Quantum sensing in the SC platform:

(i) qubits

(ii) quantum-limited parametric amplifiers

(iii) 3D resonators

General considerations on quantum sensing with SC devices

→ compared to WP2, not (yet) ready for building collaborations?
significant breakthroughs in the past few months

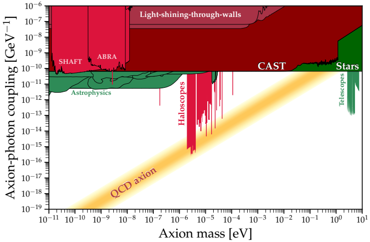
→ SC sensing technologies meant for **heavier DM candidates**
from a few μeV up to tens of μeV

→ the range is not that broad as for clocks or atom interferometers, but it is really **well motivated**
QCD lattice simulations, beyond astrophysical hints

→ in principle, there is **sensitivity** to test QCD benchmark models in the whole range
just need to gain a factor 10^3 … ⊙⊙

(I) QUBITS: WHERE ARE WE?

- qubits are **building blocks for single microwave photon detection (SMPD)**
  SMPD enables higher scan rates, allowing to gain the factor $\geqslant 10^3$ in sensitivity required at high frequency
  (say, 10 GHz compared to 1 GHz, as $df/dt \propto \nu_c^{-3}$)



https://cajohare.github.io/AxionLimits/

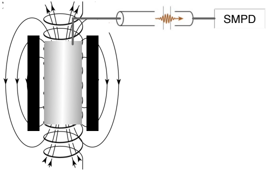
- needed: large bandwidth ($>$ 100 MHz), operation in B fields, low dark counts (100 s^{-1})

⊙⊙ a number of experiments (Italy, Germany, CERN, US, Korea, Australia, Taiwan, ...) would benefit from this sensing method

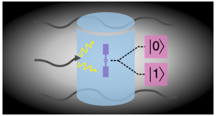
a real (B field, tunable) DM search with a QIS device

→ *itinerant* vs *cavity* single microwave photon counter (SMPD)

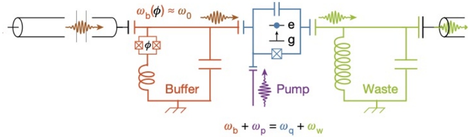
ITINERANT PHOTONS



CAVITY PHOTONS



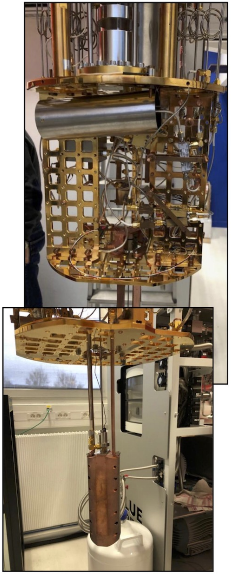
Phys. Rev. Lett. 126, 141302 (2021)



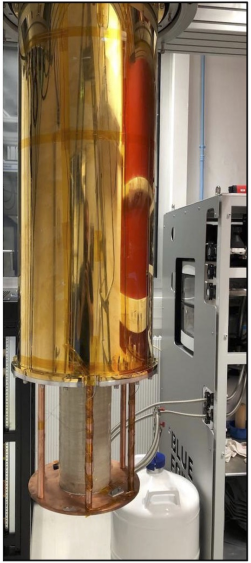
- ⊙ low dark counts ⟹ sensitivity
- ⊙ tunability
  static ($\simeq$ 100 kHz), dynamical ($\simeq$ 100 MHz)
  + Josephson mixer
- ⊙ metrological methods from QIS field
- ⊙ on/off resonance studies

SMPD-HALOSCOPE experiment

- hybrid (normal-superconducting) cavity 7.37 GHz, tunable, $Q_0 = 9 \times 10^5$ (at 14 mK, under 2 T)
- T=14 mK delfridge base temperature @ Quantronics lab (CEA, Saclay)
- a thousandfold acceleration of the search
- spin-off company in 2024



SMPD (top) and cavity



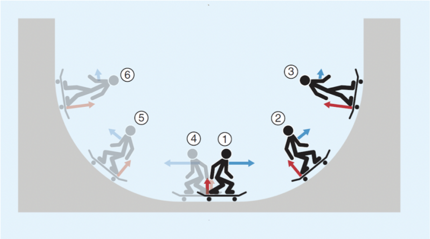
SC magnet

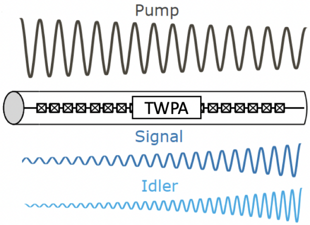
(II) parametric amplifiers: where are we?

$df/dt \propto V_{\rm eff}^2 \; Q_L \; T_{sys}^{-2}$

Josephson Parametric Amplifiers (JPAs) introduce the lowest level of noise (SQL noise).
They are central in DM search for low noise **readout of a cavity field** and to learn about **the state of qubits**.

Recently developed TWPAs offer **much broader amplification bandwidths** ($\sim$ GHz).

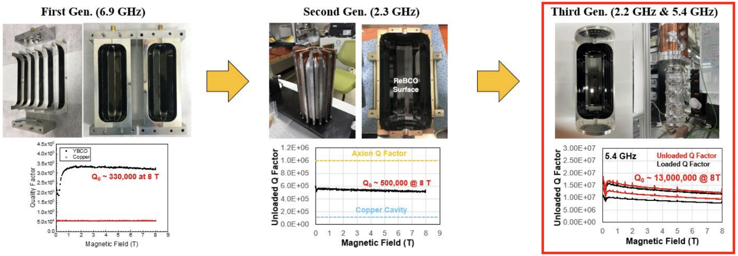




- ongoing projects within INFN (nanofab at FBK)
- ww: MIT, NIST (Boulder), Grenoble (spin-off company), Caltech

(II) 3D RESONATORS

$Q_{3D} \simeq Q_a$, with Q_a linewidth of searched signal is no more an issue



Generation	Material	Substrate	Volume [liters]	Frequency [GHz]	Q-factor
1st Gen	YBCO	NiW	0.3	6.9	150,000 @ 8 T 330,000 @ 8 T
2nd Gen	GdBCO	Hastelloy	1.5	2.3	~ 500,000 @ 8 T
3rd Gen	EuBCO + APC	Hastelloy	1.5	2.2	4,500,000 @ 0 T Waiting for Magnet Test
	EuBCO + APC	Hastelloy	0.2	5.4	~ 13,000,000 @ 8 T

17th Patras Workshop, Mainz 2022 D. Ahn, CAPP (Korea)

→ current challenge: getting large tuning ranges with minimum number of intruder modes

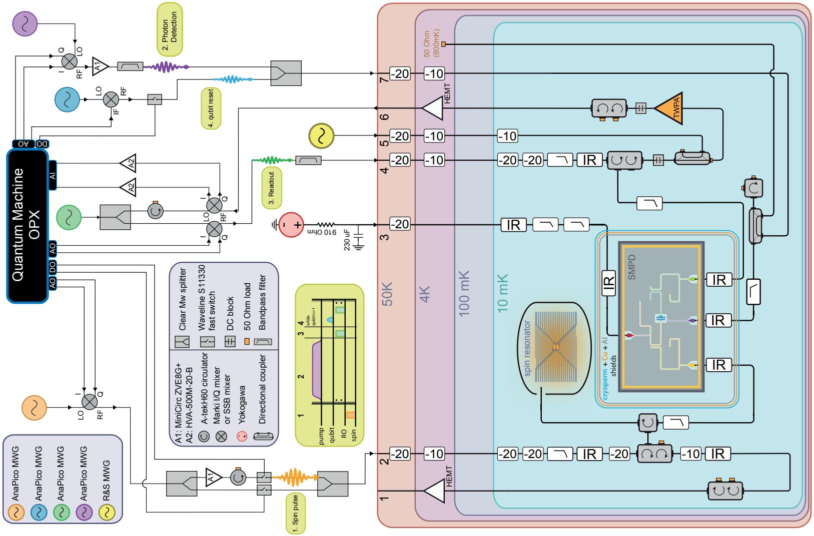
BUILDING A DRD5 COLLABORATION

there is value in forming a collaboration to bring together additional synergy from an **existing community of pixellised-groups** (table-top experiments, small-scale labs)

- to make a DM search with a microwave photon counter requires a **high level of QIS expertise**
  this entails not just knowing methods and techniques in **circuit-QED** *but also knowing how to mount and operate of several components in ultra-cryogenic environment*

- **standardisation** of electronics and procedures:
  - noise temperature measurements (→ Education Platform WP)
  - "quantum orchestration" platforms (FPGA-based controls)
  - printed circuit boards: selection of radiopure materials, cleaning
  - microwave setup engineering

- at an even higher level: **shared delfridges**
  larger ones, equipped with SC magnets and bucking coils, few M-cost



Quantum Machine OPX
AO
DO
AI
2. Photon Detection
4. qubit reset
3. Readout
1. Spin pulse
A1
A2
LO
RF
IF
I
Q
910 Ohm
230 uF
50 Ohm (800mK)
HEMT
TWPA
SMPD
spin resonator
cryoperm + Cu + Al shields
50K
4K
100 mK
10 mK
-20
-10
IR
1
2
3
4
5
6
7
pump
qubit
RO
spin
Clear Mw splitter
Waveline S11330 fast switch
DC block
50 Ohm load
Bandpass filter
A1: MiniCirc ZVE8G+
A2: HVA-500M-20-B
A-tekH60 circulator
Marki I/Q mixer or SSB mixer
Yokogawa
Directional coupler
AnaPico MWG
AnaPico MWG
AnaPico MWG
AnaPico MWG
R&S MWG

noise temperature measurements