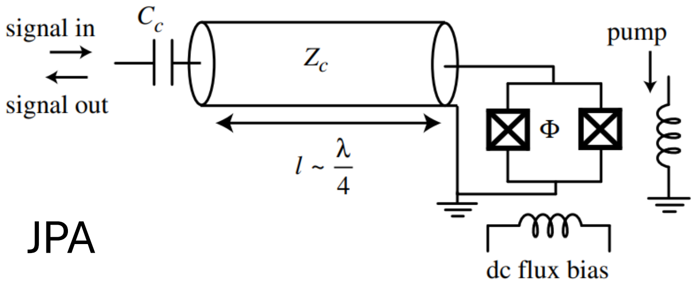
SQUID





Counter based on superconducting qubits



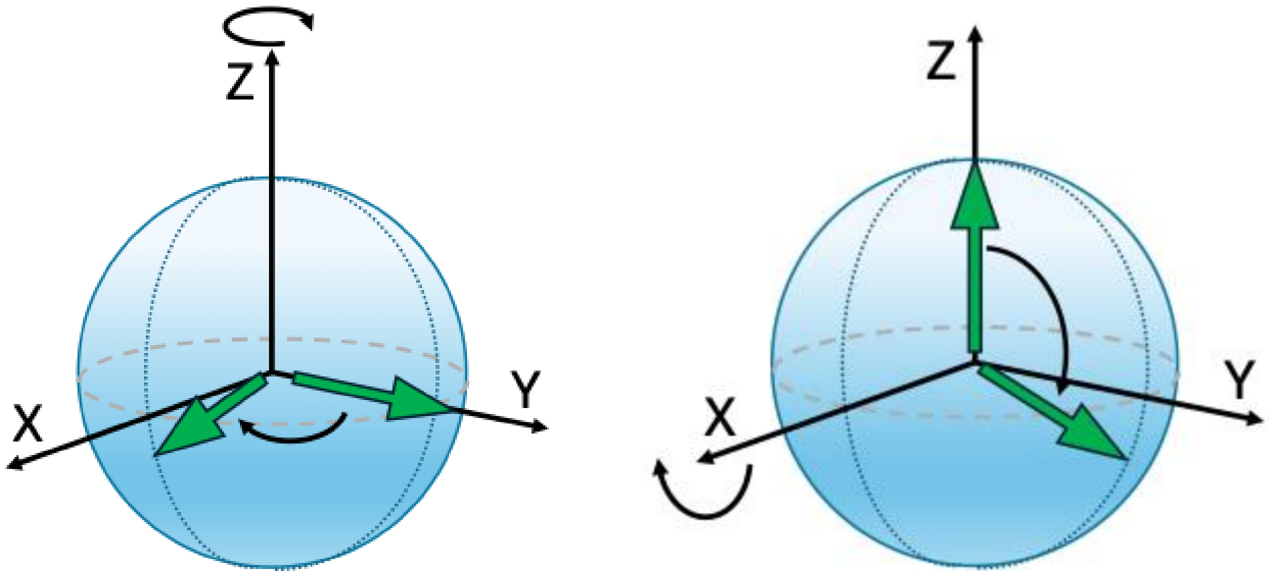


JPA

arXiv:1607.02529

PHYSICAL REVIEW D 88, 035020 (2013)

Sensing with Superconducting Qubits

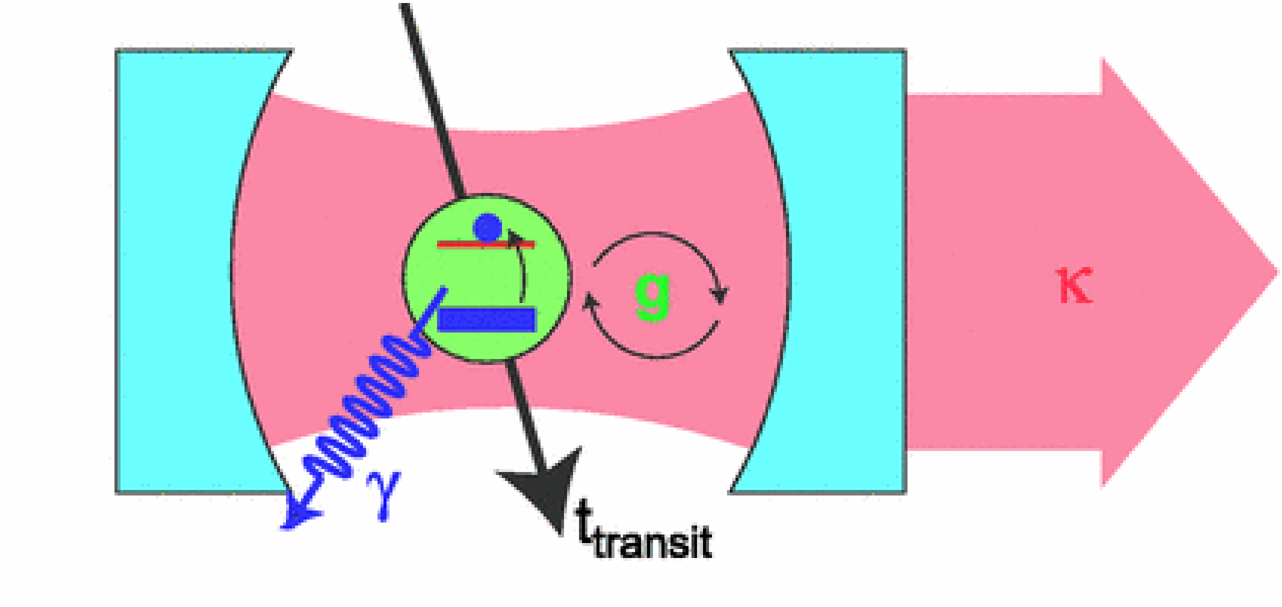


$$\begin{cases} H_{int} = \epsilon\sigma_x \\ H_{int} = \epsilon\sigma_z \end{cases}$$

$H_{int} = \epsilon\sigma_x$ → Excitation

$H_{int} = \epsilon\sigma_z$ → Phase Rotation

Qubit Cavity System



Resonator energy — Qubit energy — Qubit resonator interaction

$$H = \hbar\omega_r a^\dagger a + \frac{\hbar}{2}\tilde{\omega}_a\sigma_z + \hbar\chi a^\dagger a\sigma_z$$

$\tilde{\omega}_a \neq \omega_r$

Resonator coherent drive

$$+\hbar\left(a^\dagger\varepsilon e^{-i\omega_d t} + a\varepsilon^* e^{i\omega_d t}\right)$$

Qubit drive

$$+\frac{\hbar g}{\Delta}\left(\sigma^+\varepsilon e^{-i\omega_d t} + \sigma^-\varepsilon^* e^{i\omega_d t}\right)$$

Ramsey Sensing

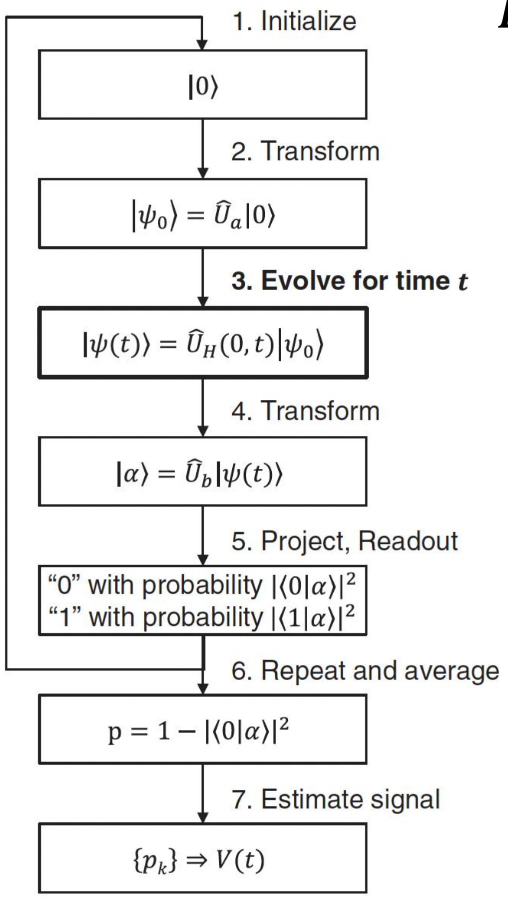
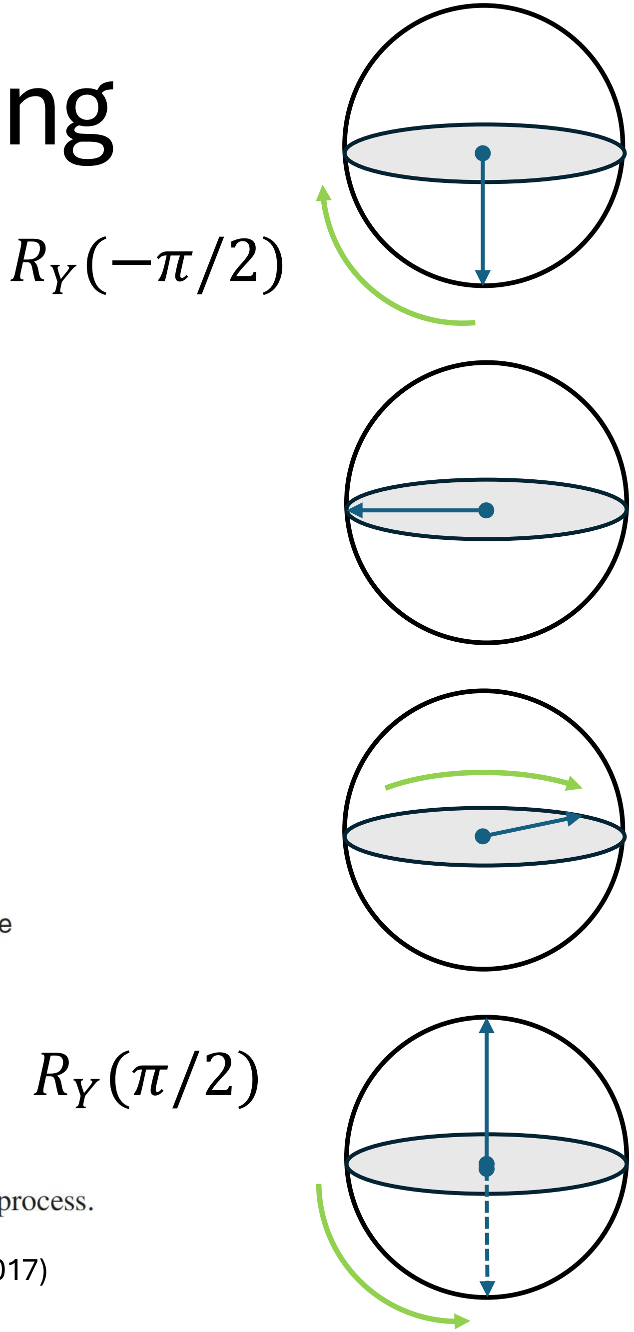


FIG. 2. Basic steps of the quantum sensing process.

REVIEWS OF MODERN PHYSICS, VOLUME 89 (2017)



$$H_{int} = \chi a^{+} a \sigma_z$$

$$\Omega = 2\chi\bar{n}$$

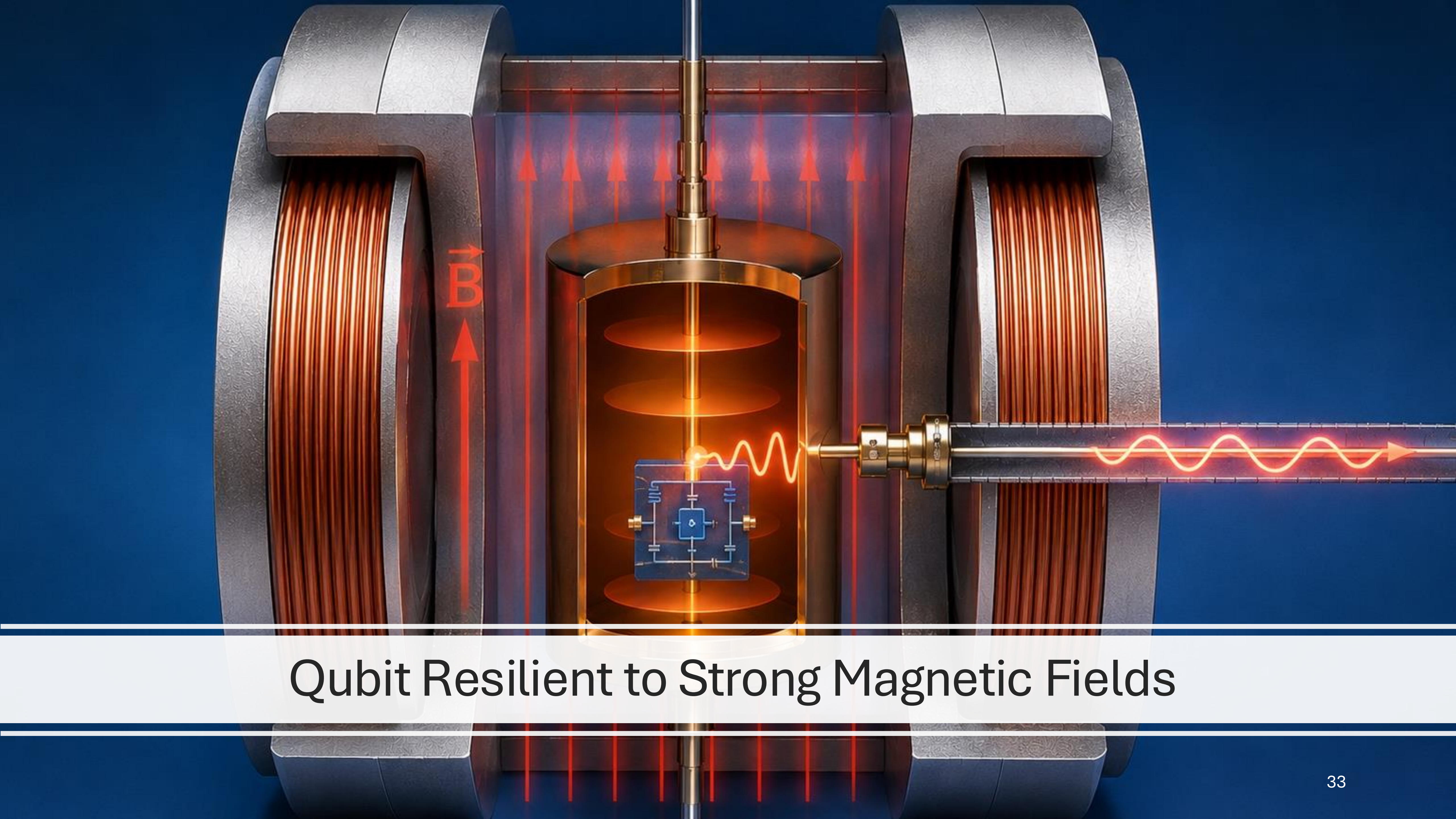
Precession frequency

$$|\psi\rangle = |0\rangle$$

$$|\psi\rangle = (|0\rangle + |1\rangle)/\sqrt{2}$$

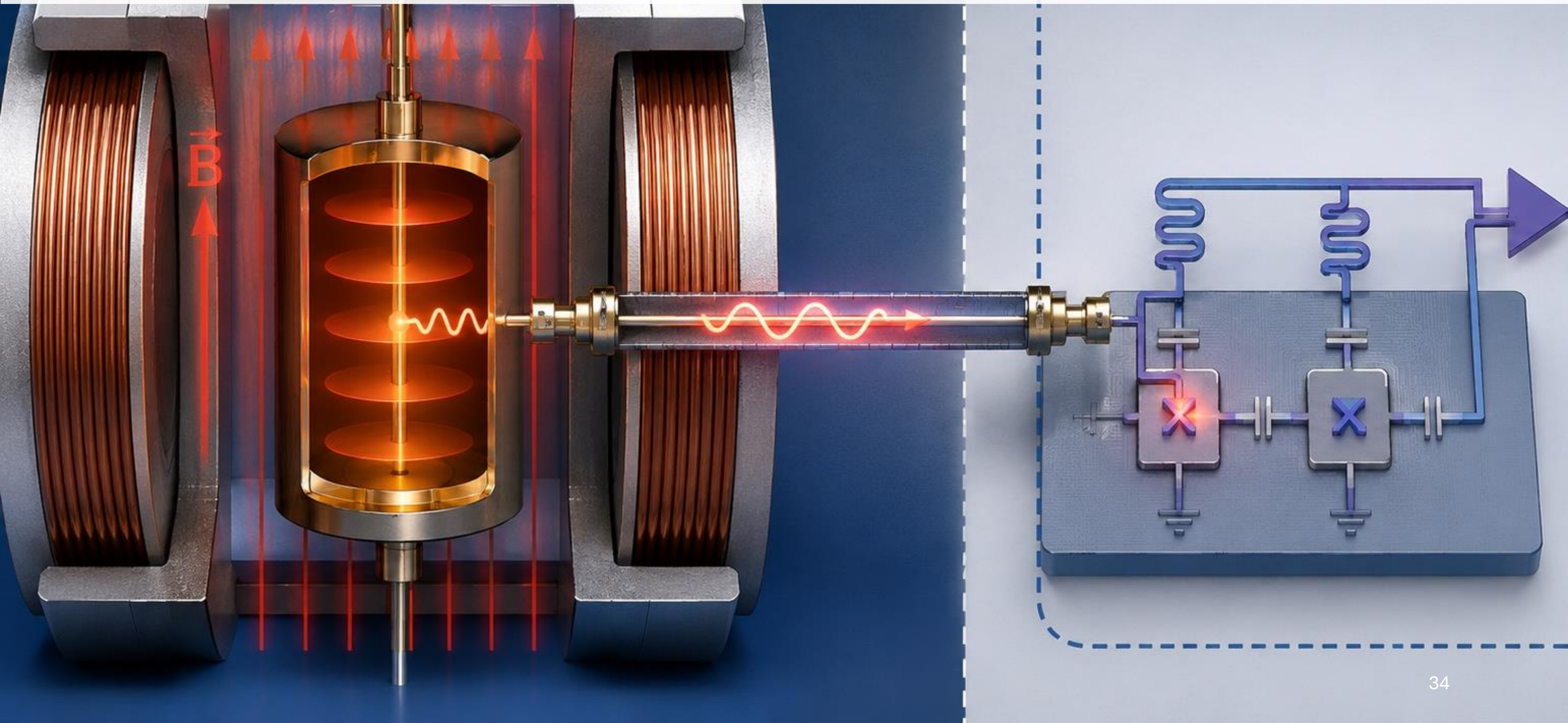
$$|\psi\rangle = \left(|0\rangle + e^{-i\Omega t}|1\rangle\right)/\sqrt{2}$$

$$P(1) = 1 - |\langle 0|\psi\rangle|^2 = \frac{1}{2}(1 - \cos\Omega t)$$



Qubit Resilient to Strong Magnetic Fields

Itinerant Photon Detection



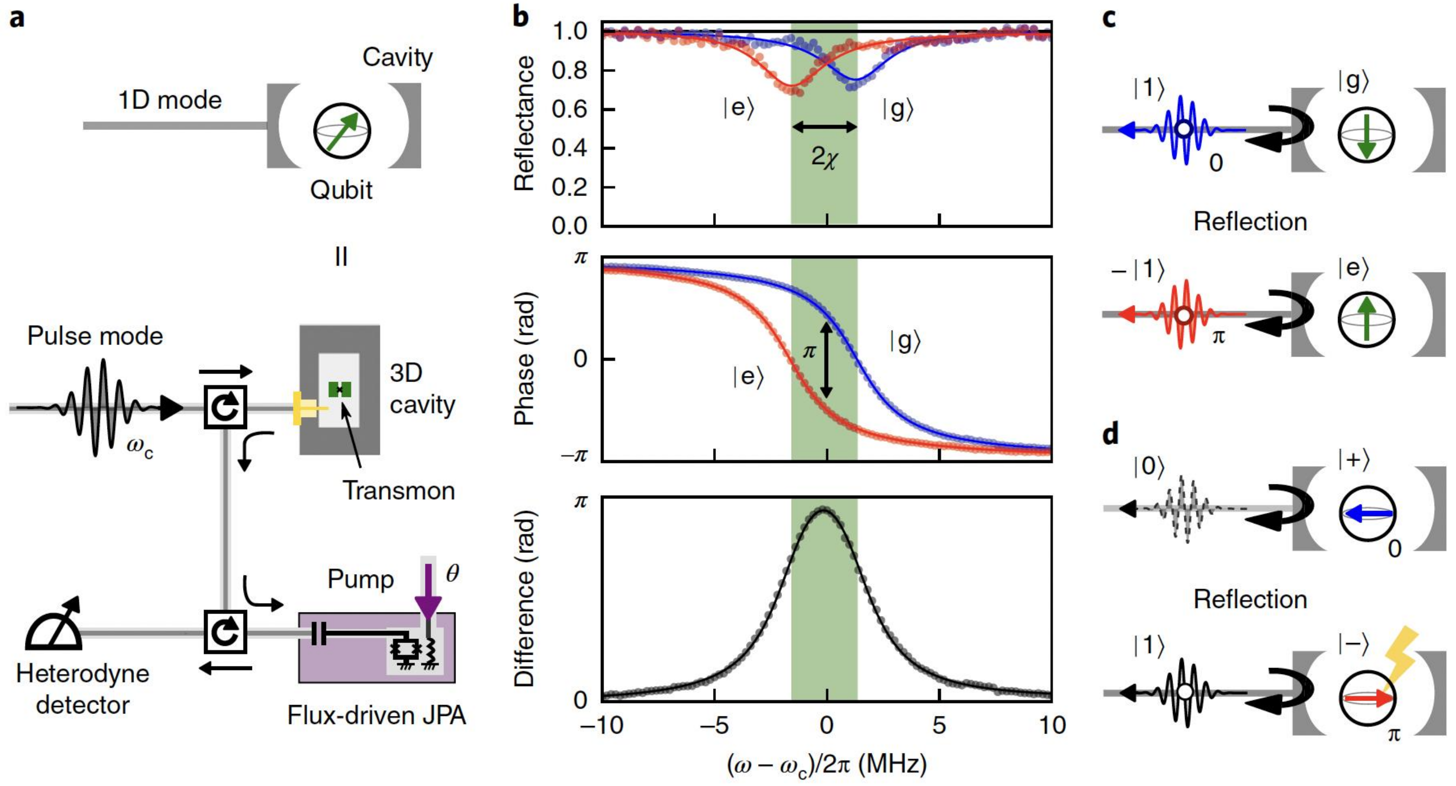
Quantum Non-Demolition Detection of an Itinerant Microwave Photon

Qubit-cavity coupling

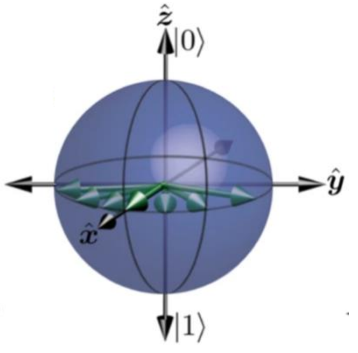
$$k = 2\chi$$

Cavity width

Itinerant photon



Ramsey measurement



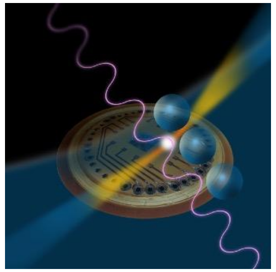
Measurement time

$$t_m = \frac{\pi}{2\chi} = \pi/k$$

https://doi.org/10.1038/s41567-018-0066-3

Development of Superconducting Quantum Circuits at INFN

Projects funded by INFN Scientific Commission 5



SIMP
Single Microwave Photon detection with a CBJJ and nano TES

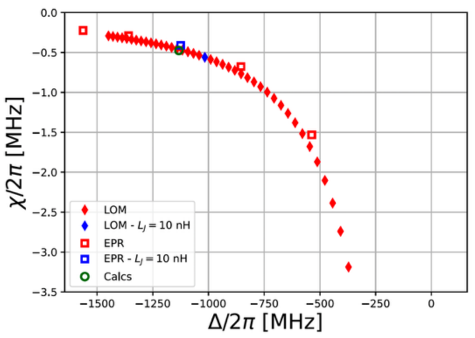
QubIT
Quantum sensing with Superconducting Qubits

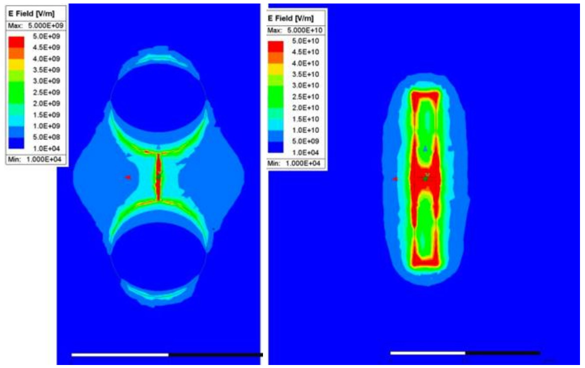
Quart&t
Quantum architectures for theory & technology

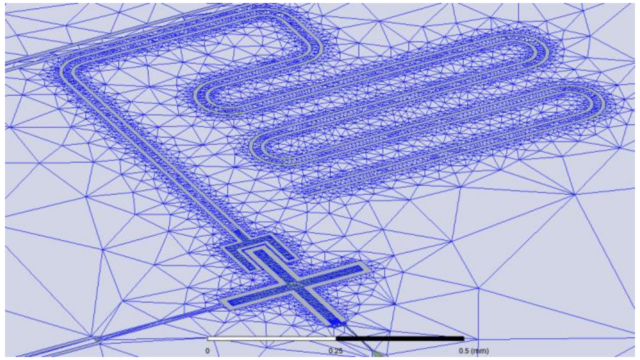
Resilience
Development of qubits resilient to magnetic field with WdW materials

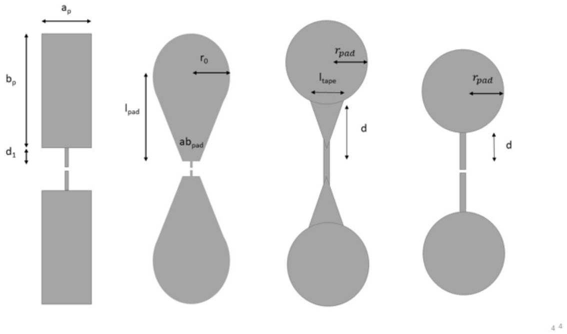
In collaboration with:

Qubit Design and Simulation



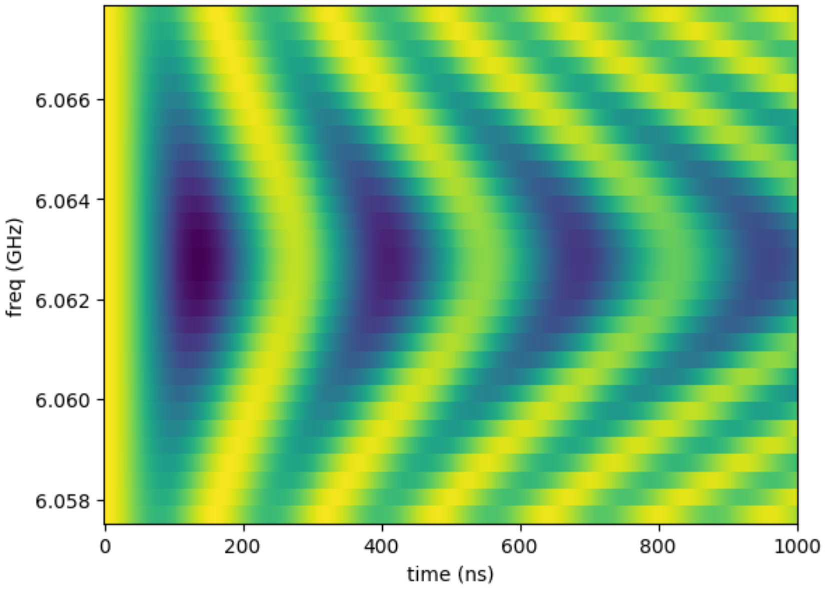






- ANSYS HFSS Electromagnetic Simulations + EPR Method https://qutip.org

Evolution of Quantum Systems with Qutip



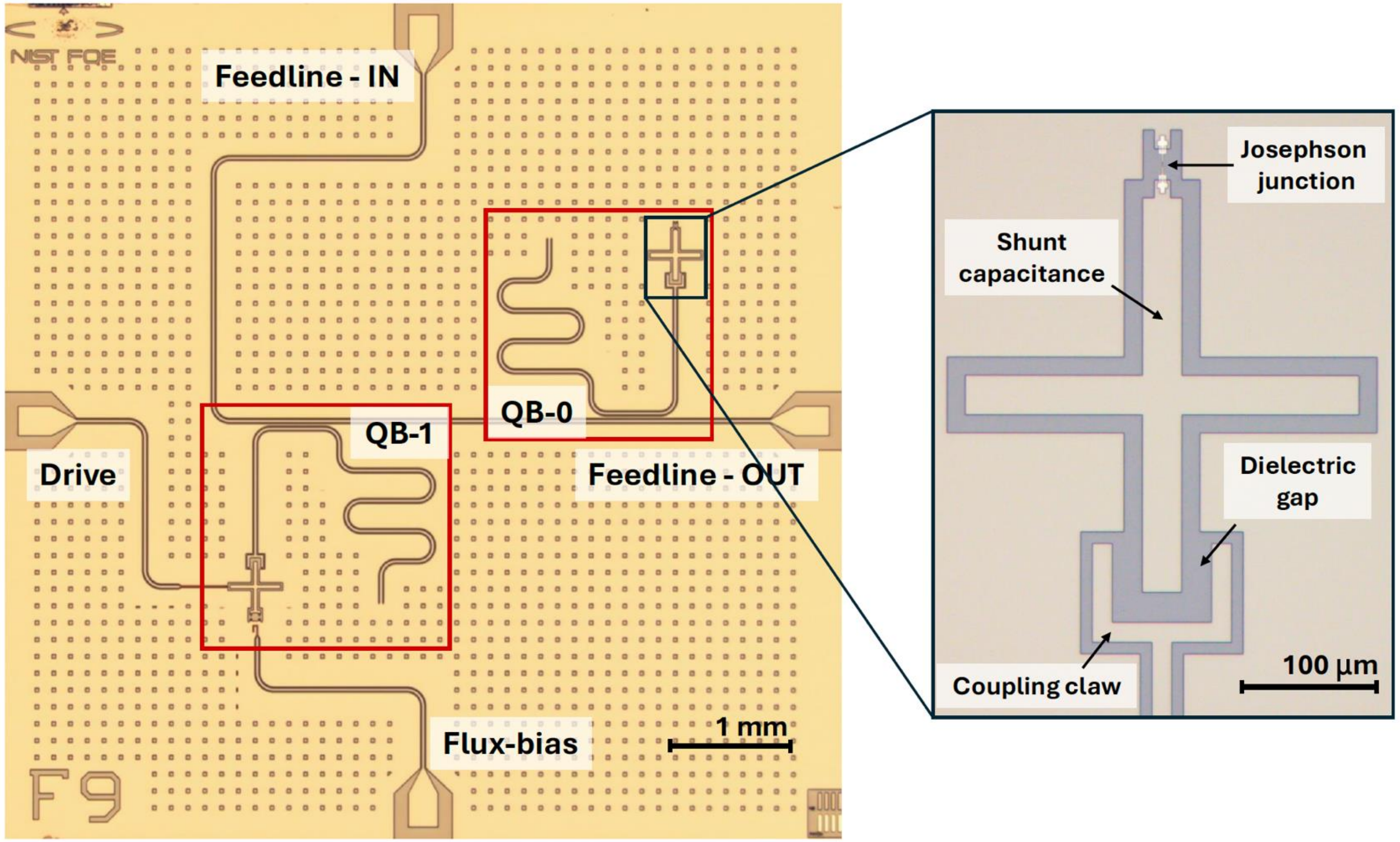

```
a = tensor(destroy(nlev), qeye(3))
adag = a.dag()
b = tensor(qeye(nlev), destroy(3))
bdag = b.dag()
P = [tensor(qeye(nlev), basis(3,klev)*basis(3,klev).dag()) for klev in range(3)] # Proiettore stati qubit

H = (wc-w)*adag*a + (wq-w)*bdag*b + alpha/2*bdag*bdag*b*b + g*(adag*b+a*bdag) + 1j*(epsilon*a-adag*epsilon)
L = [sqrt(k)*a, sqrt(1/T1)*b]

phi0 = tensor(coherent(nlev, sqrt(nph0)), basis(3,0))
t = np.linspace(0, tmax, 501)

sol = mesolve(H, phi0, t, L, e_ops=[adag*a, bdag*b, P[0], P[1], P[2], a])
```

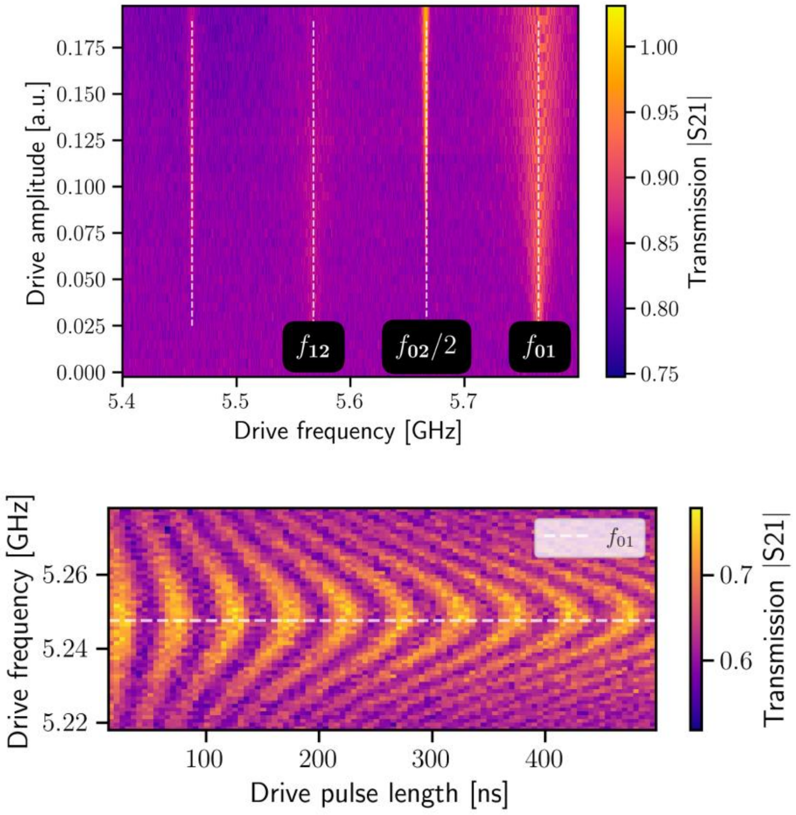
First Qubit Design and Realization



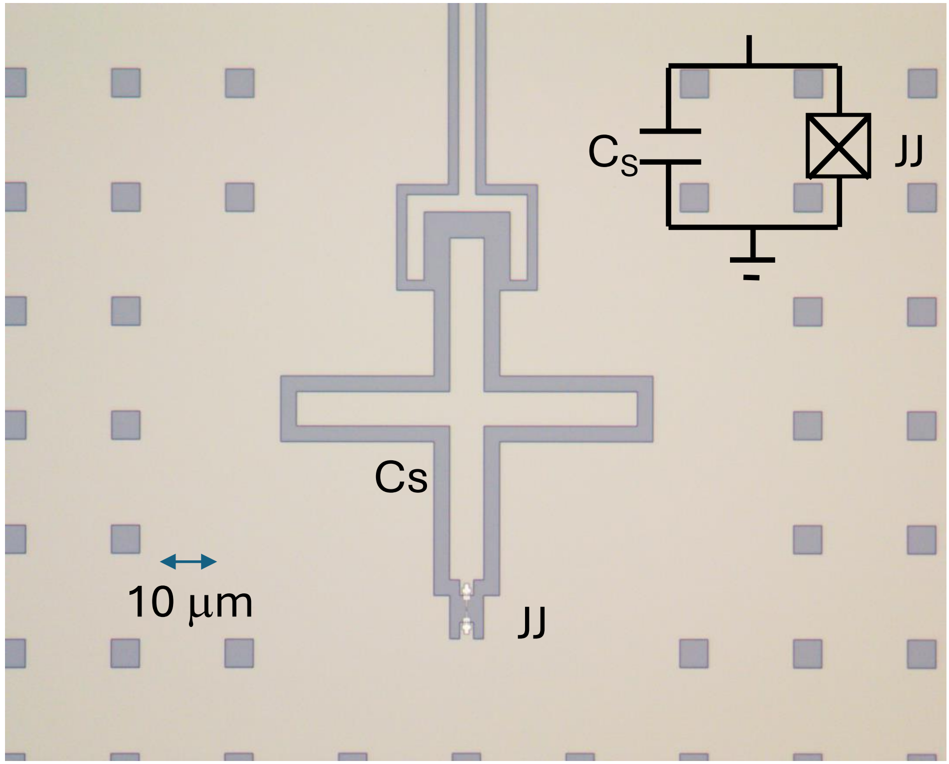
Labranca (MiB) and Corti (Firenze) PhD Thesis
Moretti et al. 10.1109/TQE.2025.3633176

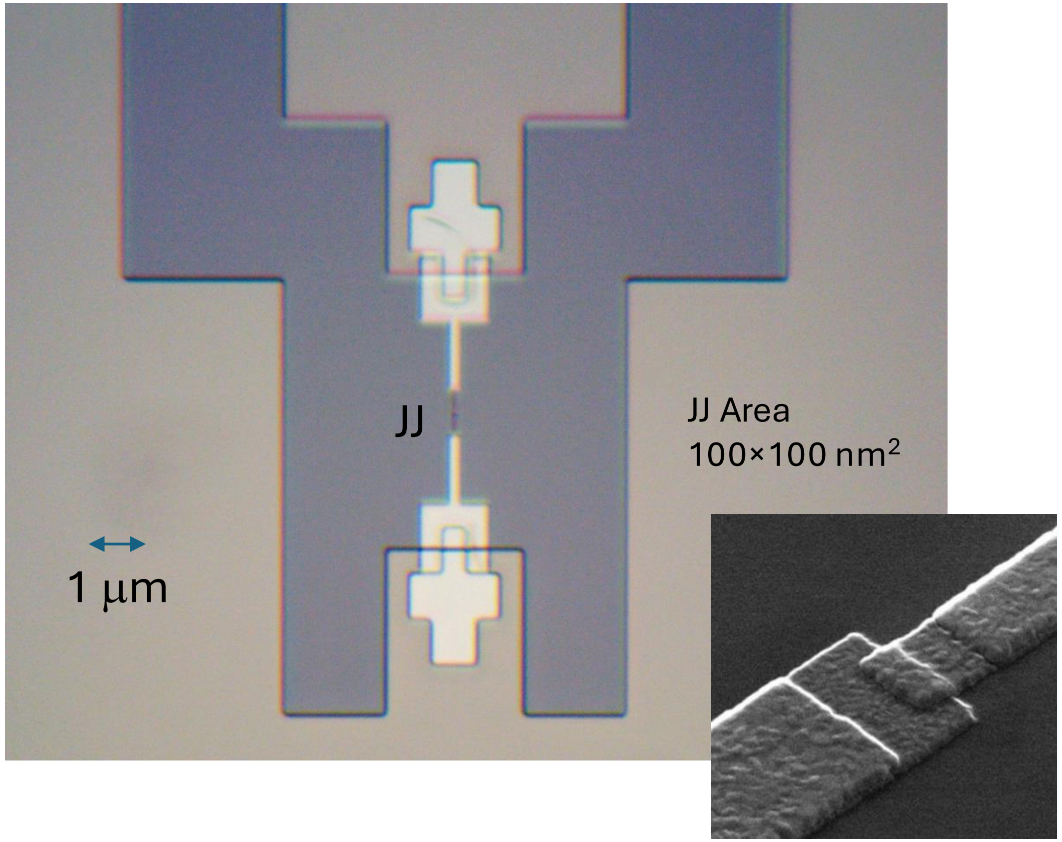
Fabrication at NIST

Qubit Characterization at Uni MiB



First Qubit Design and Realization

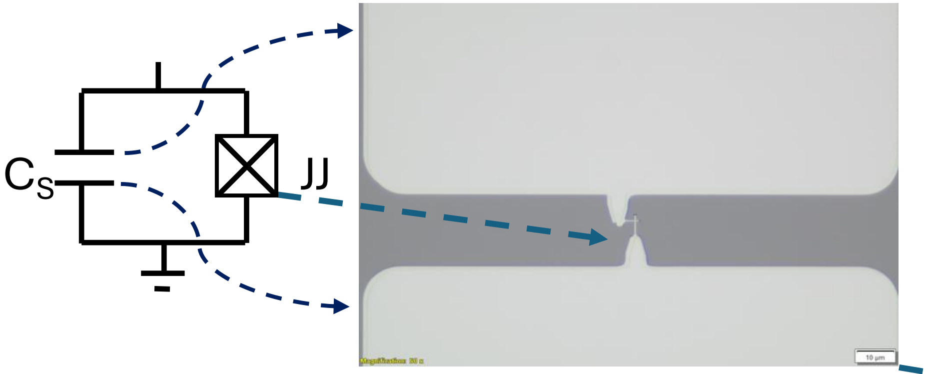


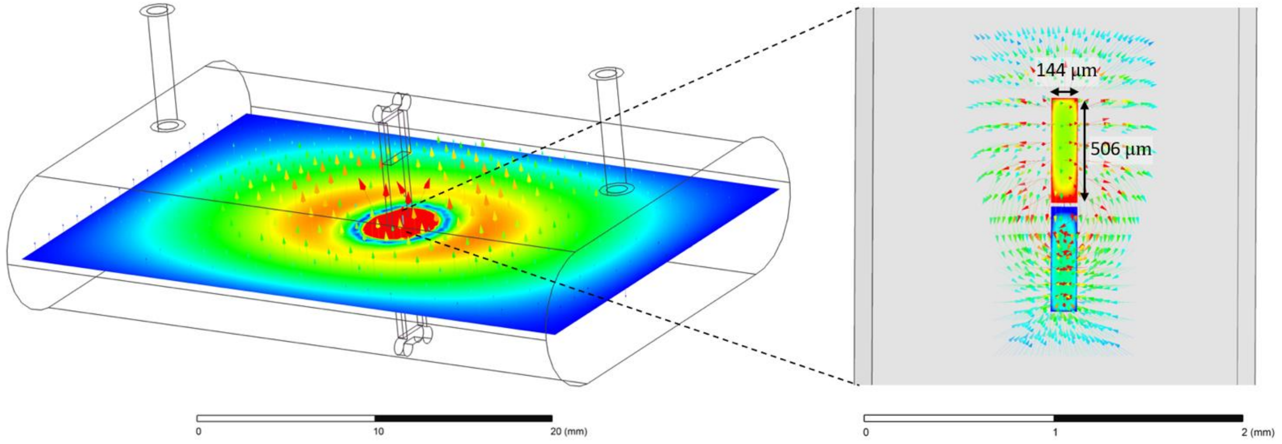


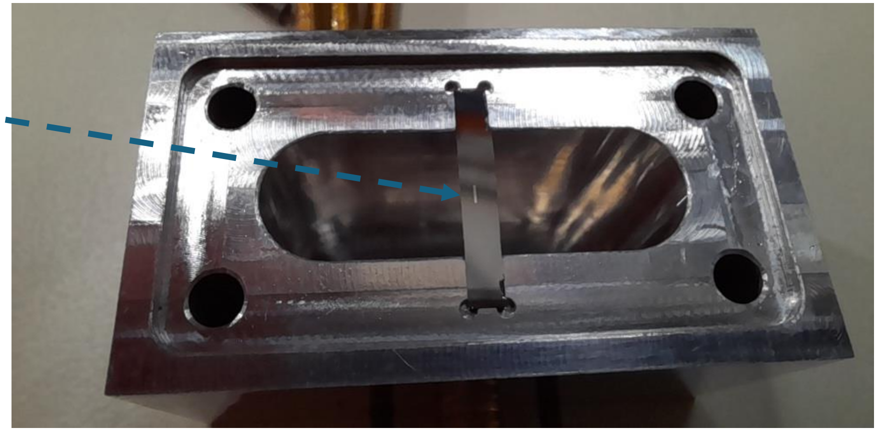
Labranca (MiB) and Corti (Firenze) PhD Thesis
Moretti et al. 10.1109/TQE.2025.3633176

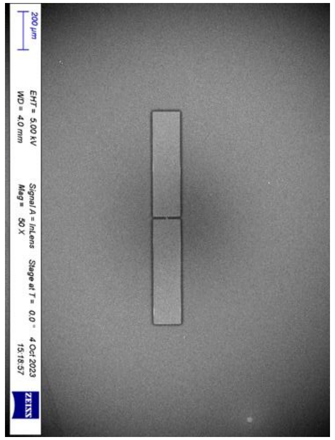
Fabrication at NIST

Qubit in a 3D Resonator





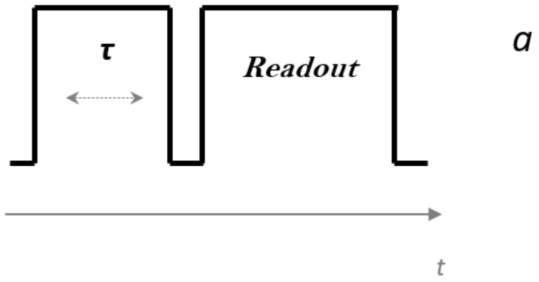


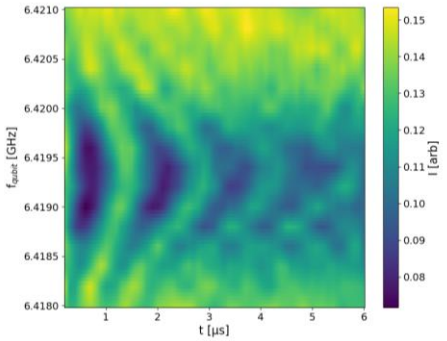


Appl. Sci. 2024, 14(4), 1478

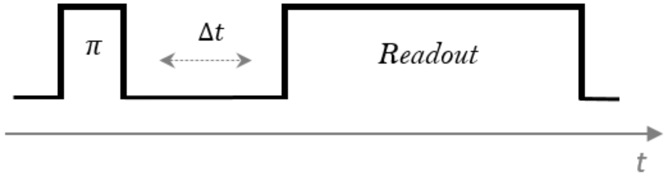
3D Qubit - Characterization

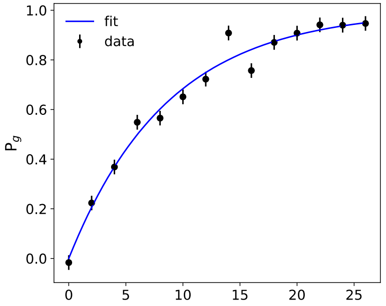
Rabi oscillations



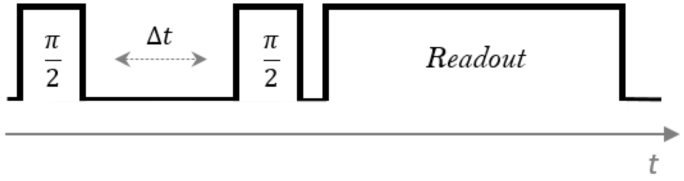


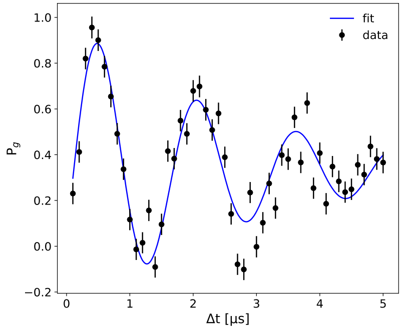
Qubit lifetime measurement





Ramsey Spectroscopy
and
T2 measurement





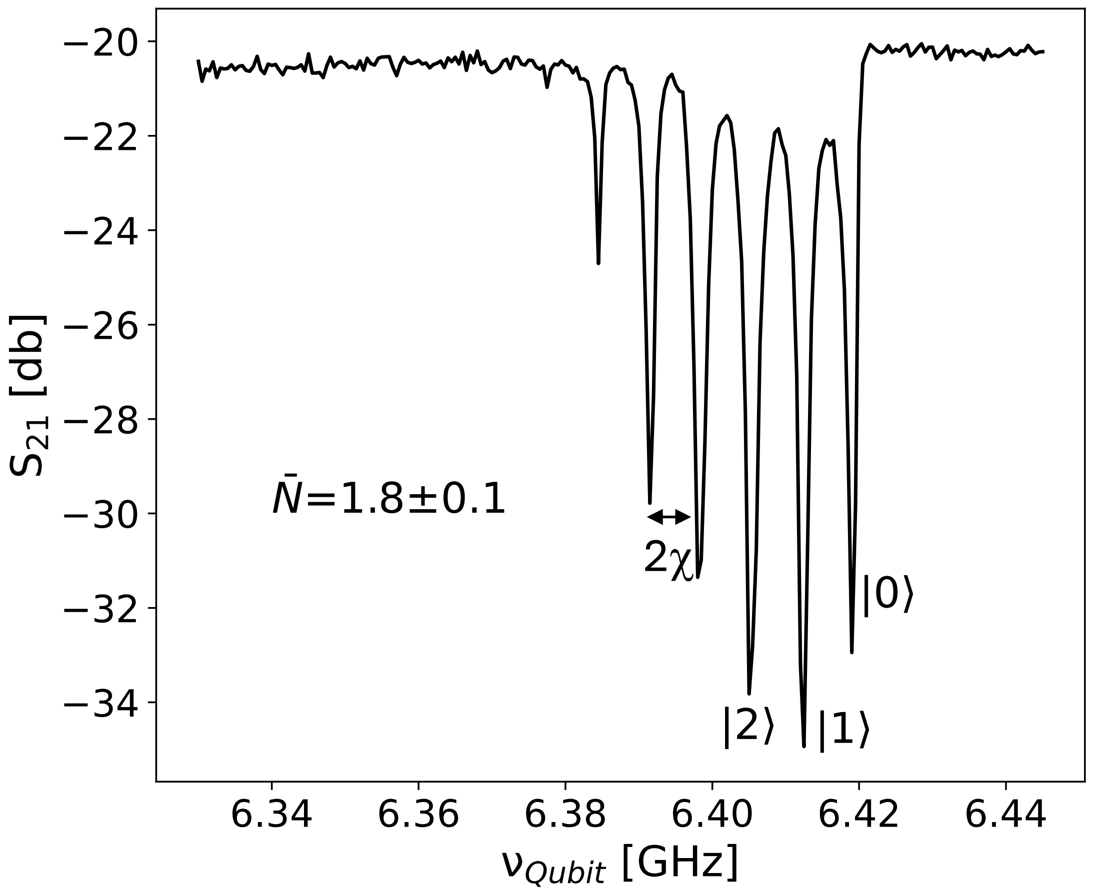
Appl. Sci. 2024, 14(4), 1478

Microwave Photon Counting with a 3D Qubit

$$\omega'_q = \omega_q + 2n_\gamma \chi$$

Photon number in resonator

Two tones spectroscopy on 3D qubit



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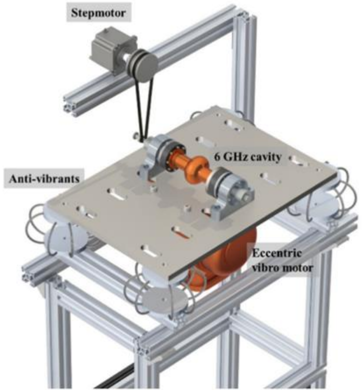
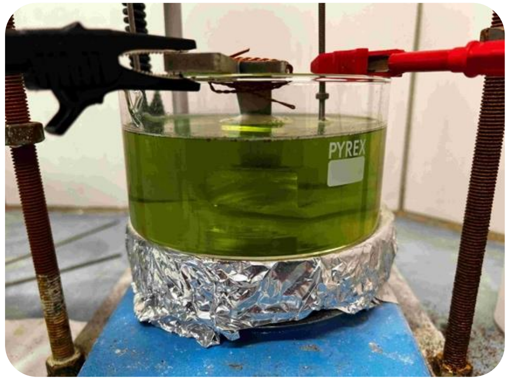
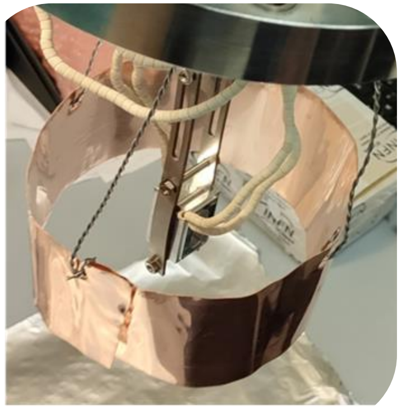
3D Qubit – Cavity Fabrication

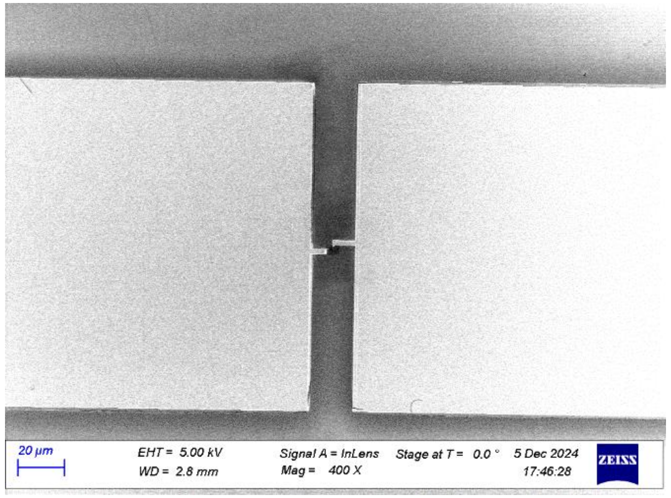


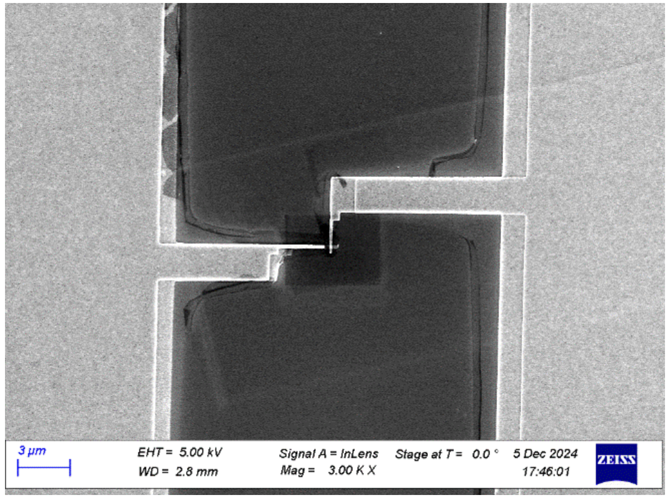


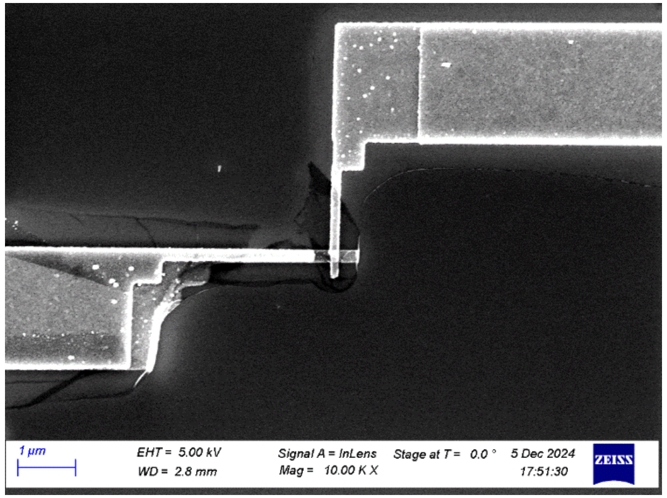


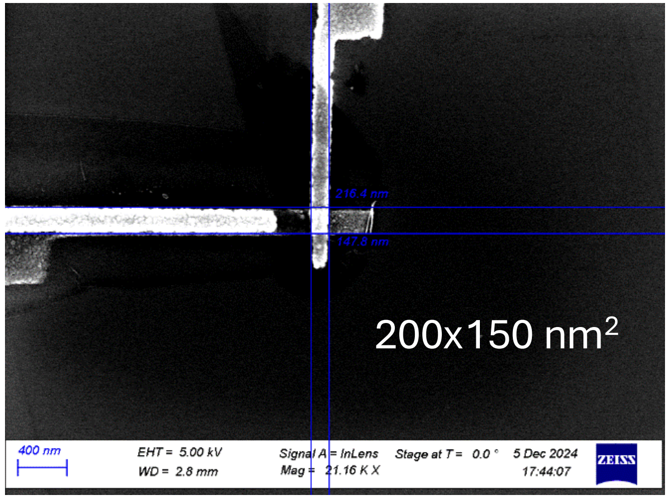
Fabrication at INFN LNL - Mechanical machining, Vibro tumbling, Electropolishing, Annealing

3D Qubit - Fabrication



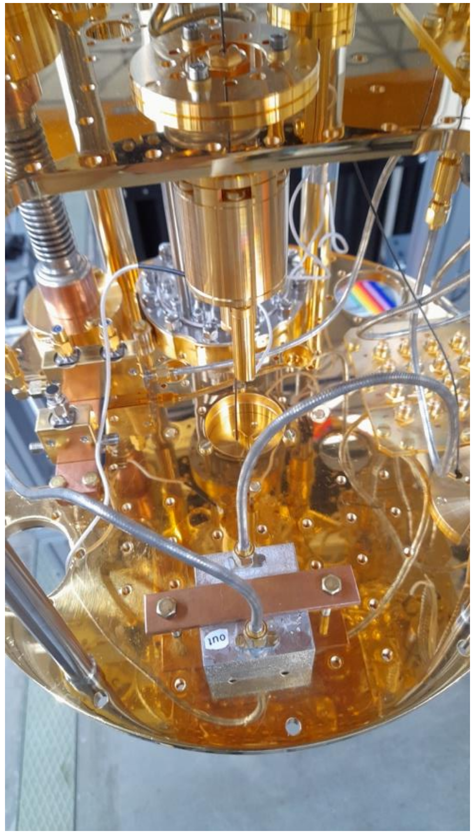


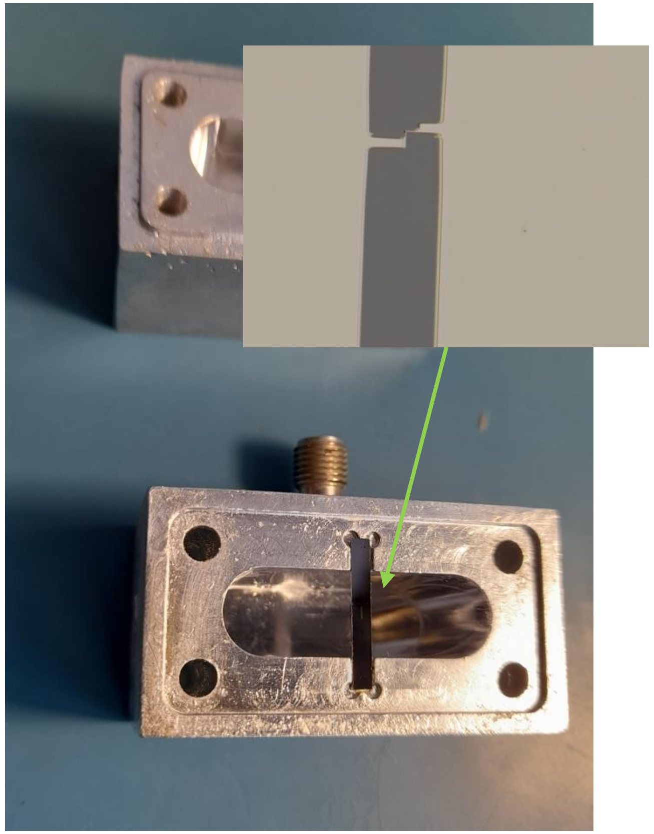




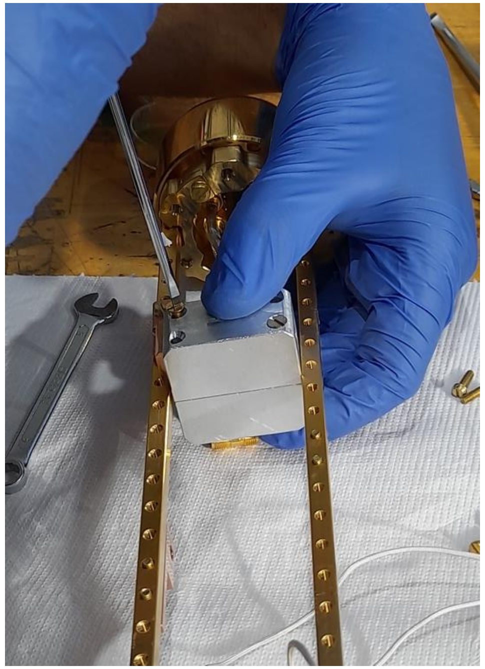
CNR IFN
Istituto di Fotonica e Nanotecnologie

3D Qubit - Measurement



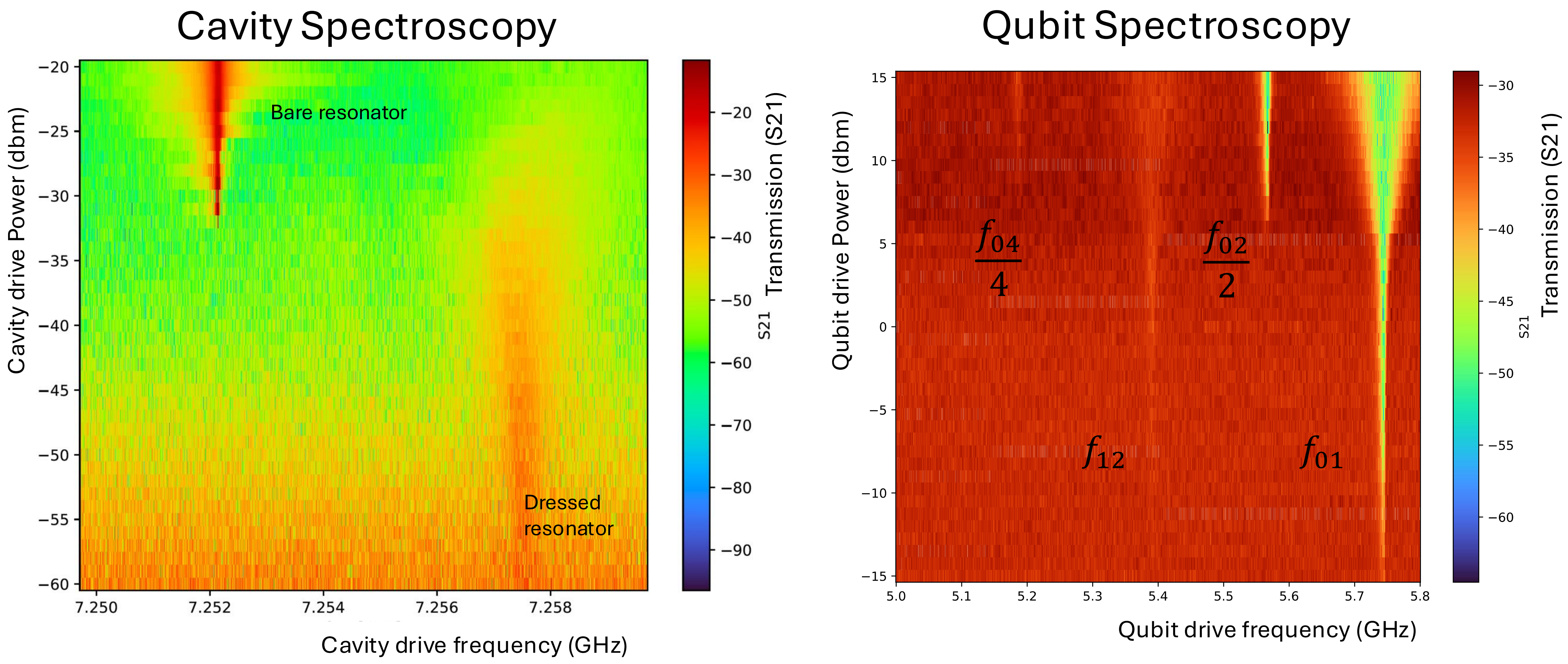


3D Qubit - Measurement



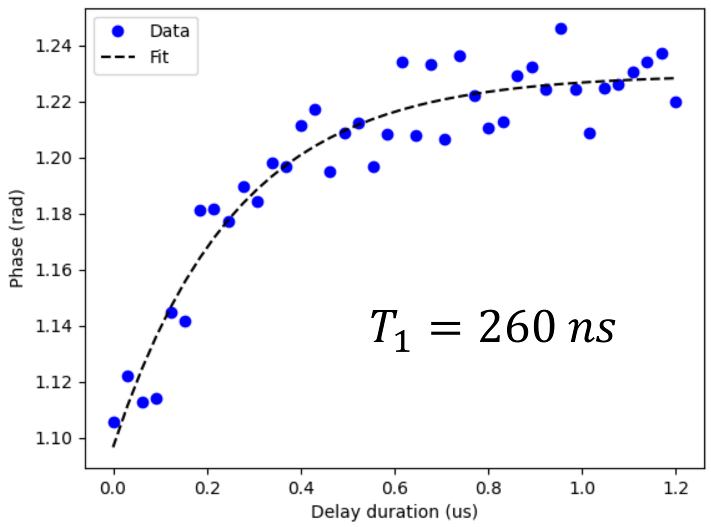
3D Qubit Spectroscopy

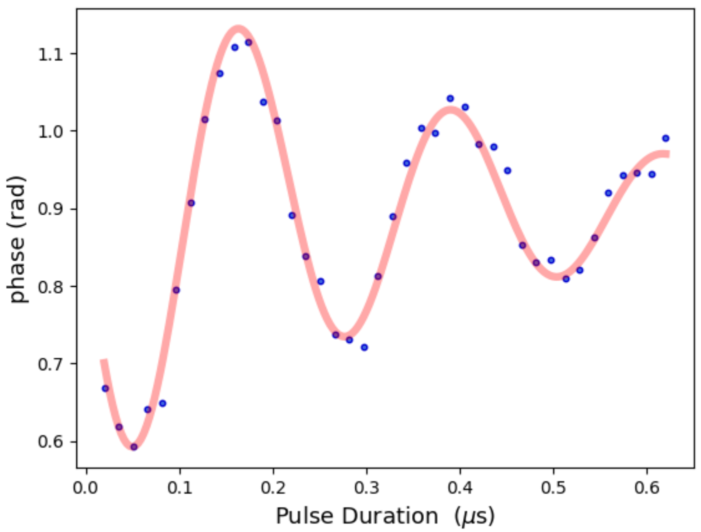
In 2024 we fabricated our first qubit showing a discrete energy spectrum … but no coherent oscillations

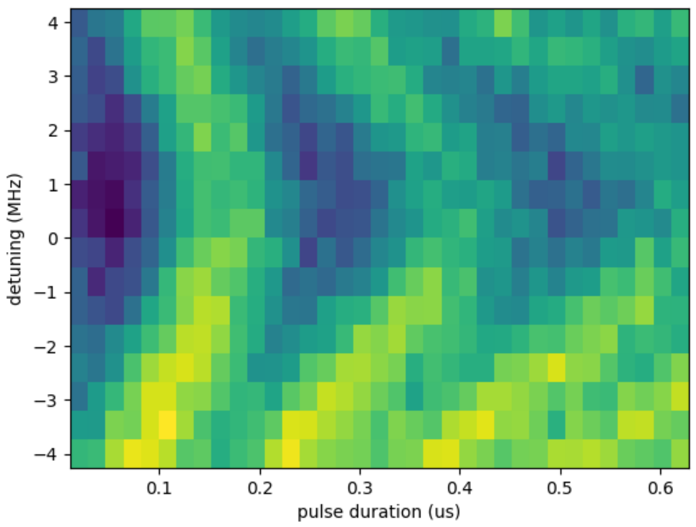


3D Superconducting Qubit

In 2026 we fabricated our first Al qubit showing coherent oscillations

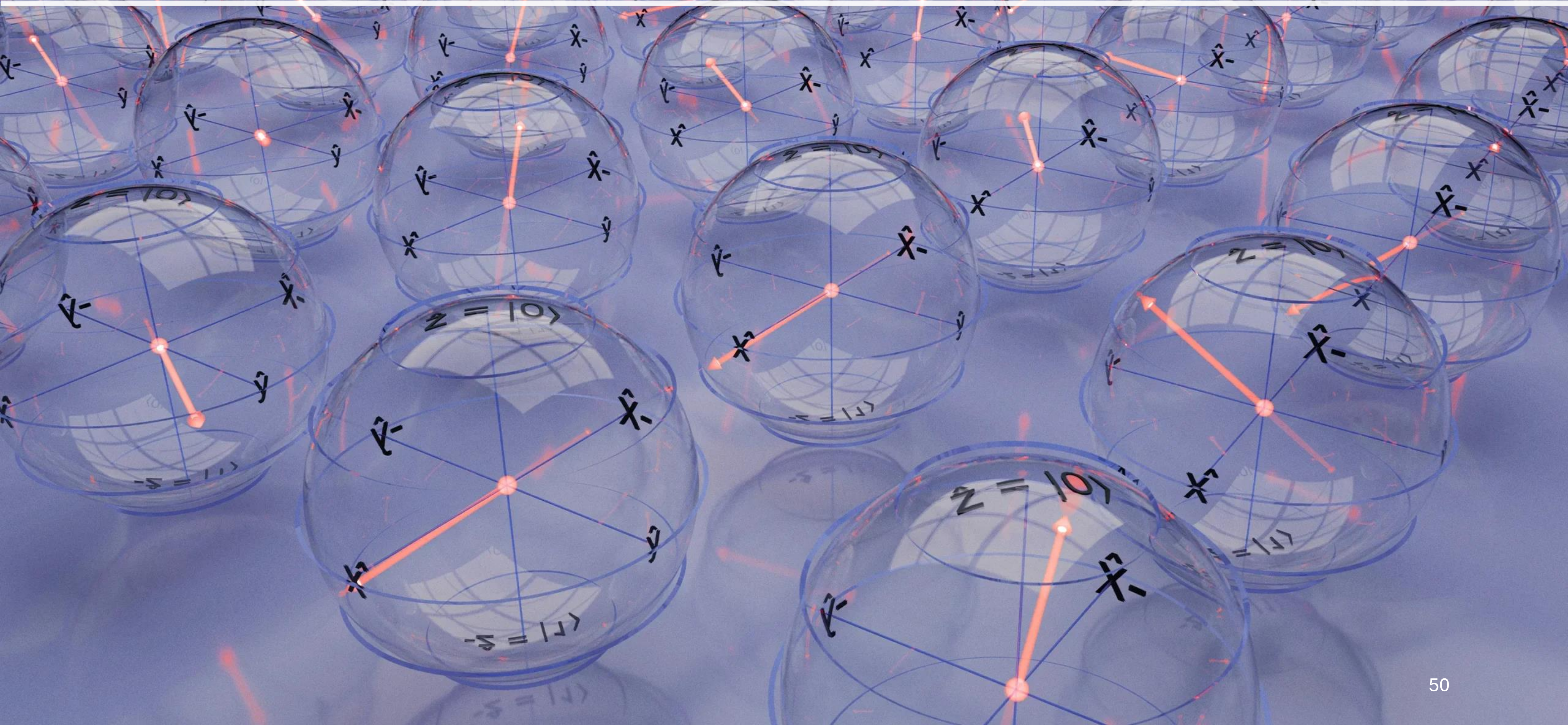






Qubit fabricated in Italy within a collaboration between INFN, CNR-IFN, TIFPA and the Universities of Milano Bicocca, Milano Statale, Pisa, Firenze, Salerno

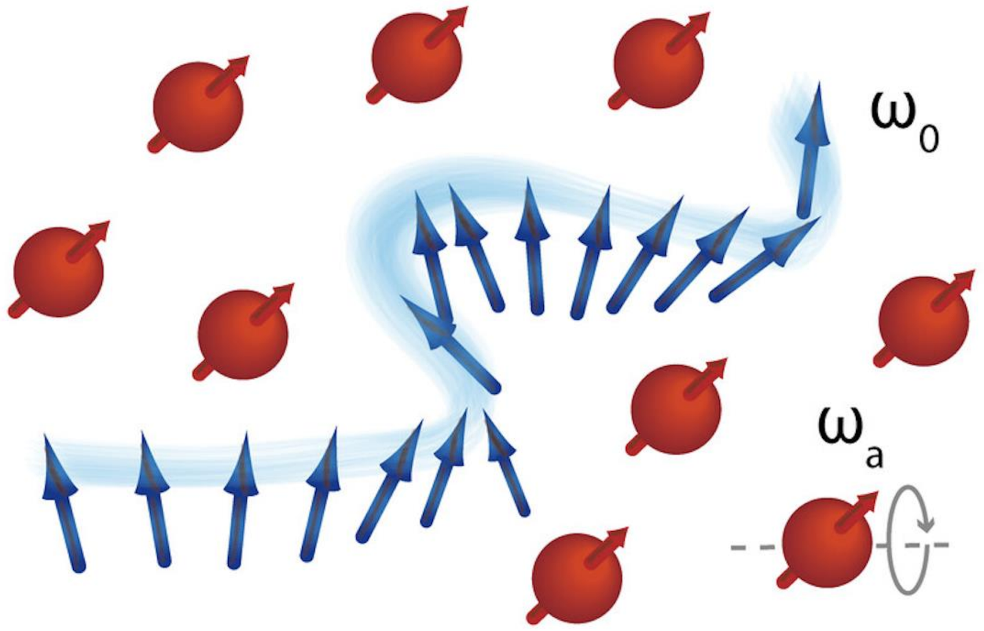
Multi Qubit Sensors



Sensing with Many Qubits

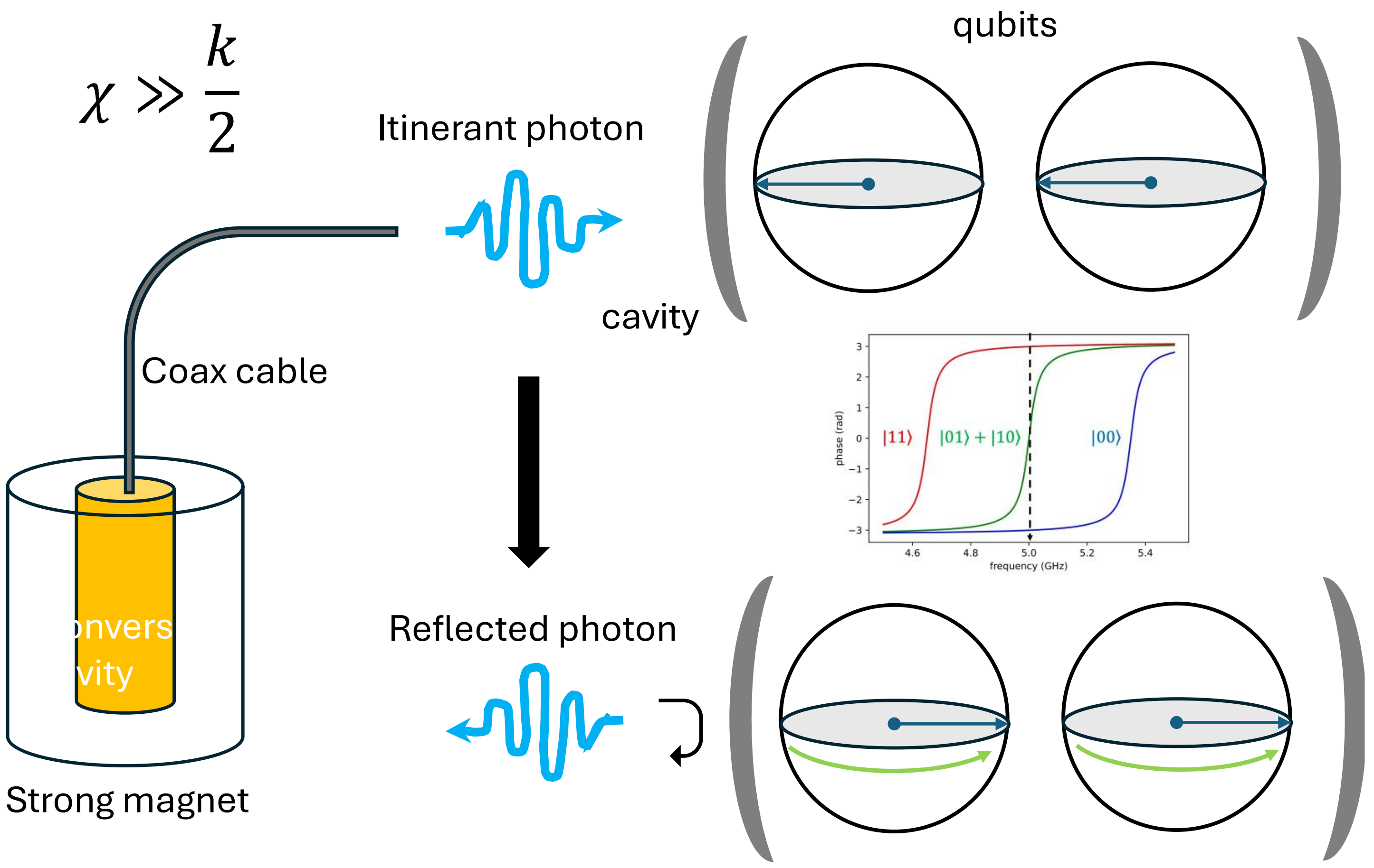
Using **many qubits** for quantum sensing can provide several advantages:

- **Higher detection efficiency** – independent qubits act like multiple detectors $\varepsilon \rightarrow N\varepsilon$
- **Increase sensitivity** – averaging over N independent detectors improves the sensitivity as $1/\sqrt{N}$. If the qubits are prepared in entangled states (for example GHZ states) the sensitivity scales $1/N$ (Heisengberg limit).
- **Collective enhancement** - If many qubits couple coherently to the same electromagnetic mode, the interaction strength increases collectively. For N identical qubits, $g_{eff} = g\sqrt{N}$, whic is known as Dicke or Tavis-Cummings enhancement.
- **Error correction and Dark count suppression** - Requiring coincidence between k qubits reduces false positives of probability p approximately as p^k.
- **QND** - Several qubits can interrogate the same photon without destroying it.



Quantum Coincidence with Superconducting Qubits

$$\chi \gg \frac{k}{2}$$



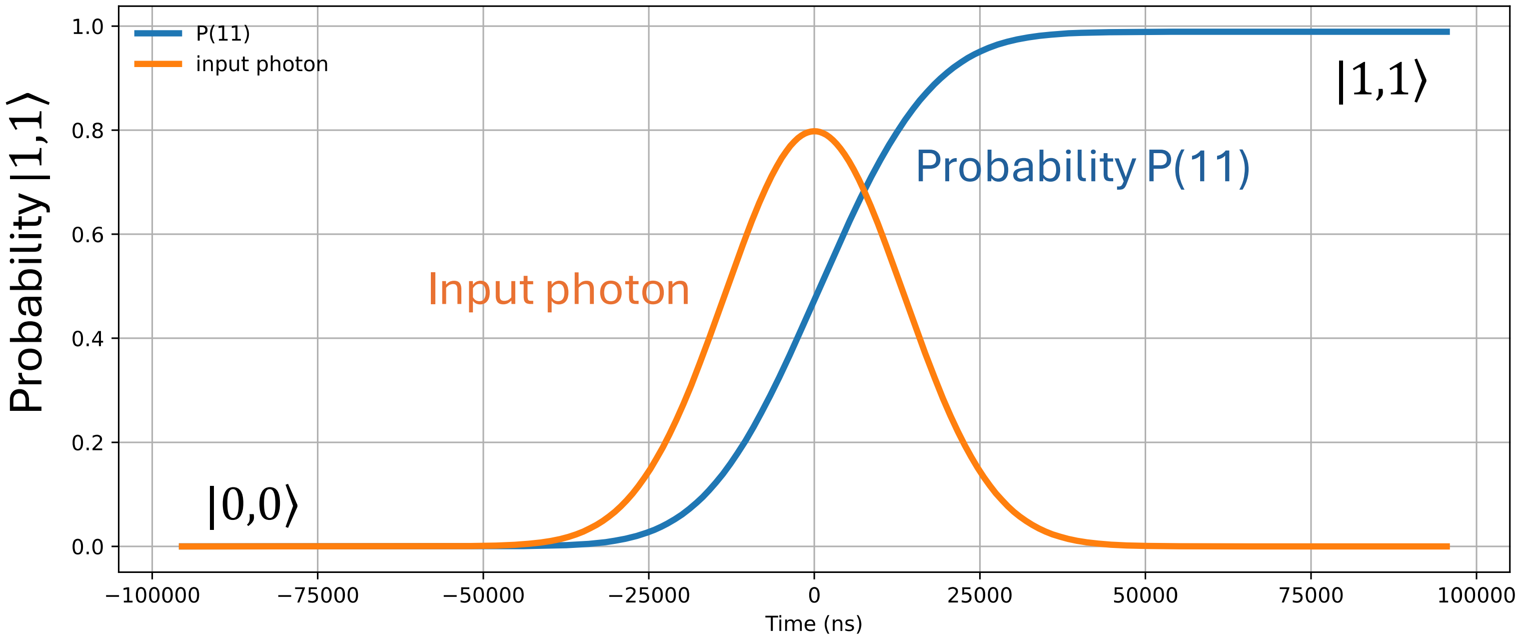
Sensing with two independent Ramsey protocols

Expected dark count rate

$$R \sim \frac{p(1|0)^2}{T_2} < \frac{1\times10^{-4}}{10\ \mu s} < 10\ Hz$$

A D’Elia Appl. Sci. 2024, 14(4), 1478

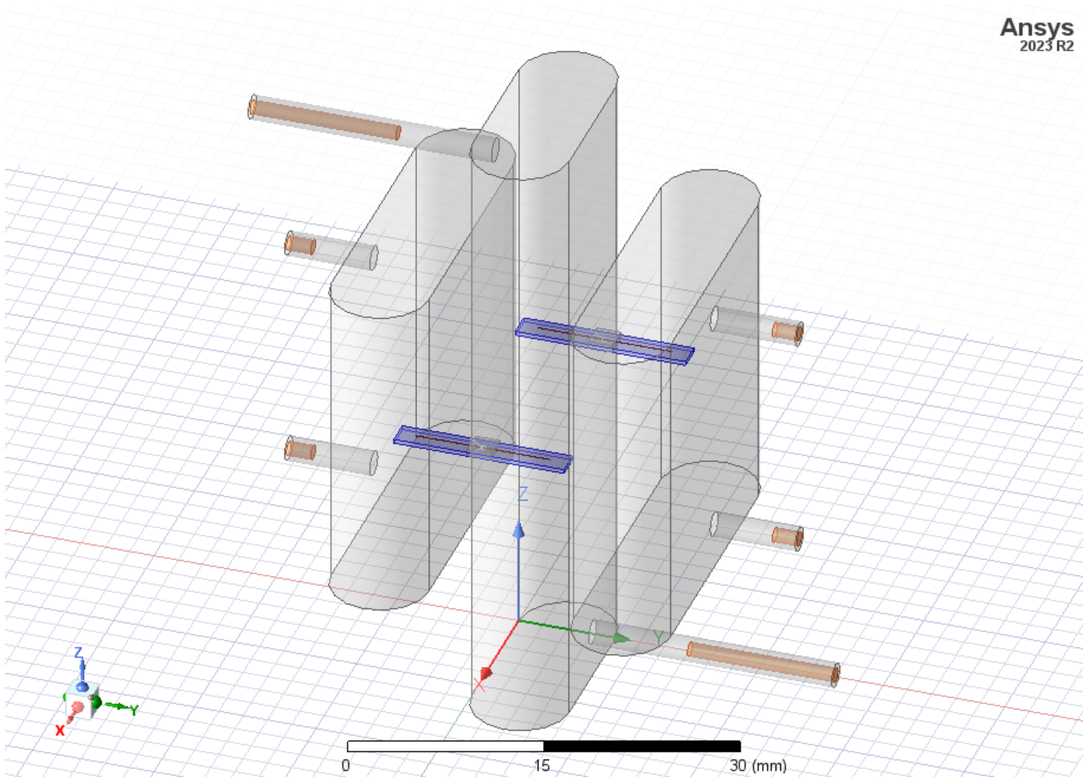
Quantum Coincidence with Superconducting Qubits

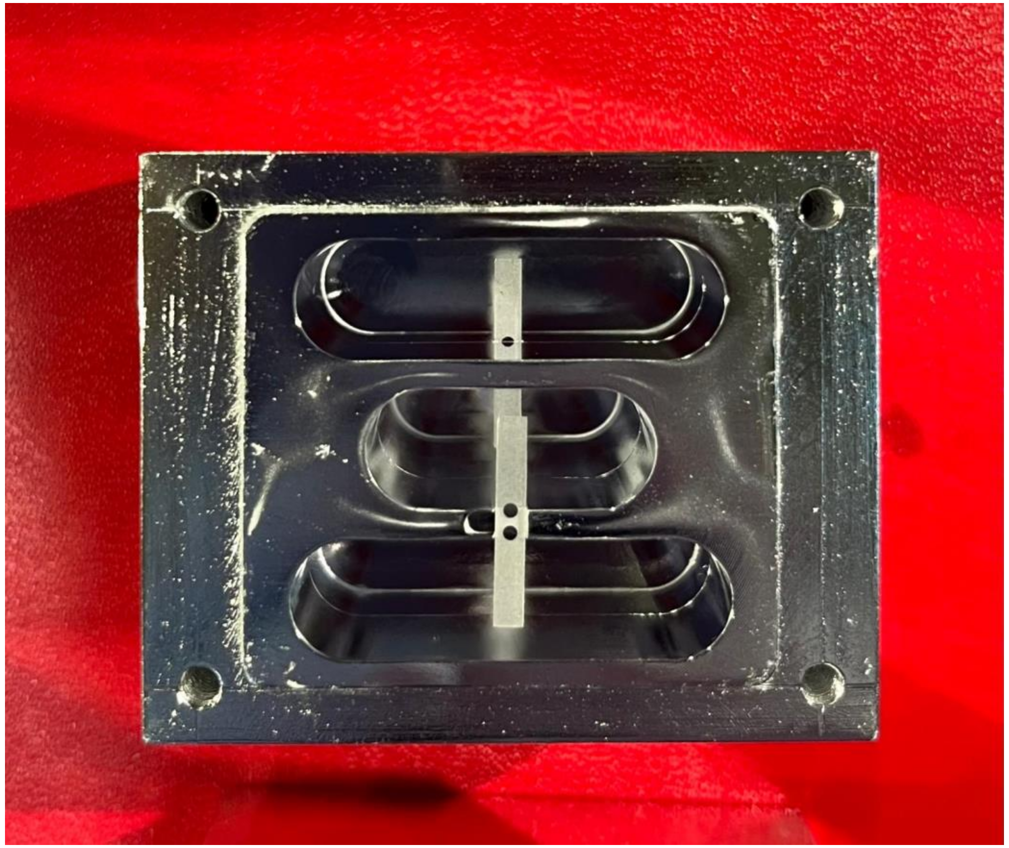


A. Piedju Komnang IL NUOVO CIMENTO 49 C (2026) 77

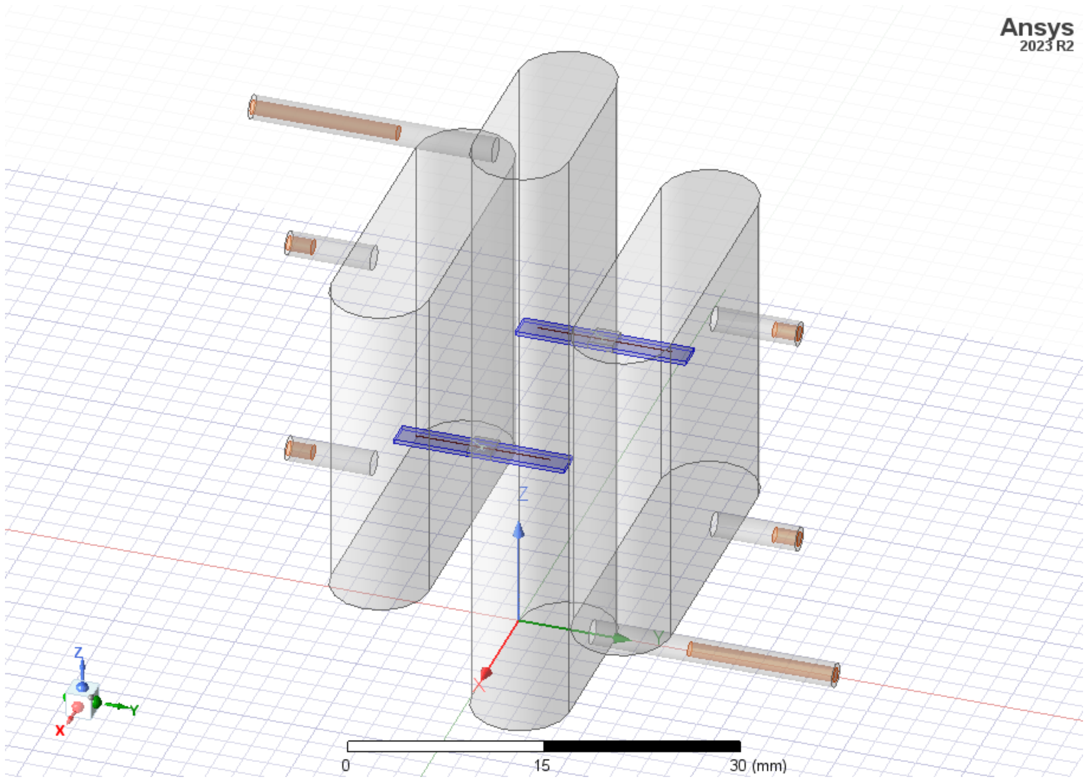
https://qutip.org

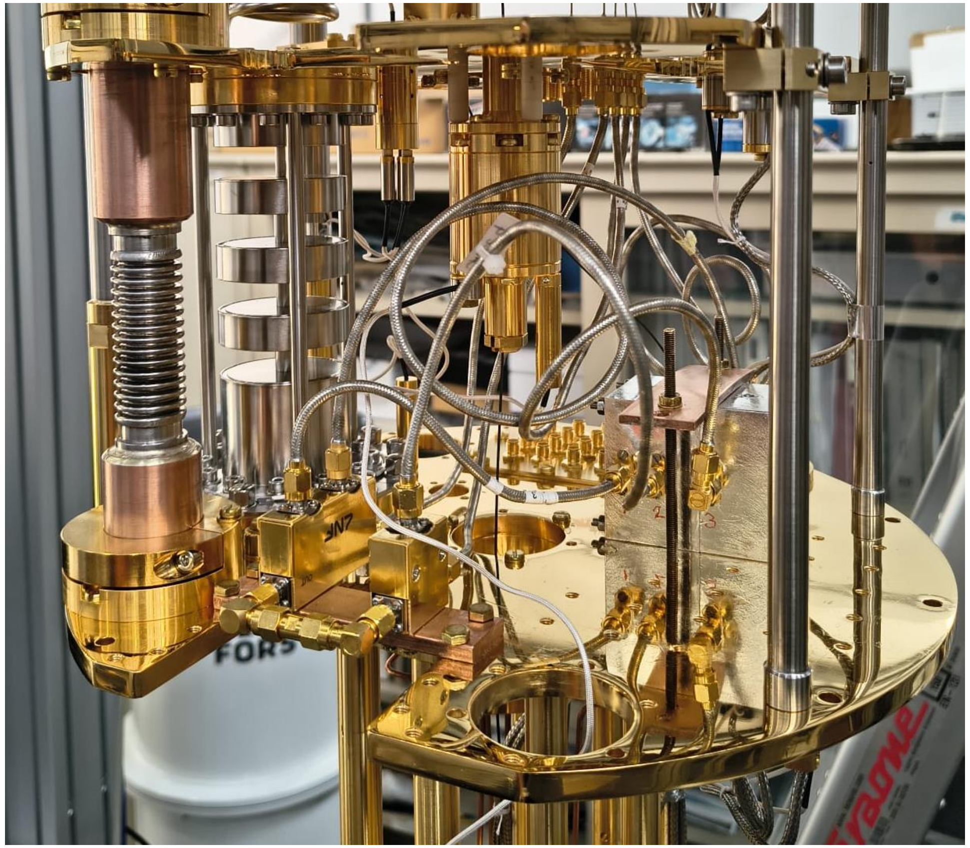
Quantum Coincidence with Superconducting Qubits

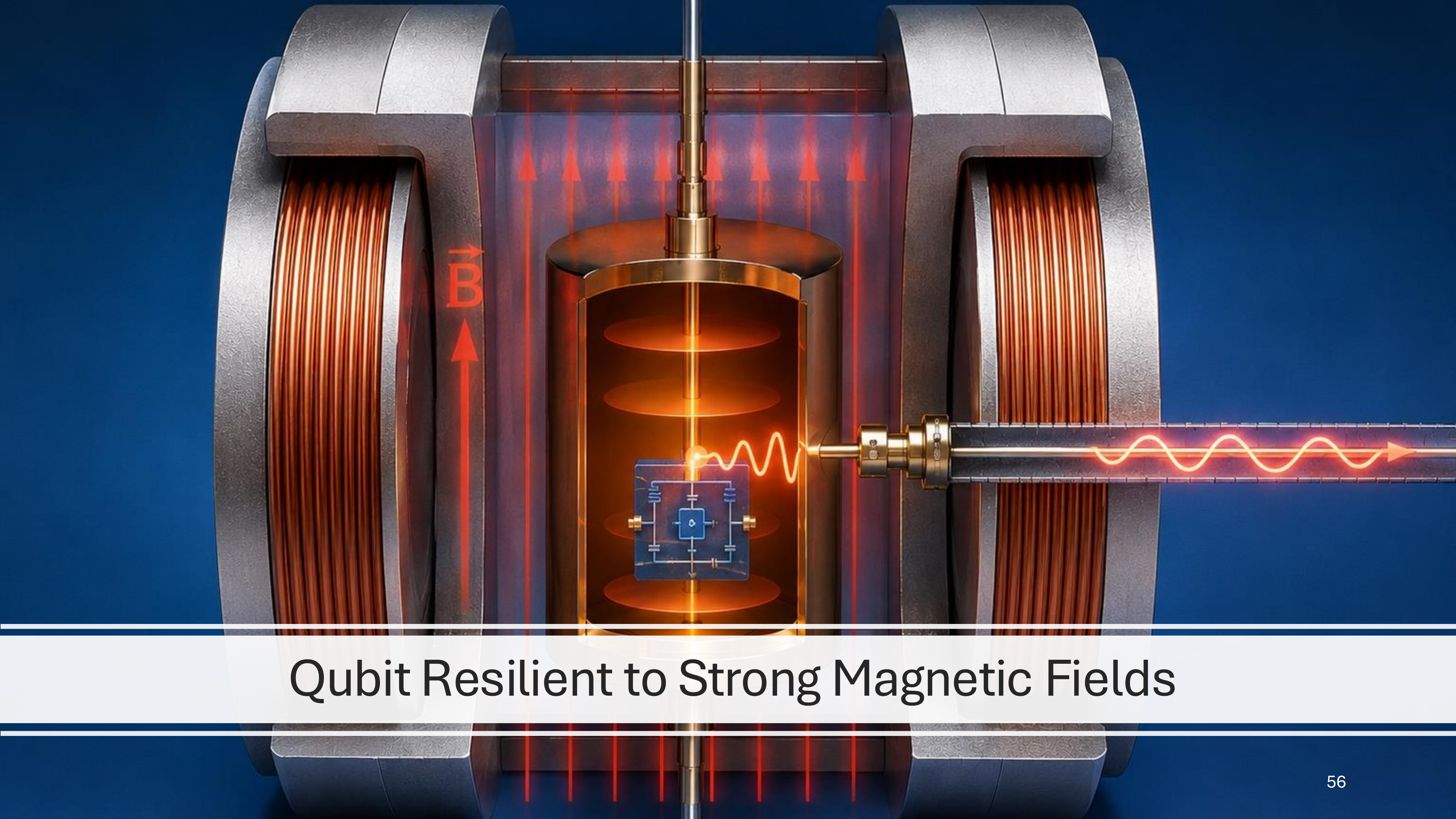




Quantum Coincidence with Superconducting Qubits

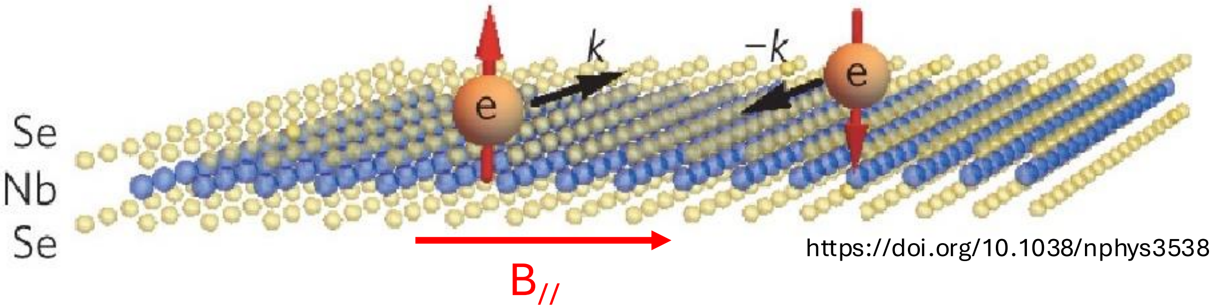






Qubit Resilient to Strong Magnetic Fields

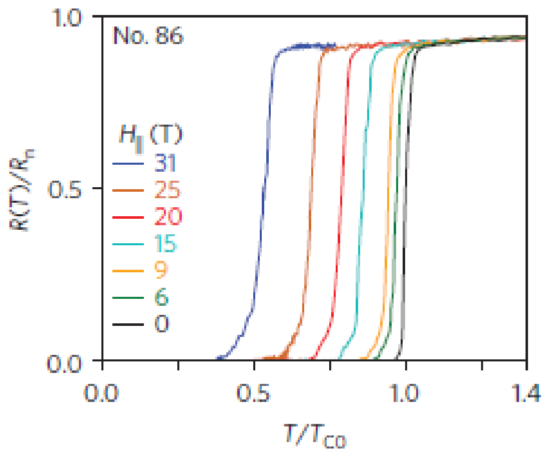
Can we Build a Magnetically Resilient Qubit?



https://doi.org/10.1038/nphys3538

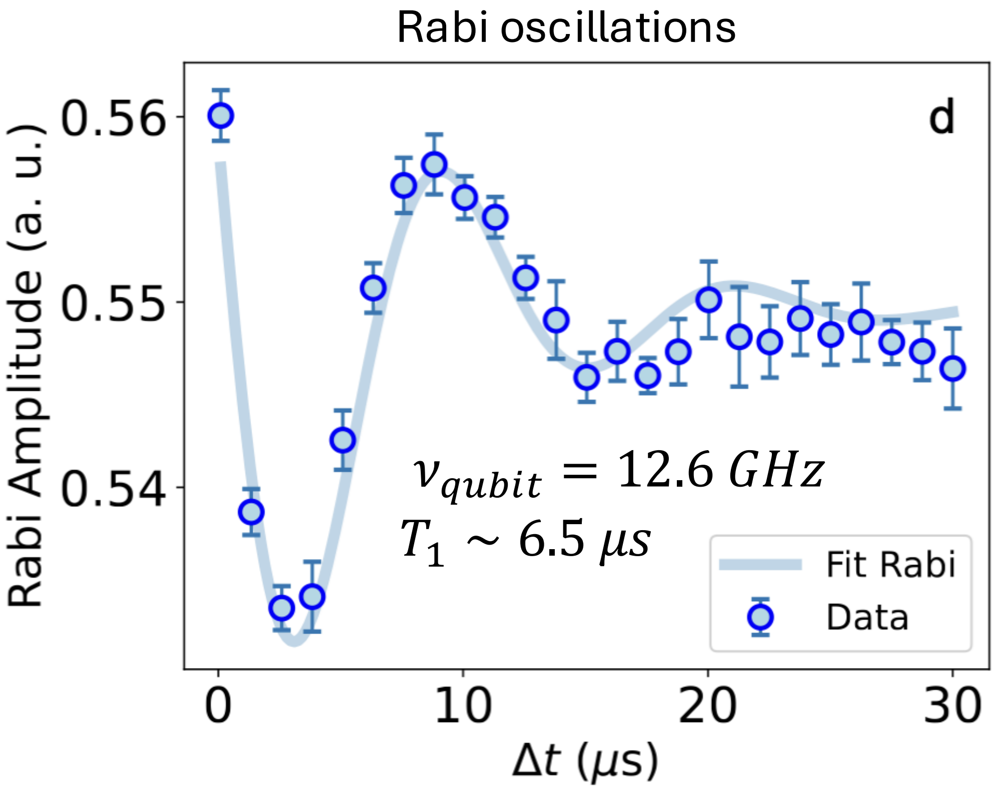
NbSe2 : Transition-metal dichalcogenide (TMD) superconductors

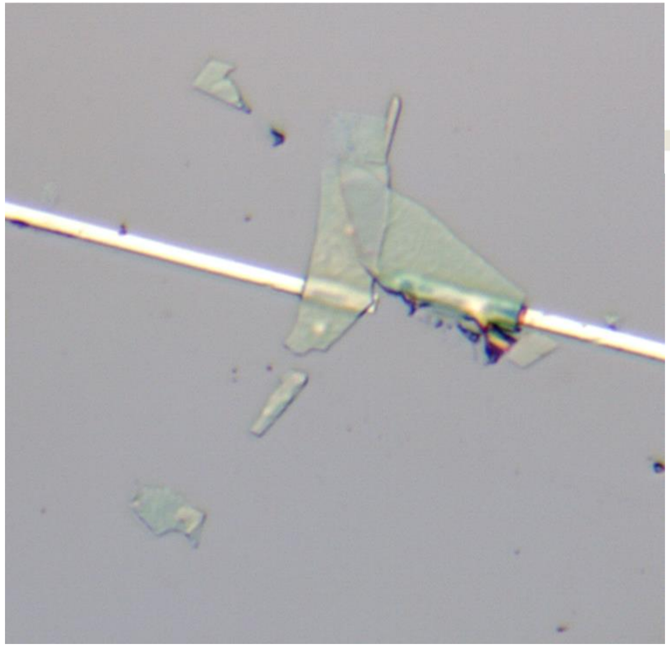
Xi, X., et al. Nature Phys (2016).



Thin $NbSe_2$ (niobium diselenide) retains superconductivity at a high **inplane** magnetic field up to 30 T! Spins pinned on the orthogonal directioin by strong spin orbit coupling are insensitive to inplane magnetic field.

Coherent Oscillation in $NbSe_2$ Qubit #1



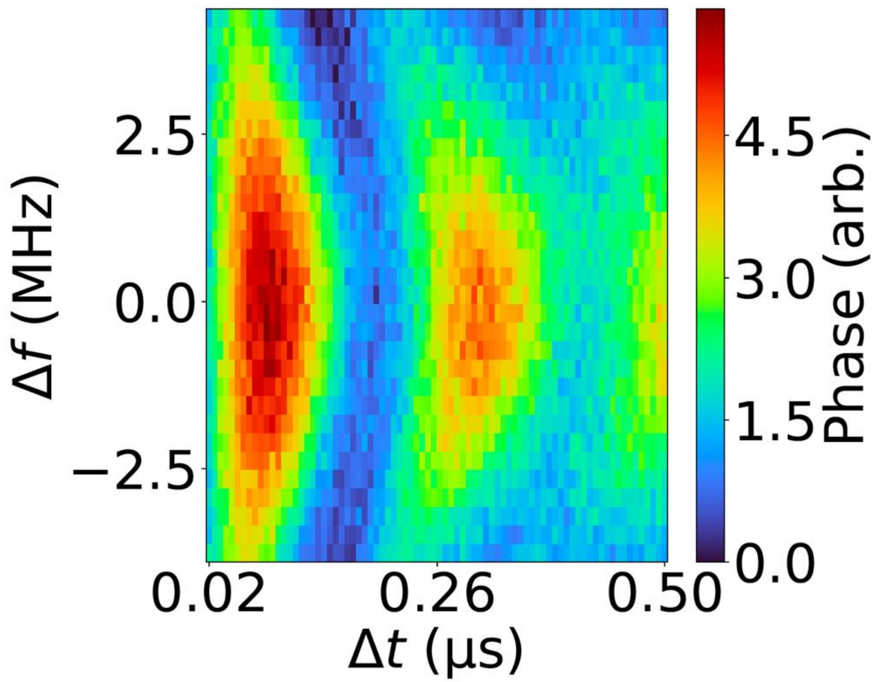


Junction Area $\sim 80\mu m^2$

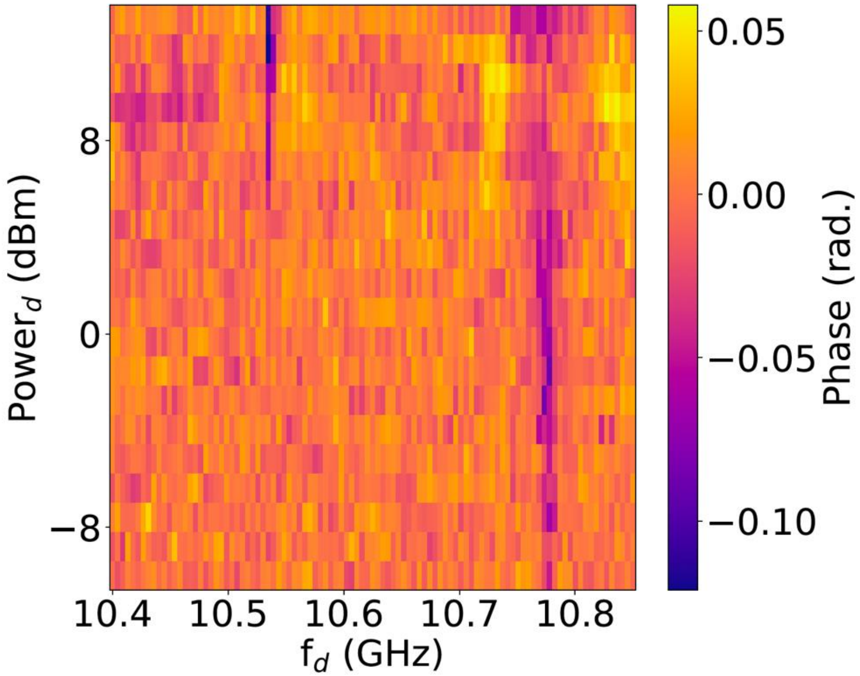
Starting Grant

A. D'Elia arXiv:2509.17160v2

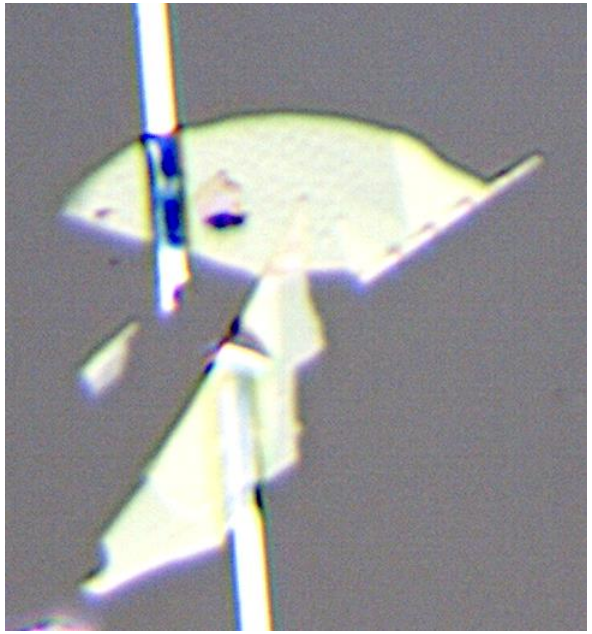
Coherent Oscillation in $NbSe_2$ Qubit #2



Rabi oscillations



300 MHz anharmonicity



Junction Area $\sim 7\mu m^2$

$\nu_{qubit} = 10.7\ GHz$

$T_1 \sim 300\ ns$

In Summary

FLASH

- 1st draft of TDR by the end of the year
- Tender for cryostat in spring 2027
- Cryostat delivery in 2029: start commissioning

QUAX@LNF

- 2026 data taking started!
- Multimode acquisition for search of axions and HFGW

Quantum Sensing at COLD Lab

- Succesful realization of our first qubit showing coherent oscillations!
- Testing the device for sensing with Quantum Coincidence.
- Realization of NbSe2 qubits → ERC Starting Grant!