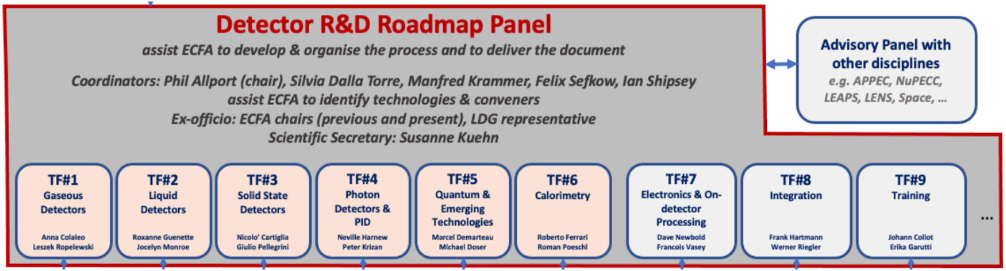
# TF#5 - Quantum and Emerging Technologies




| Convenors | Expert members | Symposium date |
|---|---|---|
| Marcel Demarteau (ORNL)<br>Michael Doser (CERN) | Caterina Braggio (Padova)<br>Andy Geraci (NWU)<br>Peter Graham (Stanford)<br>Anna Grasselino (Fermilab)<br>John March Russell (Oxford)<br>Stafford Withington (Cambridge) | Monday 12.4.2021 |

$09:15 \rightarrow 11:00$ **Science targets – Overview and Landscape**

- Axions and other DM searches
- EDM searches and tests of fundamental symmetries
- Tests of Quantum Mechanics
- Multimessenger detection (atom interferometer networks and gravitational waves)

$11:30 \rightarrow 13:00$ **Experimental methods and techniques - Overview and Landscape**

- Precision spectroscopy and clocks
- Novel ionic, atomic and molecular systems

$13:30 \rightarrow 16:00$ **Experimental and technological challenges, New Developments**

- Superconducting platforms (detectors: TES, SNSPD, Haloscopes including single photon detection and squeezing)
- High sensitivity superconducting cryogenic electronics, low noise amplifiers including TWJPA
- Broadband axion detection
- Mechanical/optomechanical detectors
- Spin-based techniques

# Searches at the precision frontier of particle physics

**sensitive, lab-scale** experiments search for tiniest deviations arising from **higher energy scales** (/weaker couplings) than can be reached at colliders

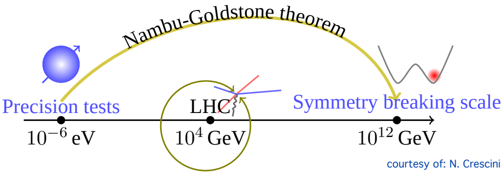
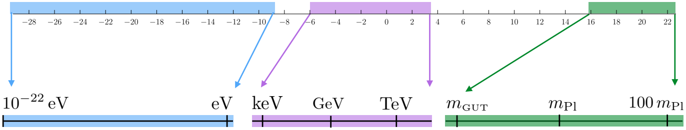



Figure credit: N. Crescini

**quantum sensors** can reach unprecedented sensitivity and probe **ultralight DM**

Dark Matter Mass $\log[m/\mathrm{GeV}]$




Bosonic Wave DM
Axion, ALPs, "Fuzzy" DM

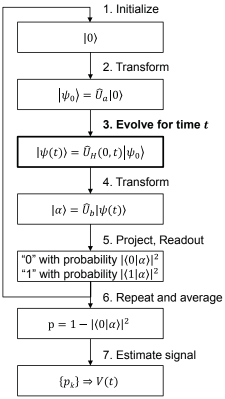
Thermal DM
Dark Sectors, WIMPs

Composite, Primordial Black Holes
WIMPzillas, Nonthermal DM

# QUANTUM SENSING

*"Quantum sensing" describes the use of a quantum system, quantum properties or quantum phenomena to perform a measurement of a physical quantity*
Rev. Mod. Phys. 89, 035002 (2017)

1. Use of a **quantum object** to measure a physical quantity (classical or quantum). The quantum object is characterized by quantized energy levels, i.e. electronic, magnetic or vibrational states of superconducting or spin qubits, neutral atoms, or trapped ions.
2. Use of **quantum coherence** (i.e., wave-like spatial or temporal superposition states) to measure a physical quantity
3. Use of **quantum entanglement** to improve the sensitivity or precision of a measurement, beyond what is possible classically.



## QUANTUM SENSING (IN THIS TALK)

**quantum sensing** techniques and devices in **quantum information science** being applied to particle detection

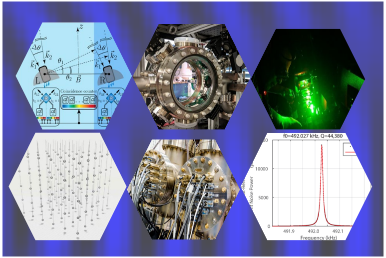
1803.11306v1 [hep-ex] 30 Mar 2018

# Quantum Sensing for High Energy Physics

Report of the first workshop to identify approaches and techniques in the domain of quantum sensing that can be utilized by future High Energy Physics applications to further the scientific goals of High Energy Physics.

Organized by the Coordinating Panel for Advanced Detectors of the Division of Particles and Fields of the American Physical Society

March 27, 2018

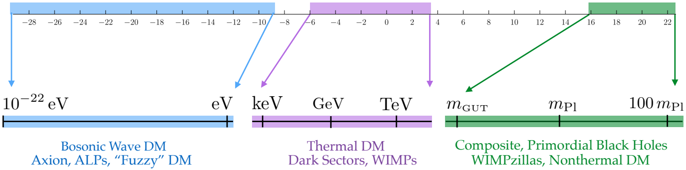



arXiv.org > physics > arXiv:2102.10996

*"Opportunities for DOE National Laboratory-led QuantISED Experiments"*

DOE program in High Energy Physics

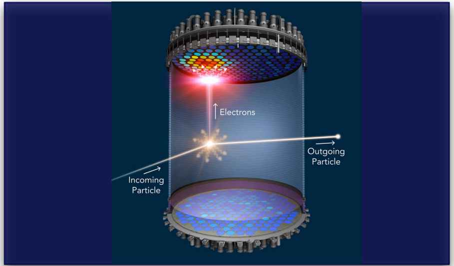
# Ultralight bosonic dark matter

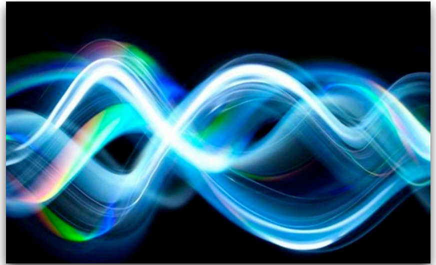



- BSM theories predict the existence of **ultralight bosons** which could be the dark matter
- $m_\chi \lesssim 1\,\mathrm{eV} \Longleftrightarrow$ **wavelike** dark matter
- wavelike dark matter can interact with Standard Model particles: photons, fermions, gluons, …
- experiments target different portals, mass (/frequency) ranges
- blooming phase

# AXION vs WIMP DETECTION

*"The axion would be something of a spiritual cousin to the photon, but with just a hint of mass"* P. Sikivie



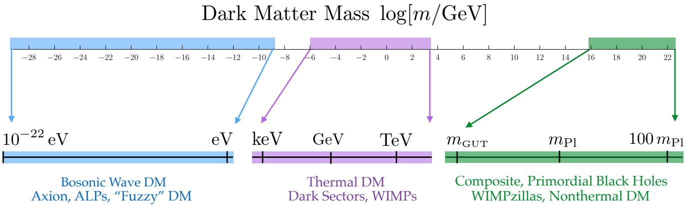
WIMP [4-1000 ] GeV
— number density is small
— tiny wavelength
— no detector-scale coherence

$\Longrightarrow$ observable: **scattering** of individual particles

AXION [$m_A \lesssim$ eV]
— number density is large (bosons)
— long wavelength
— coherence within detector

$\Longrightarrow$ observable: classical, oscillating, **background field**

# ULTRALIGHT BOSONIC DARK MATTER

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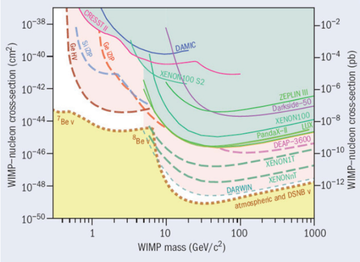
- experiments target different portals, mass (/frequency) ranges
- blooming phase!

# IS DM MADE OF AXIONS?

## ⇒ a well motivated scenario:

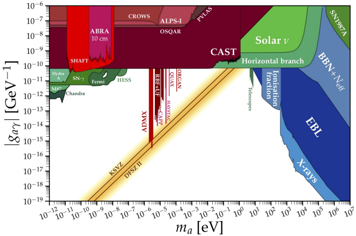
- “three birds with one particle”
  1. a CP problem solution
  2. Dark Matter candidate
  3. barion asymmetry [PRL 124, 111602 (2020)]
- SUSY is failing tests at LHC
- WIMPs searches with next generation of experiments

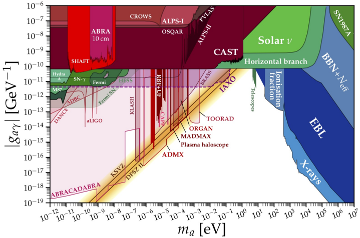



## ⇒ blooming phase:

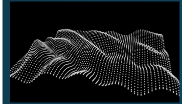
- new detection concepts
- commissioning of small-scale setups
- upgrade to *large scale* experiments for established techniques

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



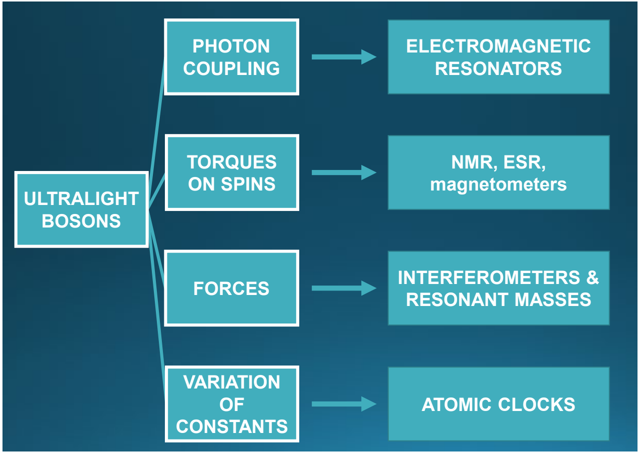
# Experimental techniques -TF5



Ultralight bosonic dark matter = oscillating field

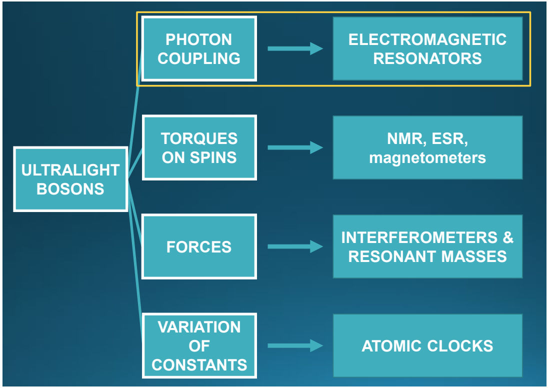
**Ultralight spin-0 & spin-1 bosons**

- QCD axion
- Axion-like particles (ALPs)
- Moduli & other scalar particles
- Dark/hidden photons




from Derek F. Jackson Kimball "*Quantum sensors for wavelike Dark Matter Searches*" Snowmass 2021

# EXPERIMENTAL TECHNIQUES -TF5



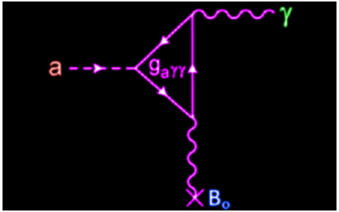

Photon counting, squeezing, quantum-limited amplifiers
RF and microwave cavities in multi-Tesla B fields

Back-action evasion, hyper-polarization, optical magnetometers networks

from Derek F. Jackson Kimball "*Quantum sensors for wavelike Dark Matter Searches*" Snowmass 2021

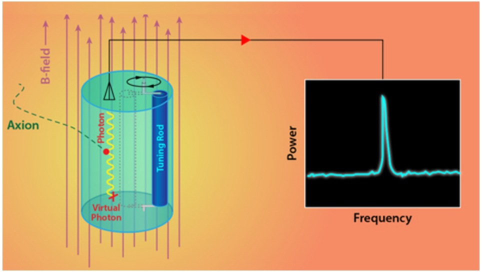
# HALOSCOPE - resonant search for axion DM in the Galactic halo

– original proposal by P. Sikivie (1983)
– search for axions as cold dark matter constituent: SHM from $\Lambda_{CDM}$, local DM density $\rho$
  $\rightarrow$ signal is a **line** with $10^{-6}$ relative width in the energy($\rightarrow$ frequency) spectrum
  $\rightarrow$ + sharp ($10^{-11}$) components due to non-thermalized
– an **axion** may interact with a **strong** $\vec{B}$ **field** to produce a **photon** of a specific frequency ($\rightarrow m_a$)



# HALOSCOPE - resonant search for axion DM in the Galactic halo

— if axions are *almost monochromatic* then their conversion to detectable particles (photons) can be accomplished using *high-Q* microwave cavities.




- $\omega_{\mathrm{TM}0nl} = \sqrt{\left(\frac{\epsilon_n}{r}\right)^2 + \left(\frac{l\pi}{h}\right)}$

  $\mathrm{TM}_{0nl}$ are the cavity modes that couple with the axion
- resonant amplification in $[m_a \pm m_a/Q]$
- data in thin slices of parameter space; typically $Q < Q_a \sim 1/\sigma_v^2 \sim 10^6$
- signal power $P_{a\to\gamma}$ is model-dependent

$$P_{a\to\gamma} \propto (B^2 VQ)(g_{a\gamma}^2 \frac{\rho}{m_a})$$

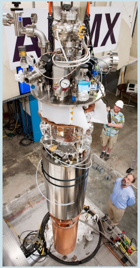
exceedingly tiny ($\sim 10^{-23}$ W)

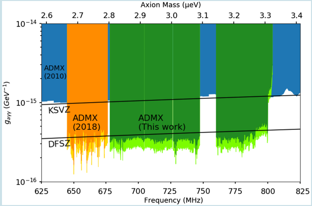
*"The last signal ever received from the 7.5 W transmitter aboard Pioneer 10 in 2002, then 12.1 billion kilometers from Earth, was a prodigious* $2.5 \times 10^{-21}$ *W. And unlike with the axion, physicists knew its frequency!"*

K. V. Bibber and L. Rosenberg, Physics Today 59, 8, 30 (2006)

# Haloscopes: 2020 results

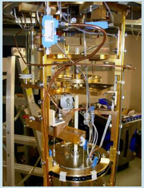
## ADMX PRL **124**, 101303 (2020)

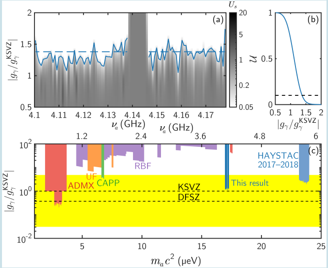





– sensitivity to QCD axion
– 2.82 – 3.31 $\mu$eV mass range
– cylindrical cavity at $T = 100$ mK,
$Q_0 \sim 30000$, $V = 1361$
– 7.6 T field

## HAYSTAC Nature 590, 238 (2021)





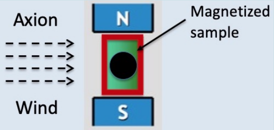

– 17.14 – 17.28 $\mu$eV axion mass range
– **squeezing** doubled the search rate
– cylindrical cavity at $T = 60$ mK
$Q_0 \sim 50000$, $V = 1.51$
– 8T magnet

*"Roberto and I spent a few months cooking up this theory, and now the experimentalists have spent 40 years looking for it "*
*H. Quinn*

# QUAX - QUAERERE AXIONS

Detection of cosmological axions through their **coupling to electrons** or **photons**

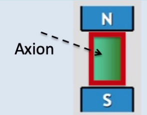
## ELECTRON COUPLING – **QUAX** *the FMR haloscope*




the axion DM cloud acts as an **effective RF magnetic field** on the electron spin exciting **magnetic transitions** in a magnetized sample (YIG) $\rightarrow$ **RF photons**

$$P_{\rm out} = \frac{P_{\rm in}}{2} = 8 \times 10^{-26} \left(\frac{m_a}{2 \cdot 10^{-4}\,{\rm eV}}\right)^3 \left(\frac{V_s}{1\ {\rm liter}}\right) \left(\frac{n_S}{10^{28}/{\rm m}^3}\right) \left(\frac{\tau_{\rm min}}{10^{-6}\,{\rm s}}\right) {\rm W},$$

## PHOTON COUPLING – **QUAX** a$\gamma$ *high frequency range* (8.5 – 11) GHz



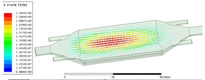
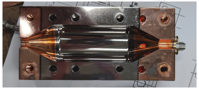
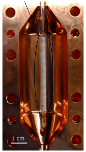

DM axions are converted into **RF photons** inside a **resonant cavity** immersed in a **strong magnetic field**

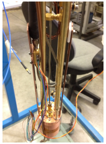
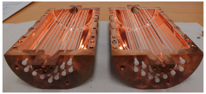
$$P_{\rm ax} = 3.3 \cdot 10^{-24}\,{\rm W} \left(\frac{V_{\rm eff}^{\rm Sa}}{2.3{\cdot}10^{-5}\,{\rm m}^3}\right) \left(\frac{B}{8\,{\rm T}}\right)^2 \times \left(\frac{g_\gamma}{-0.97}\right)^2 \left(\frac{\rho_a}{0.45\,{\rm GeV\,cm^{-3}}}\right) \left(\frac{f}{13.5\,{\rm GHz}}\right) \left(\frac{Q_L}{145\,000}\right)$$

# QUANTUM SENSING

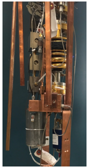
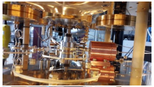
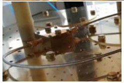
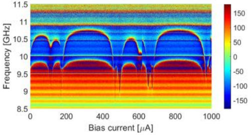
To get to **cosmologically relevant sensitivity**:

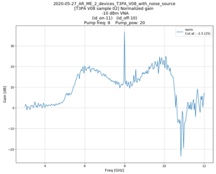
- develop **high Q** ($\gtrsim 10^6$) microwave cavities, compatible with **strong magnetic fields** ($B \gtrsim 8\,\mathrm{T}$)

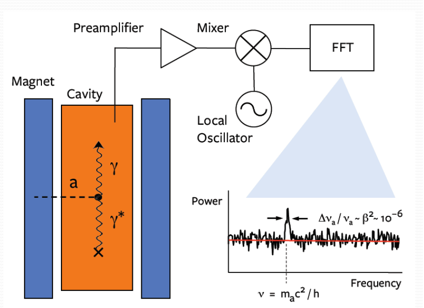

- **use quantum-limited amplifiers**
  JPA (Josephson Parametric Amplifier),
  TW (Travelling Wave) JPA (collaboration with N. Roche, Grenoble) $\rightarrow$ DARTWARS (call gr5)

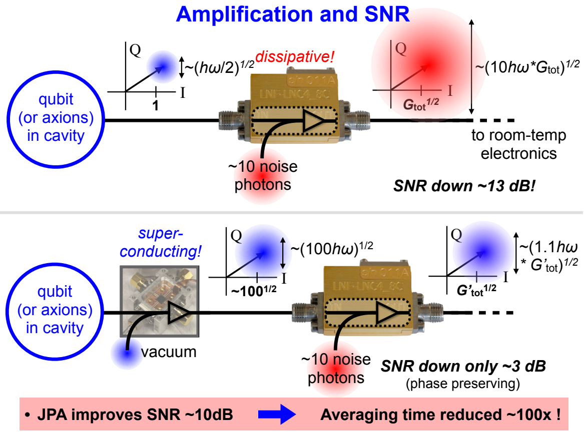








# FROM HEMT TO JPA

the Dicke's receiver noise (→ sensitivity to ultralight DM) is determined by the preamp



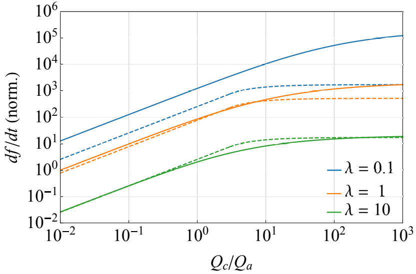

from A. Eddins "*Josephson Parametric Amplifiers: Theory and Application*"

# Scan Rate

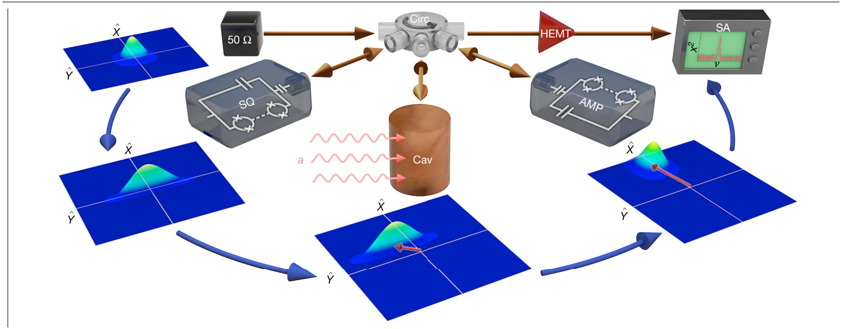
*Revisiting the detection rate for axion haloscopes* D. Kim et al JCAP03, 066 (2020)

**Abstract.** The cavity haloscope has been employed to detect microwave photons resonantly converted from invisible cosmic axions under a strong magnetic field. In this scheme, the axion-photon conversion power has been formulated to be valid for certain conditions, either $Q_{\text{cavity}} \ll Q_{\text{axion}}$ or $Q_{\text{cavity}} \gg Q_{\text{axion}}$. This remedy, however, fails when these two quantities are comparable to each other. Furthermore, the noise power flow has been treated independently of the impedance mismatch of the system, which could give rise to misleading estimates of the experimental sensitivity. We revisit the analytical approaches to derive a general description of the signal and noise power. We also optimize the coupling strength of a receiver to yield the maximal sensitivity for axion search experiments.

$$\frac{df}{dt} = \frac{1}{\text{SNR}^2}\left(\frac{P_0}{k_B T_{\text{eff}}}\right)^2 \left(\frac{\frac{\beta}{(1+\beta)}}{\frac{4\beta}{(1+\beta)^2}+\lambda}\right)^2 \frac{Q_l Q_a^2}{Q_l + Q_a}$$

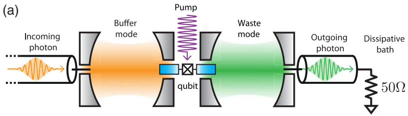


# (BLUE LINE): SQUEEZING



# QUANTUM SENSING

- (next step in sensitivity⋆) we need to be able to **count photons** $\Longleftrightarrow$ develop the **microwave SPD**
  NOTE: photon detection at optical frequencies relies on ionization, microwave photons are 5 orders of magnitude lower!




PHYSICAL REVIEW X **10,** 021038 (2020)
Quantronics Group, FR (E. Flurin)

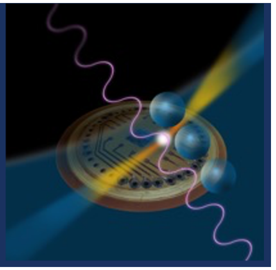
qubit frequency $\Longleftrightarrow$ number of photons in the cavity
The electric field of even a single photon will excite the non-linear response of the qubit oscillator and shift its frequency

JPA readout vs counter

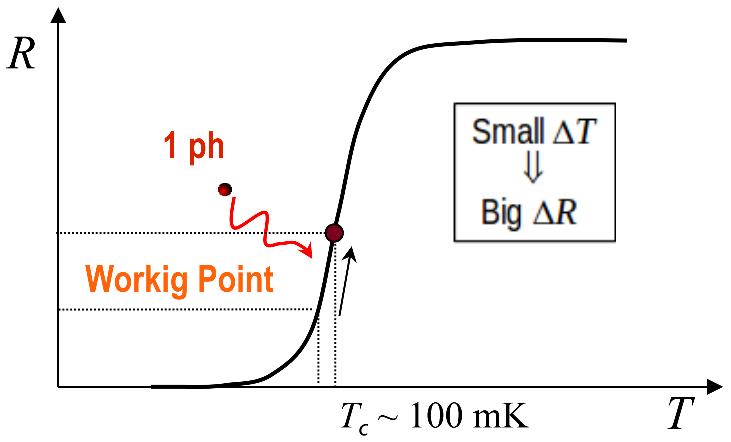
Example:
linear amplifier $\sigma^{LA}$, and quantum counter $\sigma^{QC}$ power sensitivity
$T_N^{LA} = 1\,\text{K}$,
QC noise rate $R_n = 100\,\text{Hz}$,
$f = 10$ GHz,
$Q_a = 10^6$
$\rightarrow$ sensitivity improved by a factor 14 $\Longleftrightarrow$ 200 in measurement time!

$$\frac{\sigma^{\mathrm{QC}}}{\sigma^{\mathrm{LA}}} = \frac{h}{k_B T_n^{\mathrm{LA}}} \sqrt{f Q_a R_n}$$

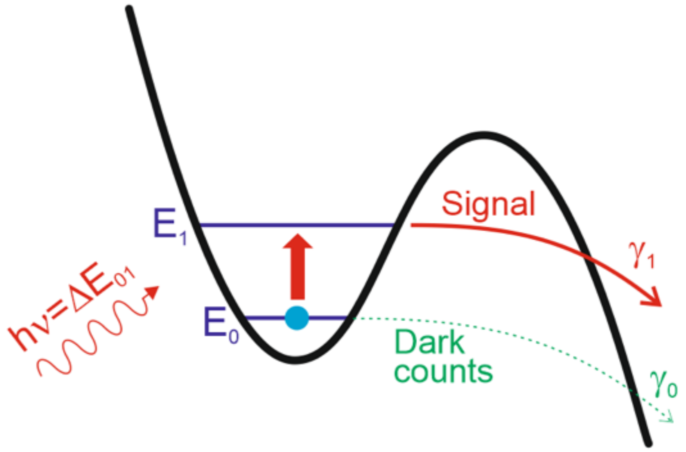
# SIMP: SINGLE MICROWAVE PHOTON DETECTION



- 3 years project funded by CSN V of INFN
- Goal: development of single microwave photon detectors with nanowire-TES and Current Biased Josephson Junction (CBJJ)
- In collaboration with CNR-IFN, CNR-Nano and INRiM

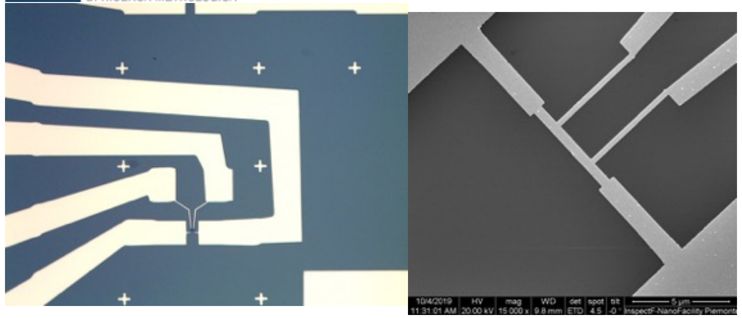


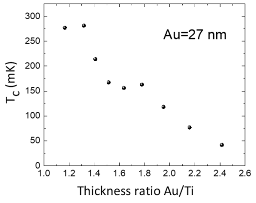

Nanowire TES
Small volume and low critical temperature allow steep variation of resistance when a single photon of 50-100 GHz is absorbed.

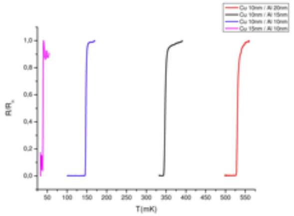



CBJJ
The absorption of a single 10 GHz photon causes the transition of the JJ from the superconducting to the resistive state.

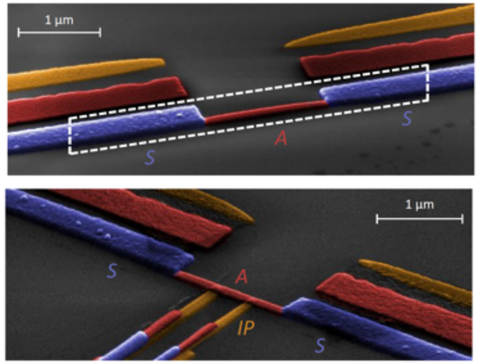
1. Nanowire TES fabricated at INRiM (Ti/Au) and CNR-Nano (Al/Cu) with typical size 20 nm x 100 nm x 1000 nm and Tc ~100 mK.





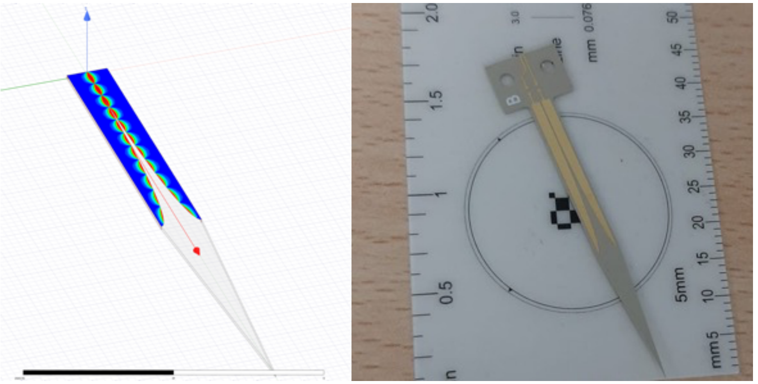



Transition measured with nano-TES coupled to DC-SQUID at INRiM

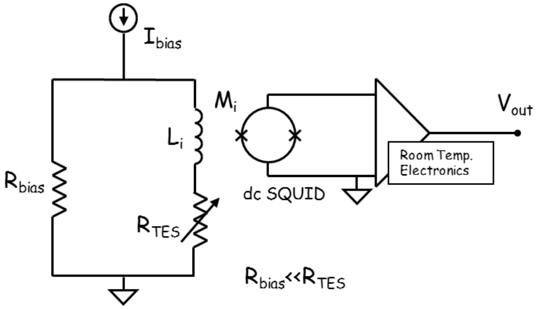



Full DC characterization in F.Paolucci et al arXiv:2007.08320

2. Waveguide photon collected with a finline terminated with the nano-TES.

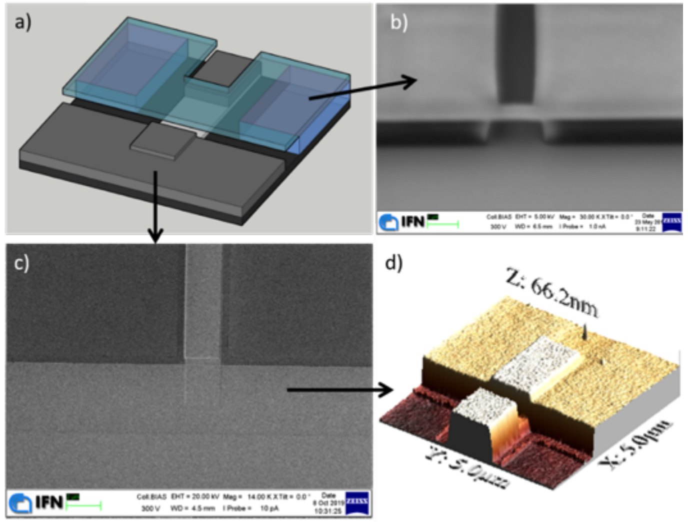


3. DC-SQUID readout and RF tests in preparation in the TIFPA (Trento) dilution refrigerator.

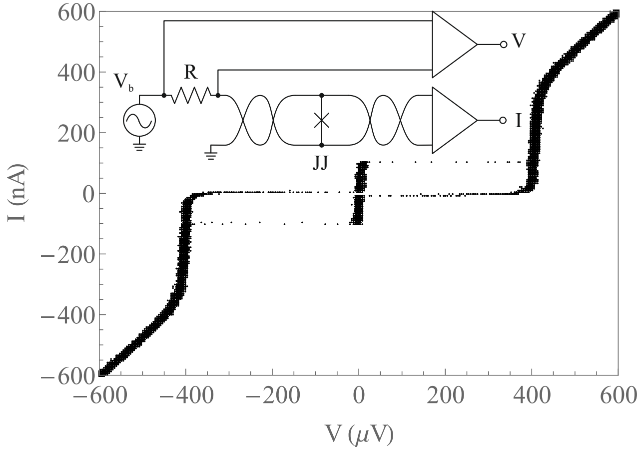


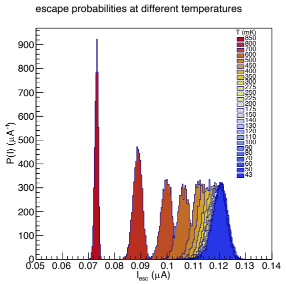

TIFPA Dilution Refrigerator

1. JJ fabricated with EBL and Al shadow evaporation technique at CNR-IFN

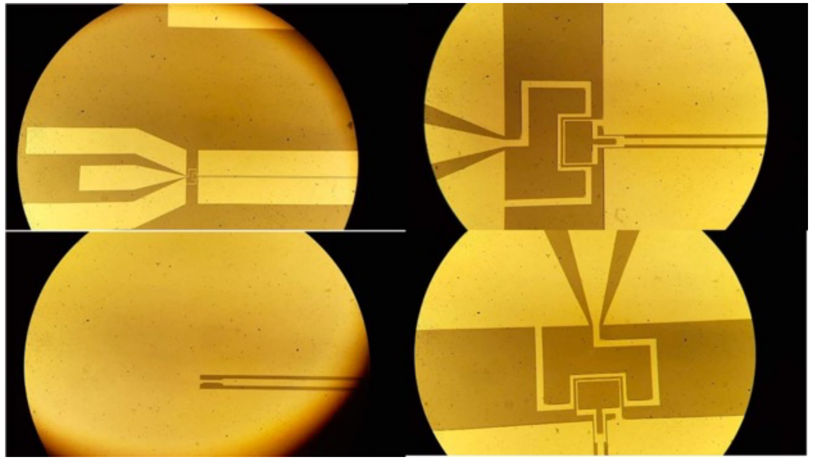


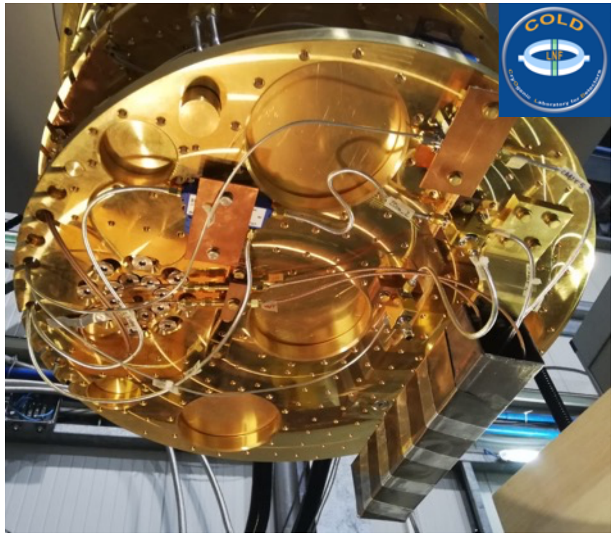

2. JJ characterization with IV measurements in a dilution refrigerators at 40 mK




3. RF tests ongoing at LNF on chip with transmission lines terminated on CBJJ or DC-SQUID. Devices tested also as JPA. T=10 mK.





- P Falferi et al. «Status of the SIMP Project: Toward the Single Microwave Photon Detection» J Low Temp Phys (LTD proceedings) DOI 10.1007/s10909-020-02381-x
- S. Pagano et al. «Development of a Josephson junction based single photon microwave detector for axion detection experiments», J. Phys.: Conf. Ser. 1559 012020 (EUCAS proceedings)
- G. Filatrella et al. «Analysis of thermal and quantum escape times of Josephson junctions for signal detection» Chaotic Modeling and Simulation CMSIM An International Journal of Nonlinear Science.
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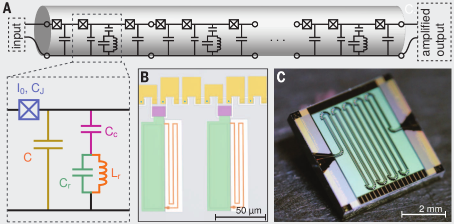
- F. Paolucci et al. «Highly sensitive nano-TESs for gigahertz astronomy and dark matter search» J. App. Phys. DOI:10.1063/5.0021996 arXiv:2007.08320
- F. Paolucci et al Phys Rev Appl 14, 034055 (2020) Hypersensitive Tunable Josephson Escape sensor for Gigahertz astronomy

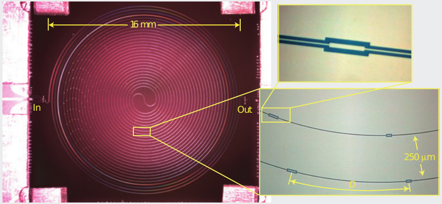
# Two different technological approaches

## Traveling Wave Josephson Parametric Amplifiers




- TWJPA implemented as a nonlinear lumped-element transmission line;
- One unit cell consists of a Josephson junction and a capacitive shunt to ground;
- Already demonstrated quantum-limited noise read out;
- High bandwidth: over a 4 GHz centred at 5 GHz;
- Limited gain: $< 20$ dB
- Small dynamic range: $< -90$ dBm

## Dispersion-engineered Traveling Wave Kinetic Inductance




- DTWKI exploits the Nonlinear kinetic inductance of TiN and NbTiN superconducting film;
- Phase matching by Coplanar Waveguide (CPW) or lumped-element artificial transmission line;
- Noise near to quantum-limited
- High bandwidth: over a 4 GHz centred at 5 GHz;
- Limited gain: $<$ 20 dB, and gain profile with large ripple
- High dynamic range: from -50 to -45 dBm

### The principal objectives of DART WARS are

1. The practical development of high performing parametric amplifiers following two different promising approaches (DTWKI, TWJPA) and exploring new design solutions, new materials and advanced fabrication processes;
2. The read out demonstration of various detectors/components (TESs, MKIDs, microwave cavities and qubits) with improved performances due to a parametric amplification with a noise at the quantum level;

### The technical goal is to achieve

- a gain value around 20 dB, comparable to HEMT;
- a high saturation power (around -50 dBm);
- quantum limited or nearly quantum limited noise (noise temperature < 600 mK)
- reduction of the gain ripple and yield improvement.

These features will lead to reading out large arrays of detectors or qubits with no noise degradation by reaching unprecedented energy resolution, noise equivalent power, energy threshold, opening future prospective toward next generation of particle, astroparticle and astrophysics experiments.