Transforming Astronomy in the 2040s
INAF HQ
May, 15th-16th, 2025

Superconducting-based technologies for VIS/NIR and sub-mm/mm domain

C. Macculi (INAF/IAPS Roma), M. Uslenghi (INAF/IASF-Mi), A. Paiella (La Sapienza Roma1),
M. Rajteri (IRNiM Torino), A. Gaggero (CNR/IFN Roma)

on behalf of a more extended team

- **sub-mm/mm**
  - KIDs → A. Paiella (La Sapienza Roma1)

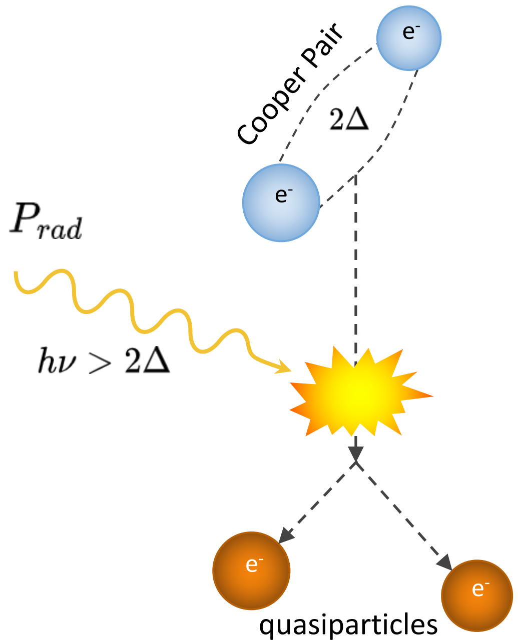
- **VIS/NIR**
  - Transition-Edge Sensors: TES → M. Rajteri (IRNiM Torino)
  - Superconducting nanowire single photon detectors: SNSPD → A. Gaggero (CNR/IFN Roma)

KIDs for sub-mm/mm @ Sapienza & IFN-CNR Roma2 Tor Vergata

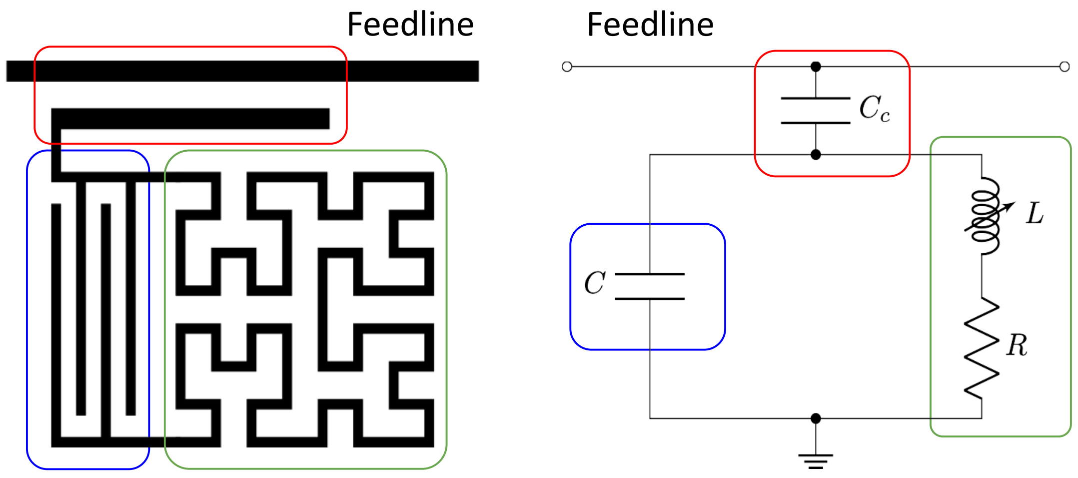
Alessandro Paiella

Contributors: P. de Bernardis, E. Battistelli, C. Bellucci, F. Cacciotti, A. Capponi, A. Coppolecchia, I. Di Nitto, G. Isopi, L. Lamagna, S. Masi, G. Pettinari, F. Piacentini

Kinetic Inductance Detectors - KIDs



- KIDs are low–temperature, fast (~ 10-100 μs), superconductive detectors, where the radiation is detected by sensing changes of the kinetic inductance.
- A superconductor, cooled below its critical temperature T_c ,presents two populations of electrons: quasiparticles and Cooper pairs (binding energy $2\Delta \approx 3.5k_BT_c$
- Pair–breaking radiation, $h\nu > 2\Delta$, can break Cooper pairs, producing a change in the population relative densities, and thus in the kinetic inductance.
- To detect the change in kinetic inductance, a superconducting film is configured to serve as the inductor in a high–quality factor (R)LC resonant circuit, realized on a dielectric wafer.



LEKID configuration

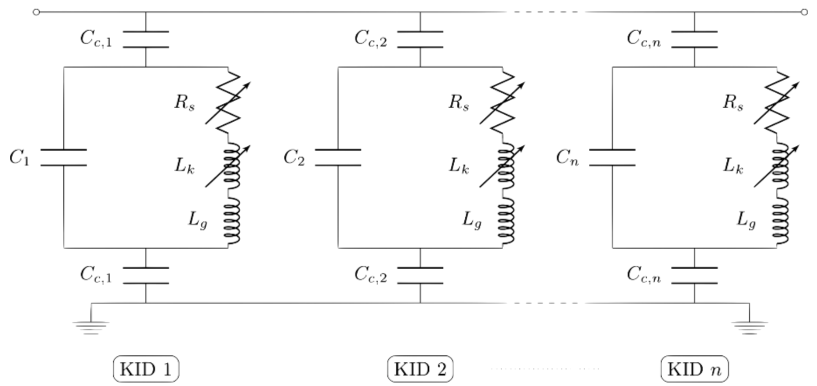
Spectral coverege vs. critical temp. vs. operating temp.

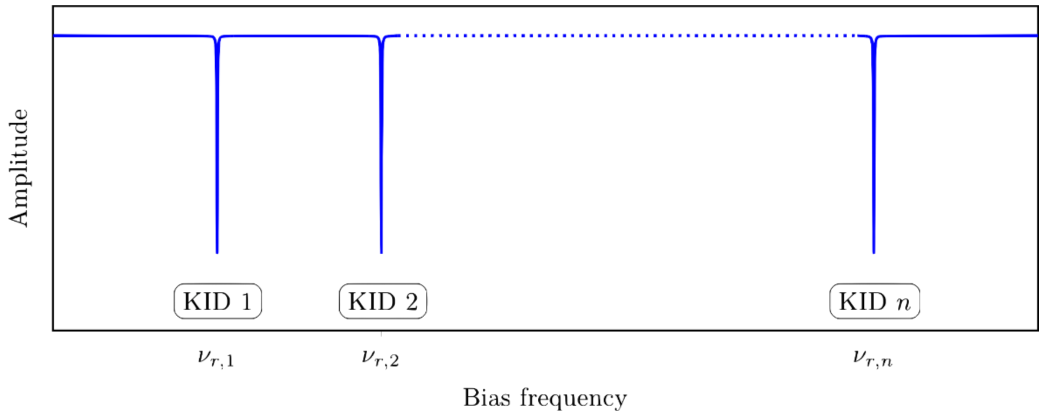
- KIDs are pair–breaking detectors, the minimum radiation frequency able to break Cooper pairs is $\nu > 2\Delta/h = 73\,T_c[K]$ GHz,
- In order to operate the detectors in the non–thermal regime, they must be cooled to a temperature: $T < T_c/5$.
- Example: for W-band (75-110 GHz), we need $T_c \sim 1$ K, and an operation temperature lower than 200 mK.

Kinetic Inductance Detectors – Advantages

The key features that make KIDs an excellent choice for a large range of applications can be summarized as follows:

- KIDs can reach **photon–noise–limited performance** under a low background power.
- KIDs are **intrinsically multiplexable** and require a few coaxial cables for the bias/readout of hundreds of independent detectors
  - large detector arrays increase the instrument sensitivity,
  - small thermal input on the cryogenic system.



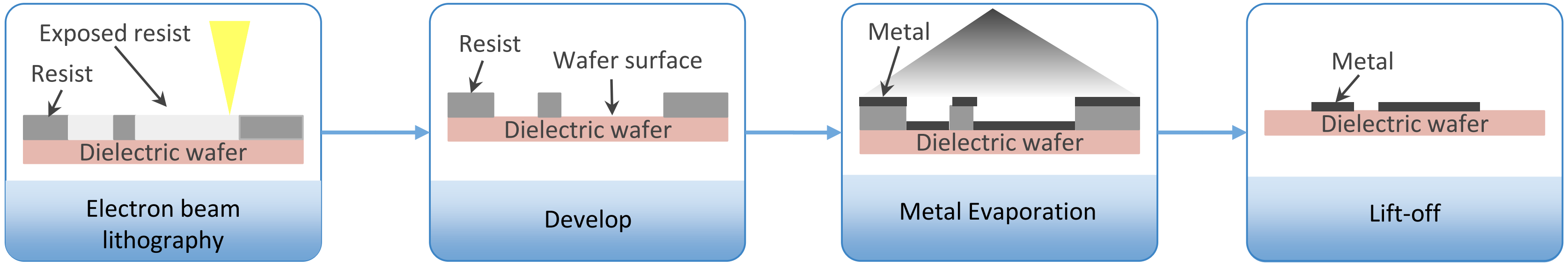


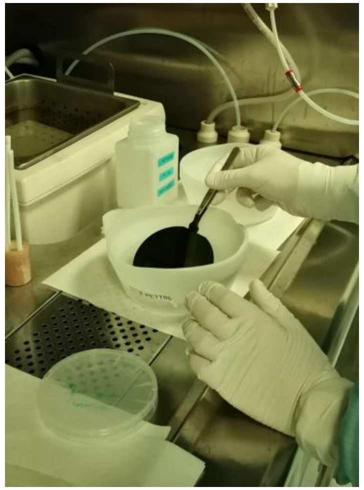
- KIDs do **not** require **complex microfabrication** techniques to be built
  - high detector array yield
    - large detector arrays, with a large number of operational detectors, increase the instrument sensitivity.
- KIDs are robust
  - they are obtained by deposition of a metal, for example Aluminum, on a dielectric wafer, usually Silicon,
    - very resistant to mechanical shock, thermal cycling and radiation.

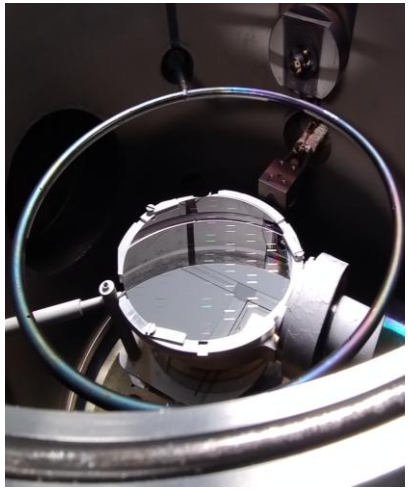
Kinetic Inductance Detectors – Fabrication

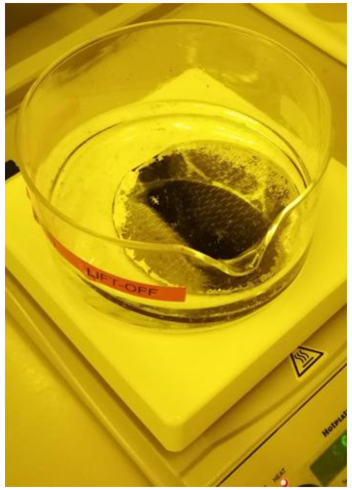
- The microfabrication process is carried out in a cleanroom and involves only a few steps.
- Our KIDs are fabricated at IFN–CNR, in Rome Tor Vergata.

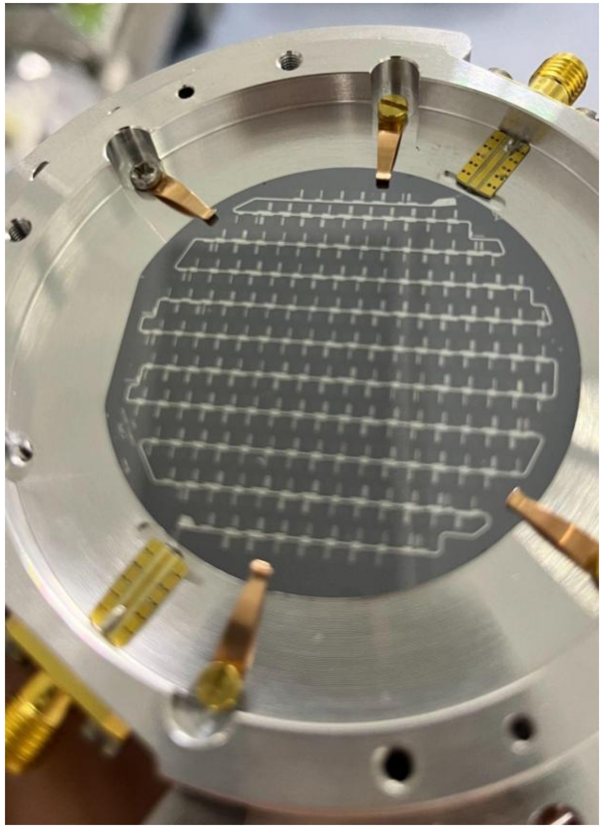
CNR IFN
Istituto di Fotonica e Nanotecnologie







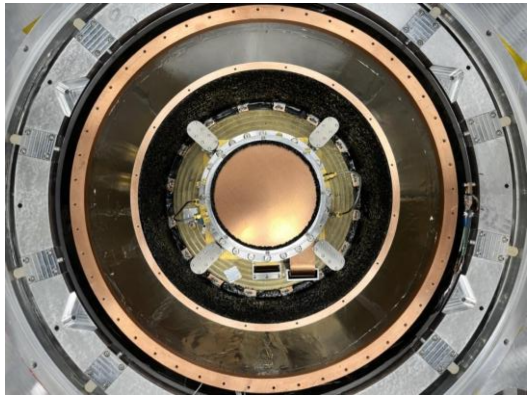
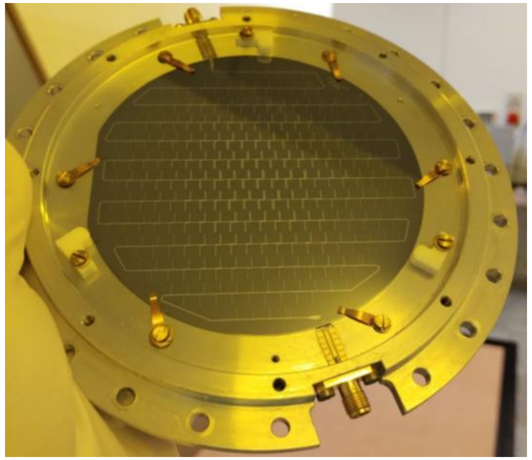




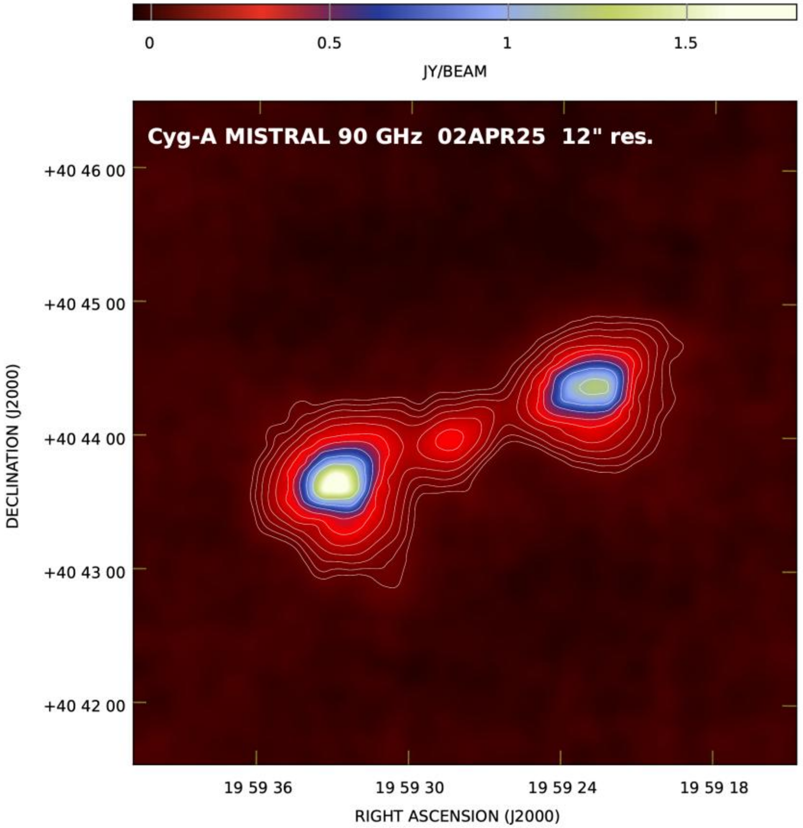
Kinetic Inductance Detectors – MISTRAL @ SRT

MISTRAL: **MI**llimetric **S**ardinia radio **T**elescope **R**eceiver based on **A**rray of **L**umped element KIDs

- MISTRAL is a cryogenic camera that houses ~ 415–pixel array of lumped element kinetic inductance detectors (LEKIDs) operating in the W–band (77–103 GHz) and cooled to about 200 mK.
- MISTRAL+SRT features a high–angular–resolution of 12’’ and a wide (instantaneous) field–of–view (FOV) of 4.2’.

Installation @ SRT: May 2023



<u>Preliminary Results:</u>

- 8 exposures,
- 0.5 hours each (4 hours in total),
- Noise ~ 12 mJ/beam,
- 302 pixel used.

MISTRAL commissioning team,
Murgia et al. in preparation

Technical & Scientific commissioning: 2024/2025

Summary

Space
Balloon-borne
Ground-based

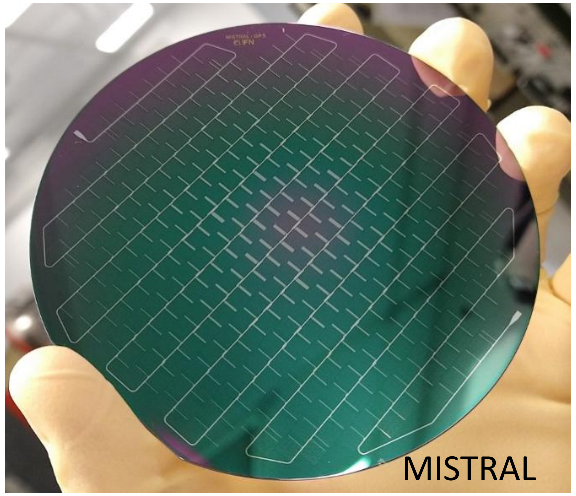
	Design								Measurements		
Experiment	Center Freq [GHz]	Band [GHz]	Array Size diameter [inch]	Pixel size [mm x mm]	Superconducting material	crit. Temp. [K]	oper. Temp [mK]	# of detectors	# of working detectors	time response [micro s]	detector NEP [aW/sqrt(Hz)]
OLIMPO	150	25 (17%)	3	2.4 x 2.4	Al (30 nm)	1.31	280	23	20 (87%)	~ 30	~ 89
	250	90 (36%)	3	2 x 2	Al (30 nm)	1.31	280	39	34 (87%)	~ 30	~ 109
	350	30 (8.5%)	2	1 x 1	Al (30 nm)	1.31	280	25	23 (92%)	~ 30	~ 83
	460	60 (13%)	2	0.78 x 0.78	Al (30 nm)	1.31	280	43	43 (100%)	~ 30	~ 178
MISTRAL	90	26 (29%)	4	3 x 3	Ti-Al (10+30 nm)	0.945	200	415	351 (85%)	~ 15	~ 400
ASI-KIDS	150	25 (17%)	3 (hexagonal)	2.4 x 2.4	Al (25 nm)	1.35	150	37	28 (76%)	~ 40	~ 12
COSMO	150	60 (40%)	4	7 x 7	Al (30 nm)	1.31	150	9	8 (89%)	~ 100	~ 100
	250	90 (36%)	4	7 x 7	Al (30 nm)	1.31	150	9			
OLIMPO-2 (proposal)	150	25 (17%)	3	2.4 x 2.4	Al (30 nm)	1.31	280	55			
	250	90 (36%)	3	2 x 2	Al (30 nm)	1.31	280	151			
	350	30 (8.5%)	2	1 x 1	Al (30 nm)	1.31	280	313	266 (86%)	~ 50	~ 15
	460	60 (13%)	2	0.78 x 0.78	Al (30 nm)	1.31	280	511			

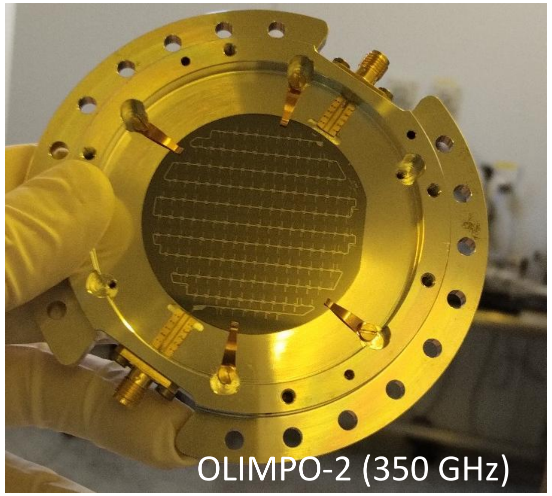
Prototypes

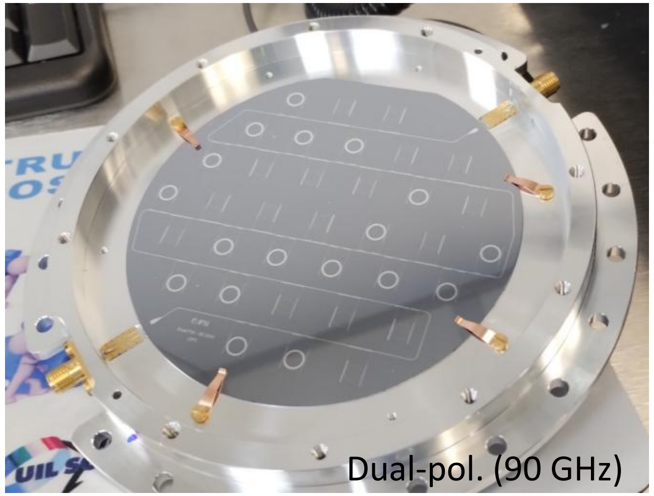
In-flight

Lab. measurements

- **Fabrication**: facilities in the clean room at IFN-CNR;
- **Other (R&D) activities**: polarization-sensitive KIDs, on-chip spectrometer, …


MISTRAL


OLIMPO-2 (350 GHz)


Dual-pol. (90 GHz)

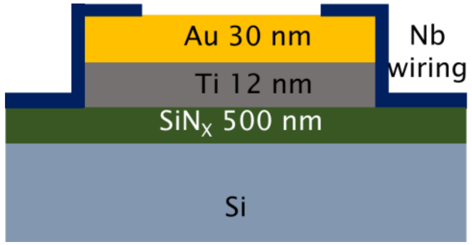
M. Rajteri

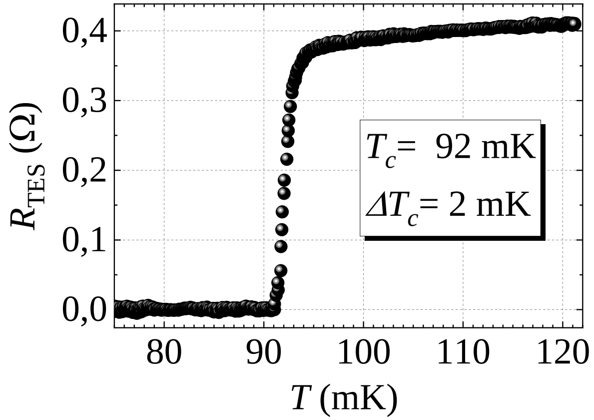
Transition-Edge Sensors: TES

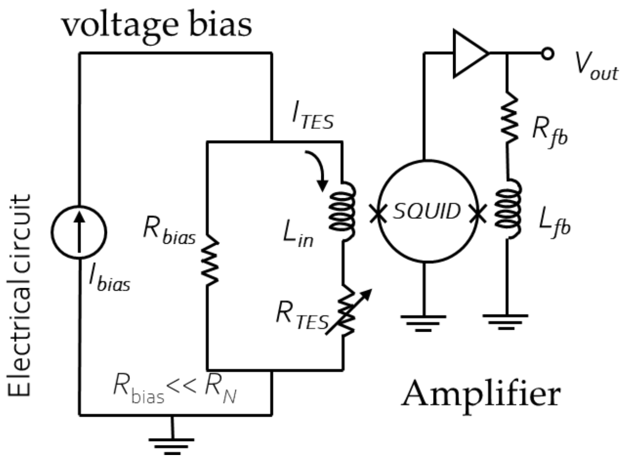
A. Giachero

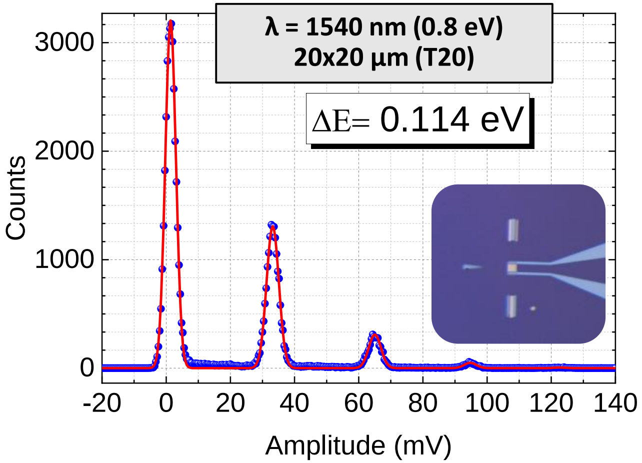
TES: microcalorimeters that use the transition of a superconducting film as a thermometer
➥Intrinsic Energy/ Photon-Number Resolution

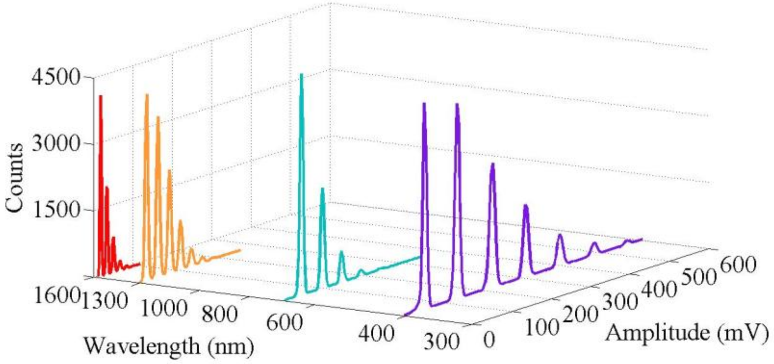
INRiM TiAu optical TES over the last 20 years	
Squared size	1-100 µm
Critical Temperature	50-350 mK
Detection efficency	85% @ 690 nm
Max count rate	1 MHz
Energy range	UV- mid IR
Energy resolution	0.11 eV @ 0.8 eV (1550nm)
Resolving Power	> 7
Number of Pixel	Under development
Dark counts rate	10^{-4} Hz



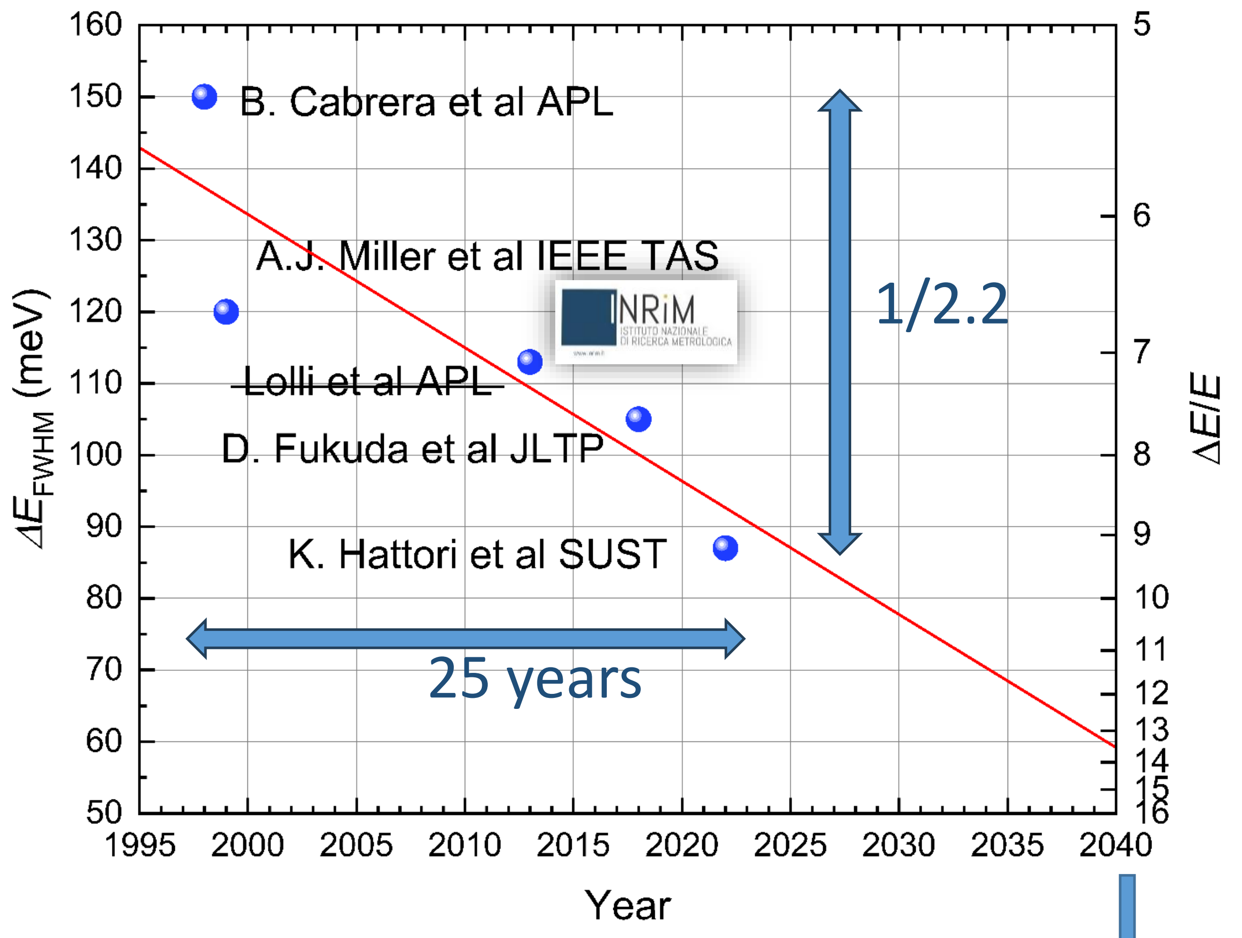


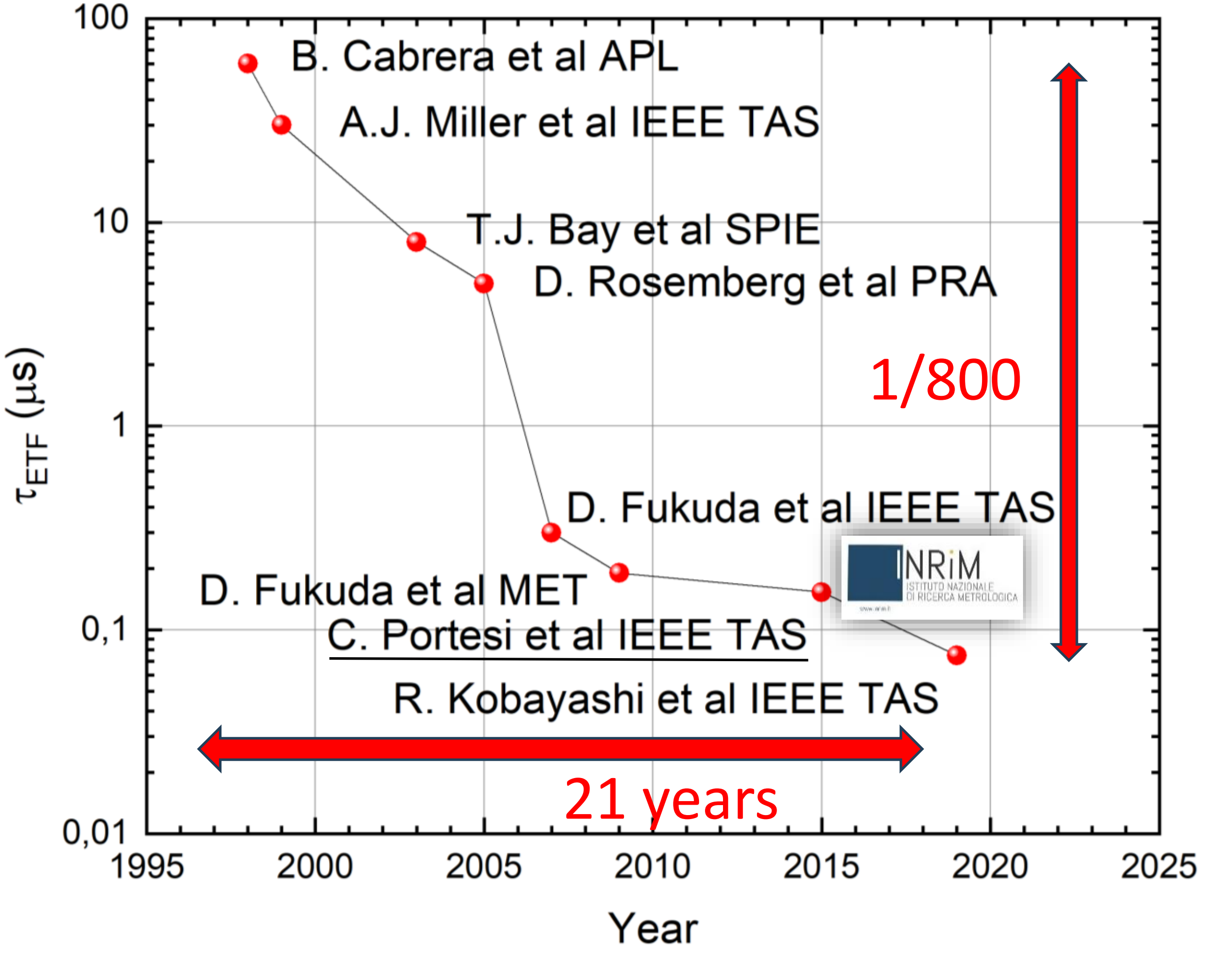






TES parameters review

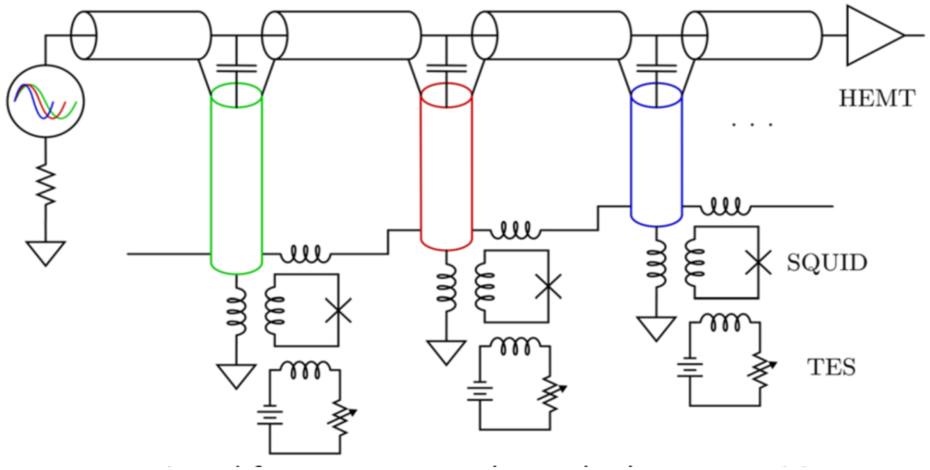




ΔE ⇨ 60 meV *E/ΔE* ⇨13 *@1550nm*

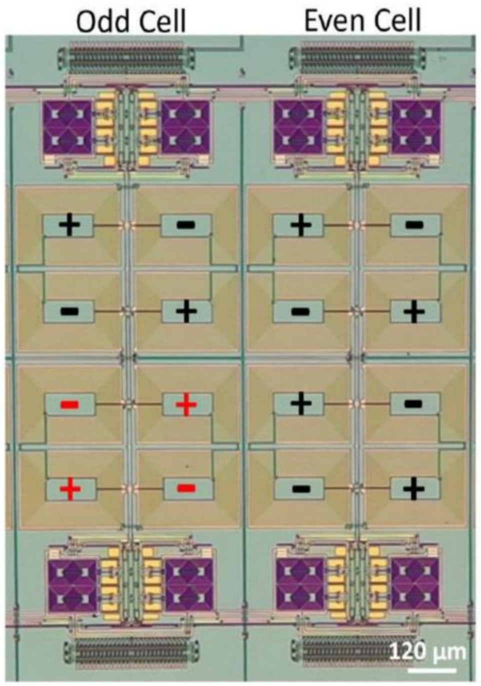
Multiplex readout of TES

- TES array read out:
  Superconducting **Qu**antum **I**nterference **D**evice (SQUID)
  - Time-division multiplexing (TDM)
  - MHz frequency-division multiplexing (FDM)
  - Microwave SQUID multiplexing (μMUX)



Appl. Phys. Lett. 111, 062601 (2017)

- **Drawbacks** for VNIR TES readout
  - Limited bandwidth – TDM/FDM ~10 MHz total bandwidth;
    μMUX flux ramp/SQUID modulation;
  - Complex fabrication, small/uniform junctions, many steps/materials;
  - Large physical footprint, typical readout cell areas > 0.4 mm^2
  - additional structures needed to reduce crosstalk/pickup

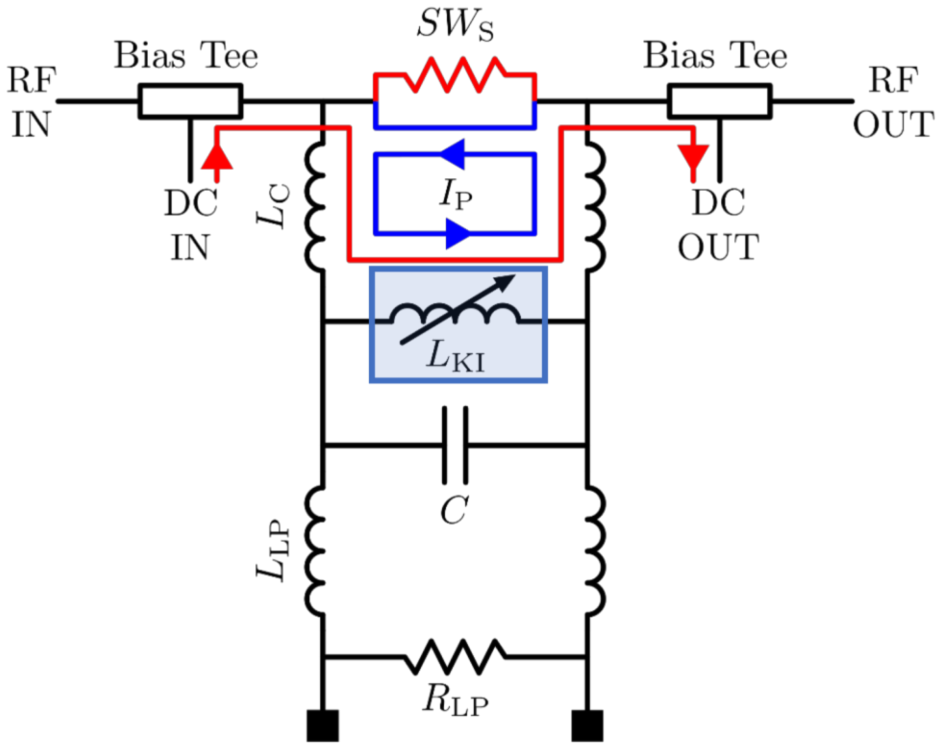


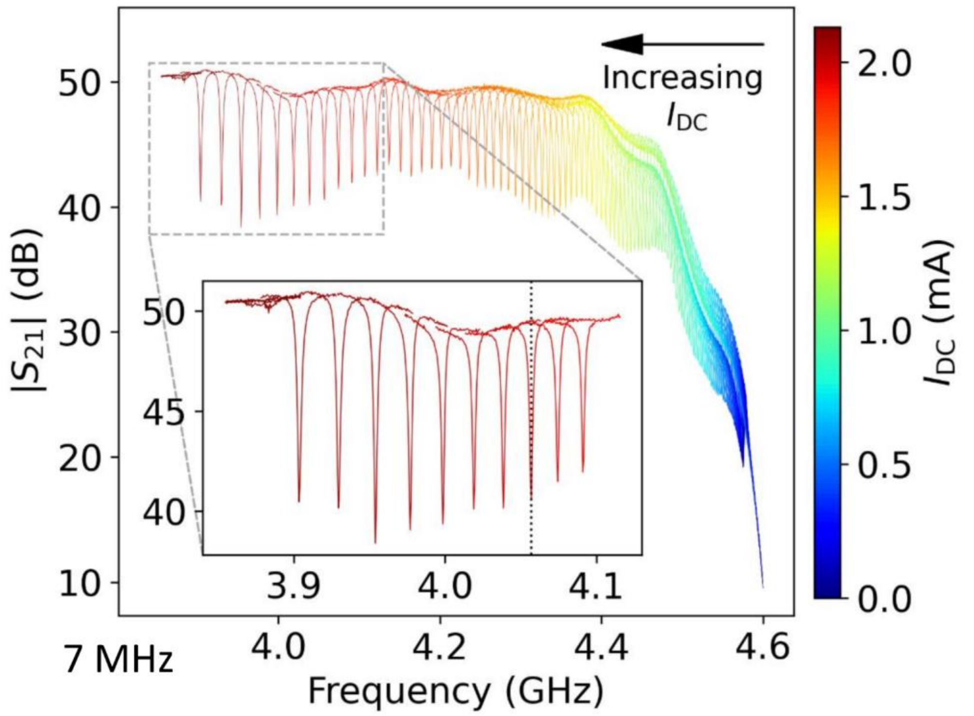
J. Low. Temp. Phys 215, 136–142 (2024)

NIST
University of Colorado Boulder

Kinetic Inductance Current Sensors (KICS)

- Nonlinear current dependence of the kinetic inductance in a superconductor with the current;



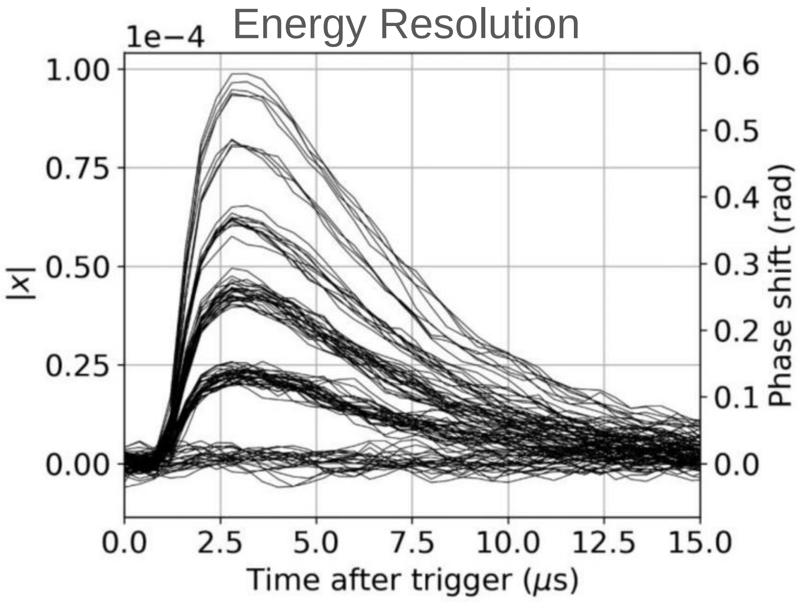


- Possibility to realize a current sensor by monitoring the position of the resonance frequency on a LC resonators;

NIST
University of Colorado Boulder

Kinetic Inductance Current Sensors (KICS)

- High bandwidth, able to measure fast VNIR TES signals
- Relatively simple fabrication → one NbTiN layer;
- Can potentially be made more compact, integrate on same chip as TES array;



Commun Eng 3, 160 (2024)

NIST

University of Colorado Boulder

- First demonstration at NIST with a optical W TES;
- Resolution of 0.137 ± 0.001 at 0.8 eV (1550 nm)

but:

- **Parallel development started in Italy in collaboration with Unimib, FBK and INRIM for funds from INFN and NQSTI;**

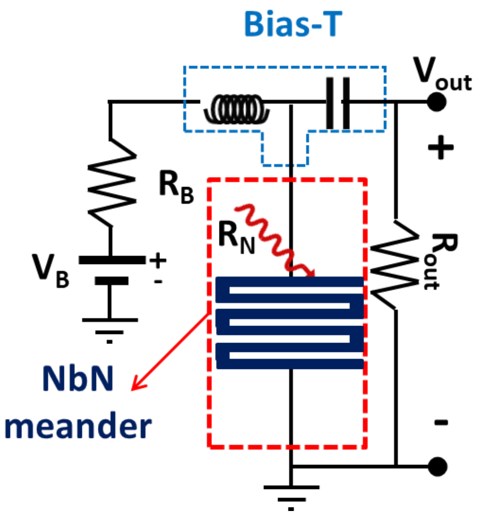
Superconducting nanowire single photon detectors (SNSPD)

Gol'tsman et al., Appl. Phys Lett. 75, 705 (2001)

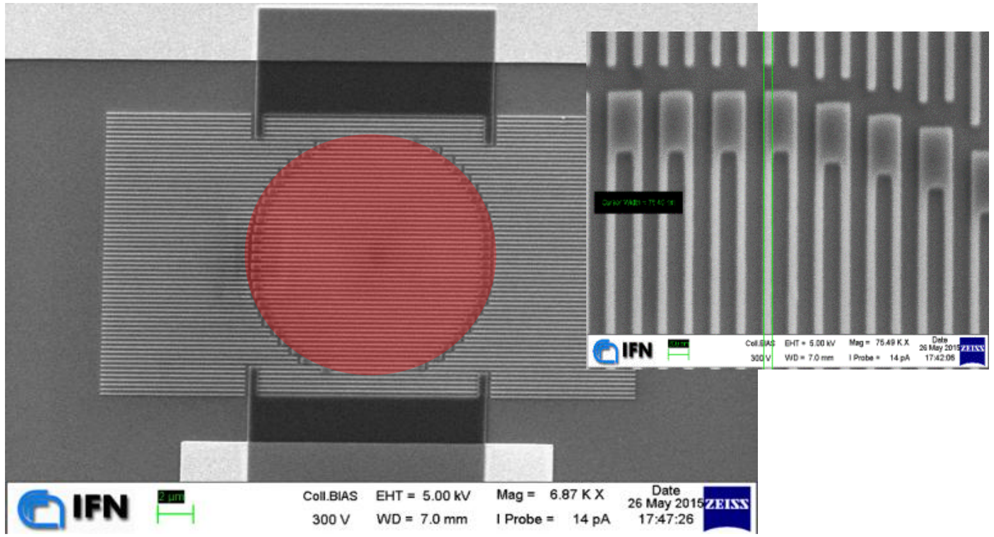
$R_N \sim 1k\Omega$;

$R_{out} = 50\ \Omega$

$V_{out} \approx I_B \times R_{out}$



Spectral Range	Vis up to 30 μm
Max Coun rate	100s MHz
DE	98%
DCR	mHz-Hz
Jitter	10s ps
Temperature	2K (GM)
Area	10s μm



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DIPARTIMENTO DI FISICA ETTORE PANCINI — **Napoli, Università Federico II**

DIPARTIMENTO DI FISICA ETTORE PANCINI
UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II

G. P. Pepe, L. Parlato, CJ Zhang, C. Bruscino, P. Ercolano, M. Peluso

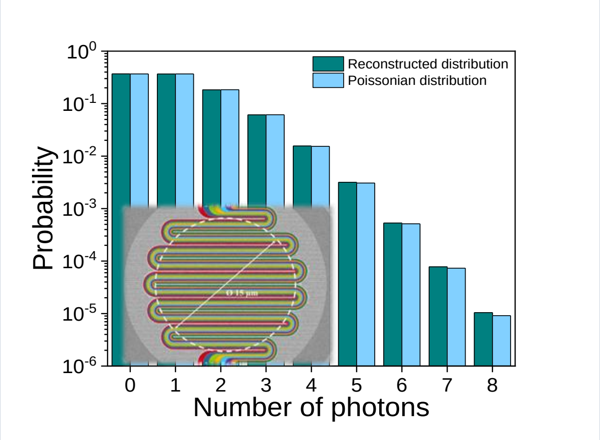
QKD network

Proceedings in SPIE Optics+Optoelectronics (2025)

In collaboration with:

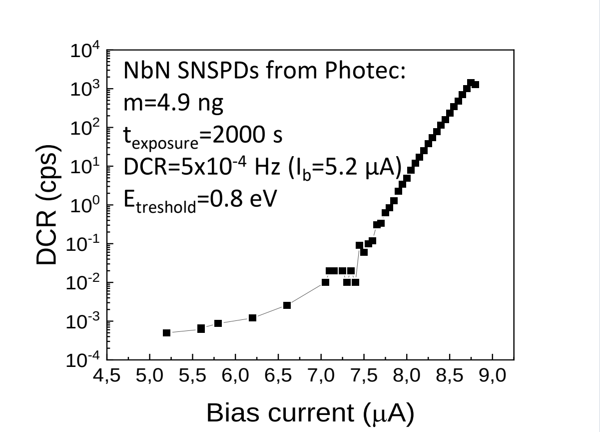
SPIN
CNRINO
ASI Agenzia Spaziale Italiana
SIMIT
MEDITECH COMPETENCE CENTER
seeqc

Quantum optics



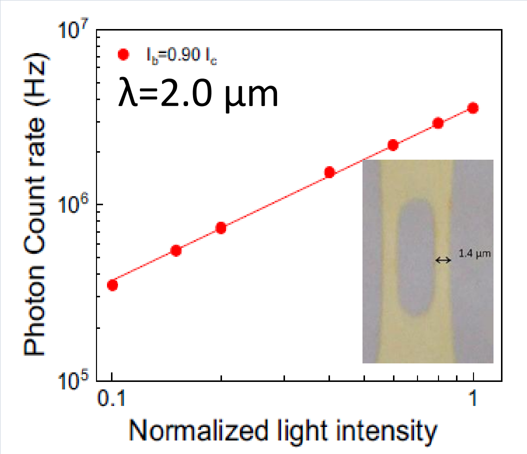
IEEE Trans. Appl. Supercond. 34, 2200105 (2024)

Dark Matter research



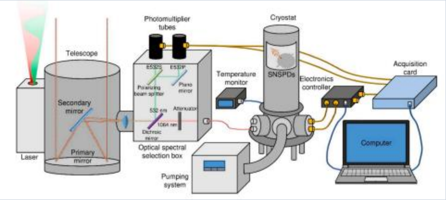
International Workshop on Light Dark Matter @ Accelerators (2025)

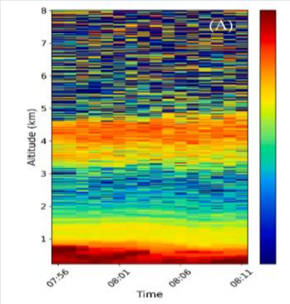
Towards MIR detection



Sci. Rep. 14, 20345 (2024)

LIDAR





Infrared Physics & Technology, 141, 105468 (2024)

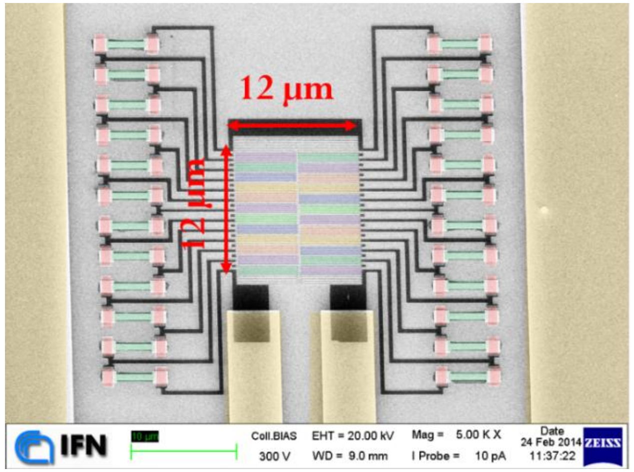
SNSPD multiplexing

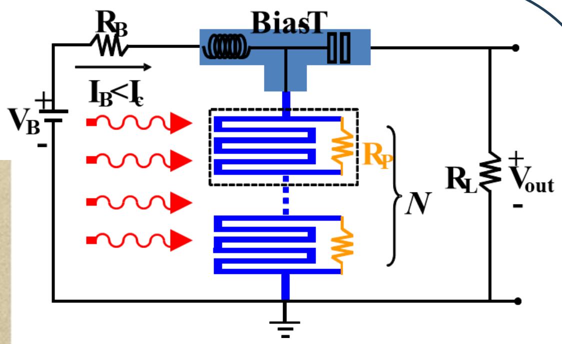
Staff: G. Torrioli, S. Cibella, F. Chiarello, F. Martini, F. Mattioli, A. Gaggero

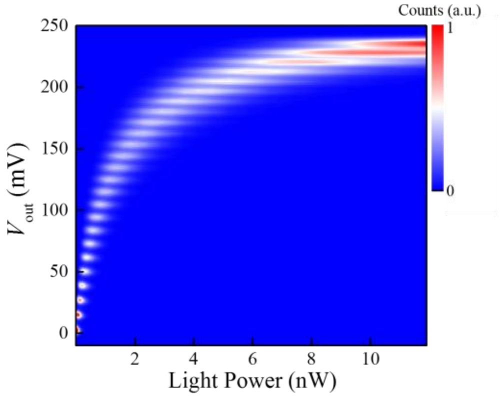
PhD: M. Gambelli, A. Rengarajan

Assegnisti: F. Conidi

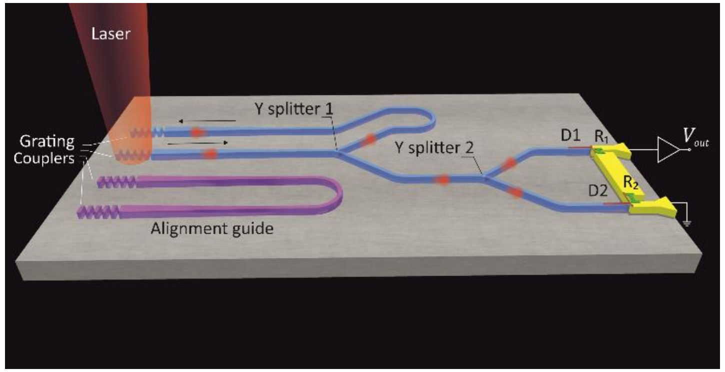
24 PNRD

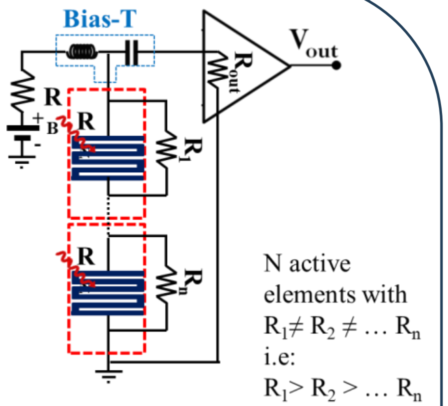




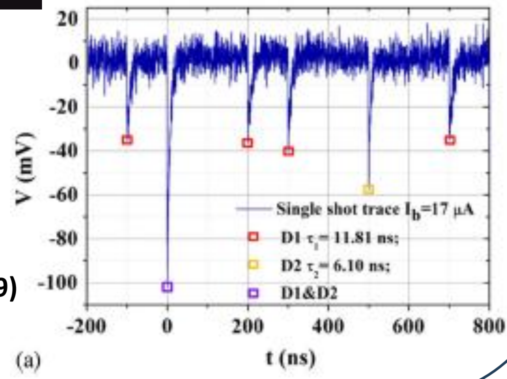


Mattioli et al., Optics Express Vol. 24, Issue 8, pp. 9067-9076 (2016)





N active elements with $R_1 \neq R_2 \neq \ldots R_n$ i.e: $R_1 > R_2 > \ldots R_n$



Gaggero et al., Optica Vol. 6, Issue 6, pp. 823-828 (2019)

TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY

EPFL

Julius-Maximilians-UNIVERSITÄT WÜRZBURG

INFN Tor Vergata

University of Southampton

FONDAZIONE BRUNO KESSLER

UNIVERSITÀ DI TRENTO

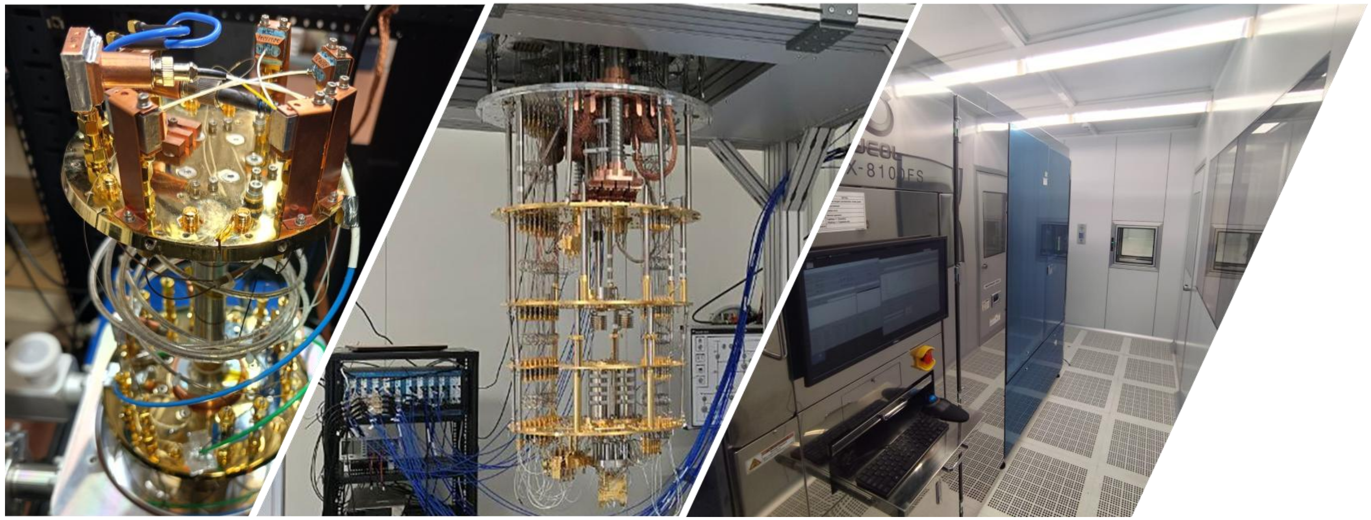
UNIVERSITÀ DI PAVIA

MOSCOW STATE UNIVERSITY OF EDUCATION MSPU

CNR IFN Istituto di Fotonica e Nanotecnologie

Facilities

Uninano fabrication center



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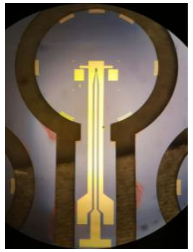
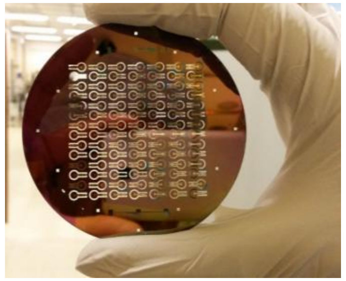
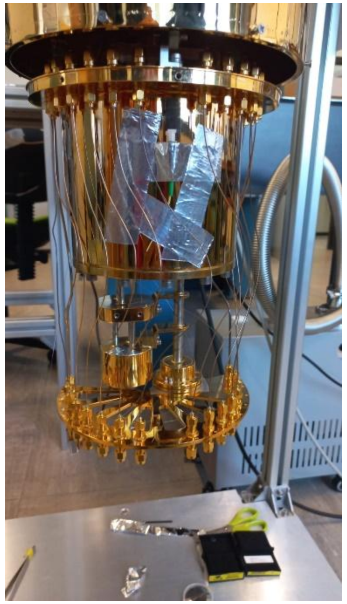
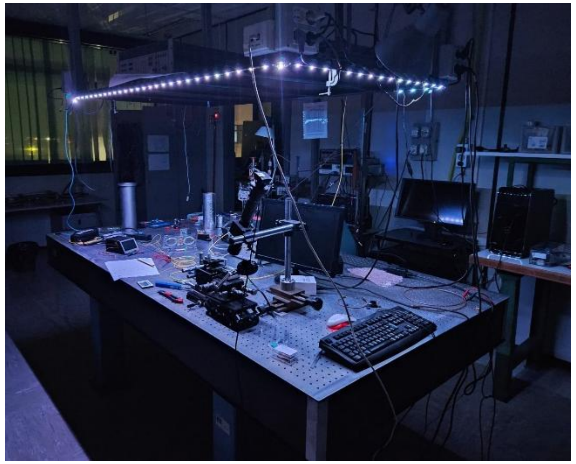
Napoli, Università Federico II

NANOMICROFAB ADVANCED LAB









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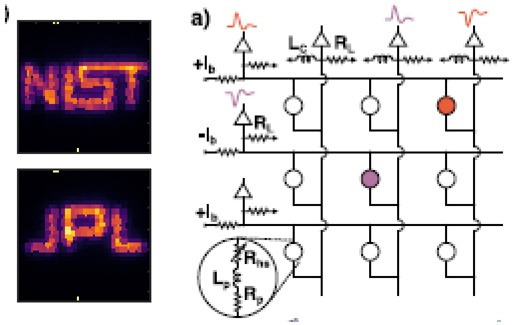
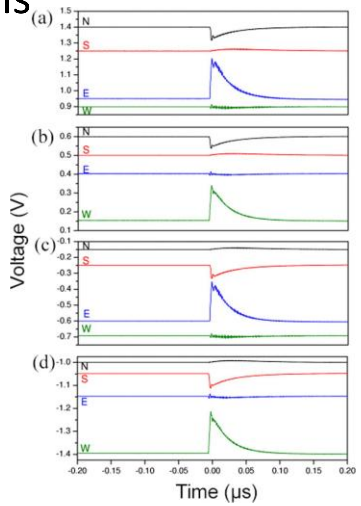
Area territorial di Ricerca CNR di Roma Tor Vergata Rm2

Stato dell'arte

Max 32x32 pixels



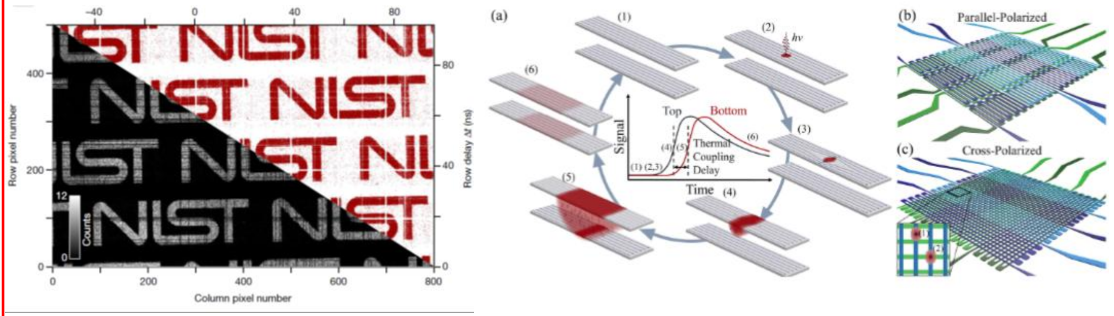
NxN detectors
2N coaxial cables



CR ~10s MHz; jitter ~250ps

Wollman et. Al, Optics Express 27, 35279 (2019)

400K pixels array SNSPD array based on thermally coupled row-column multiplexing architecture



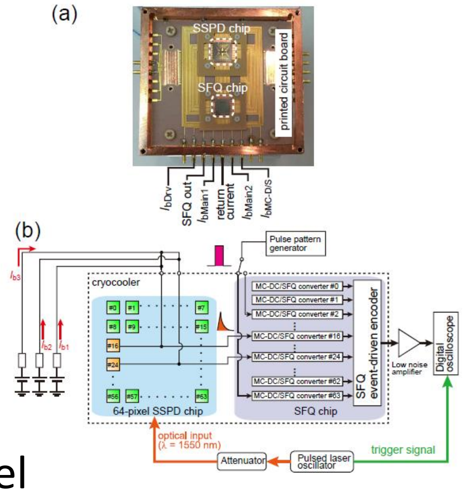
CR ~100 kHz; jitter ~300ps

Oripov et al., Nature 622, 730 (2023)

Yamashita et al.,Opt. Lett., 37, 2982 (2012)

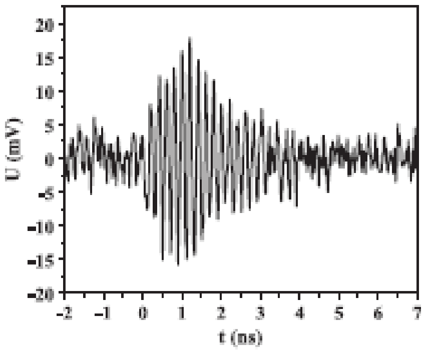
CR ~10s MHz limited by RT electronics;
jitter < 60ps,

Low temperature SFQ readout electronic
BW ~1 GHz

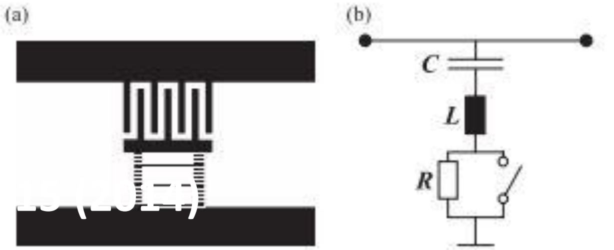


64 pixel

2 coaxial cables: frequency division multiplexing scheme (usually used for KIDs)



16 pixel



CR ~10s-100s MHz limited by RT electronics;
jitter < 60ps

Doerner et al., Ieee Trans. App. Super., 26, (2016)

Conclusions

- Superconducting detectors have proven to be breakthrough technologies in several research fields, and with targeted development, they have the potential to drive a revolution in astronomical and astrophysical instrumentation
- In Italy there is historically a community working on cryogenics and superconducting technologies
- We presented ongoing developments on TES, SNSPDs, and KIDs, that we believe align well with the aims of this workshop. A discussion on the kind of science that INAF considers important to pursue in the post-2040 era can be useful to identify targeted developments to best tailor these technologies to future astronomical needs