LABORATORIO COLD

CLAUDIO GATTI, CARLO LIGI, DANILO BABUSCI

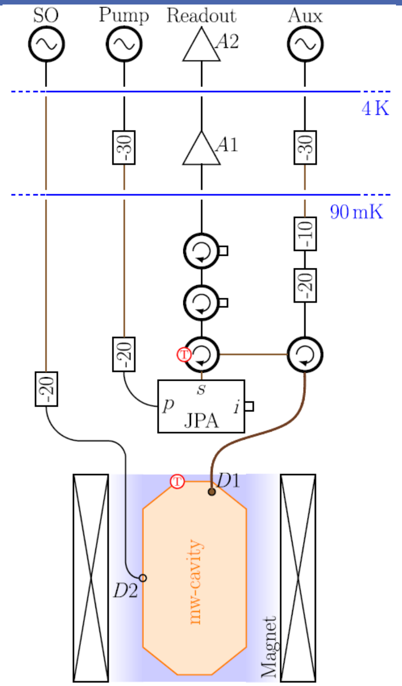
FFF meeting LNF October 27th 2020

OUTLINE

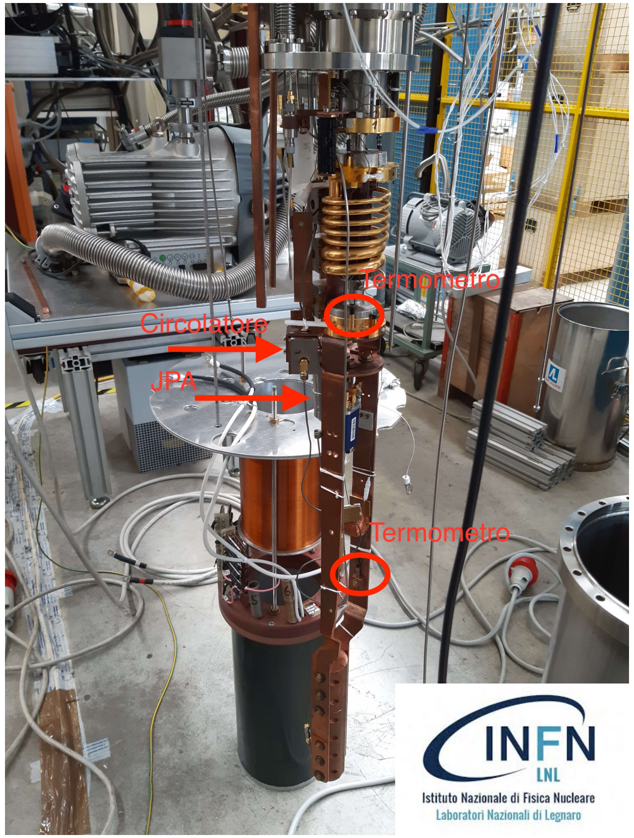
- Axions
- QUAX
- KLASH/FLASH
- COLD as a Quantum Lab

AXIONS

QUAX-aγ Searh for QCD Axion with m_a=40 μeV



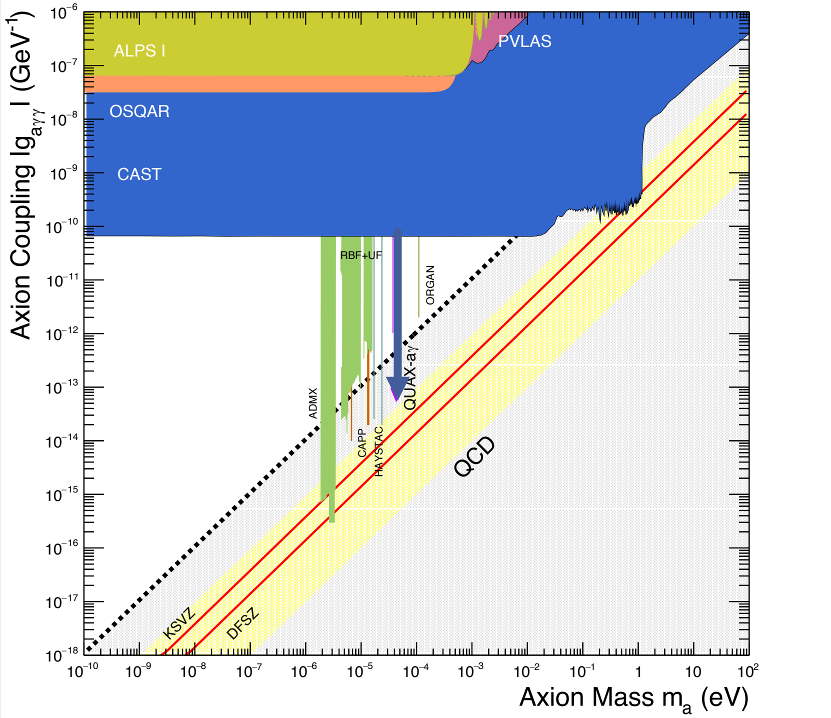
Experimental Setup	
B [T]	8
Frequency [GHz]	10.4
Cu cavity Q (mode TM010)	76,000
T_{cavity} [mK]	100
T amplifier [K] (JPA)	0.5



EPJC (2018) 78:703

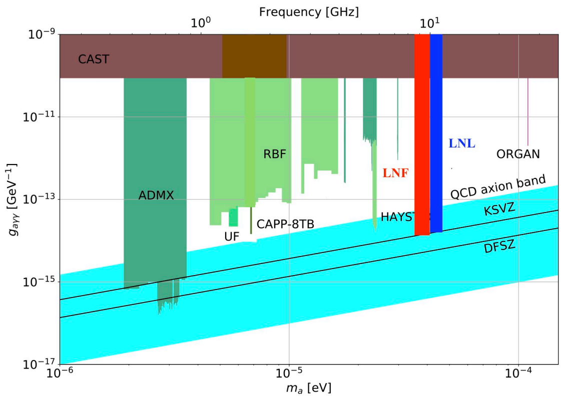
Phys. Rev. D **99**, 101101(R) (2019)

Phys. Rev. Lett. **124**, 171801 (2020)



Paper in preparation

QUAX 2021-2025



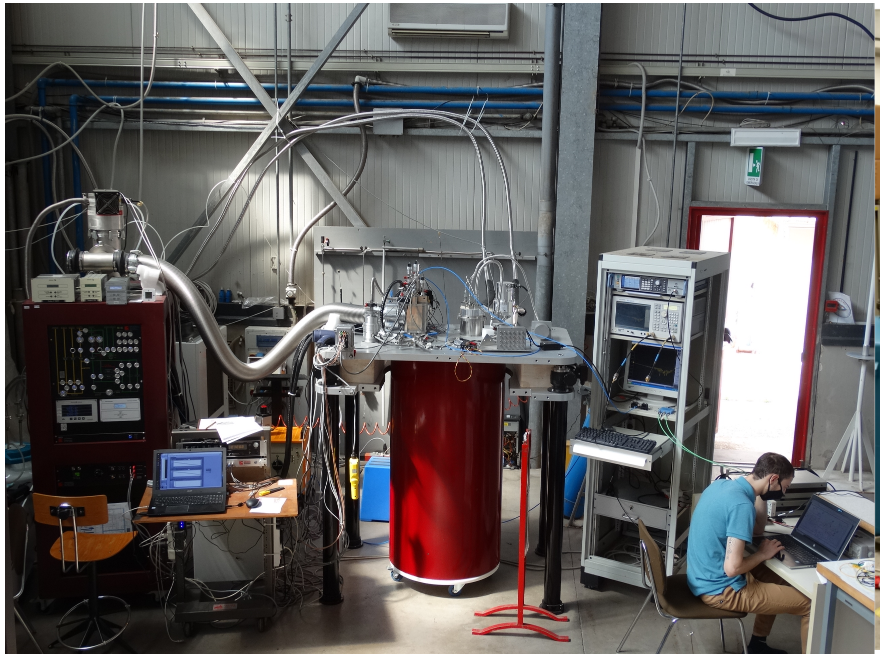
	LNF	LNL
Magnetic field	9 T	14 T
Magnet length	40 cm	50 cm
Magnet inner diameter	9 cm	12 cm
Frequency range	8.5 - 10 GHz	9.5 - 11 GHz
Cavity type	Hybrid SC	Dielectric
Scanning type	Inserted rod	Mobile cylinder
Number of cavities	7	1
Cavity length	0.3 m	0.4 m
Cavity diameter	25.5 mm	58 mm
Cavity mode	TM010	pseudoTM030
Single volume	$1.5 \cdot 10^{-4}$ m^3	$1.5 \cdot 10^{-4}$ m^3
Total volume	$7 \otimes 0.15$ liters	0.15 liters
Q_0	300 000	1 000 000
Single scan bandwidth	630 kHz	30 kHz
Axion power	$7 \otimes 1.2 \cdot 10^{-23}$ W	$0.99 \cdot 10^{-22}$ W
Preamplifier	TWJPA/INRIM	DJJAA/Grenoble
Operating temperature	30 mK	30 mK
Performance for KSVZ model at 95% c.l. with $N_A = 0.5$		
Noise Temperature	0.43 K	0.5 K
Single scan time	3100 s	69 s
Scan speed	18 MHz/day	40 MHz/day
Performance for KSVZ model at 95% c.l. with $N_A = 1.5$		
Noise Temperature	0.86 K	1 K
Single scan time	12500 s	280 s
Scan speed	4.5 MHz/day	10 MHz/day

2021	2022	2023	2024	2025

Assembly of haloscopes at LNL and LNF

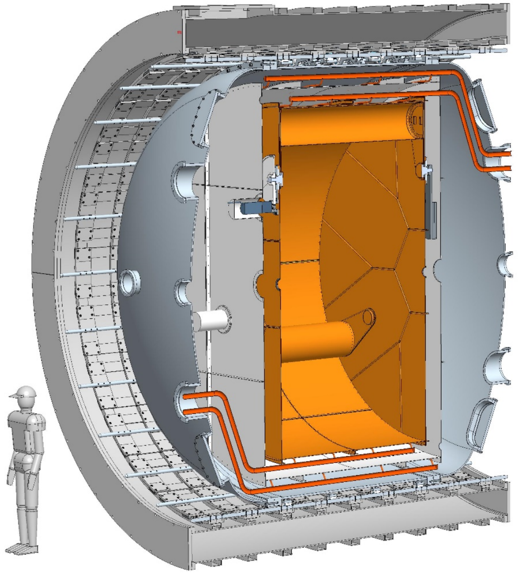
Data Taking

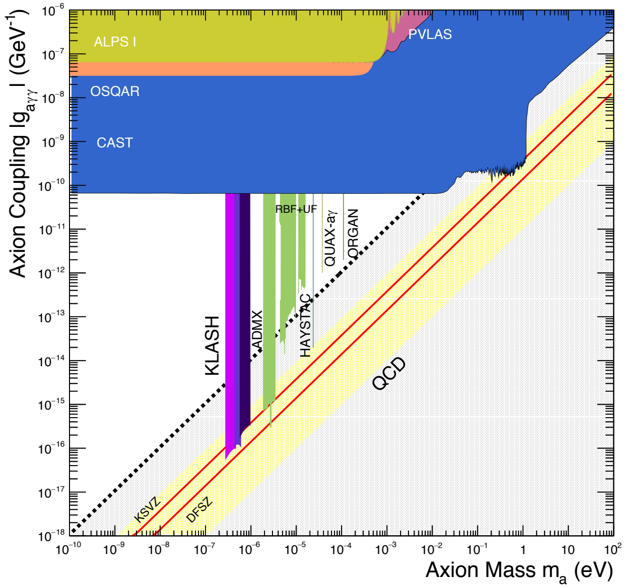
Scan in range 8.5 - 11 GHz



KLASH

- KLASH - KLoe magnet for Axions SearcH
- Proposal of a large Haloscope at LNF
- Search of galactic axions in the mass range 0.3-1 μeV
- Large volume RF Cavity (22 m^3)
- Moderate magnetic field (0.6 T)
- Copper rf cavity Q~600,000
- T 4.5 K





Experiment	$\omega B^2 V Q_L$ (rad $T^2 m^3/s$) ($\times 10^{15}$)
The KLASH	1
ADMX	4
HAYSTAC	0.05

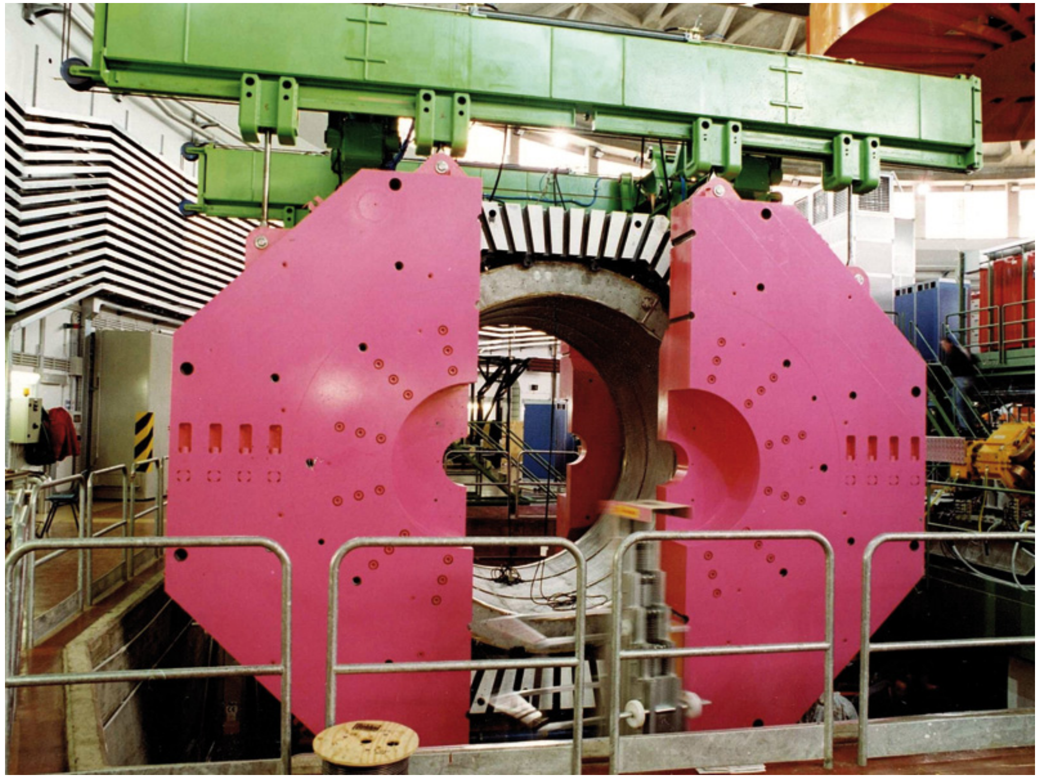
KLASH CDR arxiv:1911.02427

FLASH

KLOE magnet used for DUNE Near Detector:

- FLASH: Finuda magnet for Light Axion SearcH
- SC magnet built by Ansaldo Italia (ASG Supeconductors) for FINUDA experiment
- Similar sensitivity to galactic axions of KLASH

B(T)	1.1
R(m)	2.77
L(m)	2.52



KLASH → FLASH

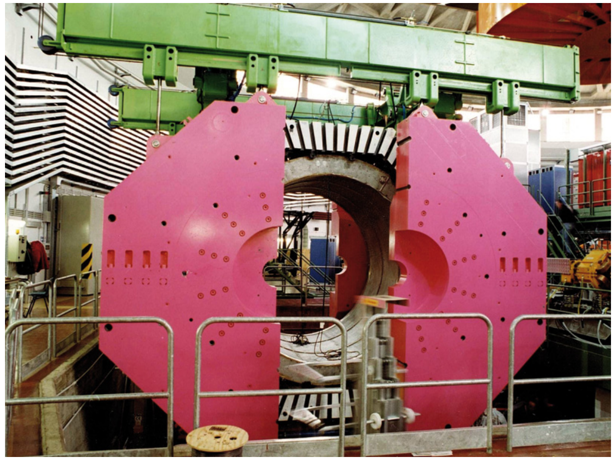
- 1) Use FINUDA where it is now:
  - Must build a concrete wall both to isolate it from the DAFNE ring e.m. emission and to have access to the experiment during DAFNE operations.
  - Must adapt the cryogenic transfer lines from the valve box to the magnet

Pros:

- ✓ *We avoid moving the magnet.*
- ✓ *We minimize the cryogenic transfer lines adaptation*

Cons:

- ✓ *hard to manage the cohabitation with DAFNE*
- ✓ *risk to found high e.m. noise when DAFNE beams circulating*



KLASH → FLASH

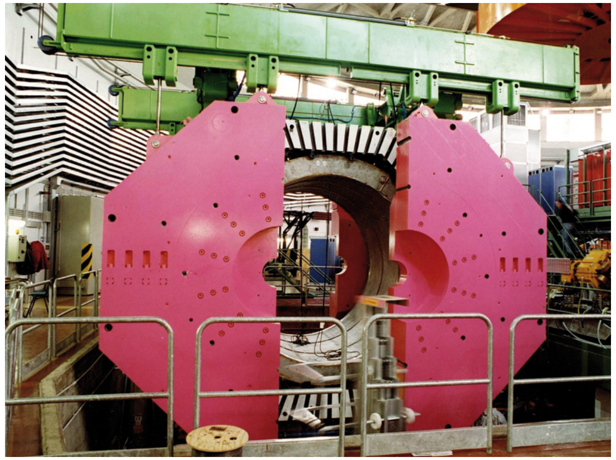
- 2) Use FINUDA in the KLOE hall:
  - Must transport the magnet outside DAFNE (can be an hard work!)
  - Must adapt the cryogenic transfer lines as foreseen for KLASH

Pros:

- ✓ *FLASH has a dedicated space, well dimensioned for the commissioning*
- ✓ *We minimize the adaptation of cryogenic transfer lines*

Cons:

- ✓ *FINUDA dismantling can be a nightmare*
- ✓ *we have to wait the KLOE removal*



KLASH → FLASH

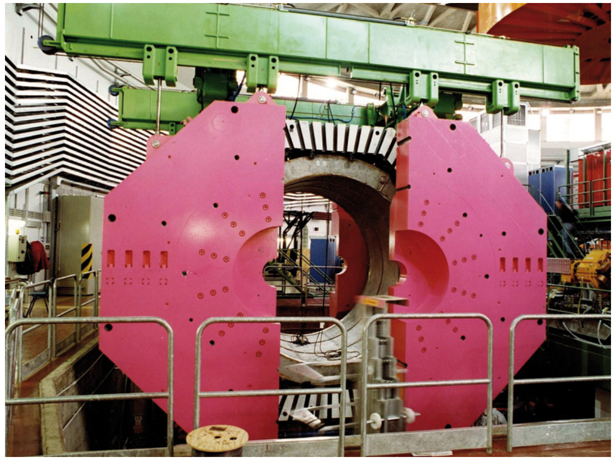
- 3) - Use FINUDA in ed. 10 (DAFNE cryogenic lab):
  - *this is only an hypotesis* – we should verify if FINUDA fit the lab
  - Must transport the magnet outside DAFNE (can be an hard work!)
  - Must change the cryogenic transfer lines with new one (but much shorter)

Pros:

- ✓ *FLASH has a dedicated space, but not so large*
- ✓ *experiment and cryogenic plant are inside the same building*

Cons:

- ✓ *FINUDA dismantling can be a nightmare (same as 2)*
- ✓ *installation of magnet and detector can be hard due to limitate space*

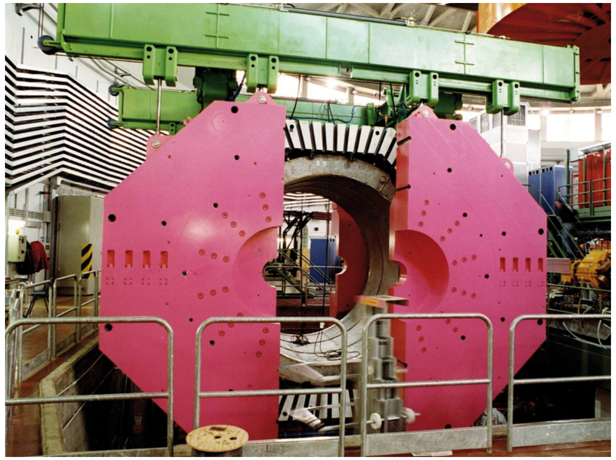


KLASH → FLASH

No matter where FINUDA will be placed, we must first test its functionality.

With the magnet where it is now, we must:

- ✓ renew the cryogenic service turret
- ✓ refurbish the ancillary systems (vacuum pumps, diagnostics etc.)
- ✓ check the magnet power supply working
- ✓ adapt the cryogenic transfer lines
  - ➢ then cool and energize the magnet



KLASH → FLASH

Next Steps:

1. Test of FINUDA Magnet
2. Site option (Dafne, KLOE hall, Dafne cryo Lab)
3. New mechanical design (and feasibility with Finuda)
4. Repeat simulation for potential discovery (expected very close to KLASH)
5. Define project timeline (check also competitor's timeline)
6. New CDR and approval in CSN2

From approval 2-3 years for construction and commissioning (?)

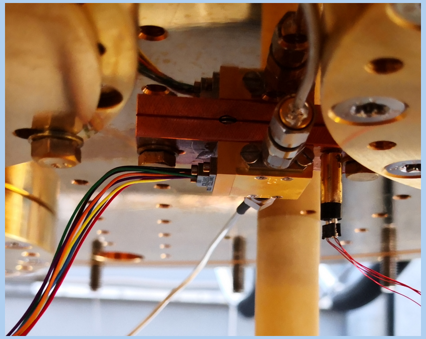
2021	2022	2023	2024	2025
Magnet Test (€)				
	New Mechanical Design (€)			
	Simulations (0.3 FTE)			
	New CDR and Collaboration			
		CSN2		
			Construction	Construction

COLD AS A QUANTUM LAB

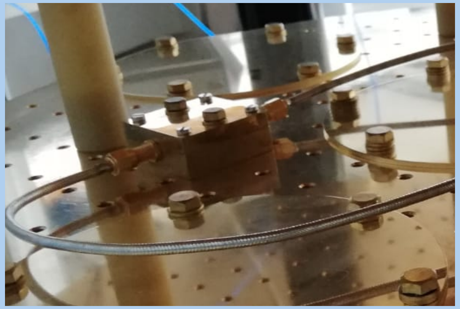
COLD LNF Cryogenic Laboratory for Detectors

INFN Istituto Nazionale di Fisica Nucleare

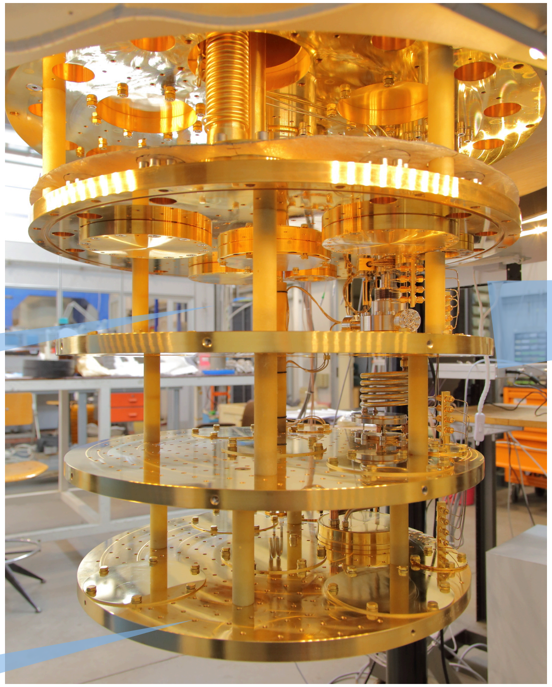
http://coldlab.lnf.infn.it



HEMT (6-20 GHz) 4K amplifier



Sample holder for SC chip at 10 mK for single photon device

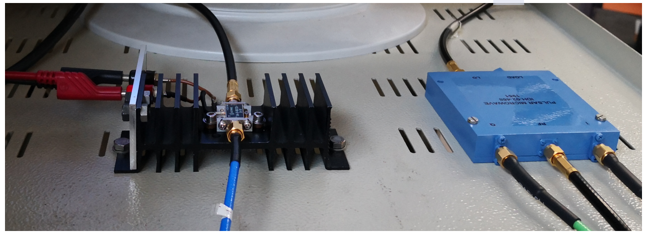


4 RF lines installed from 300 K to MixCh

Leiden CF-CS-110-1000	
Sumitomo PT	1.5 W at 4.2 K
Cooldown time (with LN)	2 days
Base temperature (measured)	8.5 mk
Cooling power at 100 mK (measured)	450 µW (up to 700 µW with a new pumping system)

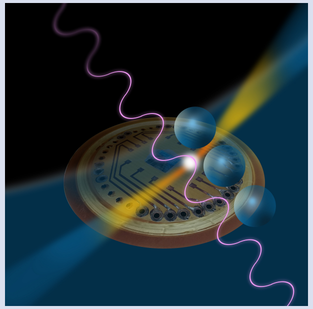
VNA 20 GHz
WFG 20GHz
SA 20 GHz

FET LNA 8-12 GHz and IQ-mixer (10-12 GHz)

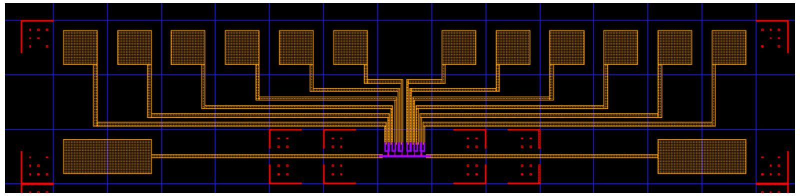


Room T ampli & DAQ

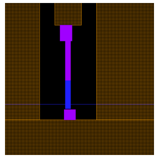
SIMP (CSN V)

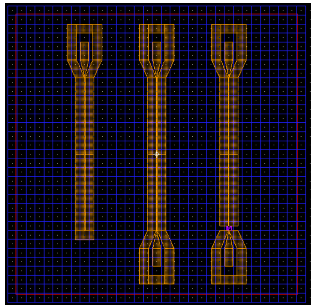


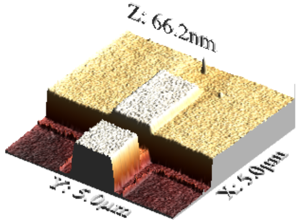
Units
LNF (Resp Naz)
INFN Pi
INFN Sa
TIFPA-FBK
CNR Nano NEST
CNR IFN
INRIM

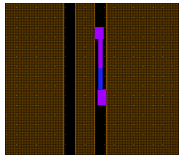


TL + CBJJ single photon counter

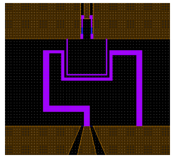






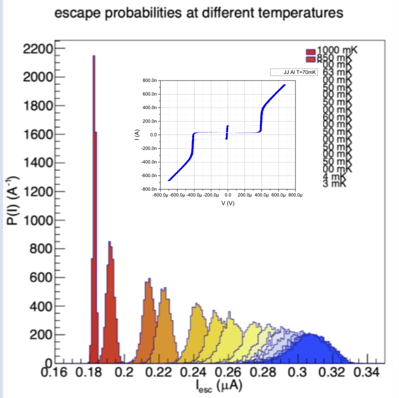


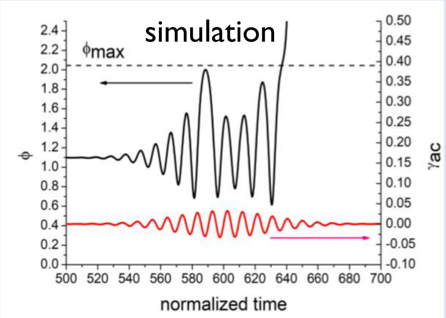
Transmission measurement

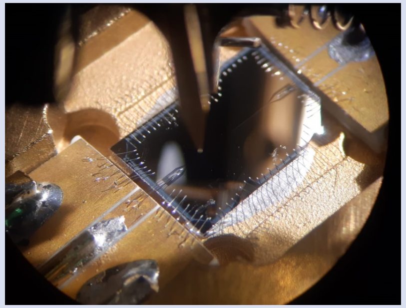


Tunable JJ

- JJ fabricated at CNR-IFN and fully characterized in DC at 40 mk.
- Device simulation
- RF tests ongoing







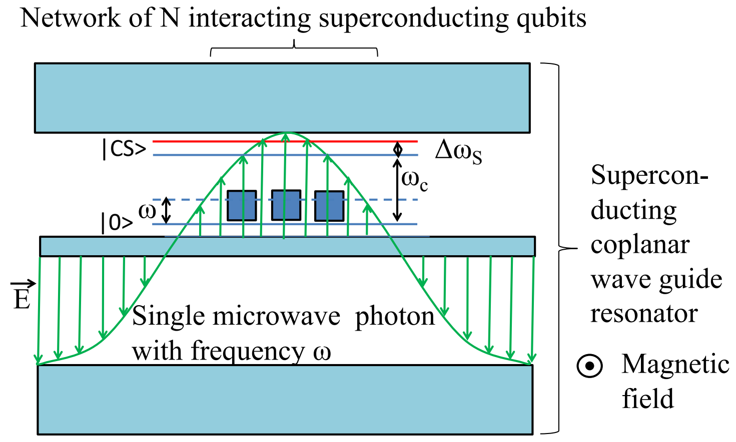
D Alesini et al Journal of Low Temperature Physics https://doi.org/10.1007/s10909-020-02381-x

D Alesini et al 2020 J. Phys.: Conf. Ser. 1559 012020

SUPERGALAX

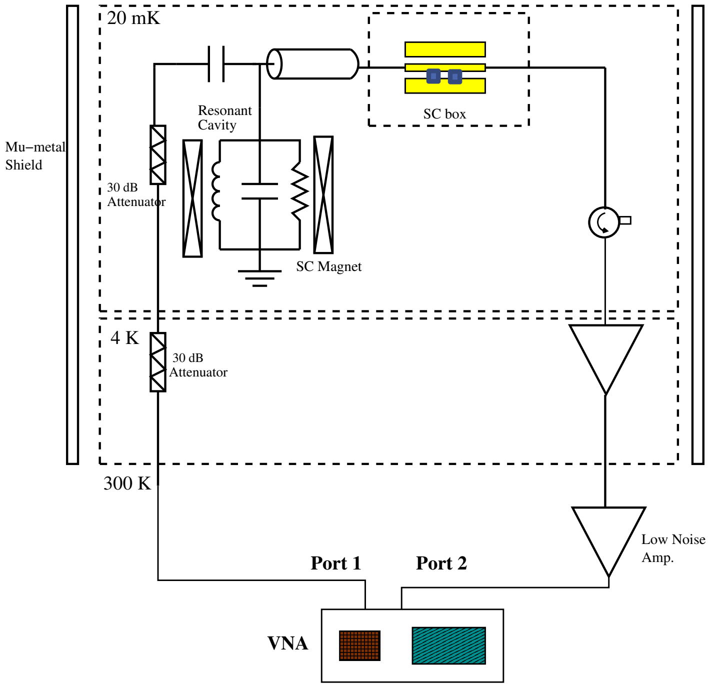
FET OPEN SUPERGALAX
CNR (IT, PI, exp)
INRIM (IT, exp)
INFN (IT, axion exp)
KIT (DE, exp)
Leibniz IPHT (DE, exp)
RUB (DE theory)
LU (UK, theory)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 863313. Grant amount 2 456 232.50 Euro.



Objective: Develop a single microwave photon detector for axion search in QUAX experiment with an array of SC qubits.

https://supergalax.eu



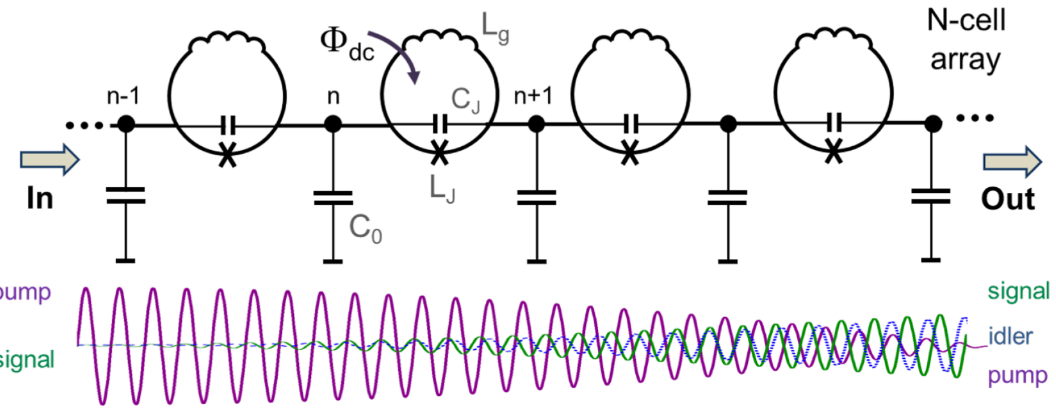
DART WARS (CSN V): TWJPA

Travelling Wave Josephson Parametric Amplifiers amplify microwave signal over a broad range adding the minimum noise set by quantum mechanics. Two devices developed in Eu with 3-wave and 4-wave mixing:

Physikalisch-Technische Bundesanstalt Braunschweig und Berlin

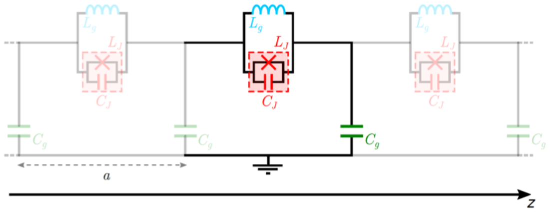
arXiv:1602.02650

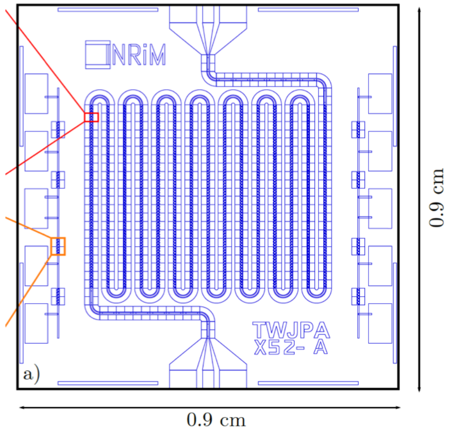
PHYS. REV. APPLIED 12, 044051 (2019)



3-wave mixing device

INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA





Cells	990
Lcell	63 μm
Ic	1.5-2 μA
Lg	40 pH
Cg	34 fF

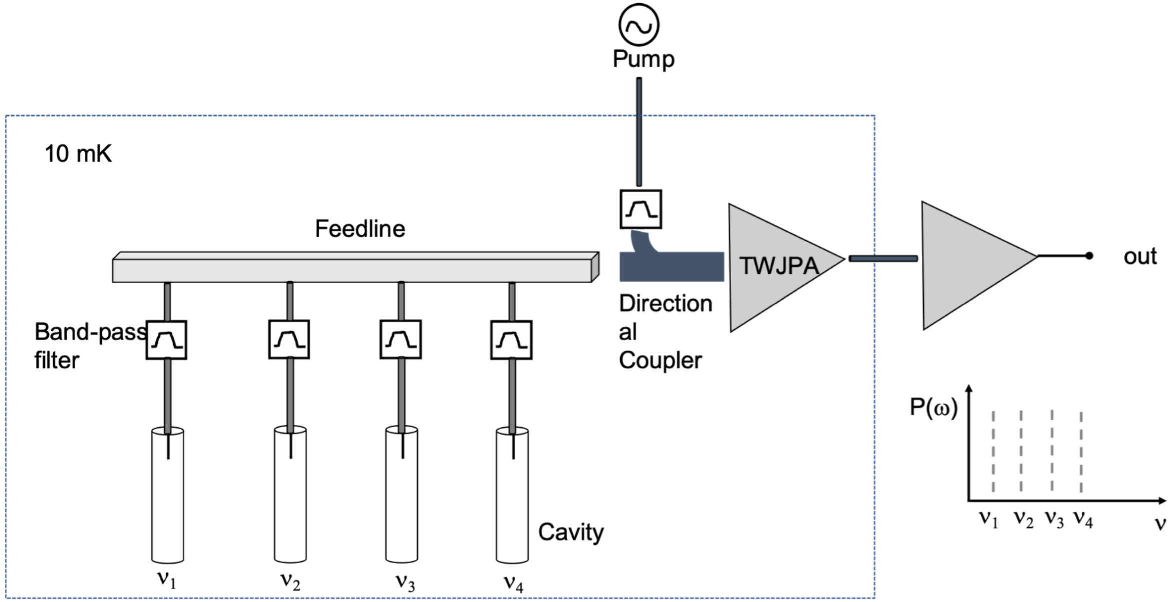
DART WARS

INFN Istituto Nazionale di Fisica Nucleare

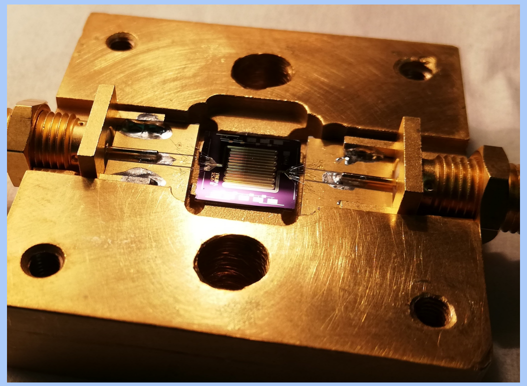
Detector Array Readout with Travelling Wave AmplifieRS project recently approved by INFN

TWJPA

Multicavity scheme with broadband amplification with a TWJPA for axion experiment

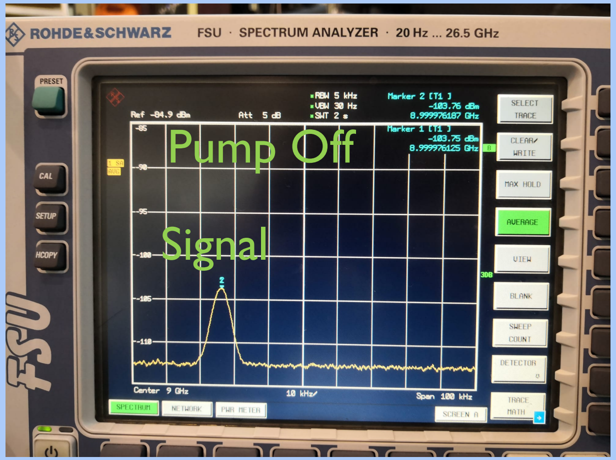


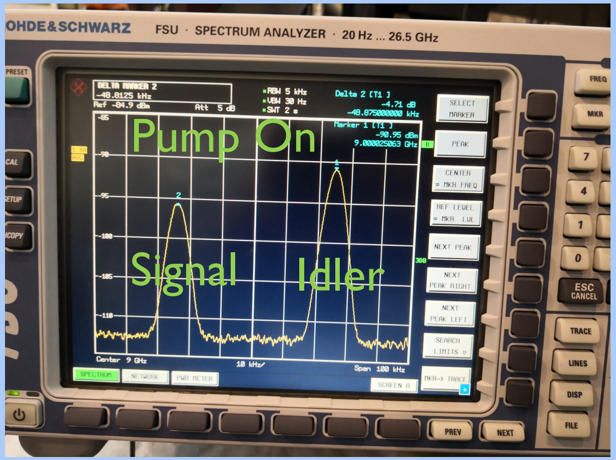
Experimental setup of 10 mK plate



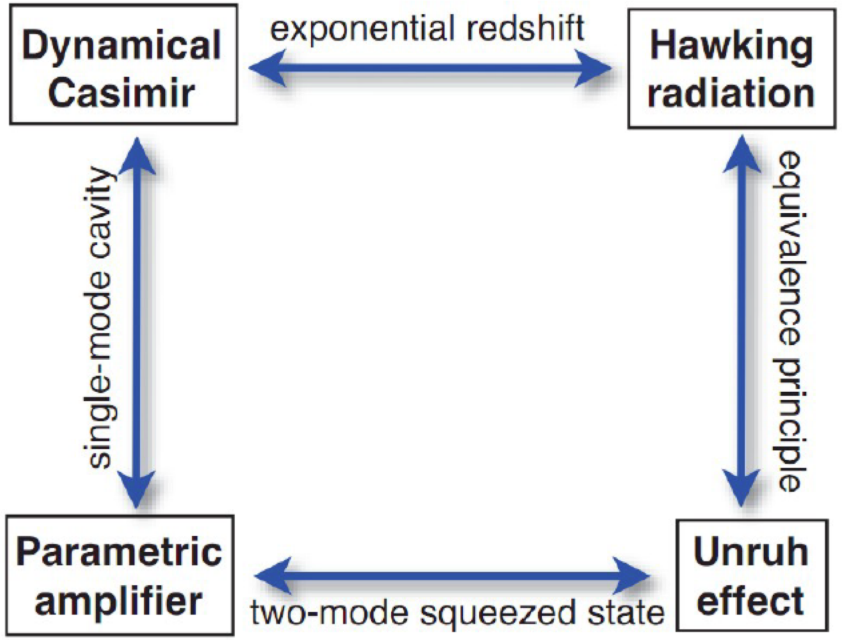
TWJPA

- Measurements ongoing at LNF
- 3-wave mixing observed

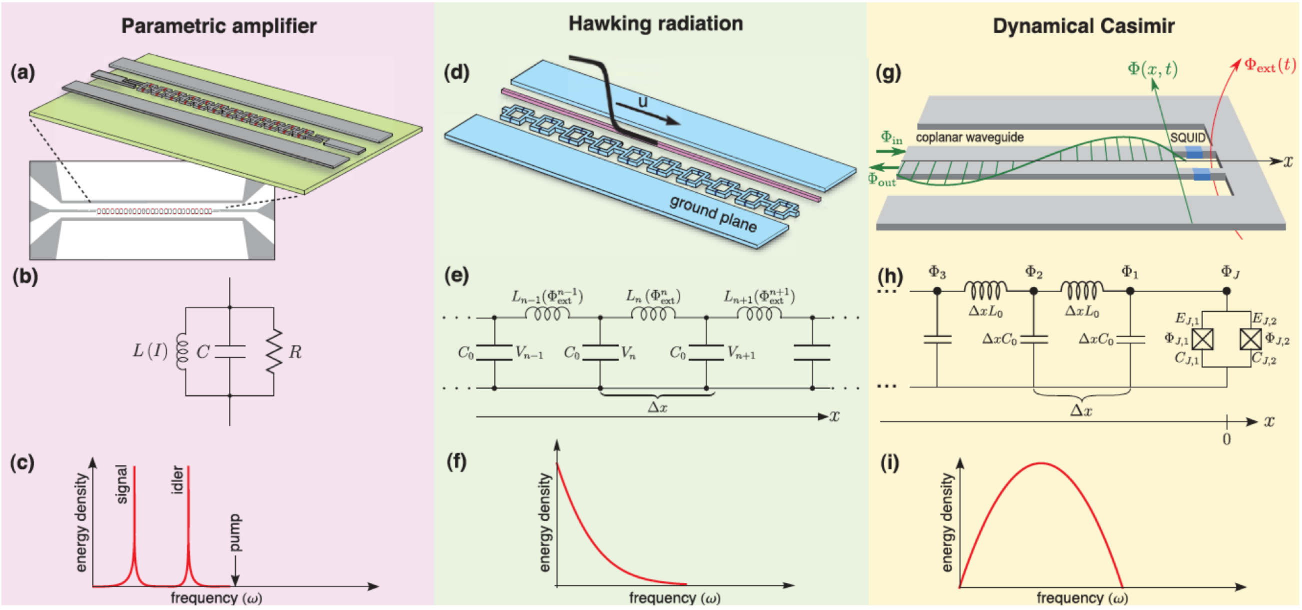




QG ANALOGUES ON SC CHIP



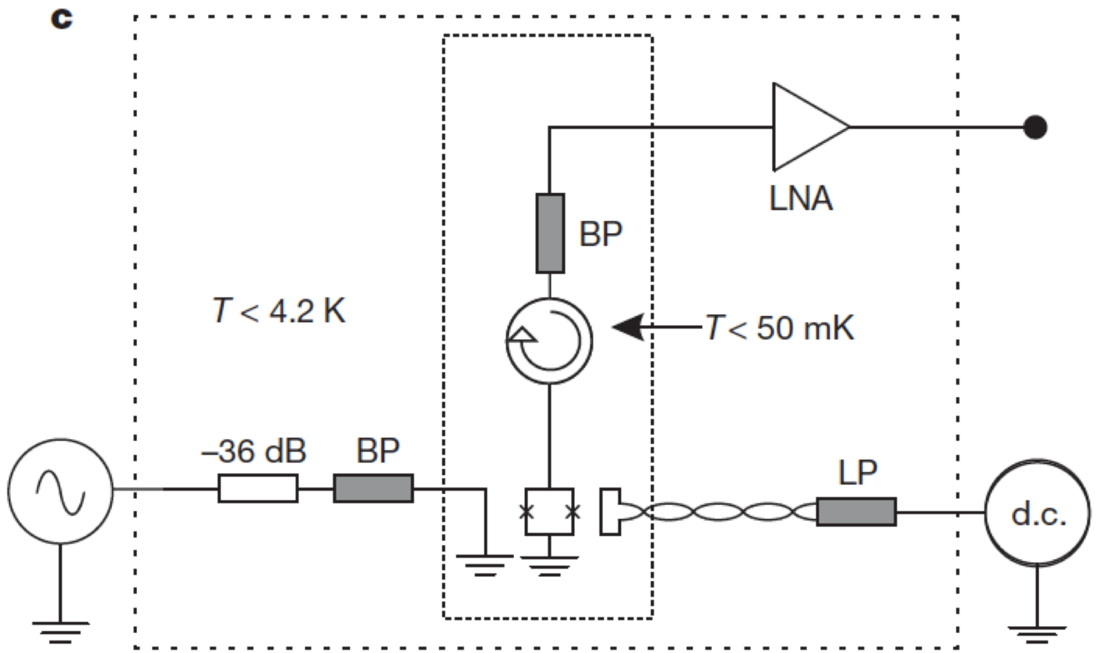
Dart Wars | See Danilo's Slides | *SIMP*

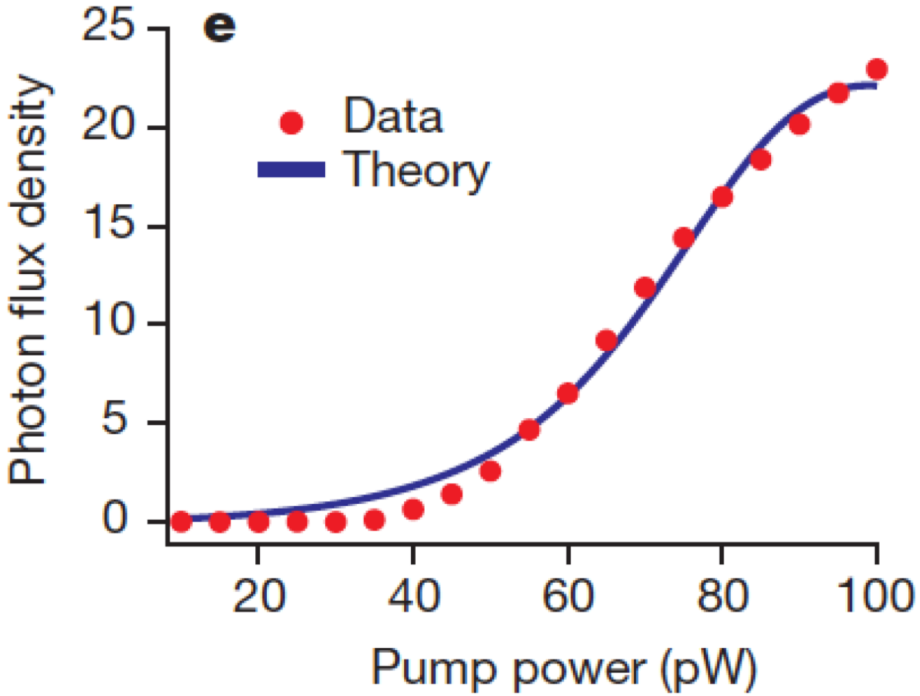


https://doi.org/10.1038/nature10561

REVIEWS OF MODERN PHYSICS, VOLUME 84, JANUARY–MARCH 2012

DYNAMICAL CASIMIR EFFECT IN A SC CIRCUIT





Wilson, C., Johansson, G., Pourkabirian, A. *et al.* Observation of the dynamical Casimir effect in a superconducting circuit. *Nature* **479,** 376–379 (2011). https://doi.org/10.1038/nature10561

ON-CHIP QUANTUM INTERFERENCE OF A SUPERCONDUCTING MICROSPHERE (in a far future …)

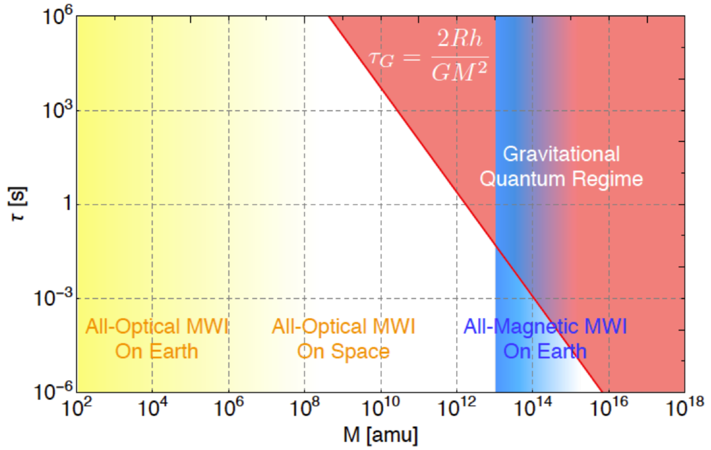


FIG. 1: Time scale $\tau_G \equiv 2Rh/(GM^2)$ is plotted as a function of the mass M for a sphere of radius R and a typical mass density of a metallic solid object 10^4 Kg/m^3.

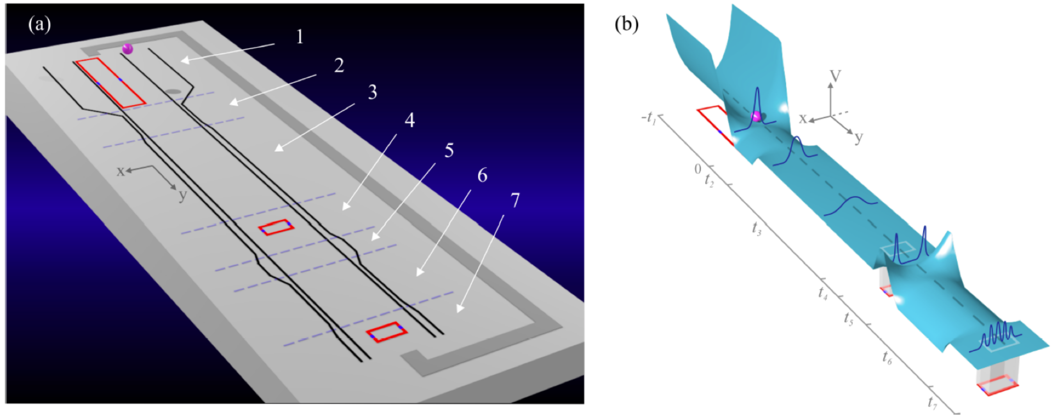


FIG. 3: (a) Sketch of the superconducting chip implementation of the quantum micromechanical interferometer protocol. Superconducting wires are shown in black and the different stages are separated by dashed lines. The SQUIDs are shown in red. (b) Illustration of the magnetic potential $V(x, y)$ in each of the steps. The position probability distribution in the x-axis is illustrated (dark blue) at the different stages of the protocol. Notice that both figures are not scaled and have only illustrative purposes.

arXiv:1603.01553v3

Analogue Gravity on a Superconducting Chip

D. Babusci

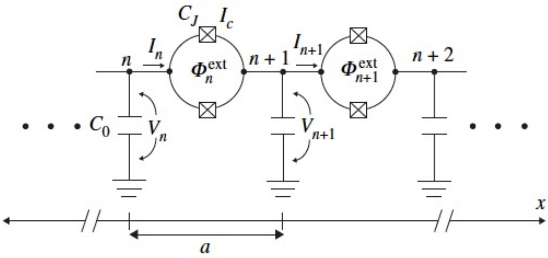
LNF

October 27, 2020

dc-SQUID array

M. P. Blencowe, H. Wang - Phil Trans. R. Soc. A**378** 201900224 (2020) - (2003.00382)

A schematic view of a dc-SQUID array transmission line (circuitry providing the space-time dependent flux bias not shown)



NB - JJ elements (crossed boxes) have the same I_c and C_J.

dc-SQUID array

dc-SQUIDs are threaded with an external magnetic flux varying from cell to cell and in time

Dynamics is more conveniently expressed in terms of the 'phase' coordinate φ_n associated with the voltages across C_0

$$V_n = \frac{\Phi_0}{2\,\pi}\,\frac{\mathrm{d}\varphi_n}{\mathrm{d}t} \qquad\qquad \left(\Phi_0 = \frac{h}{2\,e}\right)$$

Long wavelength ($\lambda \gg a$) dynamics $\rightarrow$ continuum limit $\rightarrow$ phase 'field' $\varphi(x, t)$ $\rightarrow$ wave equation (see Blencowe & Wang):

$$-\frac{\partial^2 \varphi}{\partial t^2} + \frac{\partial}{\partial x}\left[c^2(x, t)\,\frac{\partial \varphi}{\partial x}\right] = 0 \qquad (1)$$

dc-SQUID array

where the space-time dependent e.m. wave phase speed is:

$$c(x,t) = c_0 \sqrt{\cos\left(\pi \frac{\Phi^{\,\mathrm{ext}}}{\Phi_0}\right)}$$

with

$$c_0 = c(x,t)\,\big|_{\Phi^{\,\mathrm{ext}}=0} \;=\; a\sqrt{4\pi \frac{I_c}{\Phi_0\, C_0}}$$

Propagating flux front moves with speed u $\rightarrow$ going into comoving frame

$$(x,t) \;\rightarrow\; (x - u\,t, t)$$

Effective horizon

the wave equation becomes

$$\left\{-\frac{\partial^2}{\partial t^2} + 2\,u\,\frac{\partial^2}{\partial x\,\partial t} + \frac{\partial}{\partial x}\left[c^2(x) - u^2\right]\frac{\partial}{\partial x}\right\}\varphi = 0 \qquad (2)$$

that can expressed in the general covariant form ($g = \det g_{\mu\nu}$)

$$\frac{1}{\sqrt{-g}}\,\partial_\mu\left(\sqrt{-g}\,g^{\mu\nu}\,\partial_\nu\,\varphi\right) = 0$$

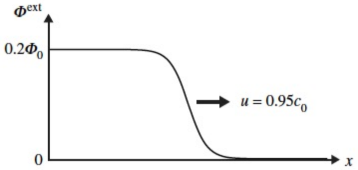
with effective metric

$$g^{\mu\nu} = \frac{1}{c(x)}\begin{pmatrix} -1 & u \\ u & c^2(x) - u^2 \end{pmatrix}$$

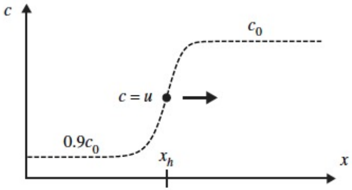
i.e., event horizon ($g_{00} = 0$) where $c(x) = u$

Effective horizon

Example - a flux step of magnitude $\Phi^{\text{ext}} = 0.2\,\Phi_0$ moving with speed $u = 0.95\,c_0$



$\rightarrow$ function $c(x, t)$



Hawking radiation

Quantization: $\varphi \to \hat{\varphi} \to$ photon pair production from e.m. vacuum near to $x_h \to$ analogue Hawking radiation with temperature

$$T_{\mathrm{H}} = \frac{\hbar}{2\pi k_{\mathrm{B}}} \mid \frac{\partial c(x)}{\partial x} \mid_{x=x_h} \tag{3}$$

Radiated power in the comoving frame (Nation et al., Phys. Rev. Lett **103**, 087004 (2009) - 0904.2589)

$$P = \frac{\pi}{12\,\hbar}\,(k_{\mathrm{B}}\,T_{\mathrm{H}})^2$$

NB - For a detector at the end of the line, the radiation will be doppler shifted yielding higher power. However, the rate of emitted photons remains approximately unchanged.

Hawking radiation

Example

- phase speed step length $\sim 10\,a$
- step height $\approx 0.1\,c_0$

$$\left|\frac{\partial c(x)}{\partial x}\right| \approx 0.01\,c_0 \qquad \to \qquad T_{\rm H} = \frac{0.01}{\pi k_{\rm B}}\sqrt{\frac{\hbar\, e\, I_c}{C_0}} \qquad (4)$$

$$I_c = 5\ \mu{\rm A}\,;\, C_0 = 1\ {\rm f}F \qquad \to \qquad T_{\rm H} \approx 70\ {\rm m}K$$

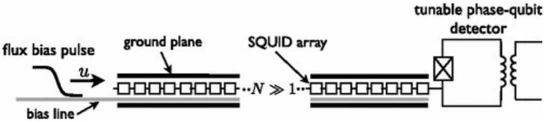
With the bias pulse considered and $T_H = 120$ mK, Nation et al. have estimated an average emission rate of one photon per pulse for ~ 4800 SQUID's. (Increase the pulse repetitions in order to accumulate sufficient photon counts to verify the HR)

Experimental detection

Unlike a real BH, both photons may be detected in this device.

LAB frame: a detector at the far end of the array will see two incoming photons. One photon in front of the horizon, and one behind, with the former having a slightly higher propagation velocity.

Single-shot detection of these photons using (one or more) tunable-phase qubit detectors coupled to the array. By repeatedly sending flux pulses down the bias line, the black body spectrum may be probed by tuning the qubit resonant frequency.



Experimental detection

Additionally, information on the cross horizon correlations between the emitted photon pairs can be established though coincidence detection $\rightarrow$ unambiguous claim of HR as the source of the emitted photons.

Other detection methods proposed (measurements of the microwave field quadrature, second order correlation of the photon number as well their entanglement) are under investigation.

The ability to realize low noise, quantum limited microwave photon detectors, and dc-SQUID arrays comprising thousands of unit cells operating at a few tens of mK and below, shows promise for demonstrating strong microwave HR signals.

Outlook

Other effects can be explored with this device (Nation et al., Rev. Mod. Phys. **84**, 1 (2012)) - (1103.0835):

- Unruh effect: an accelerated observer see the Minkowski vacuum in a thermal state with temperature $\propto$ to the acceleration
- Dynamical Casimir effect

Other issues (Cosmological particle creation; ER=EPR)??

Also from the experimental side, much remains to be explored; the JTWPA design needs to be adapted so as to enable propagating flux pulse/step biasing, and microwave photon detection circuitry suitable for verifying correlated photon pairs needs to be developed.